Fermilab U.S. DEPARTMENT OF ENERGY Office of Science

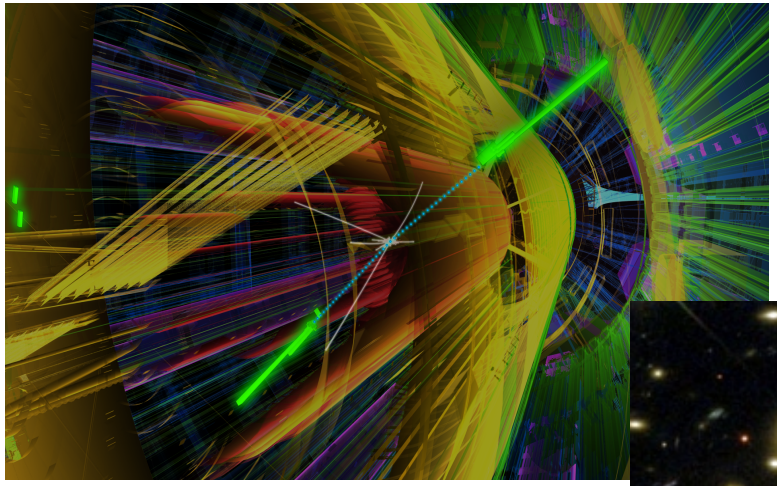
Particle Physics at Fermilab

Marcela Carena

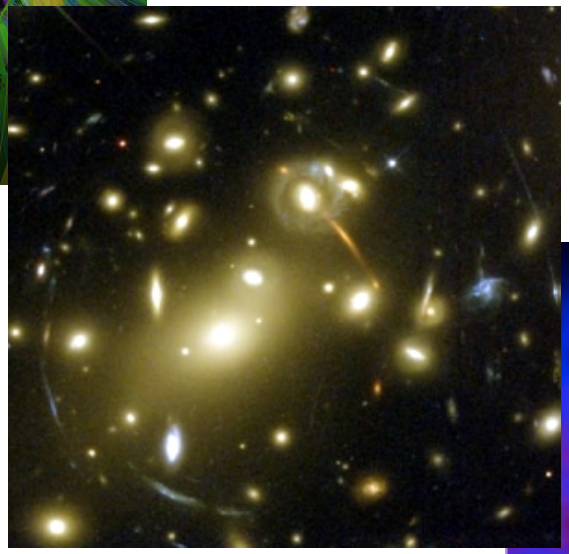
Encontro de Física 2016

Natal, September 7th, 2016

The Big Mysteries of Particles Physics

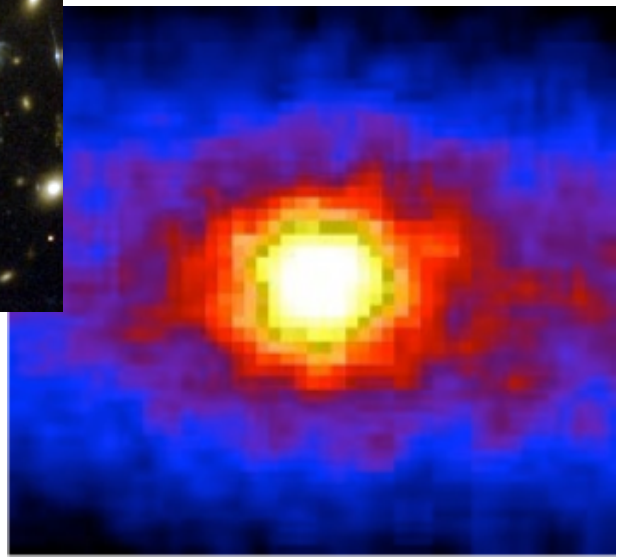


What makes particles massive and slows them down from moving at the speed of light?



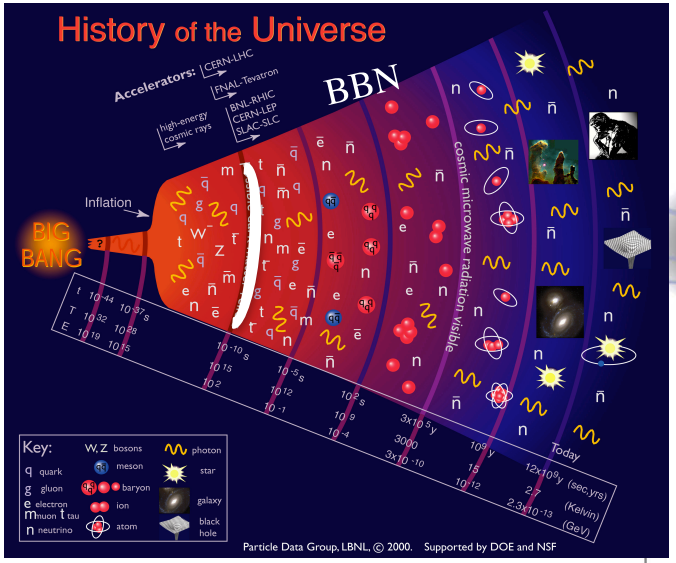
What distorts the images of distant galaxies?

What makes the fabric of the cosmos and holds it together?

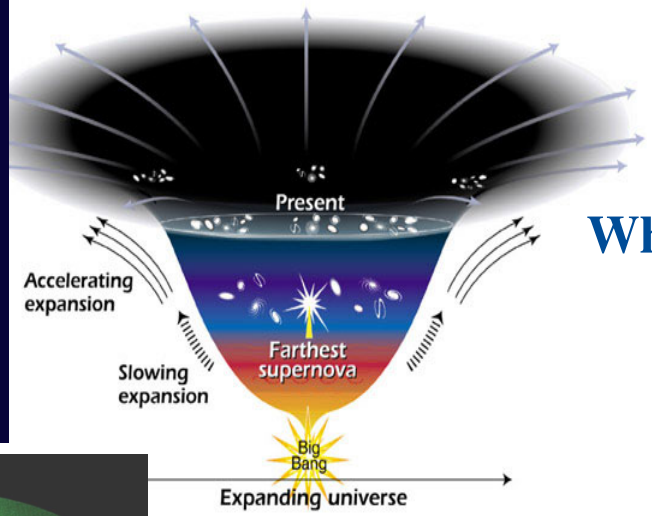


What are the secrets encoded in the tiny but mighty Neutrinos?

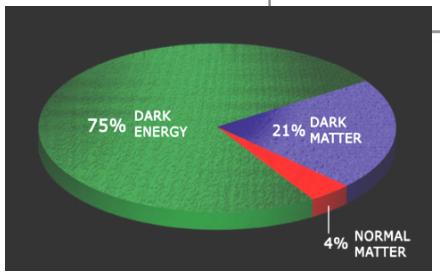
and Cosmology



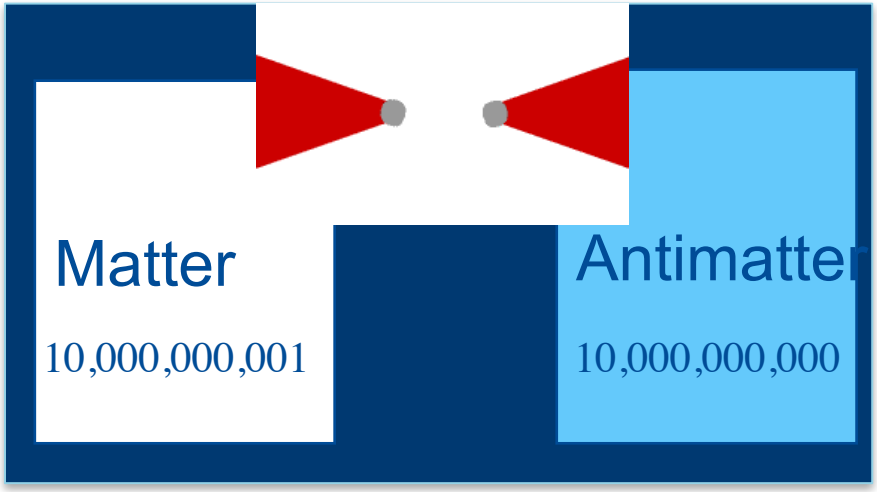
What produces cosmic acceleration?



What is the composition of our Universe ?



How we came to existence?



Big Science Questions
Require Big Ideas and Powerful Tools

- The Higgs Mechanism
- Supersymmetry
- New models of Strong Dynamics
- Models of Neutrino Masses
- Dark Matter
- Grand Unification
- Inflation
- Dark Energy
- Baryogenesis/Leptogenesis
- Large Scale structure formation

- Advanced High Energy/High Intensity Accelerators
- Forefront Detectors with many different technologies for Dark Matter, Neutrinos, New Particles, Gamma-rays
- Big Telescopes for CMB, Neutrinos, Gamma-ray, Sky Surveys

Fermilab's Role in Today's Particle Physics World

- **Lead worldwide research in Neutrino Physics based on particle accelerators**
- **Lead development of particle accelerators in the US and its use for scientific discovery**
- **Advance our understanding of the universe through Cosmic measurements**

Drive scientific discoveries in collaboration with US and international Universities and laboratories

Fermilab serves a global community of physicists

More than 3500 scientists use our facilities

They represent 450 institutions from 44 countries

We are working to become even more international

Latin America and Fermilab:
33 years of collaboration and stronger than ever

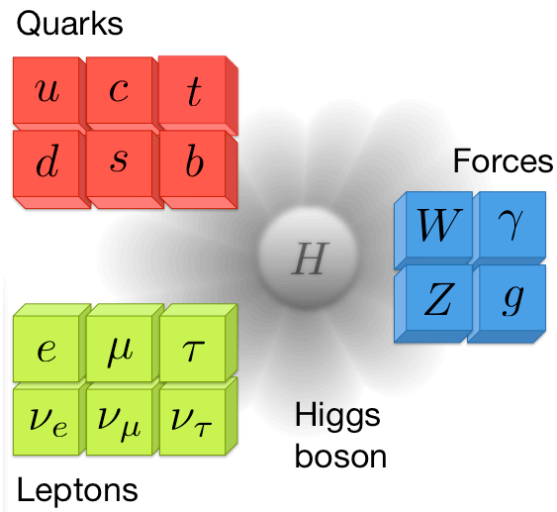
http://www.symmetrymagazine.org/article/march-2014/30-years-of-inter-american-collaboration

The discovery of the Higgs Boson (July 4th 2012)

A new Era for Particle Physics and Cosmology

- **It is a new type of particle we have never seen before**
- **It demonstrates the existence of a new force in nature**
- **Proves the existence of an invisible field that has the property to make fundamental, sub-atomic particles massive**

It completes the Standard Model of Particle Physics



Higgs connections

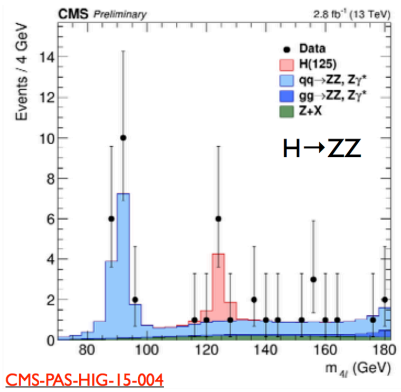
Does the Higgs field destabilize the vacuum?
How does the Higgs talk to neutrinos?
Is there a Higgs portal to dark matter?
Is the Higgs sector related to baryogenesis?
Extra credit: Is the Higgs related to inflation or dark energy?

The Higgs boson and the Naturalness Argument

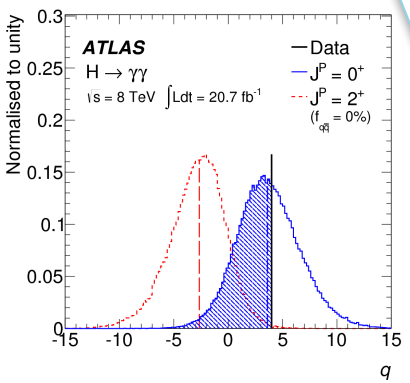
- **The Higgs restores the calculability power of the SM**

  - **The Higgs is special : it is a scalar**

G. Burdman's Talk

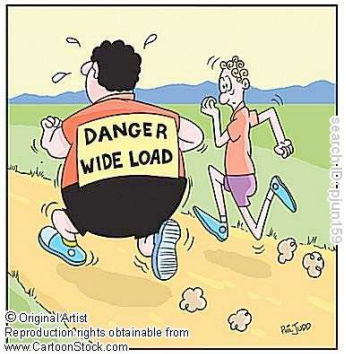


CMS-PAS-HIG-15-004



Scalar masses at quantum levelare not protected by gauge symmetries and have quadratic sensitivity to the UV physics

Although the SM with the Higgs is a consistent theory, light scalars like the Higgs cannot survive in the presence of heavy states at GUT/String/Planck scales



Fine tuning ⟷ **Naturalness problem**

Higgs, Naturalness and the need for New Physics

$m_H << M_P$?

how far are we willing to go?

Towards naturalness

No new TeV-physics

"fermionizing" the Higgs

Supersymmetry

"marrying" a fermion:

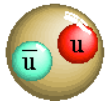
Higss ⟷ Higgsino

relaxation mechanism?

arXiv:1504.07551

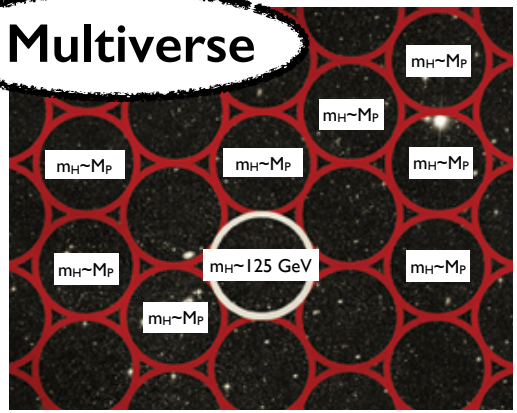
Compositeness

The "transvestite" Higgs:

H = 

new TeV-physics

Multiverse



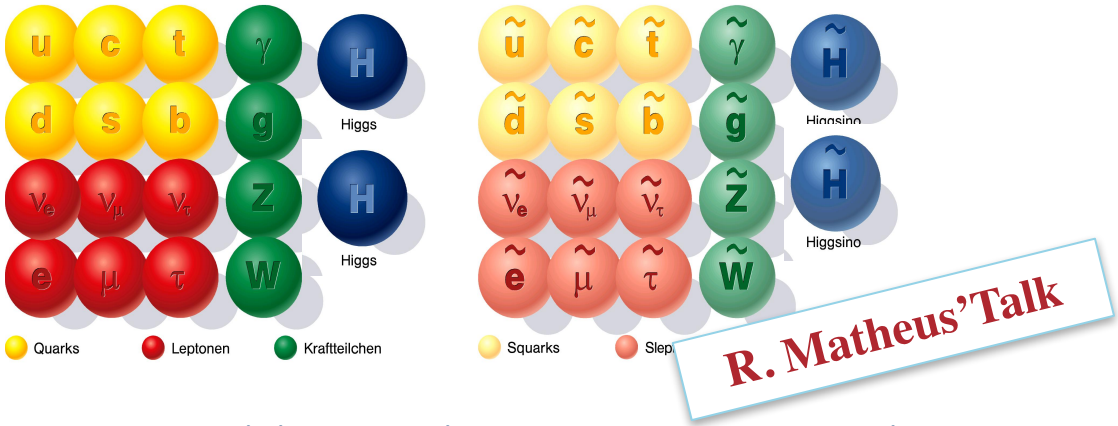
A. Pomarol, WIN2015

Supersymmetry:

a fermion-boson symmetry :

