The University of Manchester

MANCHESTER 1824

Experimental Questions in Neutrino Physics

part 1: The Known Knowns

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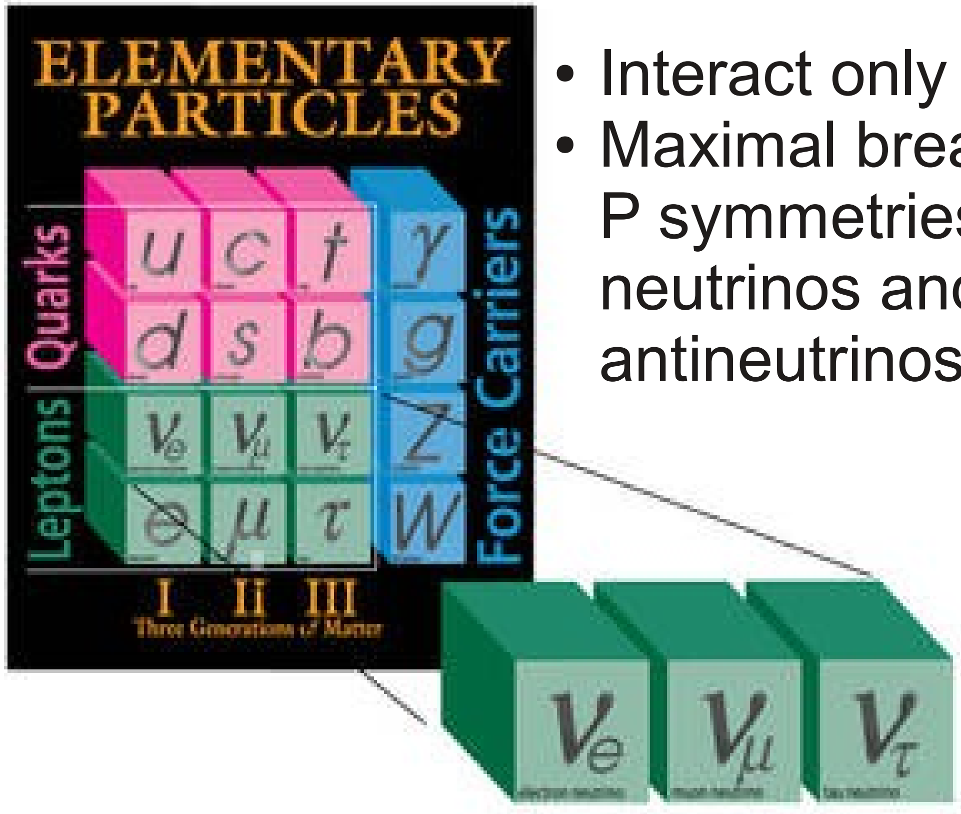
Outline

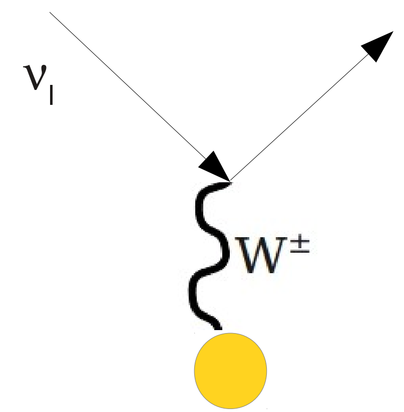
- In this lecture I will talk about the history of experimental neutrino physics and where we are now.
- Tomorrow I will talk about measurements that are ongoing or proposed that will expand out understanding of the model.
- I tried to avoid explaining experimental techniques as much as possible – which is not that much.

Neutrinos in the Standard Model

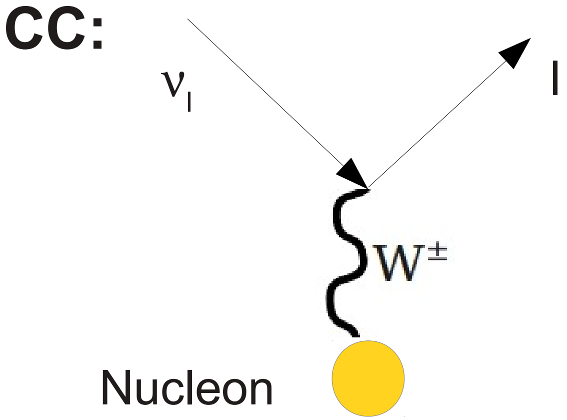


- Interact only weakly
- Maximal breaking of C and P symmetries (no R-handed neutrinos and L-handed antineutrinos.)

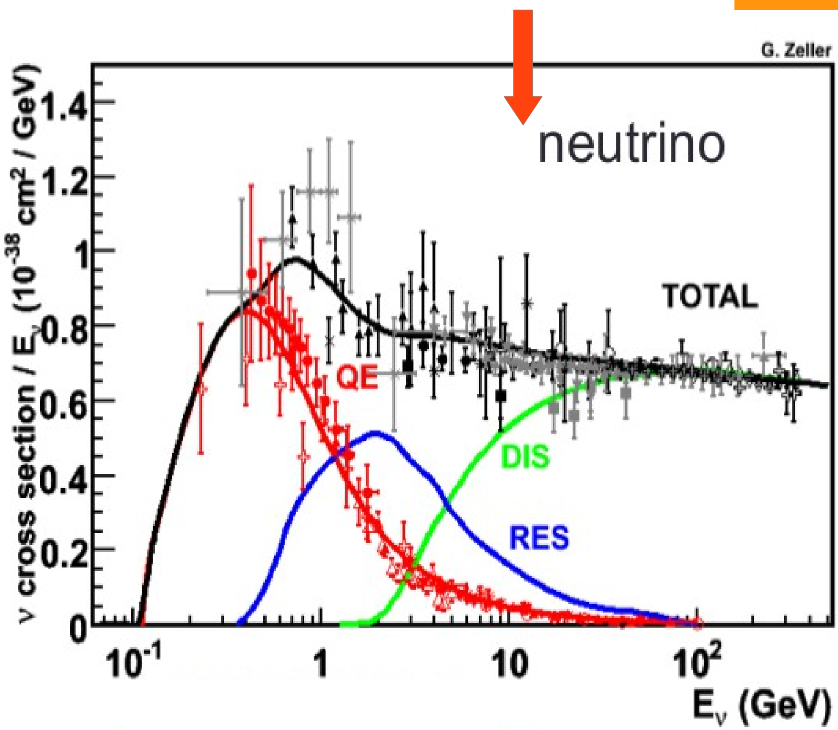
Charged Current (CC) Interaction – how we define a neutrino flavor:

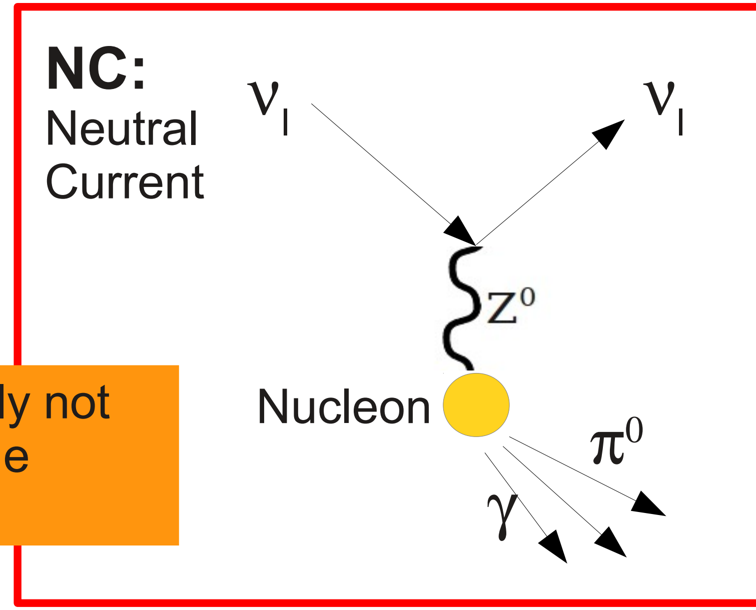


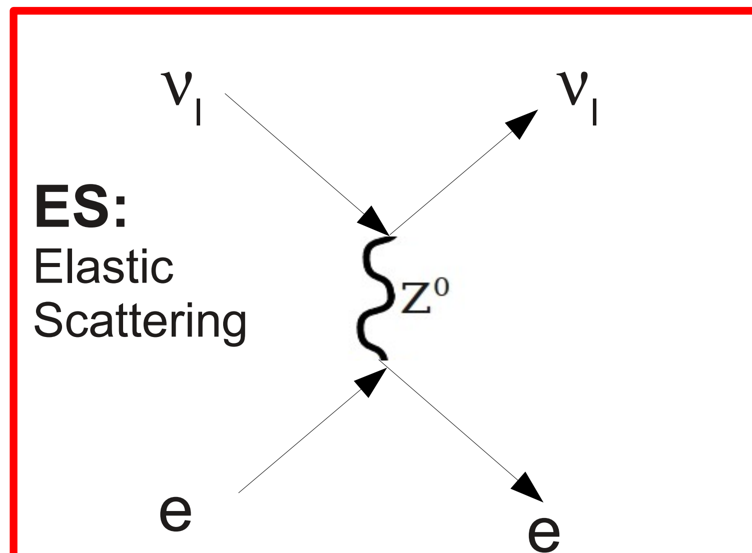
How neutrinos interact



I am deliberately not specifying single nucleons.

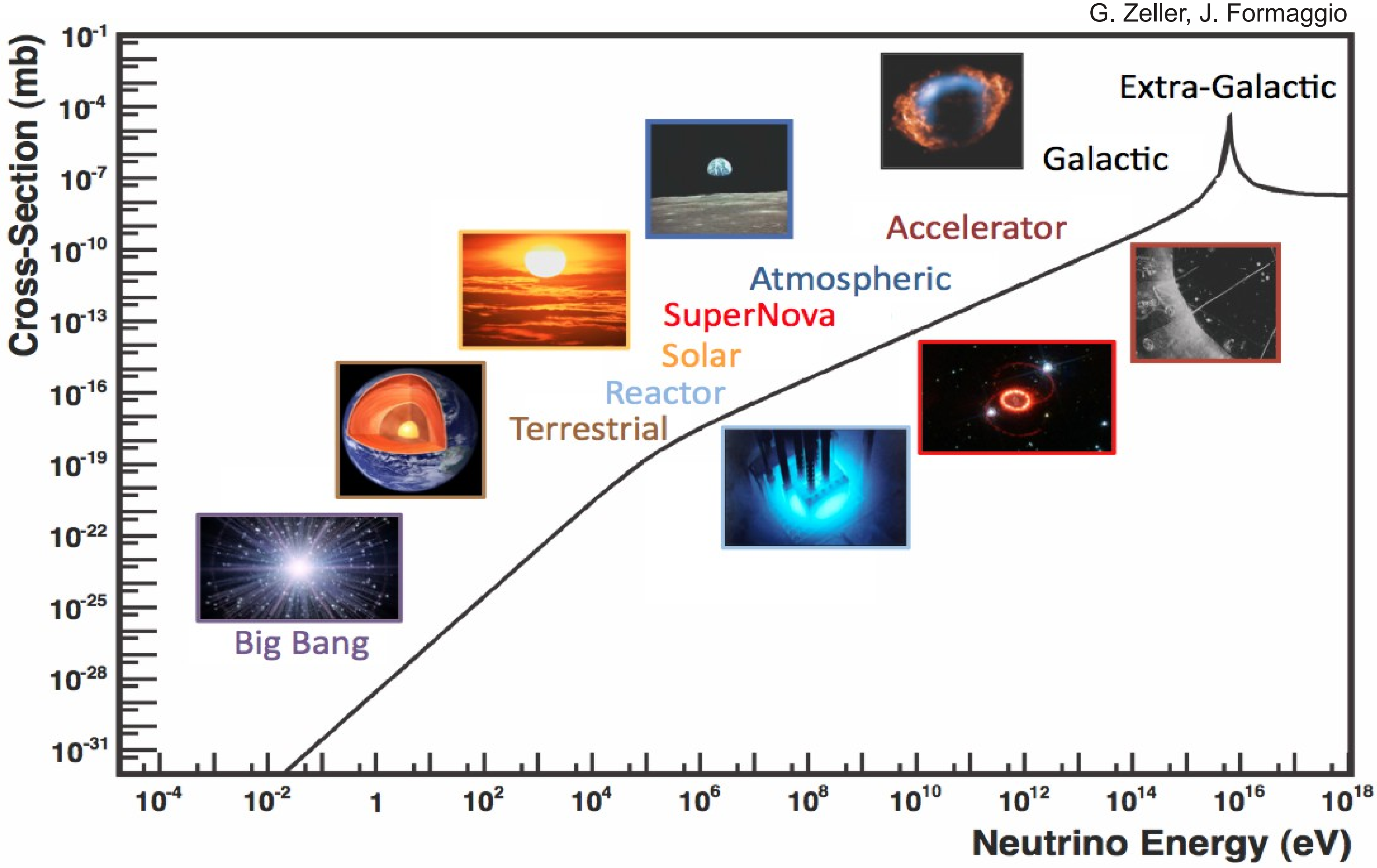






No “new” lepton in final state – cannot distinguish ν flavor.

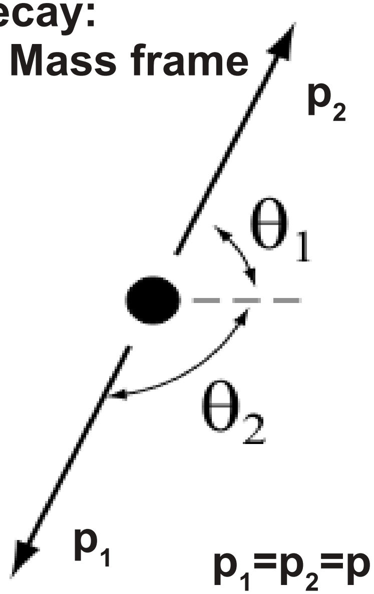
Sources of Neutrinos

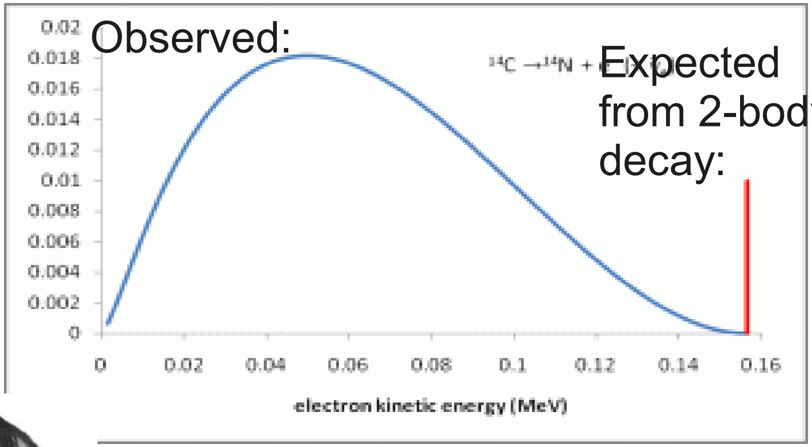


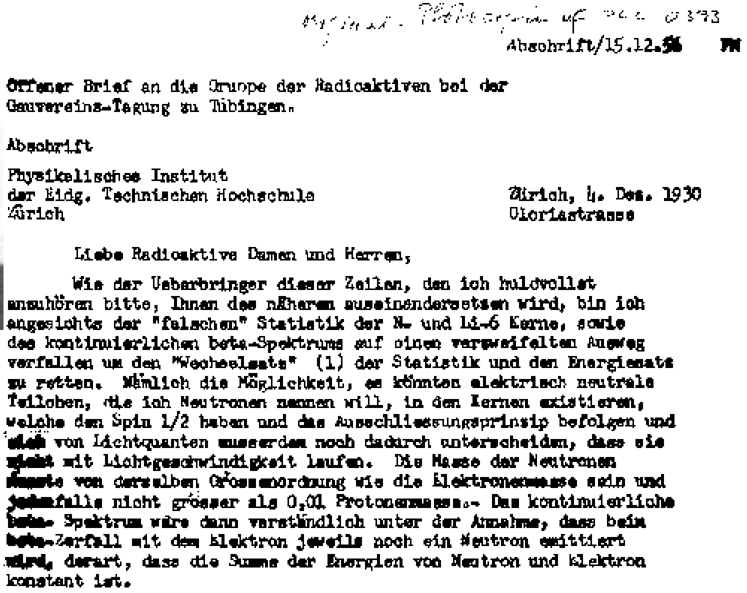
A Bit of History

β-decay spectrum

2-body decay:
Centre of Mass frame







Abschrift/15.12.56 PM

Offener Brief an die Gruppe der Radioaktiven bei der Gauvereins-Tagung zu Tübingen.

Abschrift

Physikalisches Institut
der Eidg. Technischen Hochschule
Zürich

Zürich, 4. Dez. 1930
Gloriastrasse

Liebe Radioaktive Damen und Herren,

Wie der Ueberbringer dieser Zeilen, den ich huldvollst anzuhören bitte, Ihnen des näheren auseinandersetzen wird, bin ich angesichts der "falschen" Statistik der N- und Li-6 Kerne, sowie des kontinuierlichen beta-Spektrums auf einen verzweifelten Ausweg verfallen um den "Wechselsatz" (1) der Statistik und den Energiesatz zu retten. Nämlich die Möglichkeit, es könnten elektrisch neutrale Teilchen, die ich Neutronen nennen will, in den Kernen existieren, welche den Spin 1/2 haben und das Ausschliessungsprinzip befolgen und sich von Lichtquanten ausserdem noch dadurch unterscheiden, dass sie nicht mit Lichtgeschwindigkeit laufen. Die Masse der Neutronen müsste von derselben Grössenordnung wie die Elektronenmasse sein und jedenfalls nicht grösser als 0,01 Protonenmasse.- Das kontinuierliche beta- Spektrum wäre dann verständlich unter der Annahme, dass beim beta-Zerfall mit dem Elektron jeweils noch ein Neutron emittiert wird, derart, dass die Summe der Energien von Neutron und Elektron konstant ist.

- W. Pauli proposes the neutrino (then called neutron) to solve this problem:
- ***"I have done a terrible thing, I have postulated a particle that cannot be detected."***

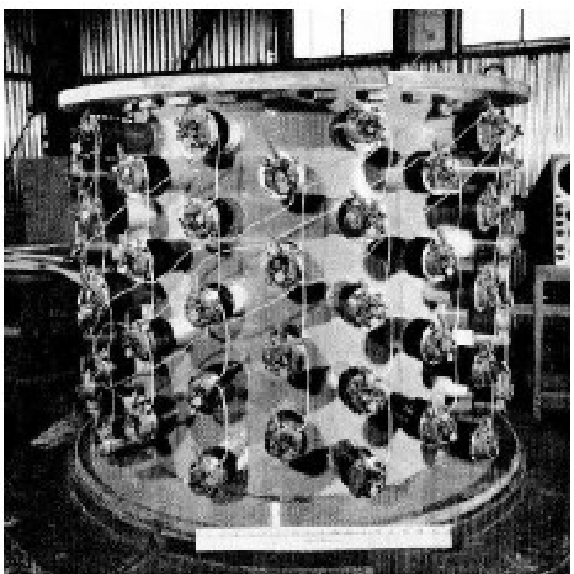
Experimental detection

- Fortunately, he was proven right (per theory prediction) and wrong (per experimental prediction) by Reines and Cowan in 1956.
- A clever signature: Inverse Beta Decay (IBD):

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

Prompt annihilation 2x 511keV γ → Unique signature of neutrino

Delayed (5×10^{-6} s) γ capture on Cd → Unique signature of neutrino



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 W E S T E R N   U N I O N
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             June 14, 1956

Dear Professor Pauli,

We are happy to inform you
that we have definitely
detected neutrinos. . .

               Fred Reines
               Clyde Cowan
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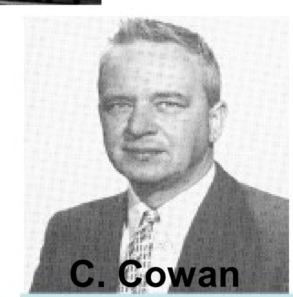
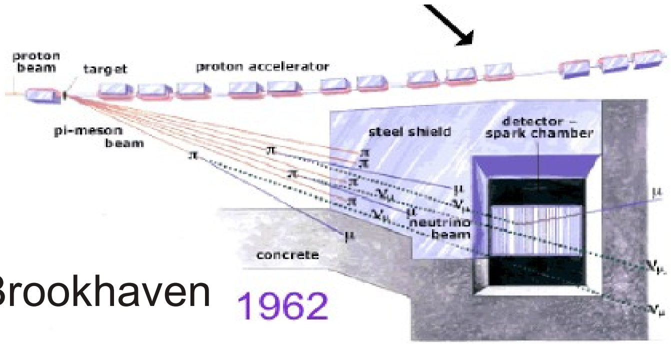


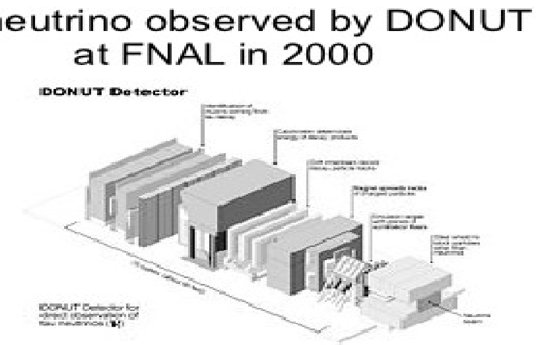
Detection of the μ and τ neutrinos

- Discovery of the muon neutrino



Brookhaven

- Discovery of the tau neutrino (ν_τ)



In both cases: shoot a

15 GeV	800GeV	proton beam at a
beryllium target	tungsten beam dump	, create
Pions	D_s mesons,	that decay into
ν_μ	ν_τ	neutrinos and detect them using
A spark chamber	emulsion detector.	

“known” Questions in ν-physics
(answered or being answered)

- Experimental neutrino physics in the last decades was driven by the following questions:

- why do we see less neutrinos from the sun?

- where are the atmospheric νs?

- could this be due to oscillations?

- What are the parameters of oscillation ?

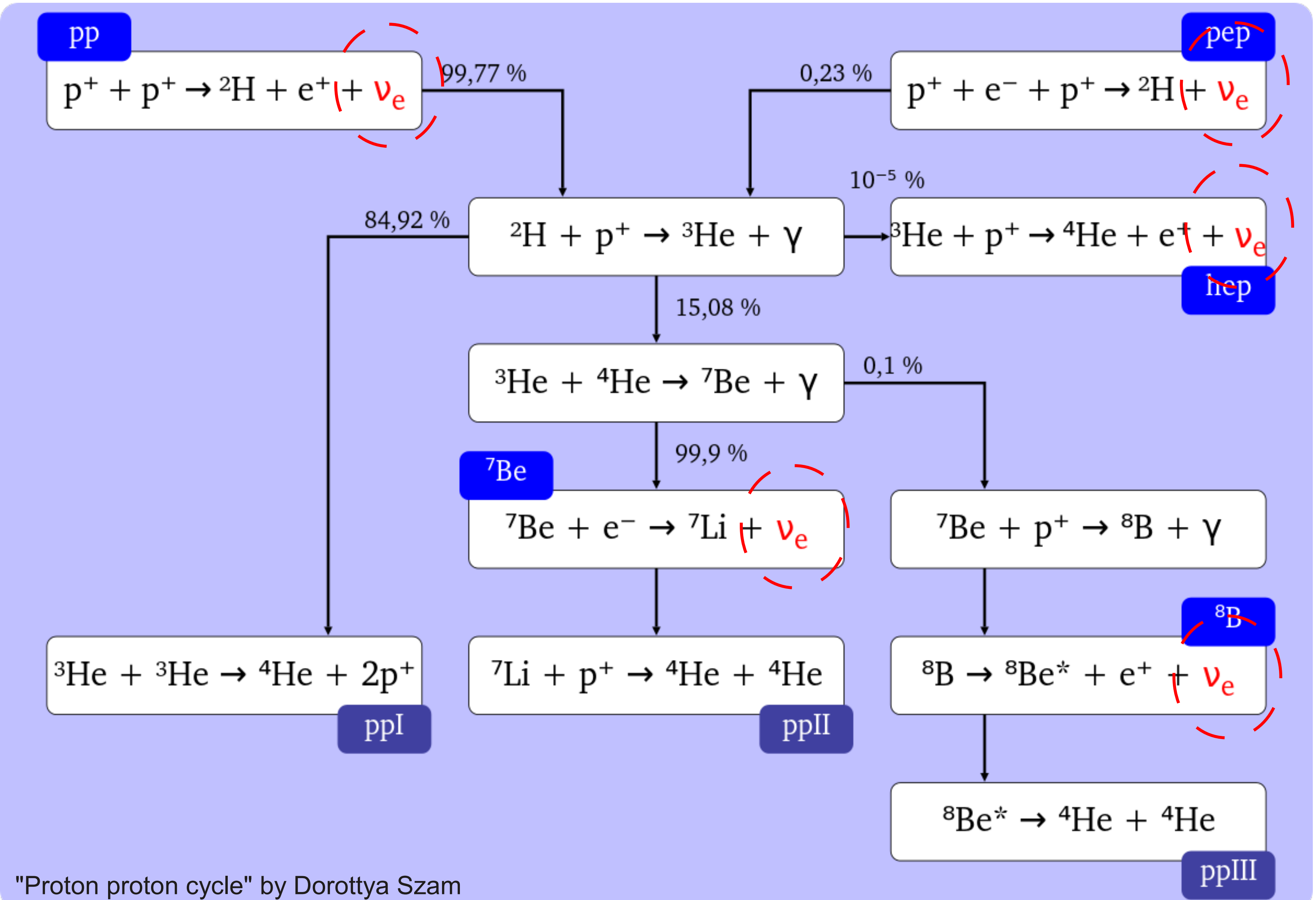
- Especially, is θ_{13} non-zero?

