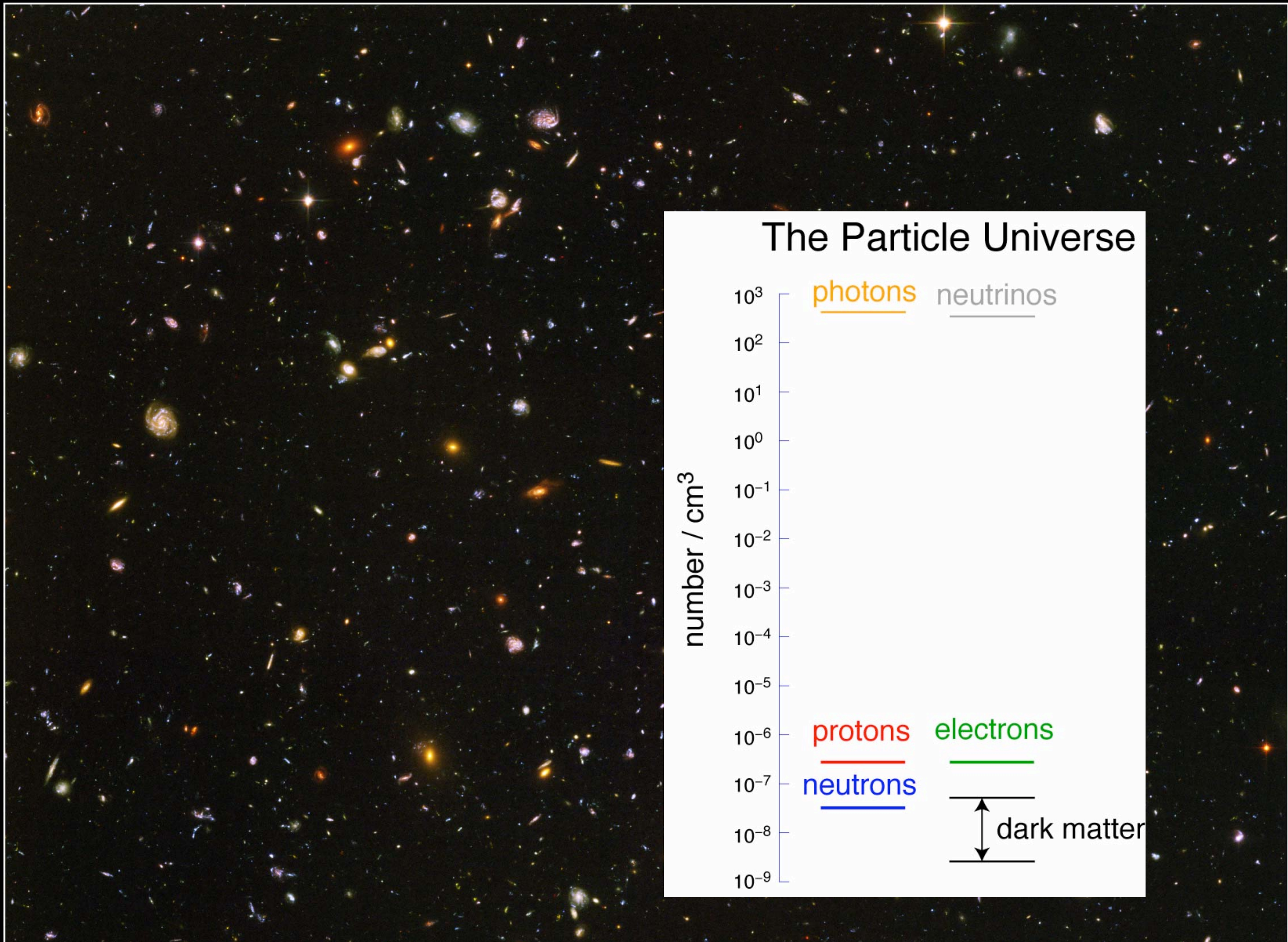
Neutrino Mass from Oscillations

Hitoshi Murayama (IPMU/Berkeley)

Mar 17, 2008

IPMU Focus Week on Neutrino Mass



The Particle Universe
number / cm3
10^3
10^2
10^1
10^0
10^-1
10^-2
10^-3
10^-4
10^-5
10^-6
10^-7
10^-8
10^-9
photons
neutrinos
protons
electrons
neutrons
dark matter

Neutrinos in the Standard Model

Neutrinos are Left-handed

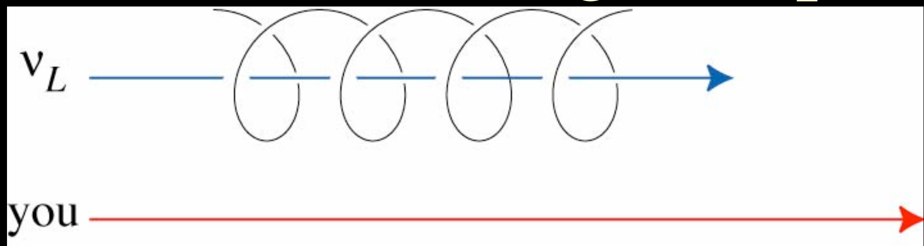
Helicity of Neutrinos*

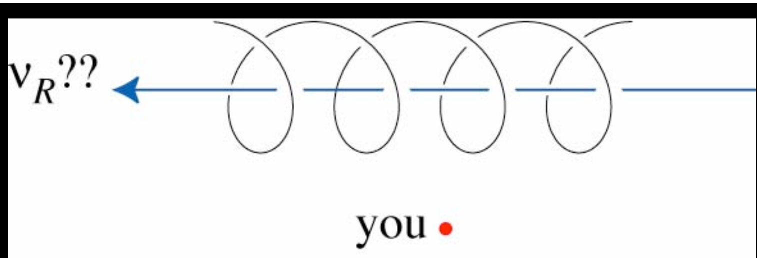
M. GOLDHABER, L. GRODZINS, AND A. W. SUNYAR
Brookhaven National Laboratory, Upton, New York
(Received December 11, 1957)

A COMBINED analysis of circular polarization and resonant scattering of γ rays following orbital electron capture measures the helicity of the neutrino. We have carried out such a measurement with Eu^{152m}, which decays by orbital electron capture. If we assume the most plausible spin-parity assignment for this isomer compatible with its decay scheme,[1] 0−, we find that the neutrino is "left-handed," i.e., $\boldsymbol{\sigma}_\nu \cdot \hat{p}_\nu = -1$ (negative helicity).

Neutrinos must be Massless

- All neutrinos left-handed ⇒ massless
- If they have mass, can't go at speed of light.



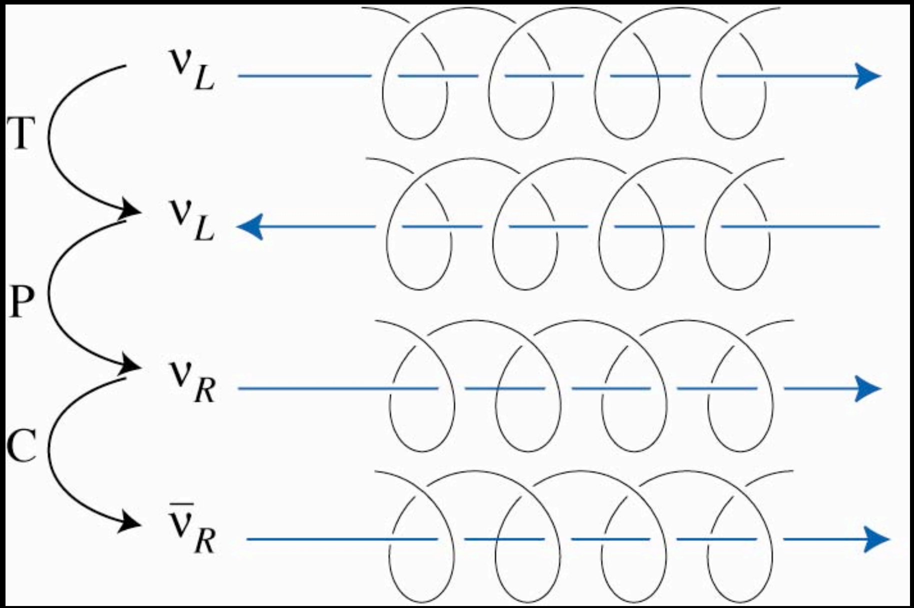


- Now neutrino right-handed??

  ⇒ contradiction ⇒ can't have a mass

Anti-Neutrinos are Right-handed

- CPT theorem in quantum field theory
  - C: interchange particles & anti-particles
  - P: parity
  - T: time-reversal
- State obtained by CPT from ν_L must exist: $\bar{\nu}_R$



Other Particles?

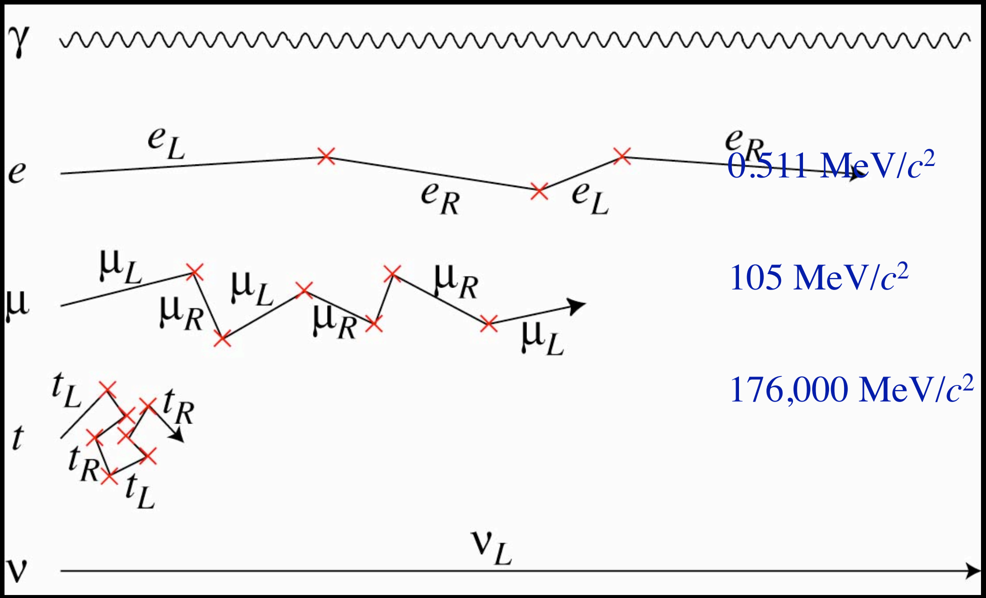
- What about other particles? Electron, muon, up-quark, down-quark, etc
- We say "weak force acts only on left-handed particles" yet they are massive.

Isn't this also a contradiction?

No, because we are swimming in a Bose-Einstein condensate in Universe

Universe is filled with Higgs

- "Empty" space filled with a BEC: cosmic superconductor
- Particles bump on it, but not photon because it is neutral.
- Can't go at speed of light (massive), and right-handed and left-handed particles mix ⇒ no contradiction



But neutrinos can't bump because there isn't a right-handed one ⇒ stays massless

Standard Model

- Therefore, neutrinos are strictly massless in the Standard Model of particle physics

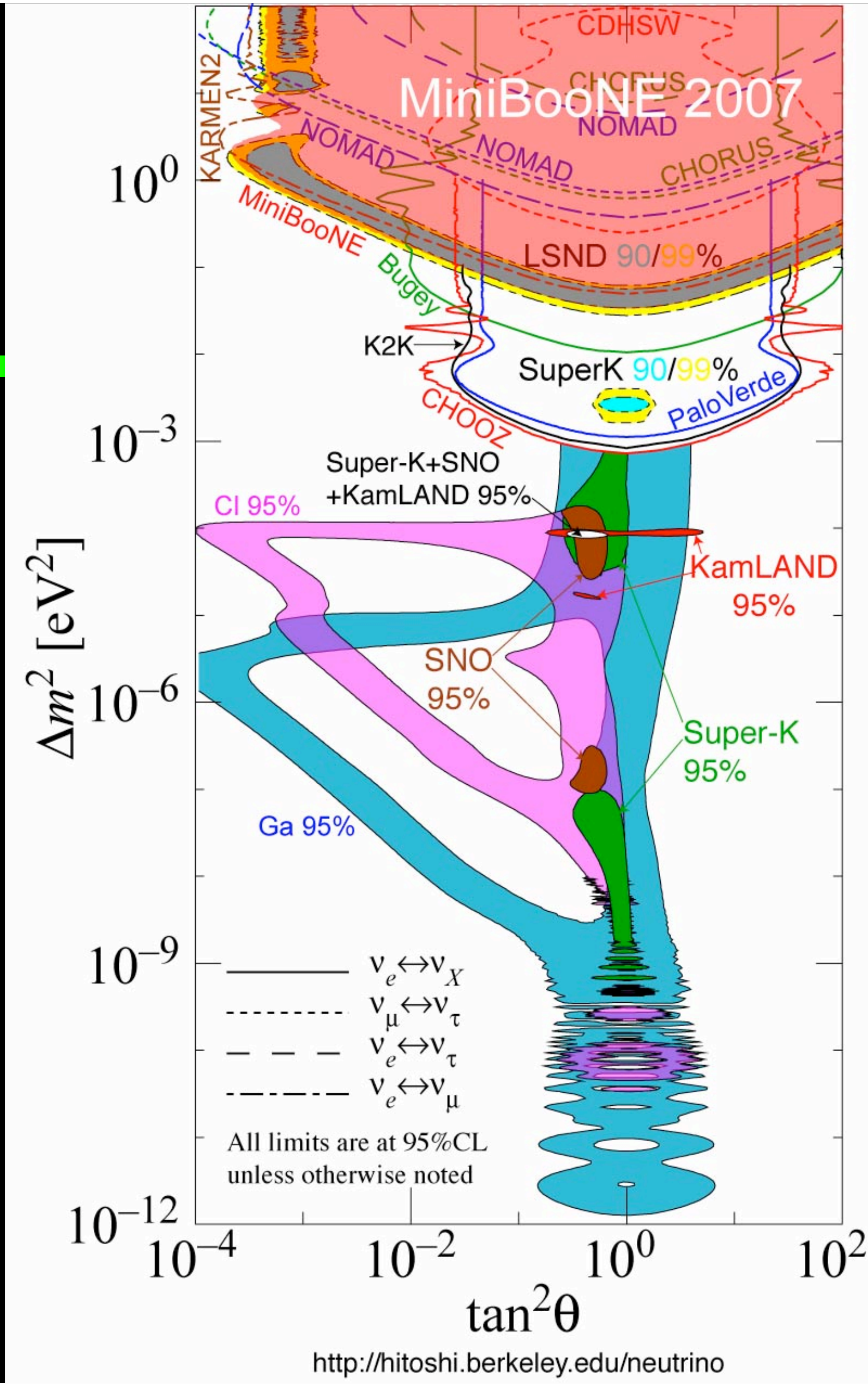
  Finite mass of neutrinos imply the Standard Model is incomplete!

