Exploring the Quantum Universe

Pathways to Innovation and Discovery in Particle Physics

Report of the 2023 Particle Physics Project Prioritization Panel

AAAC

December 15, 2023

Exploring the Quantum Universe

2023p5report.org

U.S. DEPARTMENT OF ENERGY

NSF


Great panel!

P5 Panel

Shoji Asai (University of Tokyo)
Amalia Ballarino (CERN)
Tulika Bose (Wisconsin–Madison)
Kyle Cranmer (Wisconsin–Madison)
Francis-Yan Cyr-Racine (New Mexico)
Sarah Demers (Yale)
Cameron Geddes (LBNL)
Yuri Gershtein (Rutgers)
Karsten Heeger (Yale) - *Deputy Chair*
Beate Heinemann (DESY)
JoAnne Hewett (SLAC) - HEPAP chair, ex officio until May 2023
Patrick Huber (Virginia Tech)
Kendall Mahn (Michigan State)
Rachel Mandelbaum (Carnegie Mellon)
Jelena Maricic (Hawaii)
Petra Merkel (Fermilab)
Christopher Monahan (William & Mary)
Hitoshi Murayama (Berkeley) - *Chair*
Peter Onyisi (Texas Austin)
Mark Palmer (BNL)
Tor Raubenheimer (SLAC/Stanford)
Mayly Sanchez (Florida State)
Richard Schnee (South Dakota School of Mines & Technology)
Sally Seidel (New Mexico) – interim HEPAP chair, ex officio since June 2023
Seon-Hee Seo (IBS Center for Underground Physics until Sep, Fermilab since Sep)
Jesse Thaler (MIT)
Christos Touramanis (Liverpool)
Abigail Vieregg (Chicago)
Amanda Weinstein (Iowa State)
Lindley Winslow (MIT)
Tien-Tien Yu (Oregon)
Robert Zwaska (Fermilab)

Blue: international members

Interface to EPP2024

- An NRC panel also studying the future of particle physics
- EPP2024 looks into long-term vision, dreams
  - unconstrained by budget scenarios
- I was on EPP2024 until I was appointed as the P5 chair
- JoAnne and I participated in their November & December meetings
- Karsten took part of the panel discussion in their July meeting
- We invited all EPP2024 members to P5 town halls to make sure we get the same inputs from the community
  - We overlapped at Fermilab in March
- Will keep informing EPP2024 about our progress and vice versa
- What P5 recommends should smoothly connect to their longer-term vision

P5 Charge (dated November 2, 2022) 1/8

Dear Dr. Hewett:

The 2014 report of the Particle Physics Project Prioritization Panel (P5), developed under the auspices of the High Energy Physics Advisory Panel (HEPAP), successfully laid out a compelling scientific program that recommended world-leading facilities with exciting new capabilities, as well as a robust scientific research program. That report was well received by the community, the U.S. Department of Energy (DOE) and the National Science Foundation (NSF), and Congress as a well-thought-out and strategic plan that could be successfully implemented. HEPAP's 2019 review of the implementation of this plan demonstrated that many of the report's recommendations are being realized, and the community has made excellent progress on the P5 science drivers.

As the landscape of high-energy physics continues to evolve and the decadal timeframe addressed in the 2014 P5 report nears its end, we believe it is timely to initiate the next long-range planning guidance to the DOE and NSF. To that end, we ask that you constitute a new P5 panel to develop an updated strategic plan for U.S. high-energy physics that can be executed over a 10-year timeframe in the context of a 20-year, globally aware strategy for the field.

- The 2014 report was successful
- 2019 implementation review by HEPAP showed progress on the plan

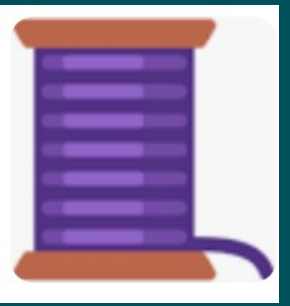
- 2023 P5 to update strategic plan over 10-yr timeframe in 20-yr context

P5 Charge 2/8

A critical element of this charge is to assess the continued importance of the science drivers identified by the 2014 P5 report and, if necessary, to identify new science drivers that have the potential to enable compelling new avenues of pursuit for particle physics. Specifically, we request that HEPAP 1) evaluate ongoing projects and identify potential new projects to address these science drivers; 2) make the science case for new facilities and capabilities that will advance the field and enhance U.S. leadership and global partnership roles; and 3) recommend a program portfolio that the agencies should pursue in this timeframe, along with any other strategic actions needed to ensure the broad success of the program in the coming decades.

In developing the plan, we would like the panel to take into consideration several particularly relevant aspects of constructing a compelling and well-balanced portfolio:

- Re-evaluate the 2014 science drivers
- Evaluate ongoing projects
- Identify new projects
- Make science case for new facilities and capabilities
- Recommend program portfolio

P5 Charge  4/8

- A successful plan should maintain a balance of large, medium, and small projects that can deliver scientific results throughout the decadal timeframe. We do not expect the panel to consider the large number of possible small-scale projects individually, but advice on research areas where focused investments in smallscale projects can have a significant impact is welcome.
- There are elements of DOE HEP-operated infrastructure that are a stewardship responsibility for HEP. Investments to maintain that infrastructure in a safe and reliable condition are an HEP responsibility and are outside the scope of the panel. Major infrastructure upgrades that create new science capabilities are within the scope of the charge and should be considered by the panel.
- Successfully exploiting a newly built project requires funding for the commissioning and operation of the project and to support the researchers who will use these new capabilities to do world-leading science. Funding is also needed for research and development (R&D) that develops new technologies for future projects. Scientists and technical personnel working in experimental particle physics often contribute to all these project phases, while theoretical physics provides both the framework to evolve our fundamental understanding of the known universe as well as the innovative concepts that will expand our knowledge into new frontiers. The panel should deliver a research portfolio that will balance all these factors and consider related issues such as training and workforce development.

- Maintain balance of large, medium & small projects
- Advise on science topics to focus small projects
- Assess infrastructure upgrades that create new science capabilities
- Remember costs of R&D, commissioning, and operations for future projects
- Remember that a balanced core research budget is paramount to producing science from current projects and developing ideas for new ones

P5 Charge 5/8

- Both NSF and DOE are deeply committed to diversity, equity, inclusion, and accessibility principles in all the scientific communities they support. Creating a more diverse and inclusive workforce in particle physics will be necessary to implement the plan that this panel recommends, and the panel may further recommend strategic actions that could be taken to address or mitigate barriers to achieving these goals.
- Broad national initiatives relevant to the science and technology of particle physics have been developed by the administration and are being implemented by the funding agencies. These include, but are not limited to, investments in advanced electronics and instrumentation, artificial intelligence and machine learning, and quantum information science. Potential synergies between these initiatives and elements of the recommended portfolio should be considered.

- Remember that a diverse workforce results in improved science

- Address synergies with broad national initiatives

P5 Charge - budget scenarios 🧵 6/8

We request that the panel include these considerations in their deliberations and discuss how they affect their recommendations in the report narrative.

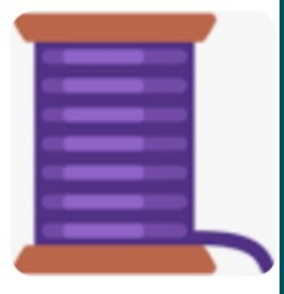
The panel's report should identify priorities and make recommendations for an optimized particle physics program over 10 years, FY 2024–FY 2033, under the following budget scenarios:

1) Increases of 2.0 percent per year during fiscal years 2024 to 2033 with the FY 2024 level calculated from the FY 2023 President's Budget Request for HEP.
2) Budget levels for HEP for fiscal years 2023 to 2027 specified in the Creating Helpful Incentives to Produce Semiconductors and Science Act of 2022, followed by increases of 3.0 percent per year from fiscal years 2028 to 2033.

The recommended projects and initiatives should be implementable under reasonable assumptions and be based on generally accepted estimates of science reach and capability. Estimated costs for future projects and facility operations should be given particular scrutiny and may be adjusted if the panel finds it prudent to do so. Given the long timescales for realizing these initiatives, we expect the funding required to enable the priorities the panel identifies may extend well past the 10-year budget profile, but any recommendation should be technically and fiscally plausible to execute in a 20-year timeframe.

- Scenario A: 2% increase per year
- Scenario B: Budgets in Chips and Science Act, followed by 3% increase per year

- Evaluate projected project costs
- Plan should be executable in 20-yr timeframe

P5 Charge  8/8

Finally, effective communication about the excitement, impact, and vitality of particle physics that can be shared with a general audience and other disciplines continues to be critical when advocating the strategic plan. It would be particularly valuable if the panel could re-state the key scientific questions that drive the field so that they are accessible to non-specialists and crisply articulate the value of basic research and the broader benefits of particle physics on other sciences and society.

We would appreciate the panel's preliminary comments by August 2023 and a final report by October 2023. We recognize that this is a challenging task; nevertheless, your assessments will be an essential input to planning at both the DOE and NSF.

Sincerely,

Asmeret Asefaw Berhe
Director, Office of Science
U.S. Department of Energy

Sean L. Jones
Assistant Director
Directorate for Mathematical and
Physical Sciences
National Science Foundation

- Effectively communicate the 2023 P5 plan once it's finished
- Preliminary comments in August 2023
- Report due by October 2023

P5 Timetable and Process

Charge issued on Nov 2, 2022
Panel formed by the end of January 2023

Information Gathering

Snowmass Report

Open Town Halls

LBNL: February (513), Fermilab/Argonne: March (797) overlapped with EPP2024
Brookhaven: April (666), SLAC: May (512)

Virtual Town Halls

UT Austin: June (159) with an exclusive session for early career scientists, Virginia Tech, June (119)

All town halls offered live captioning and ASL

Many occasions for community engagement throughout the process

Deliberation Phase

Closed meetings

Austin, Gaithersburg, Santa Monica, Denver, May to August

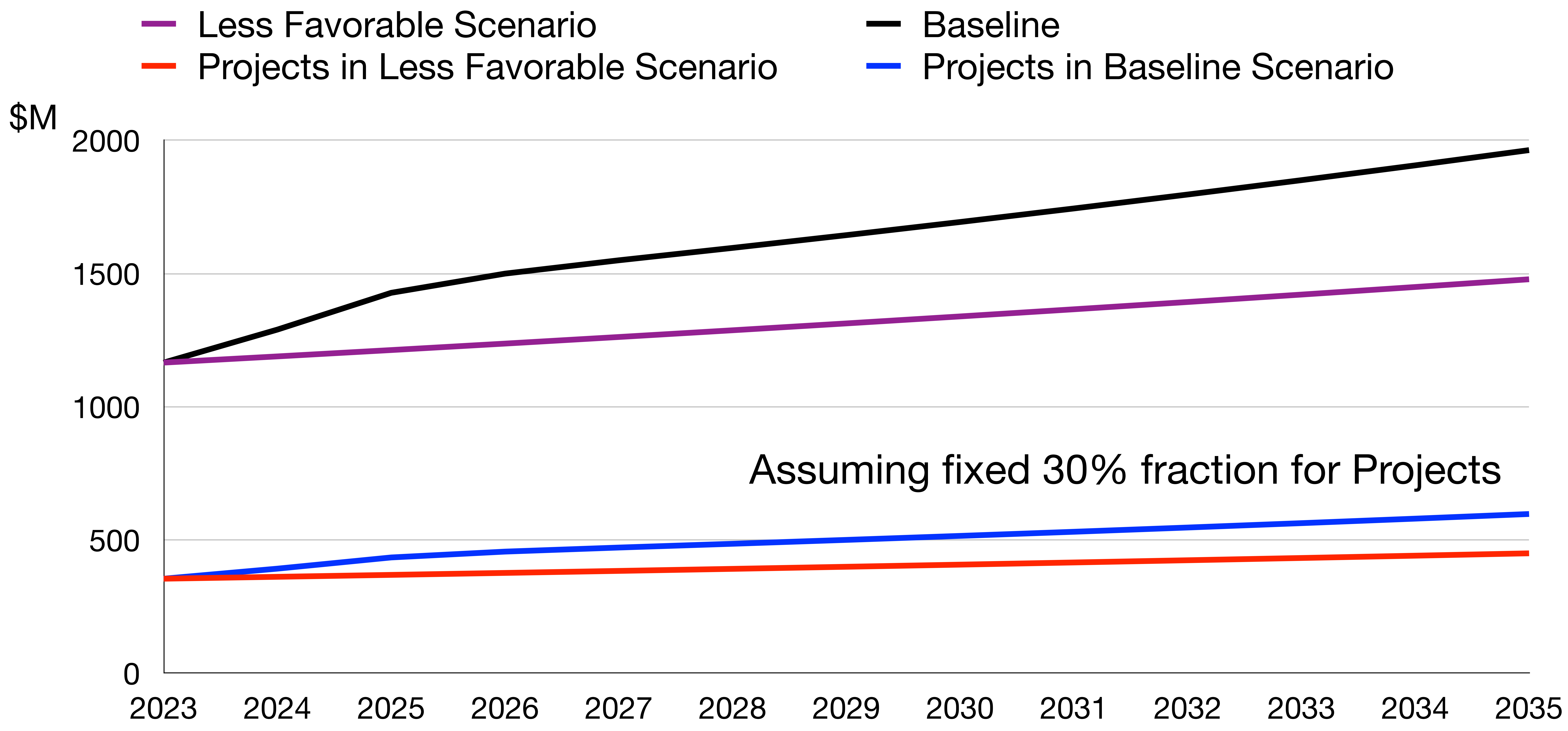
Additional input from

Agencies Asmeret Berhe, Harriet Kung (DOE), many from DOE/HEP, NSF/PHY, NSF/AST, NSF/OPP
Government Cole Donovan (State, OSTP)
Community

International Benchmarking Panel, computing frontier, DPF leadership, previous P5 (Steve Ritz, Andy Lankford), CoV reports (Ritchie Patterson, Dmitry Denisov)

