LSST/Euclid/WFIRST Synergies

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LSST/Euclid/WFIRST Synergies

* LSST, Euclid, and WFIRST are all wide, deep imaging survey missions operating in the optical/IR.
* While all three are motivated (in part) to address cosmological questions, such as the nature of dark energy, the data they provide will also enable a wide variety of other investigations in astronomy and solar system science.
* The designs of the three missions are also complementary in interesting ways.
  - LSST will provide a large number of seeing-limited optical band observations of half the sky, which will go deep, and enable time-domain studies on a wide range of timescales.
  - Euclid will provide visible band and IR imaging at higher spatial resolution over a comparable region of sky, but with many fewer visits, and at much shallower depth.
  - WFIRST will cover a smaller region of sky in the IR band at the highest spatial resolution, at comparable depth to LSST.
  - Euclid and WFIRST both also provide spectroscopic surveys in the NIR.
* A synergistic approach to the analysis of data from all three missions is clearly in the interest of extracting the optimal scientific return. However, since these are separate facilities, funded by different agencies, it will take some effort to make this work.

Outline of Talk

* Brief overview of each of the three missions.

* Comment on the scientific motivation behind various forms of joint analyses.

* Review of the discussions that have occurred to date between the three project teams with the relevant US agencies.

* Summary and closing comments.

LSST in a Nutshell

* The LSST is an integrated survey system designed to conduct a decade-long, deep, wide, fast time-domain survey of the optical sky. It consists of an 8-meter class wide-field ground based telescope, a 3.2 Gpix camera, and an automated data processing system.

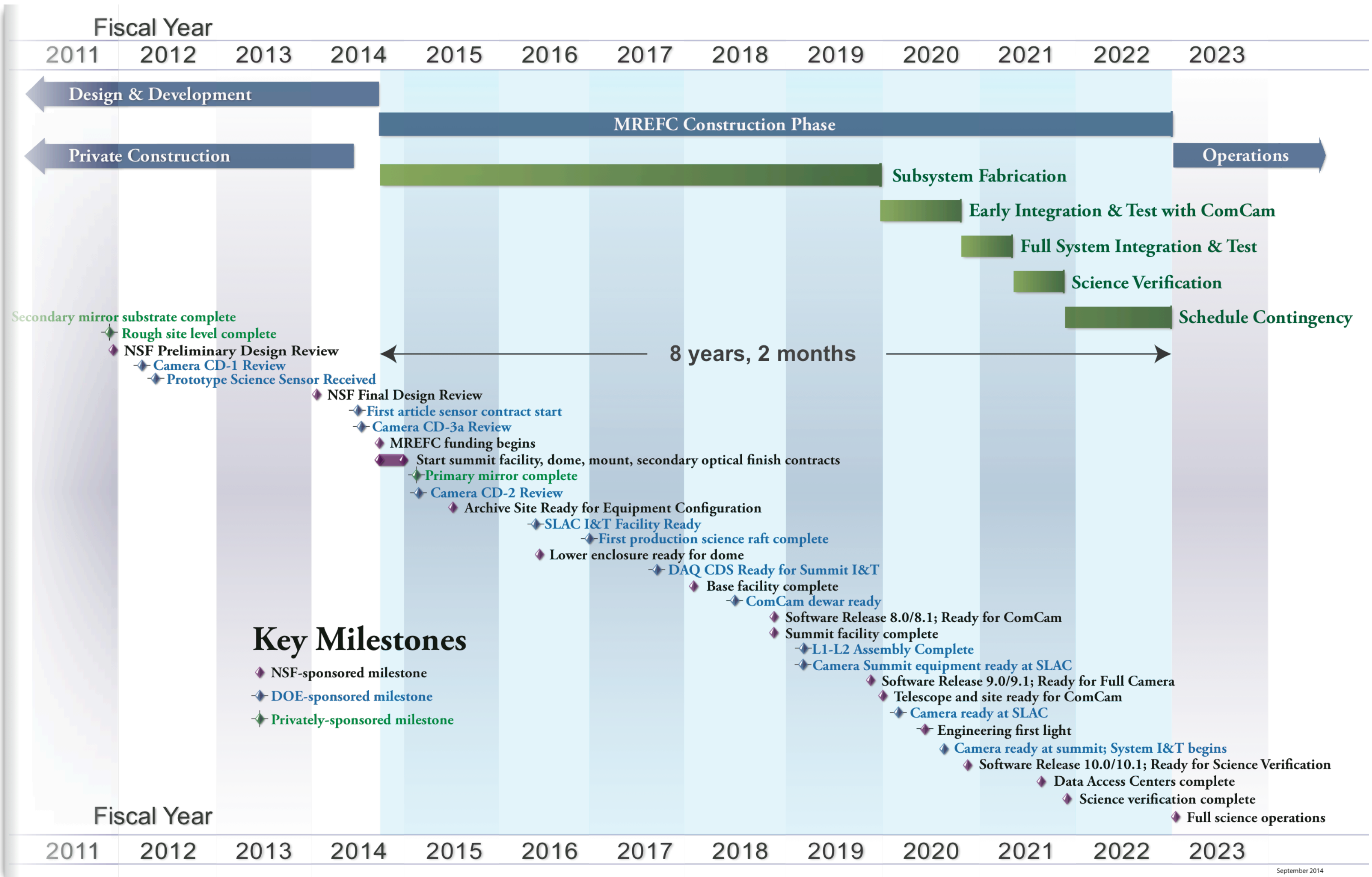
* Over a decade of operations the LSST survey will acquire, process, and make available a collection of over 5 million images and catalogs with more than 37 billion objects and 7 trillion sources. Tens of billions of time-domain events will be detect and alerted on in real-time.

* The LSST will enable a wide variety of complementary scientific investigations, utilizing a common database and alert stream. These range from searches for small bodies in the Solar System to precision astrometry of the outer regions of the Galaxy to systematic monitoring for transient phenomena in the optical sky. LSST will also provide crucial constraints on our understanding of the nature of dark energy and dark matter.

