Exploring the Quantum Universe

Pathways to Innovation and Discovery in Particle Physics

Report of the 2023 Particle Physics Project Prioritization Panel

US Particle Physics

for the Next Ten Years

Exploring the Quantum Universe

2023p5report.org

U.S. DEPARTMENT OF ENERGY

NSF

CERN 2 Feb 2024

Hitoshi Murayama on behalf of P5

Background

Sally Seidel
U New Mexico

- HEPAP (standing committee) advises DOE OHEP and NSF PHY
  - Current chair: Sally Seidel + 18 physicists
  - Sunshine law requires such advisory panels are open
  - Impossible to discuss sensitive issues such as prioritization!
- But HEPAP can create a “subpanel” whose meetings can be closed
  - HEPAP subpanels existed for a long time
- Individual projects used to be purview of lab PACs
- Around 2000, it was becoming increasingly clear that “projects” have become too big to be handled by lab PACs
- Natalie Roe: “national PAC” (Snowmass 2001)
  - A standing committee that handles decisions of mid-size and big projects in particle physics
  - Made it into the recommendation by Bagger & Barish subpanel 2001

Background

Sally Seidel
U New Mexico

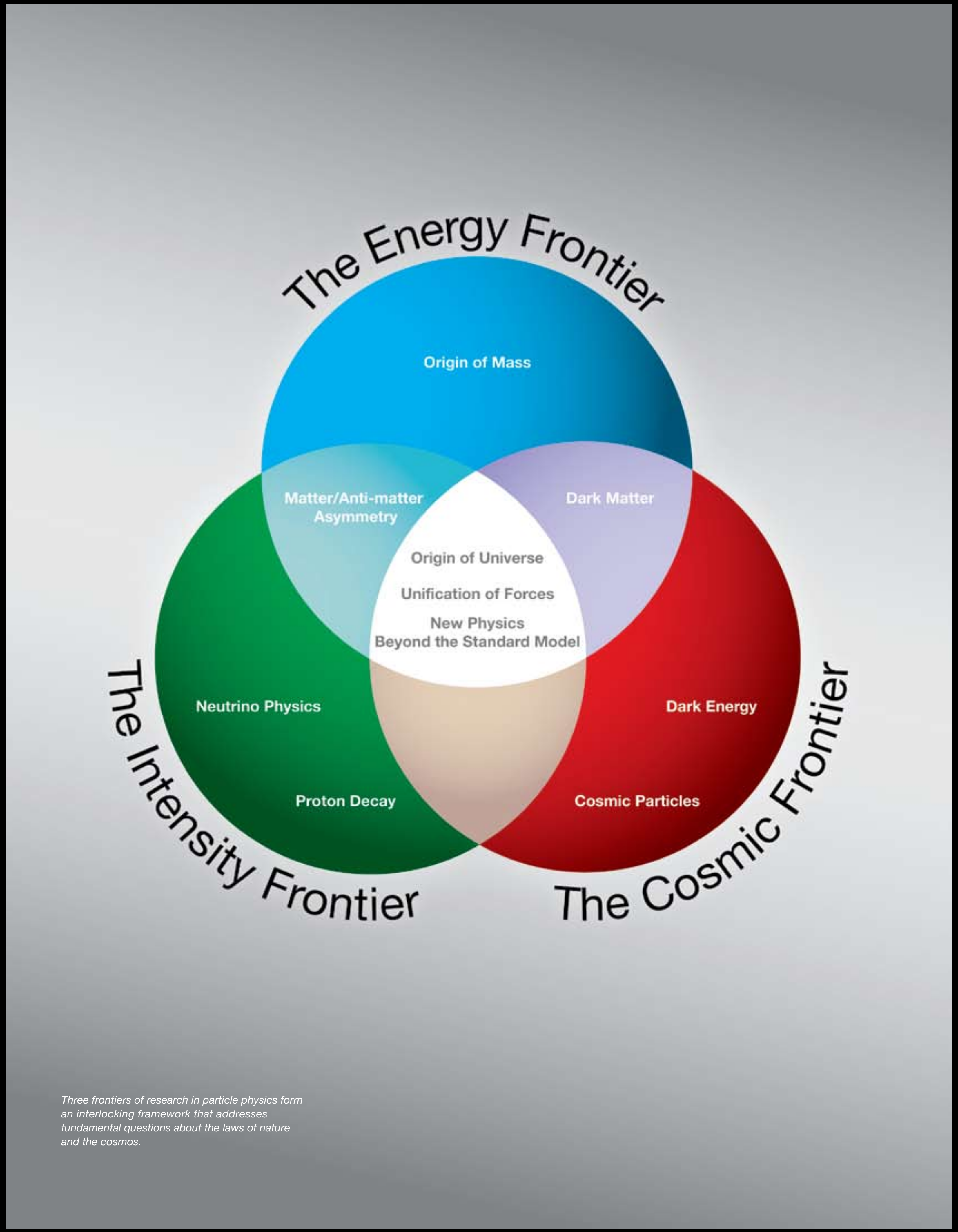
- HEPAP (standing committee) advises DOE OHEP and NSF PHY
  - Current chair: Sally Seidel + 18 physicists
  - Sunshine law requires such advisory panels are open
  - Impossible to discuss sensitive issues such as prioritization!
- But HEPAP can create a "subpanel" whose meetings can be closed
  - HEPAP subpanels existed for a long time
- Individual projects used to be purview of lab PACs
- Around 2000, it was becoming increasingly clear that "projects" have become too big to be handled by lab PACs
- Natalie Roe: "national PAC" (Snowmass 2001)
  - A ~~standing~~ committee that handles decisions of mid-size and big projects in particle physics
  - Made it into the recommendation by Bagger & Barish subpanel 2001

2003-2007 P5 (Abe Seiden)

- 2003 P5 reviewed
  - CDF/D0 Run II upgrades
  - CKM
  - BTeV
  - Terminated CKM
- 2004 P5 reviewed
  - BTeV
  - Recommended staging of BTeV
- 2007 P5
  - Tevatron beyond FY09?
  - Deferred decision

2008 P5

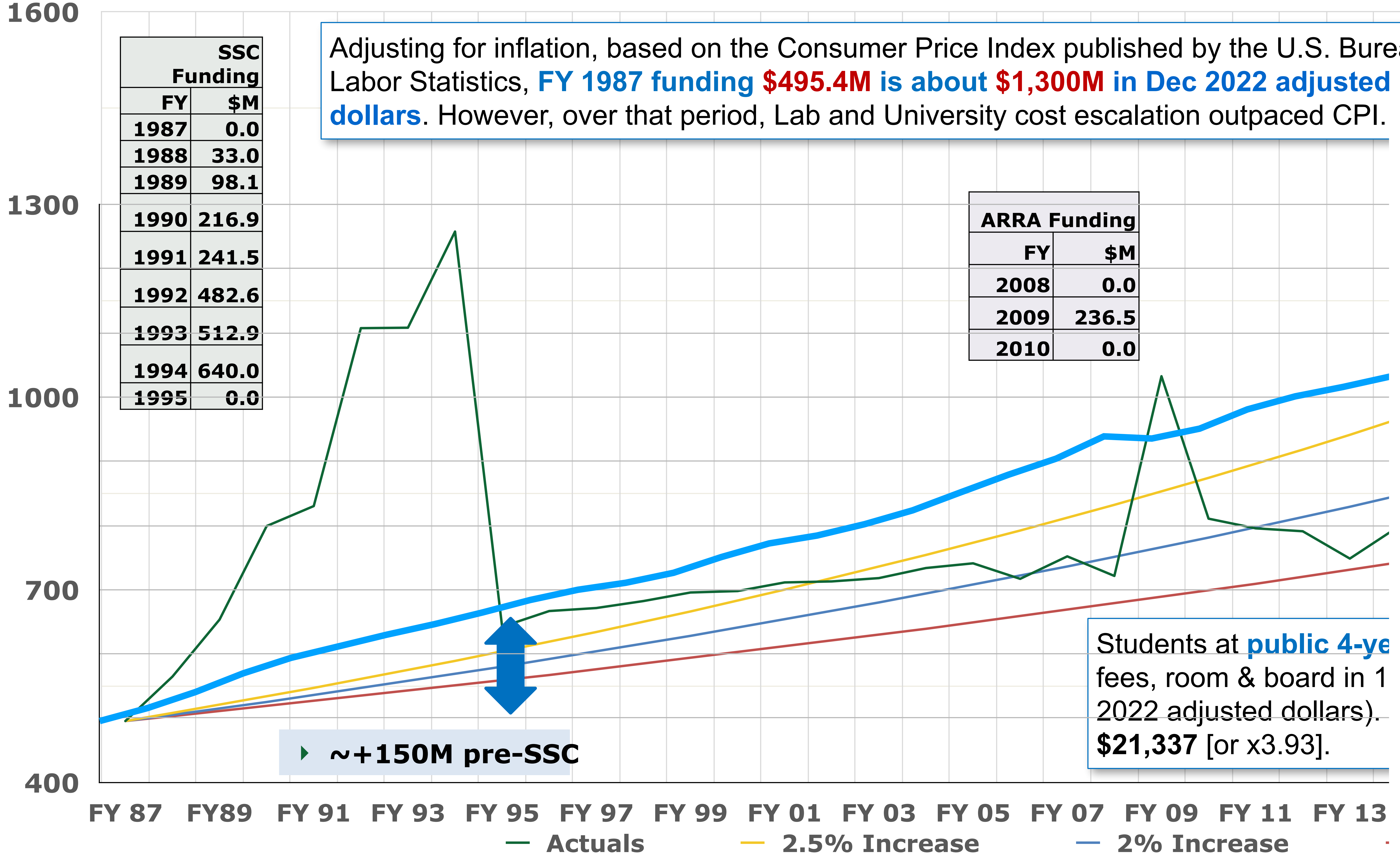
- 2008 P5 (Charles Baltay)
  - First “modern” P5 for the whole program with budget scenarios
  - Tevatron for one to two more years
  - World-class neutrino program
  - Dark matter & dark energy, LSST
- *US Particle Physics: Scientific Opportunities A Strategic Plan for the Next Ten Years*
- Coined Energy, Intensity, Cosmic Frontiers



2014 P5

- 2014 P5 (Steve Ritz)
  - Use the Higgs boson as a new tool for discovery
  - Pursue the physics associated with neutrino mass
  - Identify the new physics of dark matter
  - Understand cosmic acceleration: dark energy and inflation
  - Explore the unknown: new particles, interactions, and physical principles.
- Recommended LBNE → DUNE/LBNF
- Embraced CMB in HEP
- Finally “got it right”
  - Well received in Washington
  - increased HEP budget by ~30%
  - “*Made many hard choices*”

HEP Funding in Historical Context: 1987 to Present



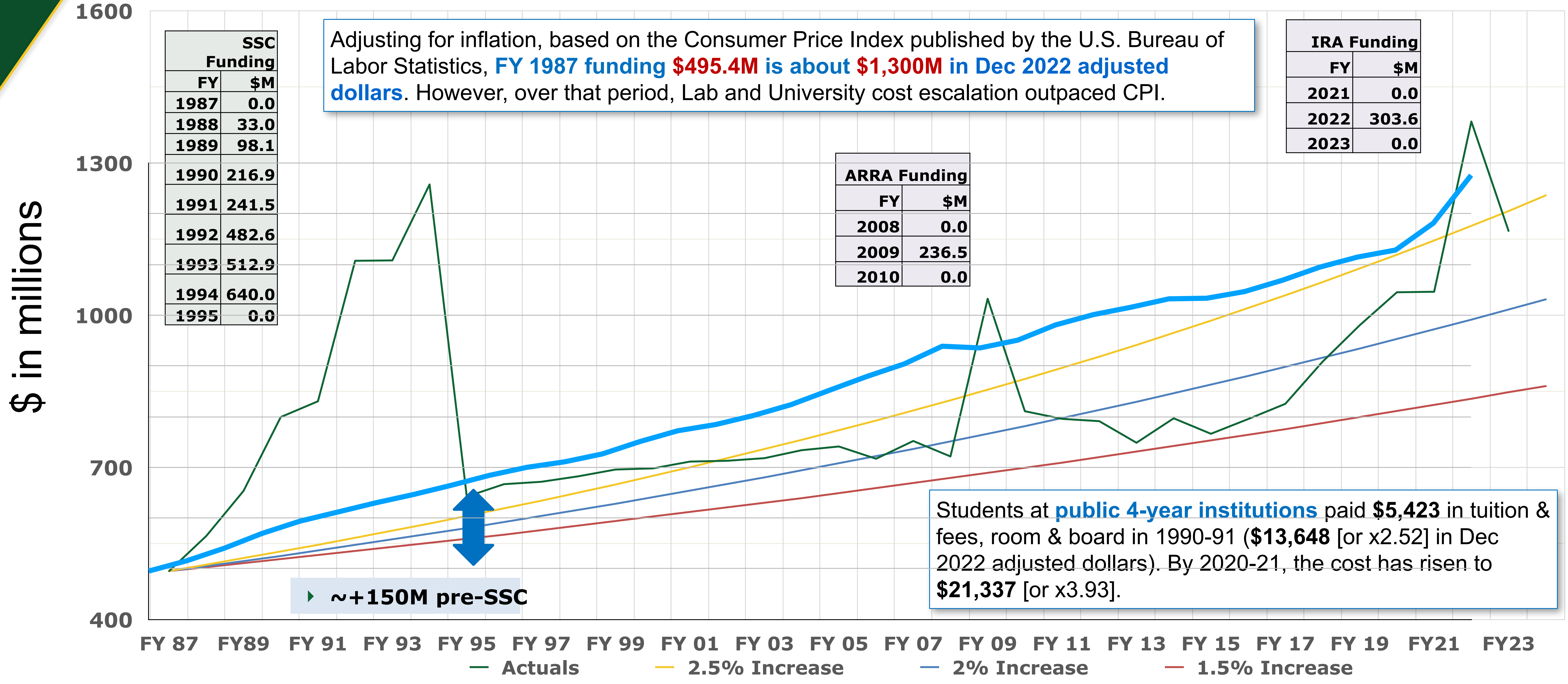
SSC Funding	
FY	$M
1987	0.0
1988	33.0
1989	98.1
1990	216.9
1991	241.5
1992	482.6
1993	512.9
1994	640.0
1995	0.0

ARRA Funding	
FY	$M
2008	0.0
2009	236.5
2010	0.0

IRA Funding	
FY	$M
2021	0.0

Before the previous P5

HEP Funding in Historical Context: 1987 to Present



SSC Funding	
FY	$M
1987	0.0
1988	33.0
1989	98.1
1990	216.9
1991	241.5
1992	482.6
1993	512.9
1994	640.0
1995	0.0

Adjusting for inflation, based on the Consumer Price Index published by the U.S. Bureau of Labor Statistics, **FY 1987 funding $495.4M is about $1,300M in Dec 2022 adjusted dollars**. However, over that period, Lab and University cost escalation outpaced CPI.

ARRA Funding	
FY	$M
2008	0.0
2009	236.5
2010	0.0

IRA Funding	
FY	$M
2021	0.0
2022	303.6
2023	0.0

Students at **public 4-year institutions** paid **$5,423** in tuition & fees, room & board in 1990-91 (**$13,648** [or x2.52] in Dec 2022 adjusted dollars). By 2020-21, the cost has risen to **$21,337** [or x3.93].


P5 Panel
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

US Process for Future Planning

Community

US Process for Future Planning

Community

"Snowmass"
Community Study

Organized by
APS / DPF

Snowmass 2021

US Process for Future Planning

Community

“Snowmass”
Community Study

Organized by
APS / DPF

Snowmass 2021

Charge
Budget scenario

DOE SC
NSF MPS

US Process for Future Planning

Community

“Snowmass”
Community Study

Organized by
APS / DPF

Snowmass 2021

Particle Physics Project
Prioritization Panel (P5)

Organized by
HEPAP

Charge
Budget scenario

DOE SC
NSF MPS

US Process for Future Planning

Community

“Snowmass”
Community Study

Organized by
APS / DPF

Snowmass 2021

Particle Physics Project
Prioritization Panel (P5)

Organized by
HEPAP

Charge
Budget scenario

DOE SC
NSF MPS

DOE HEP
NSF PHYS

OMB
OSTP
Congress

P5 Timetable and Process

Charge issued on Nov 2, 2022 by Dr. Berhe (DOE SC) and Dr. Jones (NSF MPS)
Panel formed by the end of January 2023

Information Gathering Phase

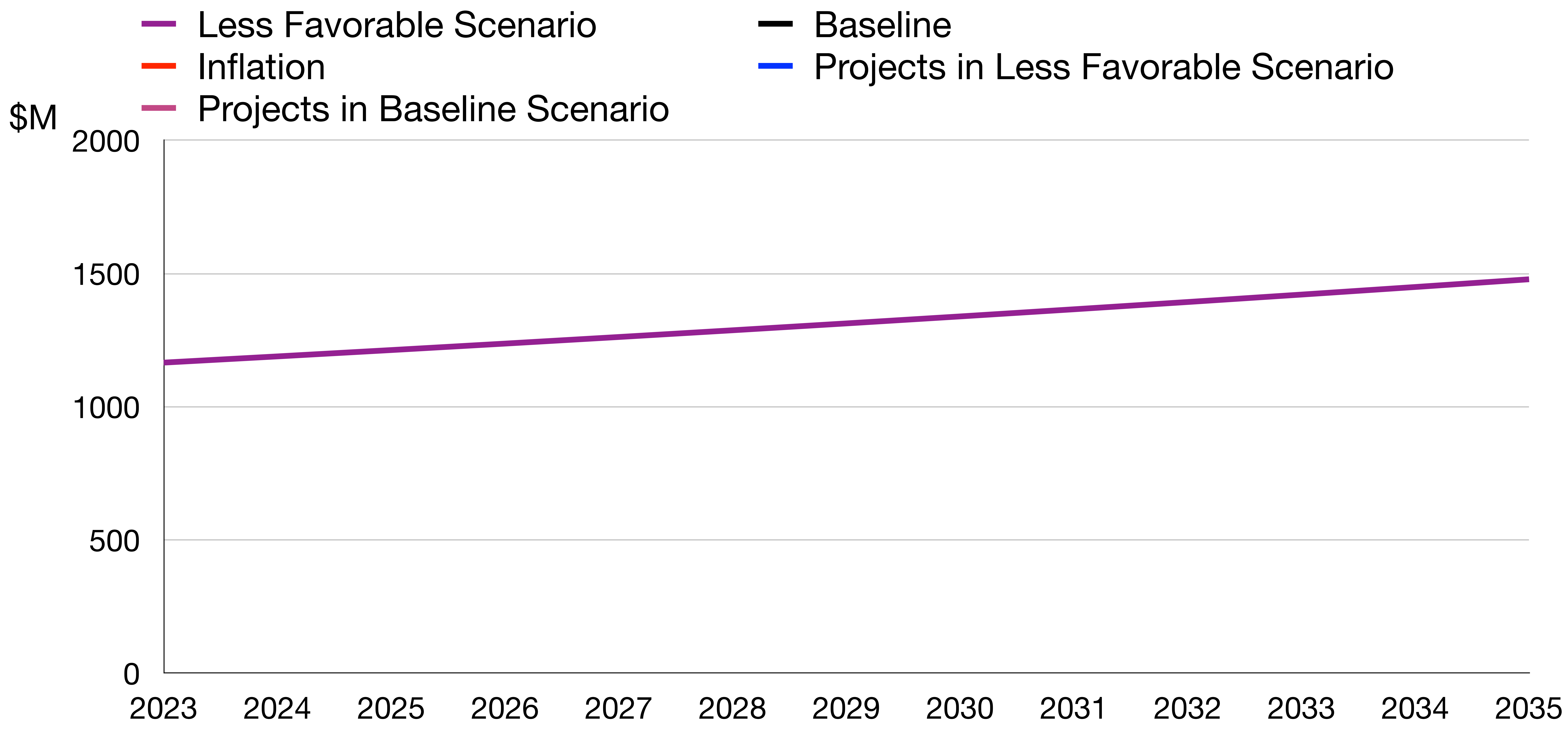
- **Snowmass Report**
- **Open Town Halls**
  - LBNL: February (513), Fermilab/Argonne: March (797) overlapped with EPP2024
  - Brookhaven: April (666), SLAC: May (512)
- **Virtual Town Halls**
  - UT Austin: June (159) with an exclusive session for early career scientists, Virginia Tech, June (119)
- **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**

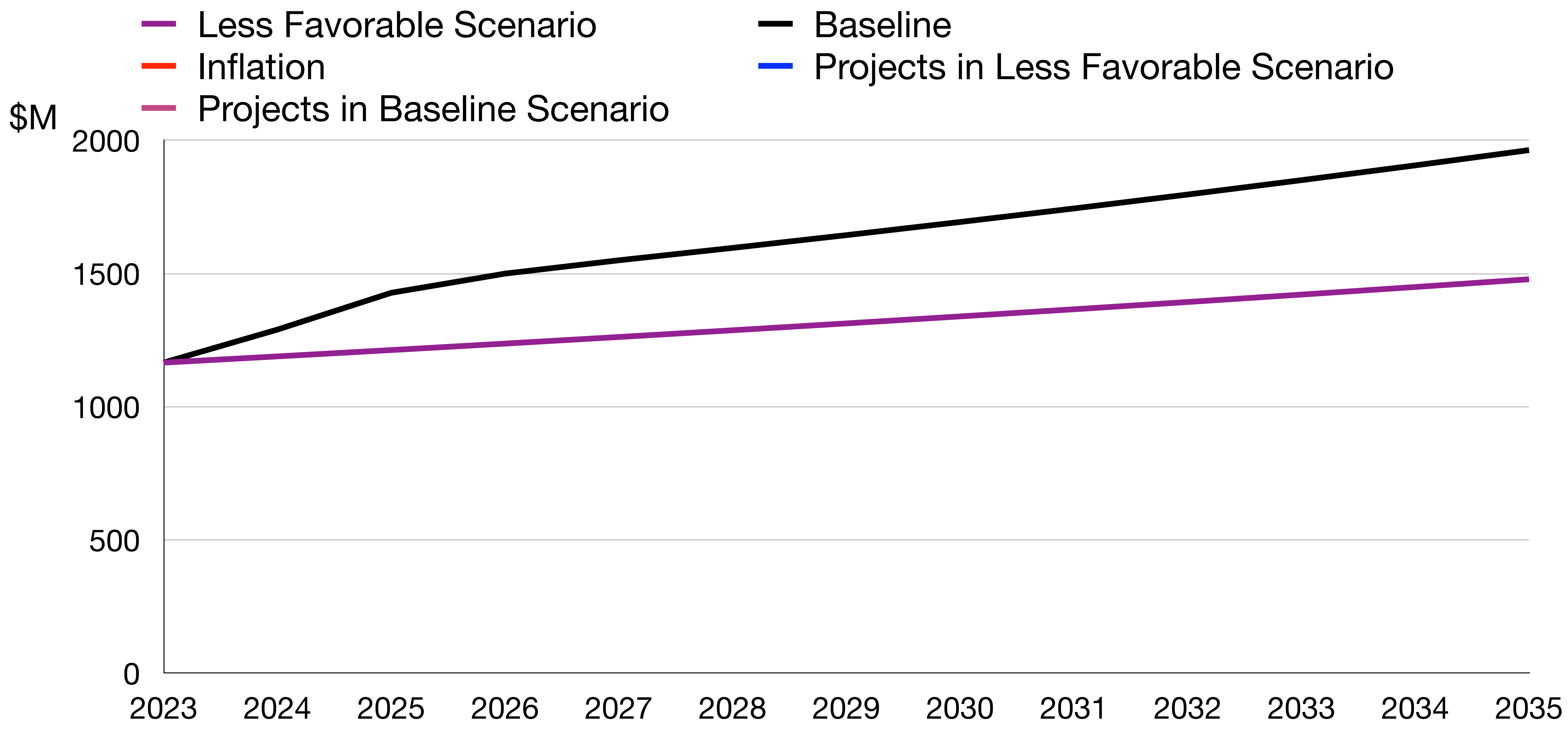
Writing Phase with many, many, zoom meetings