- Is the θ_{23} mixing maximal?

- what is going on with neutrino interactions?!

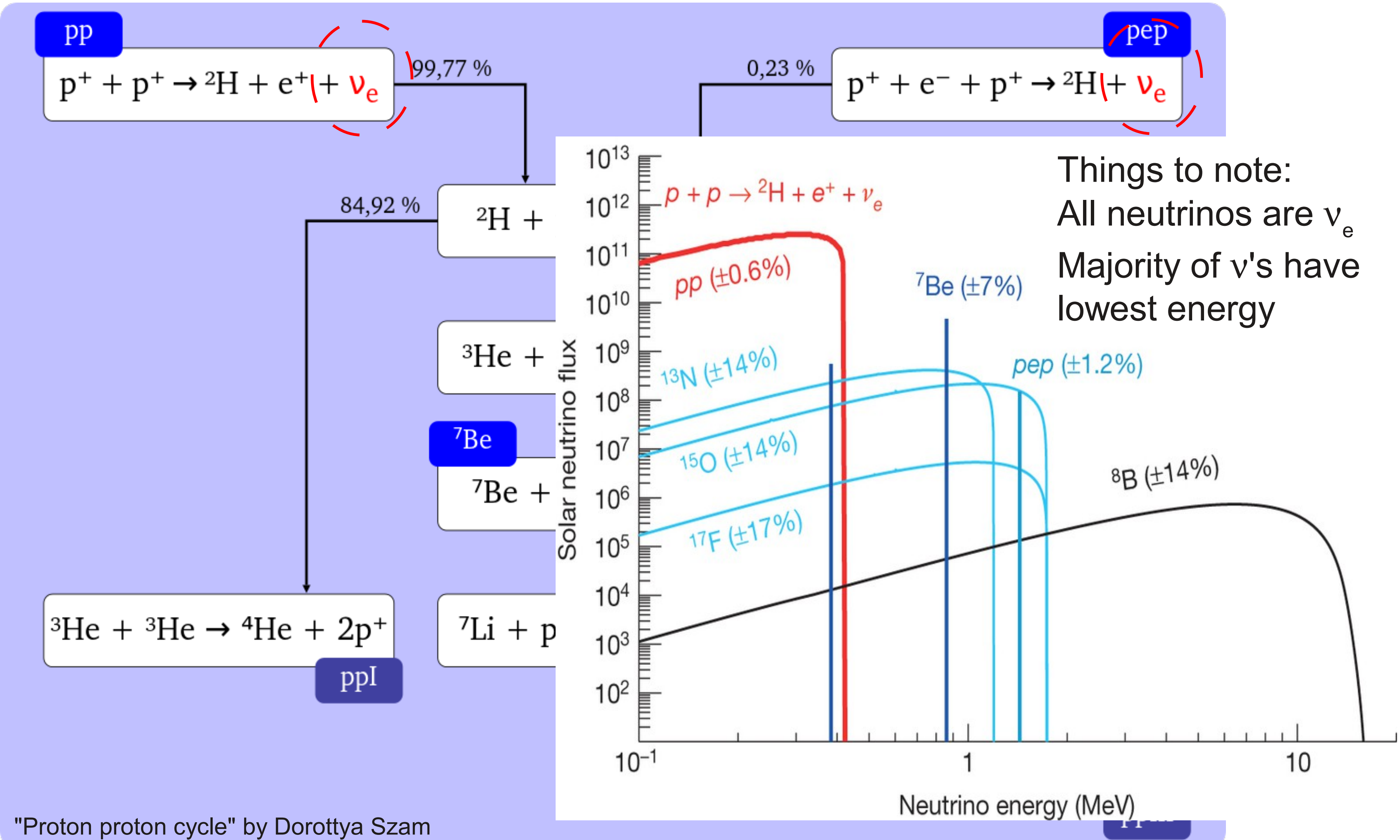
Neutrino physics is an adventurous experimental journey that may be far from over.

Solar Neutrinos



"Proton proton cycle" by Dorottya Szam

Solar Neutrinos



Things to note:

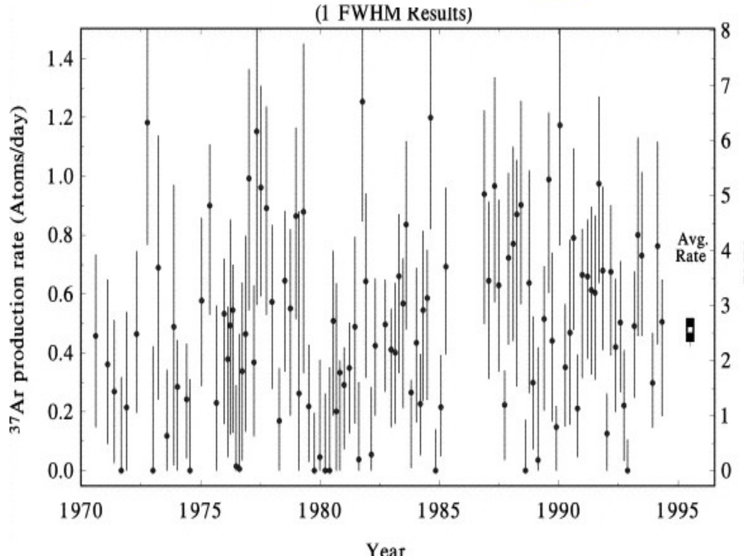
All neutrinos are ν_e

Majority of ν's have lowest energy

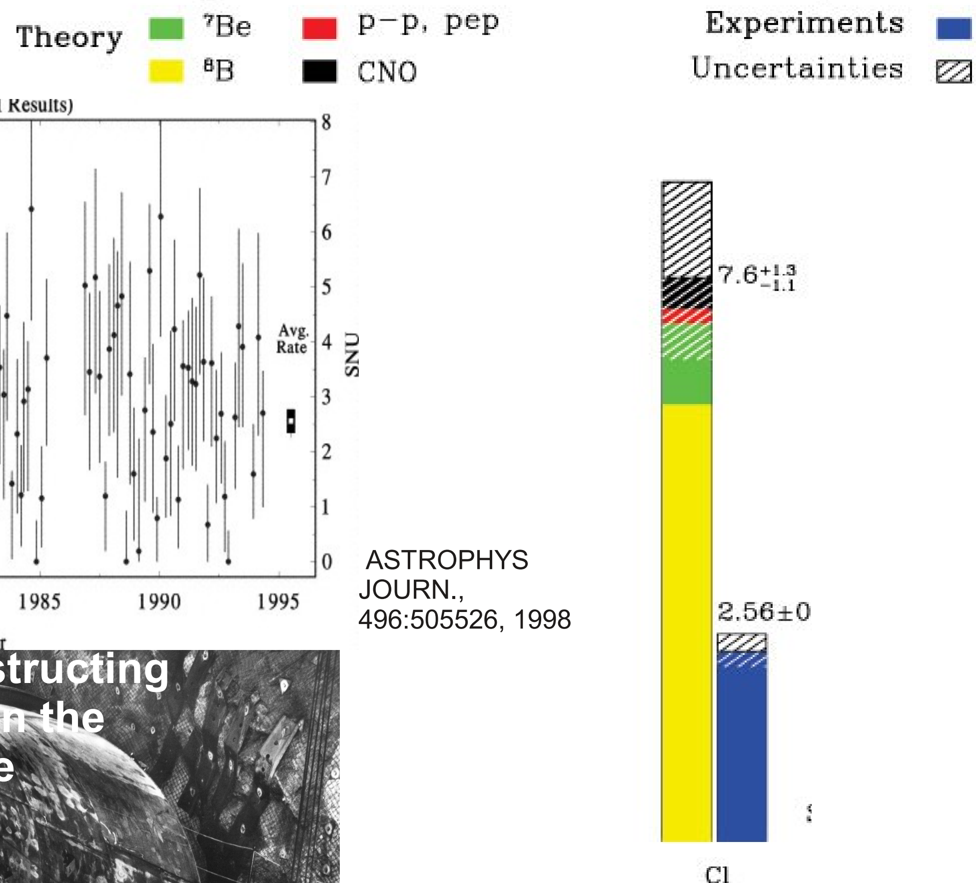
"Proton proton cycle" by Dorottya Szam

Observing Solar Neutrinos

- Used neutrino capture on ^{37}Cl, which results in ^{37}Ar which is radioactive. (0.814 MeV thresh.)
- Via ingenious chemical methods the ^{37}Ar was extracted and measured (~0.5 atoms produced/day!)
- The number of neutrinos observed was way off from expectation.



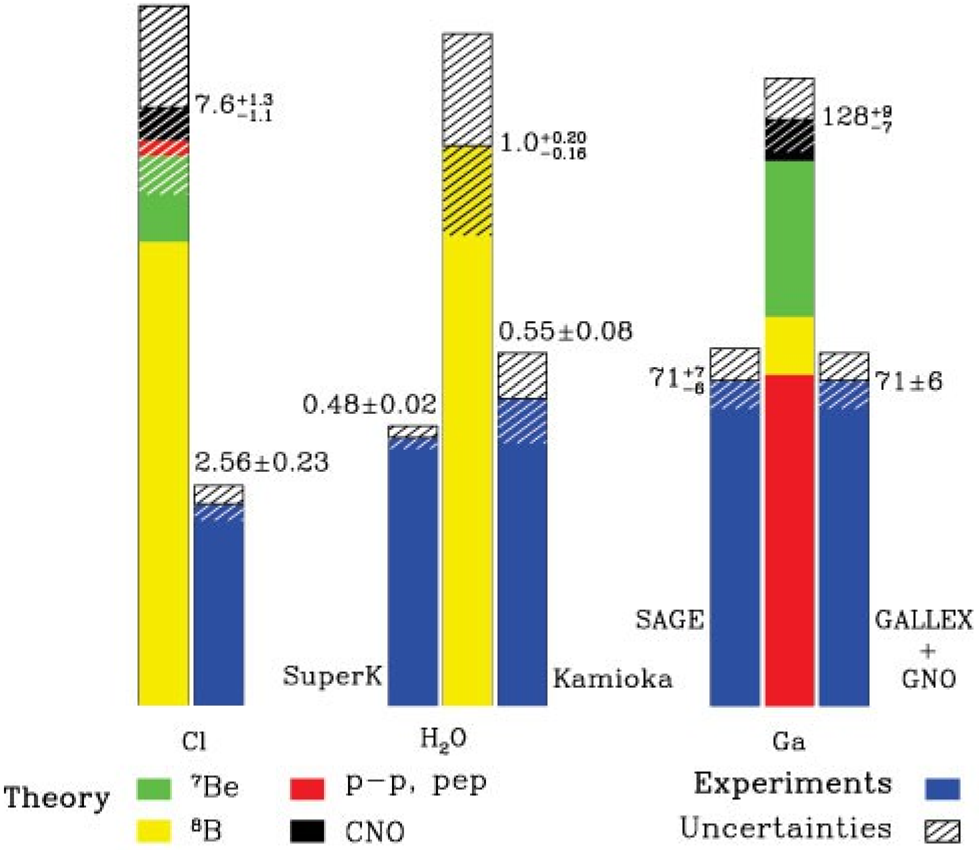
ASTROPHYS JOURN., 496:505526, 1998



- Experiment is wrong?
- Theory is wrong?
- Something fishy is going on here?

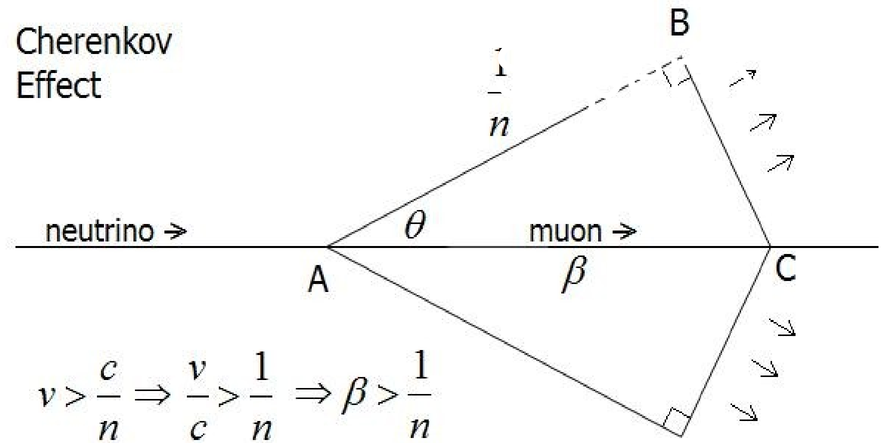
A deficit of Solar Neutrinos?

- Other experiments radiochemical using Gallium (0.2 MeV threshold) also saw a deficit.
- As did Water Cherenkov.
- But at a different rate?
- Other measurements of the Sun agree with the Solar Theoretical Model.



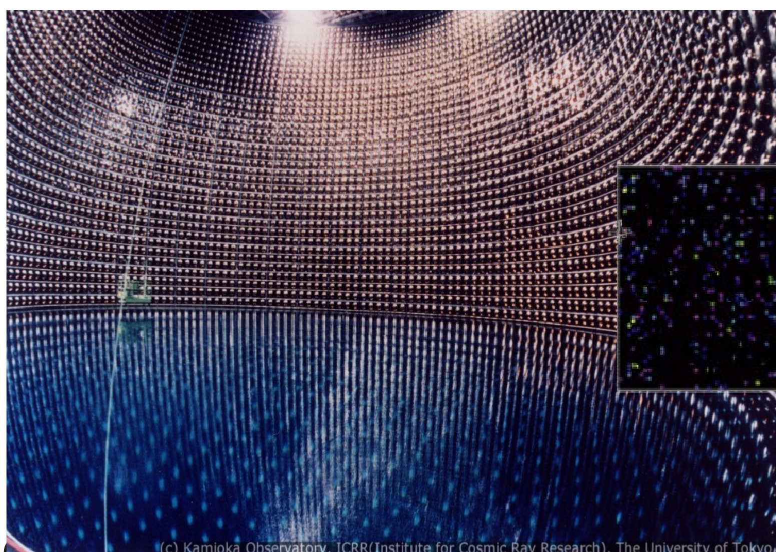
Cherenkov Detectors

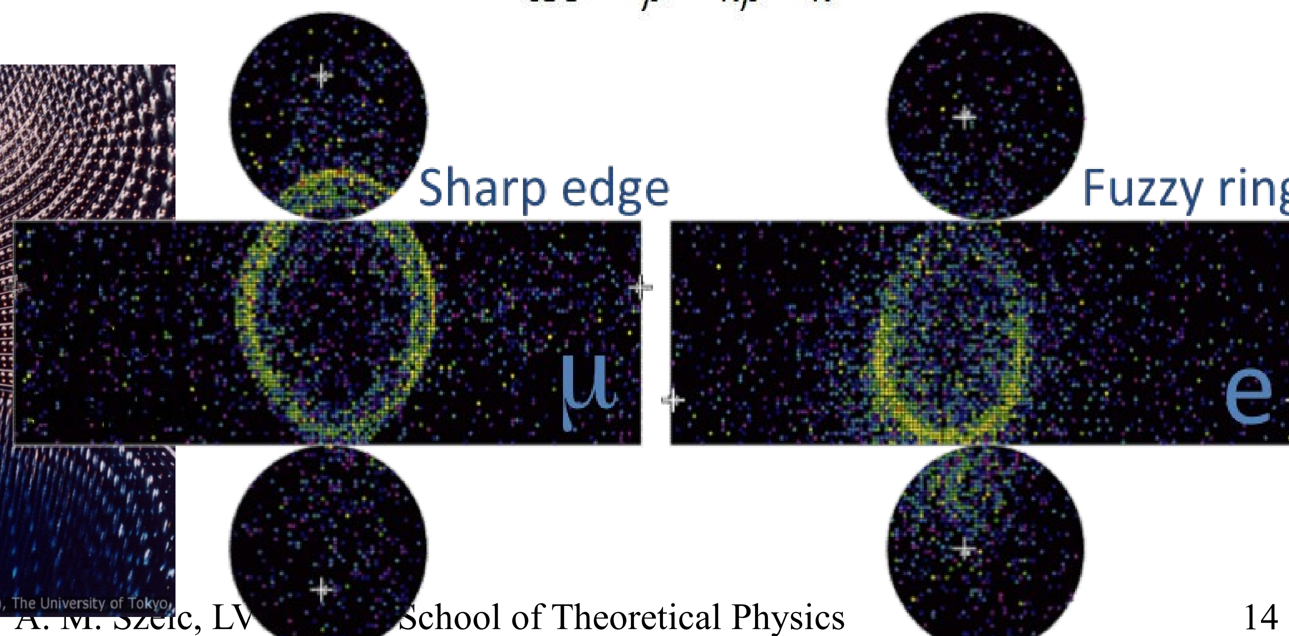
- Originally developed to look for proton-decay, but appropriated for neutrino physics.
- Cherenkov light is emitted when a particle travels faster than the speed of light (in the medium).
- Hard to see heavier particles like protons etc...
- But has directionality!



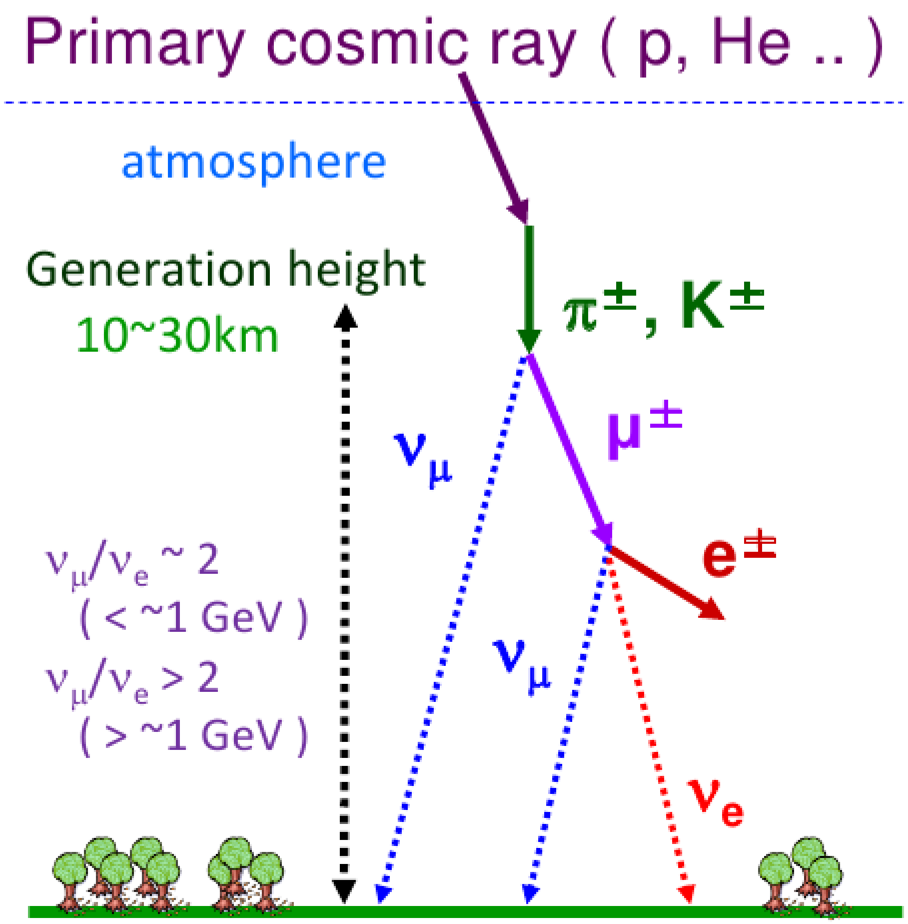
$$v > \frac{c}{n} \Rightarrow \frac{v}{c} > \frac{1}{n} \Rightarrow \beta > \frac{1}{n}$$

$$\cos\theta = \frac{AB}{AC} = \frac{1/n}{\beta} = \frac{1}{n\beta} = \frac{1}{n}$$

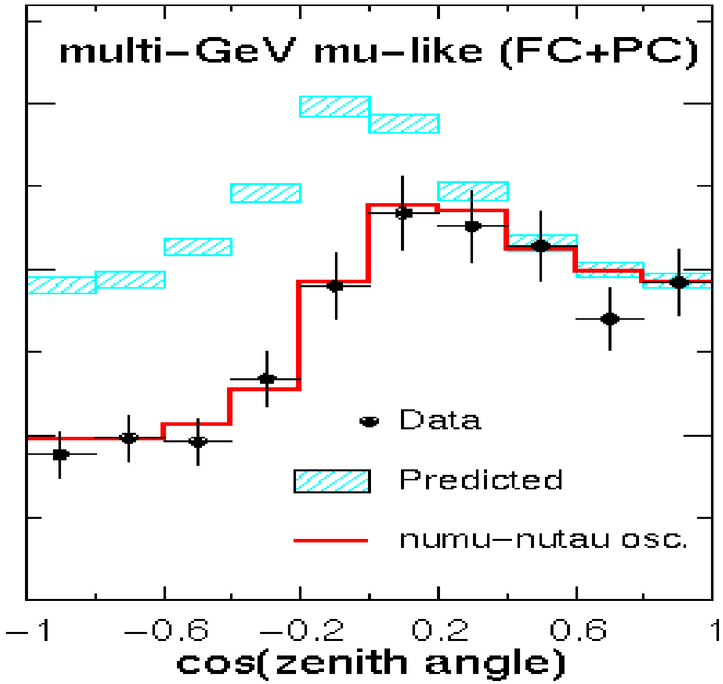




Discovery of atmospheric neutrinos and their asymmetry



Super Kamiokande detector misses muon neutrinos from the bottom (but not from the top).

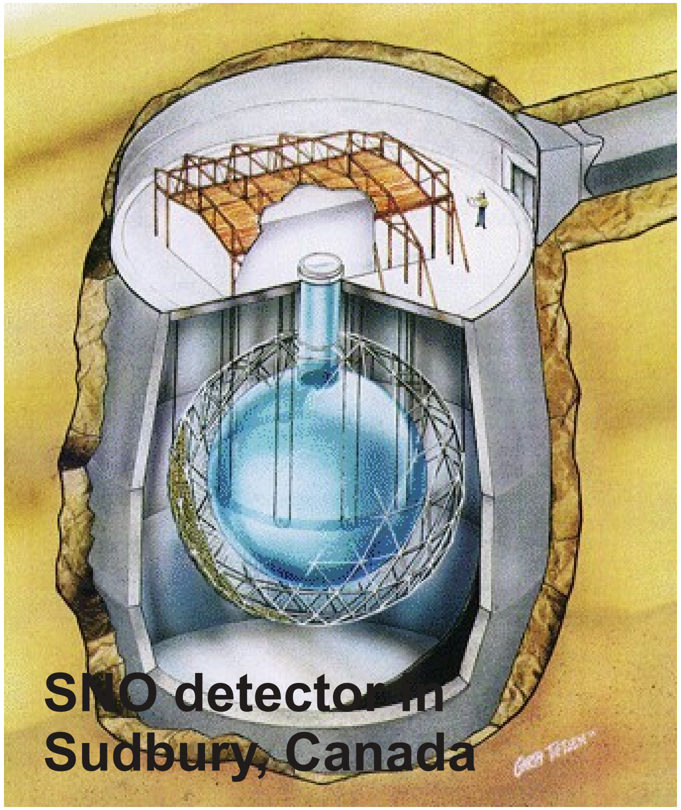


Super-Kamiokande Collaboration Phys. Rev. Lett. 81, 1562–1567 (1998)

Neutrinos are disappearing.
What is happening to them?