- Not just incomplete but probably a lot more profound

Lot of effort since ‘60s

Finally convincing evidence for “neutrino oscillation”

Neutrinos appear to have tiny but finite mass



Rare Effects from High-Energies

- Effects of physics beyond the SM as effective operators

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \frac{1}{\Lambda}\mathcal{L}_5 + \frac{1}{\Lambda^2}\mathcal{L}_6 + \cdots$$

- Can be classified systematically (Weinberg)

$$\mathcal{L}_5 = (LH)(LH) \to \frac{1}{\Lambda}(L\langle H\rangle)(L\langle H\rangle) = m_\nu \nu\nu$$

$$\begin{aligned}\mathcal{L}_6 \quad &= \quad QQQL, \bar{L}\sigma^{\mu\nu}W_{\mu\nu}He, \\ &\epsilon_{abc}W_\nu^{a\mu}W_\lambda^{b\nu}W_\mu^{c\lambda}, (H^\dagger D_\mu H)(H^\dagger D^\mu H), \cdots\end{aligned}$$

Unique Role of Neutrino Mass

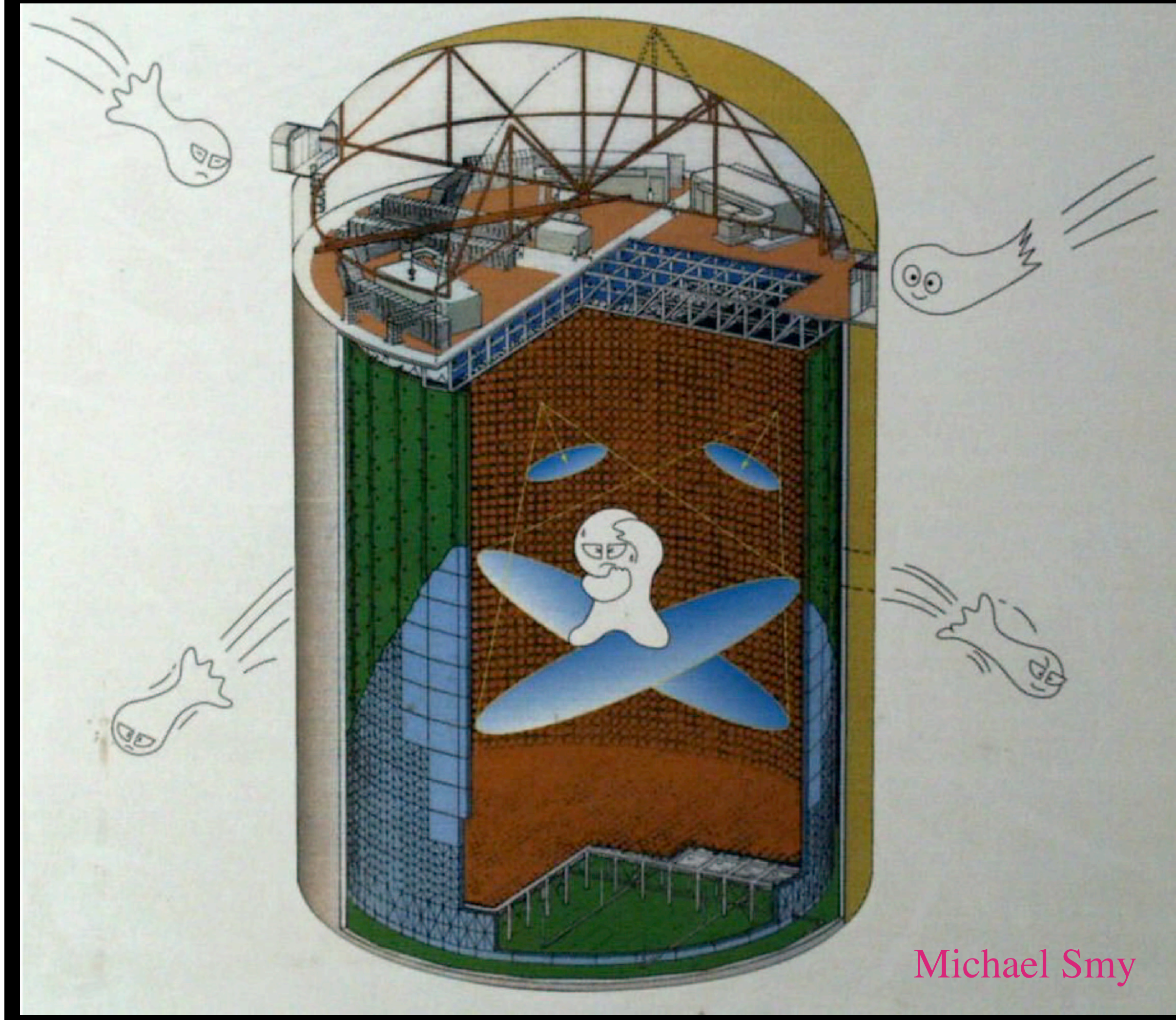
- Lowest order effect of physics at short distances
- Tiny effect $(m_\nu/E_\nu)^2 \sim (0.1\text{eV/GeV})^2 = 10^{-20}$!
- Interferometry (*i.e.*, Michaelson-Morley)
  - Need coherent source
  - Need interference (*i.e.*, large mixing angles)
  - Need long baseline

Nature was kind to provide all of them!

- "neutrino interferometry" (a.k.a. neutrino oscillation) a unique tool to study physics at very high scales

Evidence for Neutrino Mass

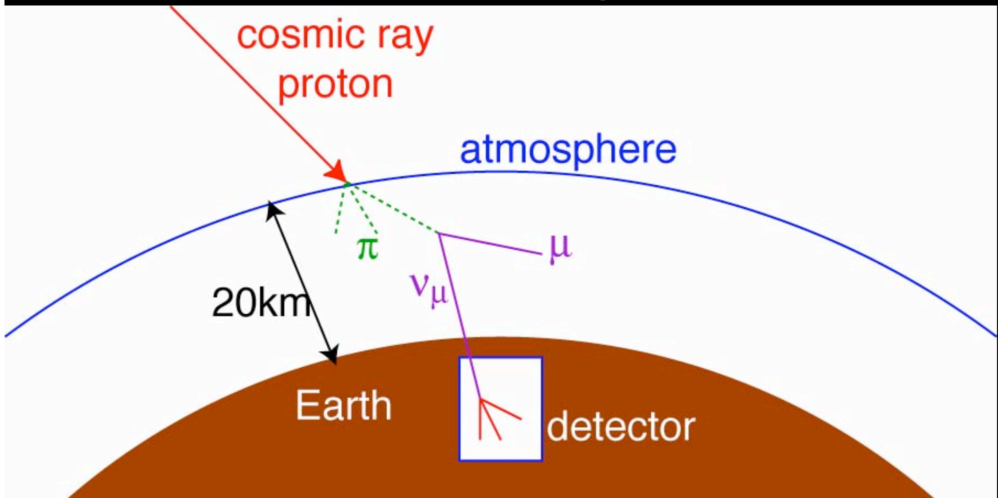
Super-Kamiokande (SuperK)



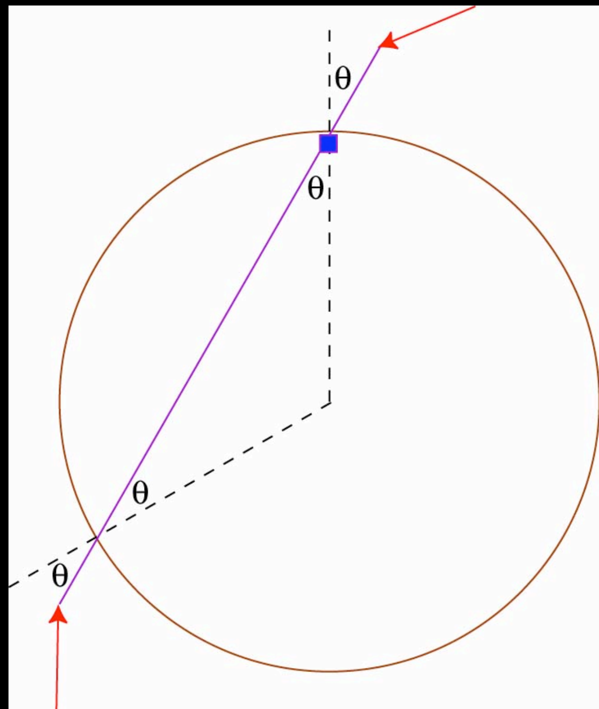
- Kamioka Mine in central Japan
- ~1000m underground
- 50kt water
- Inner Detector
  - 11,200 PMTs
- Outer Detector
  - 2,000 PMTs

SuperKamiokaNDE Nucleon Decay Experiment

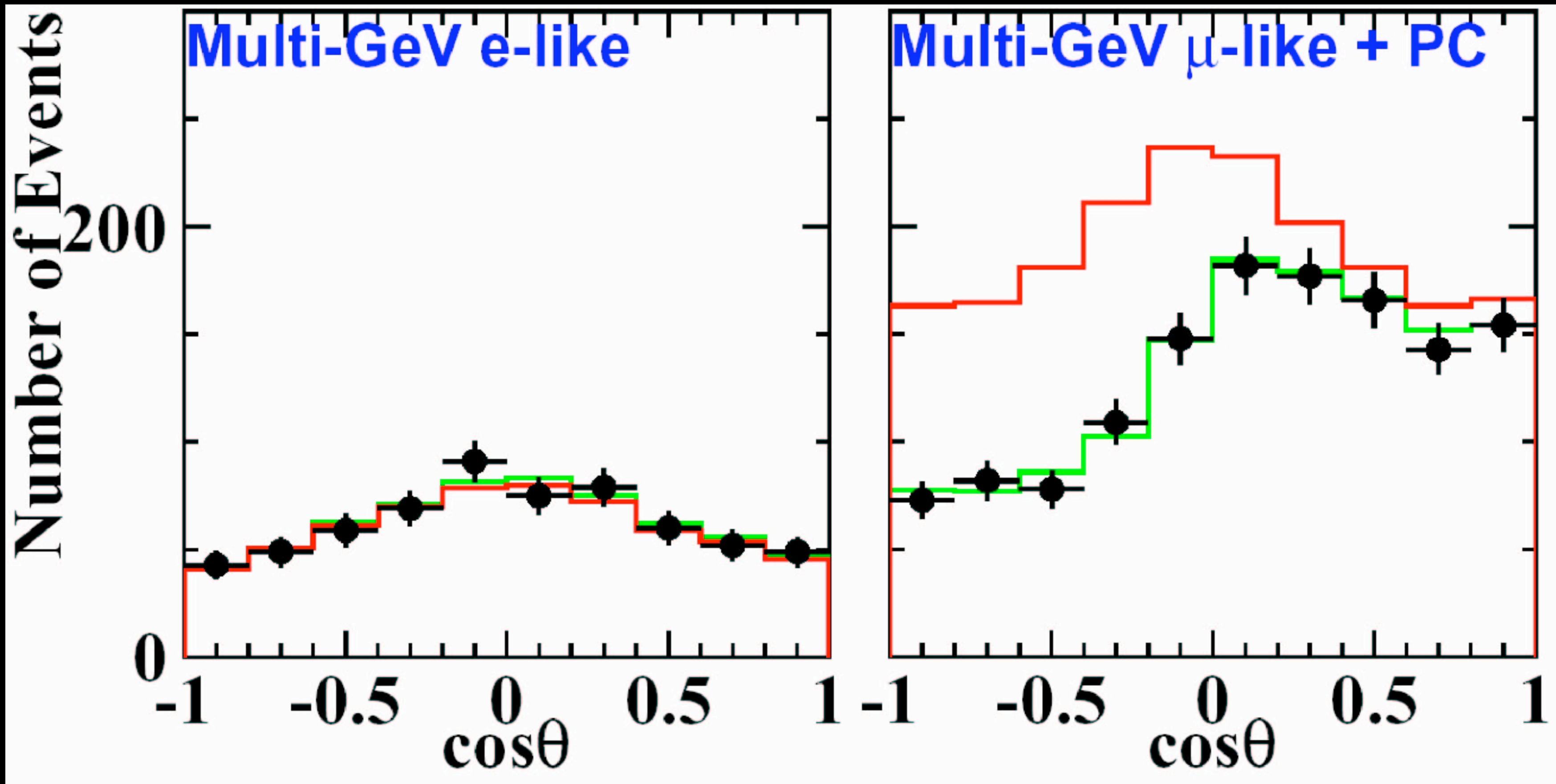
- $p \rightarrow e^+\pi^0$, $K^+\nu$, etc
  - So far not seen
  - Atmospheric neutrino main background



- Cosmic rays isotropic
  - Atmospheric neutrino up-down symmetric



A half of ν_μ lost!



Neutrino's clock

- Time-dilation: the clock goes slower

$$\Delta\tau = \Delta t\sqrt{1 - \frac{v^2}{c^2}}$$

- At speed of light $v=c$, clock stops
- But something seems to happen to neutrinos *on their own*

- Neutrinos' clock is going
- Neutrinos must be slower than speed of light

⇒Neutrinos must have a mass

The Hamiltonian

- The Hamiltonian of a freely-propagating massive neutrino is simply

$$H = \sqrt{\vec{p}^2 + m^2} \approx p + \frac{m^2}{2p}$$

- But in quantum mechanics, mass is a matrix in general. 2×2 case:

$$M^2 = \begin{pmatrix} m^2{}_{11} & m^2{}_{12} \\ m^2{}_{21} & m^2{}_{22} \end{pmatrix}$$

$$M^2|1\rangle = m_1^2|1\rangle$$

$$M^2|2\rangle = m_2^2|2\rangle$$

Two-Neutrino Oscillation

- When produced ($e.g., \pi^+ \rightarrow \mu^+ \nu_\mu$), neutrino is of a particular type

$$\left|\nu_\mu, t\right\rangle = |1\rangle \cos\theta \, e^{-im_1^2 t/4p} + |2\rangle \sin\theta \, e^{-im_2^2 t/4p}$$

Two-Neutrino Oscillation

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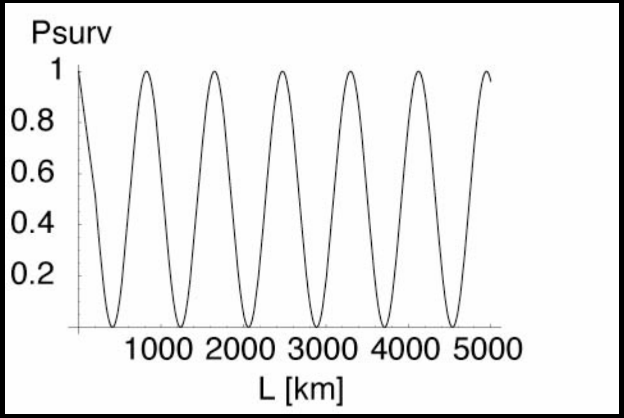
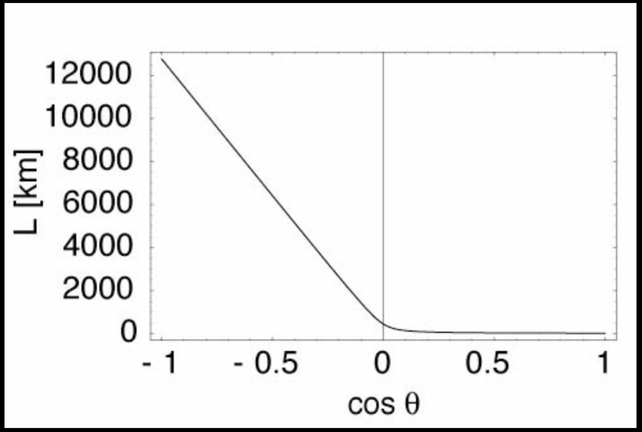
- No longer 100% ν_μ, partly ν_τ!
- "Survival probability" for ν_μ after t

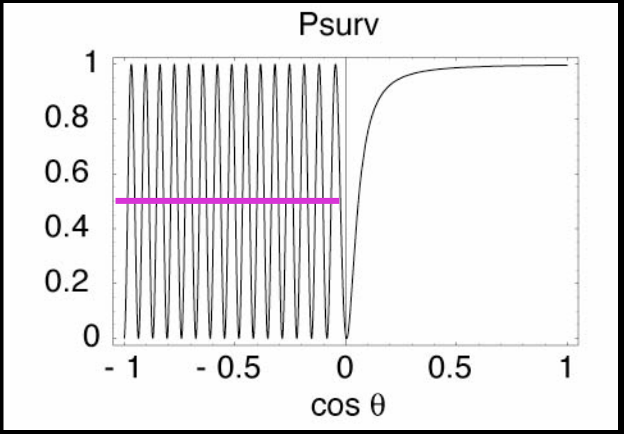
$$P = \left|\left\langle \nu_\mu \middle| \nu_\mu, t \right\rangle\right|^2 = 1 - \sin^2 2\theta \sin^2\left(1.27 \frac{\Delta m^2 c^4}{\text{eV}^2} \frac{\text{GeV}}{c|\vec{p}|} \frac{ct}{\text{km}}\right)$$