Budget Scenarios



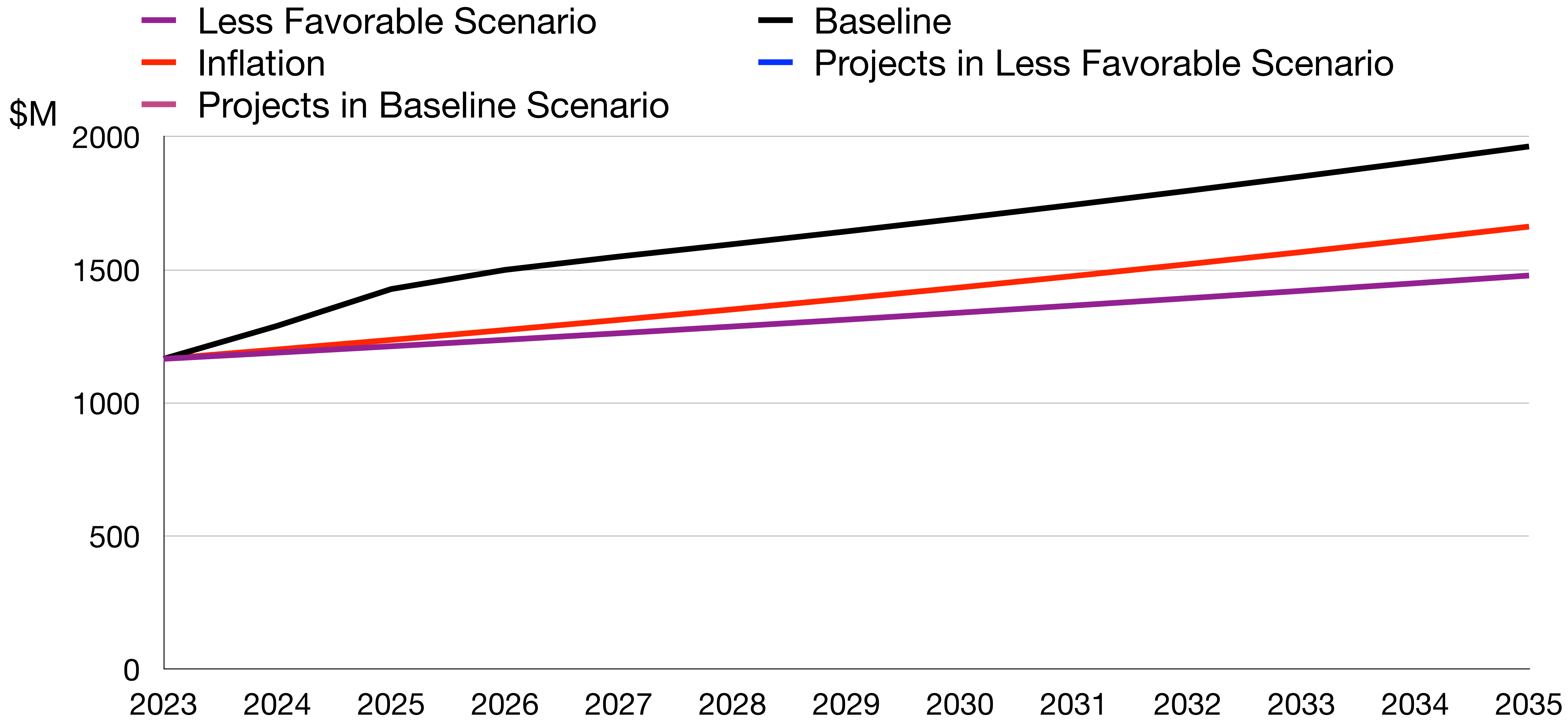
DOE only

Budget Scenarios



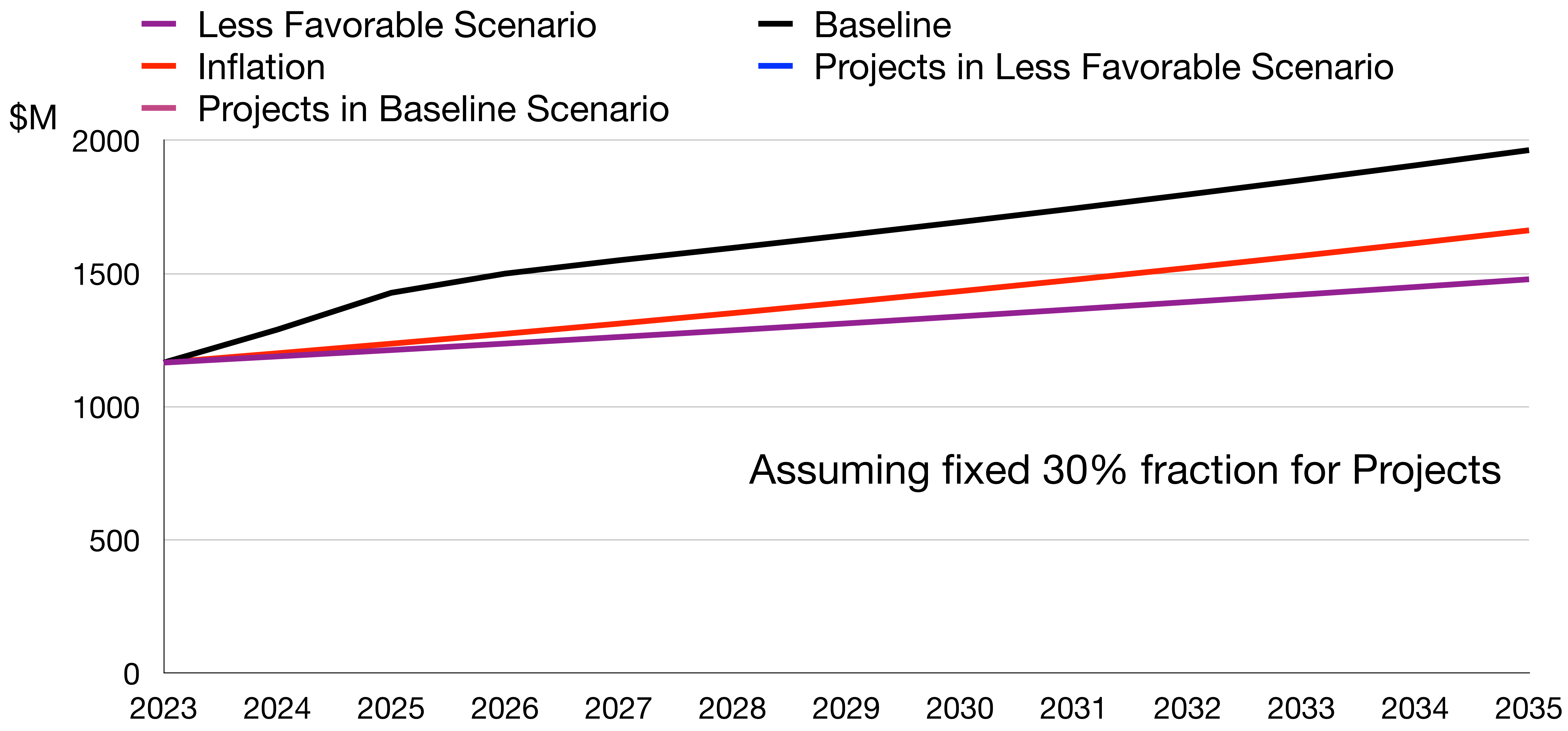
DOE only

Budget Scenarios



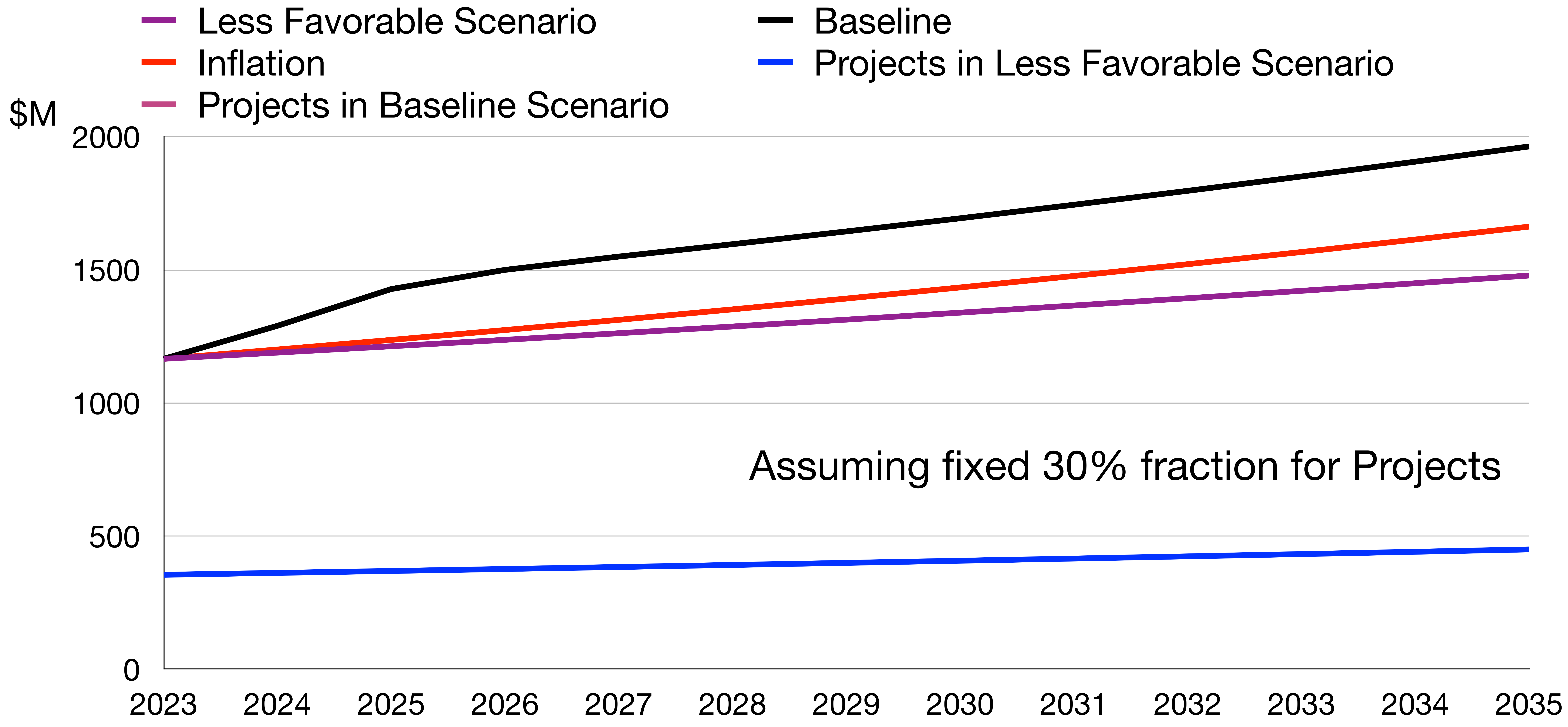
DOE only

Budget Scenarios



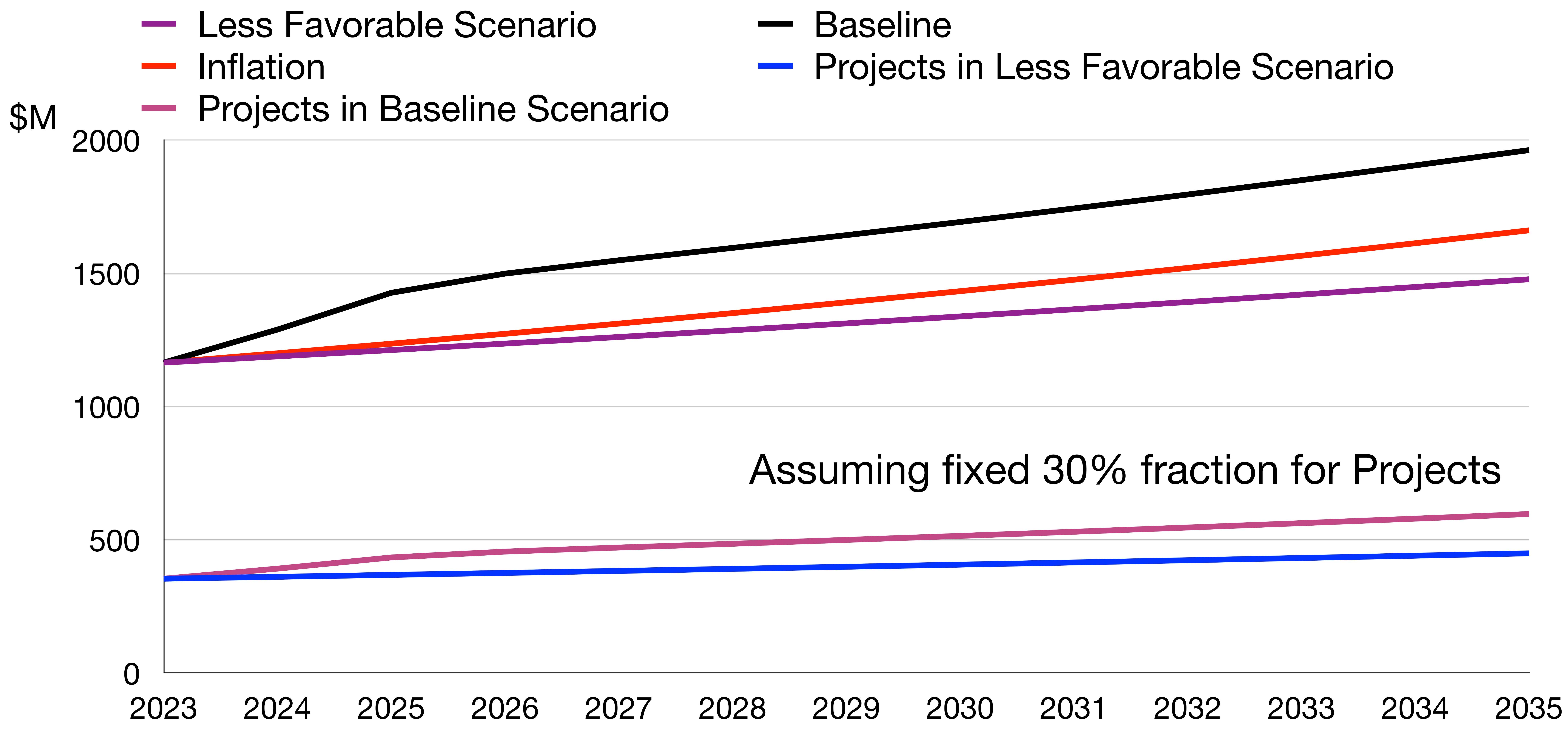
DOE only

Budget Scenarios



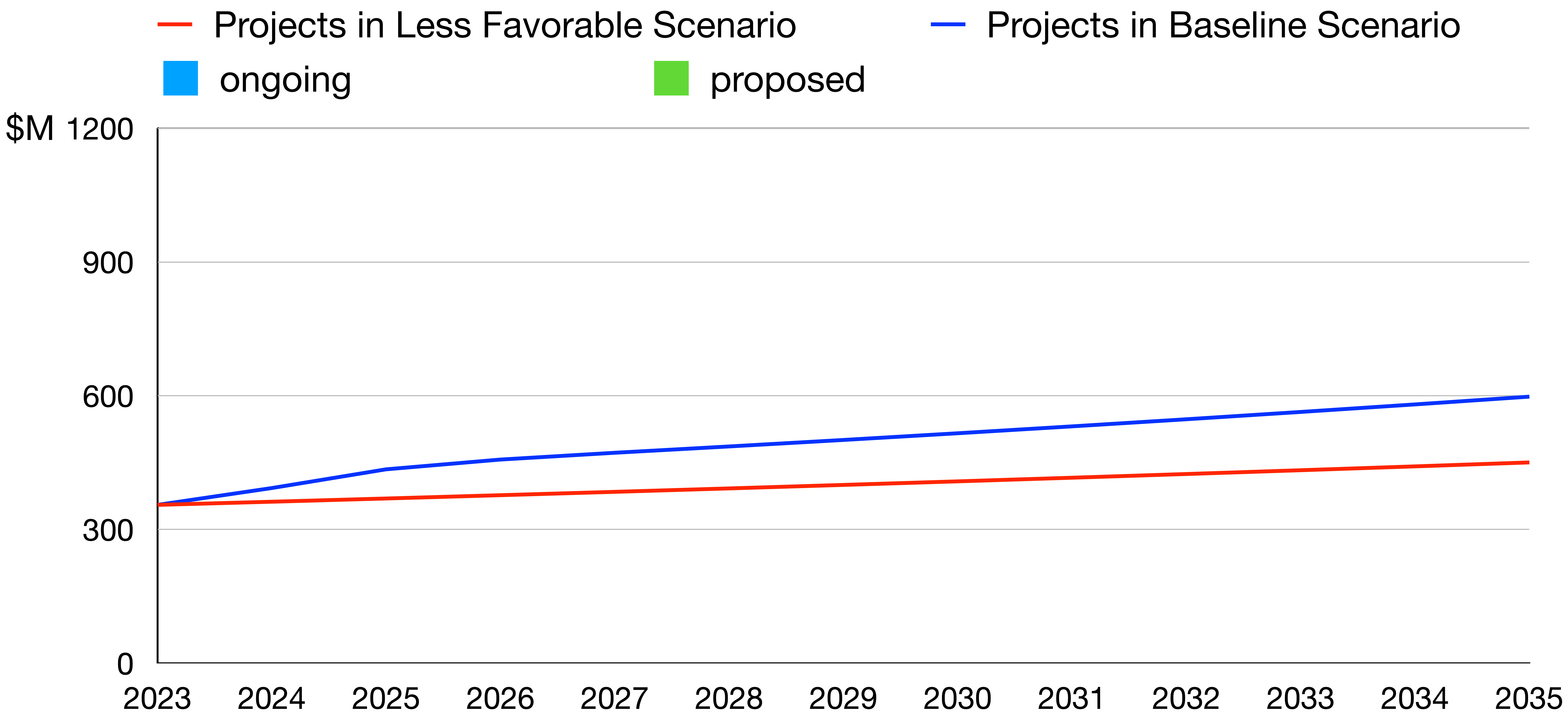
DOE only

Budget Scenarios



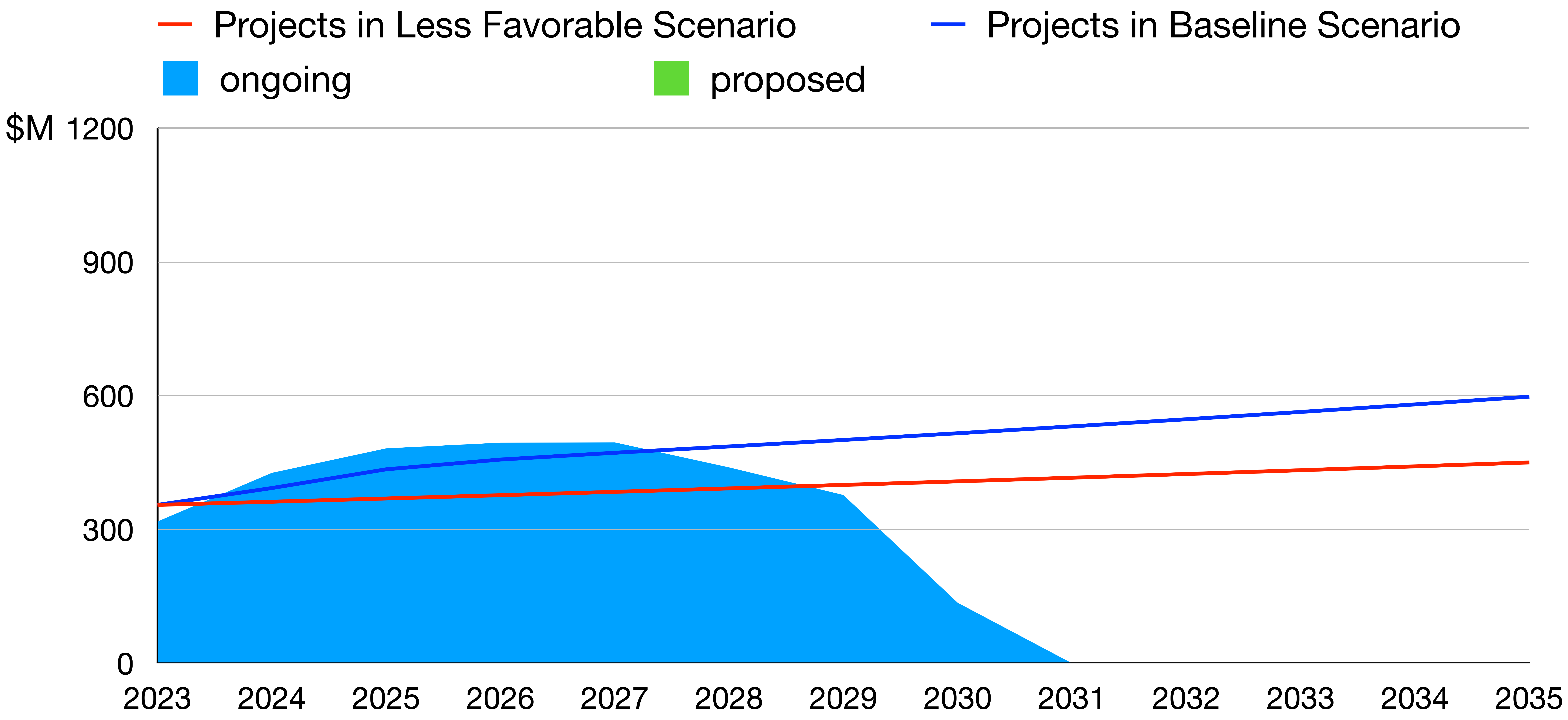
DOE only

Budget Scenarios and Projects



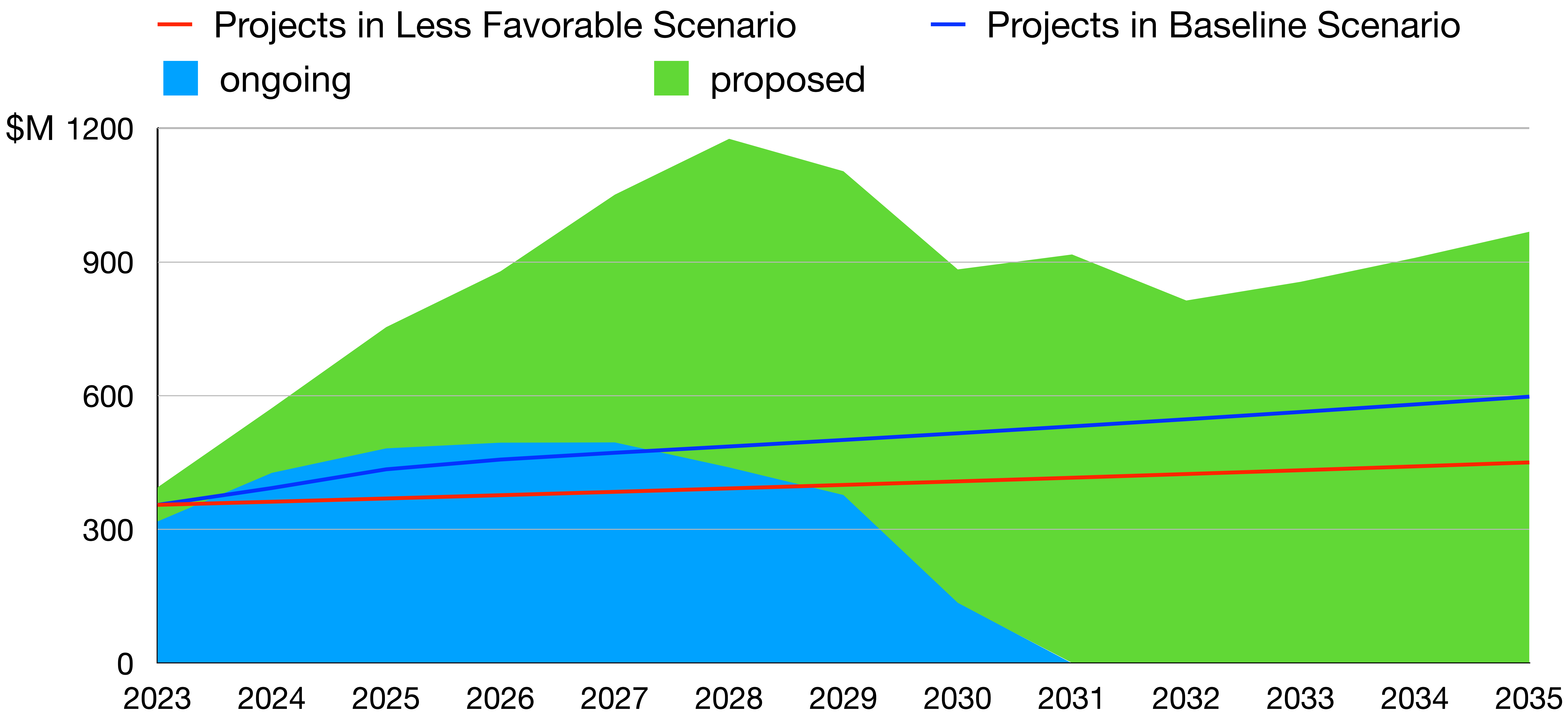
DOE only

Budget Scenarios and Projects



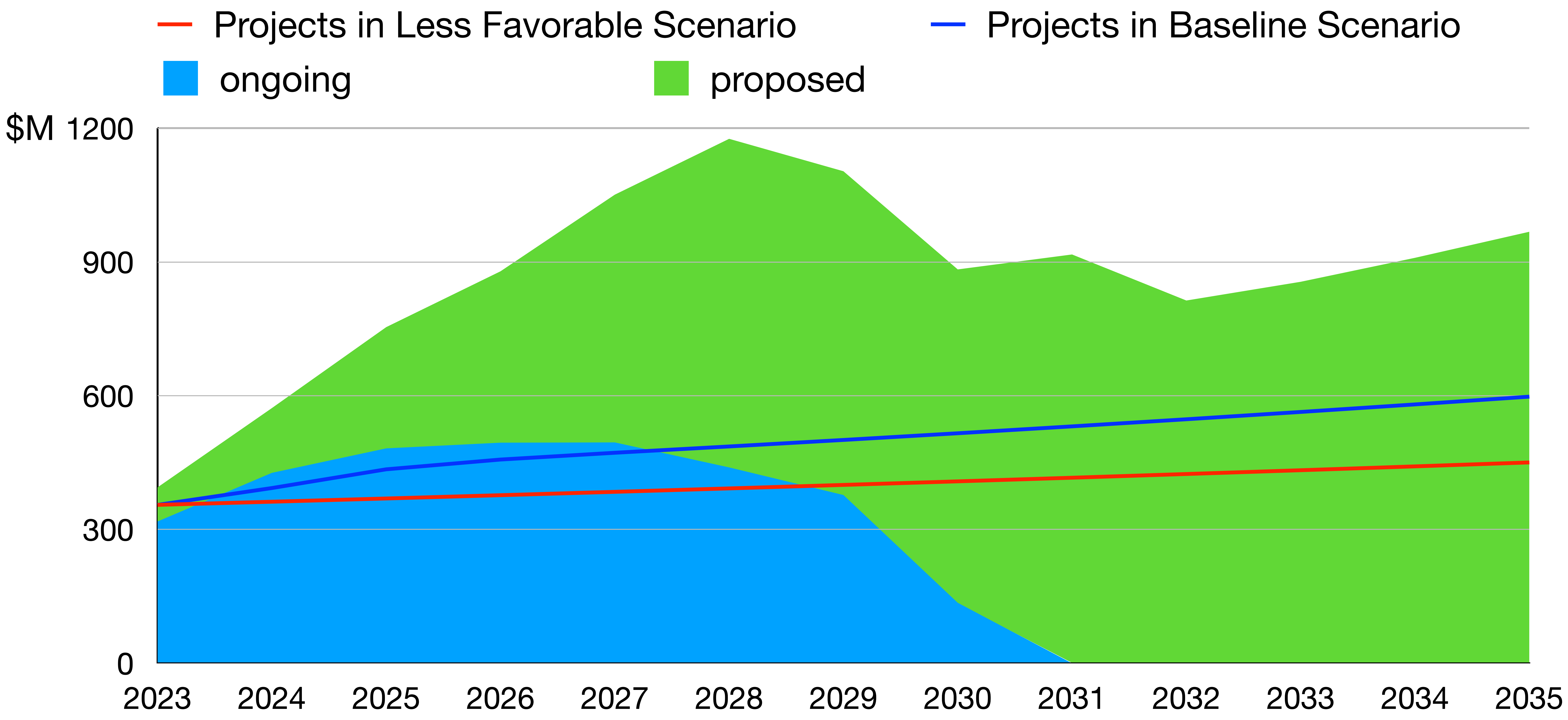
DOE only

Budget Scenarios and Projects



DOE only

Budget Scenarios and Projects



not including on-shore Higgs factory

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

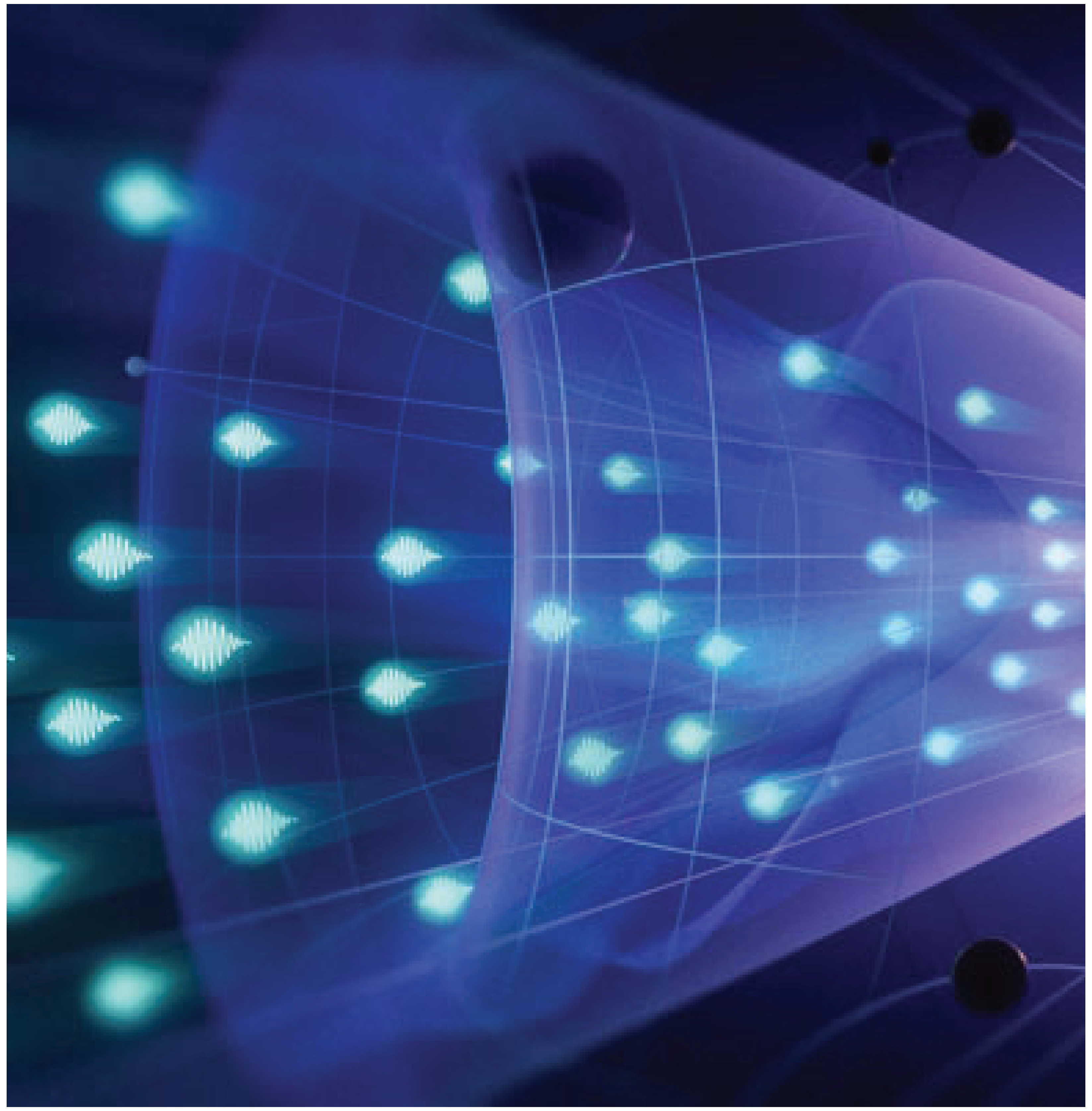
Lesson from previous P5 that some of the costs were off by a factor of ~π

Subcommittee

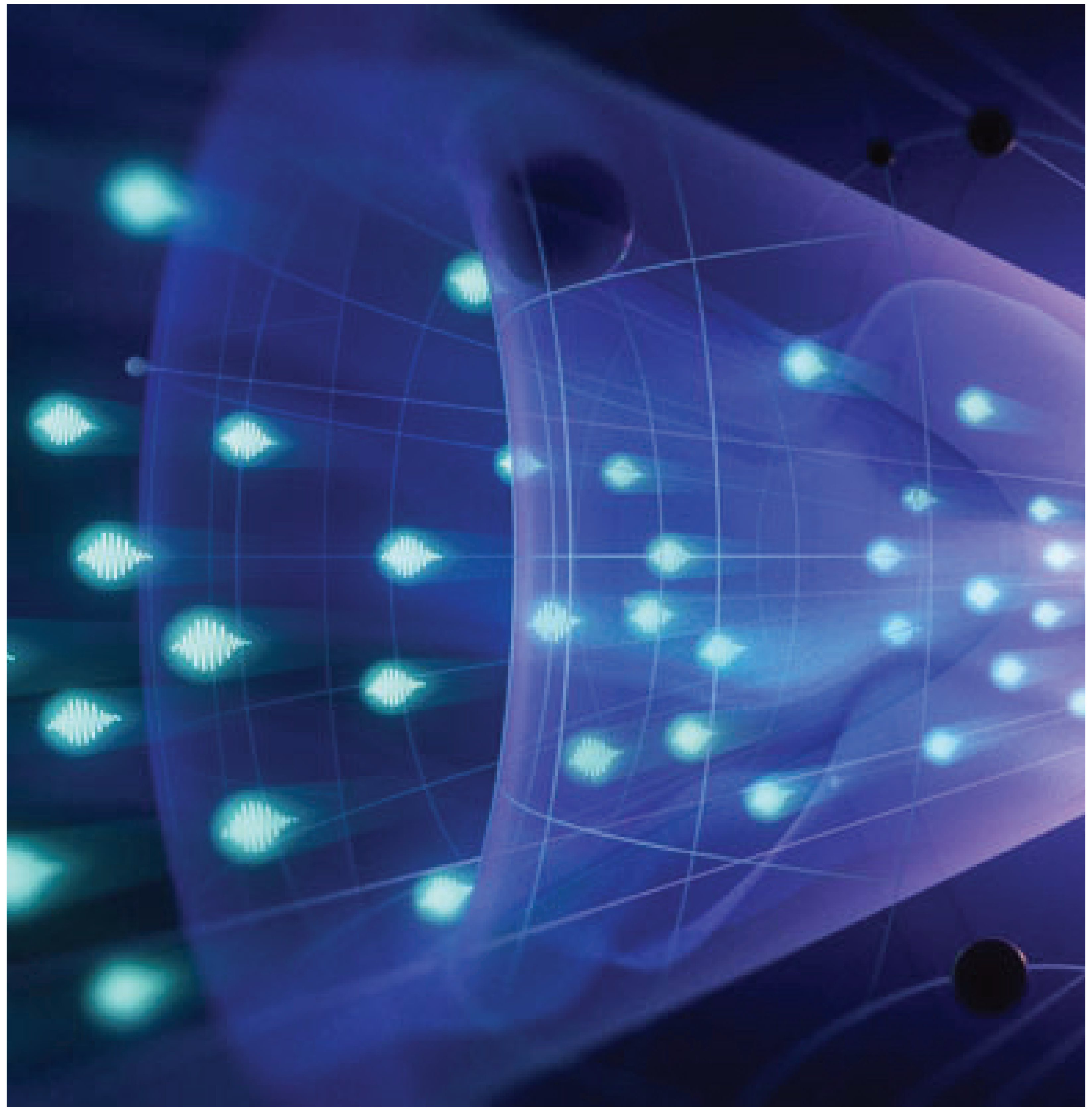
- **Jay Marx (Caltech), Chair**
- Gil Gilchriese, Matthaeus Leitner (LBNL)
- Giorgio Apollinari, Doug Glenzinski (Fermilab)
- Mark Reichanadter, Nadine Kurita, John Seeman (SLAC)
- Jon Kotcher, Srini Rajagopalan (BNL)
- Allison Lung (JLab)
- Harry Weerts (Argonne)