The Higgs remains elementary

but its mass is protected by SUSY

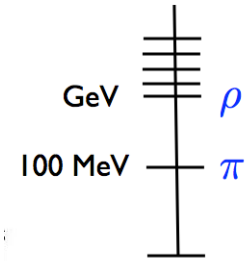


At least 2 neutral and 1 charged additional Higgs bosons must exist

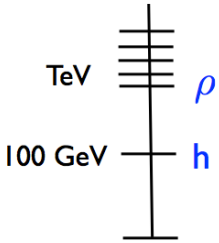
Some superpartners: stops, Higgsinos and gluinos expected to be at the TeV scale

Composite Higgs Models

The Higgs does not exist above a certain scale, at which the new strong dynamics takes place



Inspired by pions in QCD



New strong resonance must appear, with masses constrained by Precision Electroweak data and direct searches

Higgs as a pNGB➔ scalar resonance much lighter that other ones

Both options may be probed at the Large Hadron Collider (LHC),

If Nature is kind…

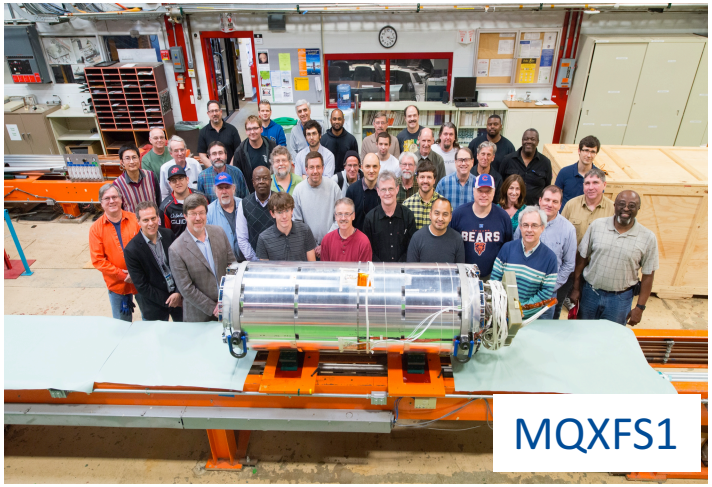
LHC at Fermilab

- Fermilab is working on models and prototypes of High-Field Magnets for CERN HL-LHC Upgrades

LHC Today: proton-proton collisions at E_{cm} = 13 TeV to recreate conditions of the early Universe

B. Heinemann's Talk

High Luminosity LHC (2026-2035) increase number of collisions per second to increase discovery power



1st short Nb_3Sn magnet (MQXFS1) successfully tested at FNAL in 02/2016.

LHC at Fermilab

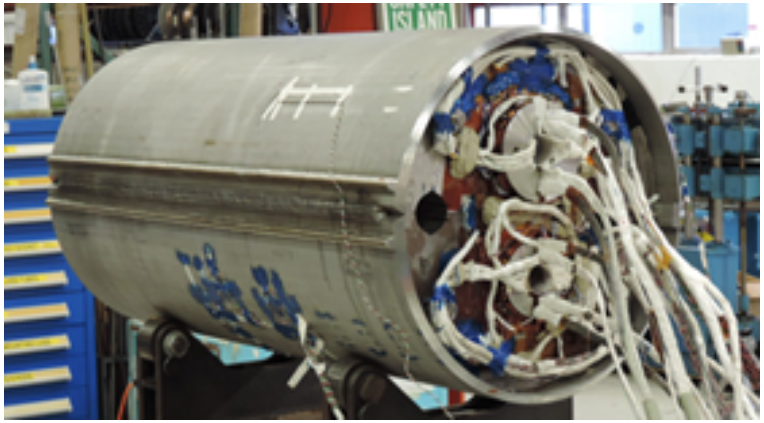
LHC Today: proton-proton collisions at E_{cm} = 13 TeV to recreate conditions of the early Universe

High Luminosity LHC (2026-2035) increase number of collisions per second to increase discovery power

- Fermilab is working on R&D for next generation High field Magnet

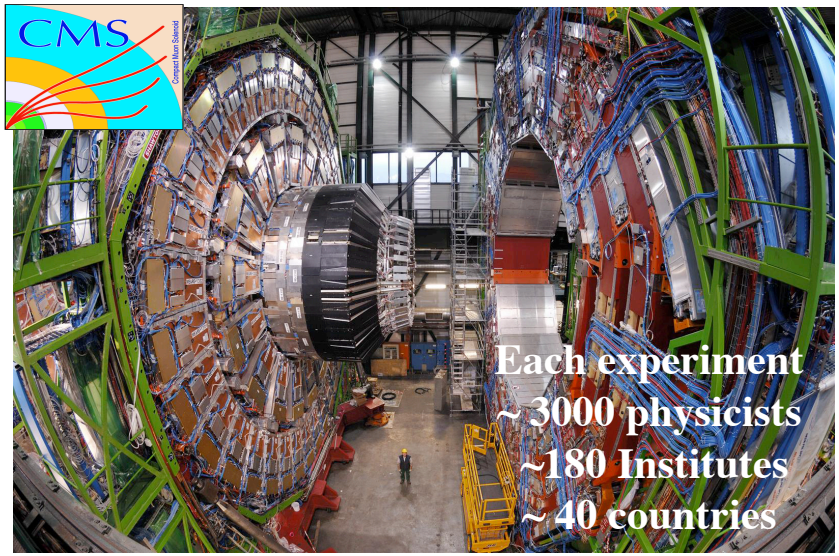
Breakthroughs in materials, systems, engineering are needed for higher fields

HE-LHC is increasingly popular path for upgrades and future of CERN's LHC



1 meter long 2-in-1 Nb_3Sn magnet
Successfully tested at Fermilab to 11.6T

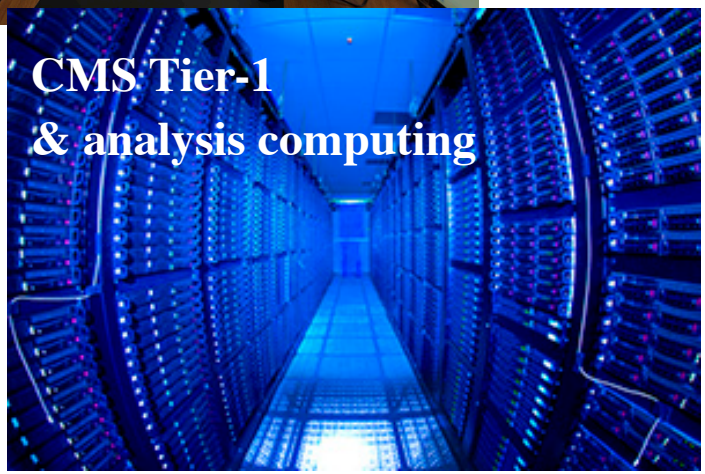
CMS at Fermilab



Powerful Detectors: ATLAS & CMS
Huge, complex objects with cutting-edge technology that take "pictures" of collisions

CMS Remote Operations Center

- Fermilab is the host lab of U.S. CMS
- U.S. CMS is 30% of CMS collaboration
- Fermilab manages U.S. CMS operations program, and HL-LHC upgrade projects
- **Fermilab's Joel Butler: CMS spokesperson**

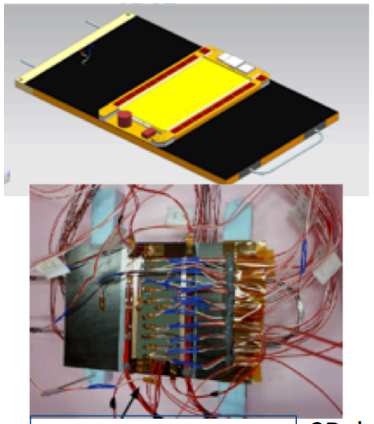


Fermilab LHC Physics Center:
150 resident users, 700 remote users

Strong Synergy of Theorists & Experimentalists!

CMS at Fermilab

Detector R&D and test beam



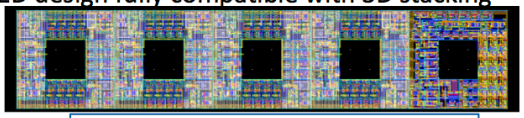
CMS PS module drawing
And thermal prototype

High Granularity Calorimeter
Thermal tests

Scintillator extrusions and chemistry

Scintillator extrusions facility

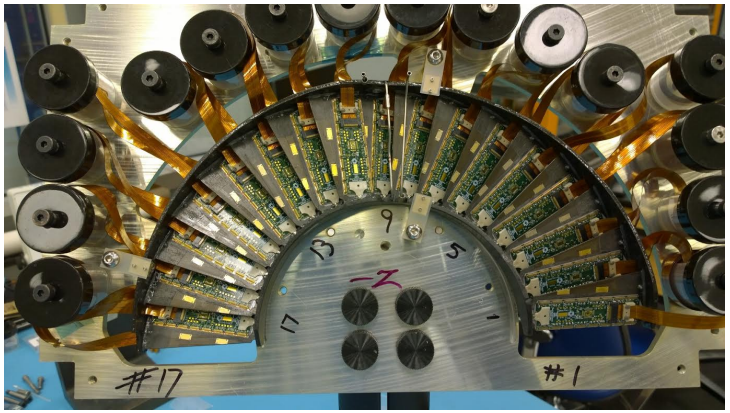
2D design fully compatible with 3D stacking



VIPRAM associative memory IC design

Ongoing CMS Detector Upgrades

- Level 1 Trigger, Many Hadronic calorimeter electronics
- Forward Pixel detector (below)



HL-LHC CMS Detector Upgrades

Science goal:

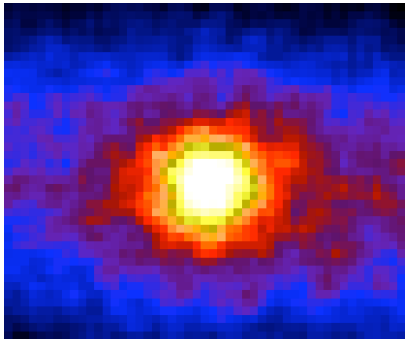
Maintain excellent detector performance during HL-LHC running (2026-2035) in a high radiation, high pileup environment.

