The Evolving Roles of the Gemini, Blanco and SOAR Telescopes

REPORT
TO THE AAAC

March 8, 2019

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Executive Summary

The 2015 NRC Report on Optimizing the U.S. Ground-Based and Infrared Astronomy System (OIR System) recommended to strengthen coordination among medium- to large-aperture U.S. telescopes to maximize scientific return in the era of LSST, ALMA and NSF's current priority of multi-messenger astrophysics (MMA). While scientific priorities of the field for the next ten-year period will be defined by the upcoming Decadal Survey, the need for feedback on shorter timescales has been identified to provide guidance on the renewal of the Gemini and SOAR partnerships. The Astronomy and Astrophysics Advisory Committee (AAAC) has been asked to establish an ad hoc subcommittee to consider the evolving roles of the Gemini, Blanco and SOAR Telescopes. The charge letter and information about committee membership are provided in the appendixes. The committee was tasked to consider these questions:

Q1: Assess to which degree each of the telescopes provides critical complementary data for LSST, MMA, time domain and dark energy science
Q2: Provide a short list describing and evaluating highest impact science in other areas given the planned suite of instruments
Q3: Assess whether the current US share in Gemini and SOAR is adequate
Q4: Evaluate modes of multi-facility use
Q5: Point out missing instrumental and adaptive optics capabilities needed for the highest priority programs

The committee reviewed the scientific opportunities afforded by the Gemini, Blanco and SOAR telescopes over the next 5 years and found them to be strong. These facilities are important and valuable assets to the US OIR system. Based on our findings and discussions as detailed in this report, the committee makes the following recommendations.

Exciting scientific opportunities warrant the extension of the Gemini and SOAR agreements. A particularly strong case is using GBS as a coordinated LSST follow-up system. It will rely on facilities being secured and optimized together rather than separately.

Recommendation 1
NSF should renew the Gemini agreement at the current level.

Recommendation 2
NSF should renew the SOAR agreement at the current level.

Recommendation 3
The Gemini, Blanco and SOAR observatories should continue to optimize and coordinate their position for follow-up observations in the LSST era and the MMA program while maintaining a strong PI based program covering a broad range of science.

In order to take full advantage of the scientific opportunities afforded by these telescopes, continuing cooperation among the observatories and coordinated development of the required tools and policies to support an OIR system will be required.

> **Recommendation 4**
> Continue to implement the OIR system related recommendations from the 2015 NRC report and support development of OIR system tools and policies.
>
> > **Recommendation 4a**
> > Engage the community in both process and development.
> > Encourage community contributions to the requirements, interfaces and functionality of software tools like the Astronomical Event Observation Network (AEON), Event Broker (i.e. Antares)/Target and Observation Managers (TOMs). Ensure that all interfaces are open and provide the options to accept inputs from 3rd party (i.e. user) applications and alert streams. Consider organizing a series of workshops on OIR system tools.
> >
> > **Recommendation 4b**
> > Coordinate efforts in software development for OIR system operation (Brokers, TOMs, Schedulers etc) to ensure cooperation, particularly between institutions and with international partners.
> >
> > **Recommendation 4c**
> > Develop the necessary policies including a protocol to avoid duplicate observations and encourage data sharing for Target of Opportunity (ToO) and follow up events. Redundant requests should be merged across the OIR system.
> >
> > **Recommendation 4d**
> > Develop strategies for coordinated, public follow-up of high value transient events such as GW alerts. Establish clear rules for proprietary data rights for target of opportunity observations.
> >
> > **Recommendation 4e**
> > Enable queue observing for Blanco and SOAR while retaining a visitor mode, possibly by adopting the Gemini model.
> >
> > **Recommendation 4f**
> > Implement the time exchange program as was recommended by the 2015 NRC report.

In order to secure the long term future of the Gemini, Blanco and SOAR (GBS) system, a science plan or roadmap is needed for these facilities.

> **Recommendation 5**
> Start development of a coordinated scientific program for GBS for the second half of the next decade (2025 - 2030).
>
> > **Recommendation 5a**
> > Continue to evolve the OIR system and define the role of the GBS system for the era of extremely large telescopes.
> >
> > **Recommendation 5b**
> > Develop an instrumentation concept for the Blanco telescope for the time following the 5-year (public) DECam period, i.e. beyond 2024.
> >
> > **Recommendation 5c**
> > Develop an instrumentation concept for the SOAR telescope that builds SOAR's strength in time domain science and fast and flexible follow-up of targets of opportunities.
> >
> > **Recommendation 5d**
> > Continue to invest in AO capabilities for Gemini North and South including wide-field and high contrast imaging, spectroscopic capabilities, and long and broad wavelength coverage.
> >
> > **Recommendation 5e**
> > While outside the scope set by the charge, we recommend to also include the Mayall telescope at Kitt Peak in this planning exercise as the DESI program will nominally end in 2025.

What instrumentation is missing from the GBS system, and what is driving those? Some of the recommendations below have also been suggested by the Elmegreen and Kavli reports on the future of the OIR system. Recommendation 6 focuses on instrumentation. See Recommendation 4 for the necessary software/system tools. The committee acknowledges that the future capabilities of the OIR system should be determined in the context of the Decadal Survey.

> **Recommendation 6**
> Continue to develop the GBS system, and more broadly the entire US OIR system, by adding capabilities currently lacking from the portfolio.
>
> > **Recommendation 6a**
> > Consider enhancing NIR imaging capabilities: a smaller field of view instrument for targeted follow up observations, e.g with SOAR, and a wide field of view instrument (~¼+ deg^2 like Newfirm), possibly for the Blanco.
> >
> > **Recommendation 6b**
> > Consider adding a high-throughput, low-resolution, single-object, optical-NIR

wavelength spectrograph capabilities with IFUs on 4-8 m class telescope to efficiently observe the broad range of target magnitudes.

Recommendation 6c

Expand support for visitor instruments, for Gemini in particular, to make them available to a larger community.

Recommendation 6d

Establish a joint university-observatory R&D program on instrumentation, detectors and adaptive optics capabilities for the next decade.

Recommendation 6e

A highly-multiplexed, multi object, wide field of view spectrograph on an 8-10 m class telescope in the southern hemisphere remains missing from the US OIR portfolio. The science case for such a facility is very strong, as detailed in many recent studies including the 2015 NRC report and the 2016 Kavli Report on Maximizing Science in the Era of LSST. Explore options with international partners to provide access to such a facility, preferably in the Southern hemisphere for the second half of the next decade, such as access to the Prime Focus Spectrograph (PFS) on Subaru and/or contributing to the Mauna Kea Spectroscopic Explorer (MSE) project at the CFHT site.

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Introduction

In this report we consider the Gemini, Blanco and SOAR telescopes to be three parts of a multi-facility "GBS" system, and develop an assessment of its scientific utility for the first half of the 2020's given the likely priorities of the US astronomical community. The purpose is to provide NSF with timely advice on the renewal of partnership agreements for two of the GBS facilities, and to advise DOE on whether the need (and if so, its priority) for the use of these facilities to enhance Dark Energy investigations.

The committee was established in August 2018 with members selected to cover most of the broad GBS science program. The start date was only a few months before the start of the Gemini partnership renewal process in November 2018 resulting in a compressed timeline that very much defined the approach the committee had to take to address the charge questions. We were not able to solicit broad community input but received information from all three observatories detailing the state of the facilities and the plans for the next five to ten years. The committee had weekly phone meetings, and a one day workshop at NOAO in Tucson, AZ. At the workshop, Prof. Debra Elmegreen reported on the state of the OIR system five years after the NRC report. The three observatory directors were invited, and we heard from members of the AEON and Antares development teams building software components needed for an efficient integrated OIR system. Furthermore, we acknowledge valuable discussions with J. Najita, V. Smith and J. Newman.

Combining the information received with our own expertise resulted in this report which is structured as follows. We begin with an overview of the components of the GBS system and the available instrumentation, introducing the many acronyms used in later sections. We then evaluate current and planned contributions by the GBS telescopes to key science cases ranging from solar system studies to cosmology. This is followed by our review of progress toward an OIR system and associated tools. We conclude with our assessment of the state of the GBS system.

The GBS System

We start this report with a brief summary of current and planned instrumentation and capabilities of the four telescopes in the GBS system. This section will provide some necessary background information for the discussion of the science cases in the following section. This section is based on information obtained from the public observatory web sites with additional details the telescope directors.

Gemini

The US currently holds a 67.3% share in the Gemini Observatory partnership. Discussions to renew the partnership agreement have begun November 2018. With two telescopes, Gemini offers bi-hemisphere access. Gemini-S has strong adaptive optics (AO) instrumentation. Similar capabilities will be developed for Gemini-N thanks to a recent NSF award. Both Gemini telescopes are gearing up for a major transient follow-up program in the LSST era. Gemini-N covers slightly more than half the LSST sky from a location 6 hours west of LSST on Cerro Pachon providing interesting ToO possibilities. Facility instruments supported by the observatory are augmented with PI-built and managed visiting instruments. The suite of instruments provides imaging and spectroscopic capabilities across a wide wavelength range in many cases with AO support.

Gemini-S currently operates these facility instruments:
GMOS - a multi-object, long-slit and IFU spectrograph and imager (0.36 - 0.95 μm)
GSAOI - high resolution, adaptive optics imager (0.9 - 2.4 μm)
GPI - adaptive optics imaging polarimeter/integral field spectrograph (0.9 - 2.4 μm)
FLAMINGOS-2 - long-slit spectrograph and image, multi-object capabilities in the future (1.0 - 2.4 μm)

The Gemini-N facility instruments are
GMOS - a multi-object, long-slit and IFU spectrograph and imager (0.36 - 0.95 μm)
NIRI - a 1 - 5 μm imager
NIFS - a near-IR (0.5 - 2.4 μm), medium resolution (R~5000) integra field spectrometer
GNIRS - a long slit (1 - 5 μm) and cross dispersed spectrograph (0.9 - 2.5 μm), IFU to be added in 2020.

The observatory is considering moving **GPI** to Gemini-N. Three new facility instruments are under development for Gemini-S:
GHOST - a high resolution (R>50,000) optical IFU spectrograph (0.36 - 0.95 μm) with a 7.5 arcmin diameter field of view in standard resolution mode.
SCORPIO - offers simultaneous multi-band imaging (0.4 -2.35 μm) in 8 channels with a 3x3 arcmin^2 field of view and a long-slit broadband spectrograph with R~4,000
IGRINS-2 - a high resolution (R ~ 45,000) long slit spectrograph

A broad range of visiting instruments providing imaging, spectroscopic, and polarimetric capabilities have been commissioned or are being planned and developed for both Gemini-N and Gemini-S. A new instrument under development is **GIRMOS**, a 1 - 2.4 μm adaptive optics spectrograph with deployable IFUs. A new adaptive optics system (GeMS-2) with the **GNAOI** instrument is under constructions for Gemini-N
Software support and reconstruction pipelines are provided by the observatory for most instruments. A new data reduction tool, **DRAGONS**, is almost complete. Gemini supports different observing mode including queue observing. The observatory participates in the AOEN project for system wide transient follow-ups.

Blanco

The main instrument for the Blanco 4m telescope on Cerro Tololo is the Dark Energy Camera **DECam**, a 520 megapixel optical imager with a 3 square degrees field of view. Up to 8 filters can be installed in the instrument at any given time. Also available is **COSMOS**, a medium resolution (R ~ 2200 - 4000) multi-slit spectrograph and imager (10x10 arcmin^2 field of view). A complete image reduction pipeline for DECam is supported and operated by NOAO. The Blanco supports traditional PI based observations with some remote observing capabilities. Participation in the AEON project is planned. The addition of queue observing is under consideration and by 2020 most Blanco time could be dynamically scheduled.

SOAR

The US (NSF/AURA) currently holds a 33% partnership in the SOAR consortium. The current agreement ends at the end of FY-2020.

The most frequently used instrument at SOAR is the **Goodman** spectrograph offering several resolution modes up to R~10,000 covering 0.32 - 0.90 μm with excellent UV/blue throughput. The instrument can also operate as imager with a 7.2 arcmin diameter field of view. **SAMI** is an optical AO imager. SOAR has a ground layer adaptive optics system with laser assistance. The **SIFS** IFU spectrograph with 1300 fibers and different gratings providing resolutions from R~4,000 - 20,000 is in commissioning and the **STELES** Echelle spectrograph (R~40,000 over 0.3 - 0.89 μm) will be available soon. **ARCoIRIS** is a mid-resolution NIR spectrograph (0.8 - 2.47 μm) moving from the Blanco to SOAR.

SOAR offers remote observing support. The addition of queue observing is planned for 2020. SOAR is participating in the AEON project. The frequently used Goodman spectrograph us supported by a data reduction pipeline.

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Science with the GBS System

For decades the Blanco, SOAR and Gemini telescopes have made contributions covering nearly every aspect of astronomy and cosmology. This section is our review of the contributions the GBS system can make to the important science cases for astronomy at the beginning of the next decade. In each case, we start with a very brief introduction to the science, and then describe the impact that the GBS system could have on it. Specifically, on a case by case basis we assess the degree to which each of the telescopes provides critical complementary data for LSST, multi-messenger and time-domain science, and dark energy science, as well as other key investigations enabled by the GBS facilities given the planned instrument complements. Where applicable we point out capabilities currently missing from the GBS portfolio and what external data sets might be needed. This addresses charge questions Q1 and Q2.

Small Bodies

This section discusses small bodies (asteroids, comets, moons) observed in our solar system, both discovery and characterization.

Science

Studying small bodies in our Solar System provides constraints on and insights into planetary formation and migration, related to big questions about how our Solar System formed.

The Large Synoptic Survey Telescope (LSST) will excel at creating large catalogs of small bodies throughout the Solar System, complete with high precision astrometry and photometry in multiple filters (typically, *griz* as most objects will be too faint in *u* and *y* for LSST's standard exposures). The LSST Science Book estimates that LSST will obtain orbits for approximately 100,000 Near Earth Objects (NEOs), 5 million Main Belt Asteroids (MBAs), 300,000 Jovian Trojans, and 20,000 TransNeptunian Objects (TNOs), generally resulting in an order of magnitude increase in size of the known populations. However, even before LSST starts operations, current projects like Catalina Sky Survey, PanSTARRS, ZTF, and independent surveys operating on the Blanco DECam, Subaru HyperSuprimeCam, or CFHT Megacam are generating thousands of new discoveries each year. Surveys such as these can also fill important niches in discovery space even after the start of LSST operations; for example, a survey with a large field of view instrument like DECam could investigate resonant populations in the Kuiper Belt fainter than the limiting magnitude of LSST by observing a smaller area of sky with a more limited cadence but with longer exposures, or search for Earth mini-moons with a faint, high-cadence survey targeted on limited areas of sky.