SNO – resolving the Solar problem

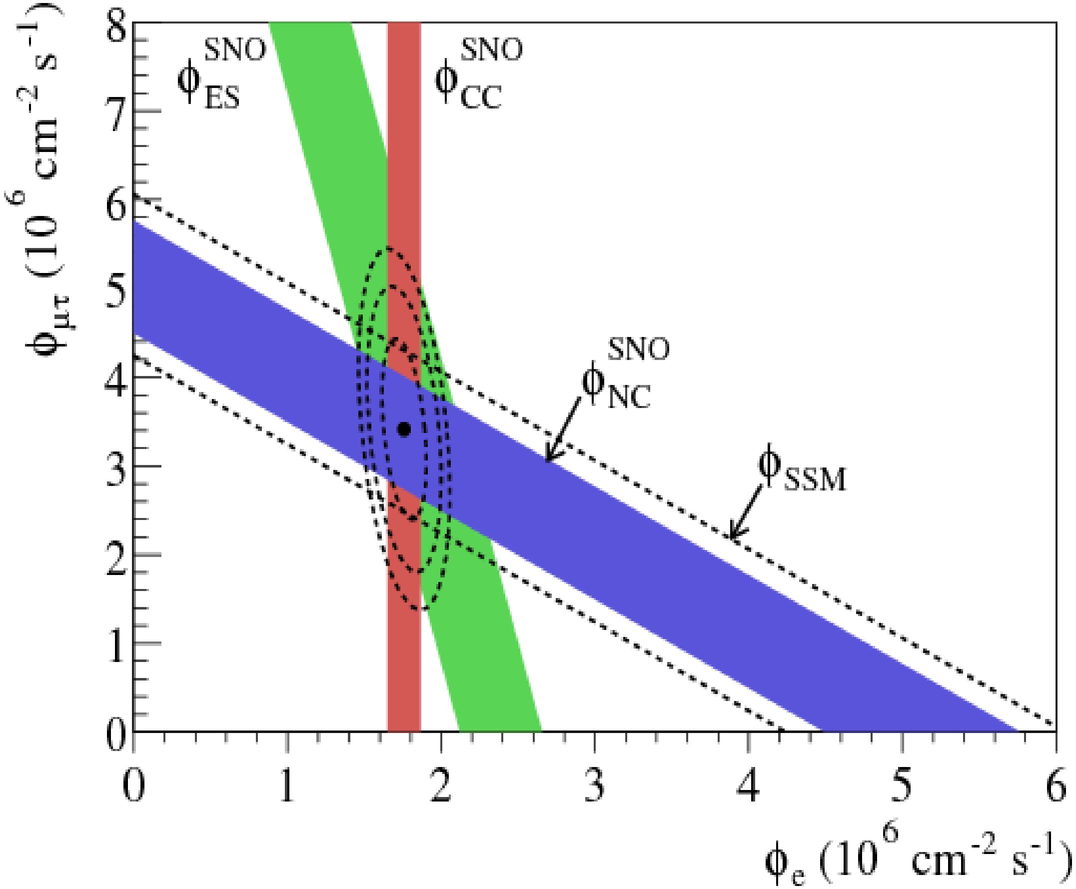
Extremely clever idea: try to observe electron and other neutrinos separately using properties of Heavy Water.

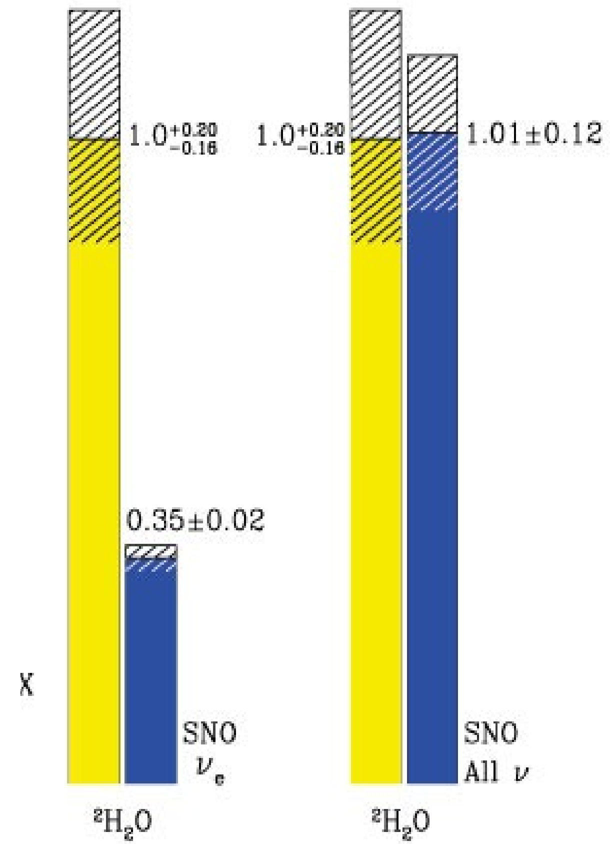


Different reactions have different signatures:
CC – isotropic Cherenkov Rings
NC – delayed neutron capture (~6.25 MeV)
ES – Cherenkov Rings pointing back to the sun

Charged Current	$\nu_e + d \rightarrow p + p + e^-$	E_{th}=1.4 MeV	$CC\ Rate \propto \Phi(\nu_e)$
Neutral Current	$\nu_x + d \rightarrow \nu_x + p + n$	E_{th}=2.2 MeV	$NC\ Rate \propto \Phi(\nu_x)$
Elastic Scattering	$\nu_x + e^- \rightarrow \nu_x + e^-$	E_{th}~ 0	$ES\ Rate \propto \Phi(\nu_e) + 0.154\,\Phi(\nu_\mu + \nu_\tau)$

SNO (2)





Total flux from the sun agrees with the model.
But, we know that the sun only produces ν_e.

“known” Questions in ν-physics

(answered or being answered)

- Experimental neutrino physics in the last decades was driven by the following questions:

- why do do we see less neutrinos from the sun?

- where are the atmospheric νs?

- could this be due to oscillations?

- What are the parameters of oscillation ?

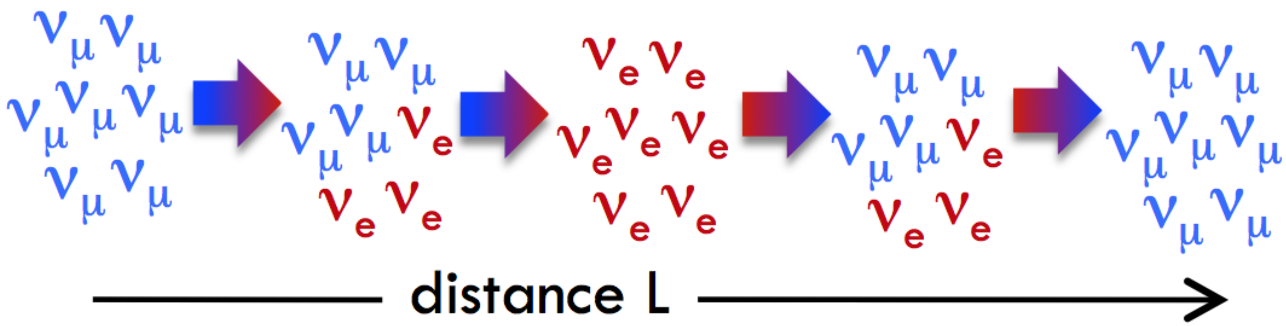
- Especially, is θ_{13} non-zero?

- Is the θ_{23} mixing maximal?

- what is going on with neutrino interactions?!

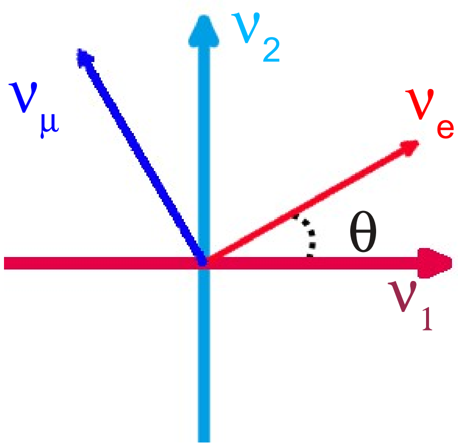
Knowing that neutrinos oscillate has opened a whole new field of experimental physics.

Neutrino Oscillations



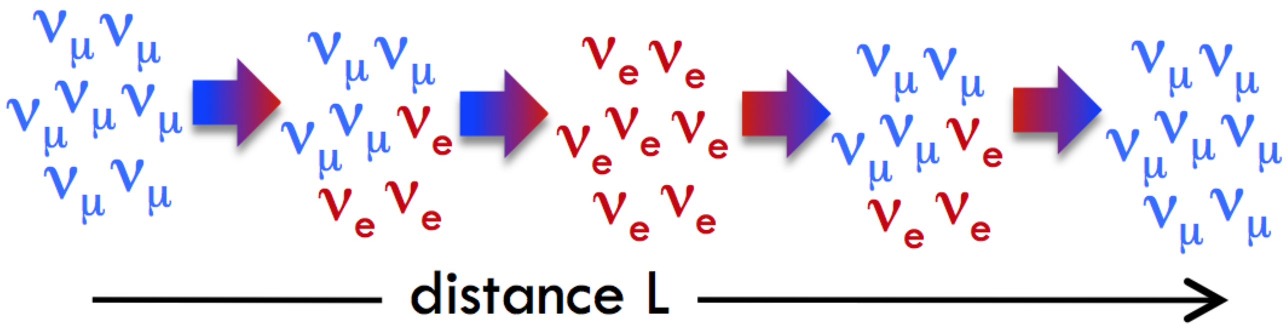
B. Pontecorvo

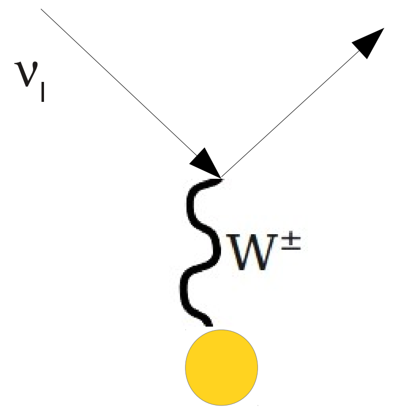
- We know three neutrino flavors: ν_e, ν_μ and ν_τ .
- SNO and Super-K tell us that neutrinos are not disappearing. They're changing into one another. Oscillating.
- Then ν_1, ν_2 - mass eigenstates = eigenstates of free Hamiltonian.
- ν_e, ν_μ eigenstates of interaction Hamiltonian



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

Measuring Neutrino Oscillations





- In oscillation physics we usually start with one type of neutrino and measure how it changes into another type.
- We can do this by detecting the new neutrinos (appearance) or registering the loss of original (disappearance).
- We can tell neutrinos apart by the effect of their "Charged Current" interactions.

In a two neutrino model, the probability of this oscillation looks like this:

$$P(\nu_\mu \rightarrow \nu_e) = \sin^2 2\theta \, \sin^2\left(\frac{\Delta m^2_{12}}{4}\frac{L}{E_\nu}\right)$$

Things to note

- Oscillations are only possible if neutrinos have mass
- But we don't know what it is, only the squared difference (a parameter).
- Mixing angles are another parameter.
- Adjusting L/E allows us to measure different mixings.

$$P(\nu_\mu \rightarrow \nu_e) = \sin^2 2\theta \, \sin^2\left(\frac{\Delta m^2}{4}\frac{L}{E_\nu}\right)$$

$$\Delta m_{12}^2 = m_1^2 - m_2^2$$

$$\frac{\Delta m^2 L}{4E} \ll 1$$

Oscillations did not have a chance to happen

$$\frac{\Delta m^2 L}{4E} \gg 1$$

Oscillations averaged out – only sensitive to mixing angle

Expanding to three flavours

$$U = \underset{\text{Atmospheric}}{\overset{23}{\begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix}}} \underset{\text{Reactor/Interference}}{\overset{13}{\begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix}}} \underset{\text{Solar}}{\overset{12}{\begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}}}$$

$\mu \Rightarrow \tau$ $\qquad \mu \Leftrightarrow e$ $\qquad e \Leftrightarrow \mu$

$$V_{MNS} \sim \begin{pmatrix} 0.8 & 0.5 & 0.2 \\ 0.4 & 0.6 & 0.7 \\ 0.4 & 0.6 & 0.7 \end{pmatrix}$$

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

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

Filling out the PMNS mixing matrix

- For precise measurements we need:
  - Large detectors (statistics)
  - Control of flux (how many neutrinos do we have?)
  - Energy resolution – both at source and in detector
  - Patience

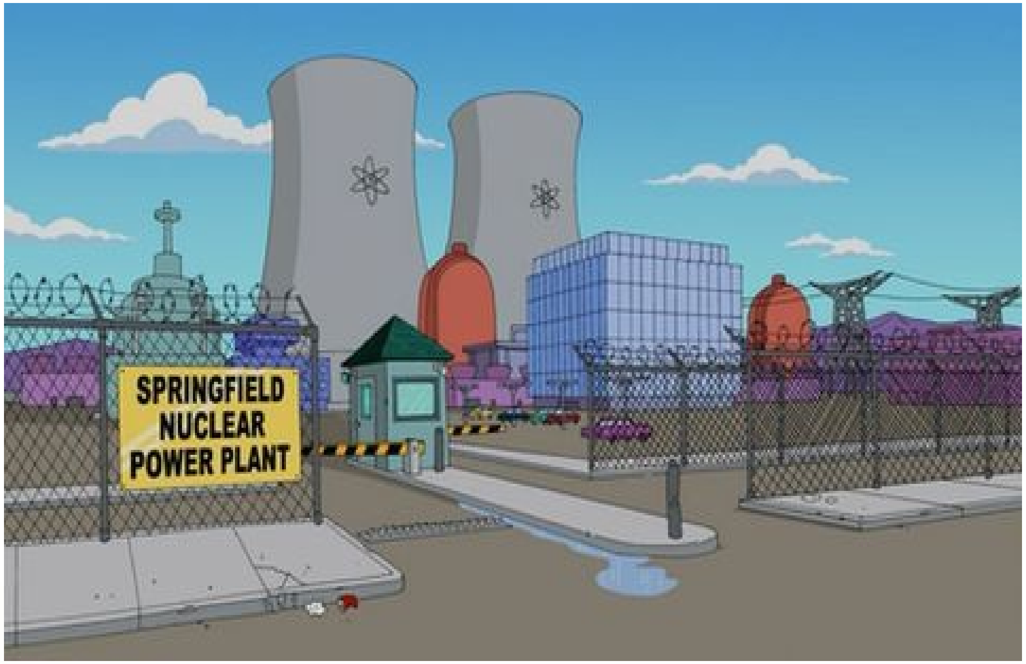
Change L/E in order to probe different Δm^2 and mixing angles.

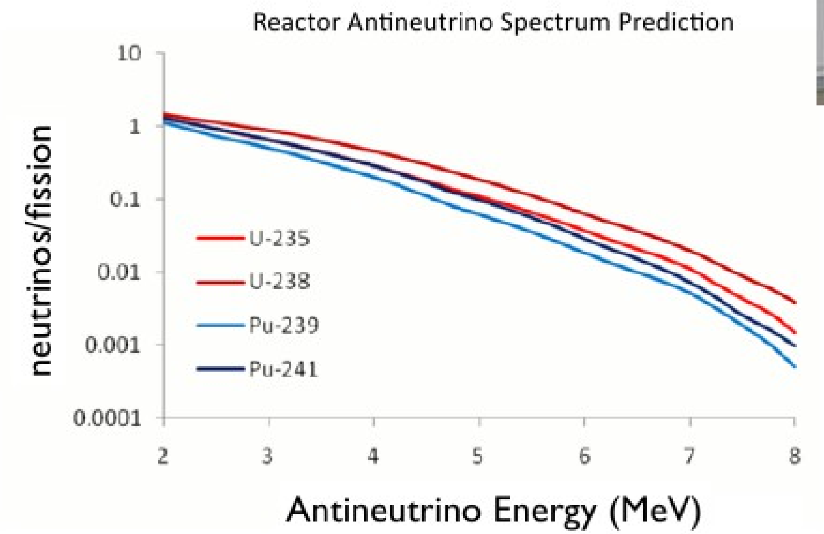
Create neutrinos to our specifications.

Experiment	L/E [km/MeV]	Δm^2 sensitivity
Reactor LBL	~1	~10^{-3} eV^2
Reactor VLBL	~100	~10^{-5} eV^2
Accelerator SBL	~10^{-3}	~10^{-5} eV^2
Accelerator LBL	~1	~10^{-3} eV^2
Atmoshperic	~10	~10^{-4} eV^2

Man-Made Neutrinos: Reactor

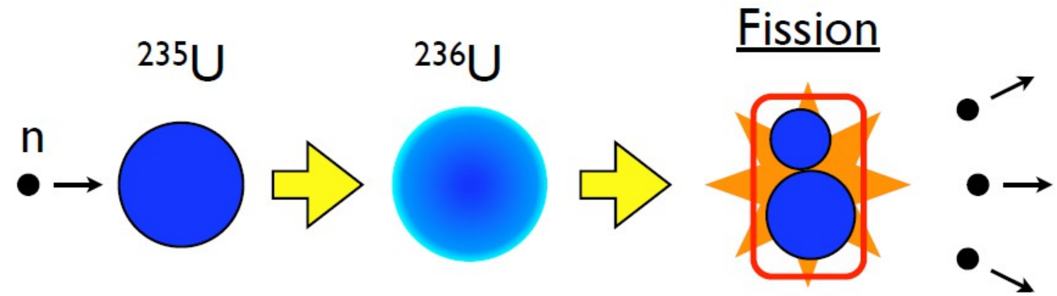
- Used to discover first neutrinos.
- Cheap (apparently people use them for other things.)

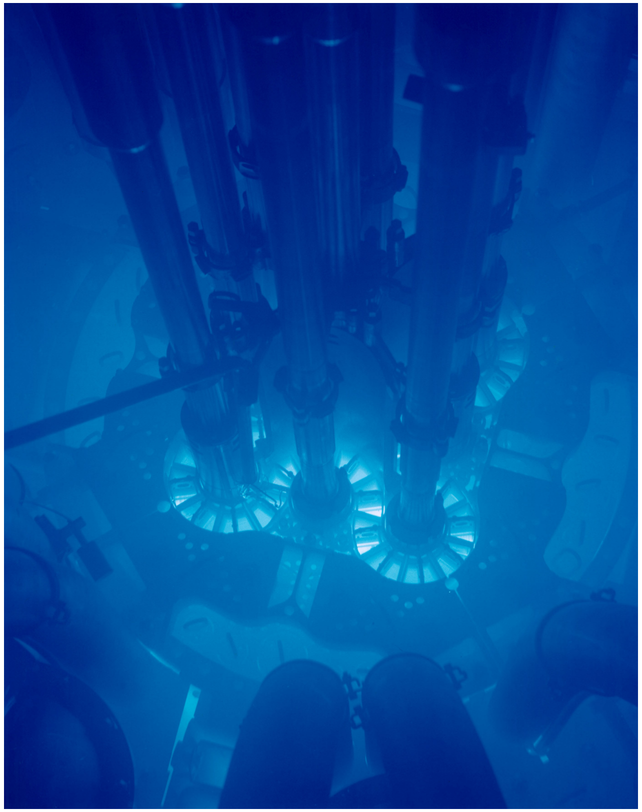




- Energy range is fixed.
- The neutrino spectrum is a result of a complicated system.

Man-Made Neutrinos: Reactor





Nuclear reactor fuel and subsequent fission fragments are neutron rich and decay by turning neutrons to protons and emitting antineutrinos.

99% of neutrinos comes from 4 isotopes ^{235}U, ^{239}Pu, ^{238}U and ^{241}Pu.

- **Ab Initio approach:**
 Calculate spectrum branch-by-branch using beta branch databases: endpoints, decay schemes → needs some guessing with rare beta decays.
- **Conversion approach**
 Measure beta spectra directly, convert to ν_e using 'virtual beta branches'. → This is not that well defined.

Carter, *et al*, Phys. Rev. 113 (1959)
King and Perkins, Phys. Rev. 113 (1958)

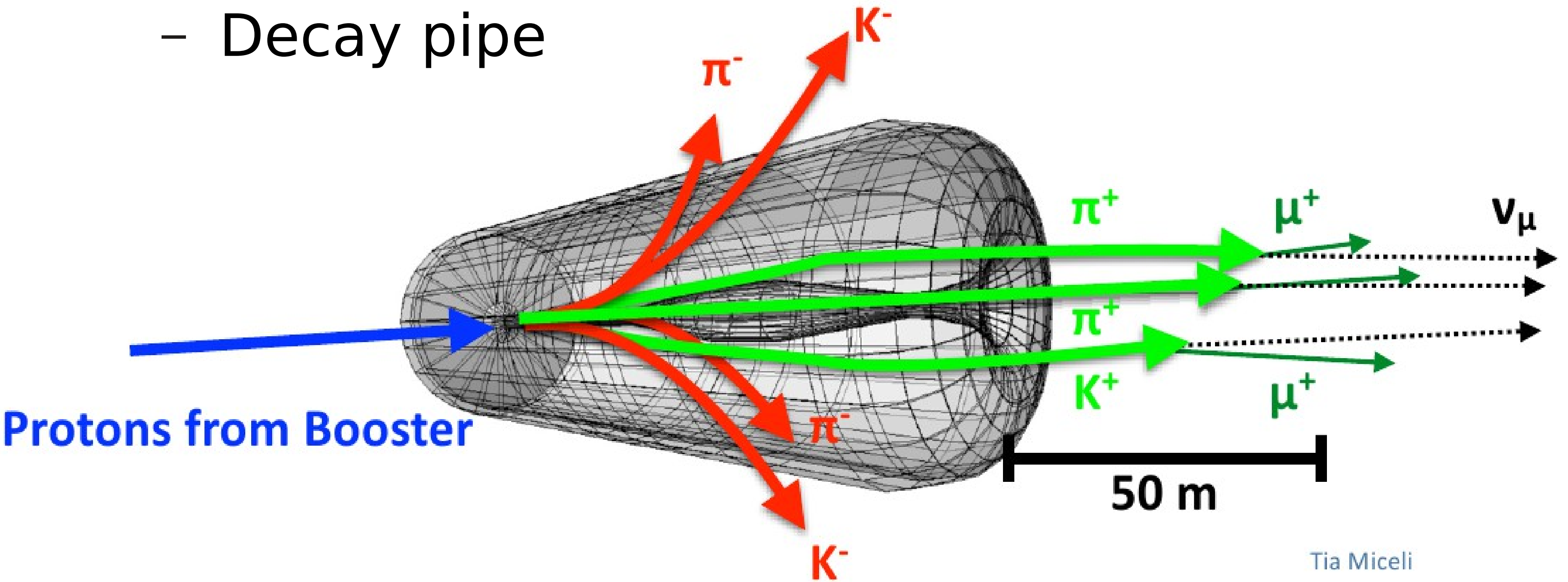
In general, anti-neutrino flux follows the heat Emission of the reactor

Man-Made neutrinos: Accelerator

- Need:
  - Beam of protons
  - Target
  - Focusing horn (magnetic field)
  - Decay pipe

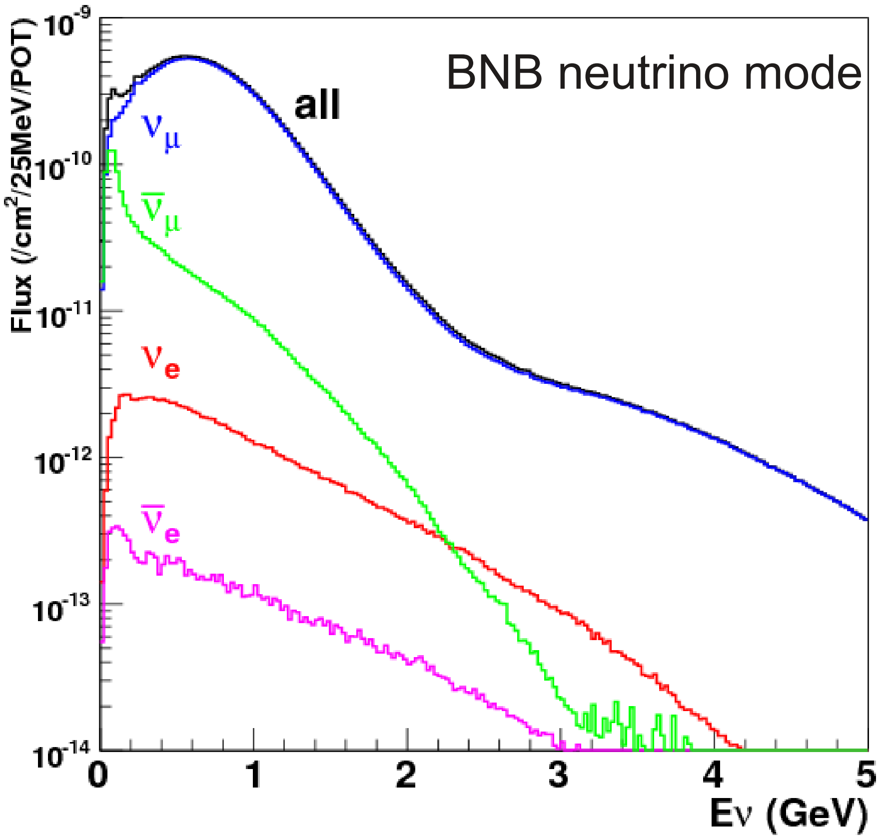
Costs more, but have more control over energy.