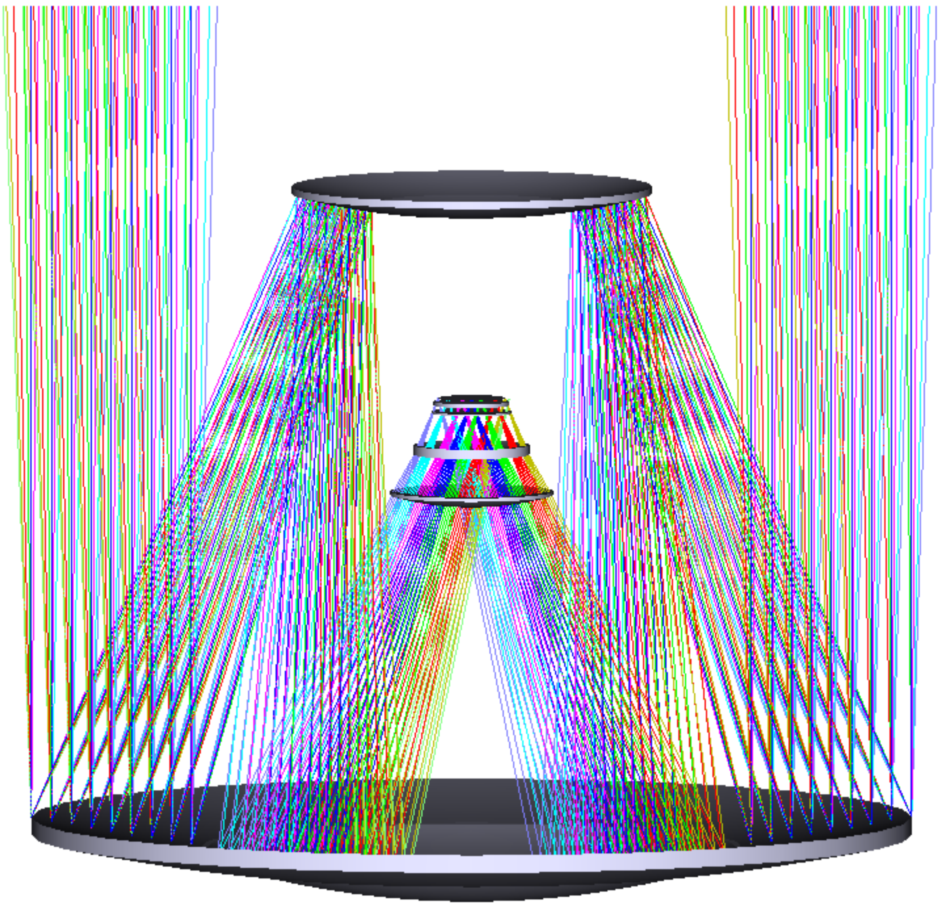
Summary of High Level Requirements

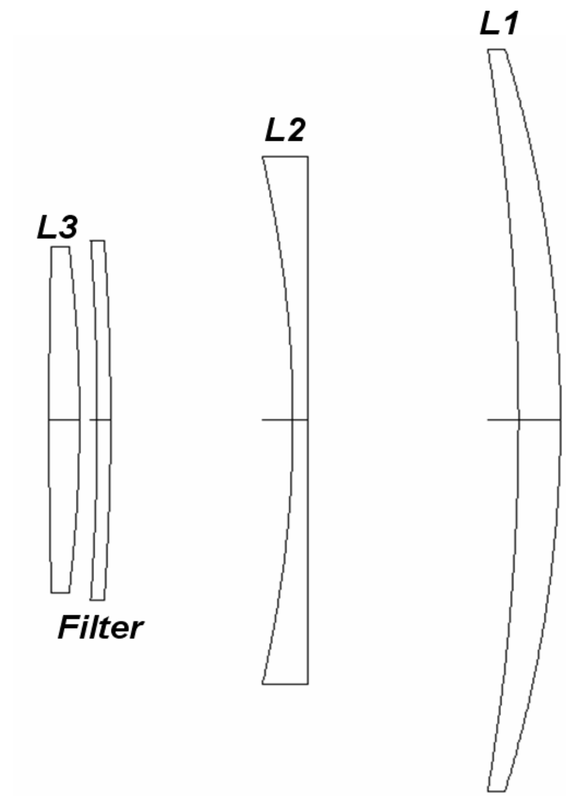
Survey Property	Performance
Main Survey Area	18000 sq. deg.
Total visits per sky patch	825
Filter set	6 filters (ugrizy) from 320 to 1050nm
Single visit	2 x 15 second exposures
Single Visit Limiting Magnitude	u = 23.5; g = 24.8; r = 24.4; I = 23.9; z = 23.3; y = 22.1
Photometric calibration	2% absolute, 0.5% repeatability & colors
Median delivered image quality	~ 0.7 arcsec. FWHM
Transient processing latency	60 sec after last visit exposure
Data release	Full reprocessing of survey data annually