The Omnipresent Neutrinos

Key actors in important physical processes on Earth & out in the Universe

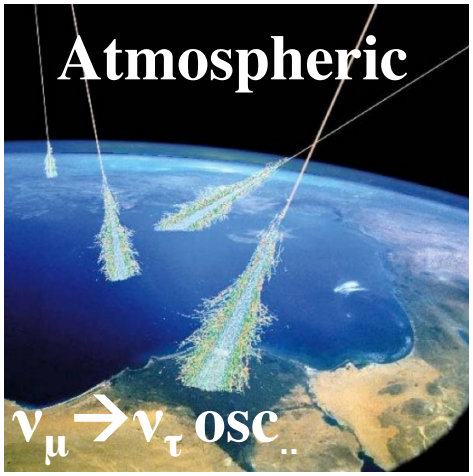
Neutrinos from many sources

Solar

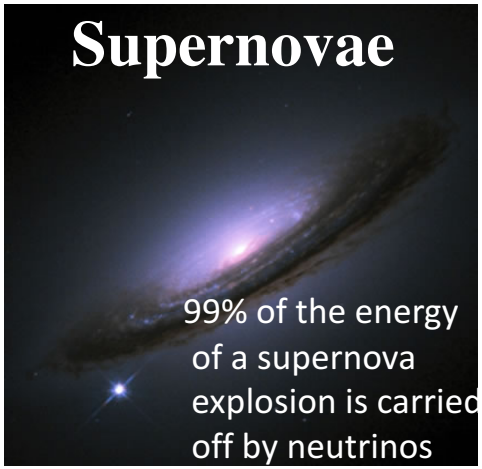


65 billion ν's per cm^2 of Earth surface facing the Sun

Atmospheric

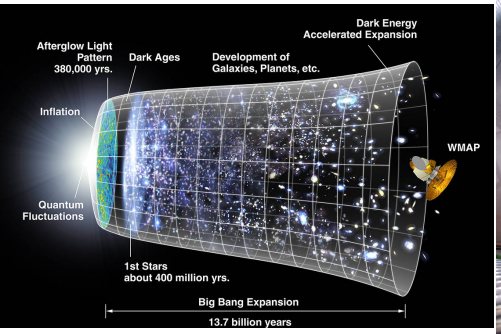


Supernovae



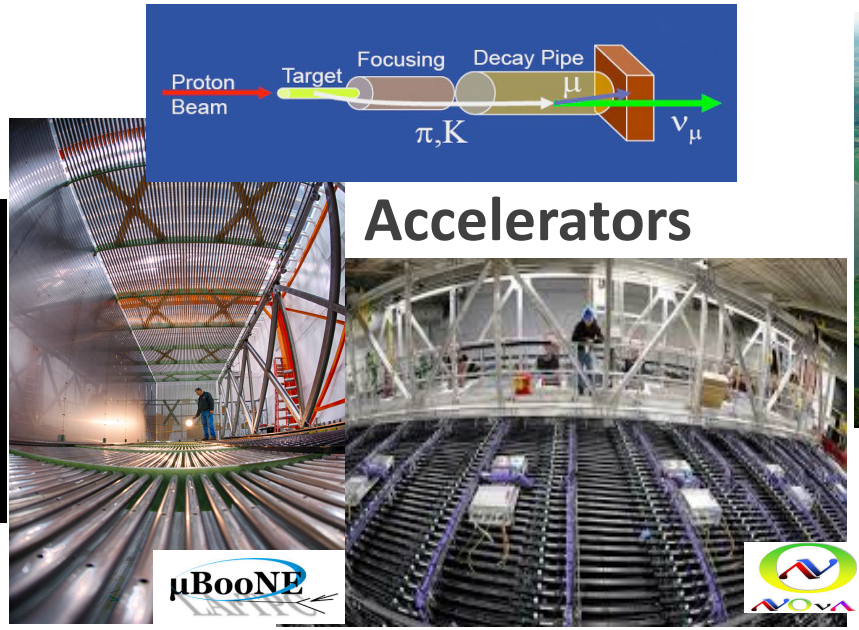
Geo

Relic



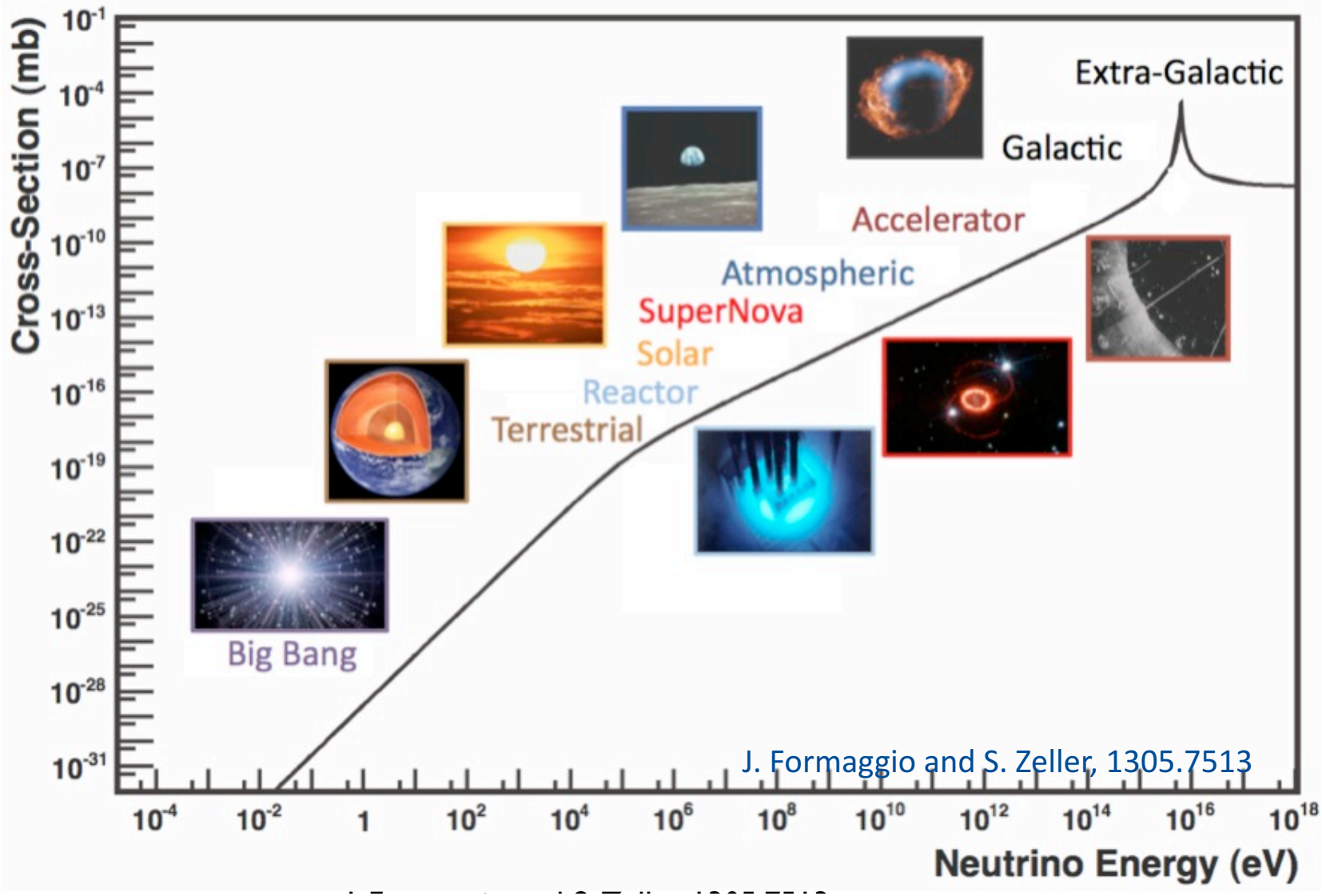
10 million ν's left over per cubic foot of space

Accelerators



Reactors

Neutrinos from many sources



Neutrinos Oscillate

Neutrino oscillations are like many other systems in QM, in which the initial state is a coherent superposition of eigenstates of a Hamiltonian

Neutrinos have mass ➔ the different massive components of the initial flavor state need to propagate with different phases

Neutrinos mix : otherwise, the flavor eigenstates would also be eigenstates of the Hamiltonian and not evolve.

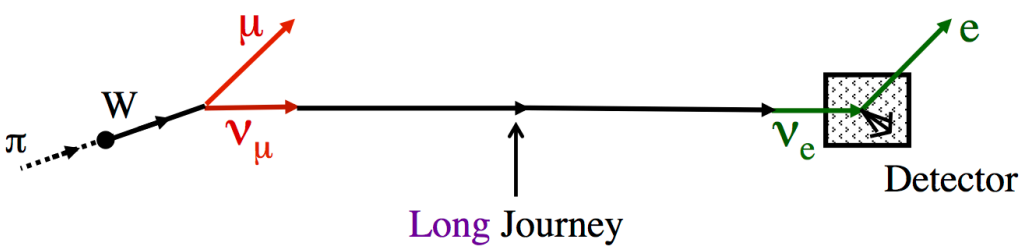
Neutrino flavor change, aka neutrino oscillation, over macroscopic distances

The **probability** for ν_μ to transform into ν_e is:

$$P(\nu_\mu \to \nu_e) = \sin^2(2\theta)\sin^2\frac{(m_2^2 - m_1^2)L}{4E}$$

Mixing angle: disalignment between flavour and mass states

Neutrino masses



Neutrinos Oscillate

Neutrinos of definite flavor ν_e , ν_μ , and ν_τ are ***superpositions*** of the mass eigenstates, ν_1, ν_2, and ν_3: $|\nu_\alpha\rangle = \Sigma\, U^*_{\alpha i}\, |\nu_i\rangle$ α = e, μ, or τ

Leptonic Mixing Matrix: Pontecorvo-Maki-Nakagawa-Sakata

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\alpha_1} & 0 \\ 0 & 0 & e^{i\alpha_2} \end{pmatrix}$$

Atmospheric — Reactor/Interference — Solar — Majorana phases

The two Majorana phases are only there if neutrinos are Majorana, and the additional CP violating phase δ is the only one that can be measured in neutrino oscillation experiments

What we know :

2 squared mass differences

$\Delta^2_{sol} \sim 7.5 \times 10^{-5}\, eV^2$ $\Delta^2_{atm} \sim 2.4 \times 10^{-3}\, eV^2$

3 mixing angles (much larger than in the quark sector) ➔ $\theta_{13} \sim 9°$, $\theta_{23} \sim 45°$, $\theta_{12} \sim 33°$

Neutrino Unknowns

How do neutrinos get mass?

- Dirac mass: Higgs Mechanism as the rest of the SM fermions

$$Y_\nu \overline{L}_L \widetilde{\phi} \nu_R \to m_\nu \bar{\nu}_L \nu_R$$

$m_\nu = Y_\nu\, v \sim 0.1$ eV ➔ $Y_\nu \lesssim 10^{-12}$ $\quad v = 174$ GeV

Allowed by experiment, but very tiny coupling

- Majorana mass => A Heavy right handed neutrino ν_R that couples to the Higgs

Seesaw Mechanism

$$Y_\nu \bar{L}_L \widetilde{\phi} \nu_R + \frac{1}{2} M \overline{\nu}^c_R \nu_R$$

$m_\nu = Y_\nu^2\, v^2/M$ ➔ $M \sim 10^{14}$ GeV $(Y_\nu \sim 1)$
or as low as 1 TeV $(Y_\nu \sim 10^{-5})$

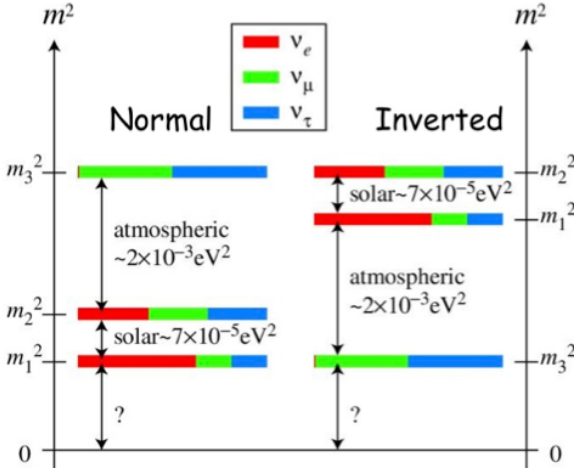
Majorana Neutrino ➔ $\nu \sim$ anti-ν ➔ Lepton # violation

The **nature of neutrinos** is linked to the conservation of the **Lepton number**

See-Saw Mechanism can be embedded in Grand Unified Theory and provide an explanation of the matter-antimmater asymmetry via Leptogenesis

Neutrino Unknowns (cont'd)

What is the Ordering of Neutrinos Masses?

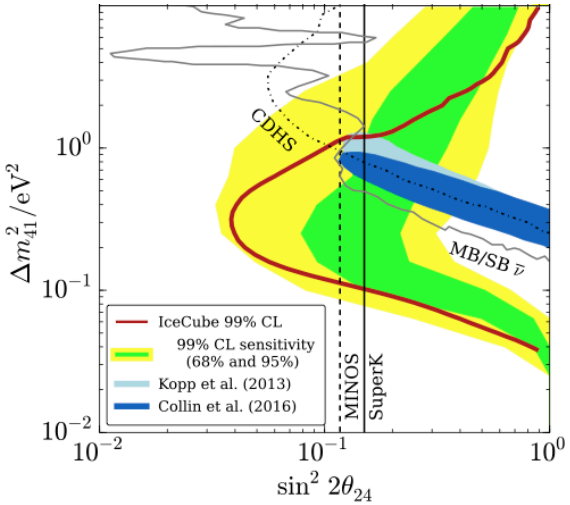


How much above zero is the whole pattern?
- is the lightest neutrino massless?-

Are neutrinos Majorana or Dirac? Aka
Do Neutrinos violate Lepton Number ?

Are there new sources of CP violation? , aka, if Majorana can we connect the new phases to an explanation of Leptogenesis?

Are there more that three Neutrinos?
Contradictory evidence on sterile neutrinos



Are there non standard Neutrino interactions?

Neutrino Future

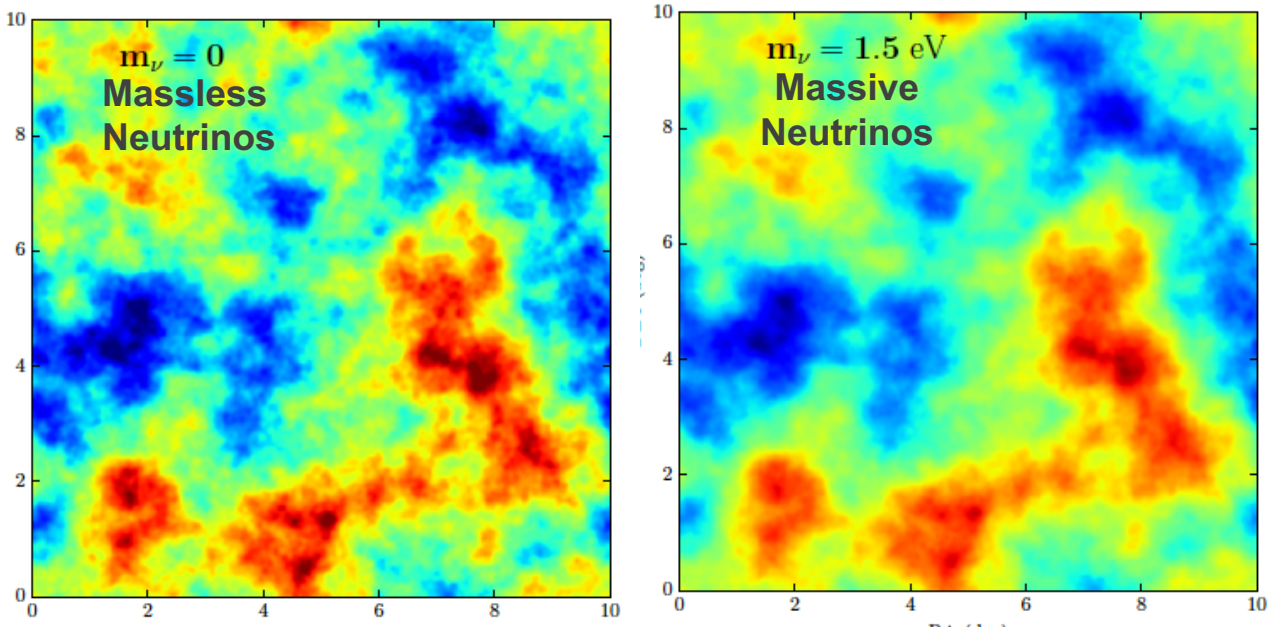
- A very large number of experiments in particle physics will cornered the neutrinos unknowns in the coming years

  this will demand: strong use of powerful controlled beams of neutrinos and large, more sensitive neutrino detectors

