Exploring the Quantum Universe

Pathways to Innovation and Discovery in Particle Physics

Report of the 2023 Particle Physics Project Prioritization Panel

Committee on Astronomy and Astrophysics

Karsten Heeger
P5 Deputy Chair,
On behalf of P5 Committee

2023p5report.org

P5 and HEPAP

- **P5 = Particle Physics Project Prioritization Panel**
- **P5 is a subpanel of HEPAP (High Energy Physics Advisory Panel)**
- P5 is an advisory body, responds to charge, makes recommendations to HEPAP
- Establishes scientific priorities taking into account cost and schedule information
- Provides a **10-year strategic plan for given budget scenarios within 20-year vision**
- P5 builds on community input, community support is essential


P5 Panel
Smash Particles

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

Charge to the 2023 P5 Subcommittee

Consider : HEP is a global field	Support decisions to retain US leadership as a global partner	Preserve essential roles of Universities and National Labs	EDIA throughout the field results in improved science
Balanced core research budget is paramount to producing science	Remember costs of R&D, commissioning, and operations for future projects	Address synergies with broad national initiatives	Assess science case for on-going projects

Issued on Nov 2, 2022
signed by Asmeret Berhe (Director of DOE Office of Science), Sean Jones (Director of NSF MPS)

US Process for HEP Planning

Community

Snowmass 2021

"Snowmass" Community Study

Organized by APS / DPF

Advisory Panel

DOE SC
NSF MPS

Charge
Budget scenario

Particle Physics Project Prioritization Panel (P5)

Organized by HEPAP

Implementation

Exploring the Quantum Universe

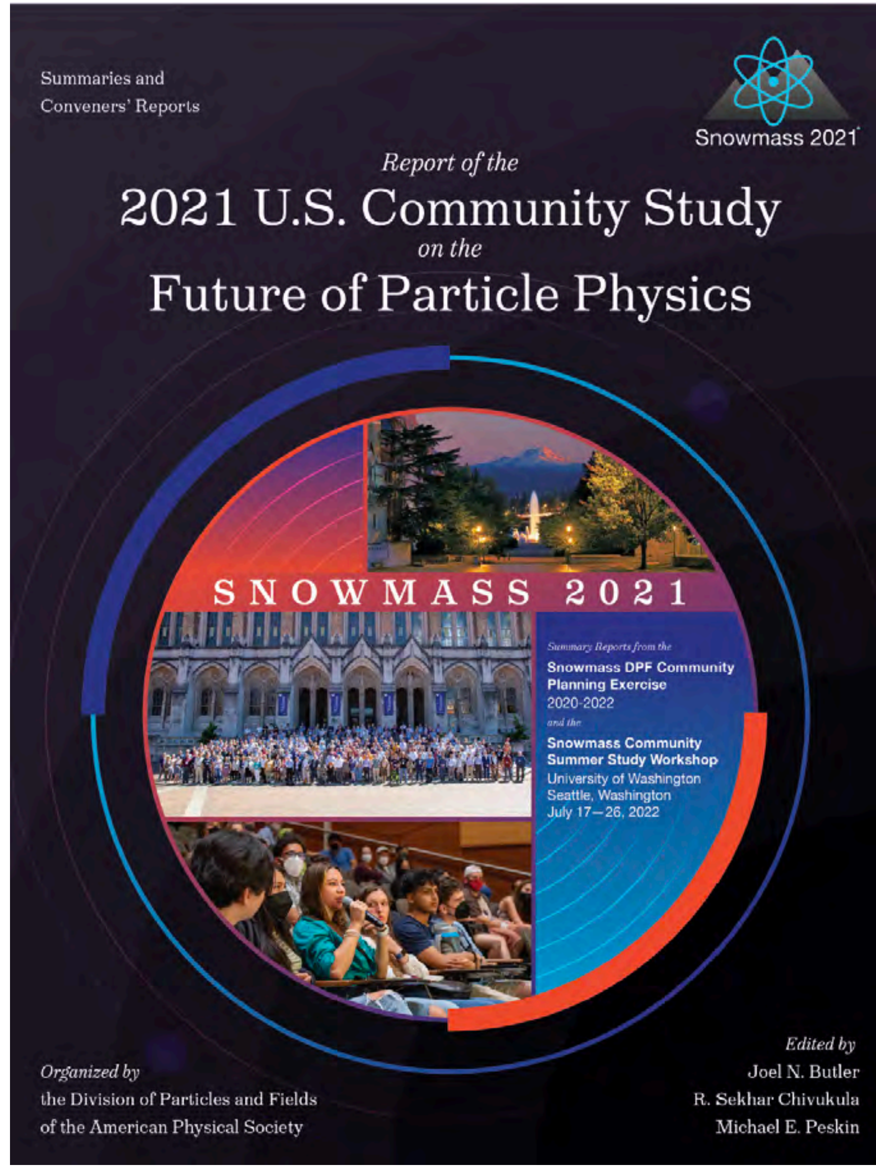
DOE HEP
NSF PHYS

OMB
OSTP
Congress

+ international partners

Final workshop of Snowmass 2021 Community Study (~2 years)
University of Washington, July 2022

Community Vision from Snowmass 2021



Summary of the 2021-2022 US HEP Community Planning Exercise

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<tr><td rowspan="2">Energy Frontier</td><td colspan="2">U.S. Initiative for the Targeted Development of Future Colliders and their Detectors</td></tr>
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<tr><td>Neutrino Frontier</td><td>LBNF/DUNE Phase I & PIP- II</td><td>DUNE Phase II (incl. proton injector)</td></tr>
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Spectroscopic Survey - S5*</td><td>Next Gen. Grav. Wave Observatory*
Line Intensity Mapping*</td></tr>
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<tr><td>Rare Process Frontier</td><td></td><td>Advanced Muon Facility</td></tr>
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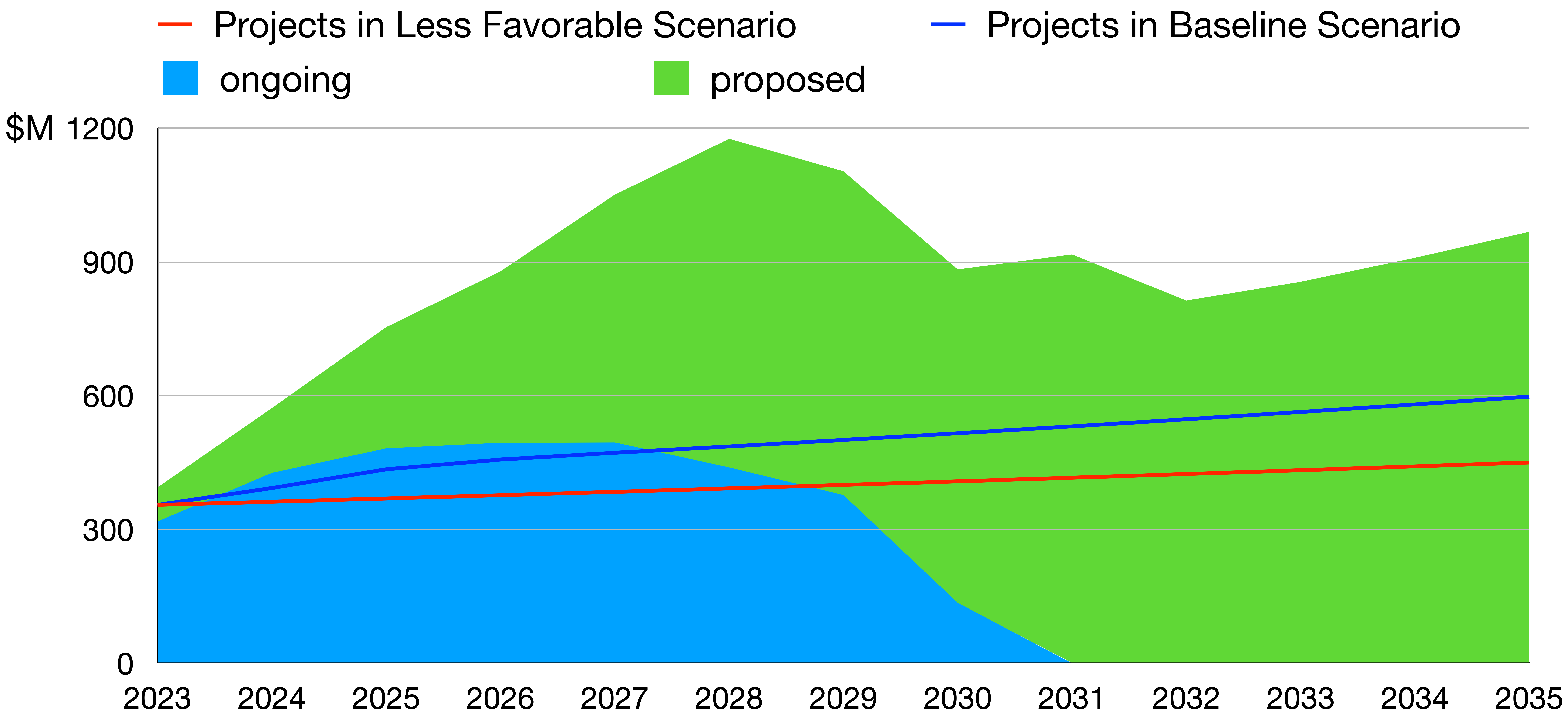
Important Lessons Learned

- Developing a compelling and fiscally responsible plan that has widespread support from the field is a must if we want sustained support
- Completing projects on schedule and within the budget is crucial to increasing our support
- A strong and broad ecosystem of theorists and experimentalists, R&D, and small & large projects is essential for the field's long-term health
- **People are our most precious resource**
- It's an honor and privilege to do research into the nature of the Universe. We must be good stewards of our field.

Budget Scenarios and Projects



not including on-shore Higgs factory

DOE only

Subcommittee on Costs/Risks/Schedule

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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)

Jay Marx

Committee provided low, medium, and high estimates with schedules

Prioritization Principles

In the process of prioritization, we considered **scientific opportunities, budgetary realism, and a balanced portfolio** as major decision drivers.

