Neutrino Experiment Overview

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WIN 2015, Heidelberg, Germany, June 8 2015

What I will cover

Status and prospects of experimental knowledge

Neutrino Oscillations

"Solar" sector
"Atmospheric" sector
The twist in the middle
Remaining unknowns in the 3-flavor picture:
MH and CP δ
Beyond 3-flavor?

The mass pattern

Absolute Mass

Status and prospects

The mass scale

Majorana vs Dirac?

Overview of NLDBD

The mass nature

Missing: cross sections, exotic ν properties, intersections w/astrophysics...

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The three-flavor paradigm

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

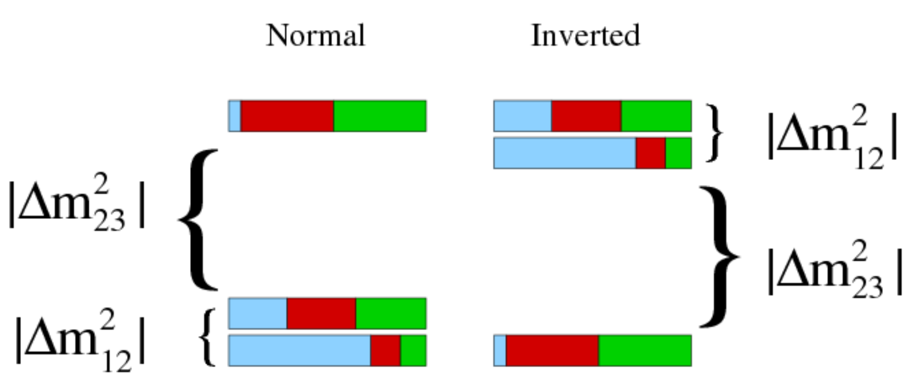
Parameterize mixing matrix U as

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

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

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

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

Oscillation probabilities in a 3-flavor context

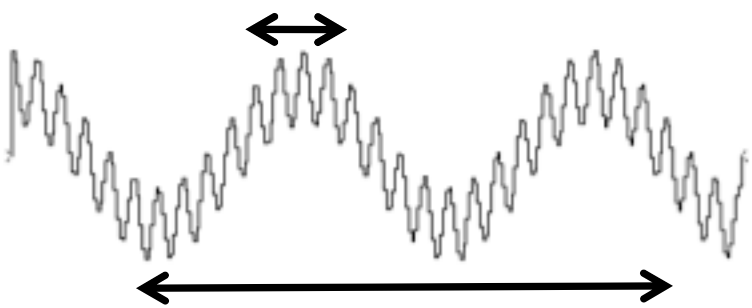
$$|\nu_f\rangle = \sum_{i=1}^{N} U_{fi}^* |\nu_i\rangle$$

$$\Delta m_{ij}^2 \equiv m_i^2 - m_j^2 \qquad (\mathrm{L\ in\ km,\ \ E\ in\ GeV,\ \ m\ in\ eV})$$

$$P(\nu_f \to \nu_g) = \delta_{fg} - 4\sum_{i>j} \Re(U_{fi}^* U_{gi} U_{fj} U_{gj}^*) \sin^2(1.27\Delta m_{ij}^2 L/E)$$

$$\pm 2\sum_{i>j} \Im(U_{fi}^* U_{gi} U_{fj} U_{gj}^*) \sin(2.54\Delta m_{ij}^2 L/E)$$

oscillatory behavior in L and E



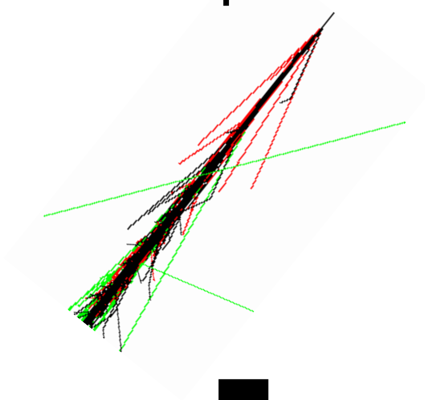
$$|\Delta m_{23}^2| >> |\Delta m_{12}^2|$$ ➔ two frequency scales

For appropriate L/E (and U_{ij}), oscillations "decouple", and probability can be described by the 2-flavor expression

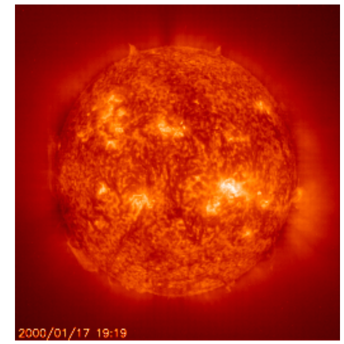
$$P(\nu_f \to \nu_g) = \sin^2 2\theta \sin^2\left(\frac{1.27\Delta m^2 L}{E}\right)$$

We now have clean flavor-transition signals in two 2-flavor sectors

atmospheric

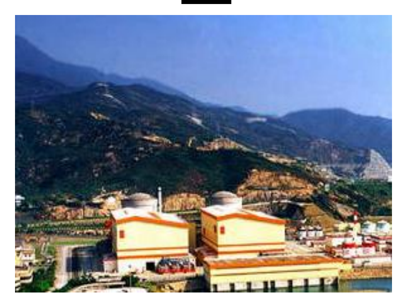


solar



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

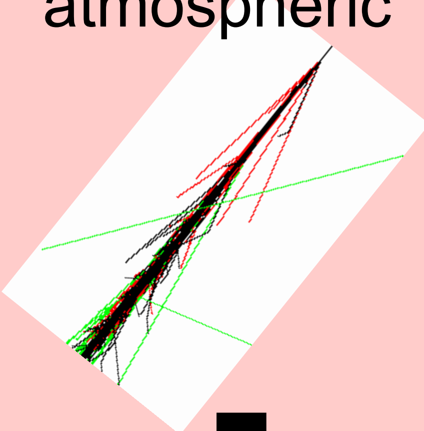
beams



reactor

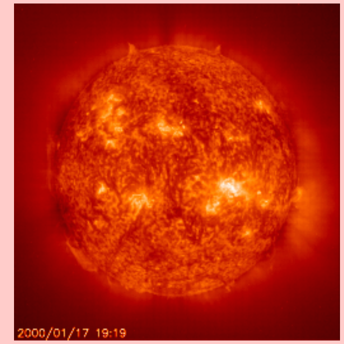
We now have clean flavor-transition signals in two 2-flavor sectors

atmospheric



signal with
“wild” neutrinos...

solar



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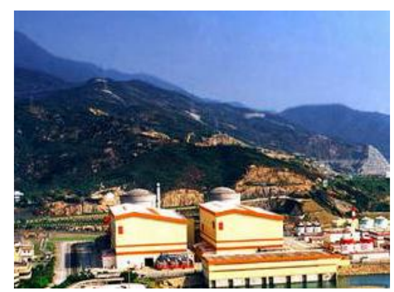
beams



reactor

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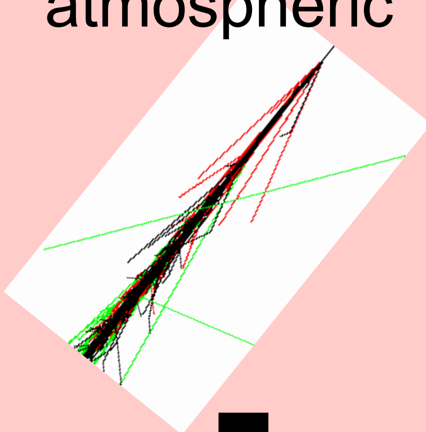
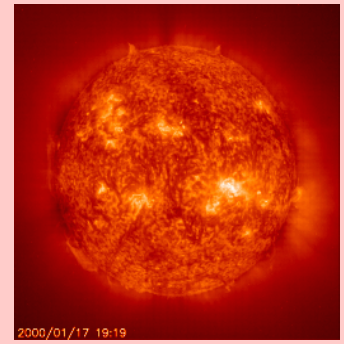
atmospheric



signal with
“wild” neutrinos...

solar



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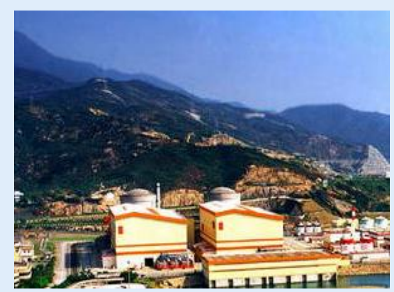
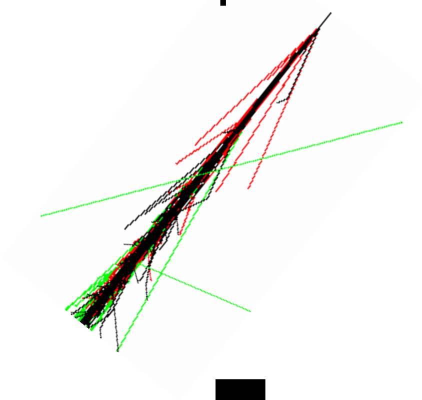
confirmed with
“tame” ones...

beams



reactor

atmospheric



$$
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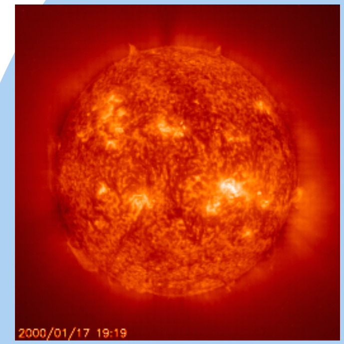
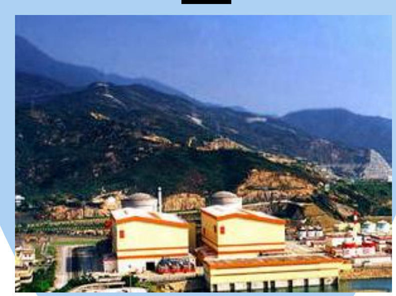
$$

beams

solar



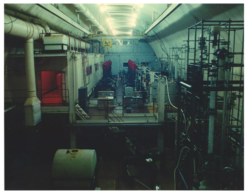
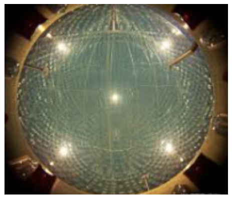


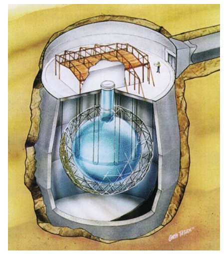
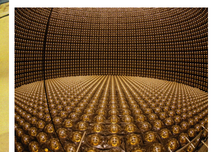
reactor

First, status of the “solar” sector

Solar and reactor neutrinos

Multiple measurements over ~5 decades

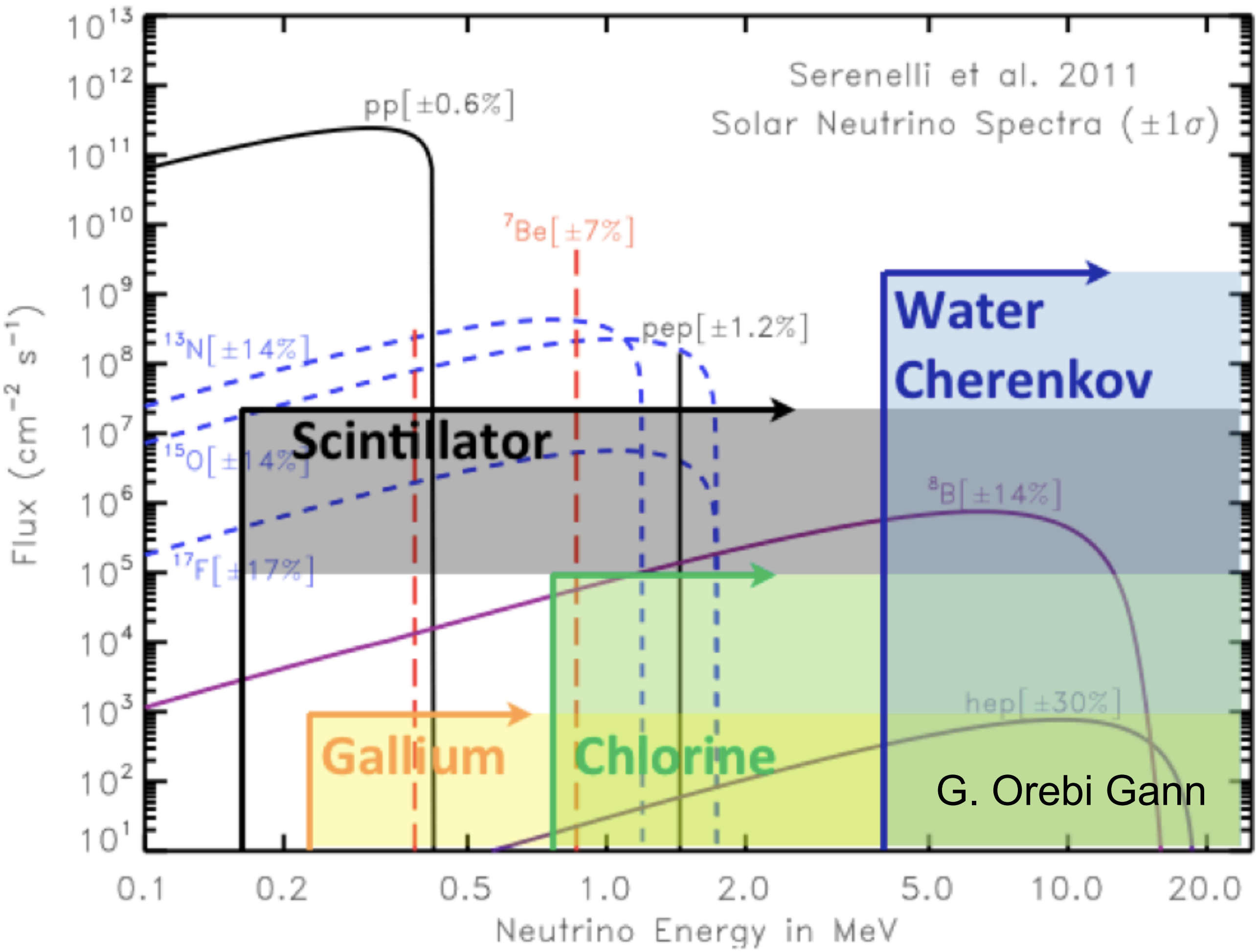




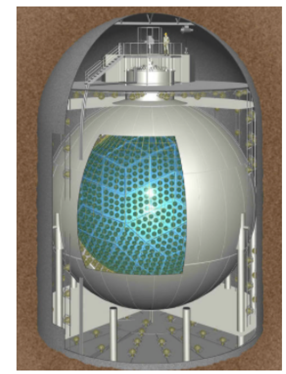
ν_e disappearance, confirmed directly as

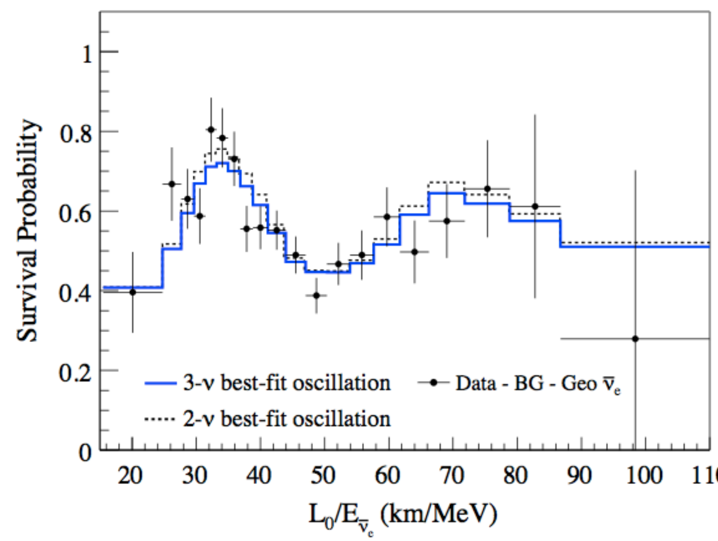
$$\nu_e \rightarrow \nu_{\mu,\tau}$$

by SNO....



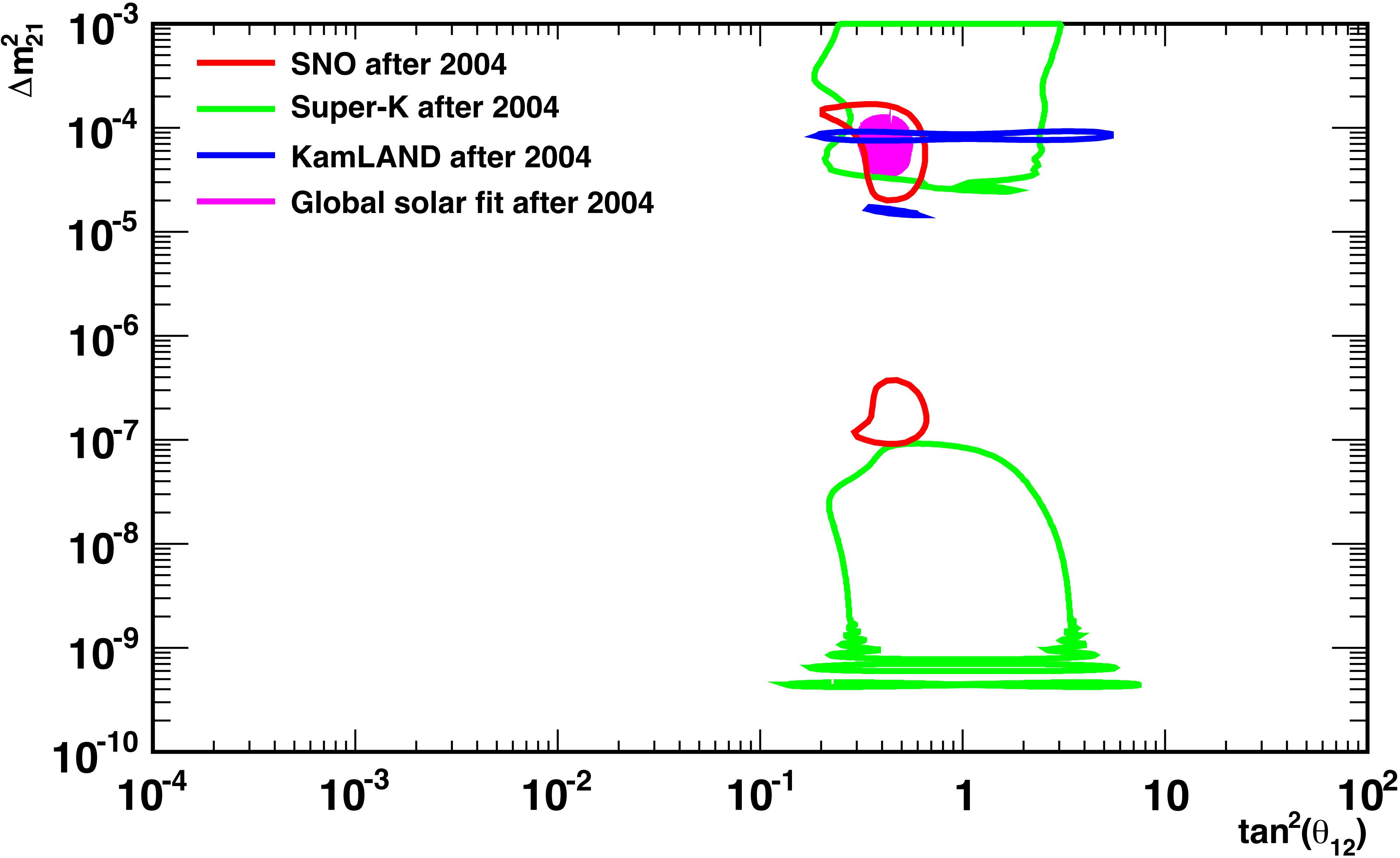
...and wavelength measured precisely w/ reactor $\bar{\nu}_e$ by KamLAND



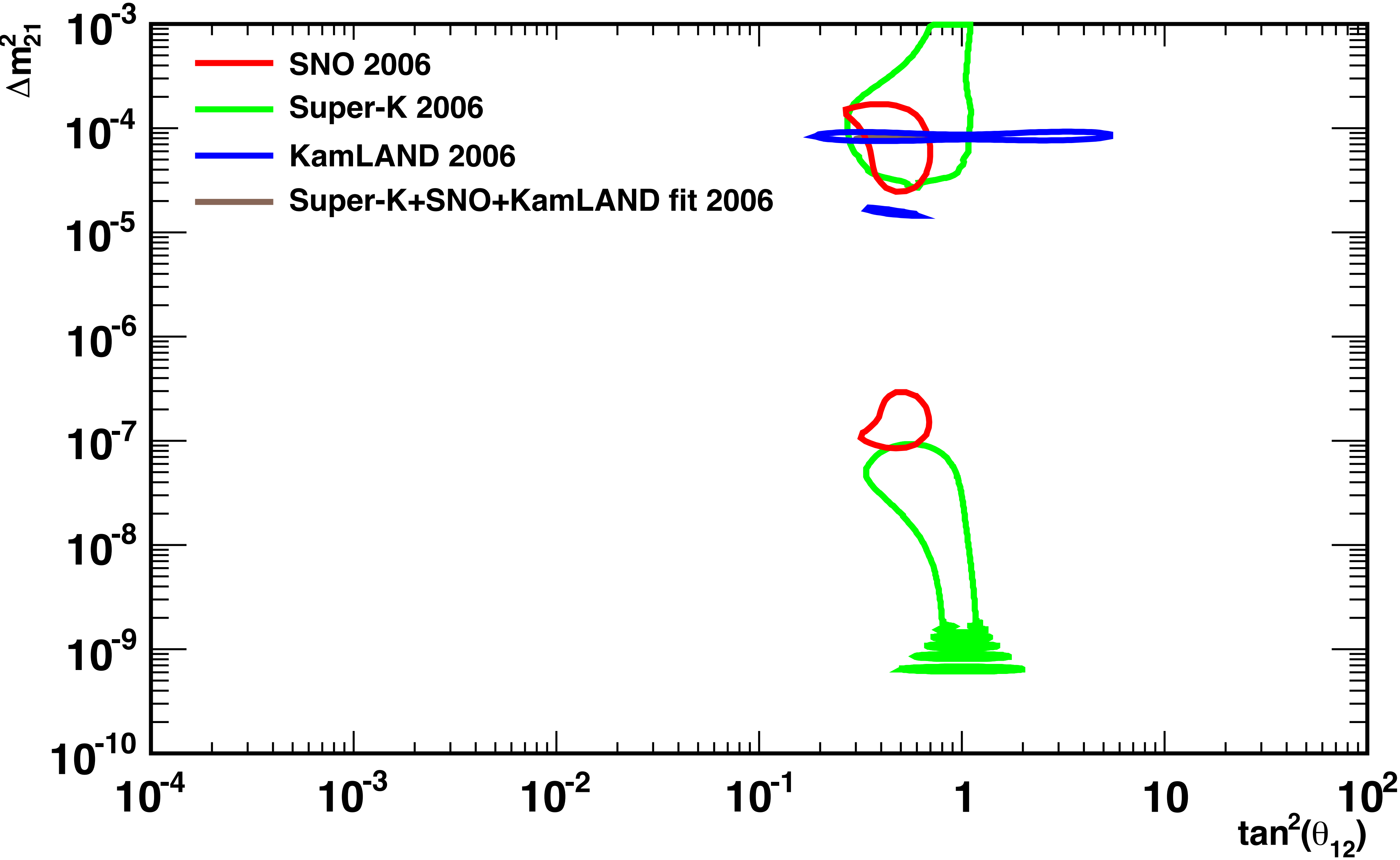


A “movie” over 8 years of solar (12) parameter space

plots made by H. Lim from
H. Murayama’s PDG web page

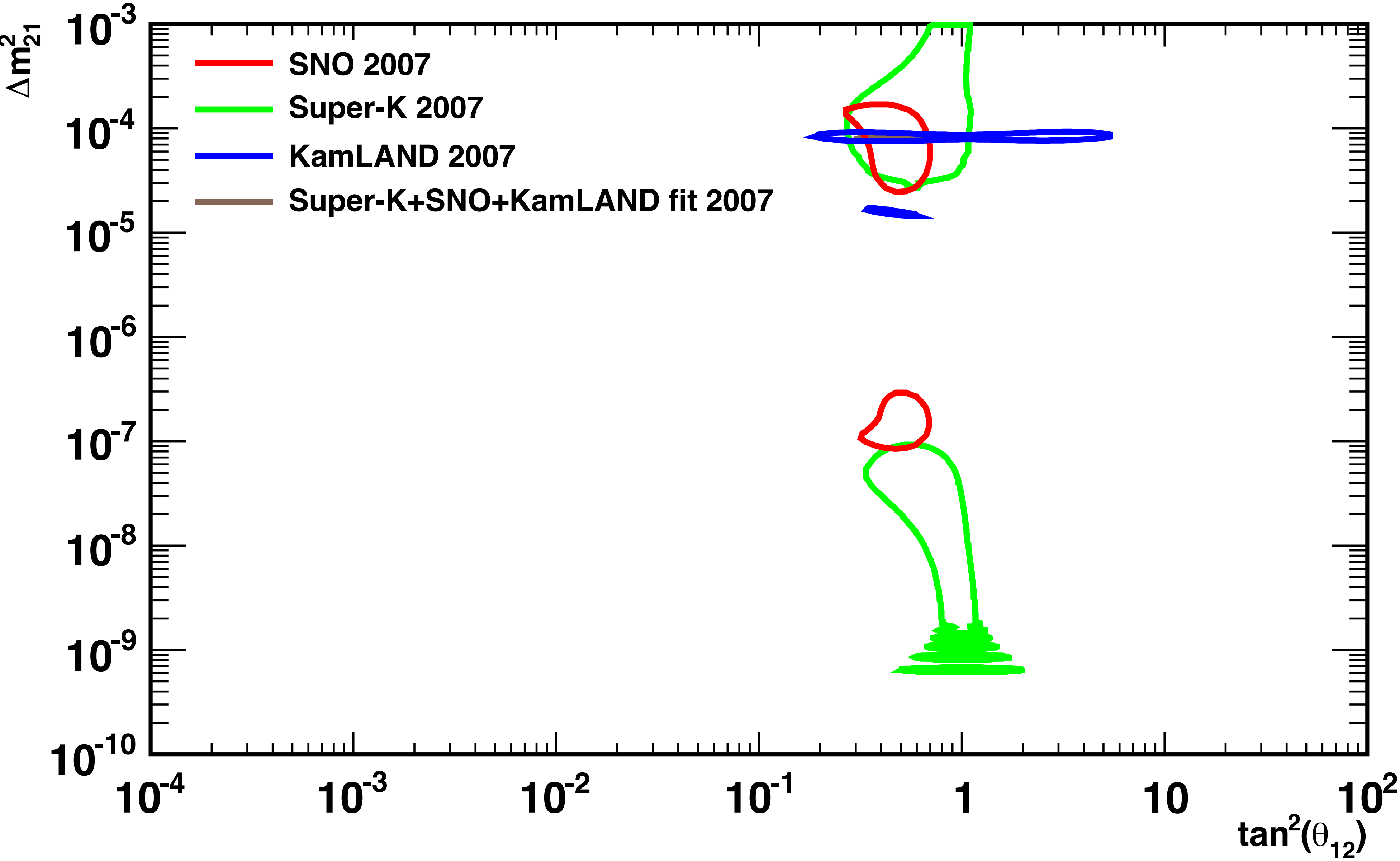

Δm^2_{21}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
SNO after 2004
Super-K after 2004
KamLAND after 2004
Global solar fit after 2004
10^{-4}
10^{-3}
10^{-2}
10^{-1}
1
10
10^{2}
$\tan^2(\theta_{12})$