The orbital parameter distributions in these large catalogs are critical for placing constraints on models of planetary formation and migration, but additional characterization of the population is needed to identify trends in composition and to accurately identify collisional families, as well as to provide additional insights that help detangle the effects of planetary formation from subsequent dynamical and thermal processing over the history of the Solar System. Characterization includes measurements of

- Broad band colors: optical and near-infrared (NIR) colors constrain the rough slope and shape of the reflectance spectra of an object, providing a pointer to its general composition. This can be sufficient to identify some broad compositional trends originating from formation conditions in the protoplanetary nebula and can help identify collisional families.
- Spectra: optical and NIR spectra constrain details of the reflectance spectra of an object, providing more in-depth insight into its chemical composition. Typically low-resolution spectra (R=50-100) are sufficient to taxonomically classify asteroids to their subtypes; high resolution spectra are useful (where possible) to identify composition in more detail. Low resolution spectra provide confirmation of family membership, as well as provide insights on asteroid surface properties such as temperature and grain size, enables

investigation of space weathering, and can identify the presence of hydrated minerals in asteroids.

- Rotation period and shapes: light curve measurements are used to calculate the rotation period and a basic shape model. The rotation period, shape and size of an object can be used to roughly constrain the density and porosity of an object (e.g. whether it is a rubble pile or monolithic body). The distribution of these properties across the population provides insight into their collisional history, particularly in conjunction with the size distribution.
- Spin states: with more photometric measurements over a longer period of time, a full shape model including spin state can be calculated. With this information, the effects of non-symmetric radiation pressure can be quantified and look for subtle effects from planetary formation.
- Binaries: identification of binaries and measurement of their relative orbits (separation, inclination, eccentricity). Binaries are useful for identifying asteroid masses and the distribution of their separations provides insights into the collisional history of a population. Adaptive optics observations can be particularly useful for close separation binaries.
- Activity (outbursts or outgassing): identification of activity and measurement of outburst timing, strength, shape and gas to dust ratios. Adaptive optics observations can be useful for better characterization of the activity, especially at small scales, and narrow band filters are useful for separating gas emission vs reflected light from dust. Characterizing activity provides additional insights into surface properties and chemical composition, particularly subsurface composition that is inaccessible through other means and provides insights into ongoing physical processing occurring on these bodies, through collisions or heating.

As we learn more about the complicated history of our solar system, including planetary migration on scales large (e.g. Nice Model) and small (e.g. migrating Neptune), the additional information from these characterization efforts is crucial to distinguishing between competing models and to provide new avenues for exploration.

An excellent example of the synergy between discovery and characterization efforts can be seen in the Outer Solar System Origins Survey (OSSOS), a large-scale survey program which operated on CFHT, and the Colors of the Outer Solar System Origins Survey (Col-OSSOS), which is operating primarily on Gemini-N. The Outer Solar System Origins Survey (OSSOS) discovered more than 800 TNOs, cataloging these objects with well-understood selection effects and measuring very precise orbits. OSSOS confirmed that there was a clearly defined cold classical Kuiper belt, and defined the range of orbital parameters for this subpopulation as well as others, including resonant and excited TNOs. The Colors of the Outer Solar System Origin Survey (Col-OSSOS) is a complementary survey to measure broad band colors (*g, r, J*, with some *z* coverage) for a well-defined subsample of the OSSOS discoveries. Col-OSSOS has so far measured precise colors for 35 TNOs from the OSSOS sample, finding that there are three general taxonomic groups of TNOs; dynamically excited neutral objects, dynamically excited red objects, and cold classical (red) objects. This suggests that beyond 20 AU, the protoplanetesimal disk was generally compositionally homogeneous with a single transition somewhere between 33-38 AU. Discovering and/or confirming the nature of this transition, linking it with changes in the protoplanetesimal disk that would have influenced Neptune's migration, and understanding the perturbations that drove planetesimals into the excited TNO population are open questions that will require larger sample sizes. Discovering how thermal processing may have affected the surface properties through retention (or loss) of volatiles will require larger sample sizes and likely also more color information (and ideally spectroscopy).

Impact of the GBS System

It is useful to consider the general constraints when observing small bodies in the solar system:

- the objects are small and distant. The majority will fall between $17 < r < 25$, most fainter than 22.
- they rotate. This results in variability, with timescales generally in the range of several hours, but potentially as short as minutes, and amplitudes up to a few magnitudes. Additionally, characterization through colors or spectroscopy must account for this rotation, as different areas of the target are visible at different times.
- they are moving targets, with widely ranging apparent velocities. This implies a loss in SNR as exposure times increase. For the fastest moving objects, exposures longer than a minute can suffer significant trailing losses.
- they are relatively sparse on the sky; at r<24.5, there are about 500 MBAs per square degree on the ecliptic, but this falls rapidly with limiting magnitude, for fields away from the ecliptic, and when considering other populations such as NEOs or TNOs. Once an object's position is predictable within a few or tens of arcseconds, large fields of view or multi-object spectrographs are not necessary.

The details of any given object or group of objects certainly vary within these boundaries, but the conclusion is that large telescopes such as Gemini, SOAR and Blanco are crucial in order to fully sample and, in particular, characterize these small body populations.

Continuing discovery surveys for small bodies is important; LSST will fill the majority of this requirement in the future, but there are target niches around the LSST sample that will be important to fill. DECam on the Blanco telescope is an excellent resource for this purpose; continuing access to DECam or an upgraded equivalent as a large scale survey instrument will have significant impact. Studies of cometary activity, particularly investigations of gas to dust ratios, will be enabled by adding narrow band filters for this camera, and further increase its capabilities.

In terms of characterizing the small body populations, follow-up imaging and spectroscopy for taxonomic classification and measuring physical properties is crucial. This will require imaging in the optical (subsets of *ugriz*, depending on the target and purpose of the observations) and NIR (typically *J* or *H*), as well as low-resolution (R~100) spectroscopy in the optical and NIR (ideally

0.4-2.5 micron). Currently, Gemini instruments such as GMOS and NIRI are important resources for this work, as are the Goodman High Throughput Spectrograph and SOI at SOAR. When available, SCORPIO on Gemini-S in imaging mode will be a fantastic resource; obtaining photometry in multiple bandpasses at the same time allows the measurement of colors without the complications of light curve variations and the measurement of light curves in multiple bands to look for color-dependent variations.

Non-sidereal tracking capabilities are important for imaging and especially spectroscopic follow-up, to enable longer exposures for these faint, moving objects.

What is missing from the GBS System to support this science case?

As discussed in the Chapter 6 of the 2016 Kavli report, a single object, broad wavelength range (0.4-2.5 micron), low-resolution (R~100) spectrograph on Gemini-S (similar to X-Shooter on VLT) would be ideal for characterization of targets from LSST. Currently, the only publicly available equivalent in the NIR is SpeX on the NASA Infrared Telescope facility (IRTF). SCORPIO covers this wavelength range, but only with either a much lower resolution (in photometry mode) or at much higher resolution.

A single object, broad-wavelength, low-resolution, high-throughput spectrograph provides a way to quickly identify absorption features and thus general mineralogical composition. This permits taxonomic classification, family identification, and insights into the composition of the protoplanetary nebula. These measurements are most useful when carried out across well-defined subsamples of the population, thus a low resolution spectrograph is ideal; broad band photometry does not uniquely distinguish between taxonomic types and the objects are generally too faint for high resolution spectroscopy.

How would this science case benefit from a coordinated OIR System?

A coordinated OIR system provides the possibility for routinely coordinating observations at different telescopes, such as obtaining broad band photometry at SOAR for lightcurve measurement over the same time period as low resolution spectroscopy (or broad band photometry in a different bandpass) at Gemini-S.
It would also make it possible to queue time-sensitive observations at whichever telescope is available, such as obtaining active optics imaging of cometary outbursts at either SOAR or with Gemini. Similarly, it allows for greater flexibility in responding to high urgency events, such as a need for rapid turn-around observations of an incoming impactor (e.g. 2008 TC3) or interstellar asteroid (e.g. ‘Oumuamua).

GBS Assessment

Table 1. For each science case, an assessment table is provided to summarize for each telescope what capabilities are used. When applicable, other tools, observations and data are needed are listed as well.

Science Case	**SOAR**	**Blanco**	**Gemini**	**Other Data Needed**	**Tools Needed**
Astrometric followup		DECam			
Broadband colors / lightcurves	Goodman	DECam	GMOS, NIRI, SCORPIO	Mid IR photometry	
Taxonomic classification/ minerology (composition)	Goodman		GMOS, SCORPIO	NASA IRTF	Single object, high throughout, wide wavelength spectrograph
Outburst activity	SAMI		GMOS, GEMS		

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Exoplanets

This section covers the indirect and direct discovery and characterization of planets around other stars (exoplanets). Formation mechanisms for exoplanets is covered in the Star and Planet Formation section.

Science

Exoplanet science is a rapidly evolving field of study that has moved from the first discovery of objects in the late 1990's, through to probing demographics and studying the detailed physical makeup of objects via a variety of specialized techniques over the past two decades.

An excellent report on the current state of the field has recently been published by the NAS, entitled, "Exoplanet Science Strategy" (hereafter ESS). The goals for the field as described in ESS include:

1) "to understand the formation and evolution of planetary systems as products of the process of star formation, and characterize and explain the diversity of planetary system architectures, planetary compositions, and planetary environments produced by these processes."

In support of this first goal, ESS recommends:

A) surveys that augment our current understanding of exoplanet demographics where our understanding is incomplete (lower mass and larger semimajor axis) as well as characterization of the atmospheres and composition of exoplanets,
B) surveys of protoplanetary disks, young planets and mature planetary systems, and
C) Characterizing masses, radii, and atmospheres of a broad sample of planetary systems.

2) “to learn enough about the properties of exoplanets to identify potentially habitable environments and their frequency, and connect these environments to the planetary systems in which they reside.”

In support of this second goal, ESS recommends:
A) studies to understand better the limits to and contributors toward exoplanet habitability, and
B) developing a framework for understanding biosignatures of exoplanetary systems.

Impact of the GBS System

The goals articulated in ESS provide useful context for understanding the role of the Gemini, Blanco, and SOAR telescopes in studying exoplanetary systems. We expect that the GBS system will provide initial reconnaissance of exoplanetary systems, such as the planet around 51 Eri b, found by the Gemini Planet Imager(GPI), as well as supporting observations for exoplanetary surveys such as was done for the Kepler mission and could be carried out for TESS.

Exoplanet Reconnaissance

The Gemini telescopes provide a range of instrumental capabilities suited for exoplanet studies. Primary among these is GPI. GPI is planned to be removed sometime after 2019A, depending on the availability of new instrumentation. The instrument provides a powerful capability for high contrast imaging. The community would benefit from its continued use and the instrument team is exploring its installation on Gemini-N. This arrangement has the potential for finding additional wide-orbit planets, extending the GPIES survey, and providing detailed atmospheric characterization of young northern systems such as HR 8799 and kappa Andromedae.

The committee supports plans by the Gemini Observatory to move the GPI instrument to Gemini-N where it will provide important follow-up capabilities that are currently unavailable in the northern hemisphere. GPI upgrades could allow for studying objects around fainter and later spectral type stars.
Gemini can also carry out characterization of exoplanet atmospheres via transit and phase-resolved spectroscopy. Observations with GNIRS and TEXES can probe the atmospheric constituents and physical parameters of close orbiting systems.

The infrared-optimized aspect of the Gemini telescopes also make it suitable for spectroscopic characterization of the coolest planets and brown dwarfs. GNIRS provides a unique capability to carry out observations in the thermal Infrared (3-5 microns) of nearby interesting objects such as WISE 0855. Further improvements could be made in this area with an upgrade of Gemini’s adaptive optics system (GNAOI) to take advantage of the-infrared performance, such as an adaptive secondary-based system.

DECam, on Blanco, via its large field-of-view and sensitive limiting magnitude could be used to carry out microlensing detection, if it were dedicated to such a survey (to allow for appropriate cadence).

Exoplanet Support Observations

High resolution capabilities on Gemini have allowed for confirmation of planetary candidates found by Kepler and K2, and will allow for similar vetting with TESS. This is a vital support observation role for both Gemini-N and Gemini-S.

High spatial resolution (adaptive optics or speckle imaging) follow-up of Kepler and now TESS objects of interest are critical for distinguishing true exoplanets from blends. These observations can be accomplished with DSSI on Gemini-S and SAM on SOAR, and could be improved with AO upgrades for Gemini-N (GNAOI).

Characterization of stellar systems with and without exoplanets provides important context for interpreting results. Such characterizations are typically done with high spectral resolution spectroscopy. The Goodman spectrograph provides suitable capabilities on SOAR for this area. With the addition of STELES soon on SOAR, this support case is well covered by the GBS system.

How can the GBS system be optimized for this science case?

The enhancement of individual instrumentation capabilities provides the best way to optimize the GBS system. This includes a GPI move and possible upgrade as well as improvements to the adaptive optics capabilities to enable low background observations at 2-5 microns and perhaps longer.

What is missing from the GBS System to support this science case?

Precision radial velocity observations provide important support but is provided separately within the US community via the NASA-supported NEID instrument, hosted at WIYN by NOAO.

High contrast imaging and infrared observations can provide prototype and exploratory type systems for similar systems on the planned Thirty Meter Telescope and Giant Magellan Telescope. While GPI is suitable as a pathfinder for this, use of the instrument as a pathfinder for TMT and/or GMT instrumentation would require a change to its mode of operation. Allowing the instrument to be used for technical experiments in high contrast imaging could benefit TMT/GMT plans in this area.

How would this science case benefit from a coordinated OIR System?

TESS followup could benefit from coordination within the OIR system to apportion targets for high resolution follow-up by brightness. Bright targets could be carried out at SOAR with fainter ones planned for larger aperture follow-up at Gemini.

