Exploring the Quantum Universe

Pathways to Innovation and Discovery in Particle Physics

Report of the 2023 Particle Physics Project Prioritization Panel

IOP APP, HEPP & NP 2024

Christos Touramanis

On behalf of P5

2023p5report.org

US Process for HEP Planning

Community

Snowmass 2021

"Snowmass" Community Study

Organized by APS / DPF

Funding Agencies

HEPAP

Charge
Budget scenario

Particle Physics Project Prioritization Panel 2023

(HEPAP subpanel)

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Implementation

DOE HEP
NSF PHYS

OMB
OSTP
Congress

+ international partners

P5 history

Initial panel: reviewing projects

- 2003, 2004, 2007

Current P5 scheme with budget scenarios and long-term vision

- 2008:
  - Energy, Intensity, Cosmic Frontiers
  - World-class neutrino program
  - Dark matter & dark energy, LSST
- 2014:
  - Recommended LBNE → DUNE/LBNF
  - Embraced CMB in HEP
- 2023: this panel

P5 2023: broad mandate and clear instructions requiring a holistic approach.
It inspired and motivated the panel.

… to develop an updated strategic plan for U.S. high-energy physics that can be executed over a 10-year timeframe in the context of a 20-year, globally aware strategy for the field.

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


P5 Panel 2023

P5 Panel

Exploring the Quantum Universe

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

Panel strengths: diversity, leadership, time, consensus

- Theory, experiment, accelerators, colliders, neutrinos, DM, CMB
- Wide spectrum of career points – experience levels
- US, with members from Asia and Europe
- Gender balance, diverse national & cultural backgrounds

- Long days in the closed meetings, months of long zoom meetings.
- Everything was on the table, no item was rushed through.

- No decisions made by vote, not even considered it at any point.

P5 Timetable and Process

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Information Gathering and Community Engagement

Open Town Halls

LBNL: February 22, 23, 2023 (513 registrants)
Fermilab/Argonne: March 21-23, 2023 (797 registrants)
Brookhaven: April 12-13, 2023 (666 registrants)
SLAC: May 3-4, 2023 (512 registrants)

Virtual Town Halls

UT Austin: June 5, 2023 (159 registrants), exclusive session for ECRs
Virginia Tech, June 27, 2023 (119 registrants)

Deliberation Phase

Closed meetings

May 31-June 2, 2023 - Austin
June 21-23, 2023 - Gaithersburg
July 11-14, 2023 - Santa Monica
August 1-4, 2023 - Denver

Additional input from

Agencies **Government**
Community **Intl. Community**

Peer Reviews

Received many invaluable comments which helped improve clarity and presentation.

Report for Approval

Presented to HEPAP on December 7-8, 2023

P5 town hall at FNAL

Context and challenges

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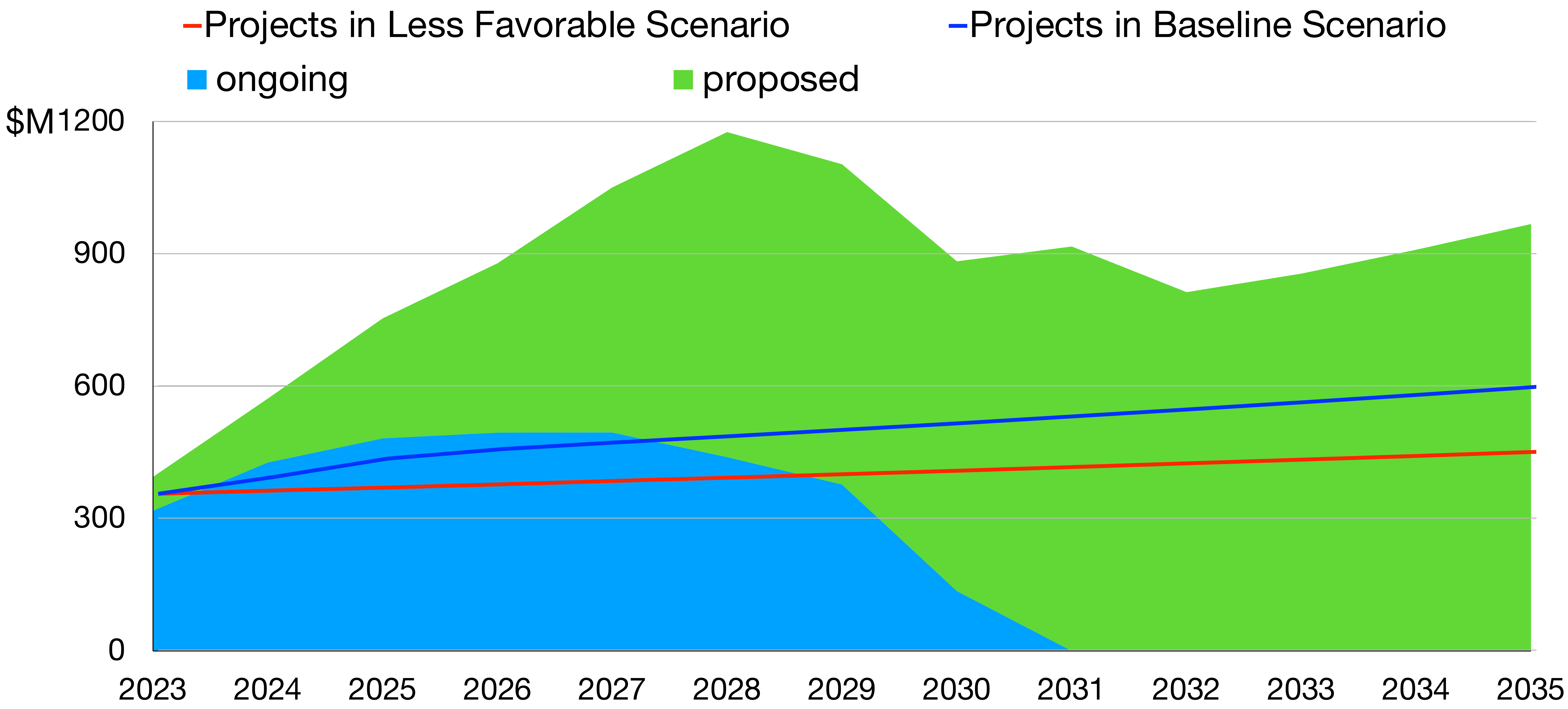
Evolving Scientific Landscape

