Fermilab U.S. DEPARTMENT OF ENERGY Office of Science

Welcome to Fermilab

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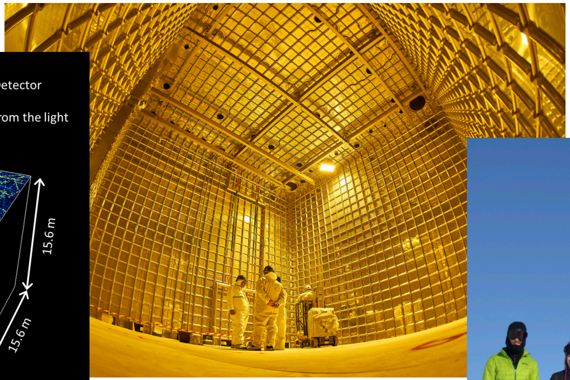
Undergraduate Summer Lectures Series

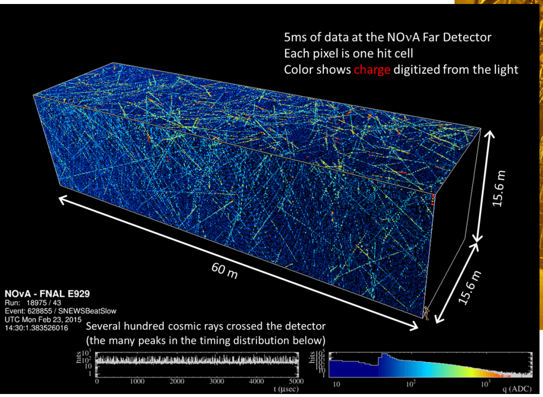
26 May 2020

Materials provided by J. Lykken

Fermilab at a glance

- The primary DOE laboratory for high energy particle physics & particle accelerators
- About 1,800 staff
- 6,800 acres of federal land including restored prairie
- 4,000 scientists from across the U.S. and 53 countries use Fermilab's facilities
- Hosting large experiments on site, at CERN, Chile, the South Pole, and other locations

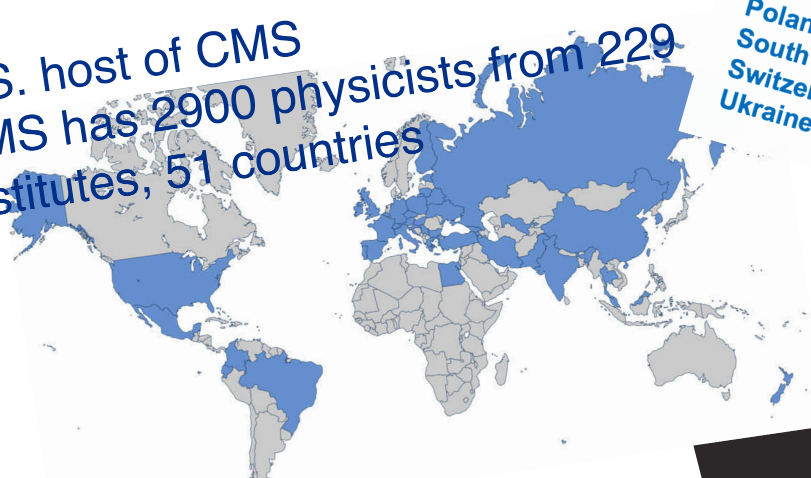


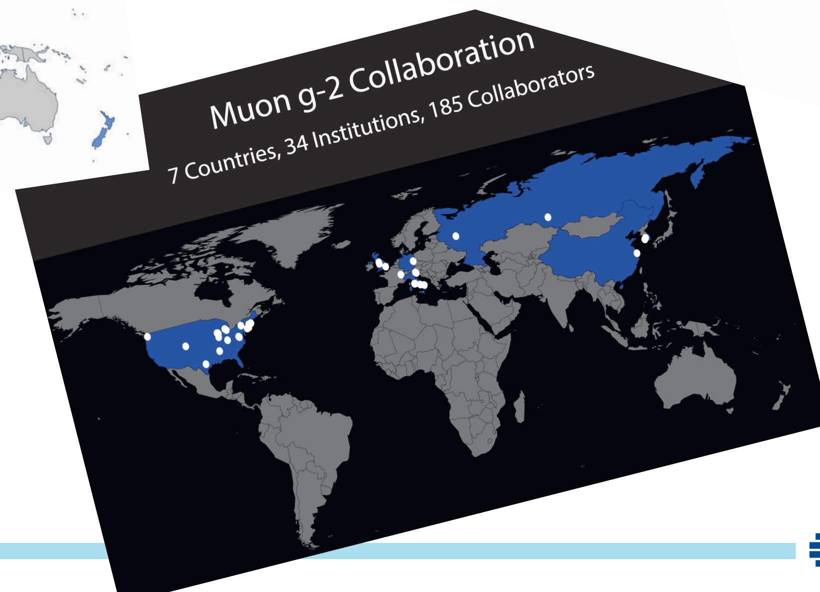


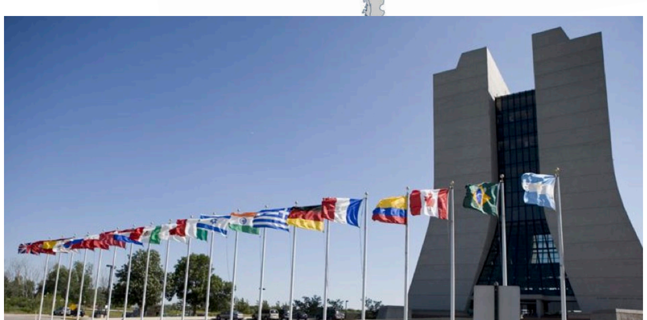
Fermilab hosts large international collaborations

Successful model developed over decades to host and support international collaborations for experiments on and off the Fermilab site

U.S. host of CMS
CMS has 2900 physicists from 229 institutes, 51 countries



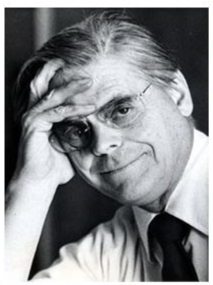




Fermilab science drives technology innovation

Superconducting magnets for the Tevatron, first industrial scale use of such magnets

MRI machines from GE and Siemens USA



Robert Rathbun Wilson

1946: R. Wilson first proposed a possible therapeutic application of proton and ion beams

R. Wilson, Radiologial use of fast protons, Radiology 47, 487-491, 1946

Radiological Use of Fast Protons

ROBERT R. WILSON

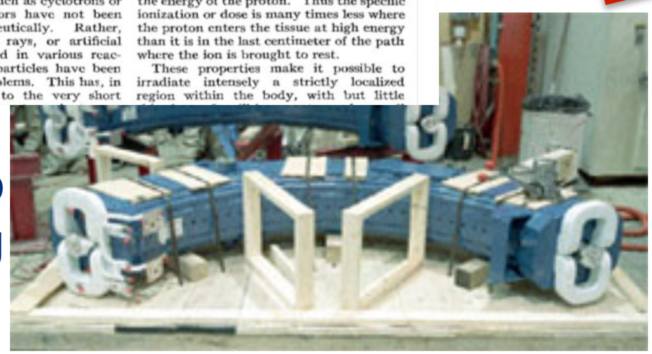
Research Laboratory of Physics, Harvard University

Cambridge, Massachusetts

EXCEPT FOR electrons, the particles which have been accelerated to high energies by machines such as cyclotrons or Van de Graaff generators have not been directly used therapeutically. Rather, the neutrons, gamma rays, or artificial radioactivities produced in various reactions of the primary particles have been applied to medical problems. This has, in large part, been due to the very short

per centimeter of path, or specific ionization, and this varies almost inversely with the energy of the proton. Thus the specific ionization or dose is many times less where the proton enters the tissue at high energy than it is in the last centimeter of the path where the ion is brought to rest.

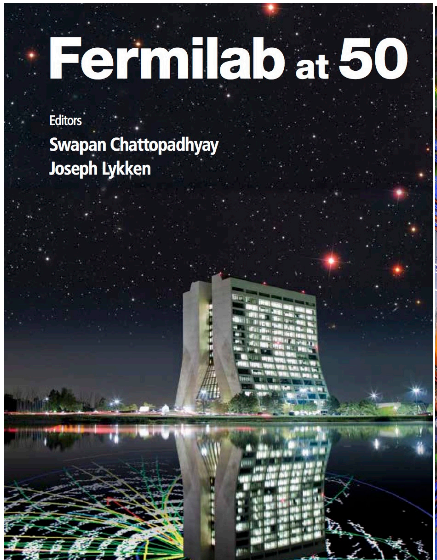
These properties make it possible to irradiate intensely a strictly localized region within the body, with but little

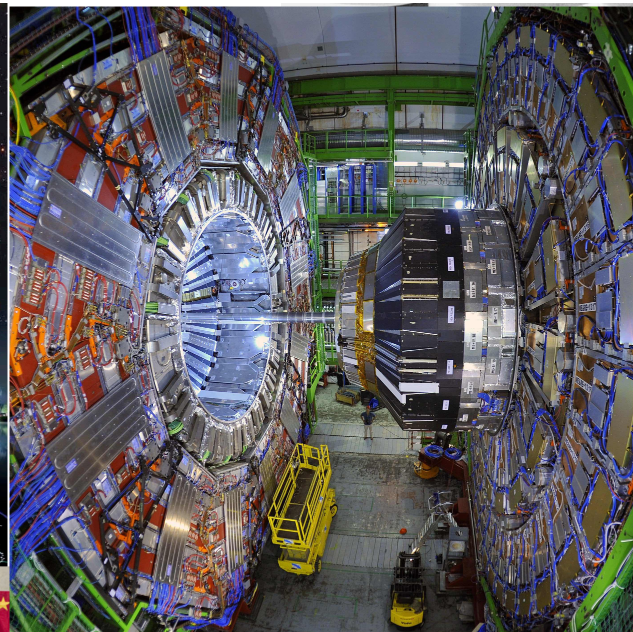


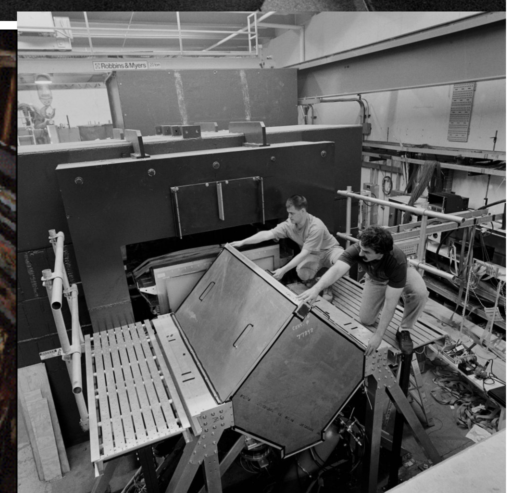
Invented by Fermilab Director, first working system built here

Loma Linda proton cancer therapy

50 Years of Discovery







Outline

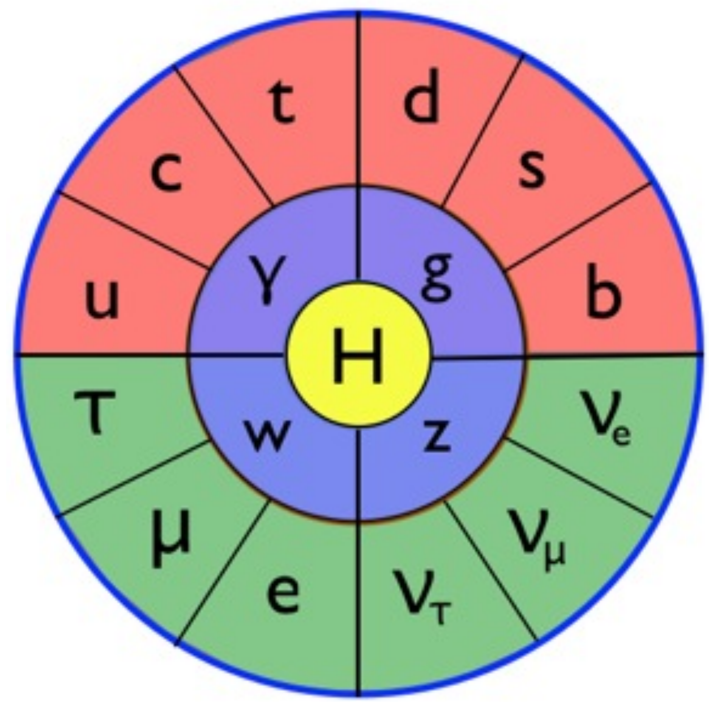
- What is particle physics?
- Outstanding mysteries of particle physics
- The Tevatron
- The Large Hadron Collider
- The future of neutrinos
- The future of dark matter
- Quantum connections

What is particle physics?

There appears to be only one consistent way of defining relativistic quantum field theory, but many possible particle physics models depending on what degrees of freedom, symmetries and interactions are assumed

Over the past 50 years experiments have confirmed a "Standard Model" with 17 different particles/fields that appear (so far) to be elementary

- 12 of these are spin ½ fermion "matter particles": 6 quarks, 3 charged leptons, and 3 neutrinos
- 4 of these are spin 1 boson "force particles" that mediate the strong, weak, and electromagnetic interactions of matter
- And the spin 0 Higgs boson



What does the Standard Model explain?

Some properties of the quantum vacuum

The quantum vacuum, being just the lowest energy state of the SM quantum fields, has physical properties just as the excited states do. Empty (quantum) space is in fact physically similar to condensed matter systems

We often say that empty space has virtual particles (because of the Uncertainty Principle) whose physical effects can be predicted and measured

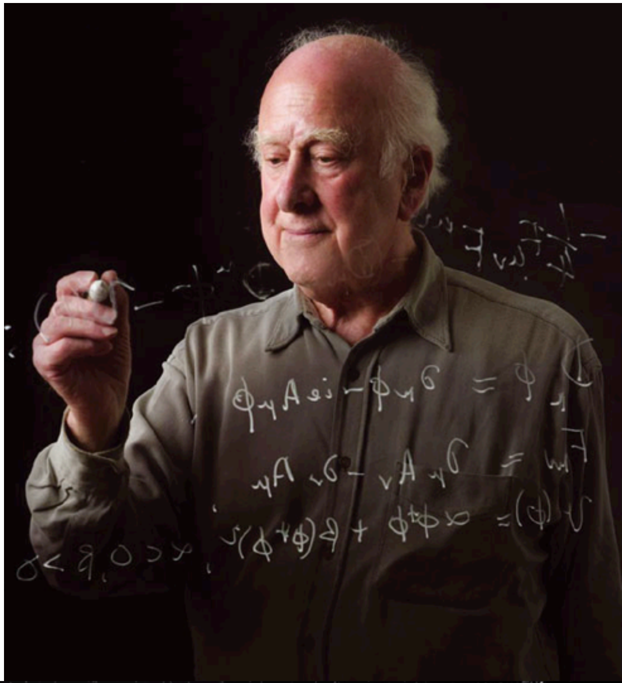
Complex virtual quantum effects on the magnetic moment of the electron are predicted and measured to better than one part per billion accuracy

The Muon g-2 experiment at Fermilab is investigating these effects for muons

What does the Standard Model explain?