GBS Assessment

Table 2. For each science case, an assessment table is provided to summarize for each telescope what capabilities are used. When applicable, other tools, observations and data are needed are listed as well.

Science Case	**SOAR**	**Blanco**	**Gemini**	**Other Data Needed**	**Tools Needed**
Wide-Orbit Giant Planet Northern Survey			GPI in North, 100 star survey		Improved WFS capability
Planet Atmospheric Characterization			GPI, GNIRS		Thermal and mid-IR high contrast capability
TESS/Kepler verification	SAM		DSSI,	Precision Radial Velocity Observations	
Transit Spectroscopy			GNIRS/ TEXES		
Host Star Characterization	Goodman, STELES				

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Supernovae, other Transients and Variable Stars

This section discusses the transient sky including explosive star death, star variability, intrinsic or geometric. We consider supernova (SN) physics, fast transients, tidal disruption events, and other variables (including stellar variability). While variables as a whole share common needs from the GBS system, the science case for SN cosmology and SNe Ia are consolidated in their own subsection.

Science

Variable stars

Stellar variability phenomena, although studied for centuries, benefited greatly from the wealth of data generated by modern surveys like Kepler, and emerging fields like asteroseismology increased dramatically our understanding of star lives and evolution. Many phenomena of interest rely on very precise photometric measurement (100ths, or 1000ths of magnitudes) on different time scales, from seconds to years. However, the wealth of photometric observations expected in the LSST era calls for photometric follow up as well as large spectroscopic surveys to match the photometry.

RR Lyrae photometry in J, H and K bands, when combined with B, V, and I band mean magnitudes, can be used to estimate the reddening, metallicity, and distance, which allows low-redshift anchoring of SN Ia cosmology.
Gyrochronology, studies of stars' activity cycles, studies of the magnetic activity, rotation, and flare of stars will largely be conducted on large synoptic photometric surveys samples, but follow up (at moderate resolution R~5000) of a large number of varying stars will be required to estimate the completeness of LSST samples and establish and consolidate the calibration between photometric observables and physical properties (rotation-age and flare rate-age relationships).

The targets of stellar variability surveys will be the galactic bulge and plane, leveraging the southern hemisphere observing facilities, as well as open clusters. The finalization of the LSST observing strategy, particularly the plans for observing the Galactic plane and bulge either in the main survey or in mini-surveys (including deep drilling fields) will determine the details of the requirements for additional and follow-up observations.

The science return of these studies include, other than advances in our understanding in stellar evolution, understanding of the structure and evolution of the Galaxy, leveraging the variability of stars as distance indicators and gyrochronology to date stellar populations, and anchoring cosmological studies at the low redshift end.

Transients

Large synoptic surveys enable the discovery of new classes of unusual and rare transients. The discovery data needs to be supported by follow-up data for detailed classification and physical understanding.

Transients that put a substantial strain on follow-up facilities include fast transients, with which we refer to both transients that are intrinsically short-lived and transients (e.g. PS 10bjp) which show short-lived features (e.g. interacting SN Ia's, SN 2017cbv, and shock breakout in core collapse SNe, SN 2008D).

Blazars are also not well characterized and show variations at multiple time scales, which can be source of contamination in Neutrino based SNe studies (see Multi-Messenger Astronomy section). Fast Radio Bursts (FRB) are another class of recently discovered and as of yet poorly understood rapid transients. These bright radio beacons in the distant Universe, that hold the promise of improving our understanding of both cosmology and fundamental physics, also will require prompt multiwavelength follow up to detect or identify an optical counterpart, and characterize the host galaxy properties. It is not clear that the LSST cadence strategy -yet to be finalized- will be able to support identification or characterization of these rapidly evolving transients. Other optical facilities (e.g. Blanco) could conduct surveys designed specifically for the detection of these intrinsically rare (hence the need for a wide field) but short lived phenomena (hence the need for dense cadence) collecting both multiple data points of photometry and multiple filters, or respond (promptly) to discovery to collect multiband photometric and spectroscopic follow-up data.

Other events that change on longer time scales (Tidal Disruption Events - TDEs, Luminous Blue Variables - LBVs) have more lenient follow-up constraints and do not require immediate follow up response. Nonetheless, the details of these events are poorly constraints, and their intrinsic rarity makes each one of them an important opportunity. Spectroscopic follow up will be required.

Transient science as a whole is intertwined with SN Ia cosmology as cosmological inference is affected by sample purity, which in turn is affected by our knowledge of SN Ia as well as all other supernovae, and possibly other transients, to optimize classification. The large numbers of photometrically discovered SNe lacking spectroscopic confirmation can only be exploited if the systematic uncertainties induced from photometric calculations are understood. A census and characterization of all transient “backgrounds” are essential for photometric SN cosmology analysis.

Type Ia Supernova Cosmology

Type Ia supernovae (SNe Ia) hold scientific interest for two principal reasons. They are bright, precise distance indicators, and they are in and of themselves extreme astronomical phenomenon of interest in their own right.

SNe Ia are standardizable candles. They provide measures of distance and peculiar velocity at the locations in which they occur that can be used to describe the dynamical evolution of the Universe on cosmological scales and the gravitationally-induced motions due to the substructures therein. Applications of SN studies include:

Investigating Dark Energy: LSST and WFIRST will increase by orders of magnitude the numbers of SN Ia discoveries, extend their redshift range, and reduce systematic uncertainties in the Hubble Diagram. SNe Ia play a major role in the community plans to determine the nature of Dark Energy in the next decade.

Improving Measurements of the Hubble Constant: The discrepancy between SN Ia and higher-redshift (BAO, CMB) measures of the Hubble constant could be an indicator of new physics or indicate bias in the population of Cepheid-calibrated supernova. Either way, this motivates high-precision measurements of all very local SNe Ia discovered, as well as studies of the local host-galaxy environment from which historical SNe arose.

A new measure of the Hubble constant is planned using strongly-lensed supernovae discovered in ongoing (ZTF) and future (LSST) surveys; time-delays between the light curves of the multiple images provide the differences in length between the geodesics. This method relies on modeling the lensing galaxy from high-resolution imaging. The requisite data are spectroscopy for classification and source / lens redshifts; high-resolution imaging for time delay monitoring or conventional imaging for systems with wide separations; high-resolution, high-S/N spectra for lens velocity dispersions.

Mapping the local velocity and mass-density fields: The relatively precise peculiar velocities available for low-redshift supernovae, in combination with maps of dark matter structures traced by galaxy surveys, provide measurements of the velocity and mass-density fields. The properties of matter clustering on small scales can be extracted from the maps. The peculiar velocities predicted at the positions of SNe Ia can remove correlated redshift errors in the Hubble diagram, improving both Hubble constant and cosmological parameter determinations.

Testing Gravity: SN Ia peculiar velocity correlations at low redshift can be compared to the expectations from the evolution of CMB fluctuations with General Relativity. Models that predict effectively stronger/weaker gravity predict higher/lower velocities. Gravitational screening can be detected using cross-correlations between the velocity and density fields.

Improving SN Ia distances: An improved understanding of the astrophysics and empirical modeling of SNe Ia are necessary to advance their accuracy as standardizable candles. As mentioned in the previous subsection, the challenge of obtaining distances from a photometric data set (no spectroscopic classification) as anticipated for LSST SNe requires improved characterization of all transients, particularly ones that can masquerade as SNe Ia.

Other SN types and Supernova Physics

Type II supernovae are also being developed as distance indicators. Their hydrogen atmospheres are relatively simple to model as a function of luminosity, whereas constraints on the date of explosion and measurements of the ejecta expansion velocity can determine the size of the expanding photosphere.

SNe are astrophysical phenomena of inherent interest. SNe Ia have long been hypothesized as being the endpoints of the stellar evolution of white dwarfs. However, we still do not know whether they are a result of single or double degenerate systems, nor the mechanism by which two stars interact to become a supernova. Indeed multiple channels may evolve into SNe Ia.

The link between progenitors and explosion is even less clear for other SN types: massive star explosions are difficult to map to progenitors at a specific point of the HR diagram. While in some cases of progenitors have been identified directly with high resolution pre-explosion images, the path to map explosion to progenitors is riddled with degeneracies on the observational side and computational and fundamental issues on the theoretical side.

SNe serve as a natural laboratory to test our theoretical understanding of and computational limits in exploring thermonuclear explosions, hydrodynamics, and radiative transfer. Combining precision observations with theory can provide clues about the Carbon-to-Oxygen ratio and radius of the progenitor; the fused Nickel mass produced; the presence and excitation level of material from the outer layers of the star, the distribution of fusion byproducts, and the geometry of the explosion.

The above science can be enabled by once in a generation very nearby supernovae such as SN 2011fe, as well as the new wealth of objects that will be discovered within hours of explosion (made possible by high-cadence searches) and observed intensively and persistently, where light emerging from close to the progenitor star can be seen.

Impact of the GBS System

GBS spectroscopic capabilities are fundamental to complement synoptic surveys' photometric observations of variable stars. The follow-up requirements include medium resolution large sample spectroscopic observations (enabled by an R~5000 MOS on a >=3m facility) especially in the early phases of LSST to anchor and refine the relationship between photometric observables and physical properties, as well as responsive dense follow-up at higher spectral resolution for flare events, events related to magnetic stars' activity (R~20,000-100,000, requiring a 8+m class telescope. Magnetic star activity benefit not only from high resolution spectroscopy (to study broadening of magnetically sensitive spectral lines) but also from spectro-polarimetry (8+m class telescope). Depending on the details of the finalized LSST strategy, additional photometric surveys may be necessary to characterize time scales that will elude the LSST observations (e.g. with Blanco, or SOAR).

GBS telescopes and facilities are fundamental in post discovery science for transients, and in some cases they could be important primary discovery machines as well (Blanco).

The broad range of redshifts and scientific interests of many transients call for a broad range of telescope resources. While ZTF and LSST will be discovering the bulk of transients (especially supernovae), and establish the variability of stars, niche cadences are planned for searches using the wide-field Blanco DECam. Fast transients require dense photometric follow up to monitor flux and color evolution leading to physical inference. Spectroscopic follow-up of transients, including SNe, and their hosts is obtained by the ZTF SED Machine for bright <19 magnitudes, the AAT 2dF-AAOmega (DESI, 4MOST) for multiplexing at moderate magnitudes, with 8-m class telescopes (e.g. with Gemini GMOS) for the faintest discoveries, and HST (WFIRST) for the NIR.

In some cases (fast transients and young SNIa) immediate follow-up is required, as these transients are maximally distinct while young, stressing the follow-up systems by requiring fast automated response to observing requests. The community is developing software that enable semi-automated follow-up strategy decision and implementation (e.g. the LCO SN-exchange https://supernova.exchange/public/)

The follow-up needs are beyond the capabilities of a single observatory. The recently concluded DES SN search utilized European, Australian, private and national ground- and space-based telescopes, but even using these broad resources DES was only able to obtain classifications and redshifts for a small fraction of their discoveries. GBS can thus play an important role in the current and future resource-limited era.

What is missing from the GBS System to support this science case?

An wide-field MOS at a 3+m class telescope is required for spectroscopic characterization of variable stars (magnetic, rotating, flaring, as well as stellar systems) in dense Galactic fields. Blanco could host a multi-object spectrograph used to obtain redshifts of high-redshift hosts and a fraction of active transients. N.B. 4MOST plans to do this as well, the added benefit of Blanco MOS on getting redshifts of LSST DDF supernova hosts is not expected to be high.

An 8-m class wide-field MOS to classify and redshift transients discovered within the LSST Deep Drilling fields. Such an instrument could increase the number of active SN classifications within these fields reducing by factors the uncertainties in the spectroscopic Hubble diagram. This is critically important because of the high-risk involved in photometric supernova cosmology. MOS could obtain host-galaxy redshifts before discovery and after the transient light has faded away. For a several-square-degree field of view, order of tens active transients would be available per exposure, whereas for host redshifts after several years of discovery would benefit from a factor of ~300 multiplex.

High signal-to-noise classification of faint transients can be achieved with existing spectroscopic capabilities (e.g. GMOS, FLAMINGO-2) but the volume of discovery will put significant strain on these existing facilities. The success of the SED Machine, a dedicated, low resolution IFU spectrograph on the Palomar 60-inch telescope that increases the number of classifications of Intermediate Palomar Transient Factory (iPTF) discoveries by 25-40%, indicates that bulk classification of transients (as well as redshift determination for nearby galaxies and determining effective temperature of stars) is possible with narrow filter instruments instead of spectrographs. This has the potential to greatly alleviate the follow-up stress on the GBS system.

SOAR and the Blanco could host an IFU to obtain spectrophotometry of brighter (low-z) targets. Spectrophotometry provides multiplexed wavelength observations and accurate measurements of spectral features. The IFU allows the subtraction of structured (galaxy) background at the position of the transient using a repeat visit; it is unclear whether this is possible with SOAR's fiber bundles. Given their relatively broad spectral features, low resolution (R<200) is sufficient.

Spectropolarimetry of transients and magnetically active stars requires an 8+m class telescope. This requirement is currently fulfilled by the GPI instrument

Plans for extending the redshift range and rest frame wavelength coverage for SN Ia cosmology include the observation of faint targets in the NIR. This need is best filled from space-based observations and hence should not be addressed by GBS.

How would this science case benefit from a coordinated OIR System?

In order to achieve precision supernova cosmology measurements, data beyond those provided by the photometric surveys is required. While such additional data includes a posteriori follow-up of host galaxies, which is not time critical, data on active transients from non-LSST instruments are required for classification, redshifts, and in some cases precision distances and physical characterization. These are necessary for developing training samples for purely-photometric methods and constructing Hubble diagrams as well as for learning the physical properties of transients.

Due to the limited follow-up resources available, the community needs to efficiently winnow by several orders of magnitude the large numbers of LSST-discovered transients to select the few on which our follow-up resources can be focussed.

At the same time, the efficiency of the winnowing process as a function of observables must be well characterized because knowledge of the sample selection is critical for science analyses. Common science interests often generate overlap in transient follow-up strategy for different teams. Therefore, measures should be taken to prevent the community from collecting redundant data in order to maximize the efficiency in the use of facilities.