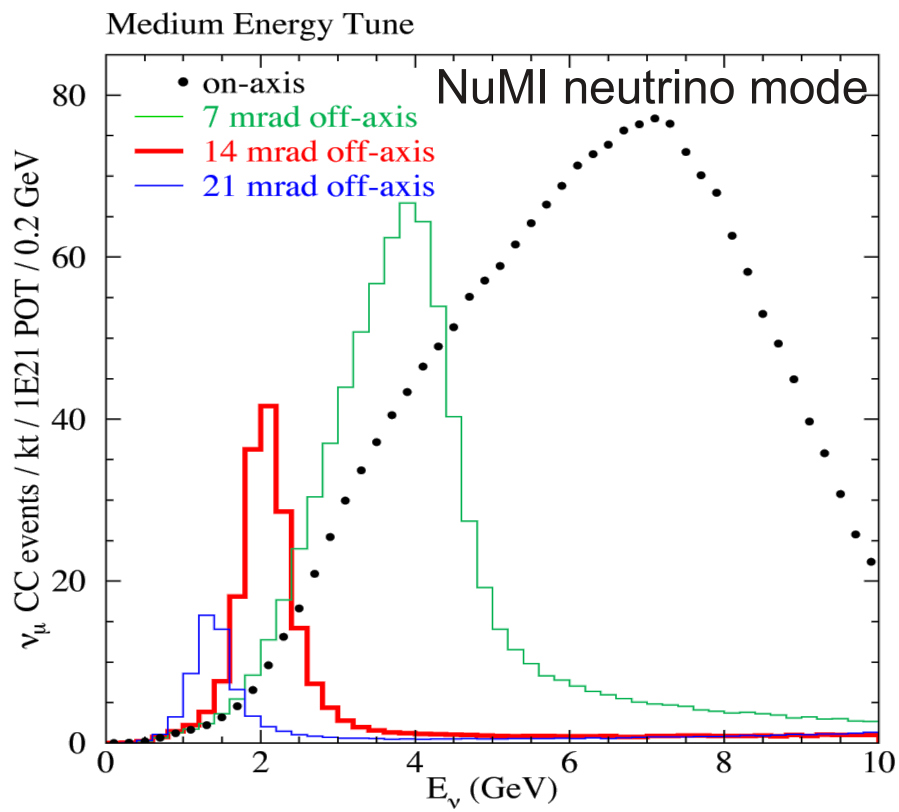
Calculating spectra is also difficult.



Man-Made neutrinos: Accelerator (2)

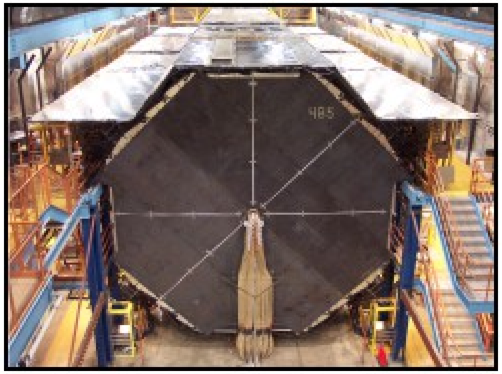
Off-axis give better energy resolution,
But less events.



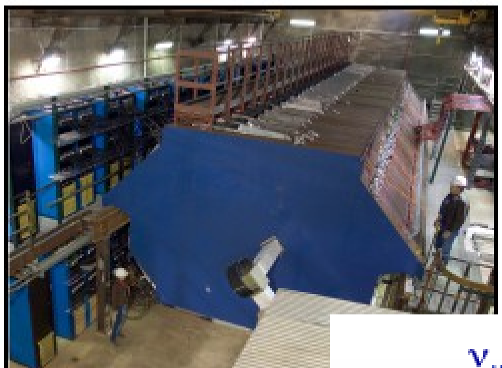


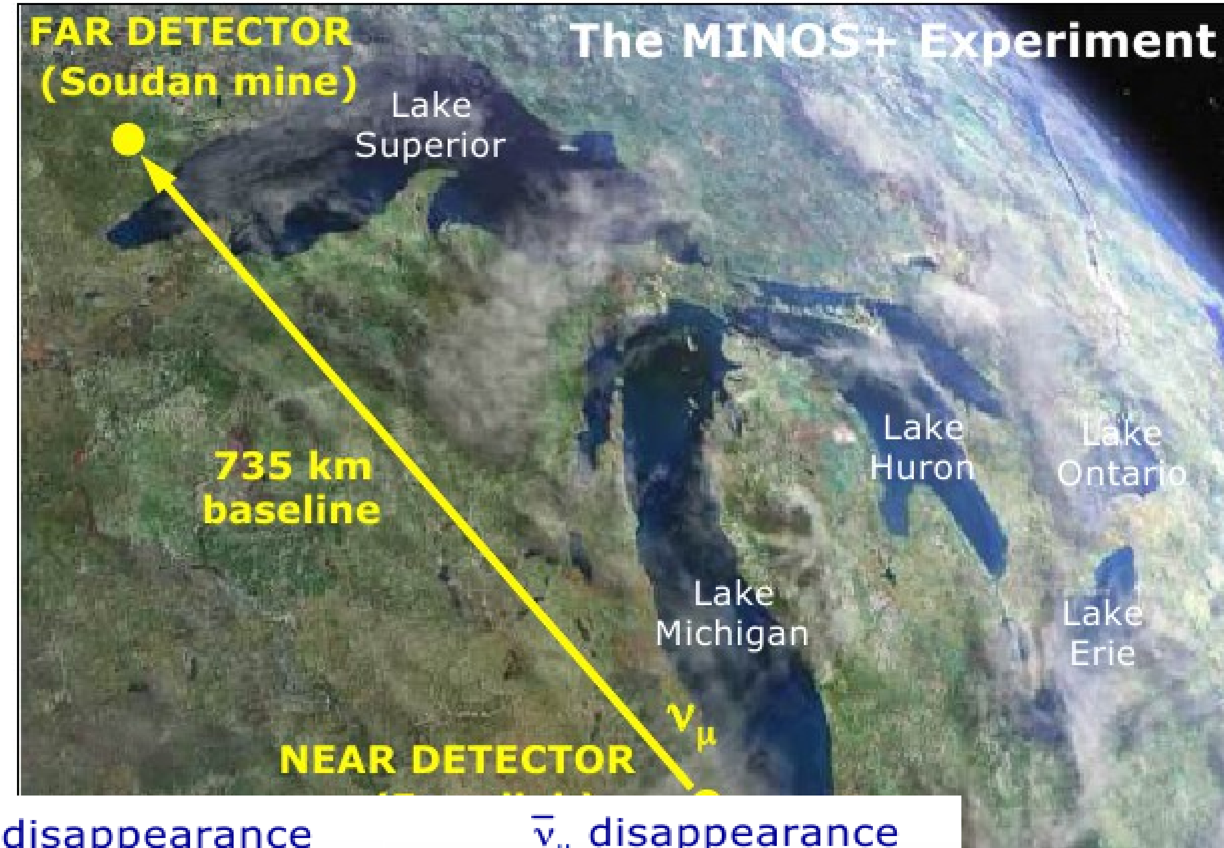
Minos/Minos+

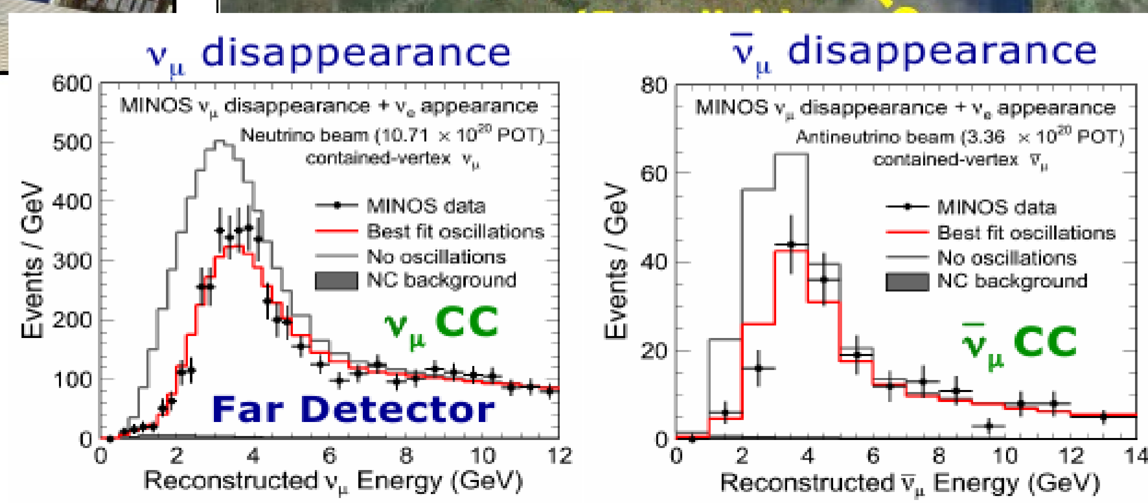
Far Detector (5.4 kton)



Near Detector (1 kton)

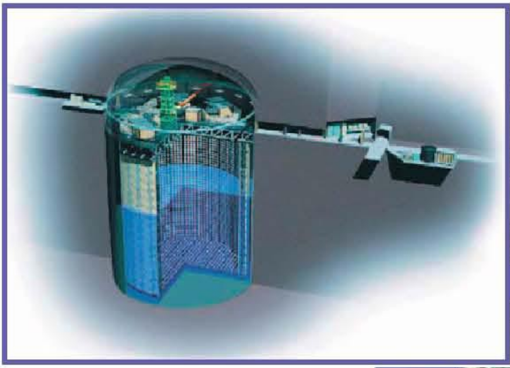


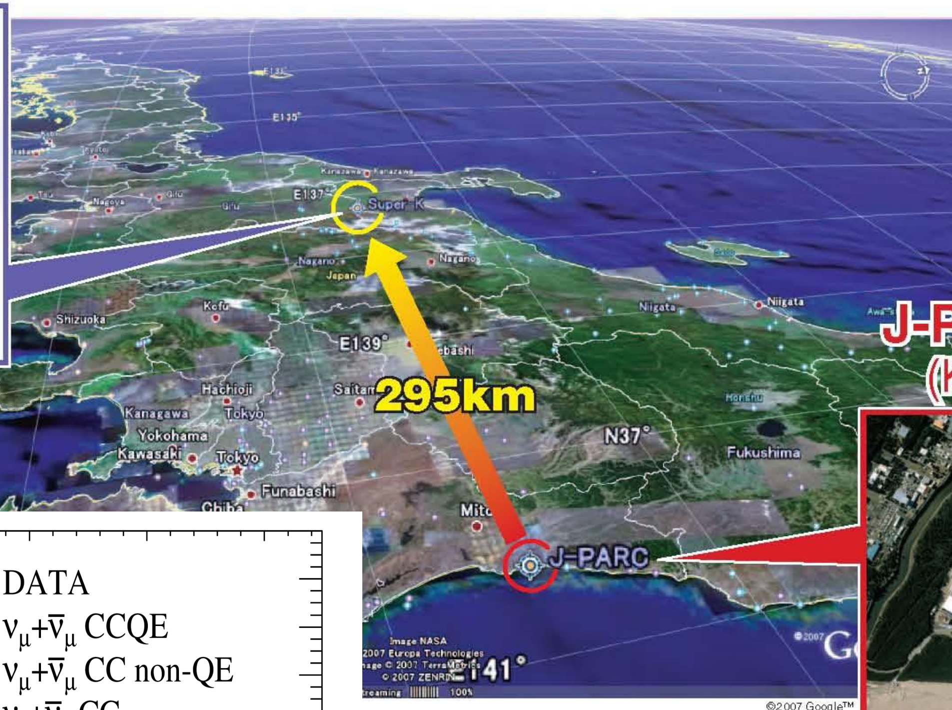




A. Blake

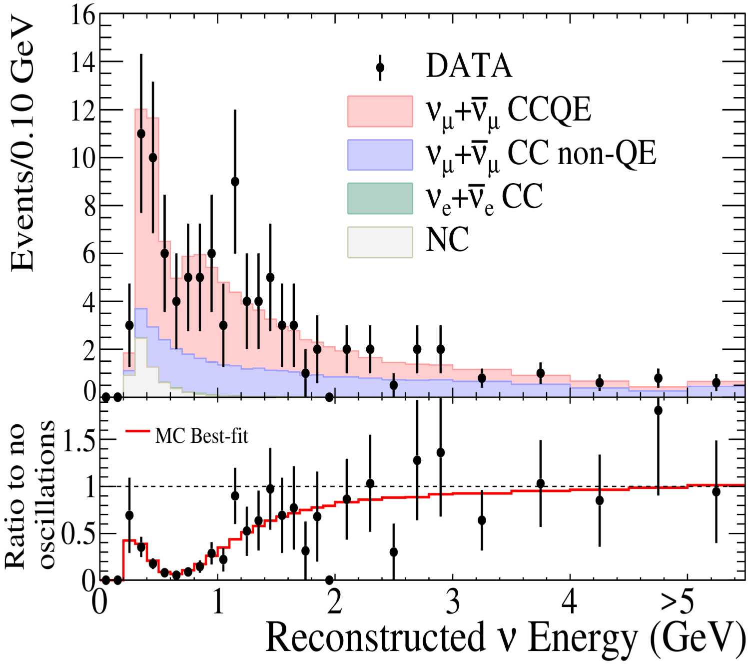
Tokai to Kamioka (T2K)

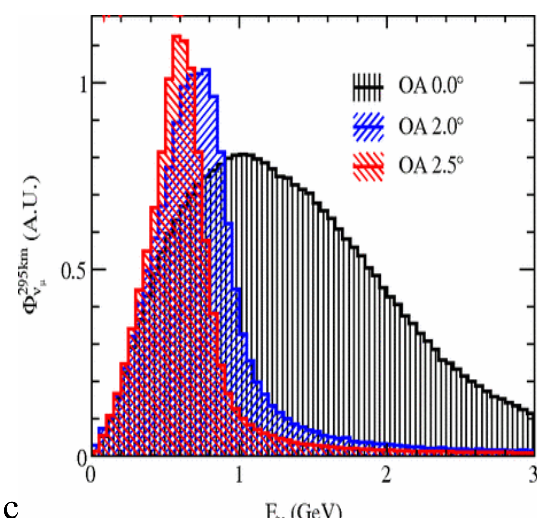




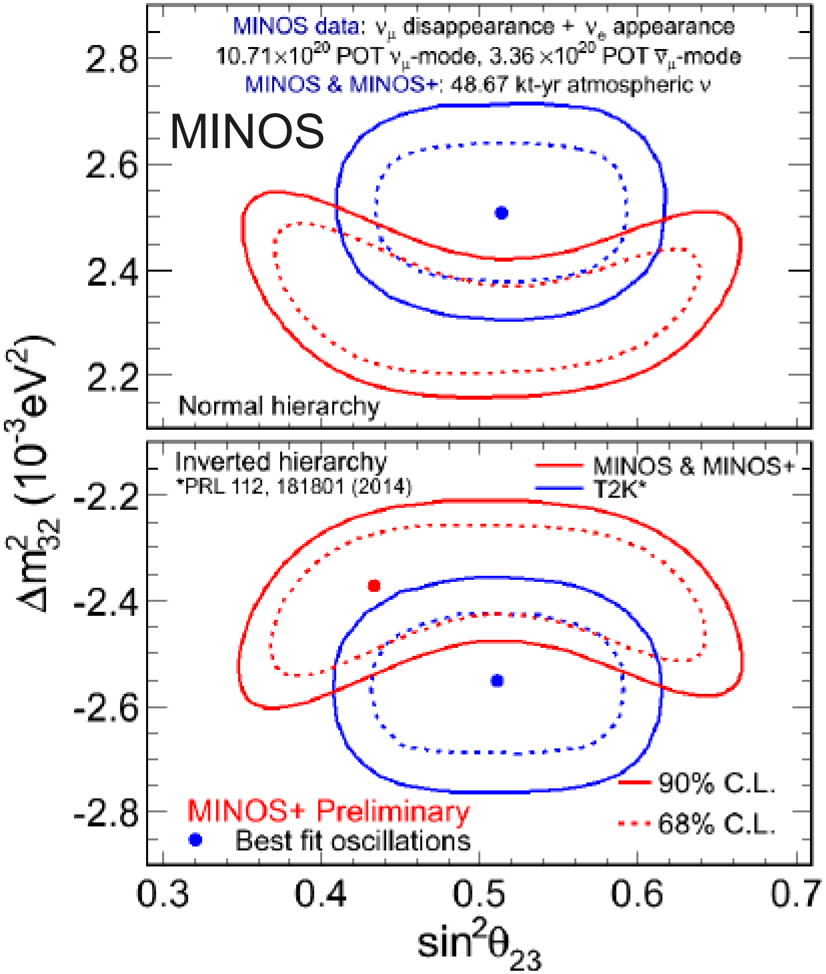
Super-Kamiokande
(ICRR, Univ. Tokyo)

J-PARC Main Ring
(KEK-JAEA, Tokai)





θ_{23} measurements



Inverted Hierarchy

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

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

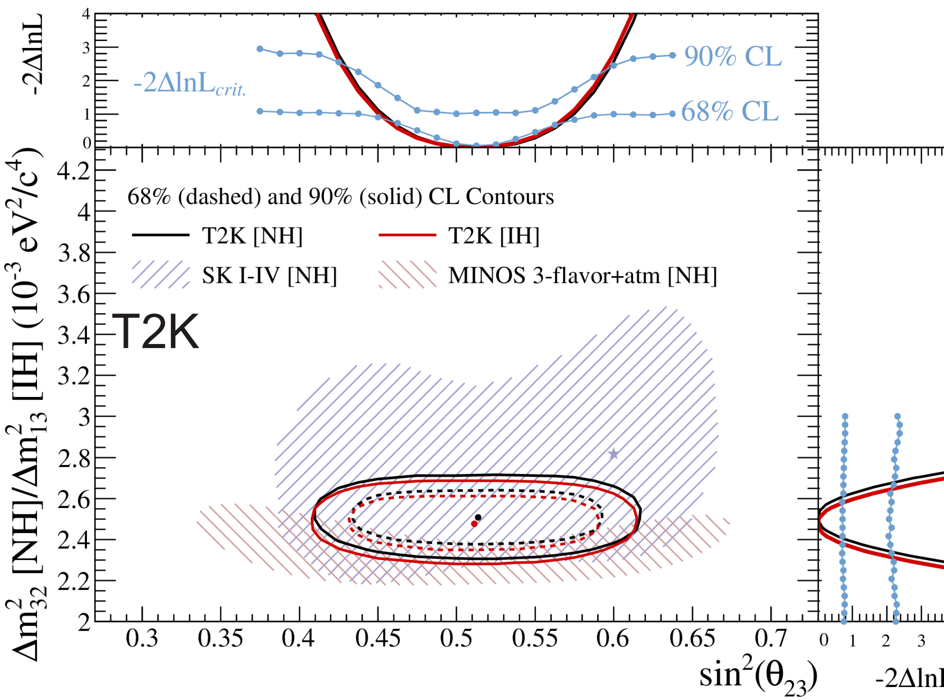
$$0.36 < \sin^2\theta_{23} < 0.65 \text{ (90\% C.L.)}$$

Normal Hierarchy

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

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

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

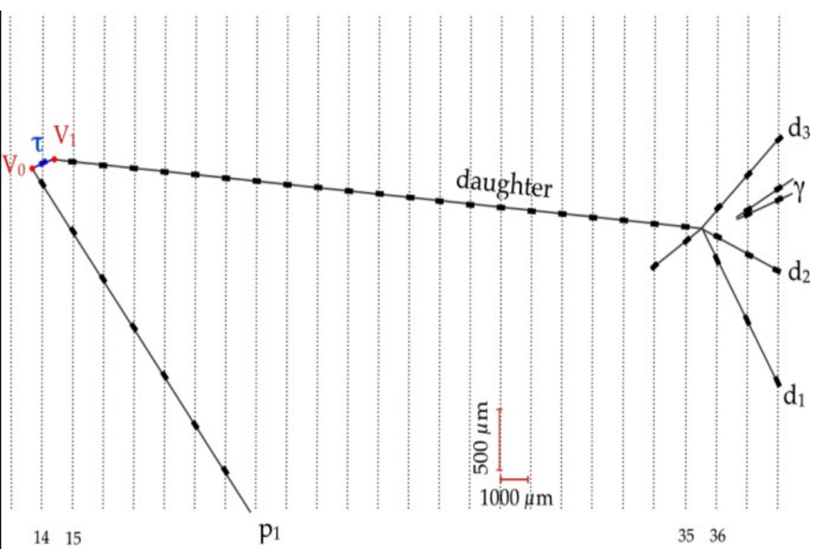


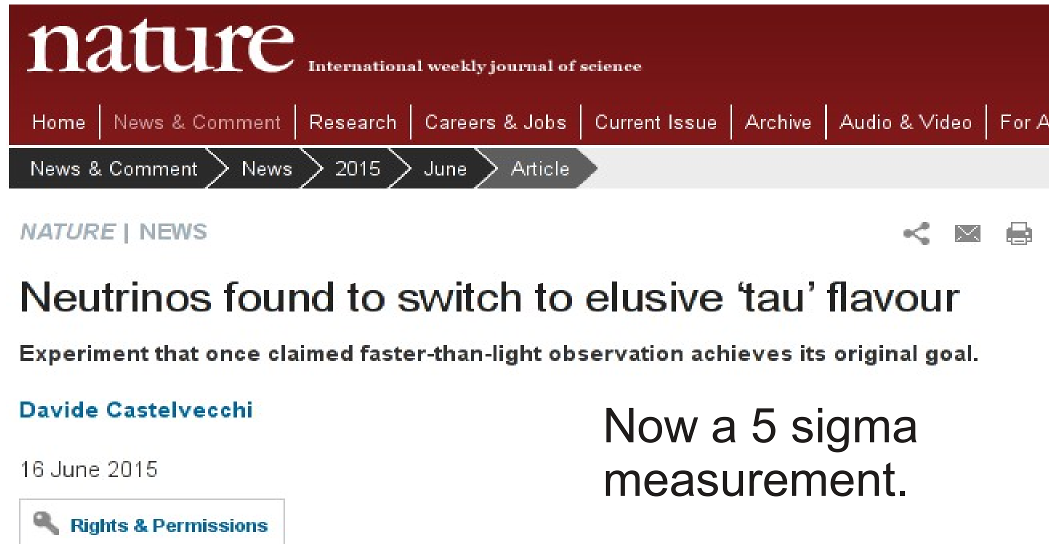
T2K favours maximum disappearance
In contrast to SK atmospheric and MINOS

OPERA and τ appearance

ν_τ extremely hard to detect – need high energy to create τ and great resolution to see it.

Emulsion detectors.




nature International weekly journal of science

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News & Comment > News > 2015 > June > Article

NATURE | NEWS

Neutrinos found to switch to elusive 'tau' flavour

Experiment that once claimed faster-than-light observation achieves its original goal.

Davide Castelvecchi

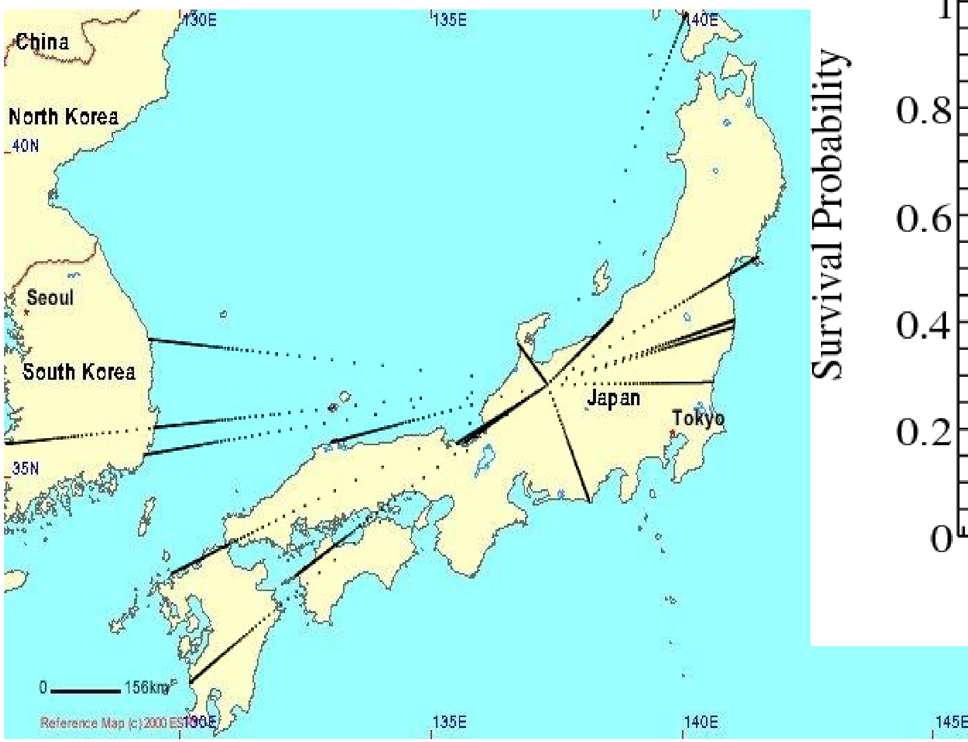
16 June 2015

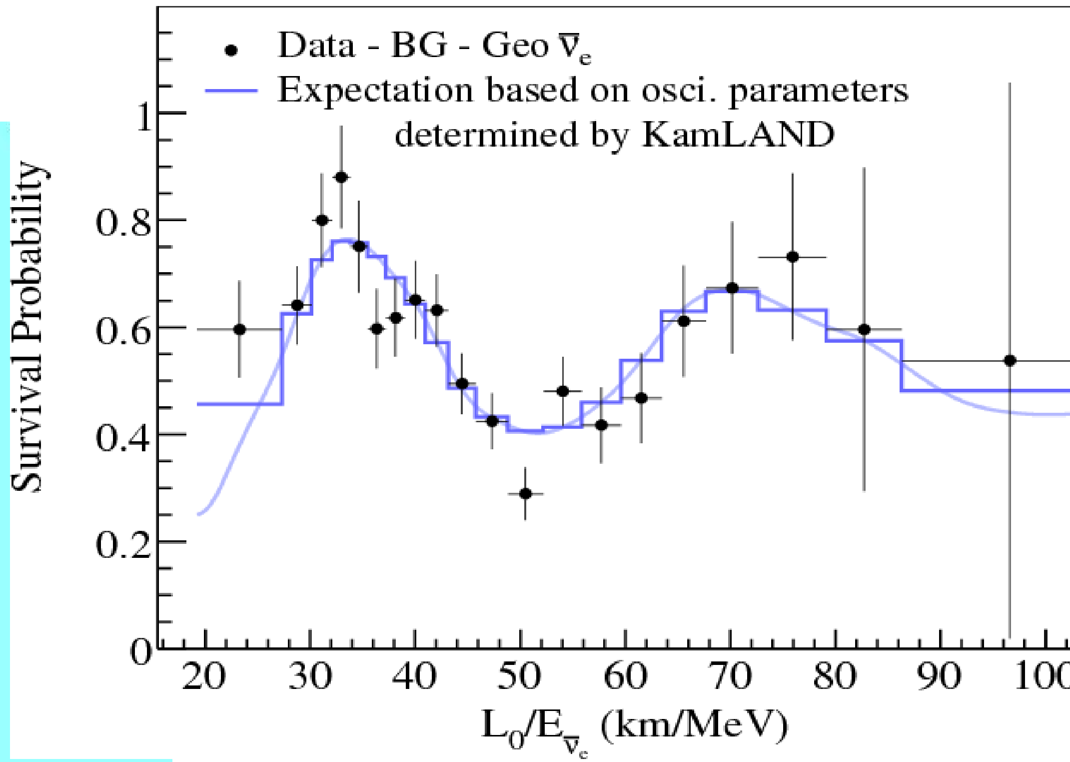
Rights & Permissions

Now a 5 sigma measurement.