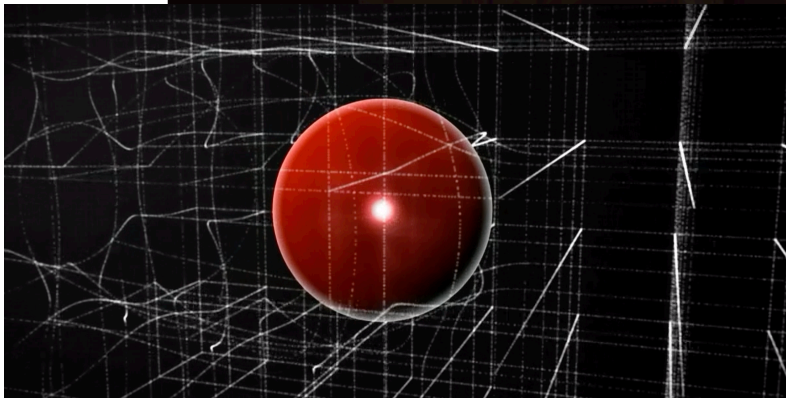
Some properties of the quantum vacuum

The Higgs field has the remarkable feature that (unlike electromagnetic fields) it can source itself.



The SM predicts that the Higgs field turned itself on everywhere in the universe in the first moments of the Big Bang (the electroweak phase transition)

Once this happened, at least 10 of the other kinds of SM particles acquired mass



What does the Standard Model NOT explain?

How neutrinos get mass

Why there is more matter than antimatter left over from the Big Bang

What is dark matter made of and how does it interact with ordinary matter

What caused a period of cosmic inflation in the first instants of the Big Bang

What is dark energy

Why are the interactions of the Higgs tuned to make the quantum vacuum metastable

What are the quantum properties of gravity, space, and time

And more ...

Fermilab's mission is to answer these fundamental questions

A Few Words about the History of the Lab

Fermilab

Director Robert Wilson offers a toast to celebrate the milestone.

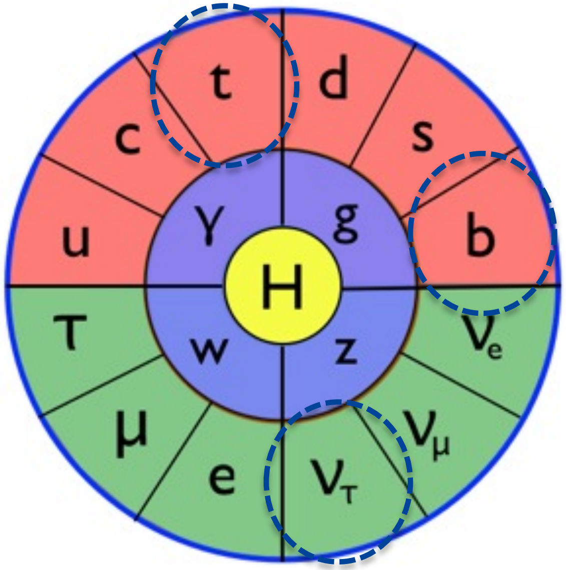
1 March 1972

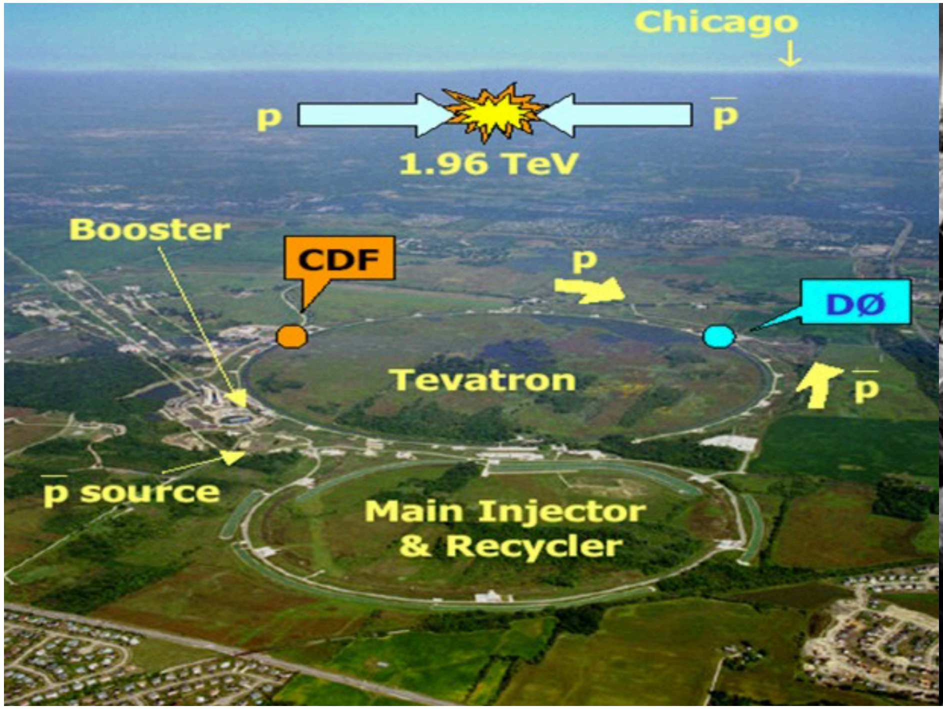
Accelerator Reaches Design Energy

After years of design and construction, the NAL Main Ring achieved its design energy of 200 GeV on March 1, 1972, ahead of schedule and under its authorized $250 million budget. It quickly surpassed that energy goal, reaching 300 GeV on July 16, 1972, and 500 GeV on May 14, 1976.

The Tevatron

Till 2010, Fermilab hosted the highest energy collider in the World producing proton-antiproton collisions at center of mass-energy of 1.96 TeV





The Large Hadron Collider

The LHC is a proton accelerator in an underground 27 km ring spanning the Swiss-French border at CERN

Protons colliding with a kinetic energy > 7,000 times their rest mass

40,000 tons of superconducting magnets cooled to 1.9 deg K

>100 tons of liquid helium

100 billion protons per bunch

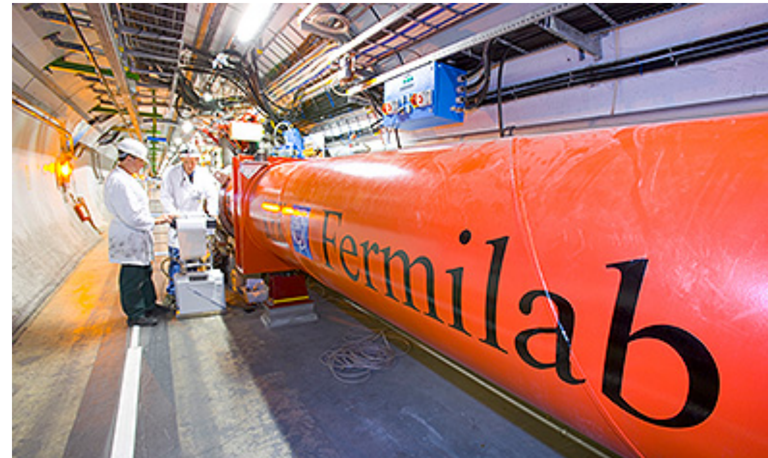
Bunches collide 40 million times per second

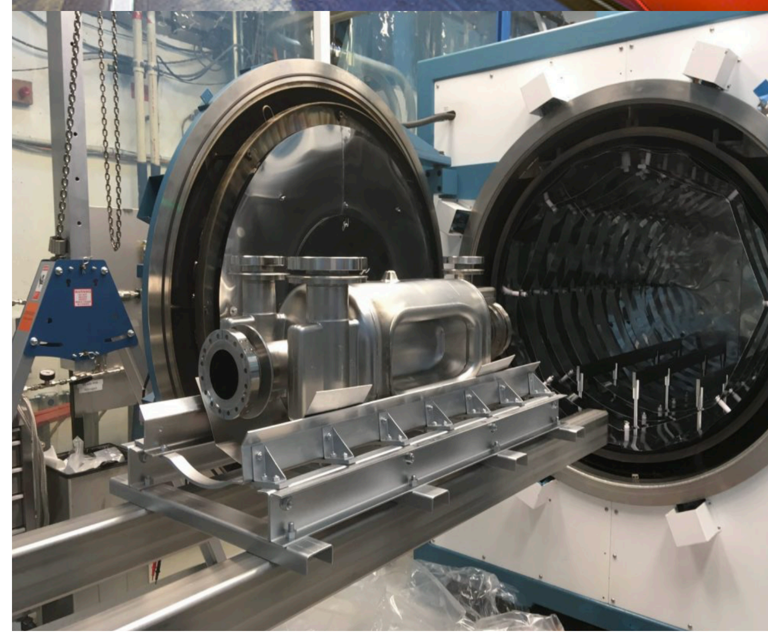
Fermilab at the HL-LHC

Fermilab participated in the construction of the LHC accelerator, contributing critical components such as the powerful magnets that focus beams into collision

Fermilab is upgrading these magnets to niobium-tin conductors that can exert a stronger force on the particles than their predecessors

Fermilab is also upgrading the accelerating cavities to “crab cavities” used to increase the overlap of the two beams