Survival Probability

p=1 GeV/c, $\sin^2 2\theta$=1
$\Delta m^2 = 3\times10^{-3}(\text{eV}/c^2)^2$

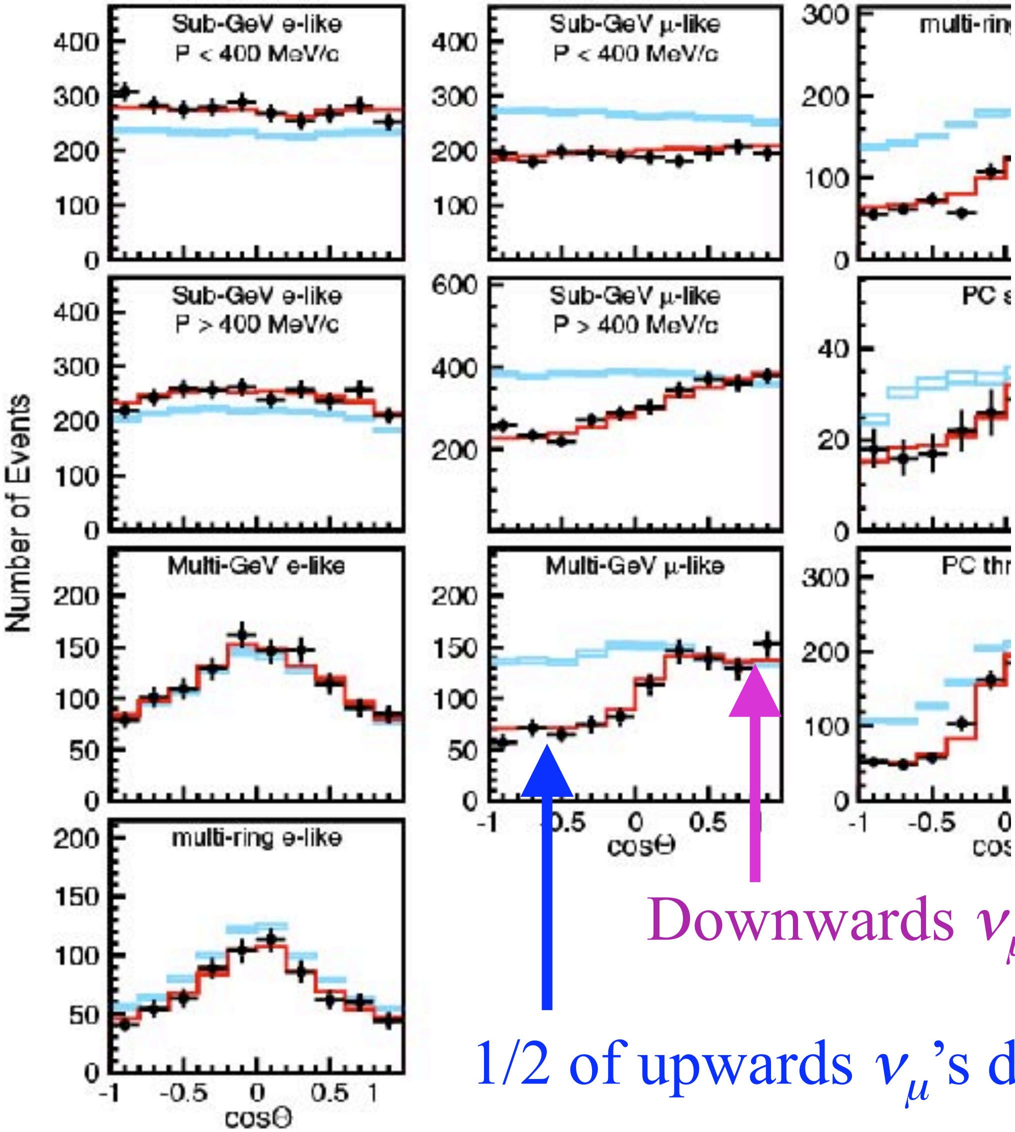


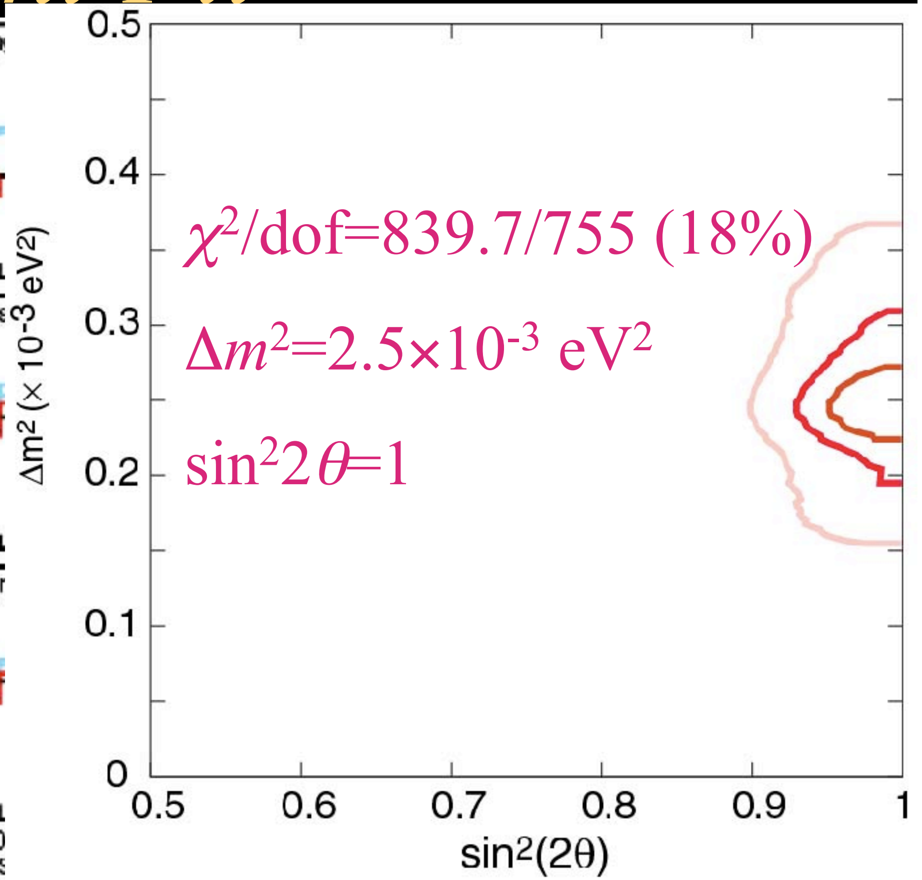




Half of the up-going ones get lost

Excellent Fit





χ^2/dof=839.7/755 (18%)

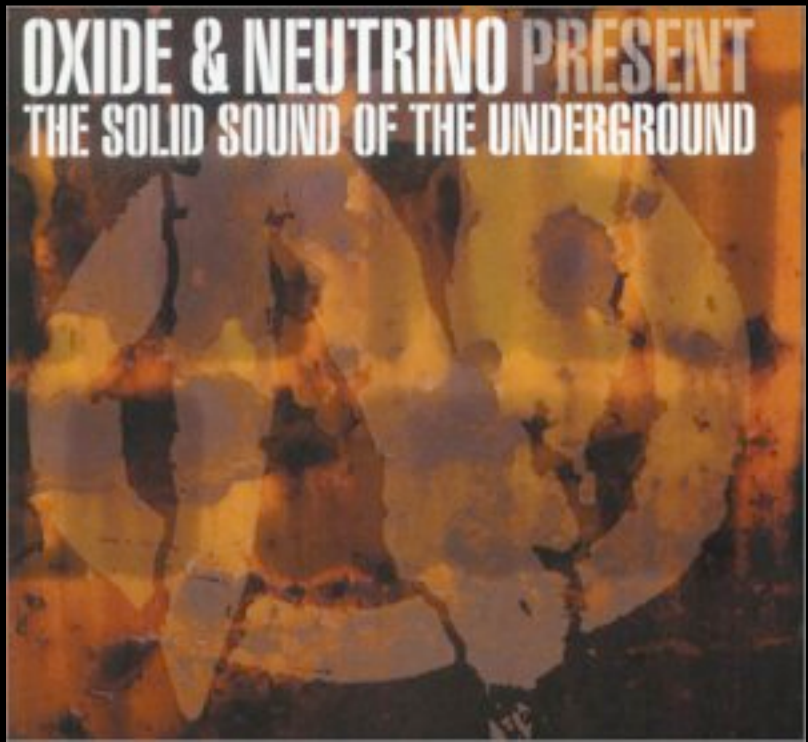
$\Delta m^2 = 2.5 \times 10^{-3}$ eV^2

$\sin^2 2\theta = 1$

Downwards ν_μ's don't disappear

1/2 of upwards ν_μ's do disappear

Public Interest in Neutrinos

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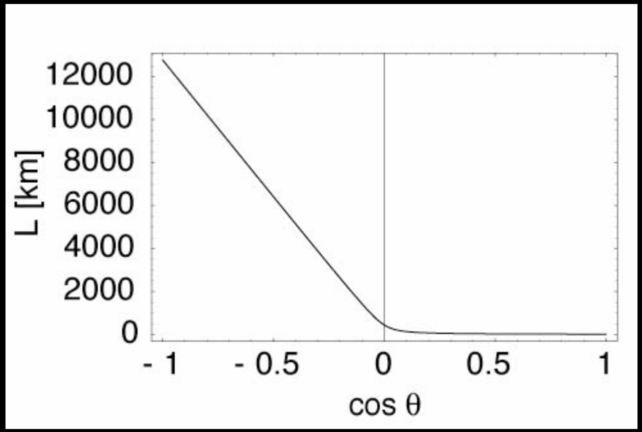
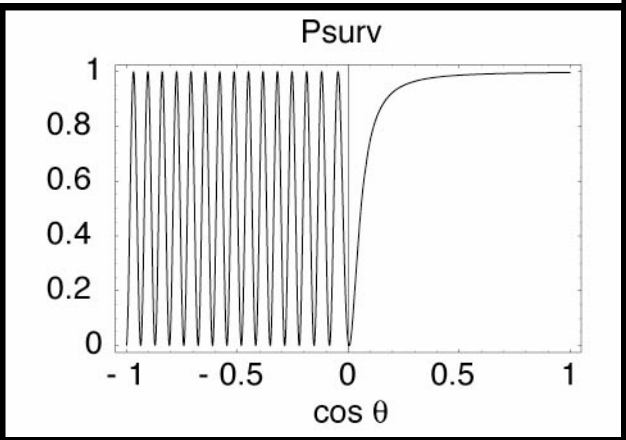
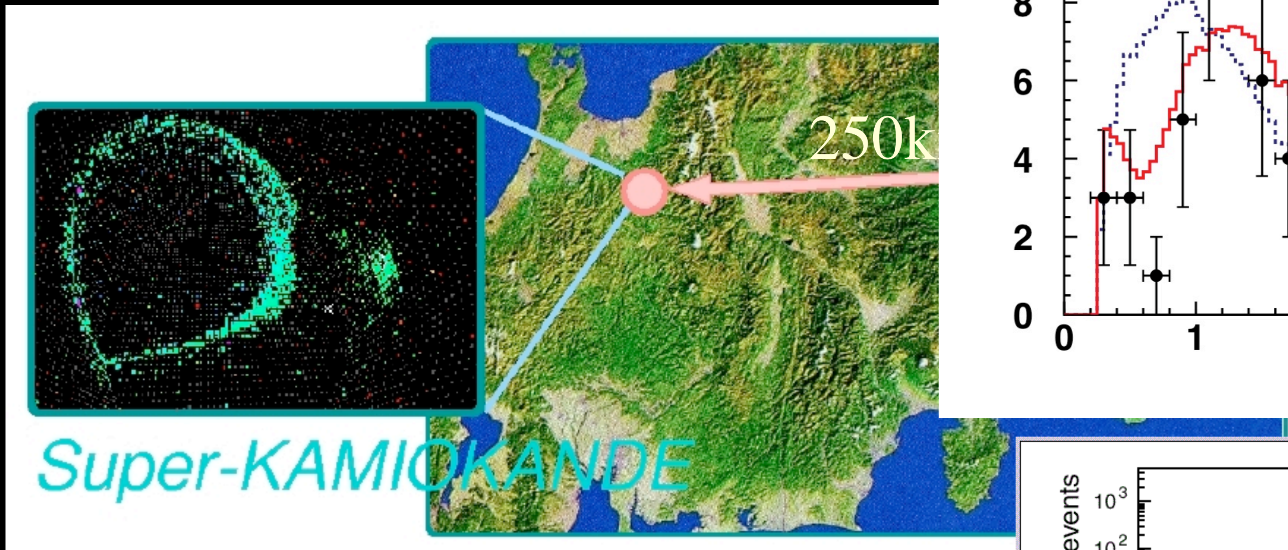
Difficult to improve

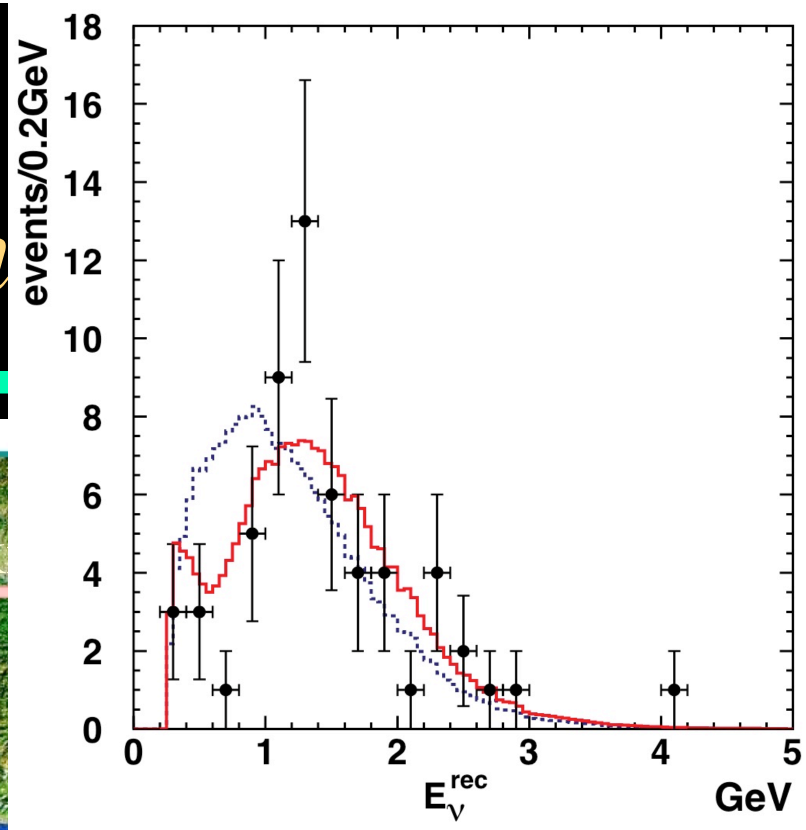
- L vs zenith angle
- Very sharp dependence where the oscillation begins
- Not enough statistics at the relevant zenith angles
- Remain statistics limited

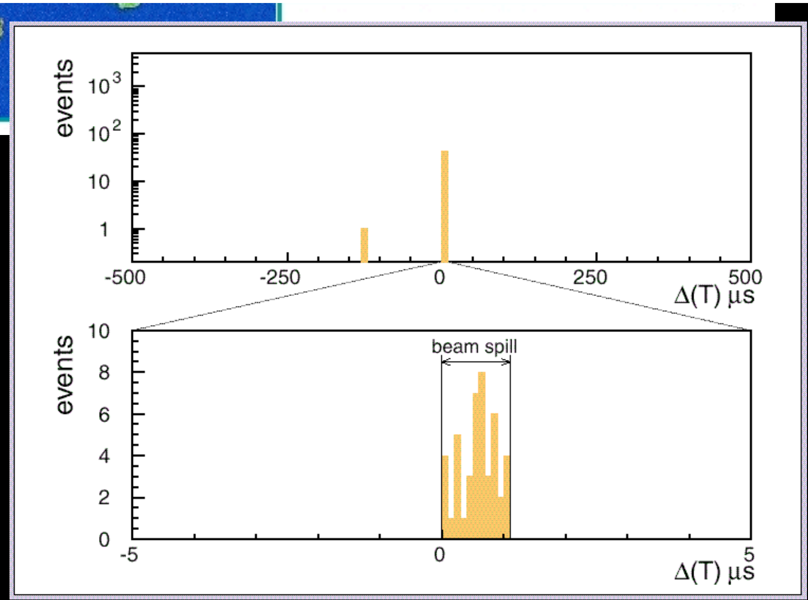




Cross check with







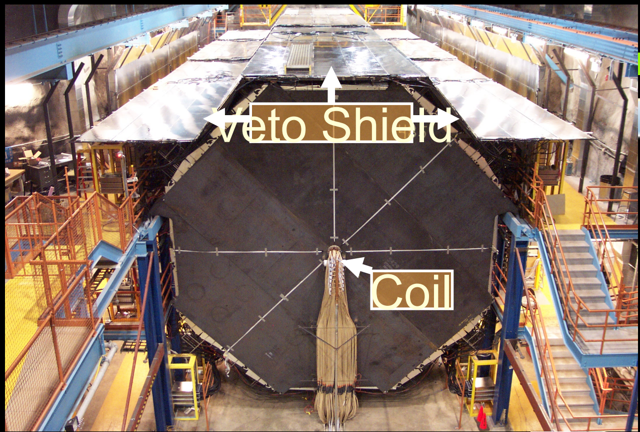
#events if no oscillation $158.1^{+9.2}_{-8.6}$