Solar neutrinos

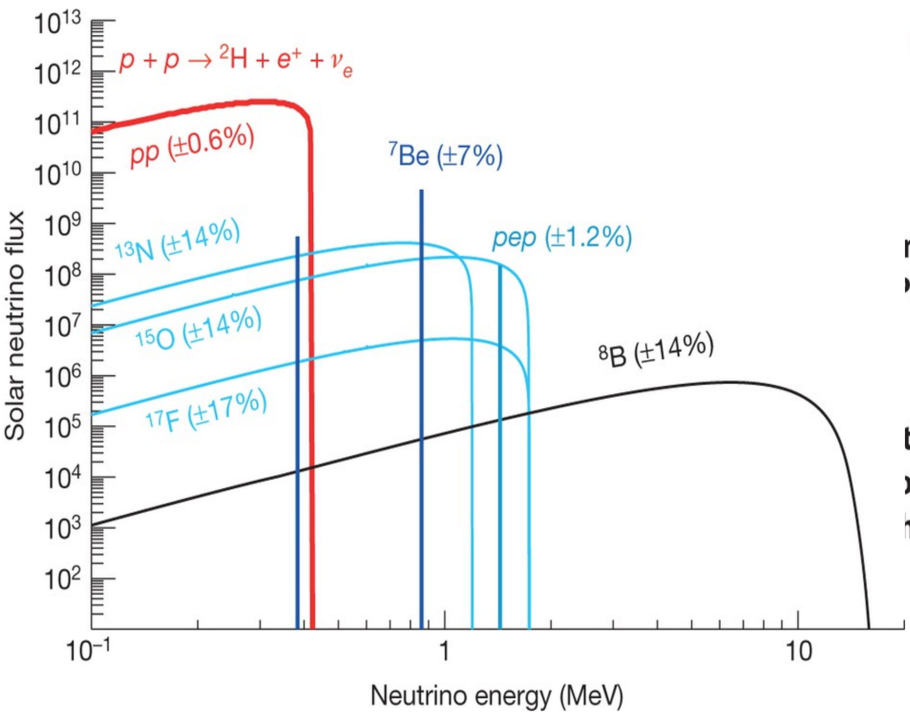
- The best measurement of the Solar Mixing angle comes from a reactor experiment (KamLand).

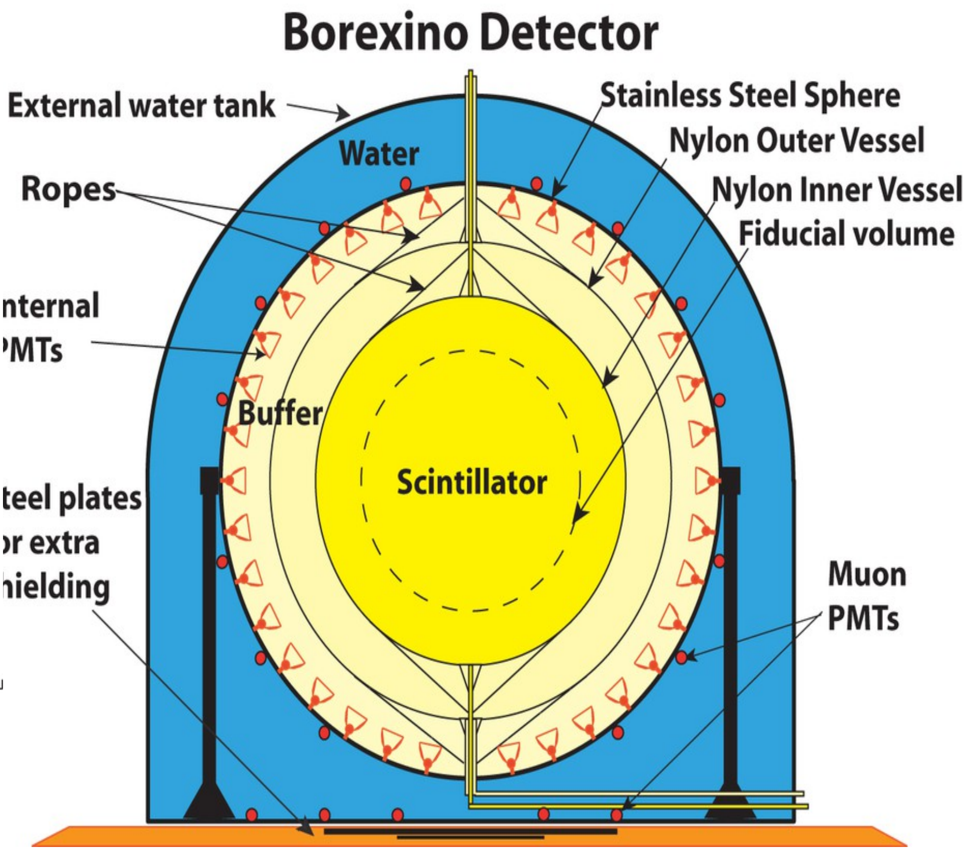




L is the effective baseline taken as a flux-weighted average (L=180km);

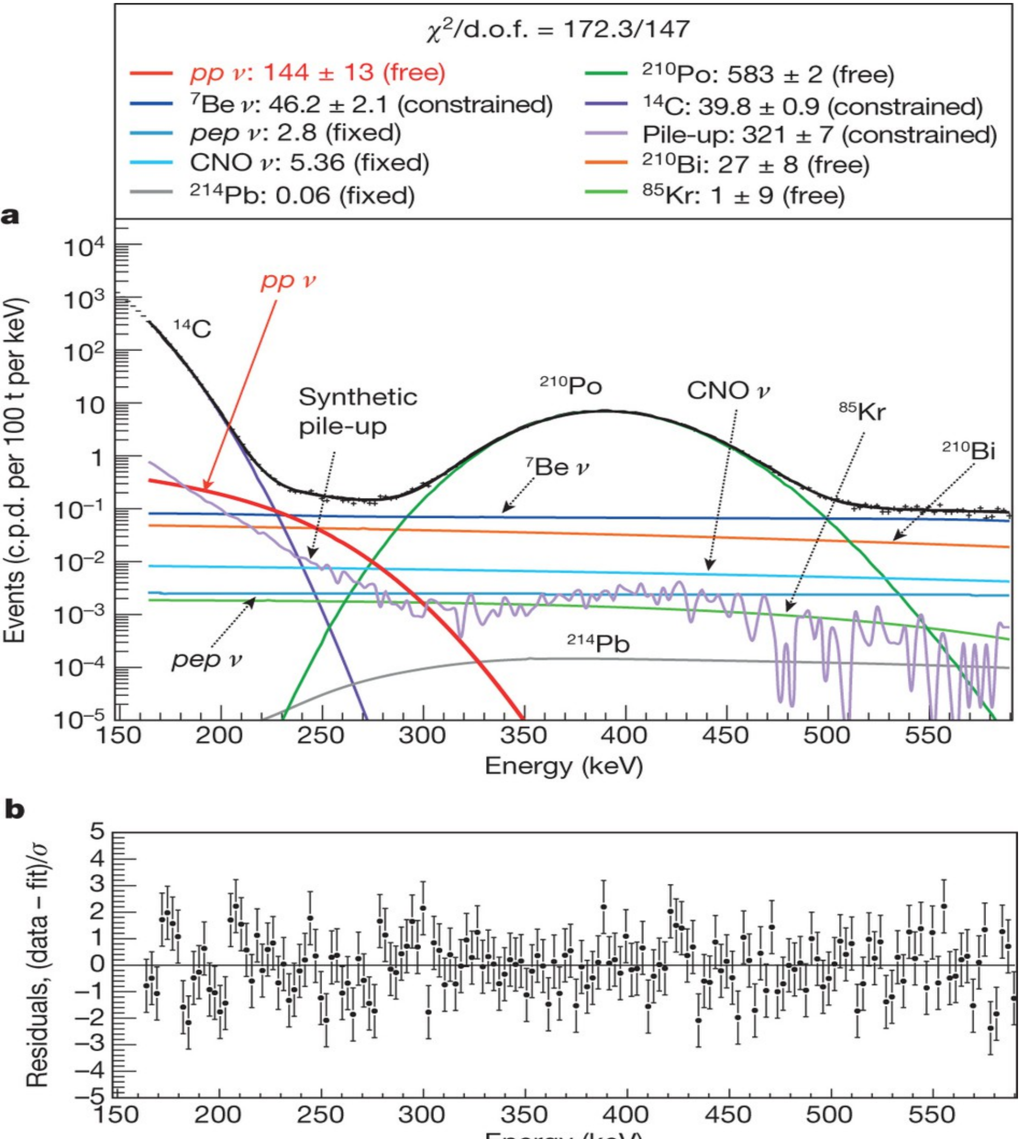
We are still looking at the Sun

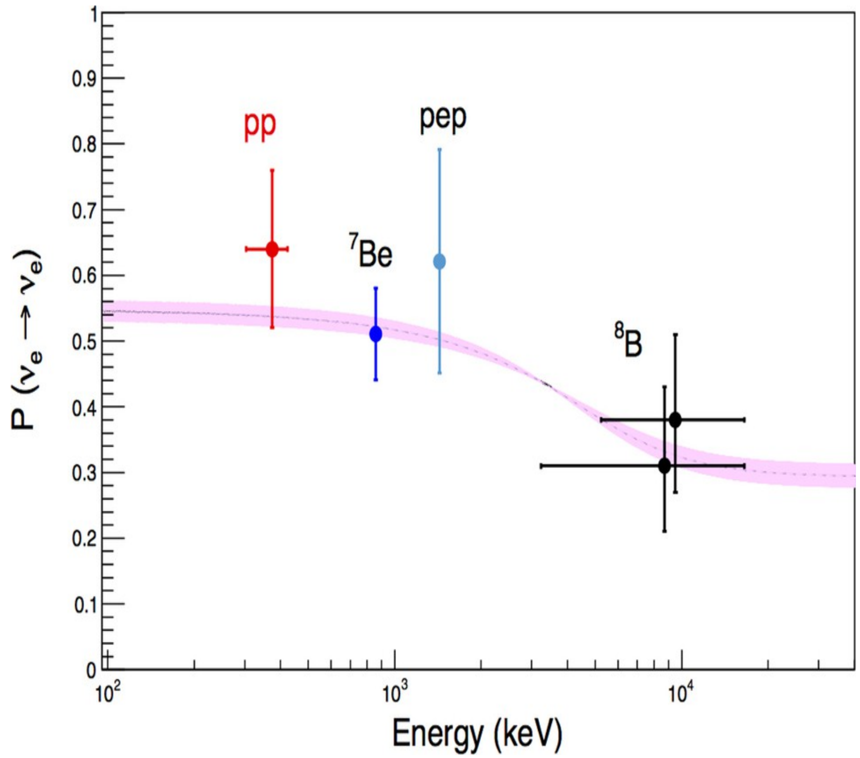




- Was able to reduce natural radioactivity enough to lower their threshold to ~100 keV

Observation of the pp-cycle in Borexino





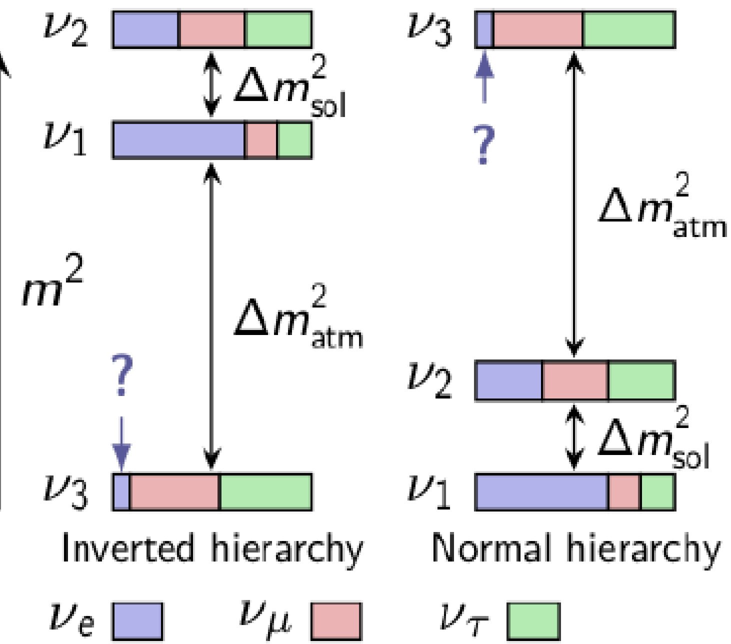
Global fit:

$\sin^2\theta_{12}$	$0.304^{+0.013}_{-0.012}$
$\dfrac{\Delta m^2_{21}}{10^{-5}\ \mathrm{eV}^2}$	$7.50^{+0.19}_{-0.17}$

JHEP 1411:052, 2014

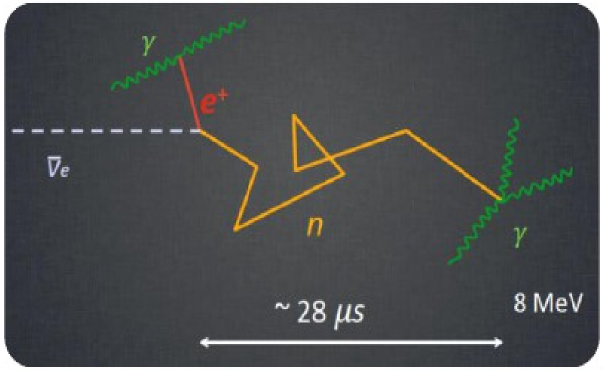
The state of affairs as of 2011

- We knew that 3 neutrinos exist.
- Two mass splittings Δm^2_{sol}, Δm^2_{atm} and mixing angles measured.
- We do not know the mass hierarchy (normal or inverted?).
- We do know the neutrino masses are very small.
- Biting our nails, hoping the mixing angle: θ_{13} is big enough so that a measurement of the CP violation phase is possible (tomorrow's lecture).

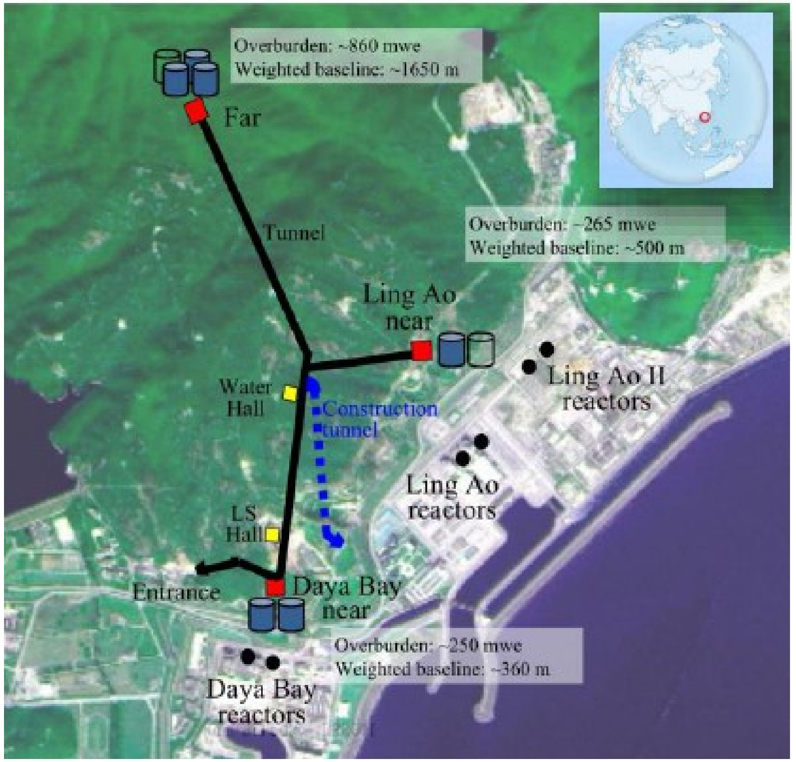


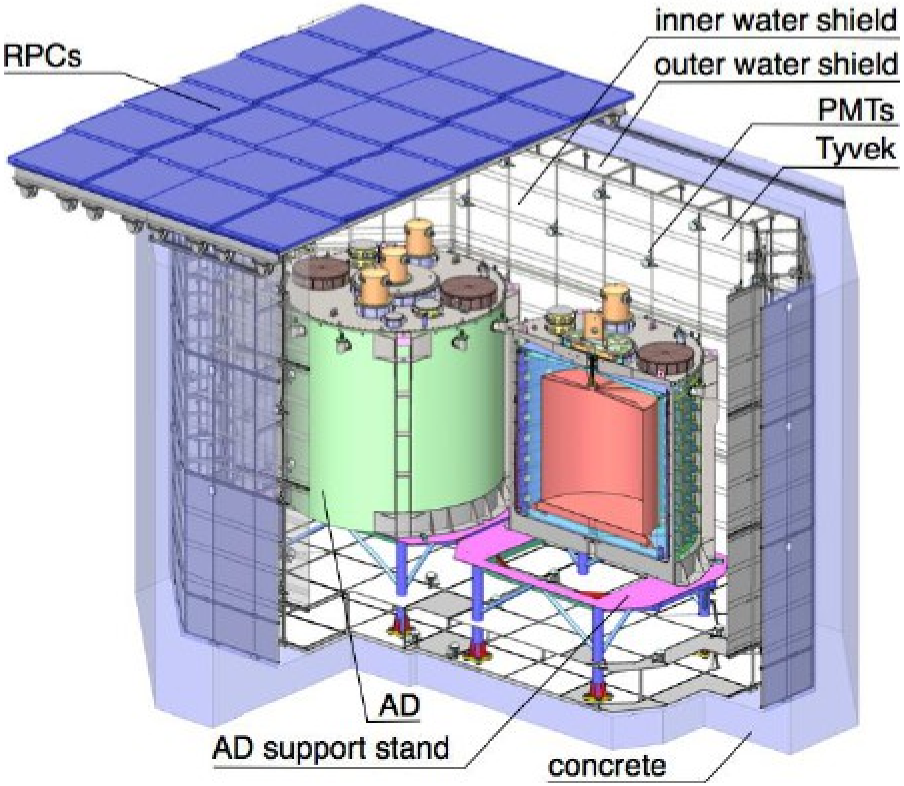
$\sin^2\theta_{23}$	~0.45	LBL Acc
Δm^2_{32}	~2.4x10^{-3}eV^2	LBL Acc
$\sin^2\theta_{12}$	~0.3	VLBL react.
Δm^2_{32}	~7.5 x 10^{-5}eV^2	VLBL Reac, SNO

Daya-Bay – an example of an LBL reactor neutrino experiment.

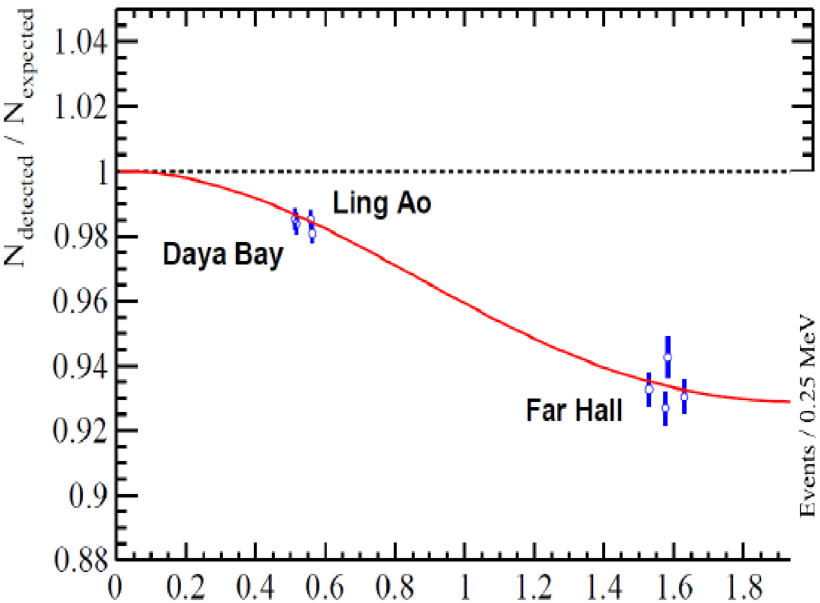


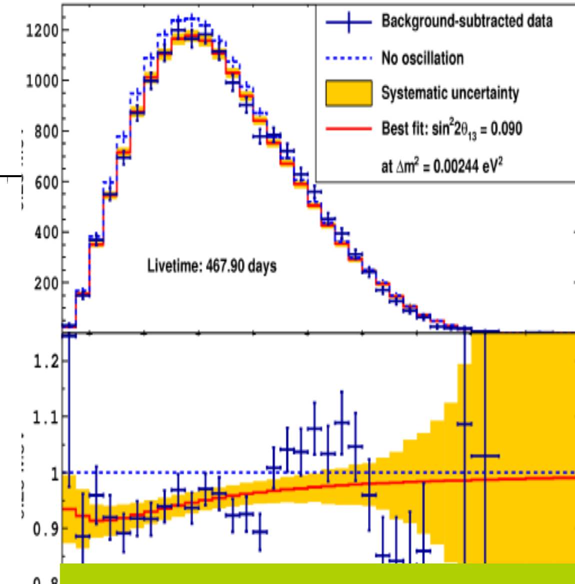
- Detection via scintillation light (liquid scintillator)
- Use Inverse Beta Decay signature.
- Doped with Gd to increase neutron capture.

