A vision for the future of particle physics

Yuri Gershtein

January 31, 2023

PASCOS

2024
QUY NHON

- This is not a “summary” talk
    - *I will try to draw a path from the current results to where the field may find itself in 10-20 years*

- This is not a “summary” talk
    - *I will try to draw a path from the current results to where the field may find itself in 10-20 years*
- I am an experimentalist
    - *The future to me is a plan of experiments, some of which may come to fruition decades from now. It’s hubris to assume that my theory colleagues wouldn’t discover a new direction for inquiry, or that a major discovery wouldn’t upend our understanding of the universe*

- This is not a “summary” talk
    - *I will try to draw a path from the current results to where the field may find itself in 10-20 years*
- I am an experimentalist
    - *The future to me is a plan of experiments, some of which may come to fruition decades from now. It’s hubris to assume that my theory colleagues wouldn’t discover a new direction for inquiry, or that a major discovery wouldn’t upend our understanding of the universe*
- Nonetheless, there are a lot of “known unknowns” and pursuing them can be expensive and often require careful international planning
    - *I.e European Startegy, US P5, etc*

A vision for the future of experimental particle physics

January 31, 2023

PASCOS

2024
QUY NHON

A vision for the future of experimental particle physics

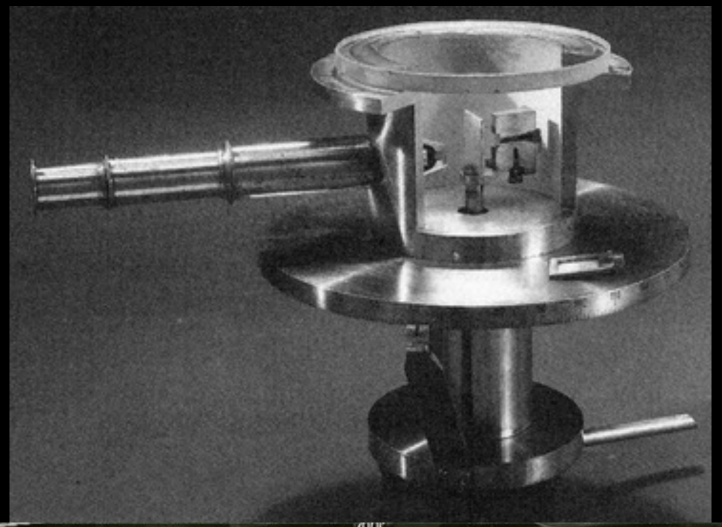
Historically an accelerator-based field, but in the last 2-3 decades it became much wider than accelerators

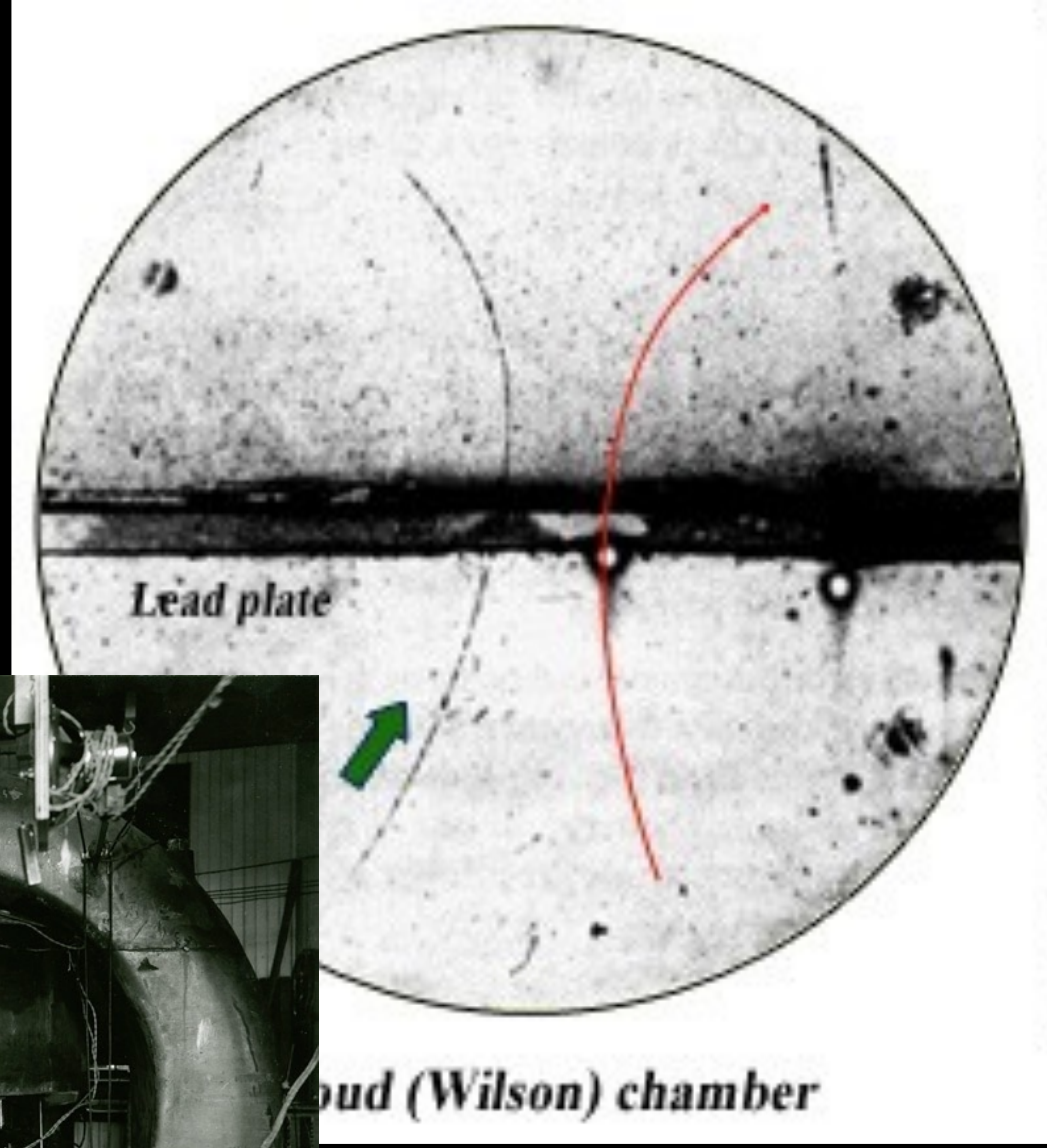
January 31, 2023

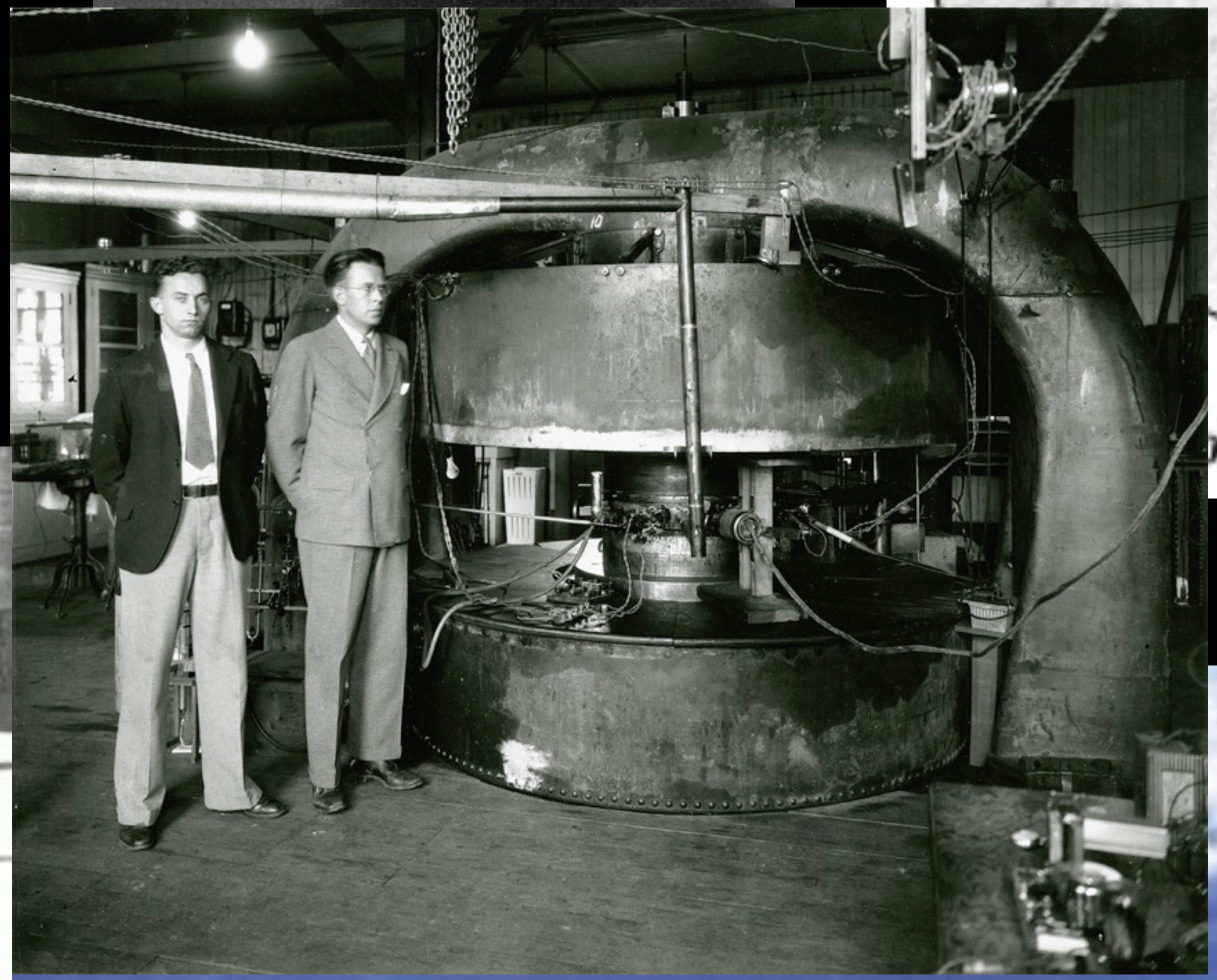
PASCOS 2024 QUY NHON

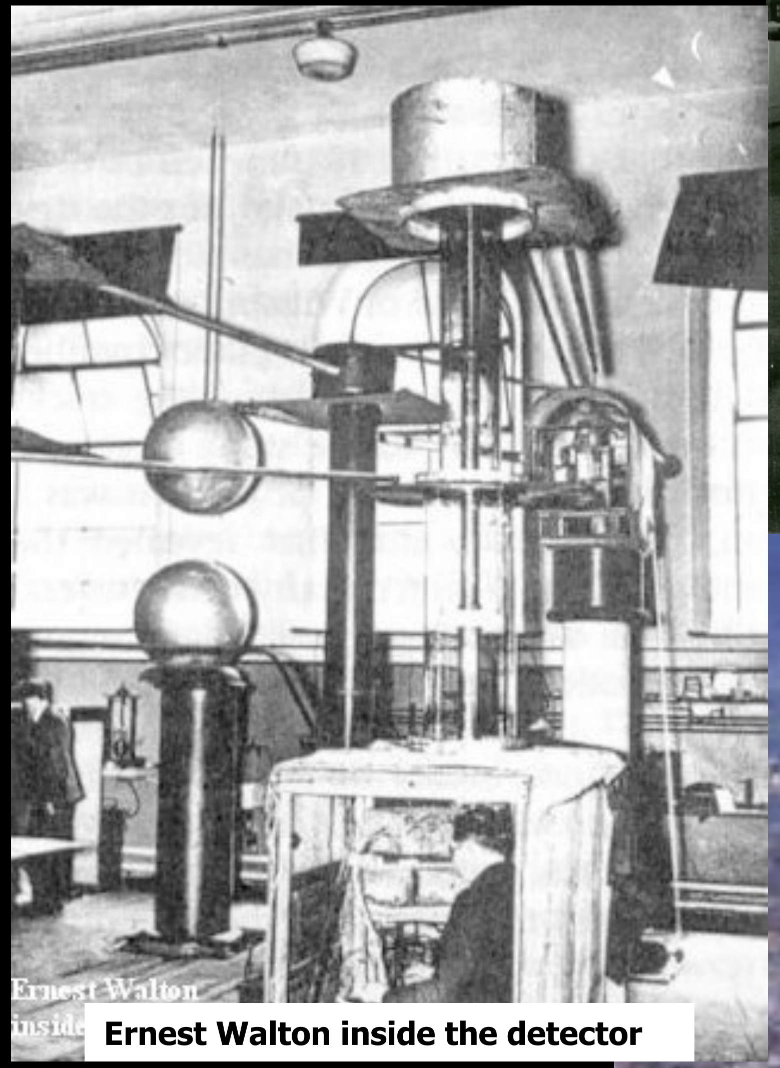
Accelerators

- 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 ($\bar{p}$ cooling: colliders)



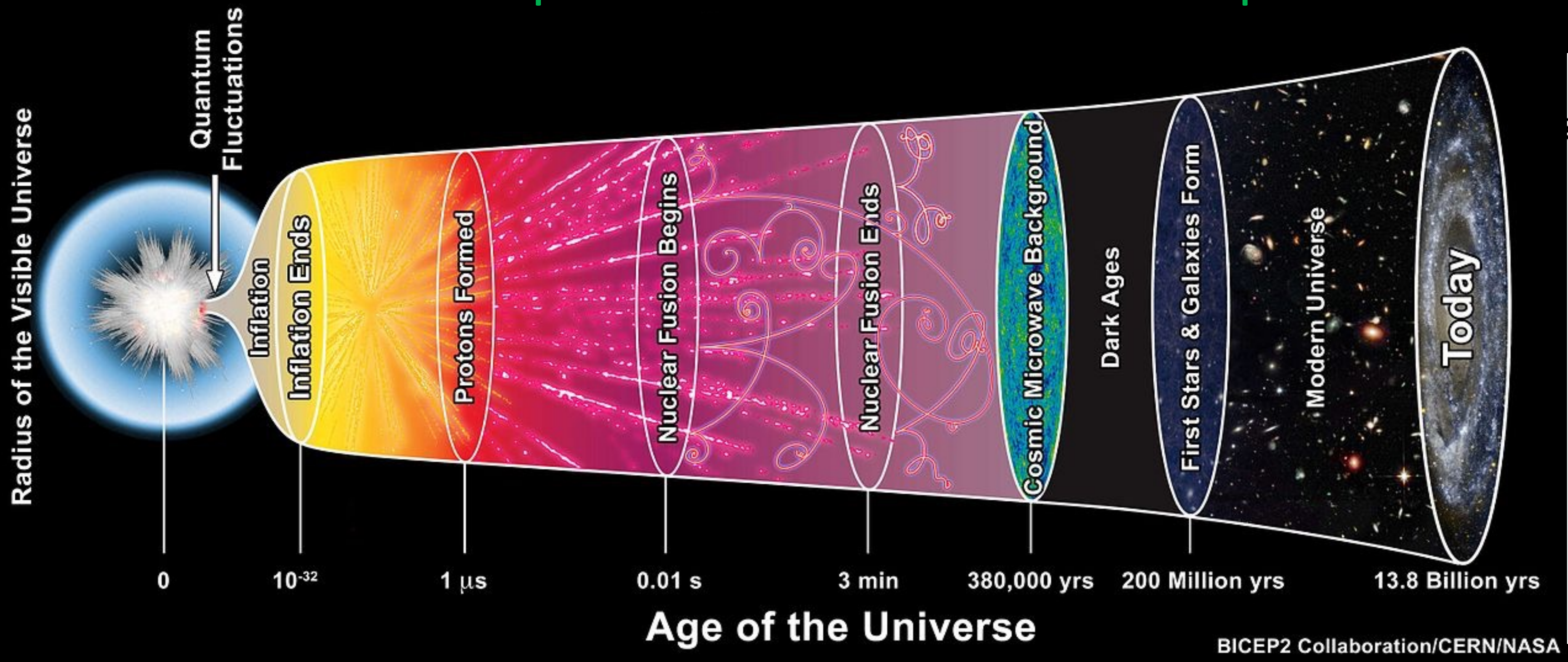


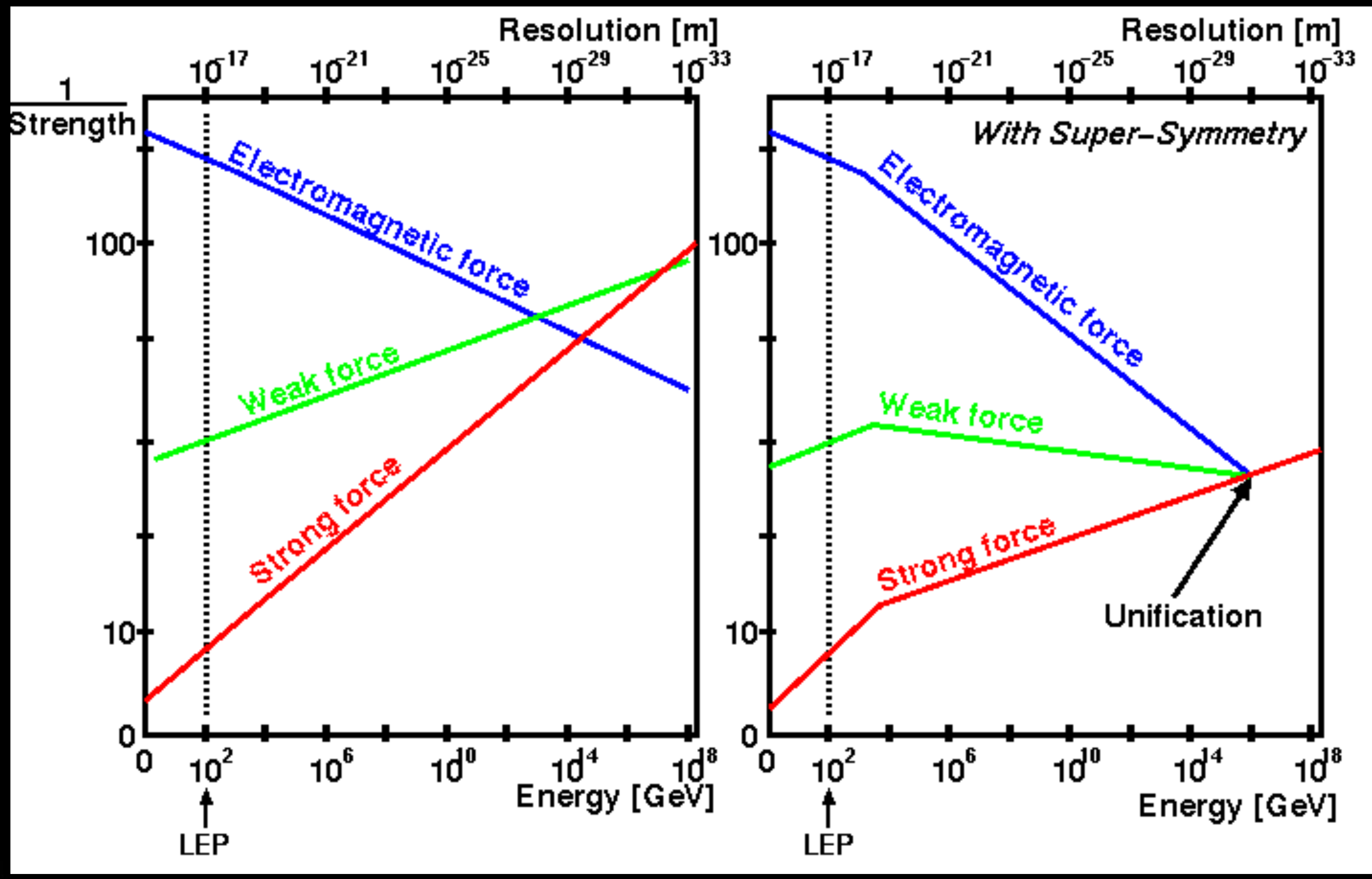




Particle Physics and the Universe

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
- Ad-hoc flavor structure
- Relies on ad-hoc Higgs potential
    - i.e. no BCS theory of the Higgs

ΛCDM

- Describes cosmological history of the Universe
    - Some tensions (i.e. H_0)
- Relies on ad-hoc Dark Matter and non-zero Cosmological Constant

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
- Ad-hoc flavor structure
- Relies on ad-hoc Higgs potential
  - i.e. no BCS theory of the Higgs

ΛCDM

- Describes cosmological history of the Universe
  - Some tensions (i.e. H_0)
- Relies on ad-hoc Dark Matter and non-zero Cosmological Constant

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

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
- Ad-hoc flavor structure
- Relies on ad-hoc Higgs potential
  - i.e. no BCS theory of the Higgs

ΛCDM

- Describes cosmological history of the Universe
  - Some tensions (i.e. H_0)
- Relies on ad-hoc Dark Matter and non-zero Cosmological Constant

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

Hierarchy / Naturalness issues

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

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
- Ad-hoc flavor structure
- Relies on ad-hoc Higgs potential
  - i.e. no BCS theory of the Higgs

ΛCDM

- Describes cosmological history of the Universe
  - Some tensions (i.e. H_0)
- Relies on ad-hoc Dark Matter and non-zero Cosmological Constant

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

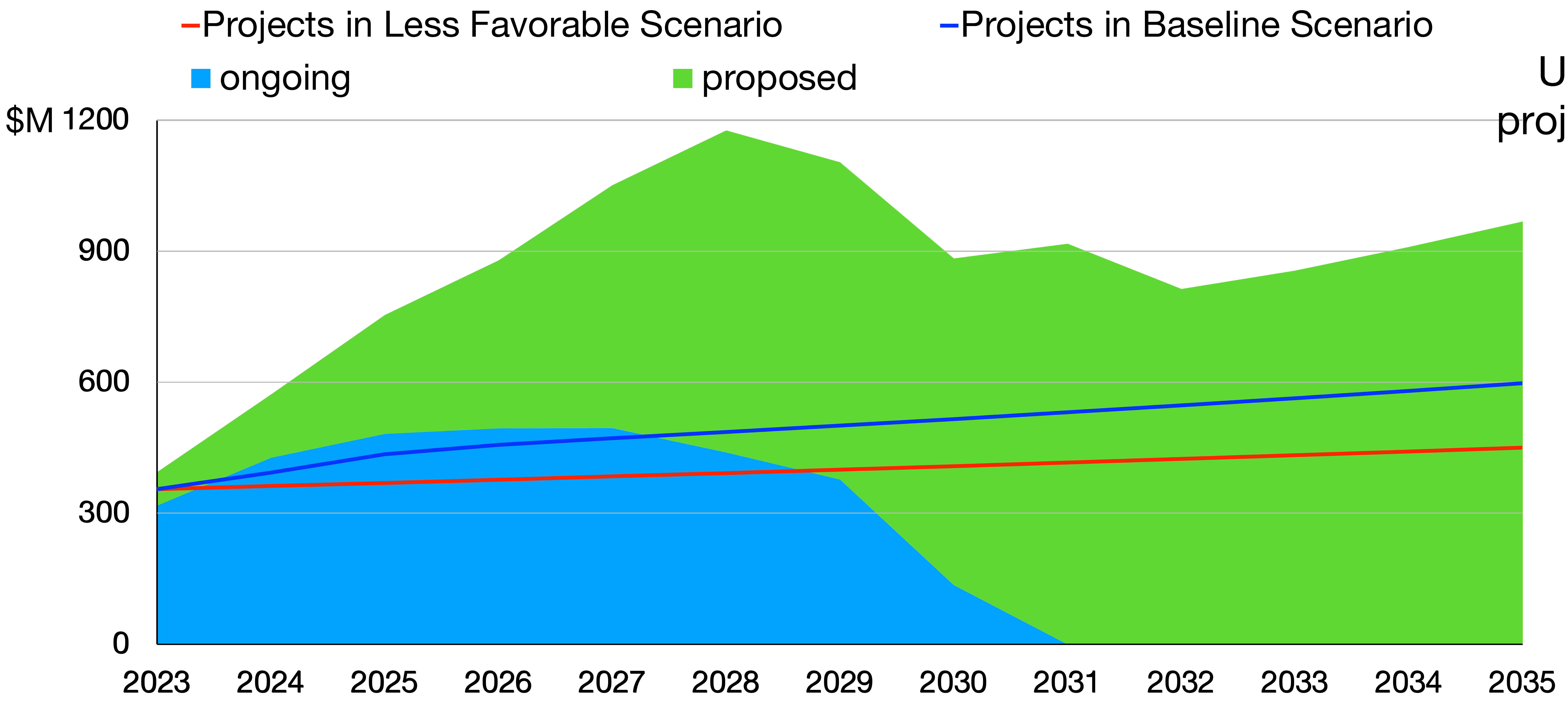
Hierarchy / Naturalness issues

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

Theory Problems!!

Experimental Problem: Particle Physics is Expensive

Experimental Problem: Particle Physics is Expensive



US DOE projects only

not including US-hosted Higgs factory proposals

The experimental program is expensive -
need strategy, prioritization, and careful planning

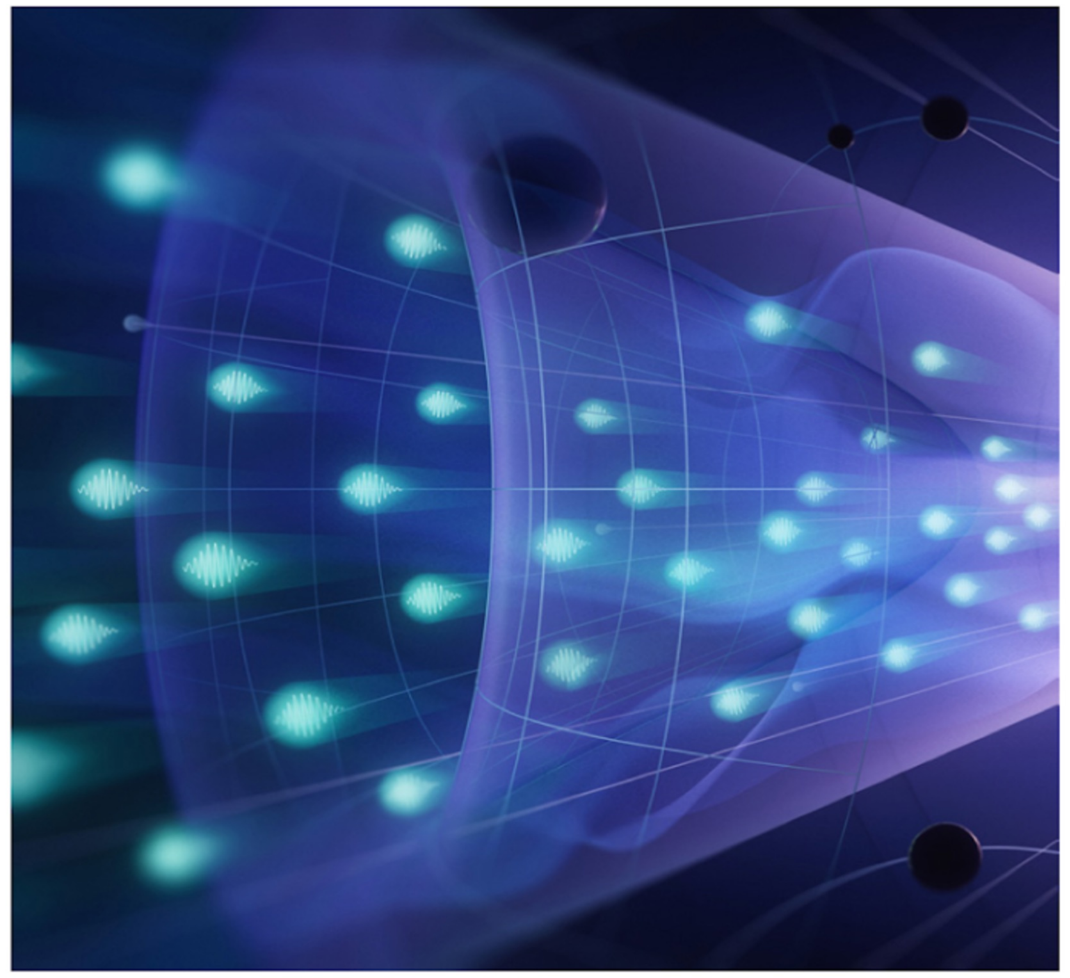
The experimental program is expensive -
need strategy, prioritization, and careful planning

And Most of All:
Global International Cooperation

In this age of economic and geopolitical challenges I surprise myself by remaining optimistic about our field


P5 Panel

A Way to Think About Particle Physics (used by US P5): 3 science themes, 6 science drivers



Decipher the Quantum Realm

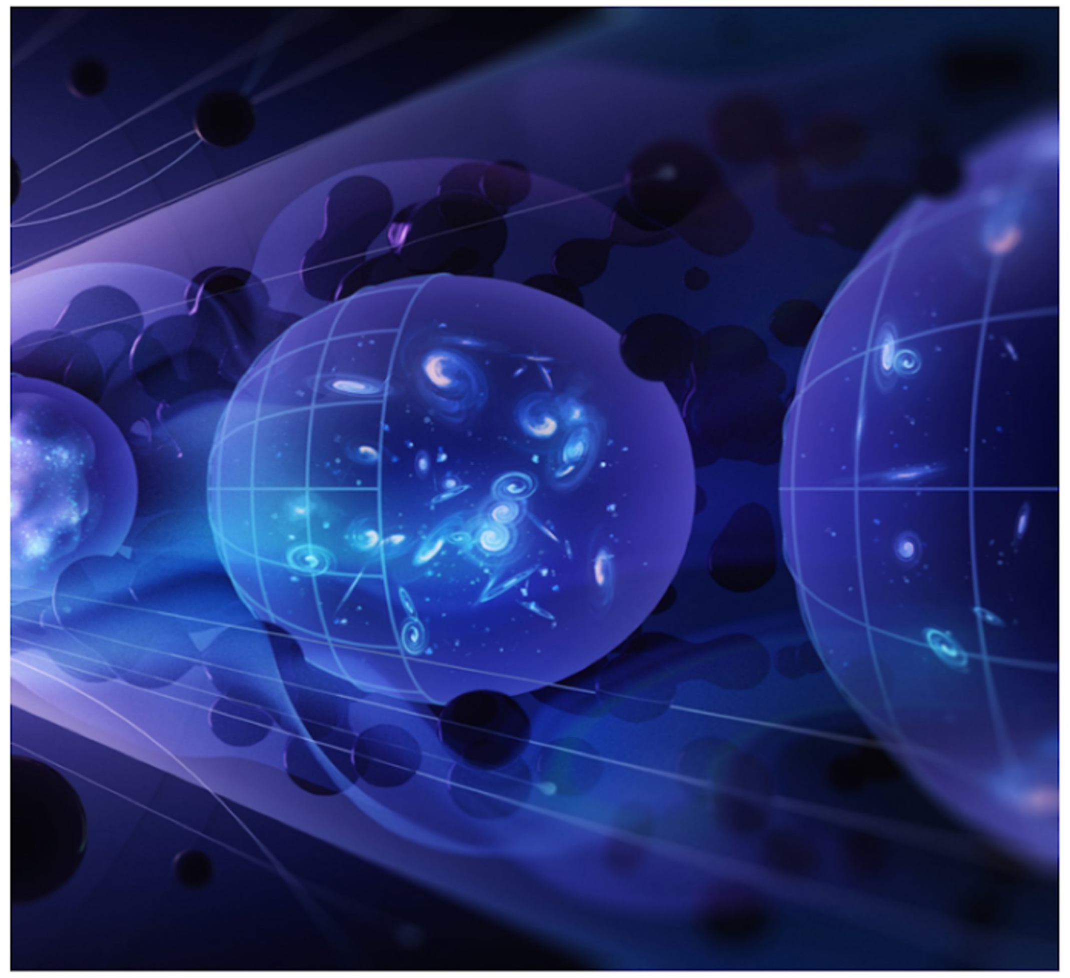
Elucidate the Mysteries of Neutrinos

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

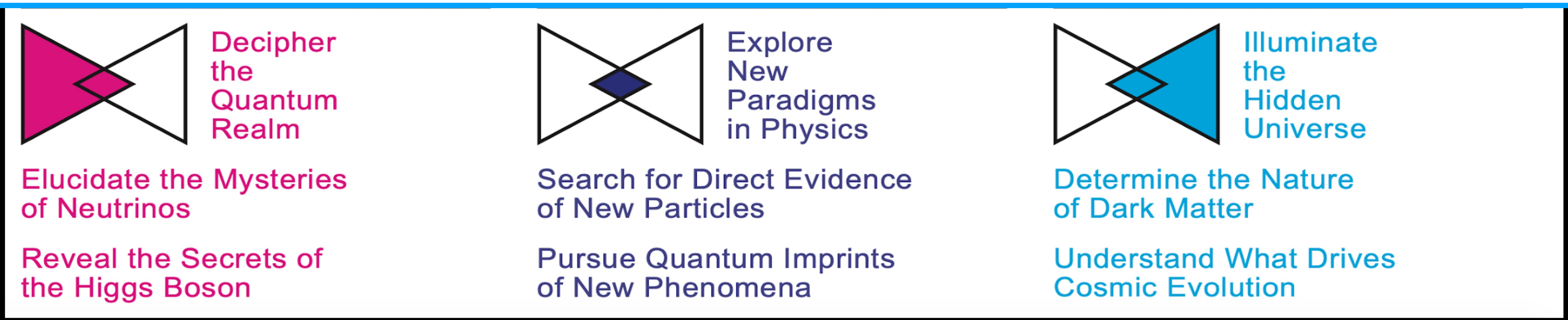
Determine the Nature of Dark Matter

Understand What Drives Cosmic Evolution

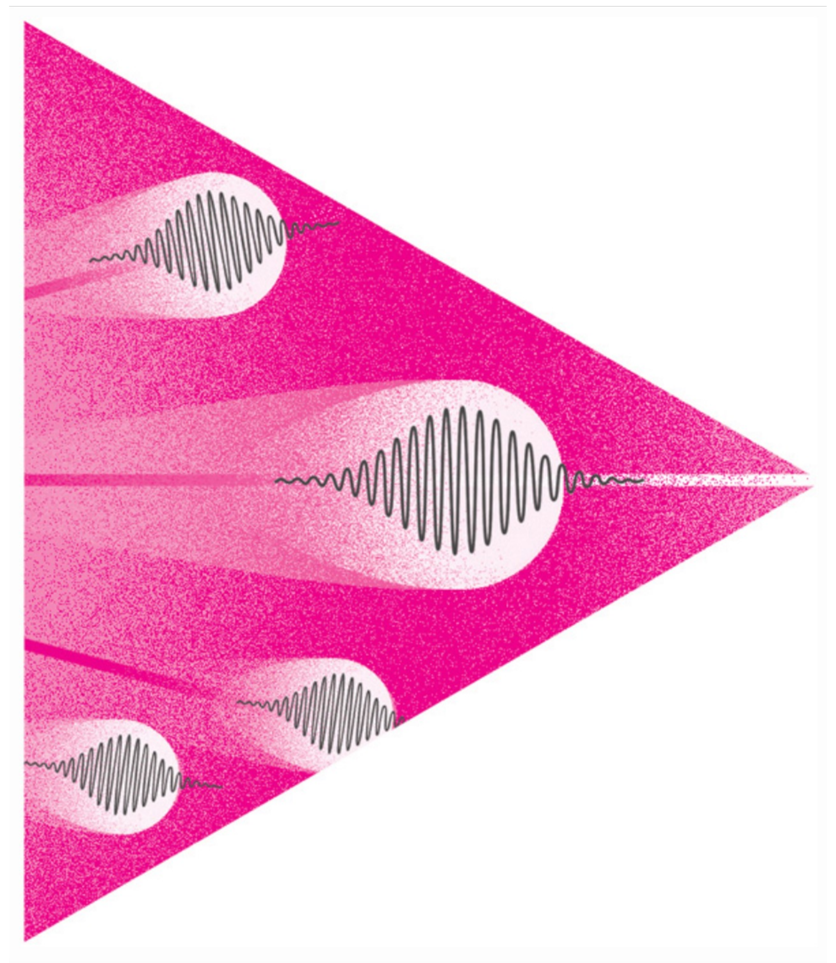
Clearly there are many interconnections between the drivers

