HEPAP Facilities Subpanel Report

HEPAP Meeting, May 9 -10, 2024

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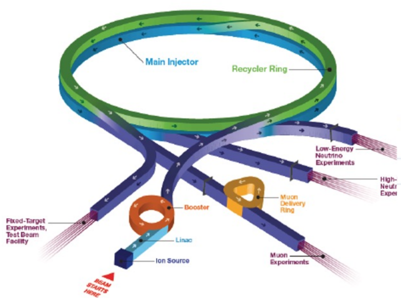
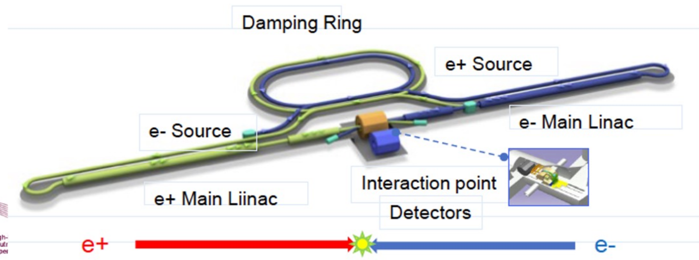
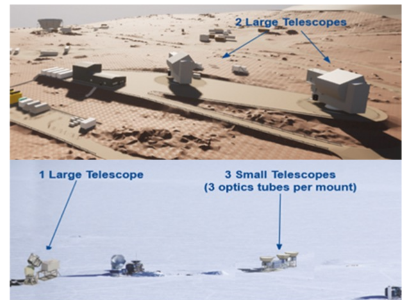
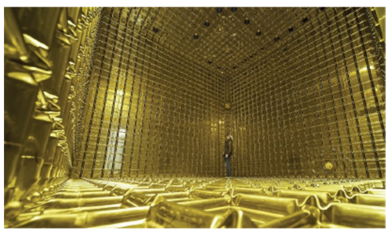
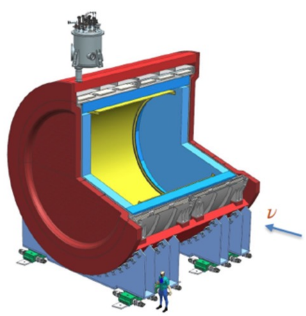
Report of the HEPAP Facilities Subpanel, May 2024

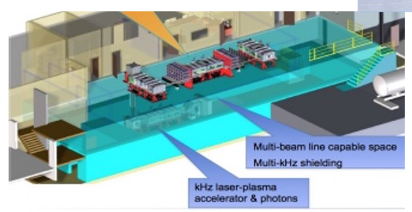


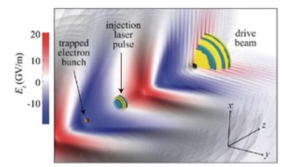


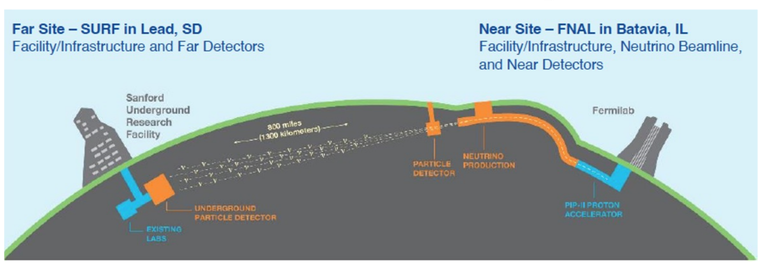


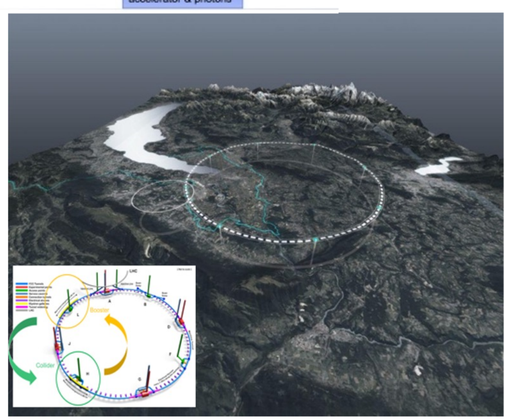


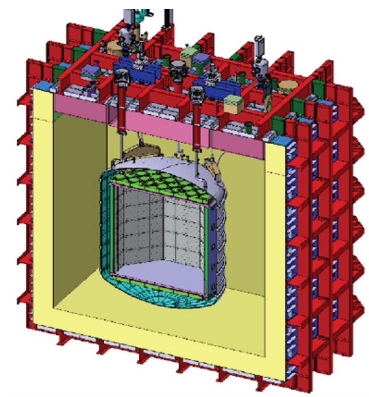


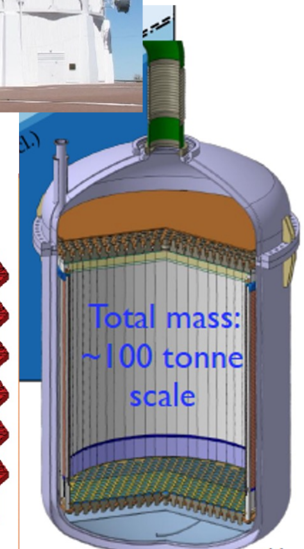












Outline

- Facilities Charge
- Subpanel membership
- HEP Facilities list
- Subpanel process
- Summary of Assessments
- Individual Facilities and Assessments
- Conclusion

Facility Assessments by the Office of Science

- First DOE SC facilities charge was issued in 2003 by Ray Orbach
  - All facilities were prioritized across SC
  - Of 28 facilities, 15 have been completed and 8 are under development (in some form)
- A second facilities charge was issued in 2013 by William Brinkman, but SC-wide prioritization was not publicly released
  - HEP facilities included Mu2e, LBNE, LSST, LHC upgrades, next generation DM and DE experiments, Project X, nuSTORM, ILC
- This is the third facilities exercise, with virtually the same charge

Charge from the Director of the DOE Office of Science

I am asking the SC advisory committees to look toward the scientific horizon and identify what new or upgraded facilities will best serve our needs in **the next ten years (2024-2034).**

More specifically, I am charging each advisory committee to establish a subcommittee to:

1. Consider what new or upgraded facilities in your disciplines will be necessary to position the Office of Science at the forefront of scientific discovery… please consider only those **that require a minimum investment of $100M.**

1. Deliver a short letter report that discusses each of these facilities in terms of the two criteria below and provide a short justification for the categorization, but **do not rank order** them:

a. The potential to contribute to **world-leading science** in the next decade. Please place each facility or upgrade in one of four categories: **(a) absolutely central; (b) important; (c) lower priority; or (d) don't know enough yet**.

b. The **readiness for construction**. Please place each facility in one of three categories: **(a) ready to initiate construction; (b) significant scientific/engineering challenges to resolve before initiating construction; or (c) mission and technical requirements not yet fully defined.**

Later addition to the charge: you are encouraged to include a section **on cross-cutting interests and connections, including the scientific interest your community has in specific facilities under consideration by other SC programs.**

Subpanel Membership

Name	Institution
Mei Bai	SLAC
Mary Bishai	BNL
Ken Bloom	U of Nebraska
Jodi Cooley	SNOLAB
Sarah Cousineau	ORNL
Gil Gilchriese	LBNL, ret
Doug Glenzinski	FNAL
Klaus Honscheid	Ohio State
Reina Maruyama	Yale
Natalie Roe (Chair)	LBNL
Anders Ryd	Cornell
Dave Stuart	UCSB
Sam Zeller	FNAL

- Panel members were assigned to assess projects in which neither they nor their institution has a significant interest
- During panel discussions, panelists were asked not to express opinions on the projects where they have a potential conflict of interest
- Fact checking was allowed

Working Definition of Assessments

Scientific assessment:

- ***Absolutely central:*** addresses the most important scientific questions of the field, is unique in its capabilities (among facilities accessible to the US scientific community), and serves a broad community of users.
- ***Important:*** addresses important scientific questions and has unique aspects.
- ***Lower priority:*** scientific goals are lower priority and/or the facility is redundant with other existing or planned facilities.
- ***Don't know***: scientific goals not yet well defined.

Technical readiness:

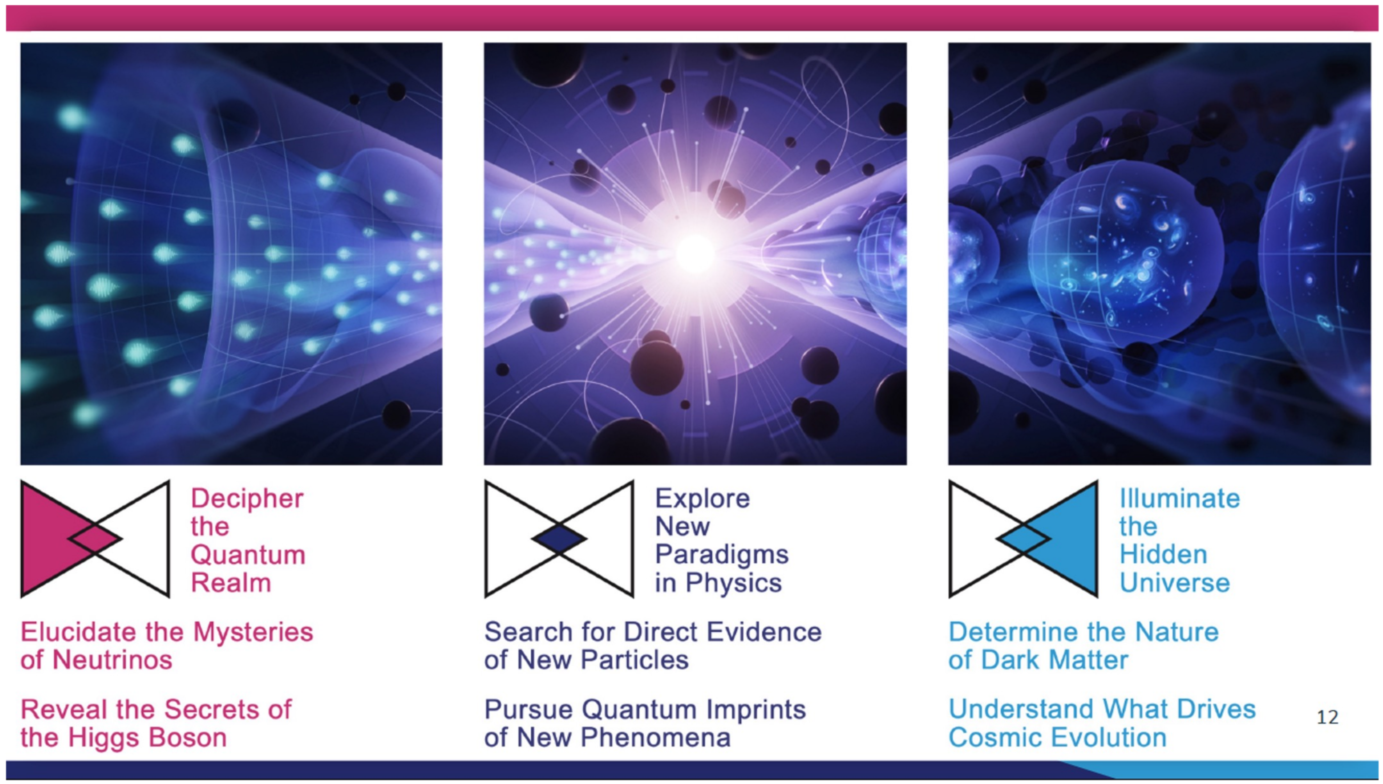
- ***Ready to initiate construction:*** could be ready soon to initiate the DOE Critical Decision process (starting with conceptual design review); beyond the basic R&D stage.
- ***Significant scientific/engineering challenges remain:*** Initiation of the Critical Decision process is at least several years away; pending selection of alternatives and/or demonstration of basic feasibility of some aspects.
- ***Mission and technical requirements not fully defined:*** scientific goals are not well defined and/or more R&D is needed to define technical requirements.