Integrated Project Schedule

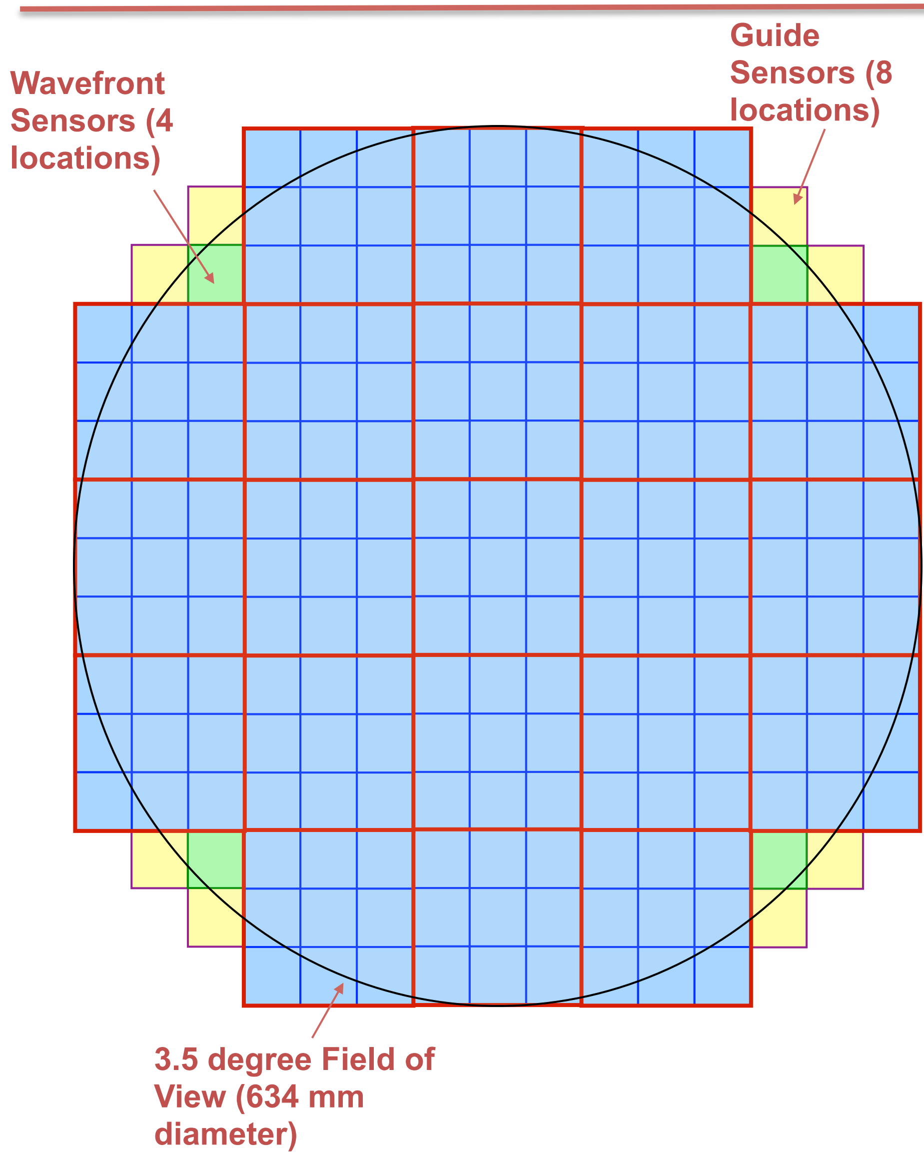


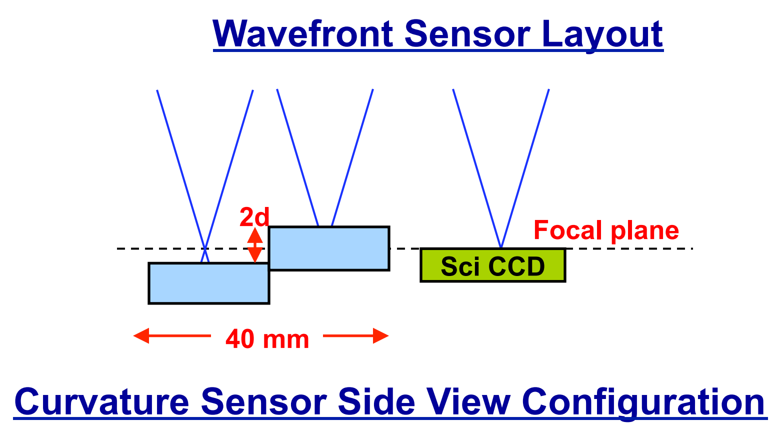
Modified Paul-Baker Optical Design





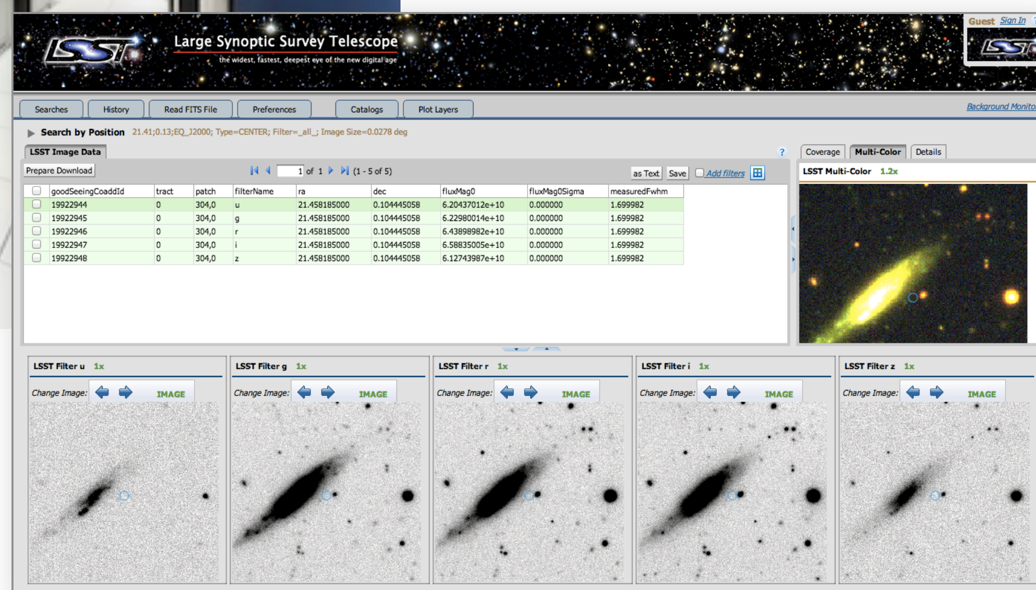
The LSST Focal Plane - 64 cm in Diameter





Ultimate LSST Deliverable: Reduced Data Products

*A petascale supercomputing system at the **LSST Archive** (at NCSA) will process the raw data, generating reduced image products, time-domain alerts, and catalogs.*



***Data Access Centers** in the U.S. and Chile will provide end-user analysis capabilities and serve the data products to LSST users.*

LSST From the User's Perspective

* A stream of ~10 million time-domain events per night, detected and transmitted to event distribution networks within 60 seconds of observation.
* A catalog of orbits for ~6 million bodies in the Solar System.

Level 1

* A catalog of ~37 billion objects (20B galaxies, 17B stars), ~7 trillion observations ("sources"), and ~30 trillion measurements ("forced sources"), produced annually, accessible through online databases.
* Deep co-added images.

Level 2

* Services and computing resources at the Data Access Centers to enable user-specified custom processing and analysis.
* Software and APIs enabling development of analysis codes.

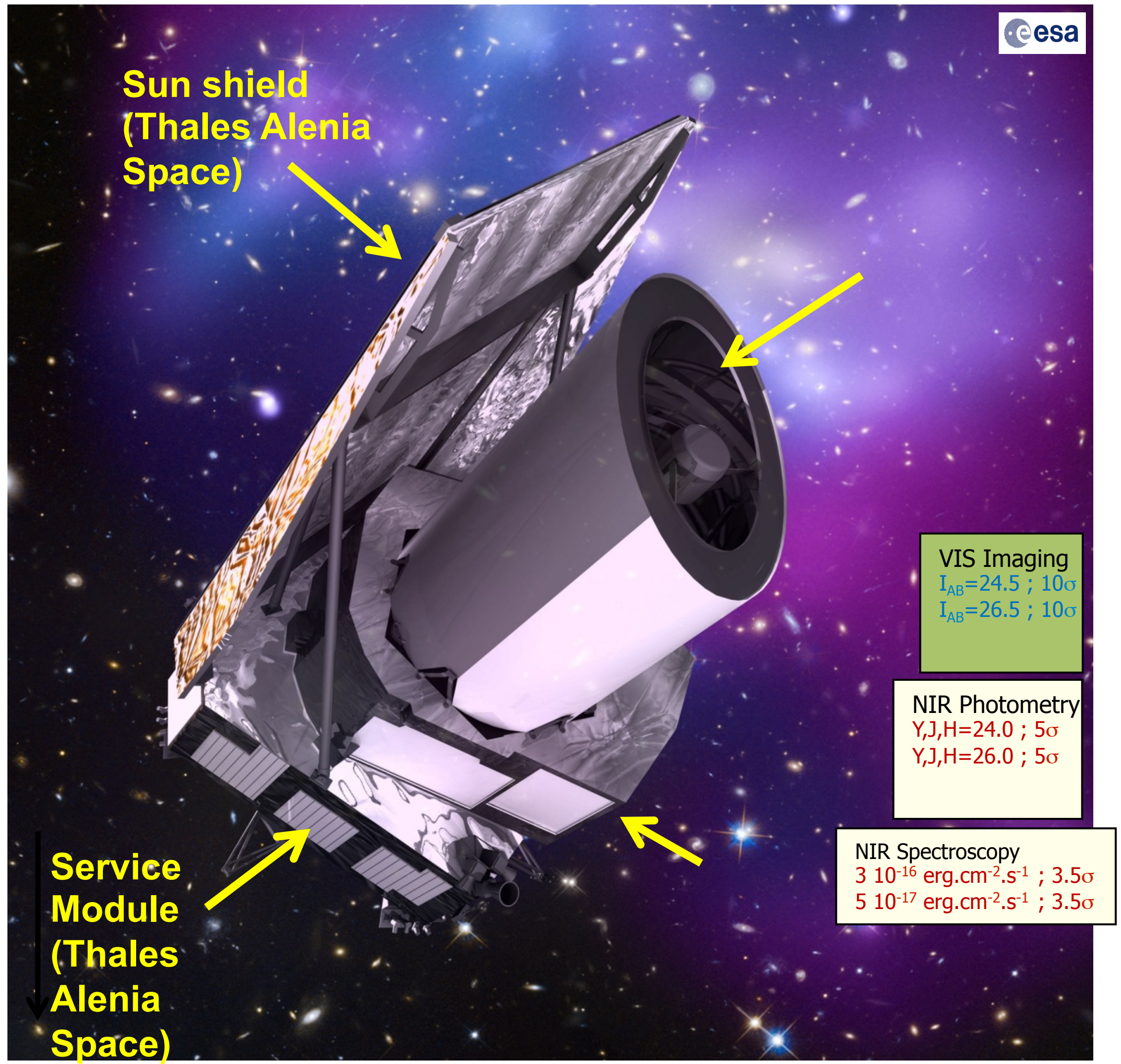
Level 3

Euclid

- Total mass satellite: 2 200 kg
- Dimensions: 4.5 m x 3 m

- Launch: end 2020 by a Soyuz rocket from Kourou spaceport
- Euclid placed in L2

- Survey: 6 years,
Wide: 15,000 deg^2 ,
12 10^9 sources,
1.5 10^9 WL galaxies,
5 10^7spectra
Deep: 2x20 deg^2



