Fermilab

Operated by Fermi Research Alliance, LLC for the U.S. Department of Energy Office of Science

Neutrinos are Everywhere:
Towards a New Understanding of the Quantum Universe

Nigel S. Lockyer
Princeton University
6/17/2016

First Baby Bison Arrives 2016…National Mammal…

Government wants to check they are Bison
Recent Genetic Analysis of Herd…they are bison

ab

Coyotes down selected in national mammal competition

International Particle Physics Community Convergence

European Strategy
for Particle Physics

- **2013: European Strategy for Particle Physics updated**
  - Endorsed high priority of neutrino physics
  - Bottom line: CERN should help the European neutrino community participate in a long-baseline program ***outside of Europe***

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

Report of the Particle Physics Project Prioritization Panel (P5)

- **2014: "P5" Plan**
  - A strategic plan for U.S. particle physics maximizing opportunities for breakthrough science
  - Explicit prioritization, hard choices made within realistic budget scenarios
  - Particle physics community unified behind the plan: 2,331 signatures on letter sent to Secretary Moniz

CERN/DOE/NSF Agreement: Signers…Moniz, Heuer, Cordova

Neutrino Protocol…signed recently at CERN

NEUTRINO PROTOCOL I

between

THE EUROPEAN ORGANIZATION
FOR NUCLEAR RESEARCH (CERN)

and

THE DEPARTMENT OF ENERGY
OF THE UNITED STATES OF AMERICA (DOE)

to

THE CO-OPERATION AGREEMENT

concerning

SCIENTIFIC AND TECHNICAL CO-OPERATION
IN NUCLEAR AND PARTICLE PHYSICS

2015

CERN and Fermilab's futures are completely intertwined for next several decades …..as never before

Fermilab

Major news: Signing of US-CERN Protocols

In December, the United States and the European physics laboratory CERN signed an agreement to partner on continued research at the Large Hadron Collider, upcoming neutrino research and a future particle collider.

Intertwined…impacts our field for next 20+ years

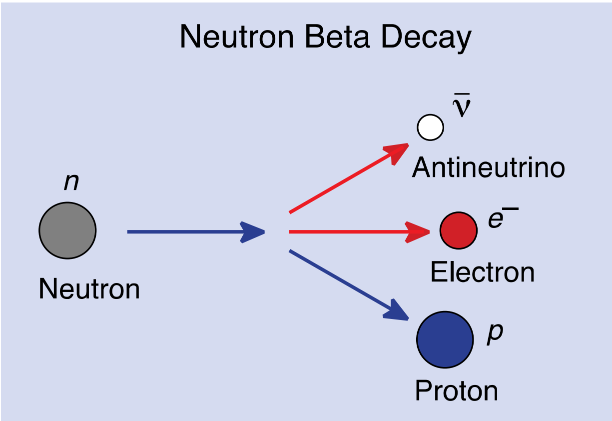
- Fermilab and CERN futures are intertwined like never before
- US contributes to Large Hadron Collider
- CERN, for first time in 60 years, invests in a science program outside of CERN
- LBNF/DUNE will be the first fully international mega science facility on US soil
- Fermilab will host LBNF just as CERN hosts the LHC
- We build on the very successful CERN model of international science…..which means any country is welcome
- CERN is a treaty organization
- Fermilab is a Department of Energy National Laboratory
- To be successful…we must adjust…so far so good

Wolfgang Pauli, 1930

- The radioactive process of nuclear "beta" decay doesn't seem to conserve energy
- How can that be?

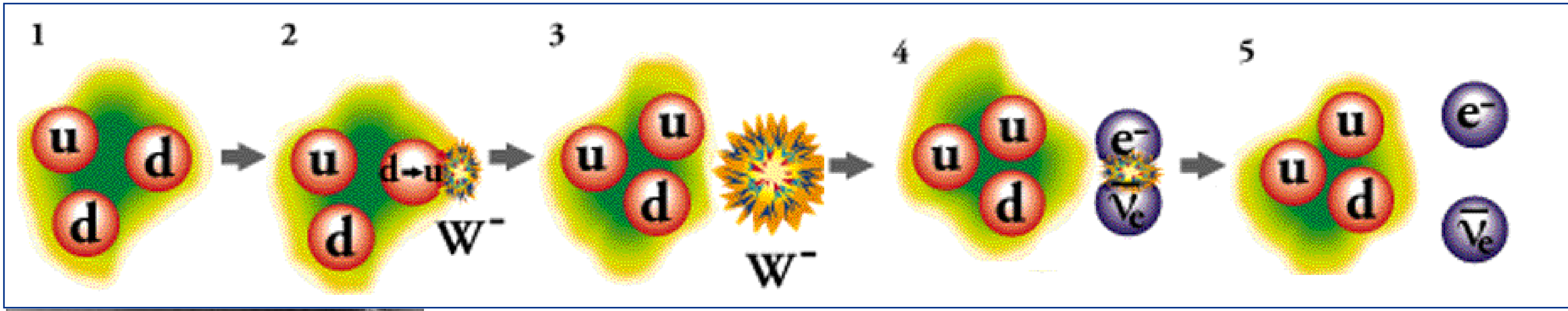
$$^{14}\mathbf{C} \rightarrow {}^{14}\mathbf{N} + \mathbf{e}^{-}$$

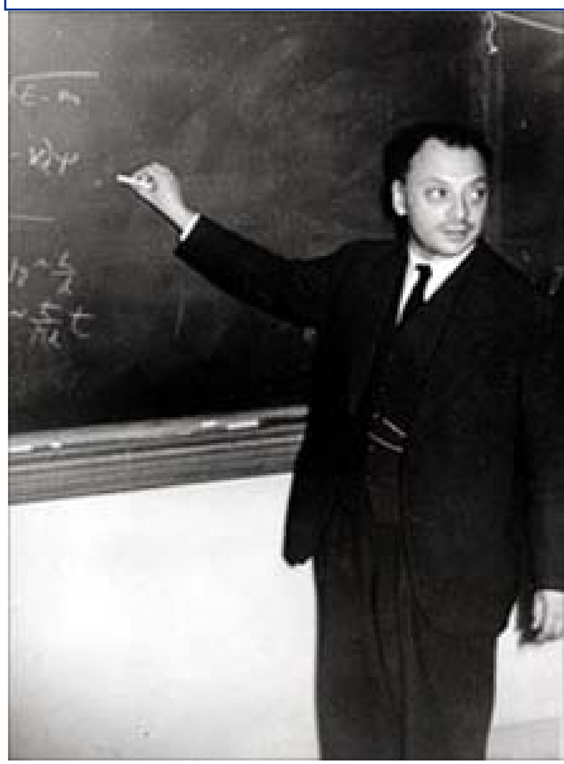
$$\mathbf{n} \rightarrow \mathbf{p} + \mathbf{e}^{-}$$



Pauli's invisible particle

$$\mathbf{n} \rightarrow \mathbf{p} + \mathbf{e}^{-} + \bar{\nu}_e$$





I have done a terrible thing.
I have postulated a particle that cannot be detected.

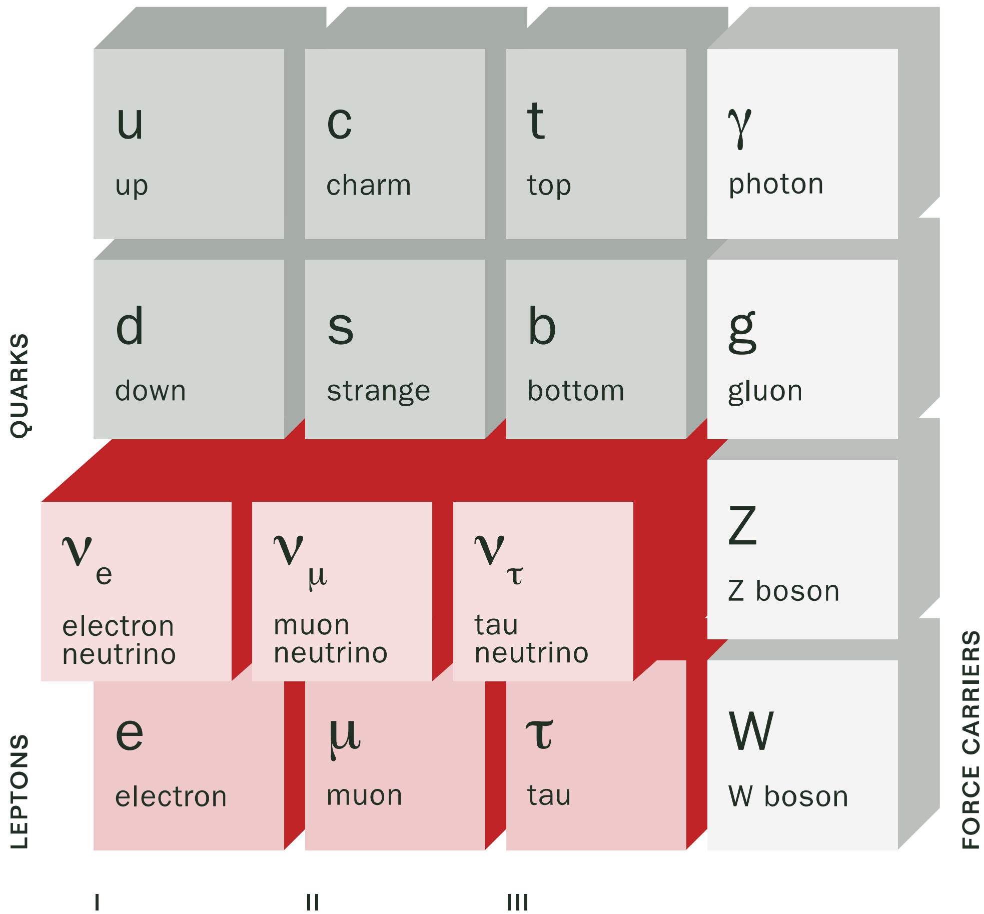
Fermi's Little Neutral One, 1933

- After the neutron was discovered in 1932, Enrico Fermi proposed that nuclear beta decay involved some new "**weak interaction**" between a neutron, proton, electron, and Pauli's invisible particle
- He coined the name "**neutrino**" in a brilliant paper submitted to the prestigious journal Nature

Fermi's Little Neutral One, 1933

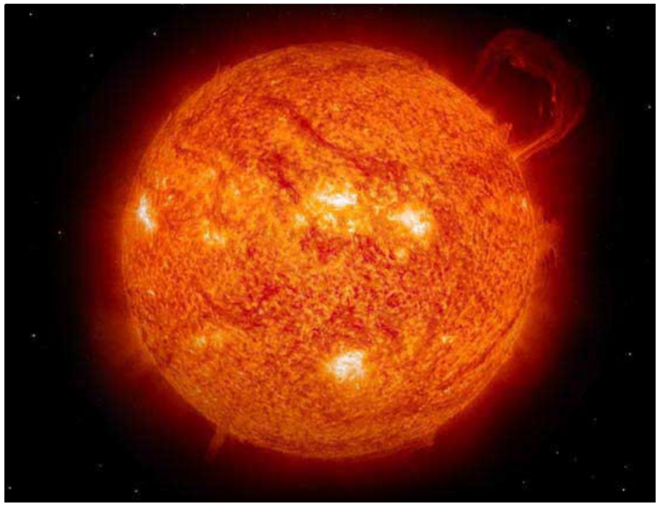
- After the neutron was discovered in 1932, Enrico Fermi proposed that nuclear beta decay involved some new "**weak interaction**" between a neutron, proton, electron, and Pauli's invisible particle
- He coined the name "**neutrino**" in a brilliant paper submitted to the prestigious journal Nature
- **The paper was rejected** for containing *"speculations too remote from reality"*

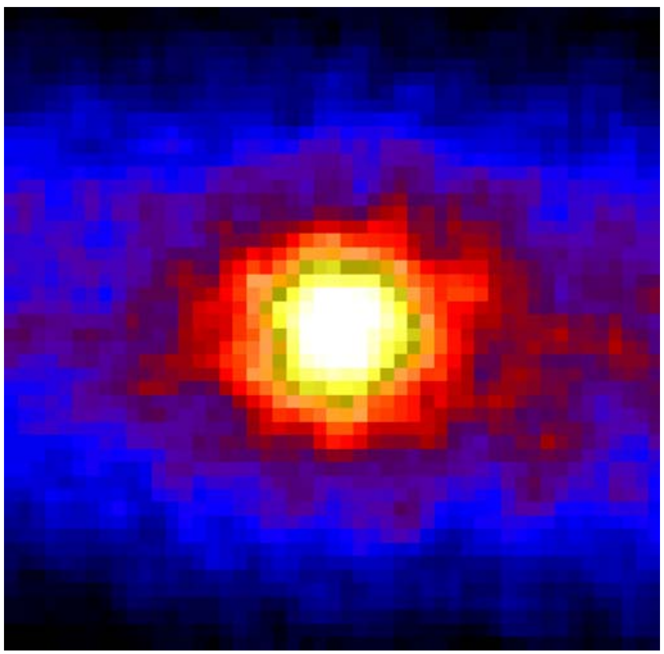
What is a neutrino?



- Elementary particles that come in (at least) three different “flavors”
- Don’t carry any charge, interact only very weakly with other kinds of matter
- Have tiny masses at least a million times smaller than other particle masses

Where do neutrinos come from?





The Sun:

- The nuclear fusion reactions that power the sun produce neutrinos
- The sun shines almost as brightly in neutrinos as it does in light…. (1-2)% of energy is in neutrinos
- Sun will shine unchanged for 10^5 yrs
- 100 billion solar neutrinos pass through your thumbnail each second

$$p + p \rightarrow D + e^{+} + \nu_e$$

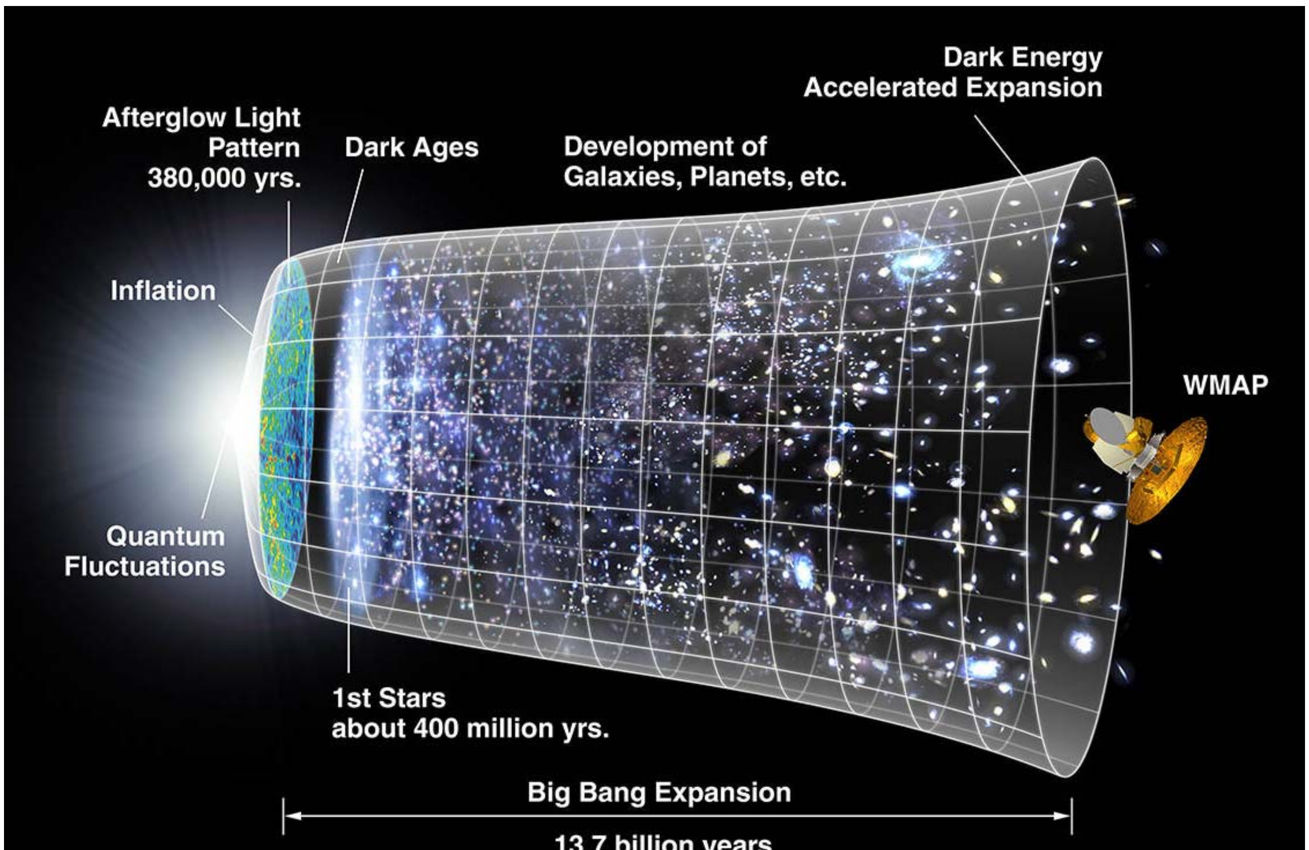
$$p + {}^{7}Be \rightarrow {}^{8}B + \gamma$$

$${}^{8}B \rightarrow {}^{8}Be + e^{+} + \nu_e$$

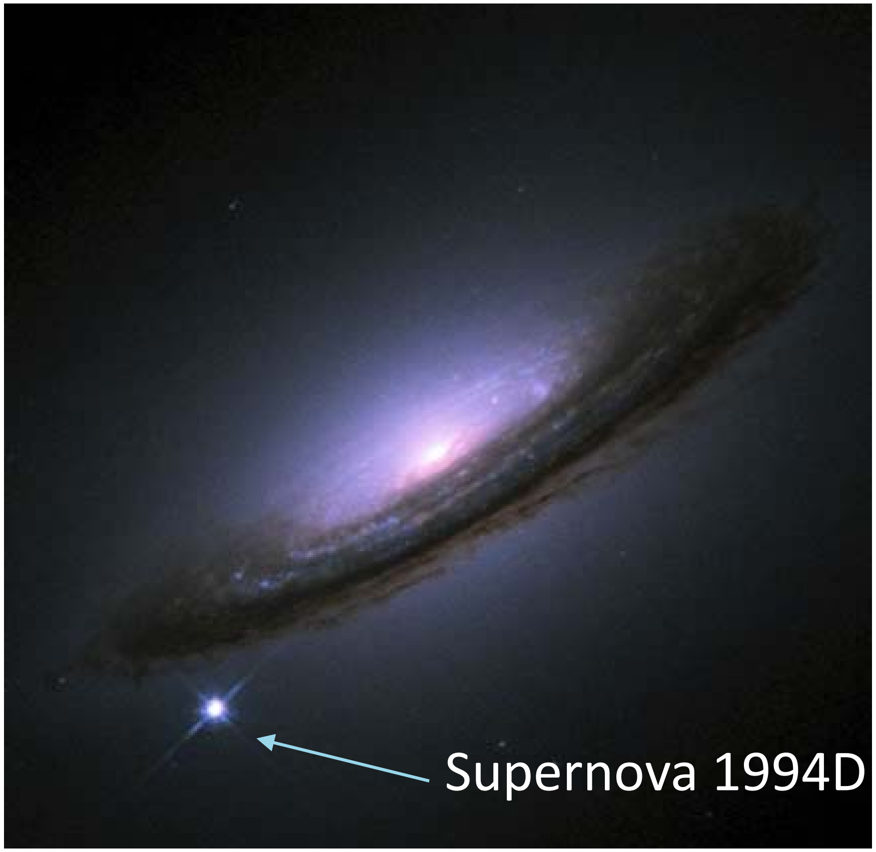
Where do neutrinos come from?

The Big Bang:

- There are 10 million neutrinos left over from the Big Bang in every cubic foot of space
- Neutrinos are by far the most prevalent form of known matter in the universe

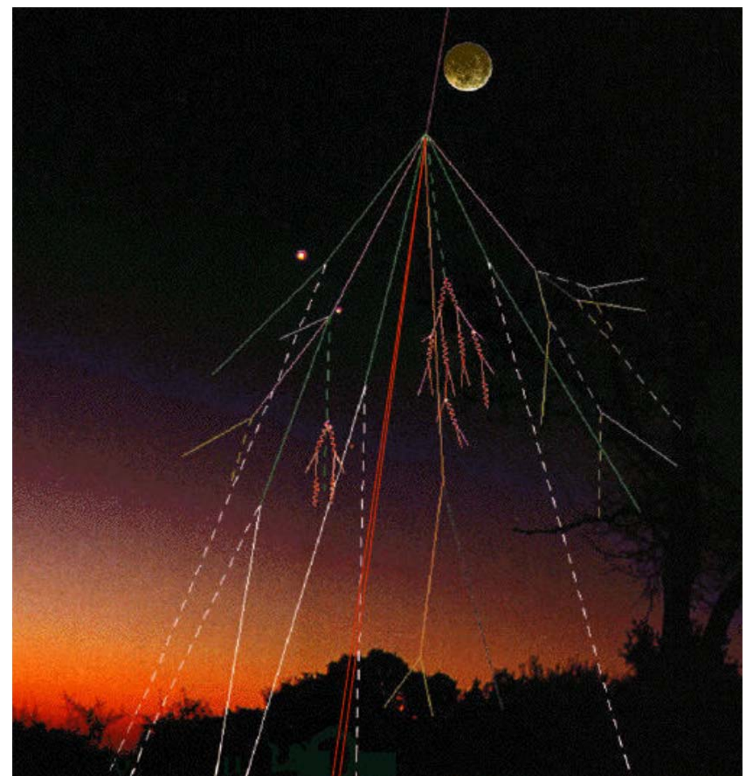


Where do neutrinos come from?



Cosmic rays:

- High energy cosmic particles hit the top of the atmosphere
- 10 atmospheric neutrinos per second through your thumbnail



Supernovae:

When a star explodes as a supernova, 99% of the energy of the explosion is carried off by neutrinos

Where do neutrinos come from?

Nuclear reactors:

2 billion nuclear reactor neutrinos pass through your thumbnail per second at 1 km from core per gW

…..same no. as sun at 200 meters

The Earth's crust:

Radioactive decay of uranium and thorium in the Earth's crust produces both neutrinos and the energy that causes volcanoes and earthquakes

Where do neutrinos come from?

