BERKELEY LAB Lawrence Berkeley National Laboratory

U.S. DEPARTMENT OF ENERGY

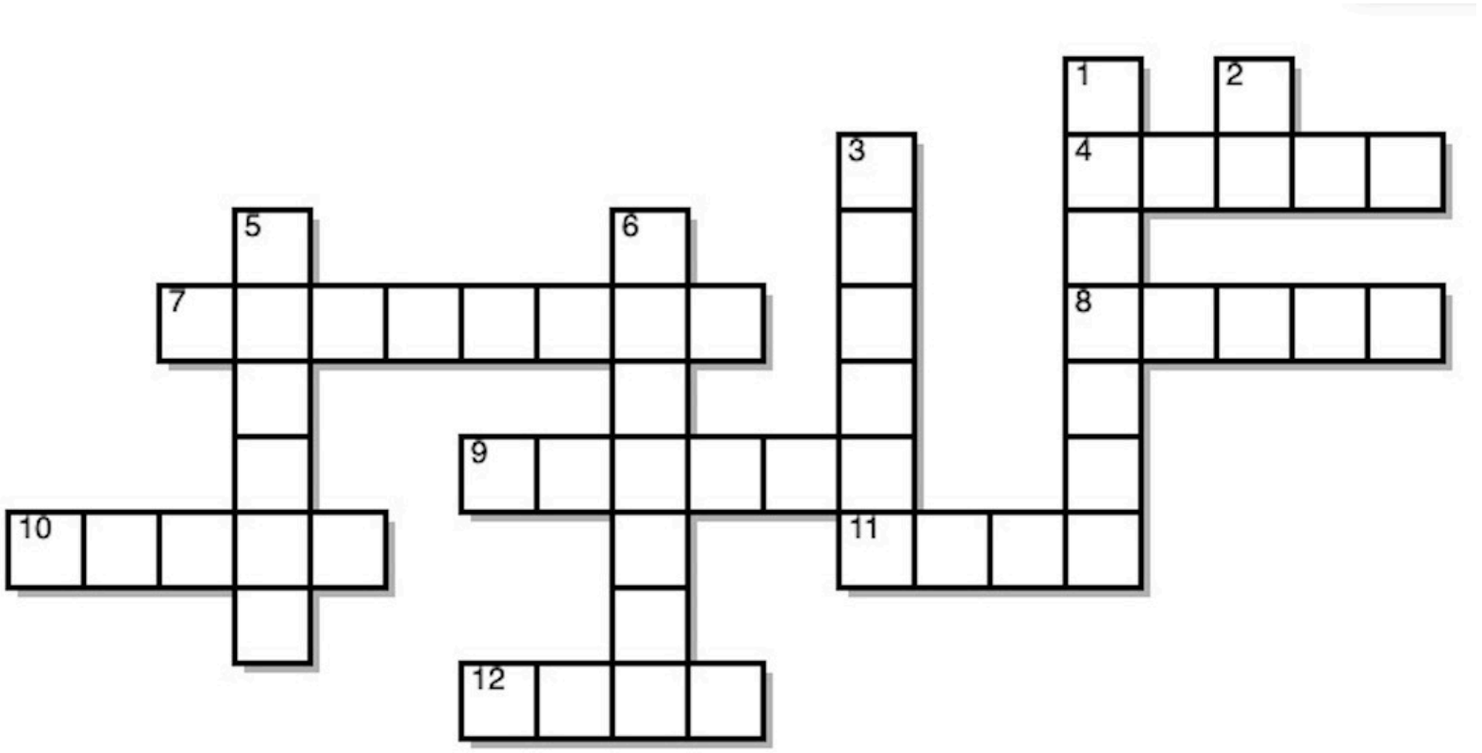
Neutrino Physics @Berkeley

Alan Poon (awpoon@lbl.gov)
Group Leader, Neutrino Astrophysics Group
Deputy Director, Nuclear Science Division

http://neutrino.lbl.gov

The Berkeley Neutrino Puzzle

Look for green bold-faced hints in this talk!



Answer key at http://neutrino.lbl.gov/crossword

ACROSS

4 This neutrinoless double-beta decay experiment is named after the god of desire, love, attraction and affection.
7 This Italian theorist investigated the case of neutrinos being their own antiparticles.
8 The neutrinoless double-beta decay experiment with a 130Te heart.
9 Neutrinoless double-beta decay experiments search for the violation of _____ number.
10 A huge, proposed water-based liquid scintillator experiment.
11 A 800-mile-long experiment.
12 Neutrino oscillation experiments proved that neutrinos have this property.

DOWN

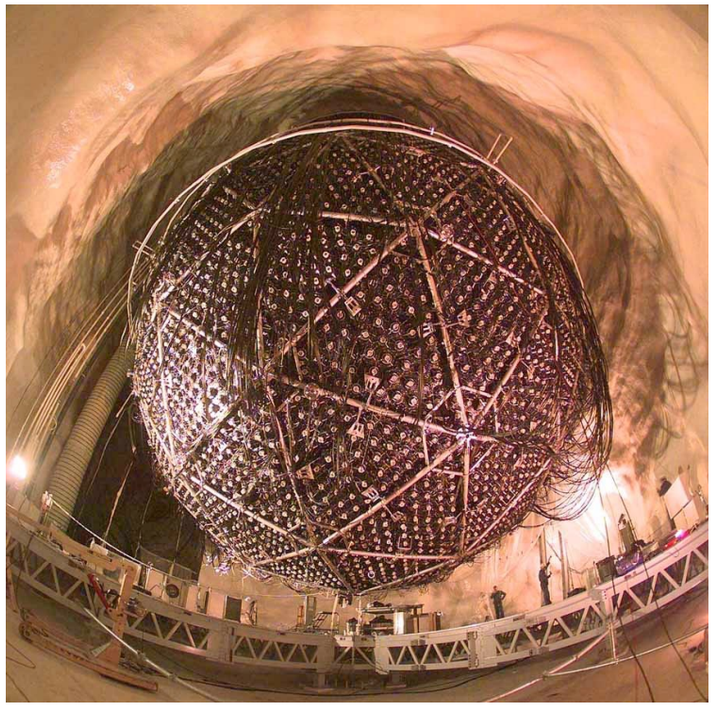
1 It's under ice.
2 Long baseline neutrino experiments search for the violation of this composite symmetry.
3 This acronym of the name of a double-beta decay experiment coincides with the screen name of the first black man to have won an Emmy, Grammy, Oscar and Tony.
5 A huge ultra-high vacuum vessel to measure the tiny neutrino mass.
6 A large 130Te experiment located a mile underground in Canada.

Neutrino Physics @Berkeley

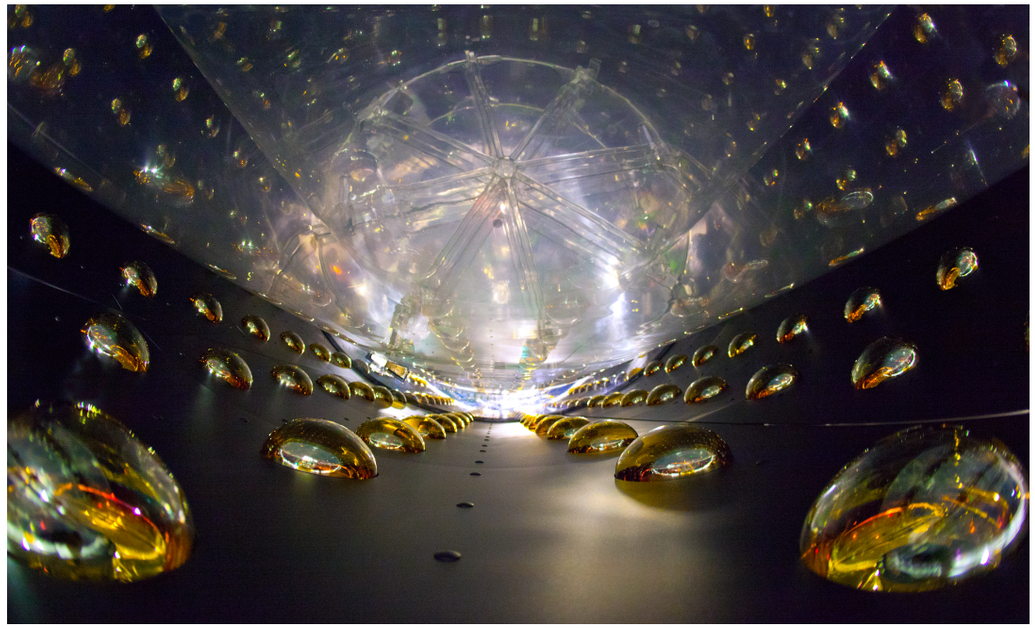
- In the past decade, LBNL's Nuclear Science and Physics Divisions played leadership roles in KamLAND and Sudbury Neutrino Observatory (SNO), which demonstrated non-zero neutrino mass and neutrino oscillations.
- In the past few years, the Daya Bay reactor neutrino experiment measured the unknown mixing angle θ_{13}. [more later]

Neutrino Physics @Berkeley

- In the past decade, LBNL's Nuclear Science and Physics Divisions played leadership roles in KamLAND and Sudbury Neutrino Observatory (SNO), which demonstrated non-zero neutrino mass and neutrino oscillations.
- In the past few years, the Daya Bay reactor neutrino experiment measured the unknown mixing angle θ_{13}. [more later]



SNO



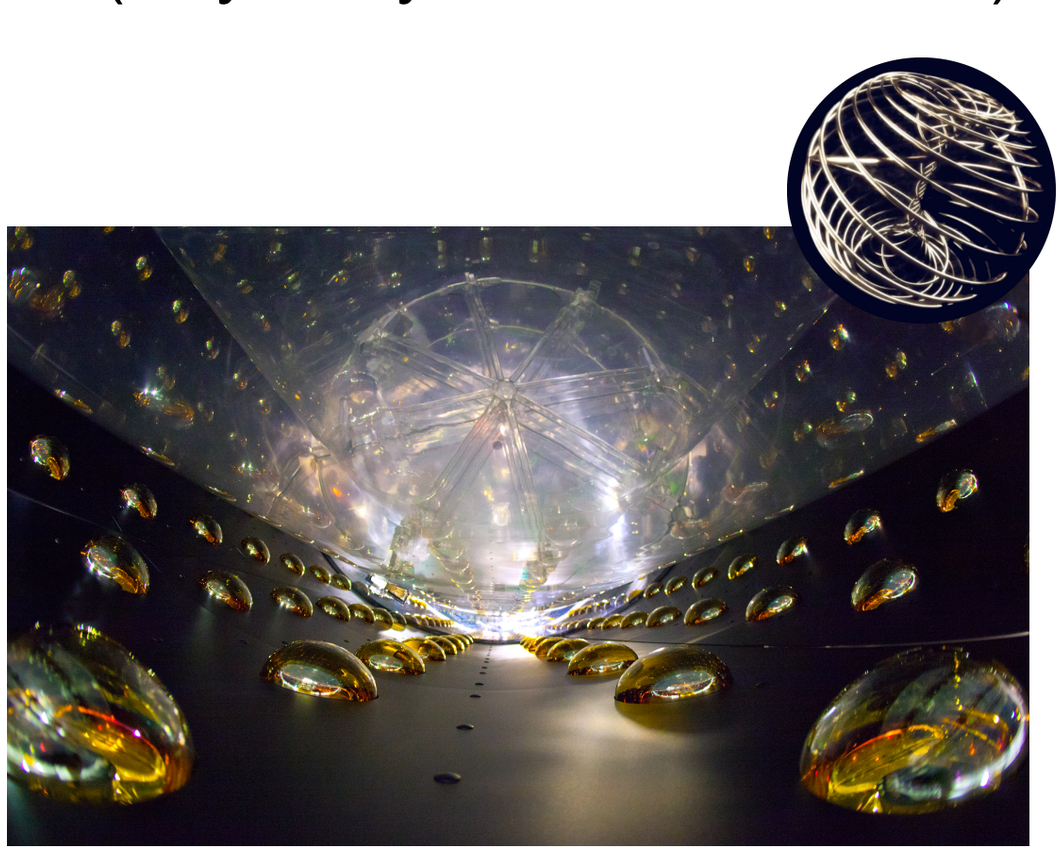
Daya Bay

KamLAND

Neutrino Physics @Berkeley

- In the past decade, LBNL's Nuclear Science and Physics Divisions played leadership roles in KamLAND and Sudbury Neutrino Observatory (SNO), which demonstrated non-zero neutrino mass and neutrino oscillations.
- In the past few years, the Daya Bay reactor neutrino experiment measured the unknown mixing angle θ_{13}.
- In 2015-2016:
  - 1 Nobel Prize (SNO)
  - 3 Breakthrough Prizes (Daya Bay, KamLAND, SNO)

SNO

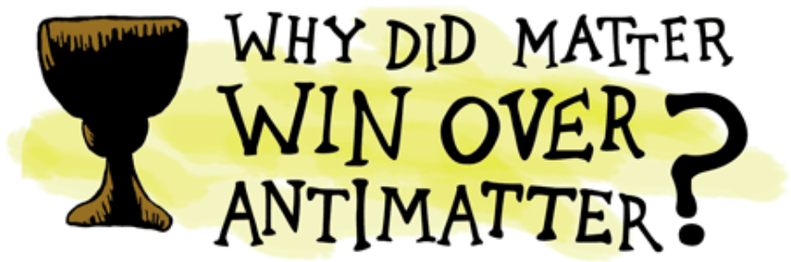


Daya Bay

KamLAND

Neutrino Physics @Berkeley

- In the coming decade, we will try to answer the following fundamental questions concerning the neutrinos:
  - **lepton number** violation
  - **CP** violation in the neutrino sector
  - neutrino mass **hierarchy**
  - absolutely mass scale of the neutrinos
  - Dirac and/or Majorana nature of the neutrinos



Graphics from Symmetry Magazine

Neutrino mixing

- A weak eigenstate $|\nu_\alpha\rangle$ is a linear combination of mass eigenstates $|\nu_i\rangle$:

$$|\nu_\alpha\rangle = \sum_{i=1}^{3} U_{\alpha i} |\nu_i\rangle$$

where U = Pontecorvo-Maki-Nakagawa-Sakata (PMNS) matrix.

$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix}$$

$$= \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix}$$ ***Atmospheric $\theta_{23} \sim 45°$***

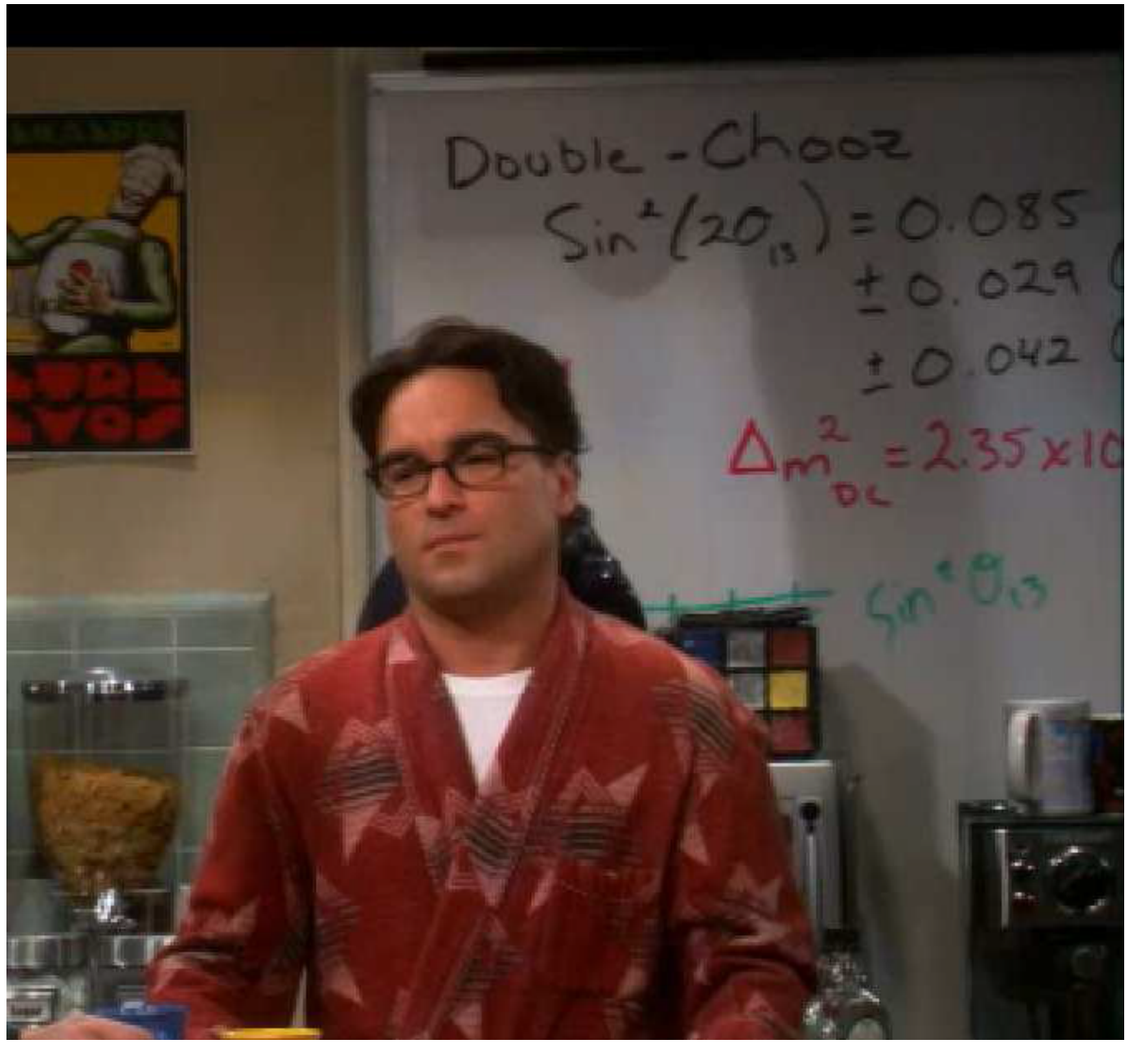
$$\times \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$ ***Solar $\theta_{12} \sim 34°$***

$$\times \begin{pmatrix} \cos\theta_{13} & 0 & e^{-i\delta_{CP}} \sin\theta_{13} \\ 0 & 1 & 0 \\ -e^{i\delta_{CP}} \sin\theta_{13} & 0 & \cos\theta_{13} \end{pmatrix}$$ ***Reactor $\theta_{13} \sim 9°$***