They gave us low, medium, and high estimates with schedules

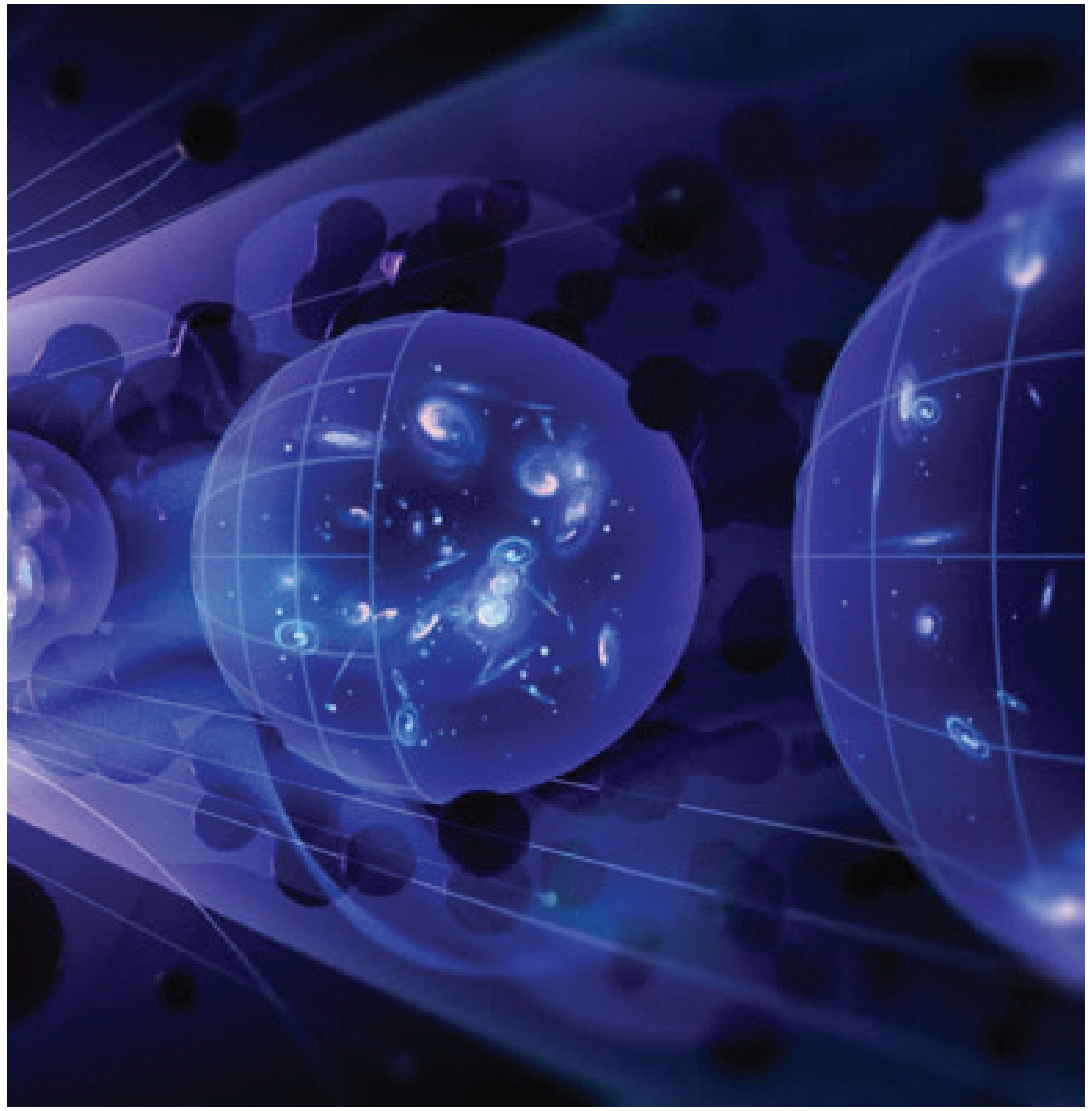
P5 town hall at FNAL



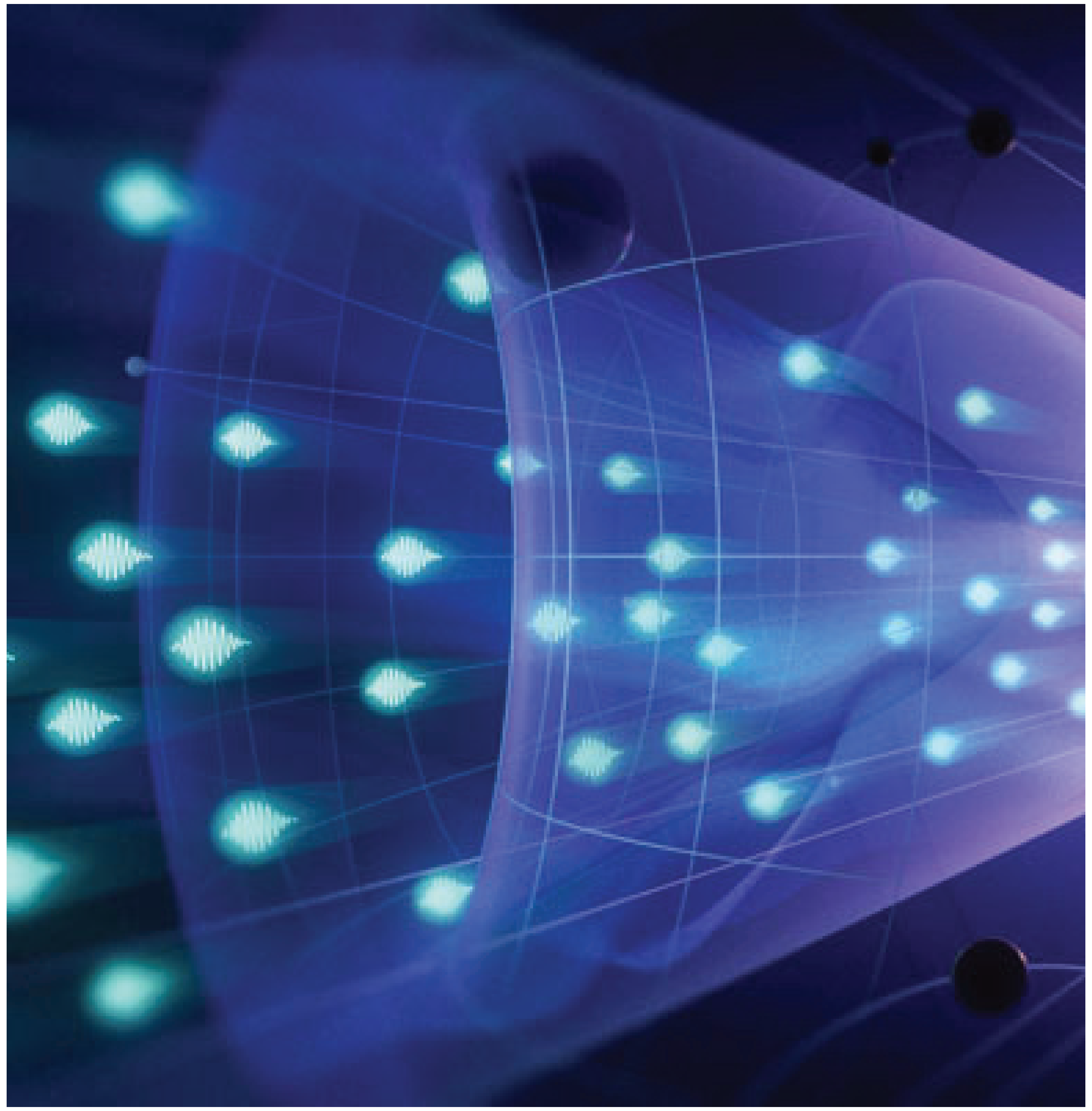
Decipher
the
Quantum
Realm

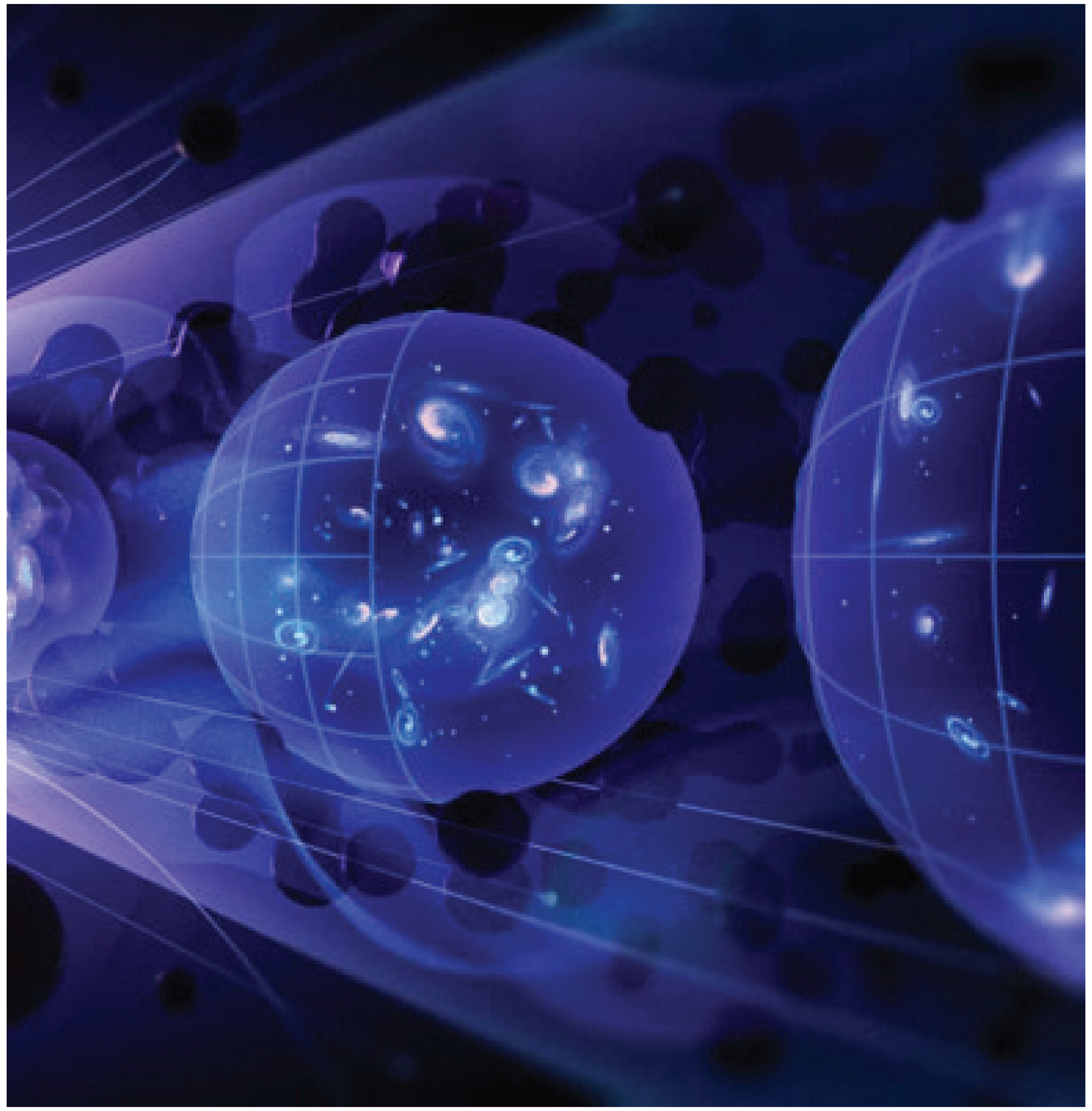


Decipher
the
Quantum
Realm



Illuminate
the
Hidden
Universe



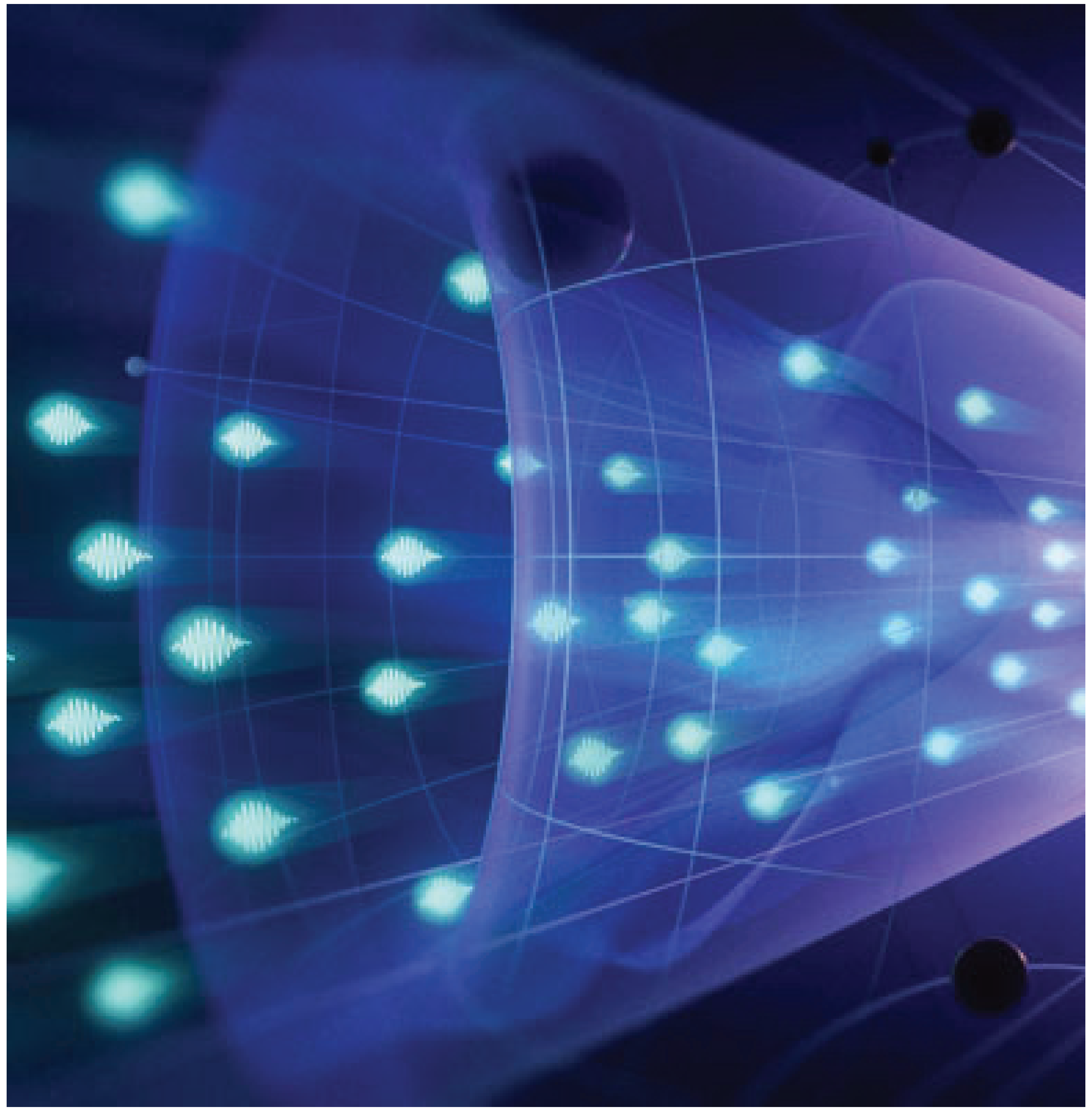


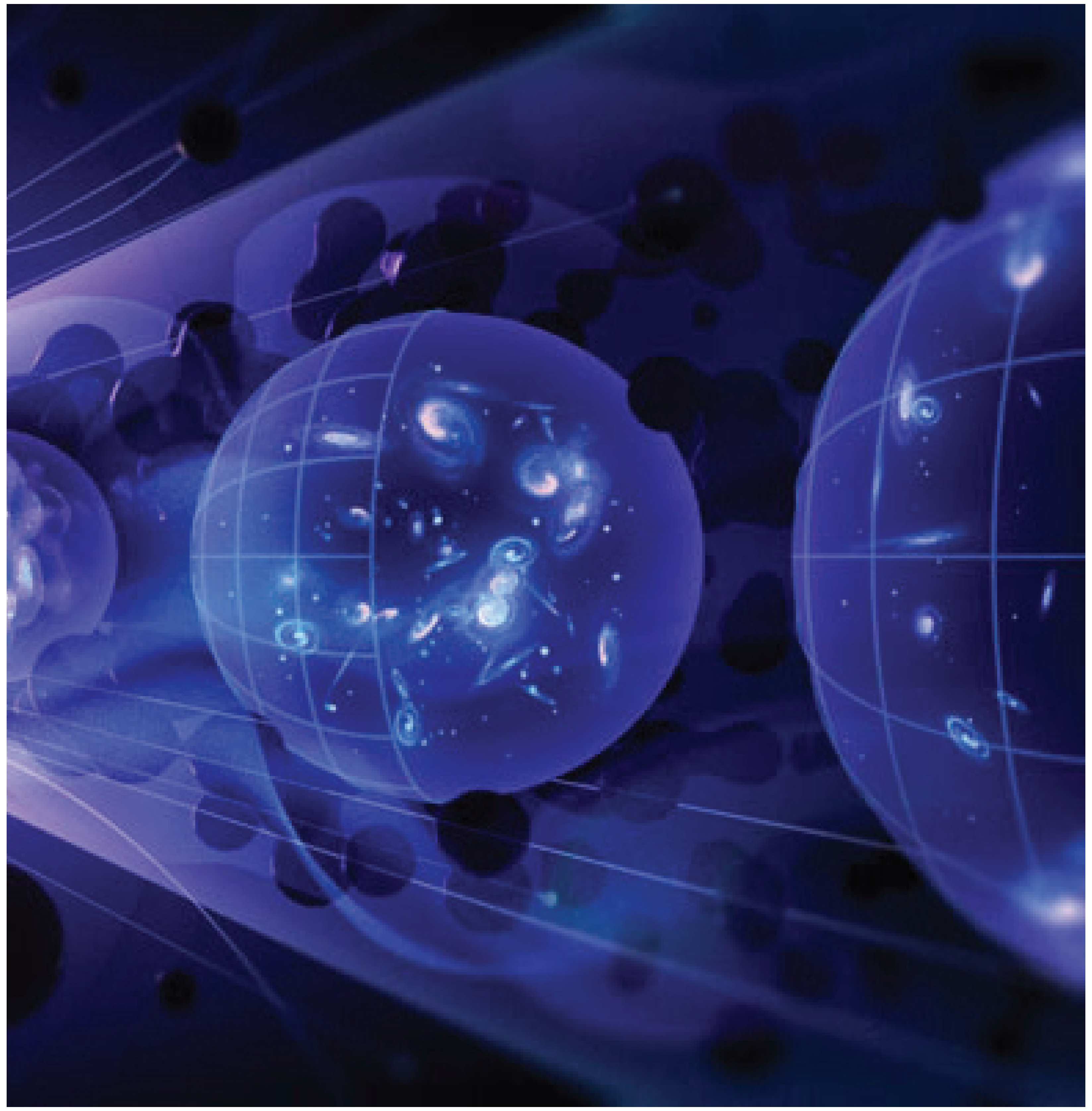
Decipher
the
Quantum
Realm

Explore
New
Paradigms in
Physics

Illuminate
the
Hidden
Universe

Explore the Quantum Universe



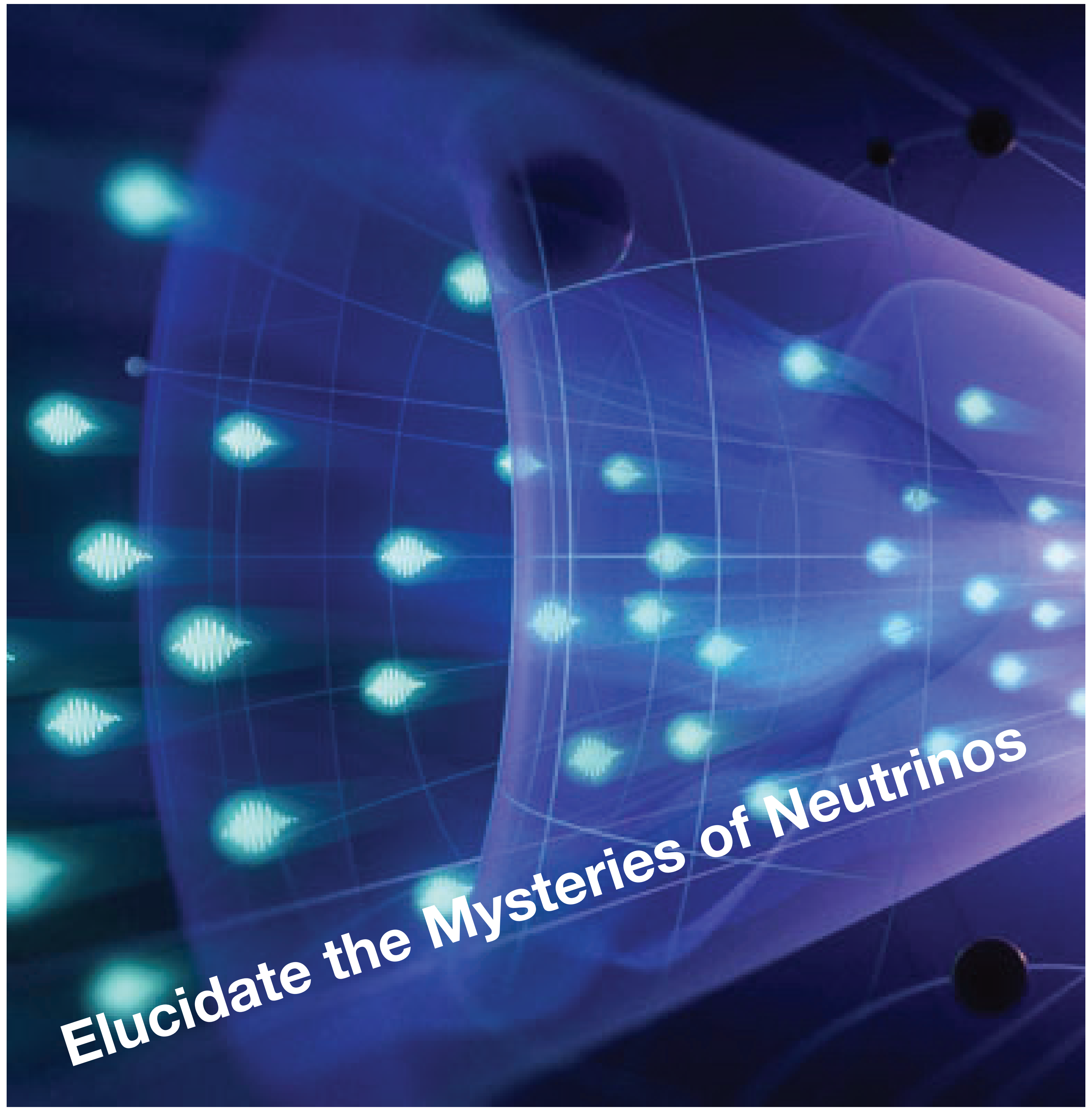


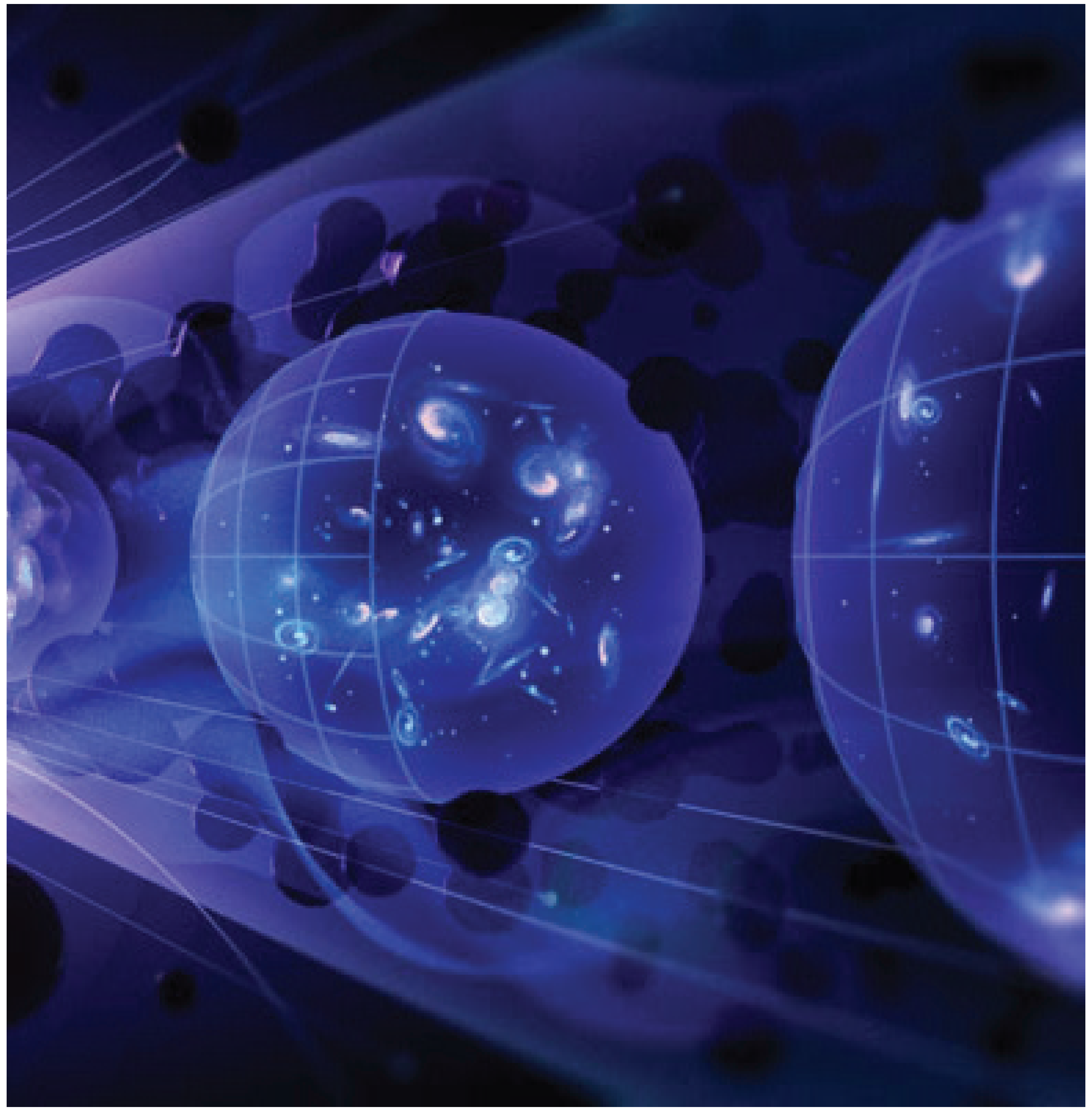
Decipher the Quantum Realm

Explore New Paradigms in Physics

Illuminate the Hidden Universe

Explore the Quantum Universe



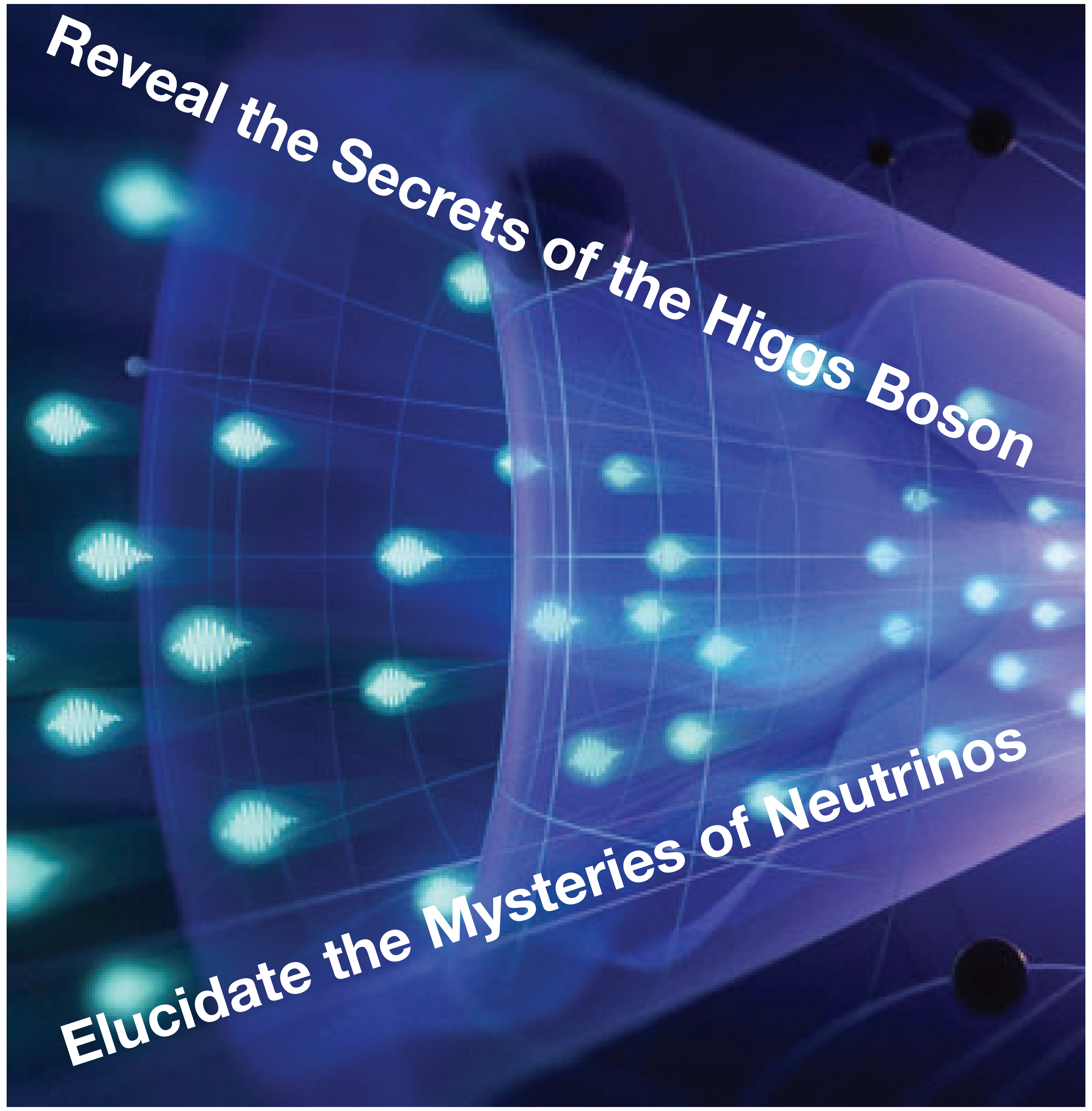


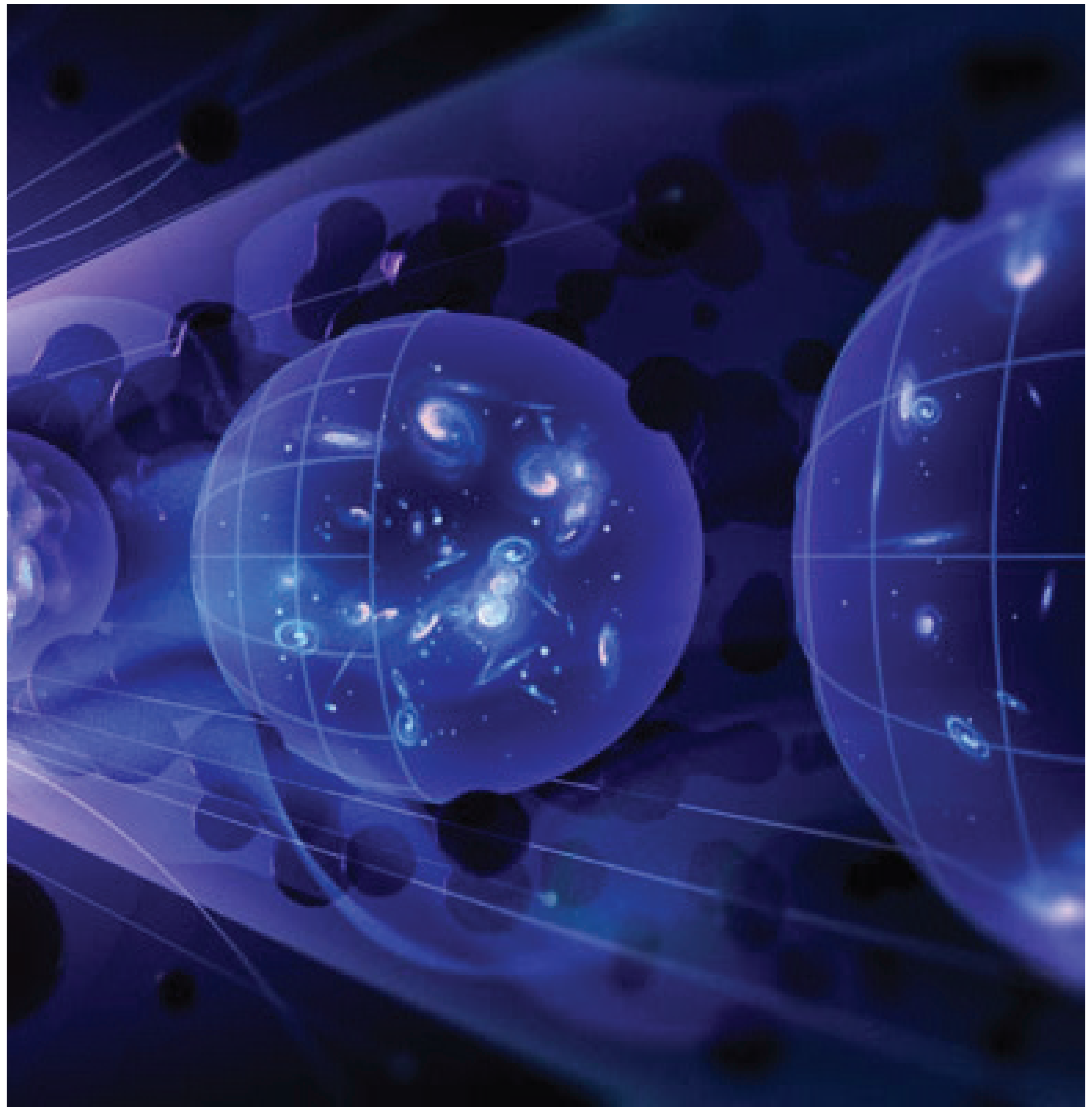
Decipher the Quantum Realm

Explore New Paradigms in Physics

Illuminate the Hidden Universe

Explore the Quantum Universe



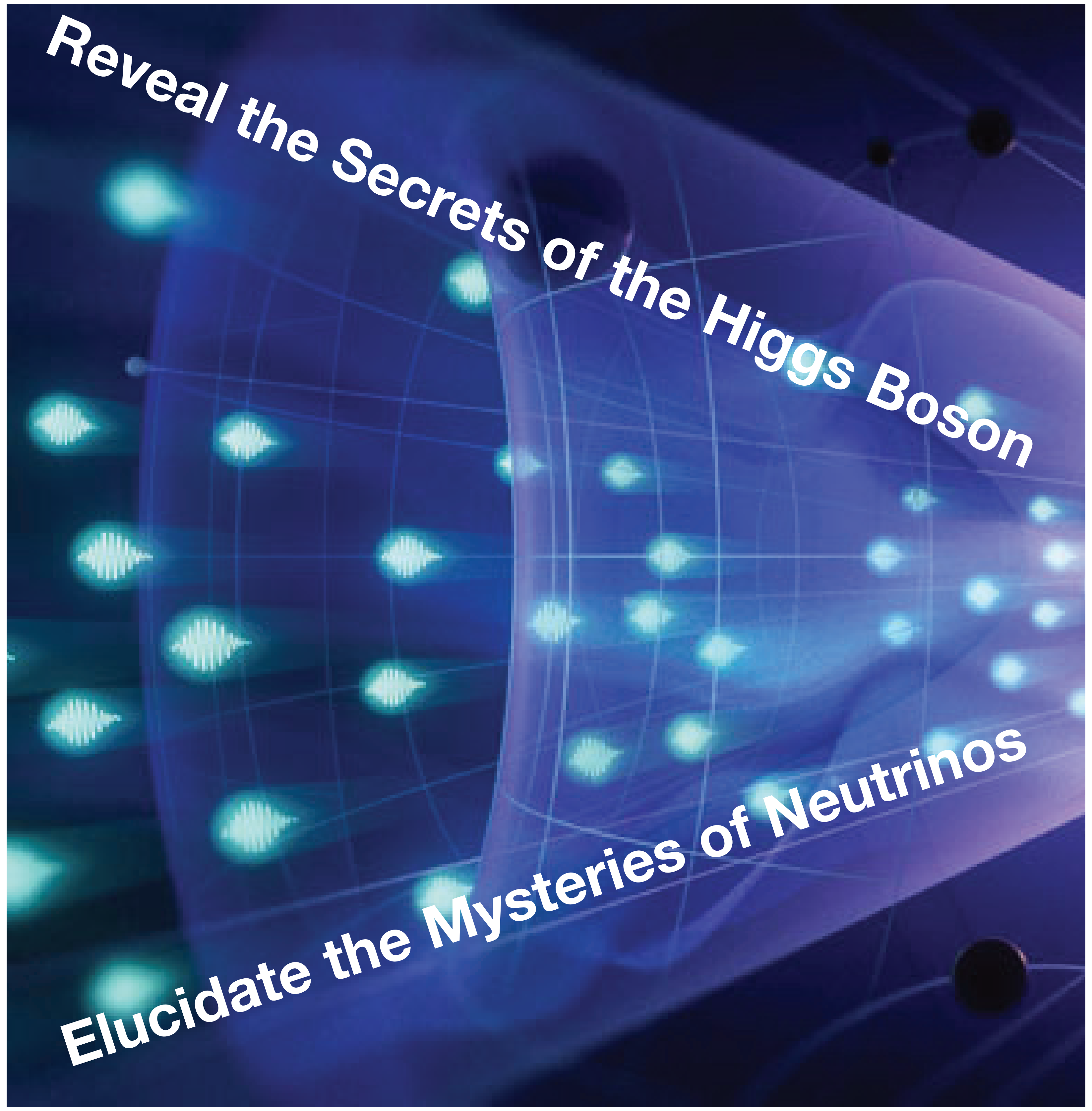


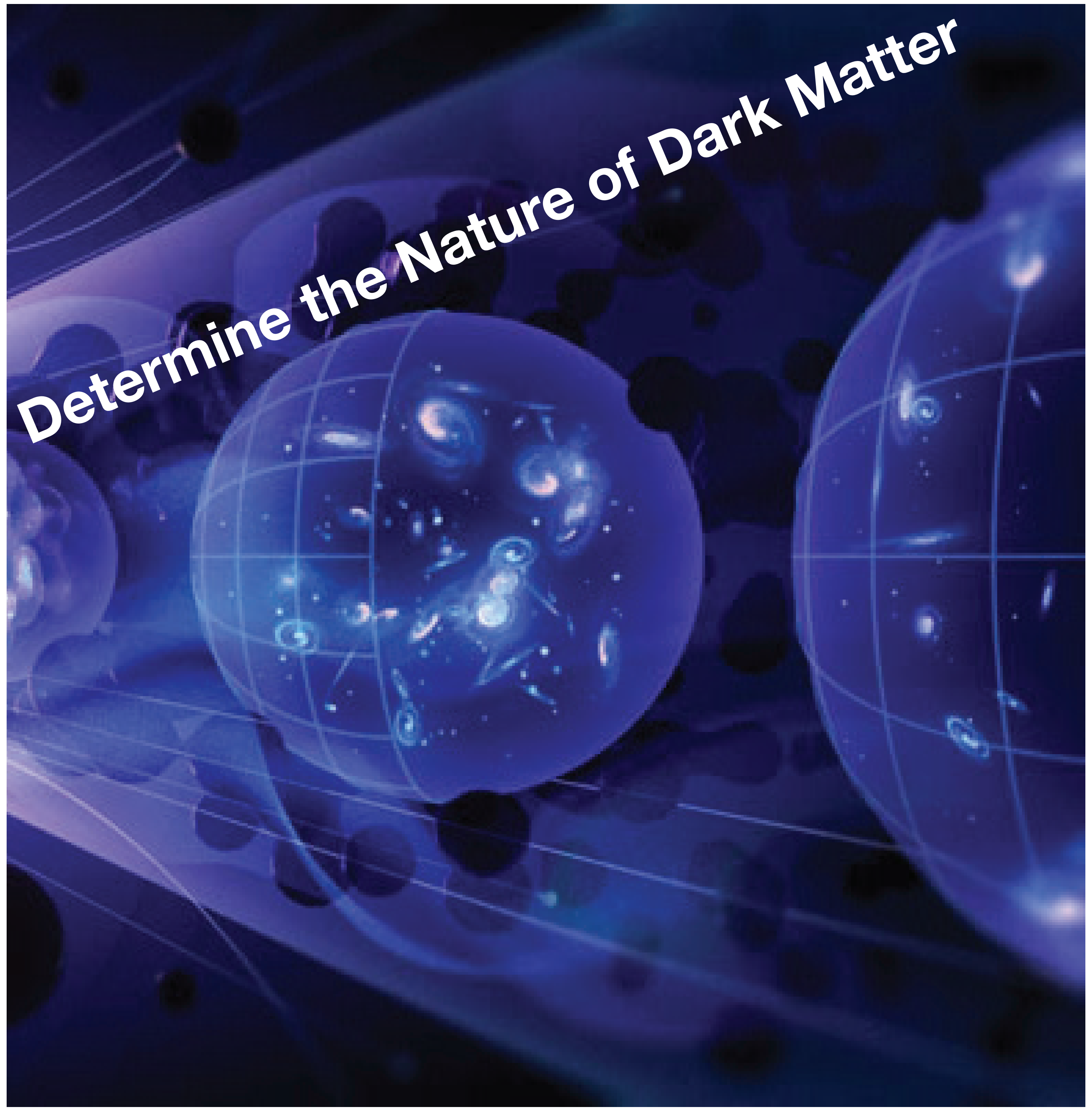
Decipher the Quantum Realm

Explore New Paradigms in Physics

Illuminate the Hidden Universe

Explore the Quantum Universe



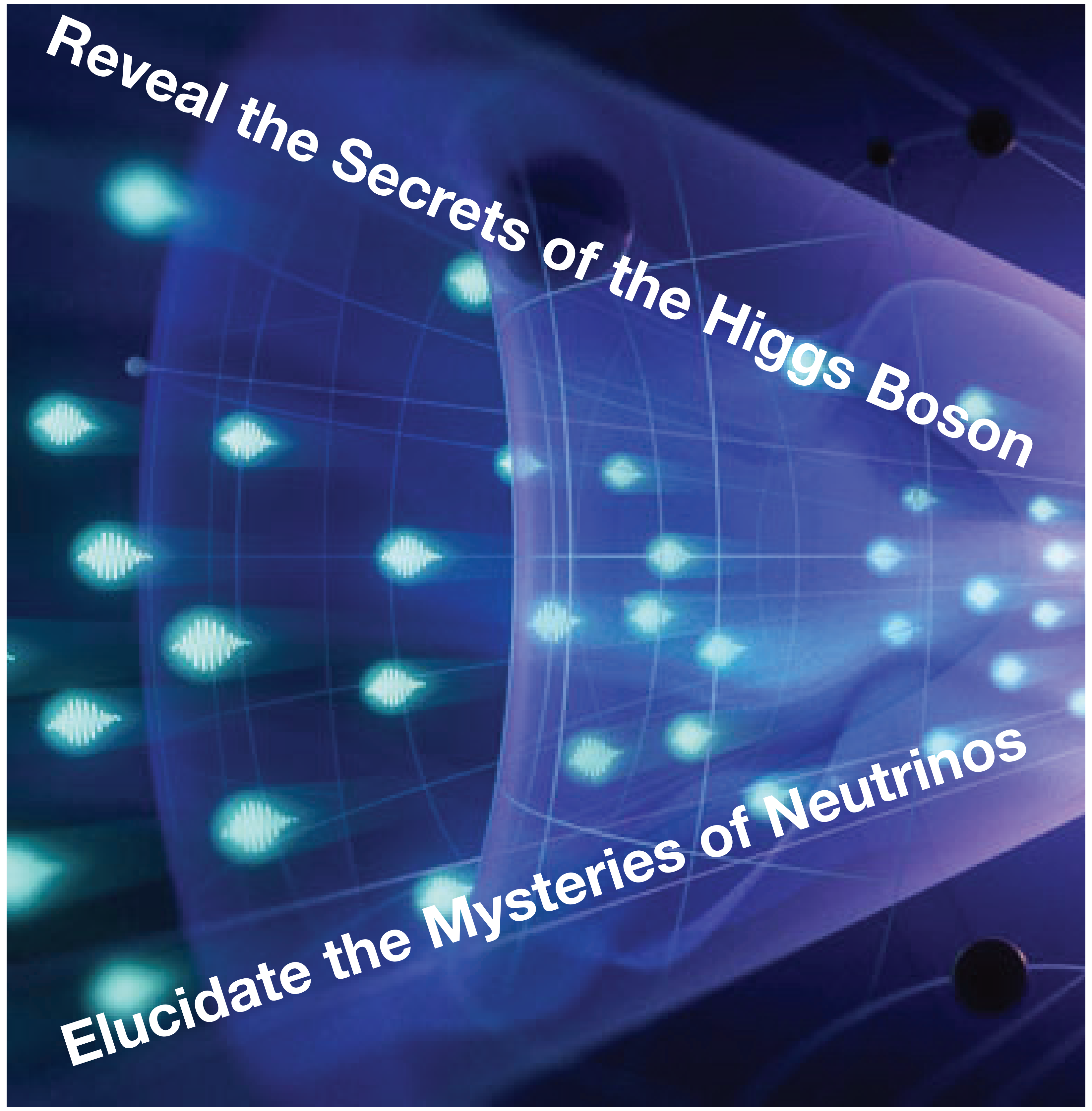


Decipher the Quantum Realm

Explore New Paradigms in Physics

Illuminate the Hidden Universe

Explore the Quantum Universe

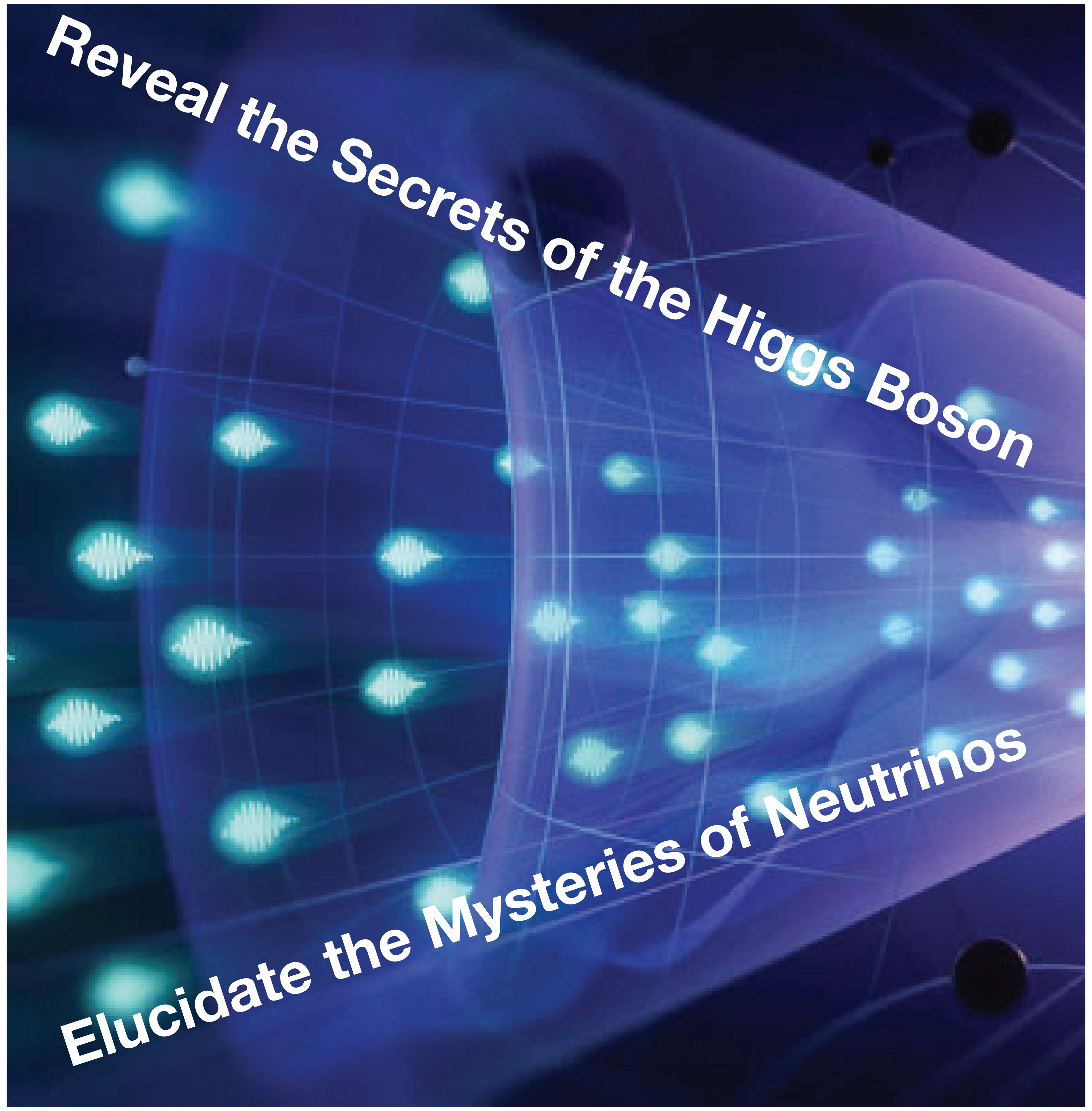


Decipher the Quantum Realm

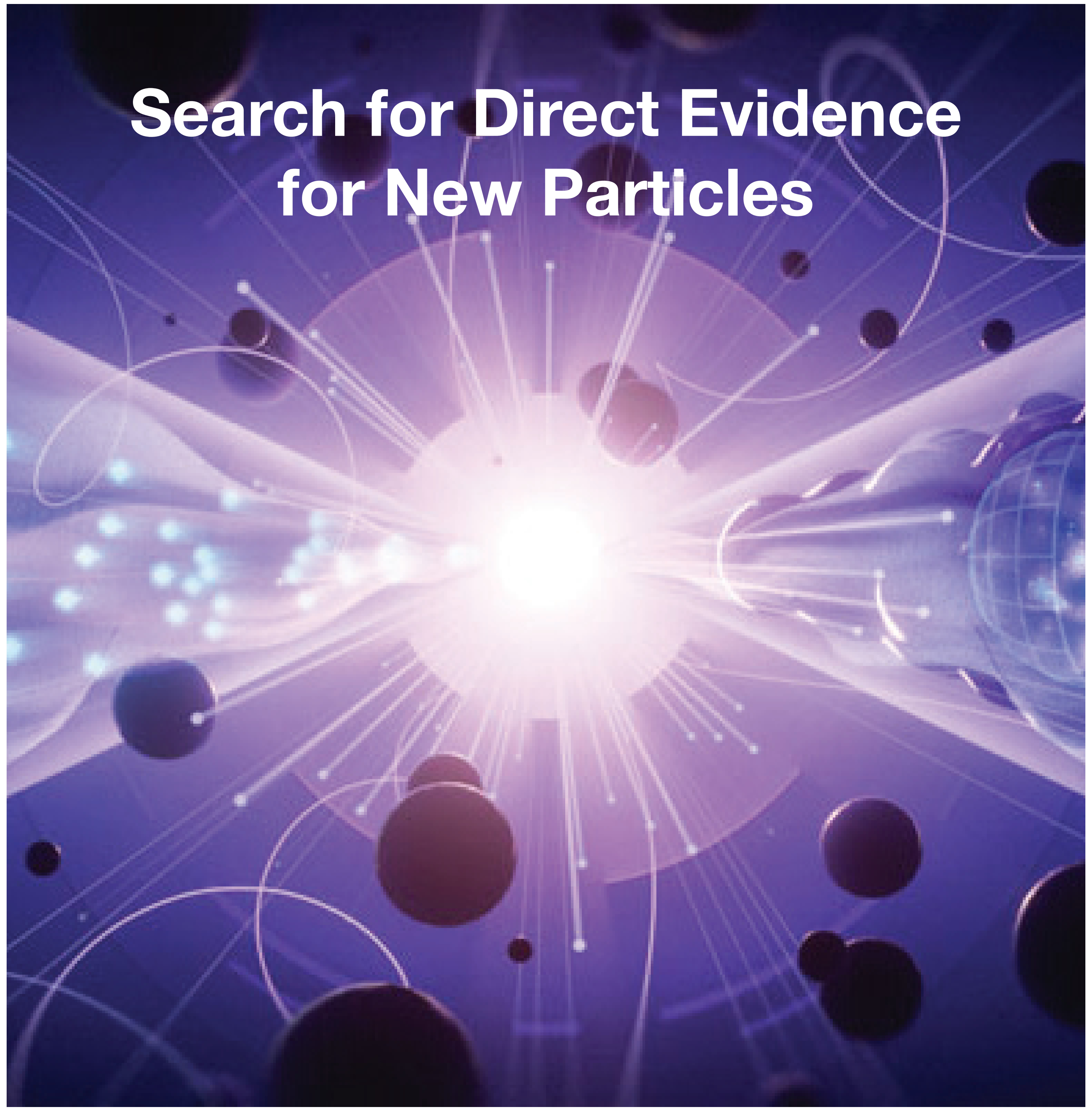
Explore New Paradigms in Physics