The Work of the Subpanel was Guided by P5

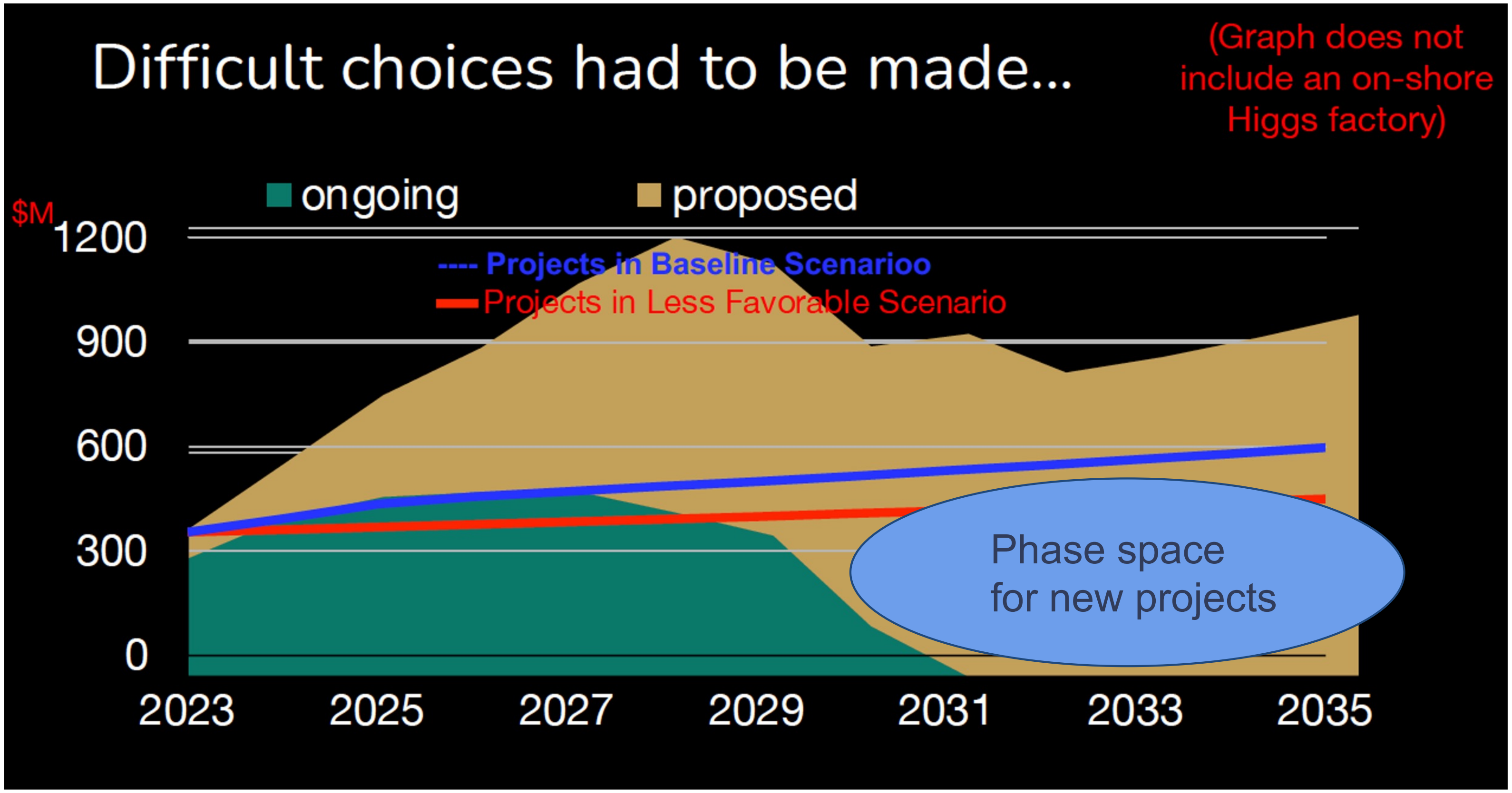
P5 was charged by DOE and NSF to develop 10 year roadmap in the context of a 20 year vision.

The P5 process built on the two-year Snowmass community workshop.

Throughout, there was strong community involvement, including international participation.



Proposed Projects Greatly Exceeded P5 Budget Scenarios



Credit: P5

P5 Project Recommendations by Budget Scenario

Figure 2 – Construction in Various Budget Scenarios

Index: N: No Y: Yes R&D: Recommend R&D but no funding for project C: Conditional yes based on review P: Primary S: Secondary
Delayed: Recommend construction but delayed to the next decade
Can be considered as part of ASTAE with reduced scope

Scenarios	Less	Baseline	More	Neutrinos	Higgs Boson	Dark Matter	Cosmic Evolution	Direct Evidence	Quantum Imprints	Astronomy & Astrophysics
US Construction Cost >$3B										
on-shore Higgs factory	N	N	N		P	S		P	P	
$1–3B										
off-shore Higgs factory	Delayed	Y	Y		P	S		P	P	
ACE-BR	R&D	R&D	C	P				P	P	
$400–1000M										
CMB-S4	Y	Y	Y	S		S	P			P
Spec-S5	R&D	R&D	Y	S		S	P			P
$100–400M										
IceCube-Gen2 *	Y	Y	Y	P		S				P
G3 Dark Matter 1	Y	Y	Y	S		P				
DUNE FD3	Y	Y	Y	P				S	S	S
test facilities & demonstrator	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 #	N	N	N	P		P		P		

* Ice Cube Gen2 is NSF ** Note: MCND cost estimate is ~$150M

The P5 report provides important guidance on scientific priorities and future projects which are reflected in the assessments.

P5 made difficult choices; the proposed project budgets exceeded the scenarios by > x2

Projects that were not recommended by P5 were not considered by the subpanel.

HEP Facilities List

- Original list of facilities has been amended in consultation with HEP:
  - LBNF/DUNE Phase 1 – 3 of 5 subprojects that are still pre-CD-3
  - DUNE High Power Far Detector Upgrade
    - DUNE Far Detector 3
    - DUNE Far Detector 4

    Considered separately per P5 recommendation; FD4 as "module of opportunity"
  - DUNE High Power Near Detector Upgrade (MCND)
  - Accelerator Complex Evolution – Main Injector Ramp + Target (ACE-MIRT)
  - Accelerator Complex Evolution – Booster Replacement (ACE-BR)
  - Advanced Accelerator Test Facilities – kBELLA
  - CMB-S4
  - Spec-S5
  - Generation 3 Dark Matter

    Added per P5 Recommendation 2
  - Future Energy Frontier Colliders
    - Higgs Factory
    - 10 TeV pCM Collider

    Split into two categories, per P5 report recommendation to participate in off-shore HF while doing R&D towards 10 TeV pCM

Subpanel Process - Timeline

- December 1, 2023: Charge letter to SC
  - December 7-8: HEPAP meeting, charge discussed by M. Procario
  - December- January: Subpanel formed
- January 29, 2024: Subpanel Kickoff meeting
- February 6: Finalized updated facilities list with HEP
- February 12: Sent out Request for Information to Projects
- February 26: RFI responses due
- March 5-6: In person meeting at FNAL with project presentations
- March - April: Meetings to develop assessments and draft report
- May 6: Draft report shared with HEPP
- May 10: HEPAP presentation

Total of 10 committee meetings and much hard work by all!

Cross Cutting Synergies with Other DOE SC Offices

- HEP is the steward of accelerator physics
  - Connections with DOE BES and NP – HEP accelerator groups contribute to SCRF, magnets, high power targets, ion sources, beam controls etc. in SC accel. projects
  - Developing new technologies in magnets, RF, controls, advanced accelerators; important for BES, NP, FES
  - Training of the next generation accelerator workforce
- HEP develops cutting edge detector technologies
  - Detector systems, Quantum sensors, Microelectronics, etc.
  - Many applications for society, security, medicine, nuclear science, photon beamlines
- HEP relies strongly on ASCR computing facilities
  - NERSC, ESNet, leadership computing facilities at ANL and ORNL
  - Future data center (HPDF) and integrated research infrastructure (IRI)
  - HEP users are early adopters for AI/ML, beta testers for new computing facilities

- Discussion

HEP Facilities Support the P5 Science Priorities

- LBNF/DUNE Phase 1
- LBNF/DUNE Phase 2
  - ACE-MIRT
  - DUNE Far Detector 3
  - MCND
- DUNE Far Detector 4
- CMB-S4
- Spec-S5
- Generation 3 Dark Matter
- ACE-BR
- Advanced Accelerator Test Facilities
- Future Energy Frontier Colliders
  - Higgs Factory
  - 10 TeV pCM Collider

Elucidate the Mysteries of Neutrinos

Understand What Drives Cosmic Evolution

Determine the Nature of Dark Matter

Reveal the Secrets of the Higgs Boson

Search for Direct Evidence of New Particles

Pursue Quantum Imprints of New Phenomena

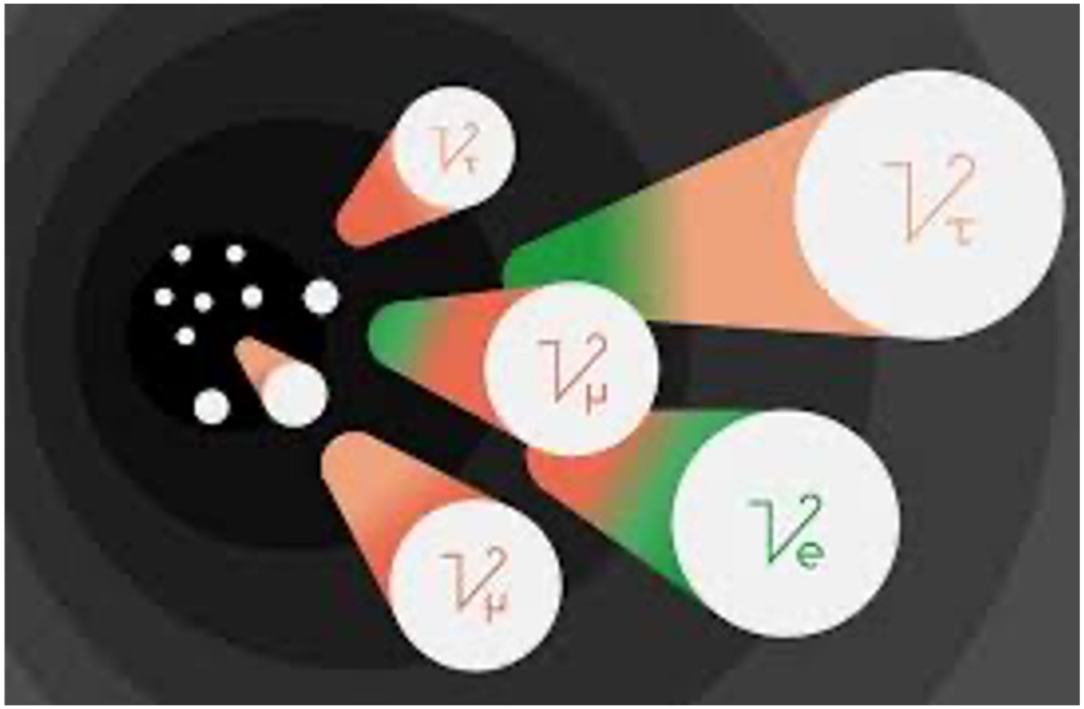
This portfolio of projects includes significant international participation and many have NSF participation.