Bananas: A banana emits about one million neutrinos per day from the radioactive decay of potassium 40…avocadoes…twice as many

Fermi's Little Neutral One, 1933

Fermi also understood that if you had a strong enough source of neutrinos, then you could eventually detect them

The nuclear beta decay process

$$\mathbf{n} \rightarrow \mathbf{p} + \mathbf{e}^- + \bar{\nu}_e$$

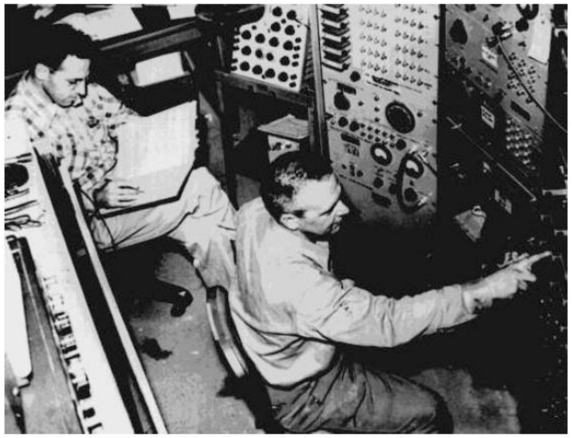
implies also this process:

$$\bar{\nu}_e + \mathbf{p} \rightarrow \mathbf{n} + \mathbf{e}^+$$

Implies need for a beam of neutrinos

More History: 1st detection of neutrinos -1950s

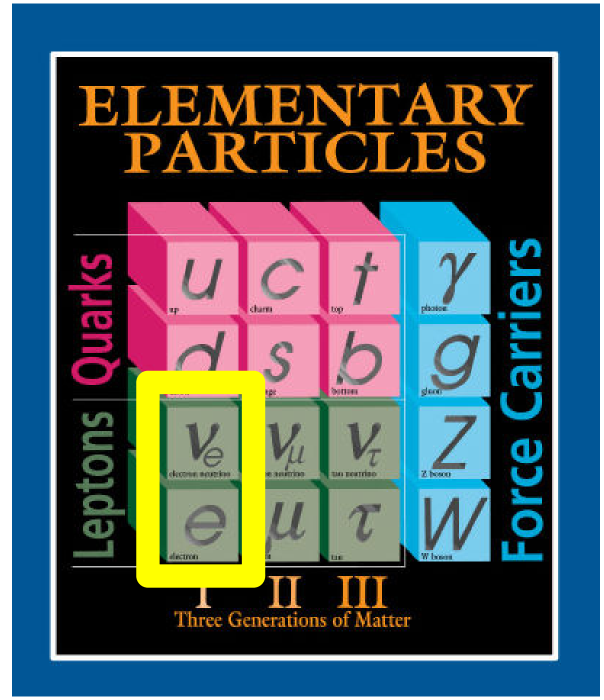
Savannah River Nuclear Reactor

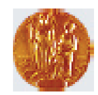


Fred Reines and Clyde Cowan at the Control Center of the Hanford Experiment (1953)

$$\bar{\nu}_e + \mathbf{p} \rightarrow \mathbf{n} + \mathbf{e}^+$$

…..and they shut off the reactor!



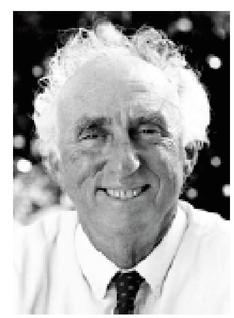


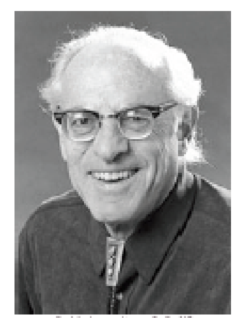
The Nobel Prize in Physics 1995

"for pioneering experimental contributions to lepton physics"

"for the discovery of the tau lepton"

"for the detection of the neutrino"





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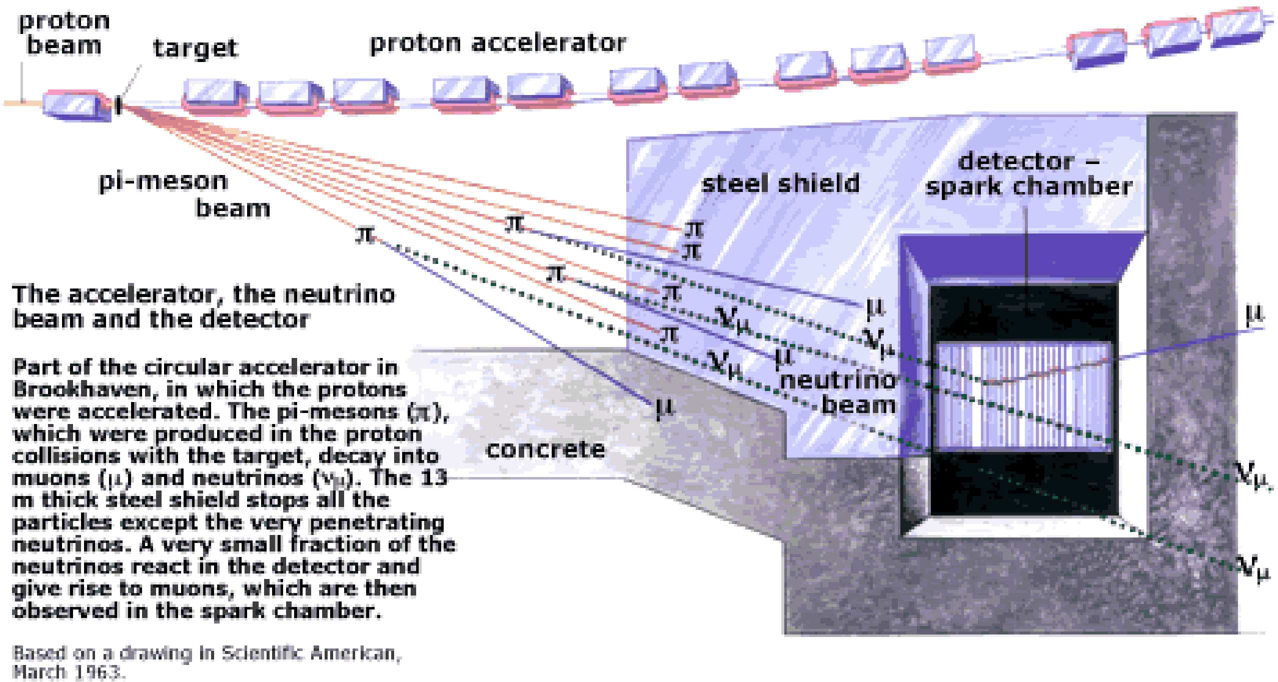
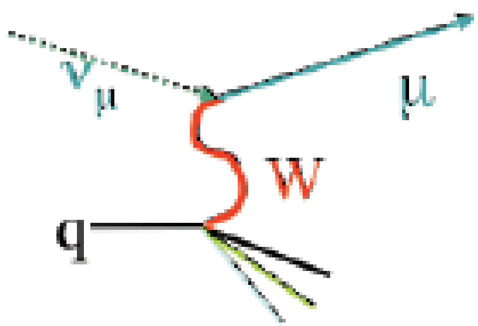
Martin L. Perl

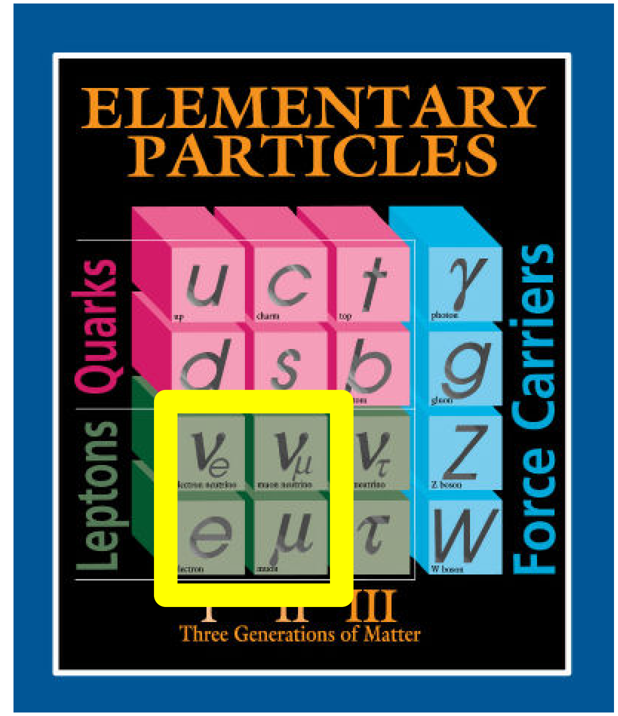
Frederick Reines

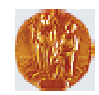
Discovery of "two neutrinos" – 1960s





$$\nu_\mu + N \rightarrow \mu^- + X$$



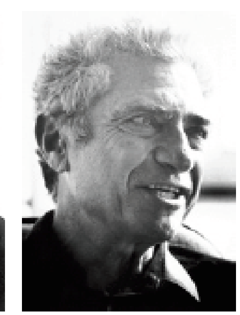


The Nobel Prize in Physics 1988

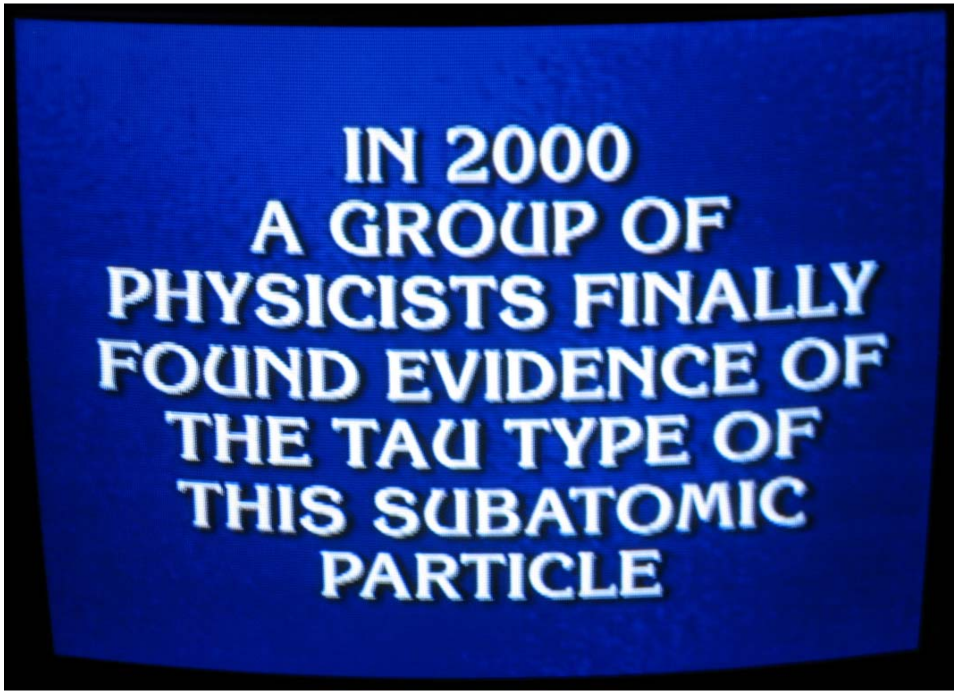
"for the neutrino beam method and the demonstration of the doublet structure of the leptons through the discovery of the muon neutrino"

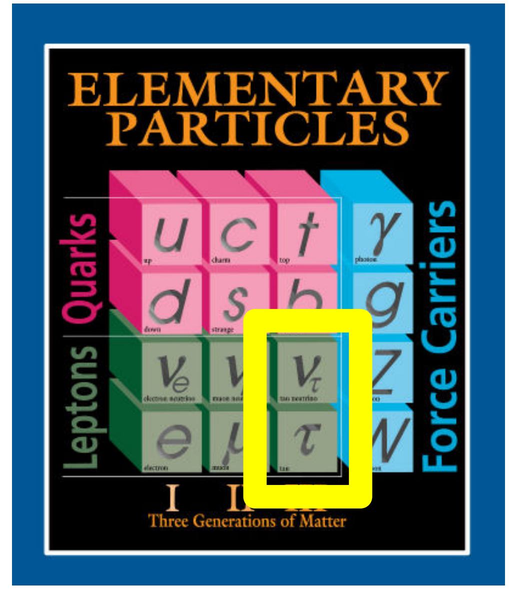

Leon M. Lederman

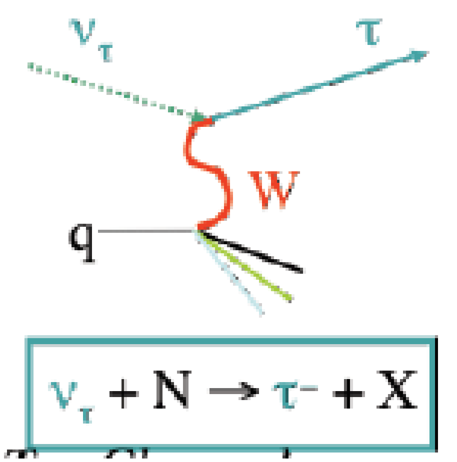

Melvin Schwartz


Jack Steinberger

Discovery of the Third Neutrino at Fermilab







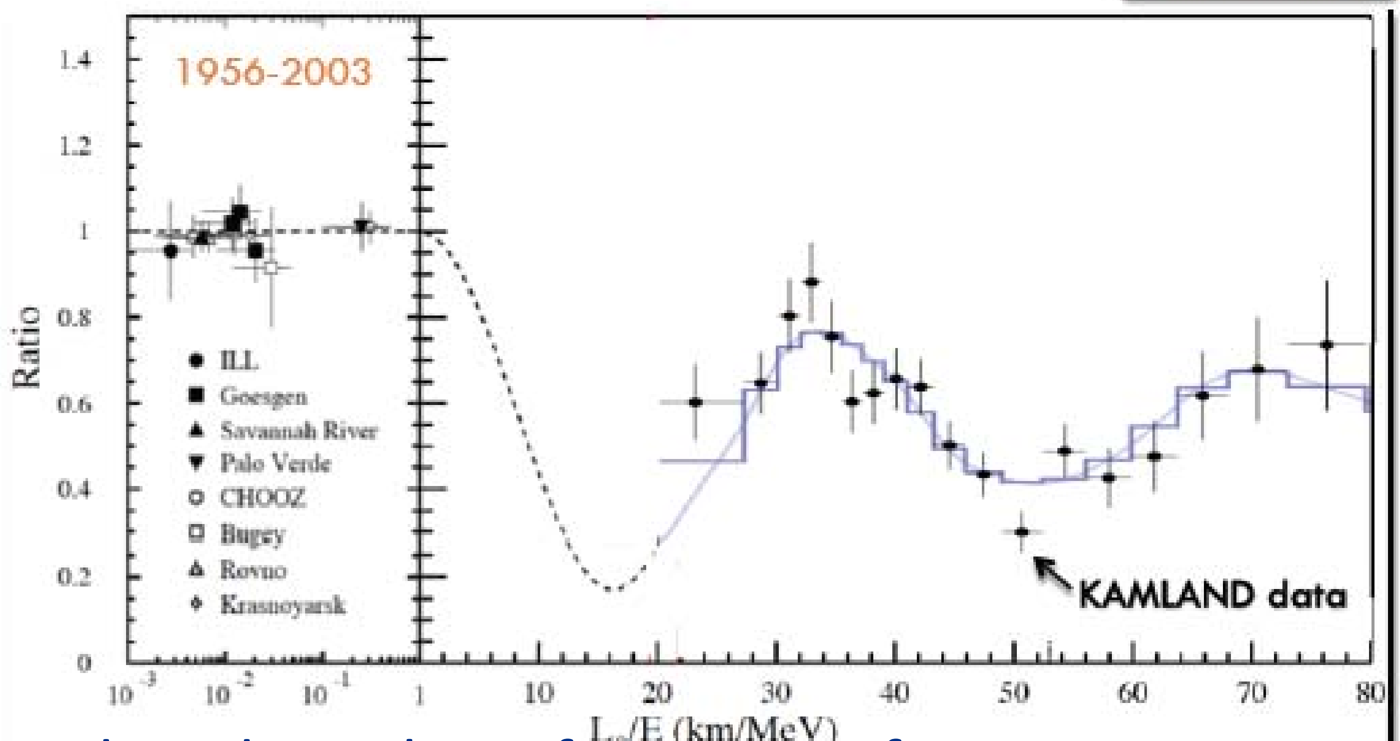
A little history…

In the 1960's physicists began to consider the possibility of neutrino "transitions" or oscillations….

35

- in the 1960's, scientists had started thinking "is there anything else?" - maybe ν transitions?

Bruno Pontecorvo



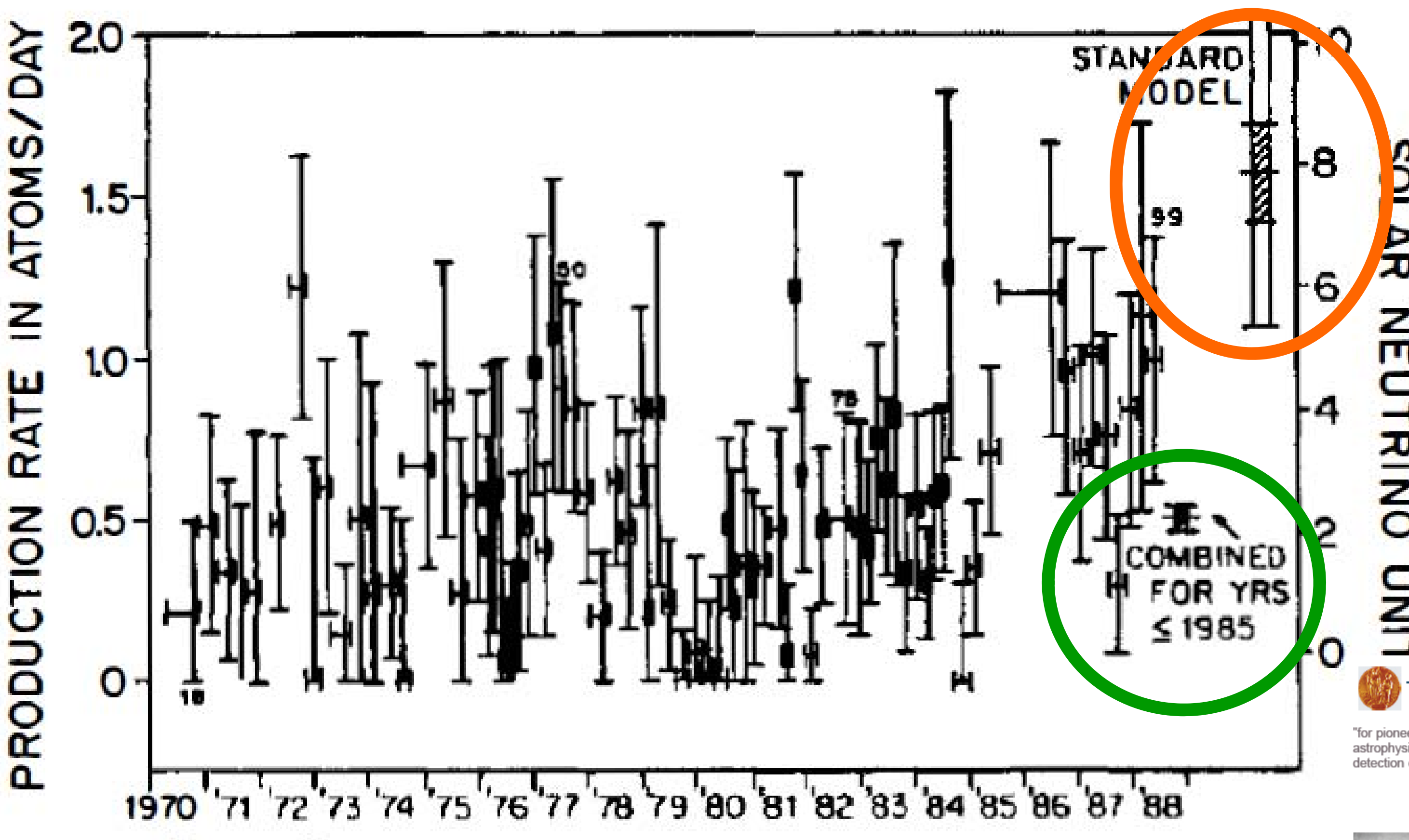
Ratio of predicted number of neutrinos from reactors at very short baselines is consistent with what is measured

Detecting neutrinos from our sun - 1970's…..a shortage

$$\nu_e + {}^{37}\text{Cl} \mapsto {}^{37}\text{Ar} + e^-$$

Homestake Mine South Dakota

First Evidence for Neutrino Mixing …late 60's



The Nobel Prize in Physics 2002

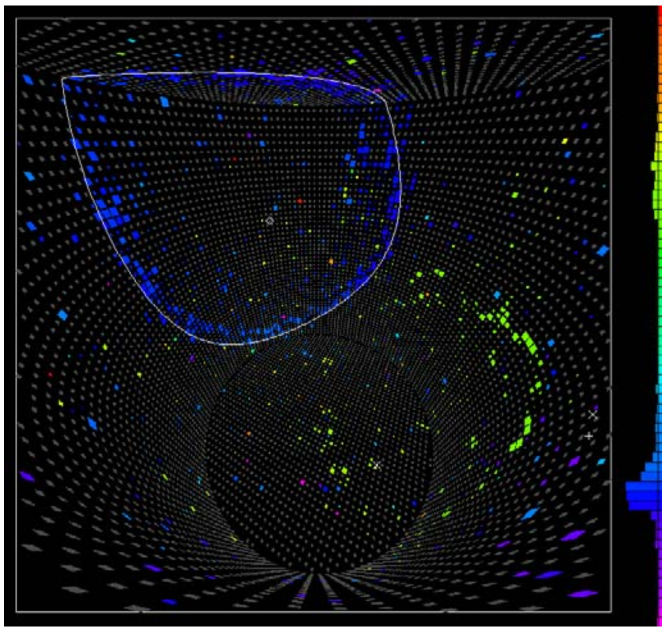
"for pioneering contributions to astrophysics, in particular for the detection of cosmic neutrinos"

