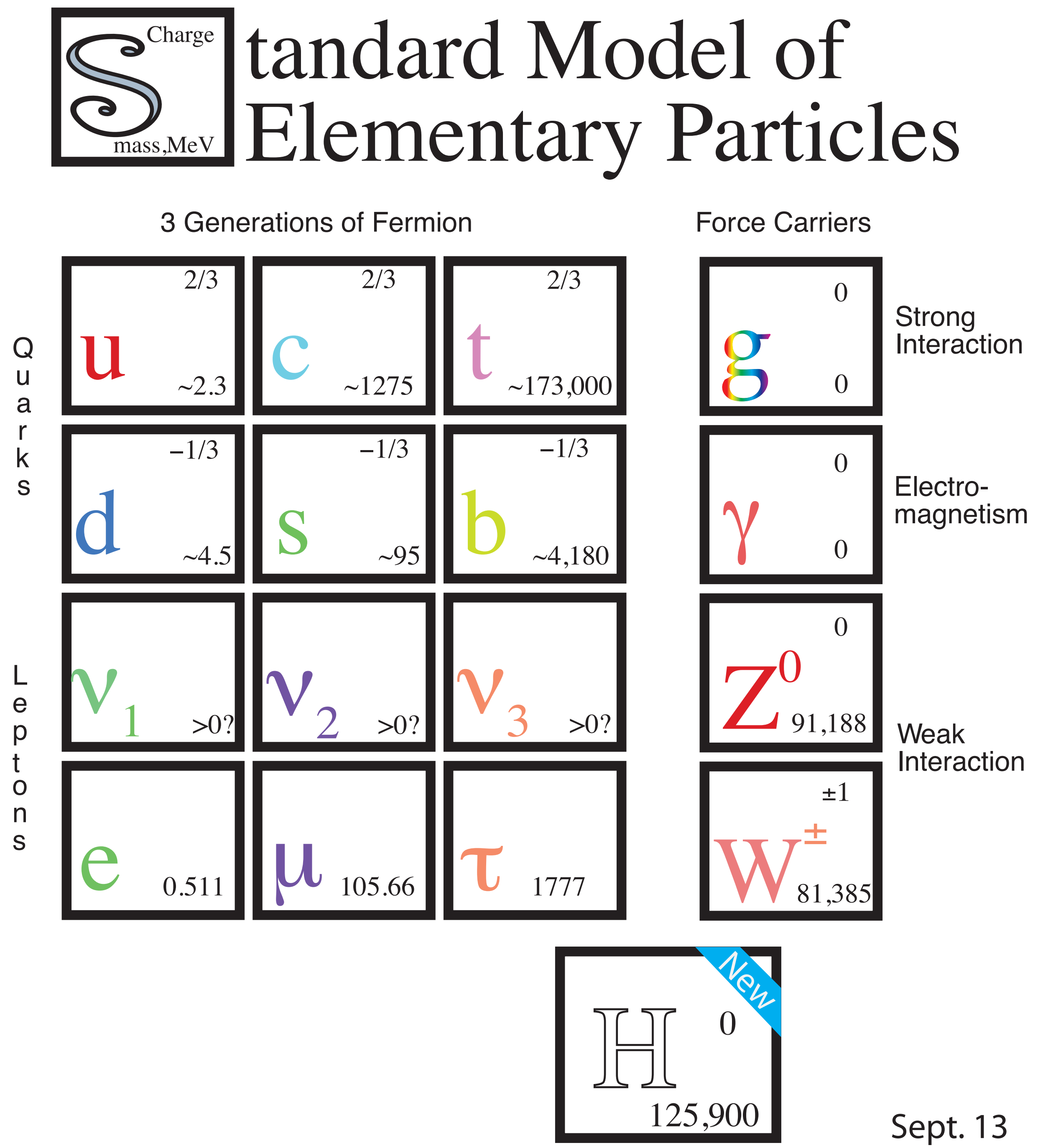
NEUTRINO MIXING AND MASSES

Heidi Schellman September 2016


Standard Model of Elementary Particles
Charge
mass,MeV
3 Generations of Fermion
Force Carriers
Quarks
u 2/3 ~2.3
c 2/3 ~1275
t 2/3 ~173,000
d −1/3 ~4.5
s −1/3 ~95
b −1/3 ~4,180
Leptons
ν1 >0?
ν2 >0?
ν3 >0?
e 0.511
μ 105.66
τ 1777
g 0 0
Strong Interaction
γ 0 0
Electro-magnetism
Z0 0 91,188
W± ±1 81,385
Weak Interaction
New
H 0 125,900

Sept. 13

Standard Model of Elementary Particles

(Key: Charge at top right, mass in MeV at bottom right)

	3 Generations of Fermion			Force Carriers	
Quarks	u 2/3 ~2.3	c 2/3 ~1275	t 2/3 ~173,000	g 0 0	Strong Interaction
Quarks	d −1/3 ~4.5	s −1/3 ~95	b −1/3 ~4,180	γ 0 0	Electro-magnetism
Leptons	ν_1 >0?	ν_2 >0?	ν_3 >0?	Z^0 0 91,188	Weak Interaction
Leptons	e 0.511	μ 105.66	τ 1777	$W^{\pm}$ ±1 81,385	Weak Interaction

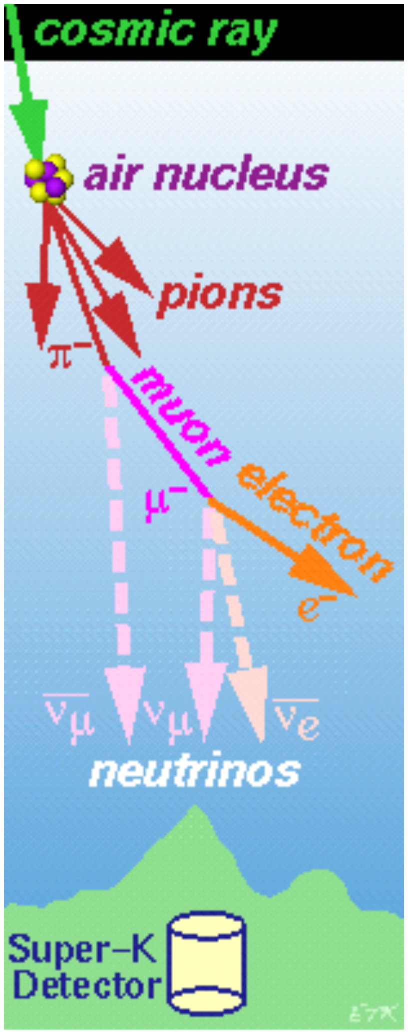
New: H 0 125,900

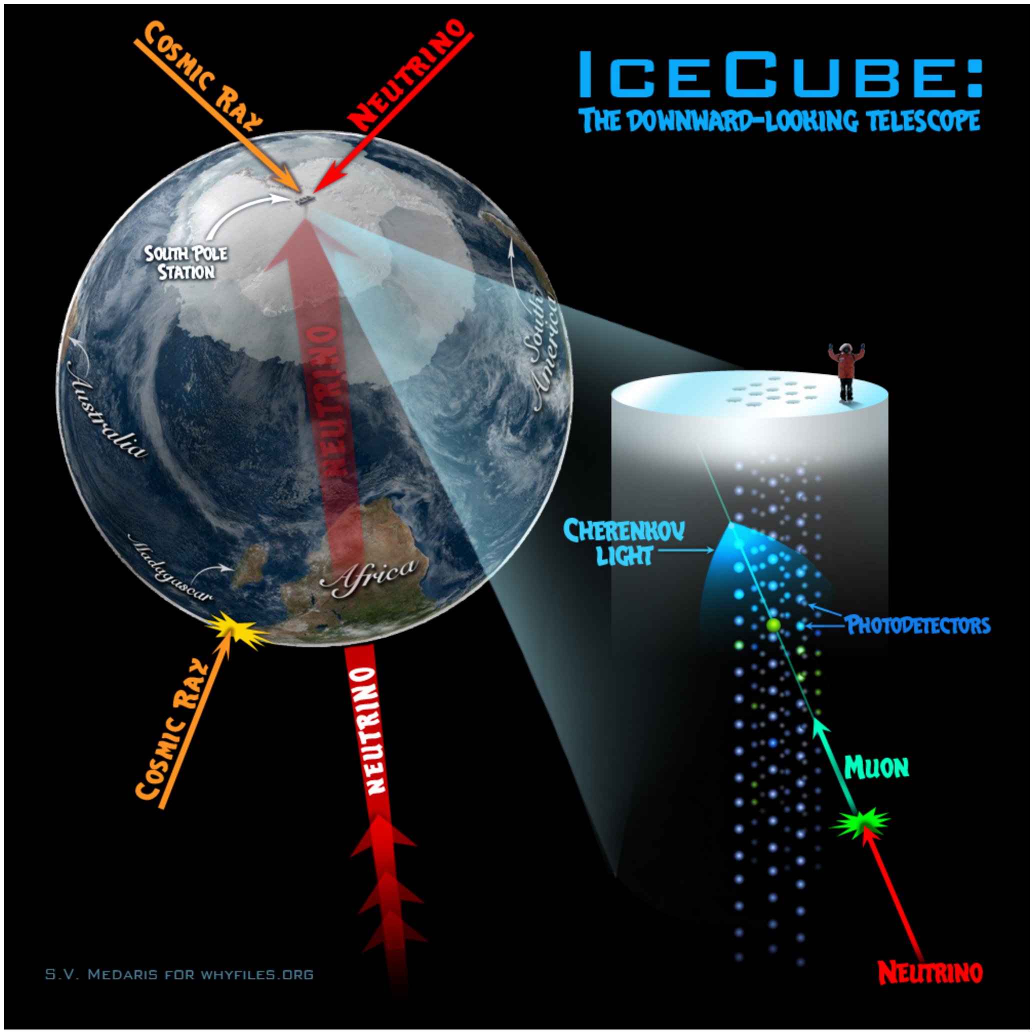
Sept. 13

Overview of mixing experiments

- Atmospheric neutrinos
- Solar neutrinos
- 3 parameter mixing
- Designing an experiment

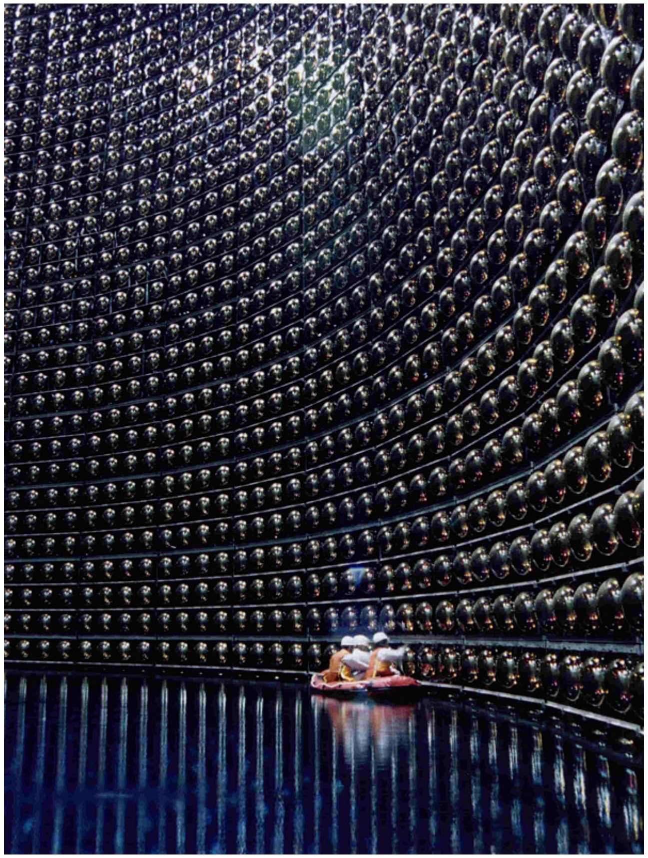
Neutrinos from the sky





Large (10-100 kilo ton) vats of water or liquid scintillator

- Dig large hole in mine
- put a very large amount of clear liquid in it
- Dope it with desirable chemicals
- Read out with photomultiplier tubes

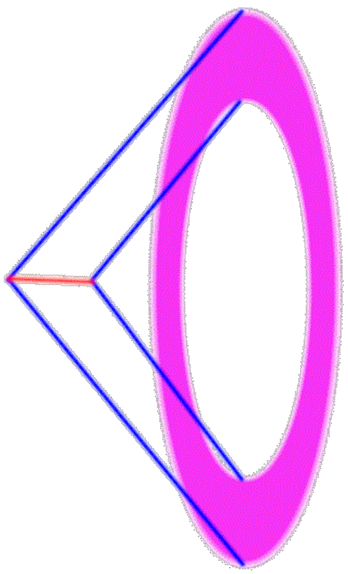


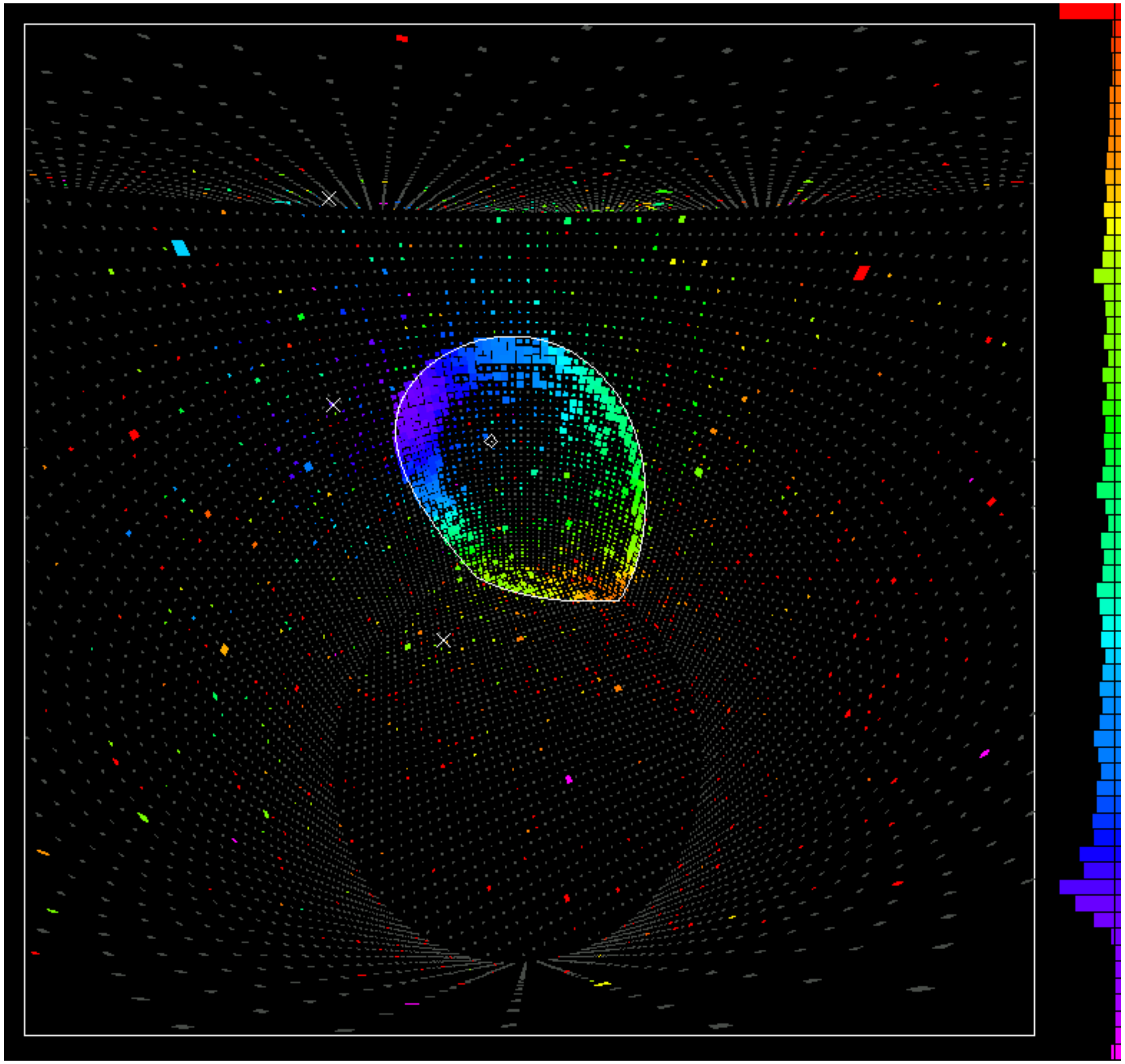
SuperKamioKande in Japan ~10,000 20” phototubes

An muon from a cosmic neutrino

$\nu_\mu + p \rightarrow \mu + X$

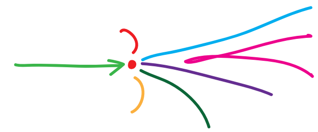
Cerenkov radiation



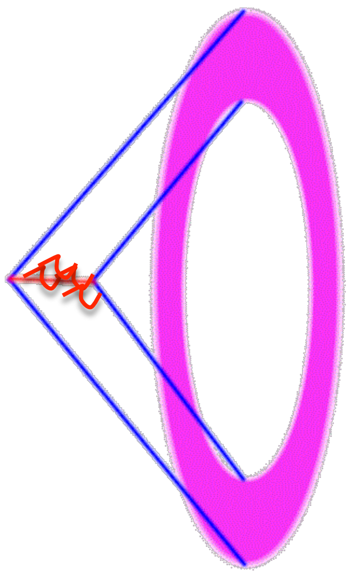


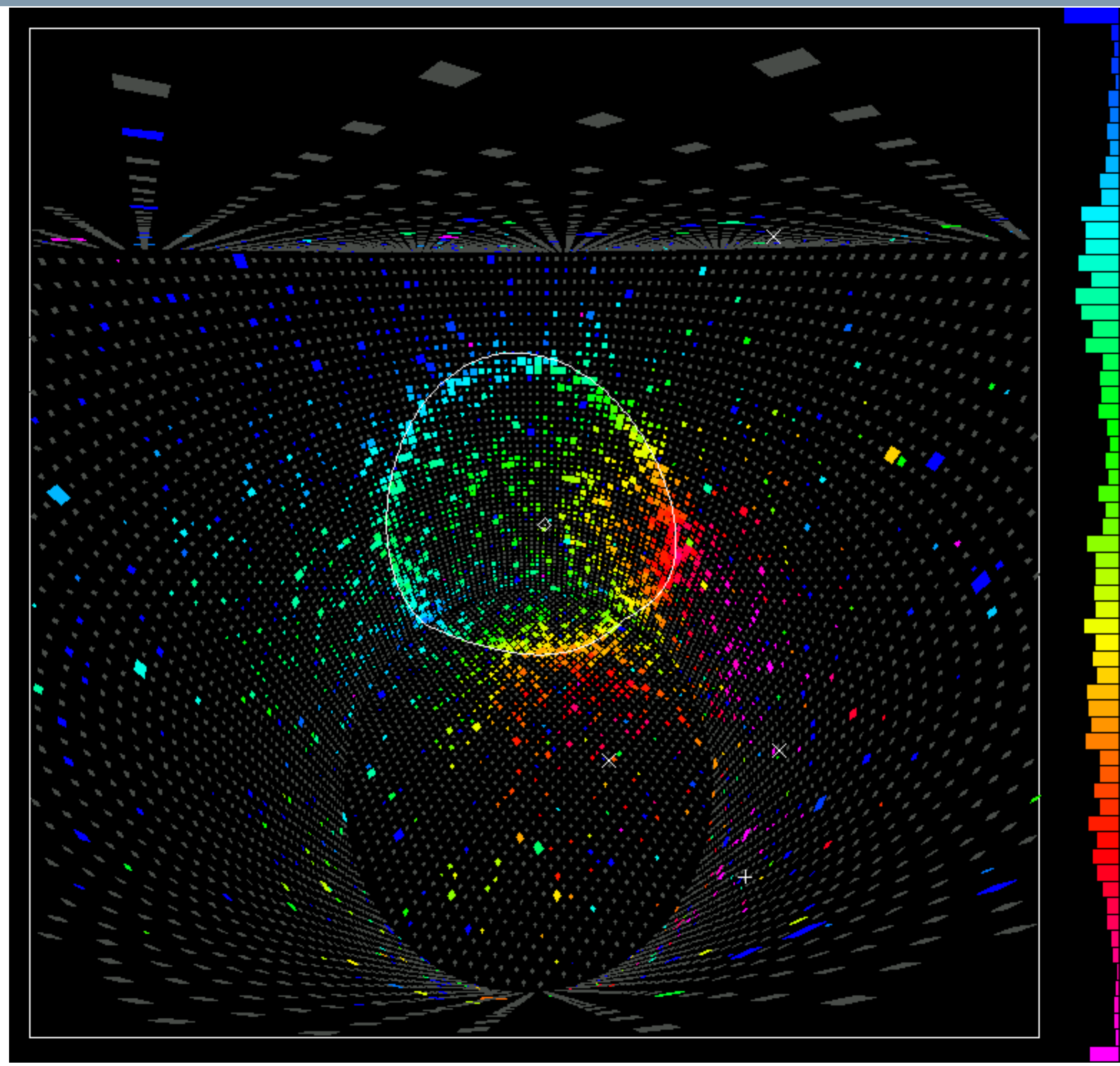
An electron from a 600 MeV cosmic neutrino

$\nu_e + p \rightarrow e + X$



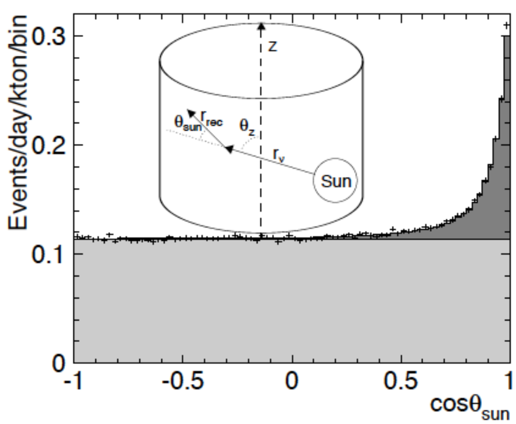
Cerenkov radiation

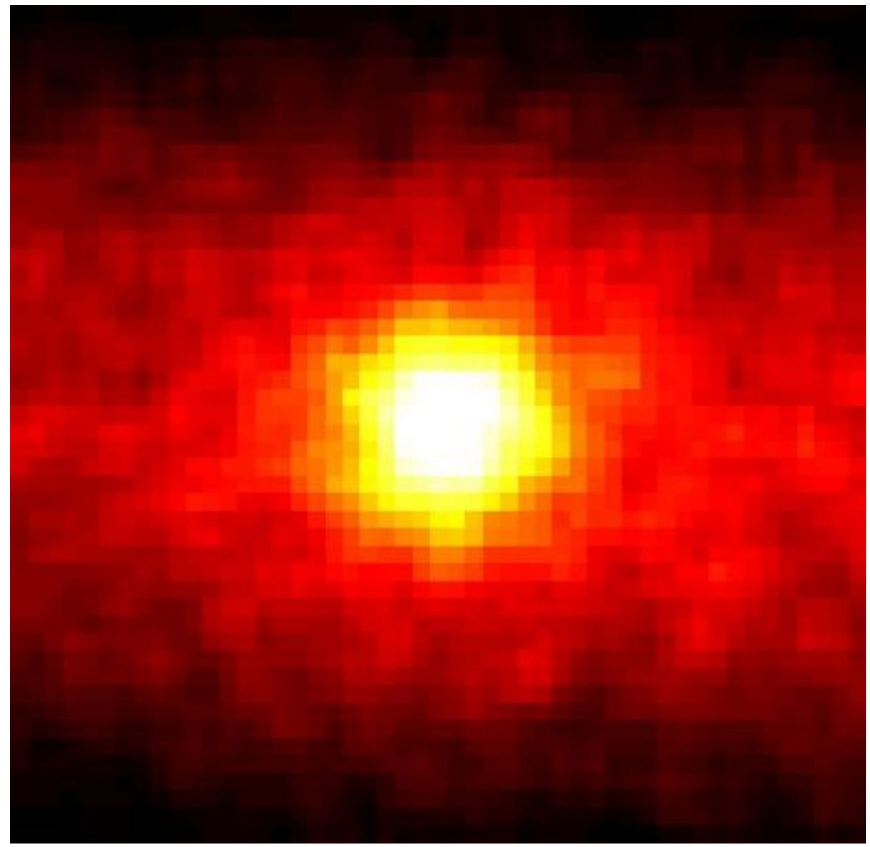




Neutrinos don’t interact much

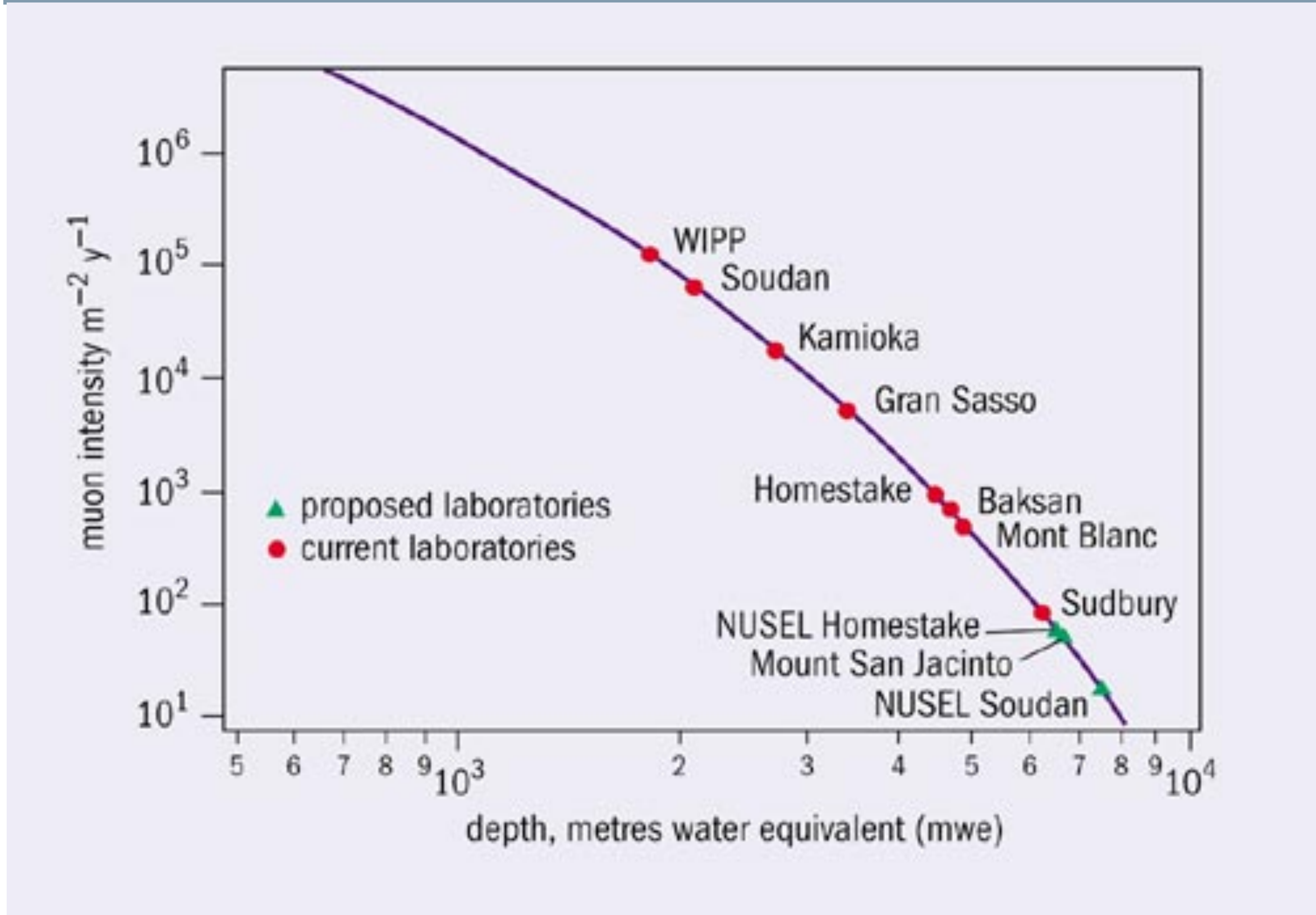
- If those 10^{11}/sec/cm^2 solar neutrinos interacted much, we’d be in trouble.
- We can see them but they interact about once/ton of material/ day.



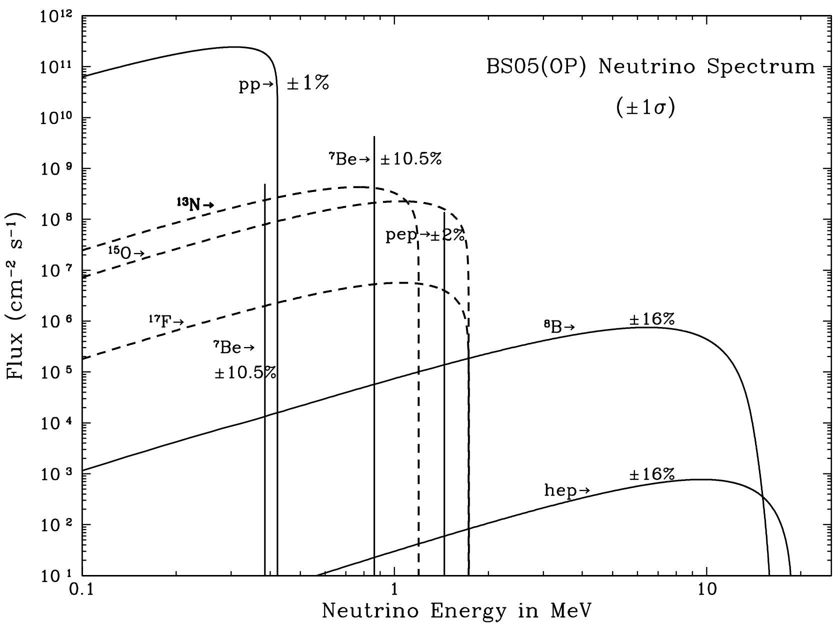


http://apod.nasa.gov/apod/ap980605.html

Needs to be deep



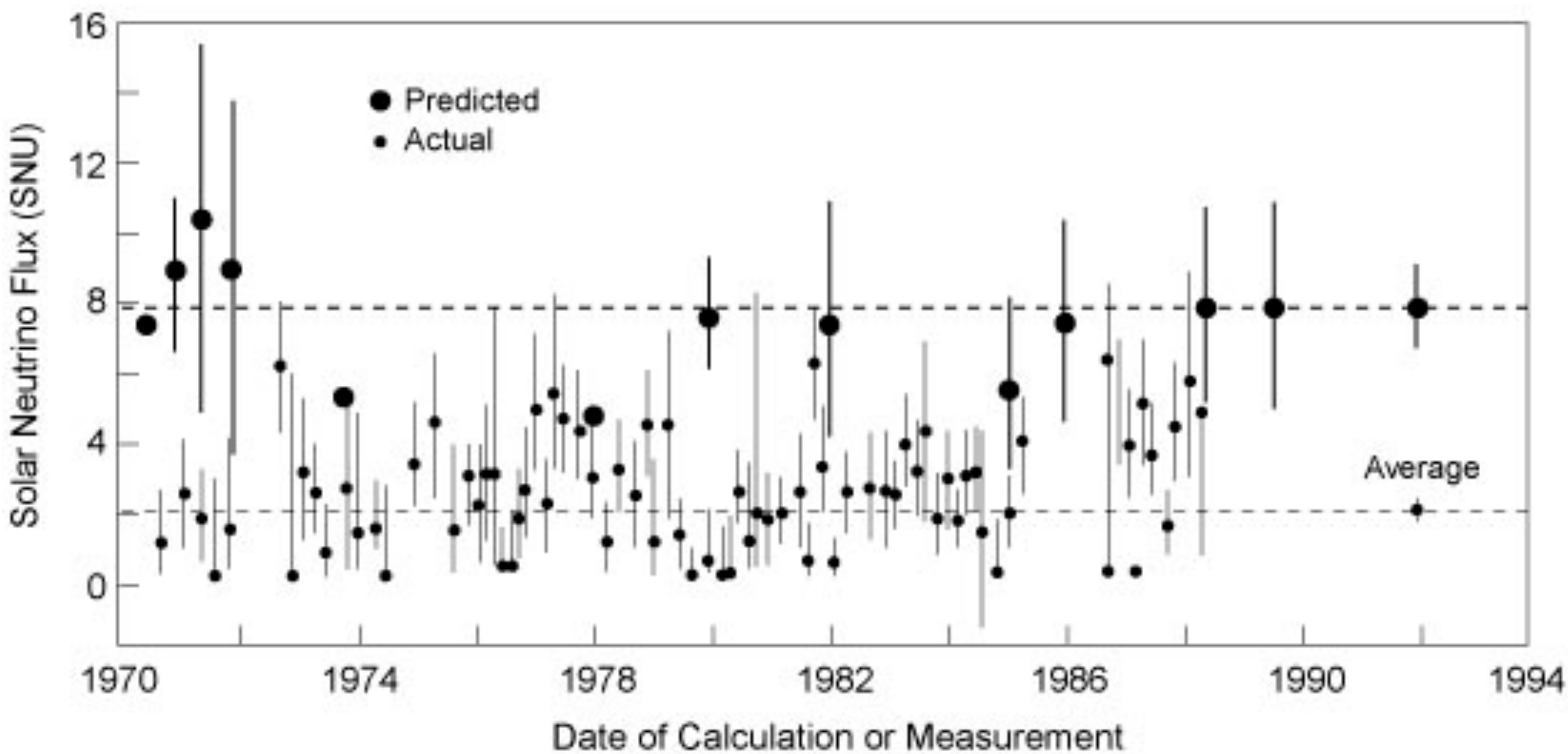
Neutrino mysteries: the missing solar neutrinos



n +^{37} Cl makes ^{37}Ar that decays back to ^{37} Cl with a half-life of 35 days. Ray Davis used this to measure neutrinos from the sun. Basically get a big vat of CCl_4 , put it 4850' deep in a gold mine, extract Argon atoms and count Ar decays.

http://www.nobelprize.org/nobel_prizes/physics/laureates/2002/

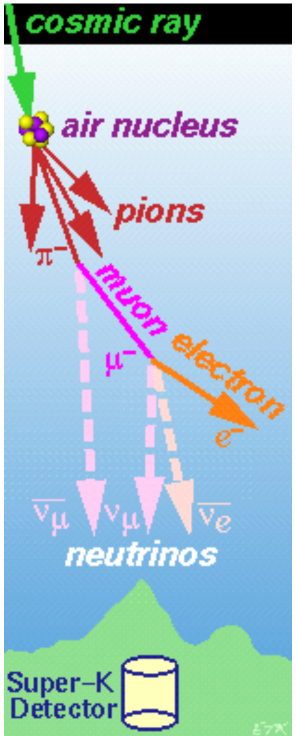
60% of solar neutrinos are missing



http://iopscience.iop.org/0004-637X/496/1/505/fulltext/34468.text.html

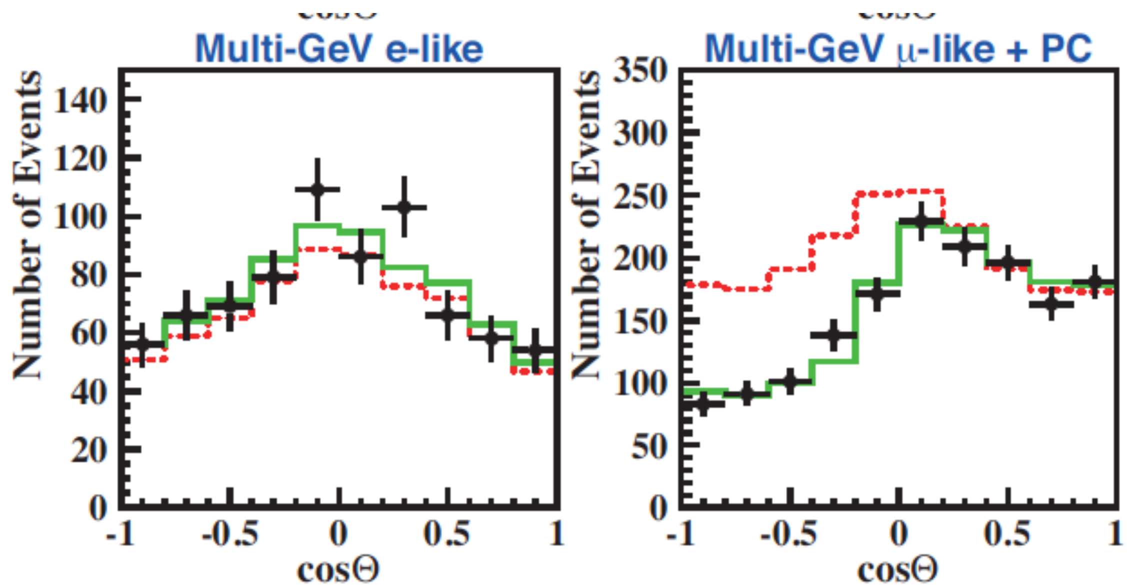
A definite oscillations signal was seen in 1997!