Large projects (>$250M)
• Paradigm-changing discovery potential, world-leading, Unique in the world

Medium projects ($50–250M)
• Excellent discovery potential or development of major tools, world-class, Competitive

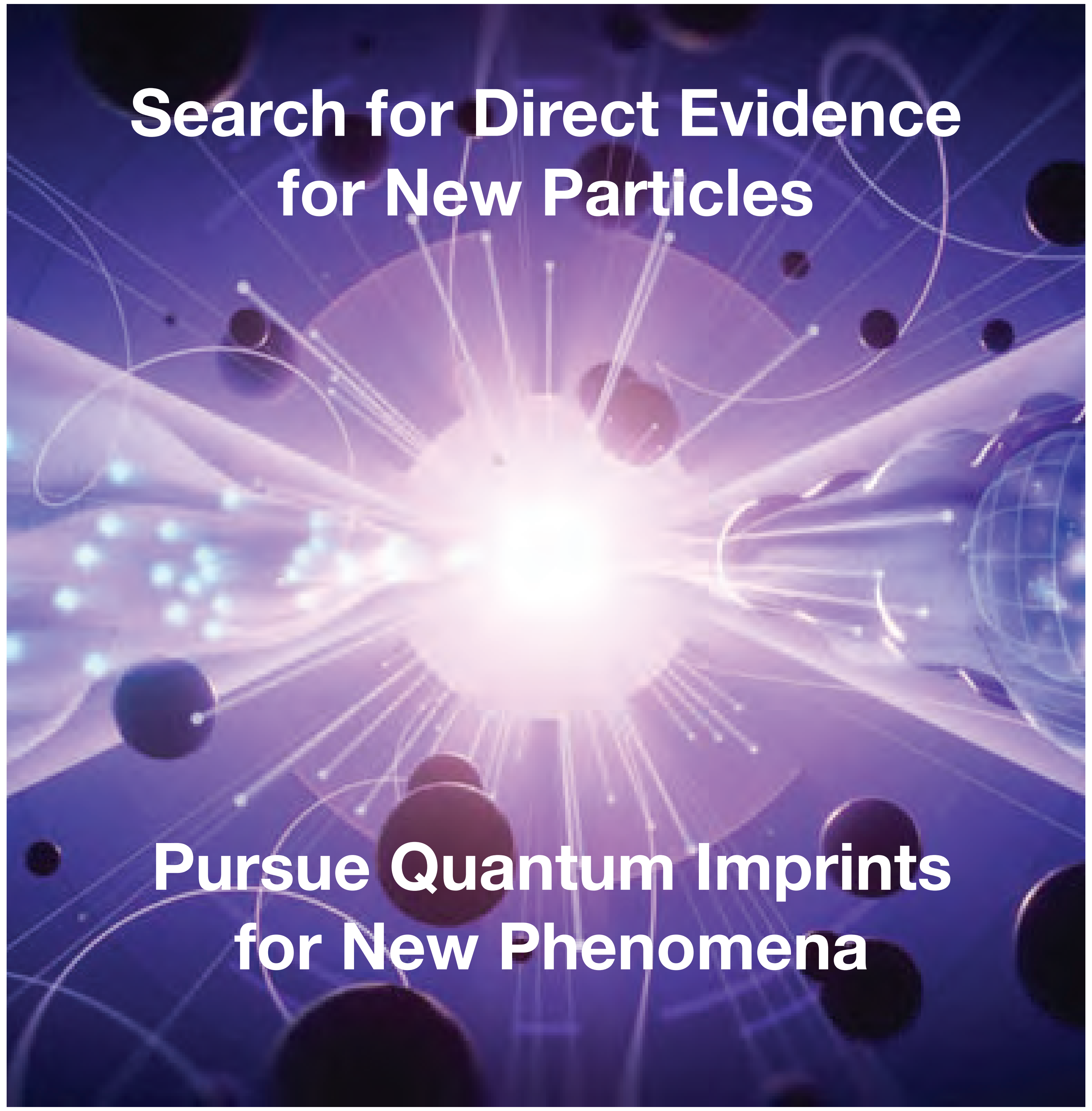
Small projects (<$50M)
• Discovery potential, well-defined measurements, or outstanding technology development, World-class, Excellent training grounds

Overall program should

- leverage **unique US facilities and capabilities,** engage with **core national initiatives** to develop key technologies,
- develop a **skilled workforce** for the future that draws on all talent
- realize **effective engagement and partnership in international endeavors**