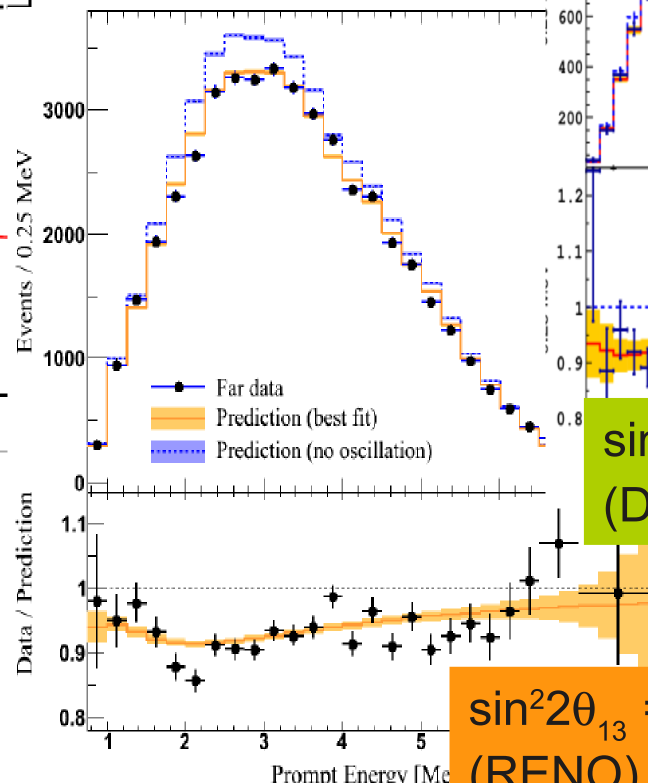


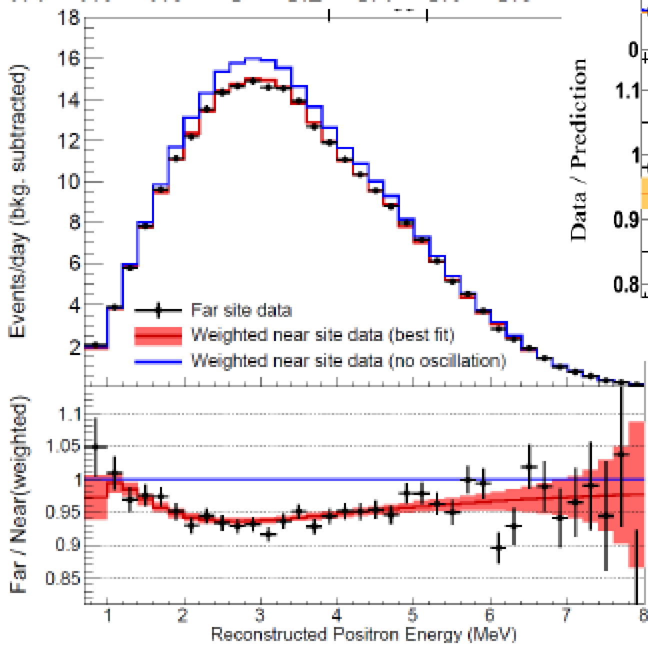


Daya-Bay/Reno/Double Chooz







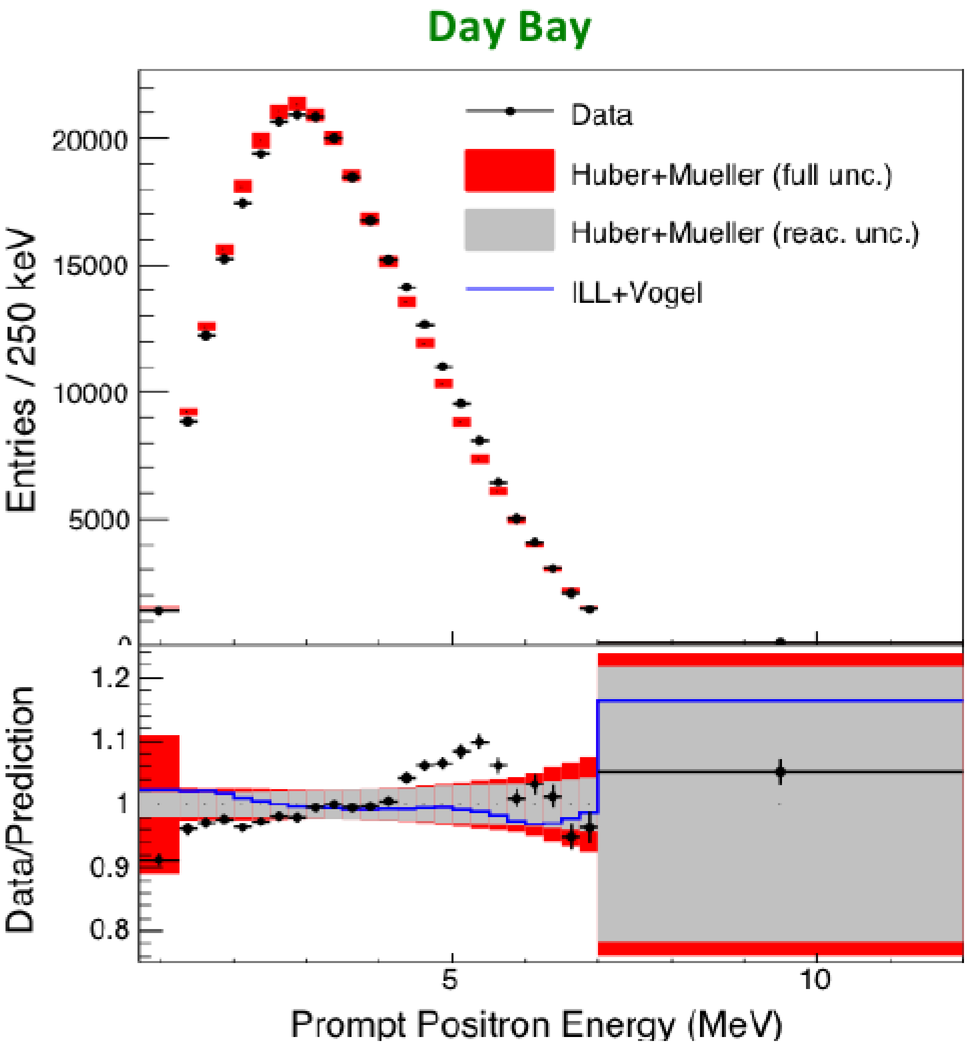


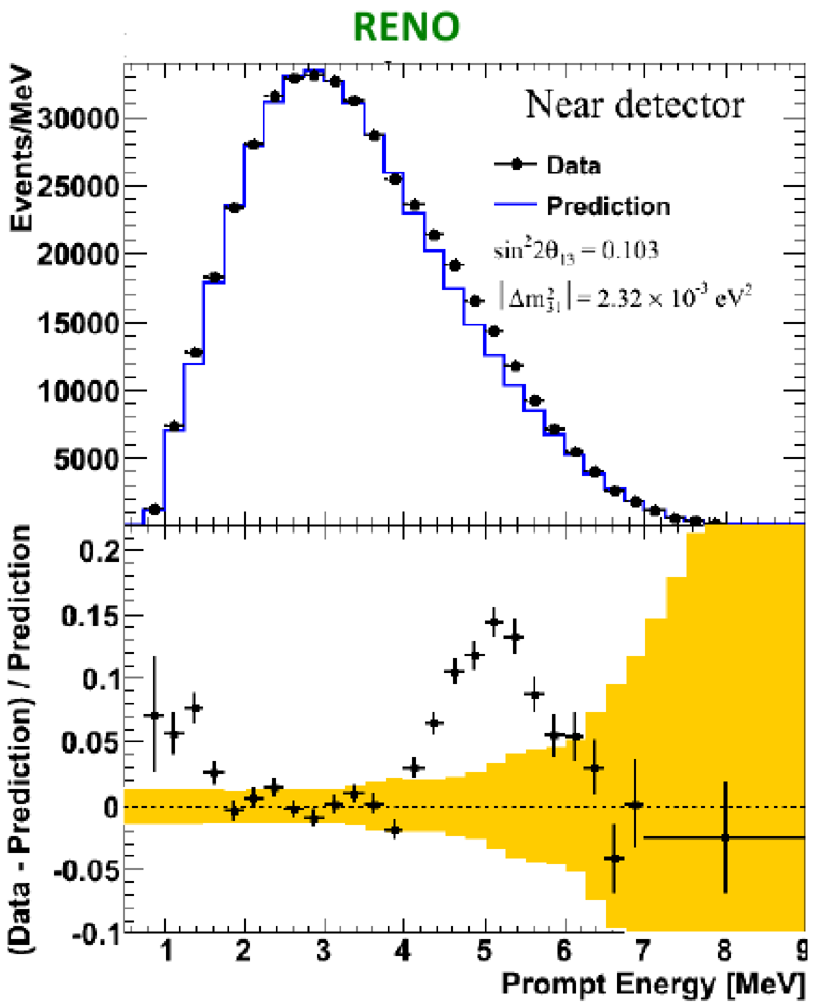
$\sin^2 2\theta_{13}$ = 0.09 +/- 0.03
(D-Chooz)

$\sin^2 2\theta_{13}$ = 0.088 +/- 0.011
(RENO)

$\sin^2 2\theta_{13}$ = 0.084 +/- 0.005
(Daya-Bay)

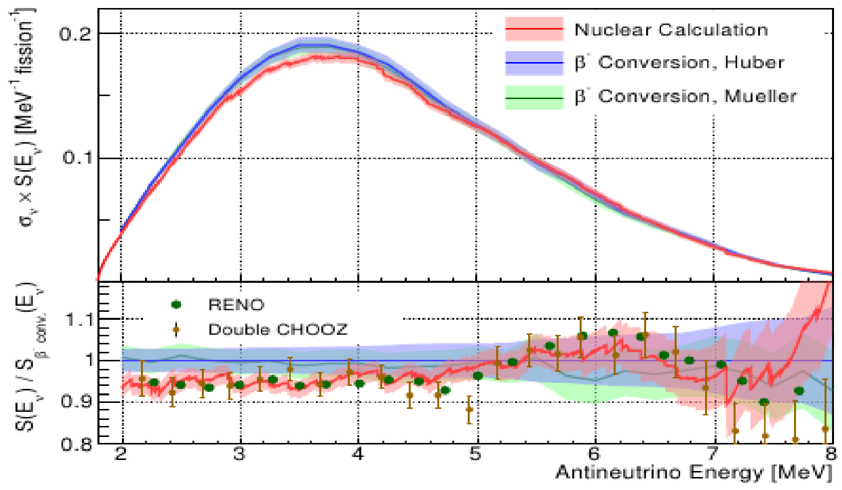
The 5 MeV bump

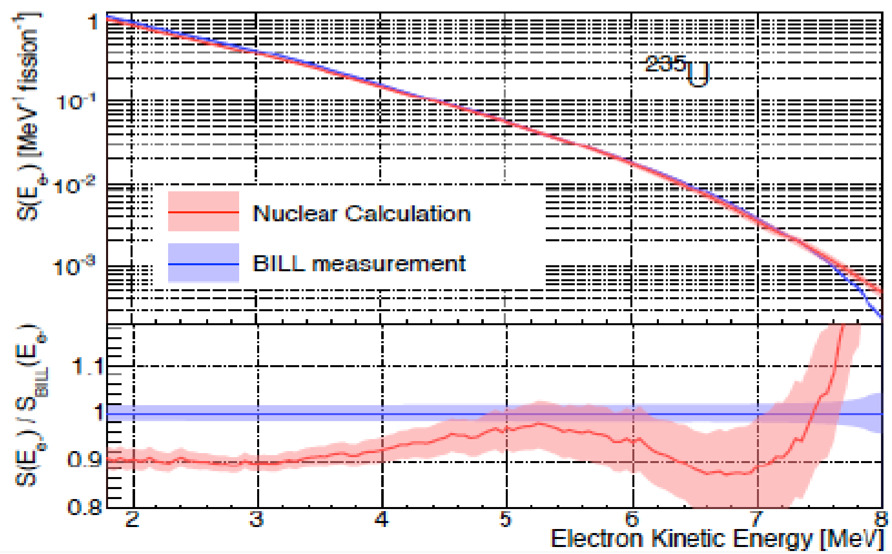




Ab-initio calculations

- Making different assumptions can reproduce bump.
- But has problems with the beta spectra.
- There are other things that are fishy with the fluxes (more on that tomorrow).



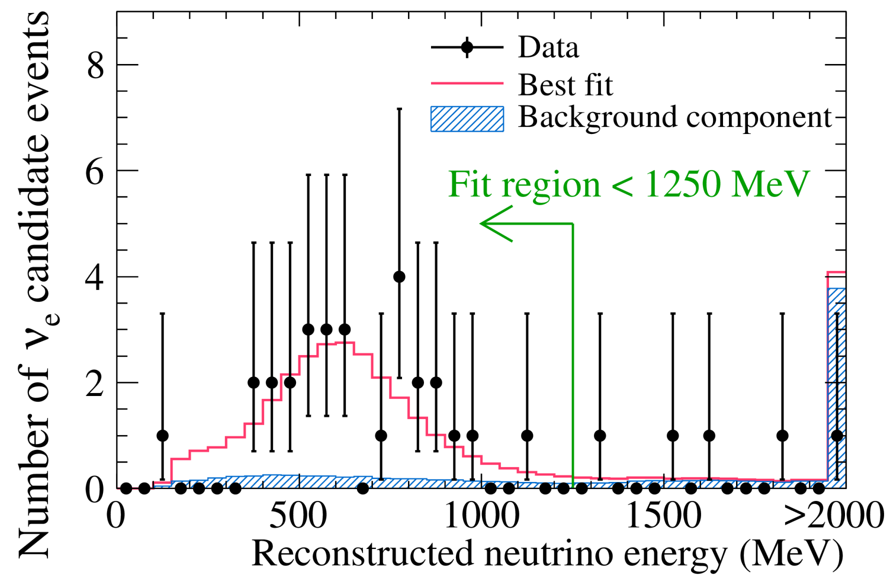


Dwyer & Langford, PRL, 114 012502 (2015)

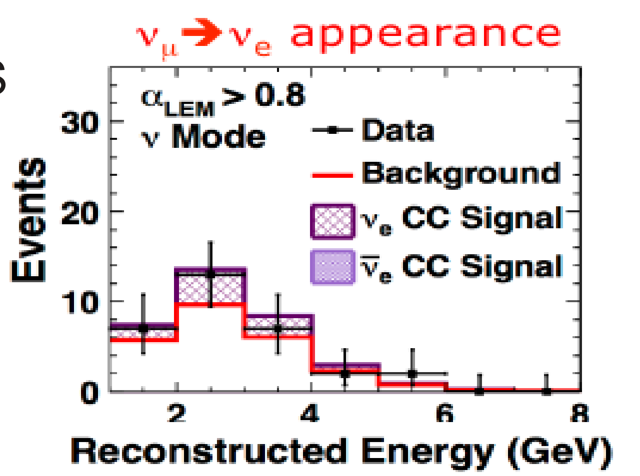
θ_{13} by ν_e appearance

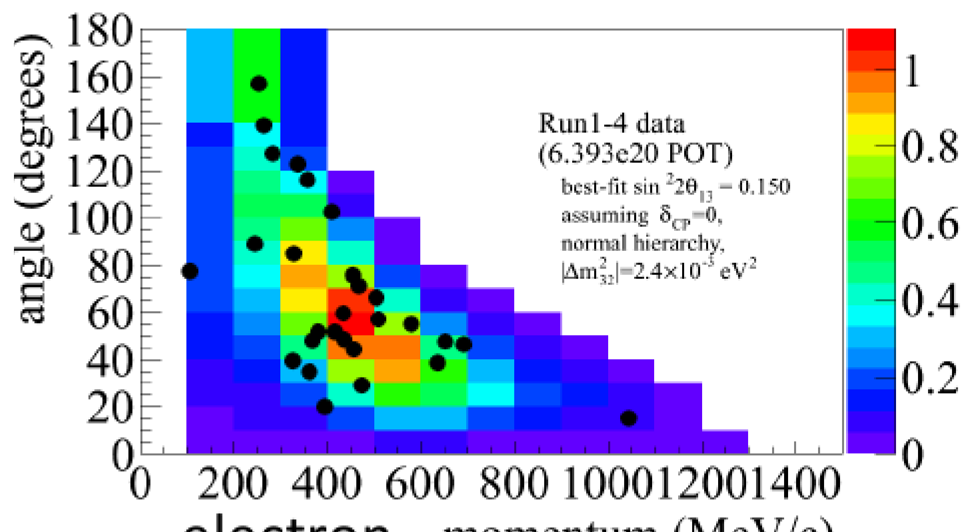
In parallel, long baseline neutrino experiments have measured ν_e appearance

7.3 sigma evidence for electron neutrino appearance in T2K.
- First ever conclusive evidence of neutrino flavour appearance



MINOS





“known” Questions in ν-physics

(answered or being answered)

- Experimental neutrino physics in the last decades was driven by the following questions:

- why do we see less neutrinos from the sun?

- where are the atmospheric νs?

- could this be due to oscillations?

- What are the parameters of Oscillation ?

- Especially, is θ_{13} non-zero?

- Is the θ_{23} mixing maximal?

- what is going on with neutrino interactions?!

Let's take a step back and see what we know.

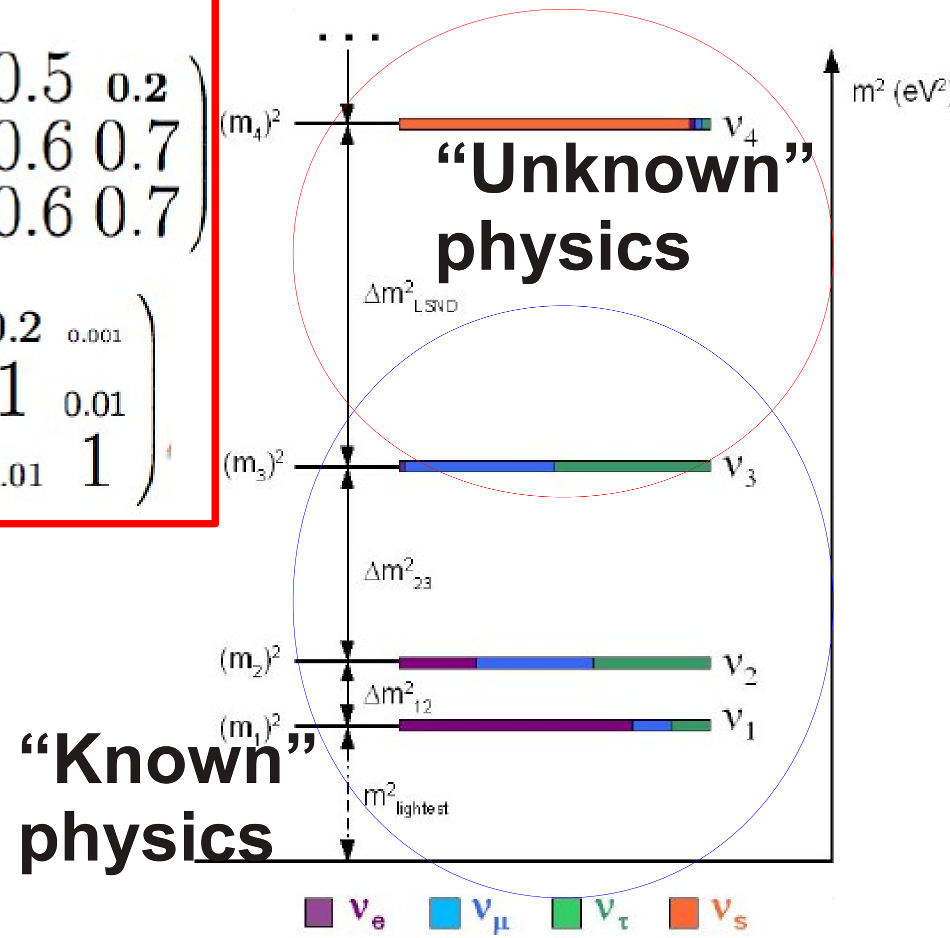
The Current State of Knowledge

The neutrino model

- Our picture of Neutrinos in the standard model is almost complete.
- Large "mixing" angle θ_{13} opens the way to measurements of CP violation in the neutrino sector (not guaranteed).
- The mixings are very different than in the quark sector.
- We do not know the absolute neutrino mass.

$$V_{MNS} \sim \begin{pmatrix} 0.8 & 0.5 & 0.2 \\ 0.4 & 0.6 & 0.7 \\ 0.4 & 0.6 & 0.7 \end{pmatrix}$$

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



“known” Questions in ν-physics

(answered or being answered)

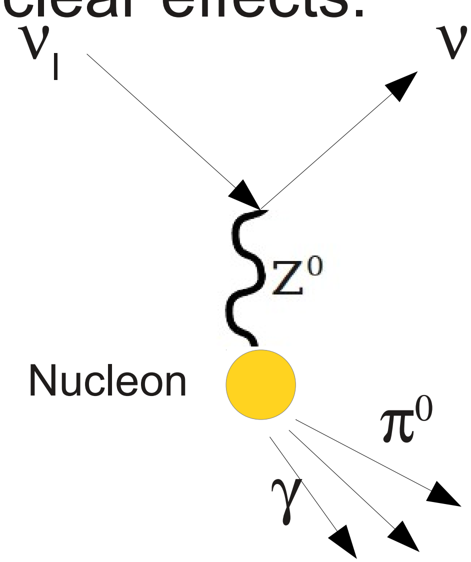
• Experimental neutrino physics in the last decades was driven by the following questions:

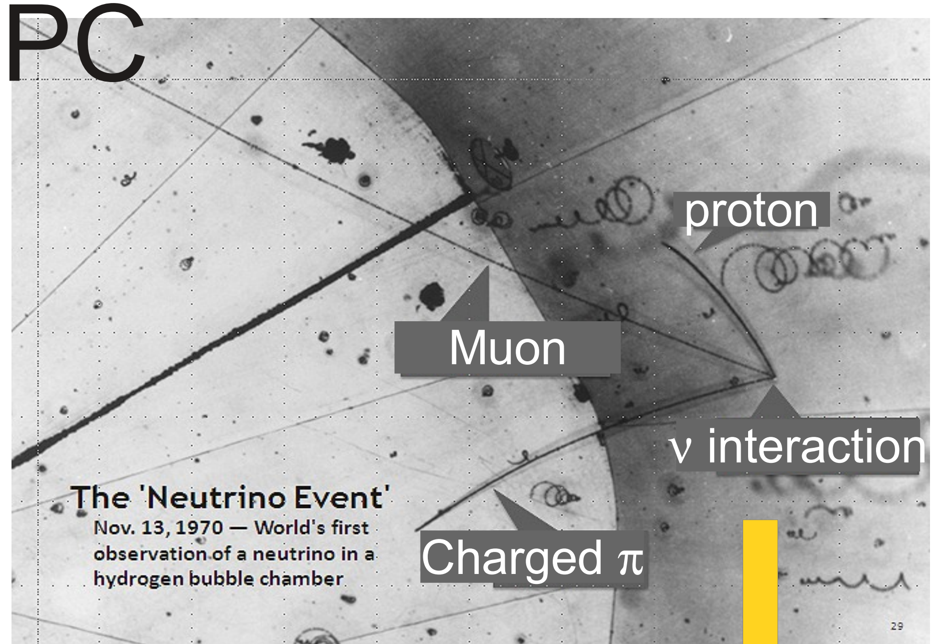
- ***why do we see less neutrinos from the sun?***
- ***where are the atmospheric νs?***
- ***could this be due to oscillations?***
- ***What are the parameters of Oscillation ?***
  - ***Especially, is θ_{13} non-zero?***
- ***Is the θ_{23} mixing maximal?***
- ***what is going on with neutrino interactions?!***

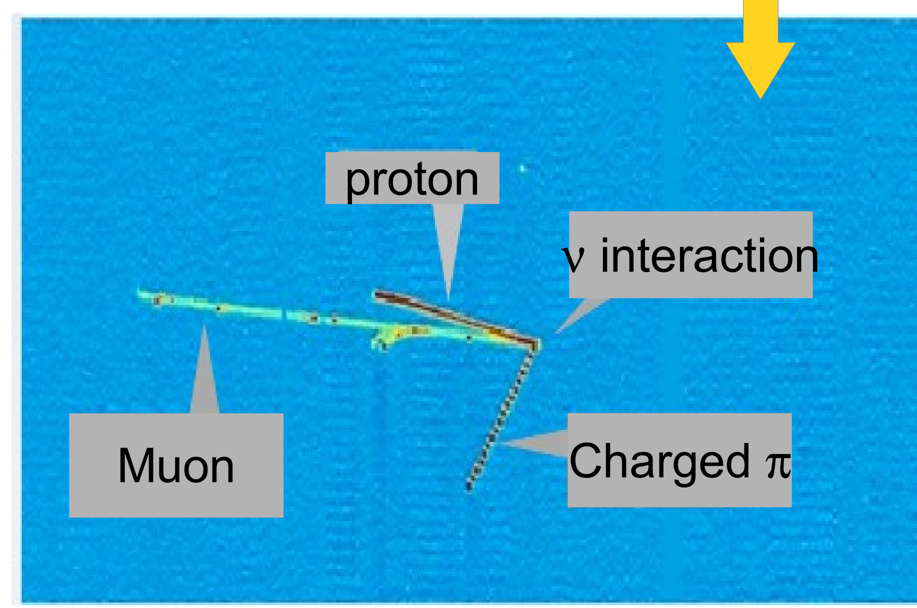
Interesting things happening in neutrino nucleus interactions

How to measure ν interactions in a LArTPC

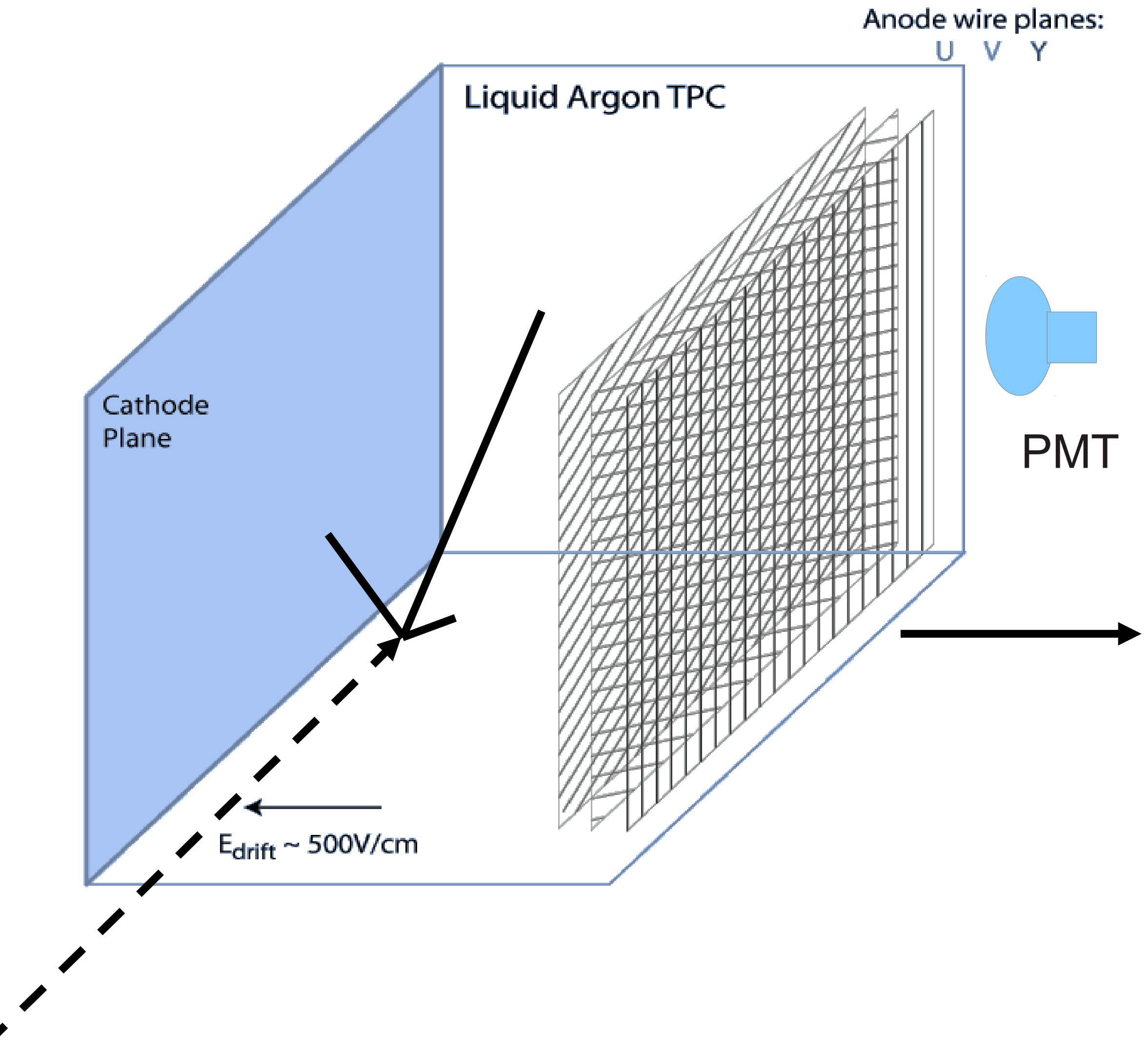
- The LArTPC and its bubble chamber like-data gives us strong background rejection tools.
- As well as extremely powerful tools to see e.g. nuclear effects.