You can measure the mixing angles with different sources

Neutrino mixing

If it is on the Big Bang Theory, it must be important



The **discovery of neutrino oscillation** (hence neutrino **mass**) provides the **first** direct evidence of **physics beyond the Standard Model of Particle Physics.**

The Big Bang Theory graphics from CBS

Neutrino mass questions

Measuring the "mass" $[m_i]$

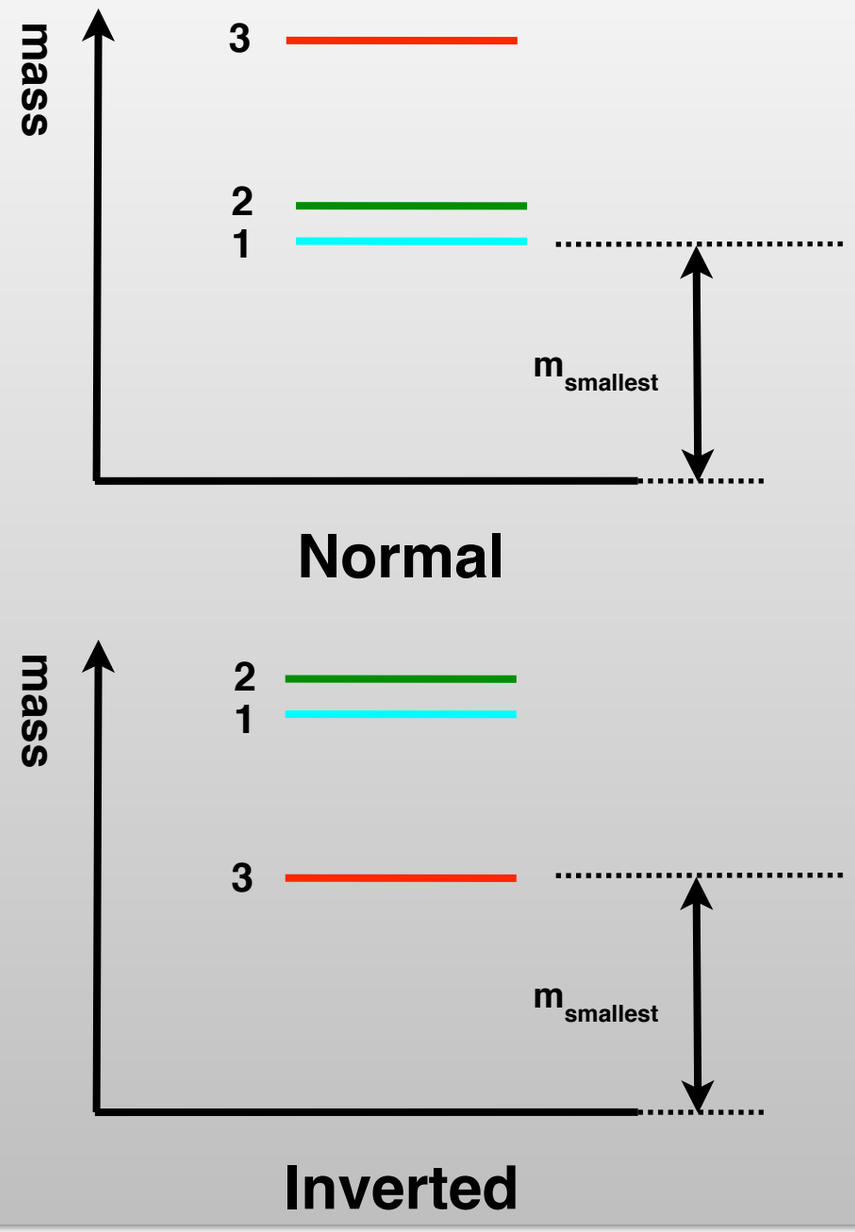
Cosmology: $\sum m = \sum_{i=1}^{3} m_i = m_1 + m_2 + m_3$

β decays: $m_\beta = \sqrt{\sum_{i=1}^{3} |U_{ei}|^2 m_i^2}$

ββ decays: $m_{\beta\beta} = \sum_{i=1}^{3} \left| U_{ei}^2 m_i \right|$

Oscillations: $\Delta m_{ij}^2 = m_j^2 - m_i^2$

Determining the hierarchy



Neutrino mass questions

Measuring the "mass" $[m_i]$

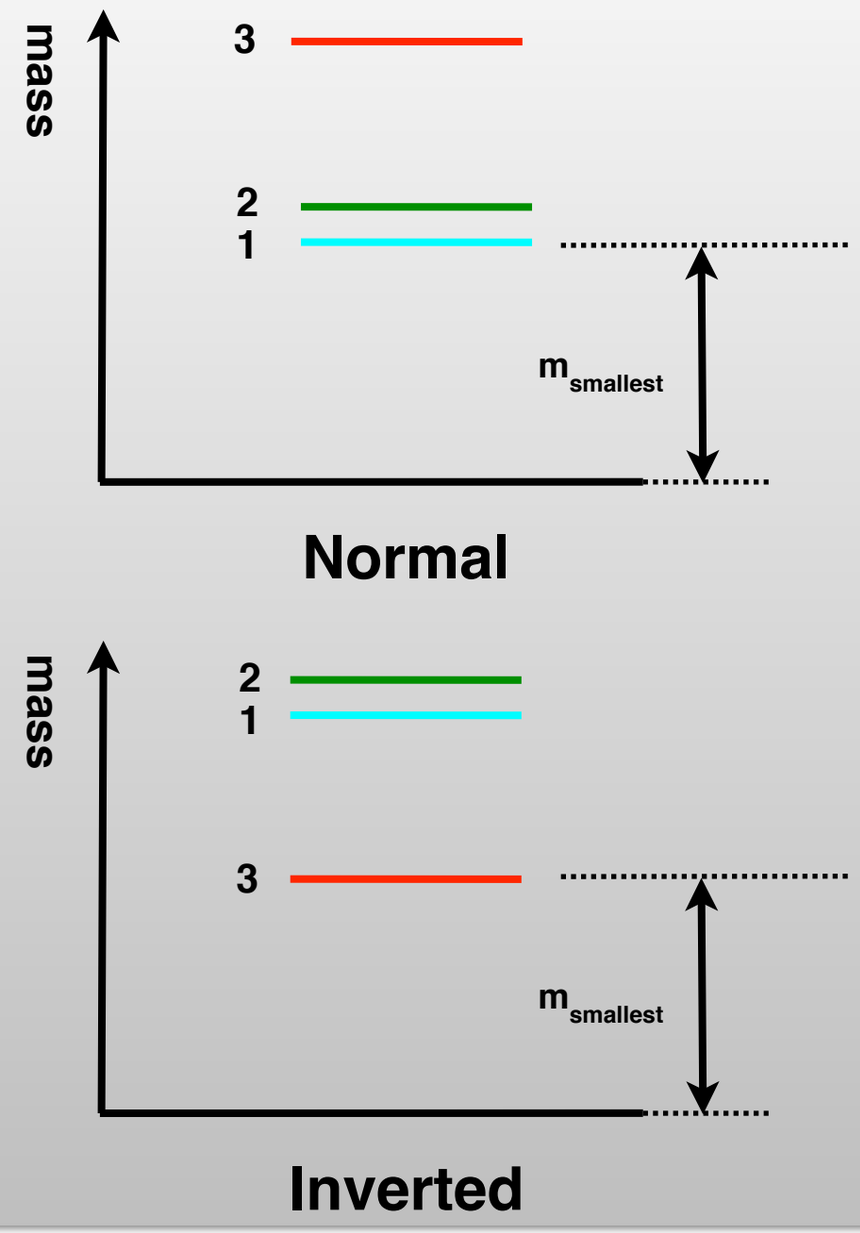
Cosmology: $\sum m = \sum_{i=1}^{3} m_i = m_1 + m_2 + m_3$

β decays: $m_\beta = \sqrt{\sum_{i=1}^{3} |U_{ei}|^2 m_i^2}$

ββ decays: $m_{\beta\beta} = \sum_{i=1}^{3} |U_{ei}^2 m_i|$

Oscillations: $\Delta m_{ij}^2 = m_j^2 - m_i^2$

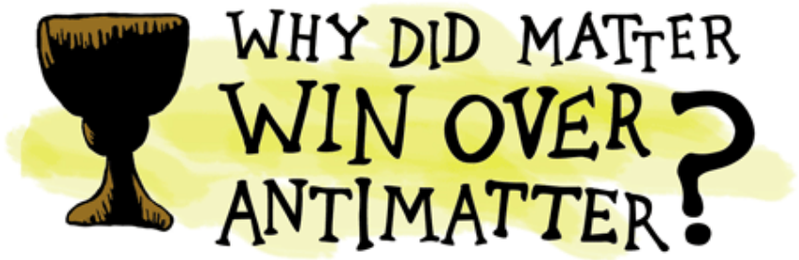
Determining the hierarchy

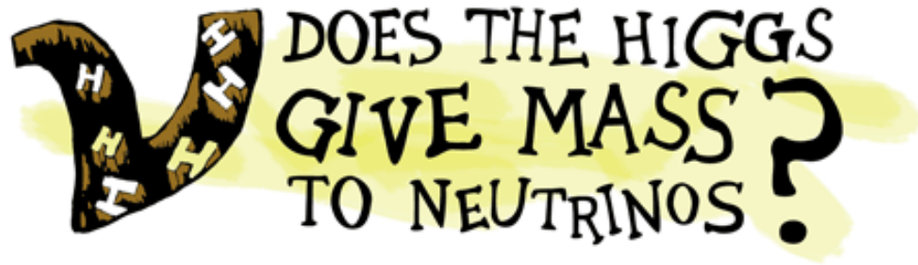


LBNL and UCB programs cover all these measurements

Neutrino Oscillation Experiments

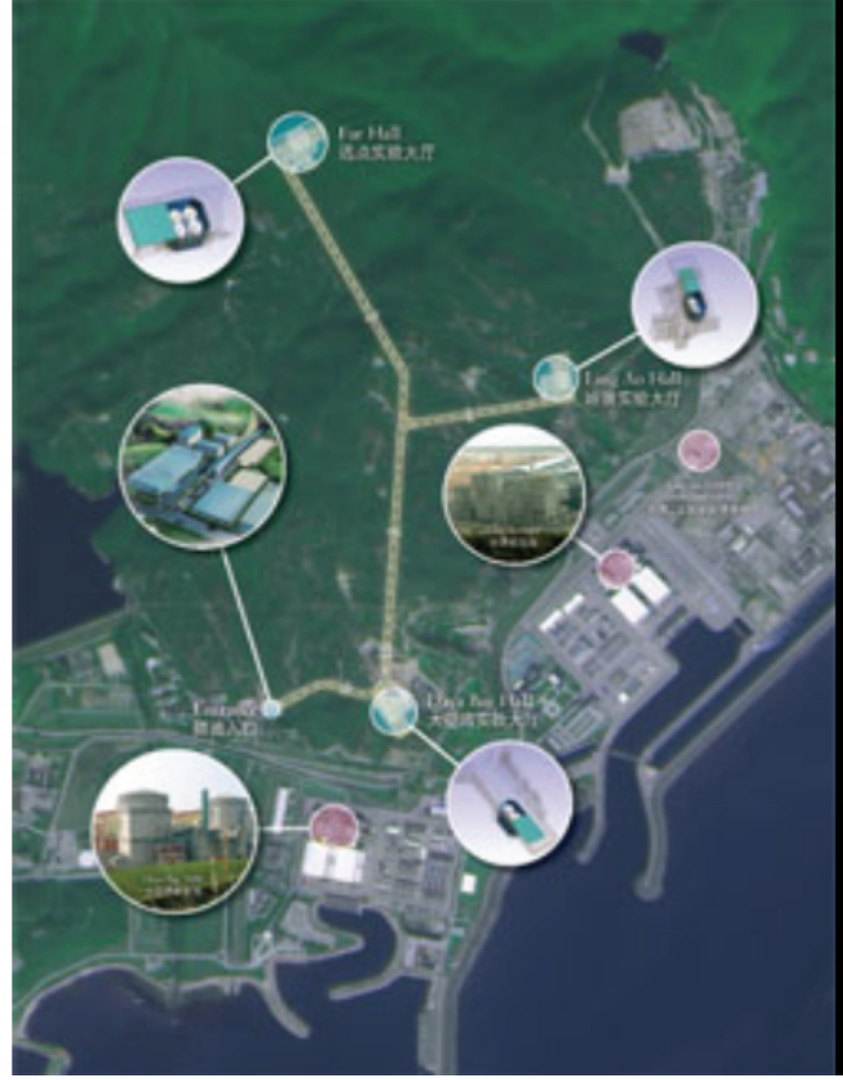
- DUNE [Kam-Biu Luk]
- THEIA [Gabriel Orebi Gann]
- IceCube [Spencer Klein]

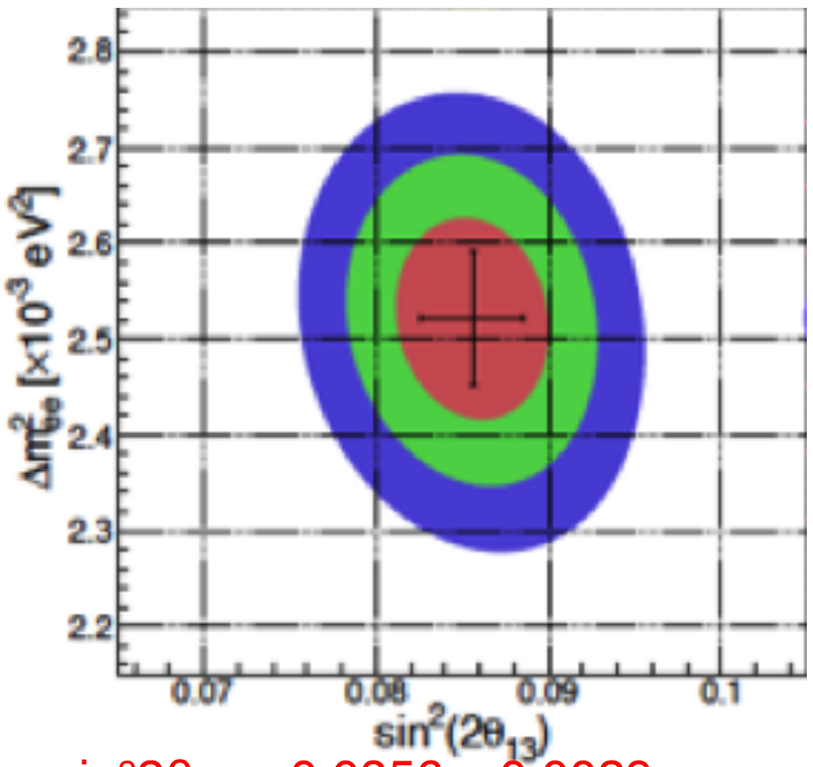




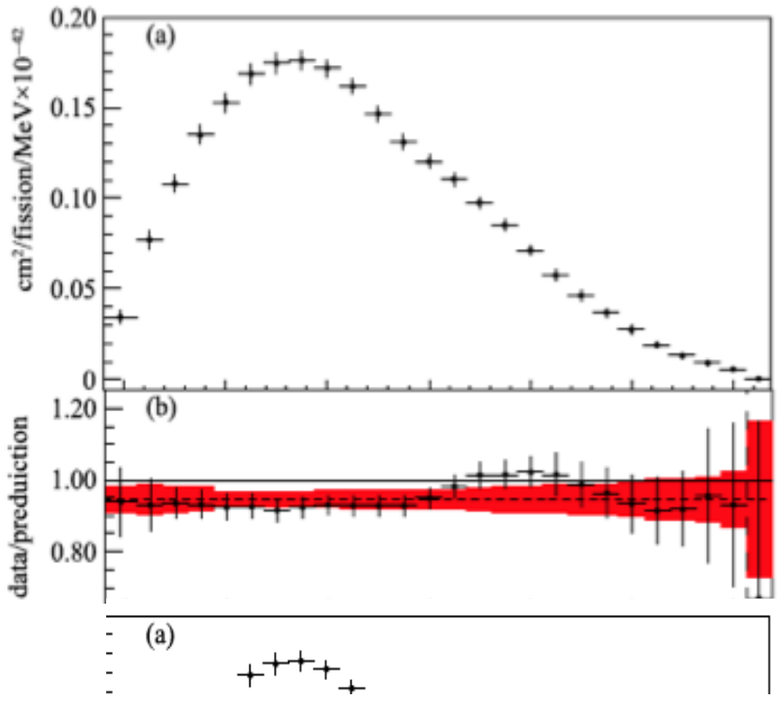
Daya Bay

- Ongoing reactor antineutrino experiment, collecting data until the end of 2020
- Science:
  - Precise measurement of mixing angle θ_{13} and mass splitting $|\Delta m^2_{32}|$
  - Precise measurement of absolute flux and energy spectrum of reactor antineutrinos
  - Search for a light sterile neutrino
  - Search for new neutrino phenomena