Explore the Quantum Universe

Explore the Quantum Universe

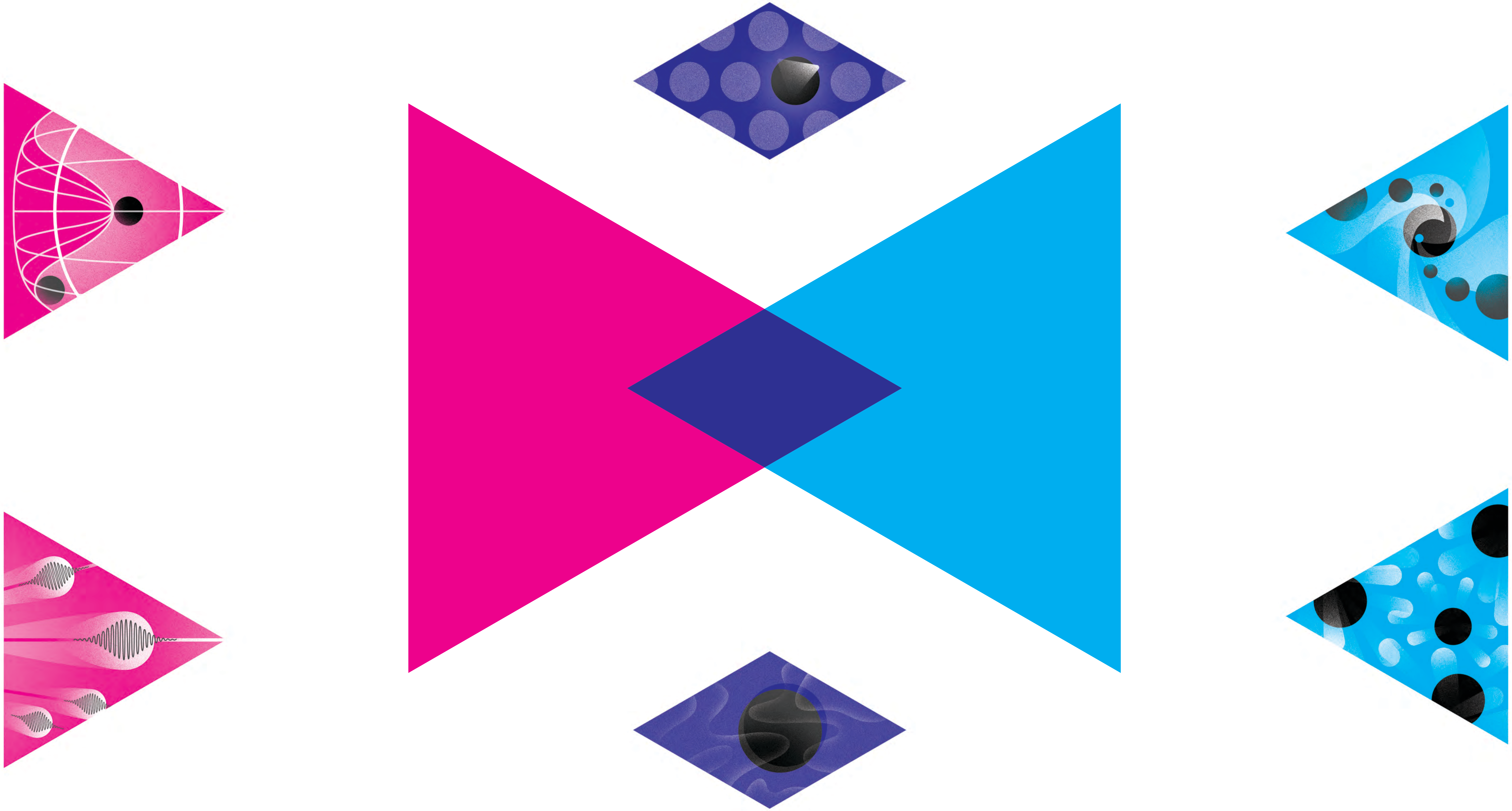


Decipher the Quantum Realm

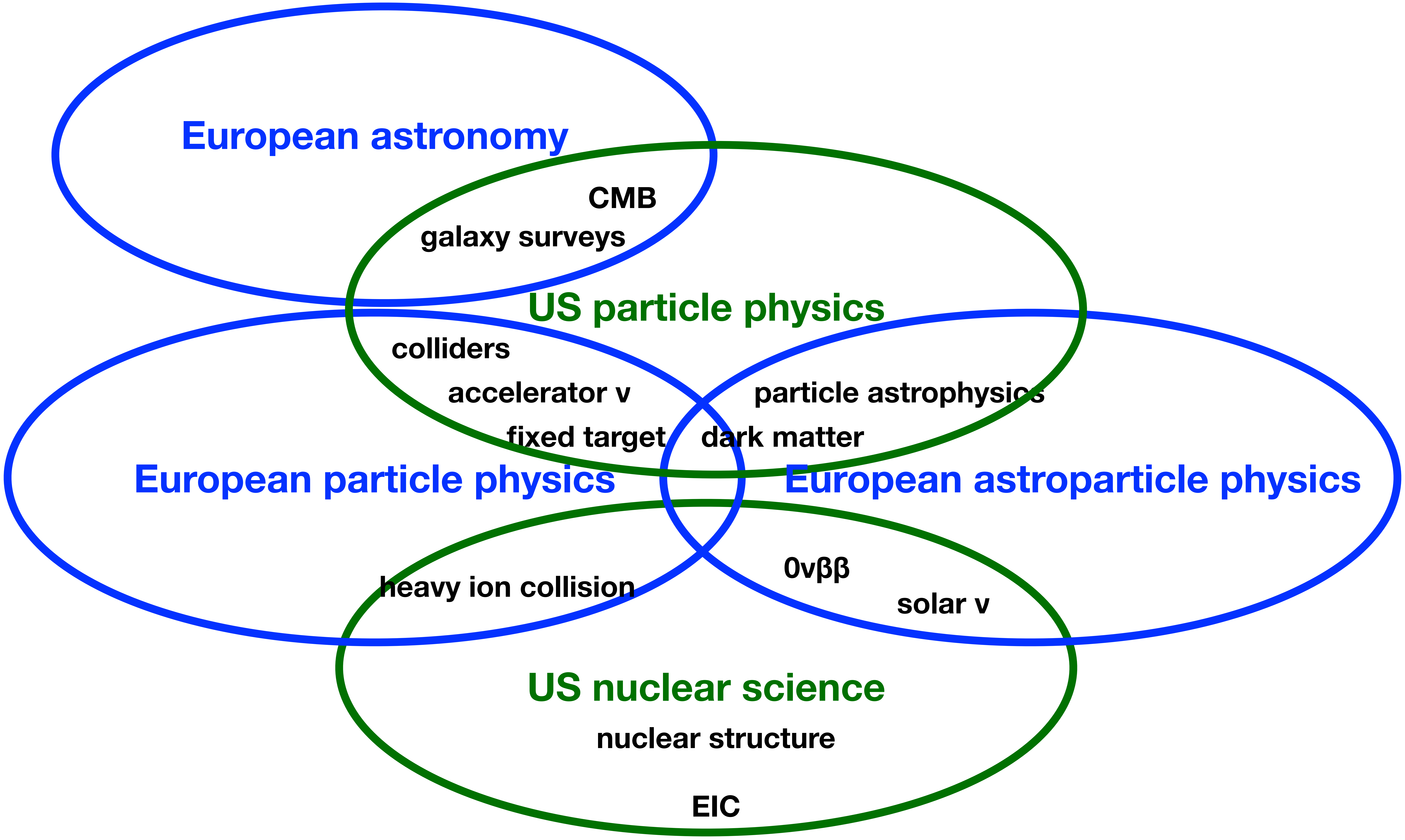
Explore New Paradigms in Physics

Illuminate the Hidden Universe

Explore the Quantum Universe



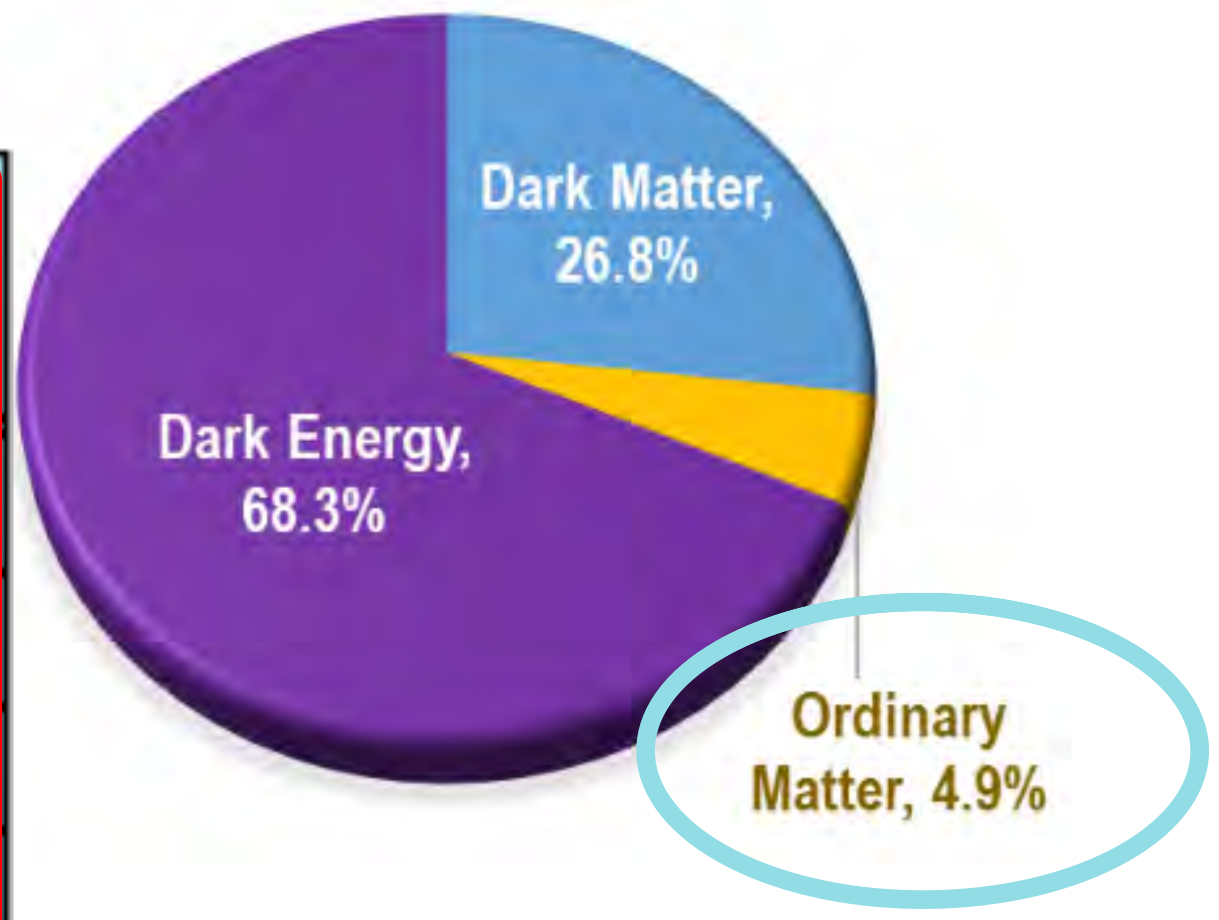
Cosmology and Astrophysics in US Particle Physics

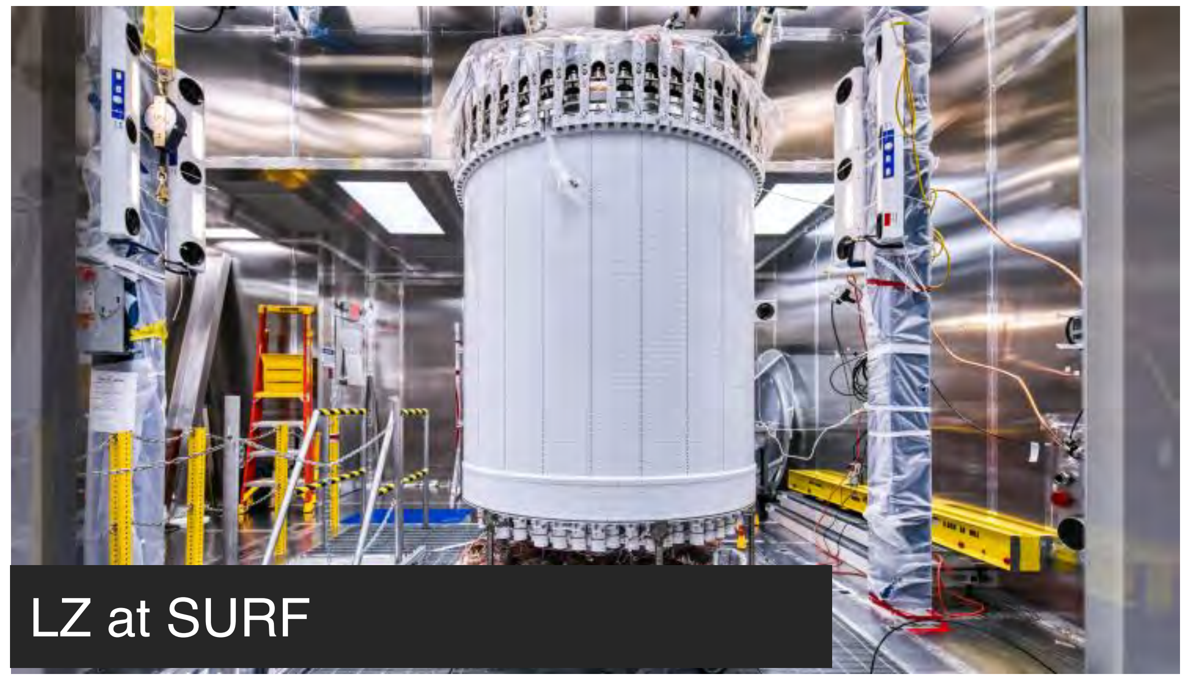


Cosmic Frontier Experiments

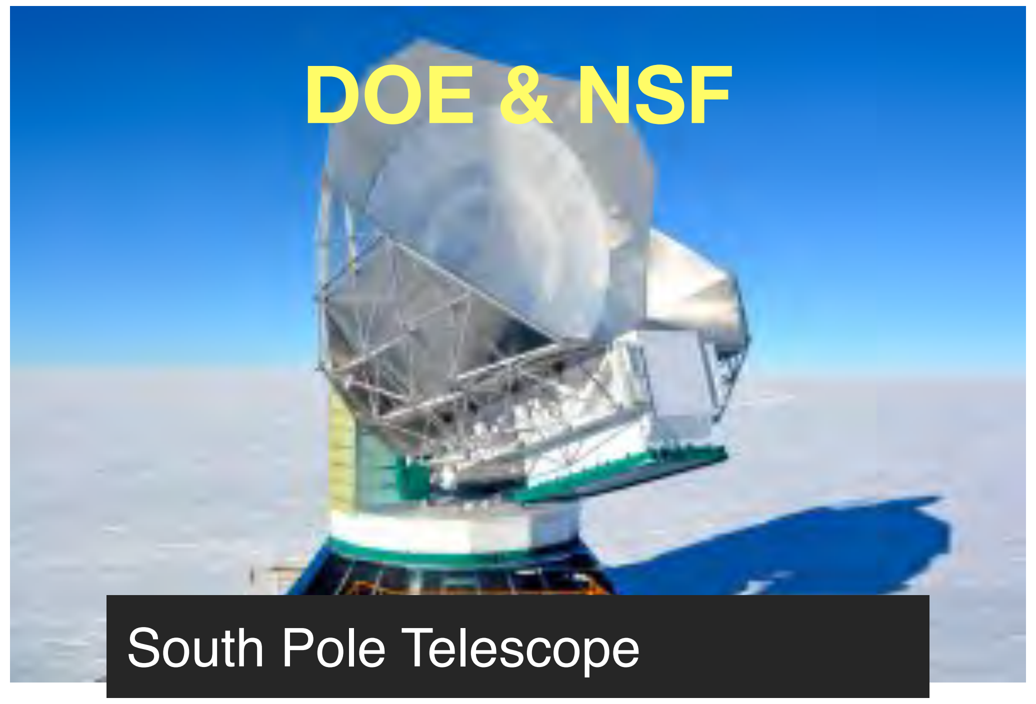
- **Cosmic Frontier experiments** address four of five science drivers
- They use naturally occurring sources to determine the fundamental energy, space and time.