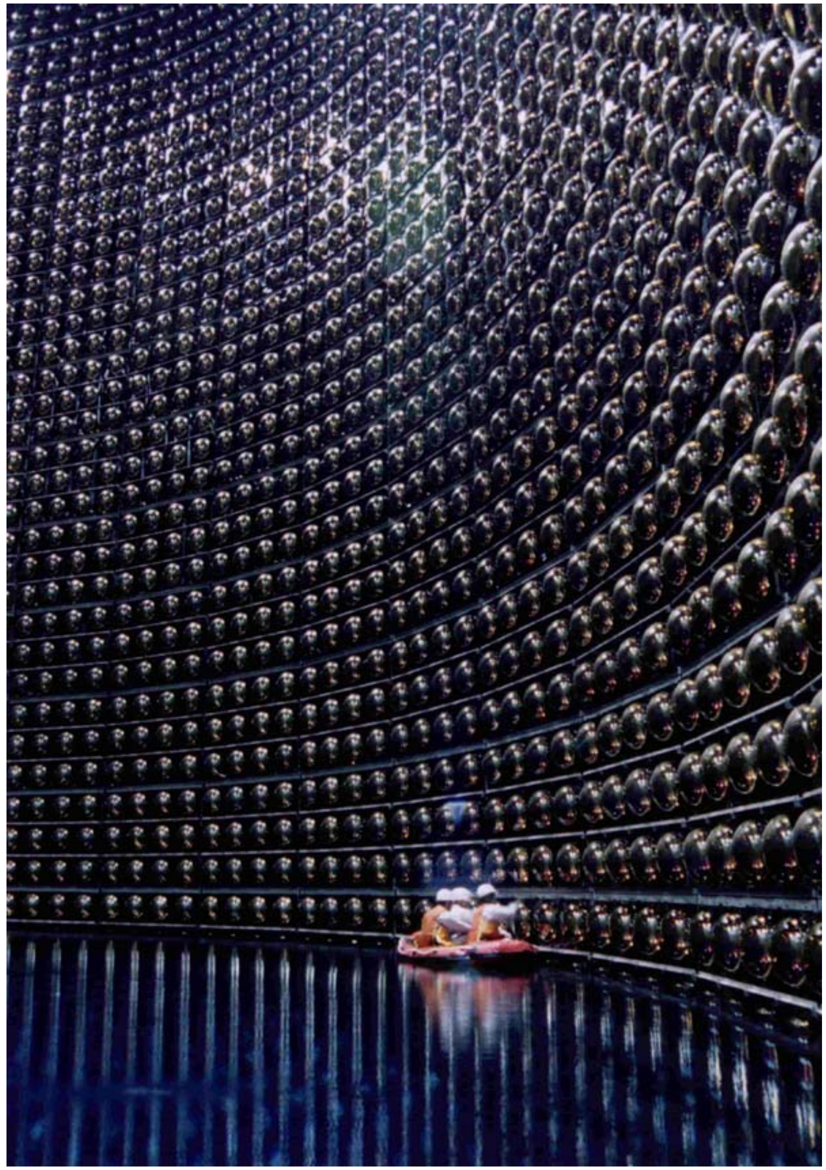
"for pioneering contributions to astrophysics, which have led to the discovery of cosmic X-ray sources"

Raymond Davis Jr.	Masatoshi Koshiba	Riccardo Giacconi
1/4 of the prize	1/4 of the prize	1/2 of the prize
USA	Japan	USA
University of Pennsylvania Philadelphia, PA, USA	University of Tokyo Tokyo, Japan	Associated Universities Inc. Washington, DC, USA
b. 1914 d. 2006	b. 1926	b. 1931 (in Genoa, Italy)

Super-K discovers that atmospheric neutrinos mix

- 50,000 ton water detector in the Kamiokande mine in Japan
- Built to look for proton decay – did not find it
- And discovered in 1998 that atmospheric neutrinos oscillate

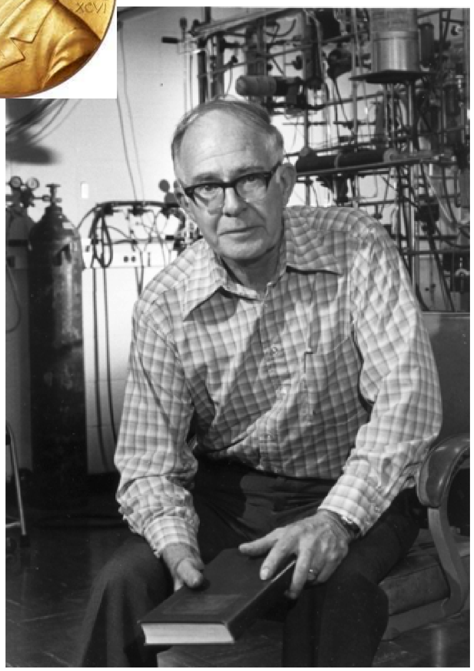




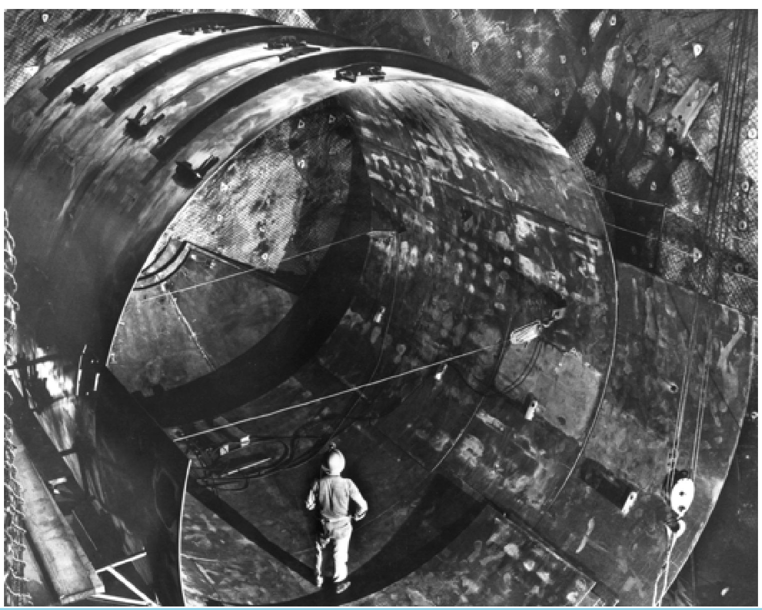
14,000 phototube detectors

2002 Nobel prize in physics:

"for pioneering contributions to astrophysics, in particular for the detection of cosmic neutrinos"



Ray Davis: Homestake Experiment



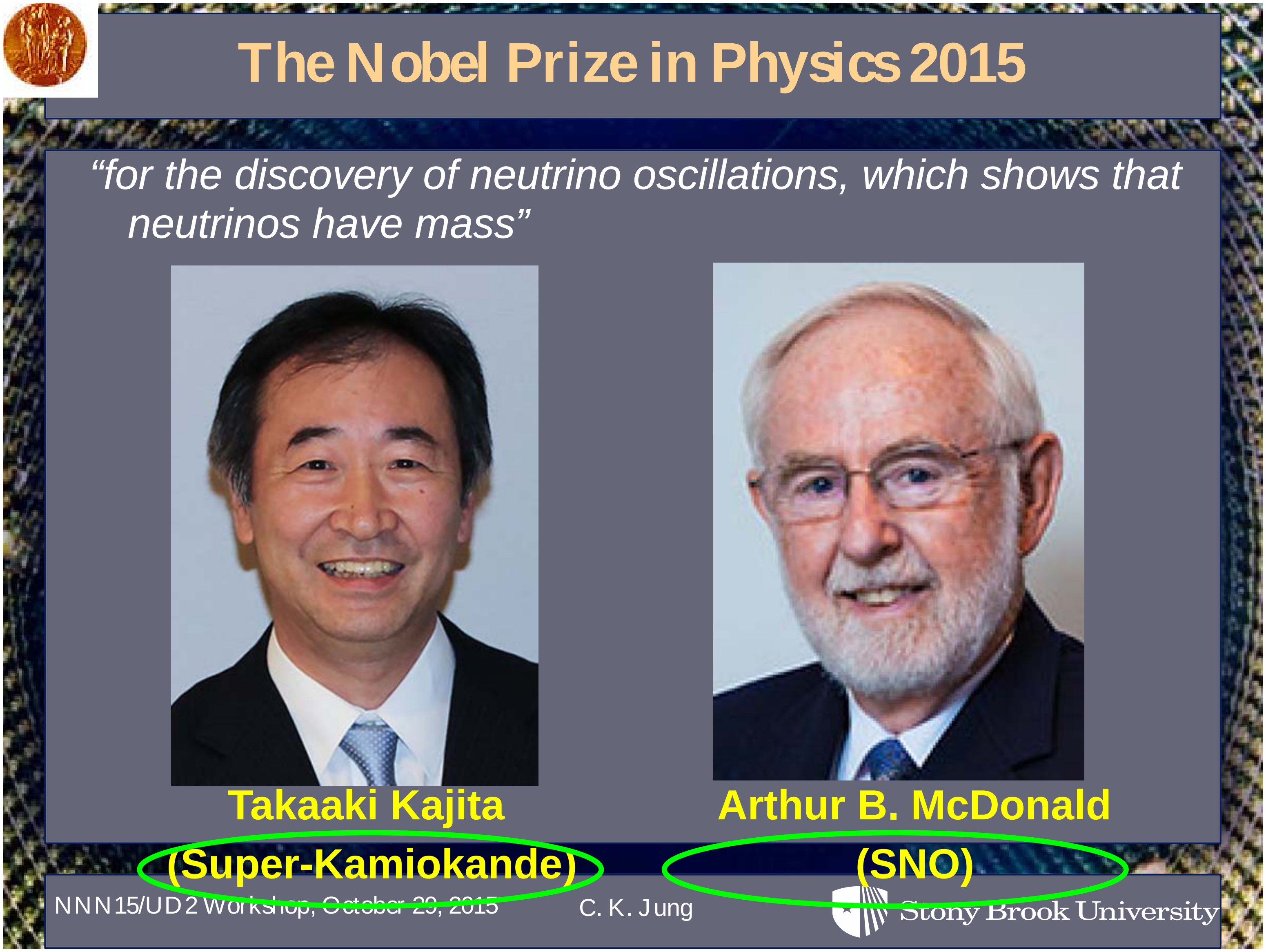
Masatoshi Koshiba: Kamioka Observatory

Blue Man Group confirms solar neutrino deficit

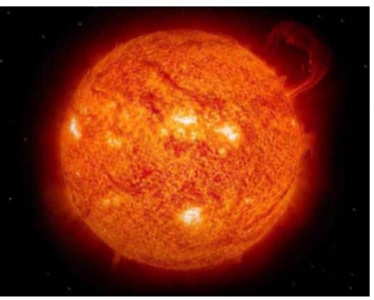
- By 2001 more powerful detectors confirmed that Davis and Bahcall were both right

SNO experiment in Sudbury Canada with US & UK

Neutrinos are hot



Neutrino flavors oscillate



8 minutes later:

ν_e

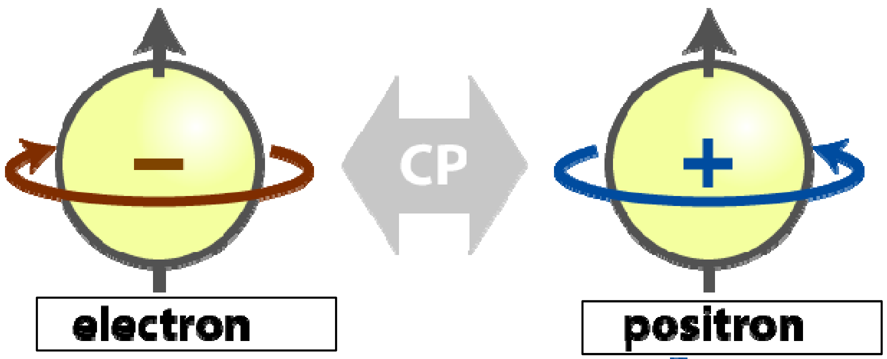
ν_e ν_μ ν_τ

Why are neutrinos interesting?

- The wide range of quark masses is puzzling
  - The top quark discovery was an exclamation mark on that
- The ultra-tiny neutrino mass doesn't fit the standard model
  - In fact we do not understand neutrinos mass…..other than it has mass
- The Higgs discovery has brought flavor and mass issues to the forefront
- One future lies in better understanding neutrinos
  - their mass ordering
  - the origin of their masses and why they are so small
  - their interactions (CP Violation)
  - how many types of neutrinos
  - relationship to matter-antimatter asymmetry in universe (leptogenesis) and structure of the universe

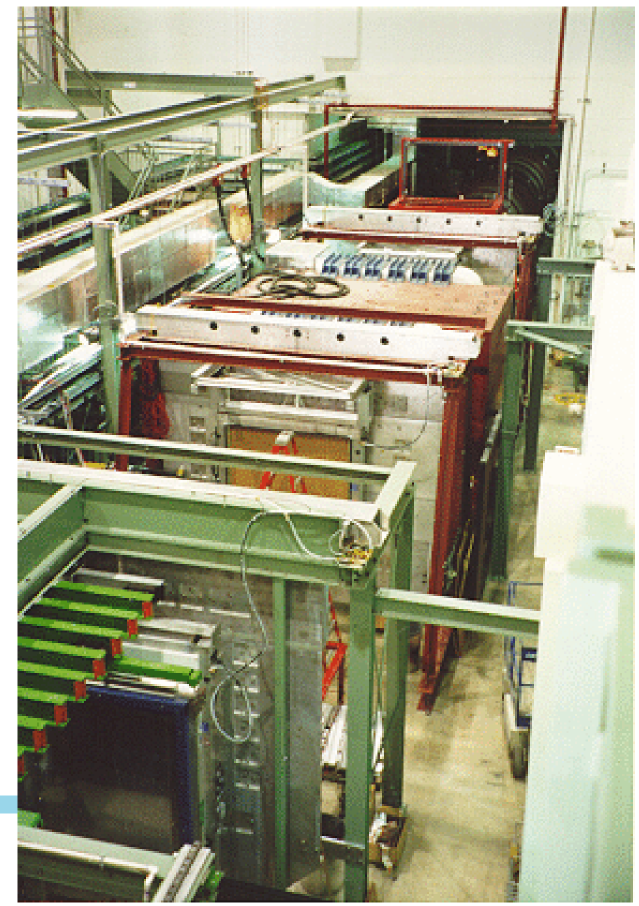
CP symmetry

- From Dirac onwards physicists assumed that Nature does not have separate rules for particles and antiparticles
- This is called CP symmetry
- Here "C" refers to charge conjugation, changing the sign of electric (and other) charges.
- "P" is parity, which changes the "handedness" of a particle, i.e. the orientation of its spin compared to its motion
- Thus CP interchanges a left-handed electron with its antiparticle, a right-handed positron



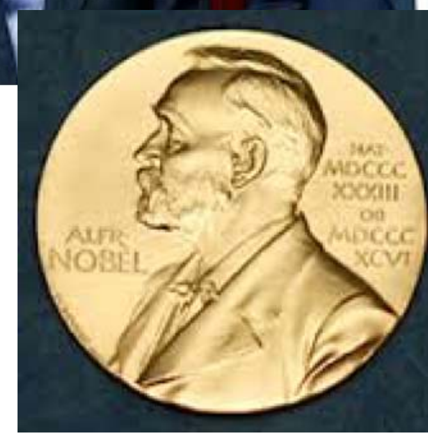
CP violation in the Quark Sector

- It was a big surprise in 1964 when Cronin and Fitch showed that neutral kaon oscillations have a small asymmetry in CP at Brookhaven
- Direct violation of CP symmetry in kaon decays was also discovered at Fermilab in 1999 with the KTEV experiment and at CERN NA31, NA48



CP violation and Quark Mixing

- Cabbibo, Kobayashi and Maskawa showed that there is one physical phase parameter in the CKM matrix, which if nonzero will cause CP violation
- This hypothesis was tested by many experiments at the B factories, at Fermilab, and at CERN
- All observed cases of CP violation appear to arise from this CKM phase, whose value is 67 degrees



$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{bmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{bmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

CP violation and neutrinos

- Strangely, the amount of CP violation seen with quarks is not nearly enough to explain the dominance of matter over antimatter in the universe
- Right idea, wrong particles?
- Neutrino oscillations show that neutrino flavors are even more mixed up than quark flavors
- It is possible that neutrinos violate CP symmetry, and by a much larger amount than do quarks

Neutrino and Quark Mixing and Masses
Pontecorvo–Maki–Nakagawa–Sakata matrix

Leptonic Mixing Matrix

flavor states participating in standard weak interactions

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

neutrino mass states

$$V_{PMNS} \approx \begin{pmatrix} 0.8 & 0.5 & 0.2 \\ 0.4 & 0.6 & 0.7 \\ 0.4 & 0.6 & 0.7 \end{pmatrix}$$

$$V_{CKM} \approx \begin{pmatrix} 1 & 0.2 & 0.001 \\ 0.2 & 1 & 0.01 \\ 0.001 & 0.01 & 1 \end{pmatrix}$$

Neutrino Masses < 2 eV

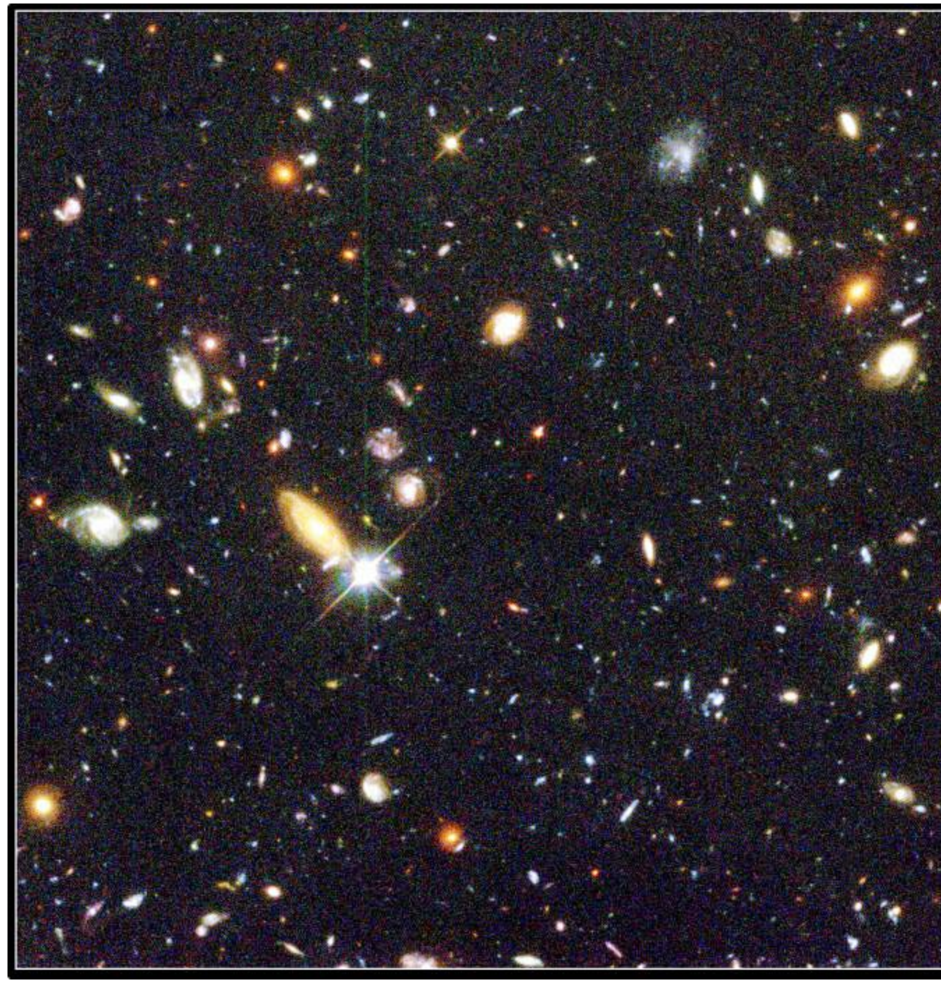
Quark Masses = 3×10^6 eV to 1.7×10^{11} eV

Very different

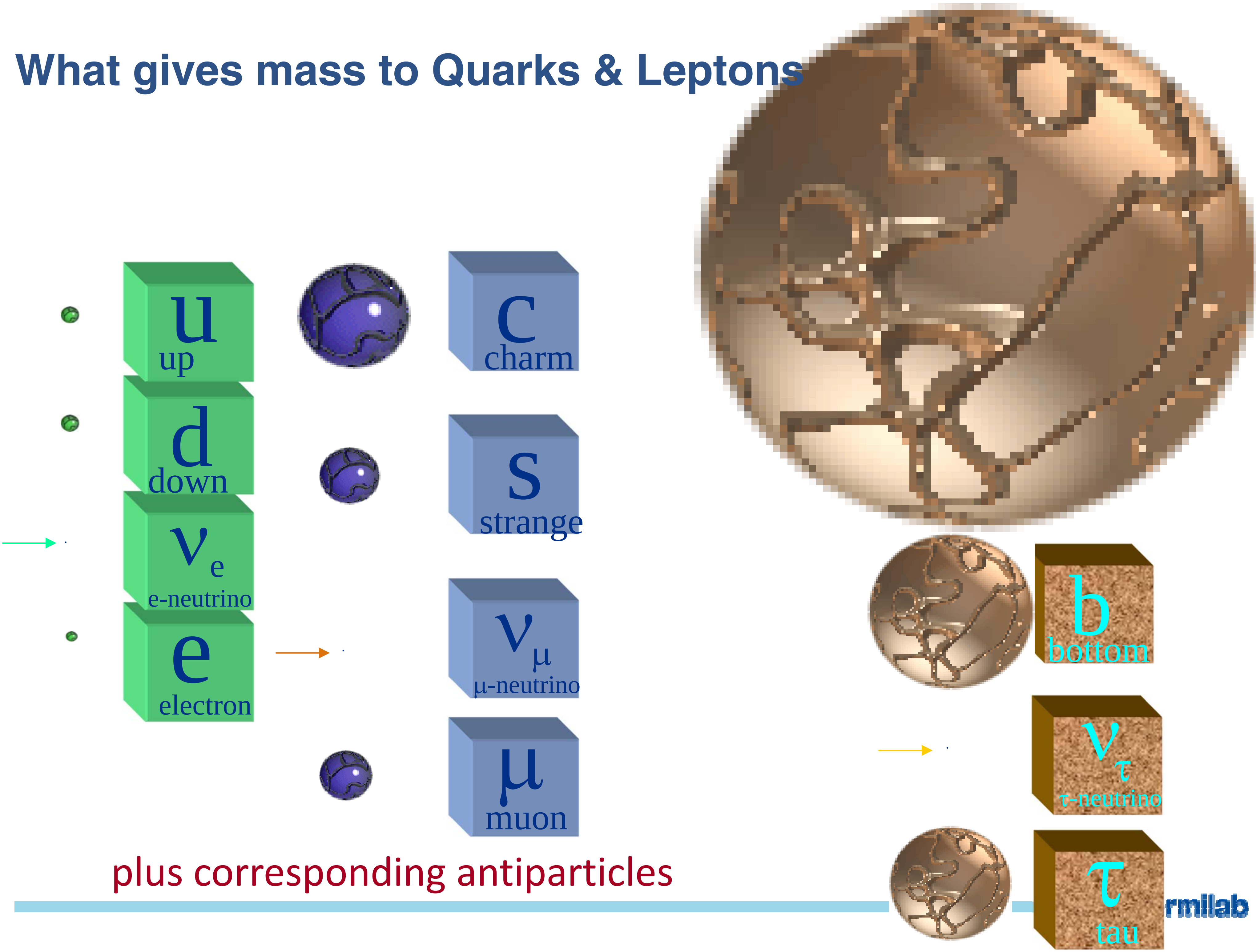
No idea why, but it is probably important