- Information on neutrino masses will also come from cosmology

Simulated maps of distortions produced by CMB gravitational lensing

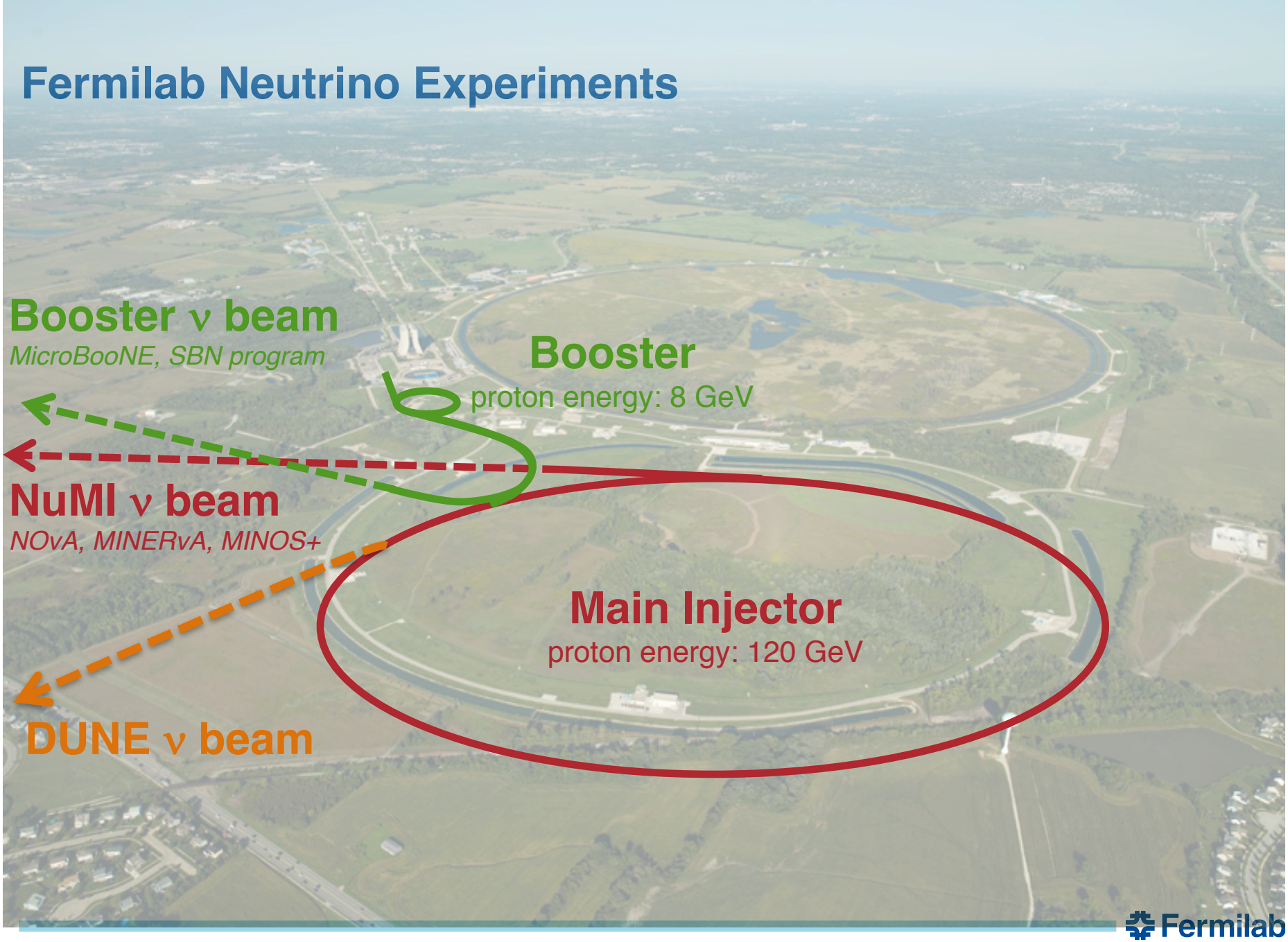
Manzotti, Dodelson' 14



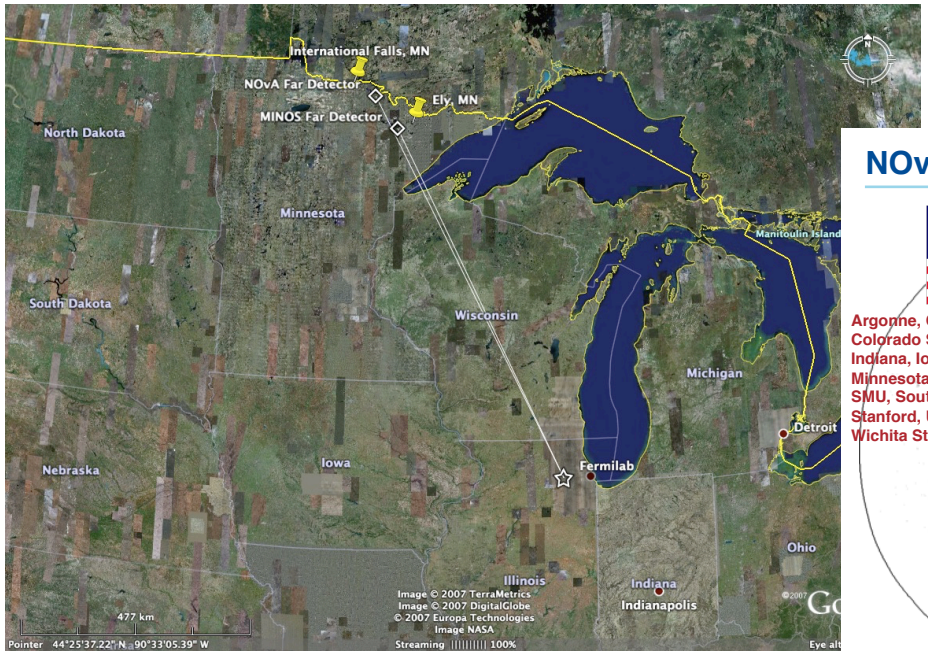
Relic neutrinos contribute to the total matter density and have an impact on structure

Standard Cosmological Model sets stringent limits on Neutrino masses $\Sigma m_i < 0.3$- 1.3 eV

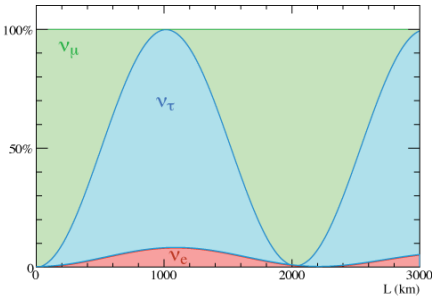
Fermilab Neutrino Experiments

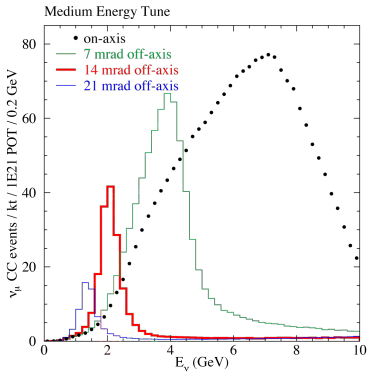


NOvA Experiment @ Fermilab



Slightly off axis, allows large flux peaking at 2 GeV, close to the maximum for ν_e oscillations

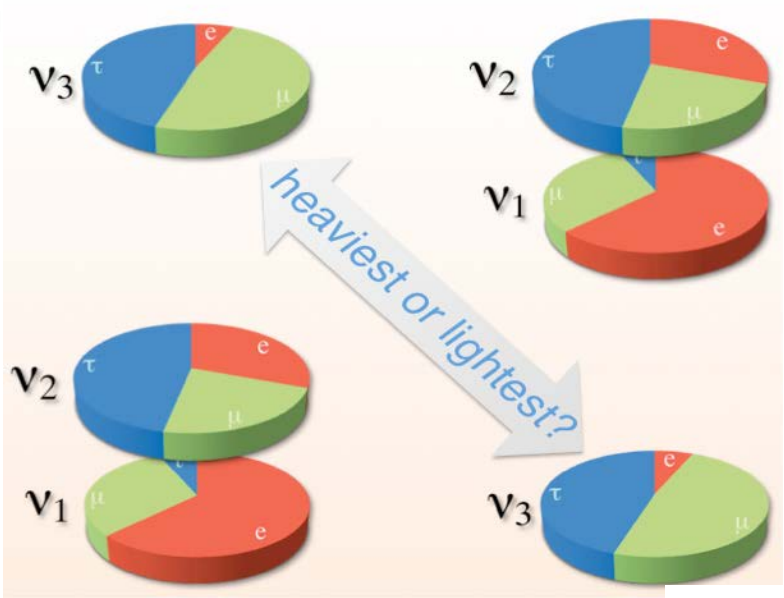




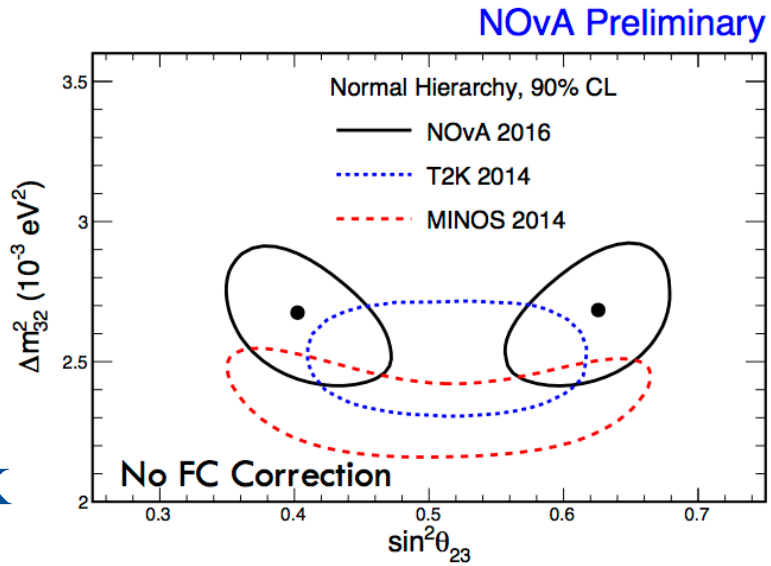
Run in both ν and anti-ν modes, until end of 2022

Nova Experiment @ Fermilab

- Mass ordering is a unique contribution from NOvA
- Nature of ν_3 - θ_{23} octant
- Is CP violated?
- Is there more to this picture?



Latest NOvA results on "the octant" (Neutrino2016):



Best Fit (in NH):

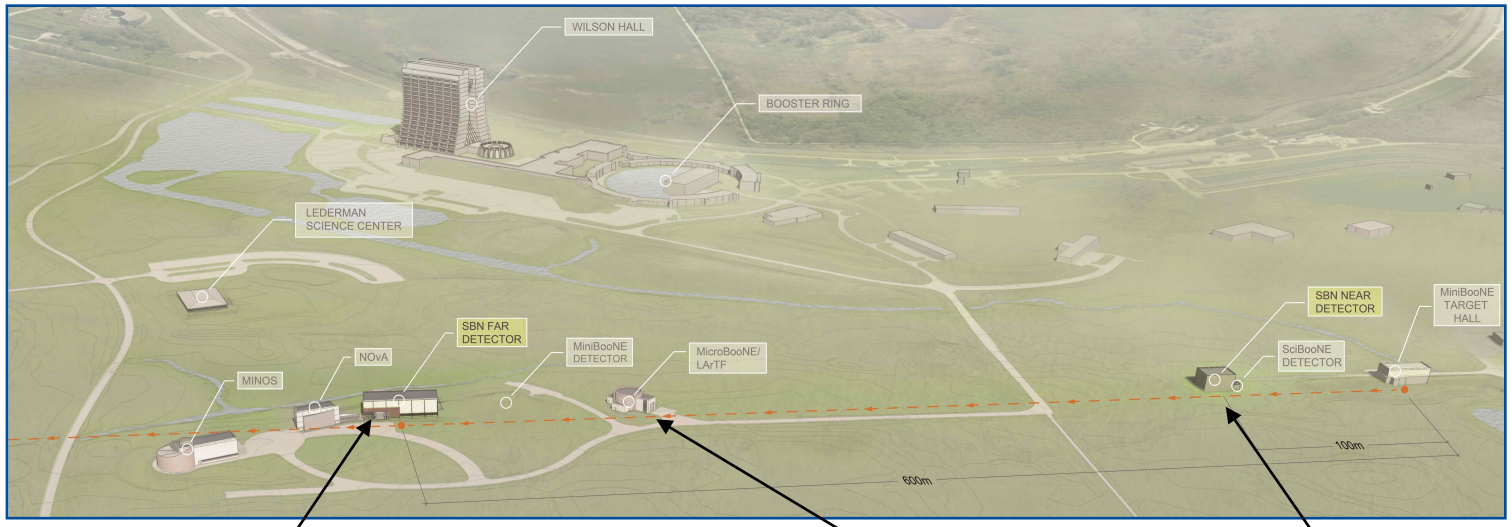
$$\left|\Delta m^2_{32}\right| = 2.67 \pm 0.12 \times 10^{-3}\mathrm{eV}^2$$

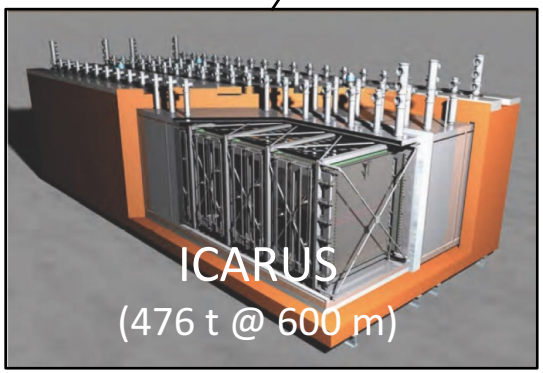
$$\sin^2\theta_{23} = 0.40^{+0.03}_{-0.02}(0.63^{+0.02}_{-0.03})$$

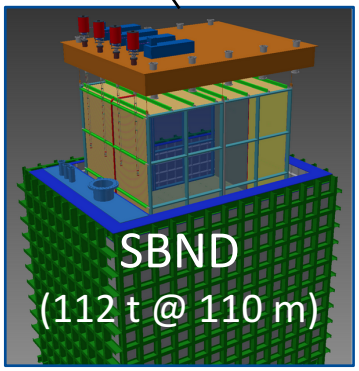
Maximal mixing excluded at 2.5 σ

interesting tension between NOvA and T2K

SBN = Short-baseline Neutrino Program

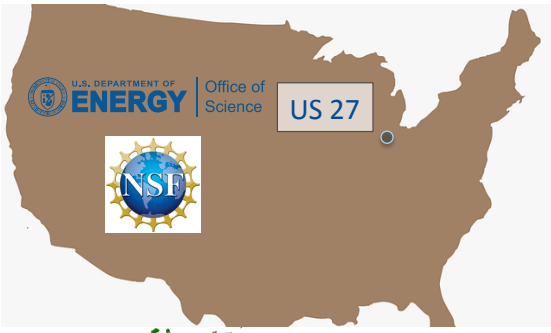


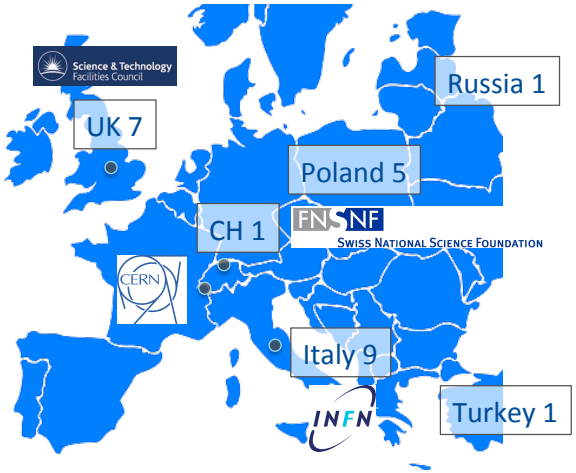




- **Sterile neutrino search with three liquid argon detectors**
- ICARUS refurbishment at CERN happening now (CERN + INFN)

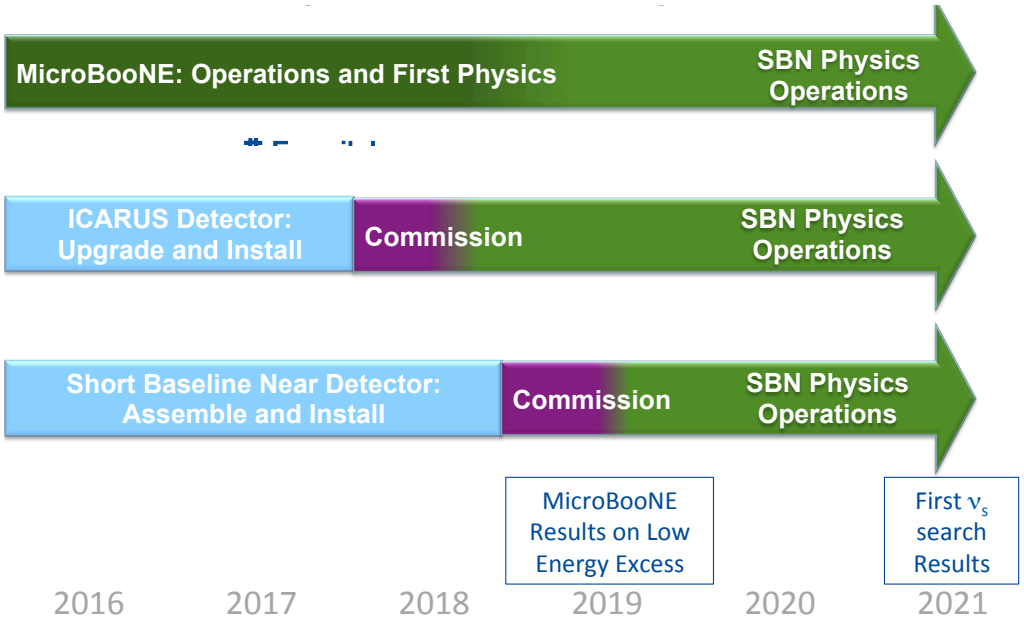
SBN Institutions - 2016





Institutions	SBN	SBN-DUNE Overlap
US	27	25
Non-US	28	24

Timeline to Physics for SBN Program



The DUNE/LBNF Project

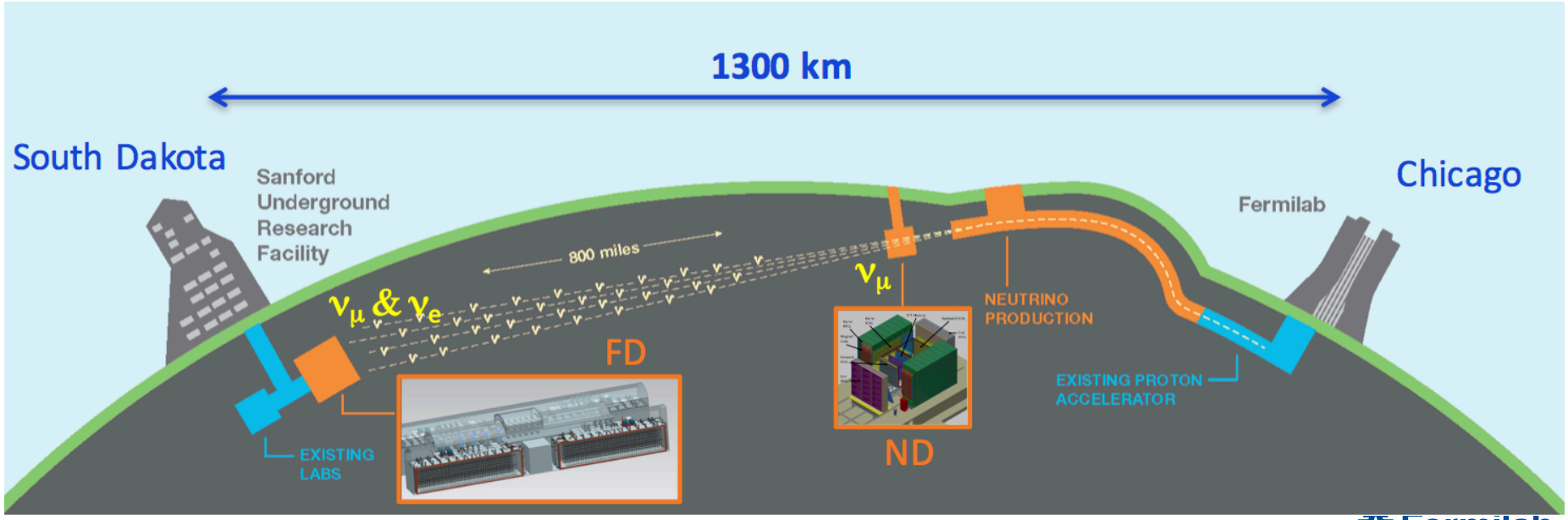
LBNF: **DOE project with support from non-DOE partners**. Provides facility infrastructure at two locations to support the experiment:

- Near site: Fermilab
- Far site: Sanford Underground Research Facility, Lead, SD

DUNE: Deep Underground Neutrino Experiment

- Near and far site detectors: **U.S. as partner in international project**

- Two ProtoDUNE detectors to operate in CERN test beam in 2018; First DUNE detector module in 2021; Neutrino beam to DUNE by 2026

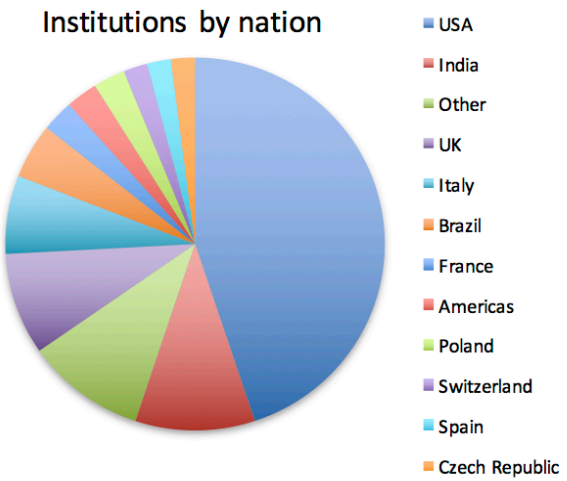


= Deep Underground Neutrino Experiment

The DUNE Collaboration

Currently: 867 Collaborators

from 153 Institutions



in 30 Nations:

Armenia, Belgium, Brazil, Bulgaria, Canada, Colombia, Czech Republic, Finland, France, Greece, India, Iran, Italy, Japan, Madagascar, Mexico, Netherlands, Peru, Poland, Romania, Russia, South Korea, Spain, Sweden, Switzerland, Turkey, UK, USA, Ukraine

DUNE already has broad international support

Crucial efforts from Brazilian Institutions:

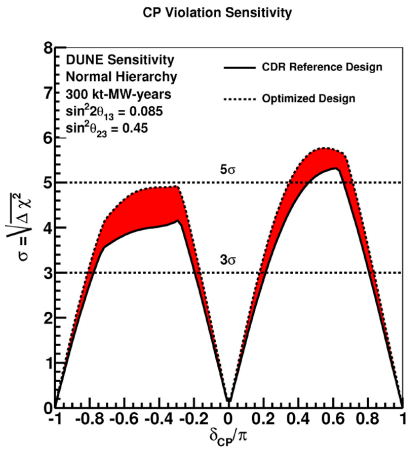
New technologies for light detection under development,

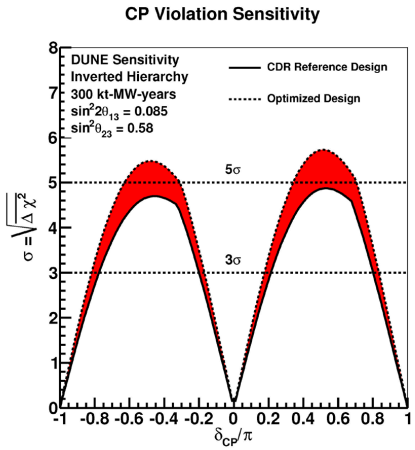
LArIAT - First Total π-Ar Cross Section Measurements and more

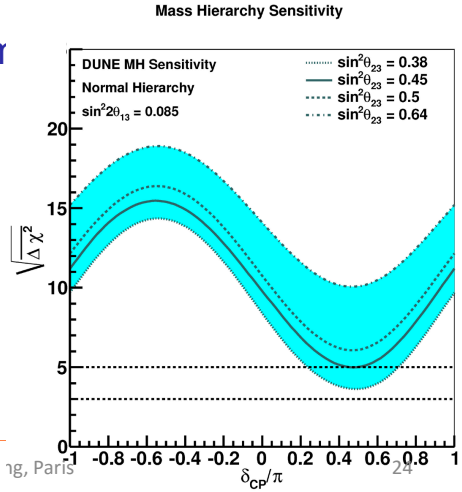
DUNE Primary Science Program

Focus on fundamental open questions in particle physics and astroparticle physics:

- **1) Neutrino Oscillation Physics**
  - **Discover CP Violation** in the leptonic sector
  - Mass Hierarchy
  - Precision Oscillation Physics:
    - e.g. parameter measurement, θ_{23} octant, testing the 3-flavor paradigm
- **2) Nucleon Decay**
  - e.g. targeting SUSY-favored modes, $p \rightarrow K^{+}\bar{\nu}$
- **3) Supernova burst physics & astrophysics**
  - Galactic core collapse supernova, sensitivity to ν_e







The Cosmic Frontier @ Fermilab

Dark Matter, Dark Energy, Inflation, Neutrinos & the unknown

- Grew out of the connection of particle physics and cosmology (inner-space – outerspace) and the close ties between the theoretical astrophysics groups at Fermilab and Chicago
- Capitalizes on scientific expertise, technical skills, and facilities developed for particle physics by applying them to cosmology projects

Science Driver	Experiments
Dark Matter	G1: SuperCDMS Soudan, COUPP/PICO, Darkside, DAMIC G2: SuperCDMS SNOLAB, LZ, ADMX G3: R&D towards advanced WIMP and Axion experiments
Dark Energy	DES, DESI, LSST
CMB	SPT-3G, CMB-S4
Exploring the Unknown	Holometer, Pierre Auger
Detector R&D	R&D on new techniques for particle astrophysics experiments
Astrophysics Th.	Strong coupling with particle astrophysics experiments

The power of the dark side

Holds the Universe together and makes *85% of all the matter in it!*

F. Iocco's Talk

Interacts very weakly
(not charged)

→ **Gravity**

→ **Higgs-like Interactions ?**

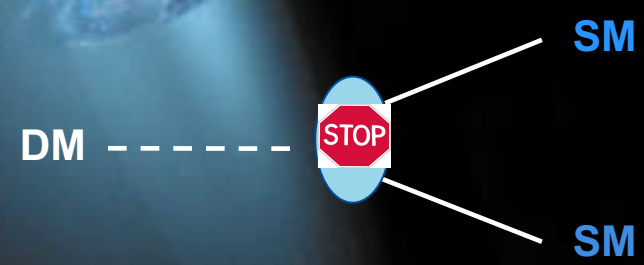
WIMP
Dark Matter ?

- DM = yet unknown, heavy, neutral elementary particle/s
- Mass estimate (model dependent) from observed DM abundance:

$M_{DM} \sim 100 - 1000$ GeV

and fits well with a weakly interacting particle = WIMP

CAVEAT: To avoid decay of a WIMP to lighter visible matter, theorists invented a symmetry: "dark matter charge" such that

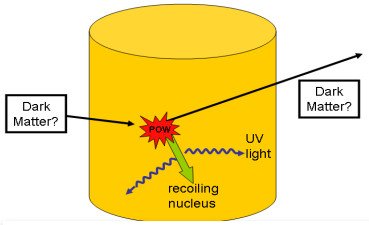


SUSY provides a natural candidate (lightest neutralino)
Many other BSM theories can also accommodate WIMPS

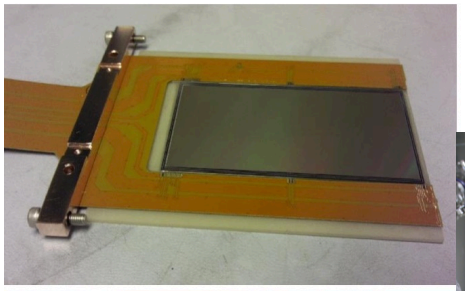
© 2003 Don Dixon/Cosmographica.com

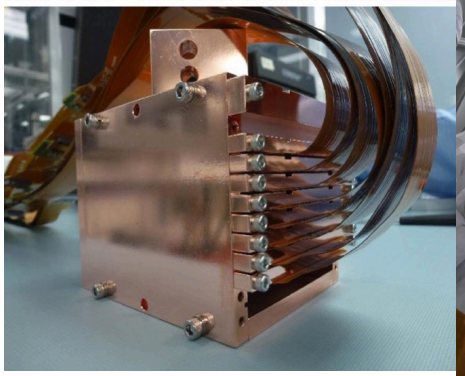
Direct Dark Matter Detection Experiments

It can collide with a single nucleus in the detector and be observed

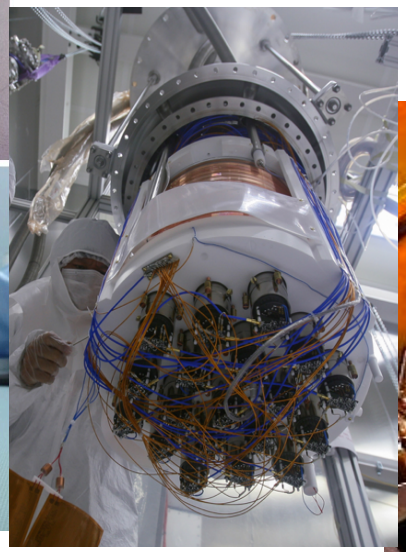


Underground detector

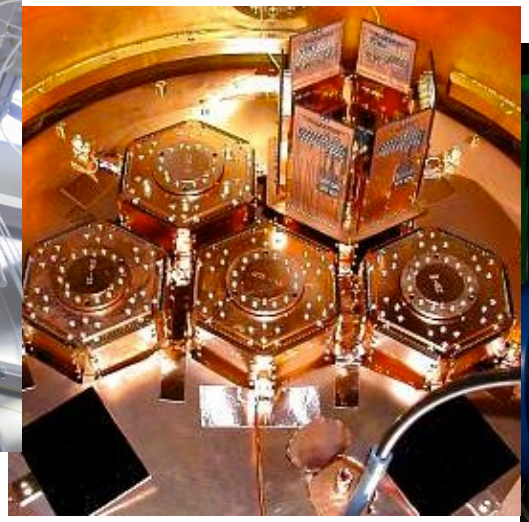




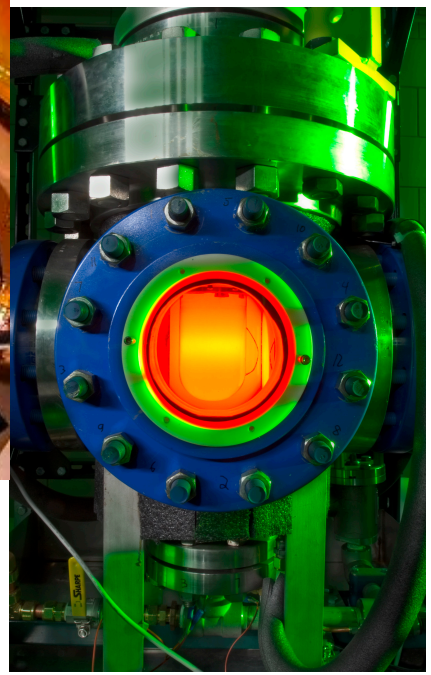
DAMIC



DarkSide



CDMS



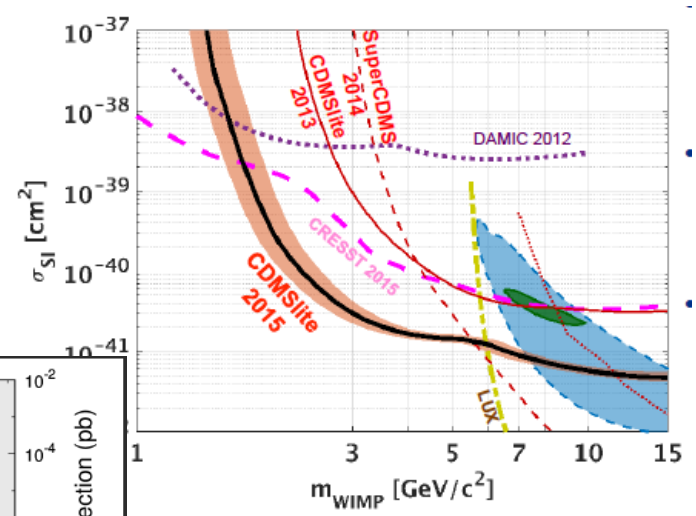
COUPP/PICO

Many different types of technologies

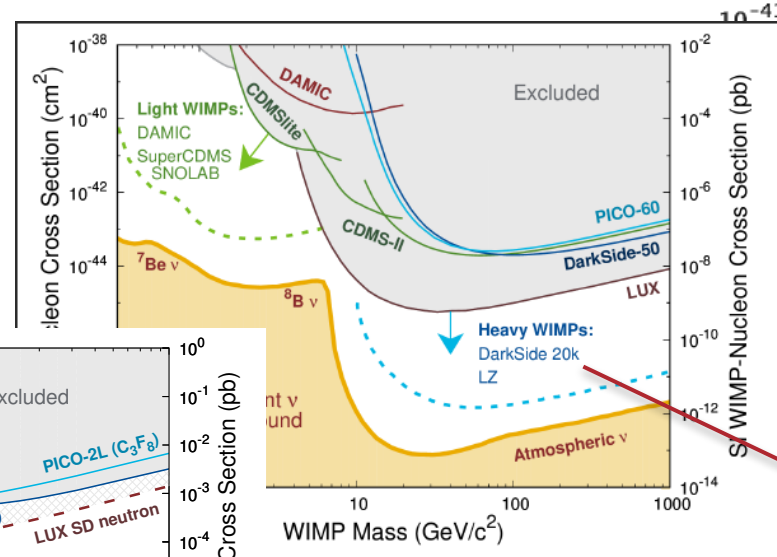
New involvement in LZ (liquid xenon) and ADMX (axion searches)