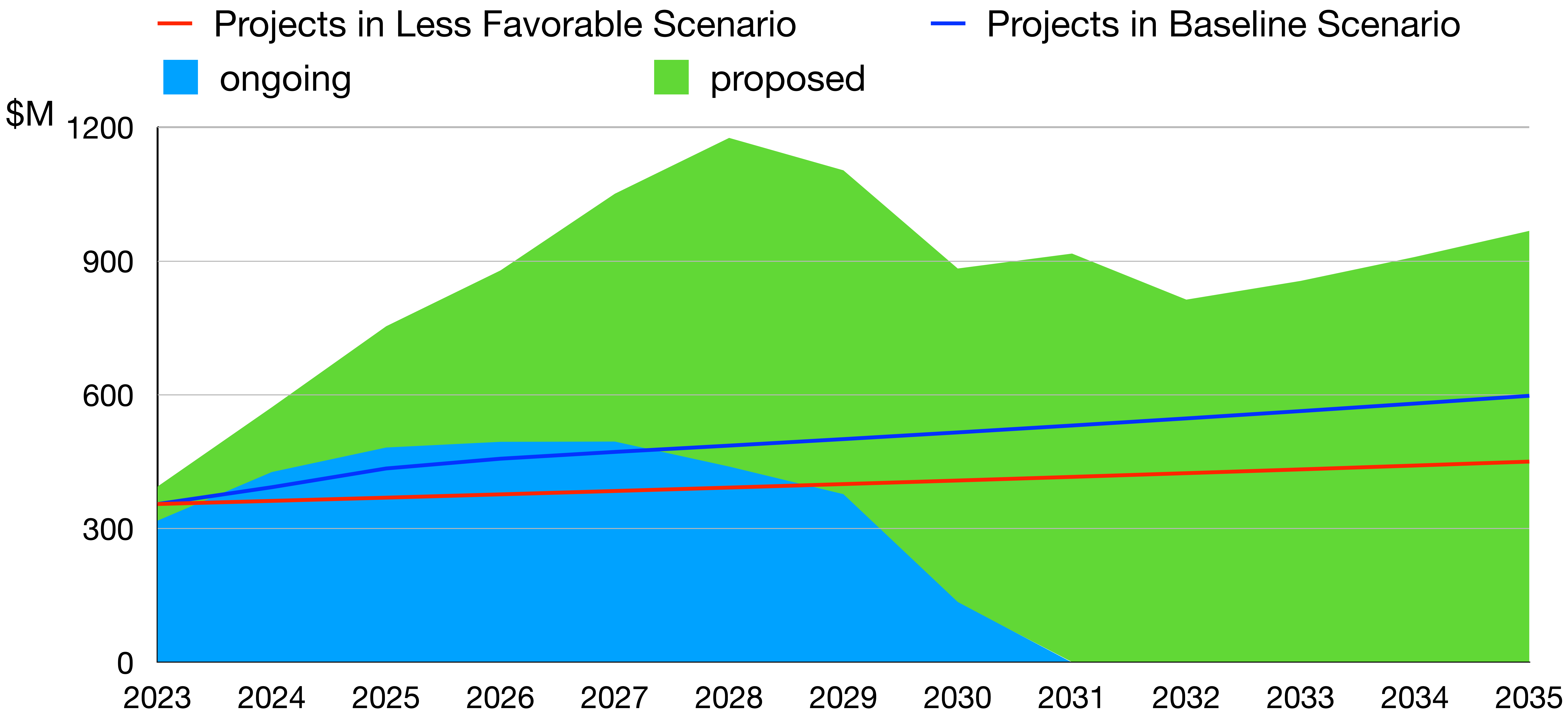
Frequent Meetings by working groups

Budget Scenarios



DOE only

Budget Scenarios and Projects



some multi-billion-dollar projects excluded

DOE only

Subcommittee on Costs/Risks/Schedule

Critical to understand maturity of cost estimates and risks and schedule for prioritization of projects within budget scenarios

Lesson from previous P5 that some of the costs were off by a factor of ~π

Subcommittee

- **Jay Marx (Caltech), Chair**
- Gil Gilchriese, Matthaeus Leitner (LBNL)
- Giorgio Apollinari, Doug Glenzinski (Fermilab)
- Mark Reichanadter, Nadine Kurita (SLAC)
- Jon Kotcher, Srini Rajagopalan (BNL)
- Allison Lung (JLab)
- Harry Weerts (Argonne)

poor people's equivalent to ASTRO2020

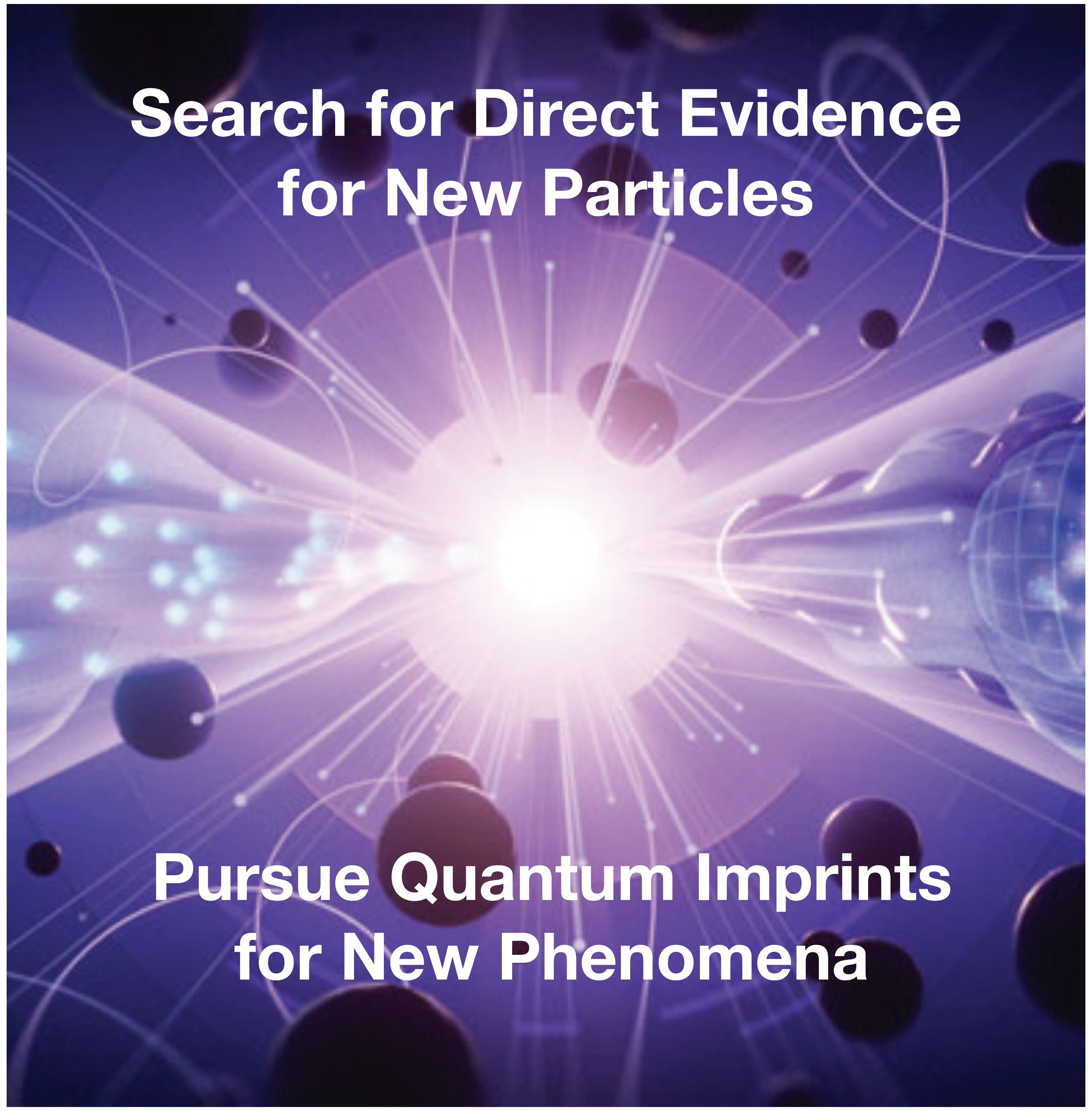
Pathways to Innovation and Discovery in Particle Physics

Report of the Particle Physics Project Prioritization Panel 2023

To be updated based on inputs from HEPAP, but content of the recommendations will remain the same.