- 125 GeV Higgs looks like SM; DM searches extending to low-E weakly coupling sectors; ΛCDM facing tensions between measurements; DUNE moving ahead but HK also in construction; Lattice vs g-2; interesting results in flavor physics; High-Energy neutrinos; Gravitational waves.

Resources

- Community aspirations greatly exceed expected US budgets.
- Projects keep increasing in cost and delivery time.
- Big projects (worldwide) can increase in cost by a factor of ~π during execution.
- The field is more global than ever, plus geopolitical and climate challenges.

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 (SLAC)
- Jon Kotcher, Srini Rajagopalan (BNL)
- Allison Lung (JLab)
- Harry Weerts (Argonne)

Jay Marx

Committee provided low, medium, and high estimates with schedules

Prioritization Principles

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

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

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

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

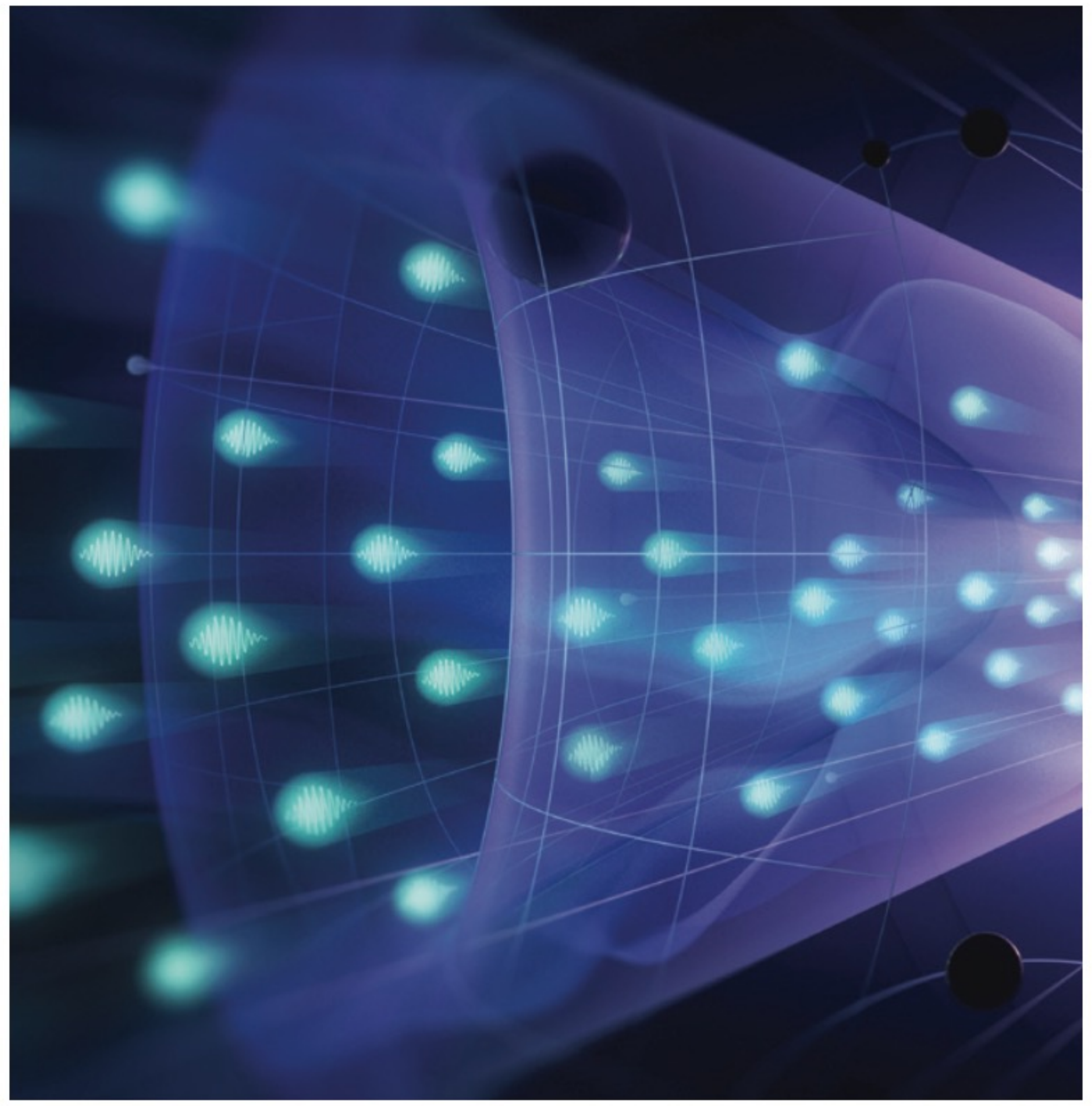
Overall program should

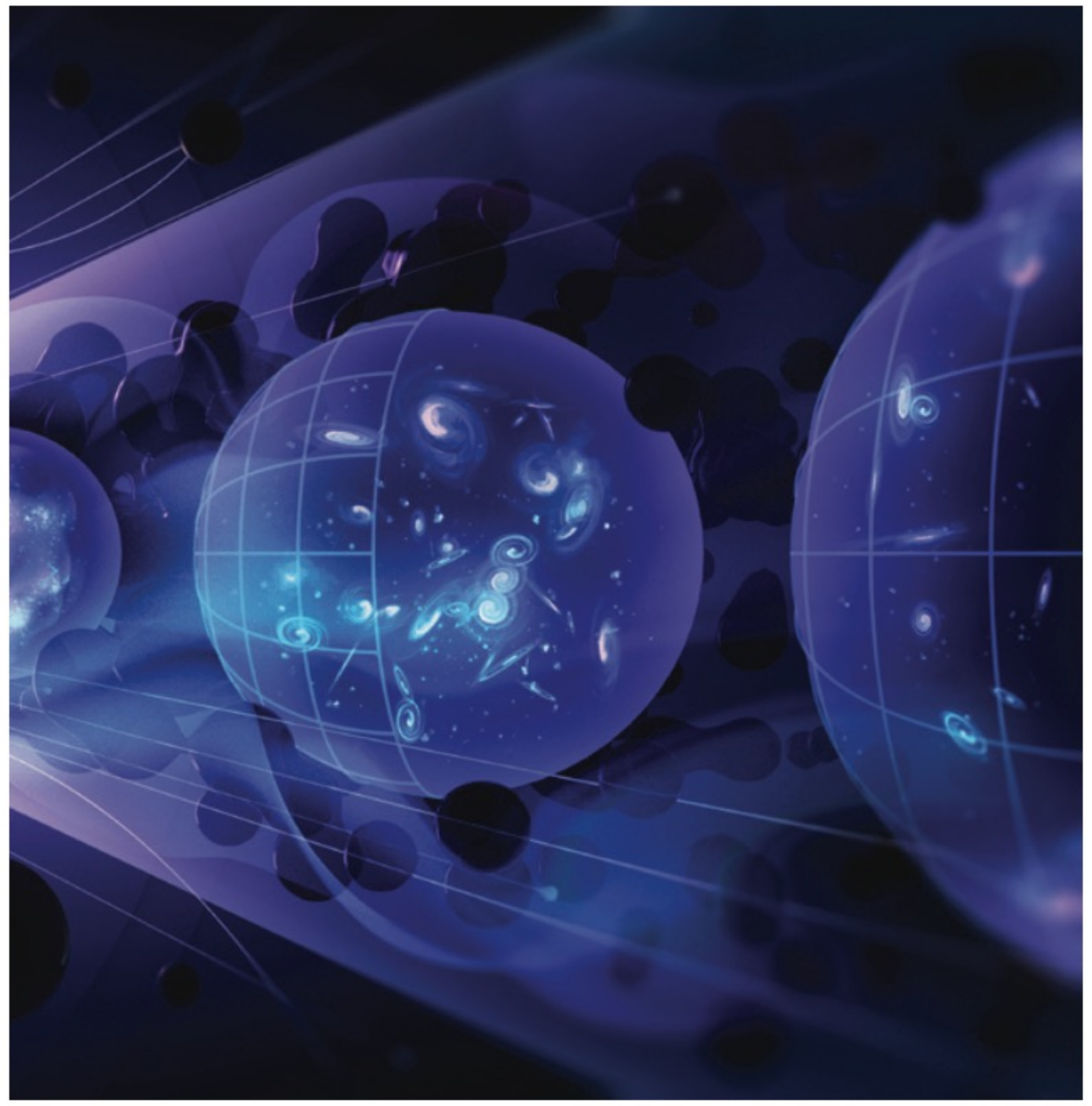
- leverage **unique US facilities and capabilities,** engage with **core national initiatives** to develop key technologies,
- develop a **skilled workforce** for the future that draws on all talent
- realize **effective engagement and partnership in international endeavors**