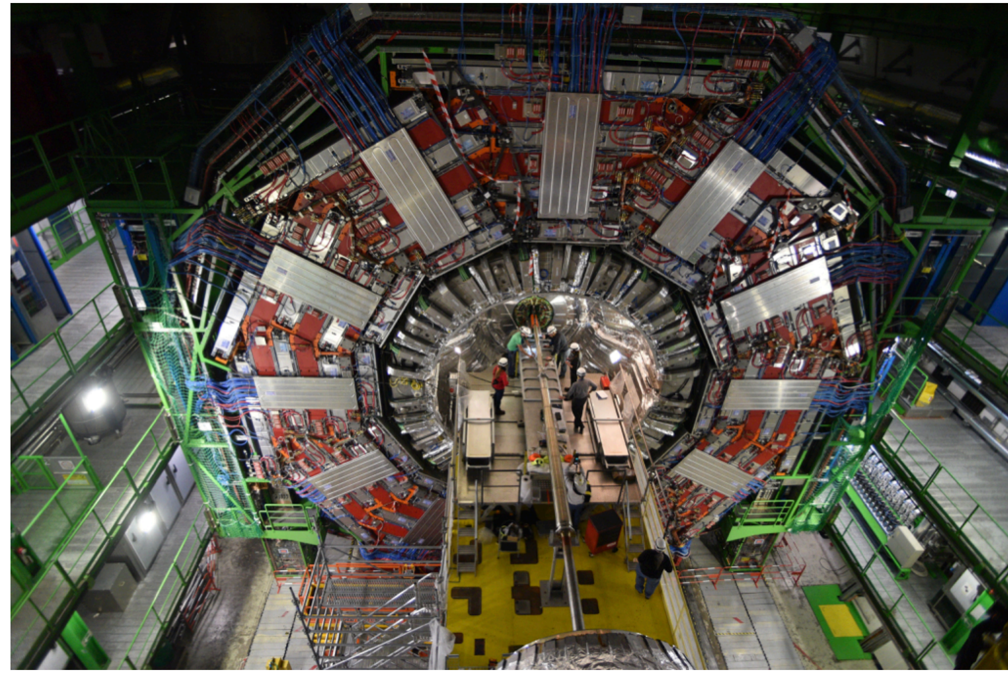


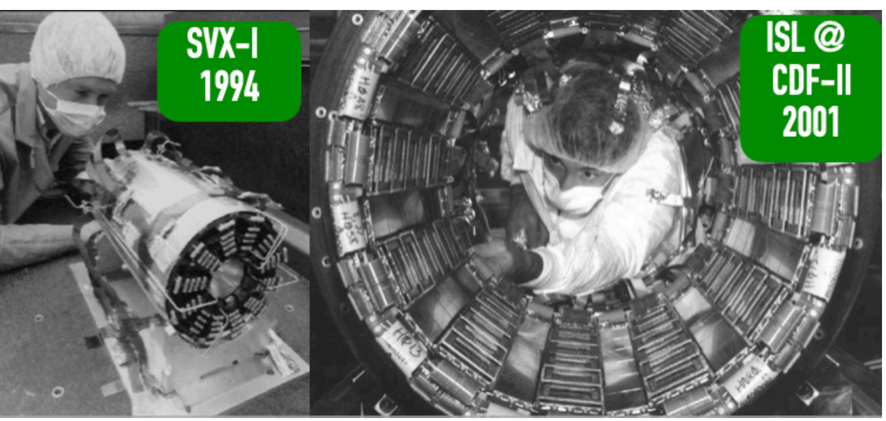


Fermilab

The CMS detector

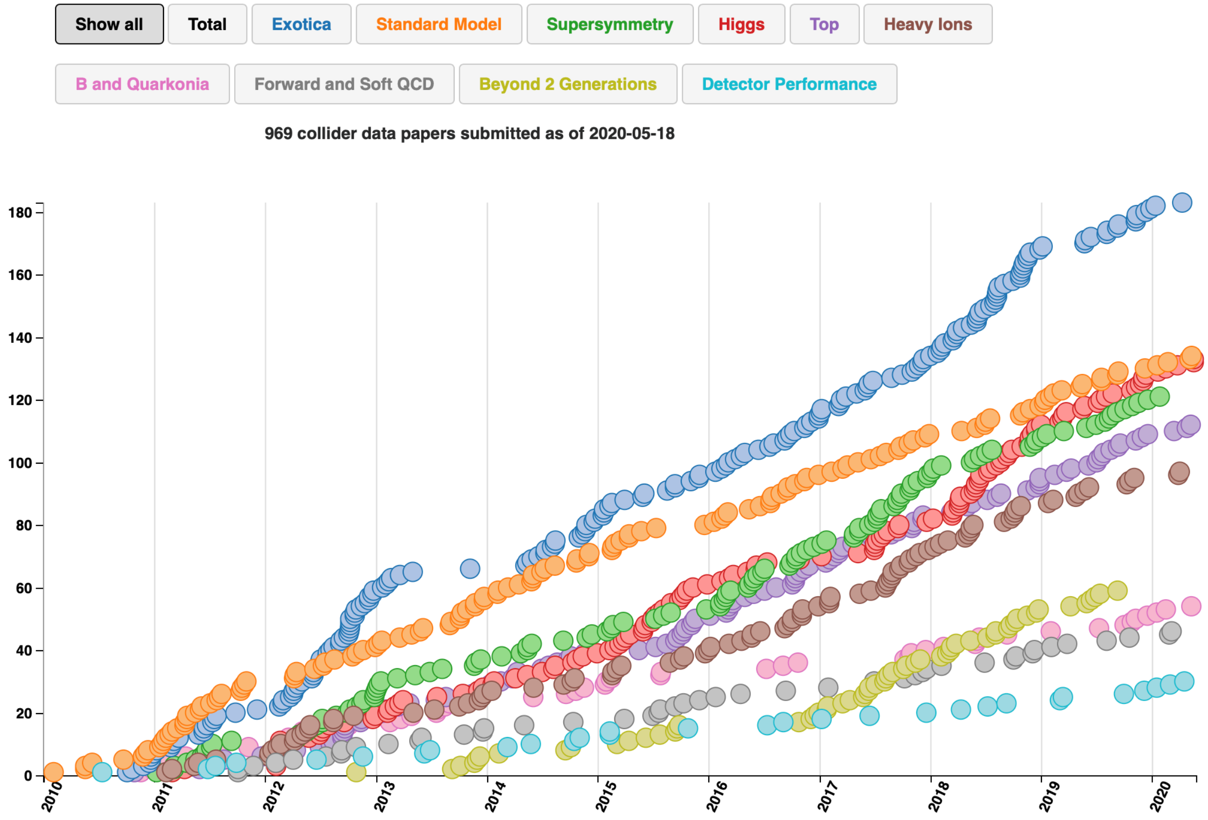
- 14,000 tons of sensors with 100 million channels of readout (40M events readout per second!)
- World’s largest superconducting solenoid magnet
- World’s largest active solid state device
  - *Building on the legacy of the CDF experiment at the Tevatron*



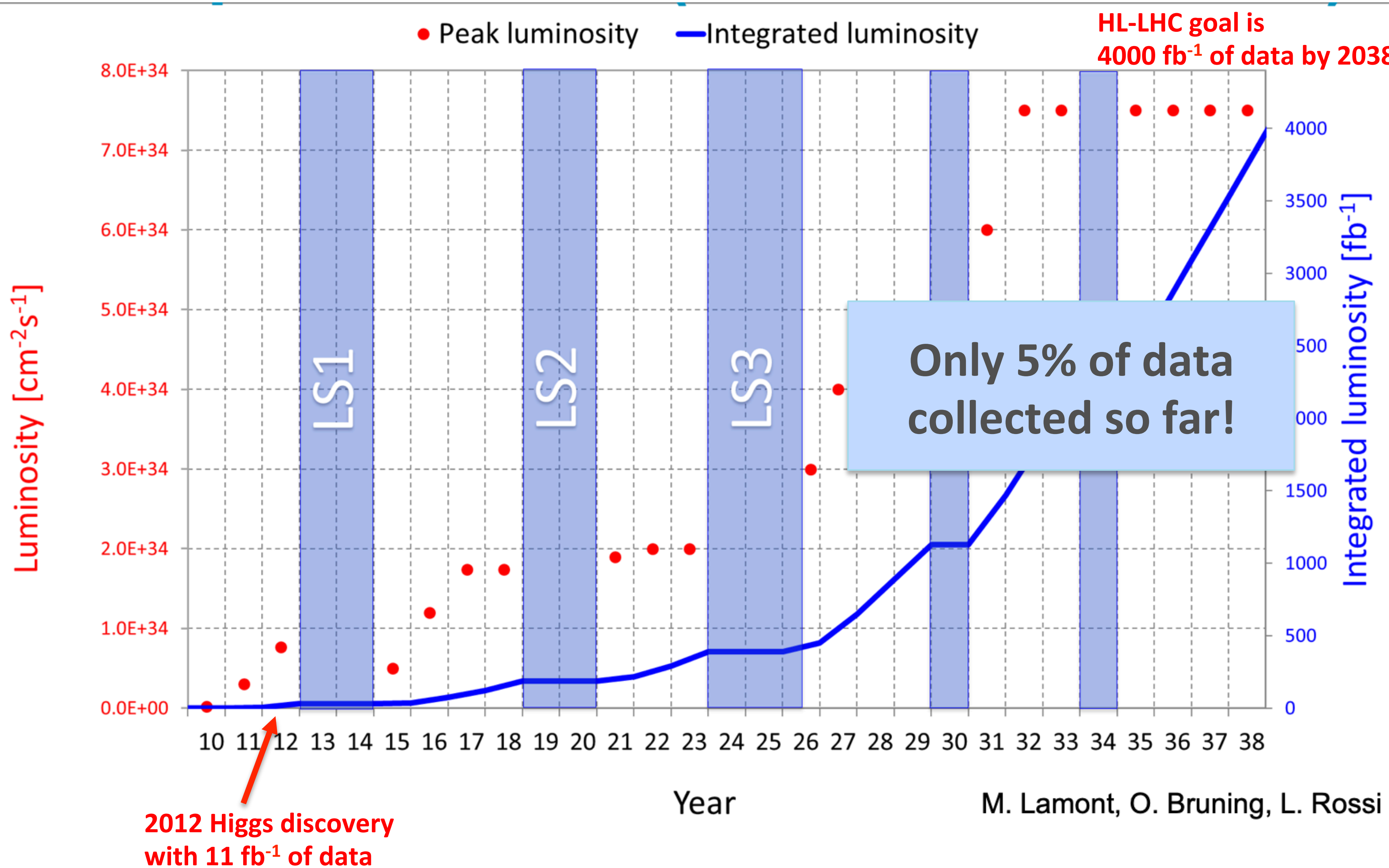


Impact of LHC experiments

- To date, the LHC experiment have produced > 2700 publications
- **Monumental advance in our knowledge**

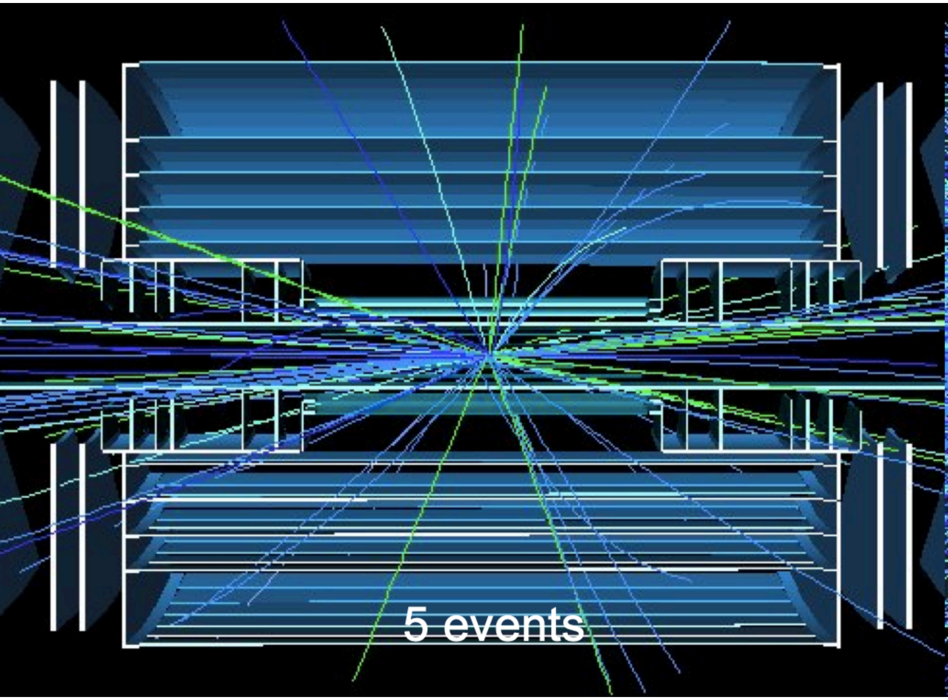


From LHC to HL-LHC: data, data, data

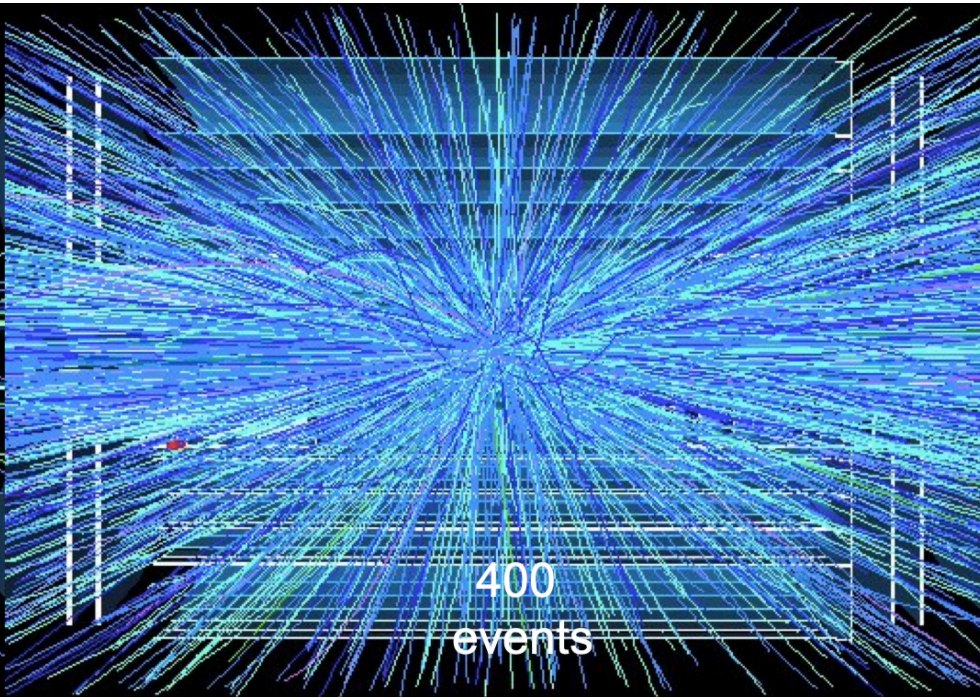


The HL-LHC environment

“Typical” LHC collision event at the time of the Higgs discovery



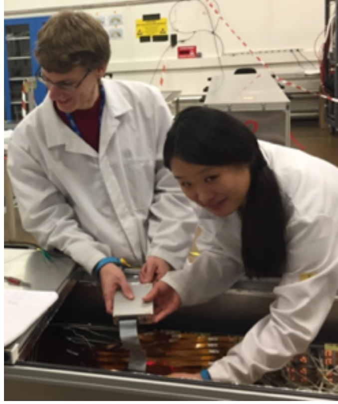
HL-LHC collision event has as many as 400 proton-proton collisions at once



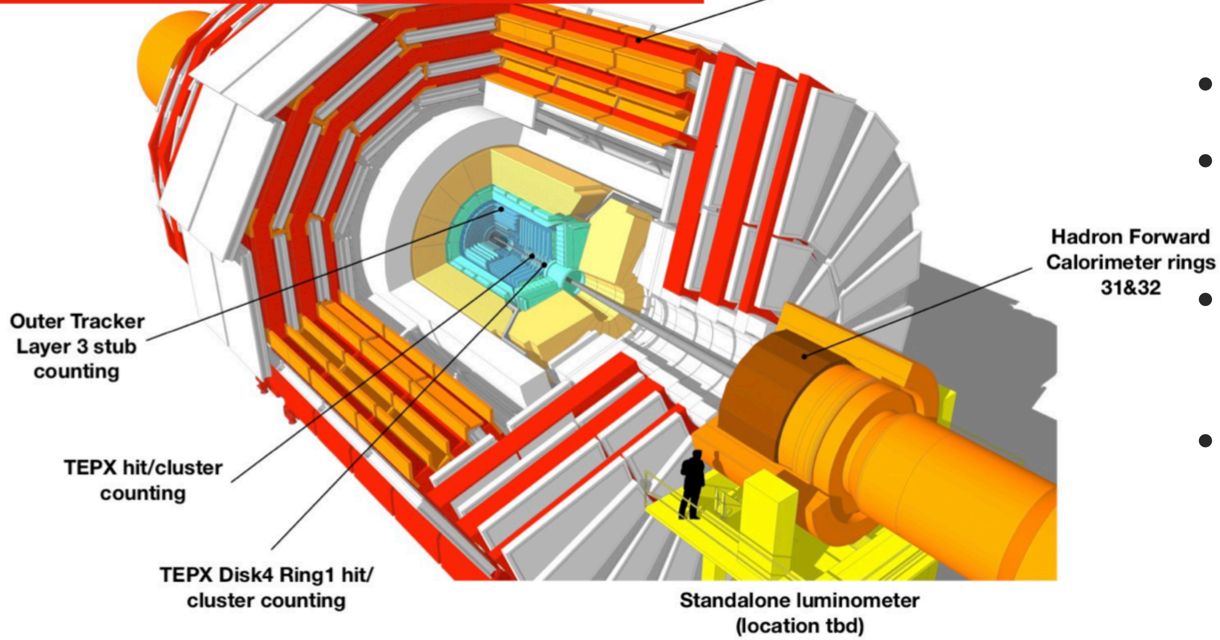
Need major upgrades of the detectors to make sense of these kind of events

Fermilab at CMS

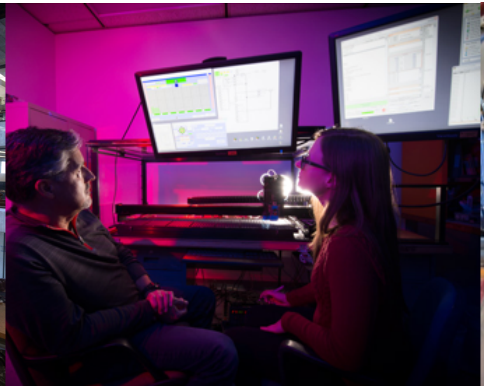
Innovation and cutting edge technologies to maximize the discovery potential of the LHC and HL-LHC