Considering all aspects of this problem, the community will need:

- Classifiers capable of providing excellent classification utilizing data from multiple sources (including external data) so that the use of follow-up resources is optimized.
- Timely output of classifiers to inform follow-up observing decisions.
- Characterization of the selection efficiency as a function of observables (necessary for cosmology and rate studies). Systems to distribute transients amongst available telescope resources, taking into account requirements to the developers (both GBS and otherwise) of the standards and infrastructure of OIR system tools.
- Anticipated or real-time observing conditions.
- Rapid reporting of the results of new observations to update future observing decisions.

The community needs to efficiently communicate their needs and requirements for transient follow-up to the scientists developing transient classifiers and brokers (e.g.

AEON/Brokers/TOMs). Some observers may want to assume responsibility for some or all of the above. Other observers may want to specify their target criteria but leave the observatory responsible for interfacing with transient streams and running target-selection and scheduling pipelines.

Specifically, with respect to the GBS system:

- Gemini's rapid ToO capability is essential
- Gemini should preserve and strengthen rapid ToO capabilities in the South to maximize synergy with LSST and improve automatic response and automatic delivery of data.
- Policies about proprietary of data will have to be carefully reviewed as the telescope follows up public discovery of large interest to the community as with the discovery rate increasing dramatically in the LSST age follow up telescopes must at all cost avoid redundant observations, without allowing the competitiveness of proposals to escalate.
- TAC processes should be revised, as putting the potentially overwhelming transient science follow up proposal in competition with static science may generate confusion
- Narrow filters observations (e.g. SED machine on the P60 Palomar telescope) are a potential source of data that enables classification of transients with less impact on observing facilities. The community needs to better understand the potential of these observations in place of spectra for classification. The addition of a very low resolution (R~100) completely automated follow-up instrument should be considered at Blanco and/or SOAR.
- SOAR should play the role as the nimble adaptable component of the GBS system, with a configurable instrumentation suite that satisfies community needs, and integration in the AEON project.
- The whole GBS system (and beyond), and its ability to identify and follow-up EM counterparts to MM events, would benefit from the time domain infrastructure being planned for the US community -- telescope automation, event brokers, telescope observation managers, data reduction pipelines, etc operating as a coordinated system. Care should be taken in planning for the specific needs of MMA here, and should not be a copy of infrastructure appropriate for supernovae, for instance.

GBS Assessment

SOAR (Goodman) and the Blanco (COSMOS) provide the capability for single (few)-object spectroscopy. These can obtain classification and redshifts for low-redshift supernovae and rare transients, whose low surface density does not benefit from multiplexing.

The Blanco (DECam) will be used to execute high-cadence searches (not planned by LSST) that discover transients promptly after explosion. DECam can supplement LSST cadencing when needed.

Gemini single-object spectroscopy (GMOS) has and will continue to obtain classification and redshifts of high-redshift supernovae and transients.

SOAR (SAMI) and Gemini (GEMS) provide AO imaging. These can be used for the mass modeling of strong gravitational lenses, and measuring the light curves of resolved lensed supernova images. Supernovae are point sources, so AO has the potential of providing high signal-to-noise photometry,

Gemini has a range of NIR spectrographs and imagers (e.g. Scorpio) that expand the SN-frame wavelengths to which we have access. Type Ia supernovae appear to be more precise standard candles at infrared wavelengths relative to the optical.

SOAR has a broad instrumental suite at the Nasmyth focus, which allows for fast instrument changes. This capability enables quick and flexible response.

Gemini NIR AO, OH-suppression could extend the redshift reach of ground-based observatories. Continued research into instrumental solutions (e.g. optical ring resonators, fiber Bragg gratings) is encouraged.

Table 3. For each science case, an assessment table is provided to summarize for each telescope what capabilities are used. When applicable, other tools, observations and data are needed are listed as well.

Science Case	**SOAR**	**Blanco**	**Gemini**	**Other Data Needed**	**Tools Needed**

SN Ia Cosmology: Hubble diagram; high redshift		WF imager (DECam) to supplement search imaging	Single-object spectroscopy: classification, redshifts of high-redshift supernova. NIR. SCORPIO OH suppression opens NIR wavelengths to extend redshift depth	High S/N NIR (space) Wide-field MOS on 10-m class telescope	Broker; Resource allocation and scheduler; Automated fast reduction and results sharing; Coordination with other institutional resources
SN Ia Cosmology: Peculiar Velocity; low redshift	Single-object spectroscopy: classification and redshifts	Single-object spectroscopy; classification and redshifts Spectro - photometry [R>75, optical-NIR)		Wide field MOS spectroscopy with DESI-like spectrograph: hosts, active transients	IFU spectrophotometry
SN Ia Cosmology: Strongly Lensed SNe	AO photometry: light curves of otherwise resolved images	WF imager: light curves for precise timing	Single-object spectroscopy: classification, redshifts of faint SNe and lenses High resolution AO imaging for mass modeling for strong lensing		
SN Ia Science	Broad instrumental suite with the flexibility of quick instrument changes	WF imager: high-cadence searches	Single-object spectroscopy: classification, redshifts of faint SNe SCORPIO		
Non-Ia SNe and fast transients	Single-object spectroscopy: classification and redshifts	DECam photometric follow up Wide field MOS spectroscopy (COSMOS)	Spectroscopy (GMOS, SCORPIO) Spectro-polarimetry (GPI)	(Low-resolution) spectro-photometry High S/N NIR observations Multiwavelen	Broker; Resource allocation and scheduler; Automated fast reduction and results

			NIR imaging (SCORPIO)	gth photometry and spectroscopy across EM spectrum	sharing; Coordination with other institutional resources Wide field MOS on 3m+ class telescope IFU to obtain spectrophotometry of brighter (low-z) targets.
Stellar variability (magnetic, rotating, flaring, as well as stellar systems,pulsating variables, eclipsing binaries)		DECam, Wide field MOS spectroscopy (COSMOS)	NIR imaging (SCORPIO) GMOS (high resolution spectra on ensamples and single objects as well)	GAIA distances and astrometry GAIA RVs for bright targets Kepler, TESS and Plato data for calibration	wide-field MOS on a 3+m telescope (R~5000) for stellar rotation + activity / (R~2000) for stellar flares
planet transits/microlensing	AO/Speckle imaging OSIRIS NIR imaging	DECam, COSMOS	GNIRS/GMOS		
Astro seismology			GMOS/GNIRS mostly on single objects	Kepler, TESS and Plato GAIA	wide-field MOS at a 3+m telescope (R~5000) for stellar rotation and activity

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Multi-Messenger Astronomy

Multi-Messenger Astronomy is an emerging, inherently multidisciplinary field that combines fast-reaction transient astronomy with our nascent ability to detect gravitational waves (GWs) from compact binary mergers, as well as high energy neutrinos from celestial objects. Each ‘messenger’ provides a complementary view and lends physical insight that cannot be gleaned from the use of a single dataset. For instance, while GWs provide information such as the exact merger time, chirp mass of the components and the rough sky location of a neutron star binary, electromagnetic observations can provide an accurate sky position (<1”), merger product information (e.g. outflow velocities and heavy element nucleosynthesis yields) and other astrophysical context (e.g. correlation with star formation/stellar populations), among other attributes.   Both fast-reaction and sustained optical-NIR observations of GW and neutrino events will have a huge impact on the emerging field of MMA (in concert with other electromagnetic data spanning the gamma-ray to radio regime), and here we discuss the role that the GBS system can play through the early 2020’s.

Science

Here is a brief assessment of the Multi-Messenger landscape between now and the early 2020's:

Gravitational Waves:
The so-called Advanced Detectors (LIGO+Virgo) are scheduled to begin their third observing run (O3) in April 2019, which will last approximately one year. For O3, LIGO will be sensitive to neutron star - neutron star mergers (NS-NS) out to ~120 Mpc, and binary black hole mergers (BBH) out to ~1 Gpc; Virgo will be sensitive to NS-NS mergers out to ~80 Mpc, and BBH mergers out to ~800 Mpc. These numbers are dependent on the mass of the binary, inclination of the event etc, but give a reasonable estimate of the expected sensitivity. The detector network will also be sensitive to BH-NS binaries, which should also produce electromagnetic counterparts. Broadly speaking, three detector events (i.e. the two LIGO detectors plus Virgo) will have sky localizations of ~10-100 deg^2. Those events only detected by the two LIGO detectors will likely have much larger sky localizations.

After the third observing run of the Advanced Detectors, a break in operations for upgrades will be followed by another run, which will be even more sensitive than that for O3. It is also likely that a fourth detector will be in operation, the Japanese KAGRA detector, which will also be sensitive to NS-NS mergers out to ~100 Mpc. There is no set date for the start of this ultimate design sensitivity run, and there are plans for further improvement to the detectors beyond this horizon.

For the purposes of this document, we will discuss the GBS system’s role in a “LIGO+Virgo

O3”-like scenario, where NS binaries will be detectable out to <150 Mpc, and the sky localizations will be ~10-100 deg^2 in the best instances, although two detector events will still have much larger search regions. In this scenario, the GBS telescopes have a large role to play in GW follow-up observations.

Neutrinos:

The primary neutrino facility that will be issuing alerts for electromagnetic follow-up over the next ~5 years is IceCube. There are several known and viable sources of astrophysical neutrinos, including active galactic nuclei/blazars, core collapse supernovae and potentially as yet undetected exotic transient events. Understanding this mix of neutrino source populations, and the physics of the engines themselves, will be a fundamental goal for the time period covered by this report.

Multi-messenger neutrino astrophysics recently received a boost with the case of IceCube-170922A, and its likely gamma-ray blazar counterpart, TXS 0506+056. TXS 0506+056 was quite bright (V~14.5 mag) and was found to brighten by ~0.5 mag in the month prior to the neutrino event, emphasizing the continuing need for nearly all-sky monitoring of the sky (although this is beyond the scope of the GBS system). Only a fraction of neutrino events are likely to be associated with blazars, and so the continued search for counterparts will be vital for this field.

As an aside, if there is a Galactic supernova in the next few years, it will likely be detected via MeV neutrinos (IceCube is sensitive to TeV-PeV neutrinos), and obviously the whole astronomical community will pursue the event -- nonetheless, we refrain from discussing a Galactic supernova further in this section.

Neutrinos point back to their source, and IceCube thus provides relatively good sky localizations, of order ~0.5--1 deg^2 for track events. These sky localizations are well-matched to Blanco+DECam in particular, and programs are already in place to image the fields of IceCube alerts to search for variable and transient events. This and similar programs should continue in the years to come in order to build a sample of astrophysical sources associated with neutrino events.

Cosmic Rays:

There is not likely to be any cosmic ray facility that issues multi-messenger alerts during the time frame covered by this document. In general, the arrival time of cosmic rays is affected by magnetic fields, and it is difficult to trace back a given event with another ‘messenger’.

General Observational Strategy and Needs

Rapid and sustained optical/NIR observations are needed to maximize science from multi-messenger astrophysics. Generally, observations will take place in two phases:

a) **Search, vetting and discovery phase** where the electromagnetic counterpart will be hunted down and vetted. For neutrino alerts, the search will be within ~1 deg^2, but for gravitational wave alerts it can be 10--100s deg^2 or more for poorly localized events. There are a couple of ways of undertaking these wide-field searches, but one straightforward way is to tile the bulk of the localization region with a wide-field imager (i.e. DECam). Also necessary in this phase is rapid spectroscopic vetting of (possibly) several candidates (Candidate A is a supernova; Candidate B looks like an AGN; Candidate C is consistent with a kilonova, etc). This whole 'search' phase would benefit from clear communication channels between observers, and a broker-like system that puts the localization region in context and broadcasts new observations as they come in.

b) **Detailed Study Phase.** Once a counterpart to a multi-messenger event is clearly identified, an intense study phase will be necessary to gain physical insight into the event.

Here we focus on the kilonova counterparts to GW events, and use more specifically the kilonova counterpart to GW170817 as an example, as this is likely to be among the most demanding scenarios envisioned in terms of the need for rapid response, a dynamic observational strategy and sustained observational cadence. Neutrino-related events may have other observational demands (i.e. long term variability studies of neutrino-emitting blazars) which will be suitable for queue-scheduled observations.

The GW170817 kilonova had a ‘blue’, short lived (few days) component which peaked in the optical and a ‘red’ longer lived (still only 1-2 weeks) component which peaked at wavelengths near 1 micron. The origin of the blue and red kilonova components is still under debate, but it is thought that it is due to viewing geometry, where the blue emission was from the polar regions of the merger and the red emission from a disk. Thus, for any given kilonova, one may expect blue and/or red emission, which can be used to constrain the geometry of the system. Therefore, to properly understand such events, one needs both optical and near-infrared imaging and spectroscopy. The preferred cadence would be daily data acquisition or better for well-studied events. Since kilonova velocities are ~0.1c or more, spectral features will be very broad, but evident; low resolution spectroscopy is sufficient. Many events will be too faint and distant for spectroscopic follow-up from telescopes smaller than 8-m, but that will not always be the case -- many events may benefit from having 8-m class telescopes focusing on spectroscopic follow-up, with 4-m class telescopes concentrating on broadband imaging. This instance would be tailor-made for a GBS ‘system’ that coordinates observations between the 4-m (i.e. SOAR & Blanco) and 8-m (Gemini) telescopes.

As MMA events can have observational signatures throughout the electromagnetic spectrum, spanning gamma-rays to the radio, it may be advantageous to have *coordinated observations* at specific epochs. These may be a scheduling challenge, but it is another good reason to optimize the GBS system for rapid and sustained time domain follow-up, communicating not only with other optical/NIR facilities, but across the electromagnetic spectrum.

The rapid evolution of kilonovae also brings up issues of automated data pipelines, schedulers and proprietary rights. In order to maximize the science yield of a given event, it is essential to have automated data analysis tools that can guide the observations -- if a kilonova evolves from blue to red in a matter of days, the observations should move from the optical to NIR in concert. Automated data pipelines will give reliable real-time results that can then feed back into the next observation request, which can be implemented by a flexible scheduling system. In such an automated system, it may be challenging to assign proprietary data rights to any given image or spectrum, or to choose between different observational programs trying to study the same MMA event. When there are sets of observations that may benefit a large community -- such as a DECam program dedicated to the 'search' phase of multi-messenger follow-up -- a public program should be considered.

