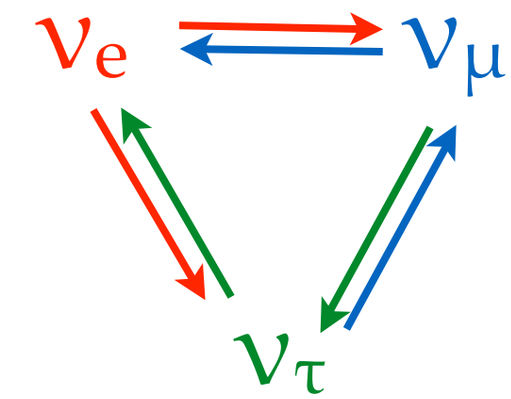
Experimental Neutrino Physics: An Overview

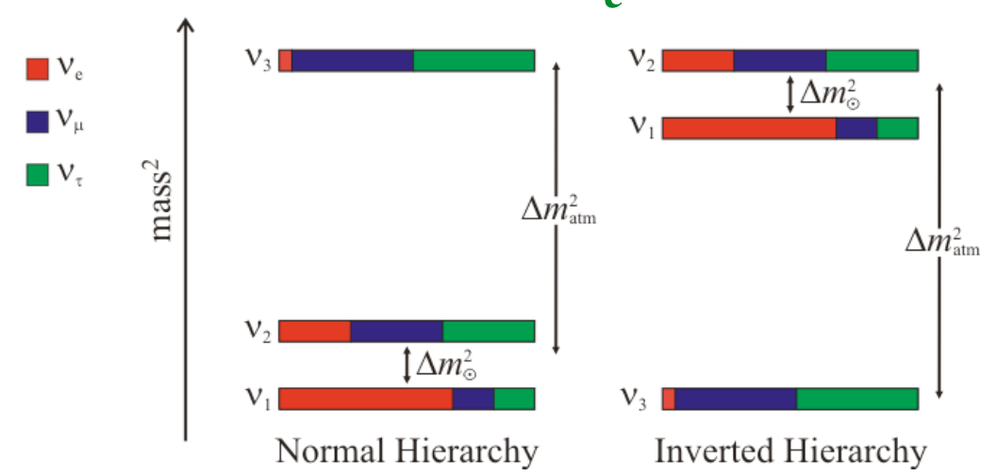
Jonathan M. Paley

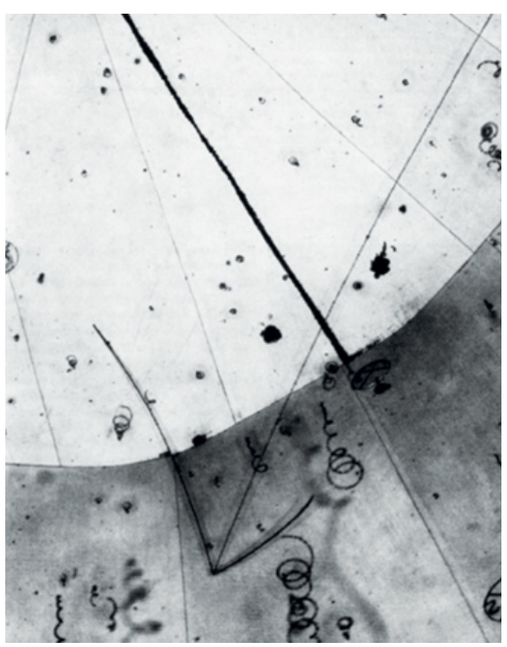
Summer Undergraduate Lecture Series

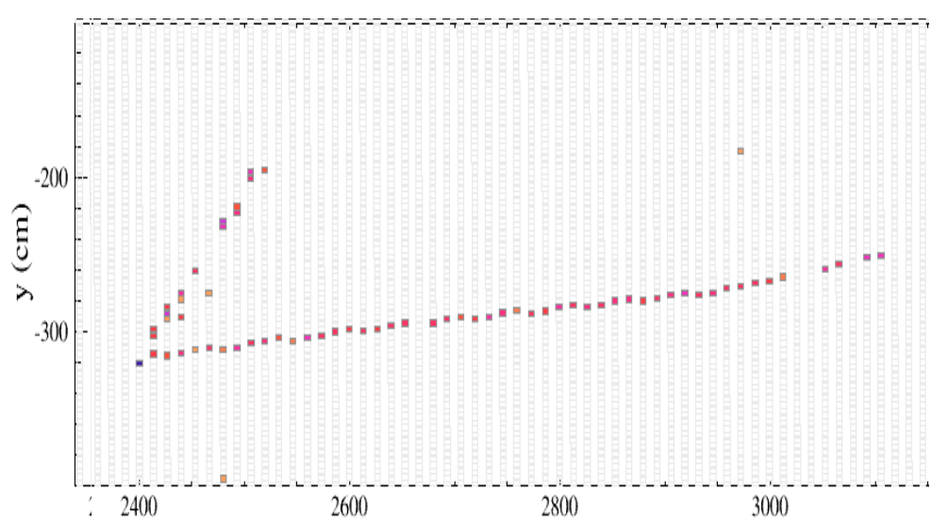
Fermilab

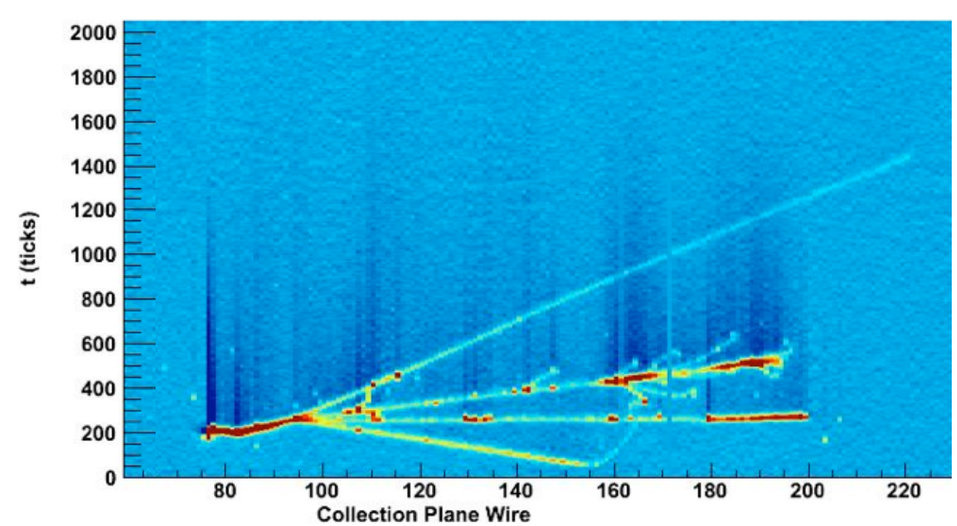
June 16, 2015









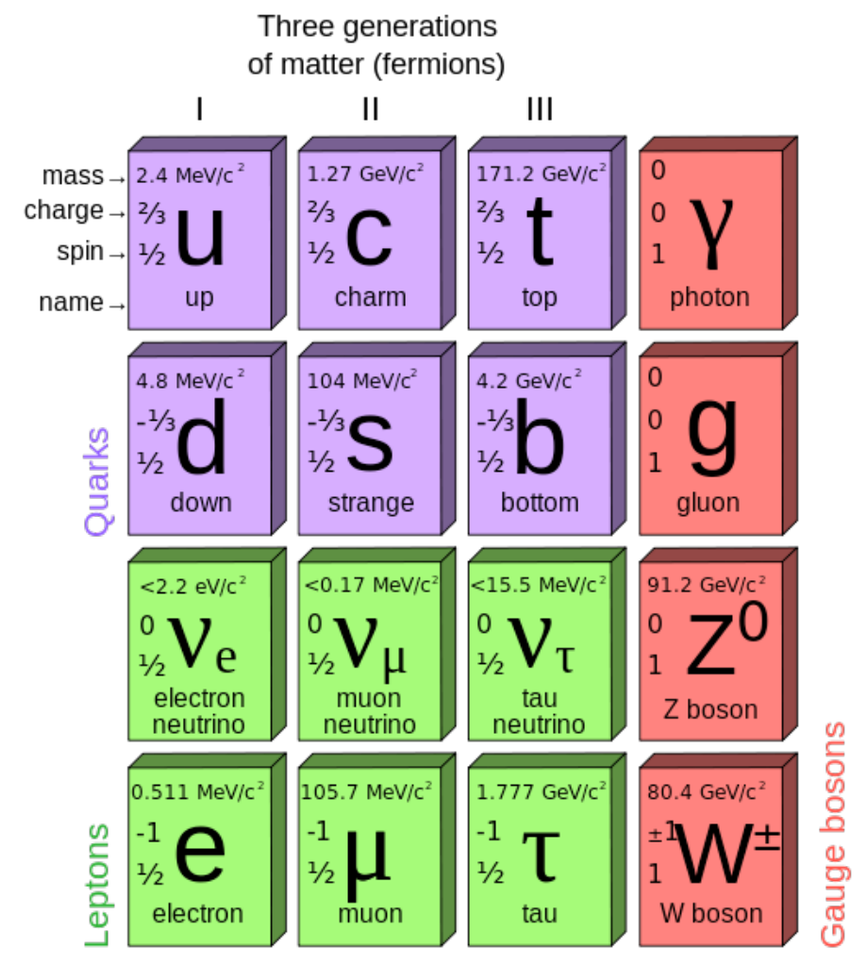


WARNING!

- There are a lot of slides here. I will not go through all of them!
- I cannot possibly cover all topics, nor all experiments, so what you see here today is just a small sample of the ***very*** active experimental side of neutrino physics.
- STOP ME IF YOU HAVE A QUESTION OR IF I SAY SOMETHING NON-SENSICAL.

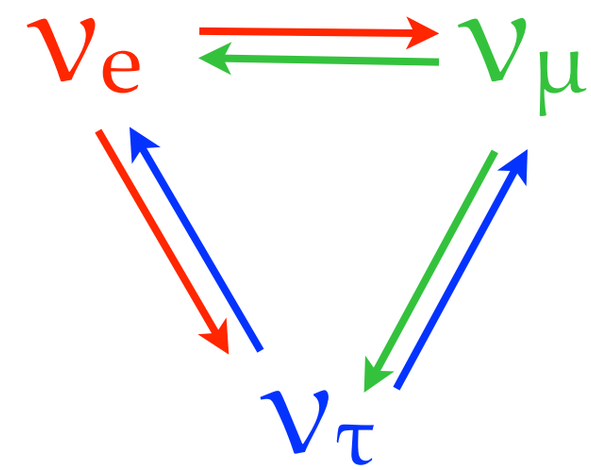
Motivations

- You might have heard that neutrinos have mass.
- Depending on your point of view, this is already BSM
- Neutrinos are extremely abundant, and yet we know relatively very little about them:
  - mass ordering
  - absolute mass
  - Dirac or Majorana
  - do they violate CP?
  - cross-sections
- Need to provide guidance to theory



- Three experimental approaches allow for clear answers to some of these questions: neutrino oscillation measurements, direct mass measurements and searches for neutrinoless double-beta decay.

Neutrino Oscillations



- Neutrino oscillations occur because ν-flavor states are a quantum superposition of mass eigen states.

$$|\nu_\alpha> \; = \sum_i U^*_{\alpha i} |\nu_i>$$

$$P(\nu_\alpha \to \nu_\alpha) = \left| \sum_j U^*_{\alpha j} e^{-i\frac{m_j^2 L}{2E}} U_{\alpha j} \right|^2$$

In vacuum:

$$P(\nu_\mu \to \nu_e) = \left| 2U^*_{\mu 3} U_{e3} \sin\Delta_{31} e^{-i\Delta_{32}} + 2U^*_{\mu 2} U_{e2} \sin\Delta_{21} \right|^2$$

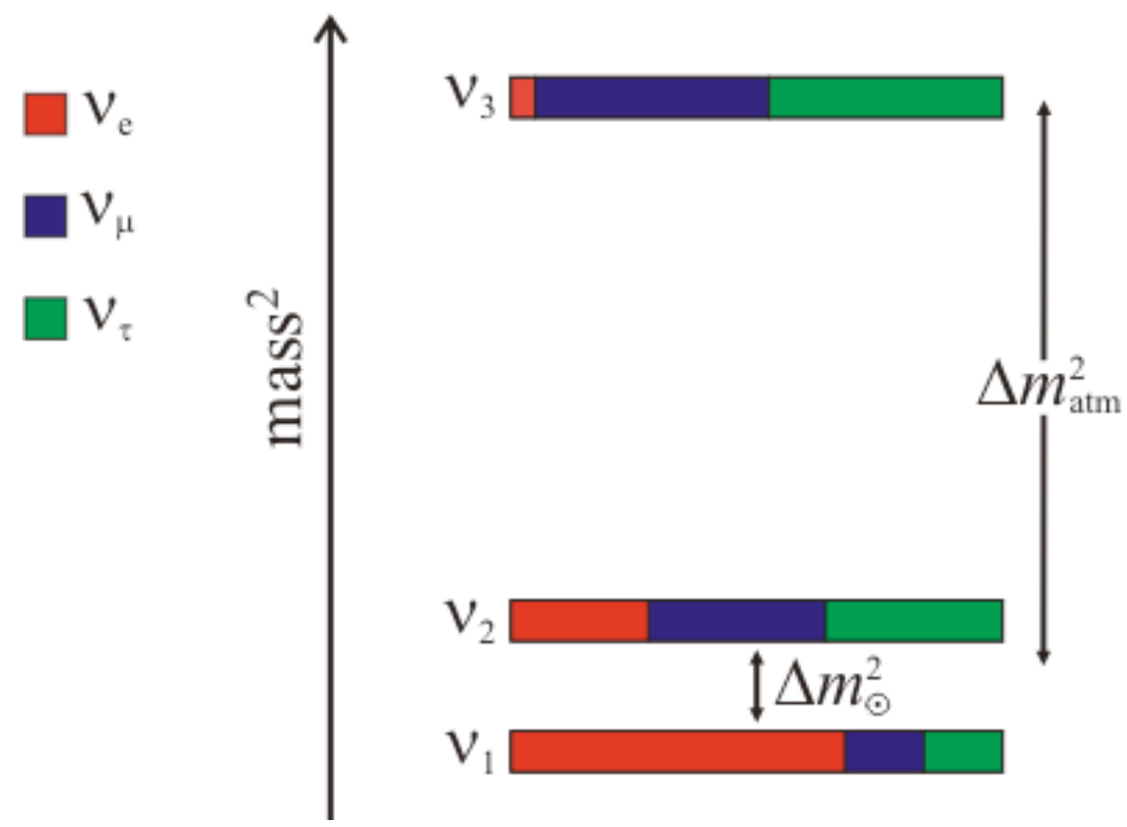
$$\Delta_{ij} \equiv \frac{1.27\Delta m^2_{ij}[\mathrm{eV}^2] L[\mathrm{km}]}{E[\mathrm{GeV}]}$$

Neutrino Oscillations

- The mixing matrix may be factorized into components that are useful to experimentalists:

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{+i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

- Furthermore, experimentally we have determined:
  - $\sin^2 2\theta_{23} \sim 1$ (SuperK, MINOS, T2K, NOvA)
  - $\Delta m^2_{32} \approx \Delta m^2_{31} \equiv \Delta m^2_{atm} \sim 2.5 \times 10^{-3}$ eV^2 (SuperK, MINOS, T2K, NOvA) with characteristic L/E ~ 500 km/GeV
  - $\sin^2\theta_{12} \sim 0.3$ (KamLAND, SNO)
  - $\Delta m^2_{21} \equiv \Delta m^2_{\odot} \sim 7.6 \times 10^{-5}$ eV^2 (KamLAND, SNO) with characteristic L/E ~ 15000 km/GeV
  - $\sin^2 2\theta_{13} \sim 0.1$ (Daya Bay, RENO, Double Chooz, T2K, NOvA)



Why Measure These Neutrino Oscillation Parameters?

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{+i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

- **If neutrinos violate CP, they could have driven leptogenesis in the early universe, which could explain the matter-antimatter asymmetry in the universe.**

Why Measure These Neutrino Oscillation Parameters?

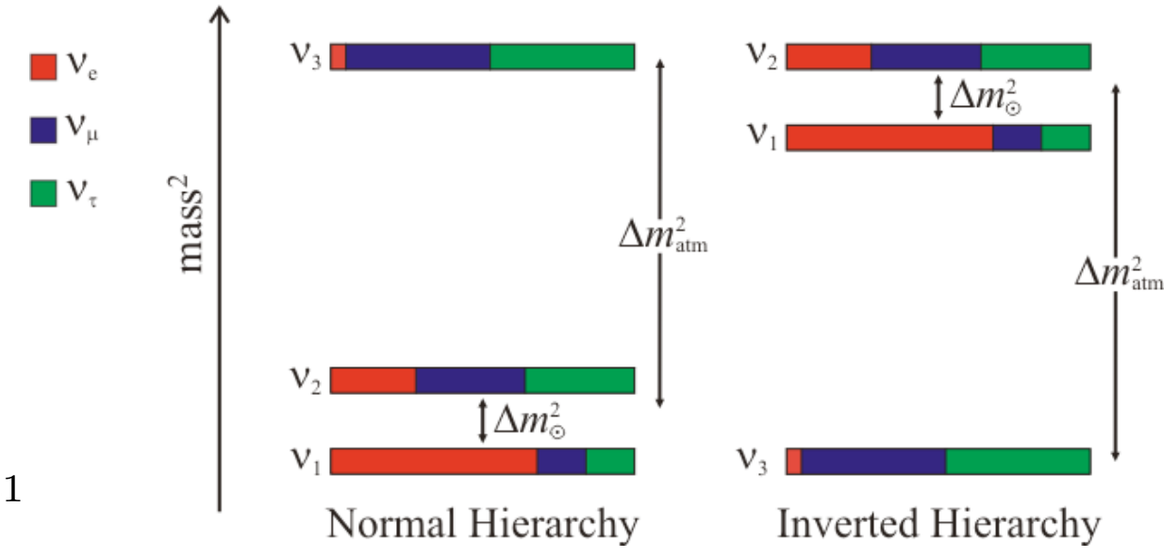
$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{+i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

- **If neutrinos violate CP, they could have driven leptogenesis in the early universe, which could explain the matter-antimatter asymmetry in the universe.**

Our holy grail…

ν_μ Oscillations in Long-Baseline Experiments

- Long-baseline $\nu_\mu \rightarrow \nu_e$ experiments have the potential to simultaneously measure **θ_{13}**, **δ_{CP}**, **sign(Δm_{31}^2)**, **sign(θ_{23}-45°)**:



$$P(\nu_\mu \rightarrow \nu_e) \approx \sin^2 2\theta_{13} \sin^2\theta_{23} \frac{\sin^2(\Delta_{31} - aL)}{(\Delta_{31} - aL)^2} \Delta_{31}^2$$
$$\alpha \sin 2\theta_{13} \cos\delta \frac{\sin(aL)}{(aL)} \frac{\sin(\Delta_{31} - aL)}{(\Delta_{31} - aL)} \cos\Delta_{32} -$$
$$\alpha \sin 2\theta_{13} \sin\delta \frac{\sin(aL)}{(aL)} \frac{\sin(\Delta_{31} - aL)}{(\Delta_{31} - aL)} \sin\Delta_{32}$$

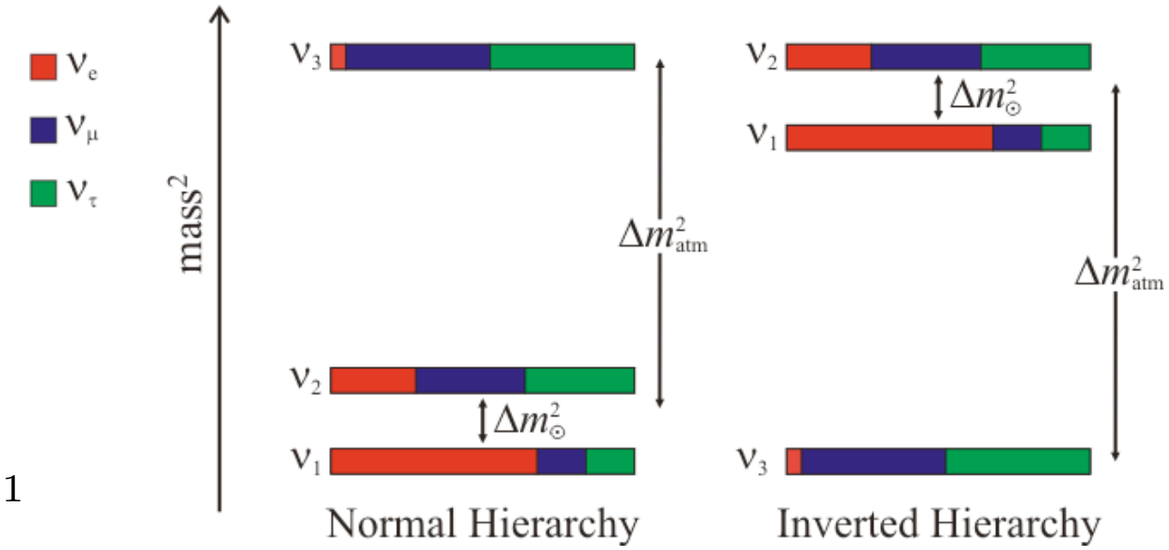
$$\Delta_{ij} \equiv \frac{1.27\Delta m_{ij}^2[\mathrm{eV}^2]L[\mathrm{km}]}{E[\mathrm{GeV}]}$$

$$a = G_F N_e \sqrt{2} \simeq (4000\ \mathrm{km})^{-1}$$

eg, in NOvA: $aL = 0.23$,
in DUNE: $aL = 0.37$

ν_μ Oscillations in Long-Baseline Experiments

- Long-baseline $\nu_\mu \rightarrow \nu_e$ experiments have the potential to simultaneously measure **θ_{13}, δ_{CP}, sign(Δm_{31}^2), sign(θ_{23}-45°)**:



$$P(\nu_\mu \rightarrow \nu_e) \approx \sin^2 2\theta_{13} \sin^2\theta_{23} \frac{\sin^2(\Delta_{31} - aL)}{(\Delta_{31} - aL)^2} \Delta_{31}^2$$
$$\alpha \sin 2\theta_{13} \cos\delta \frac{\sin(aL)}{(aL)} \frac{\sin(\Delta_{31} - aL)}{(\Delta_{31} - aL)} \cos\Delta_{32} -$$
$$\alpha \sin 2\theta_{13} \sin\delta \frac{\sin(aL)}{(aL)} \frac{\sin(\Delta_{31} - aL)}{(\Delta_{31} - aL)} \sin\Delta_{32}$$

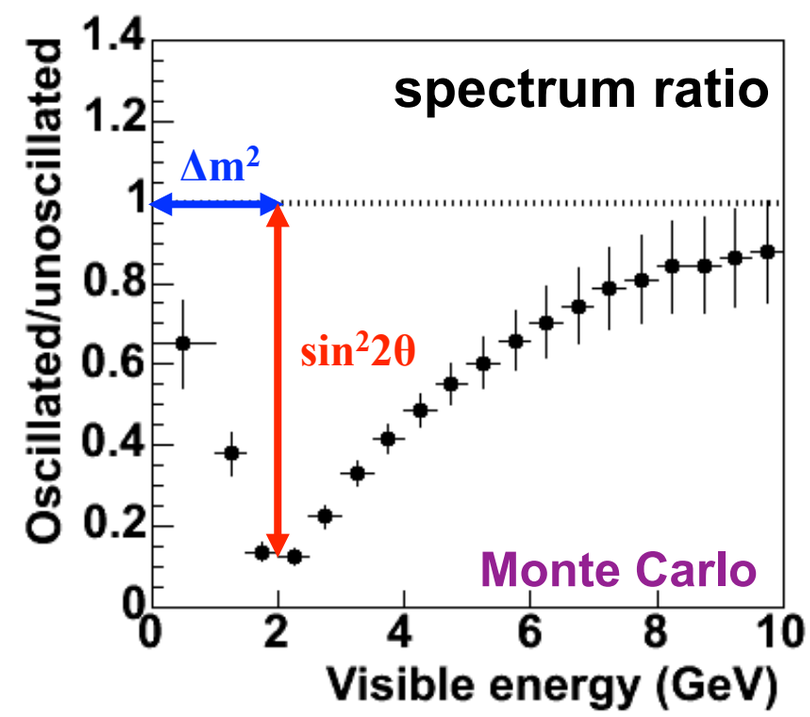
$$\Delta_{ij} \equiv \frac{1.27\Delta m_{ij}^2[\mathrm{eV}^2]L[\mathrm{km}]}{E[\mathrm{GeV}]}$$

$$a = G_F N_e \sqrt{2} \simeq (4000\ \mathrm{km})^{-1}$$

eg, in NOvA: $aL = 0.23$,
in DUNE: $aL = 0.37$

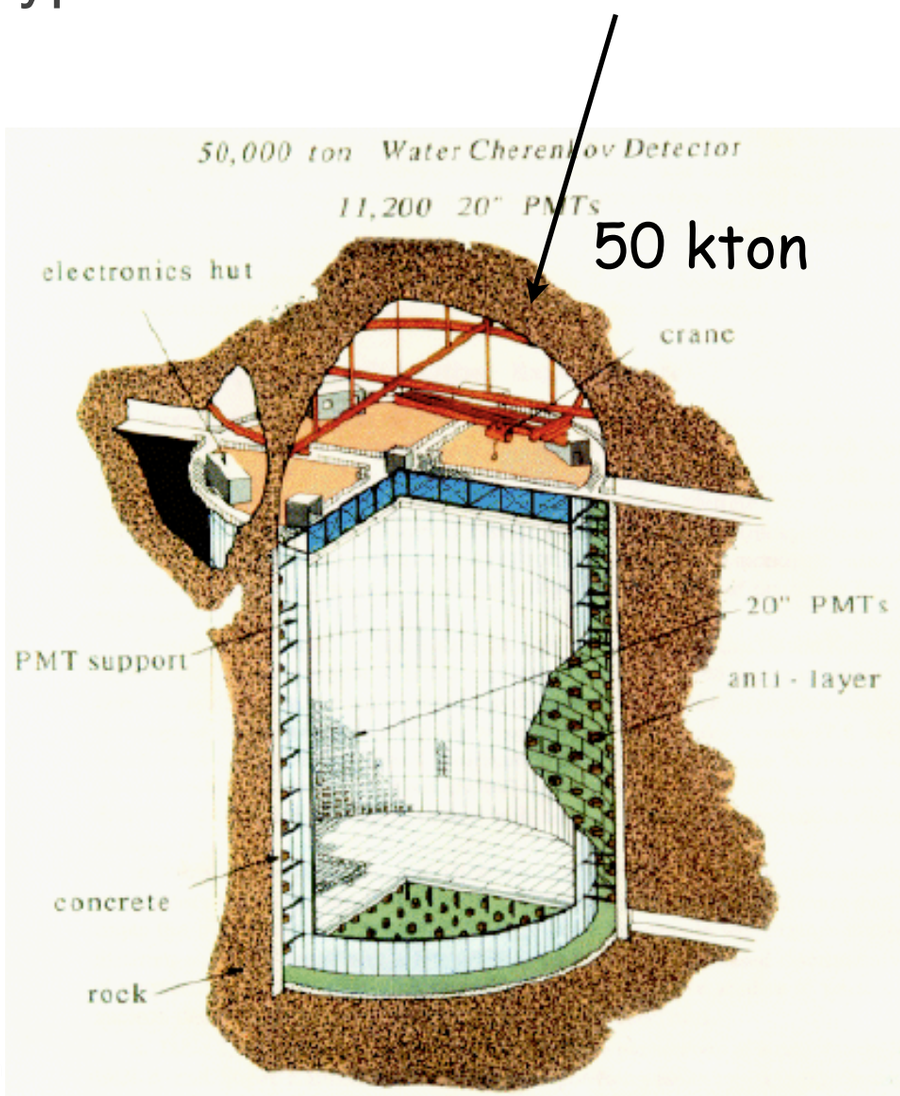
- Separate measurement of $\nu_\mu \rightarrow \nu_\mu$ gives access to $\sin^2(2\theta_{23})$ and Δm^2_{32}:

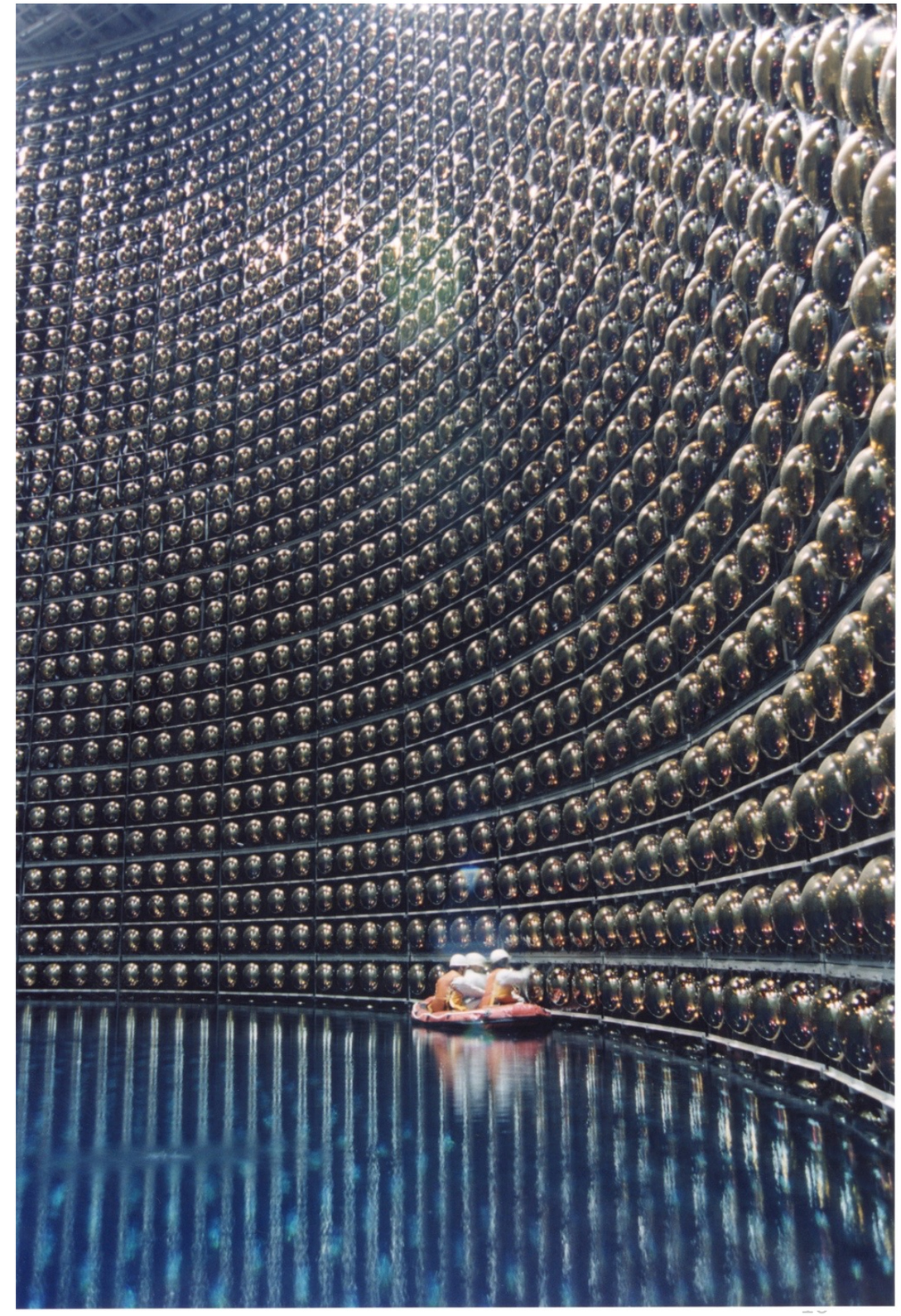
$$P(\nu_\mu \rightarrow \nu_\mu) \simeq 1 - \sin^2(2\theta_{23}) \sin^2\left(1.27\Delta m_{32}^2 \frac{L}{E}\right)$$



How Are Neutrinos Seen?

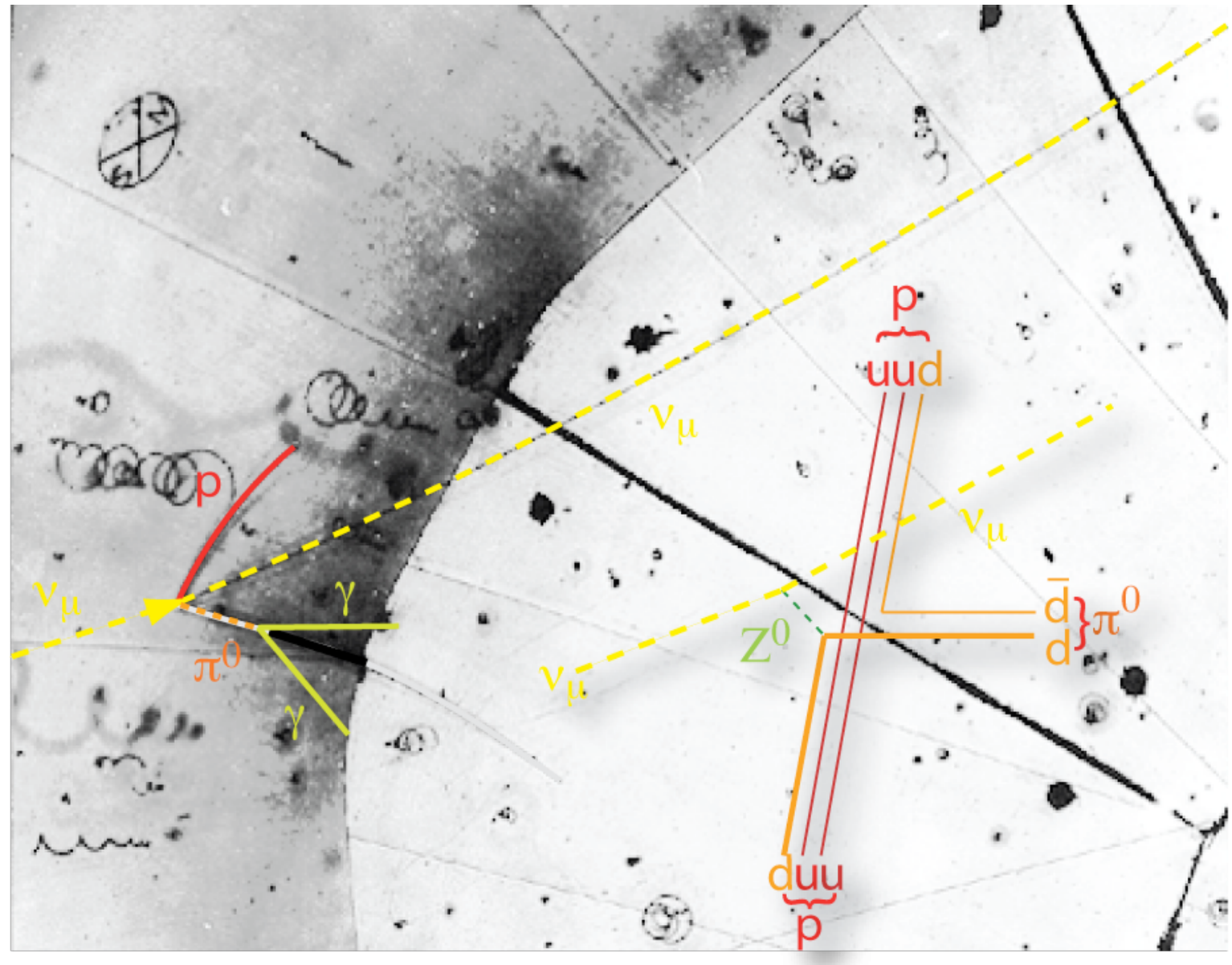
- Probability of a ~GeV neutrino interaction is ~10^{-38}/cm^2 (compare to that of a ~GeV proton, ~10^{-26}/cm^2)
- Since neutrinos don't like to interact with matter, we need HUGE detectors!
- Typical size is tens to thousands of tons





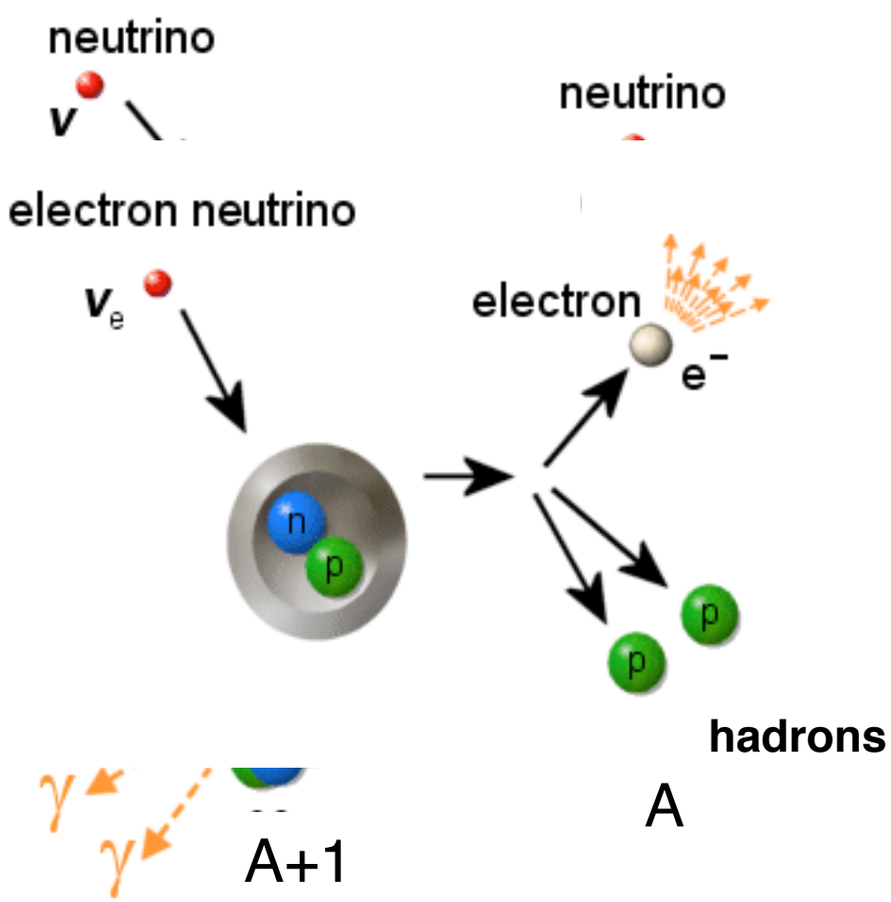
How Are Neutrinos Seen?

- We don't actually see the neutrinos, only the particles they produce when they interact with nuclei.
- Two types of neutrino interactions:
  - **Charged-current** (CC, W-boson exchange). Final state includes a lepton (e, μ or τ) + hadron.
  - **Neutral-current** (NC, Z-boson exchange). Final state includes a neutrino + hardron. Not seen until 1973!



12 foot bubble chamber, Argonne National Lab. Nov. 13, 1970

Neutrino Detection - Fundamentals



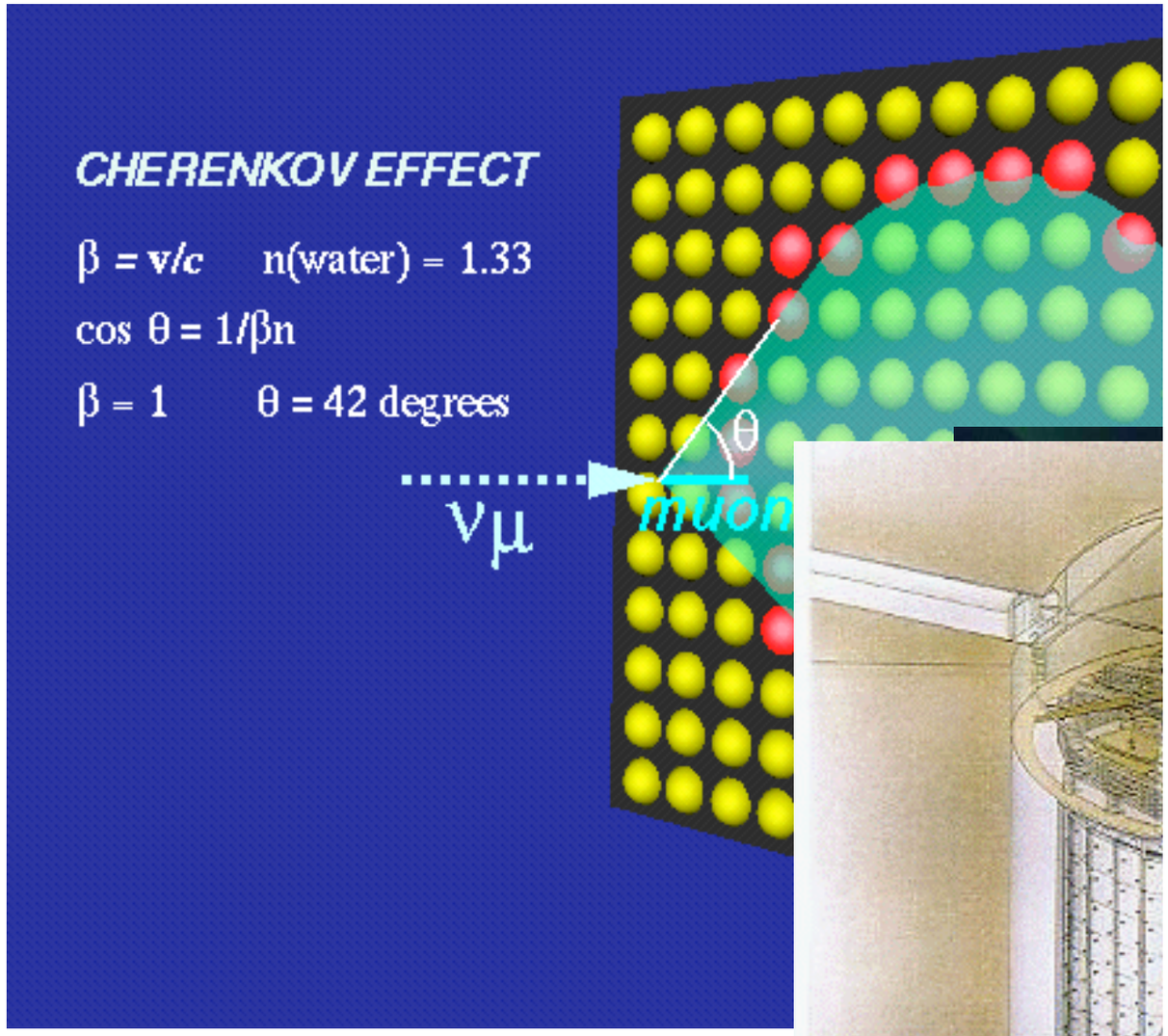
- ν_e CC off neutron
- Charged (lepton) in final state
- Experiments rely on energy
- Energy and flavor of neutrino are observable

- Nucleon (hadron) in final state
- neutrinos carries off energy
- cross section is much smaller than CC interactions with nuclei

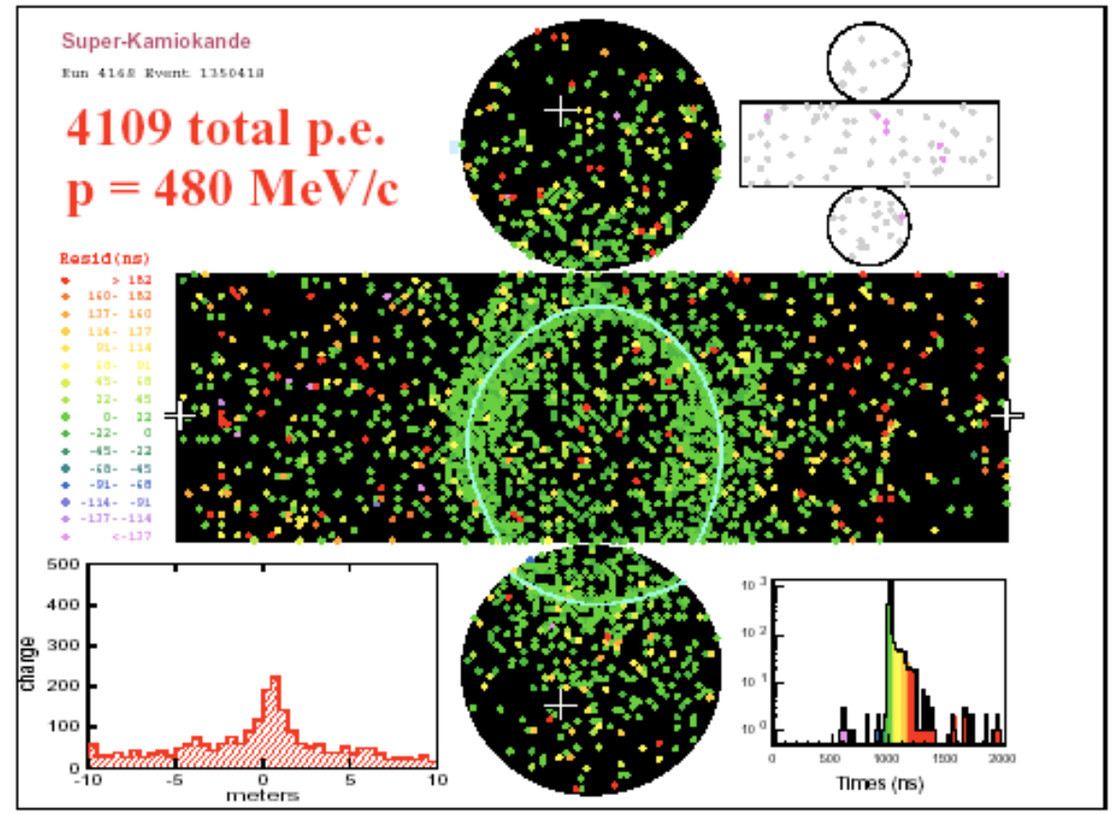
Neutrino Detection

- Signal: appearance of photons or charged particles inside a detector.
  - Require no incoming charged particle within vicinity of interaction vertex (often pushes experiments to go deep underground)
  - Interactions in detector are often very “rare”, O(0.1-1)/day
  - Signal energies can vary across many orders of magnitudes
  - Particle identification tells us the type of neutrino
  - Energy of incoming neutrino can be measured for CC events only.
  - NOTE: many commonalities between neutrino, proton-decay, dark matter and neutrino-less double beta decay search experiments!
- A VERY wide variety of detectors are used to detect neutrinos
- As in any experiment, the type of detector used depends on energy thresholds, energy resolution, signal identification (efficiency) and background rejection (purity) needed.