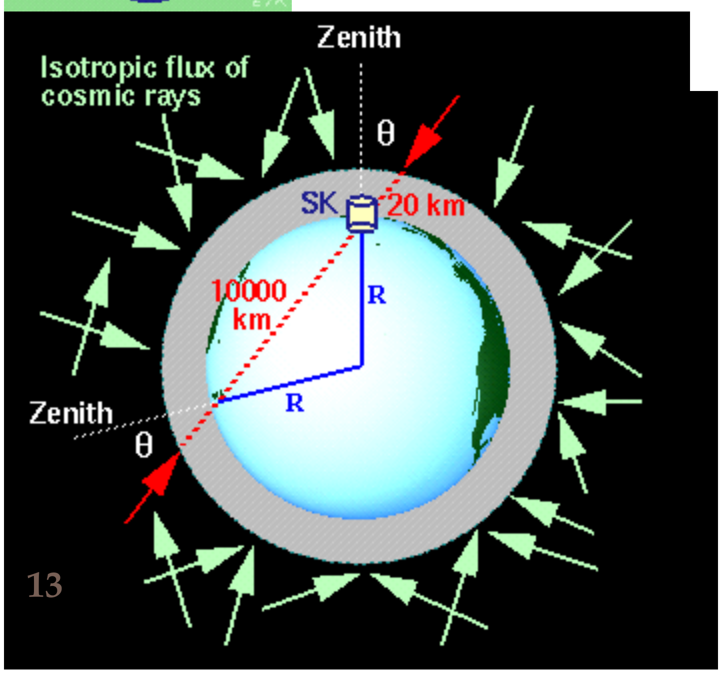
Atmospheric neutrinos



Energies in the 1-100 GeV range

Distances ~ 10,000 km





SuperKamiokande muon neutrinos

First observation of an oscillation pattern – Phys.Rev.Lett.81(1998)p.1562, Phys. Lett. B436(1998)p.33

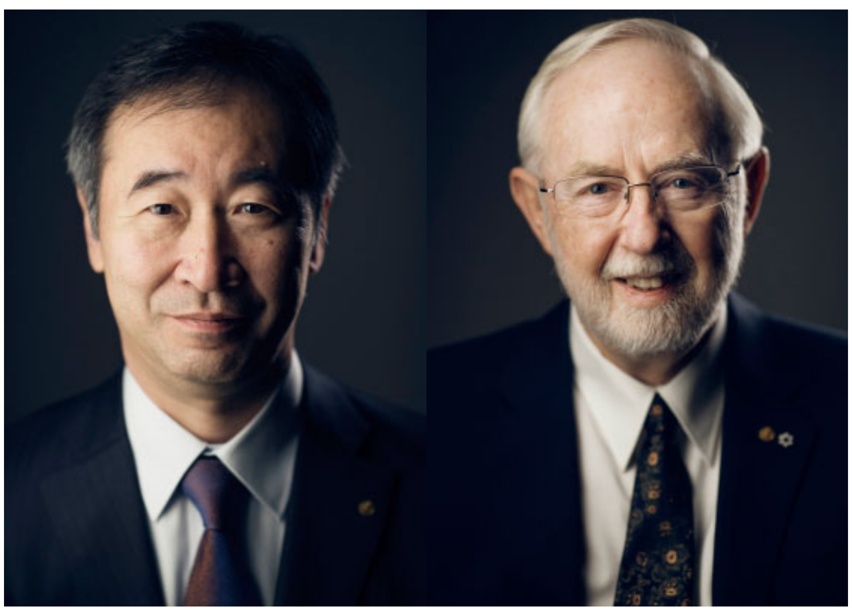
Oscillating to tau neutrinos?

Hypothesis: Neutrino mixing

- Electron and muon neutrinos are disappearing when they travel long distances.
- This is possible if the neutrinos detected in our detector are a superposition of 2 (or more) different mass states.

Hypothesis: Neutrino mixing

- Electron and muon neutrinos are disappearing when they travel long distances.
- This is possible if the neutrinos detected in our detector are a superposition of 2 (or more) different mass states.

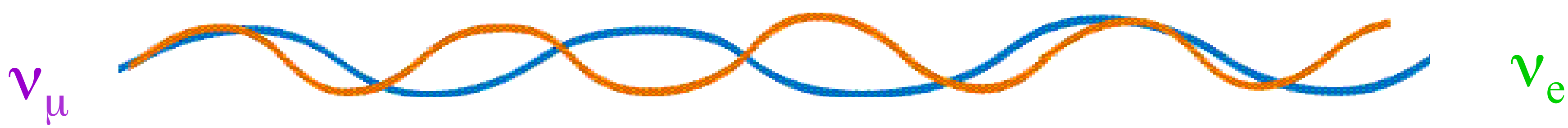


Takaaki Kajita and ArthurMcDonald
Nobel Prize 2015

Two flavor mixing

- Assume that the weak eigenstates ν_e and ν_μ are mixtures of the mass eigenstates ν_1 and ν_2

$$\begin{bmatrix} \nu_e \\ \nu_\mu \end{bmatrix} = \begin{bmatrix} \cos\theta \sin\theta \\ -\sin\theta \cos\theta \end{bmatrix} \begin{bmatrix} \nu_1 \\ \nu_2 \end{bmatrix}$$



Flavor basis | Mass basis | Flavor basis

$$\begin{bmatrix} \nu'_e \\ \nu'_\mu \end{bmatrix} = \begin{bmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{bmatrix} \begin{bmatrix} e^{i(E_1 t - p_1 L)} & 0 \\ 0 & e^{i(E_2 t - p_2 L)} \end{bmatrix} \begin{bmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{bmatrix} \begin{bmatrix} \nu_e \\ \nu_\mu \end{bmatrix}$$

Get a beat frequency that depends on $(m_1^2 - m_2^2)\, L/2E$

2 different views of the same neutrinos

ν_e

ν_μ

ν_τ

Flavor Basis

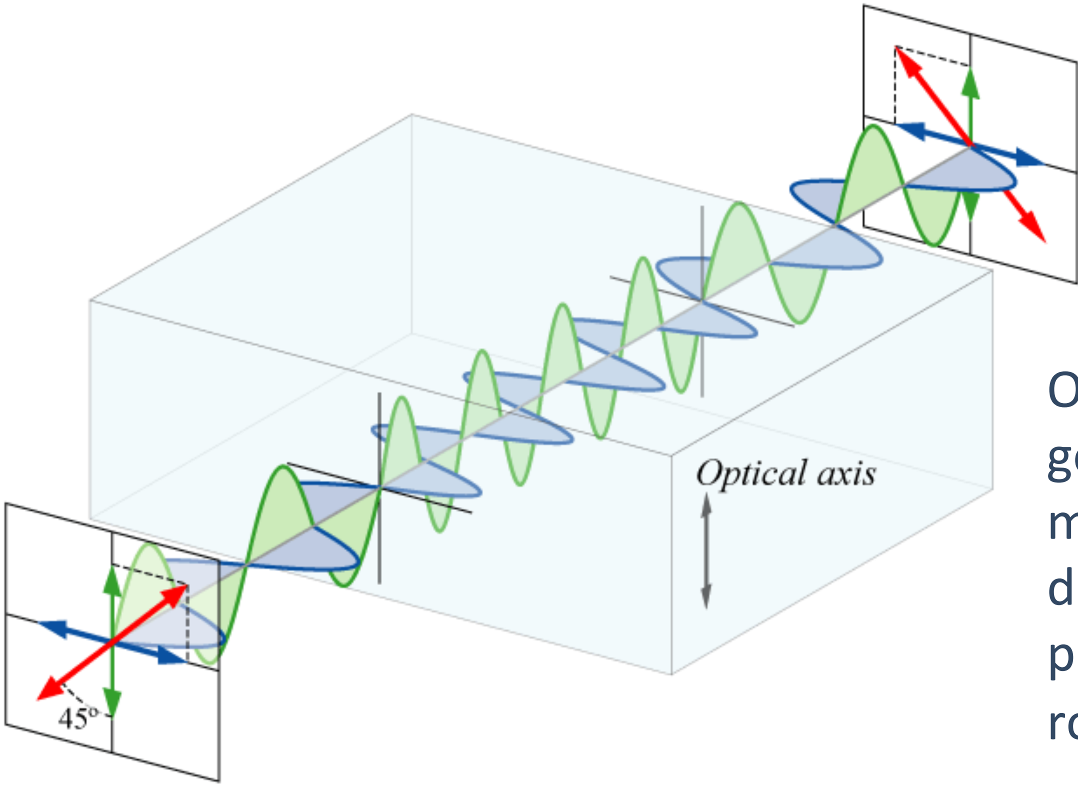
ν_1

ν_2

ν_3

Mass Basis

Optical Analog

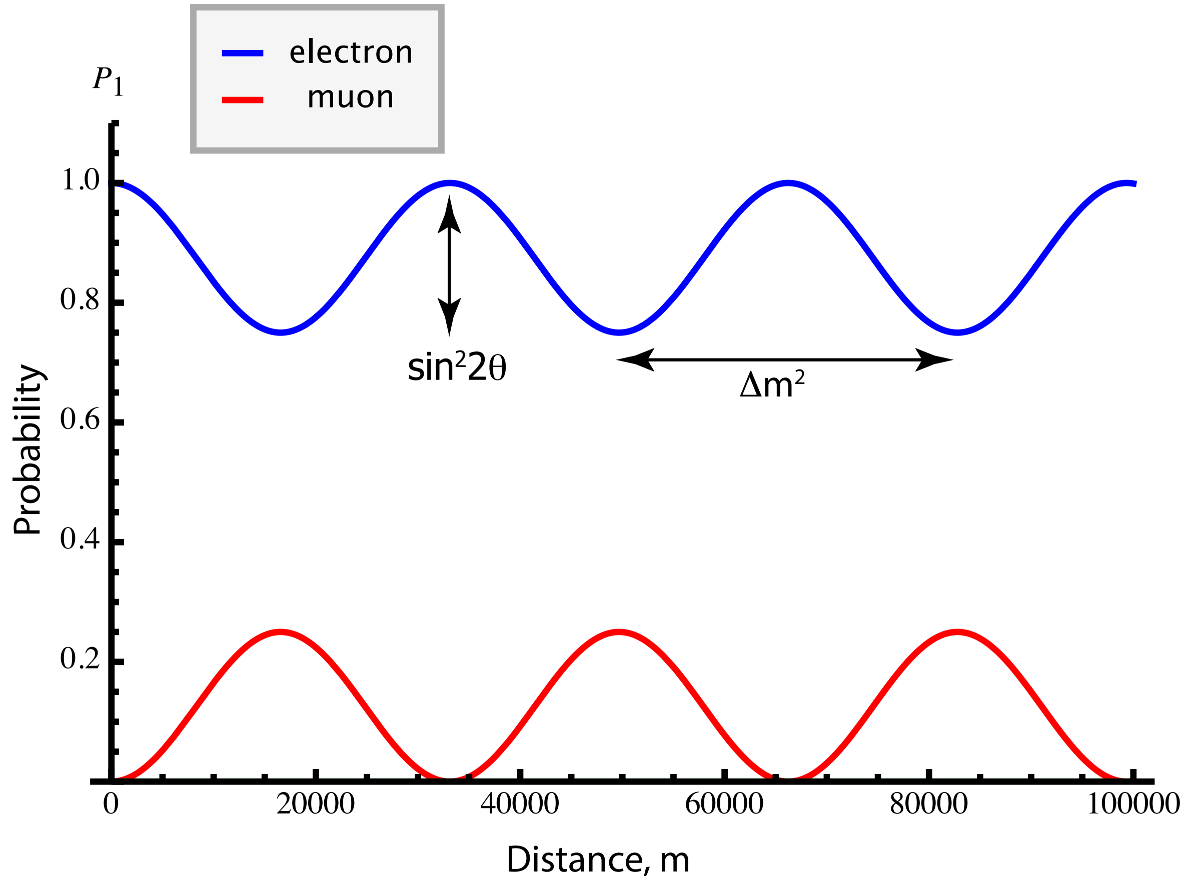


Courtesy of Wikipedia

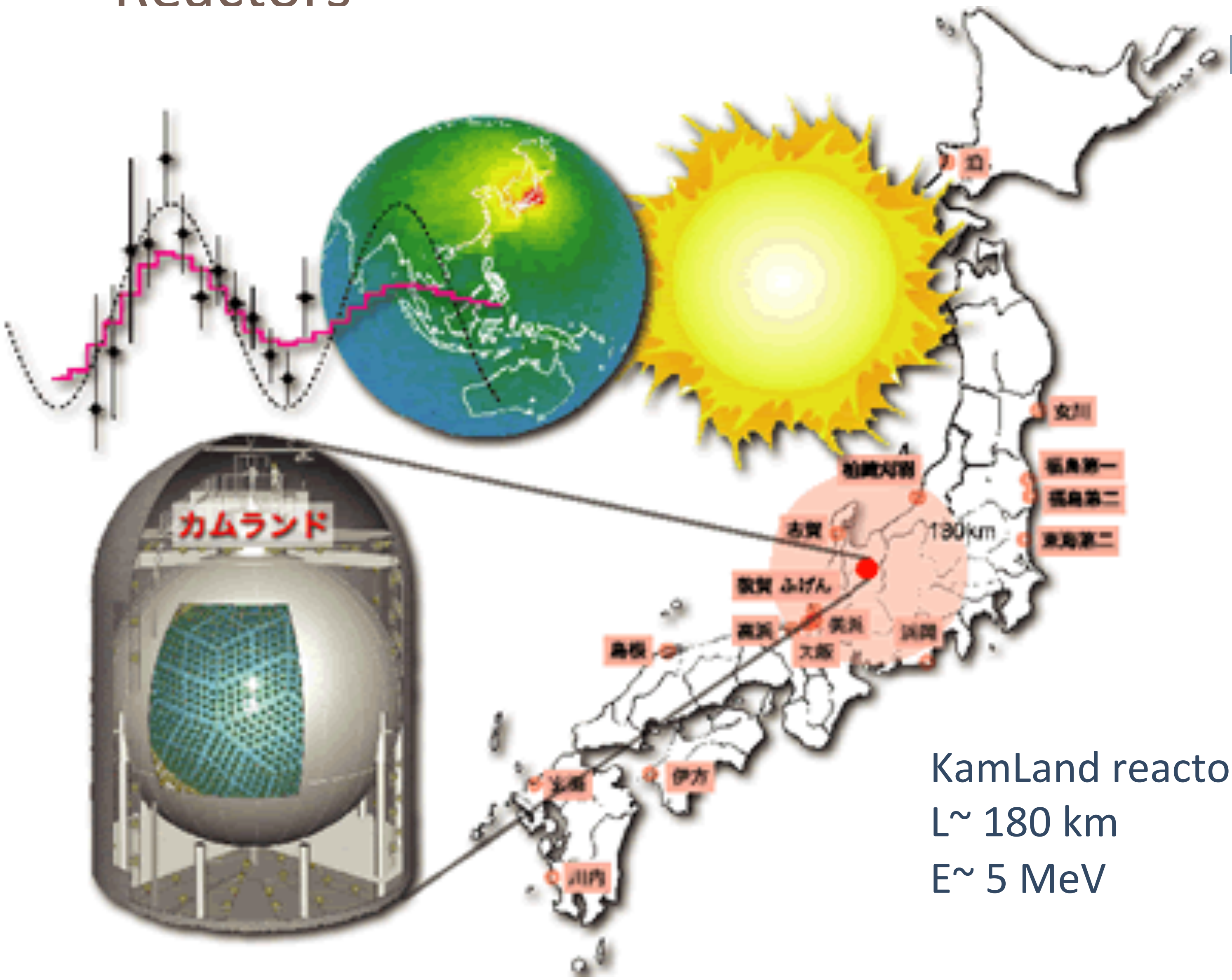
Optical analog is polarized light going through a birefringent material. The speed of light is different for different polarizations, leading to a rotation of the polarization.

The Higgs field, by coupling to mass, makes the universe birefringent for neutrinos!

$$P_{\alpha\to\beta,\alpha\neq\beta} = \sin^2(2\theta)\sin^2\left(\frac{\Delta m^2 L}{4E}\right) \text{ (natural units).}$$

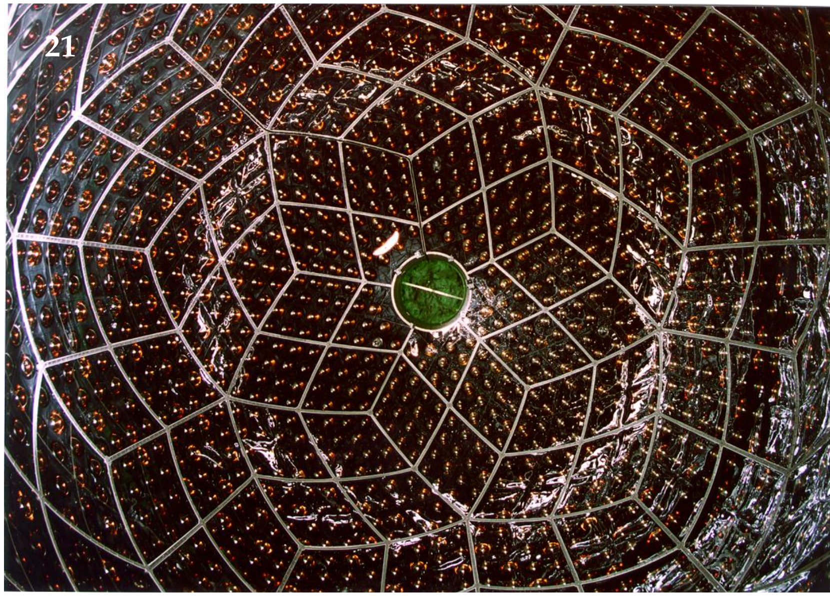


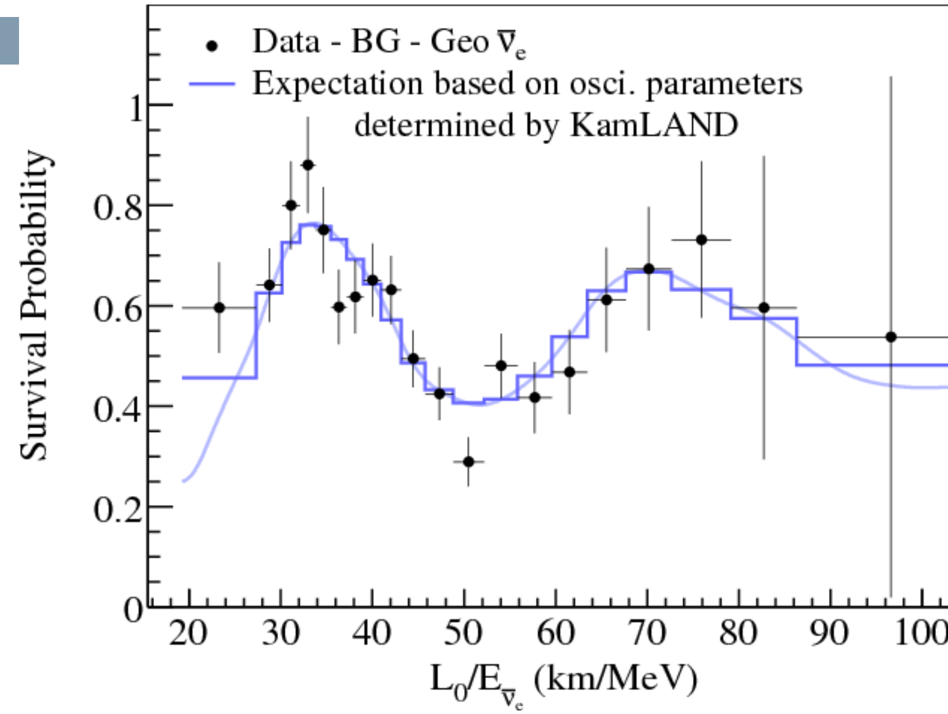
Electron anti-neutrinos on earth: Reactors



KamLand reactor $\bar{\nu}_e$
L~ 180 km
E~ 5 MeV

Can measure θ_{12} and Δm_{12} on earth

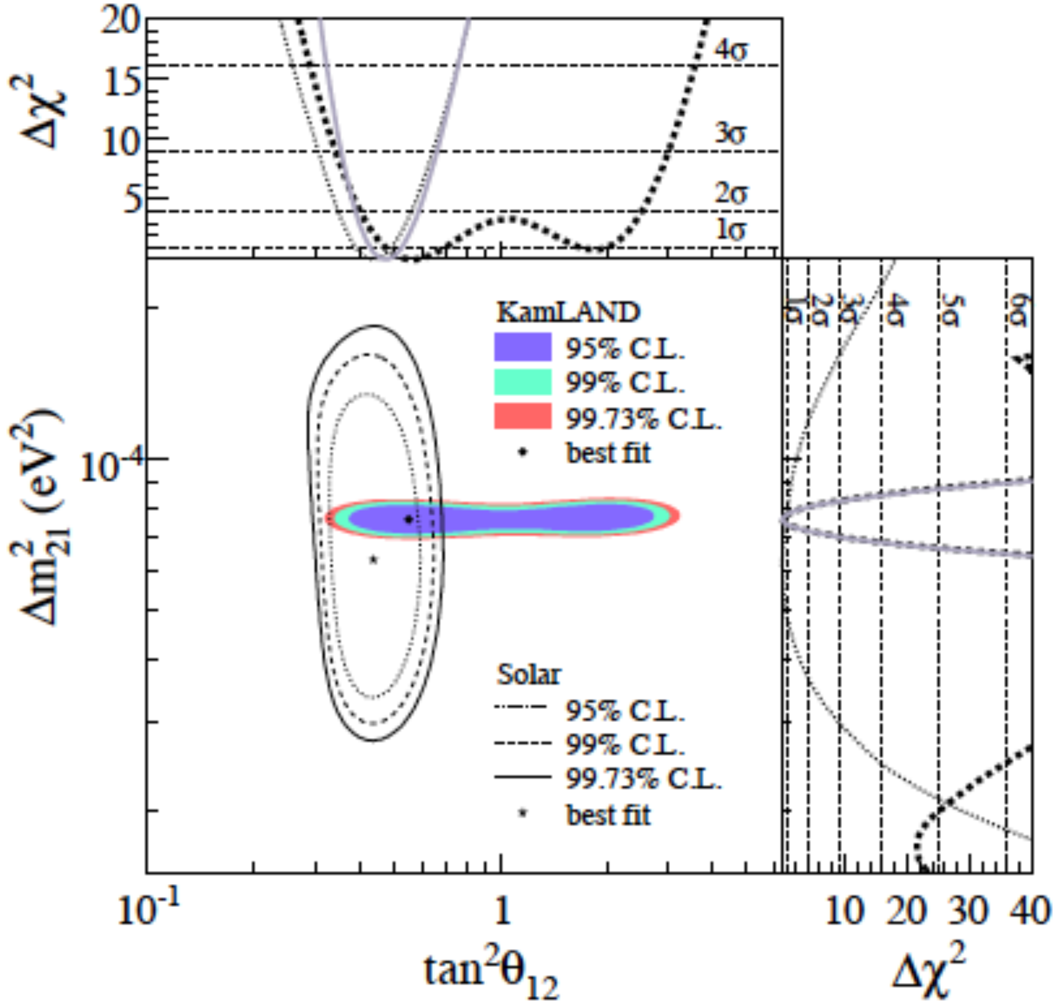




The KAMLAND neutrino experiment in Japan used nuclear reactors ~ 180 km away to measure the “solar” neutrino oscillations.

Phys.Rev.Lett.100:221803,2008

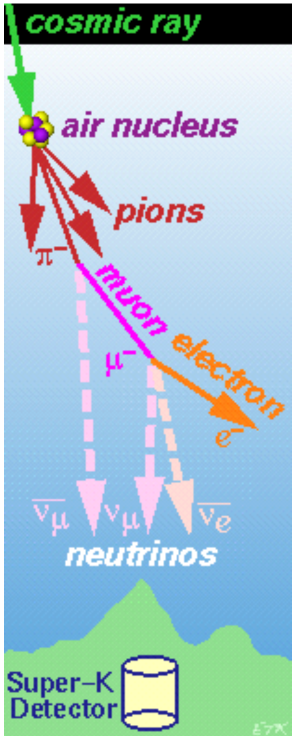
Results from KAMLAND and the sun



$$\Delta m^2_{sol} = 7.53^{+0.18}_{-0.18} \times 10^{-5}\ \mathrm{eV}^2$$
$$\sin^2(2\theta_{12}) = 0.846 +- 0.021$$

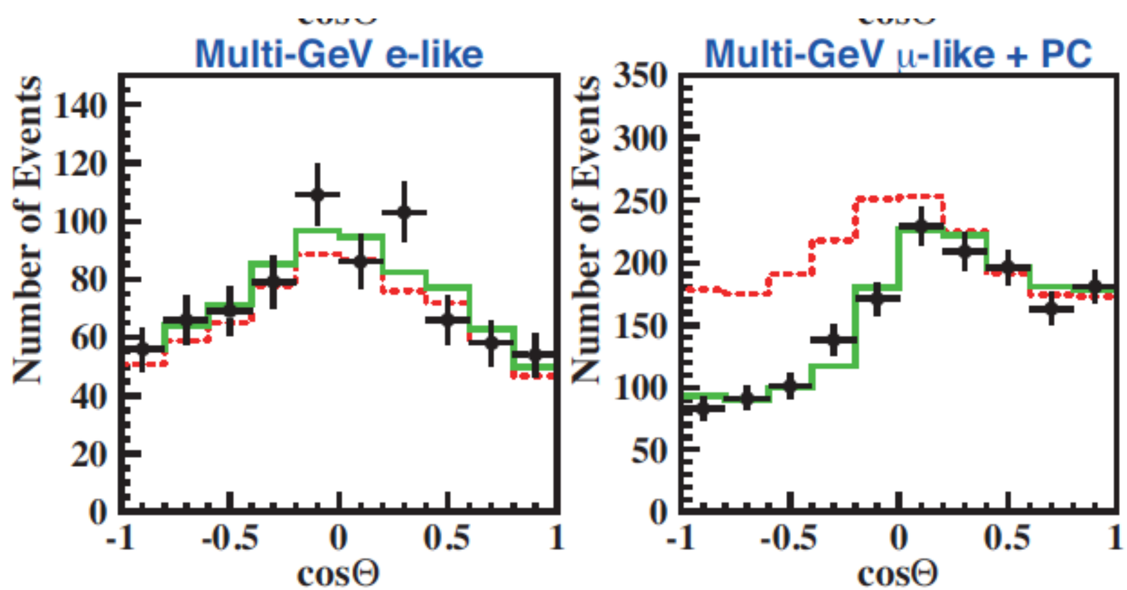
atmospheric neutrinos

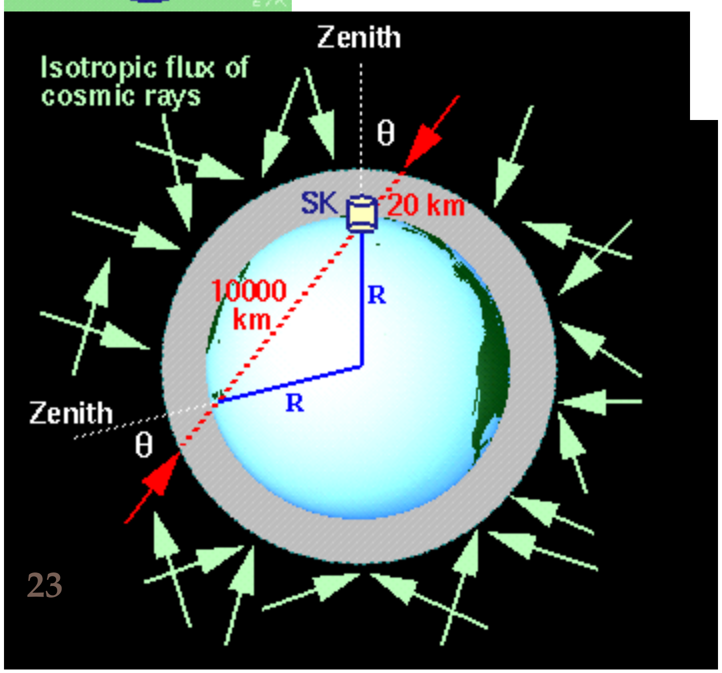
SuperKamiokande muon neutrinos
Phys. Lett. B436(1998)p.33



Energies in the 1-100 GeV range

Distances ~ 10,000 km





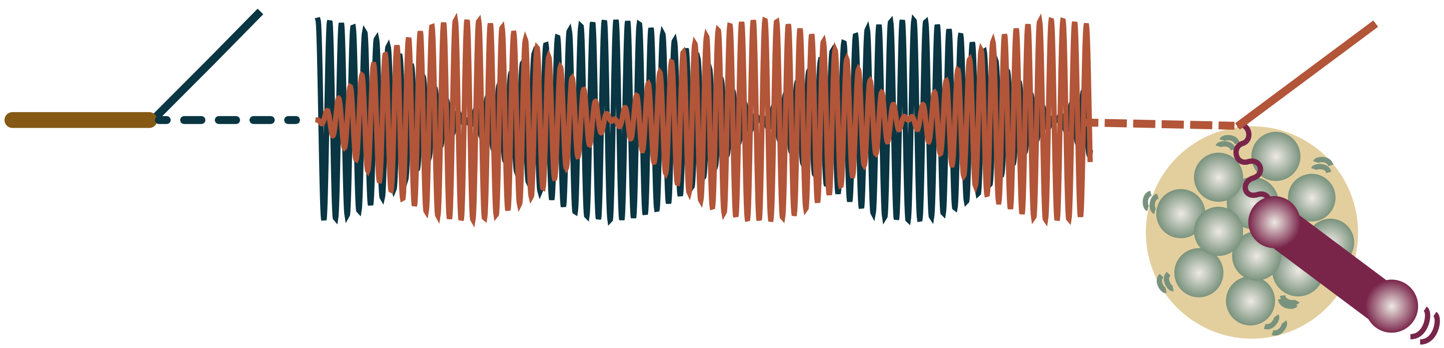
PDG best fit 2015 fpr muon disappearance.

$$\Delta m^2_{atm}\ 2.44^{+0.06}_{-0.06}\times 10^{-3}\ \text{eV}^2$$
$$\sin^2(2\theta_{atm}) > 0.92$$

Beat frequency

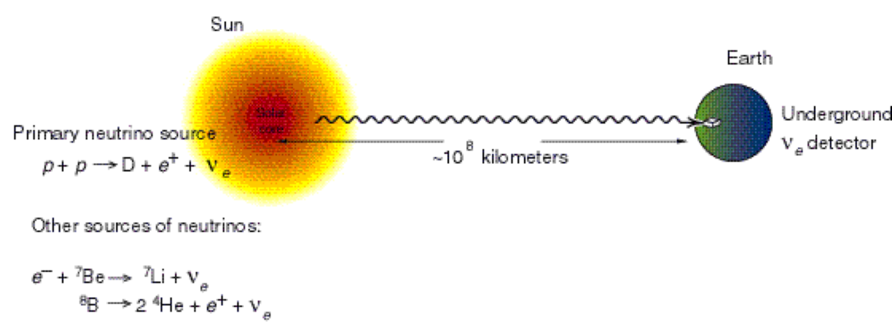
3 GeV atmospheric neutrino wavelength is ~ 10^{-16} m

Beat distances are in thousands of km so the phase difference is very small!



