Building for Discovery

Strategic Plan for U.S. Particle Physics in the Global Context

Mapa drogowa rozwoju fizyki cząstek w USA

A.F.Żarnecki

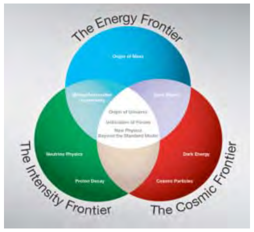
6 czerwca 2014

Report of the Particle Physics Project Prioritization Panel

May 2014

Introduction

The Ongoing Strategy Discussion in the U.S. - Background



U.S. particle physics is funded by two agencies:

- **Department of Energy (DOE) Office of High Energy Physics**
- **National Science Foundation (NSF) Physics Division**

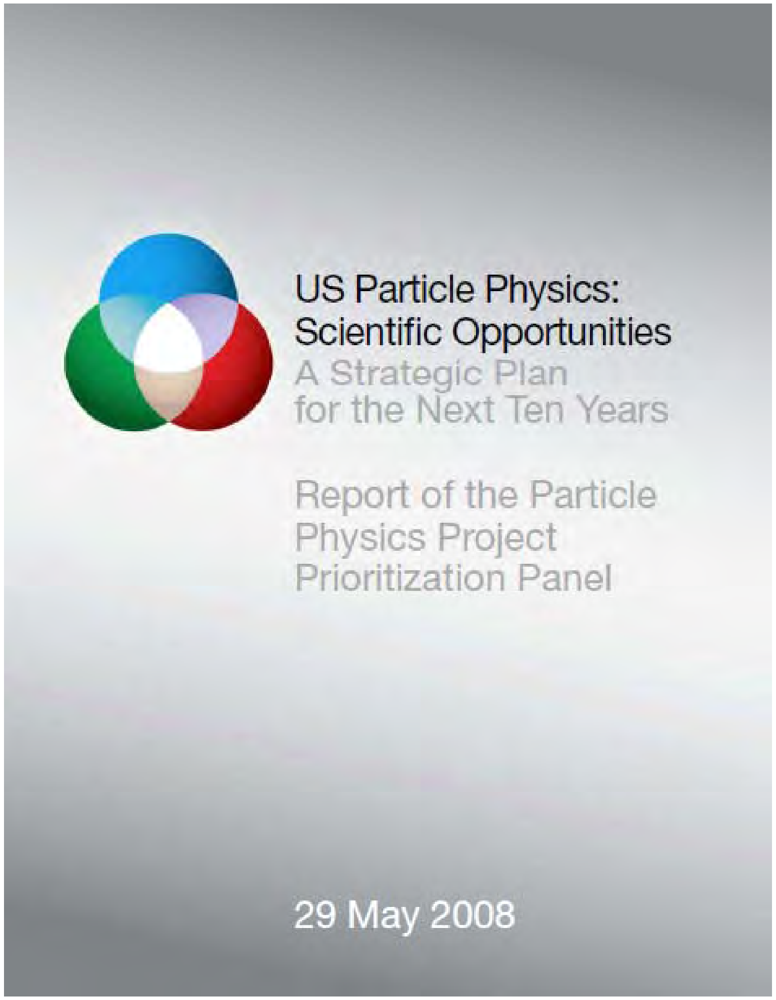
DOE & NSF advised by High Energy Physics Advisory Panel (HEPAP)

HEP program is guided by a "roadmap."

- **Roadmap is traditionally prepared by a HEPAP "subpanel"**
  - **Subpanel is dubbed "P5" - Particle Physics Project Prioritization Panel**
- **Present roadmap dates from 2008**
- **Now involved in new multi-step planning process, to chart new roadmap**

The Goal of the "Roadmap"

Address fundamental questions about the laws of nature & the cosmos



http://science.energy.gov/~/media/hep/pdf/files/pdfs/p5_report_06022008.pdf

The Quantum Universe

http://www.interactions.org/quantumuniverse/qu/index.html

ARE THERE UNDISCOVERED PRINCIPLES OF NATURE: NEW SYMMETRIES, NEW PHYSICAL LAWS?

HOW CAN WE SOLVE THE MYSTERY OF DARK ENERGY?

ARE THERE EXTRA DIMENSIONS OF SPACE?

DO ALL THE FORCES BECOME ONE?

WHY ARE THERE SO MANY KINDS OF PARTICLES?

WHAT IS DARK MATTER?
HOW CAN WE MAKE IT IN THE LABORATORY?

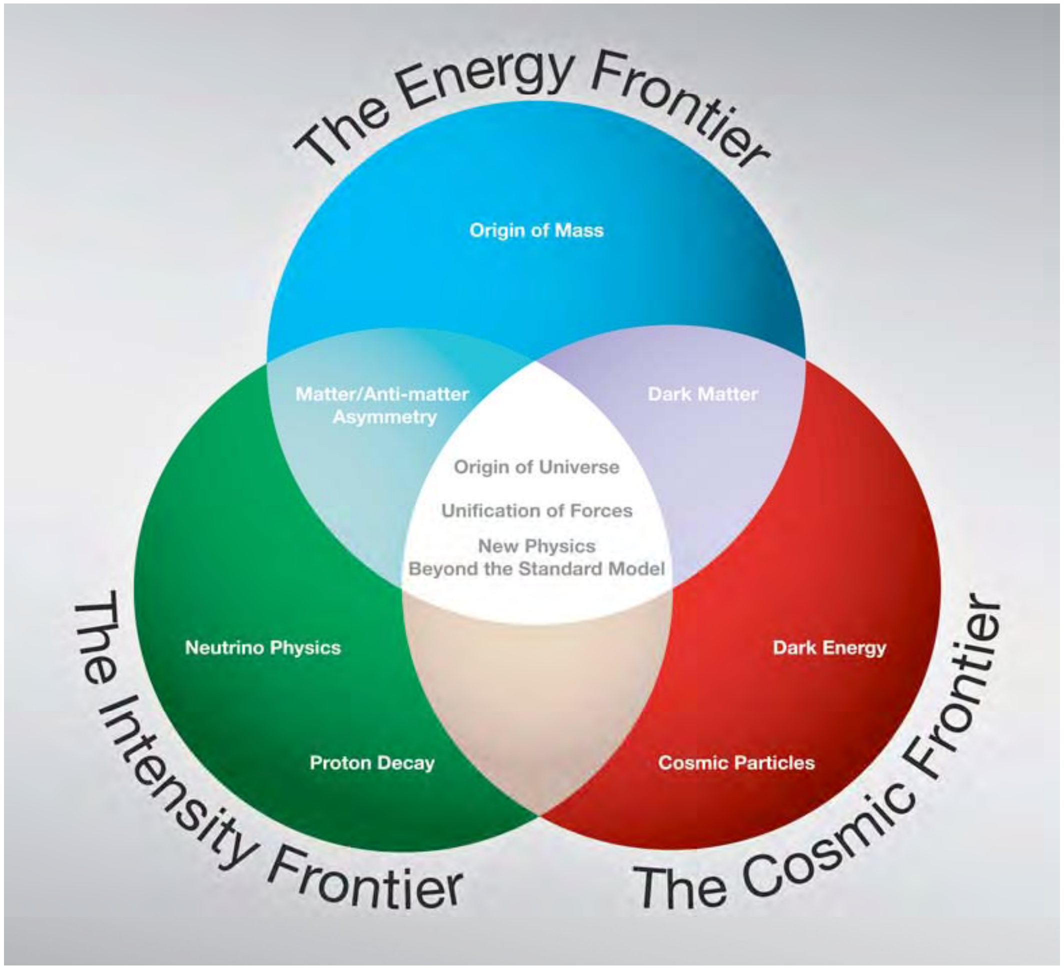
WHAT ARE NEUTRINOS TELLING US?

HOW DID THE UNIVERSE COME TO BE?

WHAT HAPPENED TO THE ANTIMATTER?

Vision of 2008 P5 :

To address these most important science questions through a balanced program on 3 frontiers



The three frontiers of research form an interlocking framework.

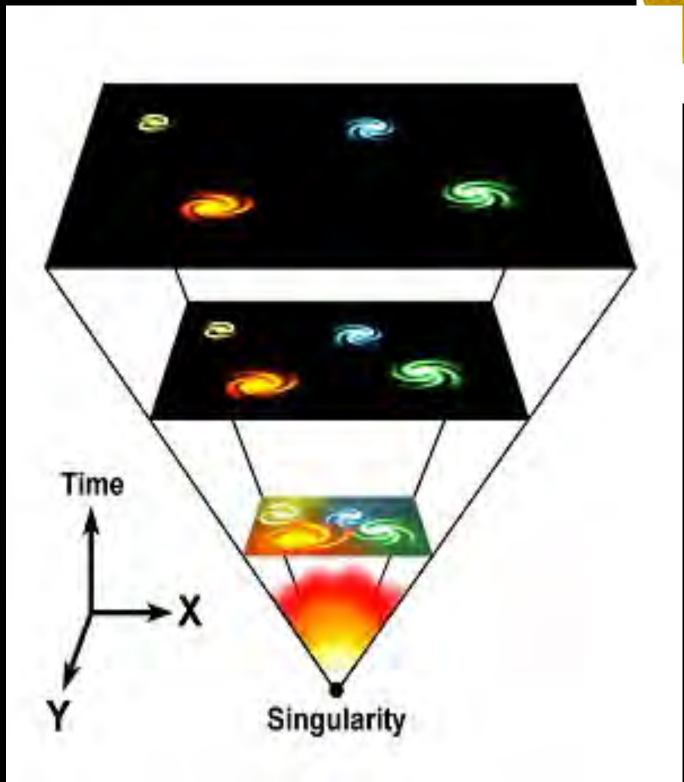
"The panel recommends a strong, integrated research program at the three frontiers of the field: the Energy Frontier, the Intensity Frontier and the Cosmic Frontier."

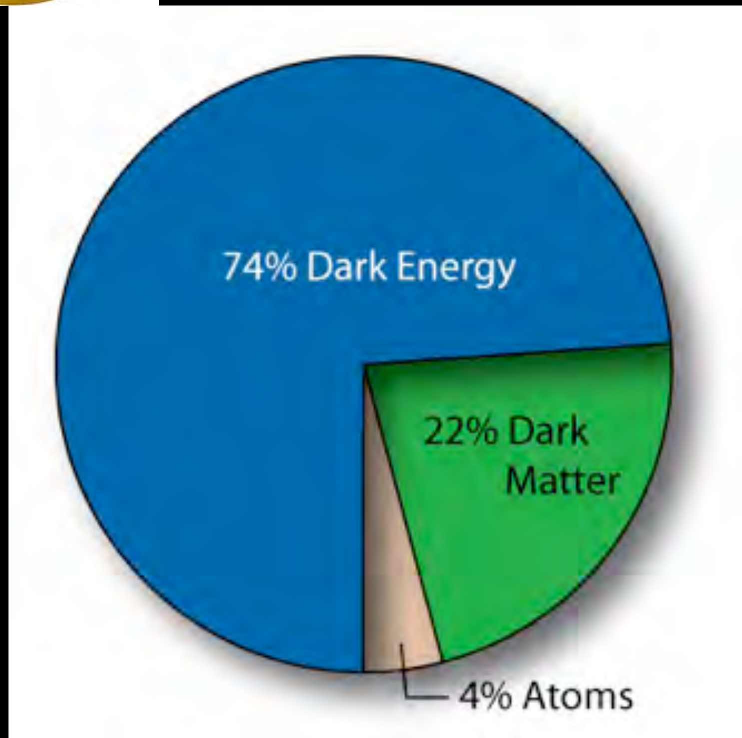
A program that:

- **continuously produces important results on each frontier**
- **harmonizes with the worldwide program**

We began the Snowmass process at a special time

- October 2011: Nobel Prize for the discovery of dark energy

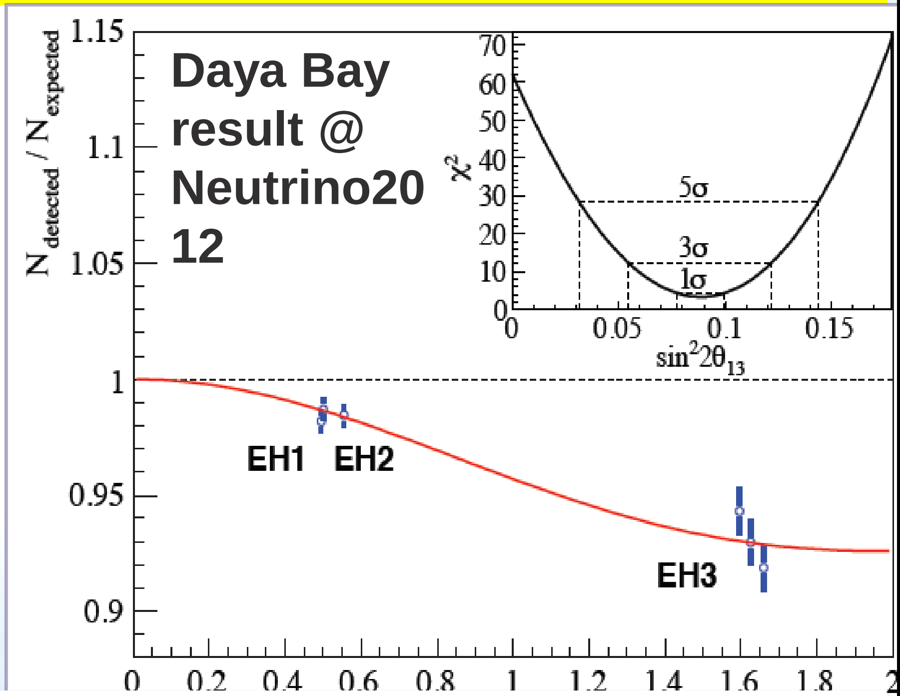




A special time….