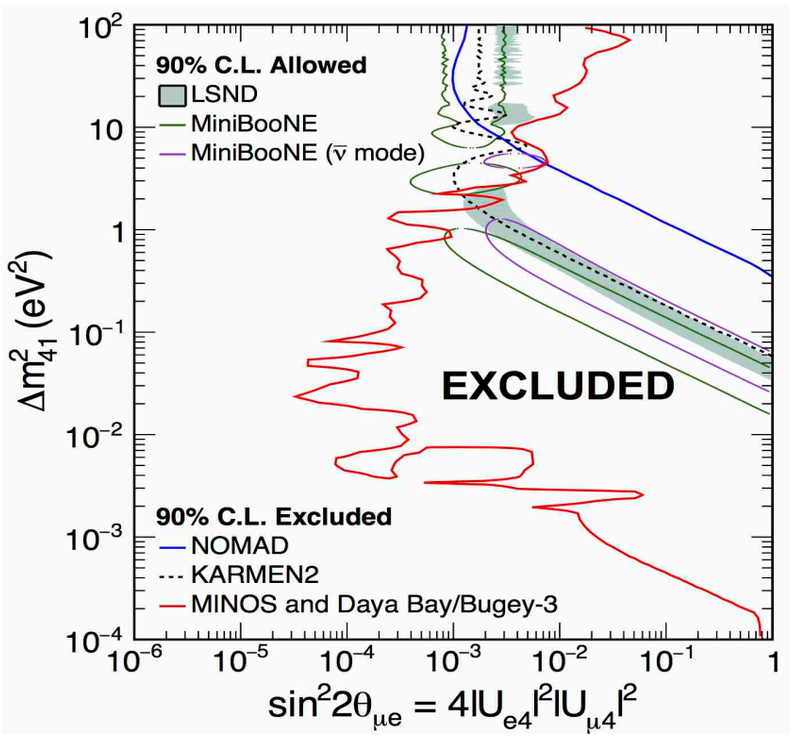




$\sin^2 2\theta_{13} = 0.0856 \pm 0.0029$
$\Delta m^2_{32} = (2.47 \pm 0.07) \times 10^{-3}$ eV^2 (NH)

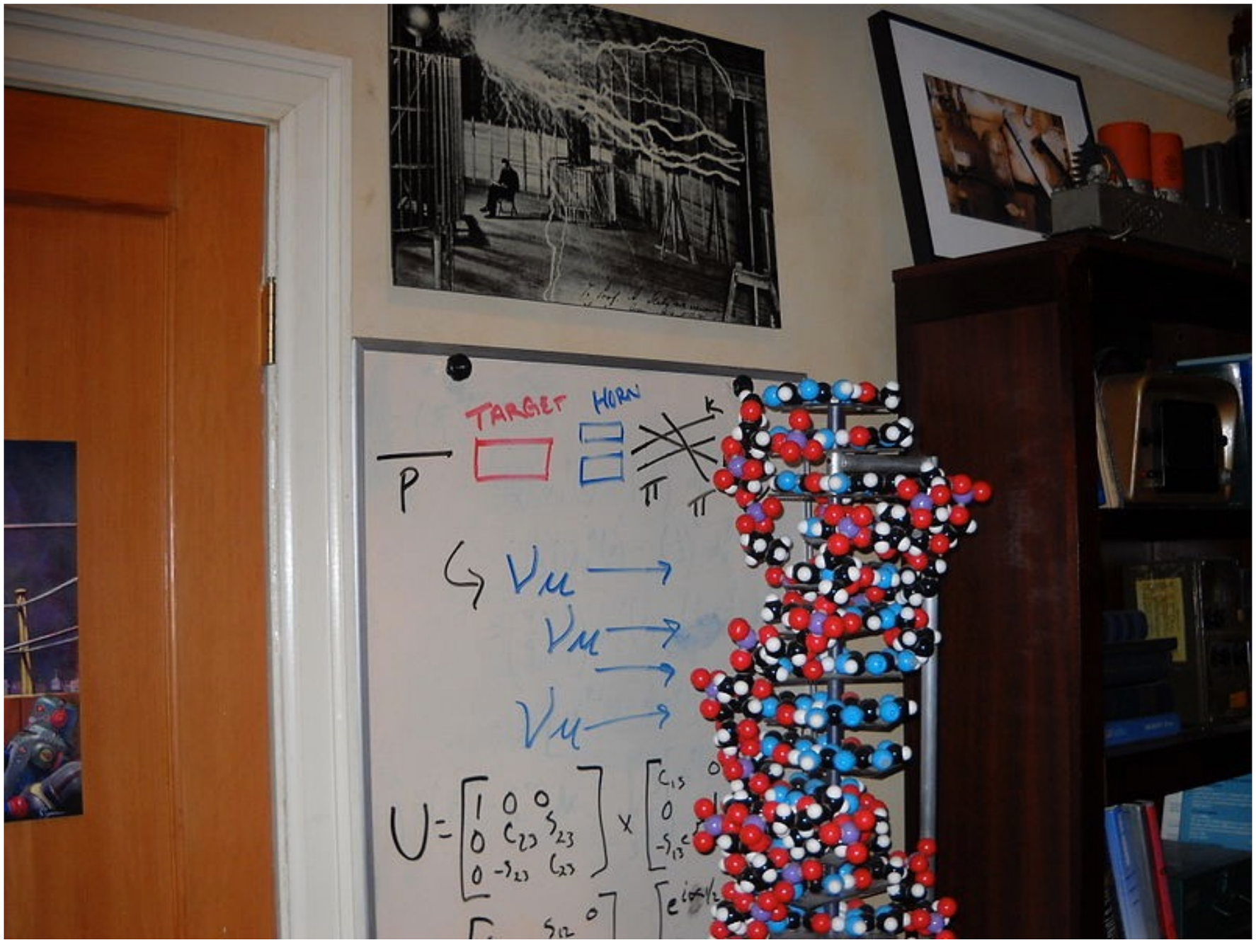


Energy spectrum of reactor antineutrinos

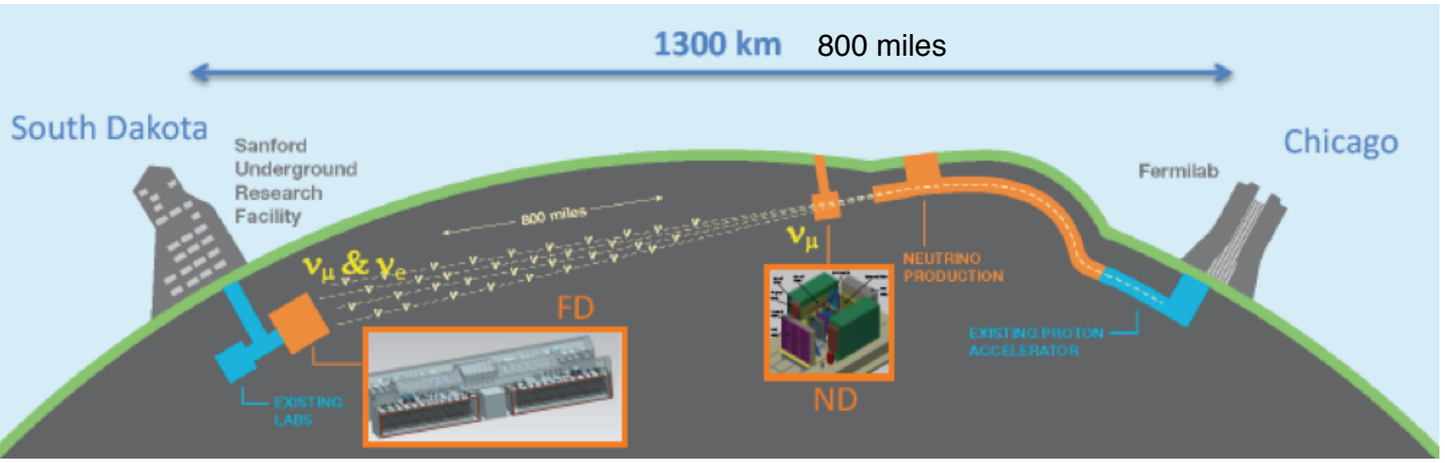


Sterile neutrino search

Neutrino oscillations - future



Deep Underground Neutrino Experiment (DUNE)



A long-baseline neutrino experiment designed for studying

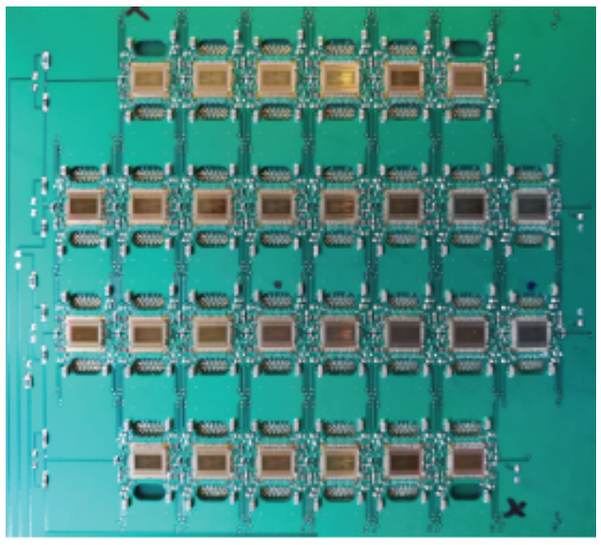
- CP violation in neutrino oscillation
- Neutrino mass-hierarchy problem
- Precise measurement of mixing angle θ_{23} and mass splitting Δm^2_{32}

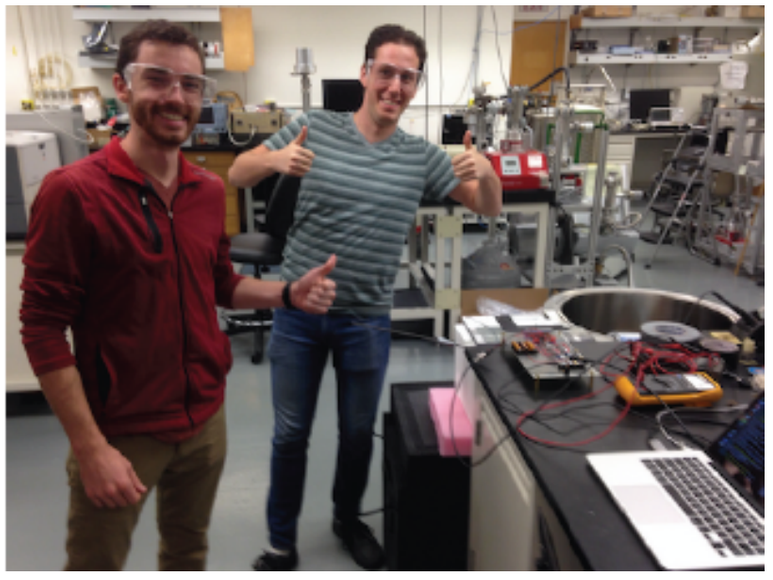
Berkeley involves in

- ProtoDUNE – beam-test of full-scale liquid-argon TPC at CERN
- Design and detector R&D of near detector
- Simulation and physics analysis using NERSC supercomputers

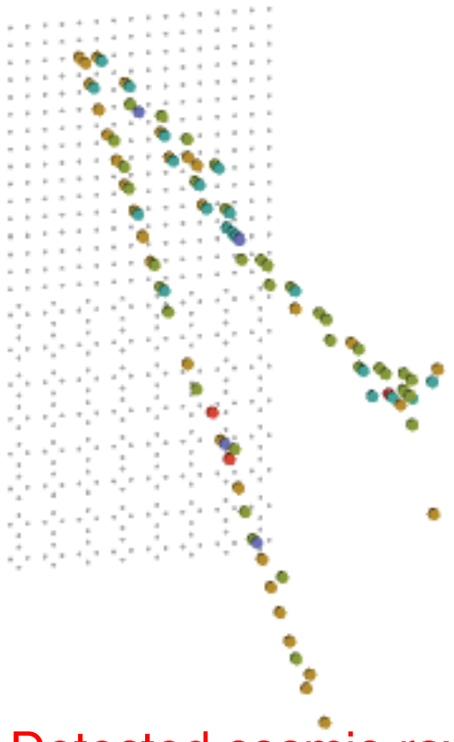
ProtoDUNE

LArPix: state-of-the-art 3-D pixelated readout for liquid argon TPCs





Developing machine-learning reconstruction package

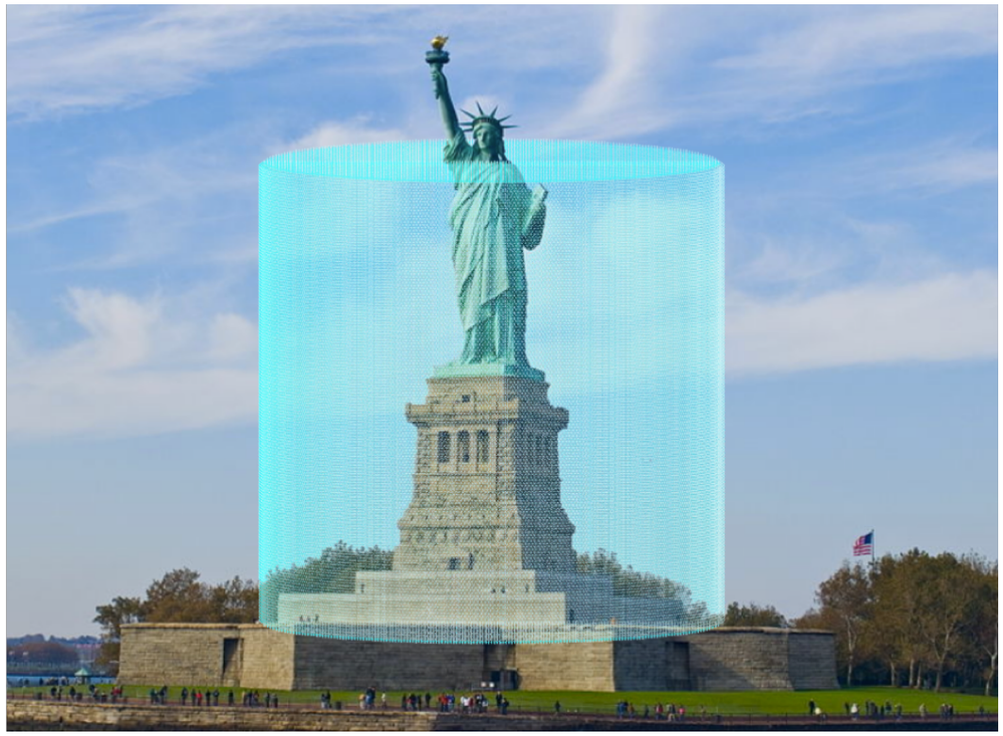


Detected cosmic-ray tracks in 3-D

R. Bonventre, J. Caravaca, B. Land, G. D. Orebi Gann, J. Wallig

THEIA

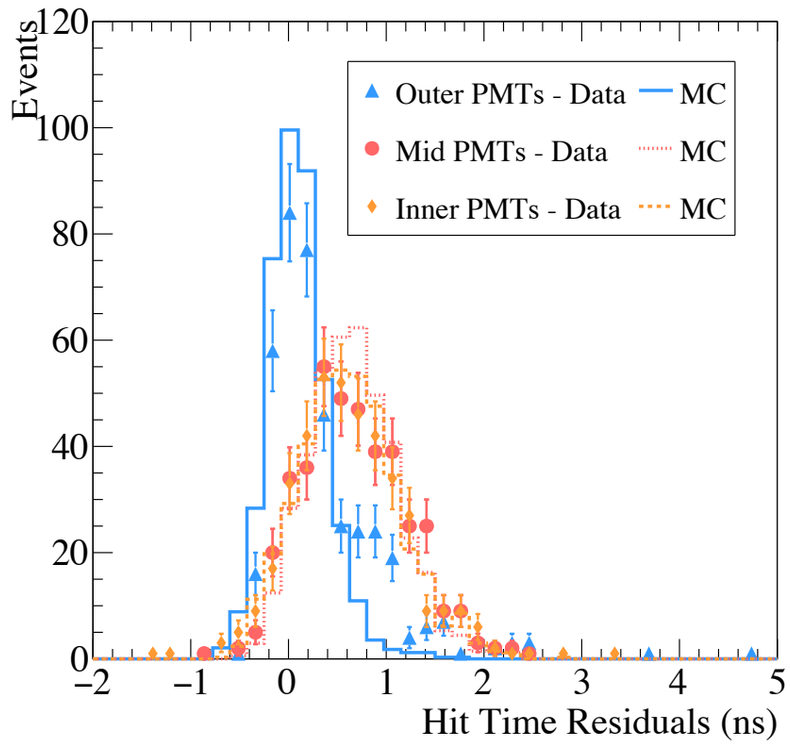
- Large WbLS detector (50-100 kton)
- Fast, high-efficiency photon detection with high coverage
- Deep underground (e.g. Homestake)
- Isotope loading (Gd, Te, Li...)
- ***Flexible***! Target, loading, configuration