Illuminate the Hidden Universe

Explore the Quantum Universe



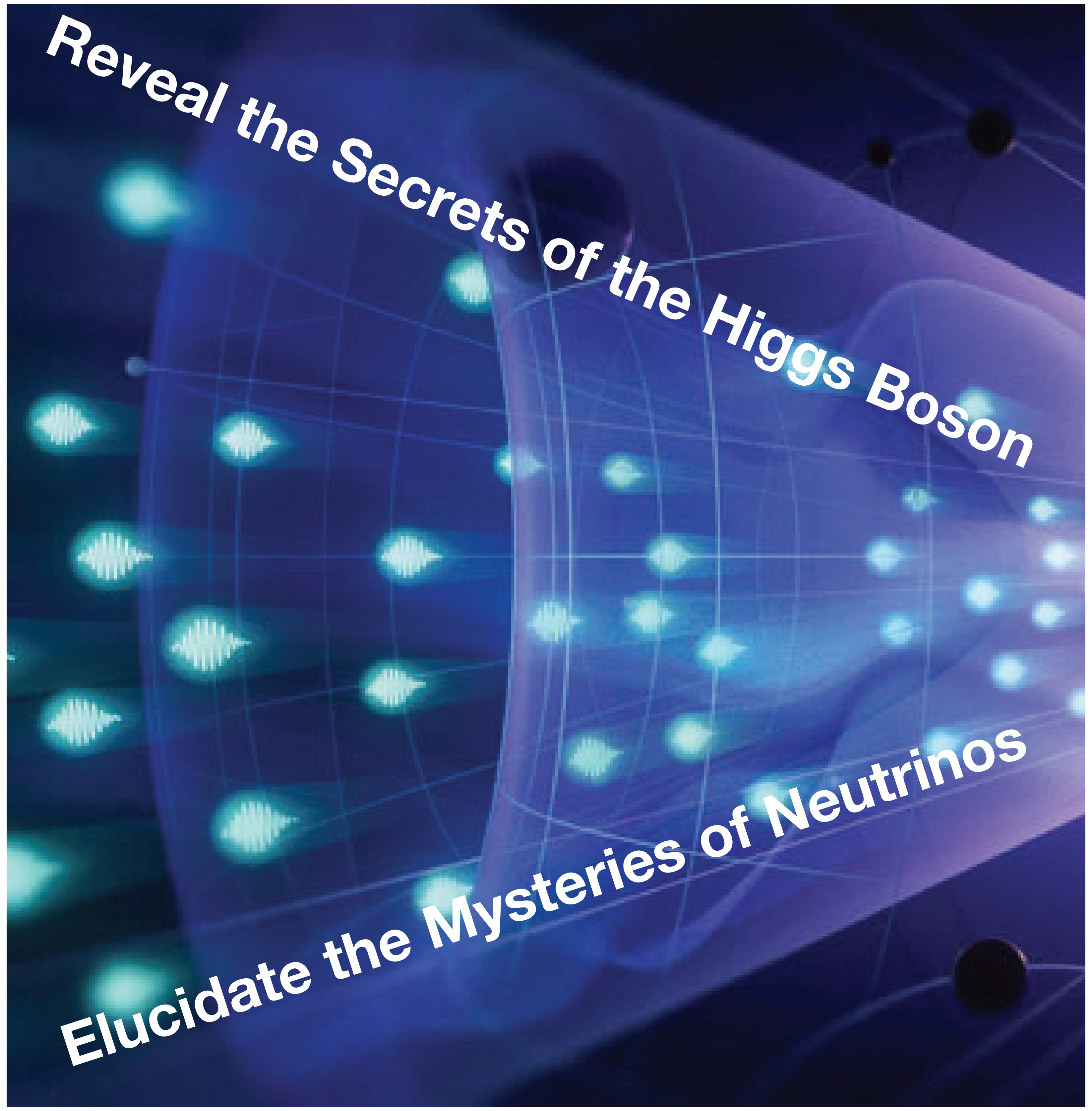
Decipher the Quantum Realm



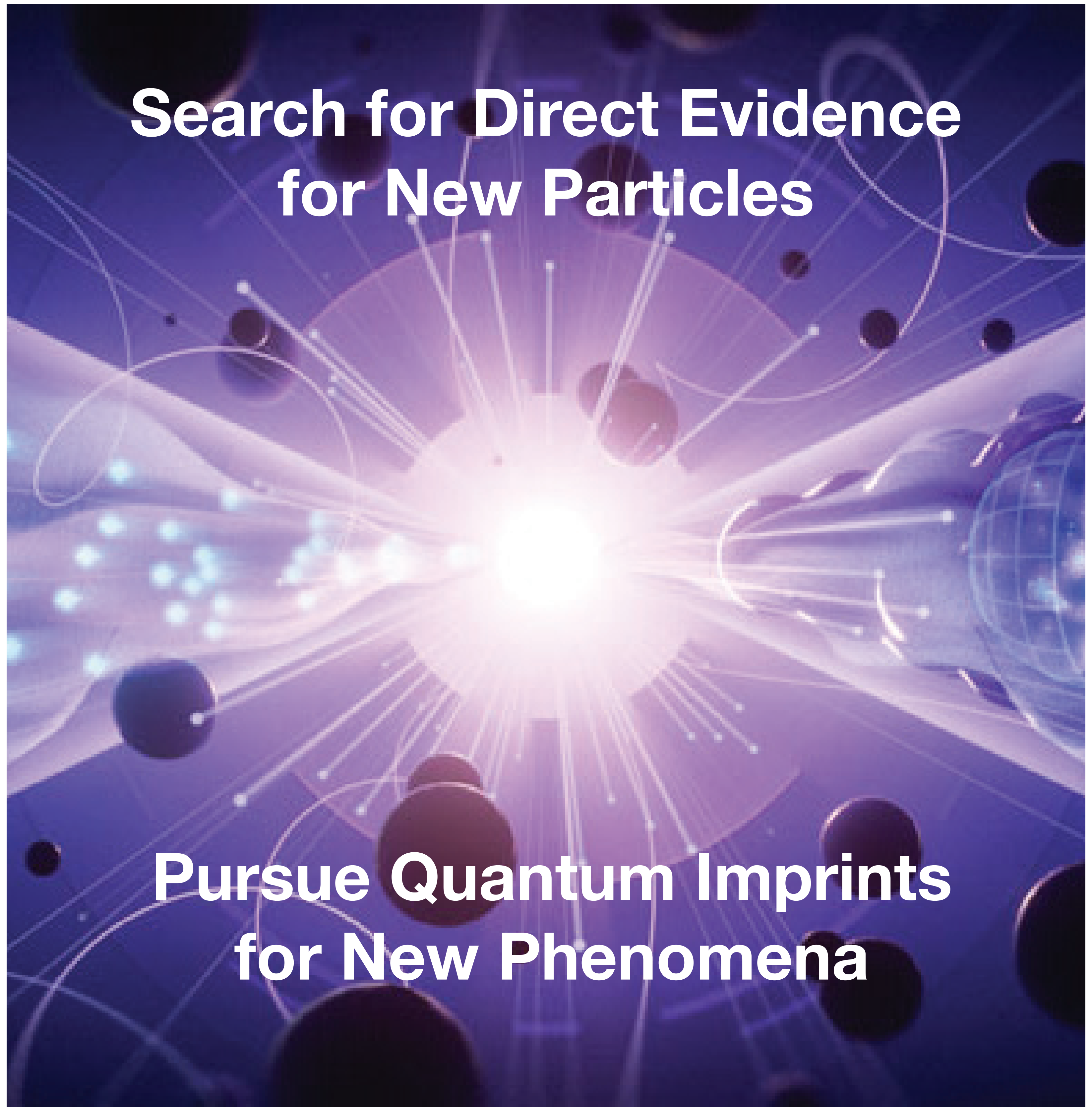
Explore New Paradigms in Physics

Illuminate the Hidden Universe

Explore the Quantum Universe

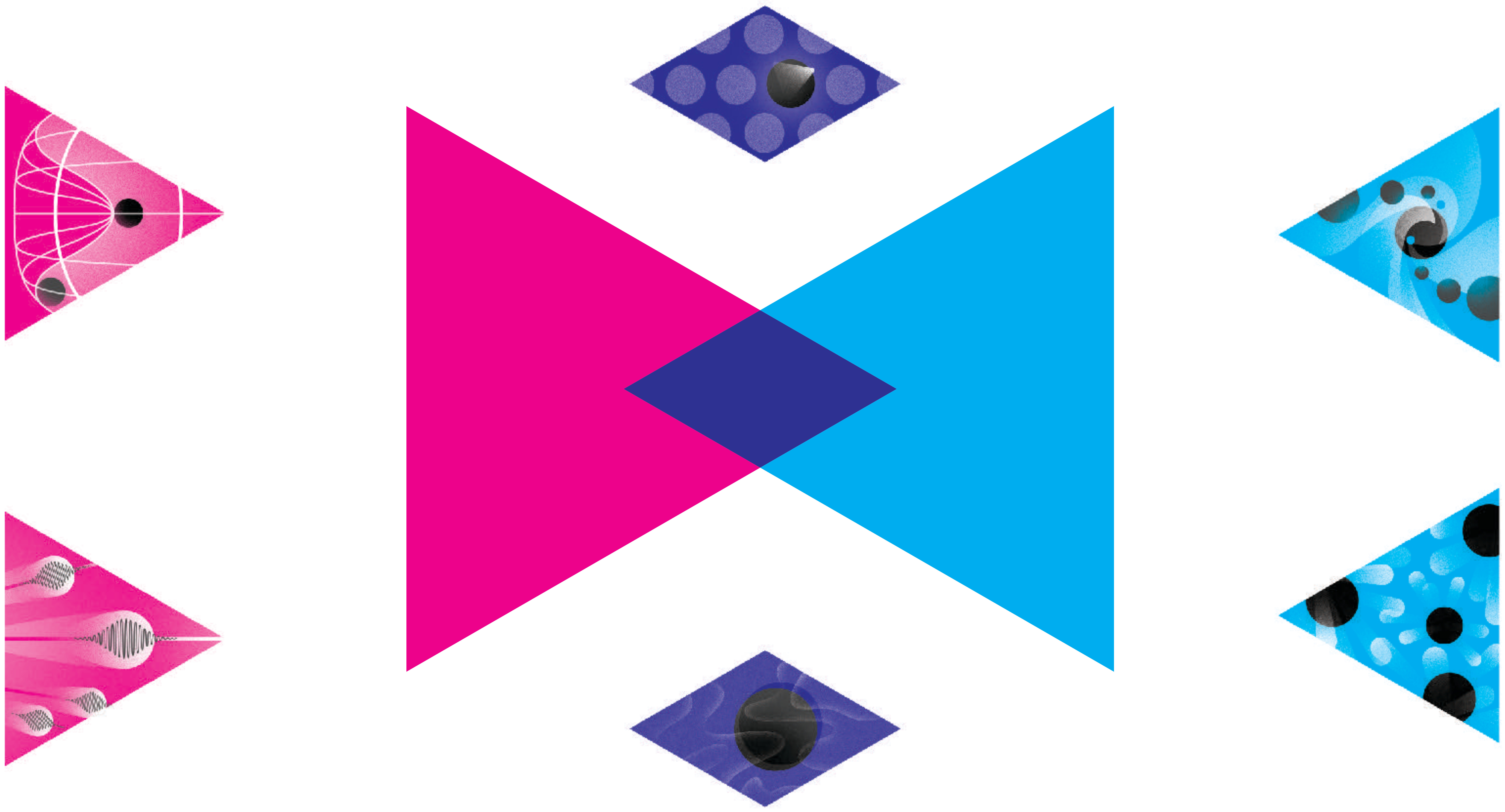


Decipher the Quantum Realm



Explore New Paradigms in Physics

Illuminate the Hidden 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.

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). DOE & NSF PHY

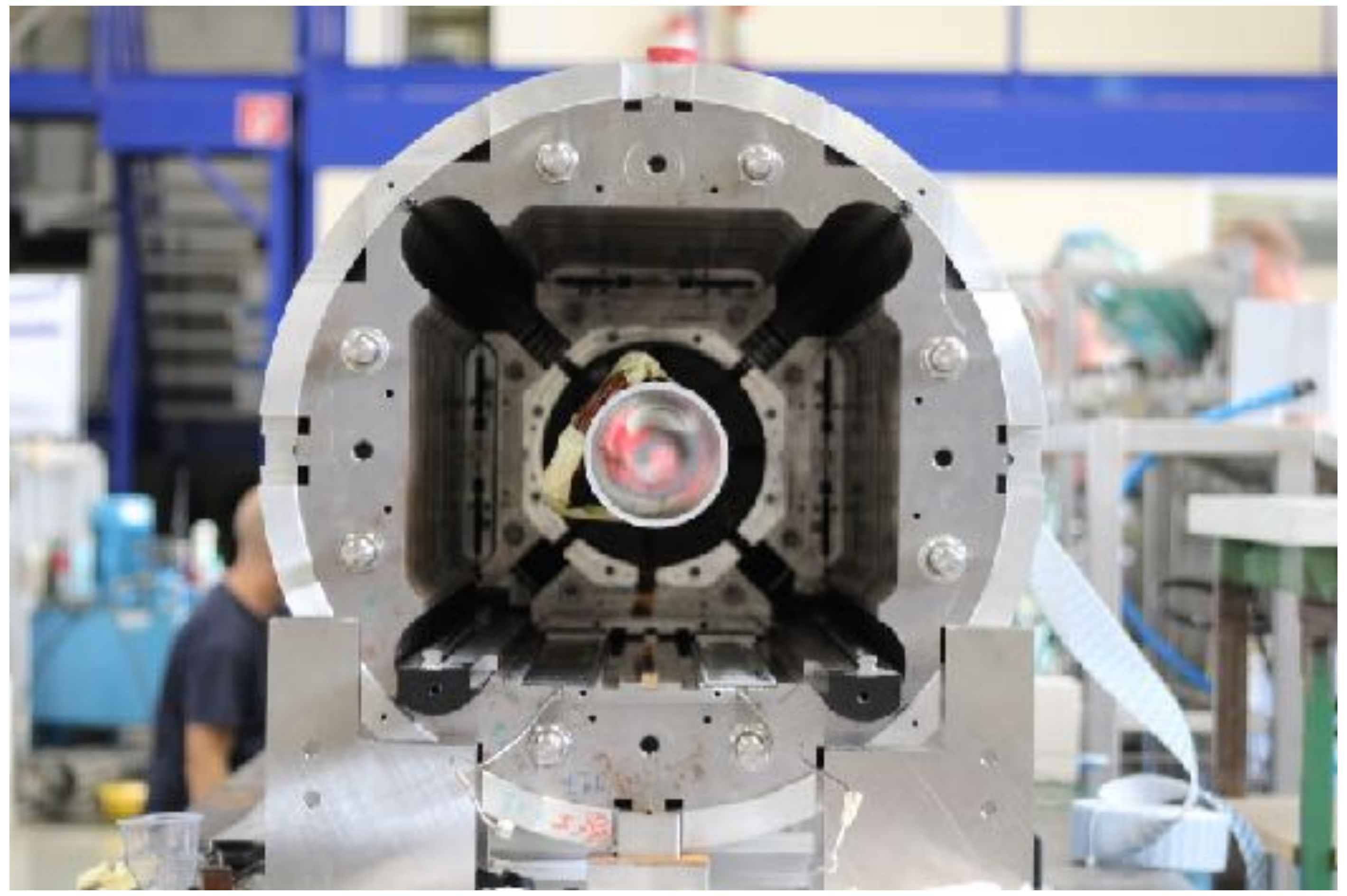
b. **The first phase of DUNE and PIP-II** to determine the mass ordering among neutrinos, a fundamental property and a crucial input to cosmology and nuclear science (elucidate the mysteries of neutrinos, section 3.1). Mostly DOE

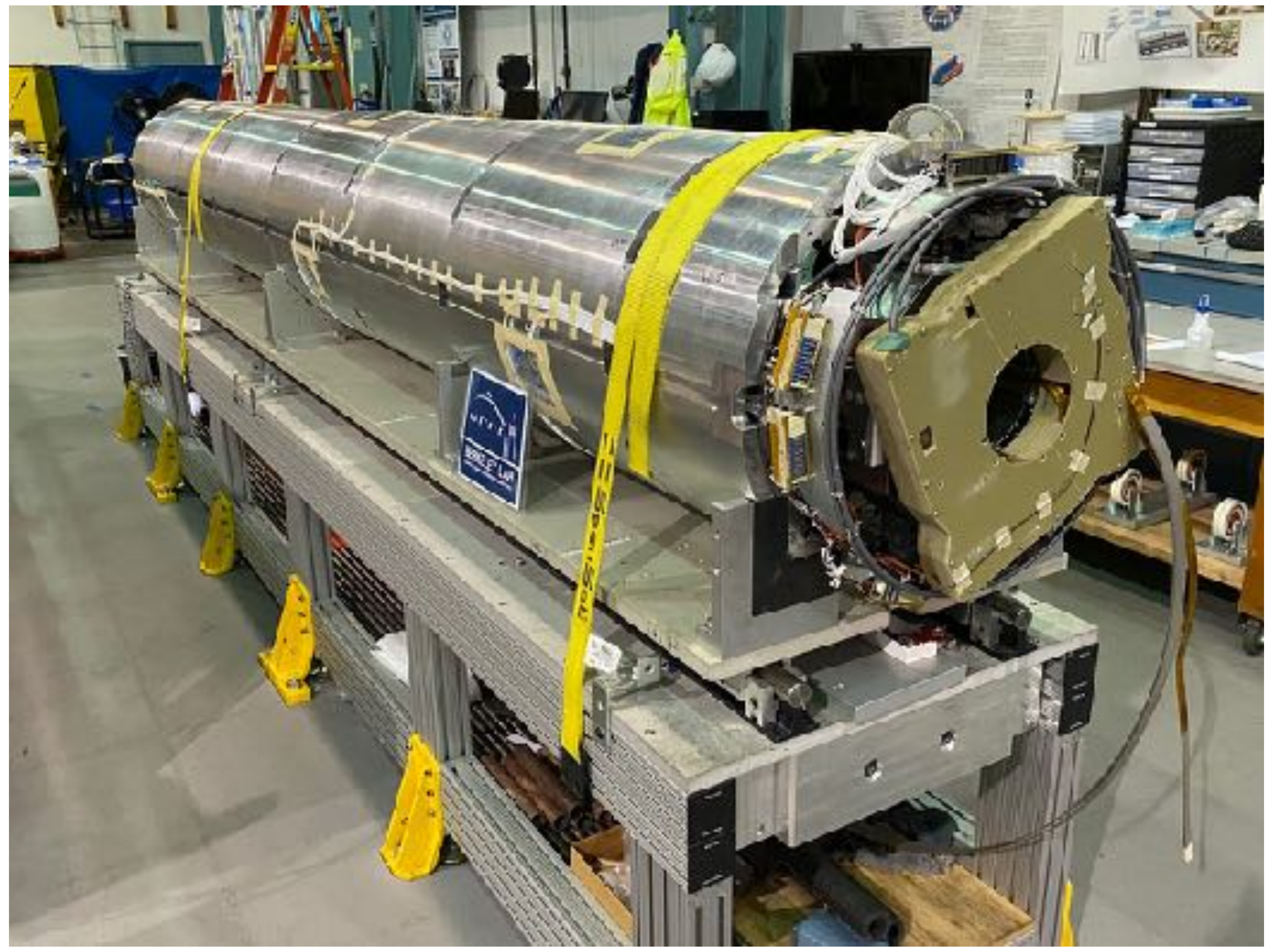
c. **The Vera C. Rubin Observatory** to carry out the LSST, and the LSST Dark Energy Science Collaboration, to understand what drives cosmic evolution (section 4.2). DOE & NSF AST

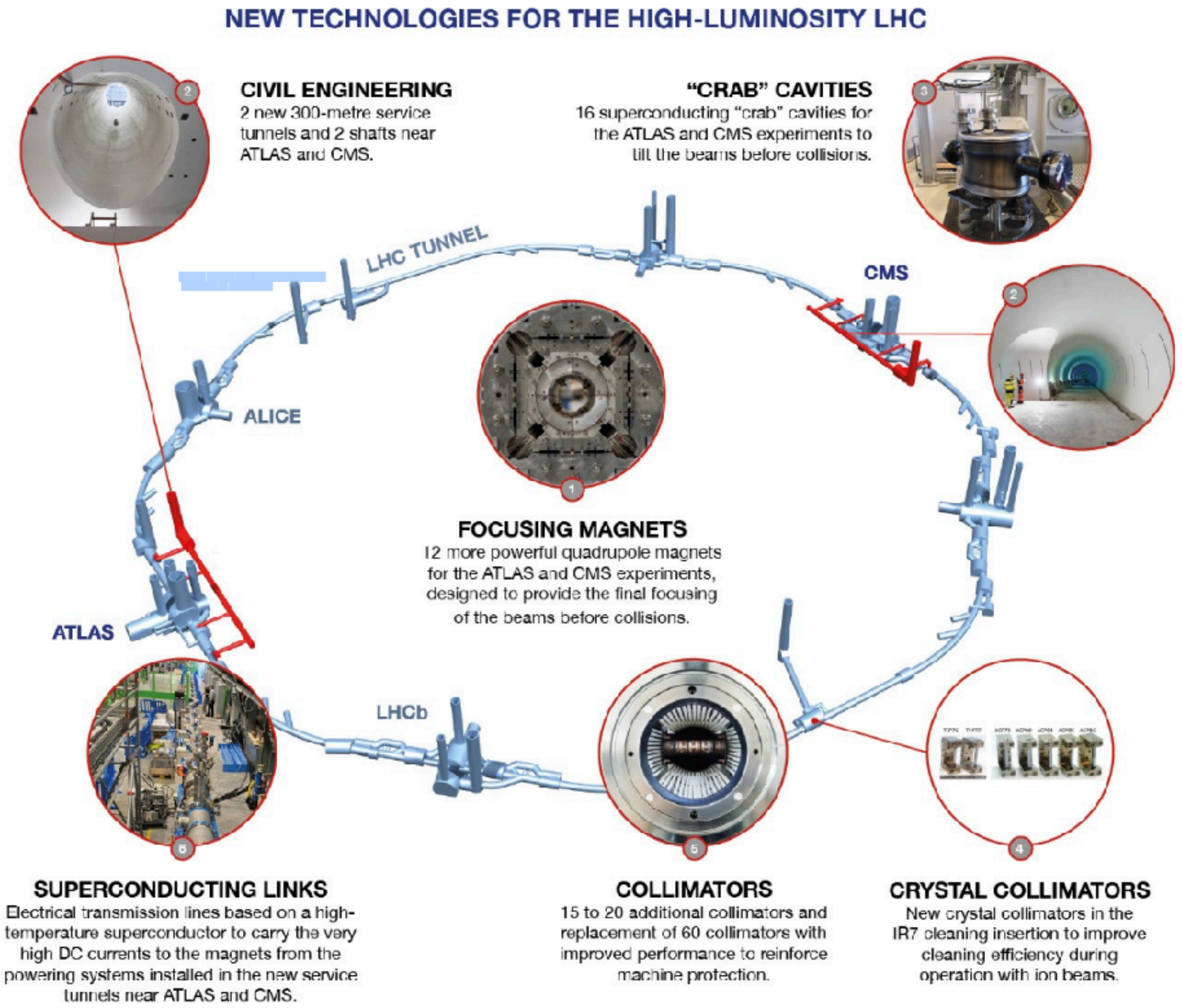
US leadership in key areas of particle physics

Exploring the Quantum Universe

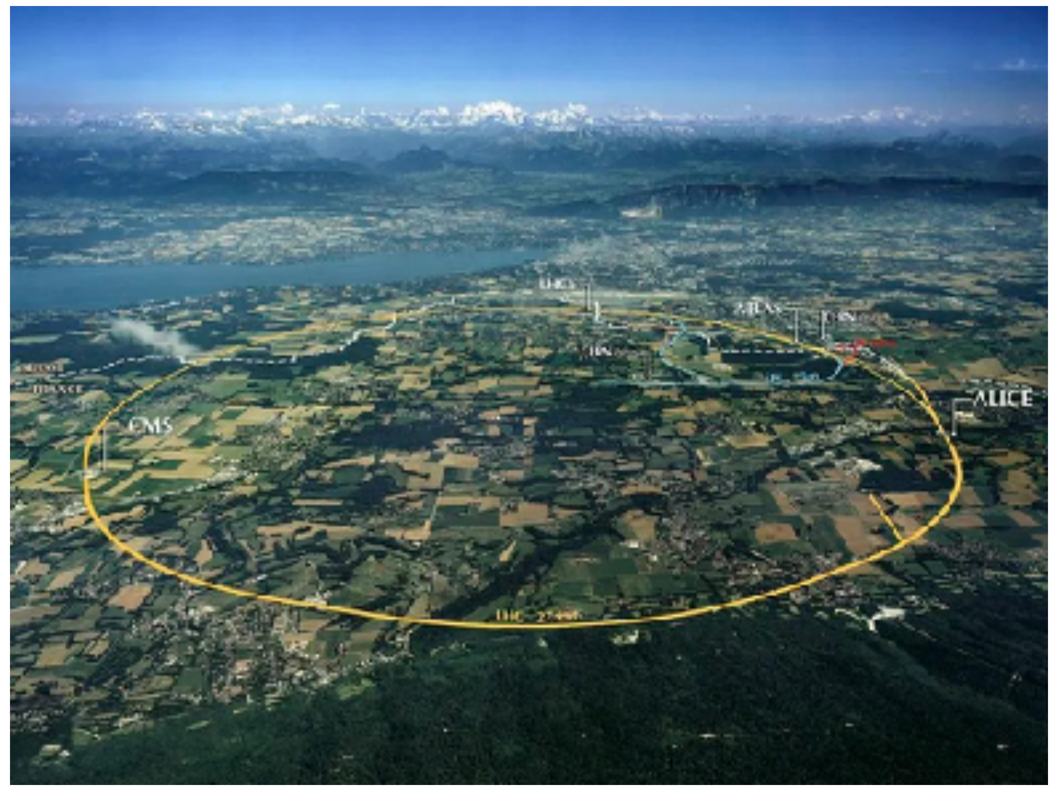
High Luminosity LHC



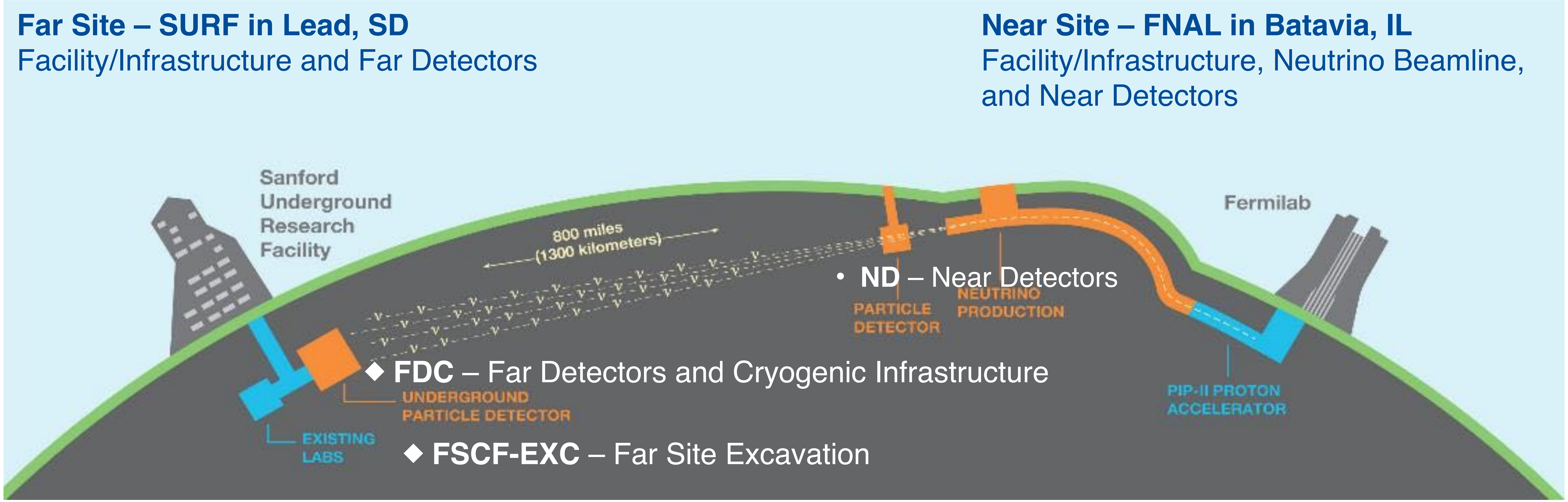




CERN



Deep Underground Neutrino Experiment (DUNE)



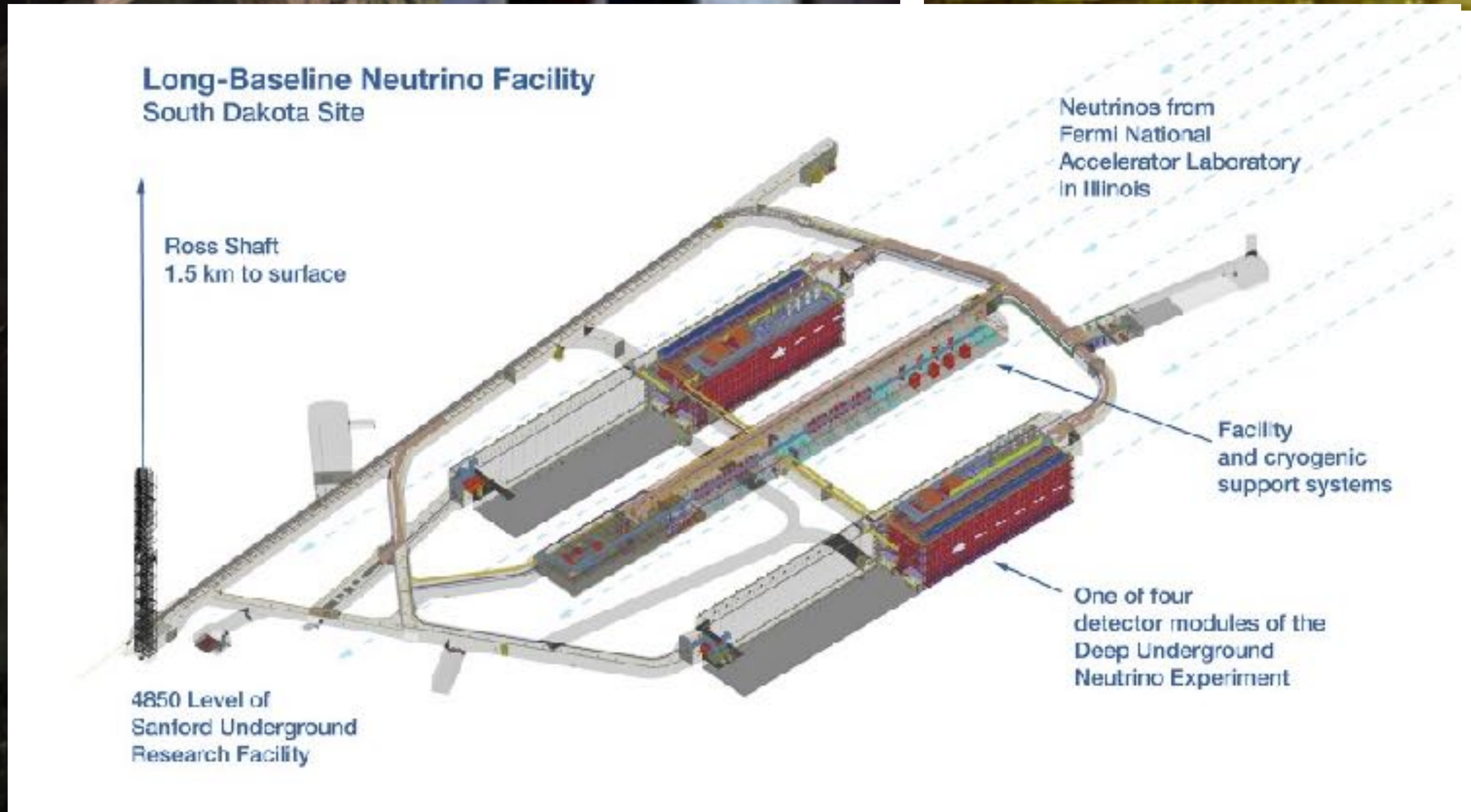
DUNE is an international science collaboration of more than 1300 scientists from 35 countries plus CERN