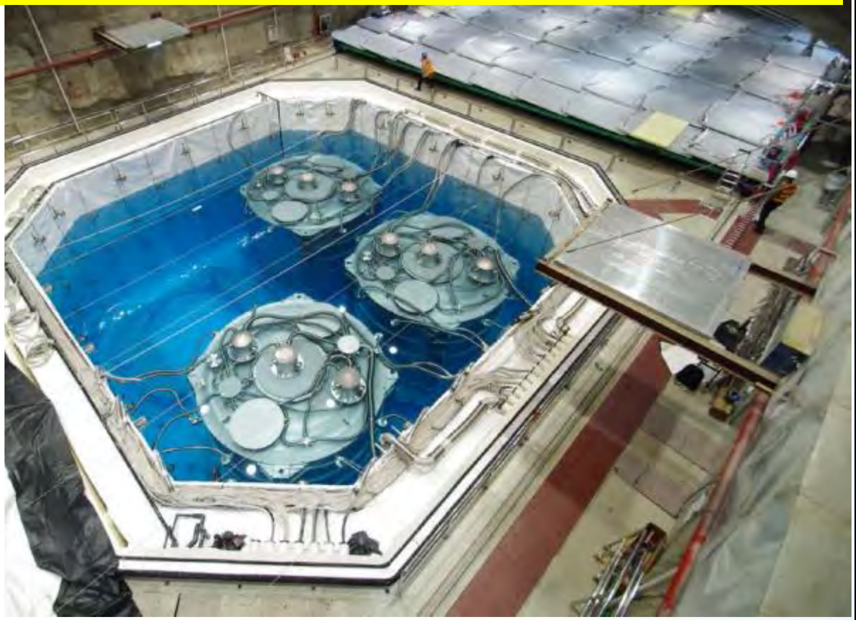
- March 2012: First results from Daya Bay:

Daya Bay - Large $Sin^2 2\theta_{13}$



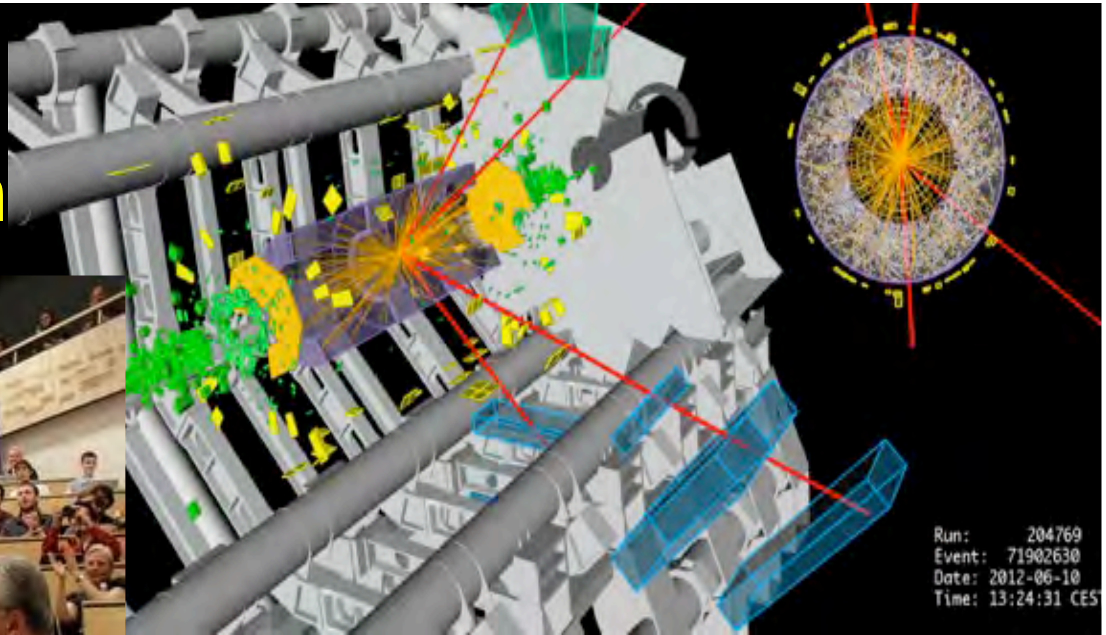
$\sin^2 2\theta_{13}$ = 0.089 ± 0.010 (stat) ± 0.005 (syst)

Daya Bay - Far Det.



2012.7.4

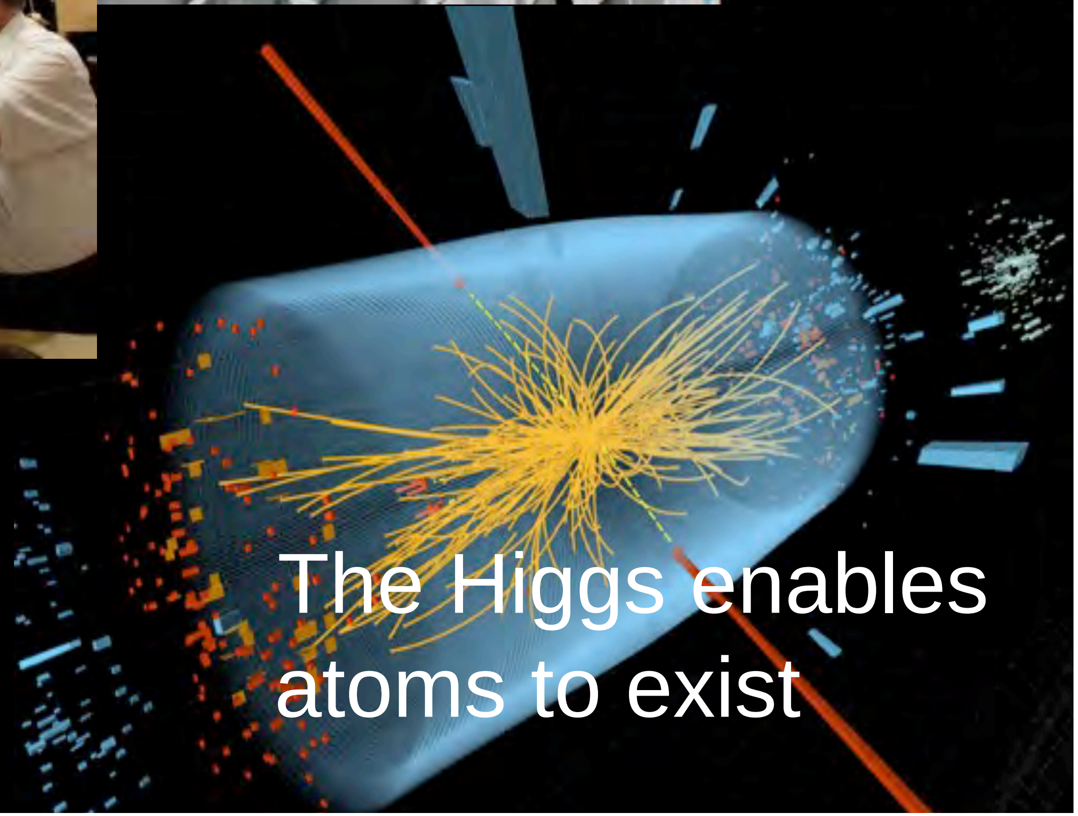
discovery of Higgs boson



theory：1964

design：1984

construction：1998



The Higgs enables atoms to exist

Japanese Report Feb. 12, 2012

The committee makes the following recommendations concerning large-scale projects, which comprise the core of future high energy physics research in Japan.

- **Should a new particle such as a Higgs boson with a mass below approximately 1 TeV be confirmed at LHC, Japan should take the leadership role in an early realization of an e^+e^- linear collider.** In particular, if the particle is light, experiments at low collision energy should be started at the earliest possible time. In parallel, continuous studies on new physics should be pursued for both LHC and the upgraded LHC version. Should the energy scale of new particles/physics be higher, accelerator R&D should be strengthened in order to realize the necessary collision energy.

- **Should the neutrino mixing angle θ_{13} be confirmed as large, Japan should aim to realize a large-scale neutrino detector through international cooperation, accompanied by the necessary reinforcement of accelerator intensity, so allowing studies on CP symmetry through neutrino oscillations.** This new large-scale neutrino detector should have sufficient sensitivity to allow the search for proton decays, which would be direct evidence of Grand Unified Theories.

It is expected that the Committee on Future Projects, which includes the High Energy Physics Committee members as its core, should be able to swiftly and flexibly update the strategies for these key, large-scale projects according to newly obtained knowledge from LHC and other sources.

The European Strategy for Particle Physics Update 2013

High-priority large-scale scientific activities

After careful analysis of many possible large-scale scientific activities requiring significant resources, sizeable collaborations and sustained commitment, the following four activities have been identified as carrying the highest priority.

c) The discovery of the Higgs boson is the start of a major programme of work to measure this particle's properties with the highest possible precision for testing the validity of the Standard Model and to search for further new physics at the energy frontier. The LHC is in a unique position to pursue this programme. *Europe's top priority should be the exploitation of the full potential of the LHC, including the high-luminosity upgrade of the machine and detectors with a view to collecting ten times more data than in the initial design, by around 2030. This upgrade programme will also provide further exciting opportunities for the study of flavour physics and the quark-gluon plasma.*

d) To stay at the forefront of particle physics, Europe needs to be in a position to propose an ambitious post-LHC accelerator project at CERN by the time of the next Strategy update, when physics results from the LHC running at 14 TeV will be available. *CERN should undertake design studies for accelerator projects in a global context, with emphasis on proton-proton and electron-positron high-energy frontier machines. These design studies should be coupled to a vigorous accelerator R&D programme, including high-field magnets and high-gradient accelerating structures, in collaboration with national institutes, laboratories and universities worldwide.*

CERN-Council-S/106

The European Strategy for Particle Physics Update 2013

High-priority large-scale scientific activities

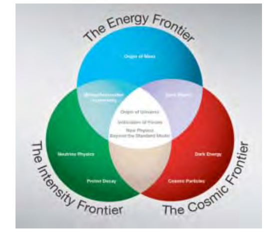
After careful analysis of many possible large-scale scientific activities requiring significant resources, sizeable collaborations and sustained commitment, the following four activities have been identified as carrying the highest priority.

e) There is a strong scientific case for an electron-positron collider, complementary to the LHC, that can study the properties of the Higgs boson and other particles with unprecedented precision and whose energy can be upgraded. The Technical Design Report of the International Linear Collider (ILC) has been completed, with large European participation. The initiative from the Japanese particle physics community to host the ILC in Japan is most welcome, and European groups are eager to participate. *Europe looks forward to a proposal from Japan to discuss a possible participation.*

f) Rapid progress in neutrino oscillation physics, with significant European involvement, has established a strong scientific case for a long-baseline neutrino programme exploring CP violation and the mass hierarchy in the neutrino sector. *CERN should develop a neutrino programme to pave the way for a substantial European role in future long-baseline experiments. Europe should explore the possibility of major participation in leading long-baseline neutrino projects in the US and Japan.*

Charge

Goal of the P5 Process



- **The P5 process takes the science vision of the community and turns it into a plan that is feasible and executable over a 10-20 year timescale.**

- **Particle Physics Project Prioritization Panel (P5)**
  - **HEPAP subpanel, appointed by HEPAP Chair**
  - **Reports to HEPAP, which reviews & approves report and submits to agencies**

- **Key elements envisioned for the P5 process:**
  - o **Build on the investment in the Snowmass process and outcomes**
  - o **4-5 public meetings, w/ "town hall" component for community input/discussion**
  - o **Revisit the questions we use to describe the field**
    - e.g., updating those of the *Quantum Universe*
  - o **Decide on the project priorities <u>within budget guidance from agencies</u>**
    - in detail for the next 10 years, in broad outline beyond that
  - o **Propose best way to describe the *value* of HEP research to society & other science**

P5 Charge

U.S. Department of Energy
and the
National Science Foundation

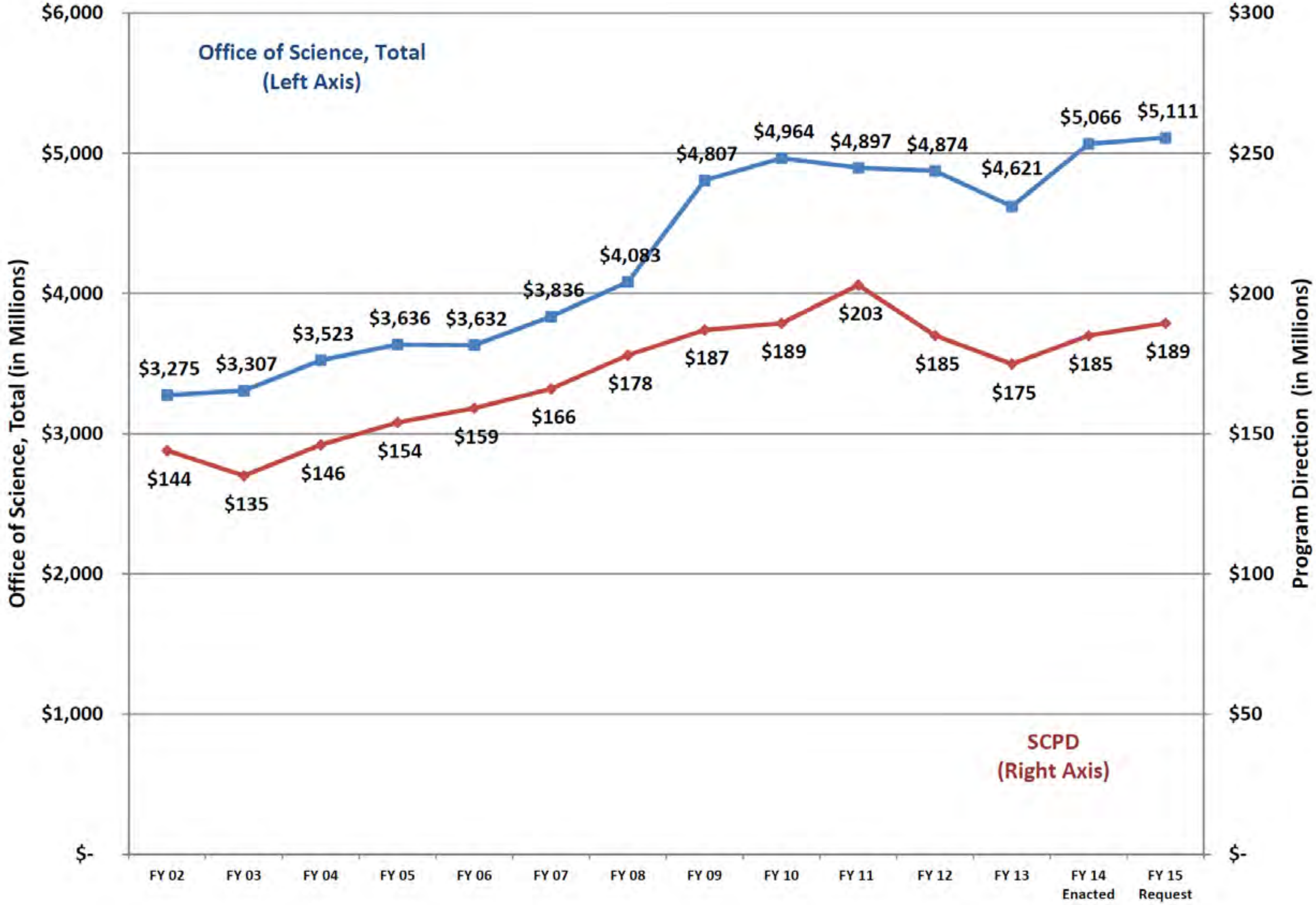
(...)