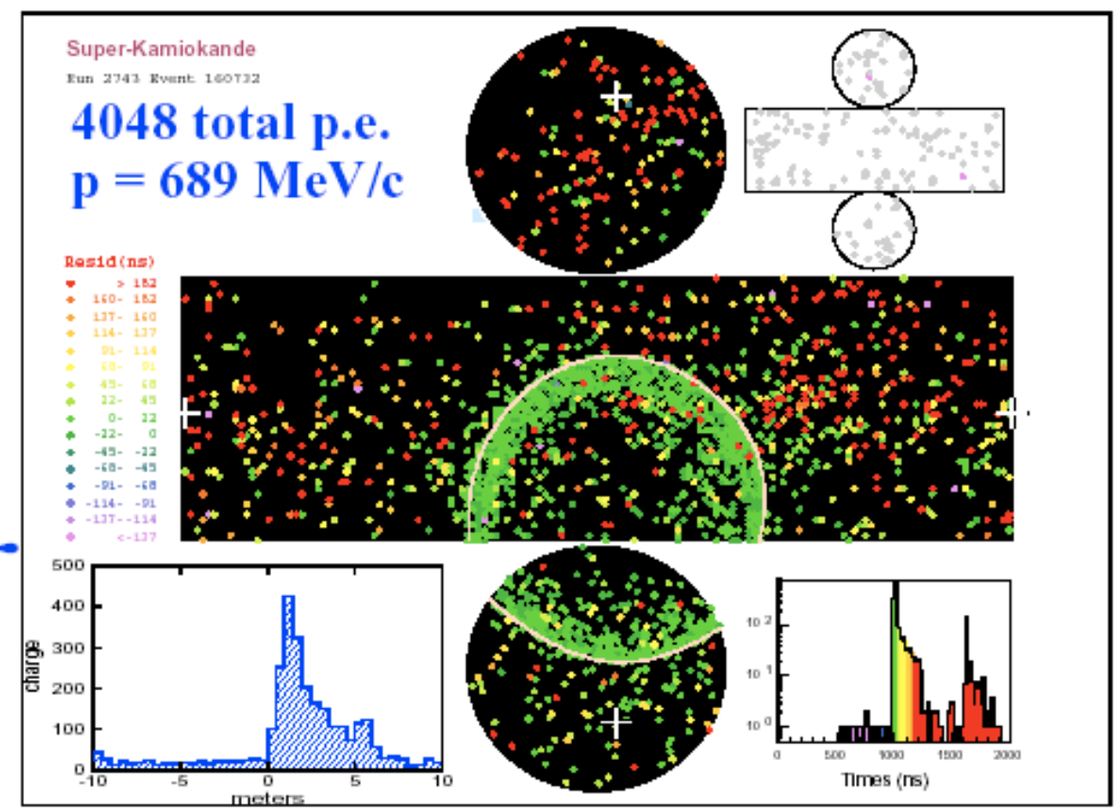
Neutrino Detectors - Some Examples



e–like

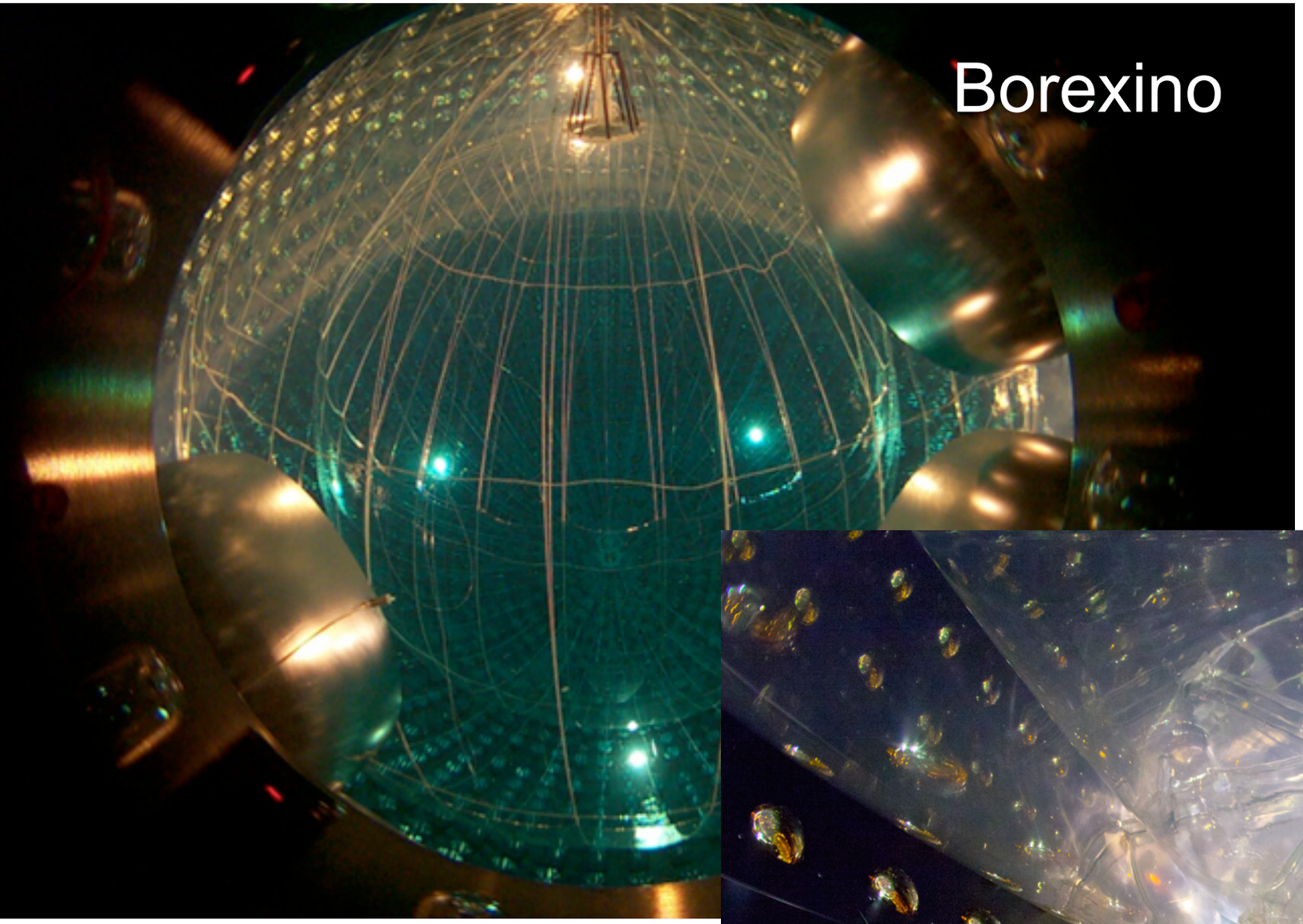


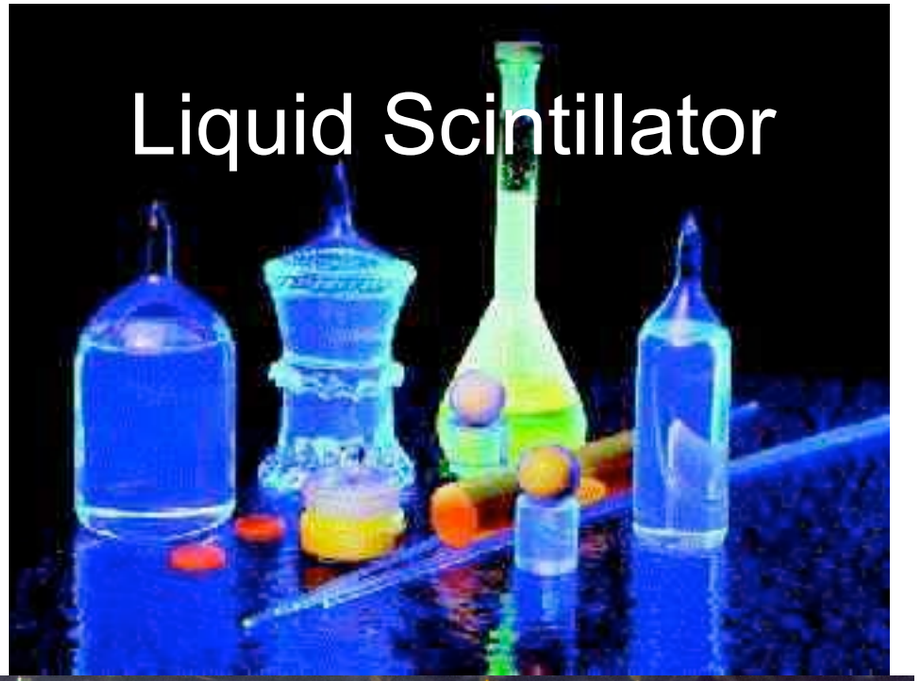
μ–like

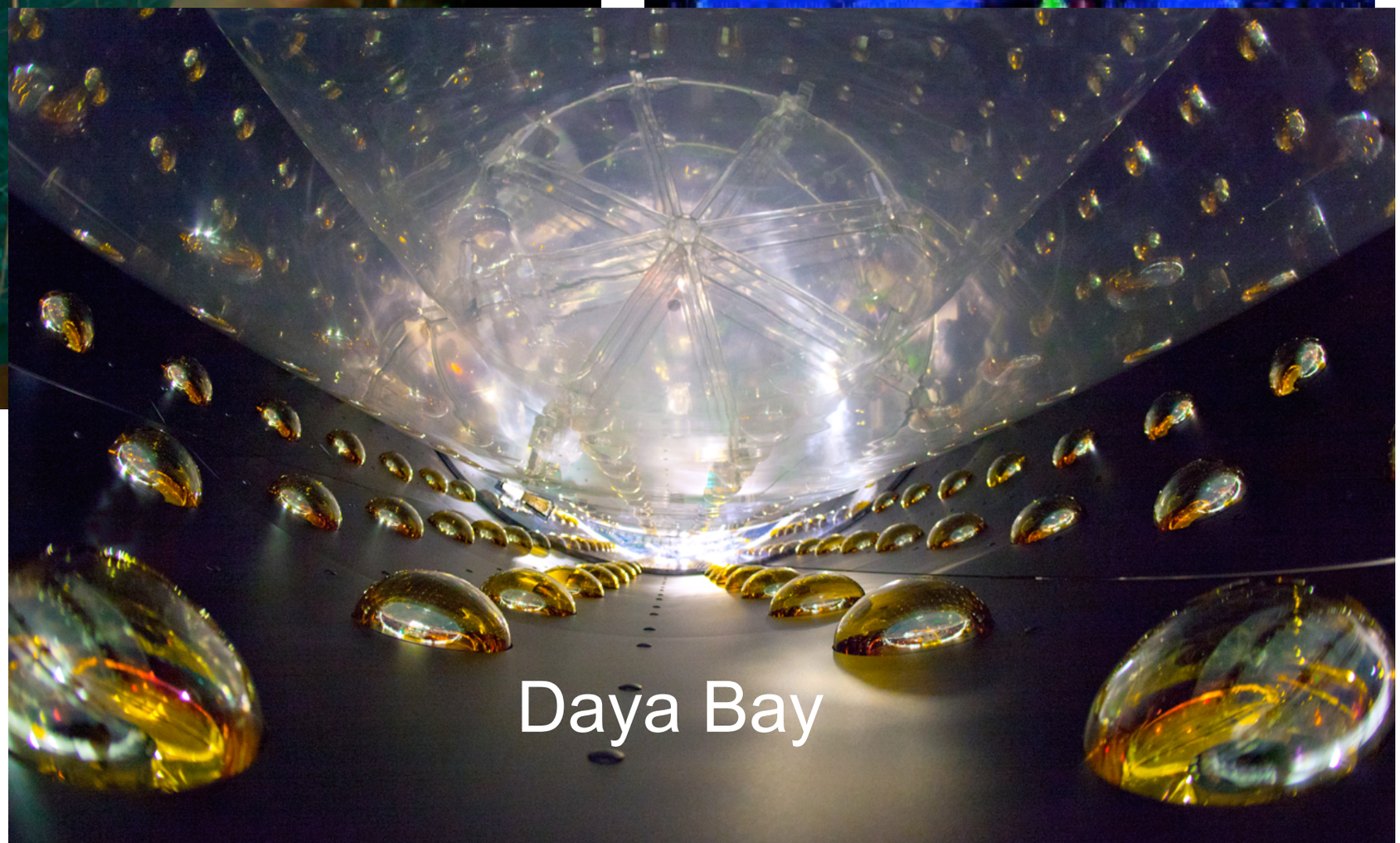


Energy thresholds:
muon: 120 MeV
proton: 1.06 GeV

Neutrino Detectors - Some Examples

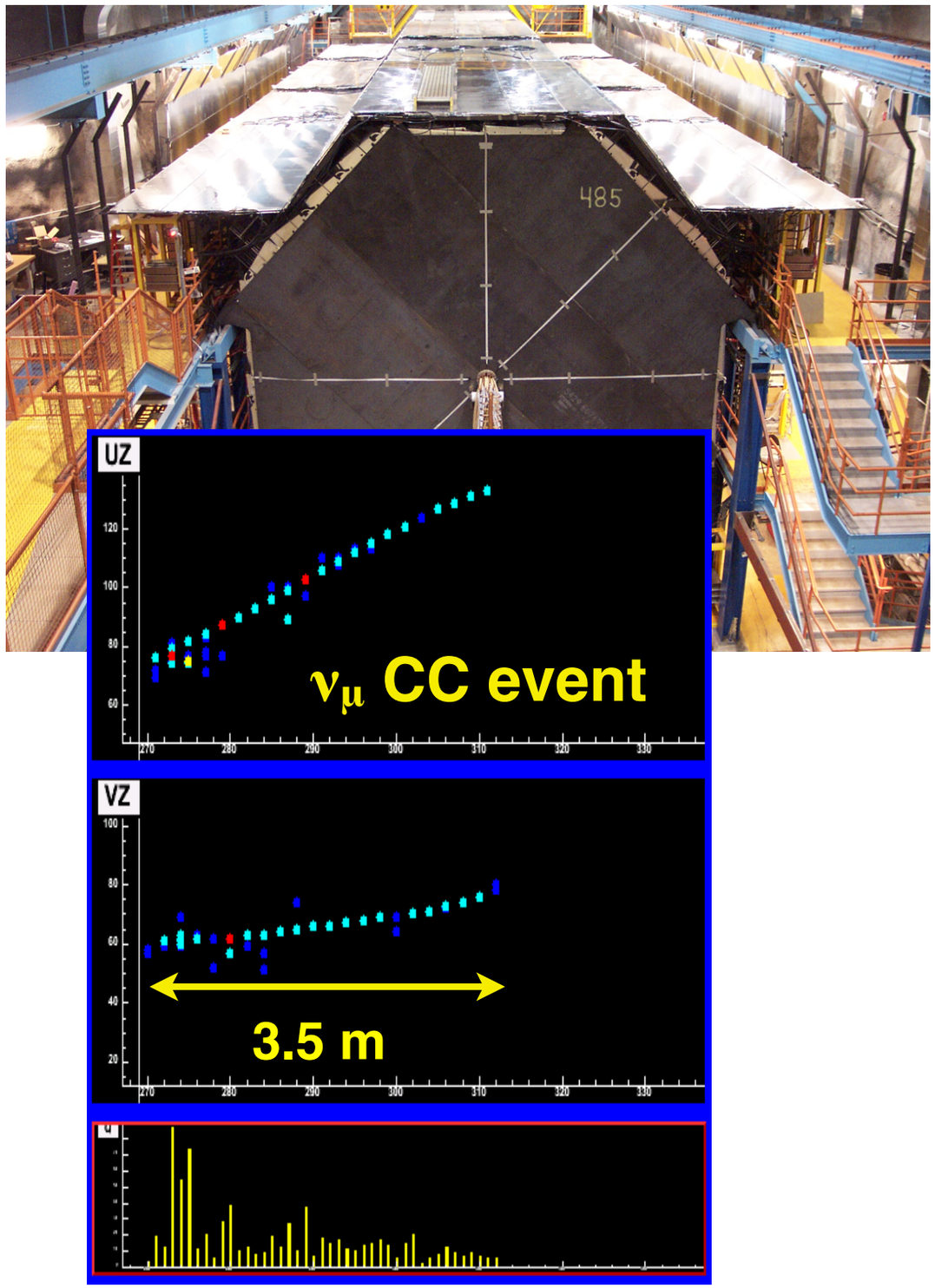




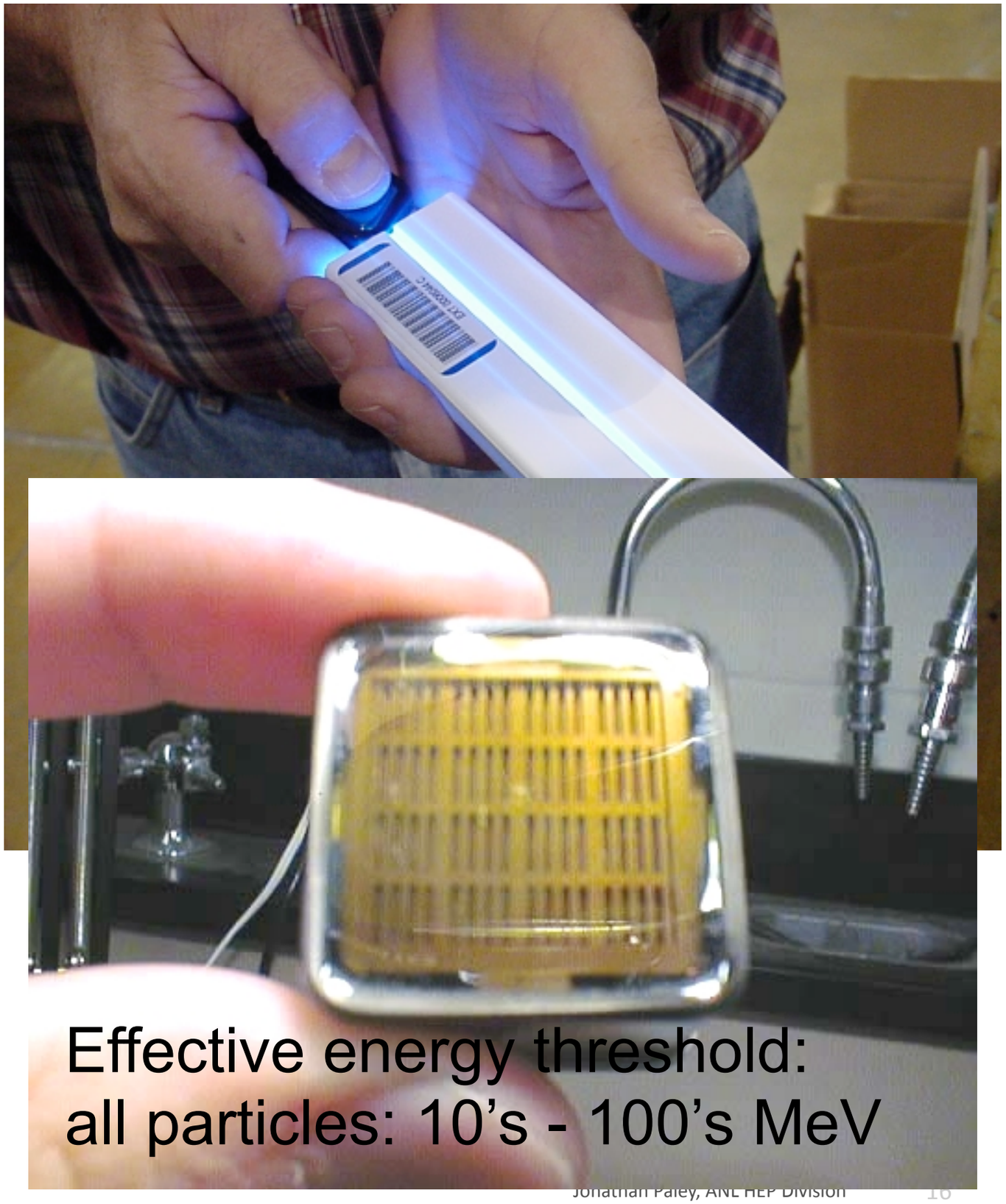


Energy threshold:
all particles: few MeV

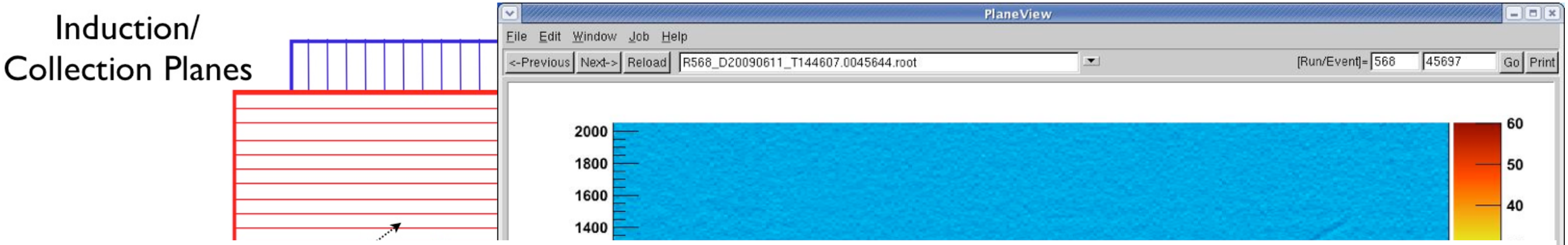
Neutrino Detectors - Some Examples



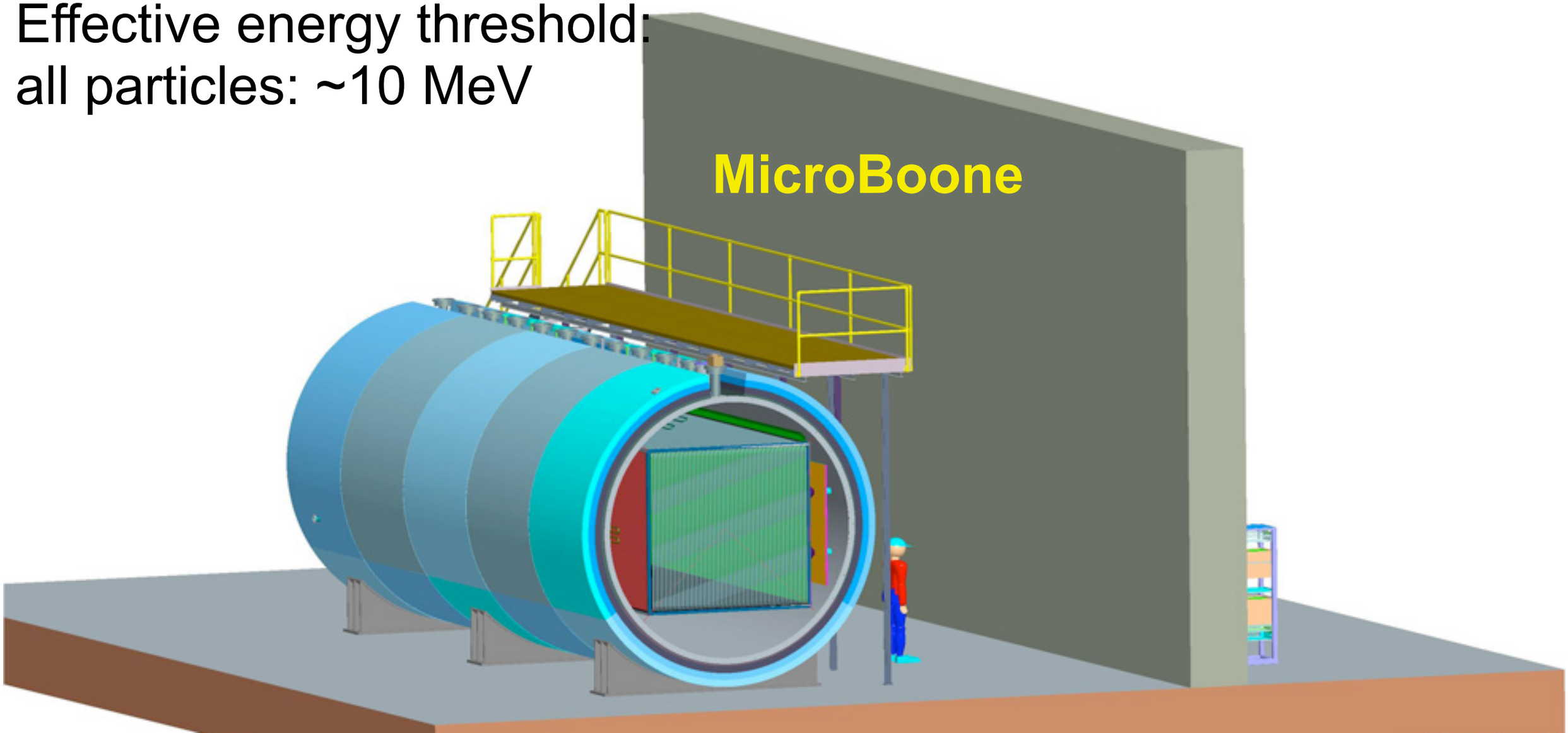
Long μ track + shower at vertex



Neutrino Detectors - Some Examples

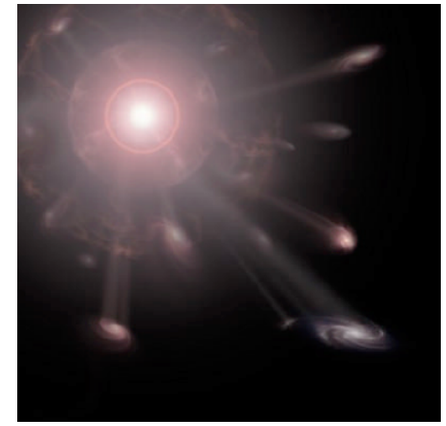


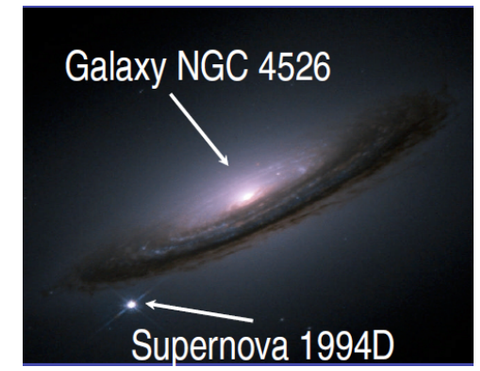
Effective energy threshold:
all particles: ~10 MeV

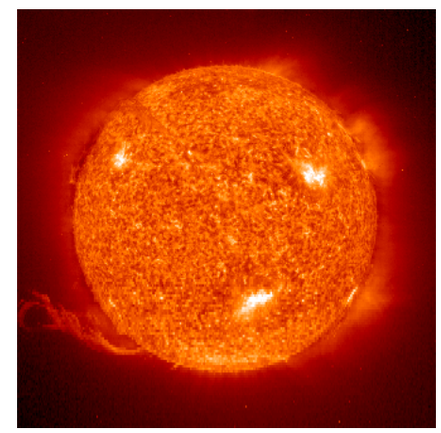


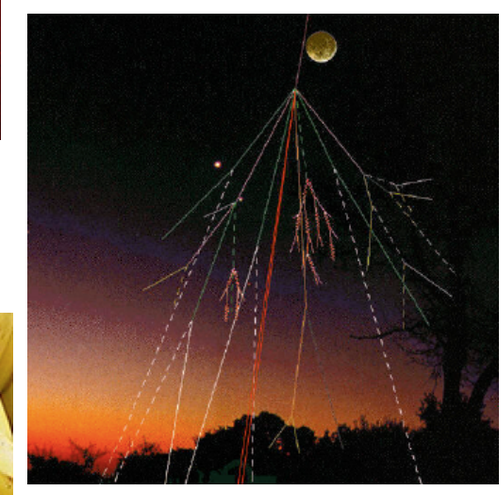
How Are Neutrinos Produced?

- The universe if full of neutrinos! About 10 x 10^{12} ν's pass through your body each second!
- Nature provides many sources of neutrinos:
  - The Big Bang (411/cm^3 everywhere in the universe)
  - Supernovae (99% of the energy in carried off by neutrinos!)
  - The sun (neutrinos regulate solar fusion)
  - Cosmic ray interactions with the upper atmosphere.
  - Bananas! (~1 million neutrinos/day!)
- Man also creates neutrinos:
  - Nuclear reactors
  - Particle accelerators

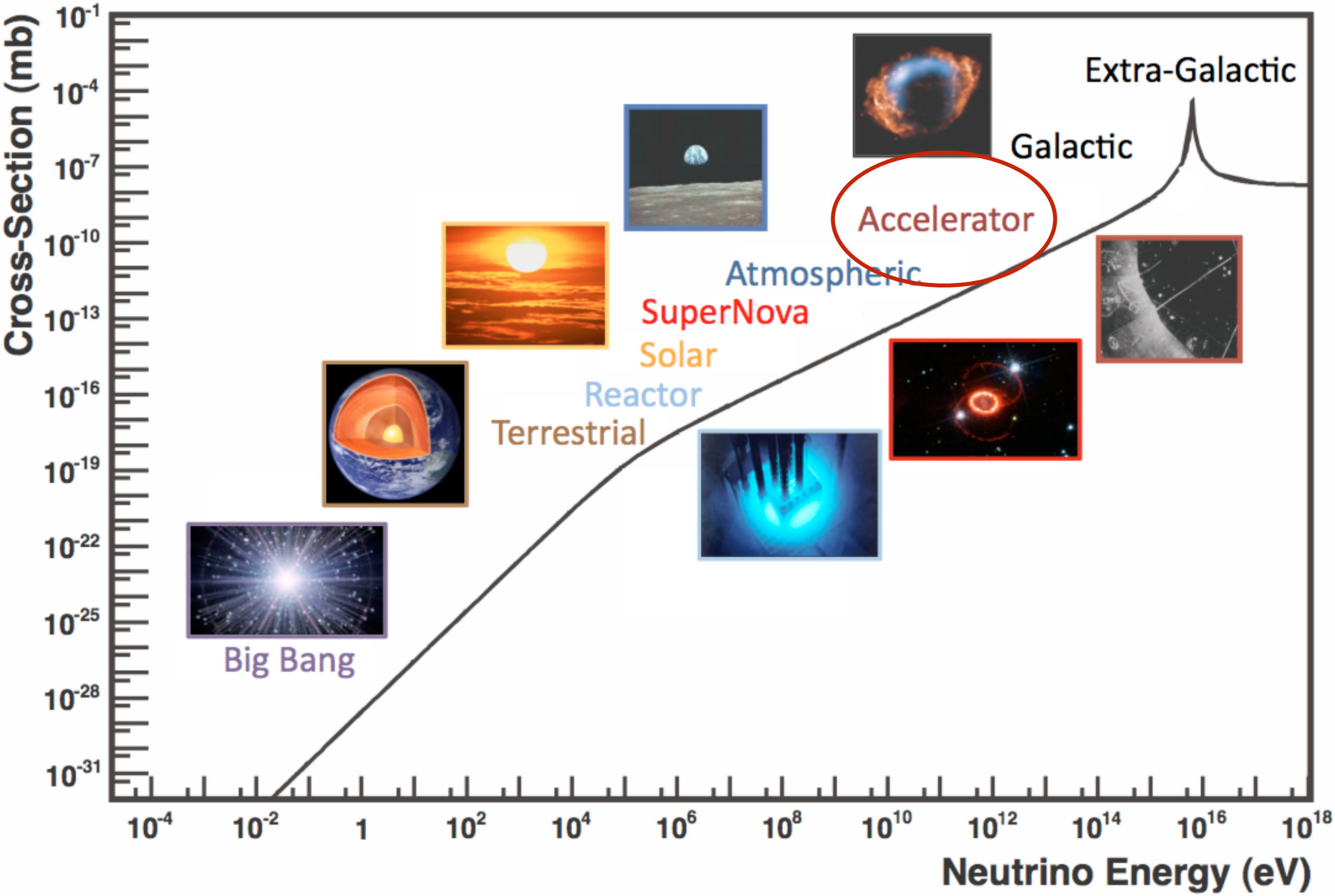






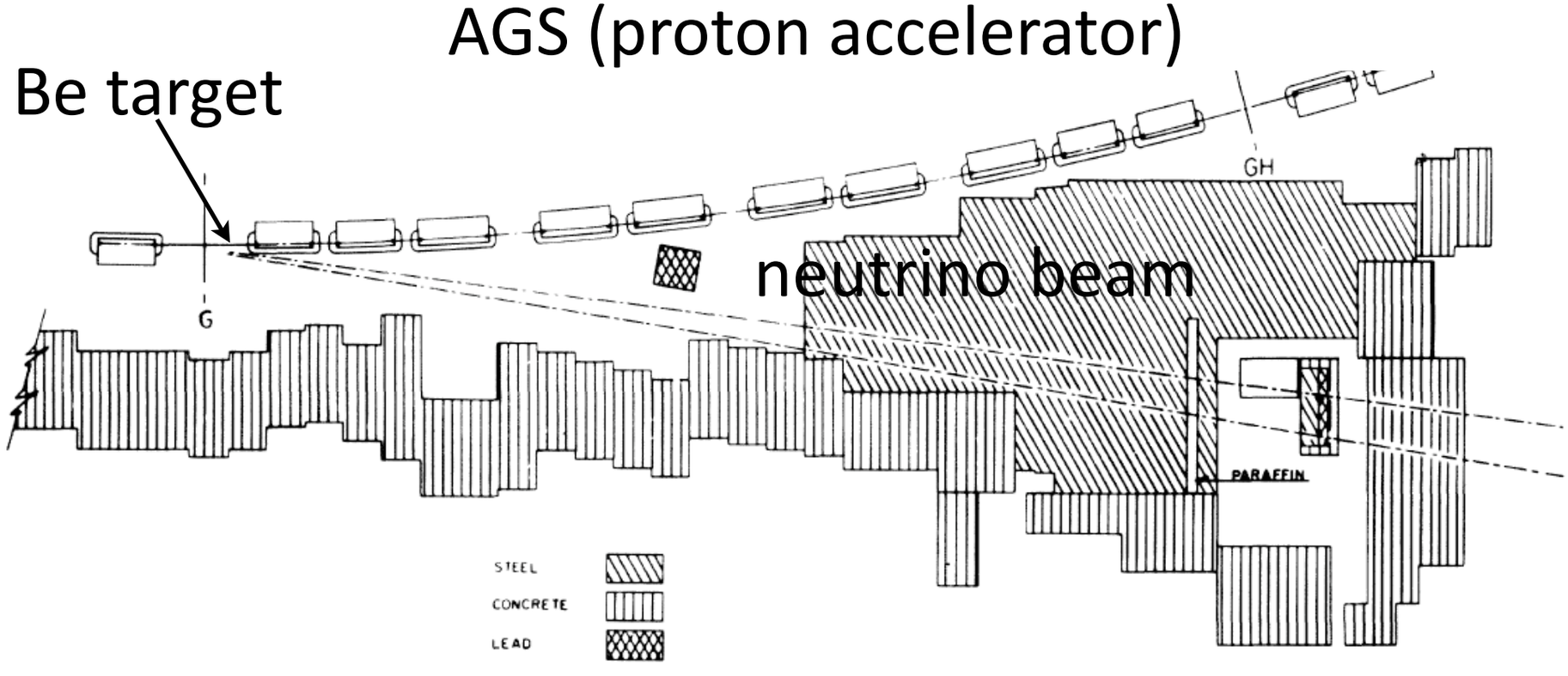


How Are Neutrinos Produced?



Neutrino Production via Accelerators

- First accelerator-based neutrino beam: Brookhaven, 1962
- 15 GeV proton beam struck Be target producing secondary hadrons (mostly π's)
- π's decay to neutrinos
- neutrinos interact in detector to produce electrons or muons
- detector: spark chamber

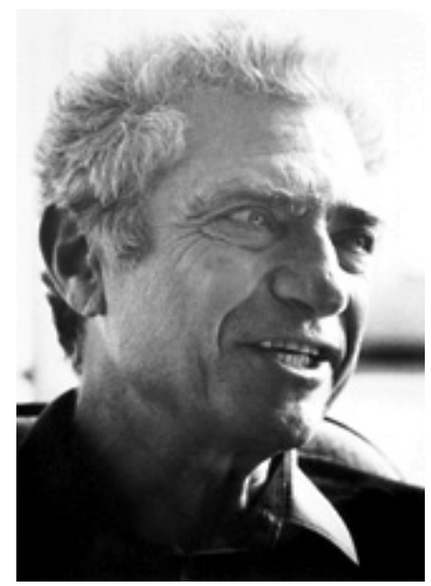


Neutrino Production via Accelerators

- First accelerator-based neutrino beam: Brookhaven, 1962
- 15 GeV proton beam struck Be target producing secondary hadrons (mostly π's)
- π's decay to neutrinos
- neutrinos interact in detector to produce electrons or muons
- detector: spark chamber

Leon Lederman

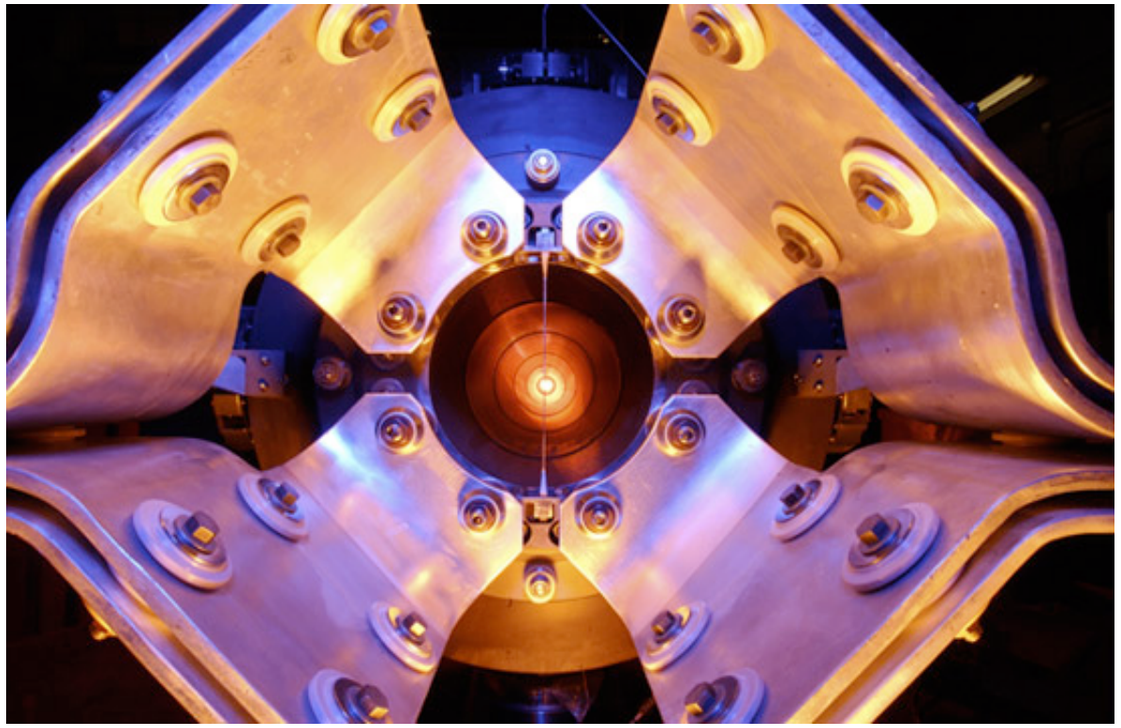
Melvin Schwartz


Jack Steinberger

Discovery of the Muon Neutrino!
PRL, 9(1):36-44, Jul 1962

Neutrino Production via Accelerators

- Modern-day neutrino beams are not all that different.
- Main improvement is use of magnetic focusing horns, increase flux by ~6x.



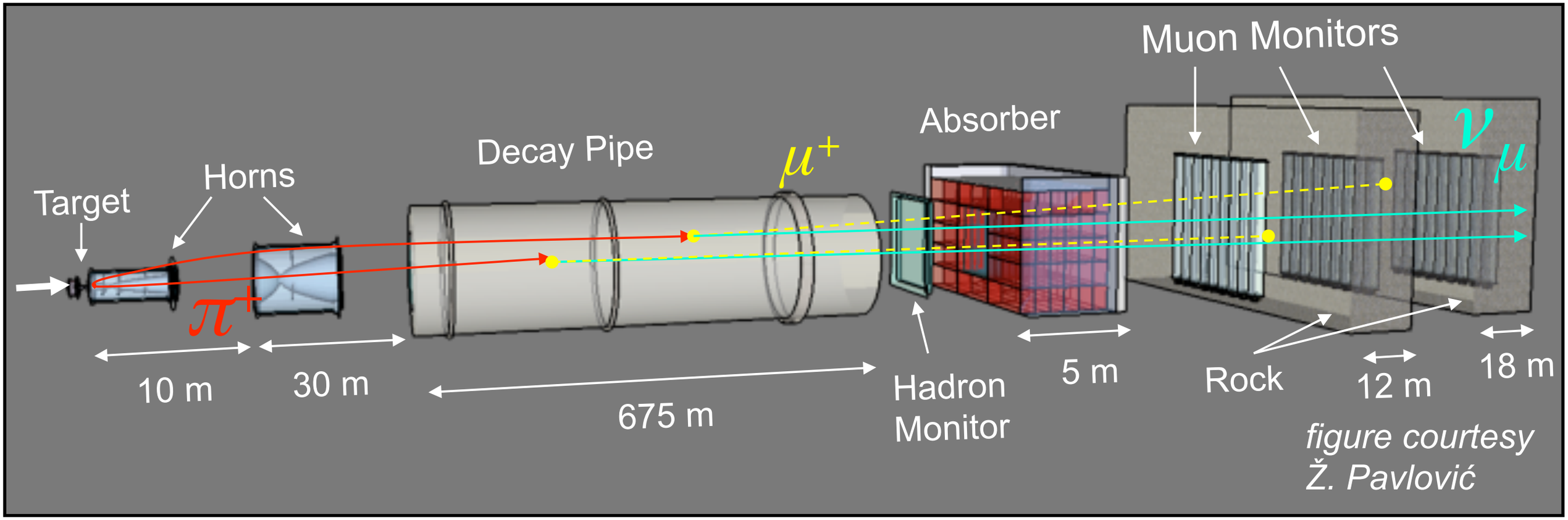
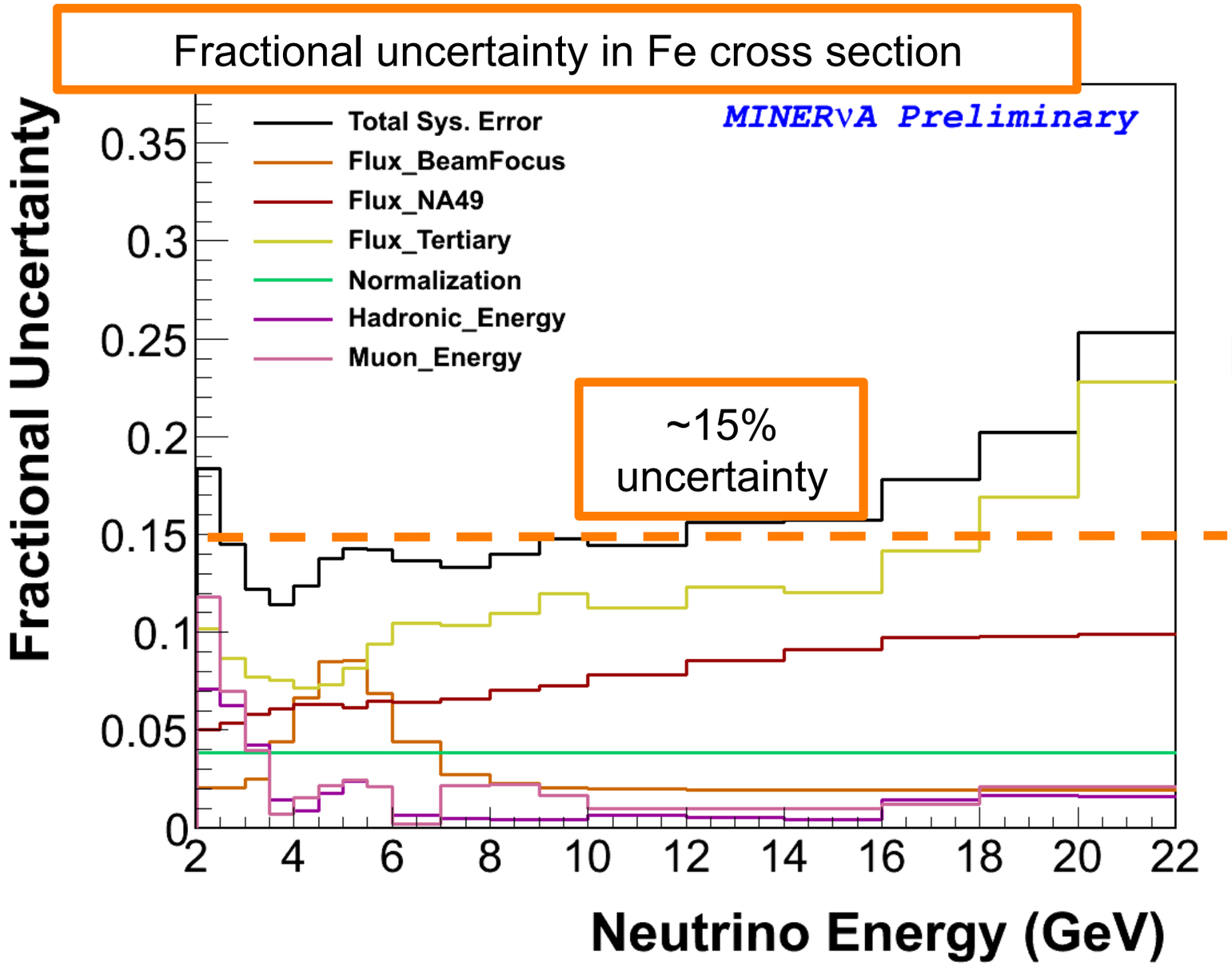


figure courtesy Ž. Pavlović

Neutrino Flux Uncertainties

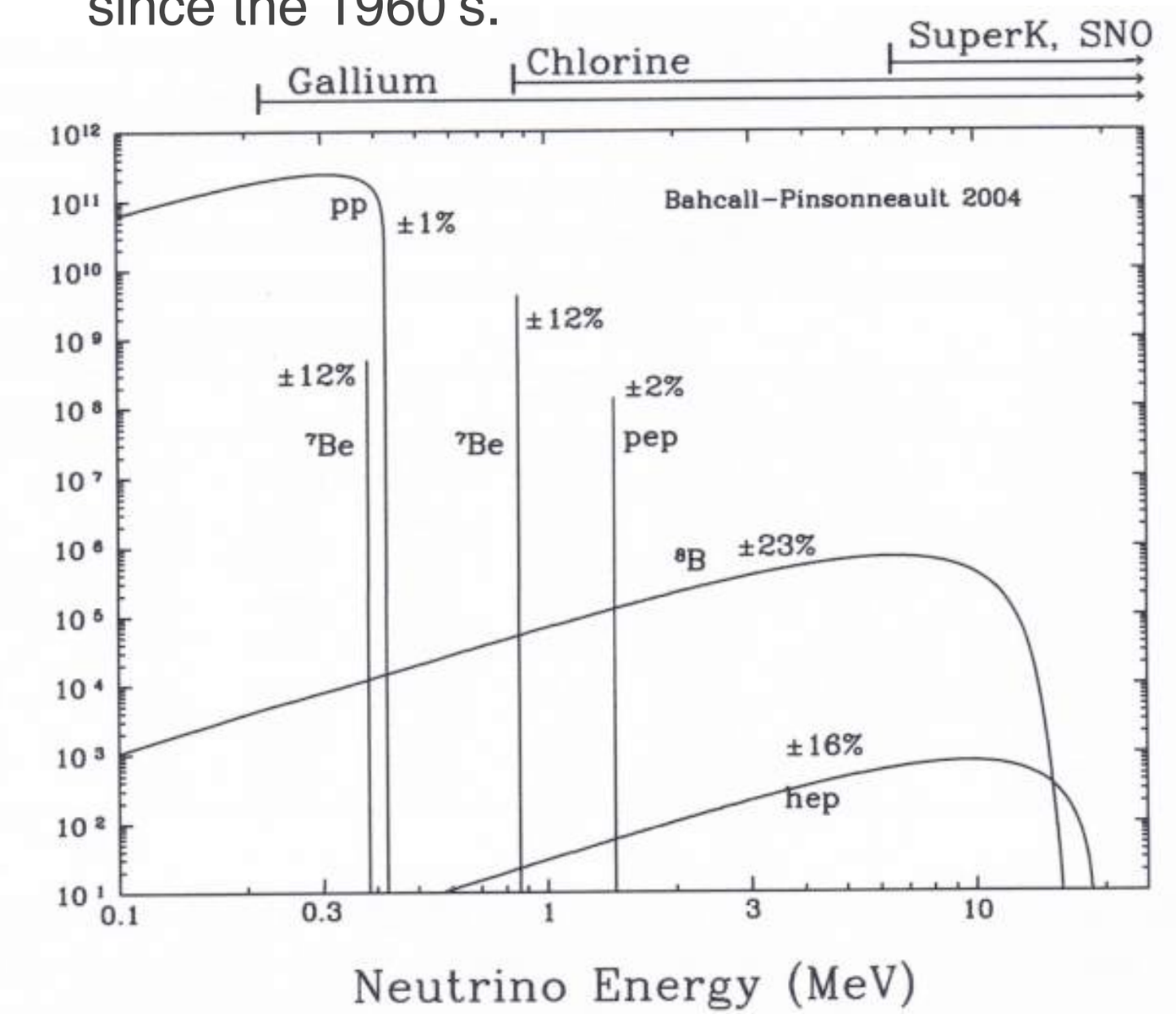


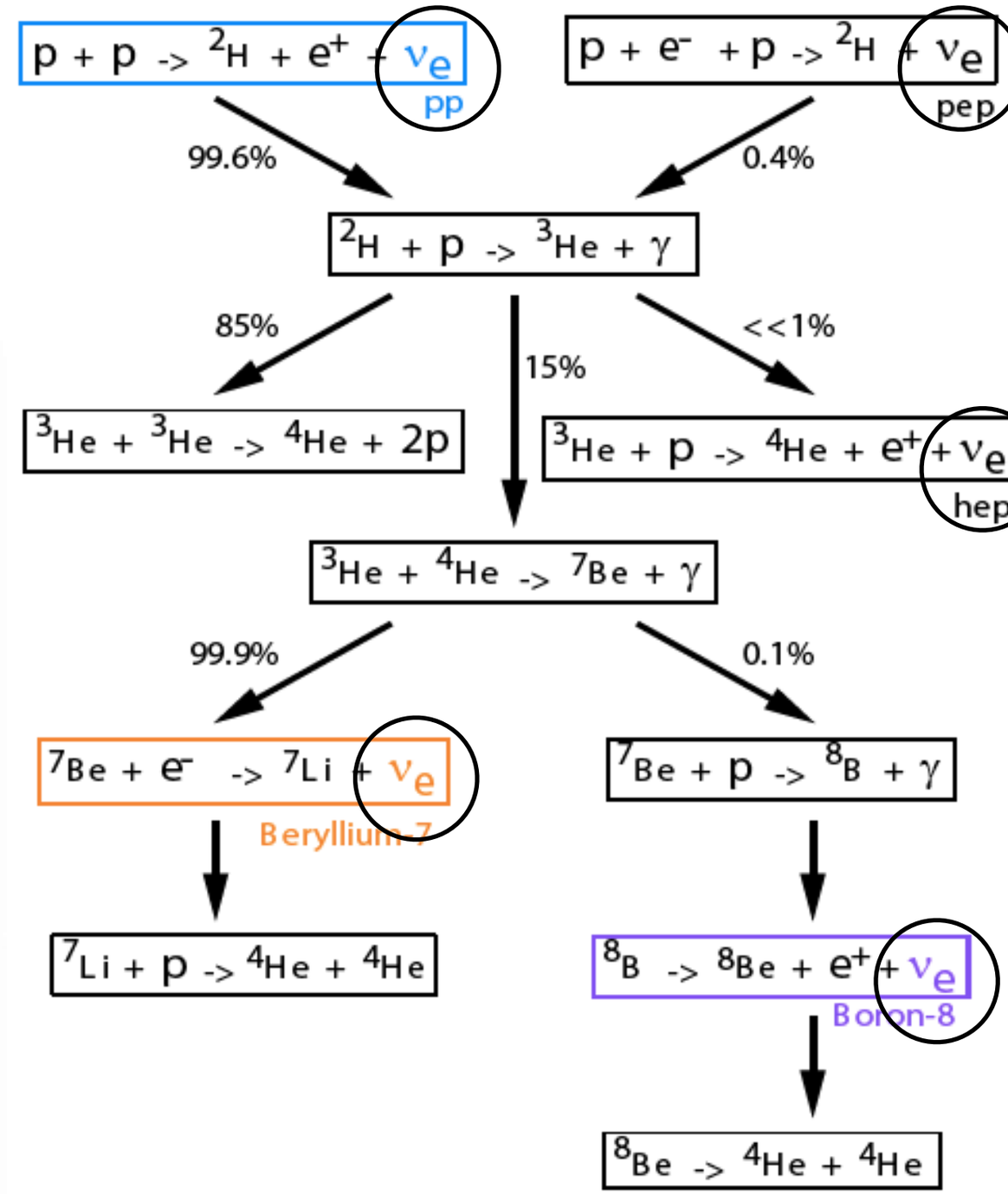
Steven Manly's NuFact 2013 MINERνA presentation

- Despite recent progress and measurements from hadron production experiments over the past 10+ years, we're *still* talking about 10-20% uncertainties in the hadron production off the NuMI target

The Solar Neutrino Problem

- We expect to see only ν_e coming from the sun.
- Precise solar models allow us to predict the energy spectra of neutrinos from the sun.
- A deficit (~1/2) of ν_es has been observed since the 1960's.



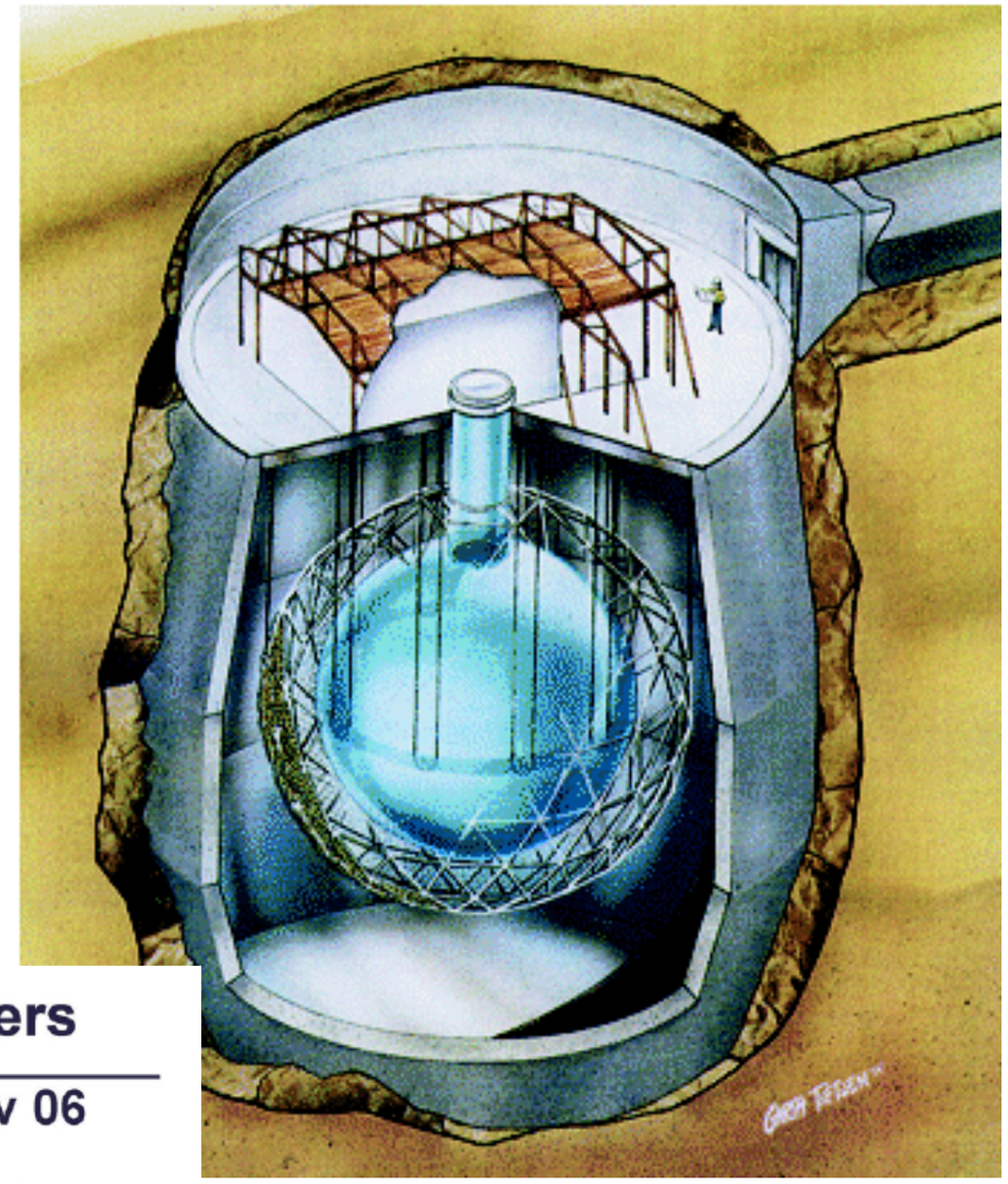


The Sudbury Neutrino Oscillation (SNO) Detector

- 1 kton of D2O (^2H_2O)
- Sensitive to:
  - CC: $\nu_e + {}^2H \rightarrow p + p + e^-$
  - ES: $\nu_\alpha + e^- \rightarrow \nu_\alpha + e^-$
  - NC: $\nu_\alpha + {}^2H \rightarrow n + p + \nu_\alpha$

$$R_E = \frac{R_{CC}}{R_{ES}} \neq 1 \quad \text{or} \quad R_N = \frac{R_{CC}}{R_{NC}} \neq 1$$

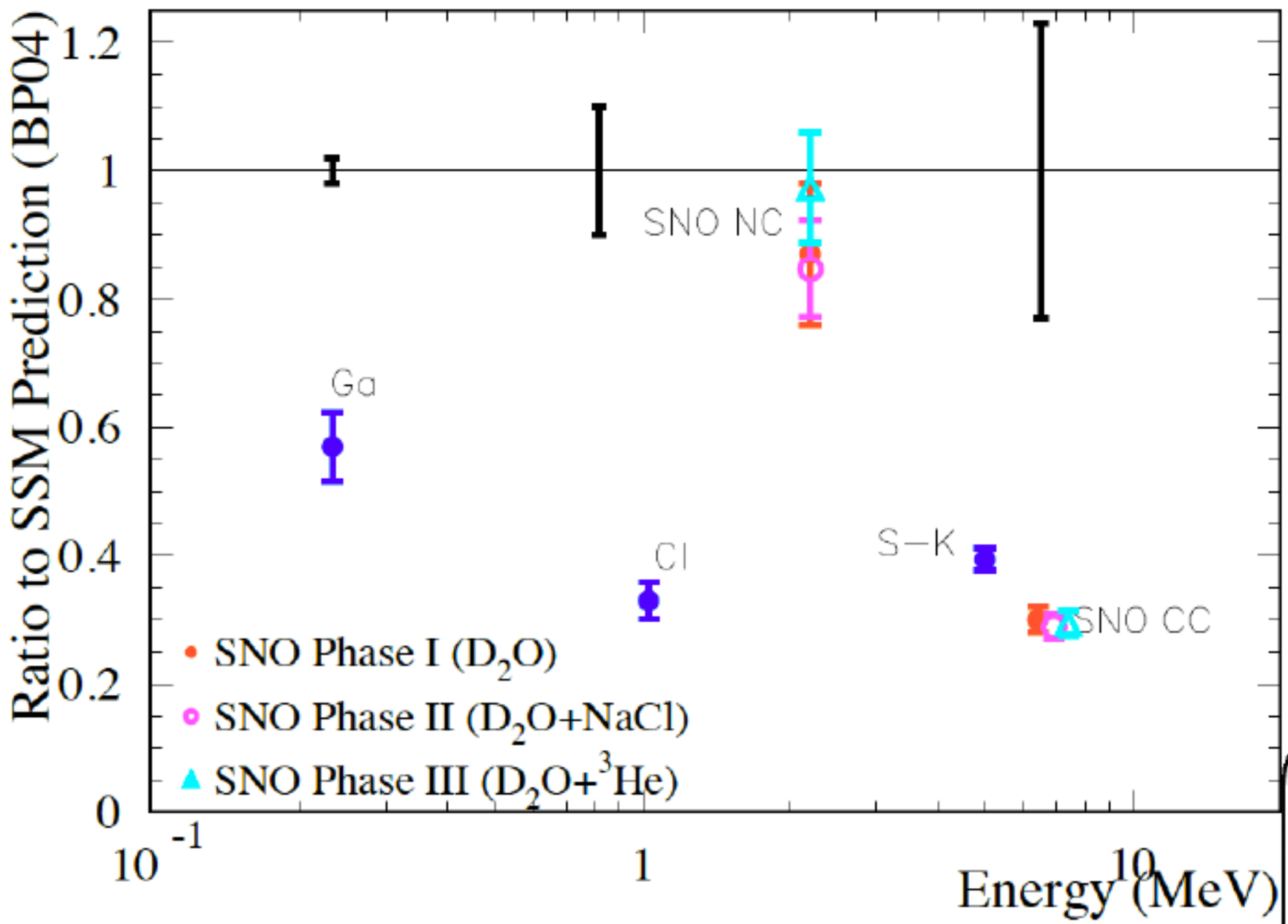
means: $\nu_e \rightarrow \nu_{\mu,\tau}$



Pure D_2O	Salt	^{3}He Counters
Nov 99 – May 01	Jul 01 – Sep 03	Nov 04 – Nov 06
$n + d \rightarrow t + \gamma$	$n + {}^{35}Cl \rightarrow {}^{36}Cl + \Sigma\gamma$	$n + {}^3He \rightarrow t + p$
(E_γ = 6.25 MeV)	($E_{\Sigma\gamma}$ = 8.6 MeV)	proportional counters σ = 5330 b
	enhanced NC rate and separation	event-by-event separation

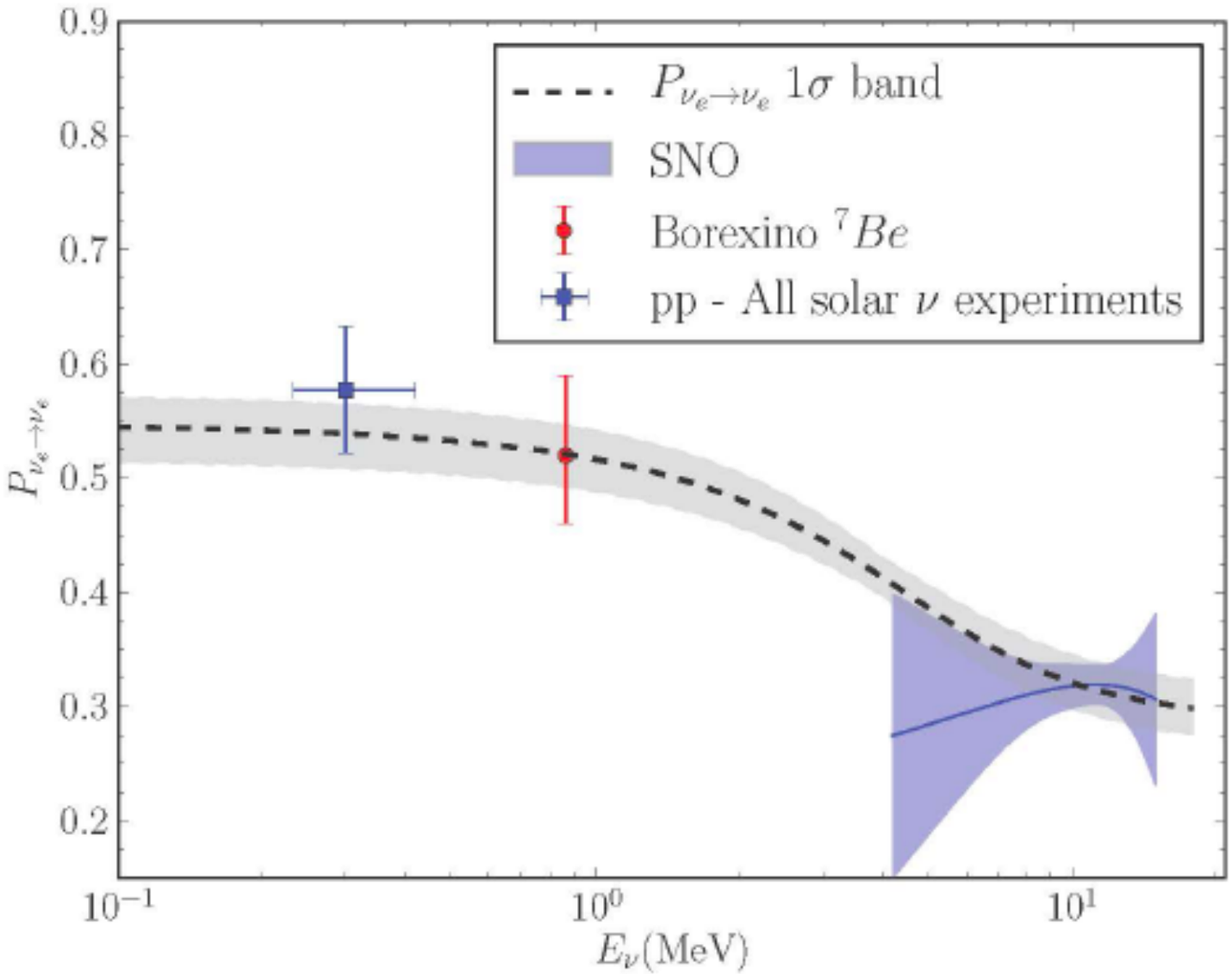
The Sudbury Neutrino Oscillation Detector

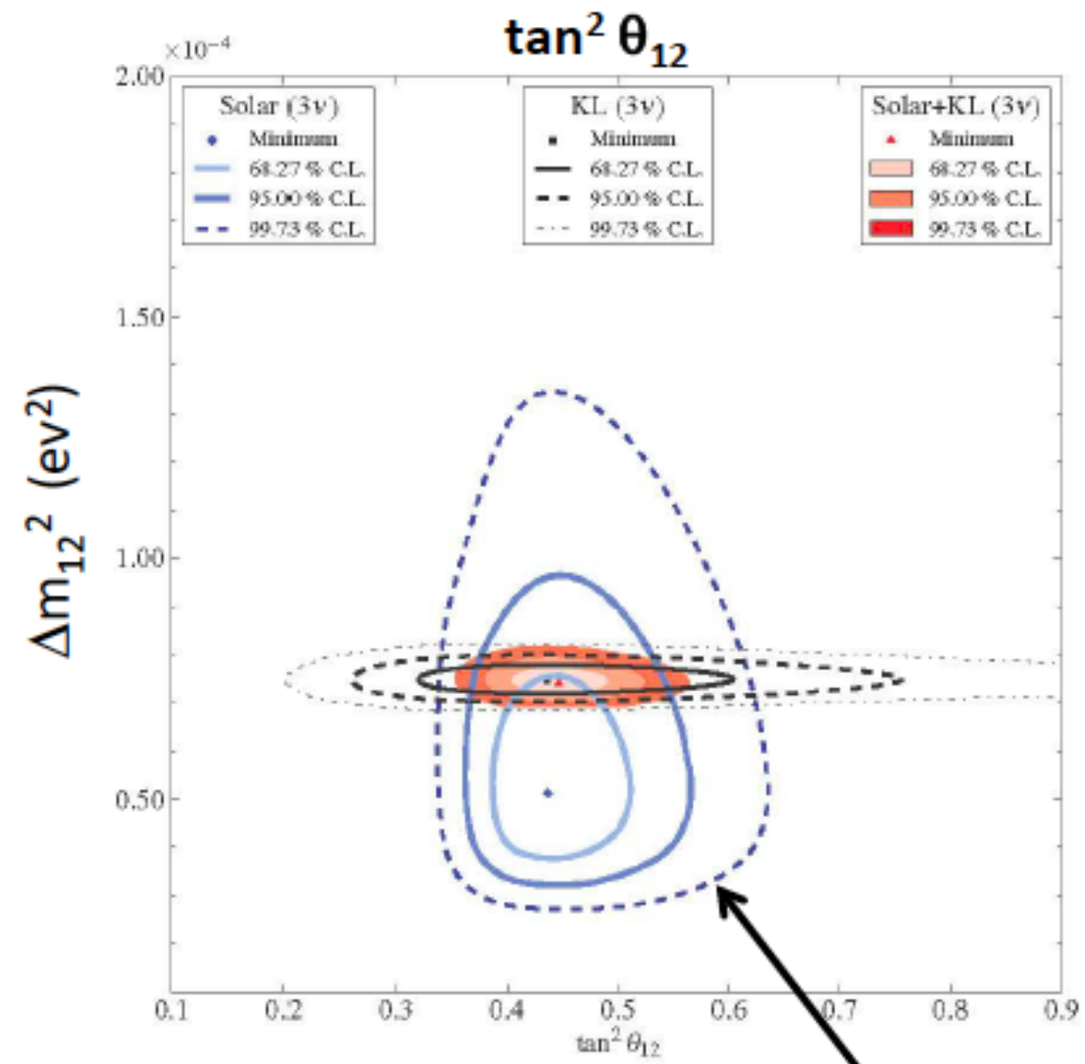
Solar Neutrino Problem Resolved



arXiv:1109.0763

The Sudbury Neutrino Oscillation Detector





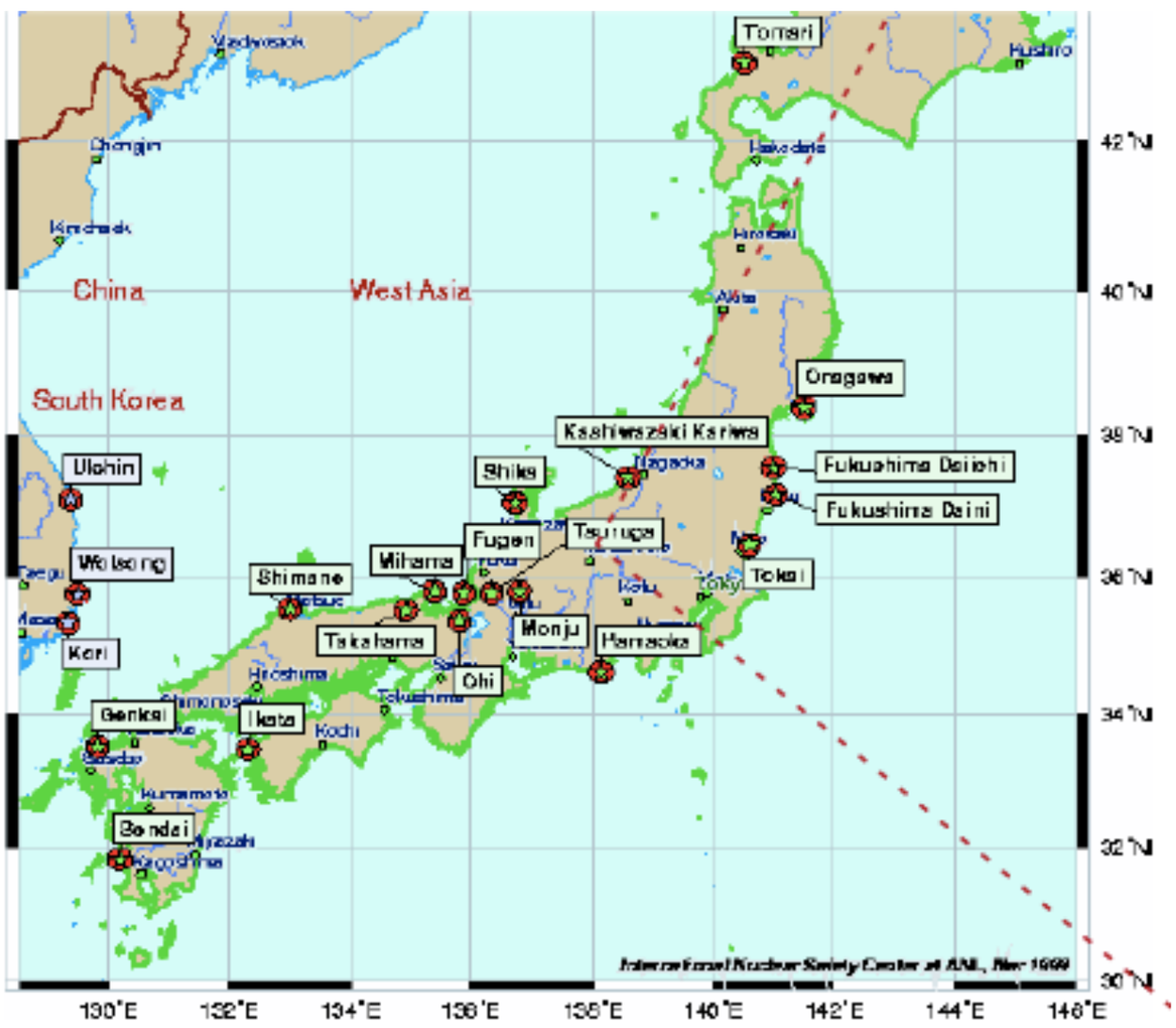
SNO defines θ_{12} to be non-maximal by more than 5 σ.