Our vision
Three themes, six science drivers

Curiosity-driven research is at the core of particle physics, a field of science in which we study the building blocks of the subatomic world. In examining these point-like particles and their interactions, we *decipher the quantum realm*. We also look out into the universe, beyond the visible stars, by building instruments that can *illuminate the hidden universe*. By studying the very small and the very large, realms that are beyond the limits of human perception, we expand our understanding of the world around us and begin to grasp our place in the cosmos. Going beyond phenomena that we can probe using current experiments, we can use theoretical principles to test our current physics understanding and predict new particles and new phenomena; in this way we *explore new paradigms in physics*.

Explore the Quantum Universe





Decipher the Quantum Realm

Elucidate the Mysteries of Neutrinos

Reveal the Secrets of the Higgs Boson

Explore New Paradigms in Physics

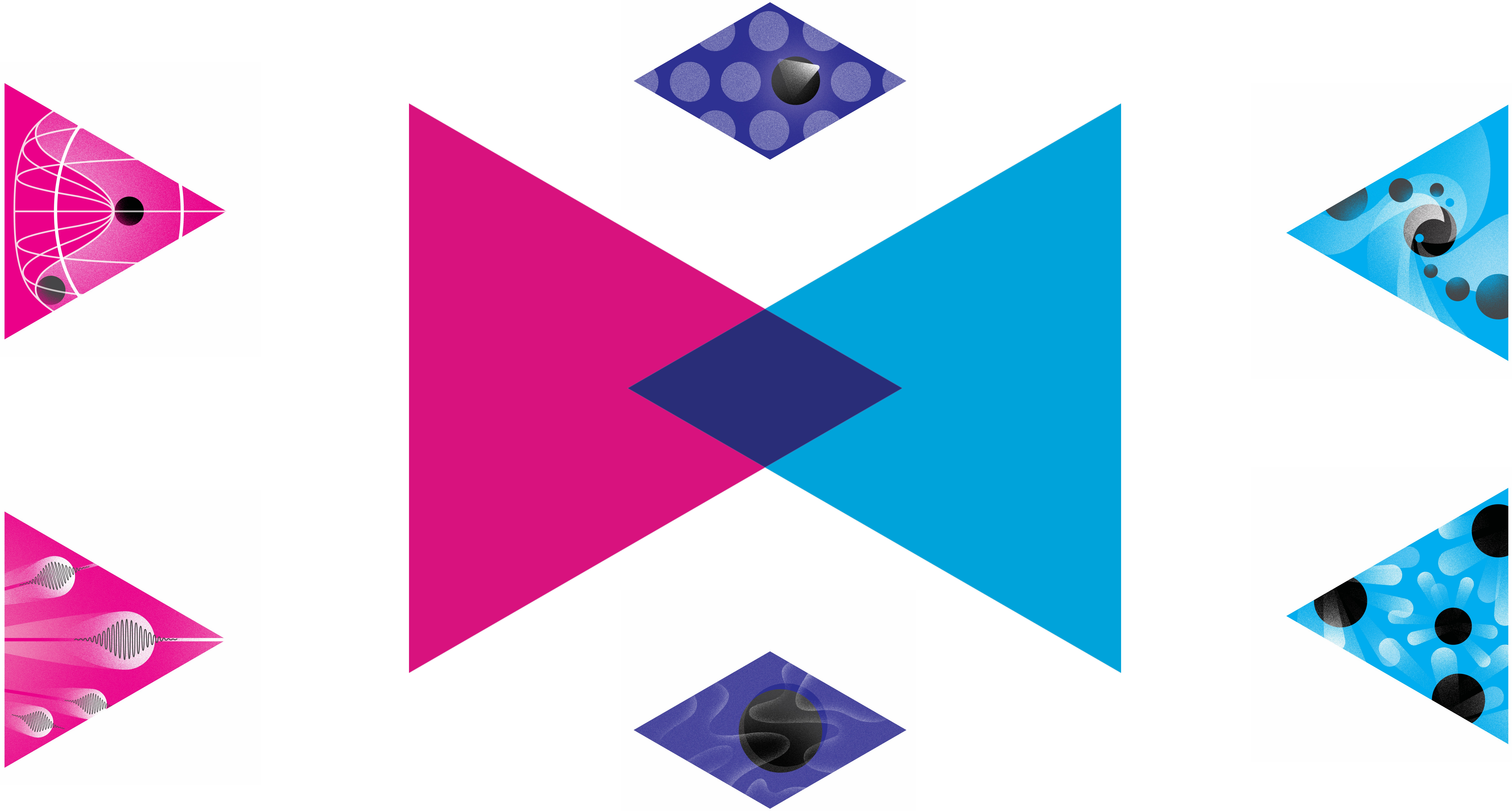
Search for Direct Evidence of New Particles