Your report should provide recommendations on the priorities for an optimized high energy physics program over the next ten years (FY 2014-2023), under the following three scenarios:

- **A** a constant level of funding for three years, followed by increases of 2.0% per year with respect to the appropriated FY 2013 budget for HEP; and
- **B** a constant level of funding for three years, followed by increases of 3.0% per year with respect to the FY 2014 President's Budget Request for HEP; and
- **C** unconstrained budget. For this scenario, please list, in priority order, specific activities, beyond those mentioned in the previous budget scenario, that are needed to mount a leadership program addressing the scientific opportunities identified by the research community.

You should consider these scenarios not as literal budget guidance but as an opportunity to identify priorities and make high-level recommendations. The programs you recommend should be (to some significant extent) implementable under reasonable assumptions. At the same time the budget scenarios should not drive the prioritization to the degree that projects are promoted solely for their ability to fit within an assumed profile.

Program Direction Funding History



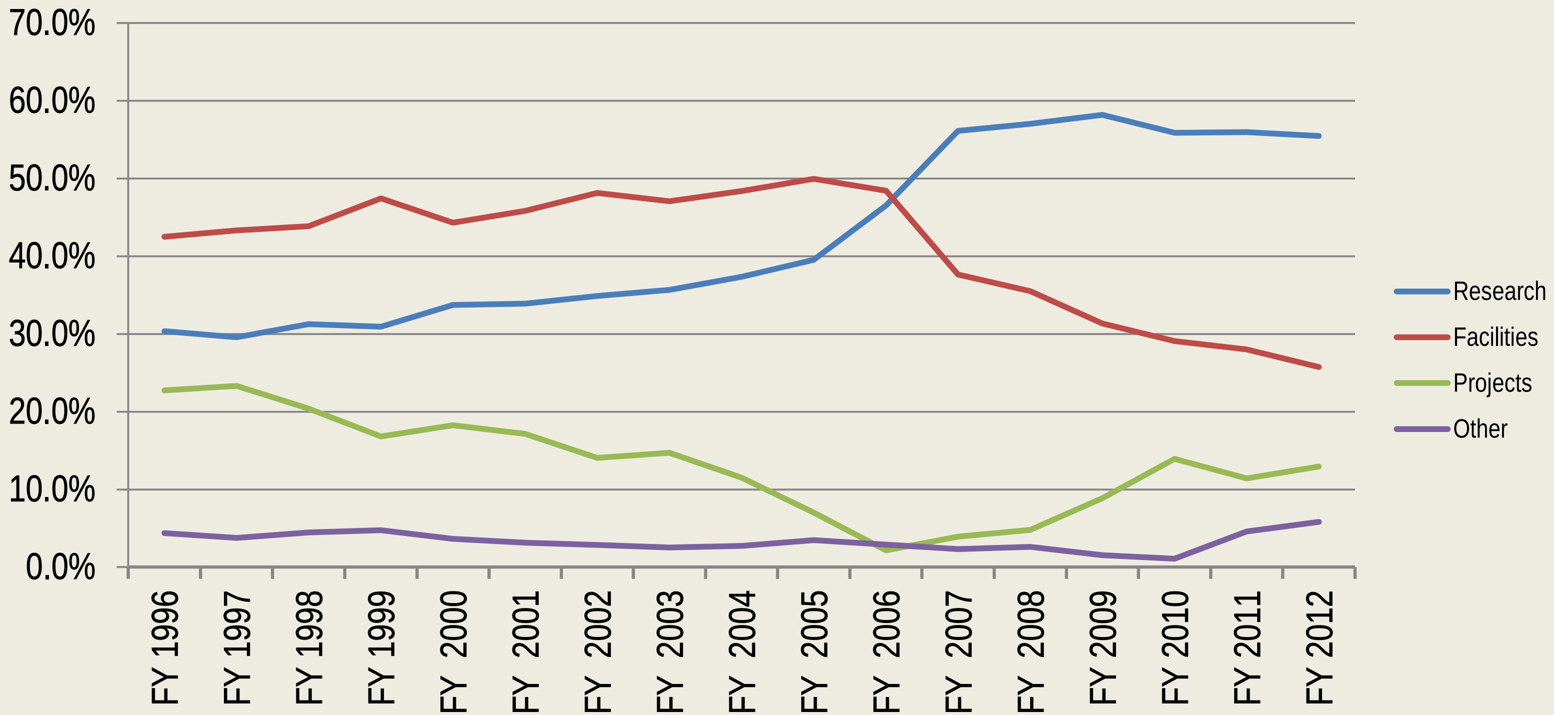
U.S. DEPARTMENT OF ENERGY | Office of Science

Office of Science FY 2015 Budget Request to Congress

(Dollars in thousands)

	FY 2013 Current (prior to SBIR/STTR)	FY 2013 Current Approp.	FY 2014 Enacted Approp.	FY 2015 President's Request	FY15 President's Request vs. FY14 Enacted Approp.	
Advanced Scientific Computing Research	417,778	405,000	478,093	541,000	+62,907	+13.2%
Basic Energy Sciences	1,596,166	1,551,256	1,711,929	1,806,500	+94,571	+5.5%
Biological and Environmental Research	578,294	560,657	609,696	628,000	+18,304	+3.0%
Fusion Energy Sciences	385,137	377,776	504,677	416,000	-88,677	-17.6%
High Energy Physics	748,314	727,523	796,521	744,000	-52,521	-6.6%
Nuclear Physics	519,859	507,248	569,138	593,573	+24,435	+4.3%
Workforce Development for Teachers and Scientists	17,486	17,486	26,500	19,500	-7,000	-26.4%
Science Laboratories Infrastructure	105,673	105,673	97,818	79,189	-18,629	-19.0%
Safeguards and Security	77,506	77,506	87,000	94,000	+7,000	+8.0%
Program Direction	174,862	174,862	185,000	189,393	+4,393	+2.4%
Subtotal, Office of Science	**4,621,075**	**4,504,987**	**5,066,372**	**5,111,155**	+44,783	+0.9%
Small Business Innovation Research/Technology Transfer	...	176,208	...	...	...	...
Use of Prior Year Balances	...	...	...	...	...	...
Total, Office of Science	**4,621,075**	**4,681,195**	**5,066,372**	**5,111,155**	+44,783	+0.9%

Recent Funding Trends



- **In the late 90's the fraction of the budget devoted to projects was about 20%.**
- **Progress in many fields require new investments to produce new capabilities.**
- **The projects started in 2006 are coming to completion.**
- **New investments are needed to continue US leadership in well defined research areas.**
- **Possibilities for future funding growth are weak. Must make do with what we have.**

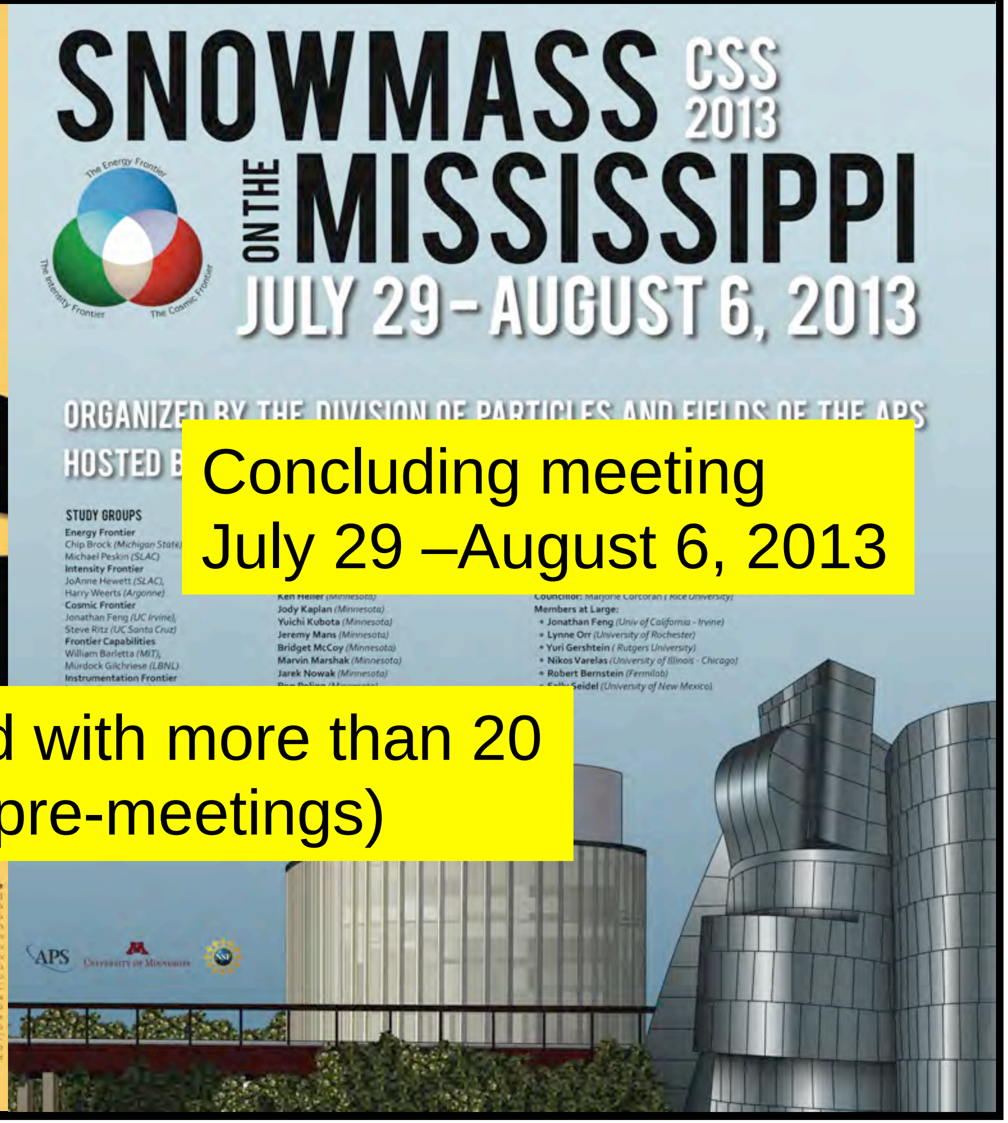
Snowmass

Snowmass 2013 has been a nine month study

Reflecting our era of high bandwidth communication, shared desktops & near effortless remote collaboration on a daily basis, Snowmass 2013 is not a 3-week meeting in Snowmass but a 9 month study

Face to face remains crucial:

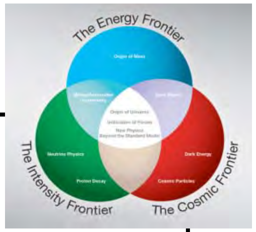
Kick Off meeting
October 2012



Concluding meeting
July 29 –August 6, 2013

interspersed with more than 20
workshops (pre-meetings)

Snowmass - Overview



An extended program of work & discussion over many months culminating in a 9-day summer workshop

Organization:

7 groups: 3 research frontiers + 4 "infrastructure" areas

3 research frontiers	4 "infrastructure" areas
Energy	**Instrumentation**
Intensity	**Facilities ("Capabilities")**
Cosmic	**Computation**
	Education & Outreach

Subgroups – each group has several subgroups

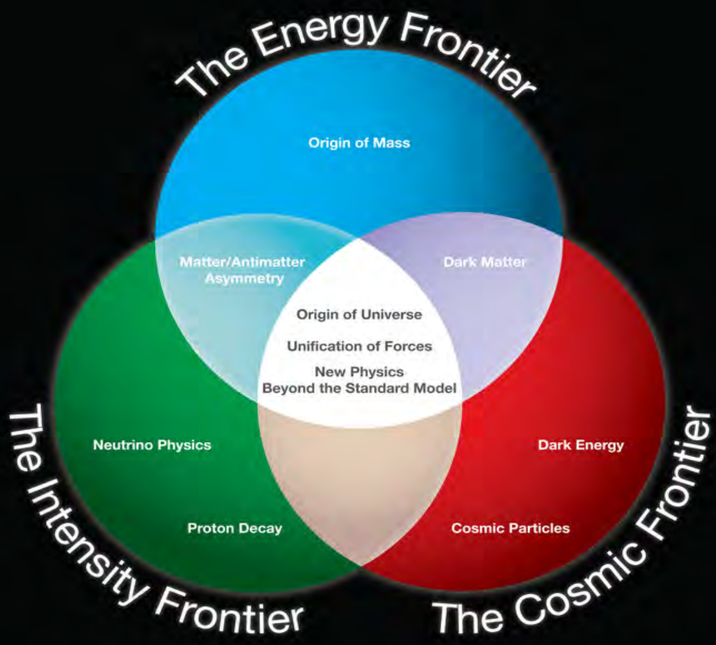
Timeline:

Initial plenary meeting – Fermilab, Oct. 2012
Many preparatory meetings held since
Snowmass on the Mississippi – Univ. of Minnesota, 29 July – 6 August 2013

Mo 29 July	- plenary talks set forth physics questions
30 July – 4 August	- inter-frontier discussions; plenary panels
Mo-Tu 5-6 August	- plans to address physics questions

https://indico.fnal.gov/conferenceTimeTable.py?confId=6890#20130729.detailed

Snowmass organizing principle is frontier-based



The frontiers are an effective way to tell the rich story of our field to non-experts

but:
we are united by physics and driven by the questions we ask not by the tools we use