Strategy to make use all possible 'existing' detectors
In addition develop <u>one</u> full dedicated unit

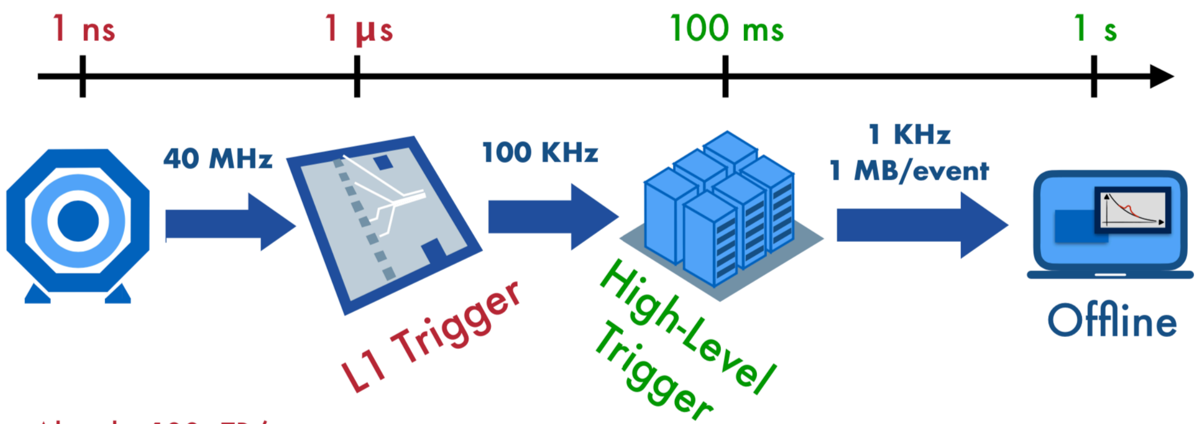


- Over 2B channels!
- Tracker measuring momentum at 40MHz
- Calorimeter with imaging capabilities
- Timing detector with 15ps resolution



Fermilab and the big data challenge



- We are leading the development of the world's fastest AI
- Machine learning inference in ~15 microseconds using FPGA/ ASIC based architectures

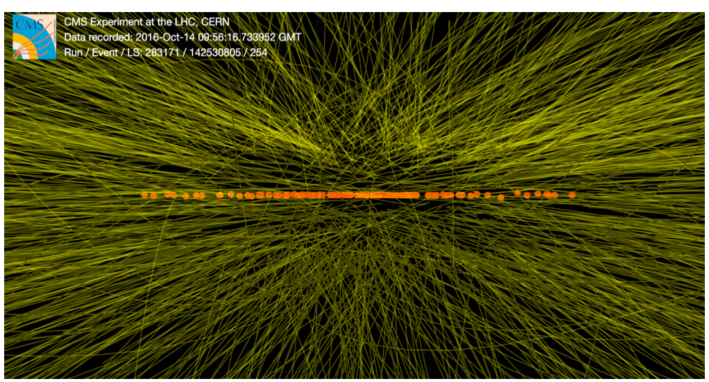
Absorbs 100s TB/s

Trigger decision to be made in O(μs)

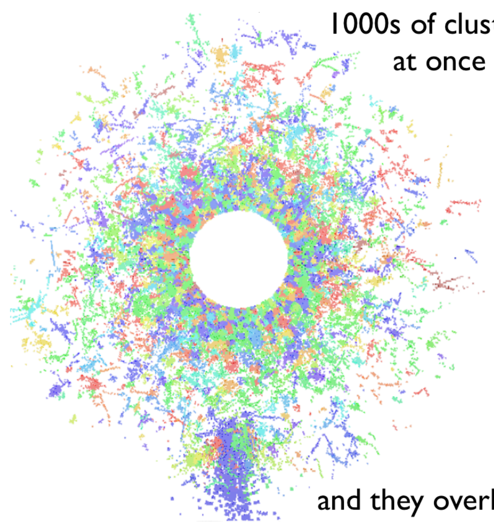
Latencies require all-FPGA design

99.75% events rejected!

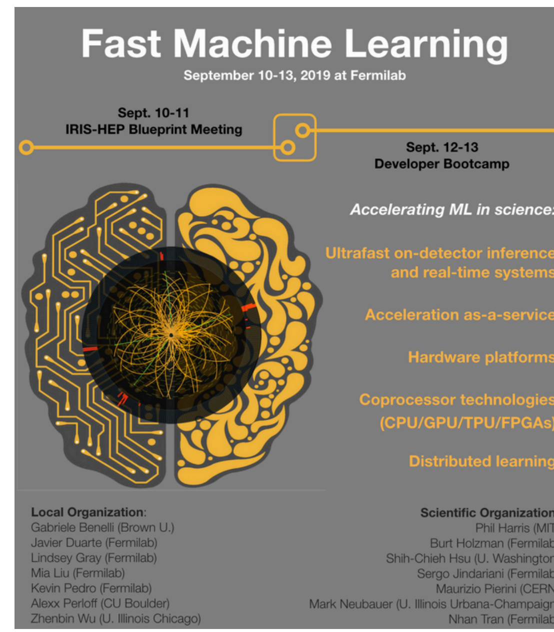
1000s of tracks at once



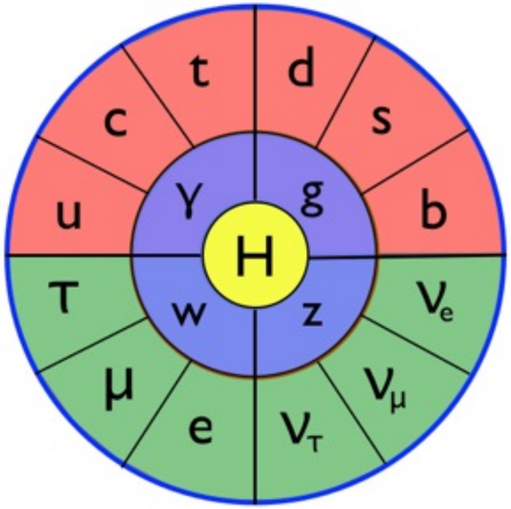
1000s of clusters at once

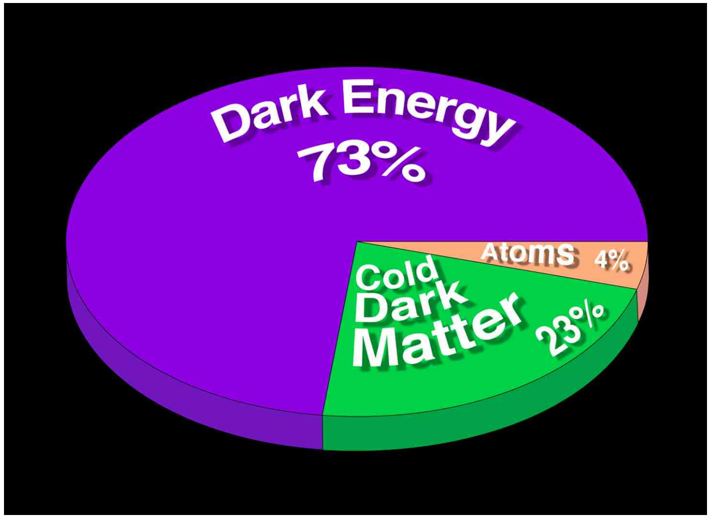


and they overlap :-)



Beyond Colliders: neutrinos and dark universe





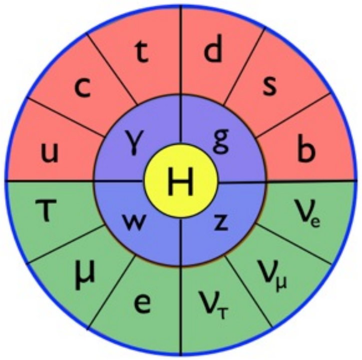
To solve the mysteries of matter, energy, space and time for the benefit of all. Fermilab strives to:

- lead the world in n**eutrino science** with particle accelerators
- lead the nation in the development of particle colliders and their use for scientific discovery
- advance particle physics through measurements of the **cosmos**

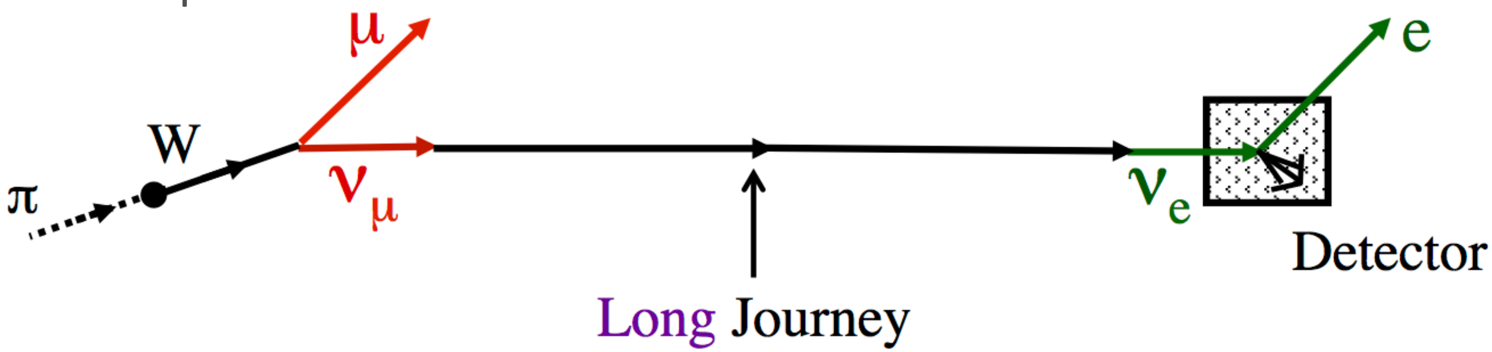
Neutrino oscillations

Each e.g. muon-flavored neutrino in a neutrino beam is a **quantum superposition** of three different neutrino mass eigenstates

$$|\nu_\mu\rangle = \theta_{\mu 1}|\nu_1\rangle + \theta_{\mu 2}|\nu_2\rangle + \theta_{\mu 3}|\nu_3\rangle$$



After traveling some distance, this superposition will change because of the different phase factors

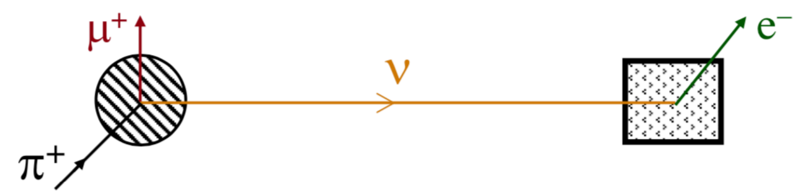


Thus even though the neutrino did not interact, there is some chance to detect it later **as a different flavor**

Neutrino oscillations and CP violation

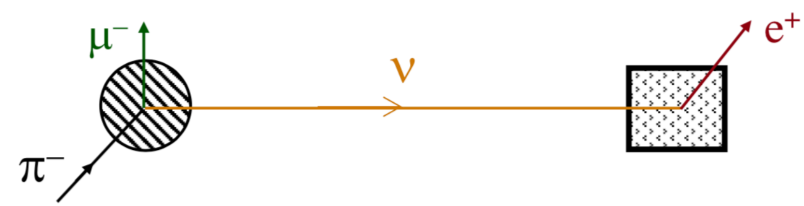
- Because the masses of neutrinos are so small, this **neutrino flavor oscillation** is seen on large distance scales ~ **hundreds of kilometers**
- We are especially interested in comparing these two processes that **interchange the roles of matter and antimatter**

