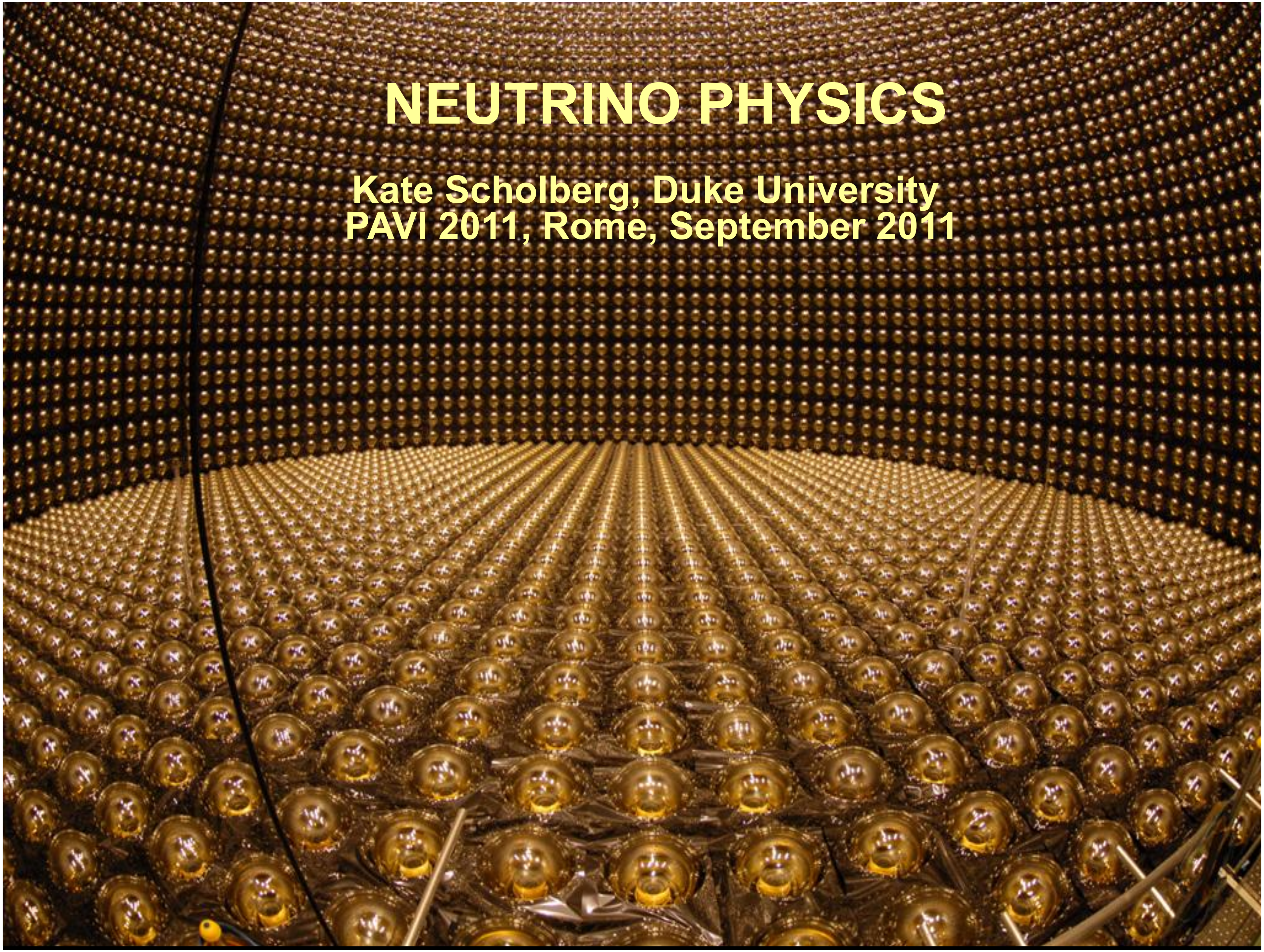
NEUTRINO PHYSICS

Kate Scholberg, Duke University
PAVI 2011, Rome, September 2011



OUTLINE

Neutrino mass and oscillations

Two-flavor oscillation results

- Solar/reactor
- Atmospheric/beam

Three-flavor mixing experiments

- Now: θ_{13}
- Next: CP δ and hierarchy

Three parentheses...

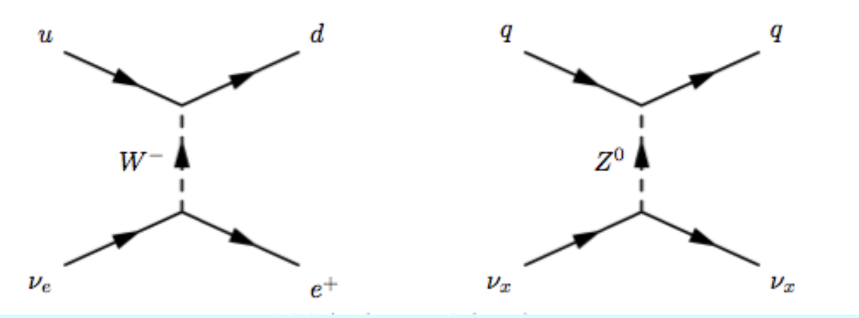
(Absolute mass)

Summary

Standard Three-Flavor Neutrino Picture

$$\begin{pmatrix} e \\ \nu_e \end{pmatrix} \begin{pmatrix} \mu \\ \nu_\mu \end{pmatrix} \begin{pmatrix} \tau \\ \nu_\tau \end{pmatrix}$$

neutral partners
to the charged leptons



Charged and neutral
current interactions

Flavor states related to mass states by a unitary mixing matrix

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

participate in
weak interactions

eigenstates of free
Hamiltonian

$$|\nu_f\rangle = \sum_{i=1}^{N} U^*_{fi} |\nu_i\rangle$$

Parameterize mixing matrix U as

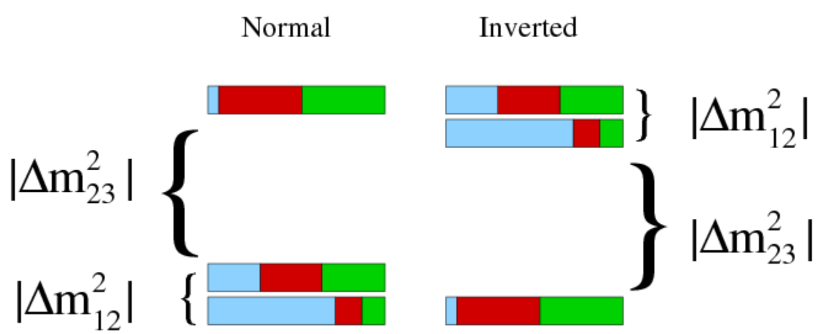
$$U = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{bmatrix} \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

$$\times \begin{bmatrix} e^{i\alpha_1/2} & 0 & 0 \\ 0 & e^{i\alpha_2/2} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

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

3 masses	m_1, m_2, m_3 (2 mass differences + absolute scale)
3 mixing angles	$\theta_{23}, \theta_{12}, \theta_{13}$
1 CP phase	δ
(2 Majorana phases)	α_1, α_2

signs of the mass differences matter



Consequence of this framework:

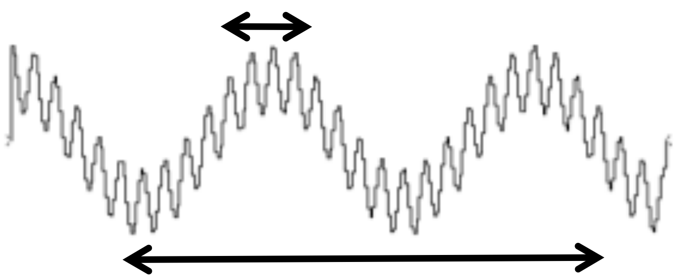
***Flavor transitions* as neutrinos propagate**

$$|\nu_f\rangle = \sum_{i=1}^{N} U^*_{fi}|\nu_i\rangle$$

$$\Delta m^2_{ij} \equiv m^2_i - m^2_j \qquad \text{(L in km, E in GeV, m in eV)}$$

$$P(\nu_f \rightarrow \nu_g) = \delta_{fg} - 4\sum_{j>i} \mathrm{Re}(U^*_{fi}U_{gi}U_{fj}U^*_{gj}) \sin^2(1.27\Delta m^2_{ij} L/E_\nu)$$
$$\pm 2\sum_{j>i} \mathrm{Im}(U^*_{fi}U_{gi}U_{fj}U^*_{gj}) \sin^2(2.54\Delta m^2_{ij} L/E_\nu)$$

oscillatory behavior in L and E



$$|\Delta m^2_{23}| >> |\Delta m^2_{12}|$$ ➔ **two frequency scales**

For appropriate L/E (and U_{ij}), oscillations "decouple", and flavor change probability can be described by:

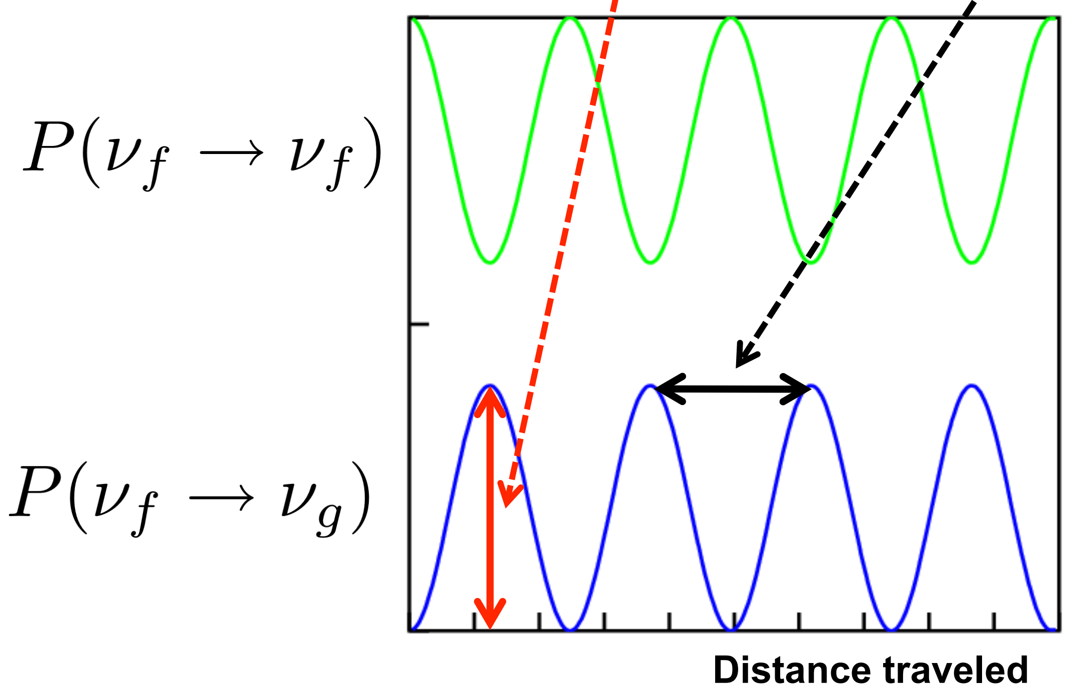
$$P(\nu_f \rightarrow \nu_g) = \sin^2 2\theta \sin^2\left(\frac{1.27\Delta m^2 L}{E}\right)$$

In 2-flavor approximation:

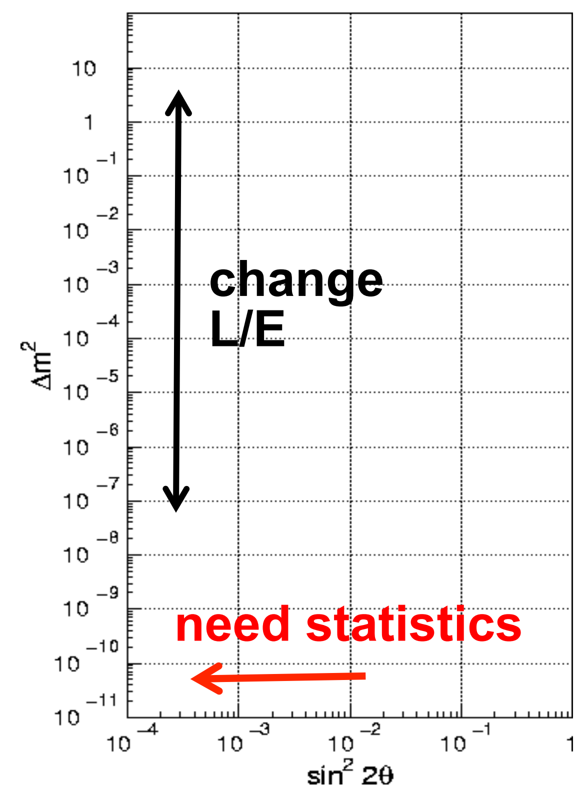
$$P(\nu_f \to \nu_g) = \sin^2 2\theta \sin^2\left(\frac{1.27\Delta m^2 L}{E}\right)$$

amplitude

wavelength= $\pi E/(1.27\Delta m^2)$



Parameter space



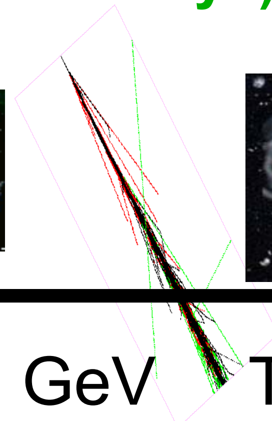
Measure disappearance of an expected flavor, or appearance of a new one

e.g. $\nu_e \to \nu_\mu$ at ~MeV

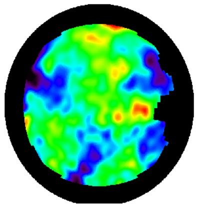
e.g. $\nu_\mu \to \nu_\tau$ at ~GeV

Sources of wild neutrinos

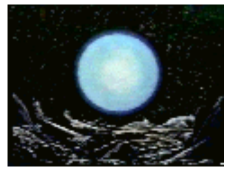
The Atmosphere
(cosmic rays)

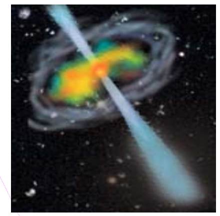


The Big Bang



Super
novae

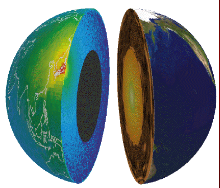


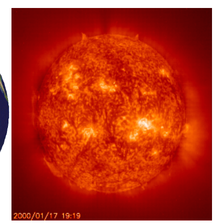


AGN's, GRB's

meV eV keV MeV GeV TeV PeV EeV

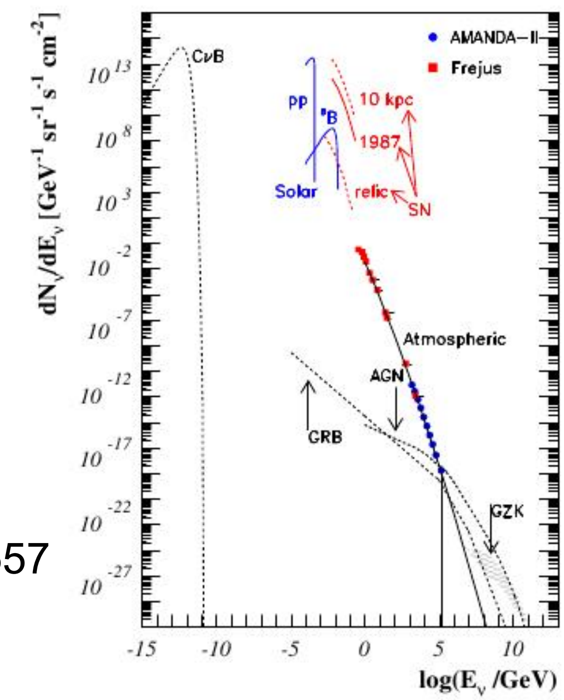
Radioactive
decay in the
Earth





The Sun

J. Becker,
arXiv:0710.1557

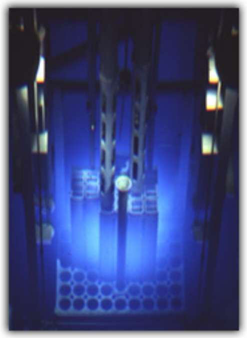


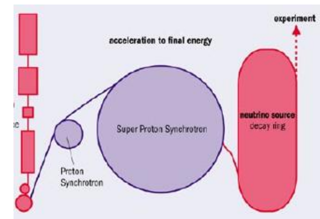
Sources of 'tame' neutrinos

Proton accelerators

Beta beams

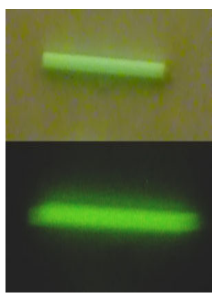
Nuclear reactors

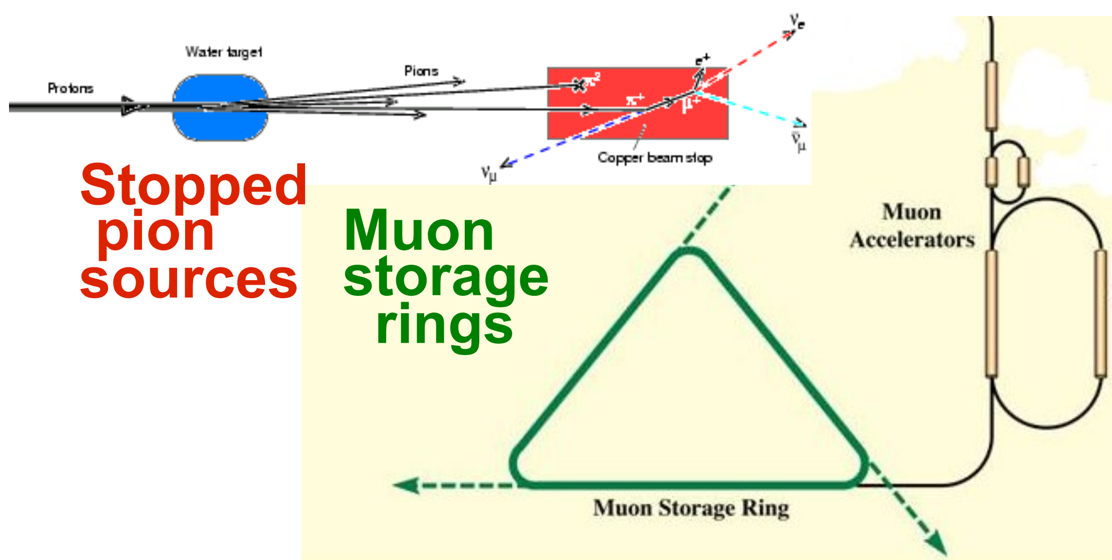




eV keV MeV GeV TeV

Artificial radioactive sources





Stopped pion sources

Muon storage rings

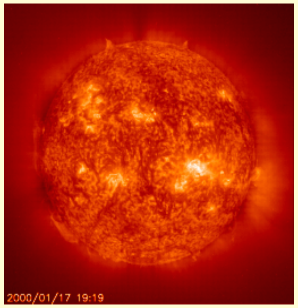
Usually (but not always) better understood...

We now have strong evidence for flavor oscillations:

In each case, first measurement with 'wild' ν's was confirmed and improved with 'tame' ones

$$P(\nu_f \to \nu_g) = \sin^2 2\theta \sin^2 \left(\frac{1.27 \Delta m^2 L}{E} \right)$$

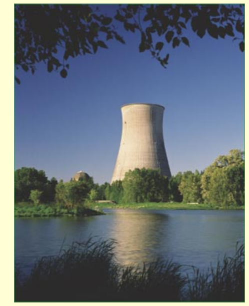
SOLAR NEUTRINOS



Electron neutrinos from the Sun are *disappearing*...

$$\nu_e \longrightarrow \nu_\mu, \nu_\tau$$

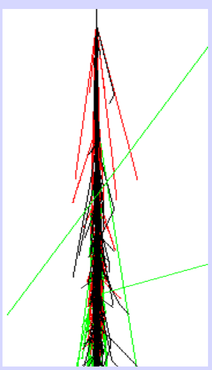
$$\bar{\nu}_e \longrightarrow \nu_x$$



... now confirmed by a reactor experiment

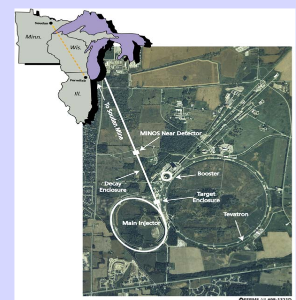
Described by θ_{12}, Δm^2_{12}

ATMOSPHERIC NEUTRINOS



Muon neutrinos created in cosmic ray showers are *disappearing* on their way through the Earth

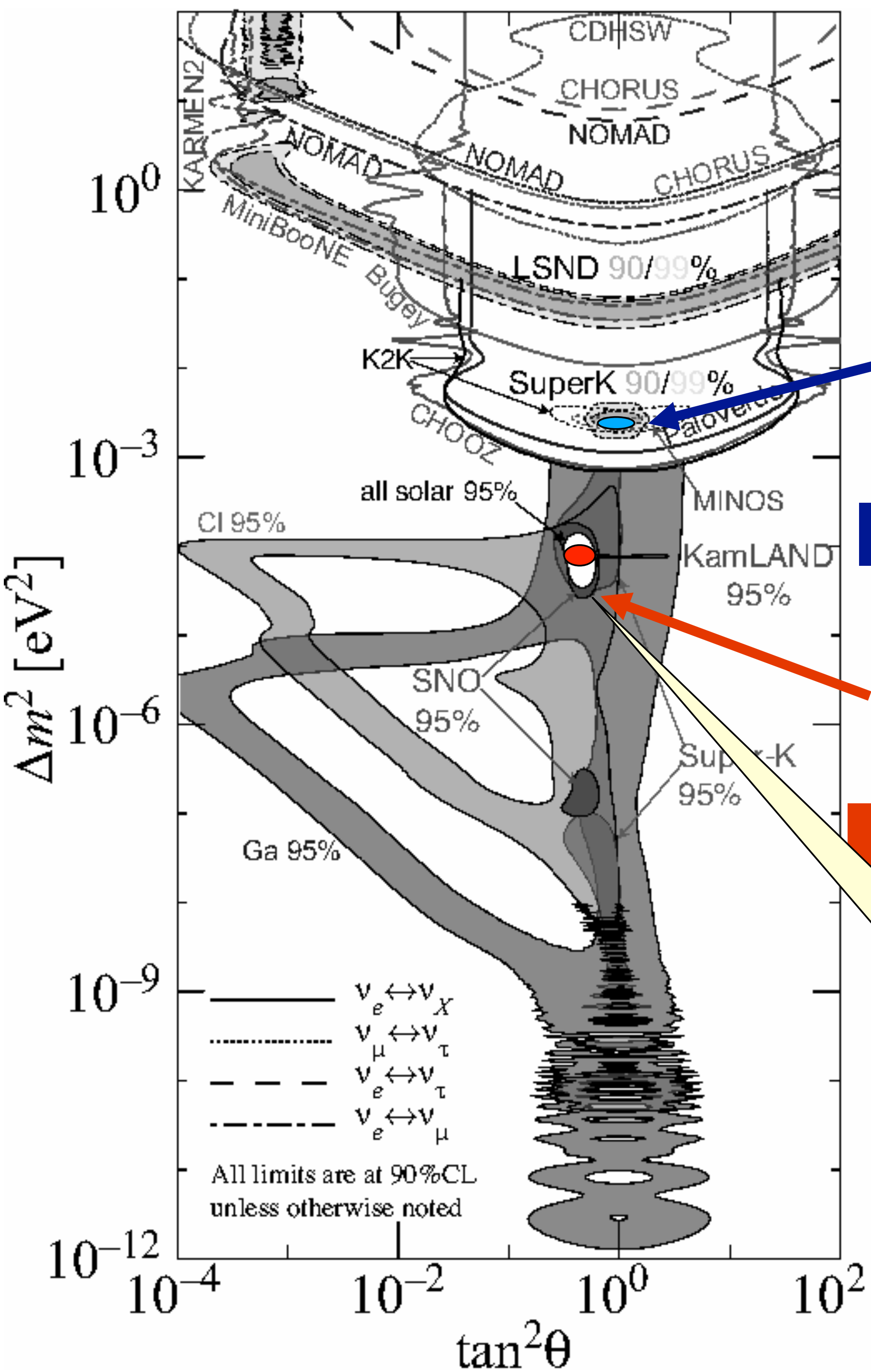
$$\nu_\mu \longrightarrow \nu_\tau$$



...now confirmed by beam experiments

Described by θ_{23}, Δm^2_{23}

In fifteen years parameters have been shrunk down many orders of magnitude!



$$P(\nu_f \to \nu_g) = \sin^2 2\theta \sin^2\left(\frac{1.27\Delta m^2 L}{E}\right)$$

atmospheric/ beam neutrinos

Described by θ_{23}, Δm^2_{23}

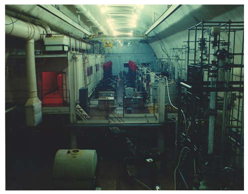
solar/reactor neutrinos

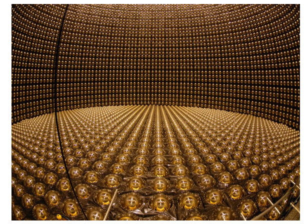
Described by θ_{12}, Δm^2_{12}

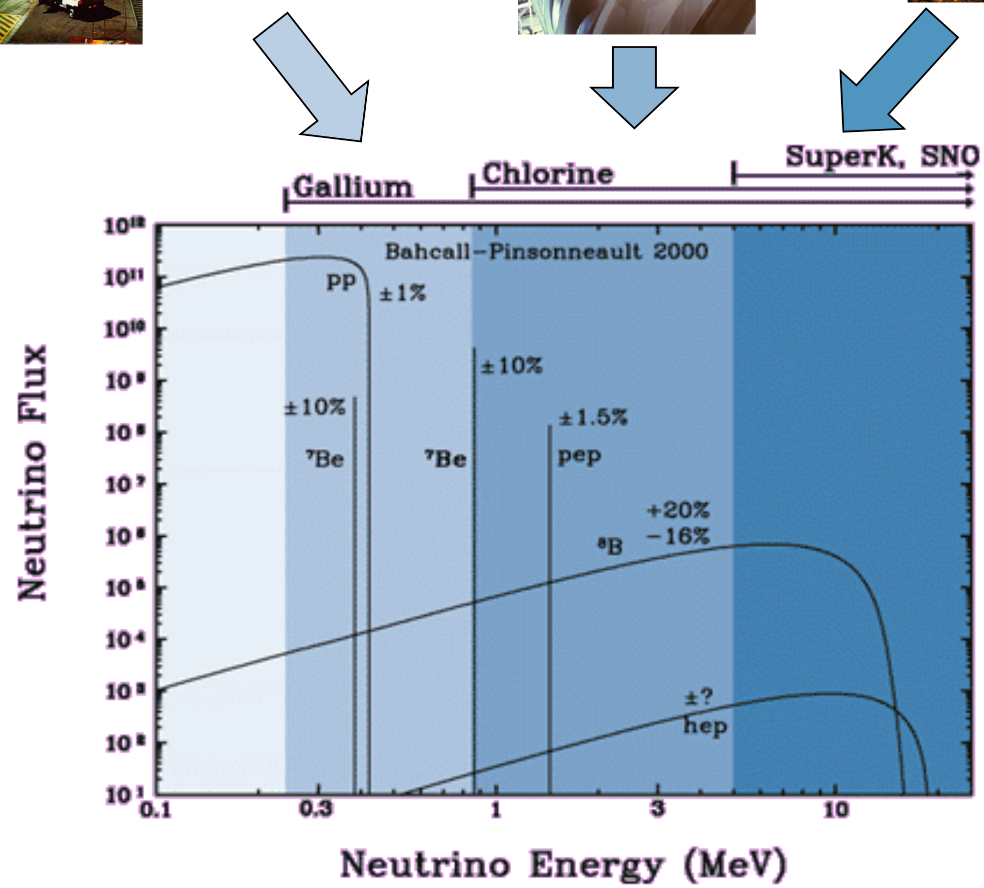
First zoom in here

Solar Neutrinos: the Classic Puzzle

Electron flavor neutrinos generated in solar fusion; spectrum is well understood from weak physics



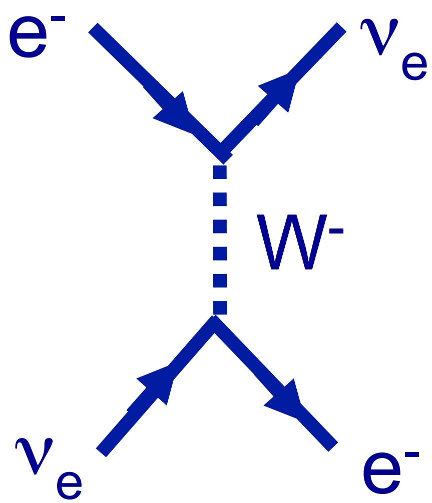




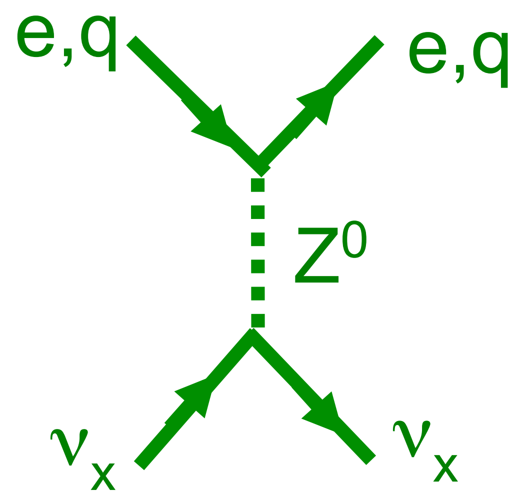
Energy-dependent **suppression points to neutrino oscillation**

The Mikheyev-Smirnov-Wolfenstein (MSW) Effect
a.k.a. "Matter Effects"

The Sun tastes like electrons to solar ν_e



vs.