Direct Dark Matter Detection at Fermilab

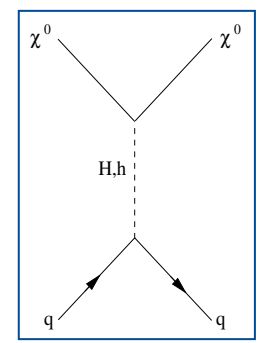
It can collide with a single nucleus in the detector and be observed

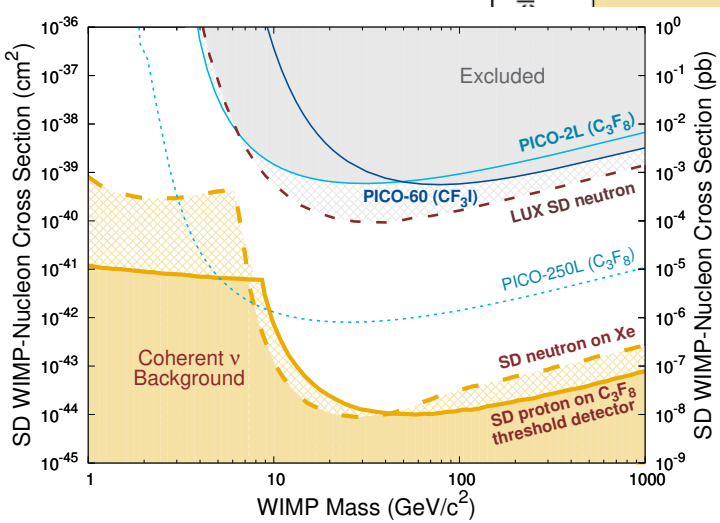


Spin-Independent



Uses phonons to amplify low-E ionization signal





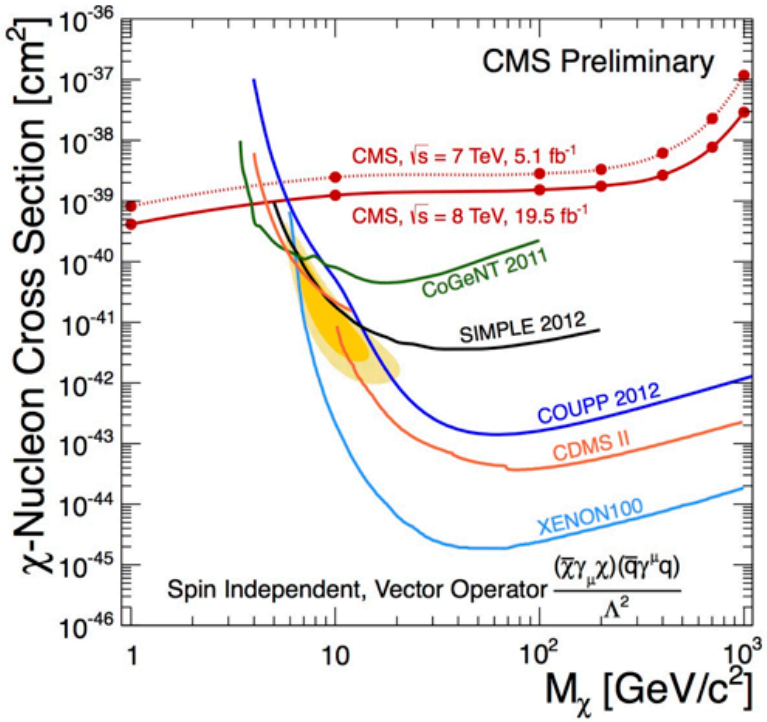
Spin-Dependent

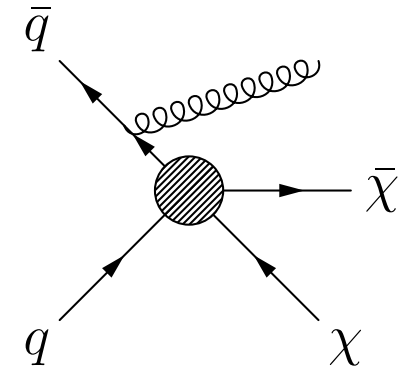
Starting to Probe the Higgs Portal

Dark Matter Searches at the LHC

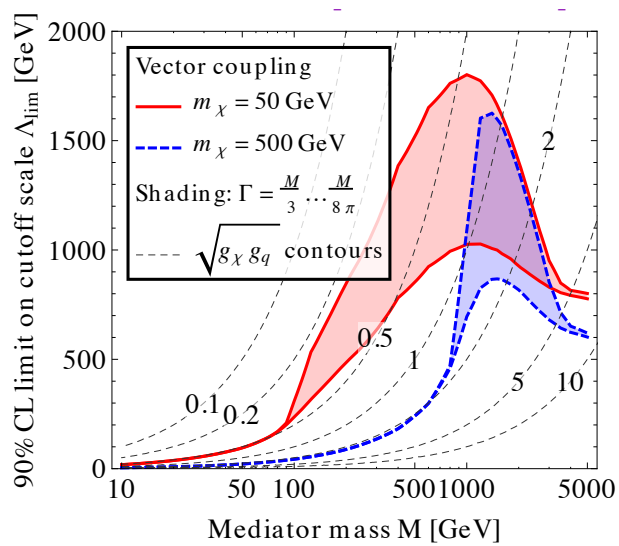
We can also manufacture Dark Matter at the LHC, and search for it using "mono"-jet/photon/Z/W/X searches (complement to direct and indirect searches)

Fermilab Theory group one of the pioneers of this idea!





Fox and Harnik



Consensus Cosmology

precision, accuracy, full accounting and consistency

- From quark soup to nuclei and atoms to galaxies and large-scale structure
- Flat, accelerating Universe
- Atoms, exotic dark matter & dark energy
- Consistent with inflation
- Precision cosmological parameters
  - $\Omega_0 = 1.005 \pm 0.005$ (uncurved = flat)
  - $\Omega_M = 0.315 \pm 0.01$
  - $\Omega_B = 0.048 \pm 0.001$
  - $\Omega_{DE} = 0.685 \pm 0.01$
  - $H_0 = 67 \pm 0.5$ km/s/Mpc
  - $t_0 = 13.80 \pm 0.02$ Gyr
  - $n_s = 0.965 \pm 0.005$
  - $N_\nu = 3.0 \pm 0.33$

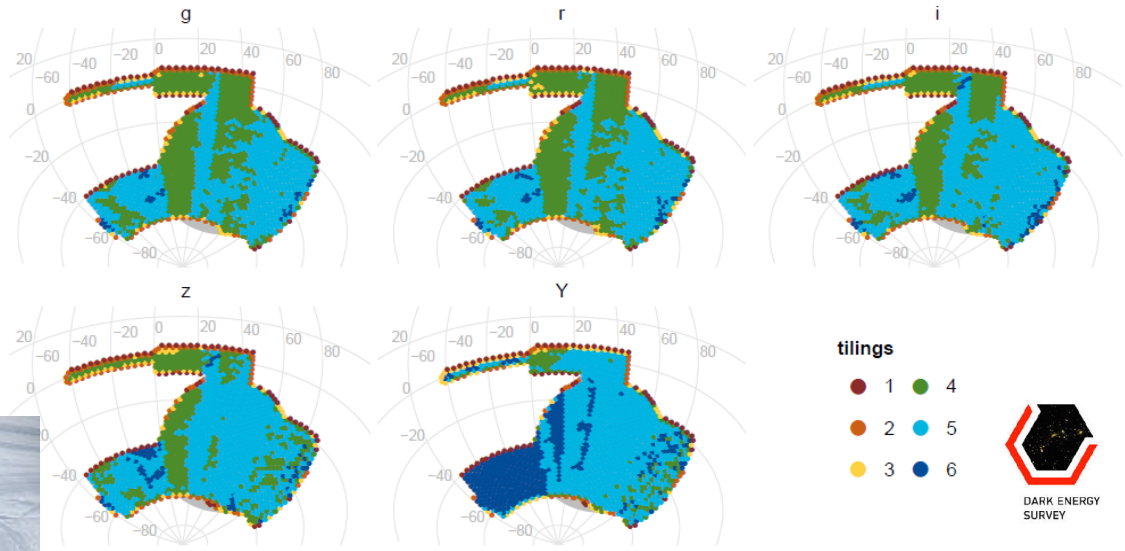
Consistent with all data, laboratory and cosmological!

DARK ENERGY MAY BE THE MOST PROFOUND PROBLEM IN ALL OF SCIENCE TODAY

Michael Turner, Cosmology Summary, 2015

Dark Energy Survey Research at Fermilab

Combining surveys: Continued work to optimize survey design to maximize sensitivity to dark energy and other cosmic parameters e.g. combining results from CMB [SPT], photometric [DES, LSST] and spectroscopic [DESI] surveys.

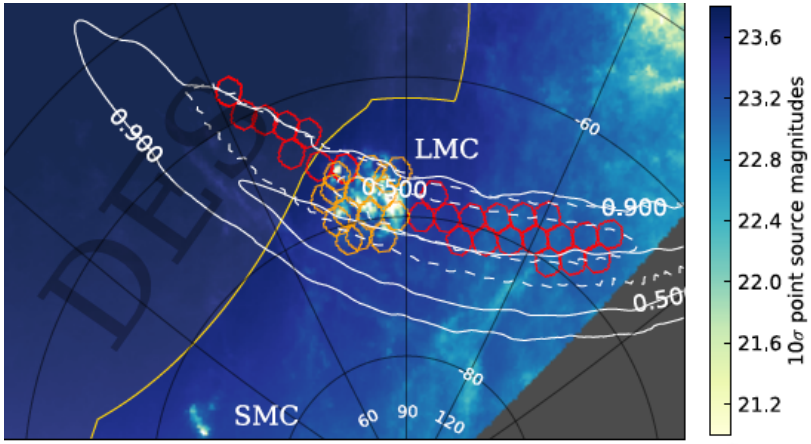


DES Overlap of ~2500 sq deg with CMB experiment South Pole Telescope

Dark Energy Survey research at Fermilab (DES-GW)

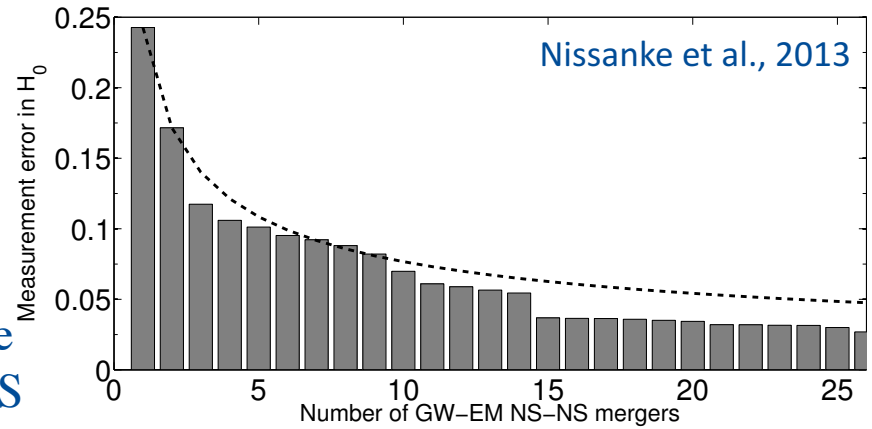
Searching for optical counterpart of LIGO events, with interest in cosmological applications

B. Krishnan'sTalk



Marcelle Soares Santos, 2015

There's an expectation that some systems will emit light at the same time as gravitational waves



GW as standard sirens

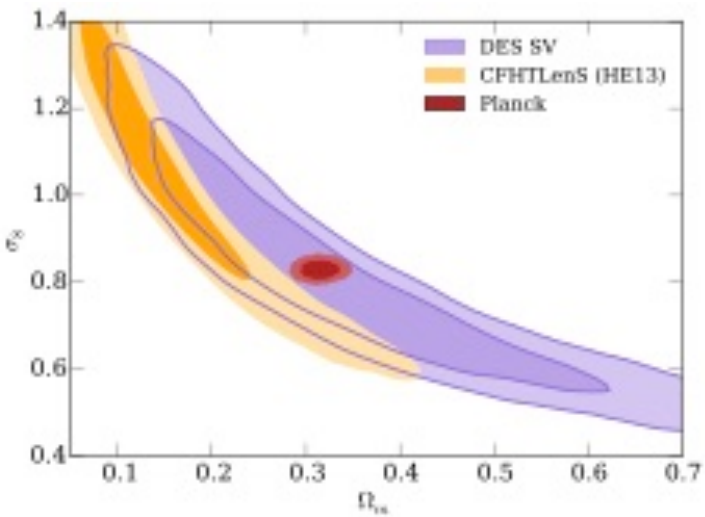
Strong Brazilian involvement

Hubble measurement error as a function of the number of multi-messenger (GW+EM) NS-NS merger events observed by a LIGO-Virgo network

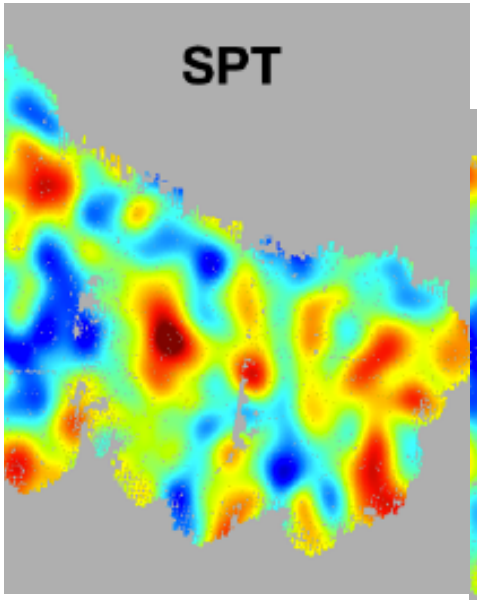
Dark Energy Survey research at Fermilab (cont'd)

Probes of the clustering of Matter and weak lensing of galaxy imagies provides information on Neutrino Mass, Dark Matter and Inflation

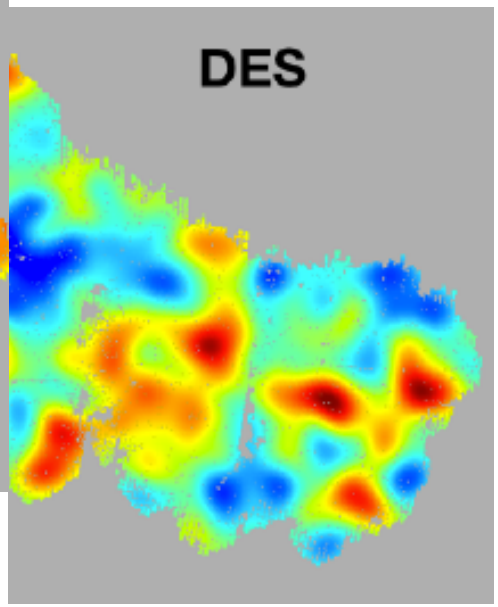
Probe the acceleration using the subtle gravitational distortion of galaxy images, known as cosmic shear.



