Neutrino Physics

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Neutrino Physics

- The last 10 years has been a period of discovery for neutrino physics.
  - Prior to 1998 neutrinos were believed to be simple massless fermions.
  - This all changed with the discovery of neutrino oscillations.
  - A new branch of flavour physics.
    - Mixing
    - CP Violation
  - Neutrinos have mass.
    - But it is very small:
      - Why?
      - How small?

Neutrino Masses and Mixing

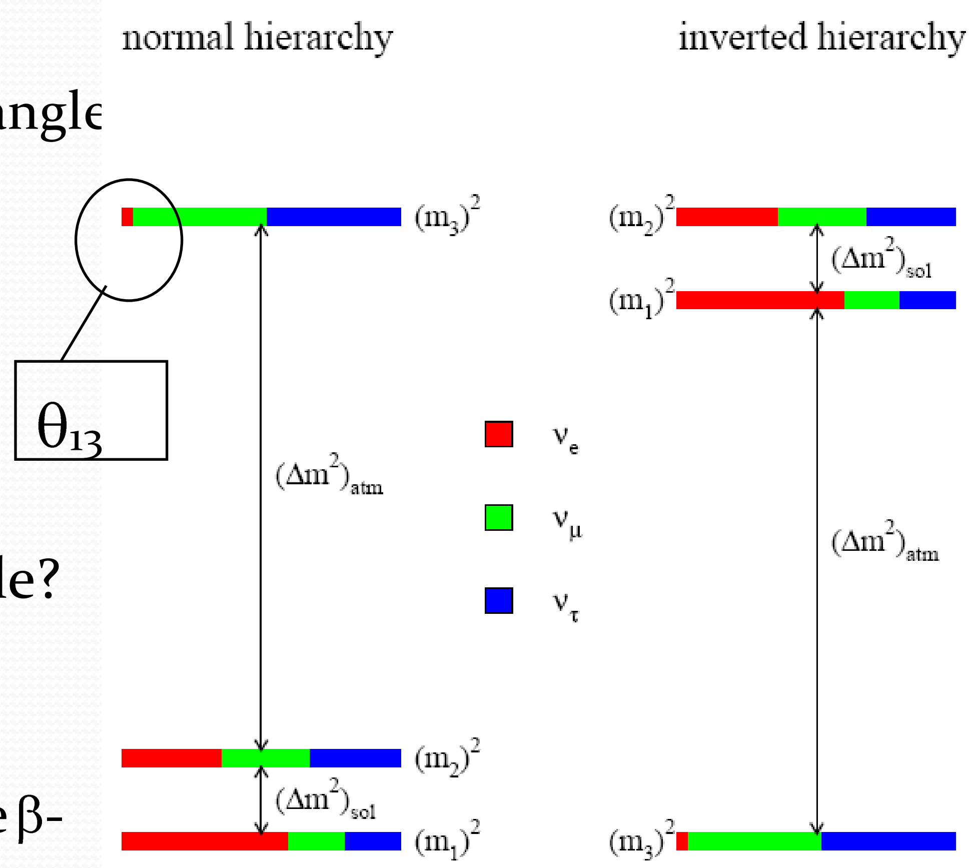
$$\mathbf{U}_{PMNS} = \underbrace{\begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}}_{\text{Solar}} \underbrace{\begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -\sin\theta_{13}e^{i\delta} & 0 & \cos\theta_{13} \end{pmatrix}}_{\text{1-3 Sector}} \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix}}_{\text{Atmospheric}} \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\alpha} & 0 \\ 0 & 0 & e^{i\beta} \end{pmatrix}}_{\text{Majorana}}$$

- Neutrino mixing is governed by the PMNS matrix.
  - Three mixing angles.
  - One Dirac Phase.
  - Two Majorana Phases.
- And three neutrino masses
- All are fundamental constants of nature.
- Two Flavour Oscillations:

$$p(\nu_e \to \nu_e) = 1 - \sin^2 2\theta \sin^2(\frac{\Delta m^2 L}{4E})$$

Unanswered Questions

- Mixing in three generations.
  - The unknown small mixing angle θ_{13}.
- CP violation δ
  - Need three generations
- Mass hierarchy
  - Is ν_3 "light" or "heavy"?
- What's the absolute mass scale?
- Are neutrinos their own antiparticle?
  - Look for neutrinoless double β-decay.



The big picture

- Many theoretical models link neutrinos to big unanswered questions.

  - GUTs
    - See-Saw Effect.

Heavy RightHanded Neutrino
At the GUT Scale.

  - Matter-Antimatter Asymmetry
    - Leptogenesis.

Heavy Right Handed Neutrino
Decays in Early Universe
Violating CP.

  - Dark Energy
    - Mass Varying Neutrinos.

Neutrino Mass Depends on
Neutrino Density.
Ties to Dark Energy.

Neutrino Oscillations

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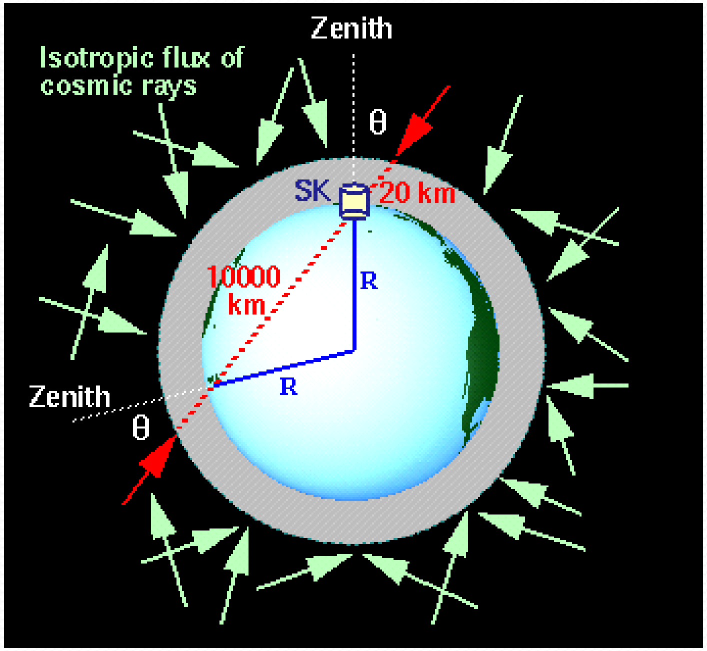
Atmospheric Neutrinos

- Neutrinos created in cosmic ray interactions.
  - Expect $2\nu_\mu:1\nu_e$
  - Not observed : Too few ν_μ
- Muon Neutrino Disappearance.
- More recent results show zenith angle dependence.
  - Baseline dependence.
- Can explain via neutrino oscillations.

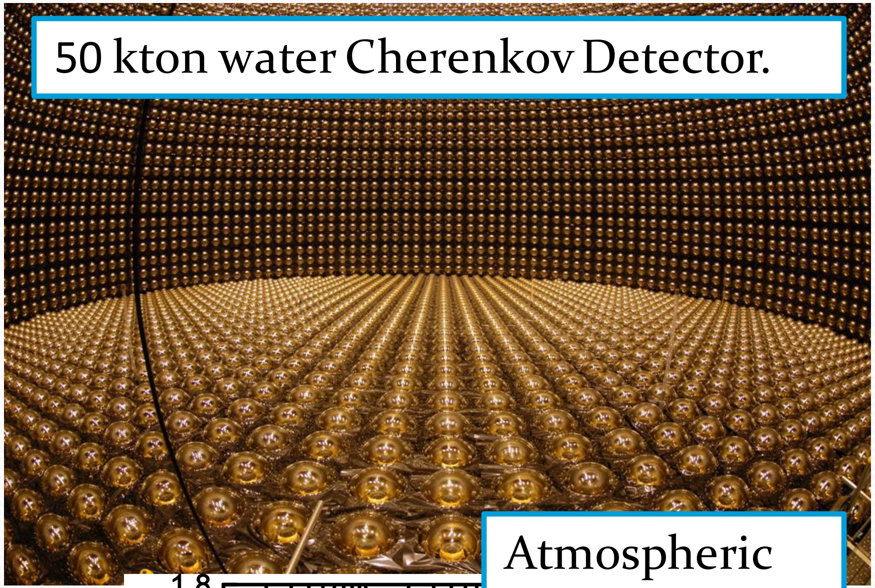


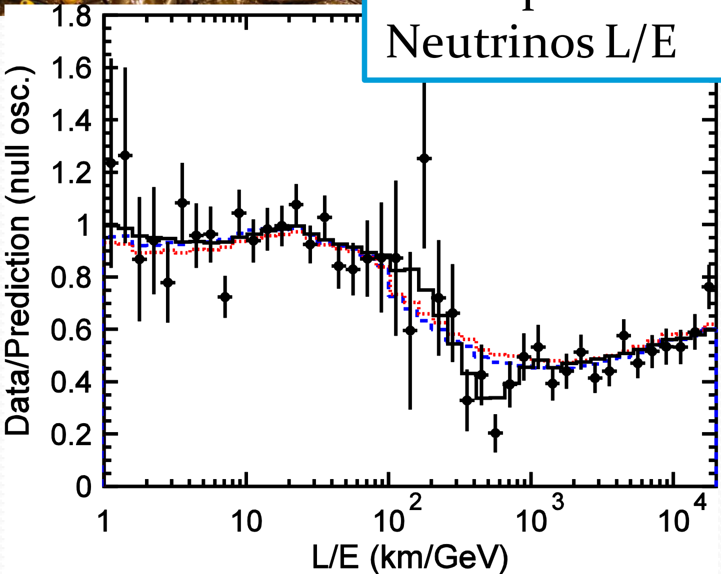
- Can be tested terrestrially using accelerator neutrinos.
  - Require a baseline of 700km for 1.5GeV neutrinos.

Super-Kamiokande, K2K

- Measure Atmospheric and Solar neutrinos.
  - Zenith angle effect in atmospheric ν_μ disappearance.
    - Disappearance depends on distance.
  - No ν_τ appearance model disfavoured at 2.4σ.