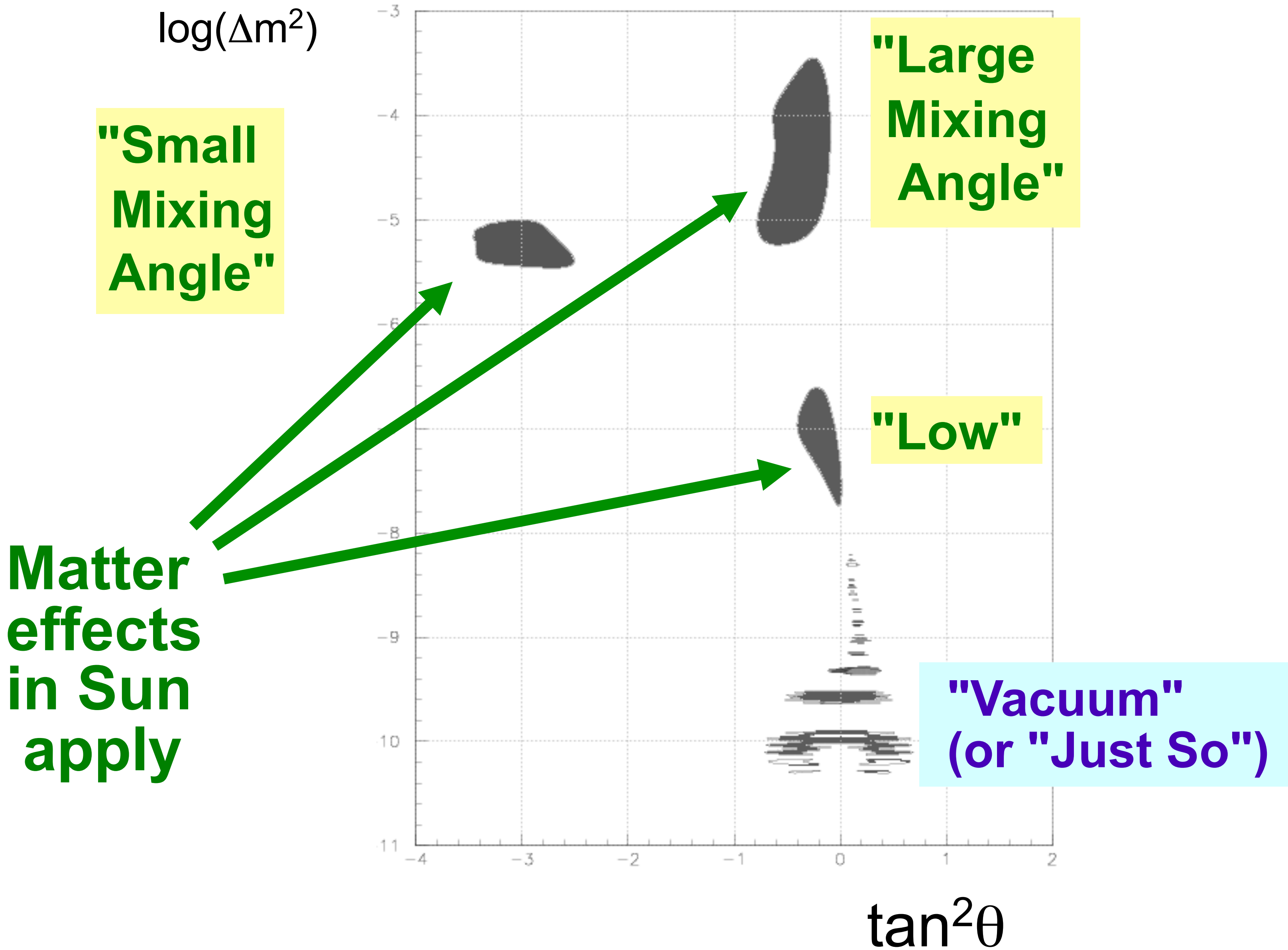
extra energy $\sqrt{2}\, G_F N_e$ for ν_e vs. **NC only for $\nu_{\mu,\tau}$**

Extra forward scattering amplitude modifies the oscillation probability, which depends on:

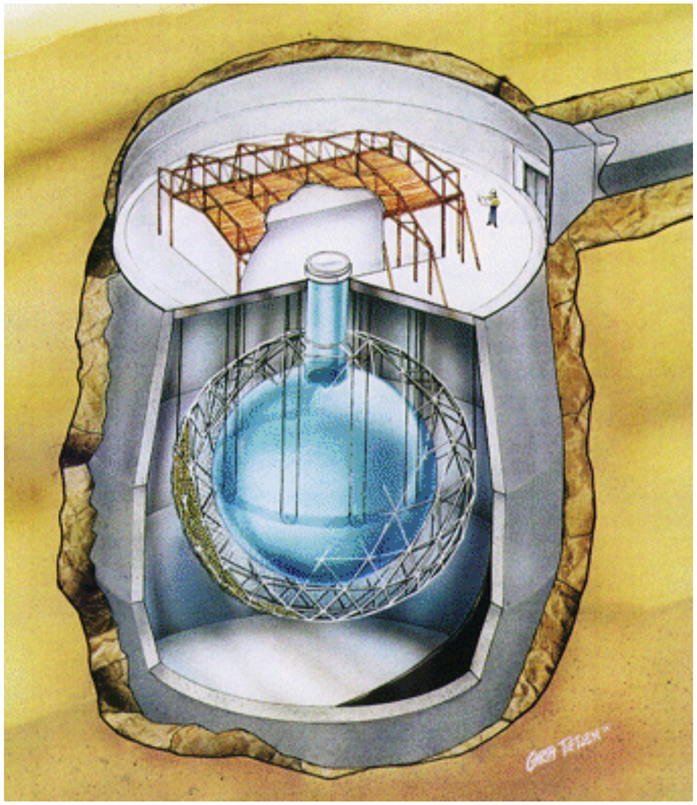
vacuum oscillation parameters
matter density profile

} **important in solar matter**

"Classic" allowed parameters for solar neutrino oscillations (Ga+Cl+ water)



The Sudbury Neutrino Observatory



Sudbury, Canada

1.7 kton D_2O

$\nu_e + d \rightarrow p + p + e^-$ **CC**

specifically tags ν_e

$\nu_x + d \rightarrow \nu_x + p + n$ **NC**

total active flux

1 kton H_2O

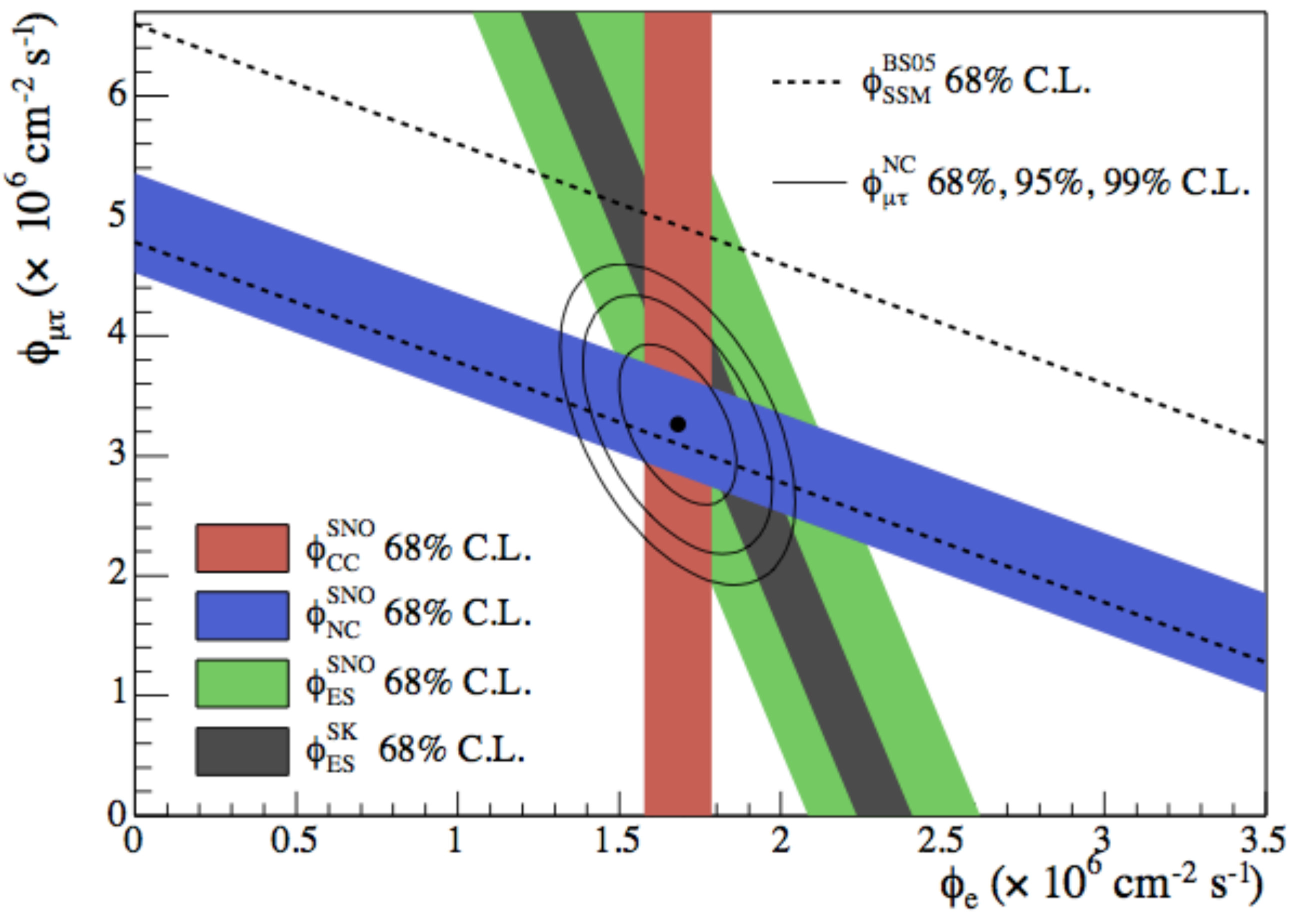
$\nu_{e,x} + e^- \rightarrow \nu_{e,x} + e^-$ Elastic scattering (CC, NC)

mixture of ν_e and all with *known ratio*

Cherenkov light from e^-

Neutron detection

Clear evidence from SNO for oscillation to $\nu_{\mu,\tau}$



$\phi_{CC}=\phi(\nu_e)$

$\phi_{NC}=\phi(\nu_e)+\phi(\nu_{\mu,\tau})$ ~ total flux

$\phi_{ES}=\phi(\nu_e)+0.15\phi(\nu_{\mu,\tau})$

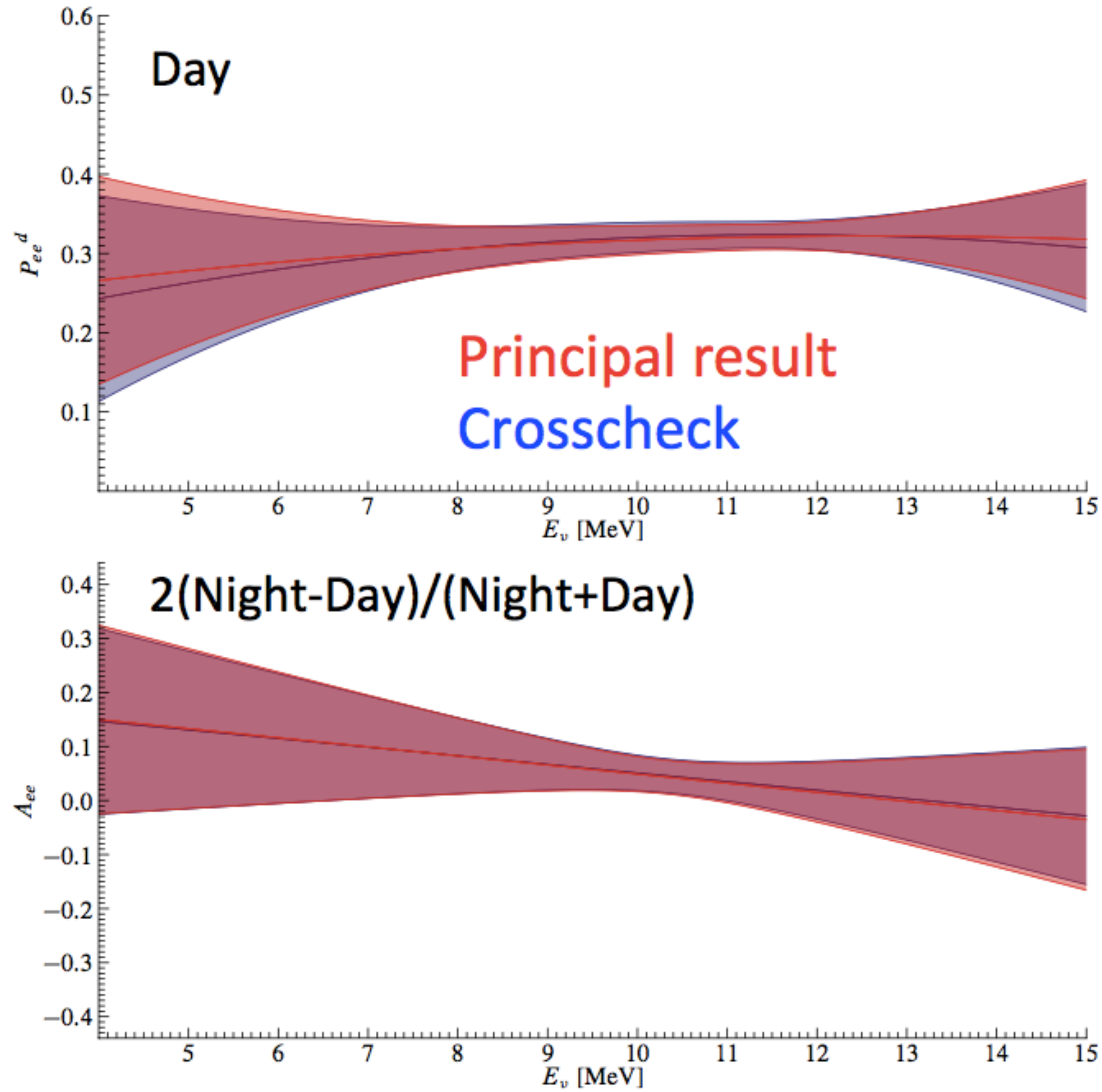
SNO Final Analysis Results

NEW

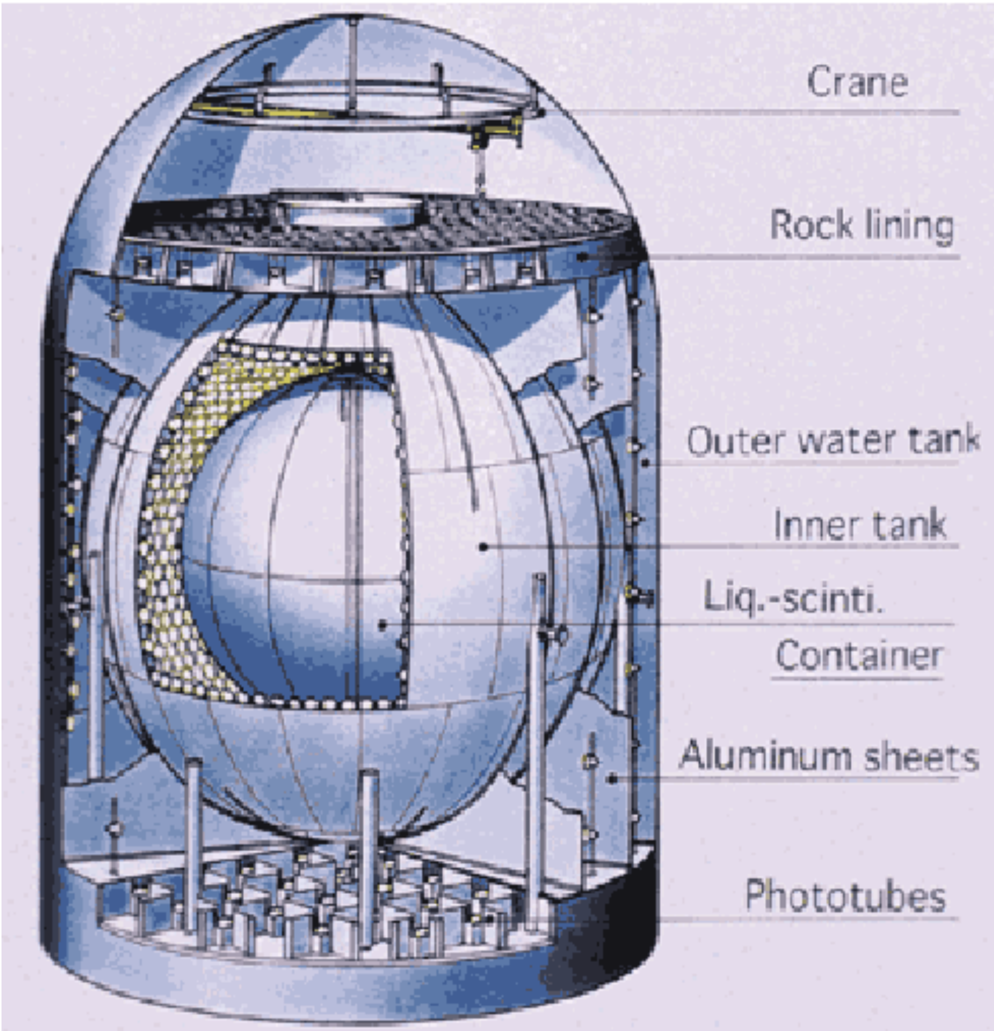
just shown at TAUP11
by N. Tolich,
arXiv:1109.0763

Energy spectrum & day/night effect (matter in Earth) from SNO & SK constrain oscillation parameters

Electron neutrino survival probability vs ν energy



The KamLAND Experiment



Mozumi, Japan

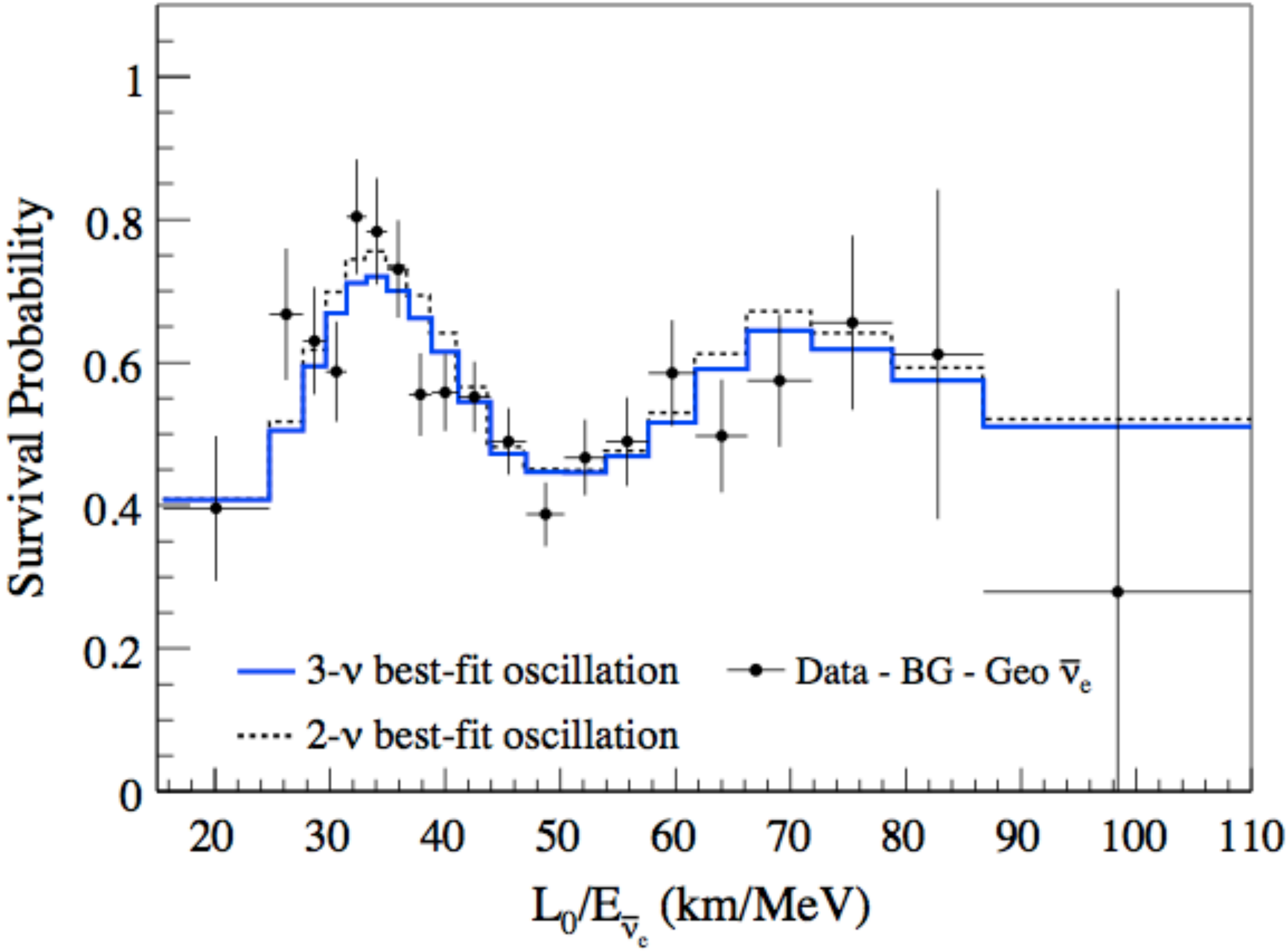
Look at LMA parameter space using *reactor antineutrinos*

Sum of reactor fluxes from Japan, Korea

E_{ν}~few MeV, L~180 km (no matter effects)

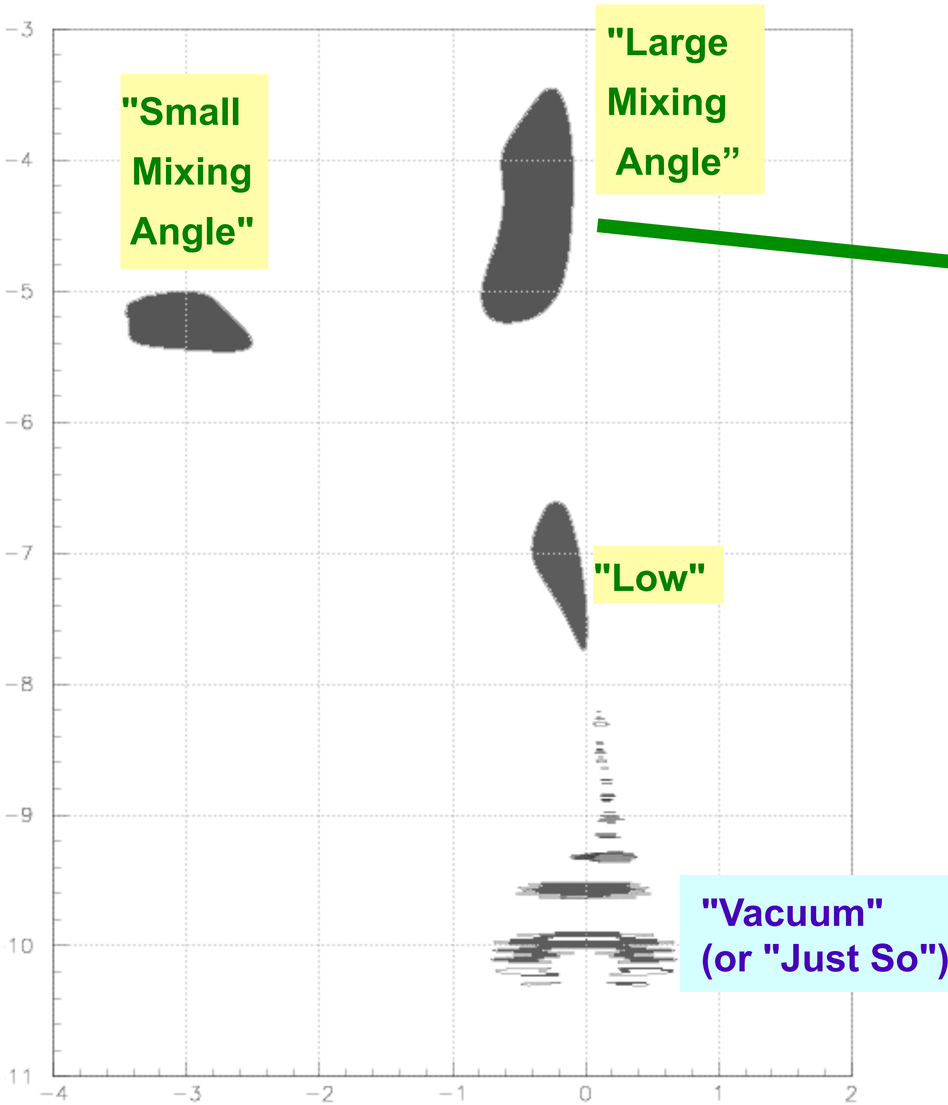
KamLAND oscillation pattern from measured antineutrino spectrum