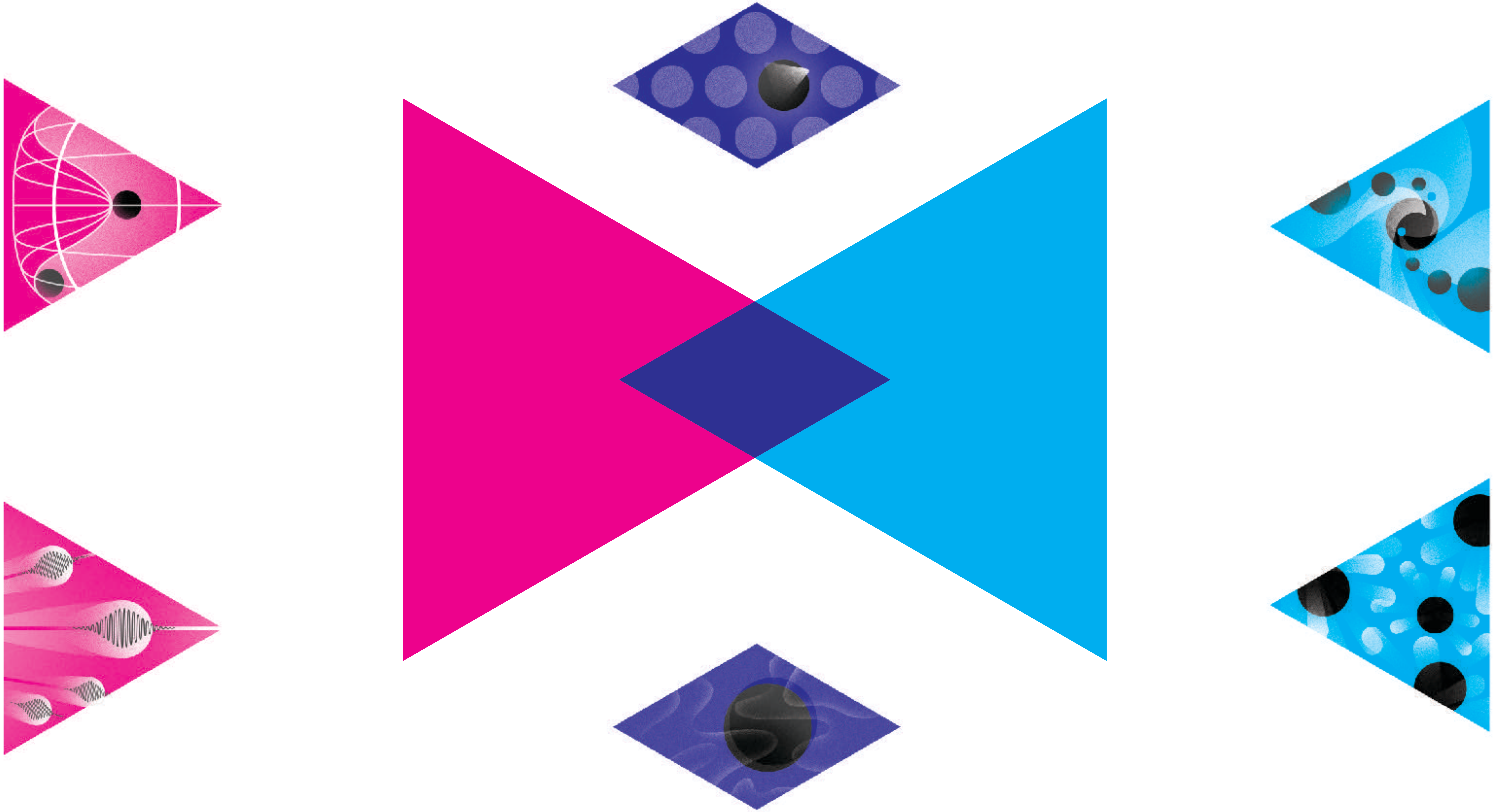
Explore the Quantum Universe

Decipher the Quantum Realm



Explore New Paradigms in Physics

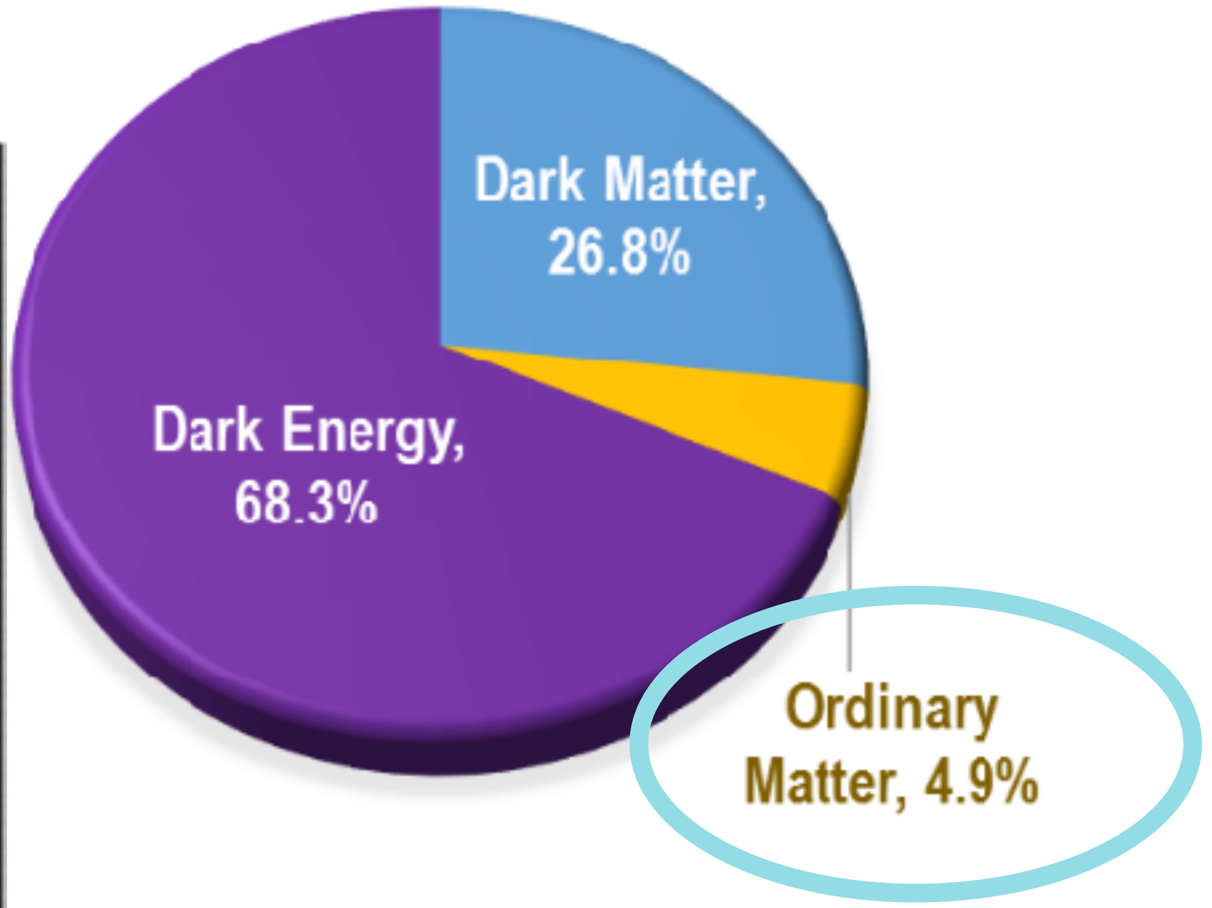
Illuminate the Hidden Universe

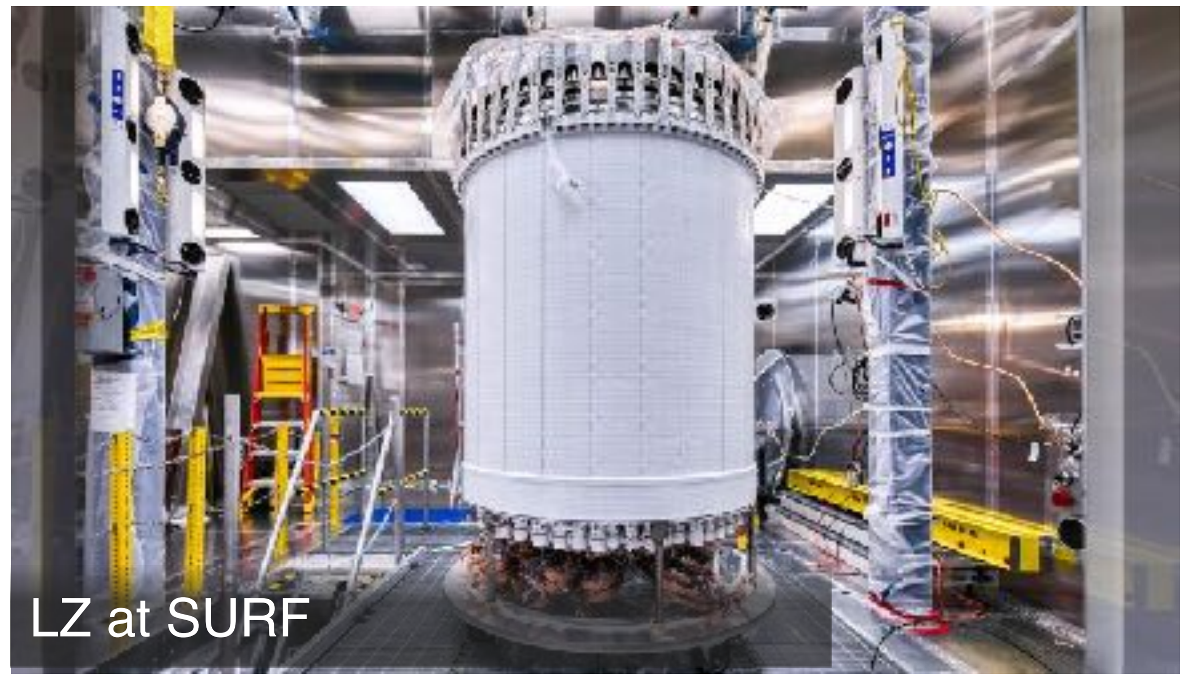


Cosmic Frontier Experiments

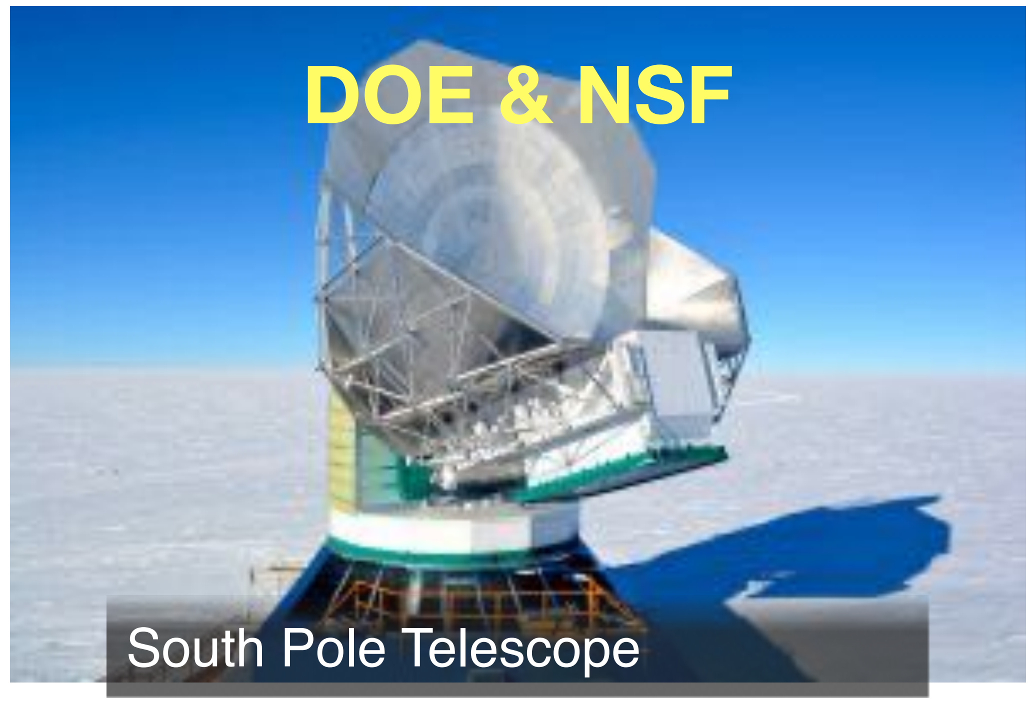
- **Cosmic Frontier experiments** address four of five science drivers
- They use naturally occurring sources to determine the fundamental energy, space and time.

	Energy Frontier	Intensity Frontier	Cosmic Frontier
Higgs Boson	●		
Neutrino Mass		●	●
Dark Matter	●	●	●
Cosmic Acceleration			●
Explore the Unknown	●	●	●




LZ at SURF

Legacy Survey of Space and Time at Vera Rubin Observatory



South Pole Telescope

AMS at ISS

DESI at Kitt Peak

- Partnerships w/NSF (PHY, AST, OPP) NASA (AST, ISS, CLPS) are essential

Recommendation 1

Not Rank-Ordered

As the highest priority independent of the budget scenarios, complete construction projects and support operations of ongoing experiments and research to enable maximum science. We reaffirm the previous P5 recommendations on major initiatives:

a. **HL-LHC** (including ATLAS and CMS detectors, as well as Accelerator Upgrade Project) to start addressing why the Higgs boson condensed in the universe (reveal the secrets of the Higgs boson, section 3.2), to search for direct evidence for new particles (section 5.1), to pursue quantum imprints of new phenomena (section 5.2), and to determine the nature of dark matter (section 4.1).

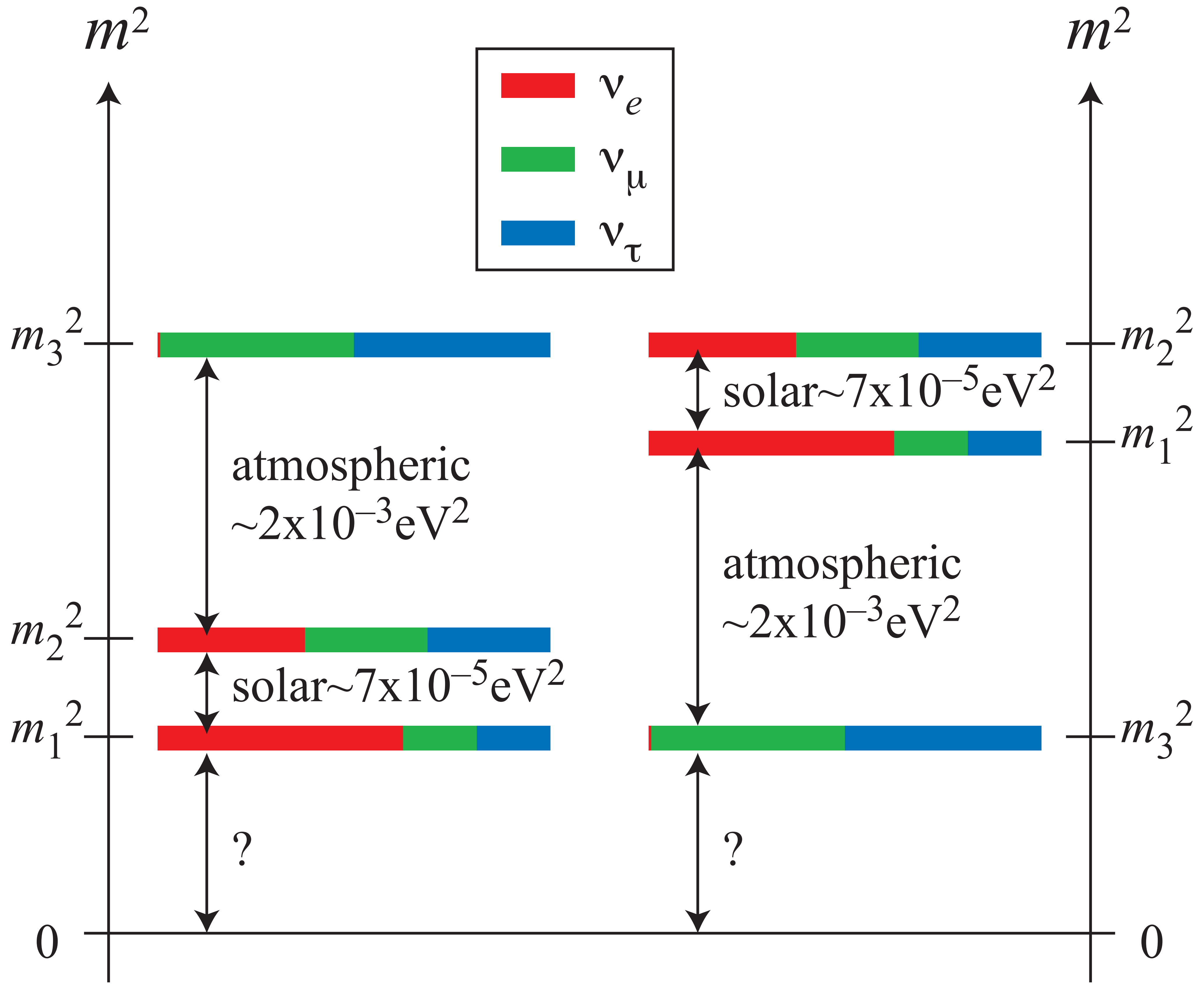
DOE & NSF PHY

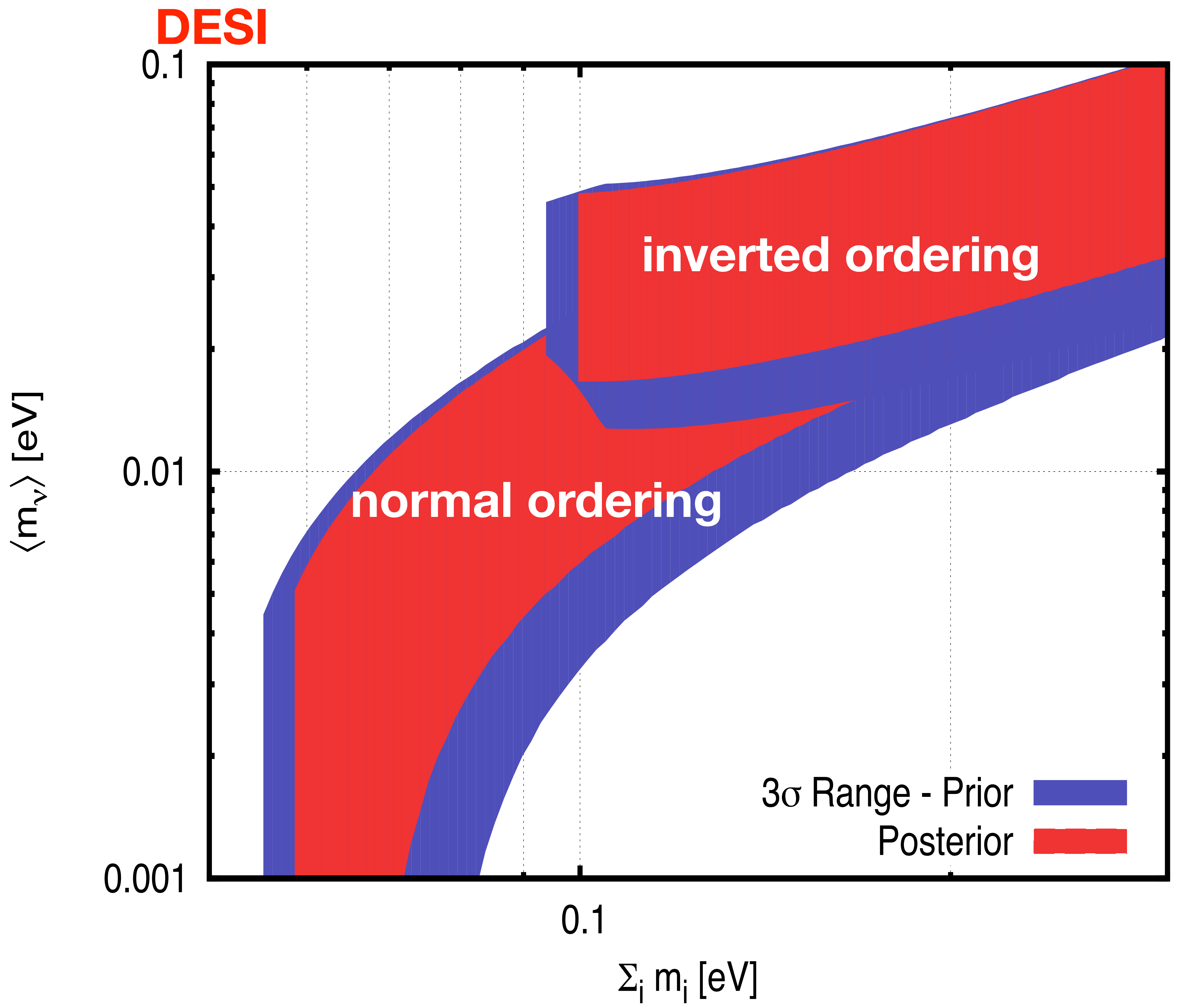
b. **The first phase of DUNE and PIP-II** to determine the mass ordering among neutrinos, a fundamental property and a crucial input to cosmology and nuclear science (elucidate the mysteries of neutrinos, section 3.1).