➡ **Broad physics program!**

➡ ***long baseline, NLDBD, solar, geonu, nucleon decay, supernova, DSNB....***

➡ *Directional info in a low-threshold detector Unprecedented level of in-situ background rejection*

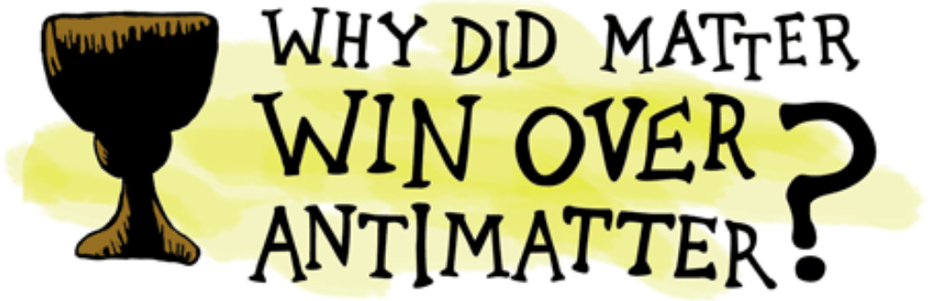


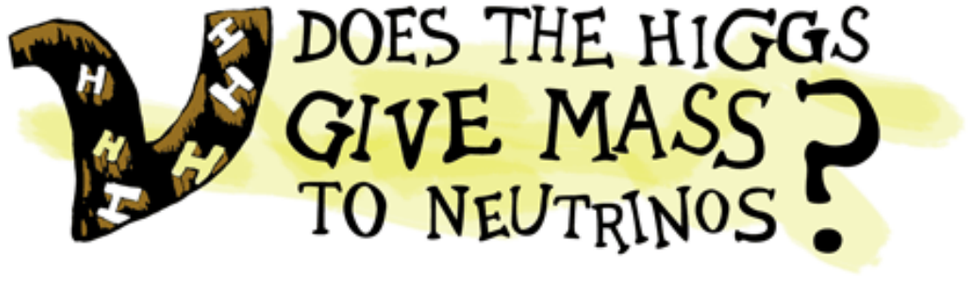
Neutrinoless Double Beta Decay Experiments

- CUORE / CUPID (^{130}Te / ^{100}Mo) [Brian Fujikawa, Yury Kolomensky]
- MAJORANA / LEGEND (^{76}Ge) [Alan Poon]
- SNO+ (^{130}Te) [Gabriel Orebi Gann]
- HP gas TPC (^{136}Xe, ^{82}Se) [Yuan Mei]

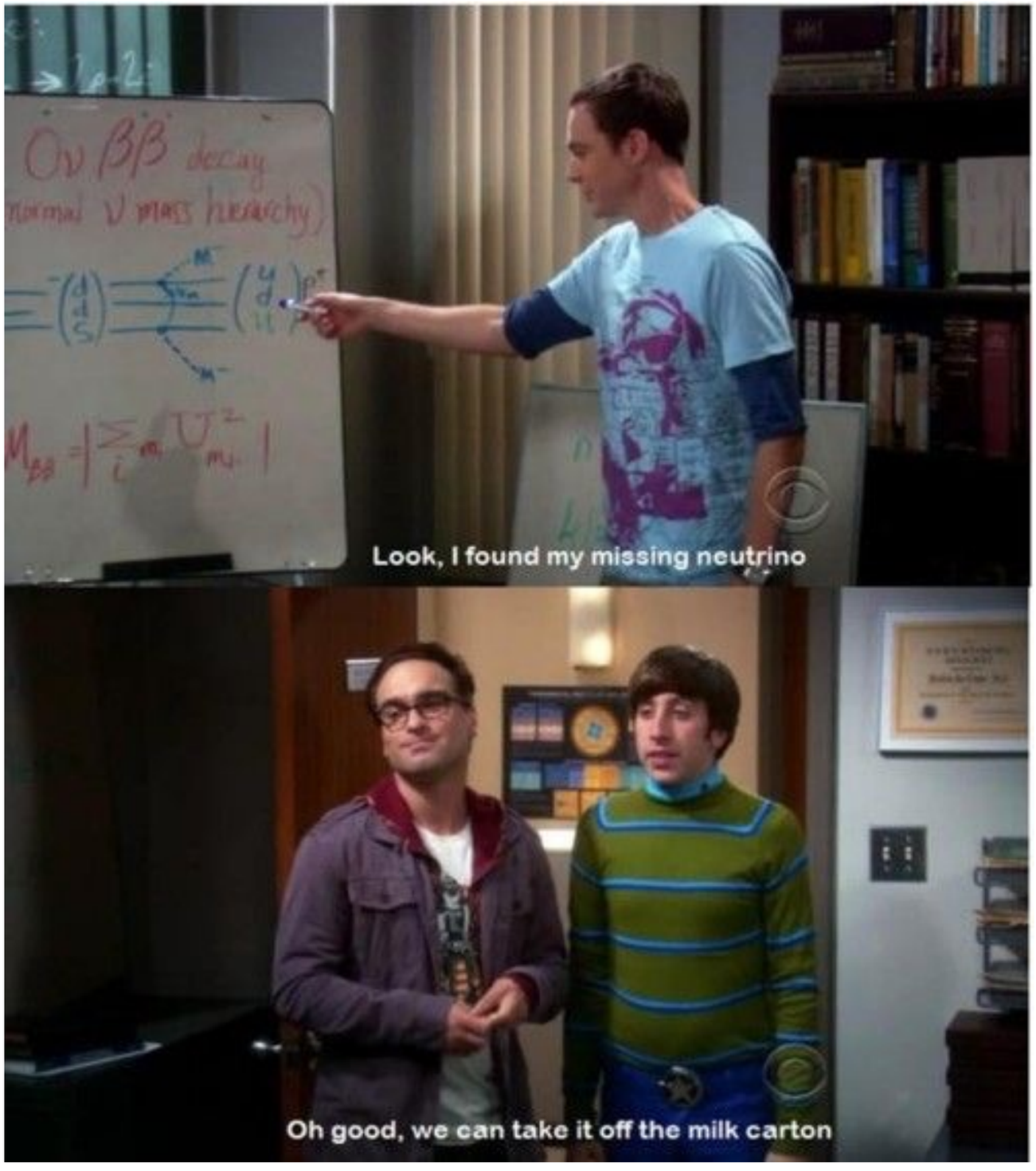
Beta Decay Experiment

- KATRIN (^{3}H) [Alan Poon]