Euclid Mission

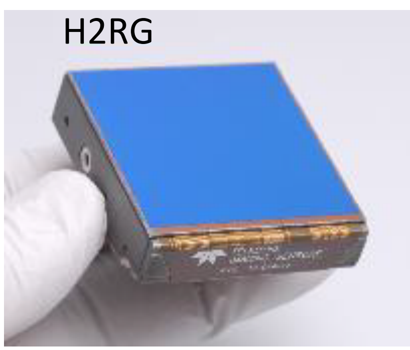
SURVEYS in 6 yrs		
	Area (deg2)	Description
Wide Survey	**15,000 deg^2**	Step and stare with 4 dither pointings per step.
Deep Survey	**40 deg^2**	In at least 2 patches of > 10 deg^2 2 magnitudes deeper than wide survey

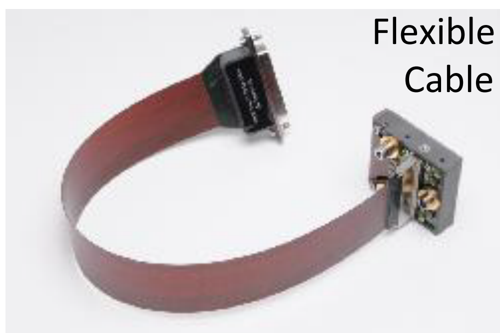
PAYLOAD					
Telescope	1.2 m Korsch, 3 mirror anastigmat, f=24.5 m				
Instrument	VIS	NISP			
Field-of-View	0.787×0.709 deg^2	0.763×0.722 deg^2			
Capability	Visual Imaging	NIR Imaging Photometry			NIR Spectroscopy
Wavelength range	550– 900 nm	Y (920-1146nm),	J (1146-1372 nm)	H (1372-2000nm)	1100-2000 nm
Sensitivity	24.5 mag 10σ extended source	24 mag 5σ point source	24 mag 5σ point source	24 mag 5σ point source	$3\ 10^{-16}$ erg cm-2 s-1 3.5σ unresolved line flux ***z* of *n*=5x10^7 galaxies**
Detector Technology	36 arrays 4k×4k CCD	16 arrays 2k×2k NIR sensitive HgCdTe detectors			
Pixel Size Spectral resolution	0.1 arcsec	0.3 arcsec			0.3 arcsec R=250

Ref: Euclid RB arXiv:1110.3193

NASA's Euclid Partnership Agreement with ESA

* ESA Responsibilities
  – Mission, Spacecraft, Launch vehicle
* Euclid Consortium (EC) responsibilities
  – 2 Instruments, Science Data Centers, science
* ESA/NASA MOU signed January 10, 2013
  – NASA responsible for Sensor Chip Systems (SCS) for Near Infrared Spectrometer and Photometer (NISP) Instrument.
    • Teledyne H2RG HgCdTe detector, SIDECAR ASIC, and flexible cryogenic cable. (16 FM and 4 FS)
  – NASA gets 40 new EC member slots, selected through NRA. ($50M lifetime science team cost); brought to 54 the number of US scientists working on Euclid
  – JPL Project Office (PM Ulf Israelsson, PS Michael Seiffert, Deputy PS Jason Rhodes)
  – Detector char. at GSFC DCL [PCOS Program Office MM Tom Griffin]
  – US Science Lead Jason Rhodes (ESA Euclid Science Team & Consortium Board)
* Euclid NASA Science Center at IPAC (ENSCI)





SIDECAR™ (system image, digitizing, enhancing, controlling, and retrieving) ASIC (Application Specific Integrated Circuit)

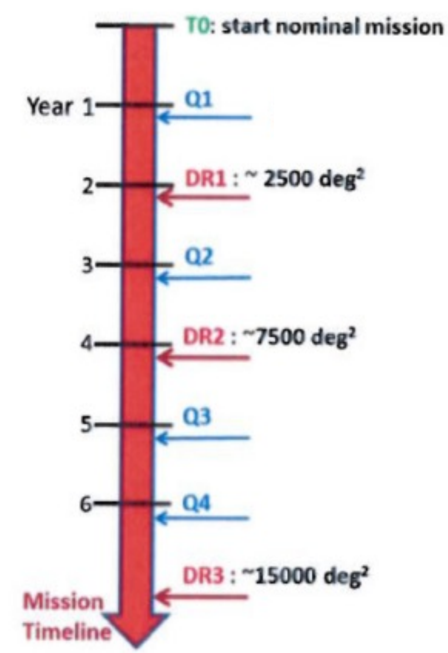
US Science Involvement

* 7 'founding members'
* 7 members of EC from LBNL, allowed membership for help on proposal phase for NISP
  - DOE funded
* In 2013 NASA/ESA MOU allowed 40 additional members
  - Rhodes team 44 members, incl. 4 postdocs (dark energy
    - 30 NASA-nominated + 7 LBNL + 7 founders
  - Kashlinsky (GSFC) team 7 members inc. 1 postdoc (NIR backgrounds)
  - Chary (IPAC) team 3 members inc. 1 postdoc (photo-z, galaxy emission)
* ENSCI member added 2014 (more coming as work ramps up)
  - ENSCI working closely with US teams (2 teams with personnel at IPAC), and will develop deep insight needed for future cross-calibration/processing/analysis activities
* 6 Detector engineers added May 2015
* 3 new scientists added (joined Rhodes team) May 2015
* Multiple grad students, 1 microlensing postdoc added
* Caltech Faculty member added in exchange for Keck time dedicated to Euclid/WFIRST spectroscopic precursor observations

Total US EC members is now ~80

Euclid Public Data Releases

- Q4 2020 launch, 3 months on-orbit verification, followed by 6 years of science survey operations
- "Quick release" of small survey areas at 14, 38, 62, 74 months after start of mission
  - Small areas only, not suitable for cosmology
- Survey will be released in stages:
  - 26 months after start (2500 deg^2, ~2023)
  - after 50 months (7500 deg^2, cumulative, ~2025)
  - after 86 months (15000 deg^2, cumulative)
- US members of the Euclid Consortium have immediate access to all data
- **Released survey data will be accessible to the entire US science community**
  - NASA has been advised to fully support US users financially (ROSES ADAP, e.g.) and scientifically/ technically (ENSCI)



ENSCI

- Euclid NASA Science Center at IPAC (ENSCI)
- ENSCI will host a Euclid 'Science Data Center (SDC)' that is a full node of the distributed Euclid Science Ground Segment (all other nodes in Europe)

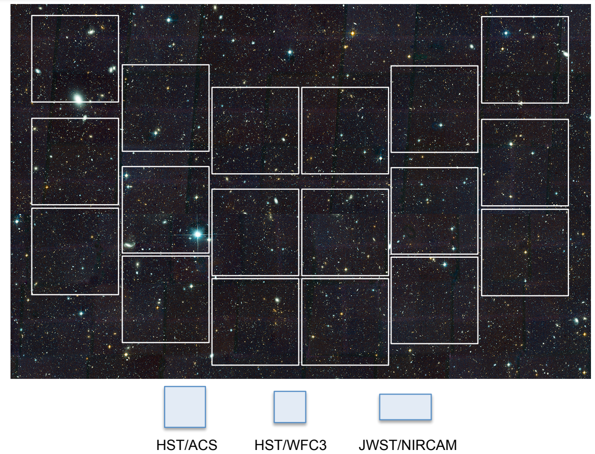
ENSCI will:

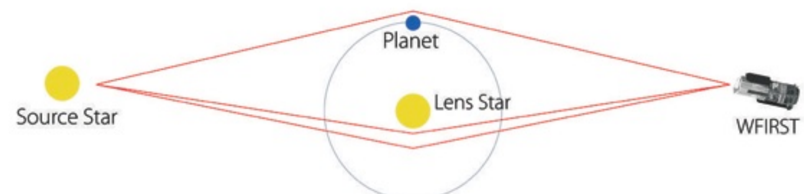
1. Support all segments of US community on Euclid
   - NASA funded science teams that have Euclid Consortium membership (with DOE participants)
   - Broader US community
2. Archive NIR detector test data
3. Support optimized exploitation of NIR detectors
   - Develop pipeline routines using US expertise

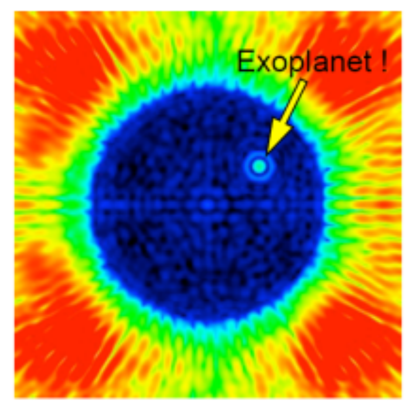
ENSCI is modeled after the successful NASA-ESA partnerships executed by IPAC, e.g. ISO, Planck, Herschel

WFIRST-AFTA Summary

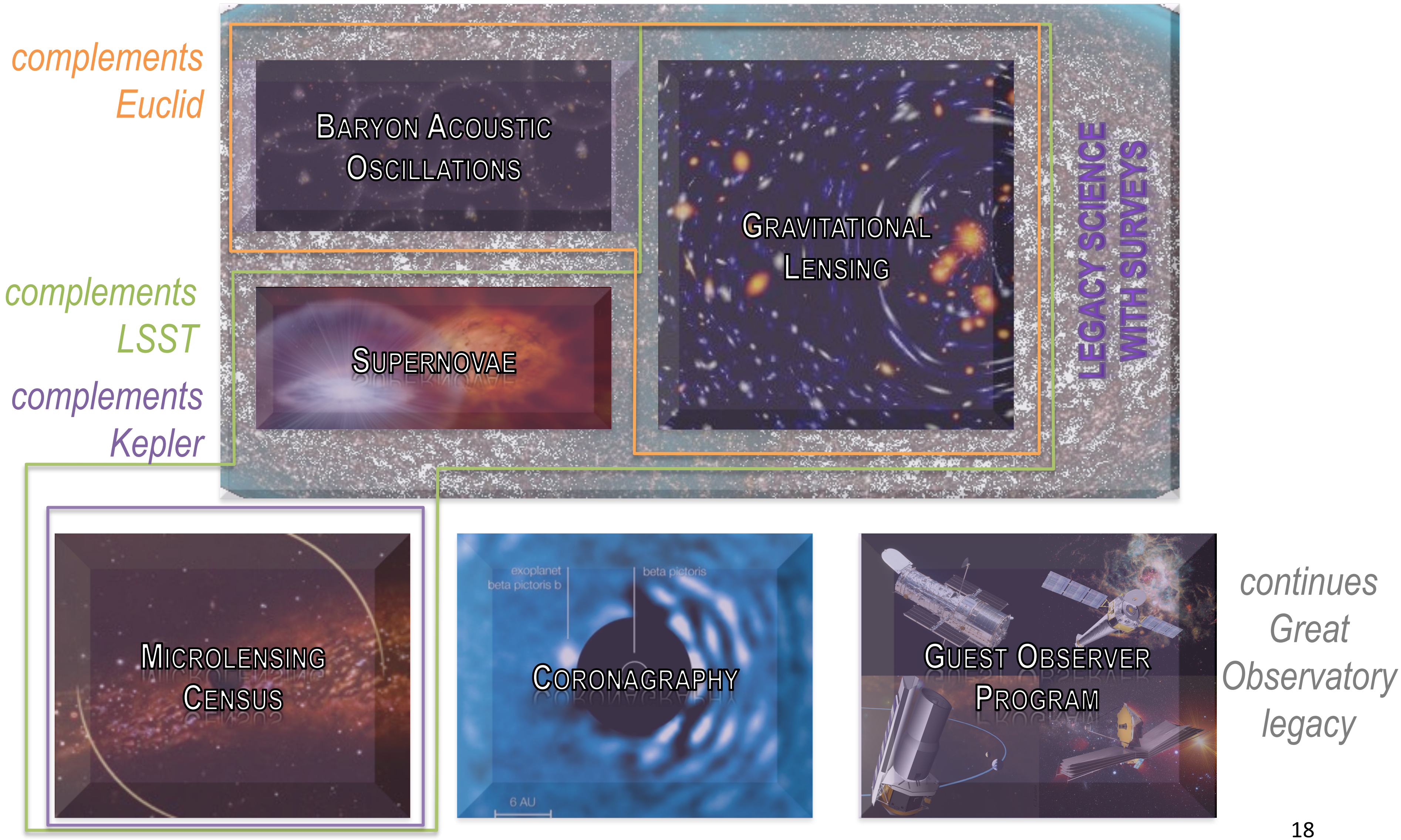
- WFIRST is the highest ranked NWNH large space mission.
  - Determine the nature of the dark energy that is driving the current accelerating expansion of the universe
  - Perform statistical census of planetary systems through microlensing survey
  - Survey the NIR sky
  - Provide the community with a wide field telescope for pointed wide observations
- Coronagraph characterizes planets and disks, broadens science program and brings humanity closer to imaging Earths.
- WFIRST gives Hubble-quality and depth imaging over thousands of square degrees
- The WFIRST-AFTA Design Reference Mission has
  - 2.4 m telescope (already exists)
  - NIR instrument with 18 H4RG detectors
  - Baseline exoplanet coronagraph
  - 6 year lifetime







WFIRST Science



WFIRST Status

* Significant WFIRST-AFTA funding added to the NASA budget by Congress for FY14 and FY15 for a total of $106.5M. FY16 budget is $90M. Expected entry into Phase A is next month for a mid-2020s launch

* Foreign contributions being actively pursued for hardware, science, and ground-based telescope time
  - Will be negotiated during Phase A, in the next ~ year, with 'Acquisition Strategy Meeting' in August, 2016.
  - Need to be decided prior to Phase B, with informal agreements in place well prior to 'Systems Requirements Review' in Summer 2017.

* Formulation Science Working Group selected last month to assist Project in requirements, methods, algorithm, simulations development through ~2021
  - Made up of 11 Science investigation Teams and 2 Adjutant Scientists

* Operations Science Working Group selected in ~2021

WFIRST FSWG

Name	Affiliation	Role
Neil Gehrels, *Chair*	NASA/GSFC	Project Scientist
David Spergel, *Deputy Chair*	Princeton University	Wide-Field Adjutant Scientist
Jeremy Kasdin, *Deputy Chair*	Princeton University	Coronagraph Adjutant Scientist
Members		
Dominic Benford, *ex officio*	NASA/HQ	Program Scientist
Dave Bennett	UMBC & GSFC	Microlensing
Ken Carpenter, *ex officio*	NASA/GSFC	Project science
Roc Cutri, *ex officio*	IPAC	Science center
Olivier Doré	NASA/JPL	Cosmology: GRS+WL
Ryan Foley	UIUC	Supernova Cosmology
Scott Gaudi	Ohio State U.	Microlensing
Chris Hirata	Ohio State U.	Cosmology: WL
Jason Kalirai	JHU & STScI	GI/GO – Galactic science
Jeff Kruk, *ex officio*	NASA/GSFC	Project science
Nikole Lewis	STScI	Coronagraph
Bruce MacIntosh	Stanford	Coronagraph
Roeland van der Marel, *ex officio*	STScI	Science center
S. Perlmutter	UC Berkeley	Supernova Cosmology
James Rhoads	Arizona State	GI/GO – Cosmic Dawn
Jason Rhodes, *ex officio*	NASA/JPL	Project science
Aki Roberge	NASA/GSFC	Coronagraph
Brant Robertson	UC Santa Cruz	GI/GO – Galaxy evolution
Alexander Szalay	Johns Hopkins	GI/GO – Archival science
Wes Traub, *ex officio*	NASA/JPL	Project science
Maggie Turnbull	GSI & SETI	Coronagraph
Yun Wang	Caltech/IPAC	Cosmology: GRS
David Weinberg	Ohio State Univ.	Cosmology: Clusters
Benjamin Williams	U. Washington, Seattle	GI/GO – Nearby Galaxies