Mostly DOE

c. **The Vera C. Rubin Observatory** to carry out the LSST, and the LSST Dark Energy Science Collaboration, to understand what drives cosmic evolution (section 4.2).

DOE & NSF AST





Shao-Feng Ge and Werner Rodejohann arXiv:1507.05514

Exploring the Quantum Universe

Recommendation 1

Not Rank-Ordered

In addition, we recommend continued support for the following ongoing experiments at the medium scale (project costs > $50M for DOE and > $4M for NSF), including completion of construction, operations, and research:

NSF

d. **NOvA**, **SBN**, **T2K**, and **IceCube** (*elucidate the mysteries of neutrinos*, section 3.1).

e. **DarkSide-20k**, **LZ**, **SuperCDMS**, and **XENONnT** (*determine the nature of dark matter*. section 4.1). **dark matter direct detection DOE+NSF**

f. **DESI** (*understand what drives cosmic evolution*, section 4.2). **DOE but on Mayall 4m Kitt Peak**

g. **Belle II**, **LHCb**, and **Mu2e** (*pursue quantum imprints of new phenomena*, section 5.2).

The agencies should work closely with each major project to carefully manage the costs and schedule to ensure that the US program has a broad and balanced portfolio.

Recommendation 2

Construct a portfolio of major projects that collectively study nearly all fundamental constituents of our universe and their interactions, as well as how those interactions determine both the cosmic past and future.

These projects have the potential to transcend and transform our current paradigms. They inspire collaboration and international cooperation in advancing the frontiers of human knowledge. Plan and start the following major initiatives **in order of priority from highest to lowest**:

Exploring the Quantum Universe

Recommendation 2

Rank-Ordered

DOE & NSF AST

a. **CMB-S4**, which looks back at the earliest moments of the universe to probe physics at the highest energy scales. It is critical to install telescopes at and observe from both the South Pole and Chile sites to achieve the science goals (section 4.2).

b. **Re-envisioned second phase of DUNE** with an early implementation of an enhanced 2.1 MW beam—ACE-MIRT—a third far detector, and an upgraded near-detector complex as the definitive long-baseline neutrino oscillation experiment of its kind (section 3.1). **Mostly DOE**

c. **An off-shore Higgs factory**, realized in collaboration with international partners, in order to reveal the secrets of the Higgs boson. The current designs of FCC-ee and ILC meet our scientific requirements. The US should actively engage in feasibility and design studies. Once a specific project is deemed feasible and well-defined (see also Recommendation 6), the US should aim for a contribution at funding levels commensurate to that of the US involvement in the LHC and HL-LHC, while maintaining a healthy US on-shore program in particle physics (section 3.2) **DOE & NSF PHY**

d. **An ultimate Generation 3 (G3) dark matter direct detection experiment** reaching the neutrino fog, in coordination with international partners and preferably sited in the US (section 4.1) **DOE & NSF PHY?**

e. **IceCube-Gen2** for study of neutrino properties using non-beam neutrinos complementary to DUNE and for indirect detection of dark matter covering higher mass ranges using neutrinos as a tool (section 4.1). **NSF PHY**

Exploring the Quantum Universe

Recommendation 2

The prioritization principles behind these recommendations can be found in sections 1.6 and 8.1.

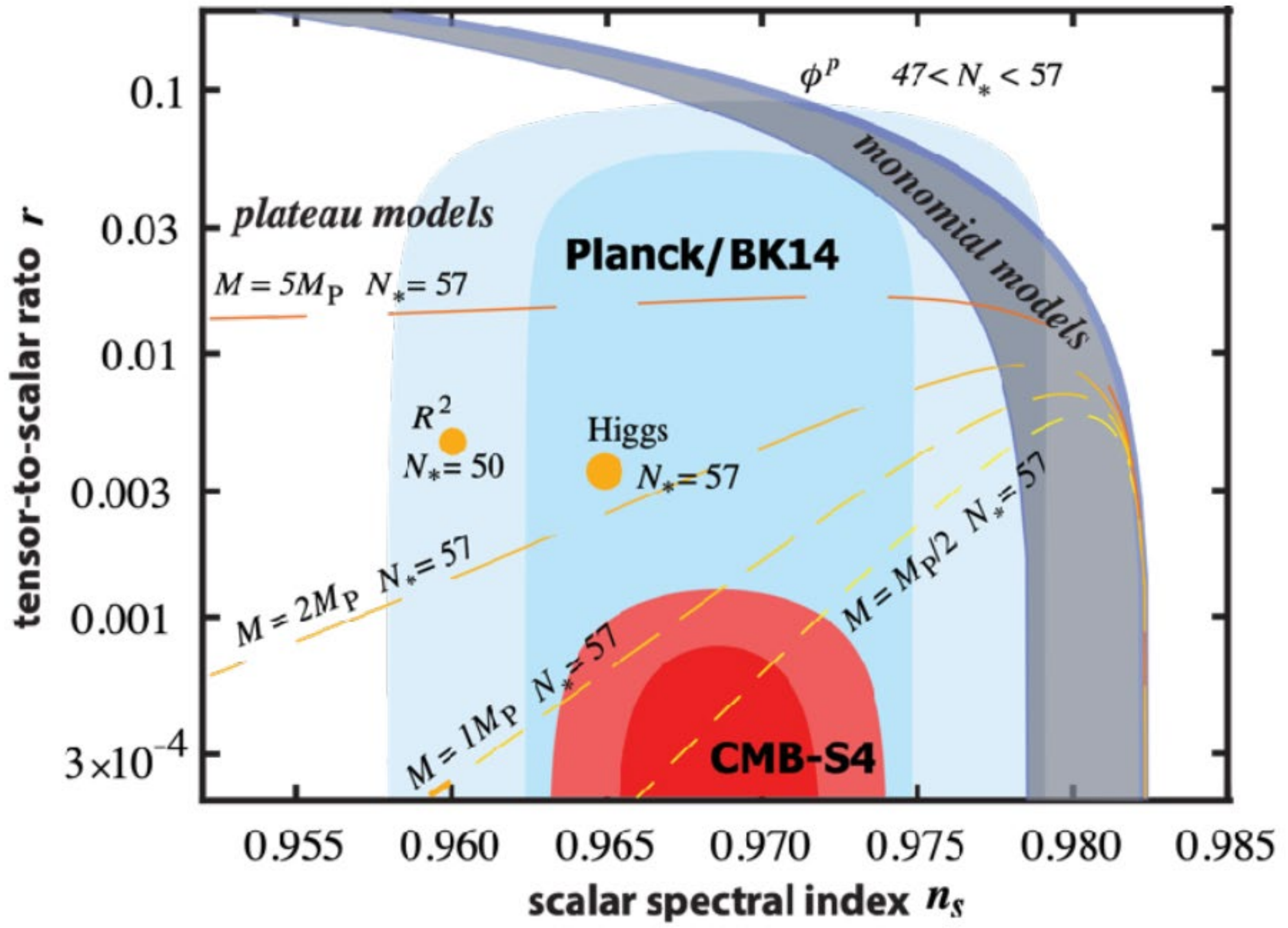
IceCube-Gen2 also has a strong science case in **multi-messenger astrophysics** together with gravitational wave observatories. We recommend that NSF expand its efforts in multi-messenger astrophysics, a unique program in the NSF Division of Physics, with US involvement in the **Cherenkov Telescope Array** (CTA; recommendation 3c), a next-generation gravitational wave observatory, and IceCube-Gen2.

The Cosmic Microwave Background Stage 4 Observatory

CMB-S4 builds on the foundation of decades of CMB measurements to take a major leap, pushing CMB science to the next level

Scientific goals

- B-mode CMB polarization signatures of primordial gravitational waves and inflation
- Maps 50% sky, every other day from 0.1- 1 cm with unprecedented sensitivity
- Broad science including systematic time domain science



CMB-S4 consists of a systematically planned suite of facilities in Antarctica and Chile designed to sample a wide range of independent frequencies, and probe a combination of large and small angular scales

The Cosmic Microwave Background Stage 4 Observatory

Key Attributes

- Balanced program between DOE (60%) and NSF (40%) for all phases

  Brings wide range of technical and scientific expertise to bear from community and national labs

- Total design, development and construction cost: $660M ⇒ **$840M**

- First observations could begin by 2030

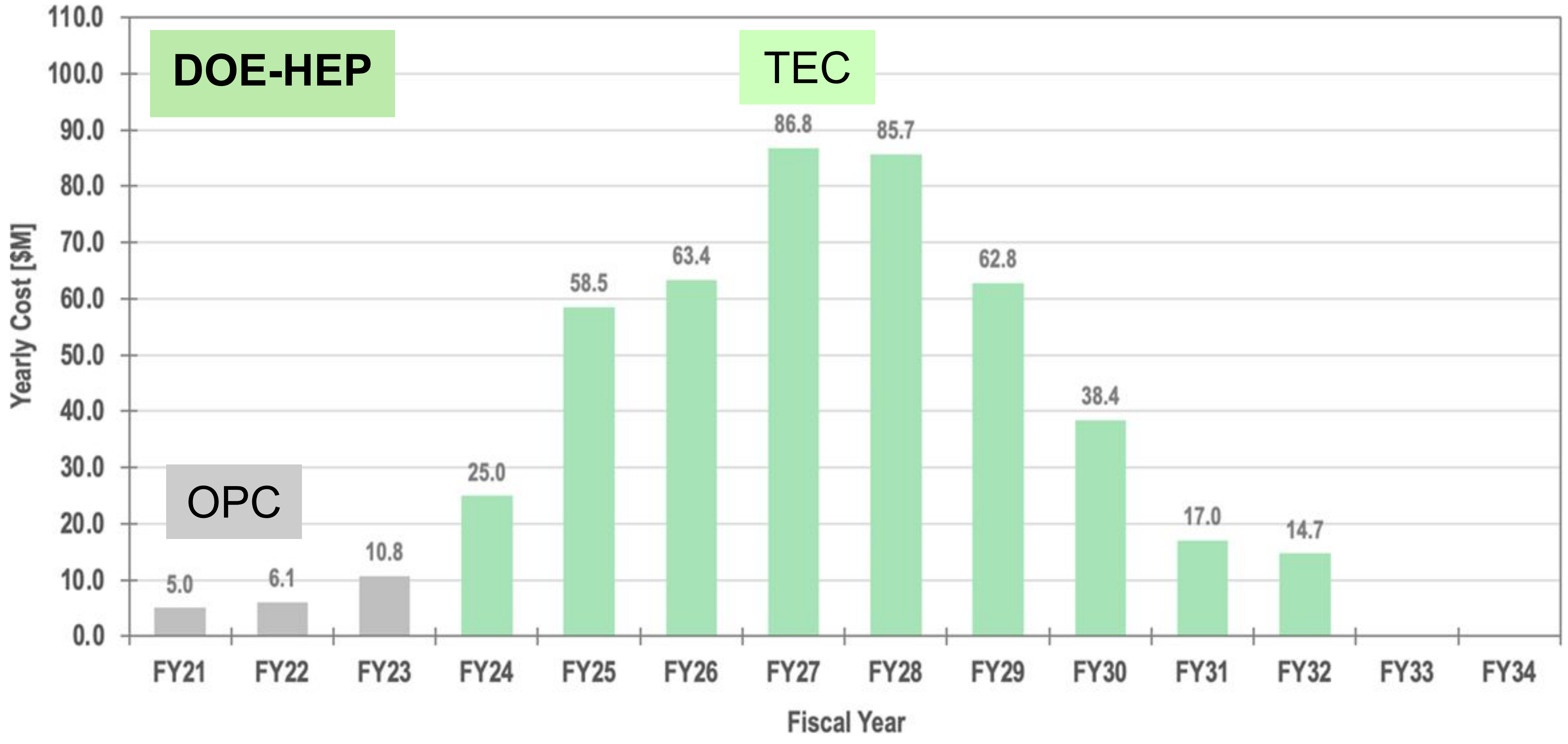
Recommendation: The NSF and DOE should jointly pursue the design and implementation of the next generation ground-based cosmic microwave background experiment (CMB-S4).