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

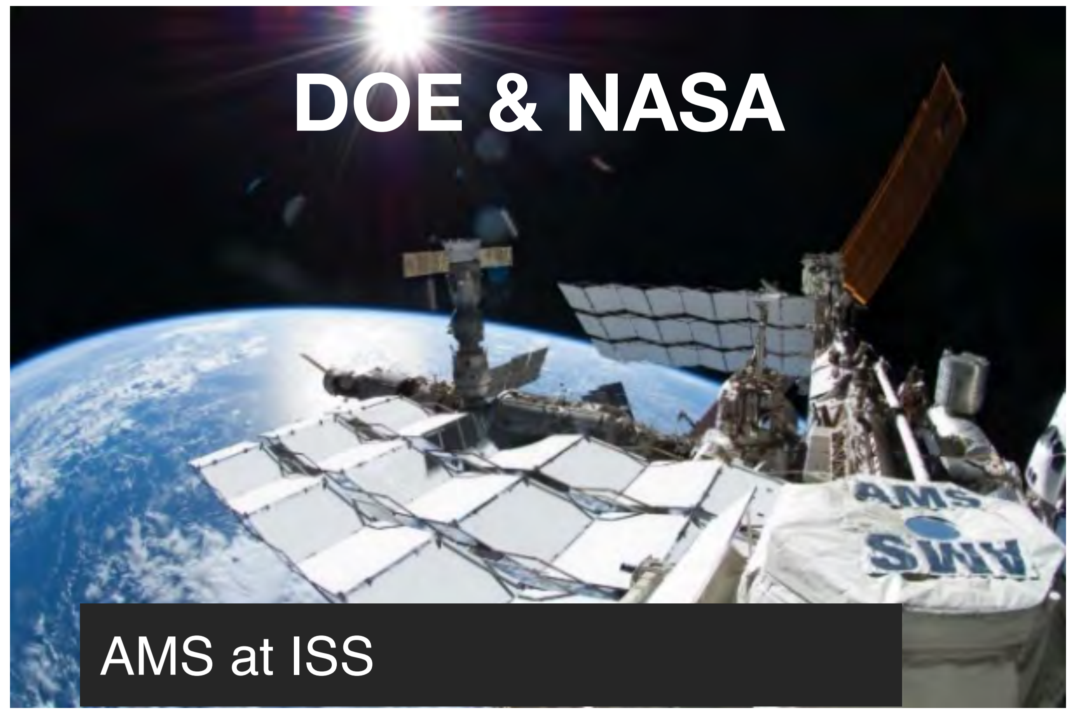



LZ at SURF

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

Exploring the Quantum Universe

1.1 Overview and Vision

We envision a new era of scientific leadership, centered on decoding the quantum realm, unveiling the hidden universe, and exploring novel paradigms. Balancing current and future large- and mid-scale projects with the agility of small projects is crucial to our vision. We emphasize the importance of investing in a highly skilled scientific workforce and enhancing computational and technological infrastructure. Acknowledging the global nature of particle physics, we recognize the importance of international cooperation and sustainability in project planning. We seek to open pathways to innovation and discovery that offer new insights into the mysteries of the quantum universe.

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Not Rank-Ordered

Recommendation 1

Reaffirm critical importance of the ongoing projects

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).

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).

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).

US leadership in key areas of particle physics

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Recommendation 1

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:

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).
f. **DESI** (*understand what drives cosmic evolution*, section 4.2).
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**:

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Recommendation 2

Rank-Ordered

New exciting initiatives

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).

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).

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).

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).

Major New initiative: CMB-S4

Constrain the energy scale of inflation, determine the abundance of light relic particles in the early universe, measure the sum of neutrino masses, and probe the physics of dark matter and dark energy…

Site in Chile

Site at the South Pole

National Science Foundation

<https://www.nsf.gov> Find Funding & Apply Manage Your Award

Home (/)

NSF 23-117

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

Jur

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The South Pole, a unique site that enables the world-leading science of CMB-S4 and IceCube-Gen2, must be maintained as a premier site of science to allow continued US leadership in these areas. (section 2.4)

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.

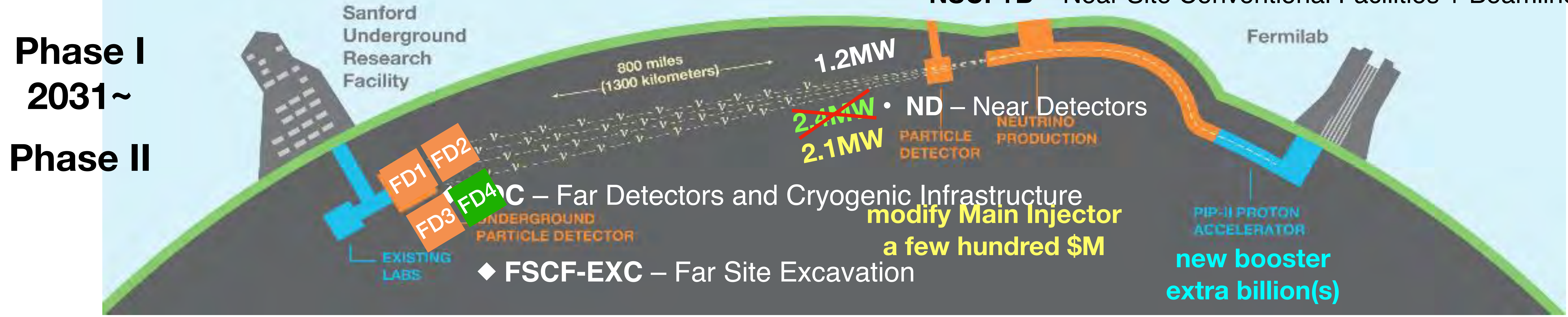
South Pole Station is saturated with already-funded projects and required critical infrastructure and maintenance activities that cannot be deferred until late in the decade. South Pole Station will continue to host the current suite of large-scale science projects; however, proposers seeking support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

Long baseline neutrino facility (LBNF) and Deep Underground Neutrino Experiment (DUNE)

Far Site – SURF in Lead, SD
Facility/Infrastructure and Far Detectors

Near Site – FNAL in Batavia, IL
Facility/Infrastructure, Neutrino Beamline, and Near Detectors

- **FSCF-BSI** – Far Site Building & Site Infrastructure
- **NSCF+B** – Near Site Conventional Facilities + Beamline



- DUNE is an international science collaboration of more than 1300 scientists from 35 countries plus CERN
  - 50 – 50 split between U.S. and non- U.S. collaborators

3.1.4 – Future Opportunities: DUNE FD4, the Module of Opportunity

An upgraded detector module will provide excellent prospects for underground physics, including direct dark matter detection, exotic dark matter searches, and expanded sensitivity to solar neutrinos. R&D for advanced detector concepts should be supported.

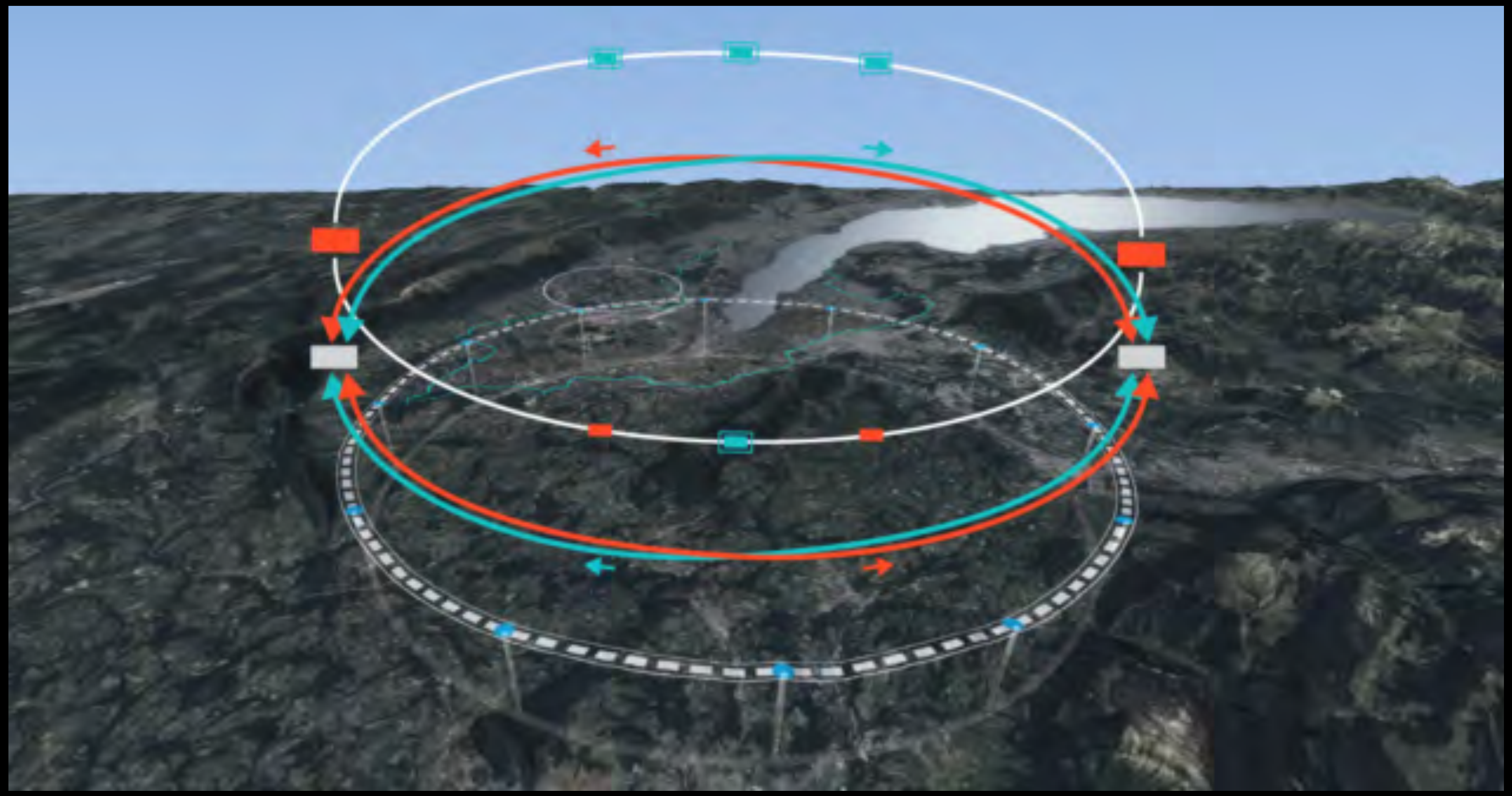
…ffice of Science (TPC = $3.2B)
…al particle physics mega-project