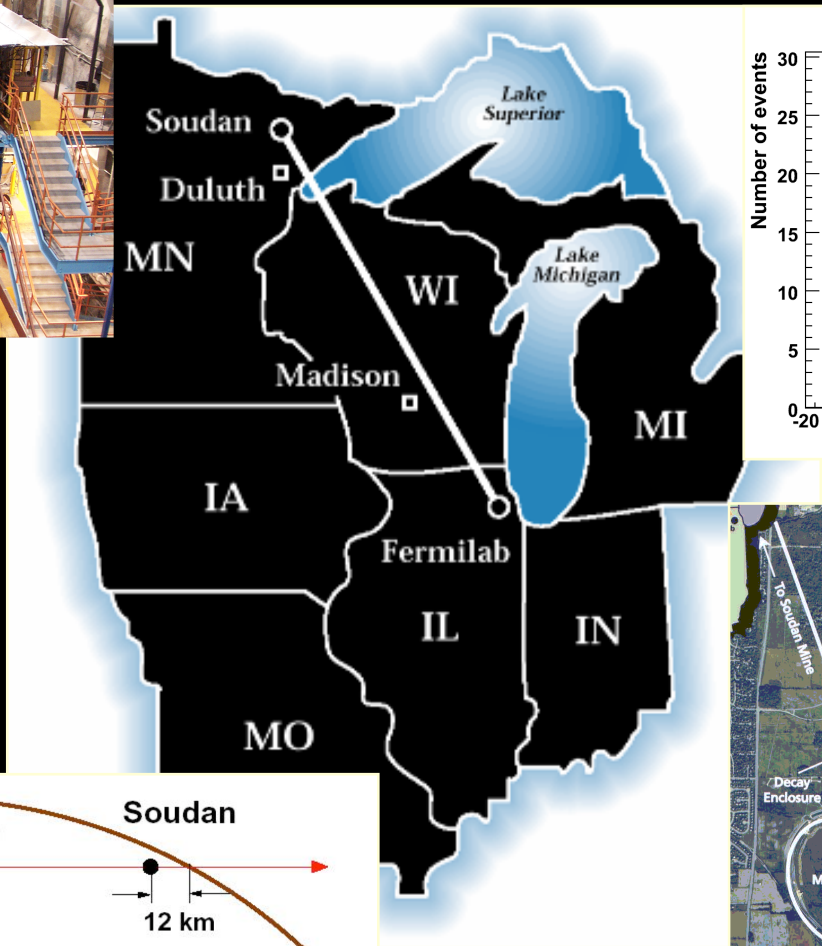
#events observed: 112

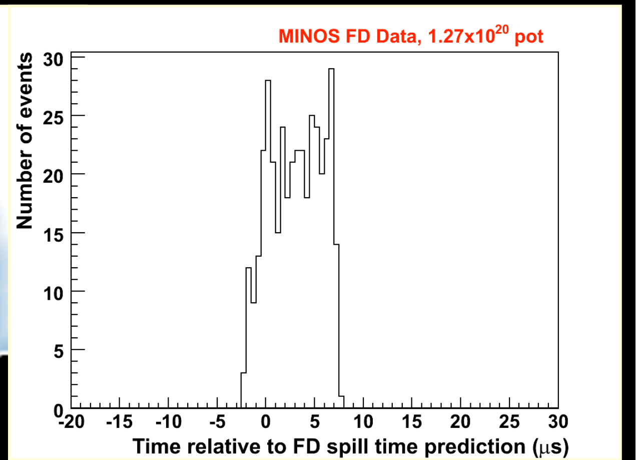
distortion of energy spectrum

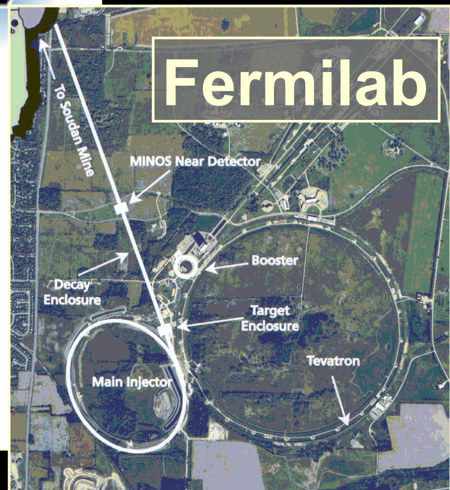
excludes no oscillation @4.3σ

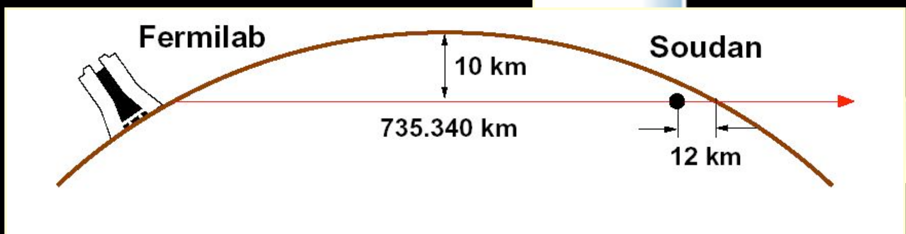
Cross check with man-made ν's





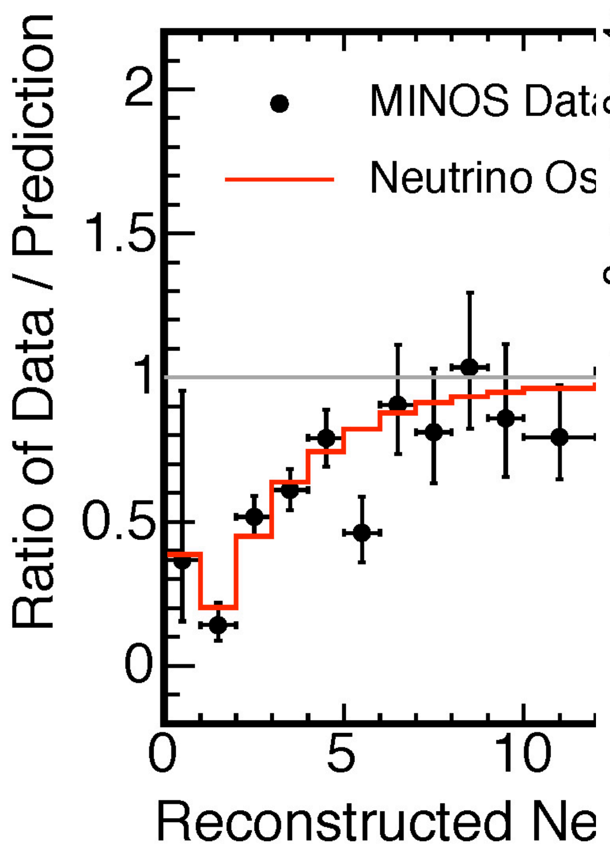


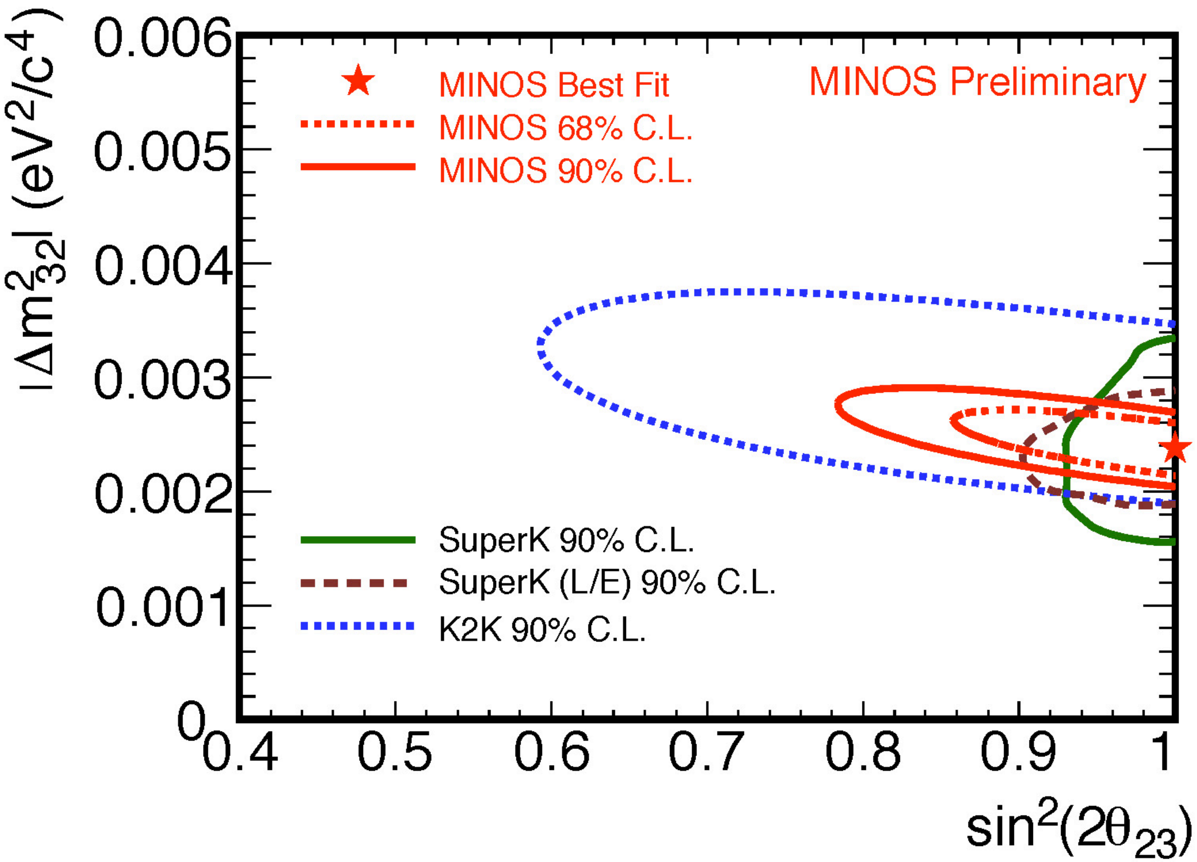




Good consistency!

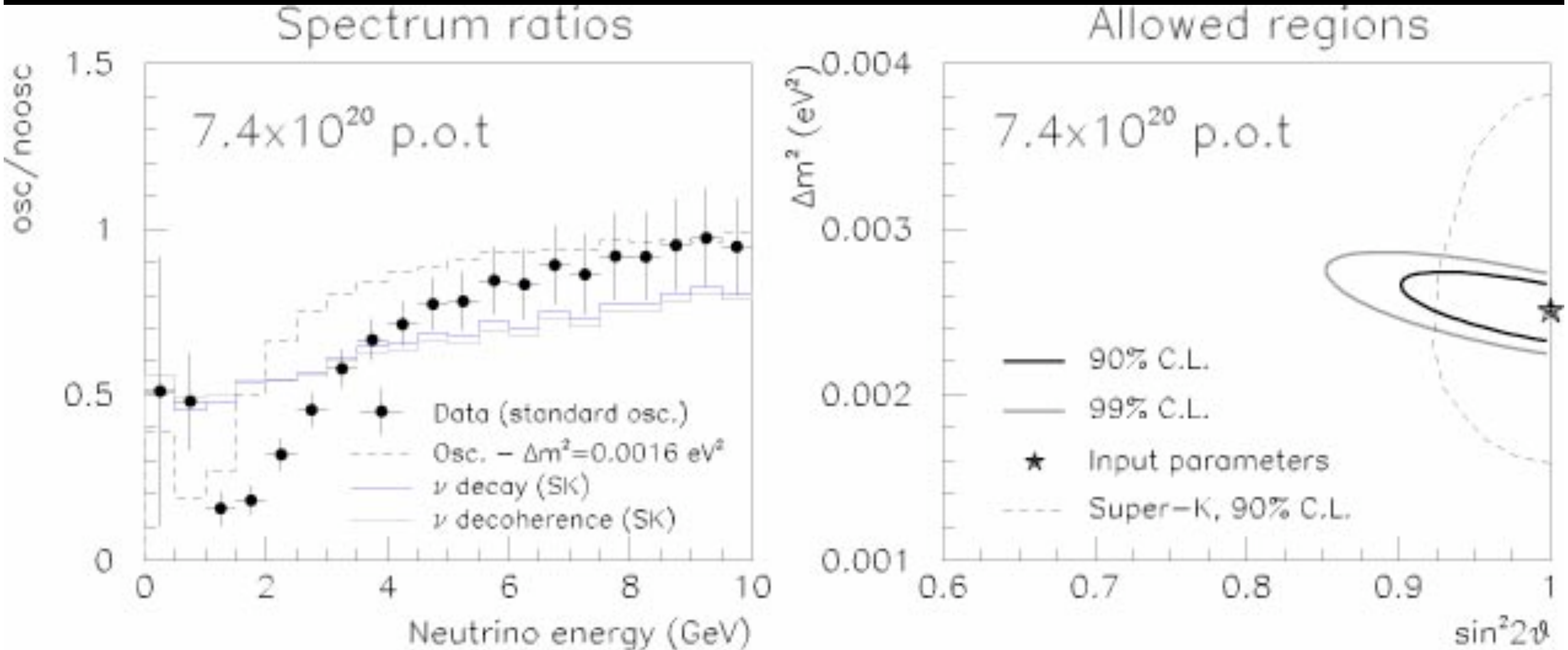
- MINOS result 2007 with 2.5×10^{20} pot



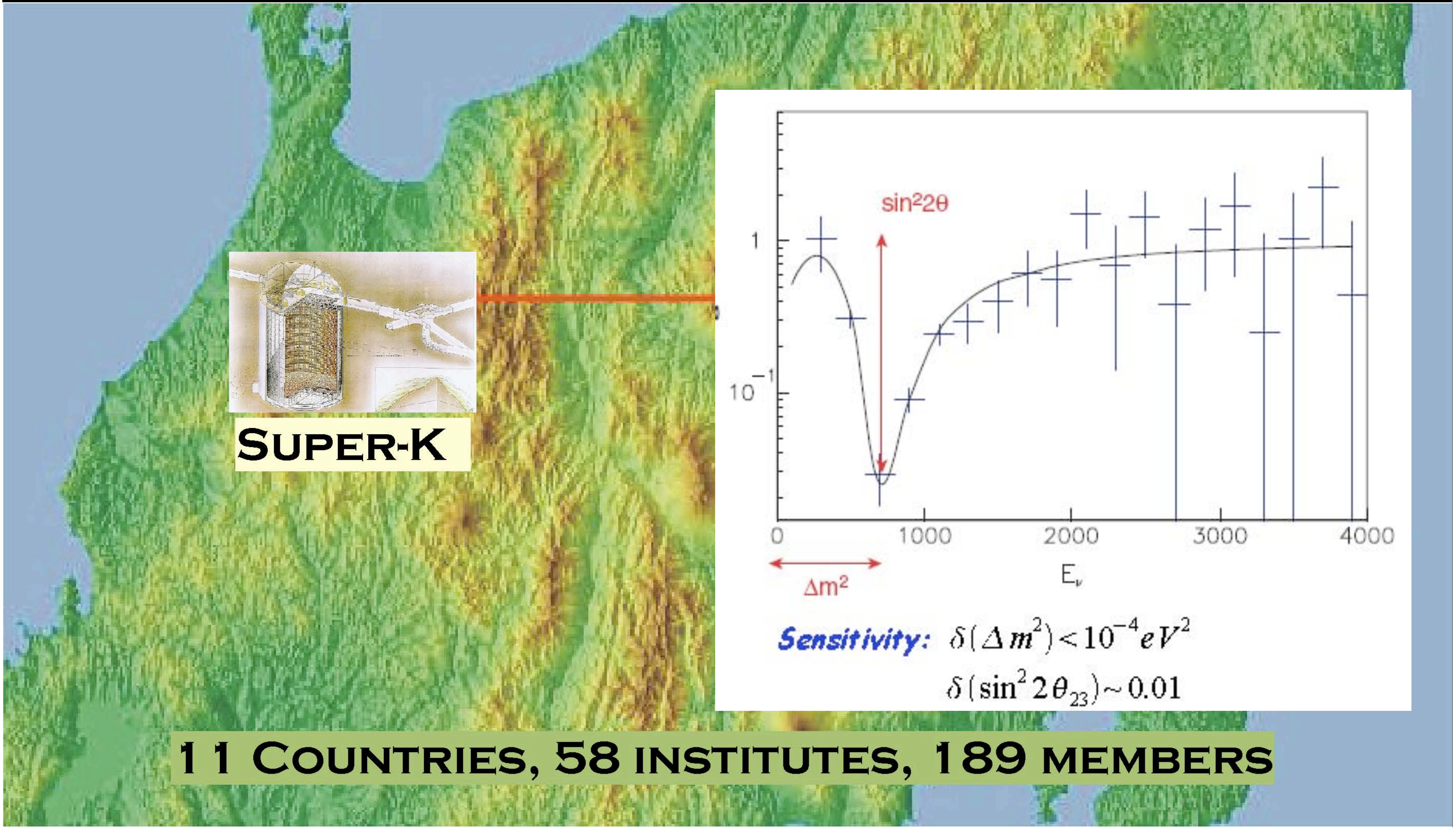


MINOS Future

- 7.4×10^{20} pot



T2K (Tokai to Kamioka)