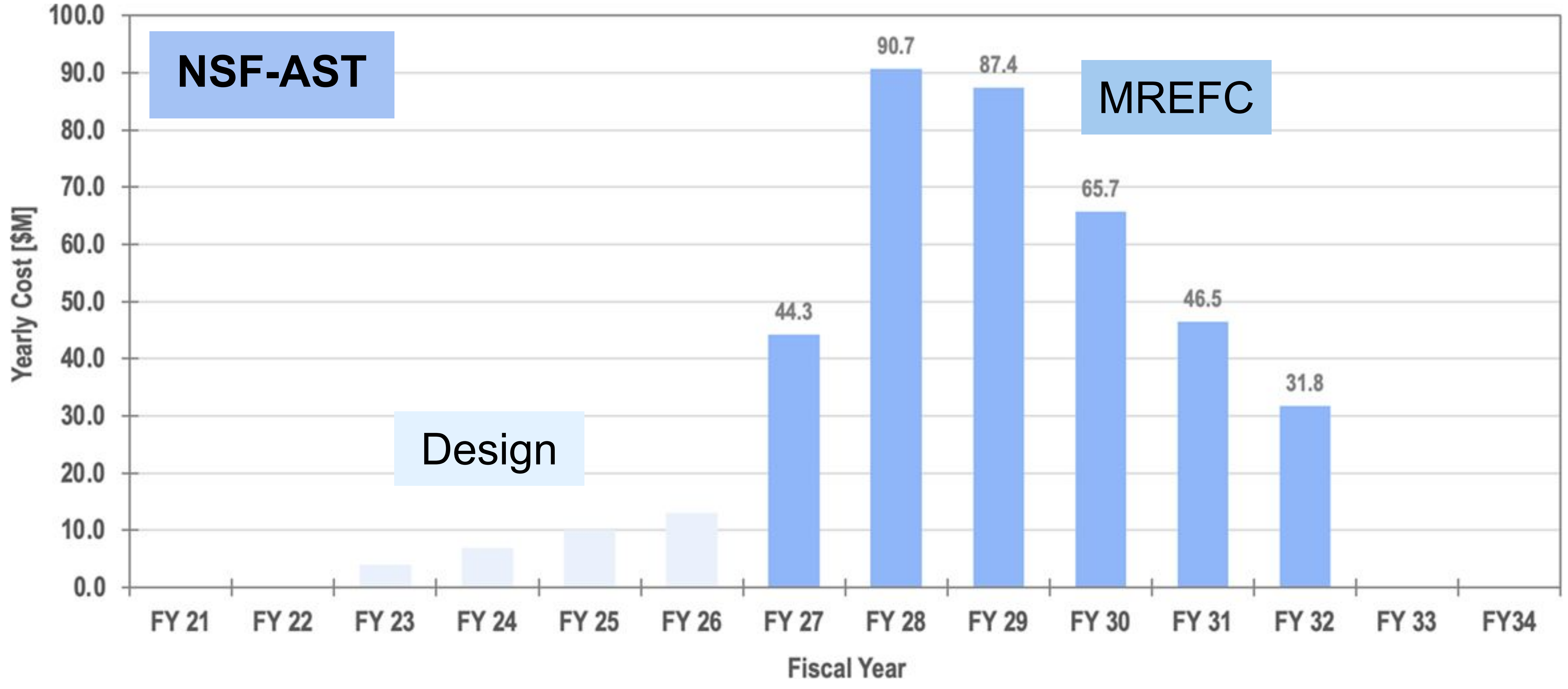
Because of its great potential to advance general astrophysics and open discovery space, it is essential that CMB-S4 produce transient alerts, as well as calibrated maps in all bands and on all angular scales that are openly usable and accessible on as rapid a cadence as practical

CMB-S4 Cost Estimates and Profiles

Bottom-up cost estimate including direct and indirect costs, escalation and contingency

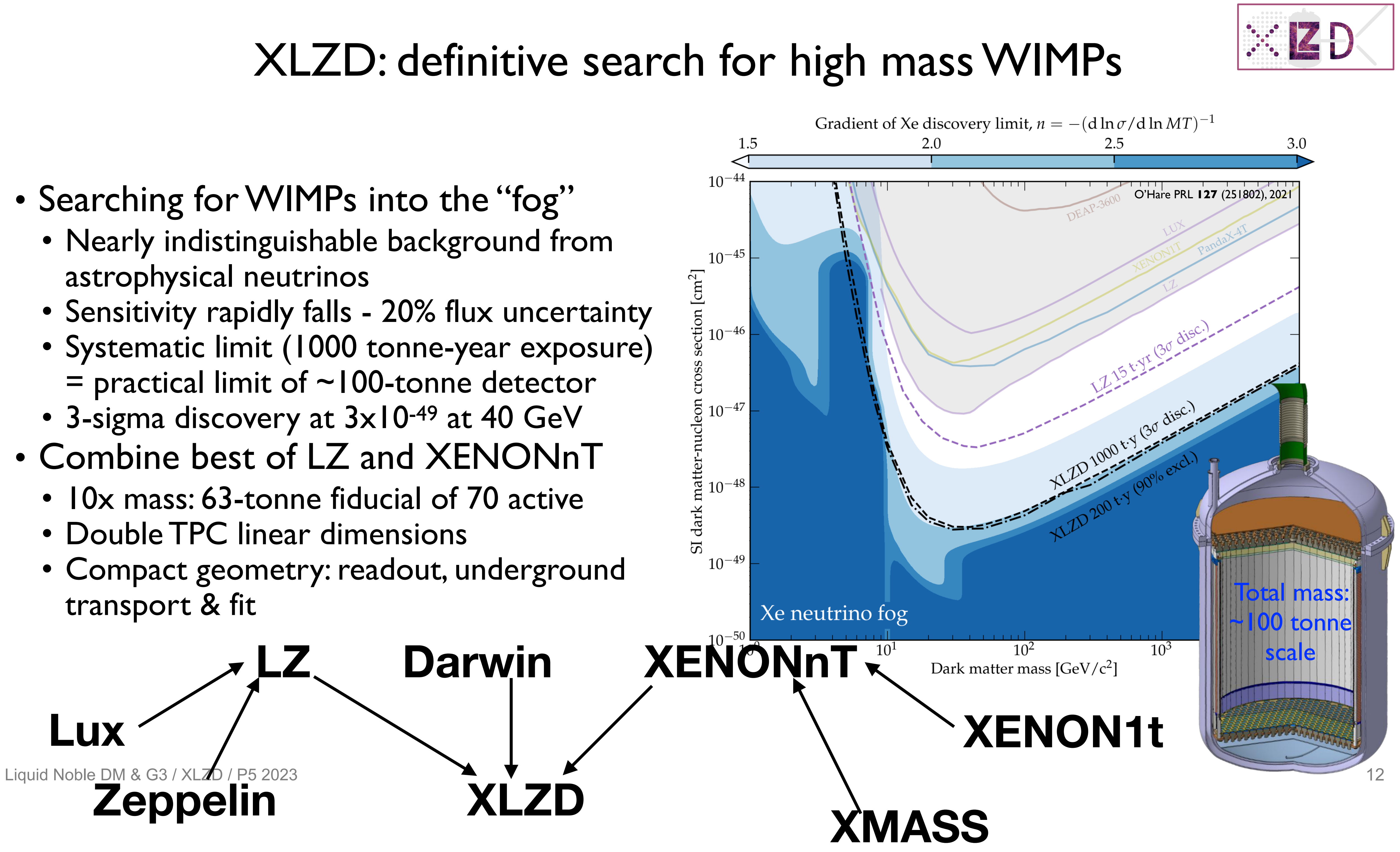
	DOE-HEP (TPC)	NSF-AST (MREFC)
1.01 Project Management & Systems Engineering	$ 68.4M	$ 16.6M
1.03 Detectors	$ 58.6M	
1.04 Readout	$ 62.8M	
1.05 Module Assembly and Test	$ 36.5M	
1.06 Large Aperture Telescope (LAT) and Receivers		$ 97.7M
1.07 Small Telescopes	$ 54.9M	
1.08 Observatory Control and Data Acquisition System	$ 17.2M	
1.09 Data Management	$ 33.5M	$ 6.4M
1.10 Chile Site	$ 6.6M	$ 47.9M
1.11 South Pole Site	$ 2.7M	$ 93.2M
SUBTOTAL	**$ 341.2M**	**$ 261.8M**
~40% contingency (developed bottom-up)	$ 133.1M	$ 104.7M
TOTAL DOE OPC+TEC and NSF MREFC Costs	**$ 474.2M**	**$ 366.5M**





G3 Dark Matter experiments

Dan Akerib, LBNL Town Hall, Feb 22, 2023



Cristiano Galbiati, SLAC Town Hall, May 3, 2023

An ultimate Generation 3 (G3) dark matter direct detection experiment reaching the neutrino fog, in coordination with international partners and preferably sited in the US

But if extra funds or NSF involvement:

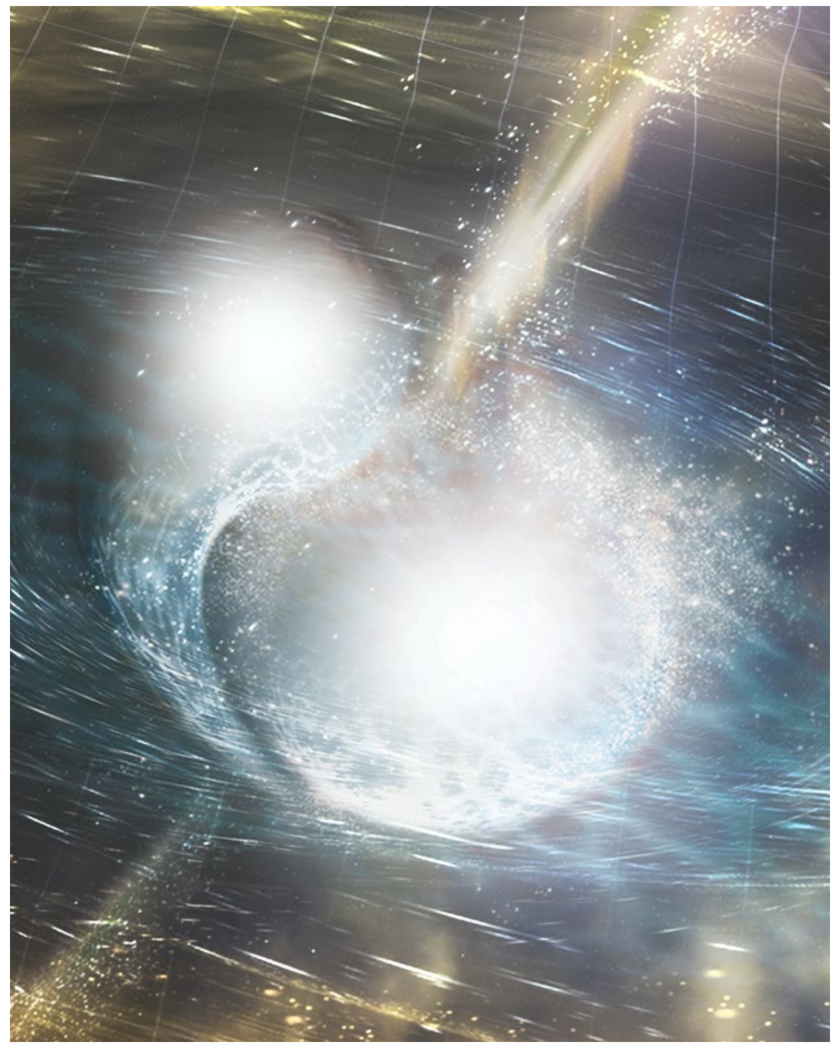
Initiate construction of **a second G3 dark matter experiment** to maximize discovery potential when combined with the first one.

Priority Area: New Windows on the Dynamic Universe

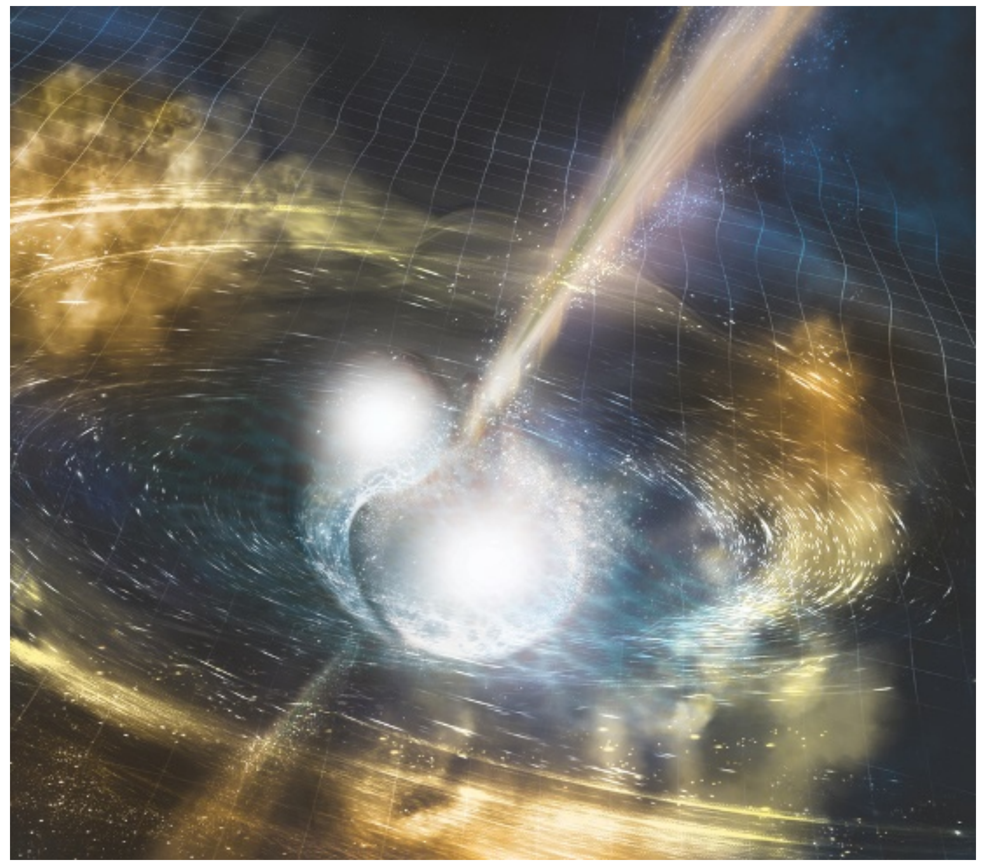
The New Windows on the Dynamic Universe priority area involves using light in all its forms, gravitational waves, and neutrinos to study cosmic explosions on all scales and the mergers of compact objects