Executive Summary

		Science Assessment				Technical Readiness		
		Absolutely central	*Important*	*Lower priority*	*Don't know*	*Ready to initiate construction*	*Significant scientific/ engineering challenges remain*	*Mission and technical requirements not fully defined*
		A	B	C	D	A	B	C
LBNF/DUNE Phase 1		●				●		
LBNF/DUNE Phase 2	ACE-MIRT	●				●		
	FD3	●				●		
	MCND	●					●	
FD4					●			●
CMB-S4		●				●		
Spec-S5		●				●		
G3 Dark Matter		●					●	
Off-Shore Higgs Factory		●				●		
AATF - kBELLA		●					●	
ACE-BR					●			●
10 TeV pCM Collider		●						●

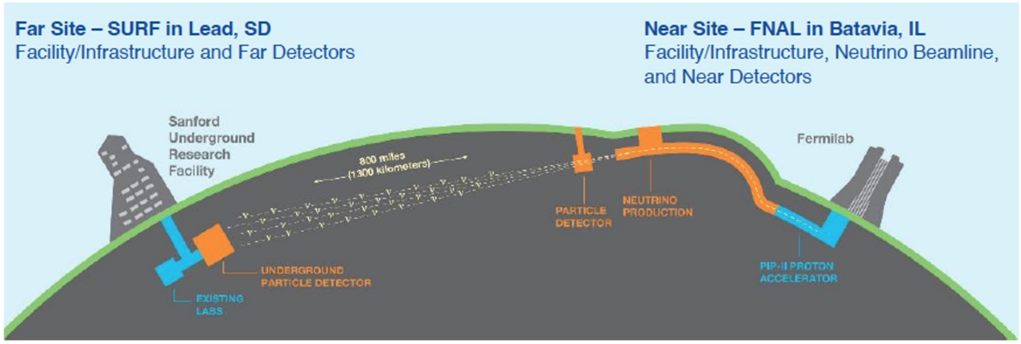
Elucidate the Mysteries of Neutrinos

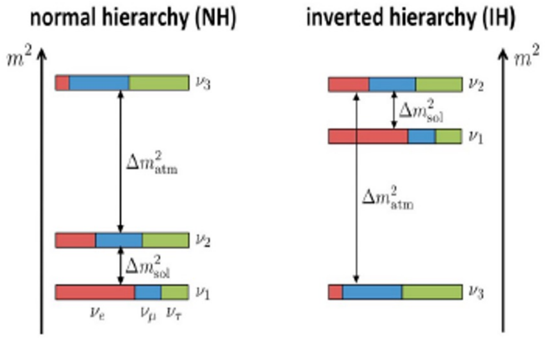
- Neutrinos are the second most abundant particle in the Universe yet their properties remain enigmatic
- Neutrino oscillations have been observed and 3 mixing angles have been measured; however the generation of neutrino masses is not understood, and neutrino mass ordering is not known
- Neutrinos may be their own anti-particles, and they may exhibit CP violation - both are intriguing possibilities with many ramifications



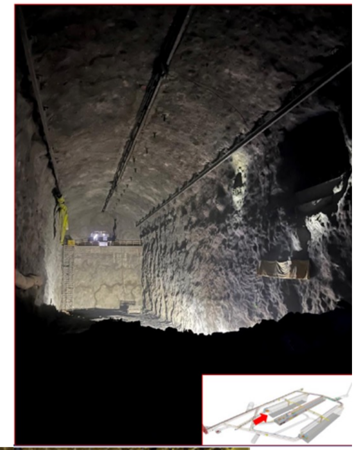
LBNF/DUNE Phase I

- LBNF/DUNE is the US flagship program in neutrino physics
  - Phase 1 will unambiguously determine the neutrino mass hierarchy, and could detect CP violation if it is near maximal
  - Additional goals include astrophysics and BSM searches
- Japan's T2HK is complementary to DUNE with a shorter baseline, off-axis neutrino beam and water Cerenkov detector
  - T2HK will likely start data taking sooner, and could detect CP violation first, if the effect is large
  - Combined results are more powerful than either alone

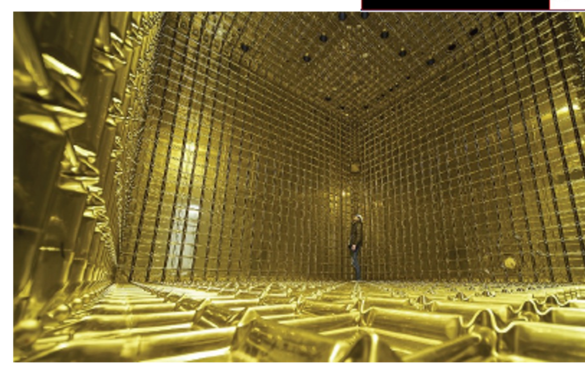




Facility Assessment: LBNF/DUNE Phase I



- Scientific Assessment: ***“absolutely central”***.
  - The Phase I LBNF/DUNE facilities will usher in the era of precision neutrino physics
  - P5 report recommends the completion of DUNE and LBNF as the highest priority in any funding scenario
  - Phase I sets the stage for future upgrades to enable even greater precision.
- Technical Assessment: ***“ready to initiate construction”***
  - The Phase I sub-projects are technically advanced:
  - Excavation of Far Site is complete and Far Site Buildings and Infrastructure subproject has CD3
  - Far Detectors and Cryogenics Systems subproject has CD-3b approval
  - Near Site Conventional and Beamline Facilities has CD-3a approval
  - Near Detector subproject has CD-1 approval

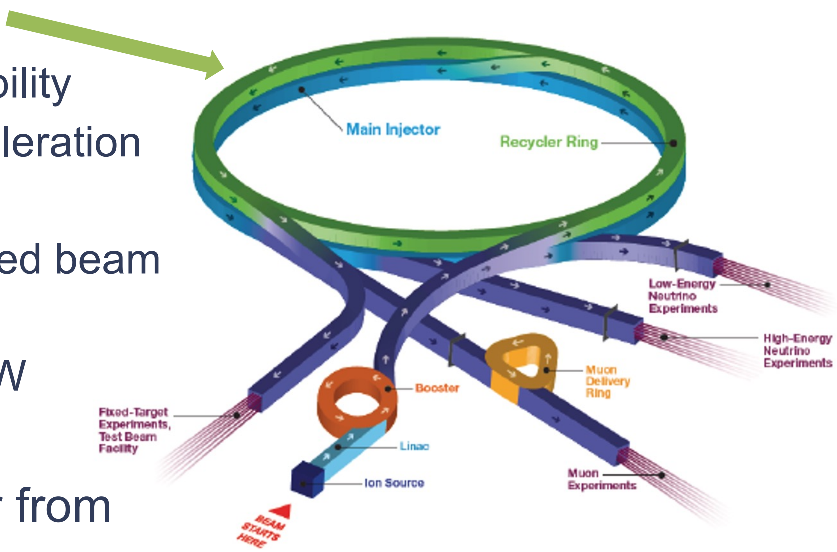


LBNF/DUNE Phase II

- LBNF/DUNE Phase II was endorsed by P5 as the second highest priority for new construction:
  - "Phase II completion leaves DUNE poised to deliver the most precise measurement of the CP phase across a range of possible CP phase space…. Thus the experiment will comprehensively test the validity of the three-flavor neutrino oscillation framework with best-in-class precision and will search for signatures of unexpected neutrino interactions."
- Phase II comprises 3 elements, each of which is essential for the physics goals:
  - Accelerator Complex Evolution Main Injector Ramp and Target (ACE-MIRT)
  - An additional far detector (FD3)
  - A more capable near detector (MCND)

Accelerator Complex Evolution –Main Injector Ramp & Target

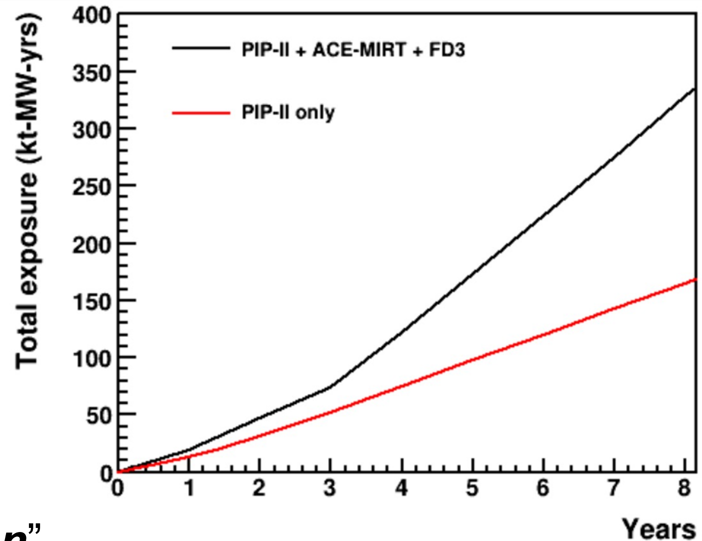
- ACE-MIRT has 4 components:
  - replace the MI quadrupole magnets for better reliability
  - upgrade the MI power system for faster beam acceleration and shorter cycle time
  - upgrade the MI RF accelerating system for increased beam flux
  - phased development and implementation of 2.1 MW capable targets and horns
- ACE-MIRT goal is a 75% increase in beam power from 1.2 MW to 2.1 MW, by taking full advantage of the increased protons from PIP-II



Credit: A. Valishev

ACE-MIRT - Facility Assessment

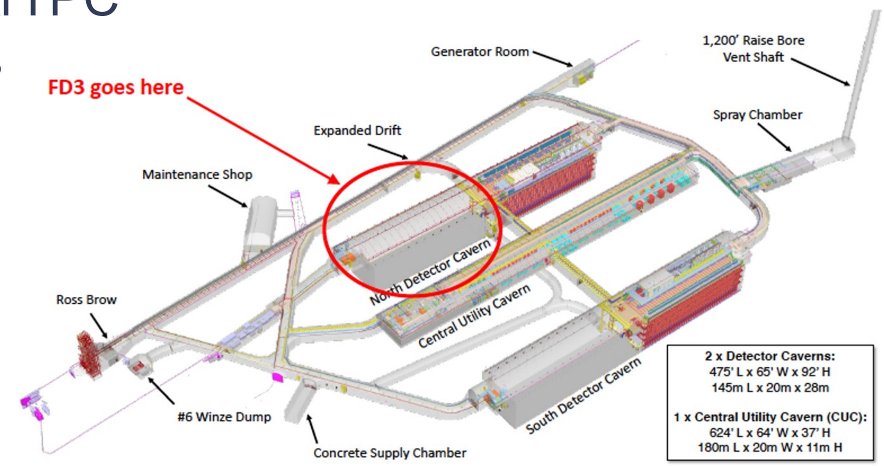
- Scientific assessment: ***"absolutely central"***
    - The P5 report stated that *"Early implementation of the accelerator upgrade ACE-MIRT advances the DUNE program significantly, hastening the definite discovery of the neutrino mass ordering."*
    - ACE-MIRT will accelerate all aspects of the DUNE scientific program through faster accumulation of neutrino data



- Technical readiness: ***"ready to initiate construction"***
    - The first three of the four essential upgrade areas rely on established technologies that have a high level of technical readiness.
    - However, the fourth requires substantial R&D to develop the 2.1 MW capable targets; a phased approach will be taken with 1.5MW as an intermediate goal