Beginning to address the tension between Optical Surveys and Planck



SPT provides lensing maps



DES galaxies provides (some of) the mass that SPT maps

Revolutionary advances in our understanding of the Universe are driven by powerful ideas and powerful instruments

Higgs Mechanism ⟷ LHC

The mysteries of particle physics and cosmology are inextricably tied together

Dark Matter, Dark Energy, the Matter-Antimatter Imbalance and the elusive Neutrinos pose grand challenges ahead

Thus, good to broaden our experimental probes and let our imagination guide us …

LBNF+DUNE = the first truly international megascience project hosted in the U.S.

- Start from the beginning designing what you wish to accomplish scientifically with international colleagues
- Funding agencies and scientists define the international governance structure
- Partners bring unique “in-kind” contributions and scientific expertise not present at host lab
- A new model for U.S. science, getting positive attention from Washington

Core Capability: Particle Physics

Particle Physics

Theory & Theoretical Astrophysics Groups

Scientists, engineers, technical and operations staff

Compact Muon Solenoid (CMS) experiment

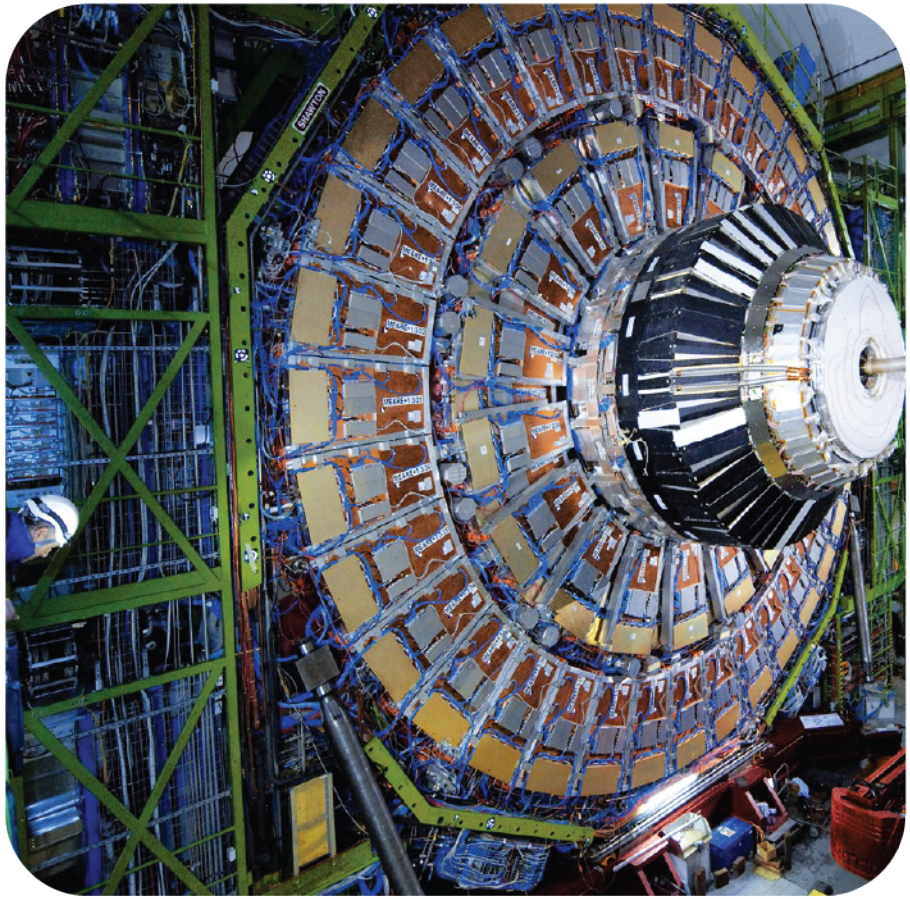
Cosmic science experiments

Neutrino science experiments

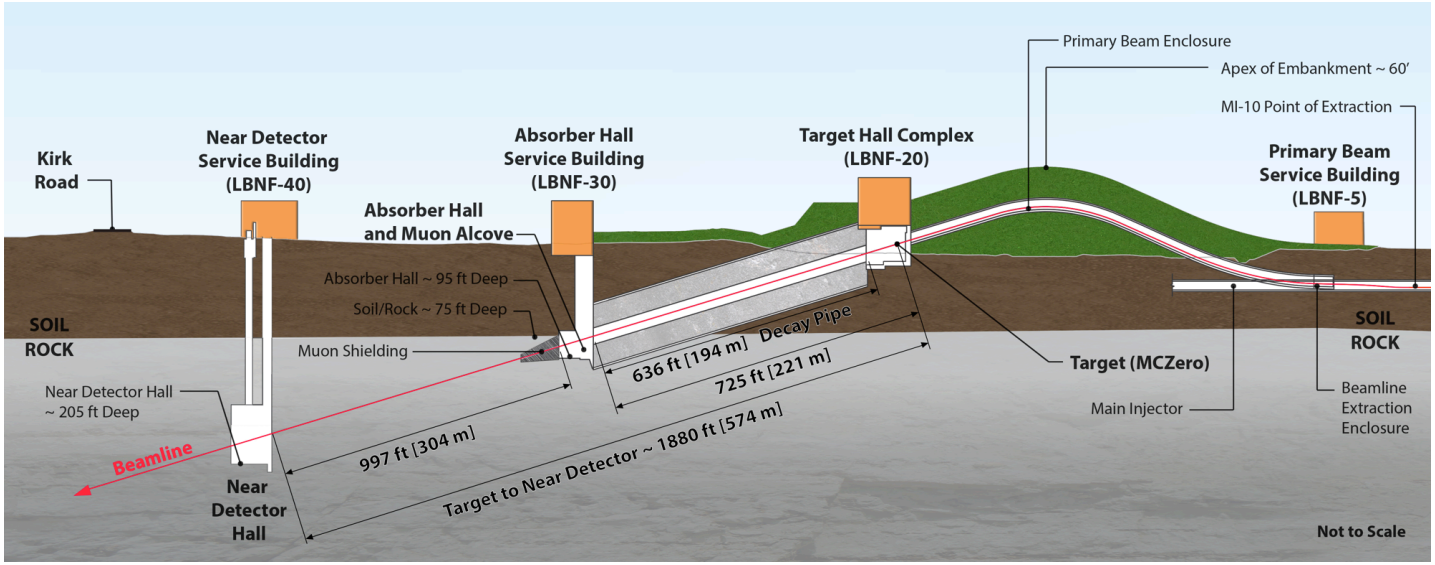
Detector R&D

Test beam facility

Education Office & Lederman Science Center



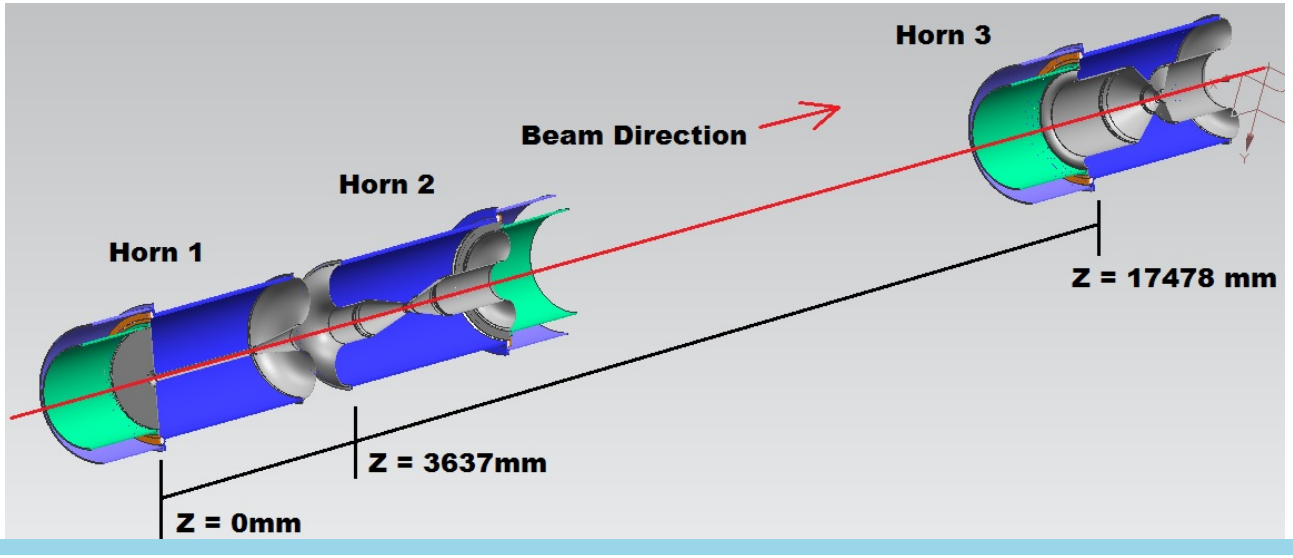
Overview - "Near Site" – LBNF/DUNE at Fermilab



- Primary proton beam @ 60-120GeV extracted from Main Injector
- Initial 1.2 MW beam power, upgradable to 2.4 MW
- Embankment allows target complex to be at grade and neutrino beam to be aimed to Lead, SD
- Decay region followed by absorber
- Four surface support buildings
- Near Detector facility
- DUNE Near Detectors (fine grained straw tube with gas targets)

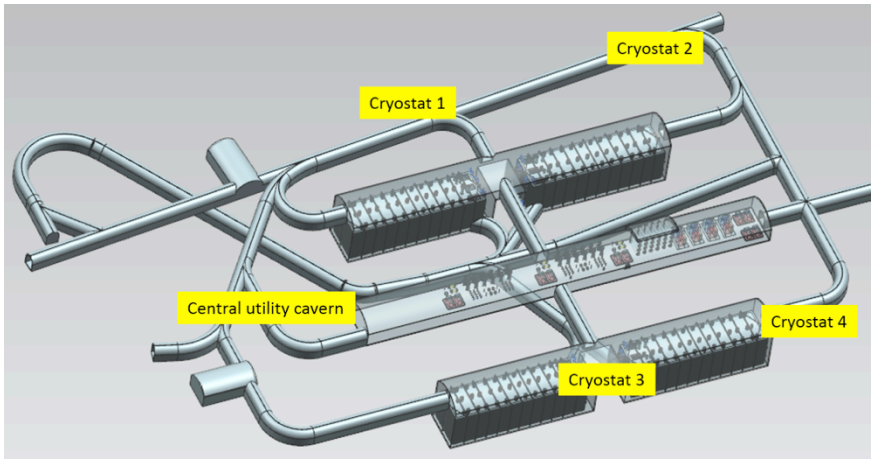
Near term activity: Beam Optimization

- At request of and in coordination with DUNE collaboration, investigating alternate neutrino beam configurations to provide better physics through 2017
- Working toward baselining an agreed-to configuration in 2019
- Requires work on targets, horns (3 vs. 2), and target chase atmosphere (He or N vs. air) in next 15 months before decisions are made prior to preliminary design.

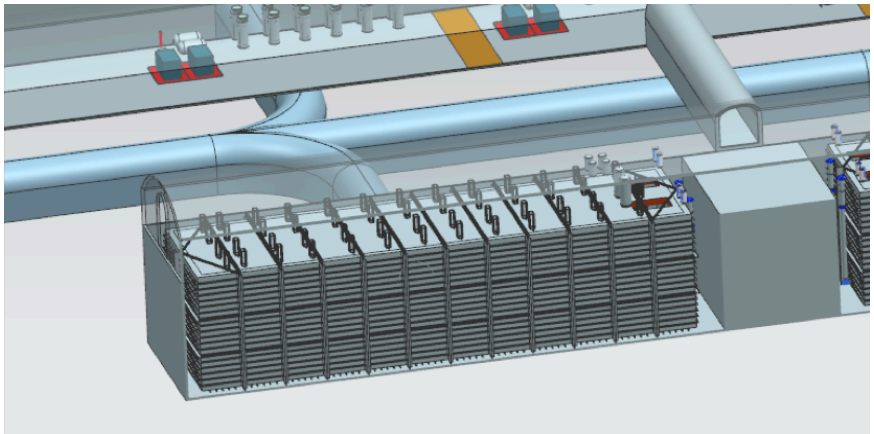


Overview – "Far Site" – LBNF/DUNE at Sanford Lab, Lead, SD

- **Conventional Facilities**:
  - Surface and shaft Infrastructure including utilities
  - Drifts and two caverns for detectors
  - Central utility cavern for conventional and cryogenic equipment
- **Cryostats**:
  - Four membrane cryostats supported by external steel frames
- **Cryogenic Systems**:
  - LN2 refrigeration system for cooling and re-condensing gaseous Argon
  - Systems for purification and recirculation of LAr
- **Liquid Argon: 70kt (~40kt "fiducial" mass)**
- **DUNE LAr-TPC Detectors**



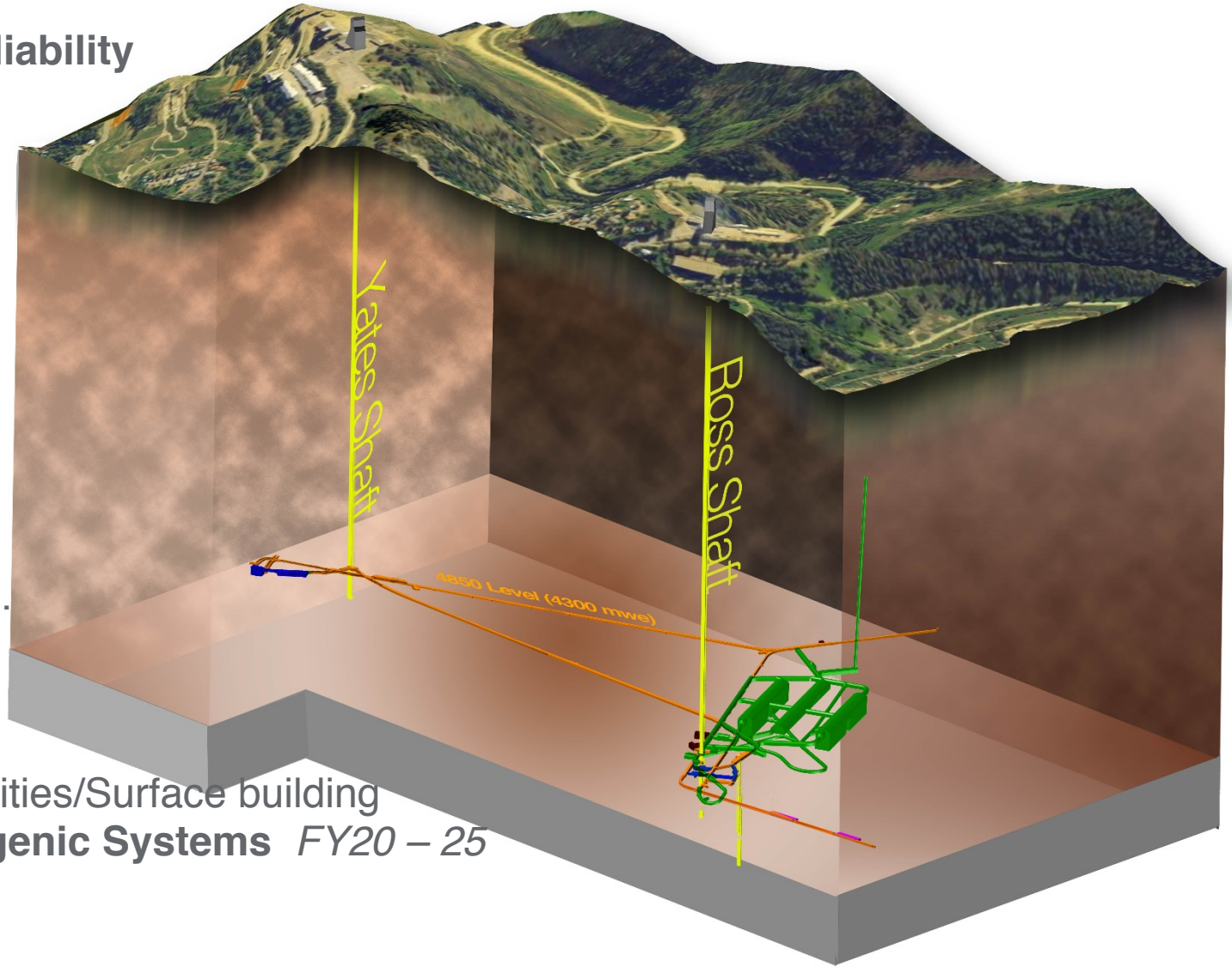
4850L cavern and drift layout



Single cryostat

Far Site Scope – Overview of Phases of Work

1. **Sanford Lab Reliability Projects**
   FY16 – 18
   - Ross shaft rehab
   - Hoist motor rebuilds, more…
2. **Pre-Excavation**
   FY17 - 20
   - Rock disposal systems
   - Ross brow expansion, more…
3. **Excavation/ Construction**
   FY18 – 22
   - Caverns/Drifts/Utilities/Surface building
4. **Cryostats/Cryogenic Systems** *FY20 – 25*