2004



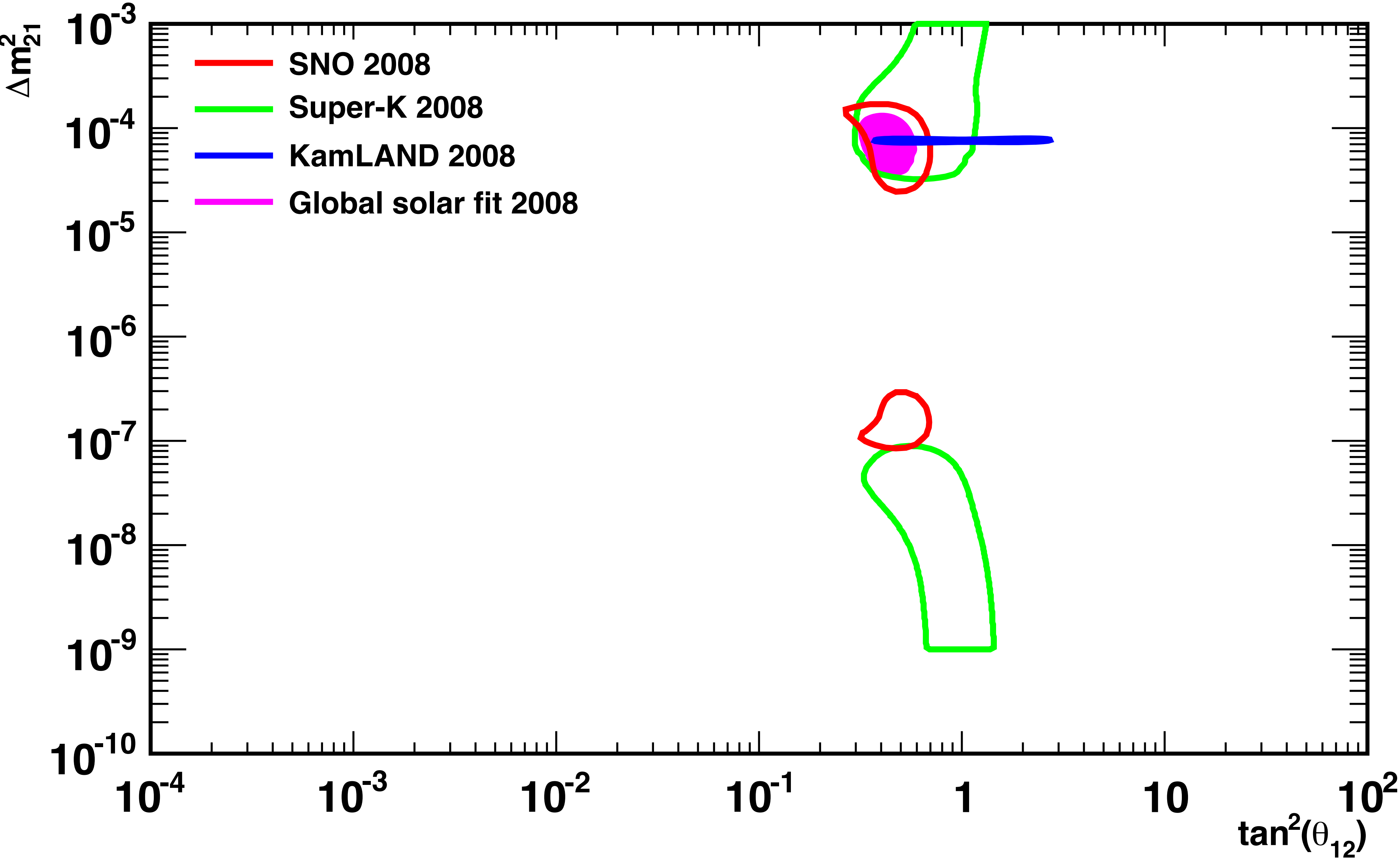
Δm^2_{21}
SNO 2006
Super-K 2006
KamLAND 2006
Super-K+SNO+KamLAND fit 2006
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-4} 10^{-3} 10^{-2} 10^{-1} 1 10 10^{2}
$\tan^2(\theta_{12})$

2006

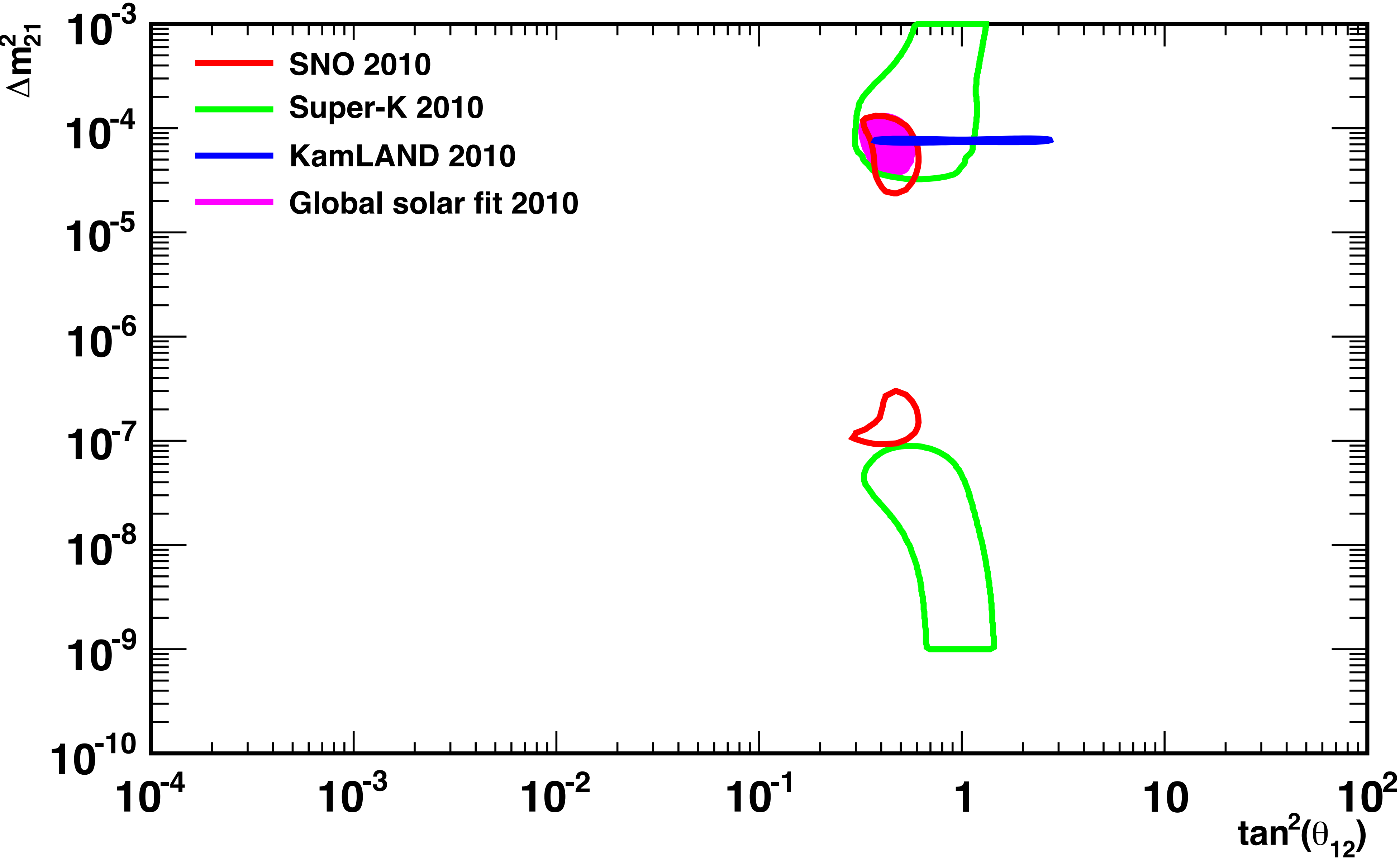


Δm^2_{21}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
SNO 2007
Super-K 2007
KamLAND 2007
Super-K+SNO+KamLAND fit 2007
10^{-4}
10^{-3}
10^{-2}
10^{-1}
1
10
10^{2}
$\tan^2(\theta_{12})$

2007

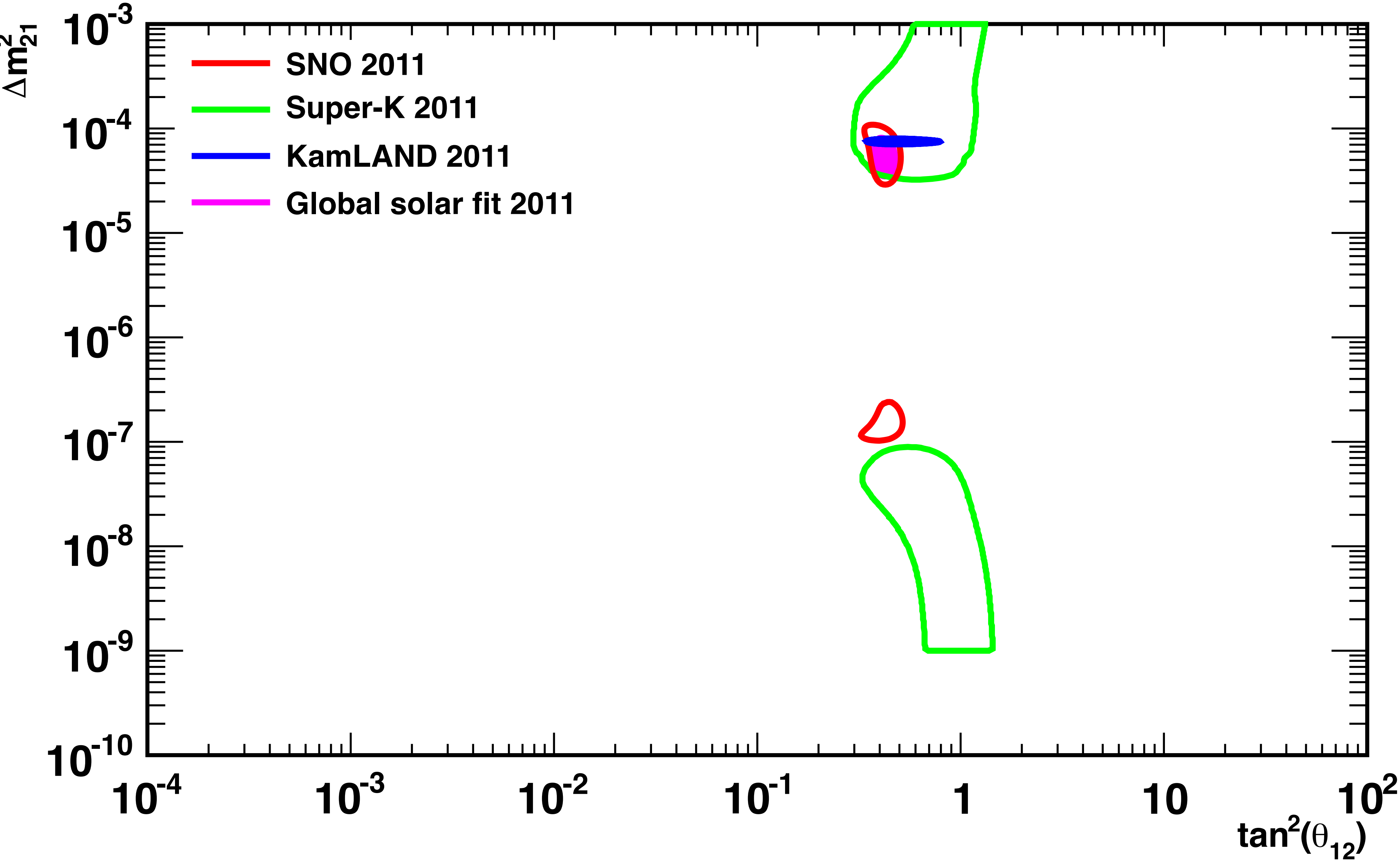

SNO 2008
Super-K 2008
KamLAND 2008
Global solar fit 2008
Δm^2_{21}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
1
10
10^{2}
$\tan^2(\theta_{12})$

2008



Δm^2_{21}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
SNO 2010
Super-K 2010
KamLAND 2010
Global solar fit 2010
10^{-4}
10^{-3}
10^{-2}
10^{-1}
1
10
10^{2}
$\tan^2(\theta_{12})$

2010



Δm^2_{21}
10^{-3}
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SNO 2011
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KamLAND 2011
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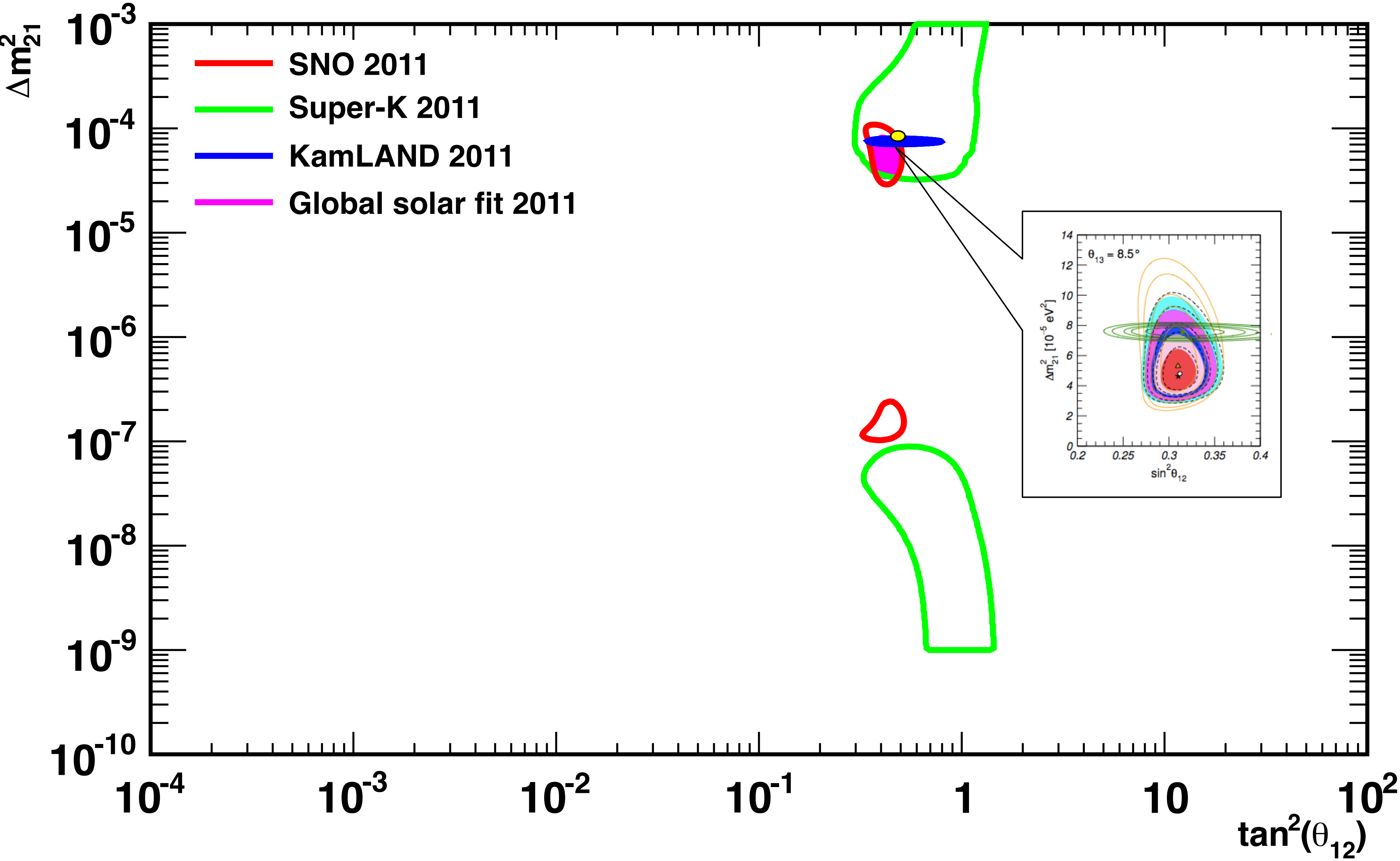
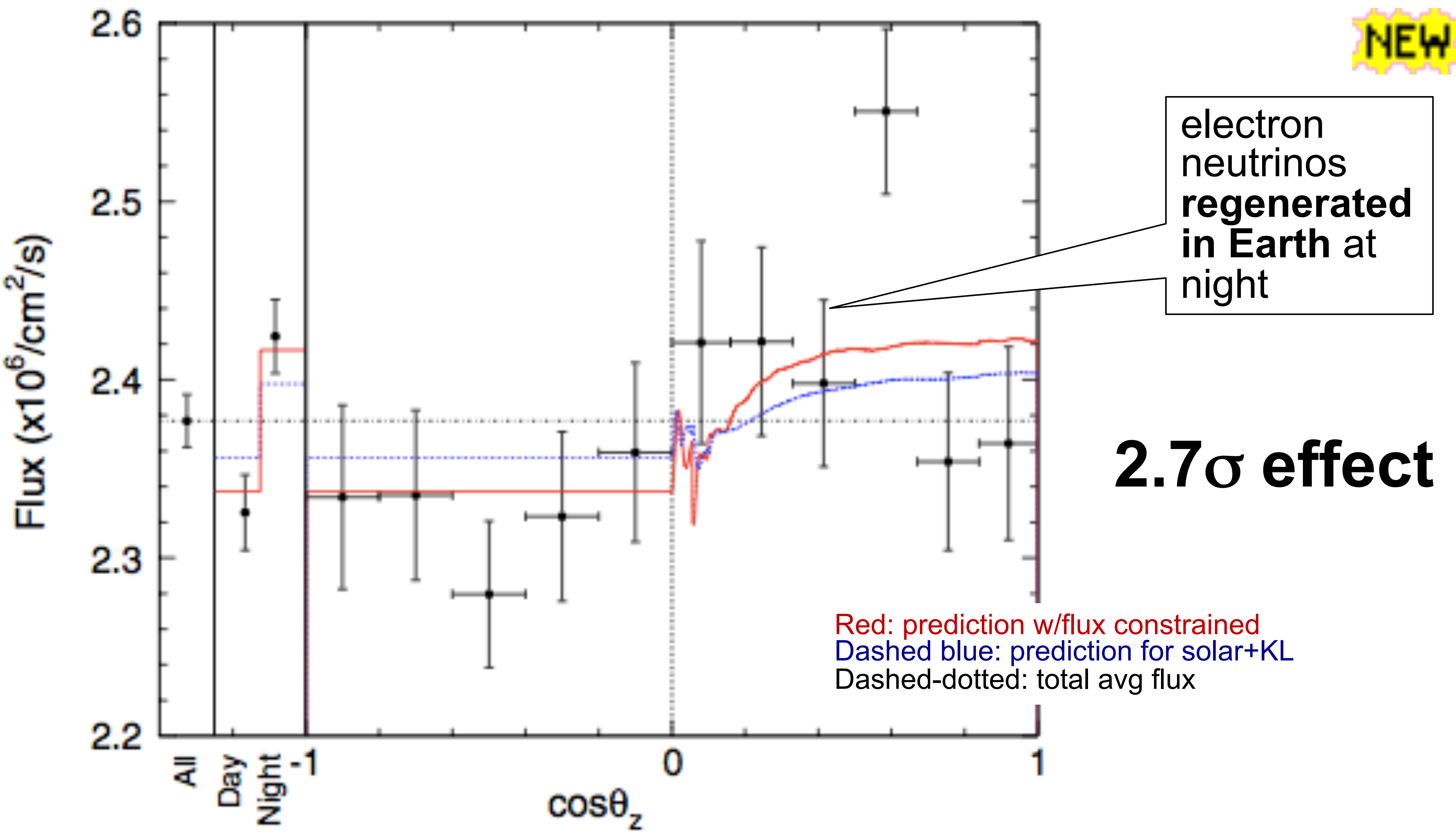
2011



2011

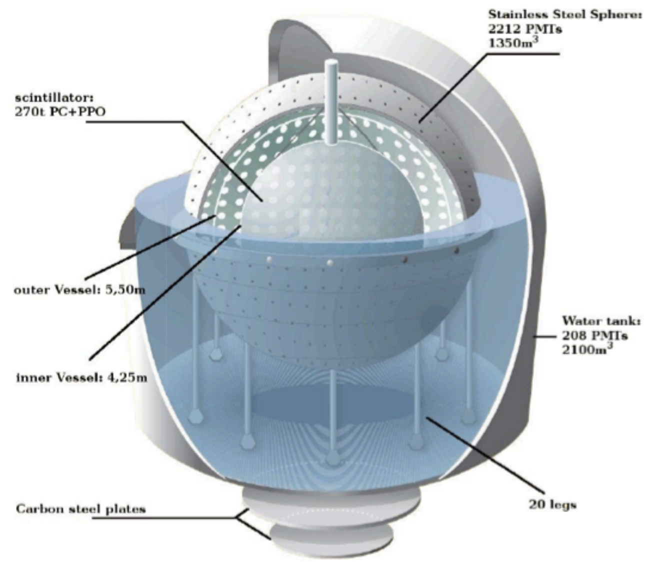
Recent global fit (solar & KL) from Gonzalez-Garcia et al., JHEP 11(2014) 052

From Super-K: **day/night asymmetry observed; first direct observation of matter effects**

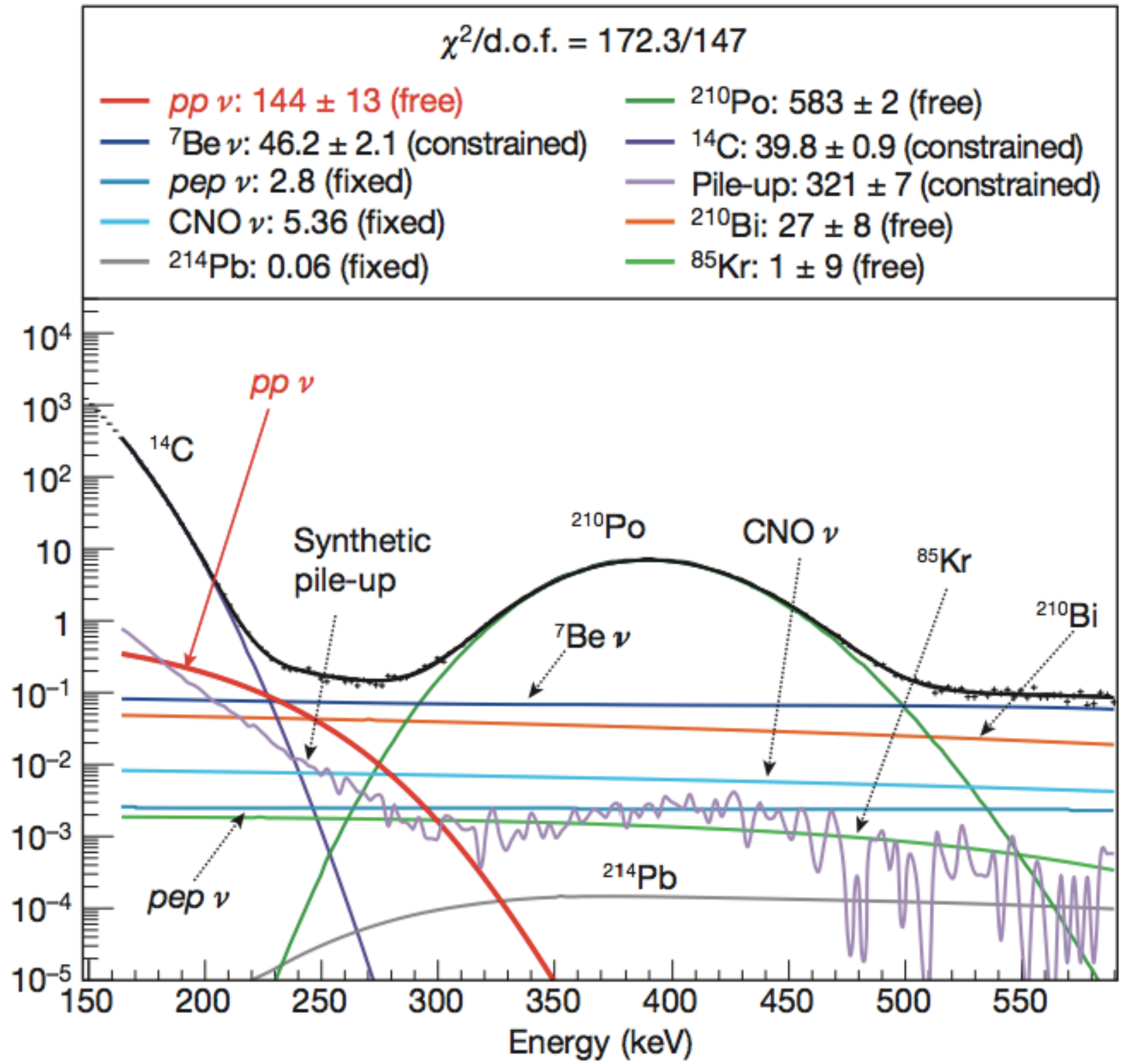


2.7σ effect

First real-time measurement of the **solar pp flux** by Borexino... a heroic victory over background



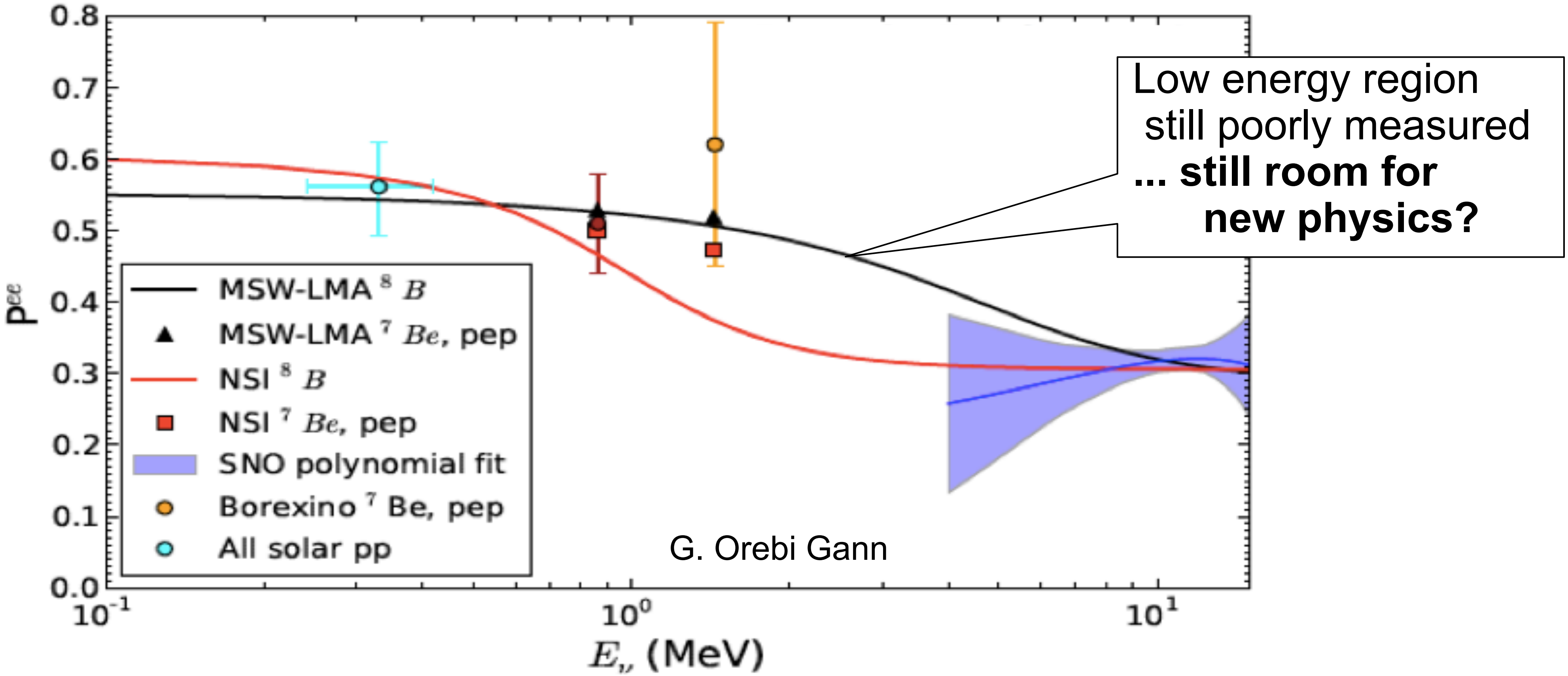
$$\nu_{e,x} + e^- \rightarrow \nu_{e,x} + e^-$$



Nature 512 (2014) 385

What's next for solar neutrinos?