- Target for first long baseline neutrino beam experiment: K2K
  - KEK→SK
  - ν_μ disappearance.
    - Expect 158±9
    - Observe 58

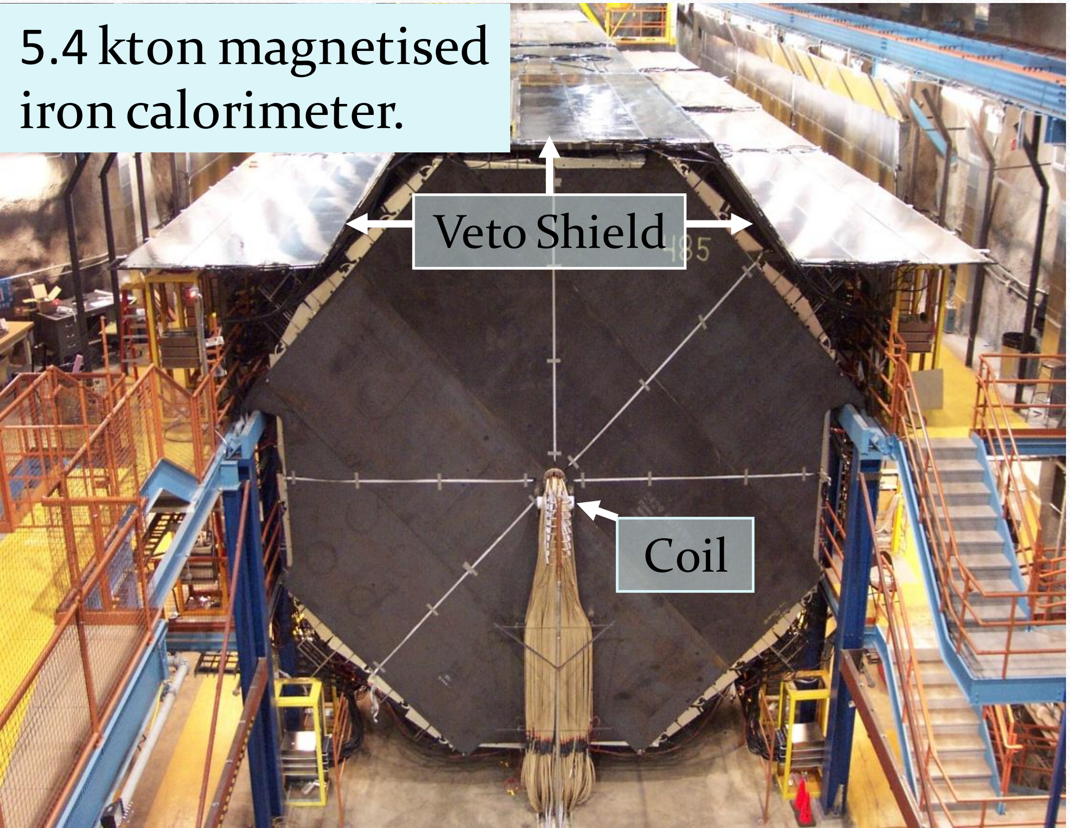




MINOS

- Long baseline ν_μ beam experiment:
  - Fermilab –Soudan 735 km
- Search for $\nu_\mu \rightarrow \nu_\mu$
  - And $\nu_\mu \rightarrow \nu_e$

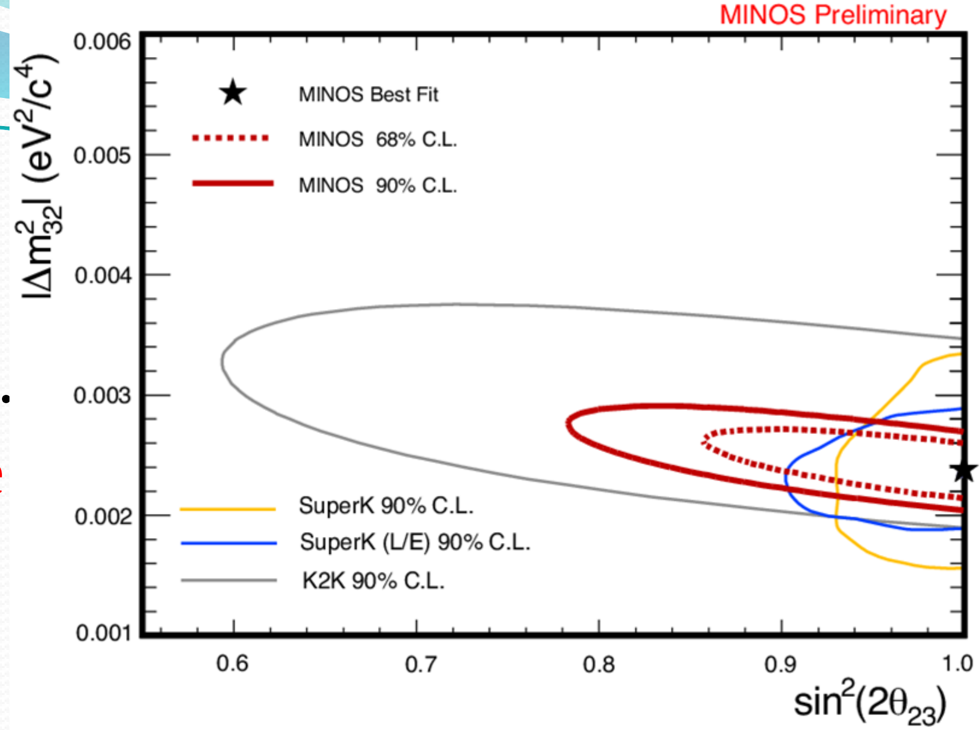
5.4 kton magnetised iron calorimeter.

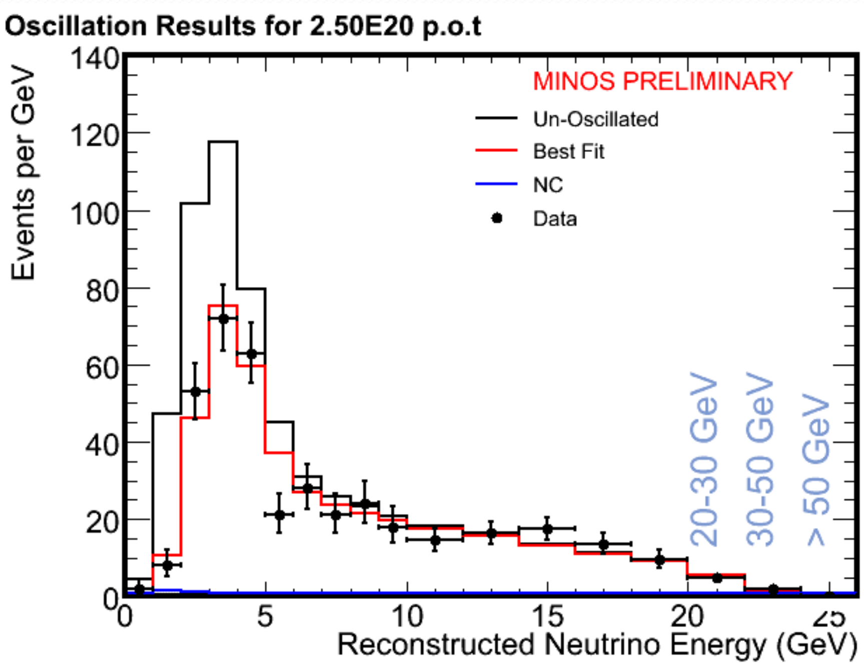


- Near and far detectors.
  - 980 : 5400 tons
  - Measure beam before and after oscillations.
- Three different beam configurations.
  - Control beam systematics.
  - Use LE for oscillation search

MINOS Results

- 2.5x10^{20} Protons on target.
- Observe ν_μ disappearance and spectral distortion.
  - Observe 563
  - Expect 738±30

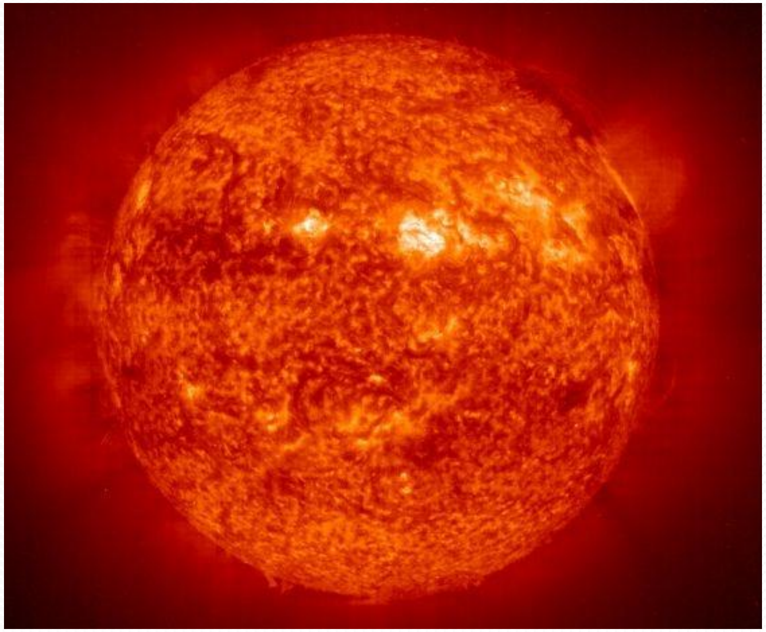


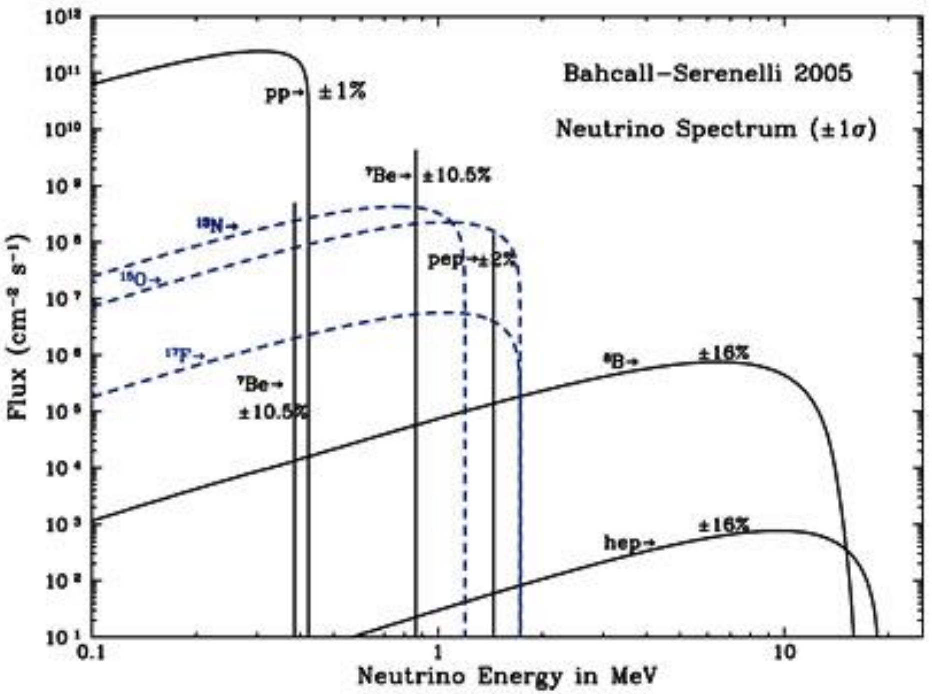


- To Come from MINOS:
  - Increased statistics:
    - Improve limits on θ_{23} & Δm_{23}^2
  - Search for Exotic neutrino models.
    - Sterile neutrinos
    - Decoherence
  - Search for electron appearance:
    - Improve limit on θ_{13}.

The Solar Neutrino Sector

- Deficit of solar neutrinos observed by a number of experiments.
  - Electron Neutrino Disappearance.
- Explain with Neutrino Oscillations?
  - Requires the matter effect.