Pursue Quantum Imprints of New Phenomena

Illuminate the Hidden Universe

Determine the Nature of Dark Matter

Understand What Drives Cosmic Evolution



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The proposed program in the baseline scenario

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Not Rank-Ordered

Recommendation 1

Reaffirm critical importance of the ongoing projects

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

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

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Recommendation 2

Rank-Ordered

New exciting initiatives

a. **CMB-S4**, which looks back at the earliest moments of the universe to probe physics at the highest energy scales. It is critical to install telescopes at and observe from both the South Pole and Chile sites to achieve the science goals (section 4.2). 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 4.1). DOE & NSF PHY

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

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Not Rank-Ordered

Recommendation 3

Balanced Portfolio from small to large

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

$35M/yr

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.

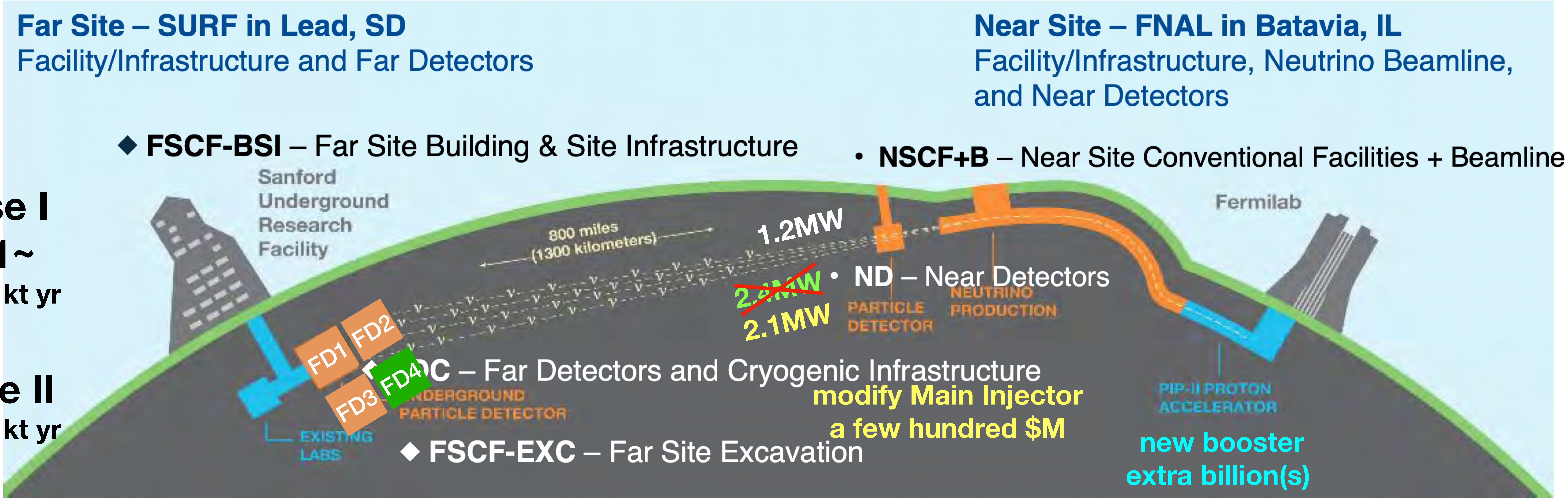
c. Support **DESI-II** for cosmic evolution, **LHCb upgrade II** and **Belle II upgrade** for quantum imprints, and **US contributions to the global CTA Observatory** for dark matter (sections 4.2, 5.2, and 4.1).