Compare



- If they are not the same, then neutrinos violate CP

with

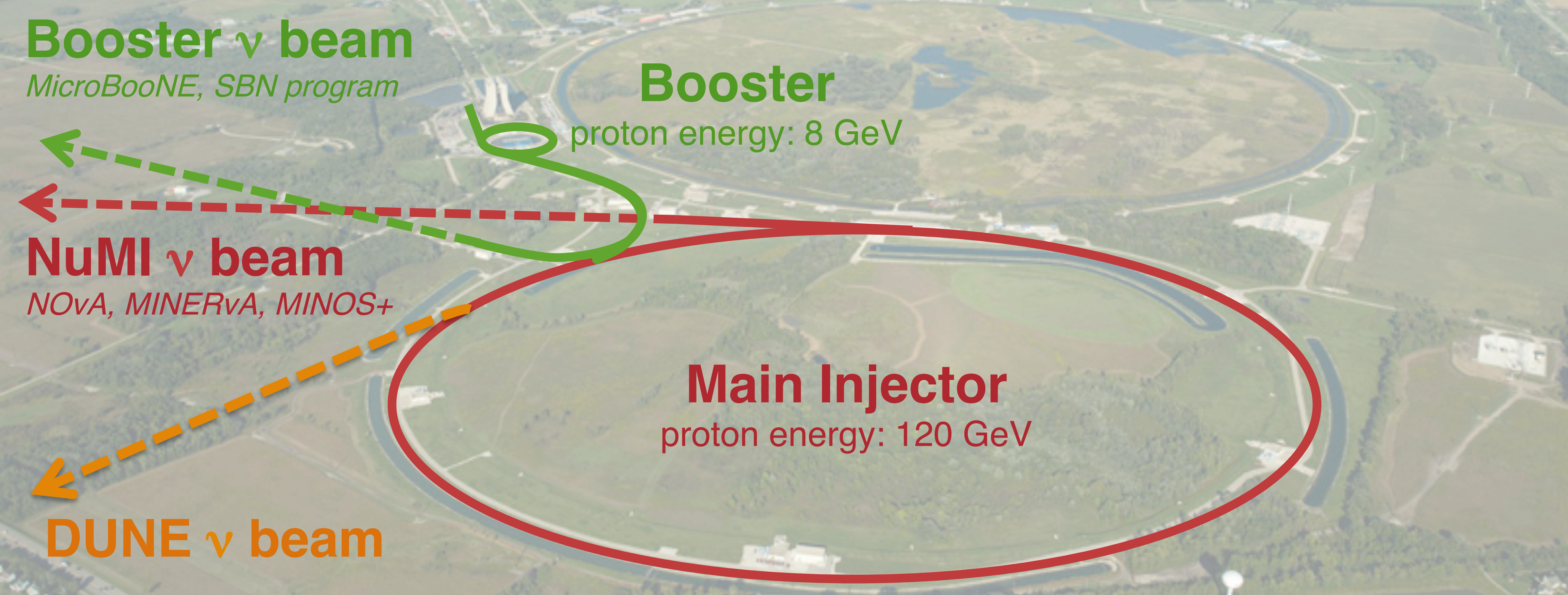


- This could be the reason why we exist

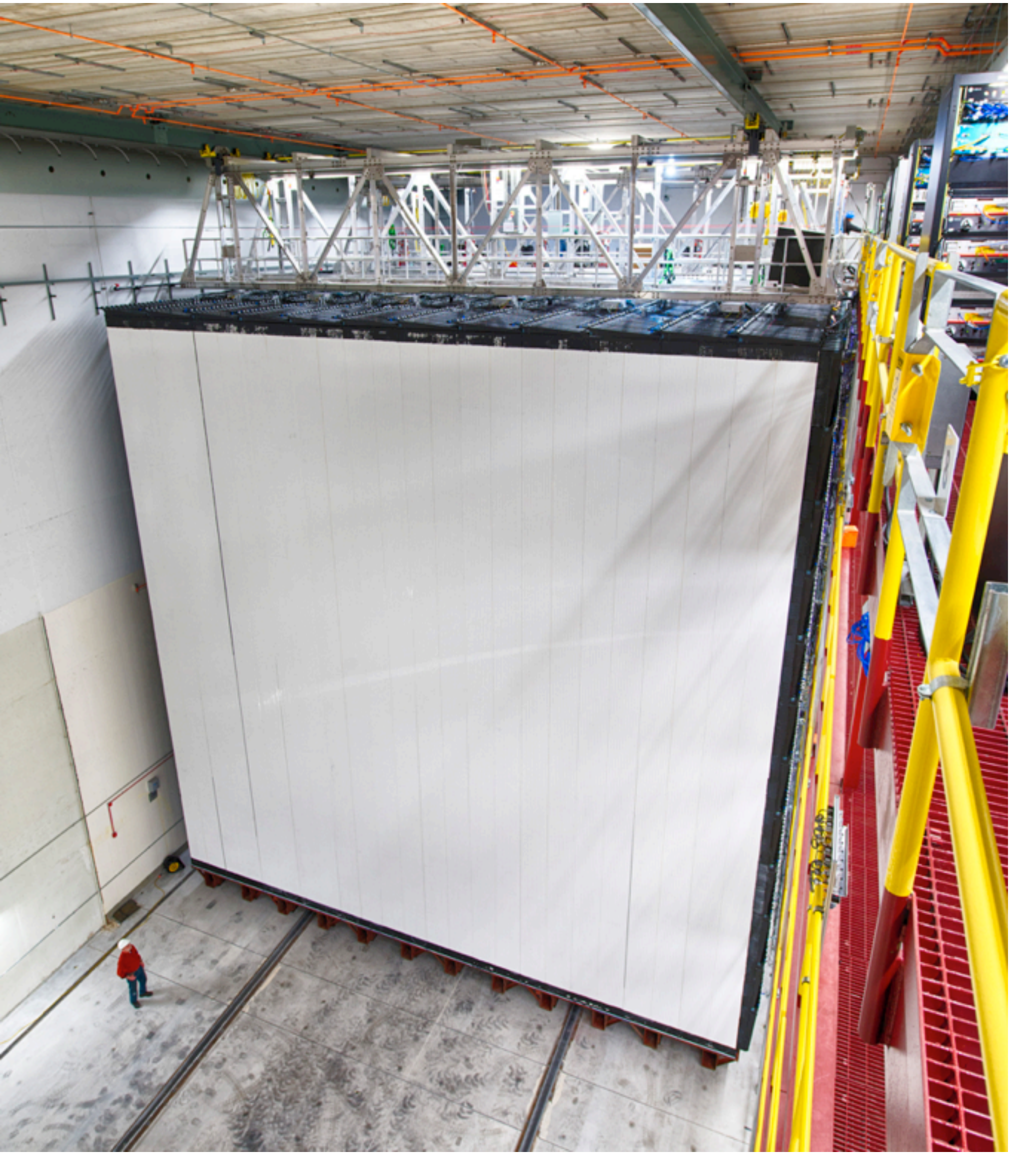
Fermilab

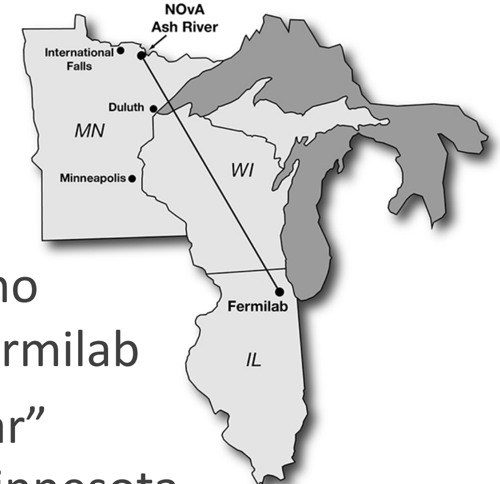
Neutrinos at Fermilab: the future

Fermilab operates the nation's largest particle accelerator complex, producing the world's most powerful neutrino beams



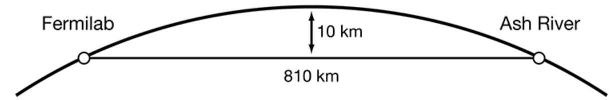
NOvA neutrino oscillation experiment

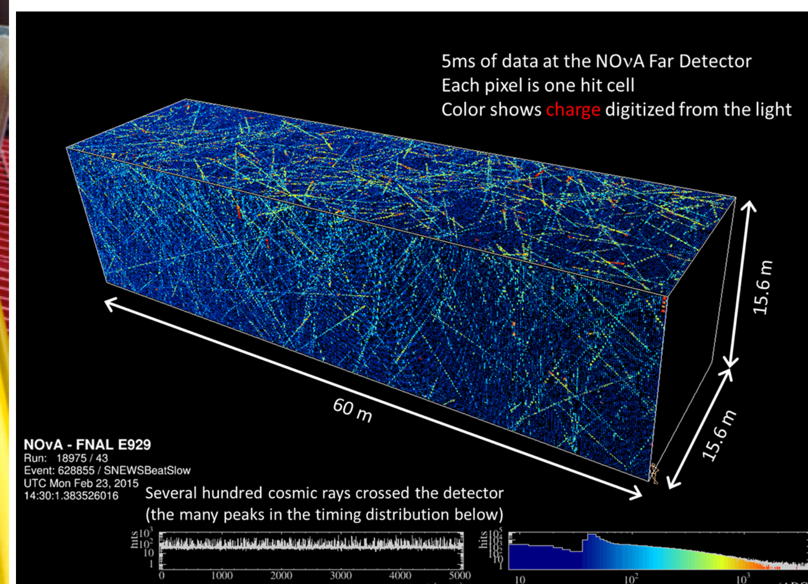




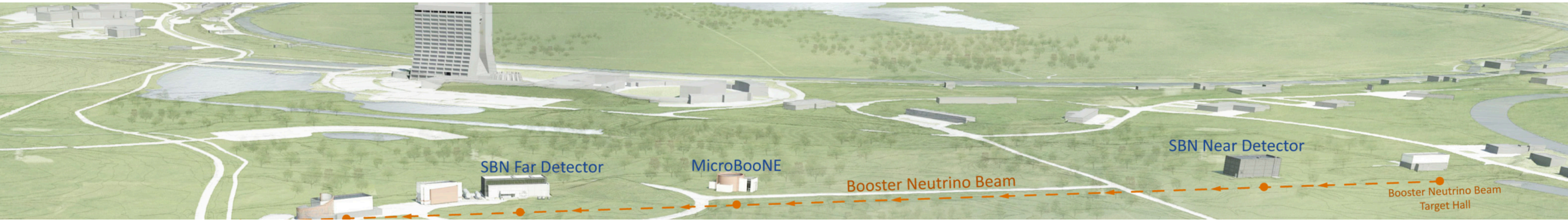
“near” neutrino detector at Fermilab

14,000 ton “far” detector in Minnesota



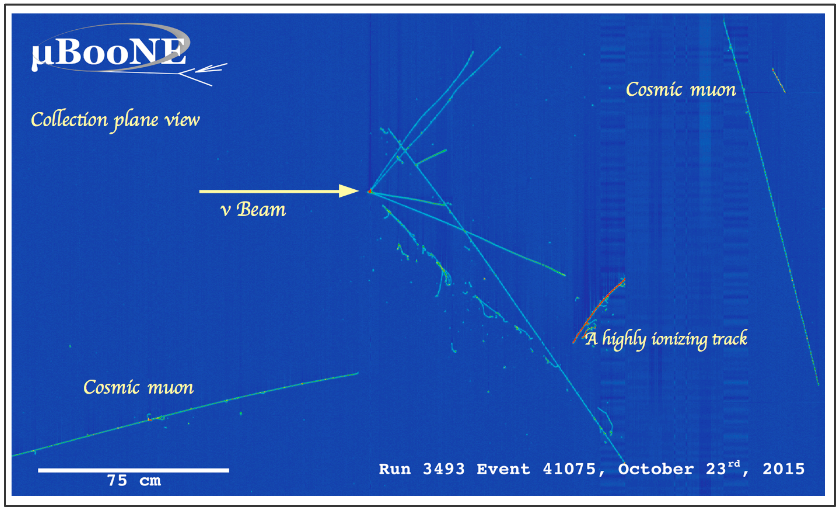


Short Baseline Program at Fermilab

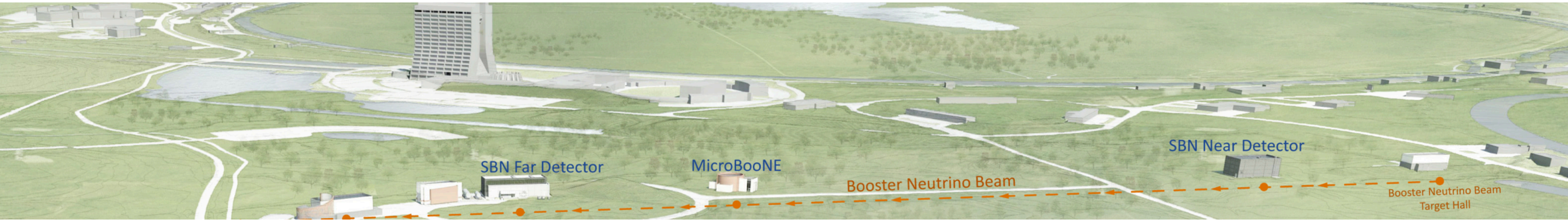


- Fermilab is producing neutrino beams for current experiment MicroBooNE, and soon ICARUS & SBN Far and Near Detector
- Probing the mysteries of neutrinos
- Advancing the technology for neutrino detection

MicroBoone 170-ton liquid-argon time projection chamber (LArTPC)



Short Baseline Program at Fermilab



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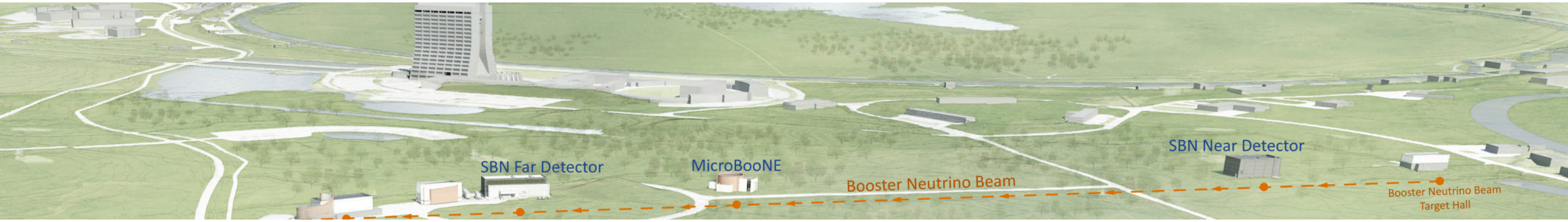
ICARUS (Far) 500-ton active volume

Short Baseline Program at Fermilab



- Fermilab is producing neutrino beams for current experiment MicroBooNE, and soon ICARUS & SBN Far and Near Detector
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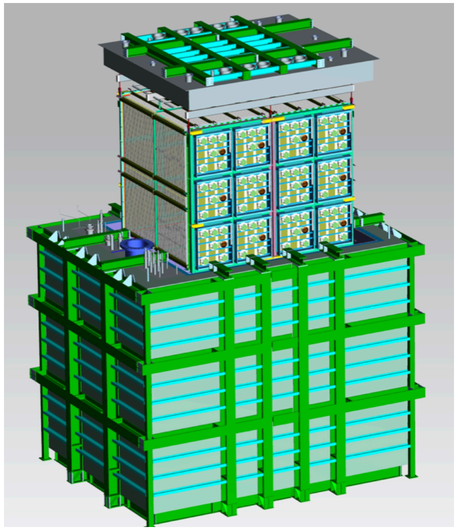
ICARUS (Far) 500-ton active volume

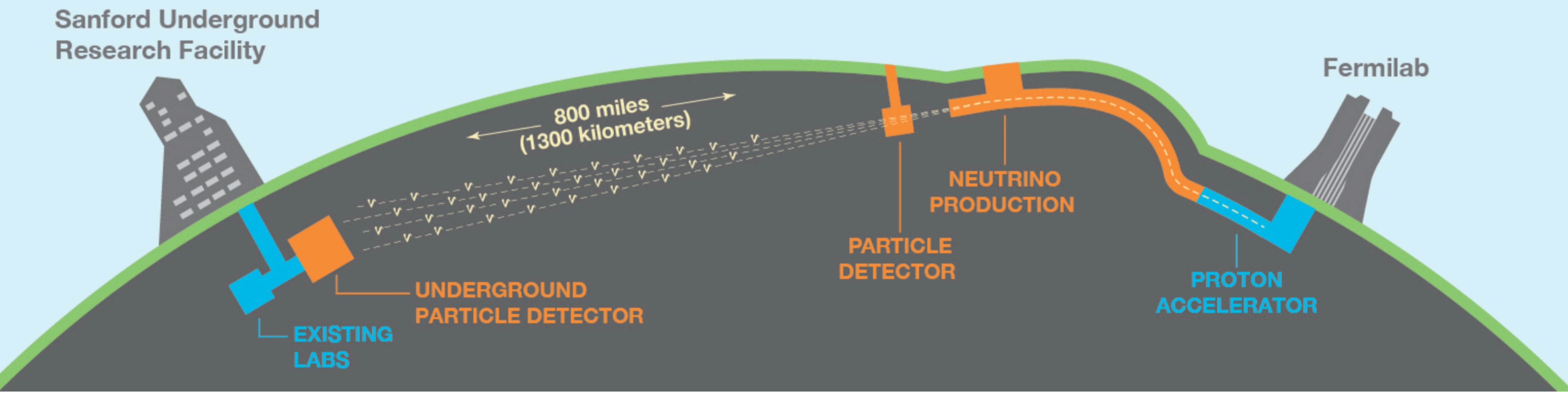
SBND 112-ton active



SBND will record over a million neutrino interactions per year.