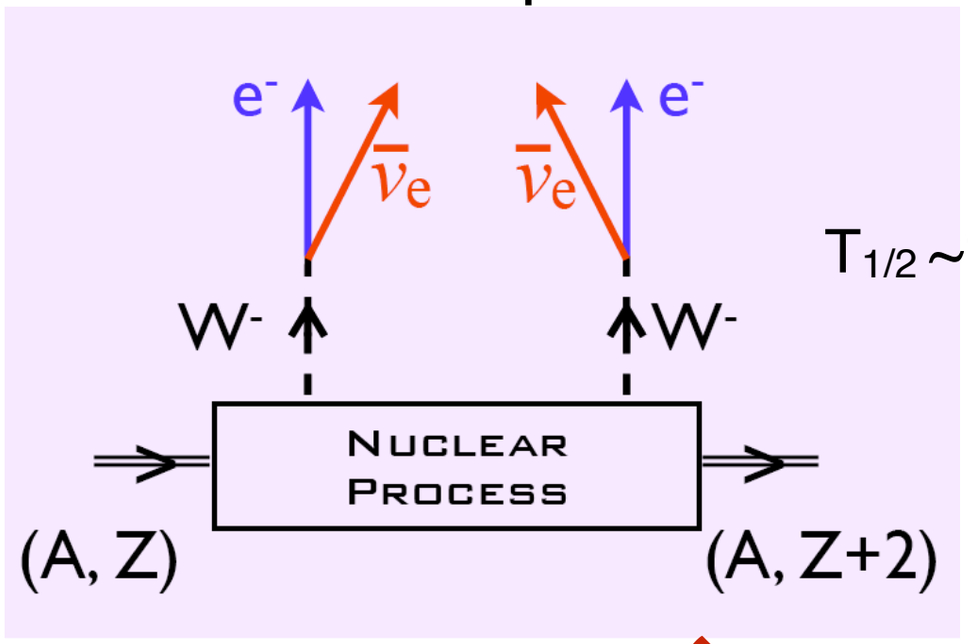


Neutrinoless double-beta decay is a big deal



Lepton number violation and Neutrinoless Double Beta Decays

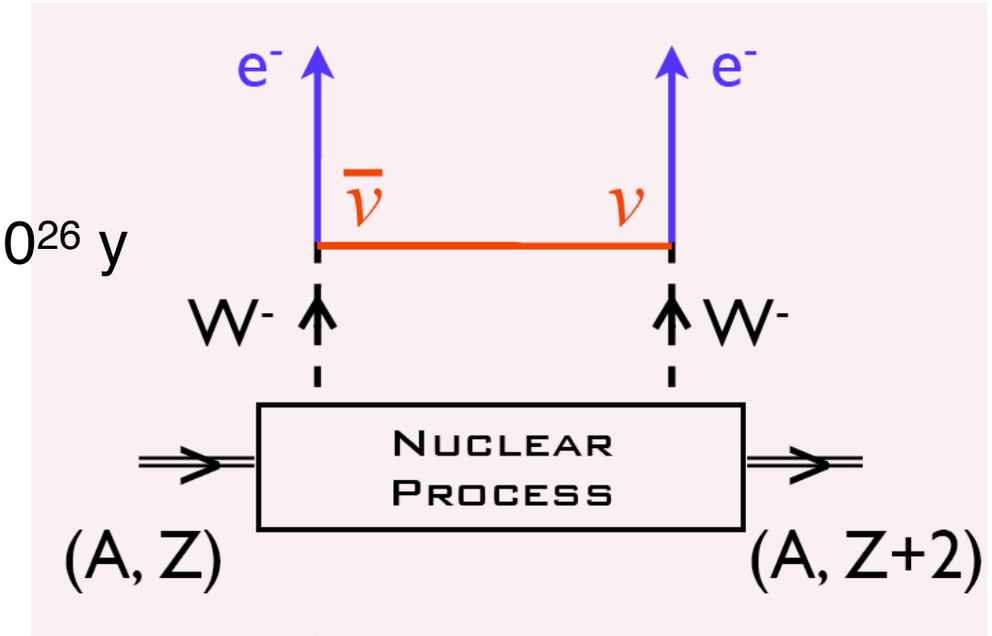
SM allowed process

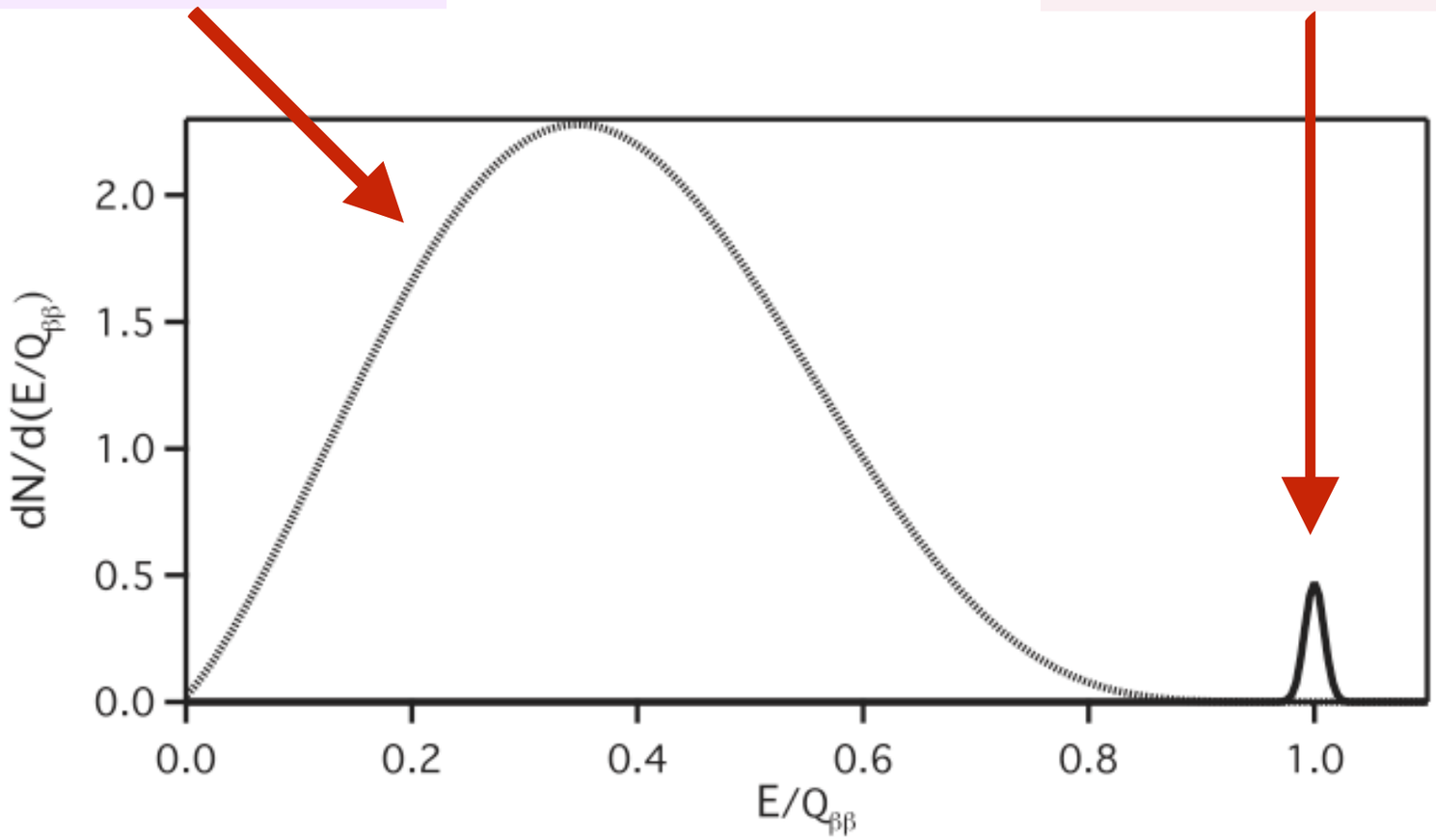


$T_{1/2} \sim 10^{18\text{-}21}$ y

$T_{1/2} > 10^{26}$ y

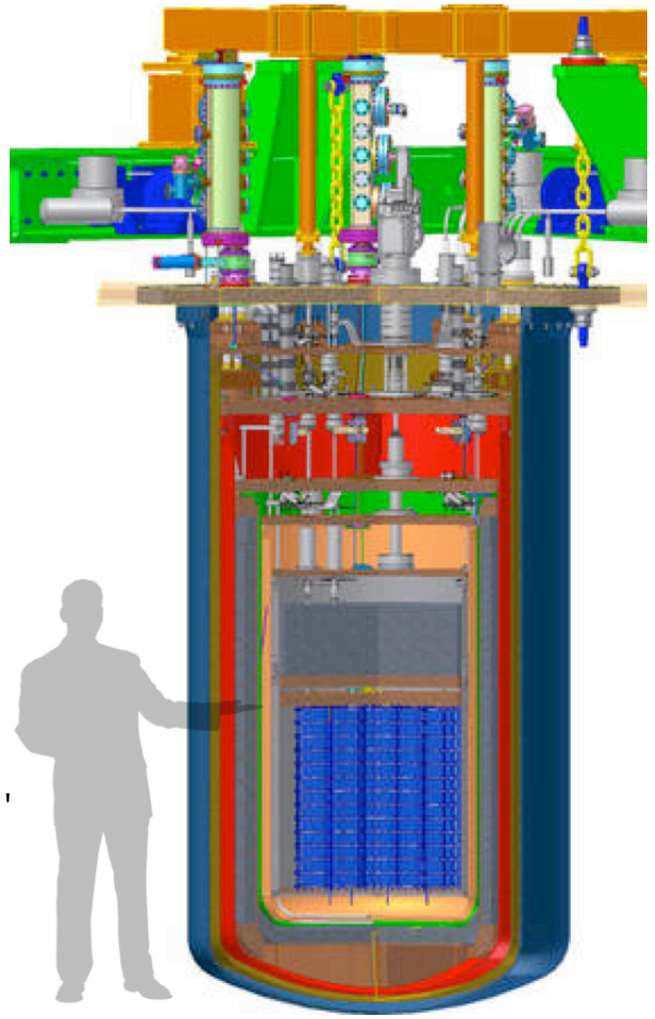
Lepton number violation



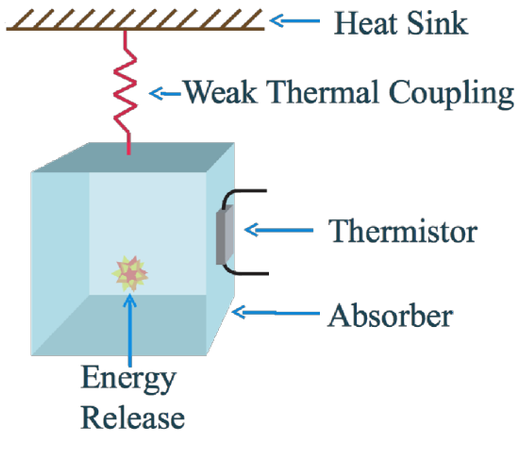


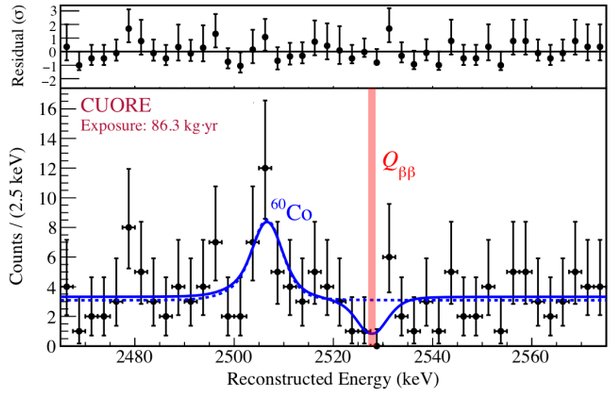
CUORE @ Berkeley

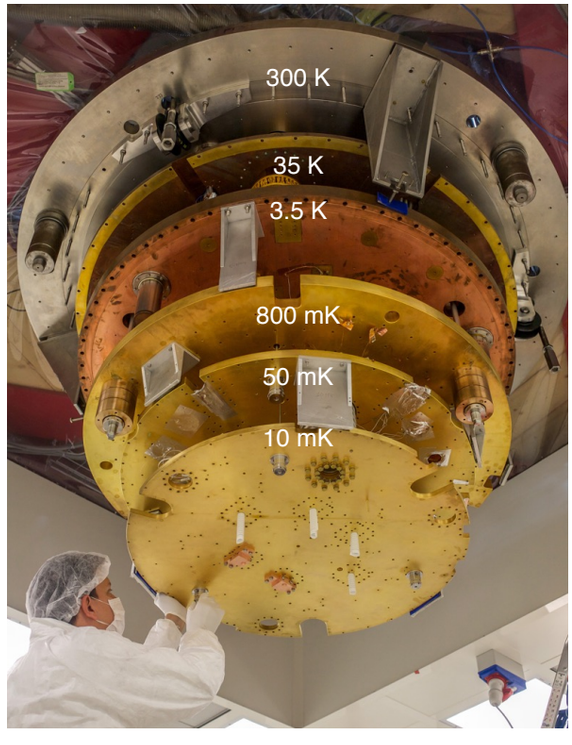
- Located in Italy (Gran Sasso)
- TeO_2 crystal serves as both source of radioactive decay and detector for resultant electrons
- Bolometer:
  - Electrons deposit energy in crystal, produce temperature spike
  - Temperature of crystal read out using ultra-sensitive thermometers
- Requires powerful cryogenics:
  - Coldest cubic meter in known Universe ! [Jon Ouellet, Ph.D. 2015]
- Taking data now !
  - ~210 kg of ^{130}Te, plan to operate to ~2022
  - One of the most sensitive current searches for $0\nu\beta\beta$!



- Next-generation detector: CUPID
  - CUORE Upgrade with Particle ID: zero-background search for $0\nu\beta\beta$

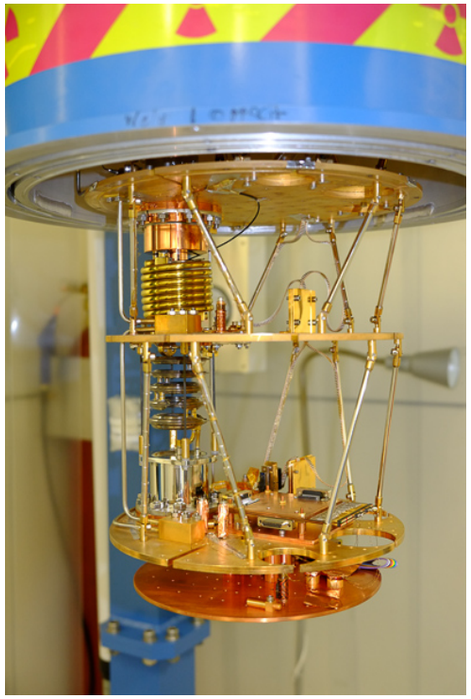


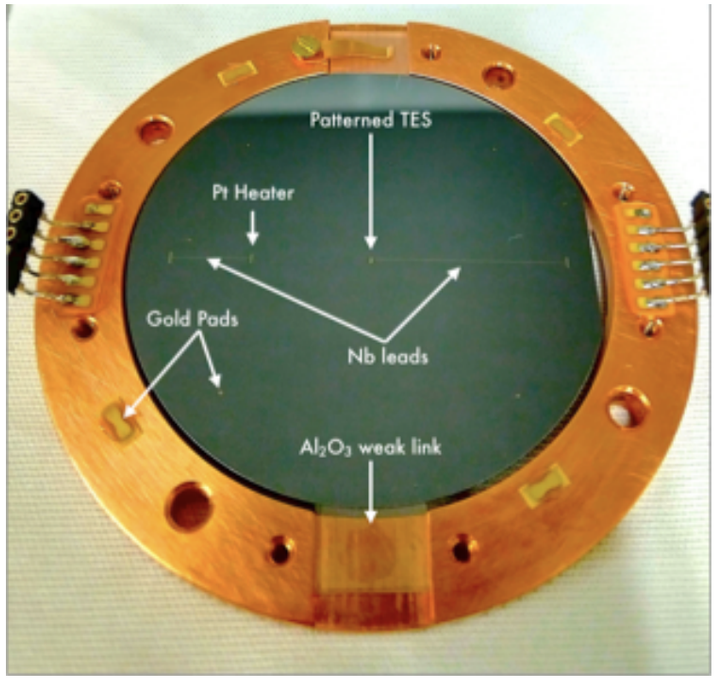




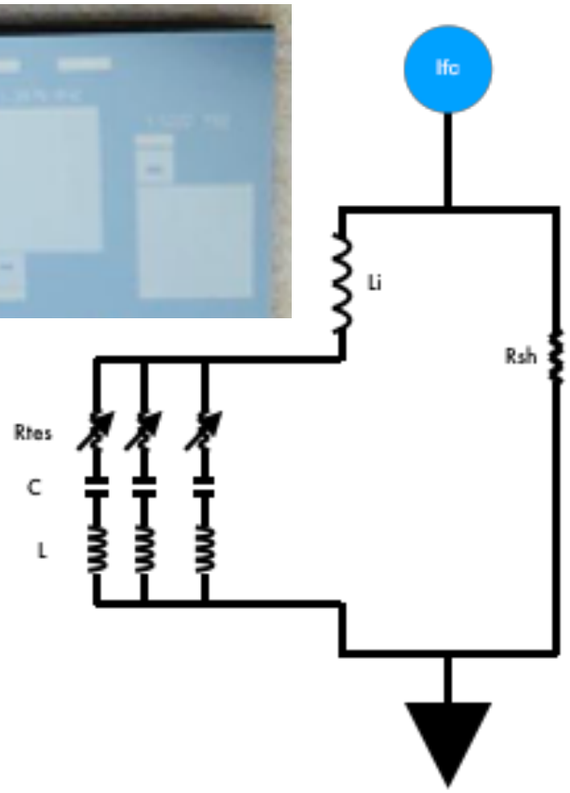
CUPID @ Berkeley

Superconducting (TES) sensor development, TES-based light detectors

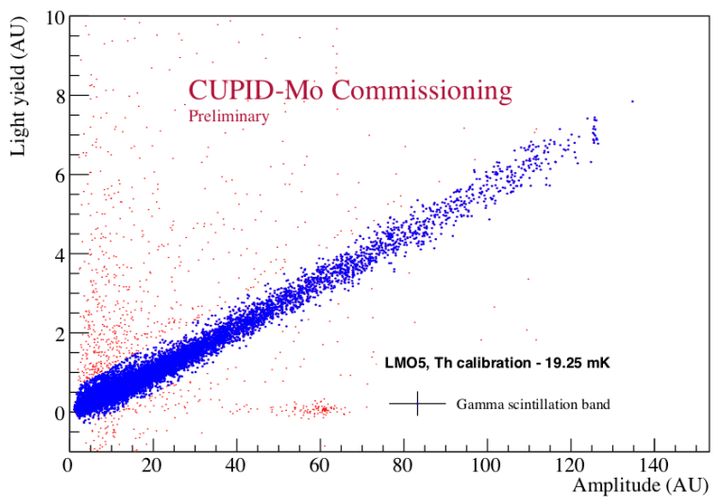




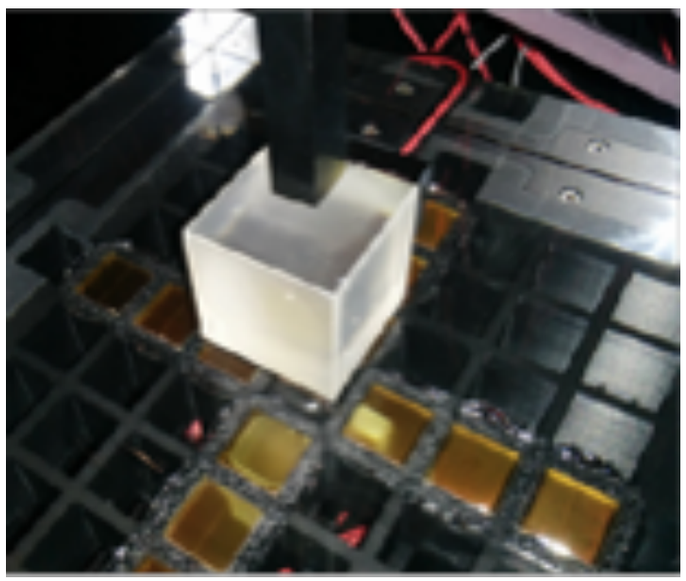
TES multiplexing - with CMB group (Physics Division)

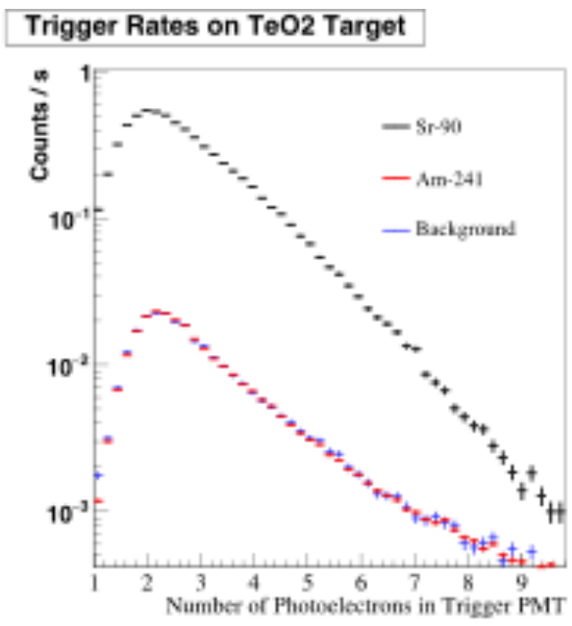


CUPID-Mo data analysis at NERSC



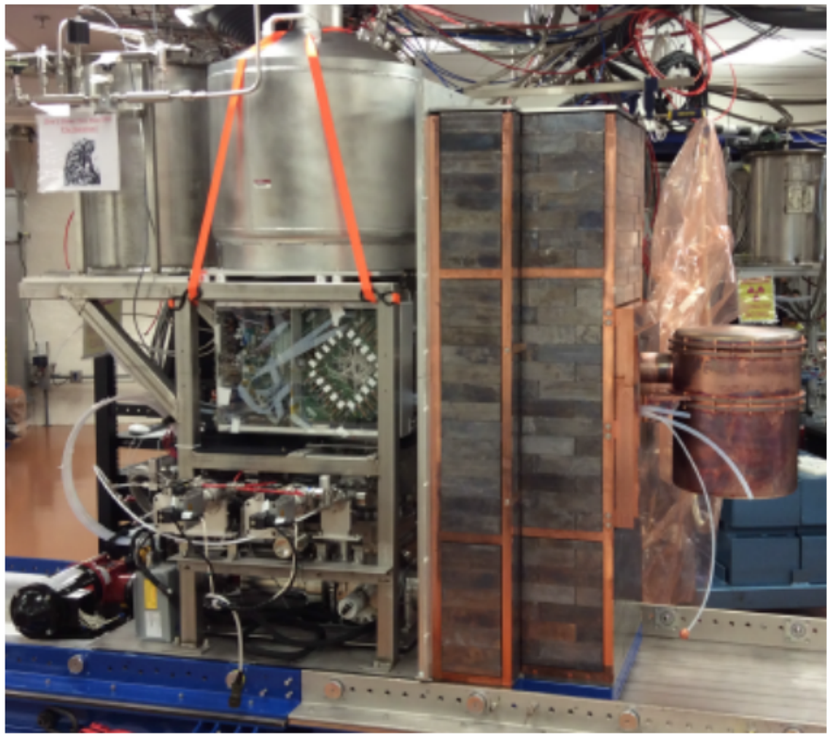
TeO_2 and Li_2MoO_4 crystal optical properties - with G.D. Orebi Gann's group

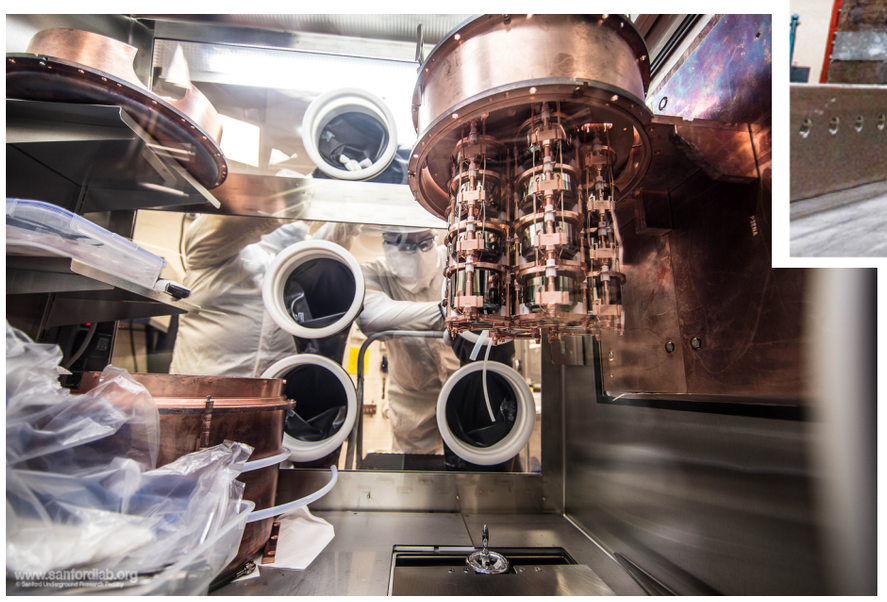




MAJORANA DEMONSTRATOR

- Physics:
  - To search for LNV via ^{76}Ge 0νββ decay
  - To search for light WIMPs (<10 GeV/c^2)
- Status:
  - Production data taking in progress
- LBNL contributions:
  - Development and procurement of ^{76}Ge detectors
  - Design and fabrication of low-noise signal processing electronics; detector construction & commissioning
  - Simulation and analysis
- Future:
  - R&D for a ton-scale experiment **LEGEND** started





BERKELEY LAB

LEGEND

Goal: To develop a phased ^{76}**Ge-based** double-beta decay experimental program with discovery potential at a **half-life significantly longer than 10^{27} years**.