We now have the basic picture, but
there are are still gaps & discrepancies...

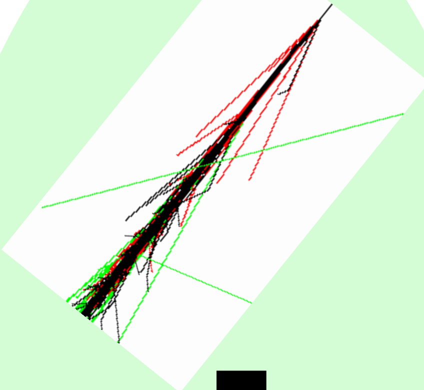


...and still some solar physics puzzles ➔ neutrino info can help

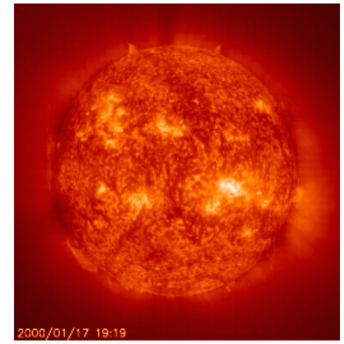
Future detectors: SNO+, Hyper-K, JUNO, DUNE
(Theia, LENA, LENS...)

See sessions Neutrino-1 and 2

atmospheric



solar



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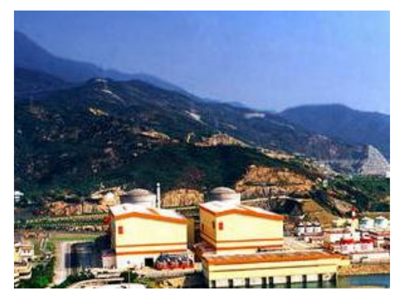
beams

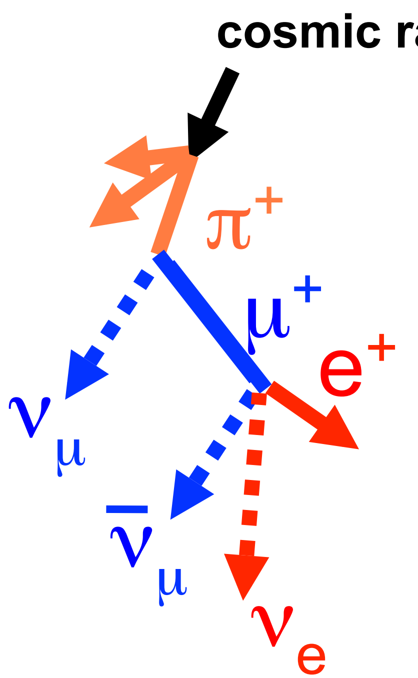


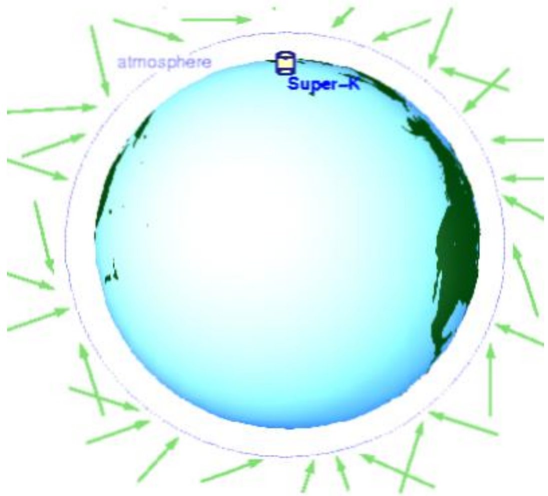
reactor

Next, the
“atmospheric”
sector

Atmospheric neutrinos

The neutrinos are free, and have
a range of baselines & energies





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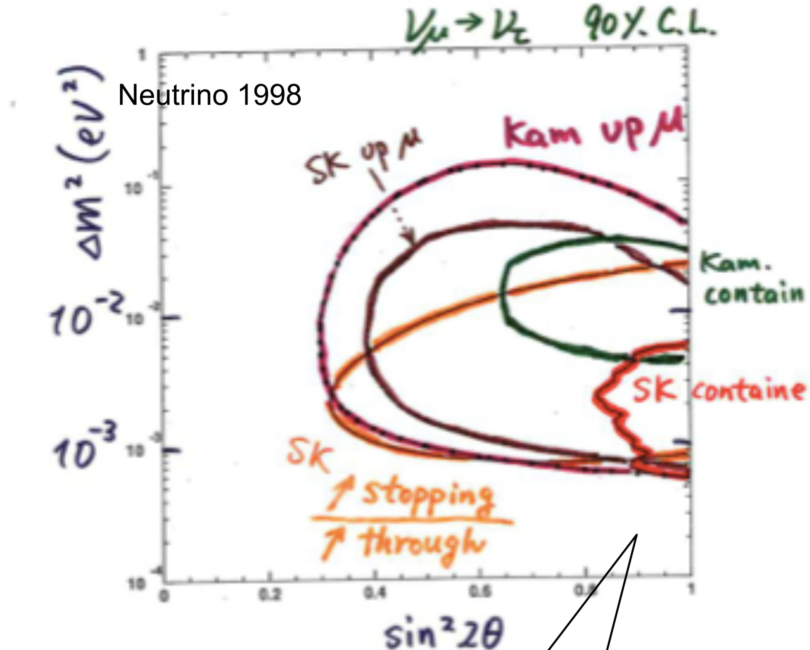

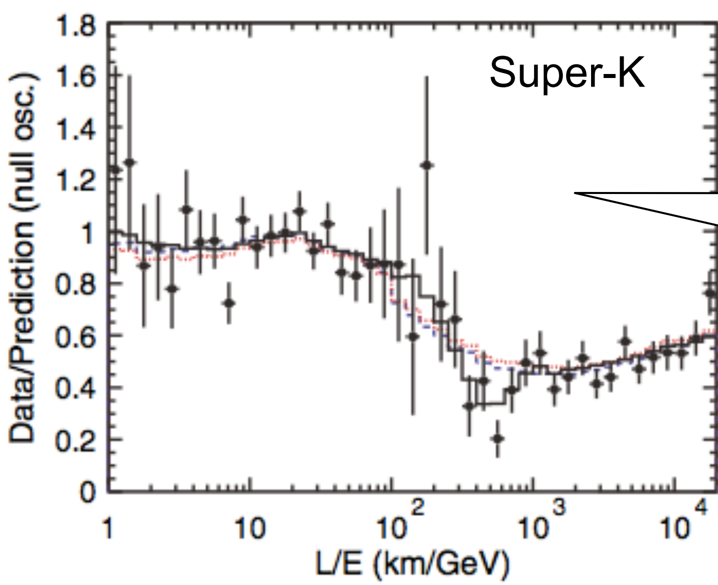

Clear ν_μ disappearance

Well described by
23 oscillation parameters:
$|\Delta m^2_{32}| \sim 2 \times 10^{-3}\ eV^2$,
~ maximal mixing

Long-baseline beam experiments: taming the source

Past Current Future

K2K

KEK to Kamioka
250 km, 5 kW

Long-baseline beam experiments: taming the source

Past — Current — Future

K2K
KEK to Kamioka
250 km, 5 kW

MINOS (+)
FNAL to Soudan
734 km, 400 kW

CNGS
CERN to LNGS
730 km, 400 kW

NOνA
FNAL to Ash River
810 km, 700 kW

T2K
J-PARC to Kamioka
295 km, 380-750 kW

Long-baseline beam experiments: taming the source

Past → Current → Future

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295 km, 380-750 kW

LBNF/DUNE
FNAL to Homestake
1300 km, 1.2 MW (➔2.3 MW)

Hyper-K
J-PARC to Kamioka
295 km, 750 kW
(➔..)

Long-baseline beam experiments: taming the source

Past — Current — Future

K2K
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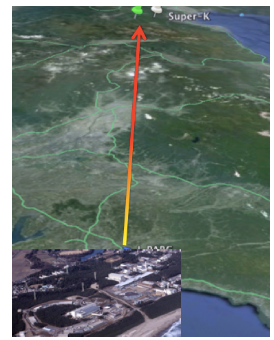
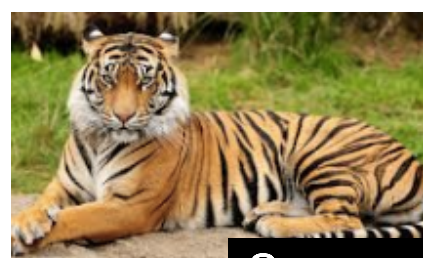


Hyper-K
J-PARC to Kamioka
295 km, 750 kW
(➔..)

And beyond...
ESSnuB,
neutrino factories

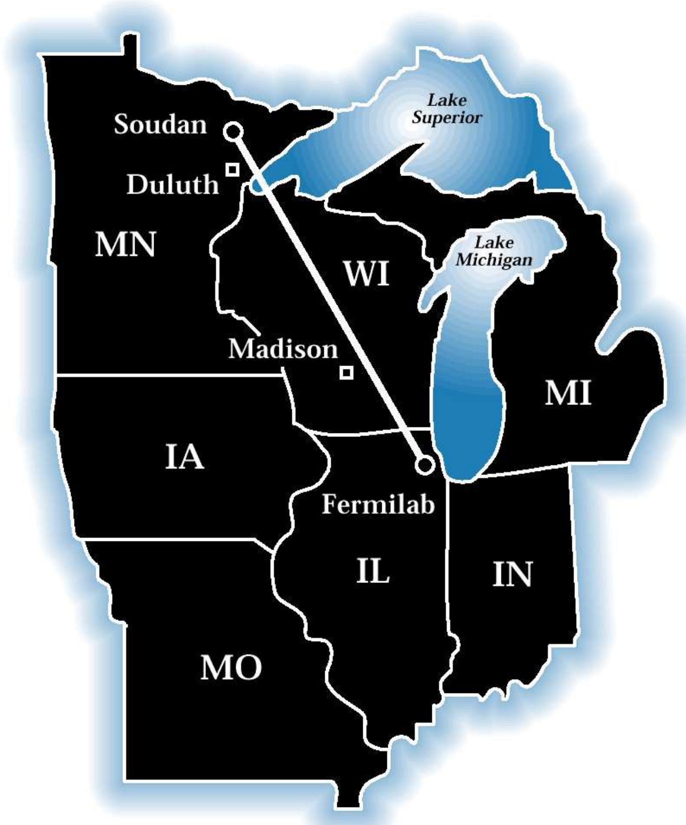


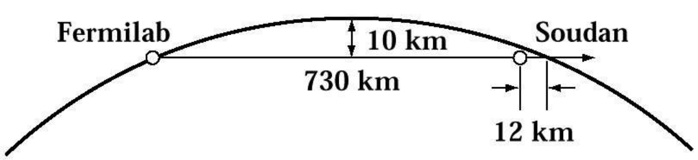



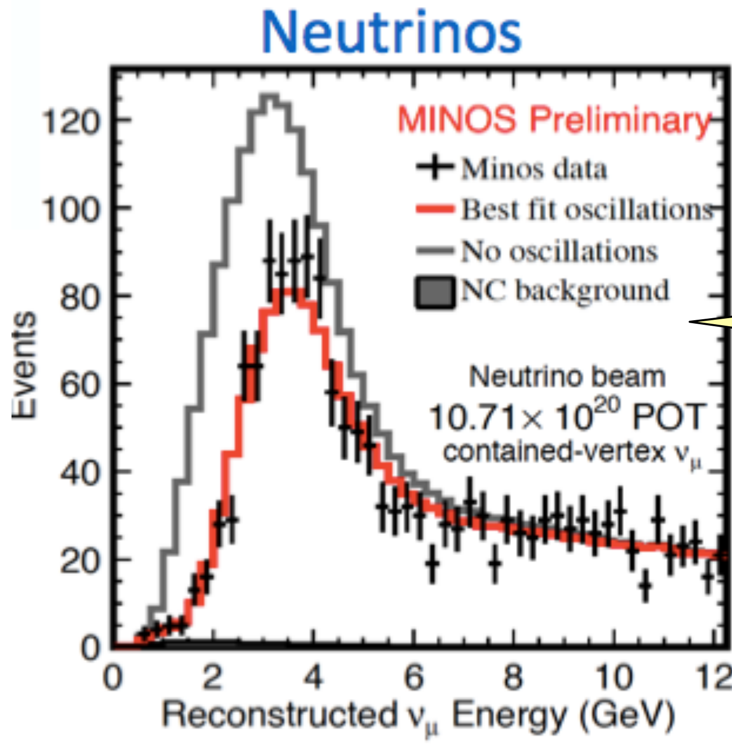

See sessions Neutrino-4,5,8

MINOS

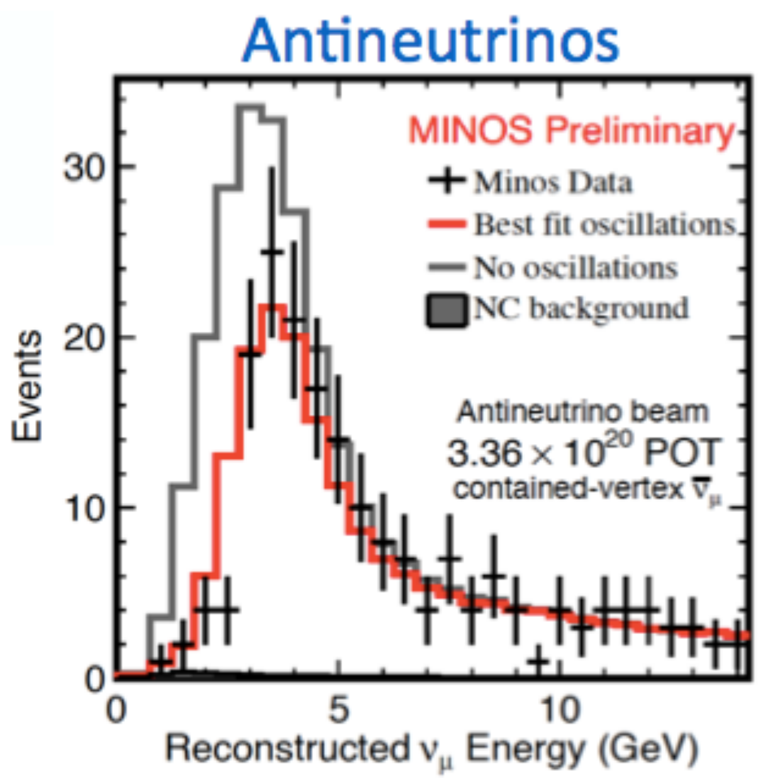
in US made precision measurements of ν_μ disappearance







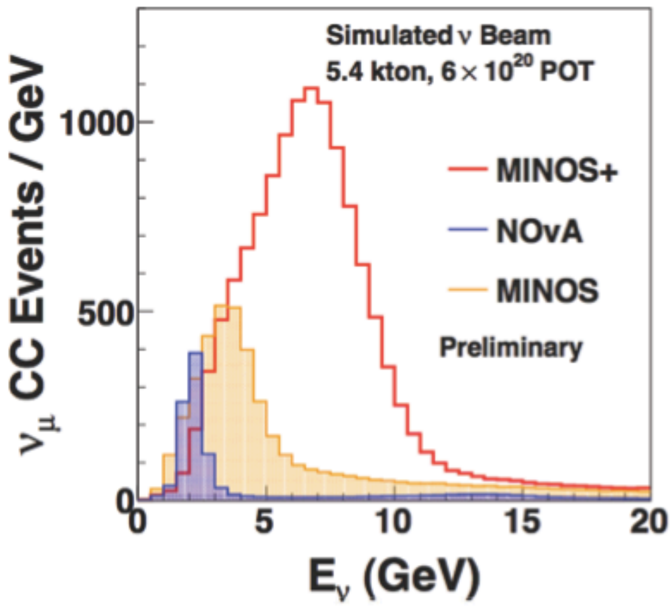
suppression of μ-like events

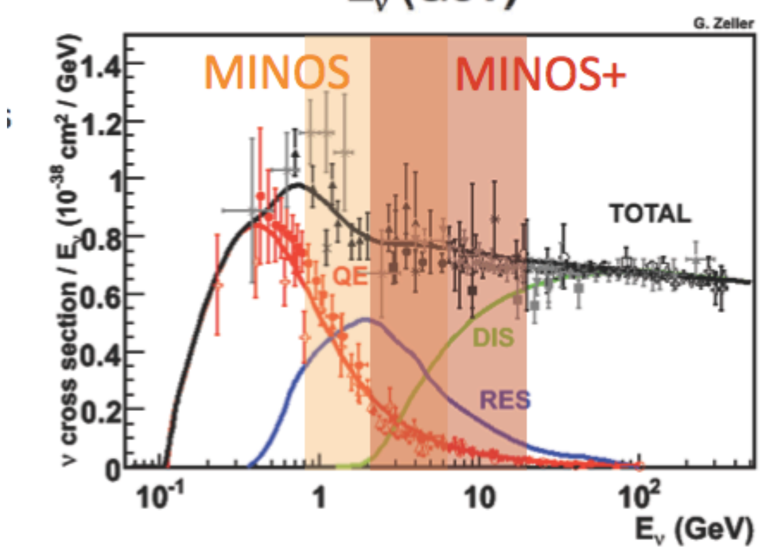


Magnetized iron tracker enables sign selection and event-by-event antineutrino selection

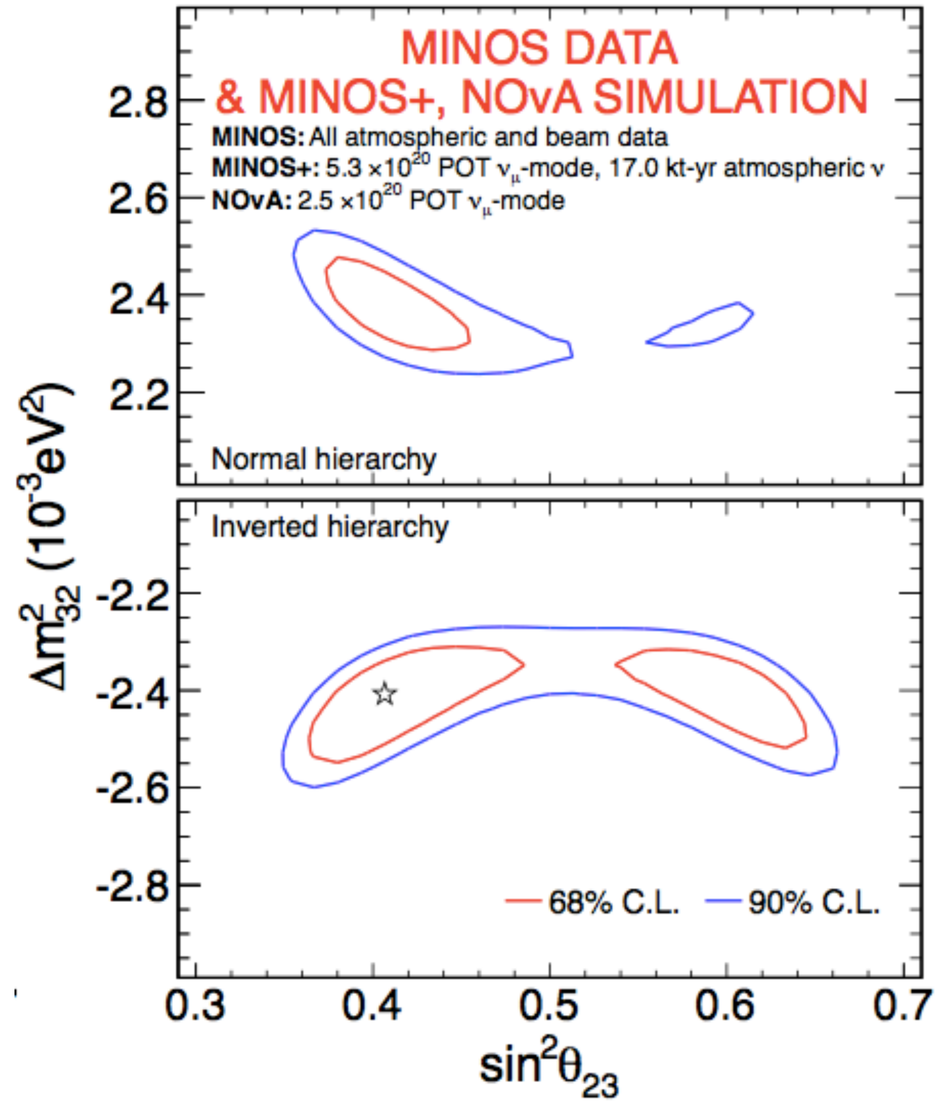
A. Timmons, CIPANP 2015

MINOS+





upgraded NuMi beam since 2013
@higher energy

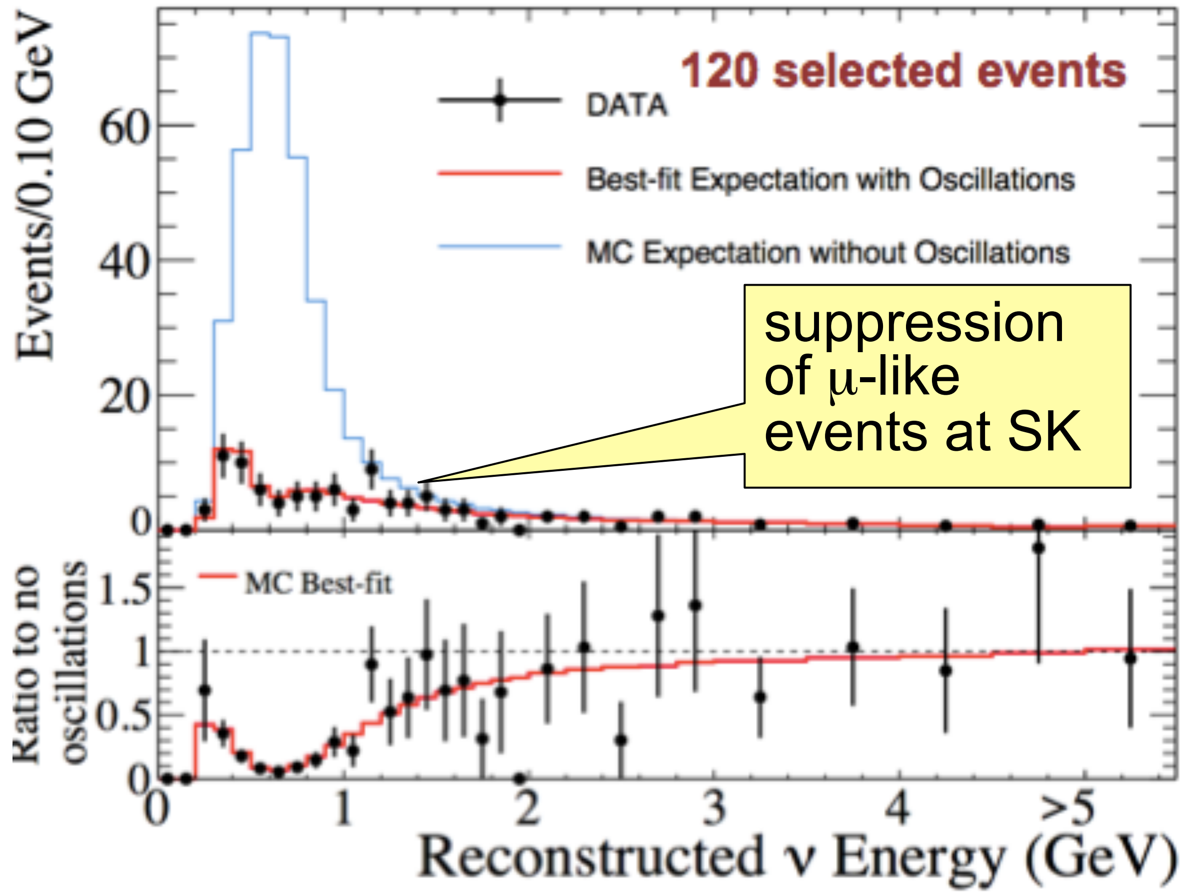


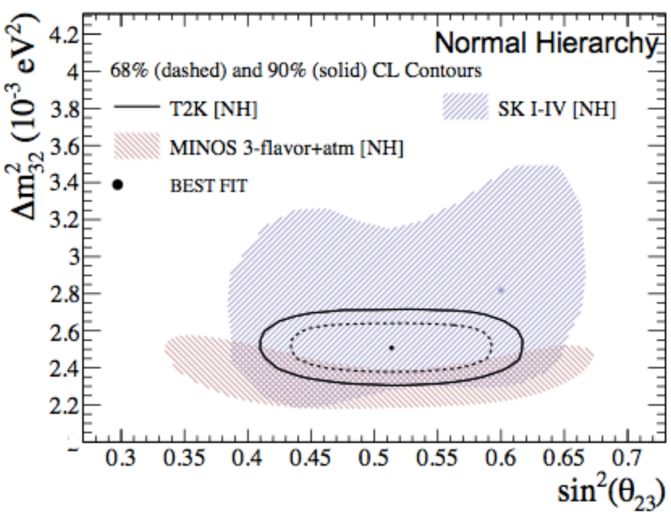
New results:
three-flavor
oscillations w/
beam &
atmospheric ν's

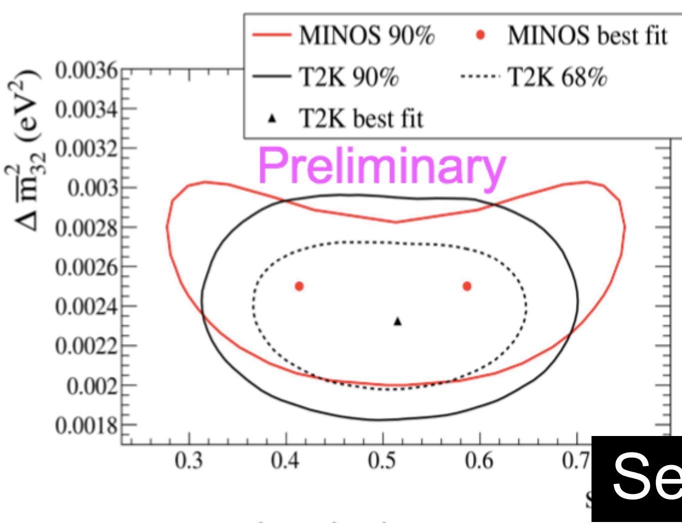
Squeezing down $|\Delta m^2_{23}|$!