A Way to Think About Particle Physics (used by US P5): 3 science themes, 6 science drivers

There are many measurements that are planned or coming soon that I am eager to see and the activities in the field that inspire me.
The topics I cover here may reflect this



Clearly there are many interconnections between the drivers

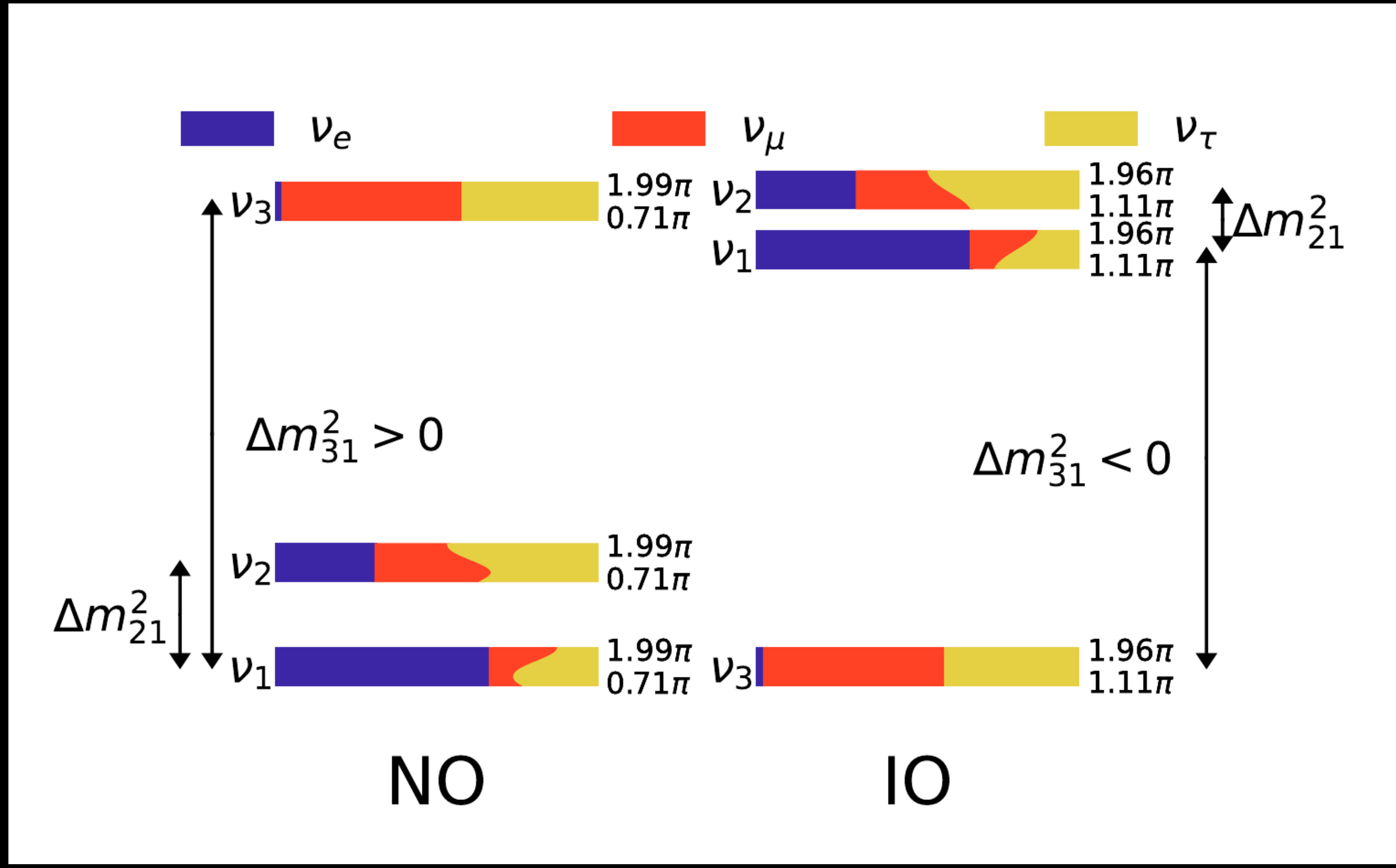


neutrinos

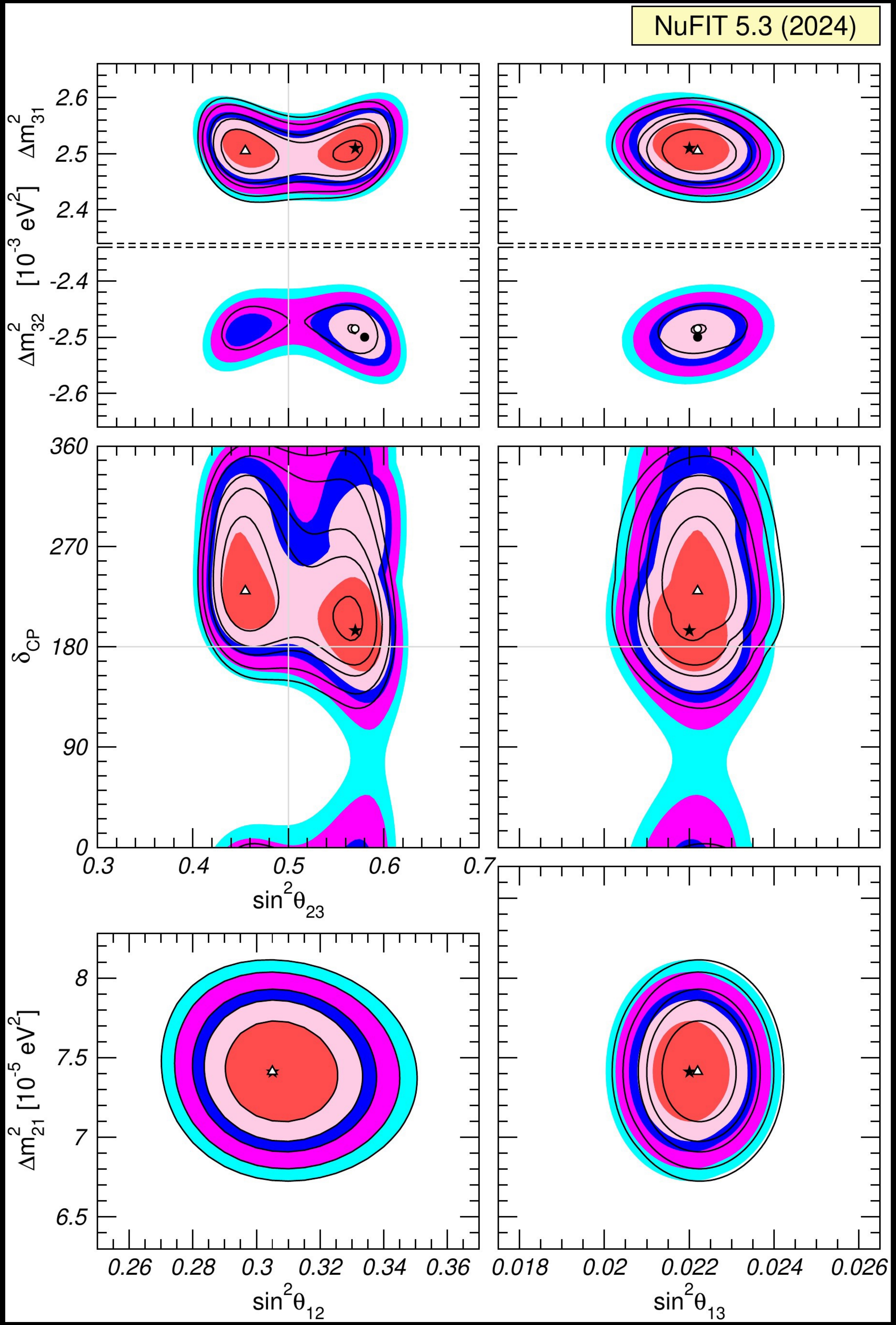
- **What are the masses of neutrinos?**

- **What is the mass ordering of neutrinos? If inverted, what causes two heavier neutrinos having similar masses?**

- **Neutrino mixing matrix values do not look like the ones in the quark sectorwith a small parameter λ**

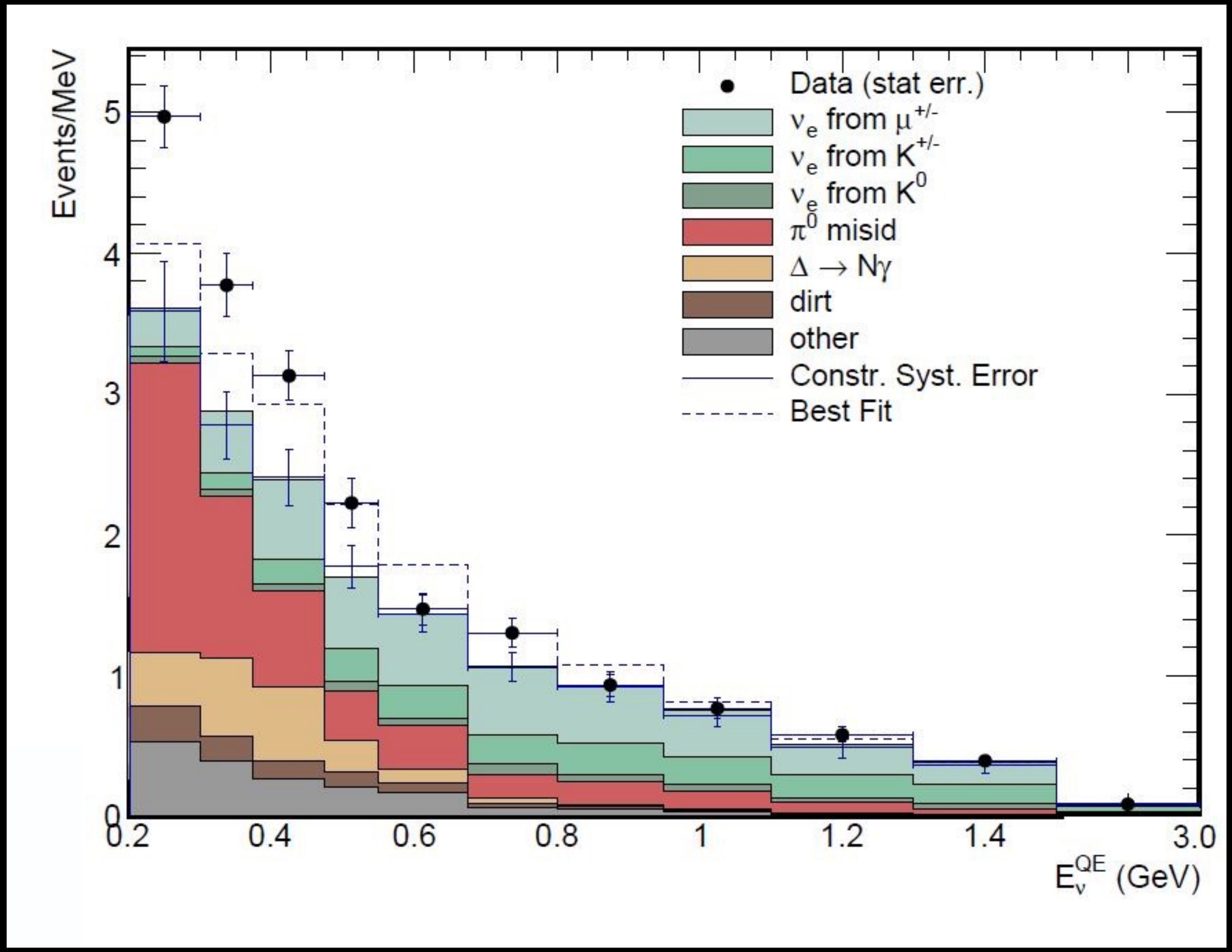


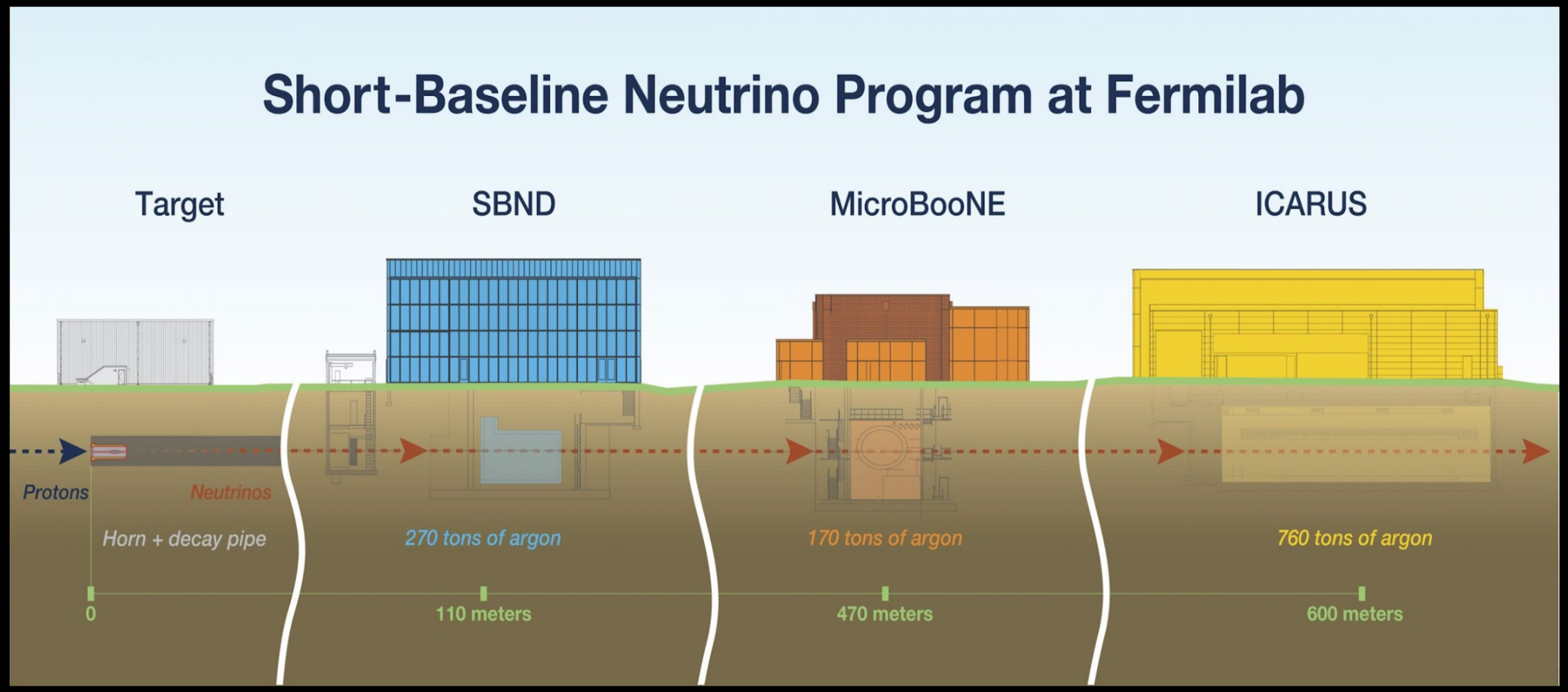
$$\theta_{12} = 33.41^{\circ}{}^{+0.75^\circ}_{-0.72^\circ}$$
$$\theta_{23} = 49.1^{\circ}{}^{+1.0^\circ}_{-1.3^\circ}$$
$$\theta_{13} = 8.54^{\circ}{}^{+0.11^\circ}_{-0.12^\circ}$$

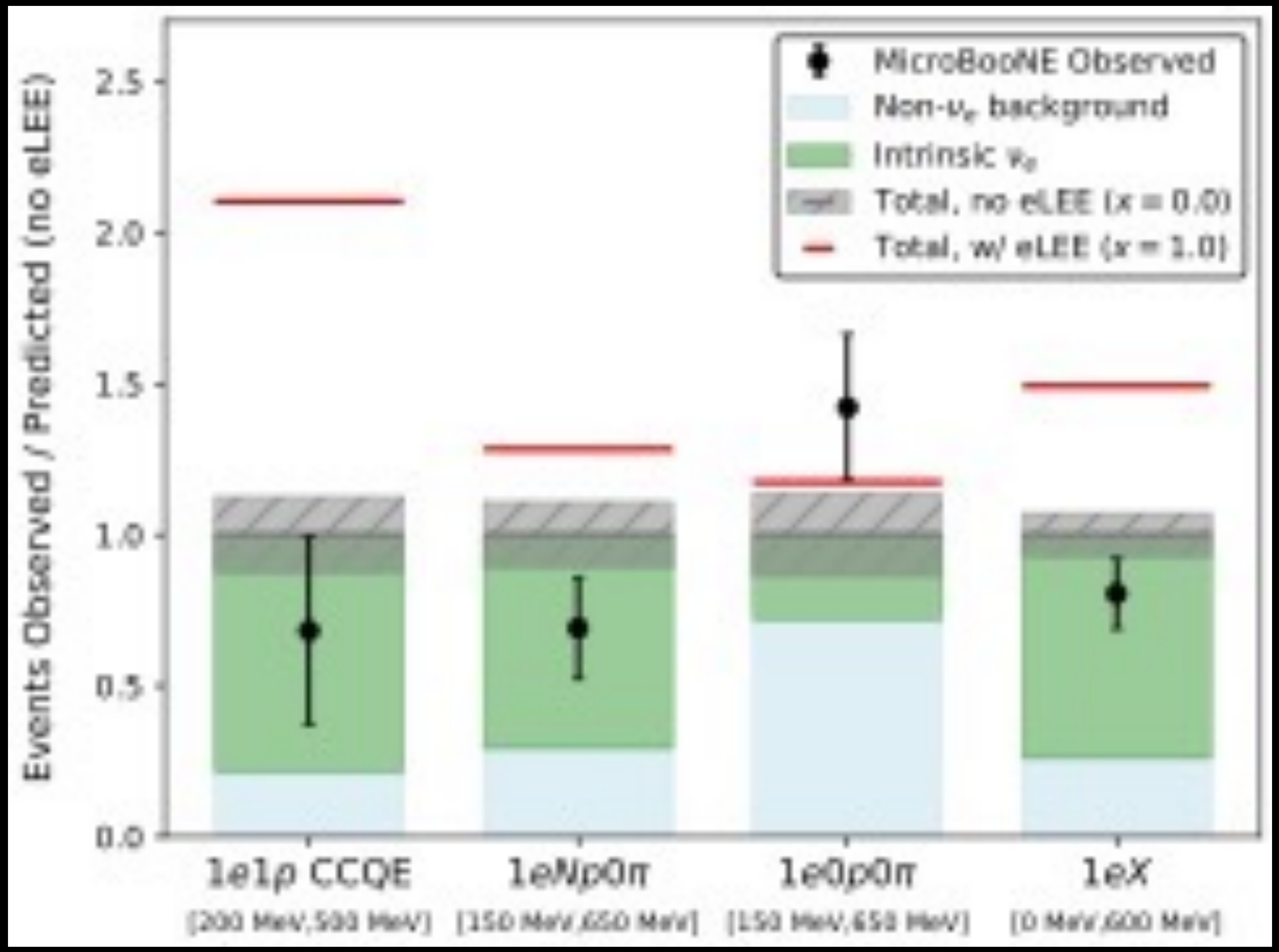


Testing the paradigm: 3 neutrinos?

Mini-Boone (following LSND)

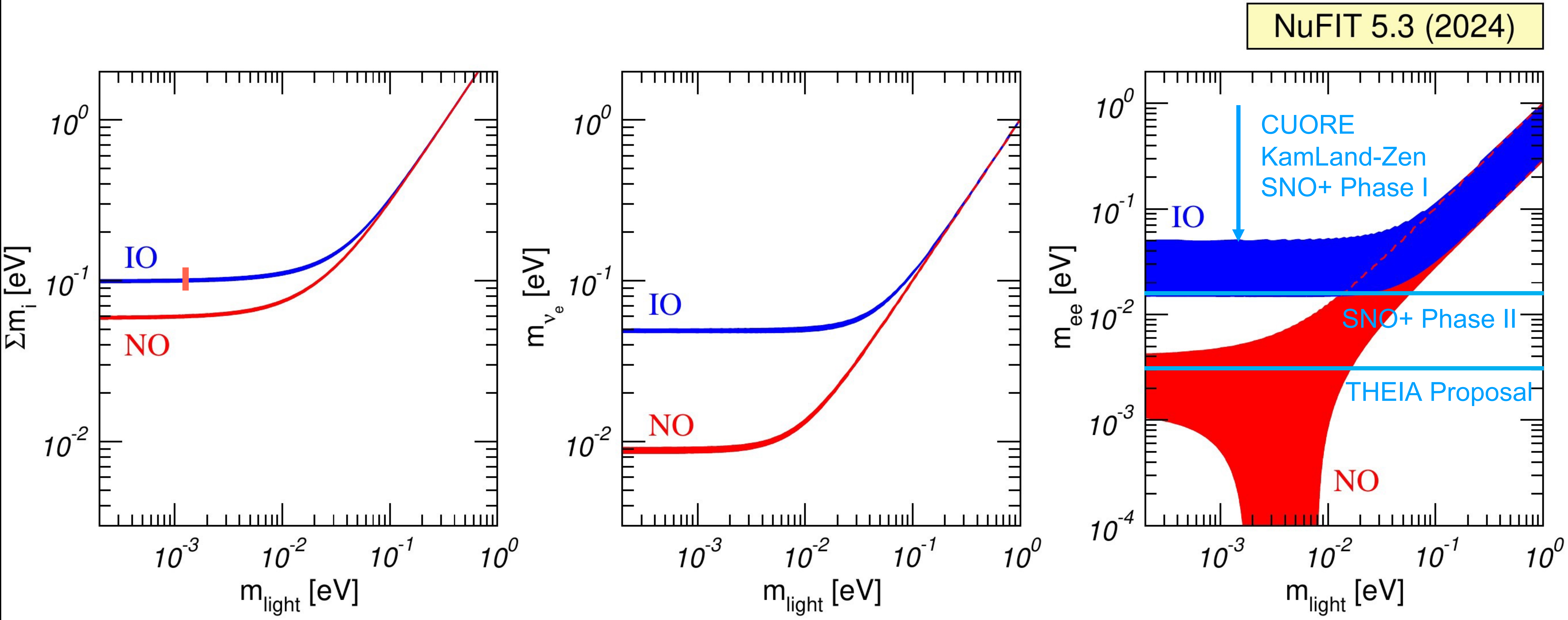






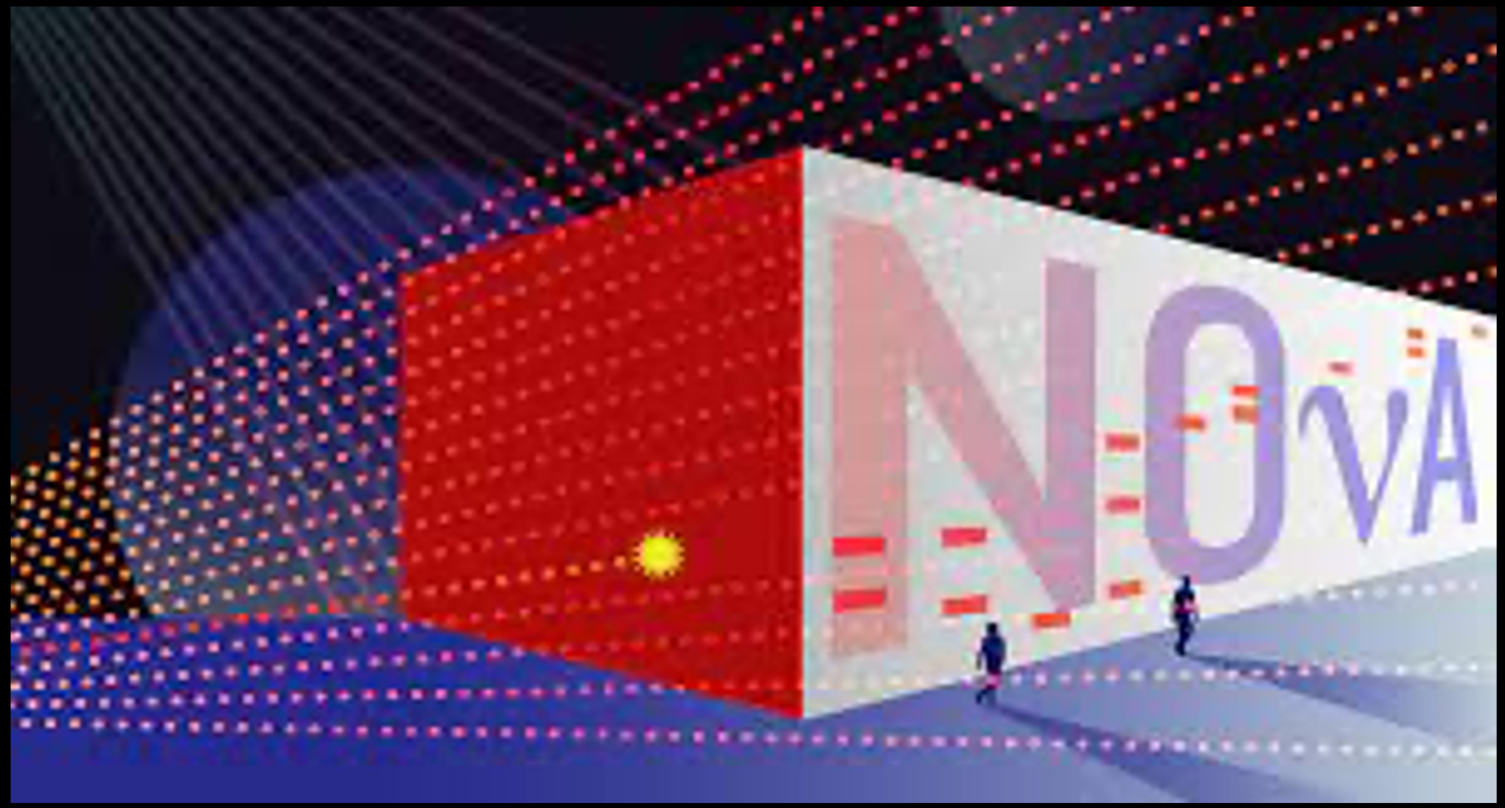
The SBN program has explored numerous anomalous results. Additionally, they have proved crucial in maturing liquid argon technology and analysis.

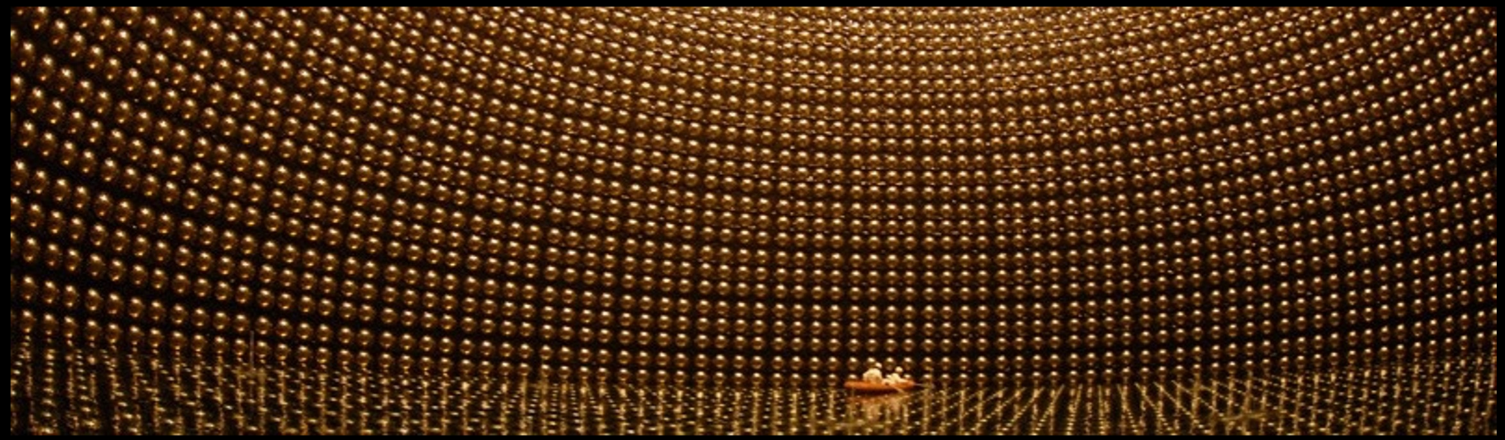
Neutrino Masses



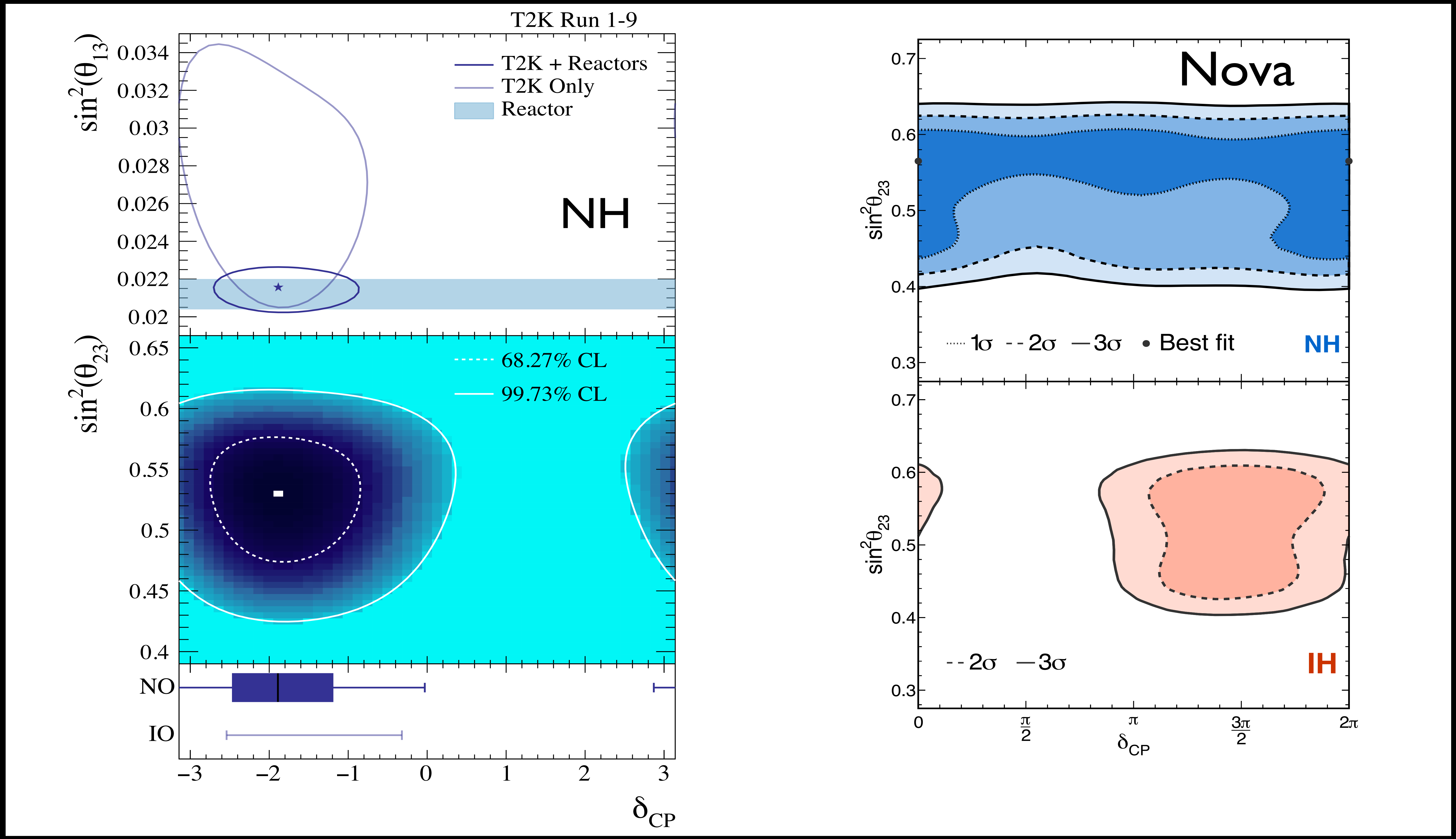
- **Future CMB measurements:** $\boldsymbol{\sigma(\Sigma m_\nu) \sim 15\ meV}$
- **Endpoint measurement sensitivity: 200 meV (KATRIN),** ***40 meV*** **(Project 8)**

Hint of CP violation?