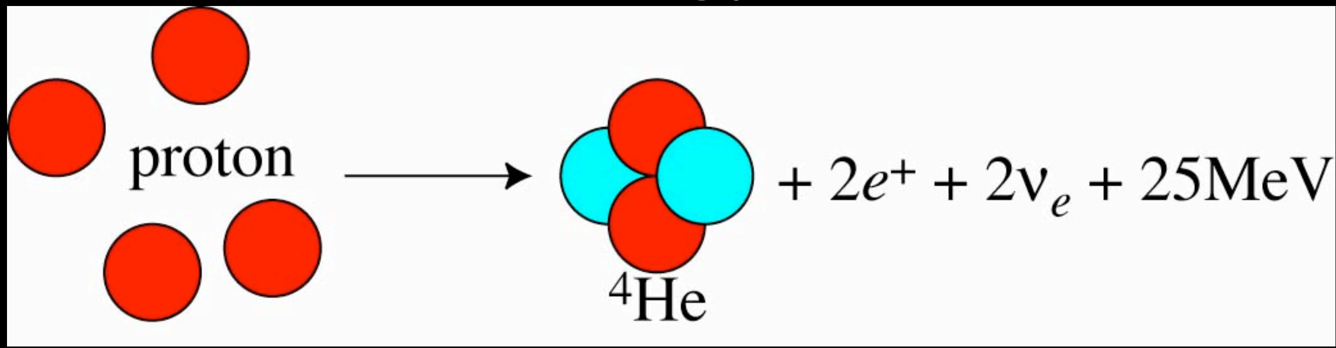


11 Countries, 58 institutes, 189 members

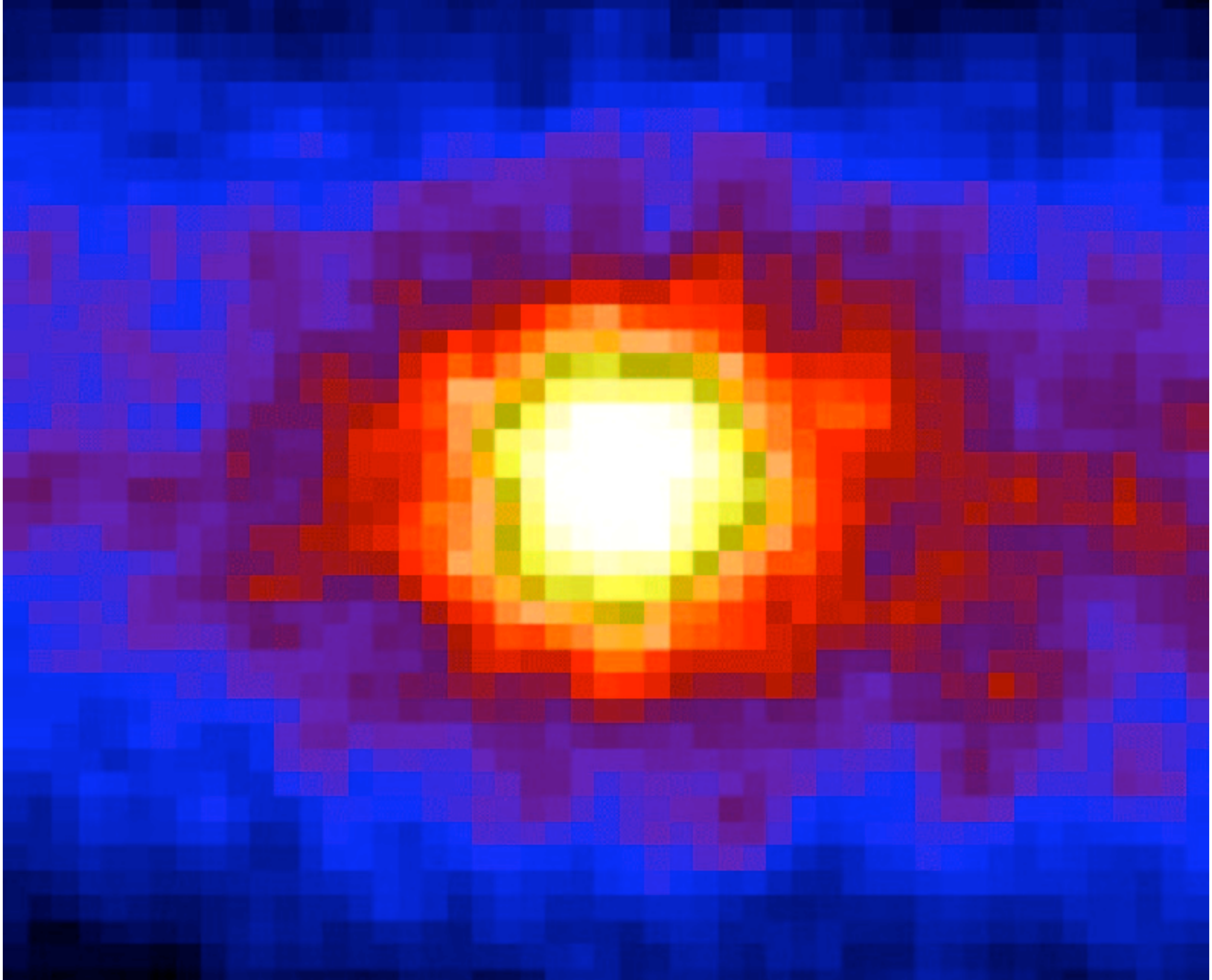
Solar Neutrinos

How the Sun burns

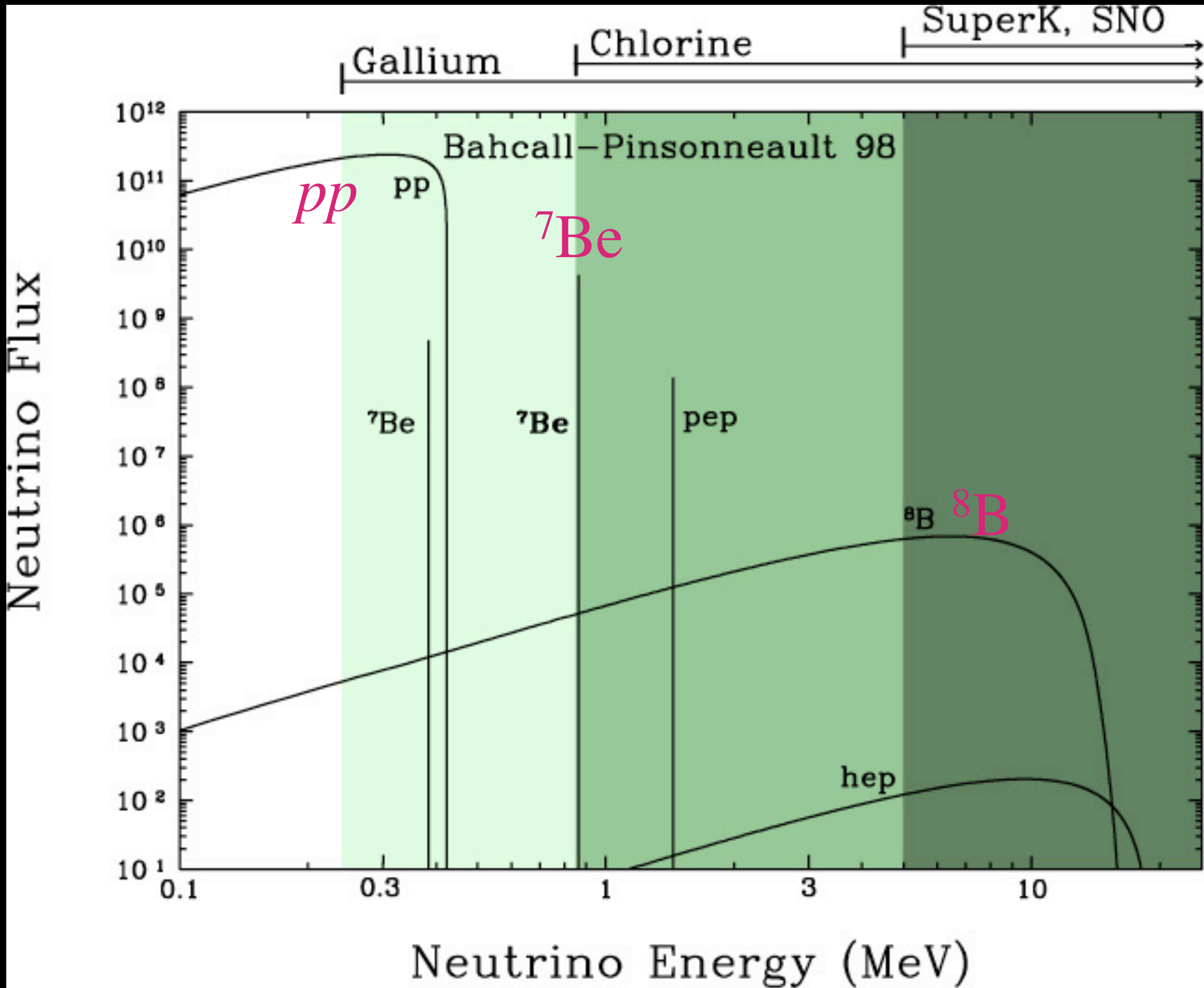
- The Sun emits light because nuclear fusion produces a lot of energy



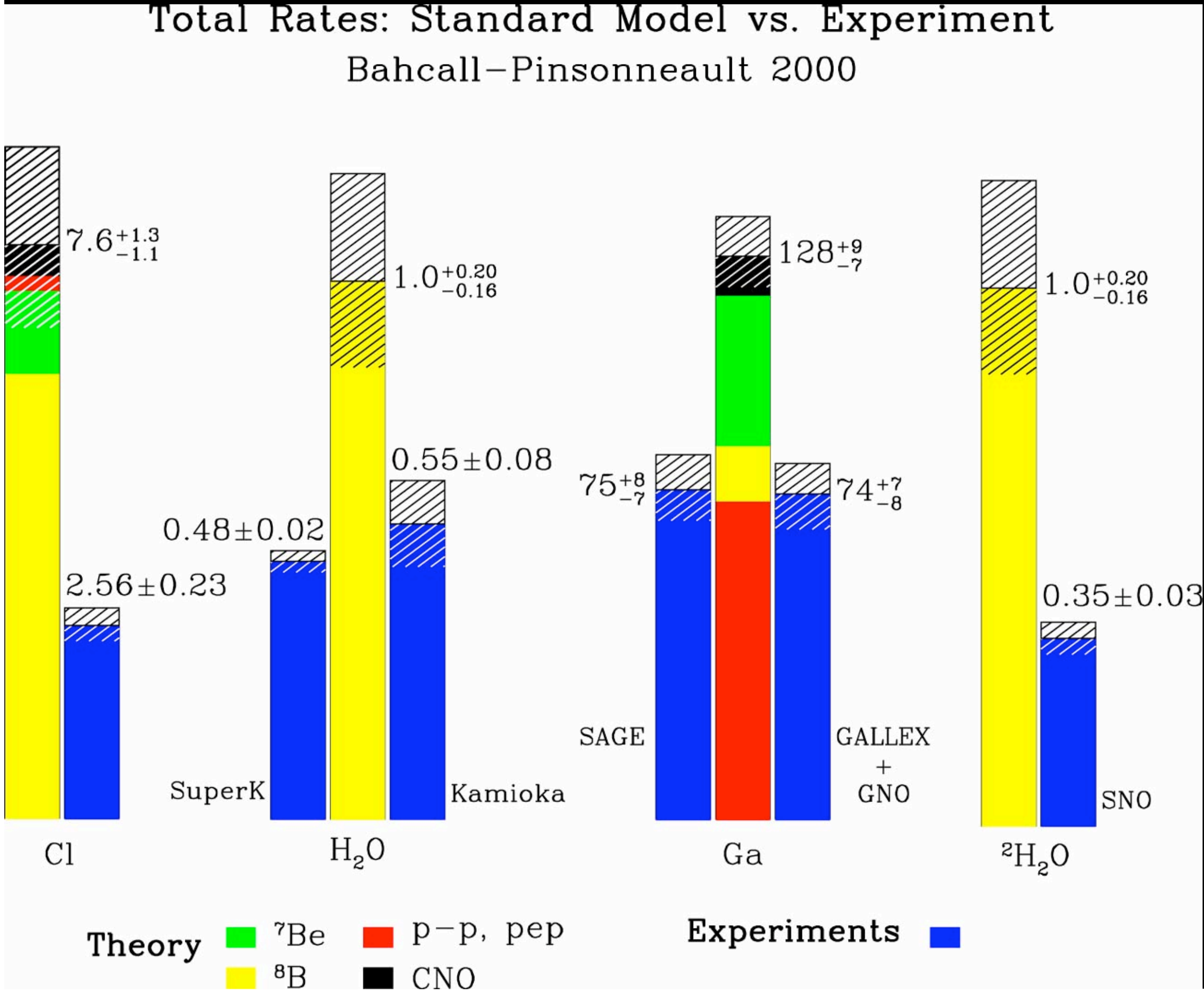
$$\Phi_\nu = \frac{2L_{\text{sun}}}{25\text{MeV}} \frac{1}{4\pi(1\text{AU})^2} = 7\cdot 10^{10}\ \text{sec}^{-1}\ \text{cm}^{-2}$$



Solar Neutrino Spectrum

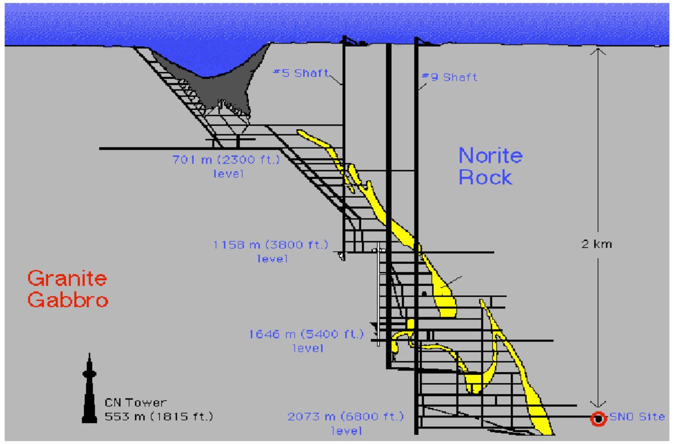


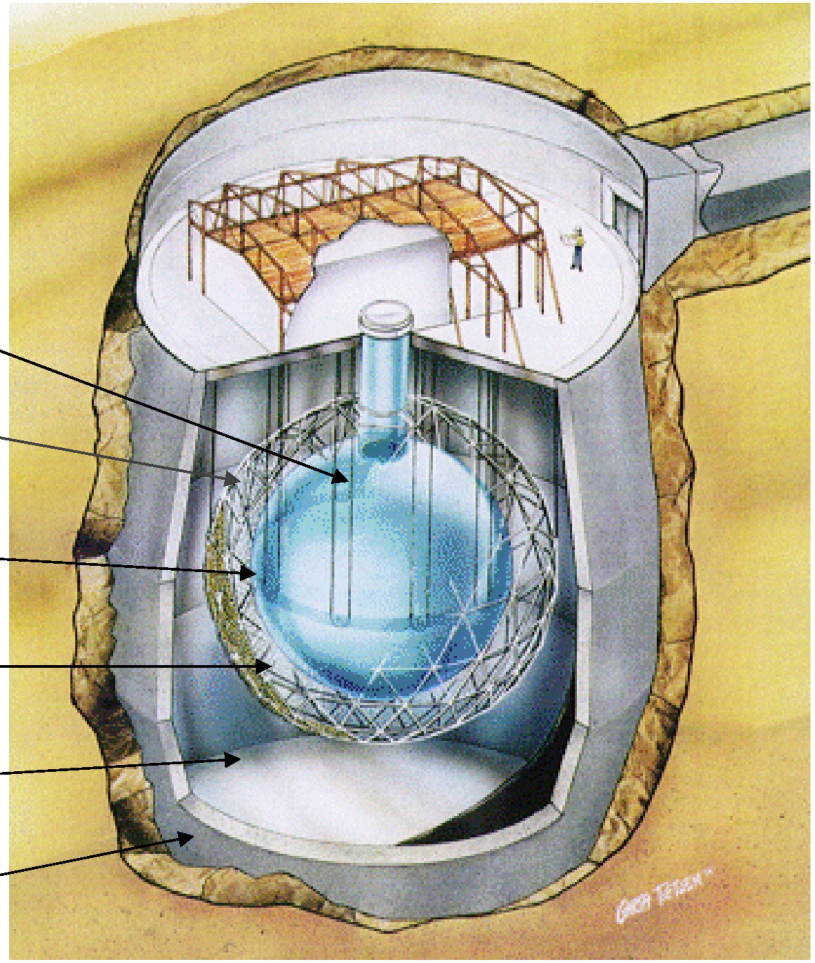
We don't get enough



- Neutrino oscillation?
- Something wrong with our understanding of the Sun?

Sudbury Neutrino Observatory

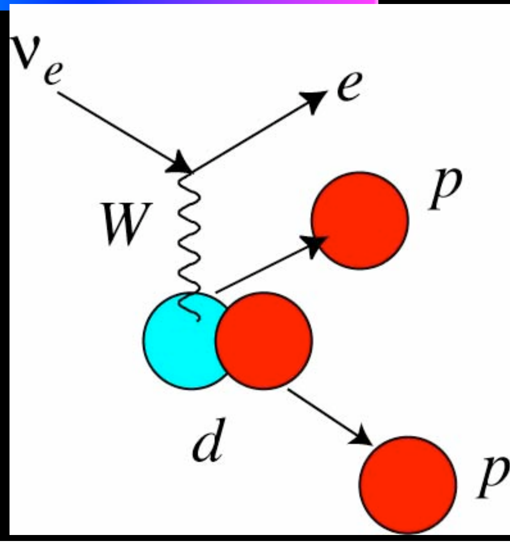




SNO comes to the rescue

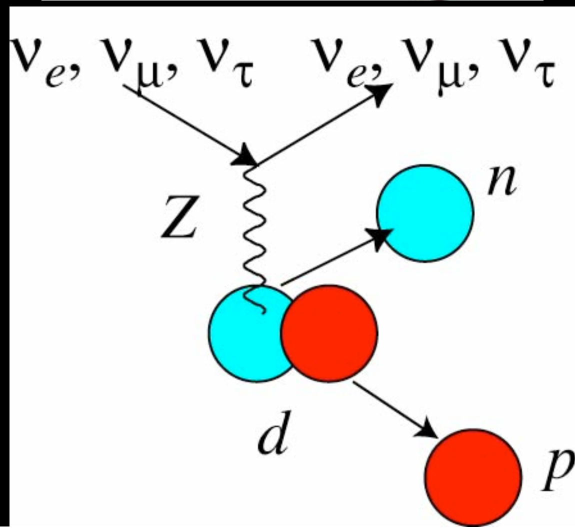
- Charged Current: ν_e

$$\Phi^{\rm SNO}_{\rm CC} = 1.59^{+0.08+0.06}_{-0.07-0.08} \times 10^6 {\rm cm}^{-2}{\rm s}^{-1}$$



- Neutral Current: $\nu_e+\nu_\mu+\nu_\tau$

$$\Phi^{\rm SNO}_{\rm NC} = 5.21 \pm 0.27 \pm 0.38 \times 10^6 {\rm cm}^{-2}{\rm s}^{-1}$$



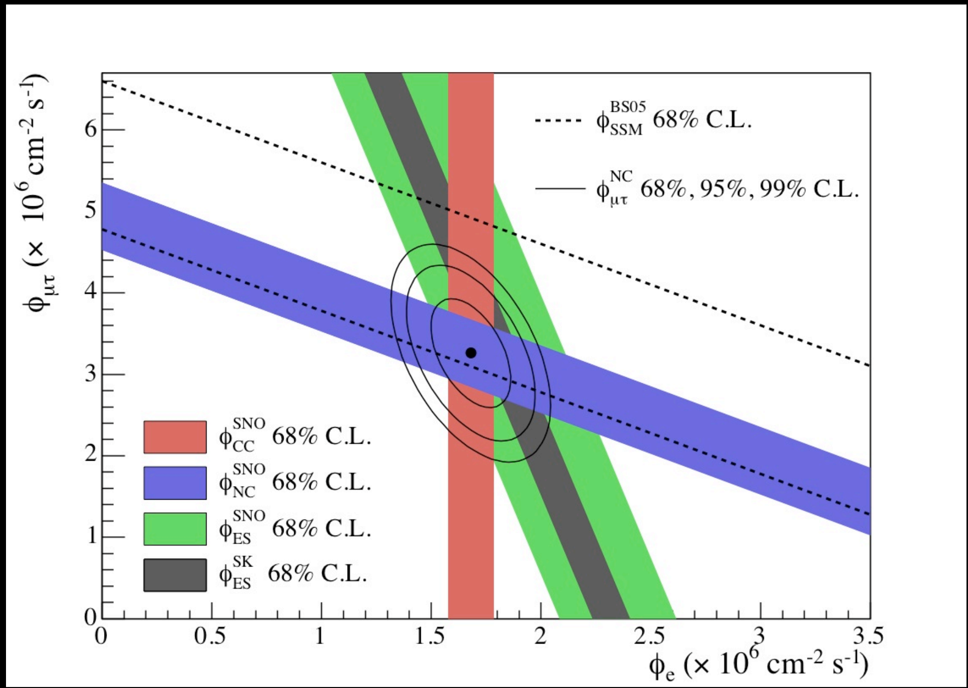
- 7.6σ difference

$\Rightarrow$ $\nu_{\mu,\tau}$ are coming from the Sun!