- To test oscillation hypothesis need to show:
  - Neutrino Flavour Change.
  - Spectral Distortion.
- Test terrestrially with reactor neutrinos at c. 200 km

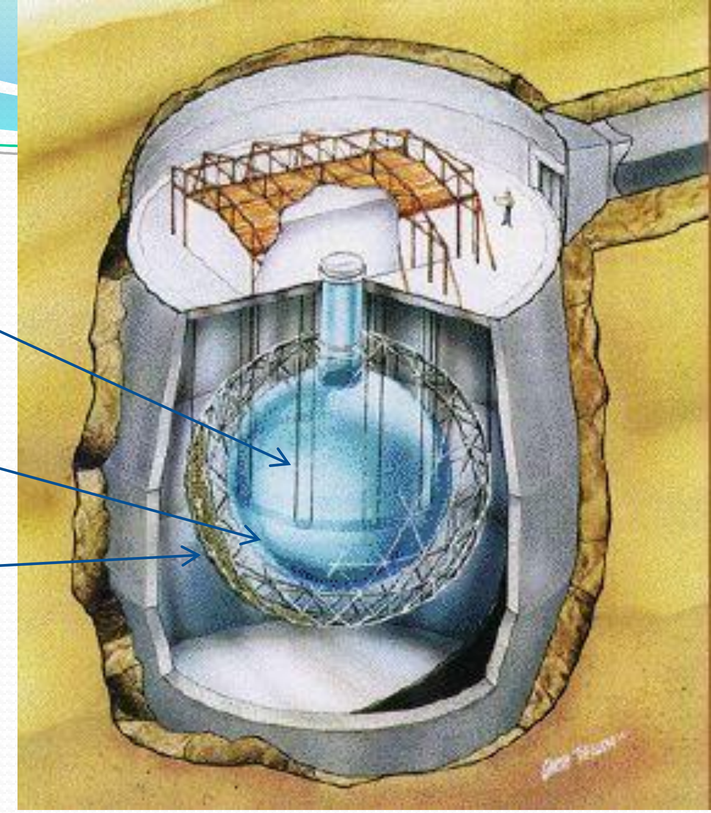
SNO

- Use heavy water (D_2O)
  - CC electrons
    - Measure ν_e flux.
  - NC neutrons
    - Measure total ν flux.

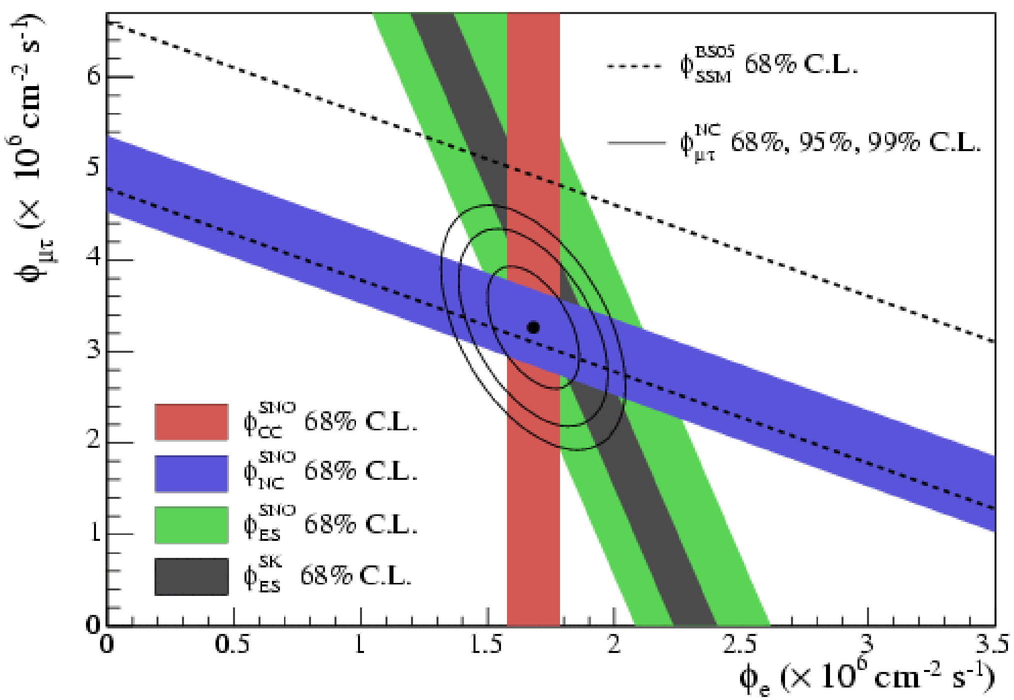
1 kton D_2O Target

12 m Acrylic Sphere

9500 PMTs



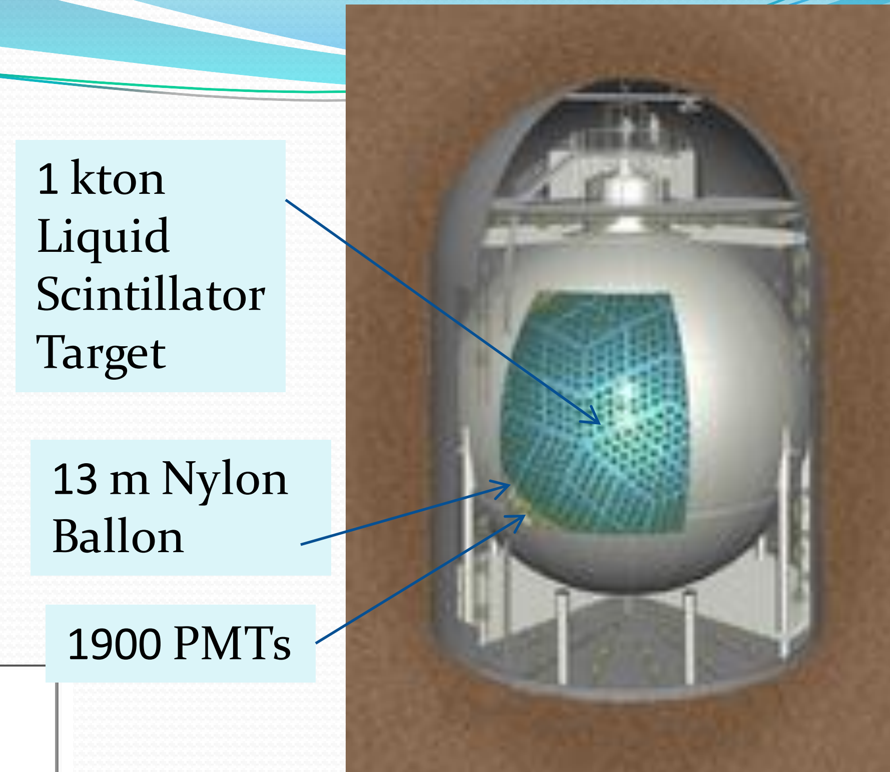
Flavour content of solar flux.

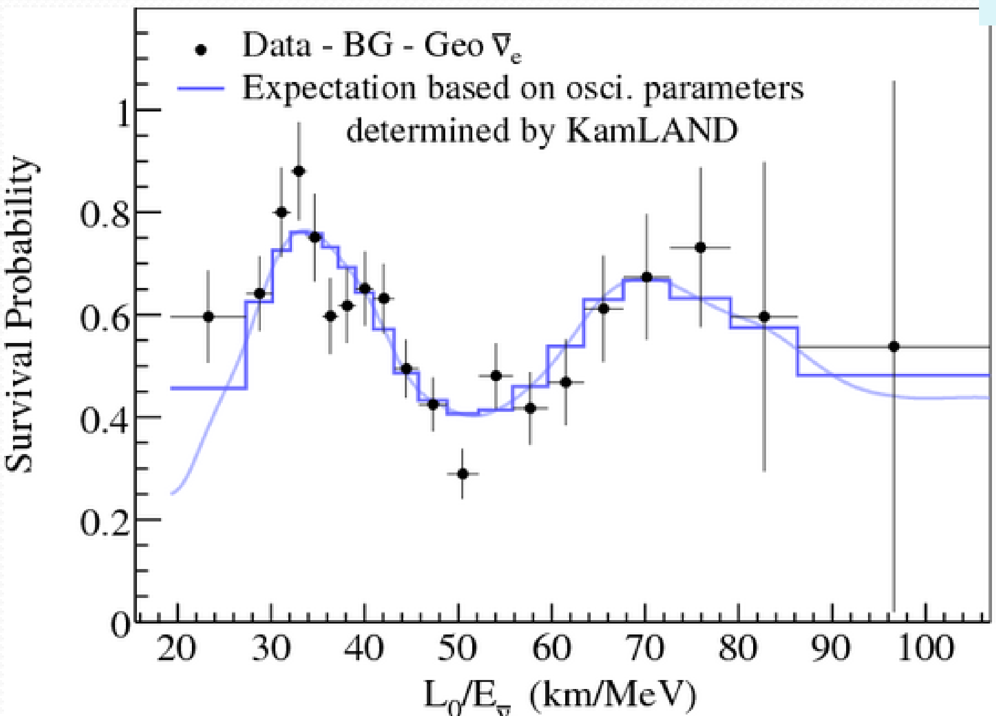


- Observe neutrino flavour change.
  - Inclusive Appearance.
- Total flux agrees with solar model prediction.

KamLAND

- Use all Japanese nuclear reactors as a neutrino source.
    - Mean baseline 180 km





- Observe spectral distortion
- Oscillation maxima and minima observed.
- Smoking Gun for Oscillations.

Current Status of Solar Oscillations.