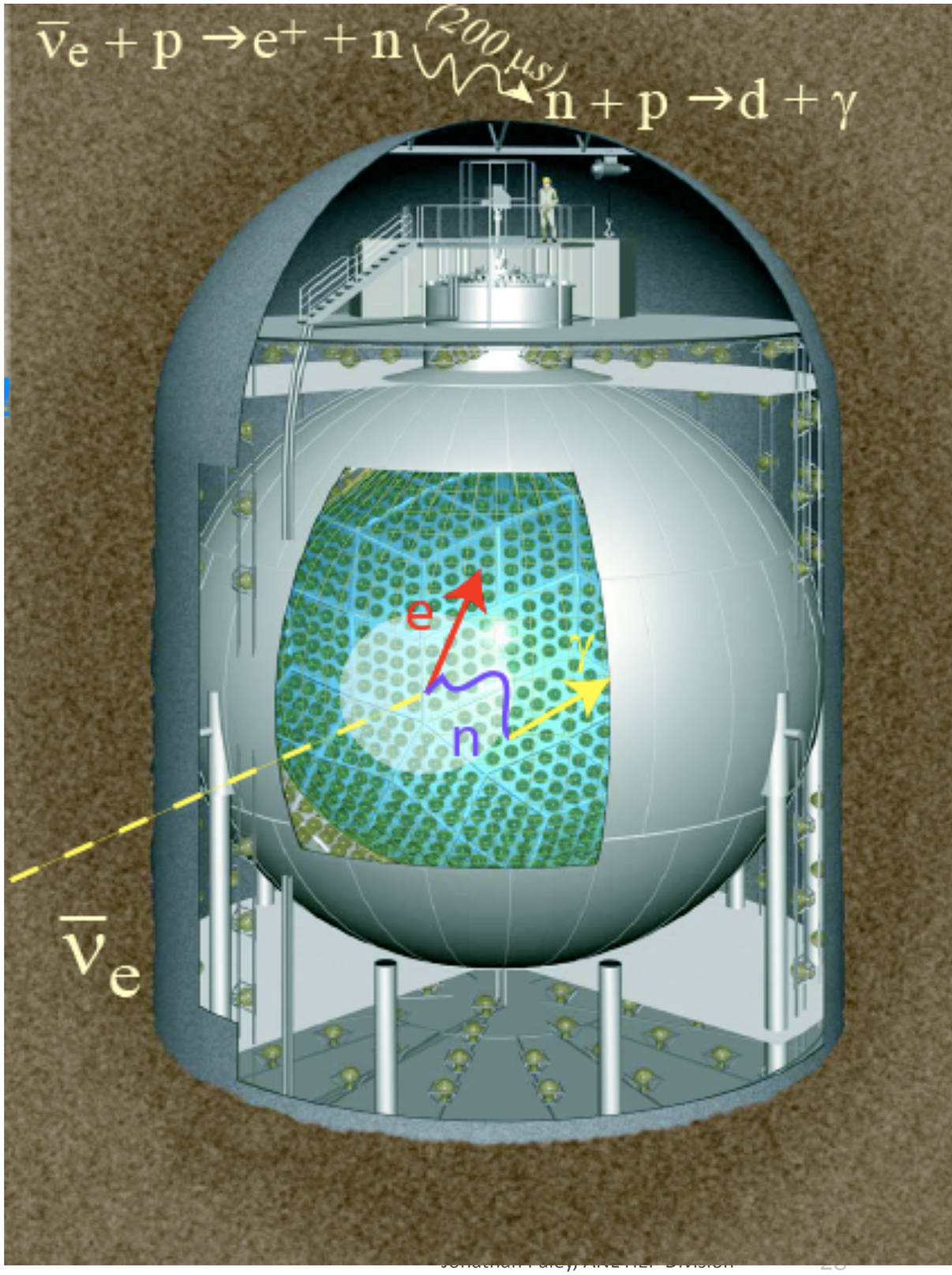
McDonald - Neutrino 2012

arXiv:1109.0763

The KamLAND Experiment

- 1 kton of liquid scintillator
- Antineutrinos came from 20 nuclear reactors in Japan and South Korea; flux weighted average baseline in ~180 km.
- Tests solar neutrino oscillations on Earth.



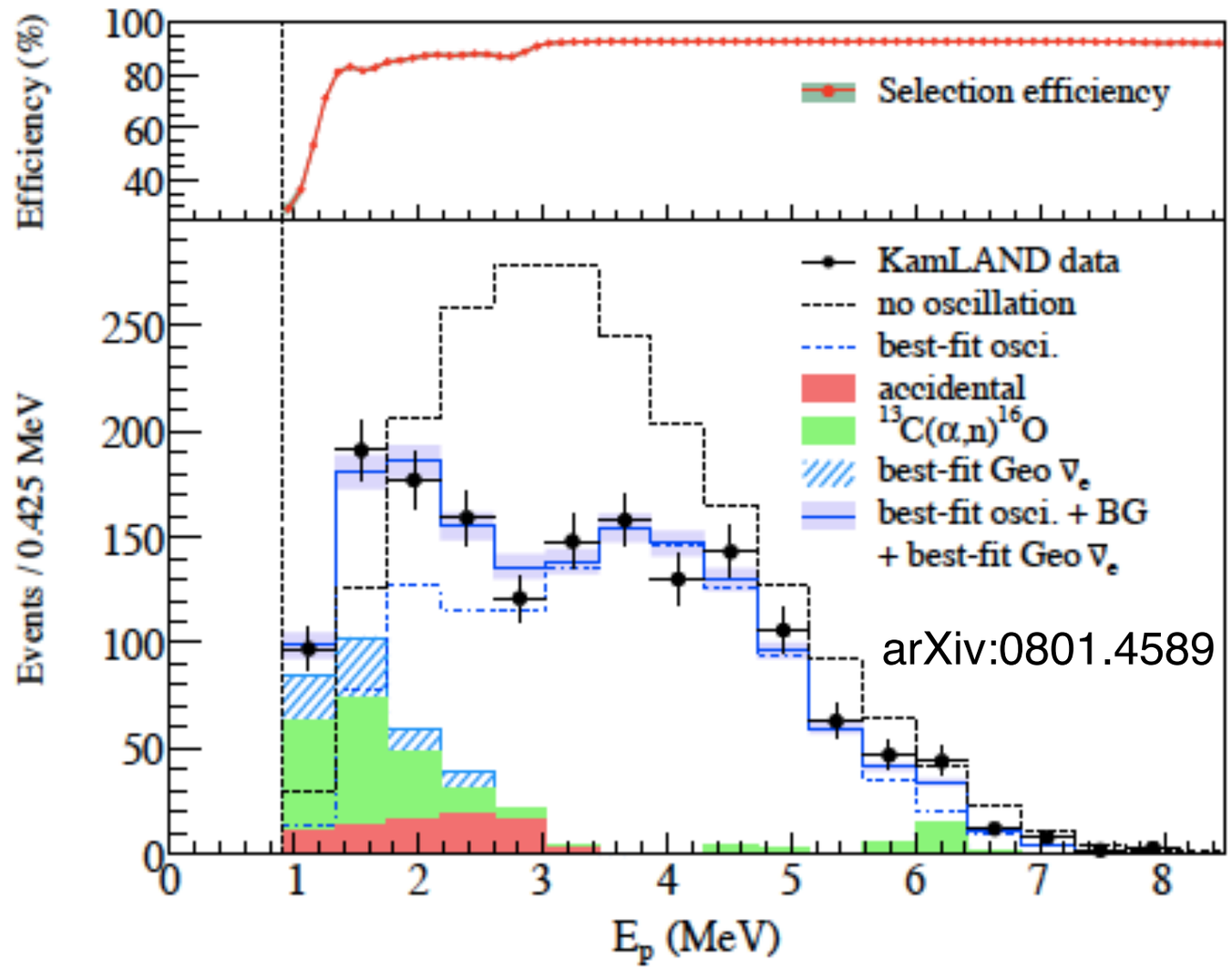


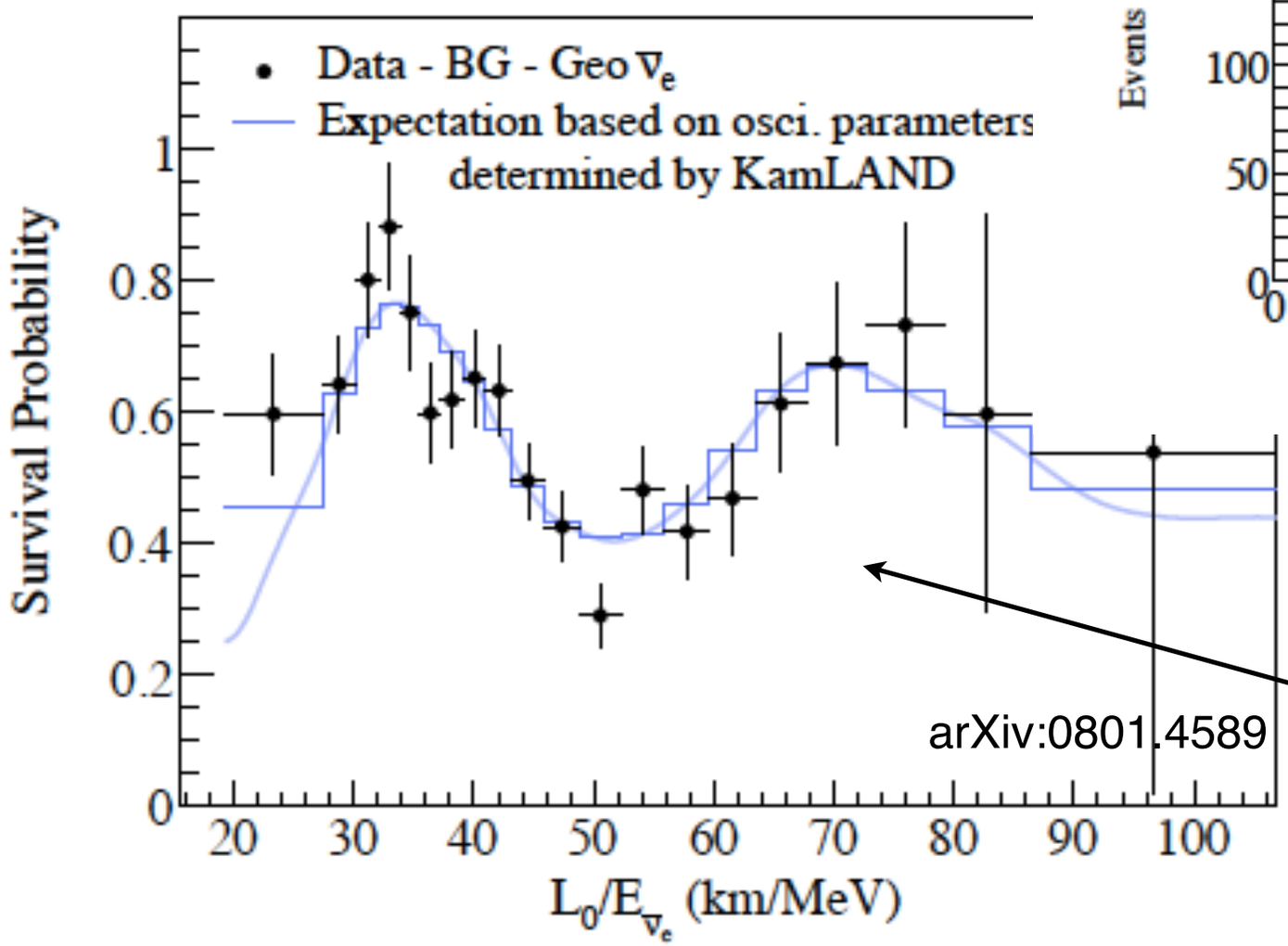
KamLAND Results

$$\Delta m^2_{21} = 7.59 \pm 0.21 \times 10^{-5}$$

$$\tan^2\theta_{12} = 0.47^{+0.06}_{-0.05}$$

(combined with solar data from SNO)

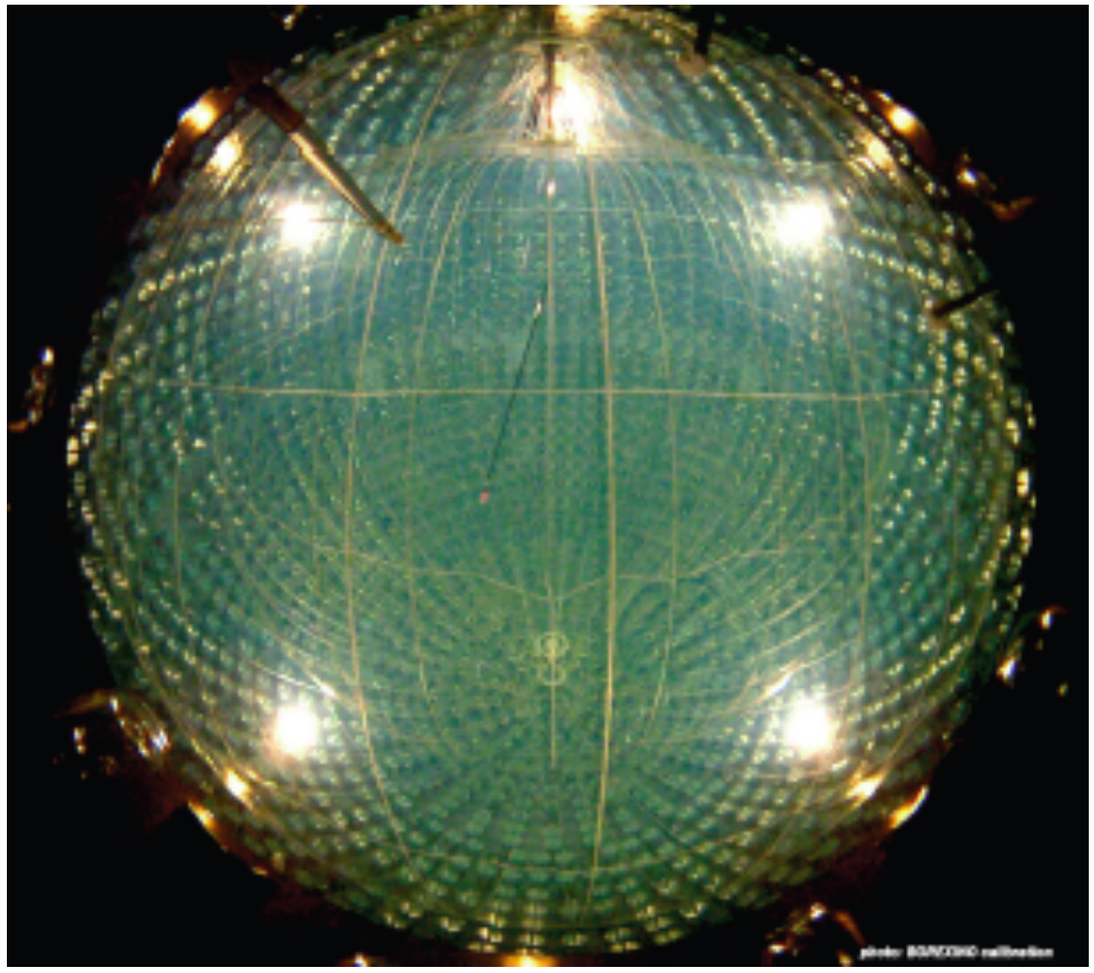


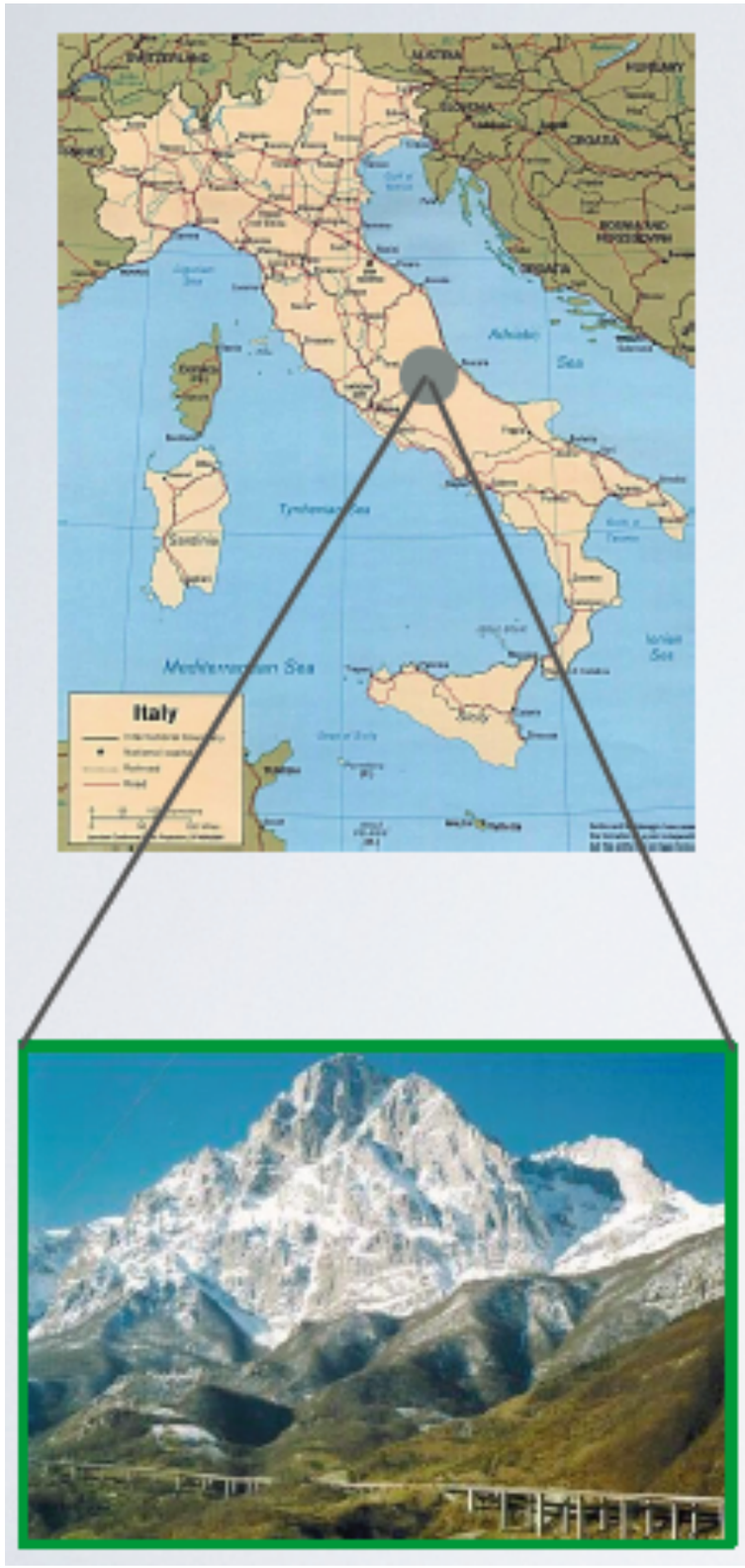


Oscillation for L = 180 km

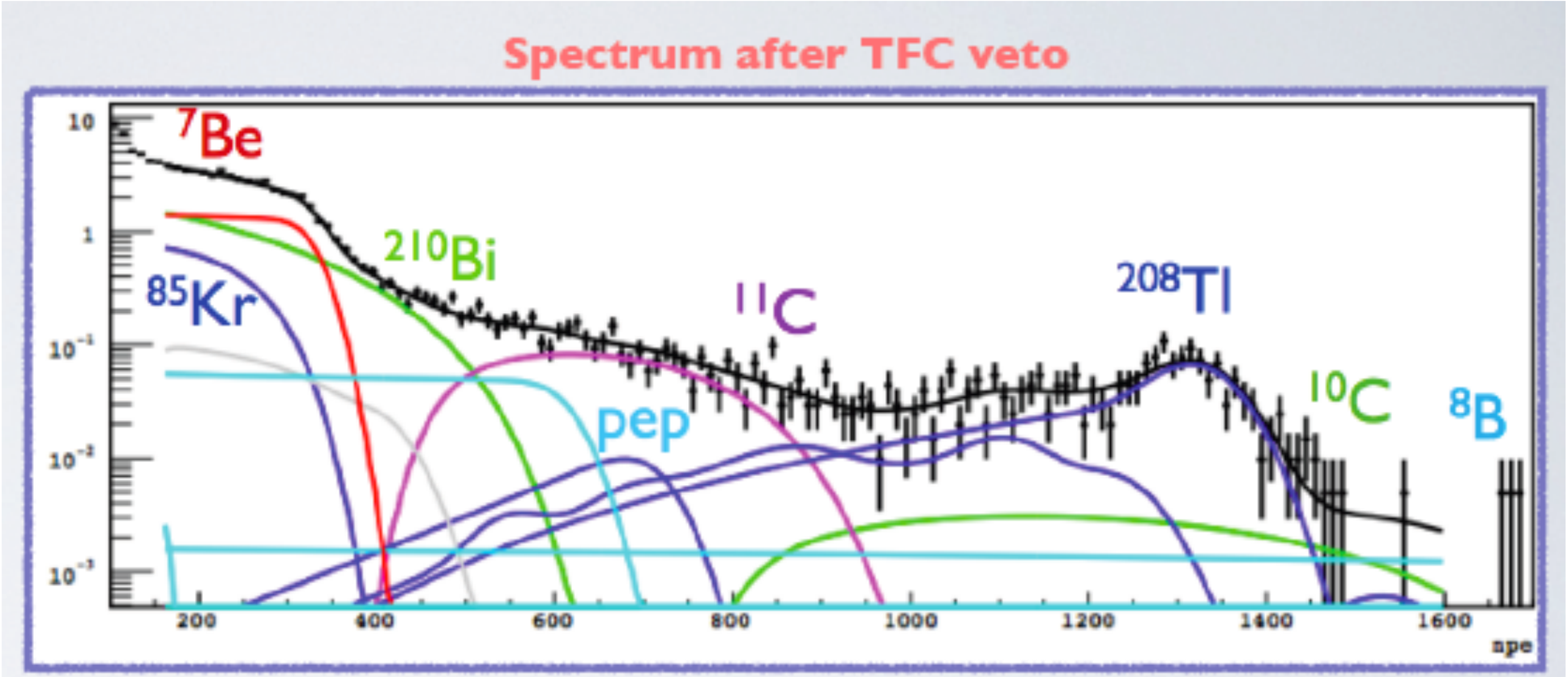
The Borexino Experiment

- 300 tons (100 ton fiducial) of liquid scintillator, surrounded by outer layer of ultra-pure water which acts as a shield against neutrons and gamma rays
- 2000 PMTs (20 cm diameter)
- Very radiopure environment
- Designed to detect very low energy solar neutrinos

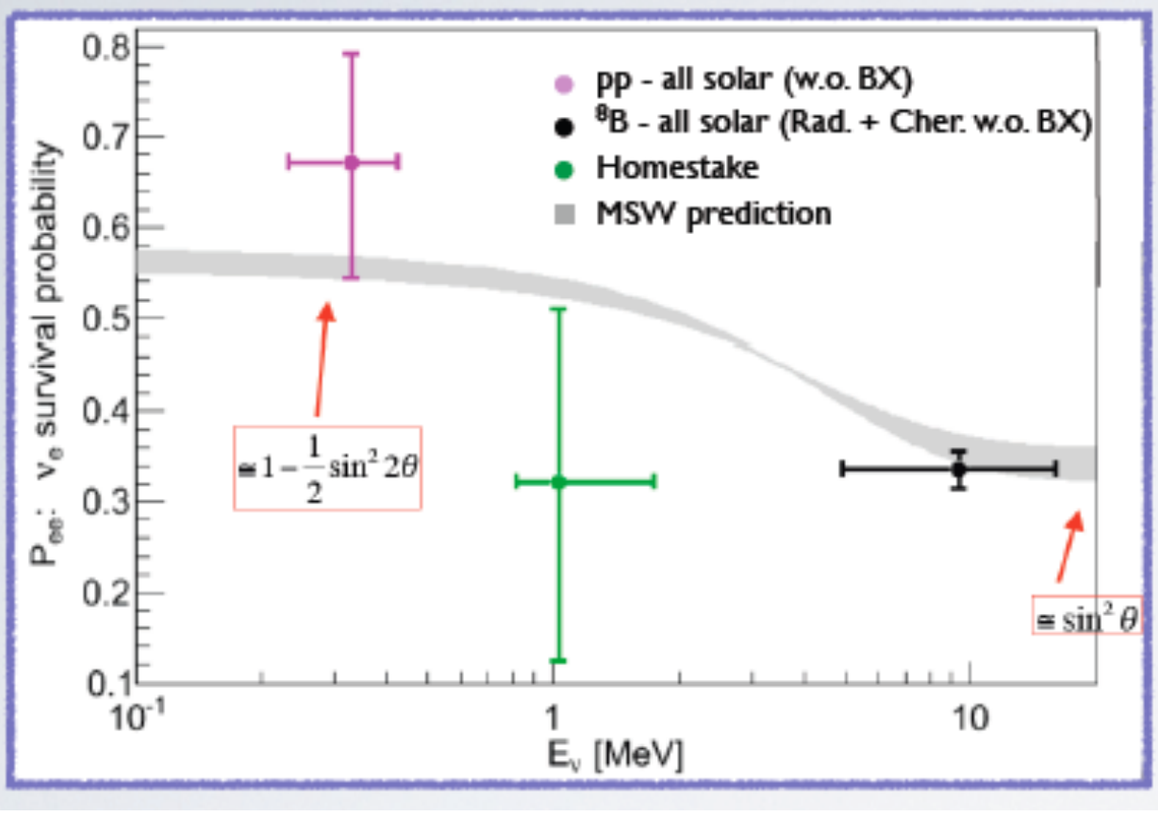


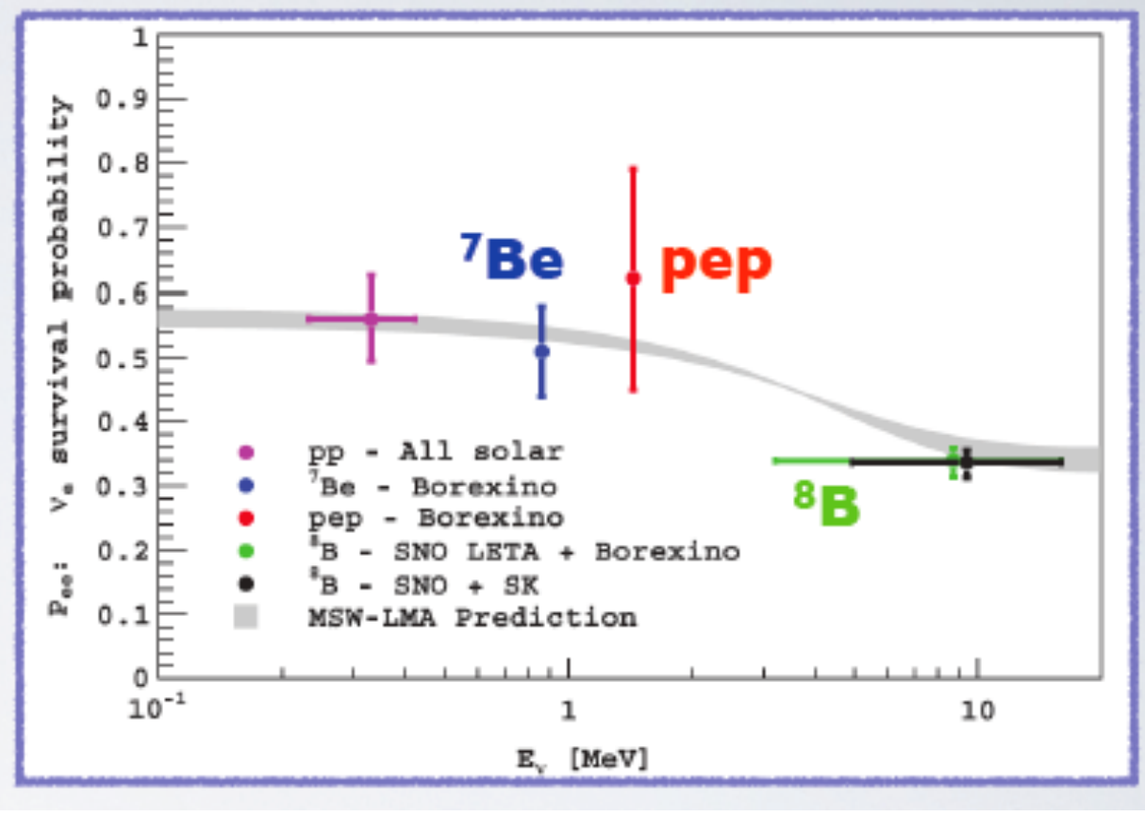


The Borexino Experiment



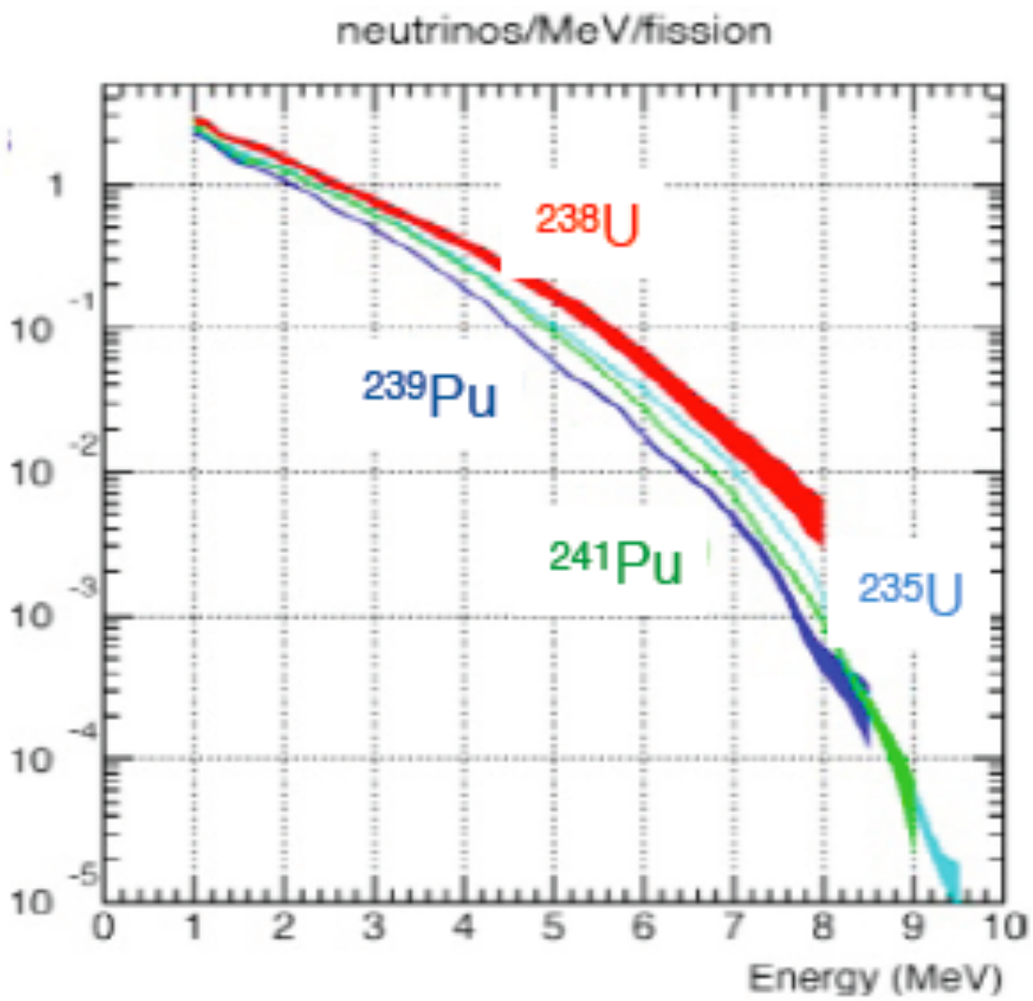
Pallavicini - Neutrino 2012

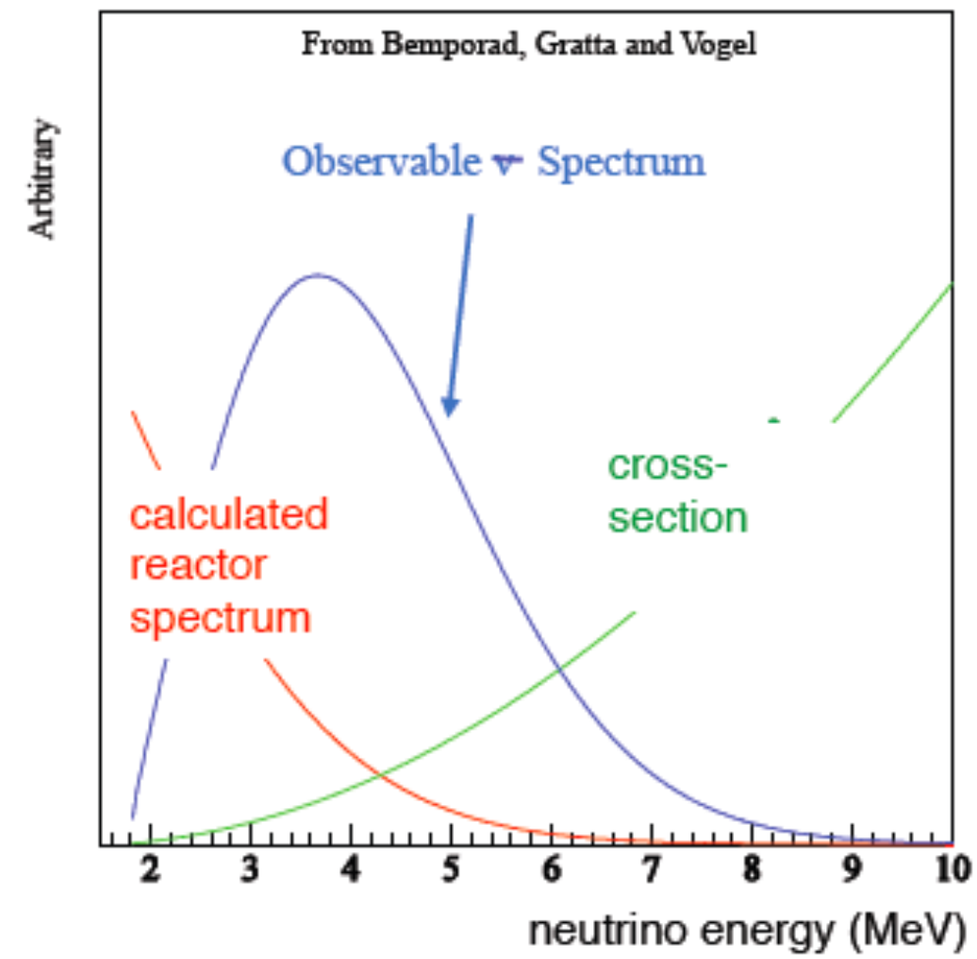




Reactor Experiments

- Measure $P(\bar{\nu}_e \rightarrow \bar{\nu}_e)$ using reactors as the anti-neutrino source





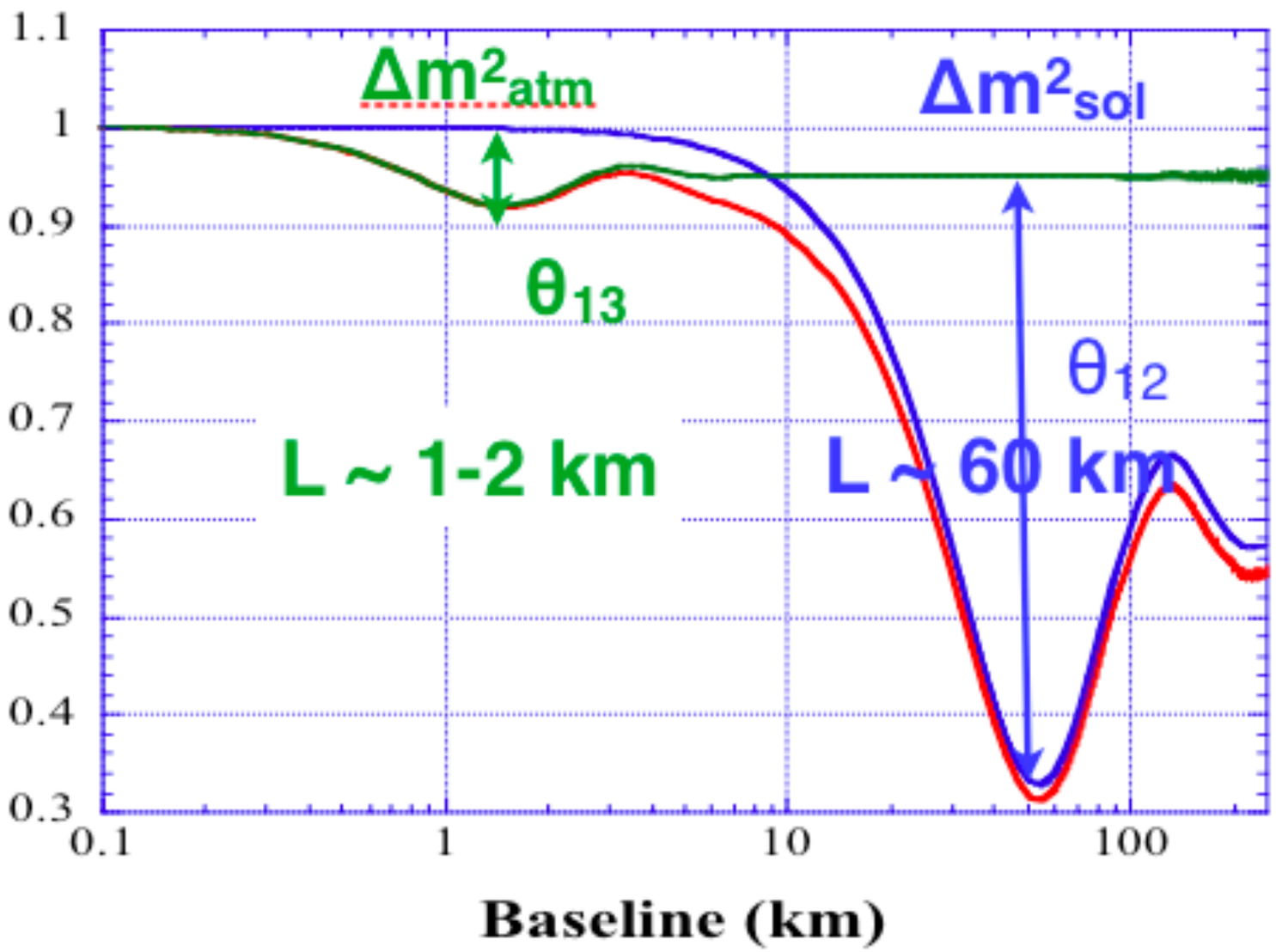
$^{235}U:^{238}U:^{239}Pu:^{241}Pu = 0.570 : 0.078 : 0.0295 : 0.057$

6 antineutrinos per fission, ~200 MeV per fission
$\sim 2 \times 10^{20}$ $\bar{\nu}_e/GW_{th}/sec$

detection method: inverse beta decay
$\bar{\nu}_e + p \rightarrow e^+ + n$

Reactor Experiments

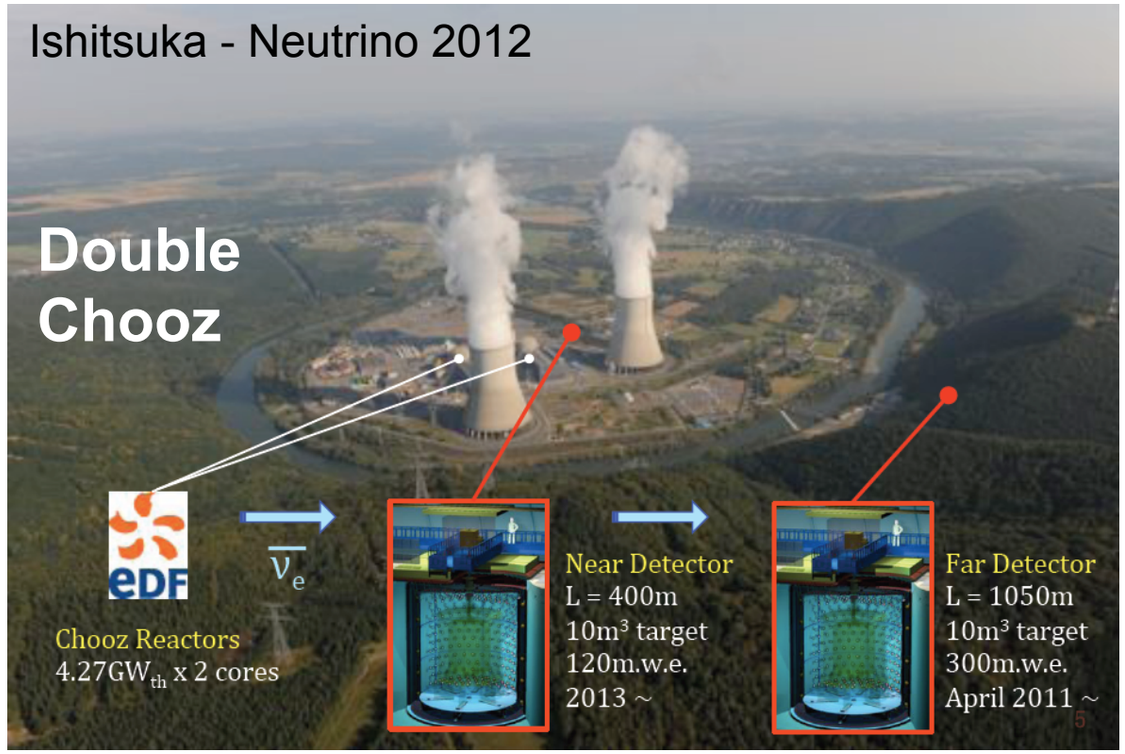
$$P_{ee} \approx 1 - \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta m_{31}{}^2 L}{4E_\nu}\right) - \cos^4\theta_{13} \sin^2 2\theta_{12} \sin^2\left(\frac{\Delta m_{21}{}^2 L}{4E_\nu}\right)$$

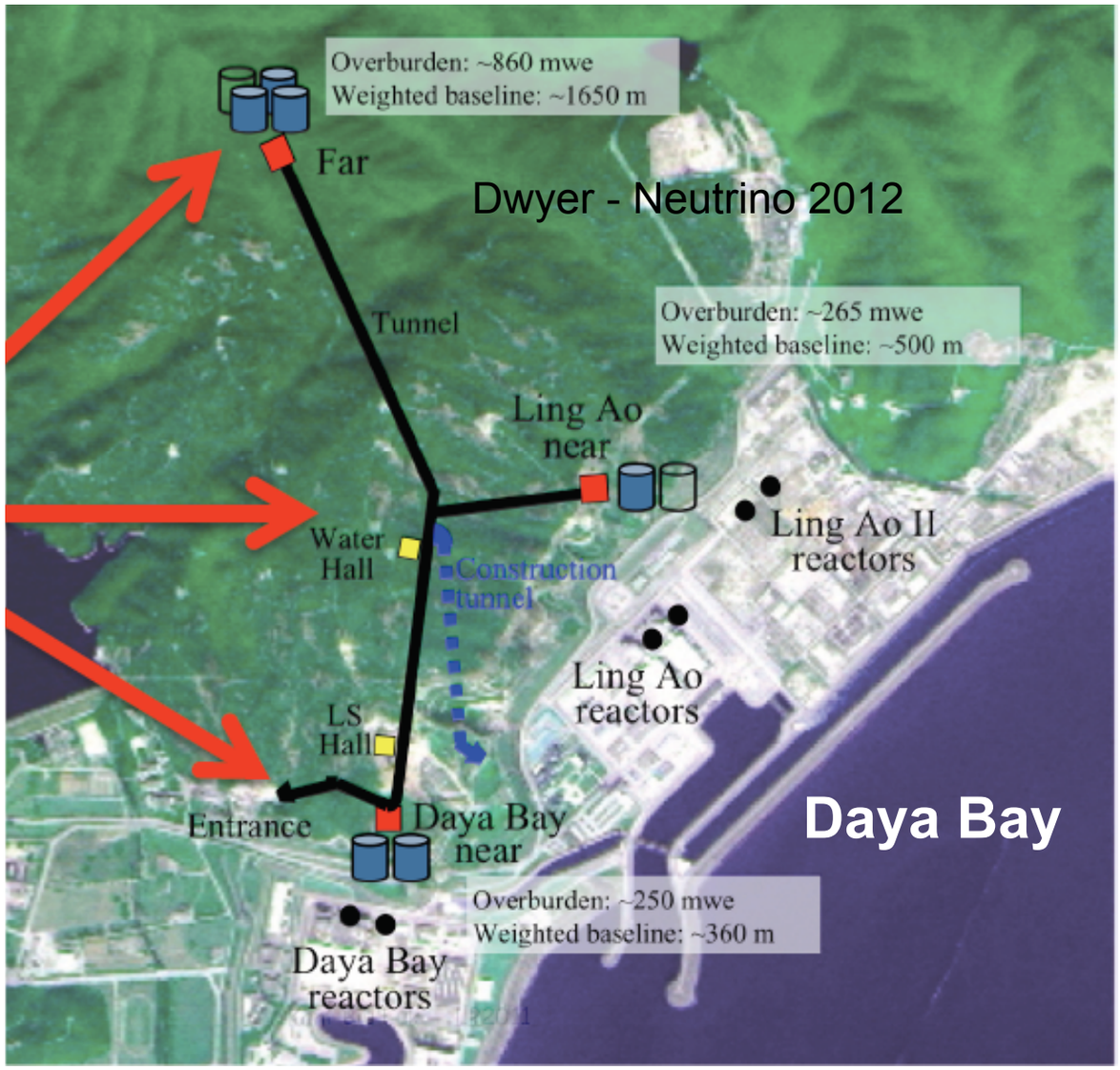


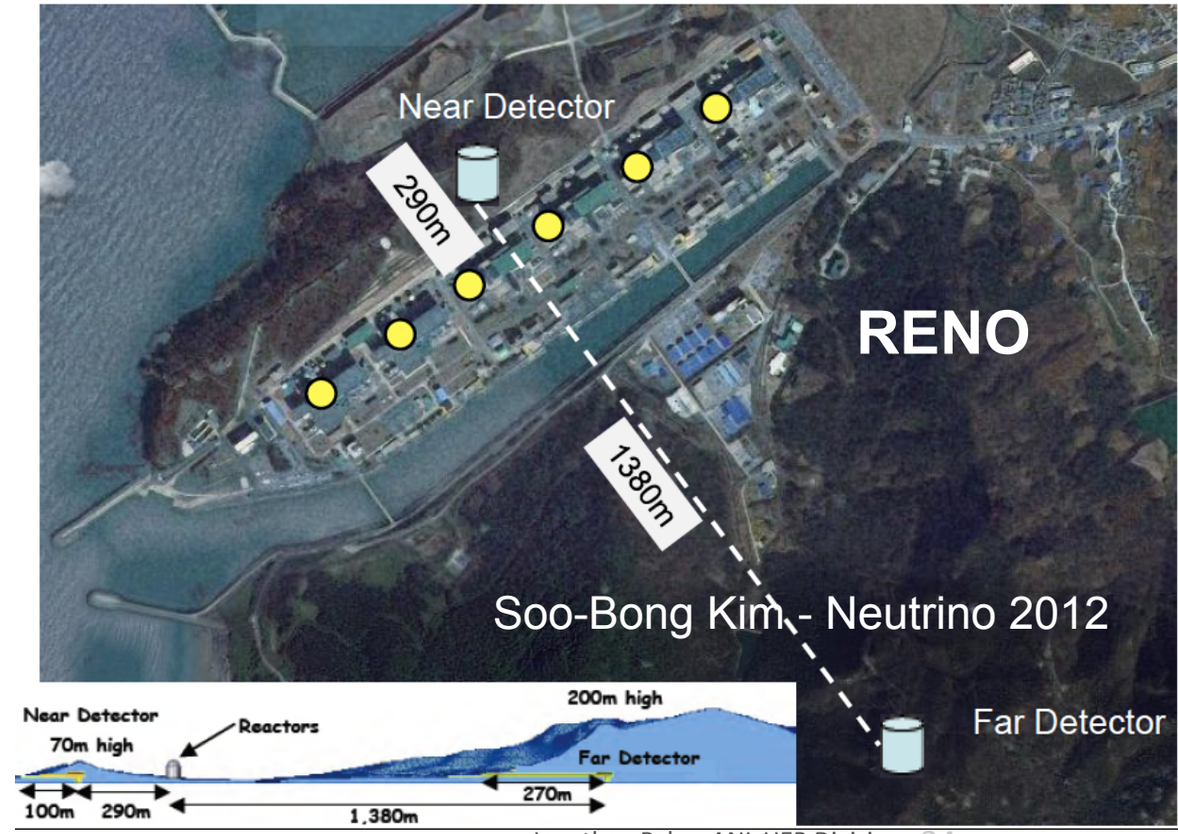
- "Long-baseline" reactor experiments (eg, KamLAND) are sensitive only to the solar mass splitting.
- "Short-baseline" reactor experiments (eg, Double Chooz, Daya Bay) are sensitive only to the atmospheric mass splitting and θ_{13}!

2012: The Year of the Reactor Experiments!

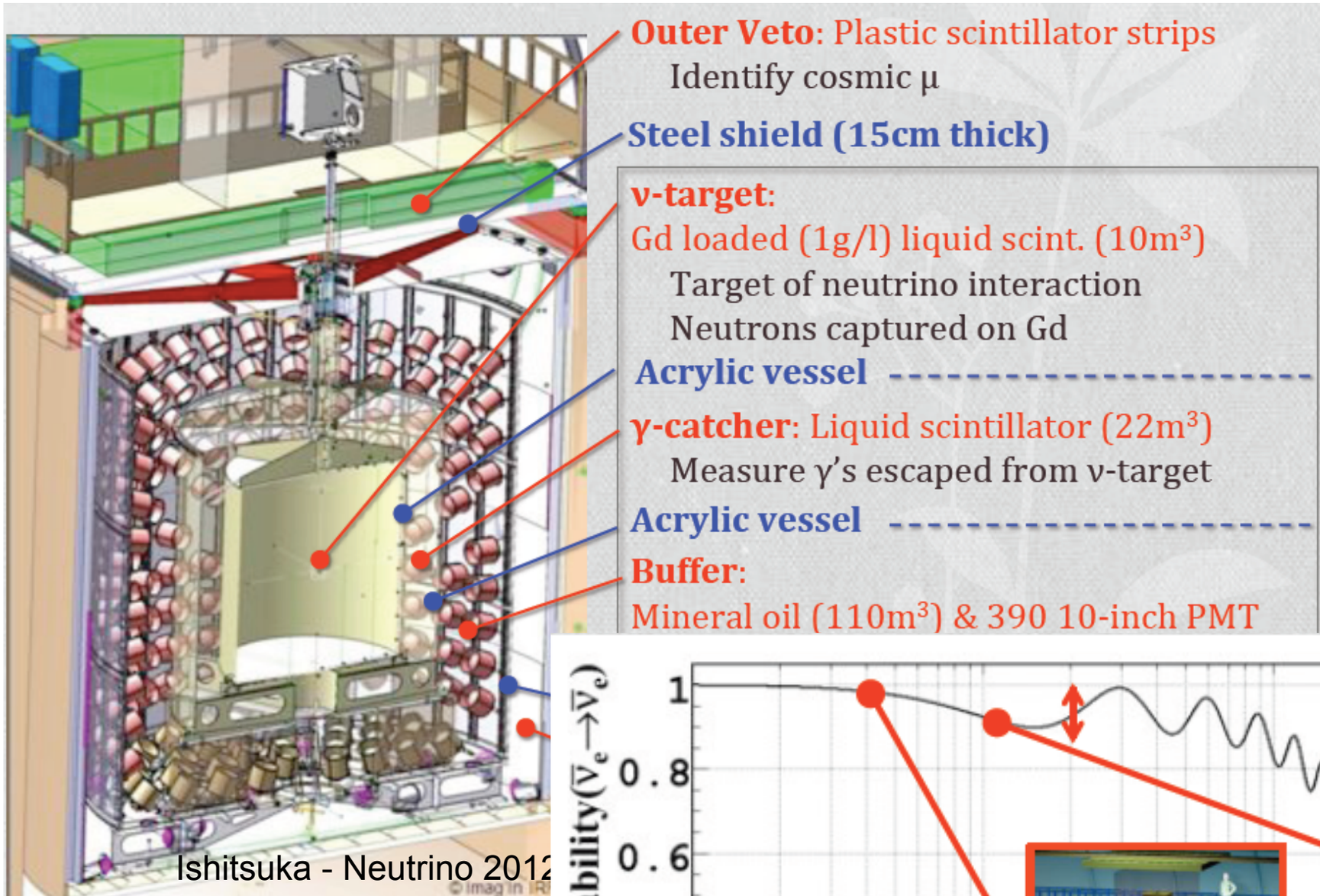
- In 2012, three reactor neutrino experiments reported measurements of θ_{13}.



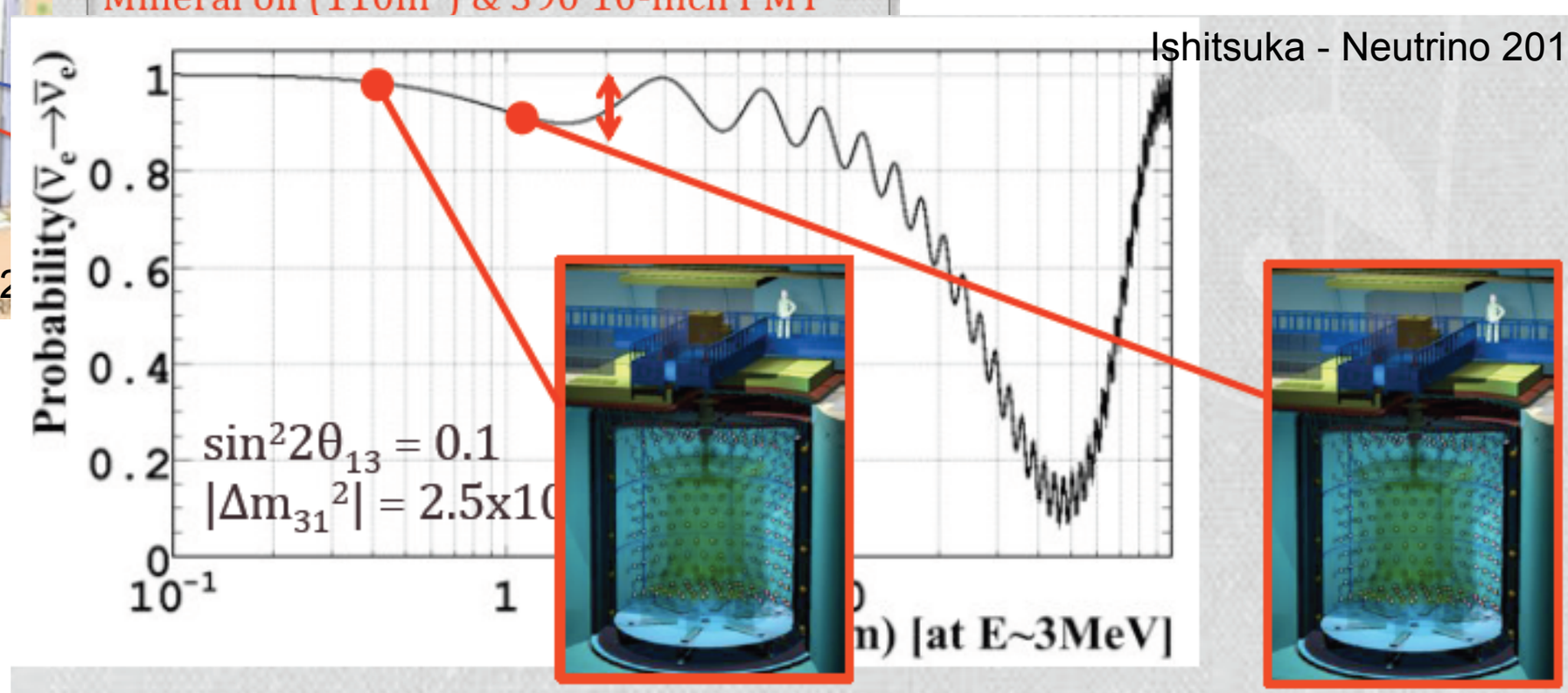




2012: The Year of the Reactor Experiments!