Largest **domestic** project in Office of Science (TPC = $3.2B), the first U.S.-hosted international particle physics mega-project

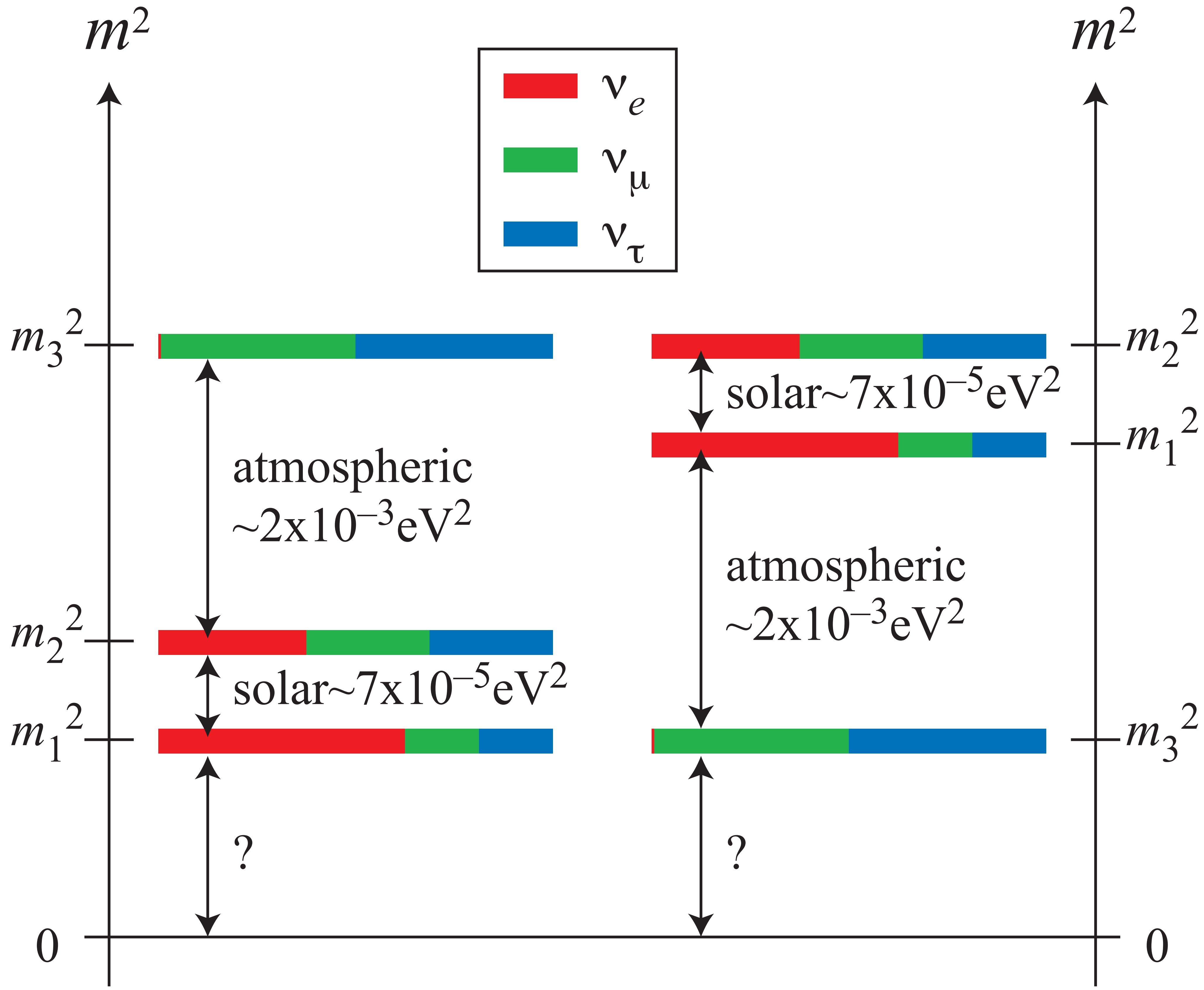
Exploring the Quantum Universe

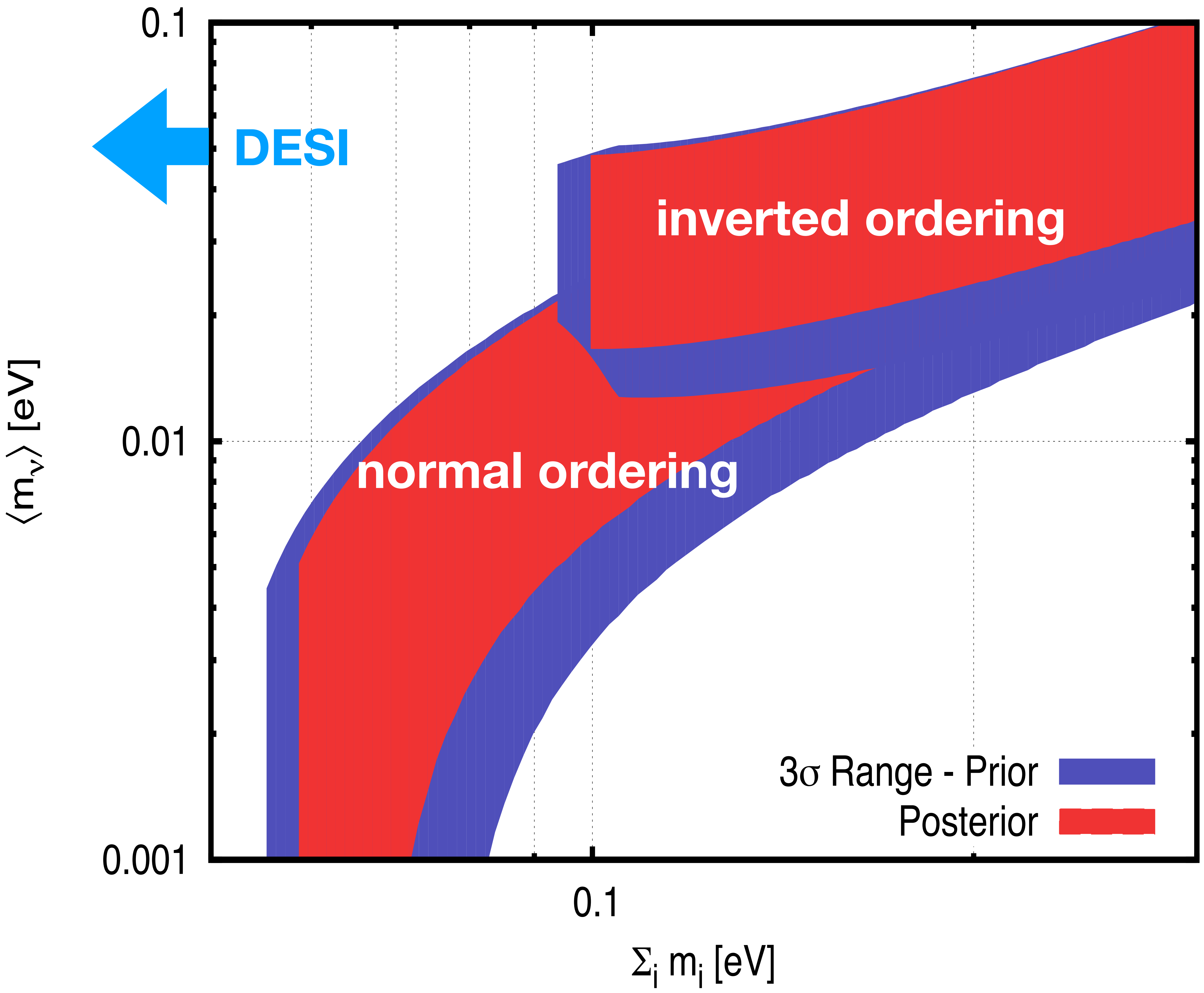
Deep Underground Neutrino Experiment (DUNE)

Far site excavation



Cryostat testing at CERN!





Shao-Feng Ge and Werner Rodejohann arXiv:1507.05514

Exploring the Quantum Universe

Vera Rubin Observatory

Exploring the Quantum Universe

Not Rank-Ordered

Recommendation 1

Reaffirm critical importance of the ongoing projects

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.

Exploring the Quantum Universe

Recommendation 2

New exciting initiatives

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

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).

DOE & NSF AST

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

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

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

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.

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.

National
Science
Foundation

<https://www.nsf.gov>

NSF
Biological Sciences
Computer and Information Science and Engineering
Engineering
Geosciences
Mathematical and Physical Sciences
Social, Behavioral and Economic Sciences

anage Your Award

Geosciences
Atmospheric and Geospace Sciences
Earth Sciences
Ocean Sciences
Office of Polar Programs

ts

Home (/)

NSF 23-117

Dear Colleague Letter: 2023 Update on Science Supp 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.

National Science Foundation

<https://www.nsf.gov>

NSF
Biological Sciences
Computer and Information Science and Engineering
Engineering
Geosciences
Mathematical and Physical Sciences
Social, Behavioral and Economic Sciences

anage Your Award

Geosciences
Atmospheric and Geospace Sciences
Earth Sciences
Ocean Sciences
Office of Polar Programs

ts

Home (/)

NSF 23-117

Dear Colleague Letter: 2023 Update on Science Supp Infrastructure in Antarctica

Jur

De

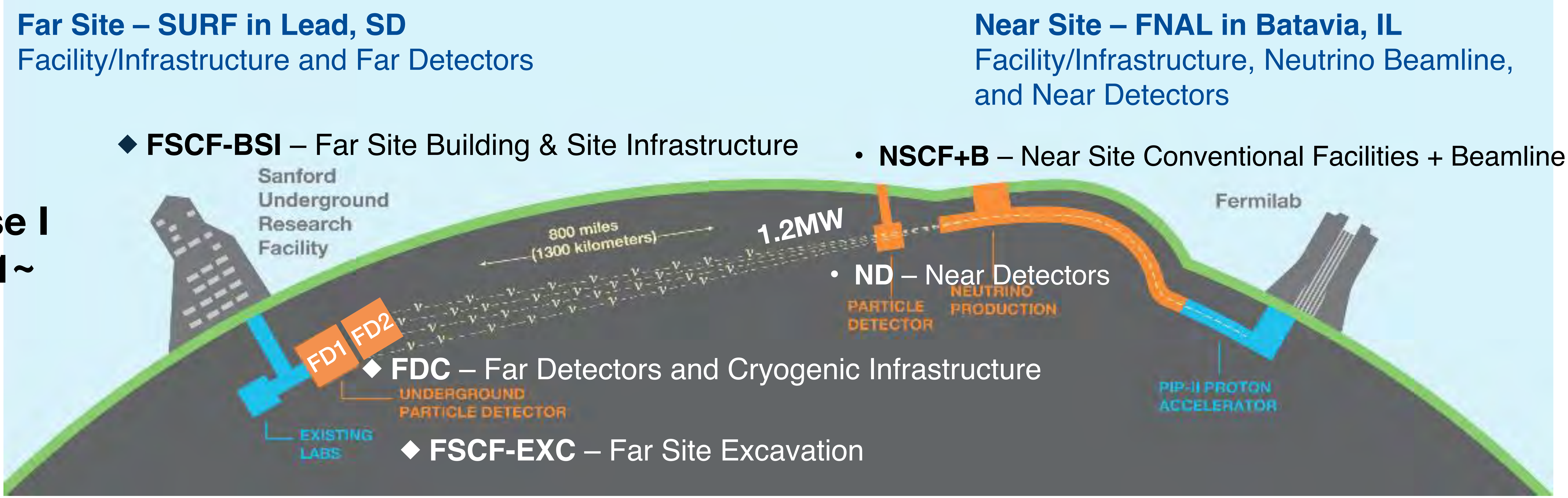
The South Pole, a unique site that enables the world-leading science of CMB-S4 and IceCube-Gen2, must be maintained as a premier site of science to allow continued US leadership in these areas. (section 2.4)

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)

Phase I
2031~



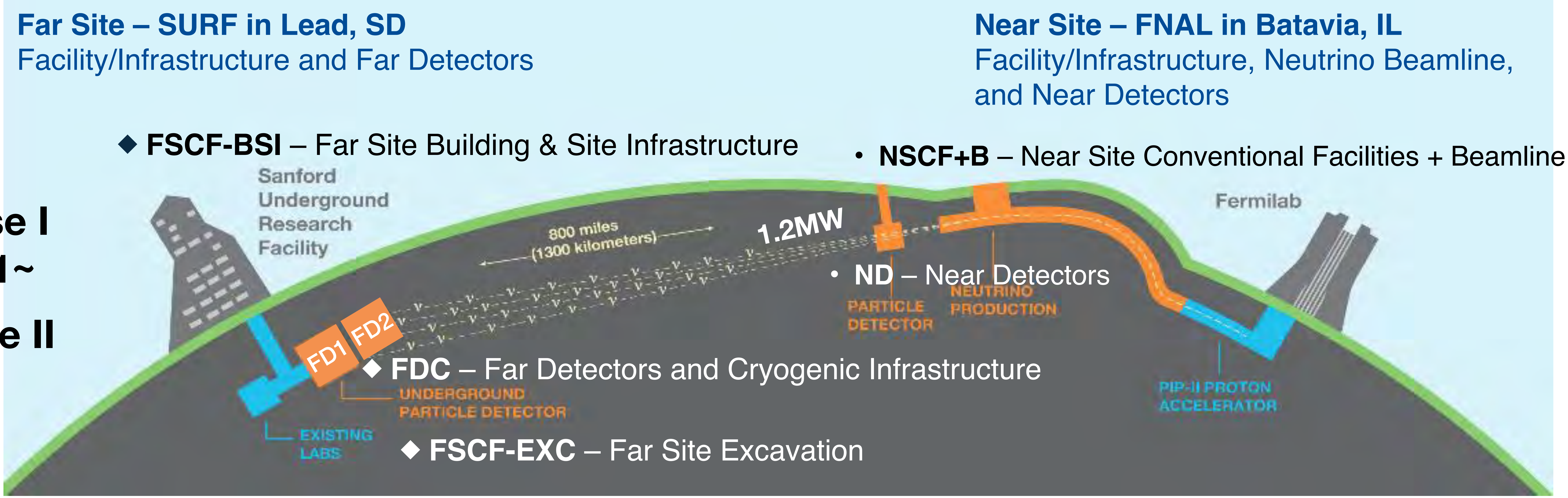
- DUNE is an international science collaboration of more than 1300 scientists from 35 countries plus CERN
  - 50 – 50 split between U.S. and non- U.S. collaborators

Largest **DOMESTIC** project in Office of Science (TPC = $3.2B)
the first U.S.-hosted international particle physics mega-project

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

Phase I
2031~

Phase II



- 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

Largest **DOMESTIC** project in Office of Science (TPC = $3.2B)
the first U.S.-hosted international particle physics mega-project

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

Phase I
2031~
Phase II

- ◆ **FSCF-BSI** – Far Site Building & Site Infrastructure
- ◆ **FDC** – Far Detectors and Cryogenic Infrastructure
- ◆ **FSCF-EXC** – Far Site Excavation
- **NSCF+B** – Near Site Conventional Facilities + Beamline
- **ND** – Near Detectors

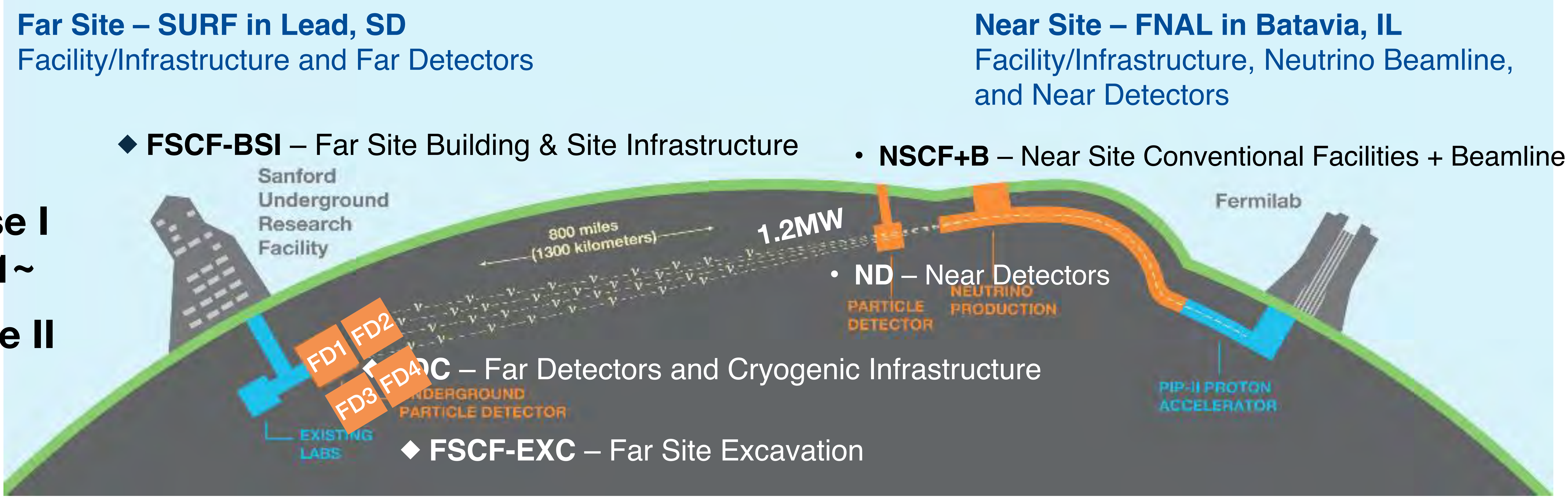
◆ DUNE is an international science collaboration of more than 1300 scientists from 35 countries plus CERN

- 50 – 50 split between U.S. and non- U.S. collaborators

Largest **DOMESTIC** project in Office of Science (TPC = $3.2B)
the first U.S.-hosted international particle physics mega-project

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

Phase I
2031~
Phase II

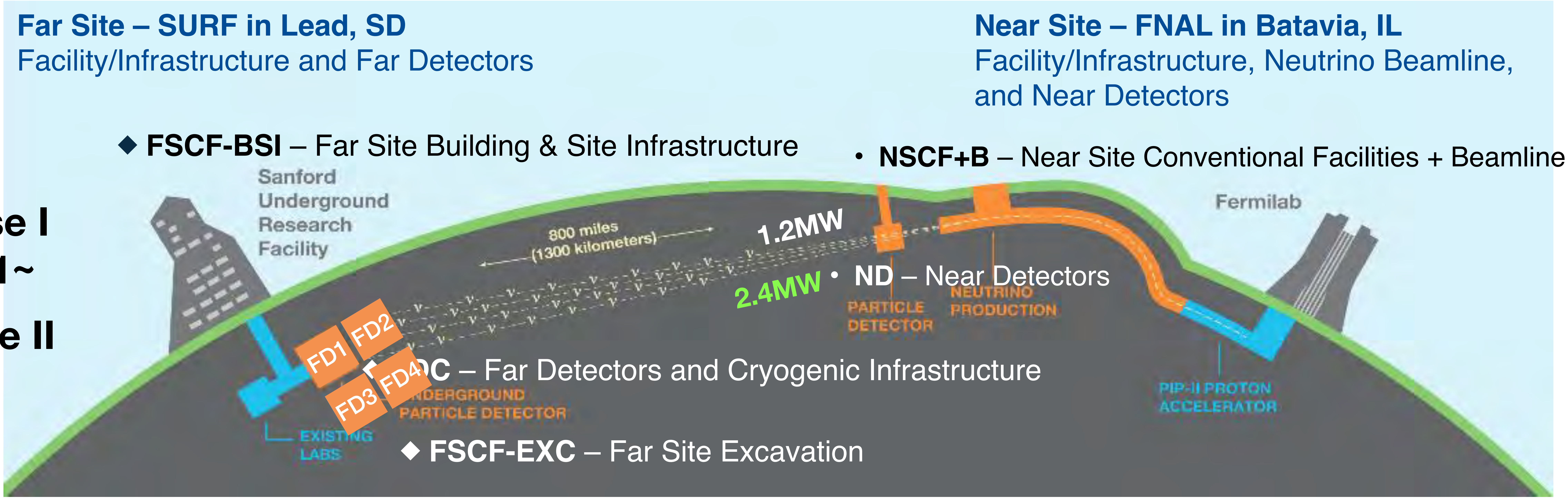


- DUNE is an international science collaboration of more than 1300 scientists from 35 countries plus CERN
  - 50 – 50 split between U.S. and non- U.S. collaborators

Largest **DOMESTIC** project in Office of Science (TPC = $3.2B)
the first U.S.-hosted international particle physics mega-project

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

Phase I
2031~
Phase II

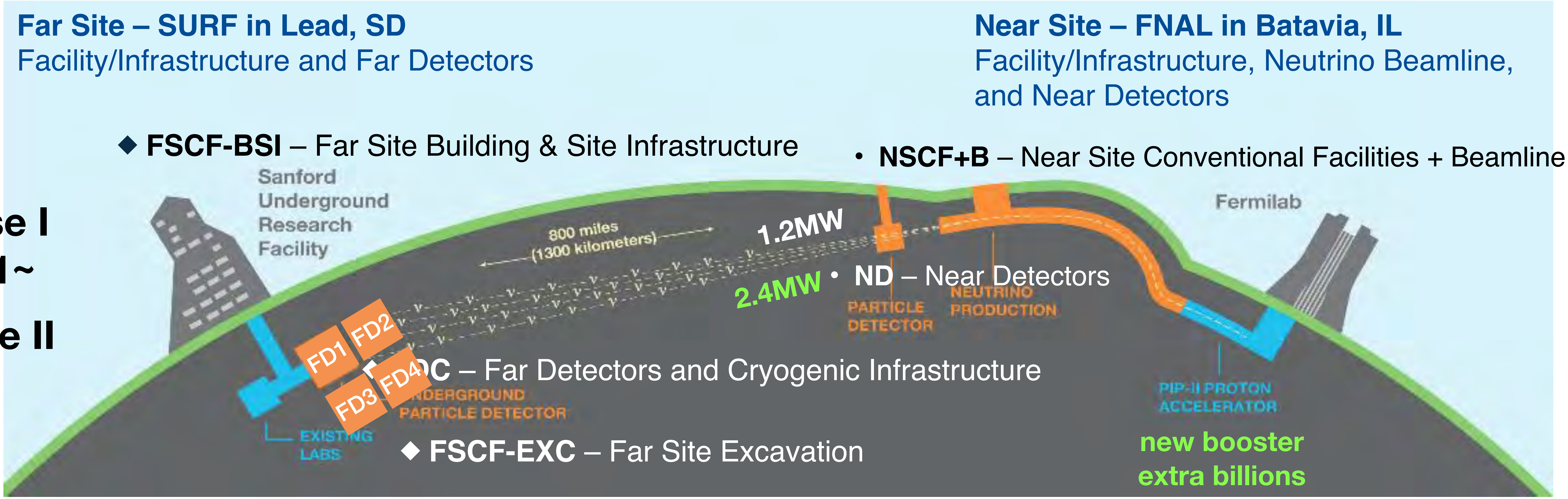


- ◆ DUNE is an international science collaboration of more than 1300 scientists from 35 countries plus CERN
  - 50 – 50 split between U.S. and non- U.S. collaborators

Largest **DOMESTIC** project in Office of Science (TPC = $3.2B)
the first U.S.-hosted international particle physics mega-project

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

Phase I
2031~
Phase II



- 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

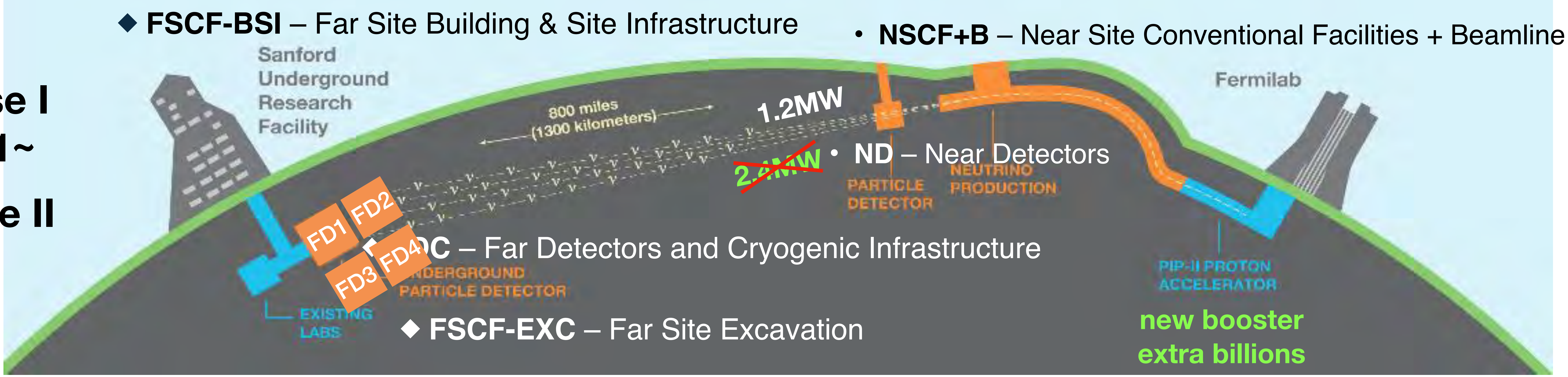
Largest **DOMESTIC** project in Office of Science (TPC = $3.2B)
the first U.S.-hosted international particle physics mega-project

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

Phase I
2031~
Phase II

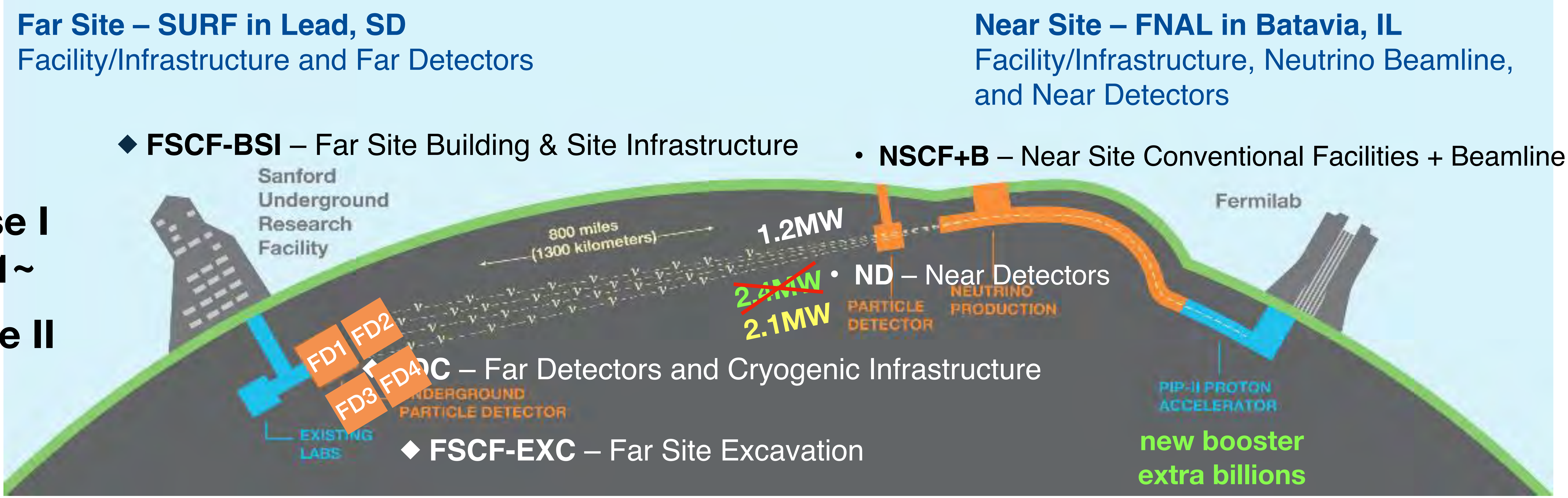


- ◆ DUNE is an international science collaboration of more than 1300 scientists from 35 countries plus CERN
  - 50 – 50 split between U.S. and non- U.S. collaborators

Largest **DOMESTIC** project in Office of Science (TPC = $3.2B)
the first U.S.-hosted international particle physics mega-project

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

Phase I
2031~
Phase II



- 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

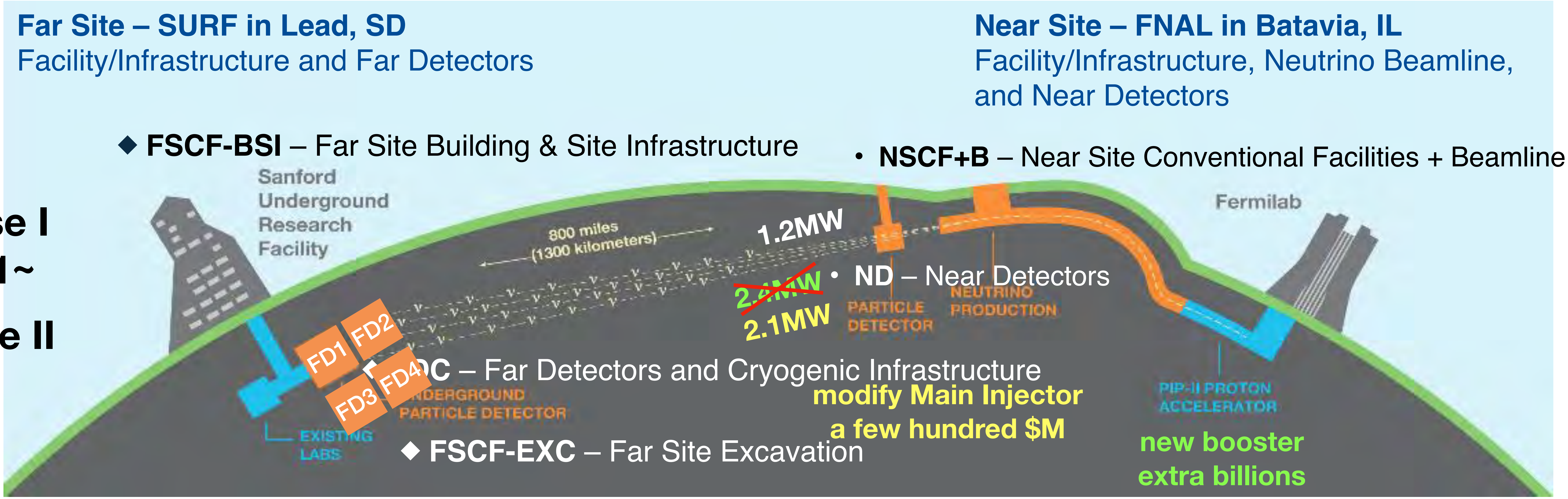
Largest **DOMESTIC** project in Office of Science (TPC = $3.2B)
the first U.S.-hosted international particle physics mega-project

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

Phase I

2031~

Phase II

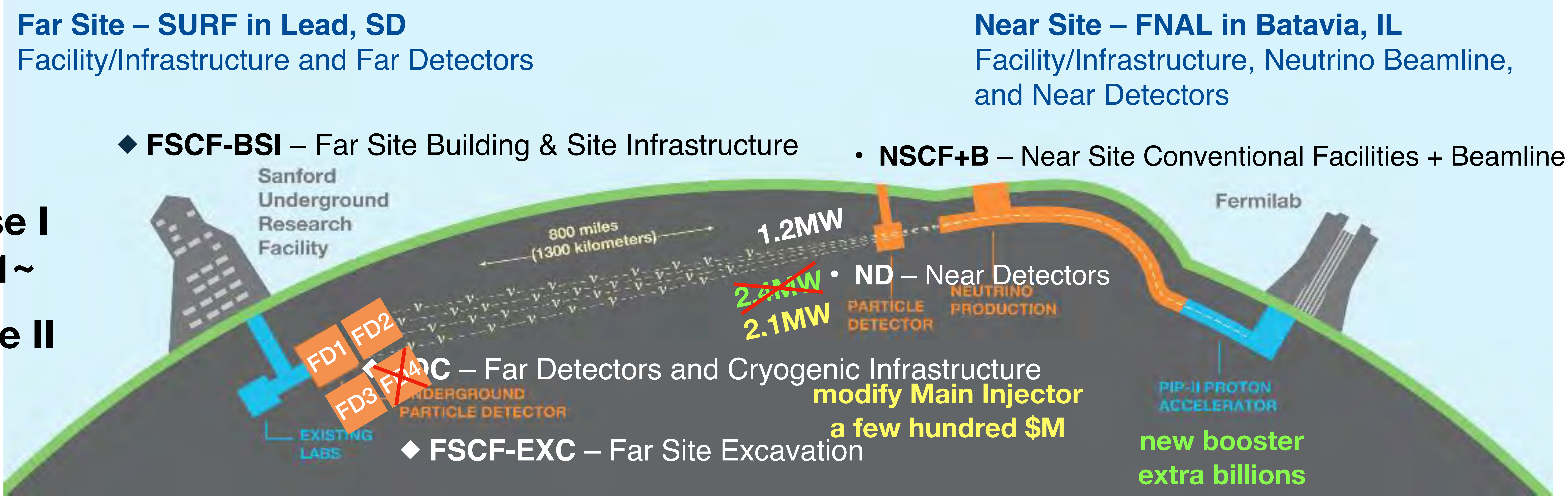


- ◆ DUNE is an international science collaboration of more than 1300 scientists from 35 countries plus CERN
  - 50 – 50 split between U.S. and non- U.S. collaborators

Largest **DOMESTIC** project in Office of Science (TPC = $3.2B)
the first U.S.-hosted international particle physics mega-project

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

Phase I
2031~
Phase II

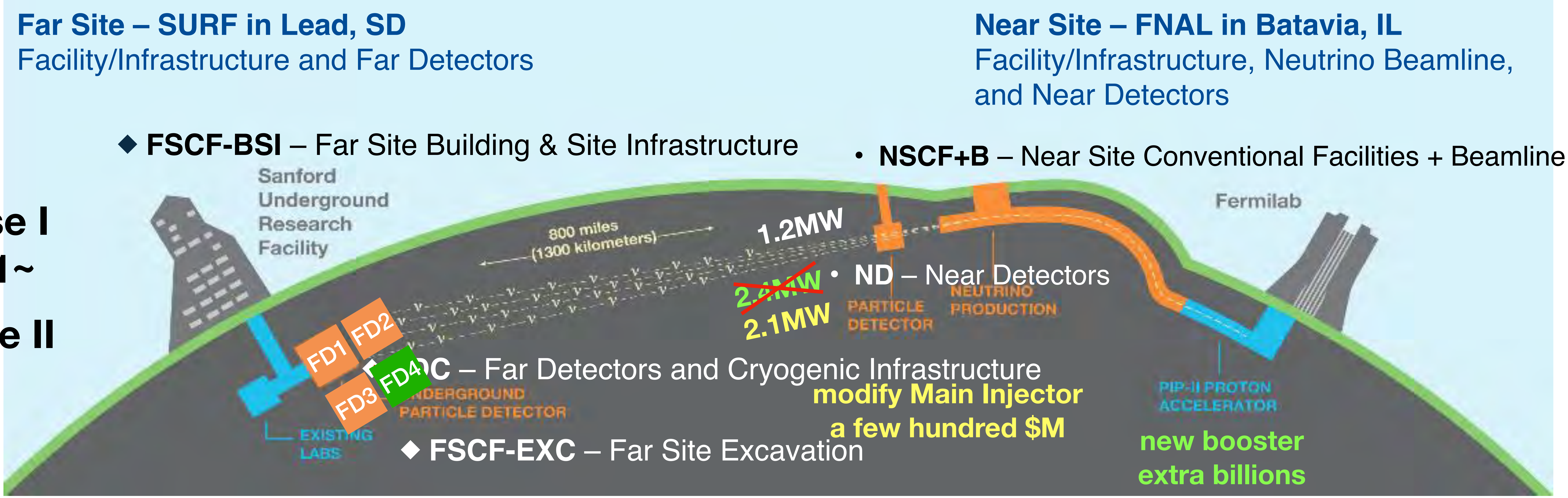


- DUNE is an international science collaboration of more than 1300 scientists from 35 countries plus CERN
  - 50 – 50 split between U.S. and non- U.S. collaborators

Largest **DOMESTIC** project in Office of Science (TPC = $3.2B)
the first U.S.-hosted international particle physics mega-project