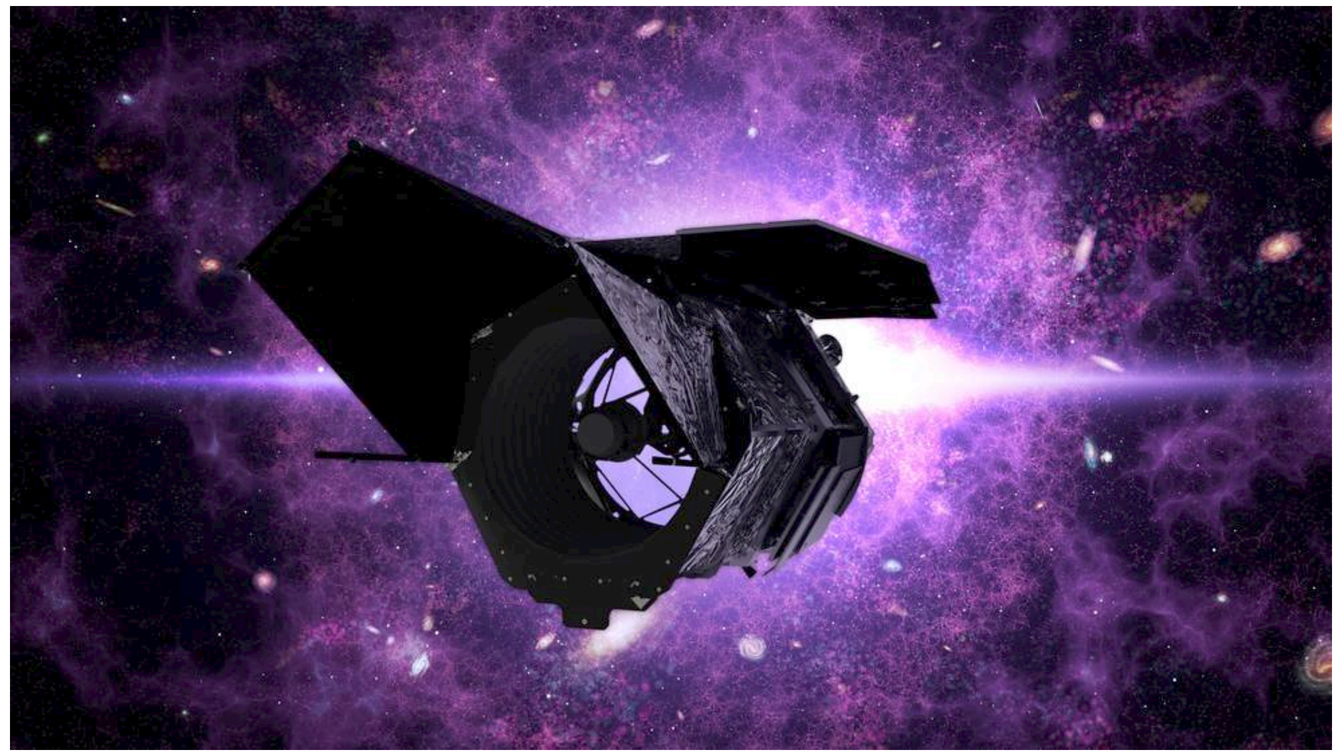
The needed capabilities include:

- Facilities to discover and characterize the brightness and spectra of transient sources as they appear and fade away
- Ground-based ELTs to see light coincident with mergers
- A next-generation radio observatory to detect the relativistic jets produced by neutron stars and black holes
- Next generation CMB telescopes to search for the polarization produced by gravitational waves in the infant universe
- Upgrades to current ground-based gravitational wave detectors, and development of next generation technologies
- Improvements in the sensitivity and angular resolution of high energy neutrino observatories



Sustaining Activities: Time Domain Astrophysics Program





New Windows on the Dynamic Universe is a priority science area where return on major US facilities (LIGO, Rubin, Roman) requires an agile fleet of small to medium scale missions

Recommendation: NASA should establish a time-domain program to realize and sustain the necessary suite of space-based electromagnetic capabilities required to study transient and time-variable phenomena, and to follow-up multi-messenger events. This program should support the targeted development and launch of competed Explorer-scale or somewhat larger missions and missions of opportunity

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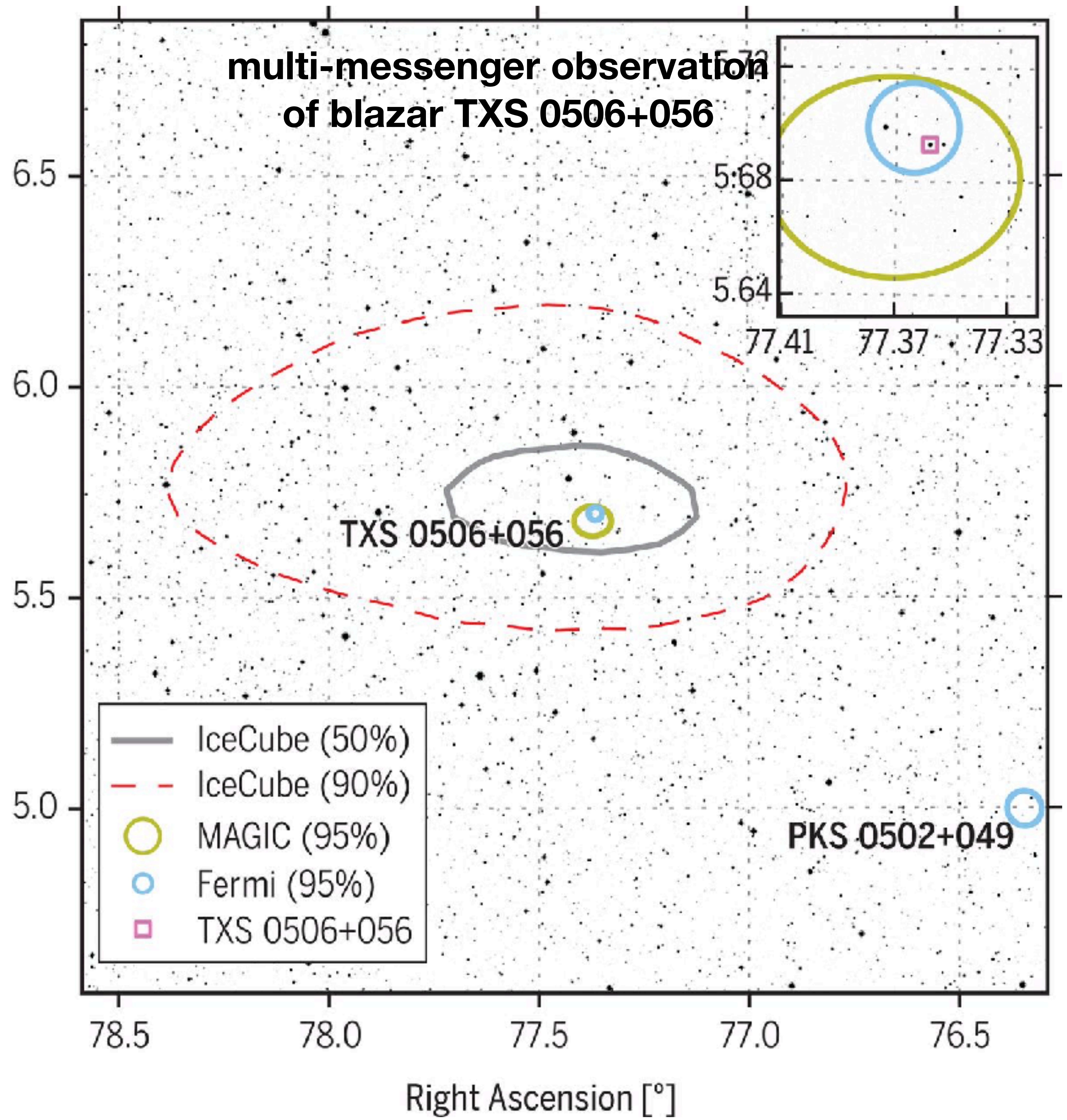
IceCube



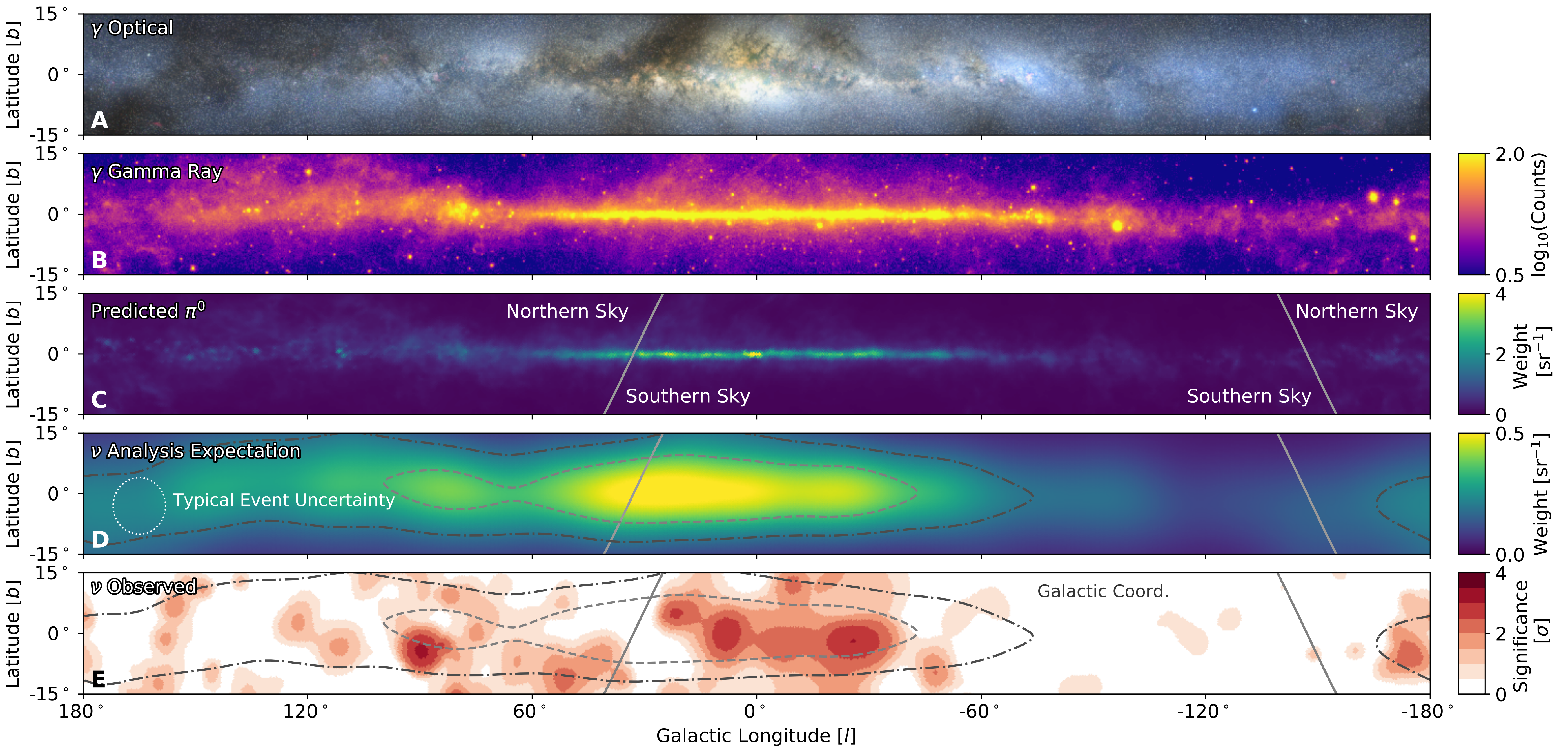


Figure 1: **The plane of the Milky Way galaxy in photons and neutrinos.** Each panel is in Galactic coordinates, with the origin being at the Galactic Center, extending ±15° in latitude and ±180° in longitude. (A) Optical color image (*39*), which is partly obscured by clouds of gas and dust that absorb optical photons. Credit A. Mellinger, used with permission. (B) The integrated flux in gamma rays from the *Fermi* Large Area Telescope (*Fermi*-LAT) 12 year survey (*40*) at energies greater than 1 GeV, obtained from the *Fermi* Science Support Center and processed with the *Fermi*-LAT ScienceTools. (C) The emission template calculated for the expected neutrino flux, derived from the π^0 template that matches the *Fermi*-LAT observations of the diffuse gamma-ray emission (*1*). (D) The emission template from panel (C) including the detector sensitivity to cascade-like neutrino events and the angular uncertainty of a typical signal event (7°, indicated by the dotted white circle). Contours indicate the central regions that contain 20% and 50% of the predicted diffuse neutrino emission signal. (E) The pre-trial significance of the IceCube neutrino observations, calculated from all-sky scan for point-like sources using the cascade neutrino event sample. Contours are the same as panel (D). Grey lines in (C) - (E) indicate the Northern-Southern sky horizon line at the IceCube detector.