ν_μ disappearance results from T2K

current best measurement of θ_{23}



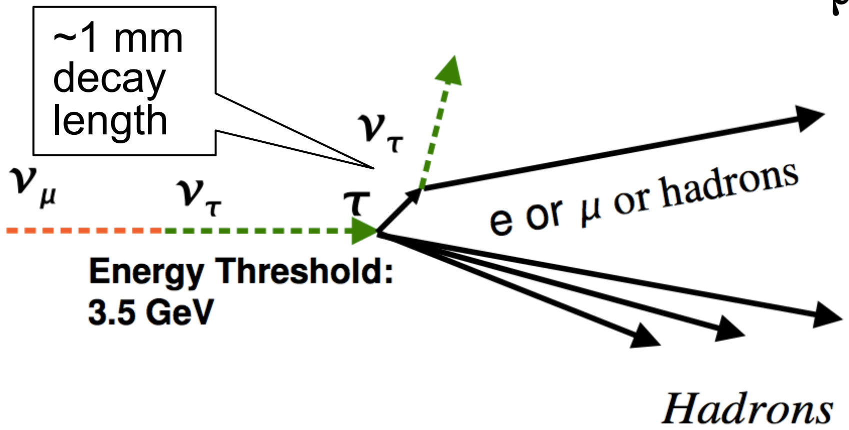




And new T2K **anti-ν_μ** result

See session Neutrino-5

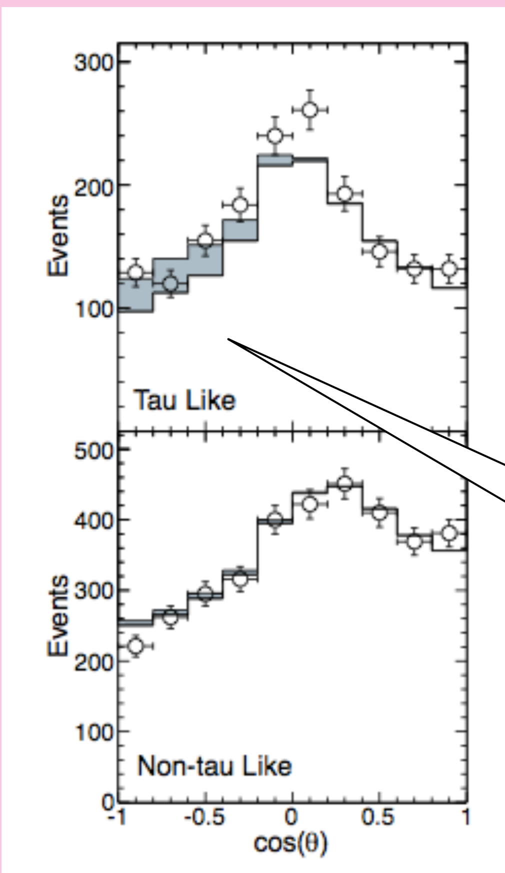
Is the disappearance $\nu_\mu \rightarrow \nu_\tau$?



Hard to see
τ's explicitly:
require >3.5 GeV,
multiple decay modes

Super-K atmospheric ν's

Phys.Rev.Lett. 110 (2013) 18, 181802

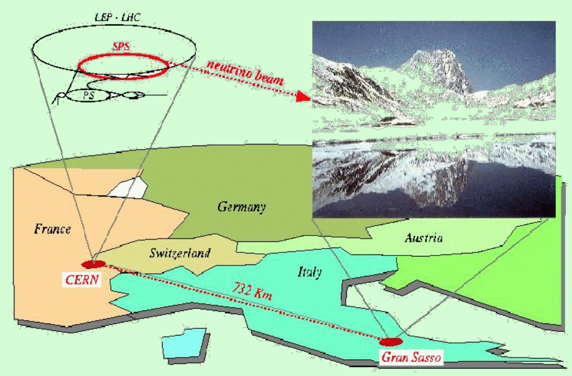


Upgoing excess of tau-like topologies

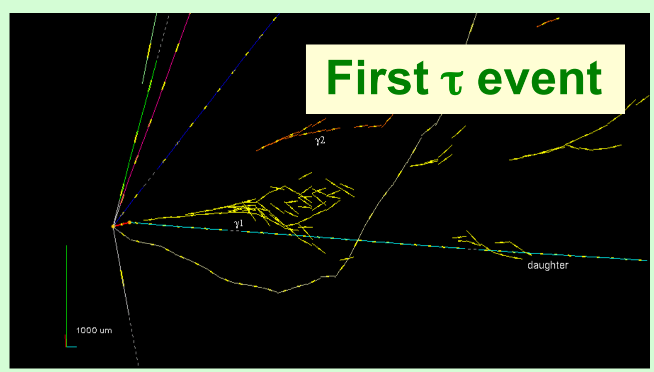
3.8σ appearance result

OPERA @ CNGS

PTEP 2014 (2014) 10, 101C01



lead/emulsion sandwich + active scint. strip planes + magnetic spectrometer, ~17 GeV beam

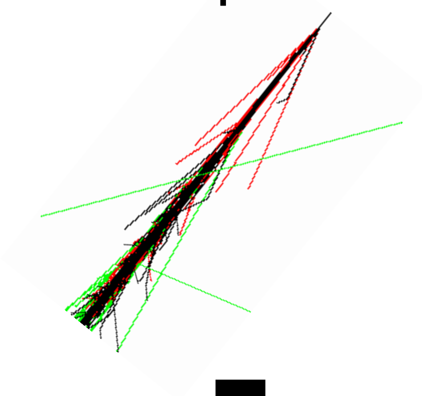


NEW

4 τ candidates, expect 0.23 ± 0.04 bg (4.2σ)

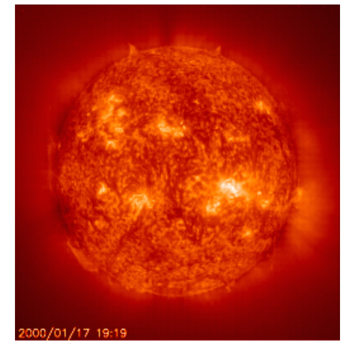
The mixing angle θ_{13}: new information from beams and burns!

atmospheric



θ_{13}, the "twist in the middle"

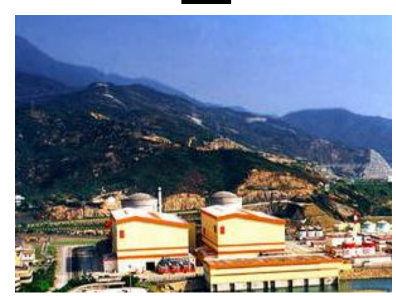
solar



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

beams

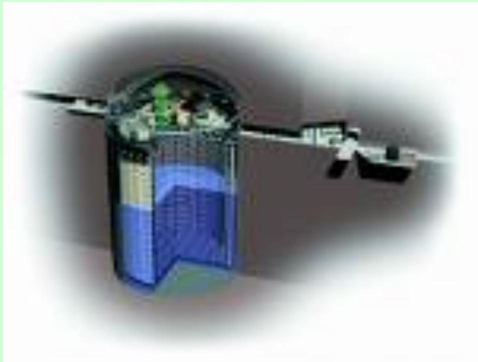
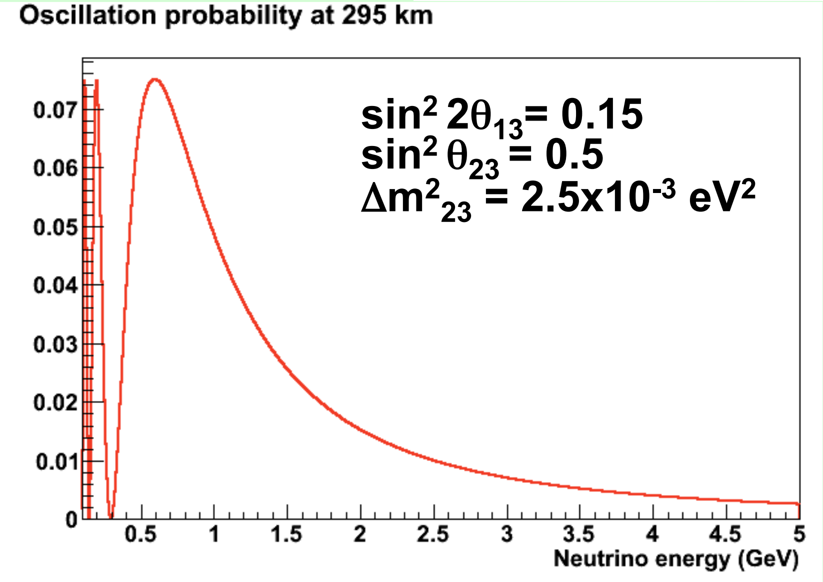
Before 2011, known to be small



reactor

How to measure θ_{13}

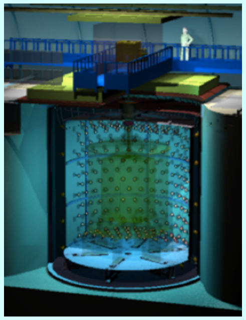
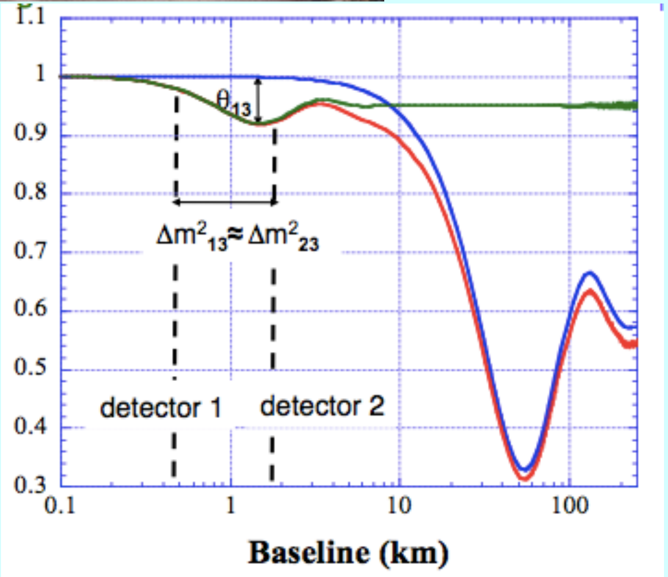
Beams

Look for *appearance* of ~GeV ν_e in ν_μ beam on ~300 km distance scale

K2K, MINOS, T2K, NOνA

Reactors

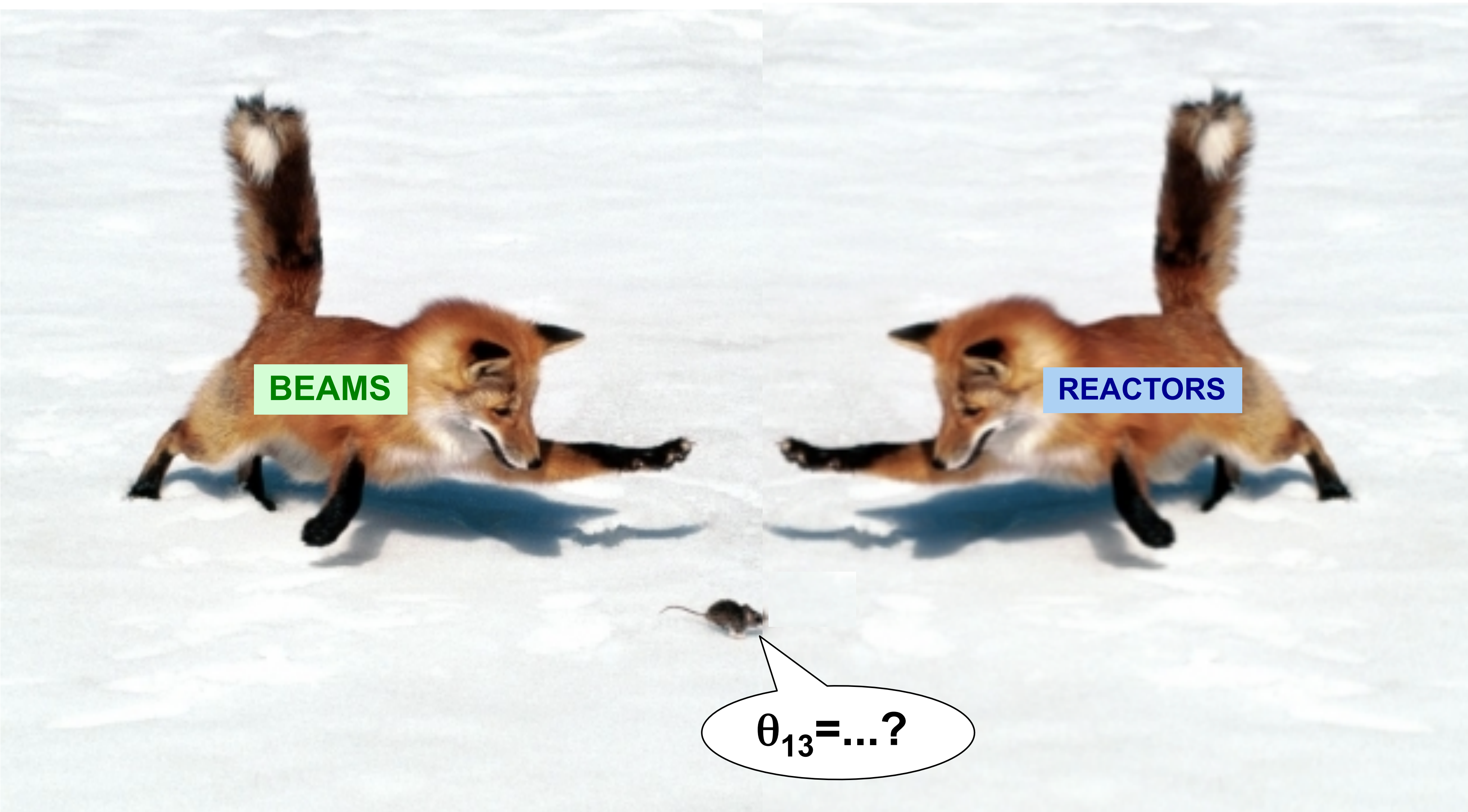




Look for *disappearance* of ~few MeV $\bar{\nu}_e$ on ~km distance scale

CHOOZ, Double Chooz, Daya Bay, RENO

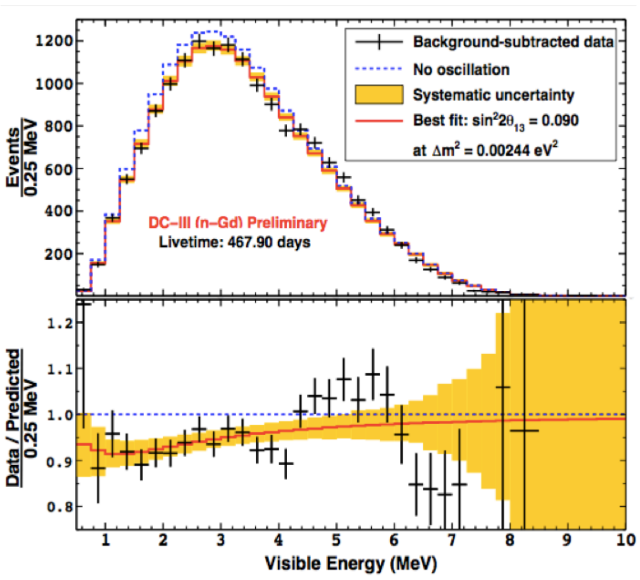
A slide from December 2011:

We're closing in on the answer...



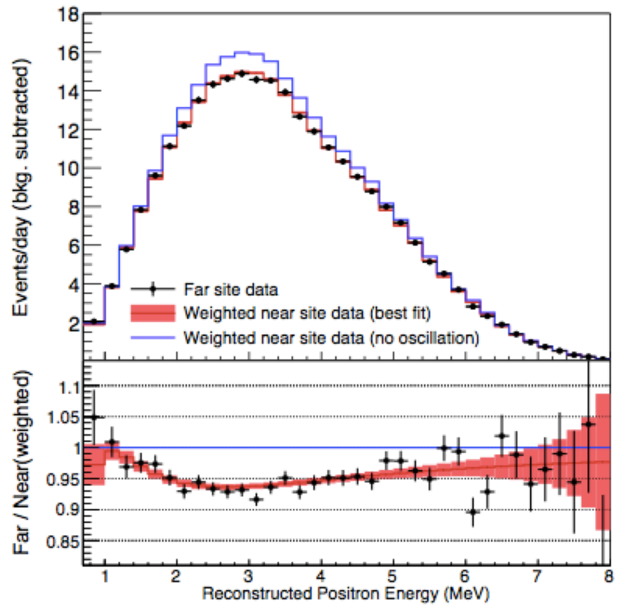
Recent tour-de-force reactor θ_{13} measurements

Double Chooz



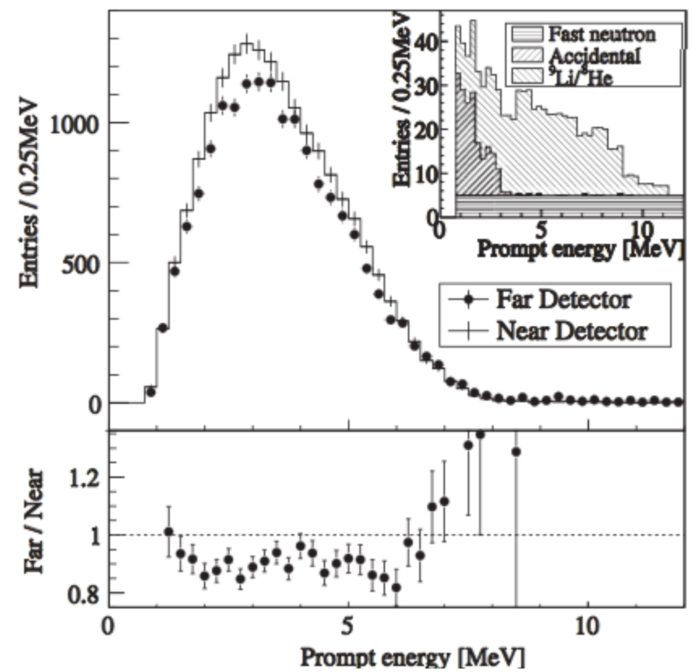
$\sin^2(2\theta_{13})=(0.09\pm0.03)$

Daya Bay



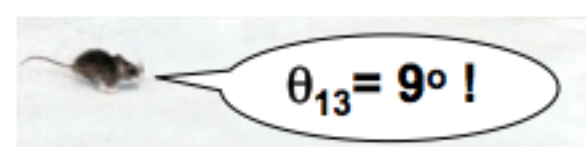
$$\sin^2 2\theta_{13} = 0.084^{+0.005}_{-0.005}$$