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

Phase I
2031~
Phase II

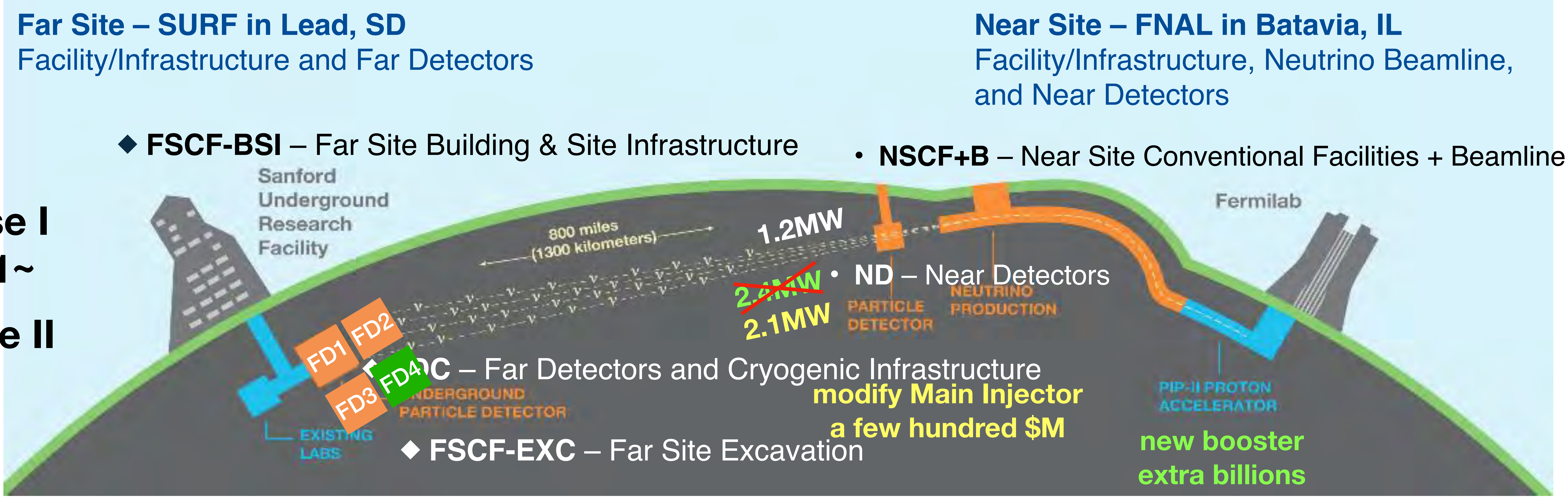


- DUNE is an international science collaboration of more than 1300 scientists from 35 countries plus CERN
  - 50 – 50 split between U.S. and non- U.S. collaborators

Largest **DOMESTIC** project in Office of Science (TPC = $3.2B)
the first U.S.-hosted international particle physics mega-project

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

Phase I
2031~
Phase II



- 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

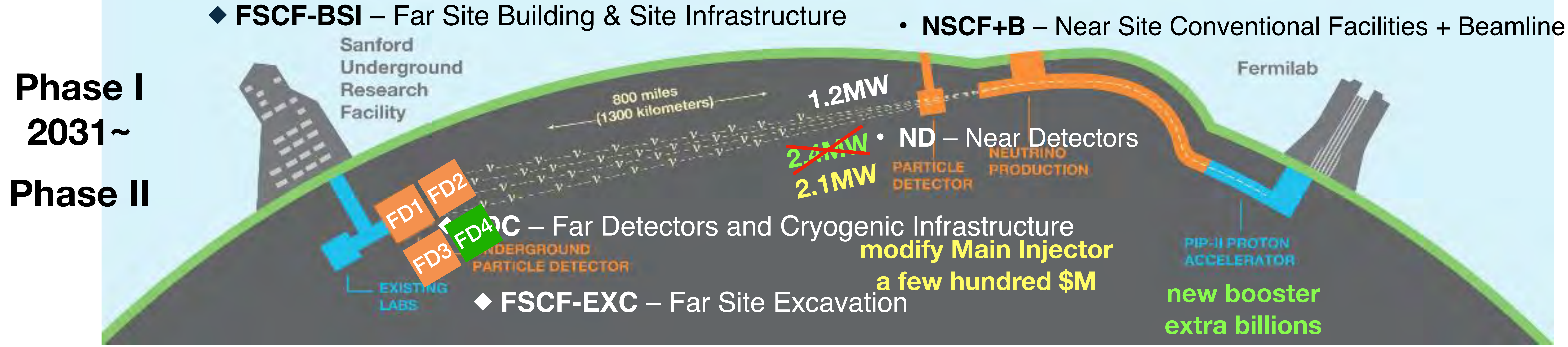
3.1.4 – Future Opportunities: DUNE FD4, the Module of Opportunity

Largest **DOMESTIC** project in Office of Science (TPC = $3.2B)
the first U.S.-hosted international particle physics mega-project

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



◆ 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

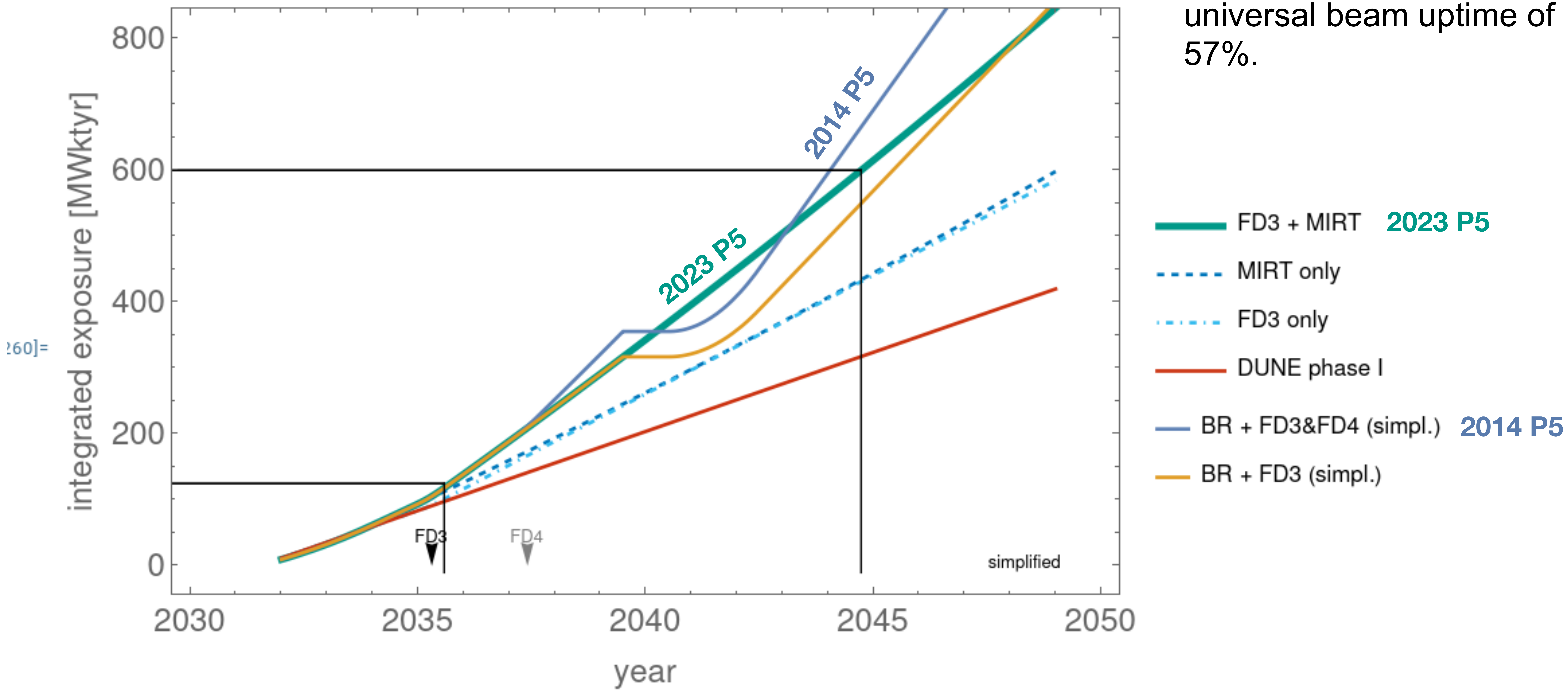
3.1.4 – Future Opportunities: DUNE FD4, the Module of Opportunity

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)
l particle physics mega-project

Not in the Report

DUNE Exposure plot



This figure is based on the beam profile submitted by FNAL/DUNE assuming a universal beam uptime of 57%.

Higgs factory summary table

- Main parameters of the submitted Higgs factory proposals.
- The cost range is for the single listed energy.
- The superscripts next to the name of the proposal in the first column indicate:
  - (1) Facility is optimized for 2 IPs. Total peak luminosity for multiple IPs is given in parenthesis;
  - (2) Energy calibration possible to 100 keV accuracy for MZ and 300 keV for MW ;
  - (3) Collisions with longitudinally polarized lepton beams have substantially higher effective cross sections for certain processes

Proposal Name	CM energy nom. (range) [TeV]	Lum./IP @ nom. CME [10^{34} cm^{-2}s^{-1}]	Years of pre-project R&D	Years to first physics	Construction cost range [2021 B$]	Est. operating electric power [MW]
FCC-ee[1,2]	0.24 (0.09-0.37)	7.7 (28.9)	0-2	13-18	12-18	290
CEPC[1,2]	0.24 (0.09-0.37)	8.3 (16.6)	0-2	13-18	12-18	340
ILC[3] - Higgs factory	0.25 (0.09-1)	2.7	0-2	<12	7-12	140
CLIC[3] - Higgs factory	0.38 (0.09-1)	2.3	0-2	13-18	7-12	110
CCC[3] (Cool Copper Collider)	0.25 (0.25-0.55)	1.3	3-5	13-18	7-12	150
CERC[3] (Circular ERL Collider)	0.24 (0.09-0.6)	78	5-10	19-24	12-30	90
ReLiC[1,3] (Recycling Linear Collider)	0.24 (0.25-1)	165 (330)	5-10	>25	7-18	315
ERLC[3] (ERL linear collider)	0.24 (0.25-0.5)	90	5-10	>25	12-18	250
XCC (FEL-based $\gamma\gamma$ collider)	0.125 (0.125-0.14)	0.1	5-10	19-24	4-7	90
Muon Collider Higgs Factory[3]	0.13	0.01	>10	19-24	4-7	200

Implementation Task Force, Thomas Roser

8.2 Hard Choices

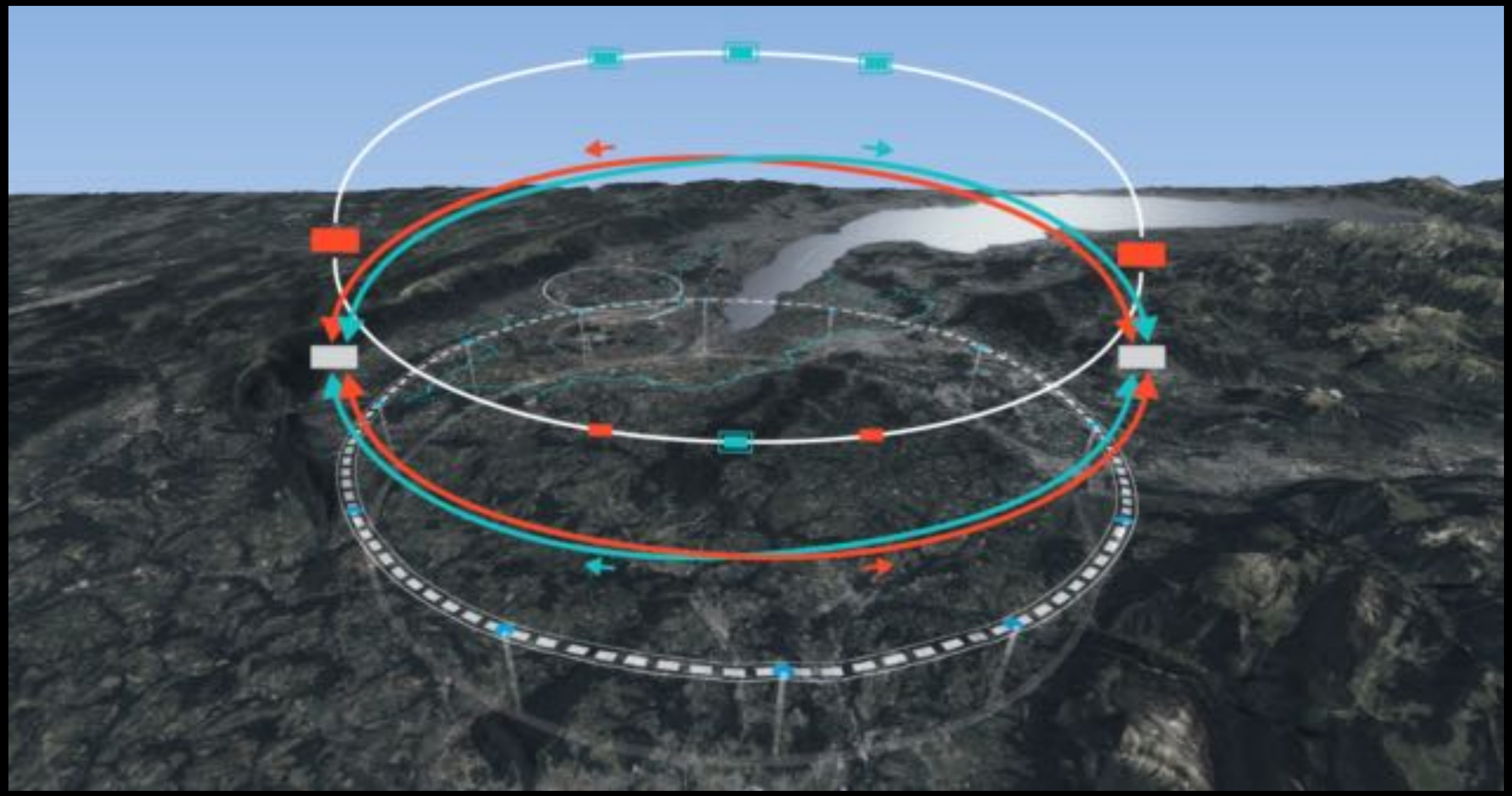
- On-shore Higgs factory. We could not identify room in the budget executable in the next twenty years for an on-shore Higgs factory unless the overall budget is increased by more than a factor of a few. On the other hand, there is an ongoing process in Europe to see if FCC-ee is feasible. The Japanese HEP community has been making an effort to realize ILC as a global project hosted in Japan. We therefore recommend exploring off-shore options and vigorously pursuing international collaborations so the US can play a major role when one of those projects becomes reality. If FCC-ee and ILC are judged to be not feasible, a new panel should revisit the possibility of bidding to host a Higgs factory potentially as a global project and including advanced technology options.

An Offshore Higgs Factory

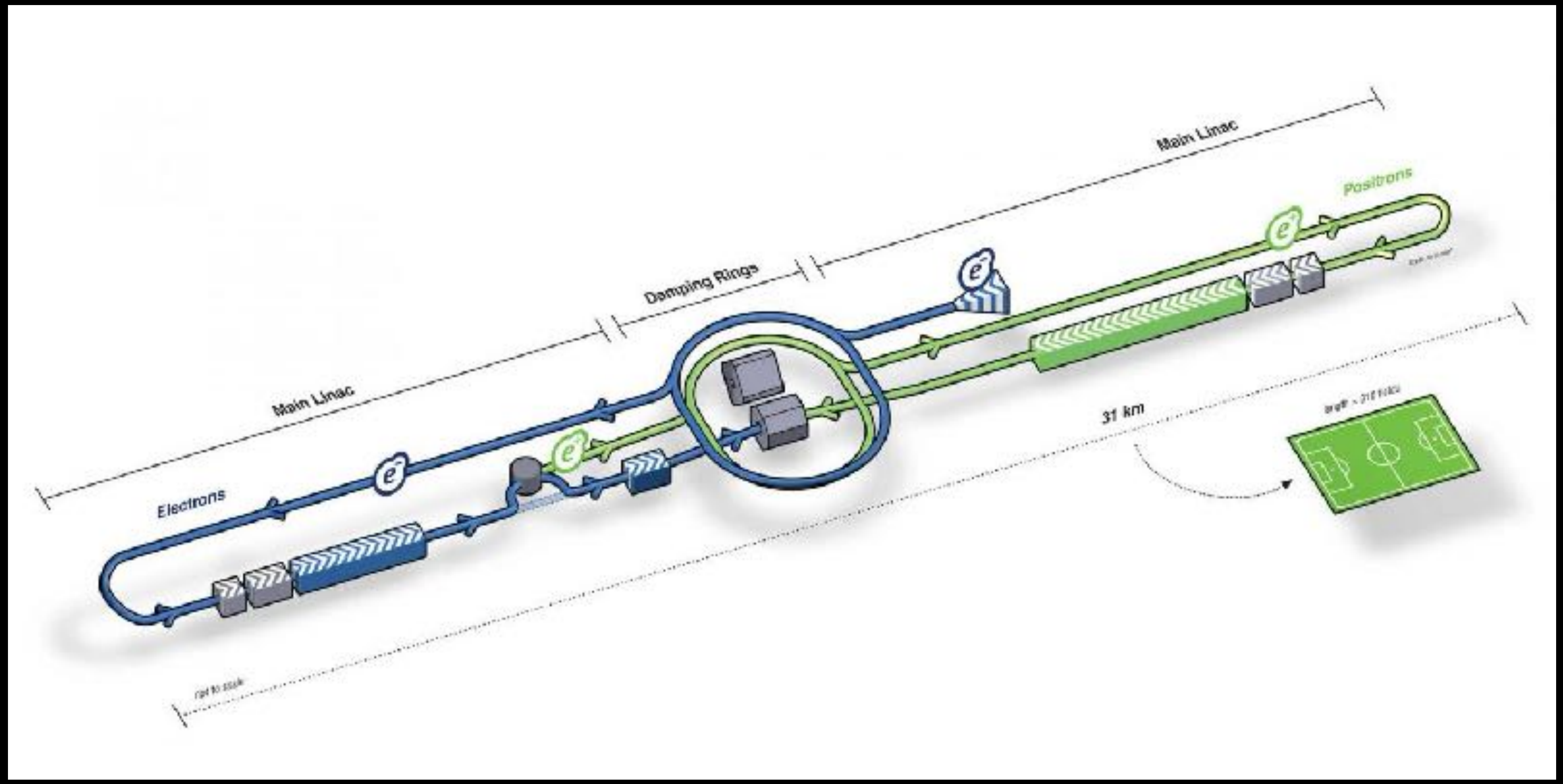
An electron-positron collider covering center-of-momentum energy range 90 - 350 GeV

- 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



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		

Exploring the Quantum Universe

2014 P5

Table 1
Summary of Scenarios

Project/Activity	low Scenario A	medium Scenario B	unlimited Scenario C	Higgs	Neutrinos	Dark Matter	Cosm. Accel.	The Unknown	Technique (Frontier)
	Scenarios			Science Drivers					
Large Projects									
Muon program: Mu2e, Muon g-2	Y, Mu2e small reprofile needed	Y	Y					✓	I
HL-LHC	Y	Y	Y	✓		✓		✓	E
LBNF + PIP-II	Y, LBNF components delayed relative to Scenario B.	Y	Y, enhanced		✓			✓	I,C
ILC	R&D only	R&D, possibly small hardware contri-butions. See text.	Y	✓		✓		✓	E
NuSTORM	N	N	N		✓				I
RADAR	N	N	N		✓				I
Medium Projects									
LSST	Y	Y	Y		✓		✓		C
DM G2	Y	Y	Y			✓			C
Small Projects Portfolio	Y	Y	Y		✓	✓	✓	✓	All
Accelerator R&D and Test Facilities	Y, reduced	Y, some reductions with redirection to PIP-II development	Y, enhanced	✓	✓	✓		✓	E,I
CMB-S4	Y	Y	Y		✓		✓		C
DM G3	Y, reduced	Y	Y			✓			C
PINGU	Further development of concept encouraged				✓	✓			C
ORKA	N	N	N					✓	I
MAP	N	N	N	✓	✓	✓		✓	E,I
CHIPS	N	N	N		✓				I
LAr1	N	N	N		✓				I
Additional Small Projects (beyond the Small Projects Portfolio above)									
DESI	N	Y	Y		✓		✓		C
Short Baseline Neutrino Portfolio	Y	Y	Y		✓				I

TABLE 1 Summary of Scenarios A, B, and C. Each major project considered by P5 is shown, grouped by project size and listed in time order based on year of peak construction. Project sizes are: Large (>$200M), Medium ($50M-$200M), and Small (<$50M). The science Drivers primarily addressed by each project are also indicated, along with the Frontier technique area (E=Energy, I=Intensity, C=Cosmic) defined in the 2008 P5 report.

2014 P5

Table 1
Summary of Scenarios

Project/Activity	Scenarios			Science Drivers					Technique (Frontier)
	low Scenario A	medium Scenario B	unlimited Scenario C	Higgs	Neutrinos	Dark Matter	Cosm. Accel.	The Unknown	
Large Projects									
Muon program: Mu2e, Muon g-2	Y, Mu2e small reprofile needed	Y	Y					✓	I
HL-LHC	Y	Y	Y	✓		✓		✓	E
LBNF + PIP-II	Y, LBNF components delayed relative to Scenario B.	Y	Y, enhanced		✓			✓	I,C
ILC	R&D only	R&D, possibly small hardware contri-butions. See text.	Y	✓		✓		✓	E
Medium Projects									
LSST	Y	Y	Y		✓		✓		C
DM G2	Y	Y	Y			✓			C
Small Projects Portfolio	Y	Y	Y		✓	✓	✓	✓	All
Accelerator R&D and Test Facilities	Y, reduced	Y, some reductions with redirection to PIP-II development	Y, enhanced	✓	✓	✓		✓	E,I
CMB-S4	Y	Y	Y		✓		✓		C
DM G3	Y, reduced	Y	Y			✓			C
Additional Small Projects (beyond the Small Projects Portfolio above)									
DESI	N	Y	Y		✓		✓		C
Short Baseline Neutrino Portfolio	Y	Y	Y		✓				I

TABLE 1 Summary of Scenarios A, B, and C. Each major project considered by P5 is shown, grouped by project size and listed in time order based on year of peak construction. Project sizes are: Large (>$200M), Medium ($50M-$200M), and Small (<$50M). The science Drivers primarily addressed by each project are also indicated, along with the Frontier technique area (E=Energy, I=Intensity, C=Cosmic) defined in the 2008 P5 report.

G3 Dark Matter experiments

Exploring the Quantum Universe

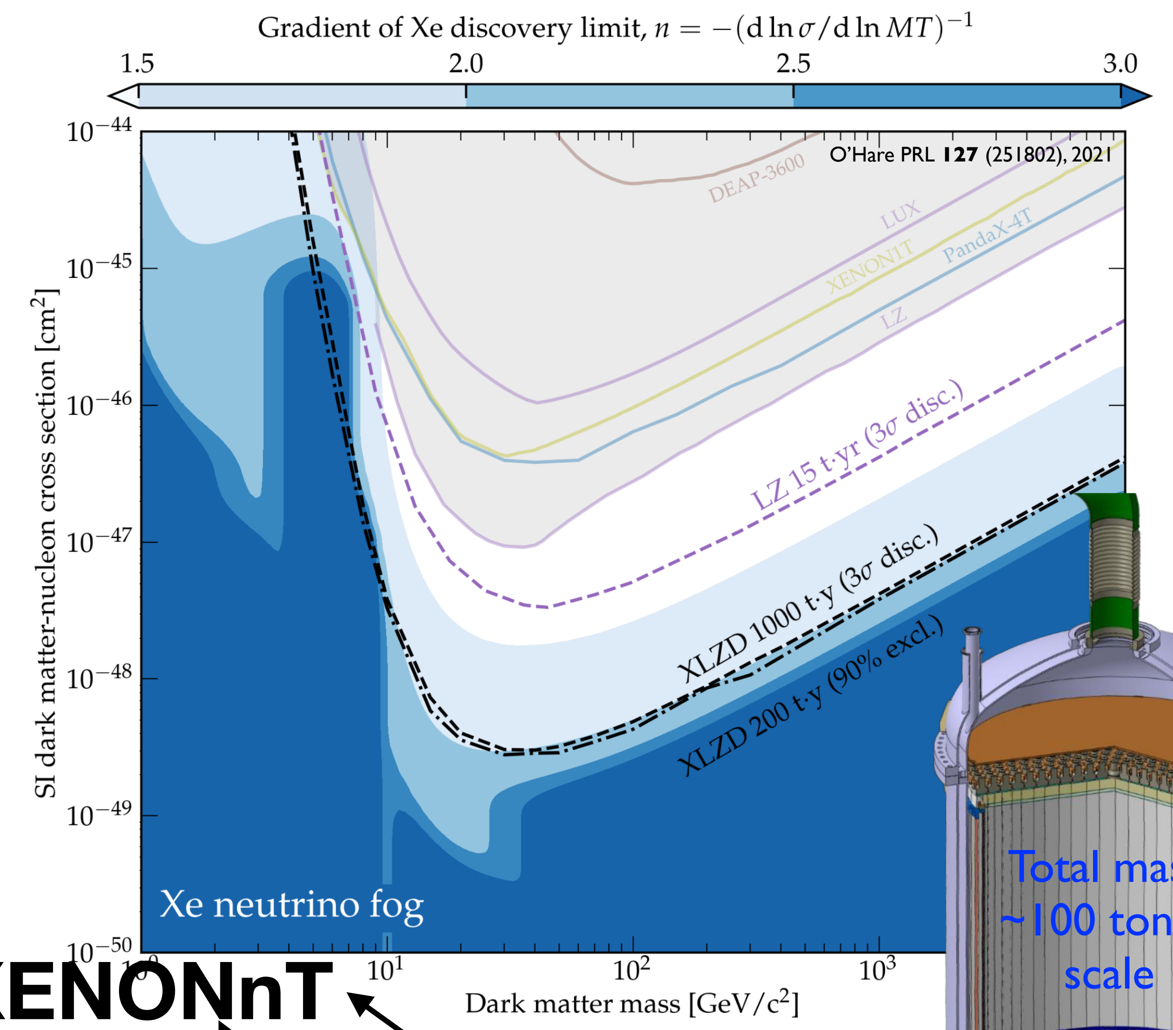
Dan Akerib, LBNL Town Hall, Feb 22, 2023

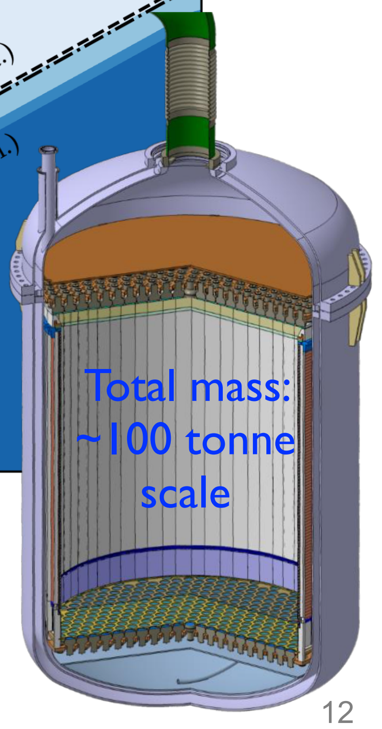
Cristiano Galbiati, SLAC Town Hall, May 3, 2023

XLZD: definitive search for high mass WIMPs

XLZD

- 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 3×10^{-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





LZ Darwin XENONnT

Lux XENON1t

Zeppelin XLZD

XMASS PandaX

Liquid Noble DM & G3 / XLZD / P5 2023 12

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

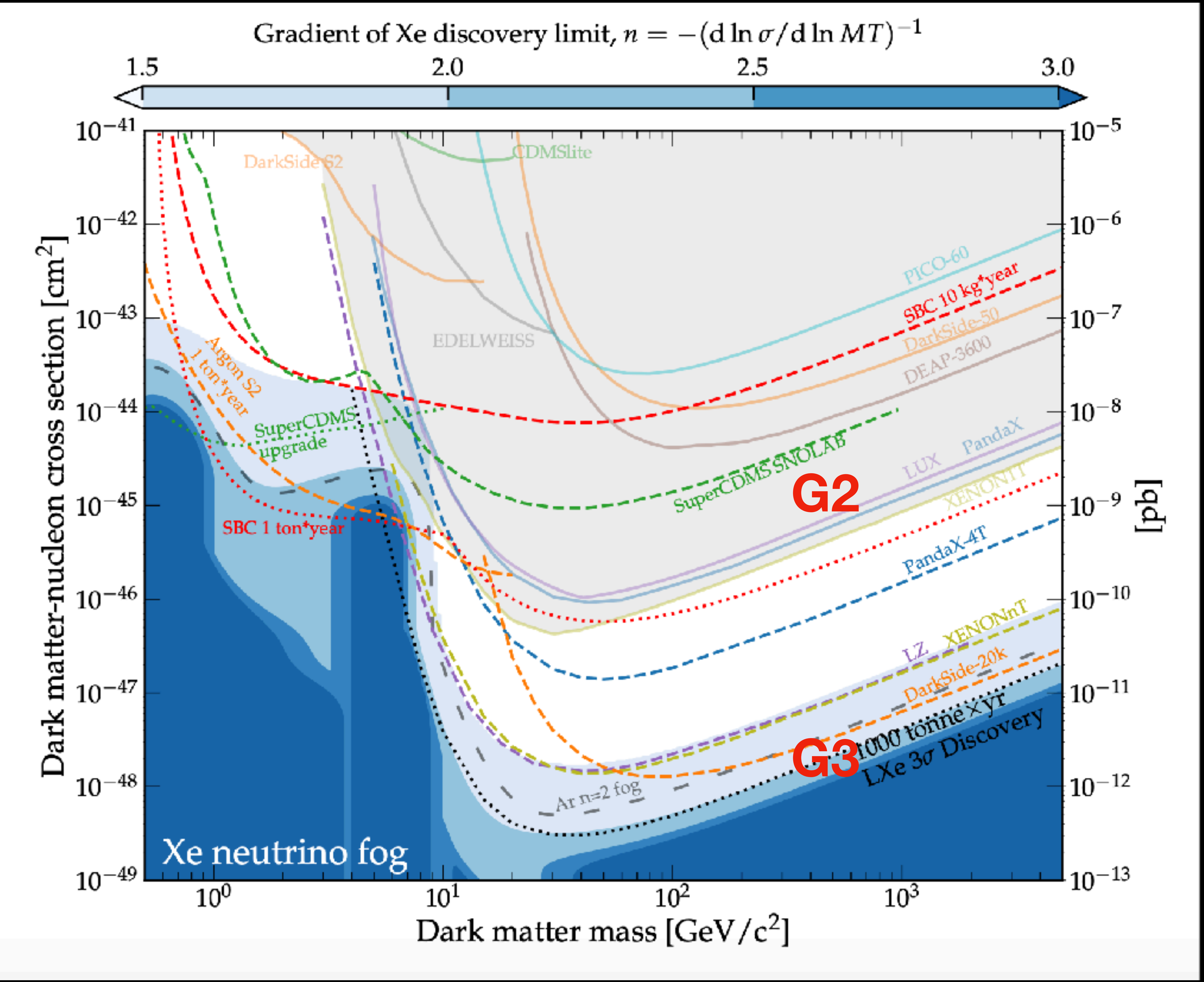
But if extra funds or NSF involvement:

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

From G2 → G3: Toward the ν fog

We can build on the most successful G2 designs with a G3 experiment to provide sensitivity to dark matter SM interactions small enough that neutrinos become an irreducible BG

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



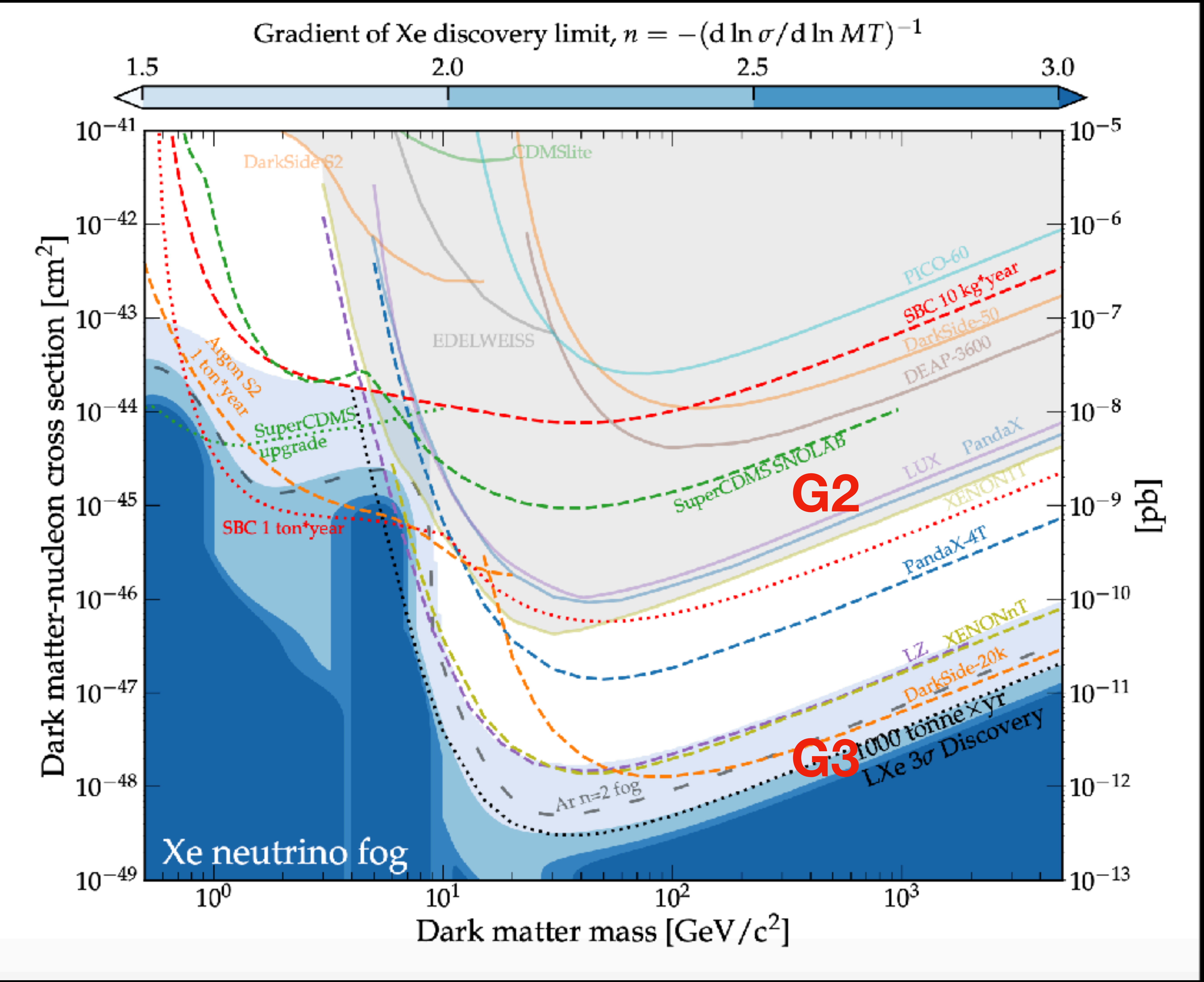
Snowmass2021 Cosmic Frontier
Dark Matter Direct Detection to the Neutrino Fog

From G2 → G3: Toward the ν fog

We can build on the most successful G2 designs with a G3 experiment to provide sensitivity to dark matter SM interactions small enough that neutrinos become an irreducible BG

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

Sanford Underground Research Facility
South Dakota Science and Technology Authority



Snowmass2021 Cosmic Frontier
Dark Matter Direct Detection to the Neutrino Fog

Exploring the Quantum Universe

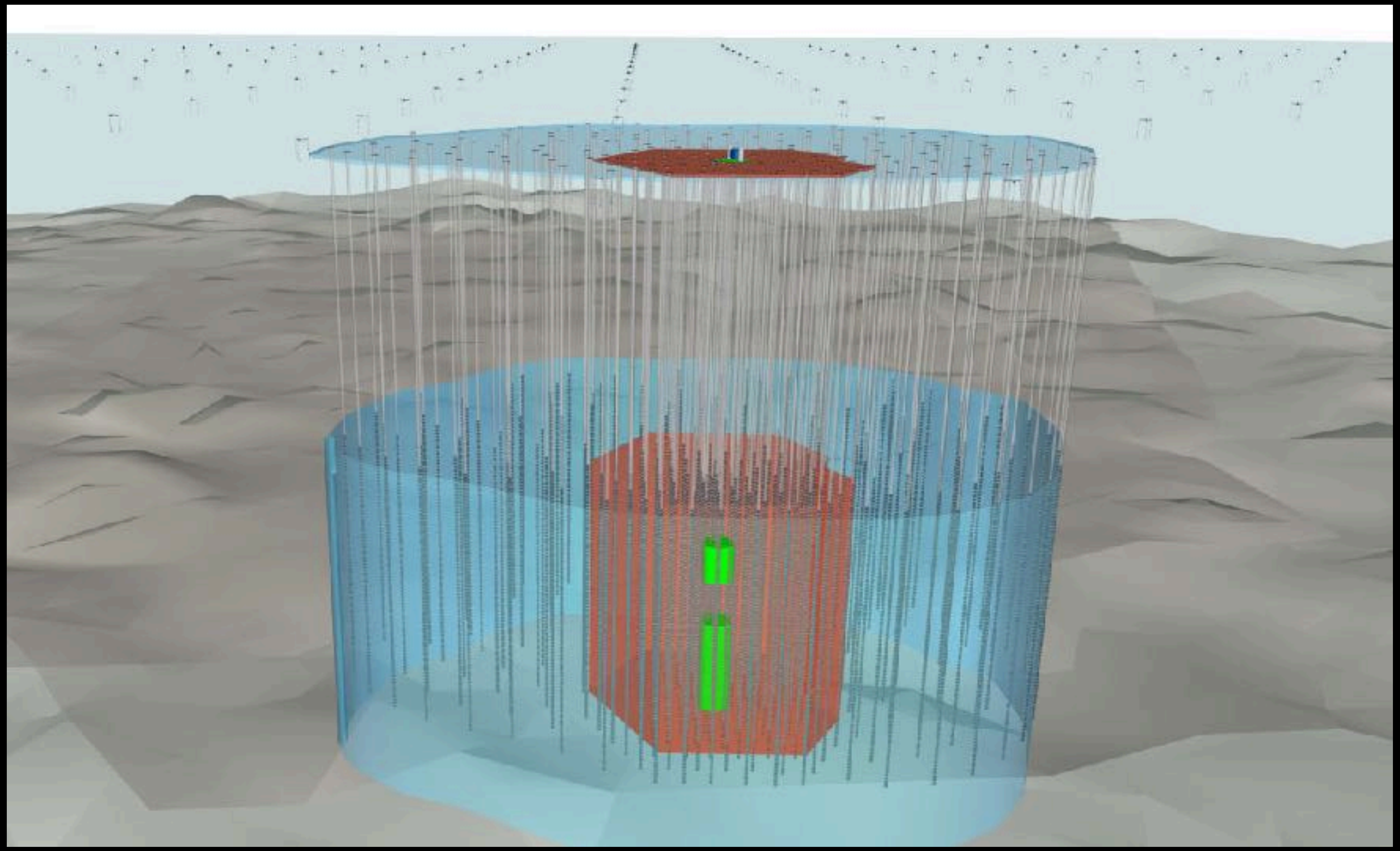
Recommendation 2

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.