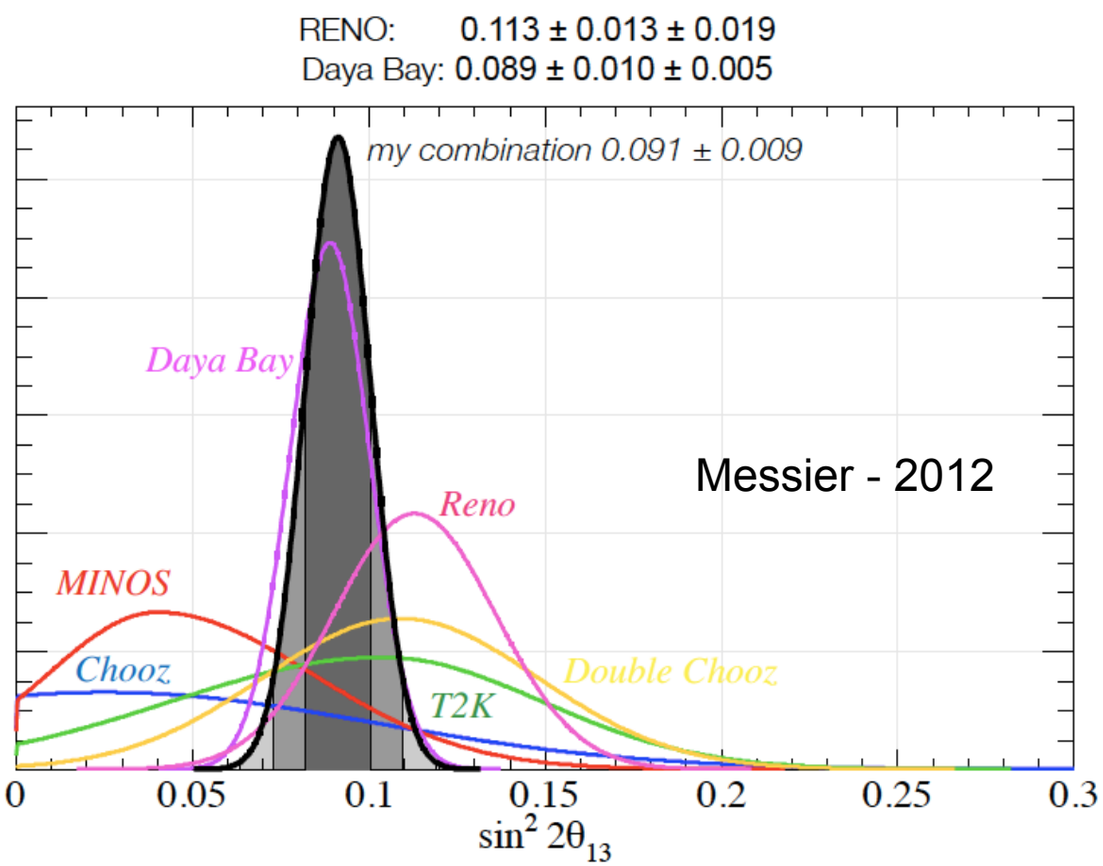


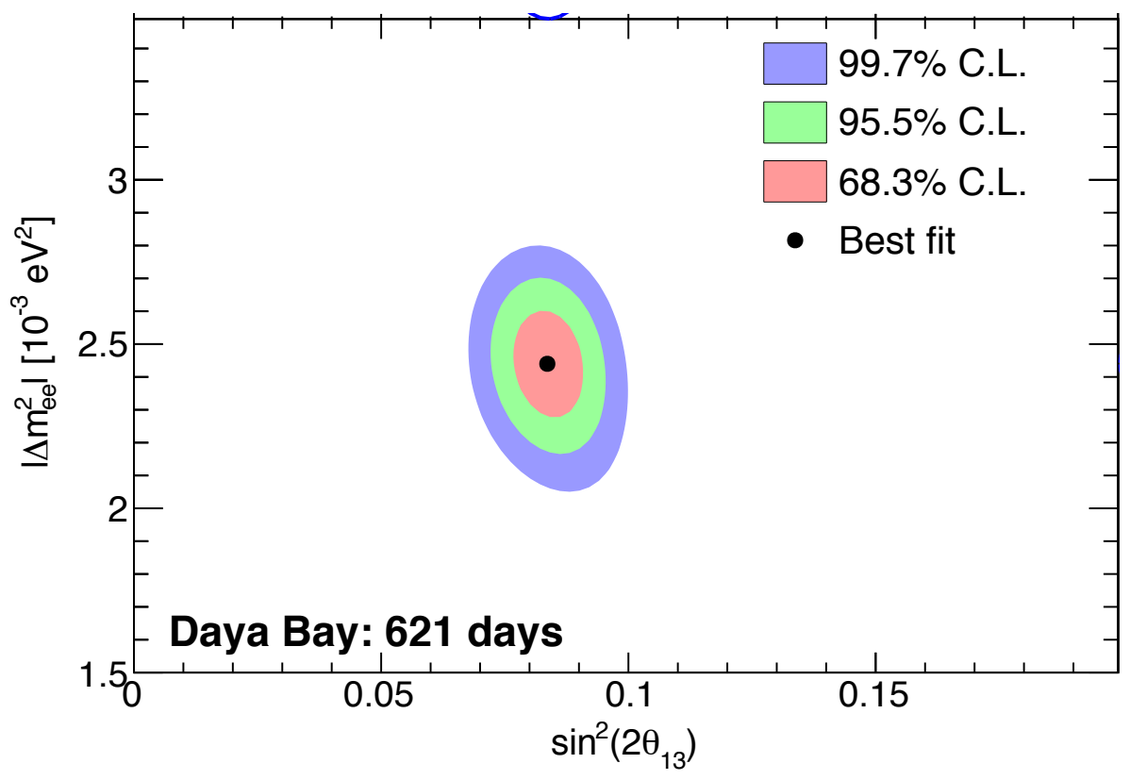
Ishitsuka - Neutrino 2012



Ishitsuka - Neutrino 2012

Two Years of Measurements of θ_{13}





Zhang - Neutrino 2014

- 11% → 6%
- spectral analysis also provides measurement of Δm^2_{31} (aka Δm^2_{ee}), consistent with MINOS results (and comparable precision)

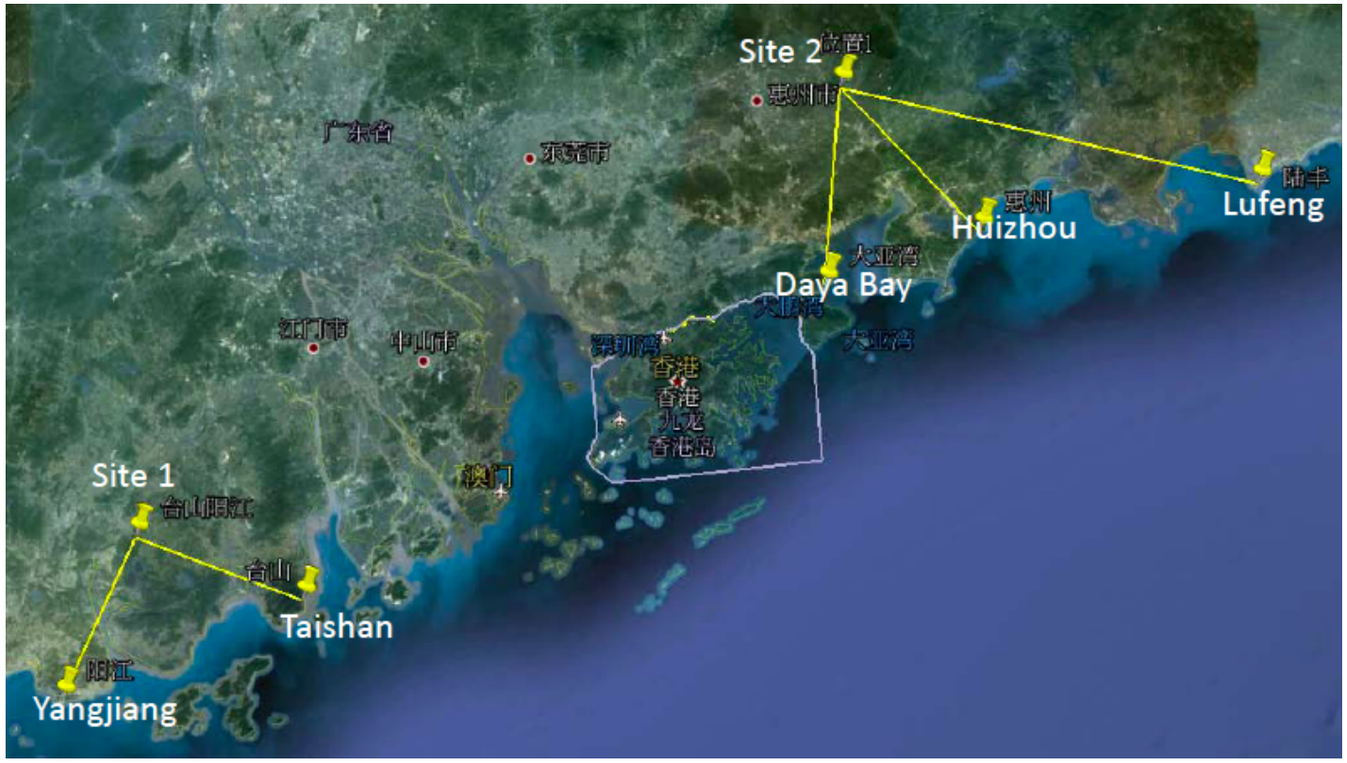
$$\sin^2 2\theta_{13} = 0.084^{+0.005}_{-0.005}$$

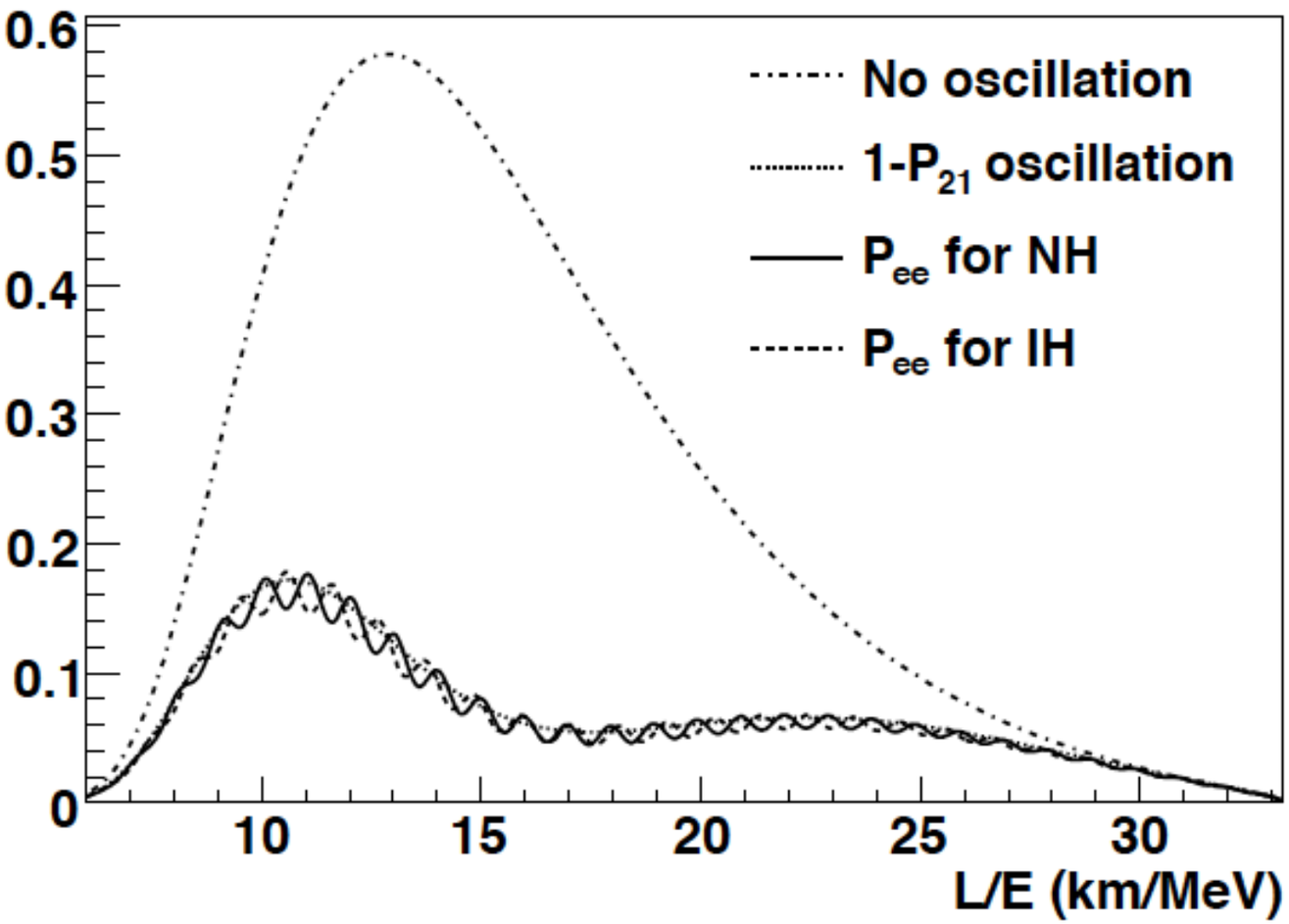
$$|\Delta m^2_{ee}| = 2.44^{+0.10}_{-0.11} \times 10^{-3}\mathrm{eV}^2$$

$$\chi^2/NDF = 134.7/146$$

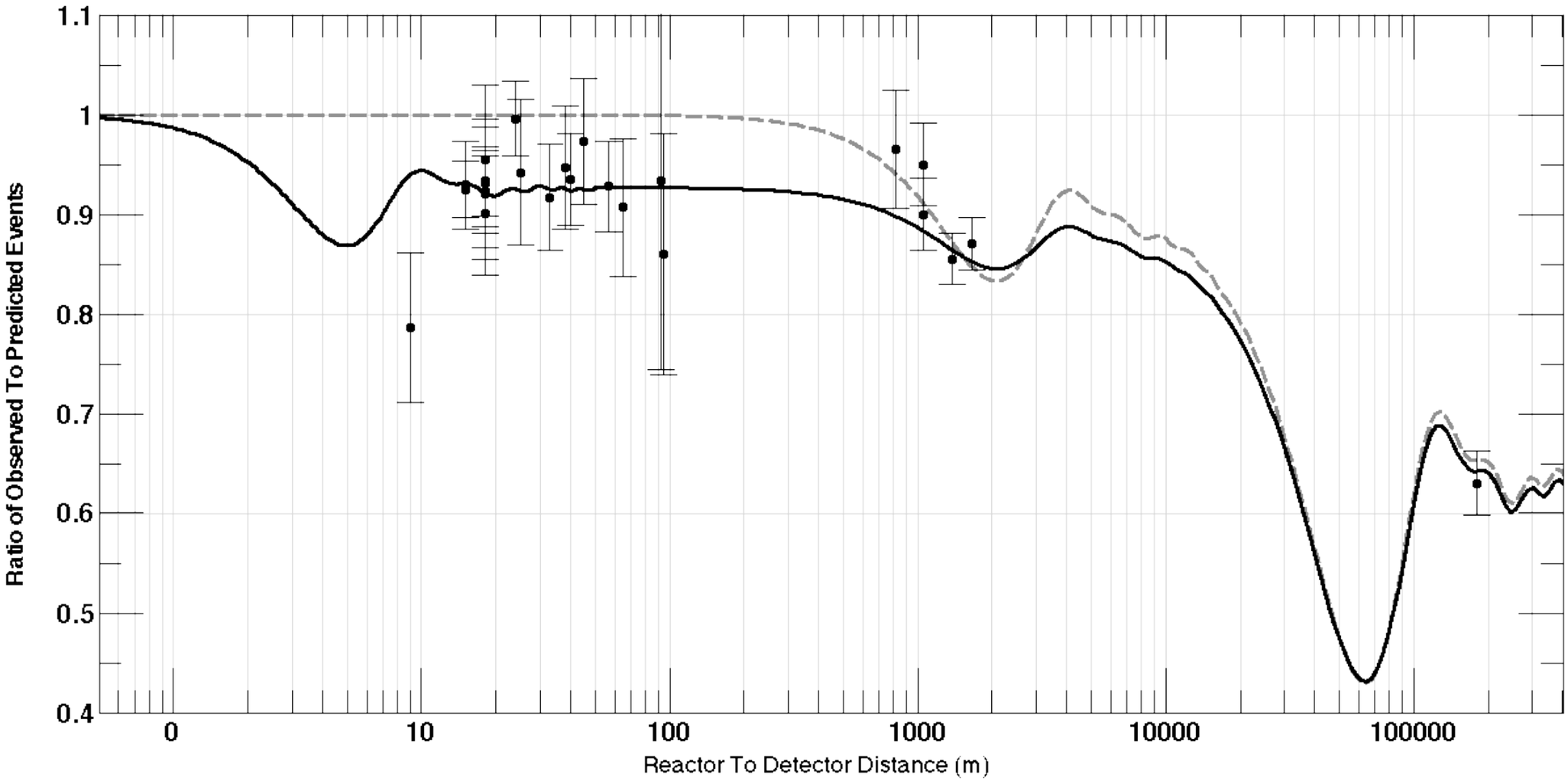
What's Next for the Reactor Experiments

- All three experiments will continue to collect statistics and reduce their systematics.
- θ_{13} will be the most precisely measured mixing angle within a couple of years, at the level of ~3%.
- Proposed JUNO and RENO 50 experiments
  - could determine the mass hierarchy as well as measure $\sin^2\theta_{12}$ to ~2%.
  - require unprecedented energy resolution = require big improvements in photodetectors



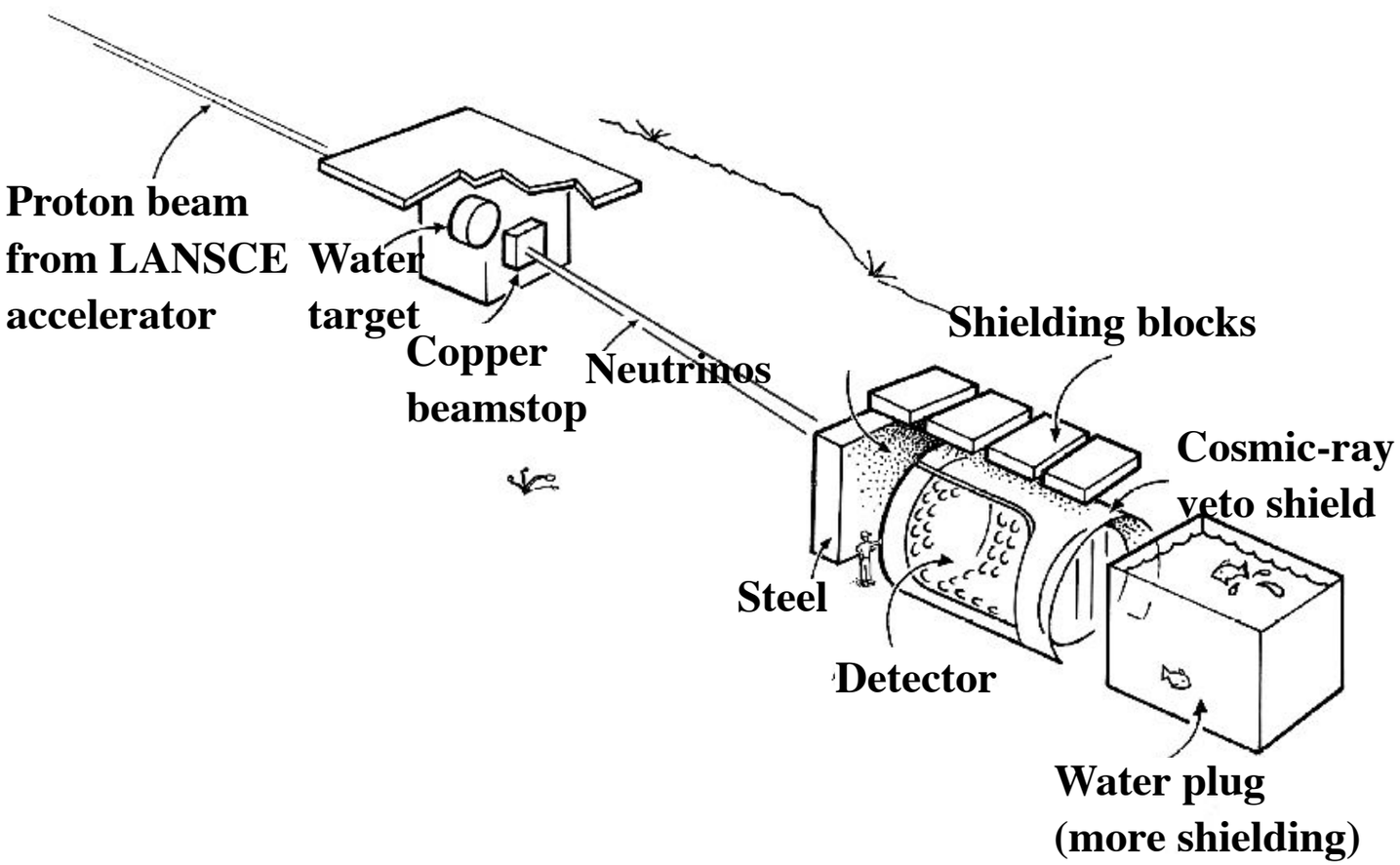


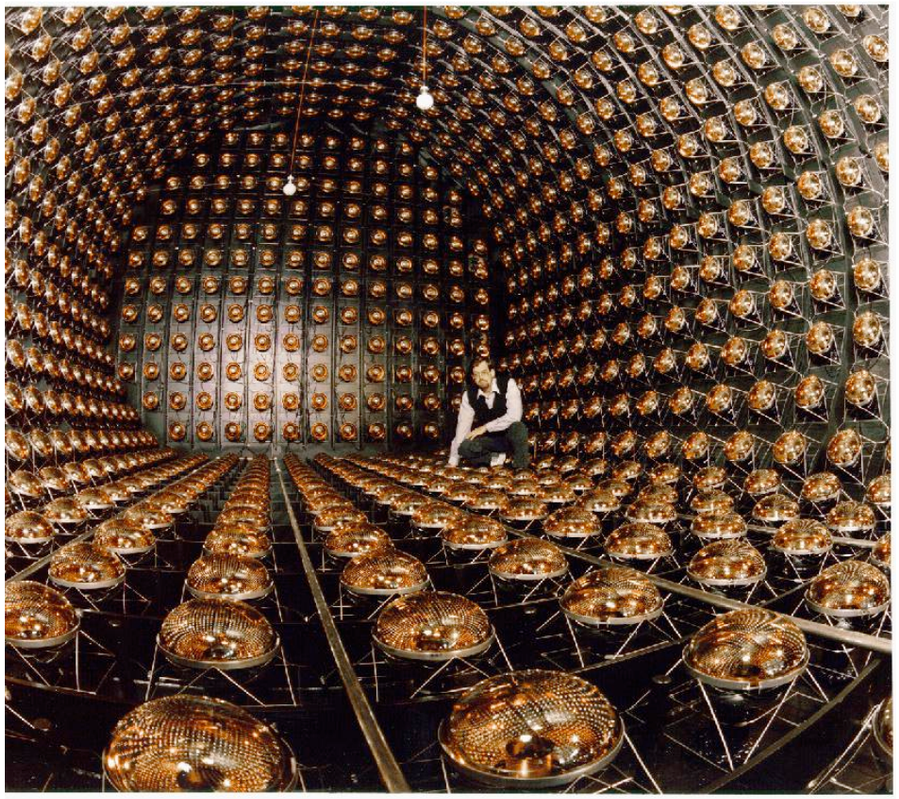
But Wait! Not All is Well in Reactor-land...



- New calculation of reactor flux (with ~2% uncertainty) predicts a higher rate than was observed in previous experiments!
- This implies that neutrinos actually DID oscillate in previous experiments.
- The only way this can happen is there is a different mass-splitting, with at least one more neutrino.

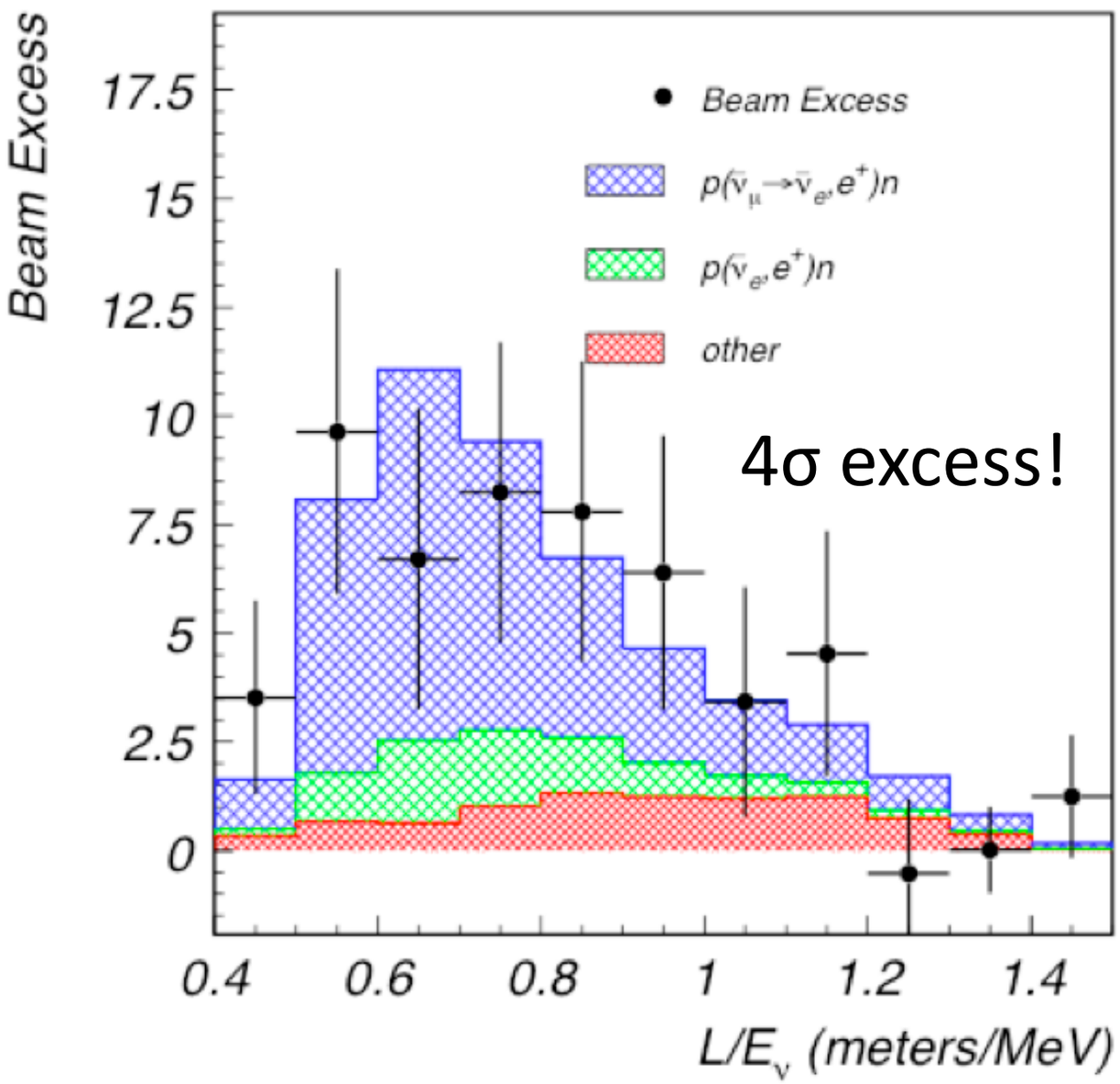
The LSND Anomaly

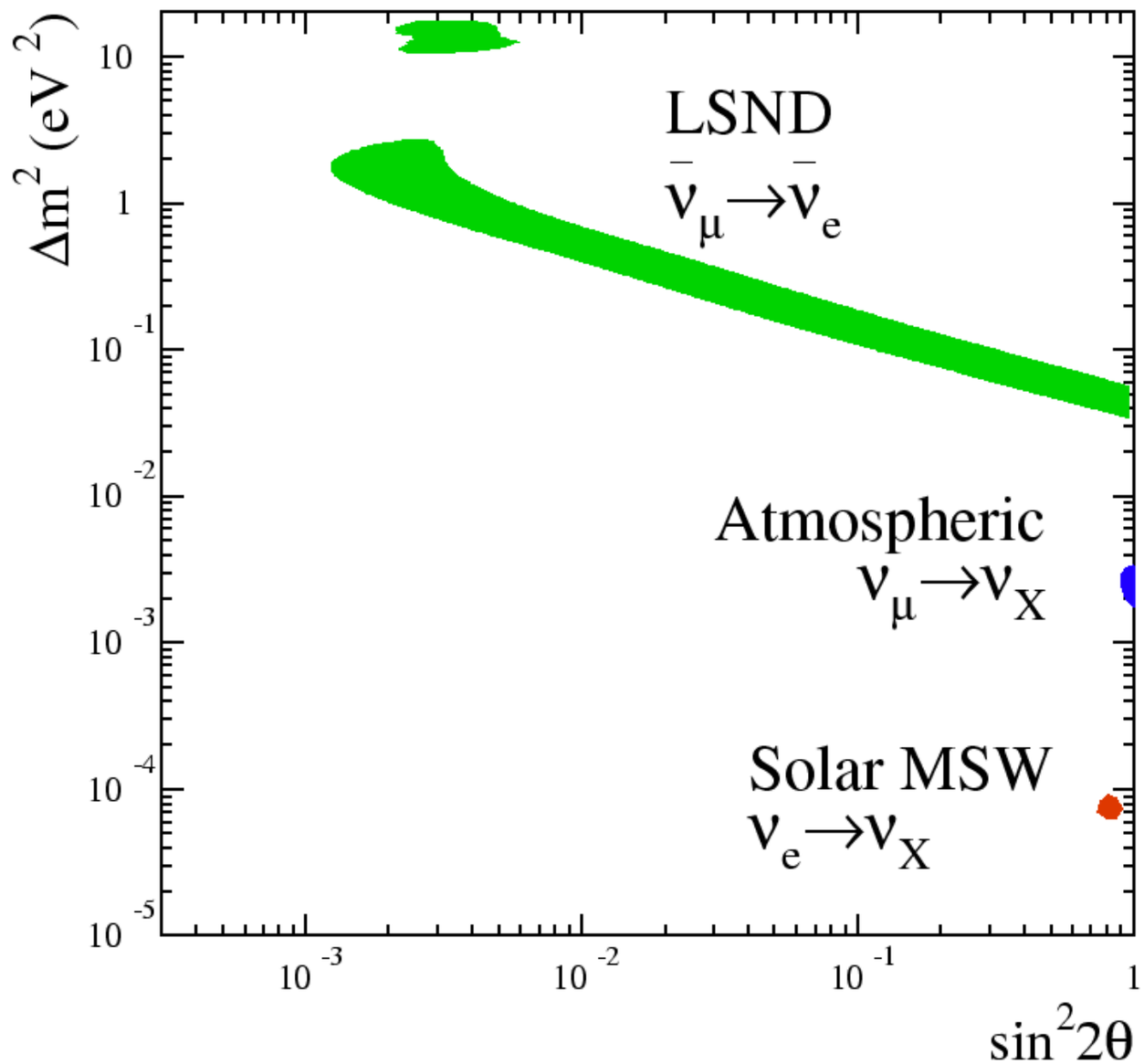




- Single 167 ton liquid scintillator detector (1000 PMTs)
- Used stopped pion beam, $E_\nu \sim 20\text{-}53$ MeV, $L \sim 30$ m

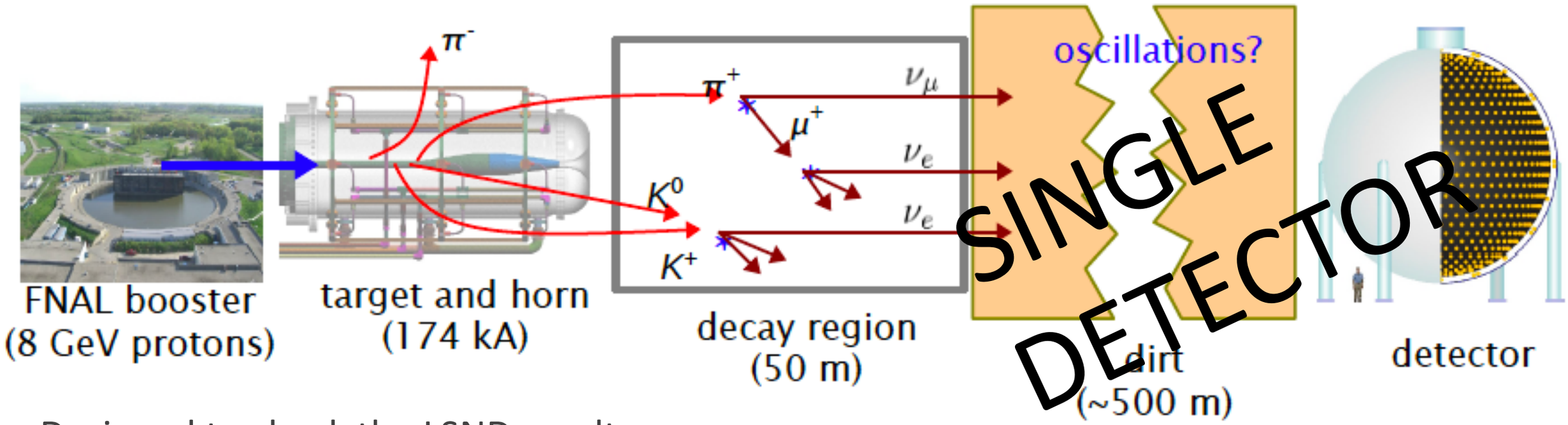
The LSND Anomaly



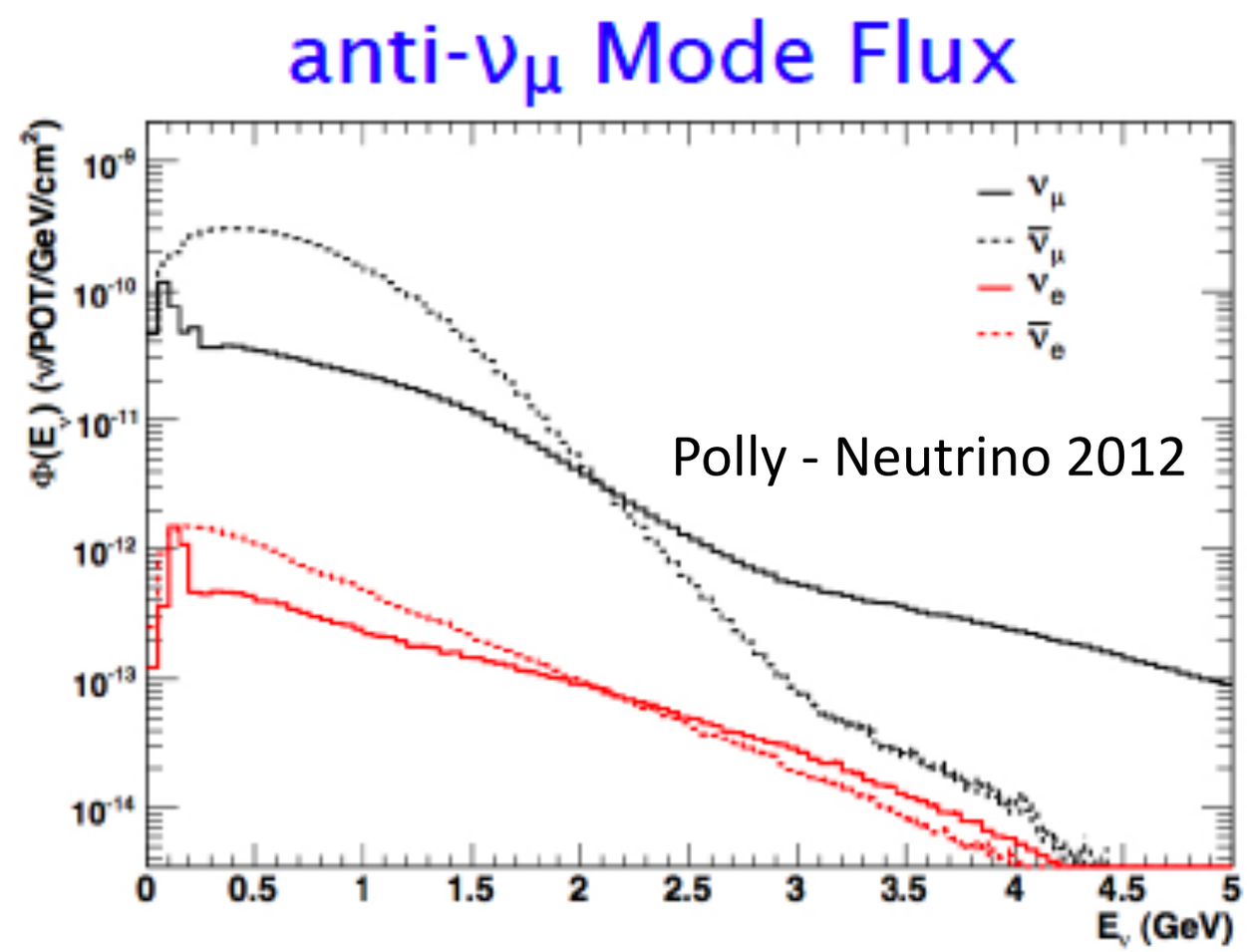


- Taking the LSND result at face value, the most straightforward explanation is the existence of another neutrino.
- Neutrino does not interact via the weak force: STERILE

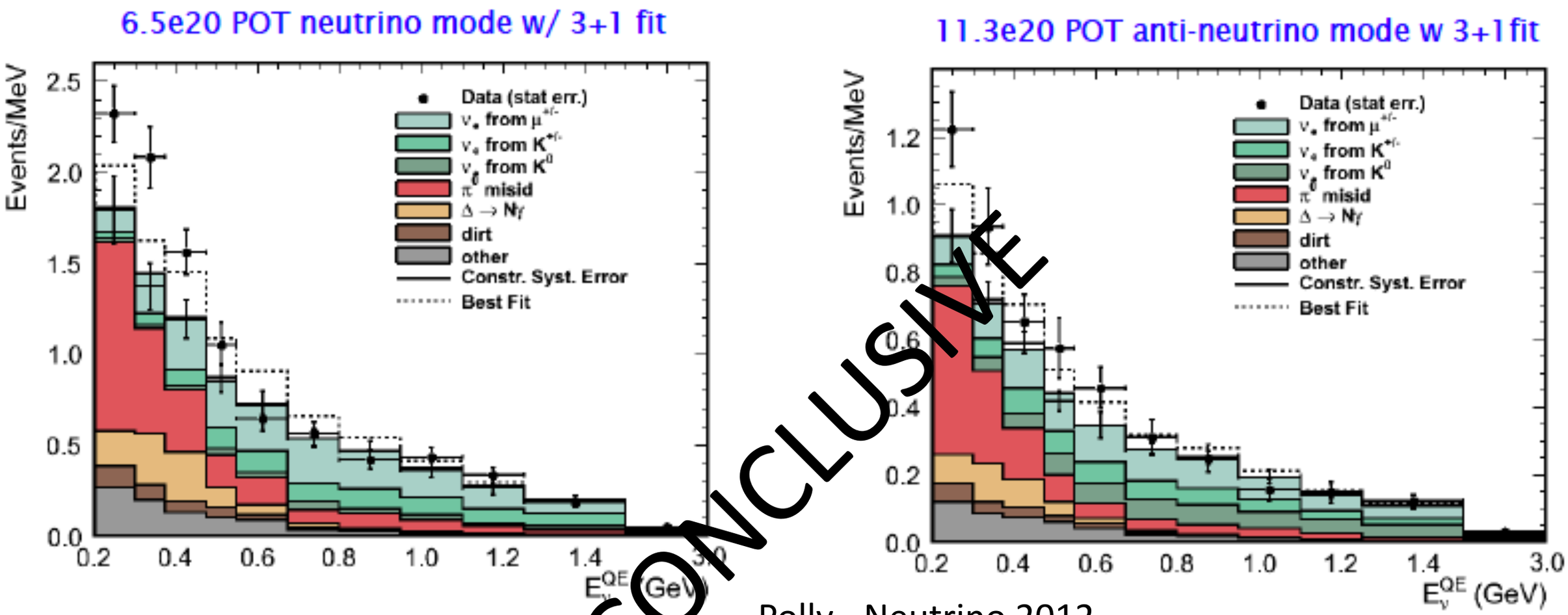
And Along Comes MiniBooNE...



- Designed to check the LSND result
- Average energy of neutrinos ~10x larger than LSND, so x10 increase in cross-section (more neutrino interactions in detector)
- Use of horn increased neutrino flux, allows one to measure rates for either neutrinos or anti-neutrinos
- However, different backgrounds than LSND, eg:
  - wrong-sign neutrinos
  - intrinsic beam ve from K-decays



MiniBooNE Results



Polly - Neutrino 2012

INCONCLUSIVE

- neutrino-mode:
  - excess of ν_e from 200-1250 MeV
  - however, excess is all at lower energies (< 475 MeV) where backgrounds are very large
  - LSND result predicts that excess should be in the range of 600-800 MeV
- Similar results in latest measurement of anti-neutrinos
- Not clear if the low-energy excesses are due to oscillations, some unrecognized background, or something else.

So... Umm... [Scratch Head...]

- We have some hints for $\Delta m^2 \sim 1\ eV^2$ oscillations:
  - LSND: 3.8σ ($\bar{\nu}_\mu \rightarrow \bar{\nu}_e$)
  - MiniBooNE: 3.8σ (combined $\nu_\mu \rightarrow \nu_e$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$)
  - Reactor: 3.0σ ($\bar{\nu}_e \rightarrow \bar{\nu}_e$)
  - Gallium/Sage: 2.7σ (solar $\nu_e \rightarrow \nu_e$)
- On the other hand, many other experiments see no such indications:
  - MiniBooNE restrictions on ν_μ and $\bar{\nu}_\mu$ disappearance
  - MINOS restrictions on $\nu_\mu \rightarrow \nu_s$
  - Super-K restrictions on $\nu_\mu \rightarrow \nu_s$
  - and many more...
- Furthermore, 3+1 models are not very compatible with the positive data. 3+2 models are a bit better, but not great.

So... Umm... [Scratch Head...]

- We have some hints for Δm
  - LSND: 3.8σ (ν
  - MiniBooNE: 3.8σ (combined ν
  - Reactor: 3.0σ (ν
  - Gallium/Sage: 2.7σ (solar ν
- On the other hand, many other experiments see no such indications:
  - MiniBooNE restrictions on ν
  - MINOS restrictions on ν
  - Super-K restrictions on ν
  - and many more...
- Furthermore, 3+1 models are not very compatible with the positive data. 3+2 models are a bit better, but not great.

Need a definitive measurement!

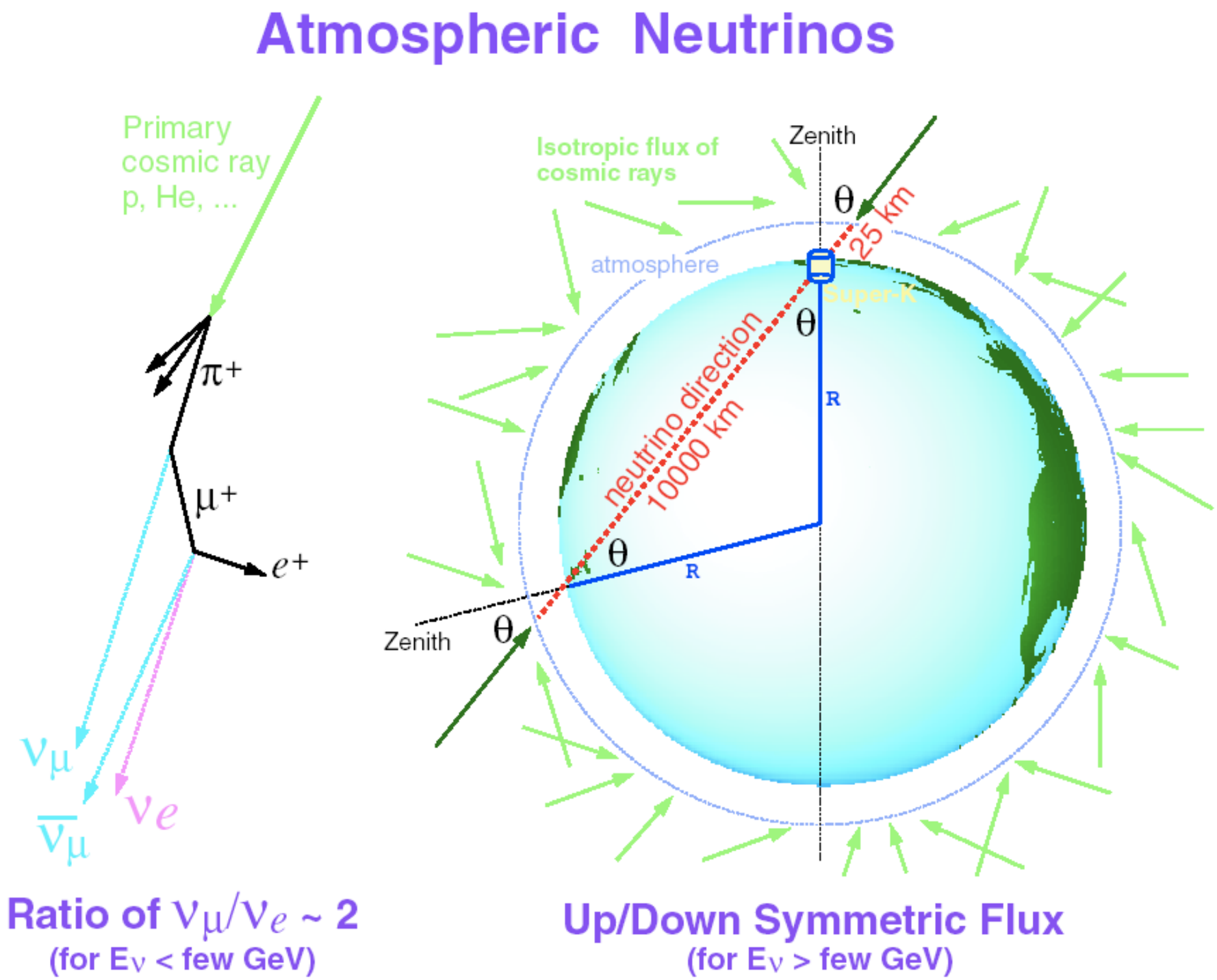
Definitive Measurements?

	Primary Channel	Other osc channels	Definitive sterile?	Other physics	Tech R&D?	Cost	Why worry?	Comment
MicroBooNE (π DIF)	$\nu_\mu \to \nu_e$	$\nu_\mu \to \nu_\mu$		GeV-scale xsec	Yes	$20M	tech, cosmics	Exists!
LAr1-ND (π DIF)	$\nu_\mu \to \nu_e$	$\nu_\mu \to \nu_\mu$		GeV-scale xsec	Yes	$13M	tech, cosmics	
ICARUS@FNAL (π DIF)	$\nu_\mu \to \nu_e$	$\nu_\mu \to \nu_\mu$		GeV-scale xsec	Yes	Under study	tech, cosmics	
TripleLAr@FNAL (π DIF)	$\nu_\mu \to \nu_e$ $\bar{\nu}_\mu \to \bar{\nu}_e$	$\nu_\mu \to \nu_\mu$ $\bar{\nu}_\mu \to \bar{\nu}_\mu$	Probably	GeV-scale xsec	Yes	Under study	tech, cosmics	Work in progress. Anti-nu?
OscSNS (π,μ DAR)	$\bar{\nu}_\mu \to \bar{\nu}_e$	$\nu_e \to \nu_e$	Yes	Supernova xsec	No	$20M	intrinsic $\bar{\nu}_e$	
JPARC MLF (π,μ,K DAR)	$\bar{\nu}_\mu \to \bar{\nu}_e$	$\nu_e \to \nu_e$ $\nu_\mu \to \nu_e$	Not in phase 1	Supernova and 235 MeV ν_μ xsec	No	$5M	intrinsic $\bar{\nu}_e$	Phase 1
IsoDAR-KamLAND (Isotope DAR)	$\bar{\nu}_e \to \bar{\nu}_e$	-	Yes	$\bar{\nu}_e e^-$ (electroweak)	Yes	$30M	timeline, tech	
nuSTORM (μ DIF)	$\nu_e \to \nu_\mu$	$\bar{\nu}_\mu \to \bar{\nu}_\mu$ $\nu_e \to \nu_e$	Yes	GeV-scale xsec	Yes	$300M	timeline, tech, cost	P5 says no

Spitz - Neutrino 2014

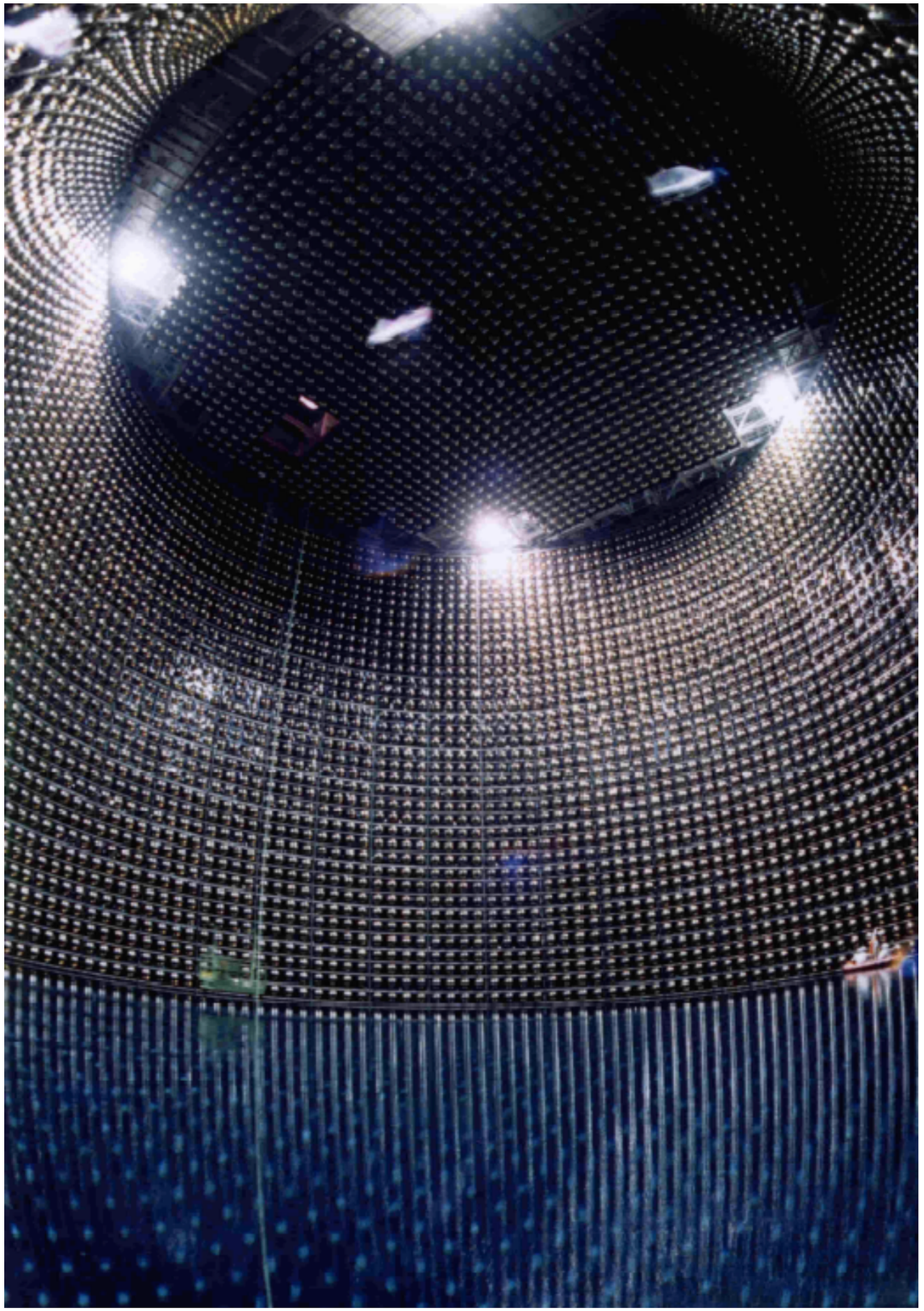
The Atmospheric Neutrino Anomaly

- We expect to see ~2x as many muon neutrinos as electron neutrinos coming from cosmic rays



The Super-Kamiokande Detector (Japan)

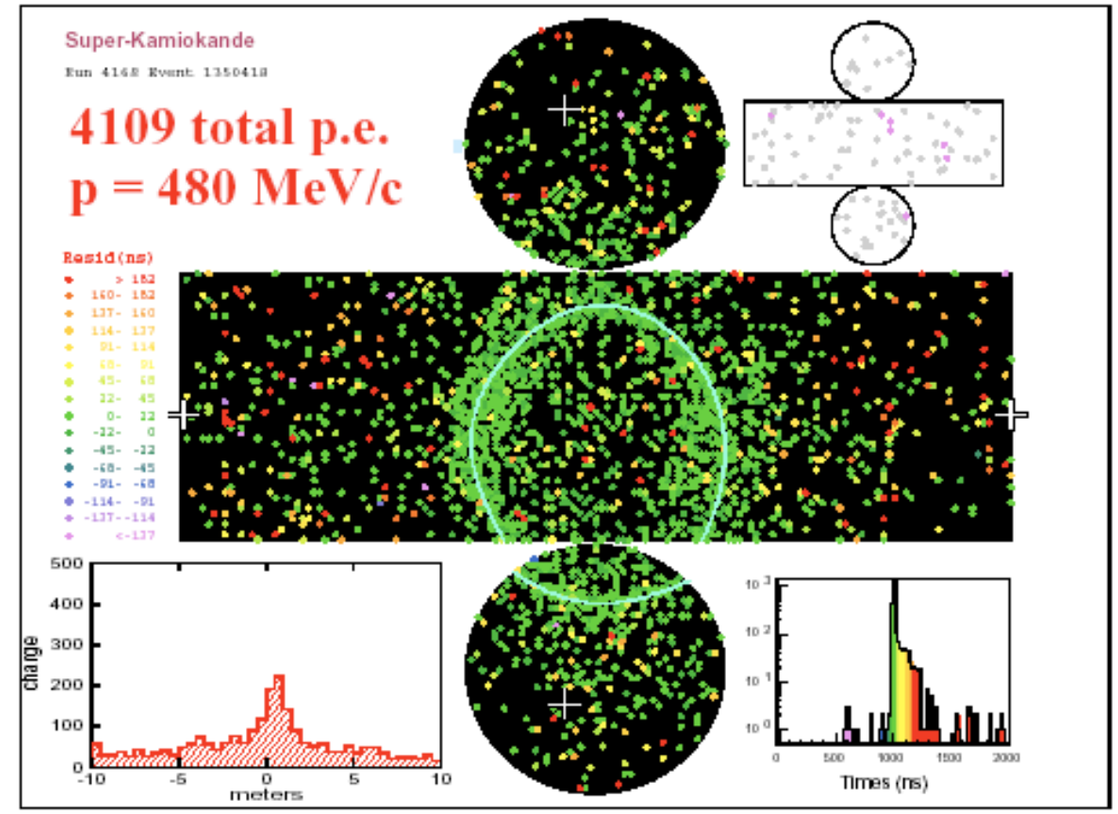
- Located in the Japanese Alps in a zinc mine.
- Covered by 1000m of rock.
- 50 kton water Cherenkov detector (39 m diameter, 42 m tall)
- Over 11,000 50 cm photomultiplier tubes (PMTs) detect faint light signals from neutrino interactions with pure water inside the tank.
- Began operation in 1996.



The Super-Kamiokande Detector (Japan)

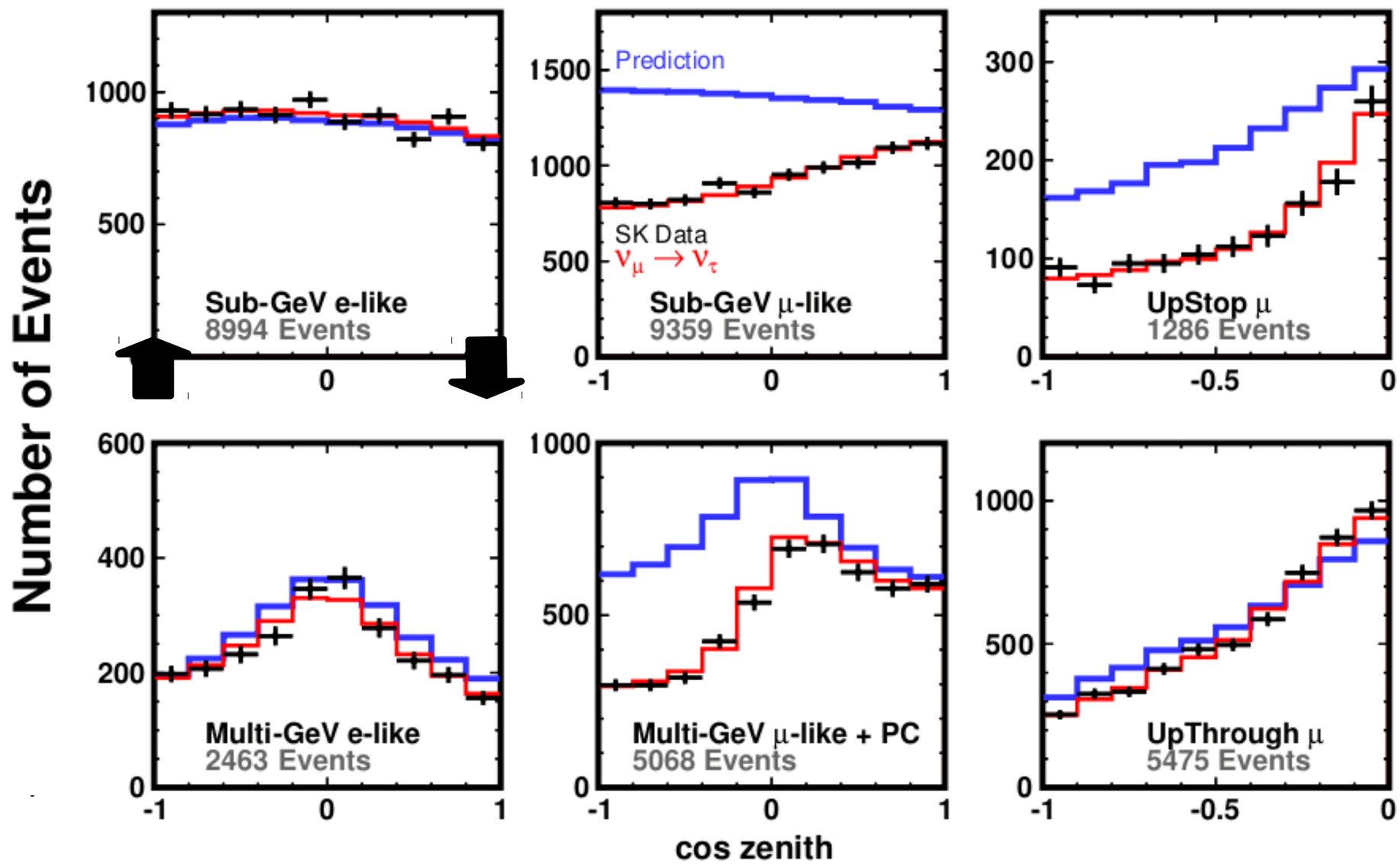
- Neutrino energy is determined by the amount of light captured by the PMTs.
- Super-K is sensitive to a very wide range neutrino energies: 4.5 MeV - 1 TeV!
- Electron and muon neutrino interactions identified (separated) by the shape ("fuzziness") of the Ckov ring.

e–like



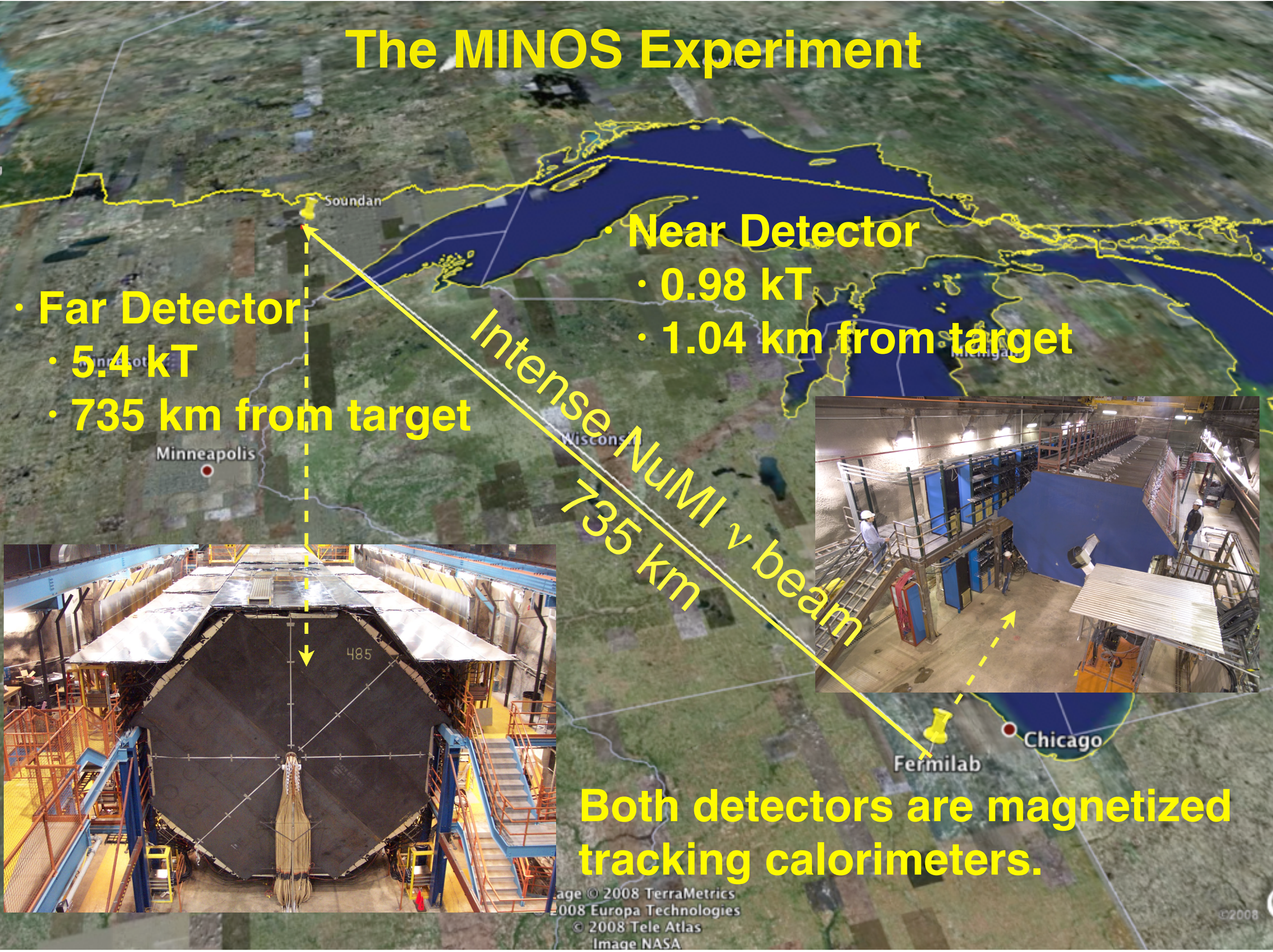
Neutrino Oscillations from Super-K

- Number of detected electron neutrino events agree very well with predicted number.
- Number of detected muon neutrino events strongly disagrees with the predicted number.
- Explained by $\nu_\mu \rightarrow \nu_\tau$ oscillations!



R. Wendell, Neutrino 2014

The MINOS Experiment

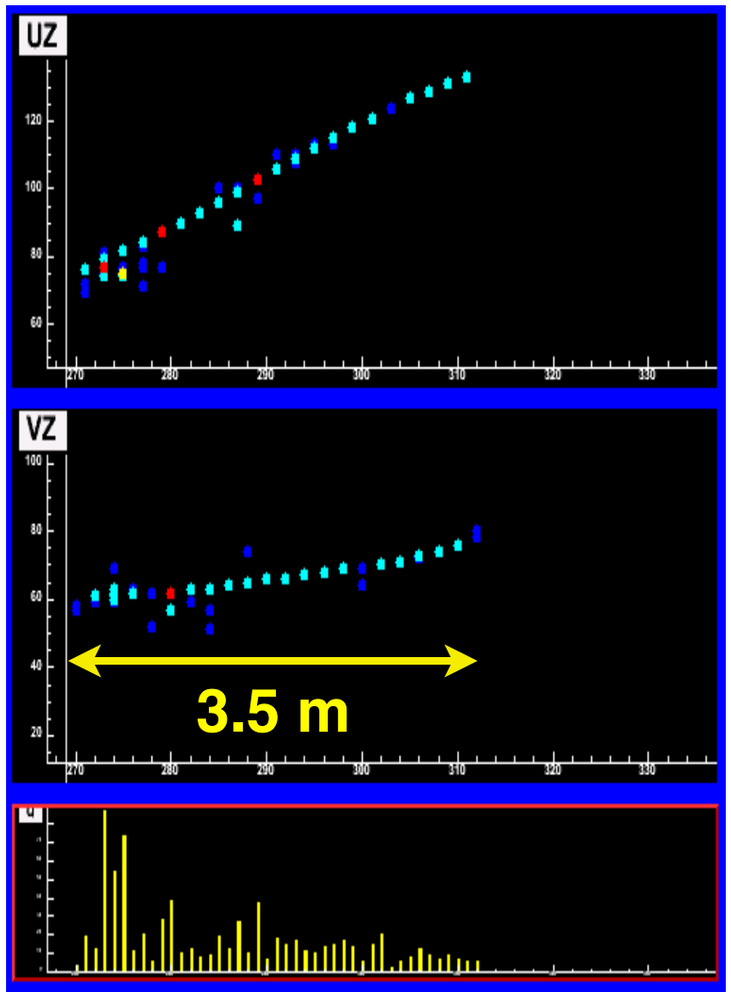


- Far Detector
  - 5.4 kT
  - 735 km from target
- Near Detector
  - 0.98 kT
  - 1.04 km from target

Both detectors are magnetized tracking calorimeters.