RENO



$$\sin^2 2\theta_{13} = 0.101 \pm 0.008(stat.) \pm 0.010(syst.)$$

Disappearance of reactor antineutrinos with characteristic spectral distortion

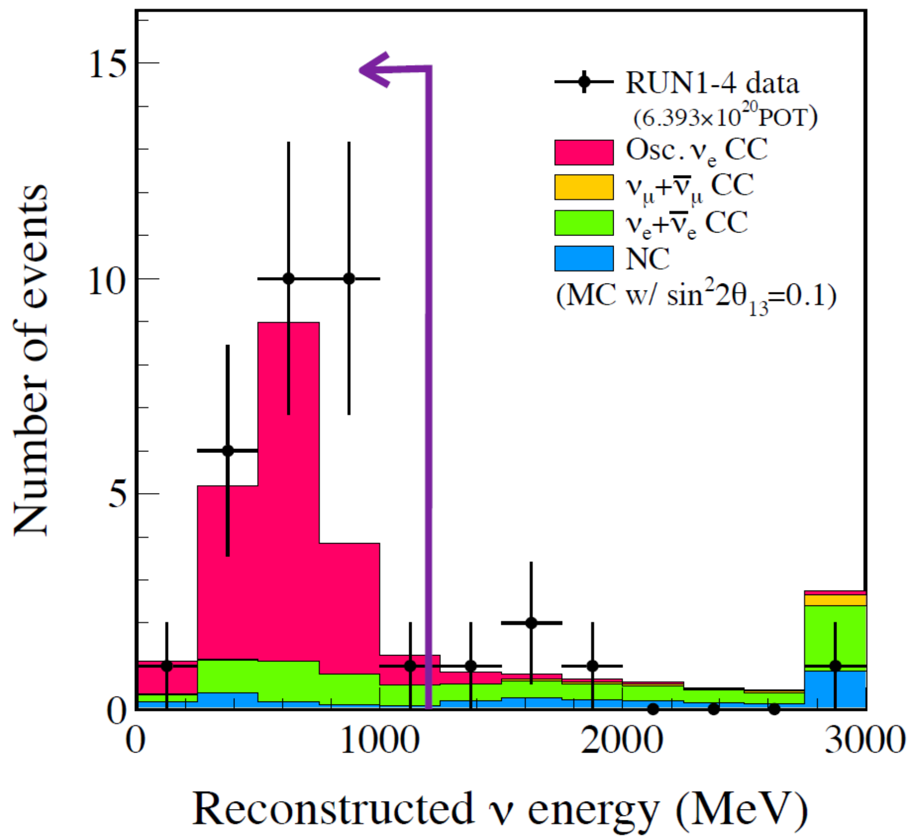


See session Neutrino-1

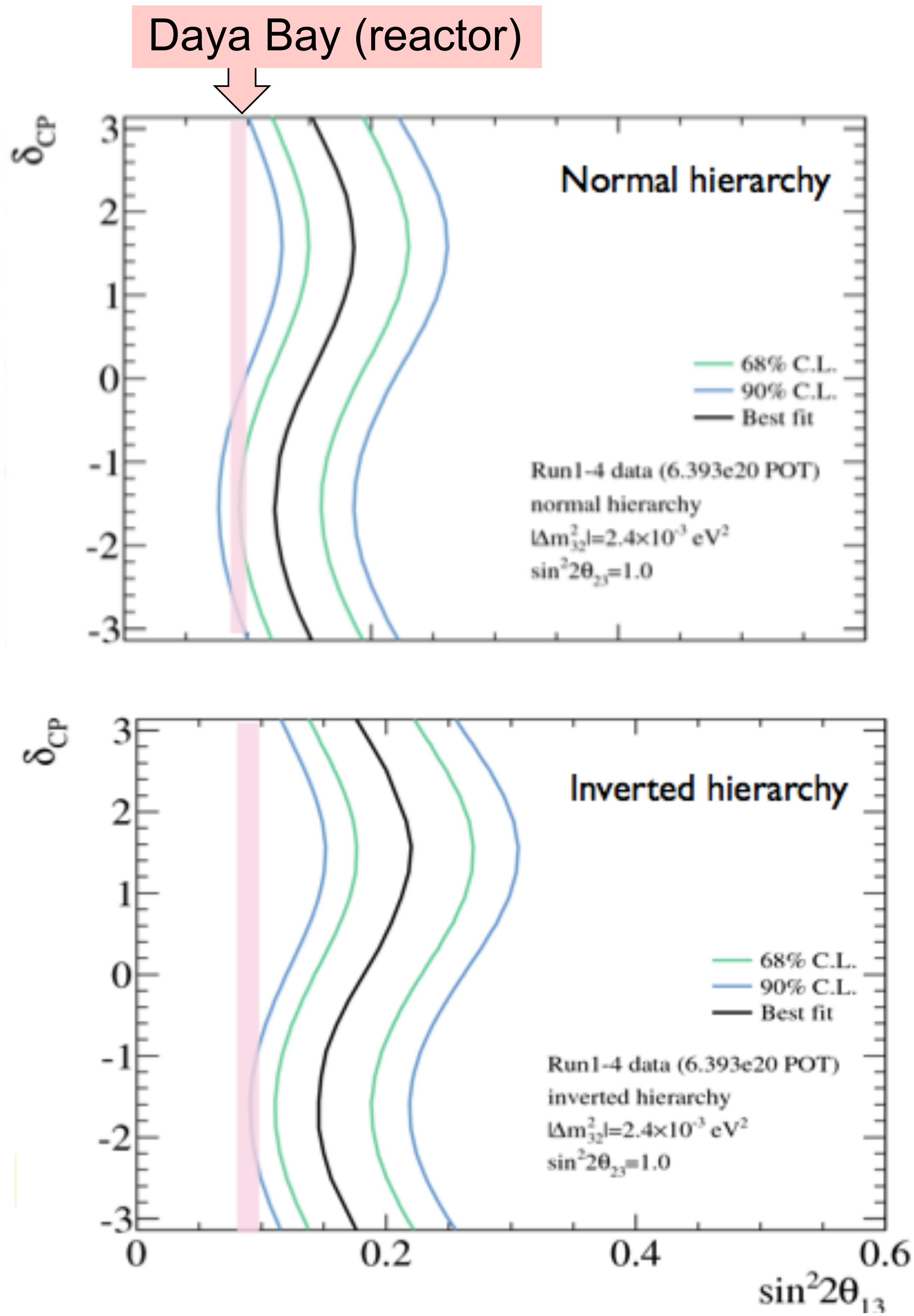
T2K result for ν_e appearance

$$\nu_\mu \rightarrow \nu_e$$

Reconstructed events after all ν_e cuts



Coming soon: **antineutrinos**

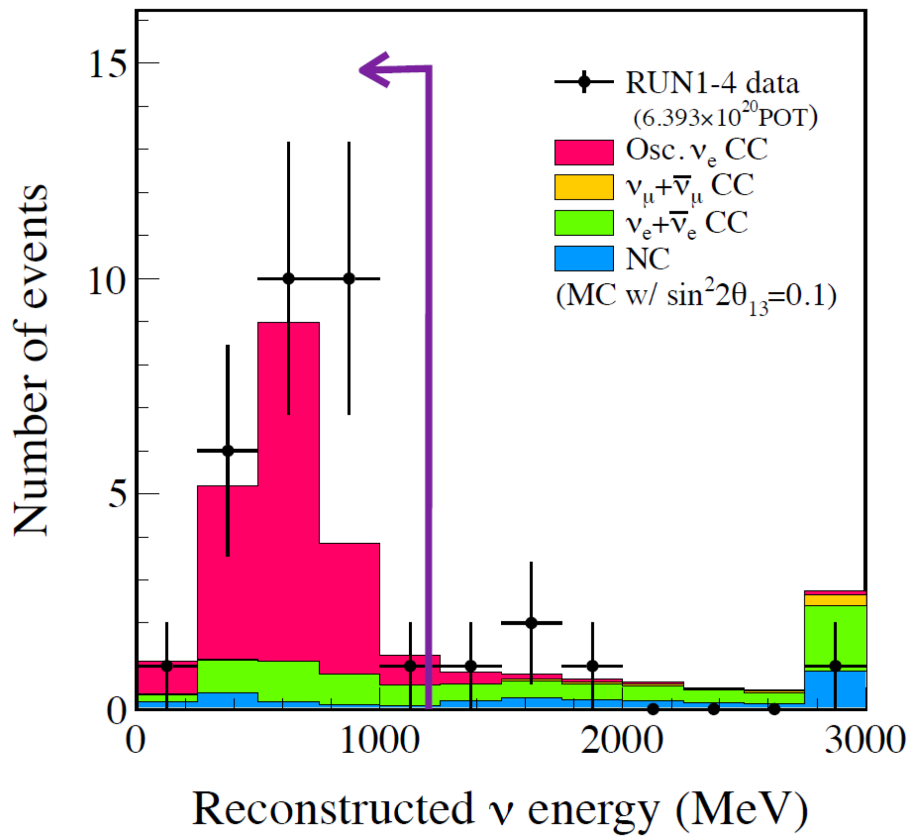


See session Neutrino-5

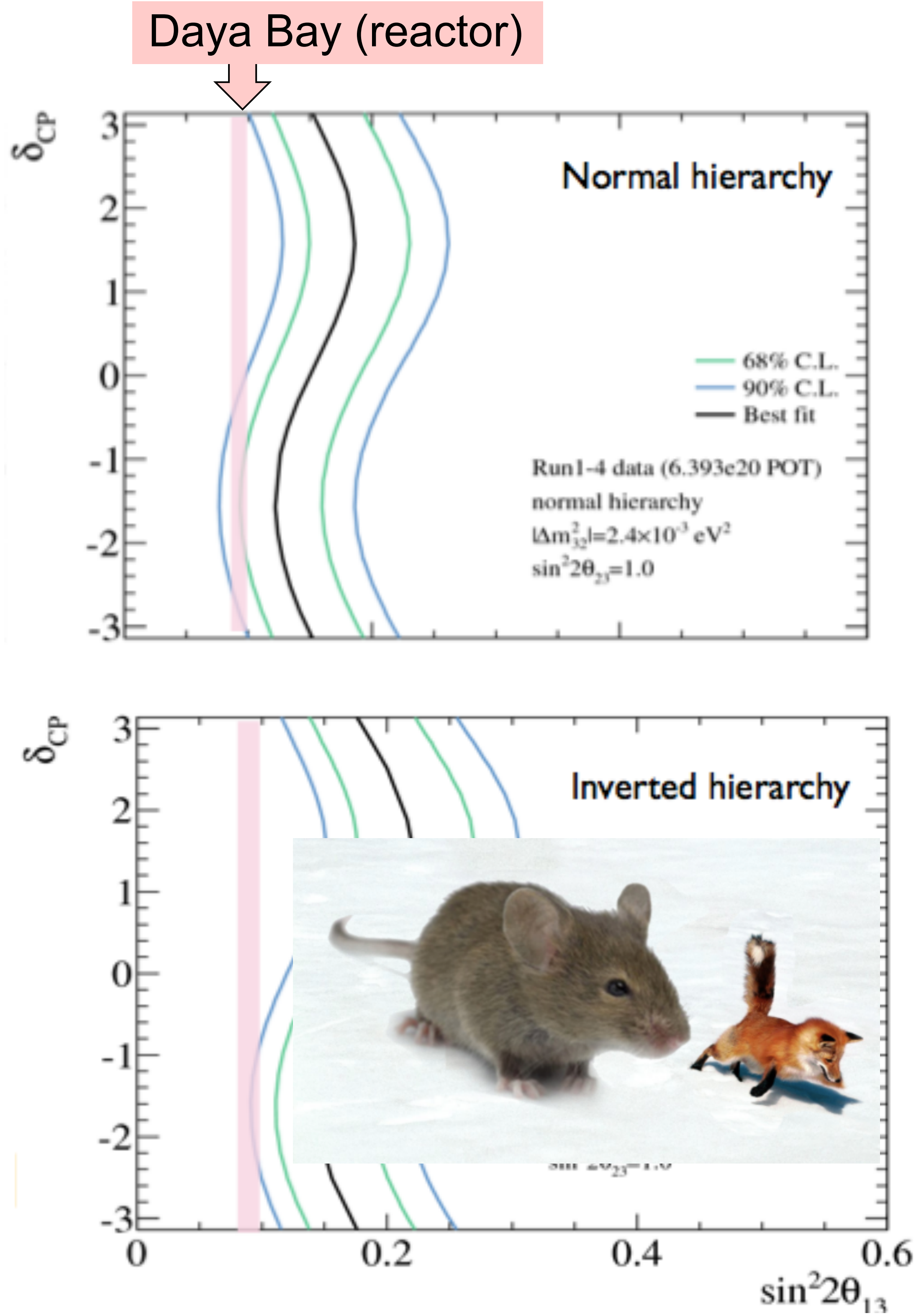
T2K result for ν_e appearance

$$\nu_\mu \rightarrow \nu_e$$

Reconstructed events after all ν_e cuts



Coming soon: **antineutrinos**



See session Neutrino-5

The three-flavor picture fits the data well

Global three-flavor fits to all data

	3σ range	3σ knowledge
$\sin^2\theta_{12}$	$0.270 \to 0.344$	
$\theta_{12}/^\circ$	$31.29 \to 35.91$	~14%
$\sin^2\theta_{23}$	$0.385 \to 0.644$	
$\theta_{23}/^\circ$	$38.3 \to 53.3$	~33%
$\sin^2\theta_{13}$	$0.0188 \to 0.0251$	
$\theta_{13}/^\circ$	$7.87 \to 9.11$	~15%
$\delta_{\mathrm{CP}}/^\circ$	$0 \to 360$	~no info
$\dfrac{\Delta m^2_{21}}{10^{-5}\ \mathrm{eV}^2}$	$7.02 \to 8.09$	~14%
$\dfrac{\Delta m^2_{3\ell}}{10^{-3}\ \mathrm{eV}^2}$	$\begin{bmatrix}+2.325 \to +2.599 \\ -2.590 \to -2.307\end{bmatrix}$	~12%

M. C. Gonzalez-Garcia, M. Maltoni, J. Salvado, T. Schwetz, 10.1007/JHEP11(2014)052

What do we *not* know about the three-flavor paradigm?

	3σ range
$\sin^2\theta_{12}$	$0.270 \rightarrow 0.344$
$\theta_{12}/^\circ$	$31.29 \rightarrow 35.91$
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Is θ_{23} non-negligibly greater or smaller than 45 deg?

What do we *not* know about the three-flavor paradigm?

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$\sin^2\theta_{12}$	$0.270 \to 0.344$
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Is θ_{23} non-negligibly greater or smaller than 45 deg?

sign of Δm^2 unknown (ordering of masses)

What do we *not* know about the three-flavor paradigm?

	3σ range
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Is θ_{23} non-negligibly greater or smaller than 45 deg?

almost unknown

sign of Δm^2 unknown (ordering of masses)

What do these parameters tell us?

Non-zero CP violation, could, in principle, inform us on leptogenesis in the context of see-saw neutrino mass models

(or maybe not...)

The God Particle

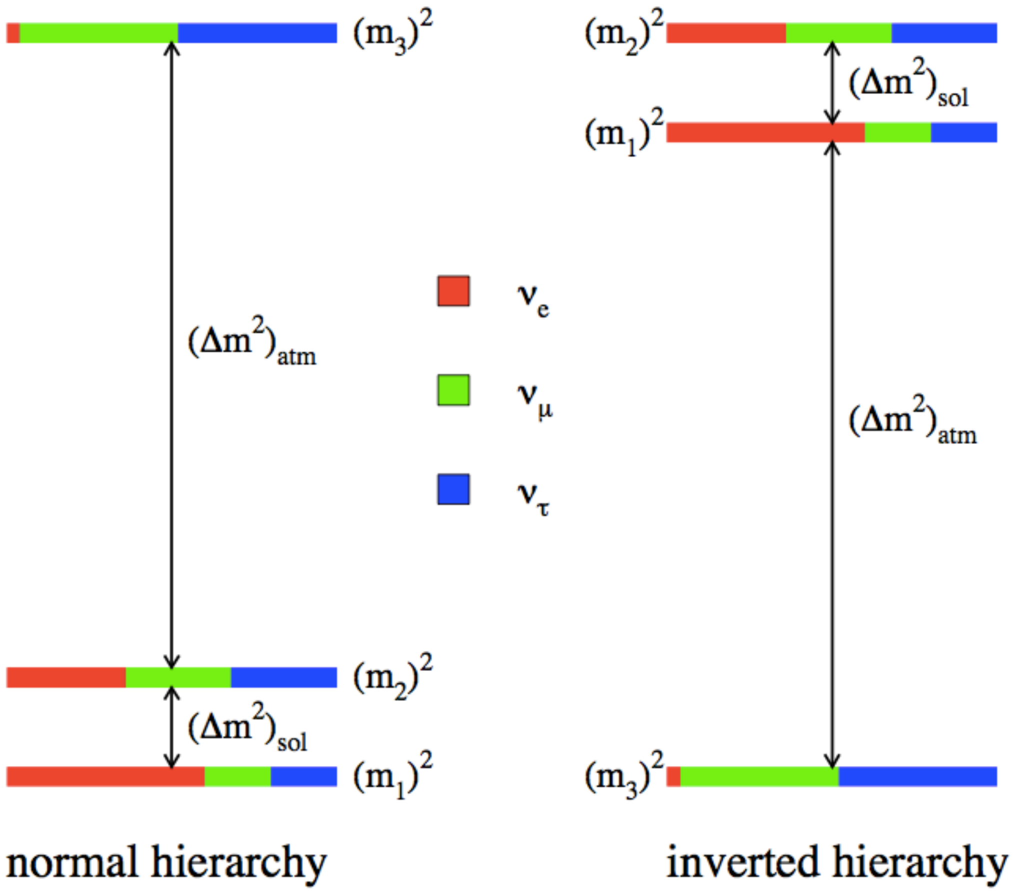
The God Particle

The Devil Phase?

Next on the list to go after experimentally:

mass hierarchy

(sign of Δm^2_{32})



$$\Delta m^2_{ij} \equiv m^2_i - m^2_j$$

There are many ways to measure the mass hierarchy

They are all challenging...

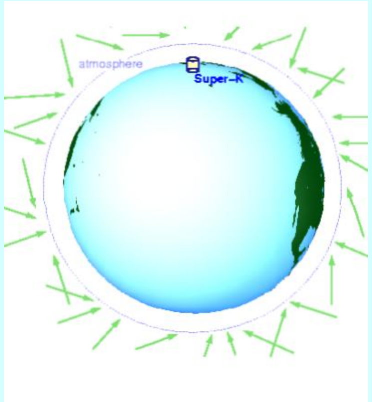
Four of the possible ways to get MH

More info in sessions Neutrino-1,5,8

Long-baseline beams

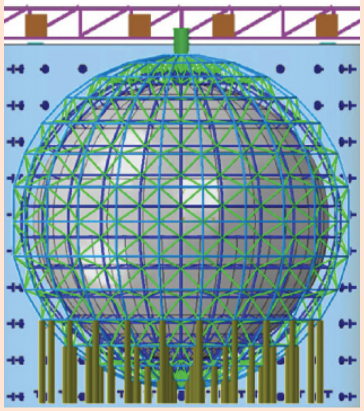
Hyper-K, LBNF/DUNE

Atmospheric neutrinos



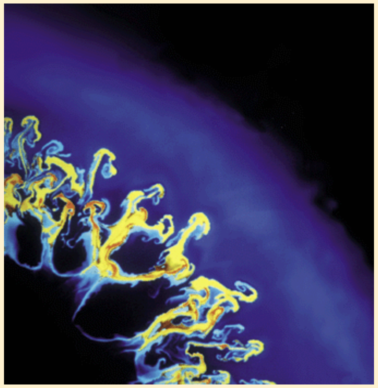
Super-K, Hyper-K, PINGU, DUNE,INO

Reactors



JUNO, RENO-50

Supernovae



Many existing & future detectors

Long-baseline beams

Other methods are very promising,
but the long-baseline method
is the only one that's ***guaranteed*** with
sufficient exposure at long baseline
(...but it's tangled with CP violation)

Long-baseline approach for going after MH and CP

Measure transition probabilities for

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

through matter

$$P_{\nu_e \nu_\mu (\bar{\nu}_e \bar{\nu}_\mu)} = s_{23}^2 \sin^2 2\theta_{13} \left(\frac{\Delta_{13}}{\tilde{B}_\mp} \right)^2 \sin^2 \left(\frac{\tilde{B}_\mp L}{2} \right)$$
$$+ c_{23}^2 \sin^2 2\theta_{12} \left(\frac{\Delta_{12}}{A} \right)^2 \sin^2 \left(\frac{A L}{2} \right)$$
$$+ \tilde{J} \frac{\Delta_{12}}{A} \frac{\Delta_{13}}{\tilde{B}_\mp} \sin \left(\frac{AL}{2} \right) \sin \left(\frac{\tilde{B}_\mp L}{2} \right) \cos \left(\pm\delta - \frac{\Delta_{13} L}{2} \right)$$

Change of sign for antineutrinos

A. Cervera et al., Nucl. Phys. B 579 (2000)

$\tilde{J} \equiv c_{13} \sin 2\theta_{12} \sin 2\theta_{23} \sin 2\theta_{13}$

$\Delta_{ij} \equiv \frac{\Delta m_{ij}^2}{2E_\nu}, \ \tilde{B}_\mp \equiv |A \mp \Delta_{13}|, \ A = \sqrt{2} G_F N_e$

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

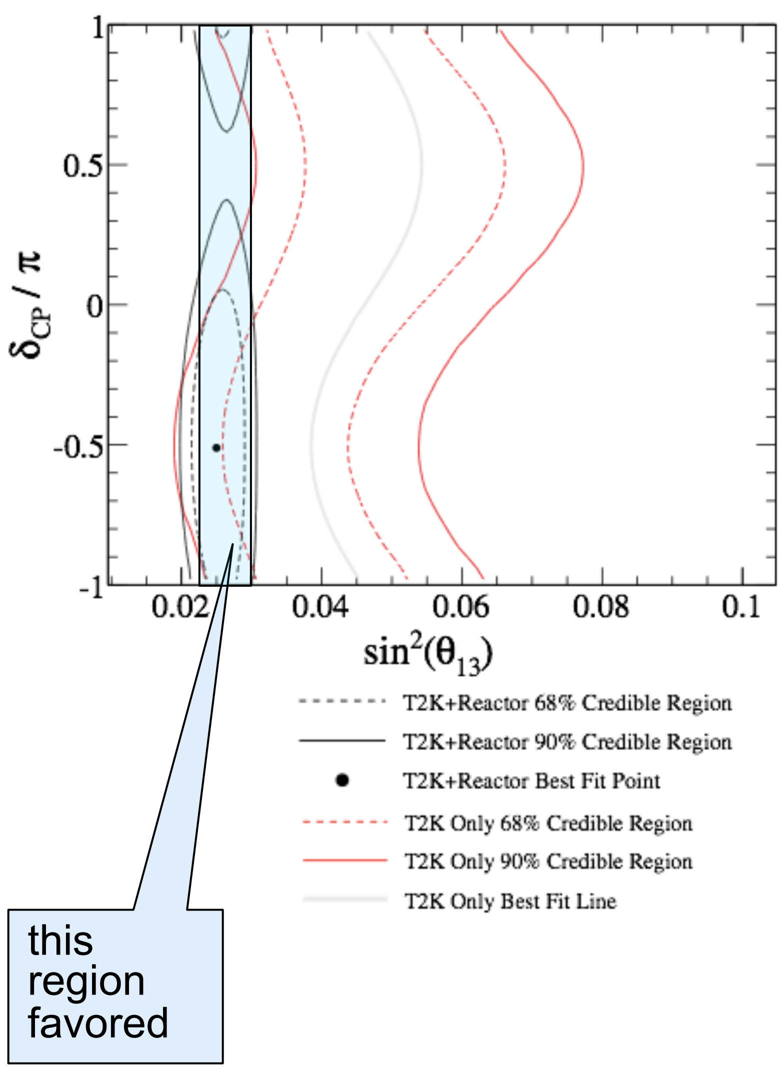
Different probabilities as a function of L& E for neutrinos and antineutrinos, depending on:

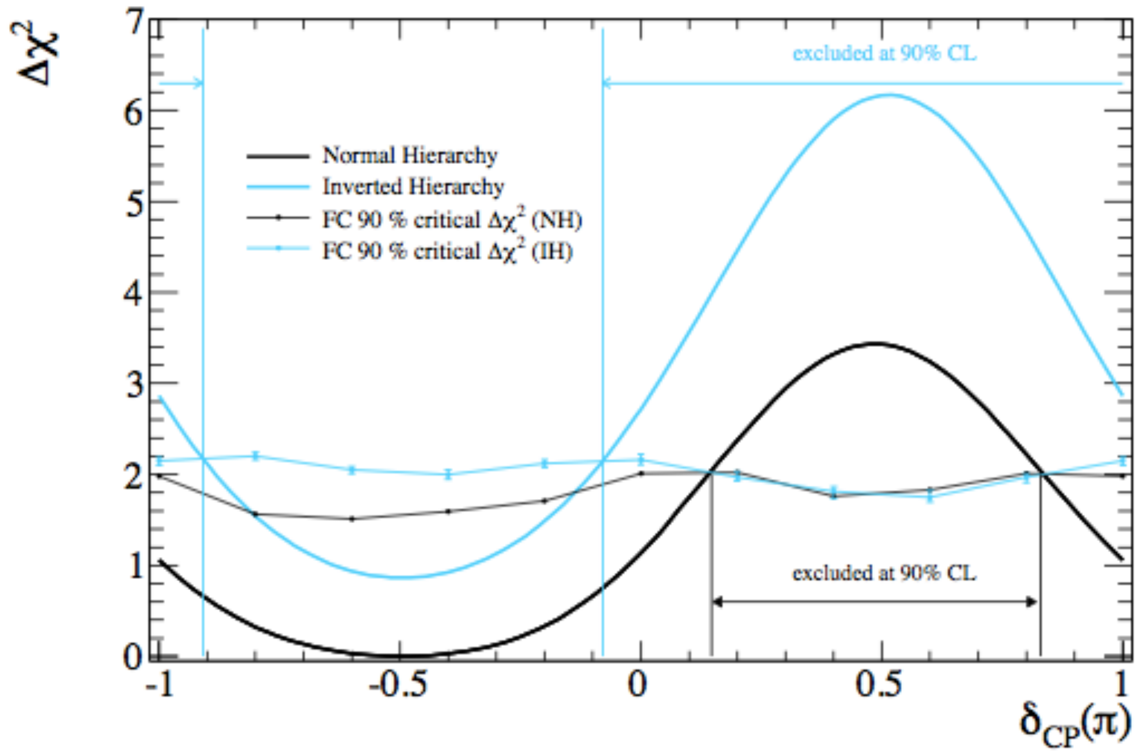
- CP δ
- matter density (Earth has electrons, not positrons)

First information from T2K (+ reactors)

NEW

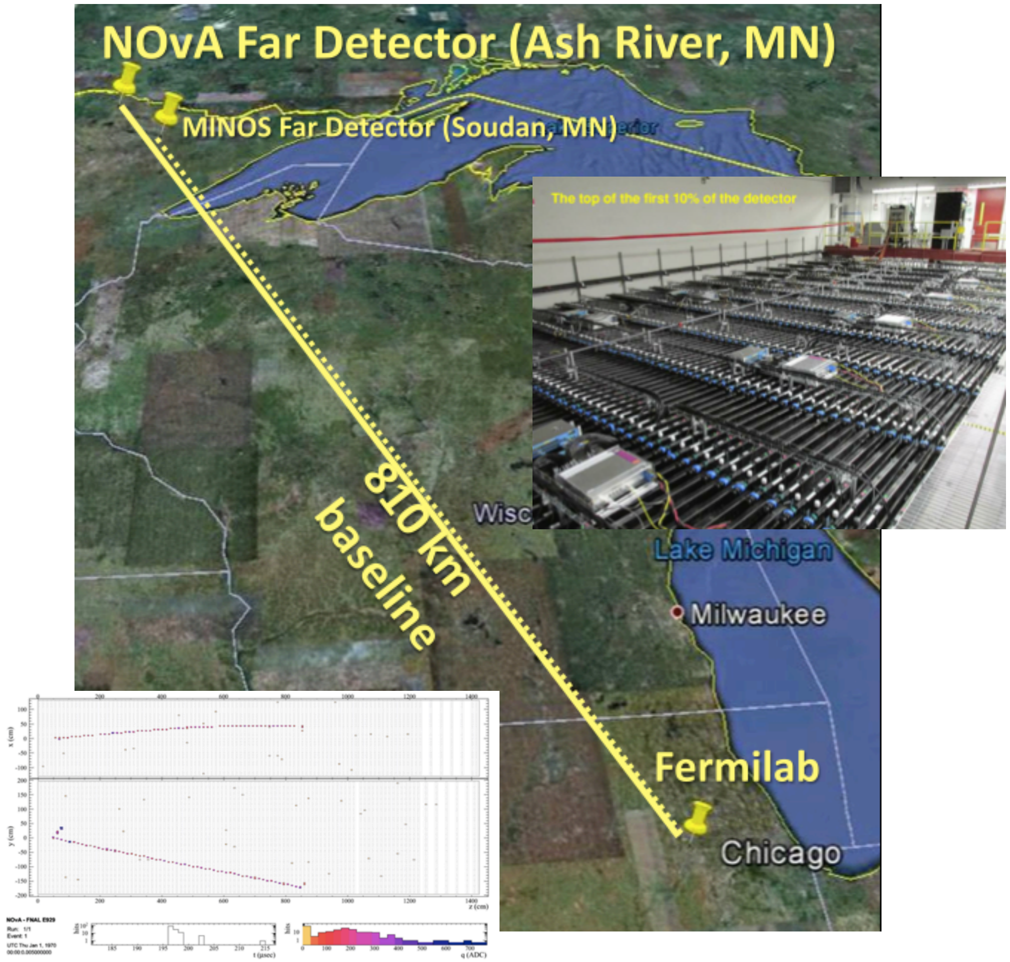
Joint ν_μ, ν_e three-flavor fit,
including reactor constraint on θ_{13} $\sin^2 2\theta_{13} = 0.095 \pm 0.010$





Mild preference for $\delta \sim -\pi/2$

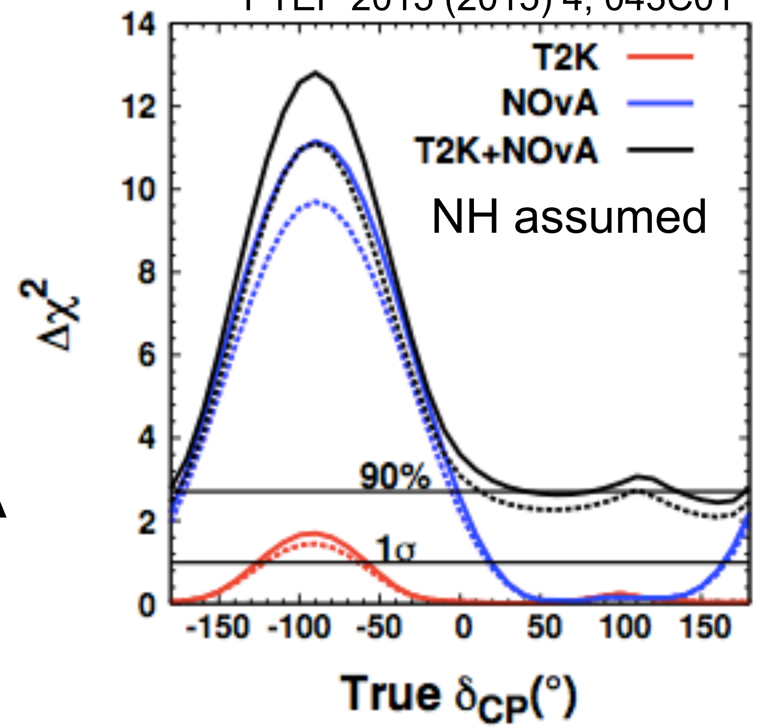
Next U.S. experiment pursuing the long-baseline strategy



NOνA
14 kt scintillator
700 kW off-axis FNAL beam
810 km baseline

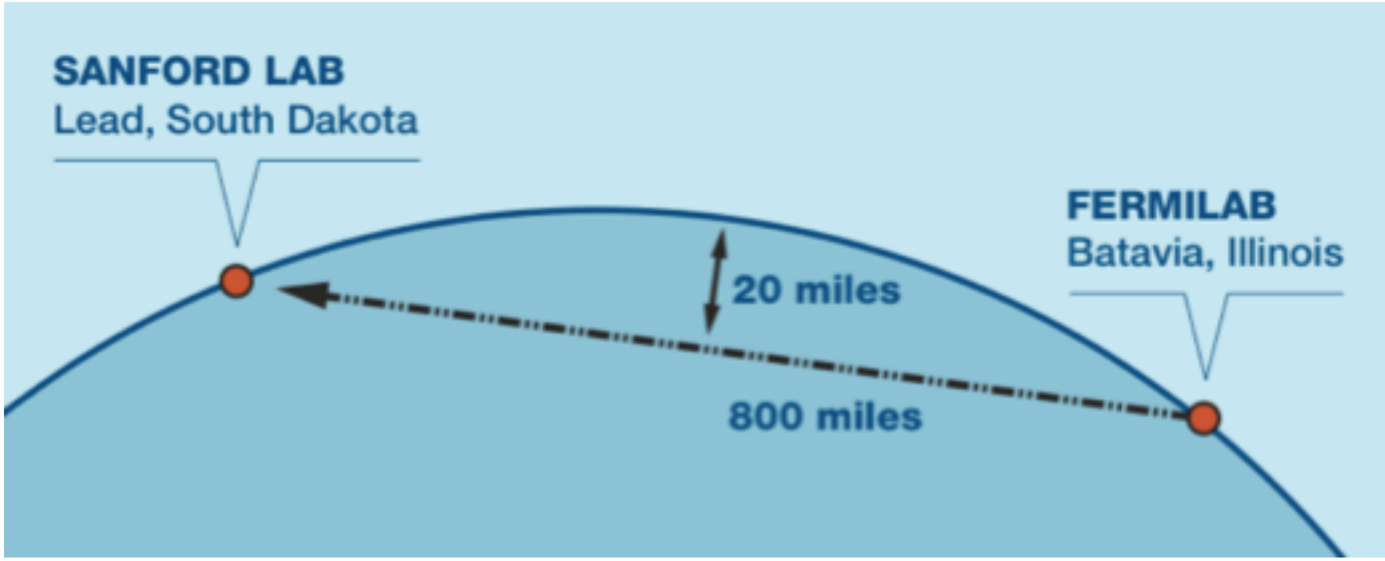
See session Neutrino-5

PTEP 2015 (2015) 4, 043C01



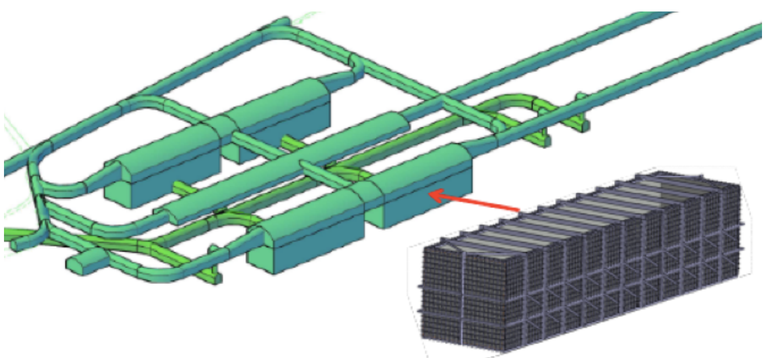
Expected MH sensitivity for T2K+NOvA
(MH sensitivity driven by NOVA thanks to longer baseline)