Wrong Neutrinos

- Only ν_e produced in the Sun
- Wrong Neutrinos $\nu_{\mu,\tau}$ are coming from the Sun!
- Somehow some of ν_e were converted to $\nu_{\mu,\tau}$ on their way from the Sun's core to the detector

  ⇒ neutrino oscillation!

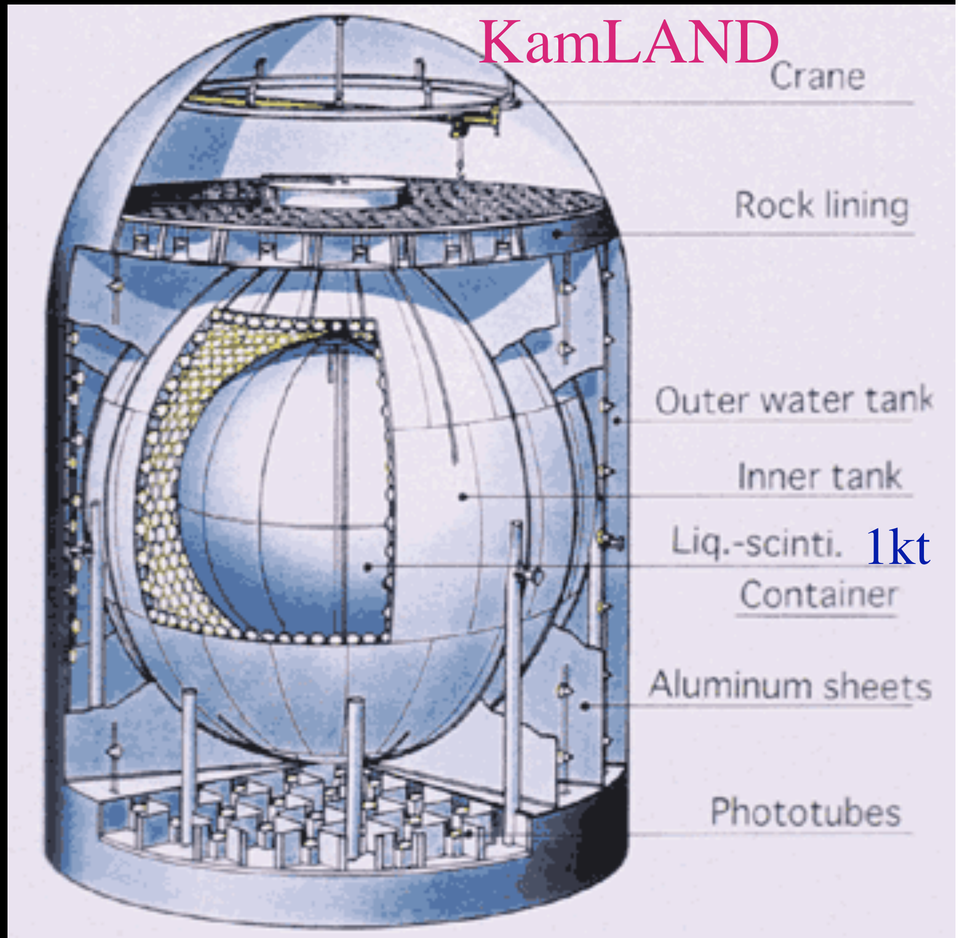


Terrestrial "Solar Neutrino"

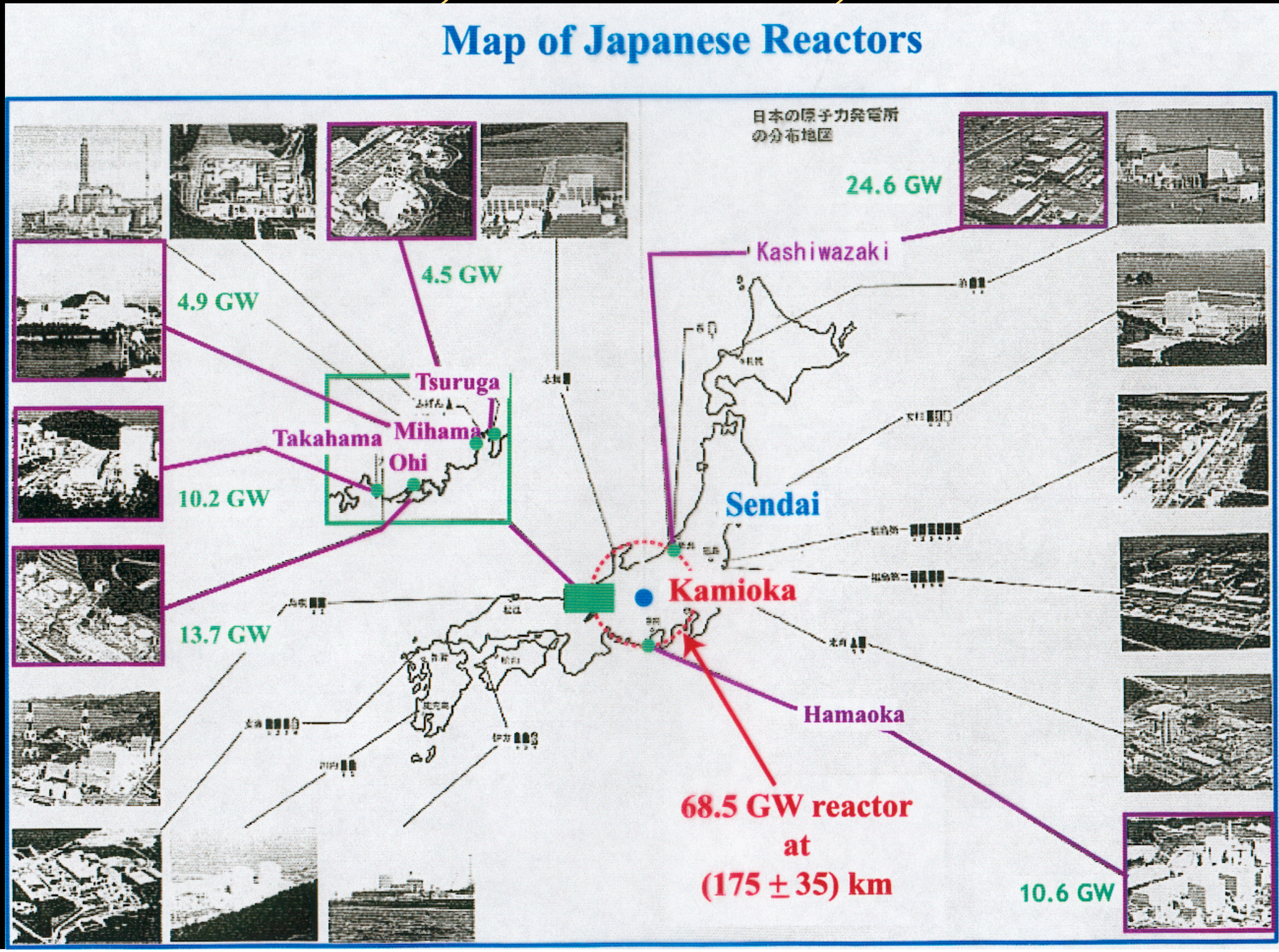
- Can we convincingly verify oscillation with man-made neutrinos?

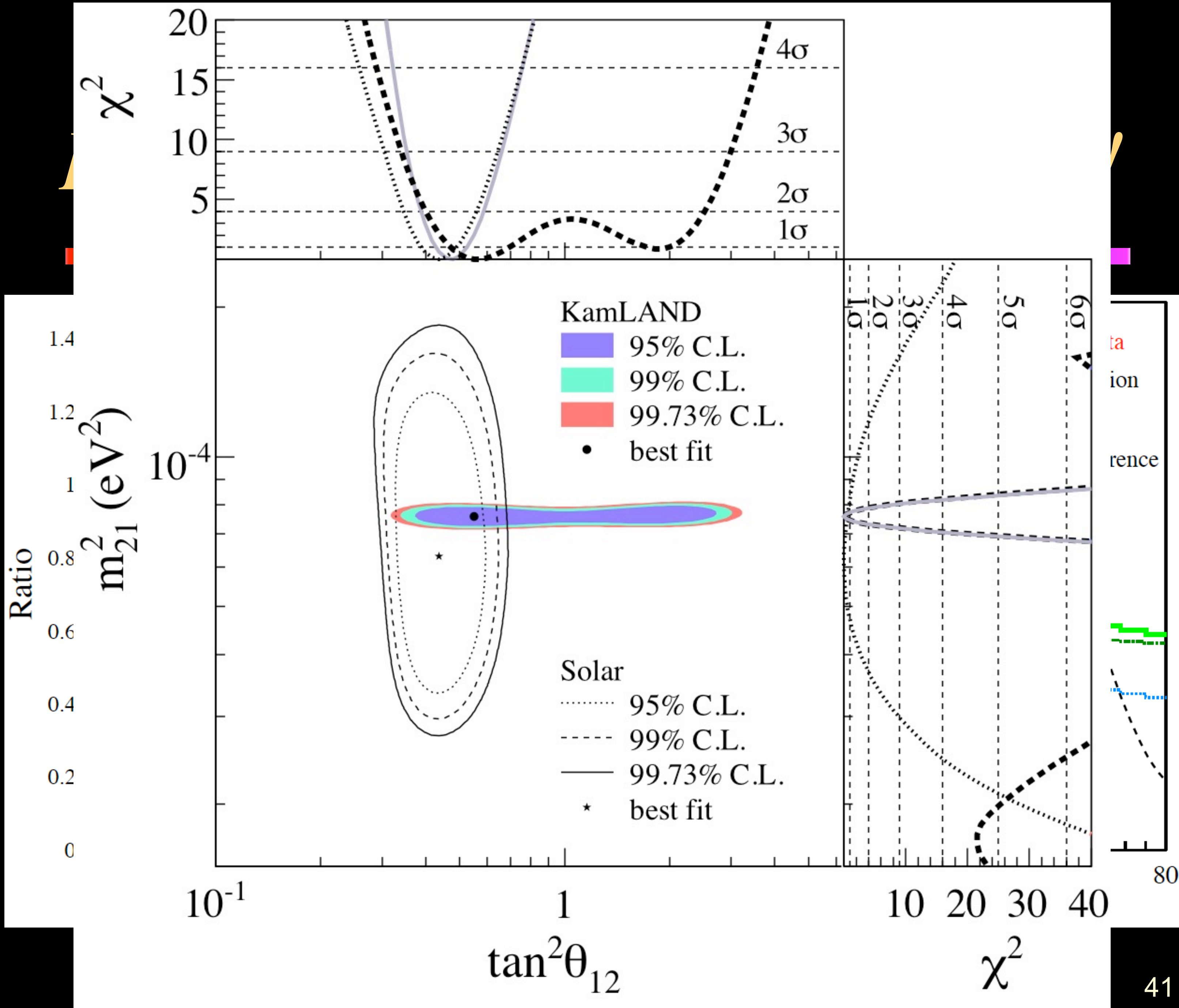
$$P_{surv} = 1 - \sin^2 2\theta \sin^2\left(1.27 \frac{\Delta m^2 c^4}{\mathrm{eV}^2} \frac{\mathrm{GeV}}{E_\nu} \frac{L}{\mathrm{km}}\right)$$

- Hard for low Δm^2
- To probe LMA, need L~100km, 1kt
- Need low E_ν, high Φ_ν
- Use neutrinos from nuclear reactors



Location, Location, Location





χ^2
20
15
10
5
4σ
3σ
2σ
1σ
Δm^2_{21} (eV^2)
10^{-4}
KamLAND
95% C.L.
99% C.L.
99.73% C.L.
best fit
Solar
95% C.L.
99% C.L.
99.73% C.L.
best fit
10^{-1}
1
$\tan^2\theta_{12}$
1σ 2σ 3σ 4σ 5σ 6σ
10 20 30 40
χ^2
Ratio
1.4
1.2
1
0.8
0.6
0.4
0.2
0
80

Reactor future

- KamLAND measurement of Δm^2 won't get much better than what it is
- Dedicated new reactor experiment to improve Δm^2?
- One reactor core with L=60-100km
- No ongoing project at this moment