- Solar results and KamLAND agree.
  - Agreement between
    - Solar-Terrestrial
    - Neutrinos – Anti Neutrinos.
- Mixing in the solar sector now a precision measurement.
- $\Delta m^2_{12} = (7.59 \pm 0.21) \times 10^{-5}\ \mathrm{ev}^2$
- $\tan^2\theta_{12} = 0.47^{+0.06}_{-0.05}$

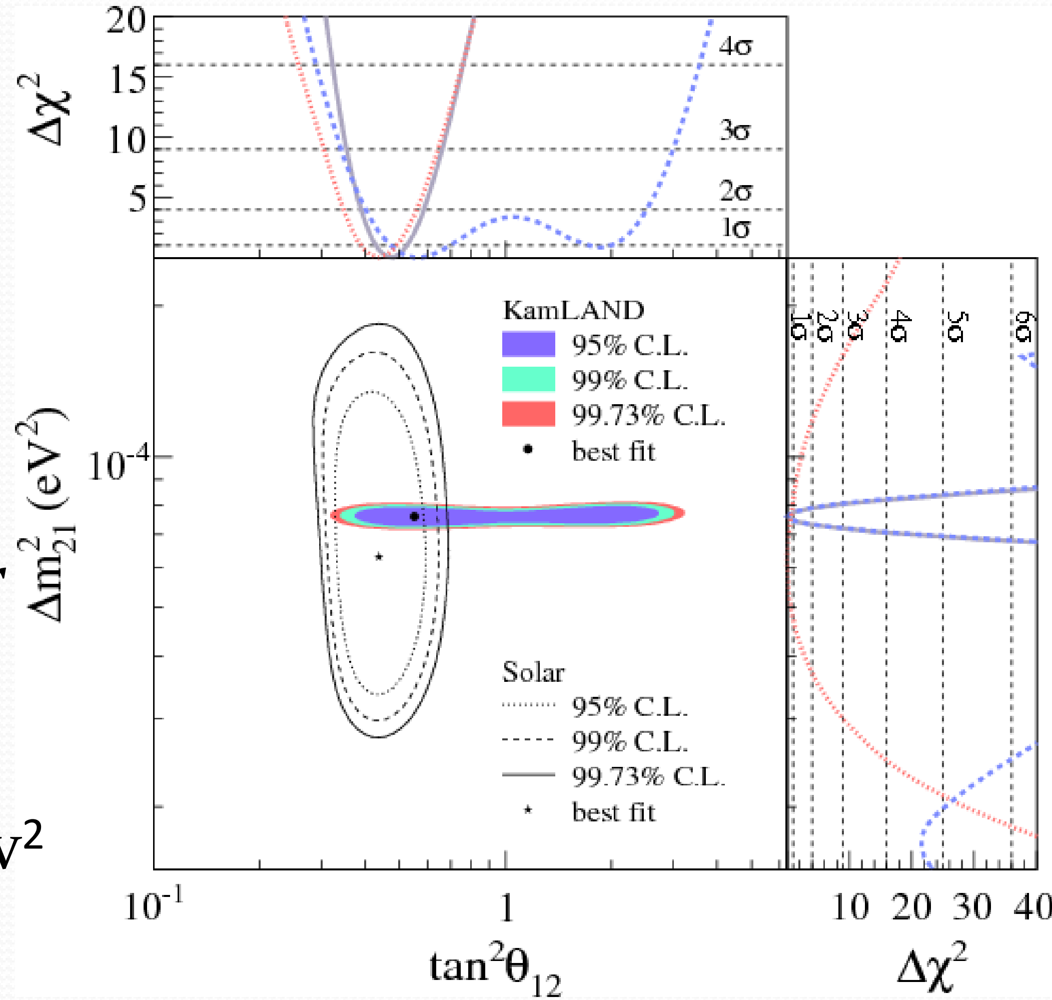
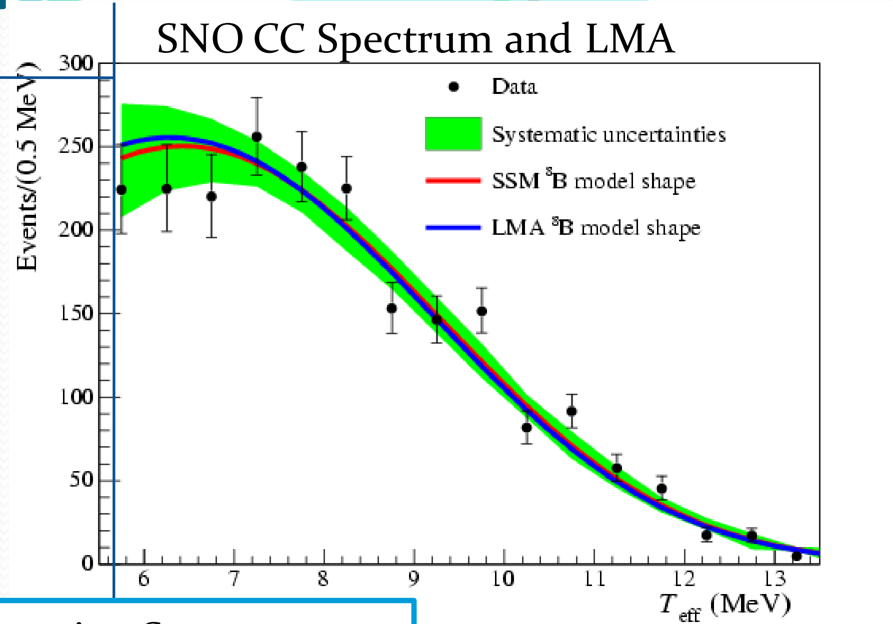


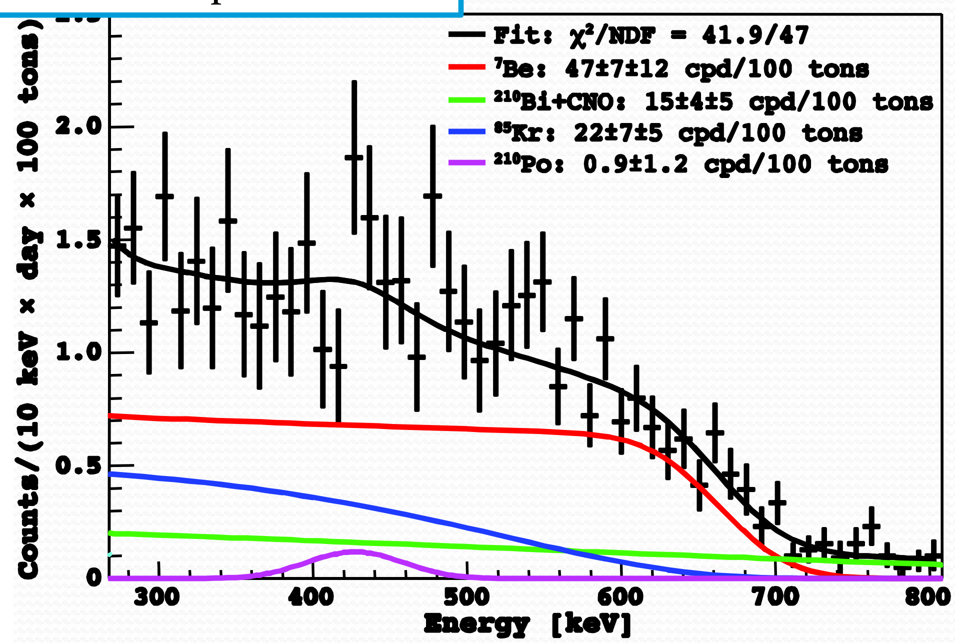
Figure from KamLAND

Upcoming Developments in the Solar Sector.

- New results from SNO
  - Phase 3 - NCDs
  - Combined phase low threshold spectral fits.
- SK phases 3-4
  - Low threshold elastic scattering spectrum
- Low energy solar neutrinos (^{7}Be, pep)
  - Borexino – First detection of ^{7}Be in 2007
  - KamLAND II
  - SNO+

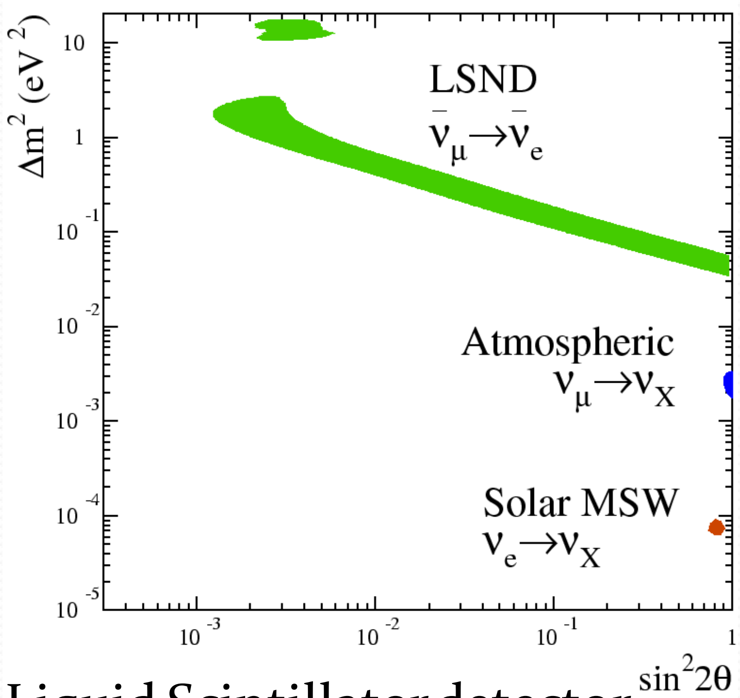


Borexino Spectrum

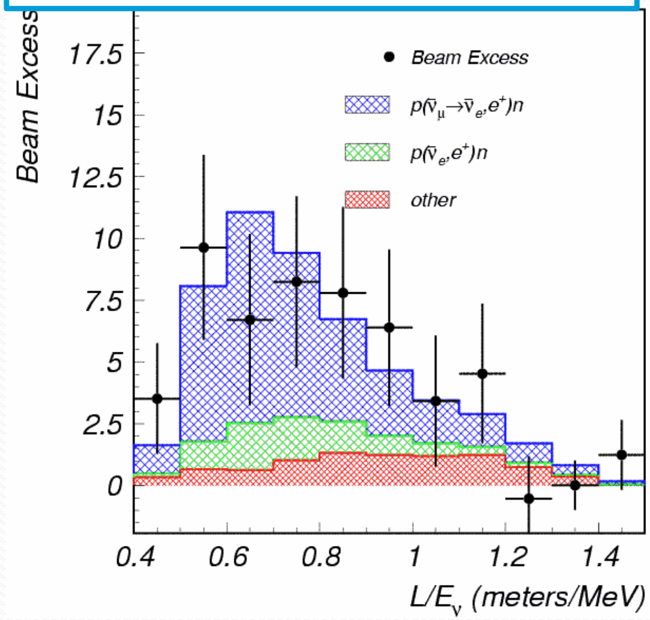


The three flavour wrinkle.

- In addition to atmospheric and solar neutrino oscillations a third signal was observed.
- Mass Scale : $\Delta m^2 \approx 1 ev^2$
  - Incompatible with 3 flavours
  - Requires a sterile neutrino.