NSF New Initiatives: IceCube-Gen2 & CTA

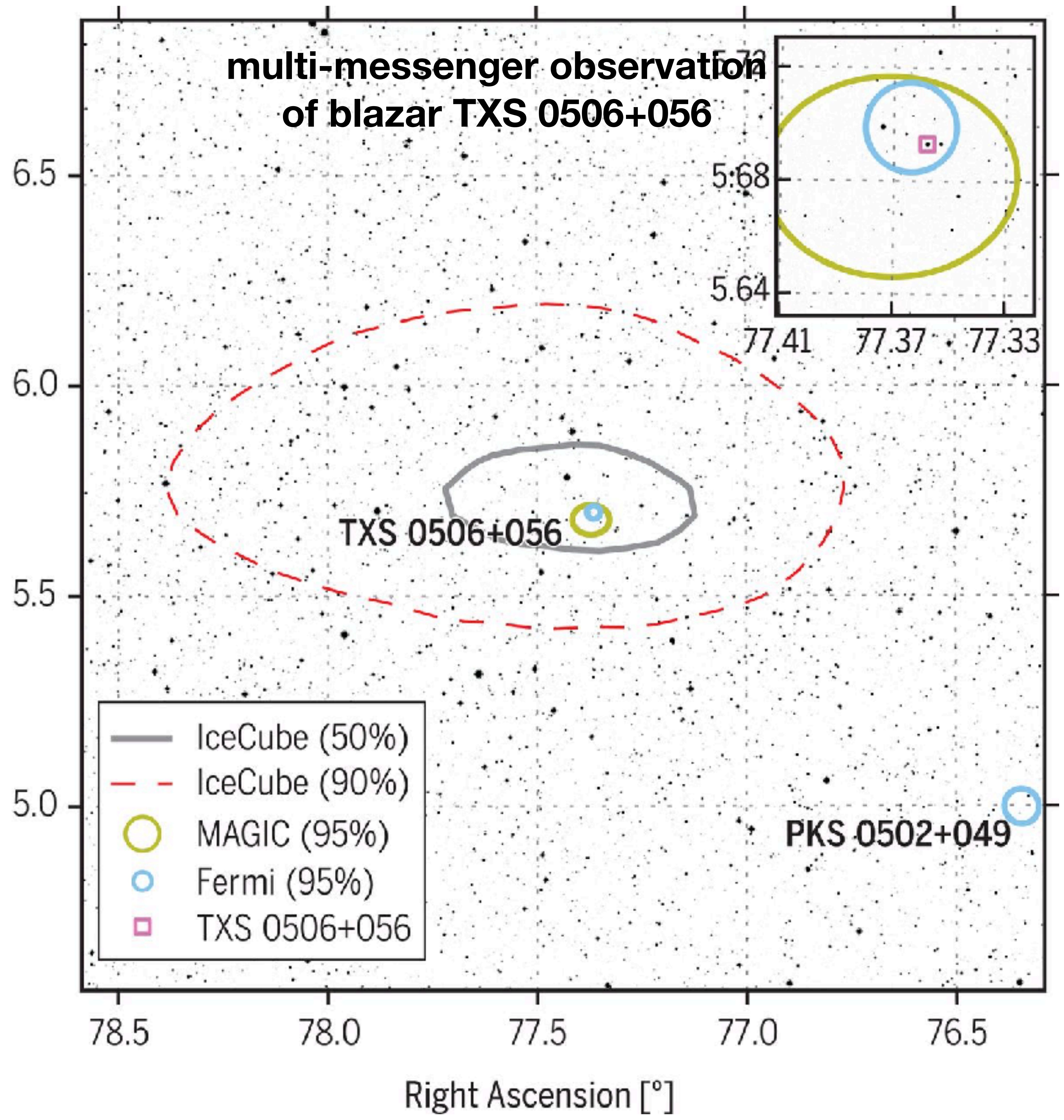
IceCube-Gen2: ten-fold improvement in sensitivity to astrophysical neutrinos over IceCube, most sensitive probe of heavy decaying dark matter.



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

IceCube



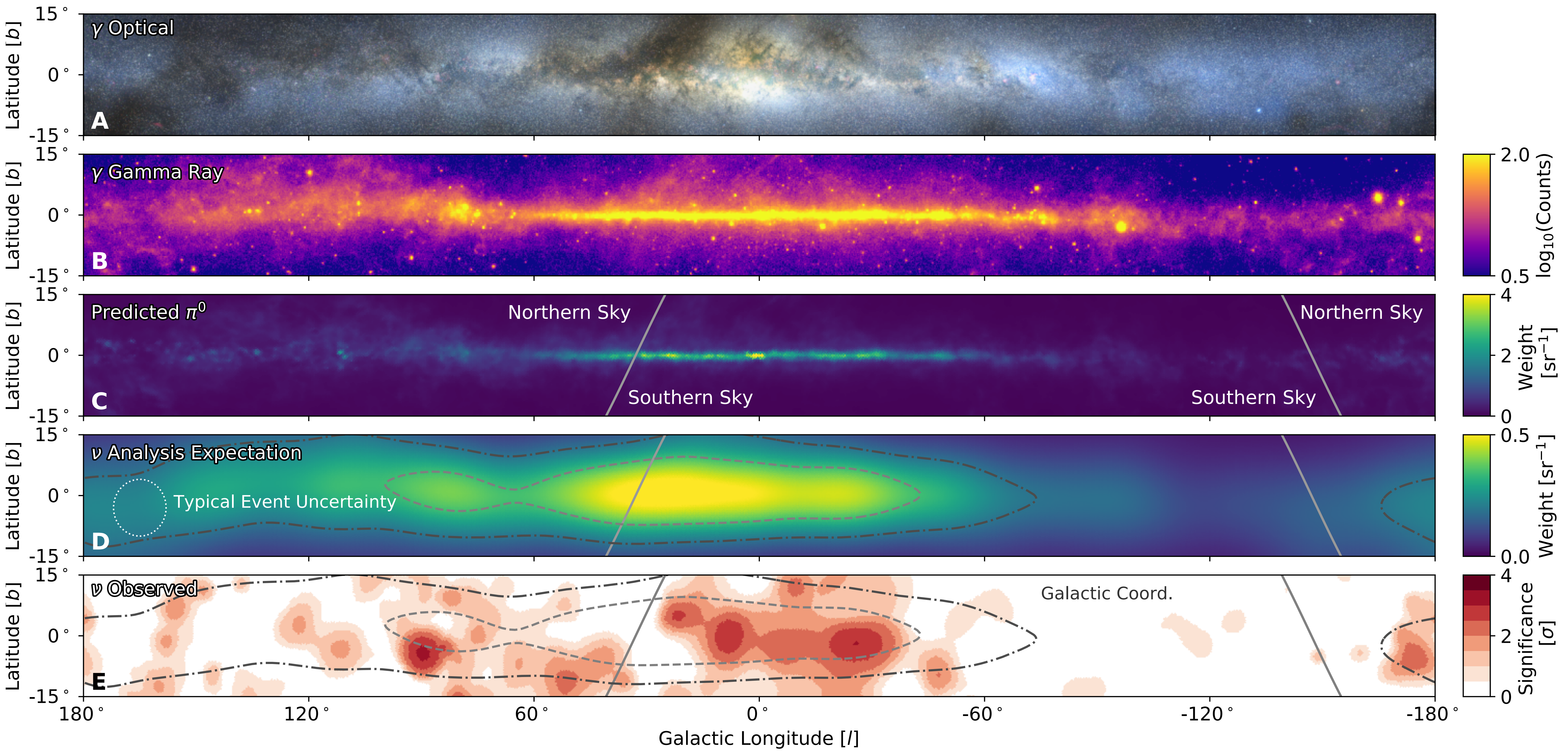


Figure 1: **The plane of the Milky Way galaxy in photons and neutrinos.** Each panel is in Galactic coordinates, with the origin being at the Galactic Center, extending ±15° in latitude and ±180° in longitude. (A) Optical color image (*39*), which is partly obscured by clouds of gas and dust that absorb 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.

Credit: Particle Data Group

Credit: Particle Data Group

Credit: Particle Data Group

Credit: Particle Data Group

Accelerators
LHC heavy ions
LHC protons
High-energy cosmic rays
Inflation
Big Bang
3min
Size
isible universe
is visible
380k yrs
TODAY
POSSIBLE DARK MATTER RELICS
NUCLEONS FORM
NUCLEI FORM
telescopes
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


Accelerators
RHIC & LHC heavy ions
LHC protons
High-energy cosmic rays
Inflation
Big Bang
$t = 10^{-36}$ s
$E = 10^{16}$ GeV
is visible
380k yrs
3min
isible universe
Size
TODAY
POSSIBLE DARK MATTER RELICS
NUCLEONS FORM
Neutrinos
telescopes
$t = 10^{-10}$ s
$E = 10^{2}$ GeV
$t = 10^{-4}$ s
$E = 10^{-1}$ GeV
$t = 10^{2}$ s
$E = 10^{-4}$ GeV
3×10^{5} y
H:He ~ 3:1 from Big Bang agrees with observation!
Credit: Particle Data Group


Accelerators
RHIC & LHC heavy ions
is visible
LHC protons
High-energy cosmic rays
Inflation
Big Bang
3min
380k yrs
Size
sible universe
TODAY
POSSIBLE DARK MATTER RELICS
dark matter
eutrinos
telescopes
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
3x10^5 y
H:He ~ 3:1 from Big Bang agrees with observation!
Credit: Particle Data Group


Accelerators
LHC protons
High-energy cosmic rays
RHIC & LHC heavy ions
is visible
3min
380k yrs
Size ... sible universe
TODAY
Inflation
Big Bang
POSSIBLE DARK MATTER RELICS
Higgs
natter
eutrinos
telescopes
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
3x10^5 y
H:He ~ 3:1 from Big Bang
agrees with observation!
Credit: Particle Data Group

Credit: Particle Data Group

Credit: Particle Data Group

Accelerators
RHIC & LHC heavy ions
LHC protons
High-energy cosmic rays
Background radiation is visible
380k yrs
3min
Size of visible universe
TODAY
Inflation
Big Bang
POSSIBLE DARK MATTER RELICS
NUCLEOSYNTHESIS
telescopes
$t = 10^{-36}$ 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
$t = 3\times10^{5}$ y
H:He ~ 3:1 from Big Bang agrees with observation!
Credit: Particle Data Group

Accelerators
RHIC & LHC heavy ions
LHC protons
High-energy cosmic rays
Inflation
Big Bang
3min
380k yrs
is visible
Size
isible universe
TODAY
POSSIBLE
TER RELICS
Inflation
rinos
atter
eutrinos
copes
$t = 10^{-36}$ 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
$t = 3 \times 10^{5}$ y
H:He ~ 3:1 from Big Bang agrees with observation!
Credit: Particle Data Group

H:He ~ 3:1 from Big Bang agrees with observation!

Credit: Particle Data Group


Accelerators
RHIC &
LHC
heavy
ions
LHC
protons
High-energy
cosmic rays
is visible
380k
yrs
3min
Size
isible universe
TODAY
Dark Energy
Galaxy Surveys
Inflation
Big
Bang
CMB-S4
Next Generation CMB Experiment
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
H:He ~ 3:1 from Big Bang
agrees with observation!
Credit: Particle Data Group

Exploring the Quantum Universe

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.

Recommendation 4

Investment in the future

Support a comprehensive effort to develop the resources—theoretical, computational, and technological—essential to our 20-year vision for the field. This includes an aggressive R&D program that, while technologically challenging, could yield revolutionary accelerator designs that chart a realistic path to a 10 TeV pCM collider.

Not Rank-Ordered

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.

Recommendation 5

Diversity, Inclusion, Equity, Relevance to society

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

Not Rank-Ordered

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.

Exploring the Quantum Universe

Not Rank-Ordered

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 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.

Exploring the Quantum Universe

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.

Recommendation

Decisions without waiting for the next P5

Convene a targeted panel with broad membership across pa decade that makes decisions on the US accelerator-based pr major decisions concerning an off-shore Higgs factory are exp adjustments within the accelerator-based R&D portfolio are likely the Fermilab accelerator complex consistent with the long-te 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.

6.5 Collider R&D

The decisions related to construction of an off-shore Higgs factory are anticipated to be made later this decade. The current designs of both FCC-ee and the ILC satisfy our scientific requirements. To secure a prominent role in a future Higgs factory project, the US should actively engage in feasibility and design studies (Recommendation 2c). Engagement with FCC-ee specifically should include design and modeling to advance the feasibility study, as well as R&D on superconducting radio frequency cavities designed for the ring and superconducting magnets designed for the interaction region. These efforts benefit from synergies in workforce development through participation in SuperKEKB and the Electron-Ion Collider.

Maintaining engagement with ILC accelerators through the ILC Technology Network can include design updates and cryomodule construction. These will support significant US contributions to potential projects. A global framework for future collider development, such as the ILC International Development Team as implemented by ICFA for the ILC, is relevant for all future colliders.

For Higgs factory detectors, a concerted effort of targeted R&D synchronized with the targeted accelerator R&D program is needed. The US should participate in international design efforts for specific collider detectors. To achieve the scientific goals, several common requirements apply to the detectors of the various collider options, including vertexing, tracking, timing, particle identification, calorimetry, muon detection, and triggering. Central coordination of these requirements is crucial. The US should engage in this coordination while taking leading roles in some of the design efforts.

Major international decisions on the route to a Higgs factory are anticipated later this decade. Supported by ICFA, the Japanese HEP community remains committed to hosting the ILC in Japan as a global project. The FCC-ee feasibility study is scheduled for completion by 2025, followed by an update by the European Strategy Group and a decision by the CERN Council. Once a specific project is deemed feasible and well-defined, the US should focus efforts towards that technology. A separate panel should determine the level and nature of US contribution while maintaining a healthy US on-shore program in particle physics (recommendation 6). In the scenario where a global consensus to move forward with the Higgs factory is not reached, the next P5 should reevaluate.

Exploring the Quantum Universe

Area Recommendations

Collider R&D

10. To enable targeted R&D before specific collider projects are established in the US, an investment in **collider detector R&D funding at the level of $20M per year** and **collider accelerator R&D at the level of $35M per year** in 2023 dollars is warranted.

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.**

Exploring the Quantum Universe

self-coupling precision

collider	Indirect-h	hh	combined
HL-LHC [78]	100-200%	50%	50%
ILC_{250}/C^3-250 [51, 52]	49%	–	49%
ILC_{500}/C^3-550 [51, 52]	38%	20%	20%
$CLIC_{380}$ [54]	50%	–	50%
$CLIC_{1500}$ [54]	49%	36%	29%
$CLIC_{3000}$ [54]	49%	9%	9%
FCC-ee [55]	33%	–	33%
FCC-ee (4 IPs) [55]	24%	–	24%
FCC-hh [79]	-	3.4-7.8%	3.4-7.8%
μ(3 TeV) [64]	-	15-30%	15-30%
μ(10 TeV) [64]	-	4%	4%

TABLE IX: Sensitivity at 68% probability on the Higgs cubic self-coupling at the various future colliders. Values for indirect extractions of the Higgs self-coupling from single Higgs determinations below the first line are taken from [2]. The values quoted here are combined with an independent determination of the self-coupling with uncertainty 50% from the HL-LHC.

2.5 International and Inter-Agency Partnerships

In the case of the Higgs factory, crucial decisions must be made in consultation with potential international partners. The FCC-ee feasibility study is expected to be completed by 2025 and will be followed by a European Strategy Group update and a CERN council decision on the 2028 timescale. The ILC design is technically ready and awaiting a formulation as a global project. **A dedicated panel should review the plan for a specific Higgs factory once it is deemed feasible and well-defined;** evaluate the schedule, budget and risks of US participation; and give recommendations to the US funding agencies later this decade (Recommendation 6). When a clear choice for a specific Higgs factory emerges, US efforts will focus on that project, and R&D related to other Higgs factory projects would ramp down.

Parallel to the R&D for a Higgs factory, **the US R&D effort should develop a 10 TeV pCM collider (design and technology)**, such as a muon collider, a proton collider, or possibly an electron-positron collider based on wakefield technology. The US should participate in the International Muon Collider Collaboration (IMCC) and take a leading role in defining a reference design. We note that there are many synergies between muon and proton colliders, especially in the area of development of high-field magnets. R&D efforts in the next 5-year timescale will define the scope of test facilities for later in the decade, paving the way for initiating **demonstrator facilities within a 10-year timescale** (Recommendation 6).

Rank-Ordered

Less Favorable Budget Scenario

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.

Exploring the Quantum Universe

Less Favorable Budget Scenario

The rationale for this prioritization is given in section 8.3. Recommendations 3 and 4 are crucial for maintaining the health and balance of the field. While these recommendations still apply, they receive reduced support in scenarios between the baseline and less favorable conditions. Reductions to all items in these two recommendations should be proportionate. Research must be supported at least at the current level. Recommendation 5 is deemed a high priority and is supported in all scenarios. Recommendation 6 applies in all scenarios.

This less favorable scenario will lead to **a loss of US leadership** in many areas, especially the science of the G3 dark matter experiment, and will damage our reputation as a reliable international host for DUNE and as a partner for a Higgs factory. We still make investments in the future, but at a significantly reduced level for small-scale experiments, including ASTAE, theory, computing, instrumentation, and collider R&D. In this scenario, it would be increasingly difficult to maintain US competitiveness as an international partner in accelerator technology. See section 8.3 for more details.

More Favorable Budget Scenario

Not Rank-Ordered

In a budget outlook more favorable than the baseline budget scenario, we urge the funding agencies to support additional scientific opportunities. Even a small increase in the overall budget enables a large return on the investment, serving as a catalyst to accelerate scientific discovery and to unlock new pathways of inquiry. The opportunities include R&D, small projects, and the construction of advanced detectors for flagship projects in the US. They are listed below in four categories from small to large in budget size:

a. R&D

i. Increase investment in **detector R&D** targeted toward future collider concepts for a Higgs factory and 10 TeV pCM collider in order to accelerate US leadership in this area.

ii. Pursue an expanded DOE **AS&T** initiative to develop foundational technologies for particle physics that can benefit applications across science, medicine, security, and industry,

iii. Pursue **broad accelerator science and technology development** at both DOE and NSF, including partnerships modeled on the plasma science partnership.

b. Small Projects

Expand the portfolio of agile experiments to pursue new science, enable discovery across the portfolio of particle physics, and provide significant training and leadership opportunities for early career scientists.

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	U.S. Initiative for the Targeted Development of Future Colliders and their Detectors	
		Higgs Factory
Neutrino Frontier	LBNF/DUNE Phase I & PIP- II	DUNE Phase II (incl. proton injector)
Cosmic Frontier	Cosmic Microwave Background - S4 Spectroscopic Survey - S5*	Next Gen. Grav. Wave Observatory* Line Intensity Mapping*
	Multi-Scale Dark Matter Program (incl. Gen-3 WIMP searches)	
Rare Process Frontier		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**

Decadal Overview of Future Large-Scale Projects		
Frontier/Decade	2025 - 2035	2035 -2045
Energy Frontier	U.S. Initiative for the Targeted Development of Future Colliders and their Detectors	
		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

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**

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

Decadal Overview of Future Large-Scale Projects		
Frontier/Decade	2025 - 2035	2035 -2045
Energy Frontier	✓ U.S. Initiative for the Targeted Development of Future Colliders and their Detectors	
		✓ 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

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**

Decadal Overview of Future Large-Scale Projects		
Frontier/Decade	2025 - 2035	2035 -2045
Energy Frontier	✓ U.S. Initiative for the Targeted Development of Future Colliders and their Detectors	
		✓ 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

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**

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

Decadal Overview of Future Large-Scale Projects		
Frontier/Decade	2025 - 2035	2035 -2045
Energy Frontier	✓ U.S. Initiative for the Targeted Development of Future Colliders and their Detectors	
		✓ 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

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**

Decadal Overview of Future Large-Scale Projects		
Frontier/Decade	2025 - 2035	2035 -2045
Energy Frontier	✓ U.S. Initiative for the Targeted Development of Future Colliders and their Detectors	
		✓ 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

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**

Decadal Overview of Future Large-Scale Projects		
Frontier/Decade	2025 - 2035	2035 -2045
Energy Frontier	✓ U.S. Initiative for the Targeted Development of Future Colliders and their Detectors	
		✓ 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

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**

Decadal Overview of Future Large-Scale Projects		
Frontier/Decade	2025 - 2035	2035 -2045
Energy Frontier	✓ U.S. Initiative for the Targeted Development of Future Colliders and their Detectors	
		✓ 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

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**

Decadal Overview of Future Large-Scale Projects		
Frontier/Decade	2025 - 2035	2035 -2045
Energy Frontier	✓ U.S. Initiative for the Targeted Development of Future Colliders and their Detectors	
		✓ 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

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**

Decadal Overview of Future Large-Scale Projects		
Frontier/Decade	2025 - 2035	2035 -2045
Energy Frontier	✓ U.S. Initiative for the Targeted Development of Future Colliders and their Detectors	
		✓ 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

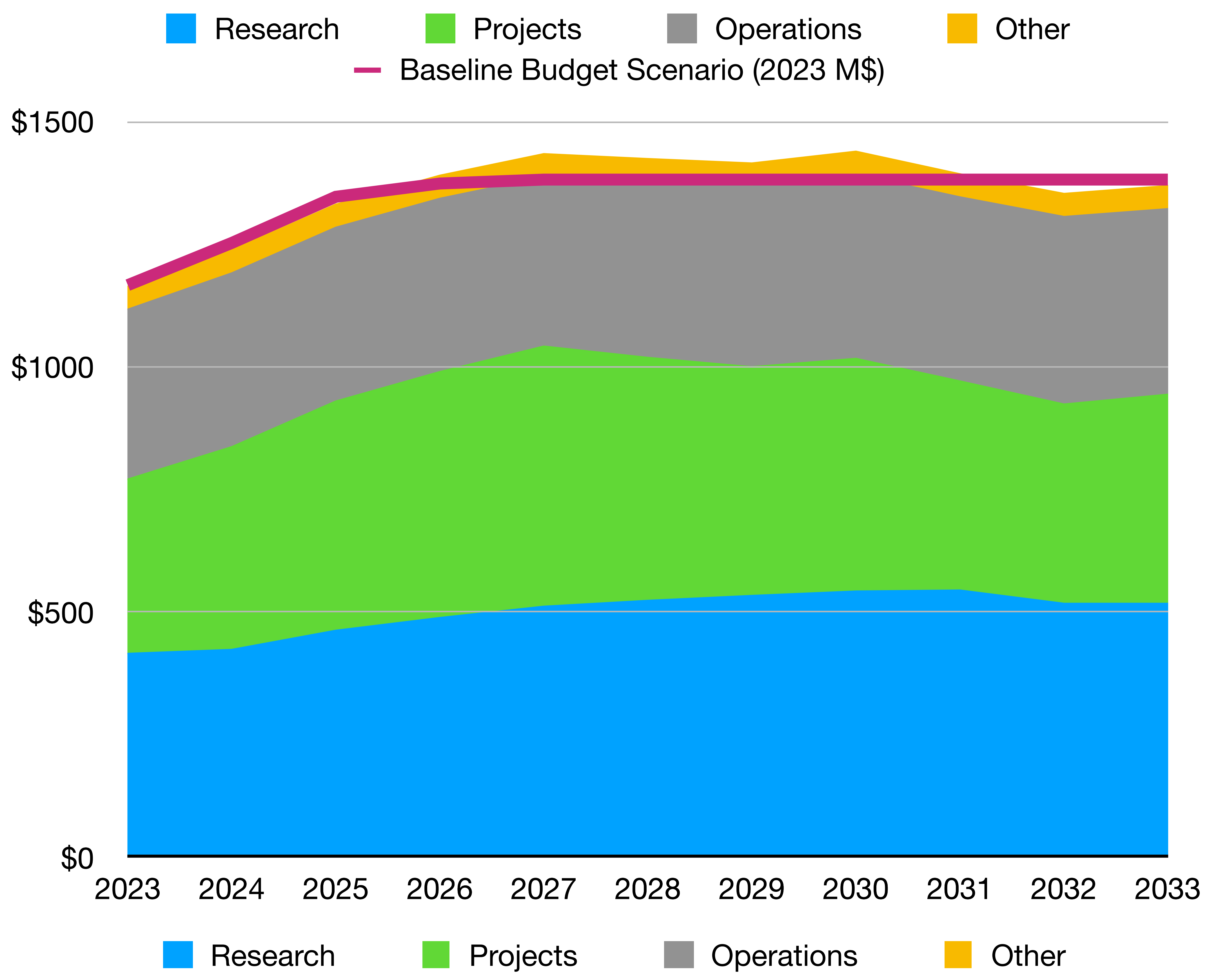
Table 1-1. *An overview, binned by decade, of future large-scale projects or programs (total projected costs of $500M or larger) endorsed by one or more of the Snowmass Frontiers to address the essential scientific goals of the next two decades. This table is not a timeline, rather large projects are 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.*

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

✓ **Recommended**

✓ **R&D**

Not in the Report



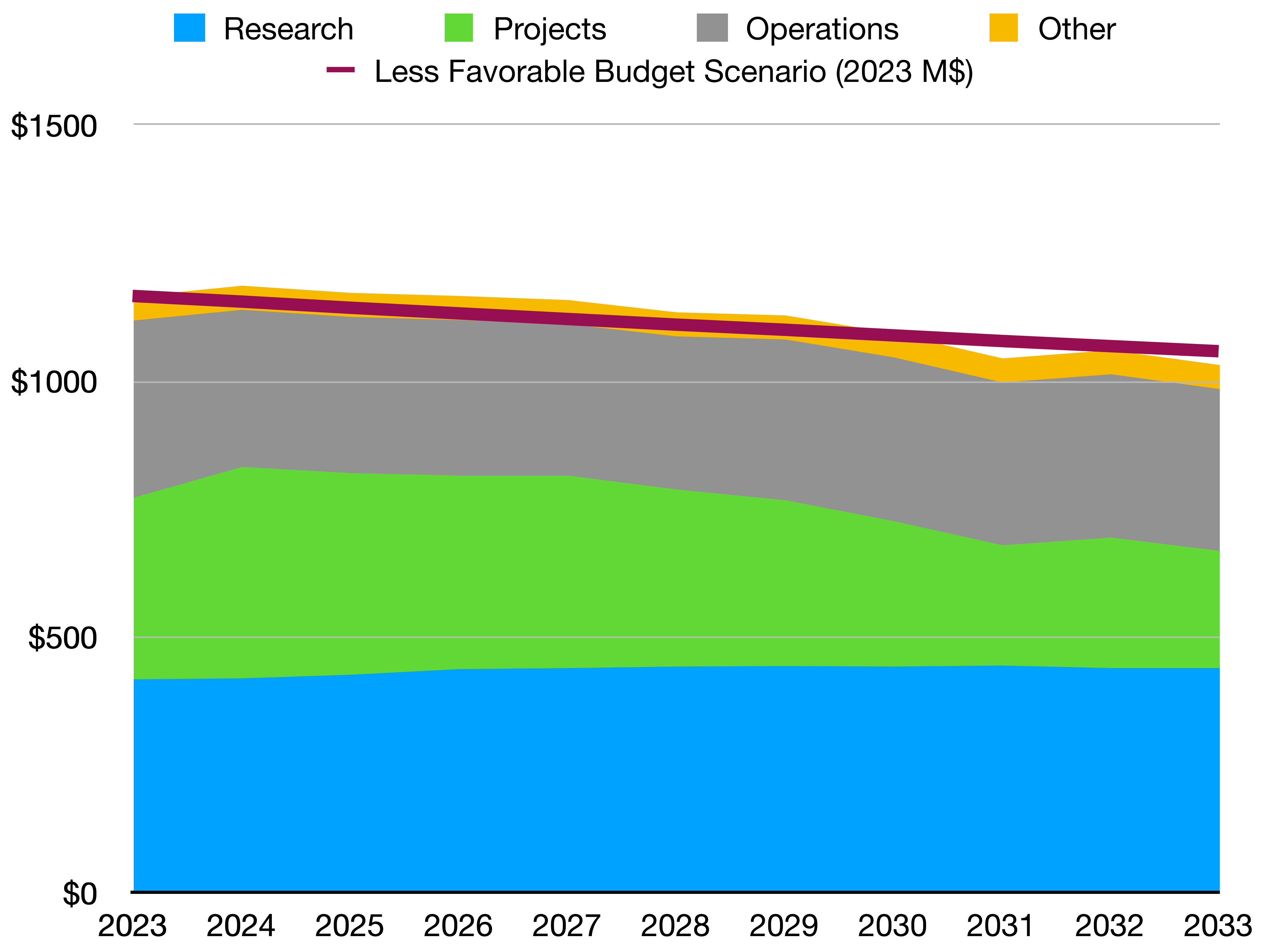


Fig. 2 Evolution of DOE budgets in Research, Projects, Operations, and Other in our budget exercise for the two budget scenarios given in the charge in 2023 dollars assuming 3% annual inflation.

Not in the Report

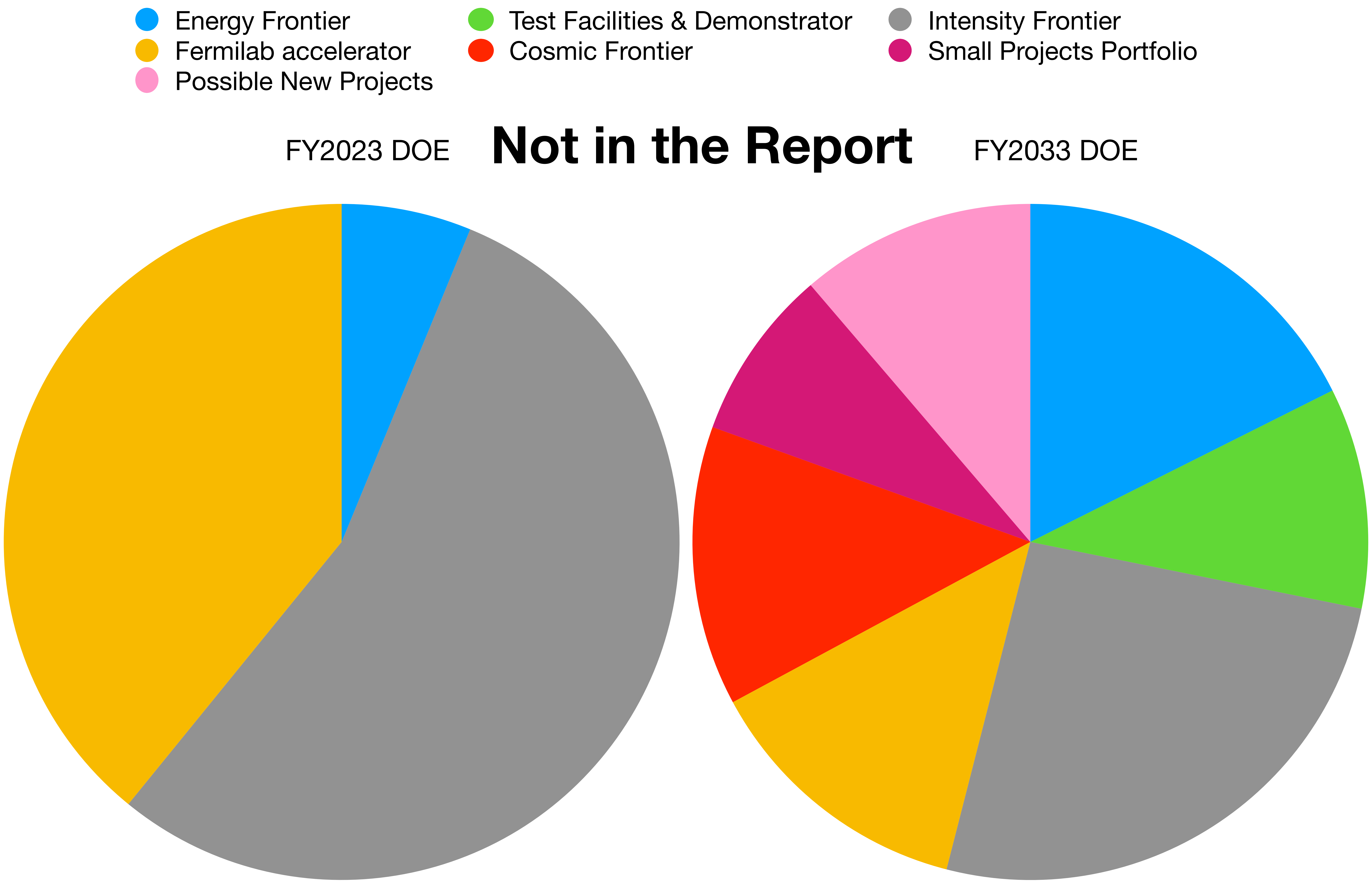


Fig. 3 Composition of DOE Projects in FY2023 (enacted) and FY2033 (recommended) in in our budget exercise. Demonstrator and Small Projects Portfolio are regarded as Projects for this pie chart.

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.

Share full article | 96

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

A major report plotting the future of U.S. particle physics calls for cuts to the beleaguered DUNE project, advocates a "muon shot" for a next-generation collider and recommends a new survey of the universe's oldest observable light

BY DANIEL GARISTO

Scientific American

A view from the subterranean excavation for the Deep Underground Neutrino Experiment (DUNE) at the Sanford Underground Research Facility in South Dakota. Credit: Sanford Underground Research Facility

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.