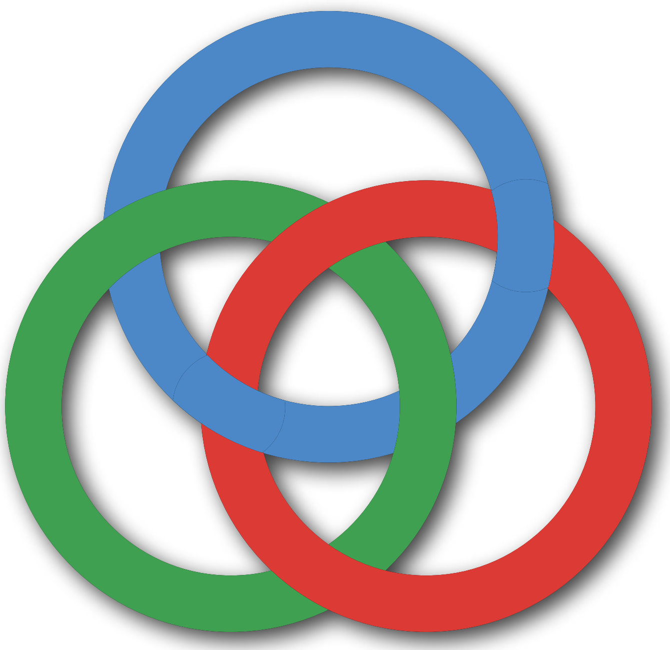
We are not the former pre-P5 classification: protons, electrons and non-accelerator

We are not the currrent post-P5 classification: energy intensity cosmic

We transcend frontiers; we are one field

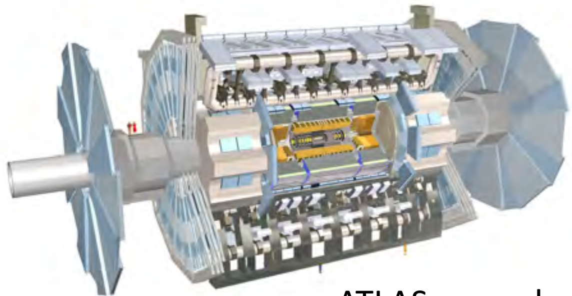
scientific reality

is more complex

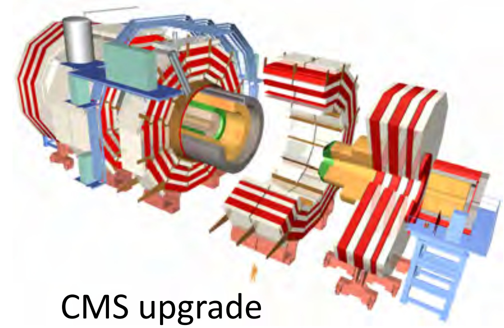


Big Ambitions …

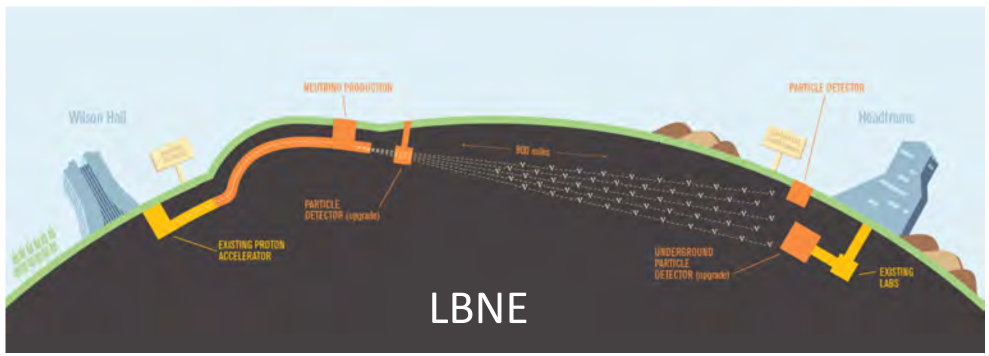
at

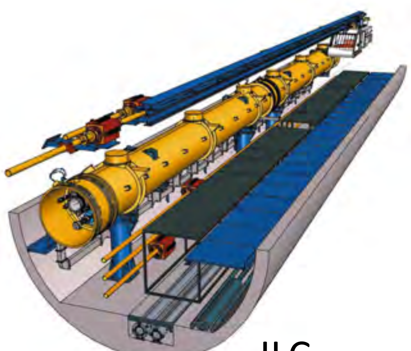


ATLAS upgrade

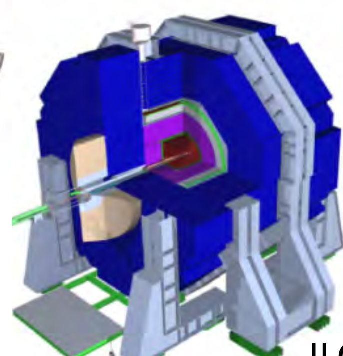


CMS upgrade

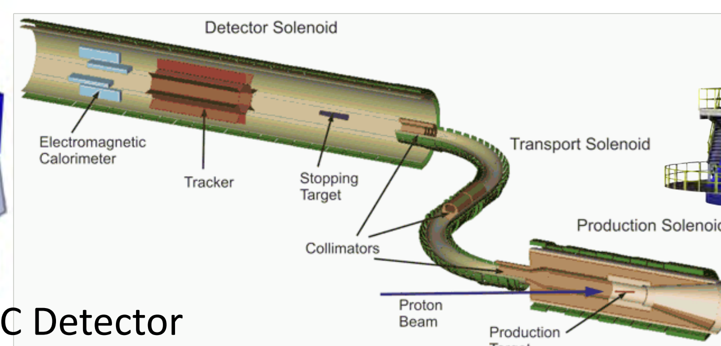




ILC



ILC Detector



Mu2e

LSST

The Real Big Question

- **How can we fit our ambitions within our budget ?**
  - Carry out a flagship domestic program, and have a leadership role in off-shore projects
  - Invest in the future such that the US is again recognized as a leader in high energy physics

- The View from, and Role of, the Instrumentation Frontier following the guidelines of the director of OHEP:
  - "... from the study process a community consensus on a 'situation analysis' for each major subsection of our field. What are our current strengths and capabilities, and what are the opportunities we face."
  - "The 'situation analysis' can be accompanied by a 'decision tree' that summarizes a range of future options."

Take a Chance !

It’s what HEP is founded on

It’s an investment in the future !

Priority: Full exploitation of LHC

- => Strong LHC Accelerator Research Program continuing to U.S.-LHC high luminosity construction project
- Continue a focused integrated laboratory program (LARP-like) emphasizing engineering readiness of technologies suitable for High Energy-LHC
  - Next generation high field Nb_3Sn magnets (~15 Tesla)
  - Beam control technology
- This is most critical technology *development* toward higher energy hadron colliders in the near to mid-term
- Reach of an LHC energy upgrade is very limited
  - No engineering materials beyond Nb_3Sn
  - Difficult synchrotron radiation management

Focused engineering development is no substitute for innovative R&D

Proton colliders beyond LHC

- US multi-lab study of VLHC is still valid (circa 2001);
  - Snowmass has stimulated renewed interest/effort in US
    - 2013 Snowmass white paper
- We recommend participating in international study for colliders in a large tunnel (CERN-led)
- Study will inform directions for expanded U.S. technology reach & guide long term roadmap
  - Beam dynamics, magnets, vacuum systems, machine protection, …

Extensive interest expressed in this possibility

We welcome the initiative for ILC in Japan

- U.S. accelerator community is capable to contribute
  - Supported by the physics case as part of a balanced program
- ILC design is technically ready to go
  - TDR incorporates leadership U.S. contributions to machine physics & technology
    - SRF, high power targetry (e+ source), beam delivery, damping rings, beam dynamics
- Important that there is an upgrade path of ILC to higher energy & luminosity (> 500 GeV, > 10^{34} $cm^{-2}s^{-1}$)

We are experienced & ready to do it

Recommendations: Increase research effort toward a compact, muli-TeV lepton collider

- ❖ Vigorous, integrated R&D program toward demonstrating feasibility of a muon collider (Muon Accelerator Program)
  - ✧ Current support insufficient for timely progress
  - ✧ Closely connected with intensity frontier & intense neutrino sources
- ❖ Stay involved in high gradient, warm linac approach (CLIC)
  - ✧ Practical energy reach: wakefield control, accelerating gradient
  - ✧ Industrialization path to be developed
- ❖ Continue R&D in wakefield accelerators (plasmas & dielectric)
  - ✧ Fruitful physics programs with high intellectual content
  - ✧ Feasibility issues: Positron acceleration, multi-stage acceleration, control of beam quality, plasma instabilities at 10's of kHz rep rate
  - ✧ All variants require an integrated proof-of-principle test

Motivations: Lower cost, smaller footprint, higher energy

Project X: a world leading facility for Intensity Frontier research

- Based on a modern multi-MW SCRF proton linac
  - Flexible "on-demand" beam structure
- Could serve multiple experiments over broad energy range
  - 0.25 – 120 GeV
- Platform for future muon facilities (νFactory/muon collider)
- Complete, integrated concept Reference Design Report
  - arXiv:1306.5022
- R&D program underway to mitigate risks in Reference Design
  - Undertaken by 12 U.S. & 4 Indian laboratories and universities

Could initiate construction in the second half of this decade

Exciting possibilities for capabilities of narrower experimental scope

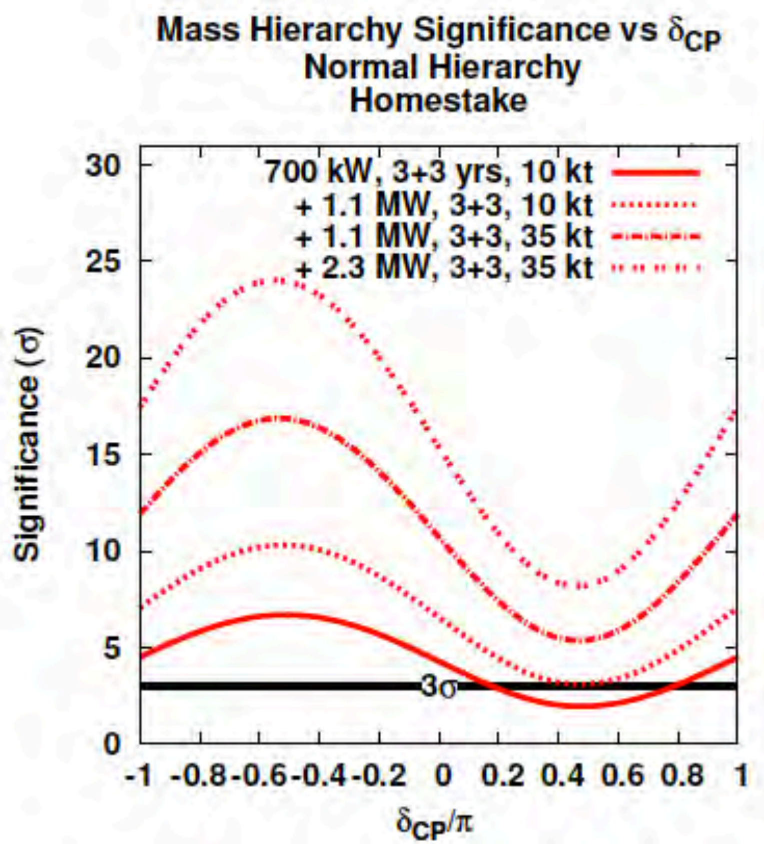
- DAEδALUS: Decay At Rest anti-neutrinos – experiments based on short baseline oscillations
  - Three Multi-MW H_2^+ cyclotrons & target stations located ~2-20km from experiment large hydrogenous detector
  - First stage: IsoDAR – compact cyclotron 15 m from Kamland
  - International collaboration with strong industry connection
- nuSTORM: Neutrinos from STORed Muons
  - Supports sterile neutrino & neutrino cross-section experimental program as well as muon accelerator R&D
  - Muon storage ring sends well-characterized beams to near & far detectors at 50 m & 1900 m
  - First step towards long baseline neutrino factory capability

LBNE – Optimal Baseline

LBNE + Project X (1.1-2.3 MW) = Comprehensive Global Science Program

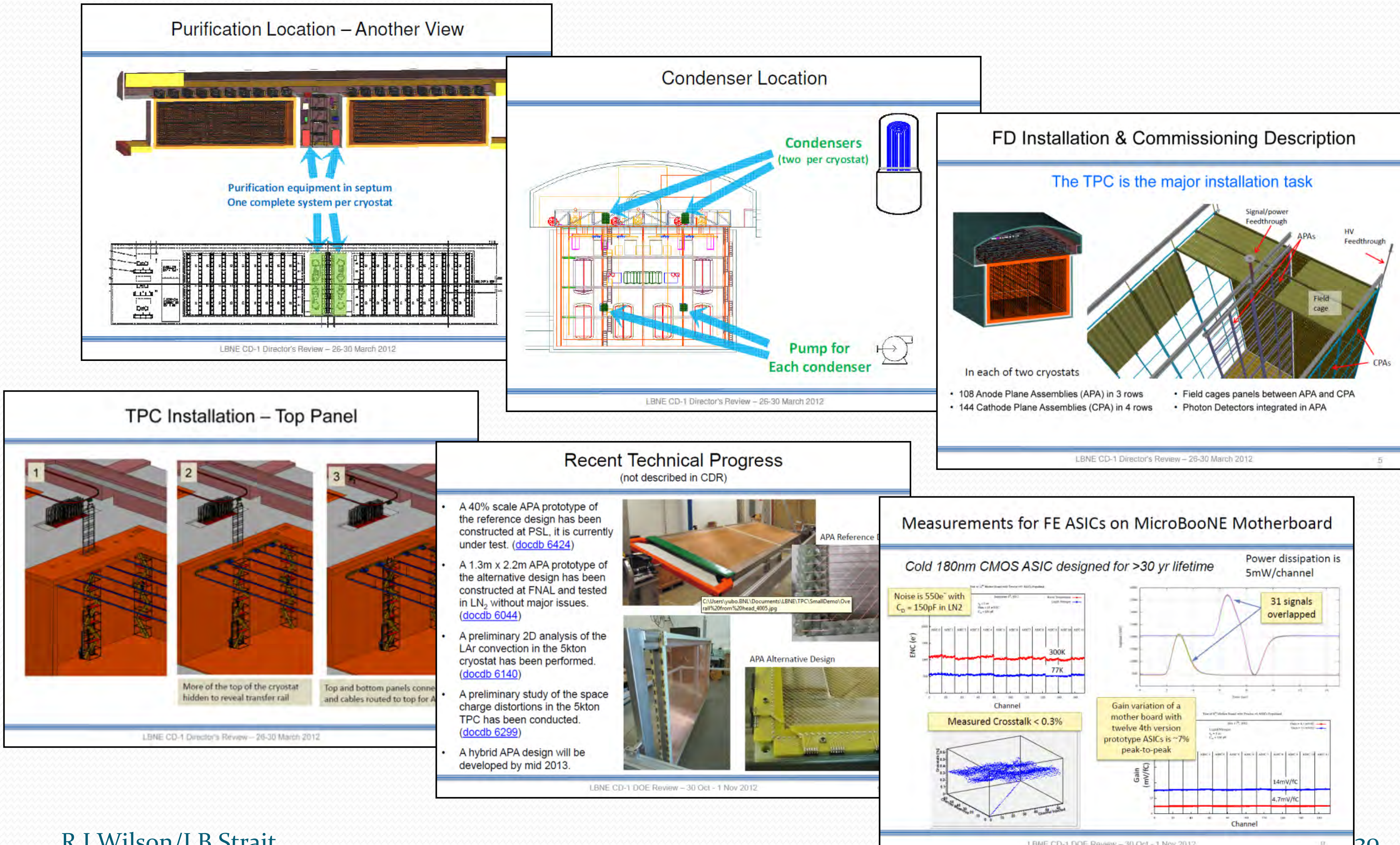
Run scenario:

- Operate w/ 700 kW w/ 10 kt LBNE
- Then 1.1 MW 1st phase Project X
- Add 25 kt LBNE FD
- Then 2.3 MW 2nd phase Project X

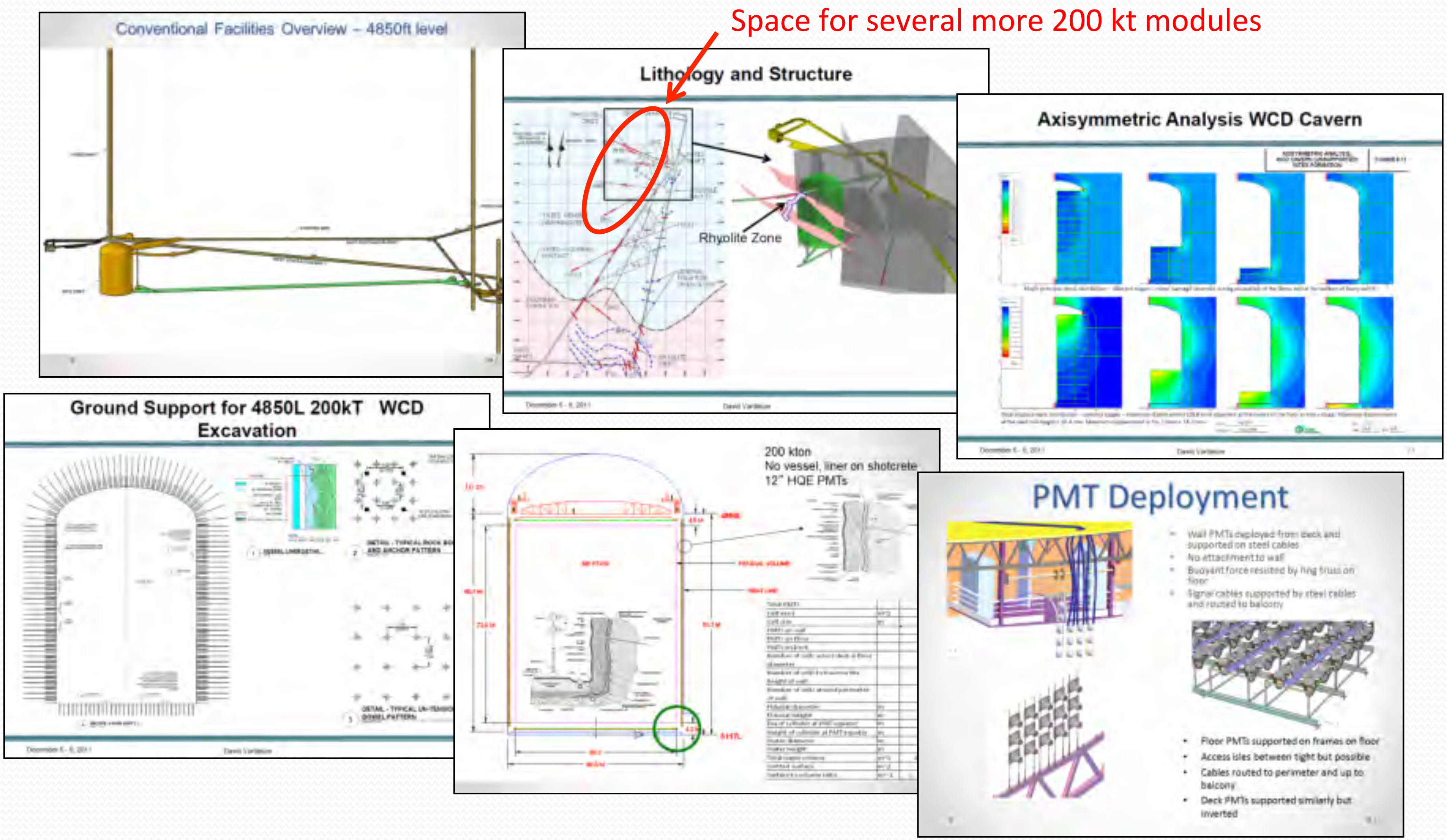


- With the Mass Hierarchy unambiguously determined in the same experiment more subtle matter effect features may be revealed

34 kt LAr Far Detector @ 4300 mwe Depth



And …. we also have a design for
a 200 kt (fiducial) Water Cherenkov Detector



Charged Lepton Flavor Violation

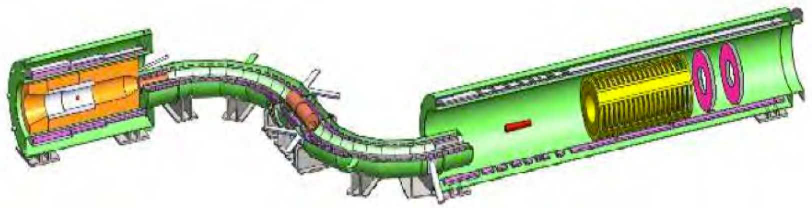
95% CL limits in CLFV with muons

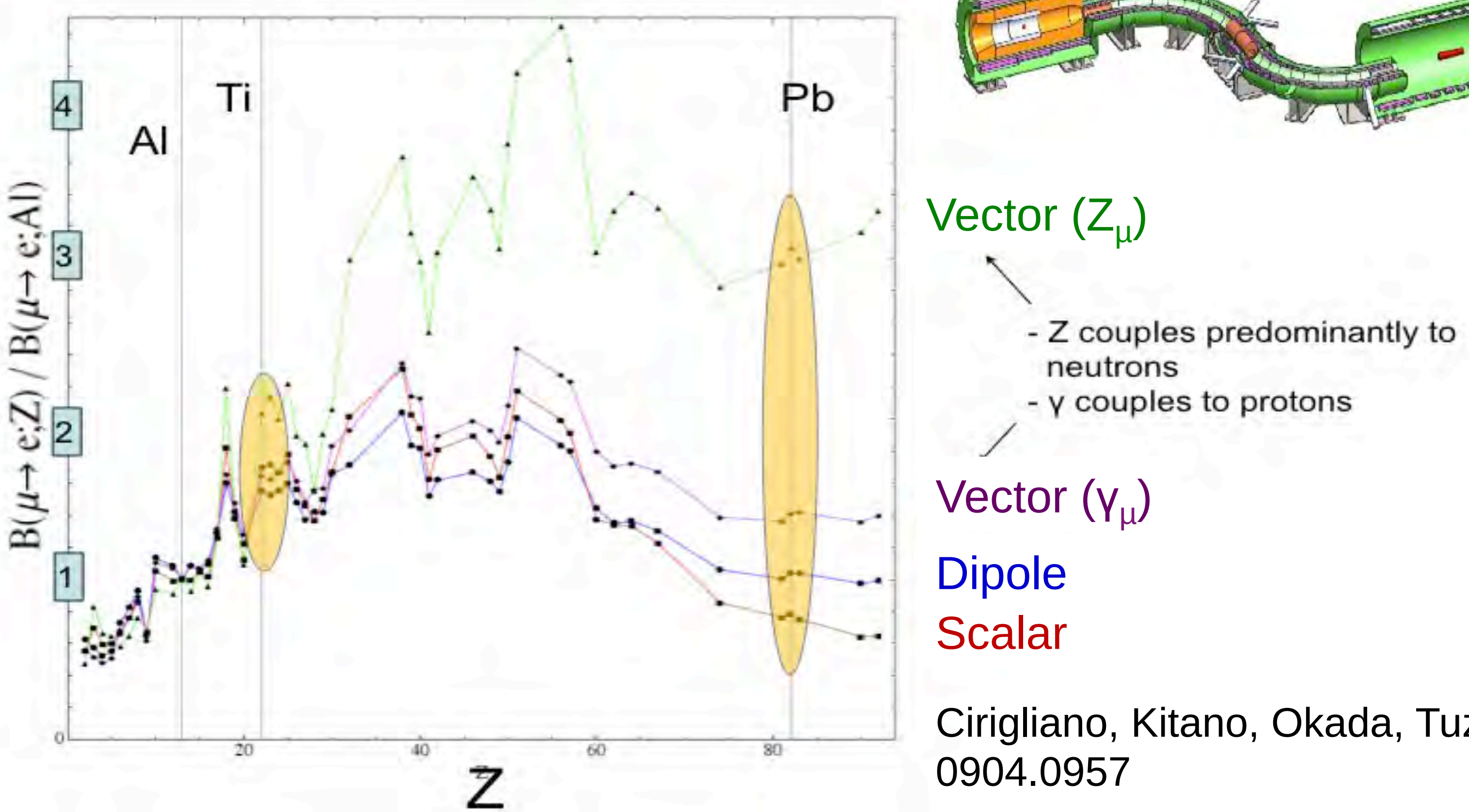
Process	Current limit	Expected limit 5-10 years		Expected limit 10-20 years
$\mu^+ \to e^+\gamma$	2.4×10^{-12} PSI/MEG (2011)	1×10^{-13} PSI/MEG		1×10^{-14} PSI, Project X
$\mu^+ \to e^+e^-e^+$	1×10^{-12} PSI/SINDRUM-I (1988)	1×10^{-15} Osaka/MuSIC	1×10^{-16} PSI/$\mu 3e$	1×10^{-17} PSI, Project X
$\mu^- N \to e^- N$	7×10^{-13} PSI/SINDRUM-II (2006)	1×10^{-14} J-PARC/DeeMee	6×10^{-17} FNAL/Mu2e	1×10^{-18} J-PARC, Project X

Table 3-1. *Evolution of the 95% CL limits on the main CLFV observables with initial state muons. The expected limits in the 5-to-10 year range are based on running or proposed experiments at existing facilities. The expected bounds in the 10-to-20 year range are based on sensitivity studies using muon rates available at proposed new facilities. The numbers quoted for $\mu^+ \to e^+\gamma$ and $\mu^+ \to e^+e^-e^+$ are limits on the branching fraction. The numbers quoted for $\mu^- N \to e^- N$ are limits on the rate with respect to the muon capture process $\mu^- N \to \nu_\mu N'$. Below the numbers are the corresponding experiments or facilities and the year the current limit was set.*

Model Determination with Mu2e

If charged lepton flavor violation is discovered, Mu2e can determine the origin!





Cirigliano, Kitano, Okada, Tuzon
0904.0957

5% measurement of the ratio Ti/Al needed to discriminate between models
Theory uncertainty mainly cancels in ratio

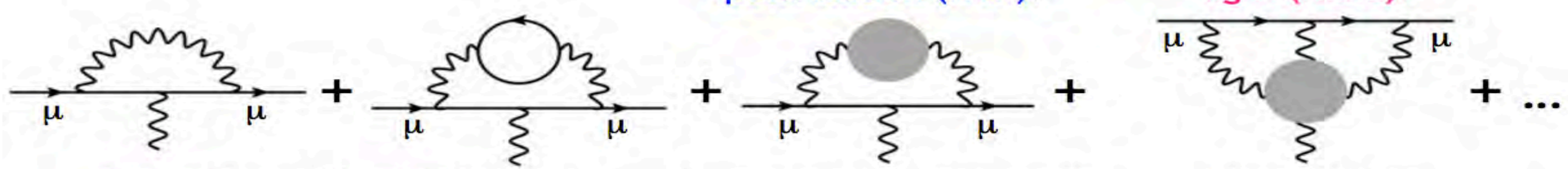
Anomalous Magnetic Moment of the Muon

- Discrepancy between exp’t and SM at 3.6σ : $\Delta a_\mu = 287(80) \times 10^{-11}$
- Ring has arrived at Fermilab
  - » Run begins 2016/17
- Lattice/analytic results can reduce theory uncertainty
  - » How well can this be calculated?

Van de Water

Hadronic vacuum polarization (HVP):

Hadronic light-by-light (HLbL):



QED (4 loops) & EW (2 loops)

from experimental result for $e^+e^- \rightarrow$ hadrons plus dispersion relation

estimated from models such as large N_c, vector meson

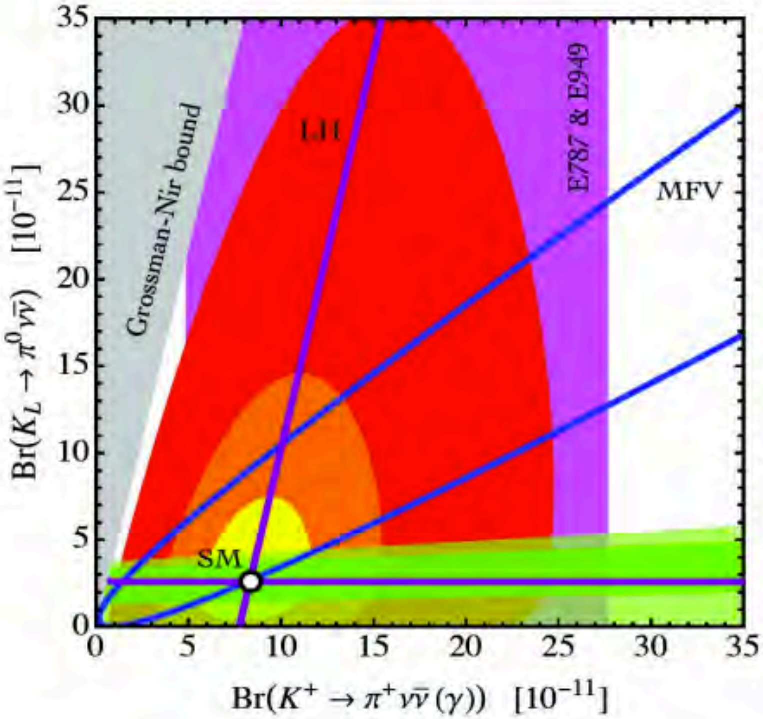
HVP: Theory error reduced to 2% due to theoretical improvements and more CPU on timescale of exp’t

HLBL: 15% precision possible, but not guaranteed. Lattice community working hard!