An Offshore Higgs Factory

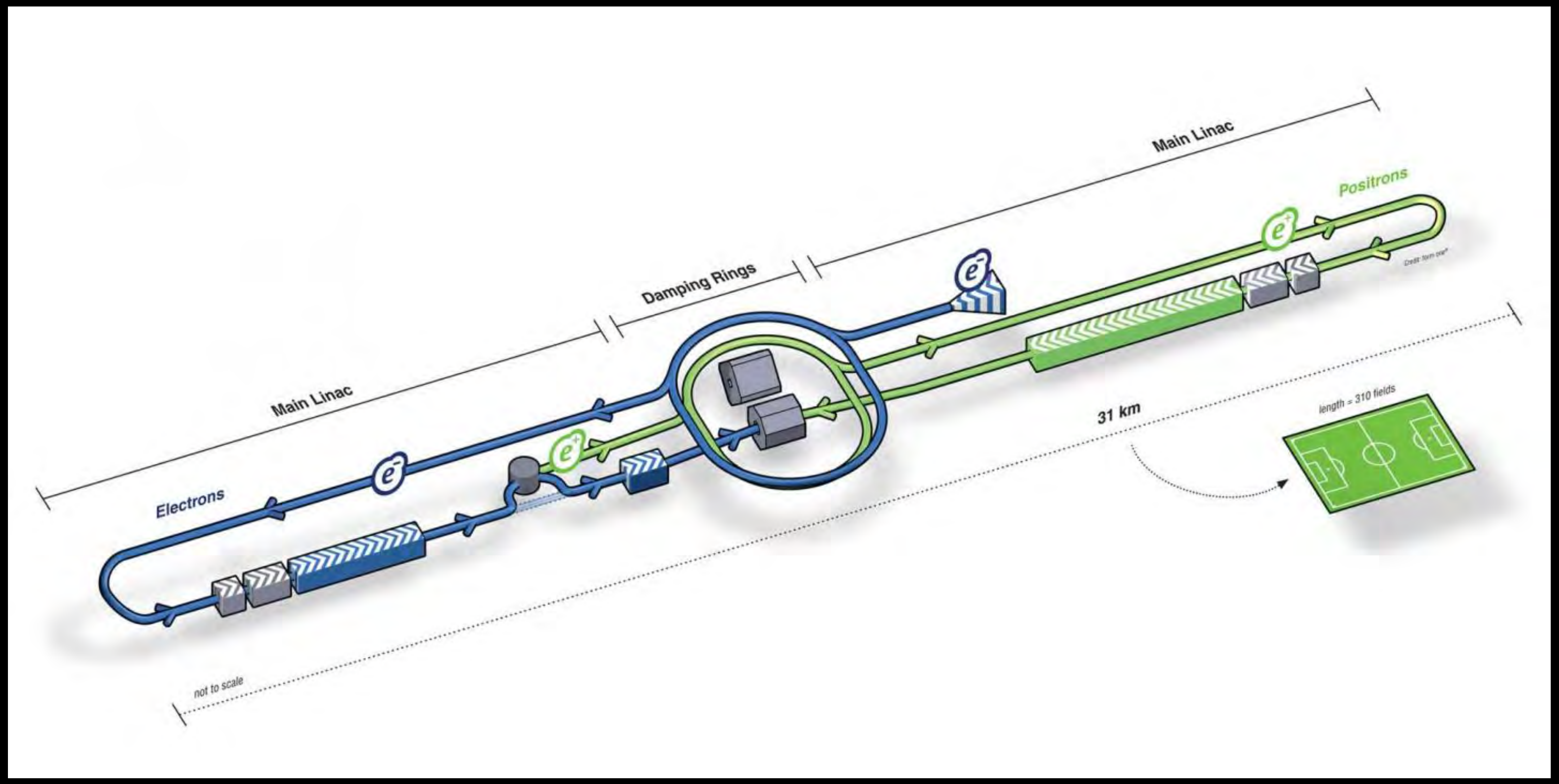
An electron-positron collider covering center-of-momentum energy range 90 - 350 GeV

- Precision measurements of couplings and some production modes
- Order of magnitude improved access to Higgs → invisible decays
- EW sector consistency checks, testing through quantum loops that relate W & Z bosons, the top quark, and the Higgs
- Improve knowledge of coupling to charm quark, potentially provide access to coupling to strange quark

FCC ee



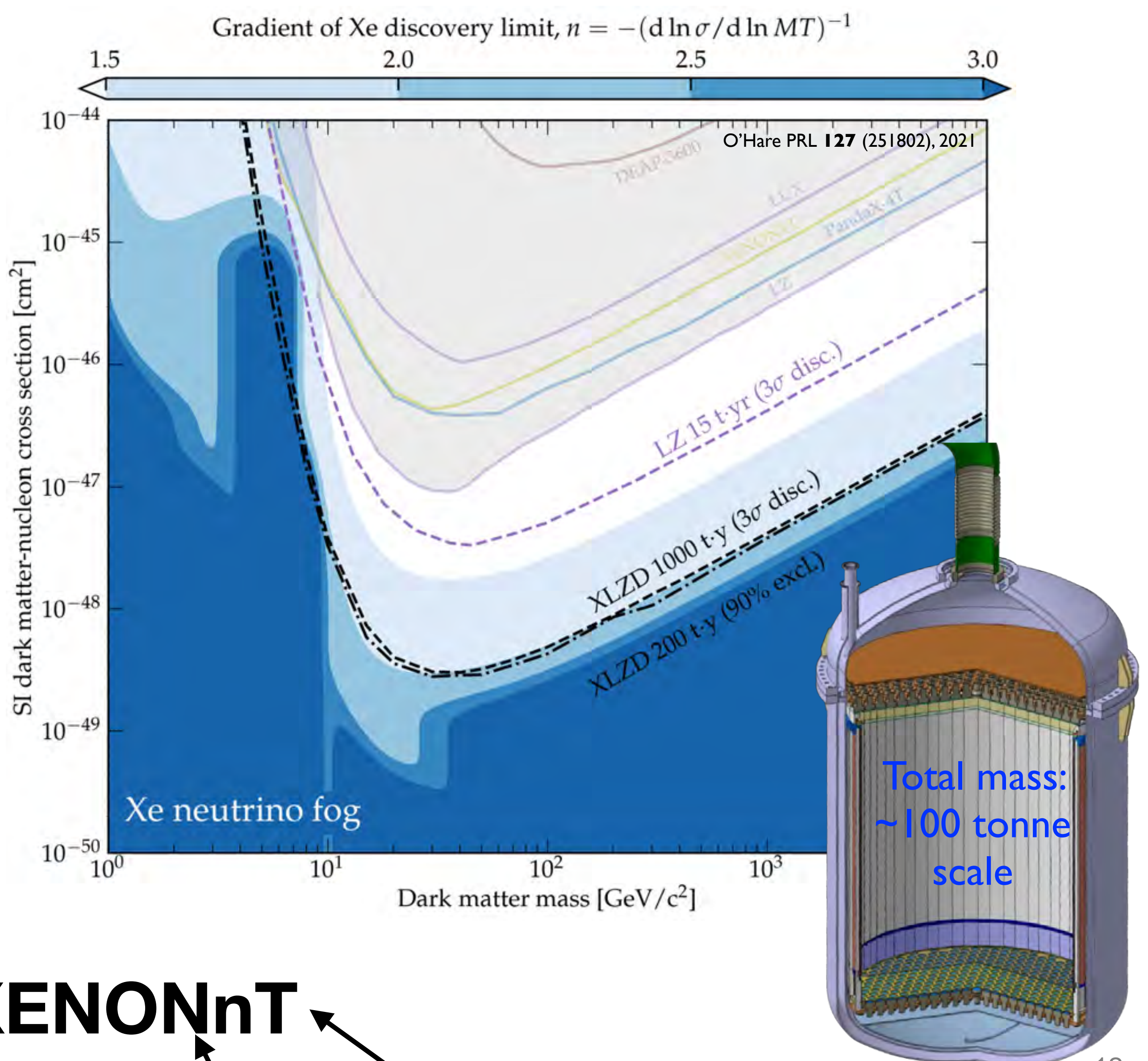
ILC



G3 Dark Matter experiments

XLZD: definitive search for high mass WIMPs

- Searching for WIMPs into the "fog"
  - Nearly indistinguishable background from astrophysical neutrinos
  - Sensitivity rapidly falls - 20% flux uncertainty
  - Systematic limit (1000 tonne-year exposure) = practical limit of ~100-tonne detector
  - 3-sigma discovery at $3x10^{-49}$ at 40 GeV
- Combine best of LZ and XENONnT
  - 10x mass: 63-tonne fiducial of 70 active
  - Double TPC linear dimensions
  - Compact geometry: readout, underground transport & fit



Liquid Noble DM & G3 / XLZD / P5 2023 12

LZ Darwin XENONnT

Lux XENON1t

Zeppelin **XLZD**

XMASS PandaX

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
(Can be hosted in the cavern made available through the SURF expansion)

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.