IceCube-Generation 2 Neutrino Observatory

IceCube at South Pole detects 100 TeV – 10 PeV cosmic neutrinos

Upgrade to Generation-2 observatory will add detector elements and a radio array to increase sensitivity (5x), detection rate (10x), and energy range (to 1000 PeV)

- resolve diffuse (currently) cosmic neutrino background
- localize, identify individual astrophysical sources
- coordinated multi-messenger observations

Conclusion: The IceCube-Generation 2 neutrino observatory would provide significantly enhanced capabilities for detecting high-energy neutrinos, including the ability to resolve the bright, hard-spectrum TeV-PeV neutrino background into discrete sources. Its capabilities are important for achieving key scientific objectives of this survey

NSF 23-117

Dear Colleague Letter: 2023 Update on Science Support and Infrastructure in Antarctica

June 12, 2023

Dear Colleagues:

This letter provides information on the status and future of science support and infrastructure recapitalization in Antarctica. Since the last NSF update <https://www.nsf.gov/publications/pub_summ.jsp?ods_key=nsf22078> in April 2022, the COVID-19 pandemic has continued to severely impact the Office of Polar Program's (OPP) ability to support science on the continent, and those impacts have been exacerbated by increasing constraints on resources arising from inflation and the need for facility renewal.

The U.S. Antarctic Program (USAP) anticipated supporting a majority of COVID-19-impacted projects and new science projects in the 2022-2023 season. The highest priority science projects included fieldwork involving international collaborations, projects with critical time-series data, and projects involving instrument maintenance to prevent irreversible damage to, or loss of, science infrastructure.

NSF 23-117

Dear Colleague Letter: 2023 Update on Science Support and Infrastructure in Antarctica

June 12, 2023

Dear Colleagues:

This letter provides information on the status and future of science support and infrastructure recapitalization in Antarctica. Since the last NSF update <https://www.nsf.gov/publications/pub_summ.jsp?ods_key=nsf22078> in April 2022, the COVID-19 pandemic has continued to severely impact the Office of Polar Program's (OPP) ability to support science on the continent, and those impacts have been exacerbated by increasing constraints on resources arising from inflation and the need for facility renewal.

South Pole Station is saturated with already-funded projects and required critical infrastructure and maintenance activities that cannot be deferred until late in the decade. South Pole Station will continue to host the current suite of large-scale science projects; however, proposers seeking support for new projects at South Pole Station should consult the cognizant program officer to discuss alternative locations to accomplish science goals.

Master planning begins for the future of the South Pole Station

June 20, 2023

The United States Antarctic Program <https://www.usap.gov/> (USAP) has begun work on a Master Plan for the Amundsen-Scott South Pole Station <https://www.nsf.gov/geo/opp/support/southp.jsp> .

Master Plans are a common tool used across research campuses and universities to ensure infrastructure projects are guided by a clear and consistent vision of the future. The South Pole Station Master Plan will inform investments planned under the Antarctic Infrastructure Recapitalization program and ensure that the future state will achieve USAP's mission and priorities.

Community and public input on the South Pole Station Master Plan will be sought through postings to the federal register and a planning charrette open to all stakeholders in August 2023. Additional information, including how to participate in the master planning process, will be posted on the Office of Polar Programs <https://www.nsf.gov/news/announcements.jsp?org=OPP> website.

There are currently Master Plans in place for Palmer Station <https://future.usap.gov/master-plan/palmer-master-plan/> and McMurdo Station <https://future.usap.gov/master-plan/mcmurdo-master-plan-page/> .

Exploring the Quantum Universe

Recommendation 3

Not Rank-Ordered

Create an improved balance between small-, medium-, and large-scale projects to open new scientific opportunities and maximize their results, enhance workforce development, promote creativity, and compete on the world stage.

In order to achieve this balance across all project sizes we recommend the following:

a. Implement a new small-project portfolio at DOE, **Advancing Science and Technology through Agile Experiments (ASTAE)**, across science themes in particle physics with a competitive program and recurring funding opportunity announcements. This program should start with the construction of experiments from the Dark Matter New Initiatives (DMNI) by DOE-HEP (section 6.2).

b. Continue Mid-Scale Research Infrastructure (**MSRI**) and Major Research Instrumentation (**MRI**) programs as a critical component of the NSF research and project portfolio.

c. Support **DESI-II** for cosmic evolution, **LHCb upgrade II** and **Belle II upgrade** for quantum imprints, and **US contributions to the global CTA Observatory** for dark matter (sections 4.2, 5.2, and 4.1).

The Belle II recommendation includes contributions towards the SuperKEKB accelerator.

Recommendation 5

Invest in initiatives aimed at developing the workforce, broadening engagement, and supporting ethical conduct in the field. This commitment nurtures an advanced technological workforce not only for particle physics, but for the nation as a whole.

Exploring the Quantum Universe

Recommendation 5

Not Rank-Ordered

The following workforce initiatives are detailed in section 7:

a. All projects, workshops, conferences, and collaborations must incorporate ethics agreements that detail expectations for professional conduct and establish mechanisms for **transparent reporting, response, and training**. These mechanisms should be supported by laboratory and funding agency infrastructure. The efficacy and coverage of this infrastructure should be reviewed by a HEPAP subpanel.

b. Funding agencies should continue to support programs that **broaden engagement** in particle physics, including strategic academic partnership programs, **traineeship programs, and programs in support of dependent care and accessibility**. A systematic review of these programs should be used to identify and **remove barriers**.

c. Comprehensive **work-climate studies** should be conducted with the support of funding agencies. Large collaborations and national laboratories should consistently undertake such studies so that issues can be identified, addressed, and monitored. Professional associations should spearhead field-wide work-climate investigations to ensure that the unique experiences of individuals engaged in smaller collaborations and university settings are effectively captured.

d. Funding agencies should strategically increase support for **research scientists, research hardware and software engineers, technicians, and other professionals** at universities.

e. A plan for **dissemination of scientific results to the public** should be included in the proposed operations and research budgets of experiments. The funding agencies should include funding for the dissemination of results to the public in operation and research budgets.

2.3 The Path to a 10 TeV pCM

Realization of a future collider will require resources at a global scale and will be built through a world-wide collaborative effort where decisions will be taken collectively from the outset by the partners. This differs from current and past international projects in particle physics, where individual laboratories started projects that were later joined by other laboratories. The proposed program aligns with **the long-term ambition of hosting a major international collider facility in the US, leading the global effort** to understand the fundamental nature of the universe.

…

In particular, a muon collider presents an attractive option both for technological innovation and for bringing energy frontier colliders back to the US. The footprint of **a 10 TeV pCM muon collider is almost exactly the size of the Fermilab campus**. A muon collider would rely on a powerful multi-megawatt proton driver delivering very intense and short beam pulses to a target, resulting in the production of pions, which in turn decay into muons. This cloud of muons needs to be captured and cooled before the bulk of the muons have decayed. Once cooled into a beam, fast acceleration is required to further suppress decay losses.

…

Although **we do not know if a muon collider is ultimately feasible**, the road toward it leads from current Fermilab strengths and capabilities to **a series of proton beam improvements and neutrino beam facilities**, each producing world-class science while performing critical R&D towards a muon collider. At the end of the path is an unparalleled global facility on US soil. **This is our Muon Shot.**

2.5 International and Inter-Agency Partnerships

…

Successful completion of the recommended major projects depends on significant coordination and collaboration among US agencies and international partners. Large international projects such as a Higgs factory and DUNE require not only DOE and NSF, but also the US Department of State and other entities in the federal government to work with global partners to establish the complex frameworks involved.

…

For studies of cosmic evolution and astrophysical studies of dark matter, inter-agency coordination and cooperation between DOE, NSF, and NASA using complementary observational approaches has been very productive in building a world-leading scientific program. Such coordination and cooperation should continue.

The field of particle physics is not an isolated endeavor, and it benefits from and contributes to neighboring areas in nuclear physics, astrophysics and astronomy, condensed matter physics, precision physics, computing, instrumentation, material science, and others. At the same time, it provides important theoretical and technological input to these areas, as well as medical, security, and many other fields, some as seemingly unrelated as archaeology. Funding agencies are urged to reach across the traditional boundaries to enhance collaboration, maximize science, and develop a strong workforce for the nation overall.

Less Favorable Budget Scenario

Rank-Ordered

In this scenario, we would aim for a program that covers most areas of particle physics for the next 10 years, maintaining continuity and exploiting the ongoing projects in Recommendation 1 as our highest priority. The agencies should launch the same major initiatives as outlined in Recommendation 2, some of them with significantly reduced scope:

a. **CMB-S4** without reduction in scope.
b. **DUNE Third Far Detector (FD3)**, but **defer ACE-MIRT** and the More Capable Near Detector (**MCND**).
c. Contribution to an **off-shore Higgs factory** delayed and at **a reduced level**.
d. Reduced participation in an **off-shore G3 dark matter experiment** and **no SURF expansion**.
e. **IceCube-Gen2** without reduction in scope.

A loss of US leadership in many areas, damage our reputation as a reliable international host/partner

Less Favorable Budget Scenario

Rank-Ordered

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a. **CMB-S4** without reduction in scope.
b. **DUNE Third Far Detector (FD3)**, but **defer ACE-MIRT** and the More Capable Near Detector (**MCND**).
c. Contribution to an **off-shore Higgs factory** delayed and at **a reduced level**.
d. Reduced participation in a **G3 dark matter experiment outside the US** and **no SURF expansion**.
e. **IceCube-Gen2** without reduction in scope.

A loss of US leadership in many areas, damage our reputation as a reliable international host/partner

More Favorable Budget Scenario

Not Rank-Ordered

c. Medium Projects

i. **Initiate construction of Spec-S5** as the world-leading study of cosmic evolution, with applications to neutrinos and dark matter, once its design matures.

ii. Initiate construction of an **advanced fourth far detector (FD4) for DUNE** that will expand its neutrino oscillation physics and broaden its science program.

iii. Initiate construction of **a second G3 dark matter experiment** to maximize discovery potential when combined with the first one.

d. Large Projects

Evolve the infrastructure of the Fermilab accelerator complex to support a future 10 TeV pCM collider as a global facility. A positive review of the design by a targeted panel may expedite its execution (Recommendation 6).

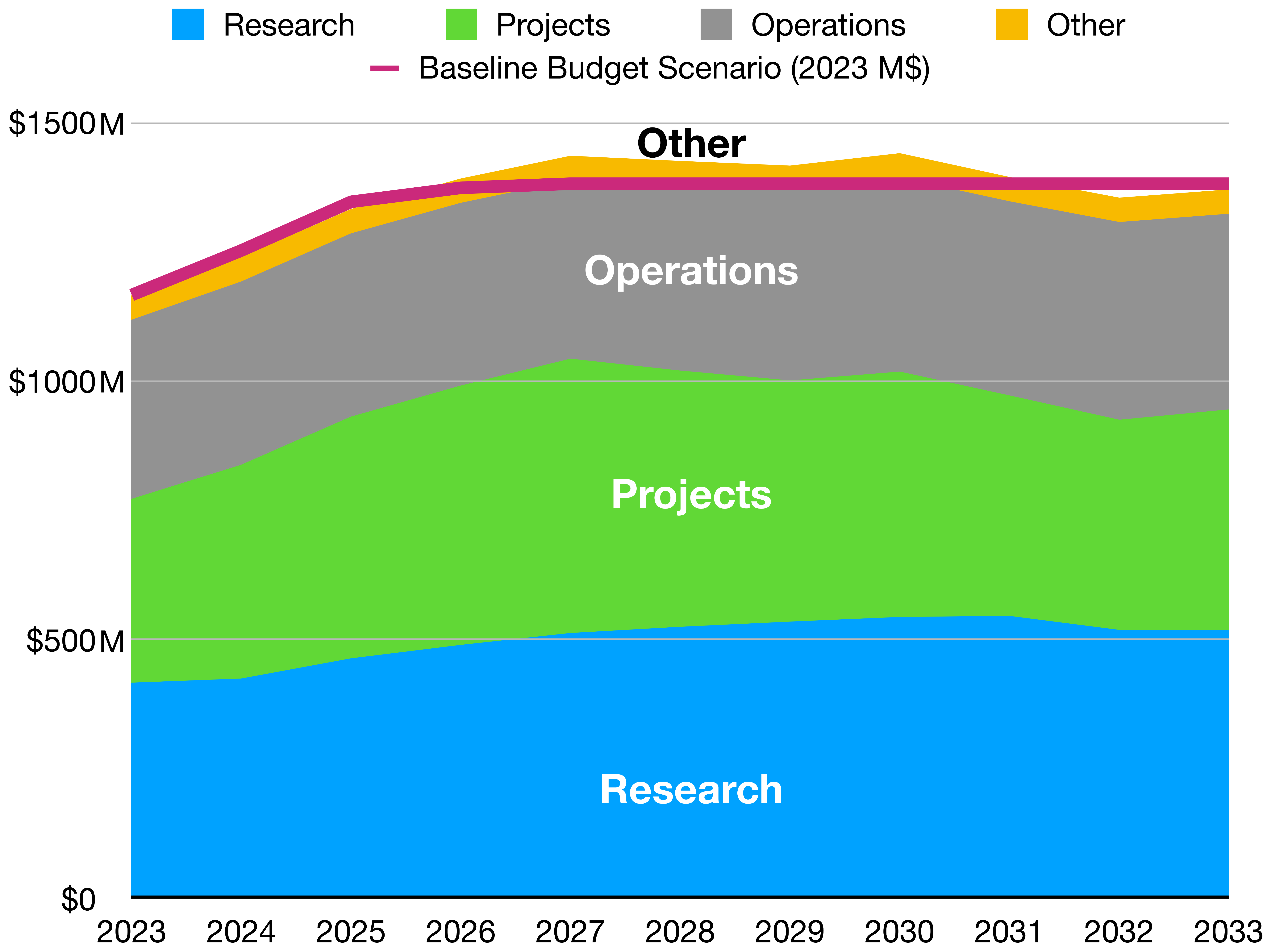
Decadal Overview of Future Large-Scale Projects		
Frontier/Decade	2025 - 2035	2035 -2045
Energy Frontier	✓ (Recommended) U.S. Initiative for the Targeted Development of Future Colliders and their Detectors	
		✓ (Recommended) Higgs Factory
Neutrino Frontier	✓ (Recommended) LBNF/DUNE Phase I & PIP- II	✓ (Recommended) DUNE Phase II (incl. proton injector)
Cosmic Frontier	✓ (Recommended) Cosmic Microwave Background - S4	Next Gen. Grav. Wave Observatory*
	✓ (R&D) Spectroscopic Survey - S5*	✓ (R&D) Line Intensity Mapping*
	✓ (Recommended) Multi-Scale Dark Matter Program (incl. Gen-3 WIMP searches)	
Rare Process Frontier		✓ (R&D) Advanced Muon Facility

Table 1-1. *An overview, binned by decade, of future large-scale projects or programs (total projected costs of $500M or larger) endorsed by one or more of the Snowmass Frontiers to address the essential scientific goals of the next two decades. This table is not a timeline, rather large projects are listed by the decade in which the preponderance of their activity is projected to occur. Projects may start sooner than indicated or may take longer to complete, as described in the frontier reports. Projects were not prioritized, nor examined in the context of budgetary scenarios. In the observational Cosmic program, project funding may come from sources other than HEP, as denoted by an asterisk.*

✓ **Recommended**

✓ **R&D**

The particle physics case for studying gravitational waves at all frequencies should be explored by expanded theory support.