To go beyond, yet longer baseline is favorable



DUNE
DEEP UNDERGROUND NEUTRINO EXPERIMENT

reformulated international collaboration



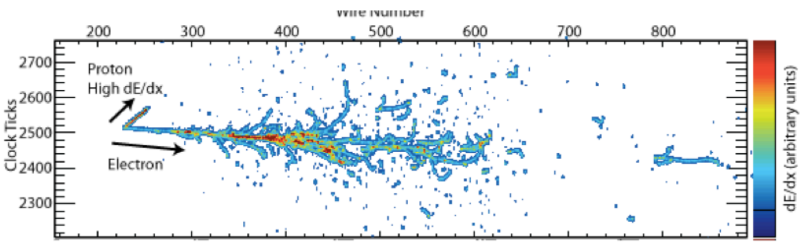
Long-Baseline Neutrino Facility/Deep Underground Neutrino Experiment

40 kton liquid argon time projection chamber in SD @ 4850 ft, 1300 km baseline
New 1200 kW beam (upgradeable to 2.3 MW)

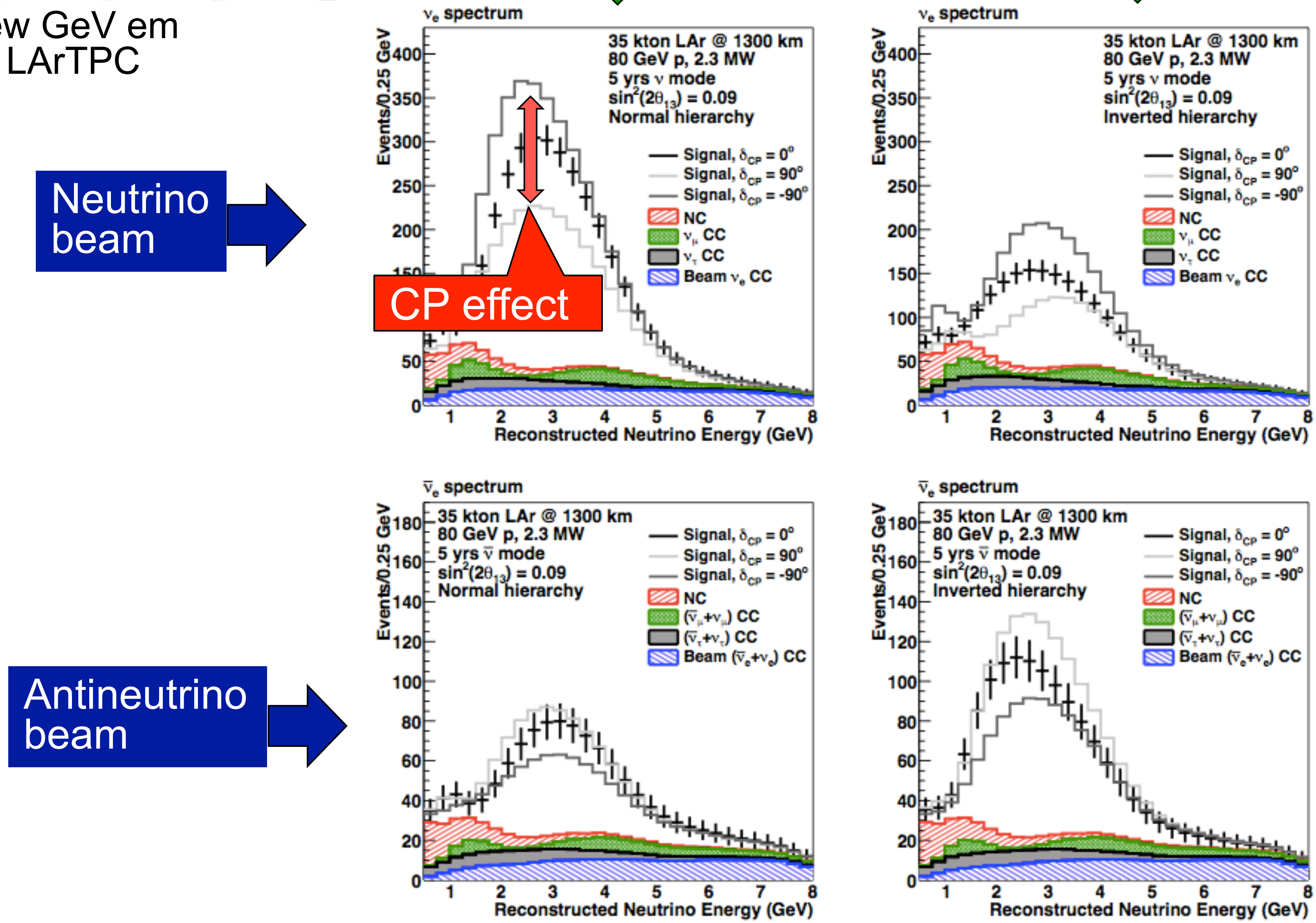
highest intermediate term priority in U.S.

See session Neutrino-5

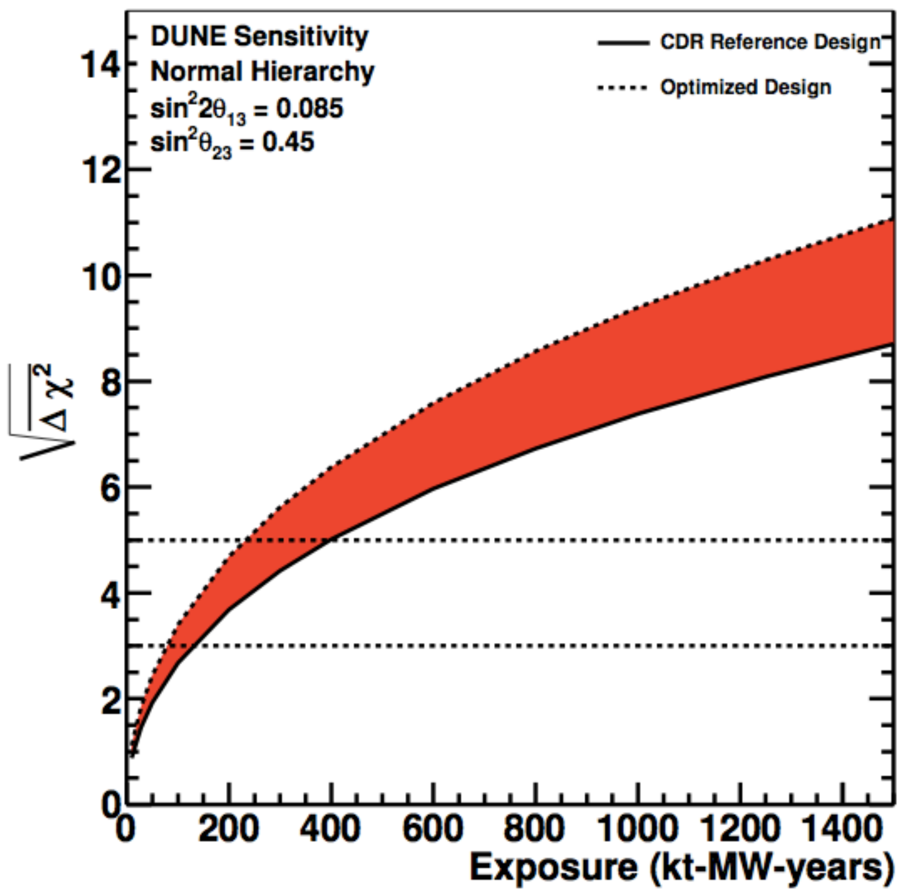
Example signal for DUNE: ν_e events



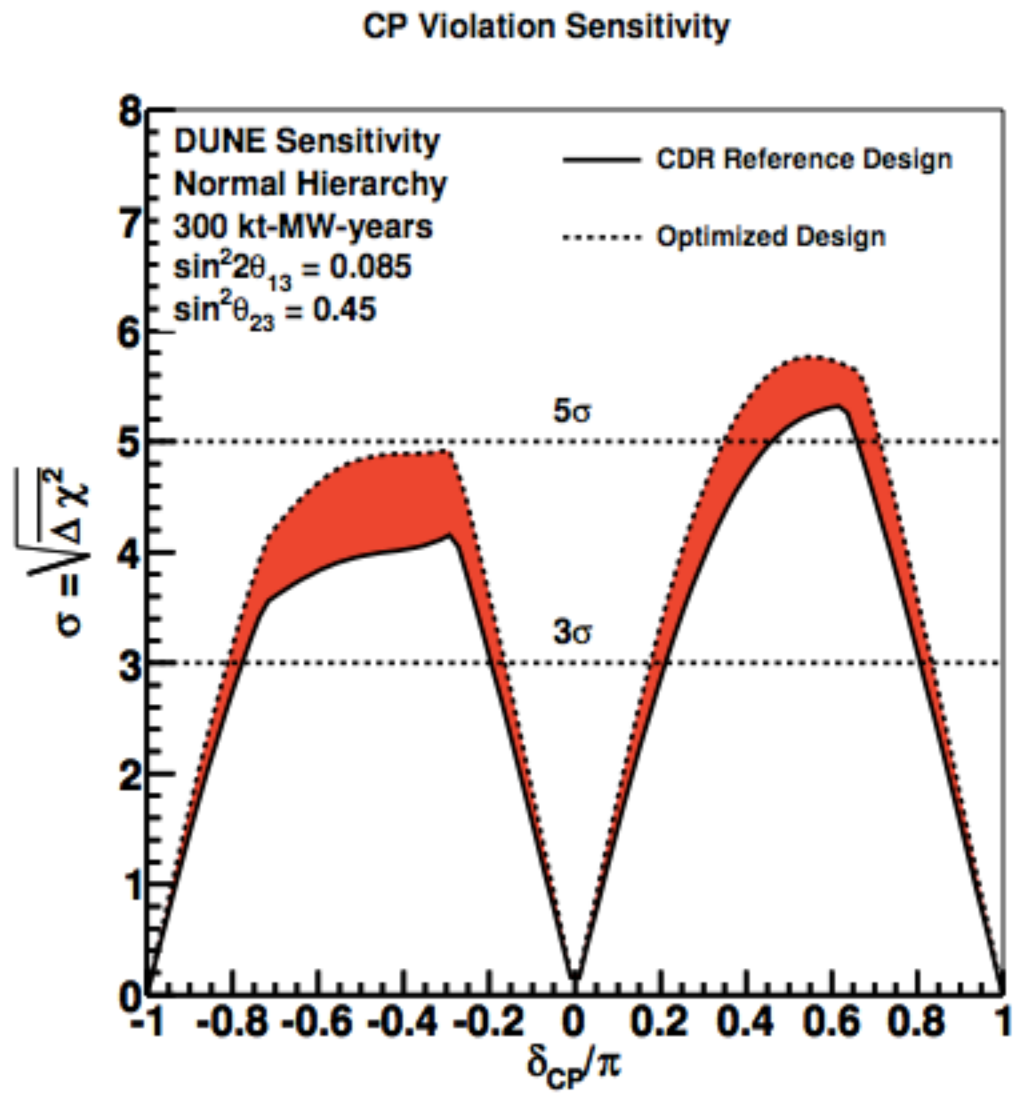
look for ~few GeV em showers in LArTPC



DUNE sensitivity

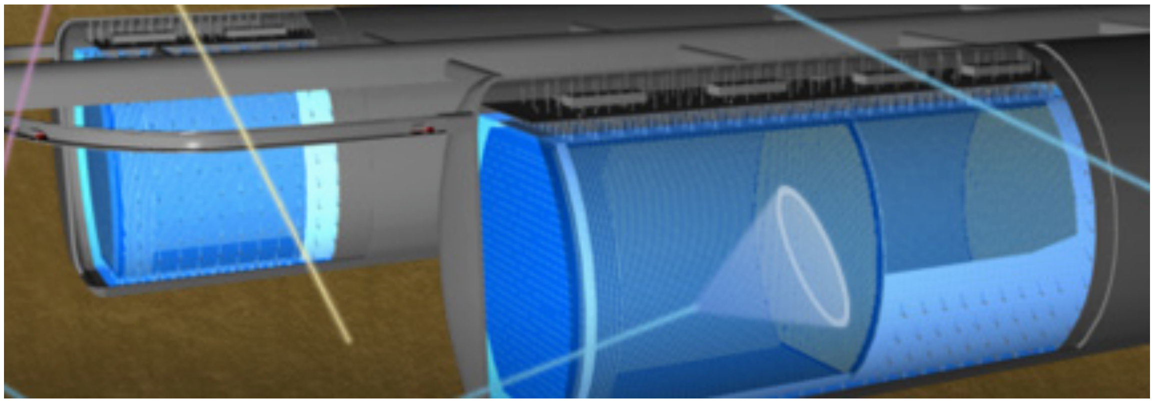


Excellent mass hierarchy reach for all CP values



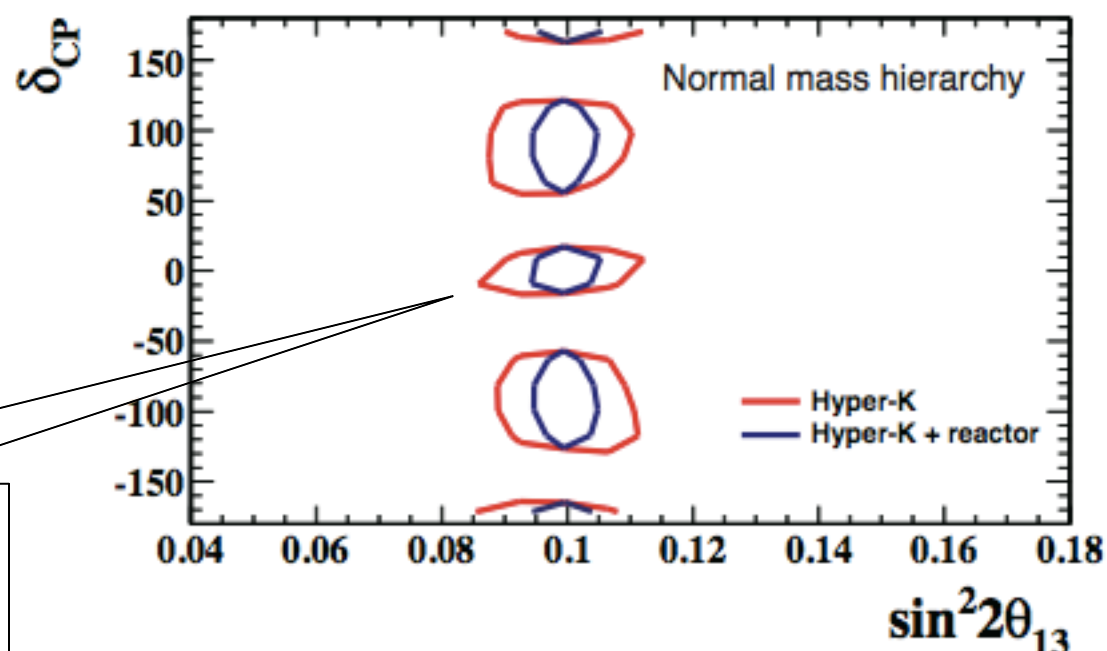
Decent chance to measure CPV

Another proposal: Hyper-K in Japan



- 300 km baseline
- 560 kton water Cherenkov detector
- upgraded J-PARC beam to 750 kW+

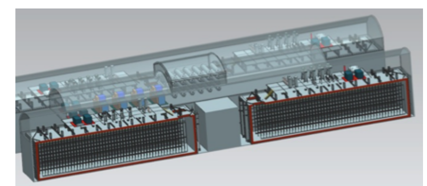
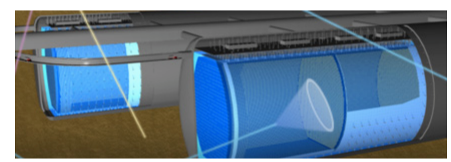
arXiv:1502.05199



shorter baseline,
so less good at MH,
but good CP sensitivity

Example measurements with Hyper-K, for different assumed true parameters

Summary of “3-flavor" oscillation physics

Observable	Signature	Next steps	
θ_{13}	Small appearance of ν_e in ν_μ beam; Disappearance of reactor anti-ν_e	Long-baseline beams; reactor experiments	
Mass hierarchy	Matter-induced ν/ anti-ν asymmetry; anti-ν_e oscillation pattern; (cosmology, 0nbbdk,...)	Long-baseline beams; reactor experiments; atmospheric neutrinos; supernova	 
CPV	ν & anti-ν oscillation	Long-baseline beams; atmospheric nus; cyclotron-based beams; neutrino factories	

Expect “indications” in coming decade; definitive measurements with next generation; could approach “CKM-level” precision with next-next+

*Note: also rich non-accelerator physics (SN, pdk, atmν,...) with different strengths for each detector type

See sessions Neutrino-2,4,5,8

All of this discussion is in the context of the standard 3-flavor picture and testing that paradigm....

There are already some slightly uncomfortable data that **don’t fit that paradigm**...

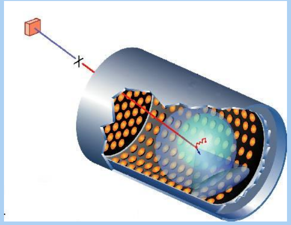
Open a parenthesis:

(

Outstanding 'anomalies'

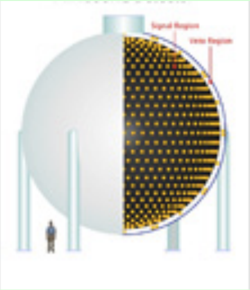
LSND @ LANL (~30 MeV, 30 m)

Excess of $\overline{\nu}_e$ interpreted as $\bar{\nu}_\mu \longrightarrow \bar{\nu}_e$



➔ $\Delta m^2 \sim 1$ eV^2: inconsistent with 3 ν masses

MiniBooNE @ FNAL ($\nu,\overline{\nu}$ ~1 GeV, 0.5 km)



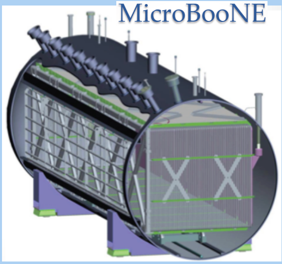
- unexplained >3 σ excess for E < 475 MeV in neutrinos
  (inconsistent w/ LSND oscillation)
- no excess for E > 475 MeV in neutrinos
  (inconsistent w/ LSND oscillation)
- small excess for E < 475 MeV in antineutrinos
  (~consistent with neutrinos)
- small excess for E > 475 MeV in antineutrinos
  (consistent w/ LSND)
- for E>200 MeV, both nu and nubar consistent with LSND

????
more data needed

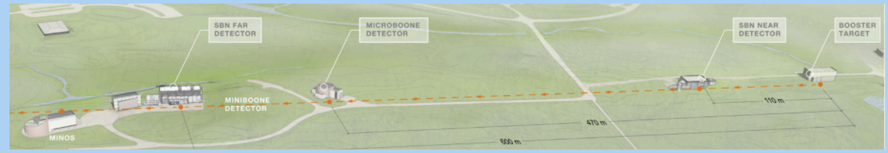
Also: possible deficits of reactor $\overline{\nu}_e$ ('reactor anomaly')
and source ν_e ('gallium anomaly')

Sterile neutrinos?? (i.e. no normal weak interactions)
Some theoretical motivations for this, both from particle & astrophysics
[cosmology w/Planck now consistent w/3 flavors... but allows 4...]
Or some other new physics??

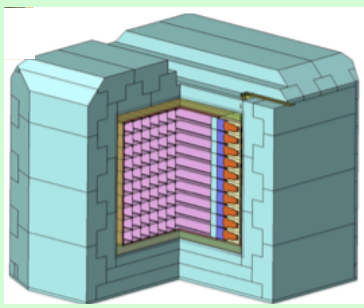
Experimental ideas to address these anomalies...



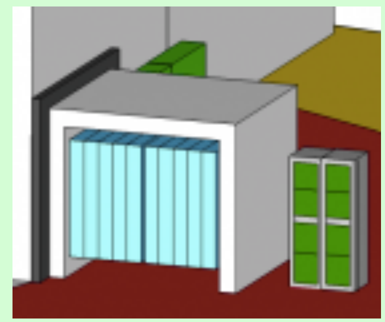
Experiments with beams
(meson decay in flight and at rest)



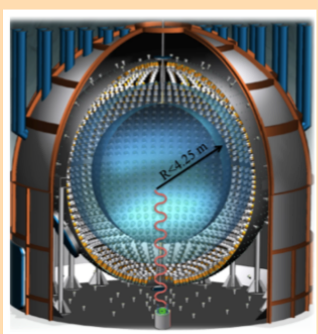
MINOS+, FNAL SBL, OscSNS, J-PARC MLF, ...



Experiments at reactors

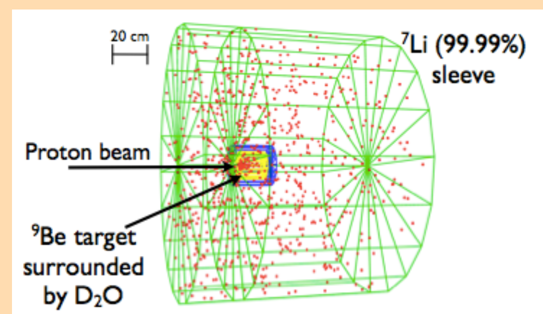


PROSPECT, SoLid, NuLAT, STEREO, DANNS, Neutrino4, Hanaro,..



Experiments with radioactive sources

SOX, CeSOX, IsoDAR, ...



Many more! see e.g., `arXiv:1204.5379` (...rapidly evolving)

See session Neutrino-3

... parenthesis not closed...

What I will cover

Status and prospects of experimental knowledge

Neutrino Oscillations

"Solar" sector

"Atmospheric" sector

The twist in the middle

Remaining unknowns in the 3-flavor picture: **MH and CP δ**

Beyond 3-flavor?

The mass pattern

But oscillations inform only about mass ***differences***...

Absolute Mass

Status and prospects

The mass scale

Majorana vs Dirac?

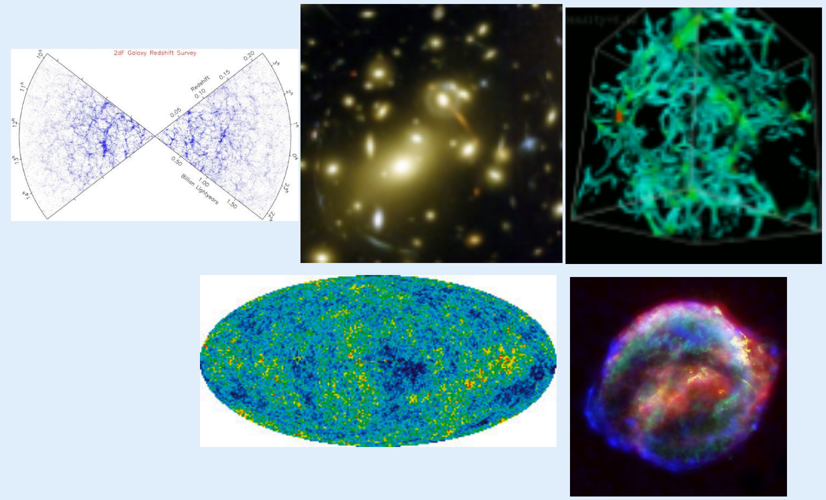
Overview of NLDBD

The mass nature

Information on absolute neutrino mass from cosmology

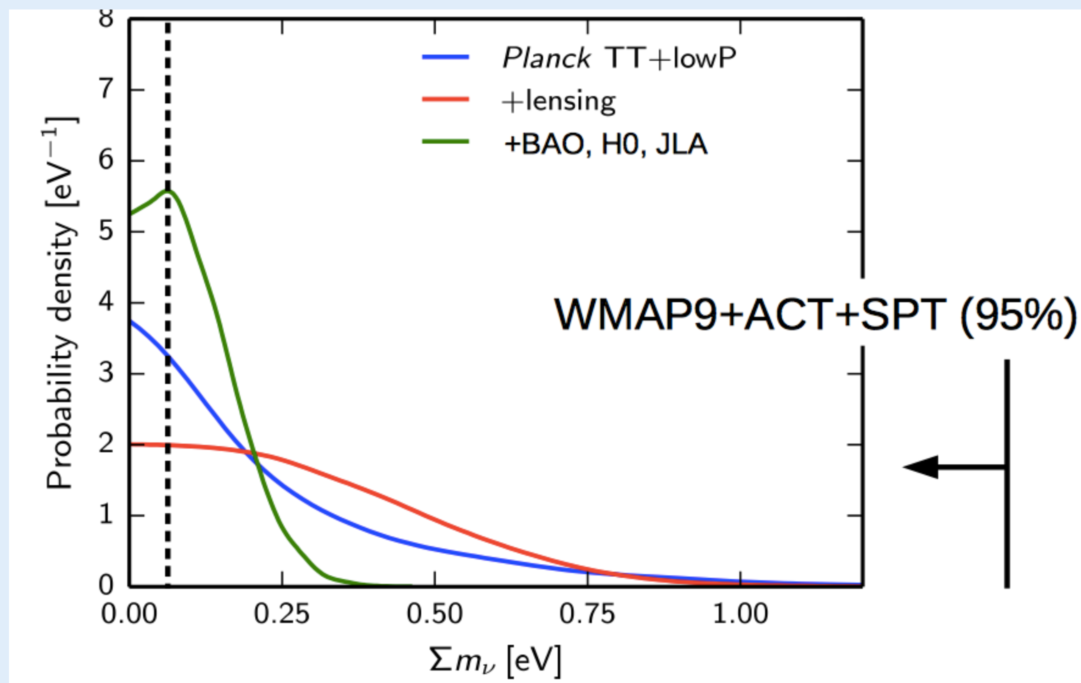
Fits to cosmological data:
CMB, large scale structure,
high Z supernovae,
weak lensing,...