Impact of the GBS System

As discussed in the previous section, both a 'search and discovery' phase followed by an 'intensive study' phase of the electromagnetic counterpart is necessary to reap the science goals of the new MMA era. The GBS system can accomplish both of these tasks. First, in the 'search and discovery' phase, Blanco+DECam is unsurpassed for doing the wide field searches which may be necessary for GW events, and this was demonstrated with the first counterpart discovery, GW170817. Another possibility is to do a pointed galaxy search in the near-infrared (for e.g. a pure red kilonova with very little optical flux), with an instrument like Gemini+FLAMINGOS-2, as was done to a limited extent for GW170817. If purely red kilonovae are relatively common, it would be advantageous to have wide-field NIR imaging capabilities in the GBS system (e.g. with a field of view of 1x1 deg^2 or larger); such instrumentation would clearly be very useful for other science cases.

Once the search has identified candidate electromagnetic counterparts, they will need to be spectroscopically vetted very quickly, and the information on the candidates must be quickly collated and disseminated to the community so that the best possible data sets can be gathered. For the spectroscopic vetting, Gemini is positioned well with its rapid target of opportunity program; SOAR can play a similar role for brighter candidates. For communication and context of the GW localization region, and the collation of candidate vetting results, a system like the ANTARES/AEON system would be ideal, although this mode is not envisioned in the current system -- we recommend that it be implemented.

Once a counterpart is confidently identified, an intense optical and NIR imaging and spectroscopy campaign must begin, and must have a high cadence (at least daily). Here again, Gemini+SOAR are well equipped. For nearby events, SOAR+Goodman can get spectra. More typically (perhaps), the twin Gemini telescopes will provide the necessary optical+NIR spectroscopy. In such instances, SOAR can provide the crucial broadband imaging; one reason it is important for SOAR to have a good NIR imager. At late times, Gemini can be used for imaging purposes to capture the fading light of the kilonova.

As alluded to earlier, there would be advantages to operating GBS as a 'system' with a set of automated data reduction tools and coordinated, flexible scheduling -- fewer 'redundant' observations would be taken, and the 'right' telescope+instrument would be assigned for a target of a given brightness and spectral energy distribution. The GBS telescopes should aggressively pursue these essential time domain era tools.

What is missing from the GBS System to support this science case?

The GBS system is in good shape, but there are some important capabilities lacking from the portfolio. OIR system aspects are discussed in the following section.

A capable near infrared imager at SOAR.
While Gemini has a capable NIR instrument in both hemispheres with both imaging and spectroscopic capabilities, SOAR is lacking in this area. As discussed above, one can easily imagine a ‘red’ kilonova, which requires an intense NIR campaign, where Gemini focuses on spectroscopic follow-up and SOAR provided the accompanying imaging. Given the f-ratio of SOAR, we understand this instrument would necessarily have a narrow field of view (i.e. several arcmin on a side), and would not fulfill any needed NIR ‘search and discovery’’. Nonetheless, a capable NIR imager on SOAR would be valuable for kilonova (and other transient) light curves.

Longer Term: Consider a wide-field NIR imager at the Blanco
There may be circumstances that demand a wide-field NIR capability for searching for the counterpart to multi-messenger events (e.g. a purely ‘red kilonova’), and this capability is not available in the GBS system. Such an instrument would be well-placed at the Blanco, given its ability to do wide-field imaging and current lack of bright time instruments. This is one path forward for Blanco broadening its useful instrument suite that would be in high demand during the LSST era, although we understand that this is a significant undertaking.

How would this science case benefit from a coordinated OIR System?

The discussion of the MMA science case clearly shows the benefits of a coordinated GBS/OIR system, which we highlight again in the bullets below. We emphasize the significant software infrastructure and policy framework necessary for such a system to work -- from automated data reduction pipelines and flexible, coordinated scheduling software to event brokers that can handle multi-messenger events to proprietary data rights.

- Increasing the speed of the ‘search and discovery’ phase of identifying the counterpart to a multi-messenger event. Once candidate counterparts are found by, e.g. Blanco+DECam, they will need to be vetted spectroscopically. A ‘system’ that can directly send DECam targets to Gemini or elsewhere for vetting would shorten the window between discovery and science.
- Coordinated observations of MMA events will allow for observing efficiency gains -- for instance, spectroscopic observations can be the focus of Gemini while concurrent imaging is obtained at SOAR. Without coordination, there will likely be duplication of effort.

Specifically, we recommend these steps:

Expand the ANTARES/AEON system for MMA alerts.
Transient brokers and observation managers such as the nascent ANTARES/AEON system will play an essential role in the coming era of time domain astronomy. The current ANTARES/AEON system plan seems geared towards transients which are precisely localized (i.e. supernovae), while electromagnetic counterparts to multi-messenger events are initially poorly localized (and may be hundreds of square degrees for gravitational wave events). If the ANTARES/AEON system could provide context to multi-messenger localization regions (i.e. galaxies at the correct distance within the localization, known variable and transients in the localization) in real time, this would be an invaluable service to the community. Additionally, if ANTARES/AEON ingested the real time observations reported by teams as they search for an electromagnetic counterpart, it will avoid duplication of effort and ultimately lead to counterpart discovery on a faster timescale. We encourage ANTARES/AEON to take input from the community if such an expansion is undertaken.

A public search for MMA counterparts with Blanco+DECam.
DECam is naturally suited for tiling and searching the large gravitational wave localization regions that will still be common in the years ahead. This is similarly true for neutrino alerts, although the areas of the sky that need to be tiled are significantly less in this case. As the entire community may rely on DECam for GW events in the South, in particular, we encourage a public program that tiles localizations regions and provides data products in real time so that any team can search for electromagnetic counterparts. We encourage public input and cooperation among all the stakeholders if such a 'public' search program is implemented.

GBS Assessment

Table 4. For each science case, an assessment table is provided to summarize for each telescope what capabilities are used. When applicable, other tools, observations and data are needed are listed as well.

Science Case	**SOAR**	**Blanco**	**Gemini**	**Other Data Needed**	**Tools Needed**
Gravitational Waves	Single object spectroscopy and imaging in both optical + NIR (Goodman, ARCOIRIS) Needed/Desired: A NIR imager for imaging follow-up of red kilonovae.	Wide field imager (DECam) Needed/Desired: A wide-field NIR imager (>30x30 arcmin^2) may be beneficial for some GW events (e.g. purely 'red' kilonovae)	Single object spectroscopy for both candidate vetting and event evolution, in both optical+NIR: SCORPIO, GMOS, Flamingos-2, GNIRS Optical+NIR imaging is also necessary to track kilonova evolution to faint magnitudes	Complementary multi-wavelength data (Gamma-ray, UV, X-ray, etc). Consider 'coordinated observations' with these facilities.	Broker tailored to multi-messenger needs; Resource allocation and scheduler, with fast interrupt capability; Automated fast reduction and results sharing; Coordination with other institutional resources; public search for MMA counterparts; NIR imager
Neutrinos	Single object spectroscopy and imaging in both optical + NIR (Goodman, ARCOIRIS)	Wide field imager (DECam)	Single object spectroscopy for counterpart candidate vetting; optical GMOS, SCORPIO	Complementary multi-wavelength data (Gamma-ray, UV, X-ray, etc). Consider 'coordinated observations' with these facilities.	Similar tools required as for GW events. NIR imager

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Star and Planet Formation

This section considers the study of star-forming regions, proto-planetary systems and newly formed stellar systems through their pre-main sequence evolution, considered either as single star systems or in young star clusters. Exoplanet characterization is excluded as it has its own section, as is the study of older star clusters and the properties of stellar populations that will be addressed in the following section.

Science

In the field of star and planet formation, one of the areas of highest priority recently has been high resolution studies of newly formed stars and their associated disks and outflow regions. This influences both our understanding of star formation and also of the environments in which exoplanets form. This science is typically done in synergy between high resolution NIR spectroscopy (often with AO and integral field spectroscopy) or high spatial resolution imaging (with AO) and radio observations with ALMA. An example of this approach is determining the structure of protostellar disks. ALMA is used to study the dust in these disks, which has settled into the optically thick midplane. Scattered light observations in the optical and NIR are then used to probe the structure of the disk significantly out of the midplane. GPI would be an ideal instrument for this measurement, although for some measurements NIRI and NIFS/Altair would be useful. However, it is important to note that GPI has not yet demonstrated a large number of discoveries, and it may be necessary to go to larger apertures than GEMINI for this science case to reach its full potential.

On the survey side, there is important work to be done to characterize the population of protoplanetary disks, low-mass Young Stellar Objects (discovered with Spitzer/Herschel/WISE, as well as those discovered via their variability in the LSST imaging of the galactic plane), characterization that will primarily require NIR spectroscopy. Another major focus will be on measuring the low-mass end of the stellar and sub-stellar IMF. This latter work would include the measurement of binary fractions. This work is primarily done with Gemini, but the brighter/closer star forming regions are accessible to NIR imaging and spectroscopy with SOAR, particularly for studies involving excited H_2 around nearby star-forming systems. Indeed, SOAR AO imaging and speckle imaging with HRCam is already being used to spatially resolve bright objects.

The wide field, multi-conjugate adaptive optics (MCAO)-enabled Gemini system, with GSAOI in the south and GNAOI in the north (under-construction), is a unique capability that could open up the study of young stars in the Milky Way and nearby galaxies. The resolution would be significantly better than HST in the NIR. As observation of faint objects in dense stellar systems is limited by the confusion limit, increases in resolution result in a direct gain in the stellar luminosity that can be reached. The wide-field of the GS(N)AOI imagers would realize this gain over a unprecedentedly large field of view with an AO correction. A GEMS or GEMS-2-enabled survey of young stellar objects is therefore possible out to the LMC and beyond to M31 and

M33. The common distances to sources in these objects and the lower obscuration afforded by the NIR would make it possible to understand the luminosity function of the stars down to low luminosities and over a range of environments with different histories and metallicities. AO-enabled spectroscopy would also be important for this effort and a GNIRS IFU fed by GEMS-2 would allow for the determination of stellar atmosphere parameters that could be used to infer the stellar masses of the YSOs to pin down the IMF.

Impact of the GBS System

The majority of the impact will come from studies in the NIR and MIR, which is where Gemini is an essential component of the US system. The biggest impact that Gemini will make to the study of star and planet formation is through its AO enabled instruments, including GPI, GSAOI/GNAOI, and the future commissioning of the GNIRS IFU. GPI will enable studies of protostellar disk structure in the Milky Way and the AO imagers and IFU will enable the study of star clusters and star-forming regions out into the local group.

NIR and MIR imaging and spectroscopy out to 10 microns is an important niche that Gemini could occupy with a “workhorse” instrument that does not require the large amount of support that an AO instrument might. As an example, moderate-to-high resolution MIR spectroscopy would yield the ability to study the chemistry of protostars and proto-planetary disks. The IGRINS visitor instrument provides NIR high resolution spectroscopy out to 2.5 microns and is currently available for use. PHOENIX provides spectroscopy out to 5 microns, but it is an aging instrument and it is not clear how well it can be maintained. The TEXES instrument extends the spectral reach of Gemini to 25 microns, but is a visitor instrument that has not been on the telescope in the past 1.5 years. Gemini staff indicated that this hiatus was because the team could not properly support the instrument for those runs. We therefore recommend that Gemini consider ways to further enable visitor instruments that occupy an important niche. Having visitor instruments with predictable availability is an important factor in building a community of observers that can take advantage of that capability.

Although Gemini is the dominant component of the GBS system for this science case, 4m telescopes can contribute to the characterization of brighter systems. However, this would require improvements to the reliability of the older SOAR NIR instrument and the improvement of the SOAR AO correction, although even with the current correction Speckle imaging is being done at SOAR to look for binarity in relatively unobscured objects. Finally ARCOIRIS on SOAR could also help with the characterization of some stellar systems in the Milky Way. All of these facilities will be crucially important for following up in more detail objects observed with ALMA and eventually with JWST.

The niche for the Blanco in this area is smaller, and although large narrow-band imaging surveys with the Blanco/DECam might make an impact, NIR observations with Gemini and SOAR are the cornerstones of star formation studies in the GBS system.

What is missing from the GBS System to support this science case?

Regularly available MIR imaging and spectroscopy instruments are currently missing from the Gemini instrument portfolio.

How would this science case benefit from a coordinated OIR System?

Most embedded sources are identified using space-based or or ground-based sub-mm/mm observations, and so the need for a coordinated OIR system is not as clear. A coherent program of source characterization could benefit from target coordination between SOAR/ARCoIris and Gemini/GNIRS for targets of different brightness.

GBS Assessment

Table 5. For each science case, an assessment table is provided to summarize for each telescope what capabilities are used. When applicable, other tools, observations and data are needed are listed as well.

Science Case	**SOAR**	**Blanco**	**Gemini**	**Other Data Needed**	**Tools Needed**
Scattered light in protoplanetary disks			GPI, NIFS (+AO), GNIRS with IFU (+AO), GSAOI, GNAOI (potentially GIRMOS)	ALMA for gas/cold dust emission,	
Surveys for young stellar objects		DECam with narrow band filters		Spitzer, WISE, Herschel	
Studies of young stellar objects			GNIRS (+AO)		
Determining the binarity of low-mass systems	AO/Speckle imaging				
Chemistry of protoplanetary disks			Reliable access to TEXES	JWST/ALMA	

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Stellar Astrophysics and Stellar Populations

This section pertains to the properties of stars during their evolution including post-main sequence evolution, with the exception of Supernovae which have their own section, as well as stellar population studies of star clusters, the milky way, satellite systems and streams, and resolved populations in other galaxies, except for the study of dark matter in dwarf satellite galaxies which is covered in the Cosmology section. This section also covers the structure of the Milky Way.

Science

Stellar astrophysics, stellar populations, and galactic structure are undergoing a renaissance thanks to the fundamentally new measurements provided by GAIA, large spectroscopic surveys (RAVE and SDSS), and the future promise of LSST and JWST. Set against this backdrop, there are multiple science topics where the GBS system can make a significant impact.

Spectroscopic studies are critically needed to complement the photometric measurements that are here and will be coming. In seeing-limited mode, a fundamental stellar astrophysics measurement is the determination of stellar masses. Direct masses for stars of a large range of mass and evolutionary states is a critical element in calibrating stellar evolution models, especially for high-mass stars or those in rare phases of evolution. Binaries that are selected by GAIA can yield direct stellar mass measurements, provided that spectroscopy is available to determine orbital velocities and spectral types. GAIA will be excellent to select these systems and its all-sky view will select rare stars, or intrinsically faint stars that are close to the earth.

