Fermilab

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

Neutrinos and the Quantum Universe…going International

more powerful accelerators are needed

Nigel S. Lockyer

Trombay Colloquium

3/31/2015

Outline

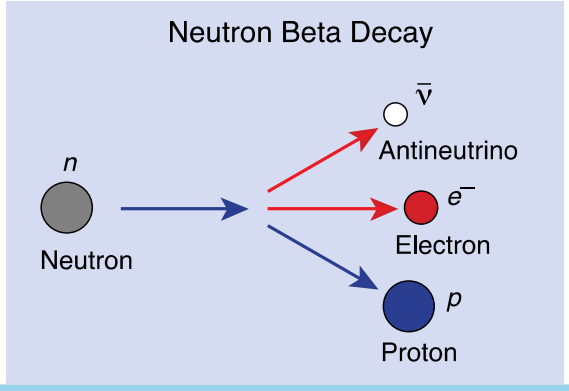
- Introduction to neutrinos
- Why they are Interesting
- Neutrino experiments and beams
- India US Collaboration
- DUNE/LBNF

Wolfgang Pauli, 1930

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

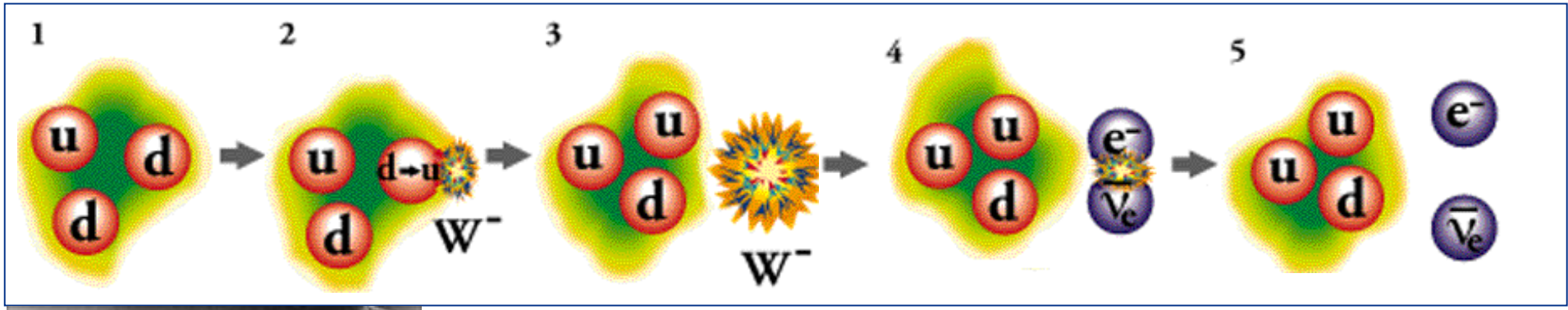
$$^{14}\mathbf{C} \rightarrow {}^{14}\mathbf{N} + \mathbf{e}^{-}$$

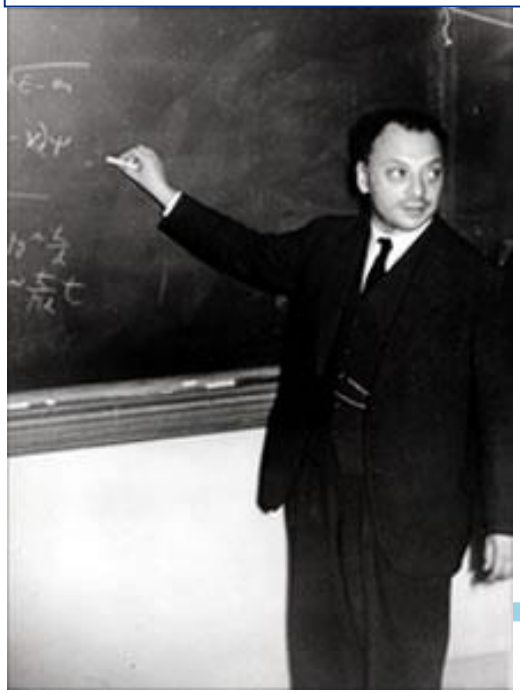
$$\mathbf{n} \rightarrow \mathbf{p} + \mathbf{e}^{-}$$



Pauli's invisible particle

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





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"*

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

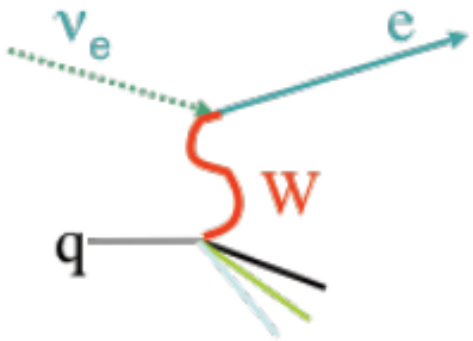
$$\mathbf{n} \rightarrow \mathbf{p} + \mathbf{e}^{-} + \bar{\nu}_e$$

implies also this process:

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

1st detection of neutrinos -1950s

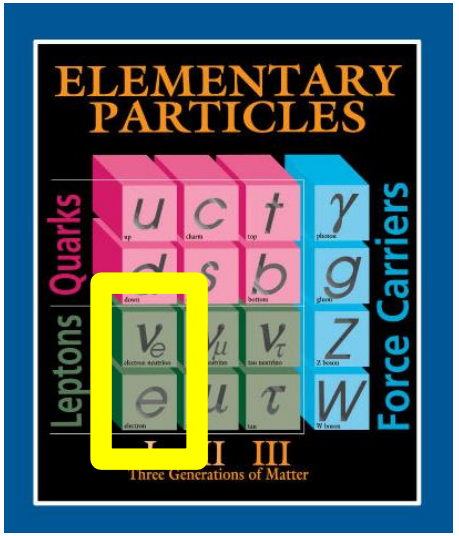
Savannah River Nuclear Reactor



$$\nu_e + N \rightarrow e^- + X$$

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

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

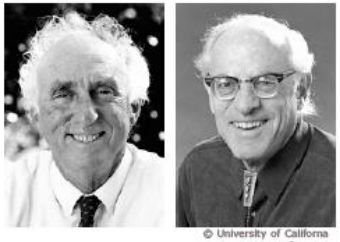


The Nobel Prize in Physics 1995

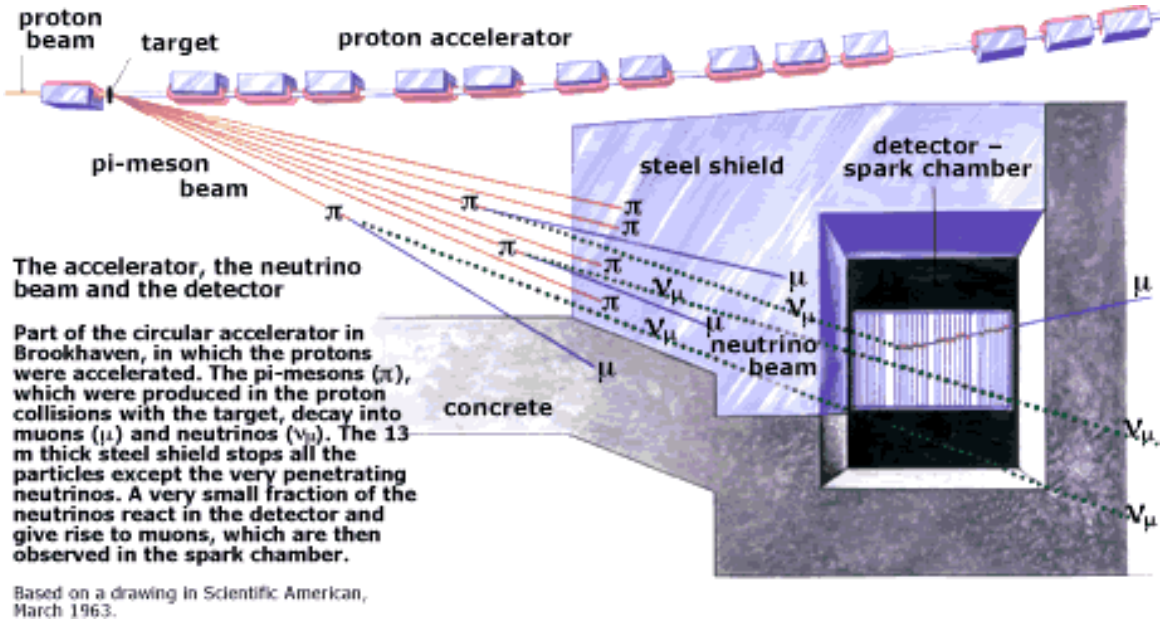
"for pioneering experimental contributions to lepton physics"

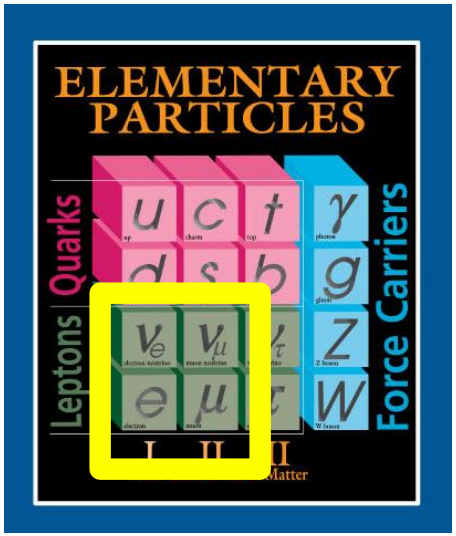
"for the discovery of the tau lepton" — Martin L. Perl

"for the detection of the neutrino" — Frederick Reines



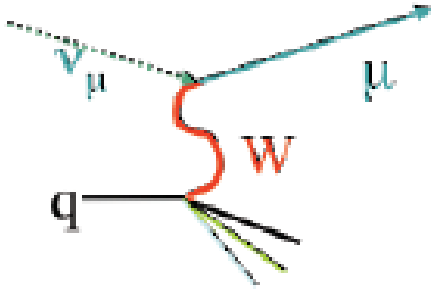
Discovery of “two neutrinos” – 1960s





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"



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

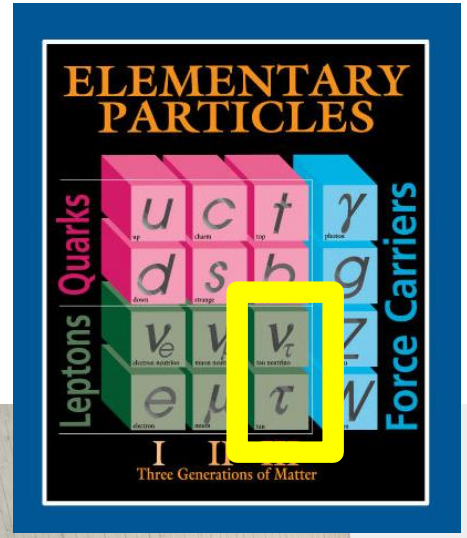

Leon M. Lederman

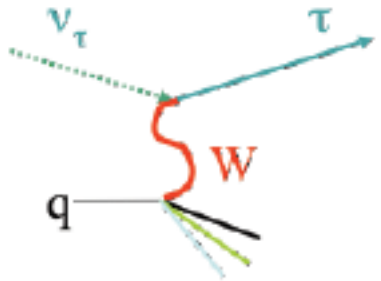

Melvin Schwartz


Jack Steinberger

Discovery of the Third Neutrino at Fermilab

IN 2000
A GROUP OF
PHYSICISTS FINALLY
FOUND EVIDENCE OF
THE TAU TYPE OF
THIS SUBATOMIC
PARTICLE





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

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A little history…

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


Bruno Pontecorvo

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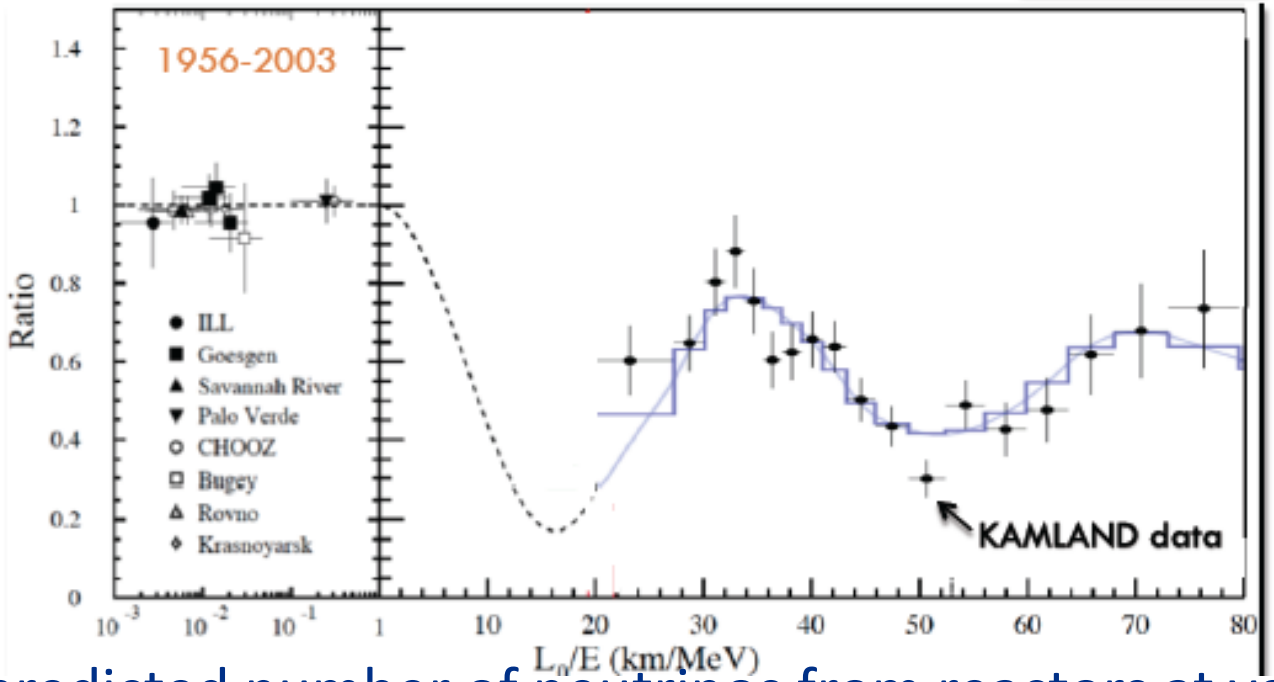
- in the 1960's, scientists had started thinking "is there anything else?" - maybe ν transitions?



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

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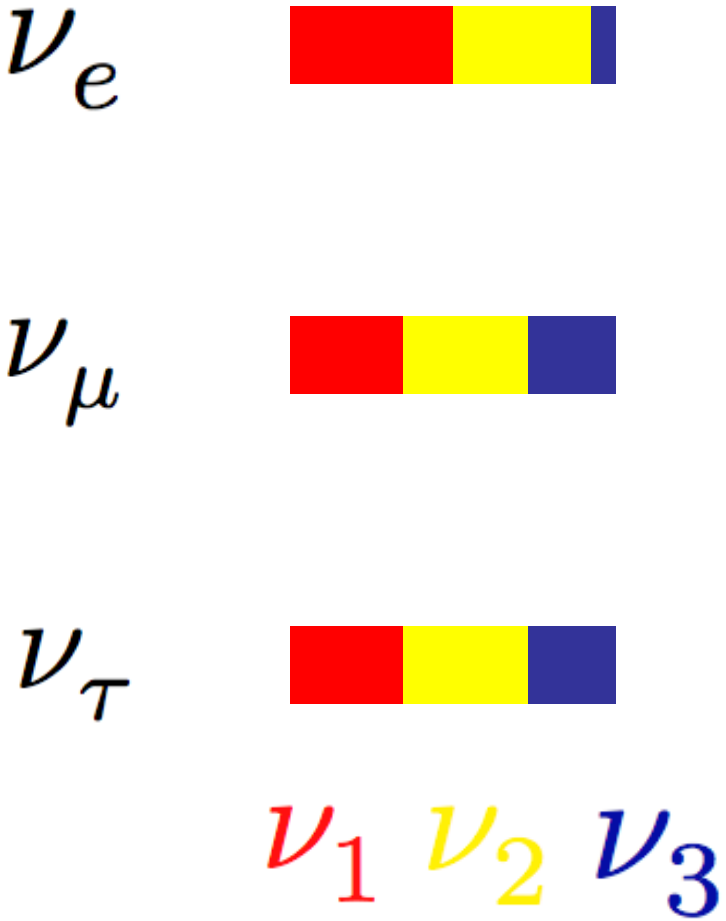
neutrinos oscillate



- The electron neutrinos produced in the Sun are actually a quantum mechanical mixture of neutrinos with three *different* (tiny) masses
- A neutrino of definite flavor does not have a definite mass
- And a neutrino of definite mass does not have a definite flavor

Neutrino and Quark Mixing and Masses

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

Neutrino Masses < 2 eV

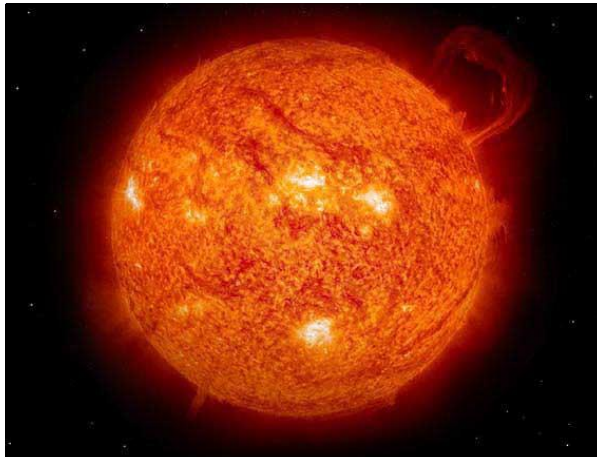
$$V_{CKM} \approx \begin{pmatrix} 1 & 0.2 & 0.001 \\ 0.2 & 1 & 0.01 \\ 0.001 & 0.01 & 1 \end{pmatrix}$$

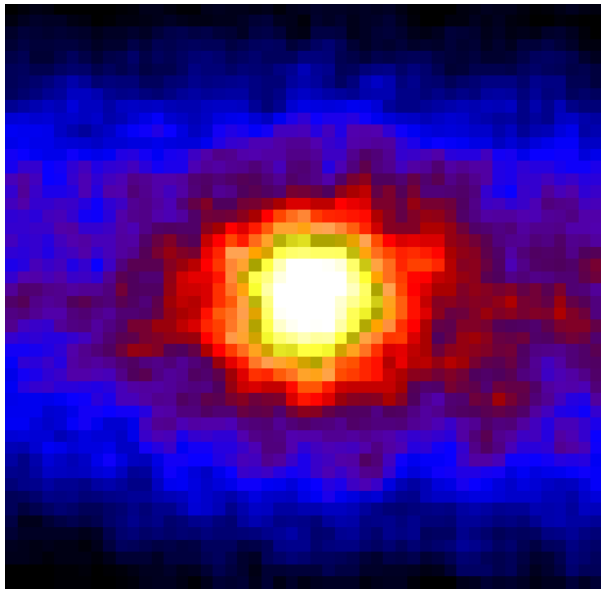
Quark Masses = 3×10^6 eV to 1.7×10^{11} eV