Distance and mass scales

- The atmospheric results do not explain missing solar neutrinos as ν_e didn't disappear in the atmospheric data
- Turns out there are two distinct mass scales (and hence two mass separations).
  - 1) The Solar mass difference Δm_{sol} that causes solar electron neutrinos to go missing between the sun and earth.

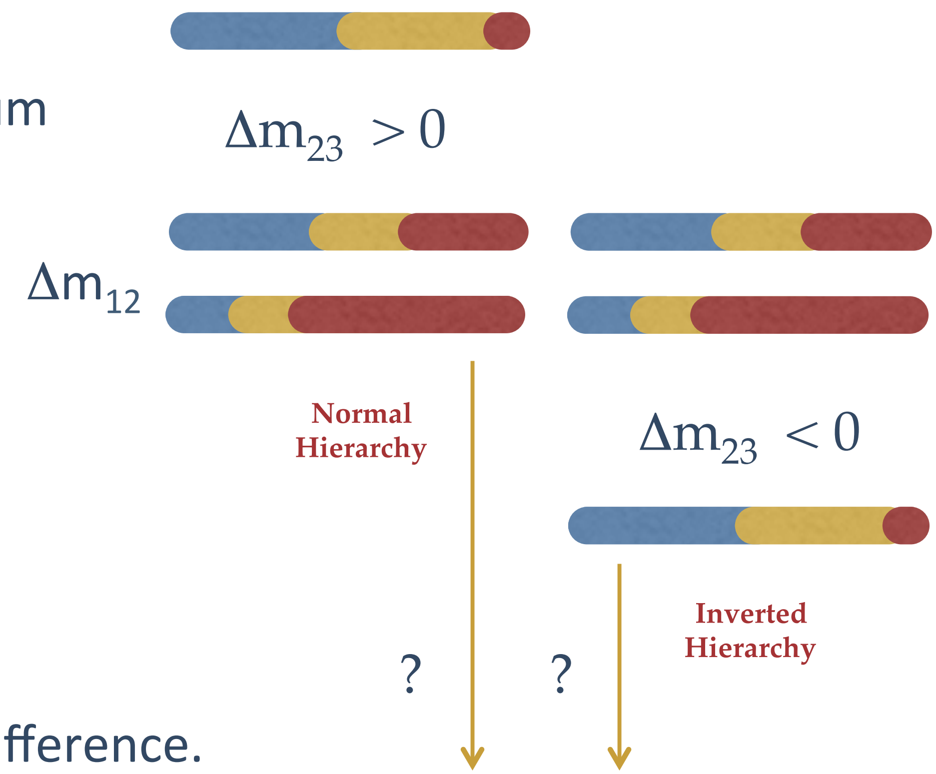


  - 2) The "Atmospheric" mass difference Δm_{atm} that explains the disappearance of muon neutrinos made in the atmosphere and accelerator experiments.

To have 2 differences you must have 3 masses!

Not unexpected as there are 3 types of charged leptons

We know the absolute value of the mass differences but not the minimum mass or the sign of Δm^2_{23}



$$|\Delta m^2_{21}| \cong 7.5 \times 10^{-5} \ \ \mathrm{eV}^2 \,,$$
$$|\Delta m^2_{31}| \cong 2.5 \times 10^{-3} \ \ \mathrm{eV}^2 \,,$$
$$|\Delta m^2_{21}|/|\Delta m^2_{31}| \cong 0.03 \,.$$

Interactions with matter can tell the difference.

$\Delta m^2_{12} > 0$ is known from solar

Sign of Δm^2_{23} is still unknown

Hypothesis: 3-flavor mixing

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

$$U = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{CP}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{CP}} & 0 & c_{13} \end{bmatrix} \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

$$= \begin{bmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta_{CP}} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta_{CP}} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta_{CP}} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta_{CP}} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta_{CP}} & c_{23}c_{13} \end{bmatrix}$$

$c_{ij} = \cos\theta_{ij}$, $s_{ij} = \sin\theta_{ij}$

3x3 unitary matrix, 3 real angles, 1 imaginary phase

Hypothesis: 3-flavor mixing

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

$\theta_{atm} \sim \theta_{23} \sim 45$ deg

$\theta_{sol} \sim \theta_{12} \sim 33$ deg

$$U = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{CP}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{CP}} & 0 & c_{13} \end{bmatrix} \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

$\theta_{13} \sim 8$ deg.

$$= \begin{bmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta_{CP}} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta_{CP}} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta_{CP}} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta_{CP}} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta_{CP}} & c_{23}c_{13} \end{bmatrix}$$

$\sin\theta_{13}e^{i\delta}$ introduces CP violation

Neutrino CP violation?

- The Universe violates CP – there is more matter than anti-matter.
- The δ term produces CP-violation for neutrinos!
- Quarks violate CP as well, but not enough to explain what we see.
- Can measure δ by comparing the oscillation rates for neutrinos and anti-neutrinos

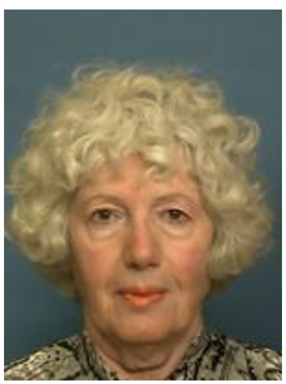
$$R(\nu_\mu \to \nu_e) \text{ to } R(\overline{\nu}_\mu \to \overline{\nu}_e)$$

The full 3-flavor formula

$$P\left(\nu_\alpha \rightarrow \nu_\beta\right) \;=\; \delta_{\alpha\beta} - 4\sum_{i<j}^{3} \mathrm{Re}\left(V_{\alpha i} V_{\beta j} V^*_{\alpha j} V^*_{\beta i}\right) \sin^2 \frac{\Delta m^2_{ji} L}{4E}$$

This term flips sign for neutrino/anti-neutrino

$$\pm 8 \mathcal{J} \sum_{\gamma} \epsilon_{\alpha\beta\gamma} \sin \frac{\Delta m^2_{21} L}{4E} \sin \frac{\Delta m^2_{31} L}{4E} \sin \frac{\Delta m^2_{32} L}{4E}$$



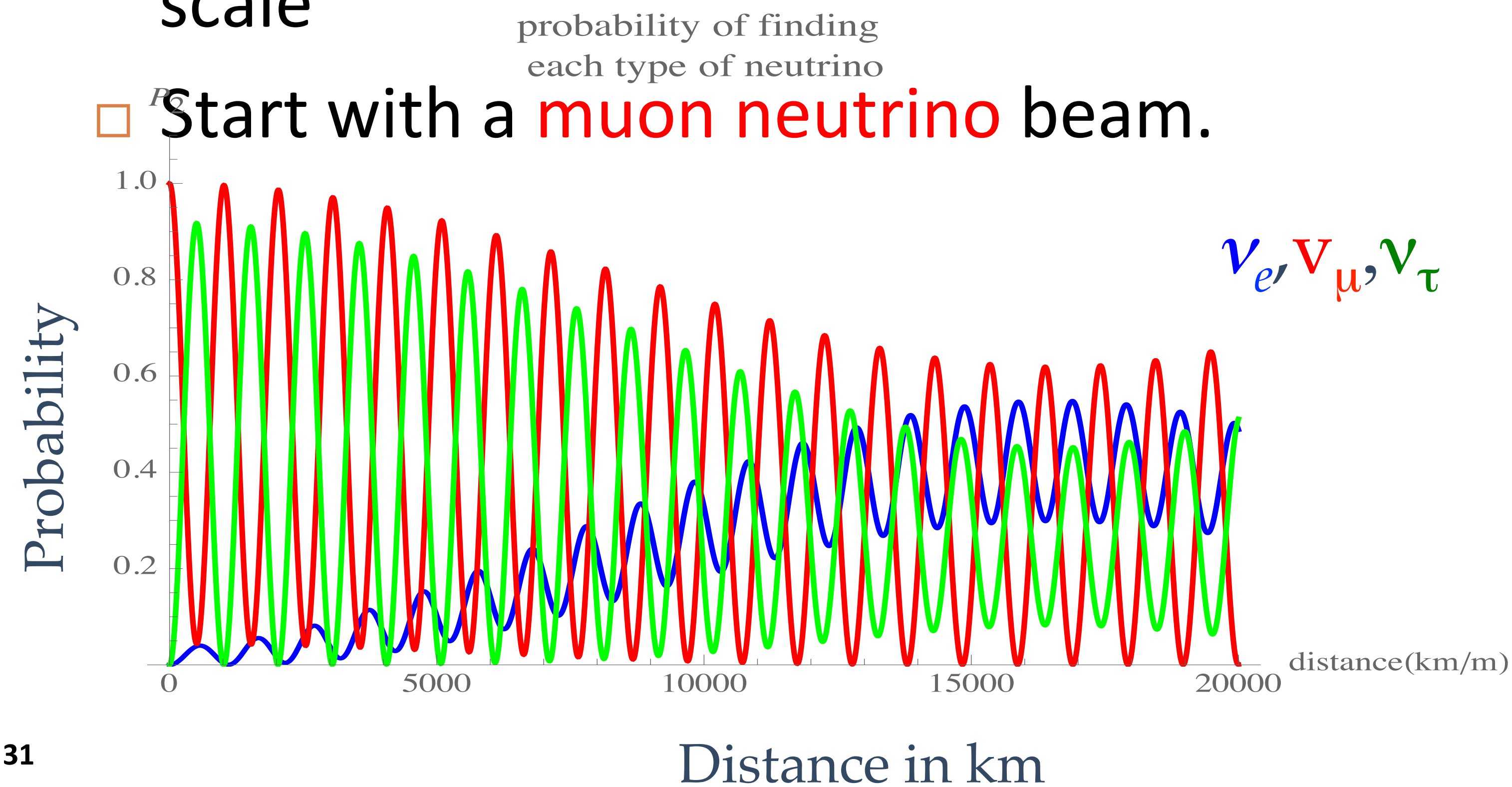
CP violation can occur if the $\mathcal{J}$arlskog invariant is nonzero. It depends on ALL if the angles and both mass scales.

$$\mathcal{J} = c_{12} c^2_{13} c_{23} s_{12} s_{13} s_{23} \sin\delta$$

Zhi-zhong Xing, lectures

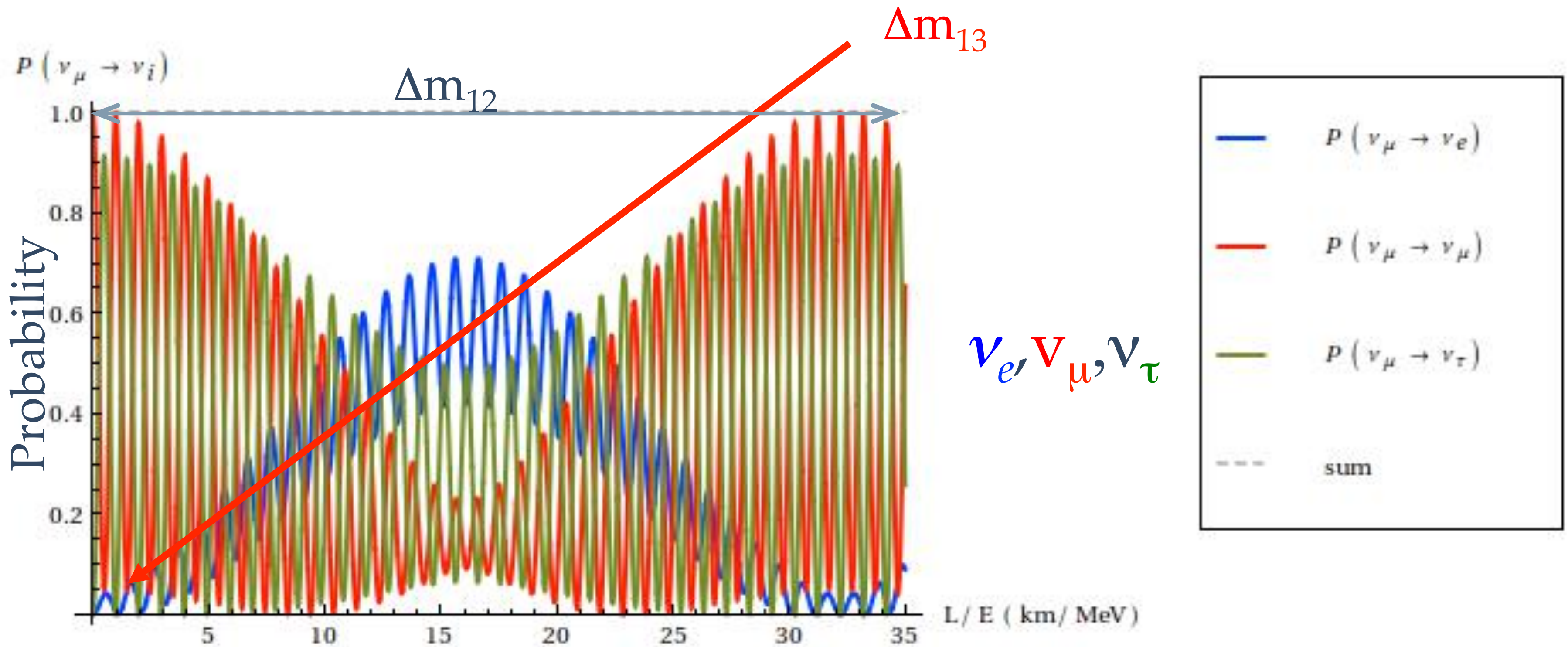
Long range behavior

- [Baseline Demo]
- This shows 1 GeV energy neutrinos on 20000 km scale
- Start with a muon neutrino beam.



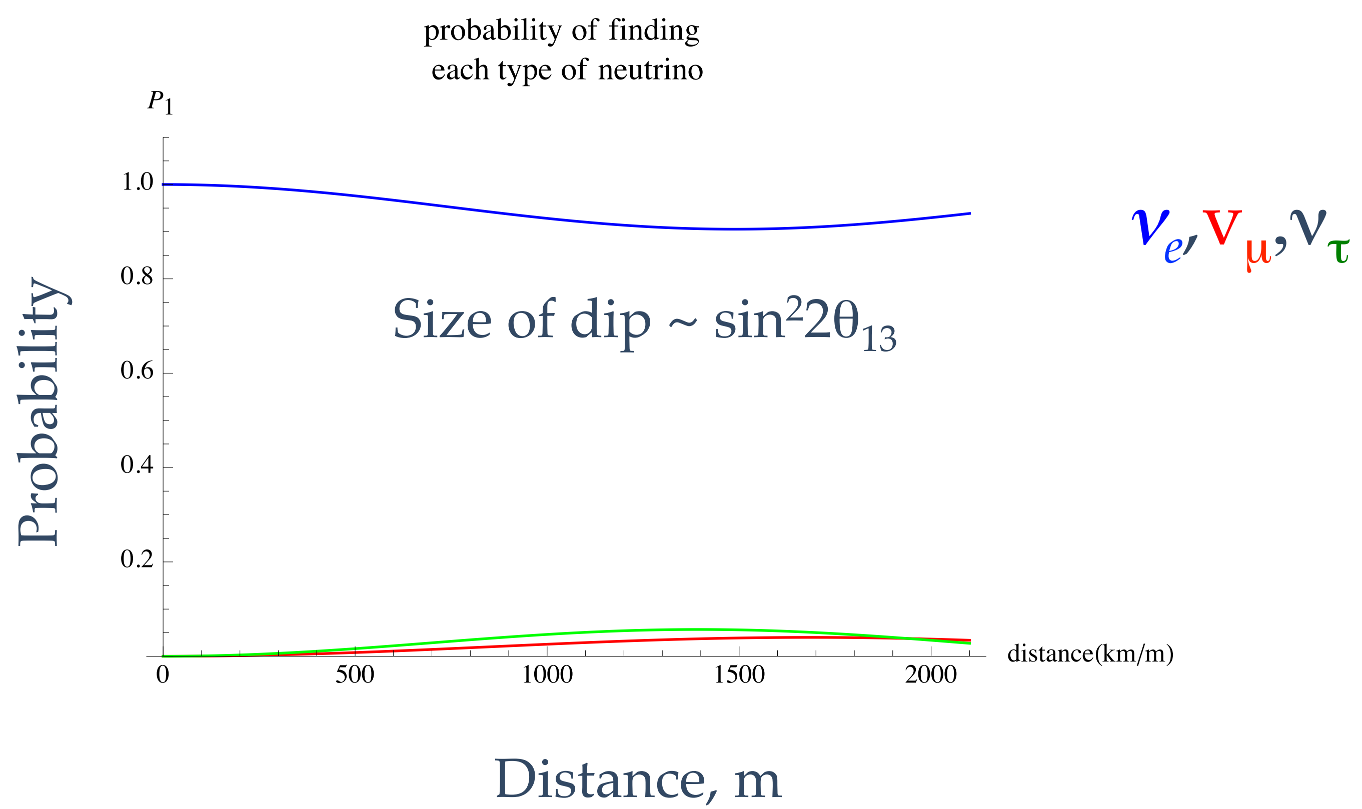
Measuring θ_{13} and δ

ν_μ-ν_e conversions mainly take place on the solar Δm_{12} length scale due to θ_{12} but there is a small Δm_{13} component due to θ_{13}. Is it big enough to see δ ?



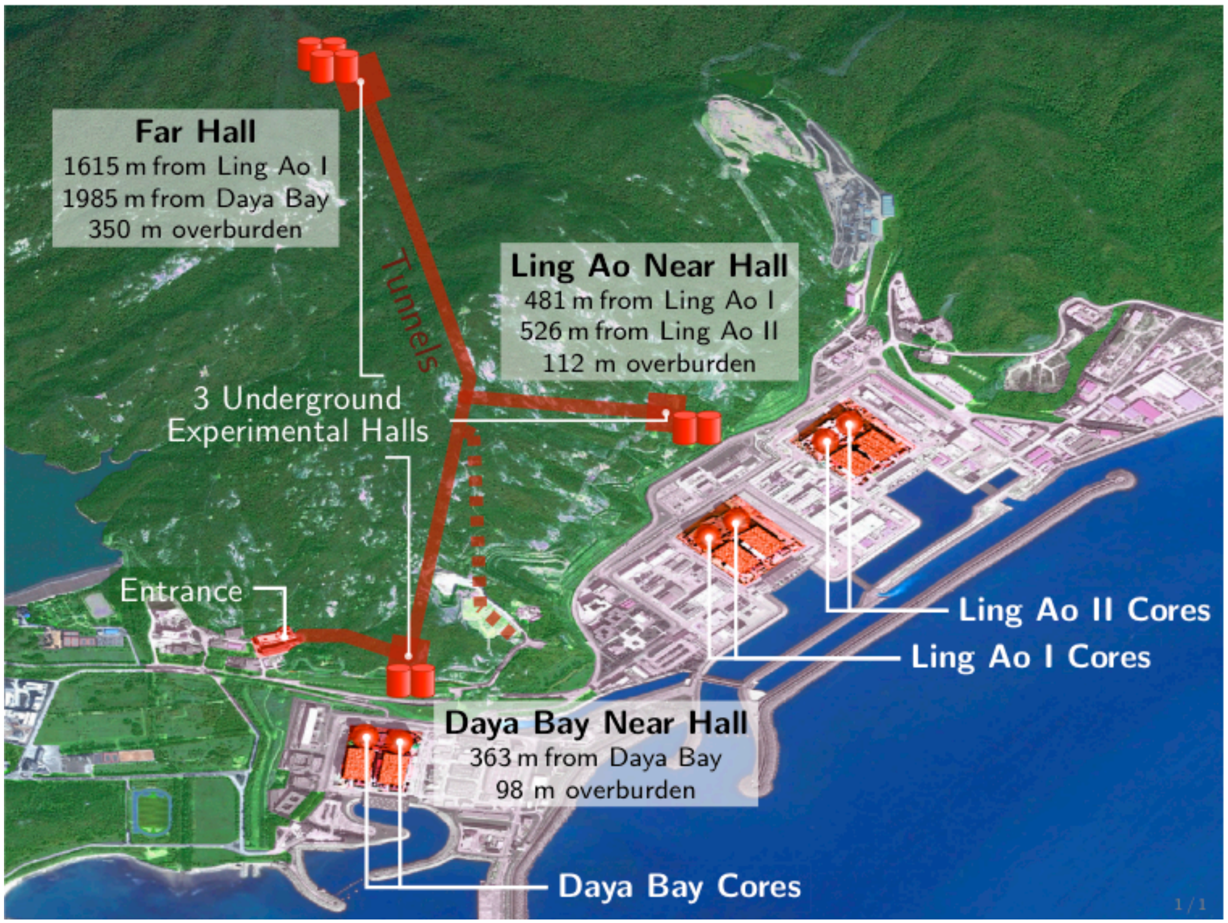
Zoom in on the small distance scale

- This shows 3 MeV electron anti-neutrinos on a 2 km distance scale, for example near a reactor.

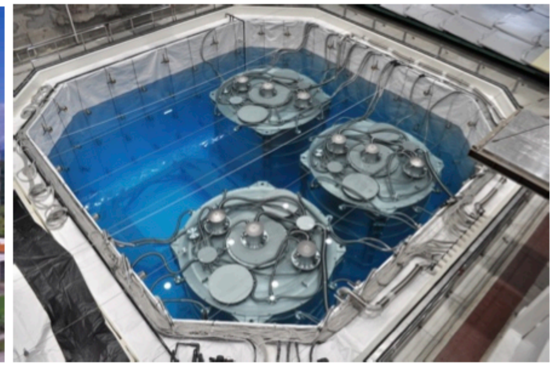


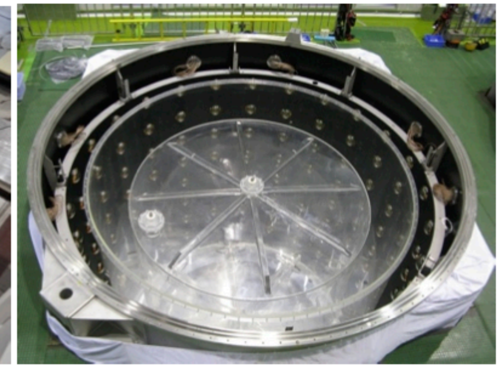
θ_{13}: Measure $\nu_\mu \rightarrow \nu_e$ on the Δm^2_{23} scale

Reactor neutrinos at 1km look at the $\Delta m_{23} \sim \Delta m_{13}$ scale

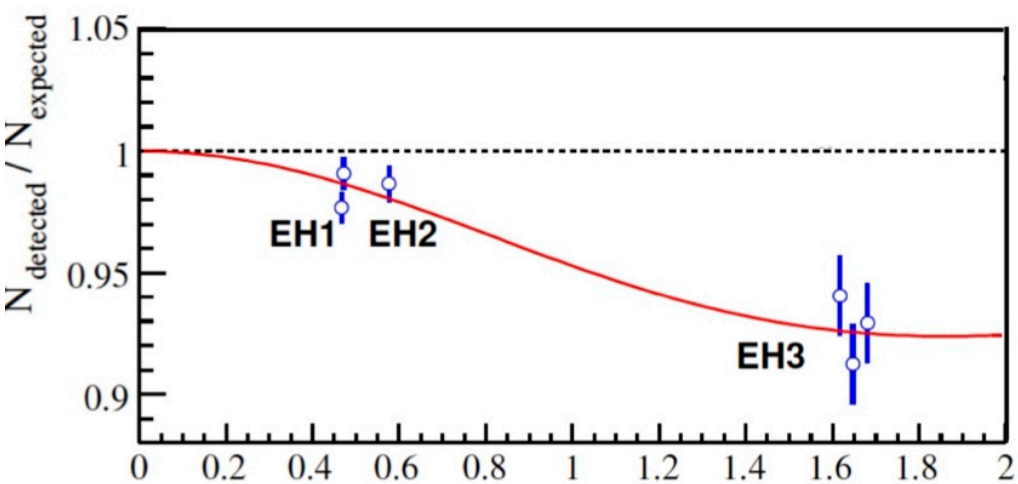


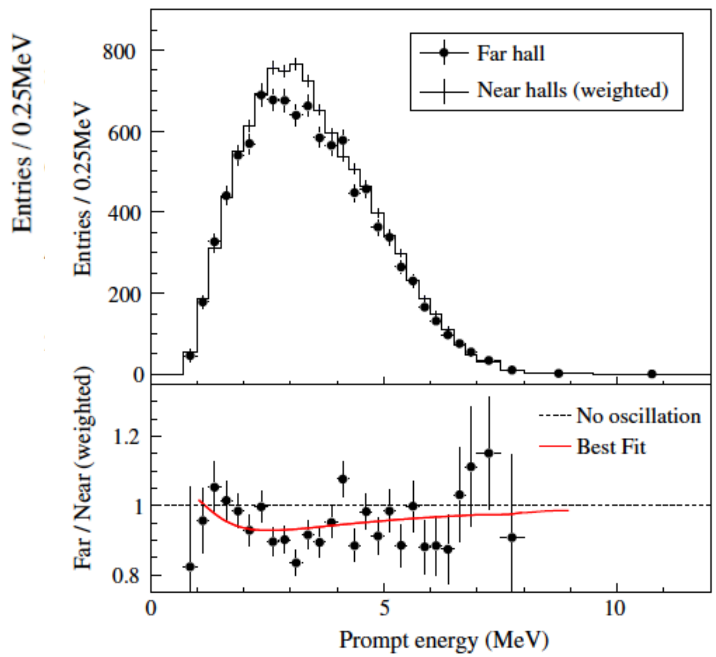
Observation of Electron Antineutrino Disappearance at Daya Bay





$$\sin^2 2\theta_{13} = 0.092 \pm 0.016(\mathrm{stat}) \pm 0.005(\mathrm{syst})$$





Distance in km

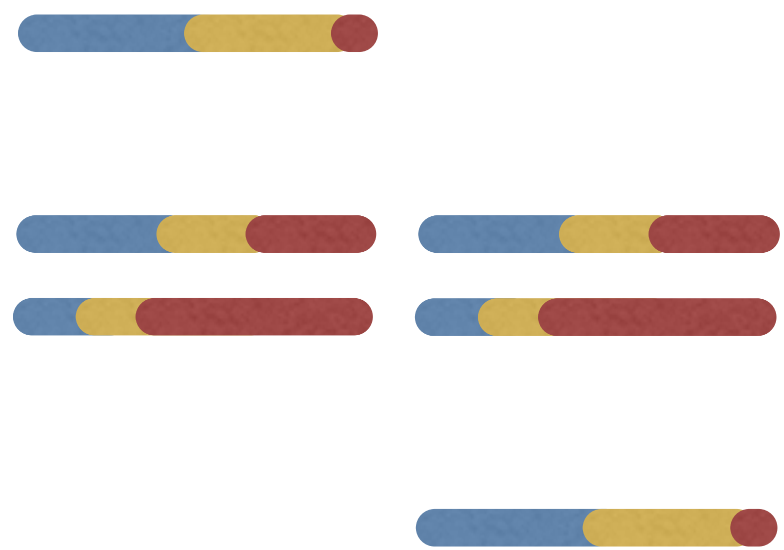
PhysRevLett.108.171803

Good news

- θ_{13} ~ 8 degrees – that's actually pretty big – we may be able to see CP violation!

Big questions still left

- So what is the mass ordering?
- What is the CP violating phase δ?



Onward to CP violation

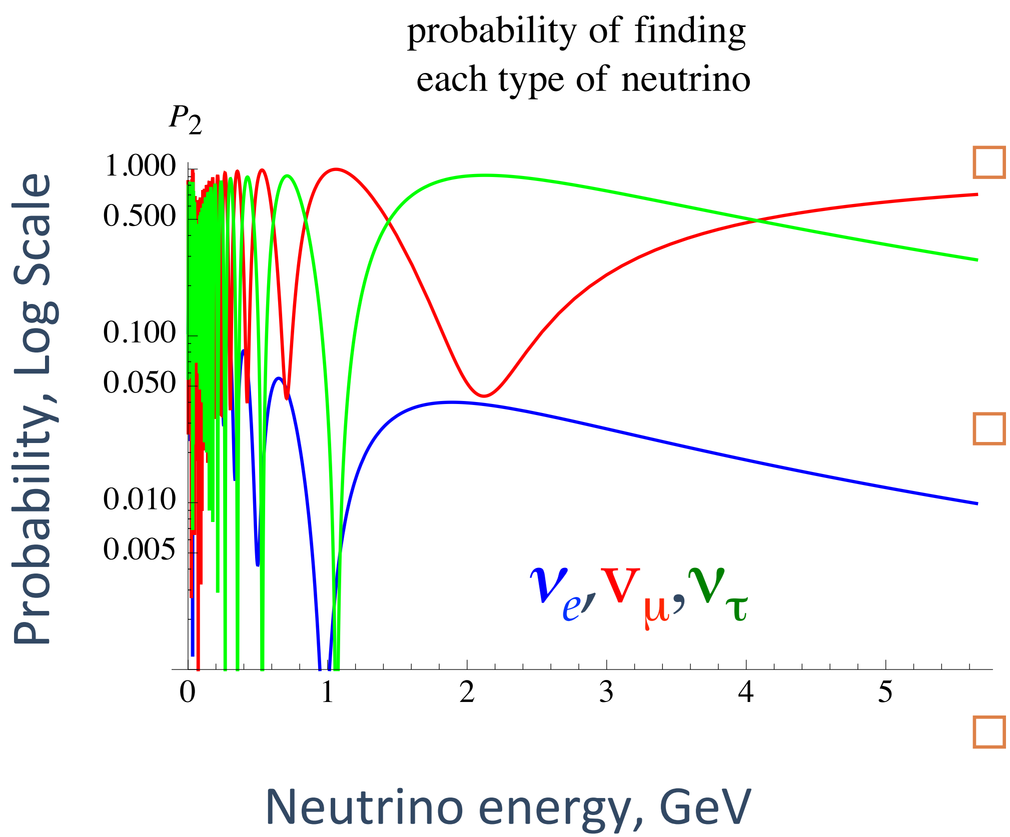
- Need to compare

$$R(\nu_\mu \rightarrow \nu_e) \text{ to } R(\overline{\nu}_\mu \rightarrow \overline{\nu}_e)$$

- Need an accelerator for that to get both types
- Need a lot of events at a long distance
  - Need a huge detector
  - Need very powerful ν and anti-ν beams
- Several current efforts
  - NOνA, DUNE, HyperK

Design an experiment

Energy Demo

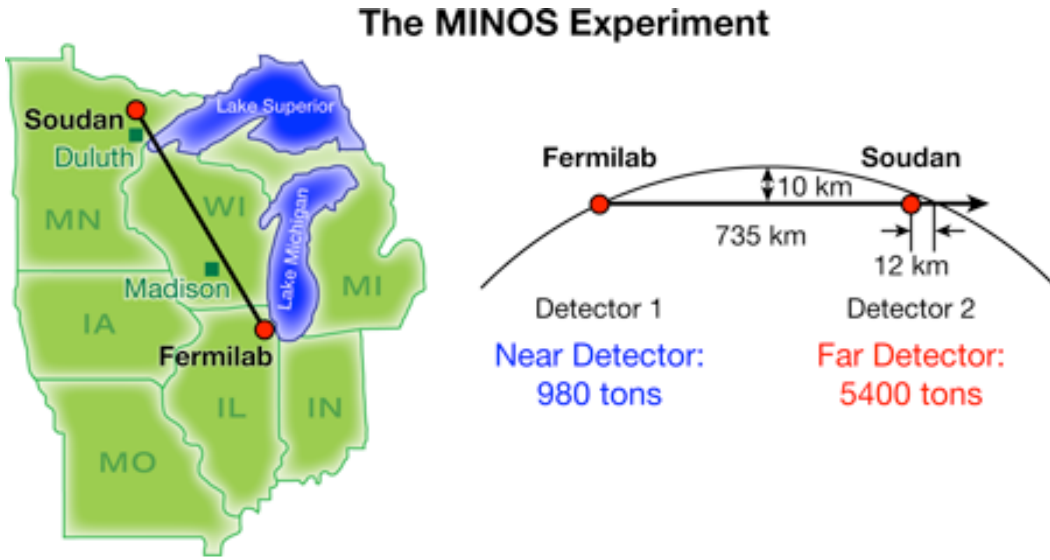


- Huge detectors are too pricey to scatter around
- Study the energy dependence at a single distance
- P ~ Sin^2 (L/E)
- Can look for 1st and 2nd oscillation peaks

Accelerator experiments

- Make an intense neutrino beam (normally muon neutrinos)
- Place detectors both near and far
- Measure the disappearance of muon neutrinos
- Measure the appearance of electron and tau neutrinos
- Can flip the beam polarity to study both neutrinos and anti-neutrinos (try doing that with a reactor)

Study "atmospheric" neutrinos on earth



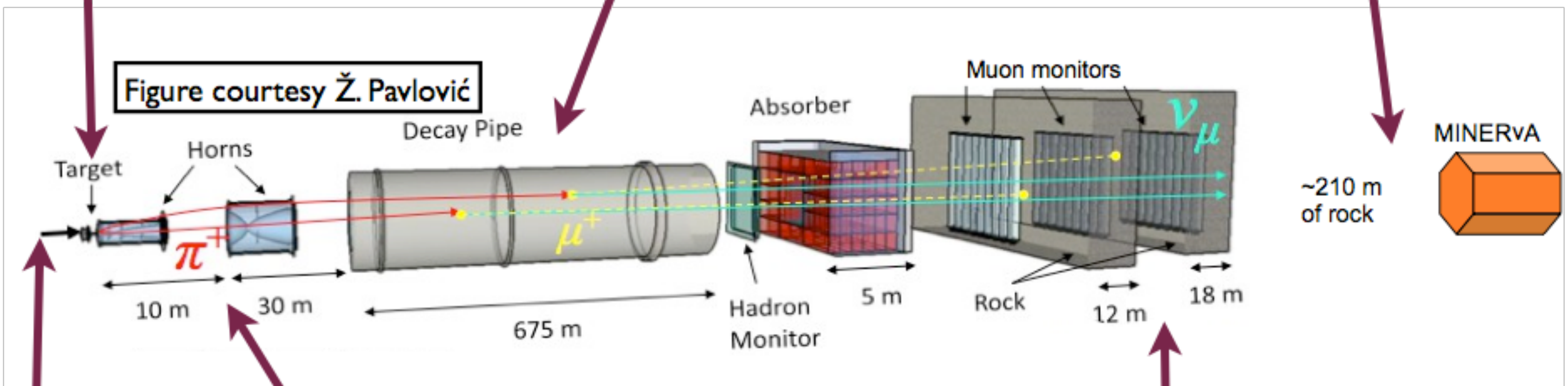
- Aim a muon neutrino beam from Fermilab to Northern Minnesota – 735 km
- Aim a muon neutrino beam from Tokai to Kamiokande, Japan – 295 km

How to make a neutrino beam

Protons hit graphite target, produce mesons (mostly pions, some kaons)

$\pi^+ \to \mu^+ + \nu_\mu$

Neutrinos!