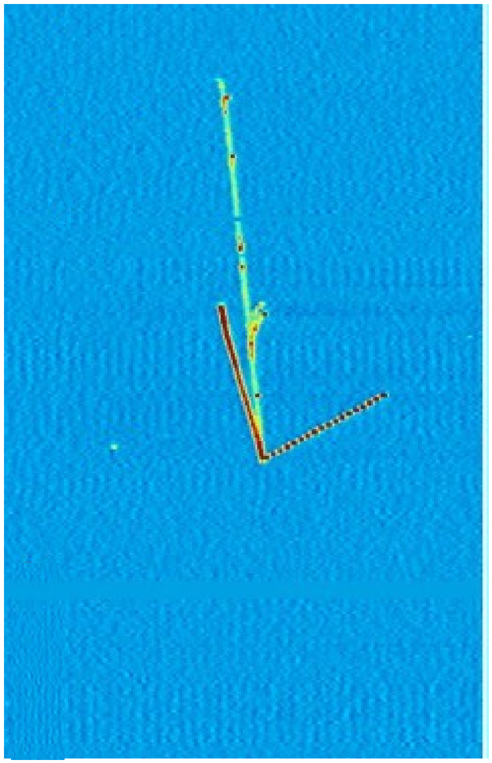






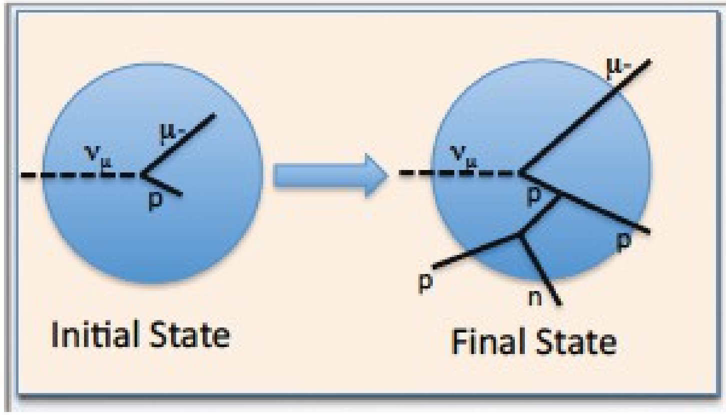
LArTPC Operation

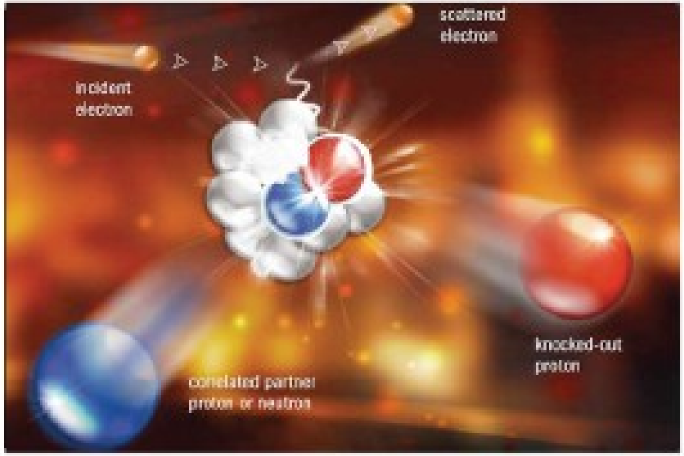




Final State Interactions

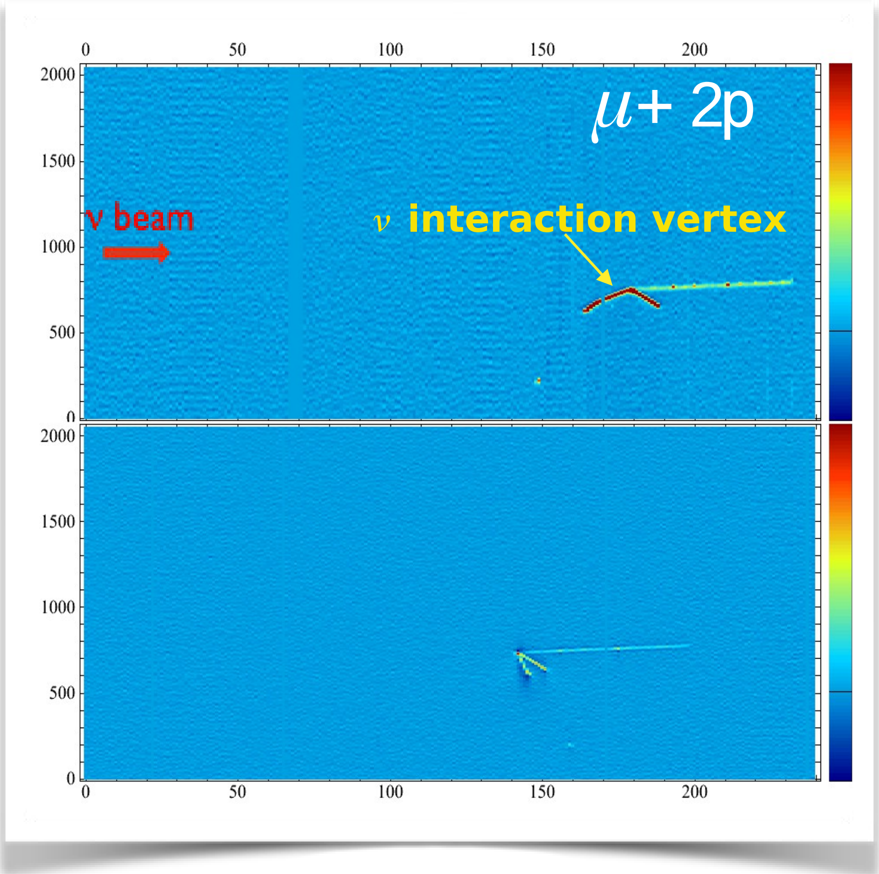
- **LArTPCs, and their resolution and calorimetric capabilities of allow us to reconstruct exclusive topologies.**
- **We can see if nuclear effects play a key role in neutrino-nucleus interactions in nuclear targets.**
- **Due to intra-nuclear re-scattering (FSI) Final State interactions additional nucleons, many de-excitation γ's and and soft pions appear in the Final State.**
- **ArgoNeuT was one of the first detectors to be able to observe these effects.**

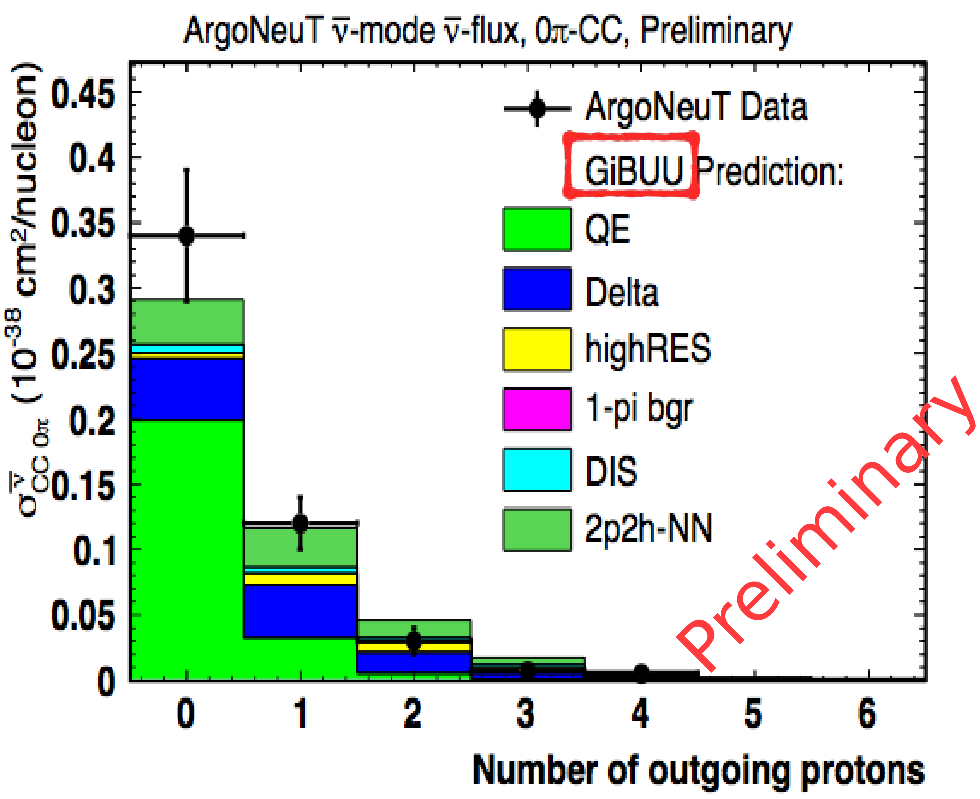




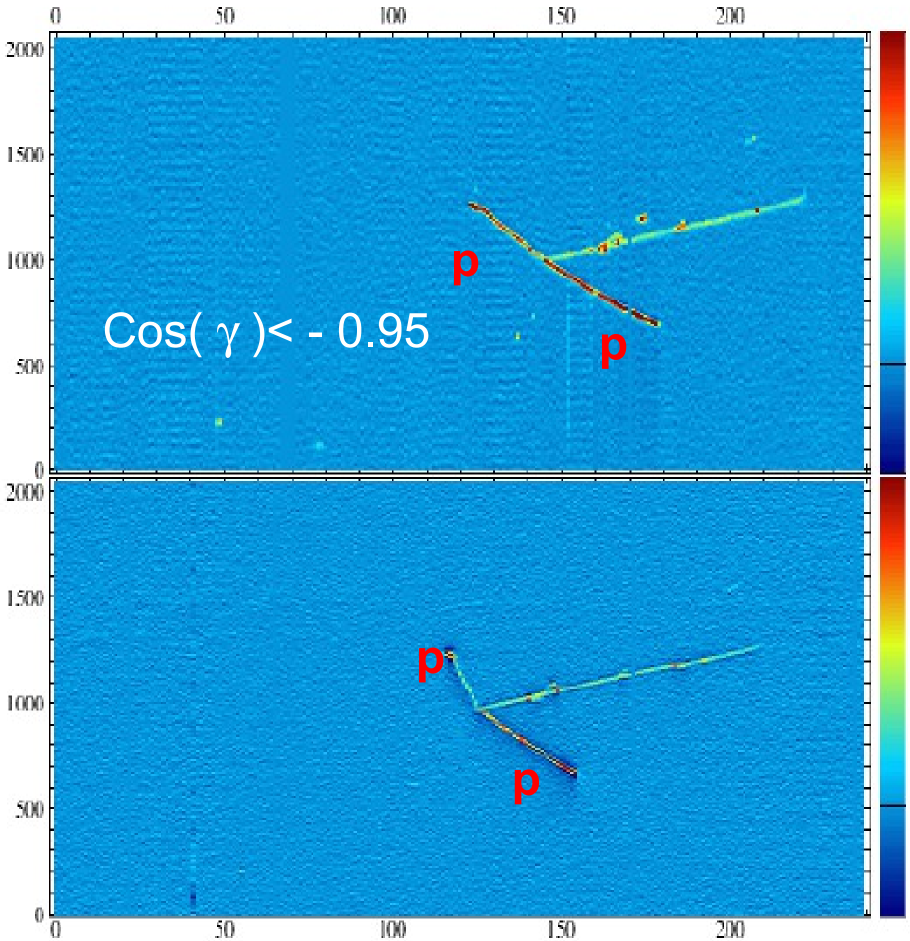
Observing proton multiplicities

- The granularity of the LArTPC allows seeing actual final state topologies.
- Measuring cross sections as a function of proton multiplicity.



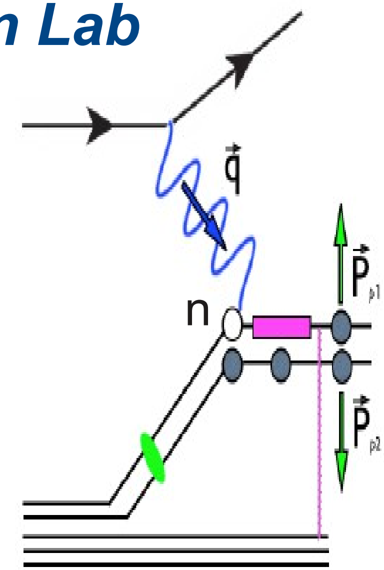


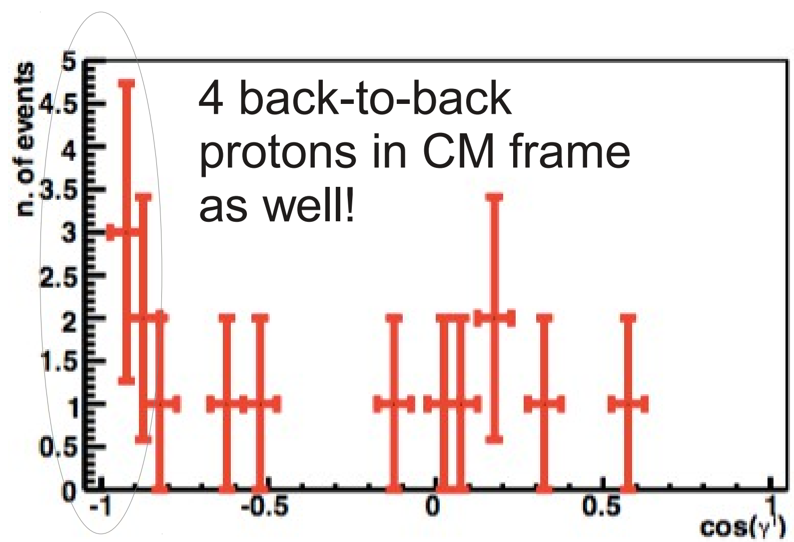
Back-to-Back Protons



4 back-to-back 2-proton events observed in Lab frame.

Possible mechanism is CC RES pionless reactions involving pre-existing SRC np pairs.





We can see nuclear effects!

ArXiv:1405.4261

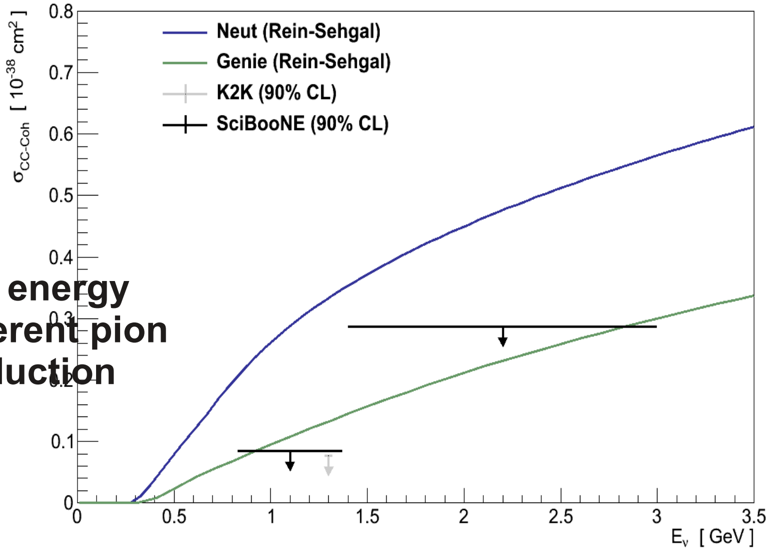
PRD**90**, 012008 (2014)

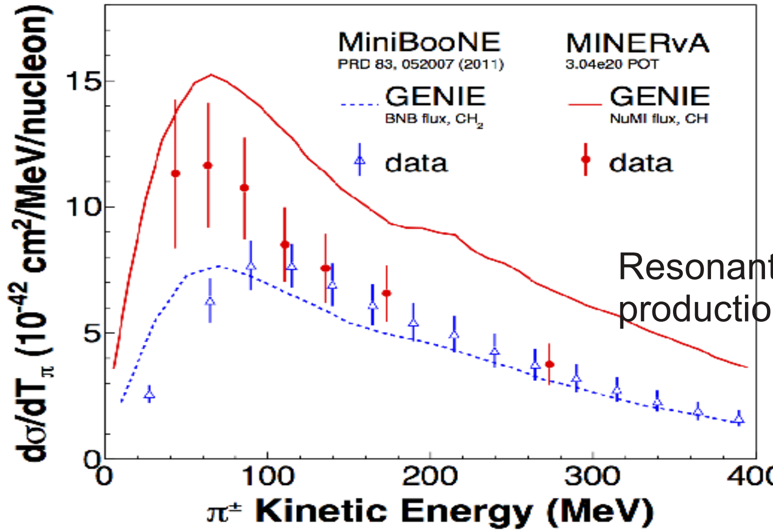
Summary of Part 1

- The 3 neutrino model seems almost sorted out.
- We have understood many of the first questions in experimental neutrino physics thanks to the phenomenon of oscillations.
- There are interesting things happening in the neutrino-nucleus interactions.
- Tomorrow: what are the experimental questions that are driving the field today and in the future.

The ν-interaction conundrums

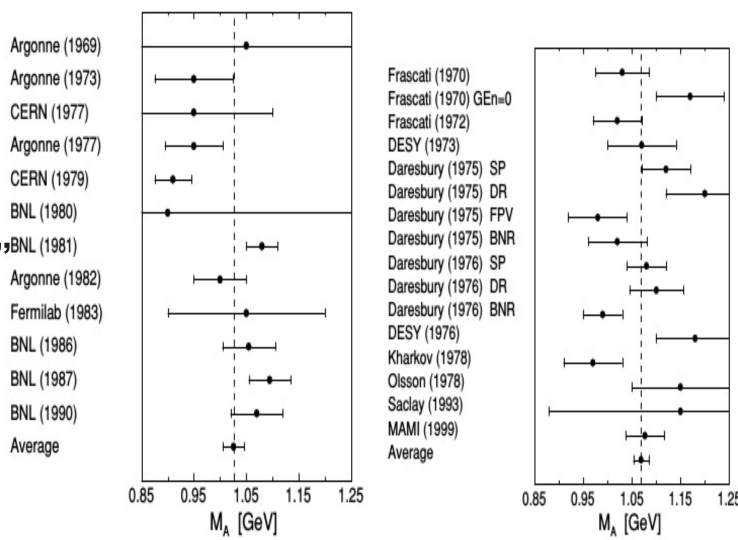
Low energy coherent pion production

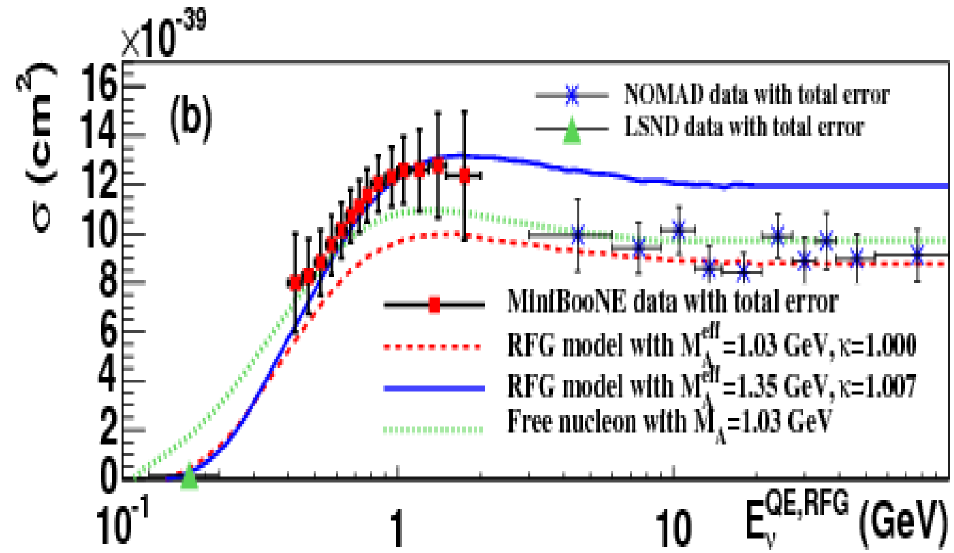




Resonant pion production

Quasi-elastic "high-MA" puzzle



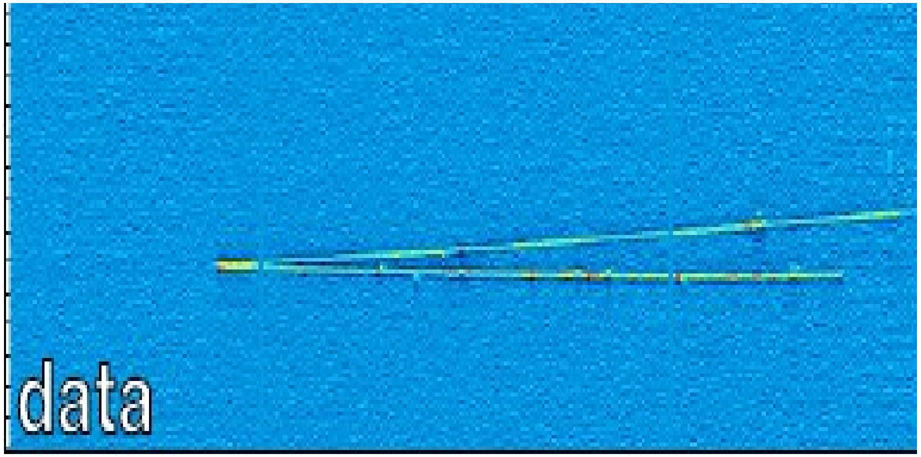


ArgoNeuT

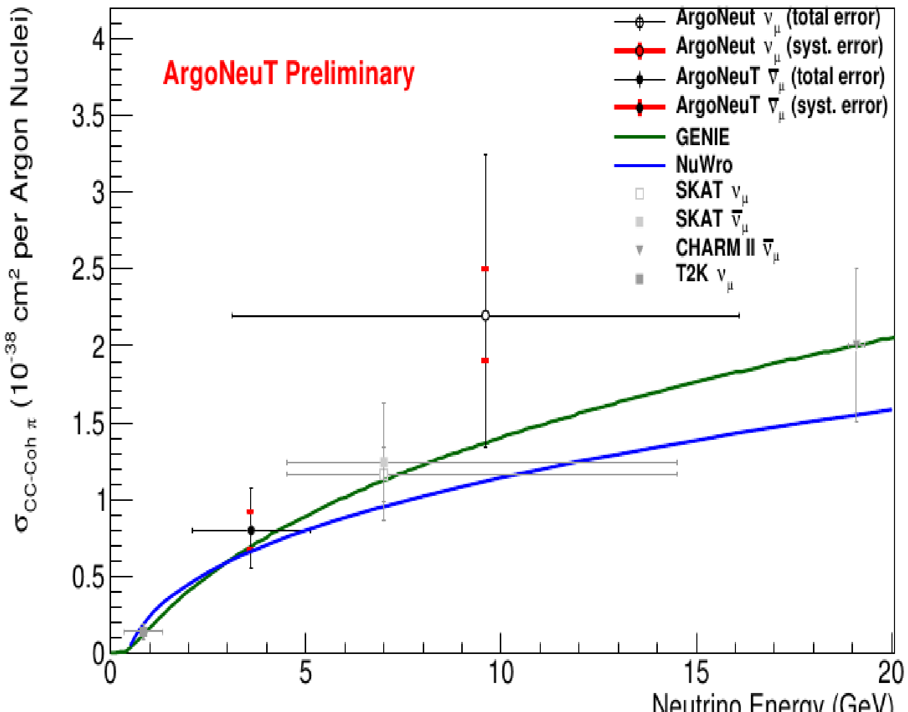
Coherent Pion Production

$$\nu_\mu + A_{g.s.} \rightarrow \mu^- + \pi^+ + A_{g.s.}$$

$$\bar{\nu}_\mu + A_{g.s.} \rightarrow \mu^+ + \pi^- + A_{g.s.}$$



*Both **ArgoNeuT** and **MINERVA** measured coherent pion production.*



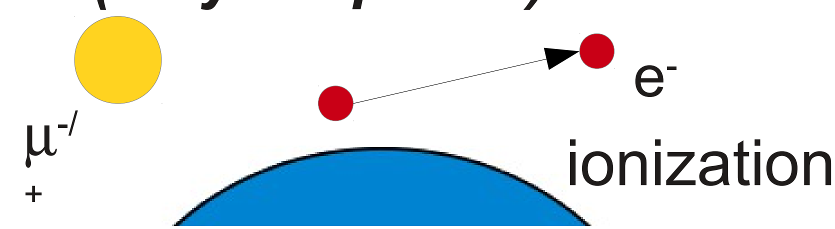
Particles Passing Through Matter

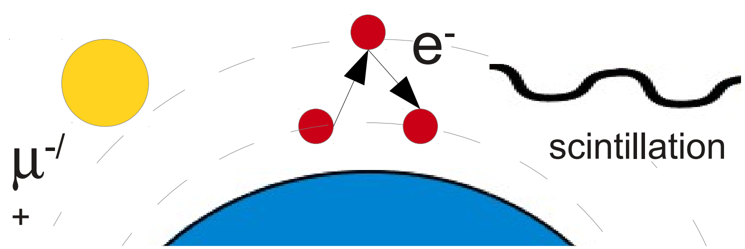
Non-charged particles (e.g. neutrinos and photons) are invisible to our detectors until they interact.