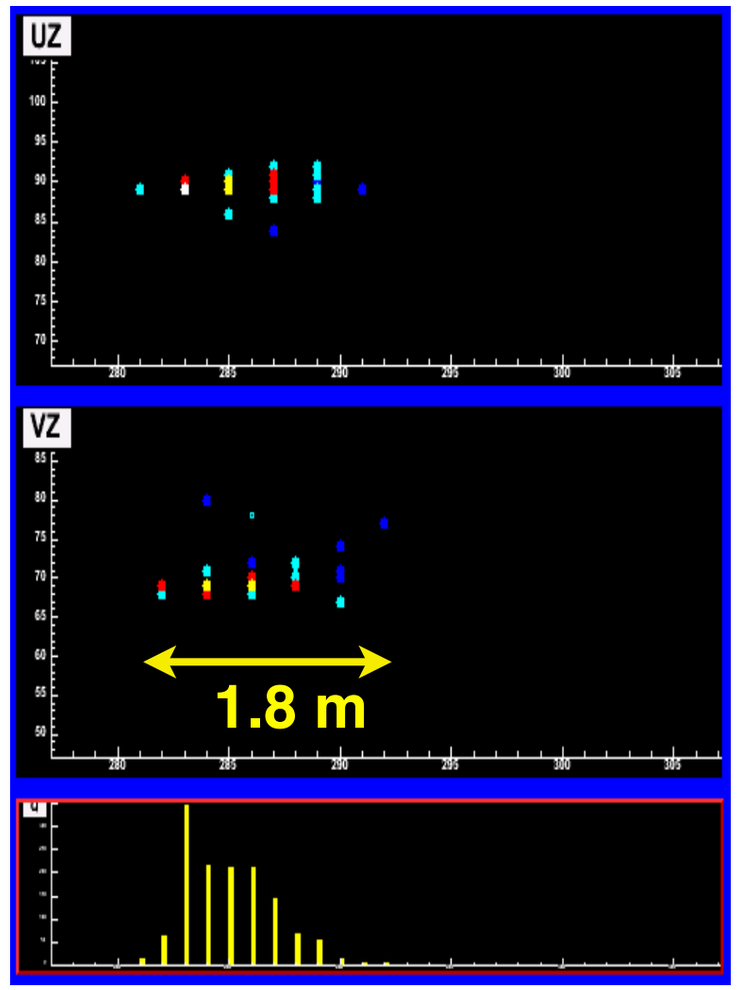
Identifying Events in MINOS

ν_μ CC event



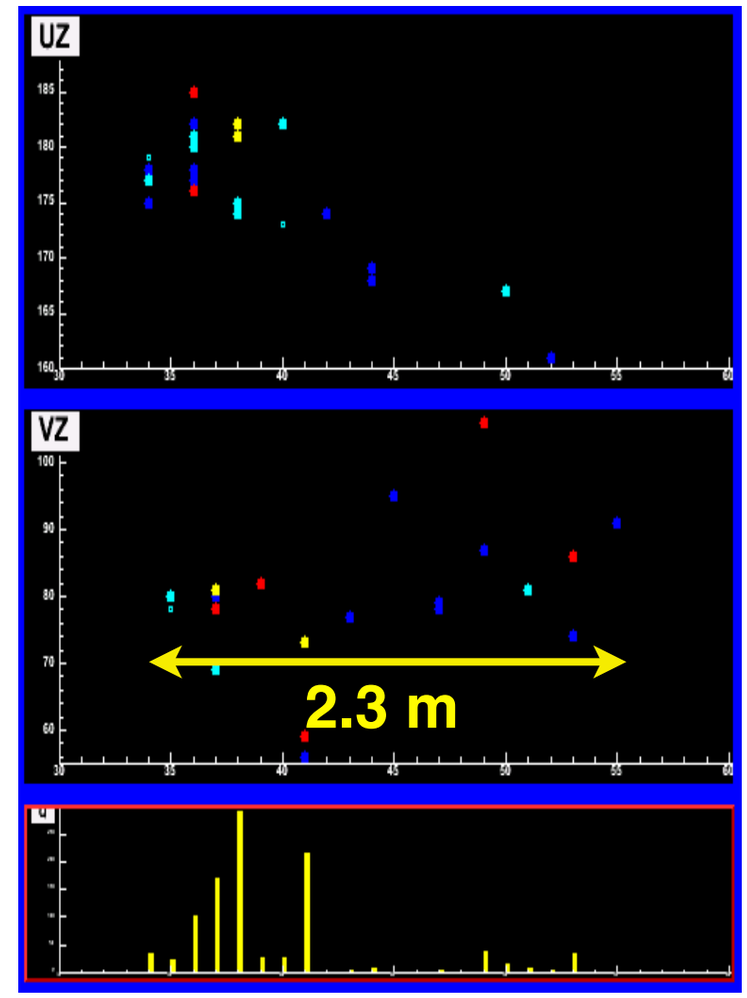
Long μ track + shower at vertex

ν_e CC event



Short event with EM shower profile.

NC event

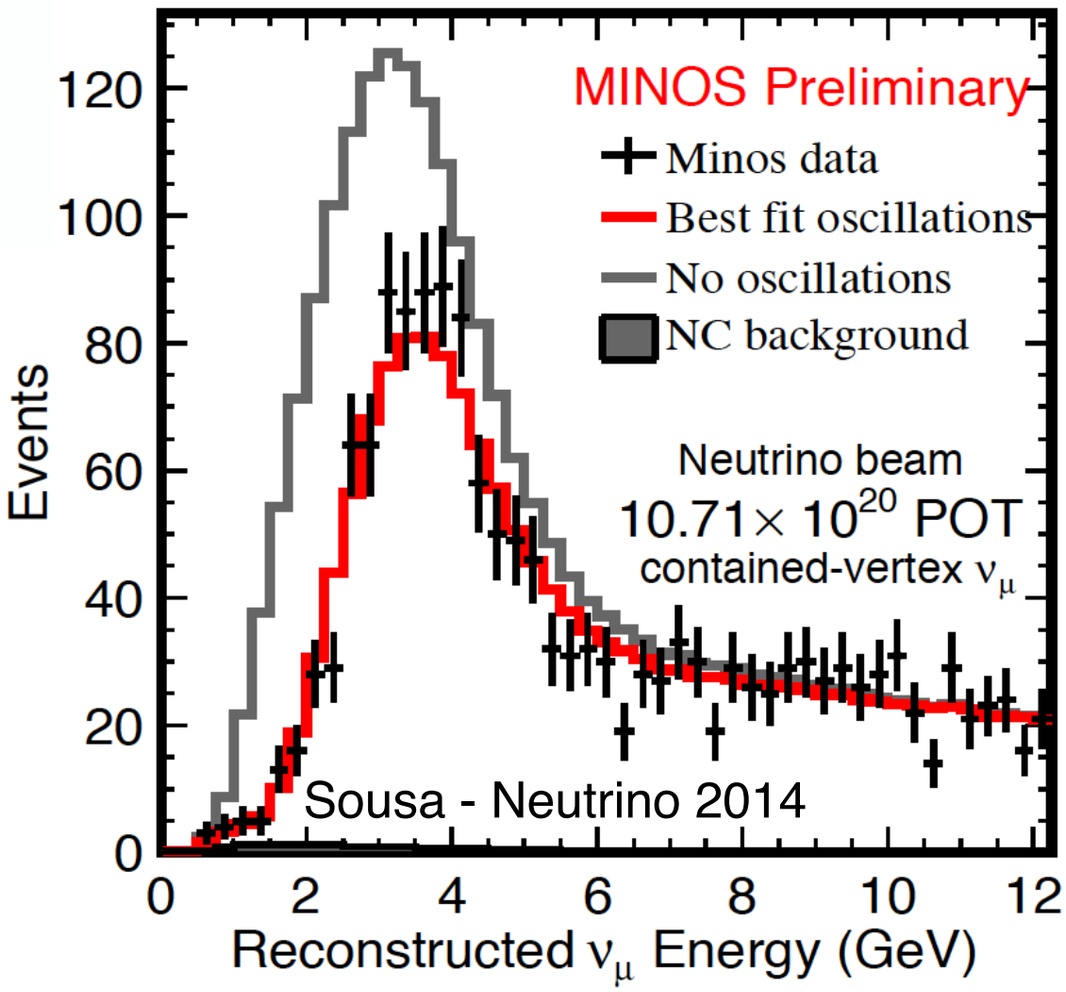


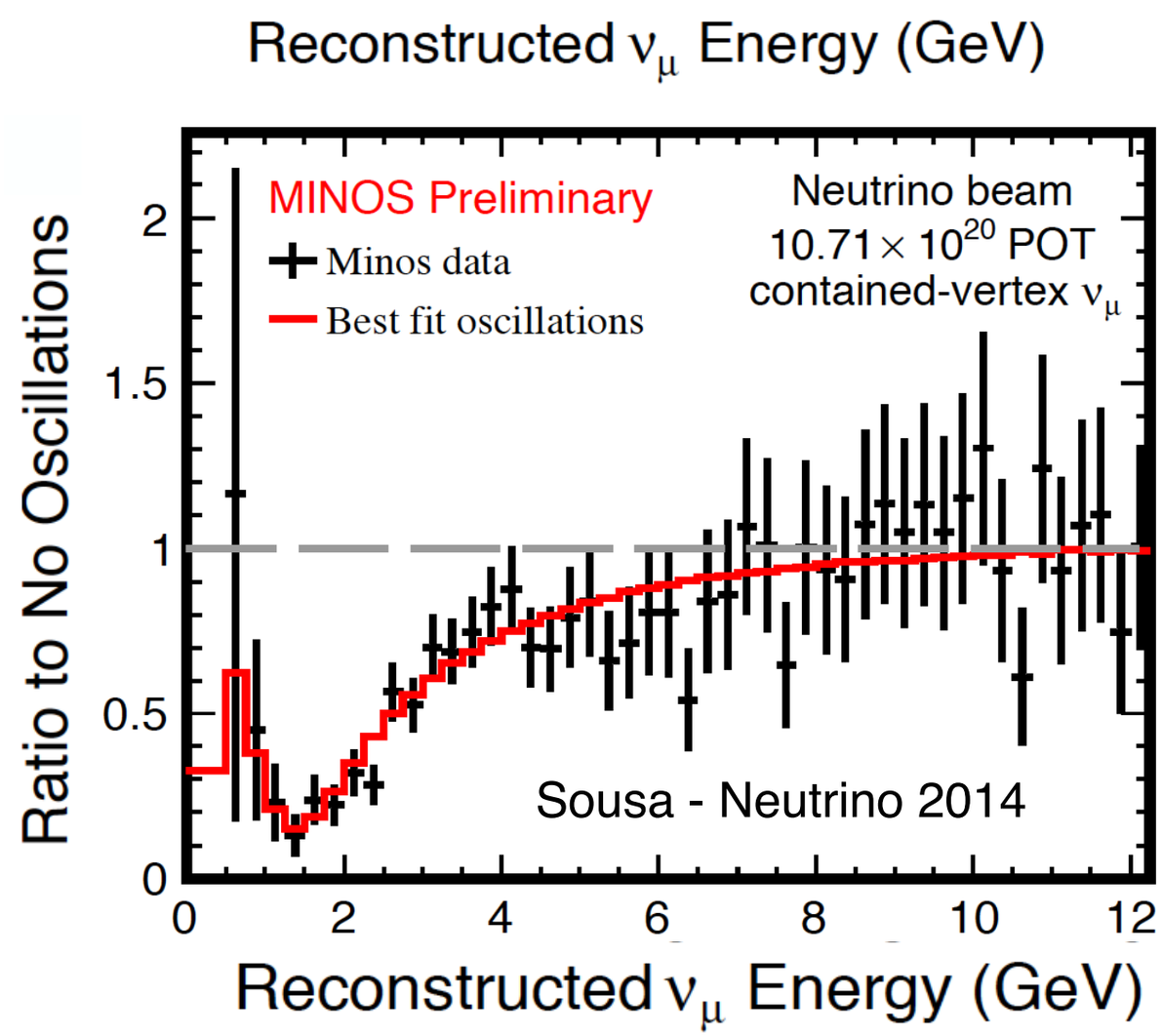
Short, diffuse event.

E_μ determined from curvature and/or range,
E_{shower} determined from MC tuned to external data.

MINOS Results

Neutrinos





Three-Flavor Oscillations Best Fit

Inverted Hierarchy

$$|\Delta m^2_{32}| = 2.37^{+0.11}_{-0.07} \times 10^{-3} \mathrm{eV}^2$$

$$\sin^2\theta_{23} = 0.43^{+0.19}_{-0.05}$$

$$0.36 < \sin^2\theta_{23} < 0.65 \ (90\% \ \mathrm{C.L.})$$

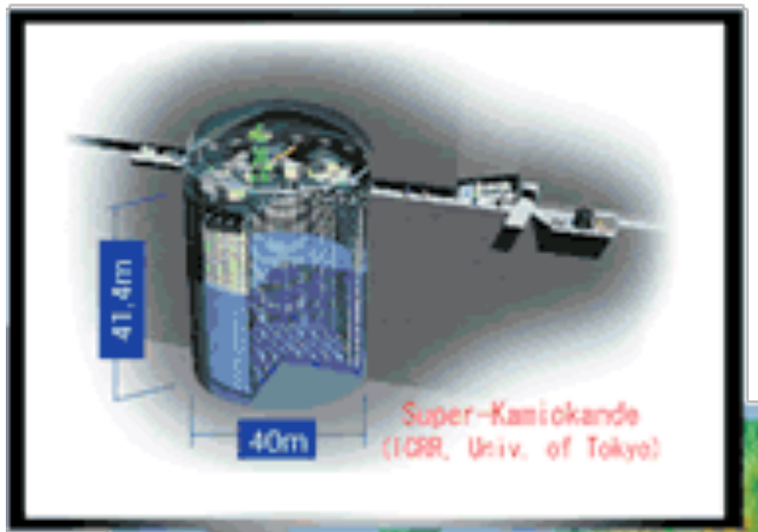
Normal Hierarchy

$$|\Delta m^2_{32}| = 2.34^{+0.09}_{-0.09} \times 10^{-3} \mathrm{eV}^2$$

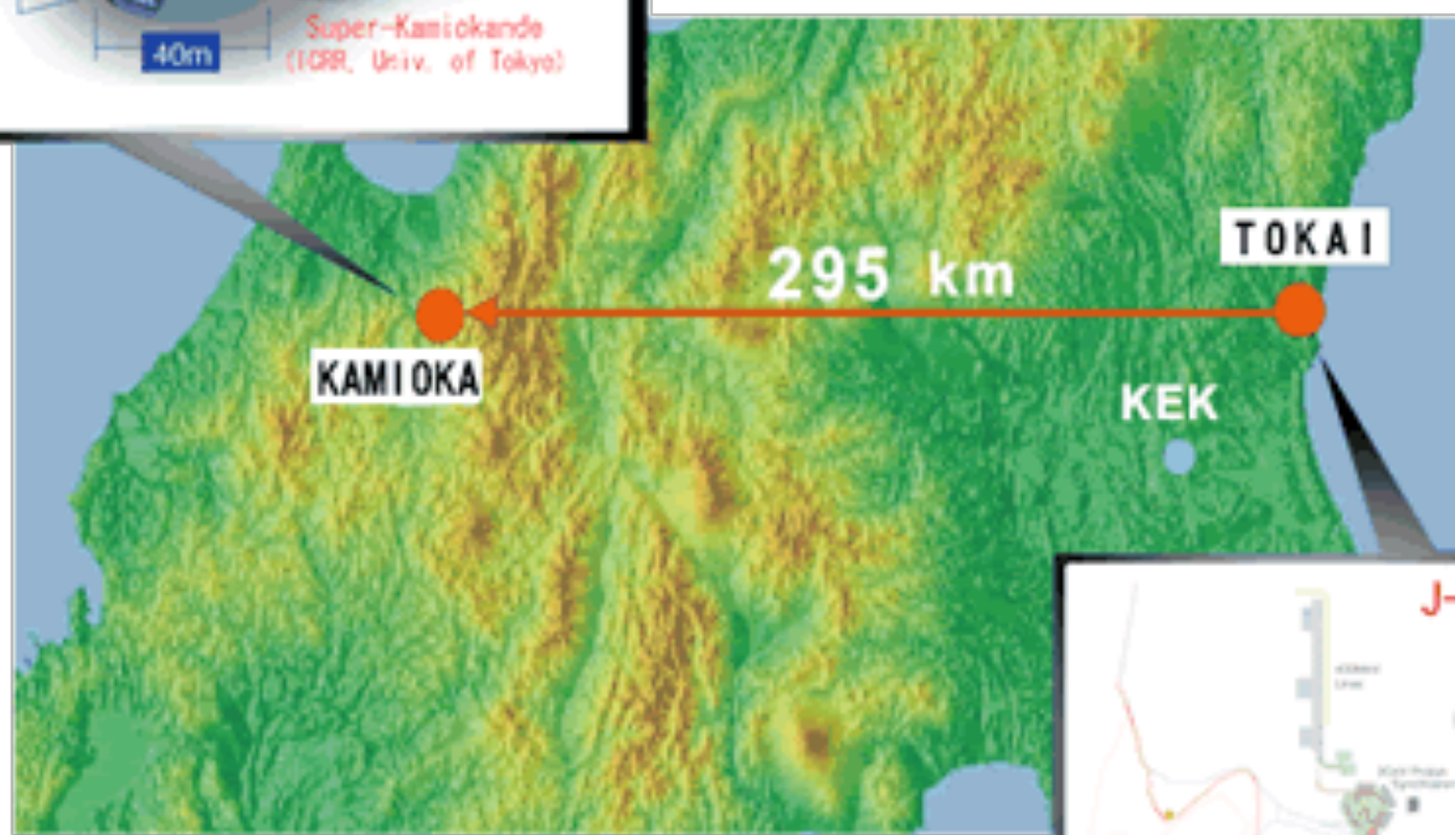
$$\sin^2\theta_{23} = 0.43^{+0.16}_{-0.04}$$

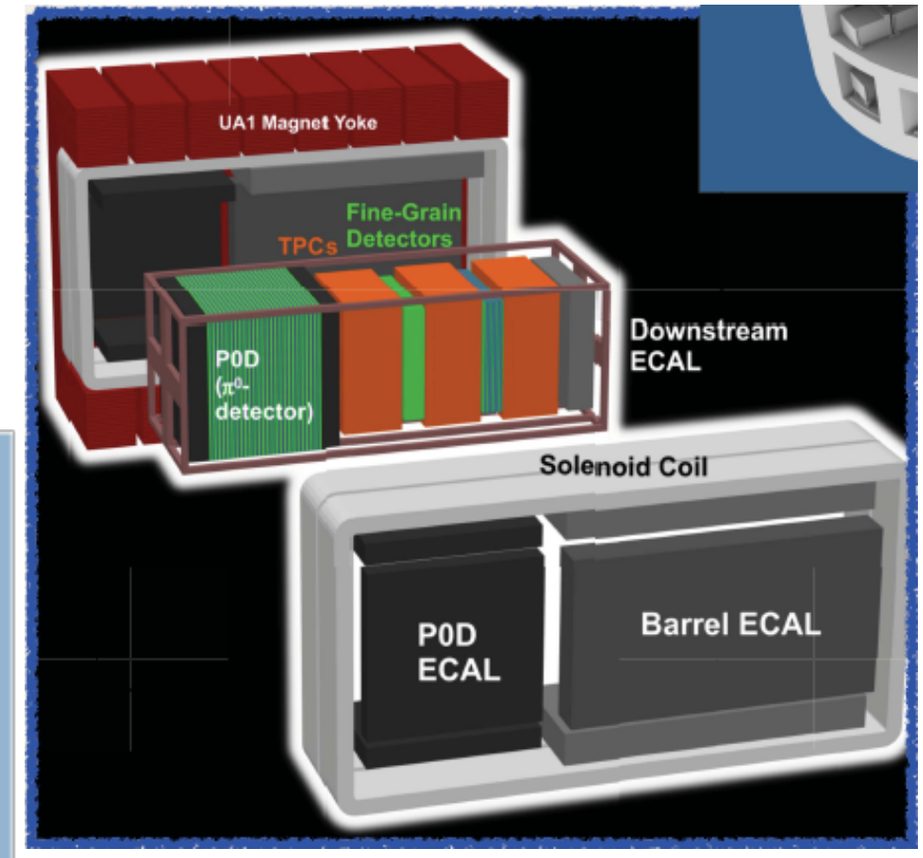
$$0.37 < \sin^2\theta_{23} < 0.64 \ (90\% \ \mathrm{C.L.})$$

The Tokai to Kamioka (T2K) Experiment



Use Super-K as far detector





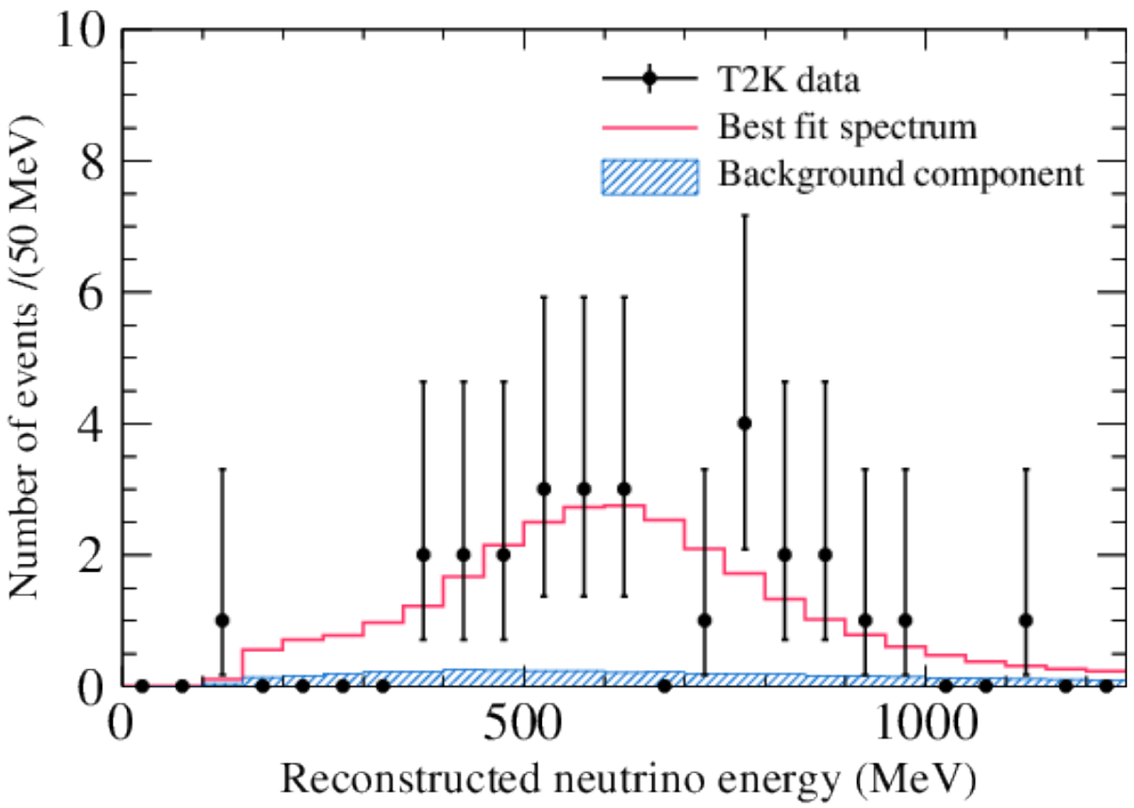
High resolution near detector

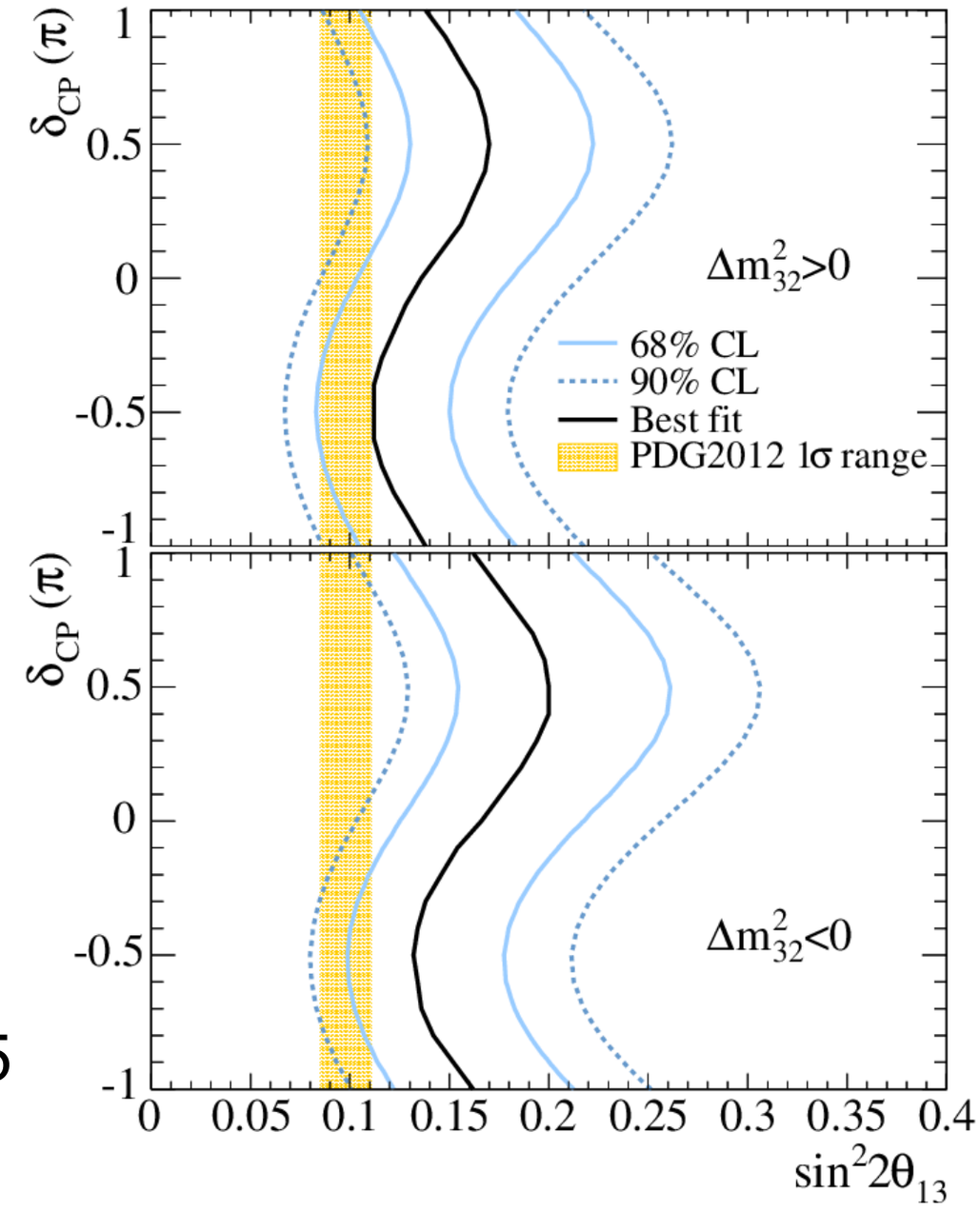
T2K Goals

- Primary goals:
  - Observe $\nu_\mu \rightarrow \nu_e$ oscillations and measure mixing angle θ_{13}
  - Search for CP violation in the neutrino sector.
- Secondary goals:
  - Improve measurement of $\sin^2(2\theta_{23})$
  - Search for sterile neutrinos
  - Measure neutrinos from galactic supernovae
  - Cross-section measurements using ND
- Currently taking data and beginning to show exciting results.

Phys. Rev. Lett. 112, 061802 (2014)

T2K observation of ν_e Appearance





4.92 ± 0.55 events expected background

28 events observed

21.6 events expected @ $\sin^2 2\theta_{13} = 0.1$

$\delta_{CP} = 0$, $\sin^2\theta_{23} = 0.5$

7.3 σ significance for non-zero θ_{13}

<u>First ever observation (>5σ) of an explicit ν appearance channel</u>

Walter - Neutrino 2014

The NuMI Off-Axis ν_e Appearance (NOνA) Experiment

Ash River, MN

14 kton, 810 km, 14.6 mrad off-axis

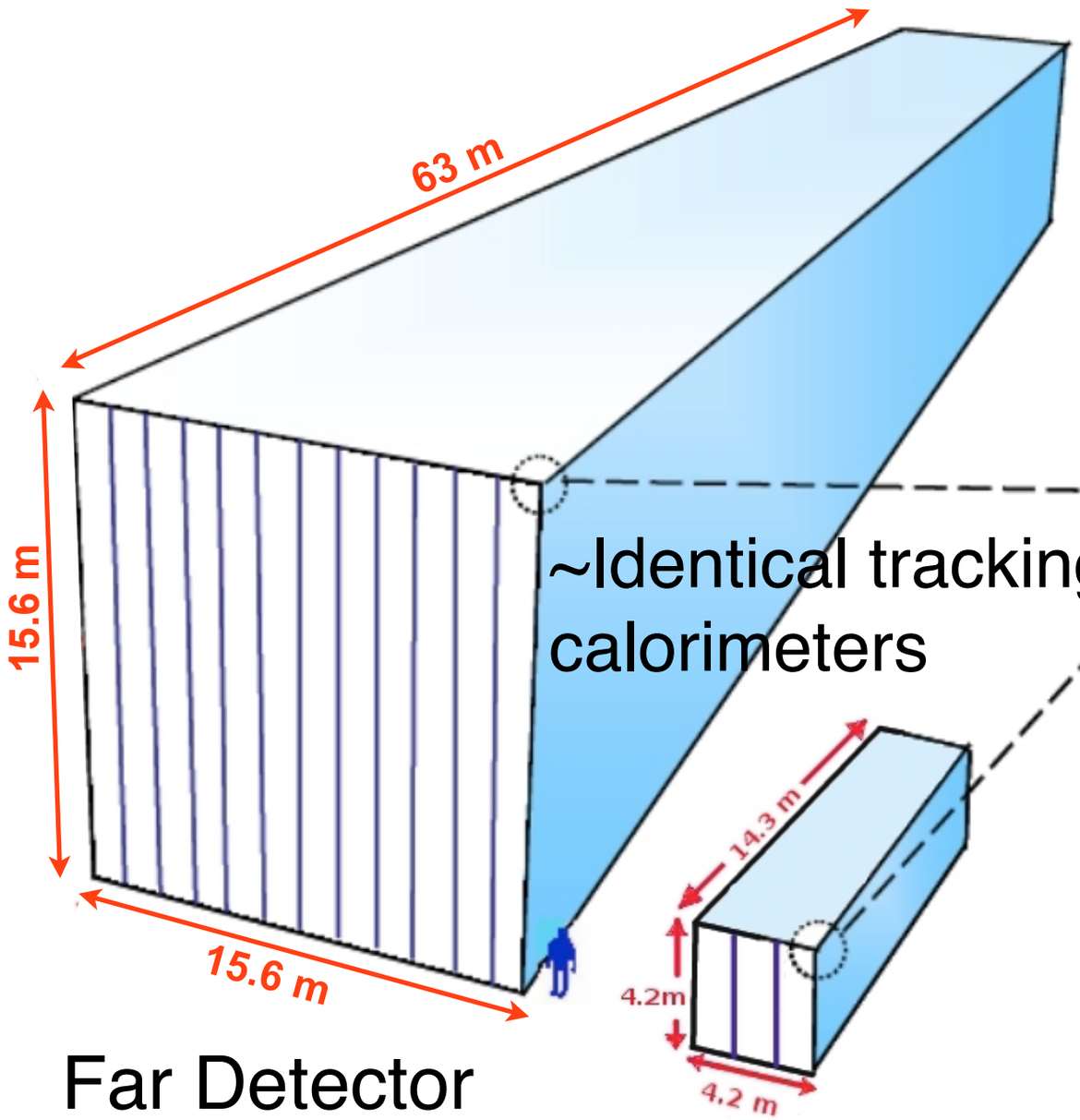
Existing NuMI Beam from FNAL

Upgrade from 330 kW to 700 kW in progress

- **Primary Goals:**
- **Observe $\nu_\mu \rightarrow \nu_e$ and measure the mixing angle θ_{13} .**
- **Resolution of the neutrino mass hierarchy**
- **Search for CP violation in the neutrino sector**
- **Improved measurements of $\sin^2(2\theta_{23})$ to within a few percent.**
- **Determine the octant of θ_{23}**

Nearly identical 330 ton detector located at FNAL, 14 mrad off-axis & 1 km from source will measure ν spectrum before oscillations occur.

The NOνA Detectors



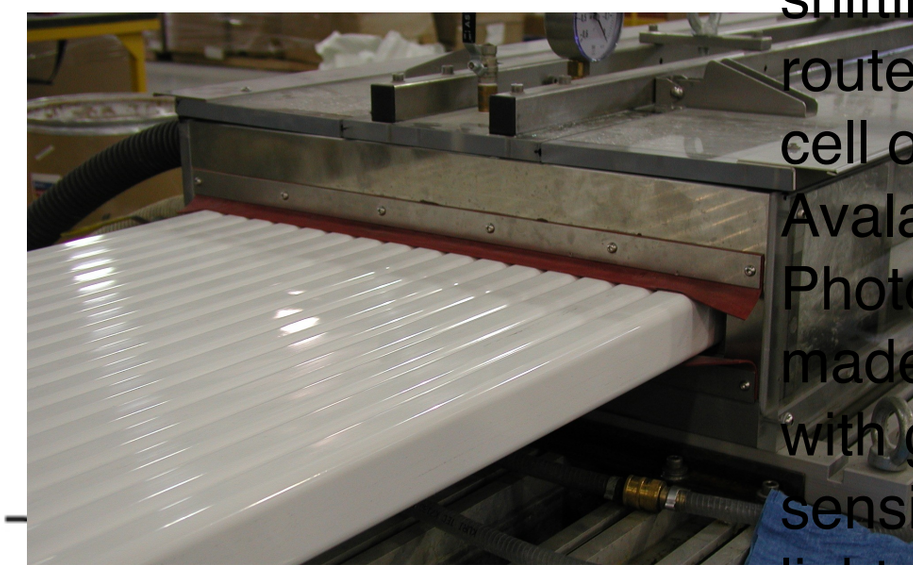
~Identical tracking calorimeters

Far Detector

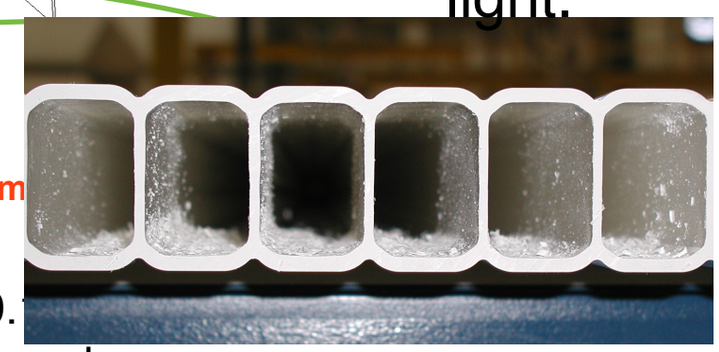
Near Detector

Tracking calorimeter:

- ~70% active
- muon energy resolution (range): few %
- Moliere radius is ~2.5 cell widths
- EM shower max at ~5 X_0

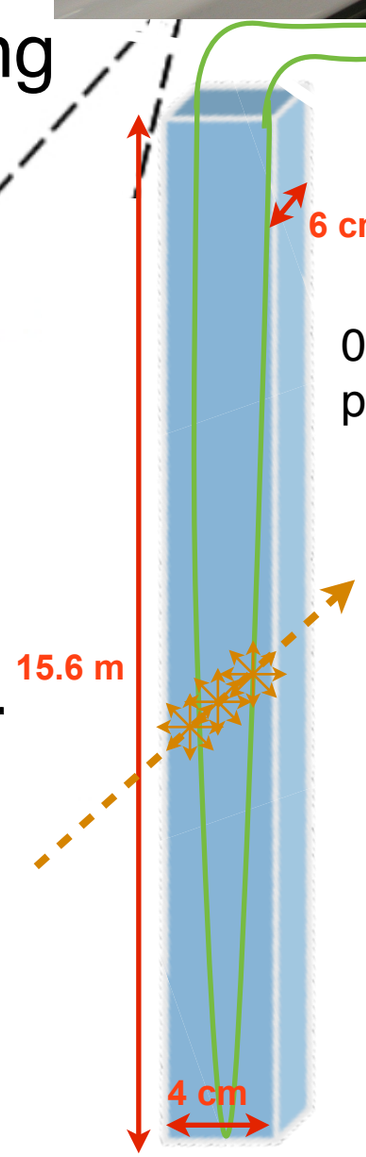


Wavelength-shifting fibers routed to a single cell on an Avalanche Photodiode (APD) made of materials with greatest sensitivity to green light.



0.

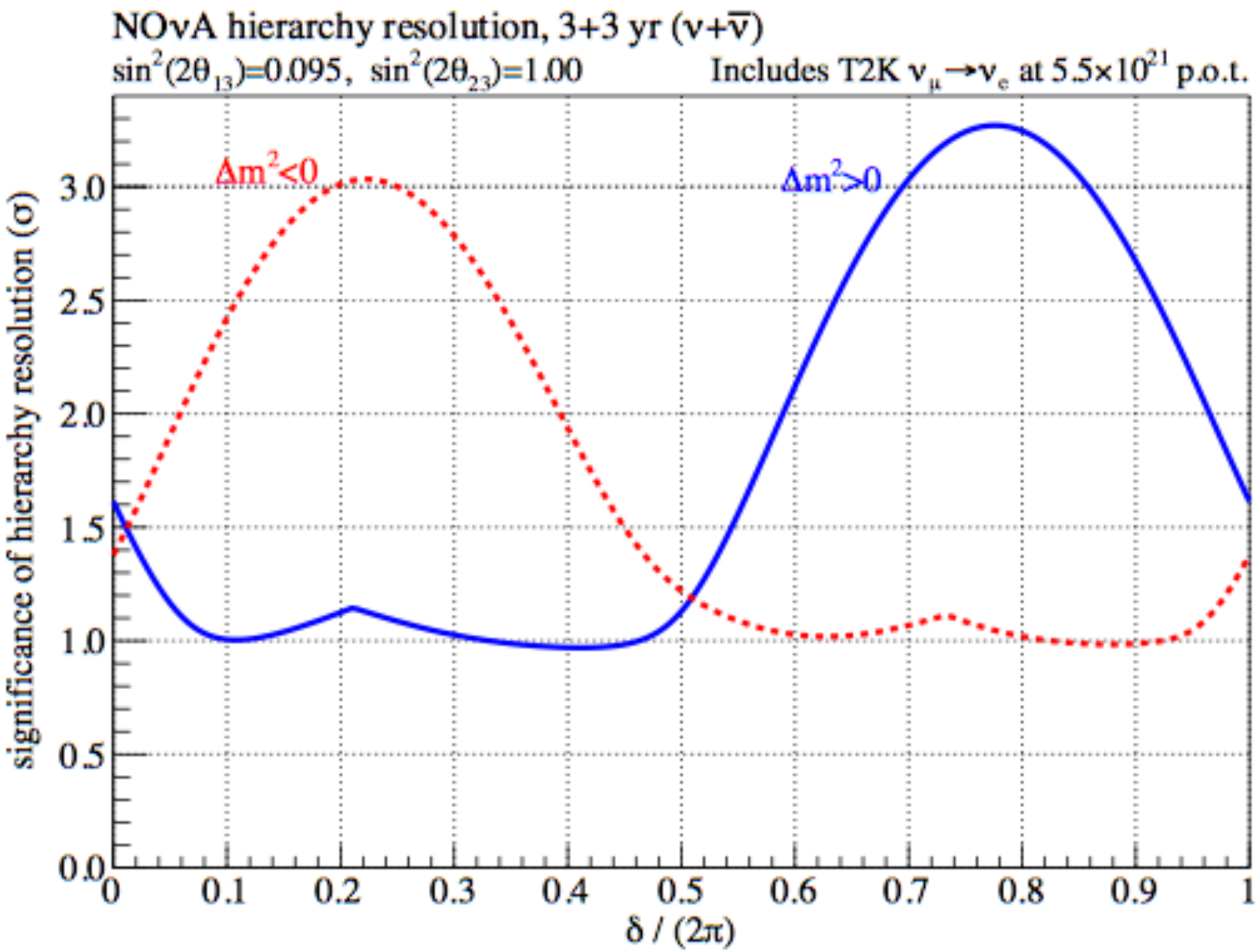
per plane.



Scintillation light (mostly blue wavelengths) emitted isotropically and captured in wavelength shifting fibers that convert blue light to green.

There are ~**344000 channels** in the NOvA Far Detector!

NOvA Sensitivities

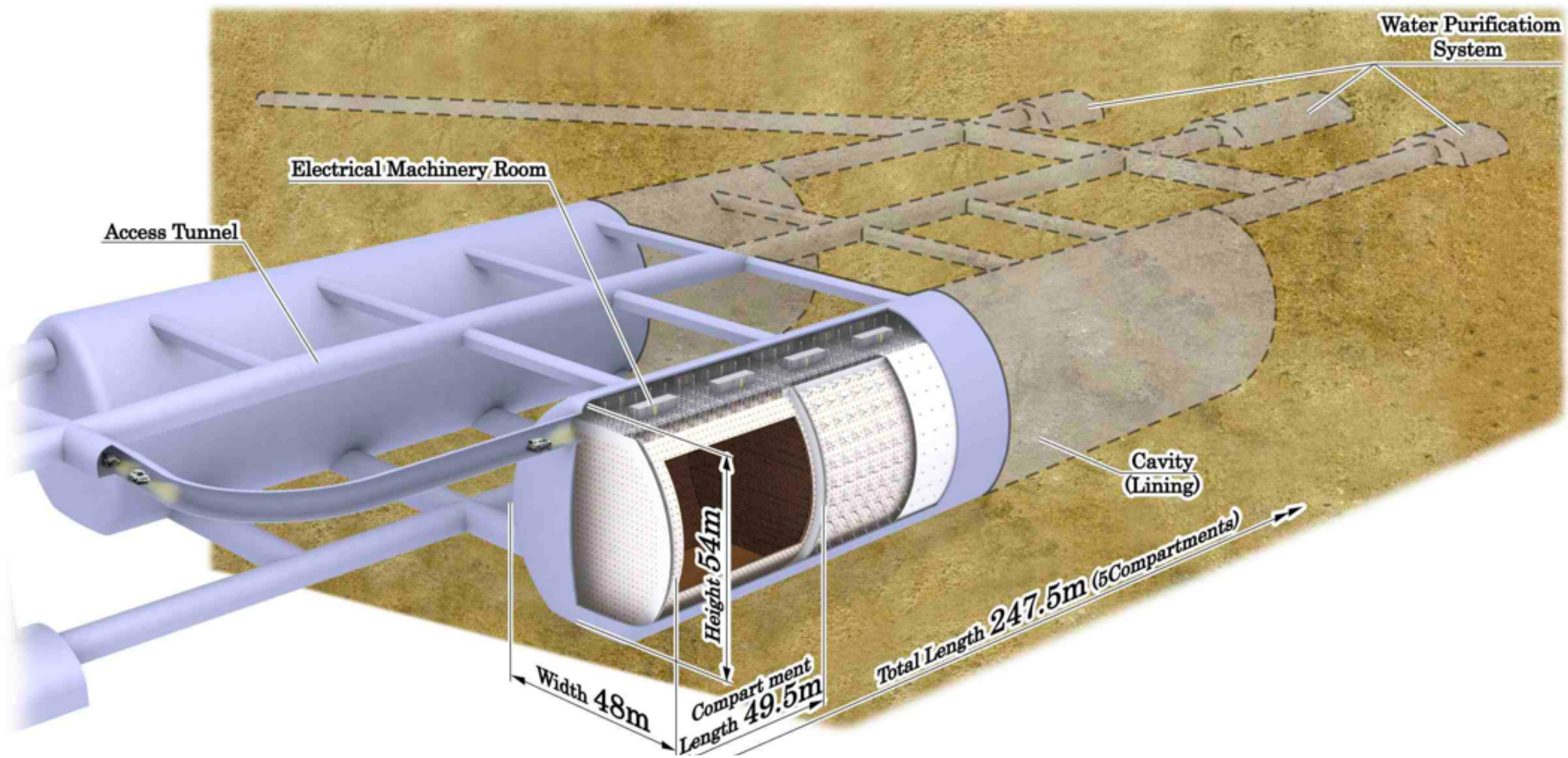


Looking to YOUR Future…

Next Generation of Neutrino Oscillation Experiments

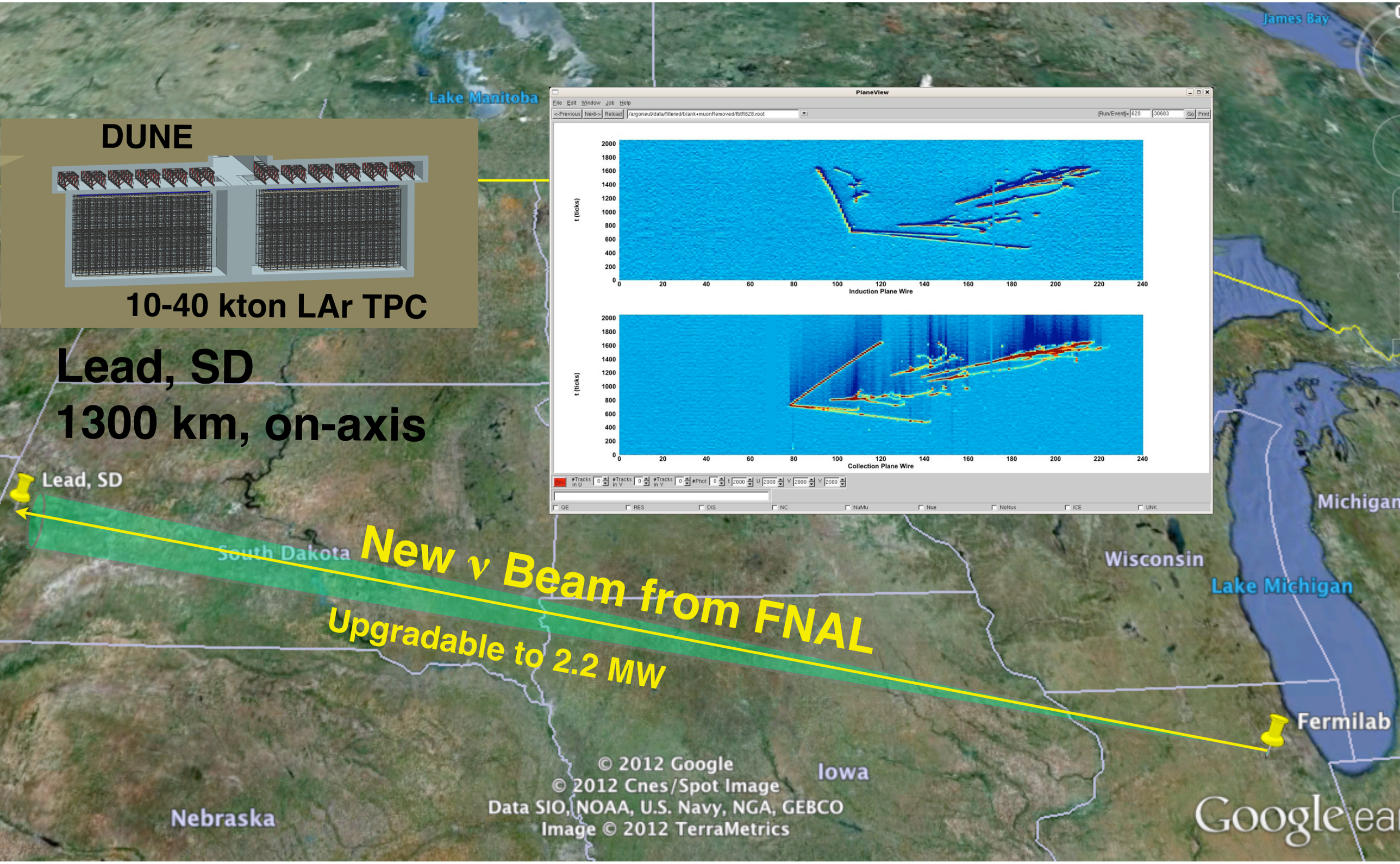
- Detectors will be HUGE:
  - MEGATON-scale H_2O Ckov detector (Japan, Europe)**
  - 10-50 kton LAr TPC detector (USA, Europe, Japan, India, Japan)**
  - 50 kton magnetized Fe calorimeter (India)
  - 20 kton liquid scintillator detector (China, S. Korea)
- Primary goals:
  - Precise determination of all neutrino oscillation parameters
  - Determination of the mass-hierarchy (guaranteed)
  - Determination of the CP-violating angle (could cover >90% of allowed values)**
- Secondary goals:
  - Search for proton decay
  - Measure neutrino spectra from galactic supernovae
  - Geoneutrinos
  - Much much more

Hyper Kamiokande (Japan)



- 1 Megaton (~20x larger than SuperK!)
- 99000 20” PMTs
- 295 km baseline
- Could also improve proton-decay limits by ~10x

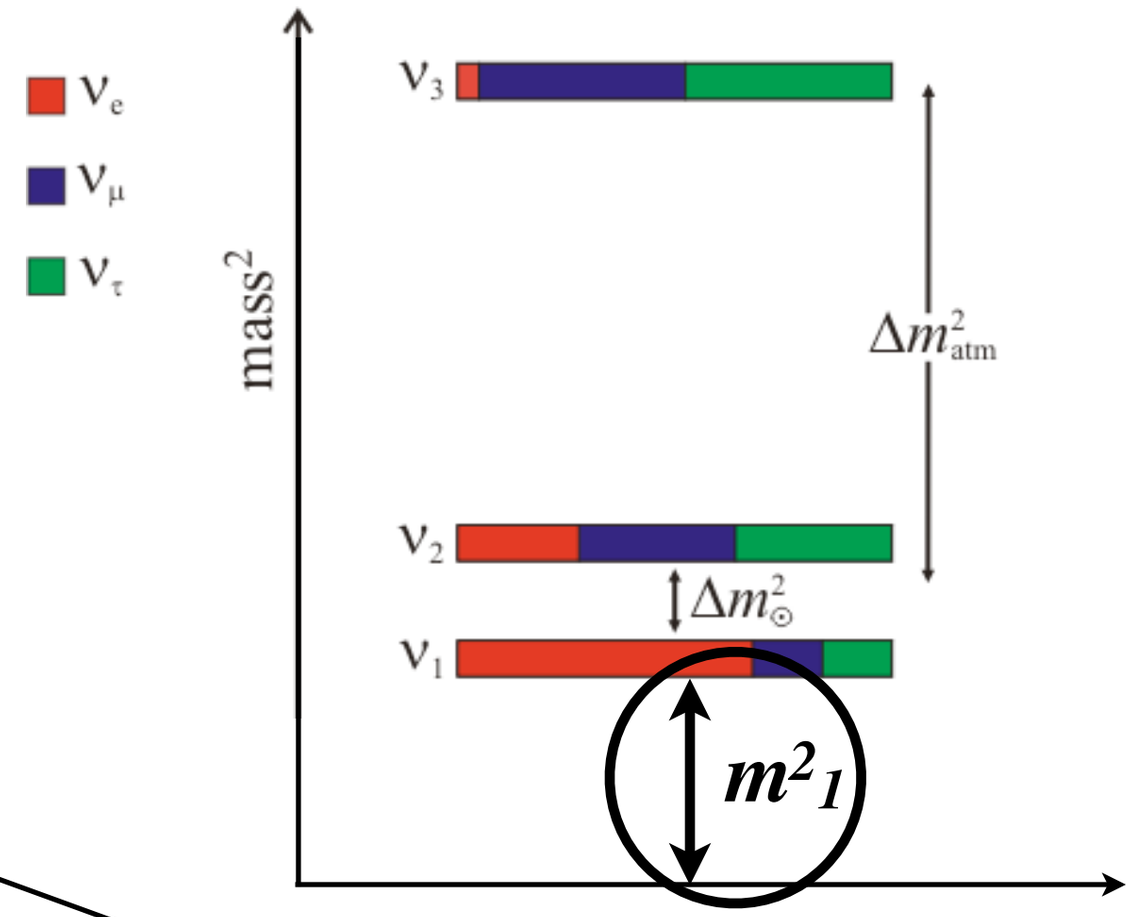
The Long-Baseline Neutrino Facility (USA)



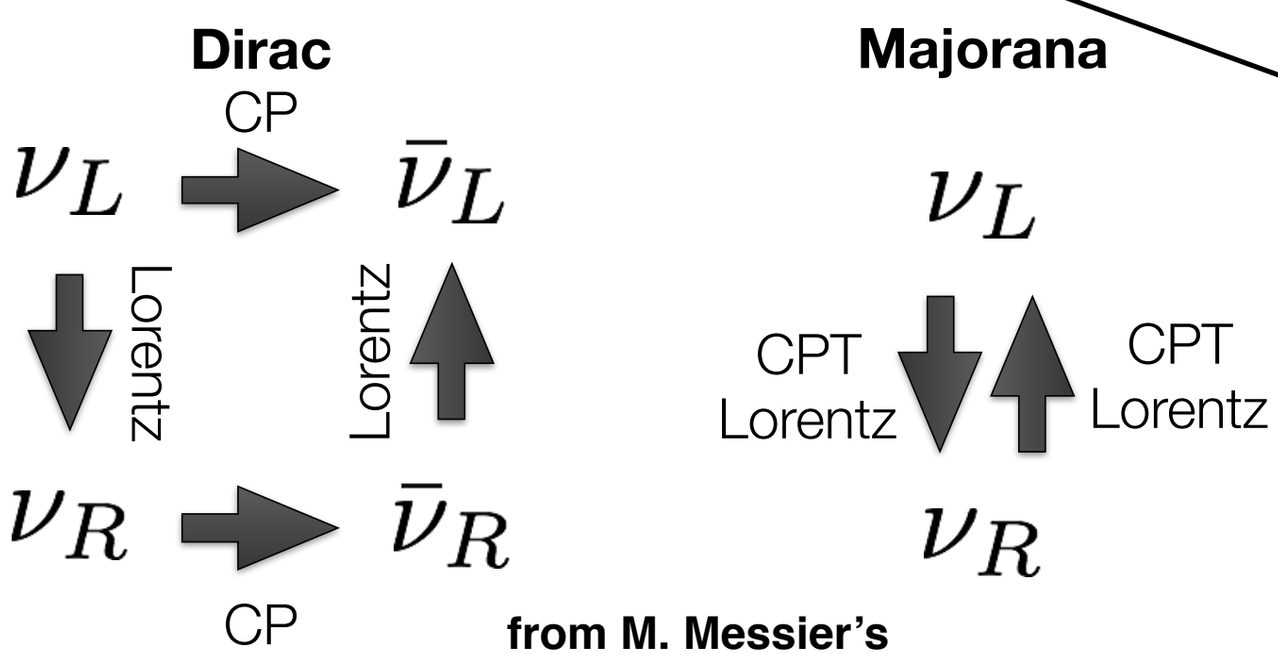
Paths to Measuring Neutrino Mass

Paths to Measuring Neutrino Mass

- Direct Measurements
  - Time-of-flight
  - Beta-decay
- Indirect Measurements
  - 0νββ
  - cosmology

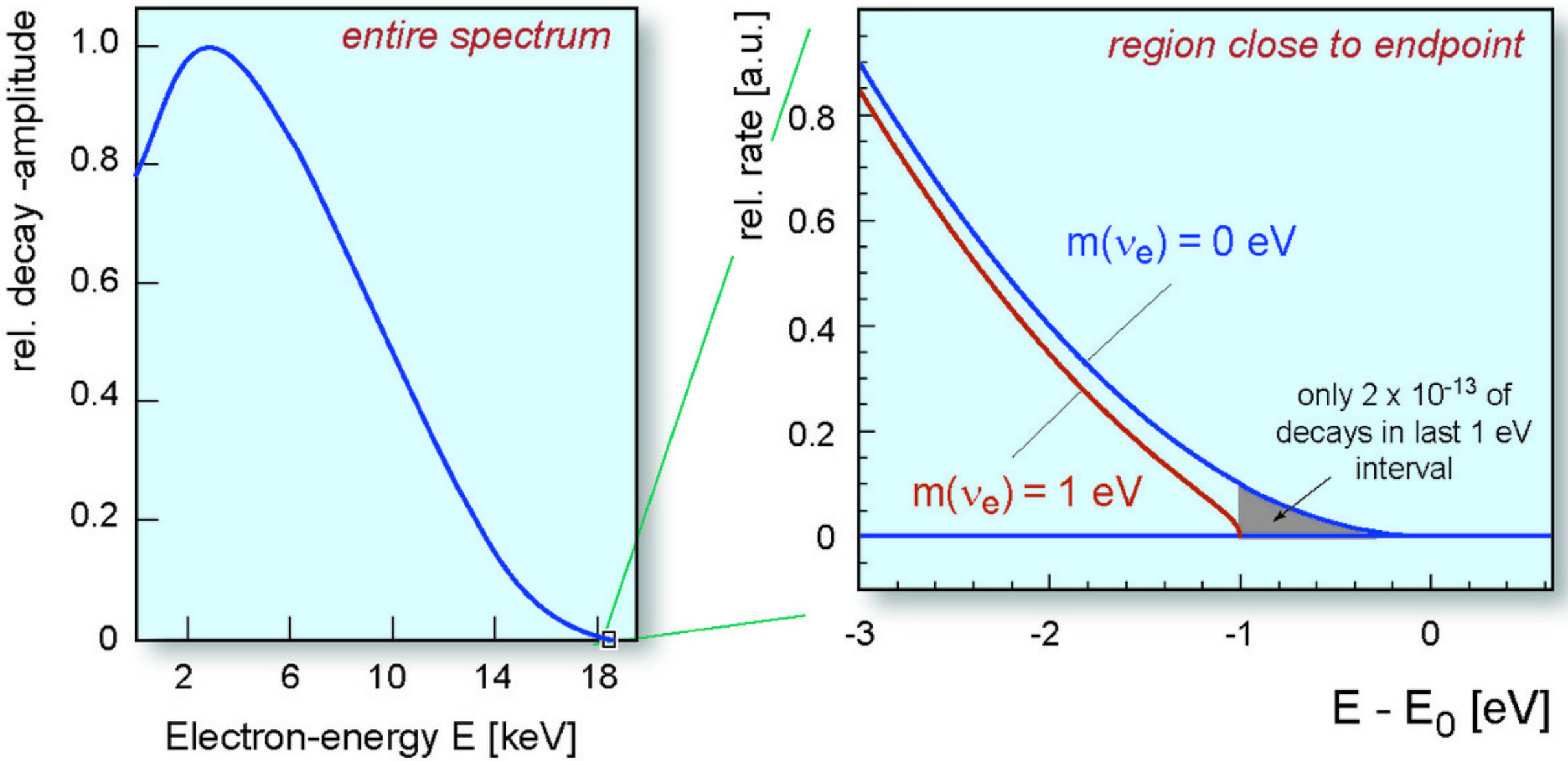


Majorana vs. Dirac!