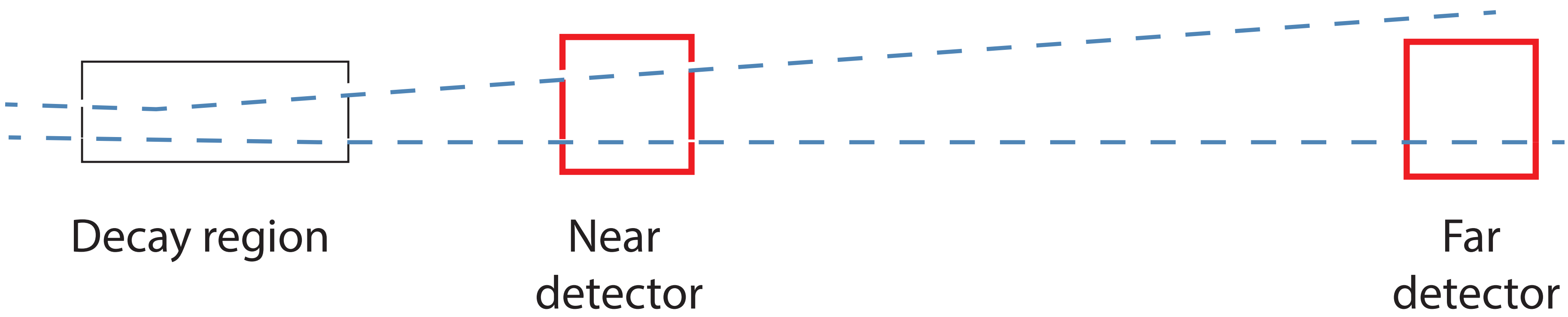


120 GeV protons

Horns focus one charge of meson and defocus the other, leading to neutrinos or antineutrinos

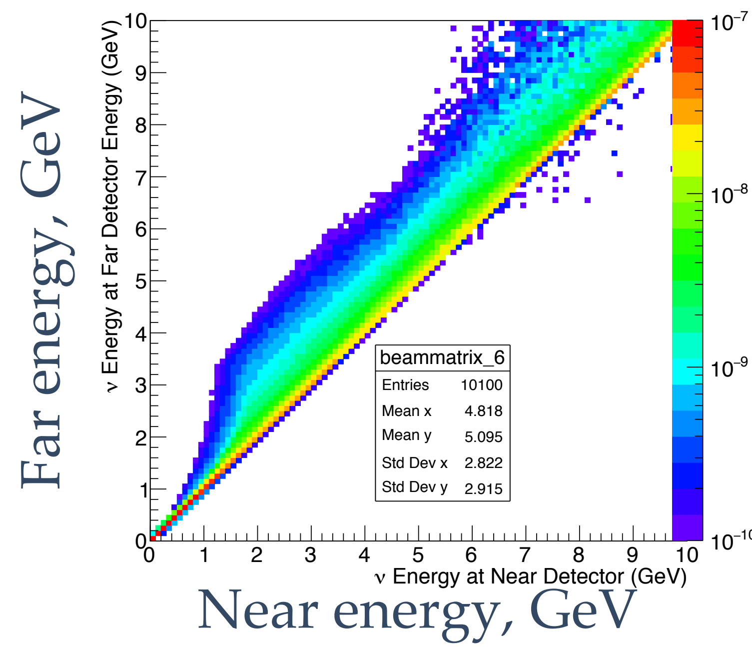
Rocks remove muons from beam

Measure twice …



Use energy profile at near detector to predict unoscillated energy profile at far detector

Compare to observed energy profile to find the oscillation probability



Do the numbers

$$N_{near}(E;\nu_\mu \to \nu_\mu) = \Phi_{near}(E;\nu_\mu) \times \sigma(E;\nu_\mu)$$

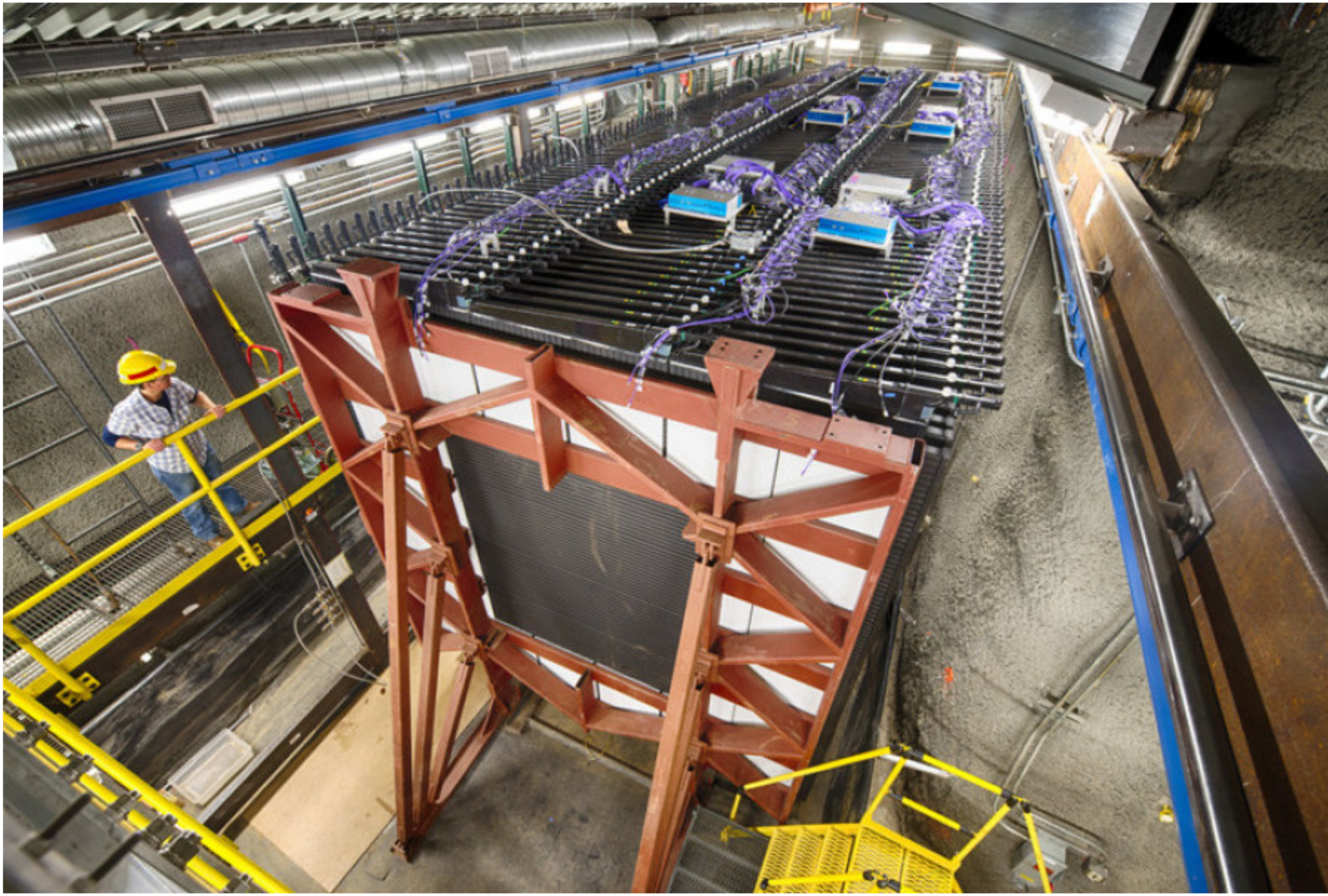
$$N_{far}(E;\nu_\mu \to \nu_e) = \Phi_{far}(E;\nu_X) \times P(\nu_\mu \to \nu_e) \times \sigma(E;\nu_e)$$

$$P(\nu_\mu \to \nu_e) \simeq \frac{N_{far}(E;\nu_\mu \to \nu_e)}{N_{near}(E;\nu_\mu \to \nu_\mu)} \times \frac{\Phi_{near}(E)}{\Phi_{far}(E)} \times \frac{\sigma_{near}(E;\nu_\mu)}{\sigma_{far}(E;\nu_e)}$$

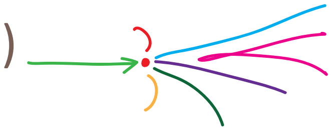
To measure the oscillation probability, P, you need to be able to estimate the ratio of the fluxes and the interaction cross sections in two different detectors.

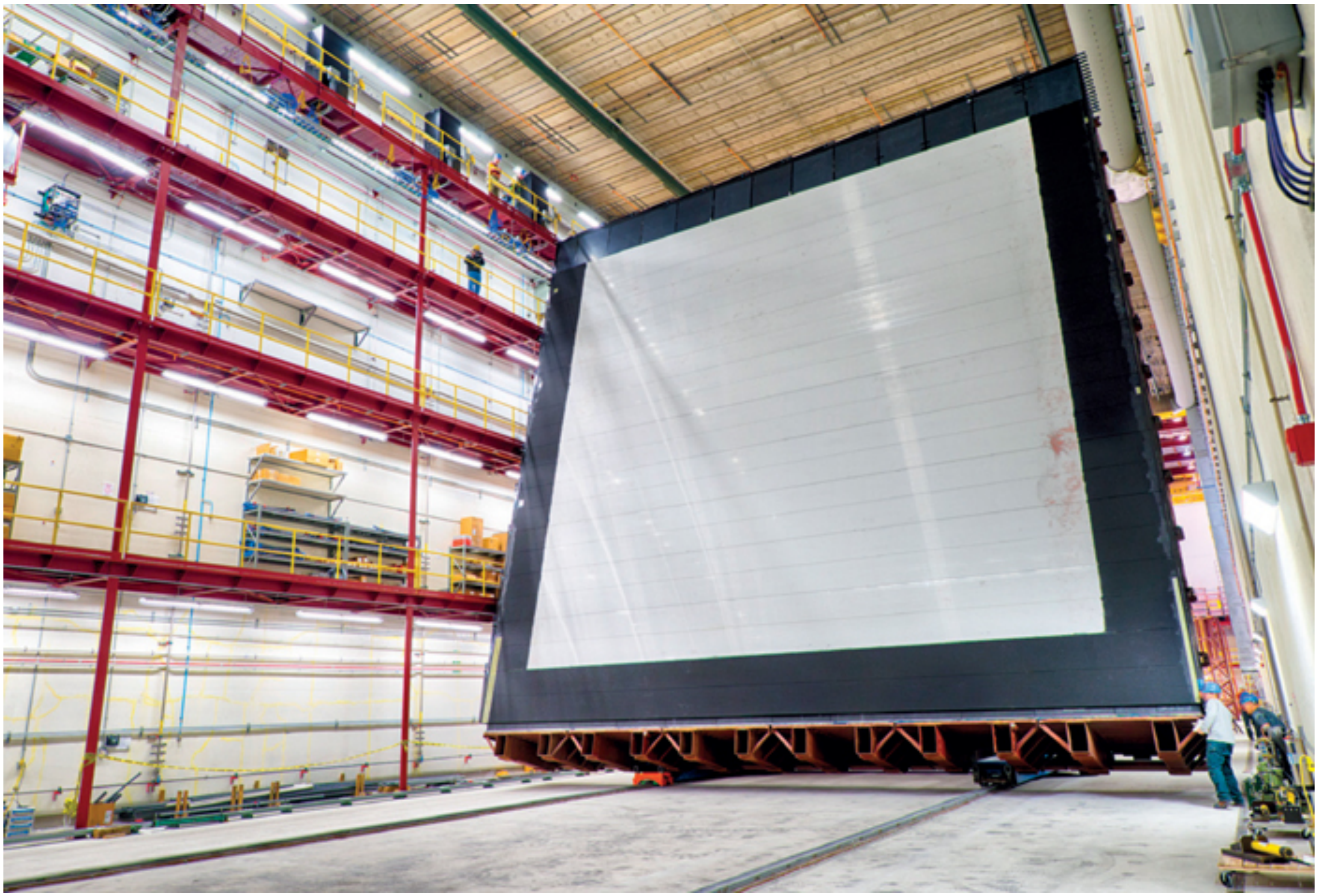
- Understand flux
- Understand cross sections both kinds of neutrinos and anti-neutrinos
- Understand detectors

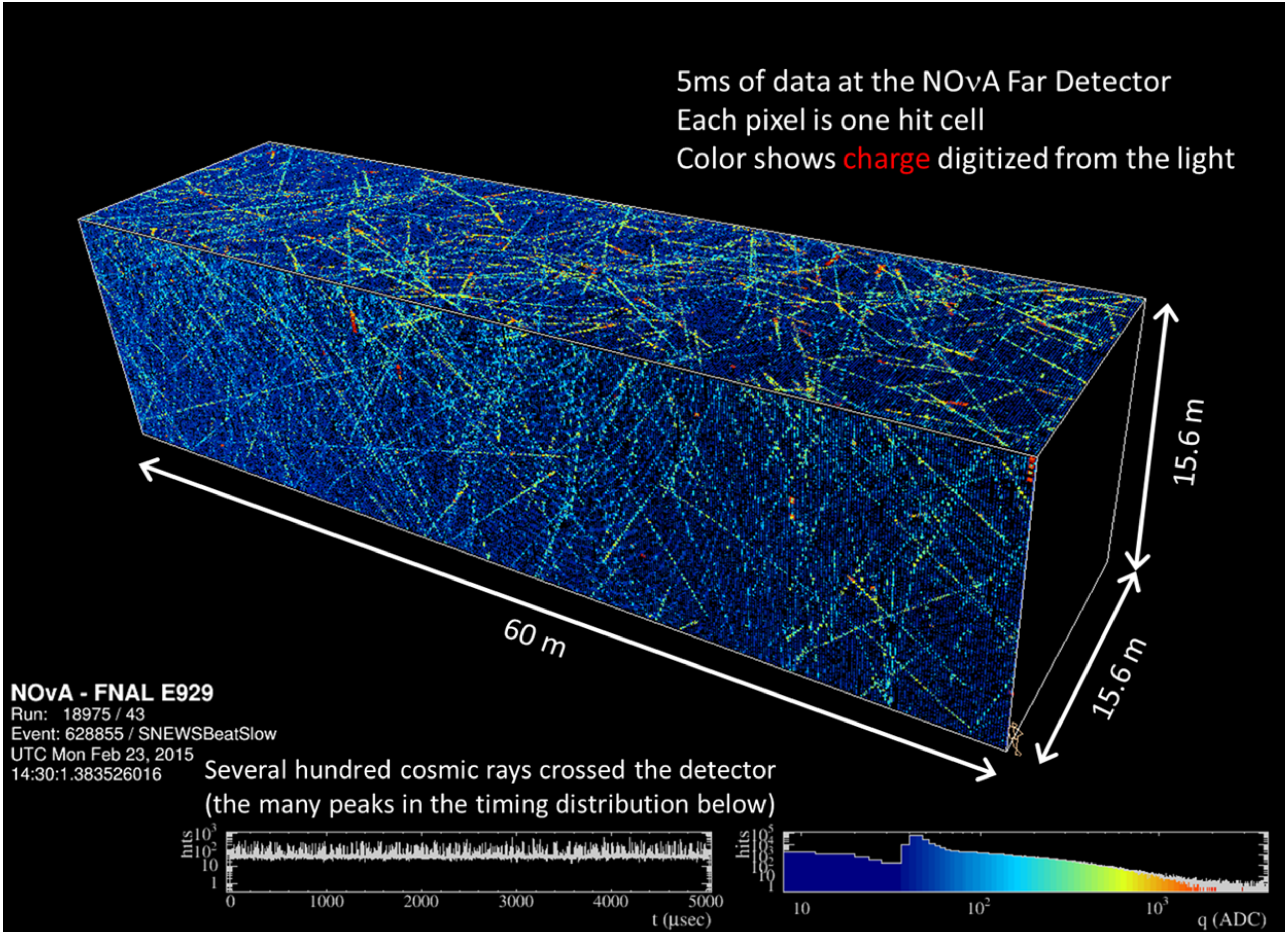
NOvA near detector



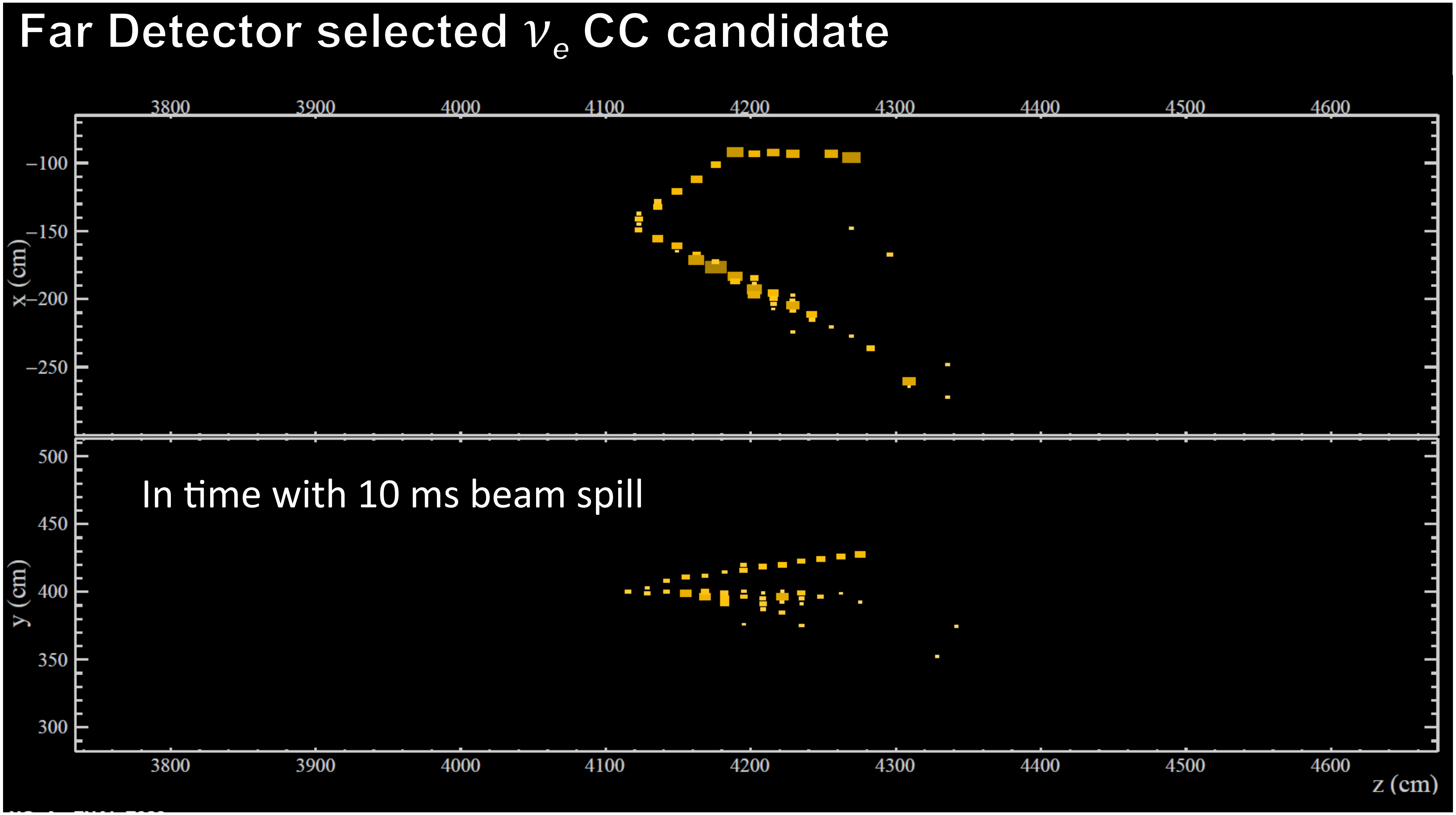
The new NOvA detector – 15 kT of liquid scintillator (50ftx50ftx250 ft) 810 km away from the near detector






5ms of data at the NOνA Far Detector
Each pixel is one hit cell
Color shows charge digitized from the light
15.6 m
60 m
15.6 m
NOvA - FNAL E929
Run: 18975 / 43
Event: 628855 / SNEWSBeatSlow
UTC Mon Feb 23, 2015
14:30:1.383526016
Several hundred cosmic rays crossed the detector
(the many peaks in the timing distribution below)
hits
t (μsec)
hits
q (ADC)

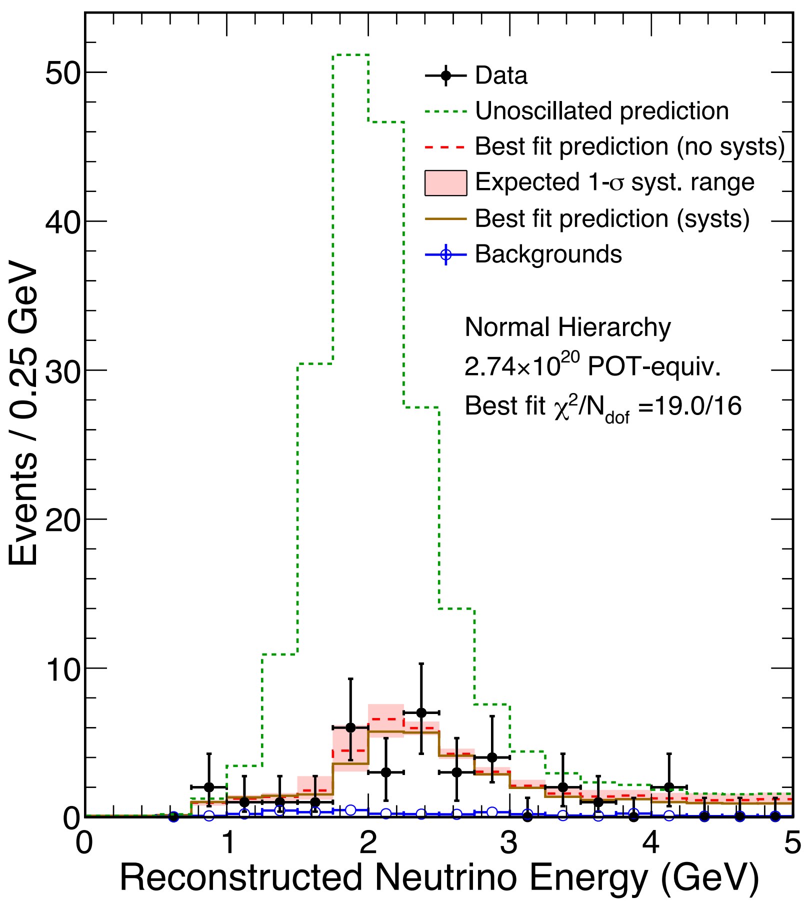
Electron appearance in NOvA

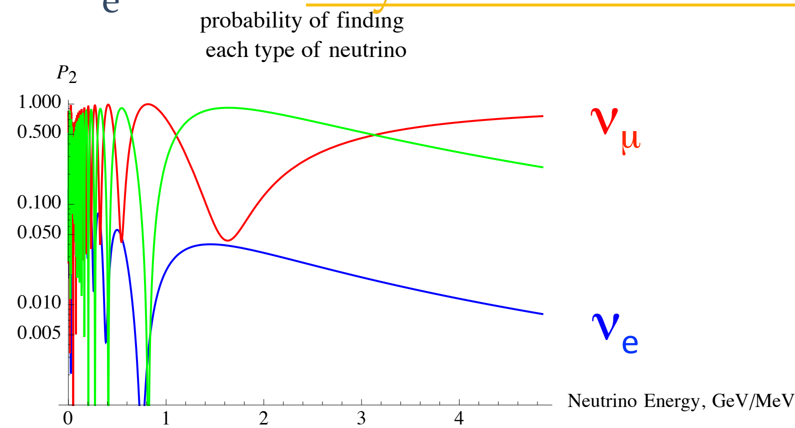


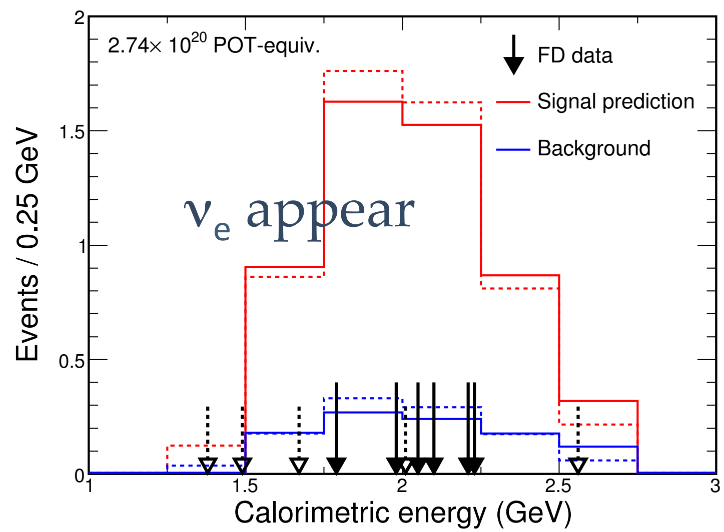
ν_e appearance in NOvA

NOvA sees 11 ν_e events PhysRevLett.116.151806

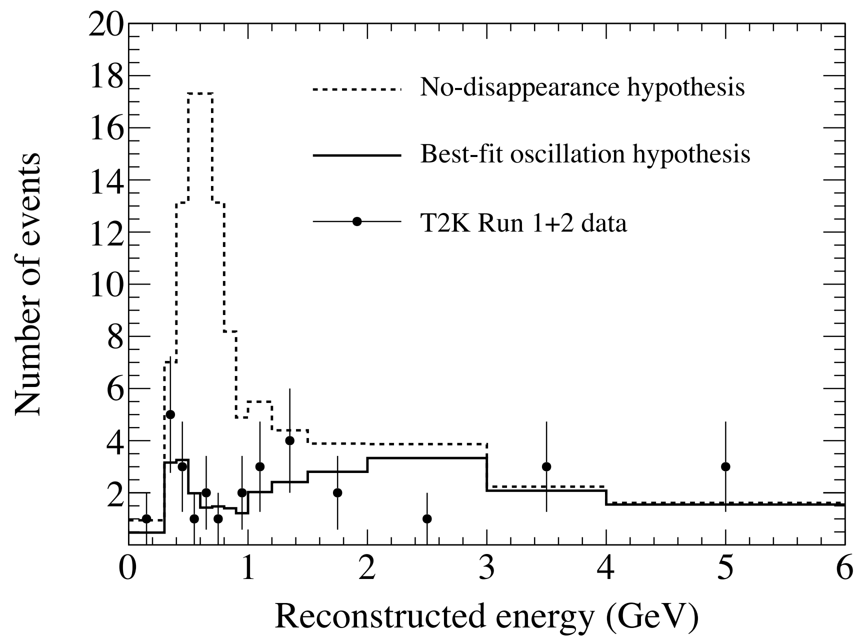
ν_μ disappear

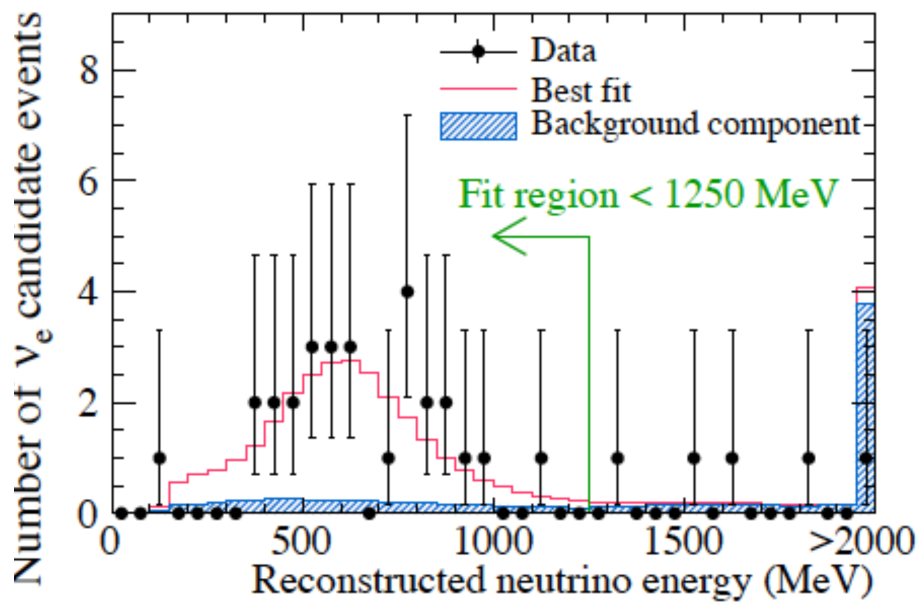






T2K results for neutrinos





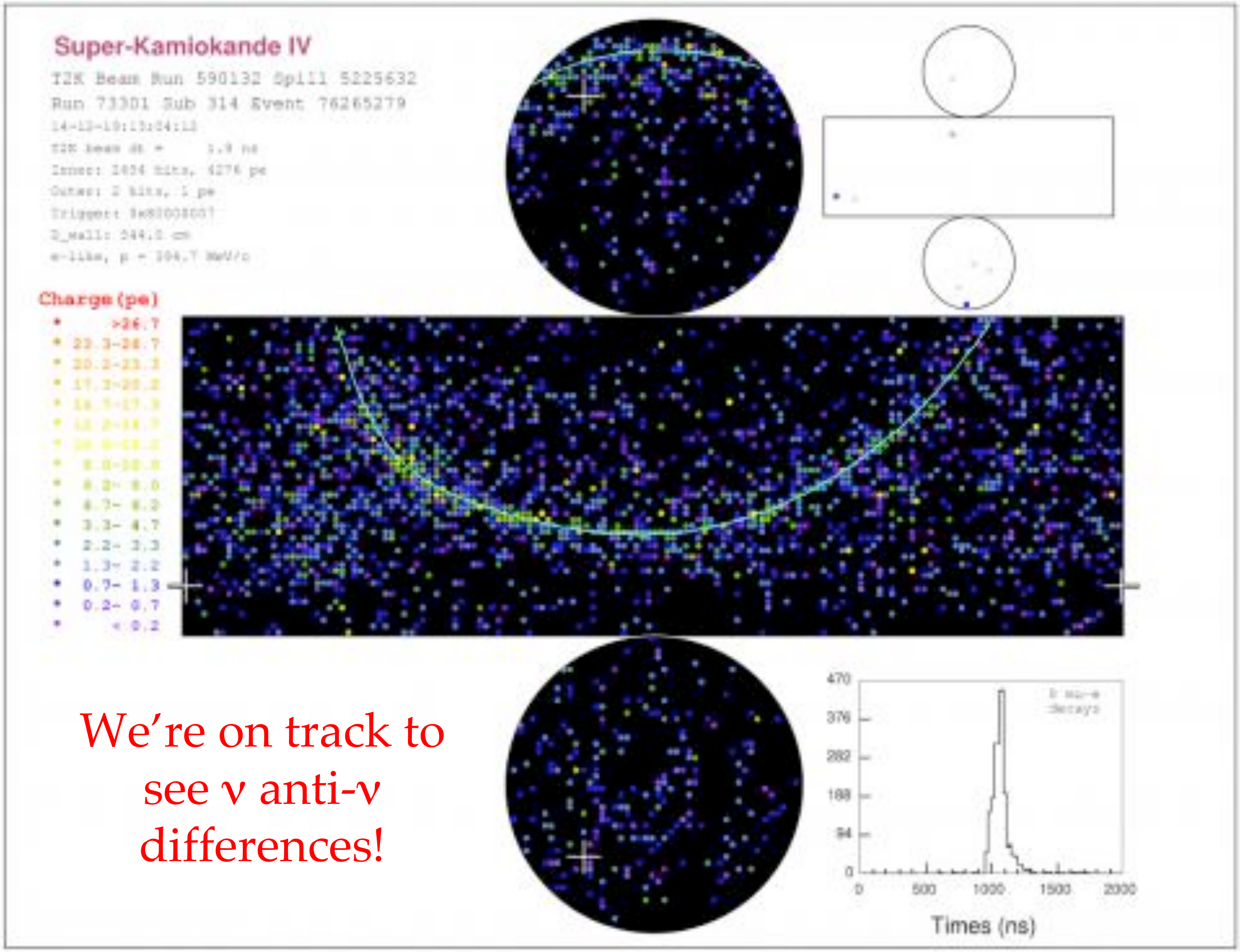
Muon disappearance

PhysRevLett.111.211803

Electron appearance

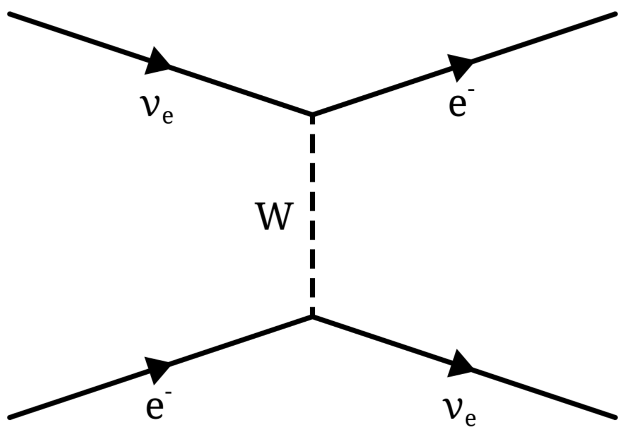
PhysRevLett.112.061802

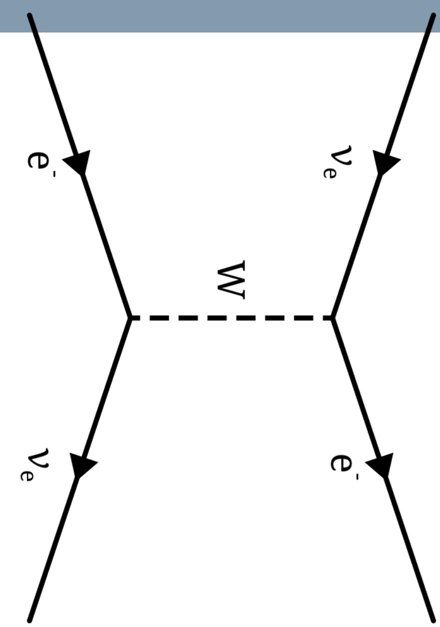
T2K anti-ν_e appearance!



