# Exploring the Quantum Universe

# Pathways to Innovation and Discovery in Particle Physics

Report of the 2023 Particle Physics Project Prioritization Panel

Yuri Gershtein
*on behalf of P5 panel*

January 31, 2023

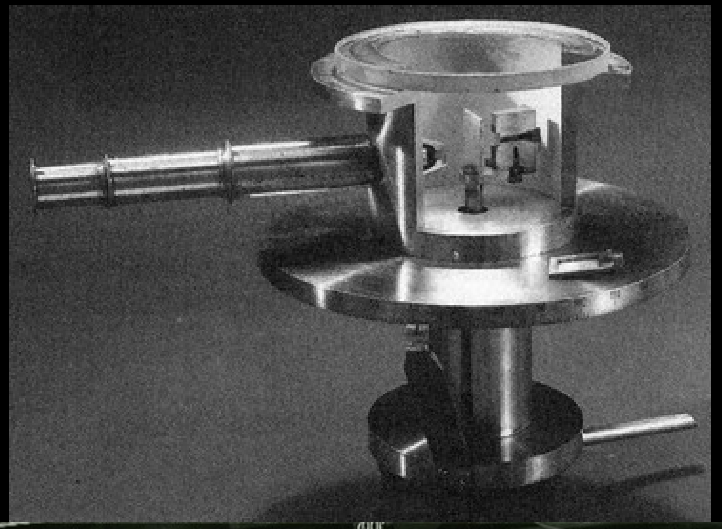
2023p5report.org

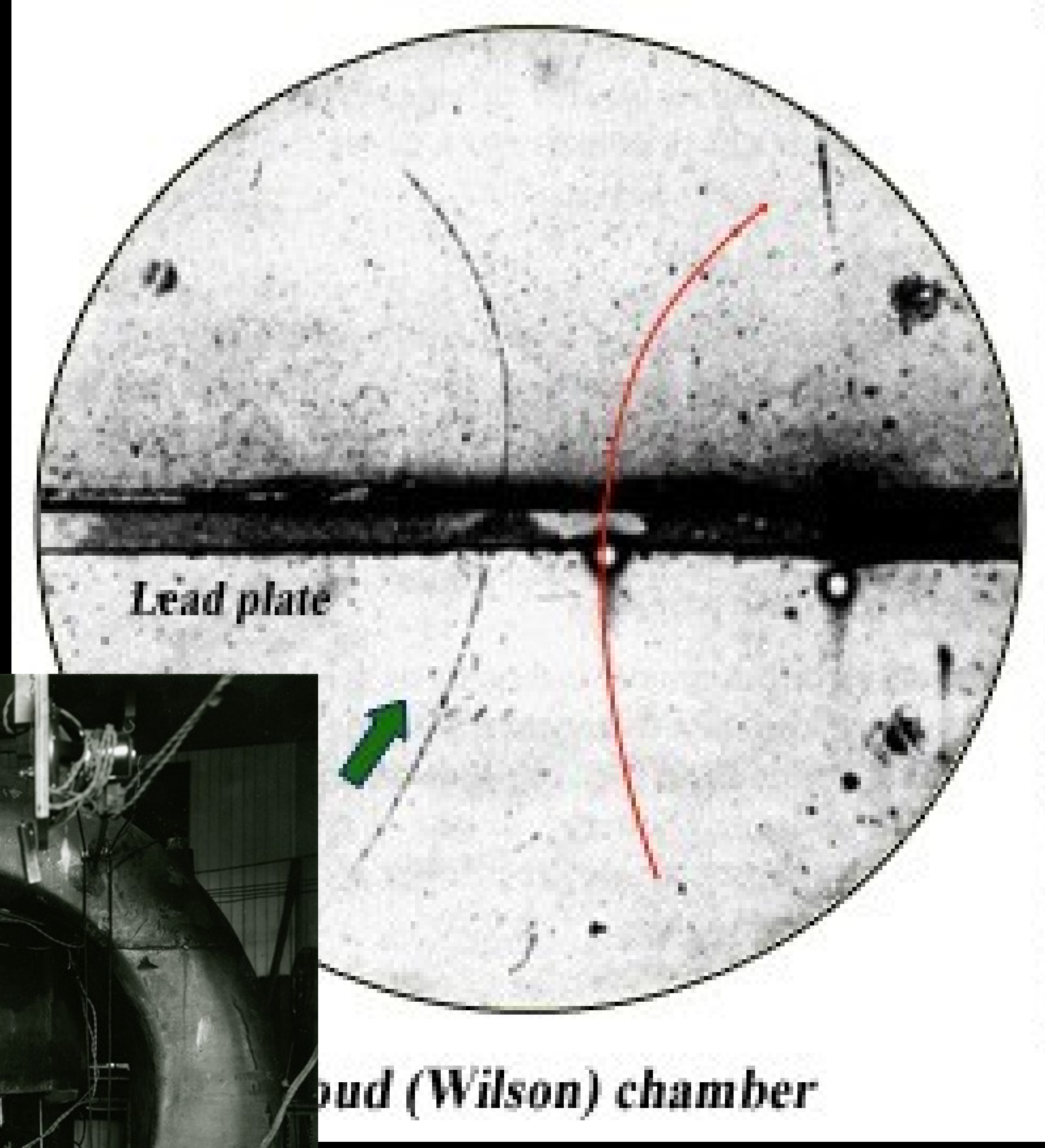
# Outline

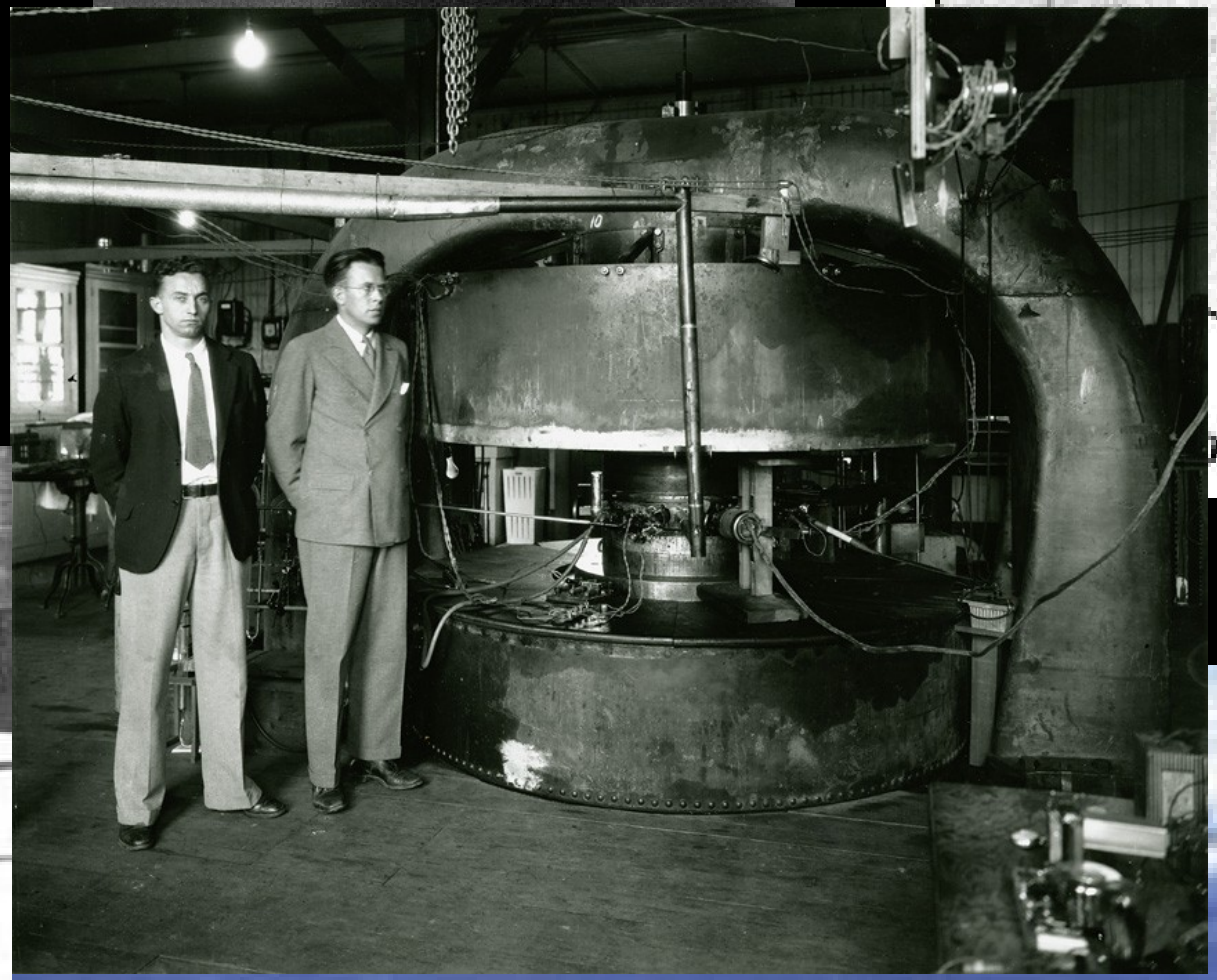
- What is Particle Physics?
  - *Hint: it's more than accelerators*
- P5 process
  - planning in big science – when you only have a few very expensive toys and have to share
- The recommendations
  - Context for our department

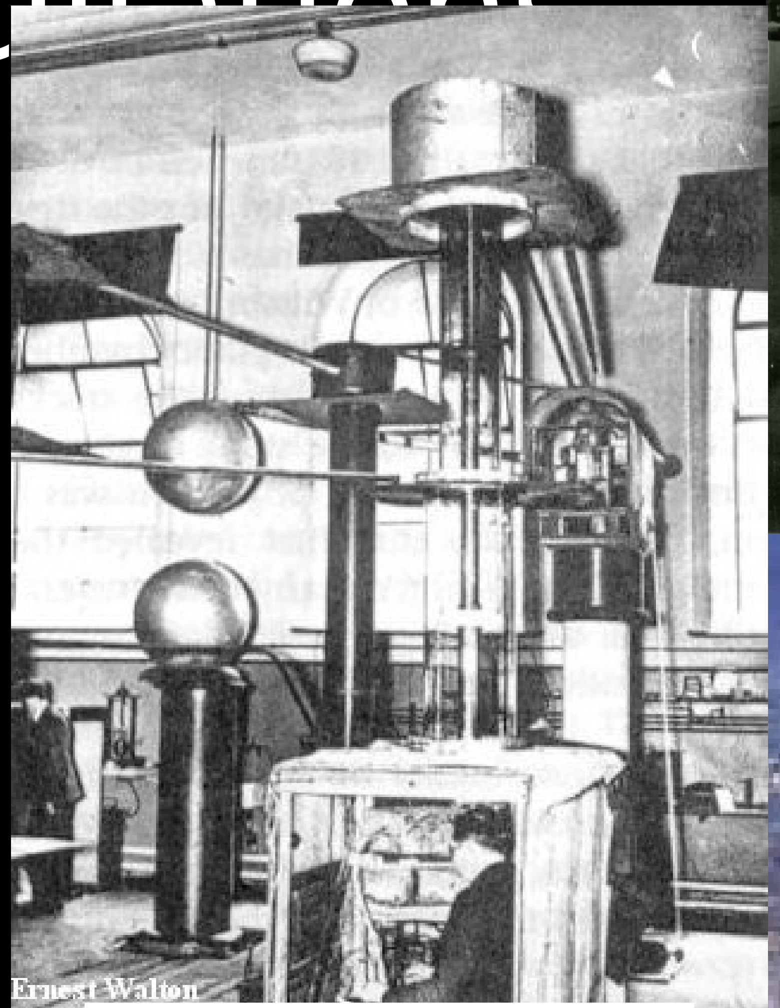
# Accelerators

- Natural accelerators
  - Nuclei – i.e. gold foil experiment
  - Cosmic rays – i.e. discovery of positron, pion, neutrino oscillations
- Human-made
  - Cockroft-Walton (linear)
  - Lawrence (cyclotron)
  - McMillan-Veksler (synchrotron)
  - Van der Meer ( cooling: colliders )



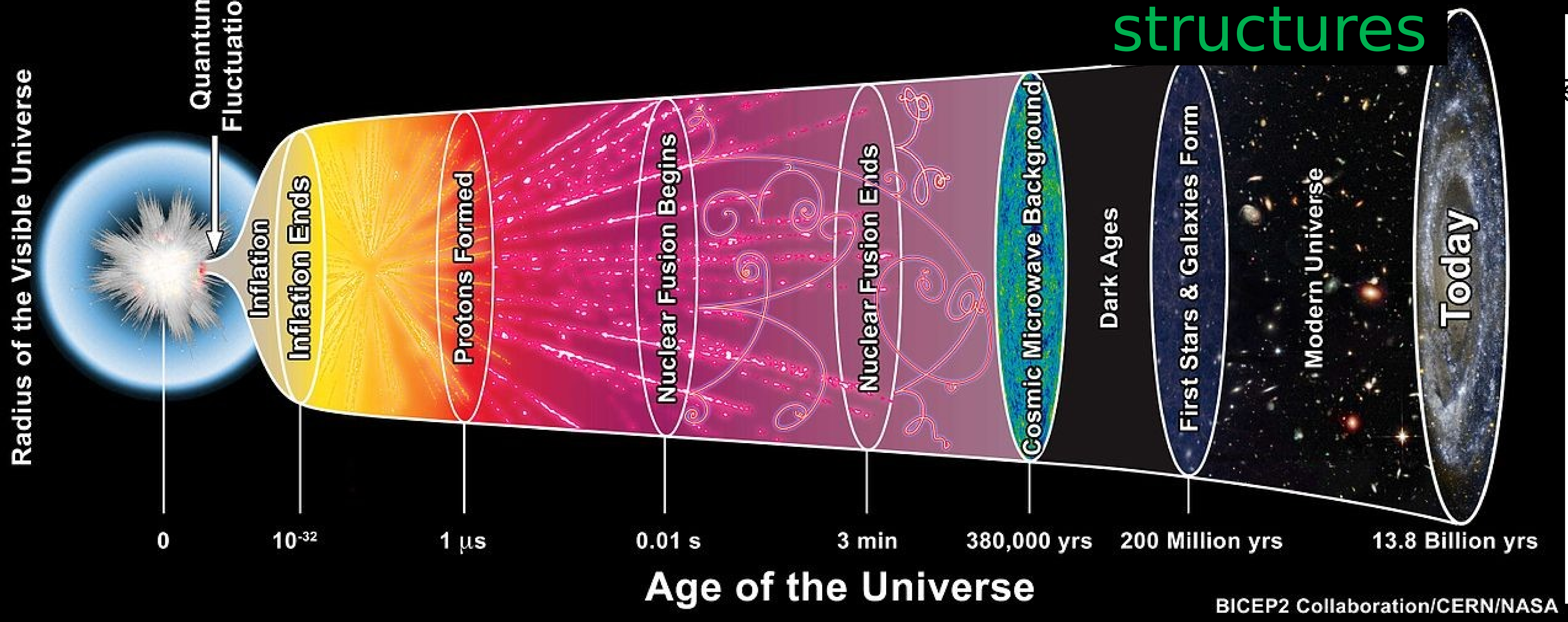


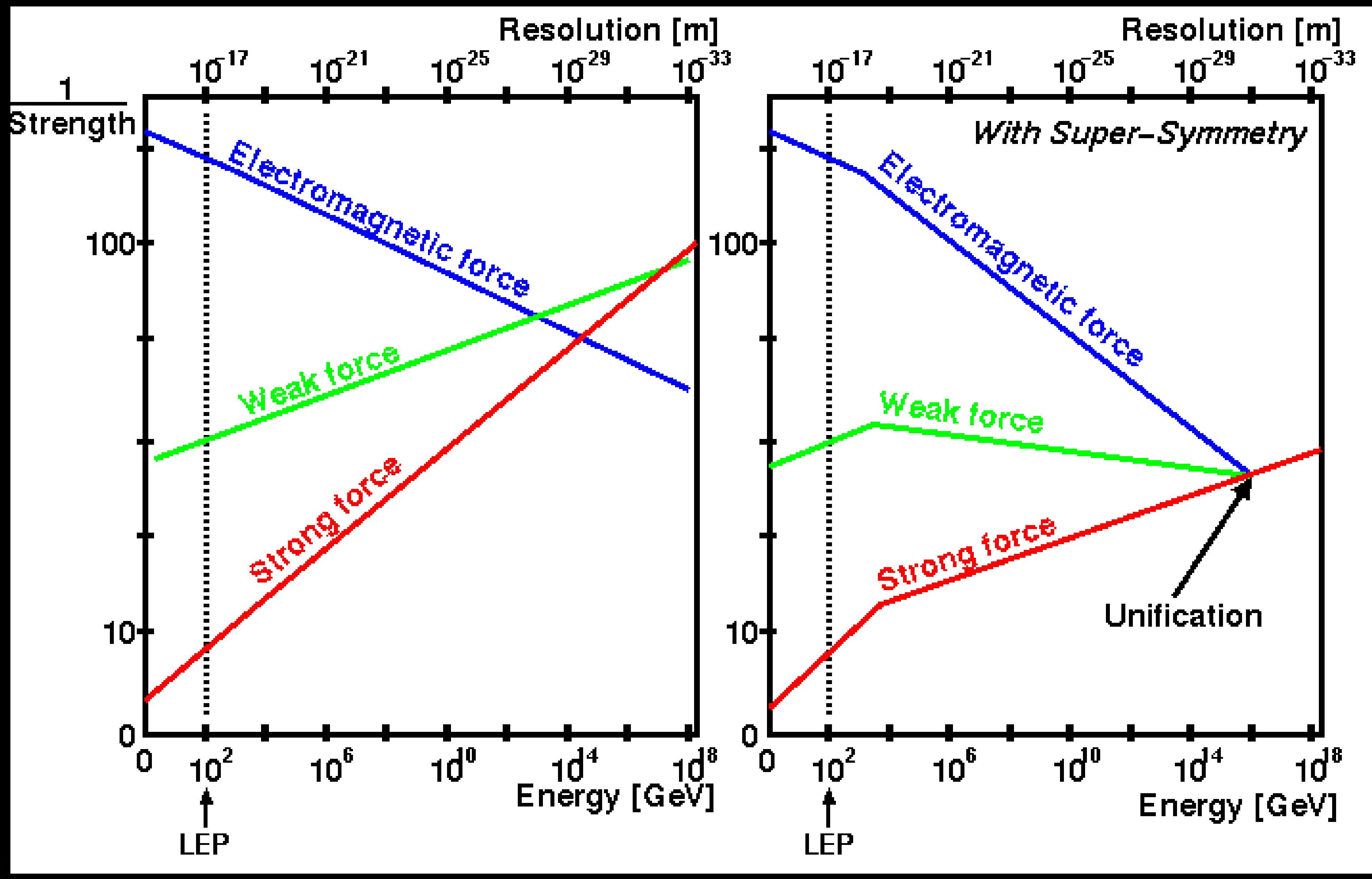




Ernest Walton inside the detector

# Particle Physics and the Universe

The quantum fluctuations are imprinted on the large scale structures




About 25 years ago: WMAP. The rise of precision cosmology. Same physics can be probed from measuring the smallest and the largest objects in the Universe

- Astro evidence for Dark Matter connects to Strong CP problem, SUSY, Hidden Sectors
- Matter abundance (baryogenesis) connects to the Higgs field and electroweak phase transition
- CMB has imprints of inflation, neutrino masses, number of light particle species, etc
- Astro observations quantify properties of DM and DE (DES, Rubin/LSST, ...)

# Two "Standard Paradigms"

## The Standard Model

- Describes quarks, leptons, and three forces that hold known matter together
  - Some tensions (i.e. g-2) but overall fantastic agreement with experiment
- Relies on ad-hoc Higgs potential
  - i.e. no BCS theory of the Higgs
- No explanation for flavor, no Dark Matter

## CDM

- Describes cosmological history of the Universe
  - Some tensions (i.e. $H_0$)
- Relies on ad-hoc Dark Matter

### *Hierarchy / Naturalness issues*

- Cosmological constant (anthropic?!)
- Higgs mass vs Planck scale
- Strong CP problem
- Neutrino masses

### *Unknown / Only guesses*

- What is Dark Matter
- What created observed matter/antimatter asymmetry (CP violation, EWK phase transition, …)
- What caused inflation
- How gravity is incorporated into quantum theory

The experimental program is expensive - need careful planning

# US Process for Future Planning

Community

“Snowmass” Community Study

Organized by APS / DPF

Snowmass 2021

Particle Physics Project Prioritization Panel (P5)

Organized by HEPAP

20-year vision, 10 year project plan

Charge
Budget scenario

DOE HEP
NSF PHYS

DOE HEP
NSF PHYS

OMB
OSTP
Congress

# 2014 P5

## Five “science drivers”

- Use Higgs Boson as a new tool for discovery
- Pursue physics associated with neutrino mass
- Identify the new physics of dark matter
- Understand cosmic acceleration
- Explore the unknown: new particles, interactions, and physics principles.

## Reactions:

- Enthusiastically endorsed by the community
- Well received in govt agencies
- HEP funding increased by ~30% - far beyond the optimistic scenario

# Changing Landscape

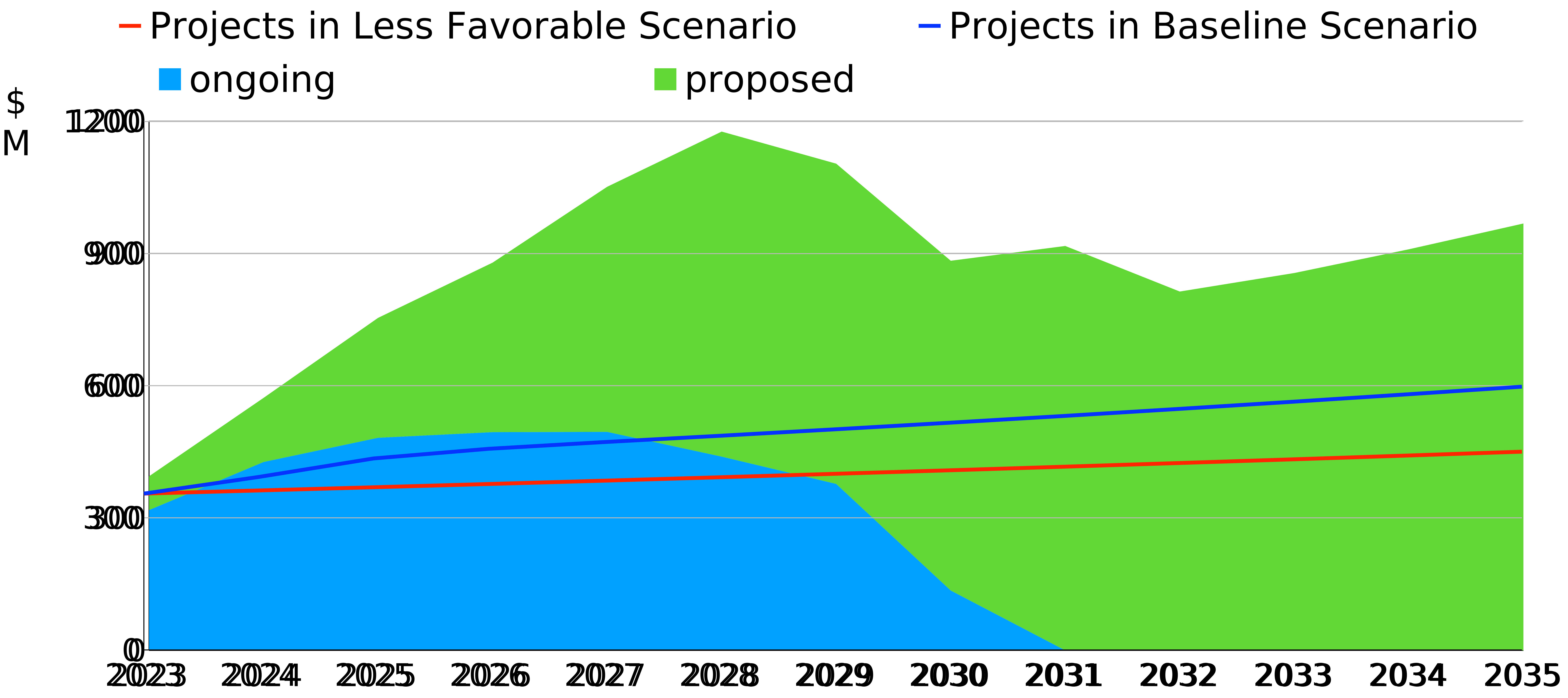
Physics & society does not stay still

- 125 GeV Higgs does look like the standard model
- No direct detection of DM or indications of new physics at colliders
- Hints of tensions (g-2, lepton universality, $H_{0, \ldots}$)
- New ideas for DM detection, Dark Sector searches, cosmological probes such as LIM and GW

- Snowmass: 10 frontiers exploring the new landscape: white papers, frontier summaries, and townhalls
- Projects from previous P5 coming online!
- Increased attention to improved estimates of cost / risk
- National Initiatives (i.e. AI/ML)
- Workforce development and DEI