Kaon Program

- Worldwide goal to achieve precision measurements

Sensitivity to new physics



SM Prediction:

$$B(K^+ \to \pi^+ \nu\bar{\nu}) = (7.81 \pm 0.75 \pm 0.29) \times 10^{-11}$$

$$B(K^0 \to \pi^0 \nu\bar{\nu}) = (2.43 \pm 0.39 \pm 0.06) \times 10^{-11}$$

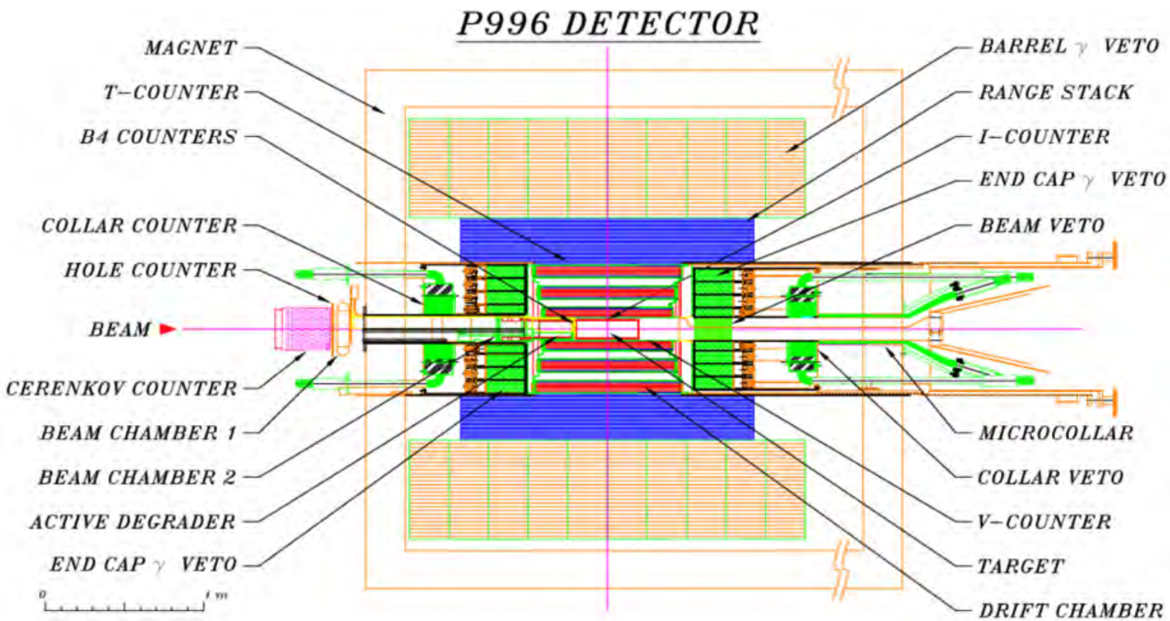
Theoretically clean decays

Charged mode:
NA62: near-term (10% precision)
ORKA: Proposed,
1000 events w/ Main Injector

Neutral mode:
KOTO: near term (few events)
Projected: 5% precision @ Project X

Haisch

ORKA



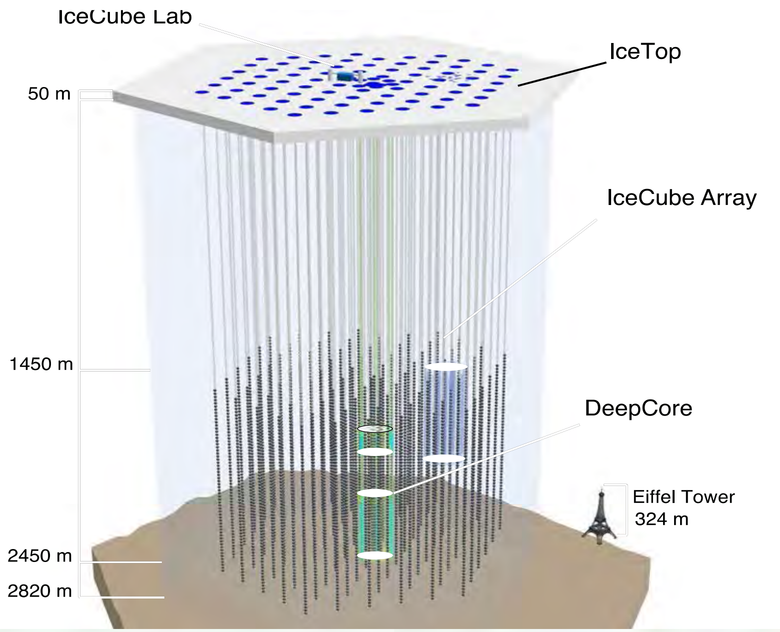
4^{th} generation detector designed around proven techniques

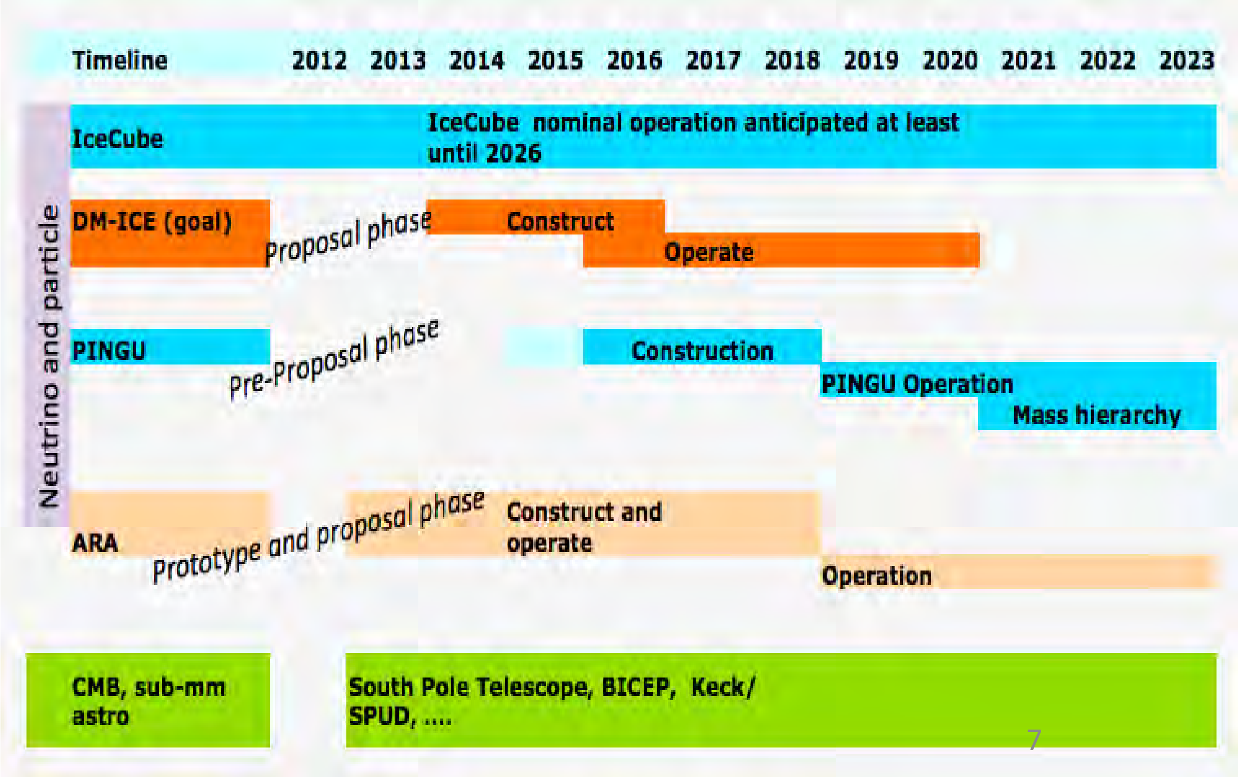
Expect ×100 sensitivity relative to BNL experiment:
×10 from beam and ×10 from detector

Already a very strong collaboration

Antarctica

- Unique, U.S. led facility. Only Southern Hemisphere site so far.
- Dark matter, neutrino program, including operation and proposals for future experiments
- Synergy with astronomy/cosmology
- Future plans
  - Continue operation of IceCube well into 2020’s
  - DM experiments proposed
  - ν experiments proposed



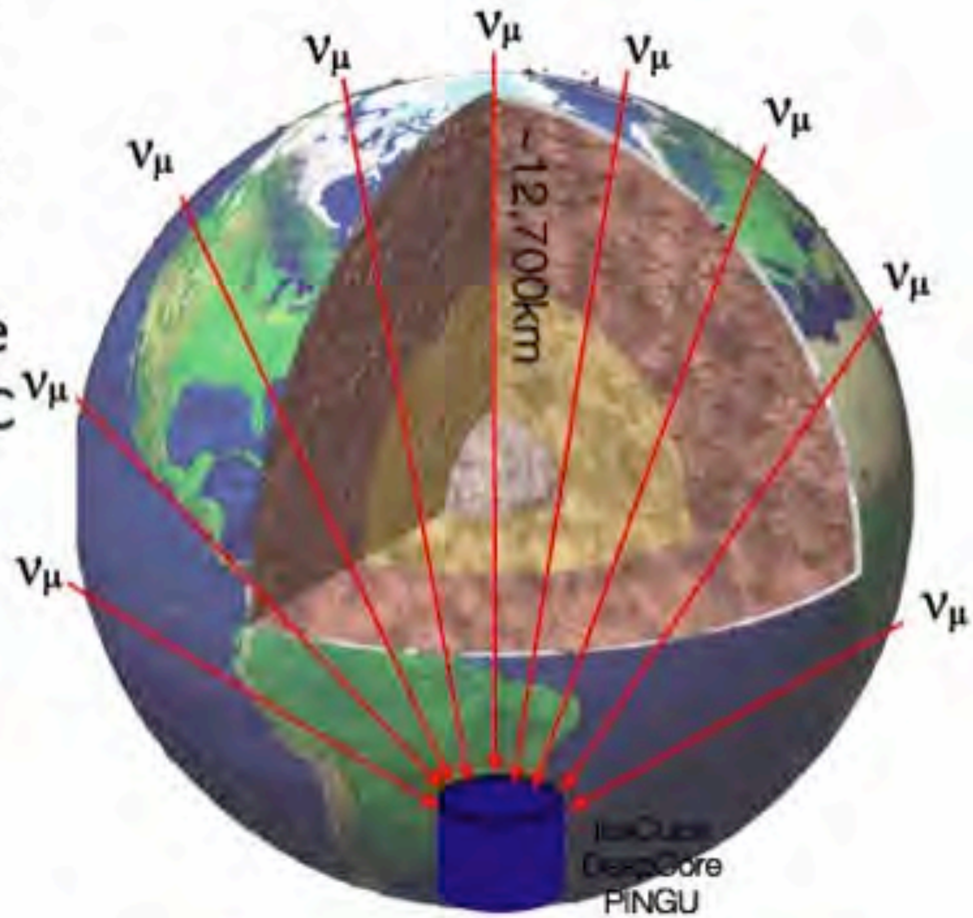


PINGU

arXiv:1306.5846v1

Atmospheric neutrinos provide many values of L and E
Very large baselines for probing matter effects (~12,700 km)
Add ~40 strings inside DeepCore
20-25m string spacing (73 for DC and 125 for IC)

Could provide very significant hierarchy information with a few years of running, improving δ_{CP} range probed by NOvA + T2K

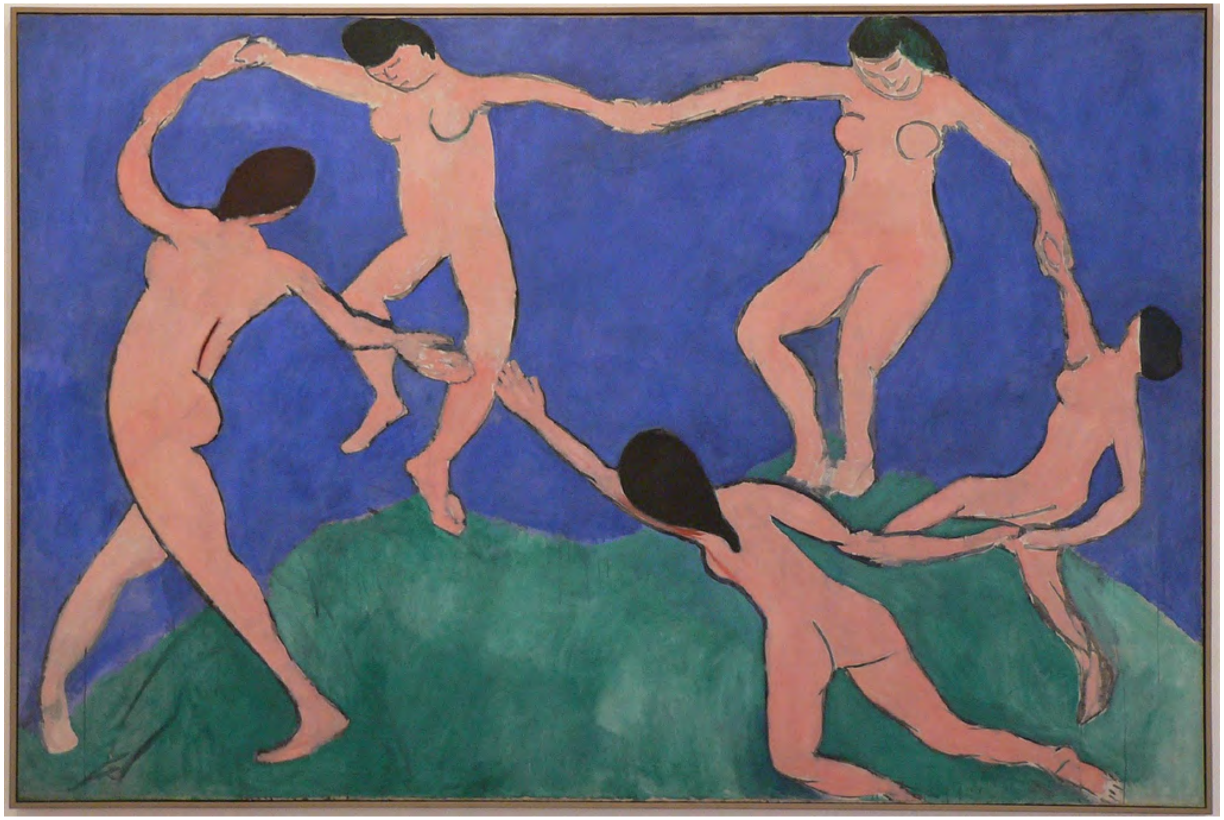


Dark Matter Complementarity

See arXiv:1305.1605

Direct Detection
Relic scattering locally, at low energy. Push to larger target mass, lower backgrounds, directional sensitivity

Accelerators
Direct production. Push to higher energy



Observations
Push toward finding and studying galactic halo objects and large scale structure.