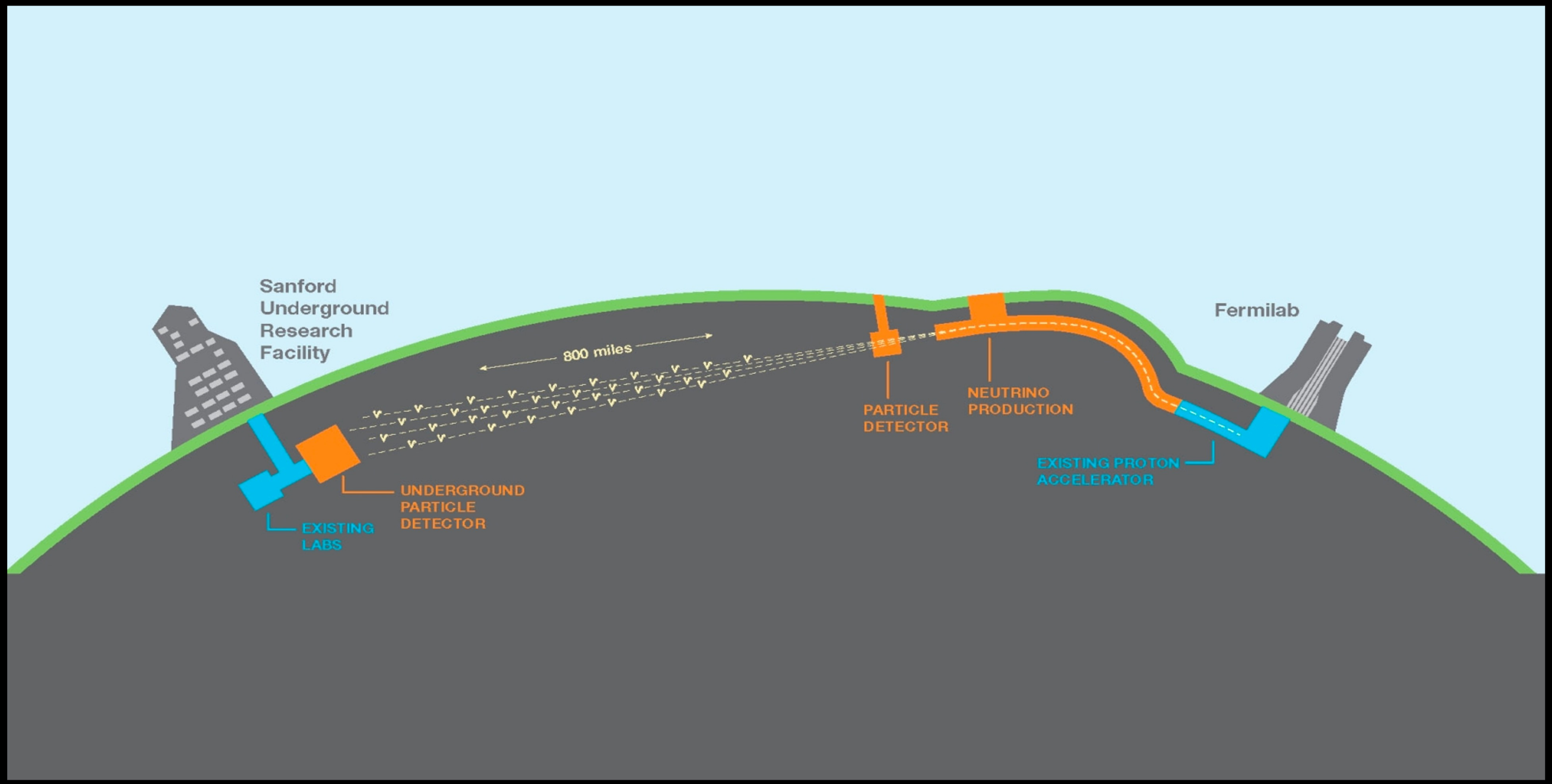


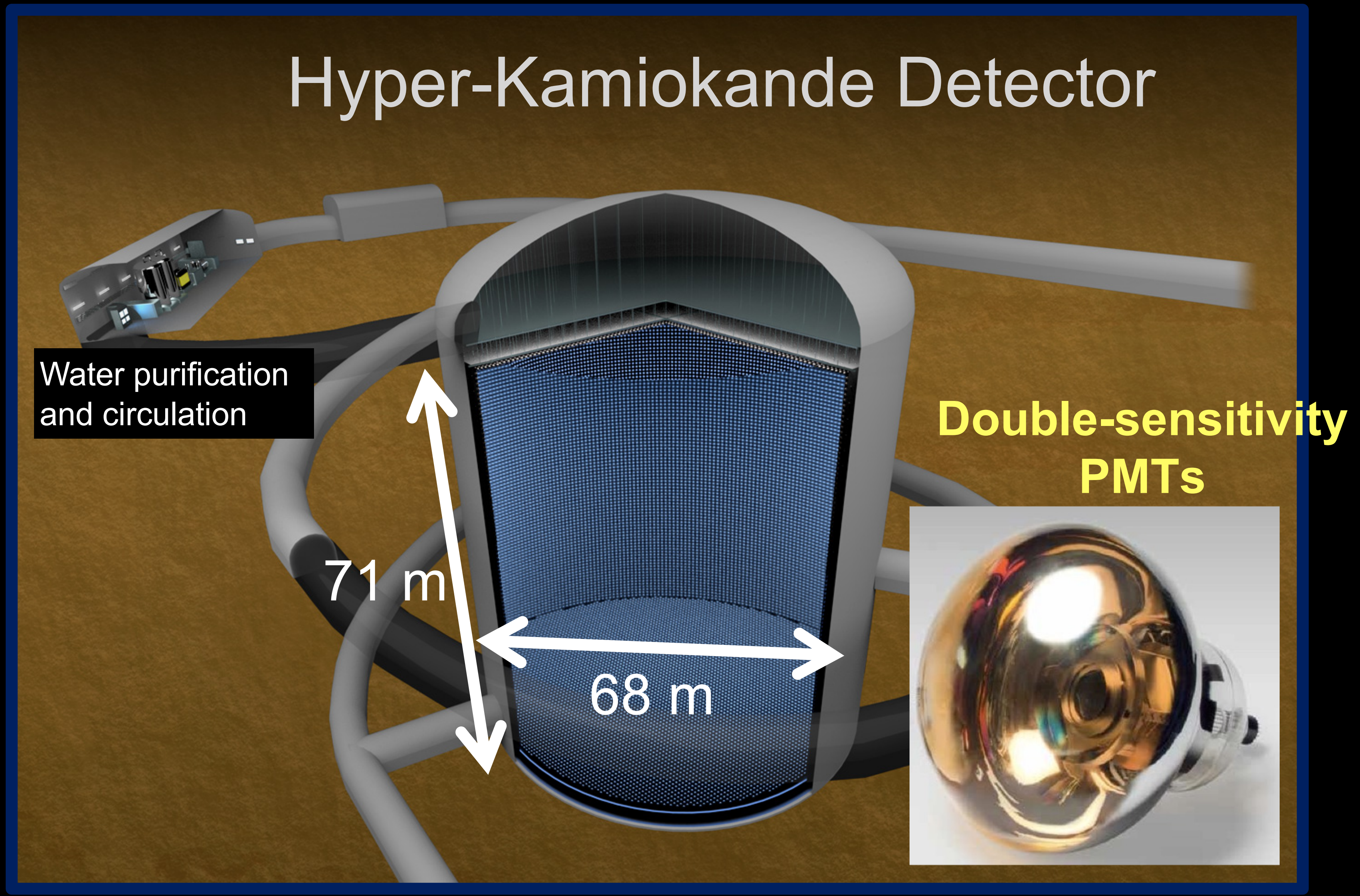
T2K

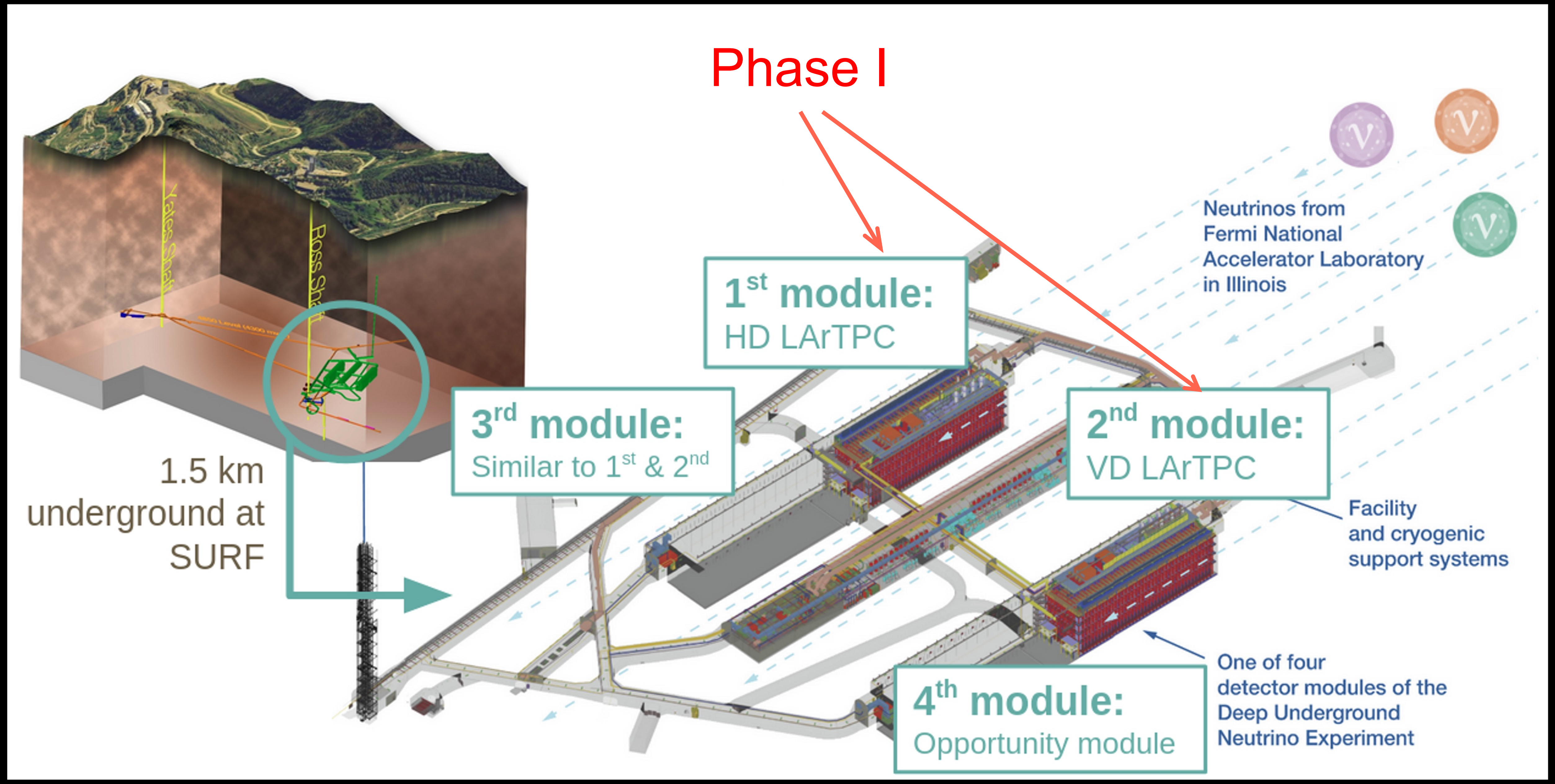


NOvA & T2K combination prefers inverse ordering
By themselves or in combinations with reactor experiments (Daya Bay, D-Chooz, Reno) prefers normal ordering: mild tension. Statistics or non standard matter interactions?

Definitive experiments: DUNE & HyperK



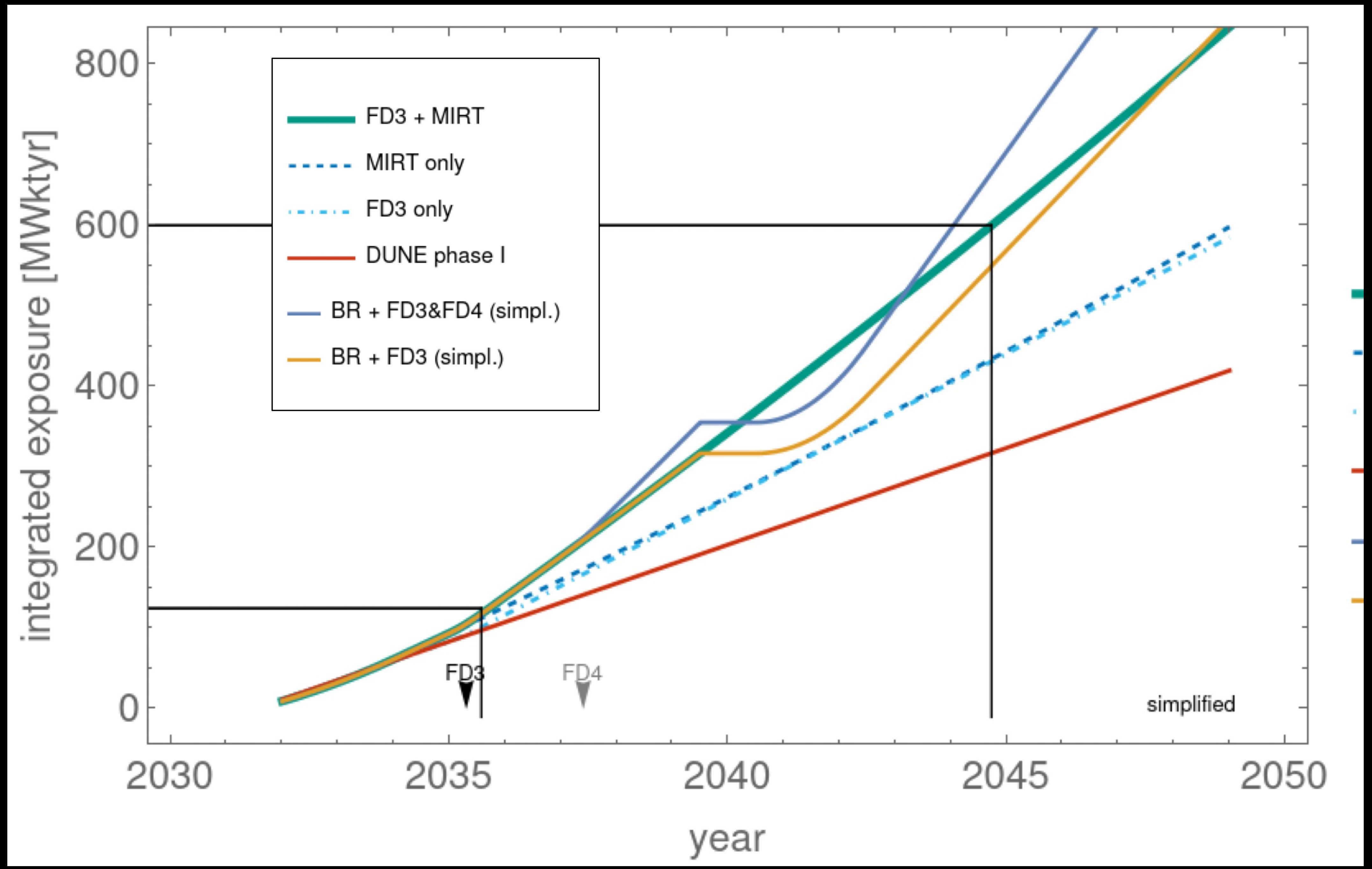




Definitive experiments: DUNE & HyperK

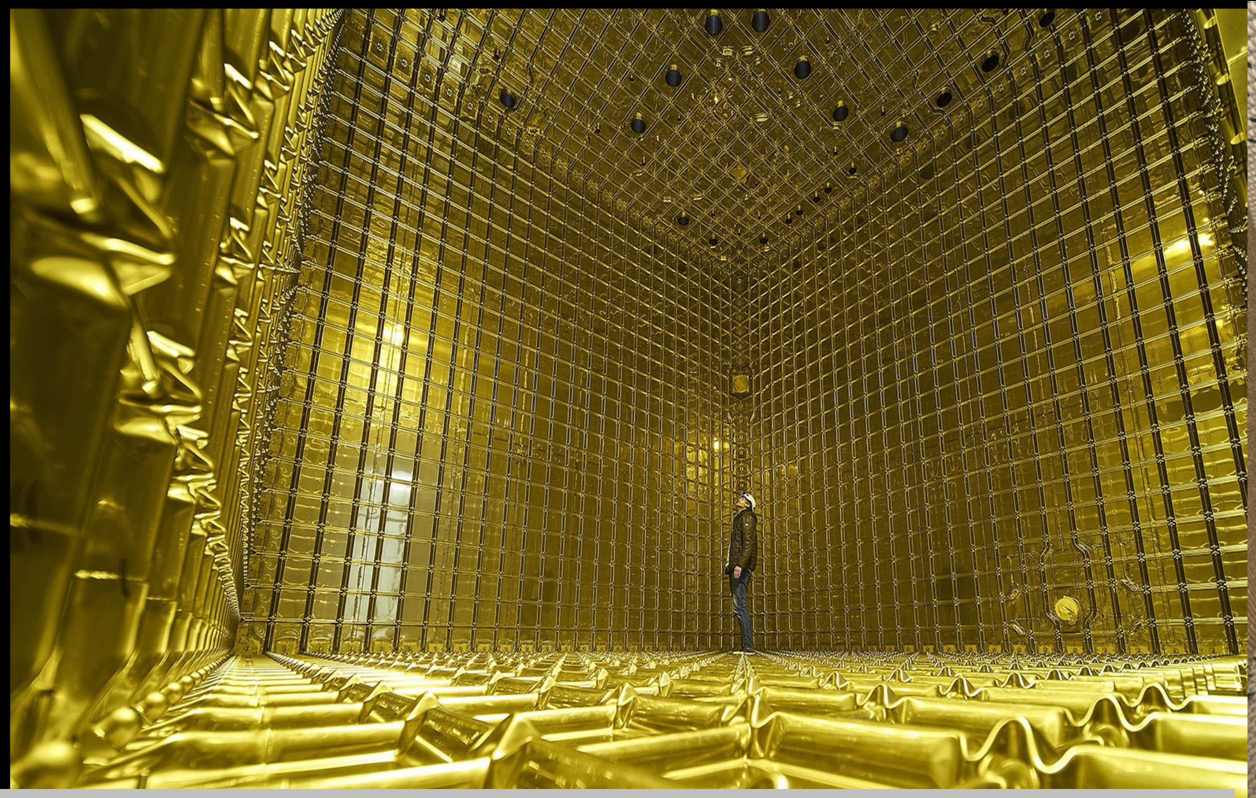
Science goals:

- **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.**

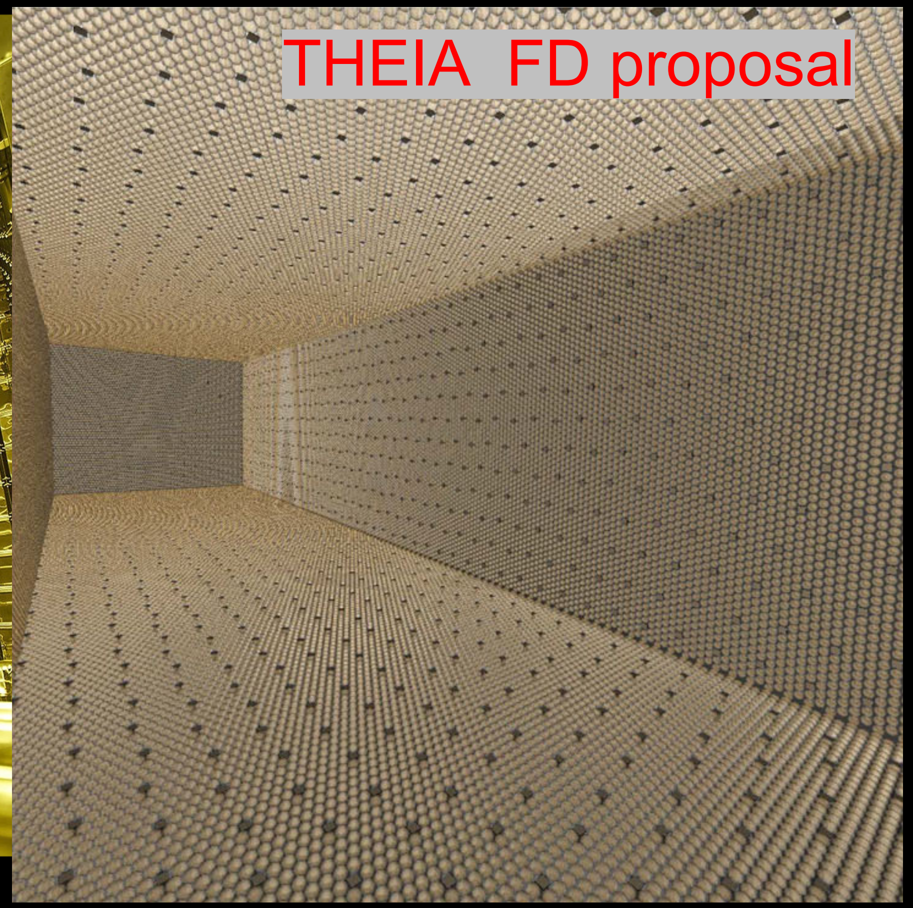


DUNE re-affirmed and re-imagined:

- **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**



ProtoDUNE – demonstrator of current FD design



THEIA FD proposal

Beyond DUNE and T2K?

DUNE and T2K are complementary – especially in the amounts of matter effects that help with the systematics

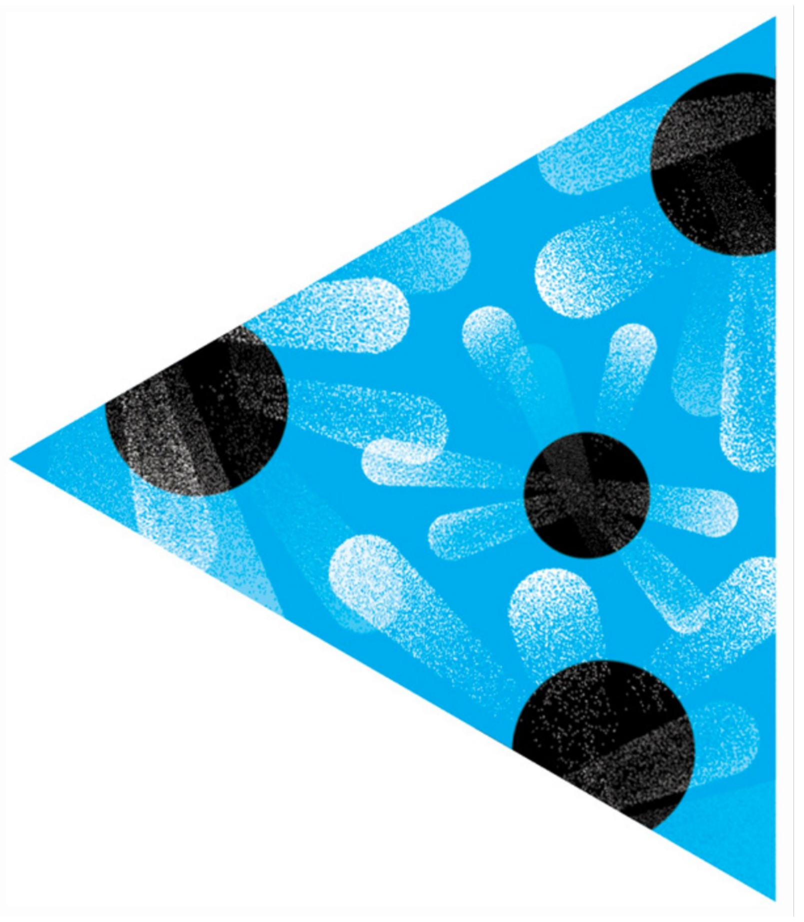
If we need more precision after completing DUNE and T2K:

Switch to muon-based neutrino beams

* low energy muon storage rings (i.e. NuSTORM)

* Higher energy if needed (neutrino factory)

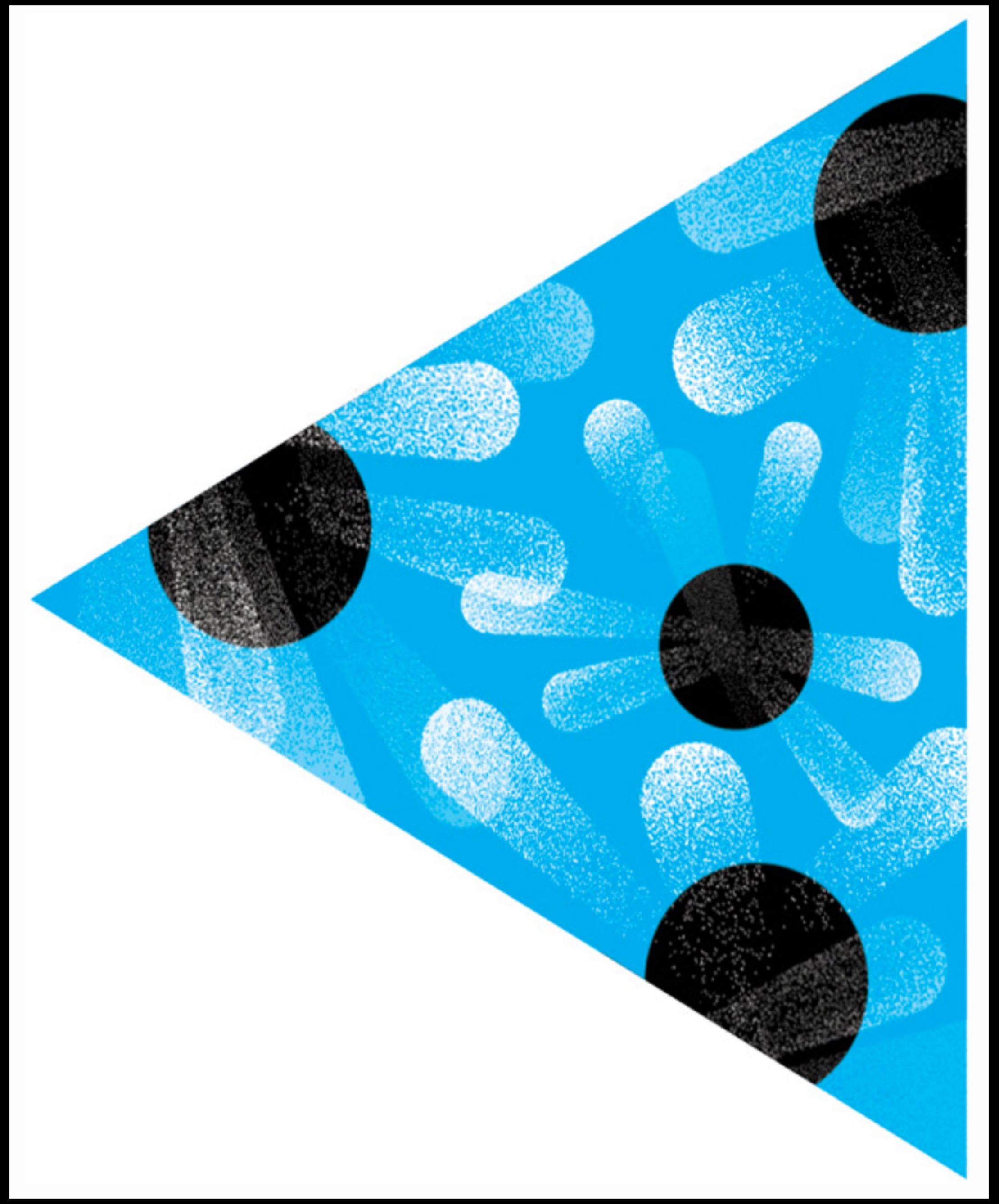
Note that there are other things that need muon beams



cosmic evolution

What Drives Cosmic Evolution?

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



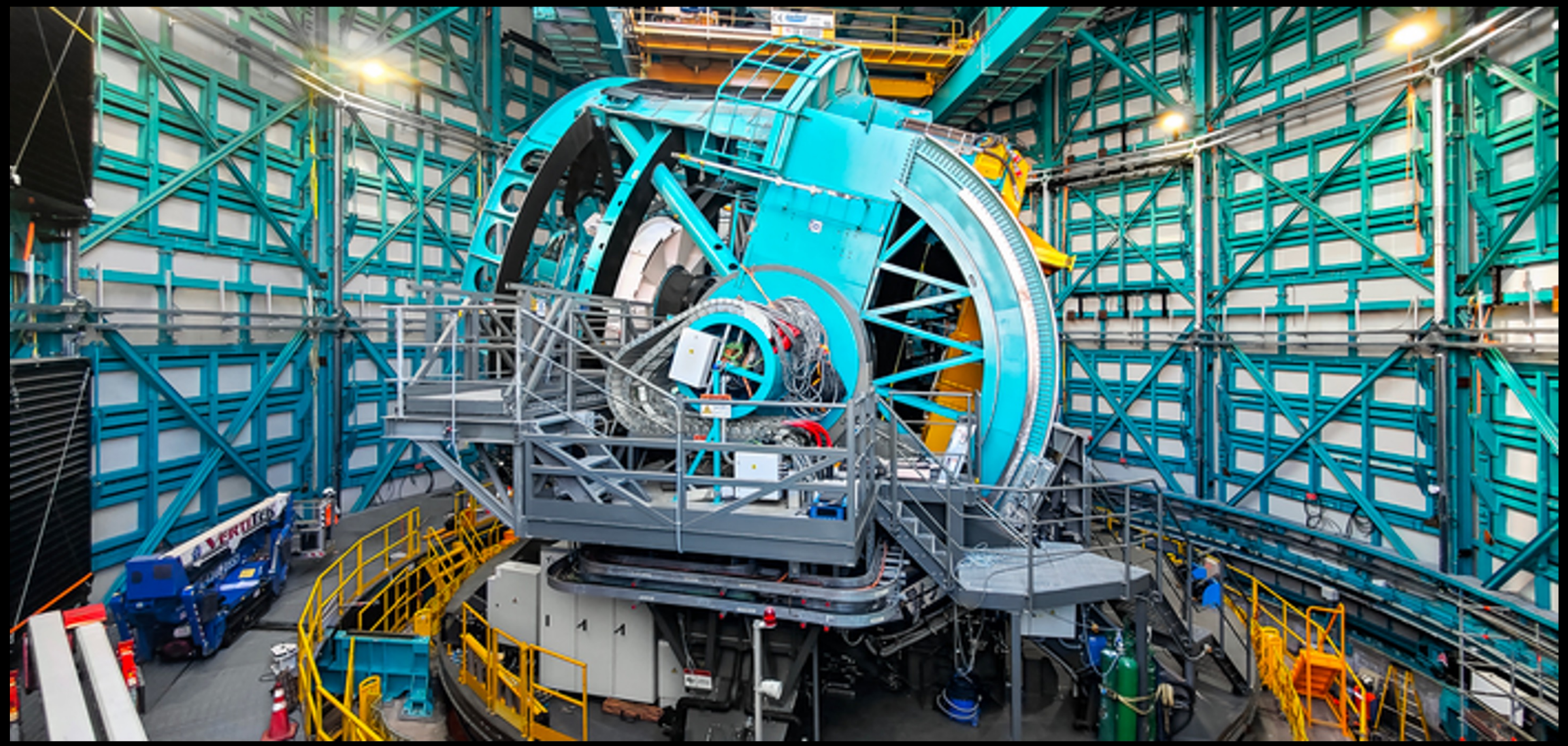
What physics is responsible for the rapid, accelerated expansion during the early inflationary era?

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.

DESI and Rubin

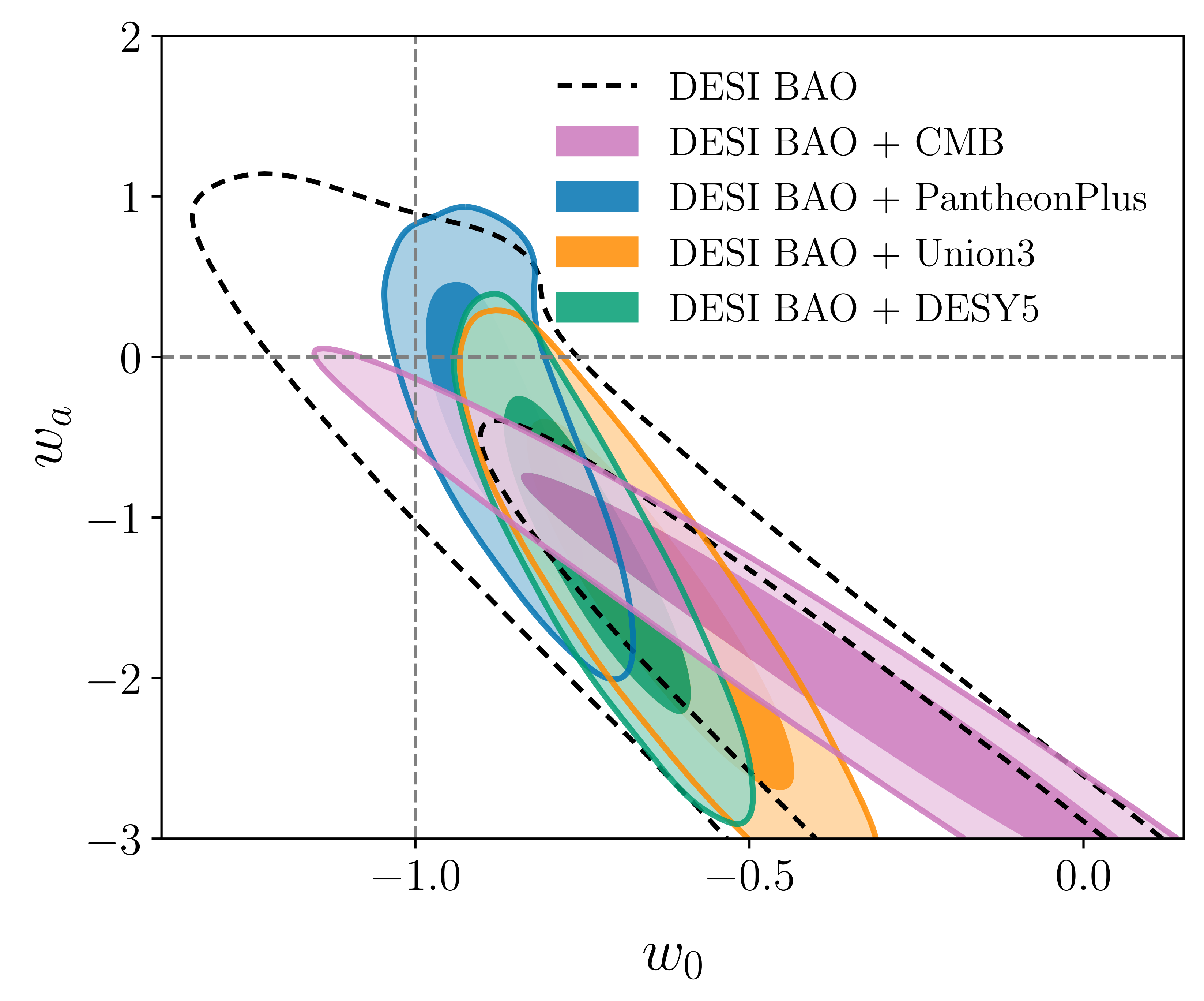
will provide constraints on cosmic acceleration, and reach back into the weakly matter-dominated era when the expansion was still decelerating. The program will stress-test the standard cosmological paradigm, where CMB surveys can benefit from combinations with space-based datasets.

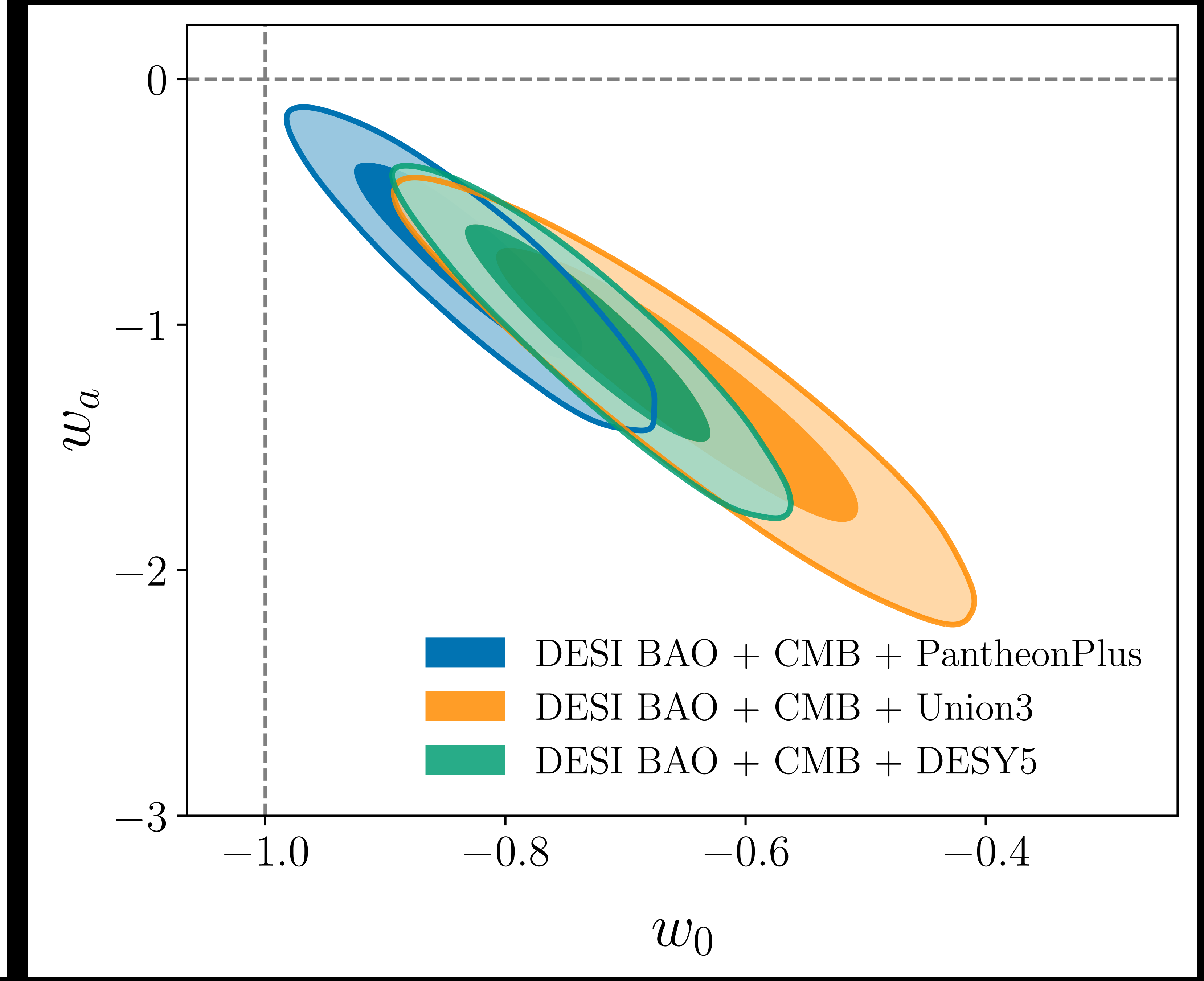


Rubin Observatory: Legacy Survey of Space and Time (LSST) and the LSST Dark Energy Science Collaboration (DESC)

DESI (a spectroscopic survey)

Cosmological non-constant?