P5 Panel
Smash Particles

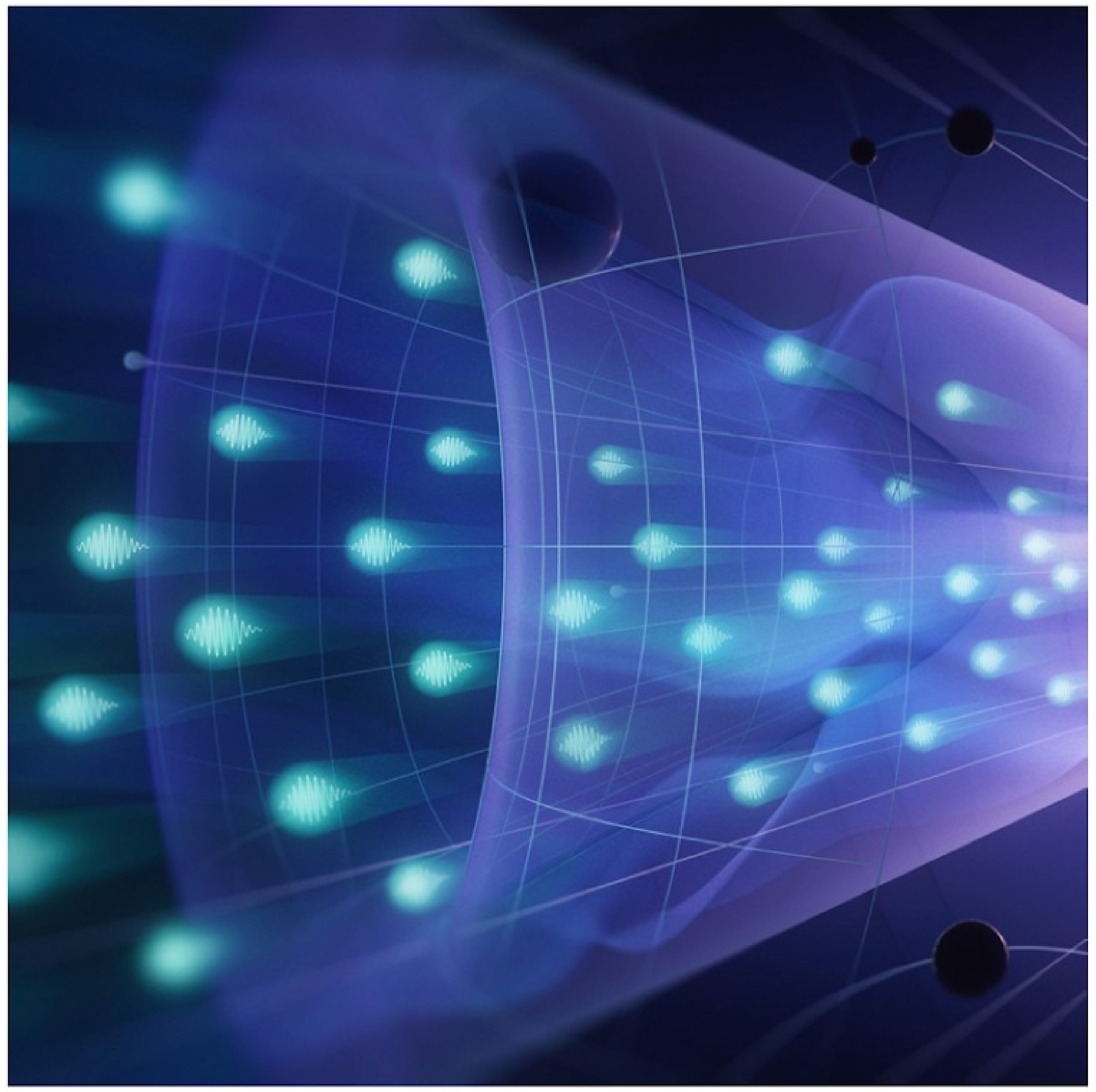
# Difficult choices had to be made…




not including on-shore Higgs factory

DOE only

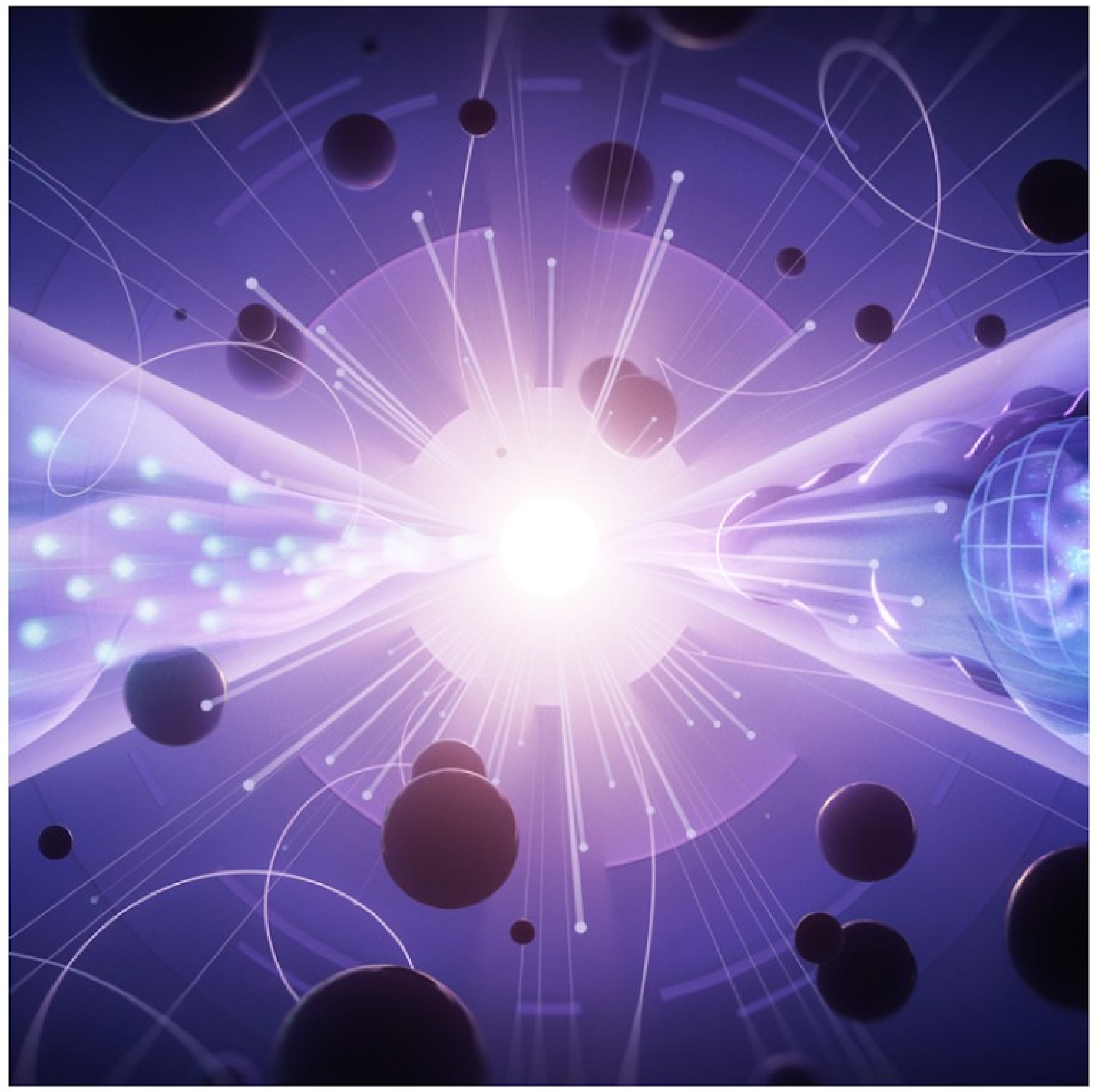
# 3 science themes, 6 science drivers



Decipher the Quantum Realm

Elucidate the Mysteries of Neutrinos

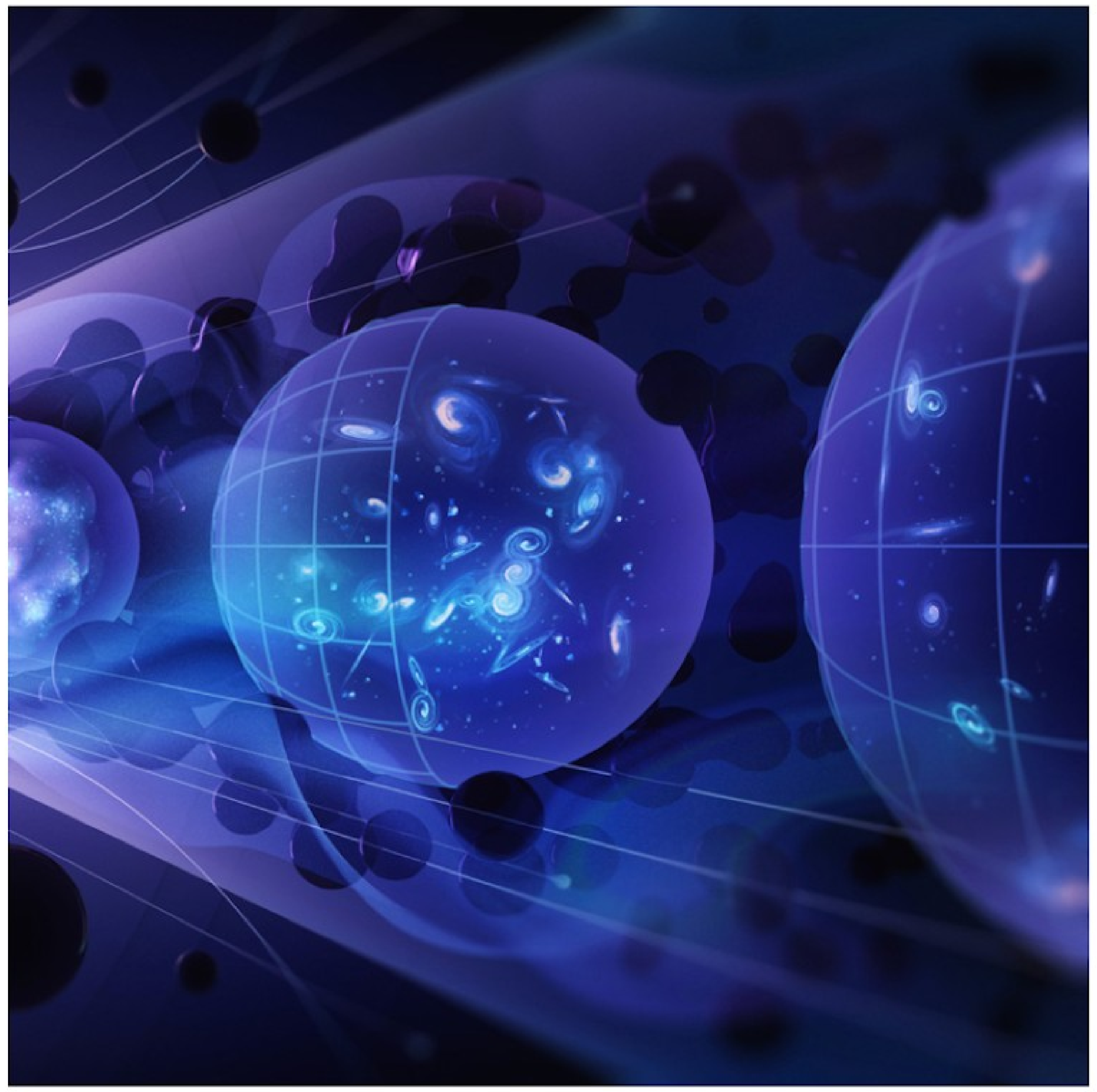
Reveal the Secrets of the Higgs Boson



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

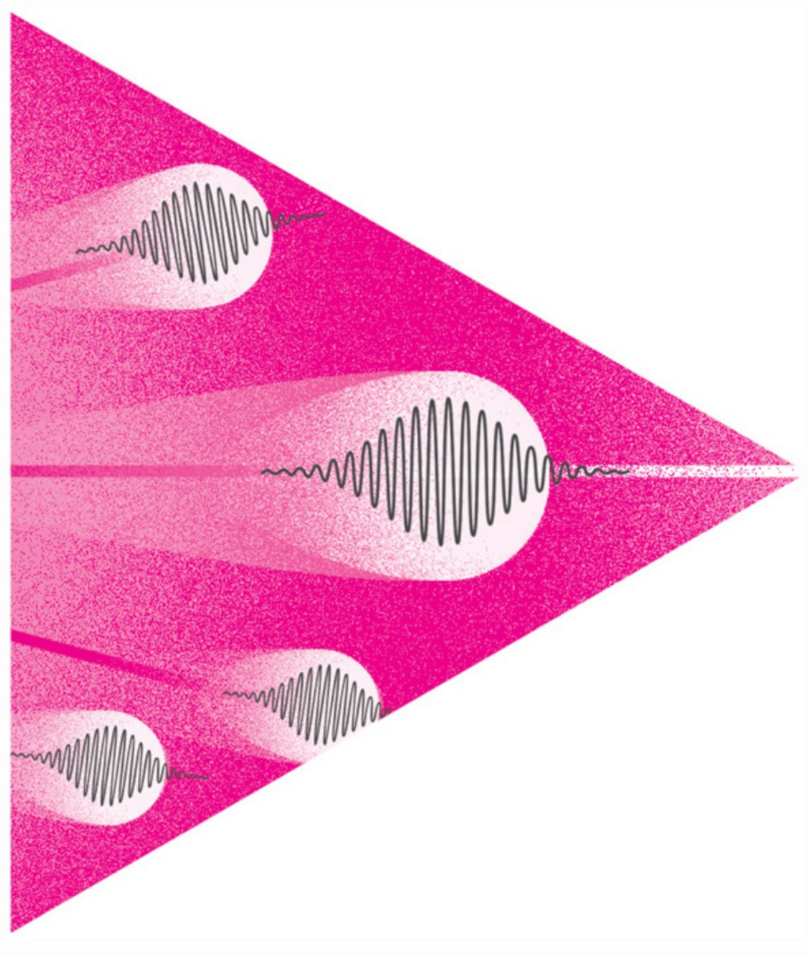
# 3 science themes, 6 science drivers

## ***Multitude of interconnections***

- Common infrastructure (South Pole, SURF)
- Accelerators
  - Contribute to multiple science themes and drivers
  - Necessity to achieve 10 TeV pCM* arises in all three science themes
- New portfolio of small-scale and agile experiments (ASTAE)
- National Initiatives (quantum, AI/ML)

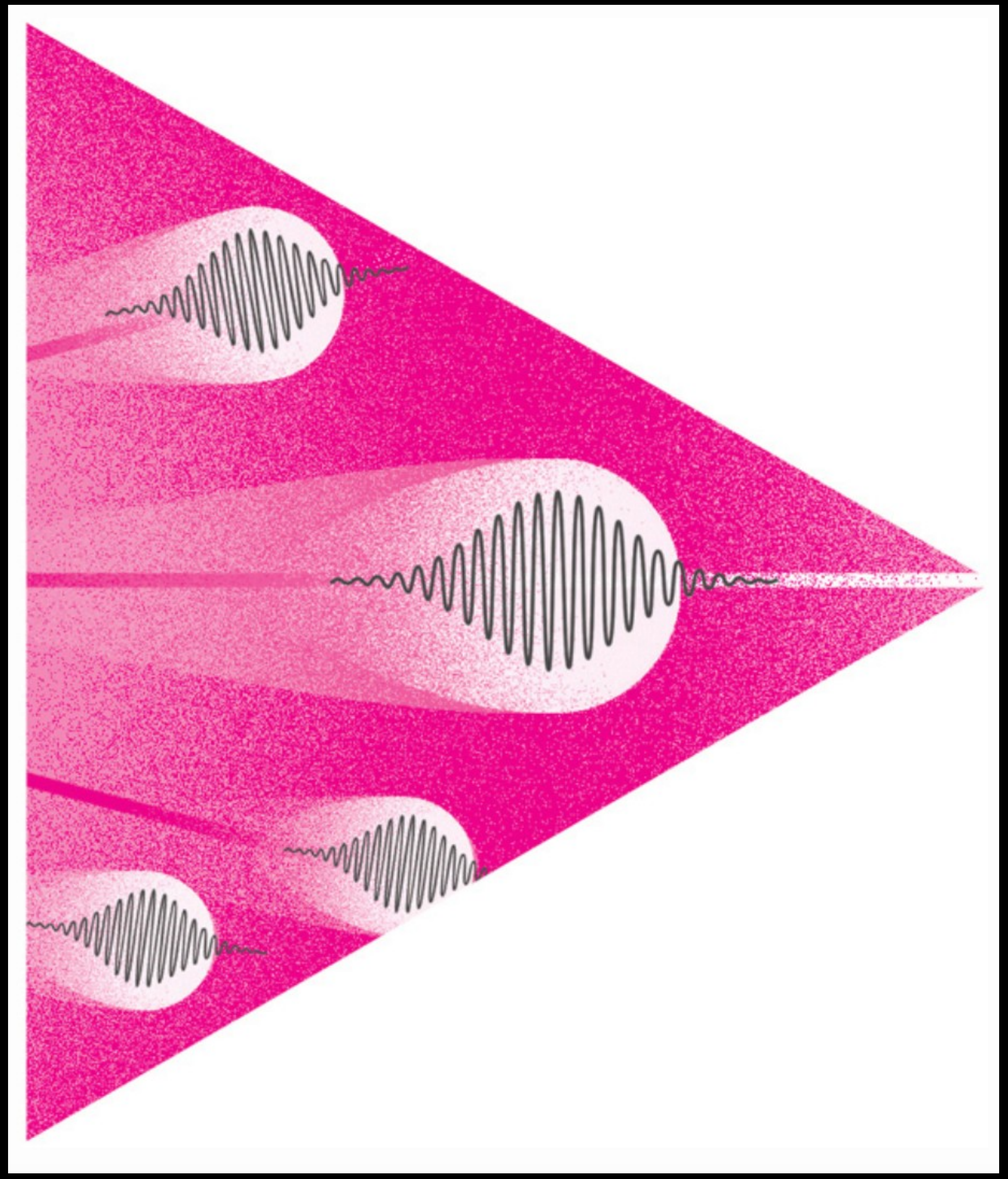
* pCM: parton center-of-momentum
~ same as CM for lepton colliders
~ 1/10 of CM for proton colliders

| Decipher the Quantum Realm | Explore New Paradigms in Physics | Illuminate the Hidden Universe |
|---|---|---|
| Elucidate the Mysteries of Neutrinos | Search for Direct Evidence of New Particles | Determine the Nature of Dark Matter |
| Reveal the Secrets of the Higgs Boson | Pursue Quantum Imprints of New Phenomena | Understand What Drives Cosmic Evolution |



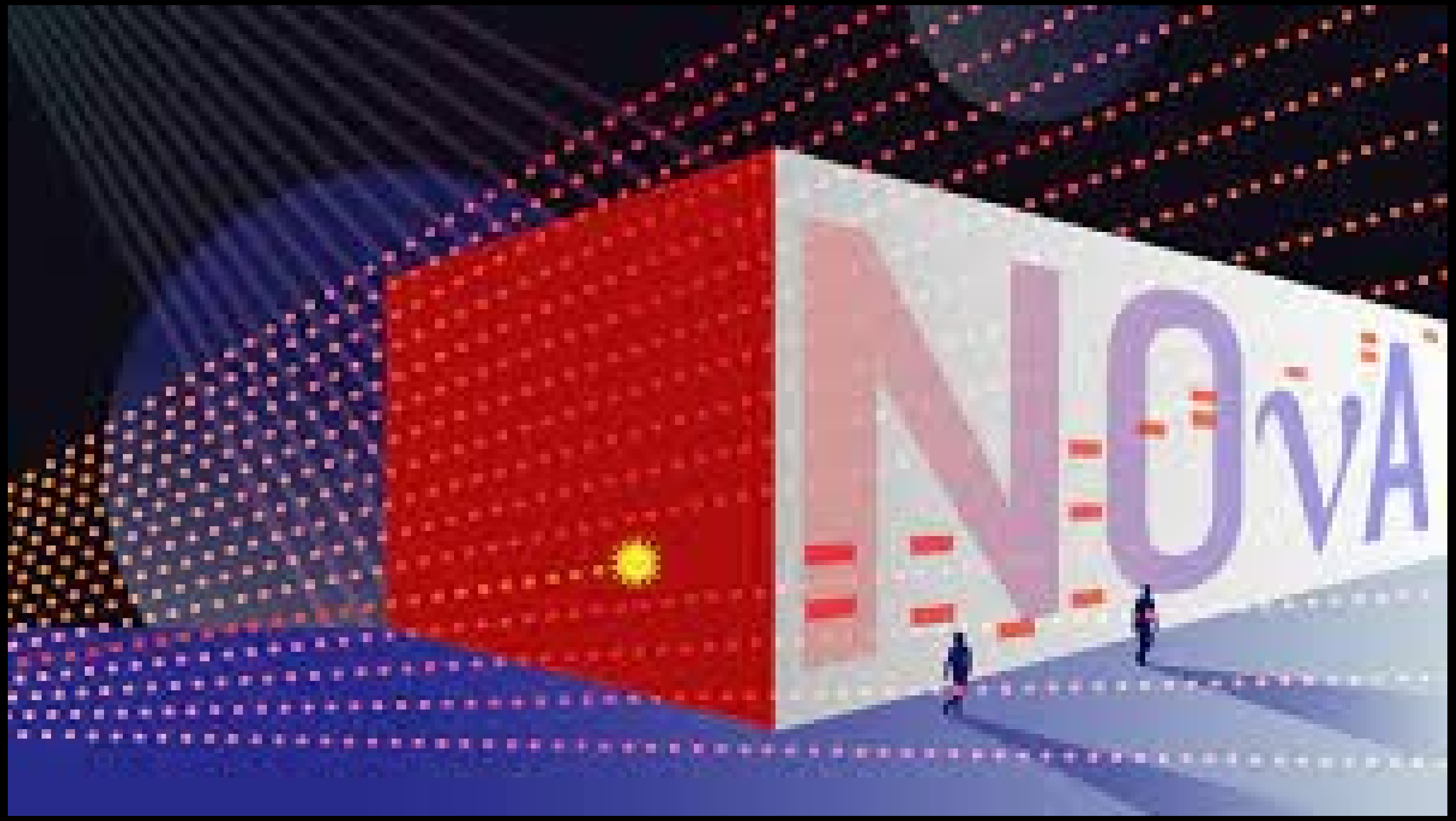
# Elucidate the mysteries of neutrinos

# Elucidate the Mysteries of Neutrinos

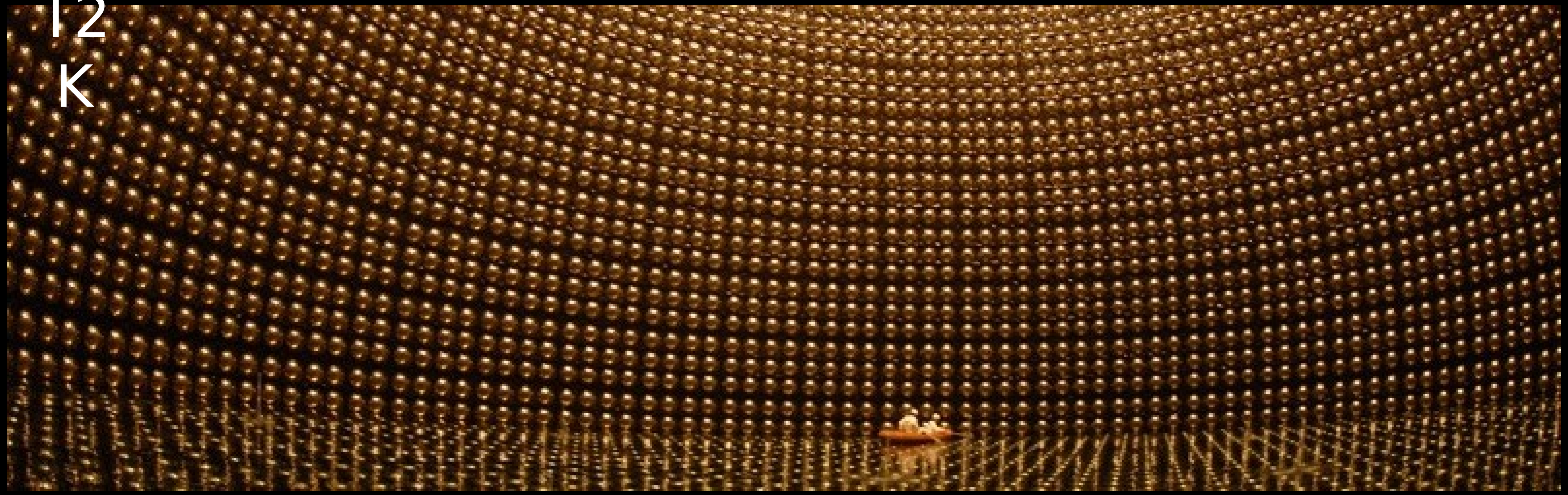


- **What are the masses of neutrinos?**
- **What is the mass ordering of neutrinos? If inverted, might a new symmetry be needed to account for two heavier neutrinos having similar masses?**
- **Are neutrinos their own antiparticles? Can this help us explain the matter-dominated universe we are in?**
- **Do antineutrinos oscillate differently than neutrinos? (Is CP symmetry violated?) Can this explain the matter-dominated universe we are in?**
- **What astrophysical phenomena can neutrinos open to us?**

# p Priority: Complete Ongoing Experiments

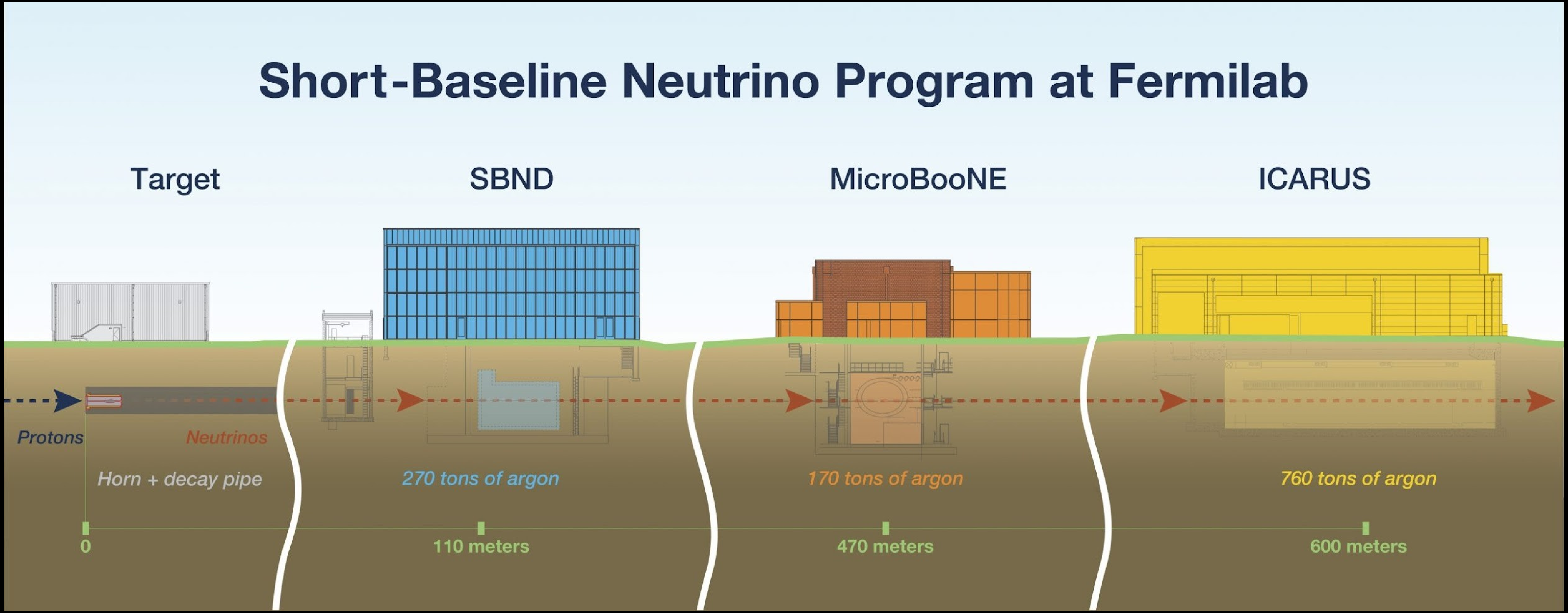



T2K



- **Nova and T2K have pioneered electron neutrino and antineutrino appearance observations.**
- **They have made tremendous contributions toward approached for dealing with systematics uncertainties for mass ordering, CP violation, and mass mixing parameter measurements.**