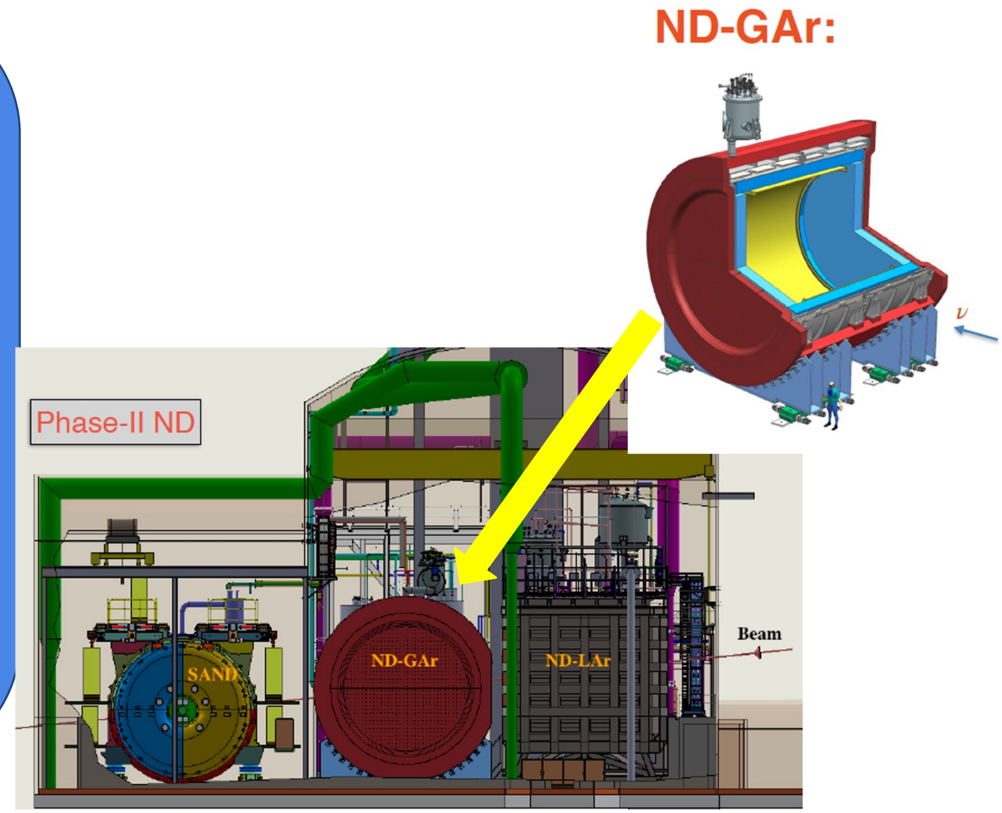
DUNE Phase II – FD3

- FD3 will increase DUNE's exposure by 50%
- The baseline FD3 design is a vertical drift LArTPC similar to one of the DUNE Phase I detectors currently under construction; only modest upgrades are envisioned
- Scientific assessment: ***"absolutely central"***
- Technical readiness: ***"ready to initiate construction"***
- R&D on improved photon detection and charge readout planes is well advanced and expected to be ready on the timescale needed. An important upcoming step is to secure formal commitments from the international partners.



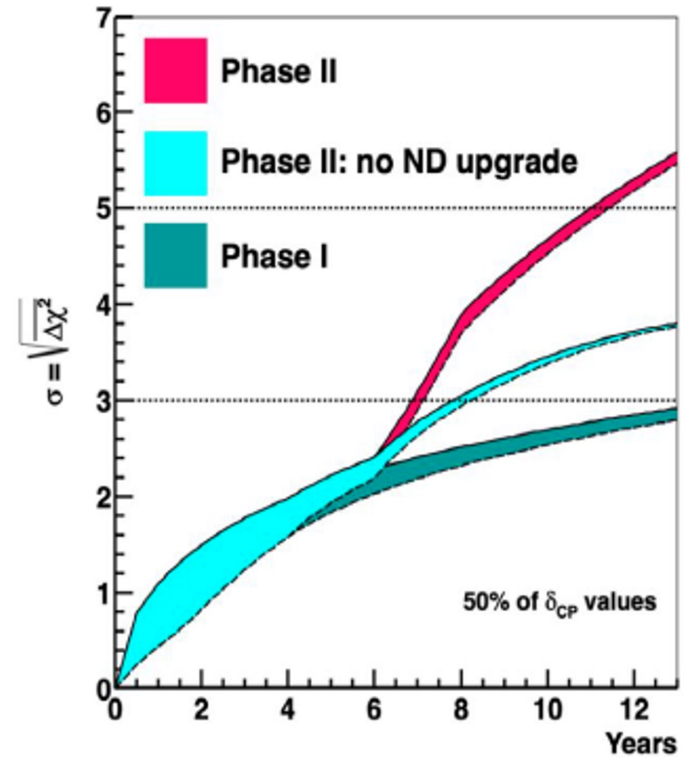
DUNE Phase II – More Capable Near Detector (MCND)

- MCND replaces the muon catcher in the Phase I near detector with a pressurized gaseous argon detector inside a magnetic field, complemented by calorimetry and muon detector systems.
- MCND will reduce the systematic uncertainties that will eventually limit the CP violation measurements, through detailed observations of argon-neutrino interactions.
- It also provides new opportunities for the observation of hypothetical particles such as neutral heavy leptons and axions



DUNE Phase II – MCND

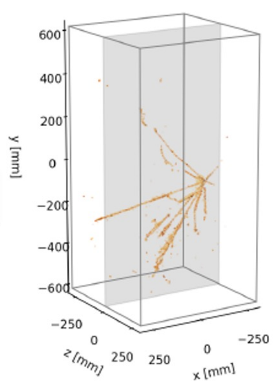
- Scientific assessment: ***"absolutely central"***
- P5: *"With higher statistics, control of systematic uncertainties (such as those arising from the interaction of neutrinos and nuclei) becomes increasingly crucial. A more capable near detector (MCND), a gas target combined with a magnetic field and electromagnetic calorimeter, is indispensable for this purpose."*
- Technical readiness: "***significant scientific/engineering challenges to resolve before initiating construction"***
- While the scientific requirements are clear for achieving the necessary reductions in systematic uncertainties, significant R&D is still needed to fully define the technical specifications and complete the design development



DUNE FD4

- This fourth “module of opportunity” could incorporate new detector capabilities to extend the DUNE physics program. Multiple technologies are under consideration, including LArTPC.
- The increased detector volume has a small effect on the primary DUNE neutrino oscillation physics program, assuming the ACE-MIRT and FD3 upgrades proceed as planned, but the detector improvements aim to extend the detector sensitivity to much lower energy (MeV) scales. Providing sensitivity to interactions at that energy scale would open new opportunities for neutrino astrophysics and BSM searches.

LArPix



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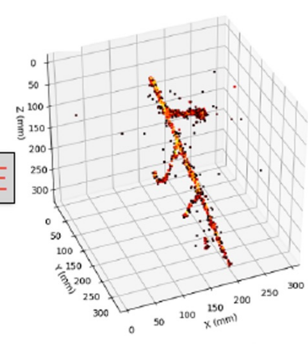

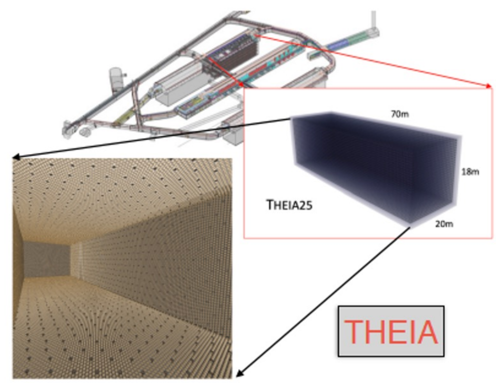

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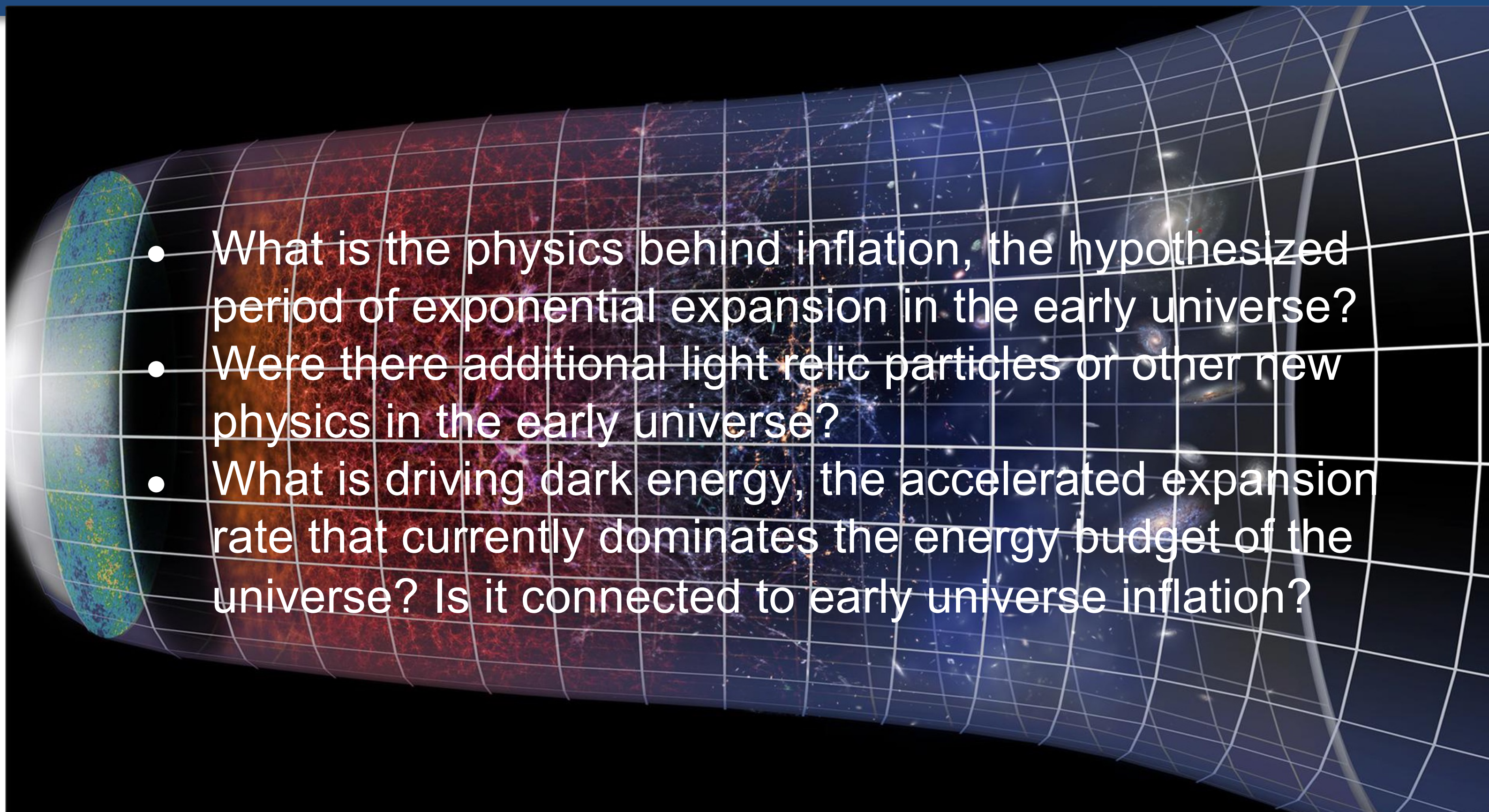
Facilities Assessments – DUNE FD4

- Scientific assessment: "***don't know enough yet."***
  - The scientific impact will depend on 1) the level of CP violation, which should be better understood in a few years, and 2) on the performance that can be achieved to extend the science reach into neutrino astrophysics and BSM physics with lower energy thresholds, which will be clarified with the R&D effort on new detector technologies.