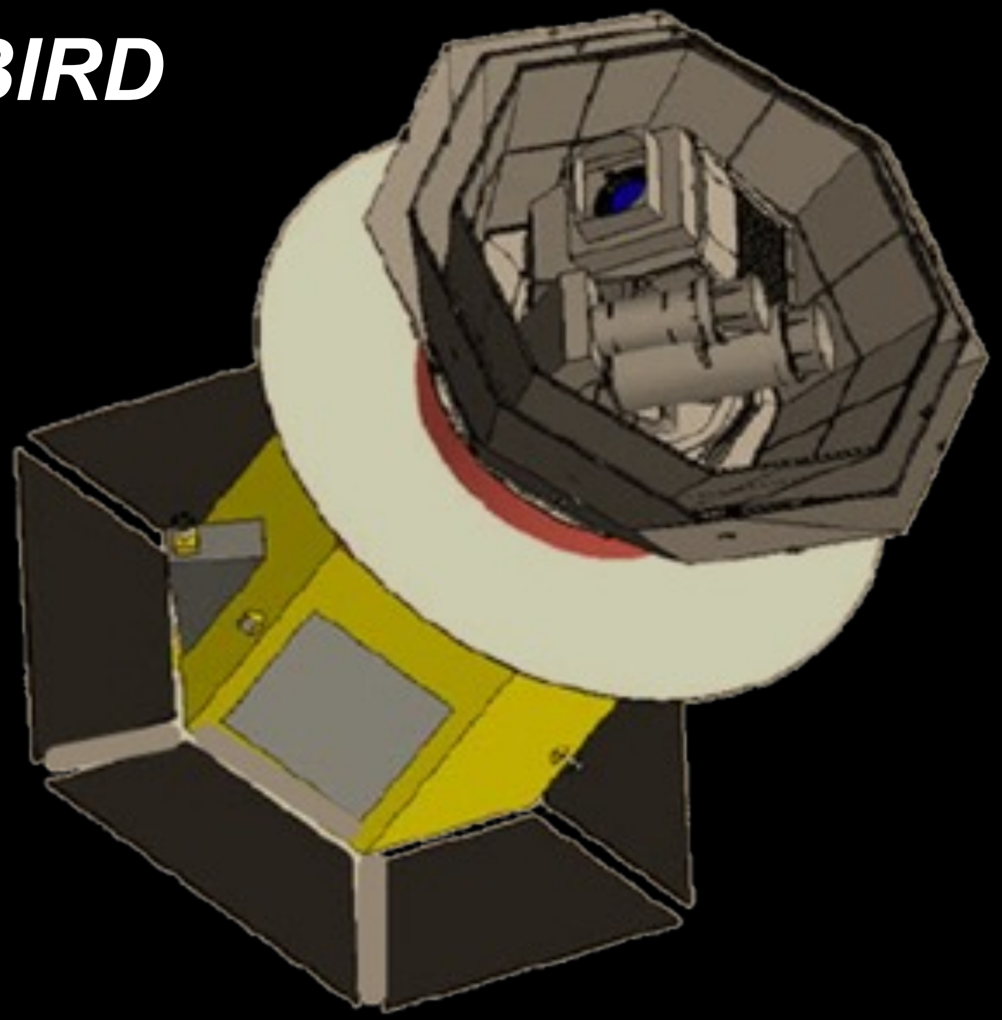


By itself DESI is ~consistent with ΛCDM
Depending on how you combine it with CMB and SN Ia one can get as much as 3.9σ from $w_0 = -1$ and $w_a = 0$

A complementary views of CMB from three locations

@ L2 Lagrange point

LiteBIRD

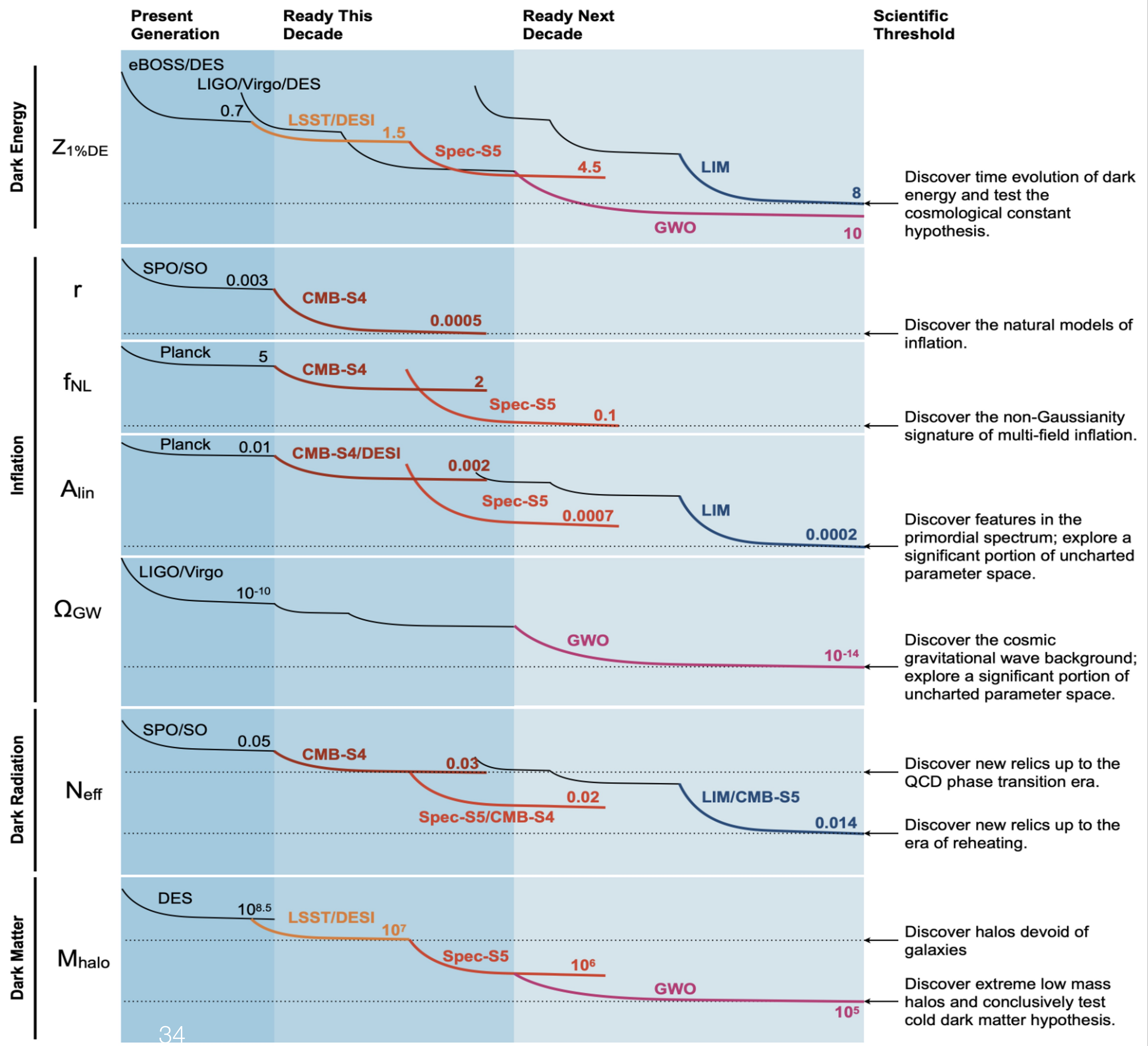


energy scale of inflation
abundance of light relic particles in the early universe
sum of neutrino masses
dark matter
dark energy

Galaxy survey and CMB outlook

- Rubin/LSST and DESI
- DESI-II
- CMB-S4
- R&D towards Spec-S5
- R&D for LIM (LuSEE-Night)

Snowmass: arxiv:2211.09978

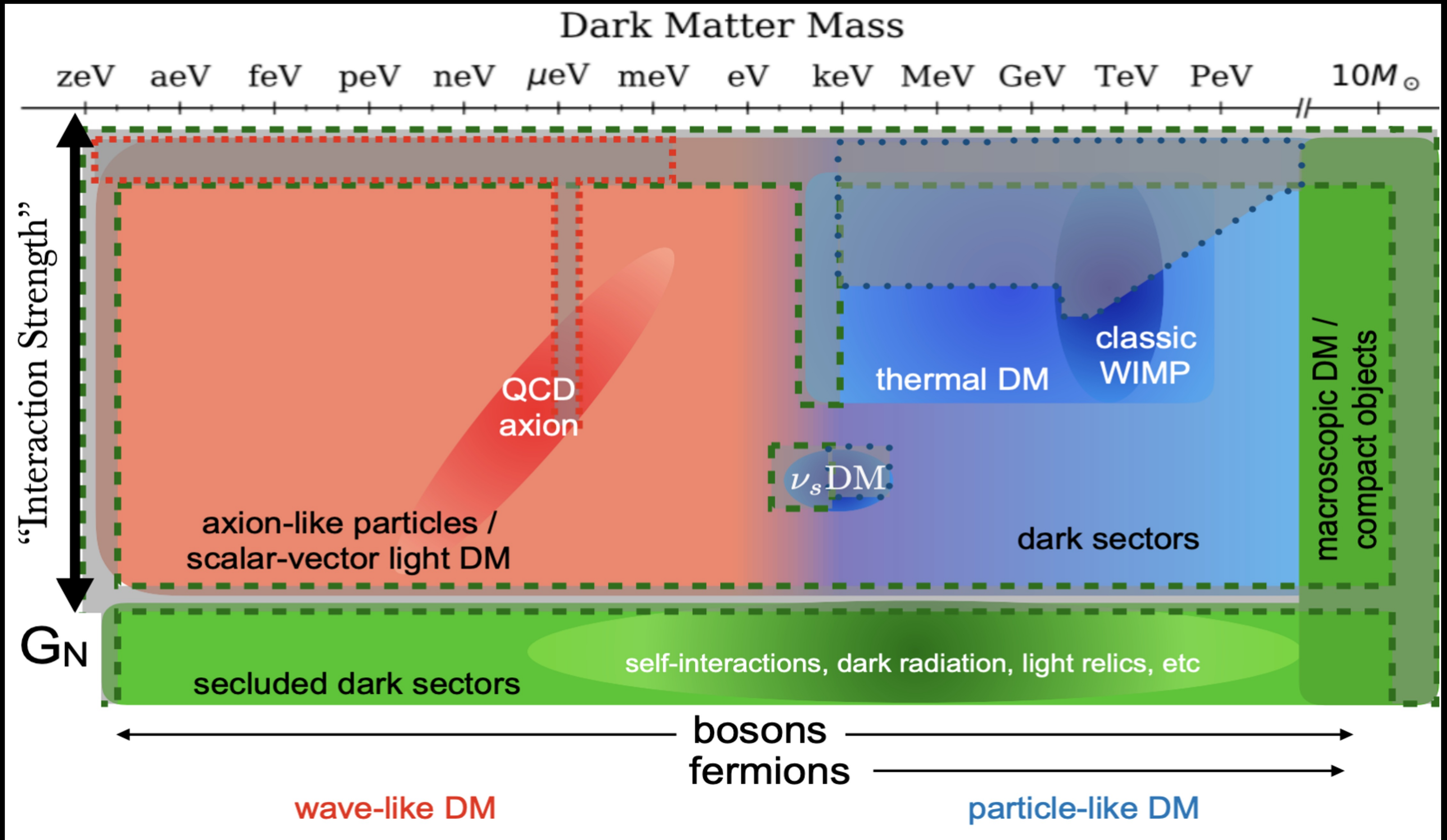


dark matter

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.



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

New Opportunities this Decade:

Cosmic Frontier:

- **ADMX Extended** (axions 2-4GHz), 9-17 μeV
- **OSCURA** (low noise "Skipper" CCD detector) 1MeV-1GeV
- **DM-Radio** (axion search), <μeV
- **TESSERACT** (Multiple detectors, w/TES readout), >10 MeV

Intensity Frontier (accelerator based)

- CCM Beam Dump exp at FNAL, ~1-40 MeV
- Light Dark Matter Experiment (LDMX) ~ 10-300 MeV

need construction funding!

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

New Opportunities this Decade: ASTAE!

Cosmic Frontier:

- **ADMX Extended** (axions 2-4GHz), 9-17 μeV
- **OSCURA** (low noise "Skipper" CCD detector) 1MeV-1GeV
- **DM-Radio** (axion search), <μeV
- **TESSERACT** (Multiple detectors, w/TES readout), >10 MeV

Intensity Frontier (accelerator based)

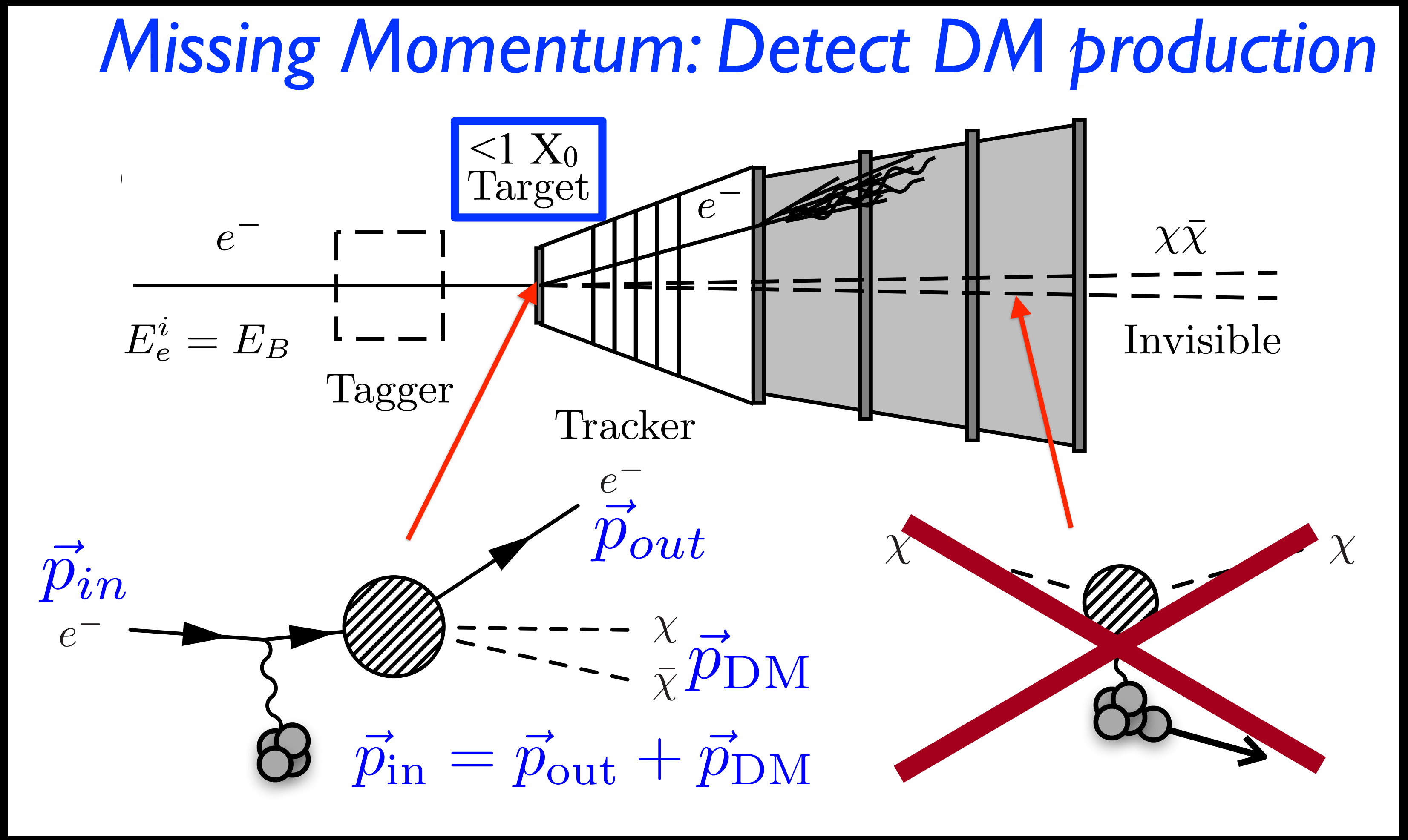
- CCM Beam Dump at FNAL, ~1-40 MeV
- Light Dark Matter Experiment (LDMX) ~ 10-300 MeV

Now a new program for agile experiments @ DOE (not only DM)

need construction funding!

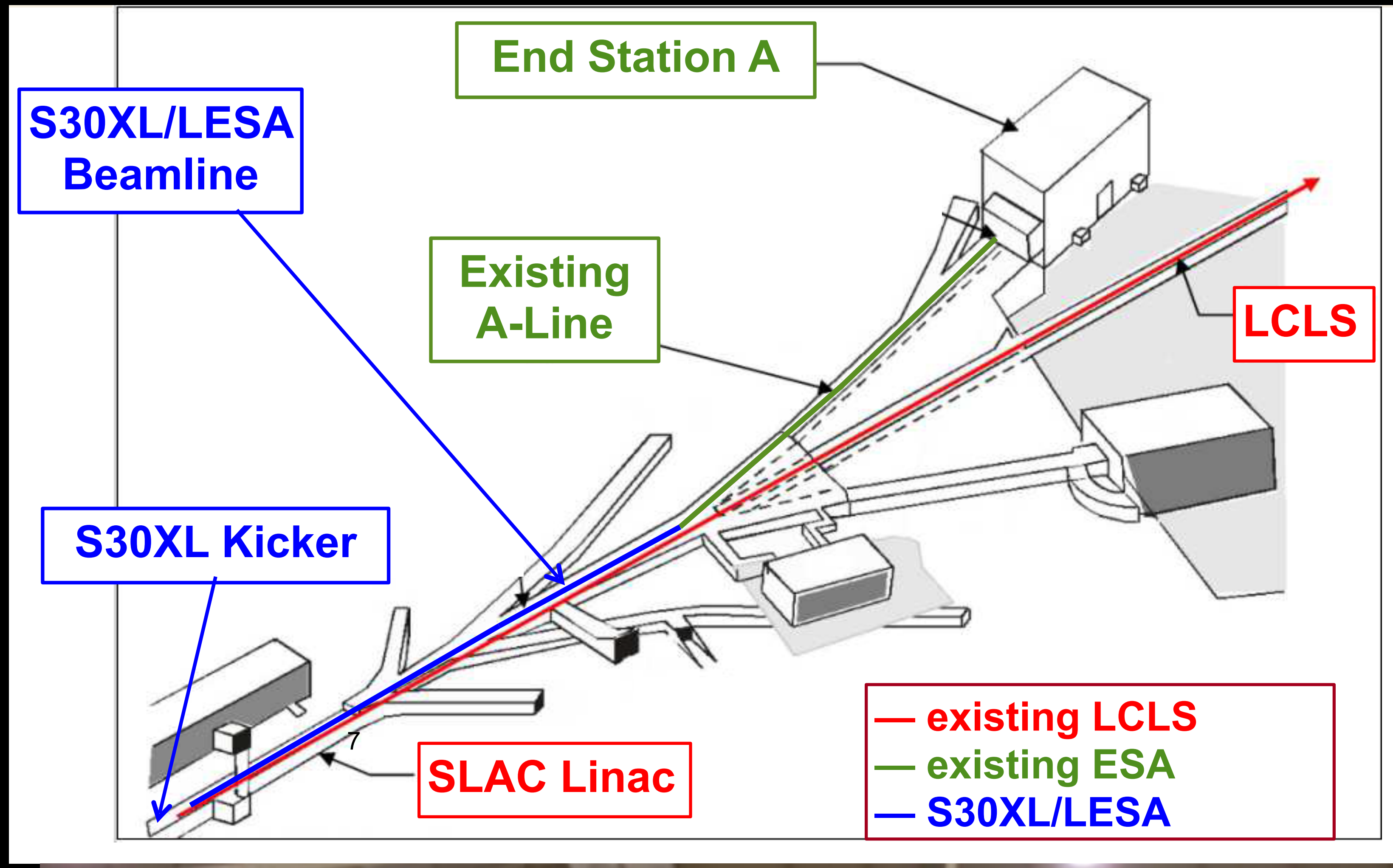
*Recommended new program: Advancing Science and Technology through Agile Experiments