Very different

No idea why, but it is probably important

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

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

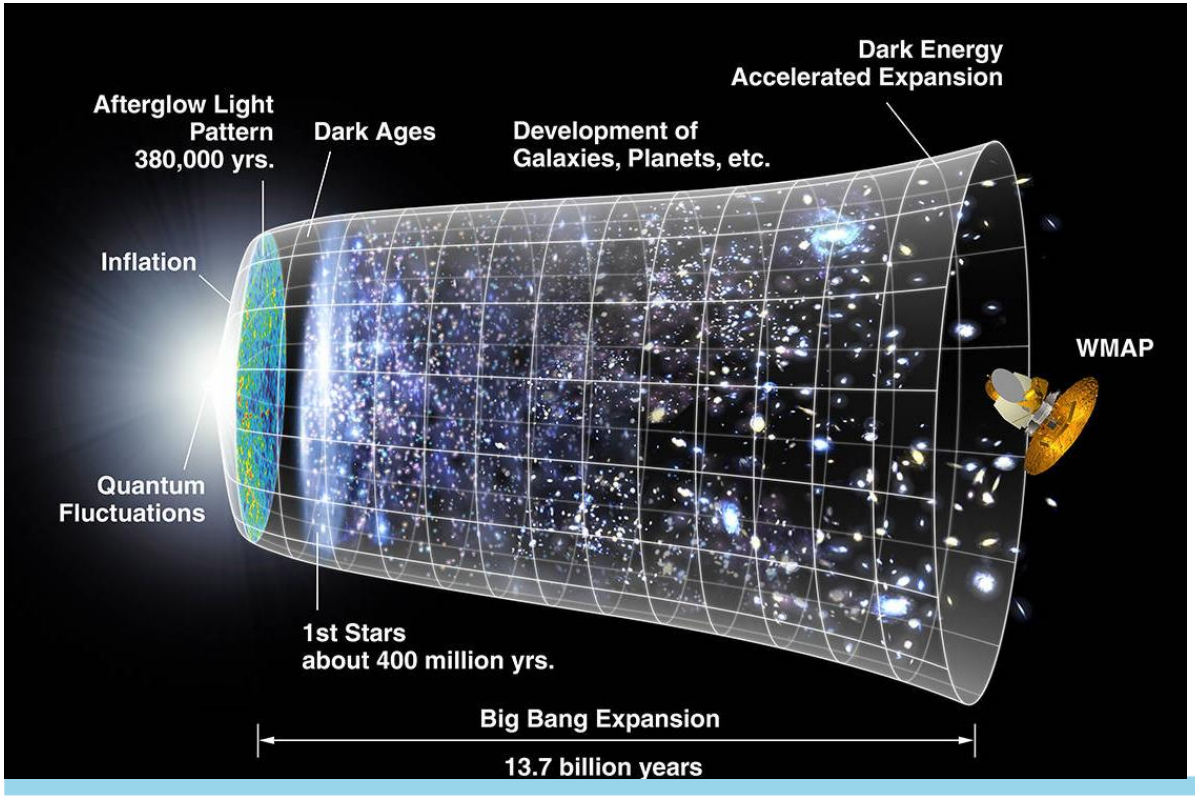
$$p + {}^{7}Be \rightarrow {}^{8}B + g$$

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

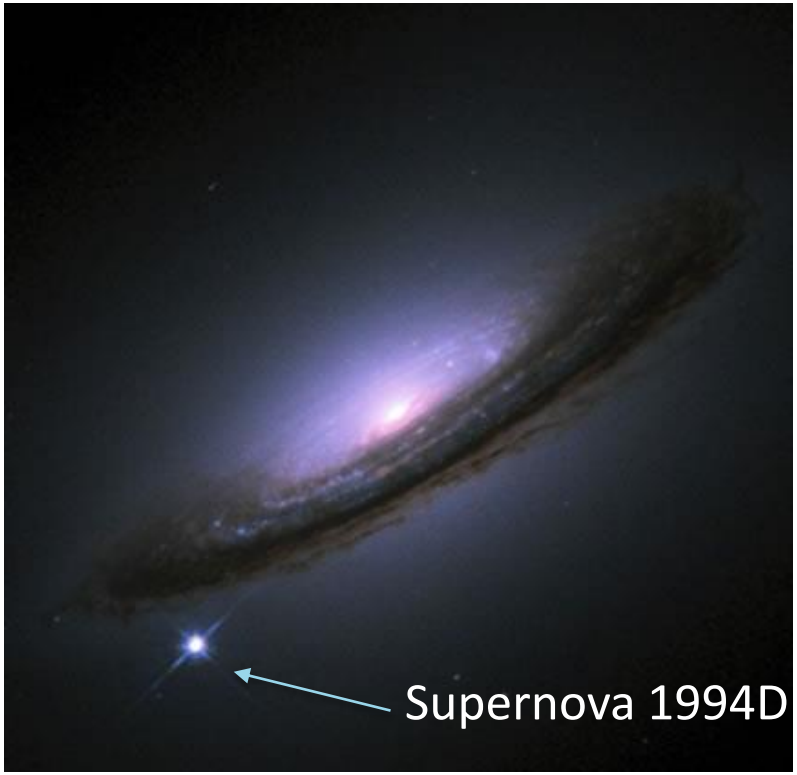
Where do neutrinos come from?

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

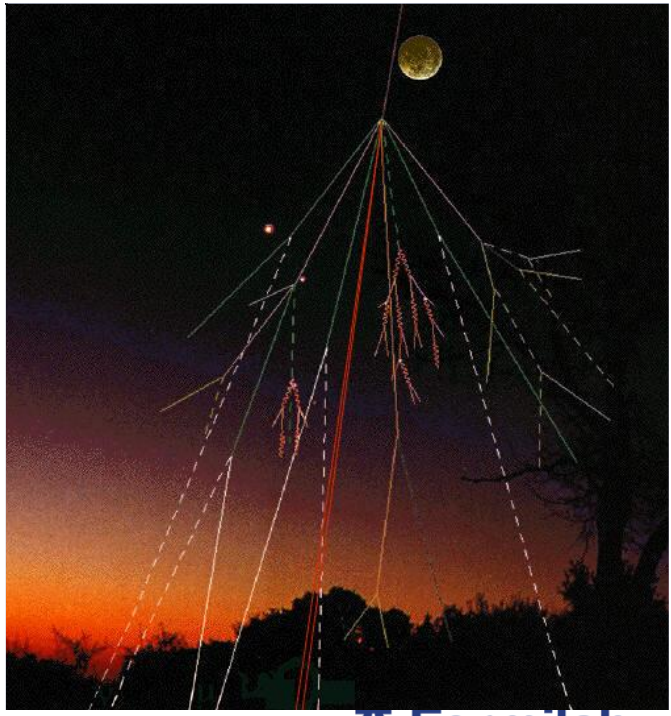


Where do neutrinos come from?



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

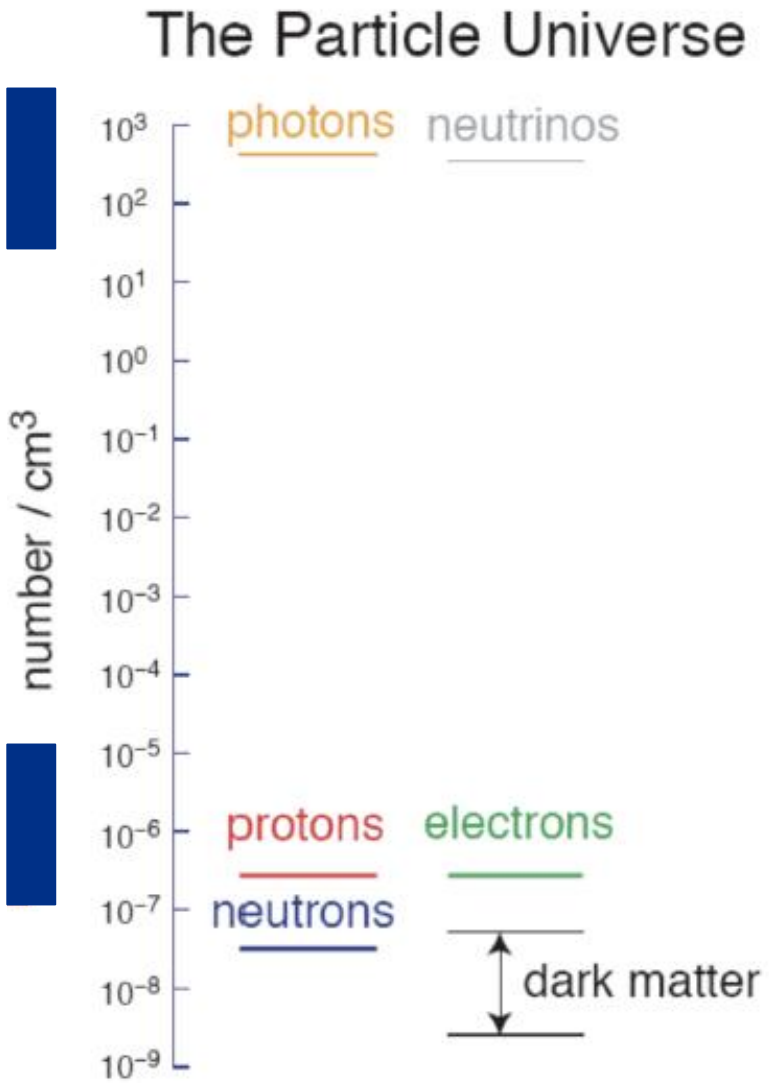
The Earth's crust:

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

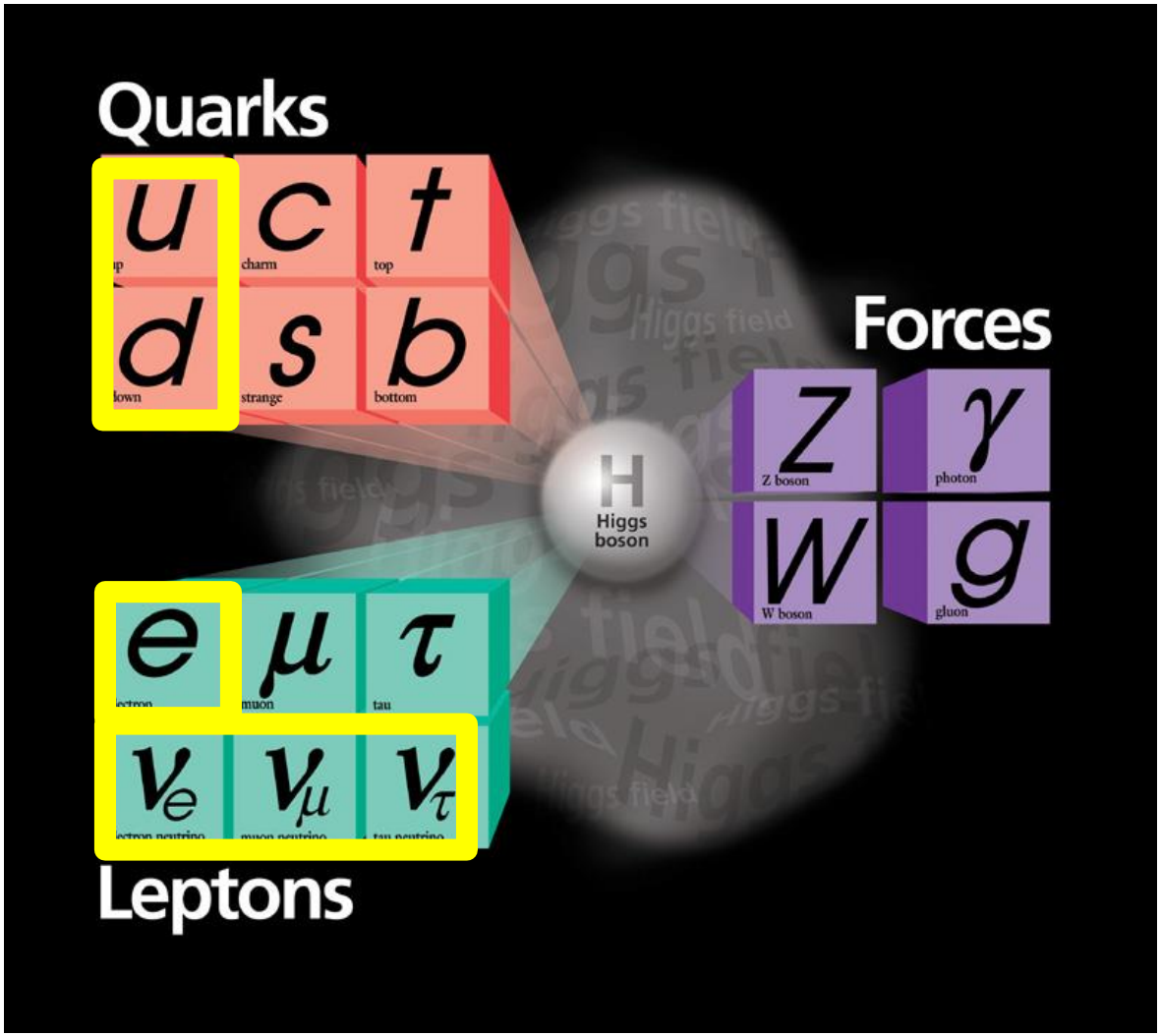
Where do neutrinos come from?

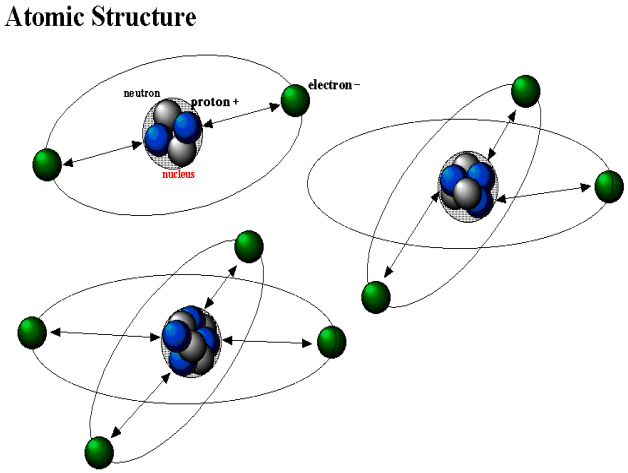
Bananas: A banana emits about one million neutrinos per day from the radioactive decay of potassium 40…avocadoes…twice as many

Neutrinos are Abundant……just as many as photons



Standard Model…..ingredients quantum universe





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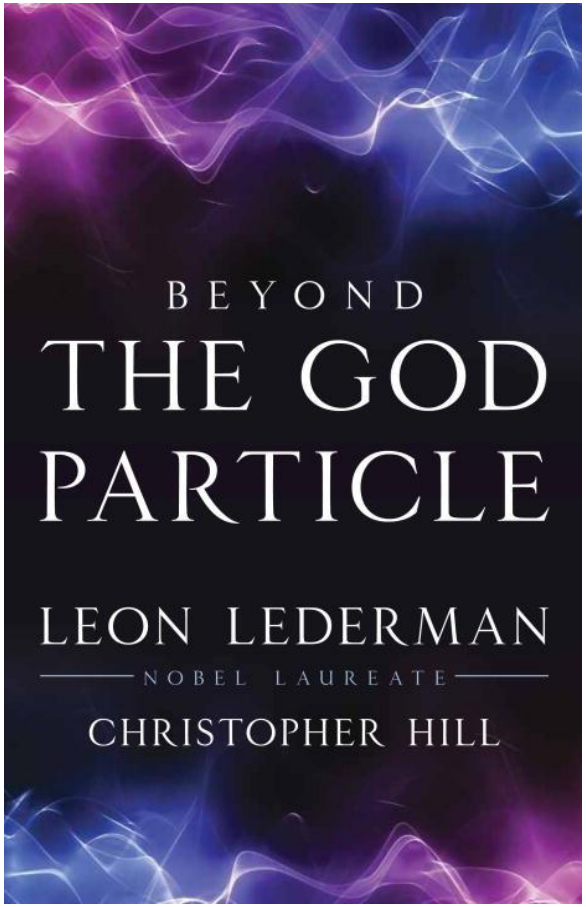
Leon Lederman



"Physics is not religion. If it were, we'd have a much easier time raising money. "

Higgs

The first time that the entire NYT Science section is devoted to a single story

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Higgs gives mass to quarks & charged leptons

u up

d down

ν_e e-neutrino

e electron

c charm

s strange

ν_μ μ-neutrino

μ muon

b bottom

ν_τ τ-neutrino

τ tau

plus corresponding antiparticles

Why are neutrinos interesting?

- Higgs discovery brings flavor & mass issues to the forefront
- The wide range of quark masses is puzzling
  - The top quark discovery is 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…do neutrinos have Majorana masses or Dirac masses?
- One future lies in better understanding neutrinos
  - their mass ordering
  - the origin of their masses and why they are so small (see-saw)
  - their interactions (CP Violation)
  - how many types of neutrinos…..3-neutrino paradigm
  - relationship to matter-antimatter asymmetry in universe (leptogenesis) and structure of the universe

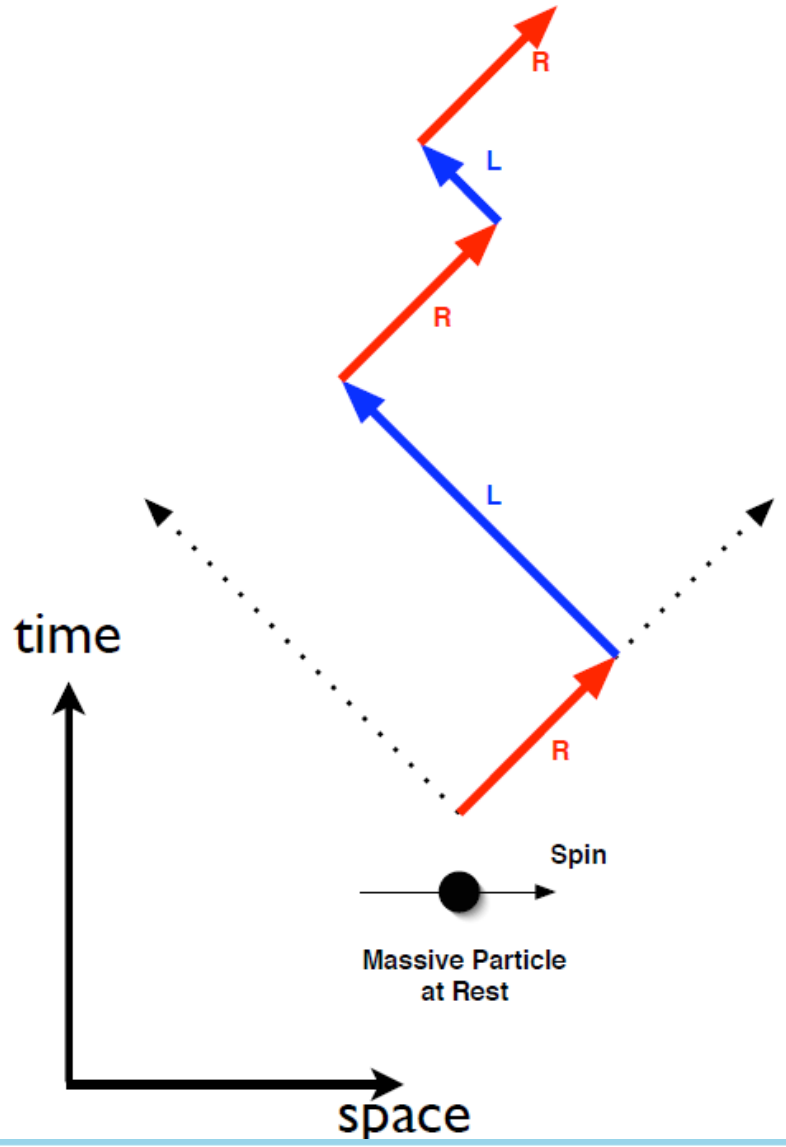
Higgs and the mysteries of mass

- 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…

The Higgs Mechanism…mass to the particles



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:

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

?