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Difficult Choices

Figure 2 – Construction in Various Budget Scenarios

Index: Y: Yes N: No R&D: Recommend R&D only C: Conditional yes based on review P: Primary S: Secondary

Delayed: Recommend construction but delayed to the next decade

† Recommend infrastructure support to enable international contributions

Can be considered as part of ASTAE with reduced scope

US Construction Cost	Scenarios: Less	Baseline	More	Science Drivers: Neutrinos	Higgs Boson	Dark Matter	Cosmic Evolution	Direct Evidence	Quantum Imprints	Astronomy & Astrophysics
>$3B										
onshore Higgs factory	N	N	N		P	S		P	P	
$1–3B										
offshore Higgs factory	Delayed	Y	Y		P	S		P	P	
ACE-BR	R&D	R&D	C	P				P	P	
$400–1000M										
CMB-S4	Y	Y	Y	S		S	P			P
Spec-S5	R&D	R&D	Y	S		S	P			P
$100–400M										
IceCube-Gen2	Y	Y	Y	P		S				P
G3 Dark Matter 1	Y	Y	Y	S		P				
DUNE FD3	Y	Y	Y	P				S	S	S
test facilities & demonstrator(s)	C	C	C		P	P		P	P	
ACE-MIRT	R&D	Y	Y	P						
DUNE FD4	R&D	R&D	Y	P				S	S	S
G3 Dark Matter 2	N	N	Y	S		P				
Mu2e-II	R&D	R&D	R&D						P	
srEDM	N	N	N						P	
$60–100M										
SURF expansion	N	Y	Y	P		P				
DUNE MCND	N†	Y	Y	P				S	S	
MATHUSLA	N#	N#	N#			P		P		
FPF trio	N#	N#	N#	P		P		P		

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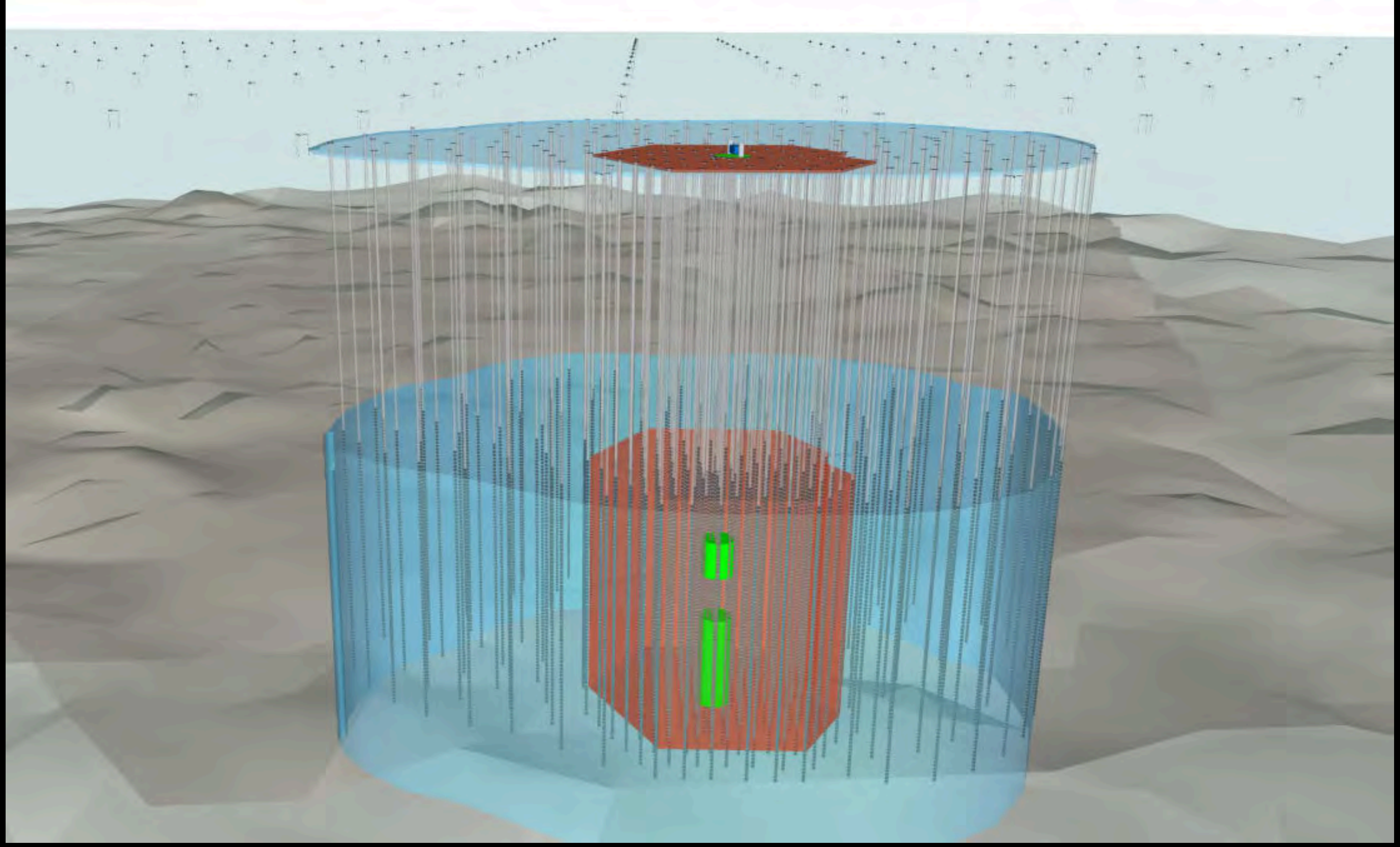
Recommendation 2

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

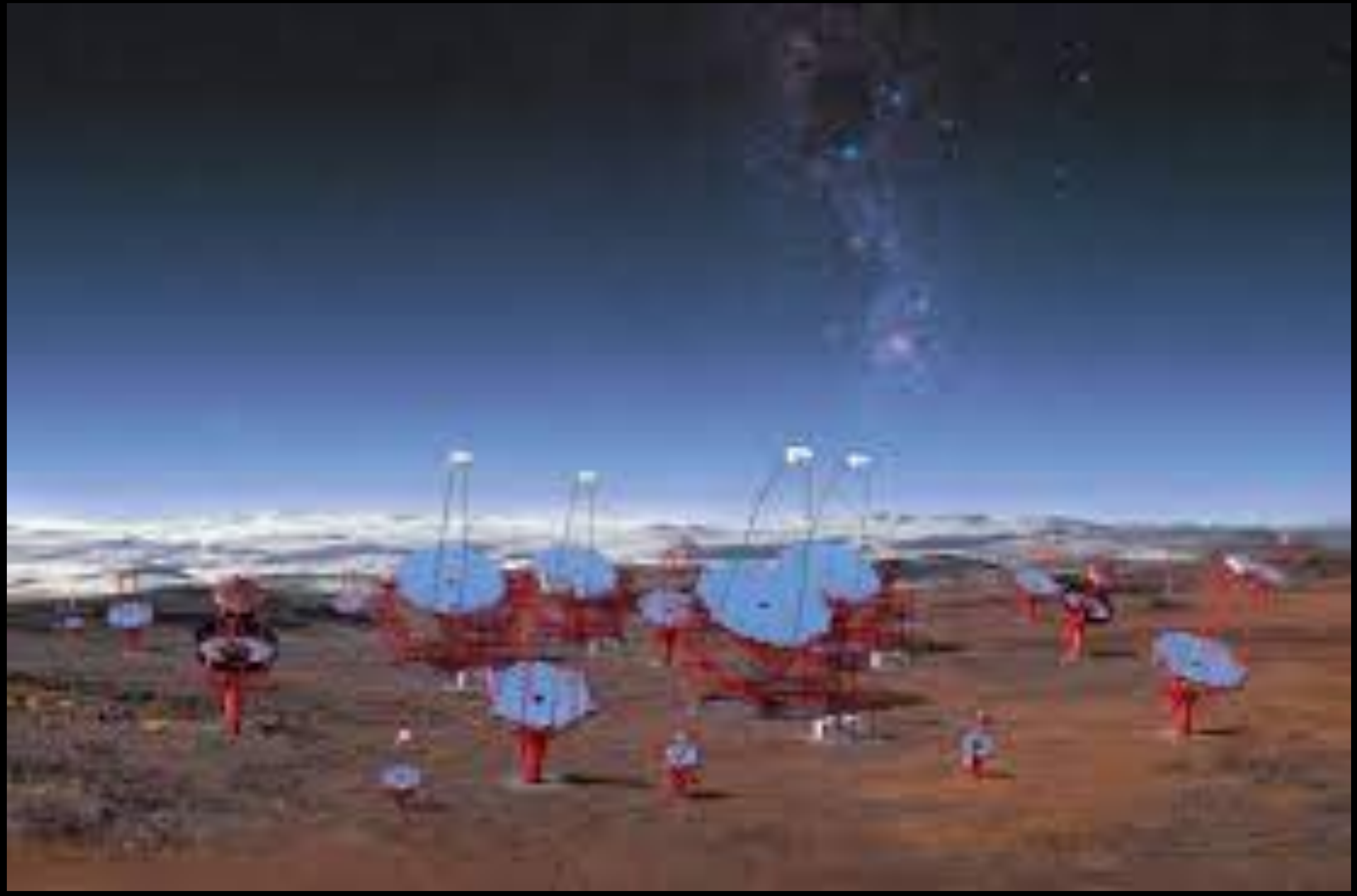
IceCube-Gen2 also has a strong science case in **multi-messenger astrophysics** together with gravitational wave observatories. We recommend that NSF expand its efforts in multi-messenger astrophysics, a unique program in the NSF Division of Physics, with US involvement in the **Cherenkov Telescope Array**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

NSF New Initiatives: IceCube-Gen2 & CTA

IceCube-Gen2: ten-fold improvement in sensitivity to astrophysical neutrinos over IceCube, most sensitive probe of heavy decaying dark matter.



Cherenkov Telescope Array (CTA) provides sensitivity to WIMP thermal targets beyond the reach of G3.