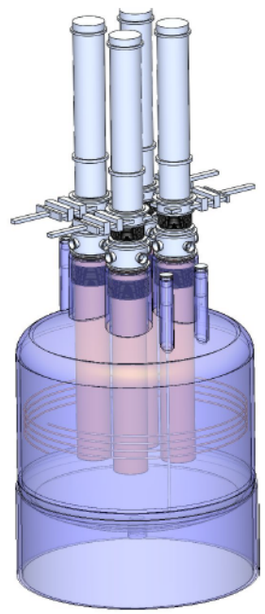
First phase (LEGEND-200):

- (up to) 200 kg
- repurpose GERDA infrastructure at LNGS
- use LAr veto
- start by 2021

Future phase (LEGEND-1000):

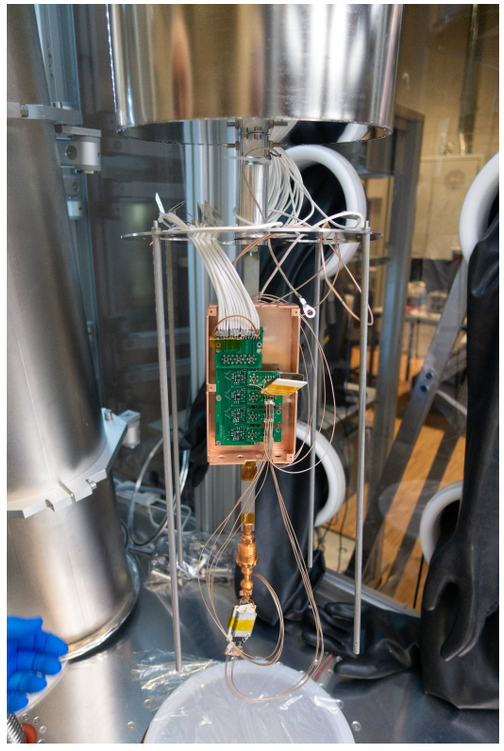
- 1000 kg
- Location to be determined
- 1/30 x background level of GERDA
- start by 202x

LEGEND-200

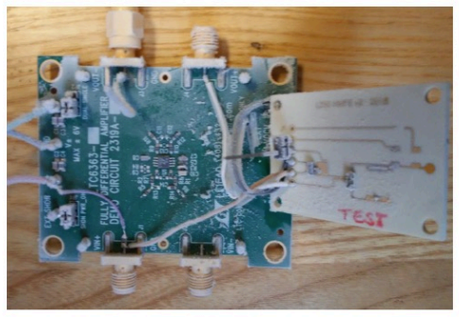


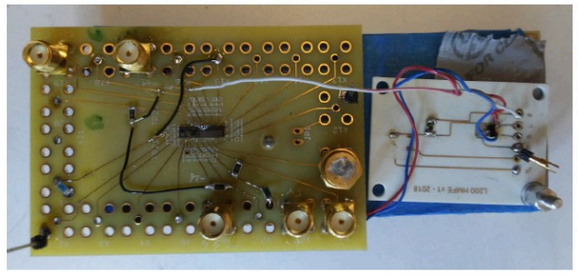
LEGEND-1000

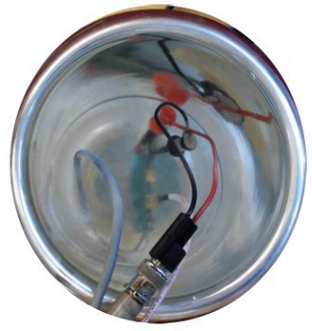
Integrated front-end / amp test



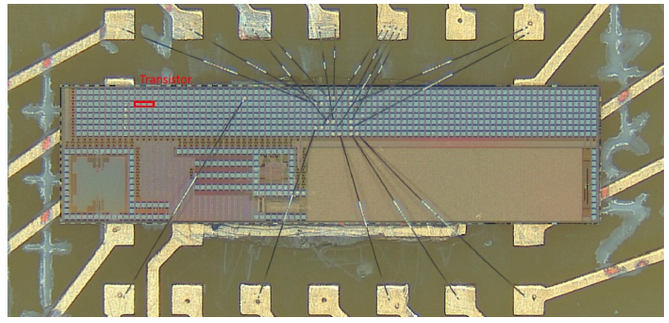
Cold electronics prototyping



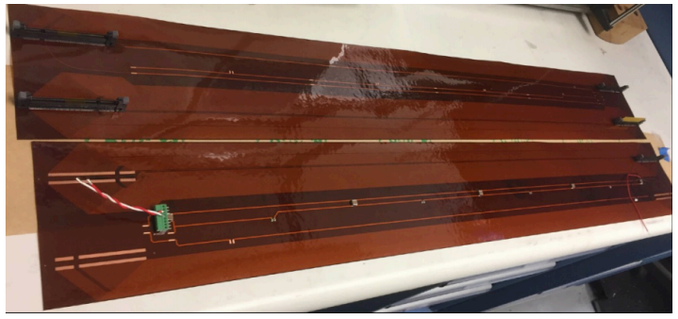




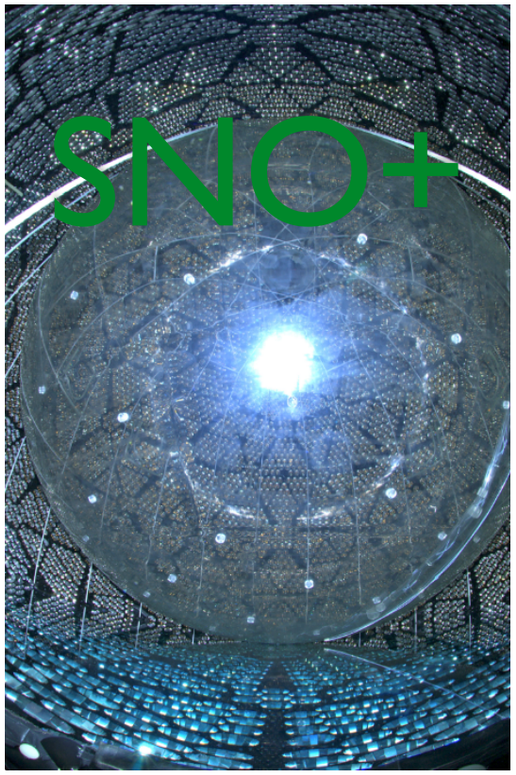
“Breadboarding” with “sea-of-transistors”

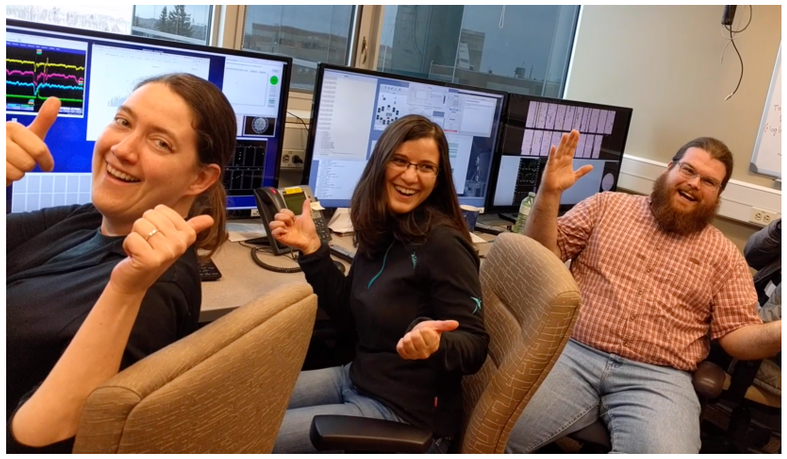


HV cable prototype



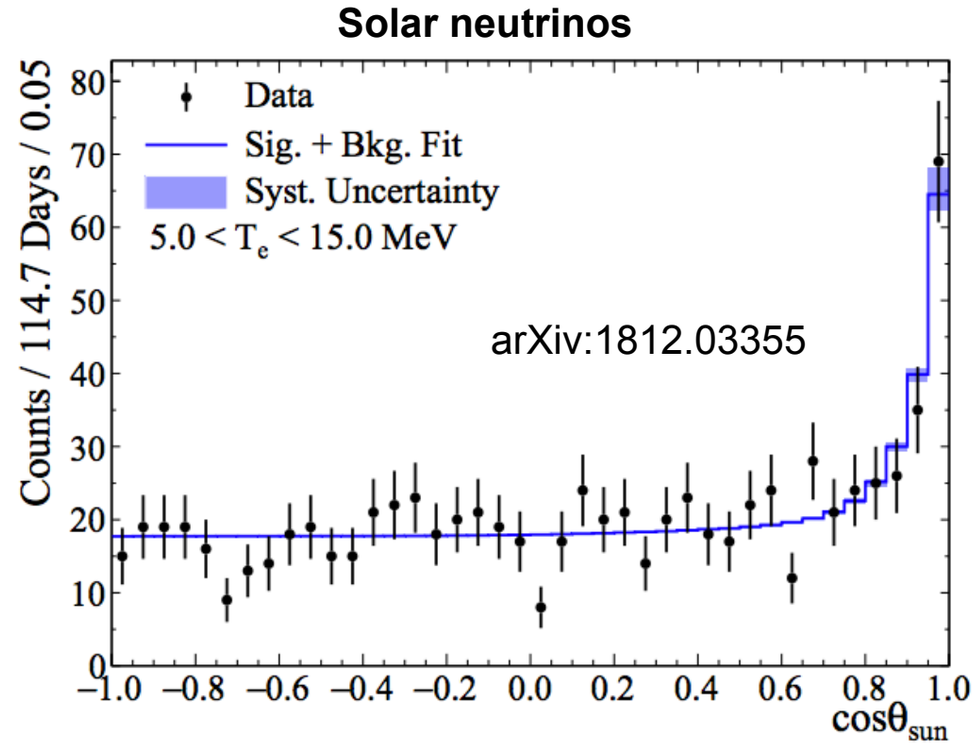
SNO+ detector

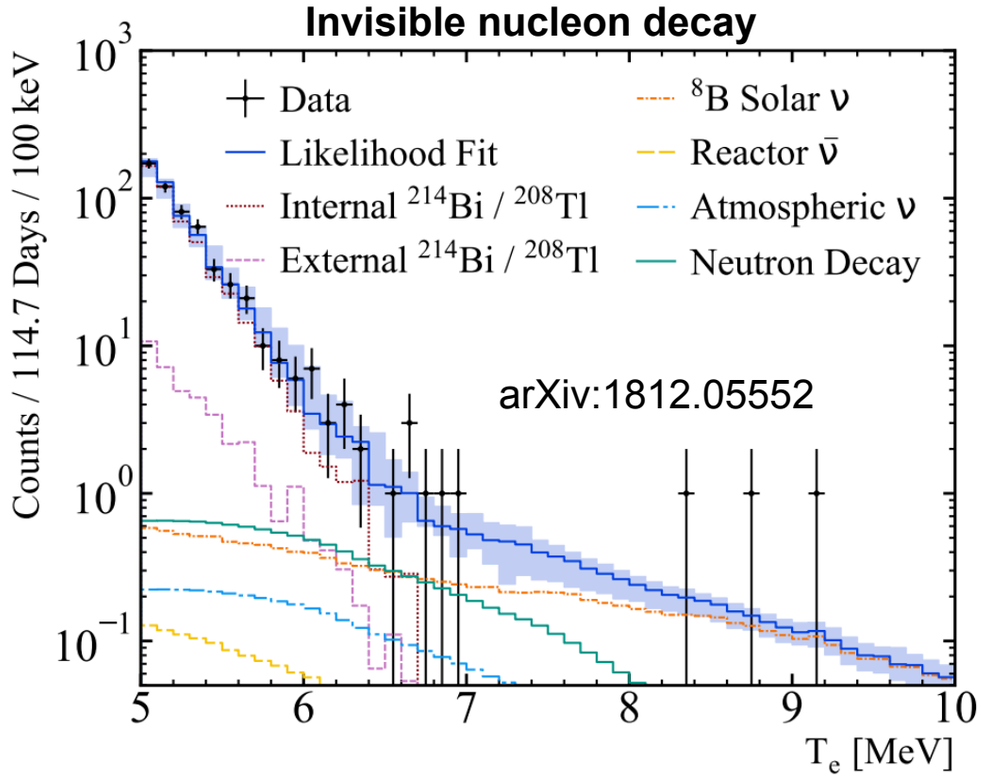




Physics data-taking since May 4th, 2017

- Physics Analysis Coordinator (PAC) + leadership of multiple working groups, including solar neutrino group
- Lead roles in both recent articles (lead author, lead analysts, critical backgrounds, coordination)
- Led DAQ rewrite & commissioning
- Designed optical calibration source, successful %-level measure of light collection
- 2 + 2 SNO papers accepted to PRD





Photon Detection R&D

Expertise in optical & VUV photon detection

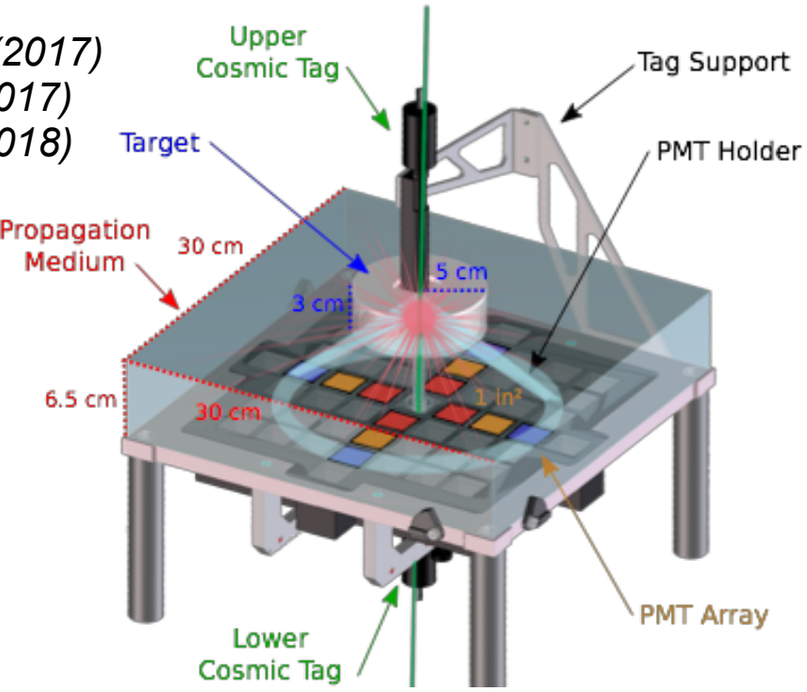
First demonstration of Cherenkov-light detection from highly scintillating media

Study of resulting sensitivity to CNO neutrinos

CHESS detector now in use for CUPID R&D

CHESS Experiment – optical photon detection

PRC95, 055801 (2017)
EPJC77 811 (2017)
EPJC78 435 (2018)



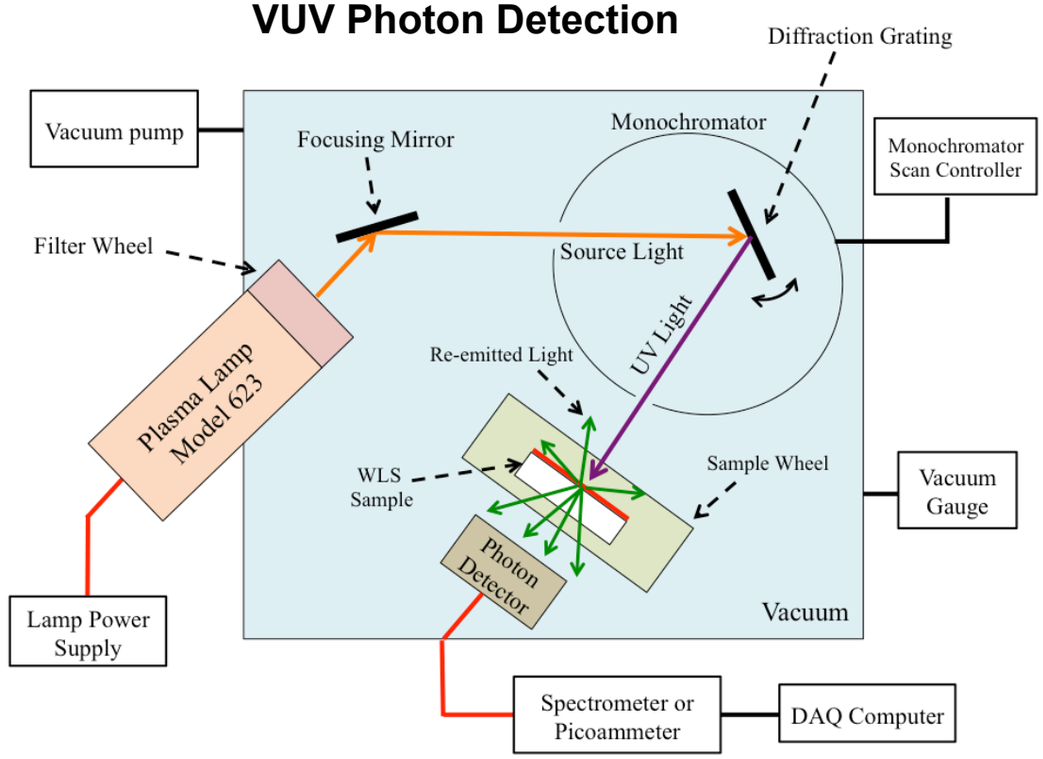
First measurement of microphysical properties of TPB (QE, attenuation, 2^0 emission)

Measurement of angular emission underway

Plans to measure material properties in VUV regime (LEGEND)

Need young scientists to do this!