LSDN Energy Spectrum



- LSND: A Liquid Scintillator detector.
  - Use ν_μ from stopped muon decay
  - Baseline 30 m.
  - Excess 87.9 ± 22.4 ± 6.0
- Test with MiniBOONE
  - Different L & E, same L/E

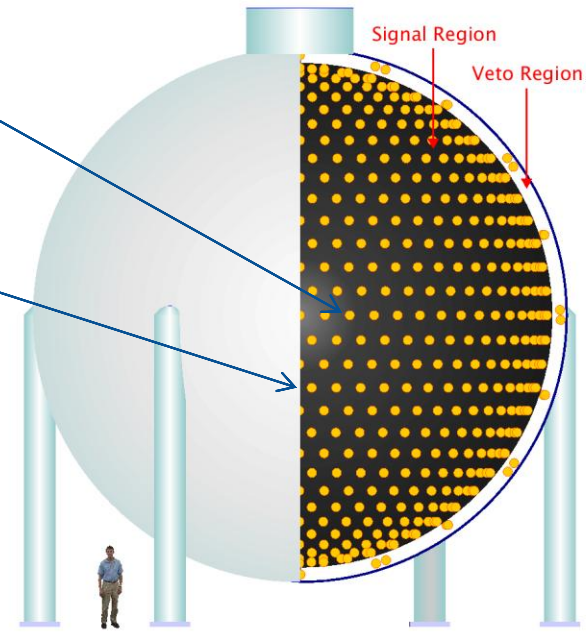
MiniBOONE

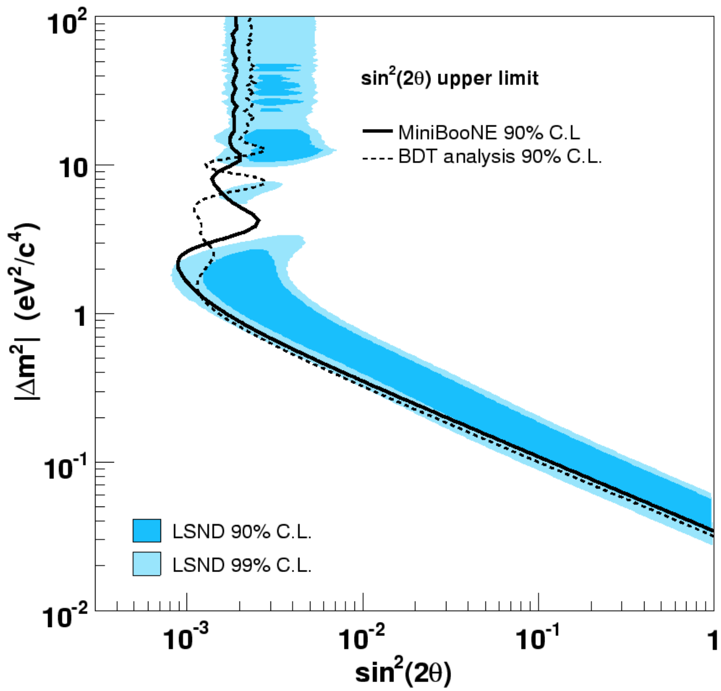
- Search for $\nu_\mu \rightarrow \nu_e$
  - Baseline 450m.
  - 5.58×10^{20} POT
- No Significant Excess over Background.
  - Refutes LSND results.

MiniBooNE Detector

900 tons mineral oil.

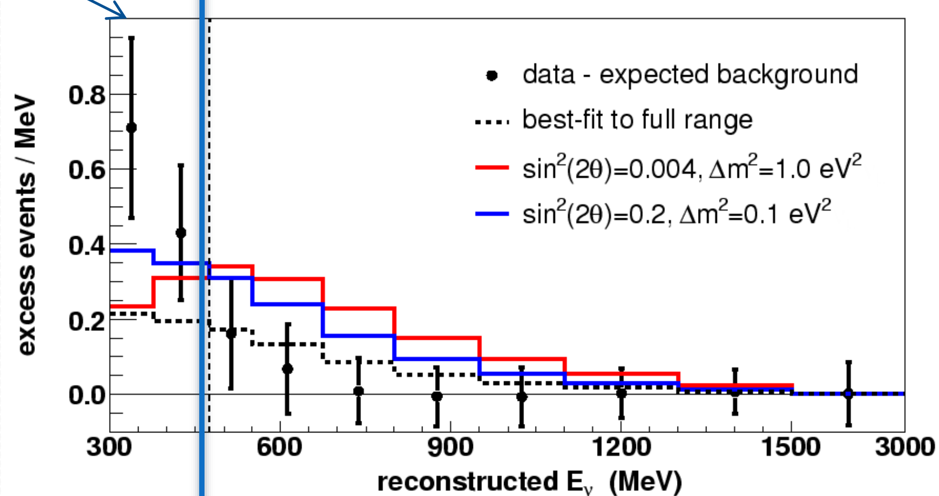
1280 PMTs





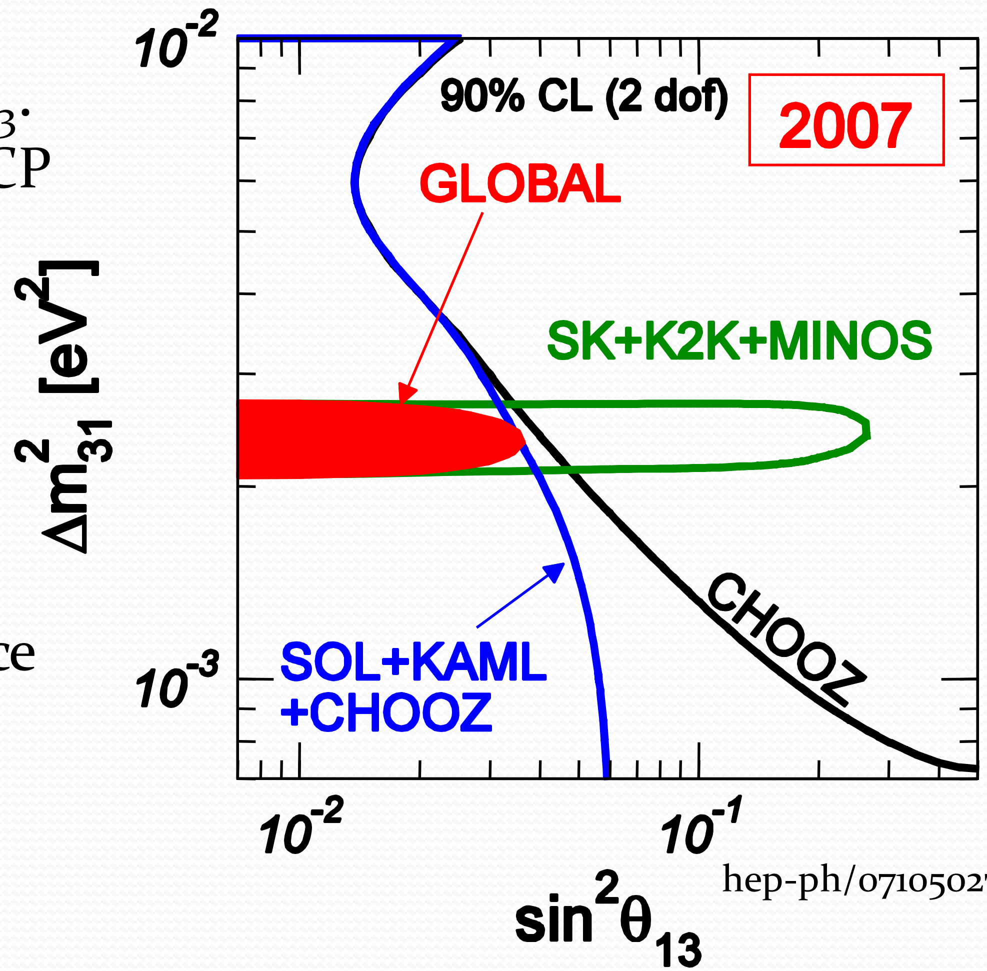
Excess of events at low energy. Origin unknown

Analysis Region



The Quest for θ_{13}.

- There is currently one unknown mixing angle: θ_{13}.
  - This is the gatekeeper to CP violation.
  - PMNS : $\sin\theta_{13} e^{i\delta}$
- Current best limit dominated by Chooz.
  - $\sin^2\theta_{13} < 0.03$
- Probe with
  - Reactors : $\overline{\nu}_e$ disappearance
  - Accelerators : $\nu_\mu \rightarrow \nu_e$
- Program for the next 5-10 years.

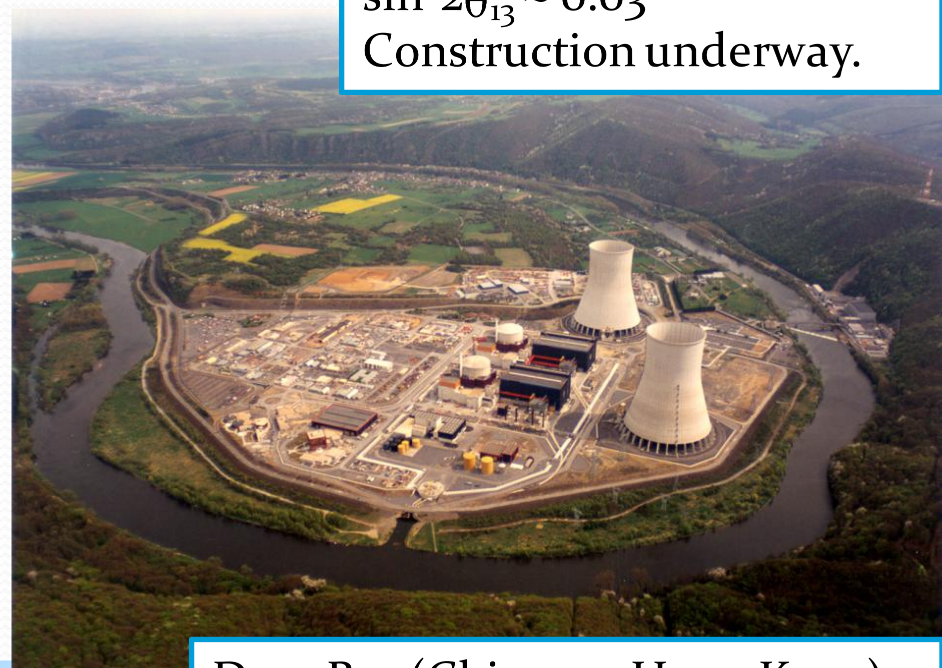


hep-ph/07105027

Reactor Experiments.

- Improve Chooz Experiment.
- Systematically Challenging
  - Disappearance at 1%.
- Two Experiments: Conceptually similar.
  - Identical near and far detectors.
  - Liquid Scintillator
    - $\bar{\nu}_e + p \rightarrow e^+ + n$
    - Enhanced neutron capture (Gd).
  - Use a vessel to contain scintillator
    - Control target mass.

Double Chooz (France)
Baseline , 300 m + 1.5 km
2 Cores, 4.3GW
Projected sensitivity
$\sin^2 2\theta_{13} \sim 0.03$
Construction underway.



Daya Bay (China, nr Hong Kong)
Multi-Core, 11.6→17.4GW
Baseline c. 2.5 km
Projected sensitivity $\sin^2 2\theta_{13} \sim 0.01$
Blasting Started Feb 2008

Long Baseline Experiments.