Nominal Capabilities
(To be discussed by FSWG)

WFI:

Imager	**0.76-2.0 microns** 0.28° FoV, 0.11" pixel scale, 18 4k by 4k H4RG
Filters:	z (0.76 - 0.98), Y (0.93-1.19), J (1.13-1.45), H(1.38-1.77), F184 (1.68-2.0), W149 (0.93-2.00)
Grism:	**1.35-1.89 microns** 0.28° FoV, R=461λ, 0.11" pixel scale
IFU:	**0.6-2.0 microns** 3" & 6" FoV, R~100, 0.075" pixel scale

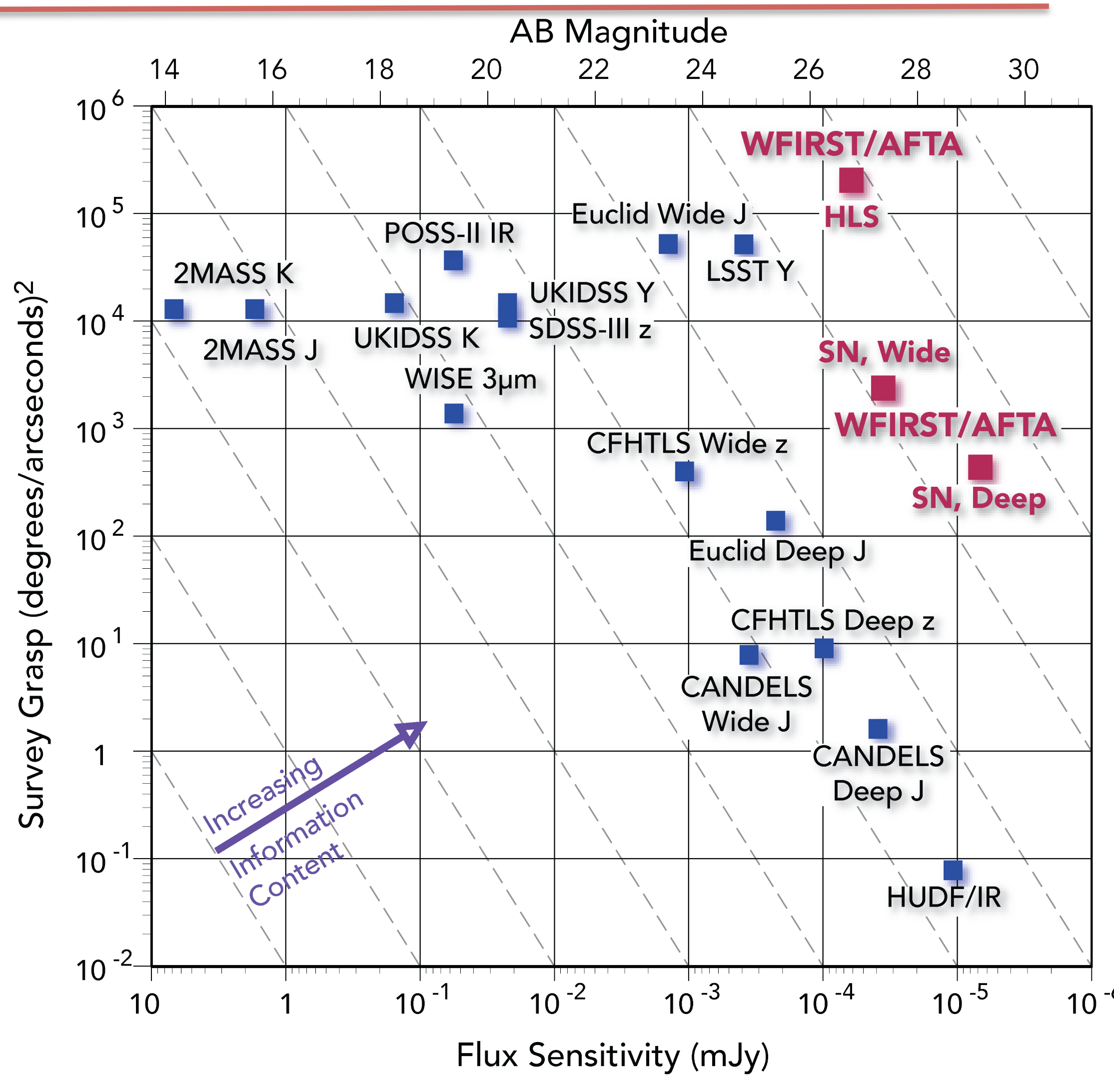
Coronagraph:

Imager:	**0.43-0.97 microns** 1.63" FoV (radius), 0.01" pixel scale, 1k x 1k EMCCD, 10^{-9} final contrast, 100-200 mas inner working angle,
IFS:	**0.60-0.97 microns** 0.82" FoV (radius), R~70

Field of Regard: 54° - 126° 60% of sky instantaneous

WFIRST-AFTA Surveys

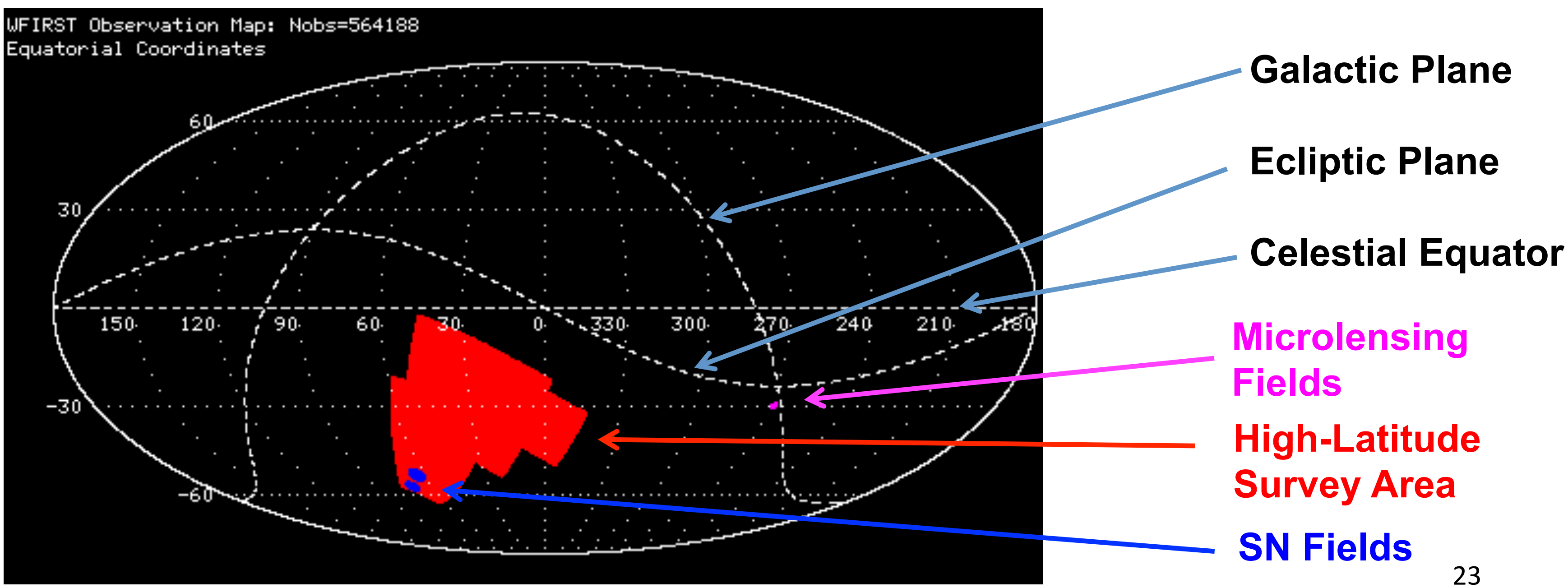
- Multiple surveys:
  - High-Latitude Survey
    - Imaging, spectroscopy, supernova monitoring
  - Repeated Observations of Bulge Fields for microlensing
  - 25% Guest Observer Program
  - Coronagraph Observations
- Flexibility to choose optimal approach