The Belle II recommendation includes contributions towards the SuperKEKB accelerator.

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

Phase I
2031~
120MW kt yr

Phase II
600MW kt yr



◆ 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

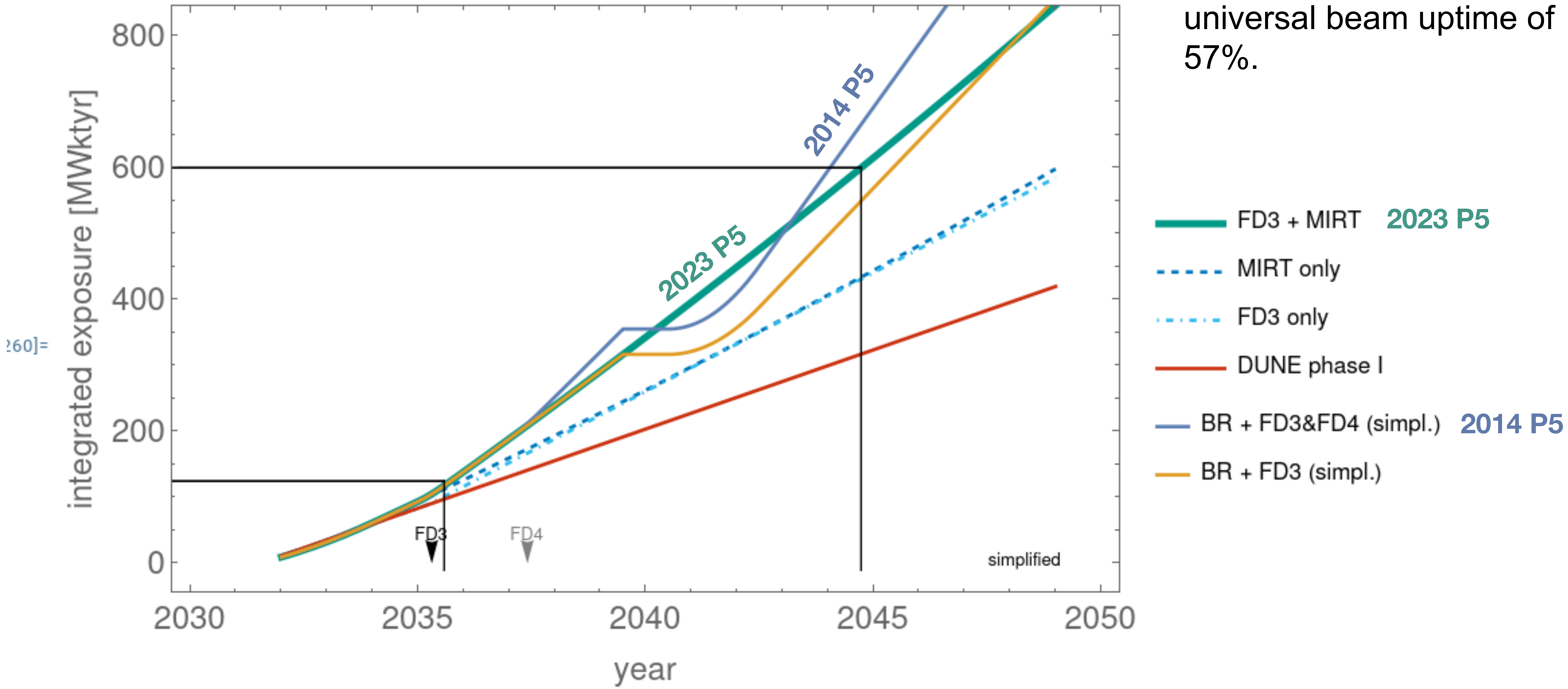
3.1.4 – Future Opportunities: DUNE FD4, the Module of Opportunity

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%.