Why most theorists expect Majorana masses

The Standard Model (SM) is defined by the fields it contains, its symmetries (notably weak isospin invariance), and its renormalizability.

Leaving neutrino masses aside, anything allowed by the SM symmetries occurs in nature.

Right-Handed Majorana mass terms
are allowed by the SM symmetries.

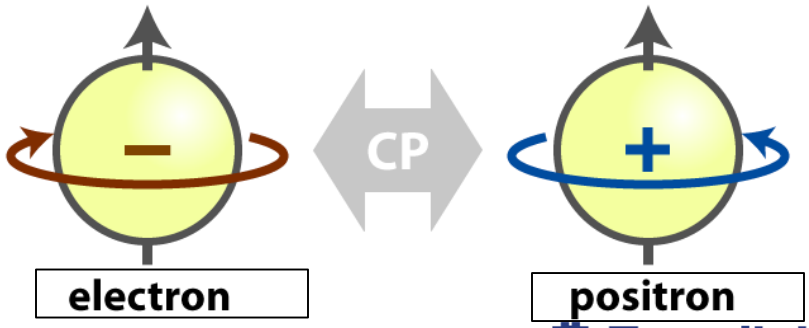
Then quite likely *Majorana masses*
occur in nature too.

7

Boris Kayser…Fermilab

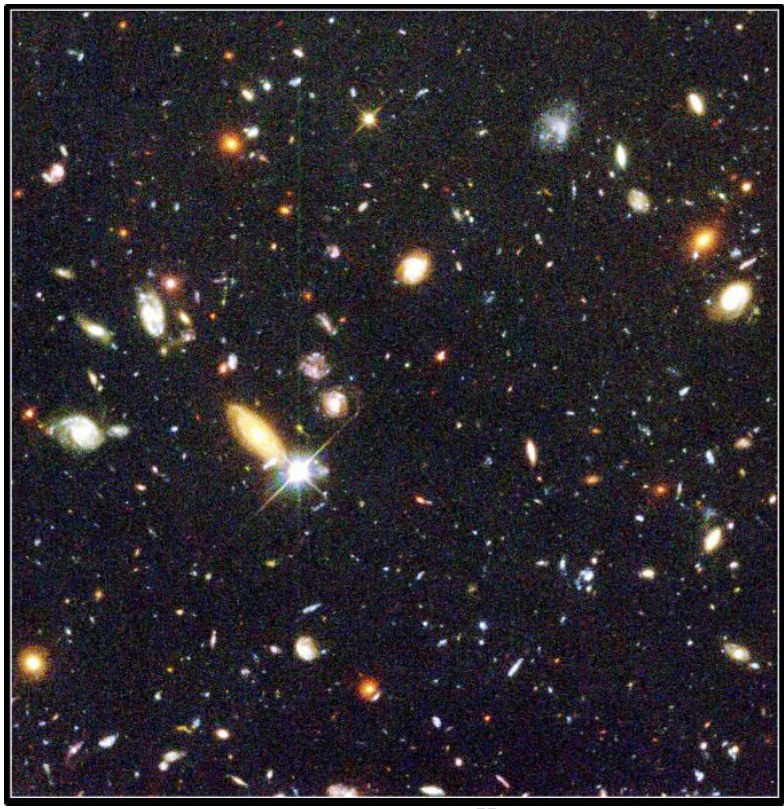
CP symmetry

- 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

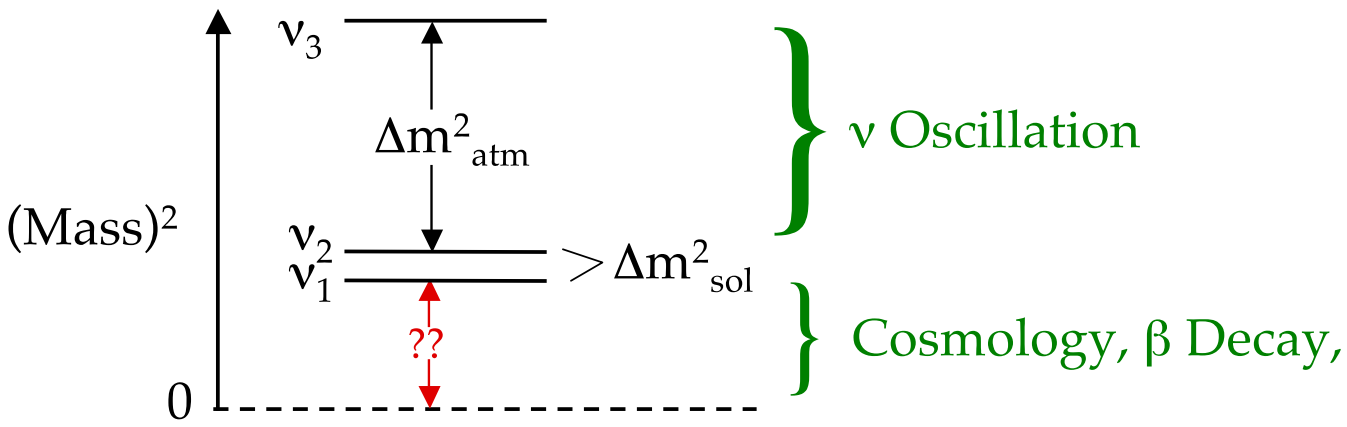


CP violation, neutrinos, and leptogenesis

- If the neutrino “see-saw” idea is correct, the early universe contained the very heavy partners (Majorana mass) of the light neutrinos
- Those 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 (CP violation in quark sector is not enough)

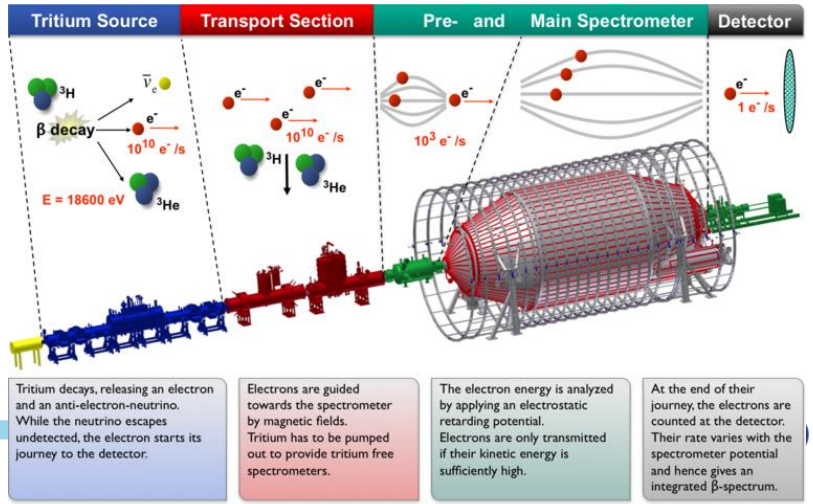


Neutrino masses: what we know and don't know

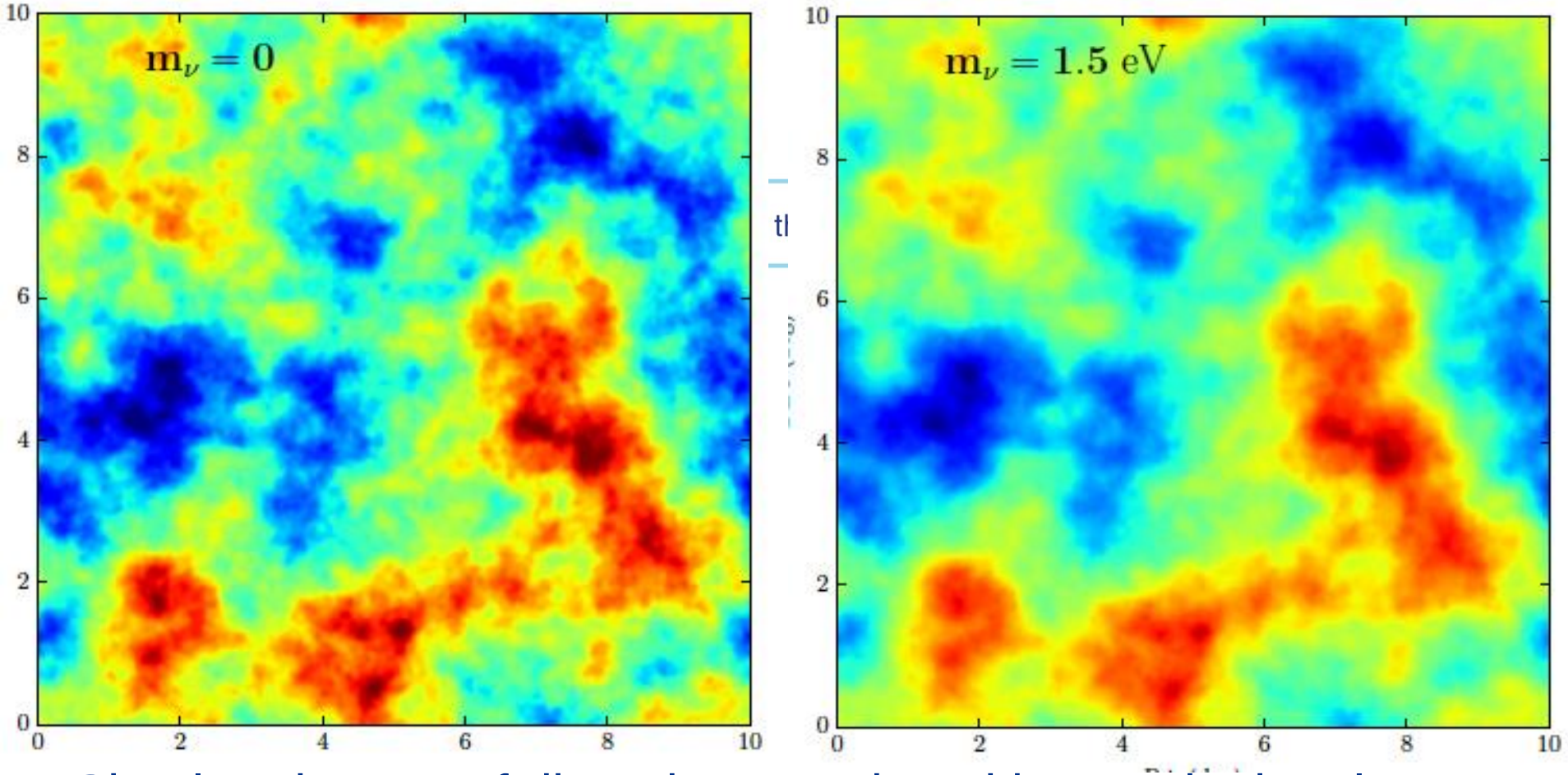


How far above zero is the whole pattern?

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



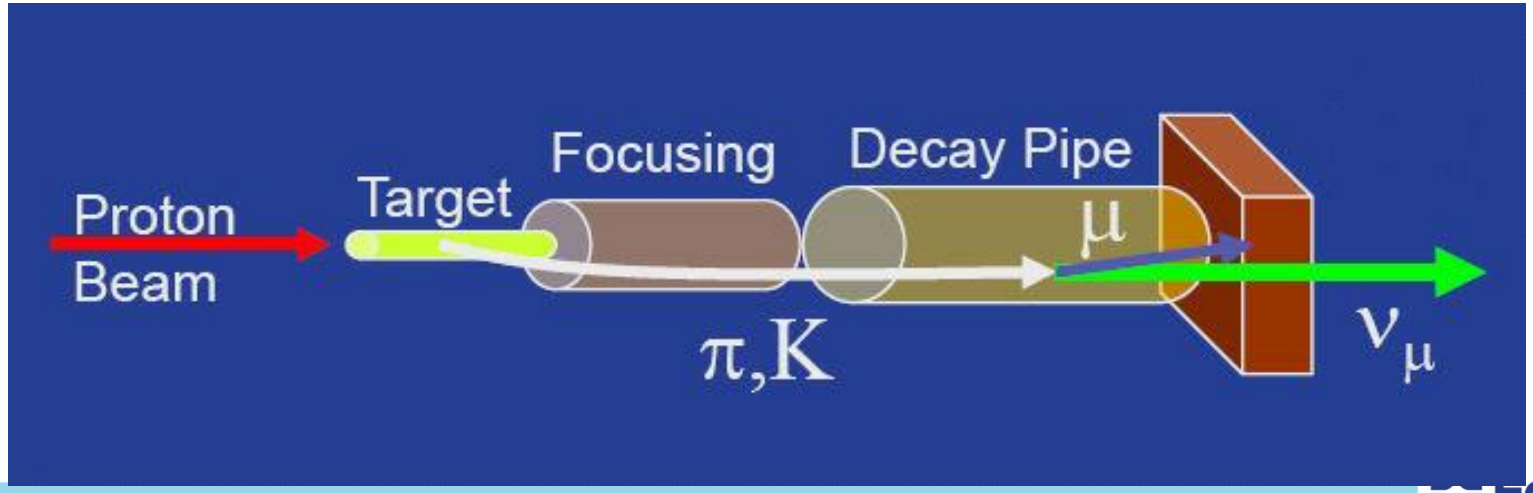
Neutrino mass affects the shape of the universe



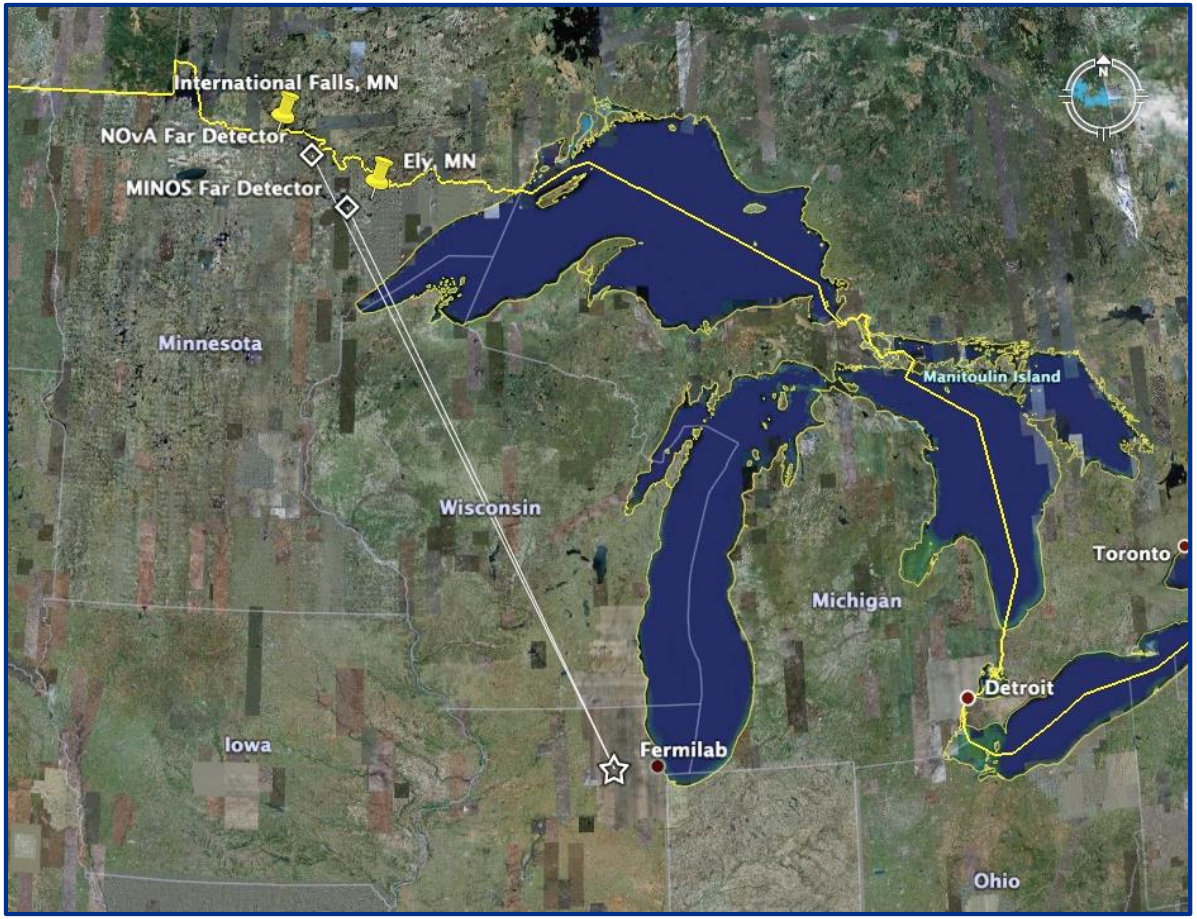
Simulated maps of distortions produced by gravitational lensing of relic cosmic radiation. Massive neutrinos produce a universe with shallower gravitational potential wells

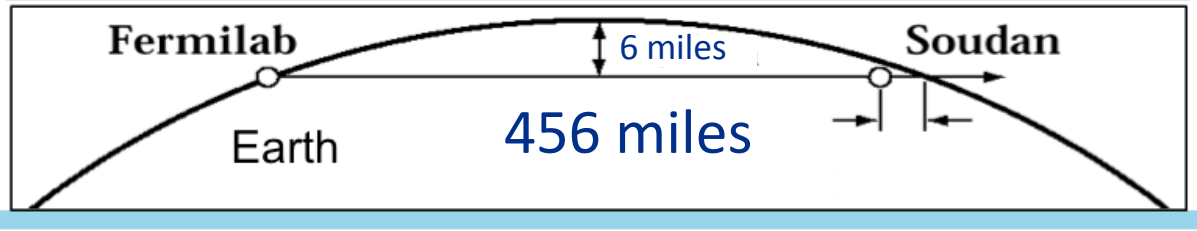
Neutrino beams from accelerators

- At Fermilab we already make the world's most powerful neutrino beams (400kW on target today)
- And we have plans to at least quadruple this power in the future



Neutrino beam to Minnesota (via Madison!)