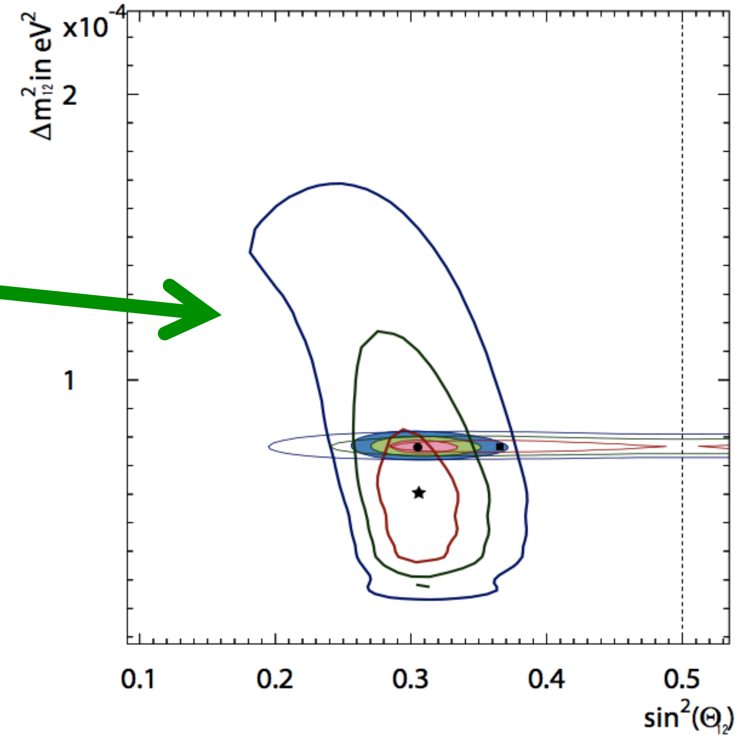
$$P(\nu_f \to \nu_g) = \sin^2 2\theta \sin^2 \left(\frac{1.27 \Delta m^2 L}{E} \right)$$



Average flux-weighted baseline L_0 =180 km

Overall fit to the solar+KamLAND data



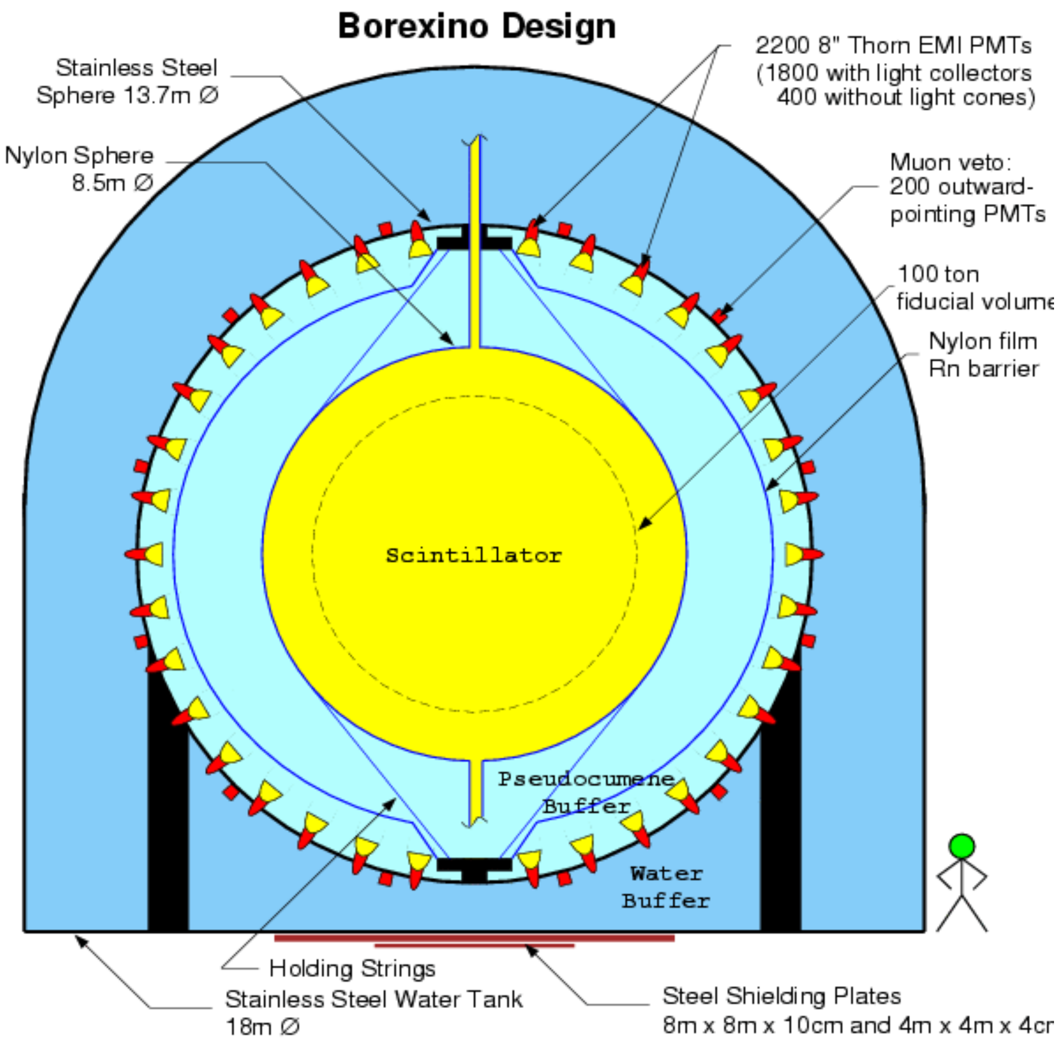


KamLAND narrows the Δm^2 range, in the LMA region

Global fit shows that mixing is *not* maximal

The Borexino Experiment

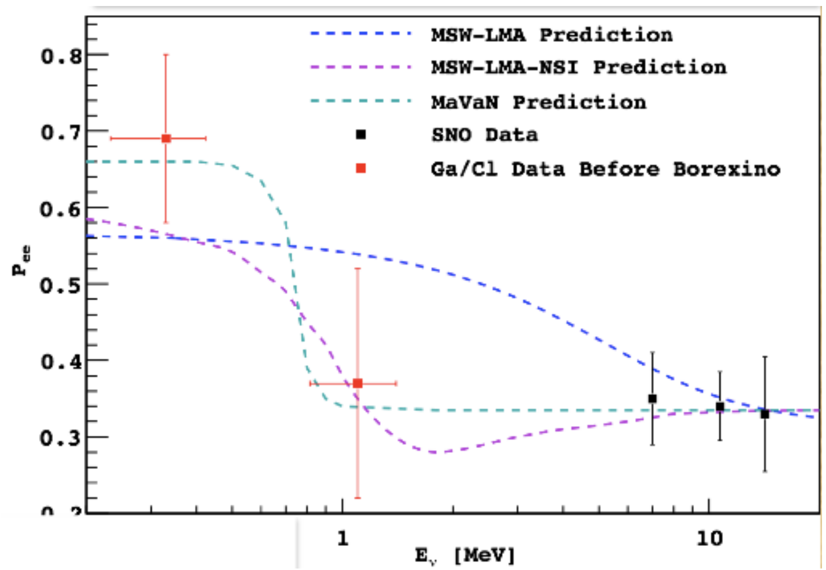
Gran Sasso, Italy

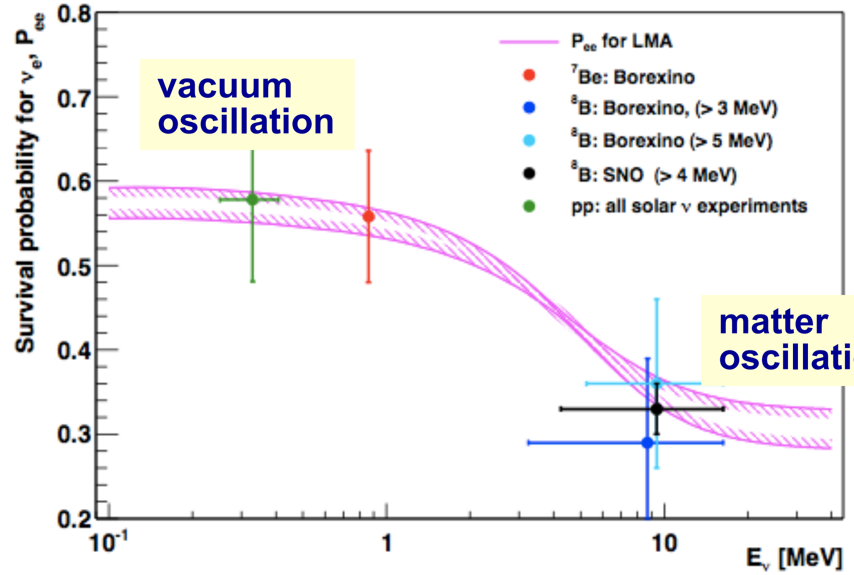


$$\nu_{e,x} + e^- \rightarrow \nu_{e,x} + e^-$$

- **Scintillator (300 ton)**
- **Very low threshold (<MeV)**
- **Very low radioactivity**
- **Real time**

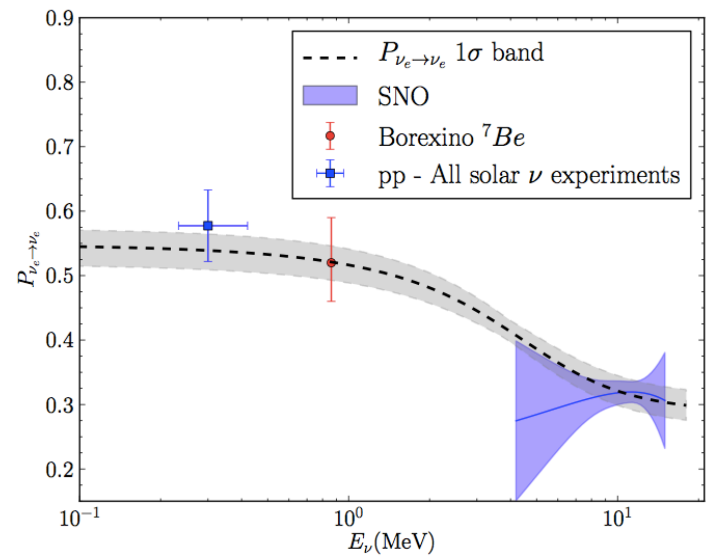
Borexino solar neutrino data at low energy can constrain exotic models





NEW

Before: exotic oscillation scenarios allowed

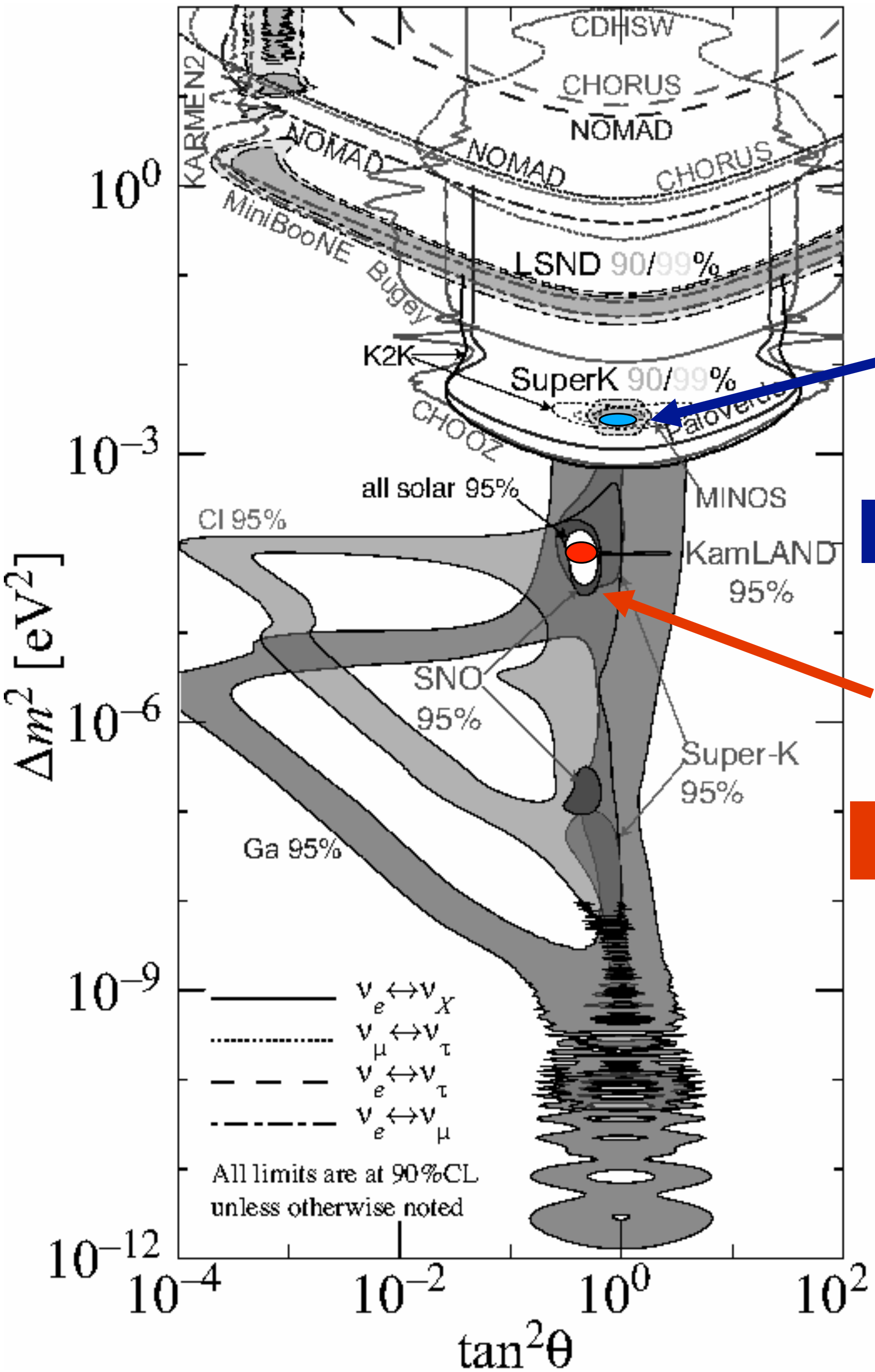


NEW

NEW

w/ latest SNO results

After: consistent with standard solar model and standard matter oscillation scenario



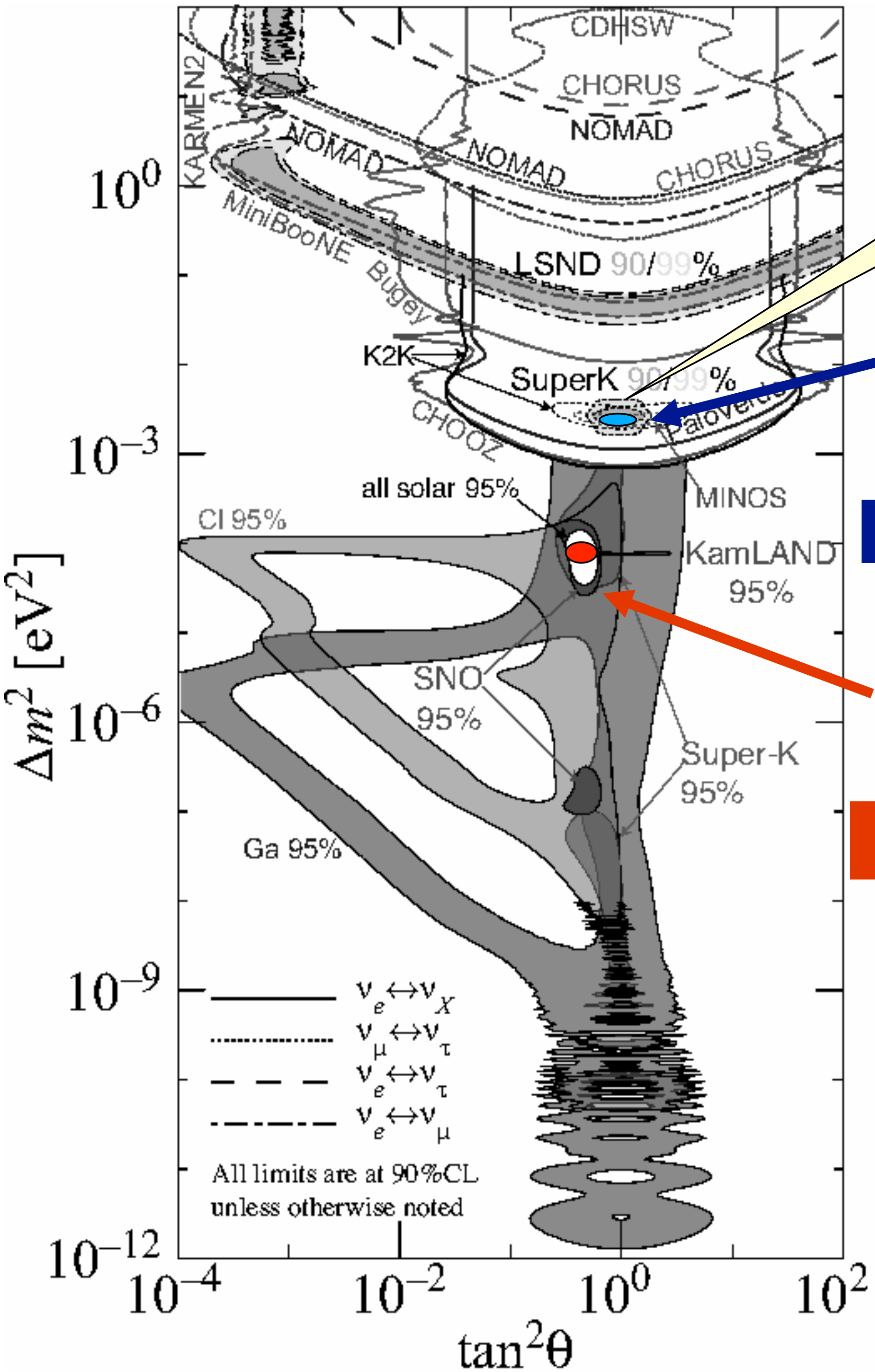
atmospheric/ beam neutrinos

Described by θ_{23}, Δm^2_{23}

solar/reactor neutrinos

Described by θ_{12}, Δm^2_{12}

Now in precision measurement era



Now zoom in here

atmospheric/ beam neutrinos

Described by θ_{23}, Δm^2_{23}

solar/reactor neutrinos

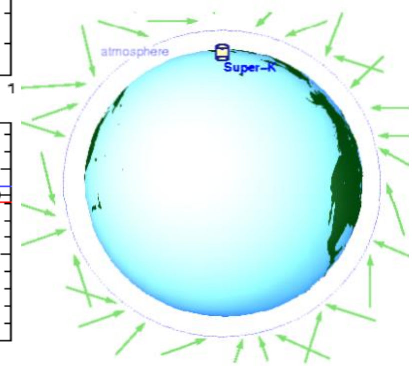
Described by θ_{12}, Δm^2_{12}

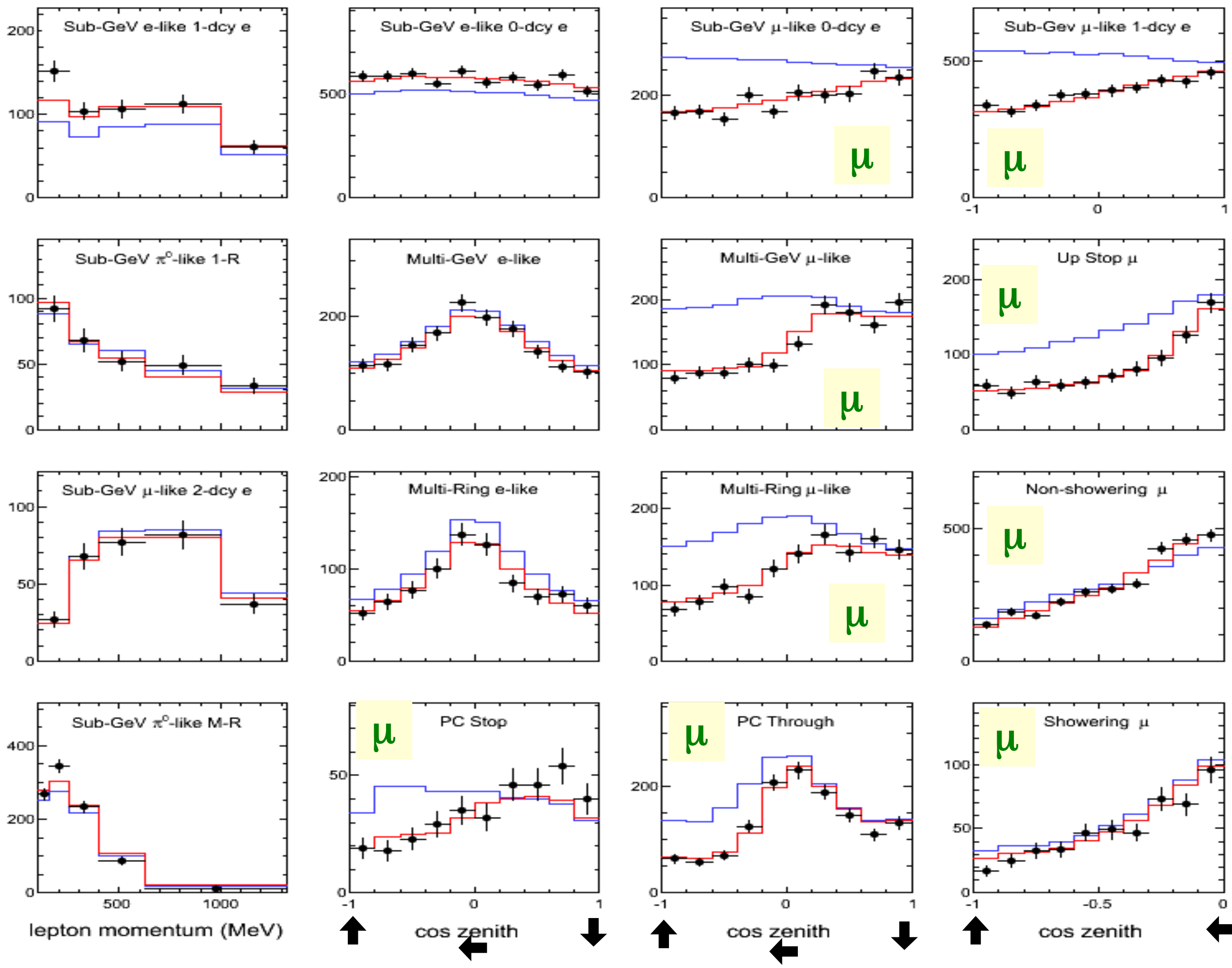
Atmospheric neutrinos: zenith angle & lepton momentum distributions

ν_μ–ν_τ oscillation (best fit)
null oscillation

SK-I+II+III

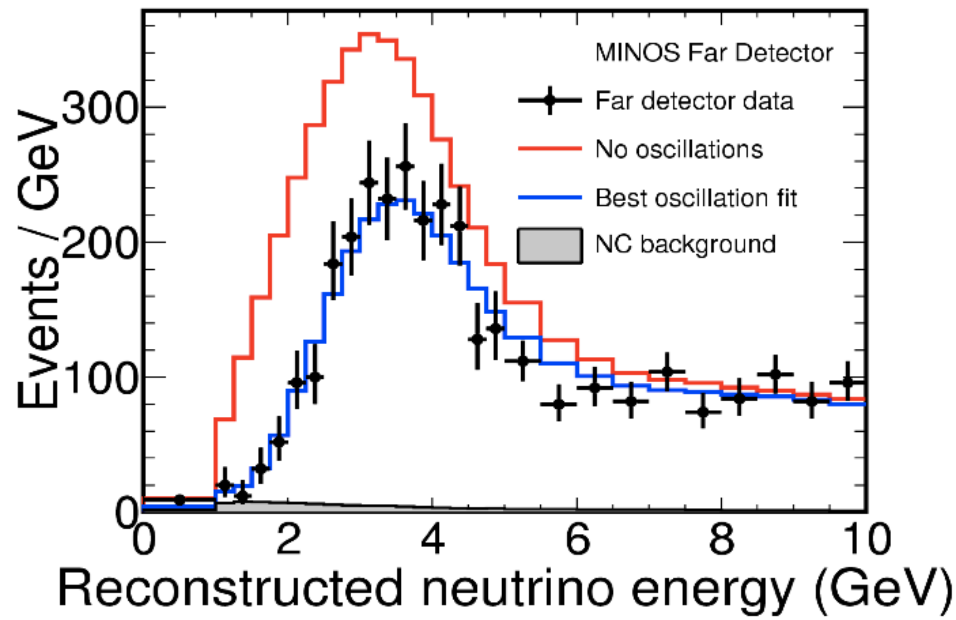
Preliminary

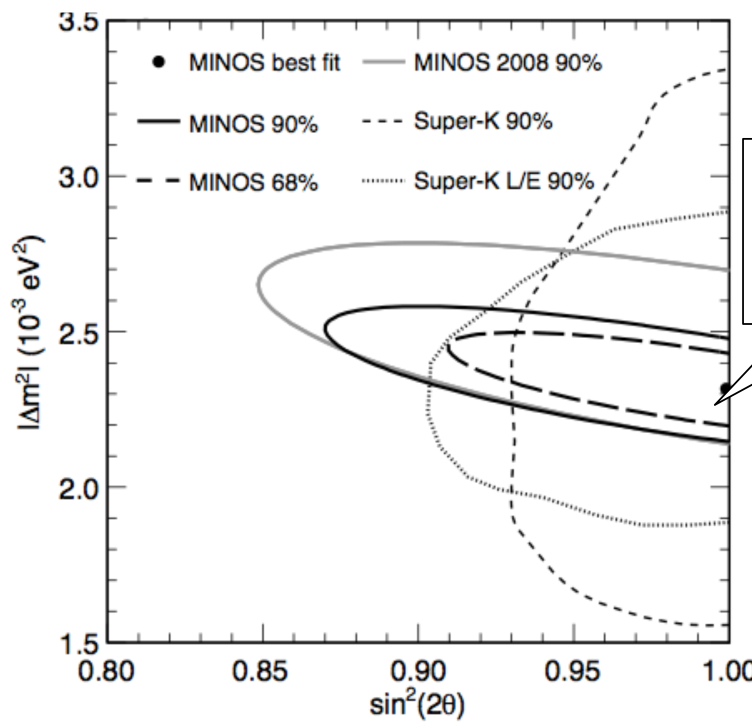




Huge deficit of ν_μ from below, consistent with oscillation... confirmed by K2K beam

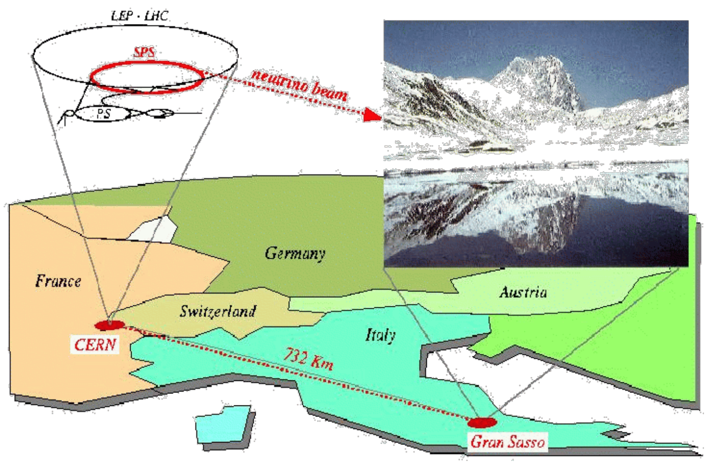
MINOS
in US making precision measurements of ν_μ disappearance





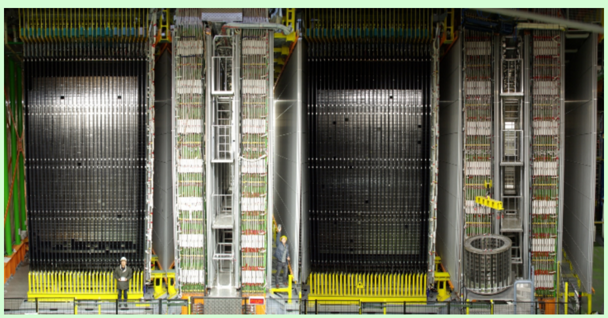
Squeezing down Δm^2_{23} !