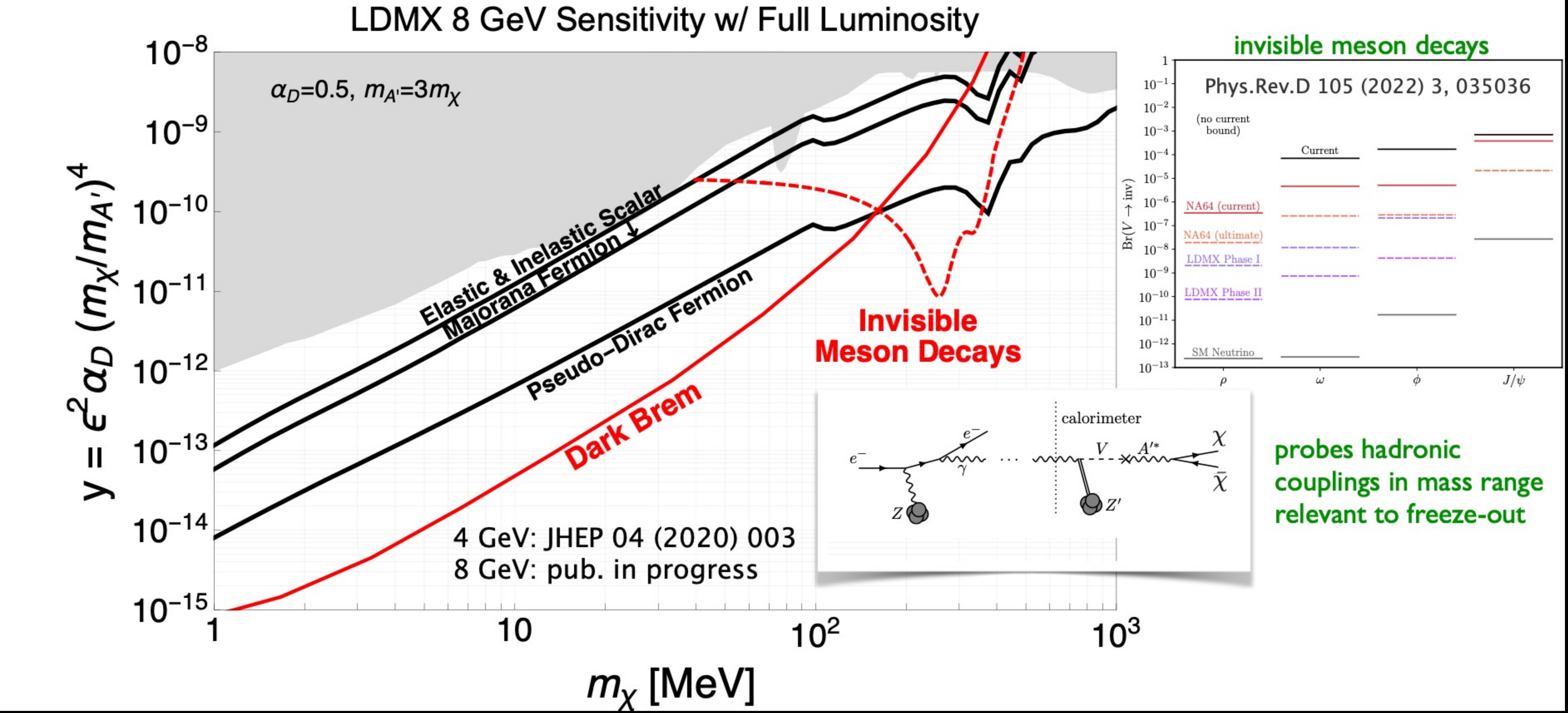
One of the examples: LDMX



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

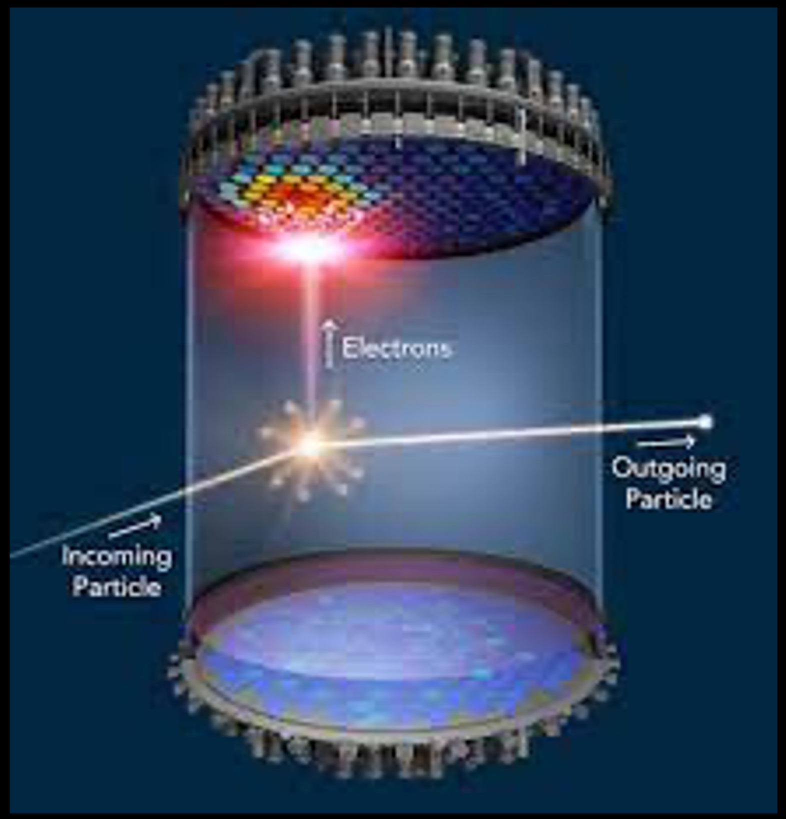




Ongoing Experiments

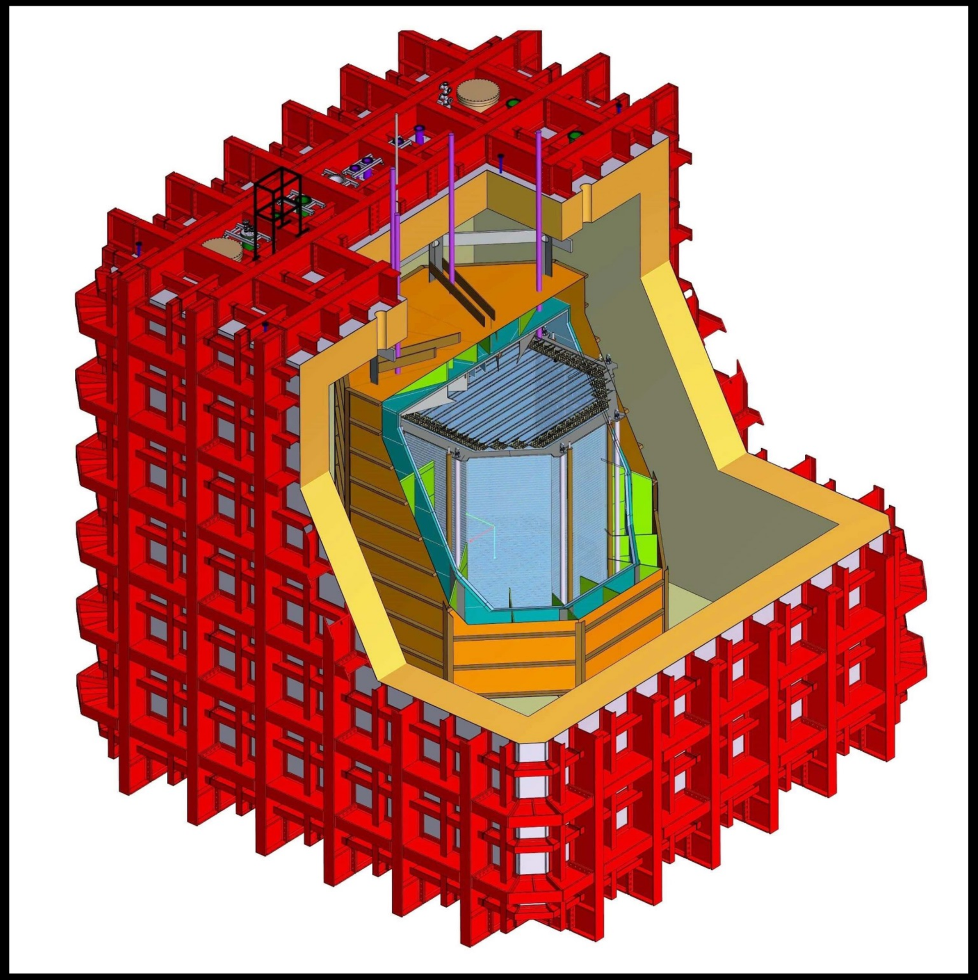
LHC: could produce EW-scale DM

LZ

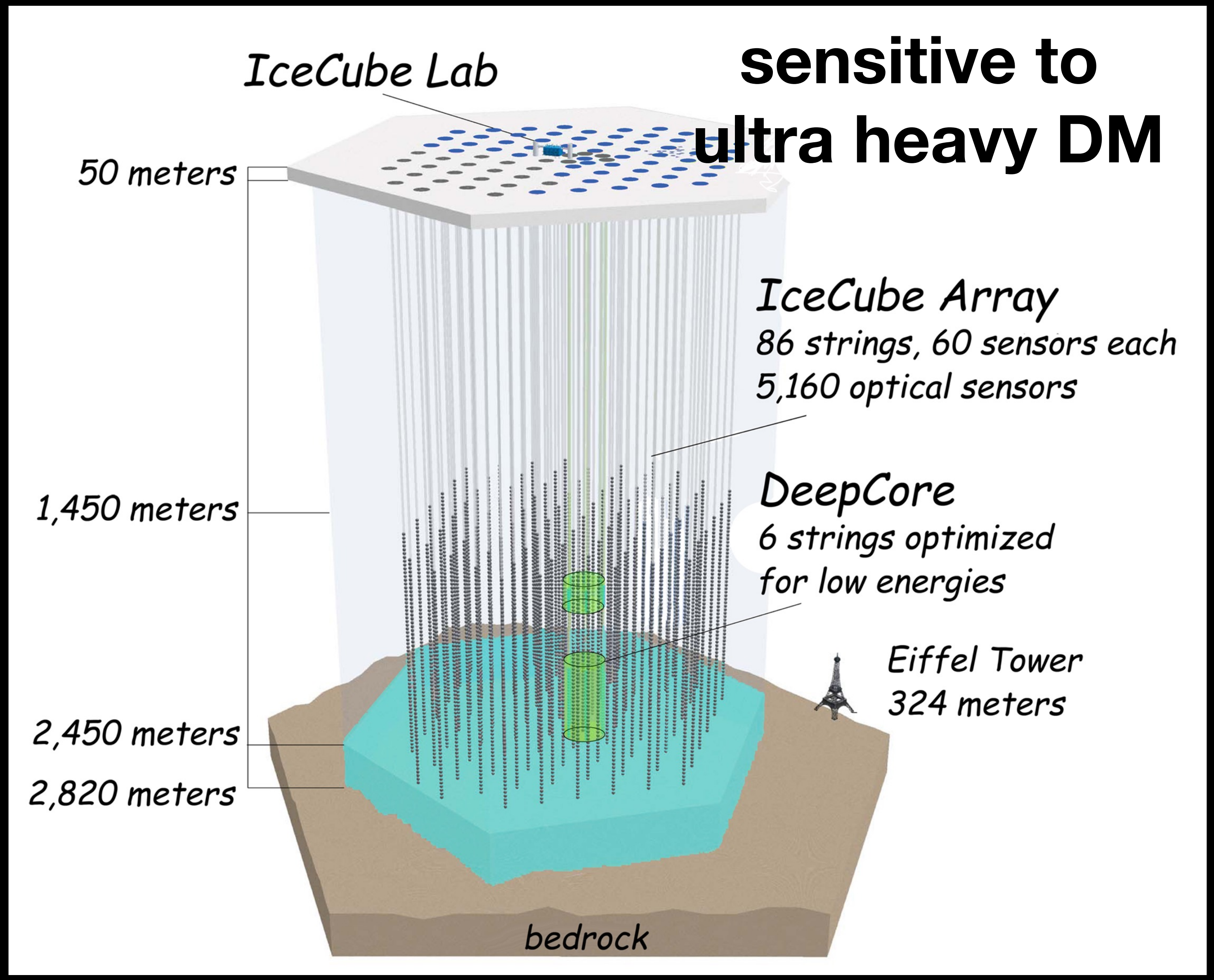


XENONnT

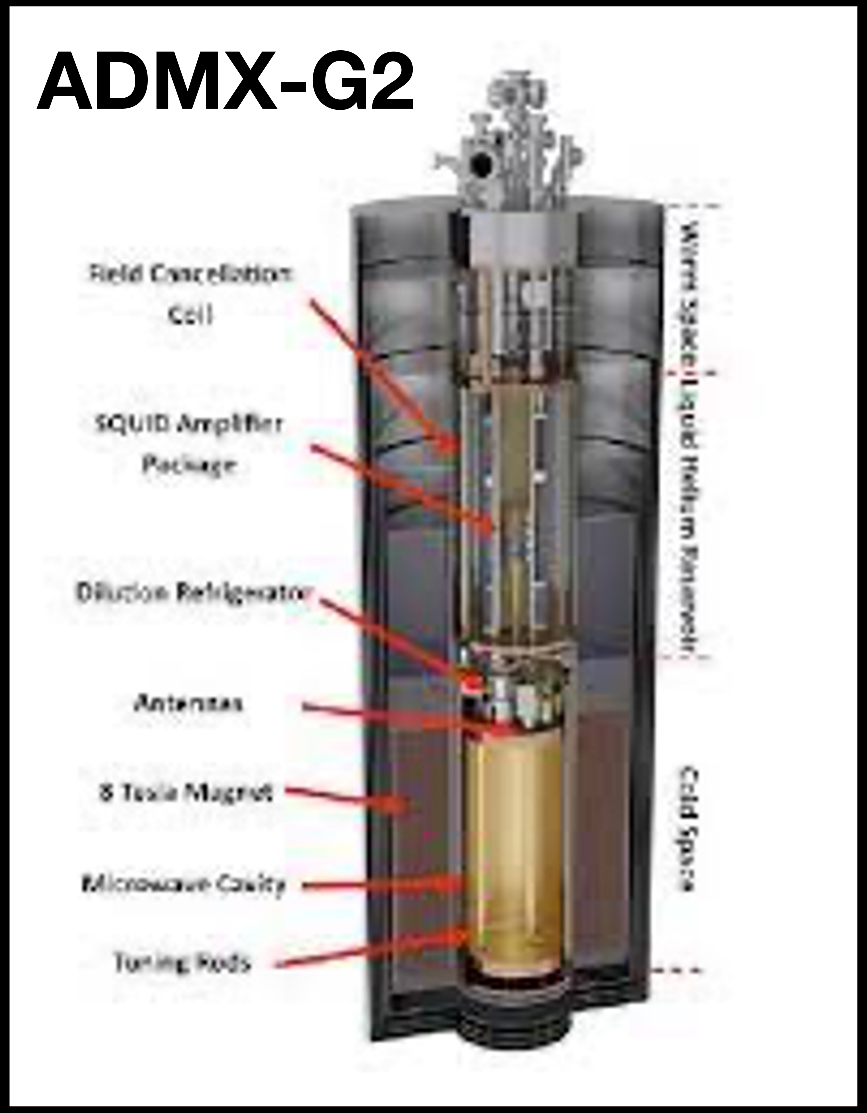
Darkside 20k

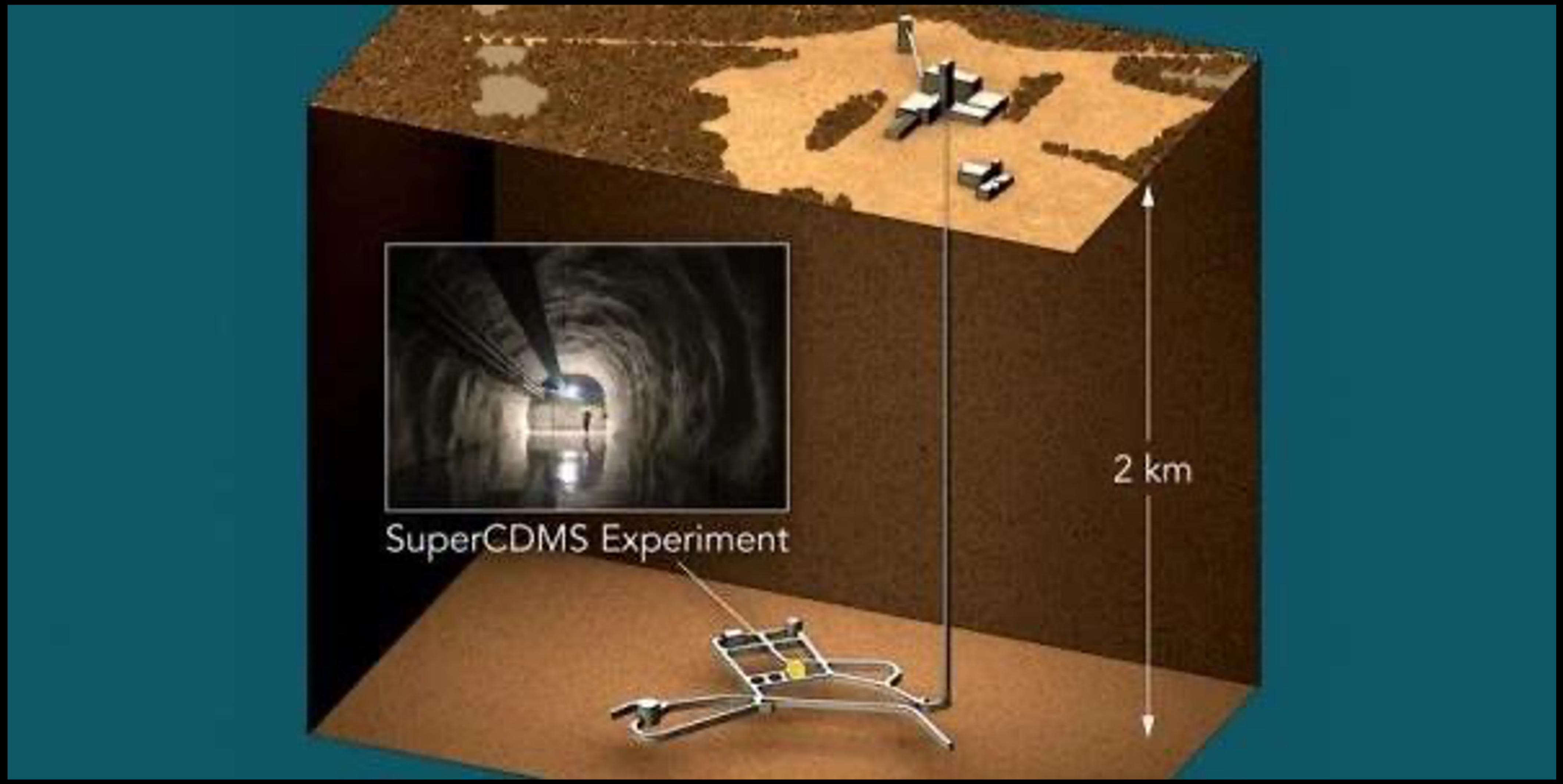


sensitive to ultra heavy DM



ADMX-G2



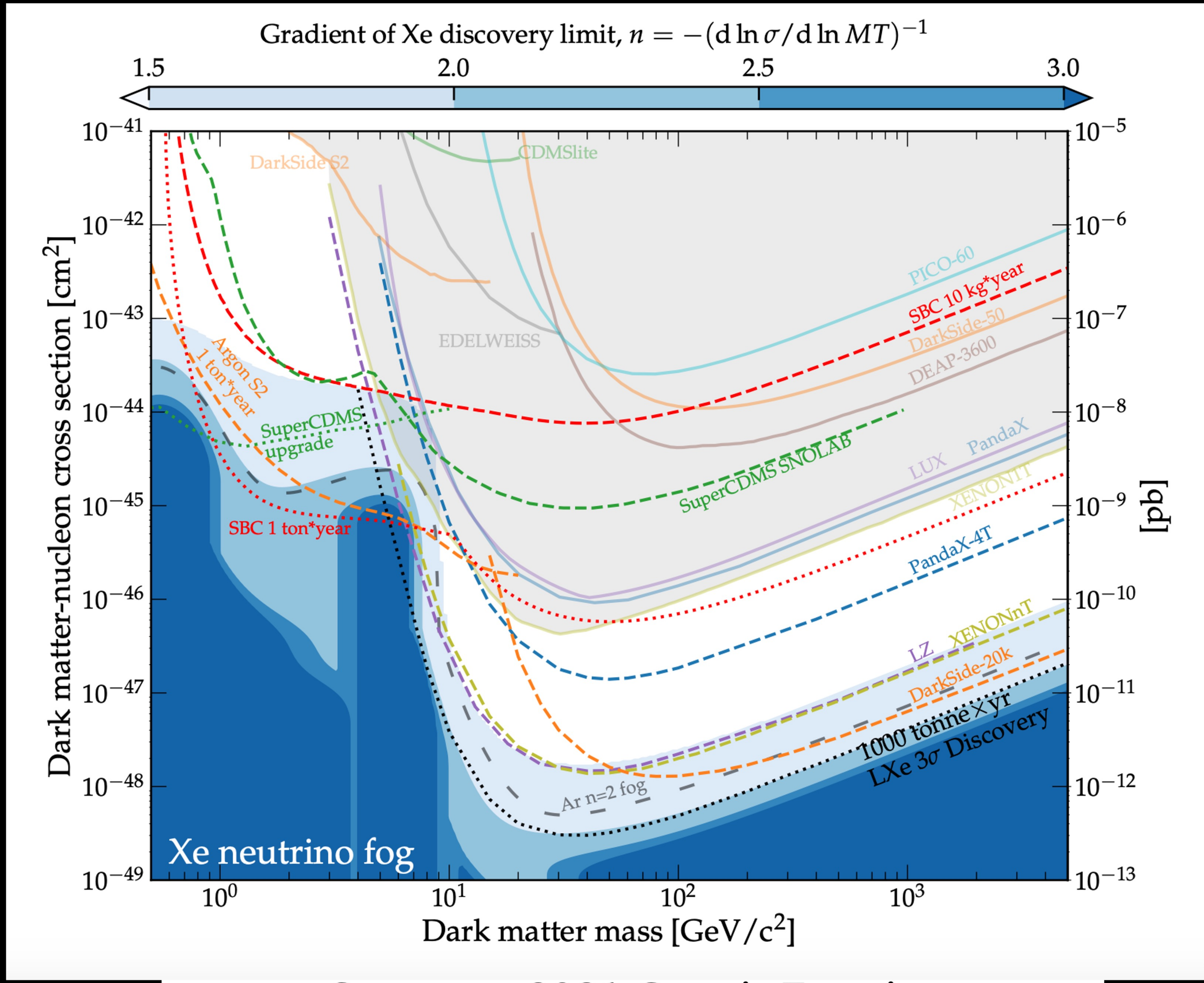


Major Project this decade: A 3rd generation (G3) WIMP experiment

- **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**

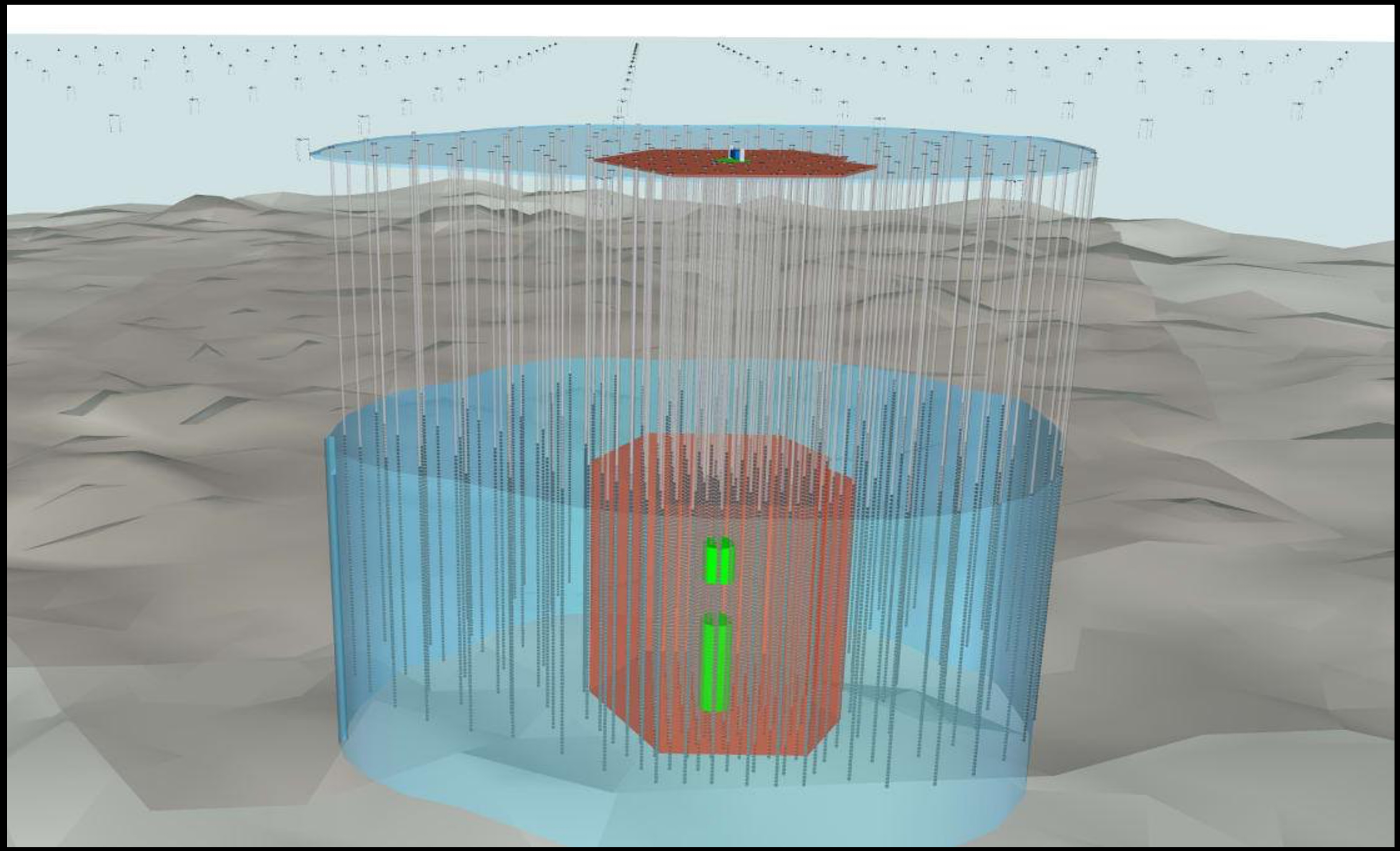
Sanford
Underground Research Facility
South Dakota Science and Technology Authority



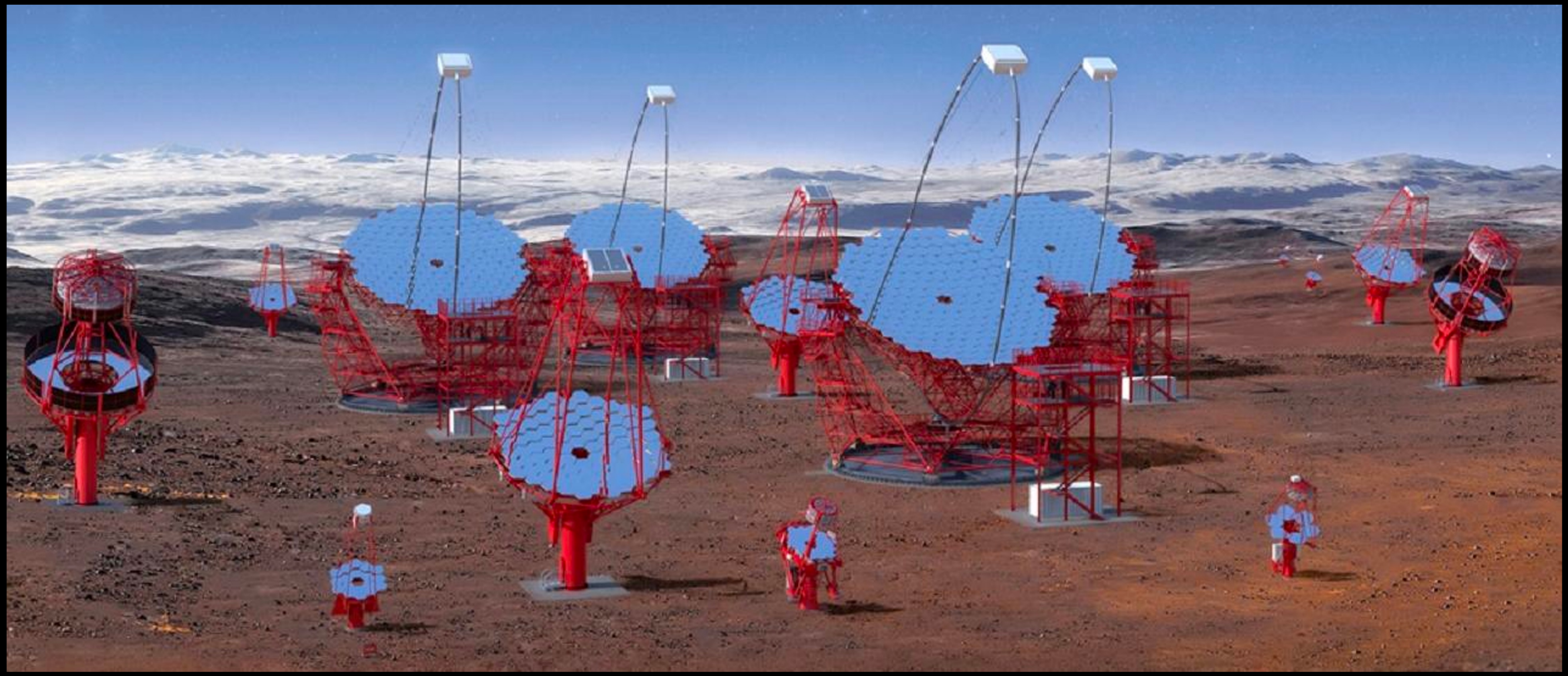
Snowmass2021 Cosmic Frontier
Dark Matter Direct Detection to the Neutrino Fog

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.



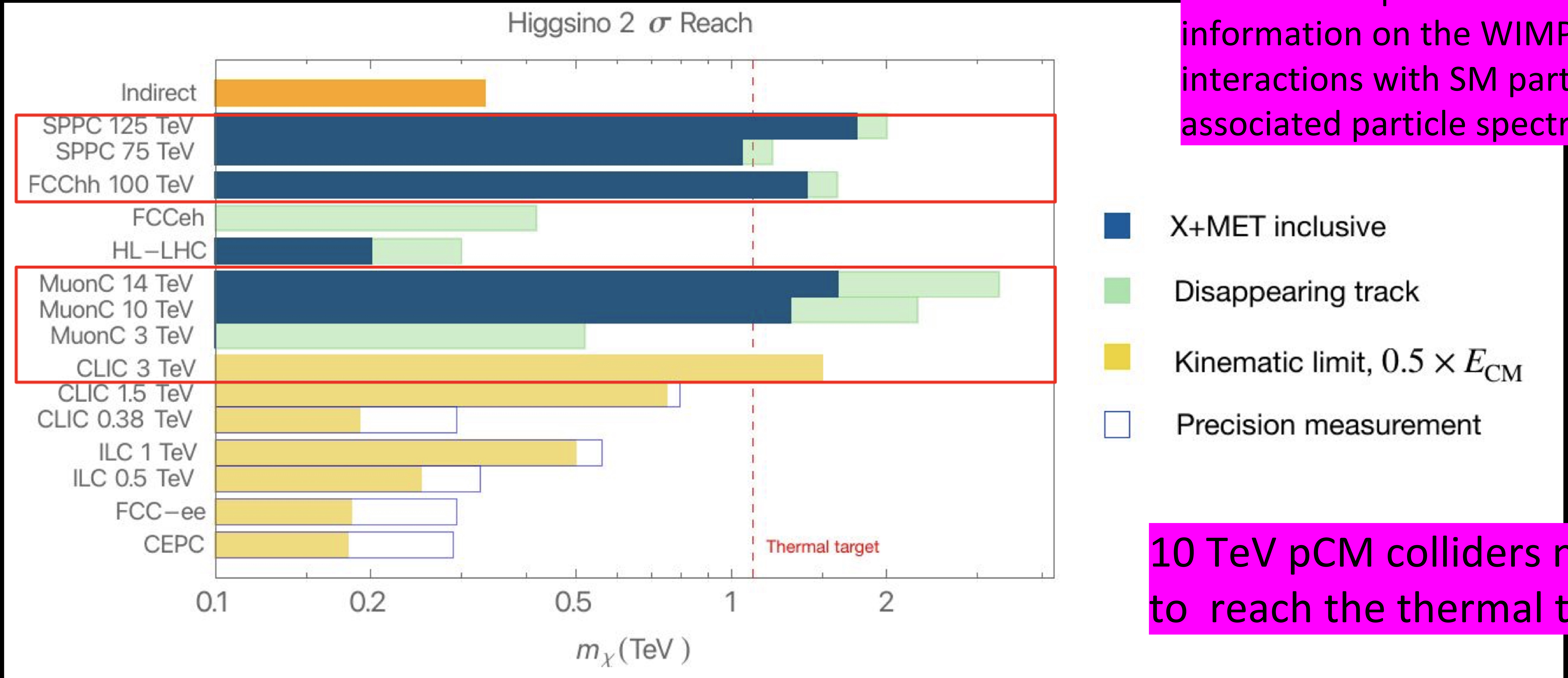
Dark Matter at Future Colliders

Dark matter searches in collider are complementary to other searches

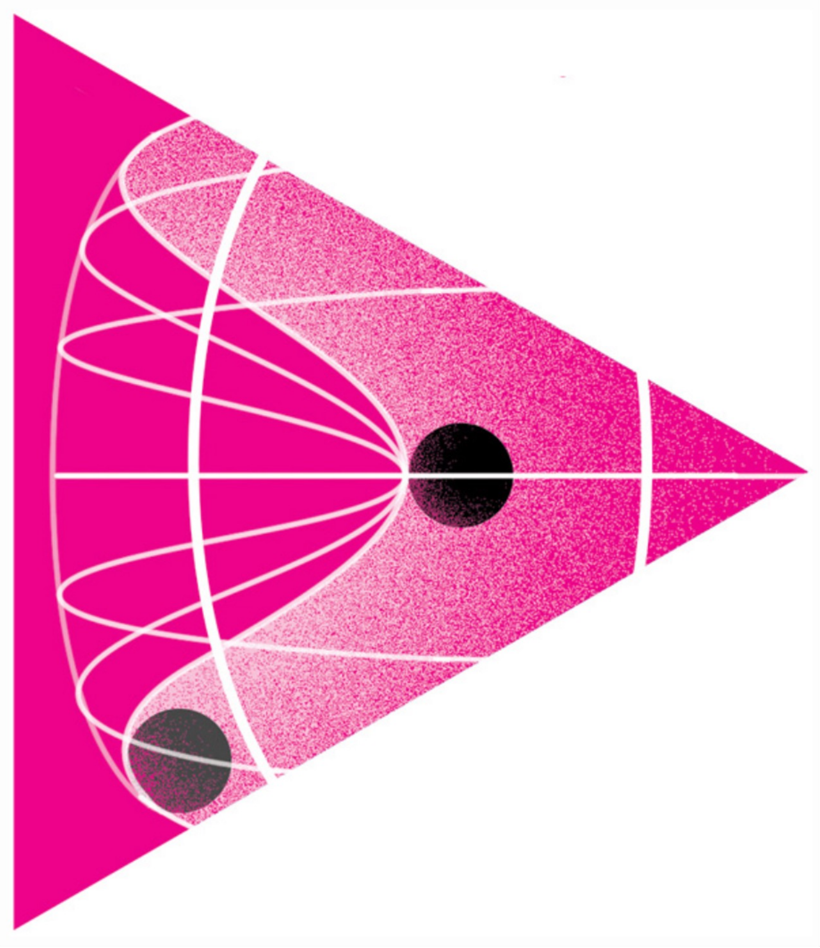
WIMP, Mediator searches, Beyond-WIMP, Higgs portal…

Benchmark/example: simple WIMP case

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



the Higgs boson

Higgs is most puzzling and ad-hoc piece of SM

What is the source of the Higgs potential?

- SM has the simplest function potential that produces EWSB
  - First time in particle physics when Occam Razor worked?!
  - Analogous to Ginsburg-Landau superconductivity and the BCS: there's a new force between electrons carried by new particles (phonons)

Higgs math is simple, but leads to mathematical problems down the line

- Higgs mass should be Planck scale without tremendous fine-tuning (hierarchy problem)
- SM Higgs introduces at least nine (or 12?) new forces that give masses to fermions, existence of only four of which have been experimentally confirmed so far. The number and strength of these forces remain unexplained
- SM Higgs potential does not allow for phase transition in the early Universe that can generate observed matter-antimatter imbalance in the Universe
  - Need to modify the potential or introduce new spin 0 particles
- Fundamental spin 0 particles are easier to fit into a coherent theory if there is more than one.
  - Are there more spin 0 particles than just SM Higgs?
  - Or is the observed Higgs boson (partially) composite?

Higgs may be connected to other mysteries

Dark Sectors

Direct and indirect searches for the Dark Matter so far yielded no discoveries

Higgs field is a fundamental feature of the vacuum we occupy together with the Dark Sector. The coupling between the Dark Sector and the Higgs, however small, is likely non-zero. Its existence can show up as rare / exotic Higgs boson decays (aka Higgs portal to DS) and could be our only connection to the Dark Sector.

Hierarchy, GUTs, and Inflation

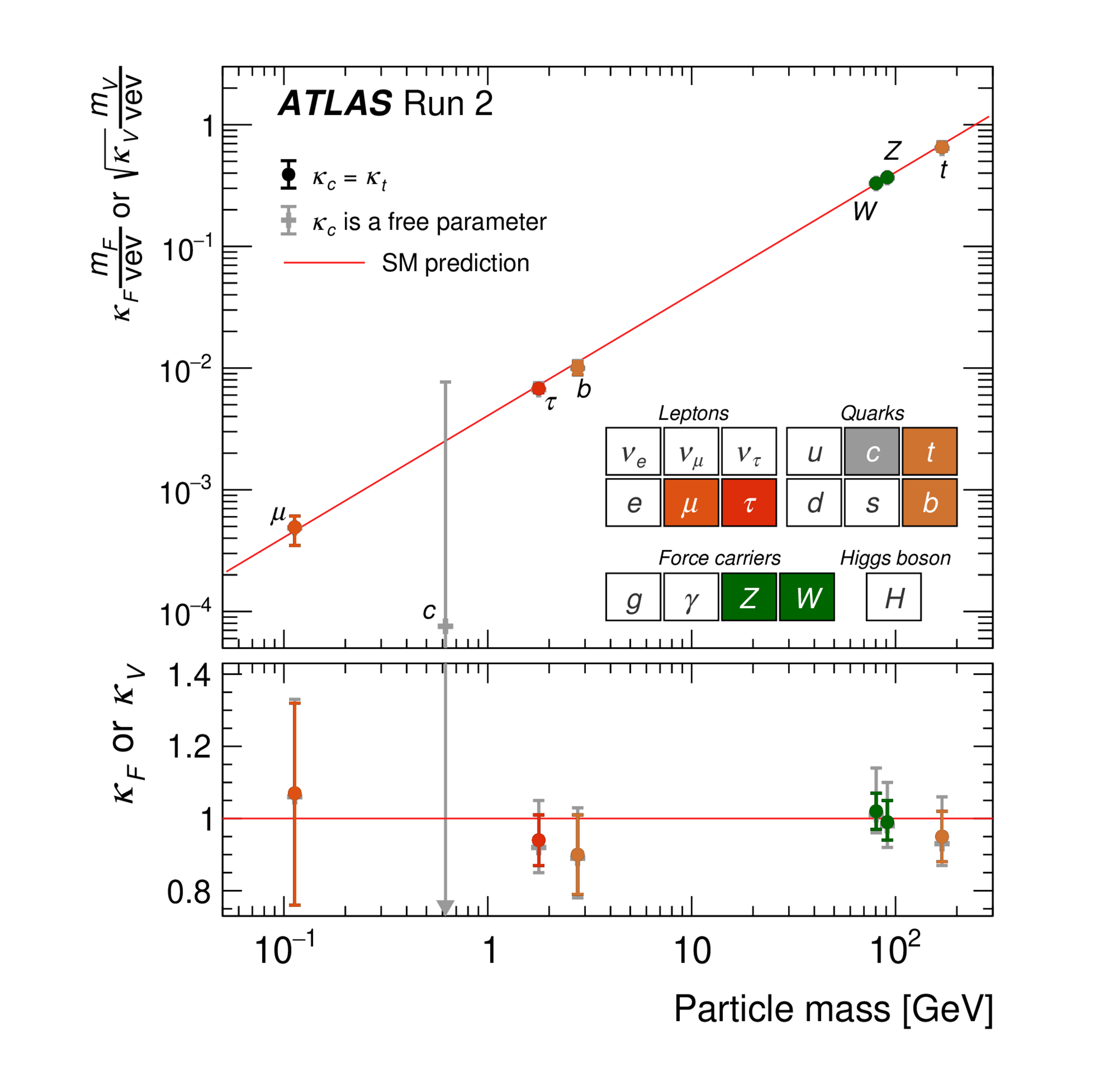
Models of Inflation require scalar fields - are our questions about the Higgs connected to them?

SM couplings extrapolated to high scale do not unify. Theories with extra particles at TeV scale (i.e. SUSY) modify the running of the couplings allowing grand unification, and require a modified Higgs sector

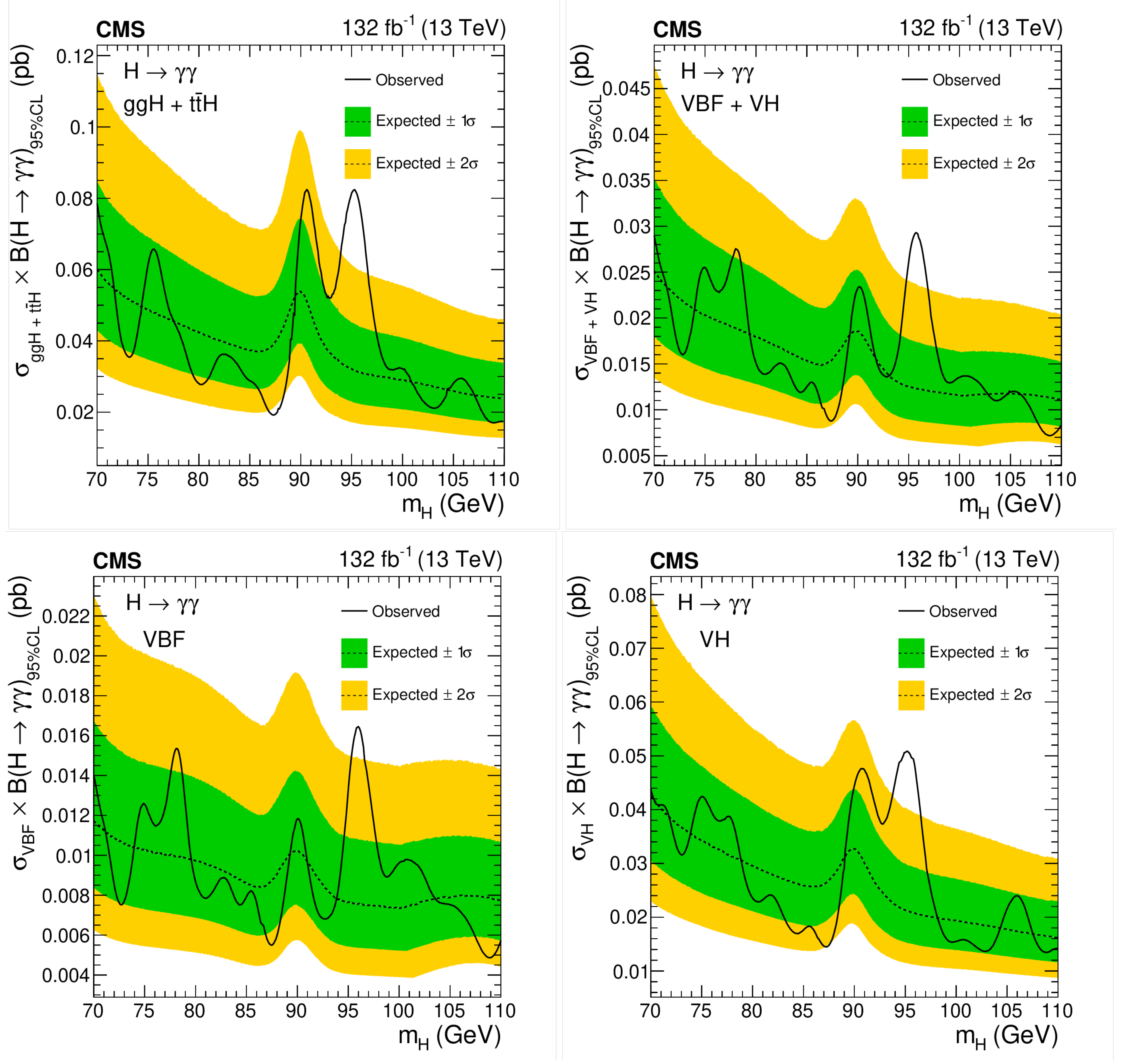
Higgs Story So Far

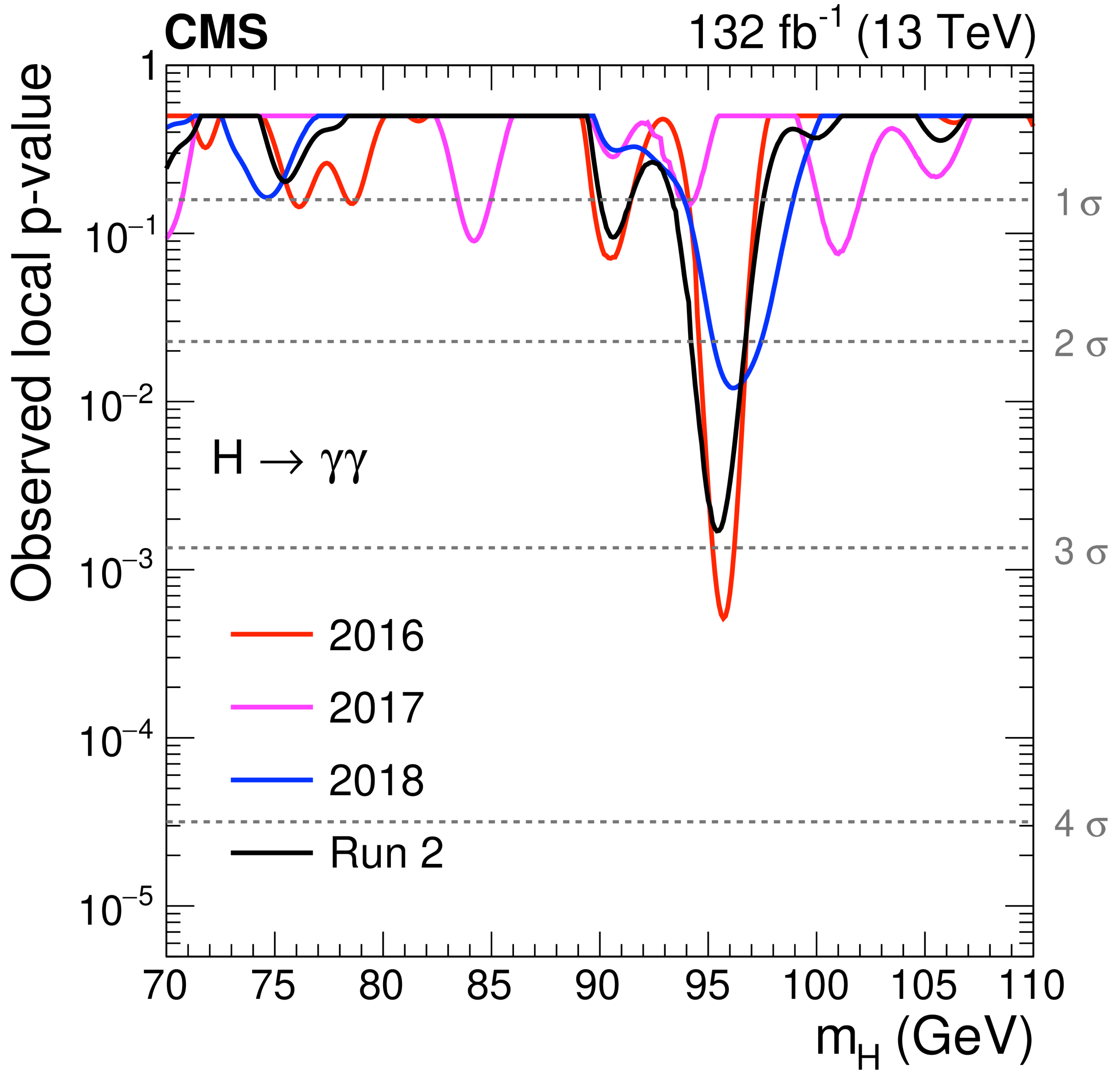
Higgs boson measurements:

- 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



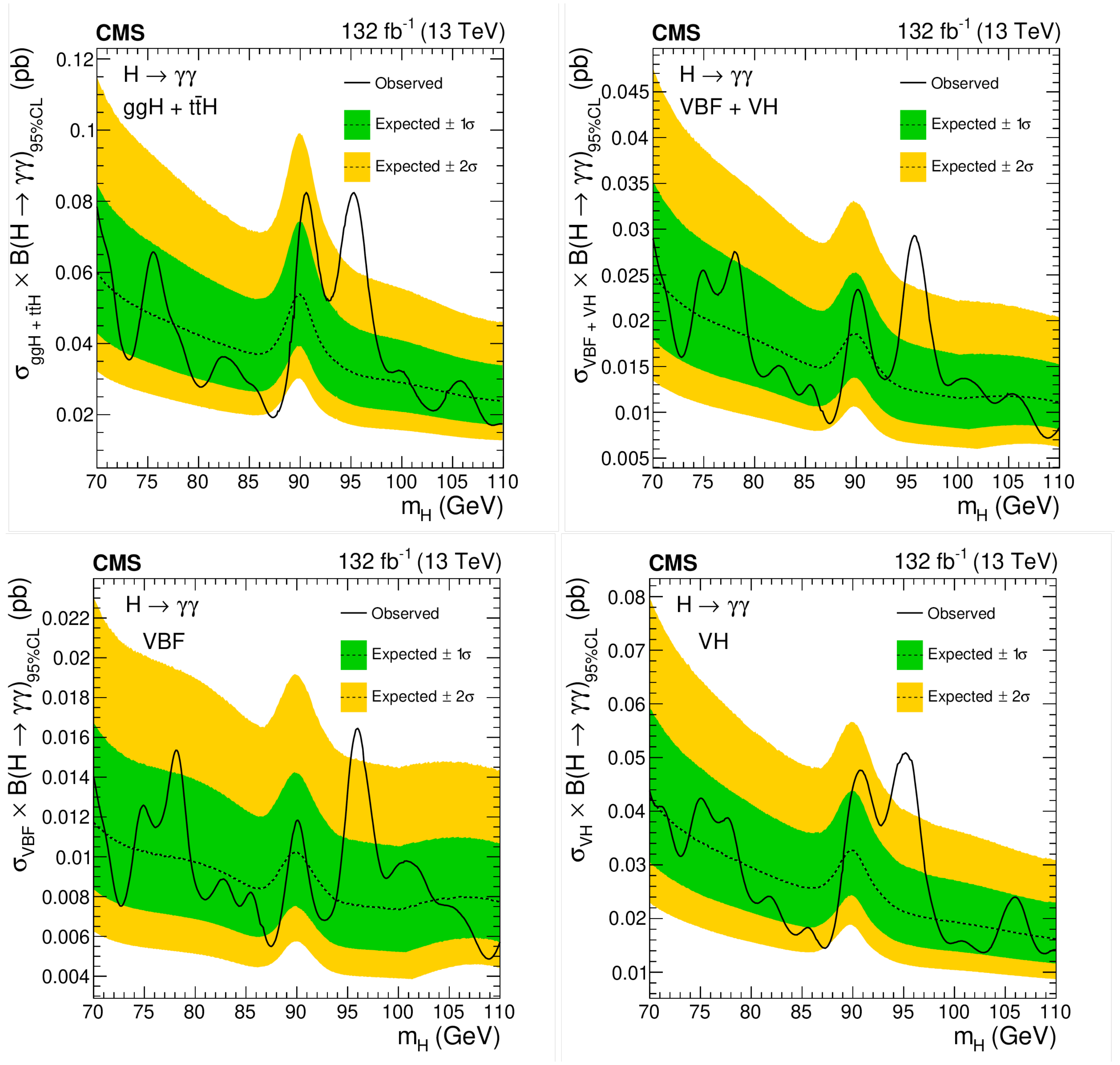
Anomalies in LHC Data?