- Technical readiness: "**significant scientific/engineering challenges to resolve before initiating construction**"
  - P5 recommended support for R&D on detector technologies towards FD4; several options are being studied.

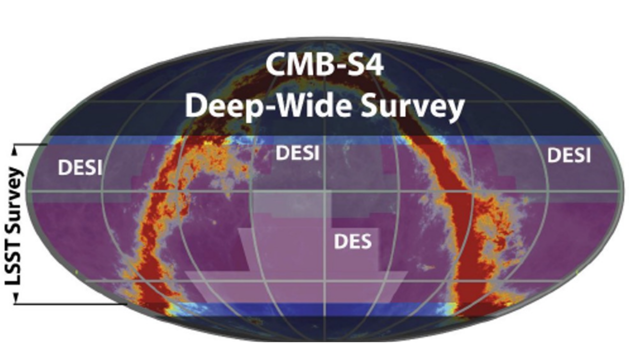
- Discussion

Understand What Drives Cosmic Evolution

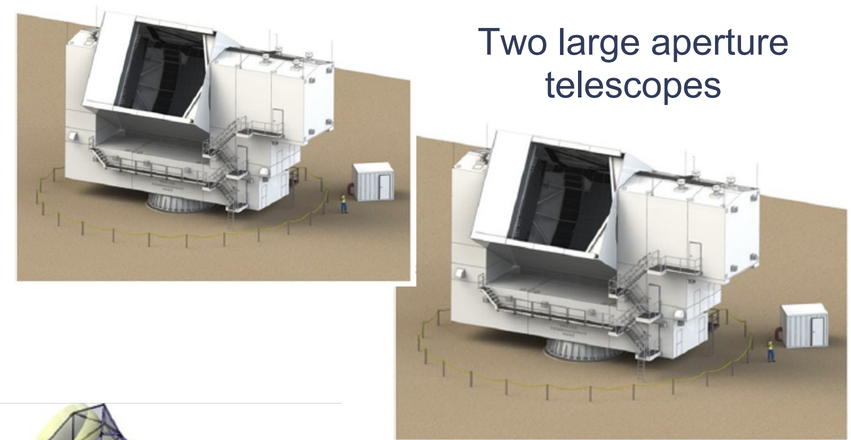


- What is the physics behind inflation, the hypothesized period of exponential expansion in the early universe?
- Were there additional light relic particles or other new physics in the early universe?
- What is driving dark energy, the accelerated expansion rate that currently dominates the energy budget of the universe? Is it connected to early universe inflation?

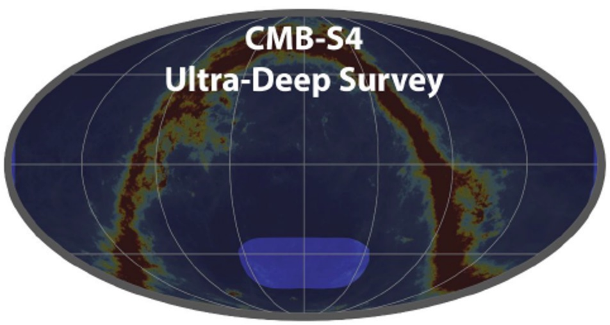
CMB-S4: Deep and Wide Surveys



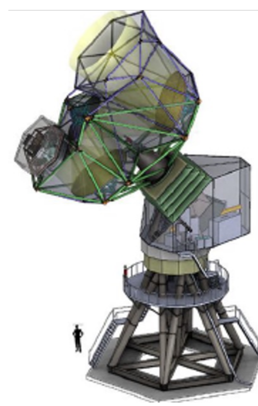
Large area survey conducted from the mid-latitude site, motivated by light relics, matter mapping, and time domain science

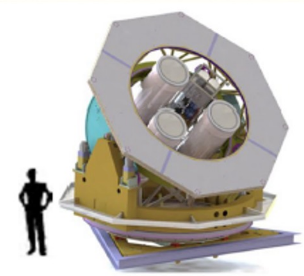


Two large aperture telescopes



Small area survey primarily targeting inflationary gravitational waves, enabled by the sky coverage, low horizon blockage, and ultra stable atmosphere of the South Pole site.





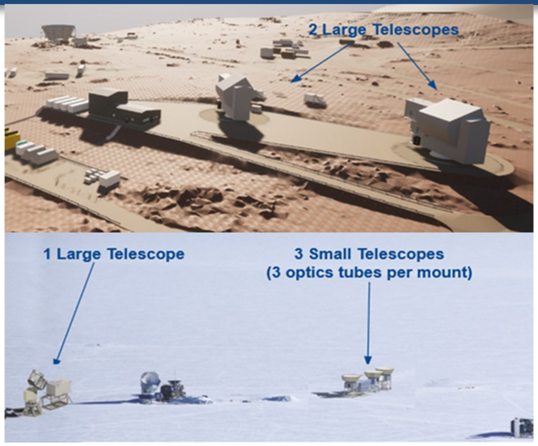
One large aperture and 9 small apertures telescopes

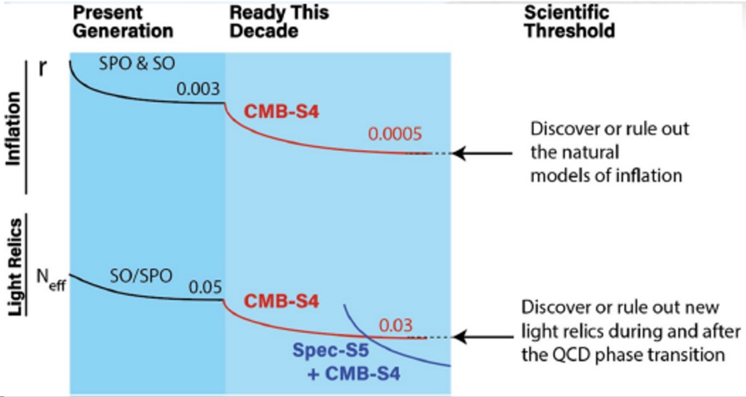
Facilities Assessment – CMB-S4

- Scientific goals: Detect CMB B mode polarization and carry out a wide survey in several bands, enabling many fundamental measurements of relic particles, neutrino mass, dark energy, dark matter, mm wave transients, and multi-messenger astrophysics

- Scientific assessment: ***absolutely central***
  - Understand what drives cosmic evolution: inflation
  - Highest priority new construction project in 2023 P5 report

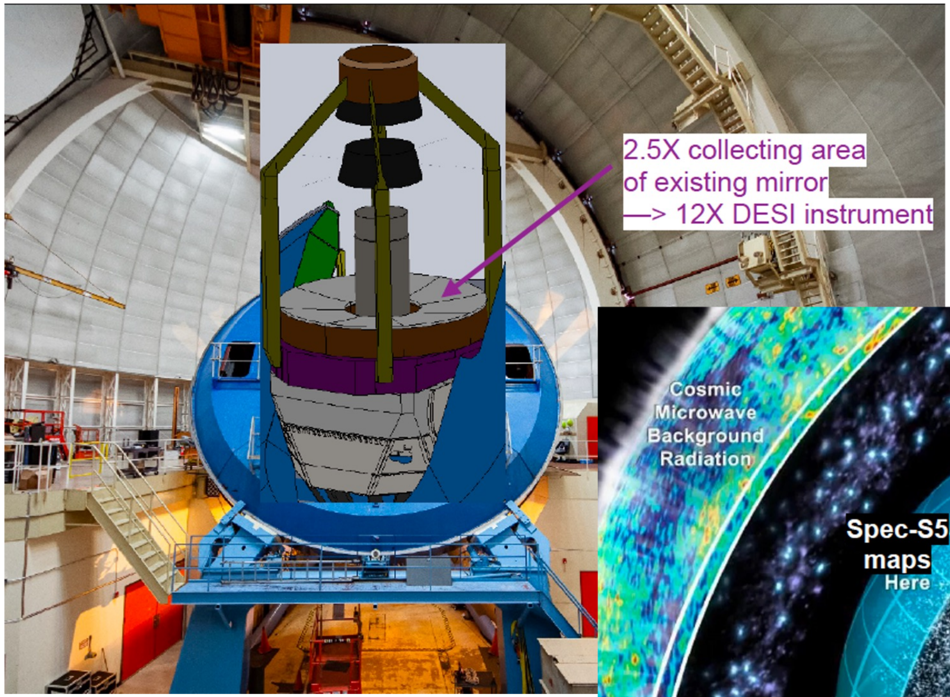
- Technical readiness: : ***ready to initiate construction***
  - CD-0 issued in 2019; technology is established; project team in place; detailed cost, schedule developed and reviewed

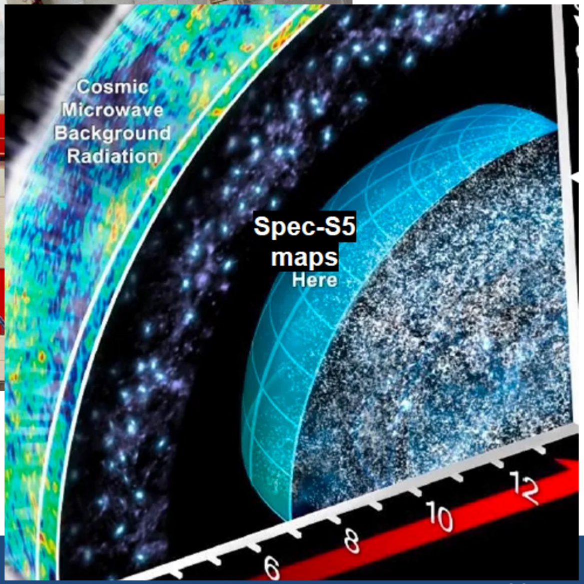




Spec-S5: Deep Spectroscopic Redshift Survey

- Spec-S5 will deploy robotic fiber-fed spectrographs on two existing telescopes
- New 6 m mirrors and 3x fiber density of DESI enable a deeper survey extending to z>2
- Significant progress on instrument design and R&D in past year
- Probes inflationary physics, dark energy and dark matter
  - Complementary to CMB-S4 and Rubin/LSST surveys





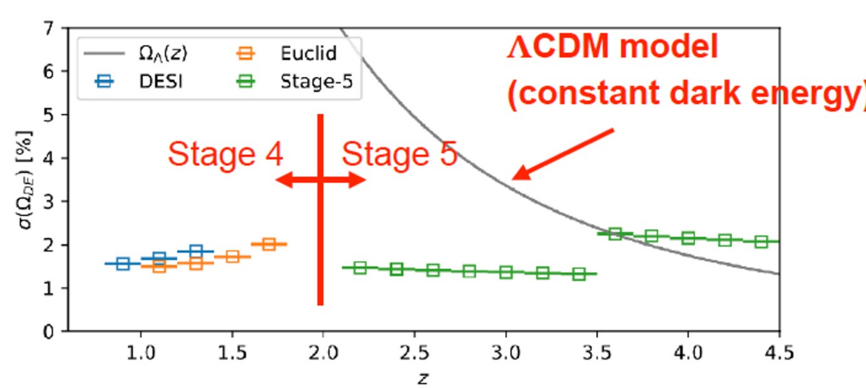
Facilities Assessment – SpecS5

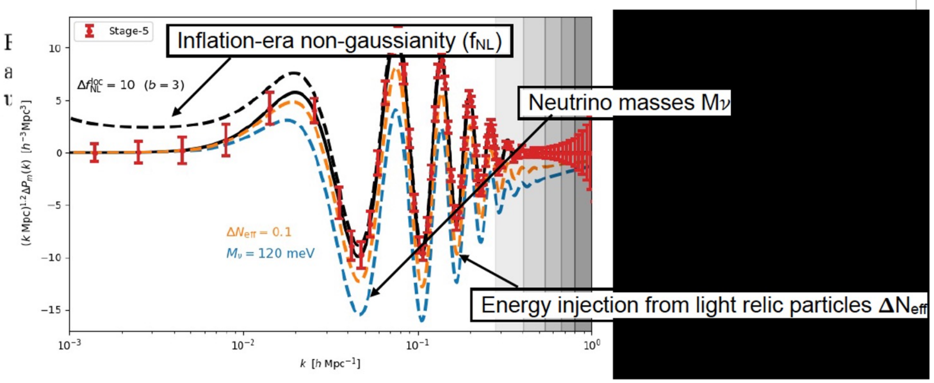
- Scientific assessment: ***"absolutely central"***

  The 2023 P5 report said Spec-S5 will "advance our understanding and reach key theoretical benchmarks in several areas" relevant to our understanding of the universe. Spec-S5 would maintain U.S. and DOE global leadership in the cosmic frontier through the 2030s.