from M. Messier's 2014 summer lecture

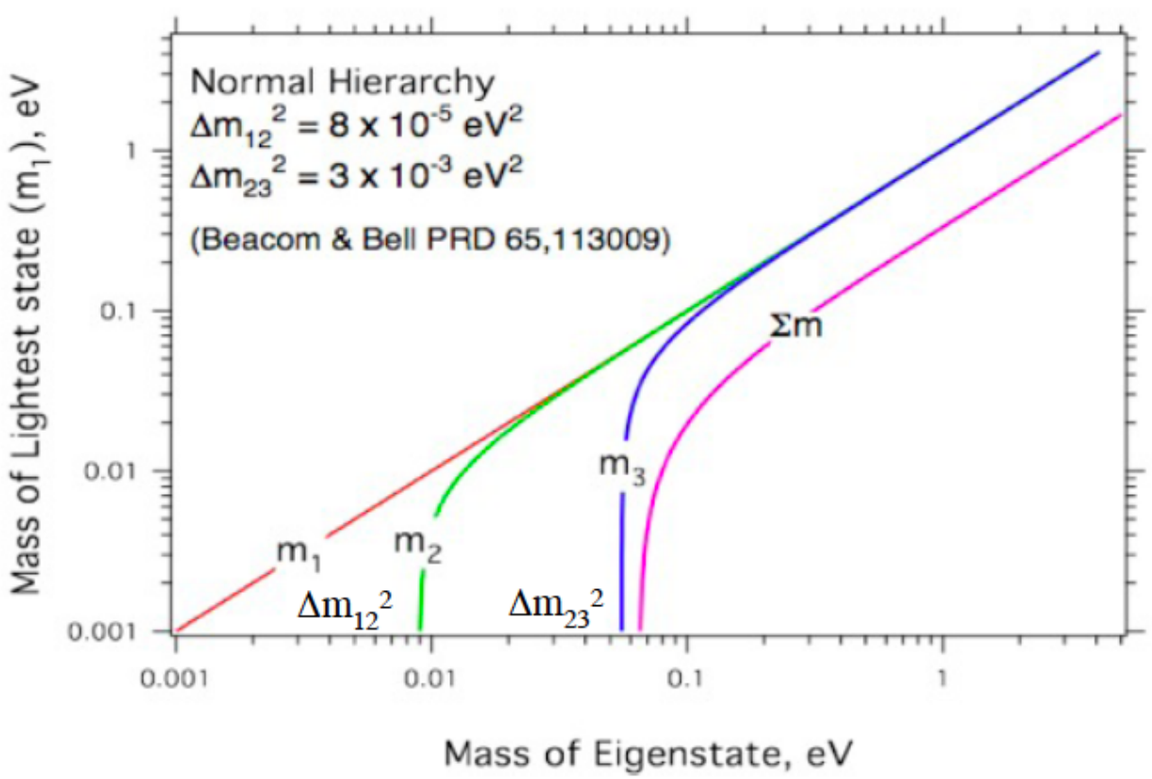
Mass Measurement Using Beta Decay



$$\frac{dN}{dE} = |< l| < \nu_l|T|I >|^2 = \left|\sum_i U_{li}^* < l| < \nu_i|T|I >\right|^2 \propto p_e E(E-E_0)^2\left[1-\frac{m_\nu^2}{(E-E_0)^2}\right]^{1/2}$$

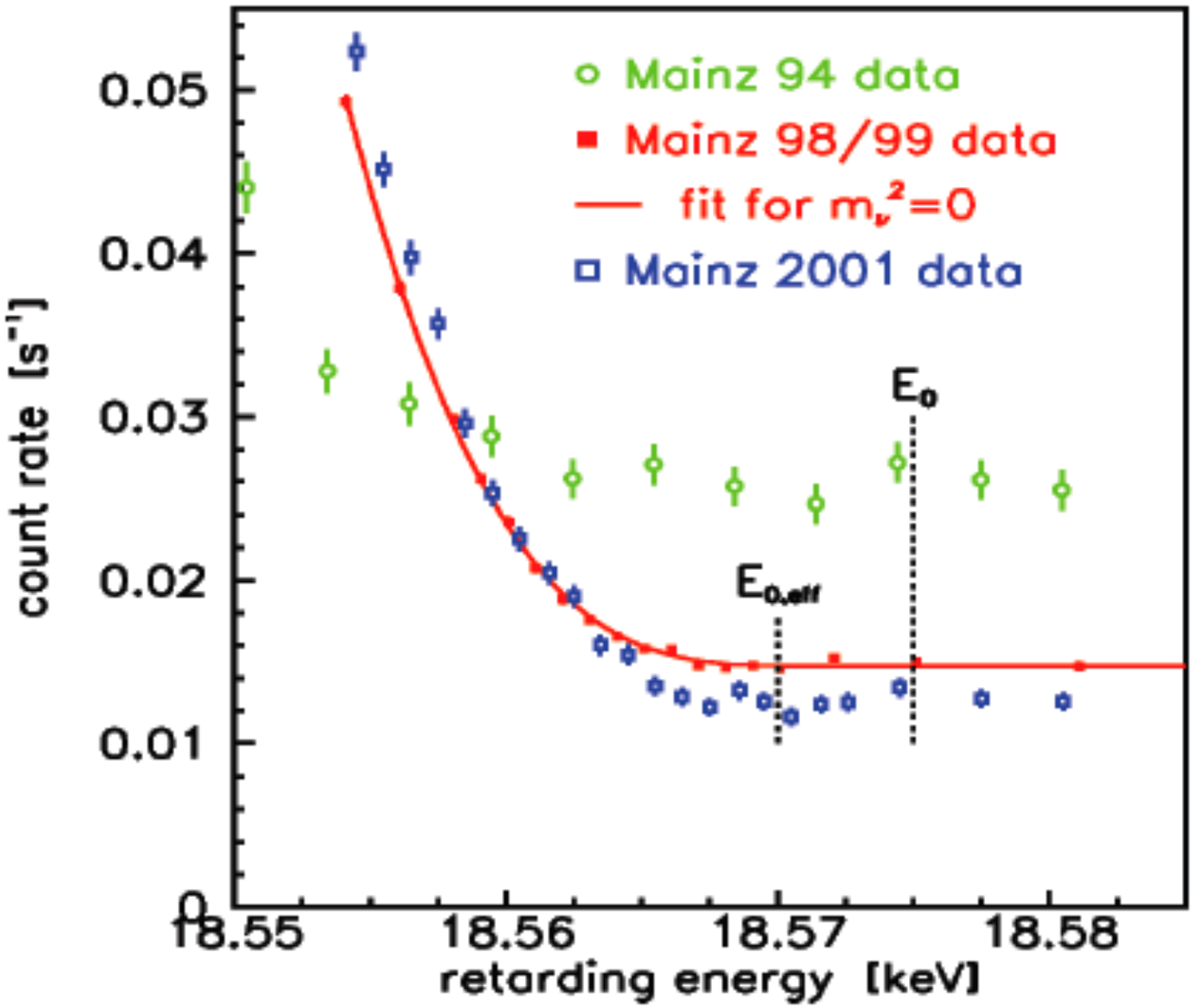
Beta-decay Experiments

- Tritium is an ideal source!
  - relatively easy to produce a strong source
  - small endpoint energy (effect of massive neutrinos has bigger effect)
  - long term stability (lifetime: 12.3 years)
  - well understood decay shape (nuclear effects are calculable)
- Need:
  - excellent energy resolution
  - low background rate
- NOTE: the neutrino emitted in beta-decay is a sum of mass eigen states!
  - for $m_1 > 100$ meV, the beta spectrum simplifies to that of an effective mass.



$$m_\beta = \left[\sum_i |U_{ei}|^2 m_i^2 \right]^{\frac{1}{2}}$$

Final Mainz Result -- Kraus et al. hep-ex/0412056



Improved S/N tenfold over 1994 data

20 weeks of data in 1998, 1999, 2001

Stable background: pulsed RF clearing field applied at 20-s intervals

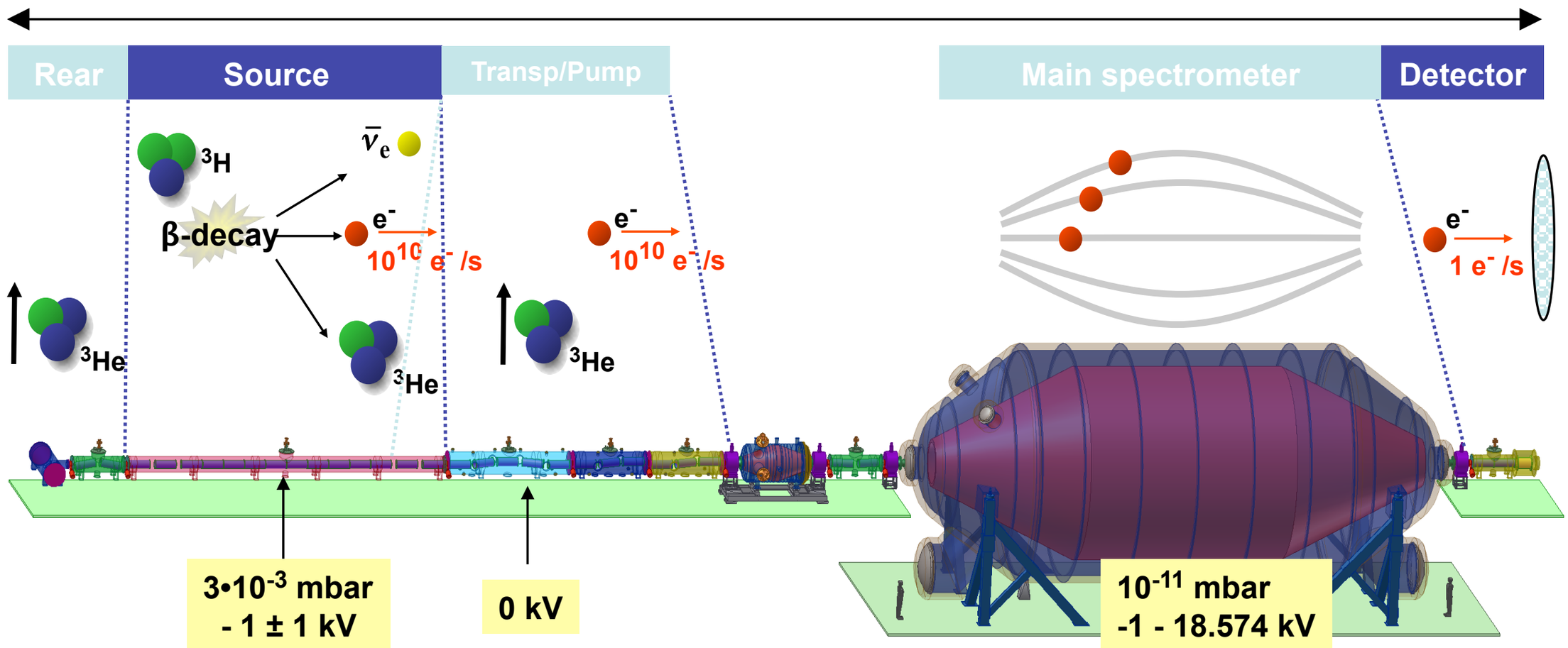
$$m^2(\nu_e) = (-0.6 \pm 2.2_{\text{stat}} \pm 2.1_{\text{syst}})\ \text{eV}^2/\text{c}^4$$

$$\chi^2/\text{d.o.f.} = 208/194$$

$$m(\nu_e) < 2.3\ \text{eV}/\text{c}^2 \quad (95\%\ \text{C.L.})$$

The KArlsruhe TRItium Neutrino (KATRIN) Experiment

- Next generation experiment, with goal of measurement down to 0.2 eV (100x improvement in energy resolution!)



Rear System:	Source:	Transp. & Pump system:	Main-spectrometer:	Detector:
Monitor source parameters	Provide the required tritium column density	Transport the electrons, adiabatically and reduce the tritium density significantly	Rejection of electrons below endpoint and adiabatic guiding of electrons	Count electrons and measure their energy

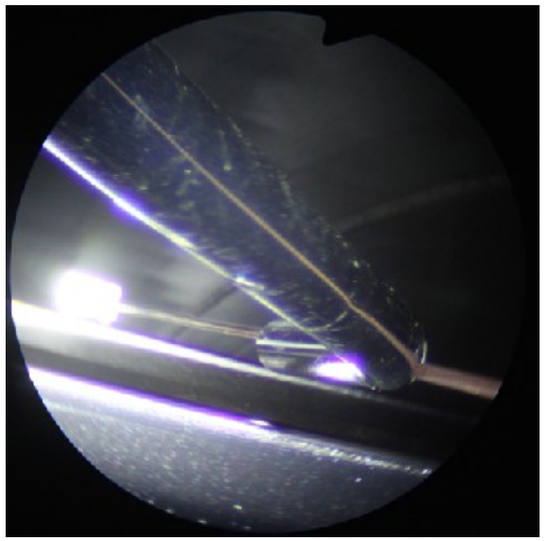
Voyage of the KATRIN Main Spectrometer

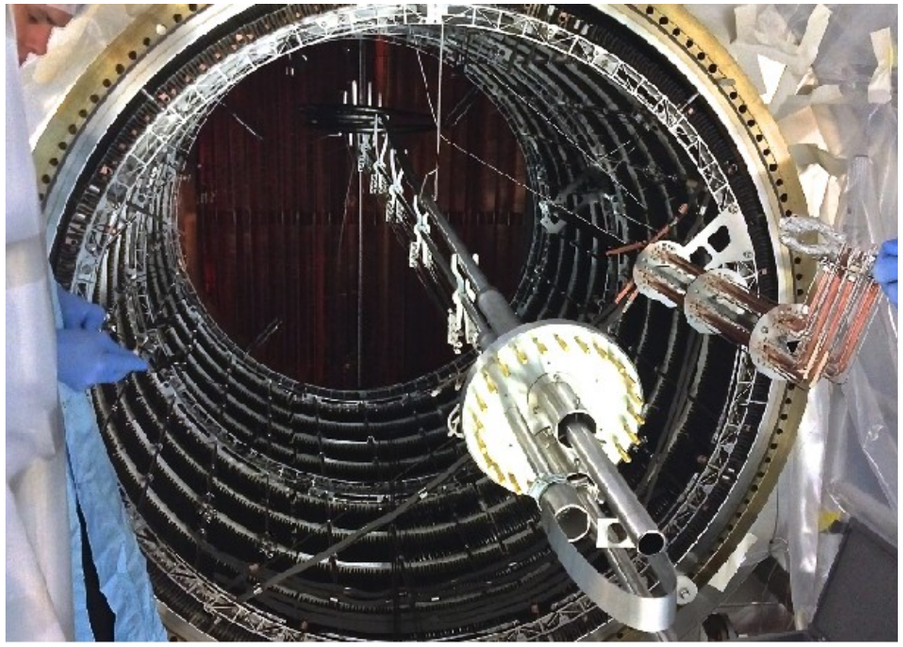
Voyage of the KATRIN Main Spectrometer

Status of KATRIN

- Commissioning spectrometer & detector phase 2 **Q3+4/2014**

* dual layer wire electrode (in central part at least)
* better egun
* better alignment
* better high voltage settings
* full magnetic zeroing
* full operational LN_2 baffles
* electrical heated NEG pumps





Weinheimer - Neutrino 2014

- Tritium retention units DPS and CPS functional **Q2/2015**

- Tritium source WGTS final mounting completed **mid-2015**

- Spectrometer upgrade completed **Q3/2015**

- All source elements & tritium loops integrated **Q4/2015**

- First tritium in source, ramp up to nominal ρd **Q1-Q2/2016**

- First tritium data with entire beam line **mid-2016**

Beyond KATRIN

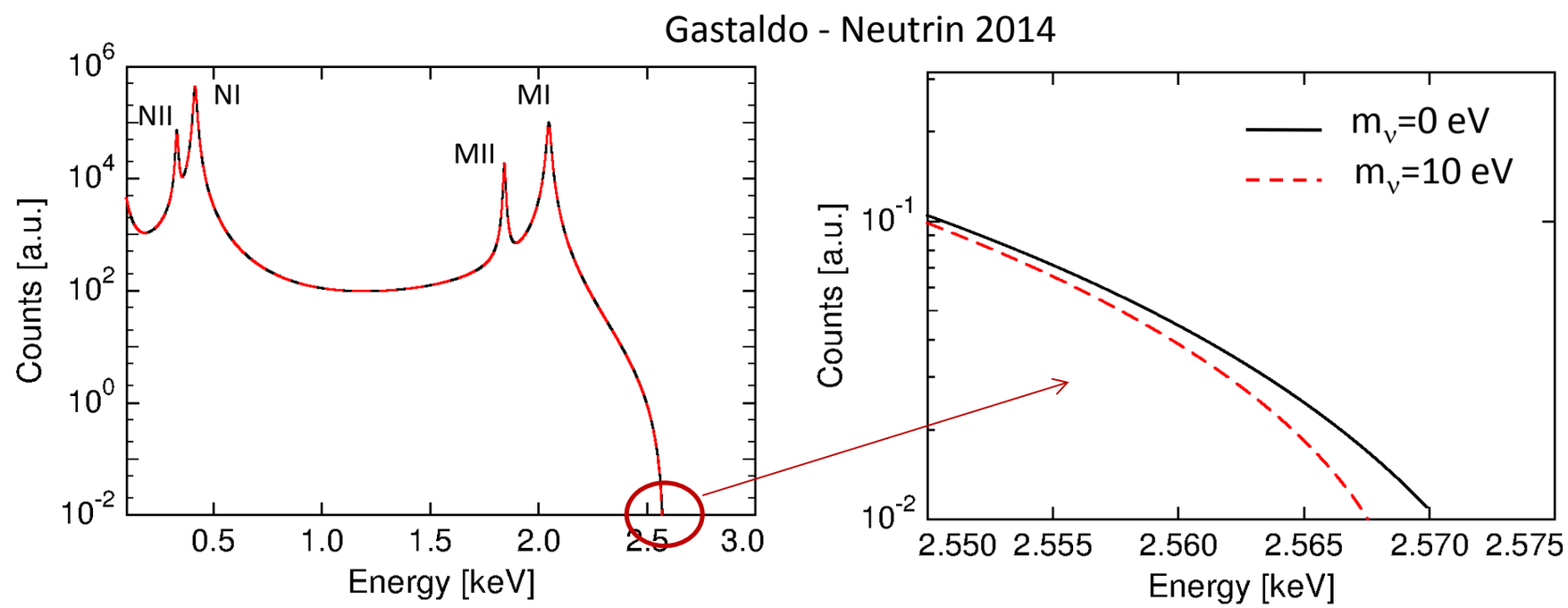
- Two very interesting prospects (IMO):

Beyond KATRIN

- Two very interesting prospects (IMO):
  - Holmium (^{163}Ho) source inside cryogenic bolometers (ECHo, HOLMES)

$$^{163}_{67}\mathrm{Ho} \rightarrow ^{163}_{66}\mathrm{Dy}^{*} + \nu_{\mathrm{e}}$$

$$^{163}_{66}\mathrm{Dy}^{*} \rightarrow ^{163}_{66}\mathrm{Dy} + E_{\mathrm{C}}$$



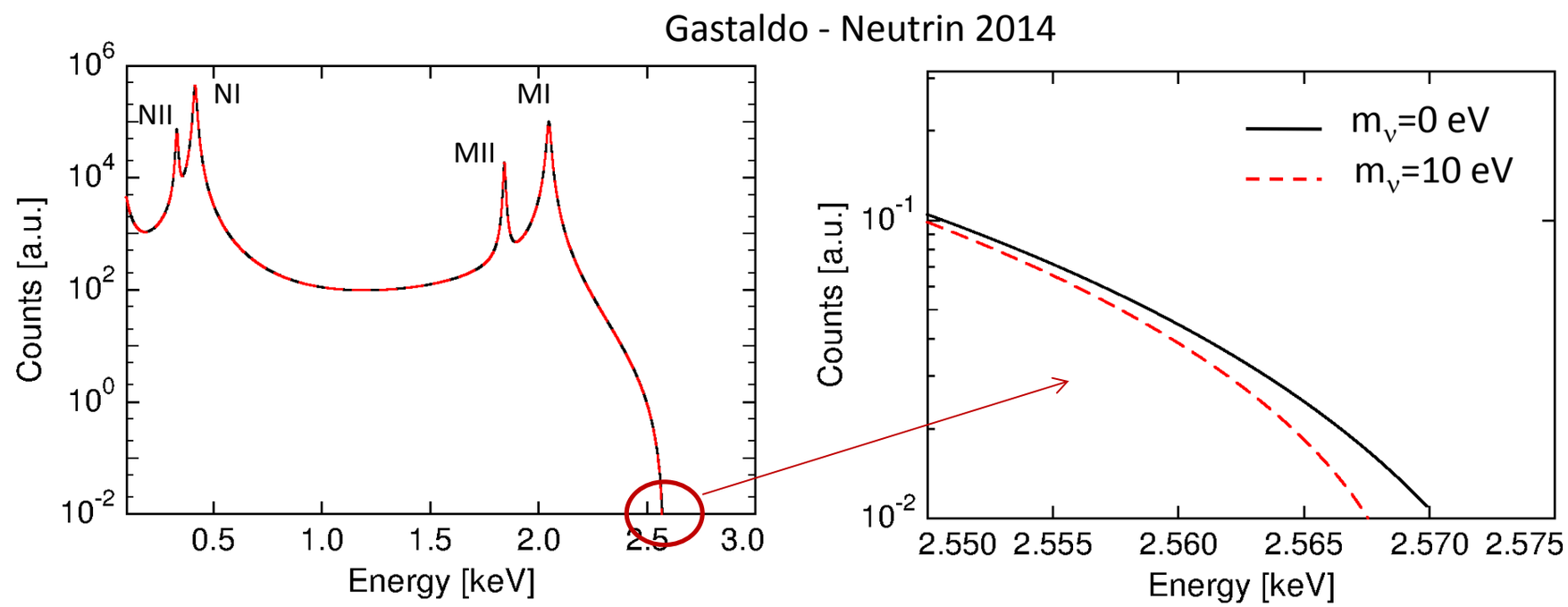
Beyond KATRIN

- Two very interesting prospects (IMO):
  - Holmium (^{163}Ho) source inside cryogenic bolometers (ECHo, HOLMES)

$$^{163}_{67}\mathrm{Ho} \rightarrow {}^{163}_{66}\mathrm{Dy}^{*} + \nu_{\mathrm{e}}$$

$$^{163}_{66}\mathrm{Dy}^{*} \rightarrow {}^{163}_{66}\mathrm{Dy} + E_{\mathrm{C}}$$

half-life of 4570 years
reasonable Q-value



Beyond KATRIN

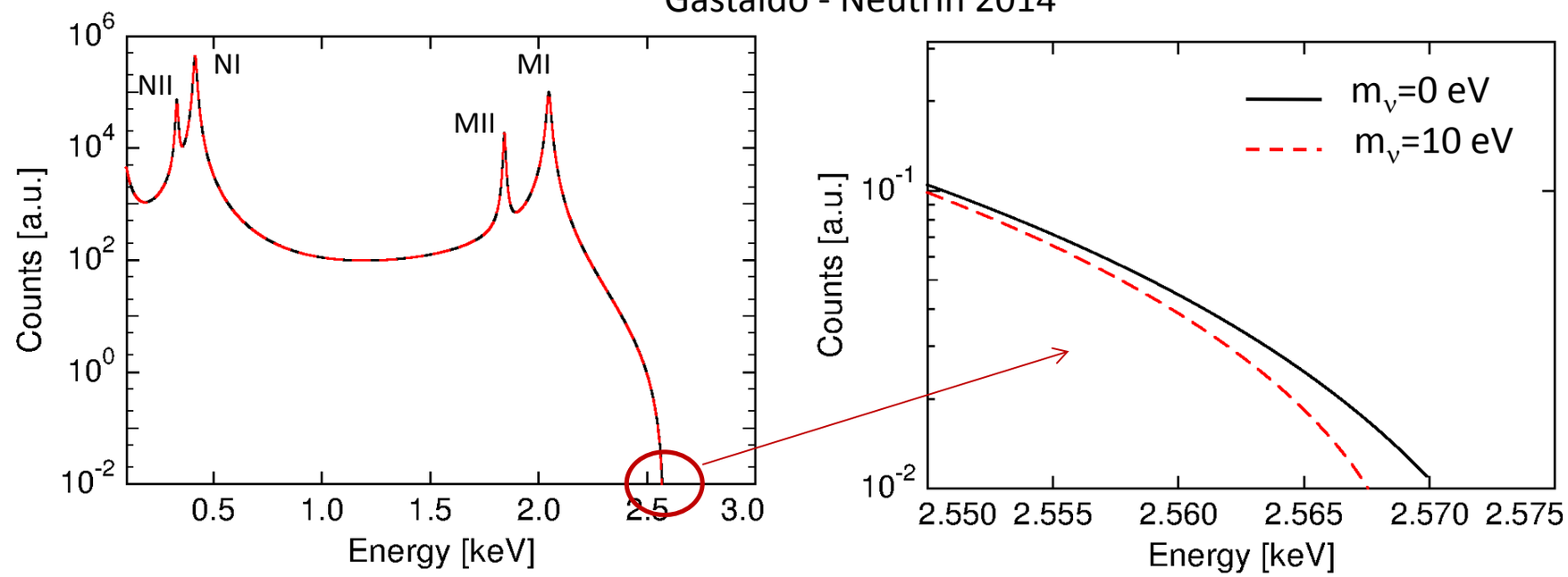
- Two very interesting prospects (IMO):
  - Holmium (^{163}Ho) source inside cryogenic bolometers (ECHo, HOLMES)

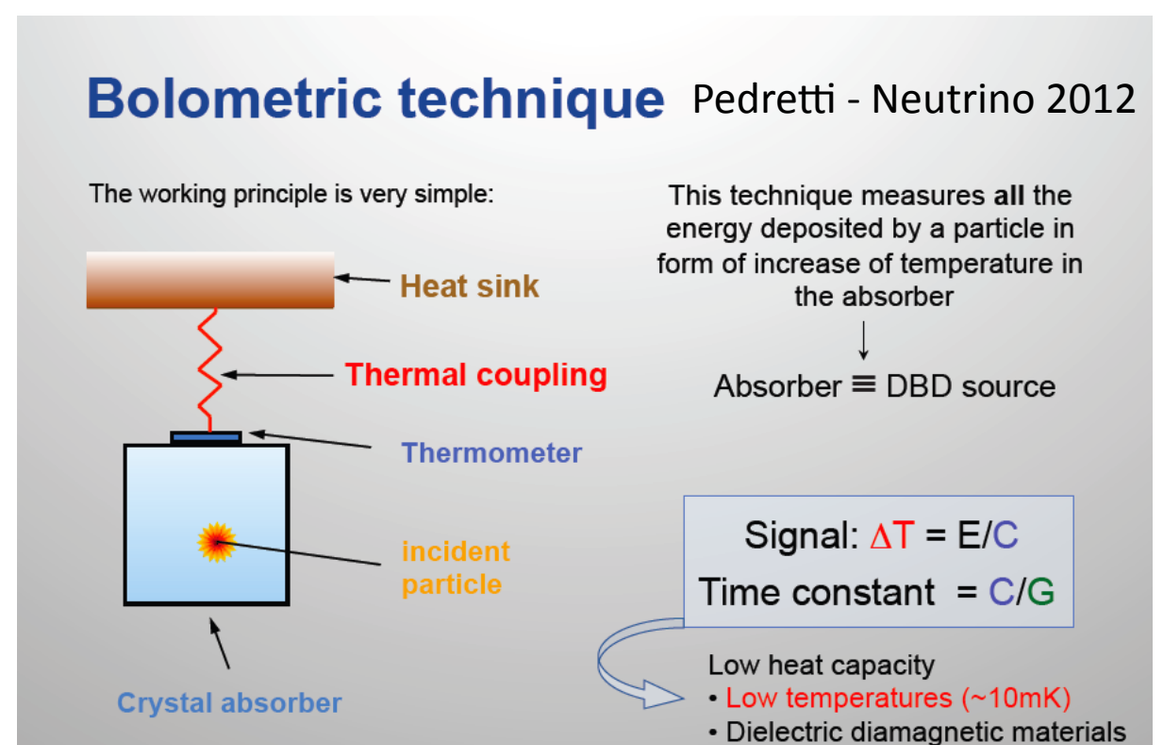
$$^{163}_{67}\mathrm{Ho} \rightarrow ^{163}_{66}\mathrm{Dy}^{*} + \nu_{\mathrm{e}}$$

$$^{163}_{66}\mathrm{Dy}^{*} \rightarrow ^{163}_{66}\mathrm{Dy} + E_{\mathrm{C}}$$

half-life of 4570 years
reasonable Q-value

Gastaldo - Neutrin 2014





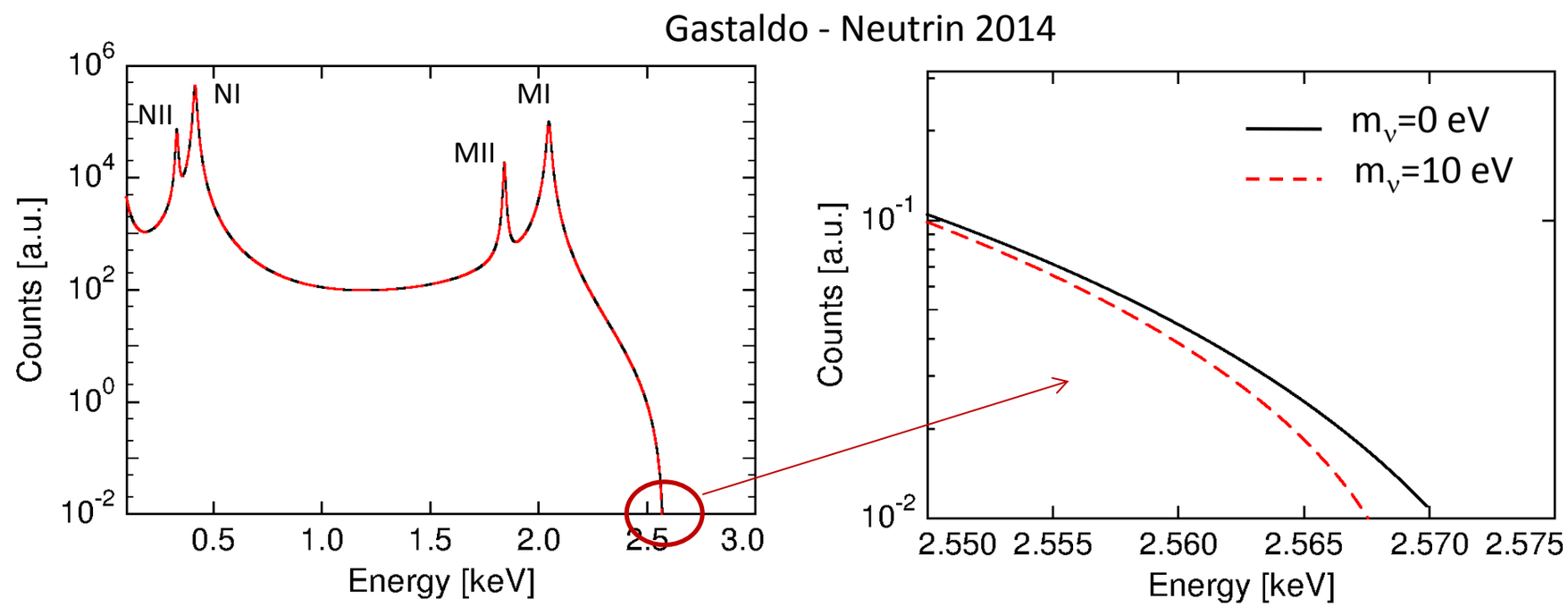
Beyond KATRIN

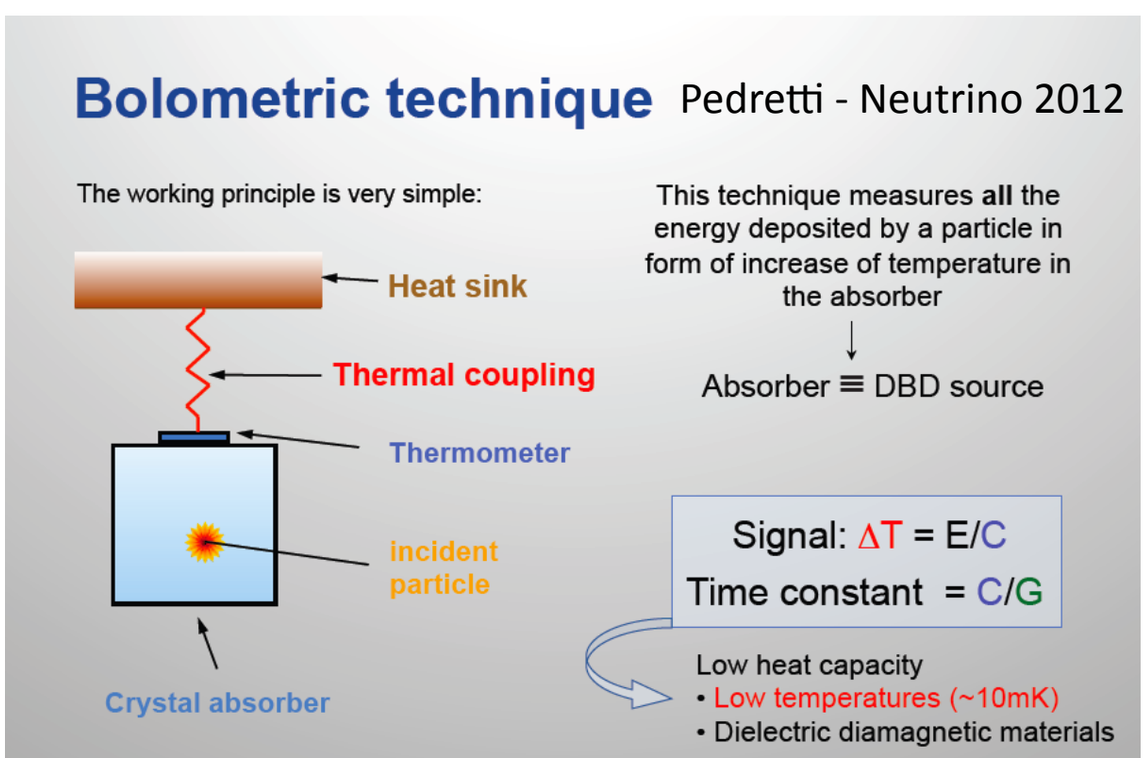
- Two very interesting prospects (IMO):
  - Holmium (^{163}Ho) source inside cryogenic bolometers (ECHo, HOLMES)

$$^{163}_{67}\mathrm{Ho} \rightarrow ^{163}_{66}\mathrm{Dy}^{*} + \nu_{\mathrm{e}}$$

$$^{163}_{66}\mathrm{Dy}^{*} \rightarrow ^{163}_{66}\mathrm{Dy} + E_{\mathrm{C}}$$

half-life of 4570 years
reasonable Q-value





- Challenges:
  - obtaining high purity ^{163}Ho source
  - background reduction
  - background rejection
  - understanding the full ^{163}Ho spectrum
- Several R&D projects underway to address these issues

Beyond KATRIN

- Two very interesting prospects (IMO):
  - Holmium (^{163}Ho) source inside cryogenic bolometers (ECHo, HOLMES)
  - Tritium beta decay electron energy measurement via coherent cyclotron radiation (Super-8)
-

General idea:

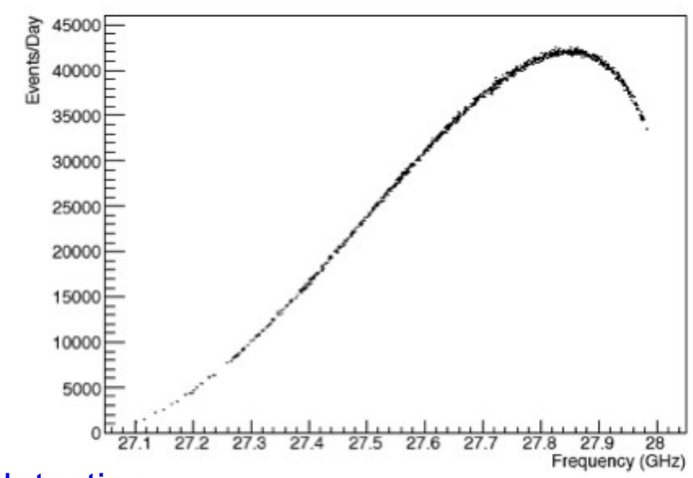
B. Monreal and J. Formaggio, PRD 80 (2009) 051301

- Source = KATRIN tritium source technology :

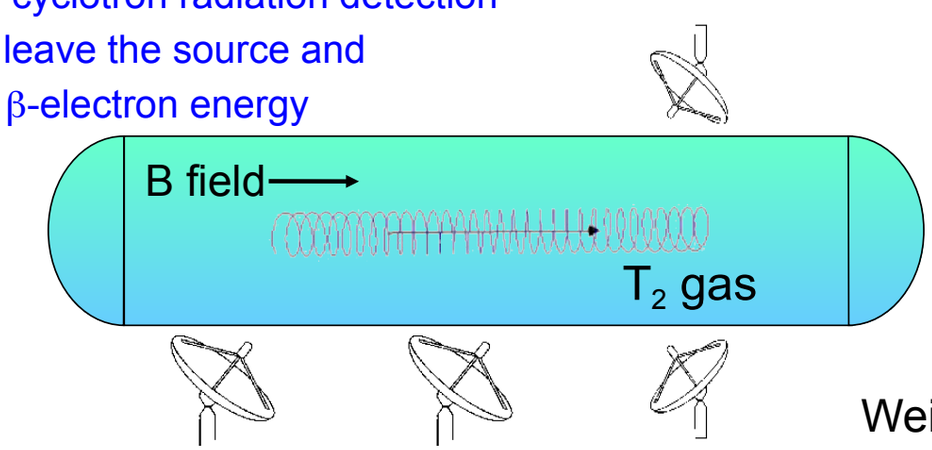
  uniform B field + low pressure T_2 gas

  β electron radiates coherent cyclotron radiation

  $$\omega(\gamma) = \frac{\omega_0}{\gamma} = \frac{eB}{K + m_e}$$



- Antenna array (interferometry) for cyclotron radiation detection since cyclotron radiation can leave the source and carries the information of the β-electron energy



Weinheimer - Neutrino 2014

Beyond KATRIN

- Two very interesting prospects (IMO):
  - Holmium (^{163}Ho) source inside cryogenic bolometers (ECHo, HOLMES)
  - Tritium beta decay electron energy measurement via coherent cyclotron radiation (Super-8)
-

General idea:

B. Monreal and J. Formaggio, PRD 80 (2009) 051301

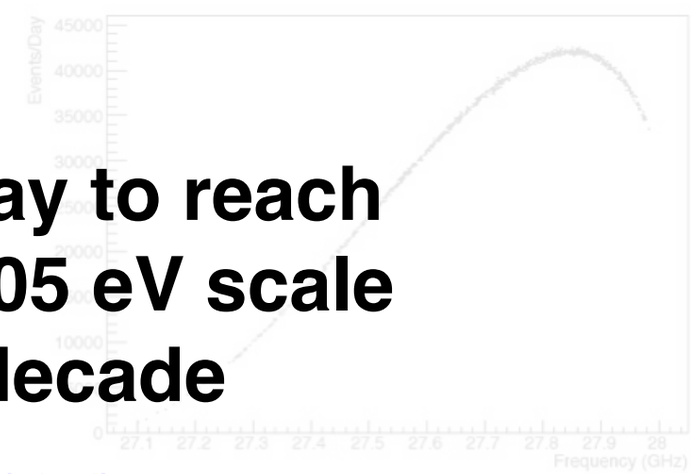
- Source = KATRIN tritium source technology :

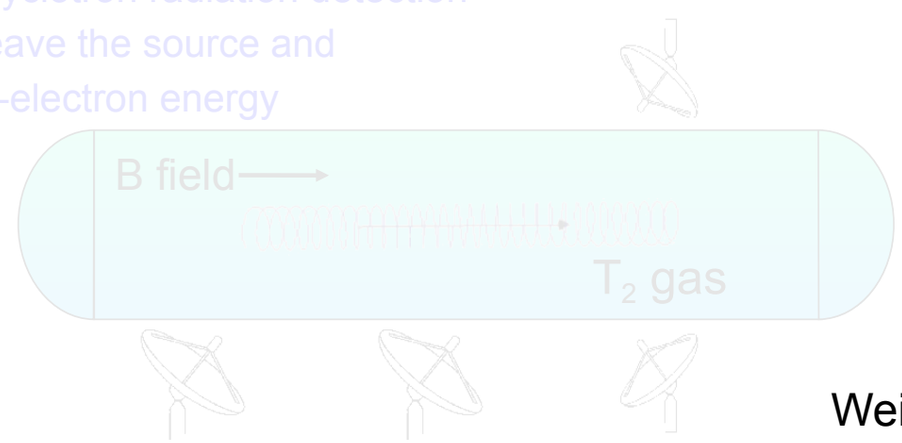
  uniform B field + low pressure T_2 gas

  β electron energy measurement via cyclotron radiation

  $$\omega(\gamma) = \frac{\omega_0}{\gamma} = \frac{eB}{\gamma m_e}$$

- Antenna array (interferometry) for cyclotron radiation detection since cyclotron radiation can leave the source and carries the information of the β-electron energy



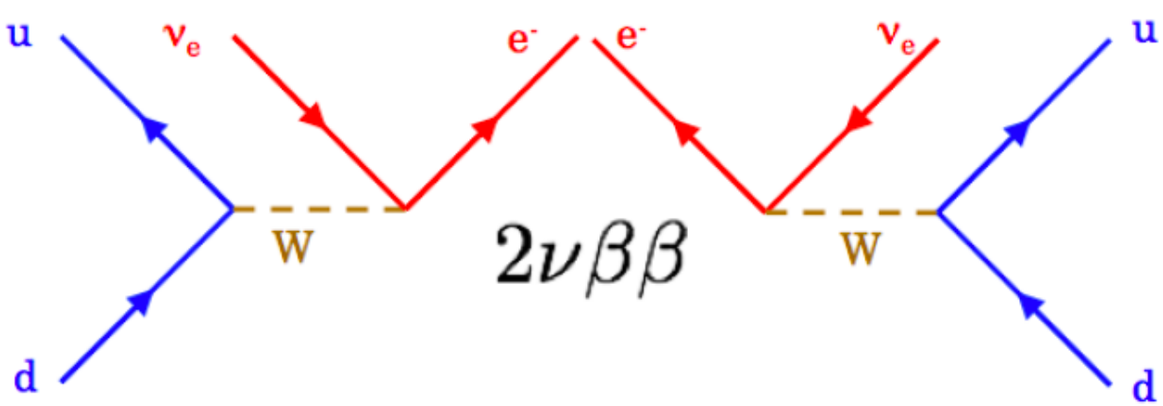


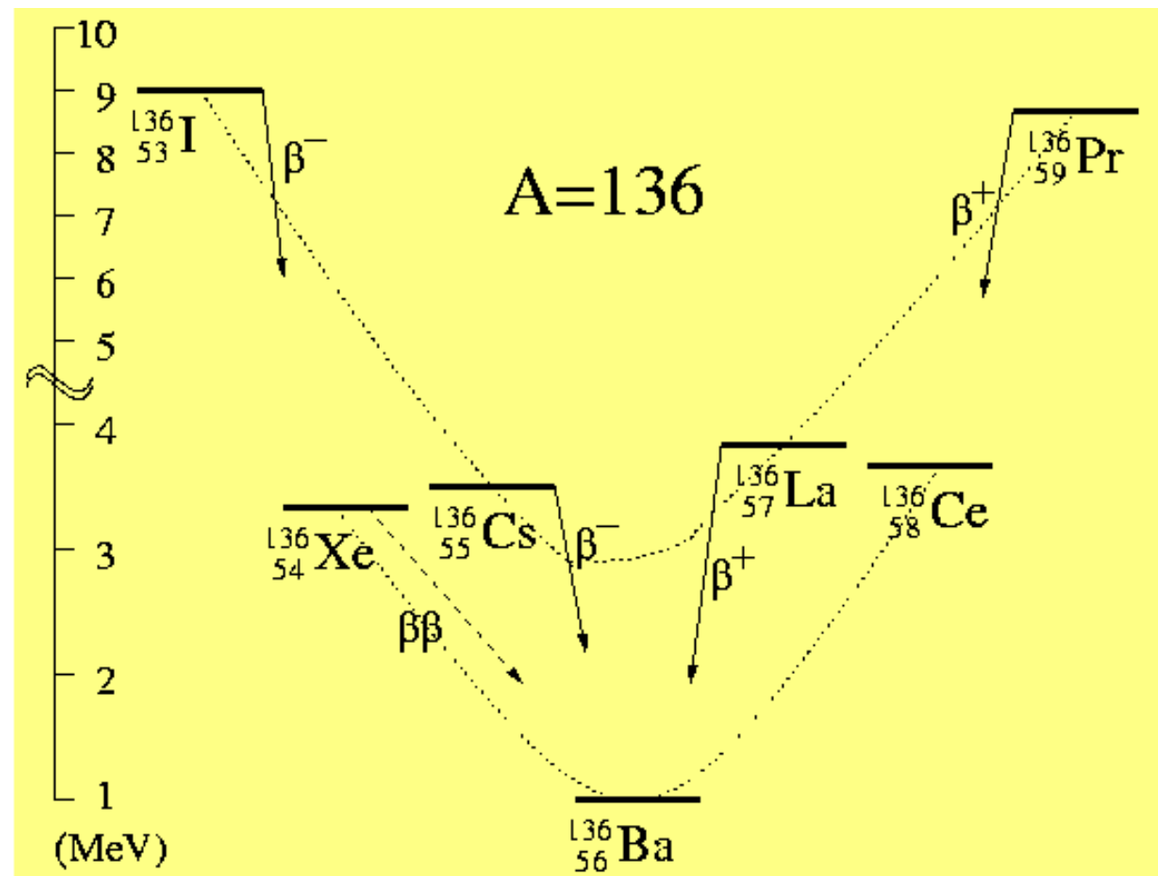
R&D effort underway to reach scientific goal of 0.05 eV scale by end of the decade

Weinheimer - Neutrino 2014

Neutrinoless Double Beta Decay

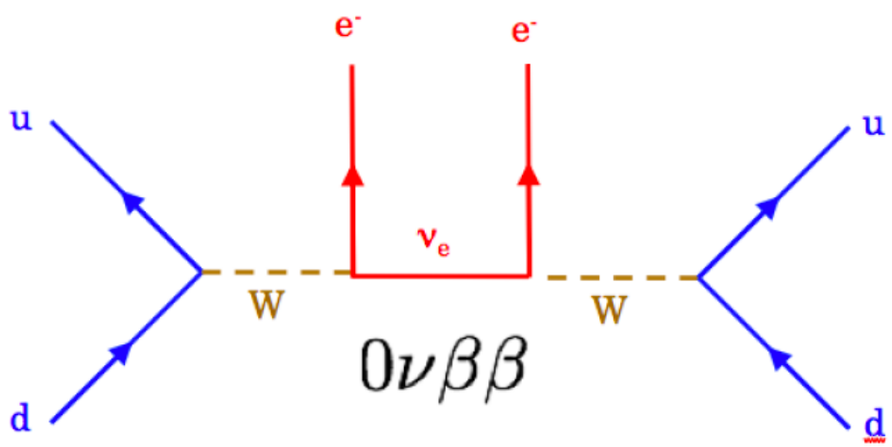
- ββ decay:
  - second-order weak process by which two neutrons decay to protons + two electrons
  - only allowed for nuclei where beta-decay is energetically forbidden or highly suppressed, eg (A,Z) = (even,even)
  - half-lives ~$10^{18\text{-}21}$ years
  - this IS a Standard Model process, so measured decay rates are used to compare various nuclear models





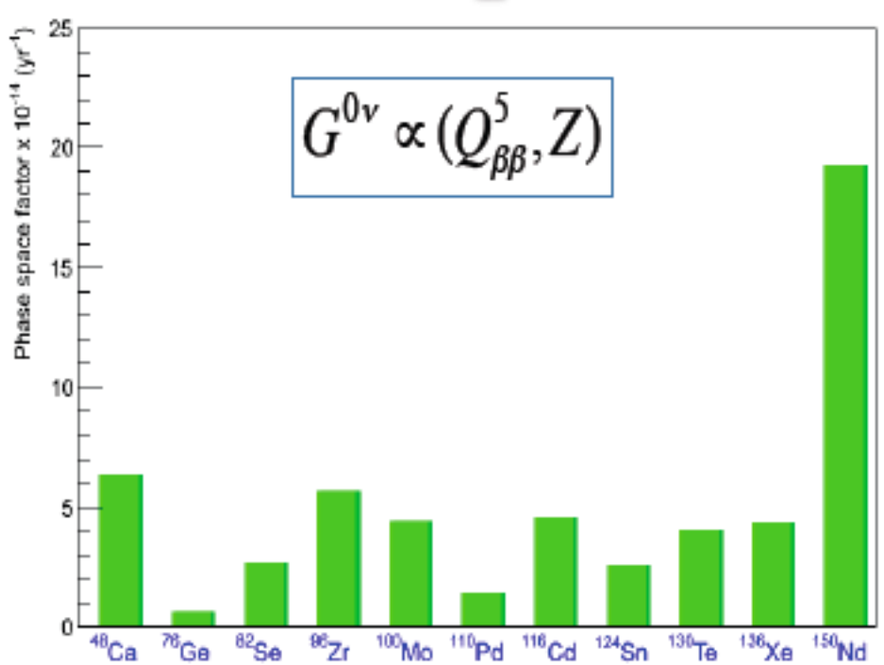
Neutrinoless Double Beta Decay

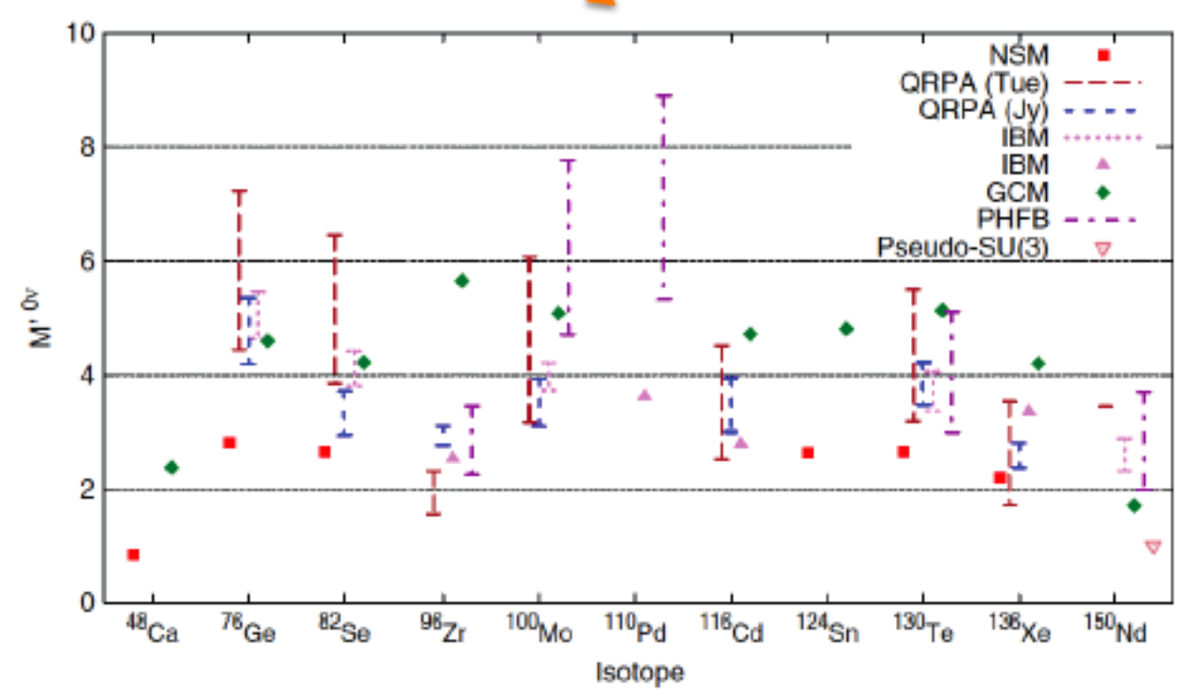
- IF 0νββ is discovered, this would be revolutionary:
  - neutrino is Majorana; if neutrinos violate CP, then there is a viable explanation for baryon asymmetry via leptogenesis.
  - RATE of decay is proportional to m_ν^2



$$\left(T_{1/2}^{0\nu}\right)^{-1} = G^{0\nu}\left|M^{0\nu}\right|^2\left(\frac{\langle m_\nu\rangle}{m_e}\right)^2$$

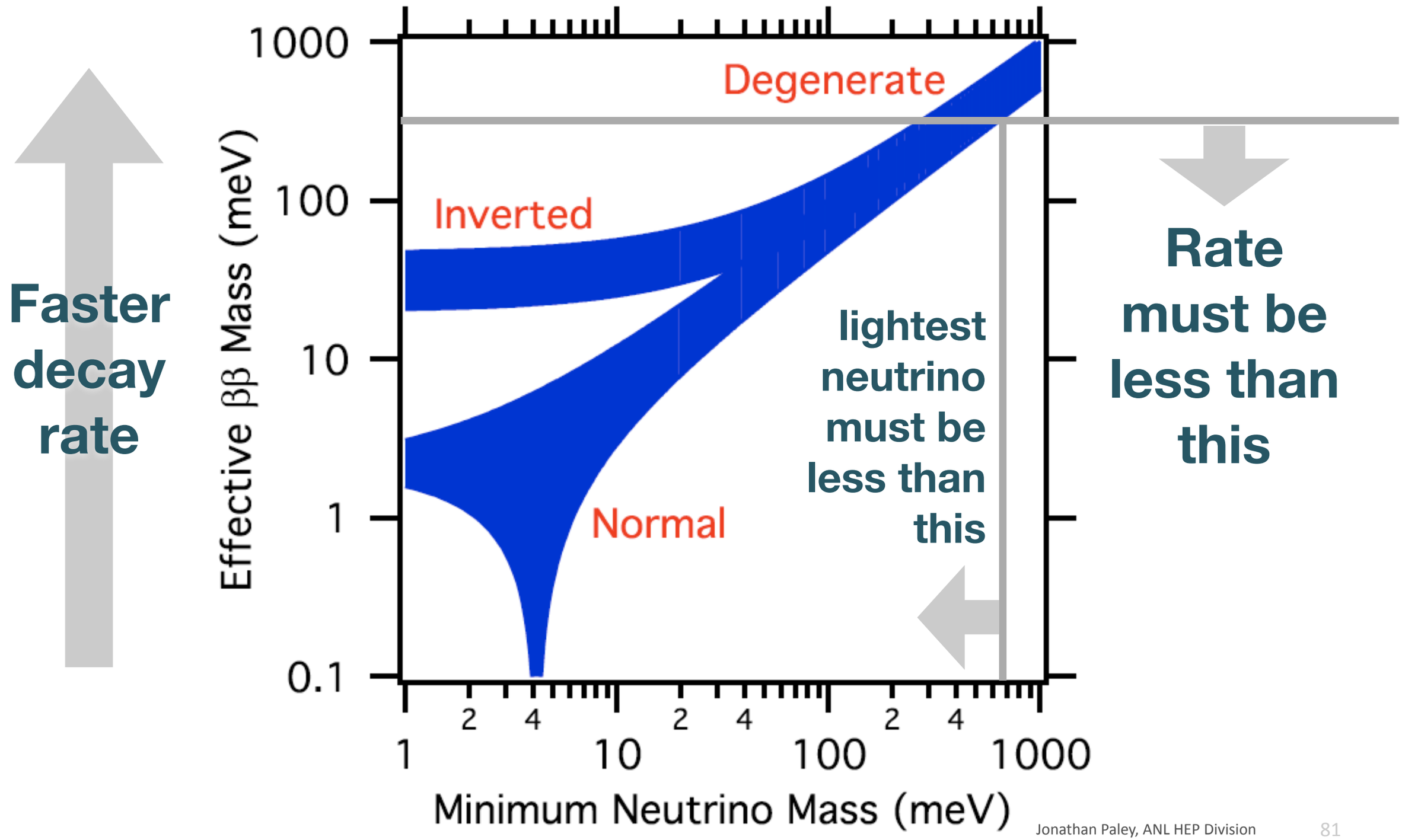
Piquemal - Neutrino 2012





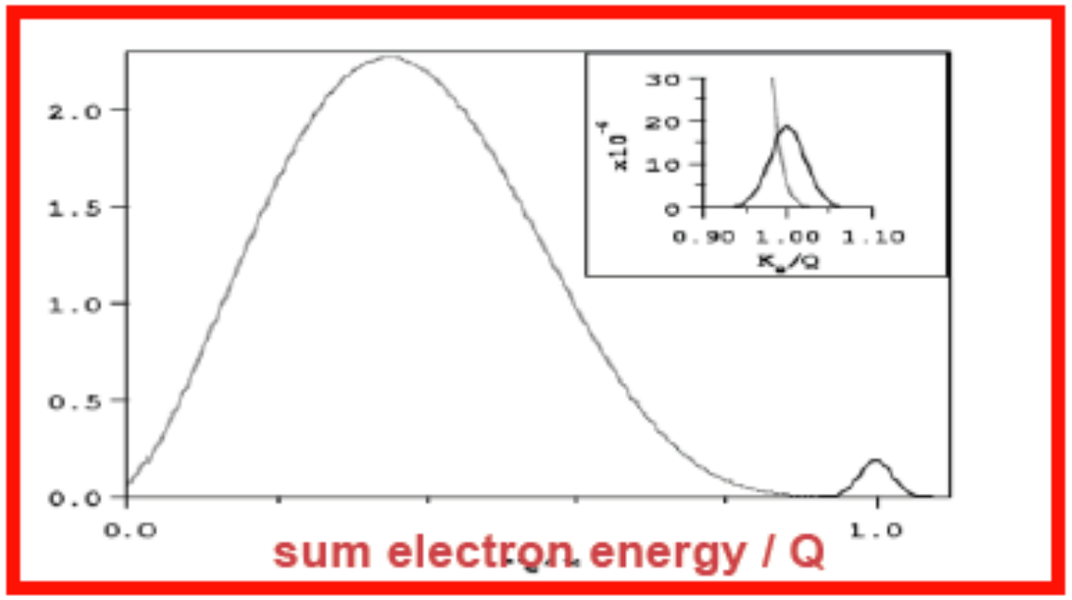
Dueck et al. Phys,. Rev. D **83** 113010(2011)

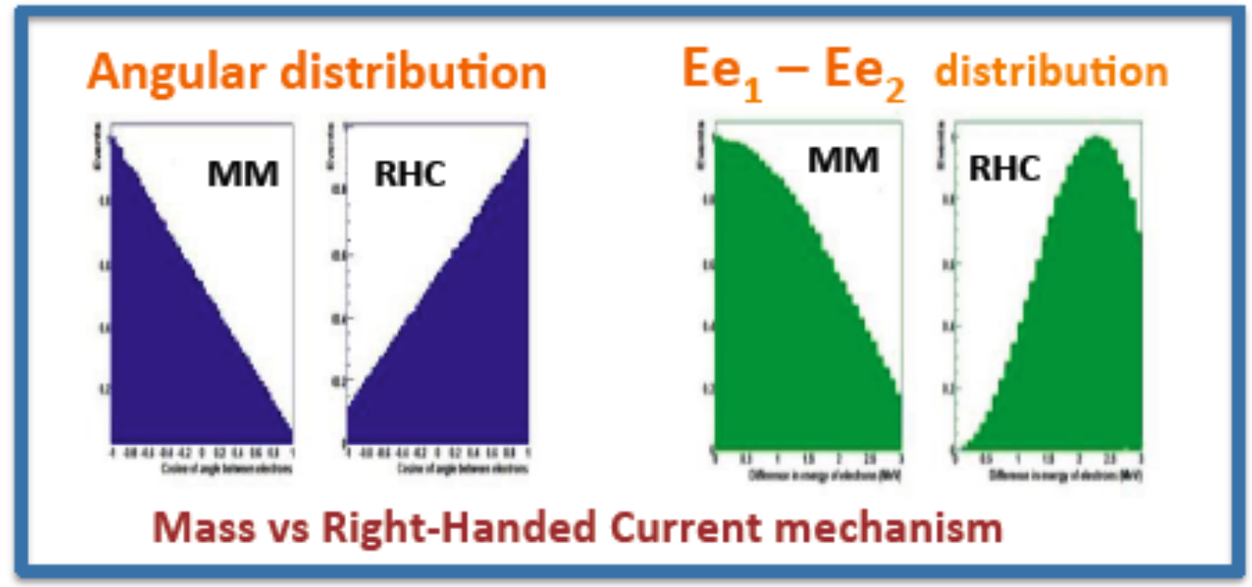
Neutrino-less double-beta decay: Absolute neutrino mass scale?