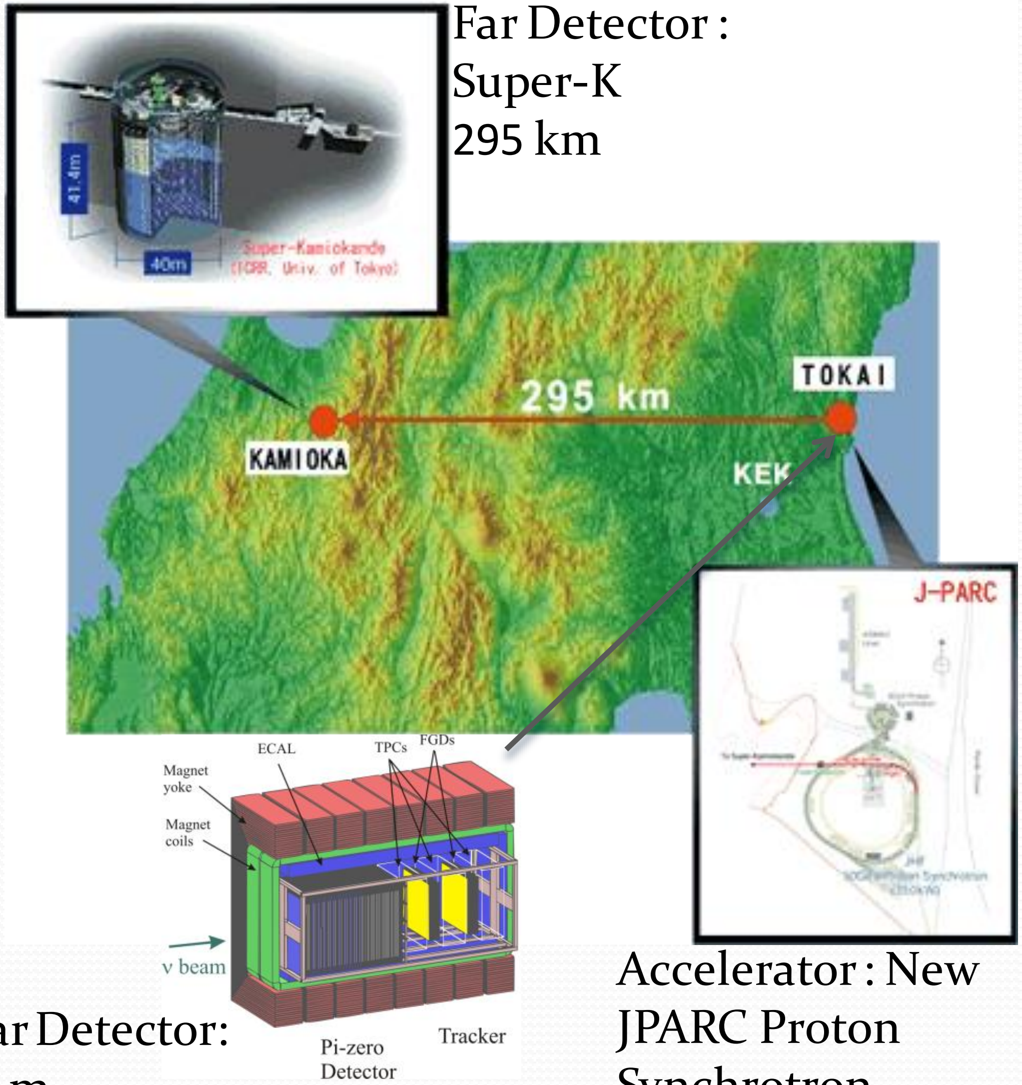
- Now/Soon/Proposed
  - Super Beams
    - MINOS
    - CNGS
      - ν_τ Appearance.
    - T2K
    - NOνA
- The Long Term
  - The Neutrino Factory
  - Beta Beams

- Search for $\nu_\mu \rightarrow \nu_e$ at atmospheric baseline.
  - Measure a combination of θ_{13} and δ.
- Improve measurement of atmospheric mixing parameters
  - Is mixing maximal?
- Resolve matter hierarchy
  - Requires a significant matter effect.
- Search for CP violation.

The T2K Experiment

- Phase 1
  - Search for θ_{13}
- Phase 2
  - CP violation.
- Off-axis beam
  - Narrow band
    - Peaked at oscillation maxima (600 MeV)
  - Reduced high energy flux
    - Fewer backgrounds.
- Super-K Electronics/DAQ Upgrade 2008.
- First beam April 2009
  - Near detector installed summer 2009.

Far Detector : Super-K 295 km

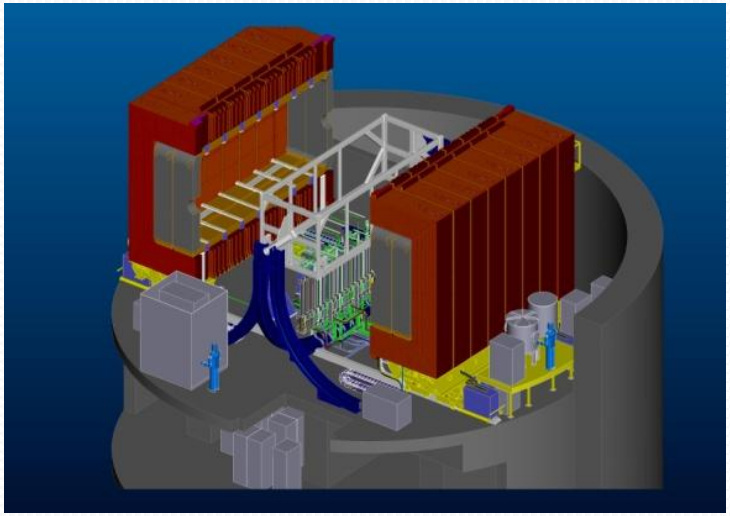


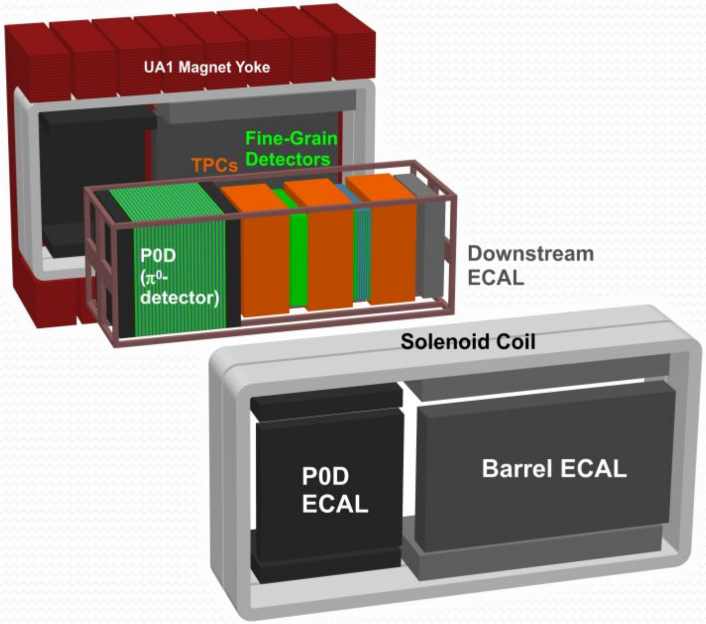
Near Detector: 280 m

Accelerator : New JPARC Proton Synchrotron.

ND280:The T2K near detector

- The near detector plays a crucial role in the experiment:
  - Spectrum and content of neutrino beam
  - Neutrino cross sections.
  - Pion production

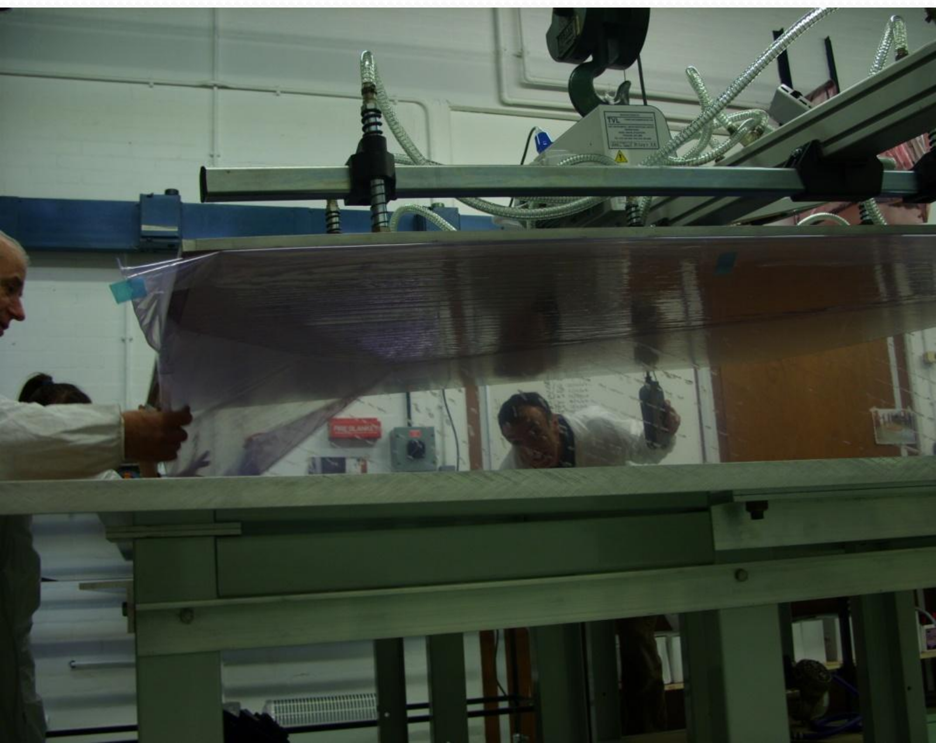




- Reuse the UA1 magnet.
  - Two regions:
    - Tracker
    - π^0 detector.
  - Surrounded by ECAL
    - DS ECAL in 2009
    - Remainder to follow.
- On Axis
  - INGRID: Monitor Neutrino Beam.

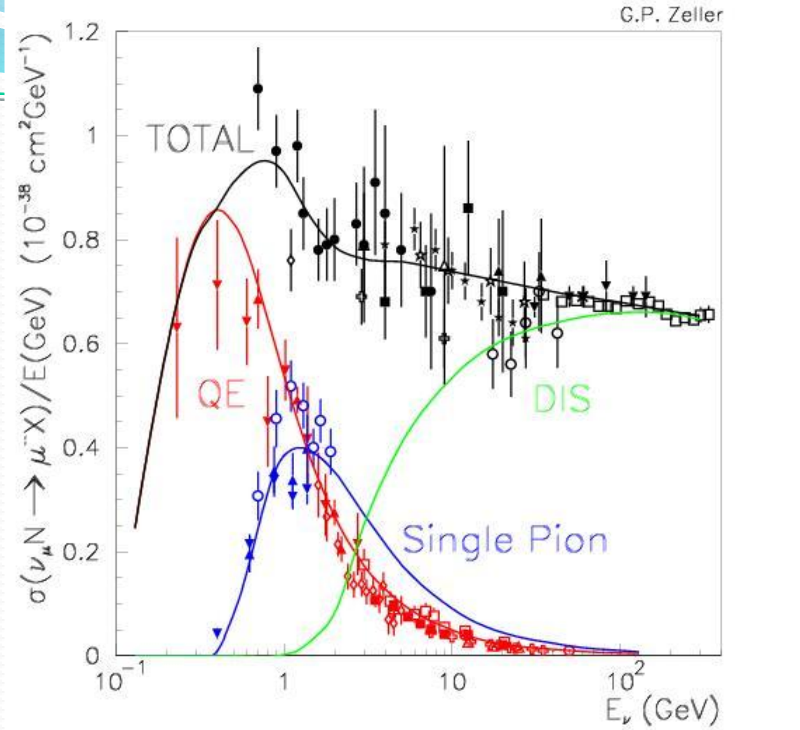
Construction of the ECAL

- Construction of the ECAL layers started last week.
  - Here is the first layer at Lancaster.