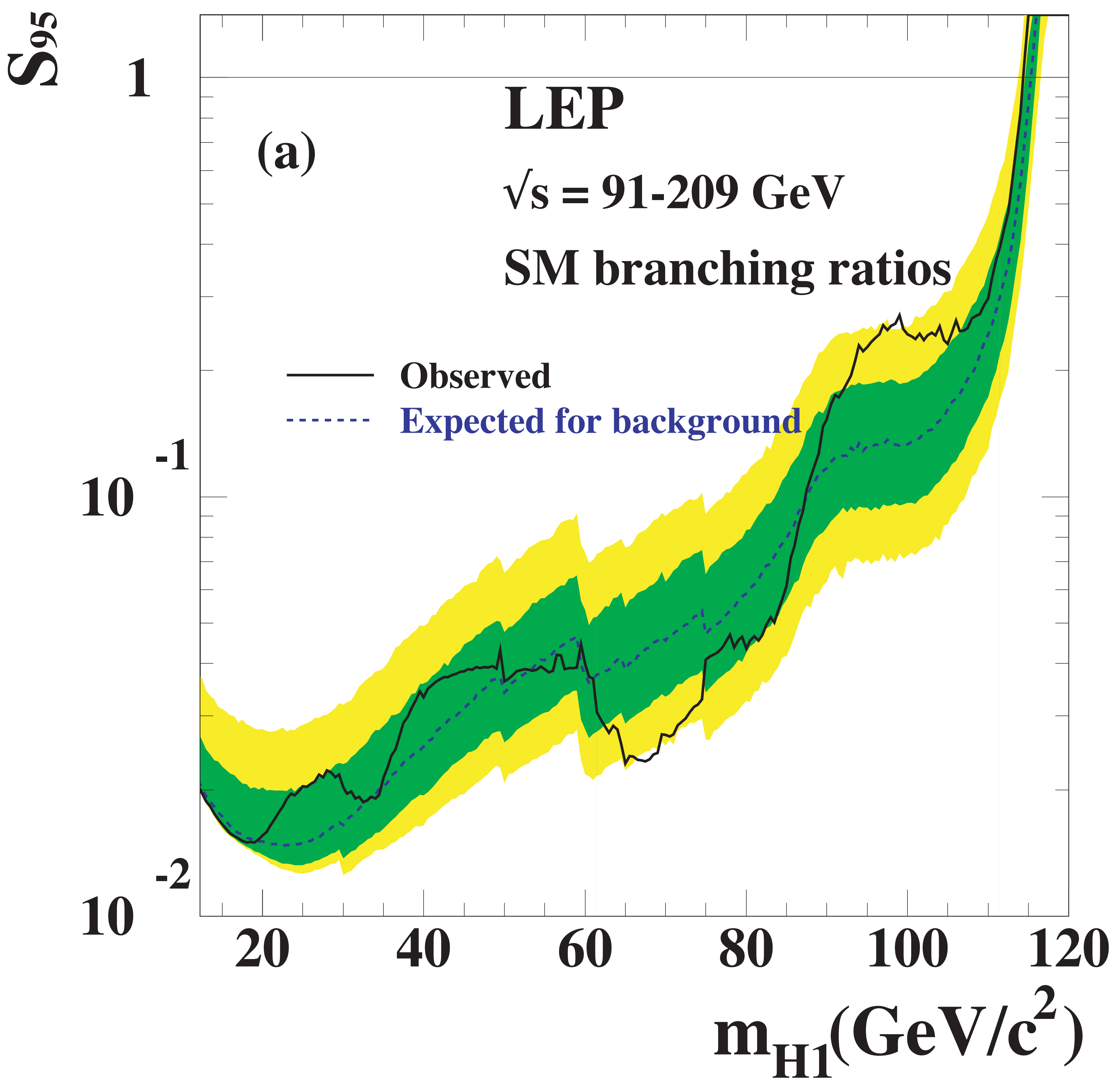




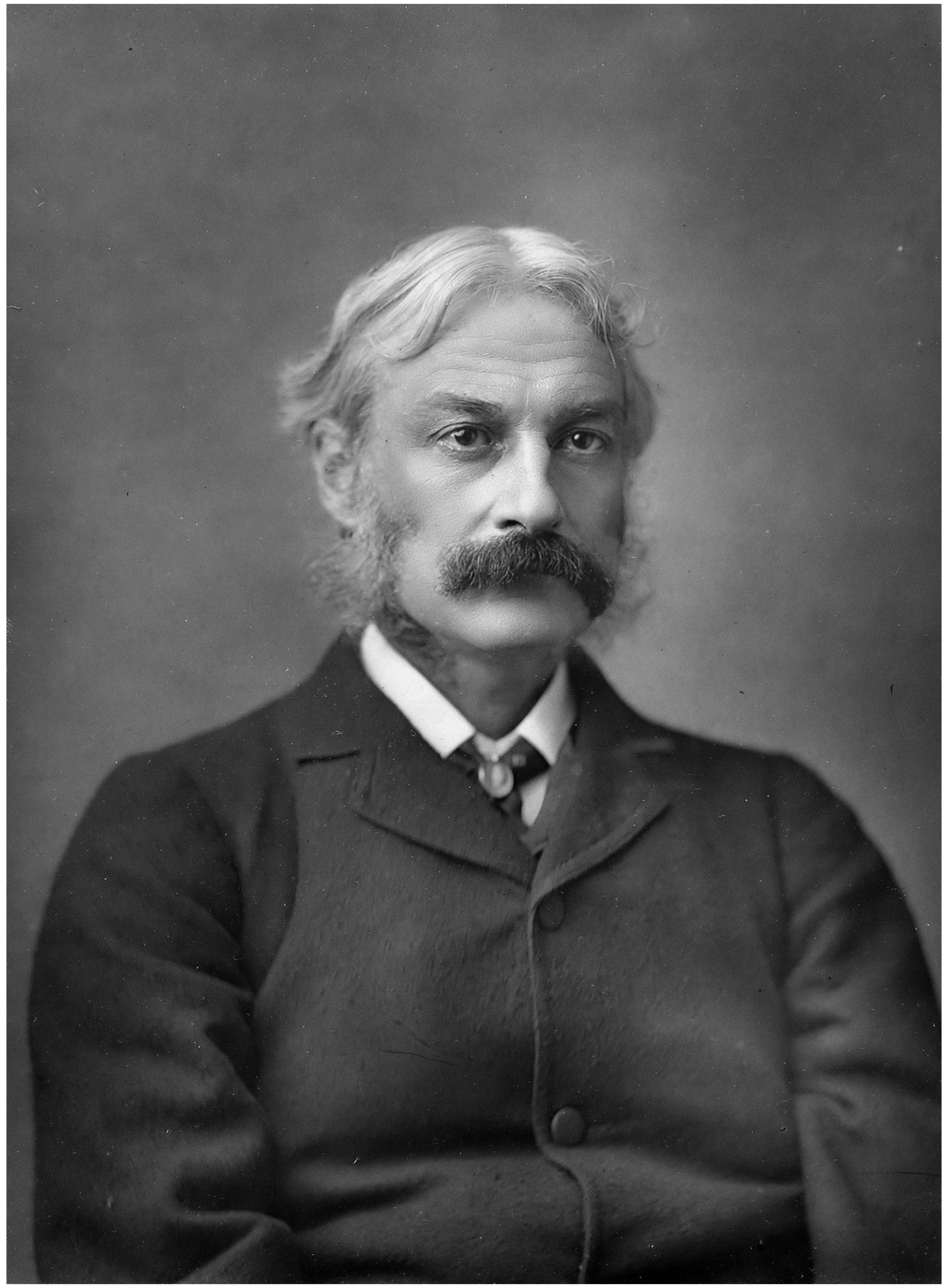
Excess consistent over channels and years.
ATLAS has (much smaller) excess, not in contradiction to CMS

Anomalies in LHC Data?





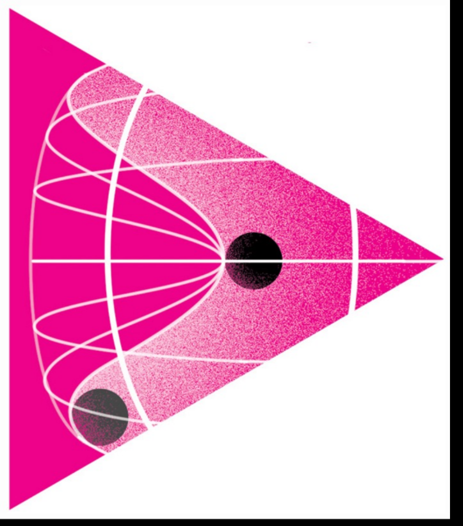
Excess consistent over channels and years.
ATLAS has (much smaller) excess, not in contradiction to CMS



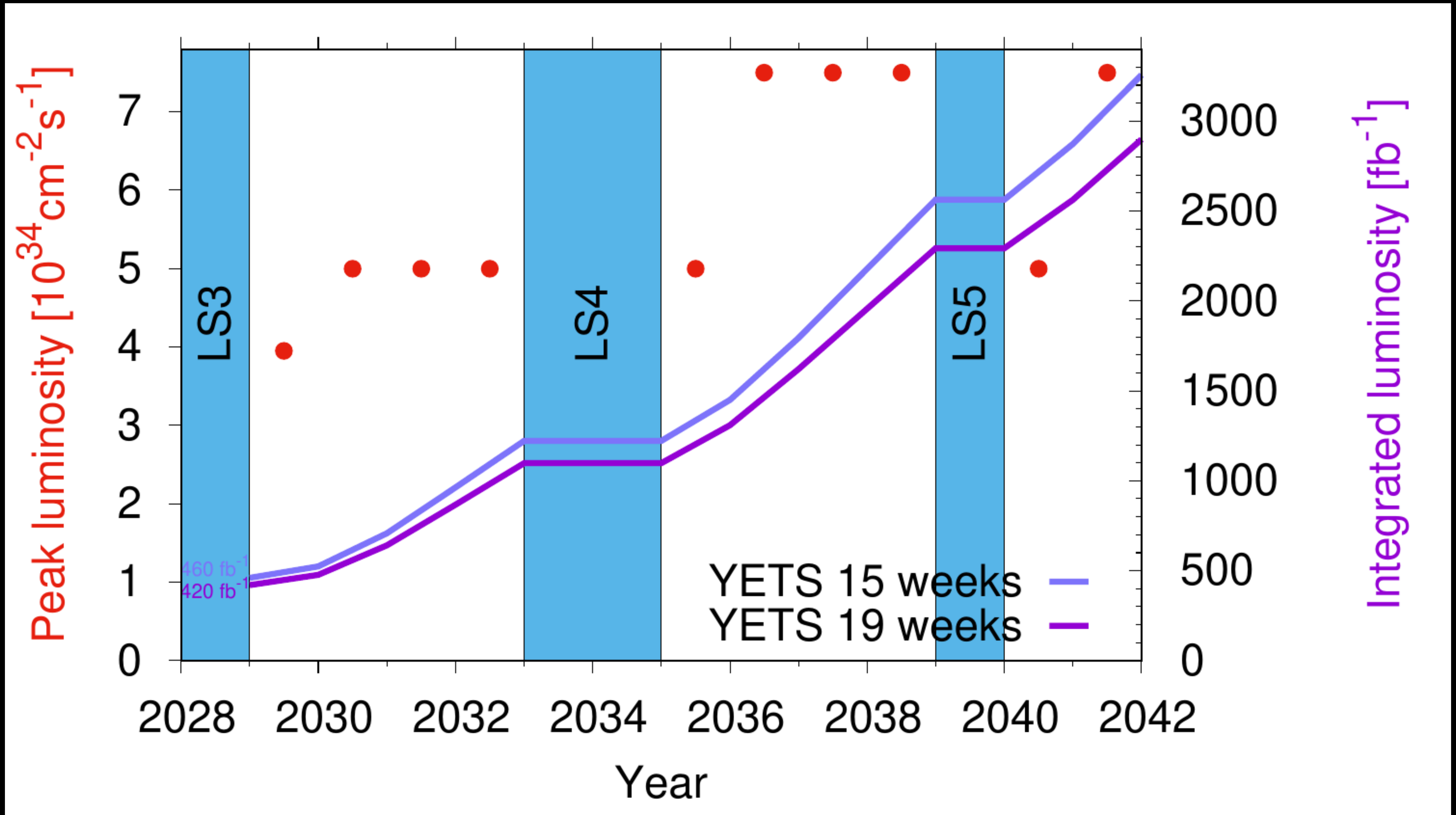
Andrew Lang
Scottish Man of Letters

He uses statistics the way a drunken man uses lamp-posts: for support rather than illumination

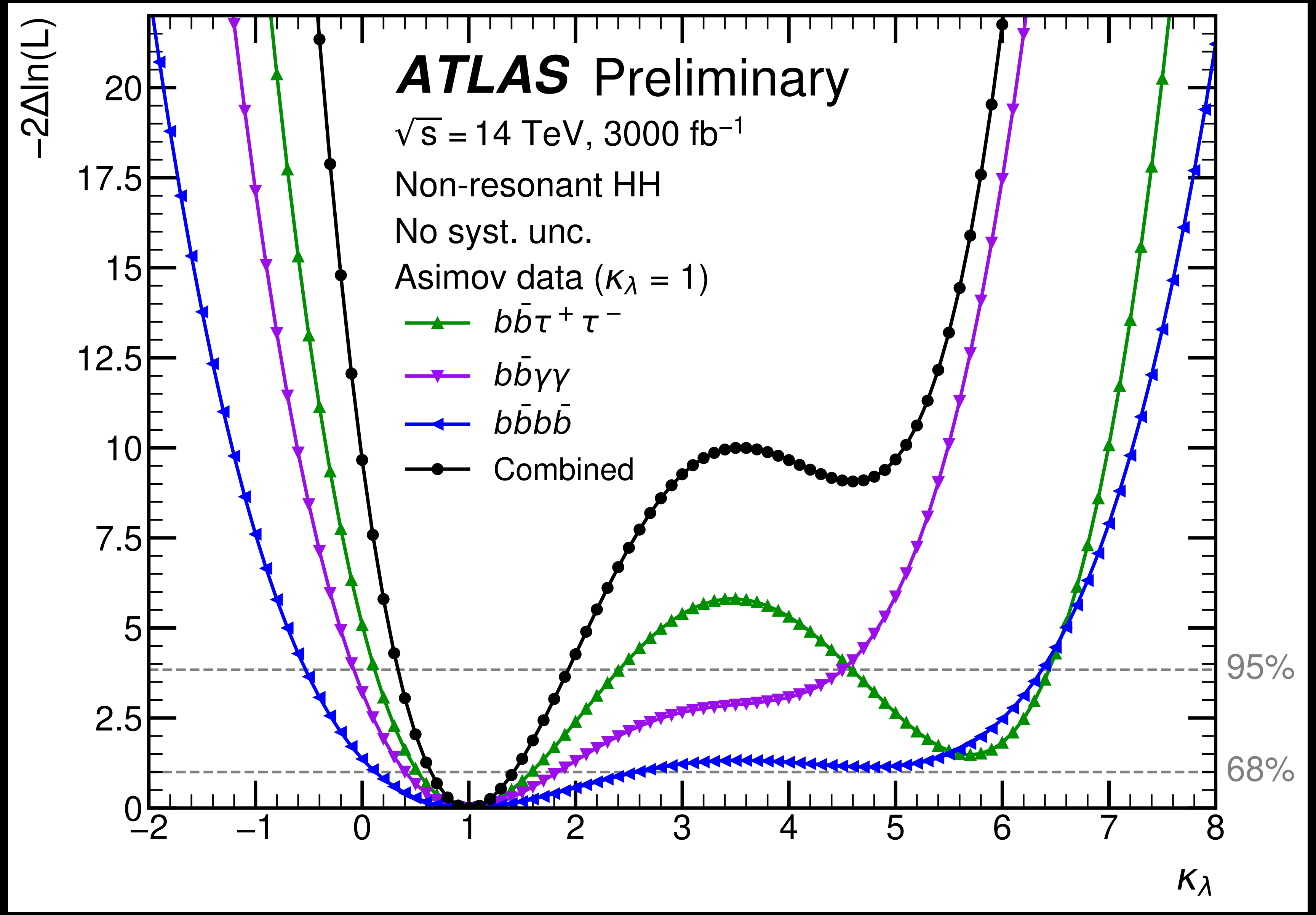
HL-LHC



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 for new physics (more on that later)



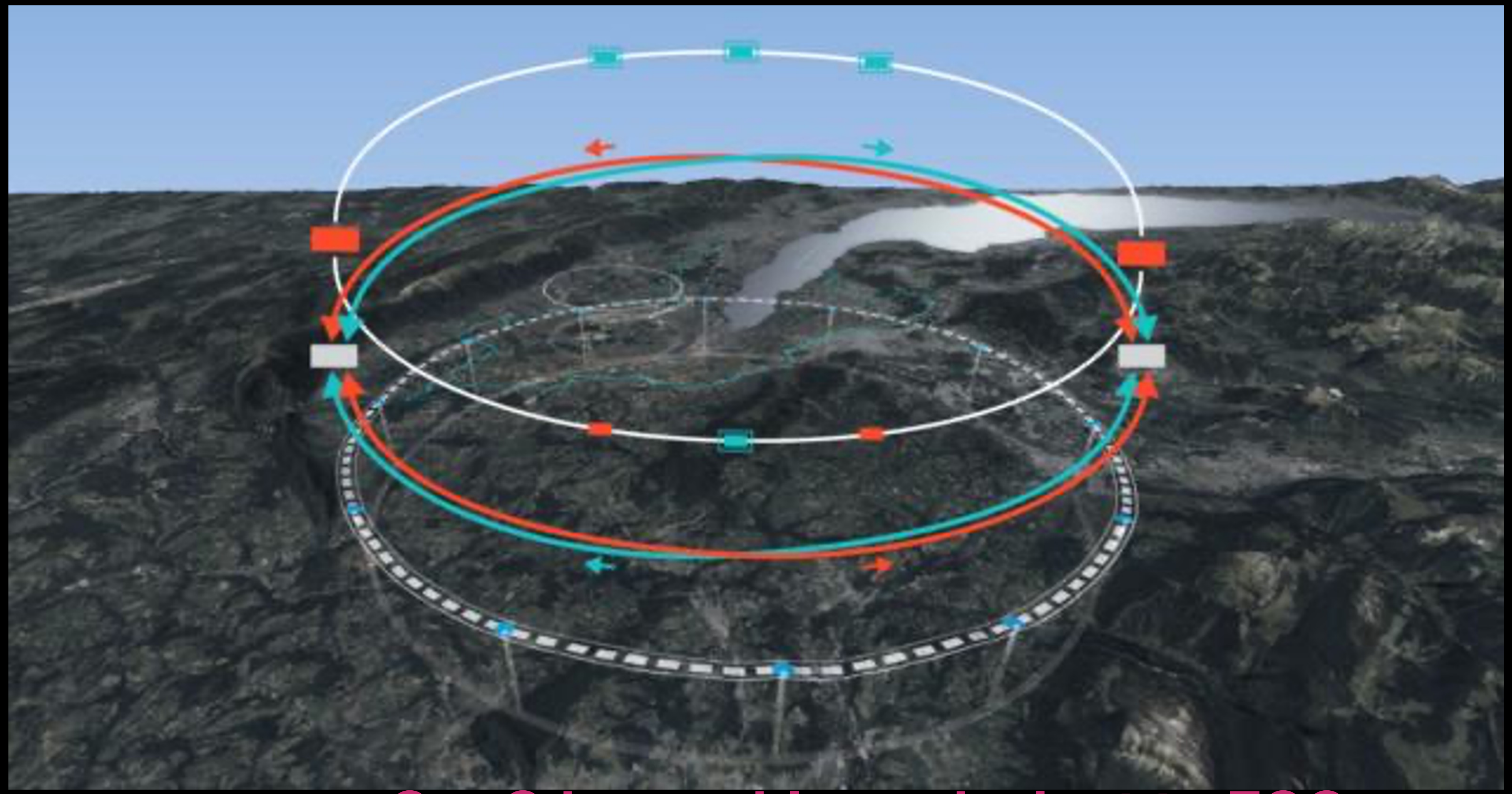
Priority: A Higgs Factory

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.**

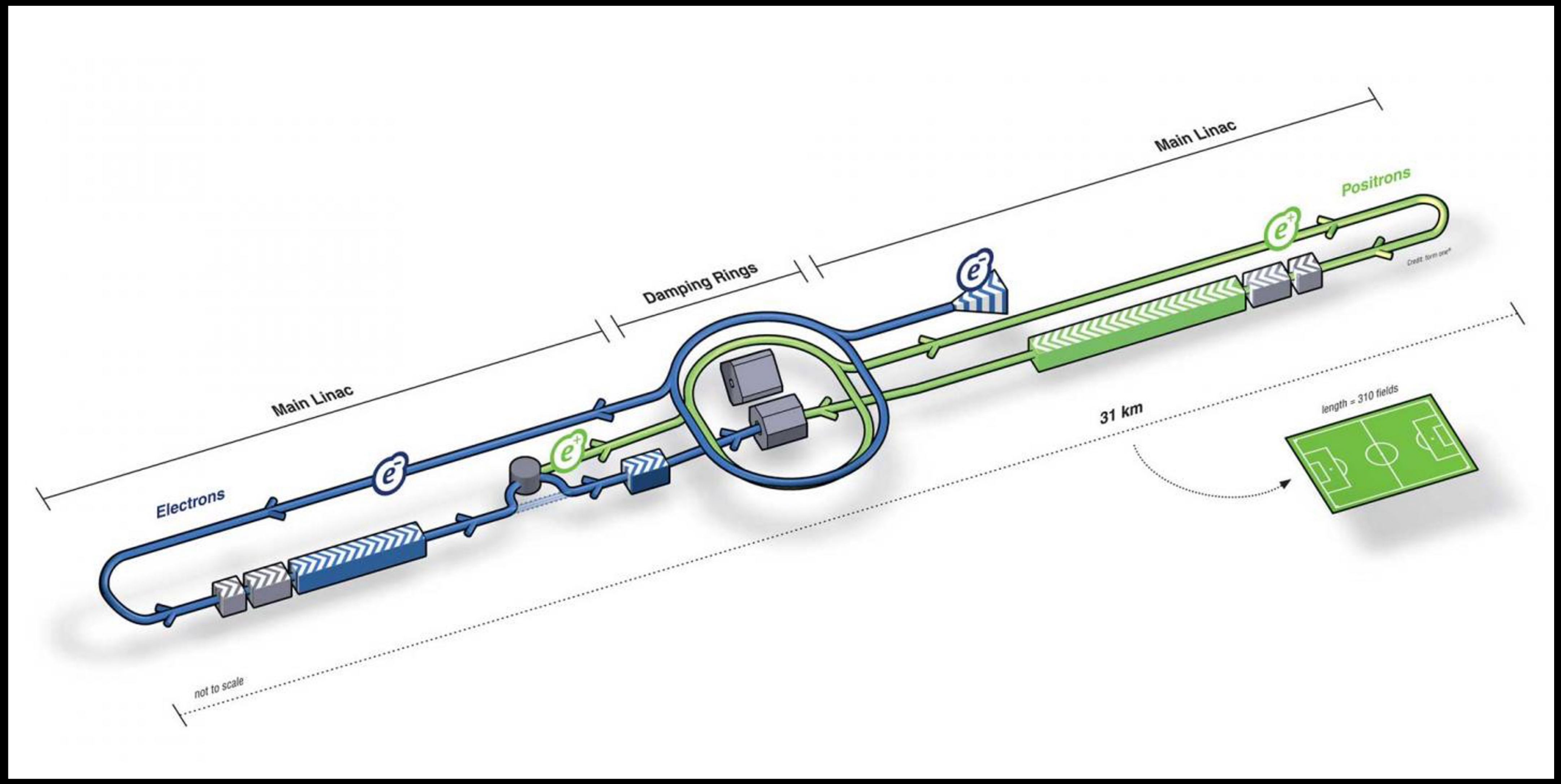
Decisions for FCC-ee, ILC, and CepC coming in the next couple of years!

FCC-ee at CERN



CepC is roughly equivalent to FCC-ee

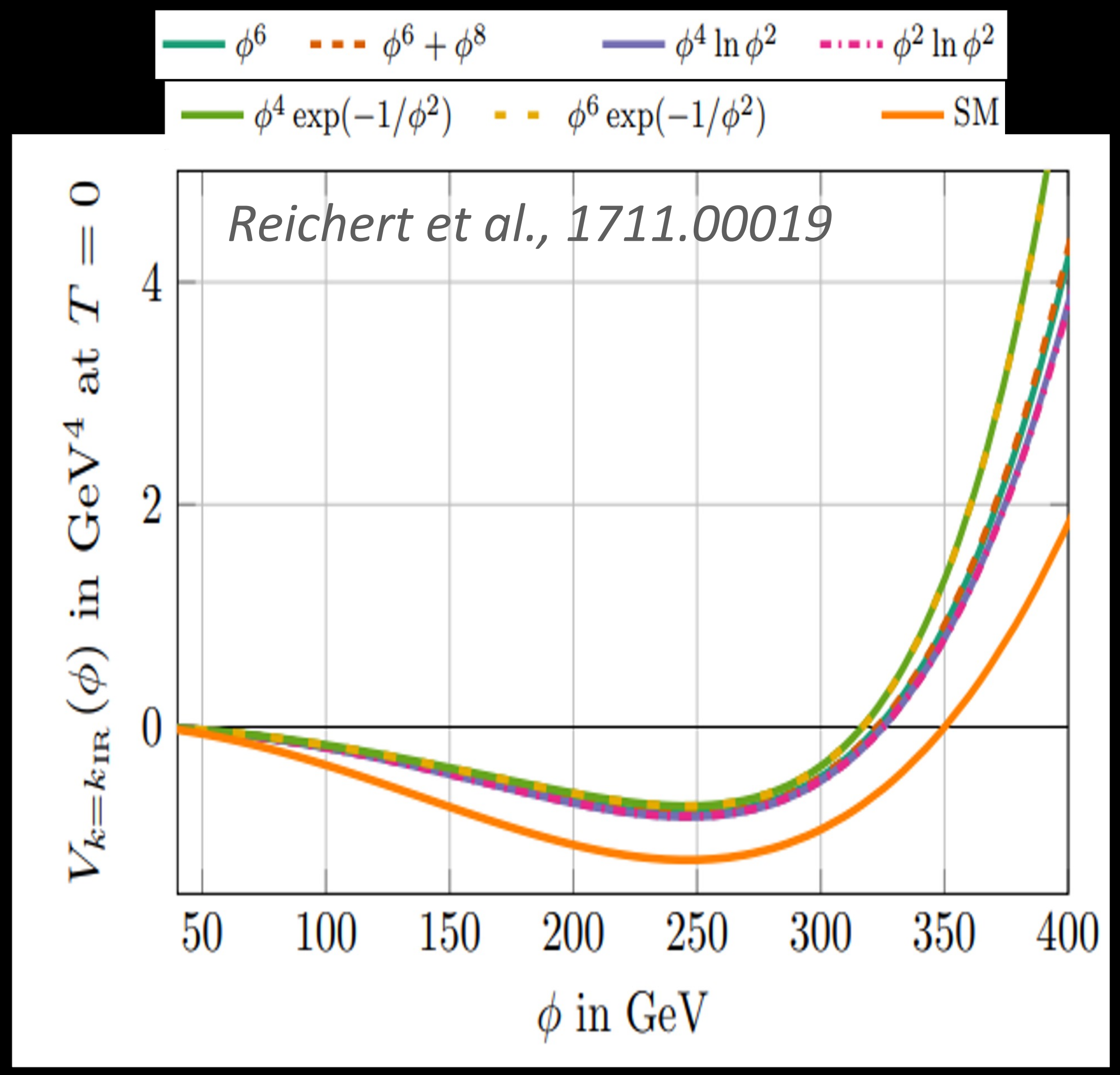
ILC in Japan



Priority: 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

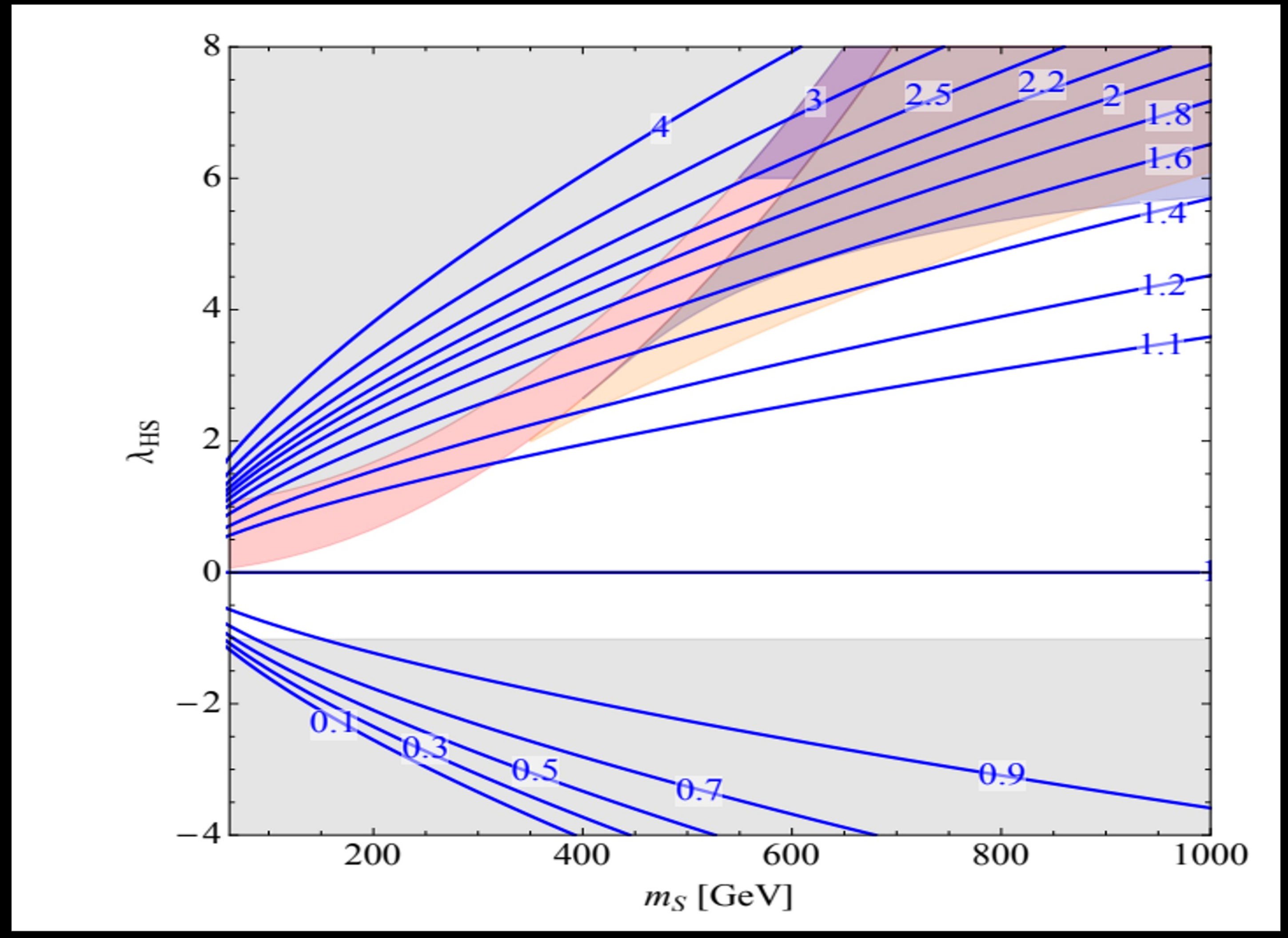


Cosmological connection: electroweak baryogenesis

- 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

Priority: 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

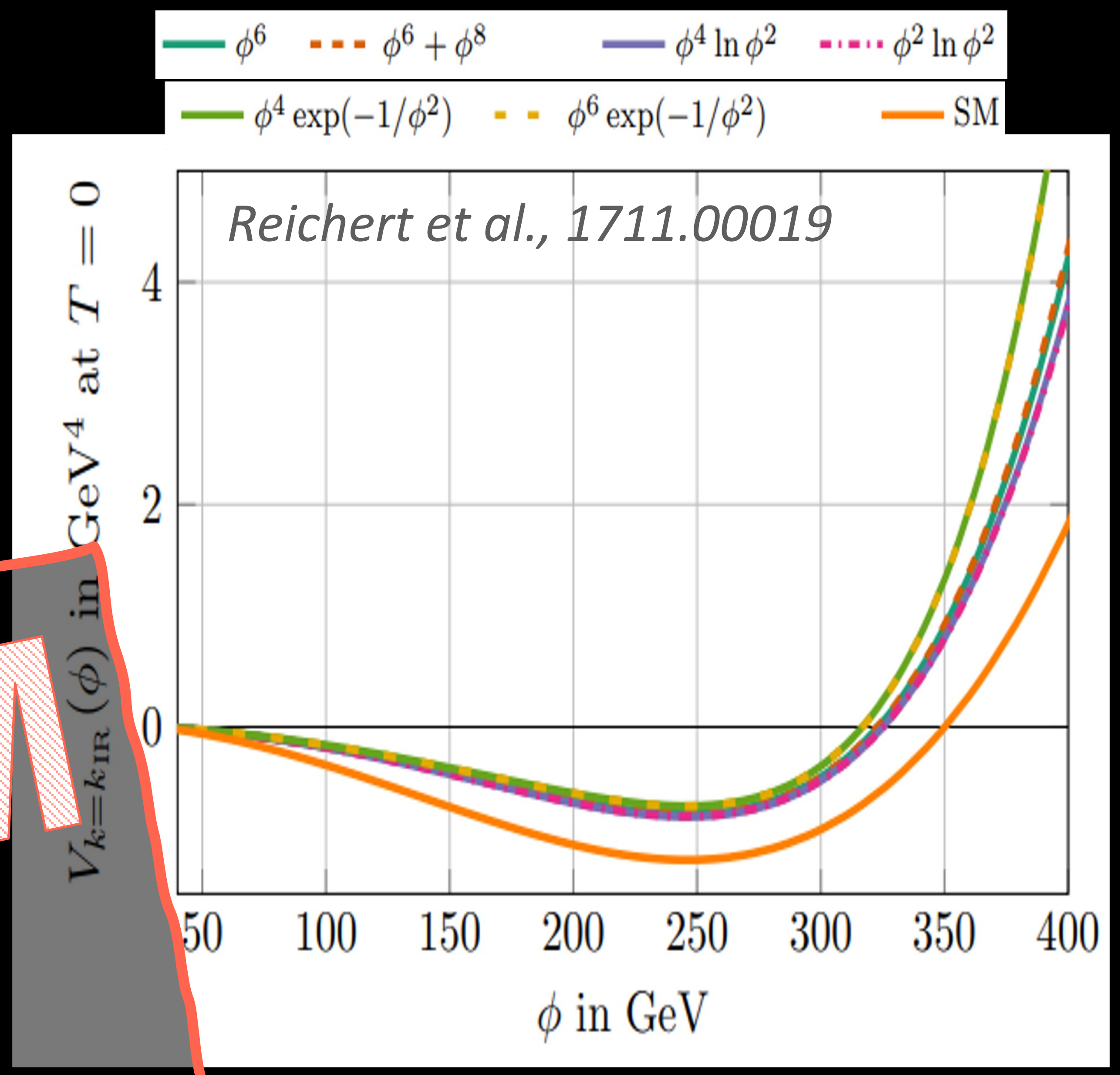
Cosmological connection: electroweak baryogenesis