Stellar populations in the Milky Way will be revolutionized with GAIA observations, coupled with precision LSST/DES photometry and spectroscopy from a host of wide-field spectroscopic surveys, including the ESO-GAIA survey, WEAVE, 4MOST, LAMOST, and SDSS. The next frontier is probing resolved stellar populations in nearby galaxies and Milky Way streams. Membership identification and abundance measurements through medium-to-high spectral resolution spectroscopy are needed to chemically tag stars in stellar streams and in nearby galaxies like the LMC. This tagging, when combined with position and velocity information, can then be used to unravel the accretion history of the Milky Way Halo and the Star Formation History (SFH) of the galaxies.

HST is providing high resolution images in the UV-through-NIR of nearby dwarfs, M31, and M33. JWST will supplement this in the NIR. By using HST's resolution to beat the confusion limit in dense stellar systems, these data are providing invaluable information on the IMF in different environments, rare phases of stellar evolution, and the spatially resolved star formation history in nearby galaxies.

What is missing is a spectroscopic view that can rival HST's imaging information. With medium-resolution spectroscopy at high spatial resolution with adaptive optics, it will be possible to measure the metallicity and chemical abundance in nearby galaxies such as M31 and M33, and at a resolution at or better than that from HST. Spectroscopic mass determinations of individual stars will improve stellar mass estimates and allow a better determination of the moderate-mass IMF. In addition to AO-fed spectroscopy, AO imaging on Gemini will exceed the spatial resolution of HST and allow lower-mass stars to be imaged above the confusion limit. These same advantage will allow Gemini to probe to low stellar masses in high density clusters in the Milky Way.

Impact of the GBS System

This science case offers many compelling questions and to address them requires a diverse set of instruments. Gemini is the primary instrument for studying the properties of stars in the US system, and a very substantial portion of the Gemini science activities centers on this area. In particular, high resolution spectroscopy, AO-assisted imaging and spectroscopy, and NIR spectroscopy of stars and star clusters will continue to be central to the US astronomy community for the foreseeable future. High resolution spectroscopy is a ``bread and butter" research tool for stellar characterization and the study of stellar evolution. This is expected to continue to be a major mode of use of Gemini (mostly in small to medium-size programs) for the coming decade. We give some examples below.

The larger aperture of Gemini will result in a spatial resolution better than that of HST. With GEMS+GNIRS (or GNIRS+Gemini-N future AO system), Gemini will therefore be able to obtain spatially resolved and diffraction-limited spectroscopy of stars in nearby galaxies, thus revealing the chemical composition for individual stars or groups of stars in clusters, and relating them to the characteristics of stars in the neighborhood as determined from HST or Gemini AO imaging. This spectroscopy will also make it possible to determine stellar masses for stars, important for derivations of the IMF. The recent availability of IGRINS as a visitor instrument at Gemini-S has provided a high-throughput and complete spectral coverage capability for stellar characterization that has proved extremely valuable and should be continued.

The Blanco with DECam serves as a discovery machine to generate targets for Gemini spectroscopy. Brighter stars in streams and nearby dwarfs found with DECam can be followed in seeing-limited mode with GHOST and GMOS to obtain medium-to-high spectral resolution measurements that will yield precision chemical abundances. DECam can (and has) identified both dwarf galaxies and stellar streams using broadband imaging. While LSST will have superior depth and sky coverage, DECam has already found multiple galaxies and streams, which can be followed up spectroscopically with GMOS and GHOST. Given the large number of potential targets, pre-selection is important both to improve the efficiency of the spectroscopic observations and to make sure that these observations are targeting sources with a range in physical parameters. DECam gives the opportunity to pre-select sources using its unique capability to employ narrow-band filters over a wide field of view. Using Ca H+K filters with DECam, it will be possible to map the metallicity distribution of these systems and to select stars for spectroscopy. Sources bright enough to have precision Blanco photometry measurements will be ideal for deep Gemini spectroscopy.

We envision the role of SOAR in this science area to primarily be enabling direct stellar mass measurements for binaries identified with GAIA.

What is missing from the GBS System to support this science case?

A fully operational MCAO system on Gemini-N (GEMS-2) coupled with both an imager (GNAOI), and a NIR IFU (GNIRS) is planned but is currently not operational. Gemini-S has GSAOI but no associated IFU. The optical spectroscopic capabilities of Gemini need to be maintained, both through the continued maintenance of GMOS and the installation of GHOST. For example, support for the continued availability of IGRINS should be ensured. Looking further into the future, GIRMOS fed by the GEMS-2 AO system will be a valuable component of Gemini-N's ability to study stellar populations in nearby galaxies.

For DECam, the investment in narrow-band filters would enable the unique contribution of DECam to the wide-field imaging portfolio of the OIR system in the age of LSST.

Wide field, medium resolution, and massively multiplexed spectroscopy will be important to identify and study bright stars in dwarf galaxies and in stellar streams. DESI on the Mayall telescope provides this ability but would first be available following the completion of the main DESI survey. The community should build a set of compelling science cases for DESI in this area.

How would this science case benefit from a coordinated OIR System?

As a spectroscopic facility, Gemini will clearly benefit from targets drawn from LSST and DECam imaging. Spectroscopic capabilities that are available elsewhere in the OIR system complement GBS very well. DESI on the Mayall provides much wider field and larger multiplex capabilities. MIKE on Magellan and MOSFIRE on Keck provide multi-object NIR spectroscopy (at different resolutions), and DEIMOS on Keck provides sensitivity in the NUV (to 3100 Angstroms). Finally, CHARA provides the interferometric measurements of stellar surfaces and sizes that complement the high resolution spectroscopy for the brightest stellar targets.

GBS Assessment

Table 6. For each science case, an assessment table is provided to summarize for each telescope what capabilities are used. When applicable, other tools, observations and data are needed are listed as well.

Science Case	**SOAR**	**Blanco**	**Gemini**	**Other Data Needed**	**Tools Needed**
Identifying and measuring stellar streams in the MW halo		DECam	GMOS	Wide-field spectroscopy with the DESI spectrograph	
Stellar populations in Dwarf Galaxies	Goodman (for the brightest targets)	DECam	GMOS, GNIRS+MCAO	HST	
Determining the binarity of low-mass systems	AO/Speckle imaging		GNIRS		
Stellar atmospheric characterization-isotope measurement			GMOS, GHOST, IGRINS		
Star clusters in MW and nearby galaxies	Goodman	COSMOS	GNIRS+MCAO, GMOS		

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Galaxies

In this section we consider the study of individual galaxy structure (but not resolved stellar populations in nearby galaxies), including: galaxy evolution, how environment affects galaxy evolution except for their use in Cosmology), the baryon cycle: global star formation, chemical properties of galaxies, inflows, outflows, and mergers and their relation to the IGM and CGM, and galaxy formation.

Science

The GBS telescopes are the primary sources of data on galaxies within the US system, although they are heavily supplemented by contributions from the Mayall through the Legacy Imaging Surveys and in the future by DESI. The key science programs the GBS system will address in the coming decade involve the evolution of galaxies, the relationship between galaxies, their supermassive black hole, and the environment surrounding the galaxies, the study of lensed systems, particularly with AO and/or spectroscopy, and very deep spectroscopy of ultra-diffuse galaxies. We discuss these areas below.

Key ingredients in understanding the formation of galaxies are spatially resolved information on their stellar mass, star formation, feedback, kinematics, and metallicity, as well as their SMBH content. These are crucial for understanding the baryon cycle through which material is fed into galaxies, processed into stars, enriched with metals, and push back into the gas around and between galaxies, the circumgalactic medium (CGM) and intergalactic medium (IGM.) Understanding this area requires a comprehensive and diverse set of observations.

Significant progress on studying large star-forming galaxies has been made using 8-10m class telescopes but fainter galaxies are currently out of reach. Gravitationally lensed galaxies with high magnification factors (>10), on the other hand, provide a way to obtain high signal-to-noise measurements of intrinsically faint galaxies and those that are not forming stars. Indeed, studies of strongly lensed galaxies have provided our most detailed information on the kinematics, structure and evolution of galaxies at high redshift. Lensed galaxies or those undergoing rare phases of galaxy evolution, e.g. extreme post-starburst galaxies, those with strong outflows, or very massive galaxies, will be found in great quantity by LSST but will require large amounts of dedicated follow-up with spectroscopic and AO facilities. These observations would be excellent complements to high resolution observations of the dust and molecular gas with ALMA.

Active galactic nuclei (AGN) have revealed themselves as powerful probes of galaxy evolution. Their study is particularly important as energy from AGN feedback is a favored mechanism for quenching star formation in galaxies. Studies of the central engine and the surrounding interstellar medium (ISM) tell us how material is fed into the black hole and how that energy is transferred directly into energy and momentum feedback in the inner regions of galaxies. Bright AGN can also be used as powerful searchlights that can illuminate the CGM in intervening systems. AO imaging and spectroscopy, as well as high spectral resolution seeing-limited spectroscopy are needed for these science cases.

LSST will return a vast trove of new AGN identified by variability measurements of spatially resolved (galaxy) targets. These AGN will be valuable on two fronts in the context of the GBS system. First, high cadence (~daily) monitoring of many AGN can be used, in combination with spectroscopic reverberation mapping on a weekly cadence, to calibrate photometric reverberation mapping estimates of SMBH masses. Photometric reverberation mapping probes variation in the continuum luminosity of the accretion disk, with different wavelength filters probing different regions of the disk. If this measure could be calibrated using spectroscopic reverberation mapping on a weekly timescale, it could enable photometrically determined black hole masses for ~10^6 AGN. Second, using spectroscopy to study the incidence of outflows in LSST discovered AGN and how that correlates with AGN luminosity or host galaxy property could help establish the role of AGN induced feedback. AGN as backlights of foreground galaxies will also be discovered by DESI, which should identify ~100 quasars per square degree. These will greatly increase the number of background sources that can be used for CGM studies.

Ultra-diffuse galaxies (UDGs) are an emerging class of extreme galaxies characterized by their extremely low surface brightness and sometimes large integrated magnitudes and dynamical masses. The study of these sources are in their infancy but they have already proven to be especially useful for understanding the extremely low efficiency end of galaxy formation, the potential for galaxies without dark matter, and the destruction of galaxies in dense environments. Deep wide-field imaging will reveal large numbers of these objects, which will require dedicated spectroscopy on large telescopes to confirm their redshifts, measure their dynamical masses, and characterize their gas content and stellar populations.

Impact of the GBS System

There are many compelling science questions and to address them requires a diverse set of instruments. Rare objects will first need to be confirmed before future follow-up resources can be committed. SOAR with SAMI imaging will be useful for looking for arcs. The next step depends on the brightness of the sources. SOAR/Goodman spectroscopy will be useful for confirming the brightest lenses and extreme sources. For fainter sources, Gemini with GMOS or SCORPIO will be necessary. SCORPIO will be efficient at confirming fainter targets, thanks to its large wavelength range. Once targets are spectroscopically confirmed, Gemini will dominate the follow-up. SCORPIO will provide medium spectral resolution and high signal-to-noise measurements of the sources from the atmospheric cutoff to 2.5 microns. GHOST will provide high resolution follow-up for the brightest lensed galaxies, especially the UV-bright galaxies at higher redshift, and will allow for excellent studies of the CGM in galaxies backlit by quasars, e.g. those discovered by LSST or DESI. GEMS-2 on Gemini-N with the GNIRS IFU will be an excellent facility for near-diffraction limited observations of the confirmed targets. For gravitationally lensed galaxies and bright extreme galaxies these observations will yield spatially resolved metallicities, stellar populations, and kinematics. One limitation of the GNIRS IFU is the limited field of view compared to the size of some giant arcs. This may be partially remedied by GIRMOS, which will have at least 2 IFU units that can be devoted to studying a larger fraction of the lens. These observations will have a high degree of synergy with ALMA and JWST, which will each enable the examination of different spectral regimes, whereas Gemini will specialize in the optical/NIR.

GEMS-2 on Gemini N with GNAOI, GNIRS, and GIRMOS will allow for high spatial resolution studies of the inner regions of galaxies. These will allow astronomers to probe the geometry of the inflow/outflow regions around the AGN. The IFU spectroscopy will enable the determination of the physical properties of the gas surrounding and will also allow us to understand the interplay of feedback from stellar and non-stellar (AGN) source.

To calibrate photometric reverberation mapping, ~daily multi-band photometric observations are necessary, coupled with ~weekly spectroscopic observations, perhaps with a program on a

DESI-like spectrograph. The ~daily cadence is not in the baseline LSST plan and therefore is best suited for a wide-field imager like DECam coupled with a wide-field spectrograph like DESI.

Spectroscopy of ultra-faint dwarf galaxies will likely be the purview of instruments like GMOS, as these very low surface-brightness systems require long exposure times with moderate resolution seeing-limited spectropraphs. GMOS is the obvious choice.

How can the GBS system be optimized for this science case?

Having GHOST, SCORPIO, GEMS-North, and GIRMOS installed on these telescopes is necessary for the science described above. GMOS should also be maintained as it is a highly demanded workhorse instrument for galaxy studies.

Having a NIR IFU with a wider field of view would be optimal, but GIRMOS will have two IFUs which serves some of the same purpose (although not until 2024). Installing GEMS-N for diffraction-limited follow-up of DESI/Legacy Survey or northern LSST targets will be important.

Additionally, if narrow-band filters were purchased for the Blanco, it could add a fundamentally new aspect to LSST fields. e.g. ultra deep Lyman-alpha or H-alpha imaging surveys of LSST deep drilling fields.

Finally, wide-field NIR imaging capability with an ~0.25 deg^2 field of view on a 4-meter class telescope will be important for imaging fields with deep optical imaging. While these data will inevitably be shallower than optical imaging from an 8-m telescope, it will still be invaluable for targeting for NIR spectroscopy with 8m-class telescopes.

What is missing from the GBS System to support this science case?