# Top Priority: Complete Ongoing Experiments

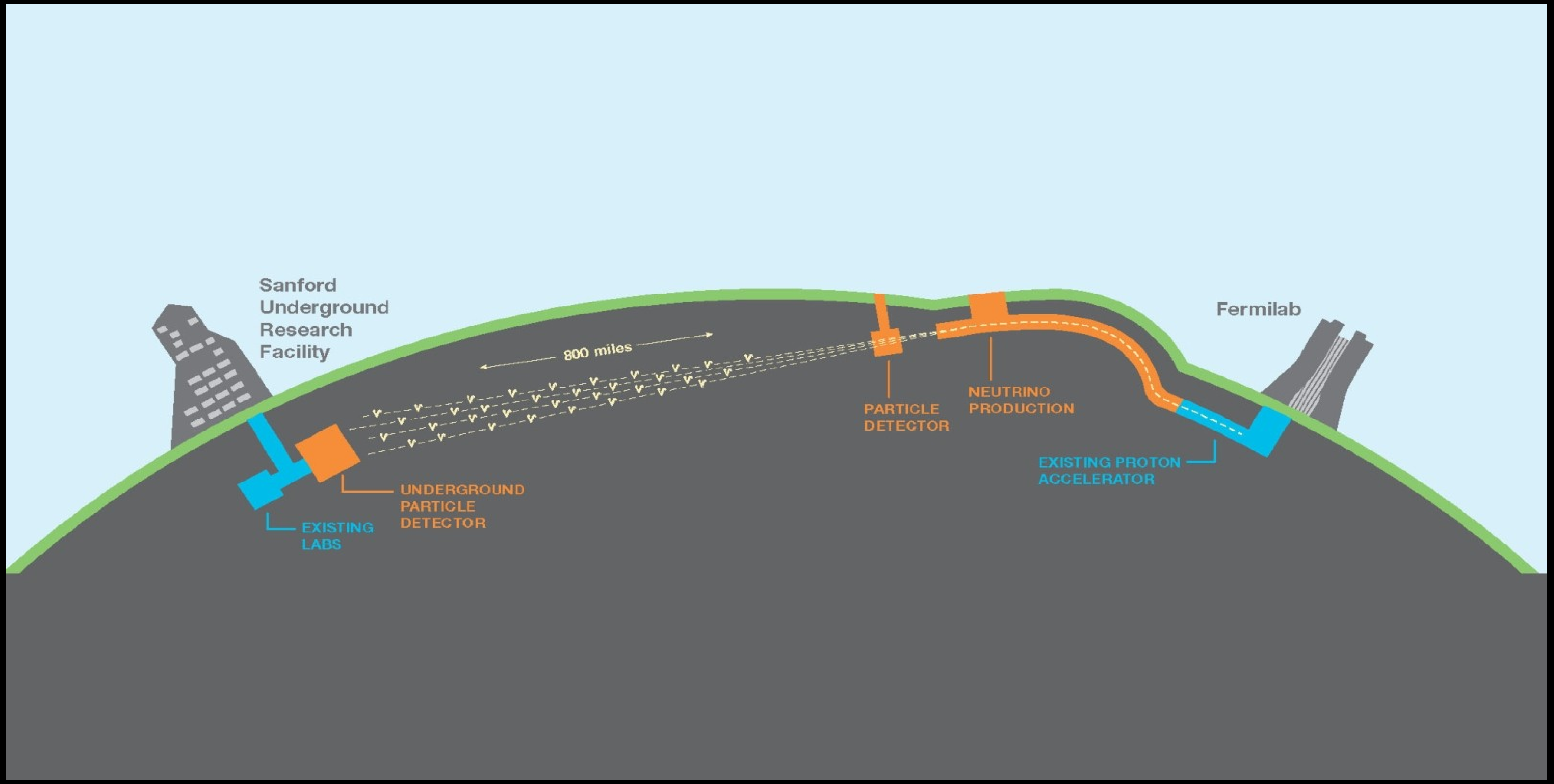


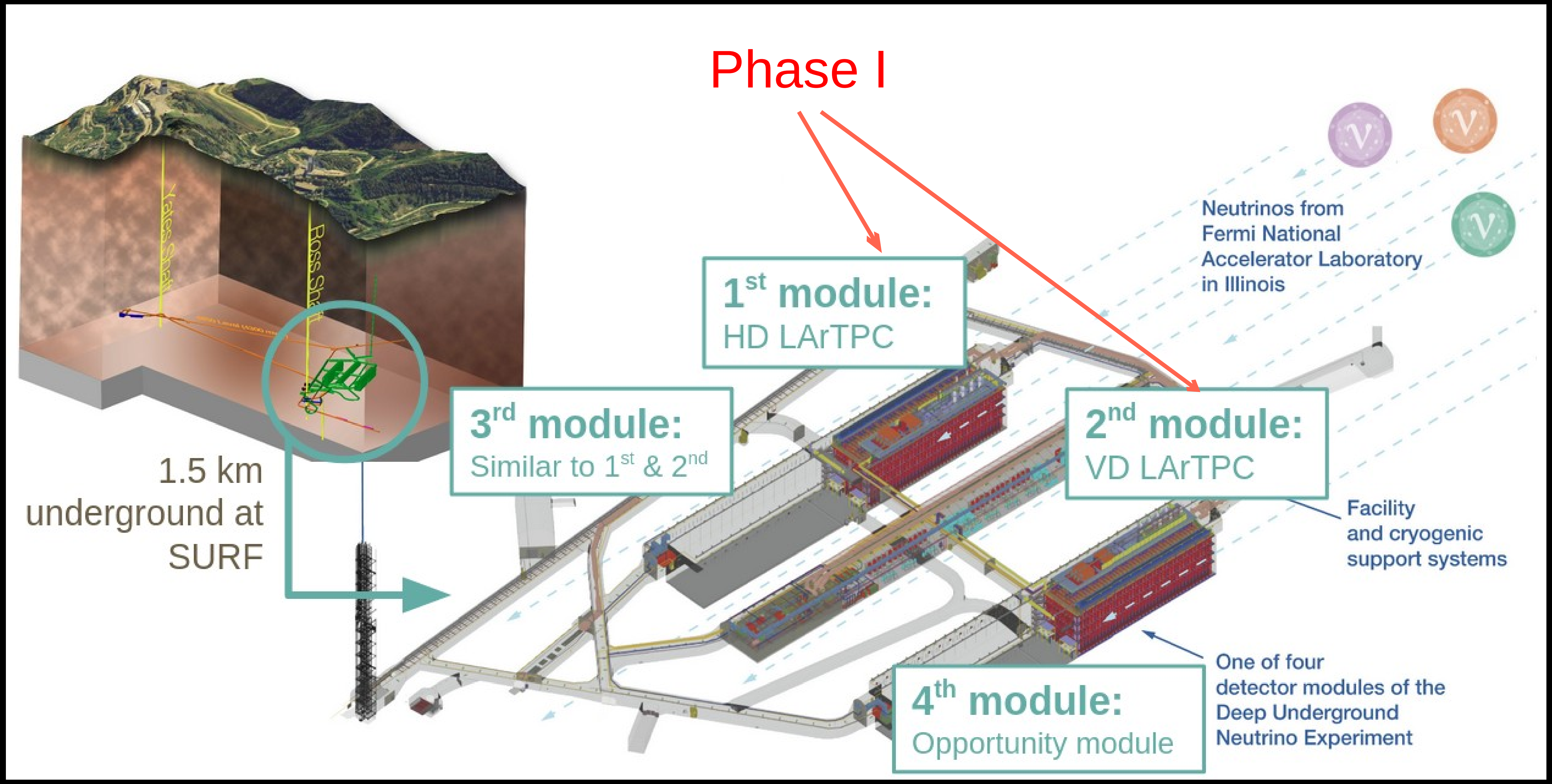

**The SBN program has explored numerous anomalous results. Additionally, they have proved crucial in maturing liquid argon technology and analysis.**

# Top Priority: Complete LBNF/DUNE Phase I

## DUNE Phase-I:

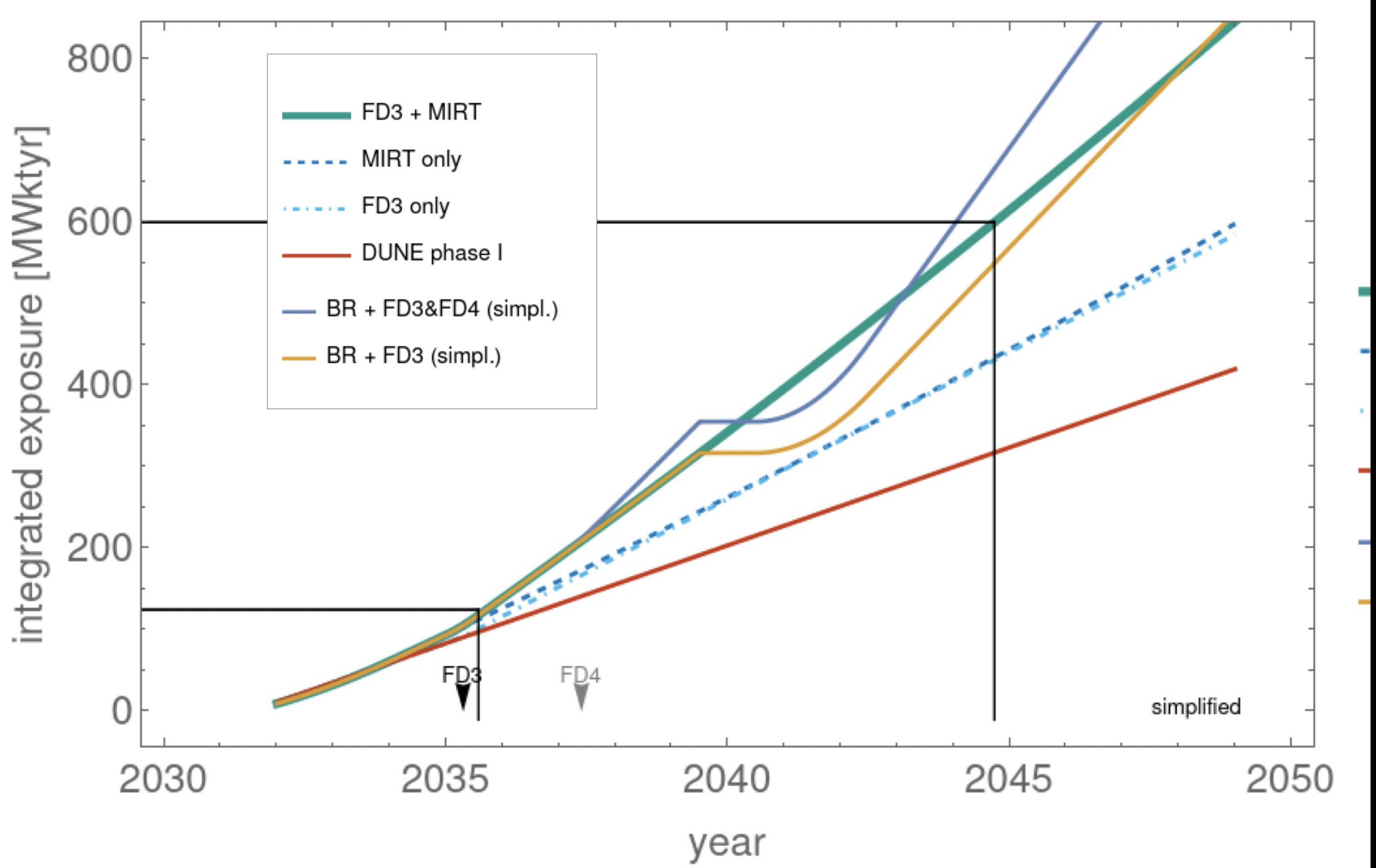
- Two **10 kt LArTPCs** at Sanford Underground Research Facilities (SURF).
- A **near detector facility**, illuminated by the **world's brightest neutrino beam.**
- The **PIP-II accelerator upgrade** under construction, which will enable a 1.2 MW proton beam.
- First goal? **Mass ordering**, with some sensitivity to the **CP-violating phase**.
- Also, sensitivity to electron neutrino component of a **supernova burst**!



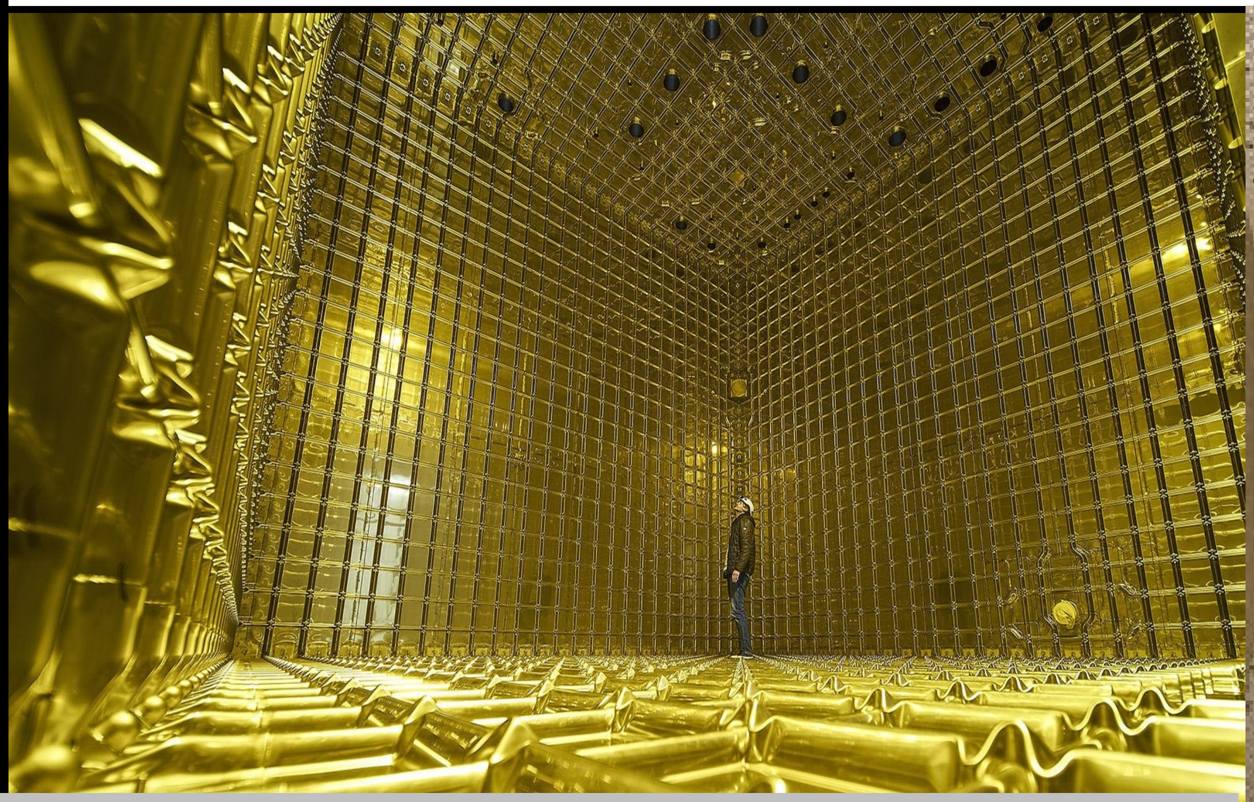
# Major Project this decade: A reimagined DUNE Phase II

- **Include an early implementation of ACE-MIRT with the enhanced 2.1-MW beam.**
- **A third far detector at SURF.**
- **An upgraded near detector complex to aid in controlling systematics and search for BSM physics.**
- **R&D for the fourth far detector technology**

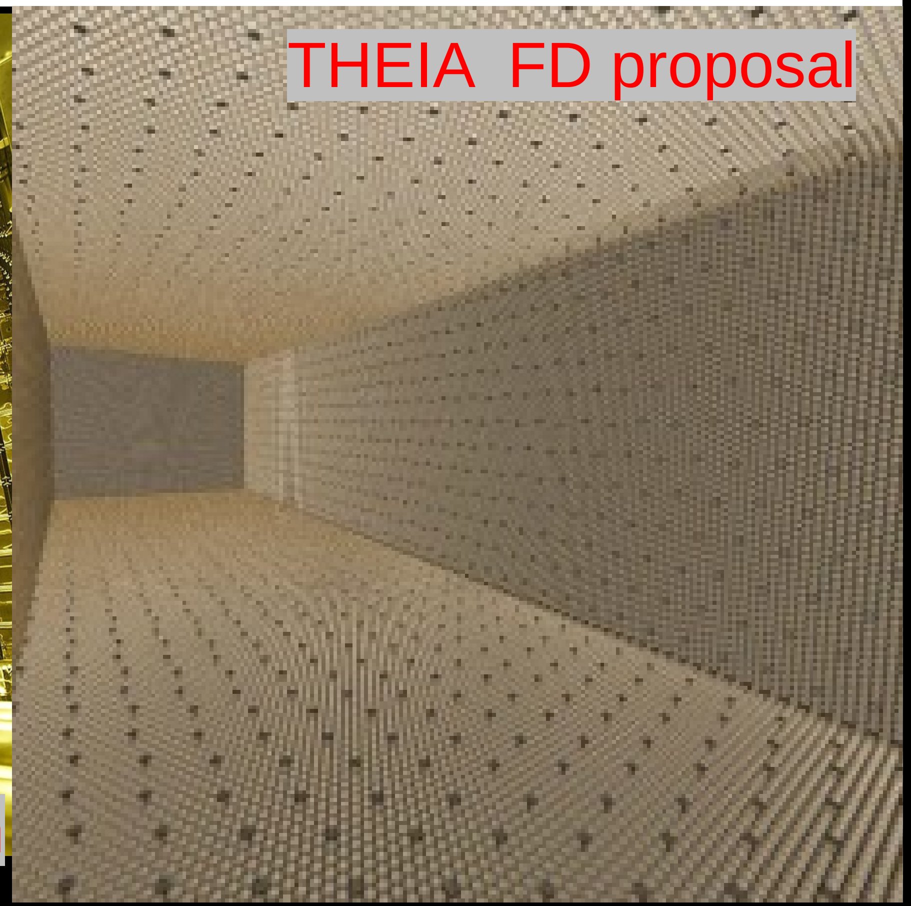



## Science goals:

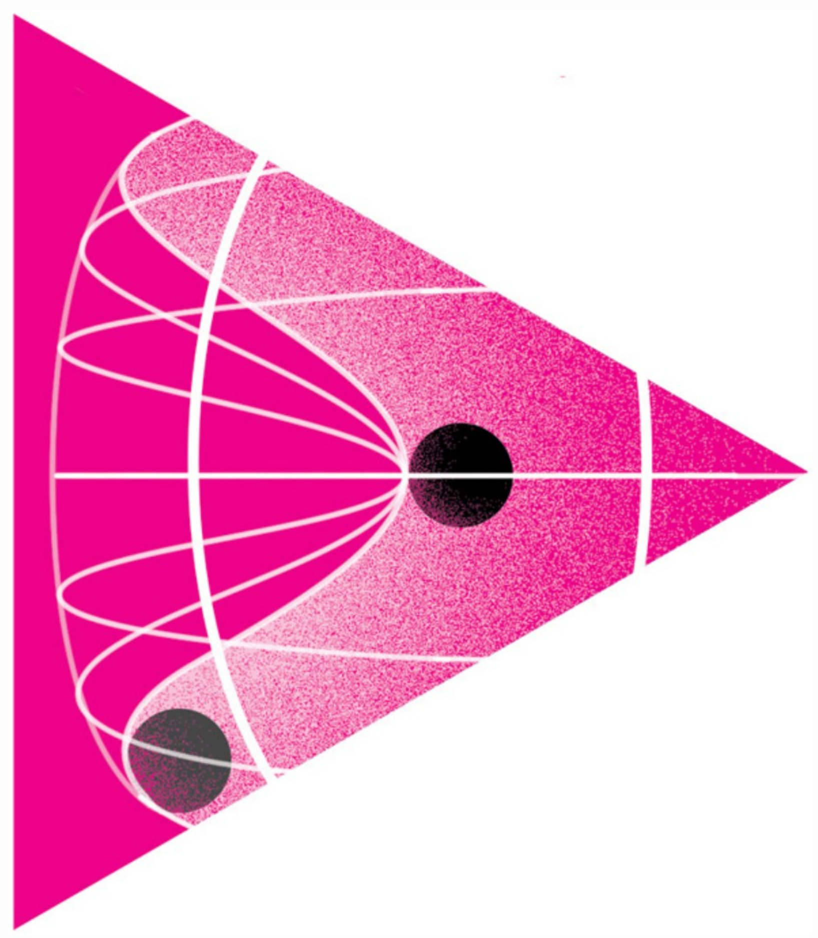
- **Most precise measurement of the CP phase across a range of possible CP phase space**
- **Comprehensively test validity of 3-neutrino framework with best-in-class precision.**
- **Search for signatures of unexpected neutrino interactions.**
- **Study direct appearance of tau neutrinos.**



ProtoDUNE – demonstrator of current FD design



THEIA FD proposal



# eveal the secrets of the Higgs boson

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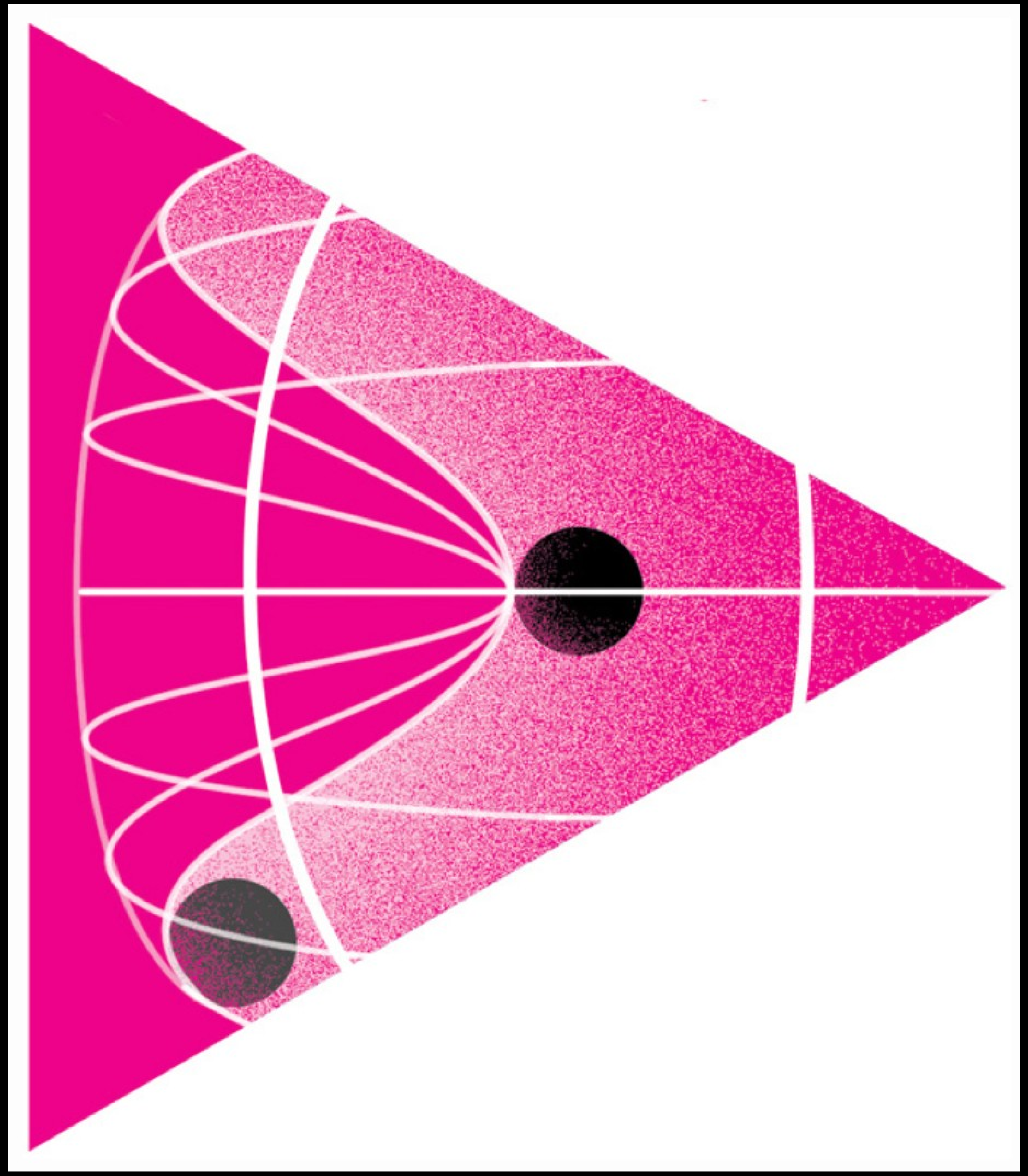
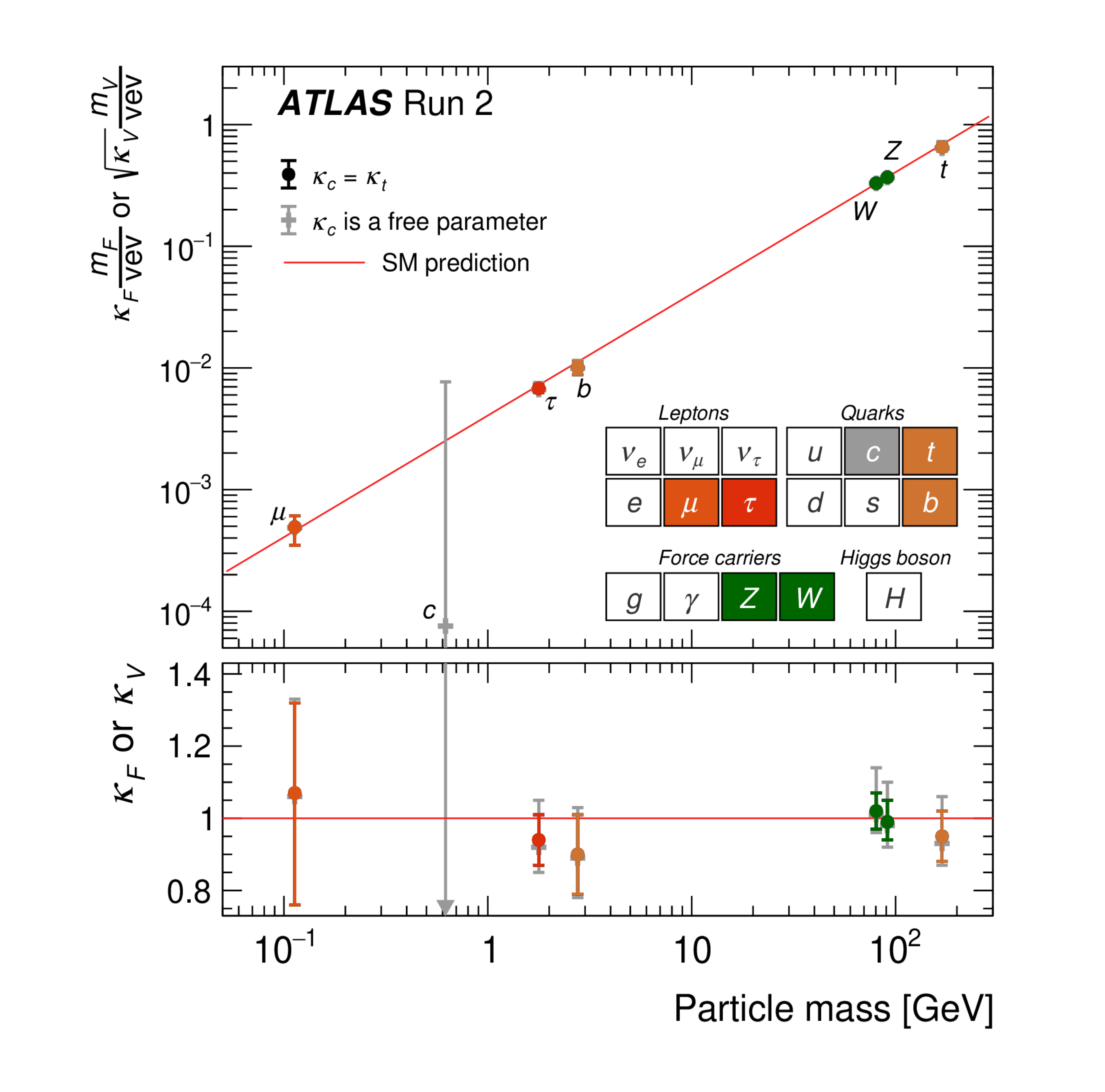


- The properties of the Higgs field are connected to many fundamental questions in particle physics, and as the only known fundamental field with a non-zero value in the vacuum state, it is unique.
- Is the Higgs field fundamental?
- Is there only one Higgs boson, or is there a richer sector containing
  related particle with new dynamics?
- How can the Higgs mass be so low - are there additional particles
  with similar masses to stabilize it?
- Can the Higgs boson decay to non-Standard Model particles?
- Why is there the huge range of coupling strengths to the Higgs
  in the Standard Model?