CP violation, neutrinos, and leptogenesis

- If the neutrino “see-saw” idea is correct, the early universe contained the very heavy partners (Majorana mass) of the light neutrinos
- Heavy neutrinos would have decayed into ordinary matter with CP violating decays
- If neutrinos violate CP, this process of “leptogenesis” could have produced the visible universe



What gives mass to Quarks & Leptons



plus corresponding antiparticles

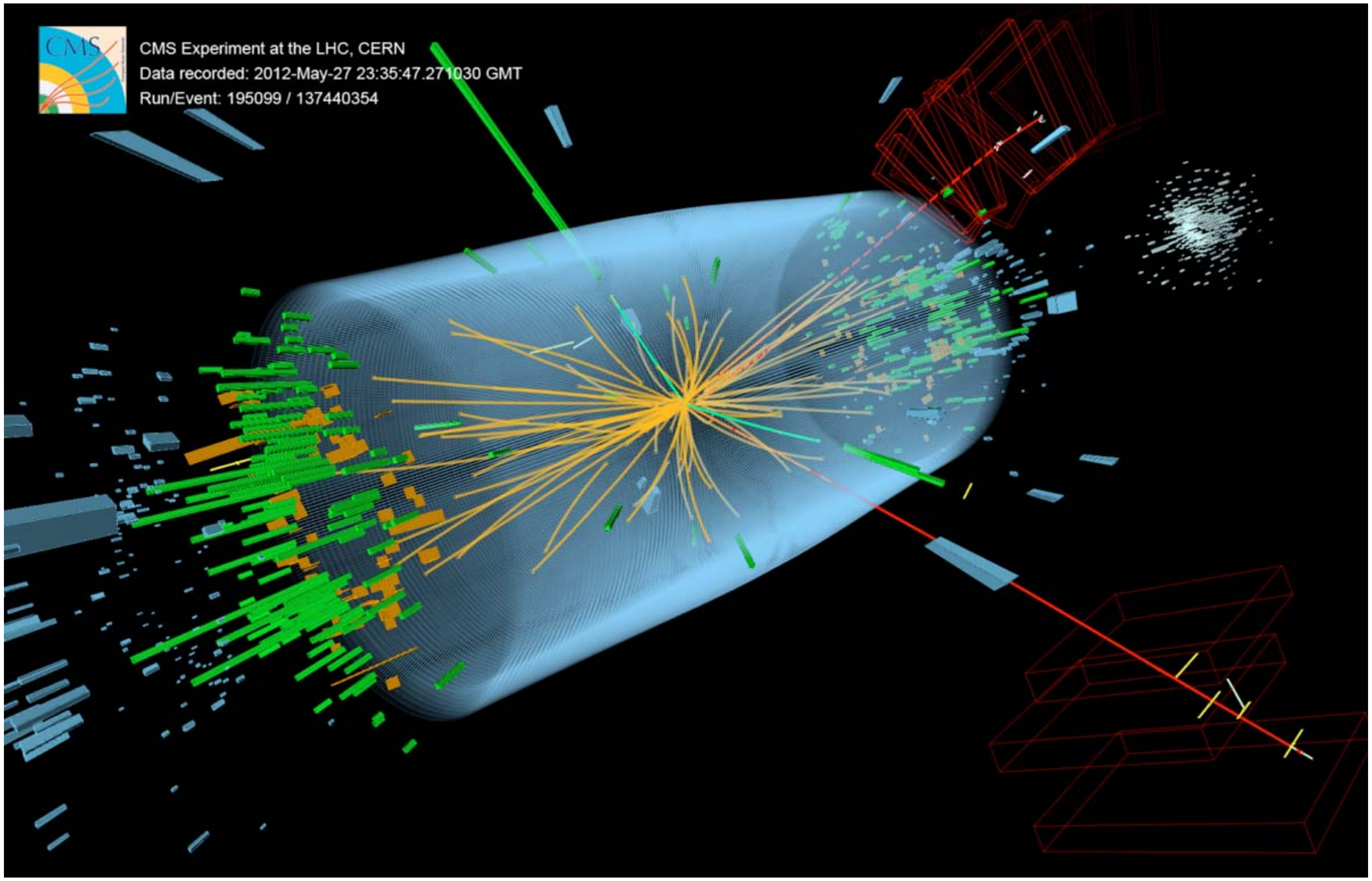
The dynamical origins of mass

- A headline of the Standard Model is that elementary particles do not naturally have mass
- Instead they can acquire mass through interactions
- Contrast to charge and spin, which appear to be immutable

Professor Higgs explains: there is an invisible force field that interacts with particles to give them mass…

… also it makes Higgs bosons at the LHC

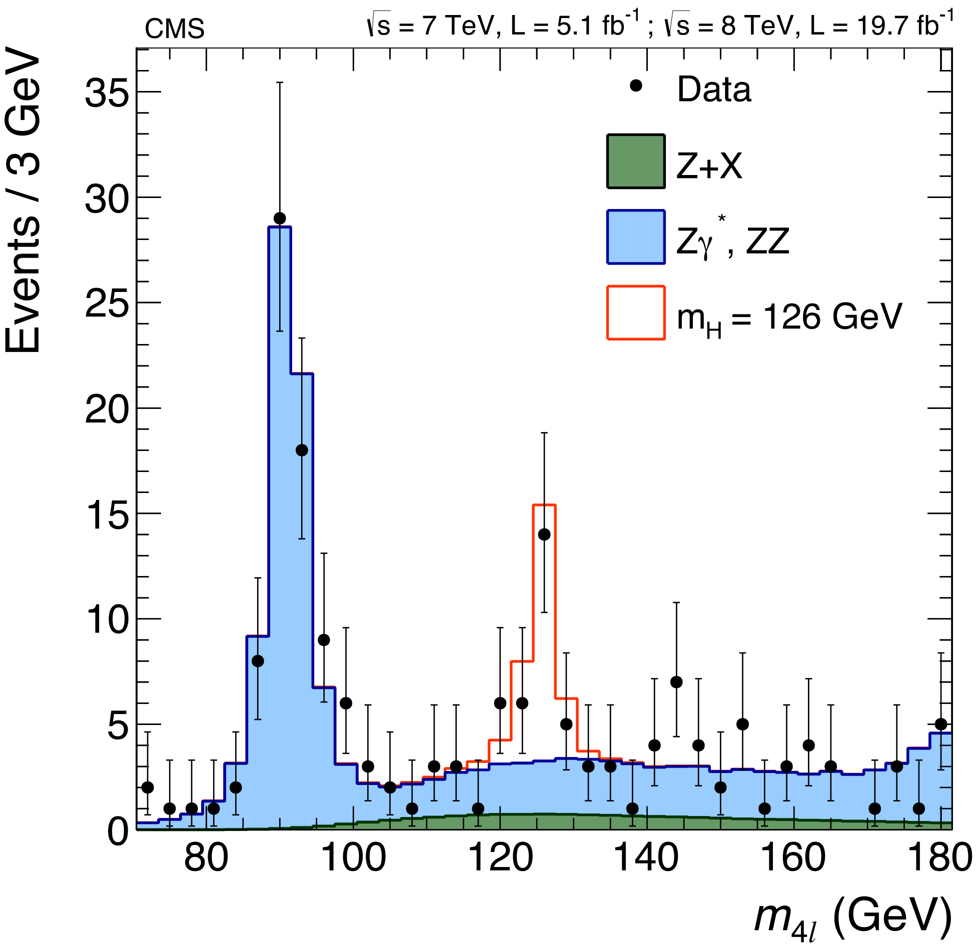
Discovery of the Higgs boson - 2012



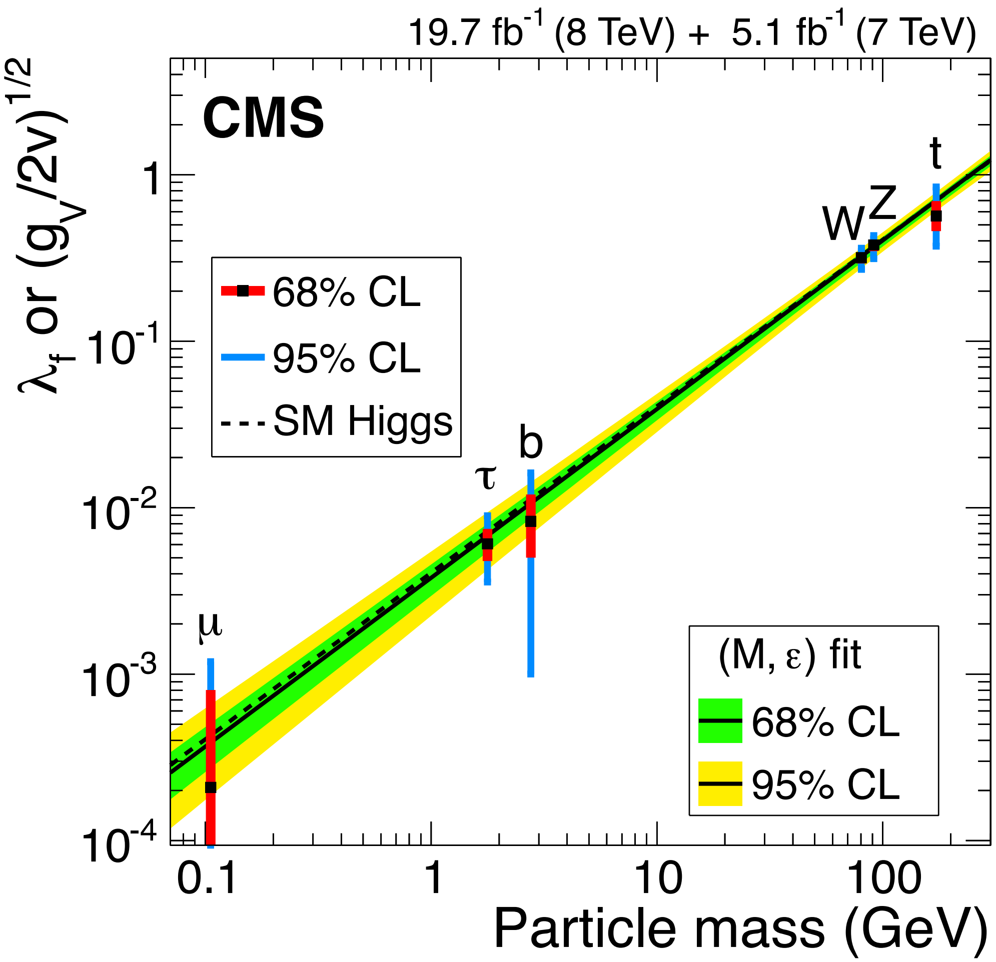
Guralnik, Hagen, and Kibble co-authored one of three original papers that described the Higgs mechanism, with the other two papers by Higgs, and Brout and Englert. (Sakurai Prize)

Precision Higgs Physics

Mass



Couplings



"This paper is dedicated to the memory of Robert Brout and Gerald Guralnik, whose seminal contributions helped elucidate the mechanism for spontaneous breaking of the electroweak symmetry"

Higgs and the mysteries of mass

- The discovery of the Higgs boson verifies the Higgs mechanism of generating mass for the W and Z bosons
- And Yukawa couplings of the Higgs field to the quarks and charged leptons can give them masses proportional to the vacuum value of the Higgs field, 174 GeV

$$y_e \bar{L} H e_R + h.c. \rightarrow y_e \frac{v}{\sqrt{2}}(\bar{e}_L e_R + \bar{e}_R e_L)$$

But this still leaves many of the mysteries unsolved…

How does the Higgs talk to Neutrinos?

Can try to copy how the electron gets a “Dirac” mass:

$$y_\nu \, \bar{L} \, H \, \nu_R + h.c. \rightarrow y_\nu \frac{v}{\sqrt{2}} (\bar{\nu}_L \nu_R + \bar{\nu}_R \nu_L)$$

Has to be

<0.000000000003

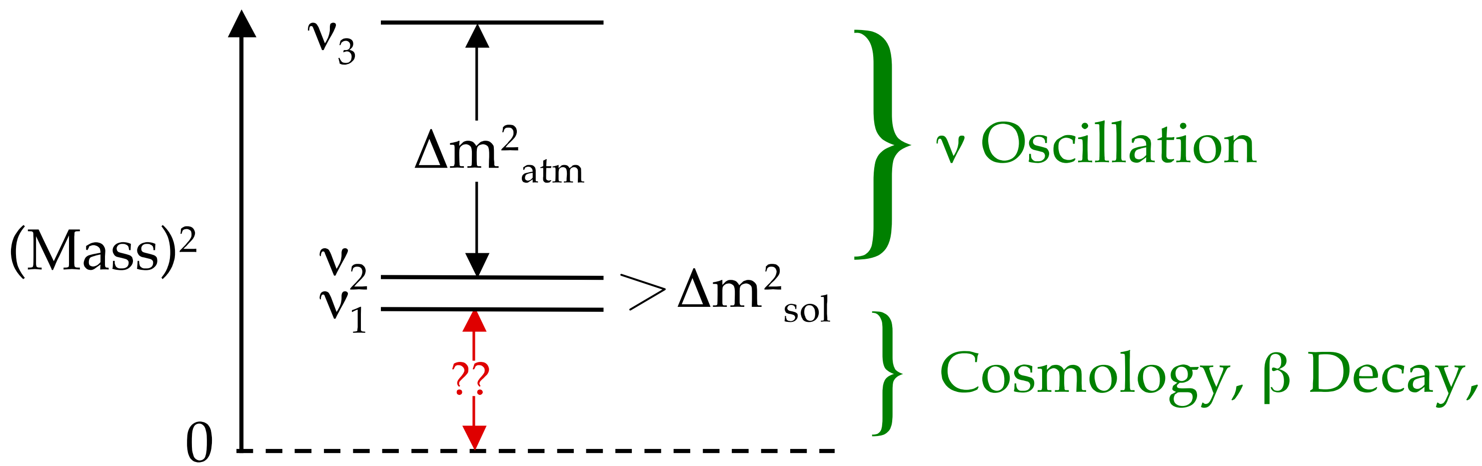
?

A new fermion that carries no Standard Model charges of any kind. Since it can be its own antiparticle, it can have its own “Majorana” mass:

$$M_R \, \bar{\nu}_R \nu_R^c$$

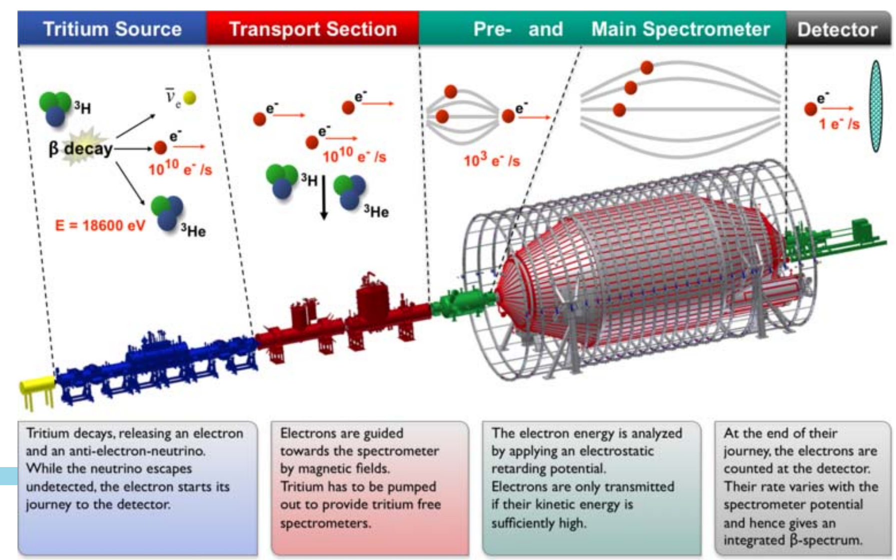
?

Neutrino masses: what we know and don't know



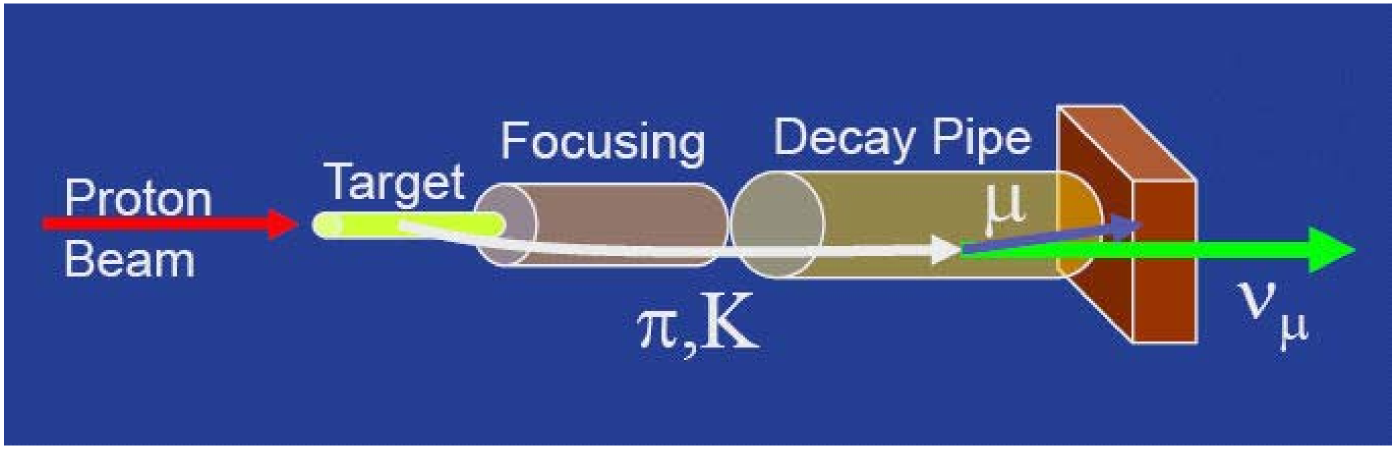
How far above zero
is the whole pattern?