- Technical readiness: ***"ready to initiate construction"***

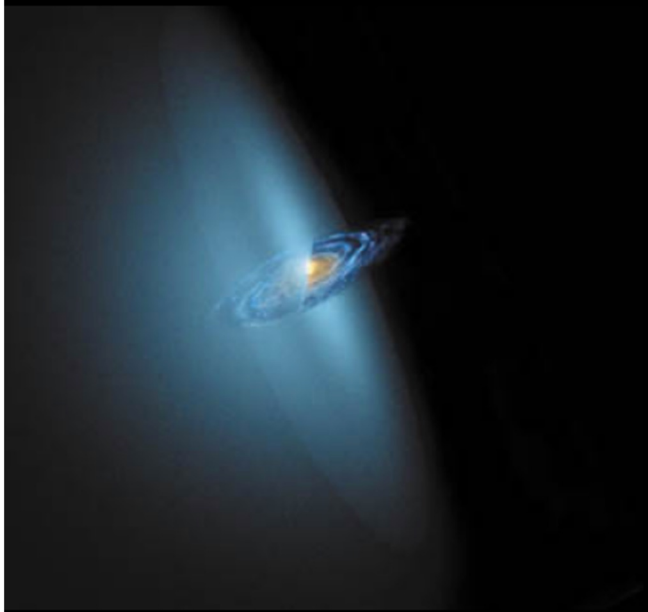
  Given the recent design and R&D progress we rate Spec-S5 as ready to initiate construction within the next decade, assuming success of the near-term R&D program, and once formal agreement is reached with NOIRlab and NSF for use of the Mayall and Blanco telescopes.



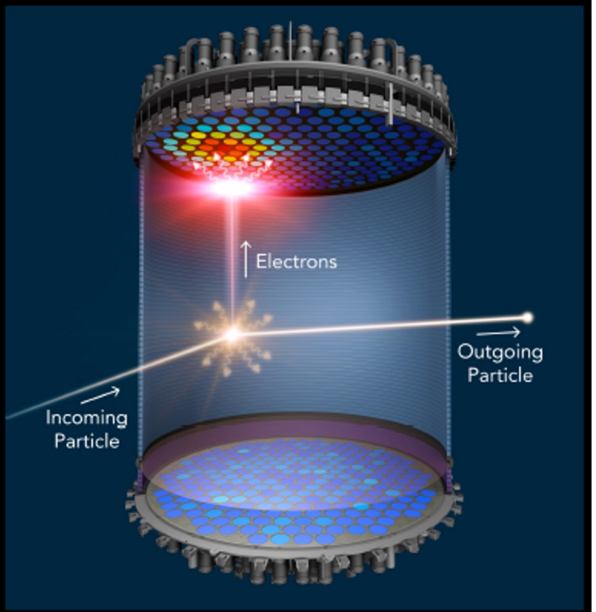


Determine the Nature of Dark Matter

- Dark Matter is not described by Standard Model of particle physics
- Revealing the nature of dark matter will dramatically change the landscape of our current understanding of the Universe.
- WIMP dark matter searches can be extended beyond current efforts to reach the "neutrino fog"



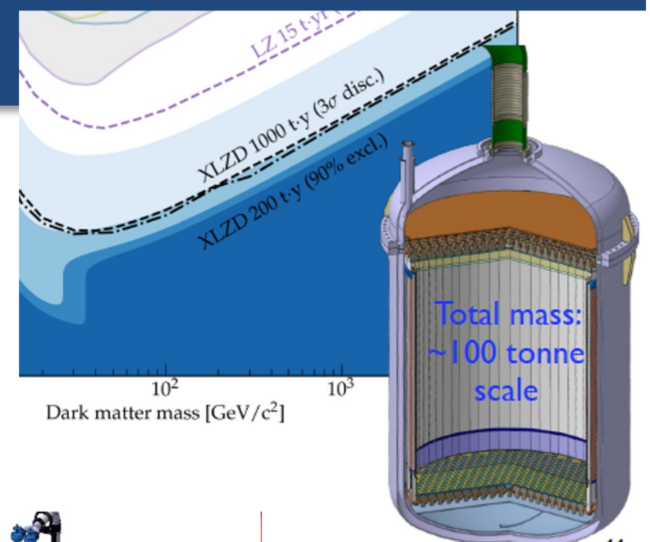
Dark Matter Halo comprised of WIMPs

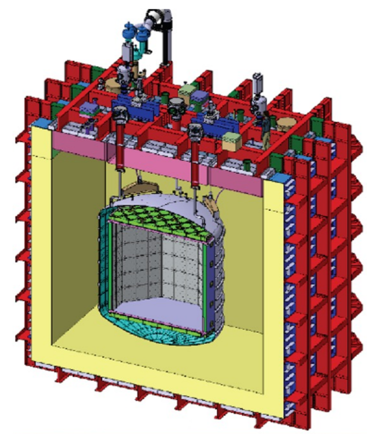


Single-scatter nuclear recoils ~ keV energy scale

G3 Dark Matter

- G3 DM experiments are 100 ton scale noble liquid detector located deep underground, approx. 10x current G2 experiments
  - XLZD experiment using xenon brings together LZ and XENONnT collaborations
  - ARGO experiment using underground-sourced argon, brings together DEAP, Darkside-20k, mini-CLEAN etc.
  - Several underground laboratories are possible sites, including SURF, SNOLAB, LNGS, Boulby, Kamioka
  - Competition: PANDAX-xT - proposed 43 ton xenon experiment in China, building on existing PandaX-4T
- Scientific goals: the ultimate search for WIMP dark matter, going down to the “neutrino fog” – irreducible background from cosmic neutrinos; variety of other measurement including solar neutrinos, 0v2b search, SNe detection etc.

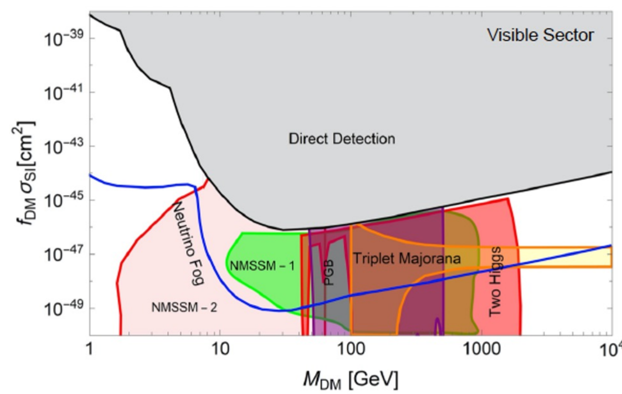




Facilities Assessments – G3 Dark Matter

- Scientific assessment: "***absolutely central***"
  - Understanding the nature of dark matter is one of the central questions for particle physics
  - P5 recommends the "*ultimate Generation 3 (G3) dark matter direct detection experiment reaching the neutrino fog, in coordination with international partners and preferably sited in the US.*"
- Technical readiness: ***"significant scientific/engineering challenges"***
  - Xenon detectors are operating at the 10 ton scale (LZ, XENONnT), while a 20 ton argon detector is being built (Darkside 20K)
  - R&D to scale up to 100 tons is needed to improve radon levels and high voltage performance over what has been achieved by the G2 experiments.
  - Procurement of large quantities of noble liquids will be challenging for both argon and xenon based experiments

Rich parameter space of well-motivated BSM particle dark matter candidates



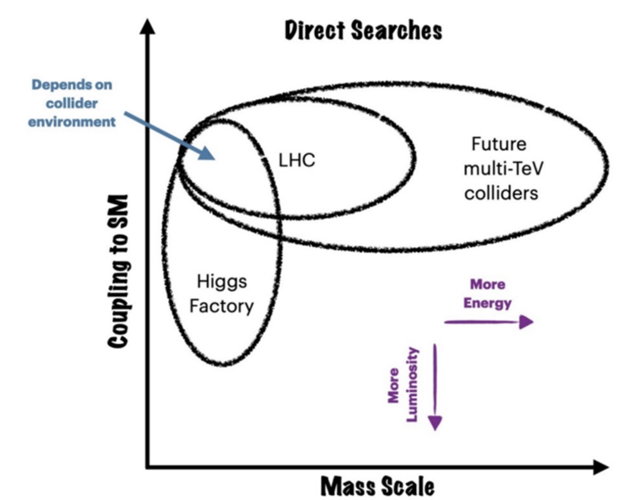
Highest risks that require early R&D	
Establish Electric Fields	Control Detector Backgrounds
Key requirements: • ⬆ grid size • ⬆ cathode HV	**Key requirements:** • ⬇ intrinsic background from radon • ⬇ accidentals (⬆surface & PMT count)
R&D and mitigations: • Alternative grid mechanics • HV component testing	**Potential R&D and mitigations:** • High-throughput in-line radon removal • Radon barrier around TPC active region

Credit: D. Akerib

- Discussion

Future Accelerators

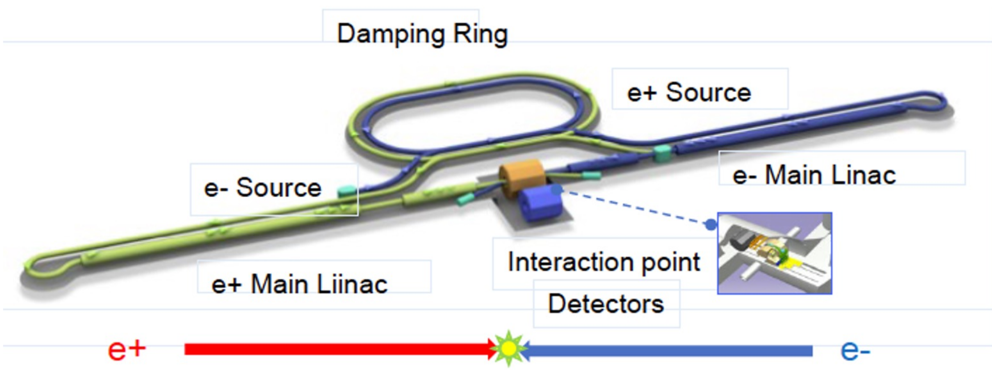
- Future Accelerators address multiple scientific priorities and are vital to a broad range of scientific priorities in particle physics, including
  - **Reveal the Secrets of the Higgs Boson**
  - **Search for Direct Evidence of New Particles**
  - **Pursue Quantum Imprints of New Phenomena**
- Future Accelerators/Test Facilities and Demonstrators considered by the subpanel:
  - **Off-shore Higgs Factory**
  - **Advanced Accelerator Test Facilities**
  - **ACE - BR: Fermilab Booster Replacement**
  - **10 TeV pCM Collider**