# Top Priority: Complete Ongoing ATLAS and CMS Experiments at the LHC

**Higgs boson measurements:**

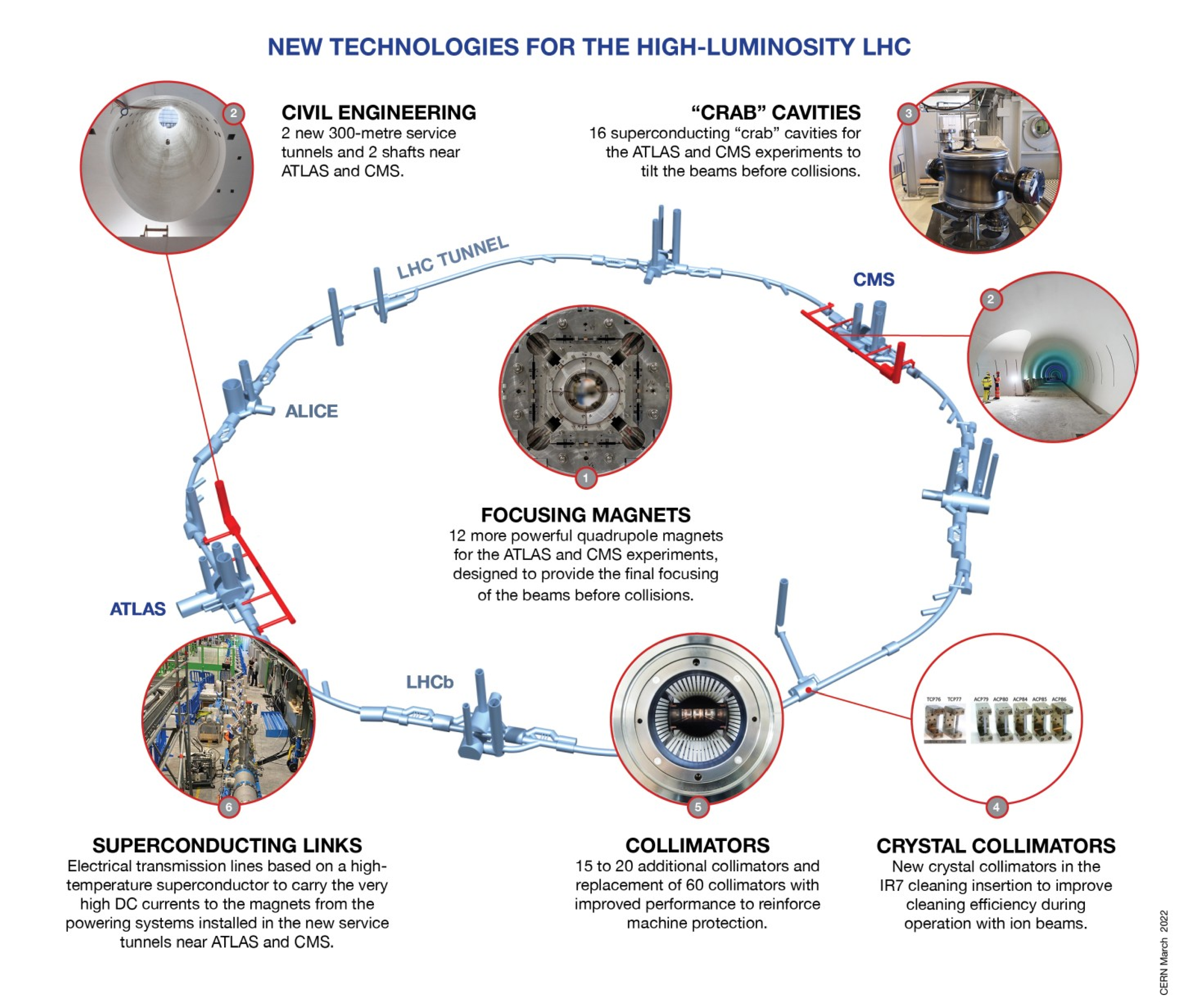
- **mass measured to better than 0.2%**
- **established to have zero spin**
- **lifetime measurements made using model-dependent quantum interference effects**
- **multiple couplings measured to 5-10% precision**
- **major production modes observed**



# Top priority: Complete the HL-LHC

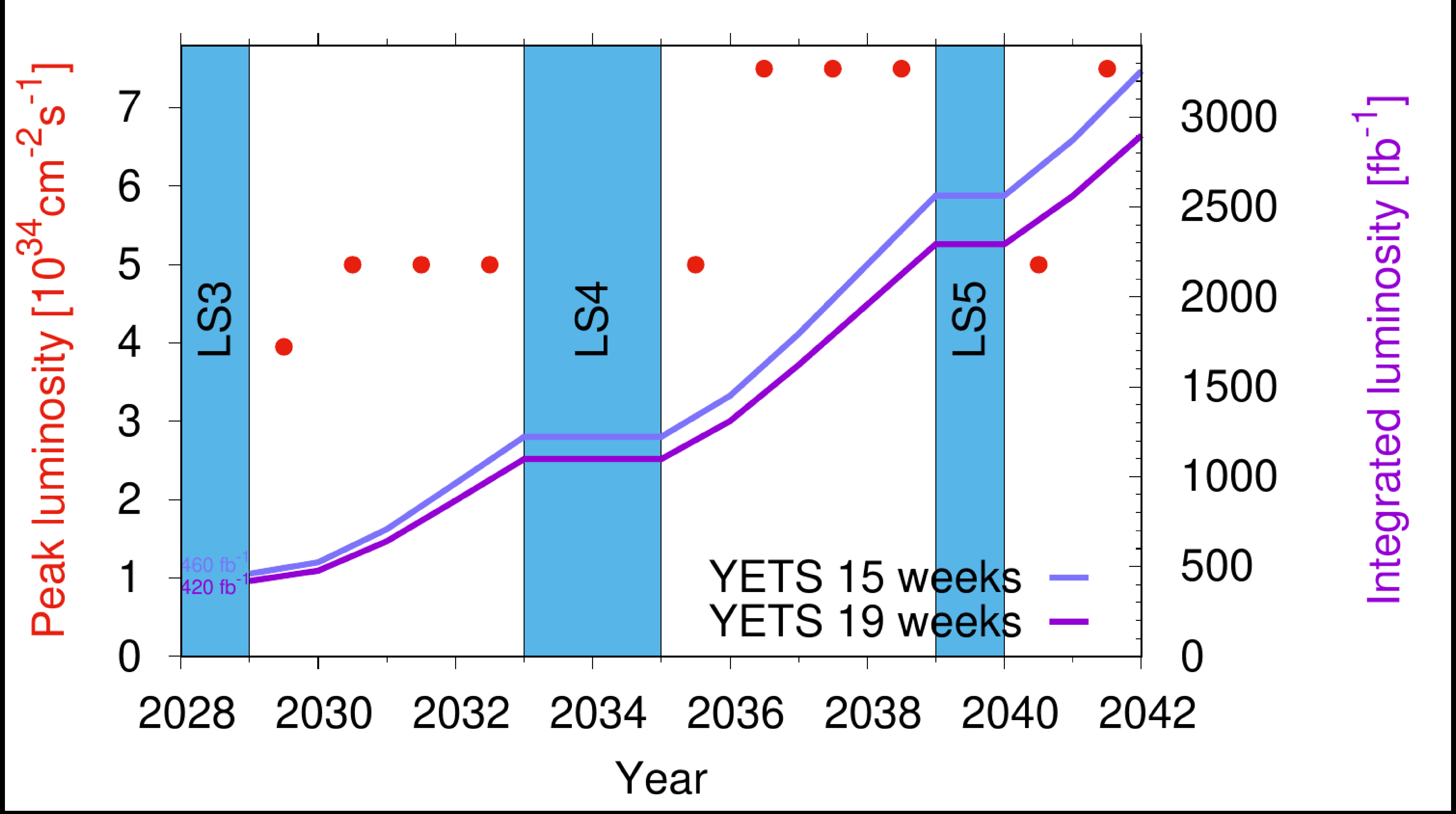
## Higgs boson measurements:

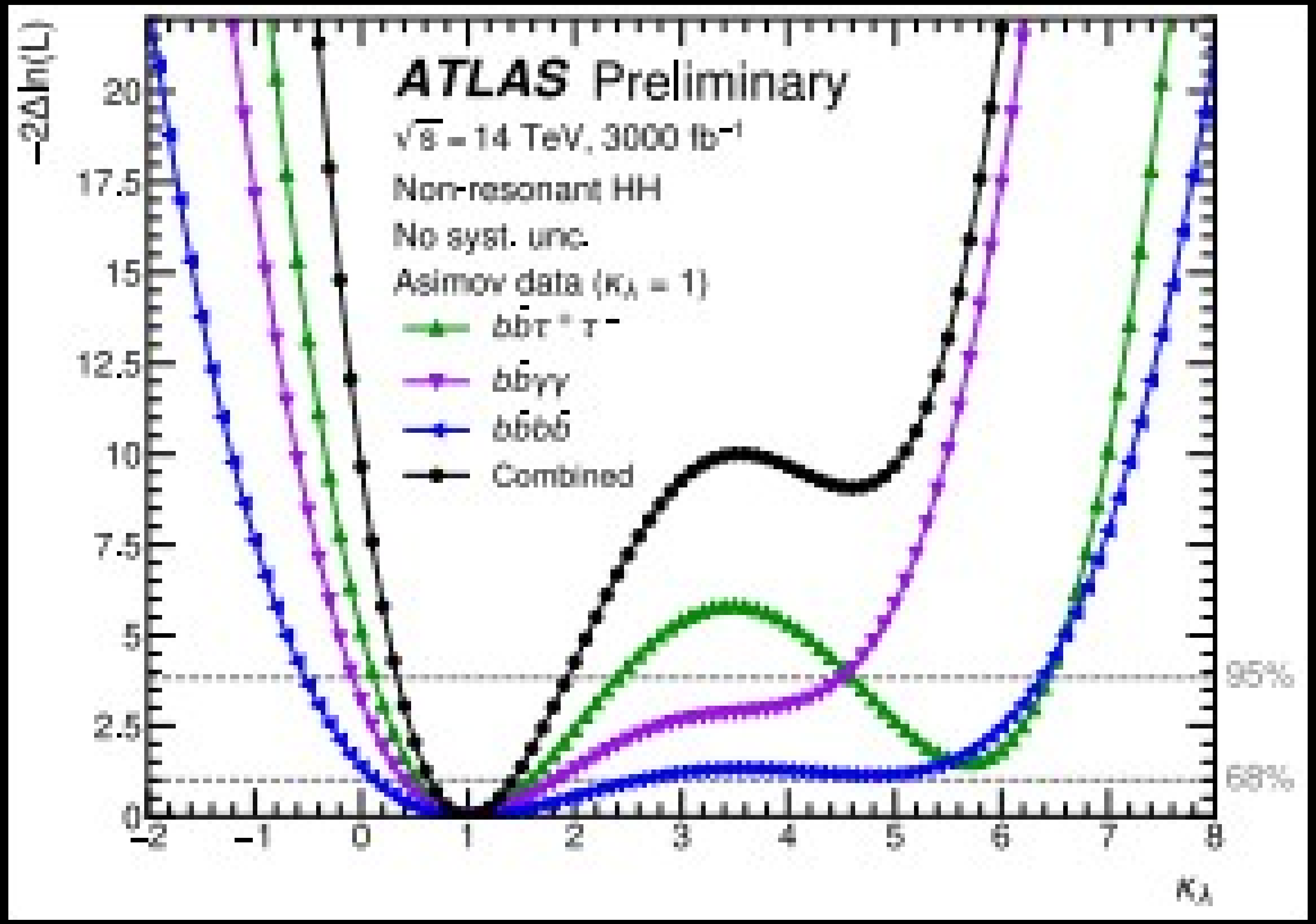
- **SM couplings measured to few percent, or lower, for many particles.**
- **Increased sensitivity to BSM physics.**
- **Probing of Higgs potential: how strongly does the Higgs boson couple to itself?**



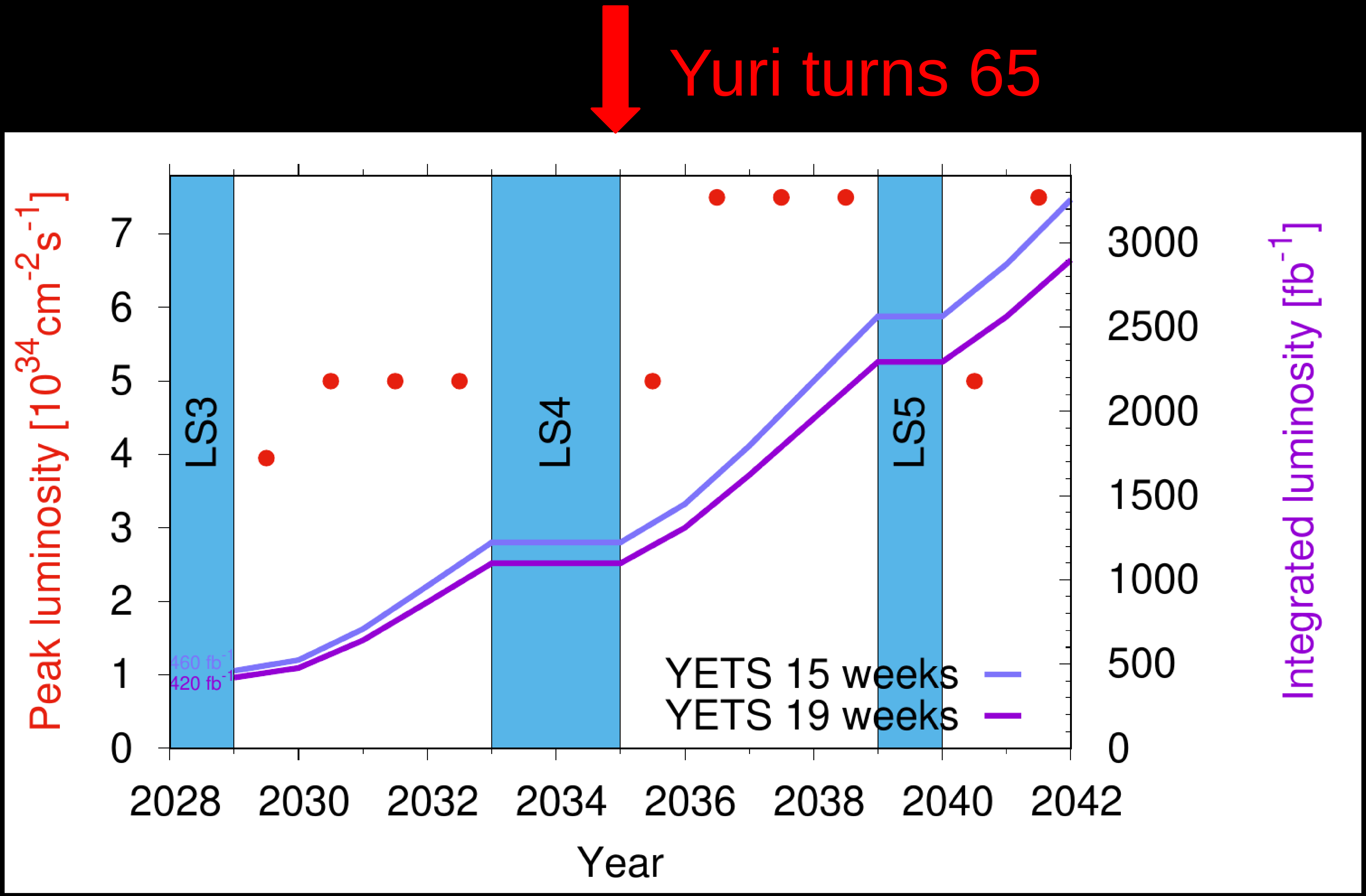
# Top priority: Complete the HL-LHC

- 200 million Higgs bosons!
  - Natural width of the Higgs is small, so even tiny couplings to dark / hidden sectors are measurable
- First real stab at Higgs self-coupling measurement
- Lots of territory yet for new physics



# Top priority: Complete the HL-LHC

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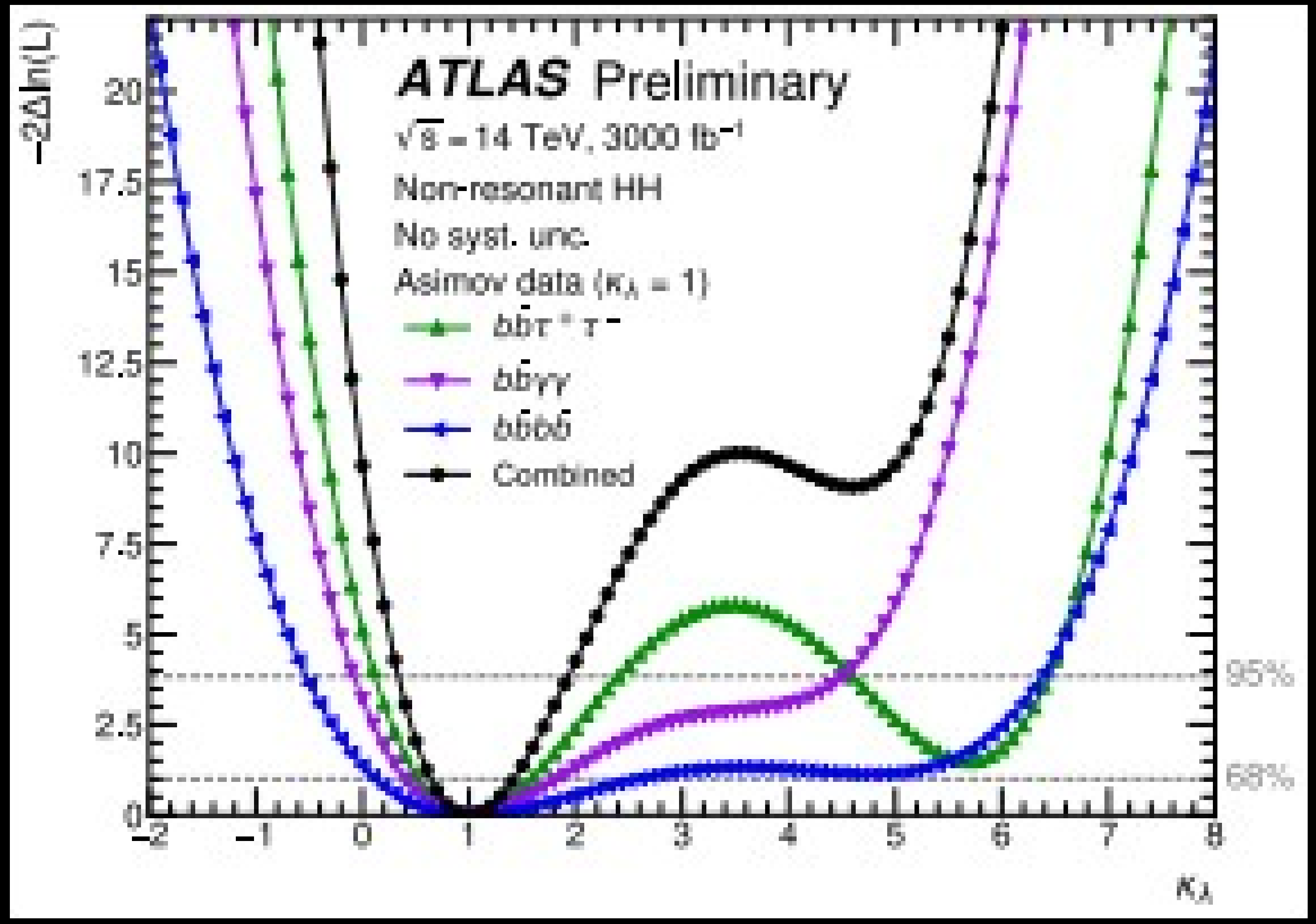


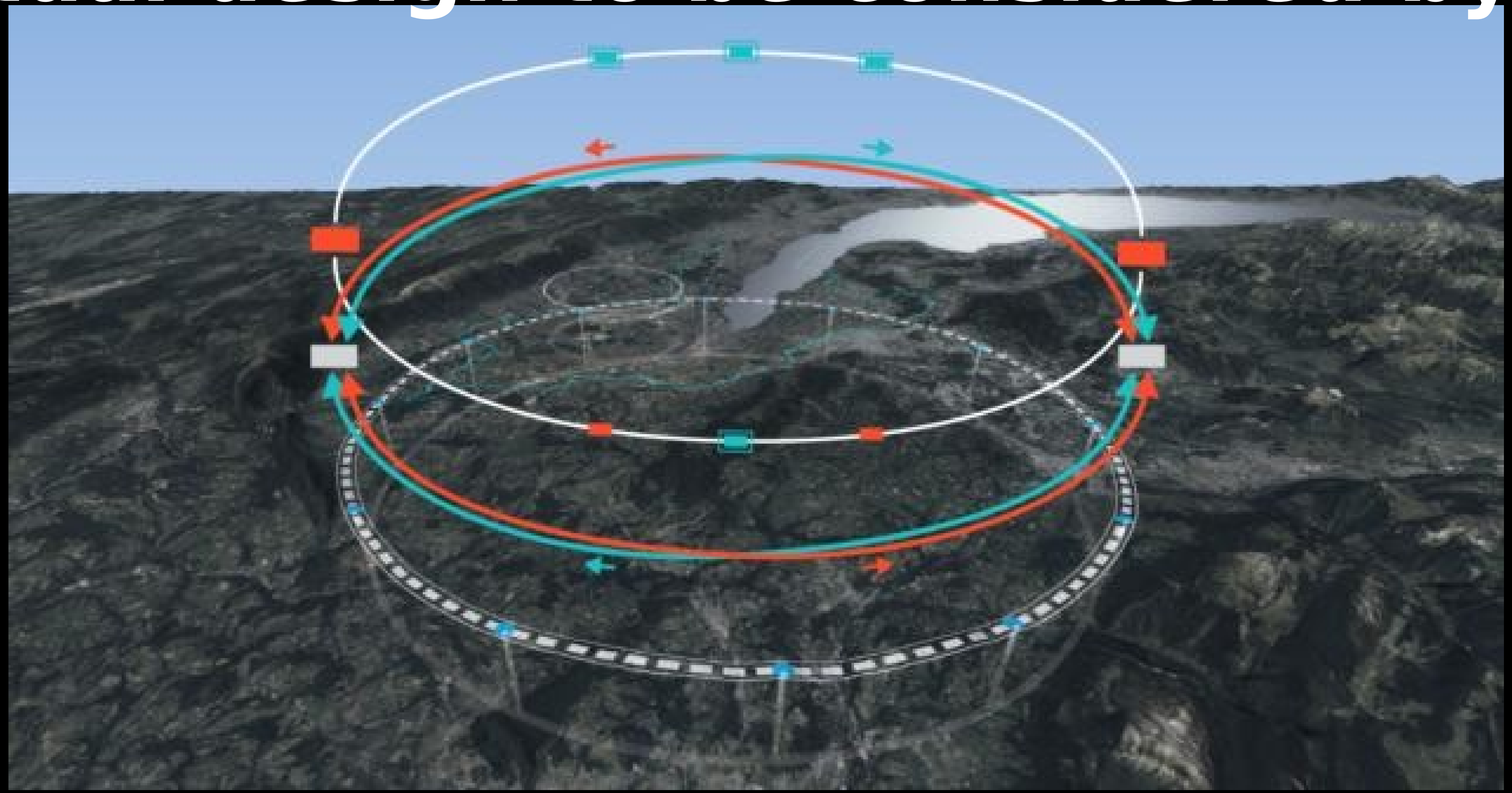
# Major Project this decade: An Offshore Higgs Factory

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

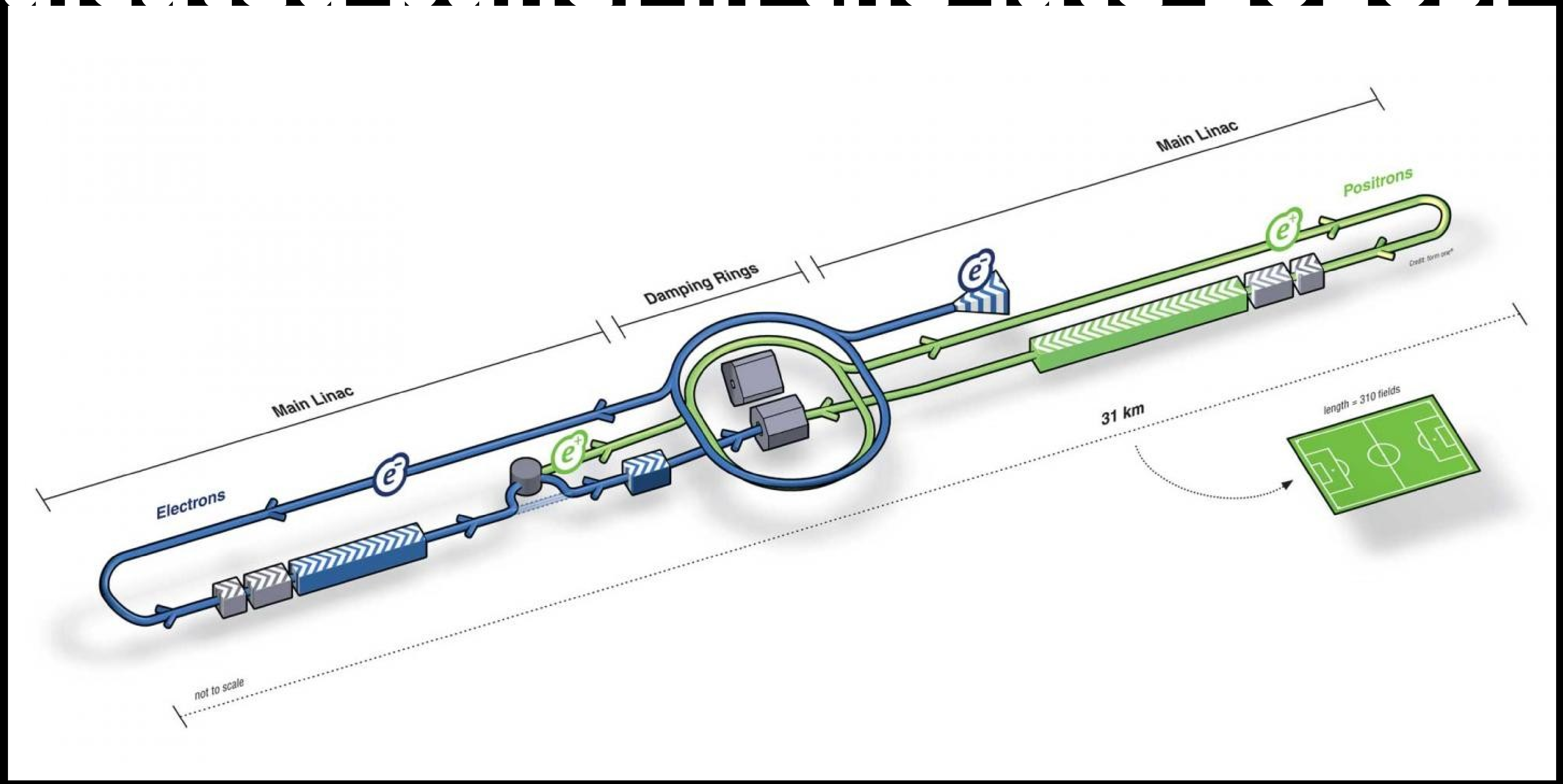
- **Clean tagged sample of Higgs bosons (same size as unbiased Higgs sample at the LHC, but much better signal/background and clean environment to identify exotic decays)**
- **Precision measurements of couplings (factors 2-10 improvement over LHC).**
- **EW sector consistency checks, testing through 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.**