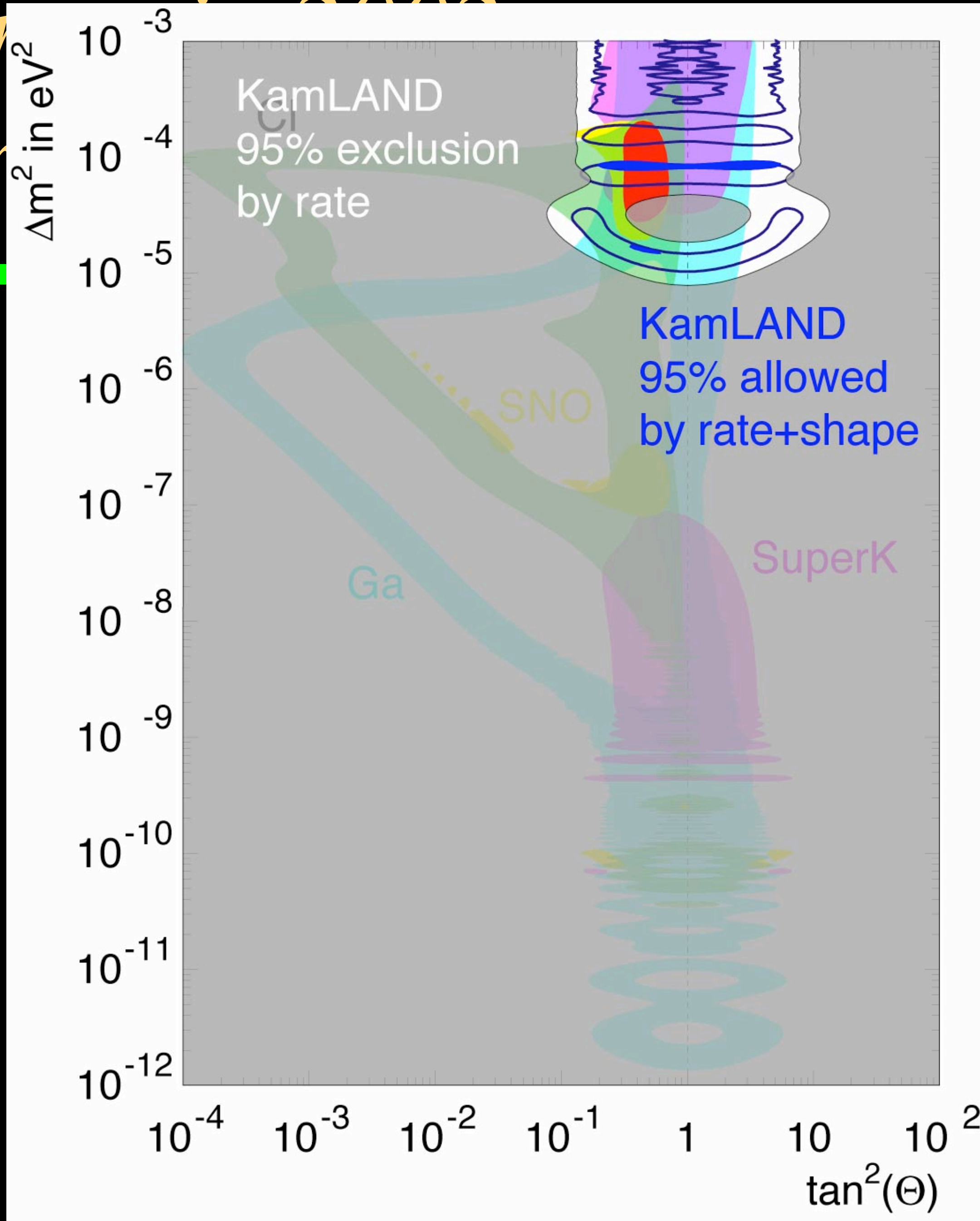
Progr
on the Solar

March 2002

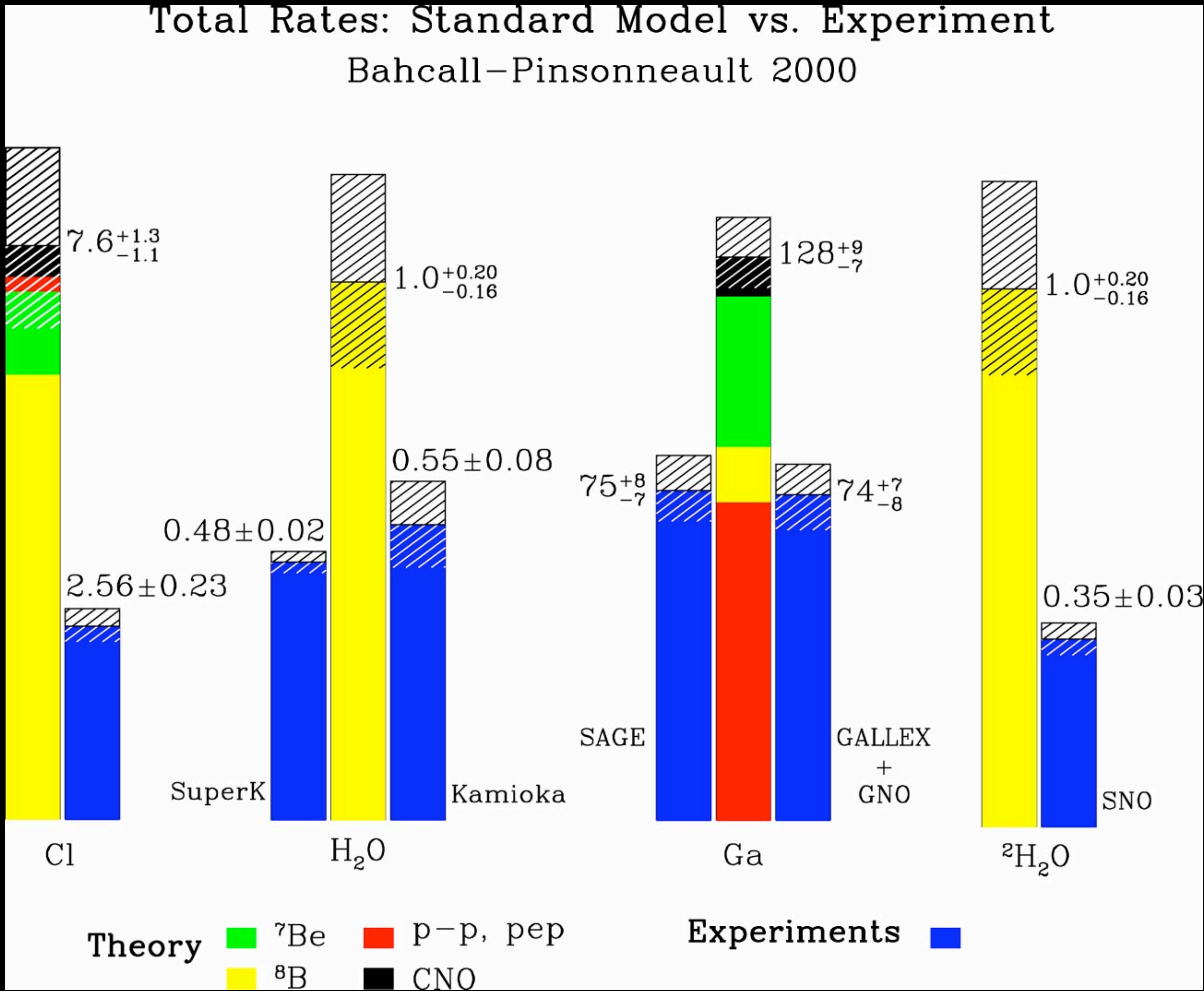
April 2002
with SNO

Dec 2002
with KamLAND

June 2004
with KamLAND



We don't get enough



We need survival probabilities of

^{8}B: ~1/3

^{7}Be: <1/3

pp: ~2/3

Can we get three numbers correctly with two parameters?

Matter Effect

- CC interaction in the presence of non-relativistic electron

$$L = -\frac{G_F}{\sqrt{2}} \bar{e}\gamma_\mu(1-\gamma_5)\nu_e \bar{\nu}_e \gamma^\mu (1-\gamma_5)e$$

$$= -\frac{G_F}{\sqrt{2}} \bar{e}\gamma_\mu(1-\gamma_5)e \bar{\nu}_e \gamma^\mu (1-\gamma_5)\nu_e$$

$$= -\sqrt{2} G_F n_e \bar{\nu}_e \gamma^0 \nu_e$$

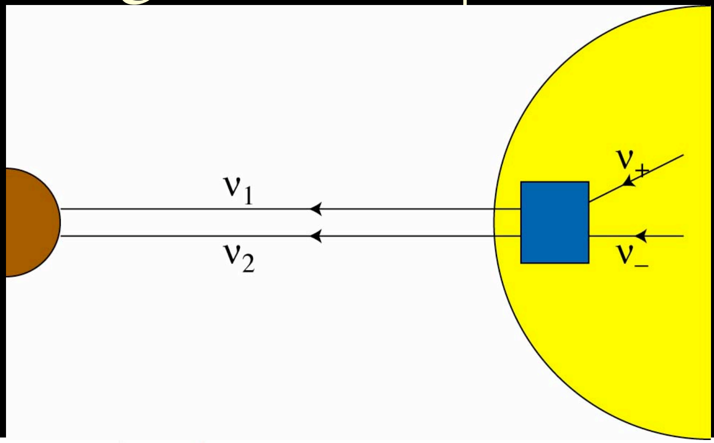
- Neutrino Hamiltonian

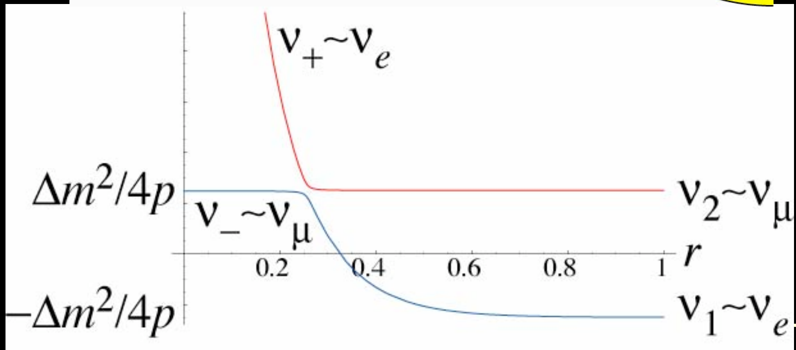
$$H = \text{common} + \frac{\Delta m^2}{4E}\begin{pmatrix} -\cos 2\theta & \sin 2\theta \\ \sin 2\theta & \cos 2\theta \end{pmatrix} + \sqrt{2} G_F n_e \begin{pmatrix} 1 & 0 \\ 0 & 0 \end{pmatrix}$$

Electron neutrino higher energy in the Sun

Adiabatic

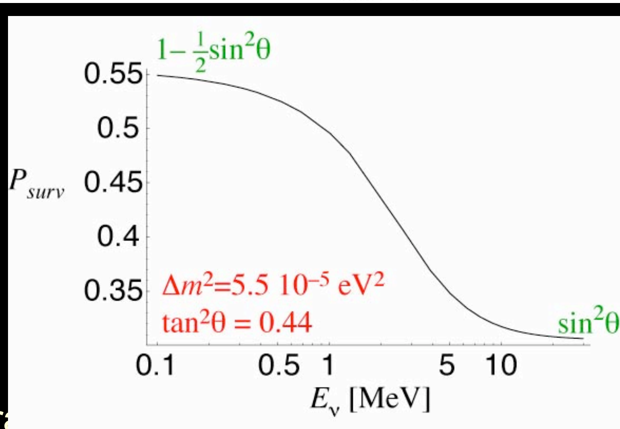
- Use "instantaneous" eigenstates ν_+ and ν_-





- For the LMA region, the dynamics is adiabatic: there is no hopping between states

$$P_{\rm surv} = \cos^2\theta \cos^2\theta_m + \sin^2\theta \sin^2\theta_m$$



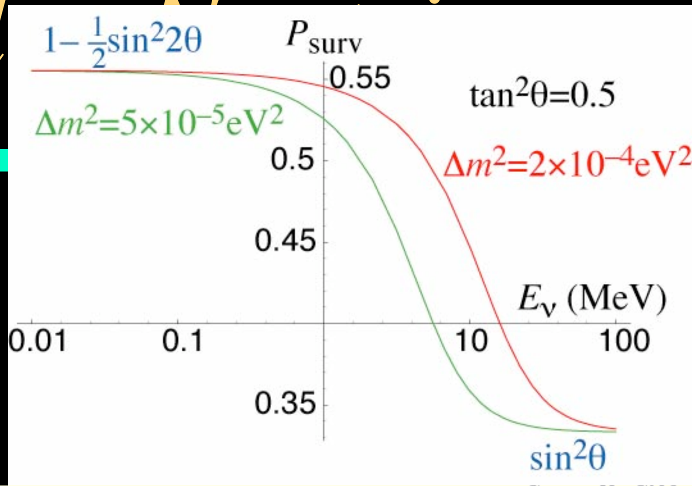
Low-Energy Sol

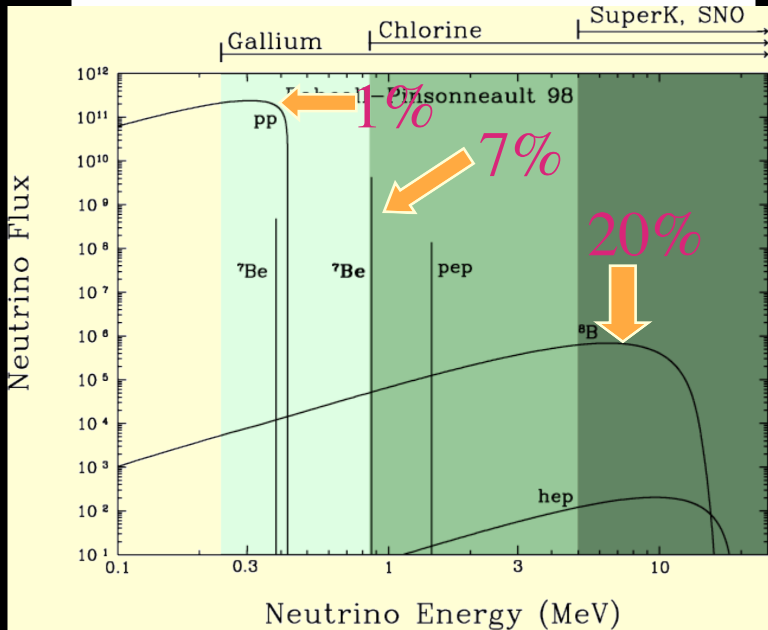
- Solar neutrino data suggest energy-dependent survival probability

  ⇒ tests MSW effect

  ⇒ θ_{12}

  ⇒ Helps interpretation of CP violation, double beta decay data





Three Generations

Three-generation Framework

- Standard parameterization of MNS matrix for 3 generations

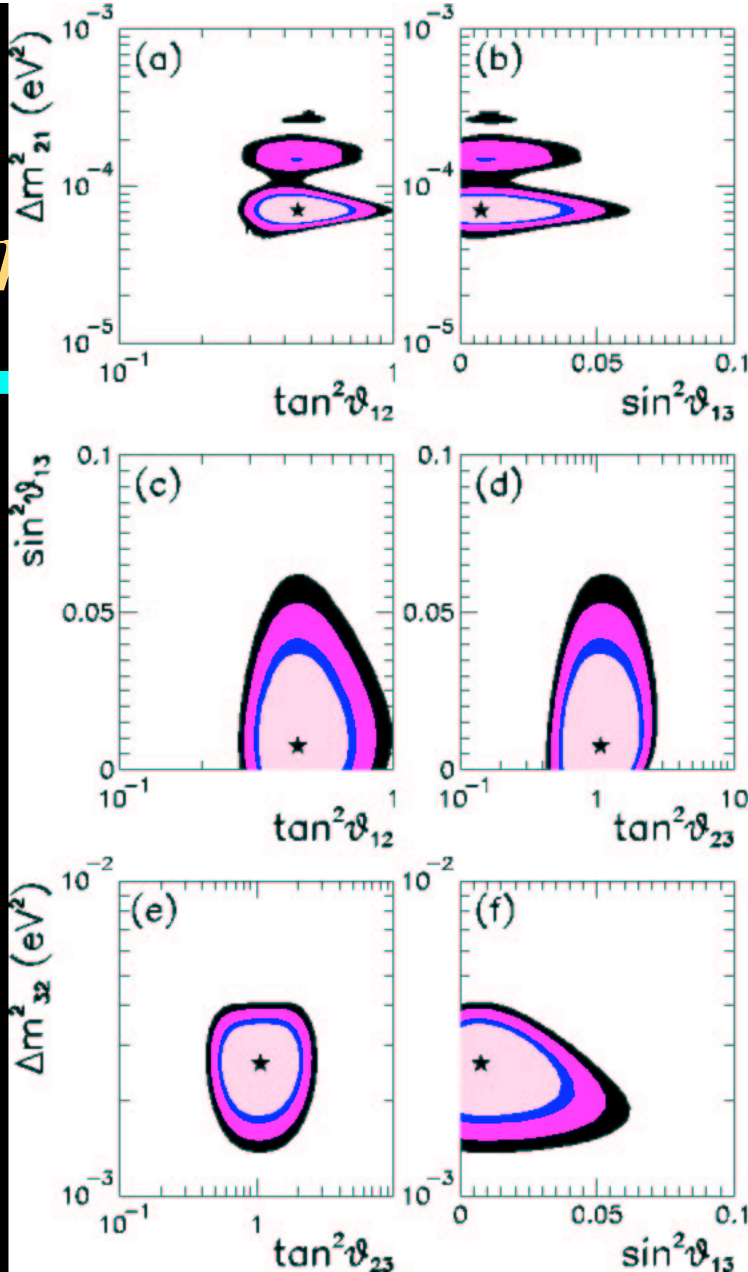
$$U_{MNS} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix}$$

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

solar ??? atmospheric

Three-gener

- Solar, reactor, atmospheric and K2K data easily accommodated within three generations
- $\sin^2 2\theta_{23}$ near maximal
  $\Delta m^2_{atm} \sim 3\times10^{-3}\mathrm{eV}^2$
- $\sin^2 2\theta_{12}$ large
  $\Delta m^2_{solar} \sim 8\times10^{-5}\mathrm{eV}^2$
- $\sin^2 2\theta_{13}=|U_{e3}|^2 < 0.05$ from CHOOZ, Palo Verde
- Because of small $\sin^2 2\theta_{13}$, solar (reactor) & atmospheric ν oscillations almost decouple

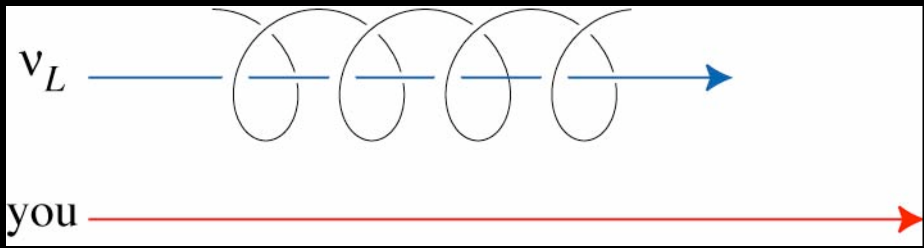


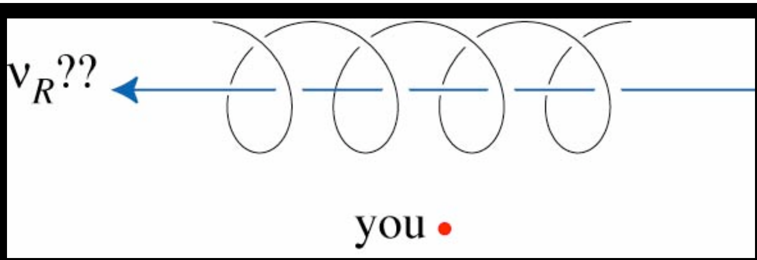
Gonzalez-Garcia, Peña-Garay

χ^2/dof=136/173

Neutrinos have mass

- They have mass. They can't go with speed of light.