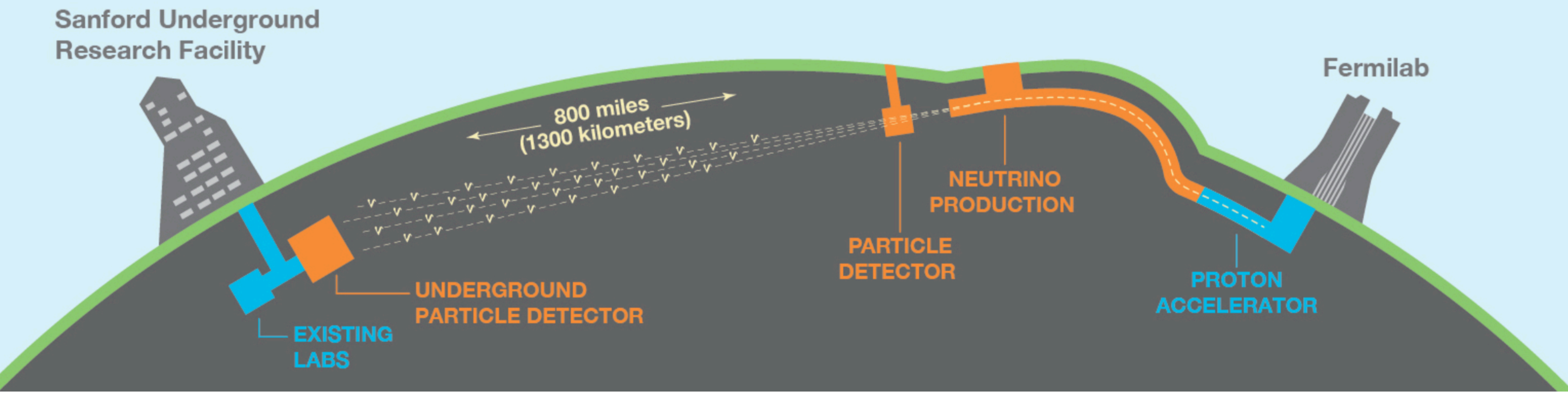
DUNE DEEP UNDERGROUND NEUTRINO EXPERIMENT

Build the world's most powerful neutrino beam at Fermilab



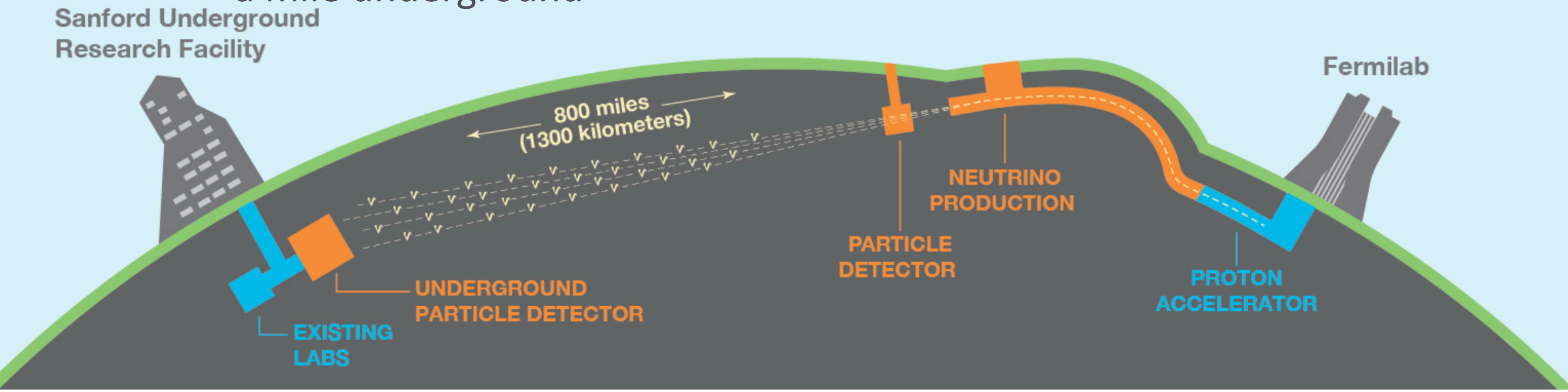
DEEP UNDERGROUND NEUTRINO EXPERIMENT

Send neutrinos 1300 km through the Earth to South Dakota



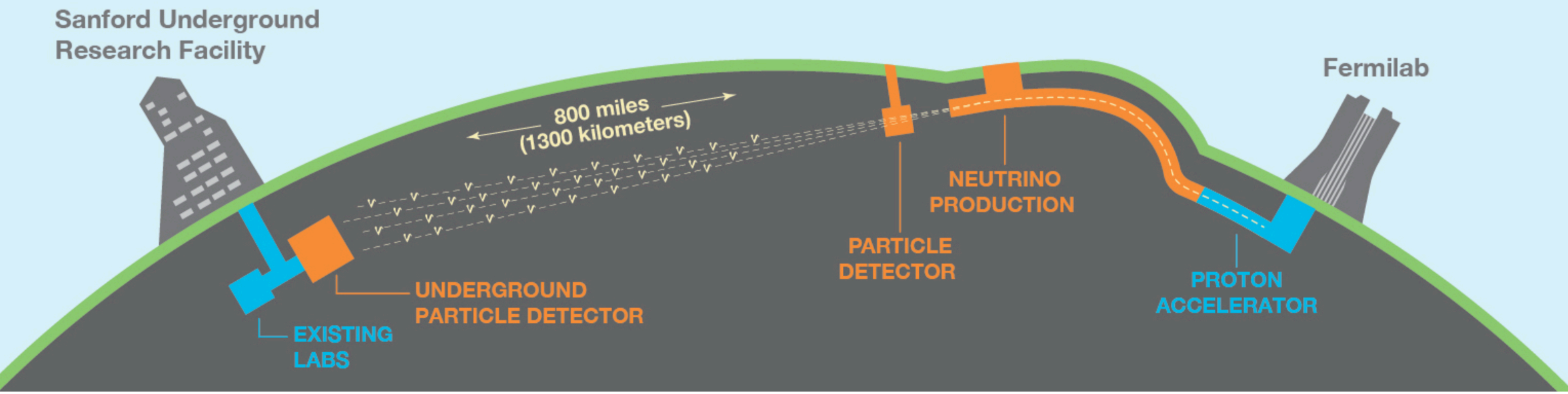
DUNE DEEP UNDERGROUND NEUTRINO EXPERIMENT

Detect them in the world’s most sophisticated neutrino detectors, a mile underground



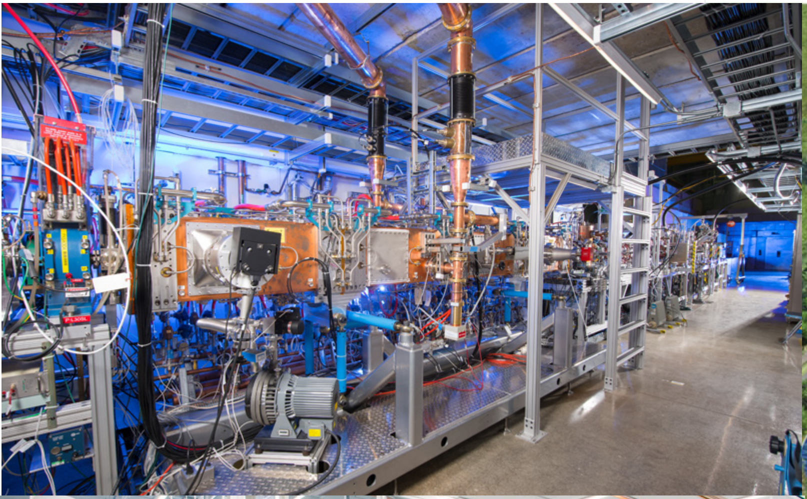
DUNE DEEP UNDERGROUND NEUTRINO EXPERIMENT

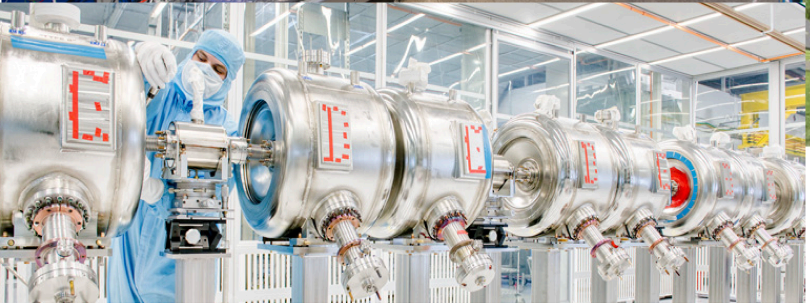
The experiment will run from approximately 2025-2045



PIP-II accelerator

PIP-II will deliver the world's most intense beam of neutrinos to the international LBNF/DUNE project, and enable a broad physics research program, powering new discoveries for decades to come.

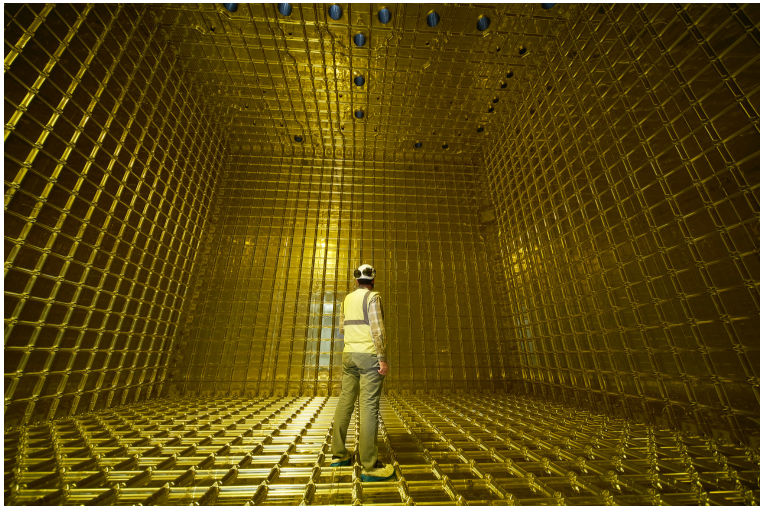


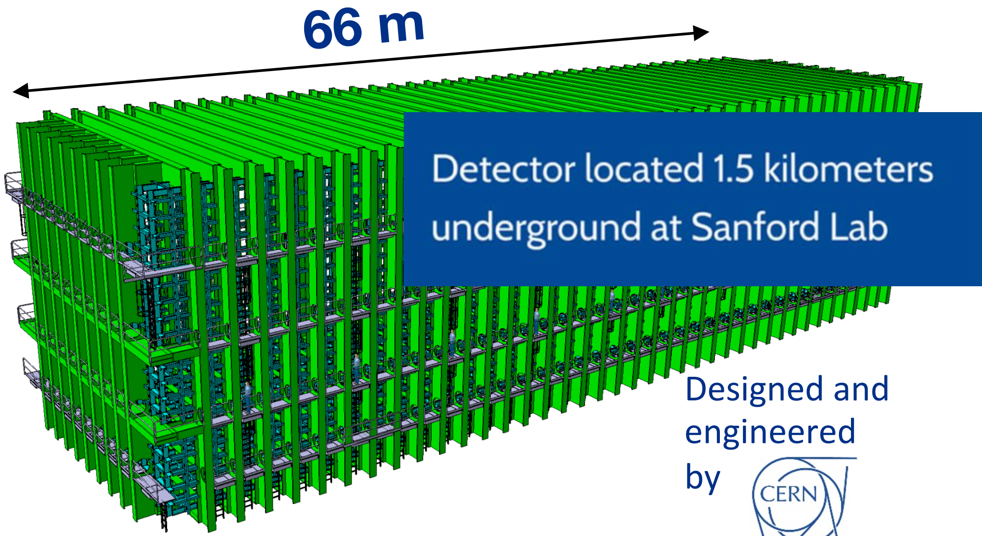


Fermilab, World's leader in SRF cavities, at the core of PIPII

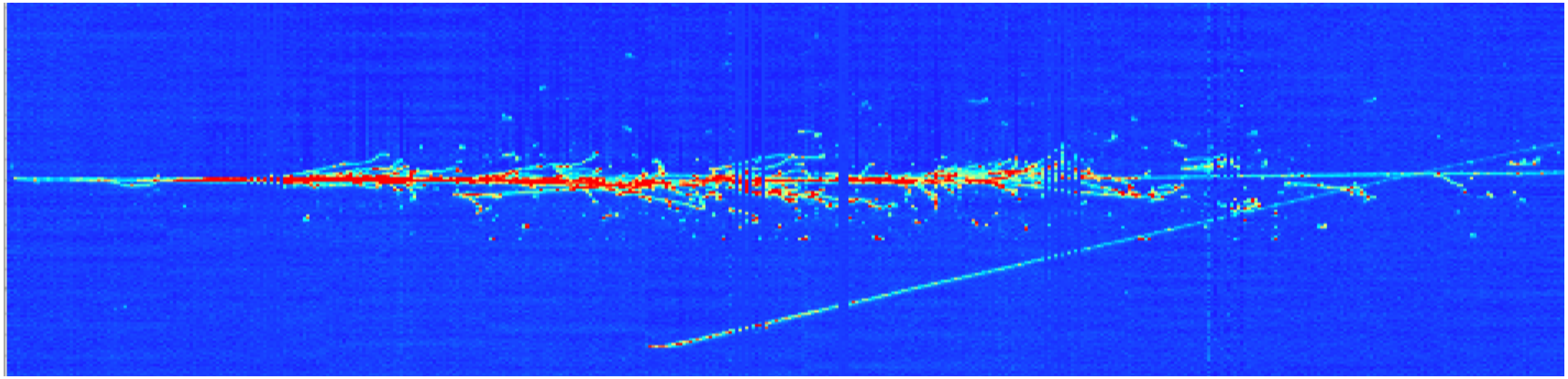
DUNE = four 70 kton Cryogenic Liquid Argon Detectors