It ”takes a village” in dark matter… CMB-S4, LSST, DESI-II, and eventually Spec-S5 all play a role

Accelerators
LHC heavy ions
LHC protons
High-energy cosmic rays
Inflation
Big Bang
3min
is visible
380k yrs
Size
sible universe
TODAY
Dark Energy Galaxy Surveys
Inflation
rinos
atter
eutrinos
CMB-S4
Next Generation CMB Experiment
POSSIBLE
RELICS
t = 10^-36 s
E = 10^16 GeV
t = 10^-10 s
E = 10^2 GeV
t = 10^-4 s
E = 10^-1 GeV
t = 10^2 s
E = 10^-4 GeV
t = 3x10^5 y
H:He ~ 3:1 from Big Bang agrees with observation!
Credit: Particle Data Group

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Not Rank-Ordered

Recommendation 3

Balanced Portfolio from small to large

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.

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Recommendation 4

Investment in the future

a. Support **vigorous R&D toward a cost-effective 10 TeV pCM collider** based on proton, muon, or possible wakefield technologies, including an evaluation of options for US siting of such a machine, with a goal of being ready to build **major test facilities and demonstrator facilities within the next 10 years** (sections 3.2, 5.1, 6.5, and Recommendation 6).

b. Enhance research in **theory** to propel innovation, maximize scientific impact of investments in experiments, and expand our understanding of the universe (section 6.1).

c. Expand the **General Accelerator R&D (GARD)** program within HEP, including stewardship (section 6.4).

d. Invest in R&D in **instrumentation** to develop innovative scientific tools (section 6.3).

e. Conduct **R&D** efforts to define and enable new projects in the next decade, including detectors for an e^+e^- Higgs factory and 10 TeV pCM collider, Spec-S5, DUNE FD4, Mu2e-II, Advanced Muon Facility, and line intensity mapping (sections 3.1, 3.2, 4.2, 5.1, 5.2, and 6.3).

f. Support key **cyberinfrastructure** components such as shared software tools and a sustained R&D effort in computing, to fully exploit emerging technologies for projects. Prioritize **computing and novel data analysis techniques** for maximizing science across the entire field (section 6.7).

g. Develop plans for improving the **Fermilab accelerator complex** that are consistent with the long-term vision of this report, including neutrinos, flavor, and a 10 TeV pCM collider (section 6.6).

We recommend specific budget levels for enhanced support of these efforts and their justifications as **Area Recommendations** in section 6.

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Recommendation 5

Diversity, Inclusion, Equity, Relevance to society

The following workforce initiatives are detailed in section 7:

a. All projects, workshops, conferences, and collaborations must incorporate ethics agreements that detail

The inherent curiosity driving our exploration of the natural world is a universal aspect of human nature. This shared curiosity serves as the driving force behind our commitment to strengthening and expanding this workforce, prompting us to actively seek talent from all corners of society, regions of the country, and on a global scale.

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

Treating others with respect requires maintaining a professional work environment, free from harassment and abuse. Discrimination, harassment, or bullying within a scientific collaboration harms individuals, disrupts scientific progress, and is therefore scientific misconduct.

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.

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Recommendation 6

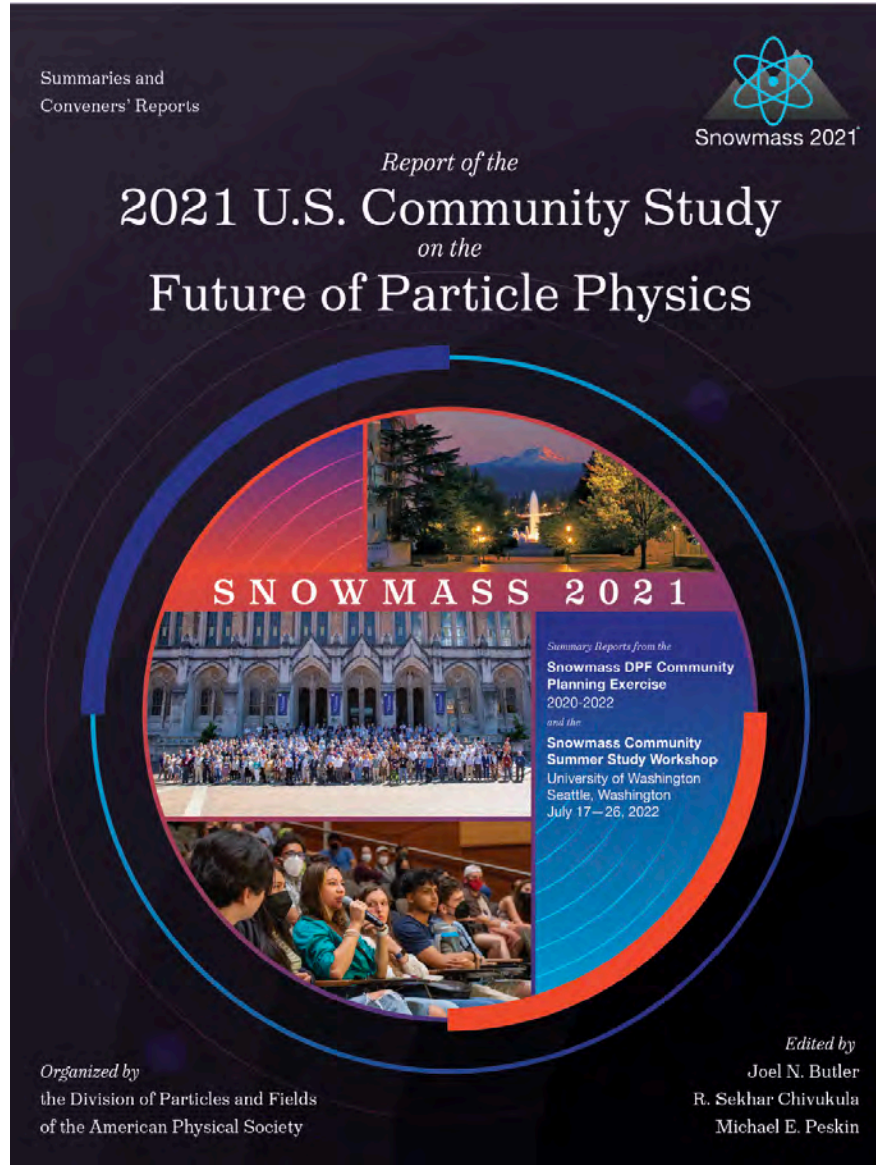
Decisions without waiting for the next P5 in 10 years

Convene a targeted panel with broad membership across particle physics later this decade that makes decisions on the US accelerator-based program at the time when major decisions concerning an off-shore Higgs factory are expected, and/or significant adjustments within the accelerator-based R&D portfolio are likely to be needed. A plan for the Fermilab accelerator complex consistent with the long-term vision in this report should also be reviewed.

The panel would consider the following:

1. The level and nature of **US contribution in a specific Higgs factory** including an evaluation of the associated schedule, budget, and risks once crucial information becomes available.
2. Mid- and large-scale **test and demonstrator facilities** in the accelerator and collider R&D portfolios.
3. A plan for the evolution of the **Fermilab accelerator complex** consistent with the longterm vision in this report, which may commence construction in the event of a more favorable budget situation.

Community Vision from Snowmass 2021



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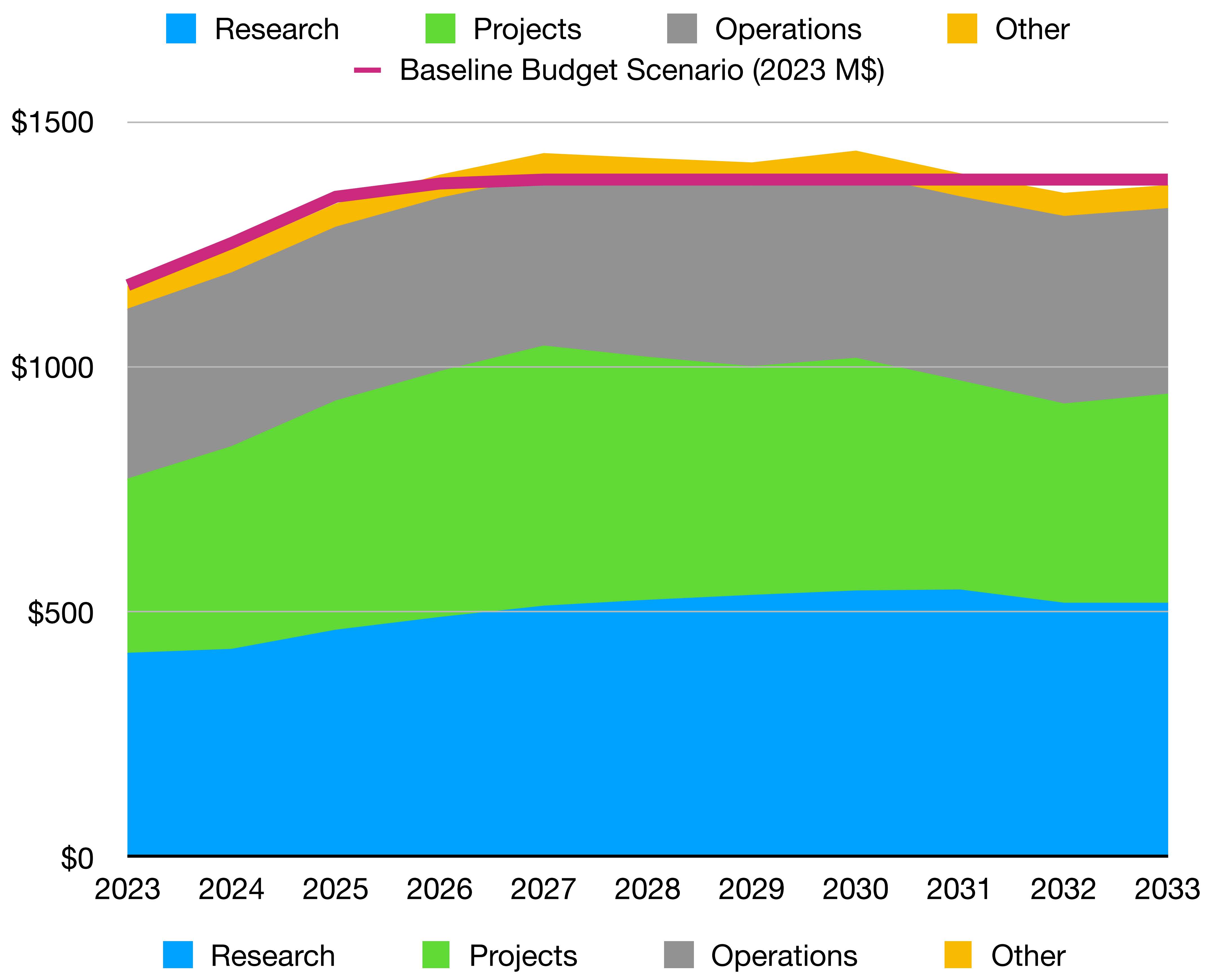
		✓ Higgs Factory
Neutrino Frontier	✓ LBNF/DUNE Phase I & PIP- II	✓ DUNE Phase II (incl. proton injector)
Cosmic Frontier	✓ Cosmic Microwave Background - S4	Next Gen. Grav. Wave Observatory*
	✓ Spectroscopic Survey - S5*	✓ Line Intensity Mapping*
	✓ Multi-Scale Dark Matter Program (incl. Gen-3 WIMP searches)	
Rare Process Frontier		✓ Advanced Muon Facility