- Right now we are shooting high energy neutrinos 500 miles through the Earth to Minnesota
- 1/400 of a second later, some of them interact with large detectors called NOvA and MINOS

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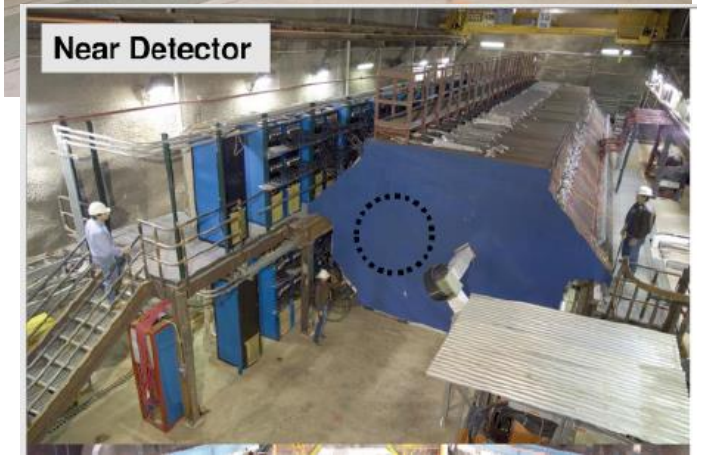
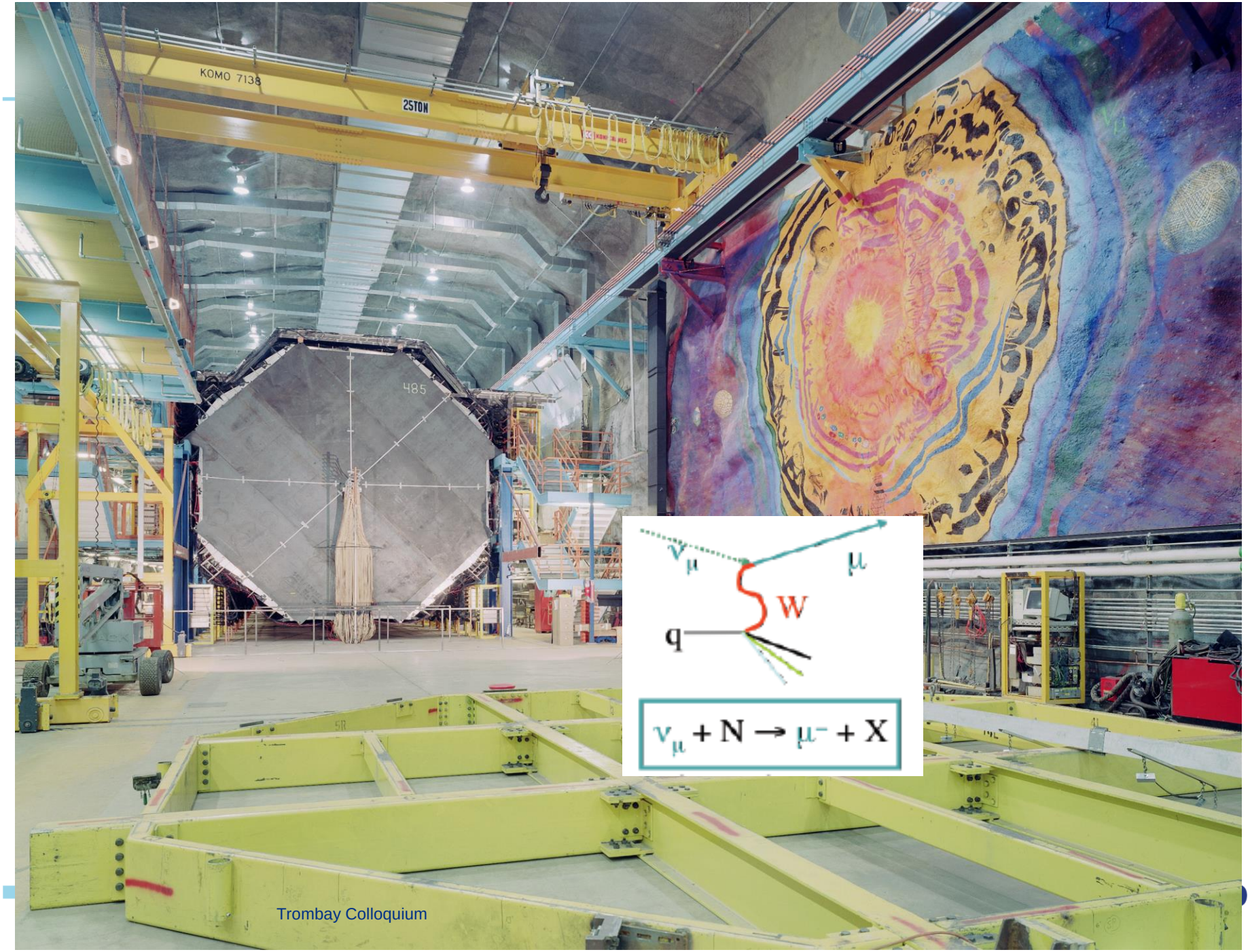
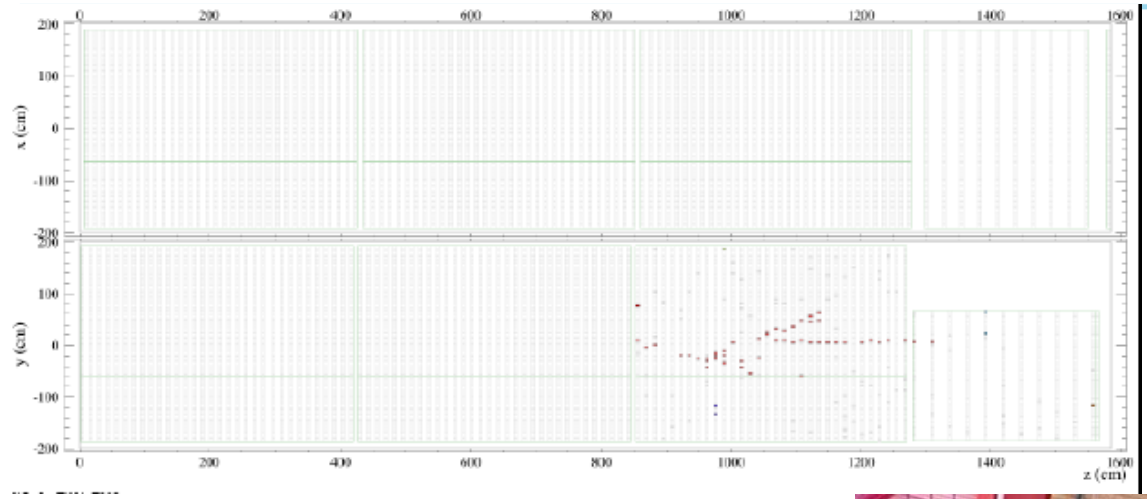
MINOS Near Detector




KOMO 7138
25TON
485
ν_μ
μ
W
q
$\nu_\mu + N \rightarrow \mu^- + X$

Near & Far Detector up and running : NOvA



Data taking started

Running at 400kW now

Working toward 700 kW

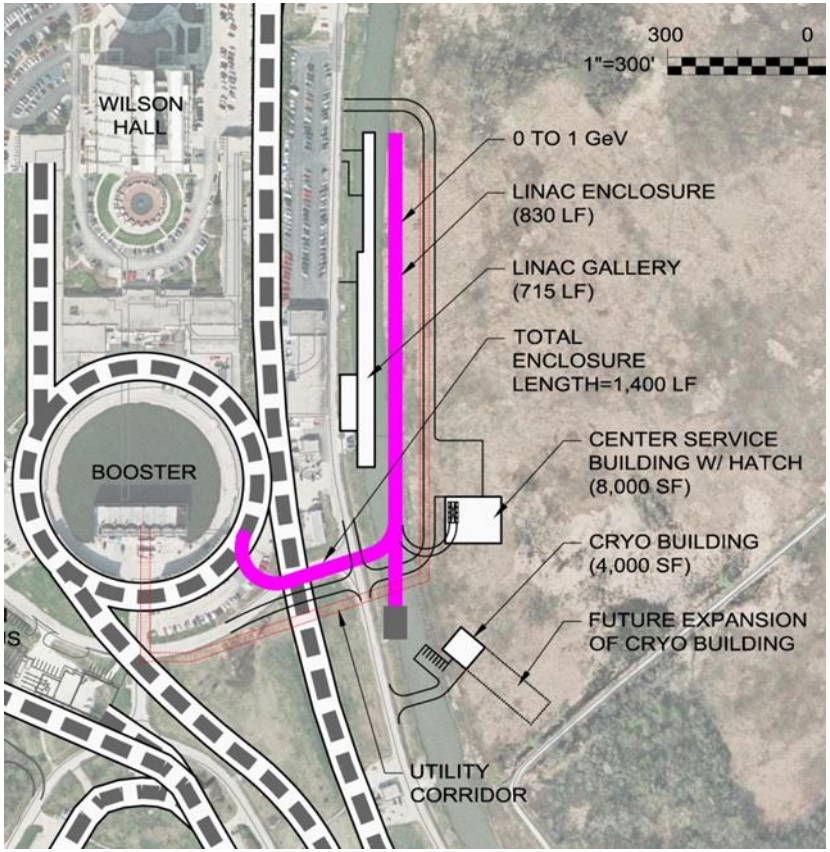
IIFC – νP Collaboration Today

- Eight Indian Institutions have joined the Fermilab Neutrino Physics Program.
  - MINOS, MINOS+
  - NOvA
  - LBNF/DUNE
- We are expecting several Ph.D. students from India under this program.
  - 1st student graduated
- Collaboration is growing
  - Indian Infrastructure Development
  - continue to include more institutions

Beyond NoVA

Fermilab: PIP-II CD0 2015……. 2019 (start construction)

- High Intensity Superconducting Proton Accelerator (HISPA) (aka PIP-II) is a ~1 GeV Linac.
  - design of this machine is similar to the two proposed Indian accelerators.
  - design to provide 1.2 MW of beam for Deep Underground Neutrino Experiment (DUNE) on day one of its operation.
  - Complex upgradable to 2.3 MW.
- PIP-II will be built with significant "in-kind" contributions of accelerator components from non-US partner countries.
  - India is a significant partner
- R&D thru 2018…risk reduction



DOE-DAE Implementing Agreement and Annex I

IMPLEMENTING AGREEMENT

BETWEEN

THE DEPARTMENT OF ENERGY OF THE UNITED STATES OF AMERICA

AND

THE DEPARTMENT OF ATOMIC ENERGY

OF THE REPUBLIC OF INDIA

FOR COOPERATION

IN THE AREA OF ACCELERATOR AND PARTICLE DETECTOR RESEARCH

AND DEVELOPMENT FOR DISCOVERY SCIENCE

DONE at New Delhi, in duplicate, this 19th day of July 2011, in the English and Hindi languages, each text being equally authentic.

FOR THE DEPARTMENT OF ENERGY OF THE UNITED STATES OF AMERICA:

FOR THE DEPARTMENT OF ATOMIC ENERGY OF THE REPUBLIC OF INDIA:

PROJECT ANNEX I

TO THE IMPLEMENTING AGREEMENT
BETWEEN
THE DEPARTMENT OF ENERGY OF THE UNITED STATES OF AMERICA
AND
THE DEPARTMENT OF ATOMIC ENERGY OF THE REPUBLIC OF INDIA
FOR COOPERATION
IN THE AREA OF ACCELERATOR AND PARTICLE DETECTOR RESEARCH AND DEVELOPMENT FOR DISCOVERY SCIENCE
FOR
HIGH INTENSITY PROTON ACCELERATORS

DONE at Mumbai, in duplicate, this 6th day of Nov. 2014.

FOR THE DEPARTMENT OF ENERGY OF THE UNITED STATES OF AMERICA:

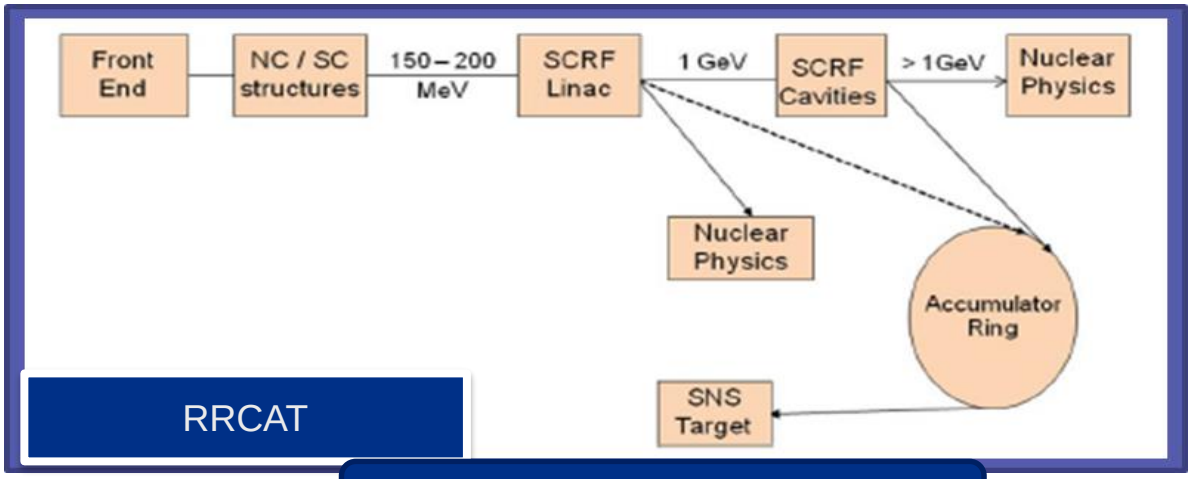
Washington
January 21, 2015

FOR THE DEPARTMENT OF ATOMIC ENERGY OF THE REPUBLIC OF INDIA:

Indian Strategy on PIP-II

- Annex I provides framework for Indian participation in R&D and construction phases
- Current focus is on defining R&D deliverables, under assumption these will be aligned with construction deliverables
  - IIFC is jointly working to retire all the critical (PIP-II) R&D by CY2018.
- Joint DAE-DOE review at end of R&D phase to provide go ahead for construction deliverables.
  - Indian Institutions to establish infrastructure and industry
- Team integration: Six Indian engineers are coming to Fermilab this summer for 2+ year residencies

Goal: Two Indian Accelerator Projects

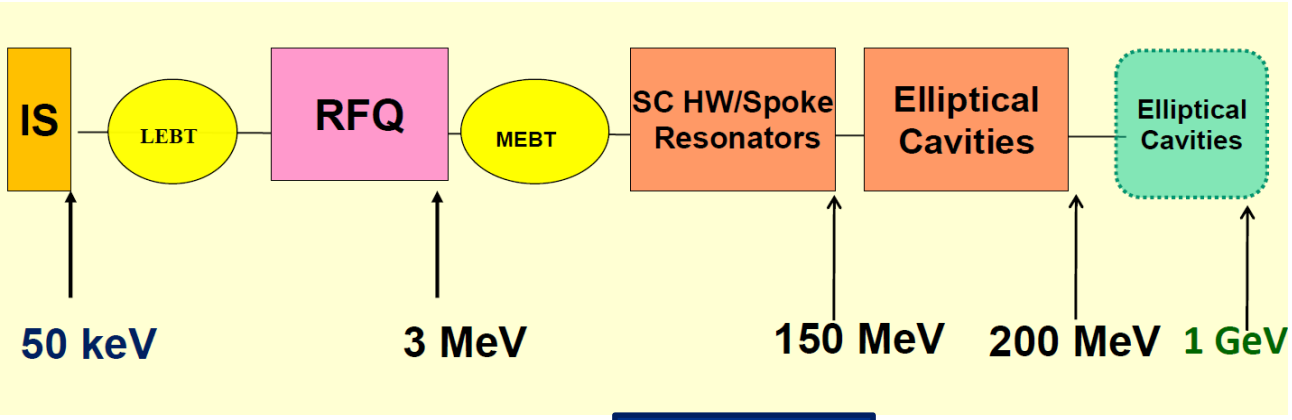


RRCAT

Material Science

RRCAT: ISNS

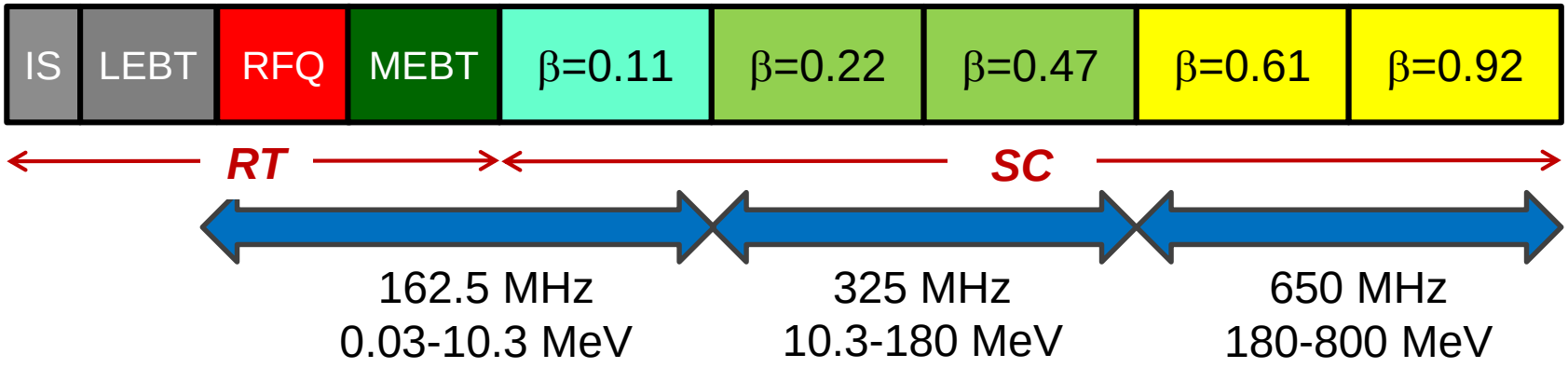
BARC: Energy



BARC

Energy and Medical

Indian Collaboration on PIP-II R&D



High power tested dressed SRF Cavities Non SRF components (BARC)

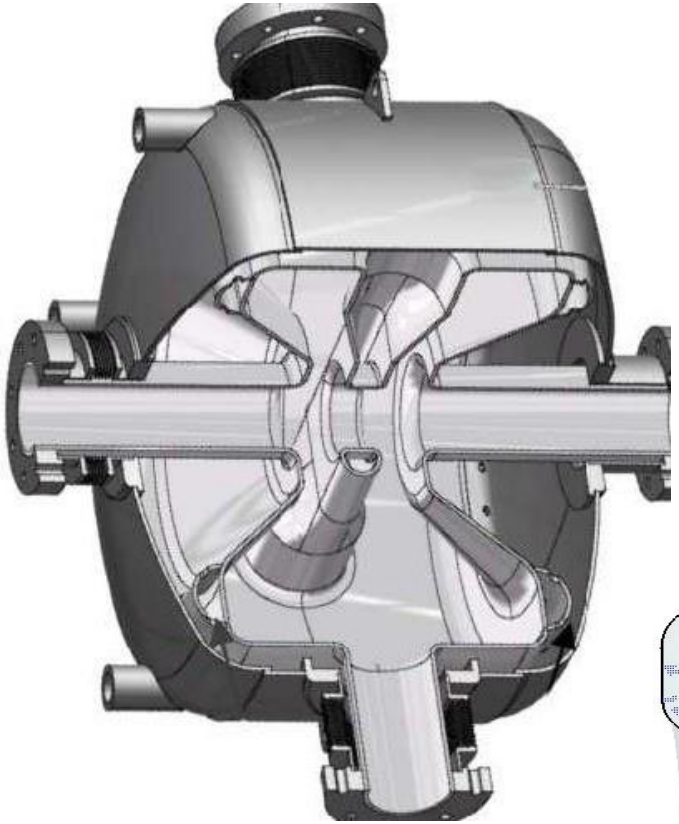
- β = 0.22: IUAC & VECC
- β = 0.47: BARC & IUAC
- β = 0.61: VECC (CERN, UK?)
- β = 0.92: RRCAT
- 325 MHz RF Power: BARC
- 650 MHz RF Power: RRCAT

- Cryogenic Plant and Distribution
- RF
  - LLRF
  - Protection System
- Instrumentation: BPM, BLM
- Controls
- MEBT Magnets