We're on track to see ν anti-ν differences!

Caveat, there is a complication: Matter effects and the mass hierarchy

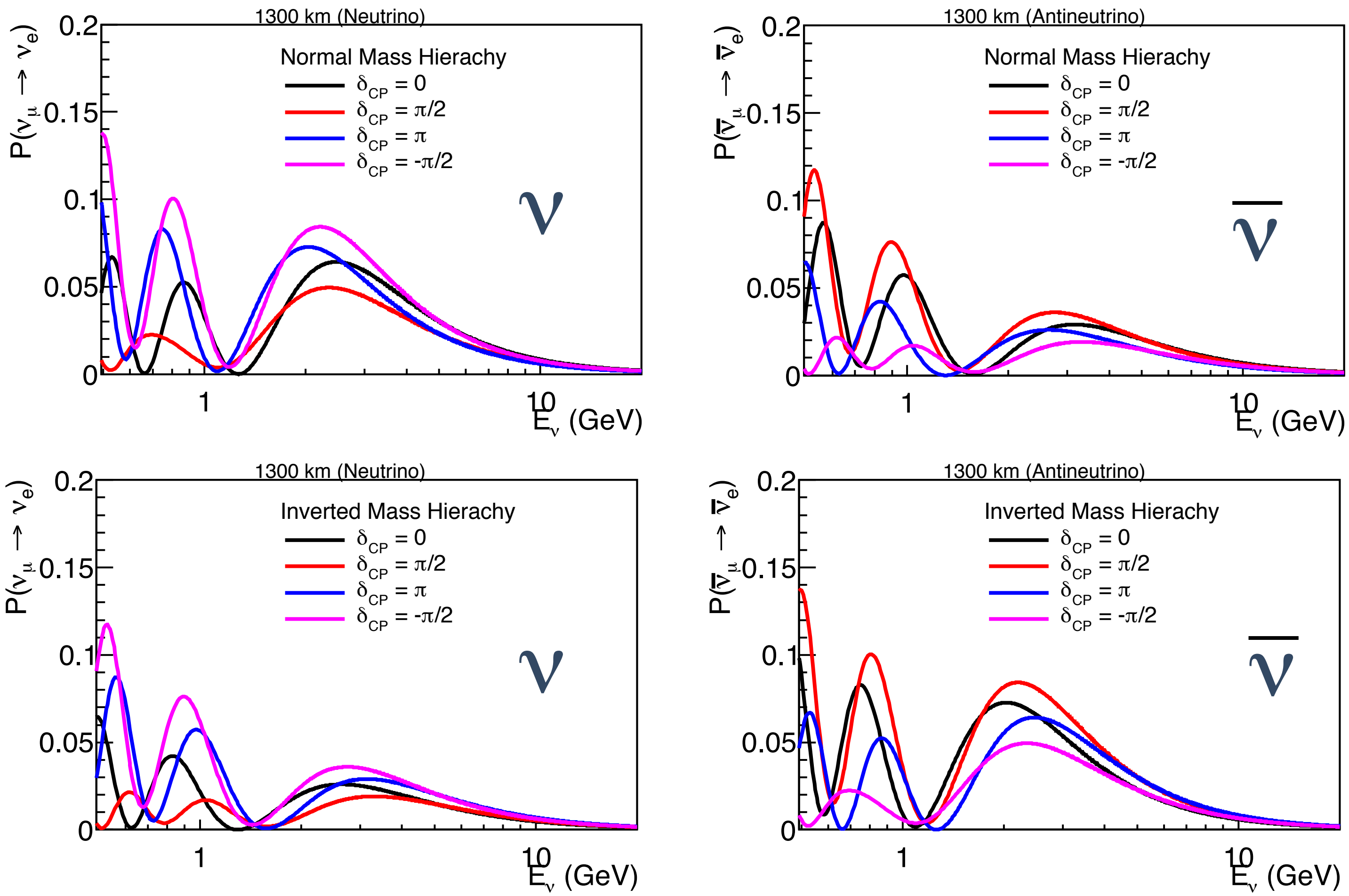




These diagrams affect only electron (anti)neutrino propagation in matter, with a sign that depends on Δm^2 and the amount of matter traversed

$$V_e = \pm\sqrt{2}G_F N_e$$

Observed $\nu_\mu \rightarrow \nu_e$ rates will also depend on the sign of Δm^2



$\Delta m_{23}^2 > 0$

$\Delta m_{23}^2 < 0$

T2K and NOvA have different matter effects, can disentangle this

http://arxiv.org/format/1505.01891v1

Measuring CP violation more precisely

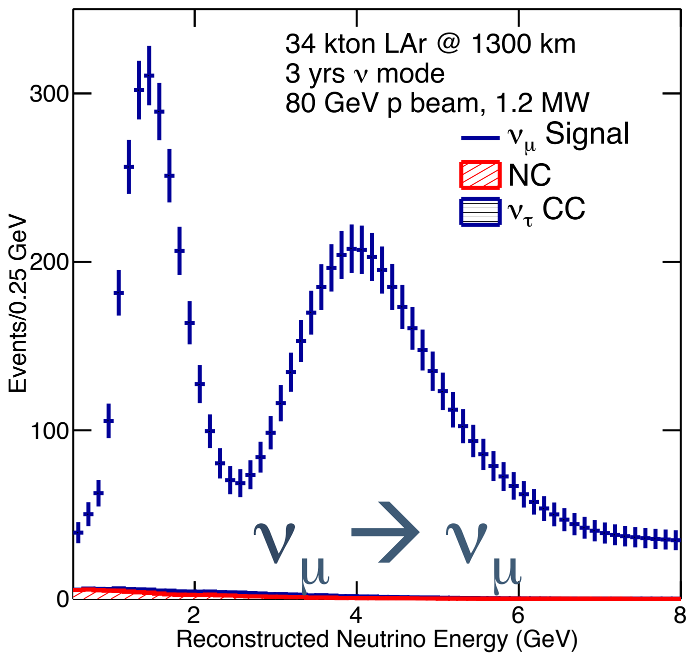
- Need bigger detectors
- Need more beam
- Need low backgrounds for electron neutrinos
- Need higher detection efficiency for electron neutrinos
- New technology – Noble Liquid Time projection chambers!

The next level: DUNE

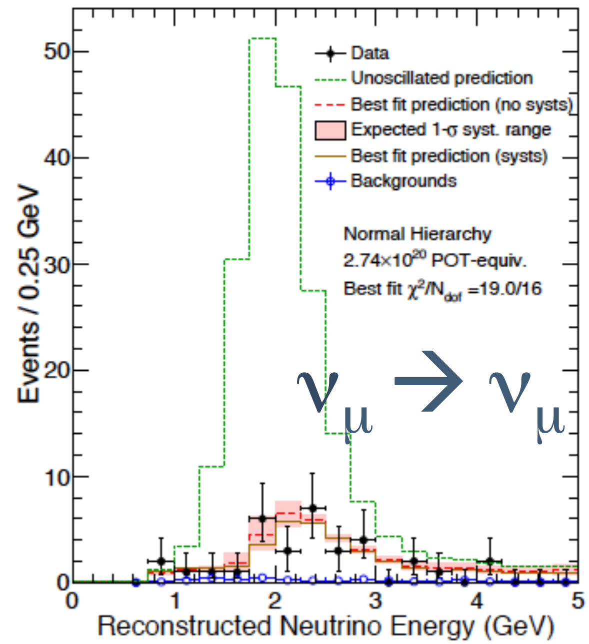
- The Deep Underground Neutrino Experiment
  - LBNE + International collaborators
  - 149 Institutions > 800 Collaborators
- Optimized baseline of 1300 km
- 3 x beam intensity
- 2.5 x detector mass
- More efficient detectors with better background rejection

Examples from DUNE proposal

DUNE Proposed



NOvA now

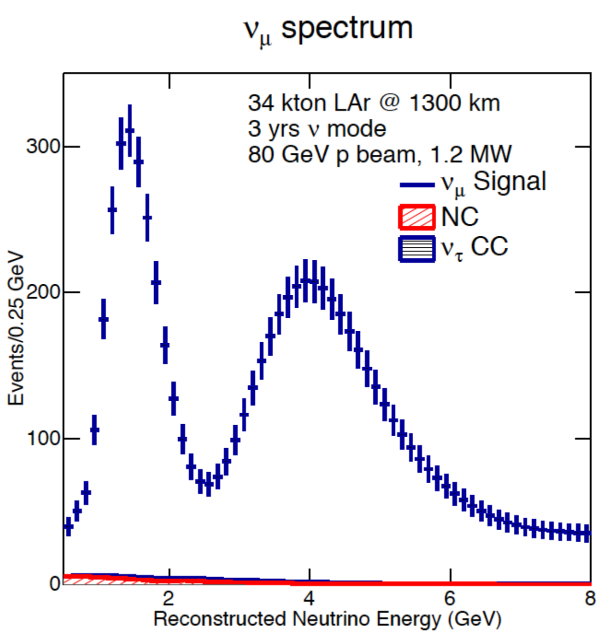


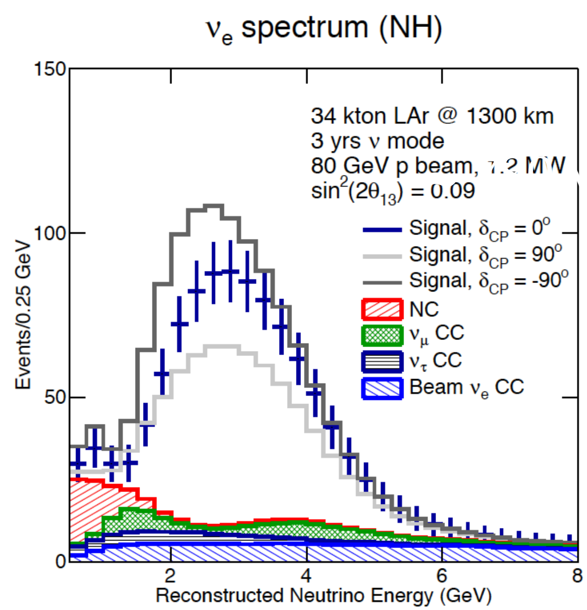
3 years of neutrino data with 34 kT Lar + 1.2MW beam

NOvA will also get more statistics in 6 year run

Goals: Mass Hierarchy and CP violation

- A ~ pure ν_μ beam generated by the ~120 GeV MI proton beam.
- Wide-band matched to the L/E for the first and second oscillation maxima for a 1300 km oscillation length.
- 6 years x 3 times intensity x 2.5 time mass = 45 Current NOvA statistics





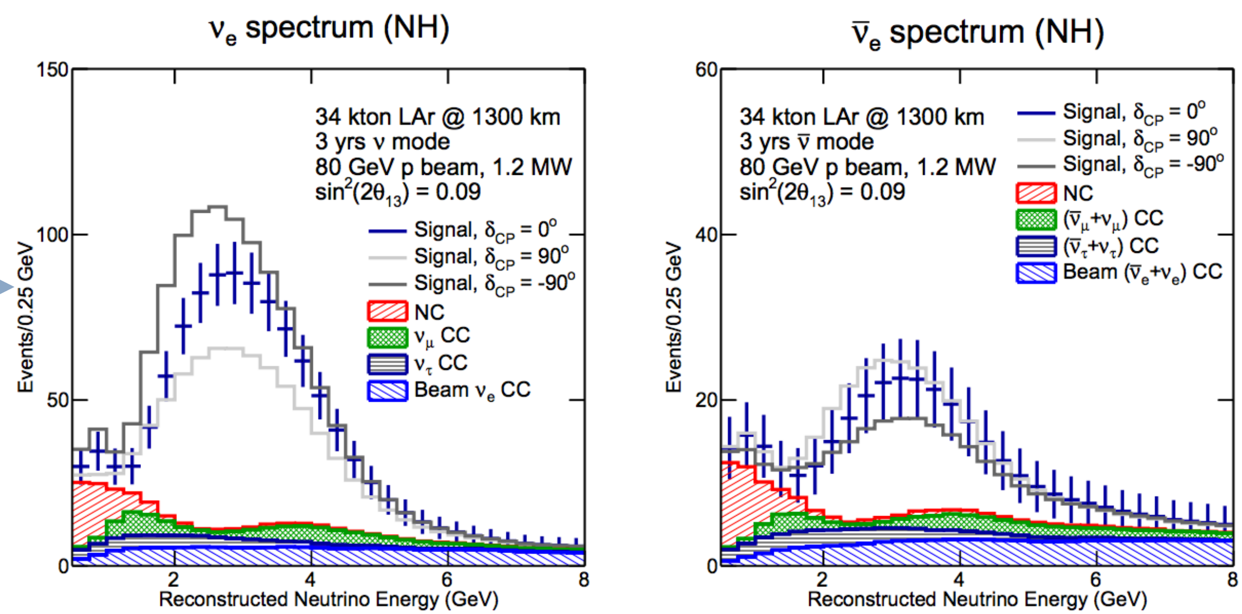
$\approx$ 7000 ν_μ events

Several hundred $\nu_\mu \rightarrow \nu_e$ oscillation events

DUNE

$\nu_\mu \rightarrow \nu_e$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillations

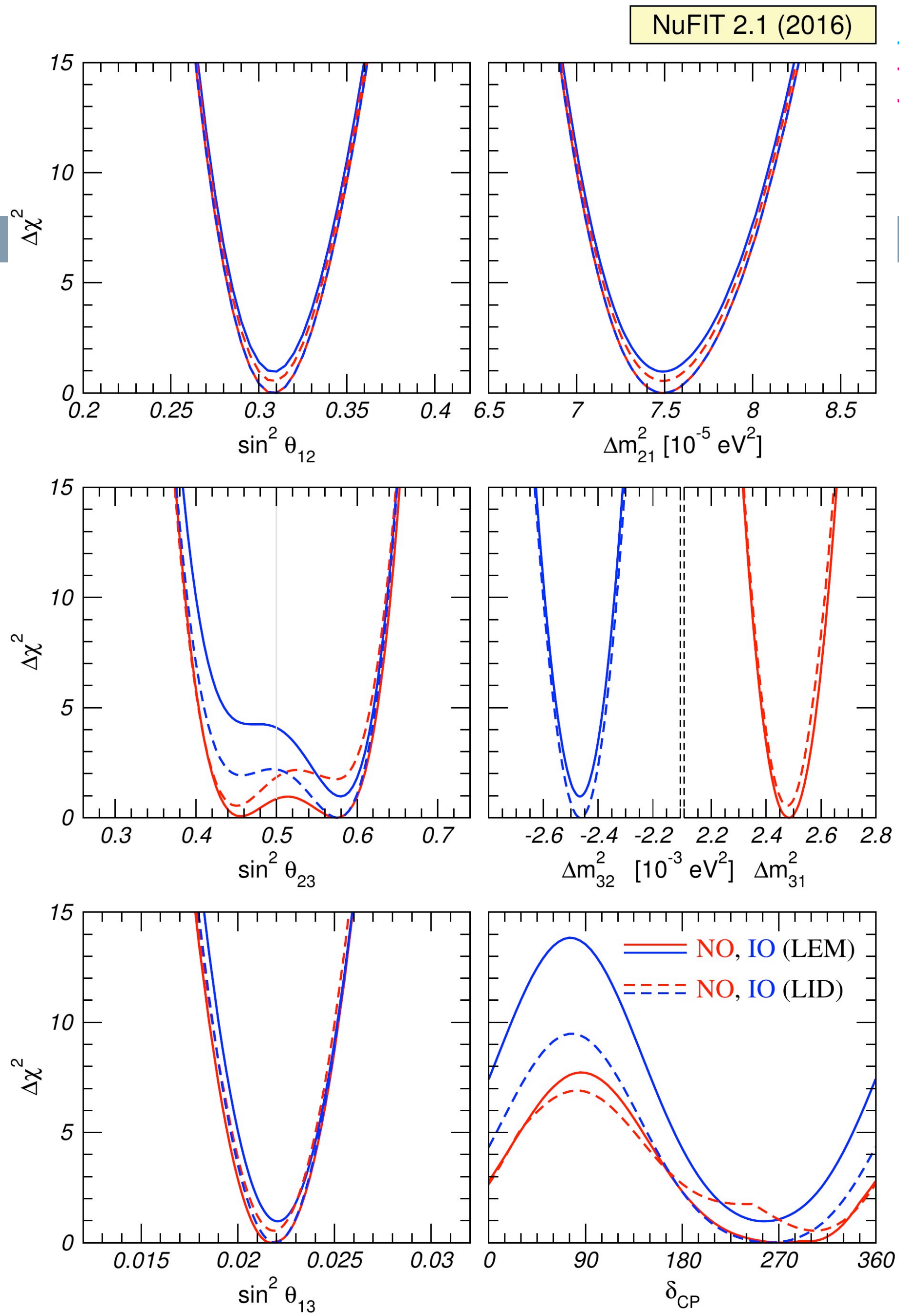
Expected ν_e and $\bar{\nu}_e$ energy spectra that will be observed at DUNE, for different values of δ_{CP}



δ subtly shifts the ν and anti-ν distributions in opposite directions

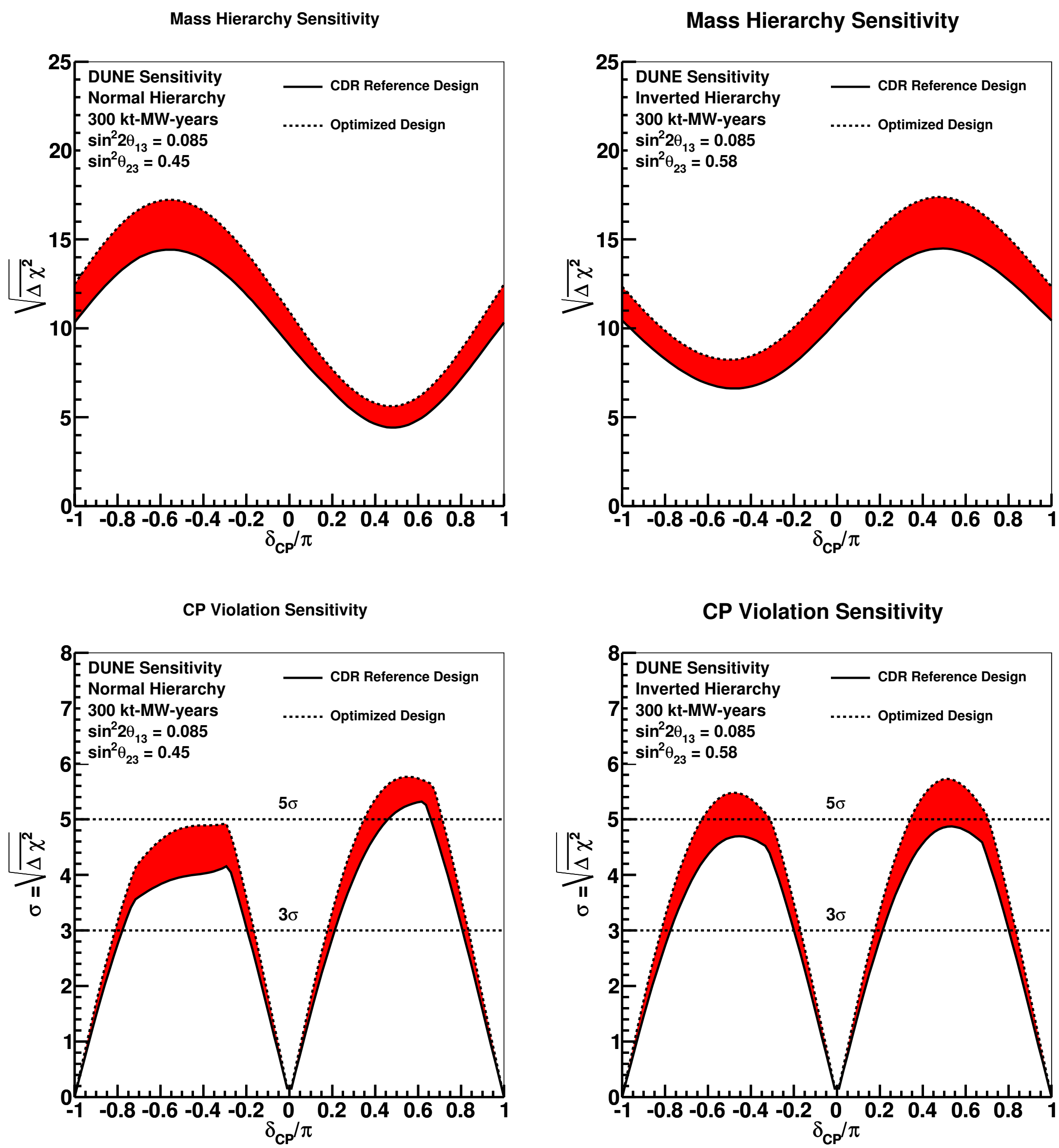
Current fit results

nu-fit.org May 2016



Johannes Bergström
Ivan Esteban
Concha Gonzalez Garcia
Michele Maltoni
Ivan Martinez Soler
Thomas Schwetz

DUNE MH and CP Sensitivities



Top of band:

Best case beam and interaction systematics (with near detector)

Bottom of band:

Worst case beam and interaction

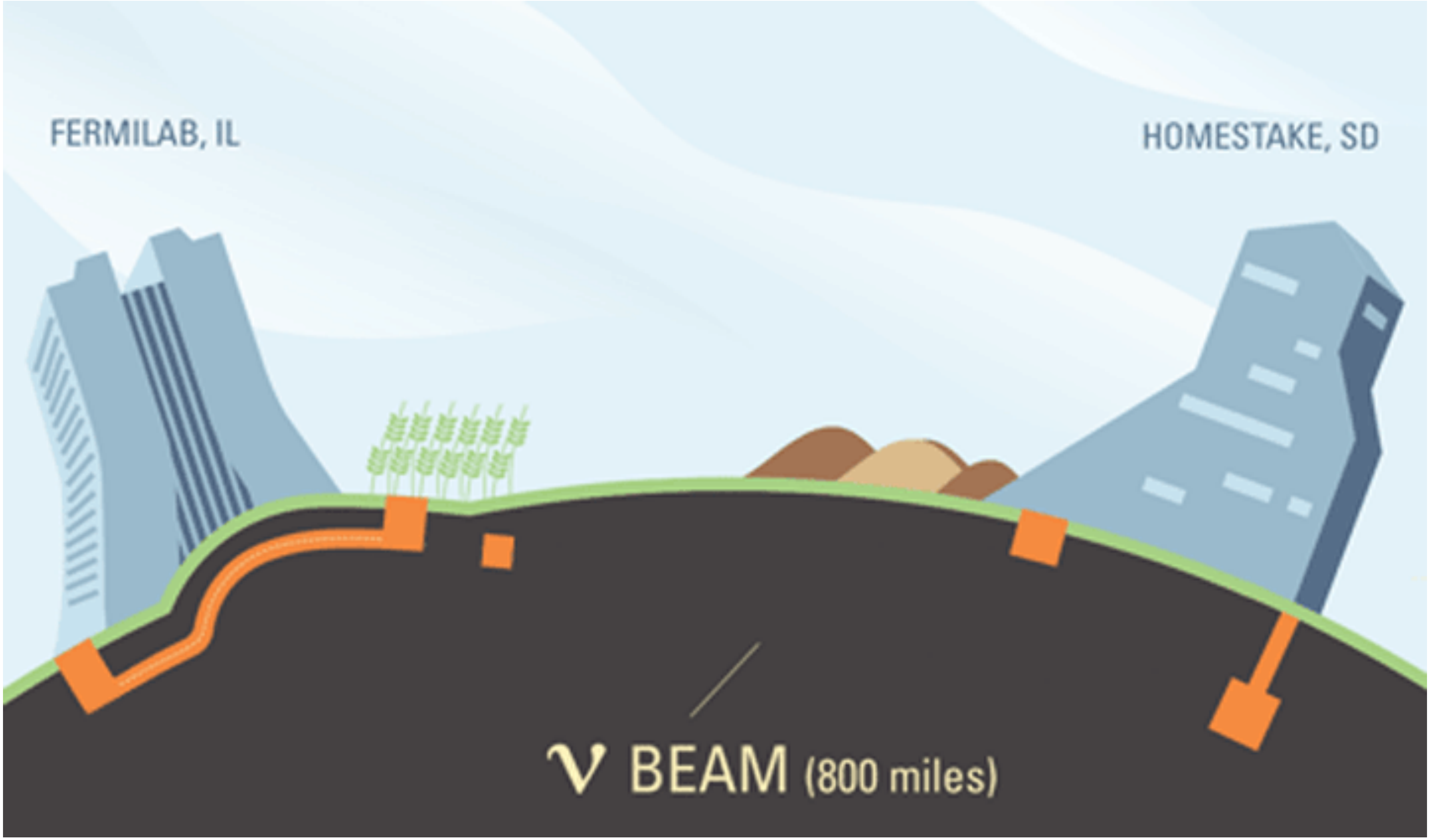
Exposure:

34 kt x 1.2 MW x 6 years
(half ν + anti-ν)

.

The plan

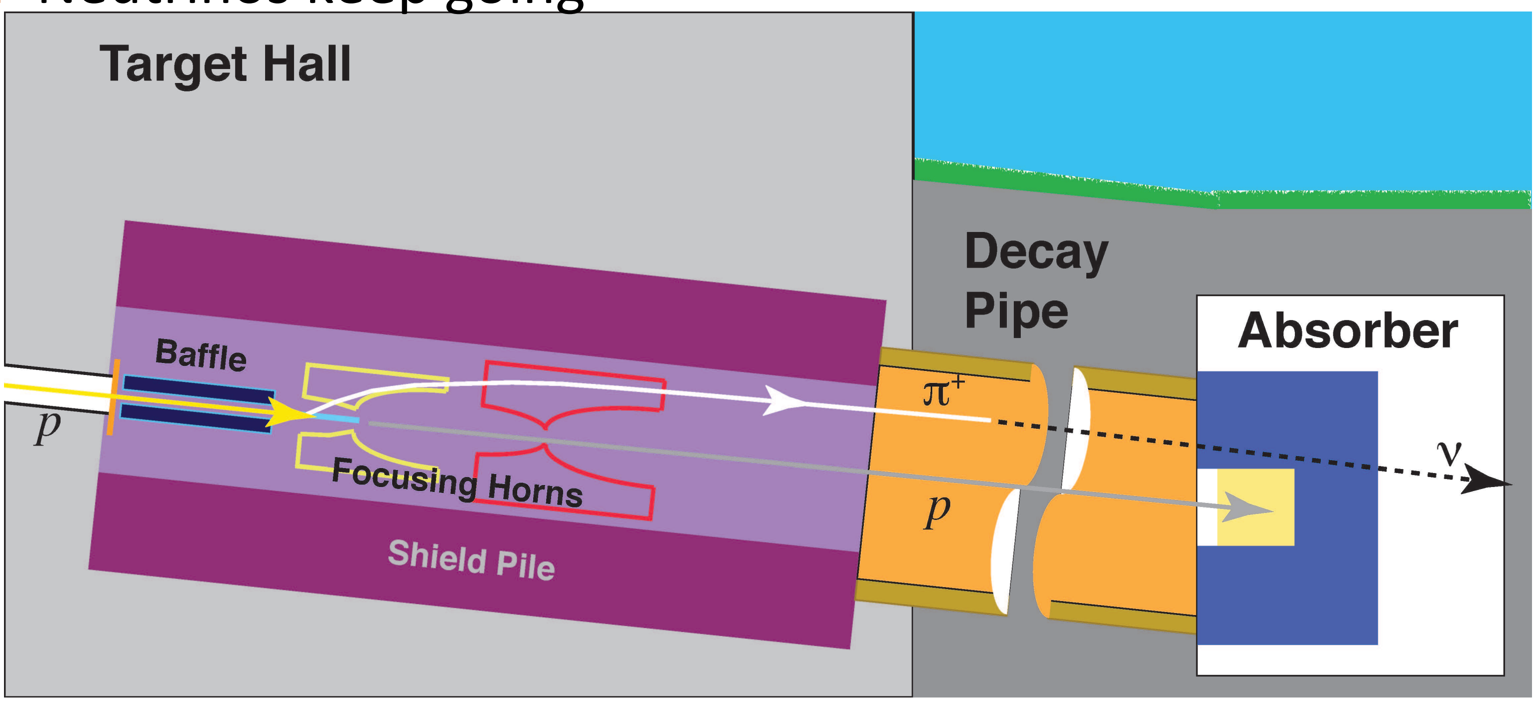
- Write a REALLY good grant application
  - Yay! CD3a just last week!
- Build a 1.2 MW neutrino beam (500 kW now)
- Dig very large holes in a mine 1300 km away
- Build multiple 10kT detector modules
- Run for several years with both neutrino and anti-neutrino beams.
- Understand neutrino CP violation