KArlsruhe **TRI**tium **N**eutrino
Experiment (KATRIN)



Neutrino beams from accelerators

- At Fermilab we already make the world's most powerful neutrino beams…low & high energy
- Will not discuss low energy program
- Plans to quadruple the beam in the future**…targets are the limits**
- **Achieved 700 kW this week**

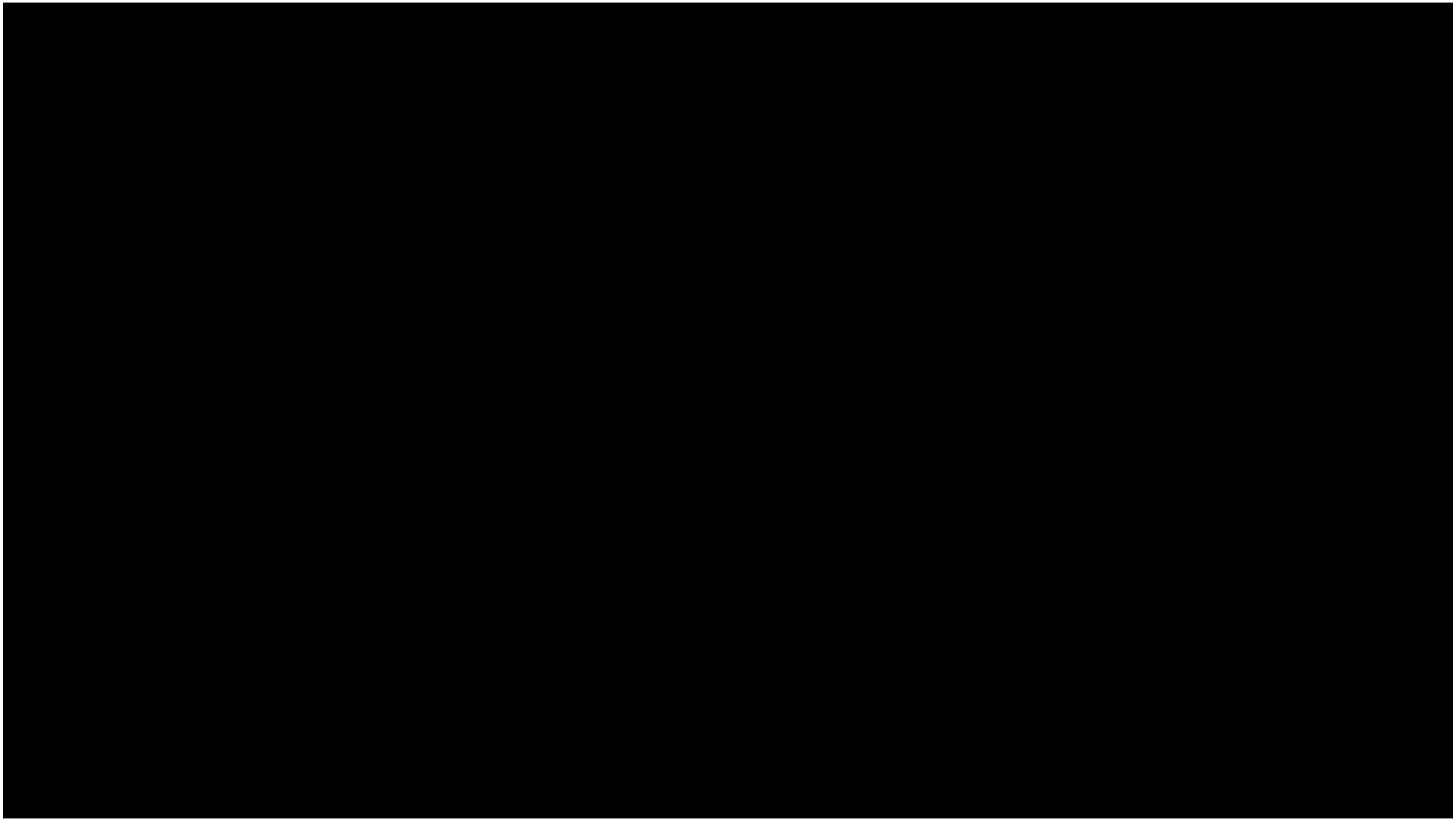


Return To Davis's Homestake Mine?
SANFORD UNDERGROUND LABORATORY AT HOMESTAKE
Underground Lab
South Dakota
Minnesota
MINOS Neutrino Detector
Nebraska
800 miles
Wisconsin
Iowa
Milwaukee
Michig
Fermilab
Chicago
Image © 2008 TerraMetrics
© 2008 Europa Technologies
Image NASA
© 2008 Tele Atlas
Google
Missouri
43°14'04.36" N 92°07'15.58" W
Eye alt 678.31 km

NOvA…our present flagship neutrino experiment

The NOvA neutrino detector….14,000 tons liquid scintillator …….one "event" per day…results in London Neutrino 2016

LBNF/DUNE



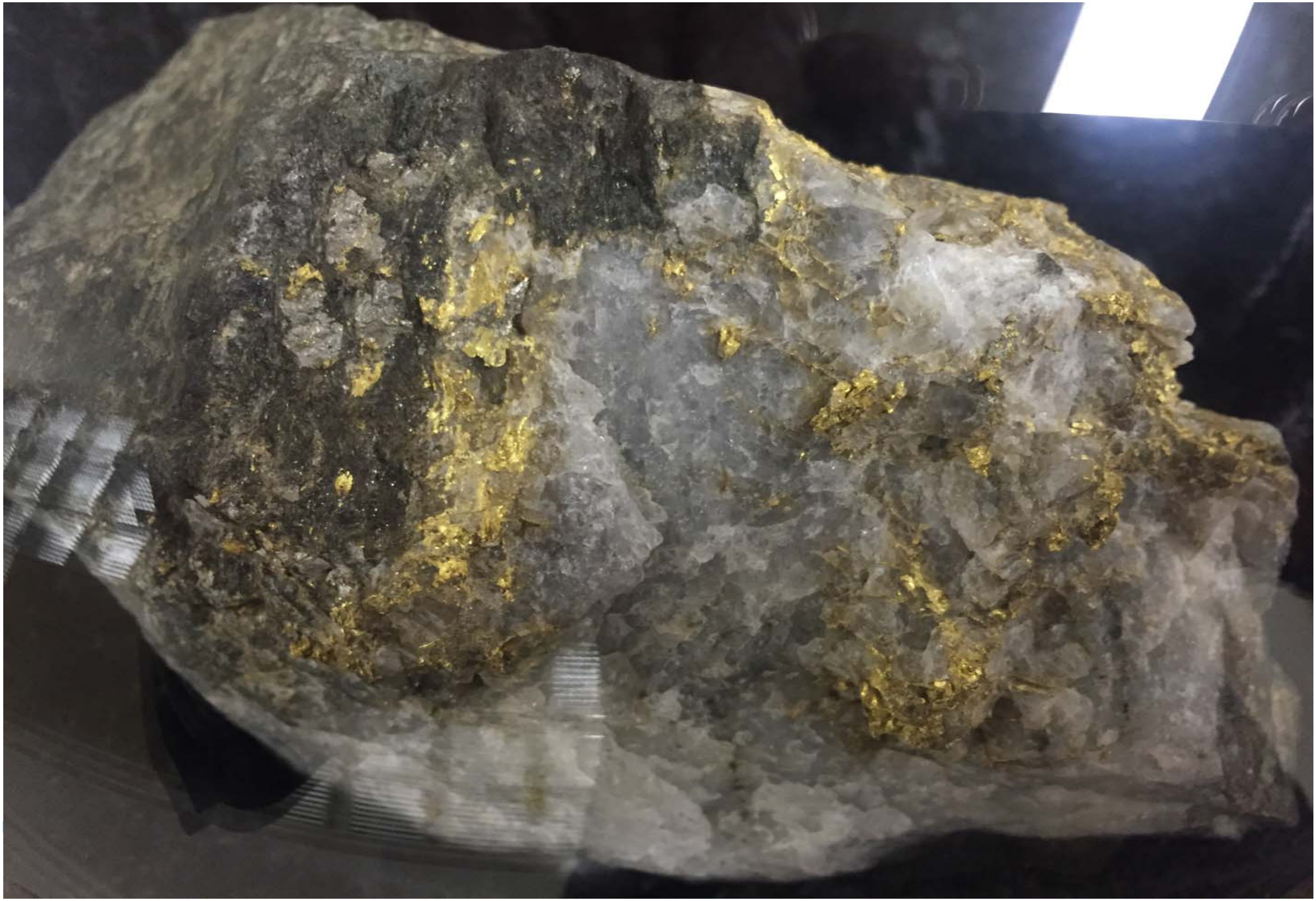
Lead South Dakota
Sanford Underground Research Lab

The location is very picturesque, in the Black Hills (Pahasapa)

Homestake Gold Mine…most productive in the world at one time

41 million ounces from a 167 million tons of rock…quarter of an ounce per ton

Neutrinos and Gold…..

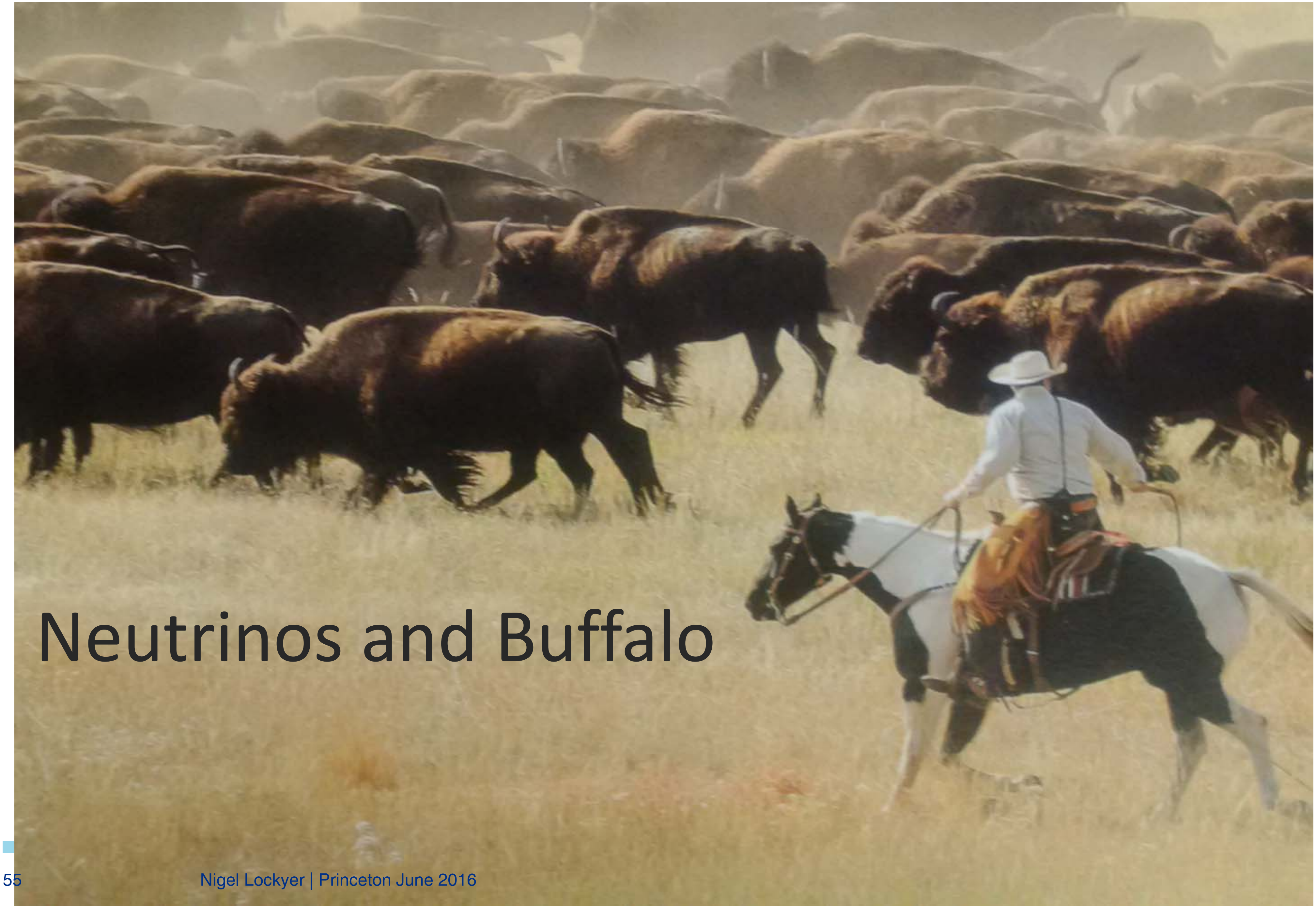


Senator Rounds & Governor Daugaard South Dakota

Senator asks about neutron star formation

Governor is explaining neutrinos to community for 20 minutes

Custer State Park, Annual Buffalo Round up



What's a DUNE? What's an LBNF?

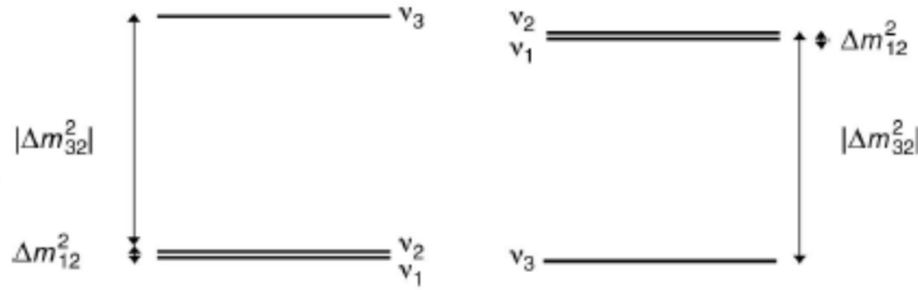
- The **D**eep **U**nderground **N**eutrino **E**xperiment is an experiment for **neutrino science**
- The **L**ong-**B**aseline **N**eutrino **F**acility is the infrastructure necessary to send a powerful beam of neutrinos 1300km through the earth, and measure them deep underground at South Dakota's Sanford Underground Research Facility.

- The DUNE/LBNF project will be the first internationally conceived, constructed, and operated mega-science project hosted by the Department of Energy in the United States.
  - DUNE is an international science collaboration (25% US and 75% International)
  - LBNF is a US hosted facility (75% US and 25% international)

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, $p \to K^+\overline{\nu}$
- **3) Supernova burst physics & astrophysics**
  - Galactic core collapse supernova, sensitivity to ν_e

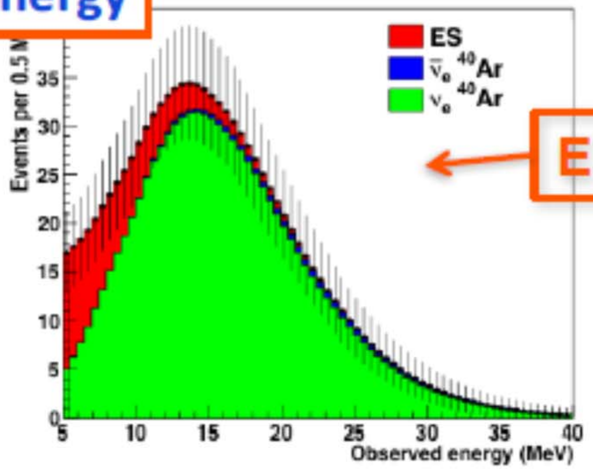
3.3 Supernova νs

A core collapse supernova produces an incredibly intense burst of neutrinos

- Measure energies and times of neutrinos from galactic supernova bursts
  - In argon (uniquely) the largest sensitivity is to ν_e

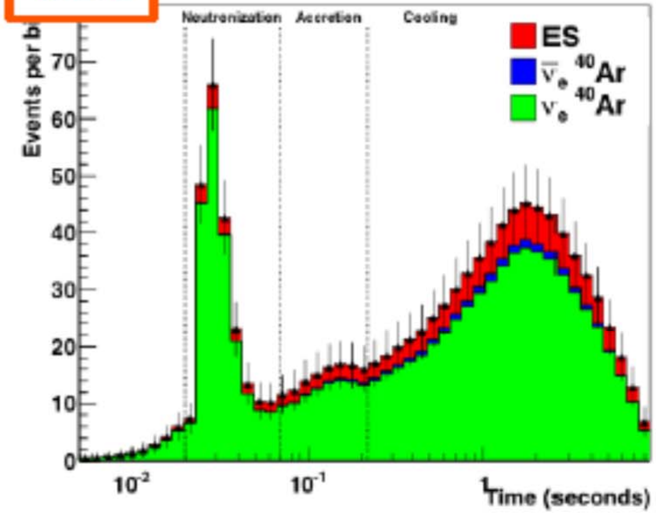
$$\nu_e + {}^{40}\mathrm{Ar} \rightarrow e^- + {}^{40}\mathrm{K}^*$$

Energy



E ~ O(10 MeV)

time



Physics Highlights include:

- Possibility to "see" neutron star formation stage
- Even the potential to see black hole formation…

Timescales: year zero = 2026

Rapidly reach scientifically interesting sensitivities:

- e.g. in best-case scenario for Mass Hierarchy :
  - **Reach 5σ MH sensitivity with ~20 kt.MW.year**

  Discovery — ~2 years

- e.g. in best-case scenario for CPV ($\delta_{CP} = +\pi/2$) :
  - **Reach 3σ CPV sensitivity with ~60 kt.MW.year**

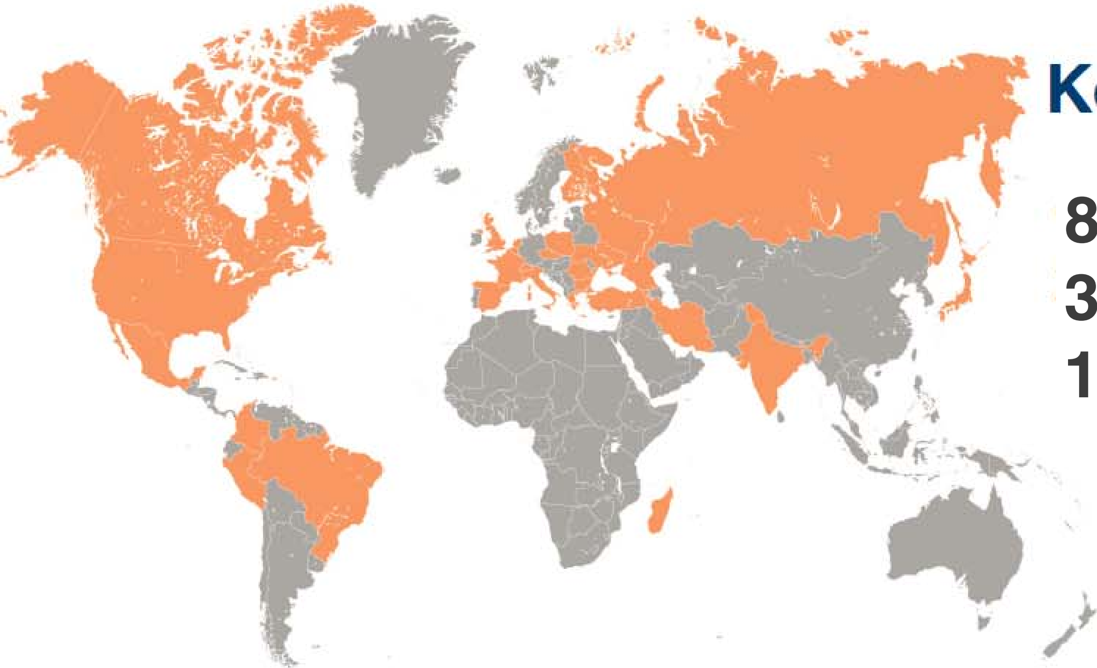
  Strong evidence — ~3-4 years

- e.g. in best-case scenario for CPV ($\delta_{CP} = +\pi/2$) :
  - **Reach 5σ CPV sensitivity with ~210 kt.MW.year**

  Discovery — ~6-7 years

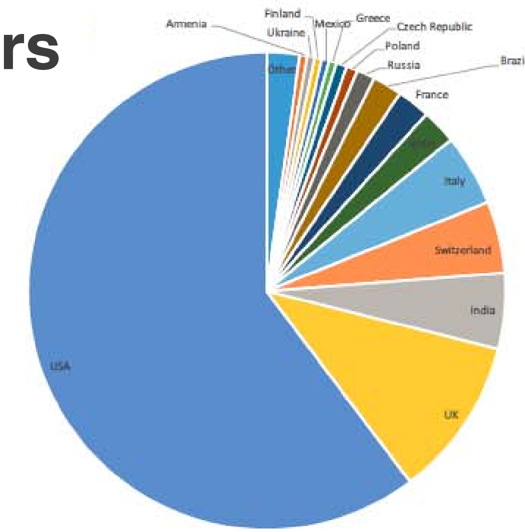
★ **Genuine potential for early physics discovery**

The DUNE Collaboration



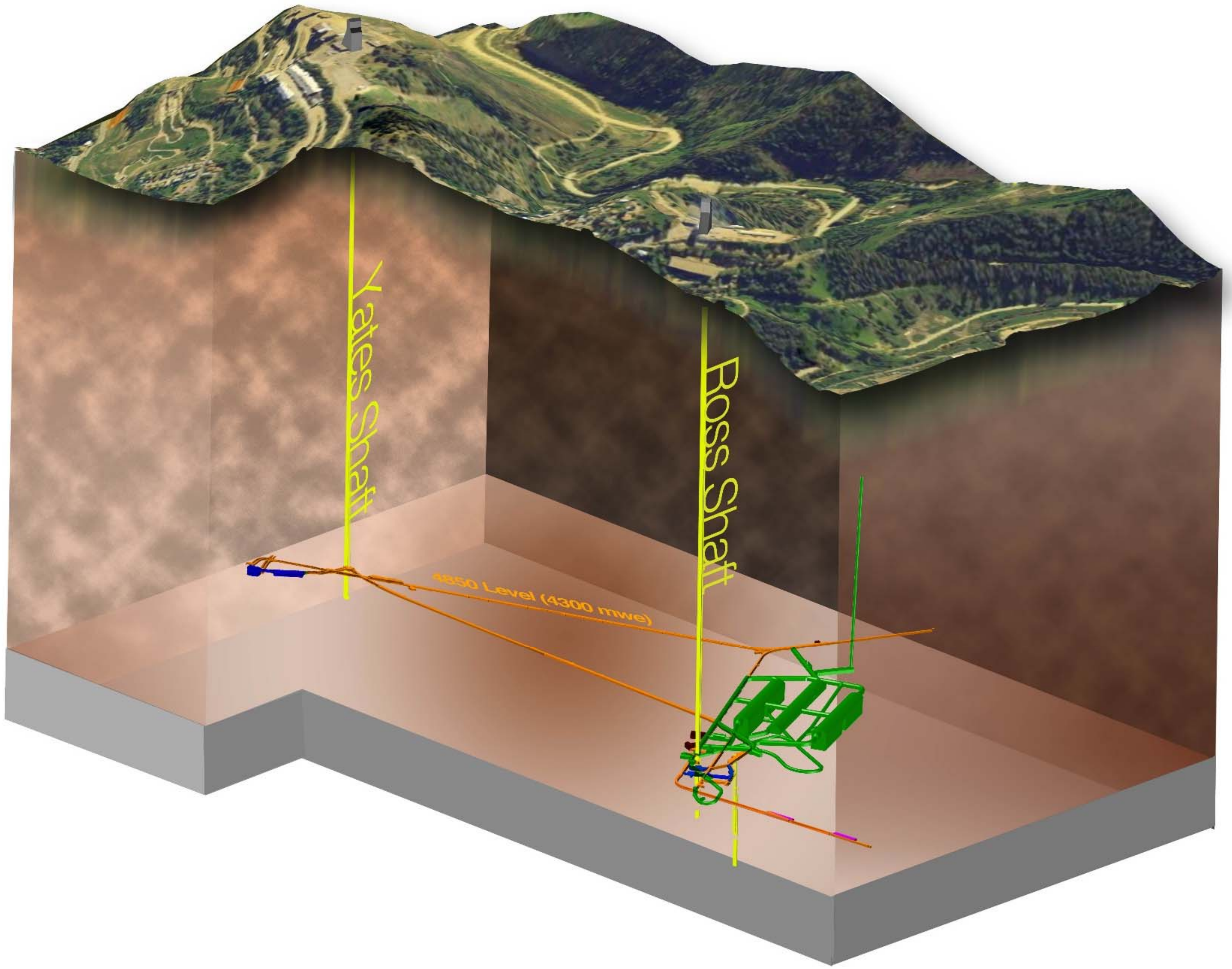
Keeps growing:

867 Collaborators
30 Nations
153 Institutions

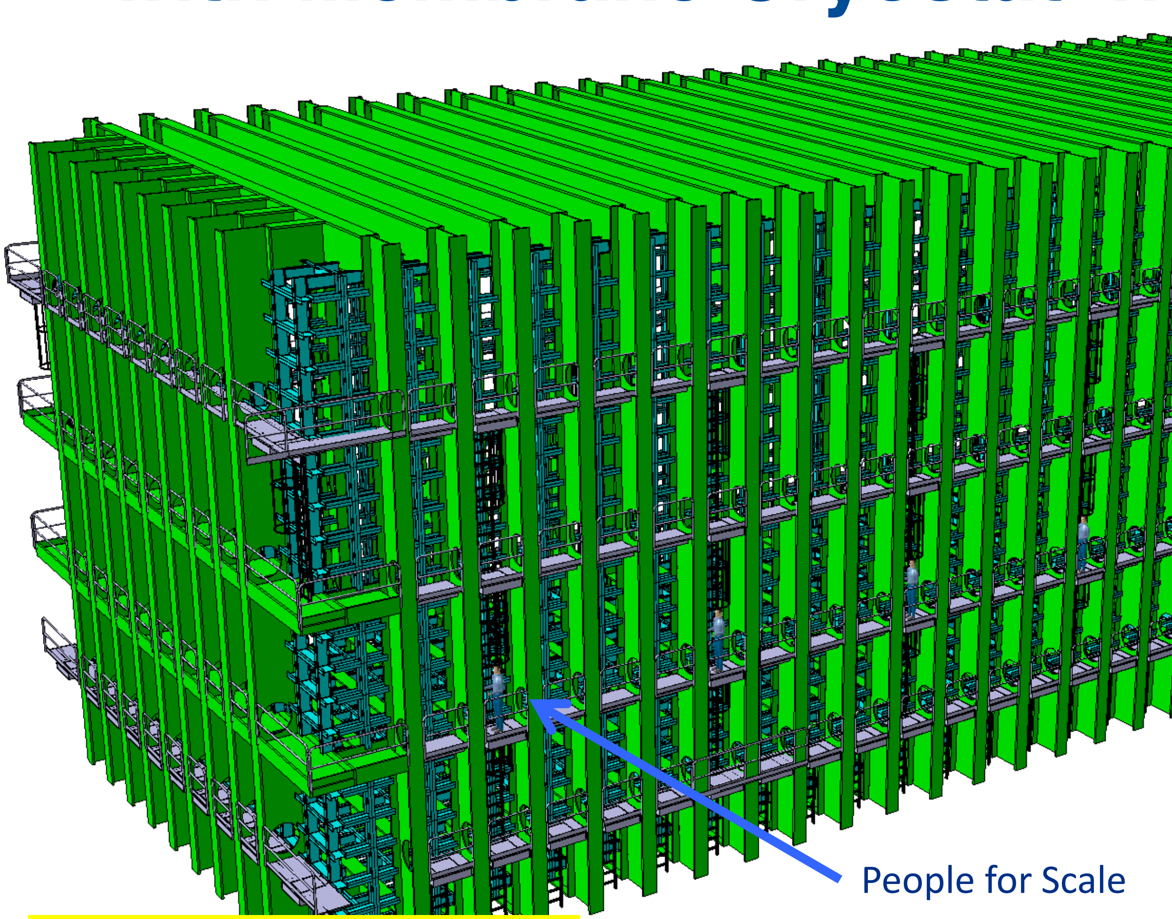


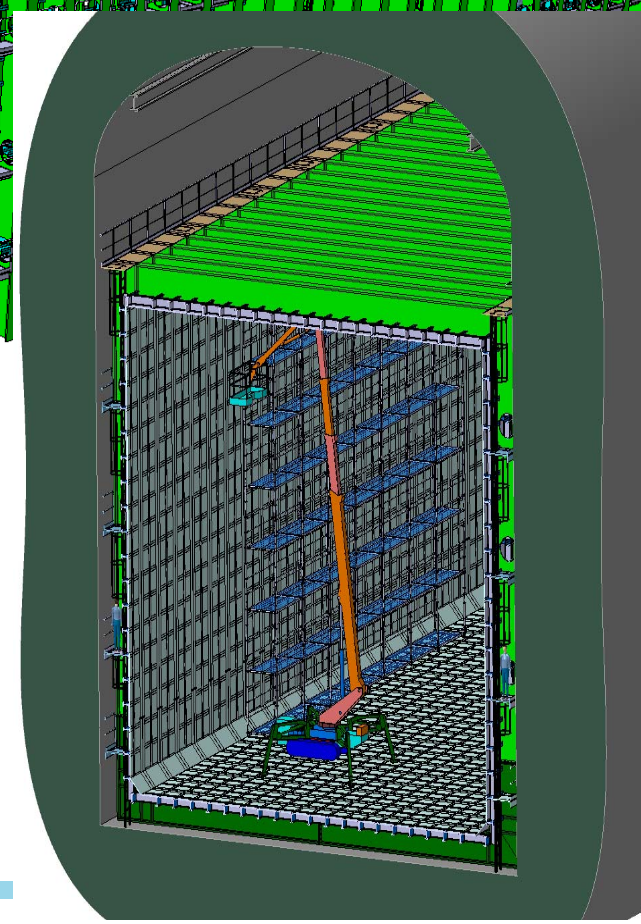
Armenia Yerevan Inst. for Theoretical Physics and Modeling
Belgium Univ. de Liege
Brazil Univ. Federal do ABC; Univ. Federal de Alfenas em Poços de Caldas; Univ. de Campinas; Univ. Estadual de Feira de Santana; Univ. Federal de Goias; Observatorio Nacional
Bulgaria Univ. of Sofia
Canada York University
Colombia Univ. del Atlantico
Czech Republic Charles University, Prague; Czech Technical University, Prague; Institute of Physics ASCR, Prague
France Lab. d'Annecy-le-Vieux de Phys. des Particules; Inst. de Physique Nucleaire de Lyon; APC-Paris; CEA/Saclay
Finland Jyväskylä
Greece Athens
India Aligarh Muslim University; Banaras Hindu University; Bhabha Atomic Research Center; Univ. of Delhi; Indian Inst. of Technology, Guwahati; Harish-Chandra Research Institute; Indian Inst. of Technology, Hyderabad; Univ. of Hyderabad; Univ. of Jammu; Jawaharlal Nehru University; Koneru Lakshmaiah; Univ. of Lucknow; Panjab University; Punjab Agri. University; Variable Energy Cyclotron Centre
Iran Inst. for Research in Fundamental Sciences
Italy Lab. Nazionali del Gran Sasso, Assergi; Univ. di Catania; Gran Sasso Science Institute; Univ. di Milano; INFN Sezione di Milano Bicocca; INFN Sezione di Napoli; Univ. of Padova; Univ. of Pavia, INFN Sezione di Pavia; CNI Pisa; Univ. di Pisa
Japan KEK; Kavli IPMU, Univ. of Tokyo
Madagascar Univ. of Antananarivo
Mexico Univ. de Colima; CINVESTAV
Netherlands NIKHEF
Peru PUCP
Poland Inst. of Nuclear Physics, Krakow; National Centre for Nuclear Research, Warsaw; Univ. of Warsaw; Wroclaw University
Romania Horia Hulubei National Institute
Russia Inst. for Nuclear Research, Moscow
Spain Inst. de Fisica d'Altas Energias, Barcelona; CIEMAT; Inst. de Fisica Corpuscular, Madrid
Switzerland Univ. of Bern; CERN; ETH Zurich
Turkey TUBITAK Space Technologies Research Institute
Ukraine Kyiv National University
United Kingdom Univ. of Cambridge; Univ. of Durham; Univ. of Huddersfield; Imperial College of Science, Tech. & Medicine; Lancaster University; Univ. of Liverpool; University College London; Univ. of Manchester; Univ. of Oxford; STFC Rutherford Appleton Laboratory; Univ. of Sheffield; Univ. of Sussex; Univ. of Warwick
USA Univ. of Alabama; Argonne National Lab; Boston University; Brookhaven National Lab; Univ. of California, Berkeley; Univ. of California, Davis; Univ. of California, Irvine; Univ. of California, Los Angeles; California Inst. of Technology; Univ. of Chicago; Univ. of Cincinnati; Univ. of Colorado; Colorado State University; Columbia University; Cornell University; Dakota State University; Drexel University; Duke University; Fermi National Accelerator Lab; Univ. of Hawaii; Univ. of Houston; Idaho State University; Illinois Institute of Technology; Indiana University; Iowa State University; Kansas State University; Lawrence Berkeley National Lab; Los Alamos National Lab; Louisiana State University; Univ. of Maryland; Massachusetts Institute of Technology; Michigan State University; Univ. of Minnesota; Univ. of Minnesota (Duluth); Univ. of New Mexico; Northwestern University; Univ. of Notre Dame; Ohio State University; Oregon State University; Pacific Northwest National Lab; Univ. of Pennsylvania; Pennsylvania State University; Univ. of Pittsburgh; Princeton University; Univ. of Puerto Rico; Univ. of Rochester; SLAC National Accelerator Lab; Univ. of South Carolina; Univ. of South Dakota; South Dakota School of Mines and Technology; South Dakota Science And Technology Authority; South Dakota State University; Southern Methodist University; Stanford University; Stony Brook University; Syracuse University; Univ. of Tennessee; Univ. of Texas at Arlington; Univ. of Texas at Austin; Tufts University; Virginia Tech; Wichita State University; College of William and Mary; Univ. of Wisconsin; Yale University

Far Site 4850 level…in need of caverns for DUNE



CERN Design for Free-Standing Steel Cryostat with Membrane Cryostat Interior



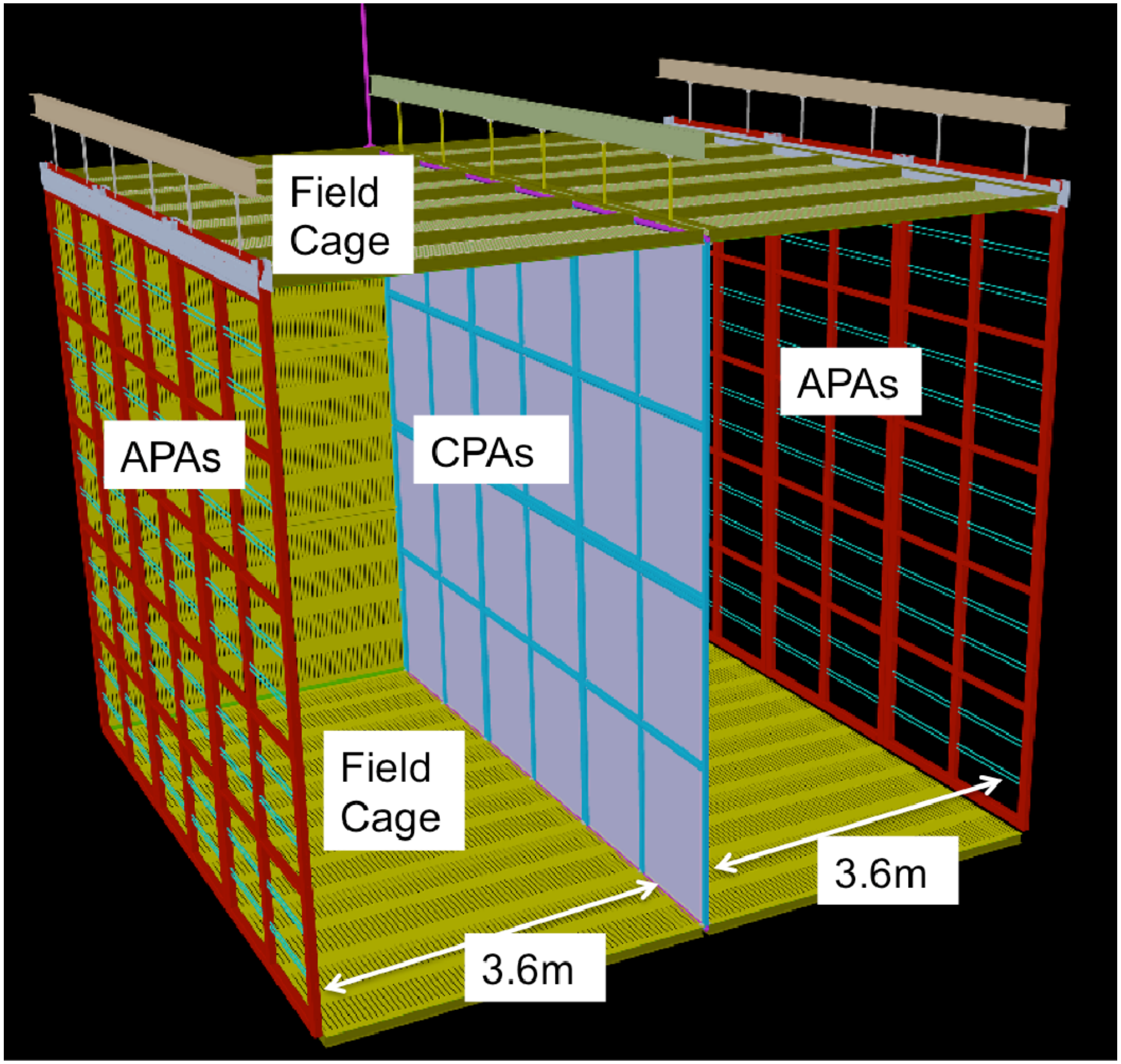


External (Internal) Dimensions

19.1m (15.1m) W x
18.0m (14.0m) H x
66.0m (62.0m) L

Single Phase Detectors inside the Cryostats

- Detectors consist of:
  - Anode Plane Arrays
  - Cathode Plane Arrays
  - Field Cage
  - Photon detectors
  - Readout electronics and DAQ
- How they work:
  - Neutrinos (occasionally) collide with Argon atom.
  - Resulting particles cause electrons to be knocked loose from liquid argon atoms, which "drift" to the APAs



Single Phase Detectors inside the Cryostats

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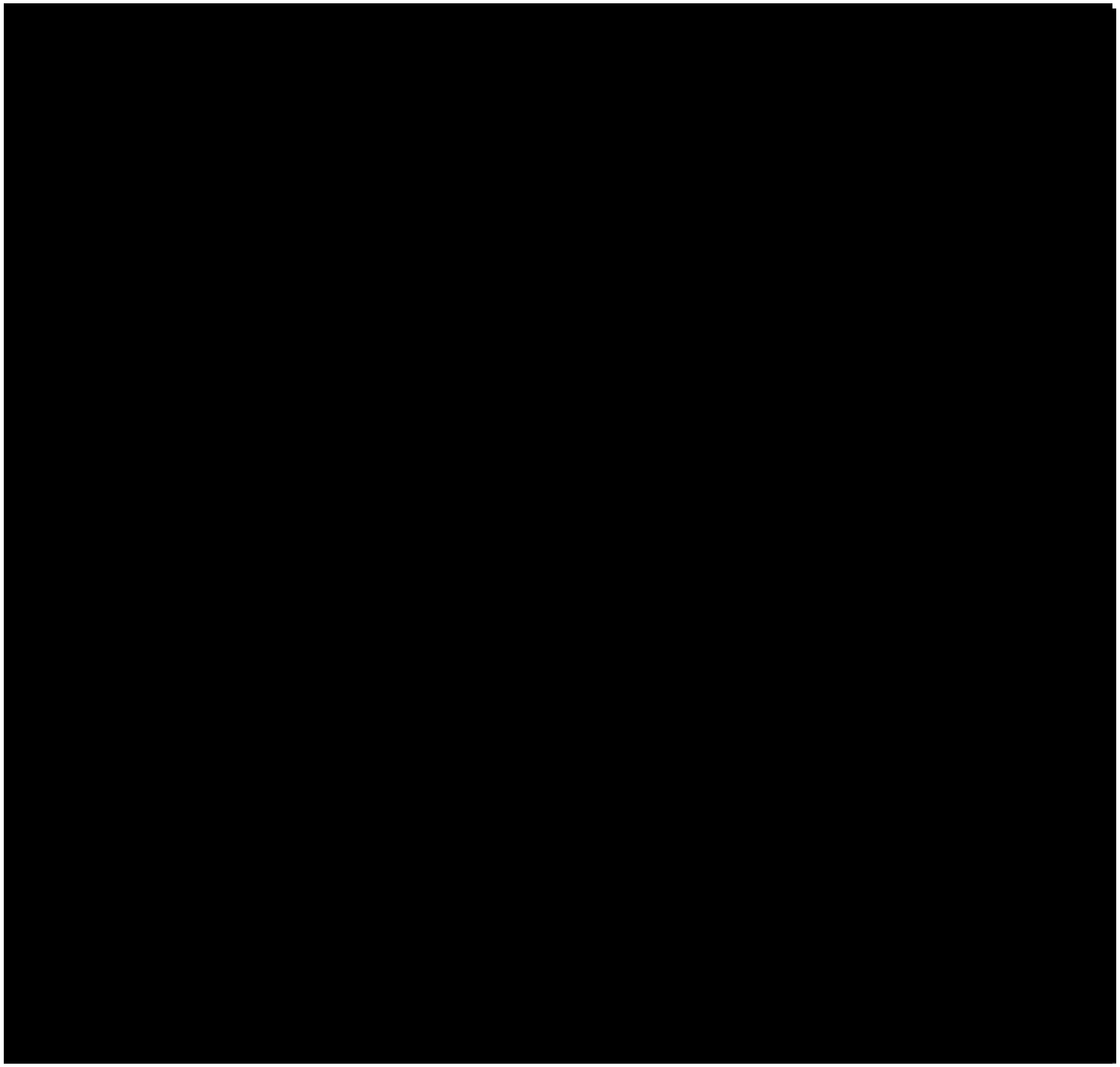
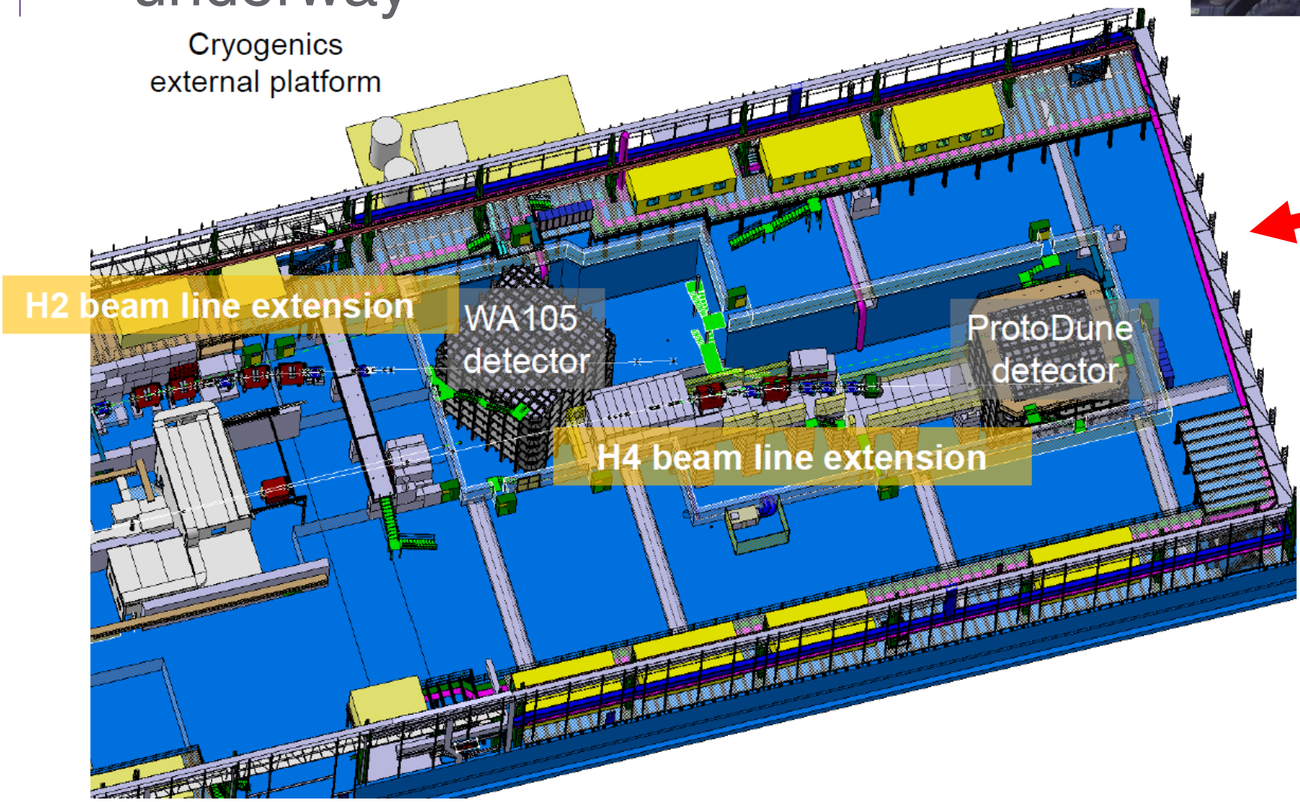


CERN Test Beam Infrastructure

- protoDUNE facility at CERN will include 2 test beams, 2 cryostats
  - CERN invested intoeach prototype
- Construction of detector hall well underway