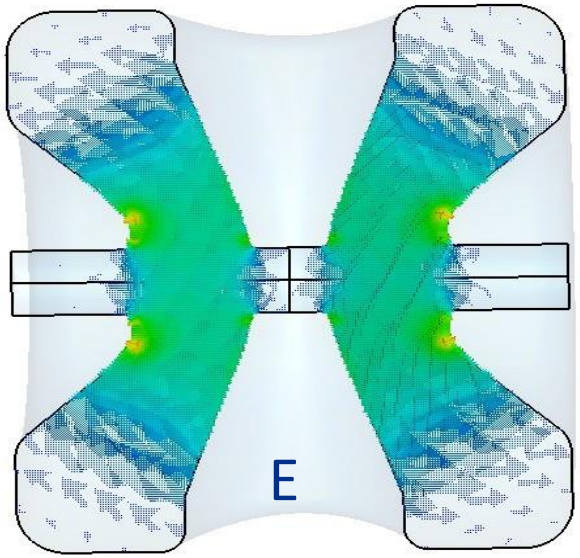
β = 0.22 R&D: IUAC and VECC

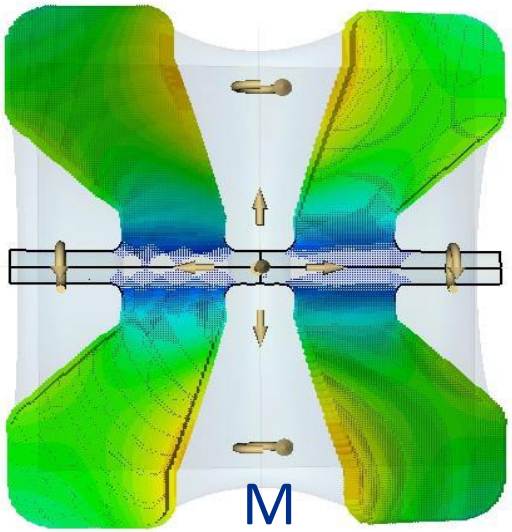
- IUAC has finished fabrication of two SSR1 cavities.
- Being shipped to Fermilab in June
- Will be processed at ANL and VTS at Fermilab
- Cavities will be returned to VECC for He jacket, tuner and coupler attachment
- Results should be presented at SRF2015

β = 0.47: BARC & IUAC



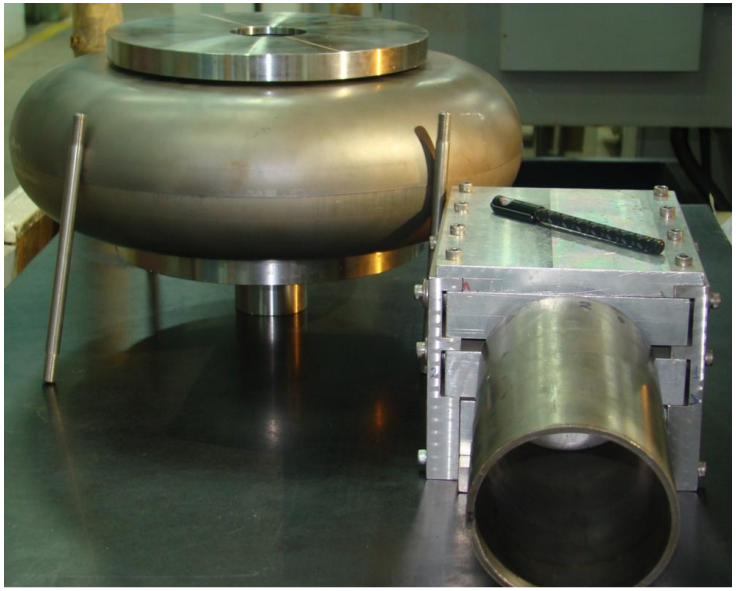
- BARC has initiated SSR2 design and will fabricate 1st prototype in collaboration with IUAC.
- Investigating details of cavity fabrication, including E-beam facility





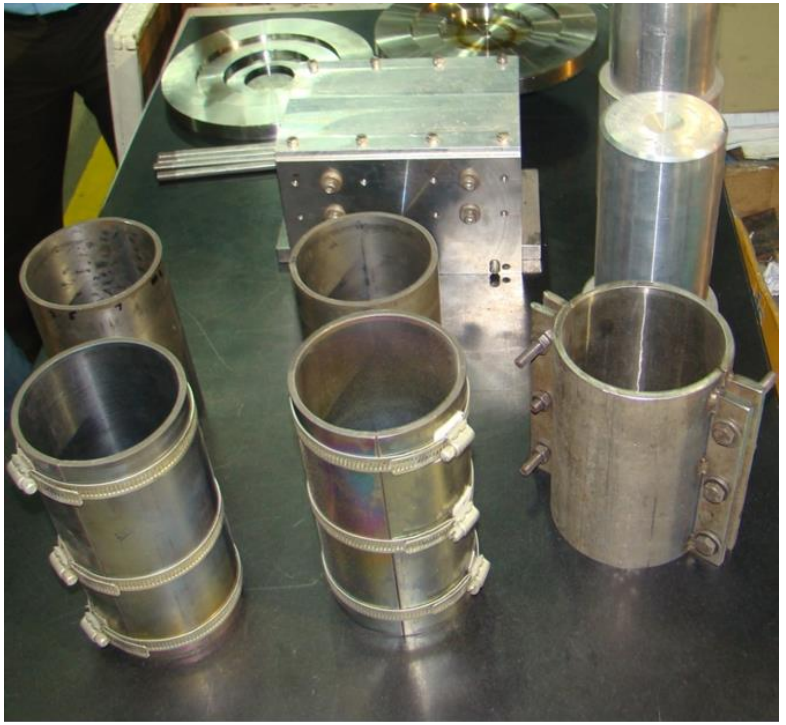
VECC: Development of β = 0.61, 1-cell Nb cavity

- **VECC** has carried out a complete comparative design of β=0.61 5-cell cavity



- Welding of cavity is planned at IUAC
- Processing and testing at Fermilab

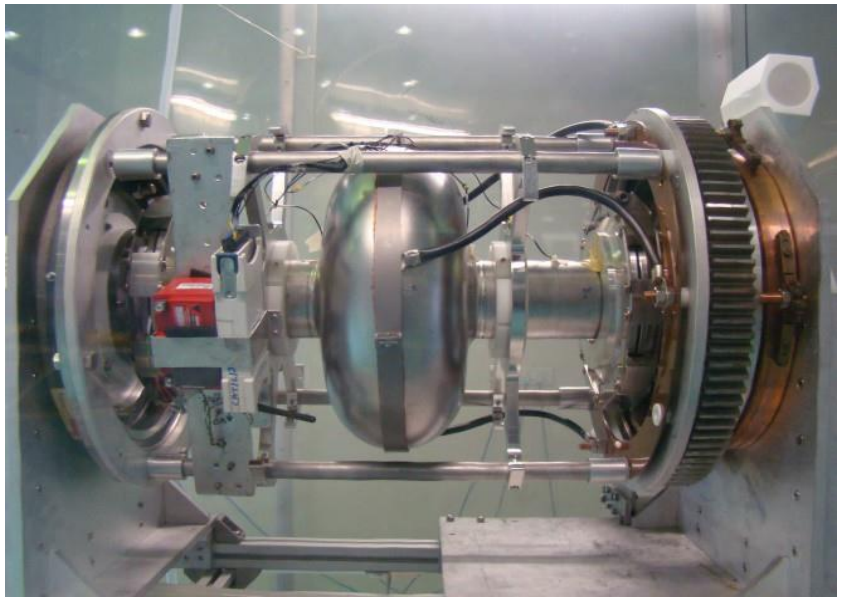
Niobium Half cells , beam pipes and necessary fixtures



SRF Infrastructure Development at RRCAT: β = 0.92

RRCAT: Status of 650 MHz Beta=0.9 single-cell cavity

Second cavity was processed (EP~ 50 micron) at RRCAT and tested in Dec 2014.

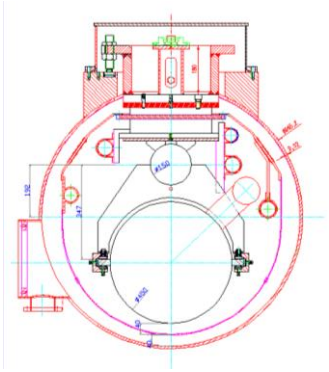


Electro-polishing of 650 MHz single-cell cavity

HPR of 650 MHz single-cell cavity

650 MHz single-cell cavity on VTS insert

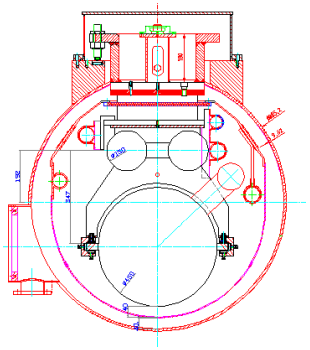
RRCAT: 650 MHz Cryomodule Design



Possible Options & their evaluation

Goal :Use Popular T4CM Cryomodule design

-(Although cavity size is up by a factor of 2)

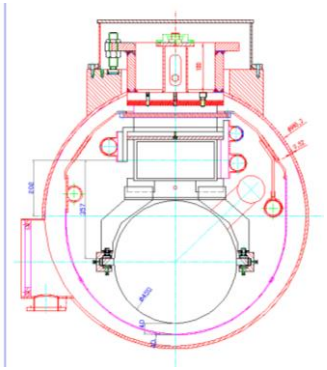


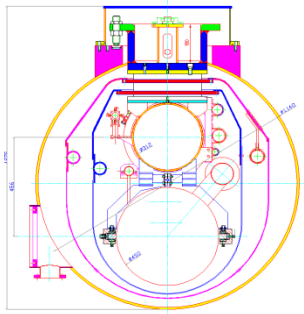
Option A- Single Pipe Support

Option B- Support on two pipes

Evaluation Based on:

- Static heat leaks (approximations)
- Stiffness of the cavity support system (approx)
- Availability of pipes
- General Mech. Engineering issues

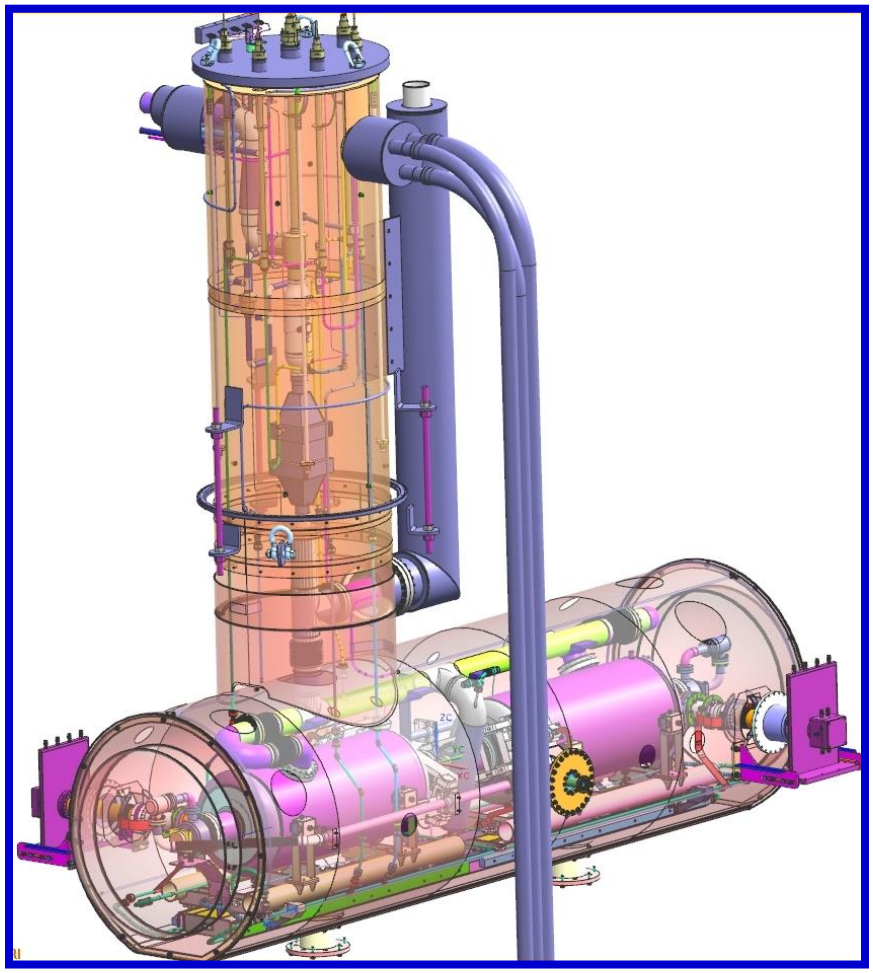


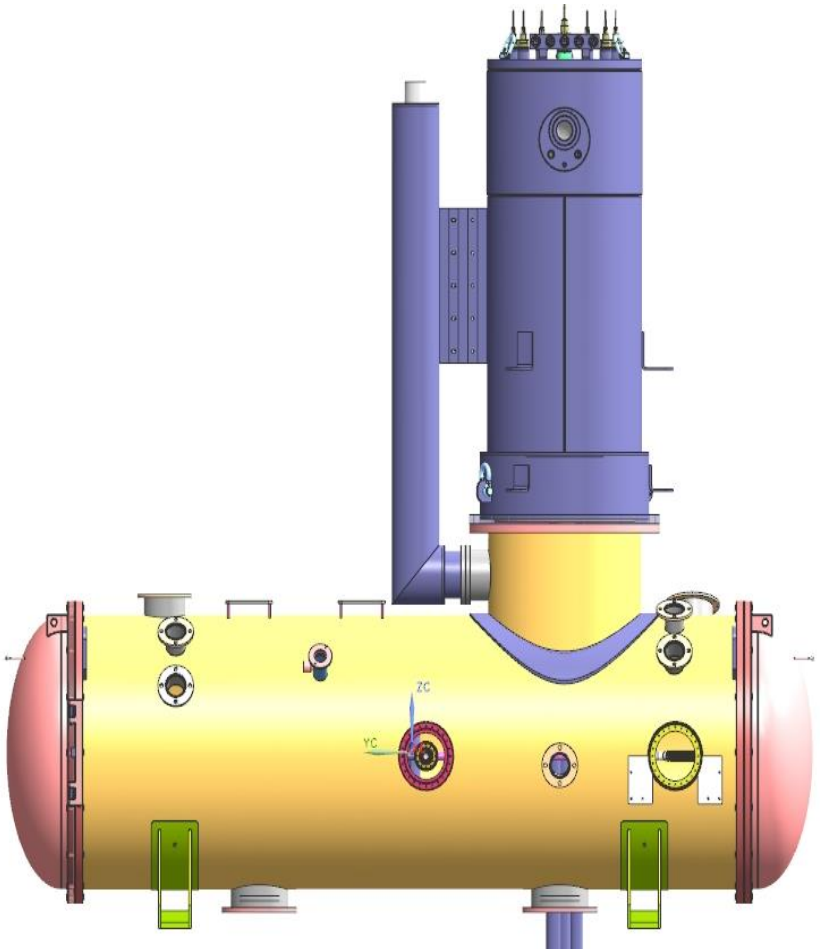


Option C- Rectangular Duct support

Option D- Finalized 200 mm pipe config.

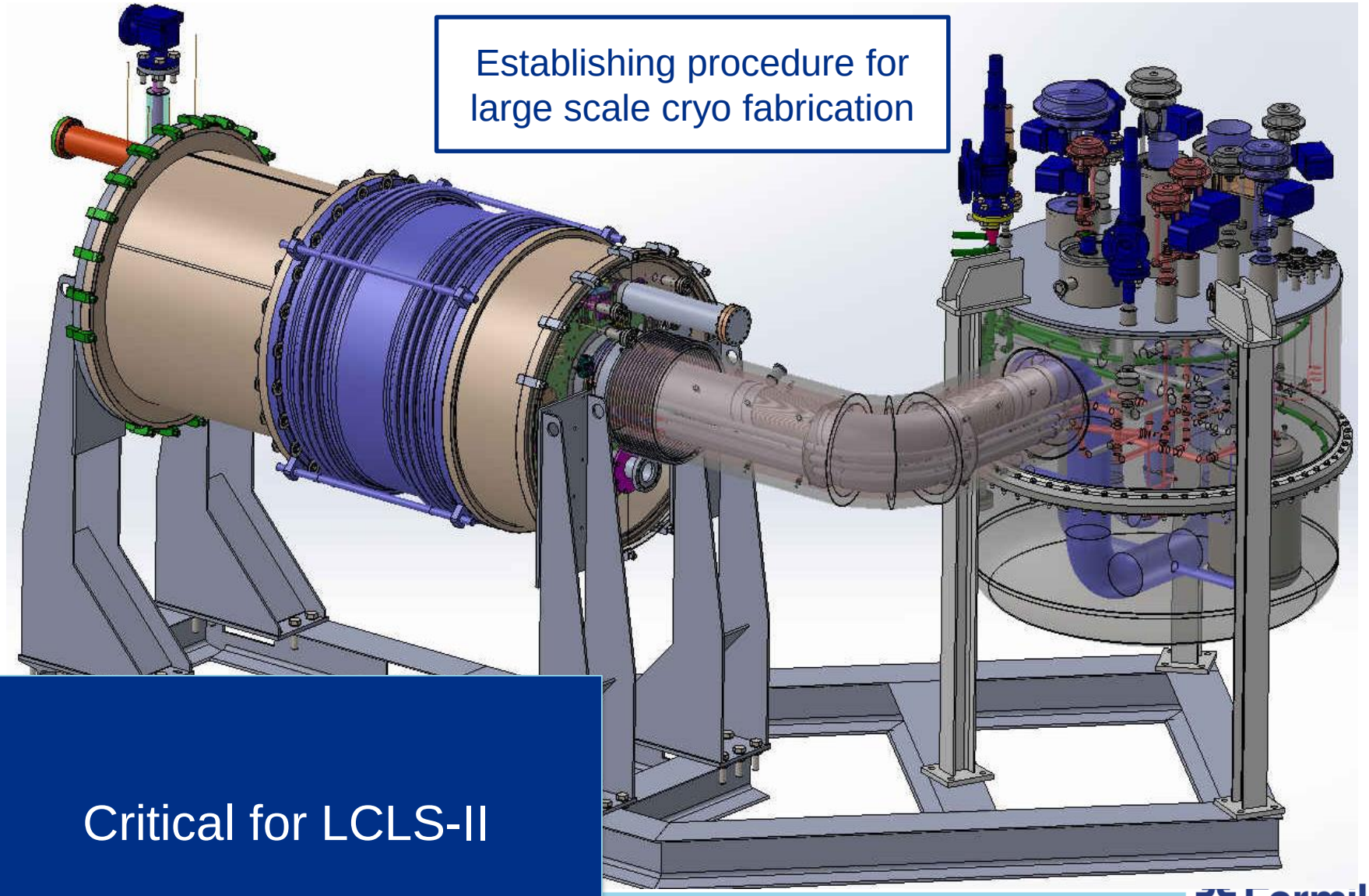
650 MHz Horizontal Test Stand: RRCAT and Fermilab