**Actual design to be considered by a dedicated panel in the late 2020s.**

**FCC-ee at CERN**



**ILC in Japan**



# Definitively explore Higgs potential

Higgs potential is an ad-hoc part of the Standard Model

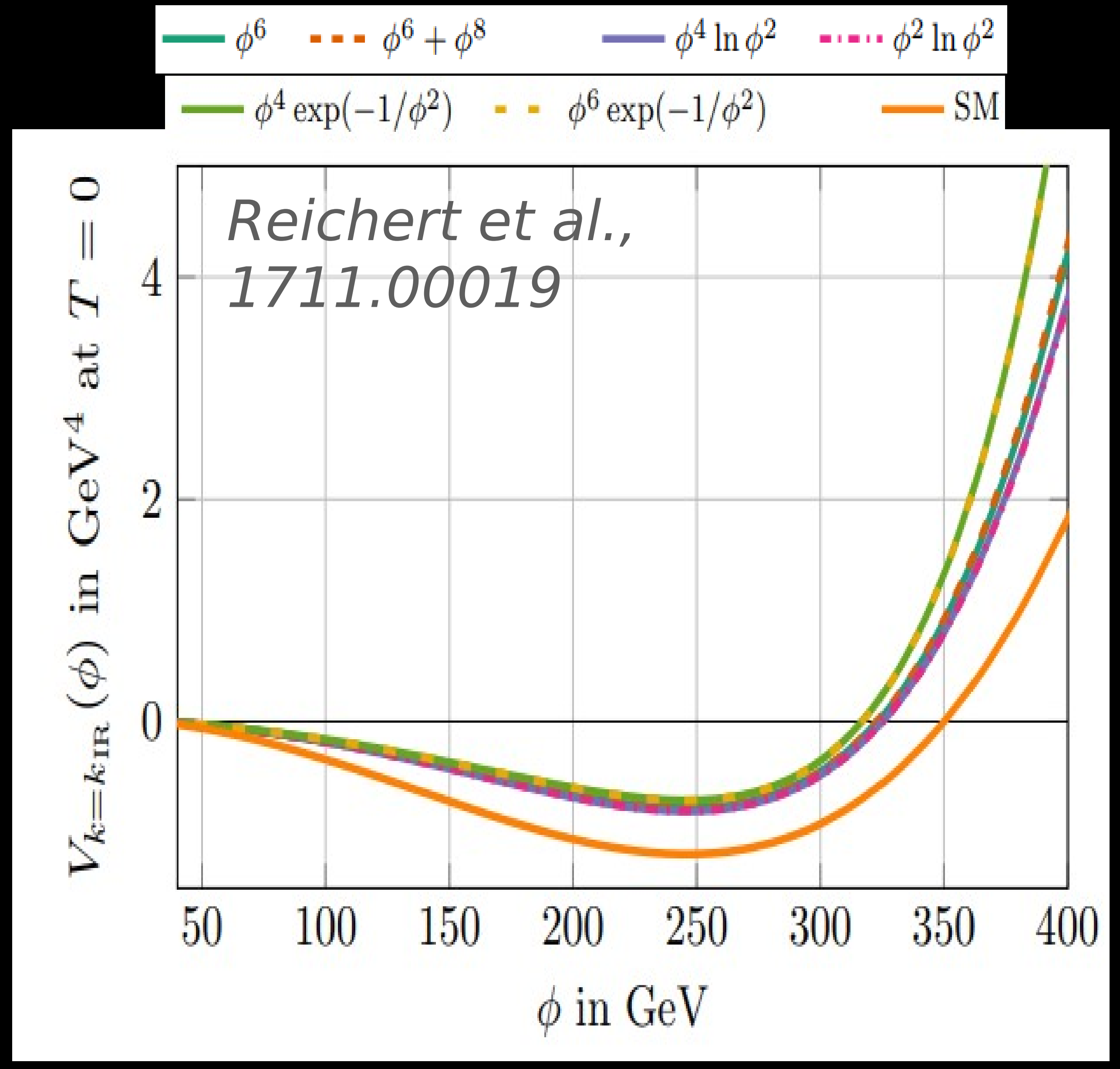
- Ginsburg-Landau as opposed to BCS
- Measuring it can reveal the underlying fundamental theory

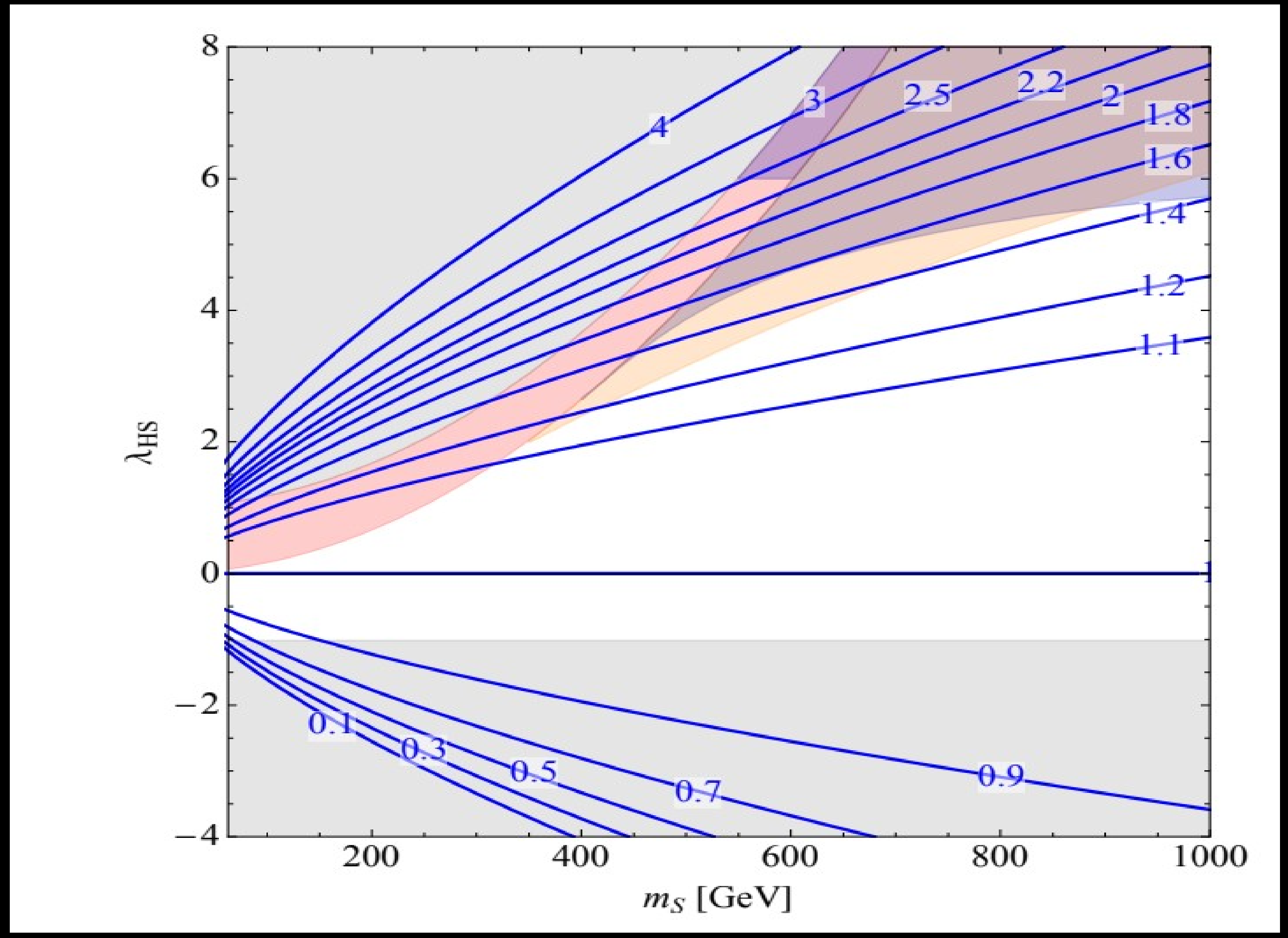
Cosmological connection: electroweak baryogenesis

- SM Higgs potential does not result in strong type 1 EWK phase transition necessary for baryogenesis – but slight modifications of the potential could, and they would be detectable at high energy (10 TeV pCM* or larger) collider

Additional scalars

- Can solve hierarchy and EWK baryogenesis. Even simple extensions of the Higgs sector are hard to discover. Studies suggest at least 10 TeV pCM* for good coverage



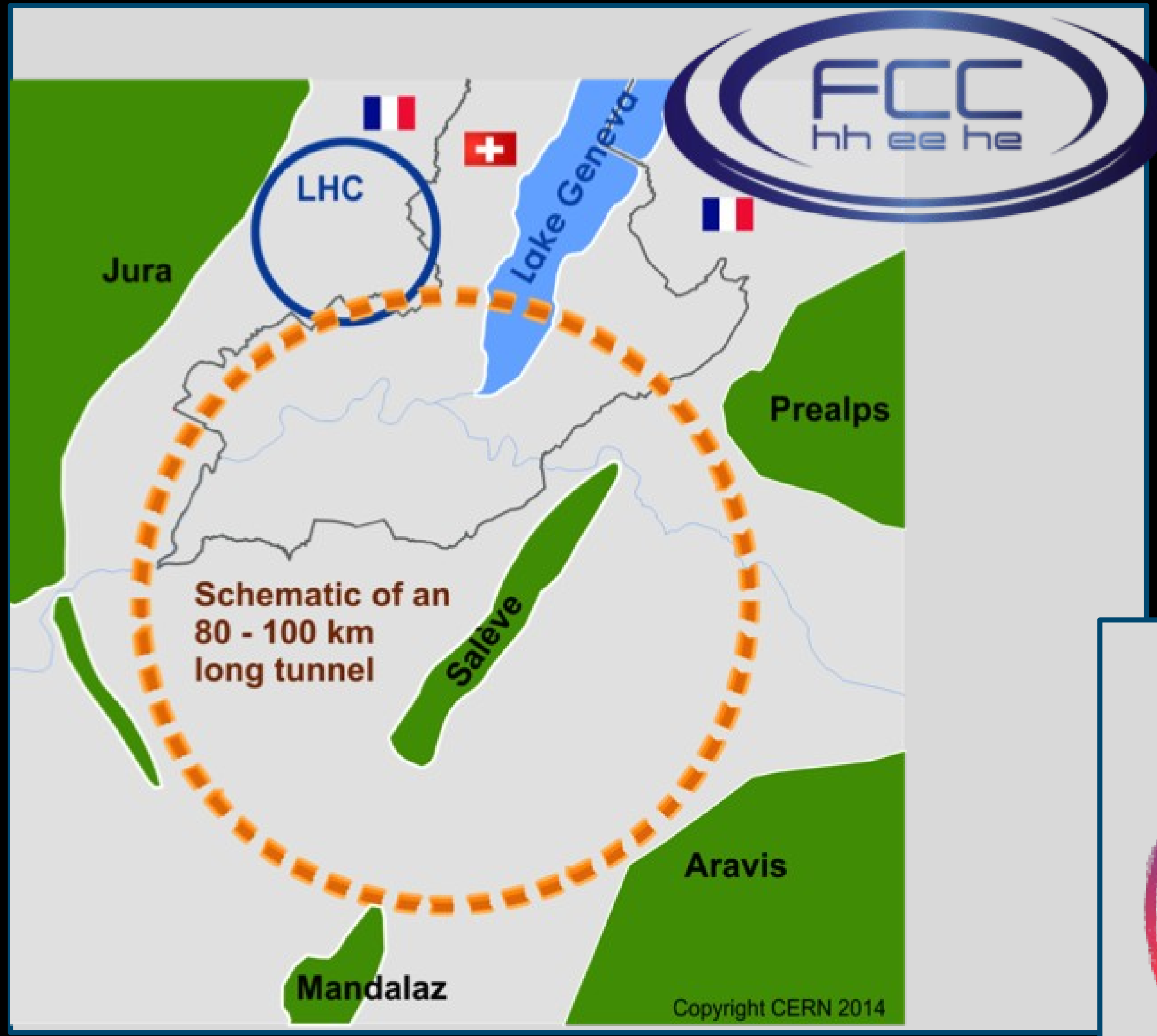




Curtin et al., 1409.0005

*Parton center-of-momentum

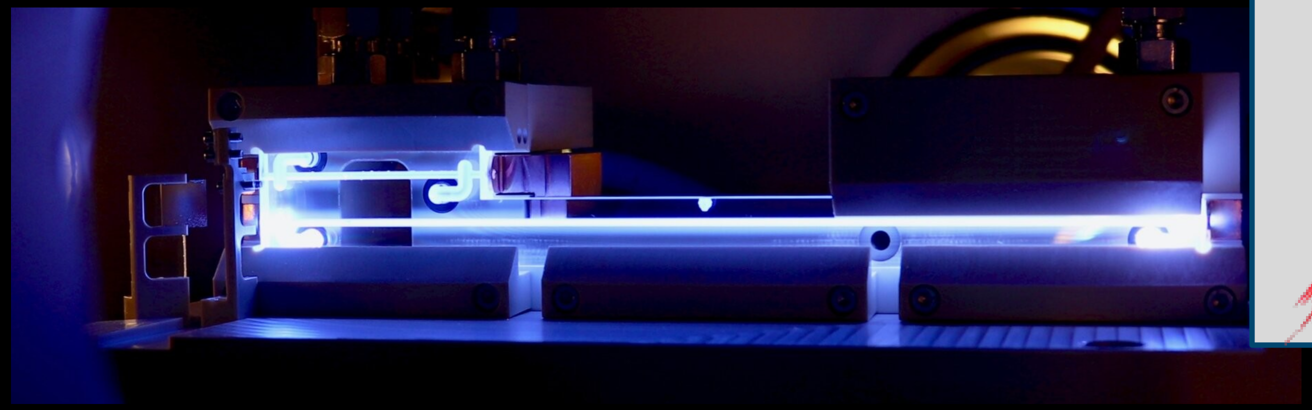
# Investing in the future: R&D towards a 10 TeV pCM* collider

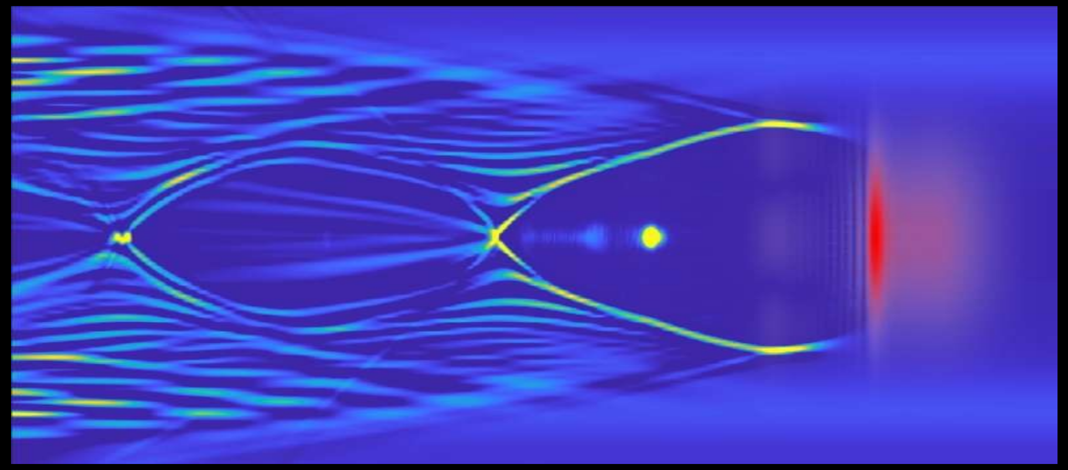
- **Next frontier of high-energy physics is at the 10-TeV scale per parton.**
- **Don’t currently have the technology to build such a machine in a cost-effective way.**
- **Recommend a dedicated R&D effort towards such a machine with the goal of having demonstrator facilities by the end of this decade.**




## Three possible concepts:

- **Proton collider (huge tunnel and high field magnets).**
- **Wakefield $e^+e^-$ collider (efficiency and luminosity)**
- **Muon Collider (muon cooling, fast cycling her challenges)**





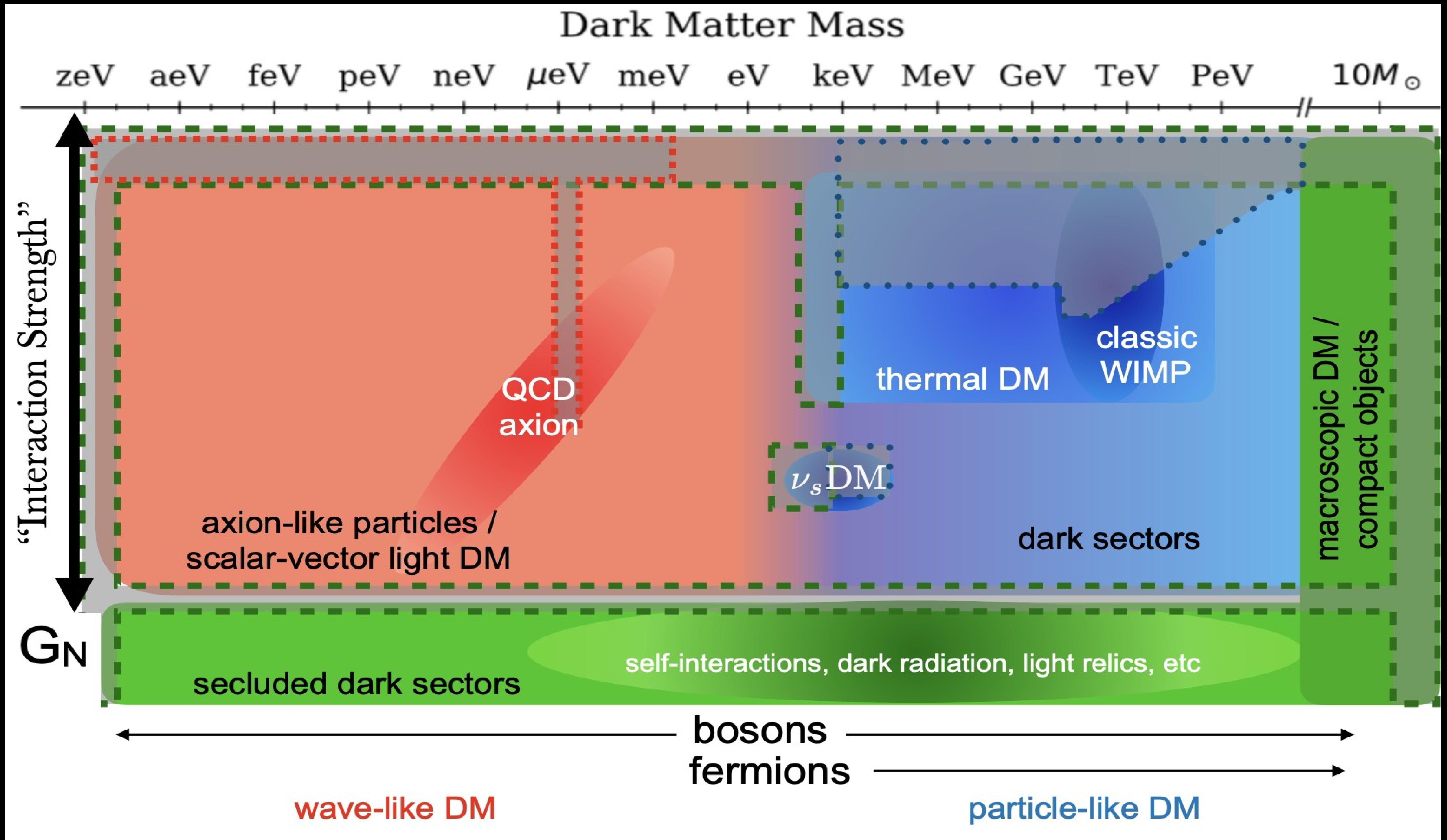
*Parton center-of-momentum

# Determine the nature of dark matter

# Determine the Nature of Dark Matter

- Dark matter constitutes the majority of the universe's mass, but its interactions beyond gravity remain unknown.
- Cosmic Surveys: probe the distribution of dark matter on a variety of length scales.
- Accelerator-based experiments: attempt to produce dark matter particles.
- Indirect detection experiments: look for cosmic messengers resulting from dark matter interactions
- Direct detection: focus on detecting dark matter's interactions here on Earth.

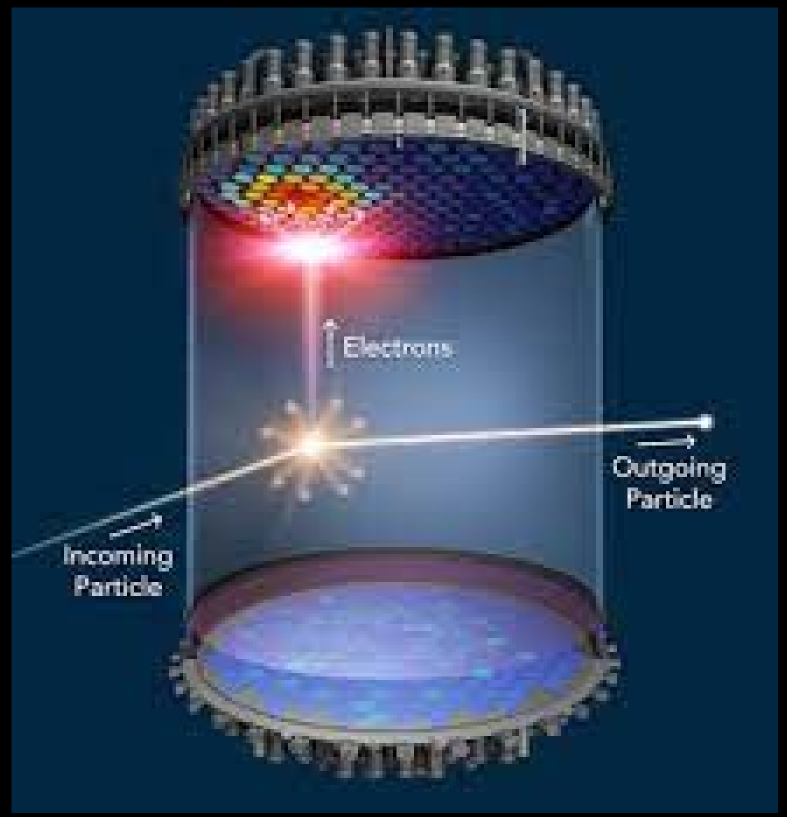
- Enormous range of possibilities for what dark matter can be.
  - Handful of particularly compelling candidates.
    - WIMPs may help explain stabilization of particle masses.
    - QCD axions would explain why strong force does not appear to show CP violation.
    - Hidden-sector dark matter and axion-like particles also well motivated.