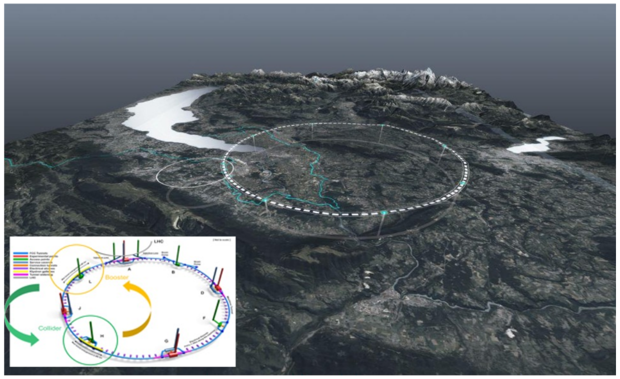


- While some of these are beyond the 10 year horizon, they all require near term investments in R&D, ramping up to significant levels to support demonstrators and/or test facilities

Off-shore Higgs Factory

- A Higgs factory is an e^- - e^+ collider facility that can cover the center-of-momentum energy range of 90 GeV to 350 GeV.
- A Higgs factory will produce large numbers of Higgs bosons with small backgrounds to enable more detailed studies of the Higgs boson properties and interactions. It will be a sensitive probe of the quantum imprints of new phenomena and enable precision electroweak studies by producing large numbers of ZZ and WW events, and top quark pairs.
- P5 recommends US support for the development of the Future Circular Collider (FCC-ee) at CERN or the International Linear Collider (ILC) in Japan; decision to be taken later this decade





Facilities Assessments – Off-shore Higgs Factory

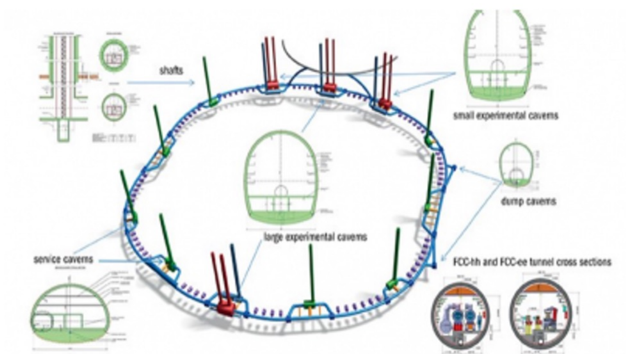
- Scientific assessment: ***"absolutely central"***. Community input through the Snowmass process and the P5 planning process has identified the off-shore Higgs factory as an essential element of the U.S. particle physics program. P5 ranked it third for new projects after CMB-S4 and LBNF/DUNE Phase II:
  - "The US should actively engage in feasibility and design studies. Once a specific project is deemed feasible and well-defined the US should aim for a contribution at funding levels commensurate to that of the US involvement in the LHC and HL-LHC"
- Technical readiness: ***"ready to initiate construction."*** The designs of the ILC and FCC-ee are based on mature technologies.
  - Ongoing accelerator R&D aims to reduce cost, complexity, improve sustainability and reliability, but construction could start very soon
  - Detector R&D is still important to meet performance requirements.
- The scope of either project is very large, and complex international agreements are needed to provide the design personnel, technical resources and financial support to initiate construction.

Beyond the Higgs Factory

- Multiple Options - proton collider, muon collider, linear wakefield lepton collider
- All require significant development
- Time-scale is at least 20 years away, but R&D is needed now

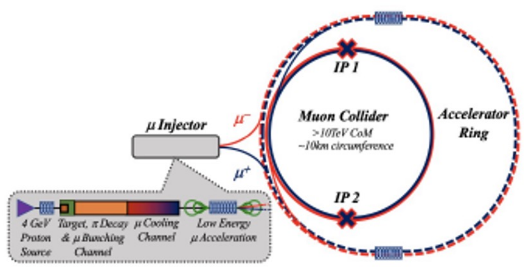
Proton collider

Key need: high field magnets



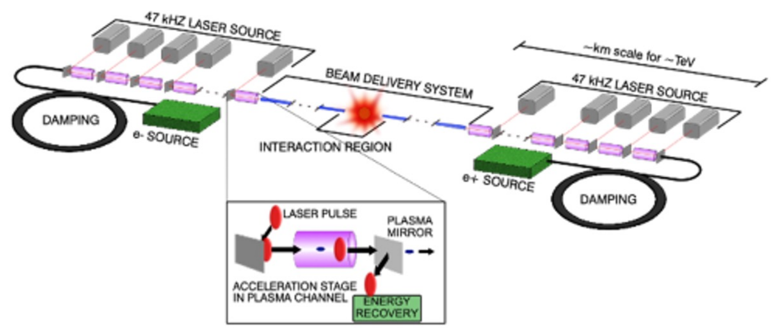
Muon collider

Needs: targets, cooling…



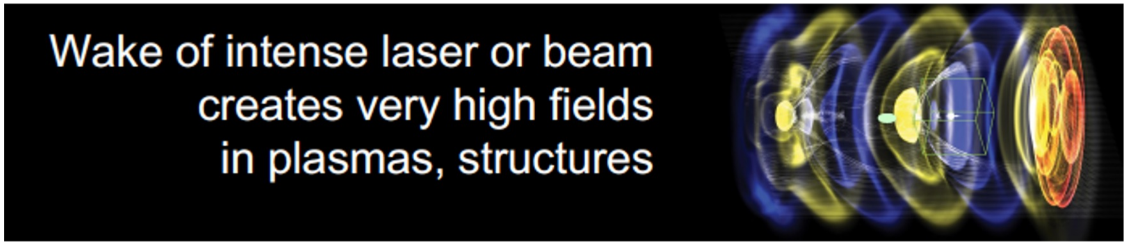
Linear wakefield lepton collider

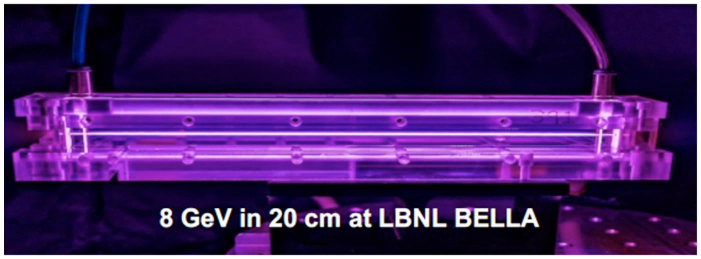
Test facility needs:
kBELLA (avg. power, efficiency, precision)
FACET-II (positrons), AWA (transformer ratio)



Advanced Accelerator Test Facilities

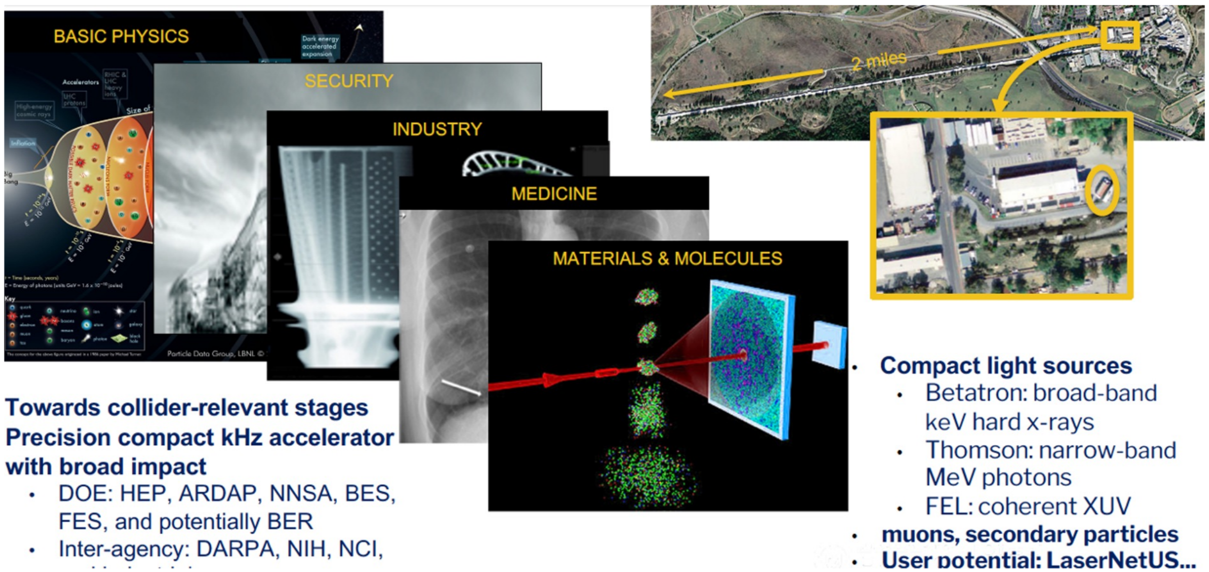
- P5 recommended an ambitious future 10 TeV pCM collider to search for direct evidence and quantum imprints of new physics at unprecedented energies.
- A plasma wakefield accelerator is on one of 3 possibilities; it offers a compact, potentially cost effective solution
- R&D on plasma wakefield acceleration is carried out at FACET-II at SLAC, BELLA at LBNL and AWA at ANL
- All 3 facilities have upgrade plans, but only kBELLA exceeds $100M
- We considered kBELLA as an “exemplar” of the AATF program; the options will be decided by the accelerator panel recommended by P5 later in the decade





AATF R&D Synergies

- The cost-effective kW-kHz ultrafast laser technology that kBELLA aims to develop can be of interest to many applications such as security, medicine, industry etc. and supports US leadership in lasers
- The targeted beam parameters of kBELLA, i.e. a high brightness GeV electron beam with 100 pC bunch intensity and AI/ML controls is also highly desired for a next generation compact X-FEL



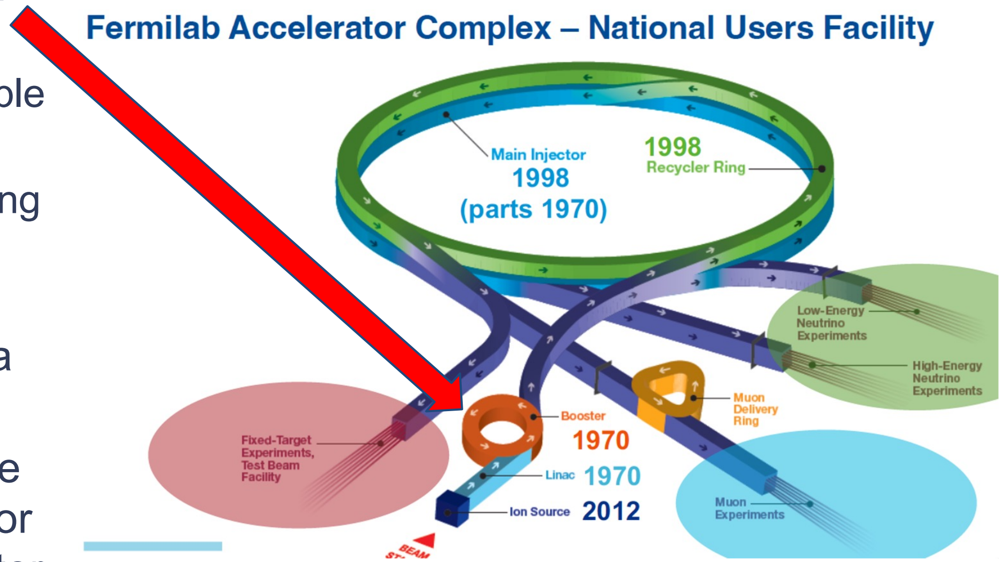
Credit: C. Geddes

Facilities Assessments – AATF (kBELLA)

- The kBELLA project aims to extend the current capability of BELLA with a kW-kHz class ultrafast laser and develop technologies in controls & diagnostics that will be critical for a 10 TeV pCM collider.
- Scientific assessment: ***"absolutely central"*** for the Advanced Acceleration Concept Thrust of the HEP Generic Accelerator Research and Development program (GARD).
  - Advancing accelerator technologies beyond the current state of the art will be important for several of the P5 scientific priorities that require going to higher energies to search for new particles, pursue quantum imprints of new physics and reveal the secrets of the Higgs boson.
  - Many applications beyond HEP are also likely
- Technical readiness: ***"needs significant development"***
  - The recent R&D on coherent combination of multiple fiber lasers has demonstrated it is feasible to achieve a high-power, high repetition-rate laser. However, to meet the stringent requirements of kBELLA — specifically, a 3 J, 30 fs laser at kilohertz repetition rates — further progress is required.