CERN Neutrinos to Gran Sasso

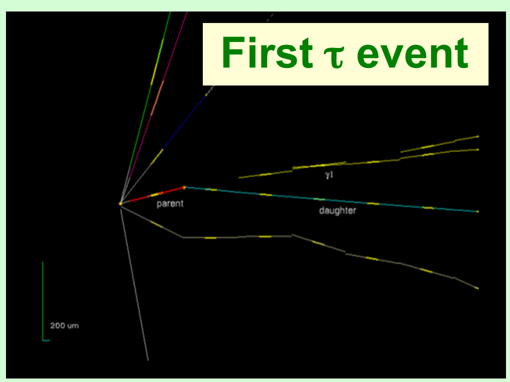


higher energy beam
(~17 GeV,
above τ threshold),
fine-grained
tracking detectors

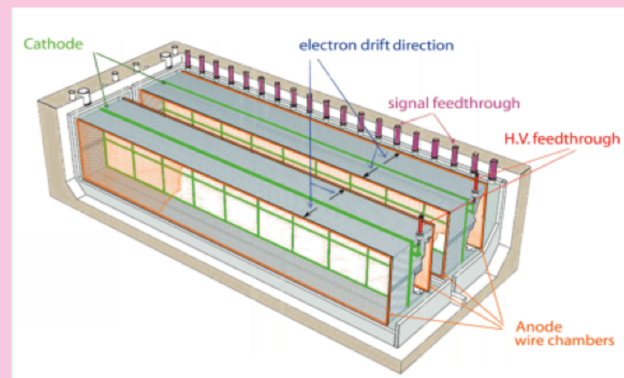
OPERA

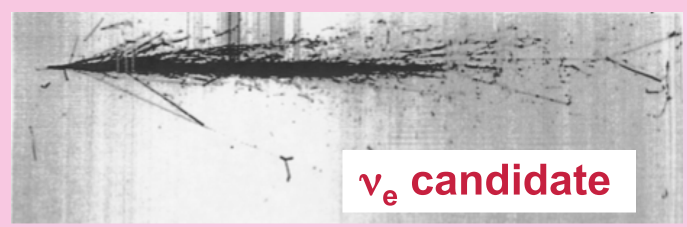


lead/emulsion sandwich + active scintillator strip planes + magnetic spectrometer

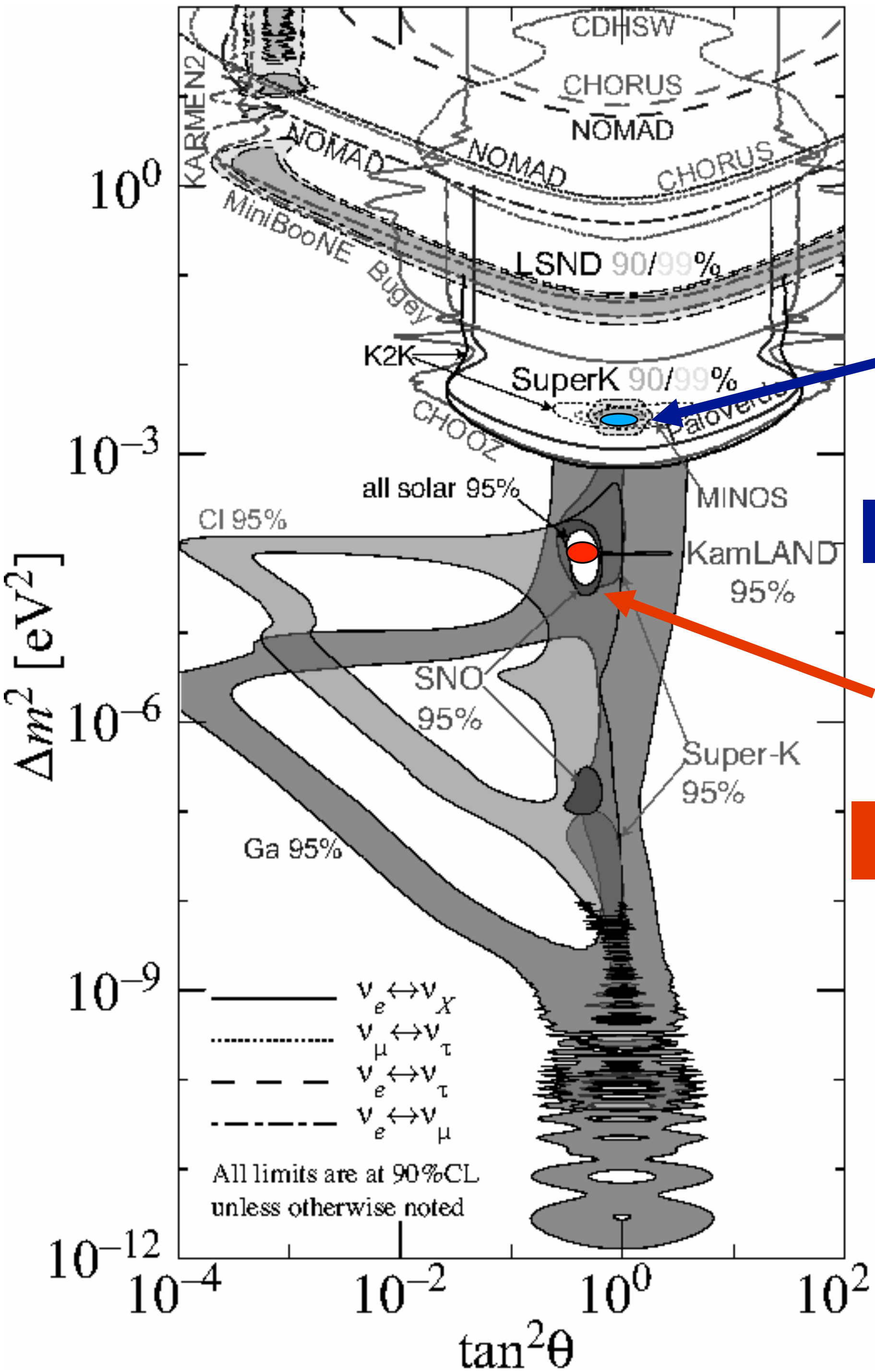


ICARUS





600 ton liquid argon TPC



Again, precision era... dotting i's & crossing t's

atmospheric/ beam neutrinos

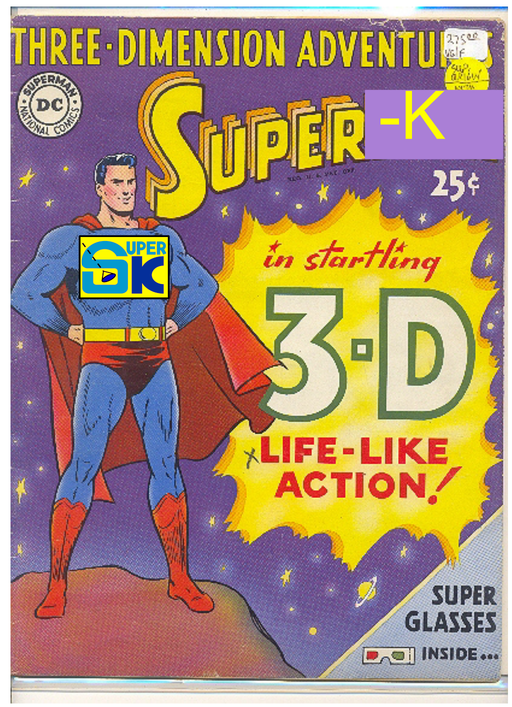
Described by θ_{23}, Δm^2_{23}

solar/reactor neutrinos

Described by θ_{12}, Δm^2_{12}

But there's more than just squeezing down 2-flavor parameters ...

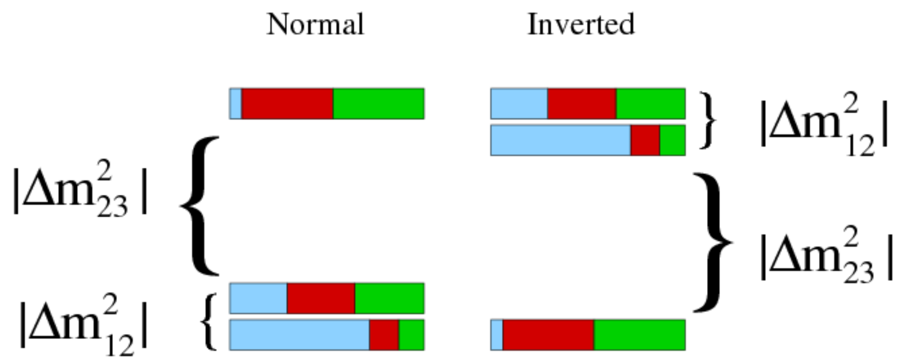
<u>Beyond 2-flavor</u>: explore neutrino mixing in a *3-flavor* context



Remaining unknowns in the 3-flavor picture

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

atmospheric ? solar



Masses

$$m_1,\ m_2,\ m_3 \leftrightarrow \Delta m^2_{12}, |\Delta m^2_{23}|, sign(\Delta m^2_{23}), m_i$$

✔ ✔ ? ?

Angles

(plus Majorana phases)

$$\theta_{12},\quad \theta_{23},\quad \theta_{13},\quad \delta$$

✔ ✔ close! ?

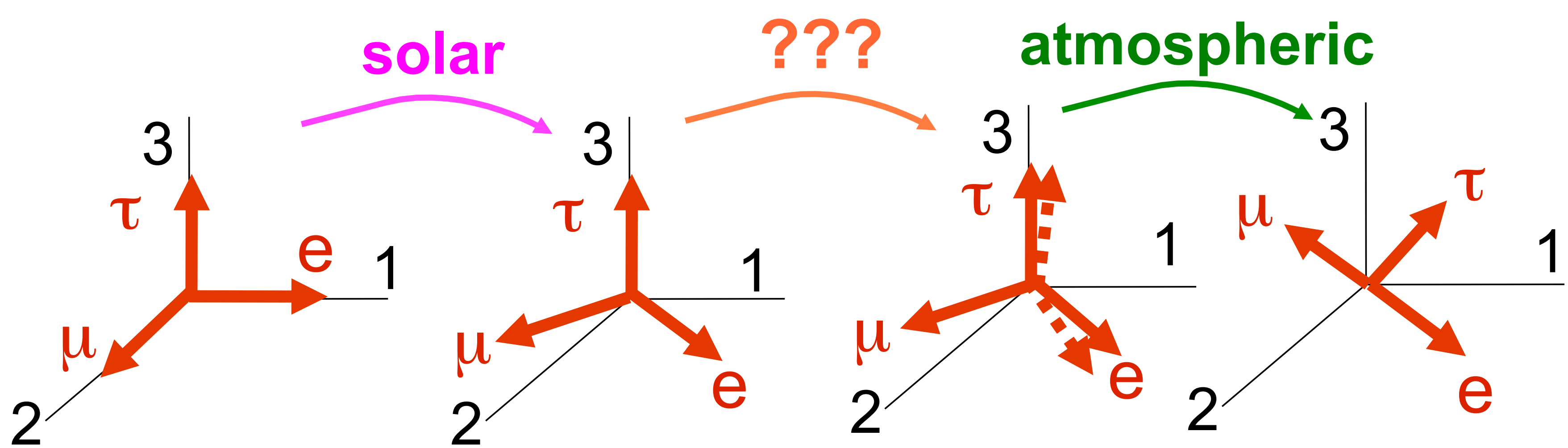
maximal?

First, θ_{13}: 'the twist in the middle'

$$|\nu_f\rangle = \sum_{i=1}^{N} U^*_{fi} |\nu_i\rangle$$

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

atmospheric ??? solar

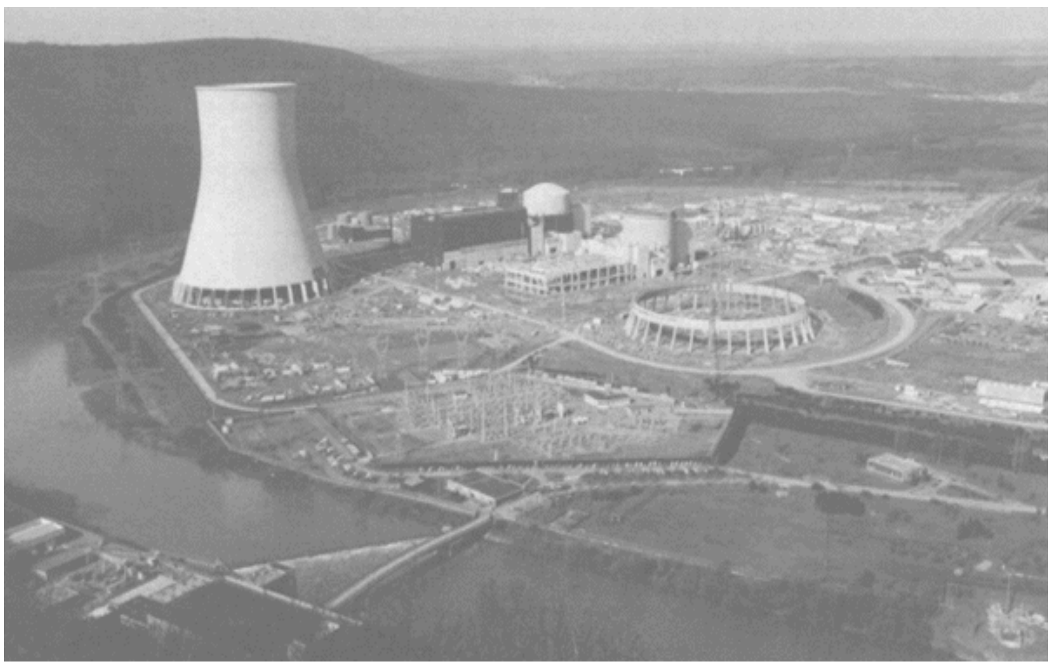


Getting at θ_{13} experimentally: look for disappearance of reactor $\bar{\nu}_e$

$$1 - P(\bar{\nu}_e \rightarrow \bar{\nu}_e) \sim \sin^2 2\theta_{13} \sin^2 \left(\frac{\Delta m^2_{13} L}{4E} \right)$$

(few MeV, ~ km)

Current best limits for θ_{13} from CHOOZ



$$\bar{\nu}_e \longrightarrow \nu_x$$

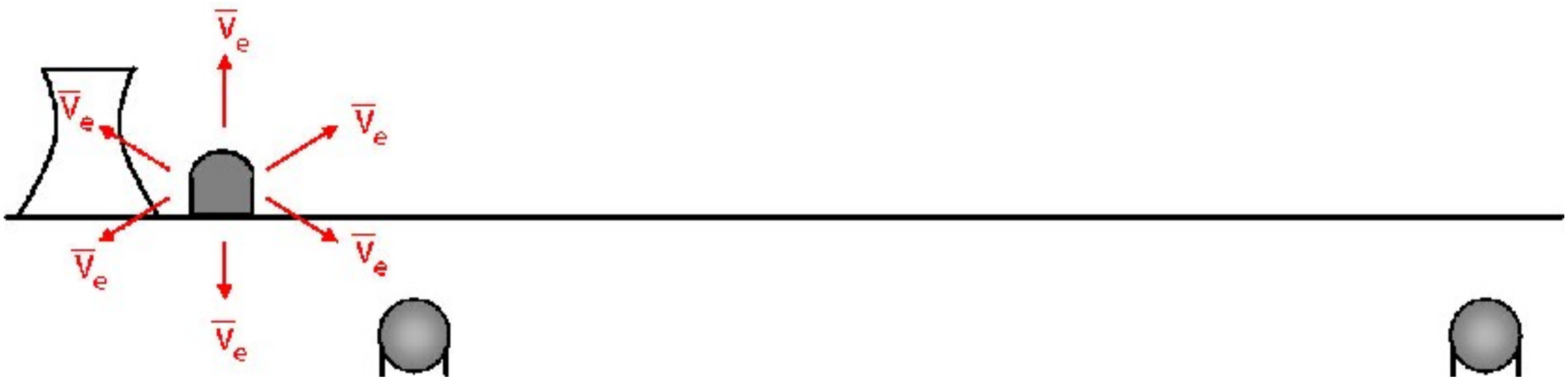
$\Rightarrow$ **disappearance amplitude < 5-10%**

Next generation of proposed experiments: improved reactor disappearance search

$$1 - P(\bar{\nu}_e \to \bar{\nu}_e) \sim \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta m^2_{13} L}{4E}\right)$$

Need <1% systematics!

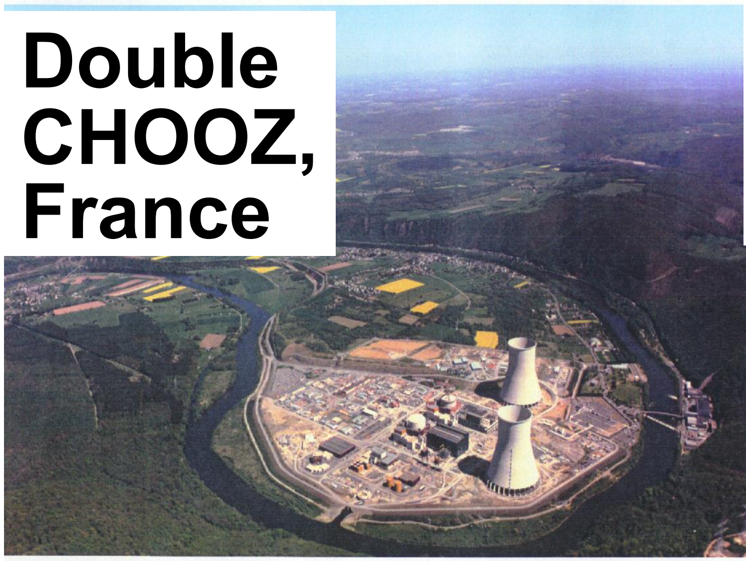
Cancel systematics w/ 2 detectors

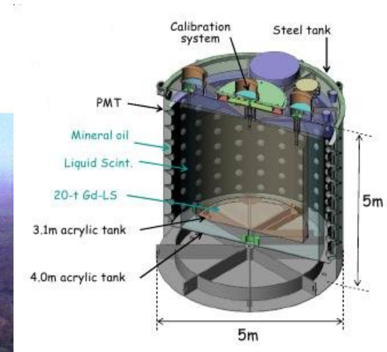


M. Shaevitz

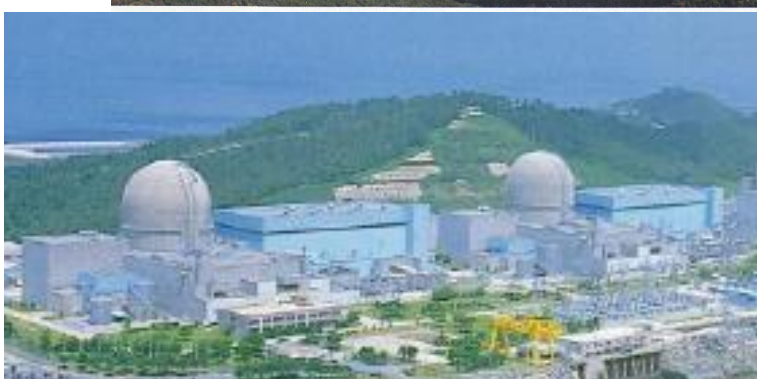
New reactor oscillation experiments

Double CHOOZ, France





Daya Bay, China



RENO, South Korea

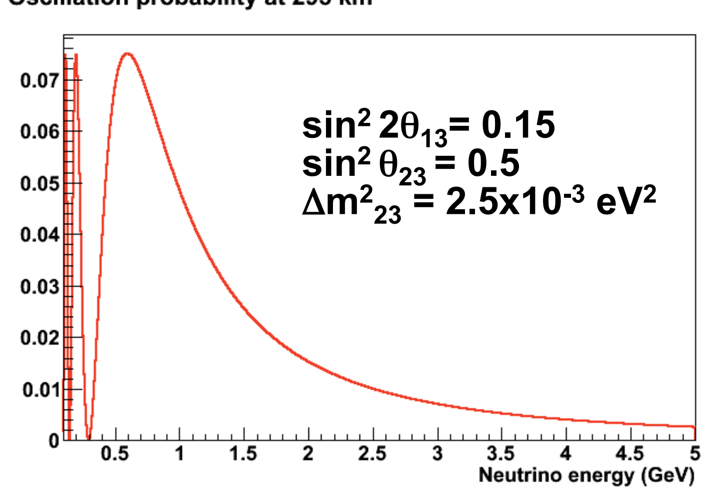
- Gd-loaded scintillator
- Aiming for sensitivity to $\sin^2 2\theta_{13}$ of ~0.01 on ~5 year timescale

Another experimental approach:

θ_{13} signature: look for *small* ν_e *appearance* in a ν_μ beam

$\nu_\mu \rightarrow \nu_{\mu,\tau}$

$\nu_\mu \rightarrow \nu_e$



$$P(\nu_\mu \to \nu_e) = \sin^2 2\theta_{13} \sin^2 \theta_{23} \sin^2\left(\frac{\Delta m^2_{23} L}{4E}\right)$$

- $\sin^2 2\theta_{13}$: small modulation
- $\sin^2 \theta_{23}$: ~ 1/2
- $\sin^2\left(\frac{\Delta m^2_{23} L}{4E}\right)$: atmospheric-like wiggling

for $\Delta m_{23}^2 \gg \Delta m_{12}^2$ and $E_\nu \sim L\Delta m_{23}^2$ (in vacuum), $\delta=0$

Hard to measure... known from the CHOOZ reactor experiment that it's a *small* modulation!
Need good statistics, clean sample

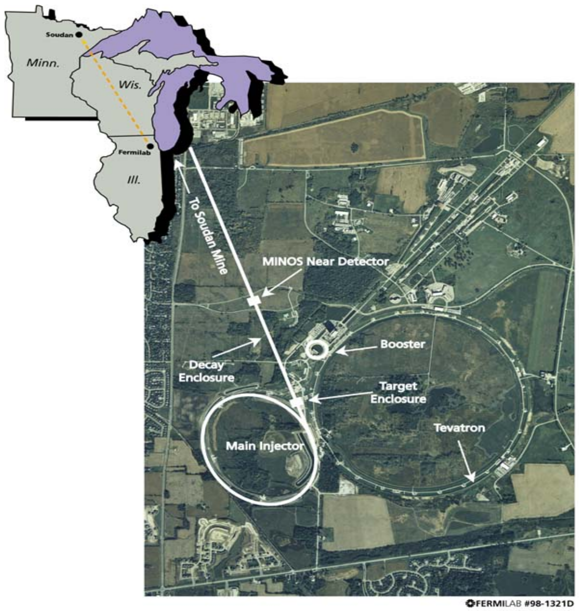
Next Long Baseline Beam Projects

Aim for: ~1% on 2-3 mixing, factor of ~10-20 for θ_{13} mixing

T2K: "Tokai to Kamioka"

Pre-existing detector: Super-K
295 km, <1 GeV 0.75 MW beam
(30 times K2K)
Water Cherenkov detector

NOνA at NuMi

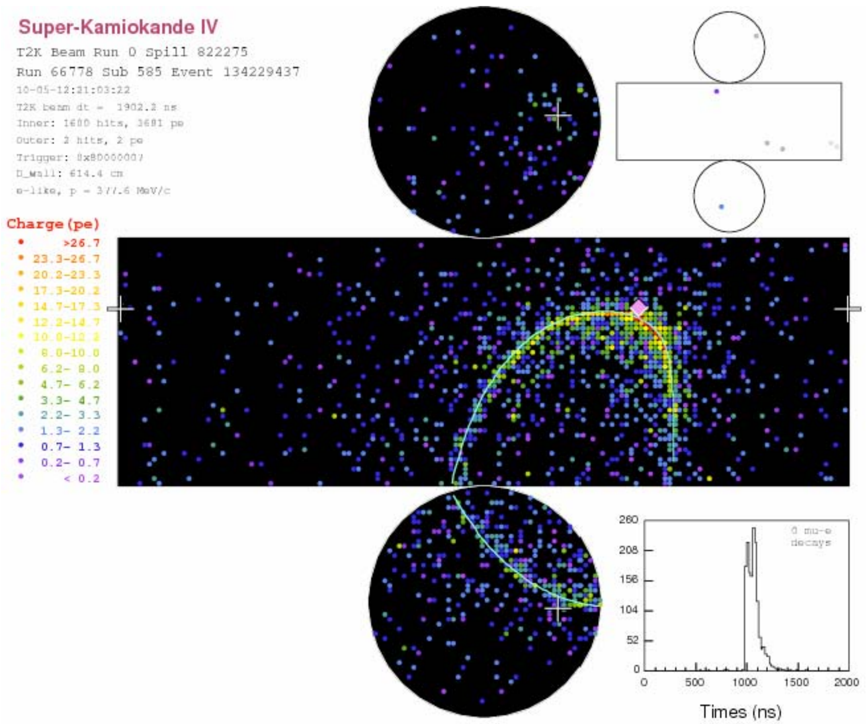


Pre-existing beam:
NuMi upgrade to 0.7 MW
810 km, few GeV beam
Scintillator detector