# Top Priority: Complete Ongoing Experiments

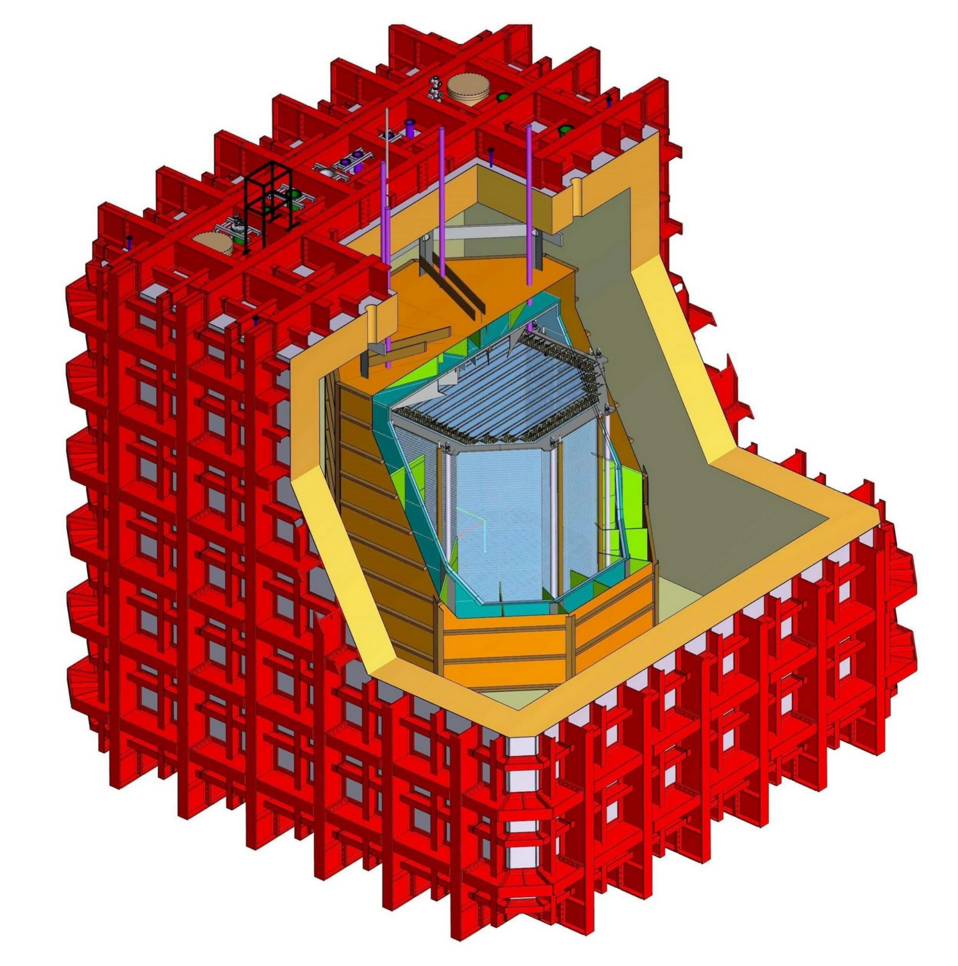
**LHC: could produce EW-scale DM**

**LZ**

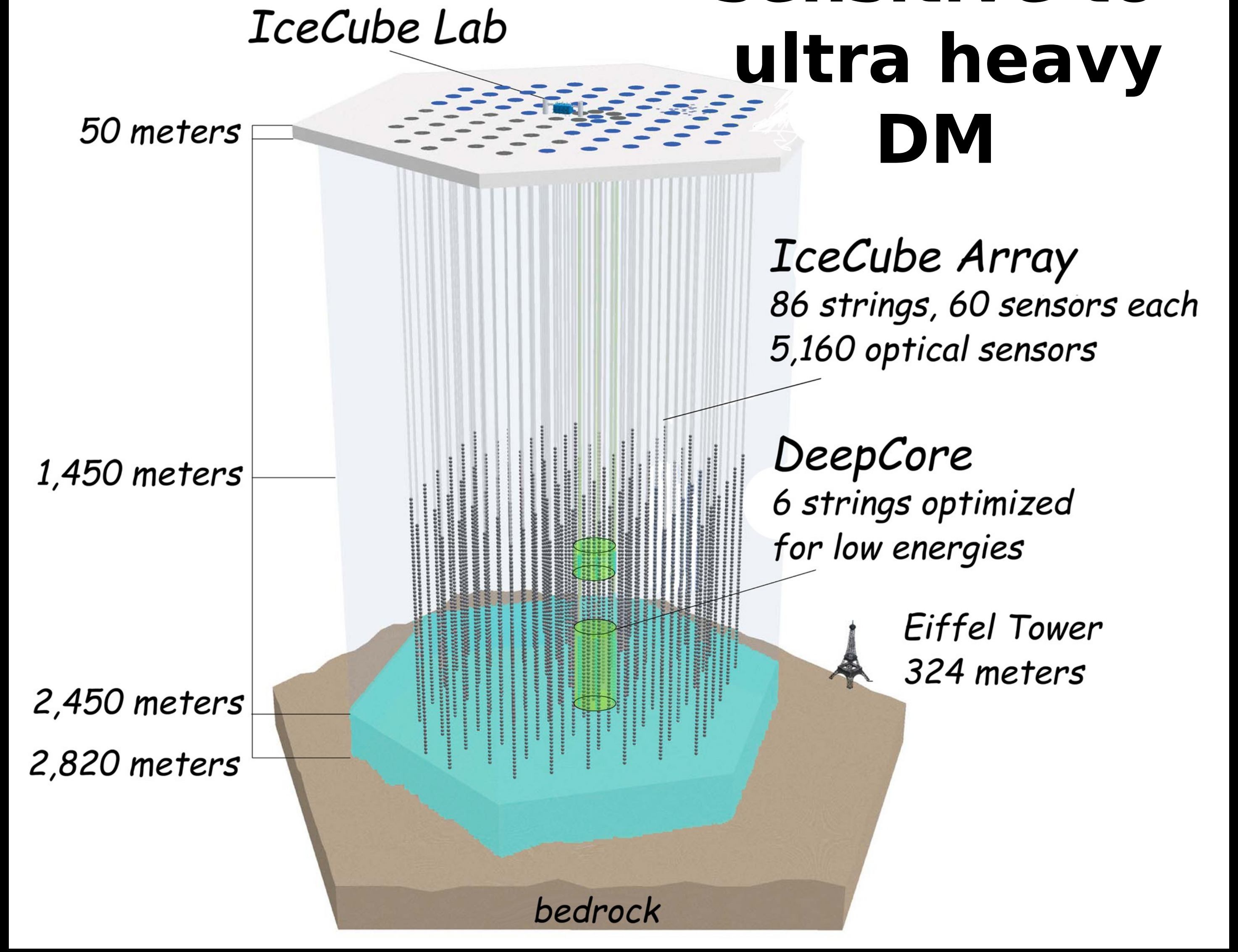



**XENONnT**

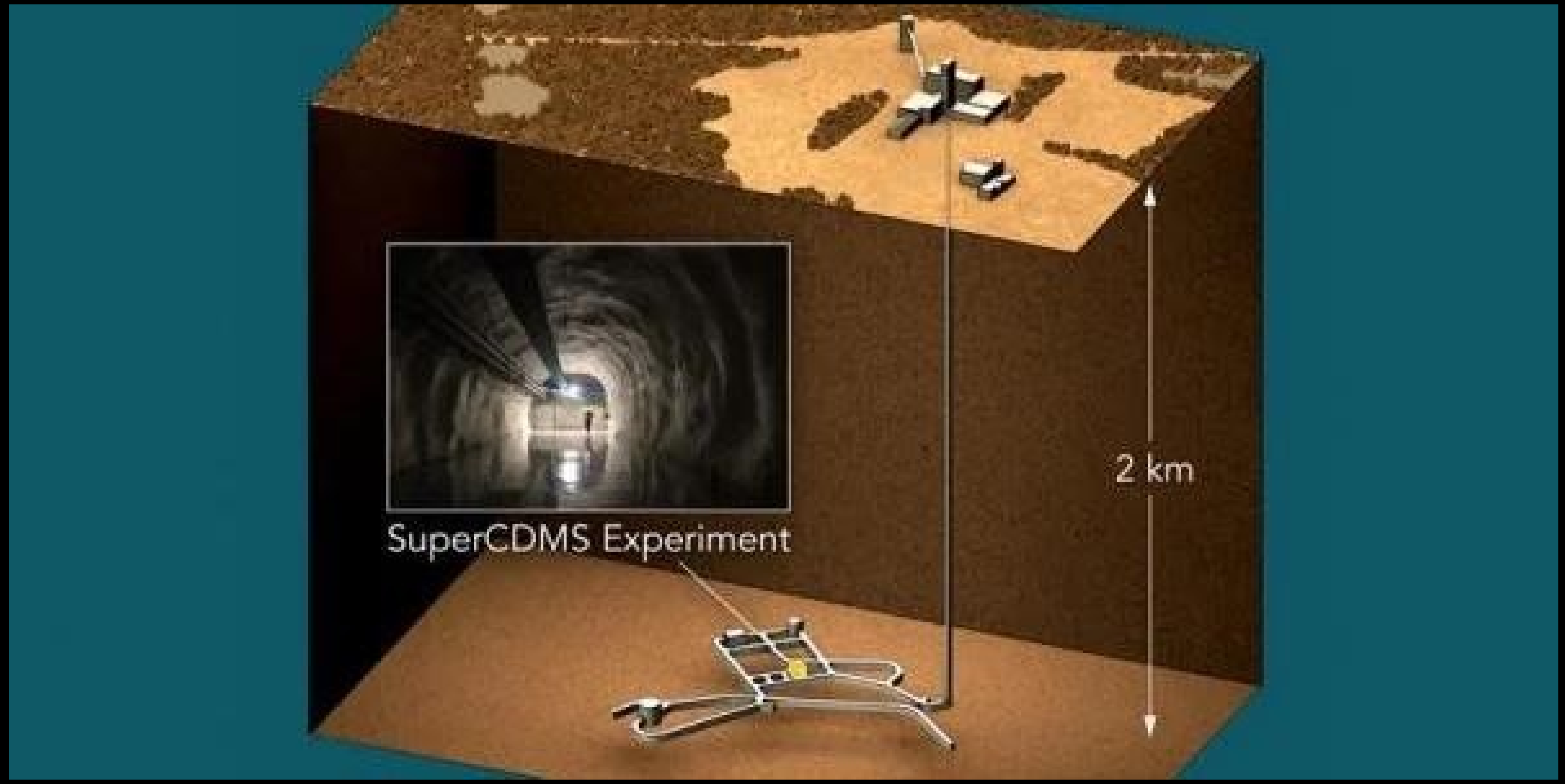
**Darkside 20k**



**sensitive to ultra heavy DM**




**ADMX-G2**

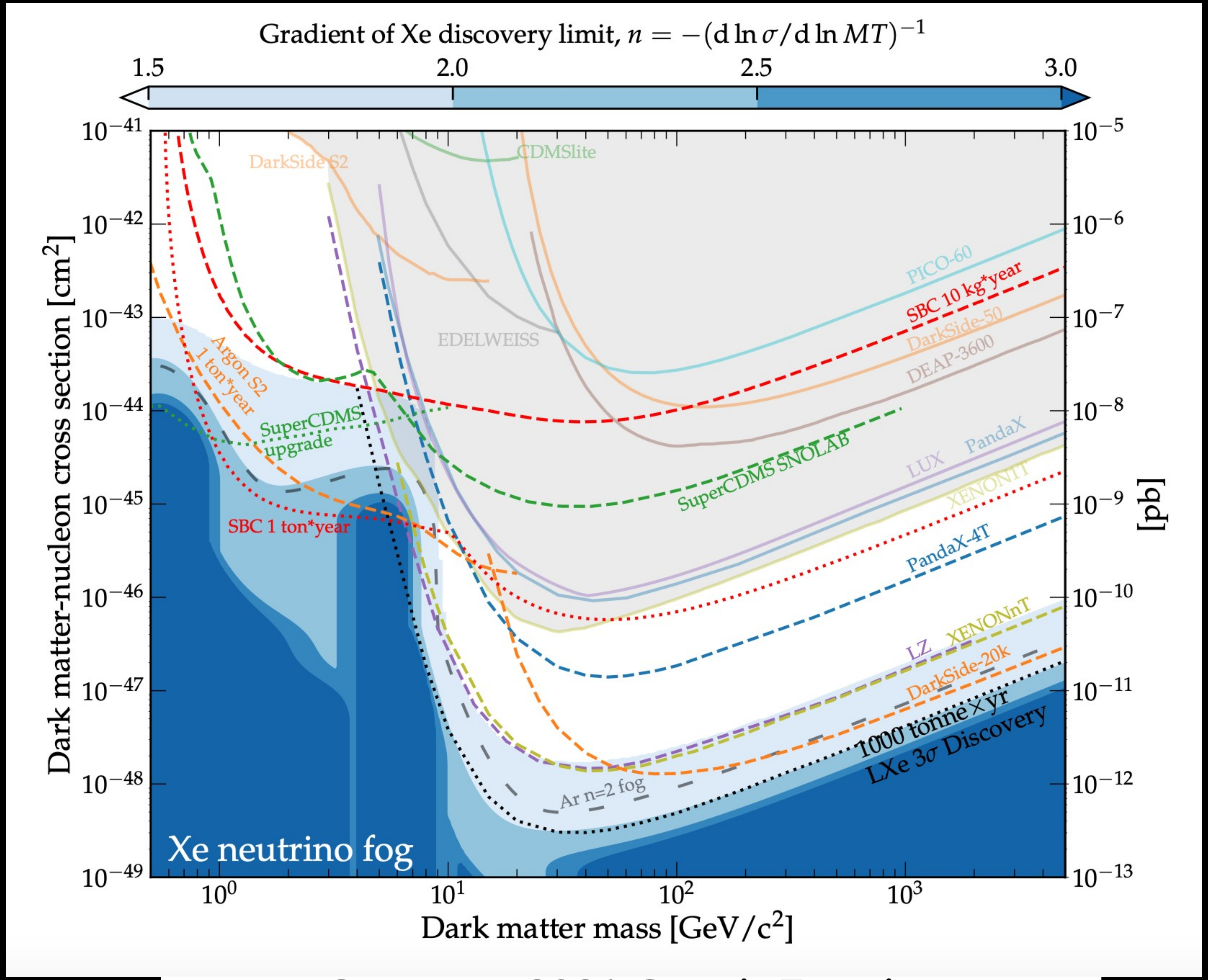



# Major Project this decade: A 3rd generation (G3) WIMP experiment

- **G3 WIMP experiment will be so sensitive to dark matter SM interactions that neutrinos become an irreducible background -> the neutrino fog.**

- **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

# New Opportunities this Decade: ASTAE*

Office of Science

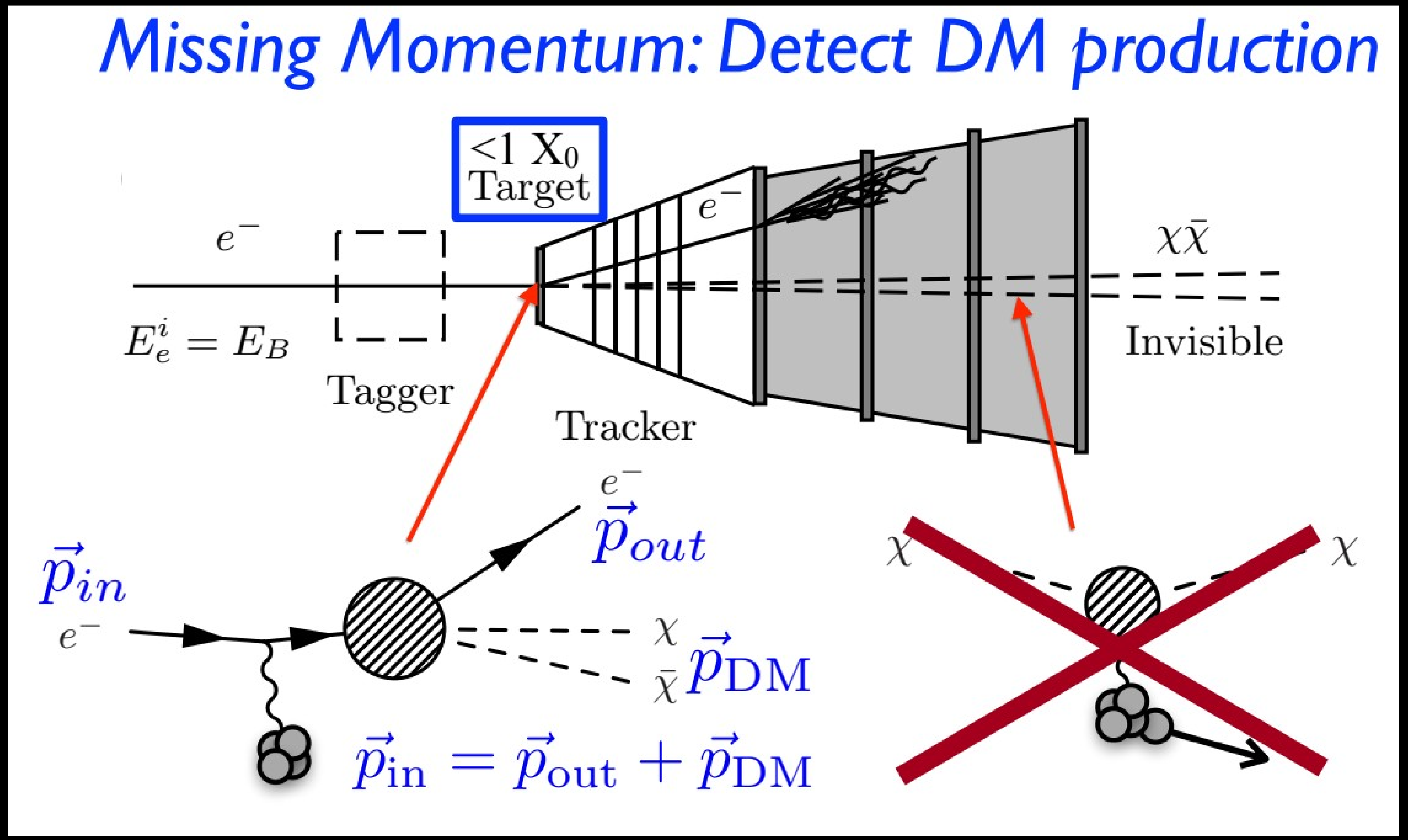
## Department of Energy Announces $6.6 Million to Study Dark Matter

OCTOBER 1, 2019

**The Dark Matter New Initiatives (DMNI) Program was a huge success. The successful projects now need construction funding!**

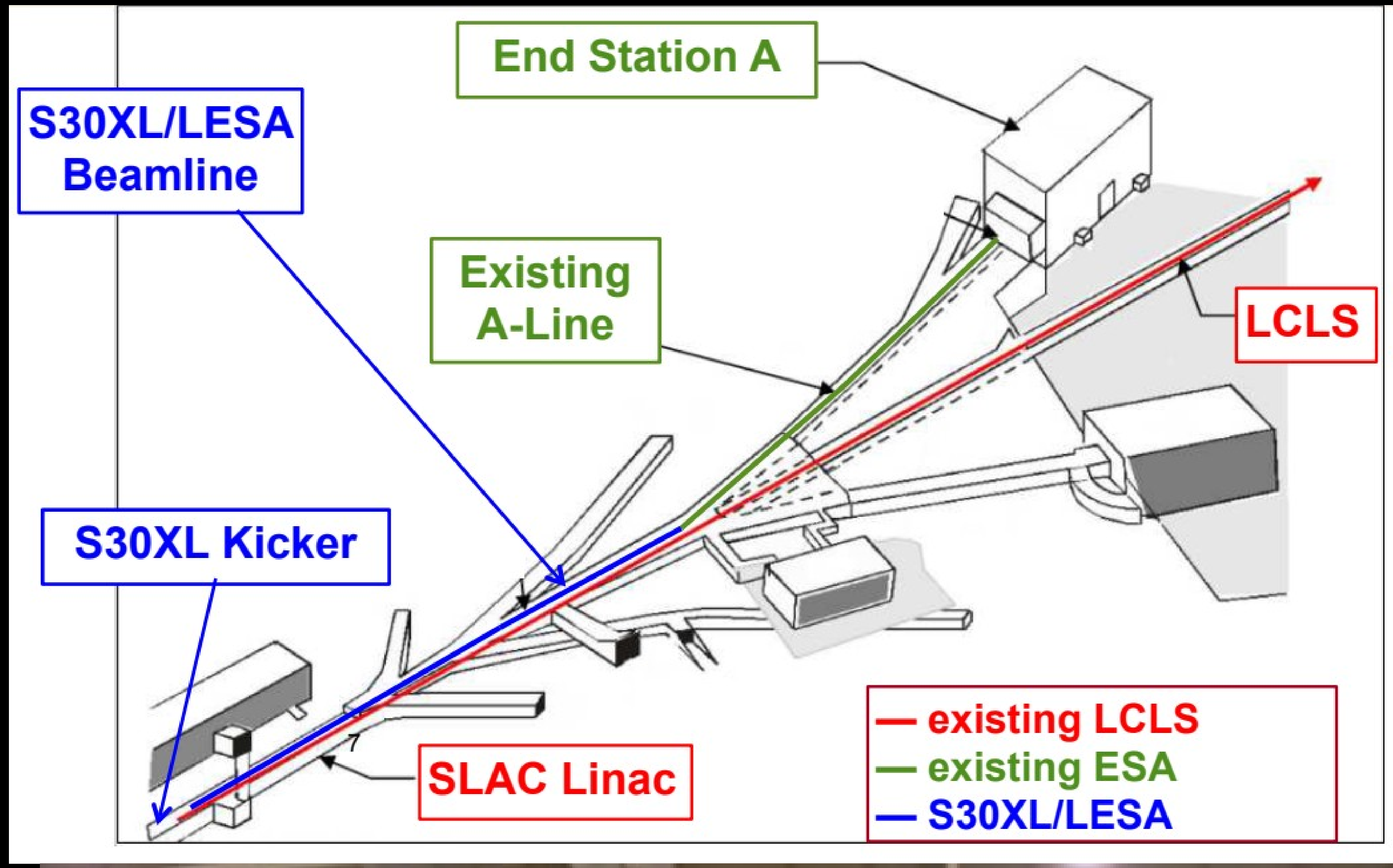
*Recommended new program: Advancing Science and Technology through Agile Experiments