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

✓ **Recommended**
✓ **R&D**

Budget Scenarios



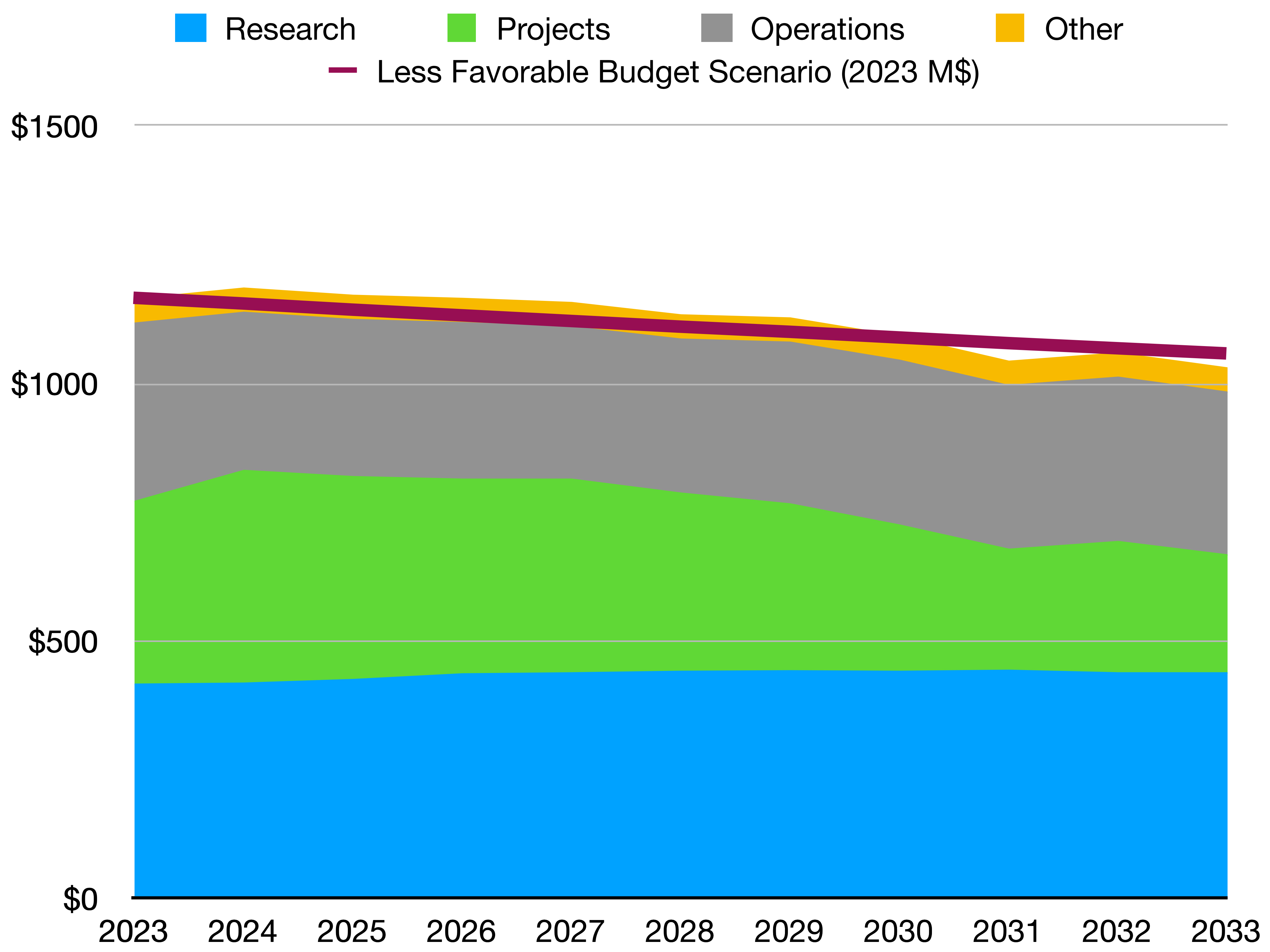


Fig. 2 Evolution of DOE budgets in Research, Projects, Operations, and Other in our budget exercise for the two budget scenarios given in the charge in 2023 dollars assuming 3% annual inflation.

Not in the Report

Broad and Diverse Program

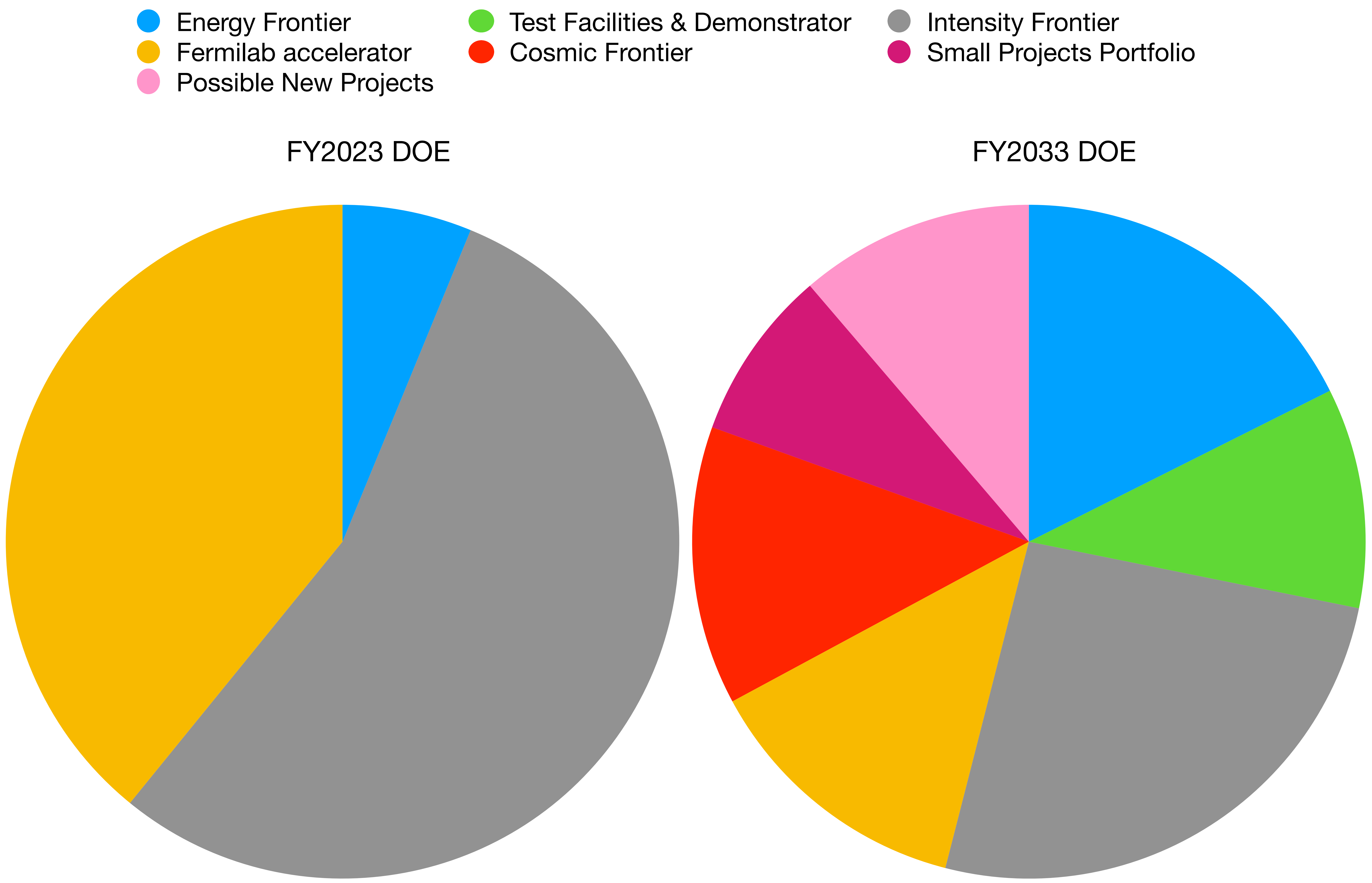


Fig. 3 Composition of DOE Projects in FY2023 (enacted) and FY2033 (recommended) in in our budget exercise. Demonstrator and Small Projects Portfolio are regarded as Projects for this pie chart.

Not in the Report

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

DECEMBER 13, 2023 | 8 MIN READ

Road Map for U.S. Particle Physics Wins Broad Approval

Dan Garisto
@dangaristo

When Snowmass ended last year, I wondered how particle physicists were ever going to reach consensus that worked within a budget, was still ambitious, and didn't alienate huge swathes of the community. Somehow, the P5 report does all this.

My reporting:

12:22 AM · Dec 14, 2023 · **5,343** Views

1 14 27 4

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