Detectors are few degrees off beam axis

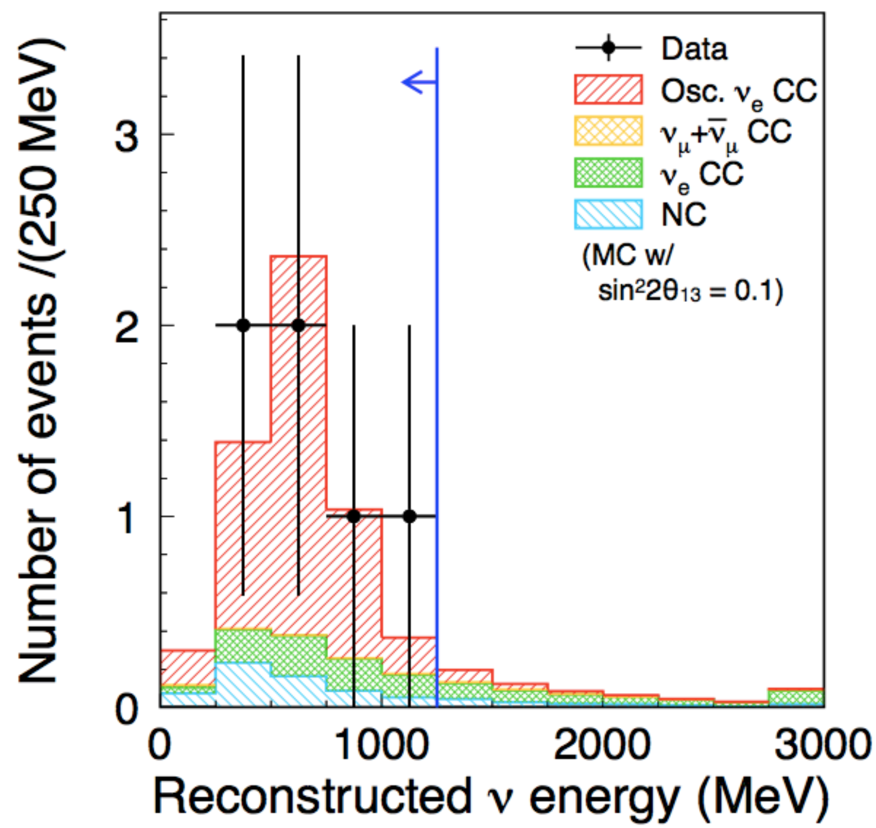
Excess of ν_e -like events seen in T2K, consistent with non-zero θ_{13}

NEW



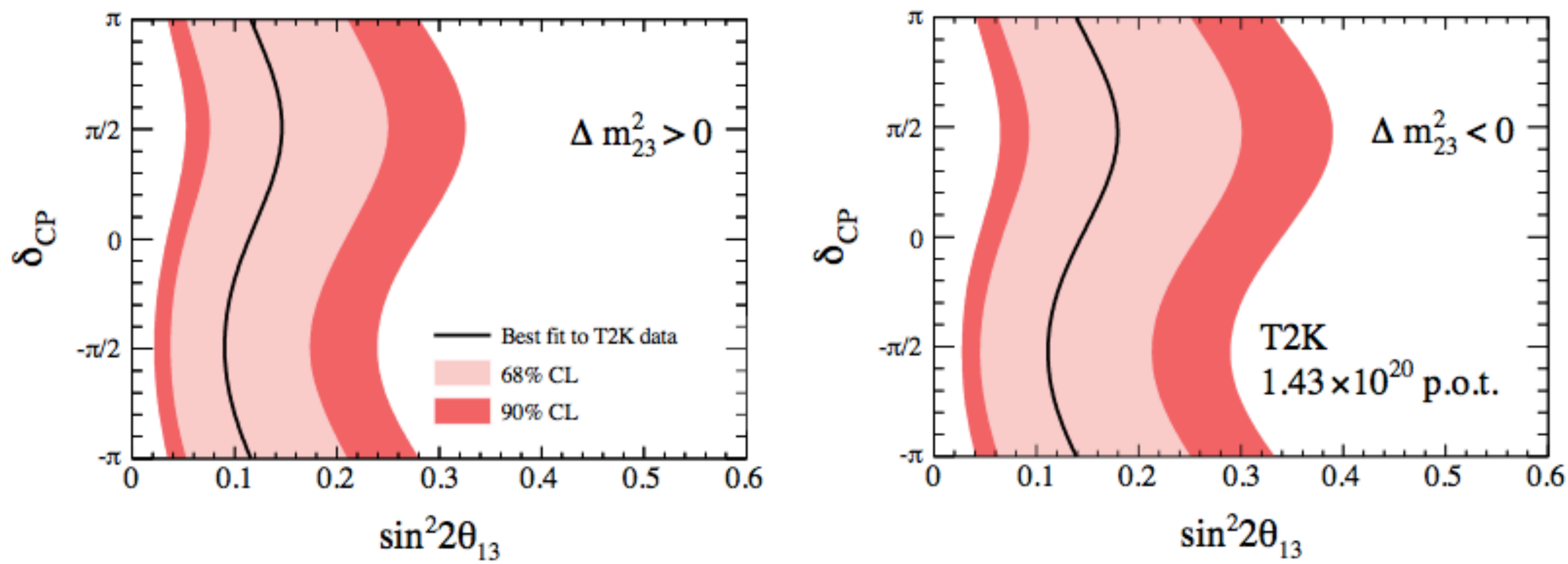
6 ν_e candidate e-like rings seen, 1.5 bg expected

Reconstructed energies after all ν_e cuts



Allowed region in $\sin^2 2\theta_{13}$ and CP δ

(assuming Δm^2_{23}=2.4 x 10^{-3} eV^2, $\sin^2 2\theta_{23}$=1)



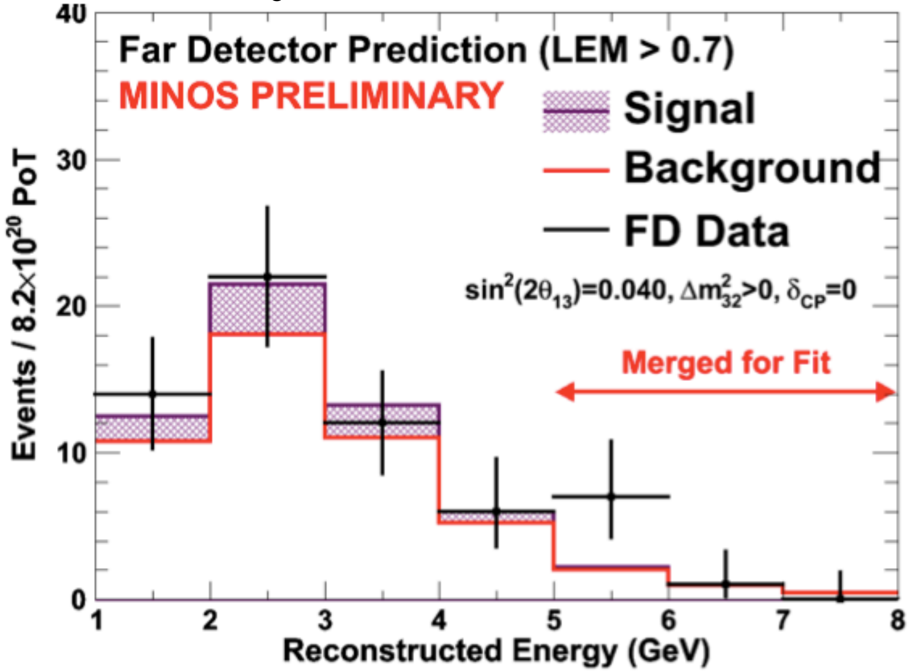
90% C.L. interval & Best fit point (assuming Δm^2_{23}=2.4 x 10^{-3} eV^2, $\sin^2 2\theta_{23}$=1, δ_{CP}=0)

$0.03 < \sin^2 2\theta_{13} < 0.28$	$0.04 < \sin^2 2\theta_{13} < 0.34$
$\sin^2 2\theta_{13} = 0.11$	$\sin^2 2\theta_{13} = 0.14$

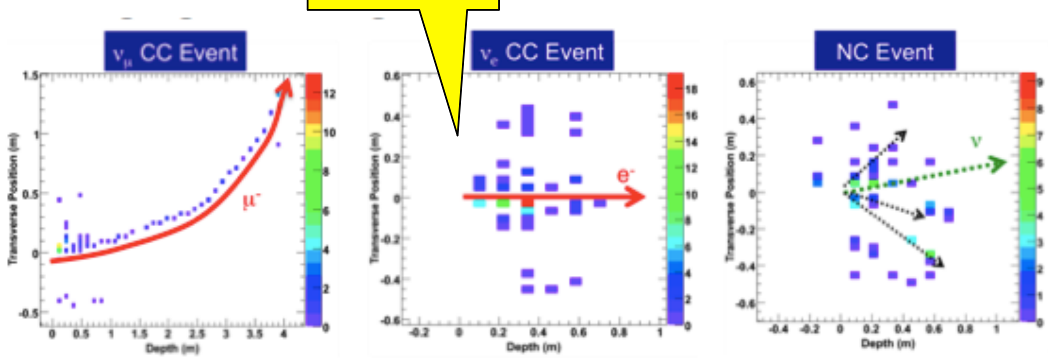
ν_e appearance results from MINOS are consistent

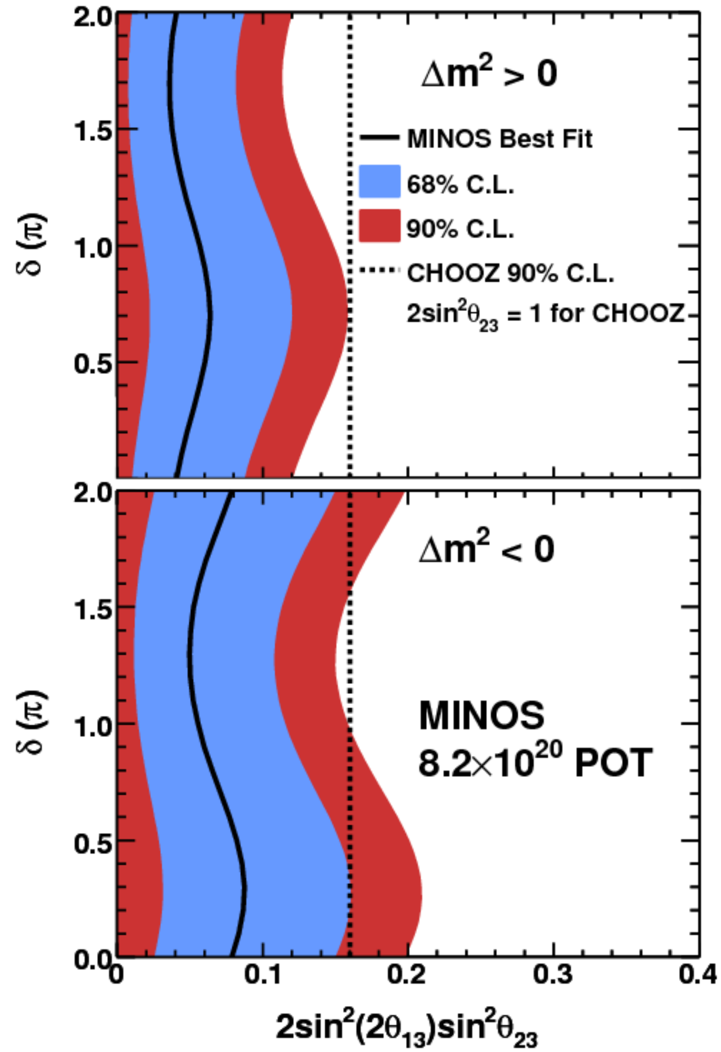
NEW

Spectrum of ν_e -like events

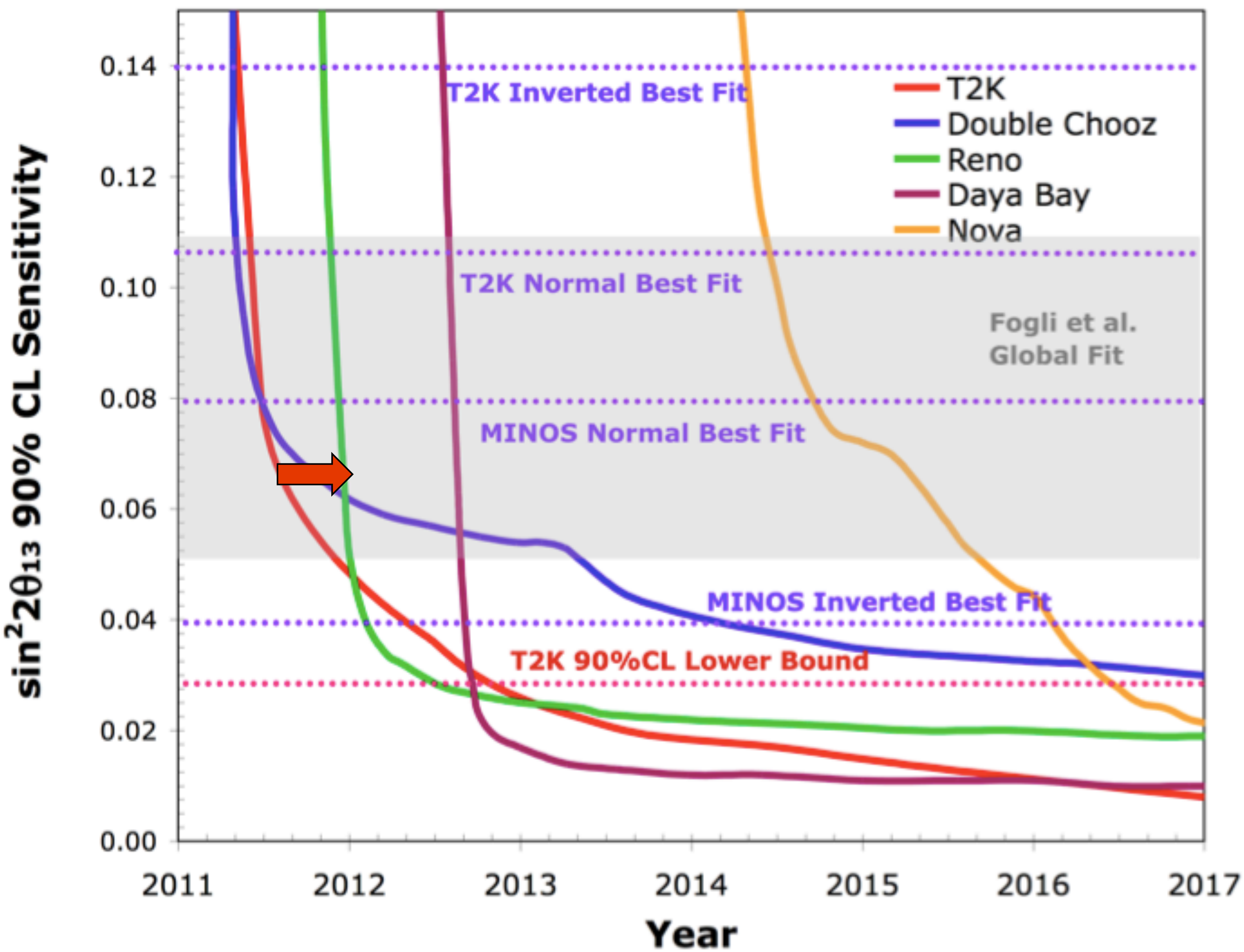


look for these





Future θ_{13} sensitivity



M. Shaevitz
PANIC 11

And beyond: getting at CP Violation

Observed for quarks; how about leptons?

phase δ in mixing matrix

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

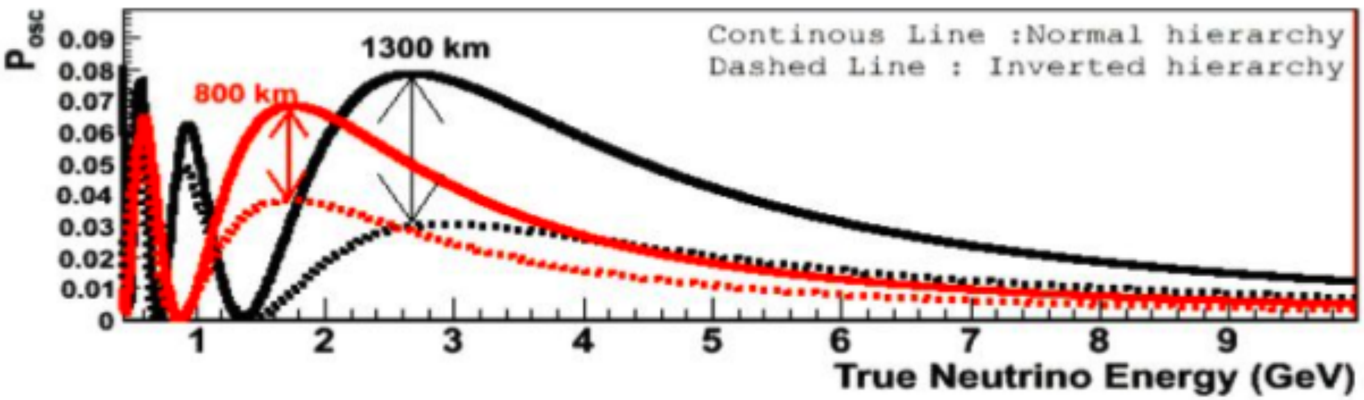
Compare transition probabilities for

$\nu_\mu \longrightarrow \nu_e$ **and** $\bar{\nu}_\mu \longrightarrow \bar{\nu}_e$

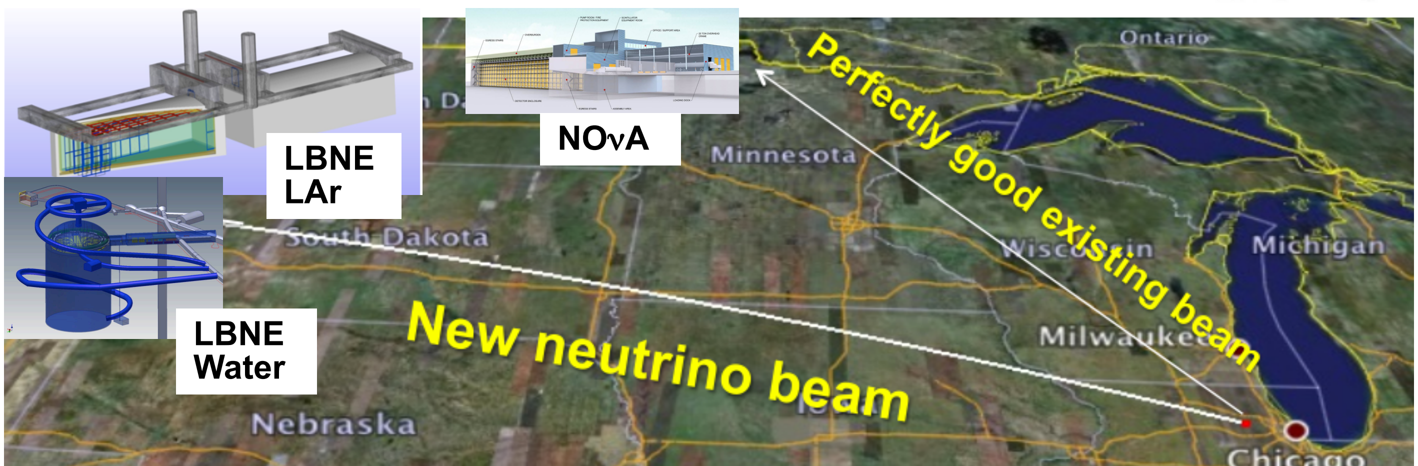
But not simple to extract CP violating phase δ...
transition rates depend on all
MNS parameters, plus matter effects...

Multiple measurements (L, E, ν, $\bar{\nu}$) needed

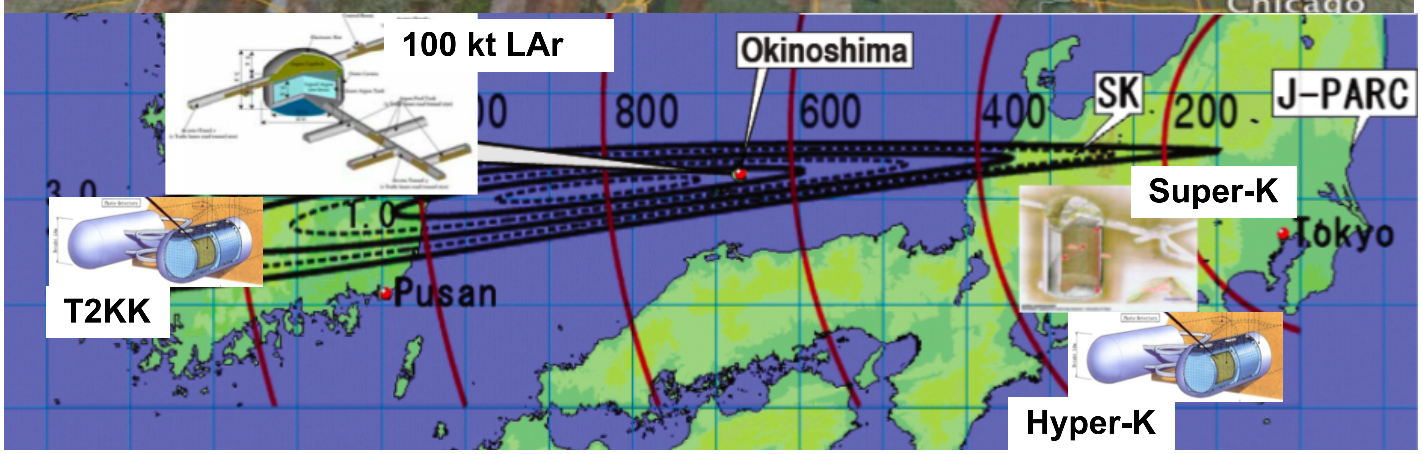
Next, and next-next-generation super-beams: hierarchy + CP



$\nu_\mu \rightarrow \nu_e$ oscillation probabilities depend on mass hierarchy and CP δ



good sensitivity at ~1000 km baseline, ~few GeV energy



Many other future ideas (+ Europe):
β beams,
ν factories,
cyclotrons,...