Detector hall construction



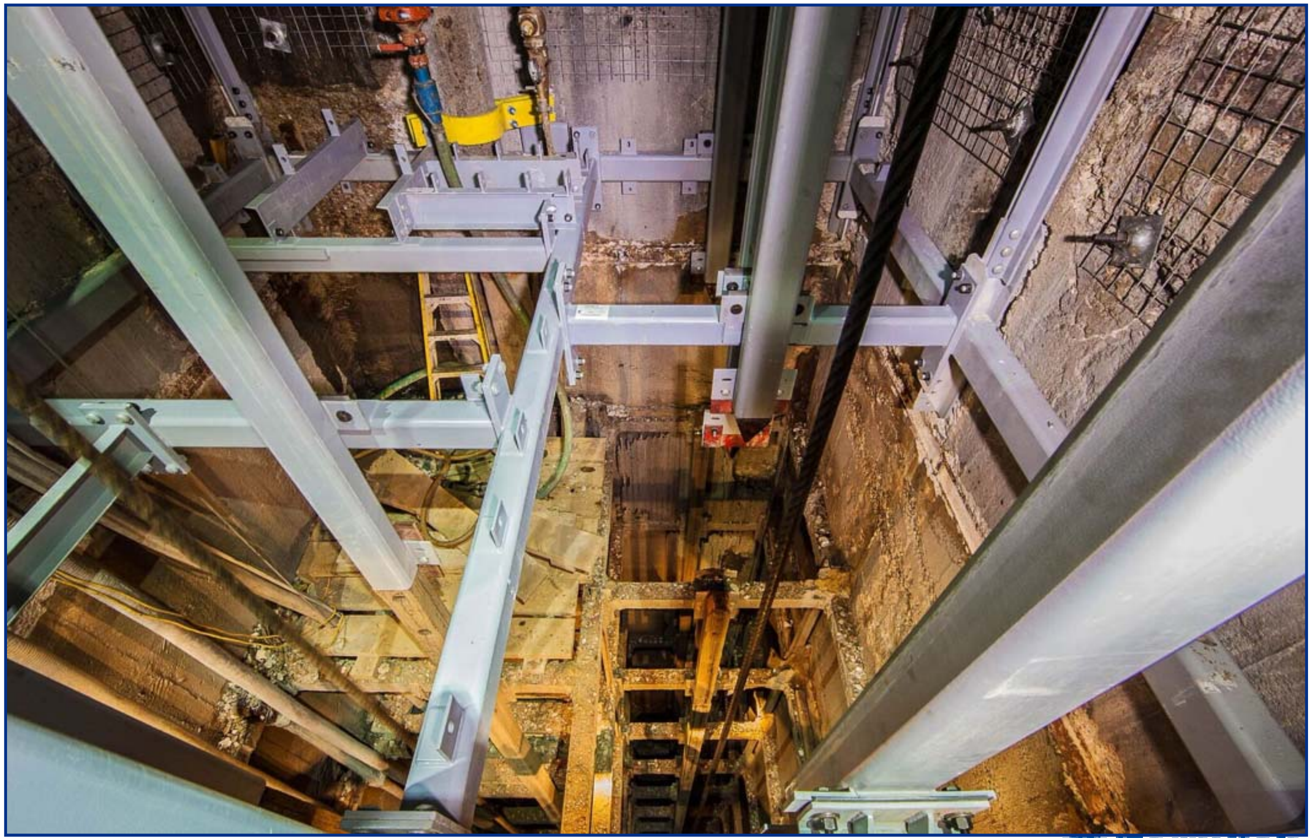
⊗ Construction photo view

Ross Shaft Refurbishment On Track….its really happening

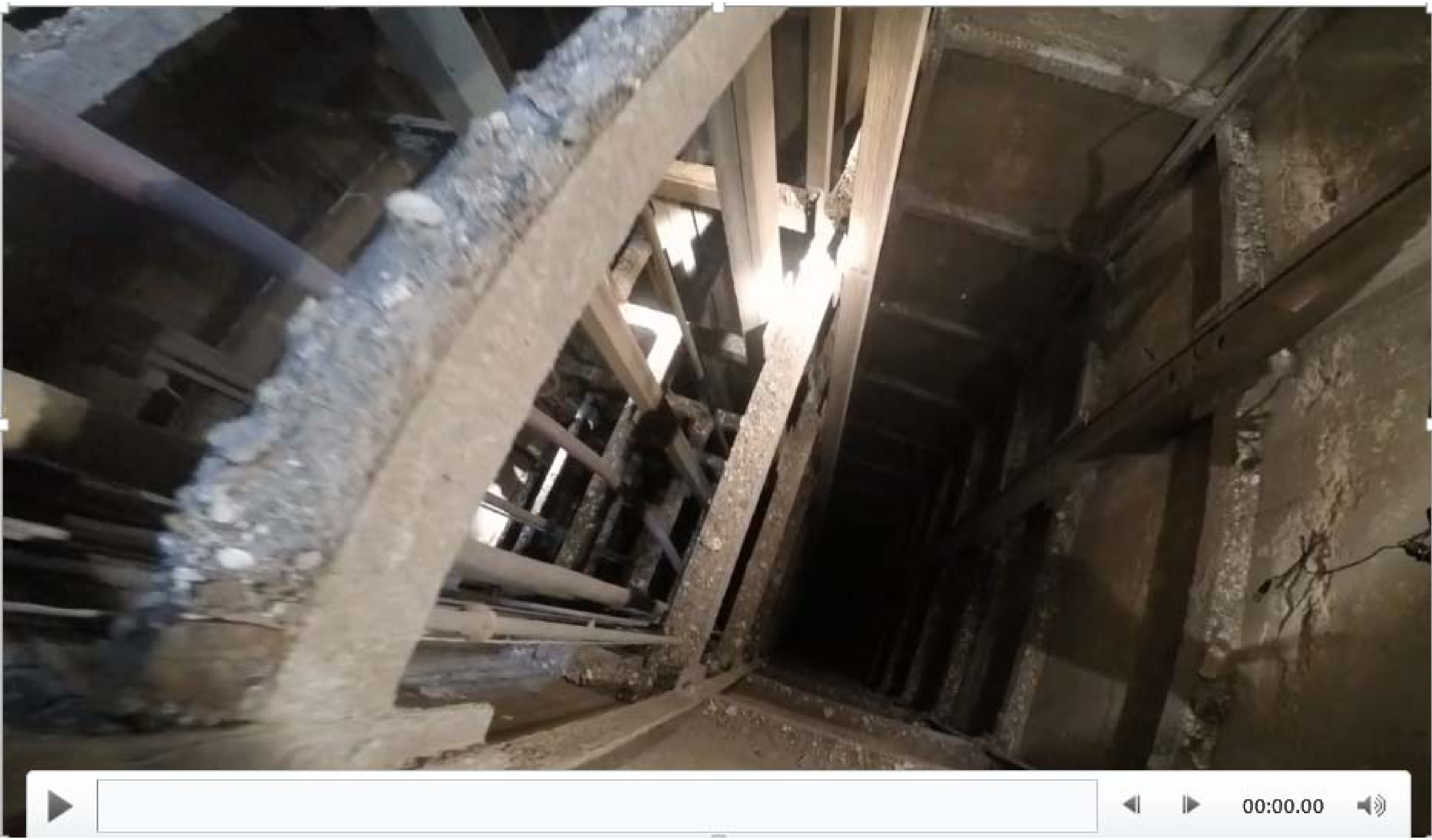
		Schedule
Surface		
Tramway	Completed	
	Completed	
300 L	Completed	
	Completed	
	Completed	
800 L	Completed	
	Completed	
1250 L	Completed	Q1 CY2014
1400 L	Completed	
1550 L	Completed	
1700 L	Completed	
1850 L	Completed	
2000 L	Completed	
2150 L	Completed	
2300 L	Completed	
2450 L	Completed	Q1 CY2015
2600 L	Completed	
2750 L	Completed	
2900 L	Completed	
3050 L	Completed	
3200 L	Completed	
3350 L	Completed	
3500 L	Completed	Q1 CY2016
3650 L	Completed	
3800 L		
3950 L		
4100 L		
4250 L		
4400 L		
4550 L		Q1 CY2017
4700 L		
4850 L		
5000 L		Mid CY2017

- Ross Shaft refurbishment required to support construction of the Long-Baseline Neutrino Facility (LBNF) Project. Shaft originally build in 1930's.
- The Ross Shaft has been refurbished to 3,765 feet from surface (75% completed). On track for a 2017 completion and a transition to LBNF construction.

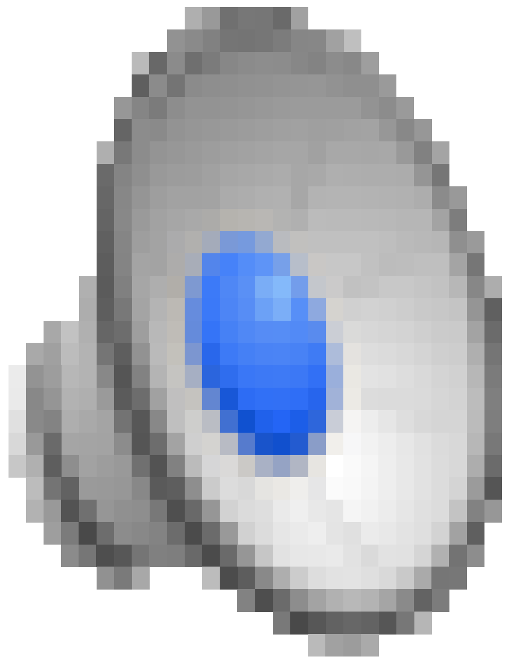
New Shaft Steel Recently Installed



Traversing Up the Ross Shaft Video - from old steel into new



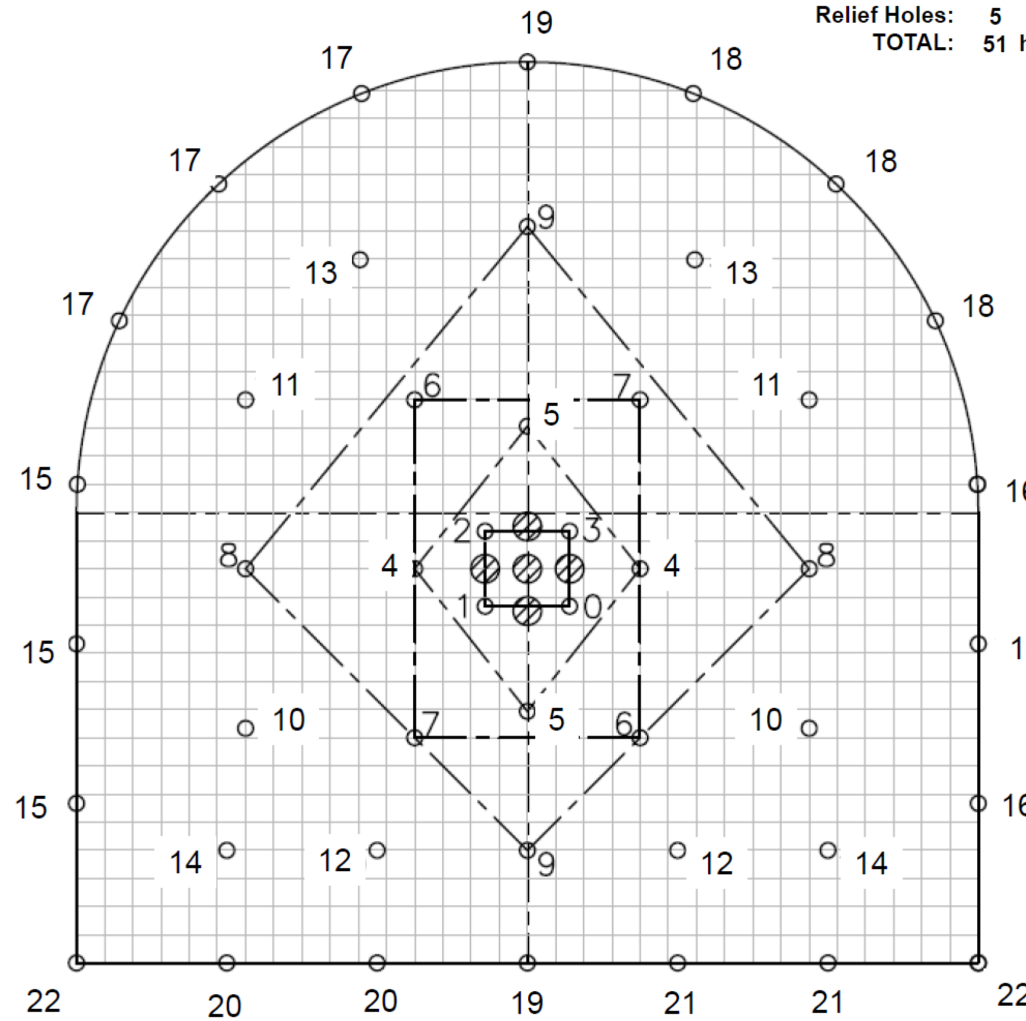
Traversing Up the Ross Shaft Video - from old steel into new



Construction Logistics Planning: Test Blast Program

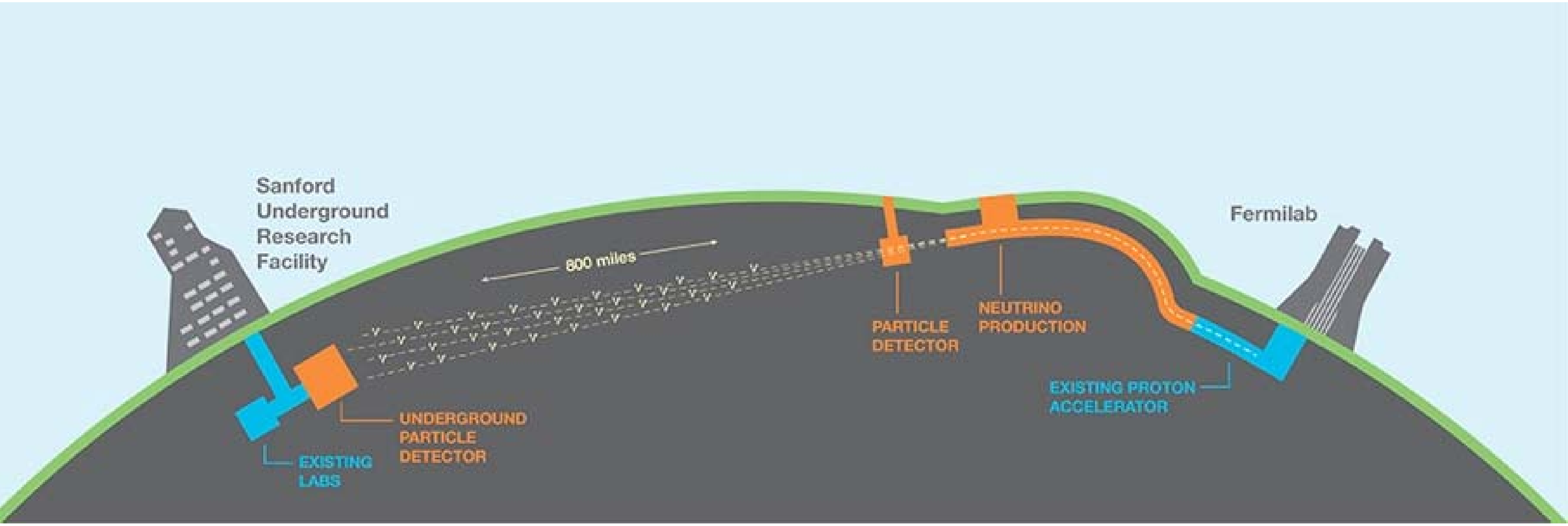
- Excavation design includes a model for vibration & blast air overpressure
  - Based on industry experience and geotechnical site investigation
  - Potential risks to other 4850L experiments discussed during Logistics Workshop
- Completed test program in March to validate assumptions and provide input to final design

Burn Holes	4
Production Holes	22
Perimeter Holes:	13
Lifters:	7
	46 holes
Relief Holes:	5
TOTAL:	51 holes



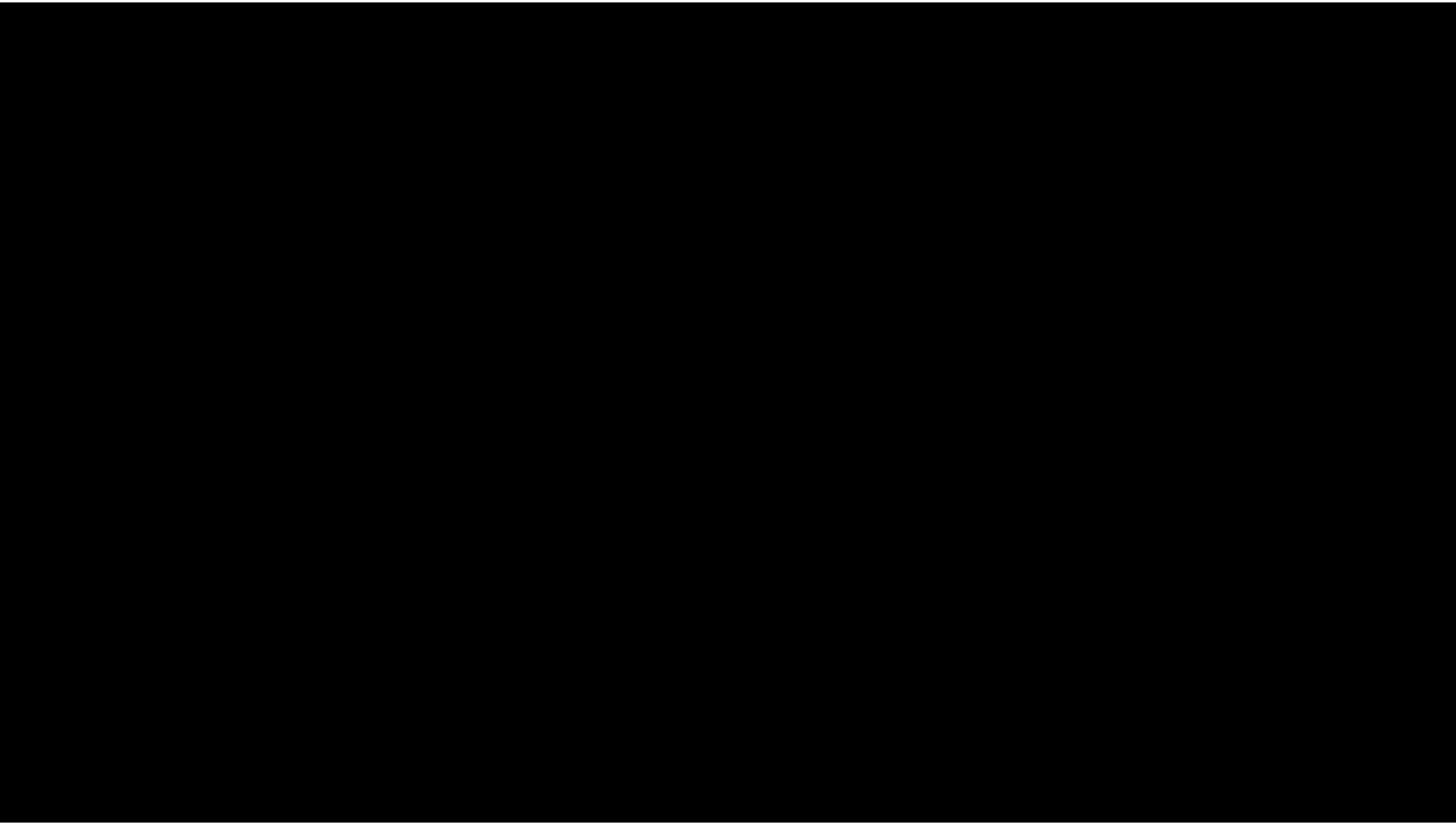
Fermilab

Thank You.



- Thanks to Mark Thomson (Cambridge), Andre Rubbia (ETH)…DUNE spokespeople
- Thanks to Fermilab: Chris Mossey, Mike Headley, Elaine McCluskey and LBNF team
- Thanks to Marzio Nessi (CERN)
- Thanks Eric James (TC) and C. K. Jung (RC)
- Thanks to the DUNE Collaboration

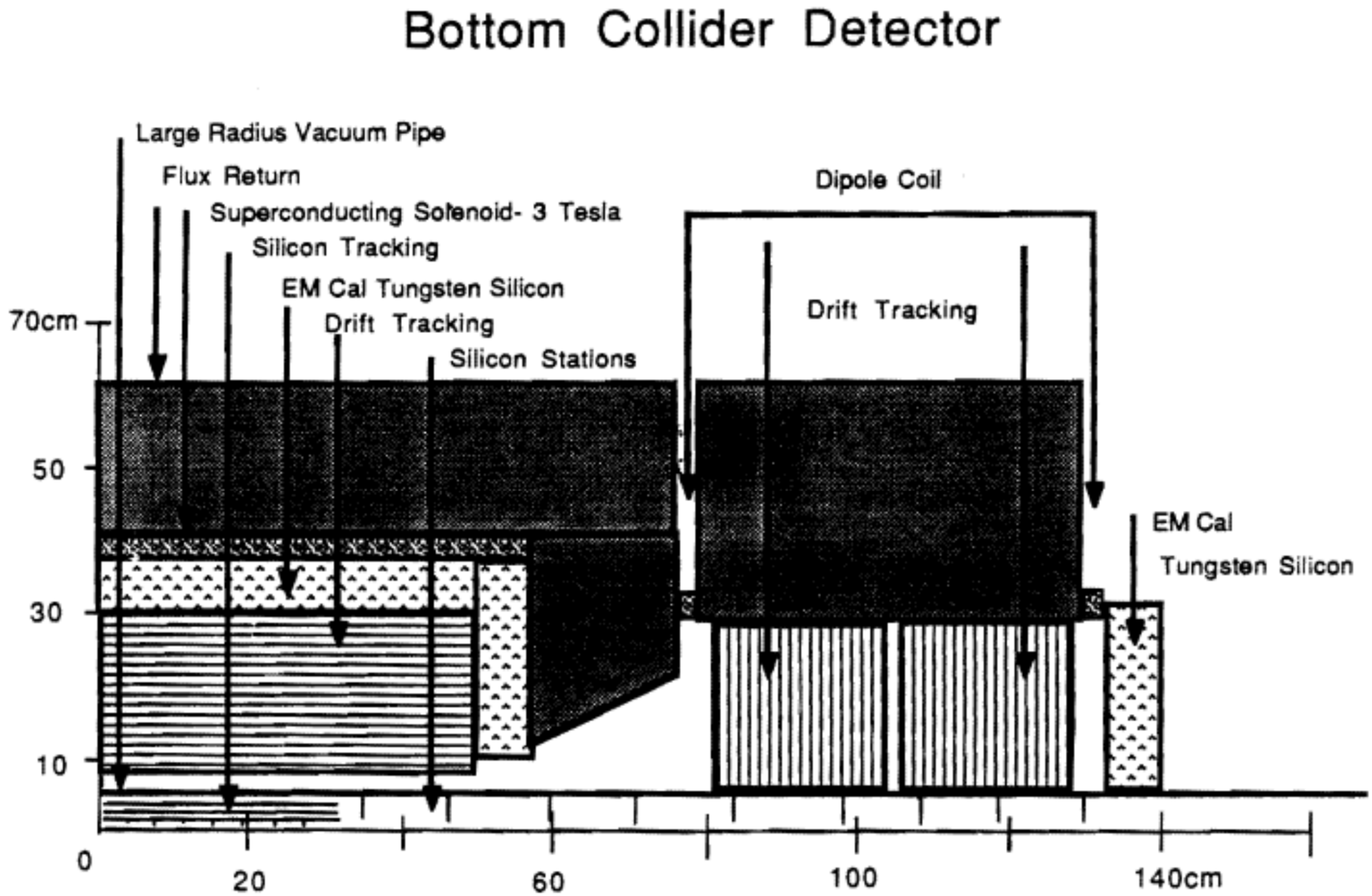
National Mammal Dance video: Fermilab's Derek Plant