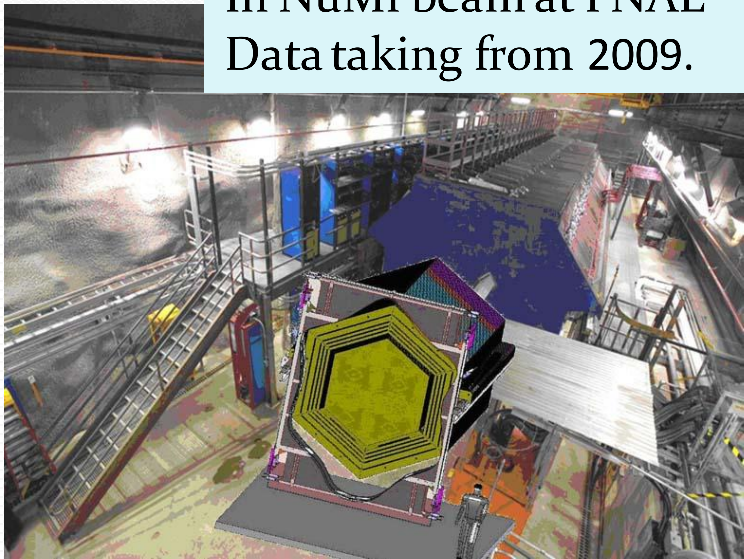


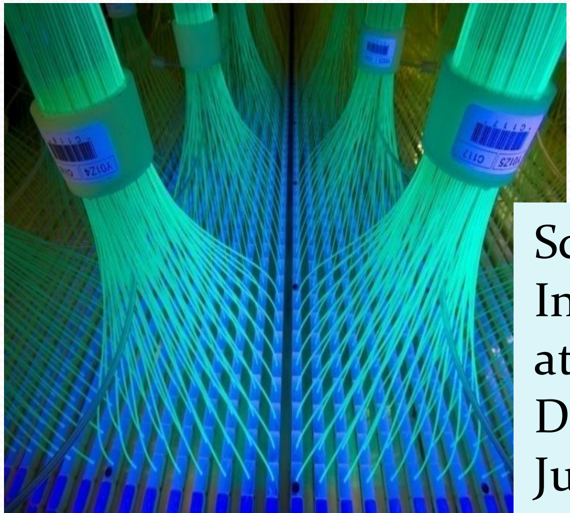
Neutrino Interactions

- To understand long baseline results:
  - Need to understand neutrino interactions.
    - Cross sections.
    - Pion production.
  - Data is currently sparse



Minerva
In NuMi beam at FNAL
Data taking from 2009.





SciBoone
In Booster beam at FNAL
Data taking since June 2007

Absolute Neutrino Mass

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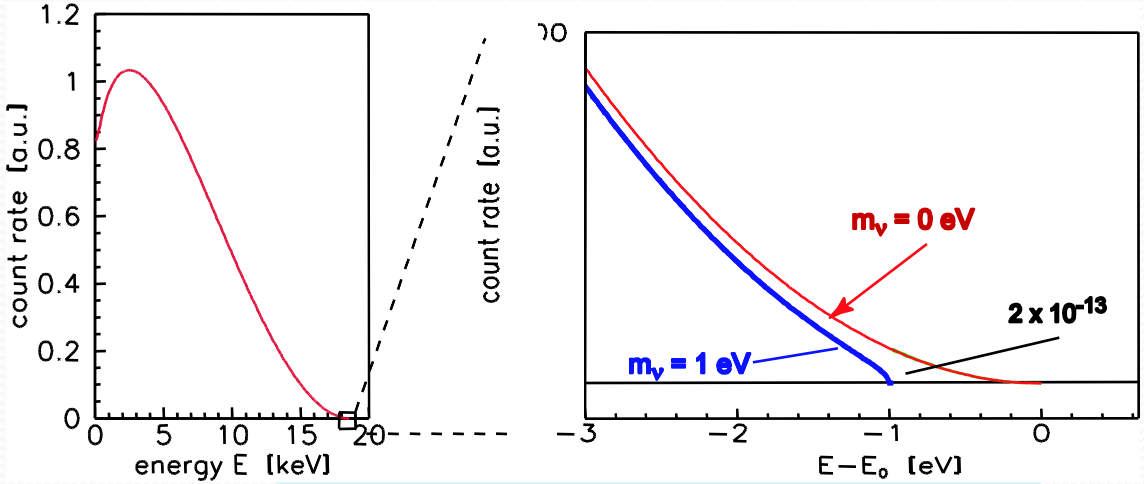
The Neutrino Mass Scale

- Neutrino Oscillations cannot address the neutrino mass scale.
  - Need a different type of experiment.
- Mass experiments measure effective neutrino masses
  - Combine masses and mixing.
- Tritium β decay
  - $m_\nu < 2.2$ eV (Mainz, Troitsk).
- Neutrinoless double β decay.
  - Only for Majorana Neutrinos.
  - $\langle m_\nu \rangle < 0.19\text{-}0.68$eV (Cuoricino)
  - Claim KK&K $\langle m_\nu \rangle = 0.22\text{-}1.19$eV
- Cosmology
  - Neutrinos are hot dark matter.
  - 10% of the Universe at recombination.
  - $\Sigma m_\nu < \sim 1$ eV
    - Strongly model dependant.

KATRIN

- Study the end point of Tritium β-decay.
  - Electron neutrino mass to 0.2 eV

- Need a large spectrometer:
  - Statistics
  - Energy resolution.

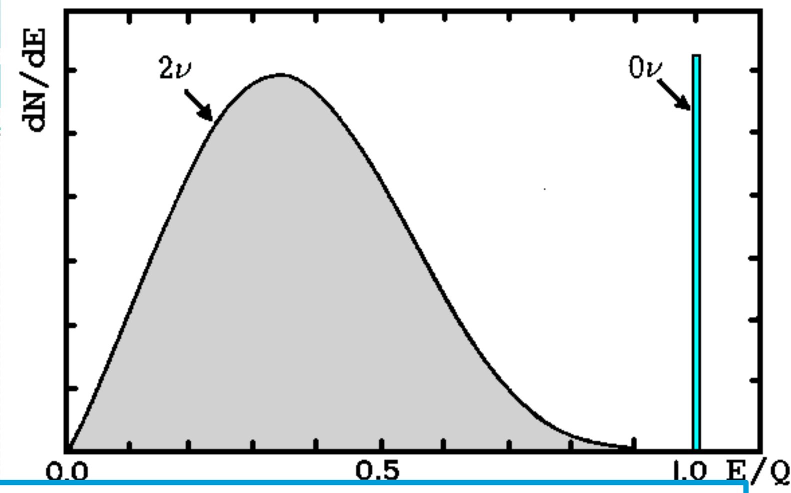


Tritium decay spectral distortion.

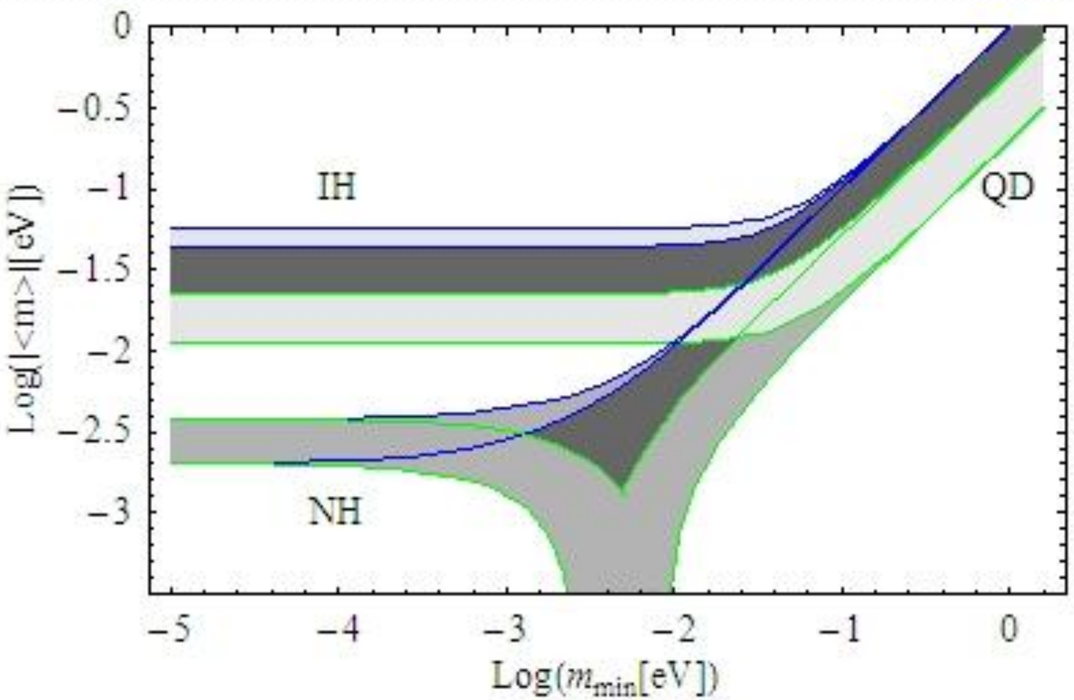
A 9000 km journey for 400 km trip.

Neutrinoless ββ

- If neutrino are Majorana particles:
  - Expect neurtinoless ββ decay
  - Rate depends on effective mass.
- A number of isotopes
  - Big uncertainties from nuclear matrix elements.



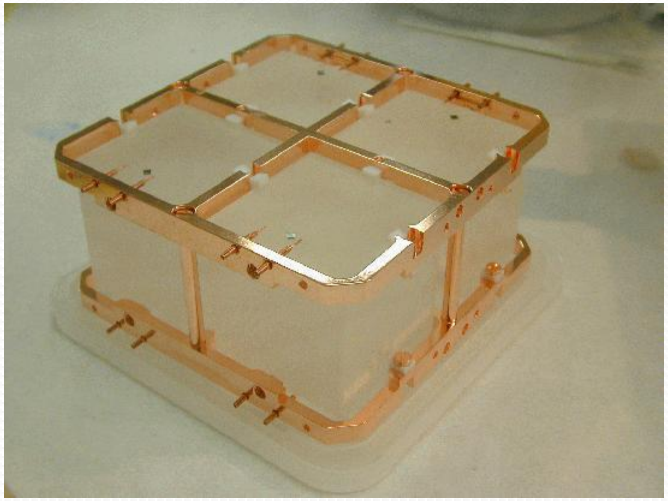
Must reduce radioactive background
Good energy resolution: 2ν background.