A Different Approach for ν CPV: DAEδALUS

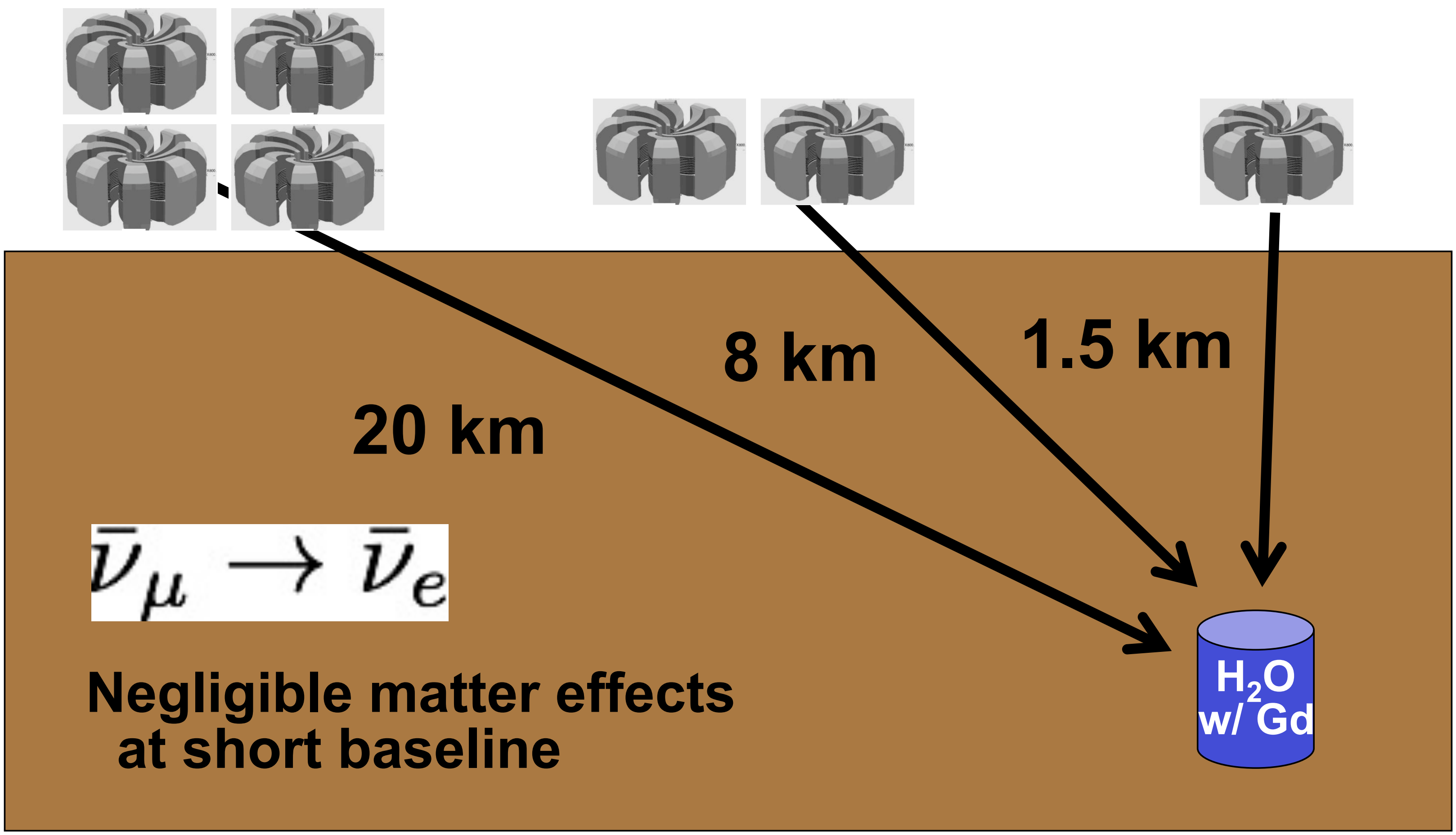
NEW

Multiple stopped-pion neutrino sources:

L ~1.5-20 km

E ~10-50 MeV

$$\frac{L}{E} \sim \frac{1000\ \mathrm{km}}{3000\ \mathrm{MeV}} \sim \frac{10\ \mathrm{km}}{30\ \mathrm{MeV}}$$

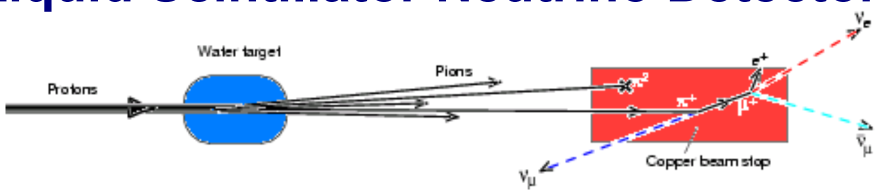


J. Conrad & M. Shaevitz, Multiple Cyclotron Method to Search for CP Violation in the Neutrino Sector, arXiv:0912.4079, Phys. Rev. Lett. 104, 141802 (2010)

(Parenthesis 1

LSND at Los Alamos

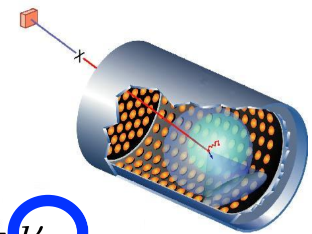
Liquid Scintillator Neutrino Detector



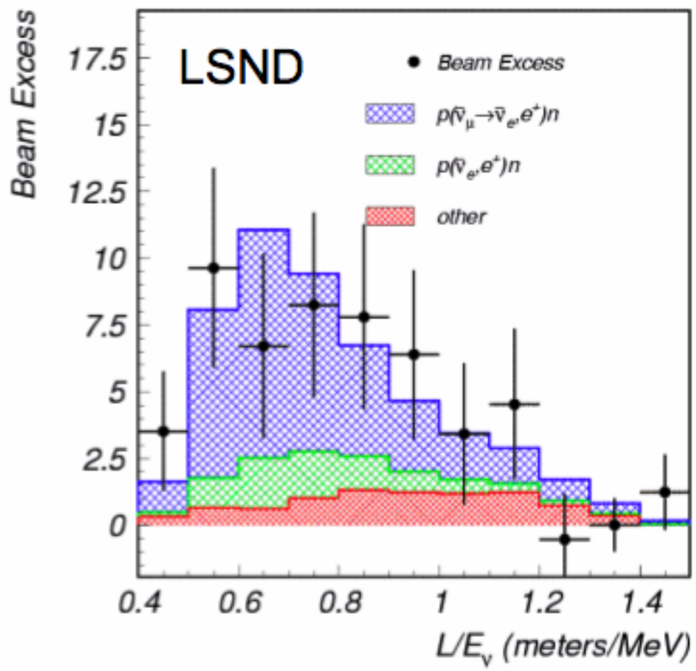
$$\pi^+ \longrightarrow \mu^+ + \nu_\mu$$

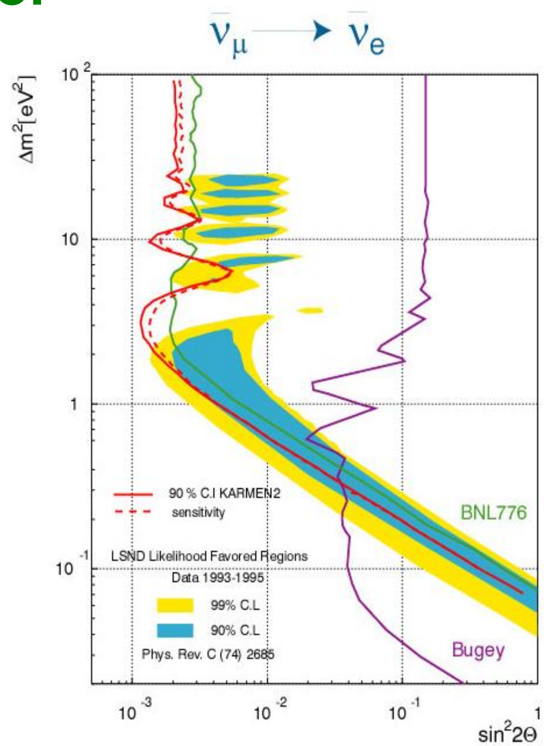
$$\downarrow$$

$$\mu^+ \longrightarrow e^+ + \bar{\nu}_\mu + \nu_e$$



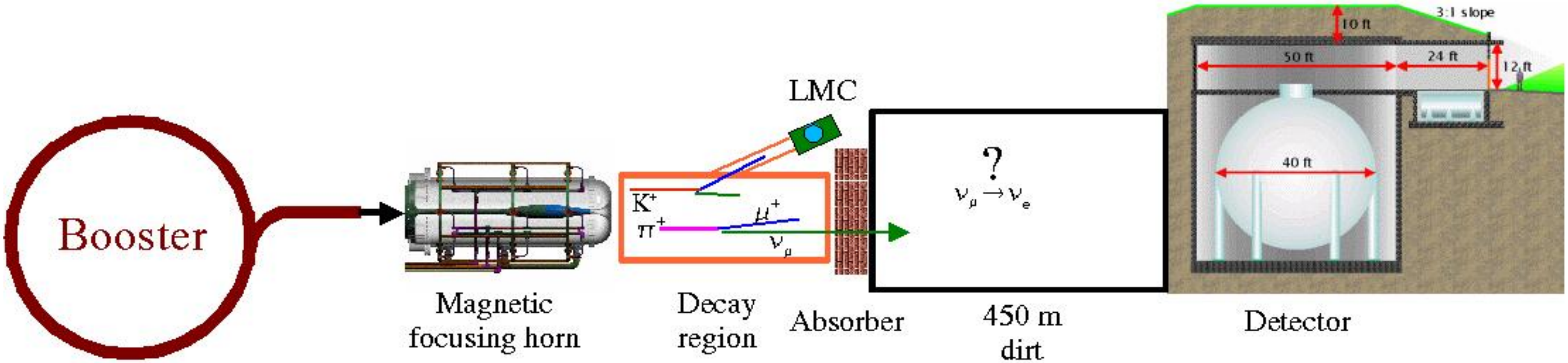
- 30 m baseline, 167 tons scintillator
- stopped pion source





Excess of $\bar{\nu}_e$ interpreted as $\bar{\nu}_\mu \longrightarrow \bar{\nu}_e$ ➔ does not fit in 3 flavor picture

MiniBooNE
Booster Neutrino Experiment at Fermilab



L~ 500 m

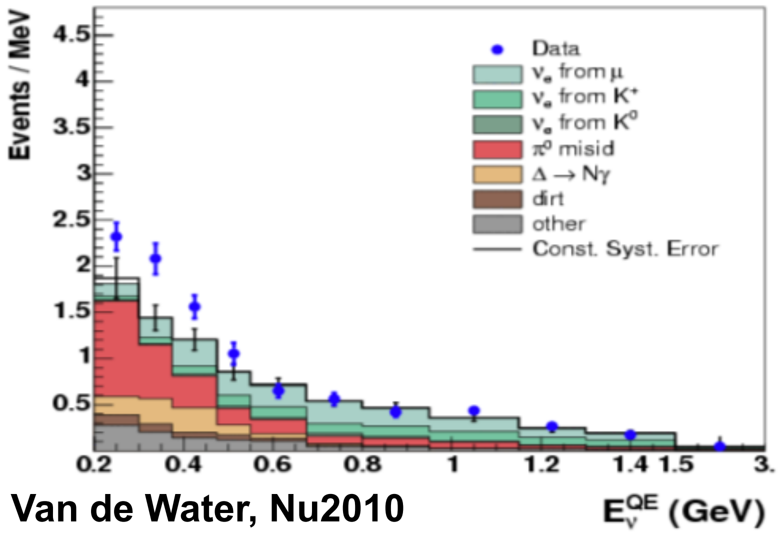
E_ν~ 1 GeV from 8 GeV booster

0.8 kton of mineral oil

Test $\nu_\mu \rightarrow \nu_e$ at same L/E as LSND with both neutrinos and antineutrinos

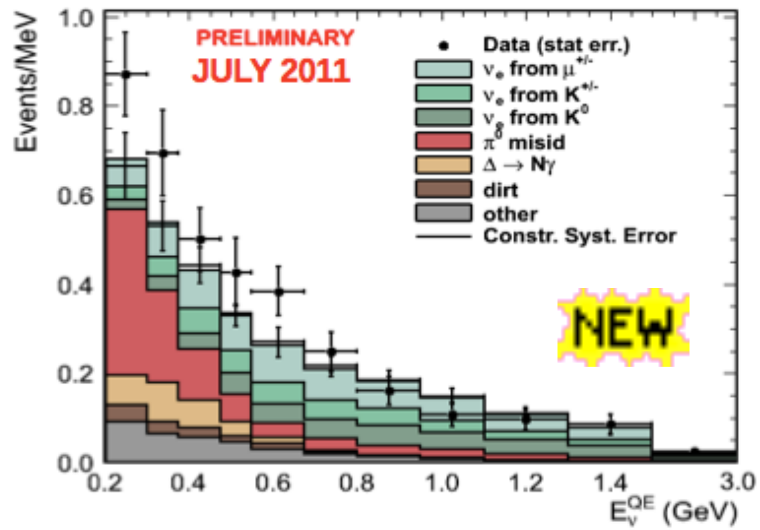
L↑, E↑ : different systematics

Neutrinos



R. Van de Water, Nu2010

Antineutrinos



Neutrinos:

- unexplained 3 σ excess for E < 475 MeV
  (inconsistent w/ LSND oscillation)
- no excess for E > 475 MeV
  (inconsistent w/ LSND oscillation)

????

Antineutrinos:

- small excess for E < 475 MeV, ~consistent with neutrinos
- small excess for E > 475 MeV (less than before)
  (consistent w/ LSND, 15% consistent w/ no osc)

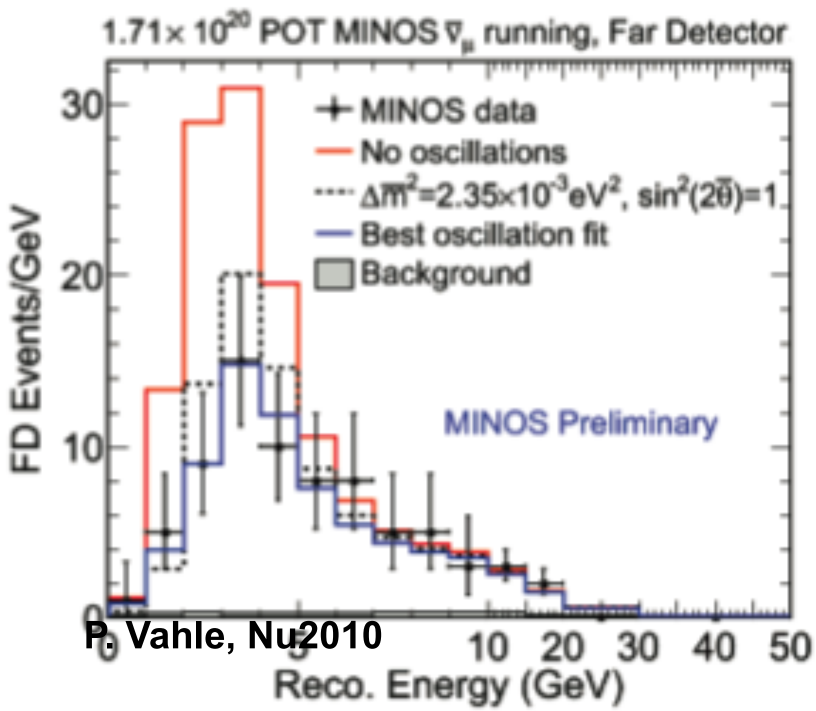
- more antineutrino running, through spring 2012
- also: μBooNE (LAr), other ideas (?)

Parenthesis 1)

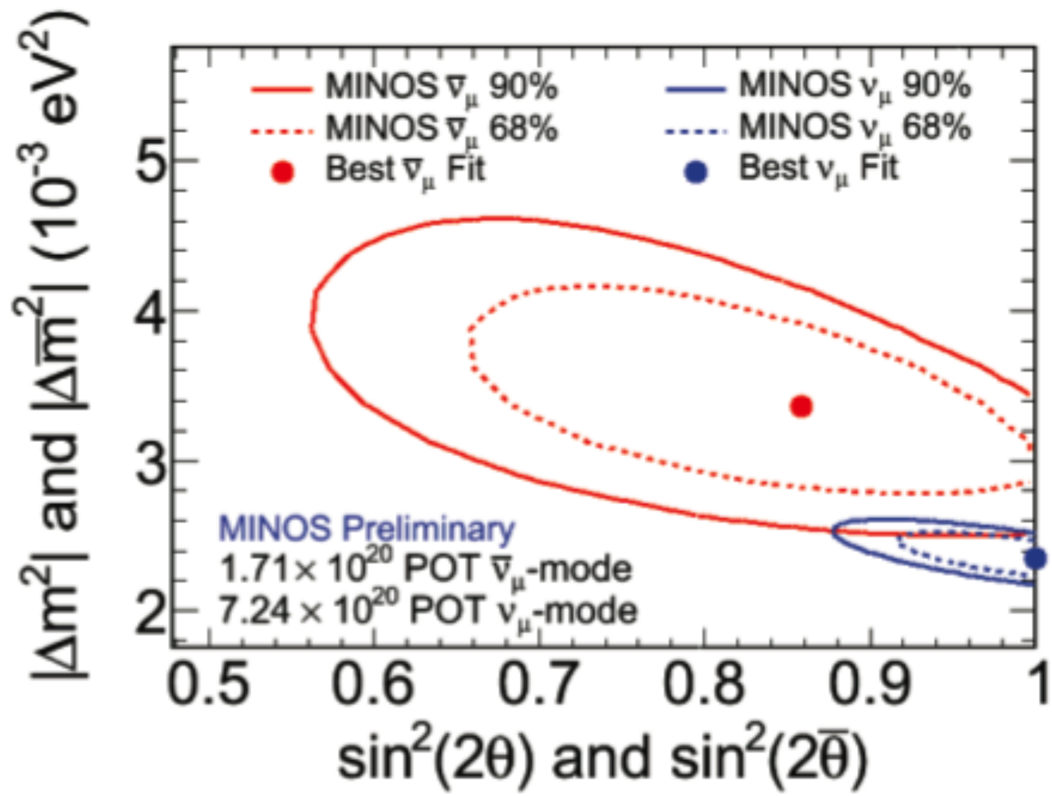
(Parenthesis 2

MINOS running with antineutrinos

Magnetic field allows antineutrino selection in detector

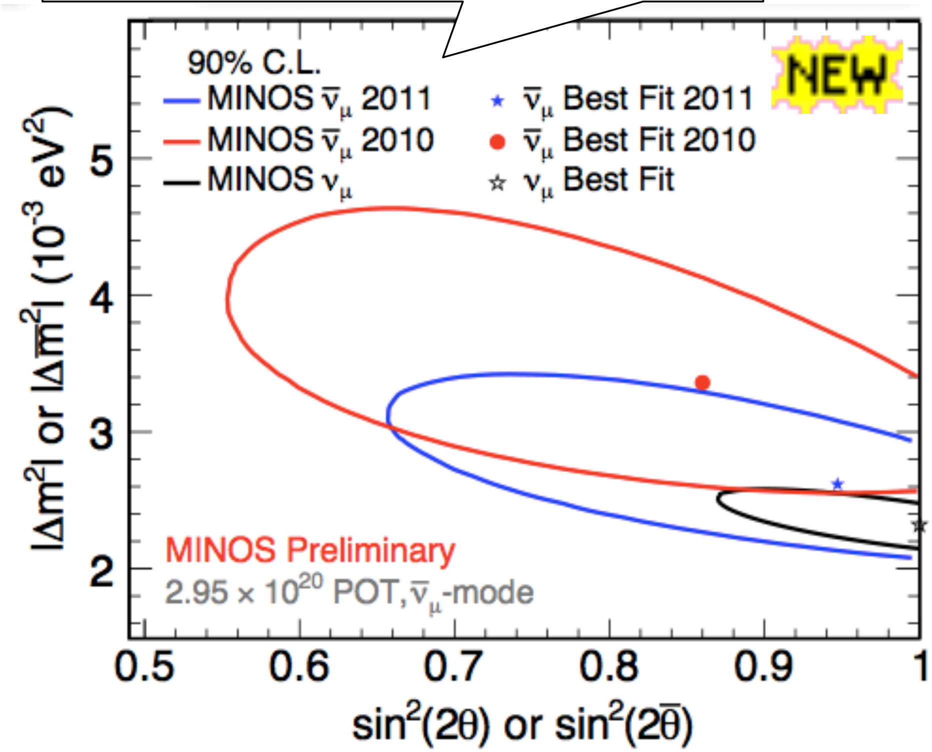


P. Vahle, Nu2010

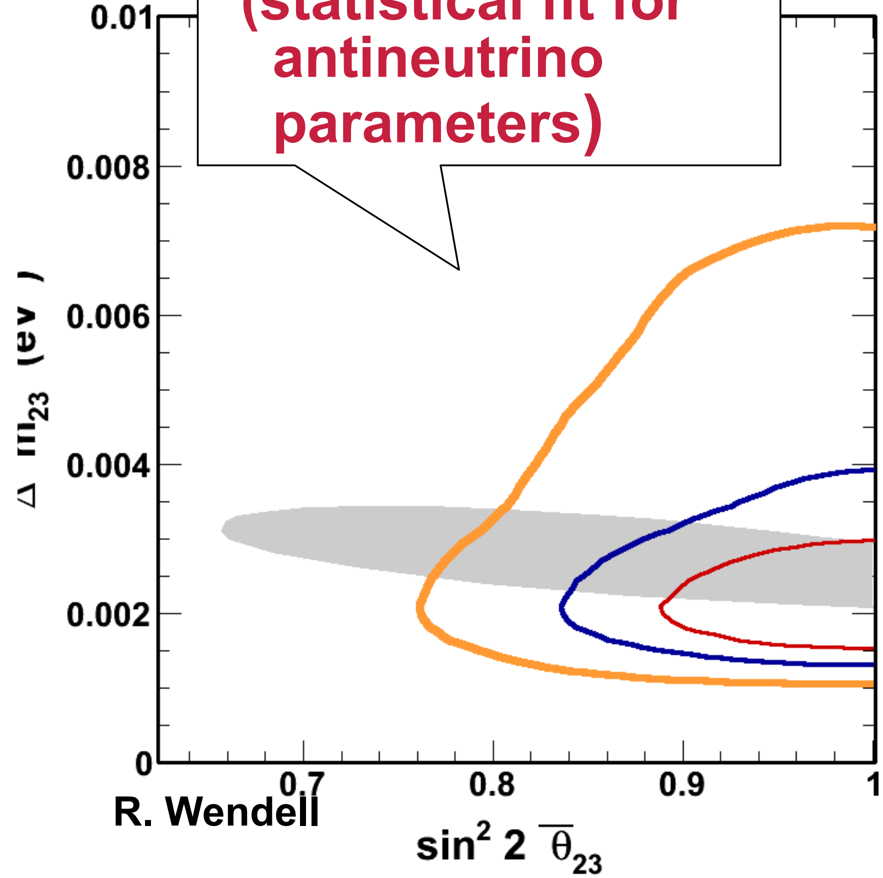


Different parameters for neutrinos and antineutrinos? Suggests CPT violation?

New MINOS result with ~twice the data... no more tension!



SK atmospheric neutrino data (statistical fit for antineutrino parameters)



Mean Scientists Dash Hopes Of ~~Life On Mars~~ CPT Violation (?)

... maybe not all hopes dashed yet, but field theory is probably still safe...

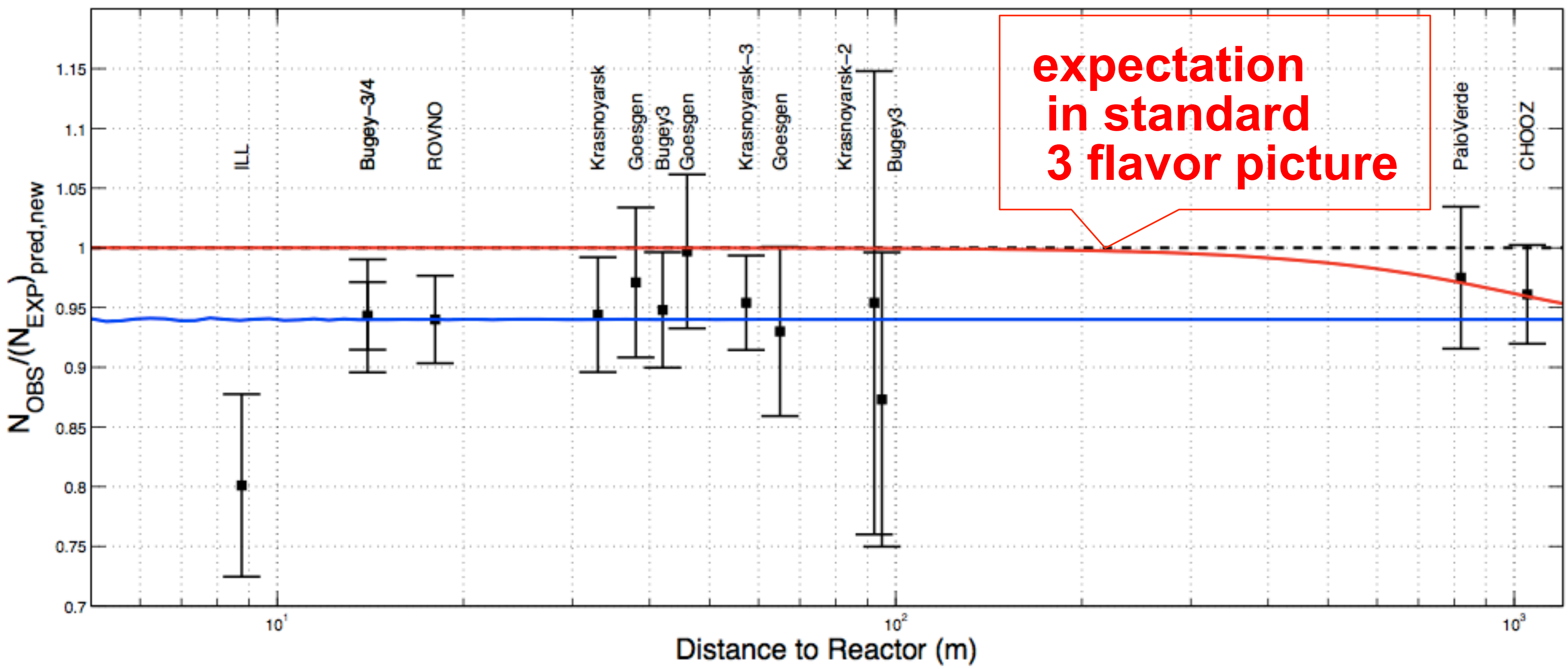
Parenthesis 2)

(Parenthesis 3

"Reactor neutrino anomaly"

NEW

arXiv:1101.2755

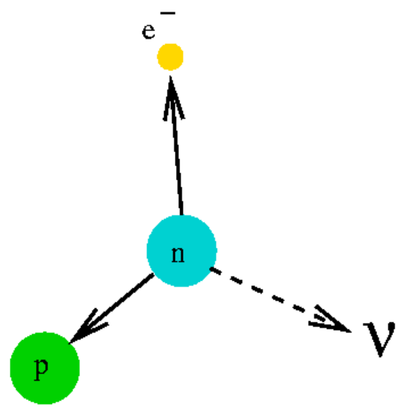


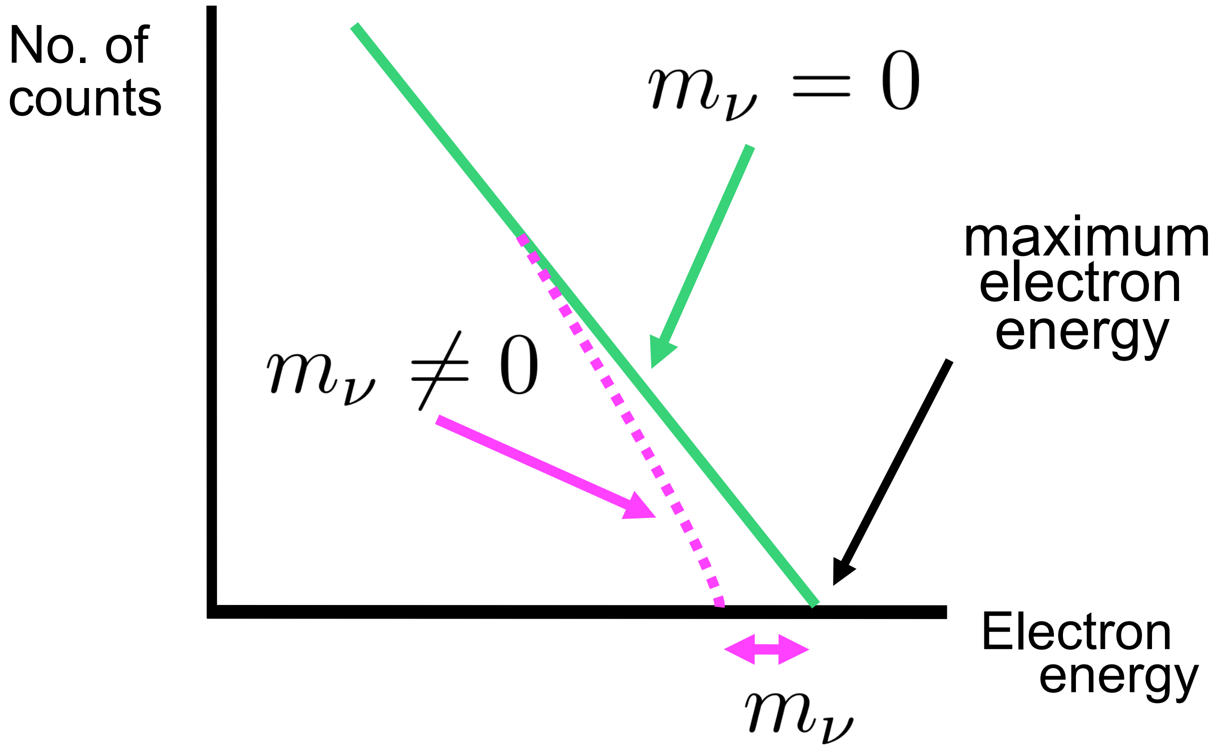
- Reactor neutrino flux calculations recently reevaluated (+3%, smaller uncertainty)
- Now historical data show deficit, <2% consistent w/expectation
- Sterile neutrino hint?