Indirect Detection
Interactions (via annihilations, decays) with SM particles. Understand the astrophysical backgrounds in signal-rich regions, and reveal the distribution of dark matter.

Simulations
Large scale structure formation. Push toward larger simulations, finer details.

WIMP Direct Detection Census

1. Experiment Status, Target Mass
2. Fiducial target mass
3. Backgrounds after passive and active shielding.
4. Detector Discrimination
5. Energy Threshold
6. Sensitivity versus WIMP mass
7. Experimental Challenges
8. Annual Modulation
9. Unique Capabilities
10. Determining WIMP properties and astrophysical parameters

http://www.snowmass2013.org/tiki-index.php?page=SLAC

Cryogenic Solid State

CDMS/SuperCDMS
EDELWEISS/CRESST/EURECA
CoGeNT/C4
TEXONO/CDEX

Liquid Xenon

LUX/LZ

XENON
PandaX
XMASS

Liquid Argon

ArDM
Darkside
DEAP
CLEAN

Crystal and Annual Modulation

DAMA/LIBRA
KIMS
ELEGANT
ANAIS
CINDMS
Princeton NaI
DM-Ice

Threshold Detectors

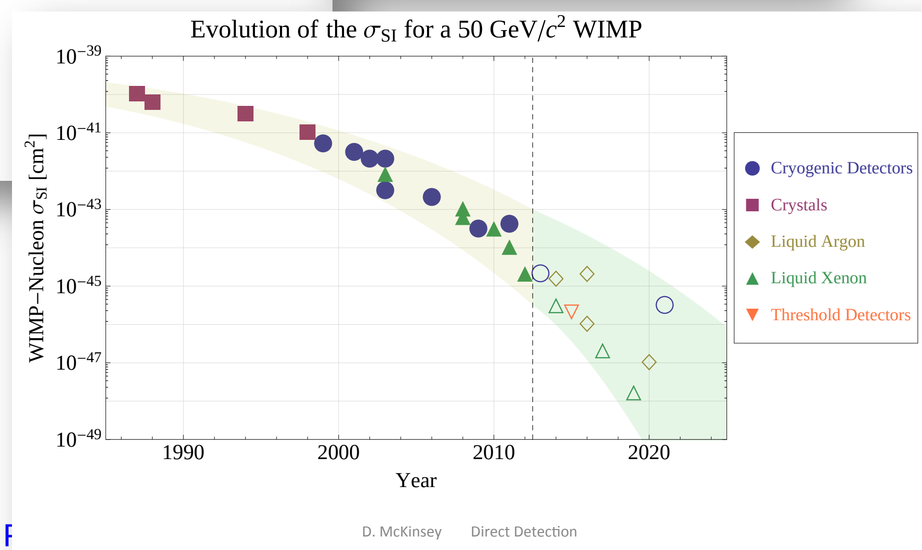
Technology Description
PICASSO
SIMPLE
COUPP

Directional Detection

DRIFT
Newage
DMTPC
MIMAC
D3

New Ideas

DAMIC
Liquid helium-4
NEXT
Nuclear emulsions (Naka, Japan)
DNA & Nano-explosions (Drukier/Cantor)



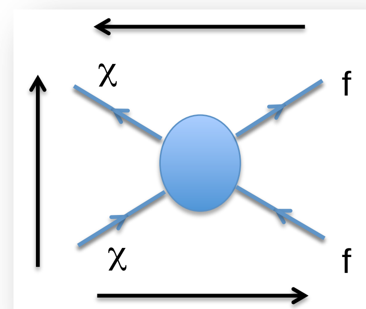
Indirect Detection and Cosmic Particles Facilities

Indirect Detection Experiments

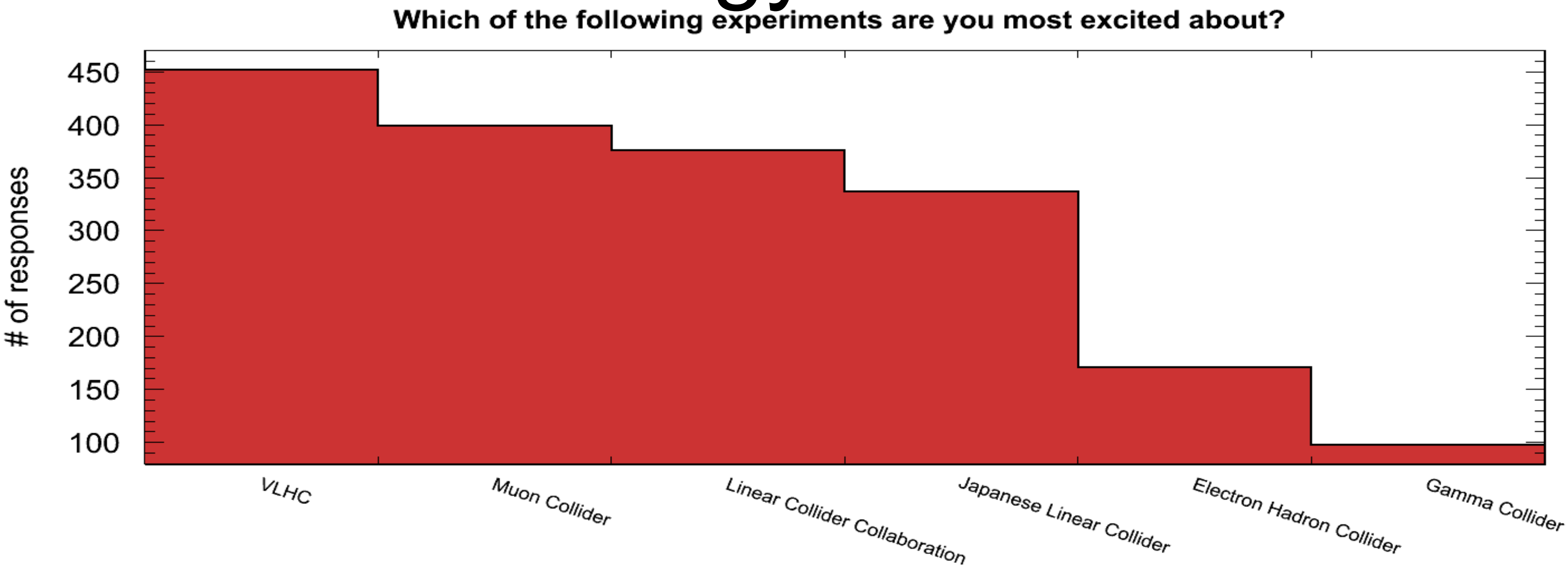
Status	Experiment	Target	Location	Major Support	Comments
Current	AMS	e+/e-, anti-nuclei	ISS	NASA	Magnet Spectrometer, Running
	Fermi	Photons, e+/e-	Satellite	NASA, DOE	Pair Telescope and Calorimeter, Running
	HESS	Photons, e-	Namibia	German BMBF, Max Planck Society, French Ministry for Research, CNRS-IN2P3, UK PPARC, South Africa	Atmospheric Cherenkov Telescope (ACT), Running
	IceCube/ DeepCore	Neutrinos	Antarctica	NSF, DOE, International: Belgium, Germany, Japan, Sweden)	Ice Cherenkov, Running
	MAGIC	Photons, e+/e-	La Palma	German BMBF and MPG, INFN, WSwiss SNF, Spanish MICINN, CPAN, Bulgarian NSF, Academy of Finland, DFG, Polish MNiSzW	ACT, Running
	PAMELA	e+/e-	Satellite		
	VERITAS	Photons, e+/e-	Arizona, USA	DOE, NSF, SAO	ACT, Running
	ANTARES	Neutrinos	Mediter-ranean	France, Italy, Germany, Netherlands, Spain, Russia, and Morocco	Running
Planned	CALET	e+/e-	ISS	Japan JAXA, Italy ASI, NASA	Calorimeter
	CTA	Photons	ground-based (site TBD)	International: MinCyT, CNEA, CONICET, CNRS-INSU, CNRS-IN2P3, Irfu-CEA, ANR, MPI, BMBF, DESY, Helmholtz Association, MIUR, NOVA, NWO, Poland, MICINN, CDTI, CPAN, Swedish Research Council, Royal Swedish Academy of Sciences, SNSF, Durham UK, NSF, DOE	ACT
	GAMMA-400	Photons	Satellite	Russian Space Agency, Russian Academy of Sciences, INFN	Pair Telescope
	GAPS	Anti-deuterons	Balloon (LDB)	NASA, JAXA	TOF, X-ray and Pion detection
	HAWC	Photons, e+/e-	Sierra Negra	NSF/DOE	Water Cherenkov, Air Shower Surface Array
	IceCube/ PINGU	Neutrinos	Antarctica	NSF, Germany, Sweden, Belgium	Ice Cherenkov
	KM3NeT	Neutrinos	Mediter-ranean	ESFRI, including France, Italy, Greece, Netherlands, Germany, Ireland, Romania, Spain, UK, Cyprus	Water Cherenkov
	ORCA	Neutrinos	Mediter-ranean	ESFRI, including France, Italy, Greece, Netherlands, Germany, Ireland, Romania, Spain, UK, Cyprus	Water Cherenkov

http://www.snowmass2013.org/tiki-index.php?page=WIMP+Dark+Matter+Indirect+Detection

Now entering very interesting sensitivity range – thermal production natural scale for WIMPs $\langle\sigma v\rangle \sim 3\times10^{-26}$ cm^3/s



Energy Frontier



- **<u>Top 3 Energy Frontier Experiments people are excited about (can select more than one)</u>**
  - Very Large Hadron Collider
  - Muon Collider
  - Linear Collider Collaboration
- **<u>We can also look so see which experiments are found most exciting by different demographics</u>**
  - Frontier (shown on the next slide)
  - Current position (to be included in the comprehensive study)

P5 Report

Particle Physics is Global

- The United States and major players in other regions can together address the full breadth of the field's most urgent scientific questions if each hosts a unique world-class facility at home and partners in high-priority facilities hosted elsewhere.
  - Hosting world-class facilities and joining partnerships in facilities hosted elsewhere are both essential components of a global vision.

- Strong foundations of international cooperation exist, with the Large Hadron Collider (LHC) at CERN serving as an example of a successful large international science project. Reliable partnerships are essential for the success of international projects. This global perspective is finding worldwide resonance in an intensely competitive field.
  - The 2013 *European Strategy for Particle Physics* report focuses at CERN on the Large Hadron Collider (LHC) program and envisions substantial participation at facilities in other regions.
  - Japan, following its 2012 *Report of the Subcommittee on Future Projects of High Energy Physics*, expresses interest in hosting the International Linear Collider (ILC), pursuing the Hyper-Kamiokande experiment, and collaborating on several other domestic and international projects.

P5 Identified Scientific Drivers for the Field

"Driver" = a compelling line of inquiry that shows great promise for major progress over the next 10-20 years. Each has the potential to be transformative. Expect surprises.

- Use the Higgs as a new tool for discovery.
- Explore the physics associated with neutrino mass.
- Identify the new physics of Dark Matter.
- Test the nature of Dark Energy in detail, and probe the physics of the highest energy scales that governed the very early Universe.
- Search for new particles and interactions; new physical principles.

These drivers are intertwined, possibly even more deeply than we currently understand. A selected set of different experimental approaches, which reinforce each other, is required. This effort also opens important discovery space beyond the drivers.

Use the Higgs boson as a new tool for discovery

- The recently discovered Higgs boson is a form of matter never before observed.
  - What principles determine its effects on other particles? How does it interact with neutrinos or with dark matter? Is there one Higgs particle or many? Is the new particle really fundamental, or is it composed of others?
  - The Higgs boson offers a unique portal into the laws of Nature, and it connects several areas of particle physics. Any small deviation in its expected properties would be a major breakthrough.

- The full discovery potential of the Higgs will be unleashed by percent-level precision studies of the Higgs properties. The measurement of these properties is a top priority in the physics program of high-energy colliders.
  - The Large Hadron Collider (**LHC)** will be the first laboratory to use the Higgs boson as a tool for discovery, initially with substantial higher energy running at 14 TeV, and then with ten times more data at the High-Luminosity LHC (**HL-LHC)**. The HL-LHC has a compelling and comprehensive program that includes essential measurements of the Higgs properties.
  - An e^+e^- collider can provide the next outstanding opportunity to investigate the properties of the Higgs in detail. The International Linear Collider (**ILC**) is the most mature in its design and readiness for construction. The ILC would greatly increase the sensitivity to the Higgs boson interactions with the Standard Model particles, with particles in the dark sector, and with other new physics. The ILC will reach the percent or sub-percent level in sensitivity.
  - Longer-term future-generation accelerators bring prospects for even better precision measurements of Higgs properties and discovery potential.

Pursue the physics associated with neutrino mass

- Propelled by surprising discoveries from a series of pioneering experiments, neutrino physics has progressed dramatically over the past two decades, with a promising future of continued discovery.
- Many aspects of neutrino physics are puzzling. Powerful new facilities are needed to move forward, addressing:
  - What is the origin of neutrino mass? How are the masses ordered (referred to as mass hierarchy)? What are the masses? Do neutrinos and anti-neutrinos oscillate differently? Are there additional neutrino types or interactions? Are neutrinos their own antiparticles?
- The U.S. is well positioned to host a world-leading neutrino physics program, which includes an optimized set of short- and long-baseline neutrino oscillation experiments
  - The long-term focus is a reformulated venture referred to here as the Long Baseline Neutrino Facility (**LBNF**), an internationally designed, coordinated, and funded program with Fermilab as host.
  - LBNF would combine a high-intensity neutrino beam and a large-volume precision detector sited underground a long distance away to make accurate measurements of the oscillated neutrino properties. This large detector would also search for proton decay and neutrinos from supernova bursts.
- A powerful, wideband neutrino beam would be realized with Fermilab's **PIP-II** upgrade project, which provides very high intensities in the Fermilab accelerator complex.
- Cosmic surveys and a variety of other small experiments will also make important progress in answering these questions.