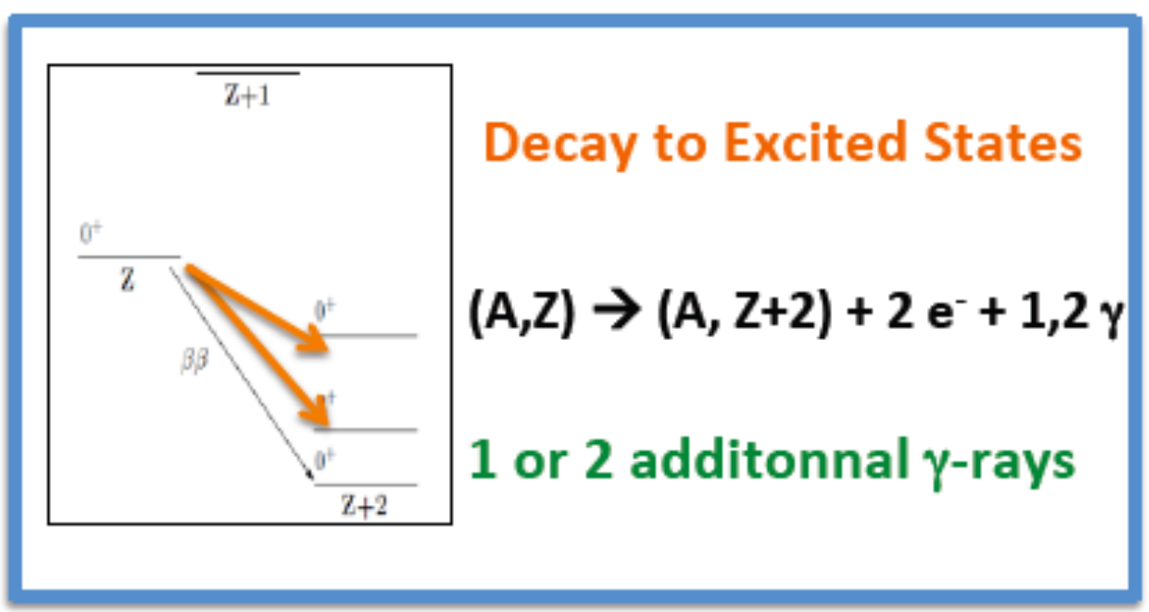
Double beta decay observables

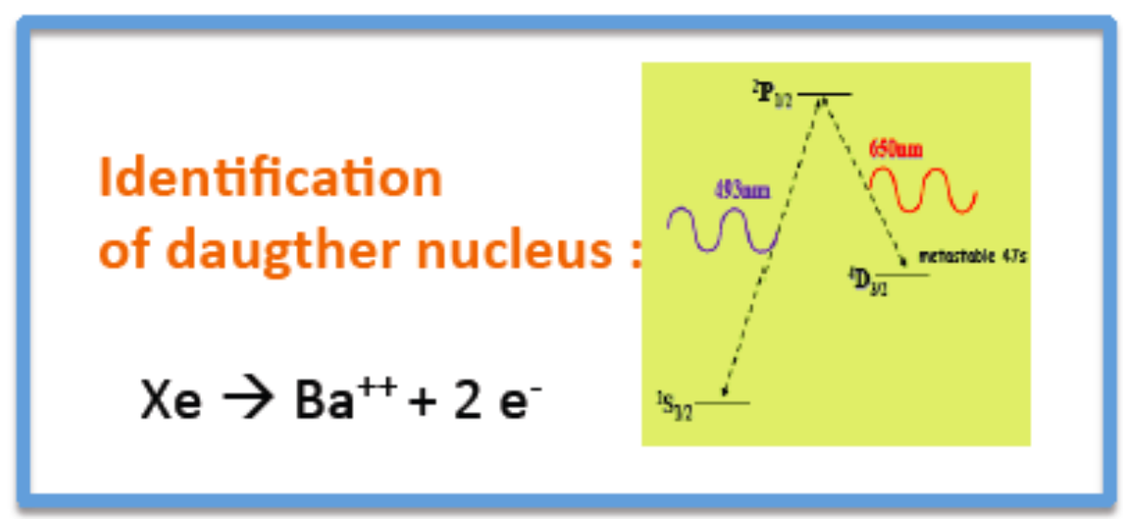
$$(A,Z) \longrightarrow (A,Z+2) + 2\,e^-$$





Piquemal - Neutrino 2012





Neutrinoless Double Beta Decay

- In general, there are two types of 0νββ experiments:
  - Tracking
  - Calorimeter
- These experiments are INCREDIBLY difficult!

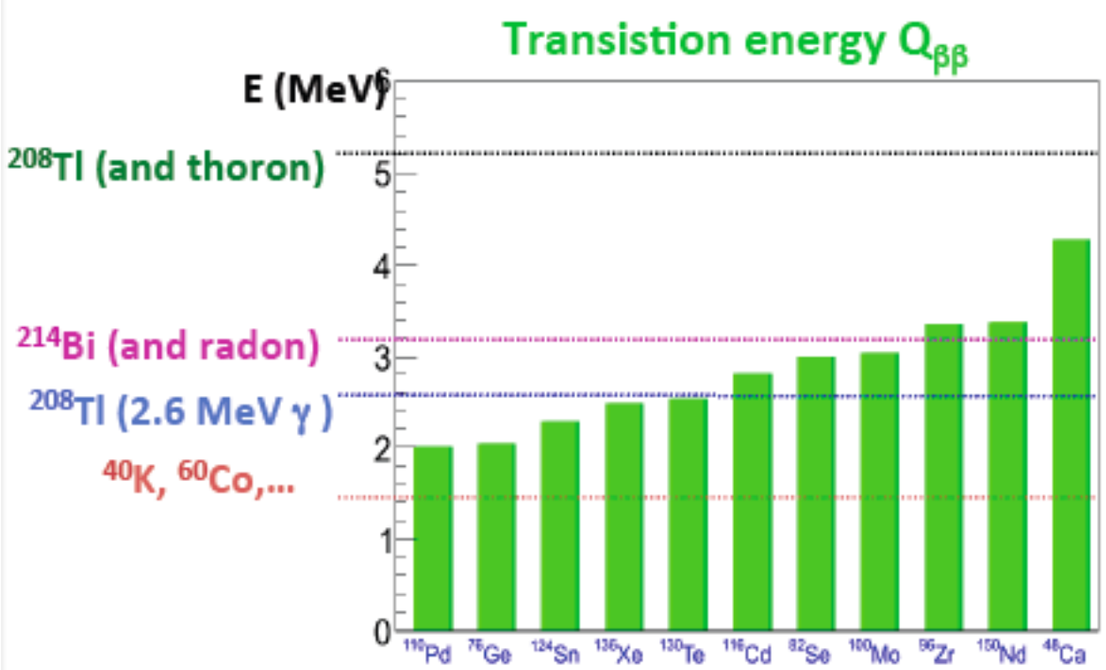
WITH Background

$$T_{1/2}^{0\nu}(y) \propto \frac{\varepsilon}{A}\sqrt{\frac{M \cdot t}{N_{Bckg} \cdot \Delta E}} \qquad \langle m_\nu \rangle \propto \sqrt[4]{M}$$

ε :efficiency, M: Mass, t: time, N_{bckg}: Background events, ΔE: energie resolution, A: isotope mass

Background origins

Natural radioactivity

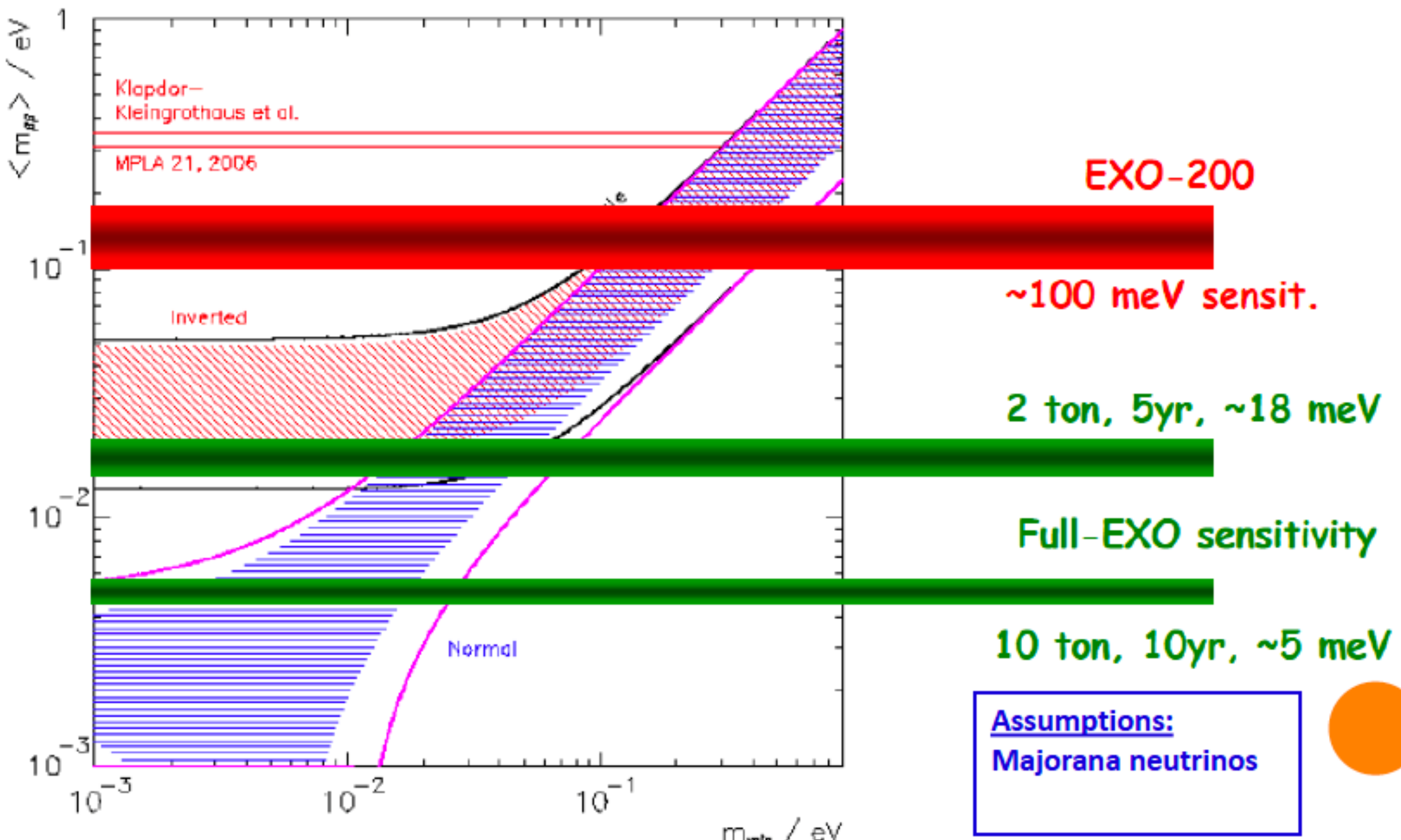


Other sources of background:

- Muons (underground labs)
- γ from ((n,γ) reactions , μ bremstrahlung
- Muon spallation products
- α emitters from bulk or surface contaminations for calorimeters
- ββ(2ν) if modest energy resolution

Neutrinoless Double Beta Decay

EXO Sensitivities

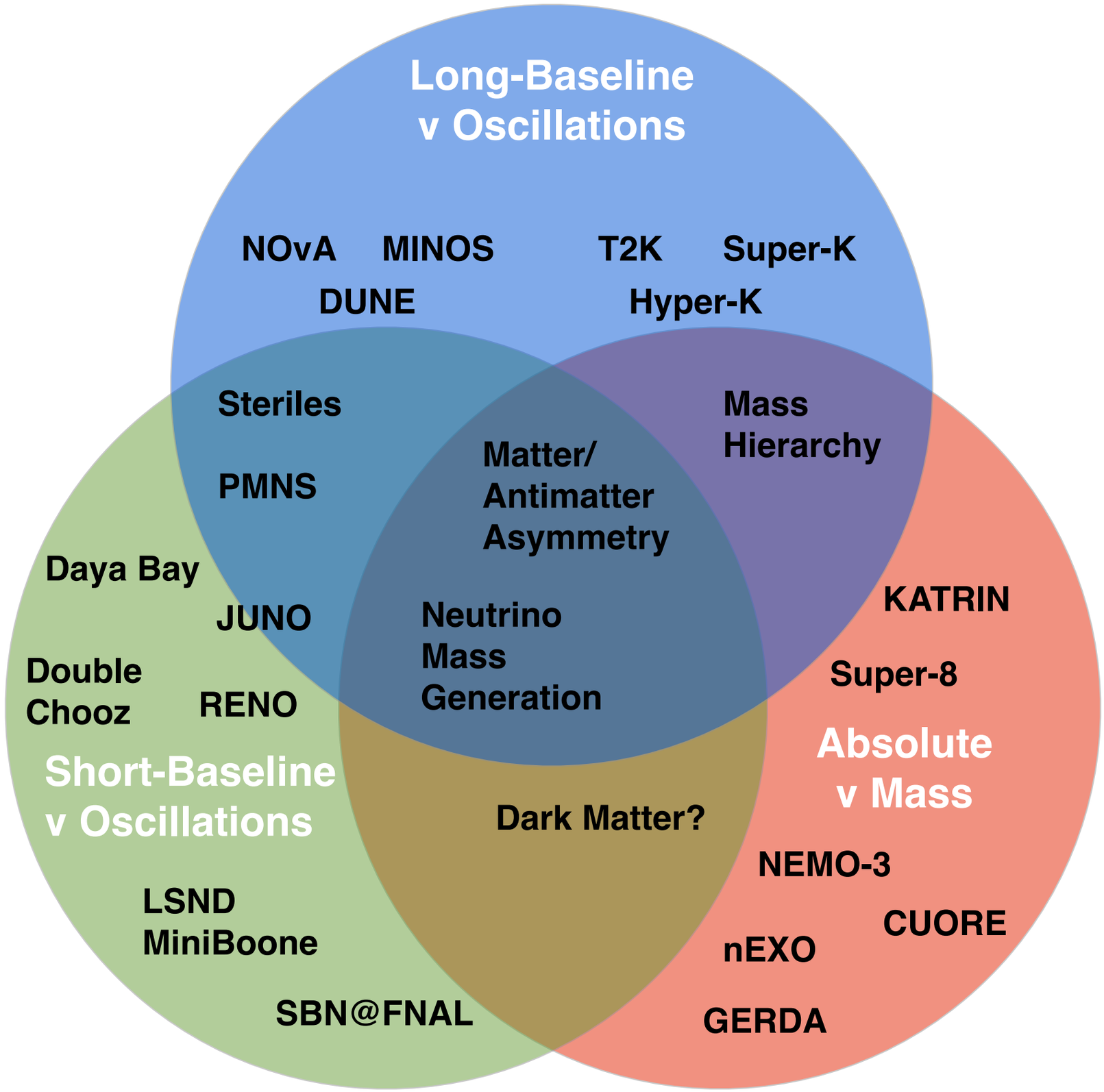


Kaufman - ANL 2012

Summary

- Long baseline experiments have guided the development of the three-flavor neutrino mixing paradigm.
- The next decade promises to be very exciting as we make better and better measurements.
- Short-baseline reactor-based experiments have resulted in precise measurements of θ_{13}, but new calculations of reactor fluxes imply existence of sterile neutrinos.
- Short-baseline accelerator-based experiments also indicate ν_e appearance, but at the wrong Δm^2. Results imply existence of sterile neutrinos.
- Short-baseline anomalies are in stark contrast with results from long-baseline measurements. Future experiments will try to put this issue to rest.
- Neutrino mass measurements are extremely challenging!
- Direct measurements provide the best way to determine the neutrino mass.
- Indirect measurements provide several cross-checks, but rather large uncertainties.
- Neutrinoless double beta decay experiments provide an opportunity to determine not only the nature of the neutrino, but also an effective mass.

Summary


Long-Baseline
ν Oscillations
NOvA
MINOS
T2K
Super-K
DUNE
Hyper-K
Steriles
PMNS
Mass
Hierarchy
Matter/
Antimatter
Asymmetry
Daya Bay
JUNO
Neutrino
Mass
Generation
KATRIN
Double
Chooz
RENO
Super-8
Absolute
ν Mass
Short-Baseline
ν Oscillations
Dark Matter?
NEMO-3
LSND
MiniBoone
CUORE
nEXO
SBN@FNAL
GERDA

QUESTIONS?

BACKUP

Limits from Cosmology

- Data from WMAP, CMB and Large-scale structure measurements place limits on Σm_i

Robust neutrino constraints… on the total mass

Reid, et al 2010, WMAP+H0+MaxBCG, SDSS DR7 P(k)

$\sigma_8(\Omega_m/0.25)^{0.41} = 0.832 \pm 0.033.$

Bayesian		upper 95% C.L. bound on $\sum m_\nu$			
model	base dataset	–	+maxBCG	$+H_0$	+maxBCG+H_0
ΛCDM	WMAP5	1.3	1.1	0.59	0.4[illegible]
ΛCDM	WMAP5+BAO+SN	0.67	0.35	0.59	[illegible]
ΛCDM $+\alpha$	WMAP5	1.34	1.25	0.[illegible]	[illegible]
ΛCDM $+r$	WMAP5	1.36	1.18	[illegible]	0.40
wCDM	WMAP5+BAO+SN	0.80	[illegible]	[illegible]	0.47

Also: Thomas et al. (2010). [illegible] et al (2010), Giusarma et al (2011)
Riemer-Sørensen (20[illegible] etc.

dePutter[illegible] (SDSS DR9 BOSS)

Σ<0.3 (95%CL) in a minimal LCDM scenario

[illegible]% CL $\sum m_\nu$[eV]	prior only	prior+CMASS,$\ell_{max} = 150$	prior+CMASS,$\ell_{max} = 200$
WMAP7 prior	1.1	0.74 (0.92)	0.56 (0.90)
WMAP7 + HST prior	0.44	0.31 (0.40)	0.26 (0.36)

TABLE 1
THE 95% CONFIDENCE LEVEL UPPER LIMITS ON THE SUM OF THE NEUTRINO MASSES Σm_ν. THE TOP ROW INVESTIGATES THE EFFECT OF ADDING THE CMASS GALAXY POWER SPECTRA TO A WMAP PRIOR WHILE THE BOTTOM ROW USES WMAP AND THE H_0 CONSTRAINT FROM HST AS A PRIOR. IN PARENTHESES WE SHOW RESULTS FOR THE MORE CONSERVATIVE MODEL MARGINALIZING OVER THE SHOT NOISE-LIKE PARAMETERS a_i.

Limits from Cosmology

- Data from WMAP, CMB and Large-scale structure measurements place limits on Σm_i

Robust neutrino constraints… on the total mass

Reid, et al 2010, WMAP+H0+MaxBCG, SDSS DR7 P(k)

$\sigma_8(\Omega_m/0.25)^{0.41} = 0.832 \pm 0.033.$

BUT systematics are not very well understood!

Bayesian		upper 95% C.L. bound on $\sum m_\nu$			
model	base dataset	–	+maxBCG	$+H_0$	+maxBCG+H_0
ΛCDM	WMAP5	1.3	1.1	0.59	0.4[illegible]
ΛCDM +α	WMAP5	[illegible]	1.34	1.25	[illegible]
ΛCDM	WMAP5+BAO+SN	[illegible]	[illegible]	[illegible]	[illegible]
wCDM	WMAP5+BAO+SN	0.80	[illegible]	[illegible]	0.47

Still, this is improving and future measurements will provide even better data sets. Could get down to 0.1 eV by the end of this decade.

Also: Thomas et al. (2010), [illegible] et al (2010), Giusarma et al (2011)

Riemer-Sørensen (20[illegible] etc.

dePutter[illegible] (SDSS DR9 BOSS)

Σ<0.3 (95%CL) in a minimal LCDM scenario

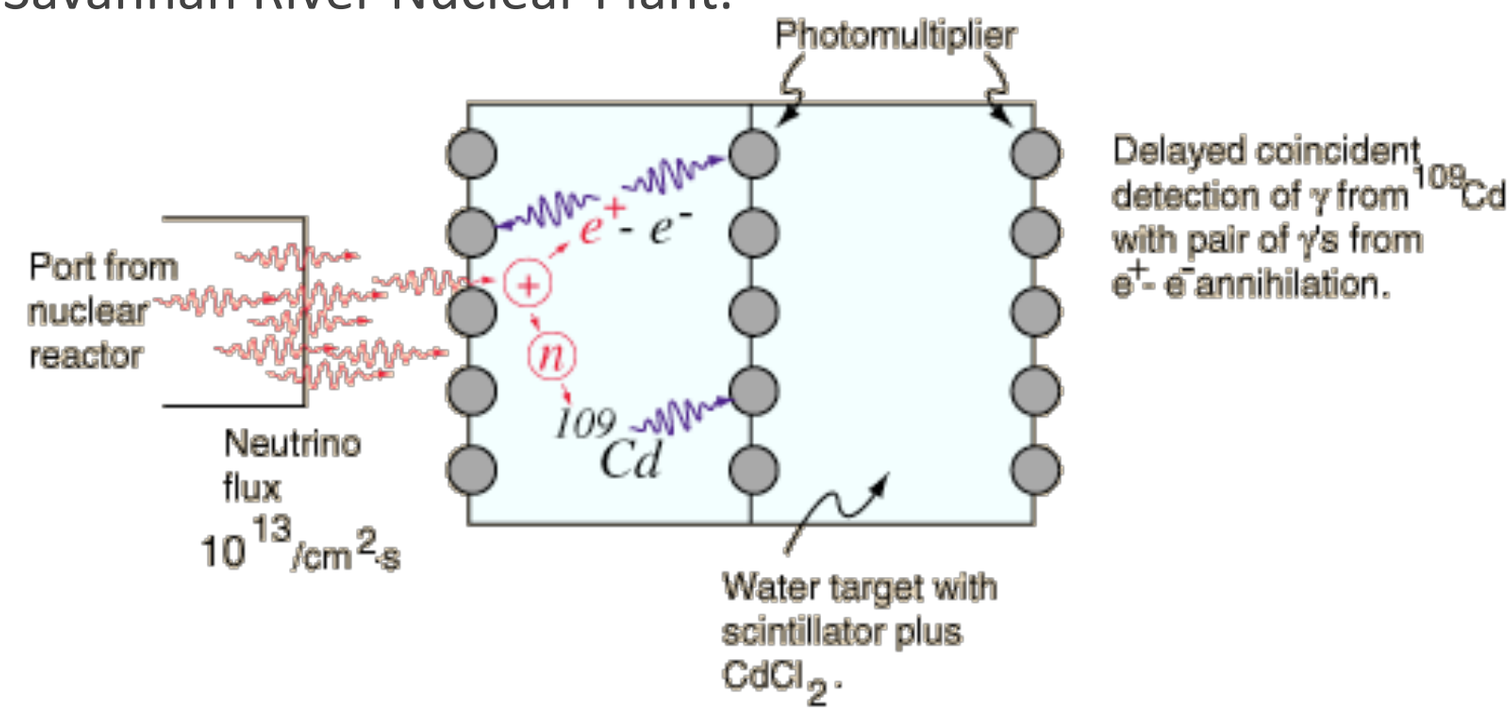
[illegible]% CL $\sum m_\nu$[eV]	prior only	prior+CMASS,$\ell_{max} = 150$	prior+CMASS,$\ell_{max} = 200$
WMAP7 prior	1.1	0.74 (0.92)	0.56 (0.90)
WMAP7 + HST prior	0.44	0.31 (0.40)	0.26 (0.36)

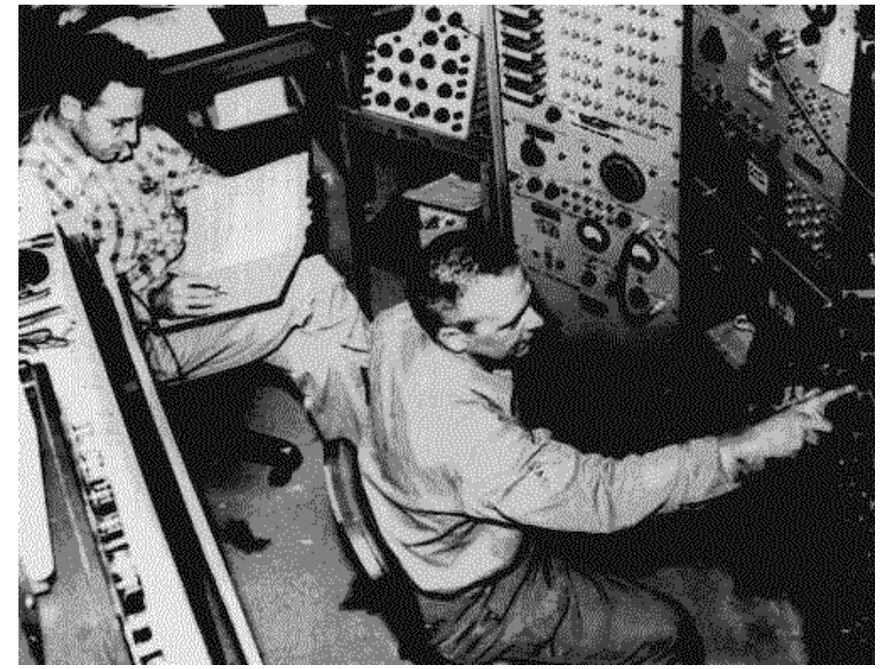
TABLE 1

THE 95% CONFIDENCE LEVEL UPPER LIMITS ON THE SUM OF THE NEUTRINO MASSES Σm_ν. THE TOP ROW INVESTIGATES THE EFFECT OF ADDING THE CMASS GALAXY POWER SPECTRA TO A WMAP PRIOR WHILE THE BOTTOM ROW USES WMAP AND THE H_0 CONSTRAINT FROM HST AS A PRIOR. IN PARENTHESES WE SHOW RESULTS FOR THE MORE CONSERVATIVE MODEL MARGINALIZING OVER THE SHOT NOISE-LIKE PARAMETERS a_i.

Some Neutrino History

- 1956: Reines and Cowan are the first to directly detect neutrinos via inverse beta decay ($\nu_e + p \rightarrow e^+ + n$) at the Savannah River Nuclear Plant.





Reines and Cowan

(L to R) Steinberger, Schwartz and Ledermen

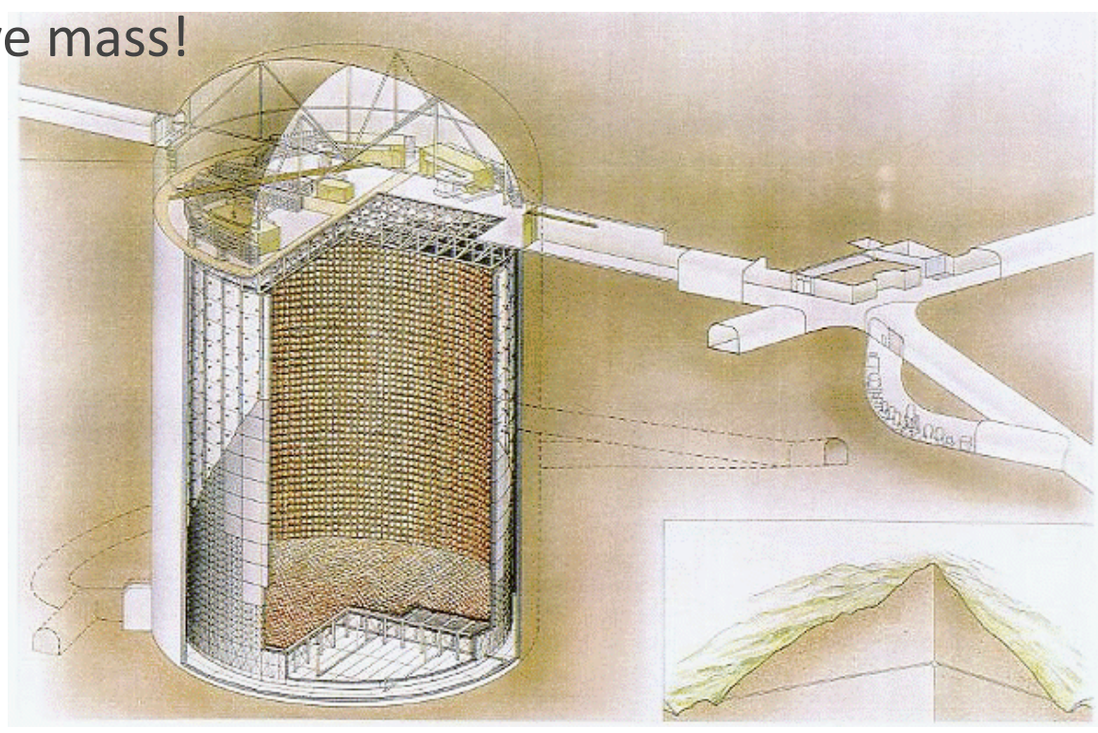
- Note: over 50 years later, modern-day experiments continue to implement this same technique of delayed coincidence!
- 1957: Neutrinos are found to be *left-handed* by Goldhaber, Grodzins and Sunyar by measuring the polarization .
- 1962: Muon neutrinos, different from electron neutrinos, are discovered by Ledermen, Schwartz, Steinberger and colleagues. *Neutrinos have **flavor**!*

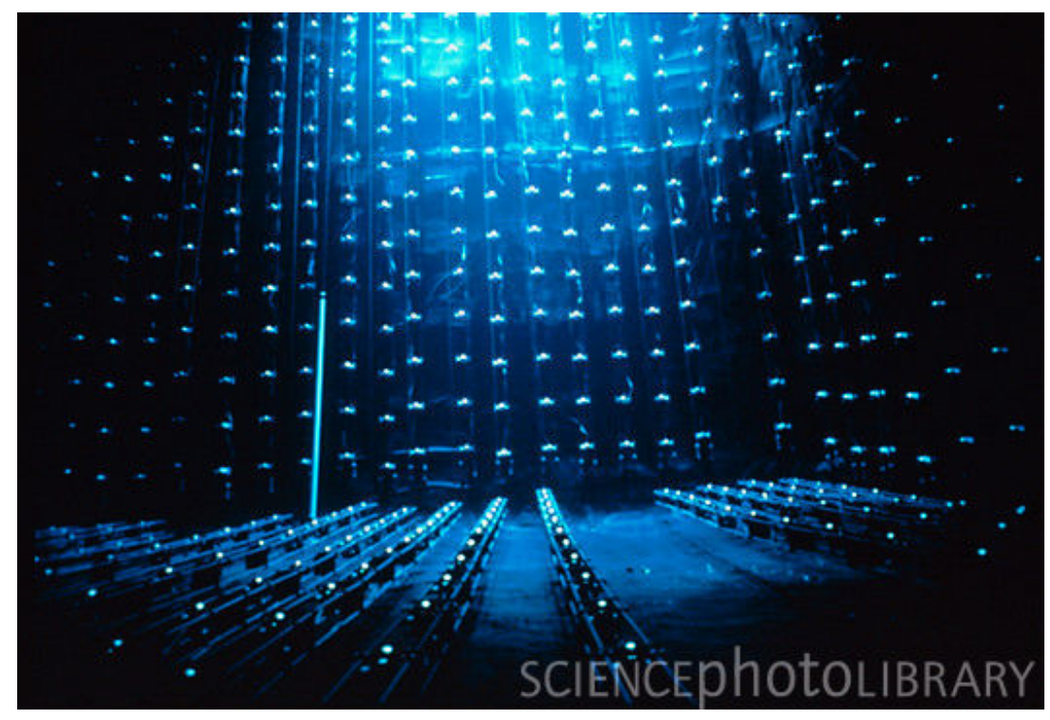
Some Neutrino History

- 1968: Ray Davis and colleagues measure neutrino solar flux in the Homestake Mine (SD). The flux is too low by ~2x; this deficit becomes known as the “solar neutrino problem”.

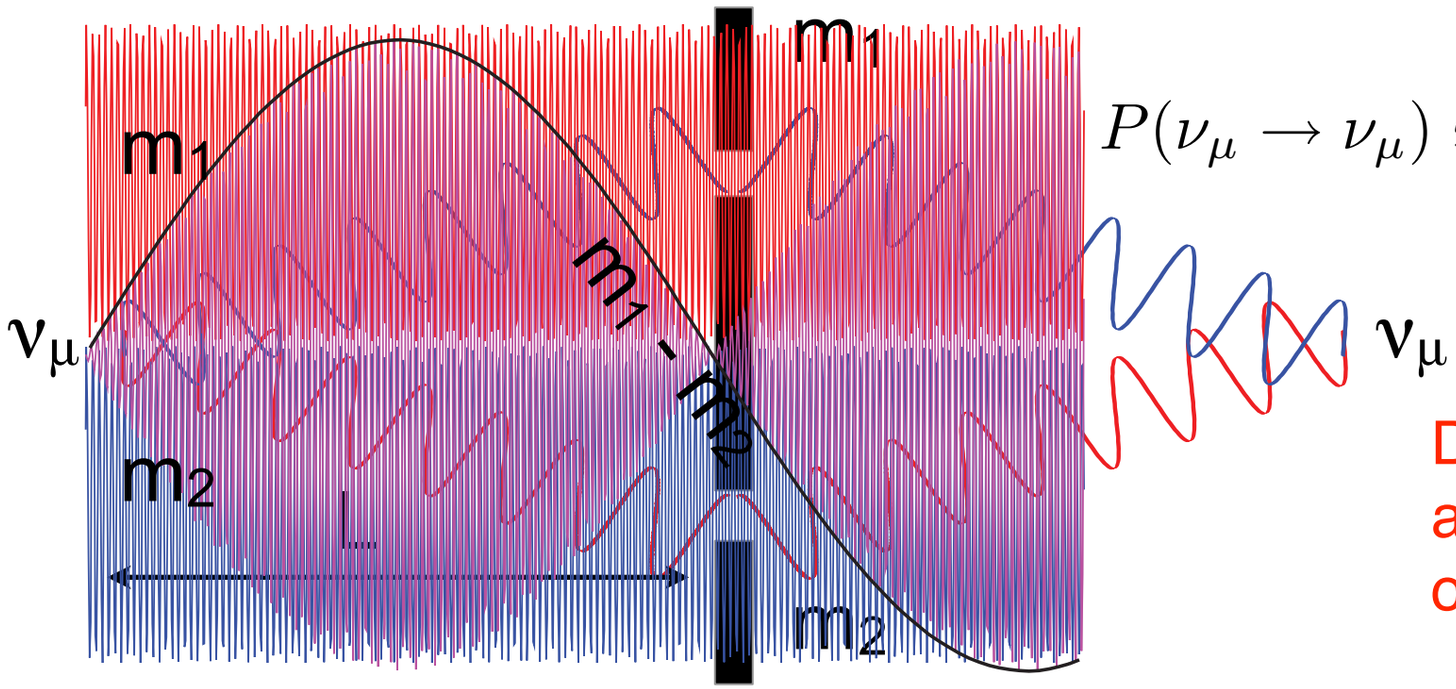
- 1985: IMB and Kamiokande experiments observe the “atmospheric neutrino anomaly”. Note: both of these experiments were originally designed to search for proton-decay!

- 1996: Super-Kamiokande collaboration reports finding neutrino oscillations; muon neutrinos have mass!





Neutrino Oscillations



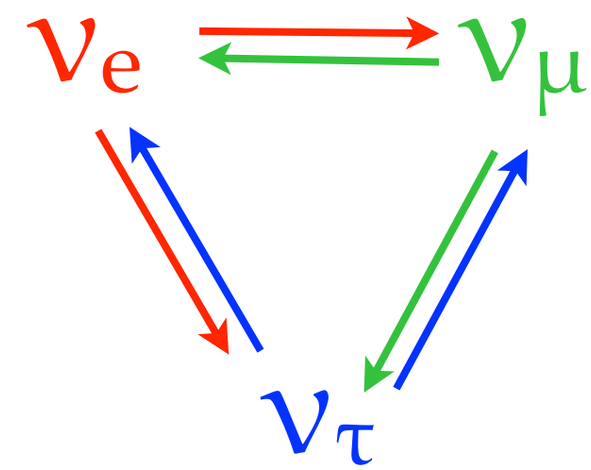
$$P(\nu_\mu \to \nu_\mu) \simeq 1 - \sin^2(2\theta)\sin^2\left(1.27\Delta m^2 \frac{L}{E}\right)$$

Describes the amplitude of the oscillations.

Determines the frequency of the oscillations.

- Neutrino masses are so small that no one has yet been able to directly measure them!
- However, if neutrinos have mass **and** if the ν-flavor states are a quantum superposition of mass eigenstates, then neutrino oscillations occur. In other words, we can see the effect of neutrino mass by measuring their interference pattern!
- **Neutrino oscillations are a quantum-mechanical phenomenon that occur over very large length-scales!**

Neutrino Oscillations



- Neutrino oscillations occur because ν-flavor states are a quantum superposition of mass eigen states.

$$|\nu_\alpha> \; = \sum_i U^*_{\alpha i} |\nu_i>$$

$$P(\nu_\alpha \to \nu_\alpha) = \left| \sum_j U^*_{\alpha j} e^{-i\frac{m_j^2 L}{2E}} U_{\alpha j} \right|^2$$

In vacuum:

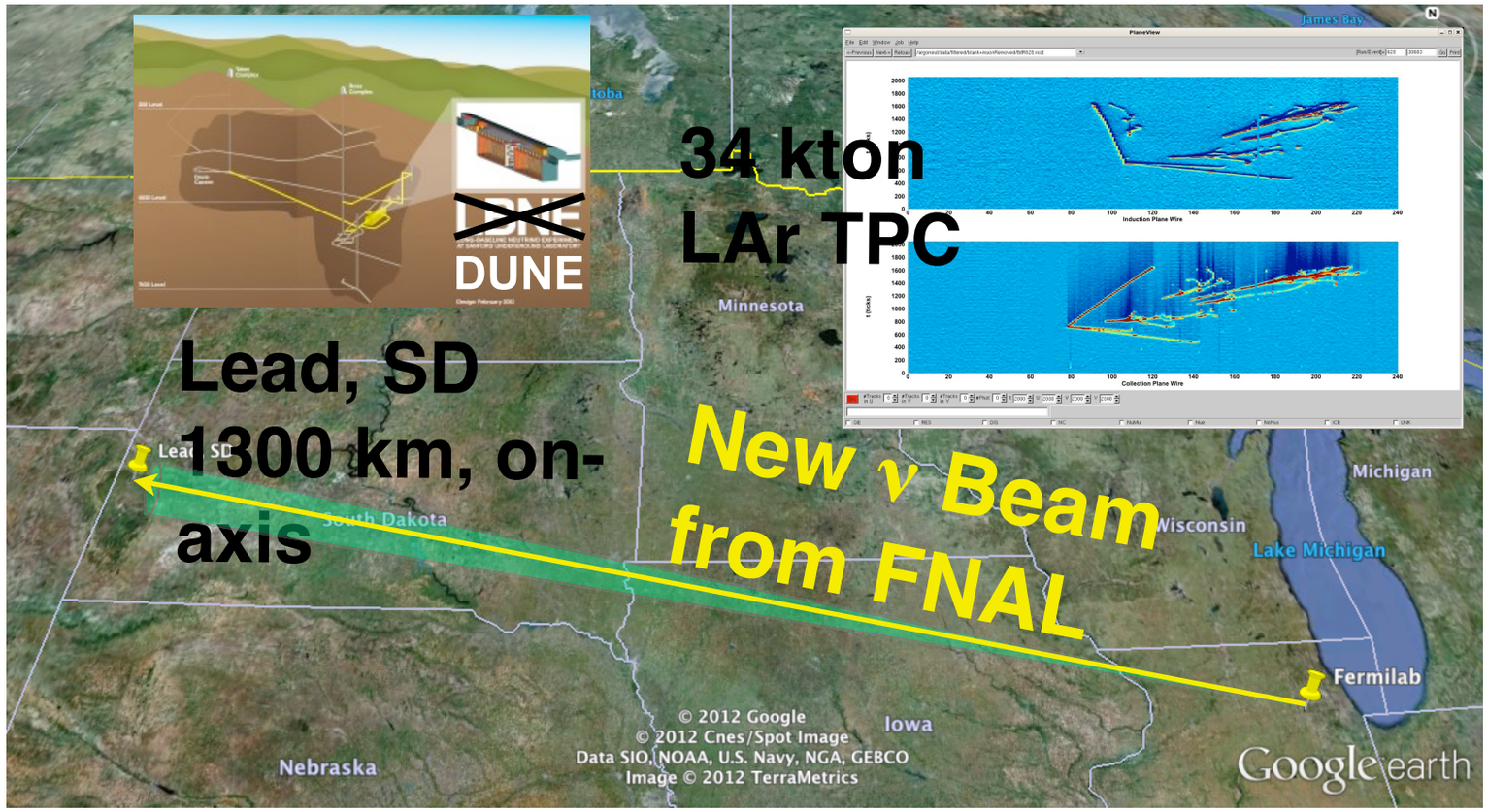
$$P(\nu_\mu \to \nu_e) = \left| 2U^*_{\mu 3} U_{e3} \sin\Delta_{31} e^{-i\Delta_{32}} + 2U^*_{\mu 2} U_{e2} \sin\Delta_{21} \right|^2$$

$$\Delta_{ij} \equiv \frac{1.27 \Delta m^2_{ij} [\mathrm{eV}^2] L[\mathrm{km}]}{E[\mathrm{GeV}]}$$

Why Measure These Neutrino Oscillation Parameters?

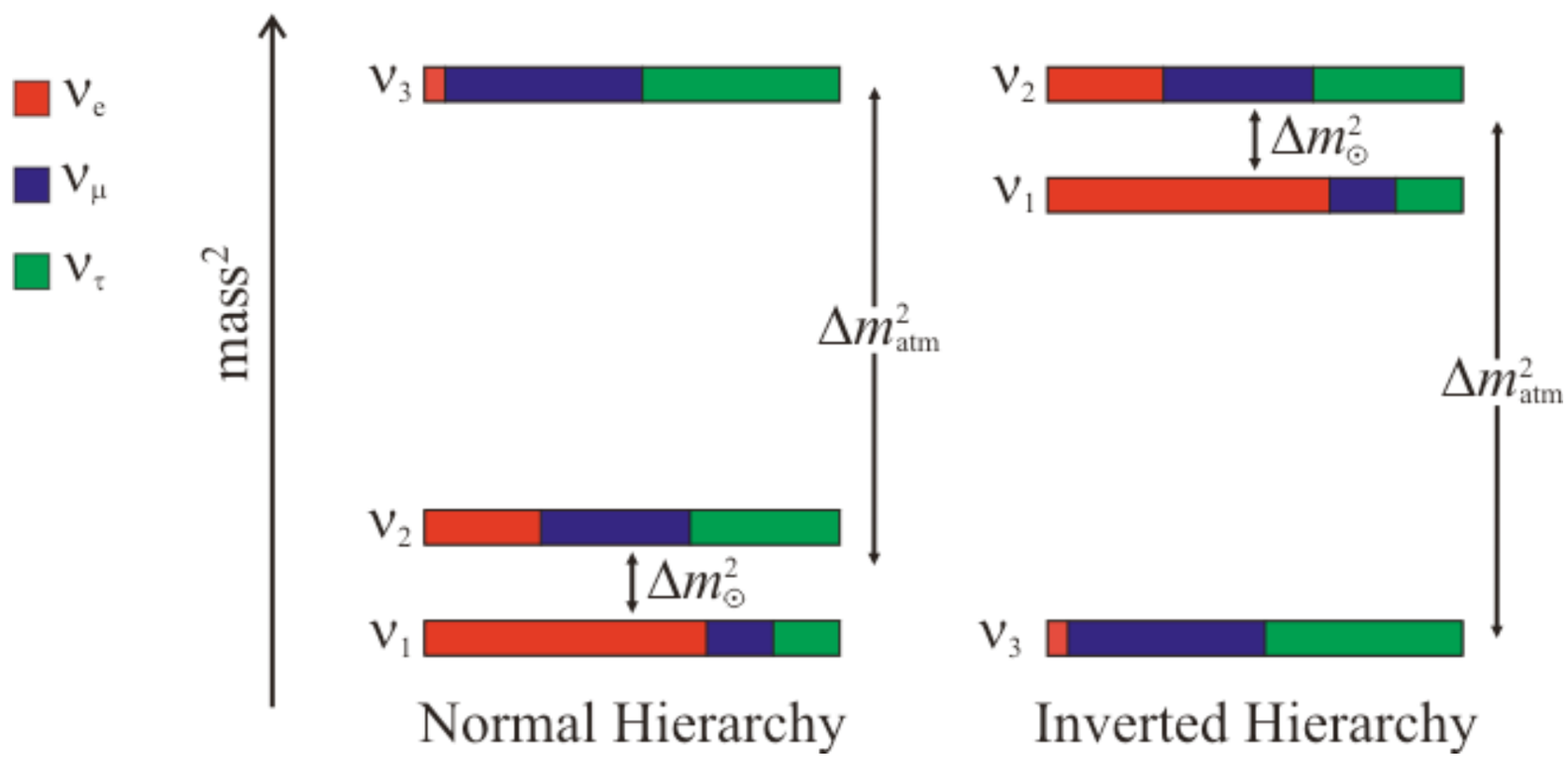
Why Measure These Neutrino Oscillation Parameters?

- If neutrinos violate CP, they could have driven leptogenesis in the early universe, which could explain the matter-antimatter asymmetry in the universe.
- These are fundamental parameters, needed for both theoretical calculations as well as for optimizing future experiments.



Why Measure These Neutrino Oscillation Parameters?

- If neutrinos violate CP, they could have driven leptogenesis in the early universe, which could explain the matter-antimatter asymmetry in the universe.
- These are fundamental parameters, needed for both theoretical calculations as well as for optimizing future experiments.
- Do the relative masses of the neutrinos follow a “normal” hierarchy ($m_3>m_2>m_1$) or an “inverted” hierarchy ($m_2>m_1>m_3$)?



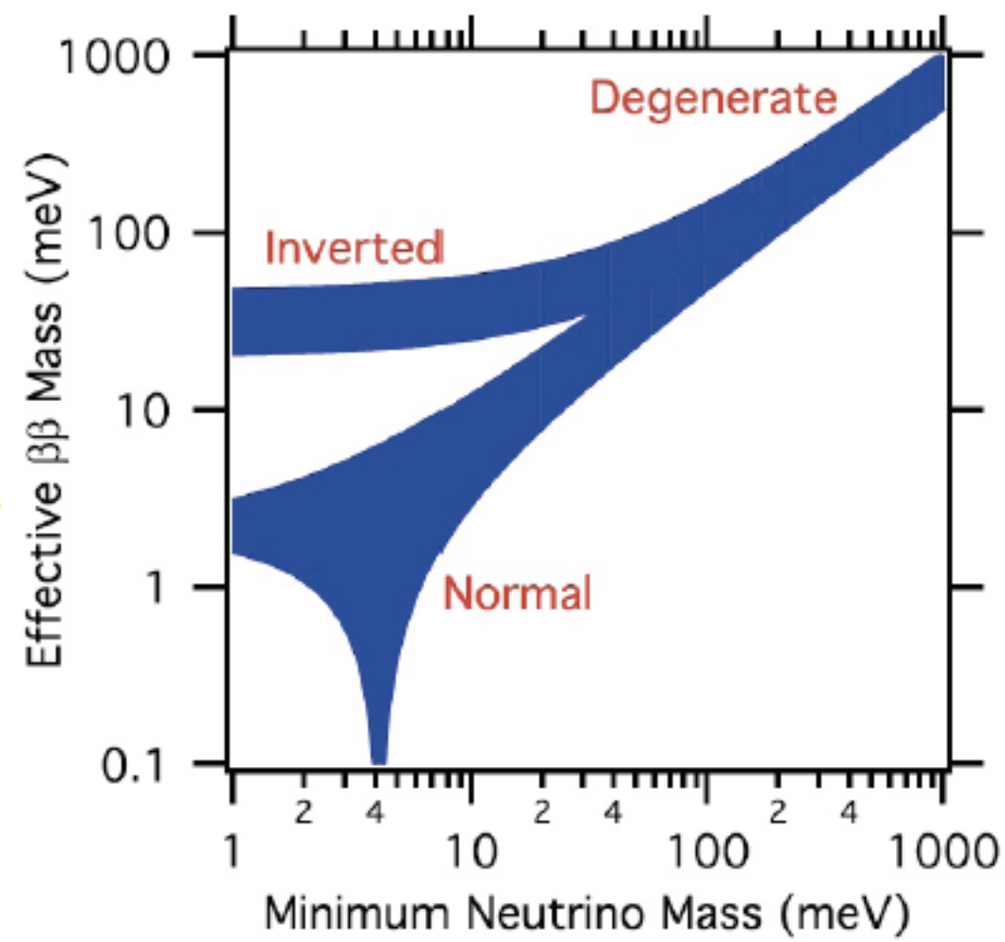
Why Measure These Neutrino Oscillation Parameters?

- If neutrinos violate CP, they could have driven leptogenesis in the early universe, which could explain the matter-antimatter asymmetry in the universe.
- These are fundamental parameters, needed for both theoretical calculations as well as for optimizing future experiments.
- Do the relative masses of the neutrinos follow a “normal” hierarchy ($m_3>m_2>m_1$) or an “inverted” hierarchy ($m_2>m_1>m_3$)?
- If θ_{23} is exactly maximal, why? The pattern of mixing angles could provide insights into unification, new symmetries, selection rules, etc.

$$U_{\mathrm{HPS}} = \begin{array}{c} \begin{array}{ccc} \nu_1 & \nu_2 & \nu_3 \end{array} \\ \begin{pmatrix} \sqrt{2/3} & 1/\sqrt{3} & 0 \\ -1/\sqrt{6} & 1/\sqrt{3} & -1/\sqrt{2} \\ -1/\sqrt{6} & 1/\sqrt{3} & 1/\sqrt{2} \end{pmatrix} \end{array} \begin{array}{c} \\ e \\ \mu \\ \tau \end{array}$$

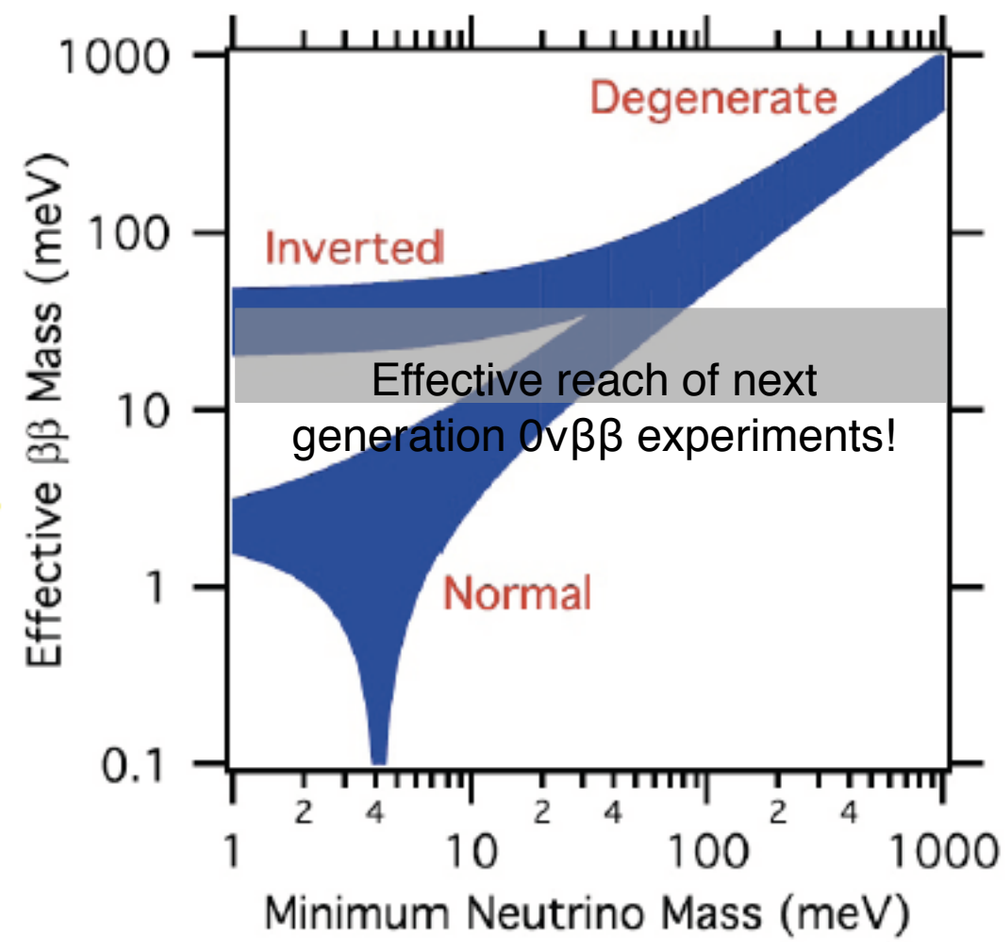
Why Measure These Neutrino Oscillation Parameters?

- If neutrinos violate CP, they could have driven leptogenesis in the early universe, which could explain the matter-antimatter asymmetry in the universe.
- These are fundamental parameters, needed for both theoretical calculations as well as for optimizing future experiments.
- Do the relative masses of the neutrinos follow a “normal” hierarchy ($m_3>m_2>m_1$) or an “inverted” hierarchy ($m_2>m_1>m_3$)?
- If θ_{23} is exactly maximal, why? The pattern of mixing angles could provide insights into unification, new symmetries, selection rules, etc.
- If neutrino oscillation experiments establish the inverted hierarchy and the next generation 0vBB experiments see nothing, then it is very likely that neutrinos are Dirac particles.



Why Measure These Neutrino Oscillation Parameters?

- If neutrinos violate CP, they could have driven leptogenesis in the early universe, which could explain the matter-antimatter asymmetry in the universe.
- These are fundamental parameters, needed for both theoretical calculations as well as for optimizing future experiments.
- Do the relative masses of the neutrinos follow a “normal” hierarchy ($m_3>m_2>m_1$) or an “inverted” hierarchy ($m_2>m_1>m_3$)?
- If θ_{23} is exactly maximal, why? The pattern of mixing angles could provide insights into unification, new symmetries, selection rules, etc.
- If neutrino oscillation experiments establish the inverted hierarchy and the next generation 0vBB experiments see nothing, then it is very likely that neutrinos are Dirac particles.



Why Measure These Neutrino Oscillation Parameters?

- If neutrinos violate CP, they could have driven leptogenesis in the early universe, which could explain the matter-antimatter asymmetry in the universe.
- These are fundamental parameters, needed for both theoretical calculations as well as for optimizing future experiments.
- Do the relative masses of the neutrinos follow a “normal” hierarchy ($m_3>m_2>m_1$) or an “inverted” hierarchy ($m_2>m_1>m_3$)?
- If θ_{23} is exactly maximal, why? The pattern of mixing angles could provide insights into unification, new symmetries, selection rules, etc.
- If neutrino oscillation experiments establish the inverted hierarchy and the next generation 0vBB experiments see nothing, then it is very likely that neutrinos are Dirac particles.
- Small neutrino masses suggest a heavy partner (eg, see-saw mechanism) - neutrinos provide a window to physics at the GUT scale!

Why Measure These Neutrino Oscillation Parameters?

- If neutrinos violate CP, they could have driven leptogenesis in the early universe, which could explain the matter-antimatter asymmetry in the universe.
- These are fundamental parameters, needed for both theoretical calculations as well as for optimizing future experiments.
- Do the relative masses of the neutrinos follow a “normal” hierarchy ($m_3>m_2>m_1$) or an “inverted” hierarchy ($m_2>m_1>m_3$)?
- If θ_{23} is exactly maximal, why? The pattern of mixing angles could provide insights into unification, new symmetries, selection rules, etc.
- If neutrino oscillation experiments establish the inverted hierarchy and the next generation 0vBB experiments see nothing, then it is very likely that neutrinos are Dirac particles.
- Small neutrino masses suggest a heavy partner (eg, see-saw mechanism) - neutrinos provide a window to physics at the GUT scale!
- Look for signs of new physics by overconstraining the theory with many precision measurements.

Cross-Sections & Fluxes

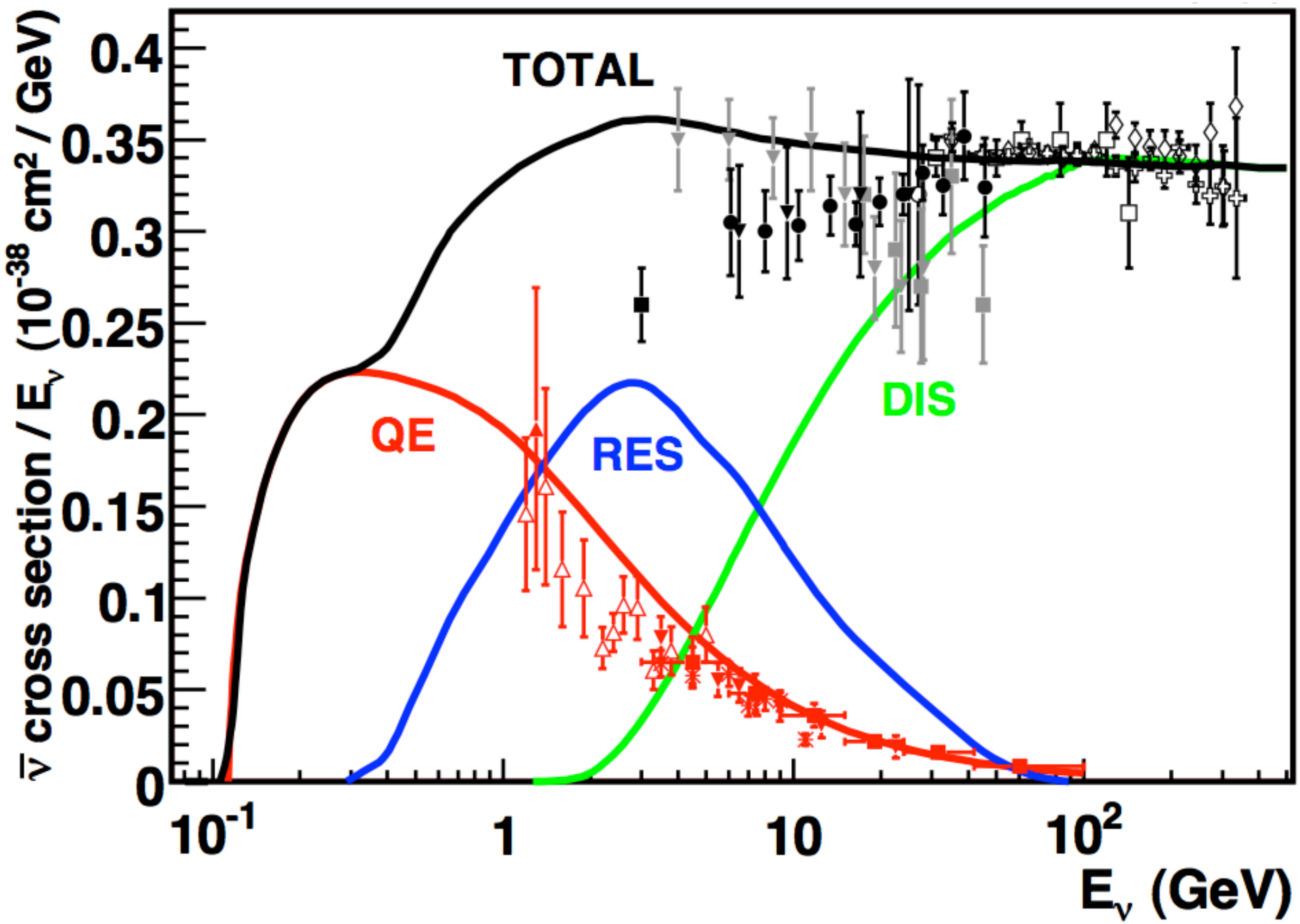
- Generally speaking, need to know how many neutrinos one expects to see in a detector

$$N_\nu(E) = \Phi_\nu(E)\sigma_\nu(E)$$

- In oscillation experiments, this knowledge can be ~circumvented by using two detectors to cancel out our ignorance. One detector located near the source to measure $N_\nu(E)$ before the ν's oscillate, one detector located farther away after ν's have oscillated.