At the moment, GMOS is performing the leading deep spectroscopic studies of dense environments at z>1. Other telescope instrument combinations such as DEIMOS/Keck, IMACS/Magellan, and eventually Binospec/MMT are more powerful for field surveys because of their wider fields of view. There is, however, a decided lack of NIR multi-object spectrographs on 8-10m telescopes, and none with general access to the US community. Having such a facility, either via time exchanges with Subaru/PFS or Keck/MOSFIRE or by finally commissioning FLAMINGOS-2 MOS mode would be very beneficial.

For studies of the CGM or spatially resolved studies for the rest-frame UV from high redshift star-forming galaxies, blue-sensitive IFU spectrographs like KCWI on Keck are ideal. Such a facility is not planned for the GBS system and is absent from the US community.

A key ingredient missing from the GBS system is wide-field highly multiplexed spectroscopy. This would be useful for a large range of science questions such as AGN spectroscopic reverberation mapping across a wide field and charting the assembly of baryons in dark matter halos through large spectroscopic surveys. The latter case was not emphasized above as it cannot be done with current or projected GBS instrumentation. However, having access to a significant amount (~100 nights) of DESI time could do some of this science, e.g. limiting to bright galaxies or AGN. Even better would be community access to the PFS instrument on Subaru. A breakthrough galaxy evolution survey as described in the 2016 Kavli report could be accomplished in a 300 night PFS survey, although even significantly less time would be very useful, resulting in a scaled back survey with somewhat less ambitious science goals.

A missing ingredient for almost all galaxy studies is the lack of deep NIR imaging over a significant fraction of the sky. Matching LSST depth with such imaging will be extremely challenging from the ground (Fourstar on Magellan is probably the closest match in the US system), but will be possible through coordinated WFIRST imaging of LSST deep drilling fields.

How would this science case benefit from a coordinated OIR System?

Currently, DECam serves to generate targets for the Gemini spectrographs. For AGN variability, coordination between LSST, SOAR and Gemini and external telescopes such as LCO would be useful for time delay measurement.

Given the limited (though growing) instrumentation suite on Gemini, having access to facilities on other large telescopes, e.g. Keck+MOSFIRE or KCWI, MMT+Binospec, LBT+Lucifer, or Subaru+PFS, that are not planned for Gemini will be critical for maximizing the science described above. Similarly access to NIR imaging at the moment would have to come from other telescopes in the US system.

Large programs will probably become critical for much of this science as the time needed is large and sometimes involves observations across different facilities, e.g. KCWI and GNIRS IFU spectroscopy. Therefore a coordinated OIR system is beneficial. However, PI programs will play a significant role as well, e.g. for bright or rare targets that don’t need huge amounts of time but do required access to the OIR system facilities.

GBS Assessment

Table 7. For each science case, an assessment table is provided to summarize for each telescope what capabilities are used. When applicable, other tools, observations and data are needed are listed as well.

Science Case	SOAR	Blanco	Gemini	Other Data Needed	Tools Needed
Lensed galaxies (dark matter distribution, background galaxies	SAMI	DECam	GMOS, GEMS, GNIRS+MCAO (especially if upgraded)		
AGN, feedback, and gas infall/outflow	Goodman (for the brightest AGN)	DECam + narrow band filters	GMOS, GNIRS+MCAO , GHOST	HST, JWST, ALMA	Wide-field NIR imager on 4m-class telescope
Galaxy Evolution, Ultra-diffuse galaxies	Goodman	DECam (and then LSST)	GMOS, GNIRS, Scorpio		Highly multiplexed spectrograph on 4-8m telescope, Wide-field NIR imager on 4m-class telescope

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Dark Matter and Dark Energy

This section discusses the contribution the GBS system can make to dark matter and dark energy science. The important case of SN Ia studies is handled in a separate section.

Science

The first few years of the next decade will see intense activity in the cosmology community as it seeks to capitalize on the spectroscopic data from DESI and the advances in survey area and depth that the LSST data will provide. High accuracy measurements of the parameters governing the dark energy equation of state parameters, modified gravity and the cosmic neutrino background will drive the analysis program: the DESI collaboration is studying how cosmological information can be extracted from the precise 3-D maps delivered by the survey using measurements of baryon acoustic oscillations, redshift space distortion and other methods while the LSST Dark Energy Science Collaboration is preparing to do this using five cosmological probes, all of which depend on additional data of one form or another. Four of these, weak lensing, galaxy clustering, the abundance of galaxy clusters, and gravitational lens time delays, involve modeling dark matter structures on a wide range of scales, from individual massive galaxies to the filaments and voids thought to fill the space between clusters of galaxies.

On galaxy scales and below, dark matter structures are insensitive to the dynamics of the expansion of the Universe, but instead contain information about the nature of dark matter itself, via the abundance and internal structure of sub-galactic halos in nearby galaxies including our own, or in massive galaxies acting as gravitational lenses. Perturbations of stellar streams in the Milky Way, and perturbations of Einstein rings in gravitational lens systems are both promising routes to constraining the physical properties of dark matter.

Impact of the GBS System

The abundance of LSST galaxy clusters is potentially a very high precision cosmological probe; its performance is limited by the accuracy with which cluster masses can be calibrated. Photo-z’s in and behind clusters can be improved with intensive multi-object spectroscopy over relatively small (e.g., 20 arcmin) fields of view to calibrate the redshift distribution in cluster fields; this is not a program that could be carried out efficiently with Gemini. The kinematics of the brightest cluster member galaxies may also provide additional useful mass information; GMOS on Gemini could support such a limited kinematics program.

Harnessing hundreds of LSST time-delay gravitational lenses for cosmology will require high resolution Einstein ring imaging and lens galaxy spectroscopy. At the faint end of the sample 30-m class telescopes will be needed, but for bright systems, AO on 8-m telescopes should be sufficient. While several hundred galaxy-scale lensed quasar systems should have time delays measured by LSST alone (Liao et al 2014), these measurements are likely to be contaminated by microlensing; meanwhile, the majority of the detectable lensed supernovae will have narrow image separations and short (few day) time delays, and thus need dedicated high cadence AO imaging monitoring to measure their time delays. This could be achieved on a 2-m or 4-m facility, given sufficient time allocation and adaptive optics capability.

Near field cosmology - i.e., probing dark matter physics using dwarf galaxies and stellar streams - also requires multi-object spectroscopy, and time-share agreements similar to those discussed above would be impactful. Blanco currently plays a role in detecting Milky Way satellites to use in the study of dark matter; with the advent of LSST, focus may shift to spectroscopy of dwarfs around nearby galaxies (that fit in the GMOS field) with Gemini. There is also potential for carrying out adaptive optics astrometric studies if GEMS reaches the required level of astrometric stability, and deep follow-up imaging with Gemini to confirm faint systems (as is currently being done for candidates found with DECam).

What is missing from the GBS System to support this science case?

The most important additional datasets needed to support LSST cosmological probes are the large spectroscopic samples of galaxies needed for photometric redshift training and calibration. Weak lensing, LSS, and galaxy cluster measurements will all depend on photometric redshifts directly; the LSST photometric redshifts will also be exploited to identify strong lensing systems and supernovae for follow-up, and used for some analyses of those objects. The Kavli report summarizes the needs as follows. Photo-z training for LSST cosmology requires a sample of around 30,000 galaxies spanning the redshift range $0<z<3$ and reaching the $i=25.3$ magnitude limit of the cosmological “Gold sample” (i.e., the sample used for weak lensing measurements of cosmology), distributed amongst as many fields as feasible to minimize the impact of sample/cosmic variance. These observations are best conducted with a highly-multiplexed, moderately wide-field medium resolution spectrograph. Such a sample could be constructed in ~1 year with PFS on Subaru through a time-share agreement, or in 5 years with a DESI-like instrument on a 4-m telescope. Given the variations in photometric quality (seeing, etc.) that may occur when LSST is pushed to high airmass, this work would be best done from a southern site to allow photometric redshift training samples to span the full range of LSST observing conditions. Photo-z calibration requires a larger sample of at least ~500,000 spectroscopic galaxy redshifts over at least 100 square degrees within the survey area. Suitable surveys are already planned with the DESI and 4MOST instruments. We refer the reader to the white papers submitted to the Astro2020 decadal survey by the LSST DESC for more information on this topic.

How would this science case benefit from a coordinated OIR System?

The cosmological samples of LSST clusters and strong lenses will cover a range of redshifts, and hence brightnesses and angular sizes: being able to follow these up via a single campaign with a coordinated OIR system would reduce observation duplication and make for a more homogeneous legacy dataset. It is likely that an integrated GBS system will be better able to obtain observing time for the GBS user community through a time-sharing scheme than Gemini would alone.

GBS Assessment

Table 8. For each science case, an assessment table is provided to summarize for each telescope what capabilities are used. When applicable, other tools, observations and data are needed are listed as well.

Science Case	SOAR	Blanco	Gemini	Other Data Needed	Tools Needed
Photo-z training				Up to 30k galaxy spectra to i=25.3 with PFS (~1 year)[1]	
Photo-z Calibration				4MOST and DESI survey spectra Up to 50k galaxy redshifts	DESI-like instrument[2]
Cluster Mass Calibration			200-500 galaxies per field, for ~100 clusters		
Time delay lens monitoring	High cadence AO imaging monitoring for several hundred lensed SNe				Integrated OIR system with alert broker to generate high quality targets;

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Science Case Summary

In the previous sections we presented the rich spectrum of scientific exploration covered and enabled by the GBS system. The GBS telescopes will remain an essential component of the U.S. astronomy community for the period considered by the committee and beyond. With the existing and planned instrumentation and the development of tools to support system wide coordination, the observatories will be well positioned to meet the challenges of LSST era and

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[1] A similar dataset could be obtained in 5 years with a DESI-like instrument on the Blanco, or in ~1 year with a new PFS-like wide field MOS instrument on Gemini.

[2] If the 4MOST and DESI surveys are found to be insufficient, a dedicated photo-z calibration survey in support of LSST would be needed.

the emerging field of Multi-Messenger Astronomy while continuing successful programs across a wide range of topics.

Here we summarize the above science cases and list in broad terms how each of the telescopes contributes and what additional instrumentation and external data sets will be needed to fully exploit each science case. This section addresses charge elements Q1 and Q2.

Table 9. For each of the science case considered, we list our assessment of the contributions provided by each of the GBS telescopes and what critical additional data and tools needed to achieve the science goals. Detailed justifications can be found in the science case sections.

Science Case	SOAR	Blanco	Gemini	Non-GBS Data Needed	Instruments & Tools Needed
Small Bodies	Spectroscopy (Goodman), AO imaging (SAMI)	Wide field imaging (DECam)	Spectroscopy (GMOS, SCORPIO), NIR (NIRI) and AO imaging		Single object, high throughout, wide wavelength spectrograph, Alert broker and scheduler
Exoplanets	AO, Speckle imaging (SAMI), Spectroscopy (Goodman/ STELES)	Microlensing observations (DECam)	AO imaging (GPI) High resolution spectroscopy (GNIRS)	Precision Radial Velocity Observations	Thermal and mid-IR high contrast imaging, AO improvements
Variables, Supernovae	Spectroscopy (Goodman, SIFS) AO imaging Multiobject spectrograph (Goodman) Single object spectrograph (ARCOIRIS)	Wide field imaging (DECam) (Multiobject) spectroscopy (COSMOS)	Spectroscopy (GMOS, SCORPIO) Spectro-polarimetry (GPI) NIR imaging (SCORPIO)	High S/N NIR (Low-resolution) spectro-photometry Multiwavelength photometry and spectroscopy across EM spectrum	Wide field MOS on a 4 to 10-m class telescope (DESI) Alert broker and scheduler Low resolution IFU/narrow filters photometer (R~100) Implementation of policies and guidelines for data sharing
Multi-Messenger Astronomy	Single-object Optical+NIR Spectroscopy (Goodman+ ARCOIRIS)	Wide field optical imaging (DECam)	Single-object Optical+NIR Spectroscopy & Imaging (GMOS, SCORPIO, GNIRS, FLAMINGOS-2)	Data is needed across the EM spectrum to get a full physical picture (gamma-ray through radio)	Alert broker tailored for MMA and rapid-response scheduler Public search for MMA counterparts Clear data

					sharing policy Capable NIR imager at SOAR Wide field NIR imager for red MMA counterparts
Star and Planet Formation	AO/Speckle imaging (SAMI), Spectroscopy (Goodman)	Wide field imager with narrow band filters (DECam)	AO imaging and spectroscopy (GPI, NIFS, GNIRS, GIRMOS)	Spitzer, WISE, Herschel, ALMA and JWST observations	MIR instrument (or reliable access to TEXES)
Stellar Astrophysics	AO/Speckle imaging (SAMI), Spectroscopy (Goodman)	Wide field imaging (DECam with narrow band filters), Spectroscopy (COSMOS)	AO imaging (GSAOI and GNAOI) and spectroscopy (GNIRS+IFU, GIRMOS). Natural seeing mode spectroscopy (GHOST, GMOS)	HST, JWST, Spectroscopic data from a wide field survey instrument like DESI	
Galaxies	AO imaging (SAMI), Spectroscopy (Goodman)	Wide field imager with narrow band filters (DECam), Spectroscopy (COSMOS)	AO Imaging (GSAOI/GNAOI, FLAMINGOS-2) and spectroscopy (GNIRS w/IFU, GIRMOS, GHOST, FLAMINGOS-2 in MOS mode) and natural seeing spectroscopy (SCORPIO, GHOST)	HST, ALMA, JWST, Spectroscopic data from a wide field survey instrument like DESI	Wide field NIR (~0.25 deg^2) imaging on a 4-meter class telescope.
Dark Matter, Dark Energy	High cadence AO imaging (SAMI)		Spectroscopy (GMOS, FLAMINGOS-2 in MOS mode) AO imaging (GSAOI)	Galaxy redshifts for photo-z training and calibration	Wide field, multi-object spectroscopy on a 4-10 m class telescope, Alert broker and scheduler

The Evolving Roles of the Gemini, Blanco and SOAR Telescopes

Following our assessment of the scientific investigations enabled by the GBS telescopes we now look at possible enhancements and investments that will help these facilities to remain successful throughout the next decade. In this section we consider aspects of operating the three telescopes as part of an OIR system, additional instruments and capabilities currently lacking from the portfolio, and a general investment in R&D to enable the next generation of instruments and facilities. This section addresses charge questions Q4 and Q5.