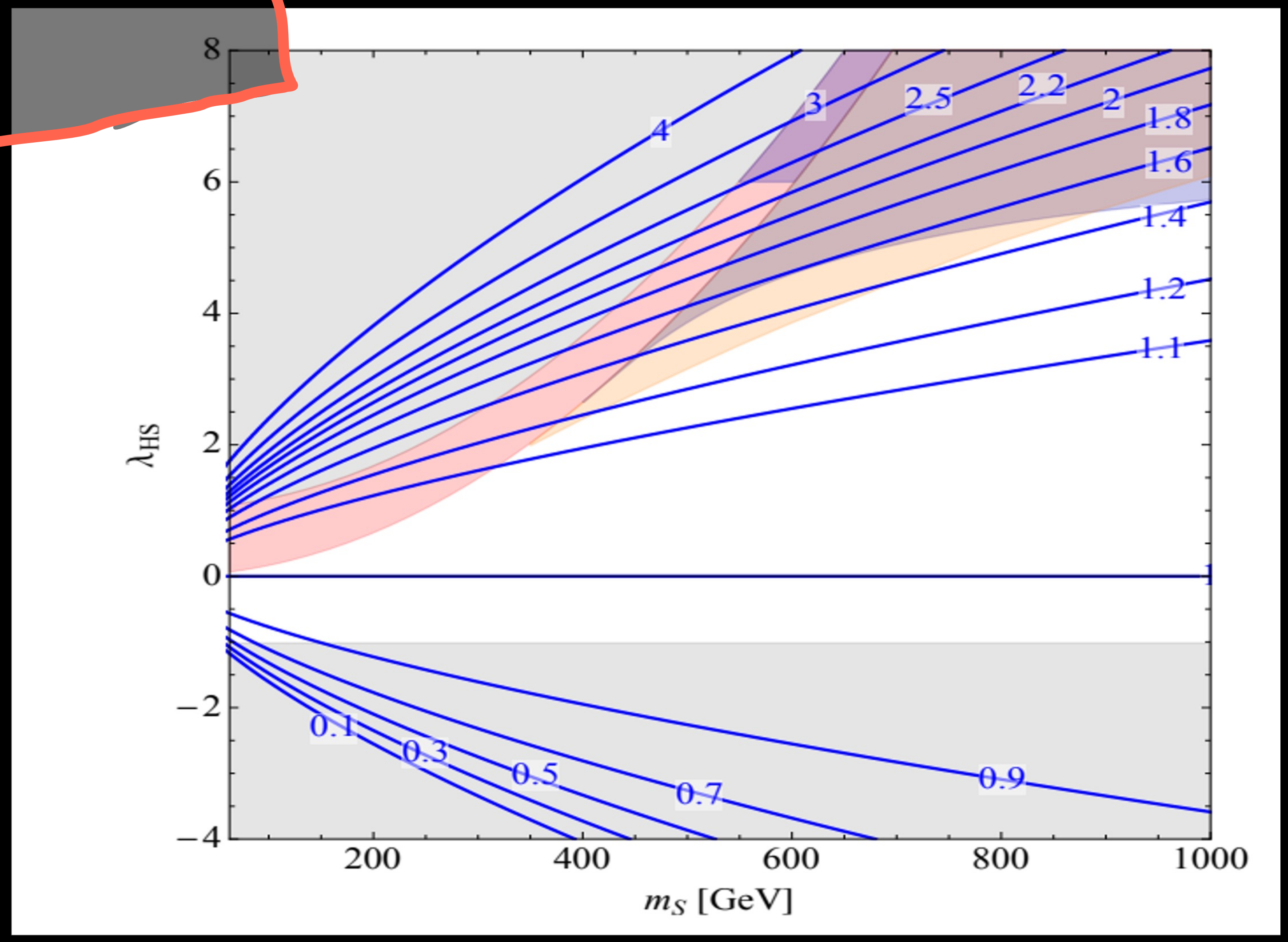
- SM Higgs potential does not result in strong type 1 EWK phase transition necessary for baryogenesis – but slight modifications of the potential could, and they would be detectable at high energy (10 TeV pCM* or larger) collider

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

Need at least 10 TeV pCM machine





Curtin et al., 1409.0005

*Parton center-of-momentum

New paradigms: direct and indirect searches

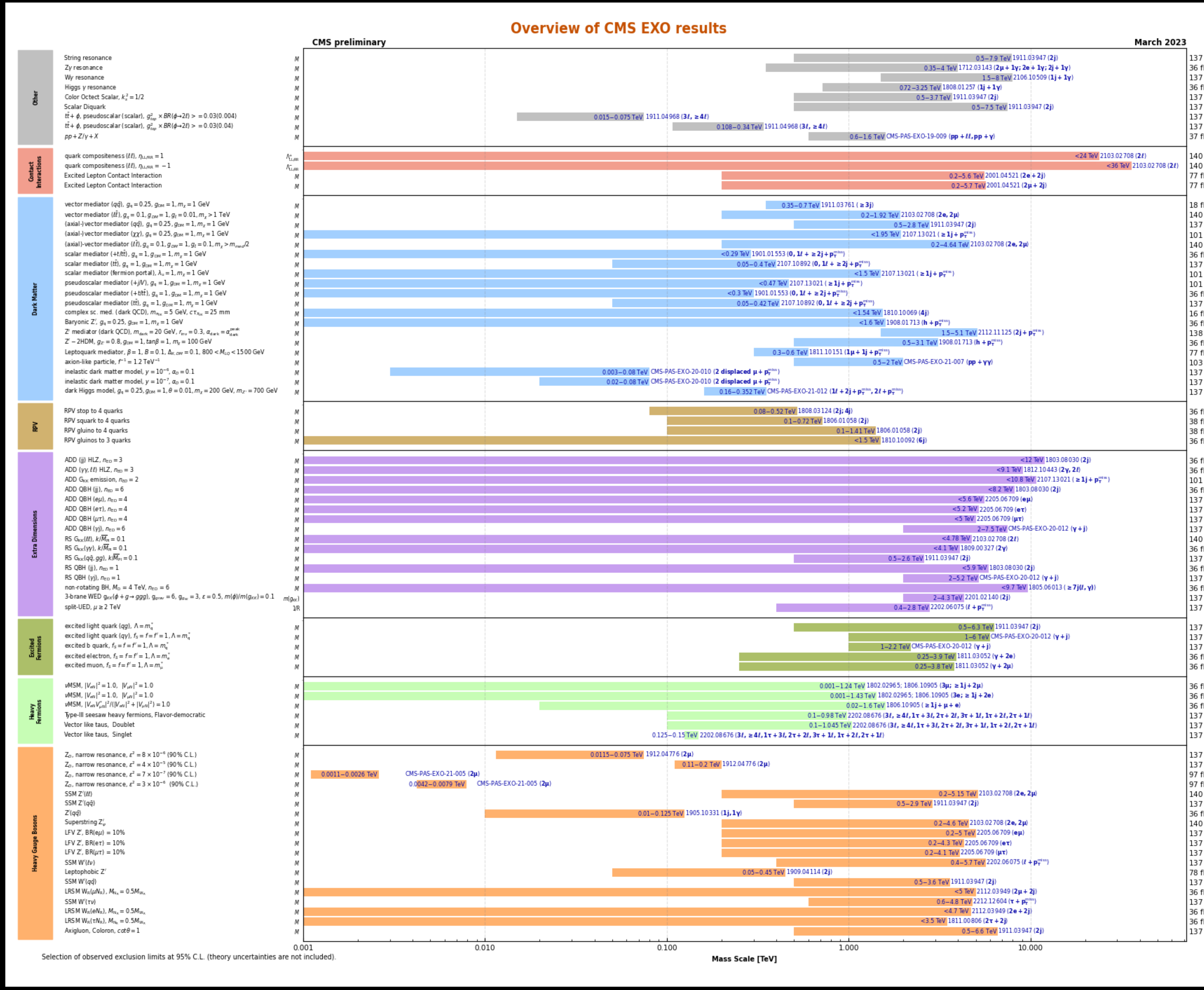
Search for Direct Evidence of New Particles

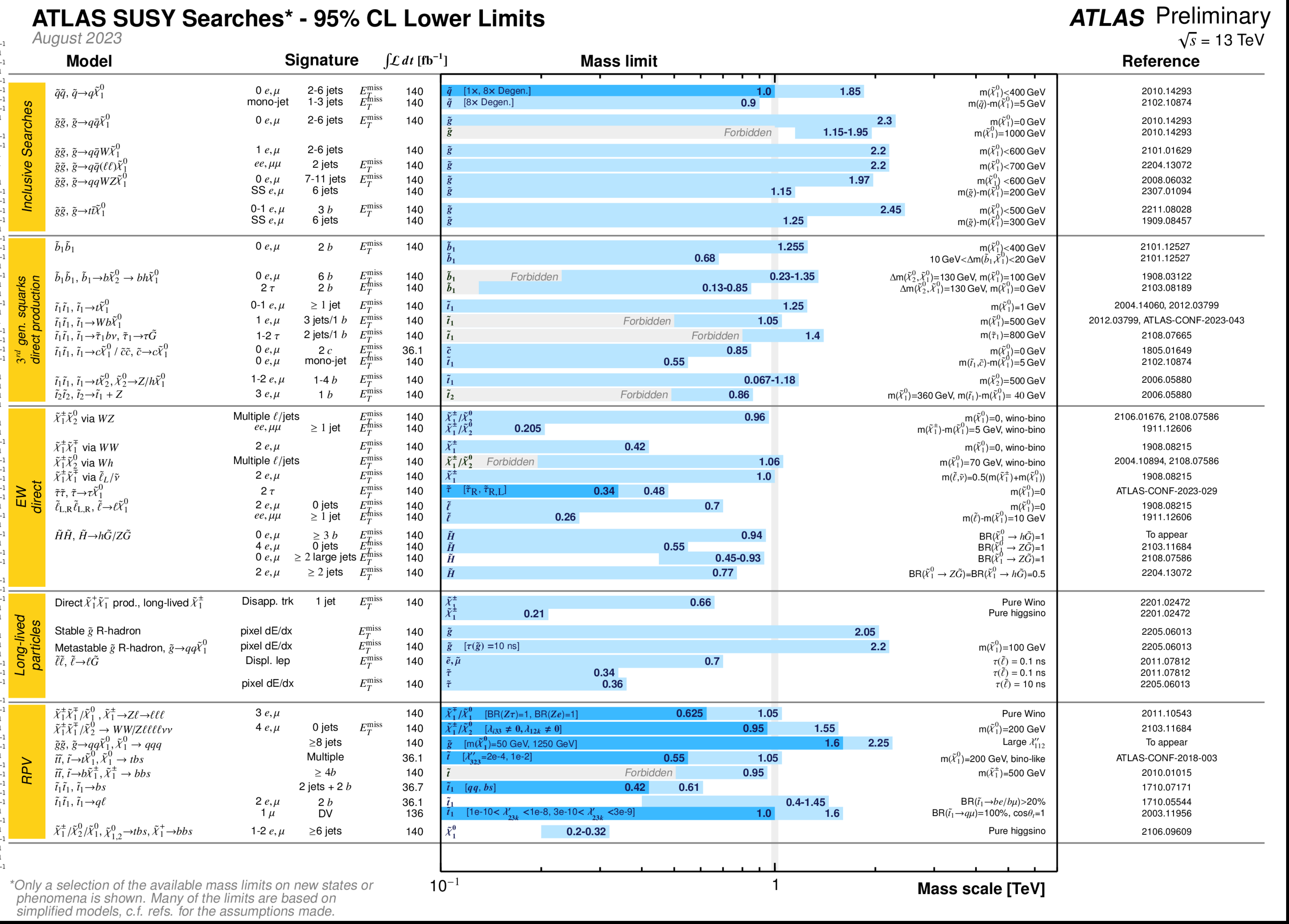
- High-energy colliders enable us to explore the unknown with the potential for discoveries beyond our current imagination, providing access to high mass scales and new physics weakly coupled to the Standard Model.

- 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.

- Now and till ~2040: ATLAS, CMS, and LHCb Experiments at the LHC
- "Small" experiments: FASER, MilliQan, LDMX, …
- 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.

Searches at the LHC and HL-LHC





Searches at the LHC and HL-LHC

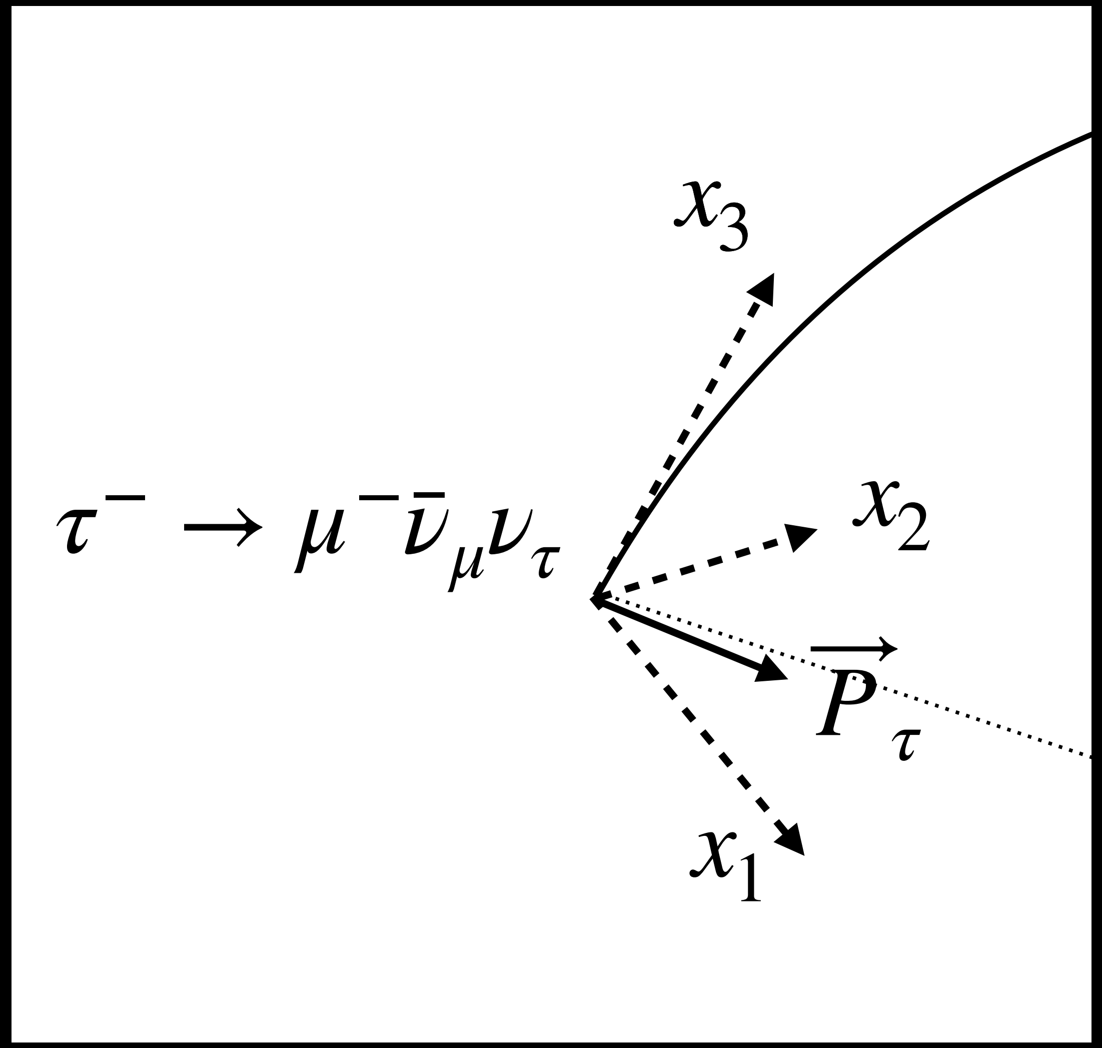
May seem depressing – especially since the direct extrapolation of existing analyses to HL-LHC gives only a $\sqrt{L}$ improvement

But I am personally still very excited about LHC searches

- A lot of ideas are still not covered well – collaborations should encourage quick searches for strange signatures
- Room for "agile" experiments that can fill the gaps in CMS/ATLAS sensitivity
- The analyses do not have to scale with $\sqrt{L}$! Huge statistics opens opportunities to new methods and new decay channels – for many, HL-LHC would bring order of magnitude increase in sensitivity
- For some final states more than that because the HL-LHC triggers are better

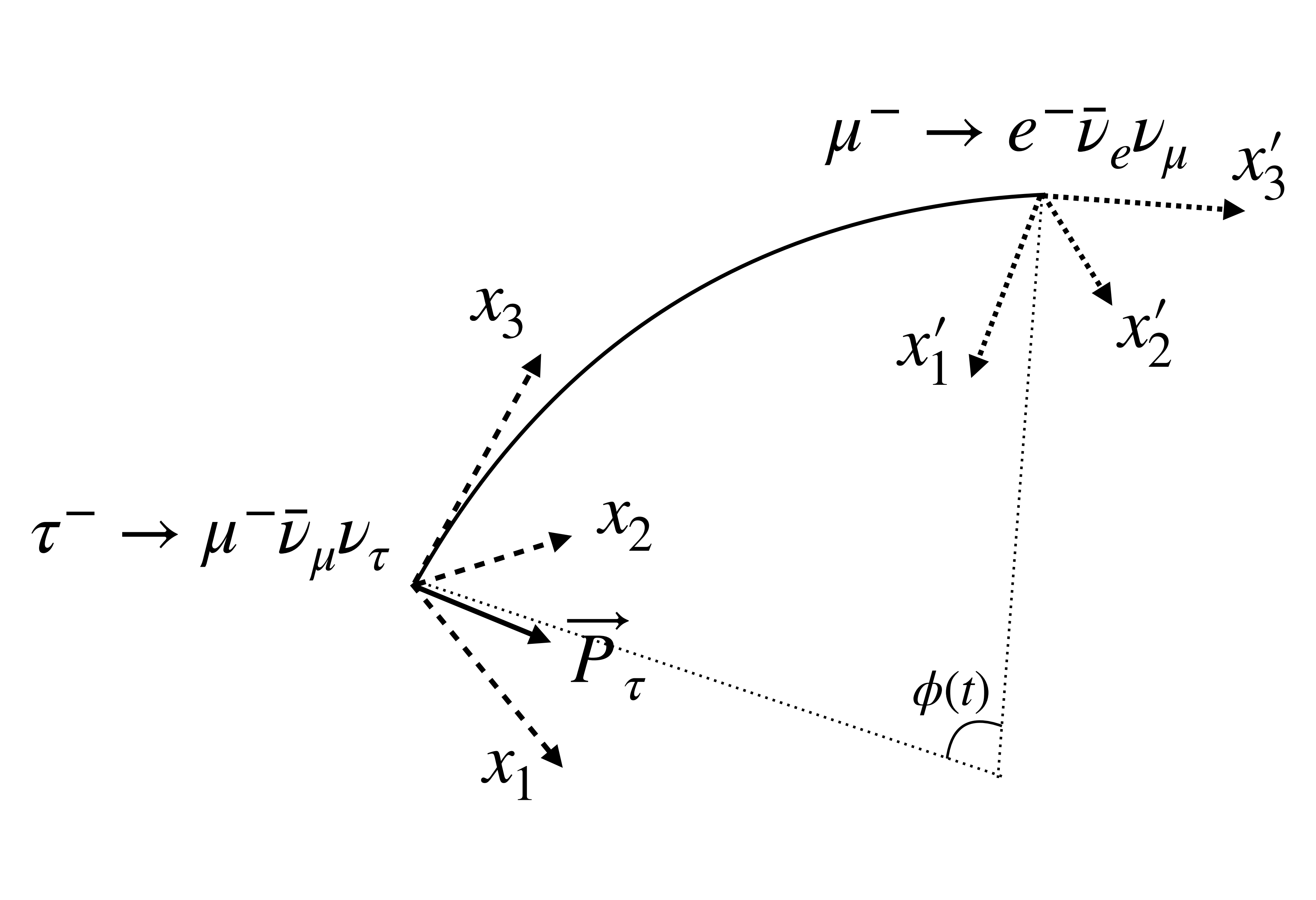
An example from Belle

Measurement of Michel parameters critically tests the SM, especially in tau lepton decays. Yet many are poorly measured because one needs to measure the polarization of the "collider-stable" muon from the decay



An example from Belle

Measurement of Michel parameters critically tests the SM, especially in tau lepton decays. Yet many are poorly measured because one needs to measure the polarization of the “collider-stable” muon from the decay



With amazing amount of data in Belle one now has a sizable sample when muons decay early – and measurement of the electron from its decay correlates with muon polarization.

Phys. Rev. Lett. 131, 021801

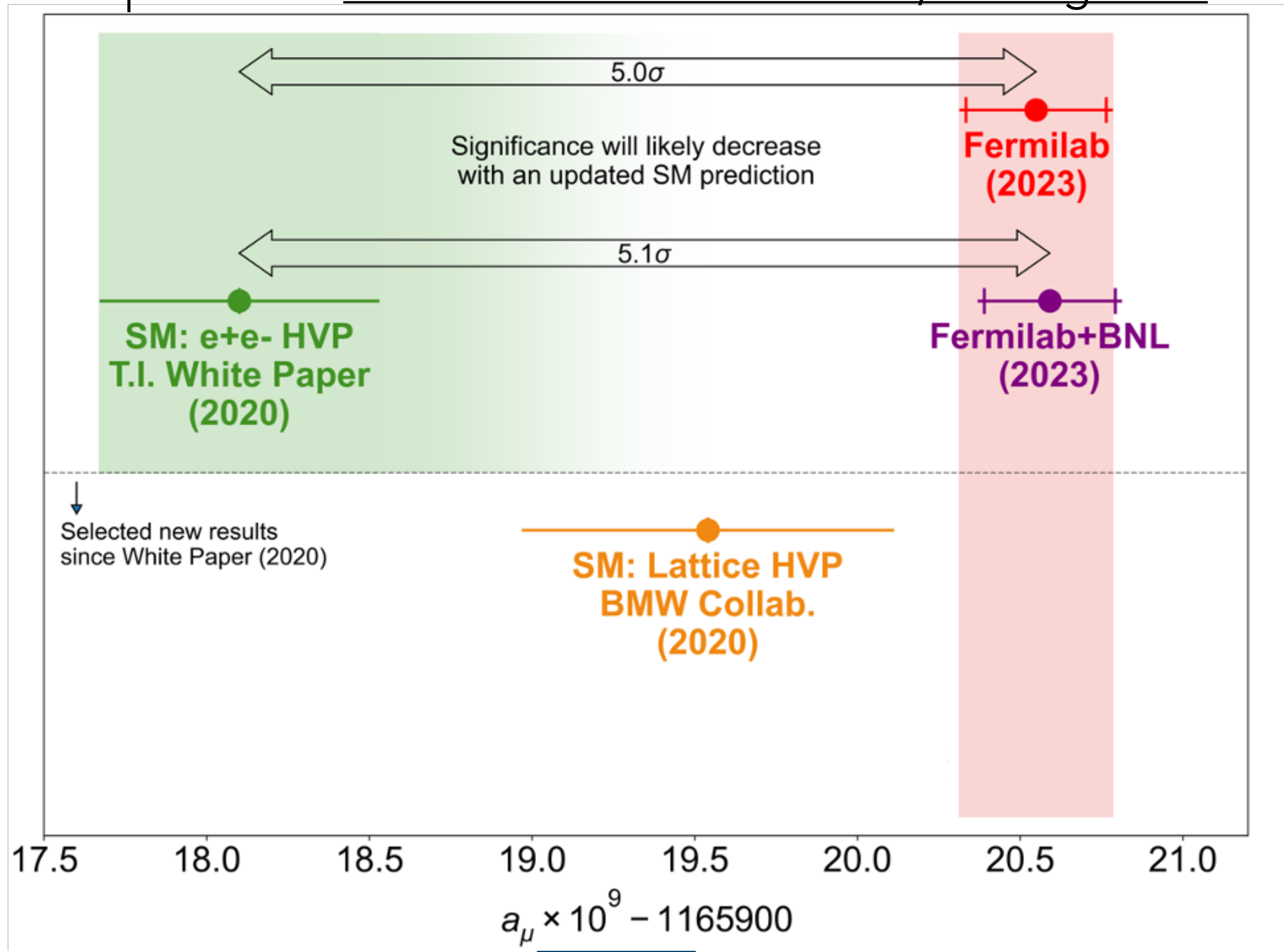
Pursue Quantum Imprints of New Phenomena

- 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.

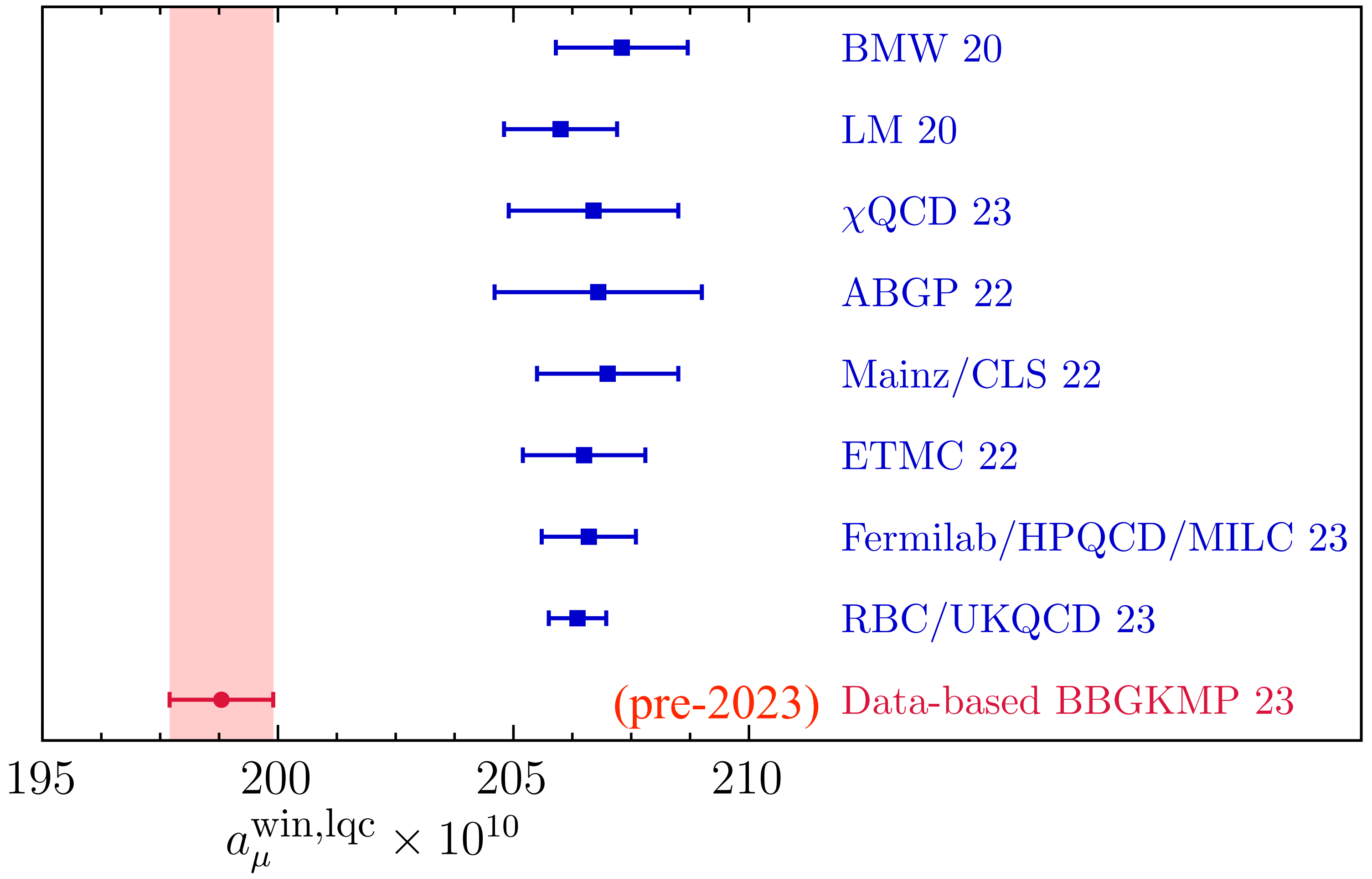
- Now: g-2, Mu2e, Belle II, LHCb, (plus ATLAS and CMS!)
  - Plus: Belle II and LHCb upgrades,
  - R&D for Mu2e II and advanced muon facility
- Major Initiative: Higgs Factory – also factory of b-quarks, top quarks, and Z bosons

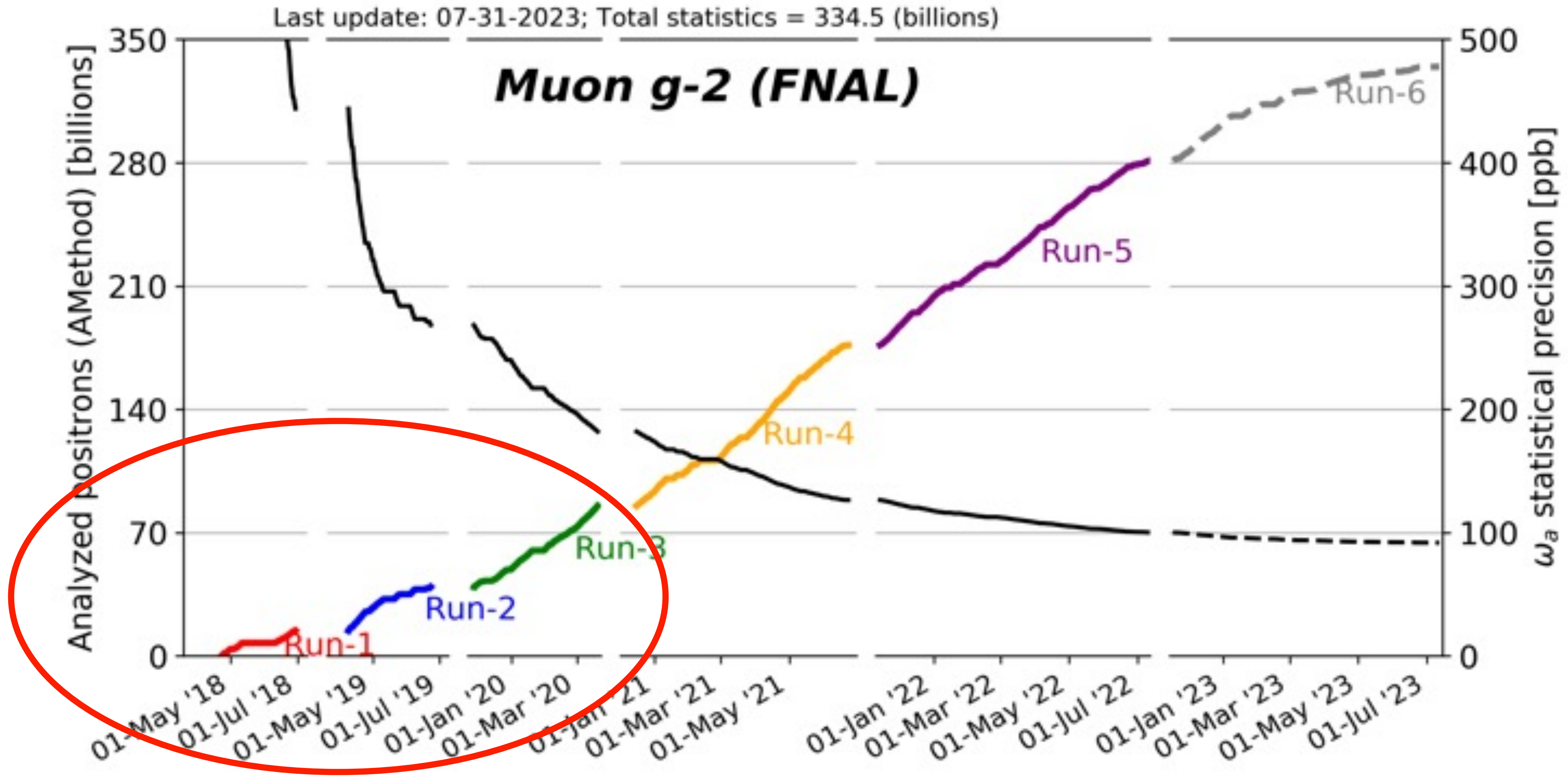
Muon g-2

adapted from J. Mott @ Scientific Seminar, 10 Aug 2023



dispersive evaluation of light-quark connected contribution [G. Benton, et al, arXiv:2306.16808]