Parenthesis 3)

Kinematic Experiments for Absolute Neutrino Mass

(oscillation experiments only inform on mass *differences*)





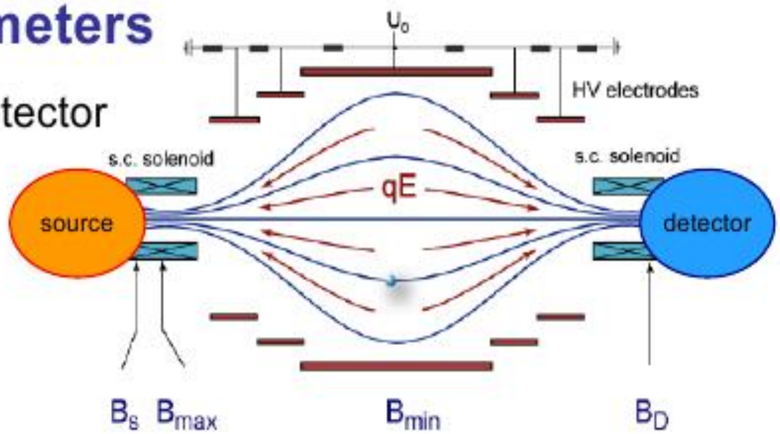
Look for distortion of β-decay spectrum near endpoint

Current best limits: Mainz, Troitsk: m_ν < 2.2 eV

Experimental approaches: aiming for sub-eV sensitivity

Spectrometers

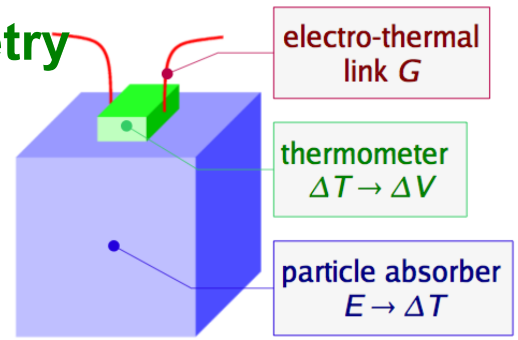
Source≠Detector



$$^3\text{H} \rightarrow ^3\text{He} + e^- + \bar{\nu}_e$$

18.6 keV endpoint
Mainz, Troitsk➔ KATRIN
(0.2 eV expected)

Thermal calorimetry

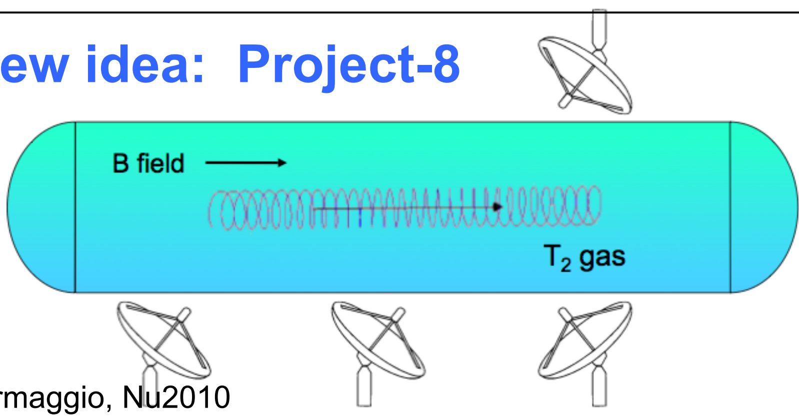


A. Nucciotti, Nu2010

$$^{187}\text{Re} \rightarrow ^{187}\text{Os} + e^- + \bar{\nu}_e$$

2.5 keV endpoint
MARE

New idea: Project-8



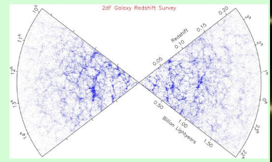
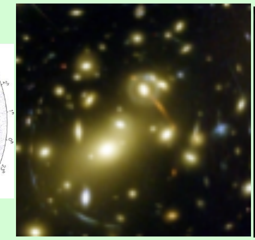
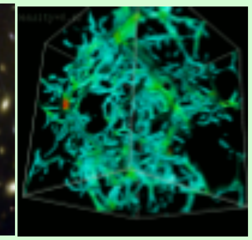
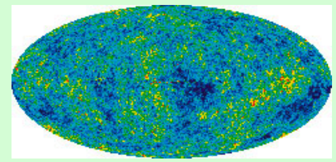
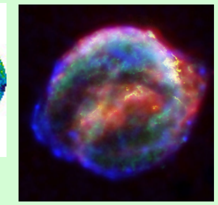
J. Formaggio, Nu2010

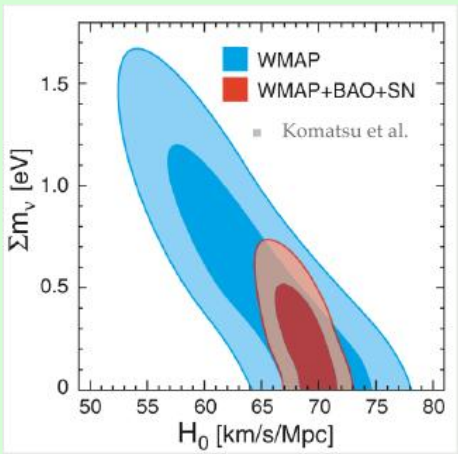
$$^3\text{H} \rightarrow ^3\text{He} + e^- + \bar{\nu}_e$$

Measure energy via cyclotron frequency

Other ways of getting at absolute neutrino mass

Fits to cosmological data:
CMB, large scale structure,
high Z supernovae,
weak lensing,...



R. Easther, Nu2008

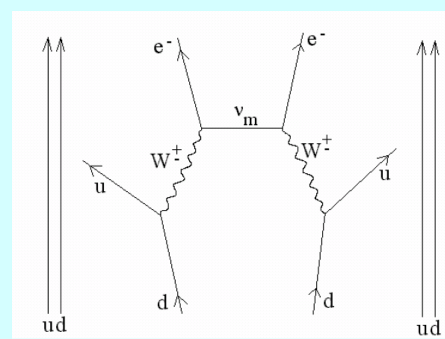
$$\sum m_i <\sim 1 \text{ eV}$$

model-dependent

Neutrinoless Double Beta Decay

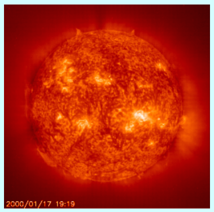
$$\langle M_{\text{eff}} \rangle^2 = |\sum_i U_{ei}^2 M_i|^2$$

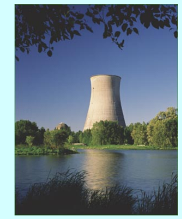
See next talk!



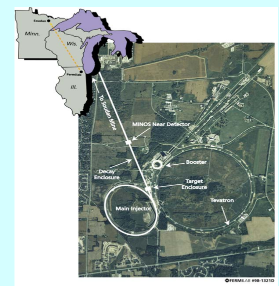
Overall Summary

Tremendous progress over the past two decades:

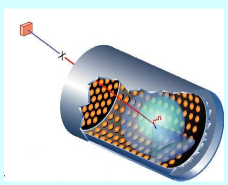


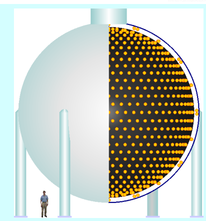


Solar oscillations confirmed by reactor experiments



Atmospheric oscillations confirmed by beams





Still some funny anomalies w/ LSND & MiniBooNE, reactors....

(MINOS $\nu/\bar{\nu}$ anomaly gone)

Next quest, in 3D: θ_{13}, mass hierarchy, CP violation, plus absolute mass...

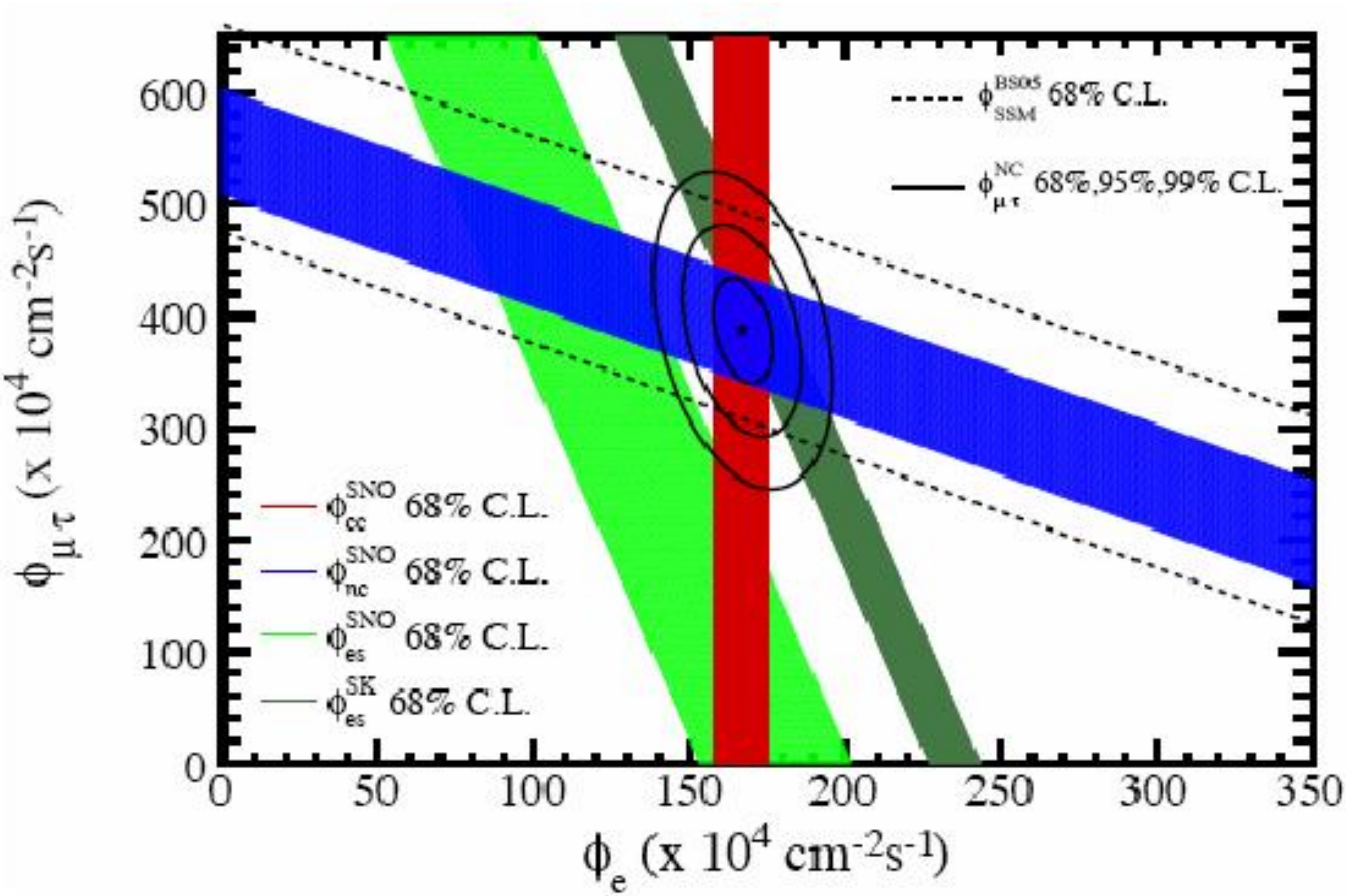
Next to watch: T2K, Double Chooz, Daya Bay, RENO, KATRIN, NOνA,...

...onward with reactors, beams & spectrometers!

Backup Slides

SNO NCD results

H. Robertson, Nu2008



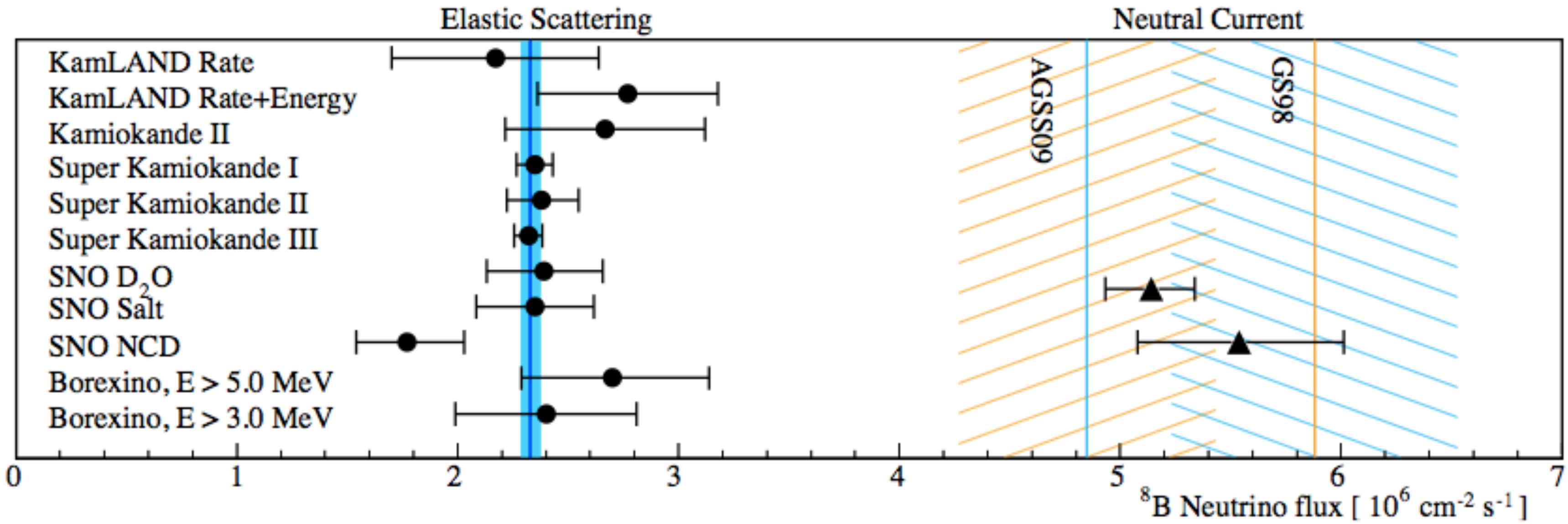
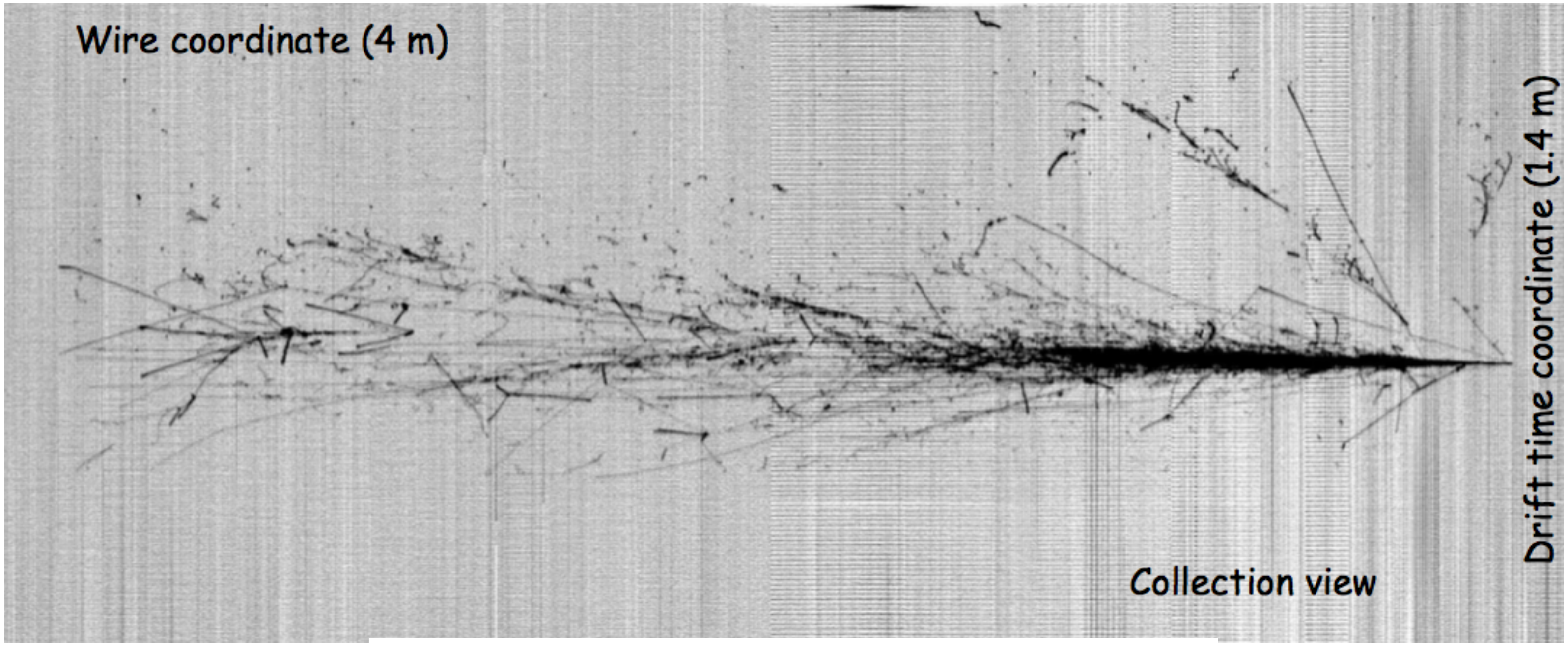
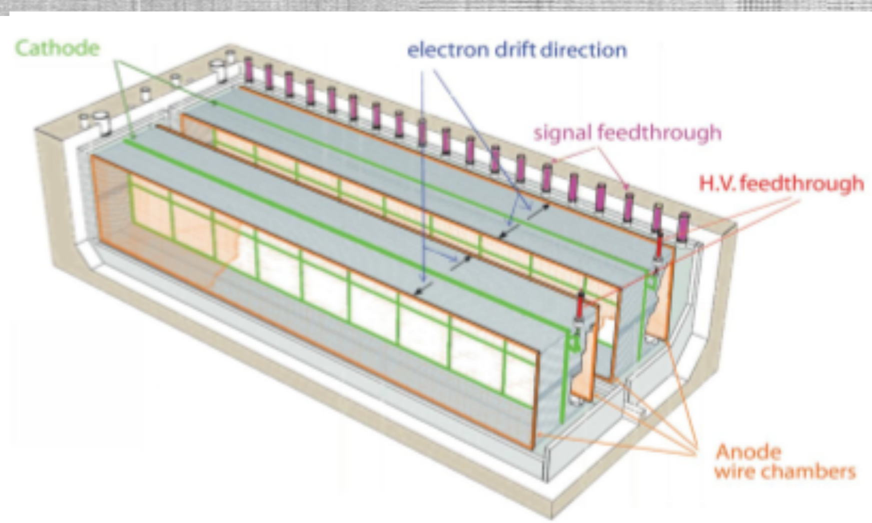


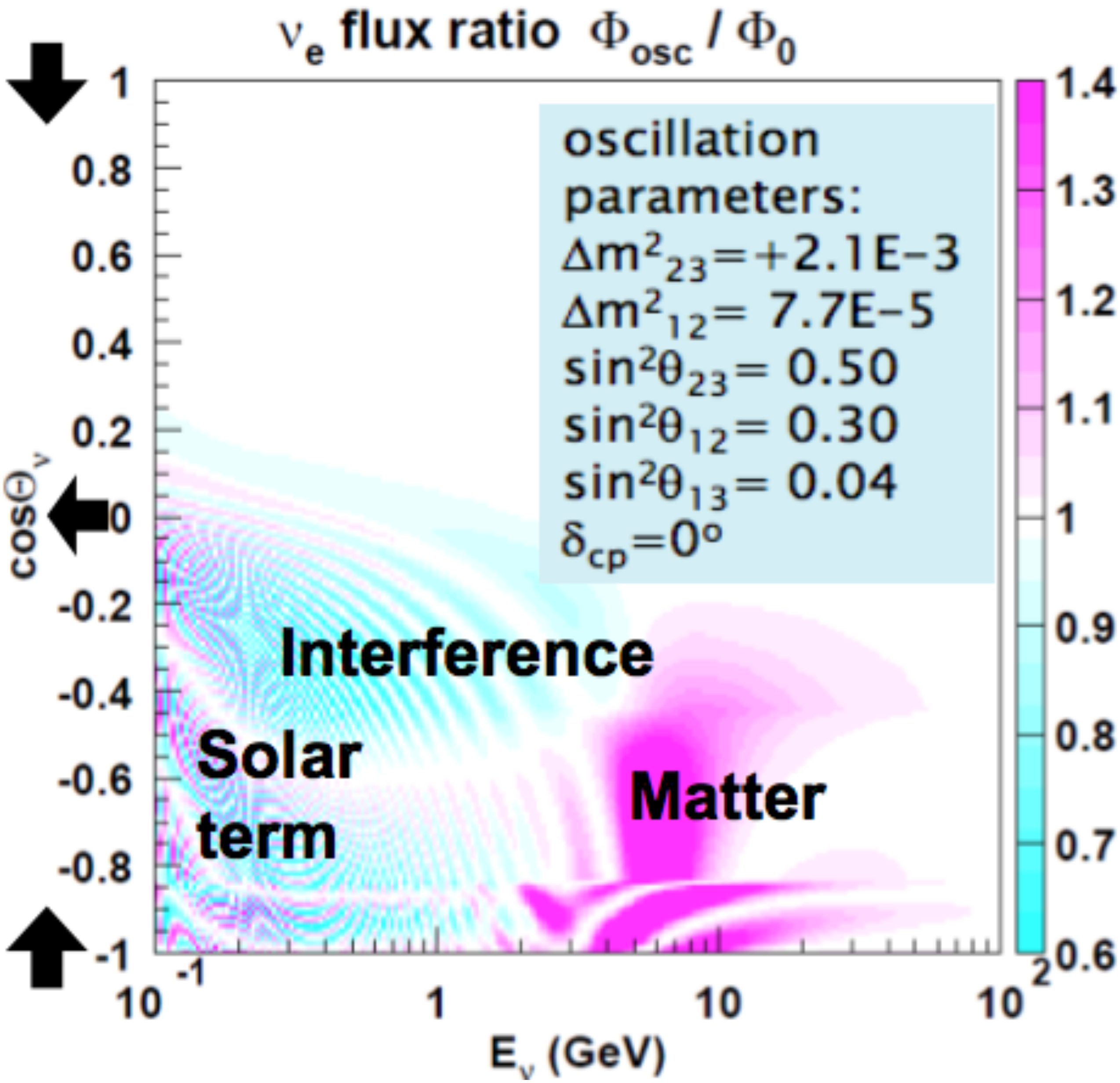
FIG. 2: Summary of measurements of the ^{8}B flux using neutrino-electron scattering: this work KamLAND, Kamiokande II [11, 12], Super Kamiokande I [5], Super Kamiokande II [6], Super Kamiokande III [13], SNO D_2O [7, 10], SNO Salt [8, 10], SNO NCD [9], and Borexino [14]. The SNO neutral current measurements [9, 10] are shown for reference with closed triangles.

First neutrino events from ICARUS
600 t LAr at LNGS

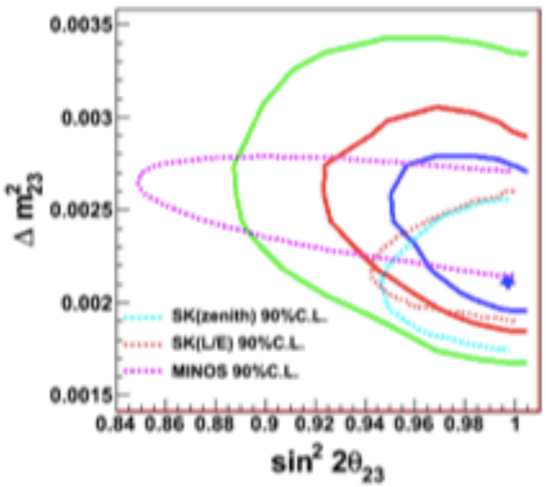


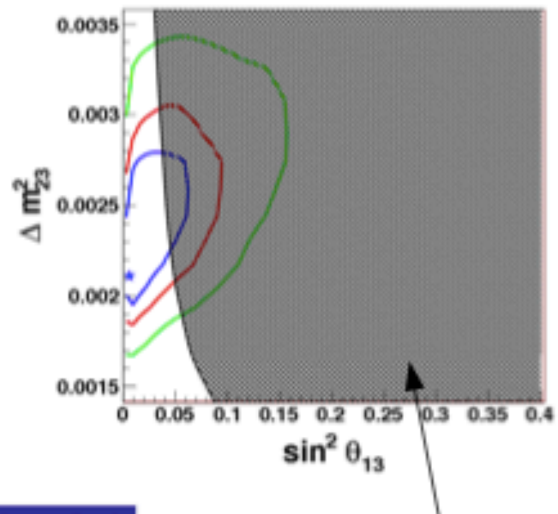


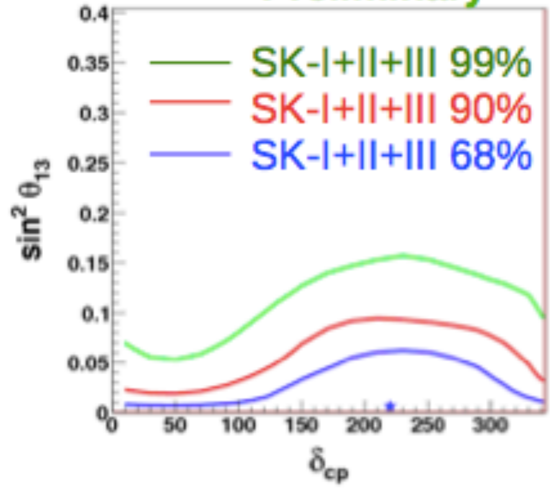
Atmospheric neutrinos in a 3 flavor context