Identify the new physics of dark matter

- Astrophysical observations imply that the known particles make up only about one-sixth of the total matter in the Universe. The rest is dark matter (DM). The properties of dark matter particles, which are all around us, are largely unknown.
- Experiments are poised to reveal the identity of dark matter, a discovery that would transform the field of particle physics, advancing the understanding of the basic building blocks of the Universe. There are many well-motivated ideas for what dark matter could be, including
  - weakly interacting massive particles (WIMPs), axions, and new kinds of neutrinos.

- Direct detection experiments are sensitive to dark matter interactions with ordinary particles in the laboratory and will follow a progression from currently proposed second-generation (**DM G2**) experiments to much larger third-generation (**DM G3**) experiments.
- Indirect detection experiments, such as the **CTA** gamma-ray observatory, can spot the particle debris from interactions of relic dark matter particles in space. Cosmic surveys are sensitive to dark matter properties through their effects on the structures of galaxies.
- Experiments now at the LHC and eventually at future colliders seek to make dark matter particles in the laboratory for detailed studies.

Understand cosmic acceleration: dark energy and inflation

- With the telescopes that peer back in time and high-energy accelerators that study elementary particles, scientists have pieced together a story of the origin and evolution of the Universe. An important part of this story is the existence of two periods during which the expansion of the Universe accelerated.
  - A primordial epoch of acceleration, called inflation, occurred during the first fraction of a second of existence. The cause is unknown -- fundamentally new physics at ultra-high energies. A second distinct epoch of accelerated expansion began more recently and continues today, presumed to be driven by some kind of dark energy, which could be related to Einstein's cosmological constant, or driven by a different type of dark energy that evolves with time.
- Understanding inflation is possible by measuring the characteristics of two sets of primordial ripples: those that grew into the galaxies observed today, and gravitational waves, undulations in space and time that may have been observed just months ago by the BICEP2 telescope looking at the cosmic microwave background (CMB). Current CMB probes will lead to a **Stage 4 Cosmic Microwave Background (CMB-S4)** experiment, with the potential for important insights into the ultra-high energy physics that drove inflation.
- Understanding the second epoch requires better measurements:
  - The Dark Energy Spectroscopic Instrument (**DESI**) can determine the properties of dark energy to the percent level over the course of billions of years. The Large Synoptic Survey Telescope (**LSST**), measuring the positions, shapes, and distances of billions of galaxies, will perform many separate tests of the properties of dark energy.
  - Together, they can also probe the possibility that, instead of dark energy, new laws beyond those introduced by Einstein are responsible for the recent cosmic acceleration.

Explore the unknown: new particles, interactions, and physical principles

- There are clear signs of new phenomena awaiting discovery beyond those of the other four Drivers. Particle physics is a discovery science defined by the search for new particles and new interactions, and by tests of physical principles.

- Producing new particles at colliders:
  - Well-motivated extensions of the Standard Model predict that a number of such particles should be within reach of LHC. HL-LHC will extend the reach for new particles that could be missed by LHC. In the event that one or more new particles are already discovered during LHC running, HL-LHC experiments will be essential to reveal the identities and underlying physics of these particles.

- Detecting the quantum influence of new particles:
  - The existence of new particles that are too heavy to be produced directly at high-energy colliders can be inferred by looking for quantum influences in lower energy phenomena, using different kinds of particles as probes that are sensitive to different types of new particles and interactions. Some notable examples are a revolutionary increase in sensitivity for the transition of a muon to an electron in the presence of a nucleus **Mu2e** (Fermilab) and **COMET** (J-PARC), further studies of rare processes involving heavy quarks or tau leptons at **Belle II** (KEK) and **LHCb** (LHC), and a search for proton decay using the large neutrino detectors of the **LBNF** and proposed **Hyper-K** experiments.

- Future Opportunities:
  - In the longer term, **very high-energy e^+e^- colliders** and **very high-energy proton colliders** could extend the search for new particles and interactions, as well as enable precision studies of the Higgs boson and top quark properties . Upgrades at Fermilab (**PIP-II** and additional improvements) will offer further opportunities to detect the influence of new particles in rare processes.

Scenarios B and A

- Scenario A is much more challenging. The reduction relative to Scenario B, which is approximately $30M per year until FY2018 and then grows over time, would have very large impacts:
  - DESI would not be possible
  - Accelerator R&D and advanced detector R&D would be reduced substantially
  - Extension of flat-flat research program funding would result in further personnel reductions and loss of research capability
  - Ramp up of funding for LBNF would be delayed relative to Scenario B (preliminary work would proceed immediately in both scenarios)
  - Third-generation direct detection dark matter capabilities would be reduced or delayed
  - A small change in the funding profile of Mu2e would be required.
- DESI should be the last project to be cut if moving from Scenario B toward Scenario A.
  - A small, limited-time increment above Scenario A would make this very important small project possible.

The return on the investment of the relatively small increment from Scenario A to Scenario B is large. It provides excellent science per incremental dollar by enabling the outstanding opportunity of DESI, sets a faster course for the long-baseline neutrino program, and preserves the long-term investments in R&D and the research program. As valuable as each of these items is, they simply do not fit in Scenario A.

Scenario B


Project
2015
2020
2025
2030
2035
Currently operating
Large Projects
Mu2e
LHC: Phase 1 upgrade
HL-LHC
LBNF
ILC
Medium and Small Projects
LSST
DESI
DM G2
DM G3
CMB S4

Summary (5/5)

- The recommendations for the unconstrained budget Scenario focus on three additional high-priority activities:
  - Develop a greatly expanded accelerator R&D program that would emphasize the ability to build very high-energy accelerators beyond the HL-LHC and ILC at dramatically lower cost.
  - Play a world-leading role in the ILC experimental program and provide critical expertise and components to the accelerator, should this exciting scientific opportunity be realized in Japan.
  - Host a large water Cherenkov neutrino detector to complement the LBNF large liquid argon detector, unifying the global long-baseline neutrino community to take full advantage of the world's highest intensity neutrino beam at Fermilab.

- With foundations set by decades of hard work and support, U.S. particle physics is poised to move forward into a new era of discovery.
- More generally, we strongly affirm the essential importance of fundamental research in all areas of science.

Disciplines with a pipeline problem

- Initial HEPAP meeting suggested three disciplines with a training shortage
  - Accelerator Science
  - Instrumentation and Detector Development
  - Large-scale computing and “Big Data”

- The shortage has a different origin in each of these fields, and the severity and remedies vary.

- Phenomenology was also suggested as an affected discipline early on. It is crucial to the OHEP mission, and lean funding has made positions scarce. However, since training is available, it falls outside this charge.

Summary

Summary (1/2)

- A vision that starts from the science Drivers, driven by community discussions and inputs, with criteria to make tough choices and develop a program.
- The enormous physics potential of the LHC, entering a new era with its planned high-luminosity upgrades, should be fully exploited.
- The U.S. should host a world-leading neutrino program.
  - An optimized set of short- and long-baseline neutrino oscillation experiments, with the long-term focus on the Long Baseline Neutrino Facility (LBNF).
  - The Proton Improvement Plan (PIP-II) project at Fermilab would provide the needed neutrino physics capability.
- Large projects are ordered by peak construction time: the Mu2e experiment completion, the high-luminosity LHC upgrades, and LBNF.
  - Based on budget constraints, physics needs, and readiness criteria.
- The interest expressed in Japan in hosting the International Linear Collider (ILC) is an exciting development.
  - Participation by the U.S. in project construction depends on a number of important factors, some of which are beyond the scope of P5 and some of which depend on budget Scenarios.
  - As the physics case is extremely strong, all Scenarios include ILC support at some level through a decision point within the next 5 years.

Summary (2/2)

- Several medium and small projects in areas especially promising for near-term discoveries and in which the U.S. is in a leadership position, should move forward under all budget scenarios.
  - Second- and third-generation dark matter direct detection experiments, the particle physics components of the Large Synoptic Survey Telescope (LSST) and cosmic microwave background (CMB) experiments, and a portfolio of small neutrino experiments.
  - Another important project of this type, the Dark Energy Spectroscopic Instrument (DESI), would also move forward, except in the lowest budget Scenario.
- With a mix of large, medium, and small projects, important physics results will be produced continuously throughout the twenty-year P5 timeframe.
  - In our budget exercises, we maintained a small projects portfolio to preserve budgetary space for a set of projects whose costs individually are not large enough to come under direct P5 review but which are of great importance to the field.
  - This is in addition to the aforementioned small neutrino experiments portfolio, which is intended to be integrated into a coherent overall neutrino program.
- Specific investments should be made in essential accelerator R&D and instrumentation R&D. The field relies on its accelerators and instrumentation and on R&D and test facilities for these technologies.

Summary of Scenarios

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

Backup slides: Recommendations

Project-specific Recommendations

#1-2:

Recommendation 1: Pursue the most important opportunities wherever they are, and host unique, world-class facilities that engage the global scientific community.

Recommendation 2: Pursue a program to address the five science Drivers.

Project-specific Recommendations

#3-9:

3: Develop a mechanism to reassess the project priority at critical decision stages if costs and/or capabilities change substantively.

4: Maintain a program of projects of all scales, from the largest international projects to mid- and small-scale projects.

5: Increase the budget fraction invested in construction of projects to the 20%–25% range.

6: In addition to reaping timely science from projects, the research program should provide the flexibility to support new ideas and developments.

7: Any further reduction in level of effort for research should be planned with care, including assessment of potential damage in addition to alignment with the P5 vision.

8: As with the research program and construction projects, facility and laboratory operations budgets should be evaluated to ensure alignment with the P5 vision.

9: Funding for participation of U.S. particle physicists in experiments hosted by other agencies and other countries is appropriate and important but should be evaluated in the context of the Drivers and the P5 Criteria and should not compromise the success of prioritized and approved particle physics experiments.

Project-specific Recommendations

#10-11:

Recommendation 10: Complete the LHC phase-1 upgrades and continue the strong collaboration in the LHC with the phase-2 (HL-LHC) upgrades of the accelerator and both general-purpose experiments (ATLAS and CMS). The LHC upgrades constitute our highest-priority near-term large project.

Recommendation 11: Motivated by the strong scientific importance of the ILC and the recent initiative in Japan to host it, the U.S. should engage in modest and appropriate levels of ILC accelerator and detector design in areas where the U.S. can contribute critical expertise. Consider higher levels of collaboration if ILC proceeds.

Project-specific Recommendations

#12-15:

Recommendation 12: In collaboration with international partners, develop a coherent short- and long-baseline neutrino program hosted at Fermilab.

Recommendation 13: Form a new international collaboration to design and execute a highly capable Long-Baseline Neutrino Facility (LBNF) hosted by the U.S. To proceed, a project plan and identified resources must exist to meet the minimum requirements in the text. LBNF is the highest-priority large project in its timeframe.

Recommendation 14: Upgrade the Fermilab proton accelerator complex to produce higher intensity beams. R&D for the Proton Improvement Plan II (PIP-II) should proceed immediately, followed by construction, to provide proton beams of >1 MW by the time of first operation of the new long-baseline neutrino facility.

Recommendation 15: Select and perform in the short term a set of small-scale short-baseline experiments that can conclusively address experimental hints of physics beyond the three-neutrino paradigm. Some of these experiments should use liquid argon to advance the technology and build the international community for LBNF at Fermilab.

Project-specific Recommendations

#16/17/18/21:

Recommendation 16: Build DESI as a major step forward in dark energy science, if funding permits (see Scenarios discussion below).

Recommendation 17: Complete LSST as planned.

Recommendation 18: Support CMB experiments as part of the core particle physics program. The multidisciplinary nature of the science warrants continued multiagency support.

Recommendation 21: Invest in CTA as part of the small projects portfolio if the critical NSF Astronomy funding can be obtained.

Project-specific Recommendations

#19-20, 22:

Recommendation 19: Proceed immediately with a broad second-generation (G2) dark matter direct detection program with capabilities described in the text. Invest in this program at a level significantly above that called for in the 2012 joint agency announcement of opportunity.

Recommendation 20: Support one or more third-generation (G3) direct detection experiments, guided by the results of the preceding searches. Seek a globally complementary program and increased international partnership in G3 experiments.

Recommendation 21: Invest in CTA as part of the small projects portfolio if the critical NSF Astronomy funding can be obtained.

Recommendation 22: Complete the Mu2e and muon g-2 projects.

Enabling R&D

23-24 & 26-29:

Recommendation 23: Support the discipline of accelerator science through advanced accelerator facilities and through funding for university programs. Strengthen national laboratory-university R&D partnerships, leveraging their diverse expertise and facilities.

Recommendation 24: Participate in global conceptual design studies and critical path R&D for future very high-energy proton-proton colliders. Continue to play a leadership role in superconducting magnet technology focused on the dual goals of increasing performance and decreasing costs.

Recommendation 26: Pursue accelerator R&D with high priority at levels consistent with budget constraints. Align the present R&D program with the P5 priorities and long-term vision, with an appropriate balance among general R&D, directed R&D, and accelerator test facilities and among short-, medium-, and long-term efforts. Focus on outcomes and capabilities that will dramatically improve cost effectiveness for mid-term and far-term accelerators.

Enabling R&D

23-24 & 26-29:

27: Focus resources toward directed instrumentation R&D in the near-term for high-priority projects. As the technical challenges of current high-priority projects are met, restore to the extent possible a balanced mix of short-term and long-term R&D.

28: Strengthen university-national laboratory partnerships in instrumentation R&D through investment in instrumentation at universities. Encourage graduate programs with a focus on instrumentation education at HEP supported universities and labs, and fully exploit the unique capabilities and facilities offered at each.

29: Strengthen the global cooperation among laboratories and universities to address computing and scientific software needs, and provide efficient training in next-generation hardware and data-science software relevant to particle physics. Investigate models for the development and maintenance of major software within and across research areas, including long-term data and software preservation.

Enabling R&D

25:

Recommendation 25: Reassess the Muon Accelerator Program (MAP). Incorporate into the GARD program the MAP activities that are of general importance to accelerator R&D, and consult with international partners on the early termination of MICE.