Fermilab

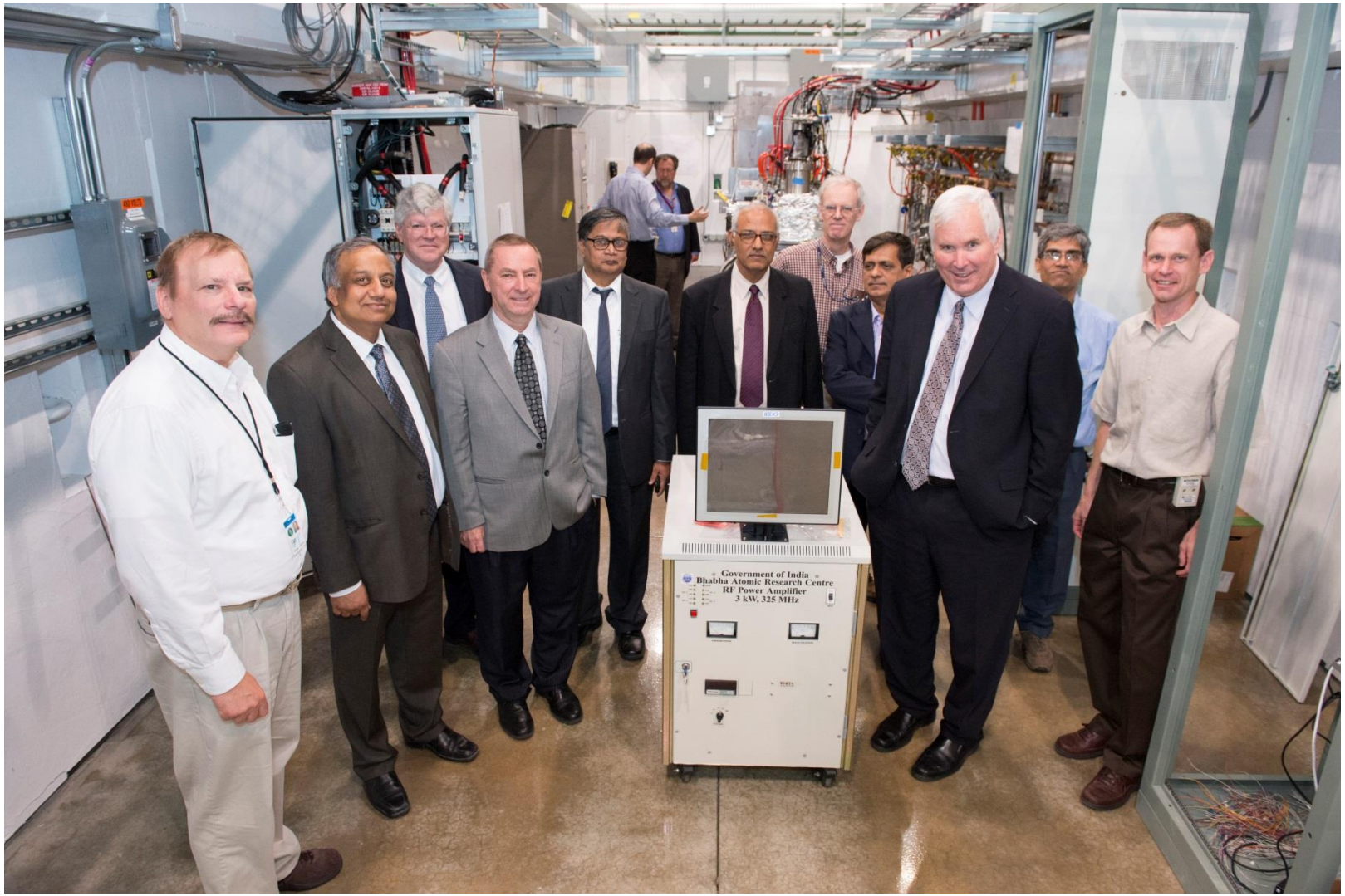
BARC: Development of 1.3 GHz Cryomodule Test Stand



Establishing procedure for large scale cryo fabrication

Critical for LCLS-II

BARC: 325 MHz, 3 kW RF at Fermilab

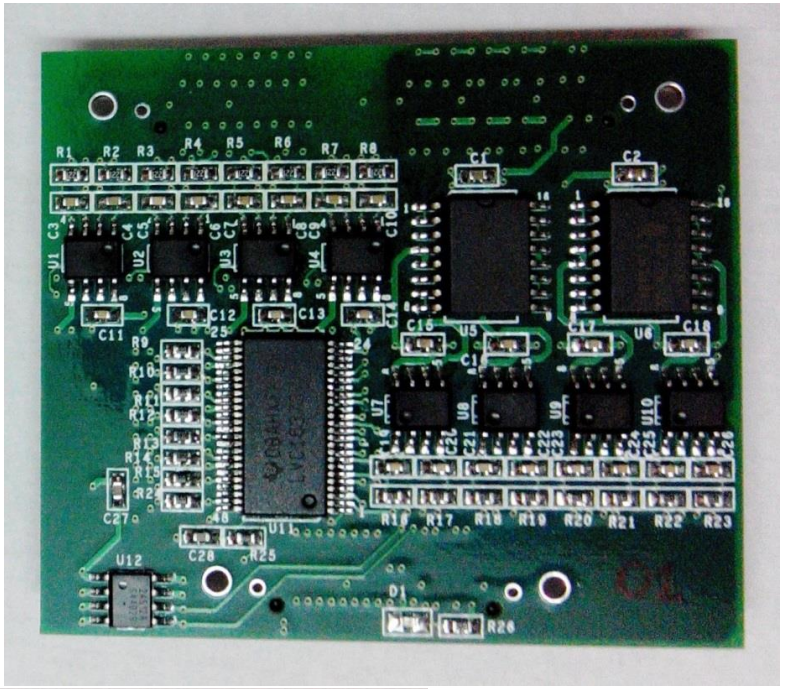


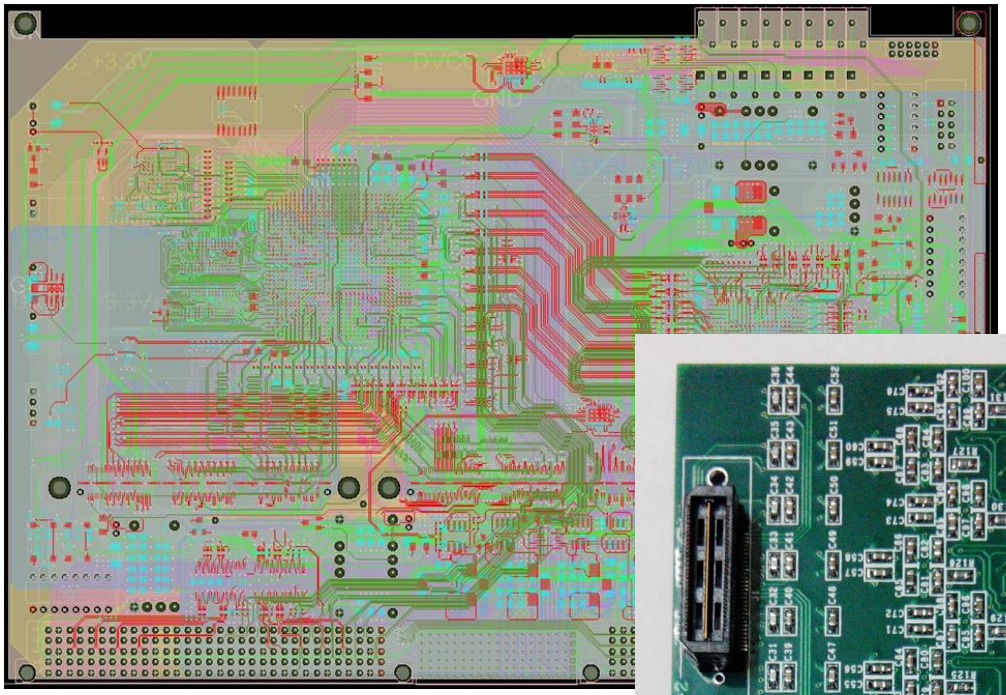
650 MHz Solid State RF Power Development at RRCAT

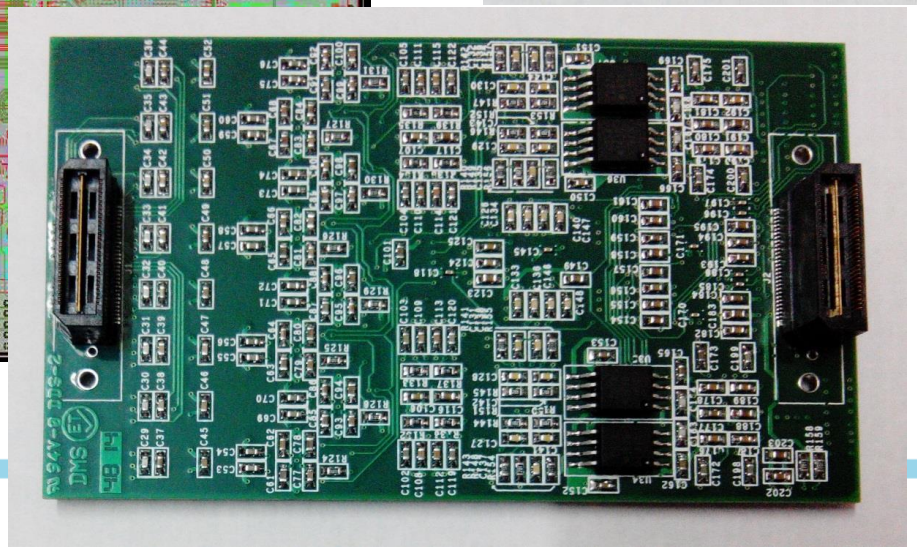
- Design and development of 15 kW, 650 MHz solid state RF power amplifier is completed.
- The high power is obtained by using several 500 W basic RF power modules.
- It is housed in a single euro rack with 40 compact amplifier modules, 40 way power divider and 40 way power combiner.

RF Protection System: BARC & Fermilab

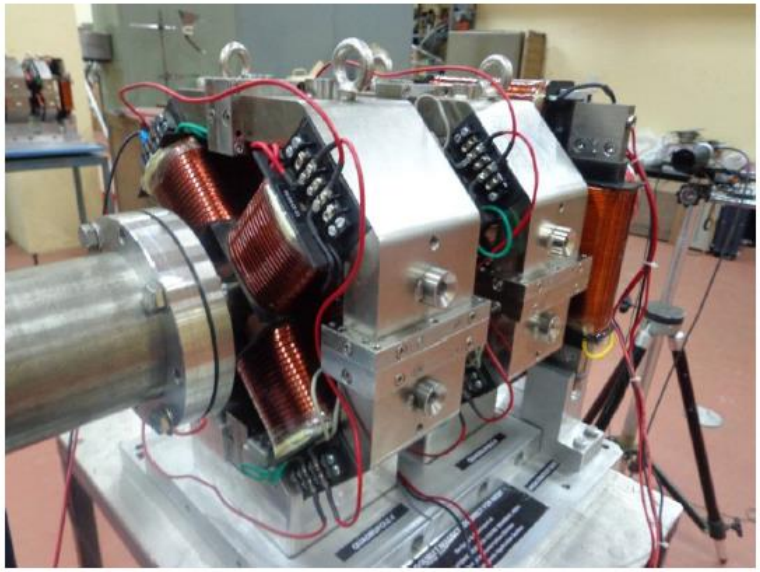
- An upgraded RF Protection system is jointly being developed by BARC and Fermilab.





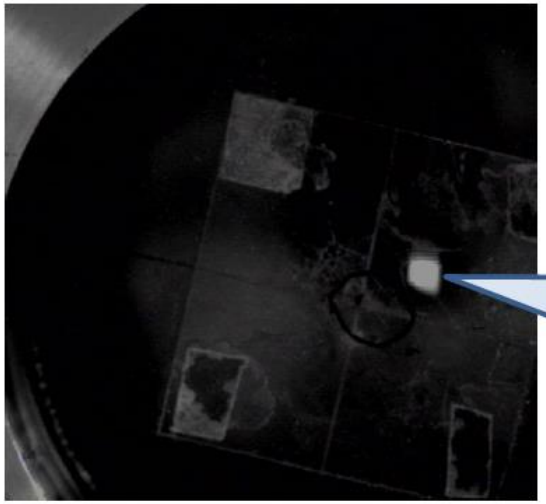


BARC: MEBT Magnets



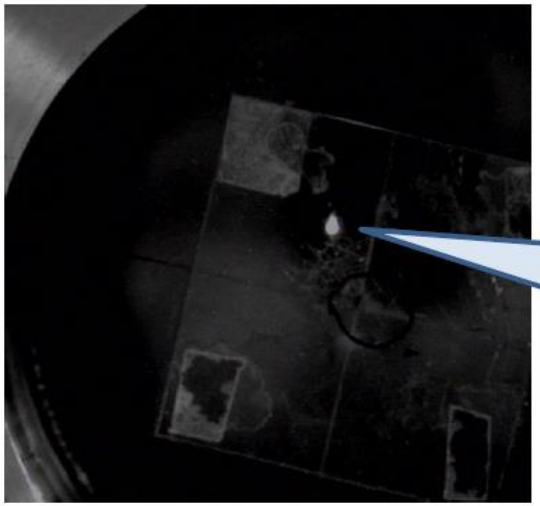
Doublet assembly at FOTIA beam line in BARC at 2.5 MeV Proton beam

Slight steering of beam due to offset between magnetic axis and beam axis



Magnets un-energized

Unfocused beam

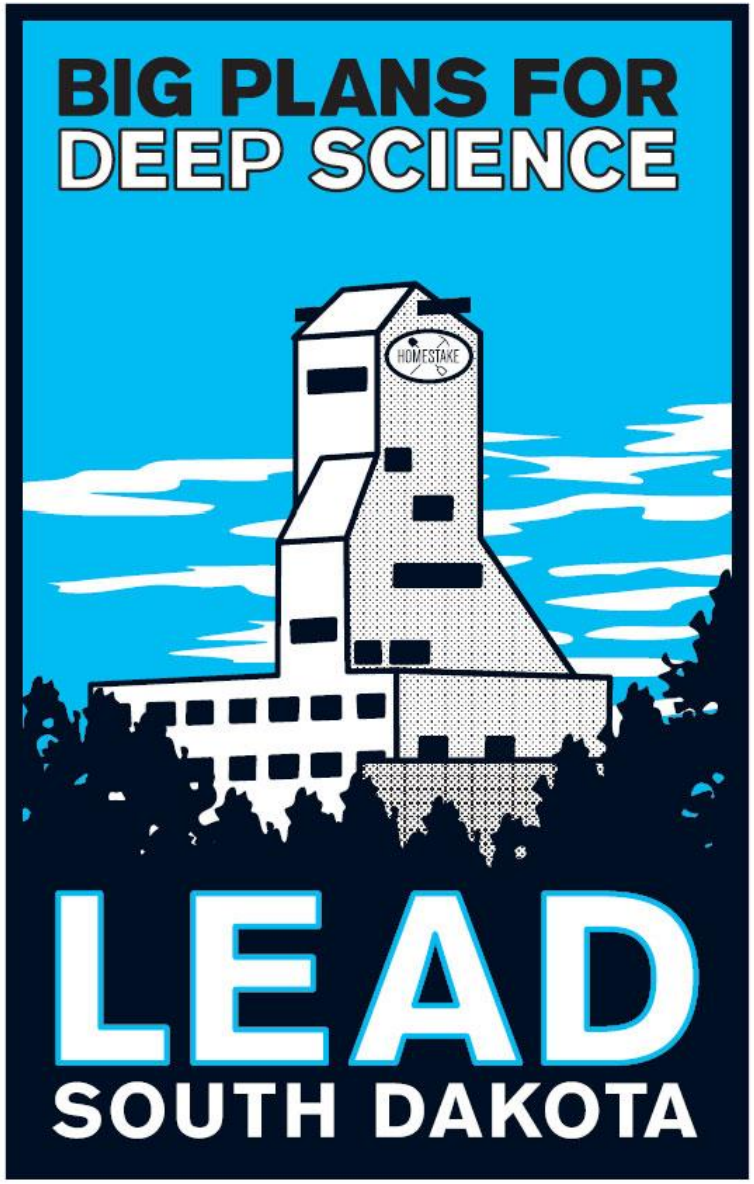


Doublet magnets energized

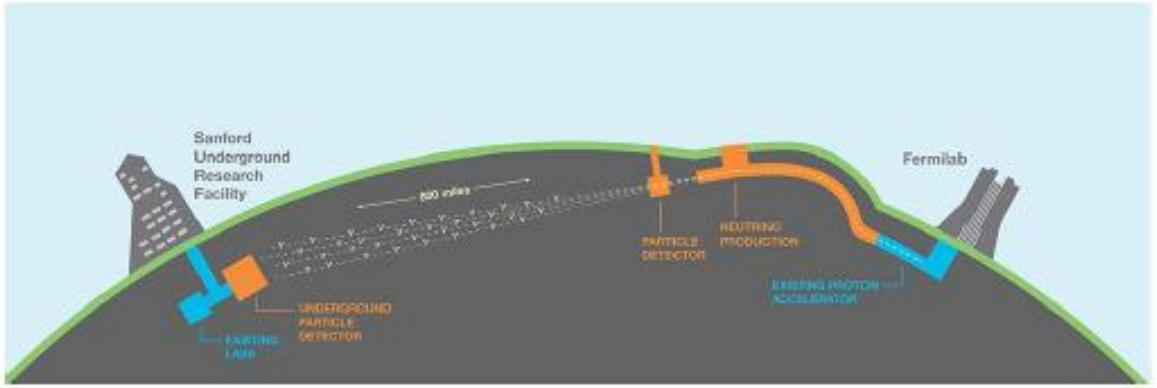
Focused beam

A golden opportunity…..

Returning to the scene of the “crime”



(my unofficial logo)



Progress in forming the international DUNE science collaboration

André Rubbia (ETH Zürich)

March 26, 2015

International Science Collaboration

- **Letter of Intent**: 503 signatures (142 Institutions of which 69 US Institutions and 73 non-US Institutions, 23 Countries)
- **Institution Board membership:**
  Armenia, Belgium, Brazil, Bulgaria, Canada, Columbia, Czech Republic, France, Germany, India, Iran, Italy, Japan, Mexico, Netherlands, Pakistan, Poland, Russia, Spain, Switzerland, Turkey, UK, USA

- **Current Collaboration membership:**
  dune-collab@fnal.gov :
  720 members and growing…

Long Baseline Neutrino Science

- The DUNE particle detector at Sanford Lab would aim to discover:
- Whether neutrinos and antineutrinos “behave” differently
- Which type of neutrino is the lightest and which is the heaviest.

- With the far detector is located deep underground to shield it from cosmic rays, scientists could use it to:

- search for proton/neutron decay and to study the quantum mechanical oscillation of neutrinos produced in the Earth's atmosphere.
- detect thousands of neutrinos from a supernova burst in our galaxy

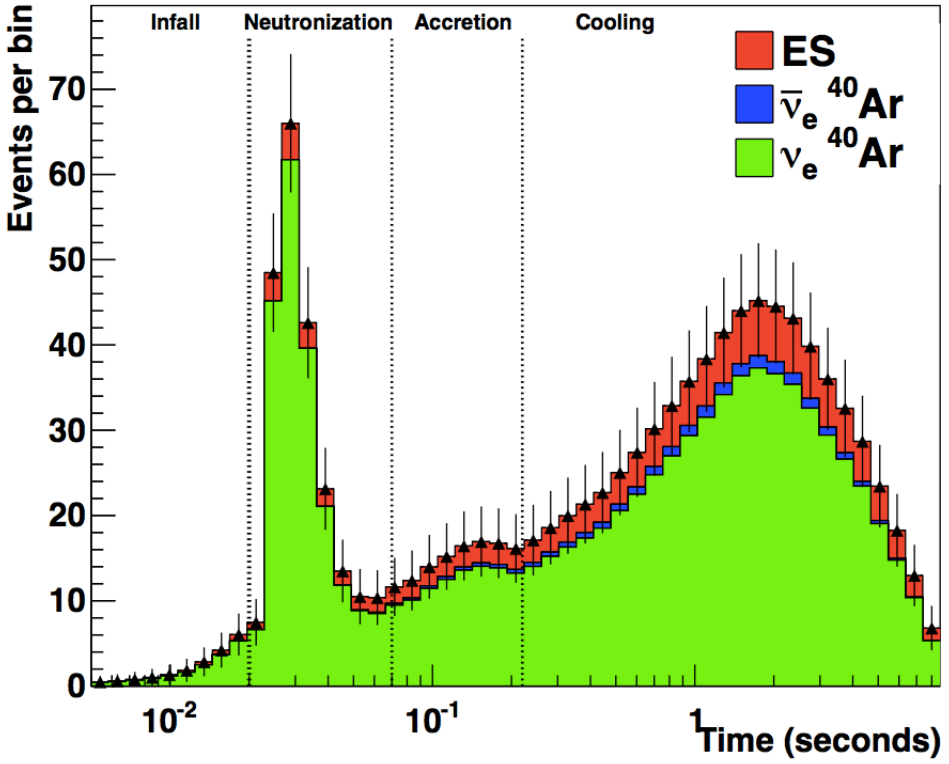
Neutrinos from core collapse

When a star's core collapses, ~99% of the gravitational binding energy of the proto-nstar goes into ν's of *all flavors* with ~tens-of-MeV energies

(Energy *can* escape via ν's)

Mostly ν-$\bar{\nu}$ pairs from proto-nstar cooling

Timescale: *prompt*
after core collapse,
overall $\Delta t \sim 10$'s
of seconds



Collaboration Meeting (FNAL, April 16-18th)

DUNE-LBNF Collaboration Meeting & Working Group Meetings

16-18 April 2015 *Check Agenda for Working Group Meeting Rooms*
US/Central timezone

Search

- **Overview**
- Timetable
- Collaboration Dinner - Friday, April 17th
- Map to Riverview Banquets
- Registration
  - Registration Form
- List of registrants
- Maps and Directions
- General Information

Welcome to the first **D**eep **U**nderground **N**eutrino **E**xperiment (***DUNE***) and **L**ong-**B**aseline **N**eutrino **F**acility Project (***LBNF***) Collaboration hosted by Fermi National Accelerator Laboratory!