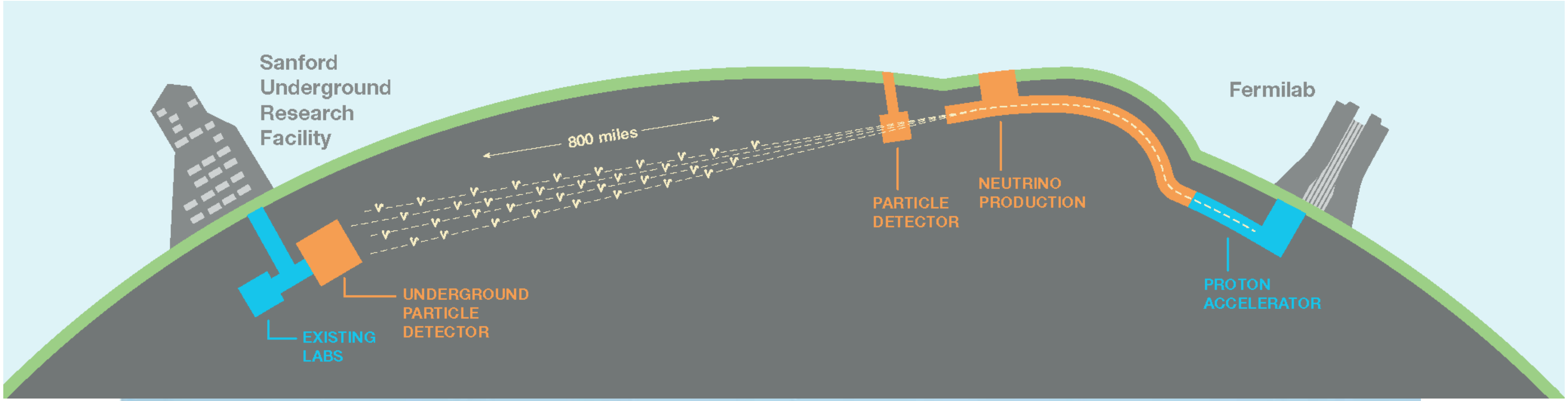


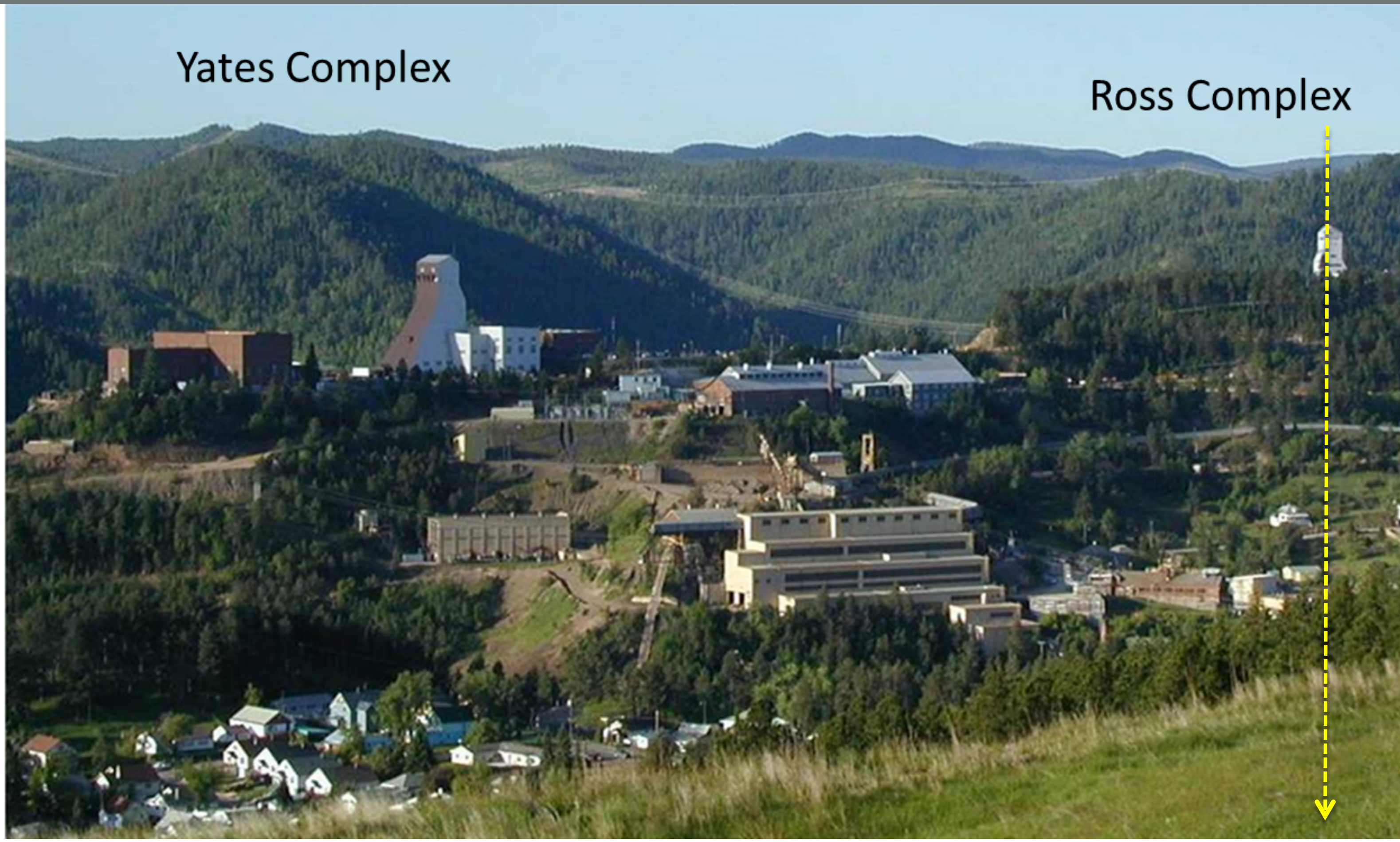
Plan is to put a future huge LAr detector
"DUNE" in the Homestake Gold Mine

1.2 MW beam

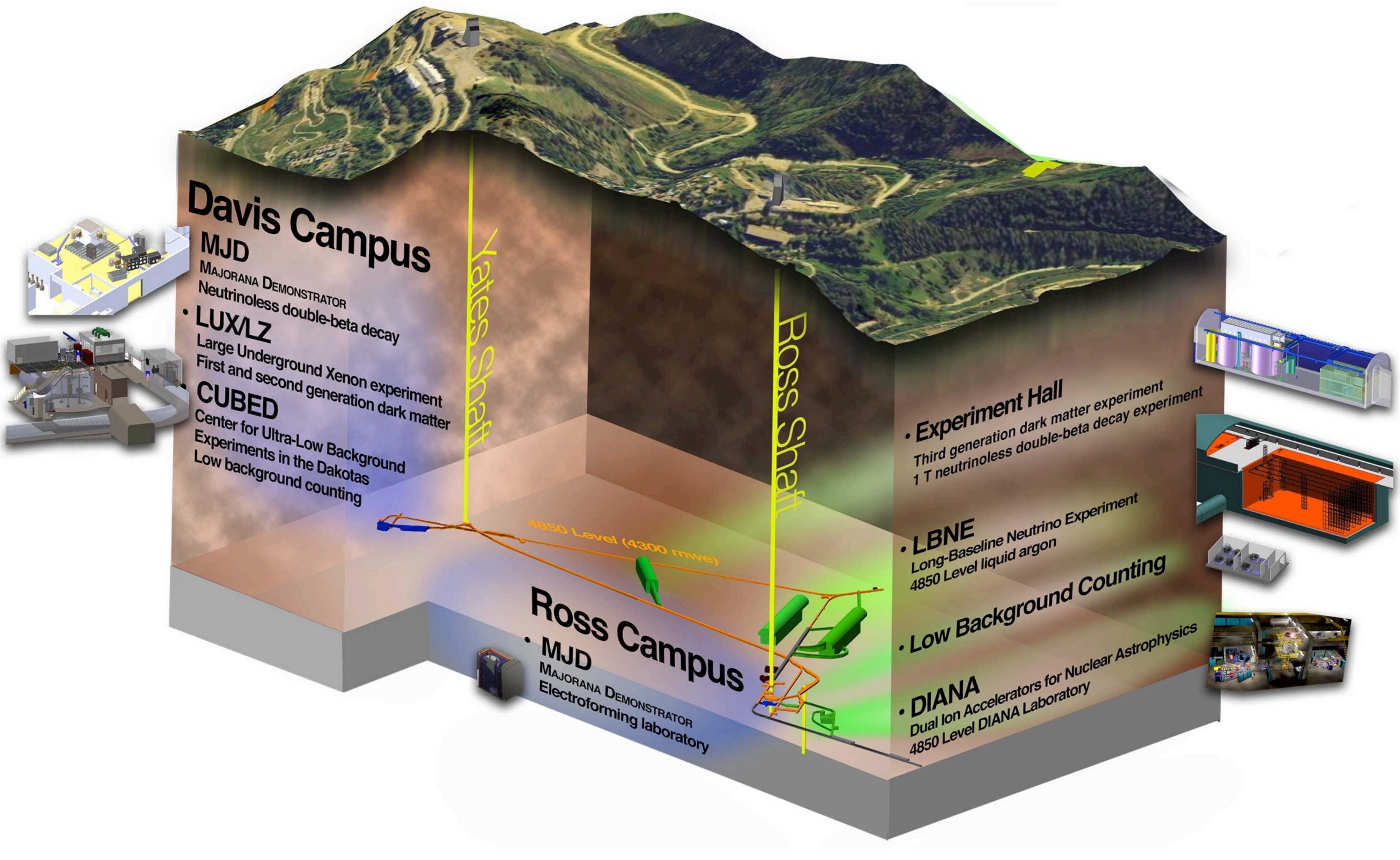
- 80 GeV protons hit a target
- Resulting pions are focused into decay pipe
- Pions decay to neutrinos, leftover protons are absorbed
- Neutrinos keep going




Sanford
Underground
Research
Facility
800 miles
Fermilab
PARTICLE
DETECTOR
NEUTRINO
PRODUCTION
UNDERGROUND
PARTICLE
DETECTOR
EXISTING
LABS
PROTON
ACCELERATOR


Yates Complex
Ross Complex

Underground view



Let’s go on a tour

Suit up and card in

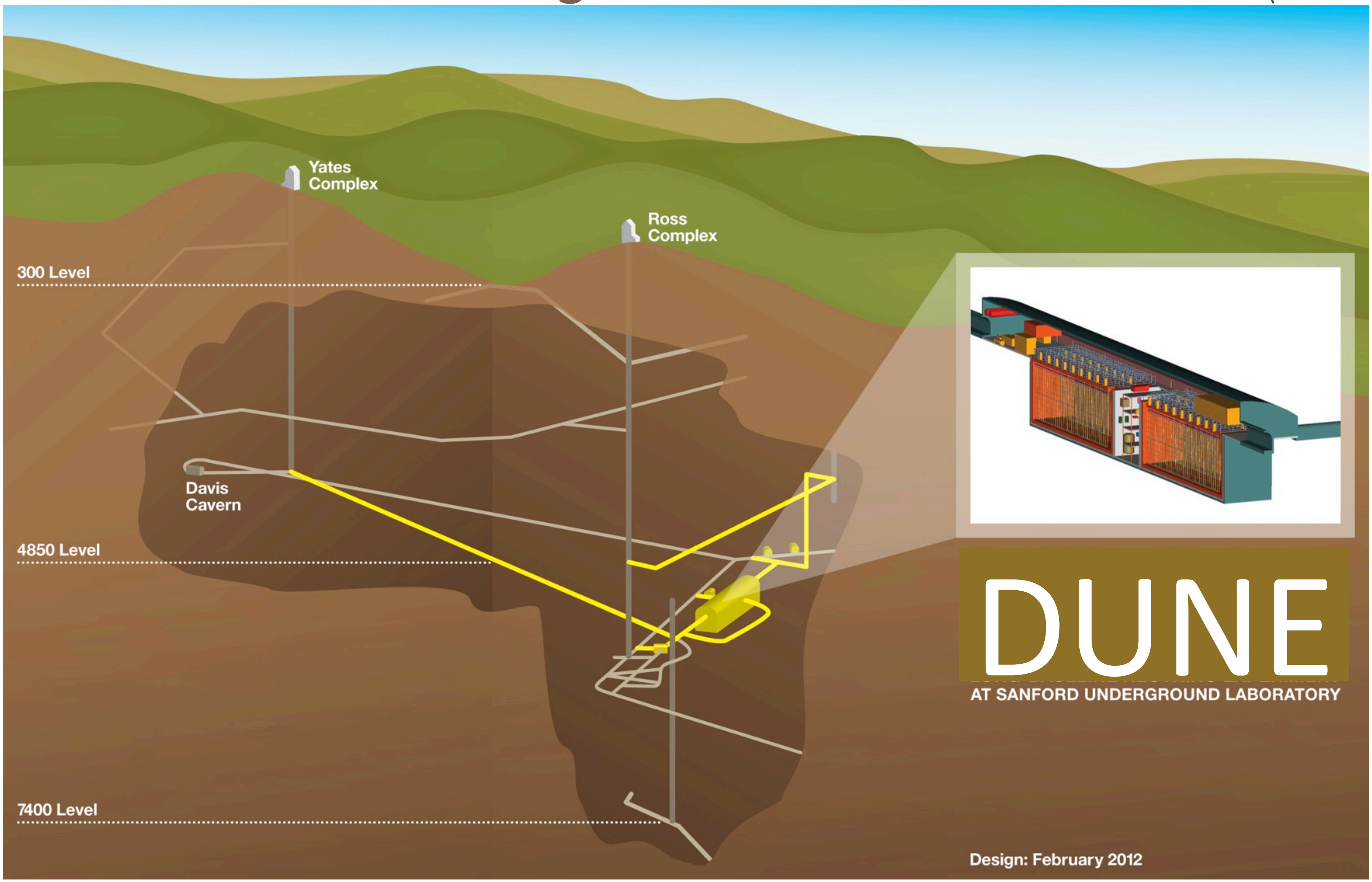
- Take an elevator 4850 ft down

Ride to the Davis cavern

The Davis cavern in late 2011

Davis cavern with the LUX detector

DUNE:
Installation starting 2020ish

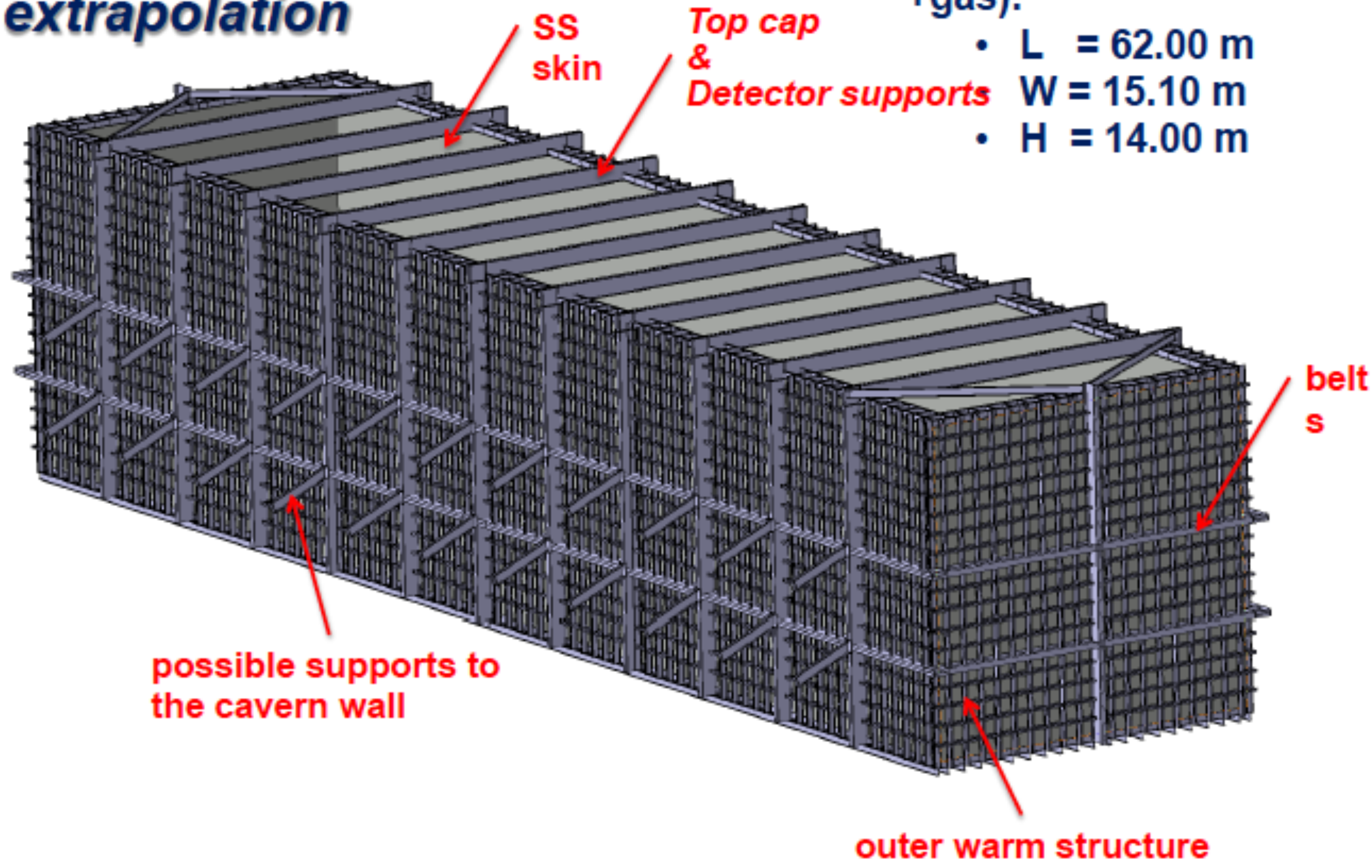


LAr Detector modules

4 LBNF Cryostats extrapolation

Inner dimension (liquid +gas):

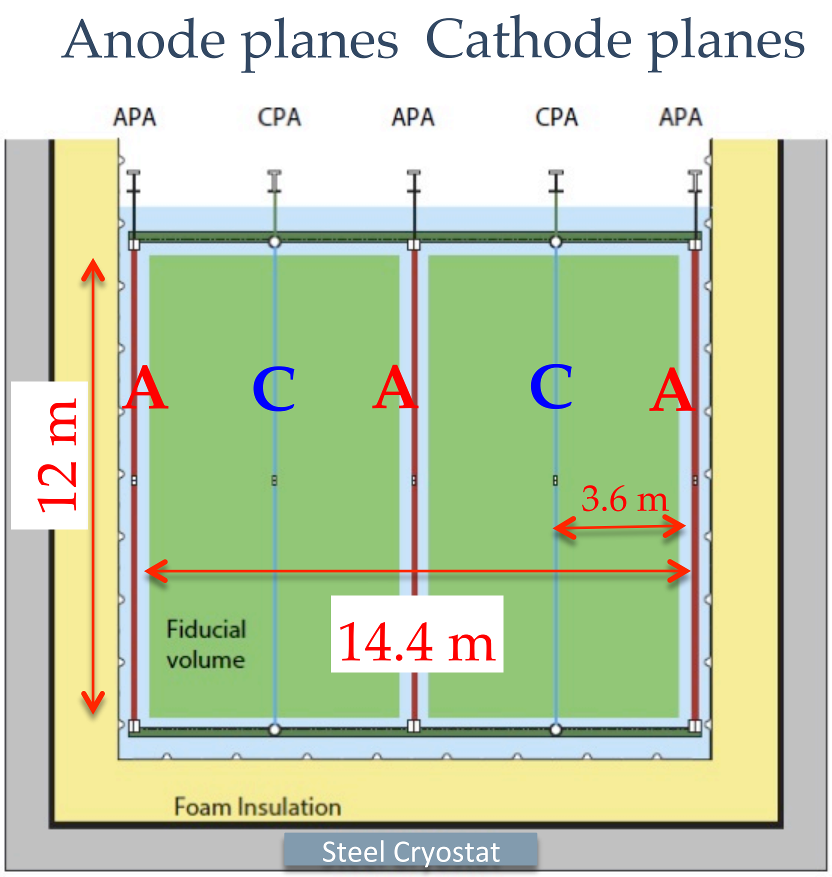
- L = 62.00 m
- W = 15.10 m
- H = 14.00 m

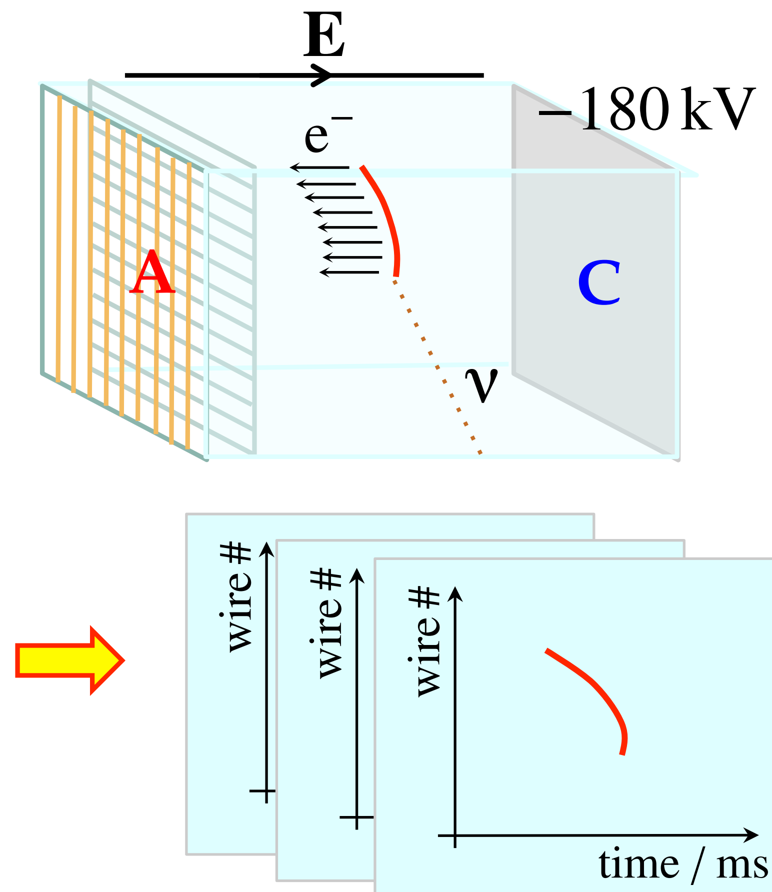


LAr = 17’432 tons (95% liquid)

Liquid Argon TPC Basics

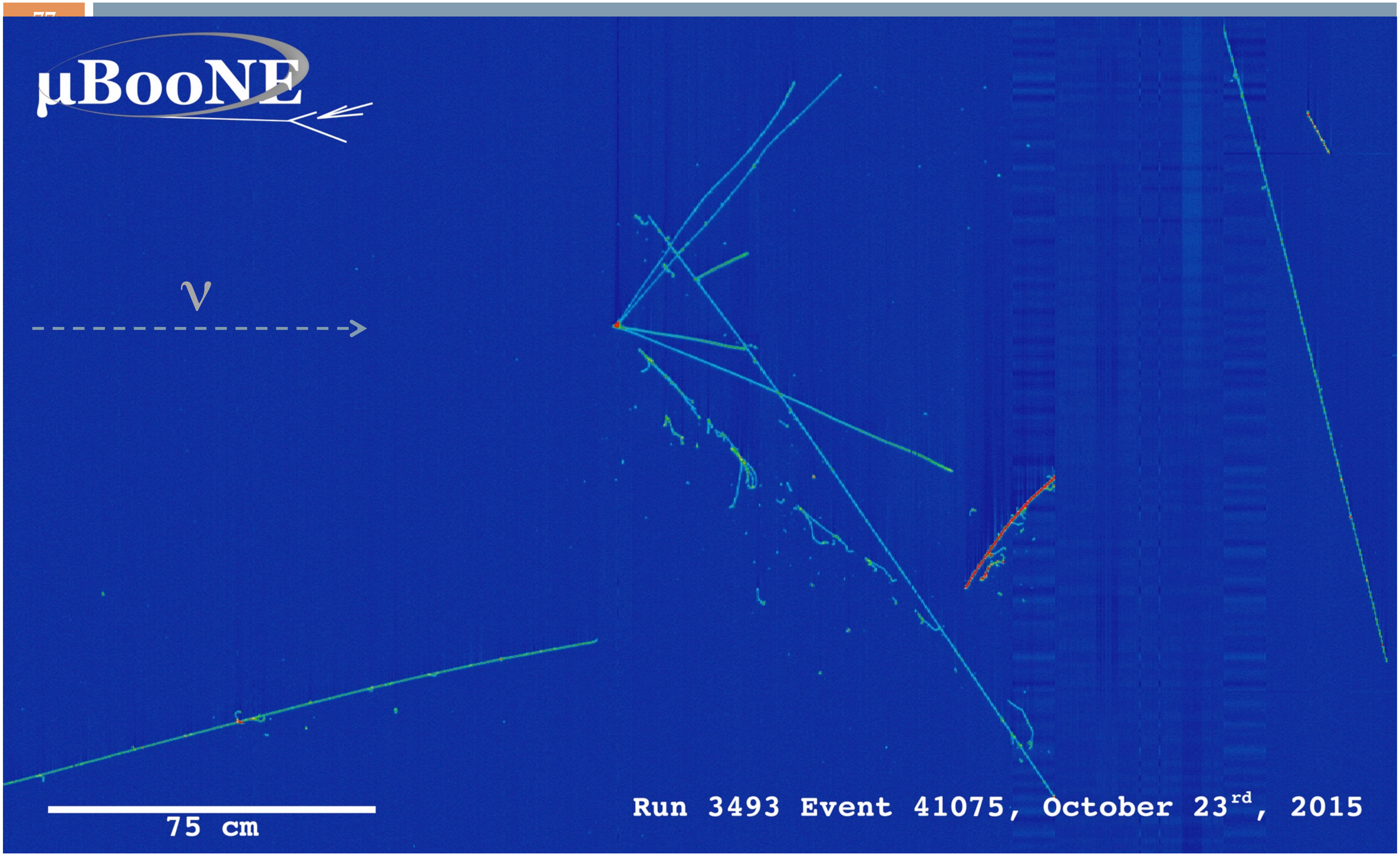
- **Large tank of Liquid Argon**
- **Apply electric field**
- **Charged particles leave ionization which you then collect.**



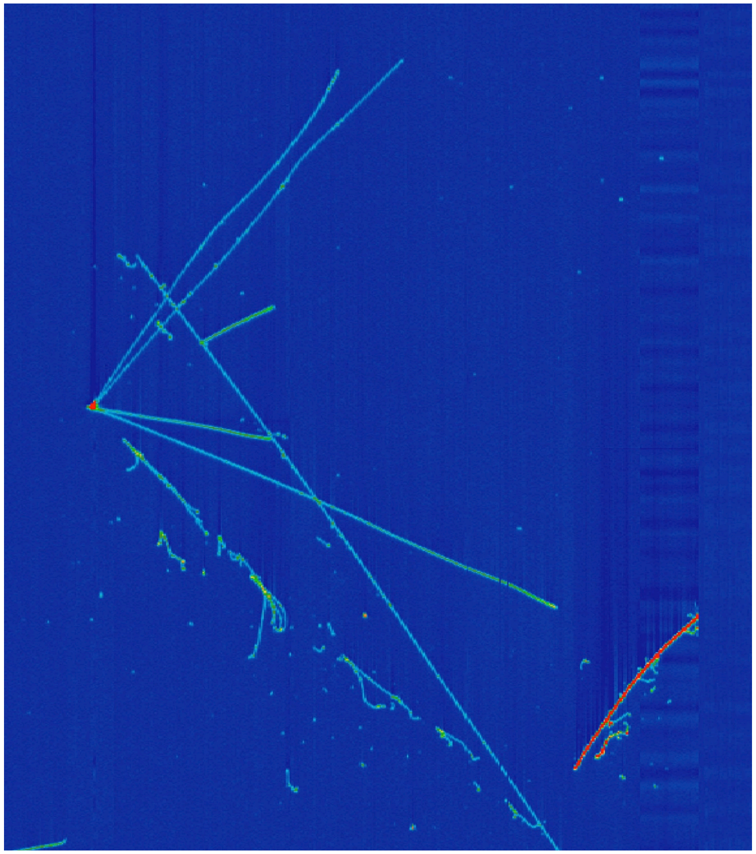



MicroBooNE @FNAL

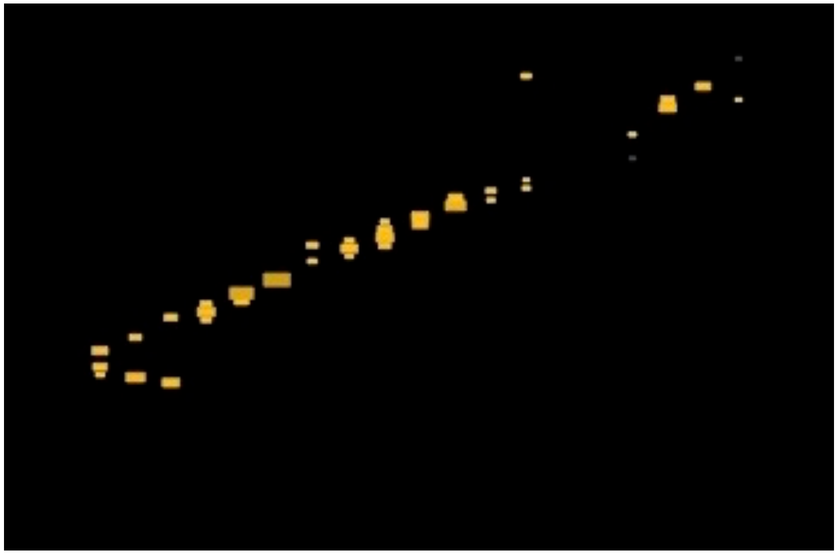
Real MicroBooNE event in LAr



Compare resolution



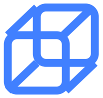
MicroBooNE



NOvA ν_e candidate

Compare resolution

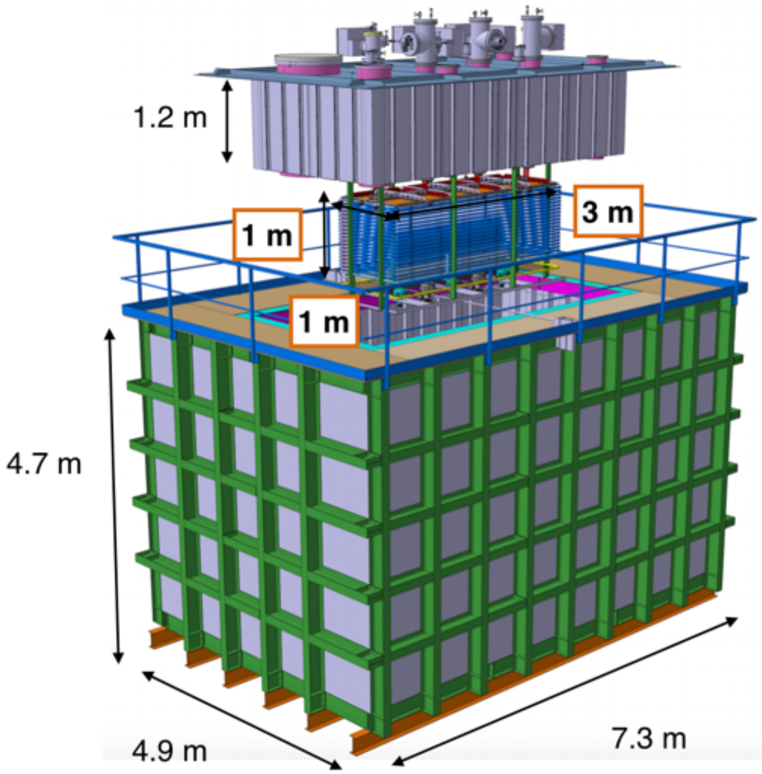
NOvA 2D pixel



Liquid argon 3-D voxel

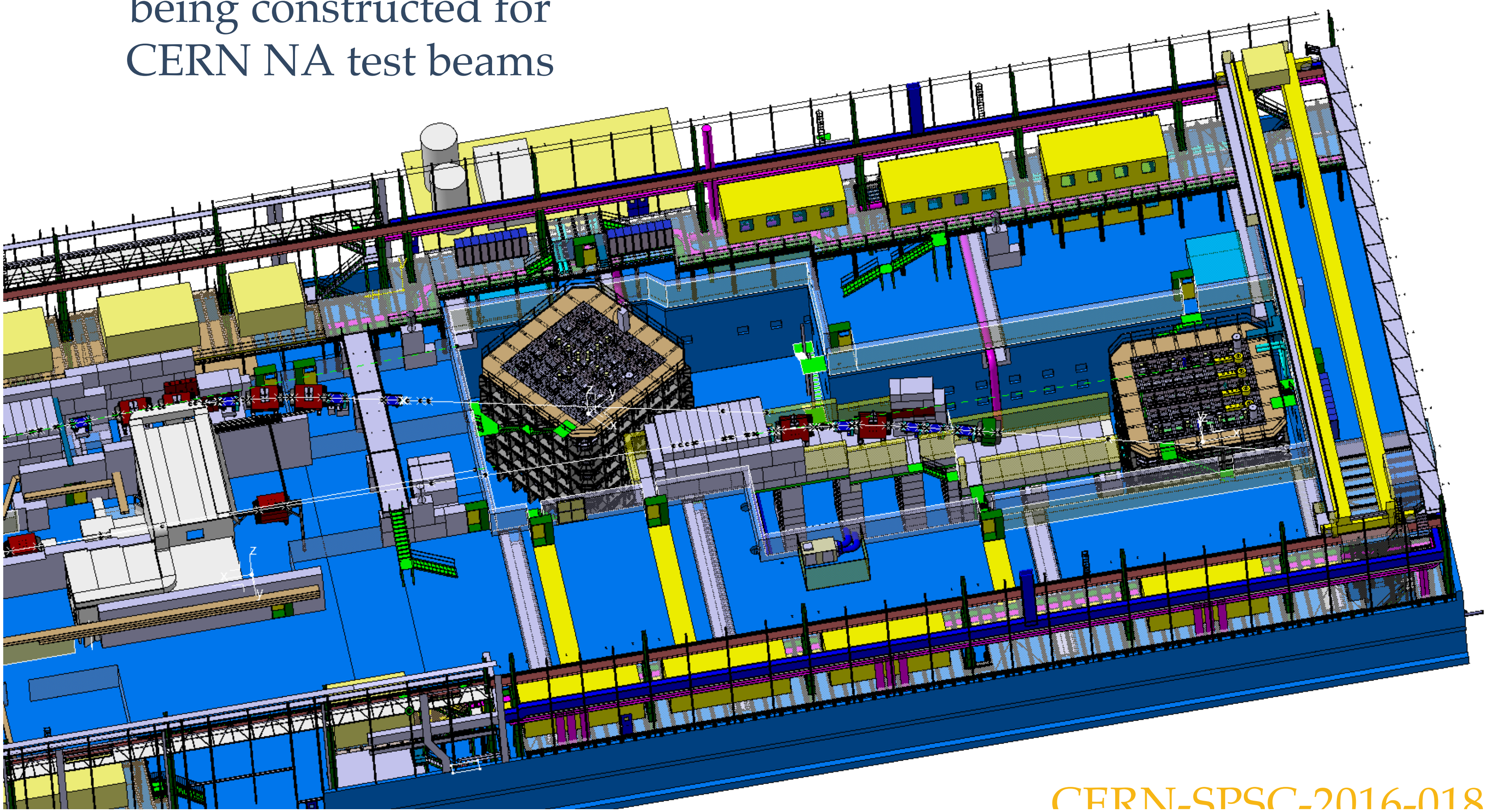
Currently @ CERN

10-ton scale Dual Phase LAr TPC
(3x1x1 m3 active 24 ton LAr total)
Cryogenic Operation: September 2016



Neutrino Platform at CERN

Two 700 t prototypes being constructed for CERN NA test beams



CERN-SPSC-2016-018

April 27, 2016

The plan

NEUTRINO EXPERIMENT

Today

A decade

From N. Lockyer, "Hands-On", 26/4/2016

- **2017**
  - Start pre-excavation construction work
- **2018**
  - Complete Sanford Laboratory "reliability projects"
  - Progress protoDUNEs to enable testing in CERN beam
  - Start major cavern excavation work
- **2021**
  - Complete first cryostat and cryo systems construction to enable DUNE detector installation to begin
- **2024**
  - Commission first DUNE detector – start science!
- **2026**
  - World's most powerful neutrino beam turns on!