A 1/20 scale prototype has successfully run at CERN





Designed and engineered by CERN



Fermilab

DUNE Science Goals

Search for the origin of matter

- Observation of of CP violation

Look for fundamental underlying symmetries of the Universe

- Measurement of mixing and mass ordering

Unification of forces

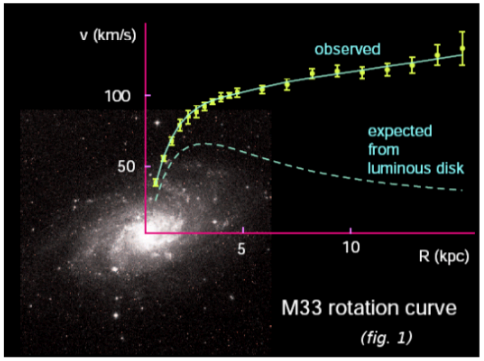
- Search for proton decays

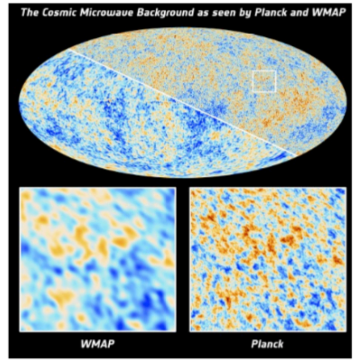
Learn about neutron stars and black holes and thus evolution of Universe

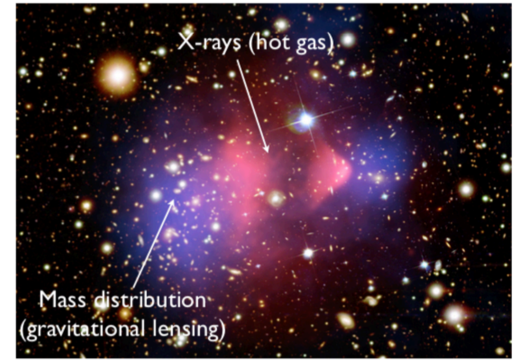
- Detection of neutrinos emitted by exploding stars

The Future of Dark Matter

- Dark Matter exists, awaiting for discovery



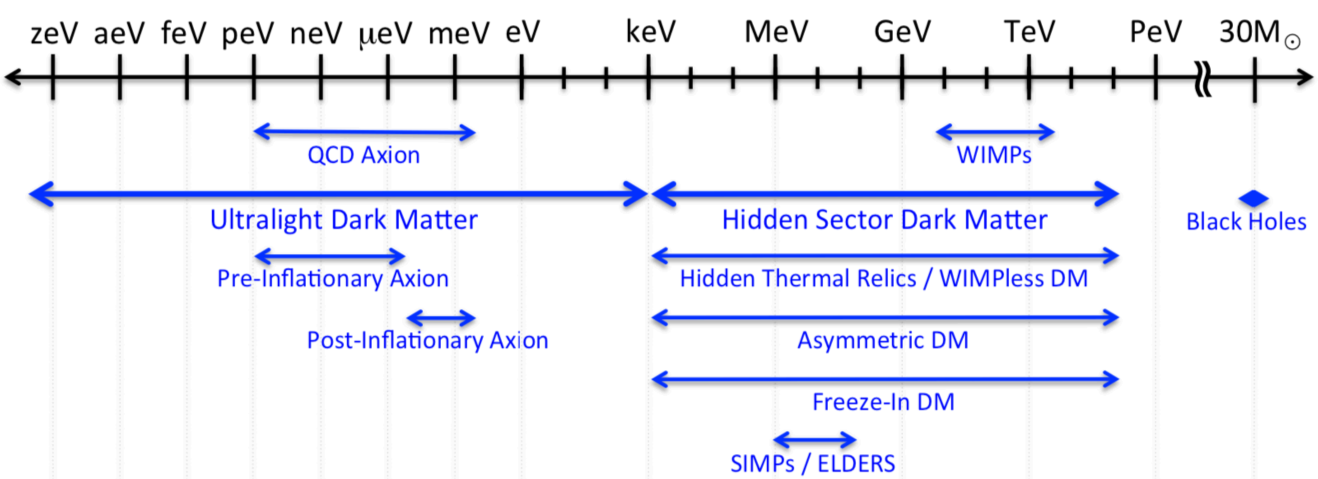




European Strategy Update

Dark Matter Candidates: Very little clue on mass scales

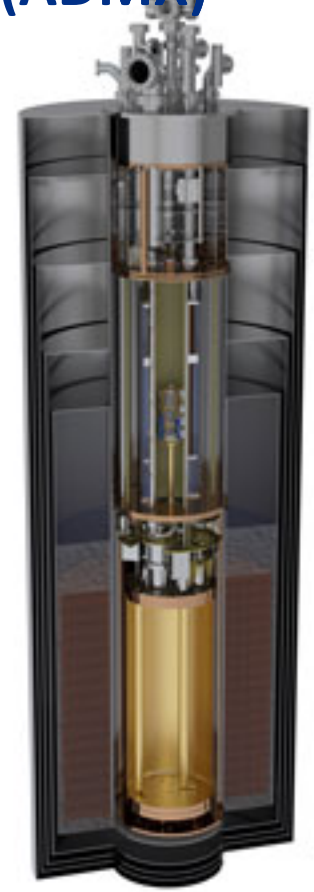
Too small mass
⇒ won't "fit"
in a galaxy!



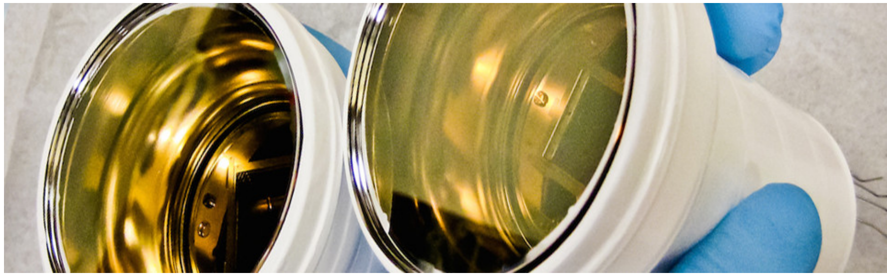
From MACHOs
searches

Dark Matter Experiments

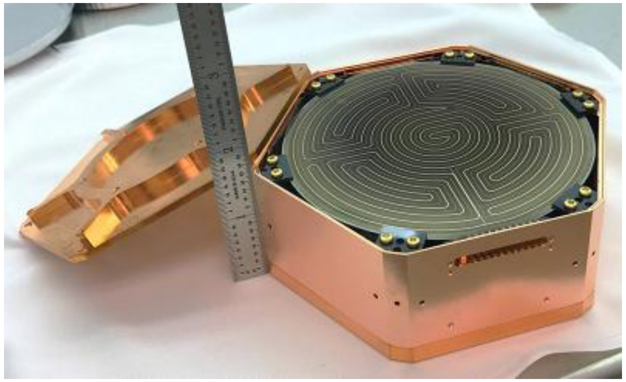
Axion Dark Matter Experiment (ADMX)



Low noise tunable receiver
Axions can convert into photons inside a cold, dark, reflective box subject to magnetic field



LZ experiment, targeting WIMPs: 10 tons of liquid xenon to detect interactions between dark matter and ordinary matter.



SuperCDMS
Super Cryogenic Dark Matter Search, targeting WIMPs
Germanium and Silicon crystal to detect phonons and charge from DM-nuclei elastic collisions

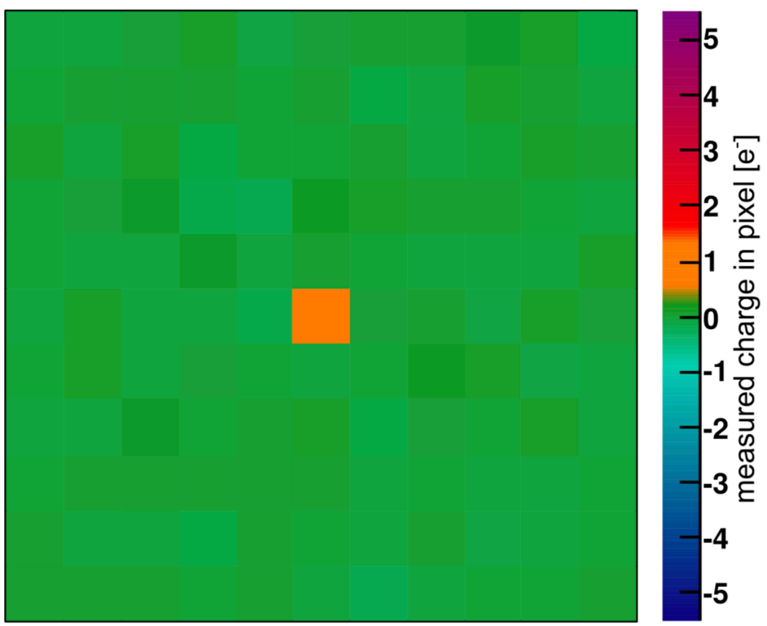
Dark Matter Experiments

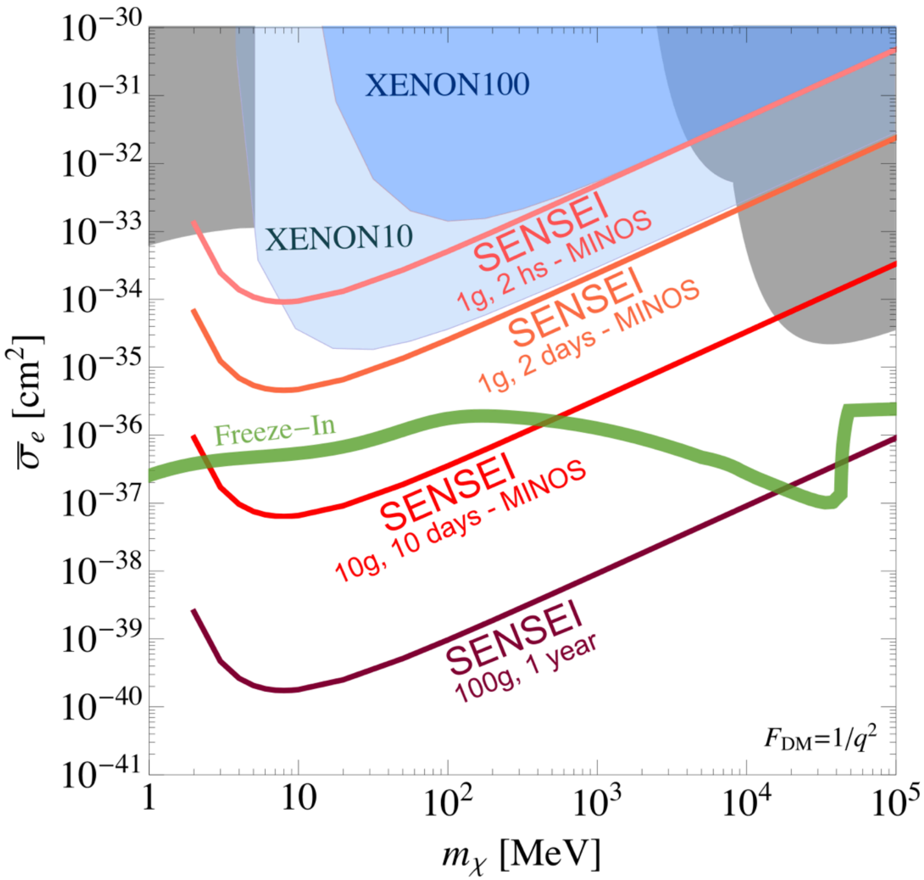
SENSEI Sub-electron-noise skipper-CCD experimental instrument

Breakthrough technology developed by FNAL and LBL

To precisely count each individual electron in each pixel of a large CCD with millions of pixels

Image taken with SENSEI individual e^- are resolved





Cosmic surveys

Dark Energy Survey (DES)

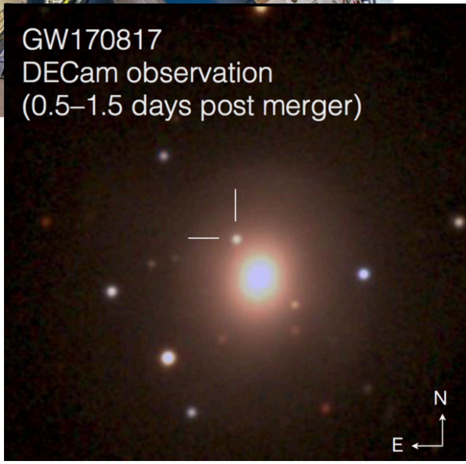
- One of the world's largest digital camera (telescope in Chile)
- In each snapshot, >100k galaxies up to 8B light-years away
- Surveyed >300 million galaxies
- Most detailed map of dark matter
- Detected gravitational wave source!