G3 Dark Matter experiments

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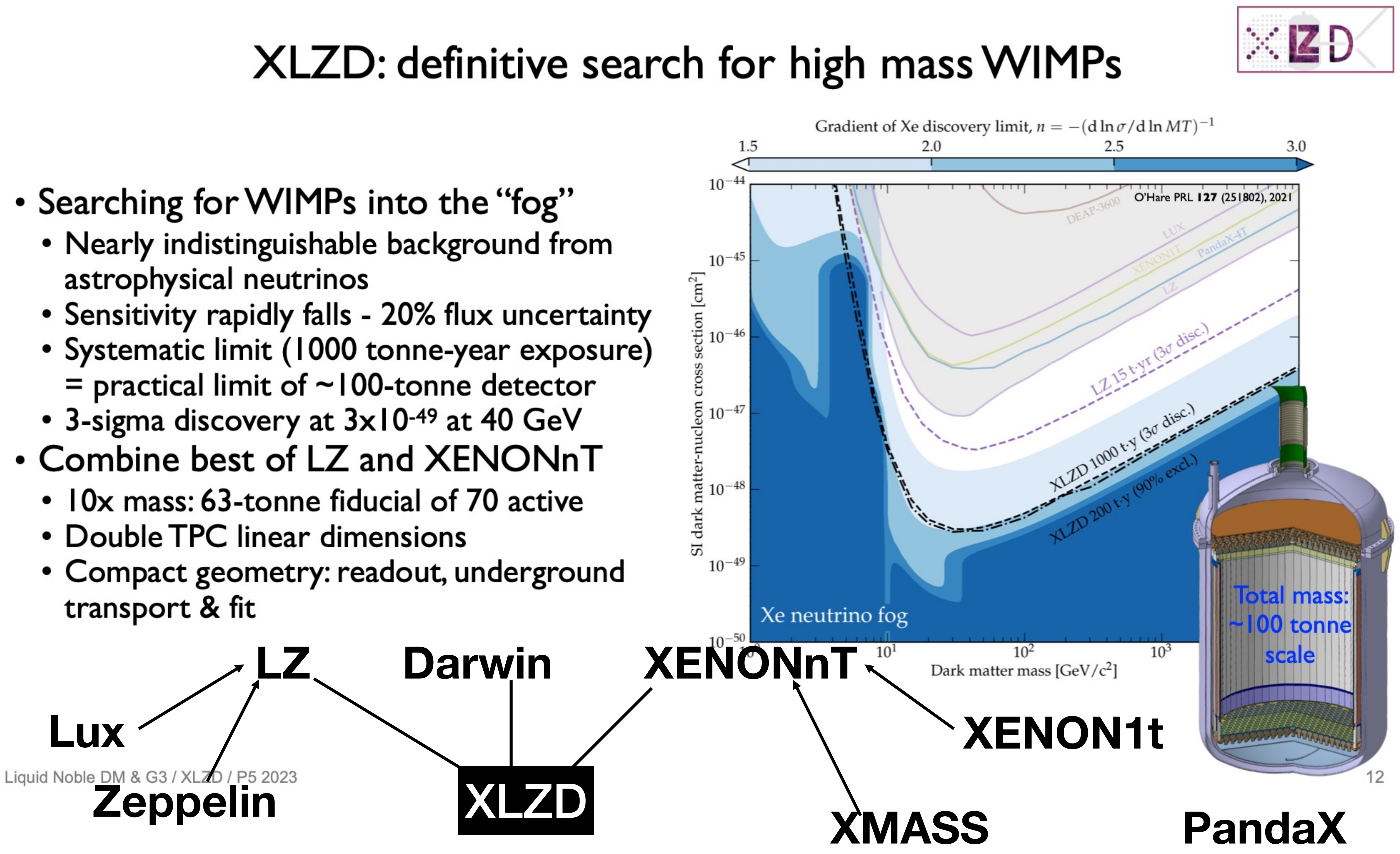
Dan Akerib, LBNL Town Hall, Feb 22, 2023

Cristiano Galbiati, SLAC Town Hall, May 3, 2023



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

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

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.**

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.

Recommendations beyond Projects

The long-term, highly technological nature of particle physics requires ongoing investment in and support of the workforce, at all career stages. The field can only thrive with high ethical standards and broad community engagement.