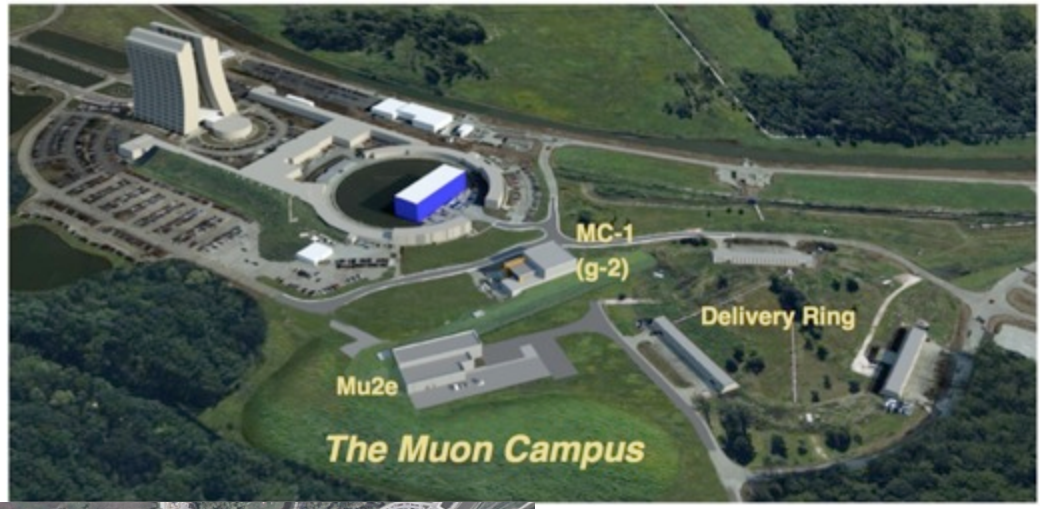
LBNF/DUNE Schedule

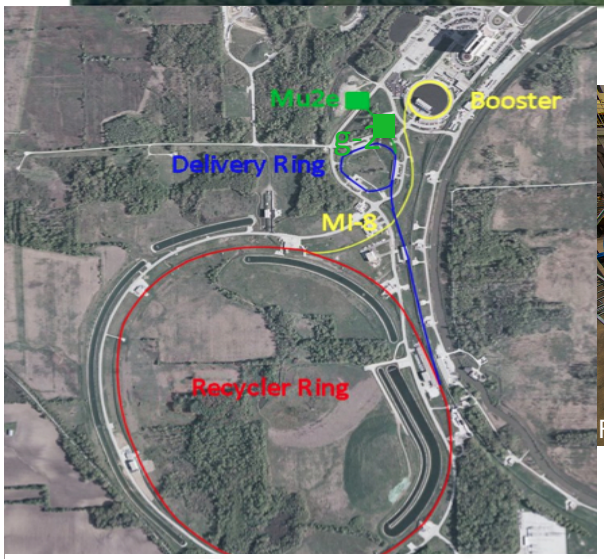
★ **Scientific priorities**
- First 20-kt FD as early as possible – early science program
- Beam as early as possible – primary neutrino oscillation science
- Near detector system in time for early beam operation

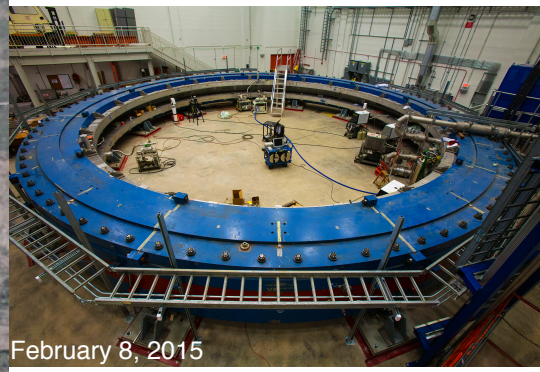
★ **Schedule based on realistic funding profile**
- DOE planned funding line
- Anticipated international contributions

★ **Key milestones:**
- **2017:** start of underground excavation at SURF
- **2018:** operation of two large-scale prototypes at CERN
- **2021:** start of installation of first 10-kt far detector module
- **2024:** start of commissioning/operation of 20-kt
- **2026:** start of beam operation (1.2 MW)

Muon Campus

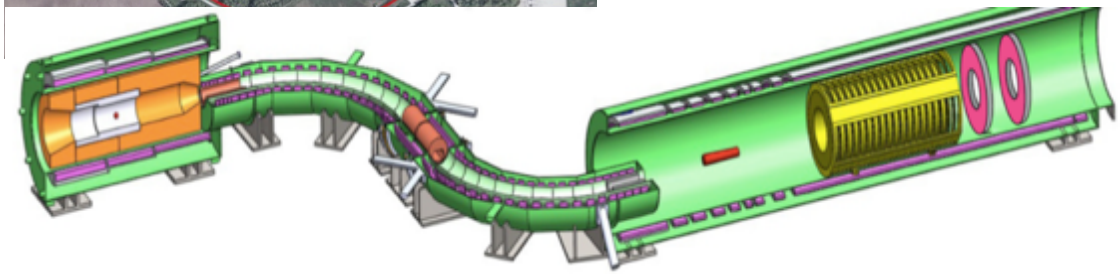






~$100M in savings by creating an integrated program

Beautiful, world-class facilities to serve the community well into next decade and beyond



Muon program: Users

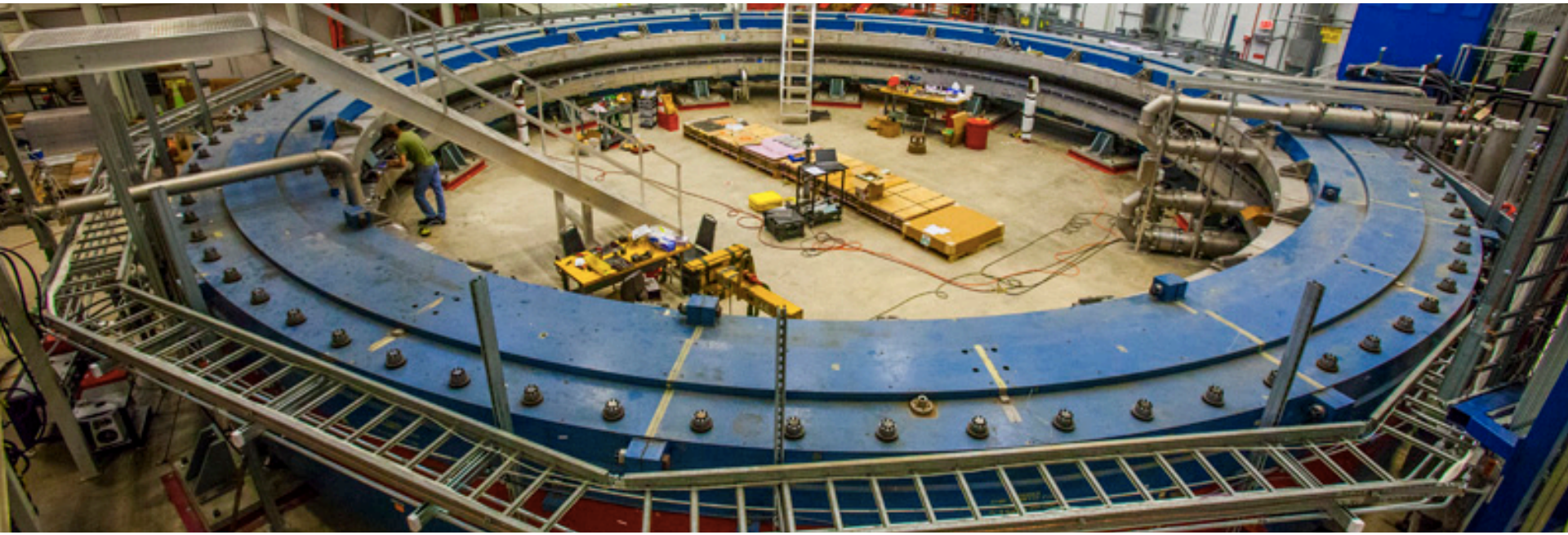
50 institutions in 8 countries

Over 300 users

Fermilab Muon g-2

Precision Science

Science goal: Confirm the present 3σ discrepancy with > 5σ discovery potential



Lab objective:

Collect 20 times Brookhaven statistics by end of 2019

Mu2e

Precision Science

Science goal:

- Improve sensitivity to $\mu^- N \rightarrow e^- N$ by factor of 10,000
- Achieve discovery sensitivity to new physics up to an effective mass scale of $\Lambda_{NP} \sim 10^4$ TeV/c^2

Lab objective:

Commissioning in 2020, full data set by 2023

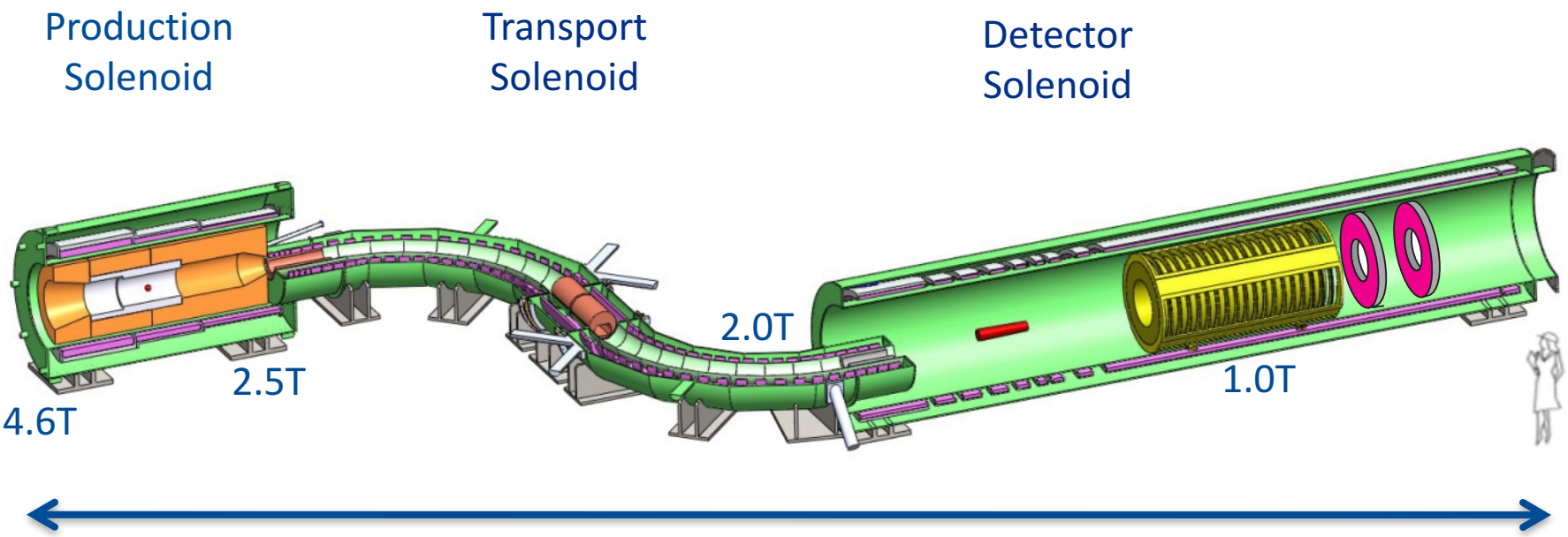
TS Coil Module testing at Fermilab

panel prototype (96 straws) for testing

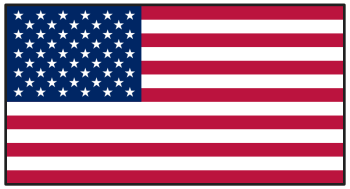
Mu2e Hall, April 2016

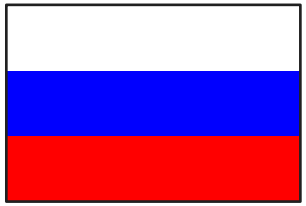
Mu2e project scope

- 3 solenoid system
- proton beam line
- detector elements
- experimental hall
- associated radiation safety infrastructure



Mu2e Collaboration - +40% over last 18 months





207 Scientists from 35 Institutions

Argonne National Laboratory, Boston University, Brookhaven National Laboratory, University of California Berkeley, University of California Irvine, California Institute of Technology, City University of New York, Joint Institute of Nuclear Research Dubna, Duke University, Fermi National Accelerator Laboratory, Laboratori Nazionale di Frascati, University of Houston, Helmholtz-Zentrum Dresden-Rossendorf, University of Illinois, INFN Genova, Lawrence Berkeley National Laboratory, INFN Lecce, University Marconi Rome, Kansas State University, Lewis University, University of Louisville, University of Minnesota, Muons Inc., Northwestern University, Institute for Nuclear Research Moscow, Northern Illinois University, INFN Pisa, Purdue University, Sun Yat-Sen University Novosibirsk State University/Budker Institute of Nuclear Physics, Rice University, University of South Alabama, University of Virginia, University of Washington, Yale University

Cosmic Program at Fermilab

- Capitalizes on scientific expertise, technical skills, and facilities developed for particle physics by applying them to cosmology projects
  - Data handling, analysis and quality control: DES, LSST
  - Silicon detectors: precision assembly, testing/characterization, integration: DES, DAMIC, DESI, CMB
  - Cryogenic engineering: DES, DAMIC, CDMS, DarkSide, LZ, CMB
  - Light Detection: Darkside, LZ
  - Bubble Chambers: COUPP/PICO
  - RF engineering: Axions

- Fermilab's expertise is unique and in demand by the cosmology community particularly as the projects have grown in size, complexity and scope