Dark Energy Spectroscopic Instrument (DESI)

- To obtain the optical spectra of tens of millions of galaxies and quasars and build a 3D map of Universe up to 11B light-years
- Measure impact of DE on Universe expansion

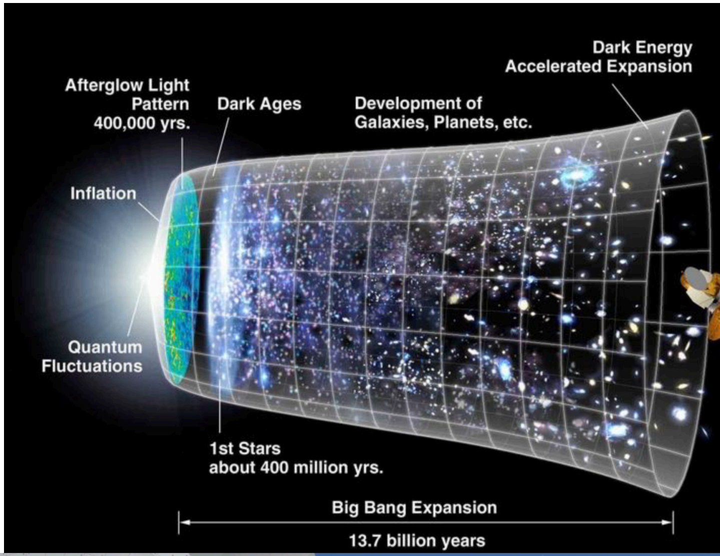
LSST

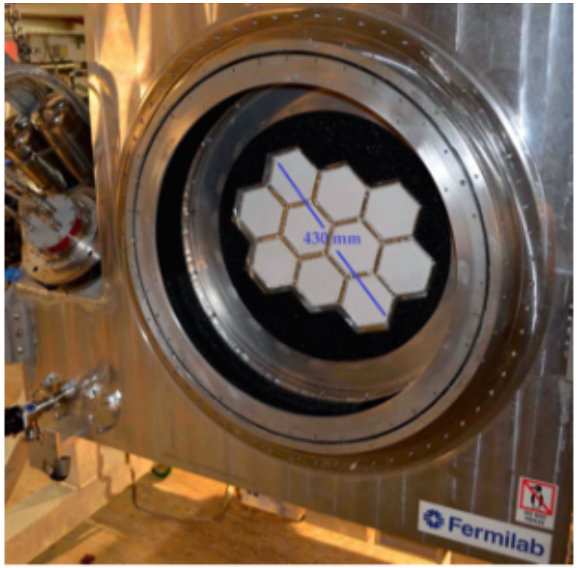
- Science running starts 2023
- Will survey >30 billion galaxies

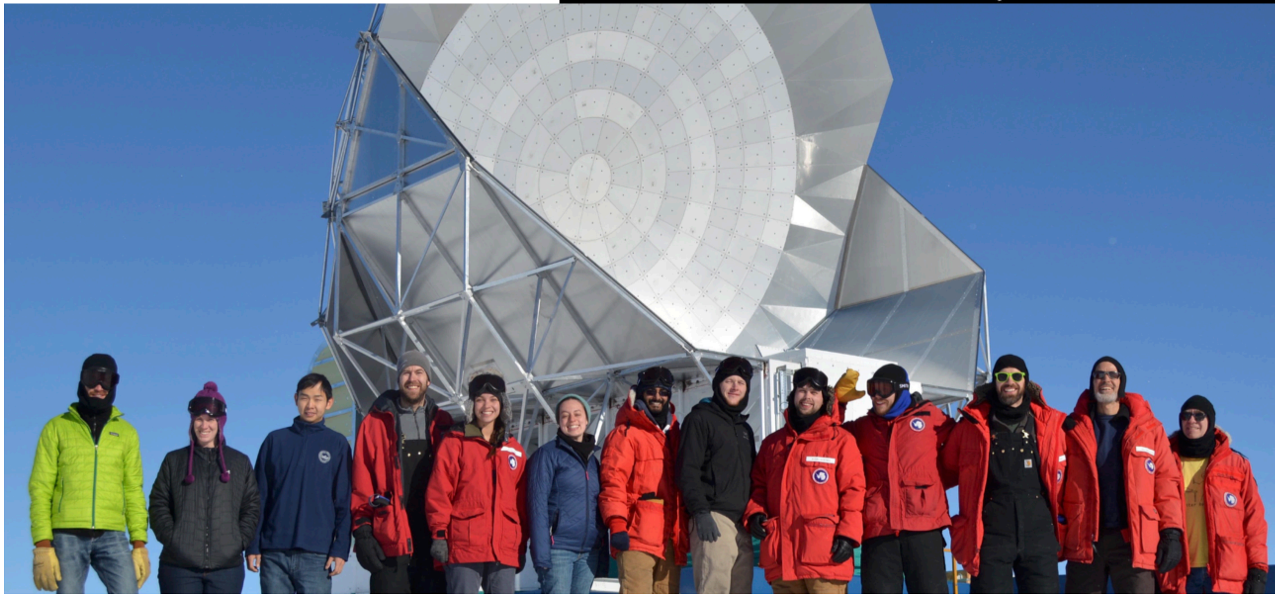


SPT-3G: Looking at the cosmos from the South Pole

- SPT-3G is a 10 meter microwave telescope with an array of 16,000 cryogenic transition-edge sensors
- Probes fine details of the Cosmic Microwave Background
- Sensitive to effects of cosmic inflation, neutrinos, and dark energy
- The next gen experiment CMB-S4 will have 500,000 sensors

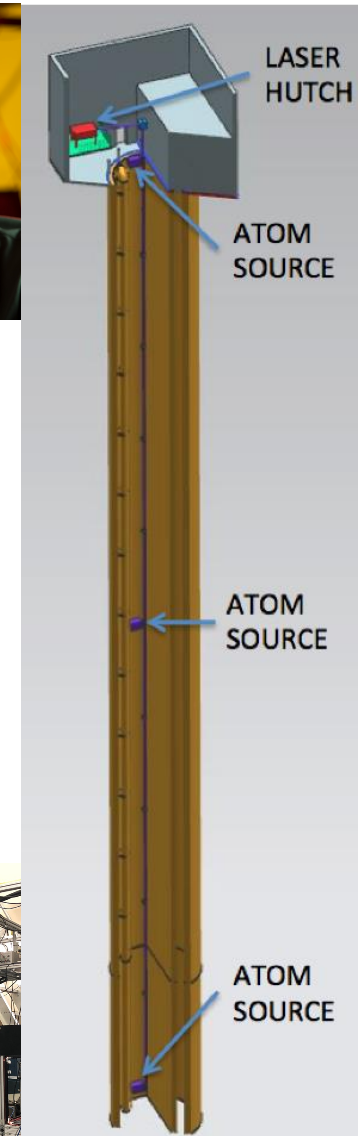


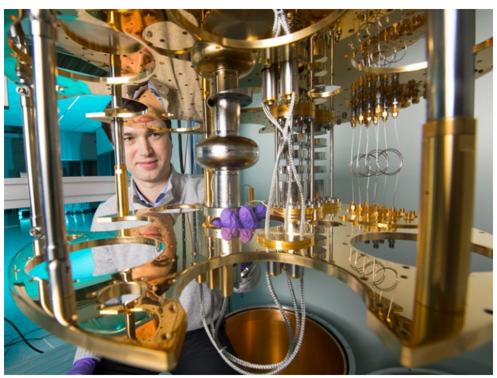


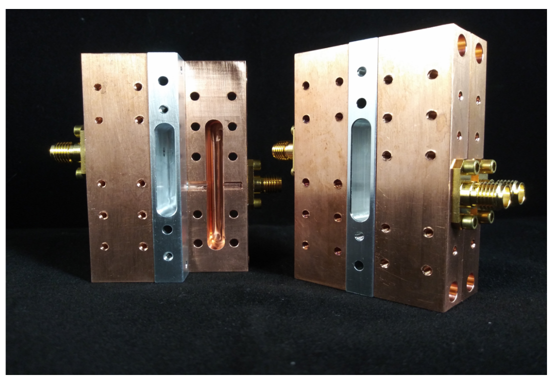


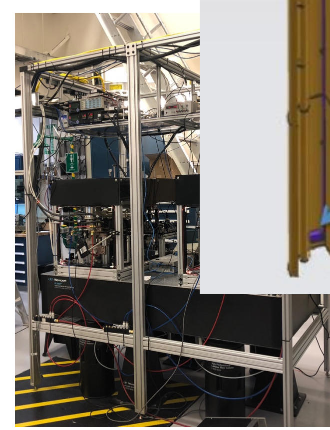
Fermilab quantum program

- Fermilab is collaborating with 22 universities and other labs on quantum science and technology
- The very challenging science goals of HEP, e.g. laboratory detection of dark matter, are now driving advances in quantum technologies; these advances will eventually have broad impact beyond HEP
- Fermilab is leveraging infrastructure and HEP expertise for the development of new quantum devices, and for the challenges of scaling up quantum systems; successes here will impact quantum computing, sensing, and communications





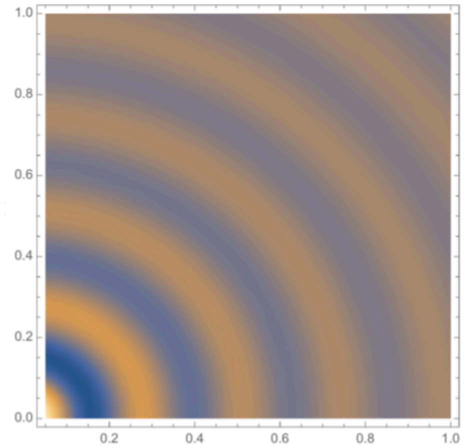




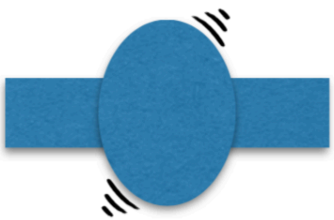
Superconducting RF cavities for dark photon detection

Dark Photon Search

The first simple setup:

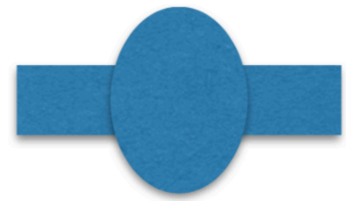


a dark photon field is radiated at 1.3 GHz.



Emitter Cavity

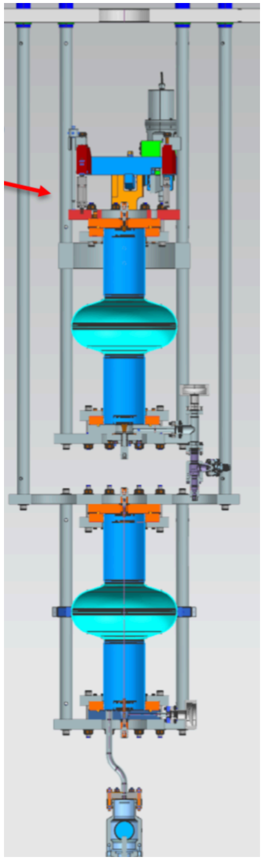
Frequency of 1.3 GHz, excited to ~ 35 MV/m. Thats ~ 10^{25} Photons!



Receiver Cavity

Tuned to 1.3 GHz. Responds to dark field. Contains only thermal noise (T=1.4 K).

Fermilab Dark Photon Experiment



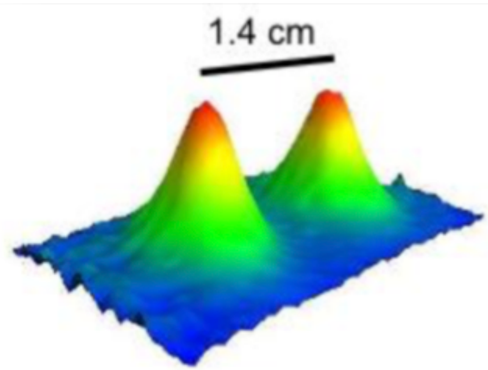
Tunable powered "Emitter" cavity and quiet "Receiver" cavity

Dark SRF experimental apparatus ready for testing

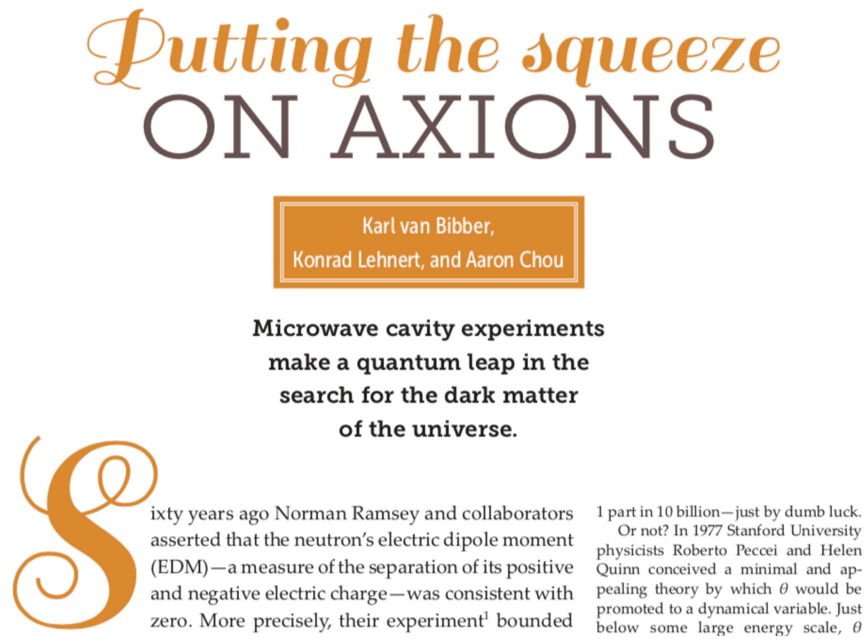
Fermilab Vertical Test Stand used for liquid helium tests of accelerator SRF cavities

Much more we could not talk about today!

MAGIS-100 a quantum measuring device enabled by quantum coherence over distances of several meters and times of several seconds



Data from Stanford setup showed single atoms in quantum superposition at world-record separations up to 54 cm


Putting the squeeze ON AXIONS

Karl van Bibber, Konrad Lehnert, and Aaron Chou

Microwave cavity experiments make a quantum leap in the search for the dark matter of the universe.

Sixty years ago Norman Ramsey and collaborators asserted that the neutron's electric dipole moment (EDM)—a measure of the separation of its positive and negative electric charge—was consistent with zero. More precisely, their experiment[1] bounded

1 part in 10 billion—just by dumb luck.

Or not? In 1977 Stanford University physicists Roberto Peccei and Helen Quinn conceived a minimal and appealing theory by which θ would be promoted to a dynamical variable. Just below some large energy scale, θ

- Axion dark matter searches are already limited by quantum noise
- new quantum sensing techniques are needed to make further progress towards higher mass axions.

Welcome to Fermilab!

Fermilab is leading in science and technology, it can make discoveries that will revolutionize our understanding of Nature

We want you to do cutting edge research, enjoy, and grow!