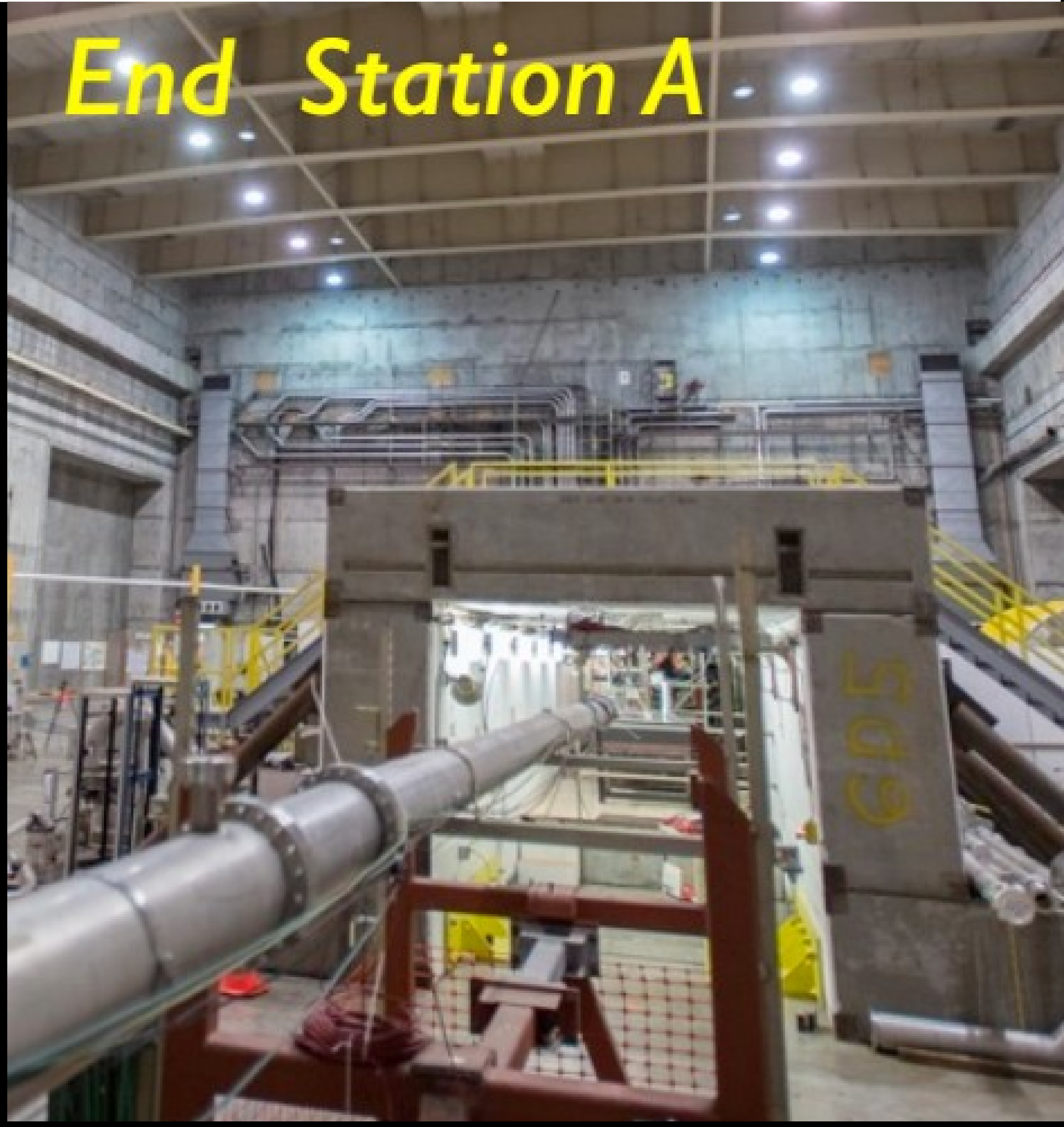
# One of the examples: LDMX

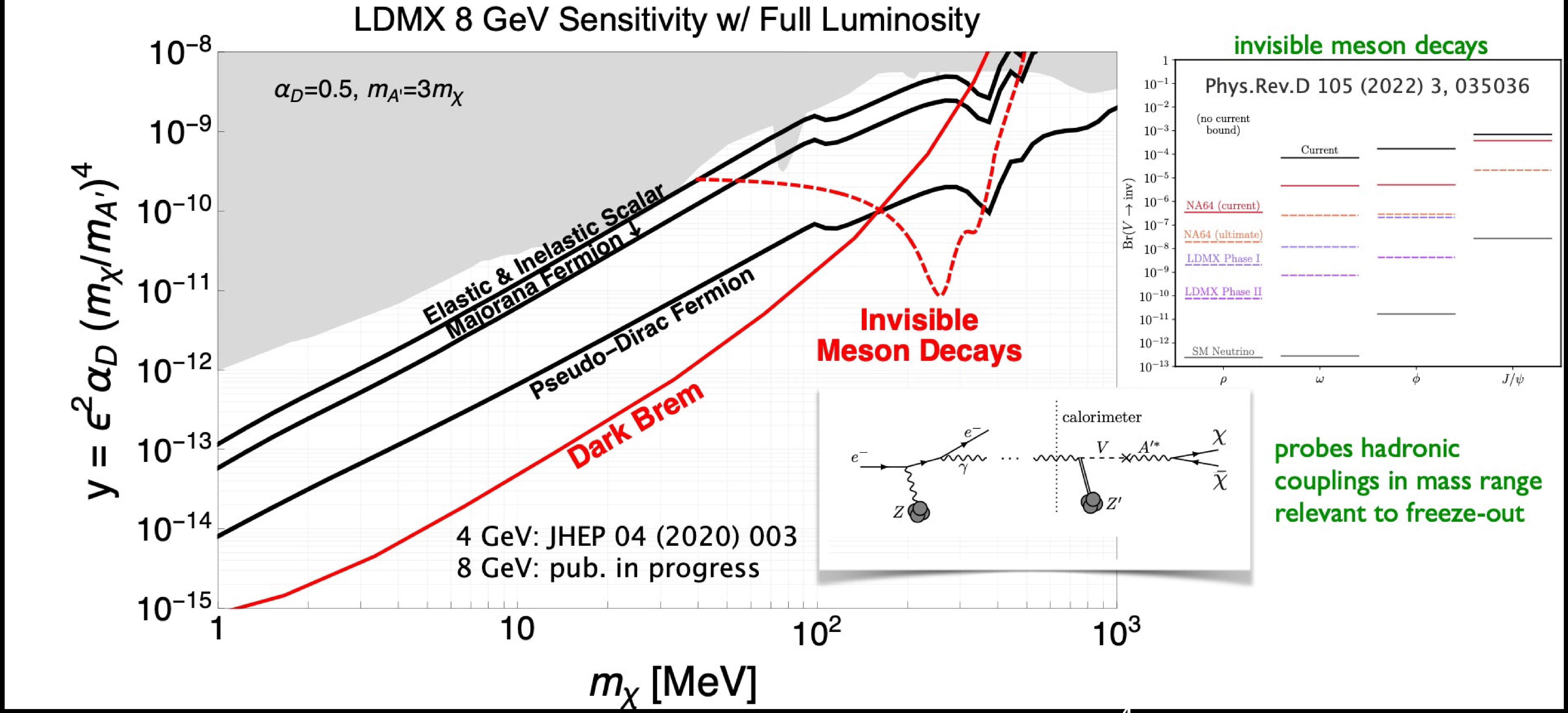



Very clever design: able to reconstruct soft electron recoil – a game changer

Also found a beam line and a hall that can fit the experiment at SLAC

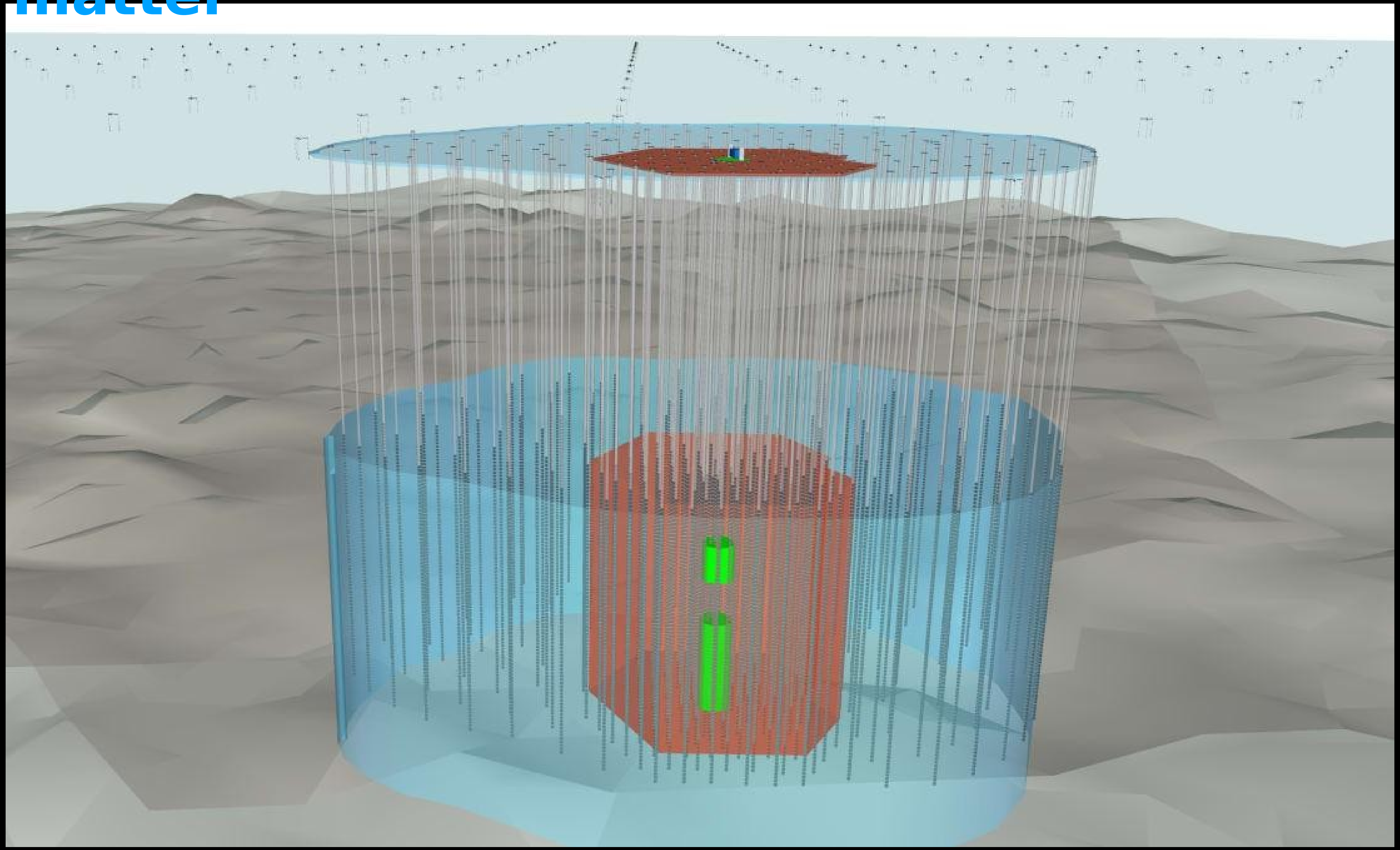


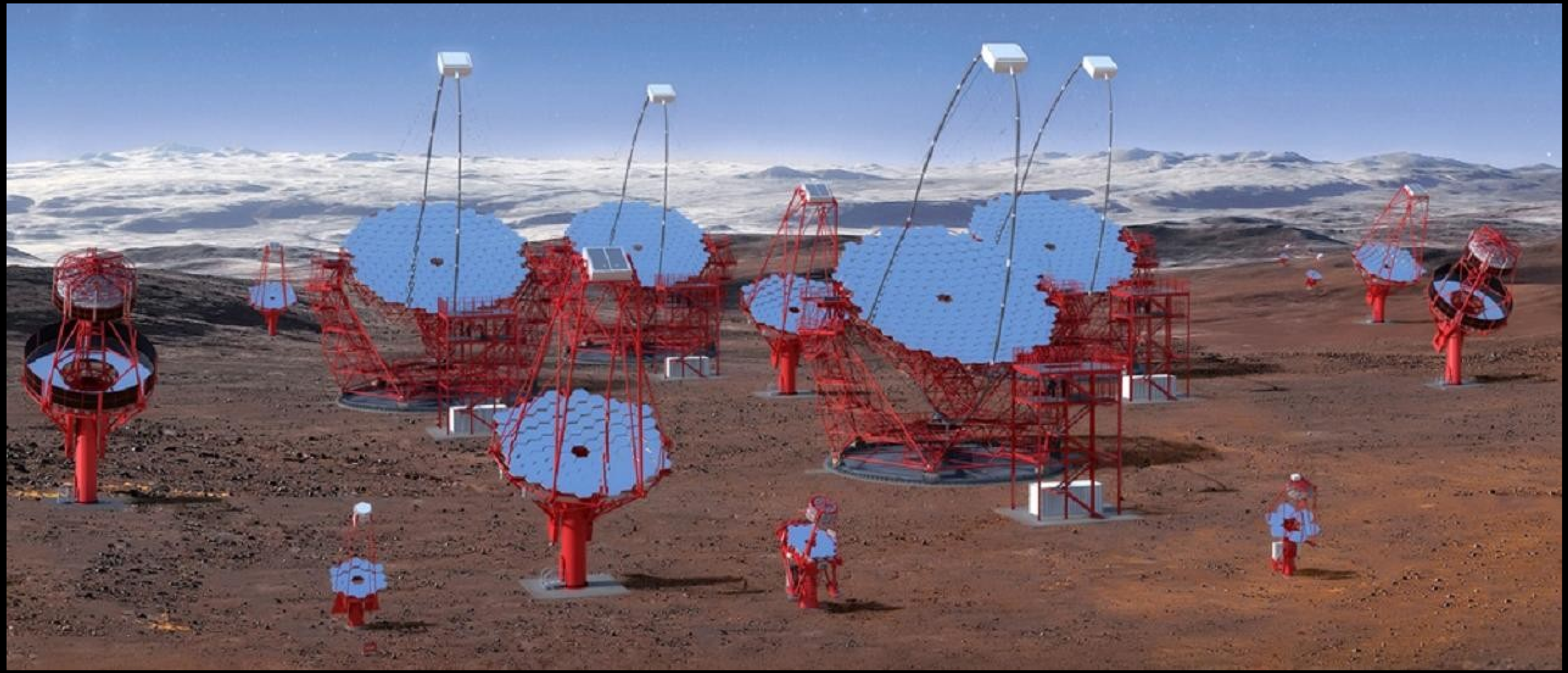



# NSF New Initiatives: IceCube-Gen2 & CTA

**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.**

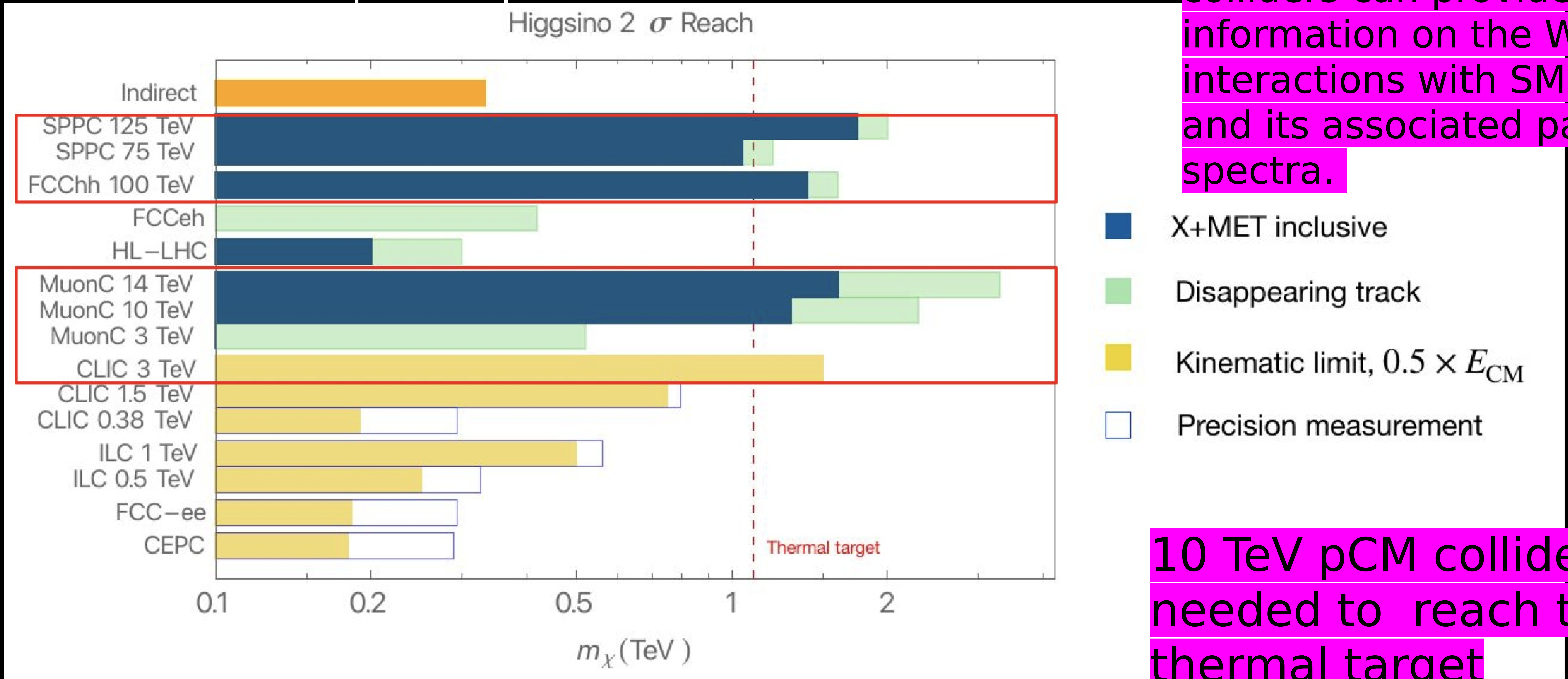


# Dark Matter at Future Colliders

**Dark matter searches in collider are complementary to other searches**

WIMP, Mediator searches, Beyond-WIMP, Higgs portal…

Benchmark/example: simple WIMP




colliders can provide in-depth information on the WIMP's interactions with SM particles and its associated particle spectra.

10 TeV pCM colliders needed to reach the thermal target

# Understand what drives cosmic evolution

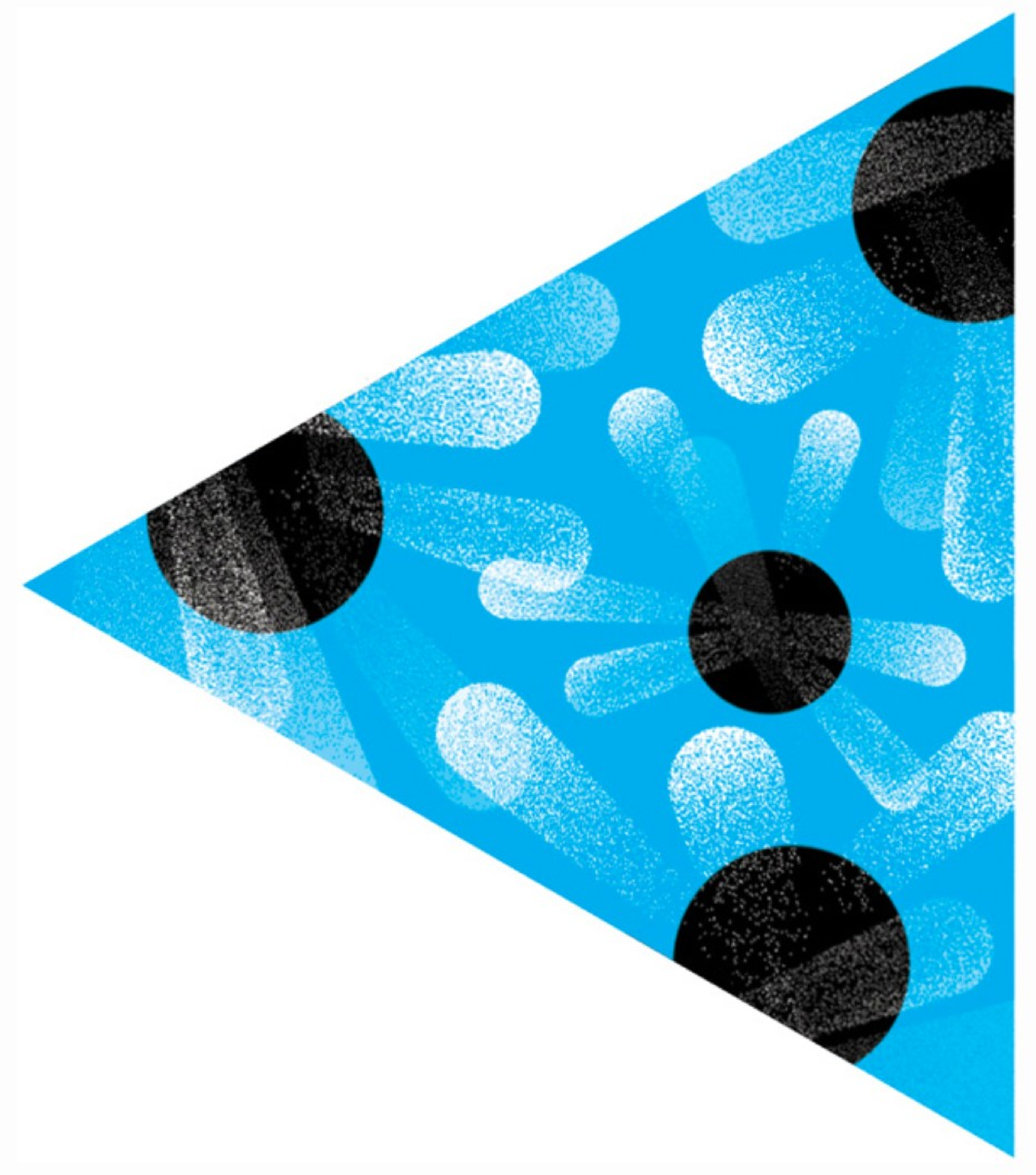
# Understand What Drives Cosmic Evolution

The dynamical evolution of the universe is deeply connected to its energy content.

What physics is responsible for the rapid, accelerated expansion during the early inflationary era?

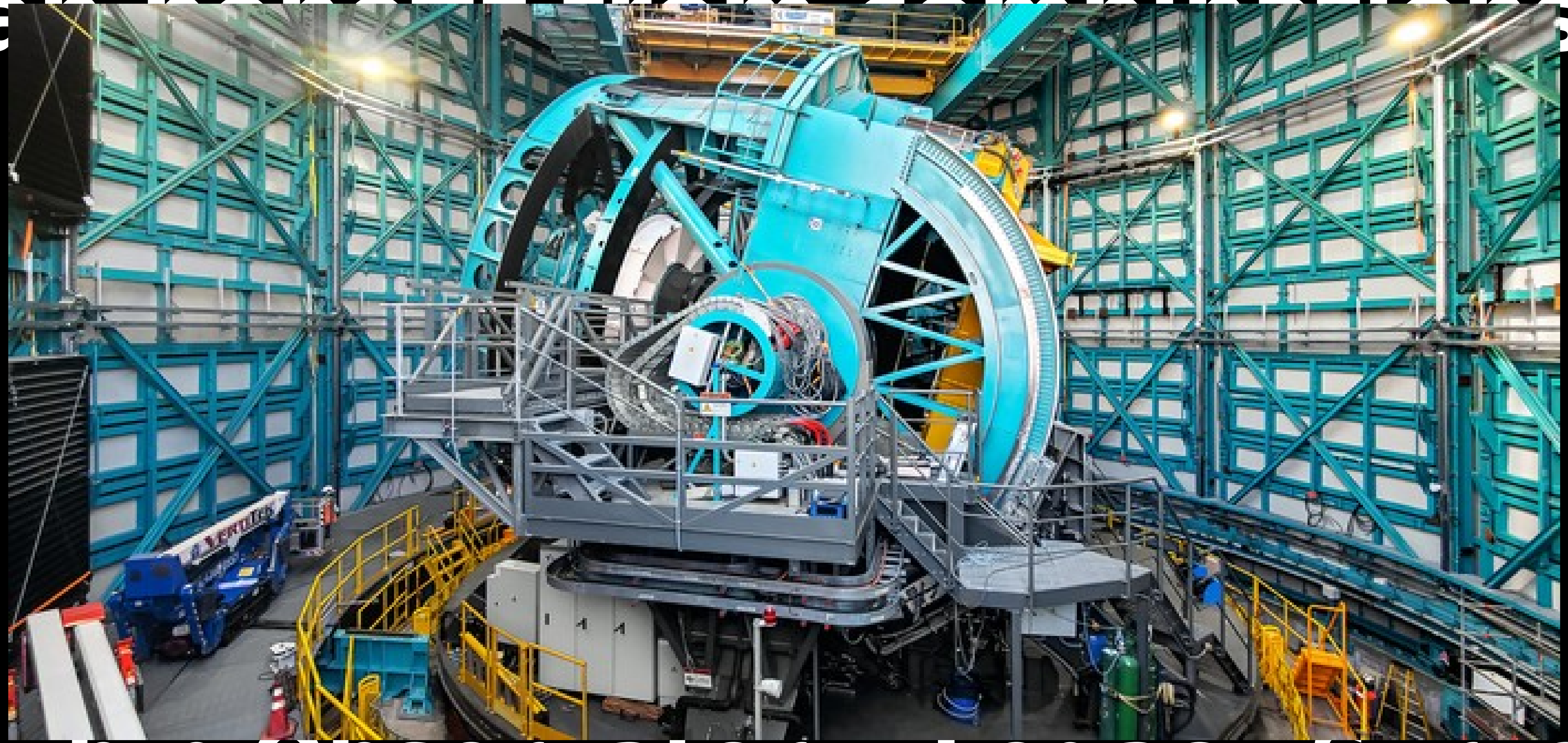
Were there extra light species beyond photons and neutrinos present in the universe during the radiation-dominated era?

What is driving the current accelerated expansion of the universe? We must investigate the nature of dark energy in the ΛCDM paradigm.



# Top Priority: Complete and operate ongoing projects

**Ongoing experiments will provide constraints on cosmic acceleration, and reach back into the weakly matter-dominated era when the expansion was still decelerating.**
**The program will stress-test the standard cosmological paradigm, where CMB surveys can benefit from combinations with space-based datasets.**



**Rubin Observatory: Legacy Survey of Space and Time (LSST) and the LSST Dark Energy Science Collaboration (DESC)**

**DESI (a spectroscopic survey)**

# Major 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**

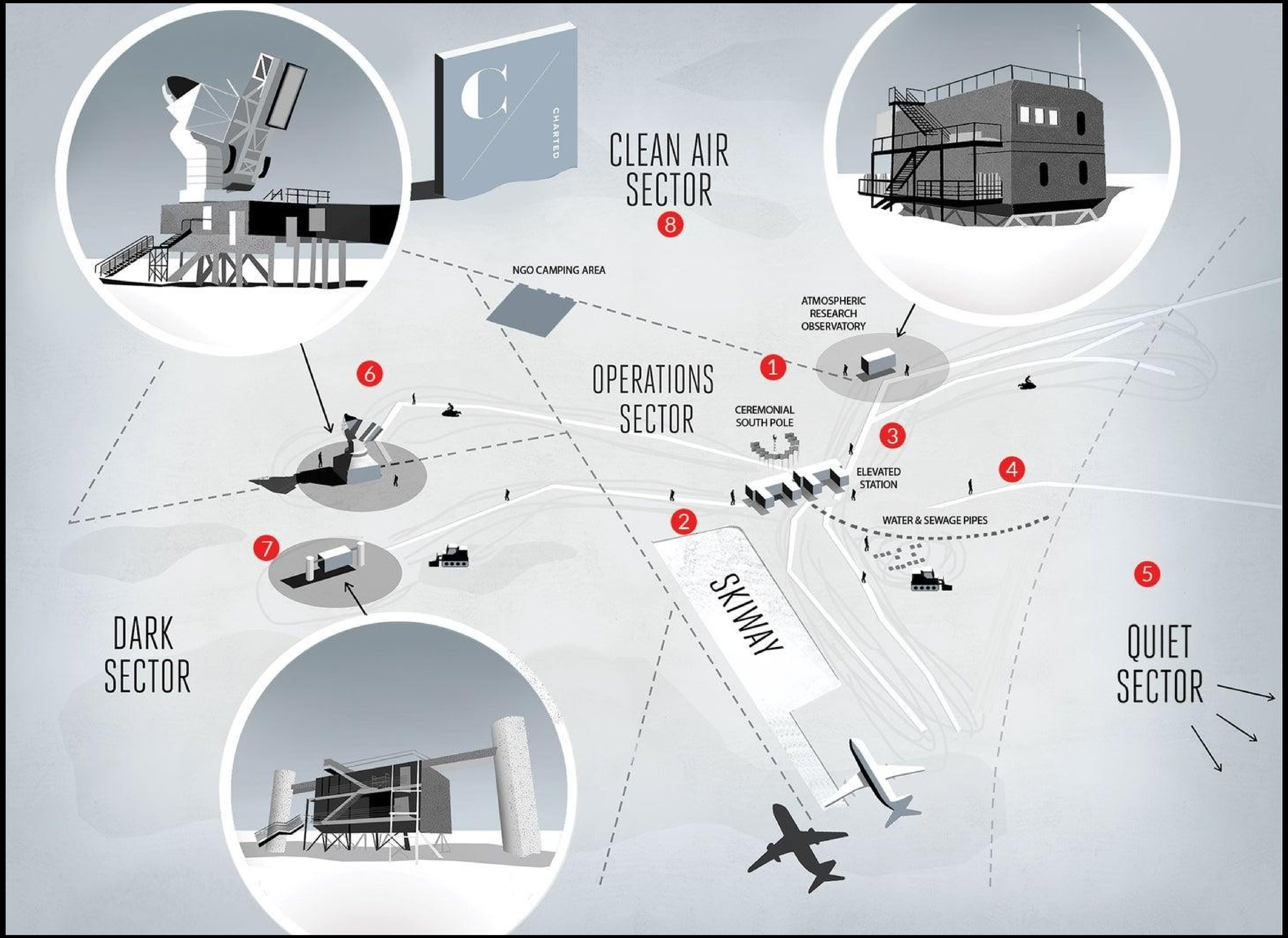
# Science at the South Pole

**Sensitivity  to physics of inflation that probes**
**the highest energy scales of the universe is**
**opened up at the South Pole.**

**The atmosphere is dry and stable, and**
**continuous observation of the same patch**
**of sky is possible.**

**A successful CMB-S4 will require coordination between**

- **DOE-HEP**
- **NSF-AST**
- **NSF-OPP**

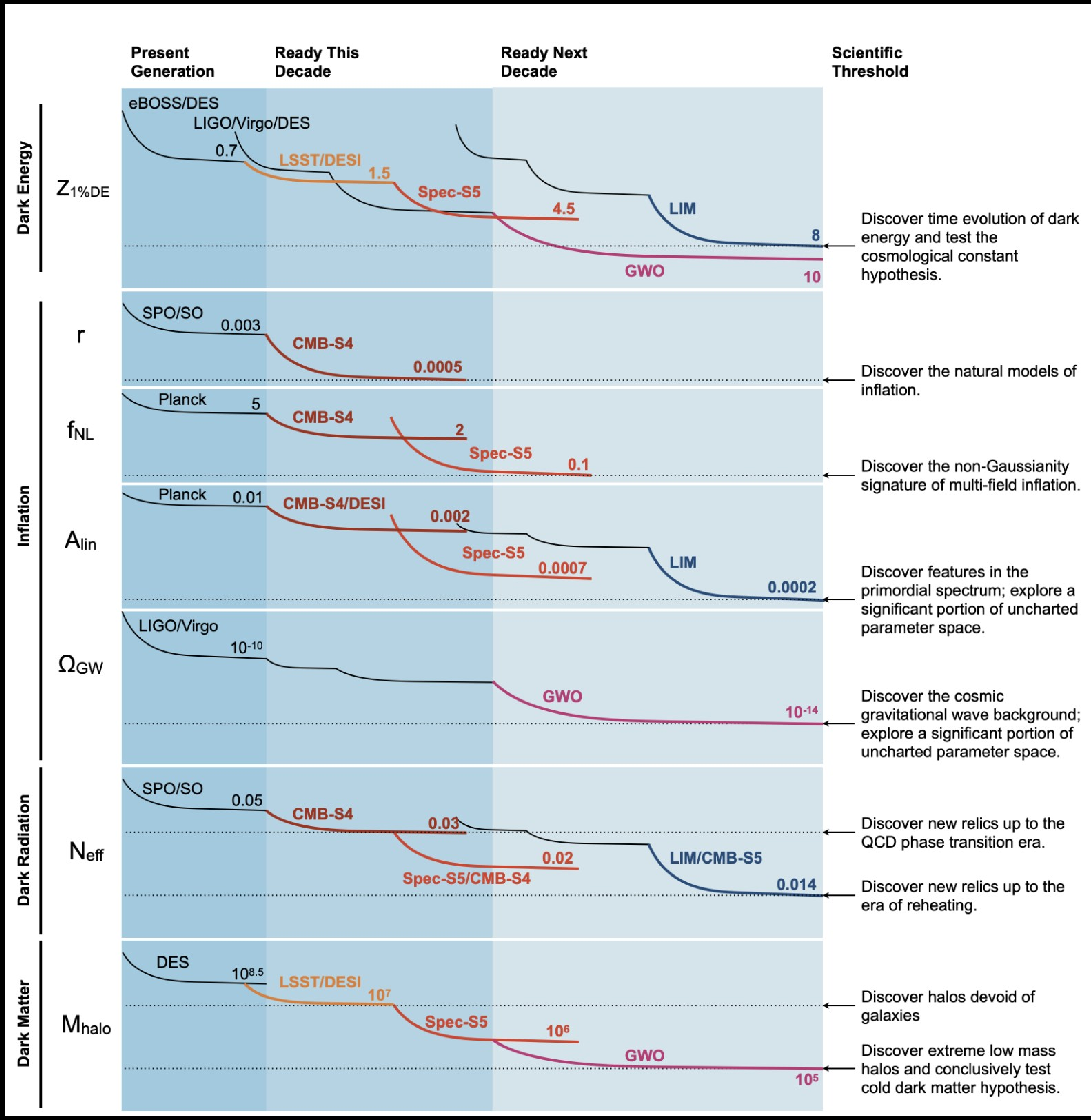


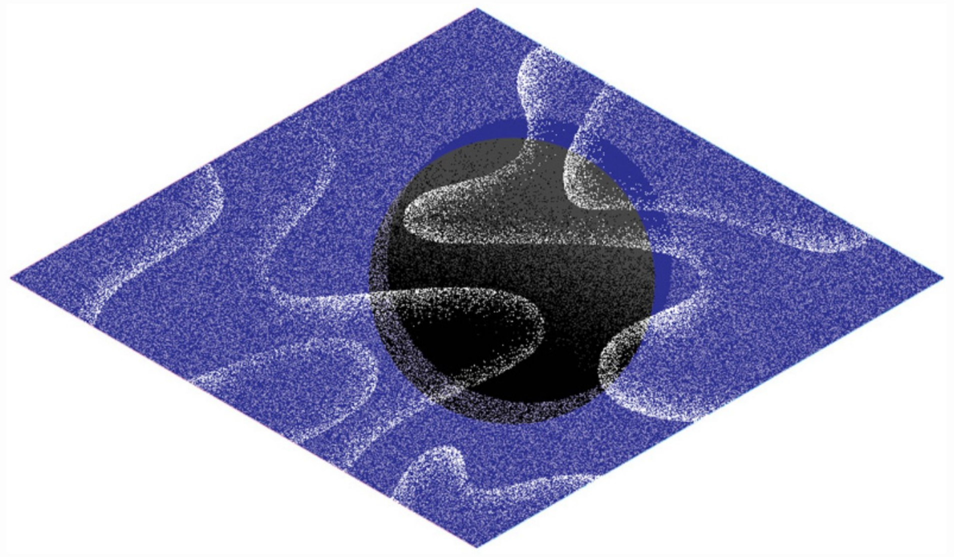
# Galaxy survey and CMB outlook

2023 P5 report recommends

- Rubin/LSST and DESI (considered "ongoing")
- DESI-II including Rubin synergies
- CMB-S4 (→mature project from the last P5)
- R&D towards Spec-S5 (→mature project concept for next P5 in baseline budget)
- R&D for LIM
- Expanded theory support for the particle physics case for GW facilities

*Snowmass:*





# Pursue quantum imprints of new phenomena

# Pursue Quantum Imprints of New Phenomena

- Even when particles are **beyond the reach of accelerators**, their **quantum imprints** might be seen.
- There is a long history of **discoveries through quantum imprints**, from radioactive beta decay leading to the neutrino to the matter-antimatter asymmetry in kaons leading to the 3rd quark generation.
- The **physics of flavor** is particularly sensitive to quantum imprints of particles that are not present in either the initial or final state of interactions. Progress necessitates clean theoretical predictions and **high precision experiments with excellent control of systematic uncertainties**.

  - Top priority: Complete ongoing Mu2e, Belle II, LHCb, ATLAS, and CMS Experiments
  - New Initiative: Belle II and LHCb upgrades,
  - New Initiative: R&D for Mu2e II and advanced muon facility
  - Major Initiative: Higgs Factory – also factory of b-quarks, top quarks, and Z bosons

# Search for direct evidence of new particles

# Search for Direct Evidence of New Particles

- **High-energy colliders enable us to explore the unknown with the potential for discoveries beyond our current imagination, providing access to high mass scales and new physics weakly coupled to the Standard Model.**

- **Some searches are guided by specific theoretical ideas, some by experimental data, and some attempt to be model-agnostic by performing a general exploration of the unknown.**

- Top priority: Complete ongoing ATLAS, CMS, and LHCb Experiments at the LHC
- New Initiative: ASTAE (small projects portfolio) – auxiliary experiments at the LHC to look for long-lived and/or feebly coupled exotic particles. Reimagined MATHUSLA (higgs portal) and some of FPF experiments (FORMOSA, FASER2 for millicharged particles and vector and heavy neutral lepton portals)
- Major Initiative: Higgs Factory – unprecedented sensitivity to exotic particles in Higgs and Z boson decays
- Future opportunities: 10+ TeV pCM collider – comprehensive exploration of the EWK scale, searches for extra scalars, Higgs potential measurement, thermal WIMP coverage.