An exciting short and long term program

- 2015-2025
  - Understand neutrino interactions
  - Develop liquid argon technology
  - Search for short baseline neutrino oscillations
    - Are there really only 3 neutrino types?
  - Design and build LBNF/DUNE
- 2025-2035
  - Get a definitive measurement of δ
  - Test the 3-flavor model
  - See a supernova?

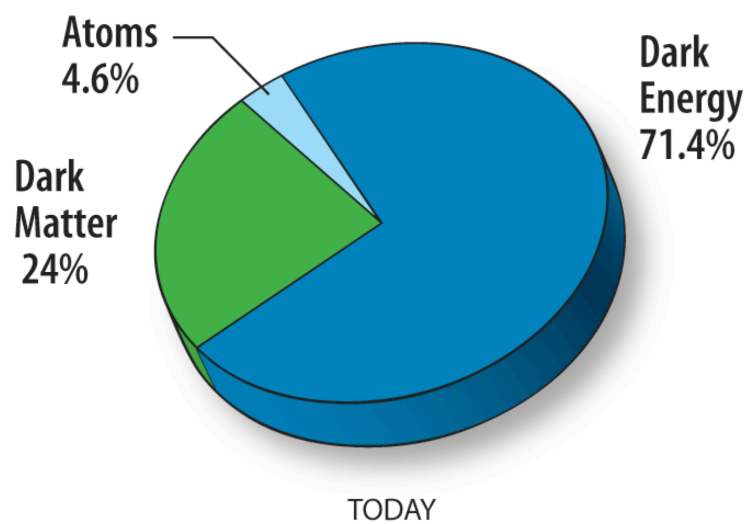
Neutrino Masses

Oscillations give us Δm not m

- We don't actually know the absolute scale of neutrino masses.
- What can we do to find out?
- Cosmology
- Direct measurements

Simple cosmological bound

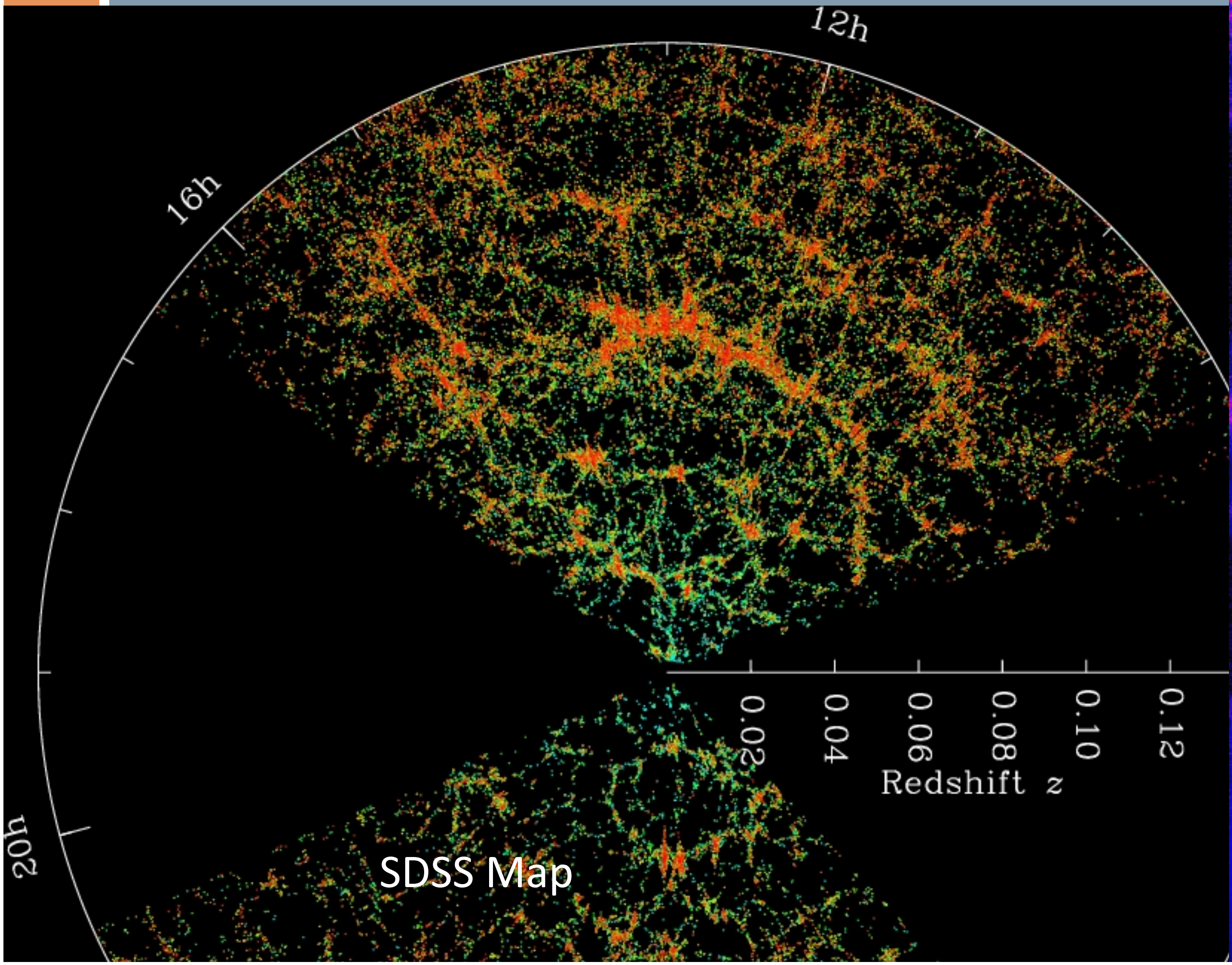
- The universe is flat and <= 28% matter.
- The neutrino density is about 9/11 n_γ ~ 336/cm^3
- The total density of matter allowed in the universe from Planck is about 4000 eV/cm^3
- If the sum of neutrino masses was more than 11.5 MeV, neutrinos would dominate the matter density in the universe.

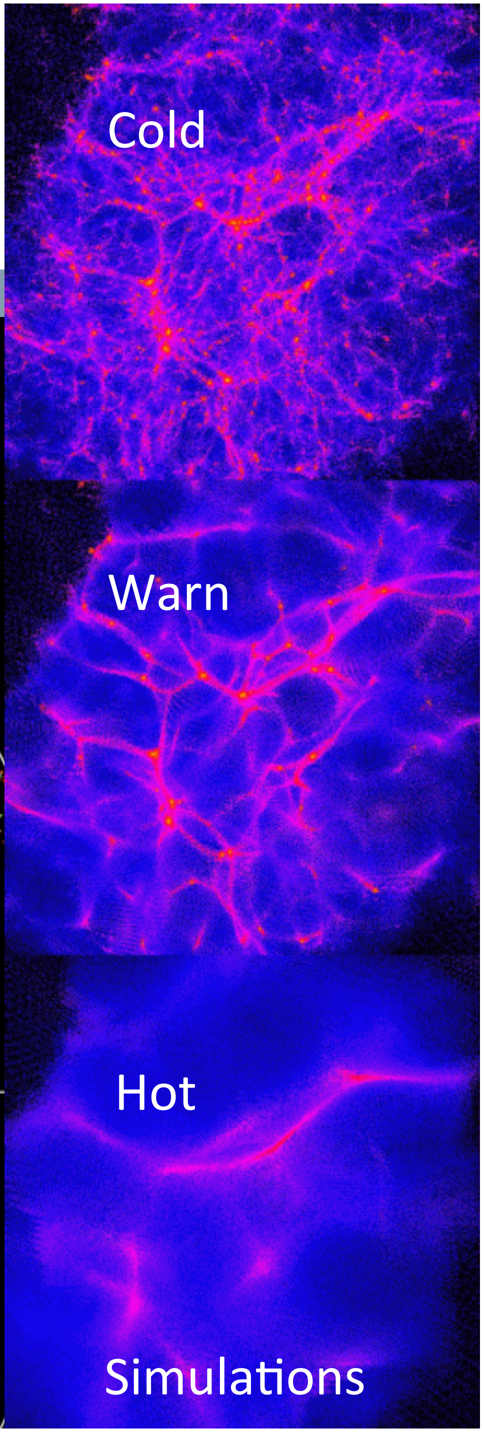


Hot dark matter

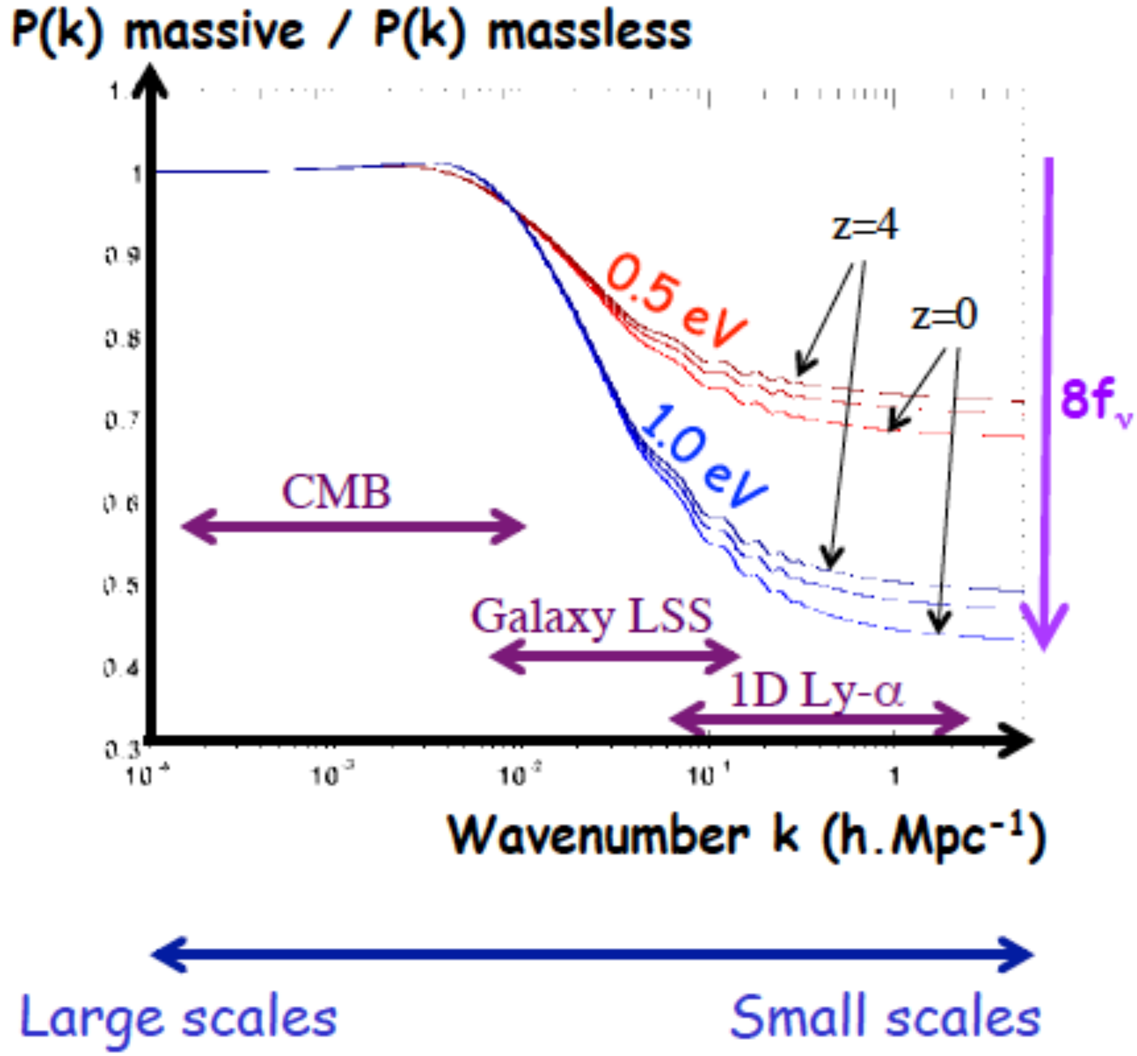
- But that assumed the "dark matter" is neutrinos.
- Cosmic neutrinos are now mostly non-relativistic as
- $T << \Delta m$ so at least one species is non-relativistic.
- But in the early universe, they would have been highly relativistic and smeared out cosmic structures.

Large scale structure



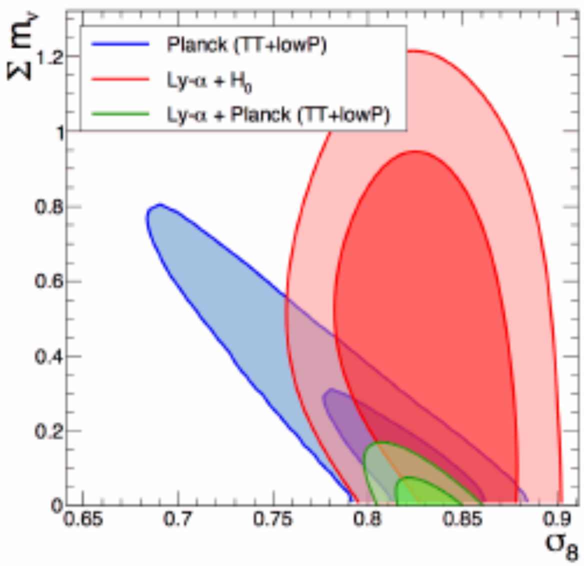


Power spectrum for structure



From Yeche et al, Moriond 2016

Constraint on Σm_ν



Limits:

- With Ly-α alone:
  $\Sigma m_\nu < 1.1$ eV @95%CL
- With Planck 2015 alone:
  $\Sigma m_\nu < 0.72$ eV @95%CL
- Combined with CMB (Planck 2015)
  $\Sigma m_\nu < 0.12$ eV @95%CL

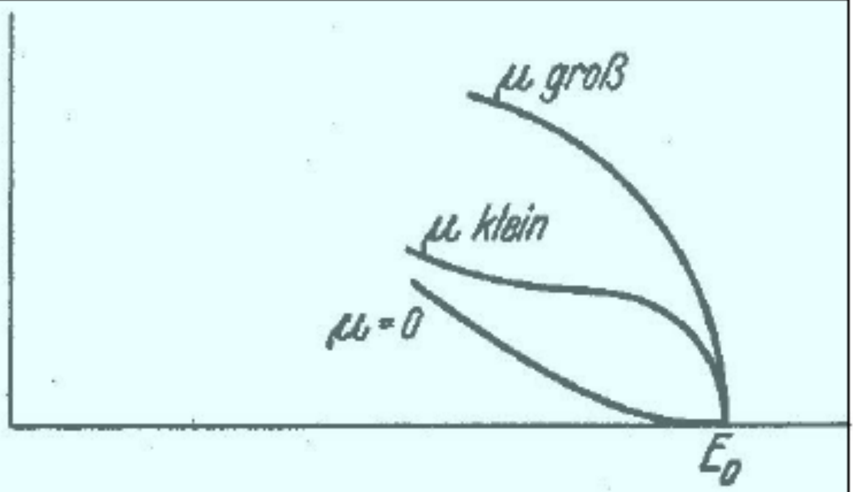
Parameter	(1) Lyα + H_0^{Gaussian} ($H_0 = 67.3 \pm 1.0$)	(2) Lyα + Planck TT+lowP	(3) Lyα + Planck TT+lowP + BAO
σ_8	0.831 ± 0.031	0.833 ± 0.011	0.845 ± 0.010
n_s	0.938 ± 0.010	0.960 ± 0.005	0.959 ± 0.004
Ω_m	0.293 ± 0.014	0.302 ± 0.014	0.311 ± 0.014
H_0 (km s^{-1} Mpc^{-1})	67.3 ± 1.0	68.1 ± 0.9	67.7 ± 1.1
$\sum m_\nu$ (eV)	< 1.1 (95% CL)	< 0.12 (95% CL)	< 0.13 (95% CL)

Palanque-Delabrouille , Yèche, Lesgourgues et al. (2014) and (2015)

Direct measurements

- Beta decay endpoint

The shape of the β decay end-point contains information about the neutrino mass (the energy of the end-point is generally not known well enough to make an absolute measurement)



Principle almost as old as neutrino itself:
E. Fermi, Z. Phys. 88 (1934) 161

For finite energy resolution what is measured is the combination:

$$m^2(\nu_e) = \sum_i |U_{ei}|^2 m_i^2$$

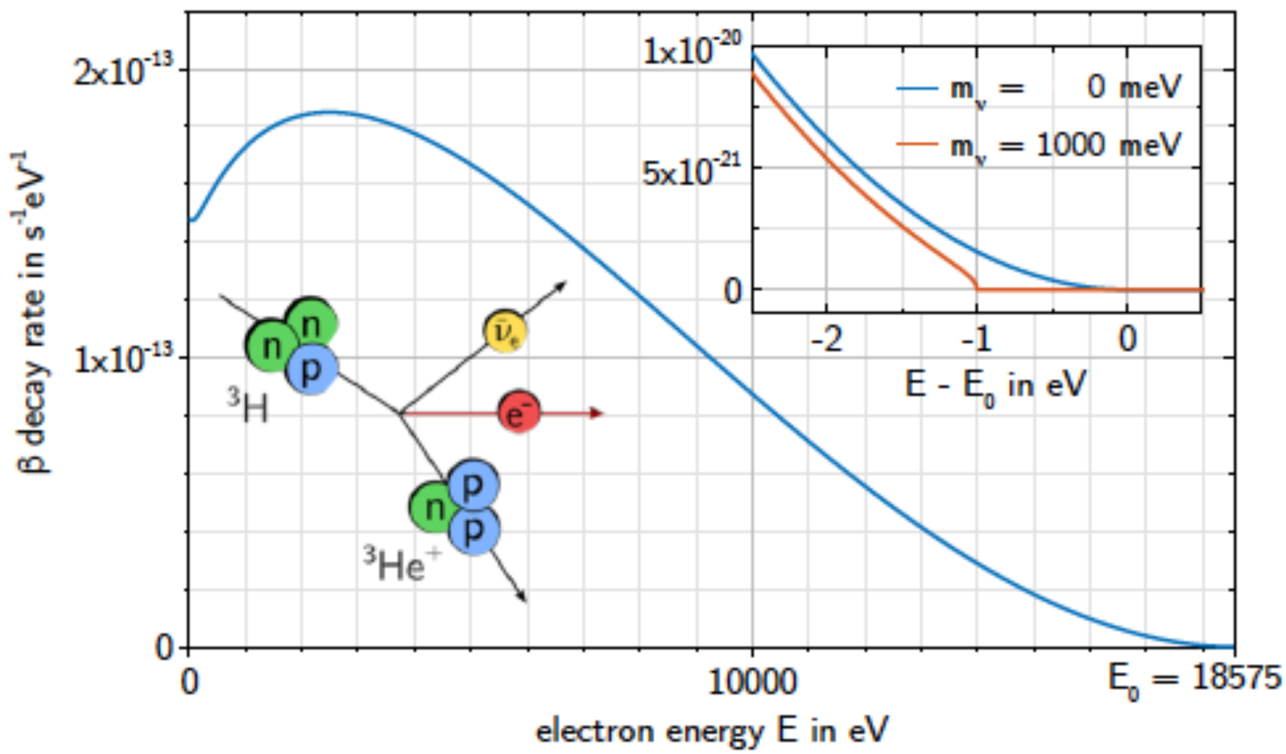
G. Gratta, ICHEP2016

Modern experiments mostly use $^{3}_{1}\mathrm{H} \rightarrow ^{3}_{2}\mathrm{He} + e^{-} + \overline{\nu}_e$

a super-allowed transition with a rather good combination of low end point (E_0=18.6 keV) and short half life ($T_{1/2}$=12.3 yr).
Still, *most* of the electrons are far from the end-point, i.e. not useful.

About 1 electron in 10^{11} emitted is close enough to the endpoint!

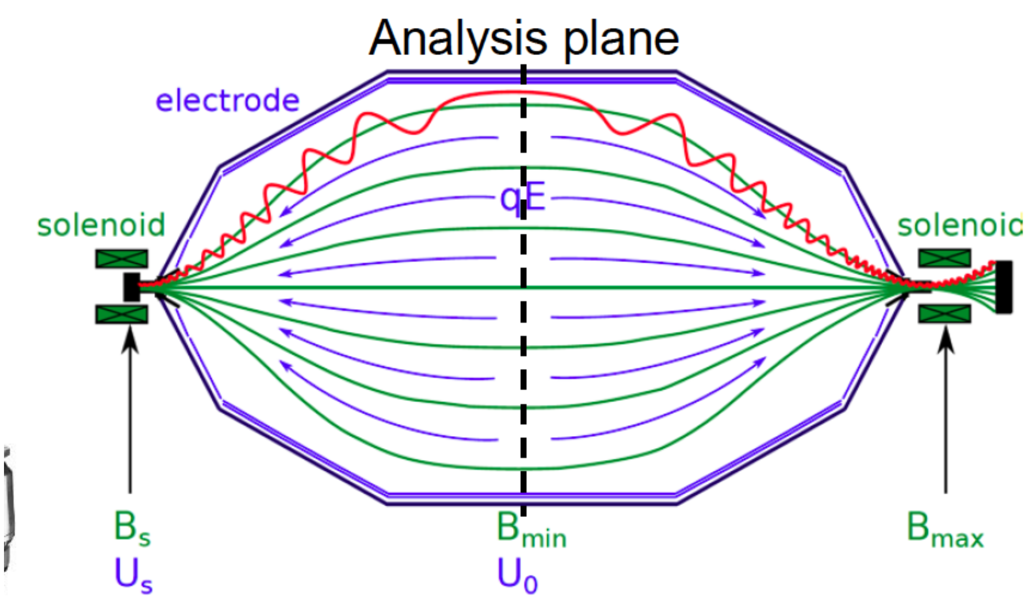
Endpoint shape



K Valerius, Neutrino 2016

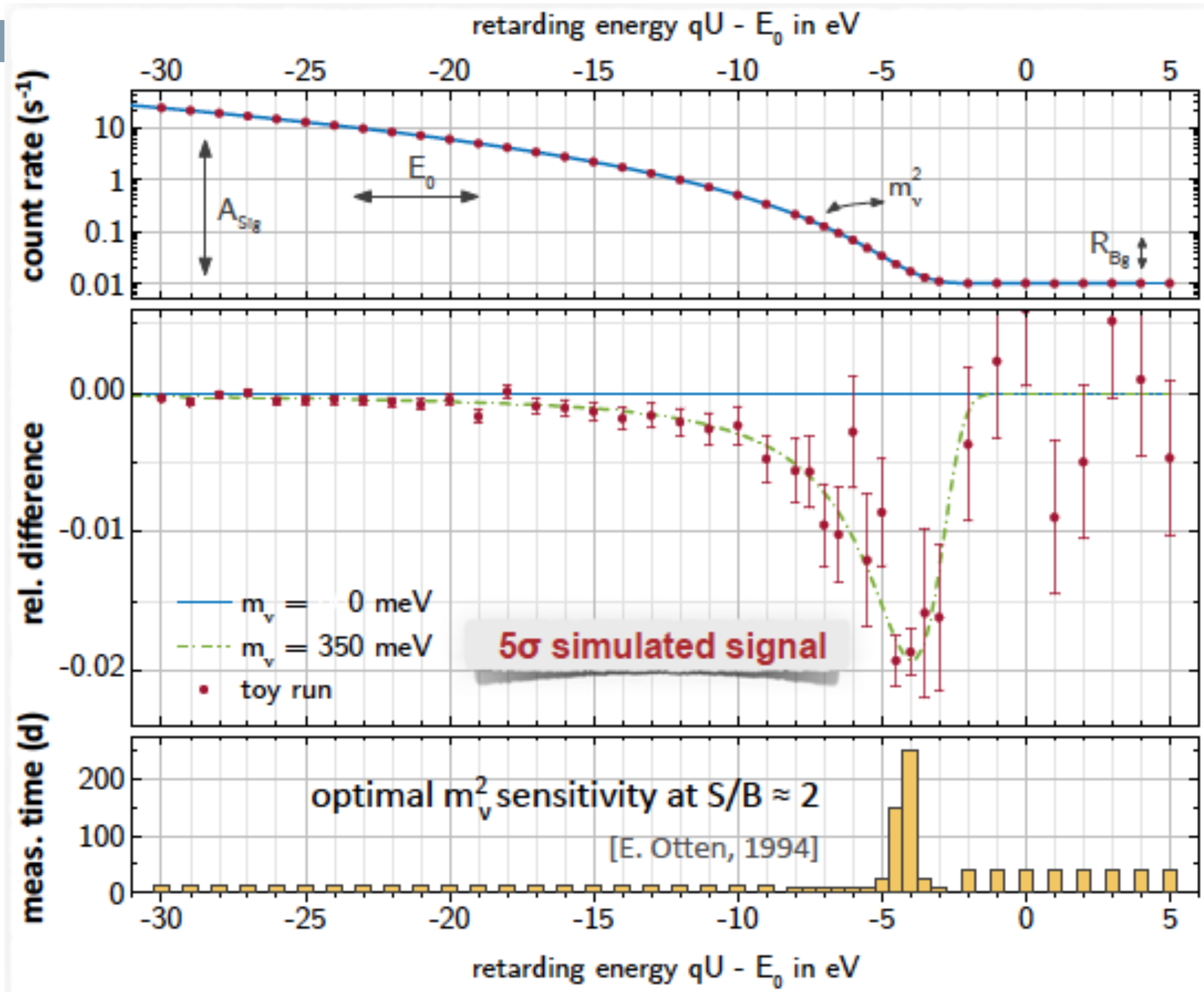
KATRIN

Tritium decays and electrons enter a varying magnetic field
Only those right at the end point can make it through to the detector at the other end



Simulation

K Valerius, Neutrino 2016



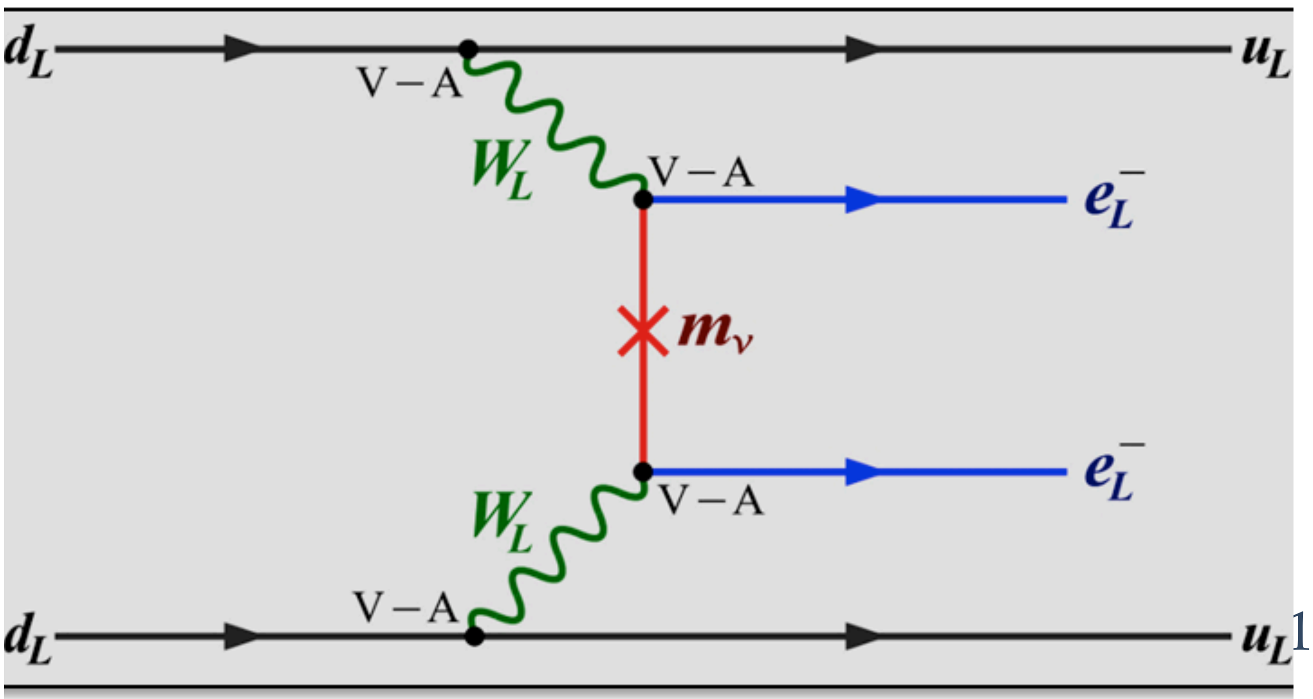
KATRIN goal

- Sensitivity of 240 meV in 3 years of running
- Starting 2018 …

Neutrino-less ββ decay

This only happens if a neutrino is its own anti-particle
Majorana neutrino!