Accelerator Complex Evolution -Booster Replacement

- ACE-BR will construct an entirely new accelerator to replace the 50-year old Booster.
    - The project is in its very early stages with multiple configuration options under consideration.
    - Extend SRF Linac, or construct new rapid-cycling synchrotron; multiple options within each
- Some configuration options are attractive for the U.S. muon collider effort, as they could serve as a front-end proton driver for this collider.
- ACE-BR will enhance the scientific reach, improve the long-term reliability, and serve as a platform for future HEP initiatives such as a muon demonstrator or a muon collider facility. It could also provide additional opportunities for experiments in the 8 GeV range (depending on the implementation).



Credit: A. Valishev

ACE-BR R&D Synergies

- High-power superconducting RF systems and fast cycling magnets
  - Connections with Fusion Energy Science and Nuclear Science
- Improved RF power systems, higher accelerating gradients for proton linac, and H-ion stripping technology
  - relevant to Nuclear Science and Basic Energy Sciences
- High-intensity beam dynamics with space charge
  - a common theme between HEP, NP, BES; common to all high-intensity machines
- Need for high-power targets cuts across NP, FES and beyond DOE

Facilities Assessments – ACE-BR

- Scientific assessment: The scientific impact will depend on the implementation options that are selected; therefore, it is rated as ***"don't know enough yet"***
  - The project will at a minimum provide reliability improvements in support of DUNE, but could also support new science utilizing multi-MW proton beams in the 8 GeV range and could even serve as the injector for a muon collider demonstration facility. The HEP far future goals are not well enough defined at this point to accurately assess the scientific impact.
- Technical readiness: ***"mission and scientific goals not yet well defined"***
  - The project is in its early conceptual design stages where major configuration decisions are still pending. All design configurations under consideration require substantial R&D.

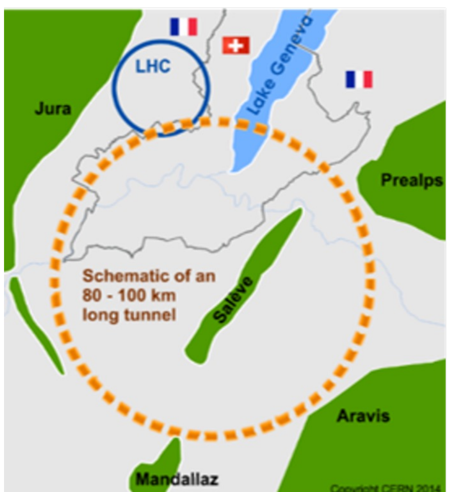
Facilities Assessments – 10 TeV pCM Collider

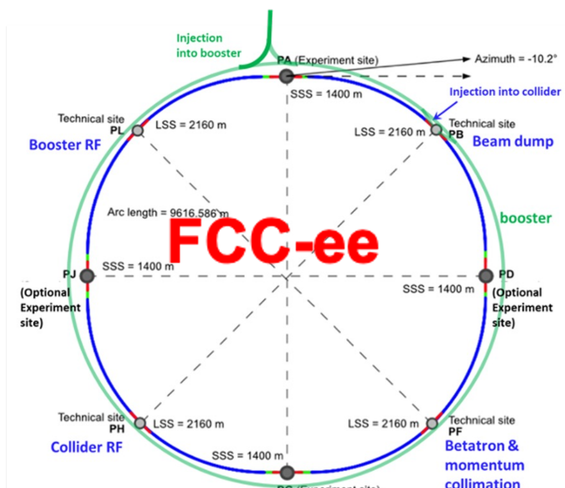
- Beyond the Higgs factory, the physics landscape that has shaped the P5 science drivers points to still higher energy scales where new physics and new higher mass particles can be manifest. To achieve a significant increase in discovery potential beyond the HL-LHC and the Higgs factories, colliders with energies of 10 TeV or more per parton (point-like constituent) center-of-mass (pCM) are needed.

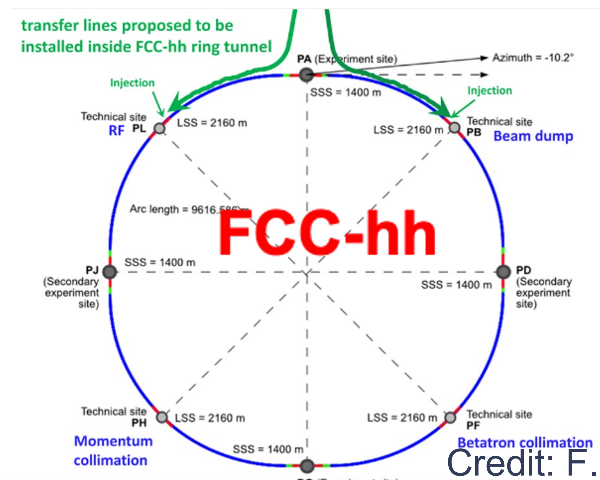
- Three approaches are under development that have the potential to enable physics exploration at this scale. They are a proton-proton collider based on very high field magnets, a muon collider, or possibly an electron-positron linear collider based on advanced wakefield technology. All three of these technologies have different appealing features and must be developed further before a decision to begin construction can be made. A comprehensive accelerator R&D program in high field magnets, RF technologies and advanced accelerator test facilities can explore technology and concepts that could significantly reduce cost and risks associated with a 10 TeV pCM collider.

FCC - hh

- FCC - hh would be installed in the FCC - ee tunnel. Requires ~4500 new dipole magnets with 14 - 20 T field. HTS magnet R&D is estimated to take years.
- A similar concept is being explored in China with the CEPC







Credit: F. Zimmerman

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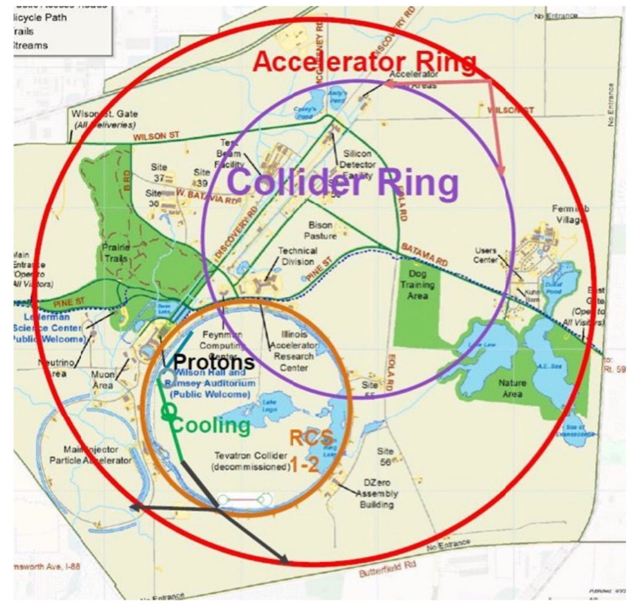
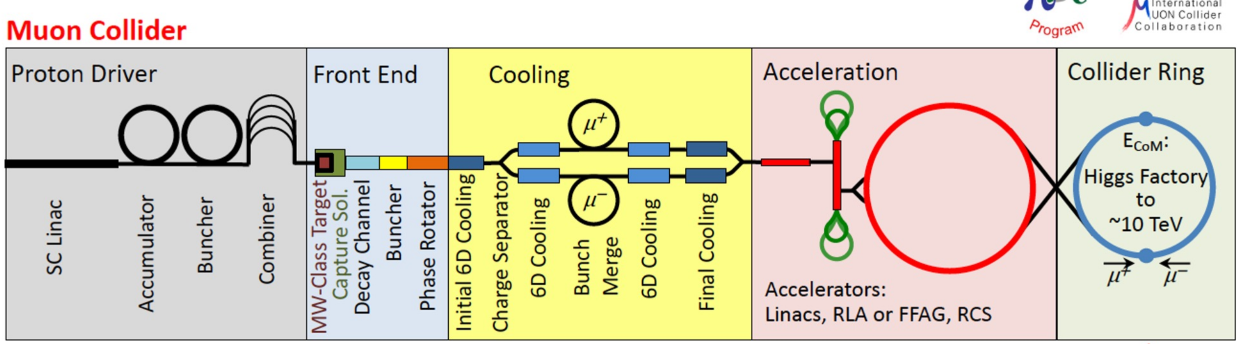
Muon Collider

- A muon collider is more compact and could potentially fit on the Fermilab site
- It requires substantial R&D on high power targetry, cooling, and magnets



Proton-driven muon collider concept



Credit: A. Valishev

Facilities Assessments – 10 TeV pCM Collider

- The scientific goals of a 10 TeV pCM collider encompass a comprehensive physics portfolio that includes ultimate measurements in the Higgs sector and also a broad search program for new phenomena and particles, with a high potential for producing additional new particles or Higgs bosons if they exist. It can also probe hidden sector physics. A future 10 TeV parton center-of-mass collider would address multiple P5 scientific priorities and the scientific impact is ***"absolutely central".***

Facilities Assessments – 10 TeV pCM Collider

- We rate the technical readiness of the muon collider as ***“mission and technical requirements not yet fully defined.”*** The basic concepts needed to realize a muon collider have been known for decades. However, each of the steps to create muon-muon collisions present considerable technical challenges, many of which have never been confronted before. The P5 plan outlines and recommends an aggressive R&D program to determine the parameters for a muon collider demonstrator test facility by the end of this decade.

- We rate the technical readiness of the FCC-hh as ***“mission and technical requirements not yet fully defined”***. The FCC-hh concept is at a very early stage with key parameters still to be defined. In particular, the high-field, superconducting dipole magnets are expected to require decades of R&D and performance will depend on what can be achieved in this technology.

- Discussion

Acknowledgements

- Many thanks to P5 for identifying the key facilities needed to stay at the forefront of scientific discovery in particle physics
- Many thanks to the subpanel members - it was a very engaged, productive group
- Many thanks to all the projects for responding to our Request for Information promptly, and for very helpful presentations and useful Q&A sessions with the subpanel
- Many thanks to Fermilab and their staff for hosting our in-person meeting and showing great hospitality to all of the participants

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Natalie Roe (Chair)	LBNL
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Sam Zeller	FNAL

Conclusion

- The field of high energy physics has developed an exciting and forward looking plan with broad community support, described in the 2023 P5 Report, Exploring the Quantum Universe: Pathways to Innovation and Discovery in Particle Physics.
- The Facilities Subpanel endorses the P5 science priorities and has evaluated the scientific impact and technical readiness of the facilities
- We have included several projects beyond the 10 year timeline, due to the need for long-term planning and significant R&D for very large and ambitious new facilities
- HEP has strong connections with other offices within DOE SC of mutual benefit, in addition to strong connections with NSF and with the global particle physics community