(model-dependent)

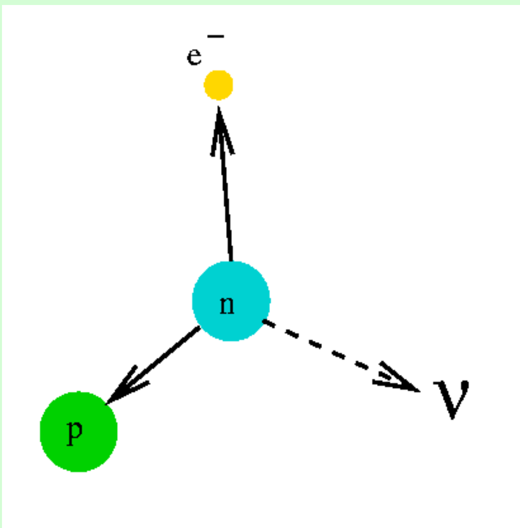


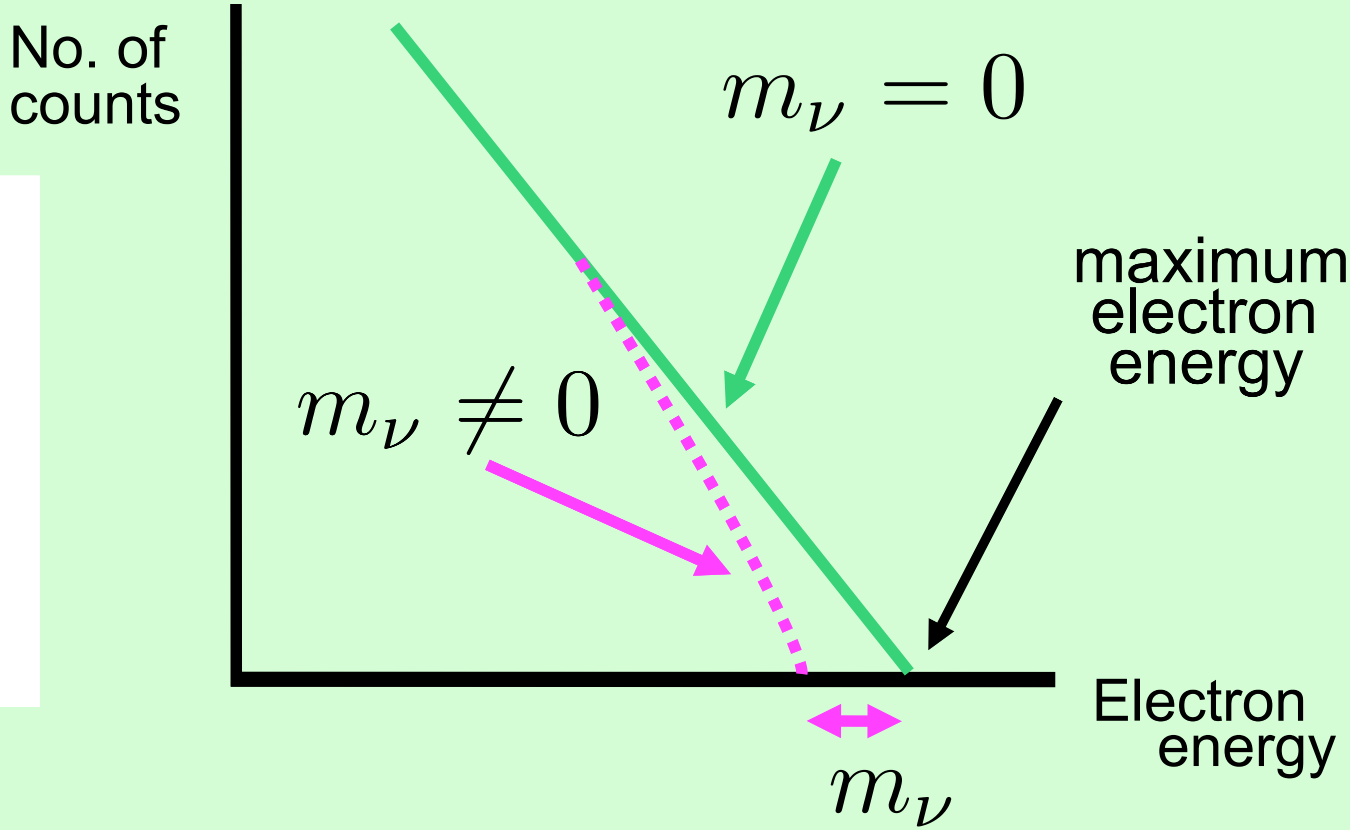
Information
on **sum** of
neutrino masses

$$\sum m_i <\sim 0.6 \text{ eV}$$



Kinematic experiments for absolute neutrino mass





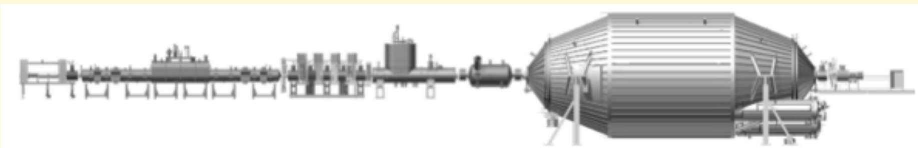
Look for distortion of β-decay spectrum near endpoint

Kinematic neutrino mass approaches

Tritium spectrometer: KATRIN

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

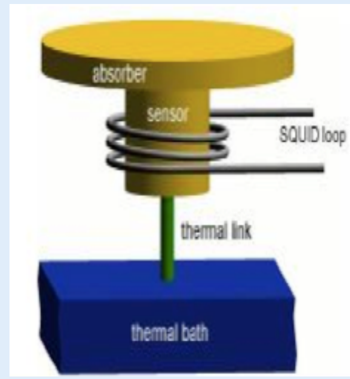
18.6 keV endpoint



Sensitivity to ~0.2 eV
Data in 2016?

turning on soon

Thermal calorimetry e.g., MARE



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

2.5 keV endpoint

Hard to scale up...

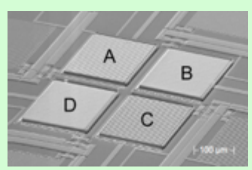
R&D...

Holmium e.g., ECHo, HOLMES

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

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

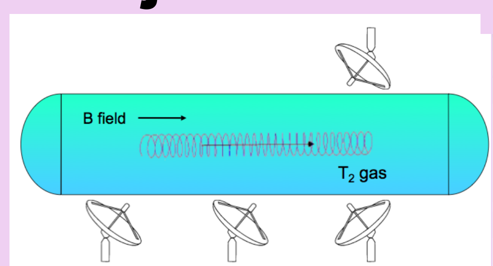
metallic magnetic calorimeters

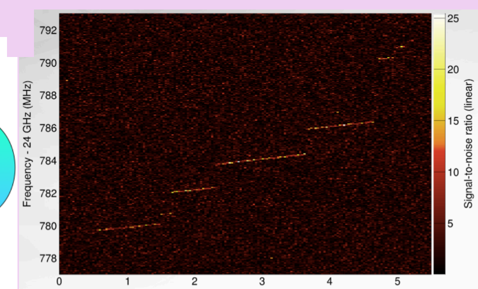


electron capture decay,
ν mass affects deexcitation spectrum
R&D in progress

R&D

Cyclotron radiation tritium spectrometer: Project 8





First single electrons seen!

R&D

What I will cover

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Majorana vs Dirac?

Overview of NLDBD

The mass nature

Are neutrinos **Majorana** or **Dirac**?

$\nu = \bar{\nu}$ 2 states Lorentz, CP $\nu_L \leftrightarrow \nu_R$	$\nu \neq \bar{\nu}$ 4 states $\nu_L \xleftrightarrow{\text{Lorentz}} \nu_R$ $\nu_L \updownarrow$; $\nu_R \updownarrow$ CP $\bar{\nu}_R \leftrightarrow \bar{\nu}_L$

Essential for ν mass understanding....

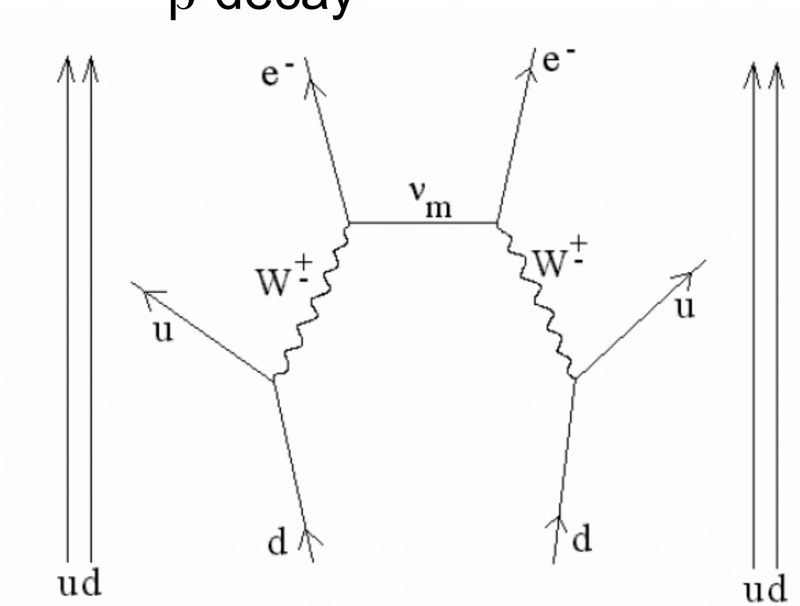
$$\mathcal{L}_m \sim m_D\,[\,\bar{\psi}_L \psi_R + \dots] + [m_L \bar{\psi}_L^c\, \psi_L + m_R \bar{\psi}_R^c\, \psi_R + h.c.]$$

e.g., "see-saw" mechanism $\Rightarrow$ Majorana ν

... may be helpful for leptogenesis...

Best (only) experimental strategy: look for **neutrinoless double beta decay**

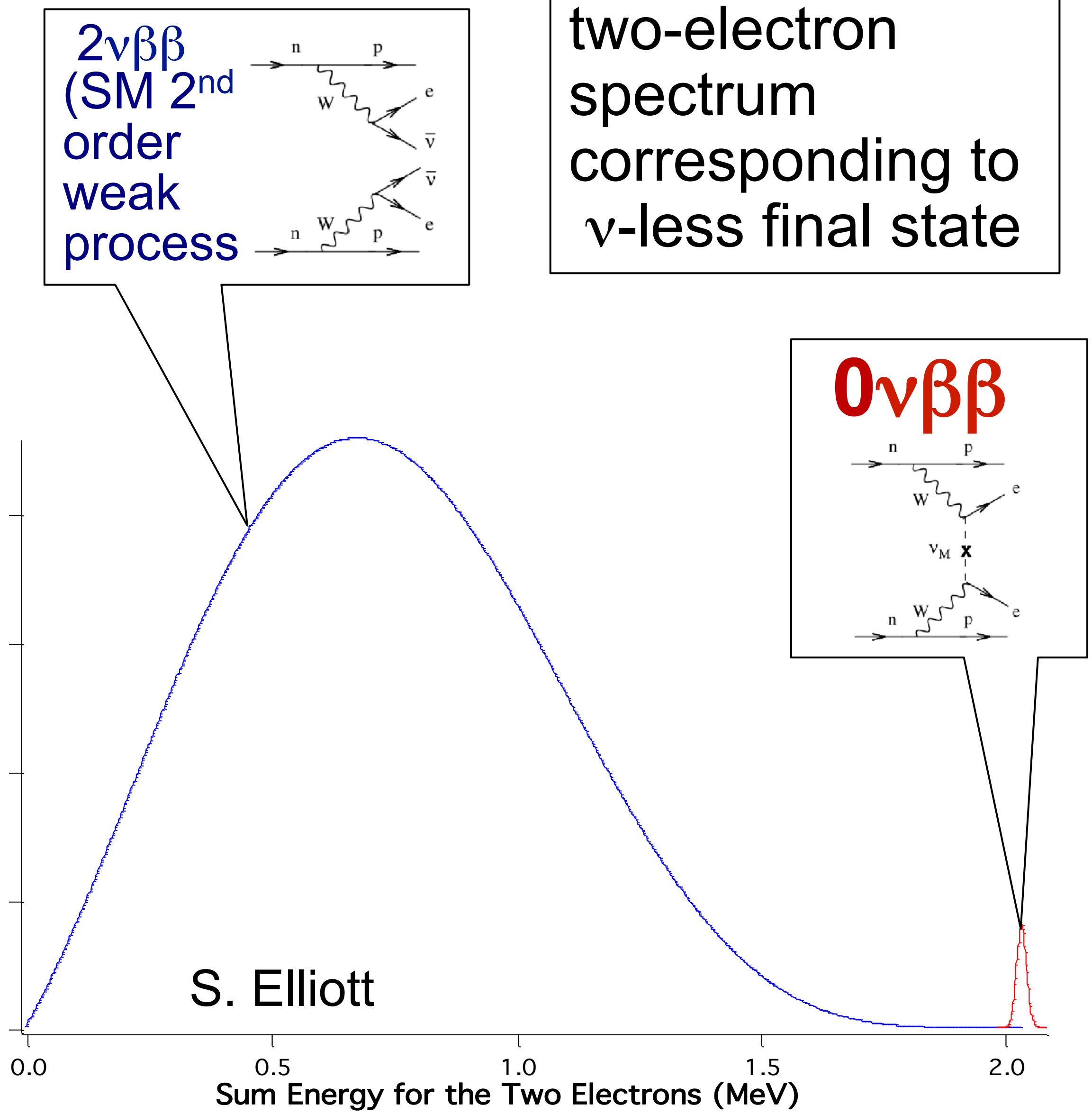
in isotopes for
which it is energetically
possible
and which don't single
β-decay



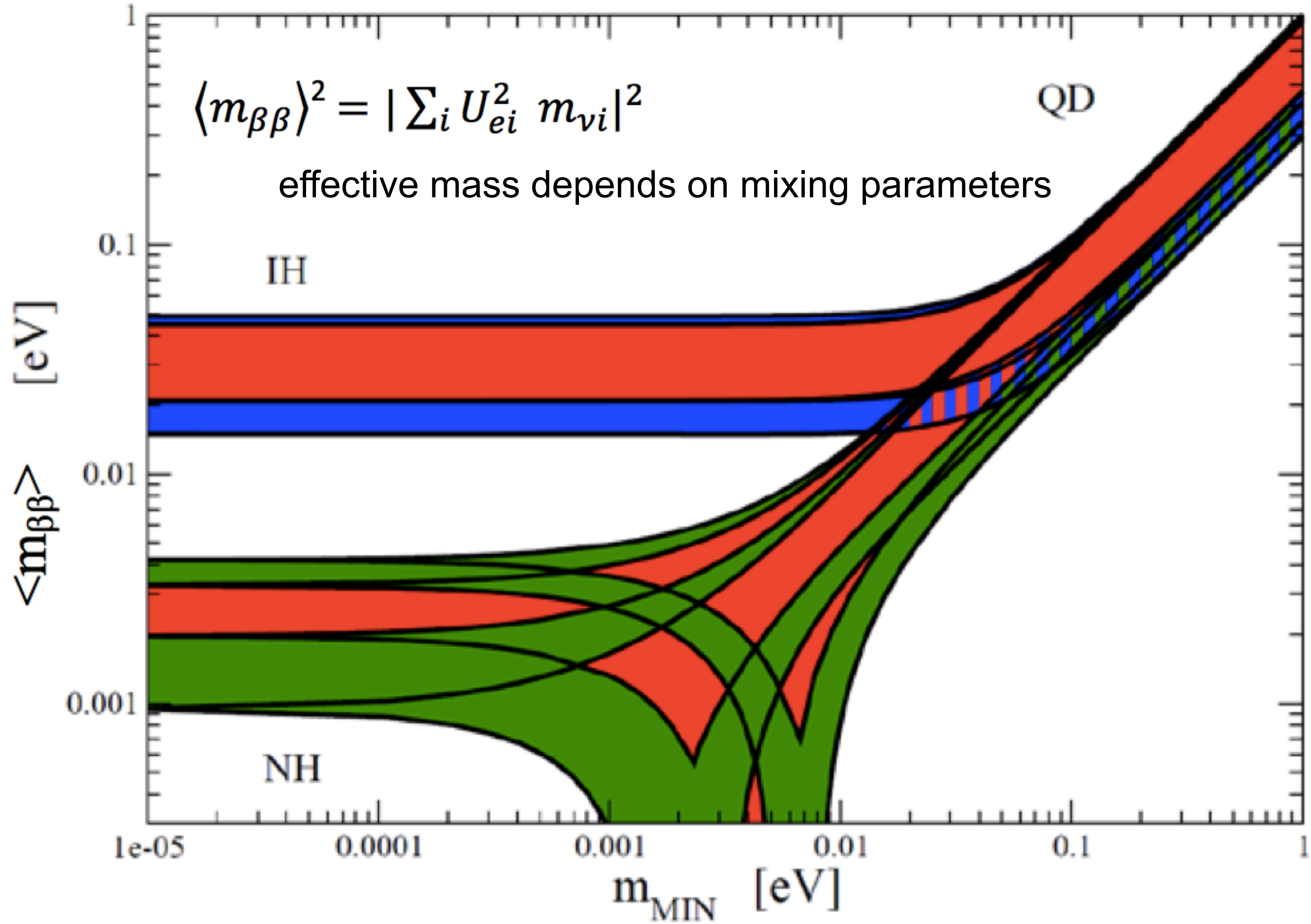
Only possible
for Majorana ν
(...or exotic physics)

$$(T_{1/2}^{0\nu})^{-1} = G^{0\nu} \cdot |M^{0\nu}|^2 \cdot \langle m_{\beta\beta} \rangle^2$$

Observable:
peak in the
two-electron
spectrum
corresponding to
ν-less final state



The NLDBD T-Shirt Plot

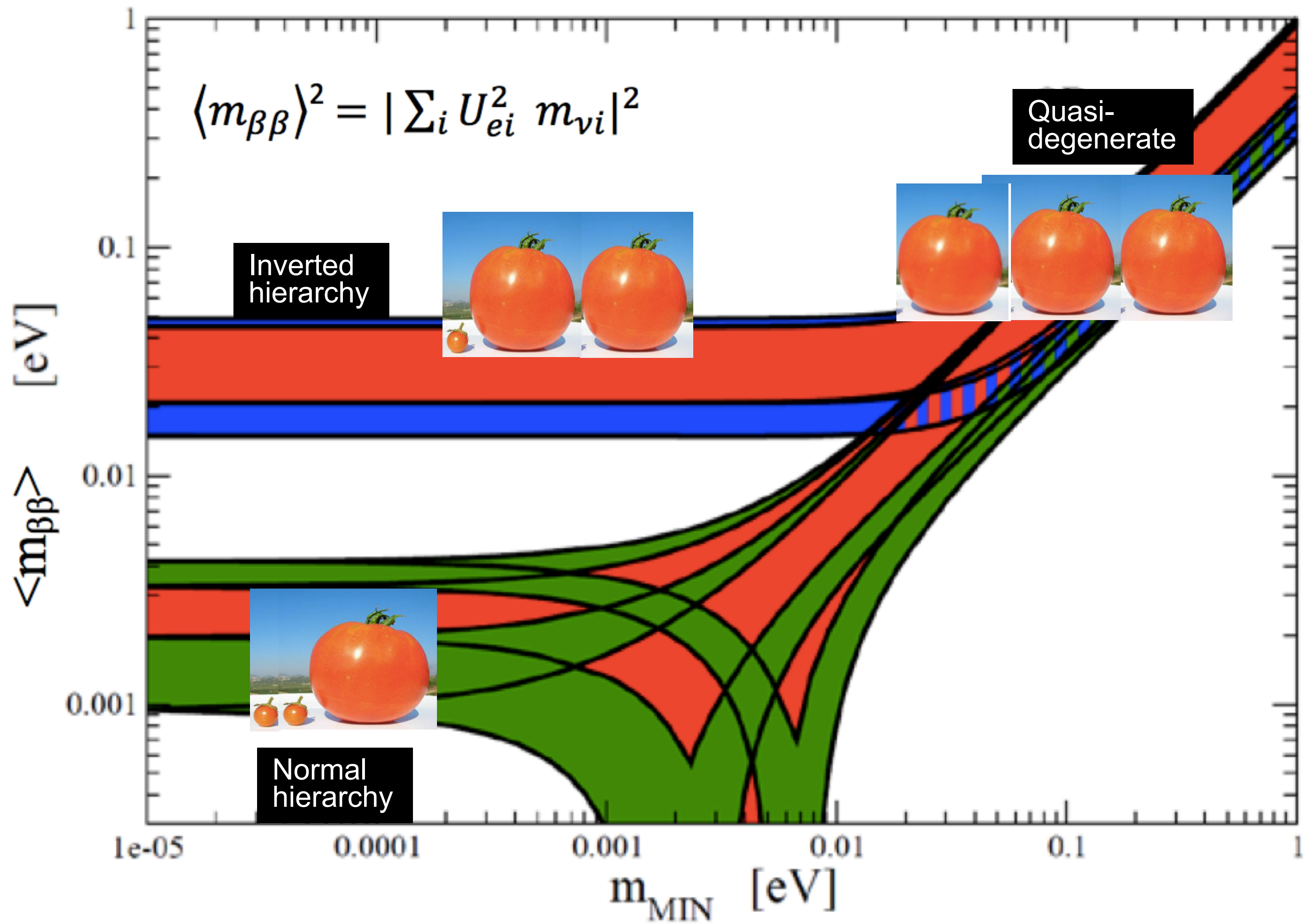


***If* neutrinos are Majorana*, experimental results must fall in the shaded regions**

Extent of the regions determined by uncertainties on mixing matrix elements and Majorana phases

*and standard 3-flavor picture

The NLDBD T-Shirt Plot



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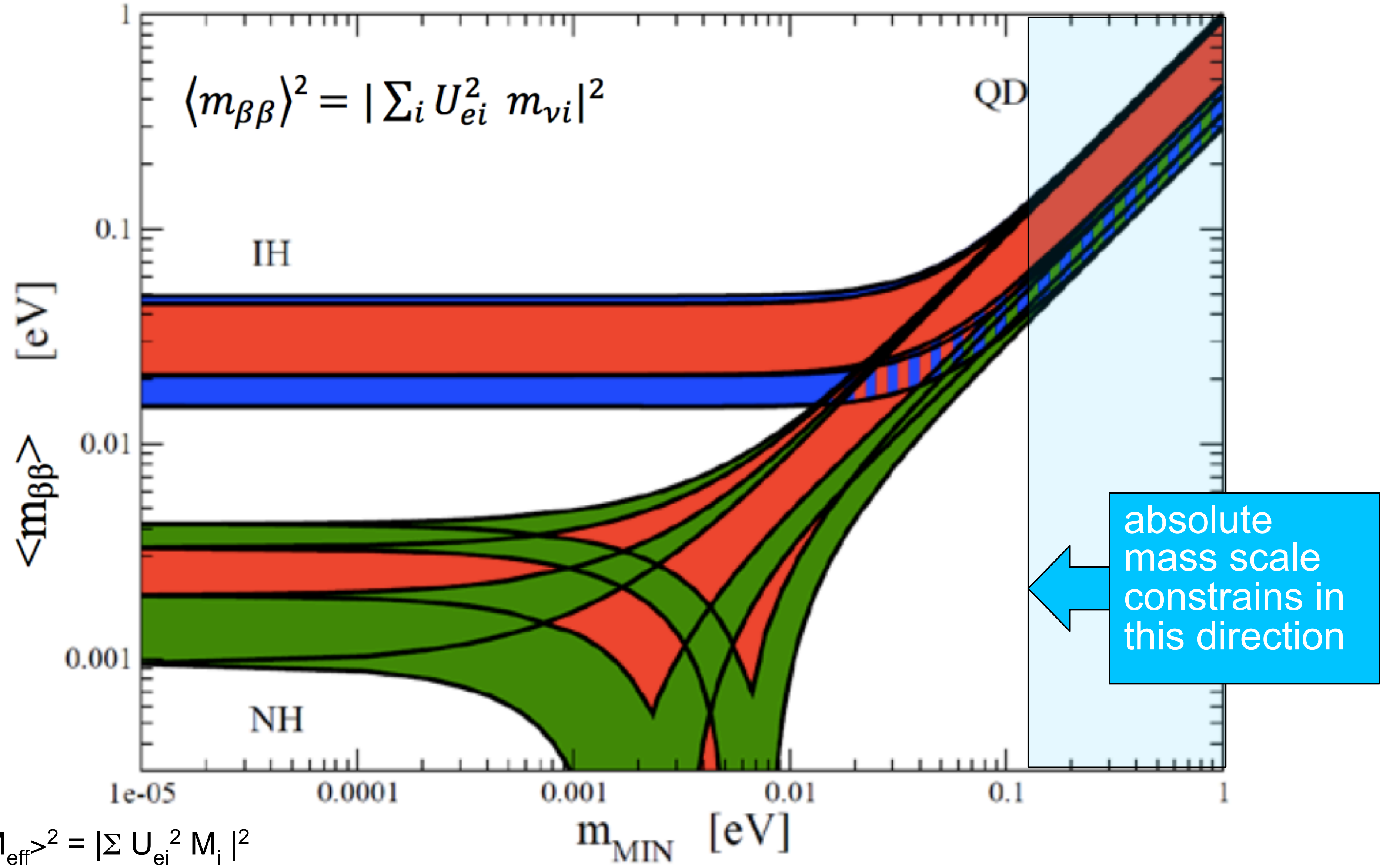
The NLDBD T-Shirt Plot