Near Infrared Surveys

Example Observing Schedule (to be revised by future science team)

- High-latitude survey (HLS: imaging + spectroscopy): 2.01 years
  - 2227 deg^2 @ ≥3 exposures in all filters (2279 deg^2 bounding box)
- 6 microlensing seasons (0.98 years, after lunar cutouts)
- SN survey in 0.63 years, field embedded in HLS footprint
- 1 year for the coronagraph, interspersed throughout the mission
- Unallocated time is 1.33 years (includes GO program)



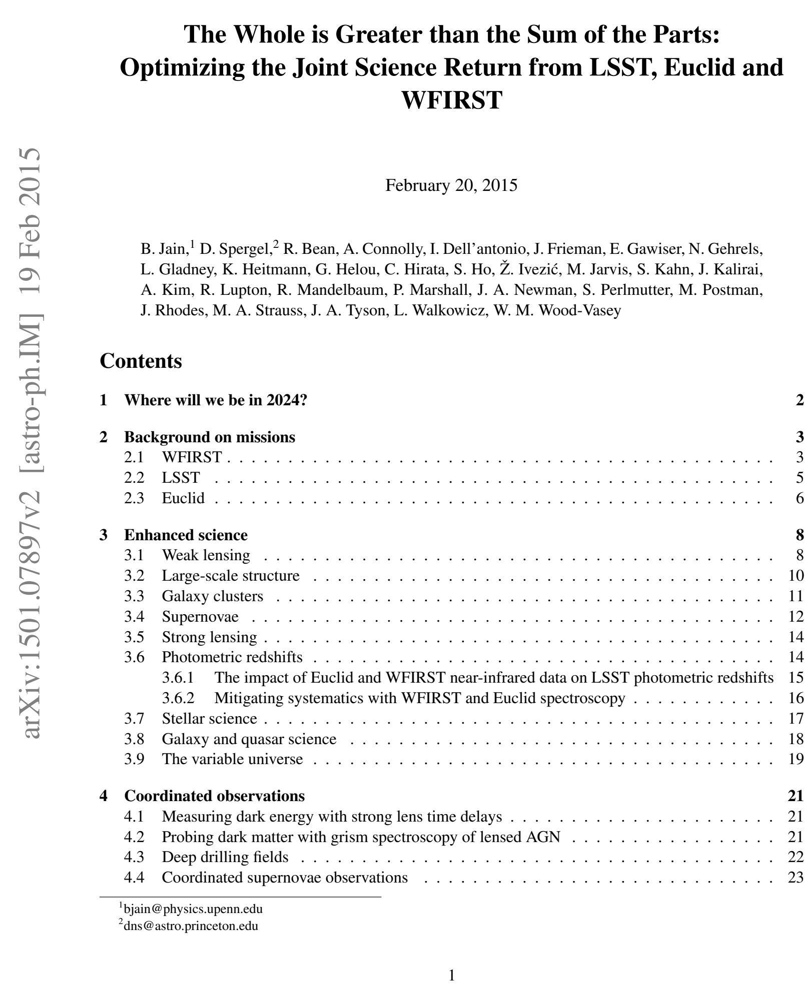
Case for Joint Analyses

* LSST, Euclid, and WFIRST are highly complementary. LSST and Euclid will cover large fractions of the sky, but at different depth, with different spatial resolution, and in different wavelength bands. WFIRST will get to comparable depth to the full LSST, but in the near infra-red, with much high spatial resolution, but over a more limited region of the sky.

* The biggest advantage of combining data will come from significant reduction in systematic errors, affecting each of the various different cosmological probes, that builds on the differences in characteristics.

* For the ultimate weak lensing and large-scale structure measurements, a combination of LSST+Euclid/WFIRST is essential to provide the multiband photometry necessary to improve photometric redshifts, in particular to narrow the error distribution and suppress catastrophic errors.

* In addition, shear comparisons over limited regions of sky between the higher spatial resolution images obtained by Euclid and WFIRST can help to calibrate both multiplicative and additive errors in the LSST shear determinations. Finally, the higher resolution imaging provided by the space missions will aid in galaxy deblending in the LSST image analyses.



The Whole is Greater than the Sum of the Parts: Optimizing the Joint Science Return from LSST, Euclid and WFIRST

February 20, 2015

B. Jain,[1] D. Spergel,[2] R. Bean, A. Connolly, I. Dell'antonio, J. Frieman, E. Gawiser, N. Gehrels, L. Gladney, K. Heitmann, G. Helou, C. Hirata, S. Ho, Ž. Ivezić, M. Jarvis, S. Kahn, J. Kalirai, A. Kim, R. Lupton, R. Mandelbaum, P. Marshall, J. A. Newman, S. Perlmutter, M. Postman, J. Rhodes, M. A. Strauss, J. A. Tyson, L. Walkowicz, W. M. Wood-Vasey

Contents

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Sensitivity Comparisons

- Surveys match in depth after different integration times
- Euclid depth shown is for NIR-WIDE and VIS-DEEP
  - VIS-WIDE is 2 mag shallower
  - Plot is from WFIRST SDT Report