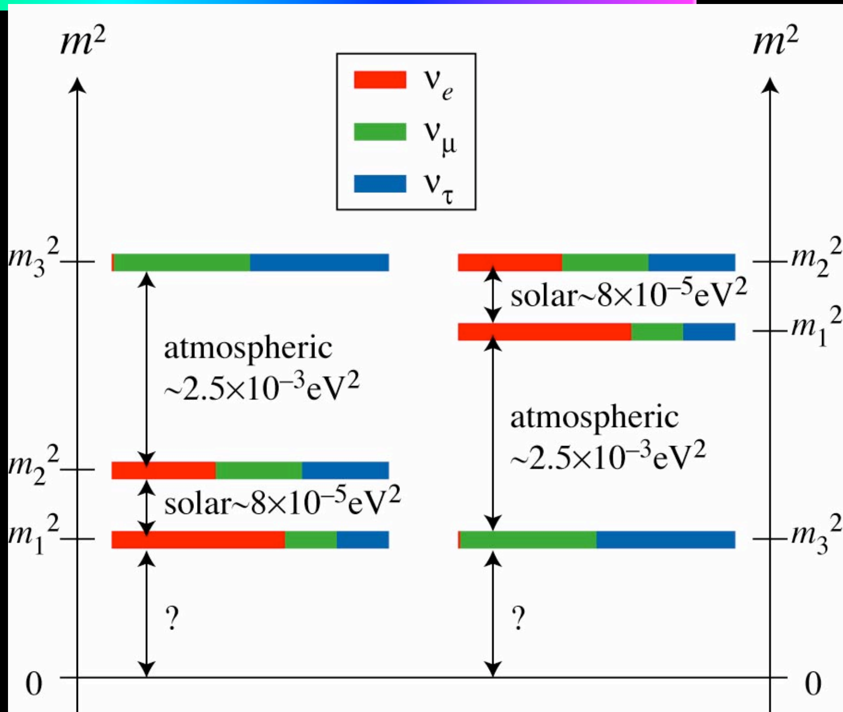




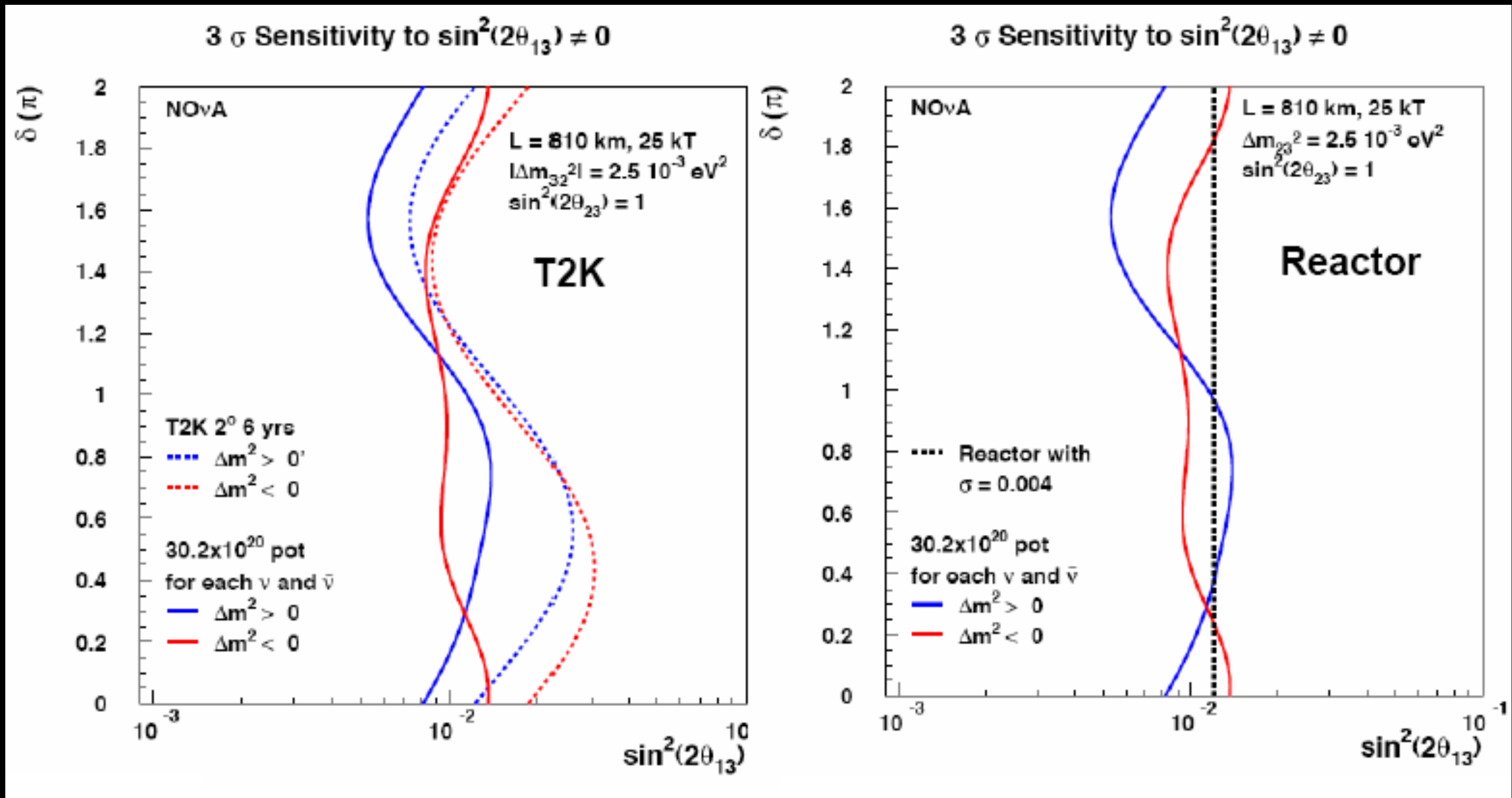
- What is this right-handed particle?
  - New particle: right-handed neutrino (Dirac)
  - Old anti-particle: right-handed anti-neutrino (Majorana)

Seven Questions

- Dirac or Majorana?
- Absolute mass scale?
- How small is θ_{13}?
- Is θ_{23} maximal?
- CP Violation?
- Mass hierarchy?
- LSND vs Mini-BooNE? Sterile neutrino(s)? CPT violation?

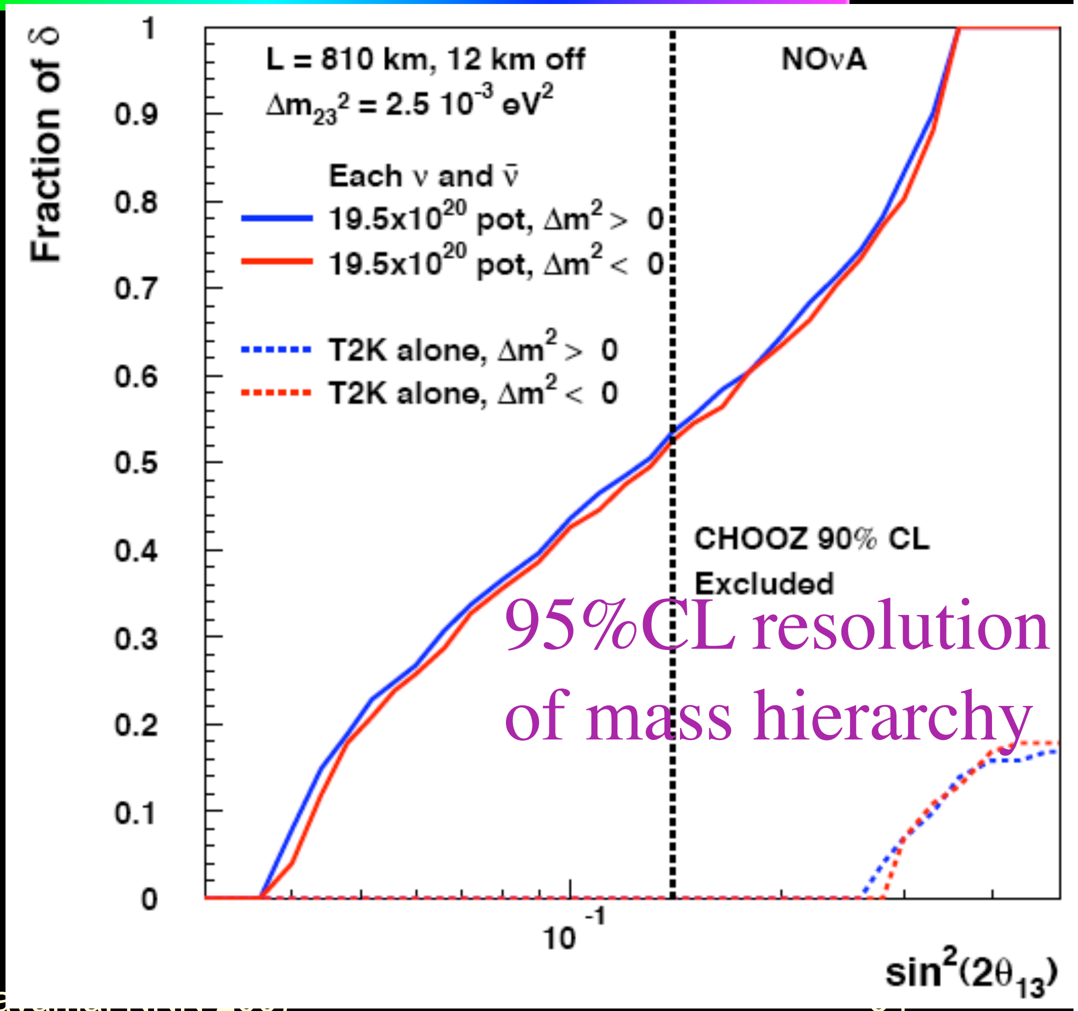


3σ *sensitivity on* $\sin^2 2\theta_{13}$

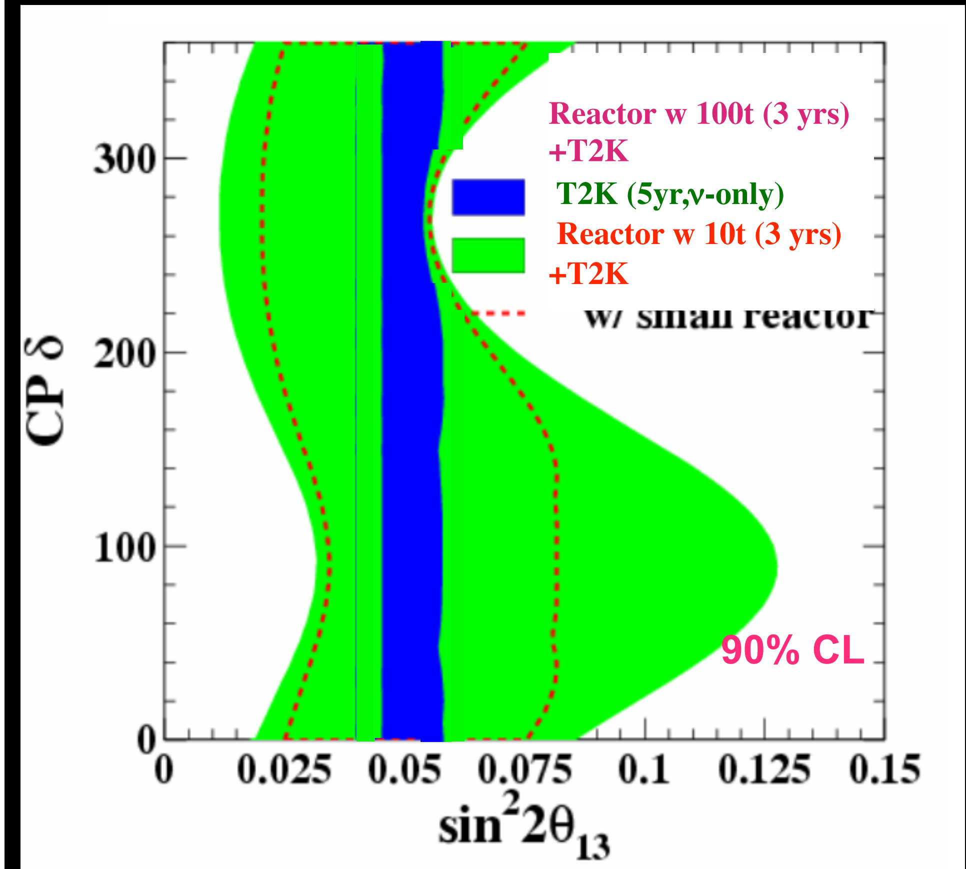


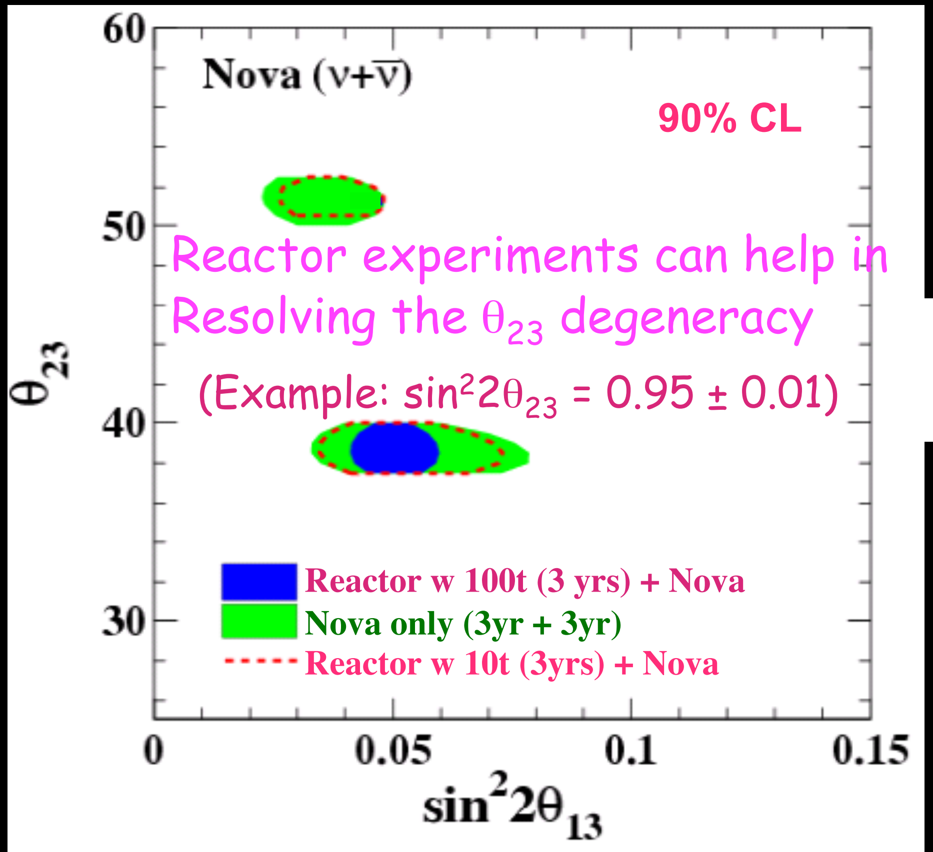
T2K vs NOνA

- LBL $\nu_\mu \rightarrow \nu_e$ appearance
- Combination of
  - $\sin^2 2\theta_{13}$
  - Matter effect
  - CP phase δ



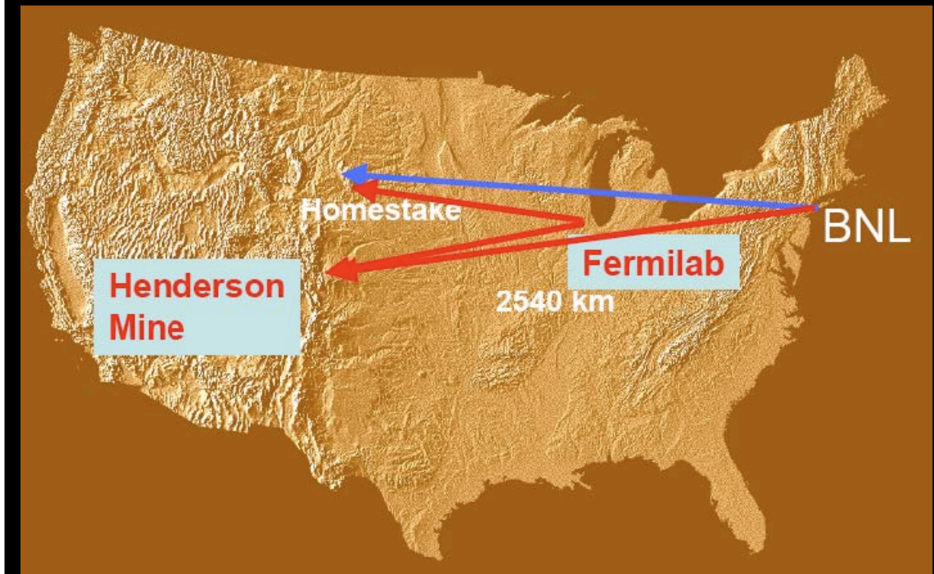
Accelerator vs Reactor

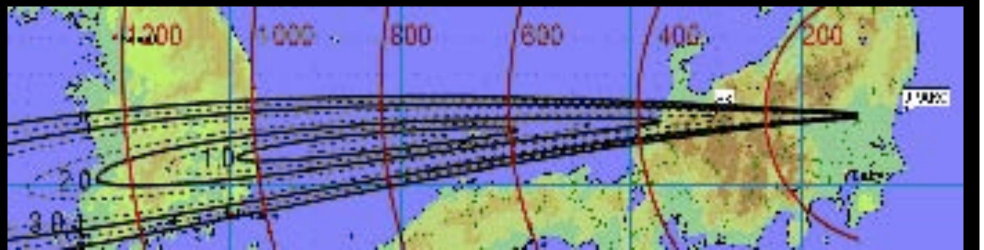




McConnel & Shaevitz, hep-ex/0409028

Very Long Baseline Experiment





(CP violation and mass hierarchy)

Conclusions

- Neutrino mass the first discovery of physics beyond the standard model
- Experiments are quite established now
- Relevant to cosmology, astrophysics
- Many remaining questions
- Do we understand systematics?
- Time for free discussions!