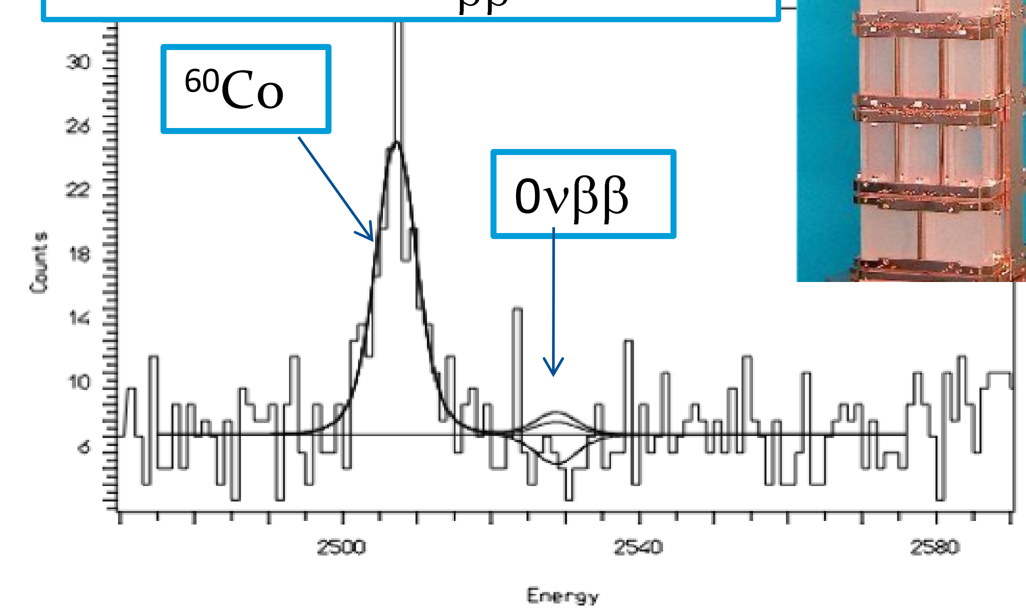
- ^{76}Ge
  - Heidleberg-Moscow, IGEX, Majorana, Gerda
- ^{82}Se
  - Nemo
- ^{100}Mo
  - Nemo, Moon
- ^{116}Cd
  - Cobra
- ^{130}Te
  - Couricino, Coure, Cobra
- ^{136}Xe
  - Gothard, EXO, Xmass
- ^{150}Nd
  - Super Nemo, SNO++

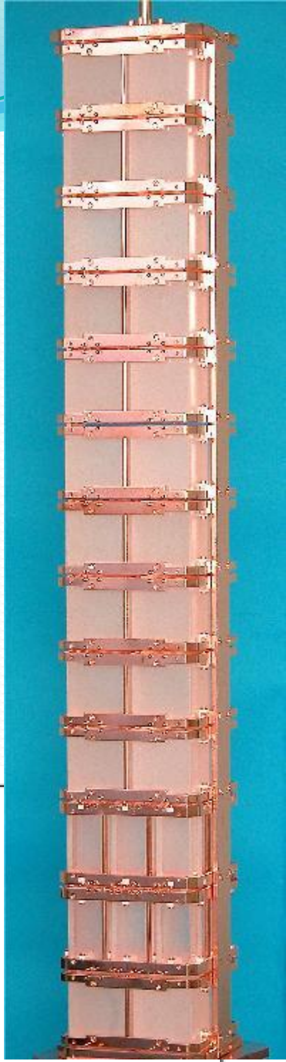
CUORICINO

- Use ^{130}Te.
- 62 TeO_2 Bolometers
  - Operating Temperature 8mK.
  - Active Mass 40.7 kg.
- 11.83kg Years
  - No Evidence for $0\nu\beta\beta$.
  - $<m_\nu> < 0.19\text{-}0.68$ eV
    - Depends on the nuclear matrix element.
    - Starts to test KK&K Claim.
- Future upgrade to CUORE
  - 19 Towers
  - 200 kg active material.

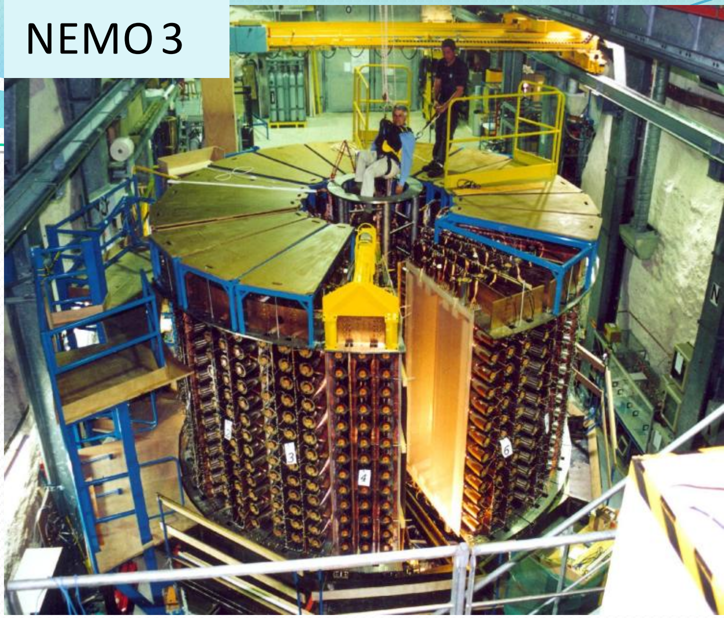


CUORICINO ^{130}Te $\beta\beta$ End Point.

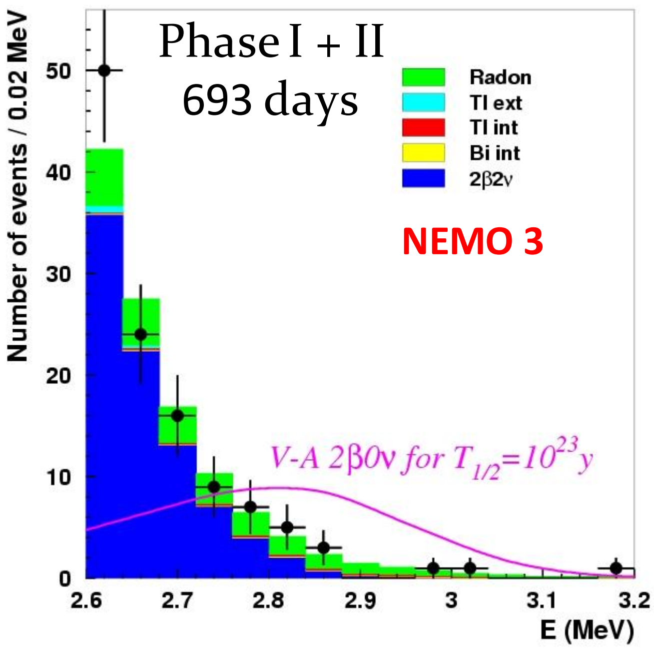




The NEMO program

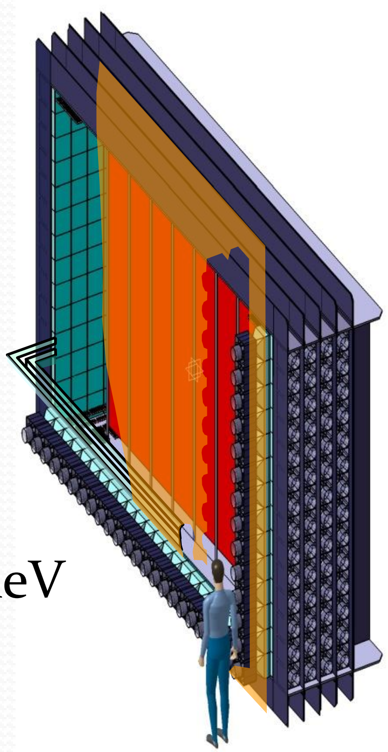


- Use tracking and full event reconstruction to search for 0ν double β-decay.
  - Suppress background by reconstruction.
- Use multiple sources to study different isotopes simultaneously.



Nemo3 Preliminary ^{100}Mo (7 kg):
$T_{1/2}(\beta\beta0\nu) > 5.8 \times 10^{23}$ (90 % CL)
$\langle m_\nu \rangle < 0.6 - 2.4$ eV

- Super-Nemo
  - Planar–Modular Design.
  - 100 kg enriched isotope.
  - Start Construction 2010
    - Full running 2013.
  - Sensitivity: $\langle m_\nu \rangle$=40-110 meV



Conclusions

- The last 10 years have been a period of discovery for neutrino physics.

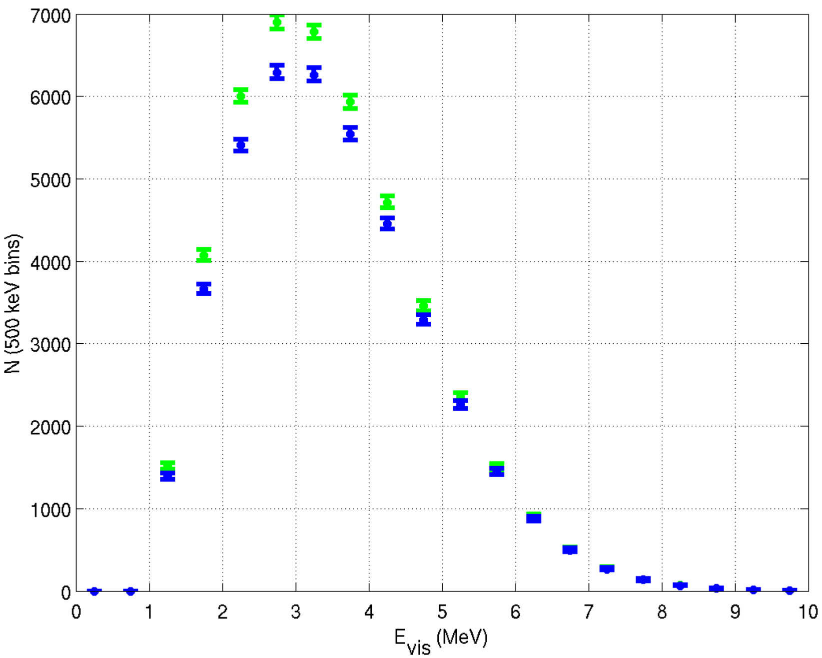
- Neutrinos Oscillate
  - Flavour Physics
  - Neutrino Mass

- A Wide and Varied Program is Ongoing to Study These Effects.

Reactor Neutrino Experiments

- Improved Chooz Experiment.
  - Directly measure θ_{13}.
  - Systematically challenging.
    - Disappearance at 1% level.
- Use 2 (or more) identical detectors.
  - Near and far.
  - More complex with multiple reactor cores.

Near and far energy spectra.



Double Chooz 3 years ,
Current θ_{13} upper limit.

Summary

- A brief outline of neutrino physics.
- Neutrino Oscillations
  - Current Status
    - Atmospheric
    - Solar
    - LSND Effect
  - Future Experiments
    - Reactor Experiments
    - Long Baseline Experiments
- Neutrino Mass Scale.
  - Tritium β-decay
  - Neutrinoless Double β-decay.