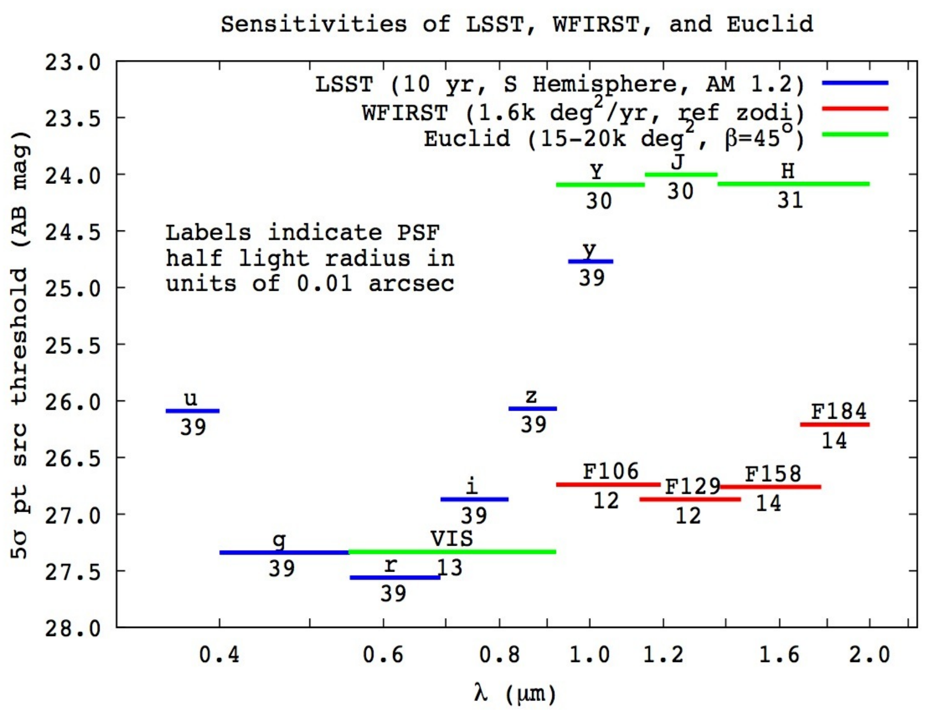

Figure 2-2: Depth in AB magnitudes of the WFIRST-2.4 high-latitude survey (blue), Euclid (green), and LSST (red) imaging surveys. Labels below each bar indicate the size of the PSF (specifically, the EE50 radius) in units of 0.01 arcsec. The near-IR depth of the WFIRST-2.4 is well matched to the optical depth of LSST (10-year co-add).

Science Gains: Cosmology

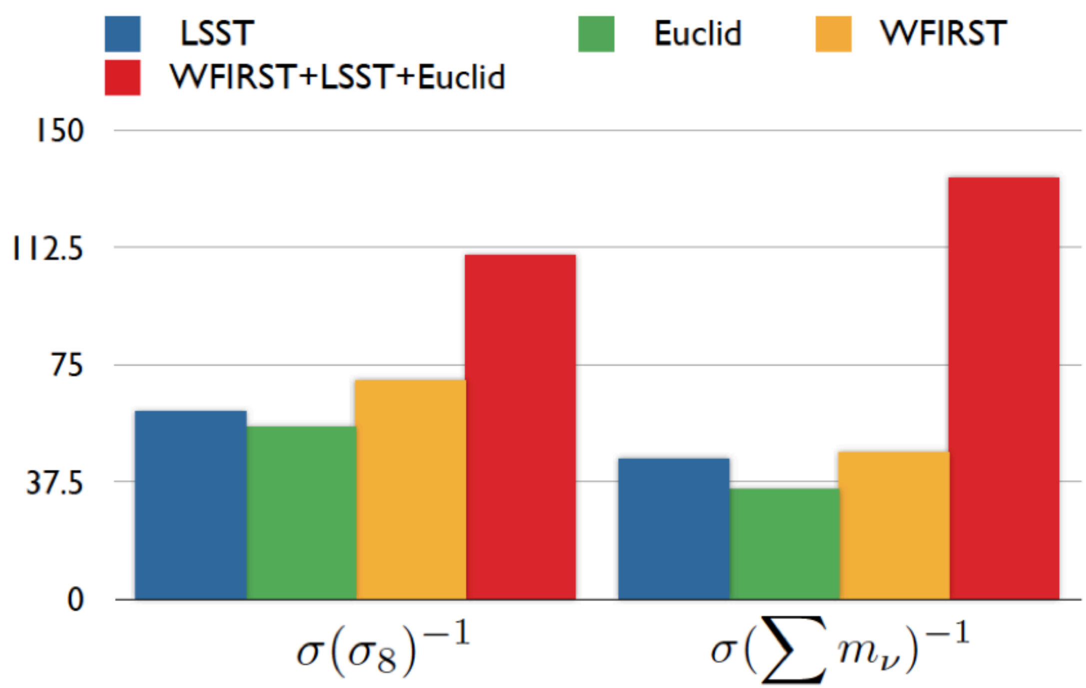

Figure 1: The chart shows how the complementarity of LSST, Euclid and WFIRST contributes to significant improvement in constraints on cosmological parameters. As described in the text, the improved constraints on σ_8 come from the mitigation of intrinsic alignment and other systematics in weak lensing; the improved constraints on the sum of neutrino masses $\sum m_\nu$ (in eV) comes from the combination of the weak lensing, CMB convergence maps, and galaxy clustering, in particular by reducing the multiplicative bias in shear measurement. Note that the space based surveys are assumed to have used ground based photometry to obtain photo-z's.

Joint Pixel Level Processing Between LSST, Euclid, and WFIRST

* There are significant systematic effects that will be encountered if we simply combine catalogued fluxes determined separately by each of the missions. The way to avoid this problem is to re-reduce all of the pixel-level data jointly, using the same apertures, centroids, etc.

* There are other benefits to joint pixel-level processing, eg using the higher resolution space-based images to deblend the LSST images, using the IR colors of stars together with LSST data for astronomical investigations, etc.

* A joint analysis of LSST data together with Euclid and WFIRST data is outside the scope of the current LSST Project. This applies to both figuring out how to do it, and implementing it in operations.

* It is also outside the scope of the NASA-supported US effort on Euclid, and the anticipated NASA-supported data processing effort for WFIRST.

* Therefore, we could not entertain serious discussions of this until we got a blessing from the agencies that they were interested in this.

* That "occurred" in December, 2014. At that time, all three expressed interest in convening a meeting on this topic. We held that meeting in June, one rep from each project, plus the appropriate people from NSF, DOE, and NASA.

Joint Pixel Level Processing Between LSST, Euclid, and WFIRST

* We have now established a Tri-Agency, Three-Project Working Group (TAG). The members are: Nigel Sharp (NSF), Kathy Turner and Eric Linder (DOE), Dominic Benford and Linda Sparke (NASA), Steve Kahn (LSST), Rachel Bean (DESC), Jason Rhodes (Euclid), Neil Gehrels (WFIRST), David Spergel (WFIRST).

* There are two sub-working groups: Pixel-level processing, and cosmological simulations.

* There are three anticipated phases for the joint pixel-level processing activity:
  - An unfunded "scoping phase", that occurred over the summer, where the two sub-working groups made a plan for investigation and estimated rough costs. We were supposed to report out at a meeting on Sept 21-22 2015, but that has now been postponed.
  - An R&D phase, jointly funded by all three agencies.
  - A construction phase, where the software to enable the processing is written.
  - An implementation phase, where the joint processing is accomplished.

* If this is implemented in the LSST processing pipeline, the cost increase is not likely to be significant, but is still non-negligible.

Joint Pixel Level Processing Between LSST, Euclid, and WFIRST

* Cooperation with Euclid requires special consideration, because, at present, most Euclid Consortium members will not have access to LSST data, and most Americans will not have access to Euclid data during the proprietary periods.

* Draft agreements between the Euclid Consortium, the LSST Project, and the LSST DESC have been generated on both sides of the Atlantic, but, to date, none has been found acceptable to all sides.

* We are now reforming a Euclid/LSST discussion group to try to work this, first by cooperatively developing the science case, and then an implementation plan.

* But this process will be drawn out, and we do not expect an agreement on a very short timescale.

Summary

* LSST, Euclid, and WFIRST are all moving forward toward the onset of operations on similar timescales.

* While there is strong overlap in the science planned for these three separate facilities, their designs are highly complementary.

* A combined analysis of the data from all three will provide a significant enhancement in scientific return. For reduction of systematics, this will probably require joint processing at the pixel level.

* That form of joint analysis is outside the current scope of all three projects in the US. It will thus require some additional funding.

* We have formed a Tri-Agency, Tri-Project Working Group to explore this. The initial reports from the technical subgroups will occur this Spring.