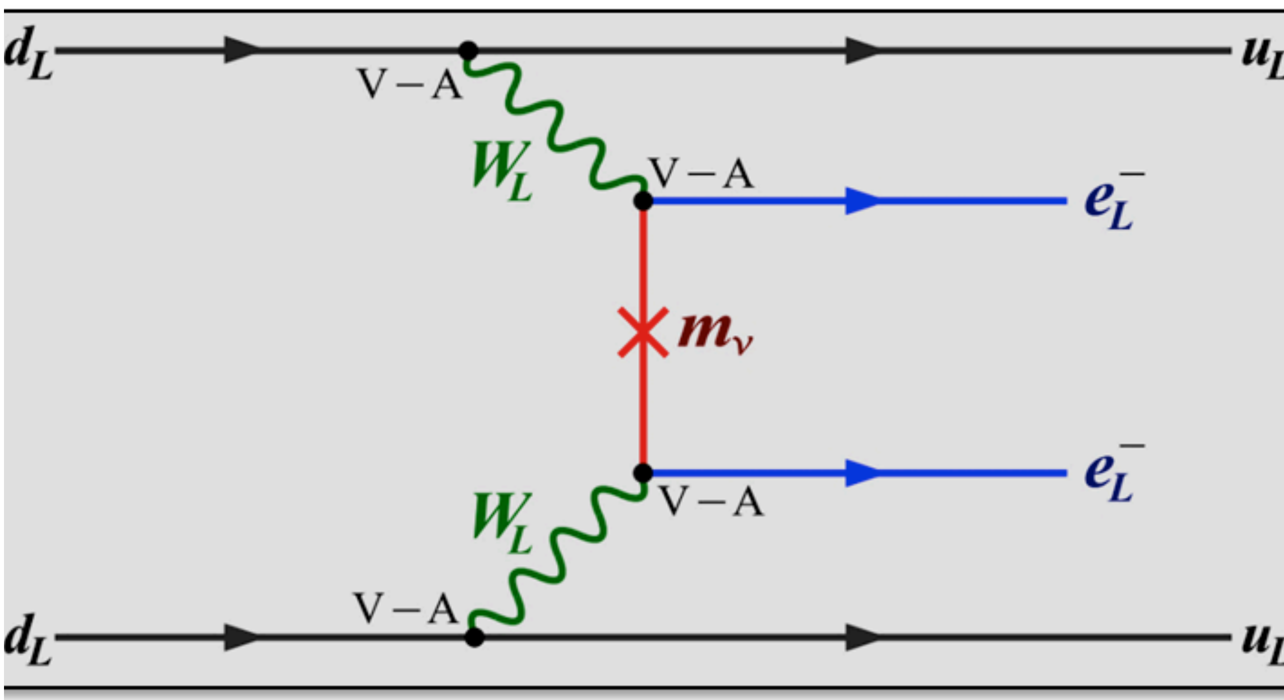
$$\mathcal{L}_M = -m_M \overline{\nu^c}_R \nu_R + h.c.$$



Neutrino-less ββ decay

This only happens if a neutrino is its own anti-particle
Majorana neutrino!

$$\mathcal{L}_M = -m_M \overline{\nu^c}_R \nu_R + h.c.$$



16

Helicity and Chirality

- Normal (for HEP people) v ~ c and Helicity and Chirality are equivalent, but

$$u_\uparrow = P_R u_\uparrow + P_L u_\uparrow = \frac{1}{2}\left(1 + \frac{|\vec{p}|}{E+m}\right) u_R + \frac{1}{2}\left(1 - \frac{|\vec{p}|}{E+m}\right) u_L$$

RH Helicity

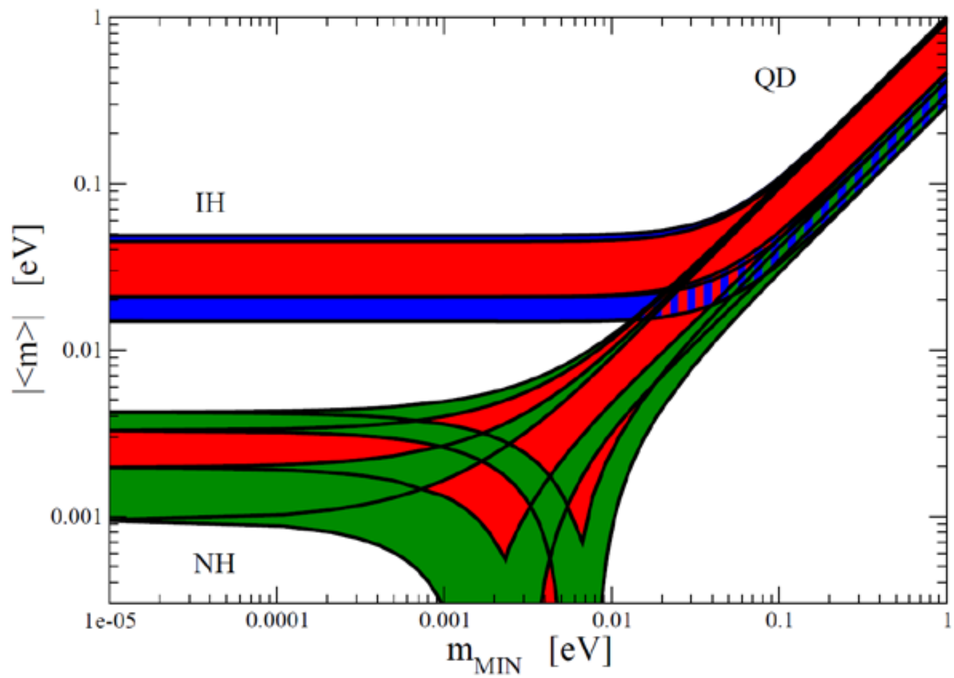
RH Chiral

LH Chiral

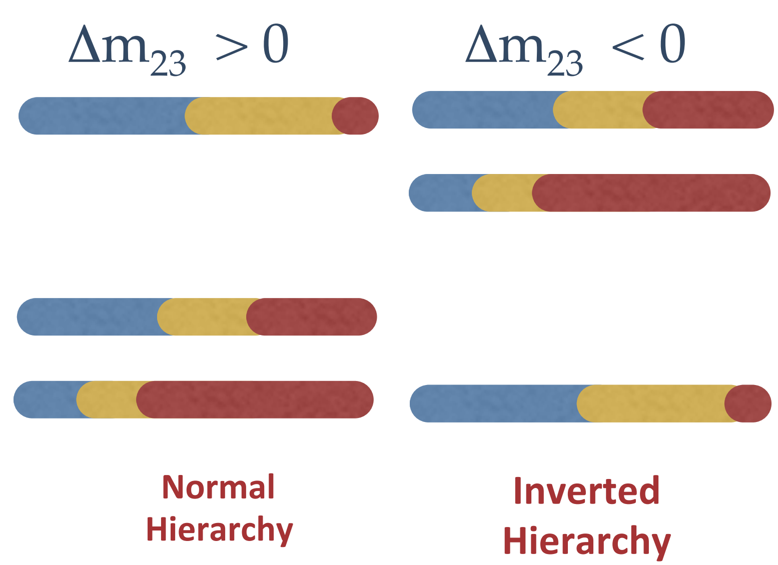
Get terms of order m_ν/Q for the helicity suppressed component.

$$\mathrm{Amp}[0\nu\beta\beta] \propto \left|\sum_i m_i U_{ei}^2\right| \equiv \langle m_{\beta\beta}\rangle$$

Effective neutrino mass vs minimum mass

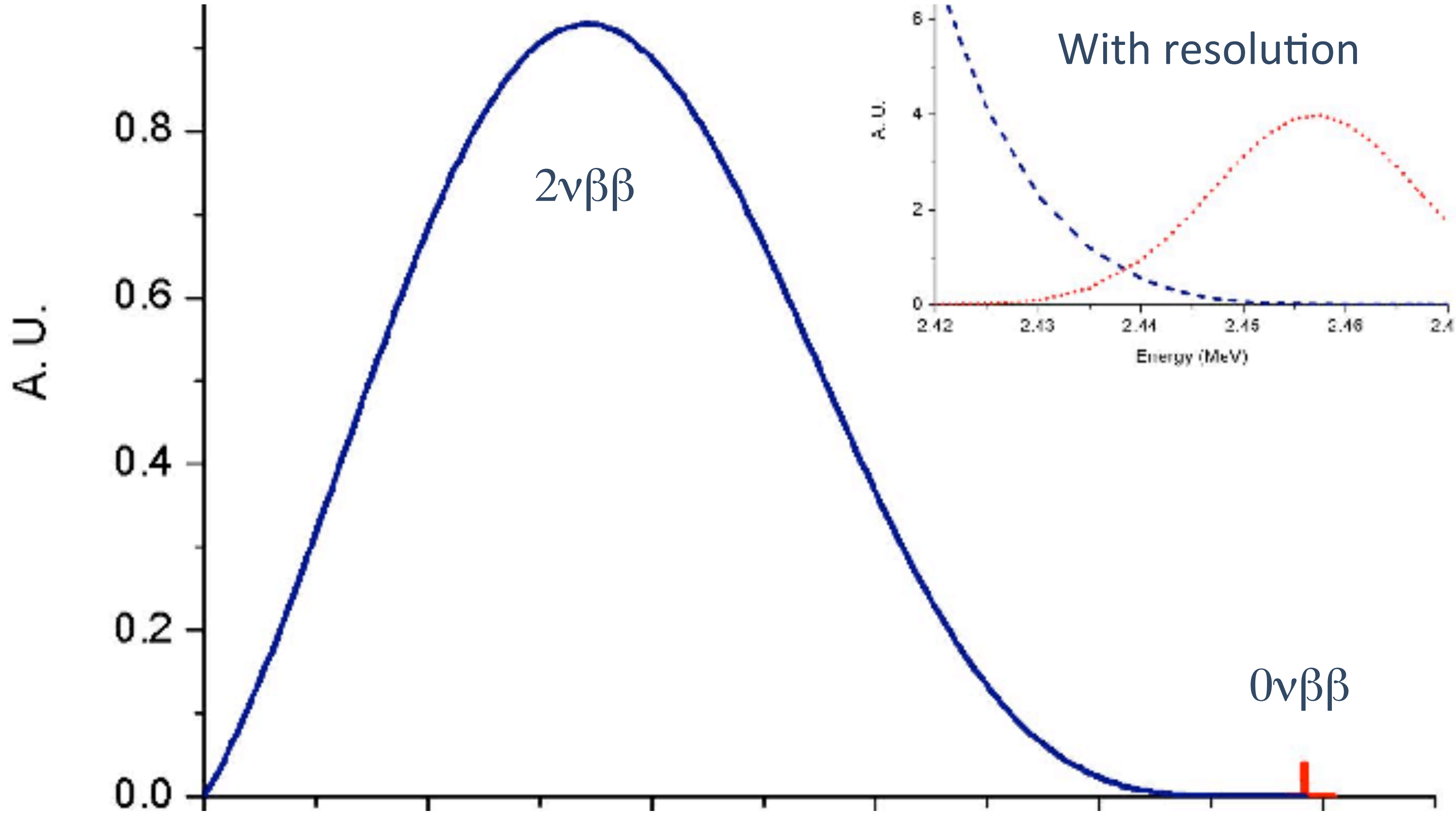


$$\mathrm{Amp}[0\nu\beta\beta] \propto \left|\sum_i m_i U_{ei}^2\right| \equiv \langle m_{\beta\beta}\rangle$$

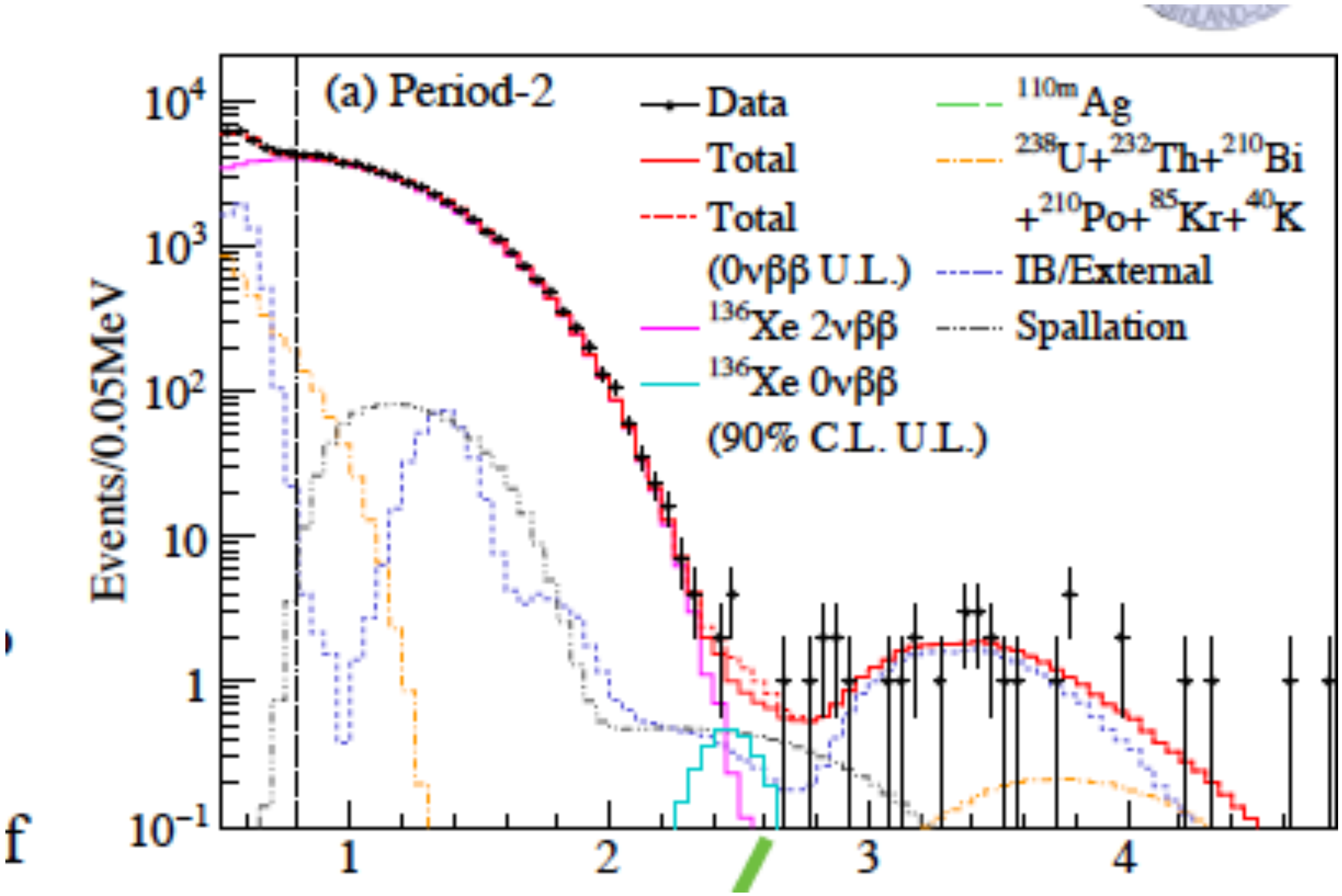


9/9/16

Beta decay rate



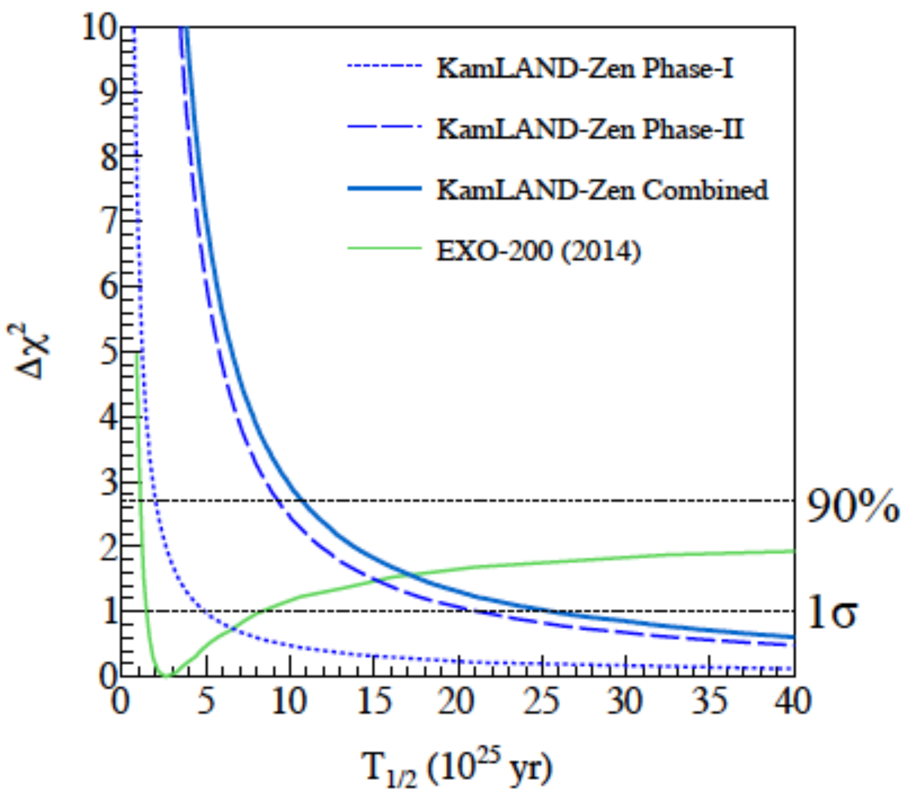
KAMLAND-ZEN Xe data, ICHEP2016

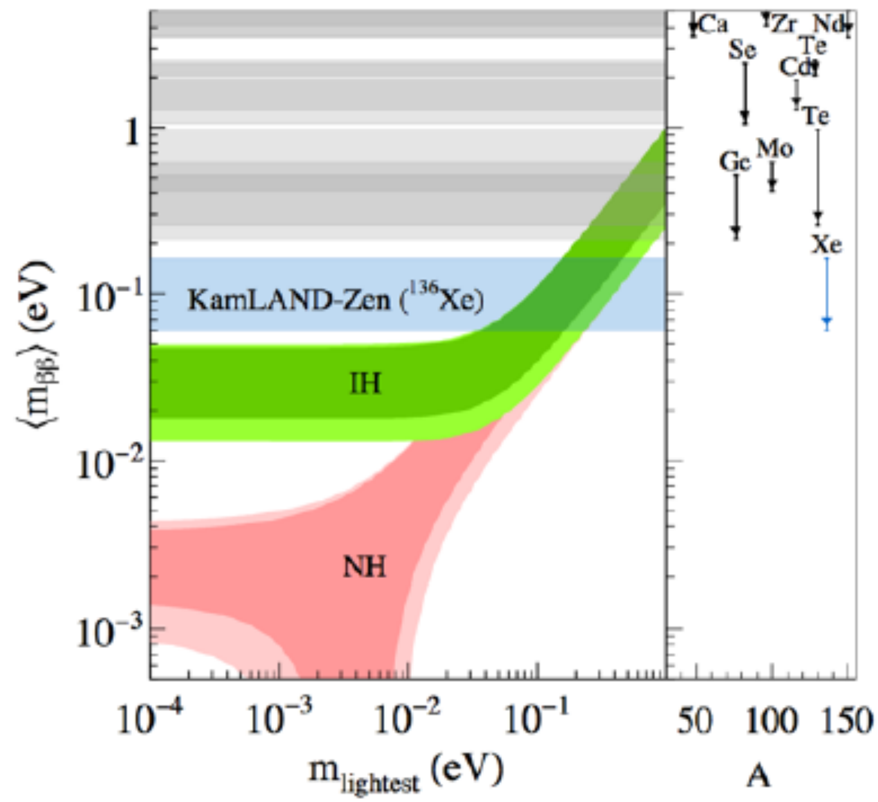


^{136}Xe $0\nu\beta\beta$ Decay Half-life

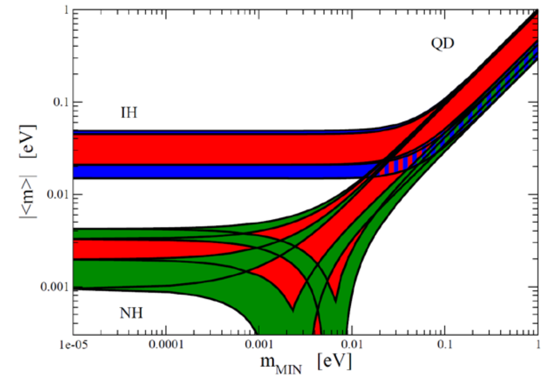
KamLAND-Zen ^{136}Xe Limits (90% C.L.)	
Phase 1	$T_{1/2}(0\nu) > 1.9 \times 10^{25}$ yr
Phase 2	$T_{1/2}(0\nu) > 9.2 \times 10^{25}$ yr
Combined	$\mathbf{T_{1/2}(0\nu) > 1.07 \times 10^{26}}$ **yr**

$\langle m_{\beta\beta}\rangle$ < 61 - 165 meV





Implications



- It's complicated
- We should be able to figure out the hierarchy elsewhere
- If we don't see double beta decay
  - Neutrinos are Dirac
  - $M_{\beta\beta}$ is very small, keep looking
- If we see double beta decay and measure $m_{\beta\beta}$.
  - IH – can't tell m_{min} but will see it faster
  - NH – can measure m_{min} someday…

Other topics

- Supernovae
- Solar physics
- Parton distributions
- Electroweak parameters
- Neutrino communication …

Maybe next time

107

Thanks to

- the organizers
- the institute
- and the students!

Extra topic – Neutrino cross sections

- We have to be able to tell neutrino oscillation effects from normal physics.

- Neutrinos like to interact with neutrons
- Anti-neutrinos prefer protons
  - Need to understand the detailed nuclear physics of neutrino interactions
- Need a detailed picture of each interaction


MINERvA Experiment - 2009
TremPro 644

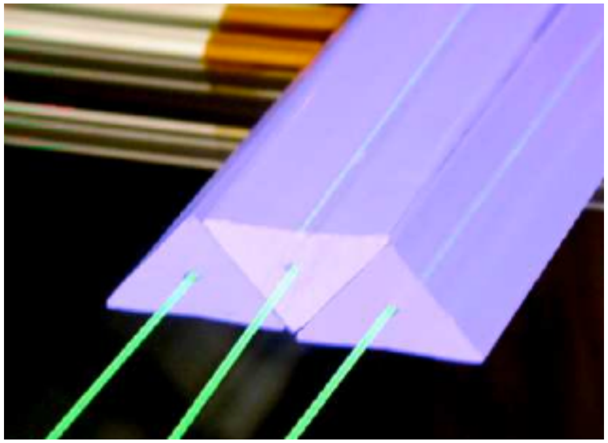
MINERvA: Detector at Fermilab

Located in NuMI beam at Fermilab upstream of the MINOS near detector

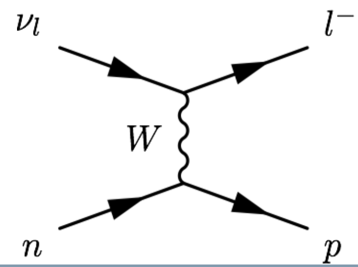
Made of > 30,000 strips of plastic scintillator interspersed with other materials

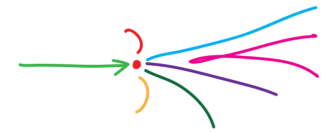
Scintillator creates light when charged particles move through it

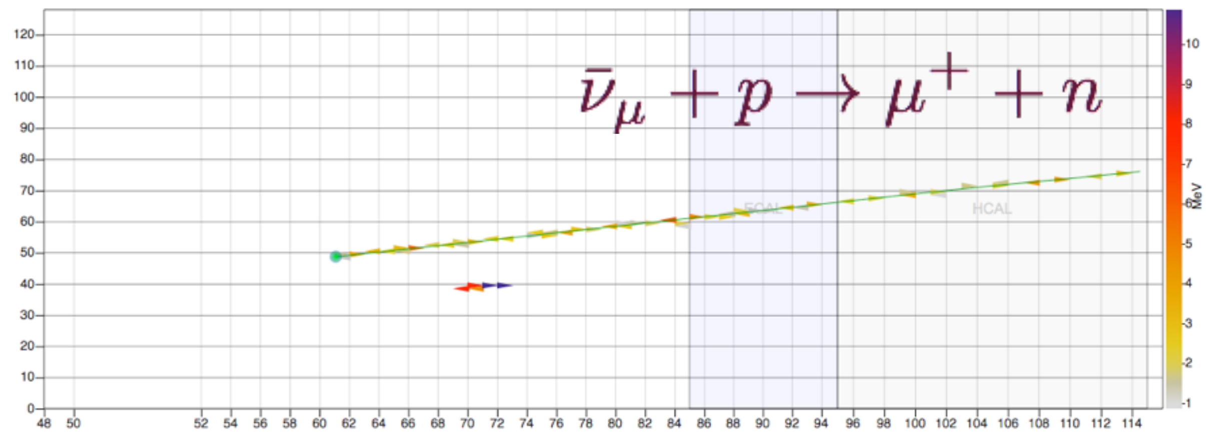
The beam is primarily muon neutrinos, with average energy near 3.5 GeV (similar to DUNE)

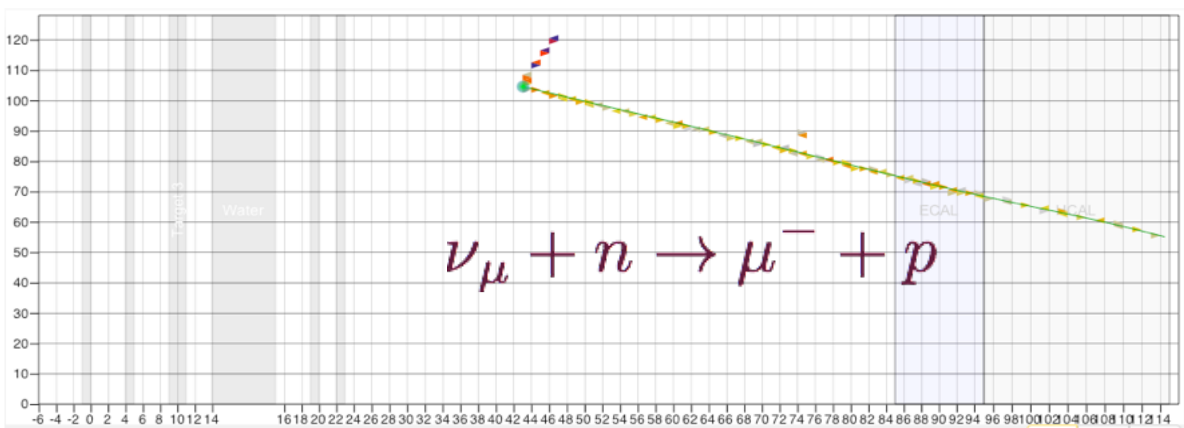


The simplest case: Quasi-elastic scattering









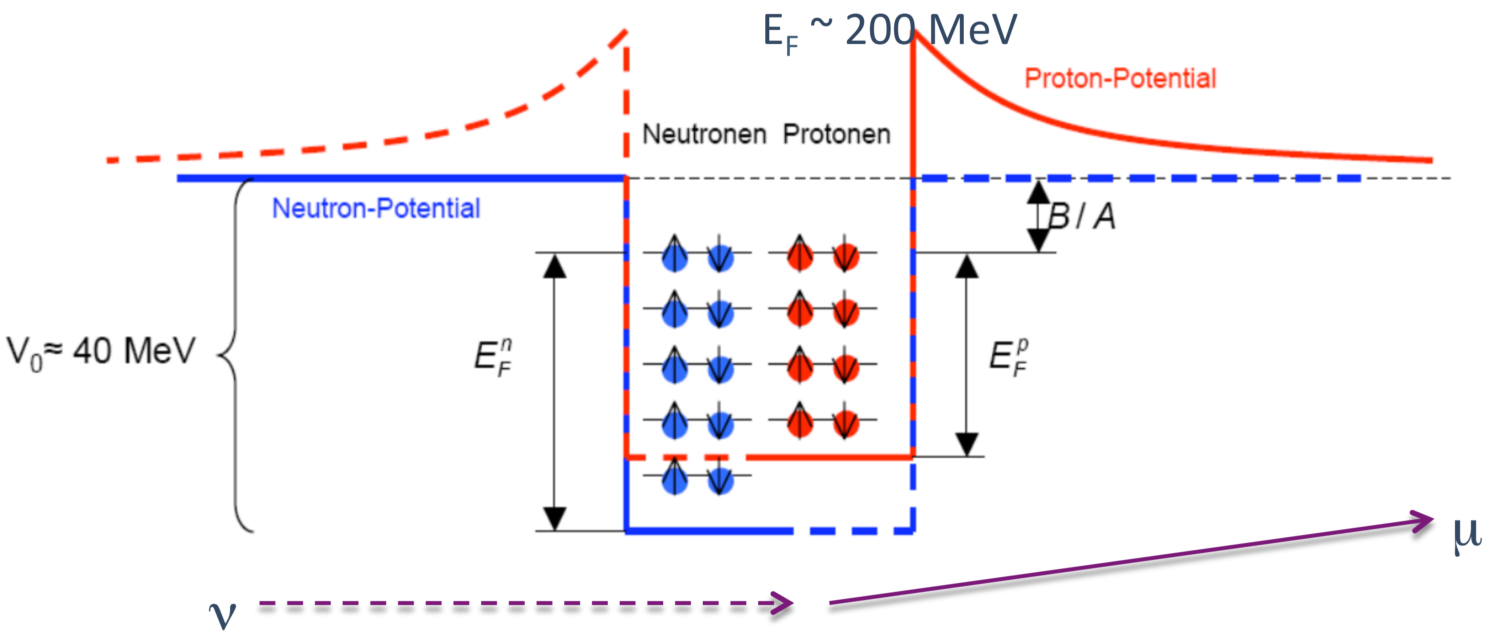
Classic signature:

- Final state muon
- Nucleon not excited

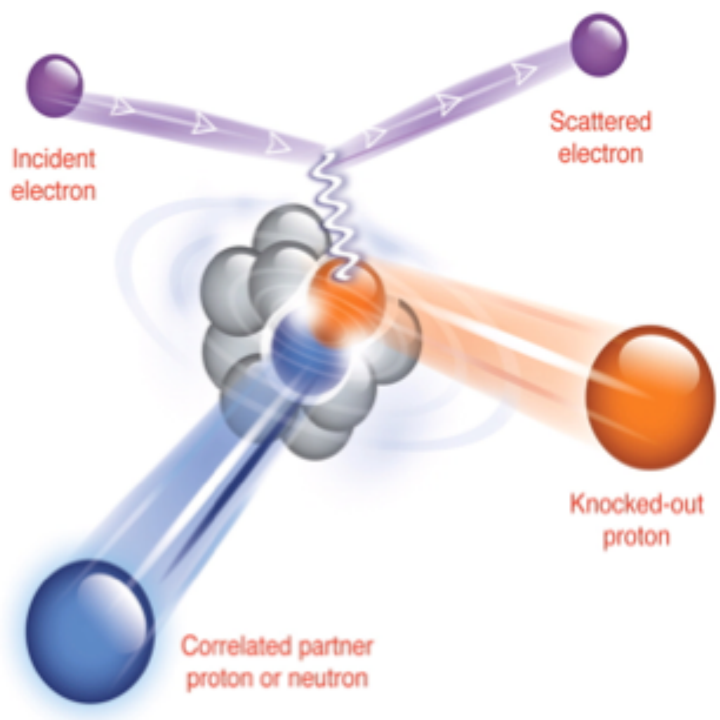
Backgrounds:

- Resonance production
- Deep inelastic scattering
- Instrumental errors

First problem: We use complex nuclei: Naïve Fermi gas model (Moniz 1969)

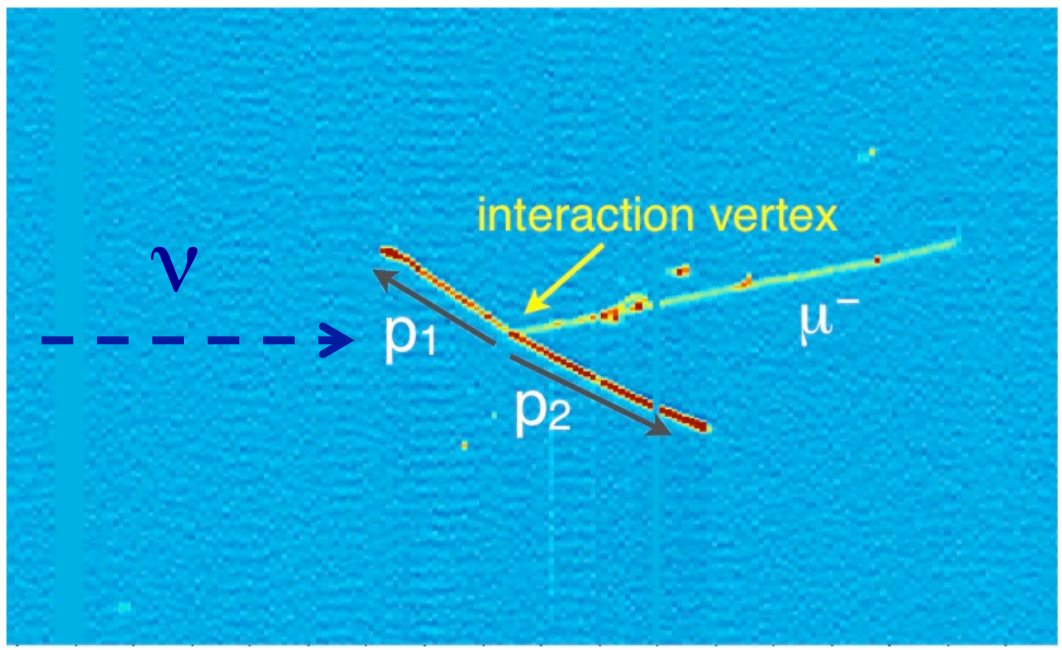


Nuclear correlations

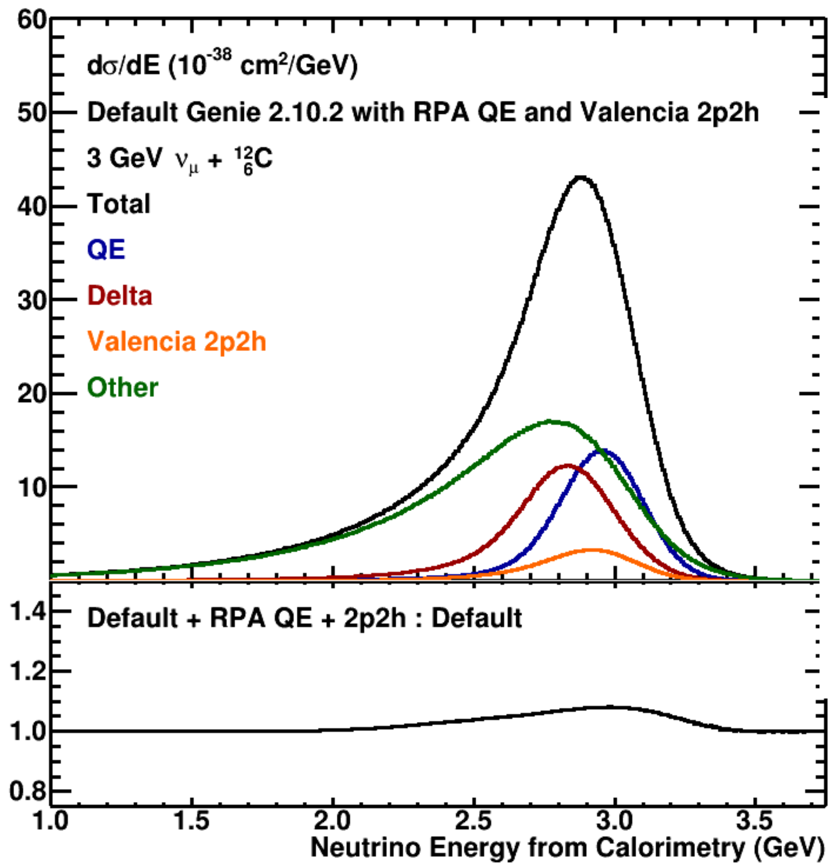


R. Subedi et al.
2008 Science 320 1476

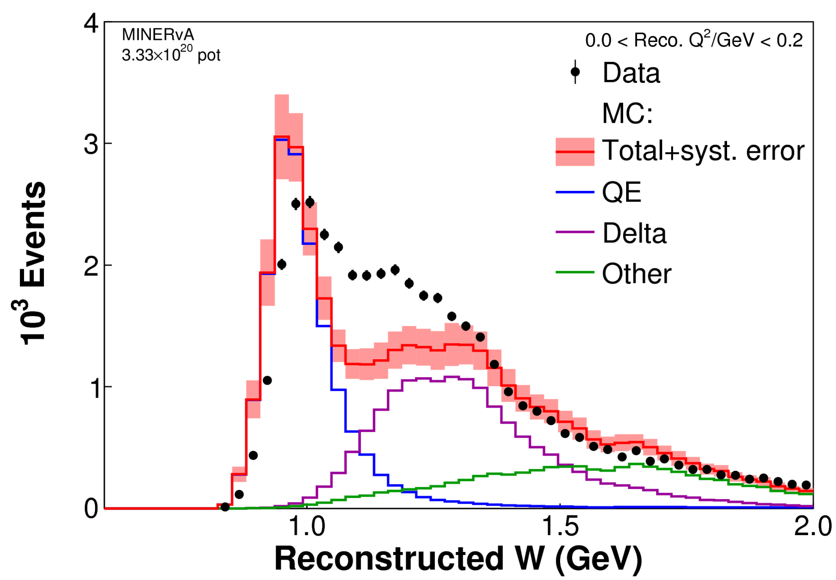
Event in ArgoNeut test



Cross sections and energy scales?



R. Gran – recent talk



MINERvA data

Prospects

- 2D differential cross sections from MINERvA, T2K and MicroBooNE (MINERvA paper in the works)
- Detailed studies of extra particles from MEC and FSI in MINERvA/MicroBooNE
- Better models → Better oscillation measurements.

Backup