The Working Group Meetings will be held on April 16 & 17, and the Collaboration Meeting will be on Saturday, April 18th in Wilson Hall, Ramsey Auditorium.

A reception will be held for the **YOUNG** collaborators on Thursday, April 16th.

The Collaboration Dinner will be held on Friday, April 17th at Riverview Banquets in Batavia.

We look forward to your participation!

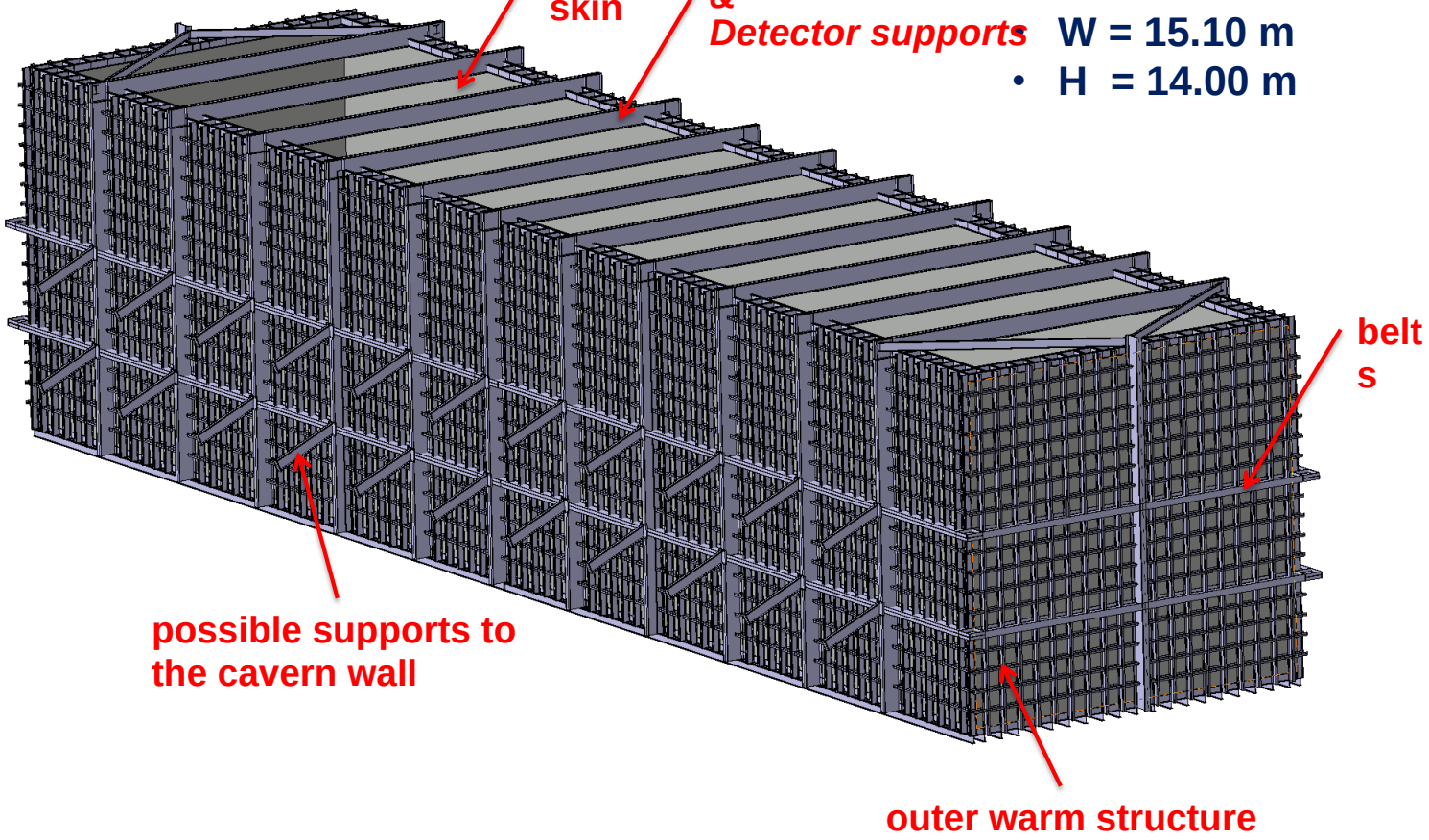
Dates:	from 16 April 2015 08:00 to 18 April 2015 21:00
Timezone:	US/Central
Location:	*Check Agenda for Working Group Meeting Rooms*
Additional info:	If you have questions about the agenda, please contact Maury Goodman at maury.goodman@anl.gov or phone 630-252-3646. Agenda is currently work in progress

Steel-supported cryostat design for DUNE/LBNF

4 LBNF Cryostats extrapolation

Inner dimension (liquid +gas):

- **L = 62.00 m**
- **W = 15.10 m**
- **H = 14.00 m**



LAr = 17’432 tons (95% liquid)

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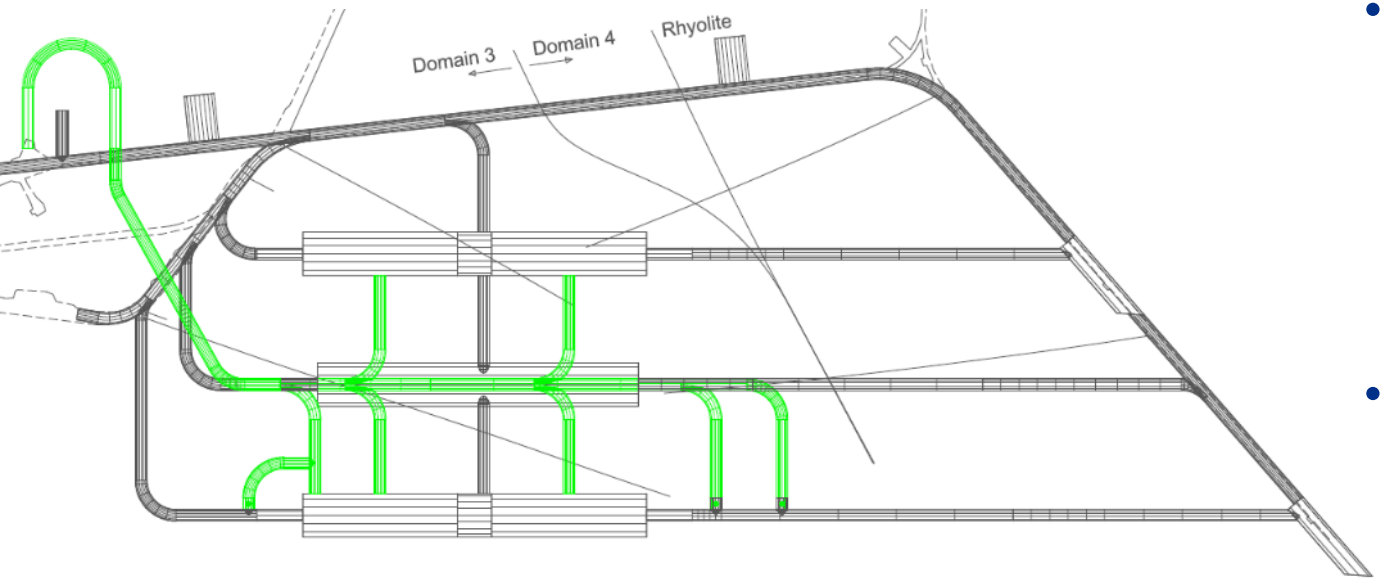
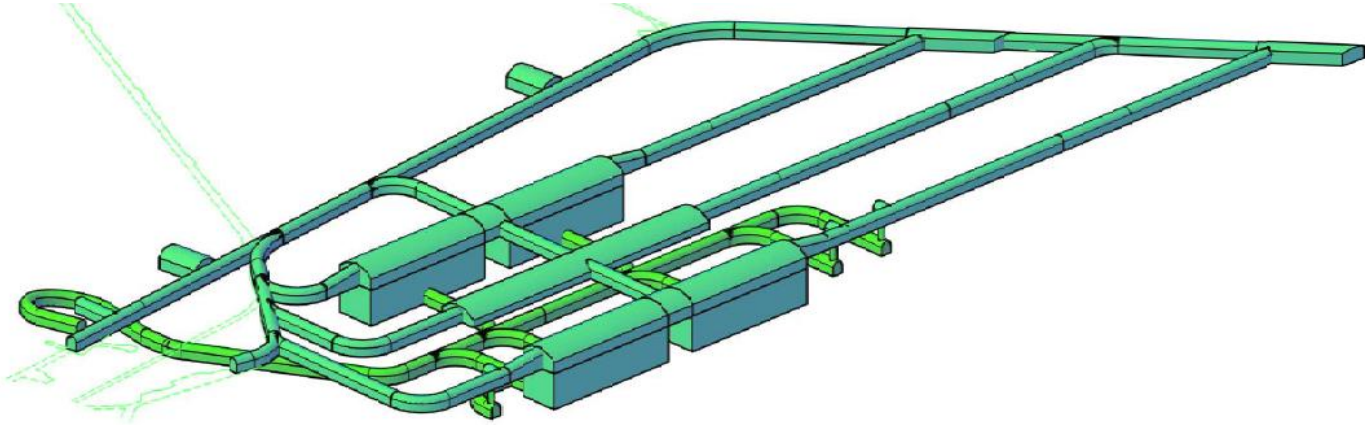
IIFC-νP: DUNE Far Detector (DUNE-FD)

- The Detailed Project Report (DPR) submitted by the collaboration to DAE/DST in 2012 also presents the possibilities of Indian Scientists and Engineers participating in the design, prototype and construction of the Far Detector.
  - The collaboration has significantly grown since the submission of the DPR.
  - In the context of the new DUNE collaboration Fermilab/DOE would like to explore how to best utilize the strength of the Indian collaboration and Indian industry for the DUNE-FD.
    - While preserving the Indian Institutions strength and desire to build the High Resolution Fine Grain Tracker DUNE-ND.
- Important to discuss with DUNE-FD collaboration after the Annex-II is signed

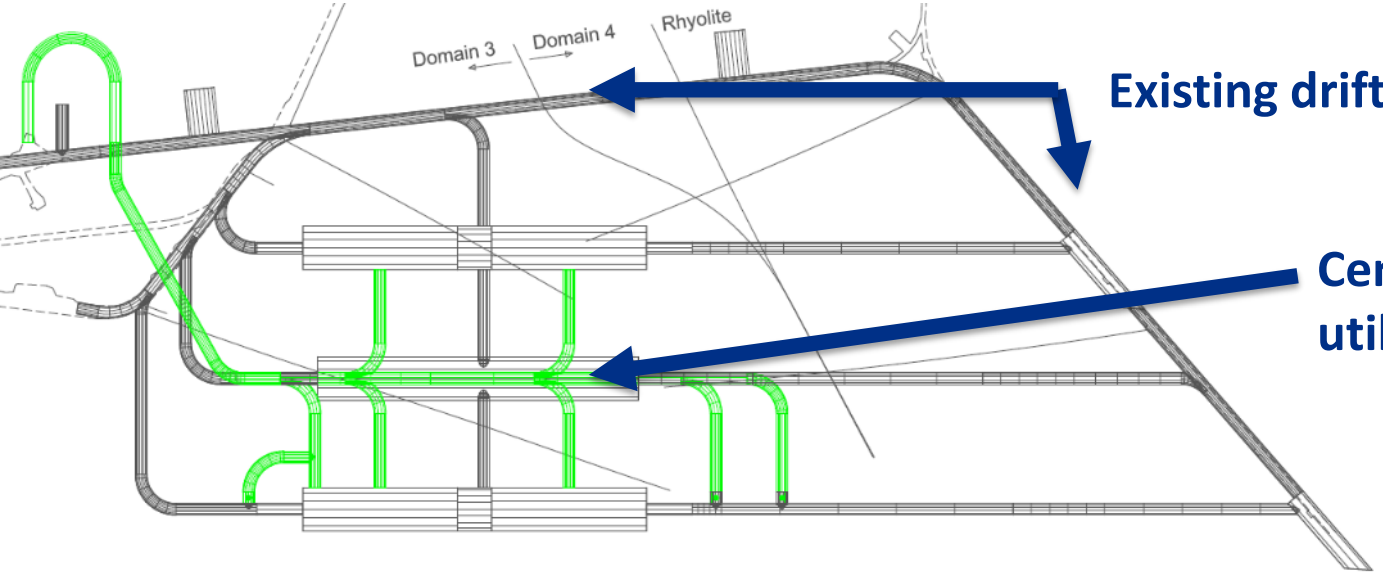
Cavern configuration for LBNF





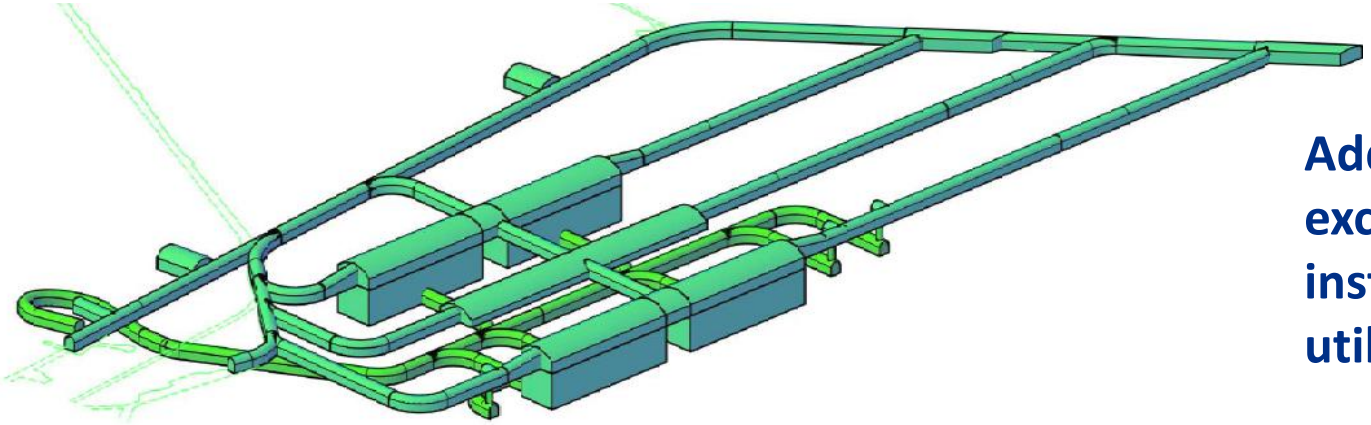
- Two parallel caverns each have two 10 kt detector pits with a laydown space in between
- The CF utilities and cryogenics are in a separate parallel chamber, thus no conflict with cryostat & detector laydown

Cavern configuration for LBNF



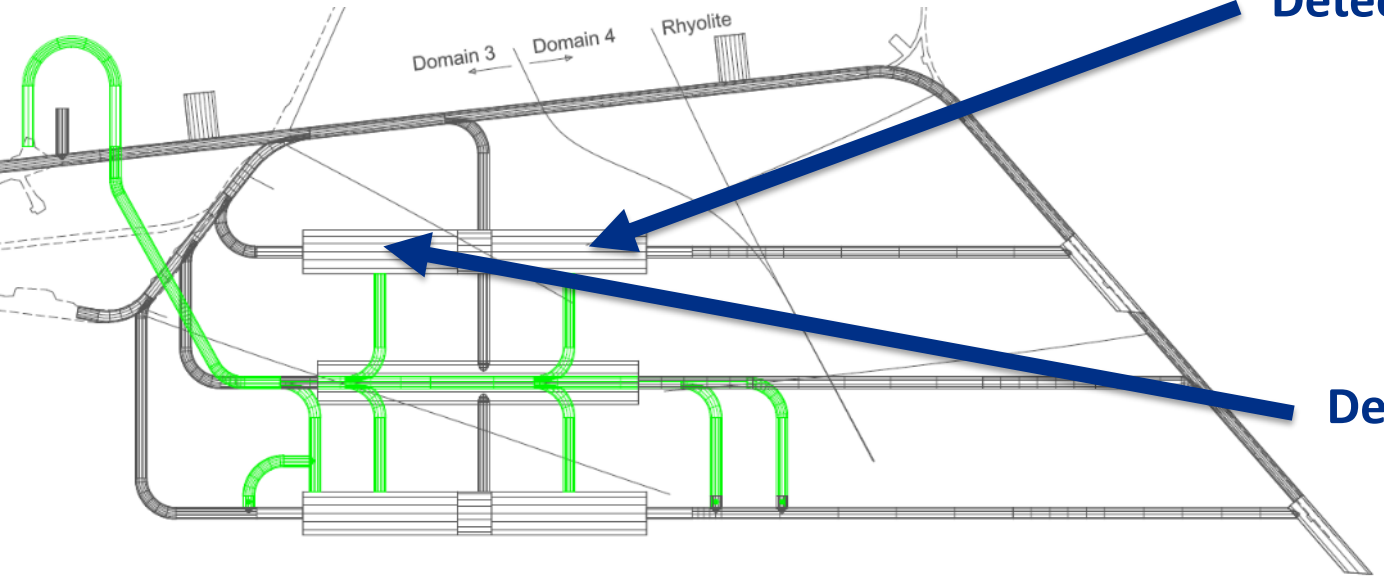
Existing drifts at 4850 foot level

Central cavern for utilities and cryo



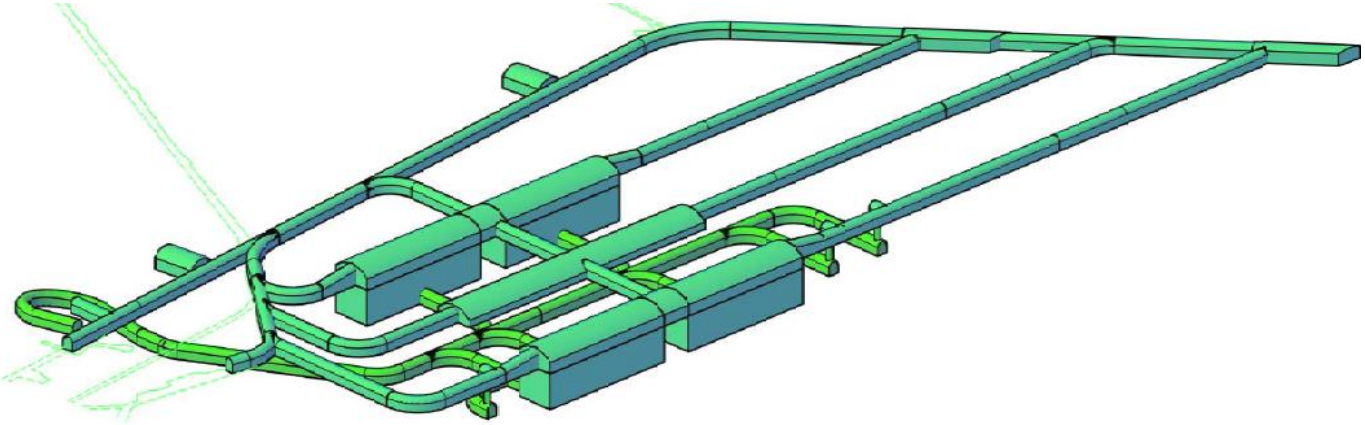
Additional drifts for excavation, air flow, installation, connecting utilities to detector pits