Charged particles ionize the medium along their path – charge and scintillation light which we can detect!

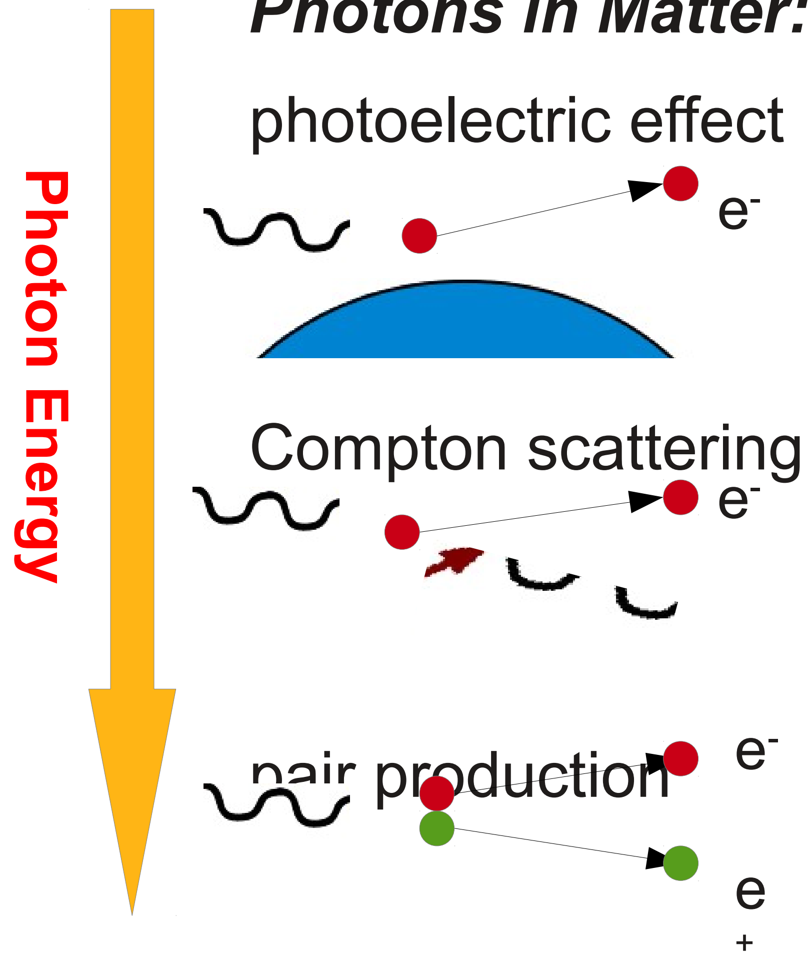
Charged Particles in Matter:

(very simplified)



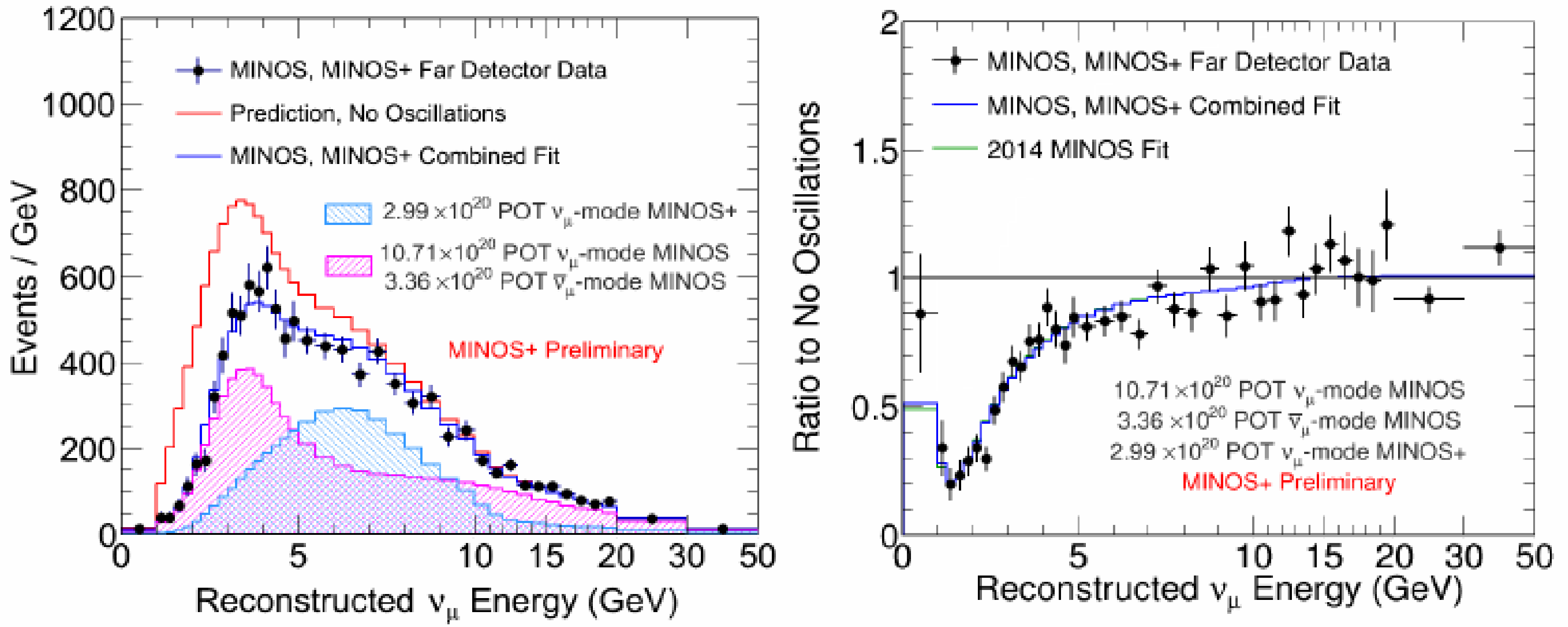


Photons in Matter:



New MINOS+ Data

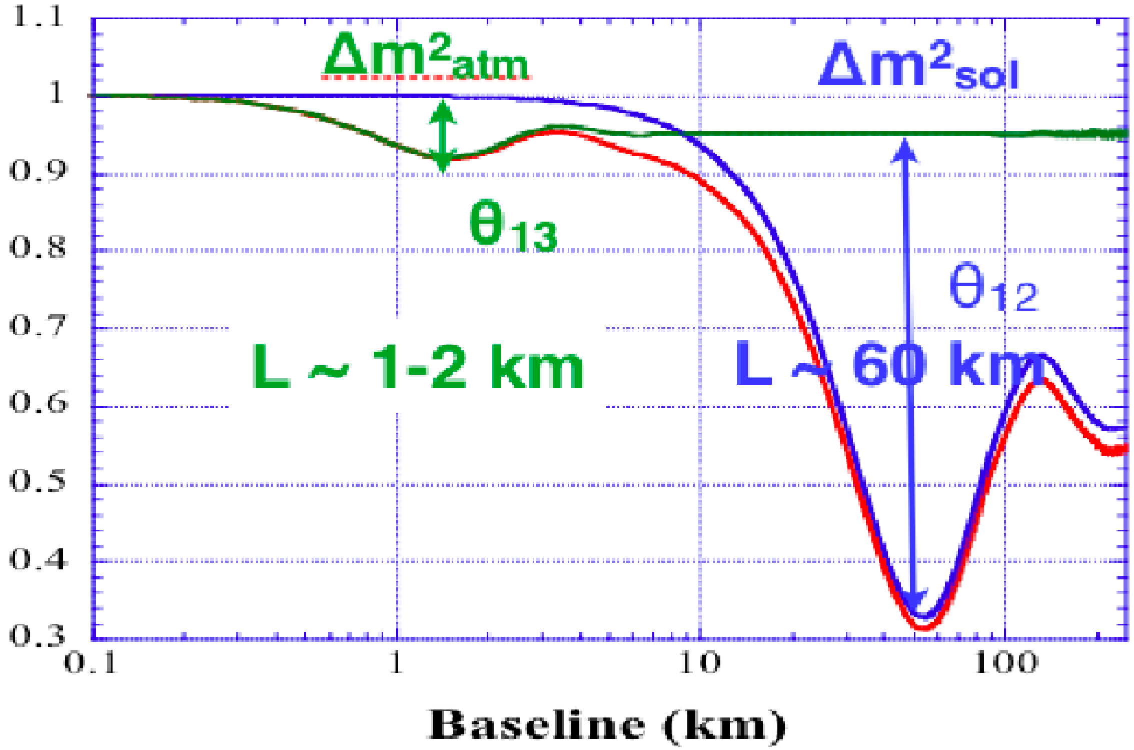
- **Combined MINOS and MINOS+ beam data are well-described by standard neutrino oscillations:**



- **MINOS+ data provide significant statistical improvement at multi-GeV energies.**
  - ★ Full MINOS+ data set (>10×10^{20} POT) will further improve precision of Δm^2_{32} measurement.

Reactor SBL oscillation

$$P_{\bar{\nu_e}\to\bar{\nu_e}} = 1 - \sin^2 2\theta_{13} \sin^2\left(\Delta m^2_{ee} \frac{L}{4E}\right) - \sin^2 2\theta_{12} \cos^4\theta_{13} \sin^2\left(\Delta m^2_{21} \frac{L}{4E}\right)$$



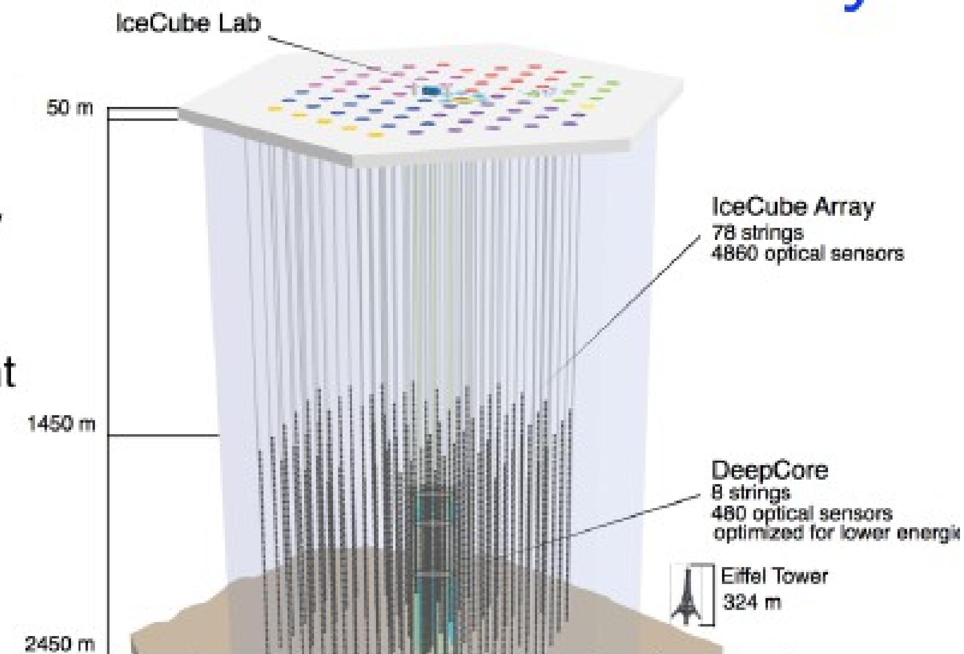
The IceCube Neutrino Observatory

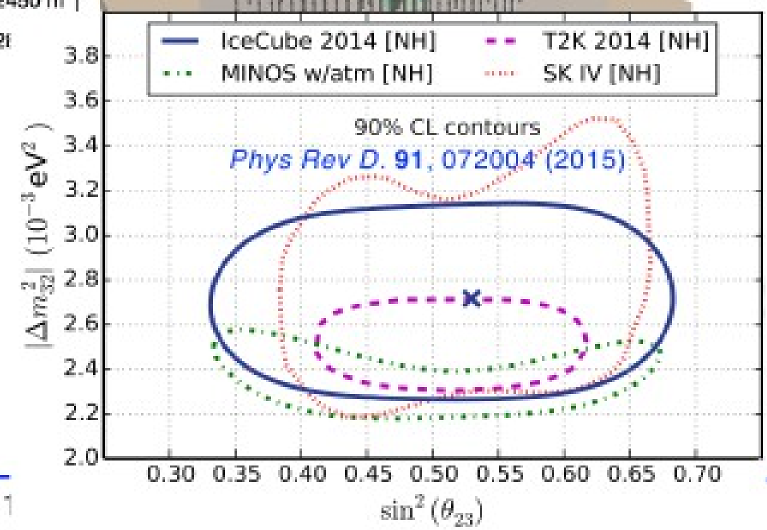
IceCube:

- 78 strings, 125 m/17 m spacing
- Energy range: ~ 100 GeV to ≳ 10 PeV
- 1 km^3 volume of south pole ice as ν target, and medium for Cherenkov light production.

DeepCore:

- 8 additional strings, ~ 40 - 70 m / 7 m spacing
- Spans ~ 10 - 100 GeV
- Targets atmospheric ν oscillations and dark matter searches



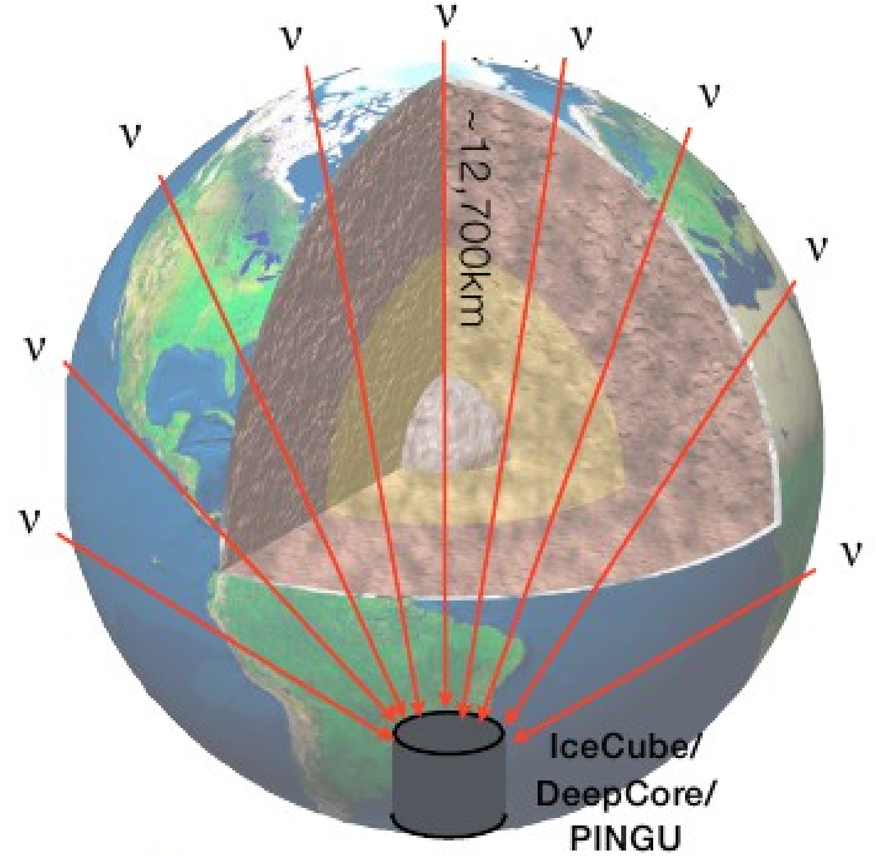


Timothy C. Arlen WIN 2015, 1 3

Atmospheric Neutrino Oscillations

- Neutrinos available over a wide range of energies and baselines
  - Oscillations produce a distinctive pattern in energy-angle space
  - ν_μ 1st survival minimum ~ 25 GeV, and hierarchy-dependent matter effects below ~ 12 GeV.
- Large detector required to provide sufficient statistics to make this approach feasible
  - DeepCore event rates

type	triggered	analysis level
ν_μ	~70 k/yr	~1-10 k/yr
ν_e	~10 k/yr	~0.1-3 k/yr

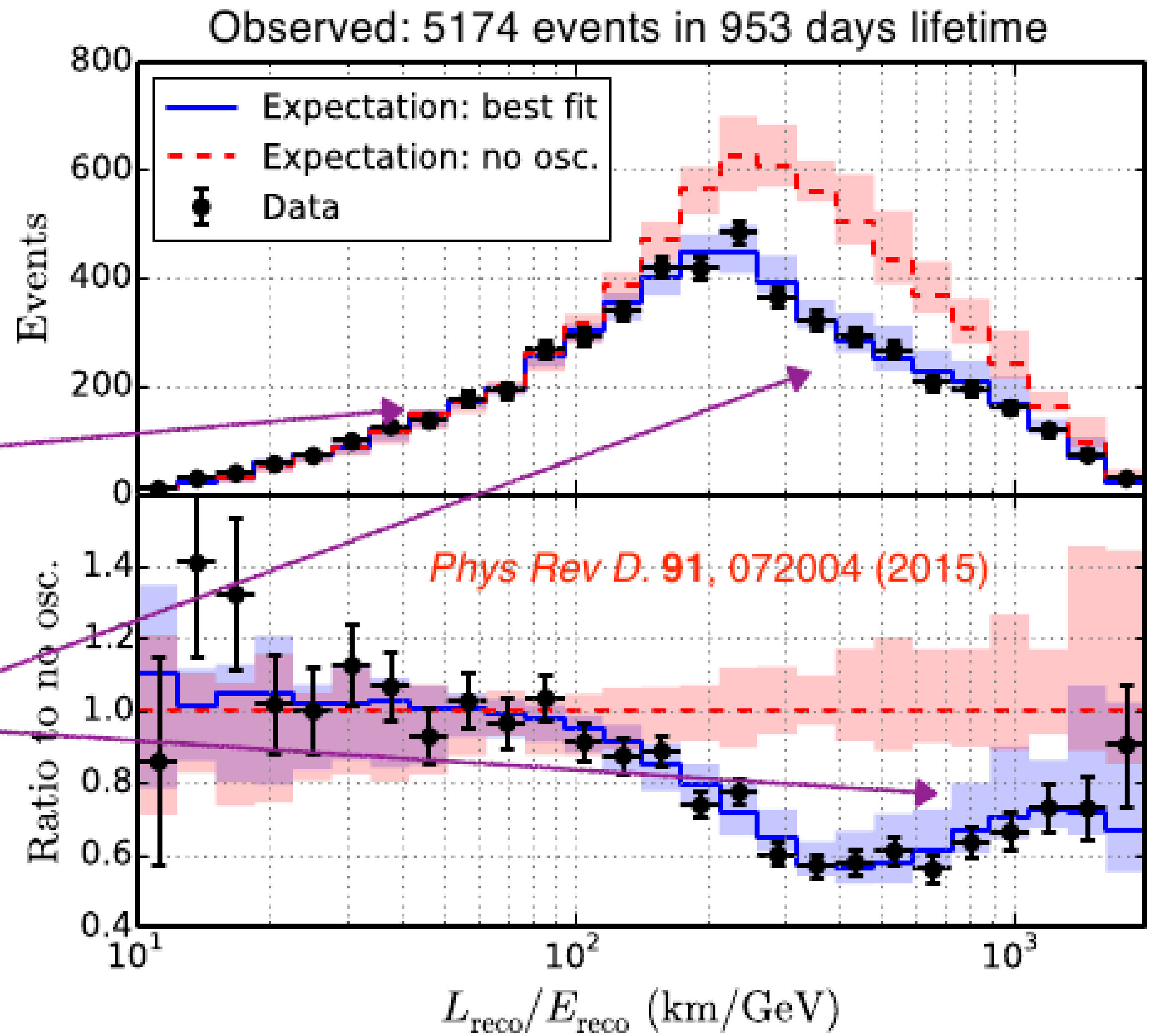


Atmospheric Oscillations with IceCube-DeepCore

- Projection onto reconstructed L/E_ν for illustration purposes
- Shaded range shows allowed systematics with constraints from current data

Good agreement in control region

Good description of oscillation region



UHE neutrinos in IceCube

Coherence of Conventional Neutrino Beams

Neutrinos are finite wave packets. Different masses should travel with different velocities – how long are they coherent?

For Pion DIF it depends on the size of the pion wave packet – clculate that and you know how long the coherence sticks.

Re(ψ) **Source** **Osc Max**

P(f)

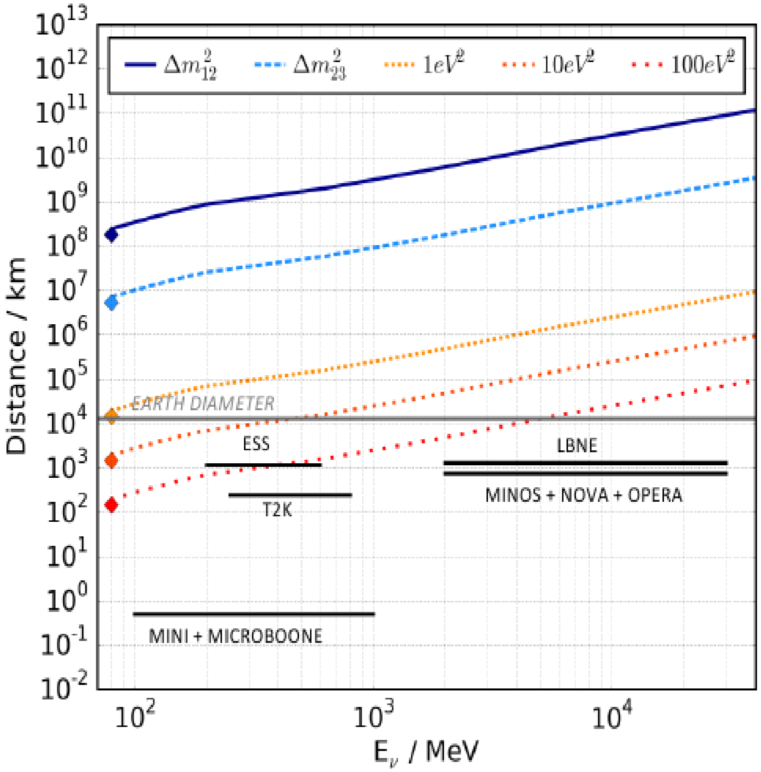
m1

m2

μ

e

Kicks in sooner with big Δm2 or small packet width



B.J.P.Jones, Phys. Rev. D 91, 053002 (2015)