GBS as part of an OIR System

The 2015 NRC report, the 2016 Kavli report and other studies have clearly established the importance of coordinated modes of operations across many facilities for time domain science and multi-messenger astronomy in the era of LSST and LIGO. The committee concurs with the findings of these previous studies. Throughout our assessments of the science cases, we discussed how coordinated observations across multiple telescopes lead to greater scientific impact. Transient science and multi-messenger astronomy are the obvious cases but many other programs can benefit from coordinated observations as well. Coordination can be achieved in a number of different ways: telescope time exchange to provide access to certain instruments, joint (public) observing campaigns of high priority alerts like GW events, alert brokers and TOMs to name just a few. We recommend that all these avenues be pursued:

- **Telescope time exchange.**This has already been recommended by the 2015 NRC report but due to some budgetary constraints no progress toward establishing such an exchange program has been made. The committee suggests to renew this effort as a successful time exchange program across all U.S. facilities could be a pathway to a larger OIR system in the future. It appears that the the initial step would be to establish a valuation of the current telescopes and instruments that could be achieved by allocating some scientist time at NOAO or at a university.

- **Software tools** like Antares, TOMs and system solutions like AEON are necessary building blocks for an OIR system. These tools should not be developed in isolation by a single group but instead we encourage world-wide collaboration. This work provides great opportunities for community engagement. User interfaces and APIs have to be thoughtfully designed to provide open access to the different stages on an OIR system. For example, it should be easy to integrate different alert streams into the system.

- Encourage the observatories together with the astronomy community to develop **guidelines and principles for data sharing** in particular for high value ToO (like GW triggers). Consider different models for how the telescope allocation committees (TACs) can support coordinated campaigns to locate and follow-up these targets efficiently, ie without duplicate observations.

Completing the Instrumentation Portfolio

Throughout the discussion of the science cases we pointed out key instruments currently available in the GBS system, and identified capabilities currently lacking from the portfolio. We summarize our findings in this section to address charge question 5. While the committee recommends that ways to add these capabilities continue to be explored, we did not interpret our charge that a complete and rank-order list must be provided. Indeed, we believe that such a rank-ordering should come through the Decadal Survey process.

- MCAO capabilities for Gemini-N. Adaptive optics capabilities are critical for many key science questions. We recommend the completion of the addition of GEMS-2 that started with a recent NSF award.
- A wide-field, medium resolution multi-object spectrograph on a 4-10m telescope in the southern hemisphere. The scientific justification for such an instrument was detailed in the 2016 Kavli report. It is a critical tool to obtain spectroscopic data samples for photometric redshift training and calibration needed to support imaging surveys such as that of the LSST. The role of the DESI instrument following the end of the DESI survey is of interest as it could also enable significant science goals in a variety of areas.
- Enhanced NIR imaging capabilities - a small field of view instrument for SOAR for targeted follow-up studies. A wide field imager similar to NEWFIRM could be a next generation instrument for the Blanco.
- A high throughput, single object, wide wavelength (400nm - 2.5 micron), low resolution (R~50-200) spectrograph would be a great instrument for many science cases, such as solar system studies.

An ambitious package of new instrumentation for Gemini and a somewhat lesser extend SOAR is under construction or being constructed and commissioned (e.g. MOS mode of FLAMINGOS-2). It should be noted that for many of the science cases described in this document our assessment is based on the assumption that these instruments will be completed in a timely manner.

Investment in Instrumentation R&D

Not too long ago, NOAO, the observatories and many university research groups were actively involved in instrumentation R&D and the construction of new instruments. This is no longer the case. Many universities have lost technical support staff and the observatories have to focus almost exclusively on operations and maintenance. For major projects like DECam, LSST and DESI, inter-agency cooperation and large collaborations have been very successful, but basic instrumentation and detector R&D is falling behind. A report by the DOE Cosmic Visions panel details numerous possibilities that warrant further studies. Examples include:

- Enhanced adaptive optics system with wider fields of view or shorter wavelengths;
- New devices and materials for detectors (CMOS, germanium, MKIDS);
- New technologies for multi-object spectrographs (fiber positioner, optical multiplexers);
- OH line suppression technologies to extend wavelength coverage.

We encourage the agencies to identify funding for basic instrumentation and detector R&D as an investment in the future of the field.

Assessment of the GBS System

This section addresses charge question Q3. Given the planned capabilities of the GBS system, and the enhancements aspired to above, we now ask: is the US share of the GBS system observing time adequate to accomplish the high impact science program defined in this report? Given over-subscription rates comparable to their current values, the available observing time is sufficient to execute a significant fraction of the high-impact science programs defined in the report.

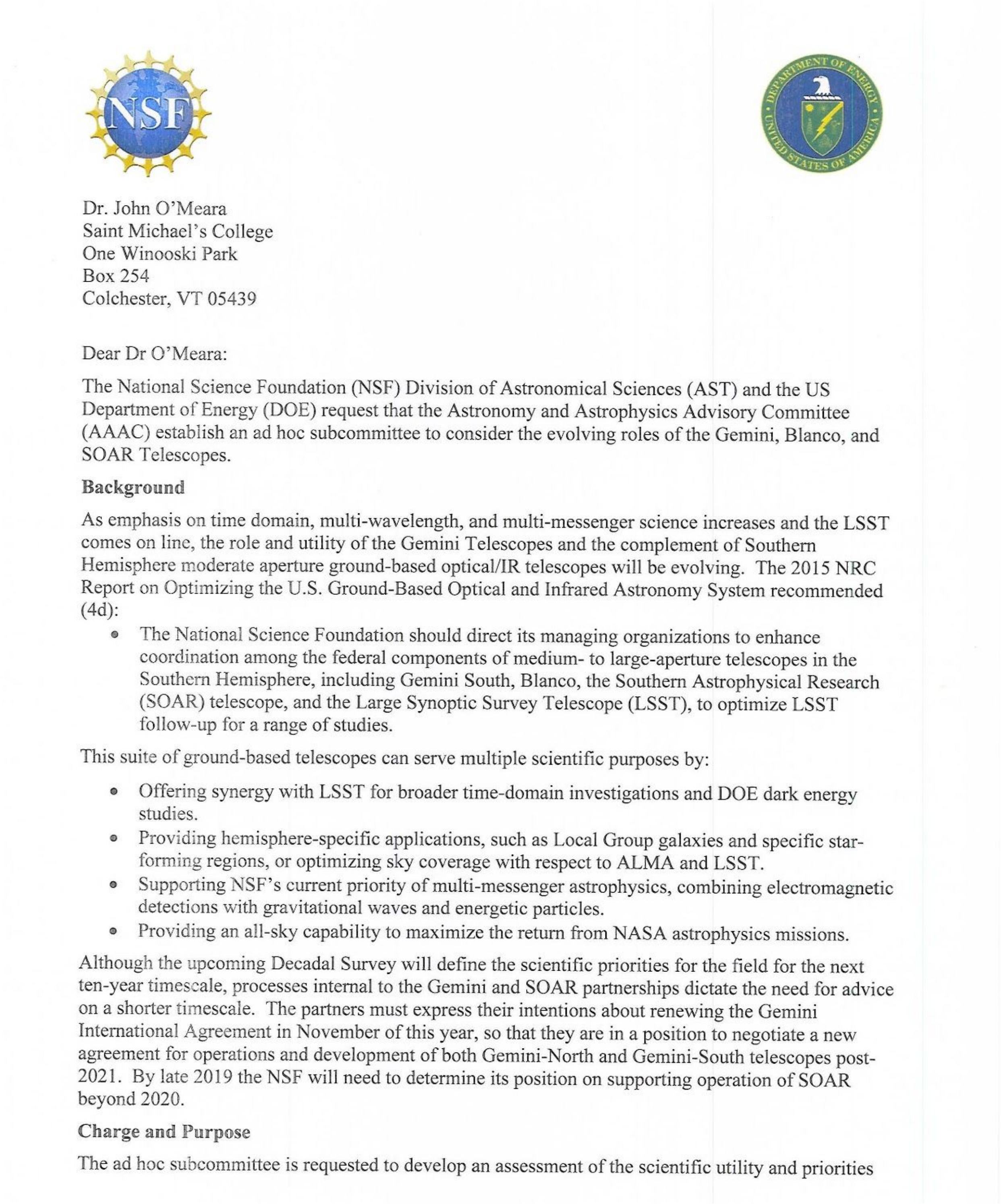
The GBS telescopes with their portfolio of existing and currently under construction instrumentation are well positioned to continue to be driving scientific forces in the field of optical astronomy. Using these facilities as an integrated OIR system with coordinated scheduling, TAC and data sharing policies will maximize scientific output.

Most of the current funding for GBS is provided to support operations and maintenance with little money available to develop new instrumentation and for R&D into new technologies, the one notable exception being the investments into OIR system software tools and the AEON project. Funding for this needs to continue and in addition we recommend that partnerships between university groups and national laboratories to support instrumentation R&D be developed.

The committee was charged to assess the scientific importance of the GBS system for the next 5 years. Looking beyond this period it is clear that plans for the long term future of the Blanco and SOAR telescopes need to be developed. We recommend that this work begin soon and that both observatories develop strategies for the 2nd half of the next decade, including any new instrumentation that might be needed.

Appendices

Charge letter



Dr. John O'Meara
Saint Michael's College
One Winooski Park
Box 254
Colchester, VT 05439

Dear Dr O'Meara:

The National Science Foundation (NSF) Division of Astronomical Sciences (AST) and the US Department of Energy (DOE) request that the Astronomy and Astrophysics Advisory Committee (AAAC) establish an ad hoc subcommittee to consider the evolving roles of the Gemini, Blanco, and SOAR Telescopes.

Background

As emphasis on time domain, multi-wavelength, and multi-messenger science increases and the LSST comes on line, the role and utility of the Gemini Telescopes and the complement of Southern Hemisphere moderate aperture ground-based optical/IR telescopes will be evolving. The 2015 NRC Report on Optimizing the U.S. Ground-Based Optical and Infrared Astronomy System recommended (4d):

- The National Science Foundation should direct its managing organizations to enhance coordination among the federal components of medium- to large-aperture telescopes in the Southern Hemisphere, including Gemini South, Blanco, the Southern Astrophysical Research (SOAR) telescope, and the Large Synoptic Survey Telescope (LSST), to optimize LSST follow-up for a range of studies.

This suite of ground-based telescopes can serve multiple scientific purposes by:

- Offering synergy with LSST for broader time-domain investigations and DOE dark energy studies.
- Providing hemisphere-specific applications, such as Local Group galaxies and specific star-forming regions, or optimizing sky coverage with respect to ALMA and LSST.
- Supporting NSF's current priority of multi-messenger astrophysics, combining electromagnetic detections with gravitational waves and energetic particles.
- Providing an all-sky capability to maximize the return from NASA astrophysics missions.

Although the upcoming Decadal Survey will define the scientific priorities for the field for the next ten-year timescale, processes internal to the Gemini and SOAR partnerships dictate the need for advice on a shorter timescale. The partners must express their intentions about renewing the Gemini International Agreement in November of this year, so that they are in a position to negotiate a new agreement for operations and development of both Gemini-North and Gemini-South telescopes post-2021. By late 2019 the NSF will need to determine its position on supporting operation of SOAR beyond 2020.

Charge and Purpose

The ad hoc subcommittee is requested to develop an assessment of the scientific utility and priorities for the US community for the Gemini Telescopes and the complementary Blanco and SOAR 4-meter telescopes for the first half of the upcoming decade. The purpose is to provide NSF timely advice on the renewal of agreements for two of the facilities and DOE on whether there is need and priority for use of these facilities to enhance Dark Energy science investigations.

Specifically, the ad hoc subcommittee is asked to deliver:

- An assessment of the degree to which each of the telescopes provides critical complementary data for LSST, multi-messenger / time-domain science, and dark energy science.
- A short list with description and evaluation of the highest impact science in other areas enabled for US observers by the facilities (separately or in combination), given the planned instrument complements.
- An assessment of whether the current US share is adequate to accomplish the highest impact scientific programs identified in the two activities above.
- Identification of modes of multi-facility use that could be further enhanced or have competitive access streamlined (e.g., GRB follow-up).
- Aspirations for improved instrumental or adaptive optics capabilities critical for the highest priority programs.

The subcommittee is therefore requested to report its preliminary findings to the AAAC at a special meeting in very early November, 2018, with a final report to be presented at the meeting in February, 2019. In accordance with Federal Advisory Committee Act (FACA) rules, the report will be discussed and approved by the AAAC at a public meeting before formal transmittal to the agencies.

We appreciate your effort in establishing this subcommittee. Its deliberations and recommendations will inform the agencies on the strategic needs for the federal ground-based OIR telescope complement and contribute to the agencies' planning activities. The formation of the ad hoc subcommittee does not imply any commitment by the agencies to specific funding or renewal of agreements for these telescopes.

We look forward to working with you in this important endeavor. The point of contact for each of the agency participants are listed below.

Sincerely,

James Siegrist

Richard Green
Division Director
Div. of Astronomical
Sciences, NSF

James Siegrist
Associate Director of Science
for High Energy Physics, DOE

12 August 2018
Date

15-Aug-2018
Date

Agency Points of Contact

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Supporting documentation:

- Gemini Board document "Beyond 2021: a Strategic Vision for the Gemini Observatory"
- Gemini International Agreement
- Report on the Kavli Futures Symposium: Maximizing Science in the Era of LSST (Oct 2016)
- Optimizing the U.S. Ground-Based Optical and Infrared Astronomy System ("Elmegreen Report")
- A System for LSST Follow-up (AURA Observatory Council slide set.)
- Dark Energy Science white papers

Committee membership

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Agenda of in-person meeting

Location: NOAO, Tucson AZ
Dates: October 9, 2018
Call-In: https://fnal.zoom.us/j/773949454

8:30 Introductions
9:00 OIR - A few years later (Elmegreen)
9:30 Tools for an OIR System (Ridgeway)
10:00 Blanco (Heathcote)
Coffee Break
11:00 Soar (Ellias)
11:30 Gemini (Lotz)
12:00 Community Perspective on LSST (Willman)

12:30 Working Lunch

1:30 Committee work session
4:30 Group reports, wrap up, next steps
5:30 Adjourn

The committee likes to thanks NOAO for their hospitality and all speakers for their time and the informative presentations and discussions.

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