Not in the Report

Not in the Report

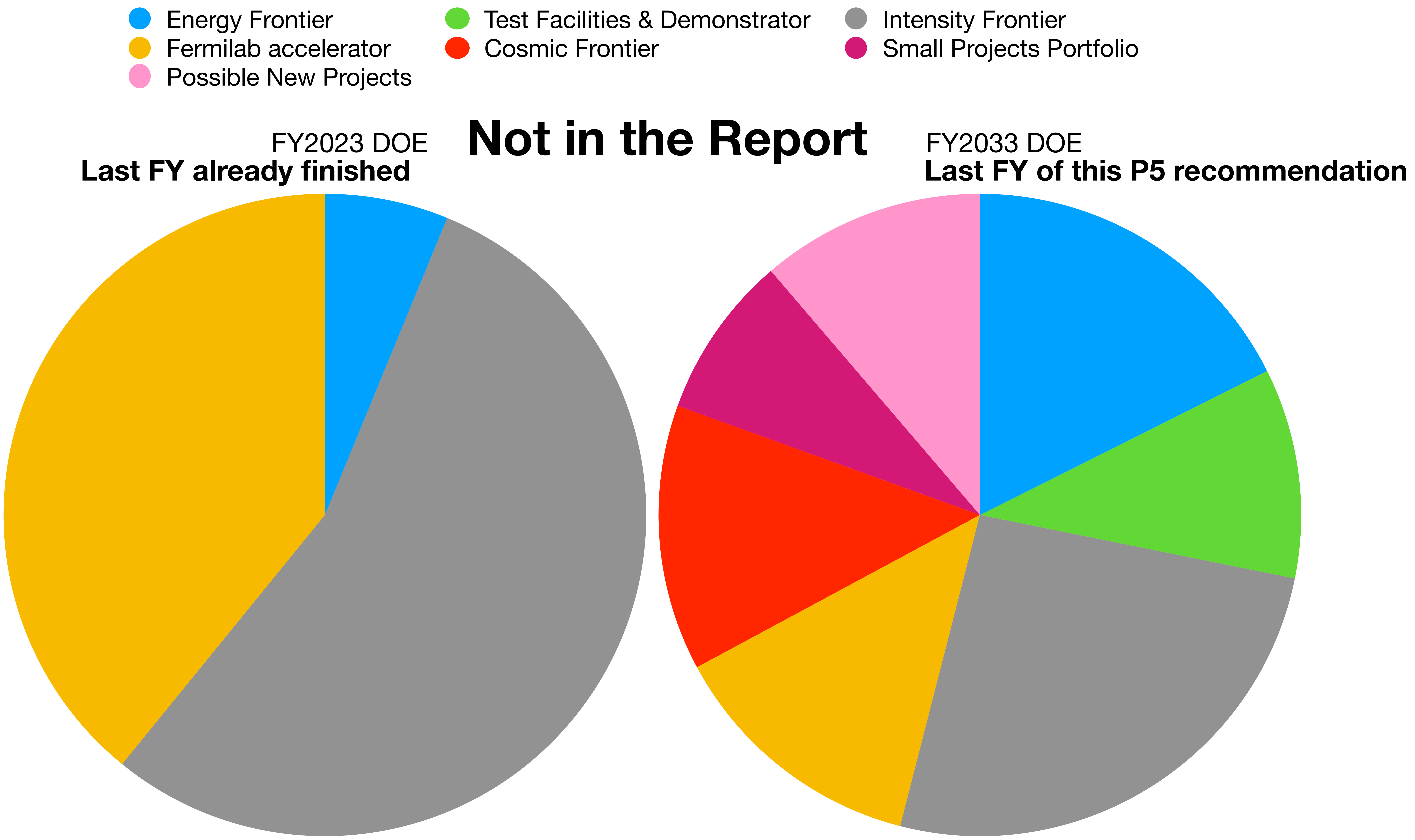


Fig. 3 Composition of DOE Projects in FY2023 (enacted) and FY2033 (recommended) in in our budget exercise. Demonstrator and Small Projects Portfolio are regarded as Projects for this pie chart.

Exploring the Quantum Universe

Acknowledgements

We thank members of the cost subcommittee for their timely and hard work, in particular its chair, Jay Marx. We also thank all the national laboratories that made their staff available for this important task. We thank people at funding agencies for providing us all necessary information and support throughout the process. We thank our peer reviewers for giving us constructive feedback under a tight deadline. We thank Lawrence Berkeley National Laboratory, Fermilab, Argonne National Laboratory, Brookhaven National Laboratory, SLAC National Laboratory, Virginia Tech University, and University of Texas Austin for hosting the town halls. We thank James Dawson and Marty Hanna for professional editing. We thank Michael Branigan, Brad Nagle, Olena Shmahalo and Abigail Malate for providing beautiful graphics and layout. We thank the Yale Physics Department for supporting the development of the website. We thank Kerri Fomby, Jody Crisp, and Taylor Pitchford at ORISE and Stephany Tone at LBNL for logistical support. We thank our families for supporting us during this year-long process. And most importantly, **we thank APS/DPF for organizing the Snowmass Community Study, and all members of our community for their bold and creative vision as well as their input to the process.**

P5 town hall at FNAL
March 21, 2023

particle physicists dream small

New effort to study the afterglow of big bang heads new decadal to-do list

8 DEC 2023 · 6:10 PM ET · BY ADRIAN CHO

CAREERS COMMENTARY JOURNALS Science

Particle physicists in the United States have released a long-range plan that looks less like a child's wish list and more like a parent's cautious budget. Although some physicists dream of exotic new particle colliders, the report of the ad hoc Particle Physics Project Prioritization Panel (P5) lists just five, mostly smaller projects, only two of which would operate by 2034. That's because the U.S. program, which is supported by the Department of Energy (DOE), is still busy with a massive neutrino project that has greatly exceeded its initially estimated cost and is behind schedule. Still, other physicists are encouraged by the report.

"This is better than I expected," says Daniel Akerib, a particle physicist at SLAC National Accelerator Laboratory. "I'm impressed that even given the constraints, they found a way to fit new things in."

The product of more than a year of deliberation, the new report, presented on 7 December to DOE's standing High Energy Physics Advisory Panel (HEPAP), represents the consensus view of the panel's 31 particle physicists, says Hitoshi Murayama, a theorist at the University of California, Berkeley and P5 chairman. "We never voted on anything," he says.

The report's first recommendation sets the tone, says Regina Rameika, associate director for DOE's high energy physics program, which has a $1.17 billion budget this year. The highest priority, the report says, is to "complete construction of projects and support operations of ongoing experiments." In other words, Rameika says, "We've got to finish what we've started."

Those commitments include a variety of neutrino experiments at Fermi National Accelerator Laboratory (Fermilab), massive underground detectors known as LZ and XENONnT that are striving to detect hypothetical particles of dark matter called weakly interacting massive particles (WIMPs), and a 4-meter telescope to probe the nature of the

The New York Times

Particle Physicists Agree on a Road Map for the Next Decade

A "muon shot" aims to study the basic forces of the cosmos. But meager federal budgets could limit its ambitions.

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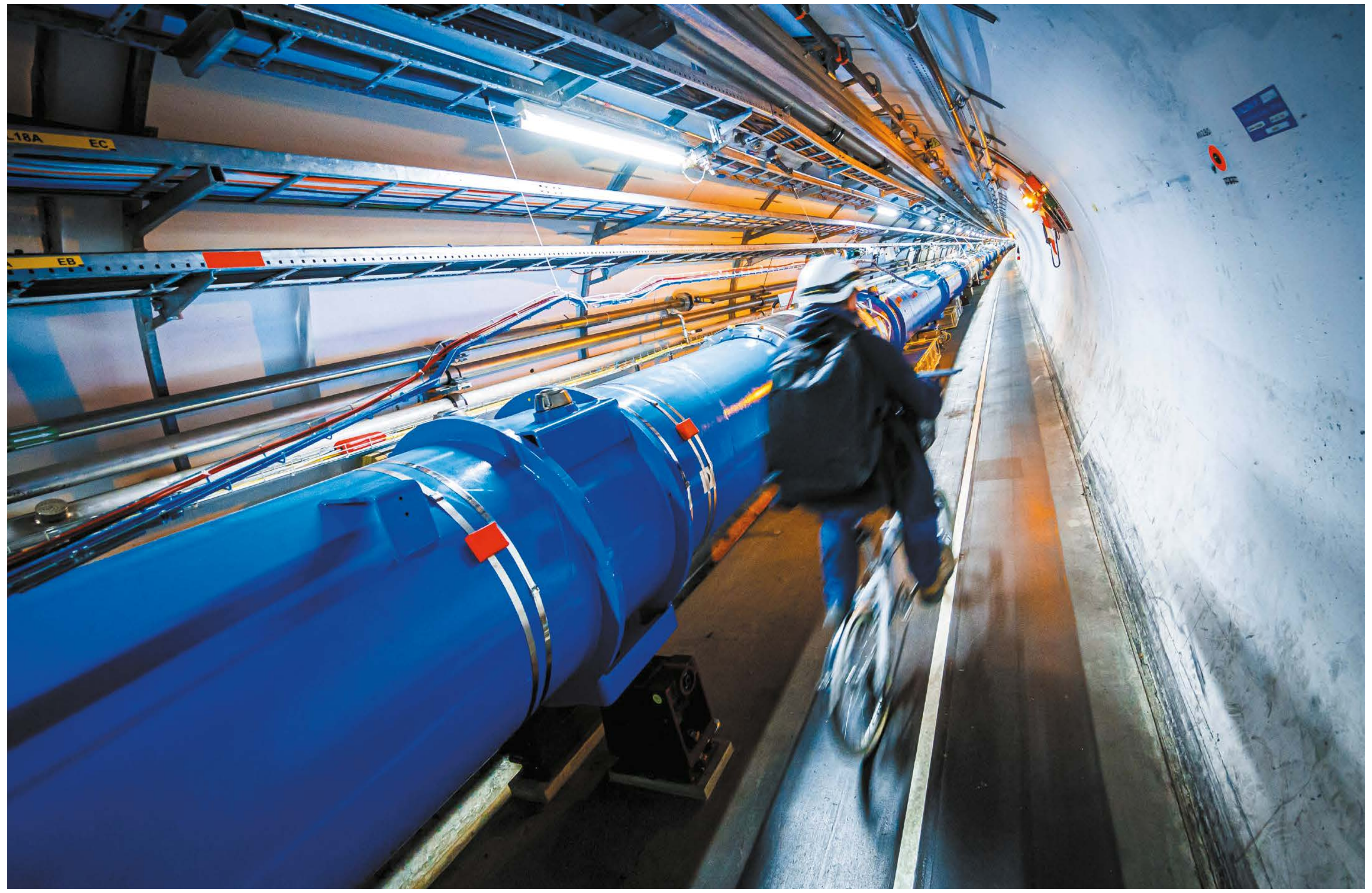
A tunnel of the Superconducting Super Collider project in 1993, which was abandoned by Congress. Ron Heflin/Associated Press

By Dennis Overbye and Katrina Miller

Published Dec. 7, 2023 Updated Dec. 8, 2023

News in focus



VALENTIN FLAURAUD/AFP VIA GETTY

The Large Hadron Collider near Geneva, Switzerland. The world's next major collider is a key focus for particle physicists.

BIG BANG OBSERVATORY TOPS WISH LIST FOR BIG US PHYSICS PROJECTS

Report also supports projects of unprecedented scale to study dark matter, neutrinos and the Higgs boson.

By Davide Castelvecchi

The United States should fund proposed projects to drastically scale up its efforts in five areas of high-energy physics, an influential panel of scientists has concluded.

Topping the ranking is the Cosmic Microwave Background–Stage 4 project, or CMB-S4, which is envisioned as an array of 12 radio telescopes split between Chile's Atacama Desert and the South Pole. It is designed to look for indirect evidence of physical processes in the instants after the Big Bang – processes that have been mostly speculative so far.

The other four priorities are experiments to study the elementary particles called neutrinos, both coming from space and made in the laboratory; the largest-ever dark-matter detector; and strong US participation in a future overseas particle collider to study the Higgs boson.

An ad hoc group called the Particle Physics Project Prioritization Panel (P5) presented the recommendations on 7 December (see go.nature.com/41jzfrf). The committee, which is convened roughly once a decade, was charged with making recommendations for the two main US agencies that fund research in high-energy physics, the Department of Energy (DoE) and the National Science Foundation (NSF).

In addition to the five key recommendations, the report says that the United States should embark on a programme to demonstrate the feasibility of two completely new kinds of particle accelerator, after a surge of grass-roots enthusiasm in the particle-physics community.

Town Hall at Fermilab, Dec 11, 2023
1397 registrants

Pathways to Innovation and Discovery in Particle Physics

Report of the Particle Physics Project Prioritization Panel 2023

Exploring the Quantum Universe

https://www.usparticlephysics.org/p5

Credit:
Yurie
Murayama

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