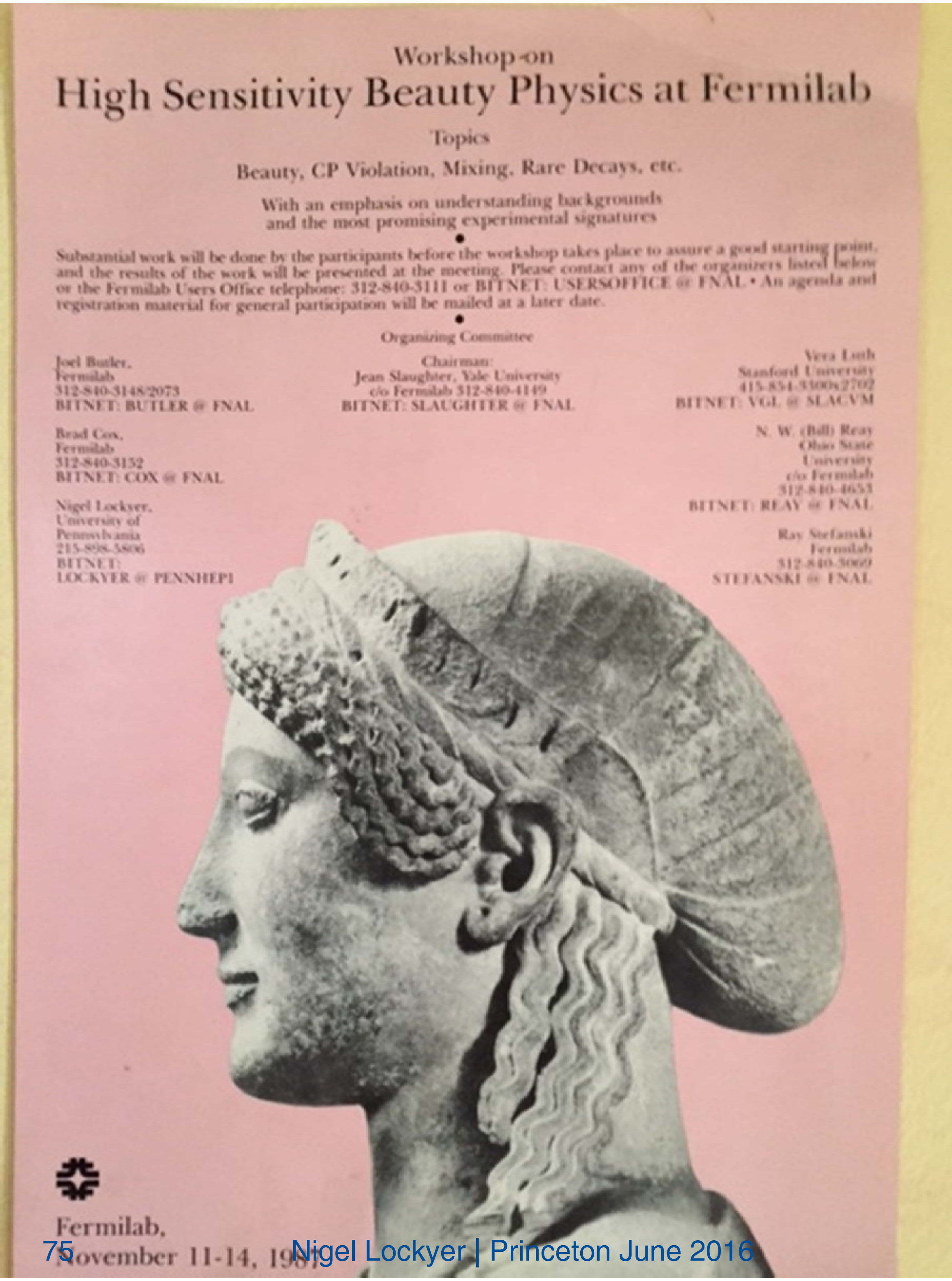


KTM

- Likes technology and likes a challenge
- BCD encapsulated Kirk's ambitions like no other experiment
- It had "more R&D needed per cm^2 than any other proposal the Fermilab PAC had encountered" Peter Sharp RAL
- Our R&D proposal was approved a T-784
  - 100MB/sec data rate…triggerless..$1M/drive movie industry
  - Hypercube computing as online trigger-i860 processors
  - RICH using csI photocathodes
  - Vertex detector inside the vacuum
  - Silicon tungsten calorimeter…hey CMS
  - Integrated circuit silicon readout chip, BVX, became SVX for CDF and D0
  - Time of Flight system….used in CDF

BCD begins March 1987…P-784

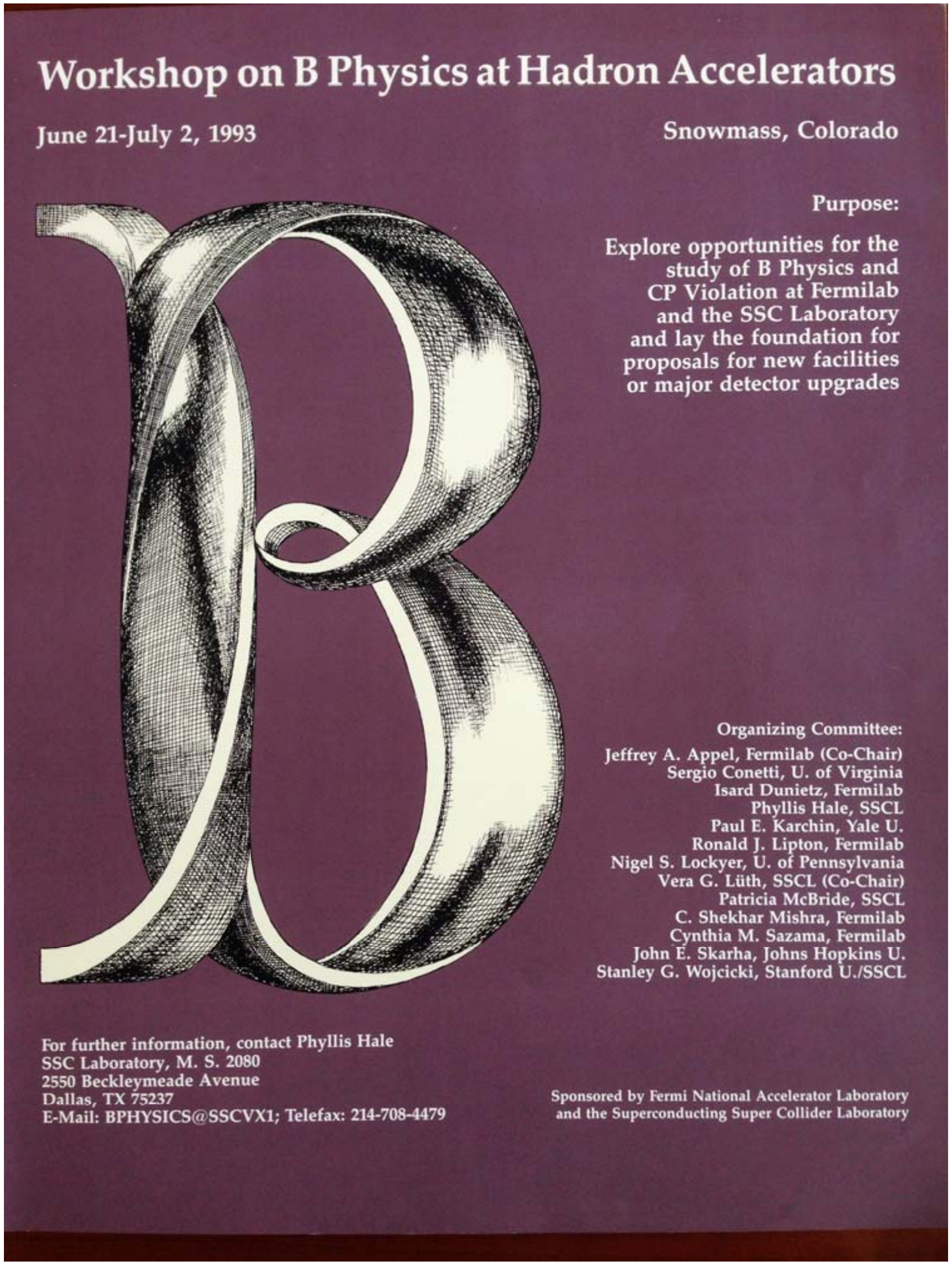




Leon wanted a workshop and eventually funded us for R&D

Predates B-factory at SLAC

The B Physics Era….



- The ideas were good
- We were prolific writers, especially KTM

11811-

Proposal for Research & Development: Vertexing, Tracking, and Data Acquisition for the Bottom Collider Detector

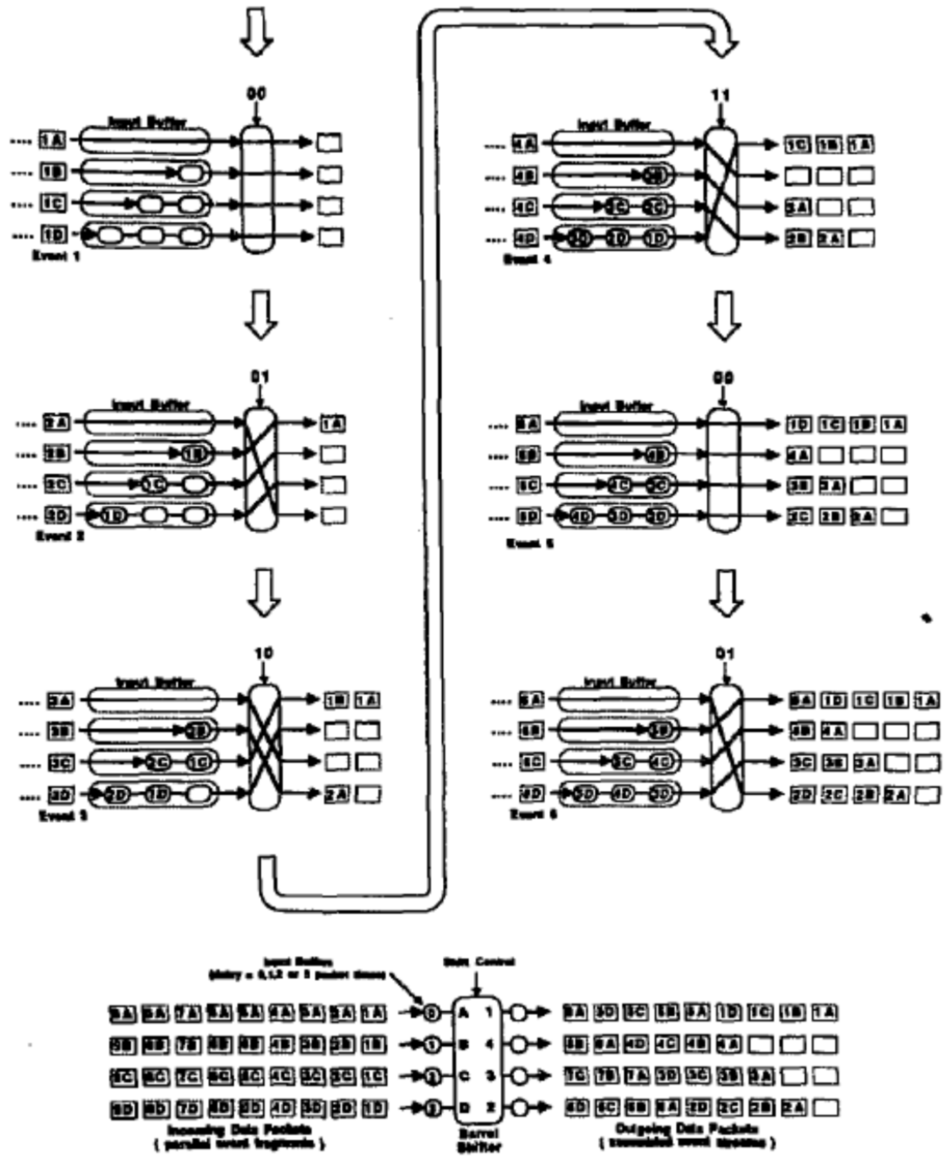
H. Castro, B. Gomez, F. Rivera, J.-C. Sanabria, *Universidad de los Andes*
P. Yager, *University of California, Davis*
E. Barsotti, M. Bowden, S. Childress, P. Lebrun, J. Morfin, L.A. Roberts, R. Stefanski, L. Stutte, C. Swoboda, *Fermilab*
P. Avery, J. Yelton, *University of Florida*
K. Lau, *University of Houston*
R. Burnstein, H. Rubin, *Illinois Institute of Technology*
E. McCliment, Y. Onel, *University of Iowa*
G. Alverson, W. Faissler, D. Garelick, M. Glaubman, I. Leedom, S. Reucroft, D. Kaplan, *Northeastern University*
S. E. Willis, *Northern Illinois University*
S. Fredricksen, N. W. Reay, C. Rush, R. A. Sidwell, N. Stanton, *Ohio State University*
G. R. Kalbfleisch, P. Skubic, J. Snow, *University of Oklahoma*
N. S. Lockyer, R. Van Berg, *University of Pennsylvania*
D. Judd, D. Wagoner, *Prairie View A&M University*
D. R. Marlow, K. T. McDonald, M.V. Purohit, *Princeton University*
A. Lopez, *Universidad de Puerto Rico*
B. Hoeneisen, *Universidad San Francisco de Quito*
S. Dhawan, P. E. Karchin, W. Ross, A. J. Slaughter, *Yale University*

(January 2, 1989)

Abstract

We propose a program of research and development into the detector systems needed for a B-physics experiment at the Fermilab p-$\bar{p}$ Collider. The initial emphasis is on the critical issues of vertexing, tracking, and data acquisition in the high-multiplicity, high-rate collider environment. R&D for the particle-identification systems (RICH counters, TRD's, and EM calorimeter) will be covered in a subsequent proposal. To help focus our efforts in a timely manner, we propose the first phase of the R&D should culminate in a system test at the C0 collider intersect during the 1990-1991 run: a small fraction of the eventual vertex detector would be used to demonstrate that secondary-decay vertices can be found at a hadron collider. The proposed budget for the R&D program is $800k in 1989, $1.5M in 1990, and $1.6M in 1991.

Event Builder Switch…telephone technology



Barrel Shift Event Builder (for fixed length event data)

Tried our luck at the SSC…lots of b's

Expression of Interest
for
A Bottom Collider Detector at the SSC

(May 25, 1990)

Executive Summary

This Expression of Interest describes a physics program to collect and analyze a sample of $> 10^{12}$ B-$\bar{B}$ pairs. The emphasis is on the study of CP violation in the Standard Model via direct measurements of CKM-matrix elements. This physics occurs at low transverse momentum and over a broad rapidity range, which complements the program of other SSC experiments that explore high-P_t and high mass.

Industrial collaborators:

A. Pitas, *Baker Manufacturing*
J. Cooper, *E-Systems Garland Division*
G. Kramer, C. Pfeiffer, S. Augustine, *Hughes Aircraft Company*
J. Rattner, *Intel Scientific Computers*

Non-leptonic Decays

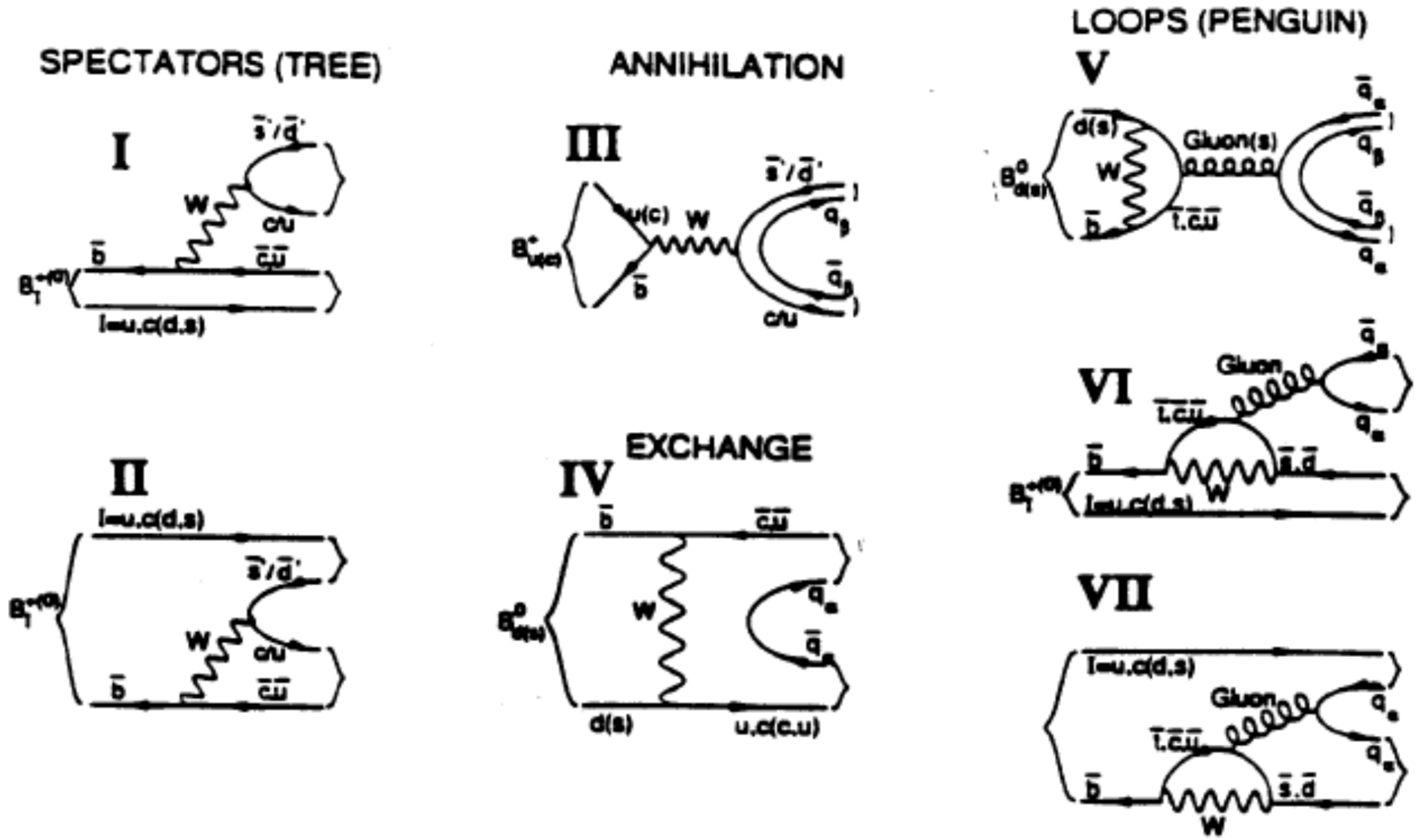


Figure 3: Seven graphs for the nonleptonic decays of B mesons. The dashed lines are W bosons; gluons are not shown.

Proposal for a B-Physics Experiment at TEV I

The μBCD

(October 8, 1990)

H. Castro, B. Gomez, F. Rivera, J.-C. Sanabria, *Universidad de los Andes*
J.F. Arens, G. Jernigan, *U.C. Berkeley, Space Sciences Lab*
P. Yager, *U.C. Davis*
J.M. Butler, L.A. Garren, S. Kwan, P. Lebrun, J. Morfin, T. Nash,
L. Stutte, *Fermilab*
P. Avery, J. Yelton, *U. Florida*
M. Adams, D. McLeod, C. Halliwell, *U. Illinois, Chicago*
R. Burnstein, H. Cease, H. Rubin, *Illinois Institute of Technology*
E.R. McCliment, Y. Onel, *U. Iowa*
D. London, *U. Montreal*
M.S. Alam, A. Deogirikar, W. Gibson, *S.U.N.Y. Albany*
C.L. Britton, K. Castleberry, C. Nowlin, C. Sohns, *Oak Ridge National Lab*
P. Gutierrez, G.R. Kalbfleisch, D.H. Kaplan, P. Skubic, J. Snow,
U. Oklahoma
L.D. Gladney, N.S. Lockyer,[1] R. Van Berg, *U. Pennsylvania*
D.J. Judd, D.E. Wagoner, K. Paick, L. Turnbull, *Prairie View A&M U.*
J.G. Heinrich, C. Lu, K.T. McDonald, *Princeton U.*
A.M. Lopez, J.C. Palathingal, A. Mendez, J. Millan, R. Palomera-Garcia,
Universidad de Puerto Rico
B. Hoeneisen, C. Marin, C. Jimenez, *Universidad San Francisco de Quito*
M. Sheaff, *U. Wisconsin*
A.J. Slaughter, E. Wolin, *Yale University*

Field trips: Bee on a Chip & fire ants SSC

- **NY Times:**
  - **Chip to Track 'Killer' Bees Is Invented**
  - The chip, which has not yet been tested in the field, can be glued to the thorax of a bee. It weighs only about 35 milligrams, so it "should not affect the bee's ability to fly," said Kelly Falter, a member of the team responsible for creation of the microchip.

KTM solves problems

Motion of a Leaky Tank Car

Kirk T. McDonald
Joseph Henry Laboratories, Princeton University, Princeton, NJ 08544
(December 4, 1989; updated October 10, 2014)

1 Problem

Describe the motion of a tank car initially at rest once an off-center drain opens. The tank car rolls without friction on a horizontal surface, and the water flows out of the drain vertically in the rest frame of the car.

2 Solution

The motion of a leaky tank car is surprisingly complex. We approach a solution in four steps: a brief discussion of the motion, a discussion of the forces that cause the motion, a general analysis, and lastly two detailed examples.

This problem has appeared in recent years on qualifying exams in Russia.[1]

Kirk Quotes

- Spend your money…you'll never get more if you save it
- Join APS, or you will never get an award
- That guy likes physics so much you don't have to pay him

Fun

We drove a long time, finally found this backwater Texas café,
Don’t remember what we ordered but it was worth the drive