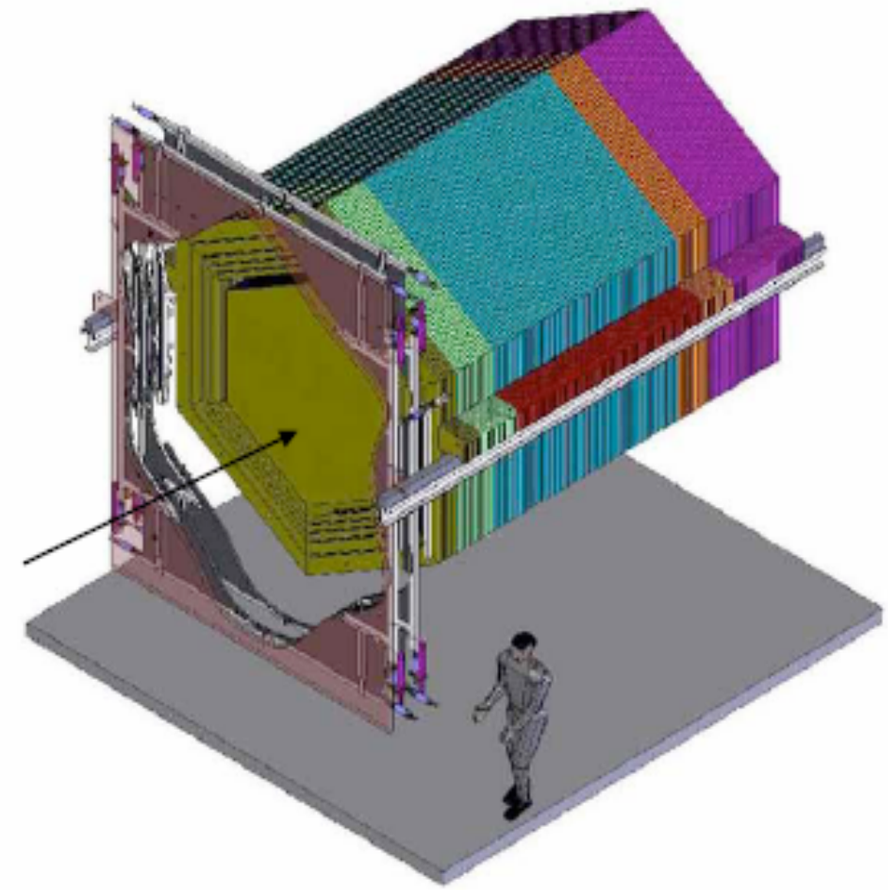
- However, this is not exactly a silver bullet:
  - some experiments only have one detector
  - some experiments have two detectors, but made of different materials/ geometry
  - some experiments want to measure the cross-section

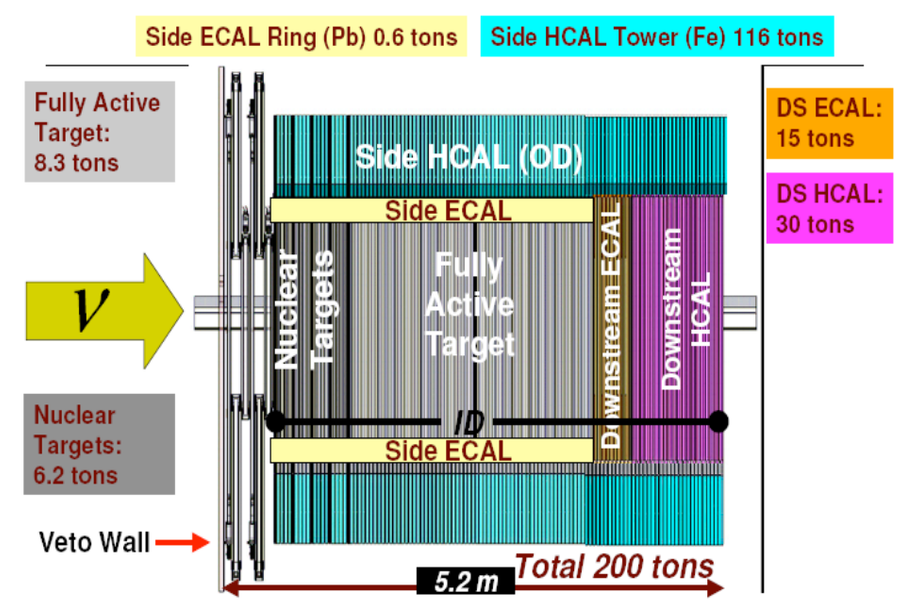
Cross-Sections



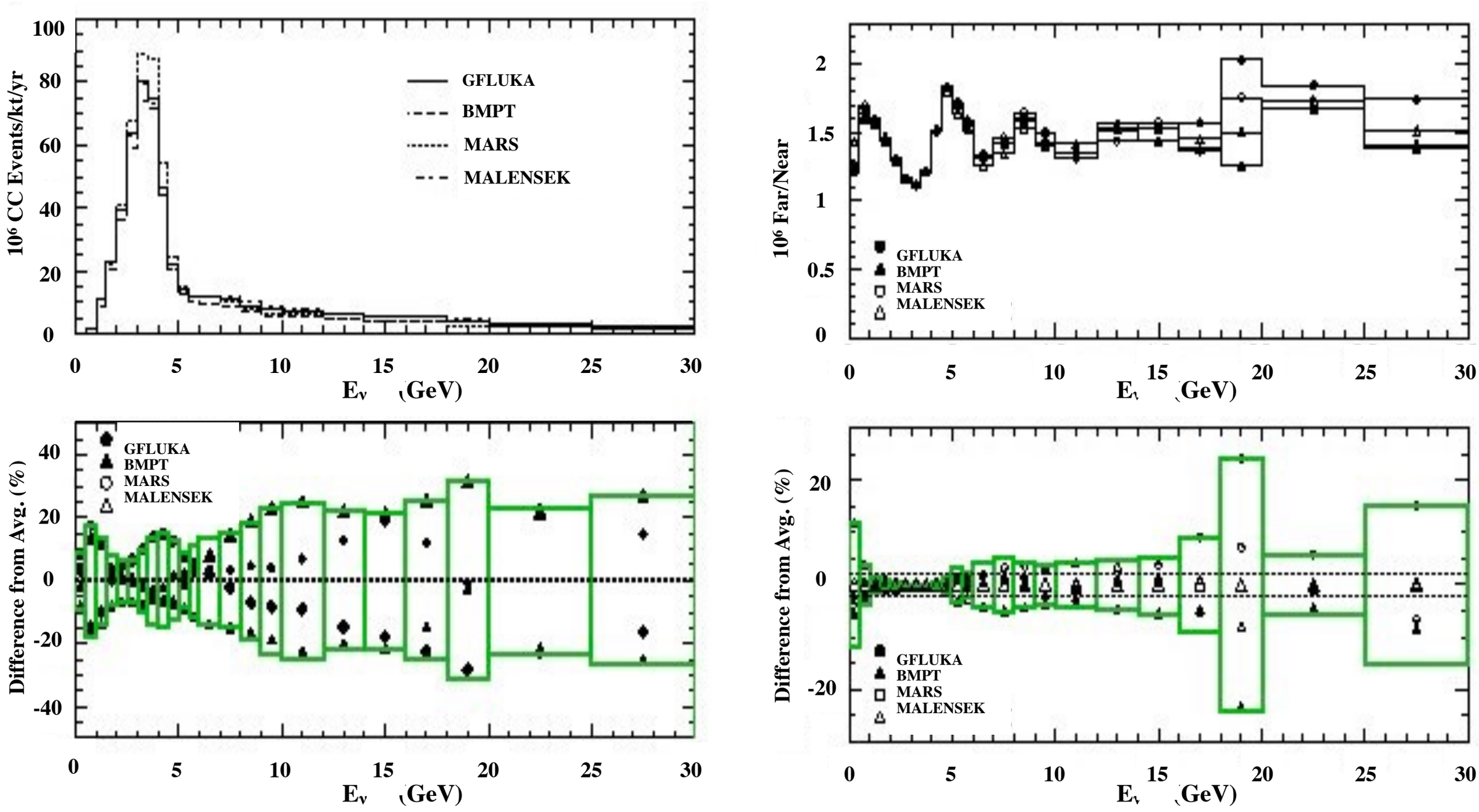
Cross-Sections & Fluxes

- MINERvA seeks to measure low-energy neutrino cross-sections to support neutrino oscillation experiments as well as to study the strong dynamics of the nucleon and nucleus that effect these interactions.
- Active core (8.3 ton): segmented solid scintillator for tracking and PID.
- Core surrounded by EM and hadronic calorimeters.
- MINOS acts as muon catcher.
- Goal is to measure quasi-elastic (QE), resonance (Res) and deep inelastic scattering (DIS) cross-sections to ~5--10% for energies of ~0.5-20 GeV.
- Various targets will cover large A-range.

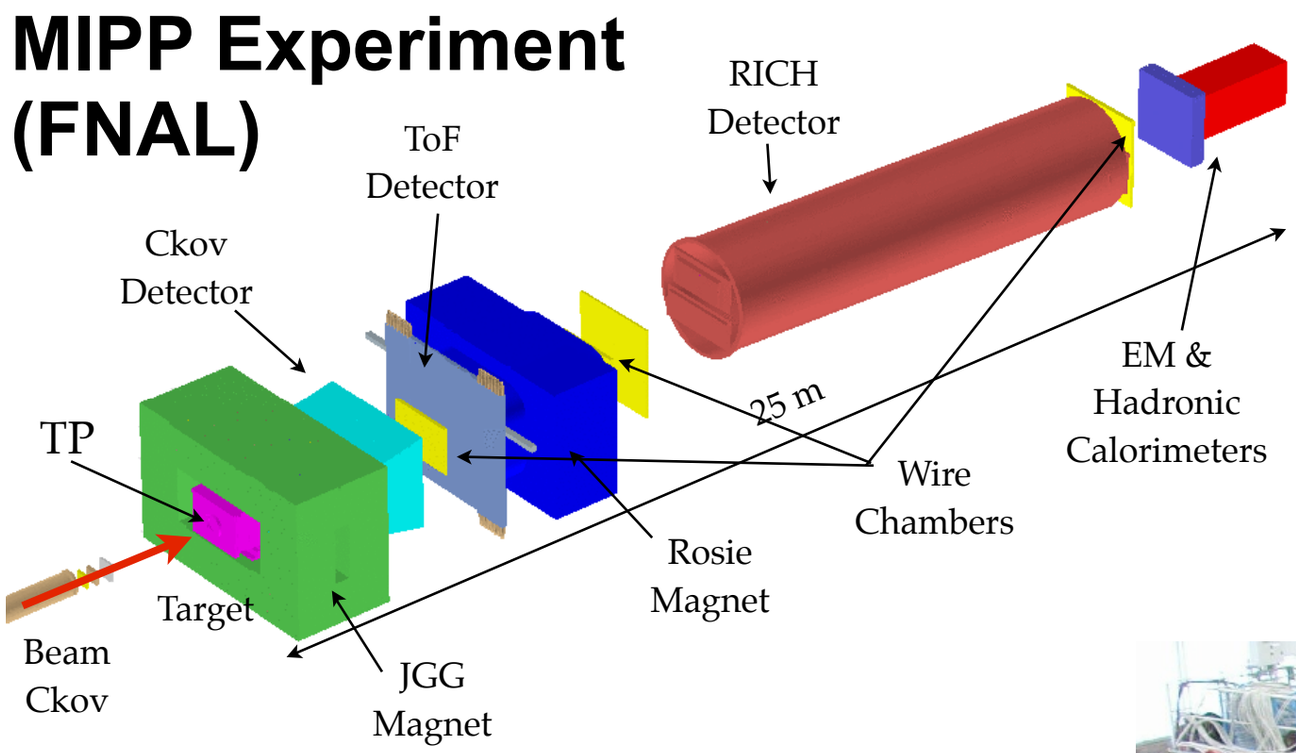


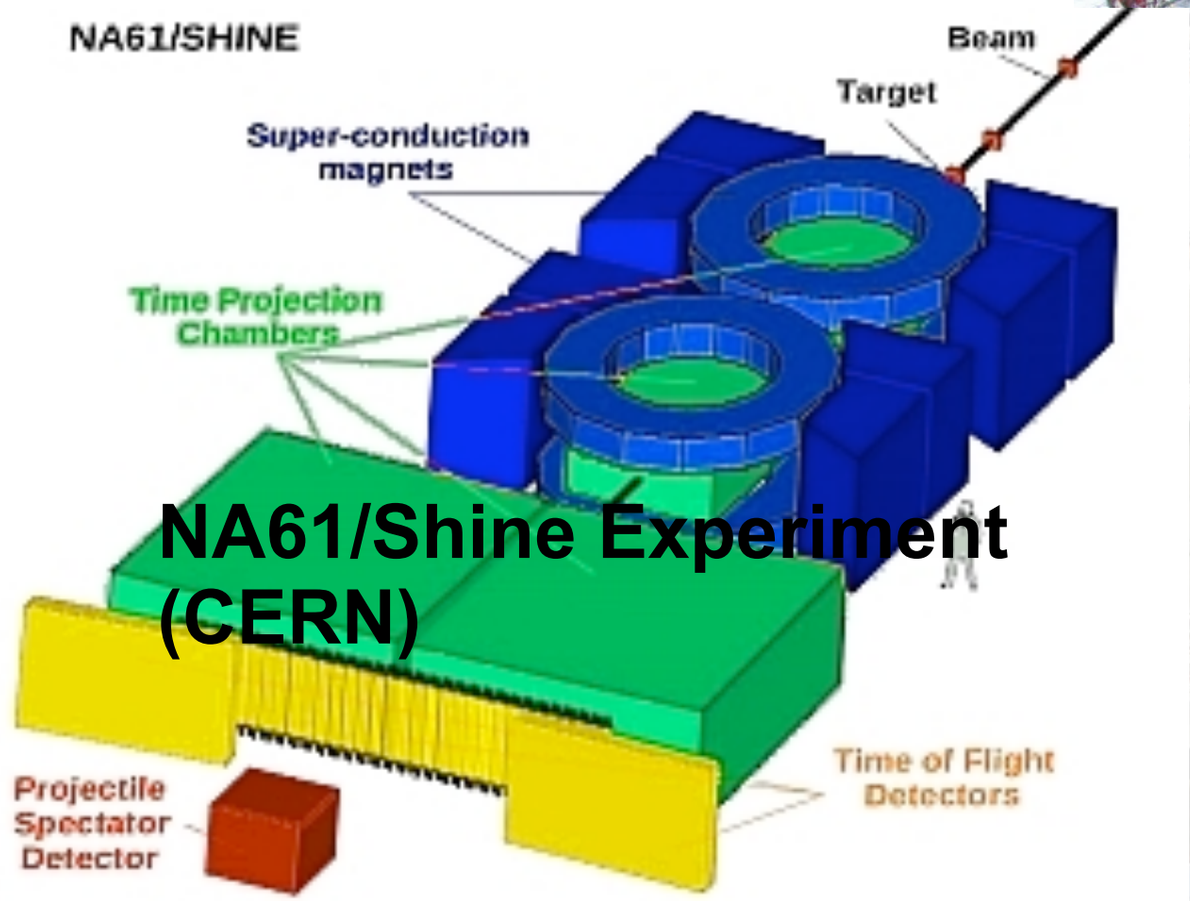


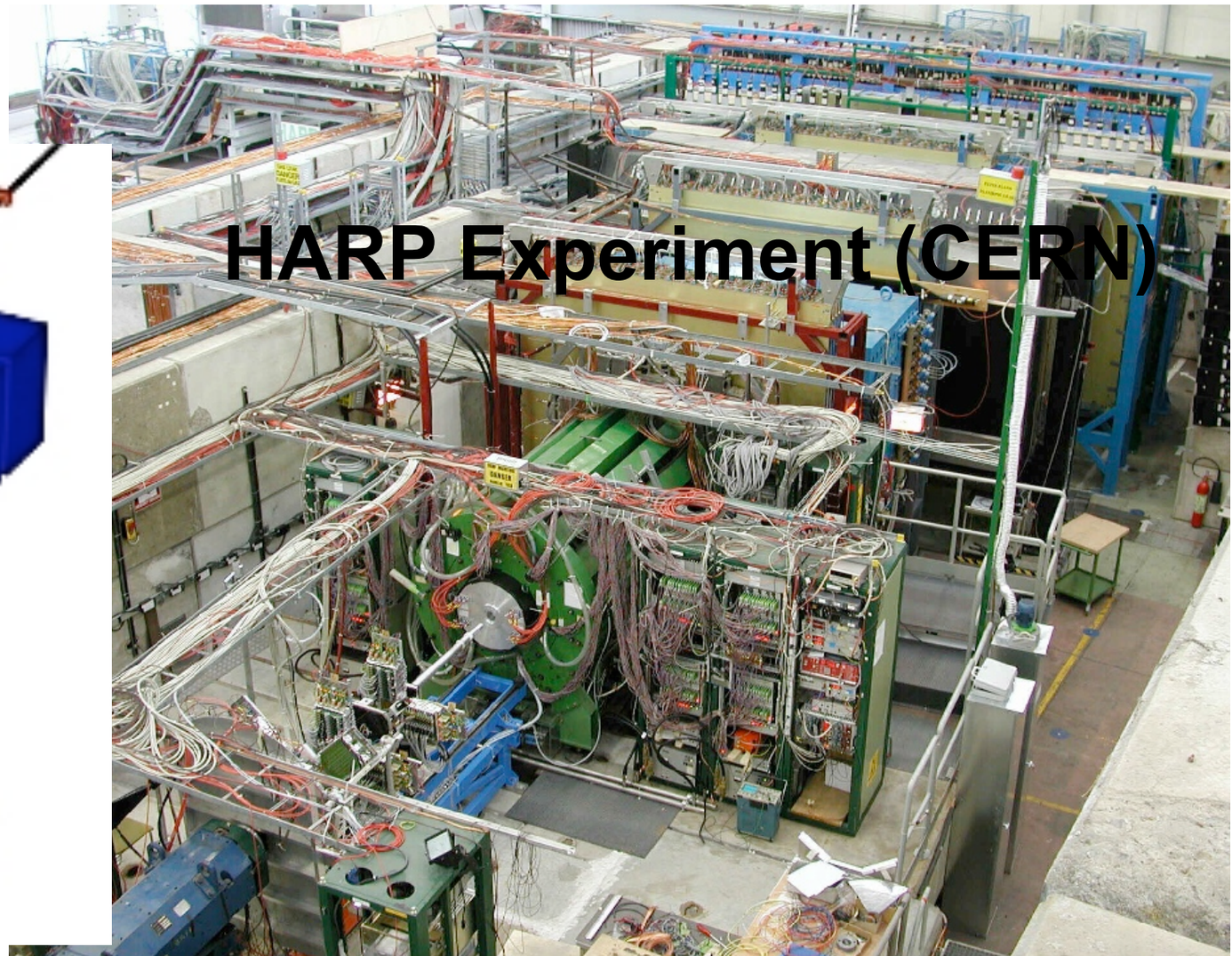
Neutrino Fluxes



Neutrino Fluxes

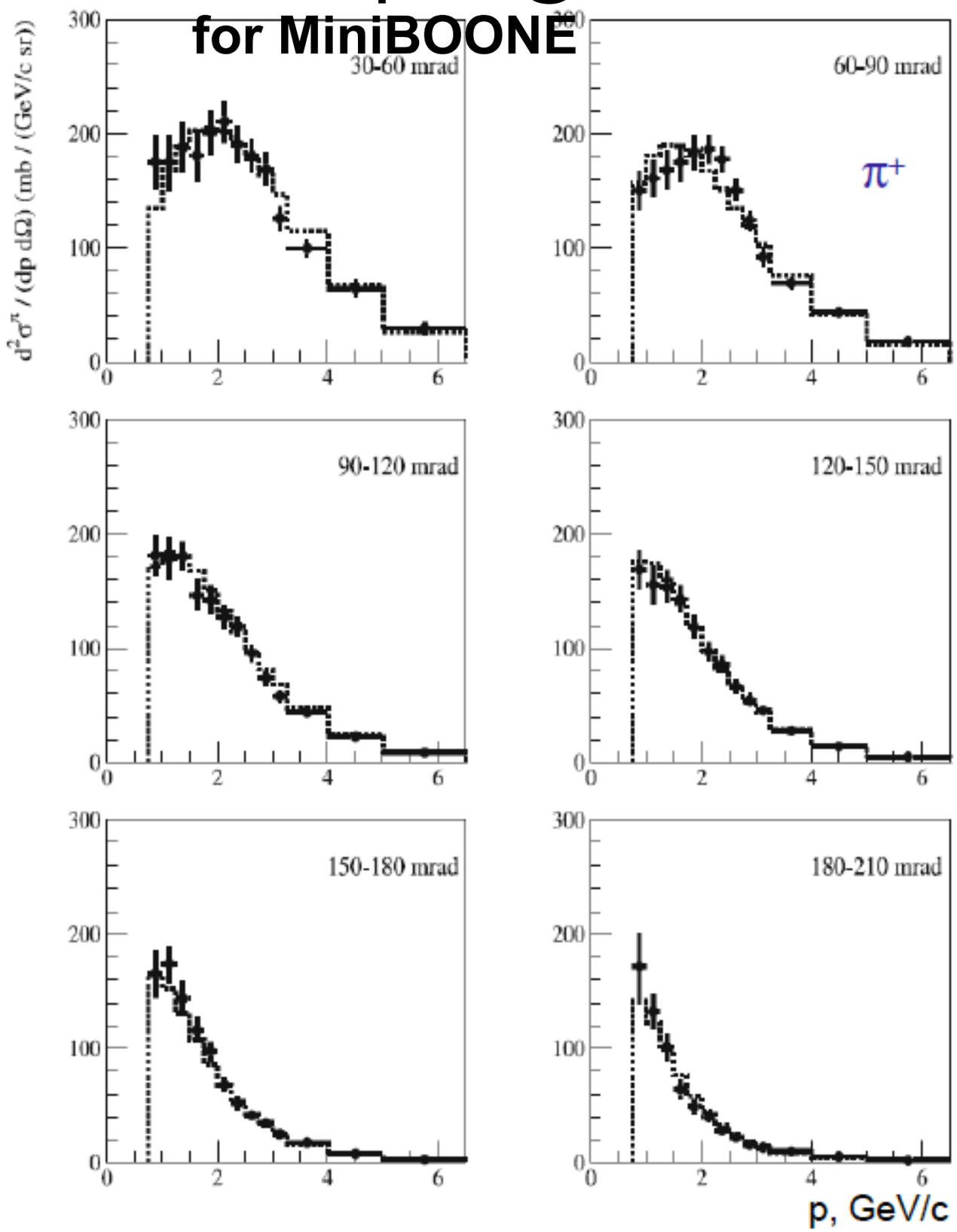






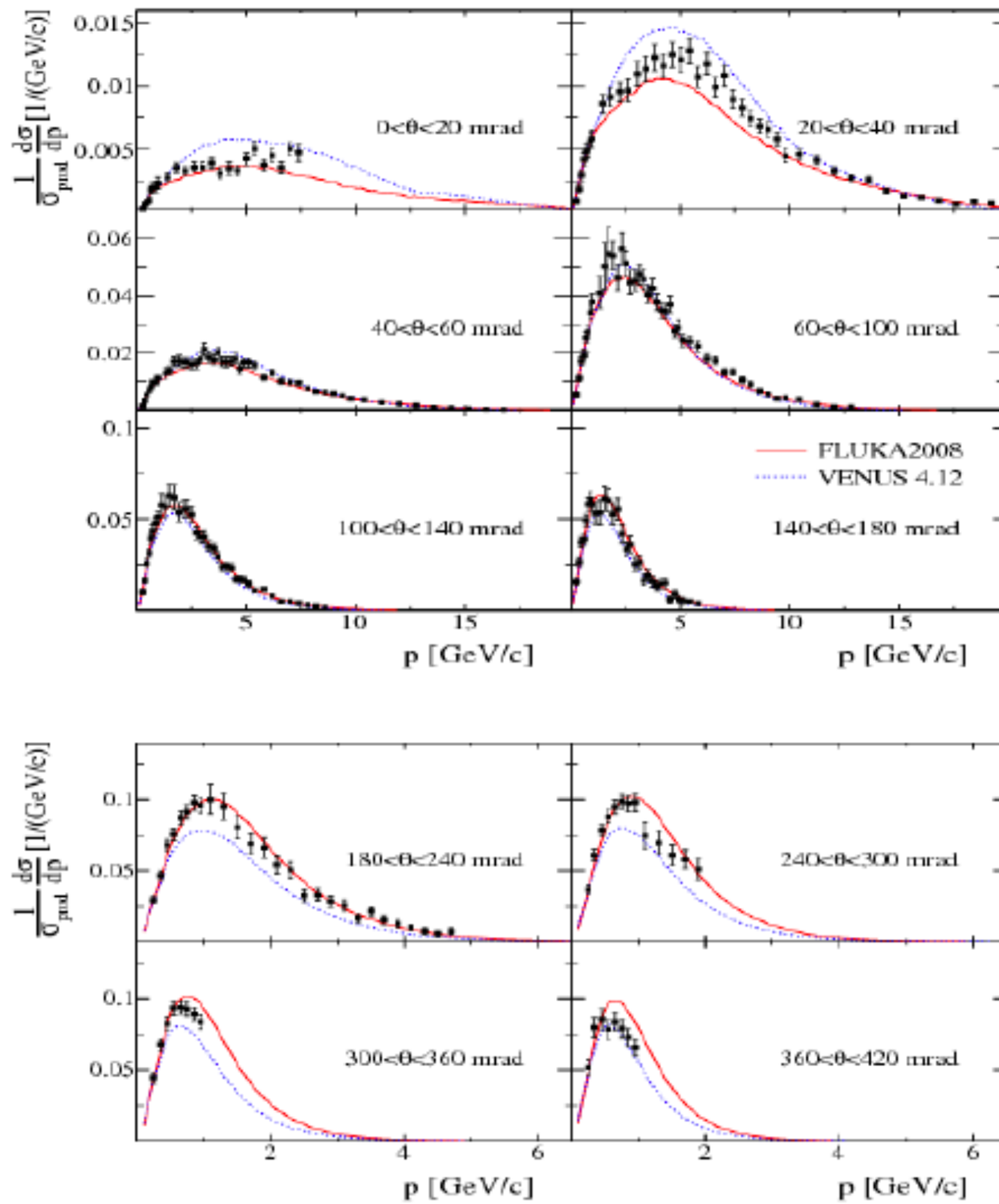
Neutrino Fluxes

HARP: p+Be @ 8.9 GeV/c for MiniBOONE



NA61: p+C @ 31 GeV/c for T2K

Published in PRC 84 (2011) 034604

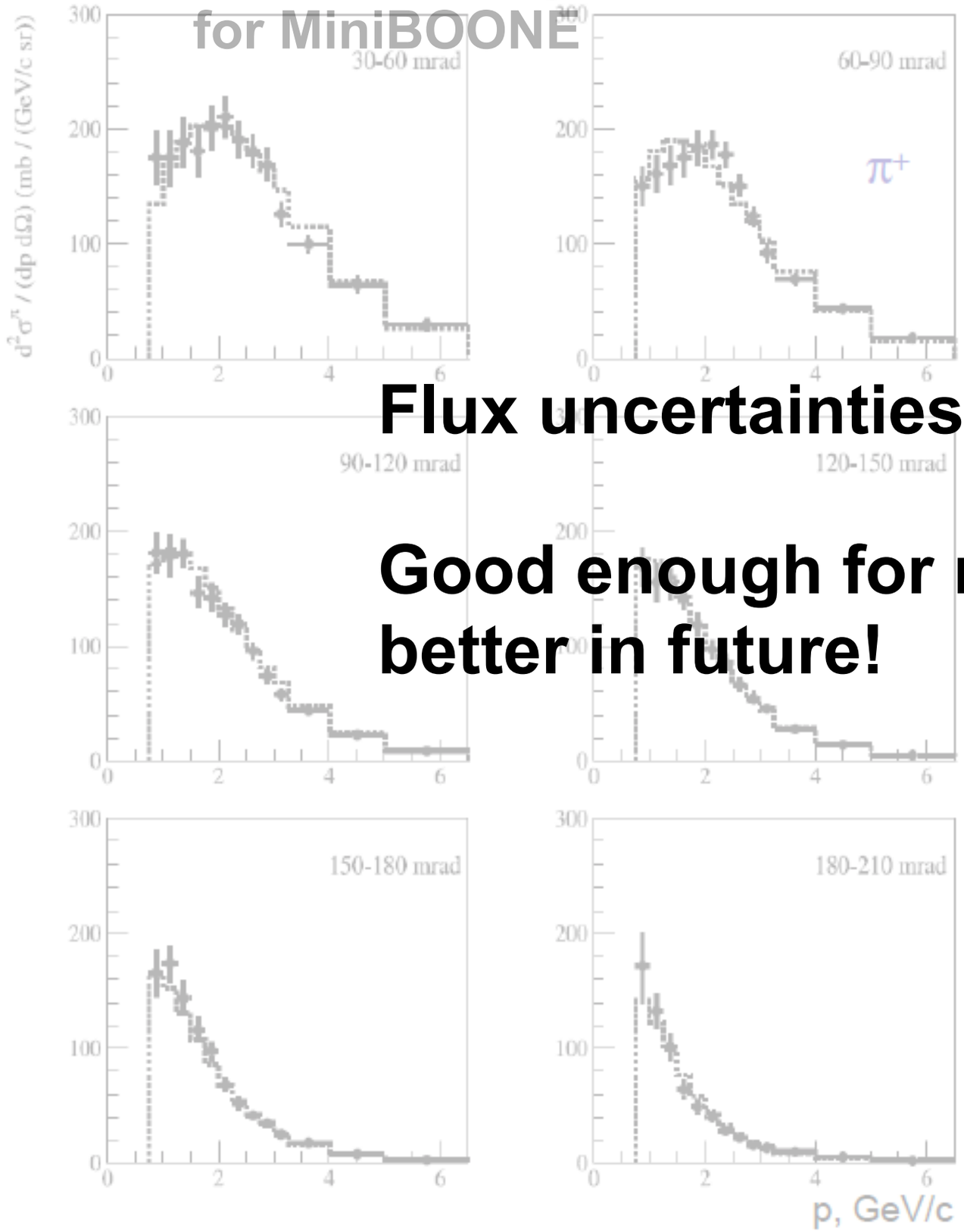


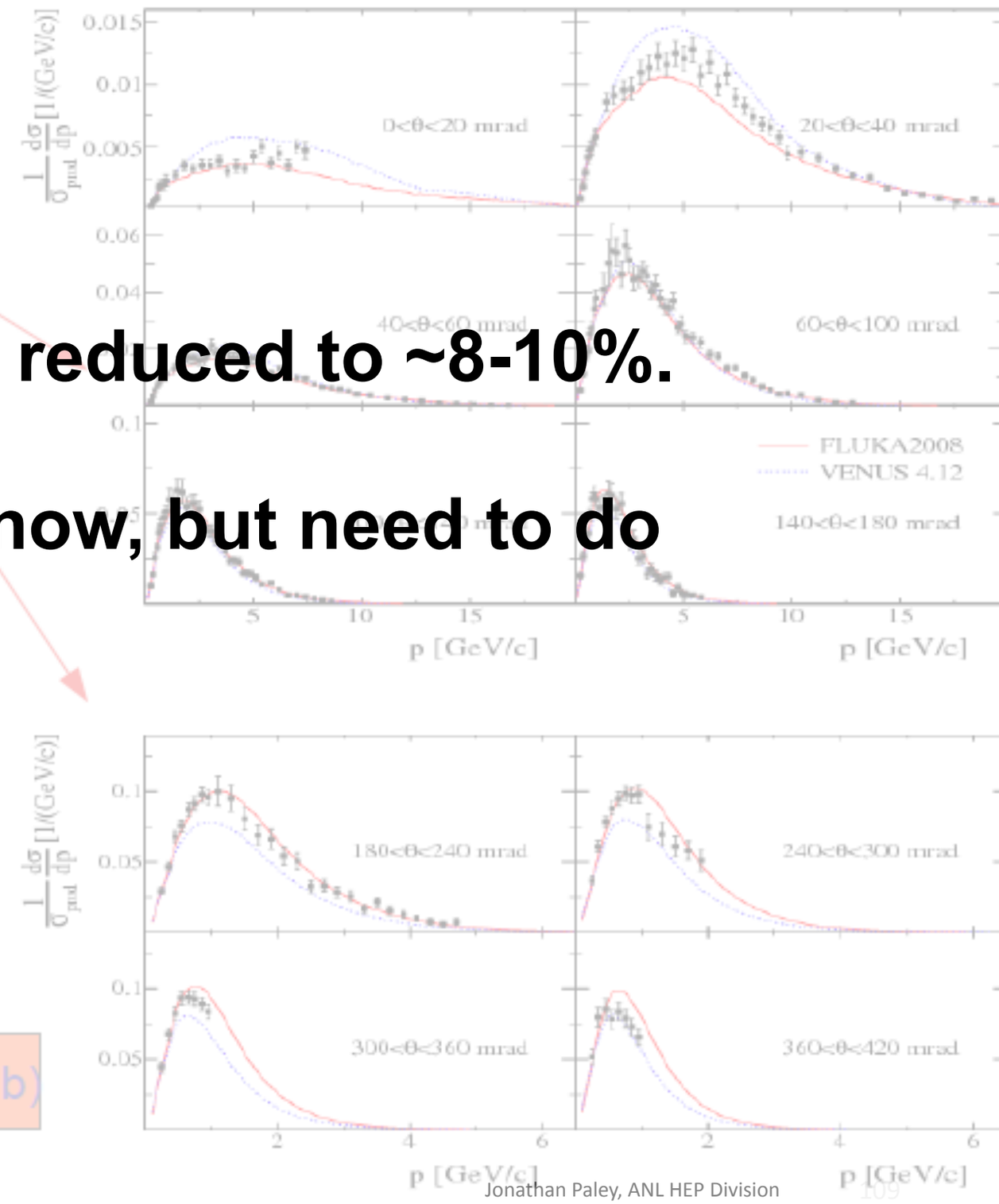
Neutrino Fluxes

HARP: p+Be @ 8.9 GeV/c for MiniBOONE

NA61: p+C @ 31 GeV/c for T2K

Published in PRC 84 (2011) 034604



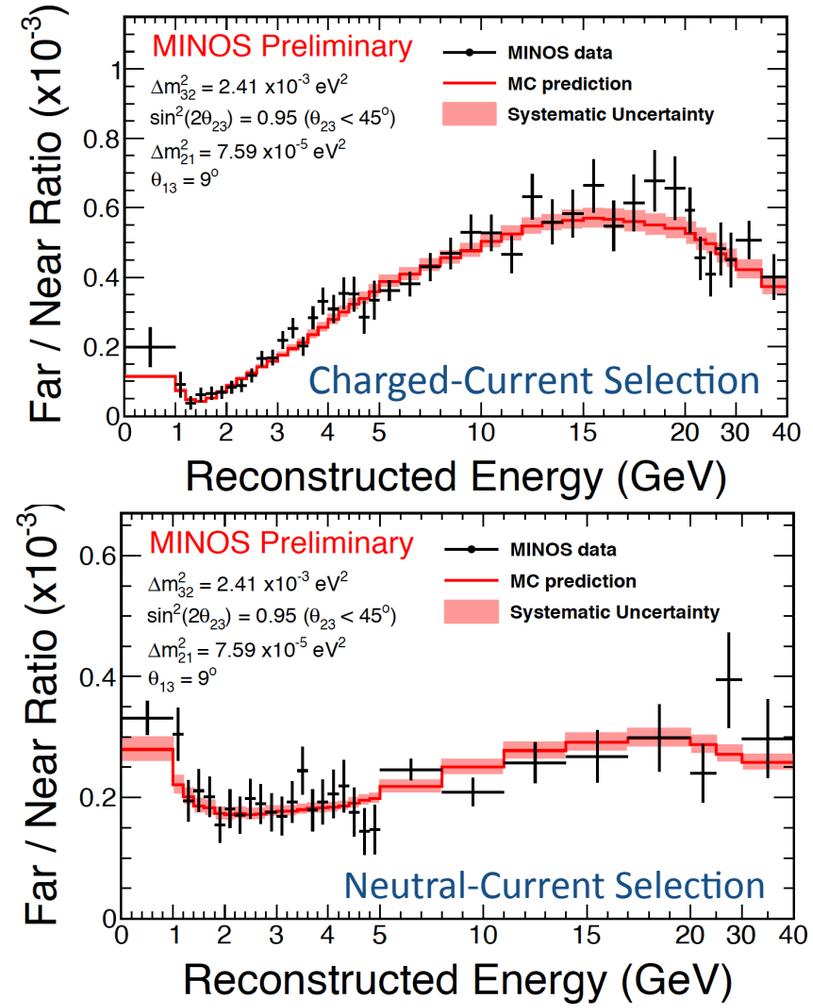


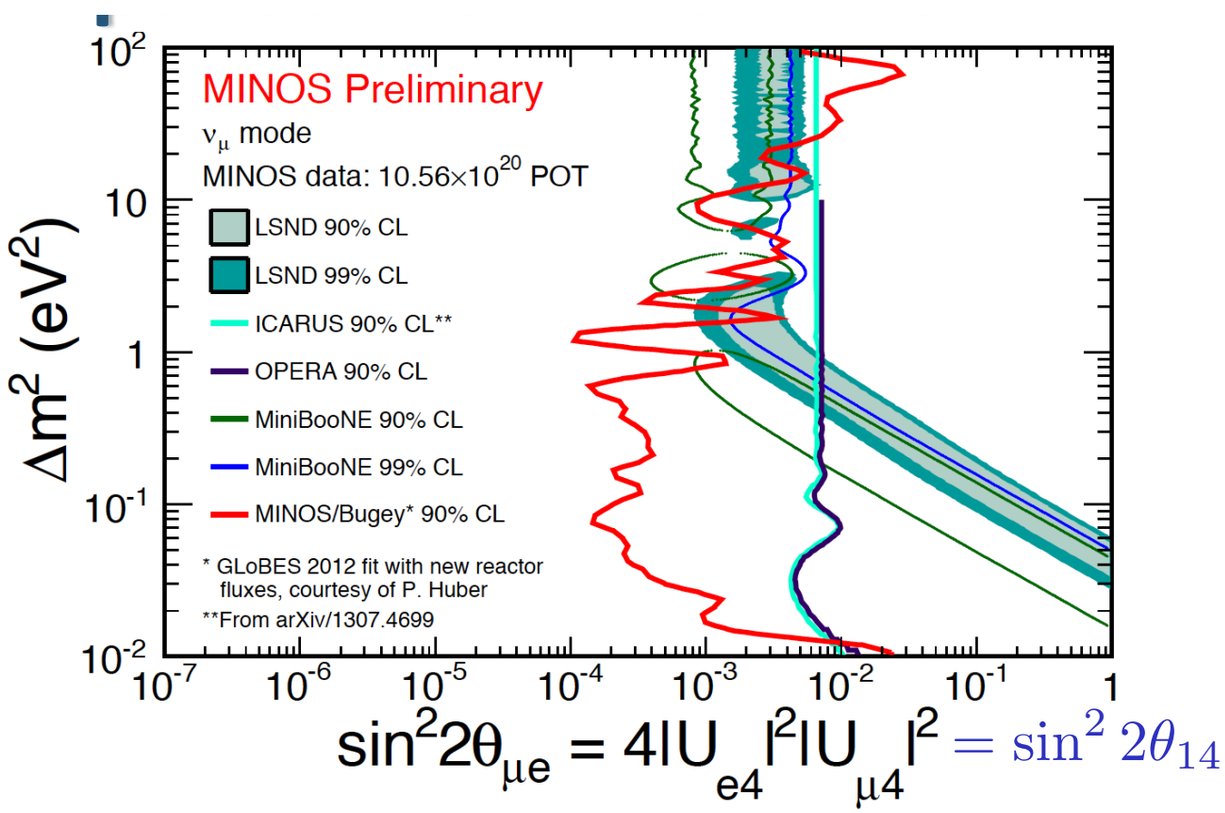
Flux uncertainties reduced to ~8-10%.

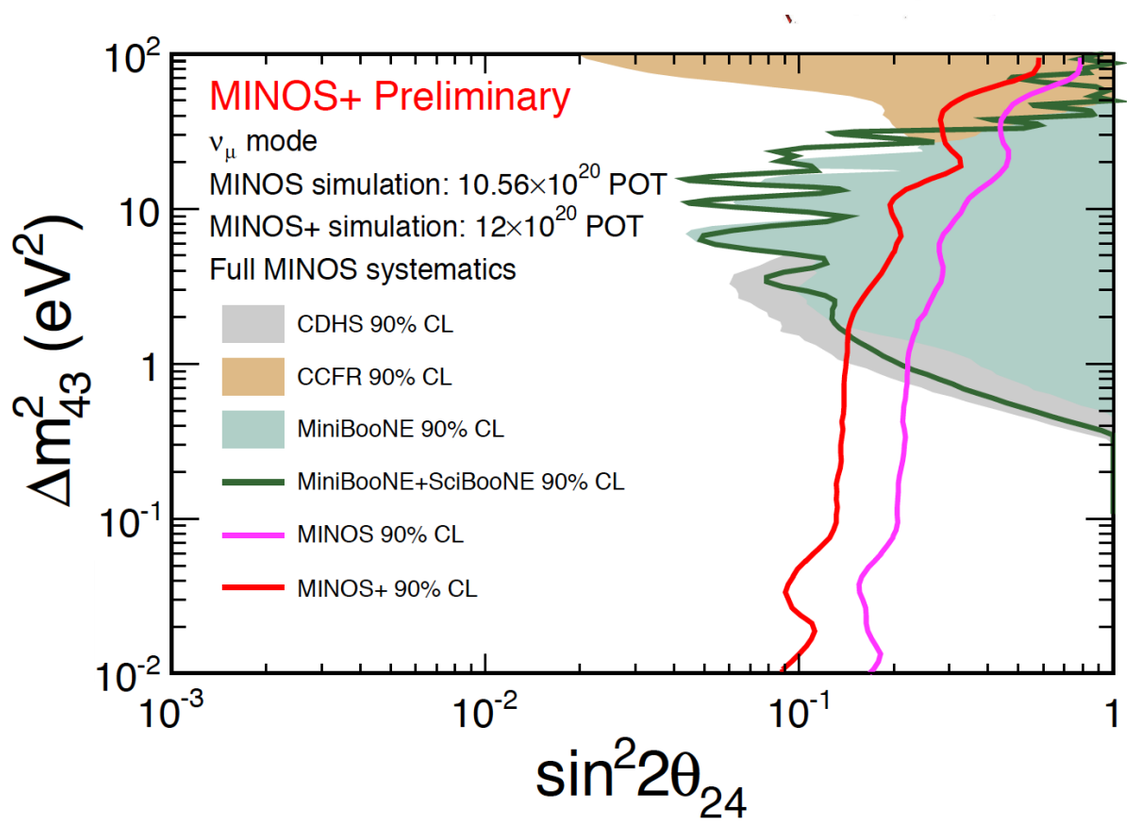
Good enough for now, but need to do better in future!

MINOS+

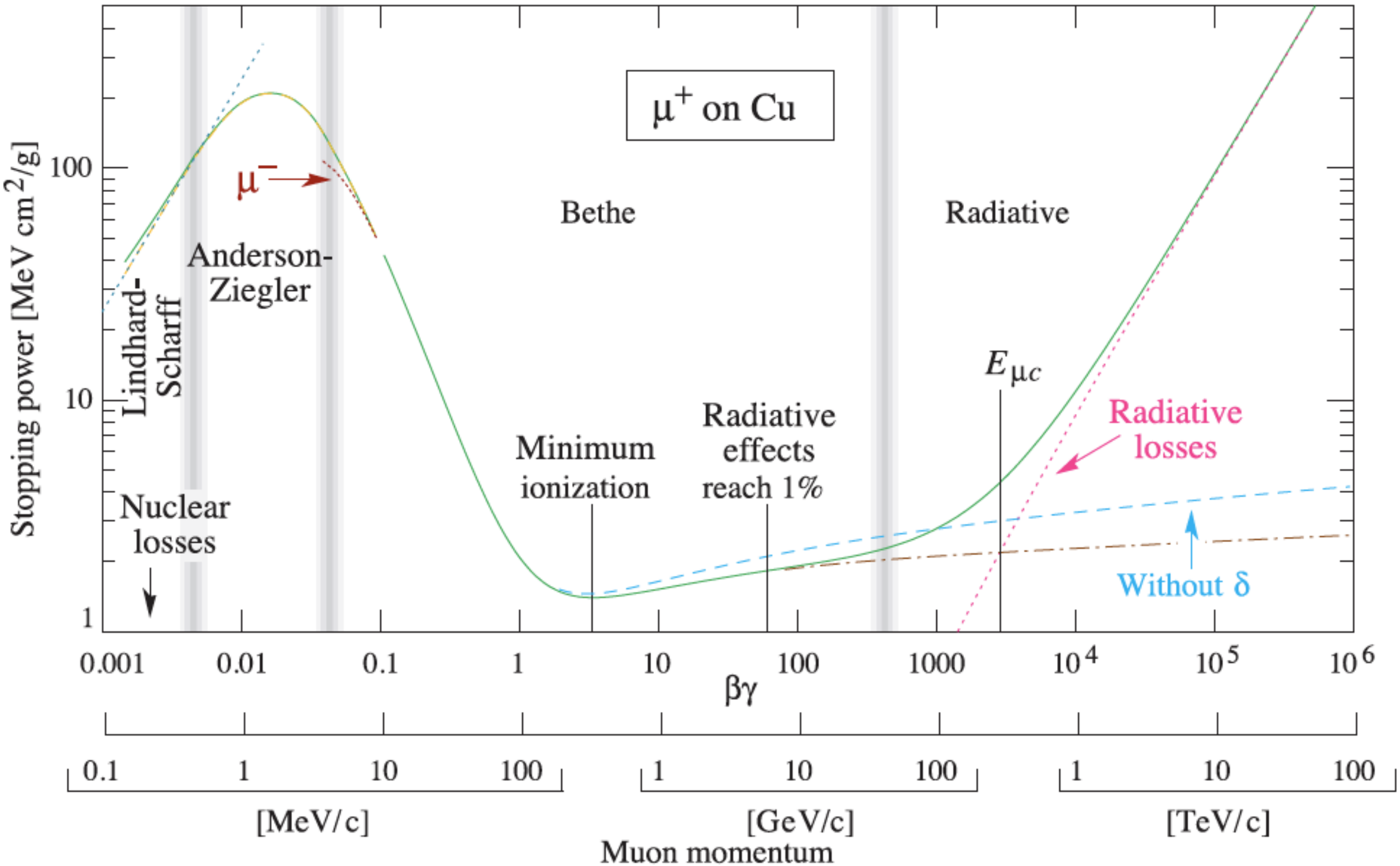
- With the recent NuMI upgrades, the MINOS FD should see ~4000 ν_μ events/ year at higher energies.
- Offers an opportunity for a precise test of three-flavor mixing paradigm.
- Also sensitive to "exotic" signals as well as ~80 ν_τ CC events.





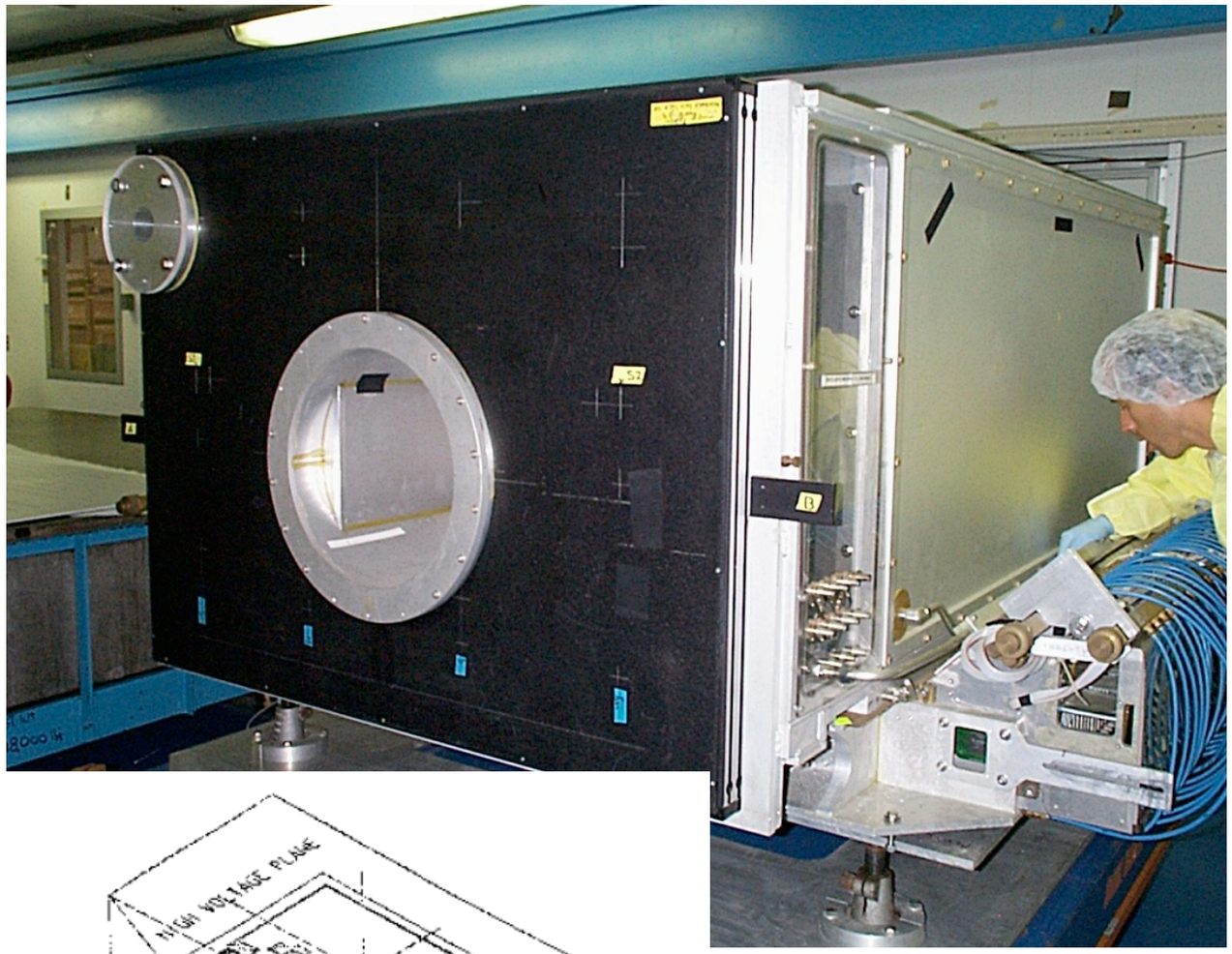


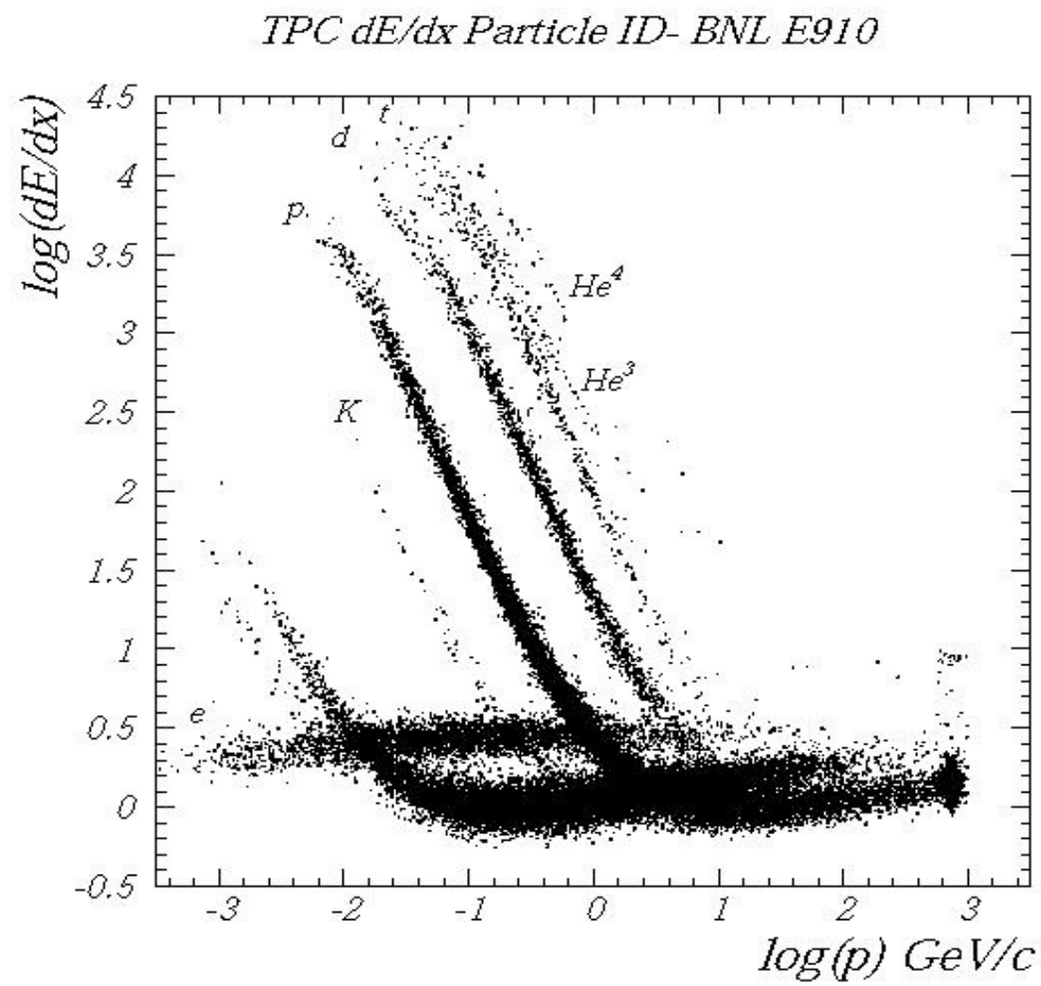
Bethe-Bloch Equation

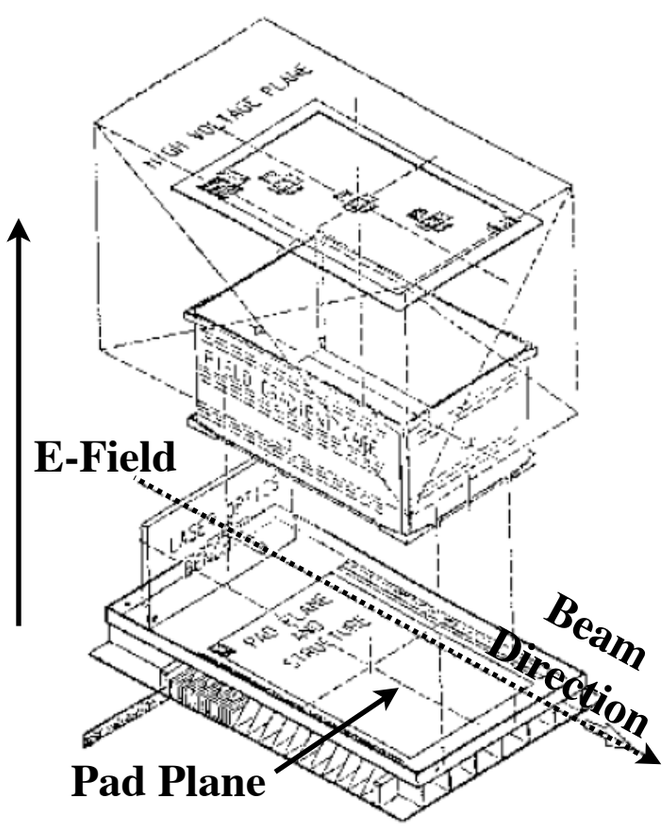


$$-\left\langle \frac{dE}{dx} \right\rangle = K z^2 \frac{Z}{A} \frac{1}{\beta^2} \left[\frac{1}{2} \ln \frac{2 m_e c^2 \beta^2 \gamma^2 T_{\max}}{I^2} - \beta^2 - \frac{\delta(\beta\gamma)}{2} \right]$$

Time Projection Chamber







- (x,z) position → pad locations, y position → drift time.
- Active volume of ~1 m^3 and a resolution of ~0.5 cm^3.
- PID via <dE/dx> below ~1 GeV/c.

Calorimeters

- Detector designed to measure energy deposition and direction for electromagnetic (EM) or hadronic (H) showers.
- EM calorimeters are characterized by distance for an EM interaction to occur, the "radiation length", X_0
  - 13.8 g cm^{-2} (Fe)
  - 6.0 g cm^{-2} (U)
- Hadronic calorimeters are characterized by distance for a nuclear interaction to occur, the "interaction length", λ_I
  - 132.1 g cm^{-2} (Fe)
  - 209 g cm^{-2} (U)
- Calorimeters are usually many "lengths" deep in order to contain as much of the energy as possible
- EM calorimeters are usually placed in front of H calorimeters

Time-of-Flight Detectors

- Some knowns:
  - momentum (p)
  - traversal time (t)
  - distance (L)

$$m^2 = p^2 \left(\frac{t^2}{L^2} - 1 \right)$$

- Note: separation "power" of detector depends on time resolution:

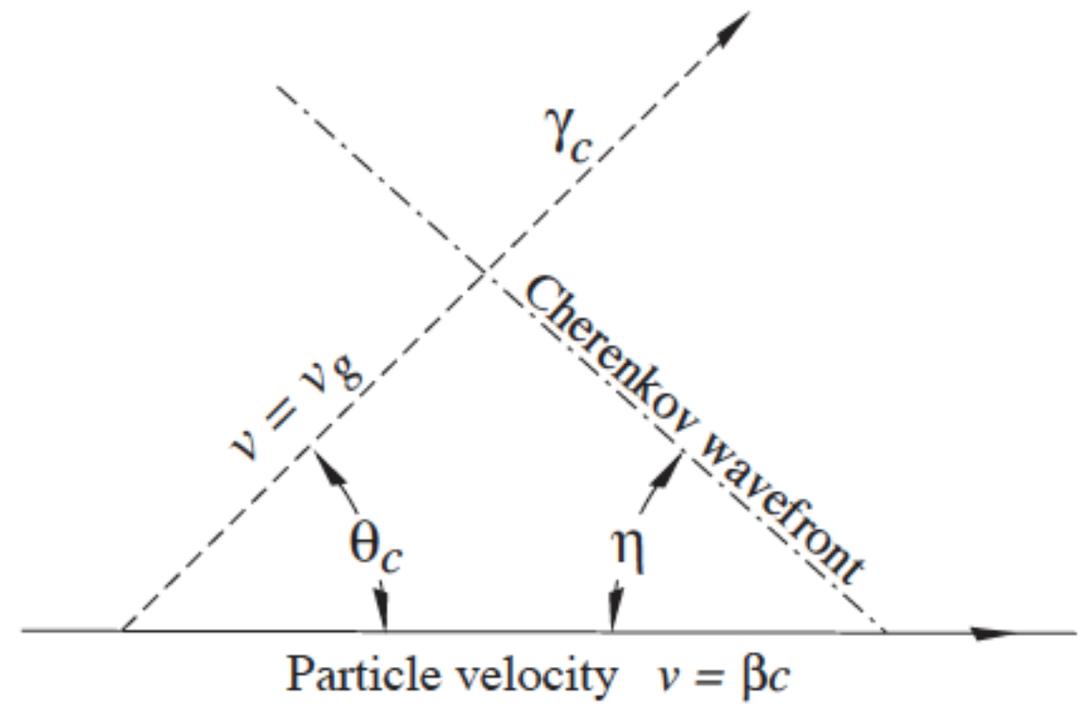
$$\delta t^2 = t_2^2 - t_1^2 = \frac{L^2}{p^2} (\Delta m^2)$$

- Typical timing resolution for ToF detectors: ~100 ps, usually good enough to separate particles up to a few GeV

Cherenkov Radiation

$$\cos\theta_c = (1/n\beta)$$

$$\frac{d^2N}{dxd\lambda} = \frac{2\pi\alpha z^2}{\lambda^2}\left(1 - \frac{1}{\beta^2 n^2(\lambda)}\right)$$



Common refractive indices & thresholds:

Material	Index	Muon momentum threshold (GeV):	Proton momentum threshold (GeV):
Air (at STP)	1.000277	4.490	39.849
CO2	1.00045	3.523	31.263
Aerogel	1.07	0.278	2.464
Water (Ice)	1.31	0.125	1.108
Water (at 20C)	1.333	0.120	1.064
Ethanol	1.361	0.114	1.016
Pyrex	1.47	0.098	0.871
Diamond	2.419	0.048	0.426