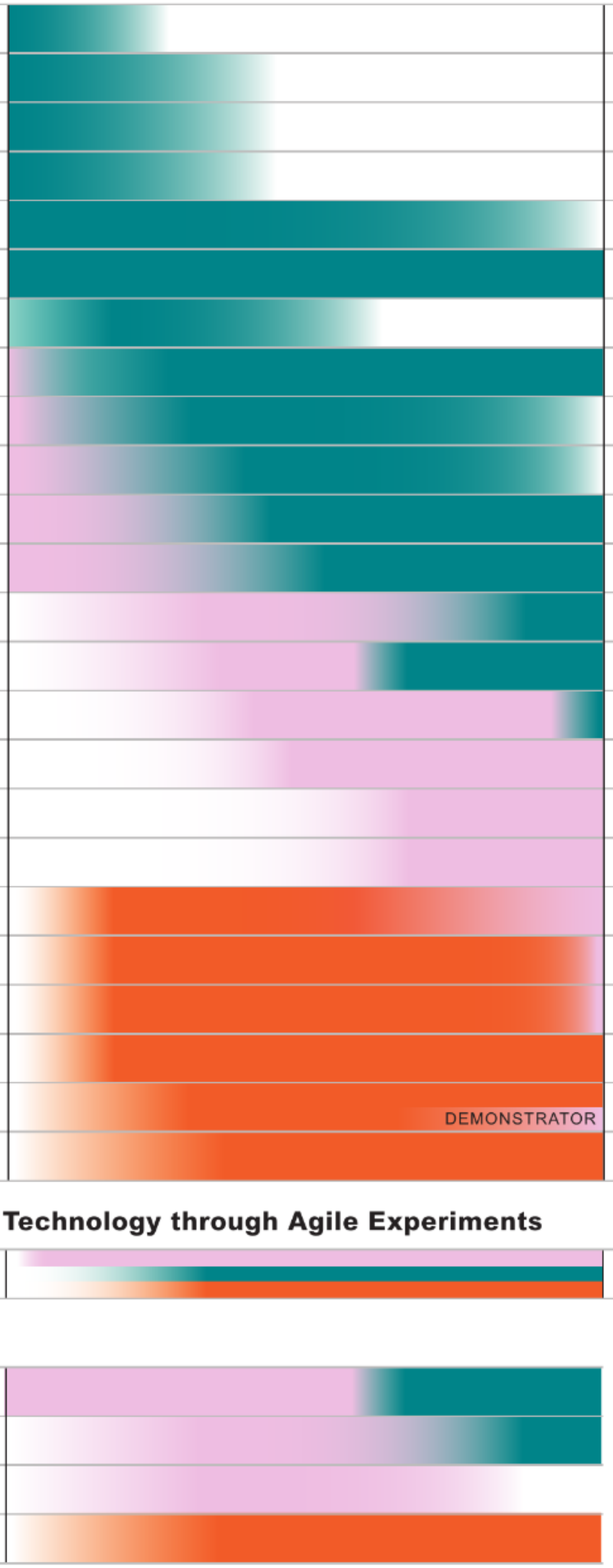
- P5 recommends increased support for career paths beyond "faculty" and "permanent lab scientist" – in particular research scientist, hardware and software engineer, and technician positions at universities.
- Funding should be available for developing partnerships to improve and broaden recruiting, to improve training and mentoring, and to retain personnel with living wages and sufficient support for caregiver and family responsibilities.
- Comprehensive work climate studies should be performed in conjunction with experts in such studies.
- The funding agencies and laboratories should provide infrastructure to report and resolve violations of ethical conduct, at scales from individual investigators to large formal collaborations.
- Dissemination of results to the public should be a standard part of operations and research budgets.

Recommended Particle Physics Program in the Baseline Scenario

Figure 1 – Program and Timeline in Baseline Scenario (B)

Index: Operation, Construction, R&D, Research, P: Primary, S: Secondary

§ Possible acceleration/expansion for more favorable budget situations



Science Experiments (Timeline 2024–2034)	Neutrinos	Higgs Boson	Dark Matter	Cosmic Evolution	Direct Evidence	Quantum Imprints	Astronomy & Astrophysics
LHC		P	P		P	P	
LZ, XENONnT			P				
NOvA/T2K	P				S		
SBN	P				S		
DESI/DESI-II	S		S	P			P
Belle II			S		S	P	
SuperCDMS			P				
Rubin/LSST & DESC	S		S	P			P
Mu2e						P	
DarkSide-20k			P				
HL-LHC		P	P		P	P	
DUNE Phase I	P				S	S	S
CMB-S4	S		S	P			P
CTA			S				P
G3 Dark Matter §	S		P				
IceCube-Gen2	P		S				P
DUNE FD3	P				S	S	S
DUNE MCND	P				S	S	
Higgs factory §		P	S		P	P	
DUNE FD4 §	P				S	S	S
Spec-S5 §	S		S	P			P
Mu2e-II						P	
Multi-TeV §		P	P		P	S	
LIM	S		P	P			P
Advancing Science and Technology through Agile Experiments							
ASTAE §	P	P	P	P	P	P	
Science Enablers							
LBNF/PIP-II							
ACE-MIRT							
SURF Expansion							
ACE-BR §, AMF							

Increase in Research and Development

Approximate timeline of the recommended program within the baseline scenario. Projects in each category are in chronological order. For IceCube-Gen2 and CTA, we do not have information on budgetary constraints and hence timelines are only technically limited. The primary/secondary driver designation

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Difficult Choices

Figure 2 – Construction in Various Budget Scenarios

Index: Y: Yes N: No R&D: Recommend R&D only C: Conditional yes based on review P: Primary S: Secondary
Delayed: Recommend construction but delayed to the next decade
† Recommend infrastructure support to enable international contributions
# Can be considered as part of ASTAE with reduced scope

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

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Thank you