Full Three-Flavor Oscillation Analysis, Normal Hierarchy

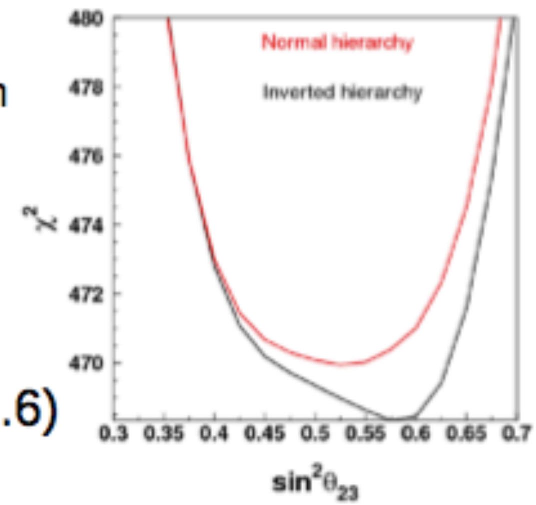






χ^2_{min} = 469.94 /416dof

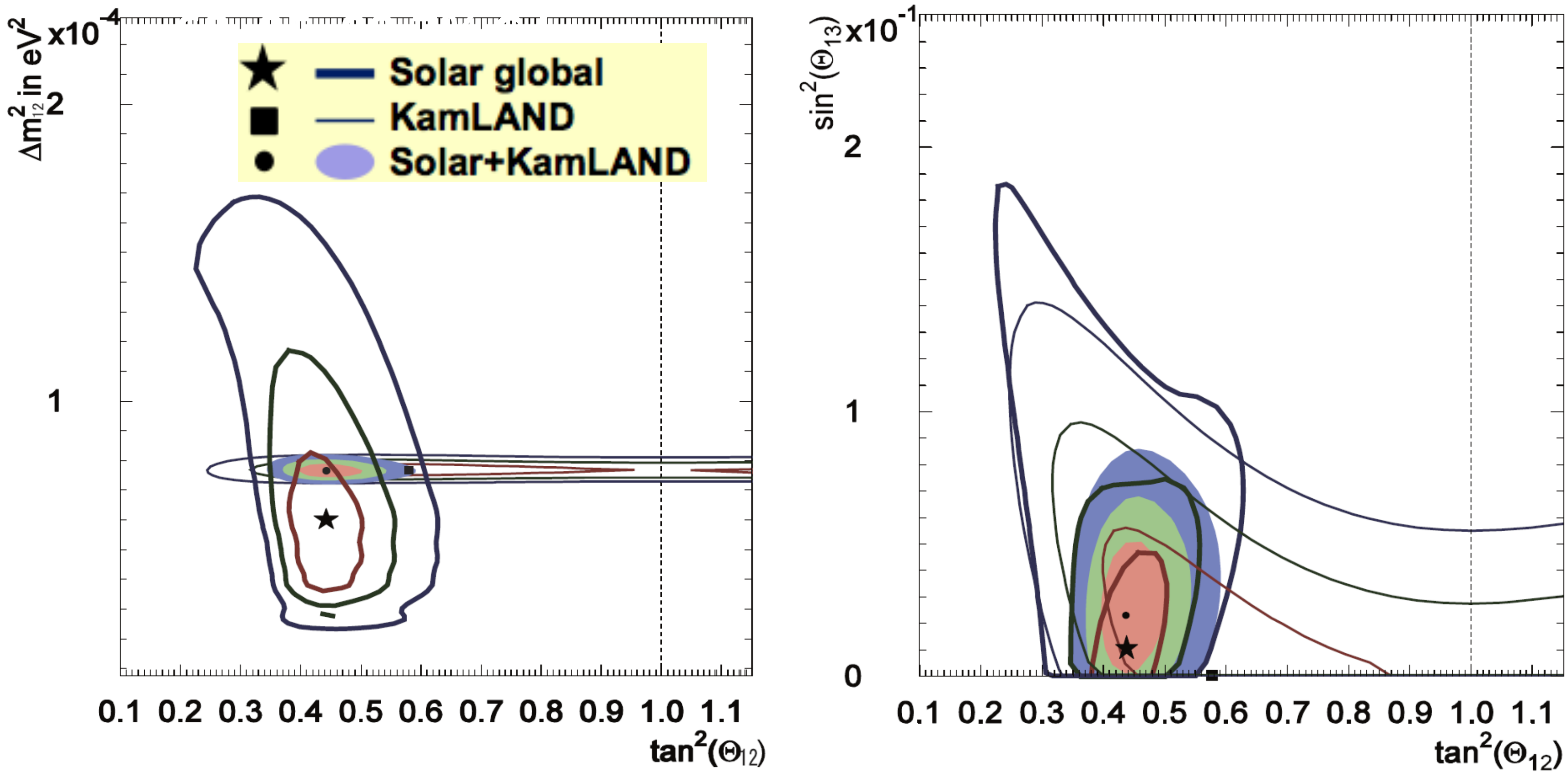
Parameter	Best point
Δm^2_{23} (x10³)	2.11 eV²
$\sin^2\theta_{23}$	0.525
$\sin^2\theta_{13}$	0.006
CP-δ	220°



- No Strong preference for either hierarchy ($\Delta\chi 2 = 1.6$)
- θ_{13} is consistent with zero and the Chooz limit
- No preference for θ_{23} octant or δ_{cp}

R. Wendell, NNN10

Super-K solar 3-flavor analysis



Y. Takeuchi, Nu2010

CP Violating Observables

$$P_{\nu_e\nu_\mu(\bar{\nu}_e\bar{\nu}_\mu)} = s_{23}^2 \sin^2 2\theta_{13} \left(\frac{\Delta_{13}}{\tilde{B}_\mp}\right)^2 \sin^2\left(\frac{\tilde{B}_\mp L}{2}\right)$$

$$+ c_{23}^2 \sin^2 2\theta_{12} \left(\frac{\Delta_{12}}{A}\right)^2 \sin^2\left(\frac{A L}{2}\right)$$

Non-CP terms

Changes sign for antineutrinos

CP violating

$$+\tilde{J}\, \frac{\Delta_{12}}{A}\, \frac{\Delta_{13}}{\tilde{B}_\mp} \sin\left(\frac{AL}{2}\right) \sin\left(\frac{\tilde{B}_\mp L}{2}\right) \cos\left(\pm\delta - \frac{\Delta_{13} L}{2}\right)$$

$$\tilde{J} \equiv c_{13}\, \sin 2\theta_{12} \sin 2\theta_{23} \sin 2\theta_{13} \qquad \Delta_{ij} \equiv \frac{\Delta m_{ij}^2}{2E_\nu},\ \tilde{B}_\mp \equiv |A \mp \Delta_{13}|,\ A = \sqrt{2} G_F N_e$$

$\theta_{13}, \Delta_{12}L, \Delta_{12}/\Delta_{13}$ are small

A. Cervera et al., Nuclear Physics B 579 (2000)

Much messier!

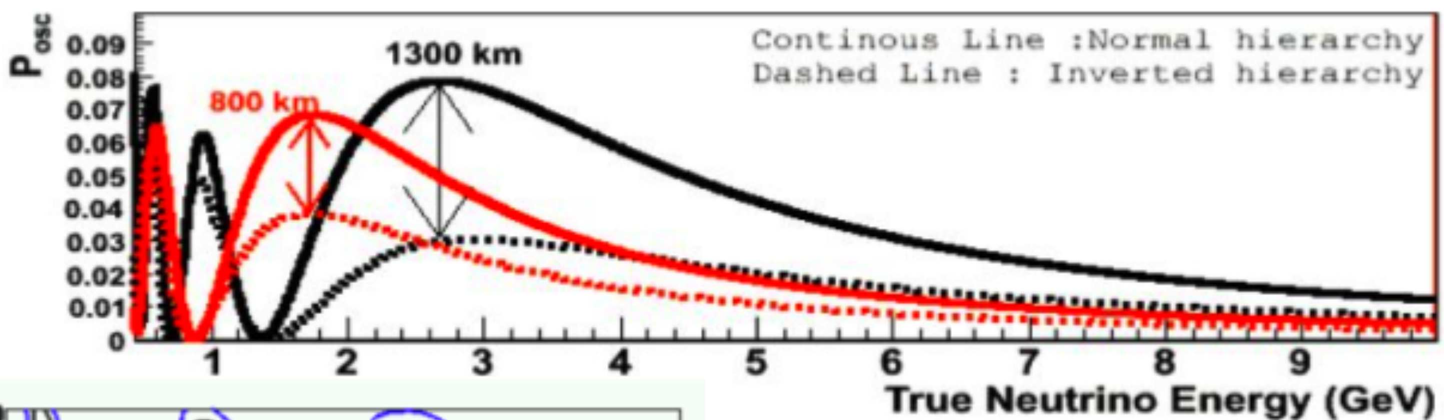
Mass hierarchy affects nu/nubar via matter effects (need long L)

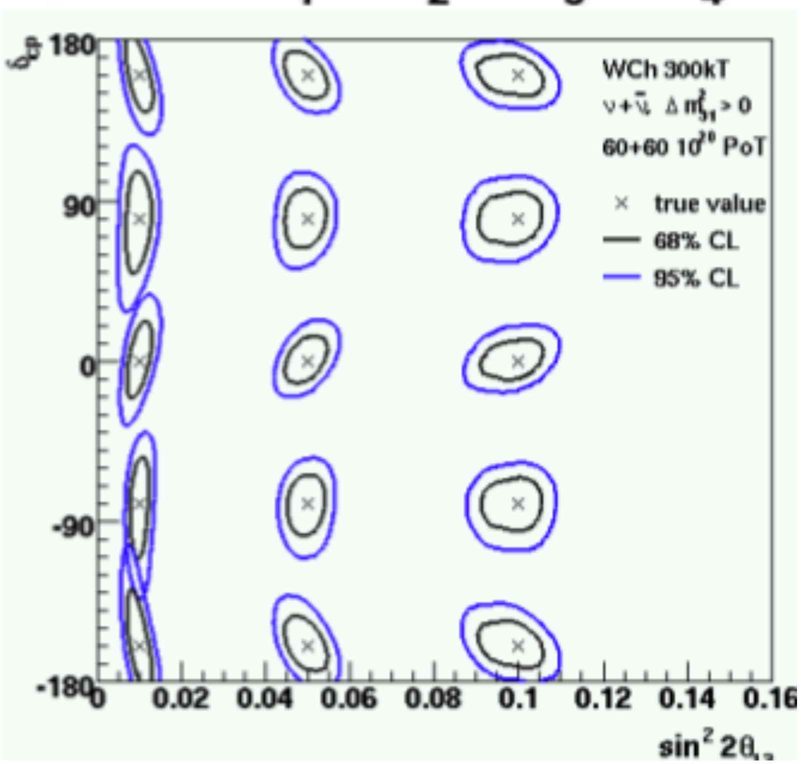
Need precision measurements of parameters....

Multiple measurements **(ν's and $\bar{\nu}$'s) at long L needed to resolve intrinsic ambiguities**

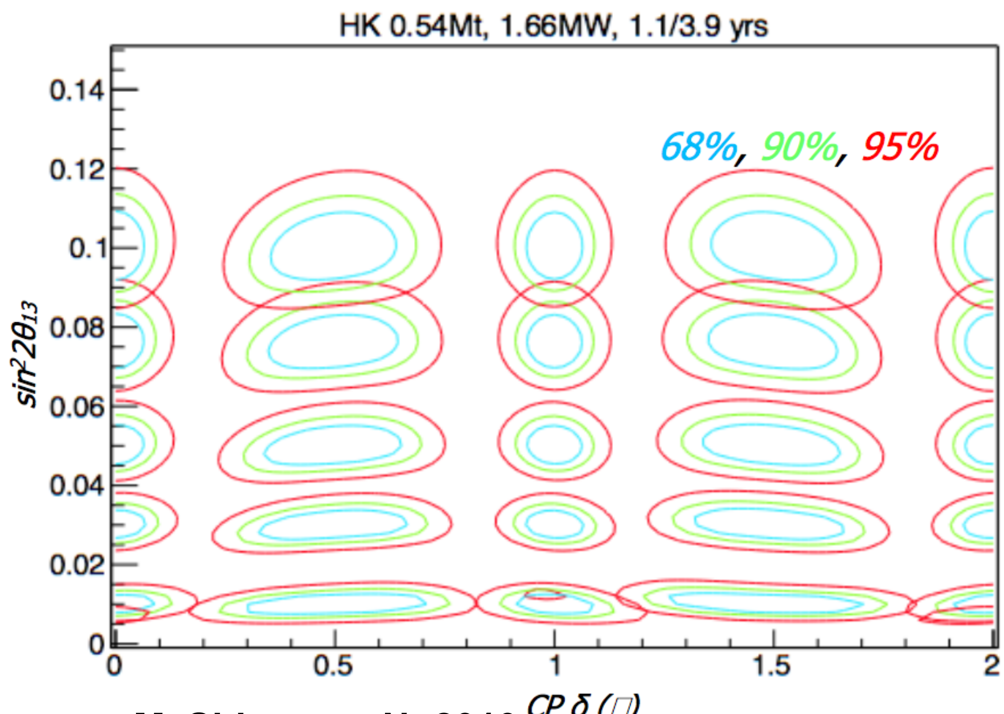
Next generation superbeam reach:

mass hierarchy and CP

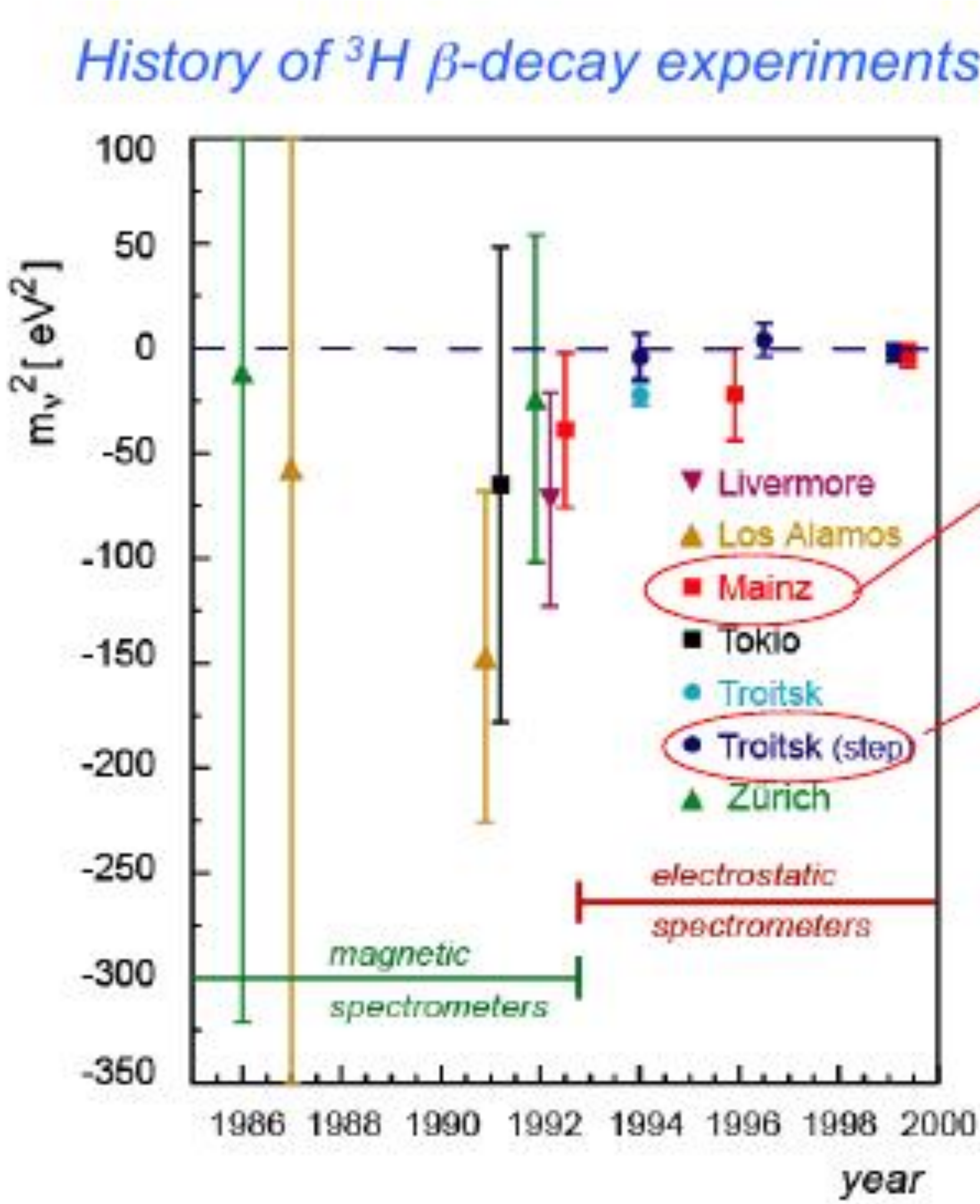




R. Svoboda, Nu2010



M. Shiozawa, Nu2010



Best so far from Mainz and Troitsk spectrometers

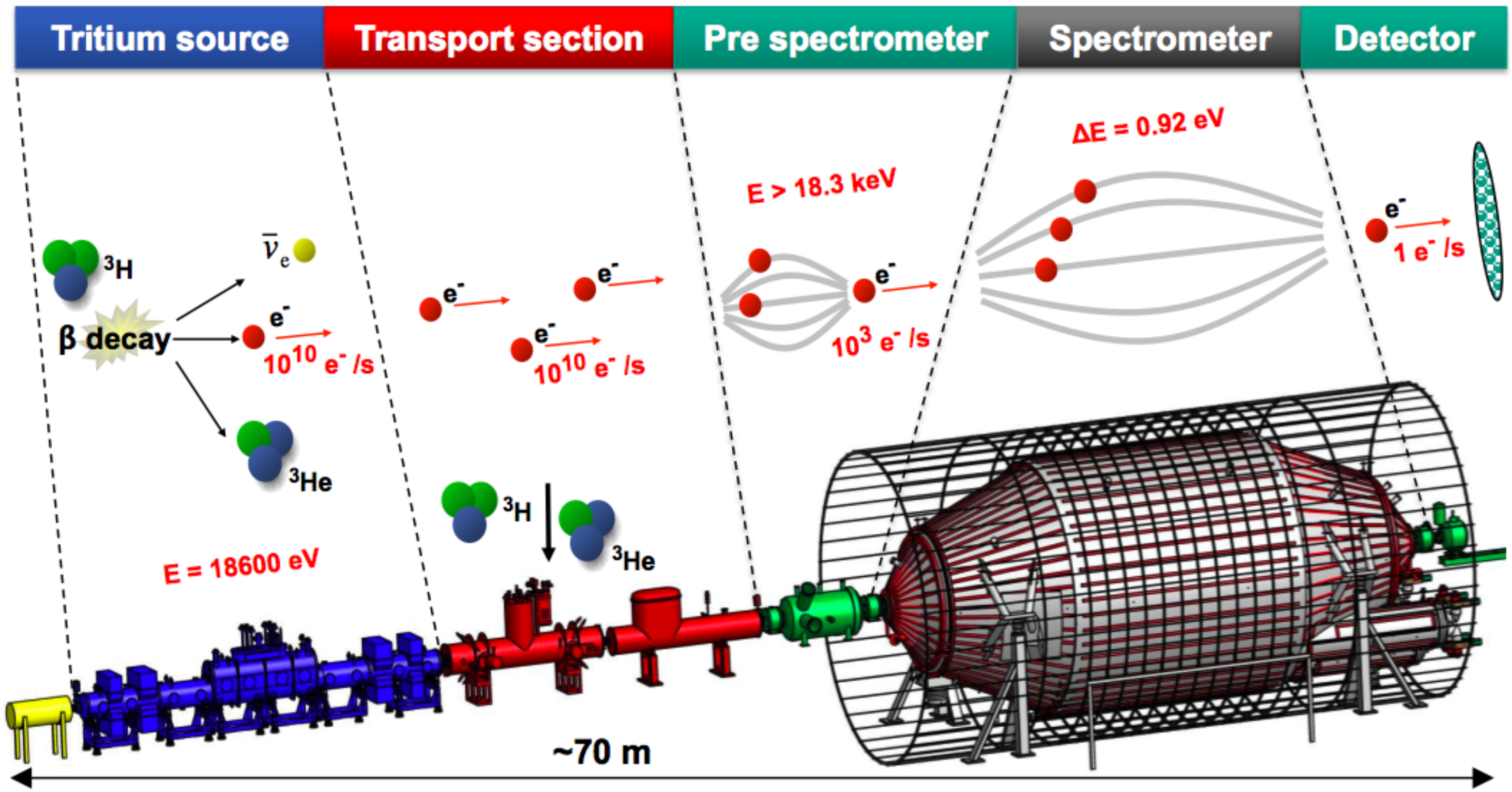
$m_\nu < 2.2$ eV

Now systematically limited

Bolometers:

$m_\nu < 15$ eV

KATRIN at Karlsruhe

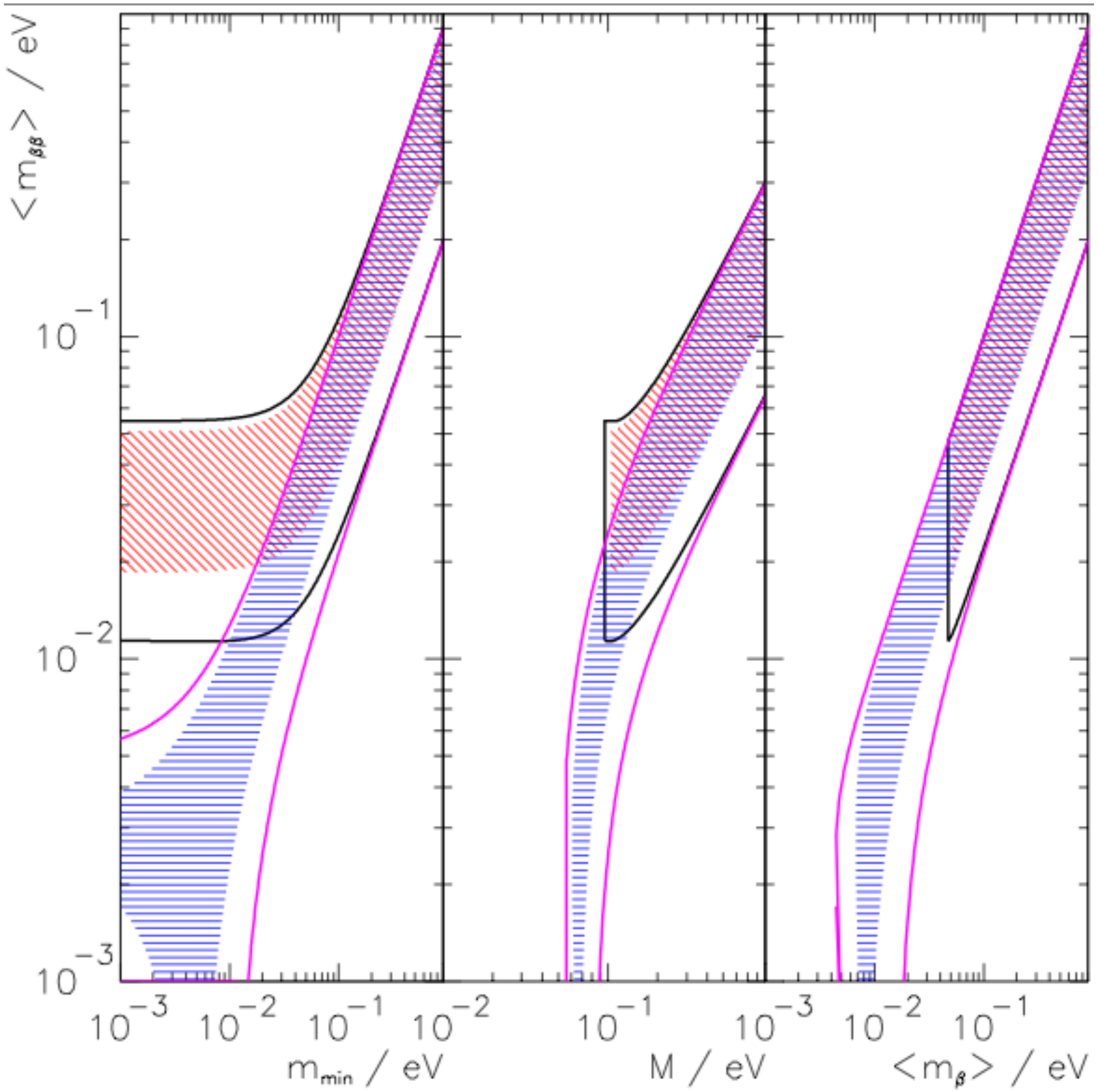


T. Thummler, Nu2010

- System integration in 2012
- Expect eventually 0.2 eV sensitivity

Neutrino absolute masses

effective
mass
in 0νββdk



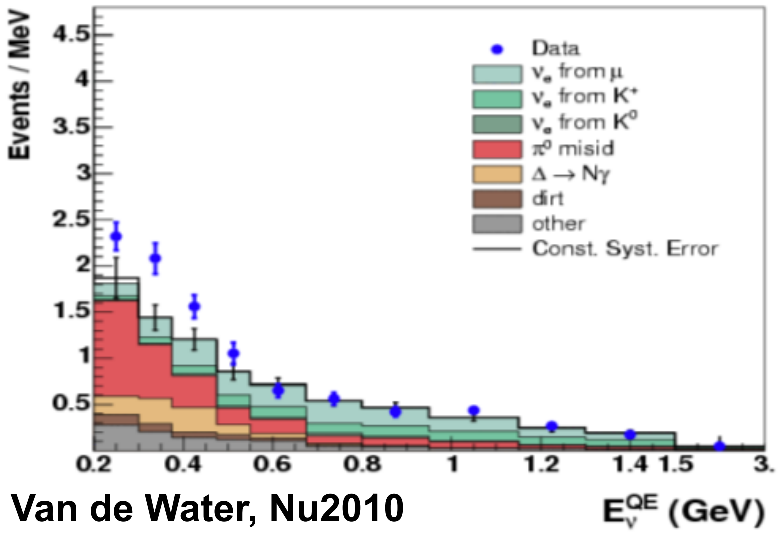
lightest mass

sum of
masses
(cosmology)

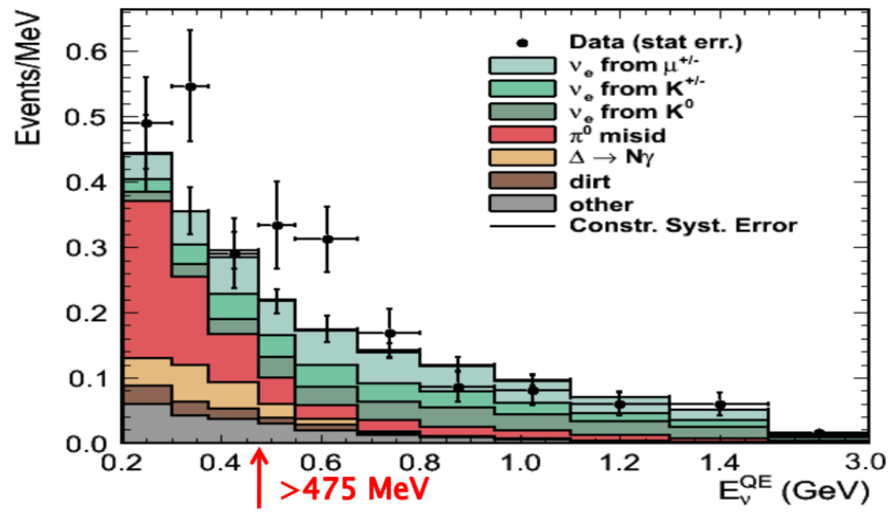
average mass
(kinematic
experiments)

Neutrinos

Antineutrinos



R. Van de Water, Nu2010



Neutrinos:

- unexplained 3 σ excess for E < 475 MeV
  (inconsistent w/ LSND oscillation)
- no excess for E > 475 MeV
  (inconsistent w/ LSND oscillation)

????

Antineutrinos:

- 1.3 σ excess for E < 475 MeV
- excess for E > 475 MeV
  (consistent w/ LSND, 3% consistent w/ no osc)

- will double statistics, at least
- also: μBooNE (LAr), other ideas (?)

Parenthesis 1)