Cavern configuration for LBNF



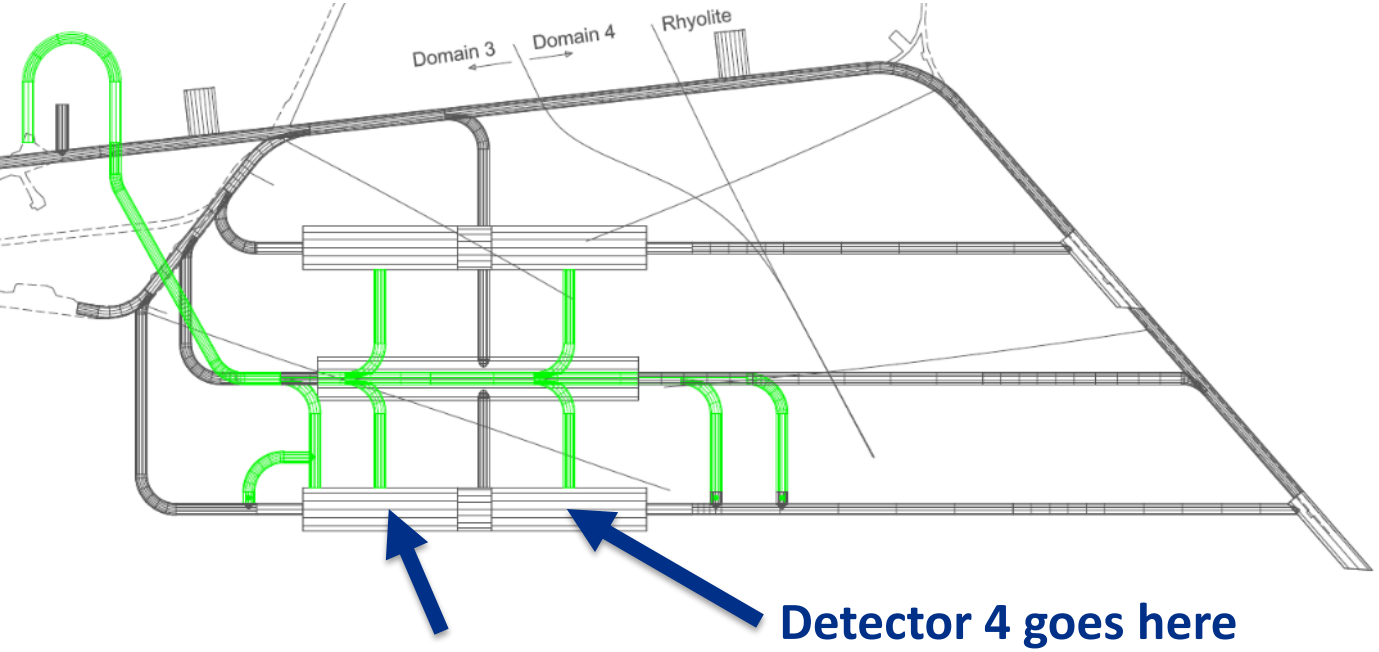
Detector 1 goes here

Detector 2 goes here



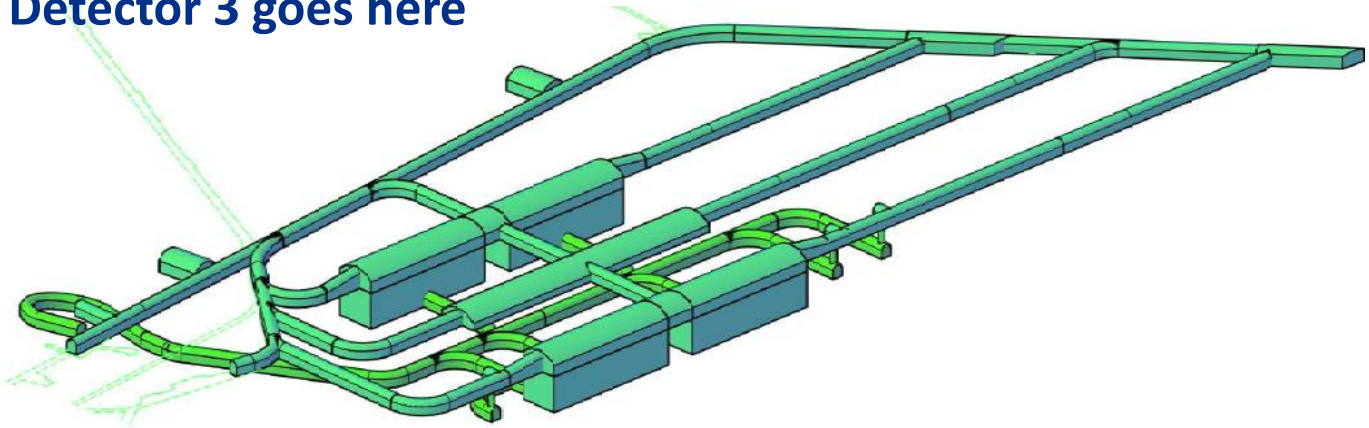
Fermilab

Cavern configuration for LBNF



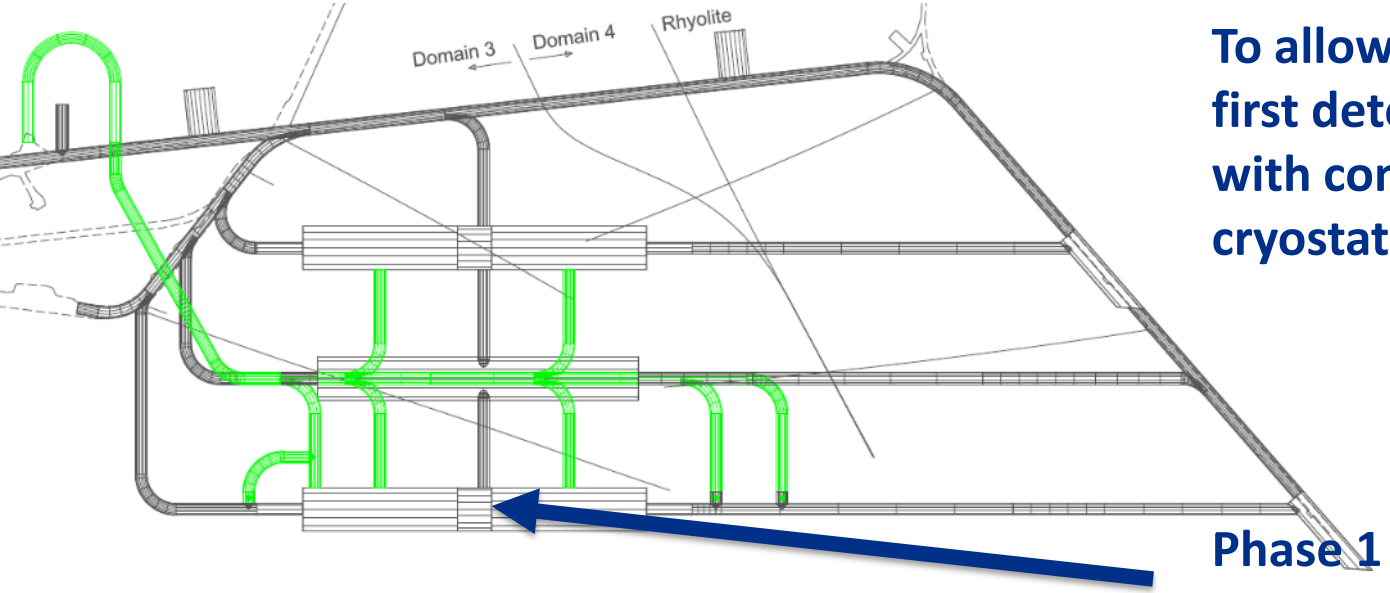
Detector 4 goes here

Detector 3 goes here



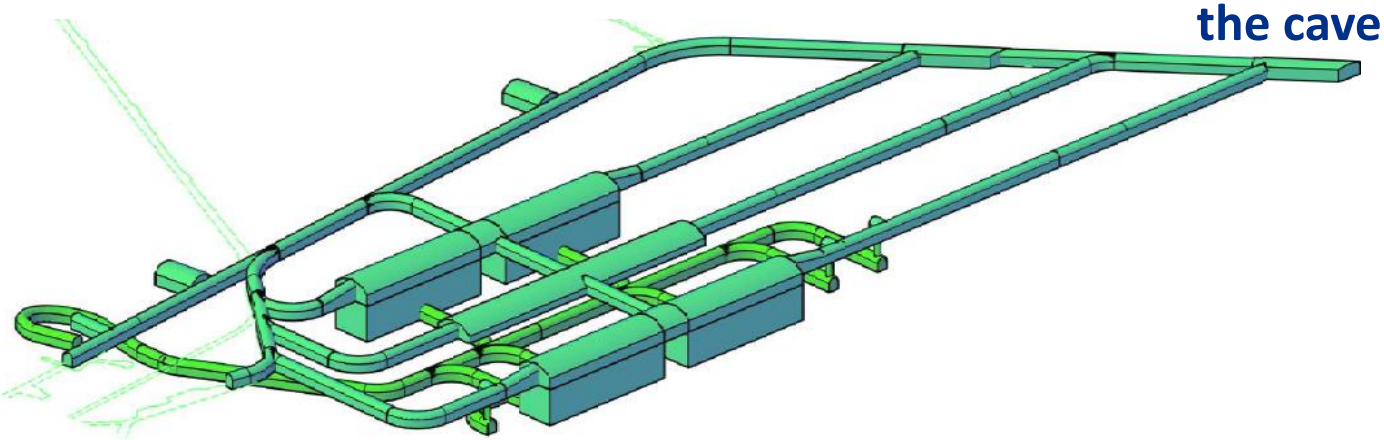
Fermilab

Cavern configuration for LBNF



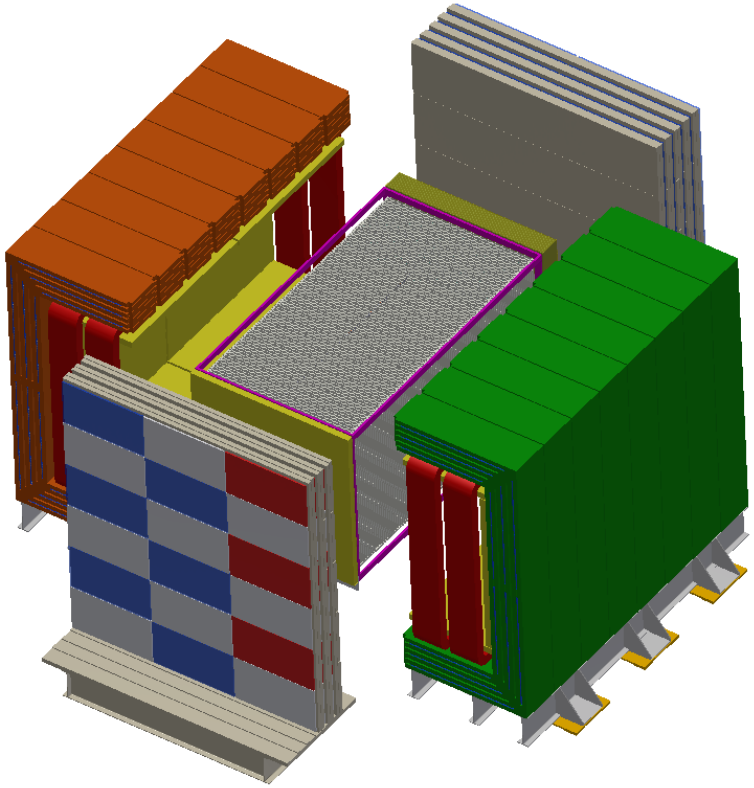
To allow LAr sloshing, filling of first detector would coincide with completion of second cryostat

Phase 1 could include excavating everything *except* the cavern for detectors 3,4



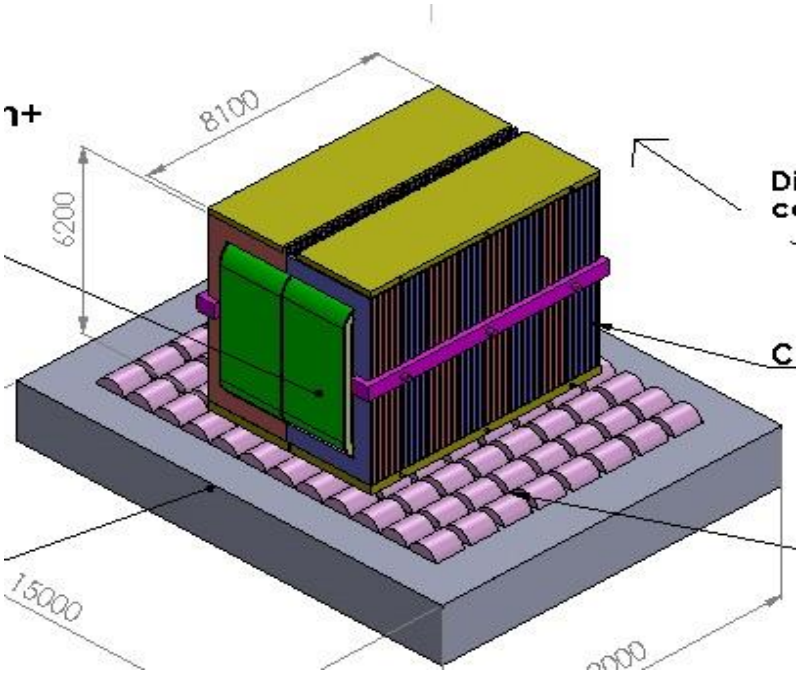
IIFC: DUNE-ND Detector……baseline for CDR/CD1-Refresh

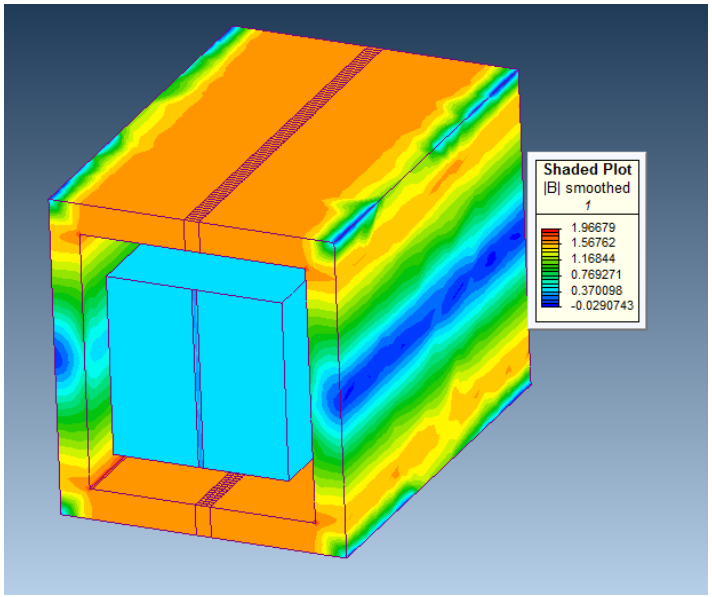
- The details of how the collaboration will develop DUNE-ND is under discussion.
  - DOE-DAE-DST-Fermilab-India Institutions
- Major Subsystems with Indian expertise
  - Straw Tube
  - Muon ID
  - ECAL
  - Magnet
  - Instrumentation and DAQ
- Proposed Schedule
  - Conceptual Design CY15
  - Preliminary Design CY 16
  - Final Design and Prototype CY17
  - Infrastructure Development CY16-18
  - Prototype Construction CY16-18



BARC: DUNE-ND Dipole

- DUNE-ND Tracking detectors and ECAL Modules will reside in 0.4T dipole magnetic field volume with inner dimensions 4.5m*4.5m*8.1m.The magnet needs to support and anchor the detectors





Volumetric Magnet field plot

DUNE…concluding remarks

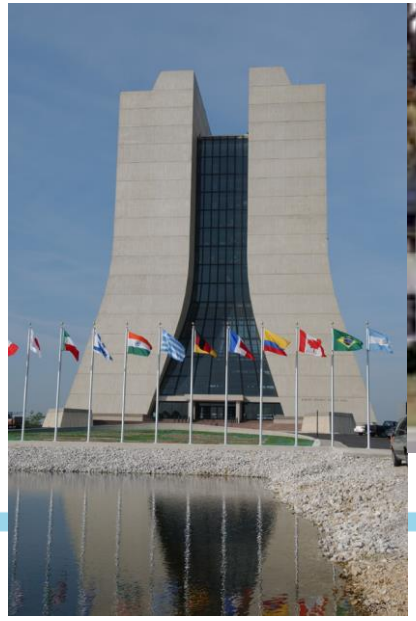
- The worldwide neutrino community is uniting here because of the remarkable opportunities
  - **Science driven**: multiple chances for major discoveries with huge DUNE detector mass and most powerful neutrino beam
  - **Technology driven**: unprecedented science enabled by the novel liquid argon technique of DUNE far detector
  - **Data driven:** ready to unveil the unexpected when mining huge amounts of data to be provided by DUNE detectors
- Very strong foundation from previous LBNE(FNAL/US) and LBNO(CERN/EU) and from elsewhere
- Everyone involved would like to see this happen (as soon as possible…).
- Expertise is there.

Summary

- India Collaboration is vital for the time execution of the PIP-II.
  - PIP-II is critical for timely start of the Neutrino Physics
- With India Institutions Fermilab is working on R&D topics that spans the whole SRF accelerator.
  - These R&D should conclude by the end of CY18.
  - We are also initiating some work on a few projects for the Phase I of Annex I consistent with our R&D and PIP-II plans.
- At the conclusion of these R&D in by the end of CY18, Fermilab, DOE and DAE will decided on the final deliverable table from DAE → DOE for PIP-II by 2023.
- Indian Institutions have joined MINOS, NOvA and LBNF/DUNE.
  - Expecting India to be a significant contributor to the development of LBNF/DUNE Near and Far Detector.

Thank you

Steve Brice
Bonnie Fleming
Boris Kayser
Ken Long
Joe Lykken
Mark Messier
Regina Rameika
Rob Roser
David Schmitz
Kate Scholberg
Shekhar Mishra
Mark Thomson
Andre Rubbia



Fermilab