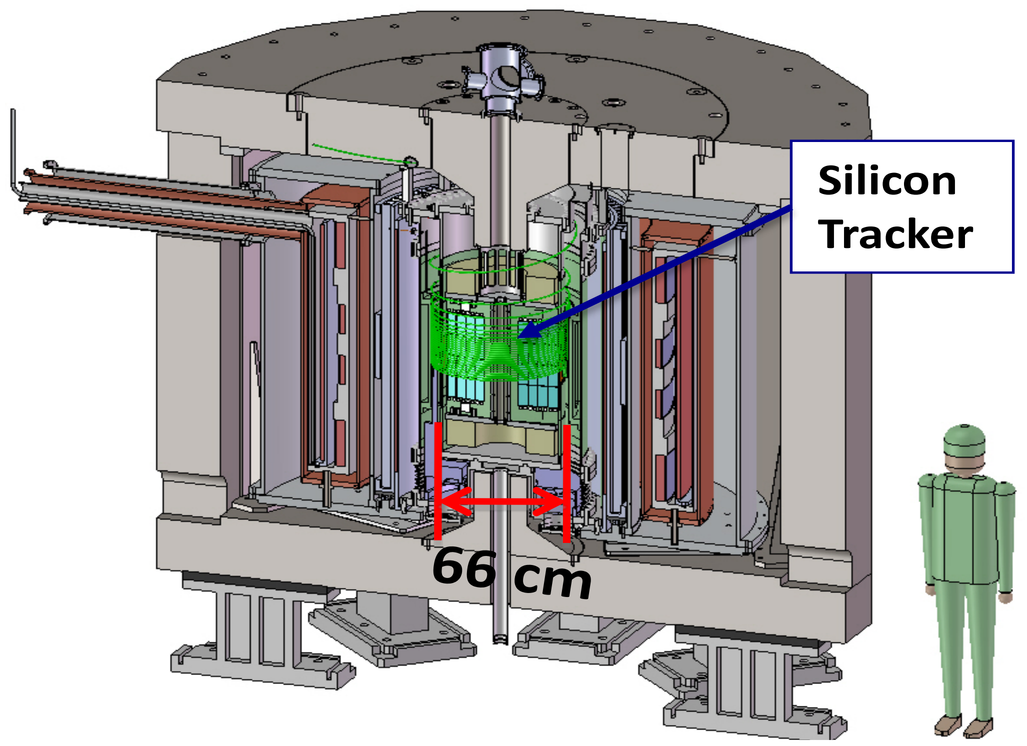
Current FNAL results: up to Run 3

In the works: MUonE to independently check HVP

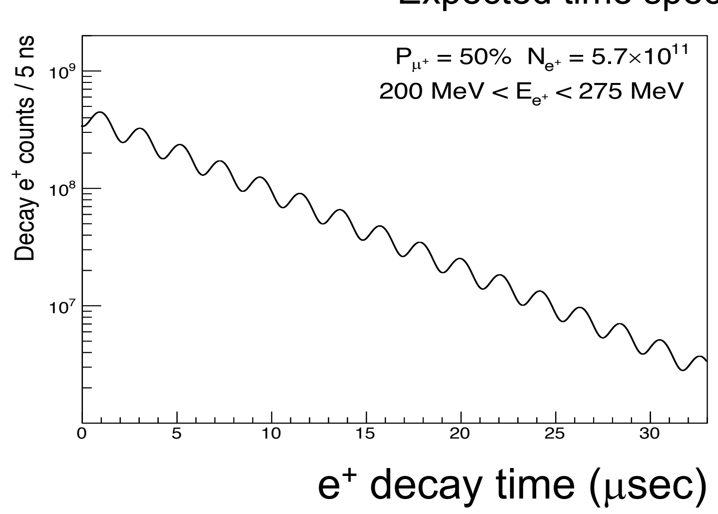
Starting soon: E34 experiment at J-PARC

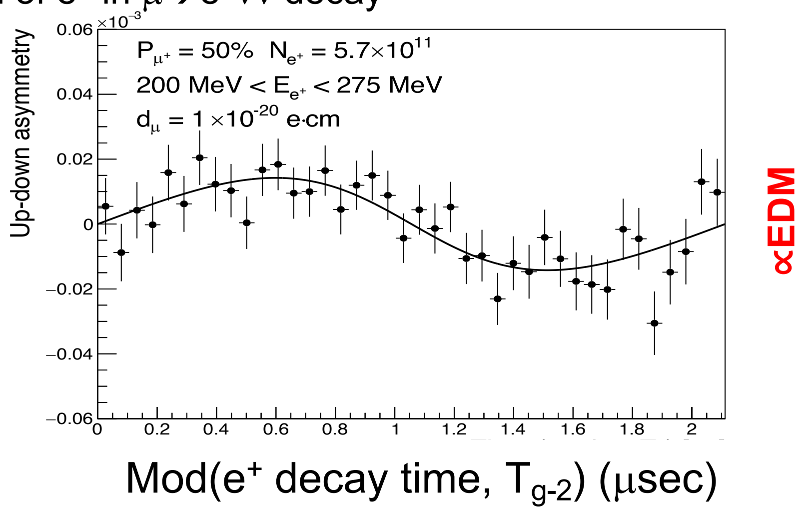
Simultaneous measurement of g-2 and EDM

completely different method from FNAL/BNL

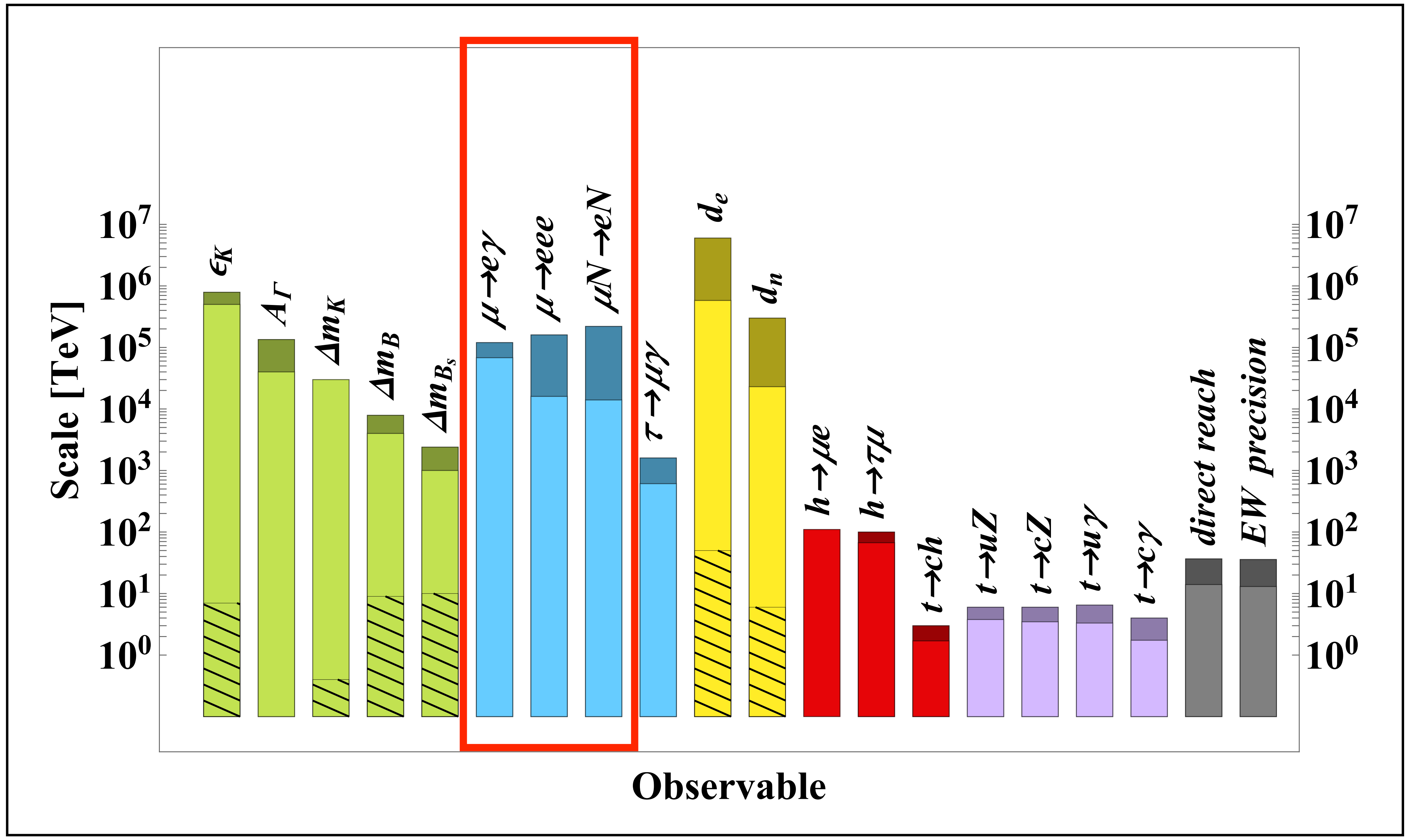


Expected time spectrum of e^+ in $\mu \rightarrow e^+ \nu\nu$ decay





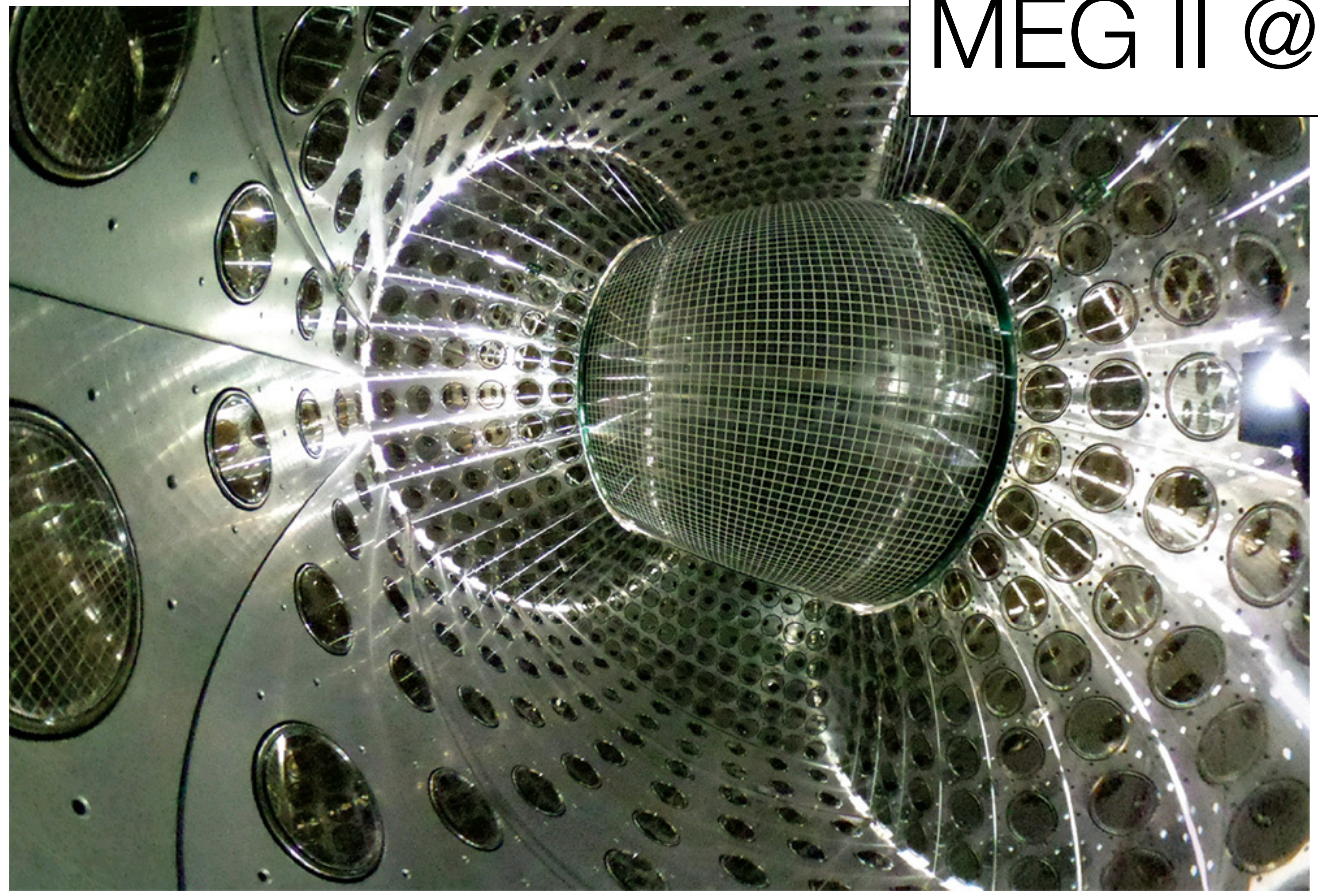
CLFV experiments: one of the best high energy scale probes

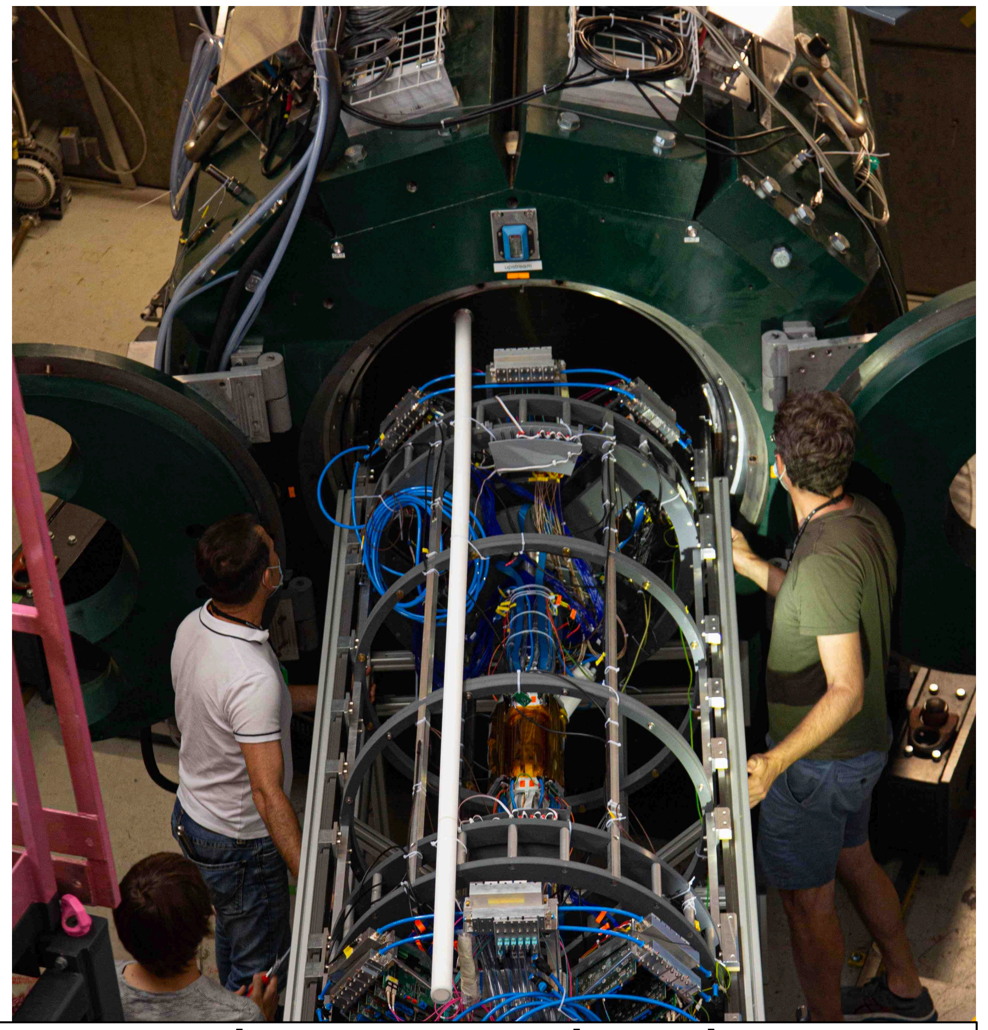


light colour: present
dark colour: future prospect

EPPSU2019 Physics Briefing Book

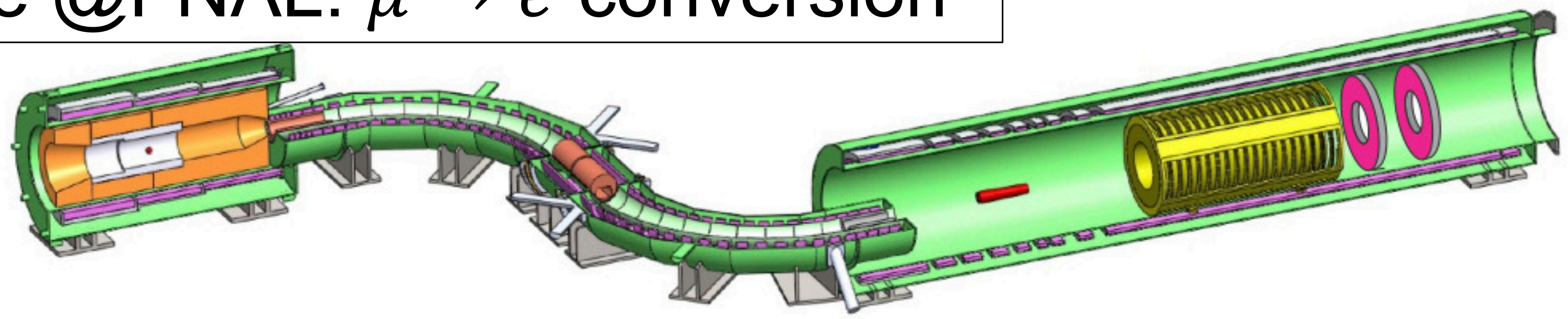
MEG II @ PSI : $\mu^+ \to e^+\gamma$





Mu3e @PSI : $\mu^+ \to e^+e^+e^-$

Mu2e @FNAL: $\mu \to e$ conversion



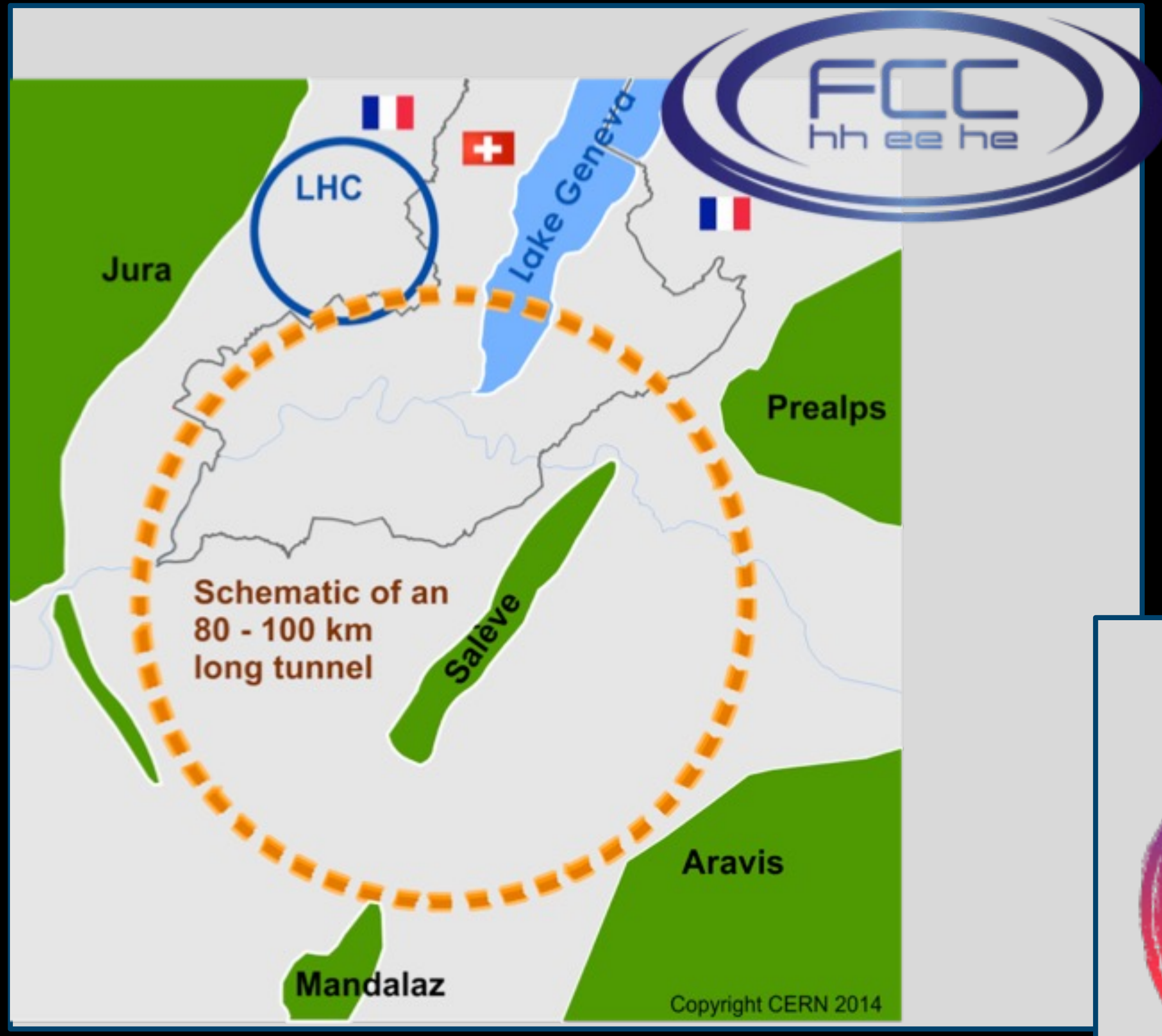
Case for 10 TeV pCM* collider

- **Higgs potential measurement**
- **Higgs friends / new fundamental scalars**
- **Thermal WIMP**
- **Examining EWK scale from above – definitive test of naturalness**

*Parton center-of-momentum

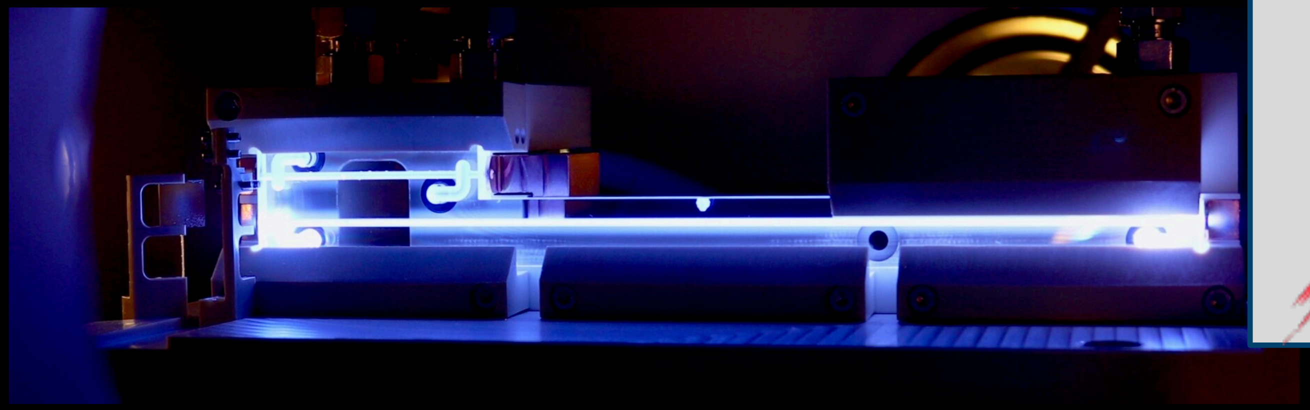
R&D towards a 10 TeV pCM* collider

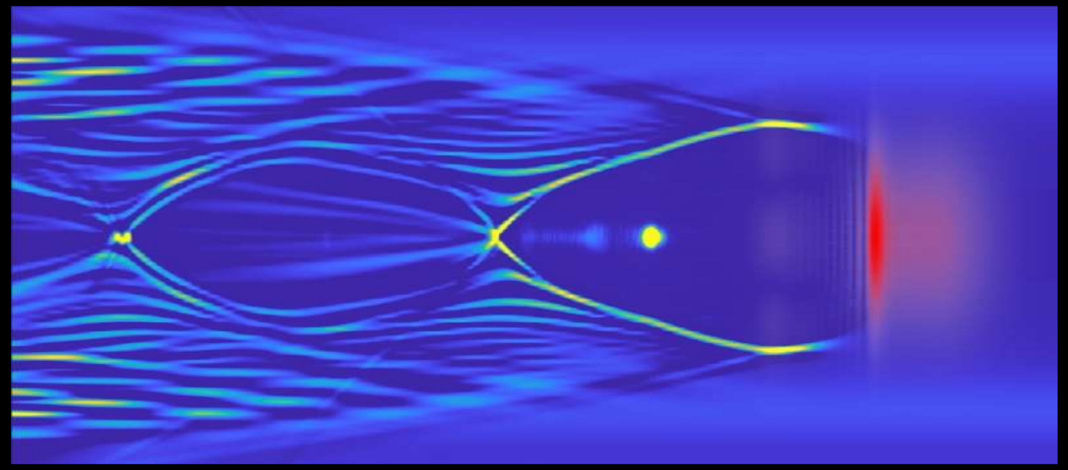
- **Next frontier of high-energy physics is at the 10-TeV scale per parton.**
- **Don’t currently have the technology to build such a machine in a cost-effective way.**
- **Recommend a dedicated R&D effort towards such a machine with the goal of having demonstrator facilities by the end of this decade.**



Three possible concepts:

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





*Parton center-of-momentum

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.

…

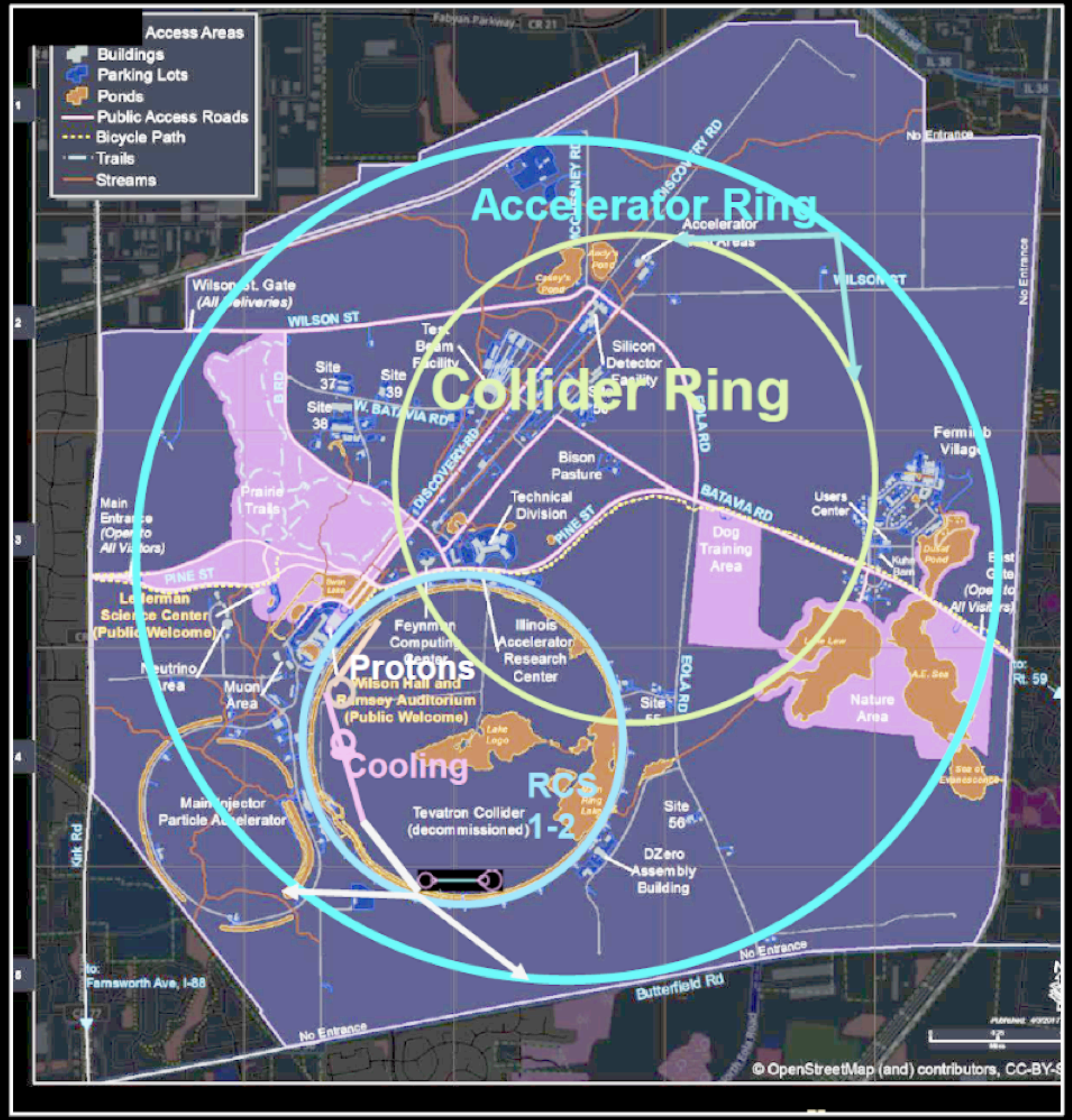
In particular, a muon collider presents an attractive option both for technological innovation and for bringing energy frontier colliders back to the US. The footprint of **a 10 TeV pCM muon collider is almost exactly the size of the Fermilab campus**. A muon collider would rely on a powerful multi-megawatt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

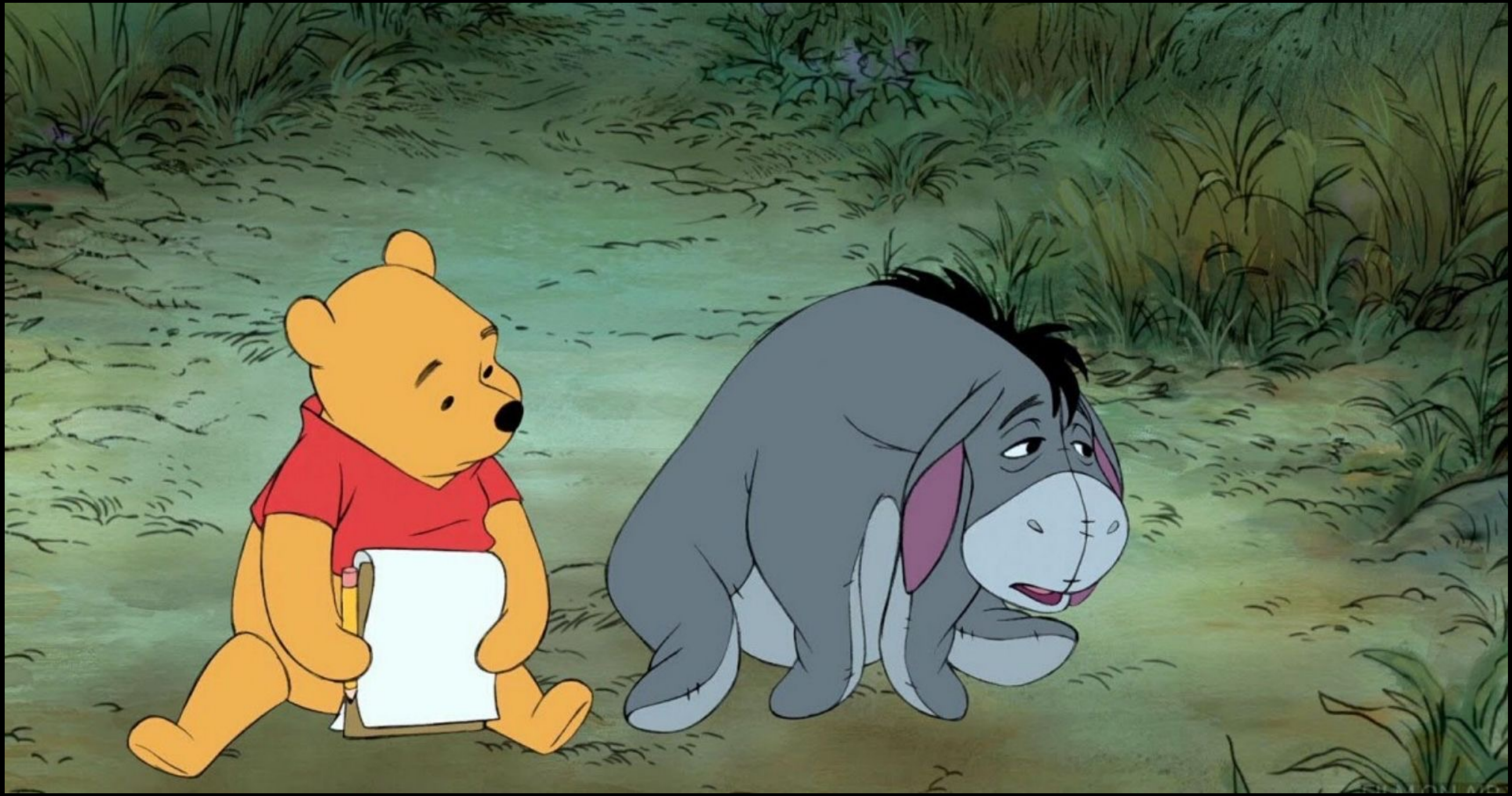
FNAL: shoot for the muon

[Bhat, Jindariani, et al 2203.08088]



Looking into 2034

Looking into 2034



Looking into 2034

- ***Colliders***
  - ***HL-LHC is in full swing: exotic Higgs decays? Evidence of compositeness? Electroweakinos? LLPs?***
  - ***Higgs Factory is being constructed somewhere in the world***
  - ***Muon Collider demonstrator is under construction***
  - ***Breakthrough in high temperature superconductor magnet technology? WFA?***
- ***Neutrinos***
  - ***Mass ordering is known!***
  - ***Will we get lucky with $0\nu\beta\beta$?***
  - ***Will we resolve MiniBooNE anomaly? Or discover new ones? Light Dark Matter?***
  - ***No CP discovery but will the tension between NOvA/DUNE and T2K/HyperK grow?***

Looking into 2034

- *Dark Matter*
  - *results from new DM initiatives (ADMX-ERF, LDMX, OSCURA, TESSERACT,...)*
  - *G3 start datataking*
- *Muons*
  - *g-2 puzzle unambiguously sorted!*
  - *CLFV @FNAL @PSI @J-PARC experiments running or completed*
- *CMB*
  - *Dynamic Dark Energy?*
  - *Hubble tension resolved or solidified?*
  - *Neutrino masses, Neff, …*
  - *Primordial B-modes*

Look into 2034

The future is very uncertain

Look into 2034

The future is very uncertain

I’m sure it will not be easy

Look into 2034

The future is very uncertain

I’m sure it will not be easy

I’m sure it will be a lot of fun

Look into 2034

And I hope we will also learn something fundamental about Nature