Exploring the Quantum Universe

# 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.

…

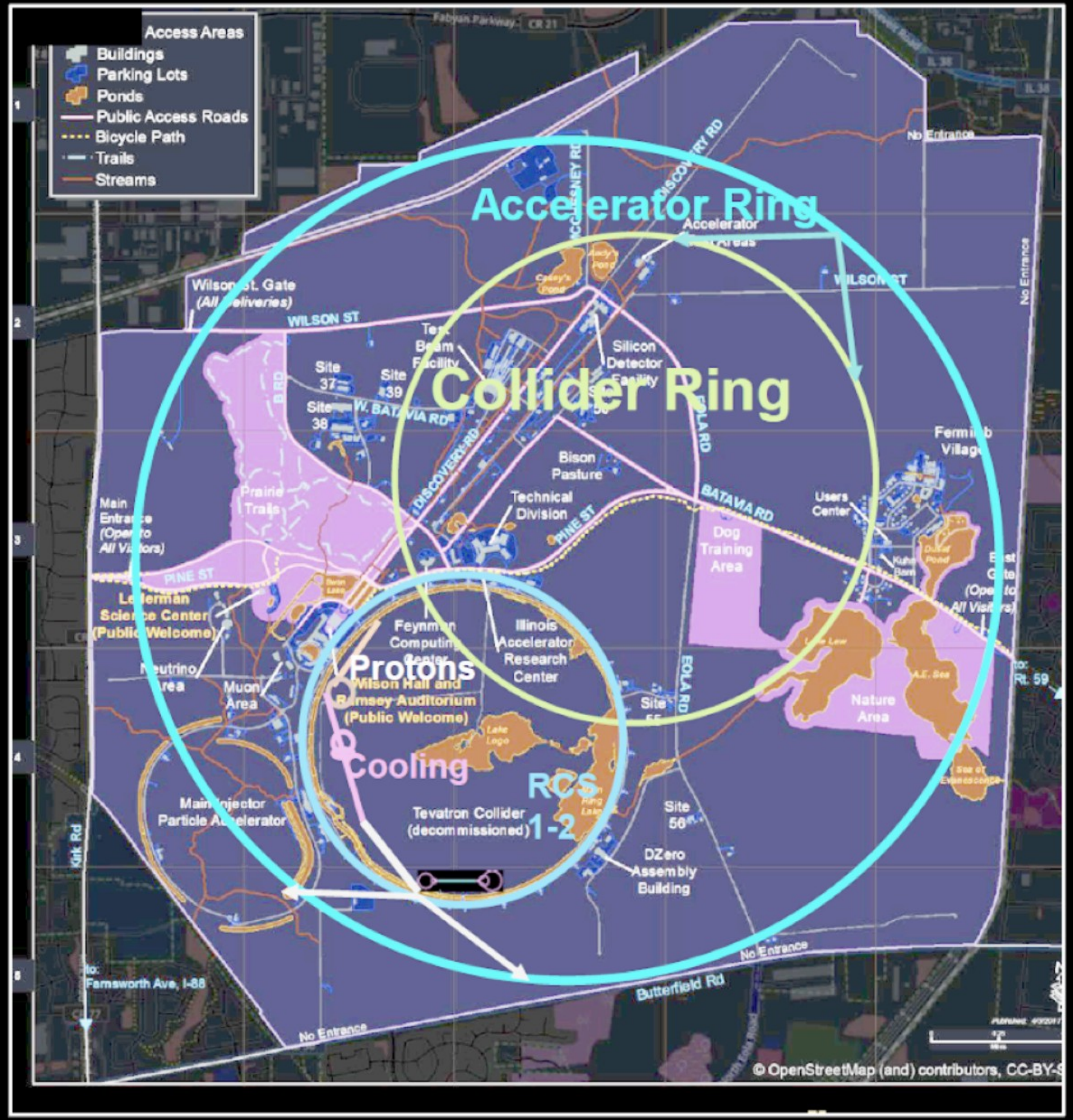
In particular, a muon collider presents an attractive option both for technological innovation and for bringing energy frontier colliders back to the US. The footprint of **a 10 TeV pCM muon collider is almost exactly the size of the Fermilab campus**. A muon collider would rely on a powerful multi-megawatt 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.**

# shoot for the muon

[Bhat, Jindariani, et al 2203.08088]

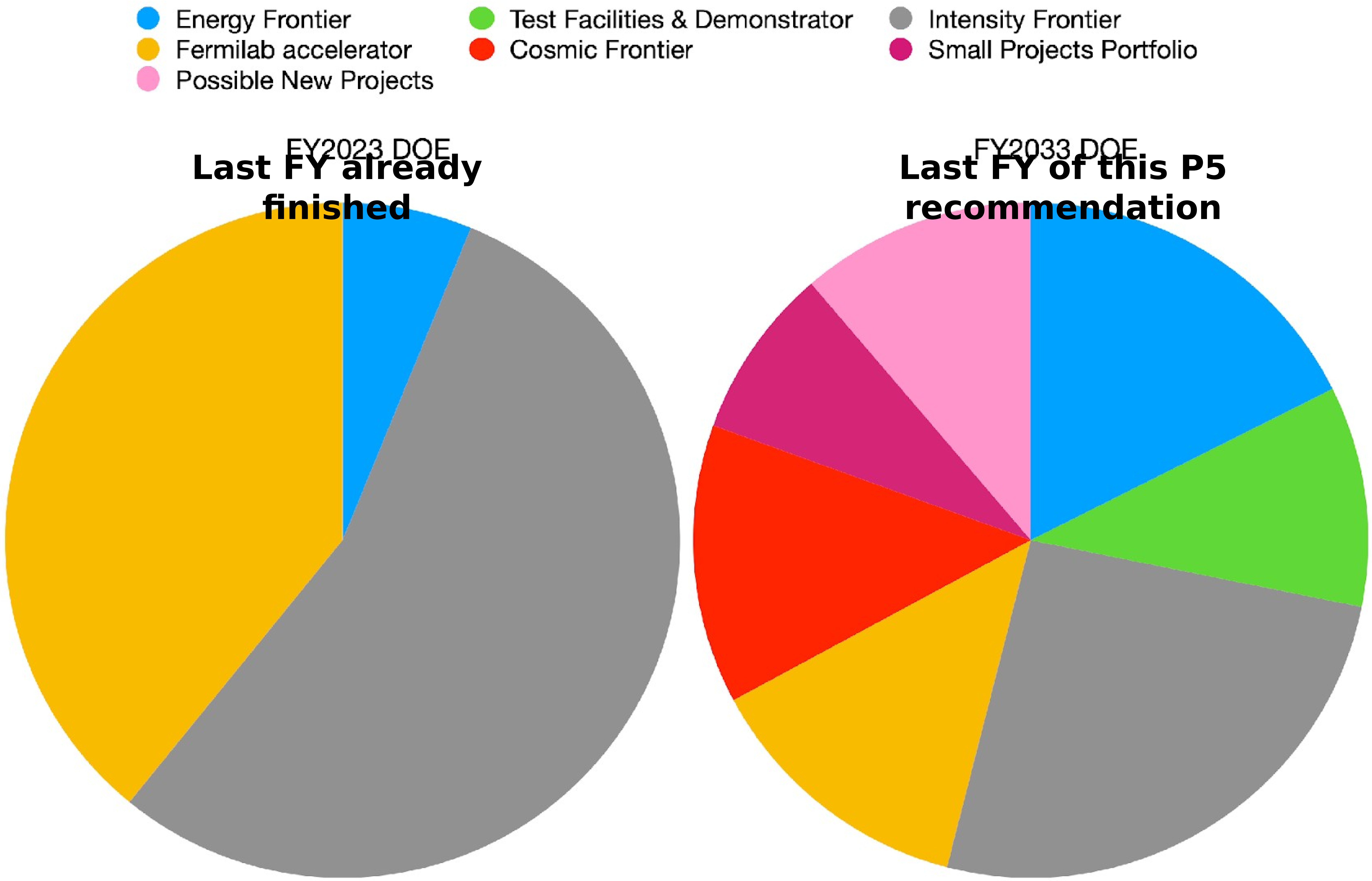



# Workforce Development

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.

# Rebalancing the HEP portfolio




**Last FY already finished**

**Last FY of this P5 recommendation**

**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.

## 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 | | | Science Drivers | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Less | Baseline | More | 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 & demonstrators | 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

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 reflects the panel's understanding of a project's focus, not the relative strength of the science cases. Projects that share a driver, whether primary or secondary, generally address that driver in different and complementary ways.

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

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

§ Possible acceleration/expansion in more favorable budget situations

**Science Experiments**

Timeline 2024 – 2034; Science Drivers

| | 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 | |
| IceCube | P | | 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 § (DEMONSTRATOR) | | P | P | | P | S | |
| LIM | S | | P | P | | | P |

**Advancing Science and Technology through Agile Experiments**

| | Neutrinos | Higgs Boson | Dark Matter | Cosmic Evolution | Direct Evidence | Quantum Imprints | Astronomy & Astrophysics |
|---|---|---|---|---|---|---|---|
| ASTAE § | P | P | P | P | P | P | |

**Science Enablers**

- LBNF/PIP-II
- ACE-MIRT
- SURF Expansion
- ACE-BR §, AMF

**Increase in Research and Development**

- GARD § (TEST FACILITIES)
- Theory
- Instrumentation
- Computing

# Summary

- The Particle Physics Prioritization Panel has reviewed proposals for projects in the next decade and beyond of particle physics.
- A diverse range of projects is recommended, both from a physics and project size perspective, also considering the global context.
- Fascinating discoveries will be enabled by the recommended projects.
- The panel also made recommendations for improving the health of the field beyond just building projects.

# Summary

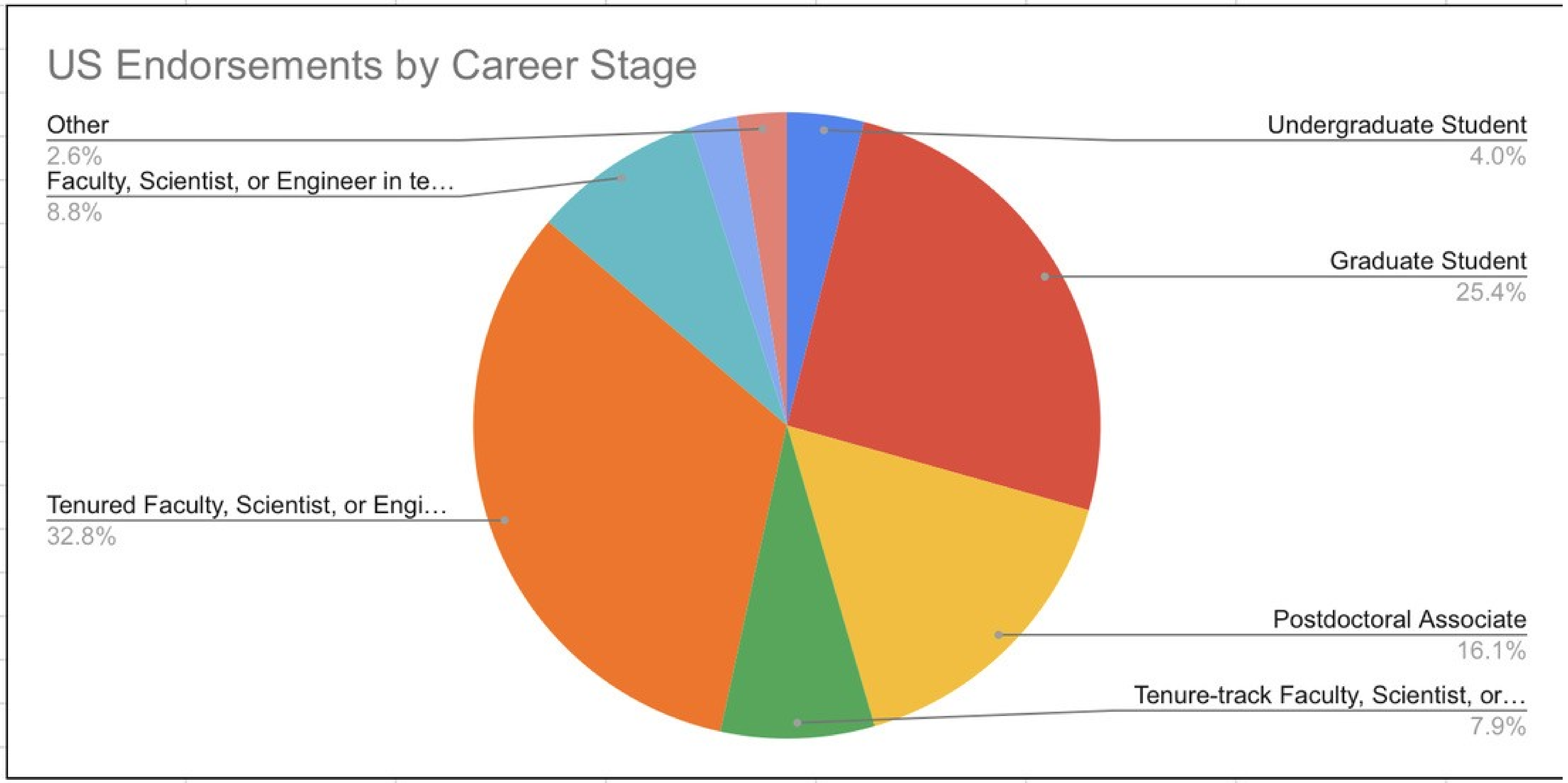
- The Particle Physics Prioritization Panel has reviewed proposals for projects in the next decade and beyond of particle physics.
- A diverse range of projects is recommended, both from a physics and project size perspective, also considering the global context.
- Fascinating discoveries will be enabled by the recommended projects.
- The panel also made recommendations for improving the health of the field beyond just building projects.

***Very exciting times in particle physics!***

# Community support is strong

Support the 2023 P5 Report : Statistics

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



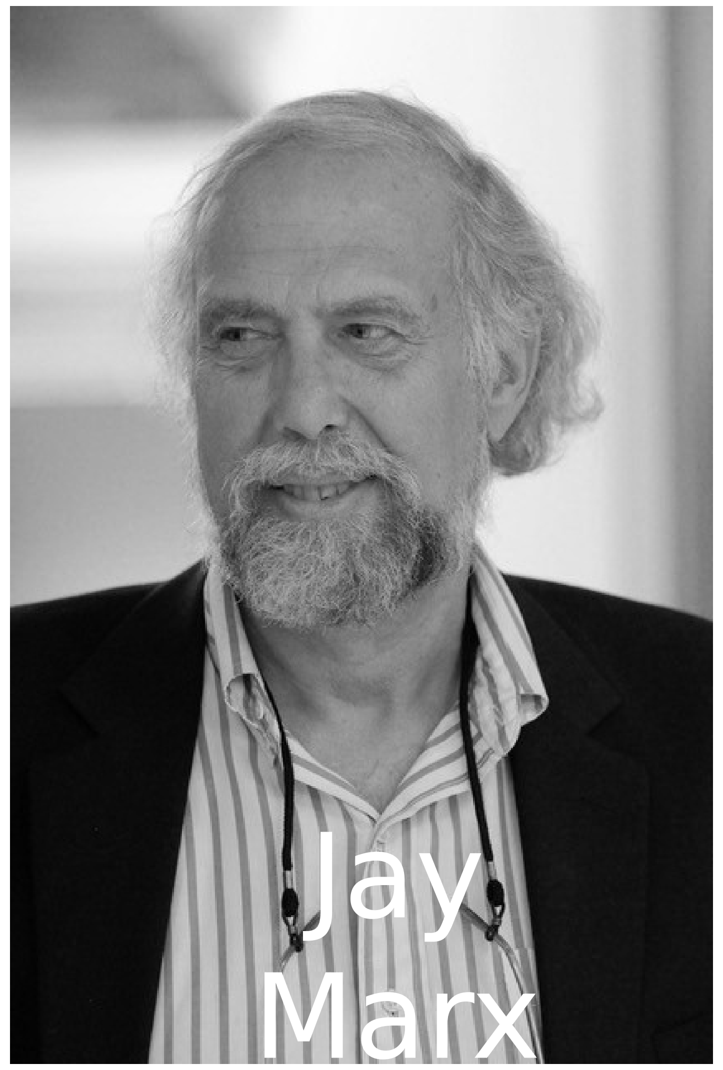
# Subcommittee on Costs/Risks/Schedule

**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)
- Norbert Holtkamp, Mark Reichanadter, Nadine Kurita (SLAC)
- Jon Kotcher, Srini Rajagopalan (BNL)
- Allison Lung (JLab)
- Harry Weerts (Argonne)



# Prioritization Principles

Overall program should **enable US leadership in core areas of particle physics**

It 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 US talent

Effective **engagement and leadership in international endeavors** were also considerations

We also **considered the uncertainties in the costs, risks, and schedule** as part of our prioritization exercise. The prioritized project portfolios were chosen to **fit within a few percent of the budget scenarios** and to ensure a reasonable outlook for continuation into the second decade, even though that is beyond the purview of this panel.

**Balance of program in terms of**

- Size and time scale of projects
- On-shore vs off-shore
- Project vs Research
- Current vs future investment

Exploring the Quantum Universe

# Recommendation 1

Not Rank-Ordered

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

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

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

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

Exploring the Quantum Universe

Not Rank-Ordered

# Recommendation 1

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

d. **NOvA**, **SBN**, **T2K**, and **IceCube** (*elucidate the mysteries of neutrinos*, section 3.1).
e. **DarkSide-20k**, **LZ**, **SuperCDMS**, and **XENONnT** (*determine the nature of dark matter*, section 4.1).
f. **DESI** (*understand what drives cosmic evolution*, section 4.2).
g. **Belle II**, **LHCb**, and **Mu2e** (*pursue quantum imprints of new phenomena*, section 5.2).

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

Exploring the Quantum Universe

# Recommendation 2

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

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

Exploring the Quantum Universe

Rank-Ordered

# Recommendation 2

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

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

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

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

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

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.

Exploring the Quantum Universe

Not Rank-Ordered

# Recommendation 3

**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

**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.**

Investing in the future of the field to fulfill this vision requires the following:

Exploring the Quantum Universe

Not Rank-Ordered

# Recommendation 4

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.

Exploring the Quantum Universe

# Recommendation 5

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

Exploring the Quantum Universe

Not Rank-Ordered

# Recommendation 5

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.

# Recommendation 6

**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.

Exploring the Quantum Universe

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.

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

Exploring the Quantum Universe

Not Rank-Ordered

# More Favorable Budget Scenario

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.

Not Rank-Ordered

# More Favorable Budget Scenario

**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 | 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**

# Area Recommendations

**Theory**

1. **Increase DOE HEP-funded university-based theory research by $15 million per year in 2023 dollars (or about 30% of the theory program)**, to propel innovation and ensure international competitiveness. Such an increase would bring theory support back to 2010 levels. Maintain DOE lab-based theory groups as an essential component of the theory community.

**ASTAE**

2. For the ASTAE program to be agile, we recommend a **broad, predictable, and recurring (preferably annual) call for proposals**. This ensures the flexibility to target emerging opportunities and fields. A program on the scale of **$35 million per year in 2023 dollars** is needed to ensure a healthy pipeline of projects.
3. To preserve the agility of the ASTAE program, **project management** requirements should be outlined for the portfolio and should be adjusted to be commensurate with the scale of the experiment.
4. A successful ASTAE experiment involves 3 phases: **design, construction, and operations**. A design phase proposal should precede a construction proposal, and construction proposals are considered from projects within the group that have successfully completed their design phase.
5. **The DMNI projects** that have successfully completed their design phase and are ready to be reviewed for construction, **should form the first set of construction proposals for ASTAE.** The corresponding design phase call would be **open to proposals from all areas of particle physics.**

Exploring the Quantum Universe

# Area Recommendations

**Instrumentation**

6. **Increase the budget for generic Detector R&D by at least $4 million per year** in 2023 dollars. This should be supplemented by additional funds for the collider R&D program
7. The detector R&D program should continue to leverage national initiatives such as QIS, microelectronics, and AI/ML.

**General Accelerator R&D**

8. **Increase annual funding to the General Accelerator R&D program by $10M per year** in 2023 dollars to ensure US leadership in key areas.
9. Support generic accelerator R&D with the construction of small scale test facilities. Initiate construction of larger test facilities based on project review, and informed by the collider R&D program.

**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.

# Area Recommendations

**Facilities and Infrastructure**

11. To successfully deliver major initiatives and leading global projects, we recommend that:
    a. National Laboratories and facilities should work with funding agencies to establish and maintain streamlined access policies enabling **efficient remote and on-site collaboration** by international and domestic partners.
    b. National Laboratories should prioritize the **facilitation of procurement processes** and ensure **robust technical support** for experimenters.
    c. National Laboratories and facilities should prioritize the creation and maintenance of a **supportive, inclusive, and welcoming culture**.
12. Form a dedicated task force, to be led by Fermilab with broad community membership. This task force is to be charged with **defining a roadmap for upgrade efforts and delivering a strategic 20-year plan for the Fermilab accelerator complex** within the next five years for consideration (Recommendation 6). Direct task force funding of up to $10M should be provided.
13. Assess the **Booster synchrotron and related systems for reliability risks** through the first decade of DUNE operation, and take measures to **preemptively address these risks**.
14. Maintaining the capabilities of **NSF's infrastructure at the South Pole**, focused on enabling future world-leading scientific discoveries, is essential. We recommend continued direct coordination and planning between NSF-OPP and the CMB-S4 and IceCube-Gen2 projects, which is of critical importance to the field of particle physics.

# Area Recommendations

**Software, Computing, and Cyberinfrastructure**

16. Resources for national initiatives in **AI/ML, quantum, computing, and microelectronics** should be leveraged and incorporated into research and R&D efforts to maximize the physics reach of the program.

17. Add support for a sustained R&D effort at the level of **$9M per year in 2023 dollars to adapt software and computing systems to emerging hardware,** incorporate other advances in computing technologies, and fund directed efforts to transition those developments into systems used for operations of experiments and facilities.

18. Through targeted investments at the level of **$8M per year in 2023 dollars**, ensure sustained support for key **cyberinfrastructure** components. This includes widely-used software packages, simulation tools, information resources such as the Particle Data Group and INSPIRE, as well as the shared infrastructure for preservation, dissemination, and analysis of the unique data collected by various experiments and surveys in order to realize their full scientific impact.

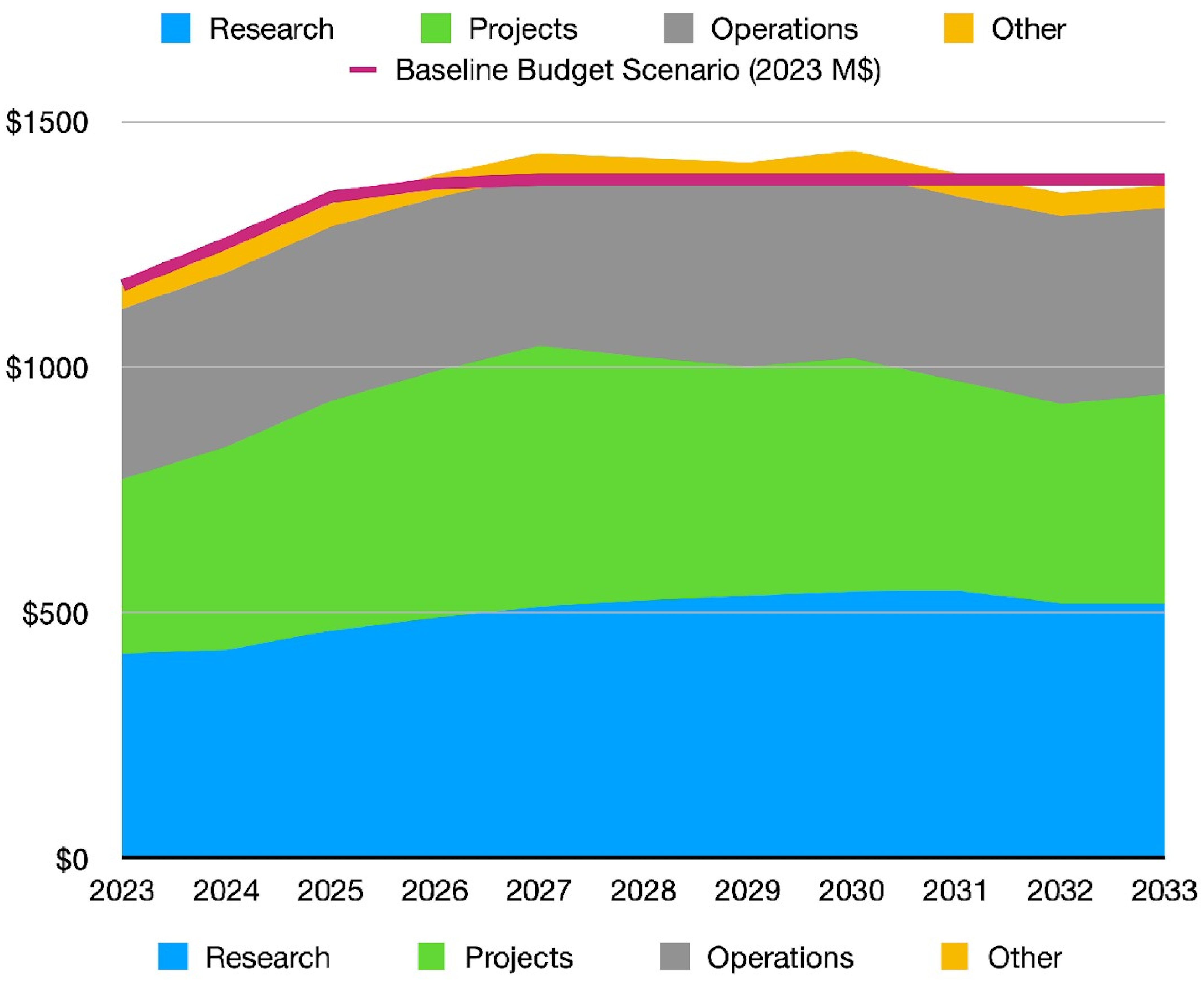
19. **Research software engineers and other professionals at universities and labs** are key to realizing the vision of the field and are critical for maintaining a technologically advanced workforce. We recommend that the funding agencies embrace these roles as a critical component of the workforce when investing in software, computing, and cyberinfrastructure.

**Sustainability**

20. HEPAP, potentially in collaboration with international partners, should conduct a dedicated study aiming at **developing a sustainability strategy for particle physics.**

Exploring the Quantum Universe

# Our proposed program vs budget scenarios



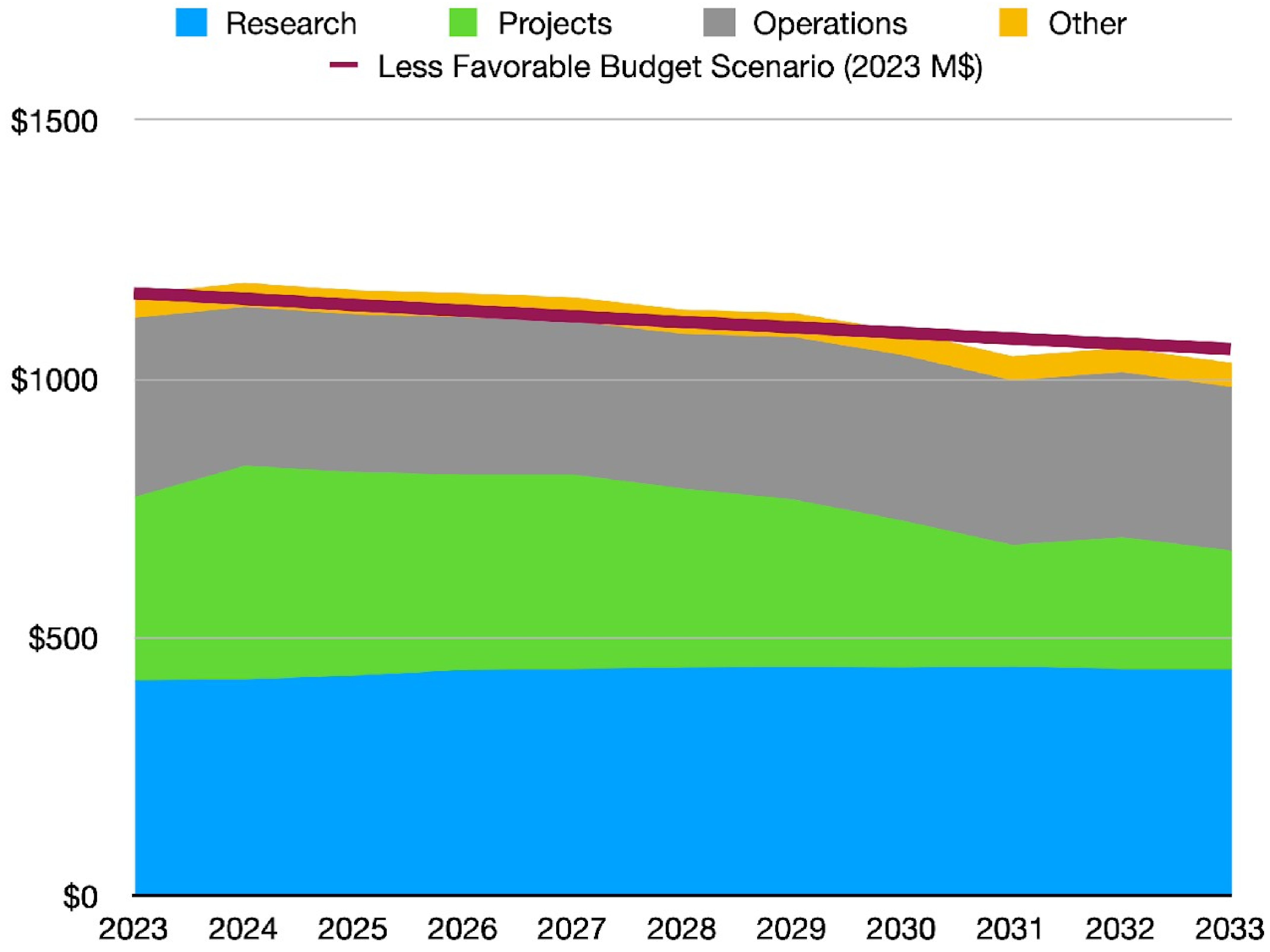




Fig. 2 Evolution of DOE budgets in Research, Projects, Operations, and Other in our budget exercise for the two budget scenarios given in the charge in 2023 dollars assuming 3% annual inflation.