Share full article 96

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:

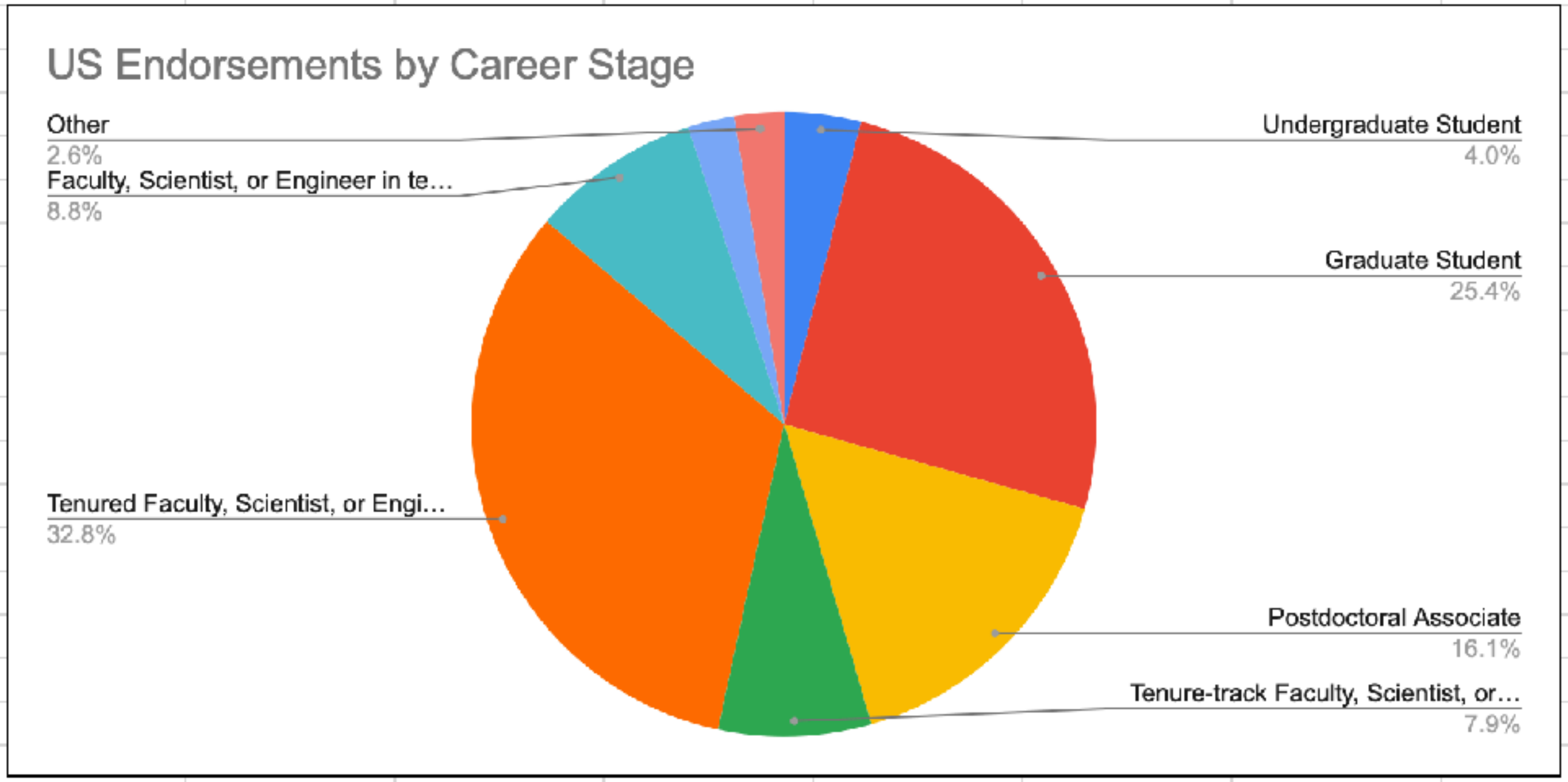
12:22 AM · Dec 14, 2023 · **5,343** Views

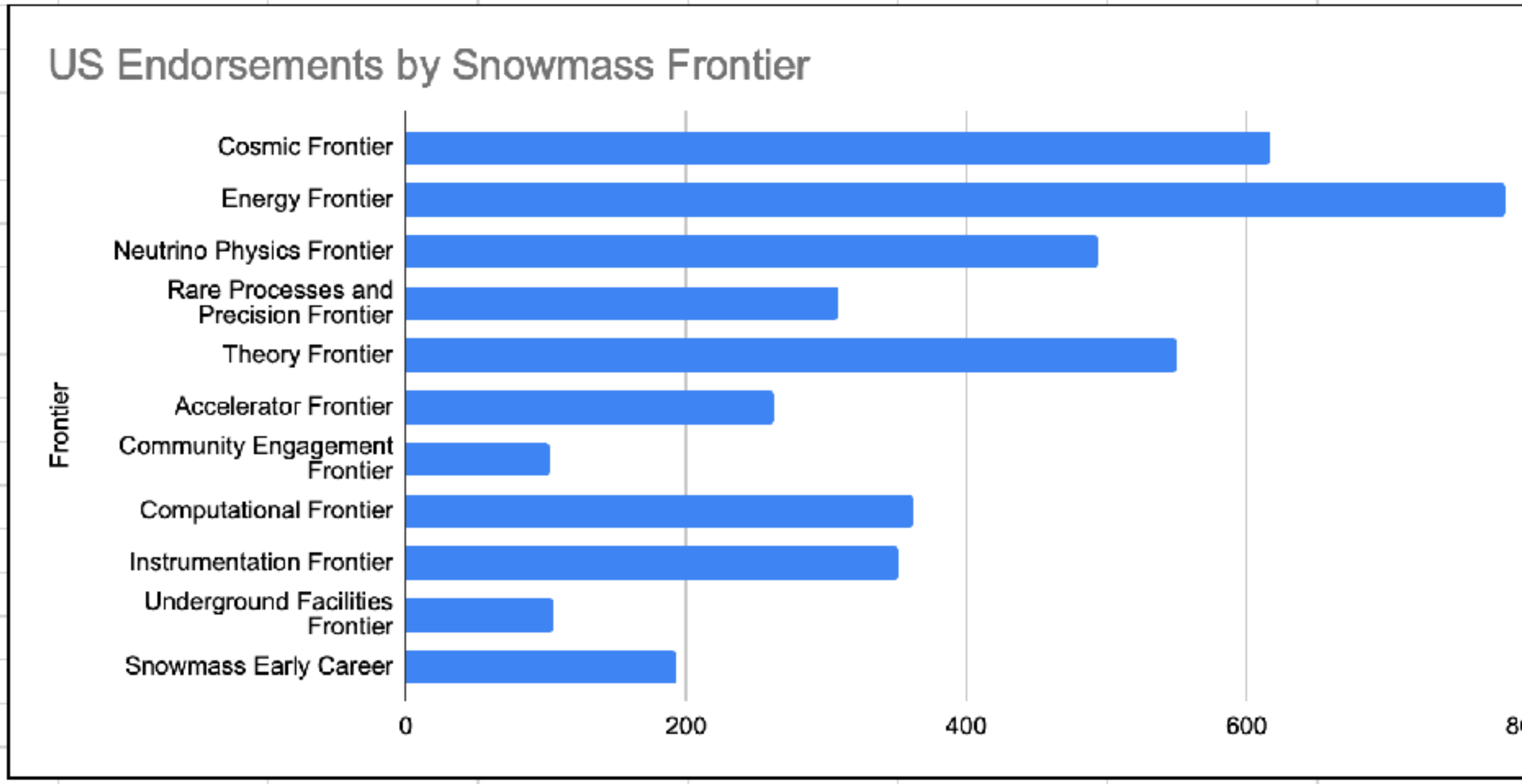
1 14 27 4

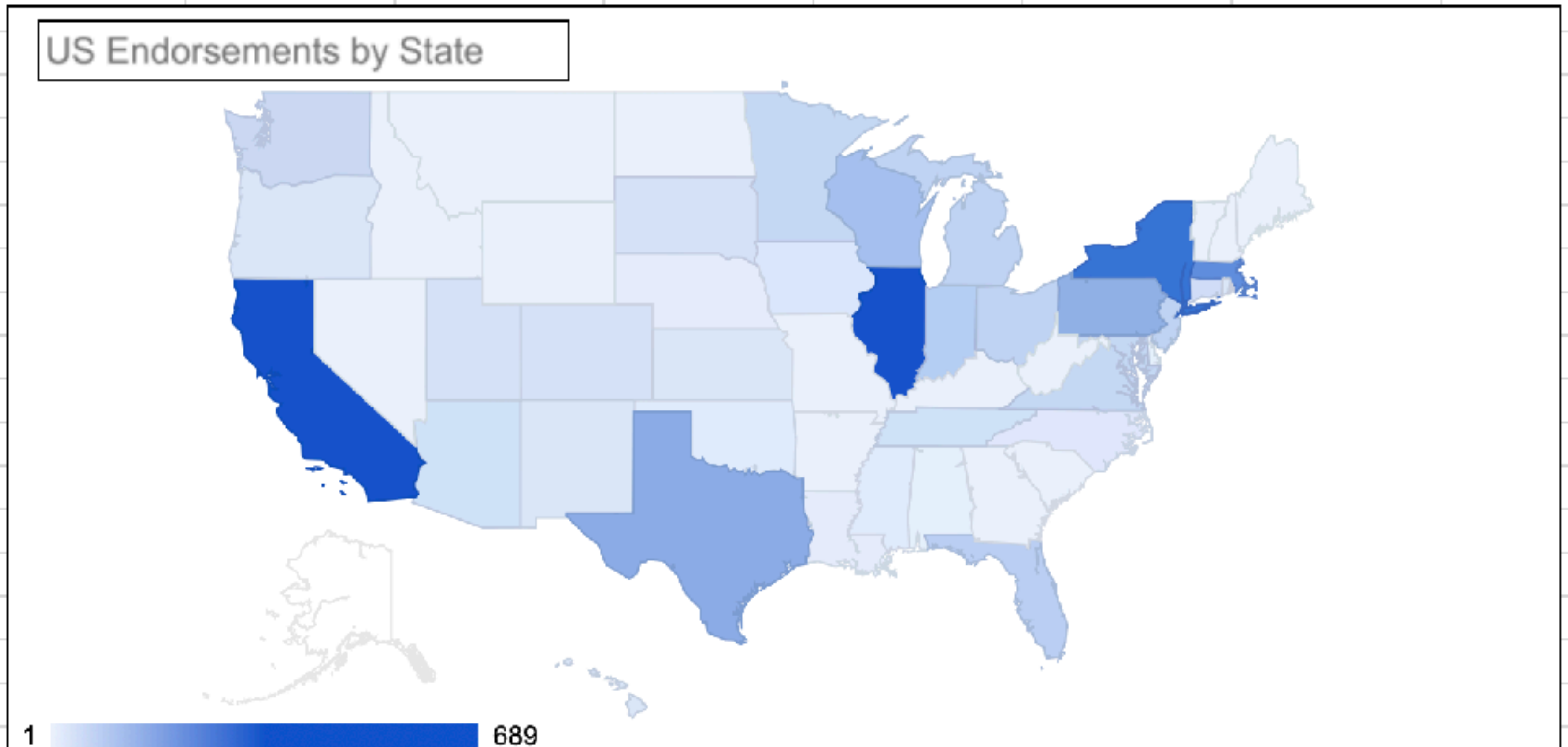
Town Hall at Fermilab, Dec 11, 2023
1397 registrants

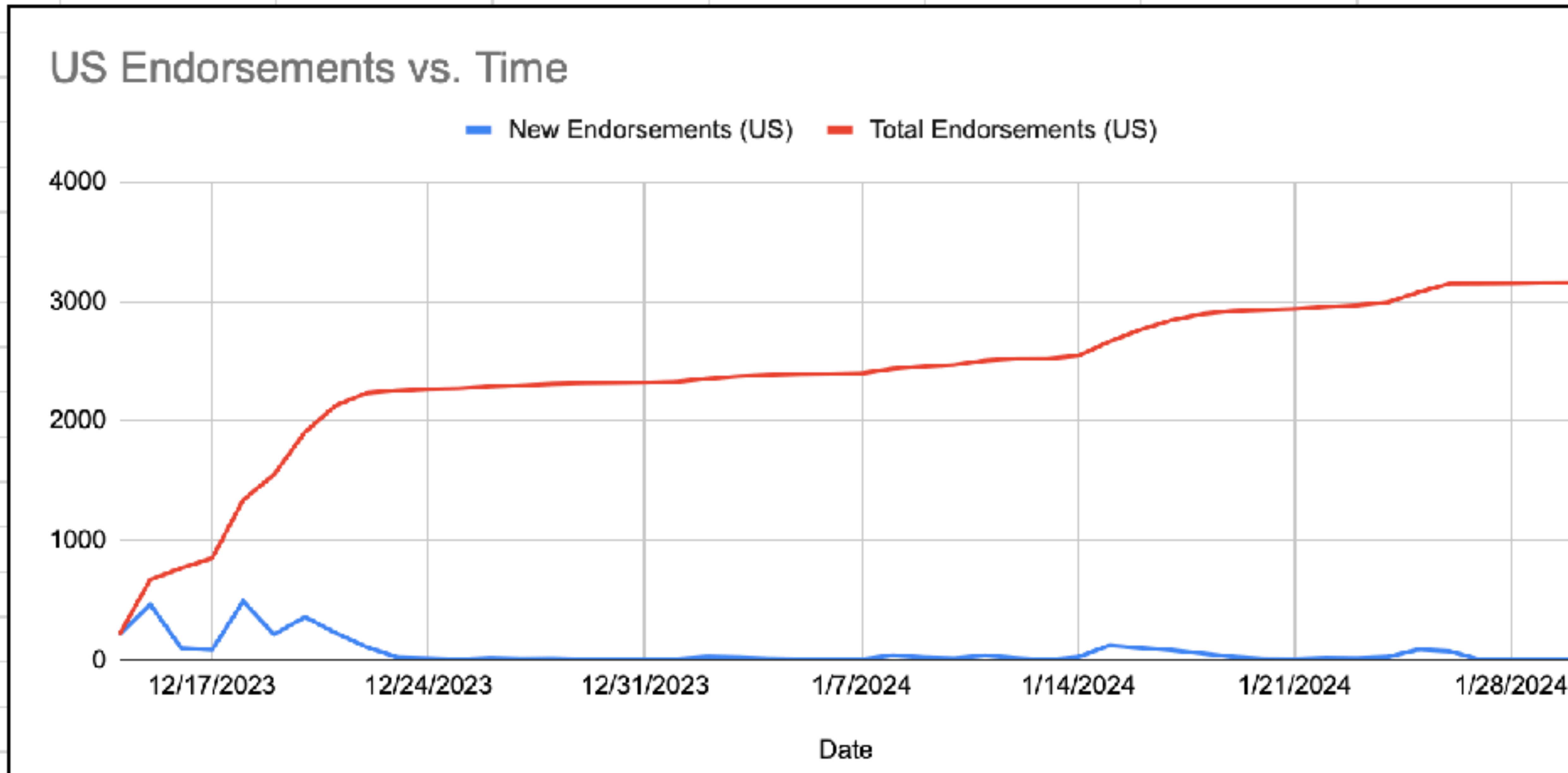
Support the 2023 P5 Report : Statistics

Number of Endorsements (Total)	Number of Endorsements (US)
3523	3157









The P5 also endorsed smaller-scale projects. But its strongest recommendation is for uninterrupted US funding of experiments that are either ongoing or under construction. These include the first major upgrade of the Large Hadron Collider (LHC), which will keep the collider — at CERN, Europe's high-energy physics lab near Geneva, Switzerland — going throughout the 2030s.

The P5's priorities were selected from proposals presented by the broader research community at the Snowmass conference last year in Seattle, Washington. These were balanced against realistic funding levels, says Hitoshi Murayama, a physicist at the University of California, Berkeley, who chaired the P5 committee.

Before any large new projects can begin, they must be approved by the DoE or the NSF, and then must win funding from Congress and, in some cases, other governments. But historically, the consensus-forming nature of the P5 process has added credibility to the community's requests, and has helped most of the projects prioritized by previous panels to come to fruition.

Nature explores the P5 report's five leading proposals, ranked in order of importance, as well the panel's discussion of future accelerators.

REIDAR HAHN/FERMILAB

An underground test blast area for the DUNE neutrino experiment in Lead, South Dakota.

Ripples from the Big Bang

The goal of CMB-S4 is to study radiation that was created around 380,000 years after the Big Bang, when the nearly uniform broth of particles in the Universe transitioned from plasma to gas. Microwave antennas will measure the polarization of the cosmic microwave background (CMB) — the angle at which most of the radiation's electric fields wiggle as they reach Earth — across a large portion of the sky. Physicists hope that the resulting polarization map will reveal a signature pattern created by gravitational waves that have been shaking the fabric of space-time since the first instant after the Big Bang. The CMB is the oldest electromagnetic radiation that can be detected, but its polarization could provide a window on much earlier times.

Multiple observatories have attempted to find signs of primordial gravitational waves in the CMB polarization, including the European space telescope Planck and the BICEP2 telescope at the South Pole. In the Atacama Desert, astronomers are building an array of dishes called the Simons Observatory, due to be completed in mid-2024. Researchers envisage CMB-S4 as a scaled-up version of the Simons Observatory that would begin observations in the mid-2030s.

Double DUNE

The Deep Underground Neutrino Experiment (DUNE) is already under construction and is expected to be completed in the early 2030s. But the P5 is already pushing for it to be expanded.

DUNE will involve two sites: the DoE's Fermi National Accelerator Laboratory (Fermilab) outside Chicago, Illinois, and the Sanford Underground Research Facility in Lead, South Dakota. An accelerator at Fermilab will create a beam of neutrinos and shoot it in a straight line through Earth's crust, from which it will re-emerge nearly 1,300 kilometres away.

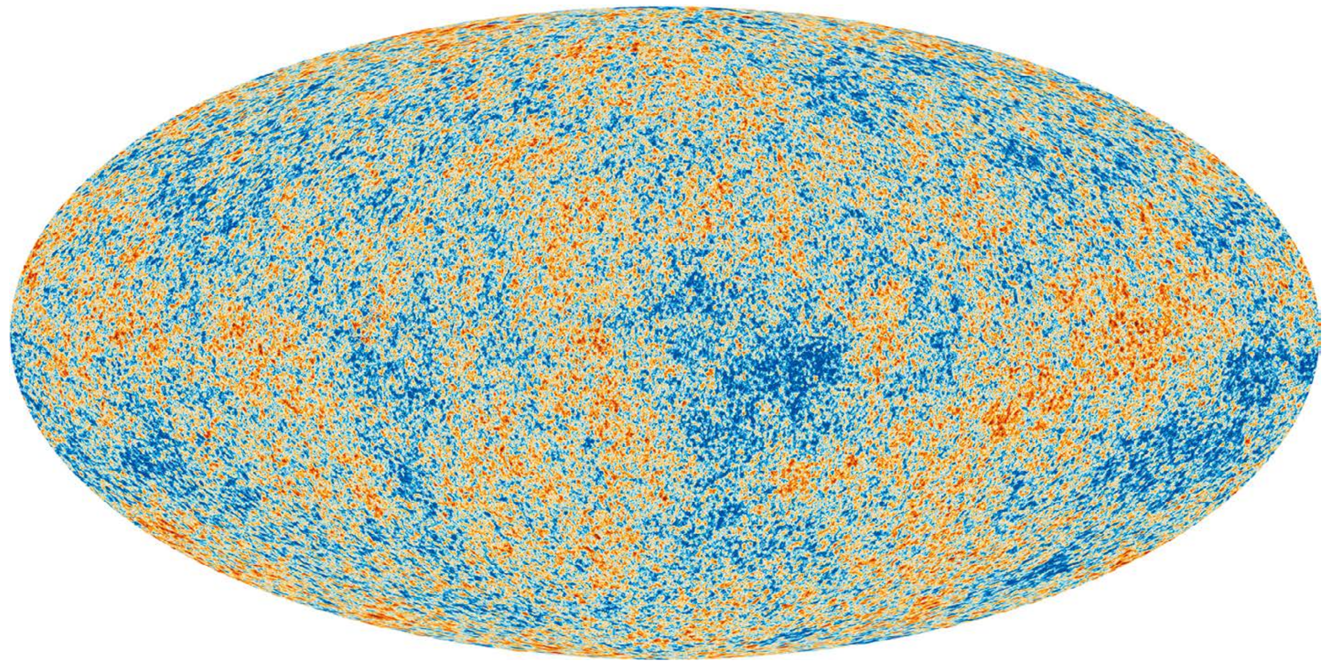
The previous P5 prioritization exercise, which took place in 2014, put DUNE — then estimated to cost US$1.9 billion — at the top of its priorities for new projects to fund. Construction has since been subject to major delays and cost overruns, which has prompted the DoE to nearly halve the size of the South Dakota detector. Even in this scaled-down version, the cost is expected to exceed $3 billion.

But the science case for DUNE remains extremely compelling, many physicists think. The P5 is now advocating a second phase that will push the detector to its original intended size, and include upgrades at Fermilab that will make its neutrino beam ten times more intense.

A factory for Higgs bosons

The LHC announced the discovery of the Higgs boson — which is thought to give other particles their mass — in 2012. It was the last particle to be found among those predicted by the standard model of particle physics. But in many respects, the Higgs remains mysterious.

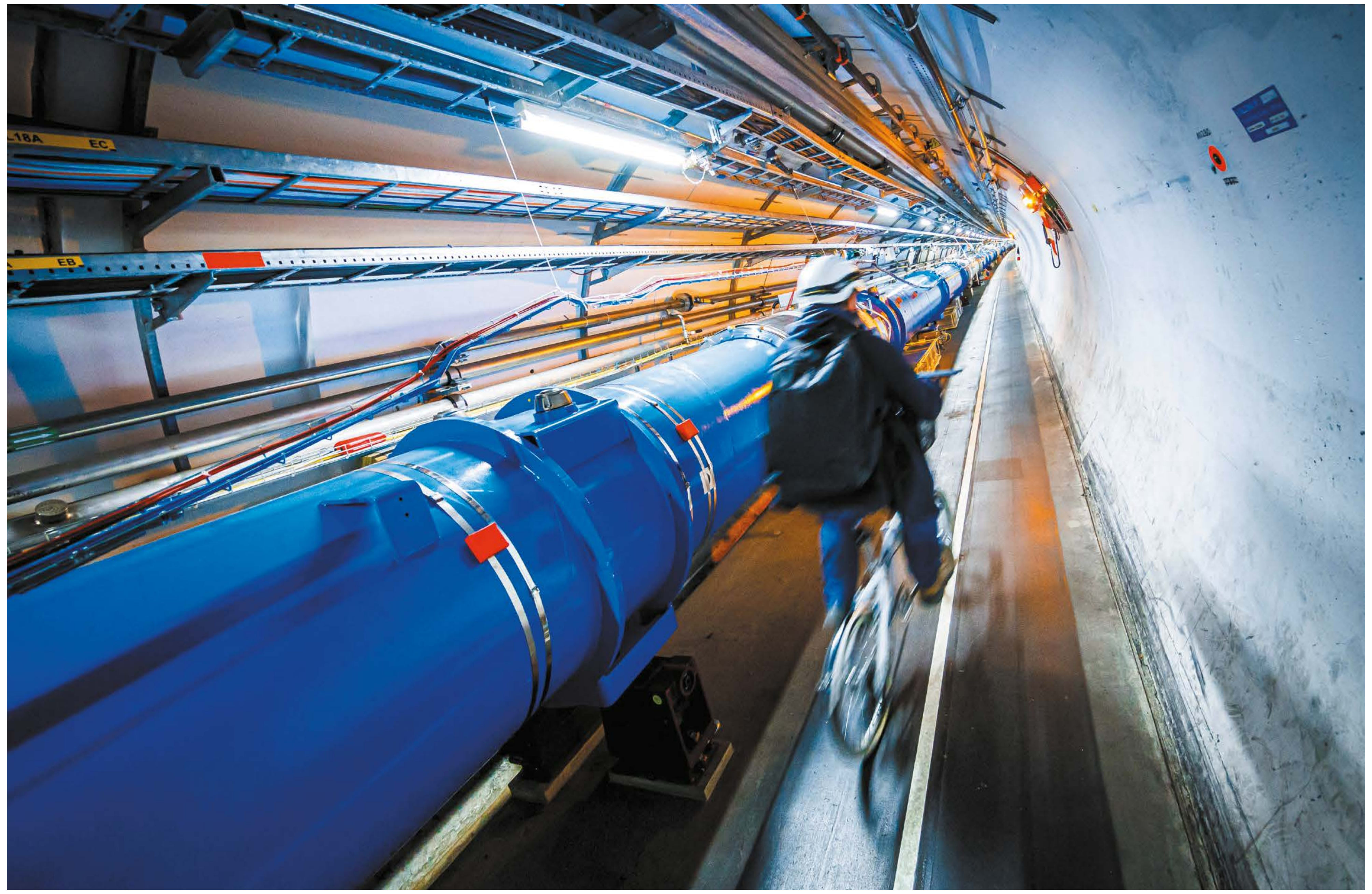
Physicists have proposed several designs for accelerators that would produce vast numbers of Higgs bosons and enable precise measurements of their interactions with other



ESA AND THE PLANCK COLLABORATION

Probing the cosmic microwave background reveals details of the instants after the Big Bang.

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.

The P5 also endorsed smaller-scale projects. But its strongest recommendation is for uninterrupted US funding of experiments that are either ongoing or under construction. These include the first major upgrade of the Large Hadron Collider (LHC), which will keep the collider — at CERN, Europe's high-energy physics lab near Geneva, Switzerland — going throughout the 2030s.

The P5's priorities were selected from proposals presented by the broader research community at the Snowmass conference last year in Seattle, Washington. These were balanced against realistic funding levels, says Hitoshi Murayama, a physicist at the University of California, Berkeley, who chaired the P5 committee.

Before any large new projects can begin, they must be approved by the DoE or the NSF, and then must win funding from Congress and, in some cases, other governments. But historically, the consensus-forming nature of the P5 process has added credibility to the community's requests, and has helped most of the projects prioritized by previous panels to come to fruition.

Nature explores the P5 report's five leading proposals, ranked in order of importance, as well the panel's discussion of future accelerators.

REIDAR HAHN/FERMILAB

An underground test blast area for the DUNE neutrino experiment in Lead, South Dakota.

Ripples from the Big Bang

The goal of CMB-S4 is to study radiation that was created around 380,000 years after the Big Bang, when the nearly uniform broth of particles in the Universe transitioned from plasma to gas. Microwave antennas will measure the polarization of the cosmic microwave background (CMB) — the angle at which most of the radiation's electric fields wiggle as they reach Earth — across a large portion of the sky. Physicists hope that the resulting polarization map will reveal a signature pattern created by gravitational waves that have been shaking the fabric of space-time since the first instant after the Big Bang. The CMB is the oldest electromagnetic radiation that can be detected, but its polarization could provide a window on much earlier times.

Multiple observatories have attempted to find signs of primordial gravitational waves in the CMB polarization, including the European space telescope Planck and the BICEP2 telescope at the South Pole. In the Atacama Desert, astronomers are building an array of dishes called the Simons Observatory, due to be completed in mid-2024. Researchers envisage CMB-S4 as a scaled-up version of the Simons Observatory that would begin observations in the mid-2030s.

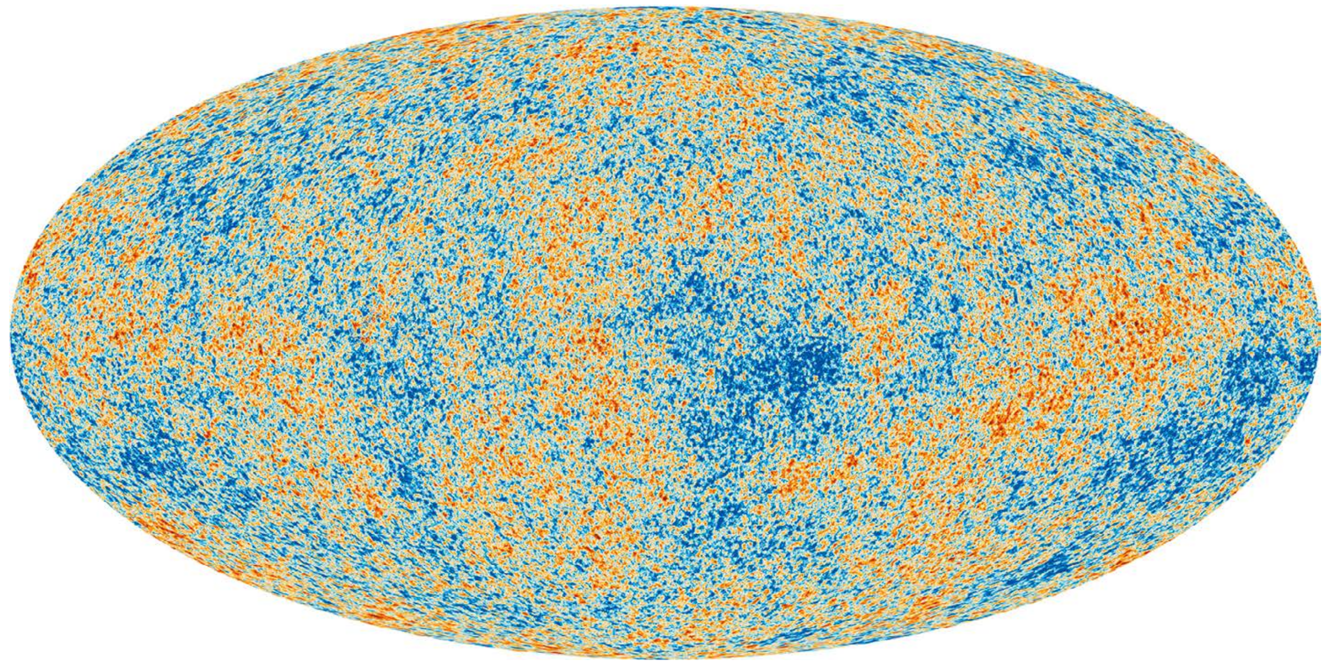
Double DUNE

The Deep Underground Neutrino Experiment (DUNE) is already under construction and is expected to be completed in the early 2030s. But the P5 is already pushing for it to be expanded.

DUNE will involve two sites: the DoE's Fermi National Accelerator Laboratory (Fermilab) outside Chicago, Illinois, and the Sanford Underground Research Facility in Lead, South Dakota. An accelerator at Fermilab will create a beam of neutrinos and shoot it in a straight line through Earth's crust, from which it will re-emerge nearly 1,300 kilometres away.

The previous P5 prioritization exercise, which took place in 2014, put DUNE — then estimated to cost US$1.9 billion — at the top of its priorities for new projects to fund. Construction has since been subject to major delays and cost overruns, which has prompted the DoE to nearly halve the size of the South Dakota detector. Even in this scaled-down version, the cost is expected to exceed $3 billion.

But the science case for DUNE remains extremely compelling, many physicists think. The P5 is now advocating a second phase that will push the detector to its original intended size, and include upgrades at Fermilab that will make its neutrino beam ten times more intense.



ESA AND THE PLANCK COLLABORATION

Probing the cosmic microwave background reveals details of the instants after the Big Bang.

A factory for Higgs bosons

The LHC announced the discovery of the Higgs boson — which is thought to give other particles their mass — in 2012. It was the last particle to be found among those predicted by the standard model of particle physics. But in many respects, the Higgs remains mysterious.

Physicists have proposed several designs for accelerators that would produce vast numbers of Higgs bosons and enable precise measurements of their interactions with other

Date	Where	talk type	Event	Who requested?	Speaker
12/7/2023	Washington, DC	committee	HEPAP	DOE/NSF	Hitoshi/Karsten
12/11/2023	Fermilab	committee	P5 Townhall	DPF/Fermilab	Hitoshi/Karsten
12/12/2023	DESY	colloquium	Helmhotlz Alliance		Beate Heinemann
12/12/2023	CERN (Meyrin)	committee	CERN SPC	SPC chair	Karsten/Hitoshi
12/13/2023	Yale	colloquium	colloquium/discussion	Yale	Karsten/Sarah
12/13/2023	Houston, TX	conference	1st Int. Workshop on Muon-Ion Colliders	Workshop SPC	Mark Palmer
12/15/2023	BNL, Brookhaven NY	seminar	town hall/discussion	BNL	Karsten Heeger
12/15/2023	AAAC	committee	AAAC	NSF	Hitoshi/Karsten
12/18/2023	Asmeret Berhe	briefing	briefing	DOE	Hitoshi/Karsten
12/19/2023	KEK, Tsukuba	seminar	seminar	Masa Yamauchi	Hitoshi Murayama
12/19/2023	BNL, Brookhaven NY	seminar	seminar for ATLAS group	Viviana Cavaliere	Sarah Demers
12/19/2023	Congressional Staffers	briefing	briefing	DOE	Hitoshi/Karsten/Abby
12/22/2023	KEK, Tsukuba	briefing	briefing	Masa Yamauchi	Hitoshi Murayama
12/21/2023	Fermilab	seminar	Colliders of Tomorrow	Sridhara Dasu	Tulika Bose
12/27/2023	MEXT	briefing	Briefing to Research Promotion Bureau	Masa Yamauchi	Hitoshi Murayama
1/5/2024	OSTP	briefing	briefing to Kei Koizumi	DOE	Hitoshi/Karsten
1/9/2024	UChicago	other	KICP/A&A Chalk Talk	Austin Joyce	Abby Vieregg
1/11/2024	University of Hawaii	colloquium	Physics colloquium	John Learned	
1/12/2024	LBNL	seminar	Annual LBNL ATLAS Meeting	Kevin Einsweiler	Hitoshi Murayama
1/12/2024	Edinburgh, Scotland (virtual)	other	LZ collaboration meeting	Sally Shaw	Richard Schnee
1/16/2024	IMCC (virtual)	briefing	IMCC Steering Cmmte.	Steinar Stapnes	Mark Palmer
1/17/2024	UT-Austin	colloquium			Peter Onyisi
1/17/2024	LSST DESC (virtual)	seminar	DESC seminar	LSST DESC spokesperson	Rachel Mandelbaum & Francis-Yan Cyr-Racine
1/17/2024	Multi-lab (virtual)	committee	MDP General Meeting	Georgui Velev (MDP Mgmt)	Mark Palmer
1/18/2024	MDP Management (virtual)	other	MDP Tech. Advisory Cmmte.	Soren Prestemon	Mark Palmer
1/19/2024	Fermilab	other	Accelerator Directorate All-Hands	Alexander Valishev	Bob Zwaska
1/22/2024	University of Washington, Seattle	colloquium		Henry Lubatti	Sarah Demers
1/22/2024	South Dakota Mines	colloquium		Jingbo Wang	Richard Schnee
1/23/2024	University of New Mexico	seminar	Particle/Cosmo Seminar	David Camarena	Francis-Yan Cyr-Racine
1/25/2024	Argonne National Lab	colloquium		Christine McLean	Petra Merkel
1/25/2024	University of Florida	colloquium		Andrey Korytov	Hitoshi Murayama
1/26/2024	William & Mary	colloquium		Marc Sher/W&M	Chris Monahan
1/30/2024	Washington, DC		URA Council of Presidents	John Mester	Hitoshi/Karsten/Sally
1/31/2024	Rutgers	colloquium			Yuri Gershtein
2/2/2024	Annecy	conference	FCC Physics WS	Patrick Janot	Hitoshi Murayama
2/2/2024	CERN (Meyrin)	colloquium	CERN colloquium	Joachim Mnich	Hitoshi Murayama
2/5/2024	UK	other	European funding agencies and community	Lia Merminga	Hitoshi/Karsten
2/5/2024	Carnegie Mellon University	colloquium	CMU/Pitt joint colloquium series	Tao Han	Rachel Mandelbaum
2/12/2024	SLAC	colloquium		Marty Breindenbach	Hitoshi Murayama
2/15/2024	MIT	colloquium		MIT	Jesse Thaler/Lindley Winslow
2/27/2024	University of Maryland	colloquium		Kaustubh Agashe	Hitoshi Murayama
3/6/2024	Indiana University	colloquium		Hal Evans	Tulika Bose
3/7/2024	Michigan State University	colloquium		Reinhard Schweinhorst	Sarah Demers
3/14/2024	University of Oregon	colloquium		UO	Tien-Tien Yu
3/24/2024	Aspen Center for Physics	conference	Aspen Winter Conference	Karri DiPetrillo	Hitoshi Murayama
3/25/2024	MIT	conference	FCCee workshop	Christoph Paus	Karsten Heeger
4/3/2024	Sacramento	conference	APS April Meeting		Hitoshi Murayama
4/8/2024	UC Berkeley	colloquium		Christopher McKee	Hitoshi Murayama
4/9-11/2024	US congress	briefing	Annual Hill Visit	URA, DPF	
5/4/2024	University of Wisconsin, Madison	colloquium		Sridhara Dasu	Hitoshi Murayama
5/15/2024	Jefferson Lab	seminar		Dave Dean	Karsten Heeger
5/16/2024	ORNL	seminar		Marcel Demarteau	Karsten Heeger

Pathways to Innovation and Discovery in Particle Physics

Report of the Particle Physics Project Prioritization Panel 2023

Credit:
Yurie
Murayama