VUV Photon Detection



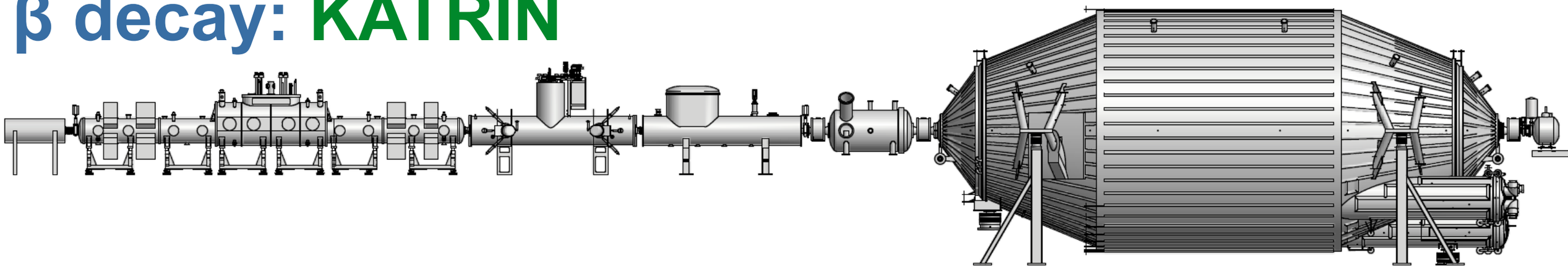
EPJC78 329 (2018)

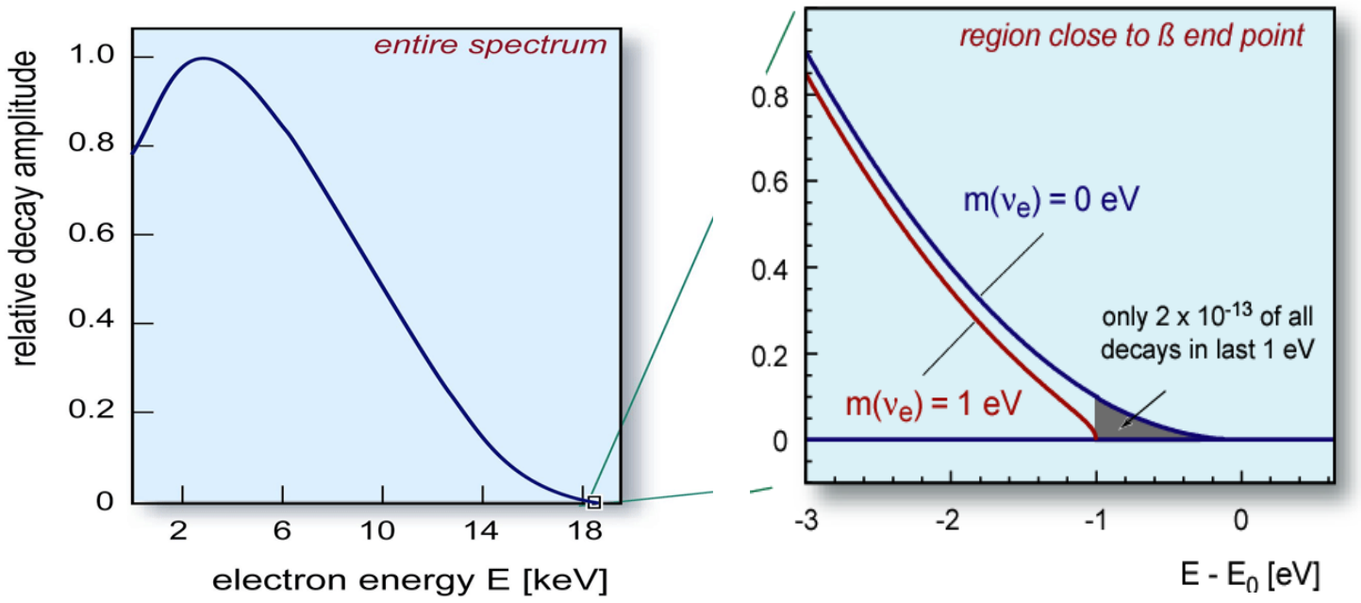
Neutrino mass

Knowing the neutrino mass is important!

$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$

β decay: KATRIN

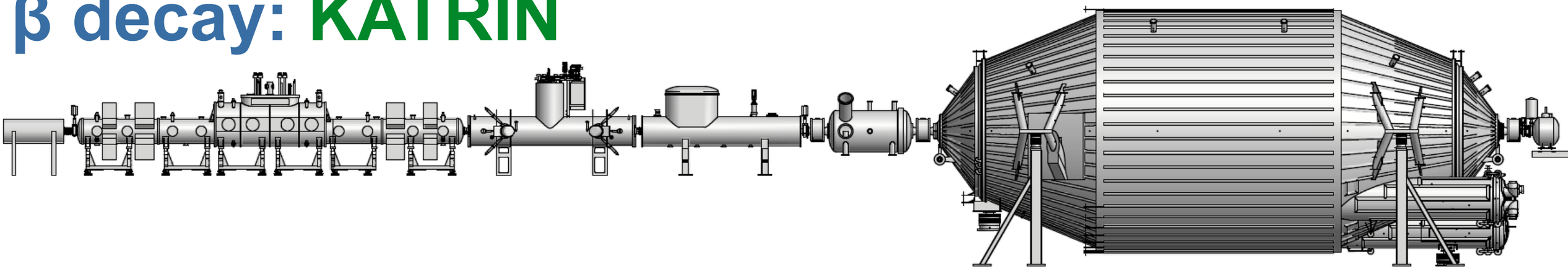


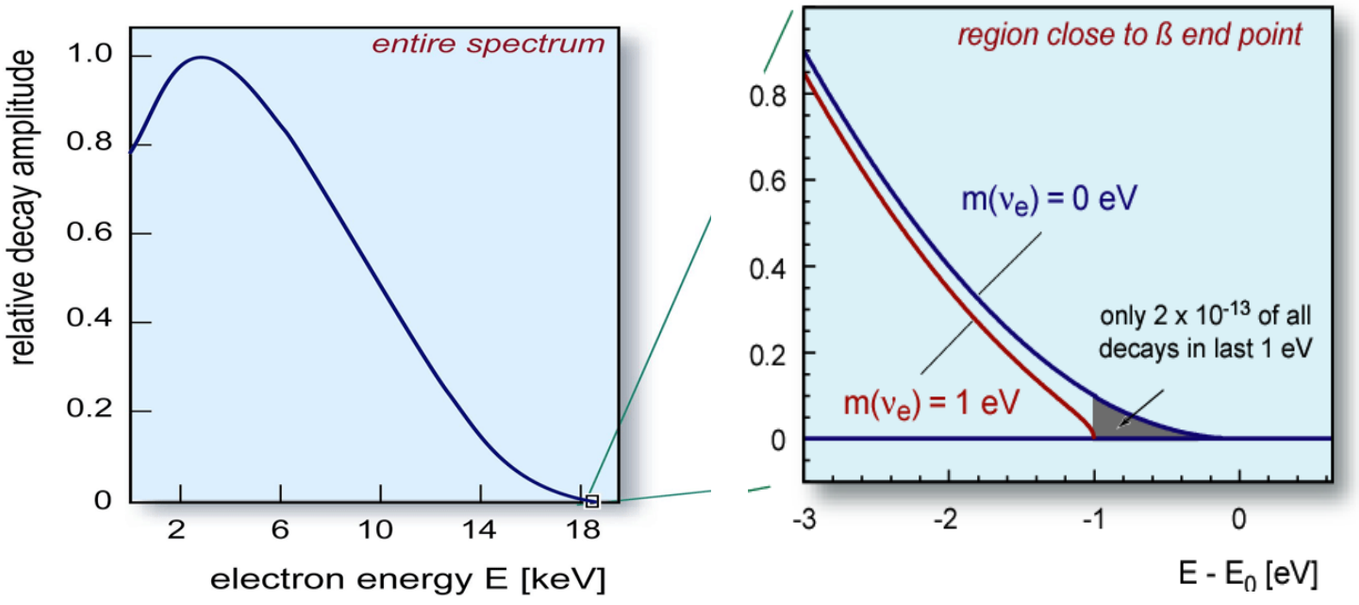


- ^{3}H beta decay
- Sensitivity: m_β<0.2 eV (90% CL)
- ^{3}H data taking started
- LBNL involves in analysis activities

BERKELEY LAB

β decay: KATRIN

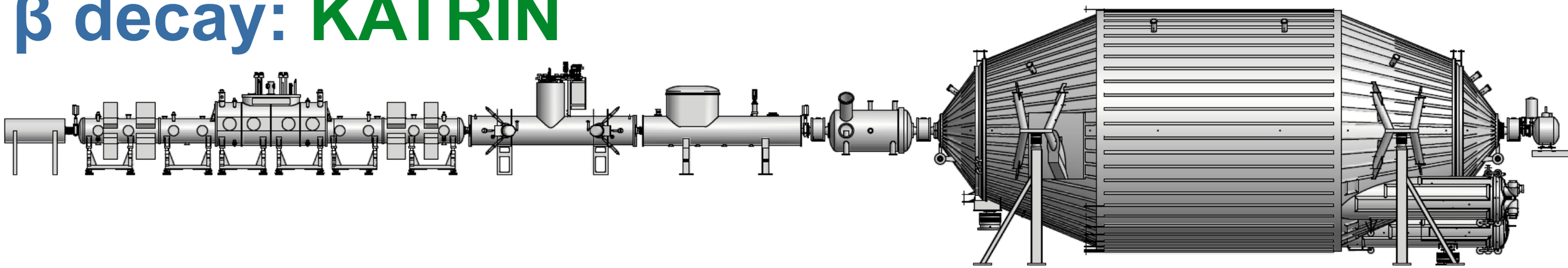


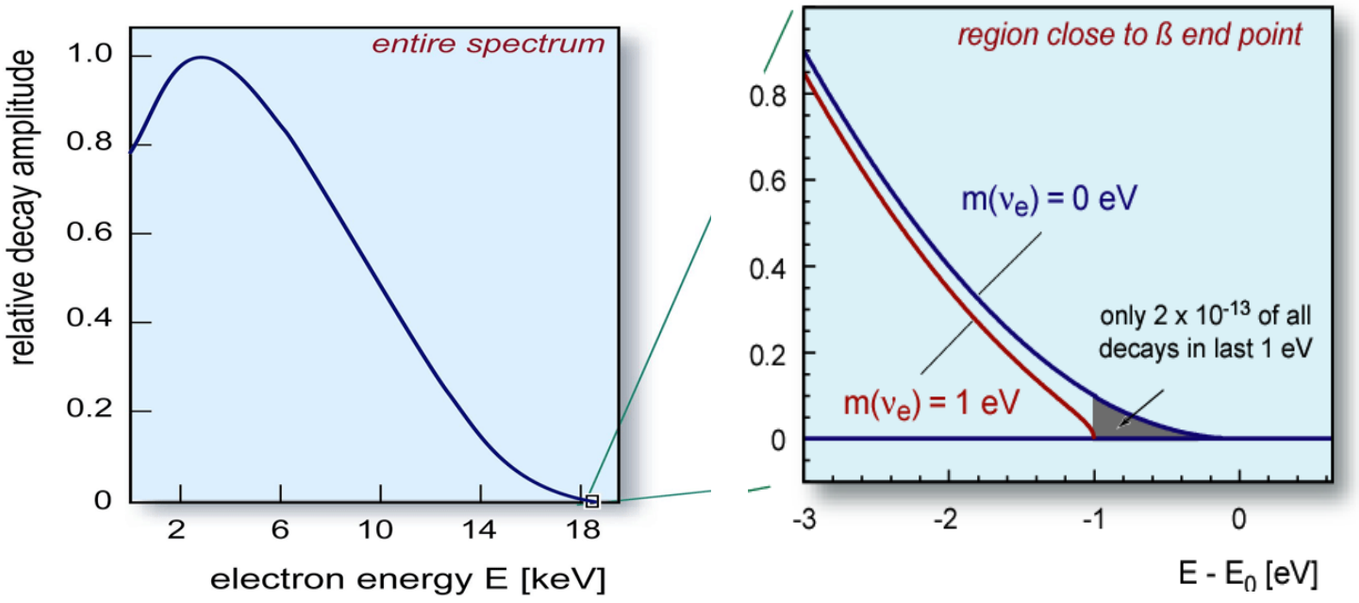


- ^{3}H beta decay
- Sensitivity: m_β<0.2 eV (90% CL)
- ^{3}H data taking started
- LBNL involves in analysis activities