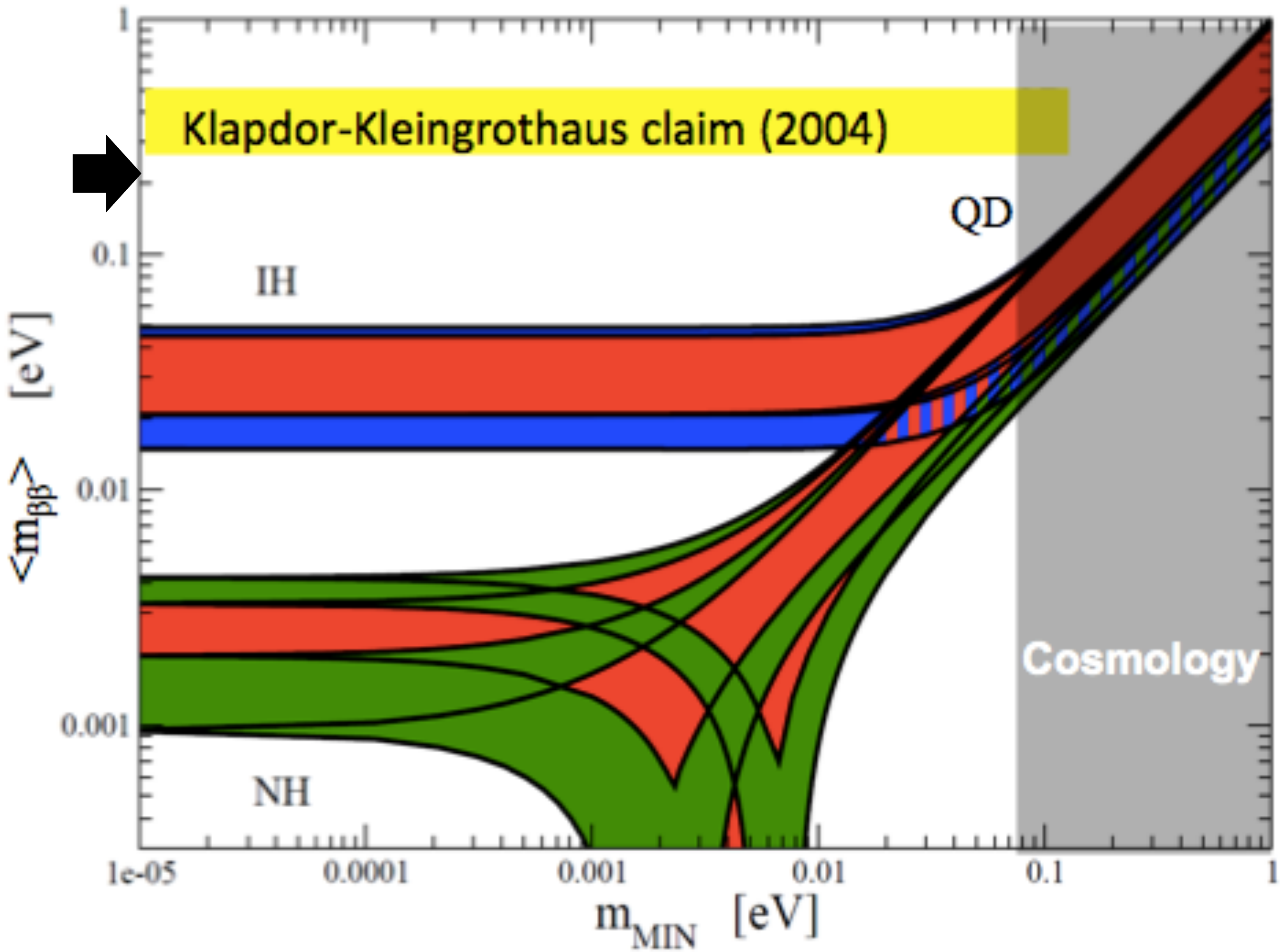


$\langle M_{eff}\rangle^2 = |\Sigma\ U_{ei}^2\ M_i\ |^2$

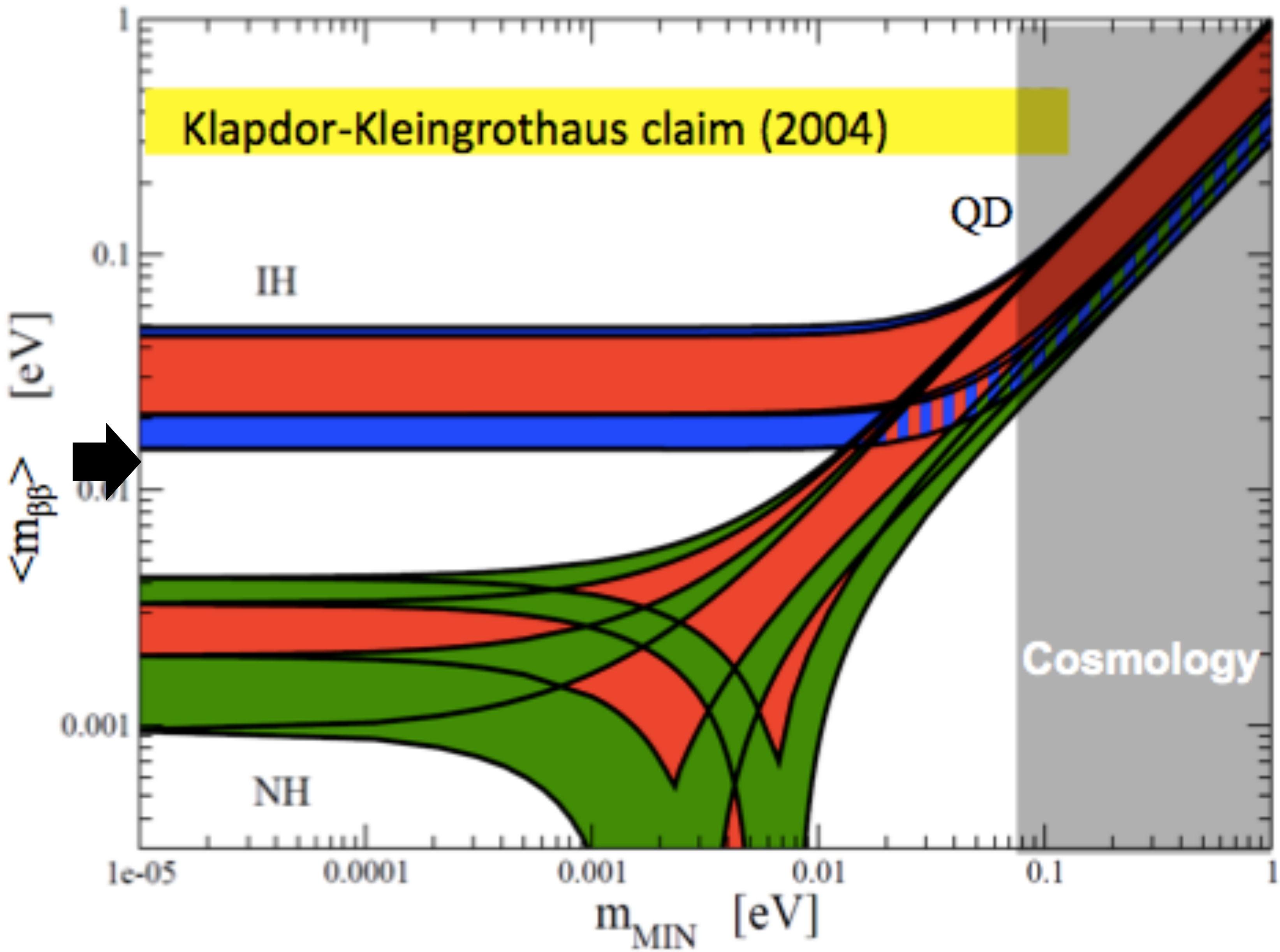
If **neutrinos are Majorana, experimental results must fall in the shaded regions**

Extent of the regions determined by uncertainties on mixing matrix elements and Majorana phases

Over the last decade the NLDBD experimental goal has been to attain sensitivity better than this claim...



New goal, however, is to get below the inverted hierarchy region



General NLDBD experiment strategies

$$T_{1/2} > \frac{\ln 2 \;\; \varepsilon \cdot N_{source} \cdot T}{UL(B(T) \cdot \Delta E)}$$

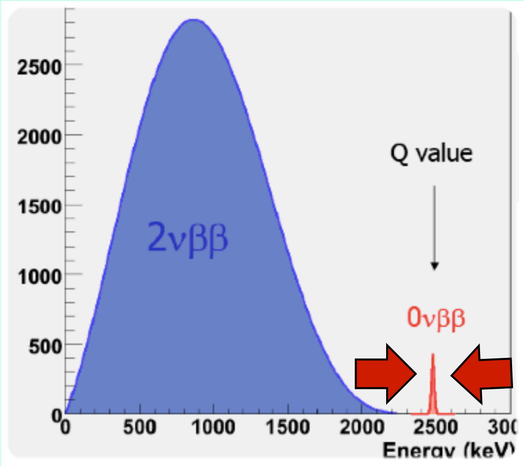
<table>
<tr>
<td>

The “Brute Force” Approach

focus on the numerator with **a huge amount of material**
(often sacrificing resolution)

</td>
<td>

The “Peak-Squeezer” Approach



focus on the denominator by **squeezing down ΔE**
(various technologies)

</td>
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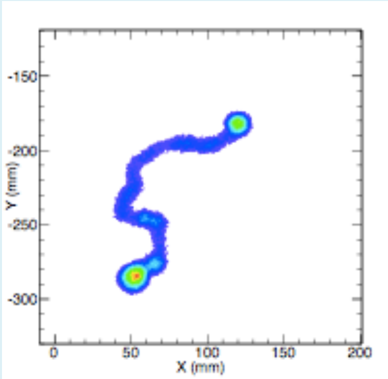
The “Final-State Judgement” Approach



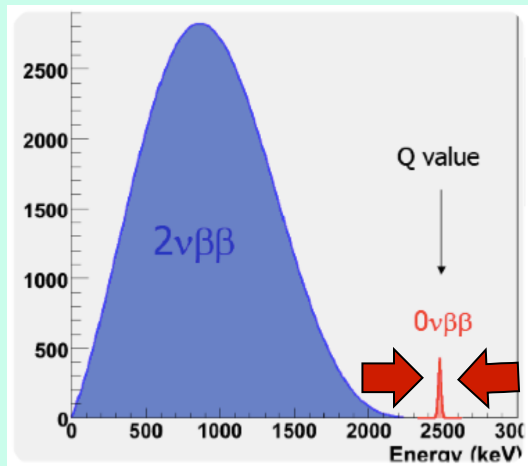
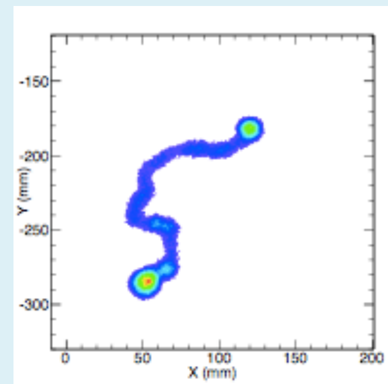
try to make the background zero by **tracking or tagging**

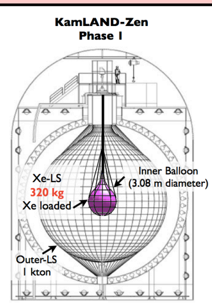
</td>
</tr>
</table>

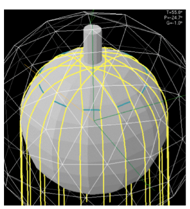
...some experiments take hybrid approaches...

General NLDBD experiment strategies

$$T_{1/2} > \frac{\ln 2 \;\; \varepsilon \cdot N_{source} \cdot T}{UL(B(T) \cdot \Delta E)}$$

The "Brute Force" Approach	The "Peak-Squeezer" Approach	The "Final-State Judgement" Approach
		





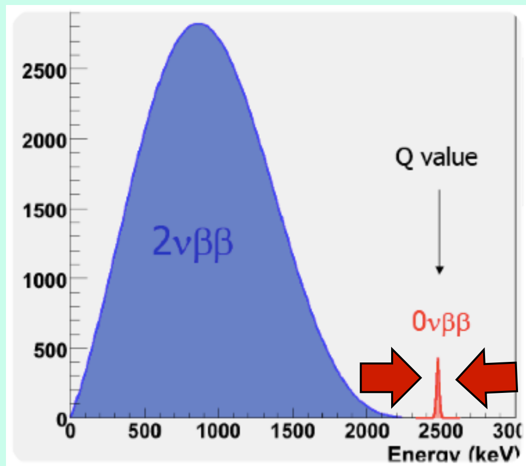
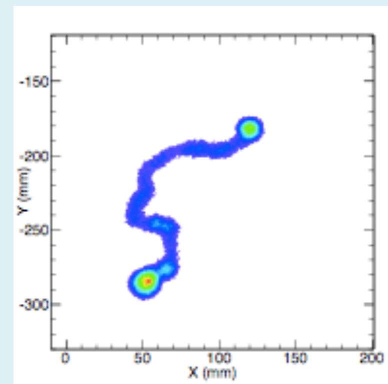
SNO+
(^{130}Te)

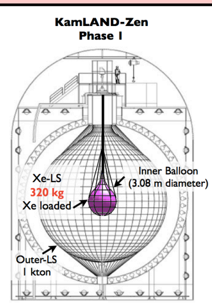
KamLAND-Zen
(^{136}Xe)

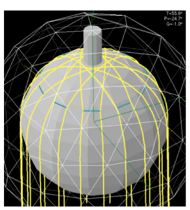
+more future ideas...

General NLDBD experiment strategies

$$T_{1/2} > \frac{\ln 2 \;\; \varepsilon \cdot N_{source} \cdot T}{UL(B(T) \cdot \Delta E)}$$

The “Brute Force” Approach	The “Peak-Squeezer” Approach	The “Final-State Judgement” Approach
		





SNO+
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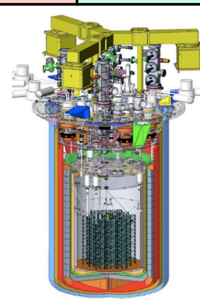
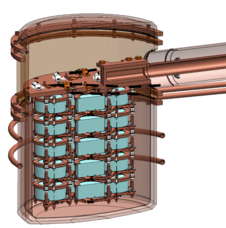
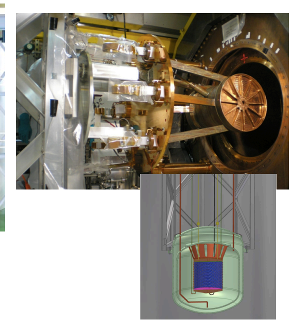


CUORICINO/
CUORE
(^{130}Te)



MAJORANA
(^{76}Ge)

GERDA
(^{76}Ge)



EXO/nEXO
(^{136}Xe)

+more future ideas...

General NLDBD experiment strategies

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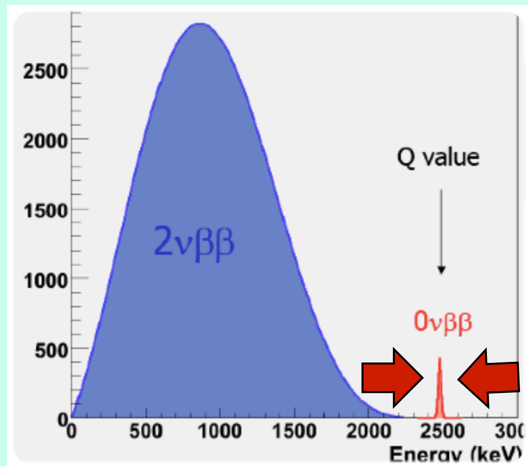
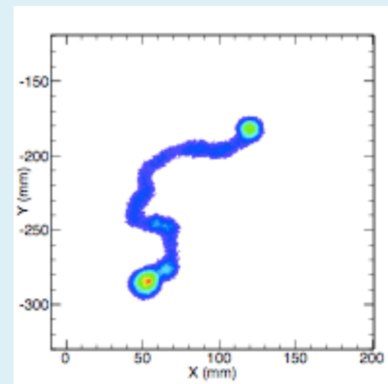
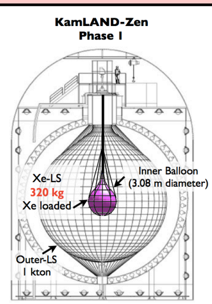
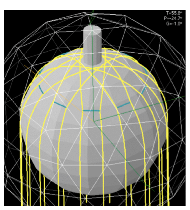
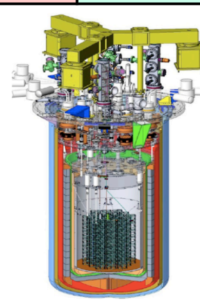
The "Brute Force" Approach	The "Peak-Squeezer" Approach	The "Final-State Judgement" Approach
		



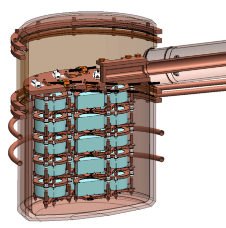
KamLAND-Zen
(^{136}Xe)



SNO+
(^{130}Te)

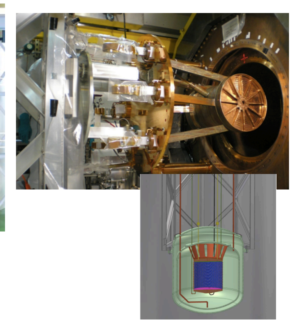


CUORICINO/
CUORE
(^{130}Te)

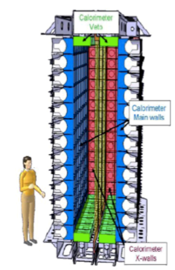


MAJORANA
(^{76}Ge)

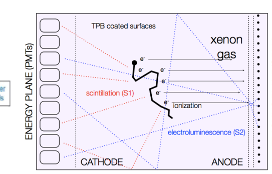
GERDA
(^{76}Ge)



EXO/nEXO
(^{136}Xe)



NEMO/
SuperNEMO
(various/^{82}Se)

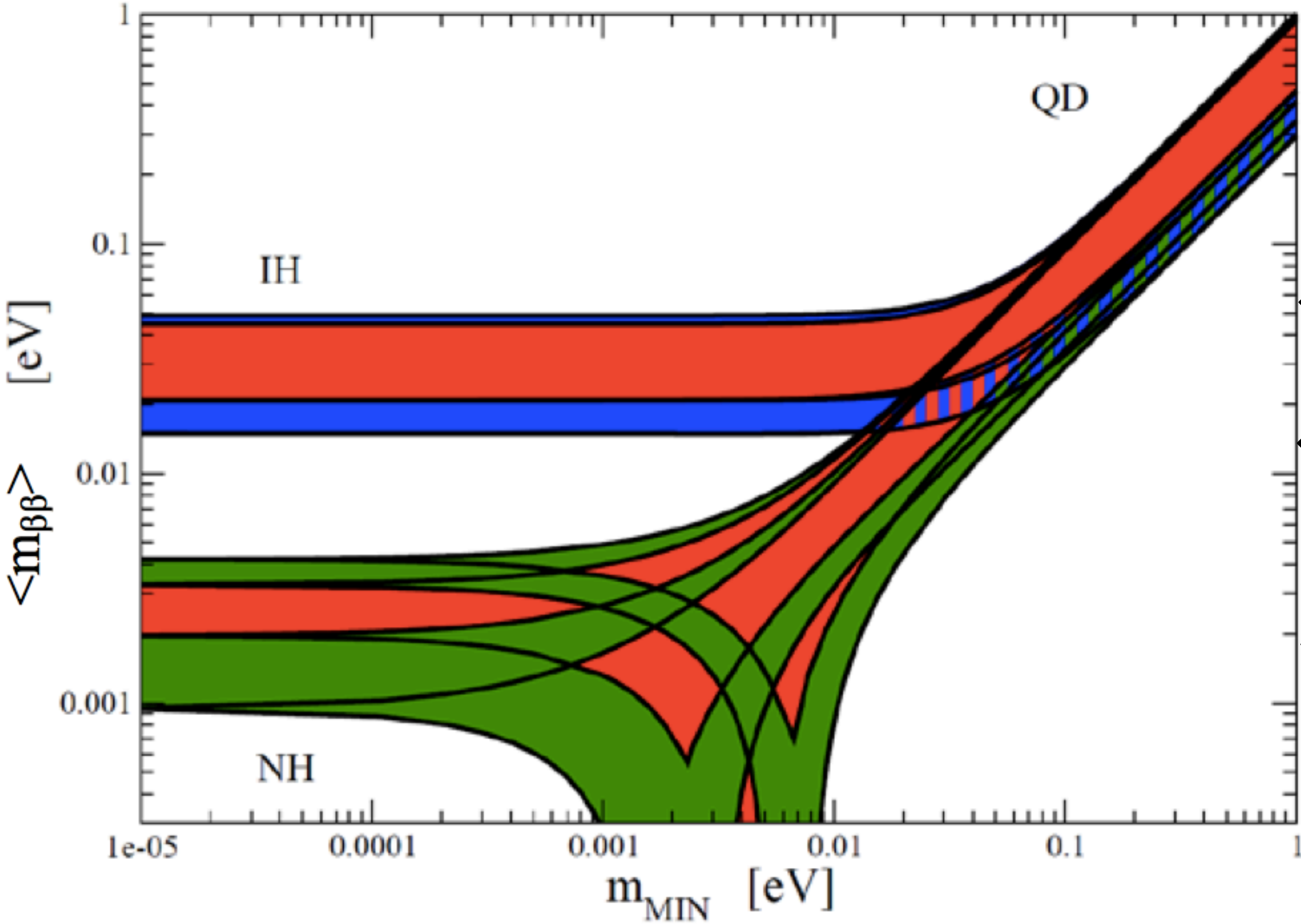


NEXT
(^{136}Xe)

+more future ideas...

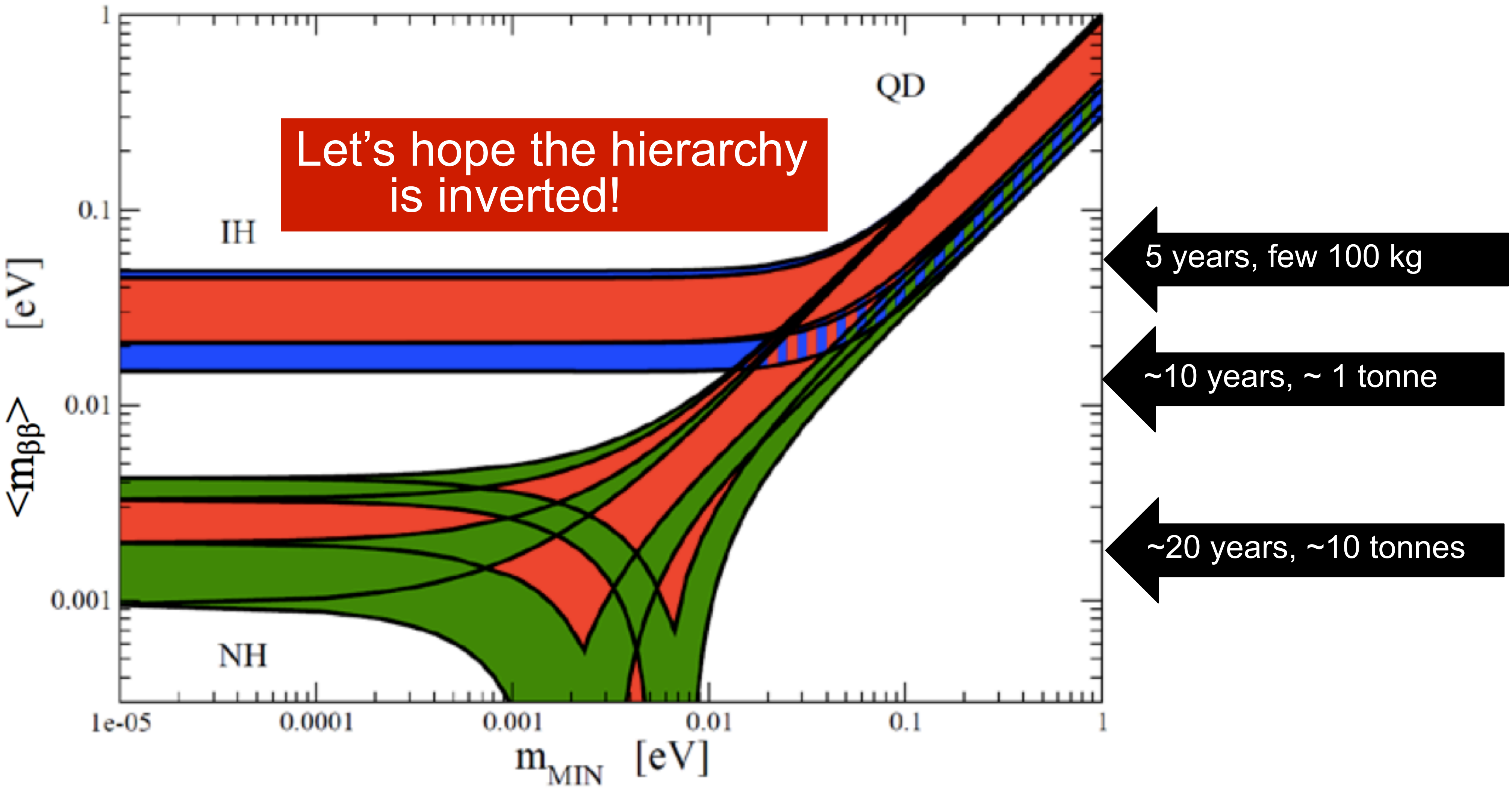
See session Neutrino-6

Overall Long-Term Prospects for NLDBD



In the long term will need more than one isotope...
theory needed too!

Overall Long-Term Prospects for NLDBD

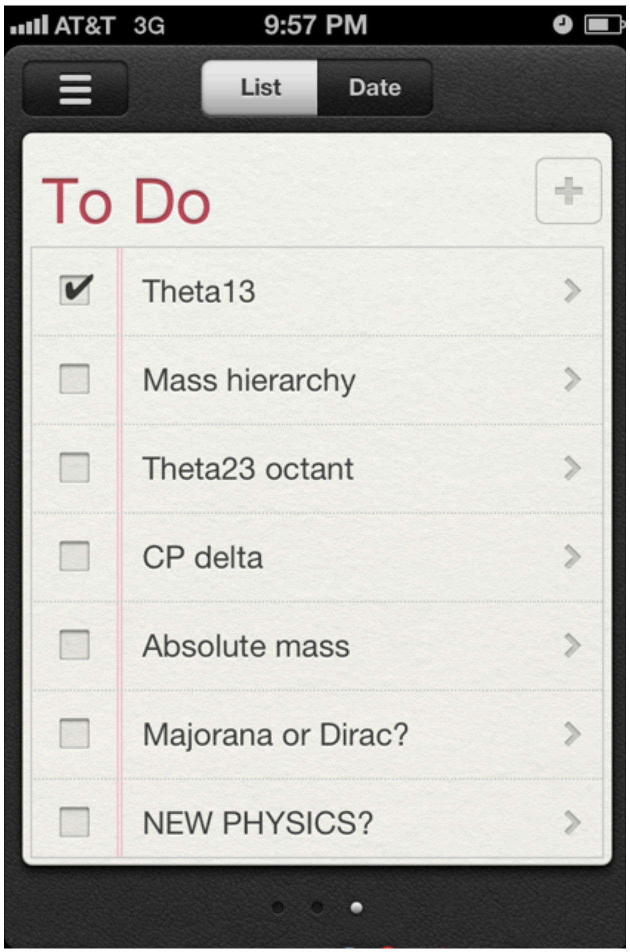


In the long term will need more than one isotope...
theory needed too!

Overall Summary

Huge progress in understanding of neutrinos over the last 20 years, **but still many outstanding questions**

What is the pattern of masses and mixings? Does the 3-flavor paradigm hold? Are there sterile neutrinos or other exotic new physics? How did the matter-antimatter asymmetry come to be? Why are neutrinos so light? ...



- **Long-baseline beams w/ multi-kton detectors** (+ reactor experiments) for oscillation parameters (and broader physics program)
- **Spectrometers & cosmology** for absolute mass
- **Deep, clean experiments** for neutrinoless double beta decay
- Possible rich program of smaller experiments for other ν physics
- Many more, not mentioned here...

More in the parallel sessions!