BERKELEY LAB

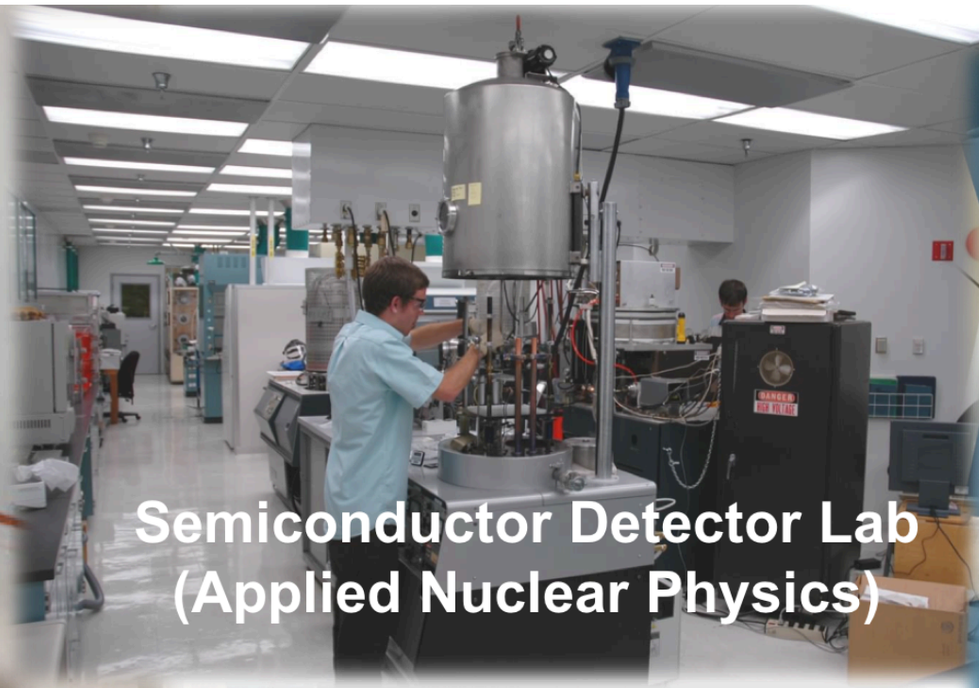
β decay: KATRIN

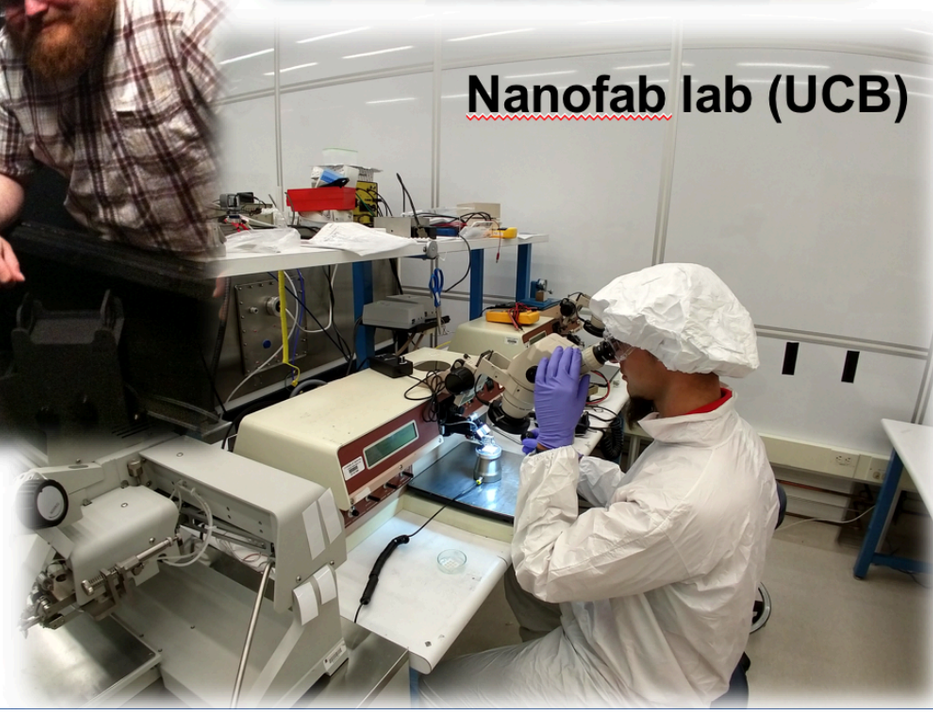


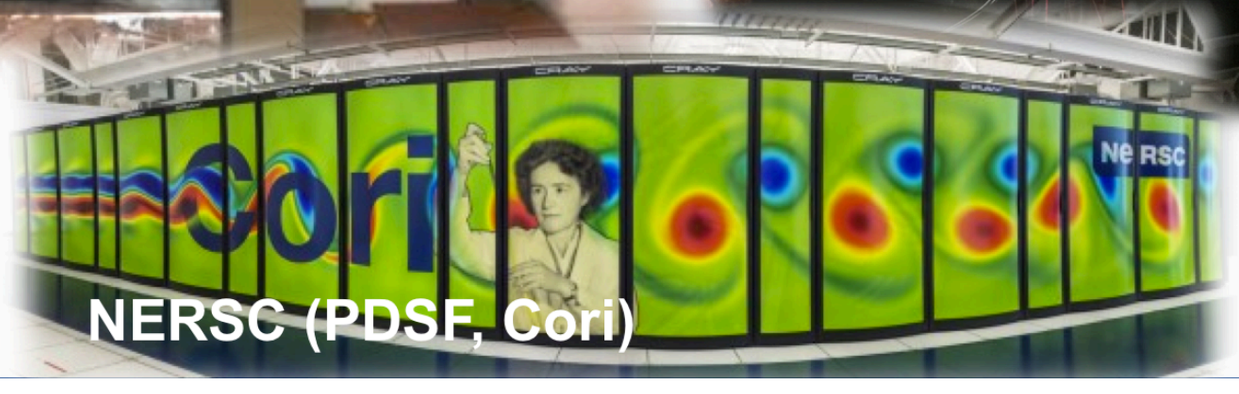


- ^{3}H beta decay
- Sensitivity: m_β<0.2 eV (90% CL)
- ^{3}H data taking started
- LBNL involves in analysis activities

Infrastructure








One more thing...

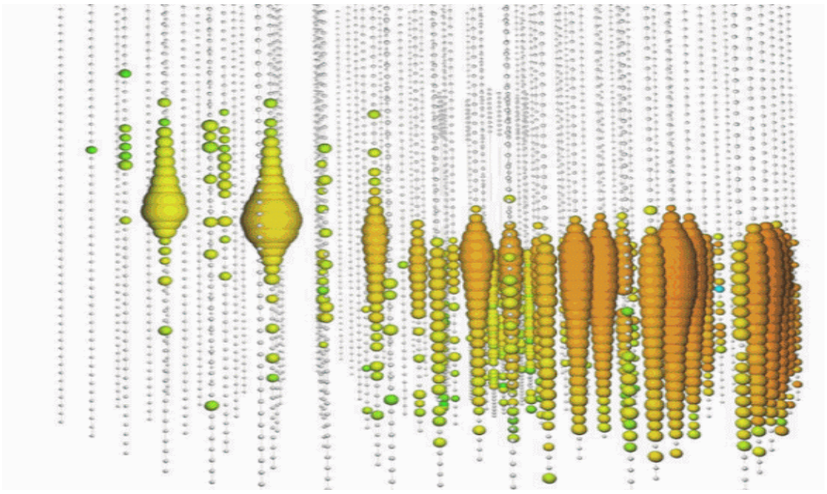
The most energetic accelerators in the universe

The UCB/LBNL IceCube Group

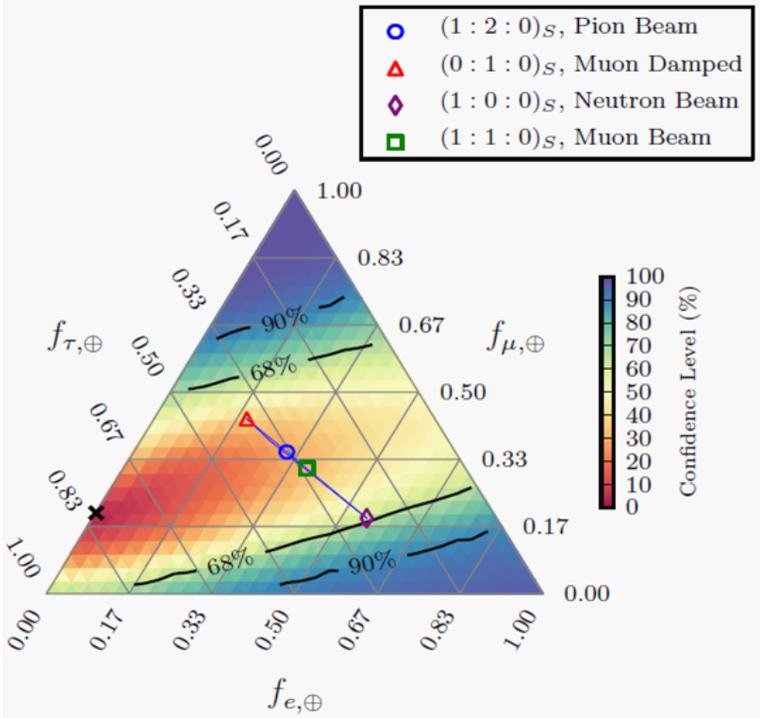
- Cosmic-rays have been observed with energies up to $3*10^{20}$ eV (50 joules!)
- Despite 100 years of effort, we have not found the accelerators that produce these particles
- Charged cosmic-rays bend in transit
- IceCube is a 1 km^3 neutrino detector at the South Pole.
- 5,160 buried optical sensors detect Cherenkov light from the charged particles produced in high-energy (>100 GeV) neutrino interactions in the polar icecap.
- We have observed cosmic neutrinos with energies up to ~5 PeV ($5*10^{15}$ eV)
- These neutrinos should (eventually) pinpoint these accelerators
- The flux is near the predicted upper limits, so sources should be easy to find.
- We have eliminated or disfavored most of the popular theories for the origins of these neutrinos: gamma-ray bursts, active galactic nuclei (galaxies containing supermassive black holes…), or supernovae.
- … a real science mystery… you can help solve it!
- IceCube also studies many other physics topics: dark matter, cosmic-ray anisotropies, magnetic monopoles, other exotica…

IceCube @ LBNL

- A friendly group with 1 senior staff, 1 postdoc, 1-2 grad and (usually) 1 undergrad
- LBNL played key roles in IceCube hardware
- Active in astrophysical neutrinos, neutrino physics & cosmic-ray physics
  - First measurement of neutrino absorption in the Earth and the neutrino-nucleon cross-section*
    - Published in Nature, Oct. 2017
  - Measurement of the astrophysical neutrino flavor (ν_e:ν_μ:ν_τ) ratio*
  - Measurement of the atmospheric ν_e energy spectrum
- Future interests include
  - New techniques to measure PeV astrophysical ν
  - Neutrino physics – measurements of neutrino inelasticity* and a precise measurement of the neutrino-nucleon cross-section
    - Leptoquarks, extra-dimensions or other exotica would affect the cross-section & inelasticity distribution
  - Unusual classes of cosmic-ray events
  - ARIANNA, a proposed 100 km^3 experiment to search for radio pulses emitted when ultra-high energy neutrinos interact in the Antarctic Ross Ice Shelf.
- If you are interested in finding out more, please contact me:
  - Spencer Klein, at (510) 486-5470, or srklein@lbl.gov



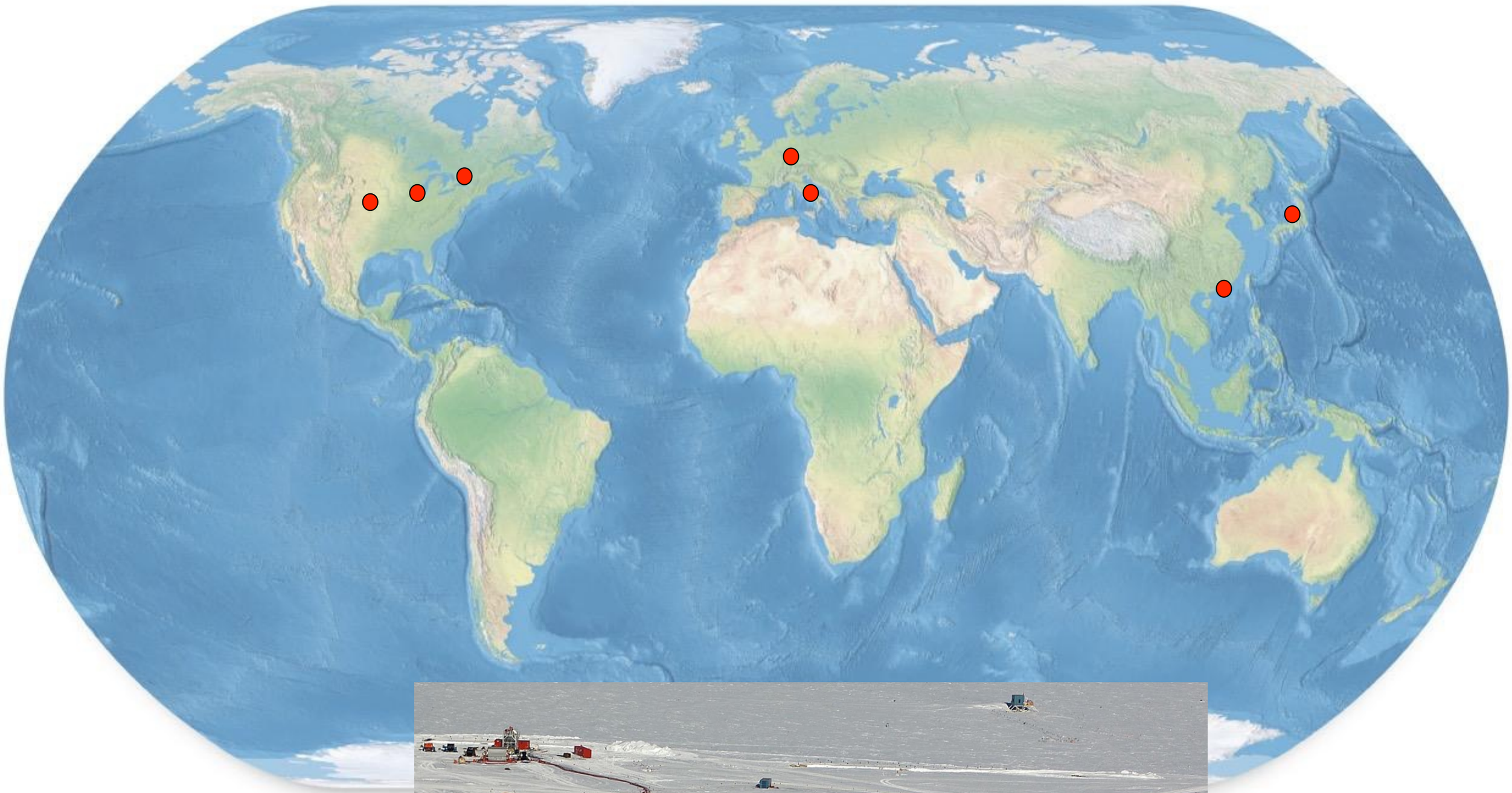
Event display of a ~ 5 PeV μ from a ~ 10 PeV ν – a 1 km long track.



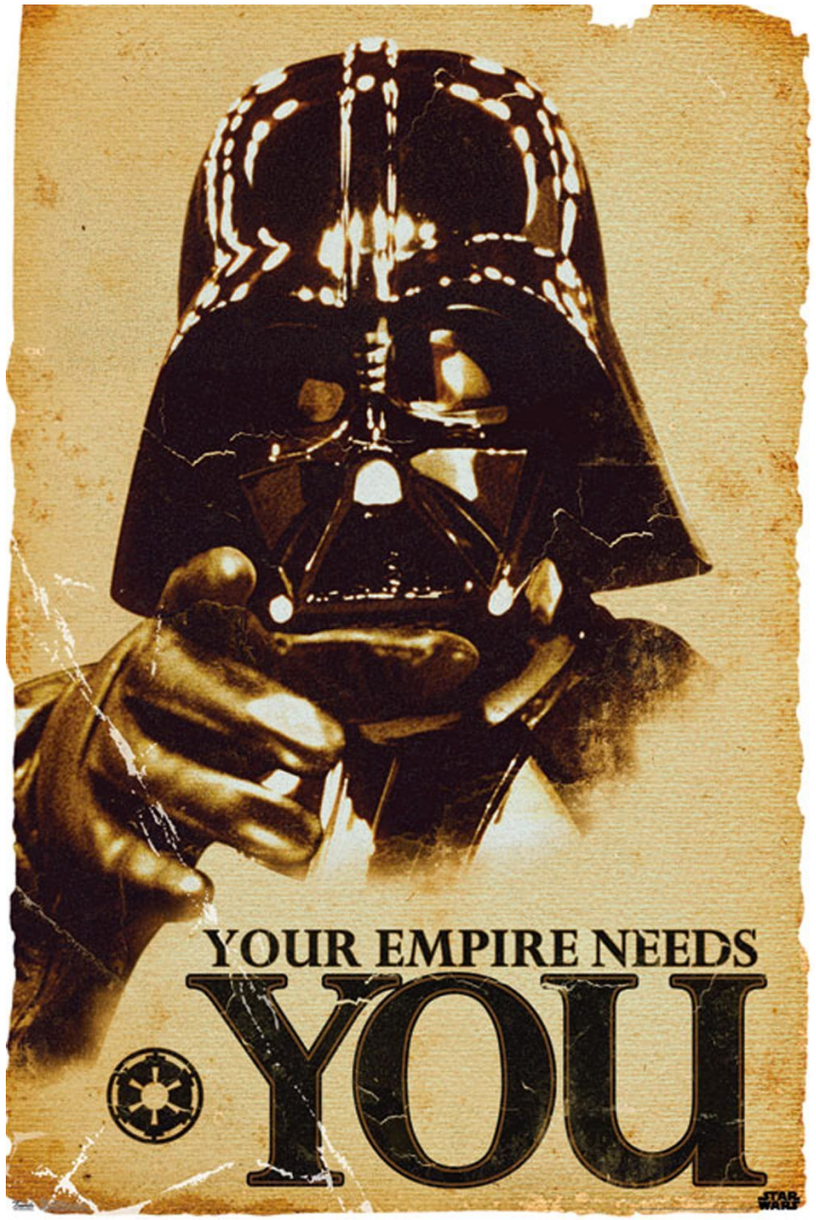
Astrophysical ν flavor ratio triangle

* Dissertation of current/past UCB student

Neutrino programs @ Berkeley



The ‘light’ (neutrino) side wants you!



And the ‘dark’ (matter) side wants you too! …next up

Backup

Double Beta Decay (ββ)

- Even-even nucleus (Z,A) whose pairing forces make it more bound than neighbor (Z+1,A), but less so than (Z+2,A).