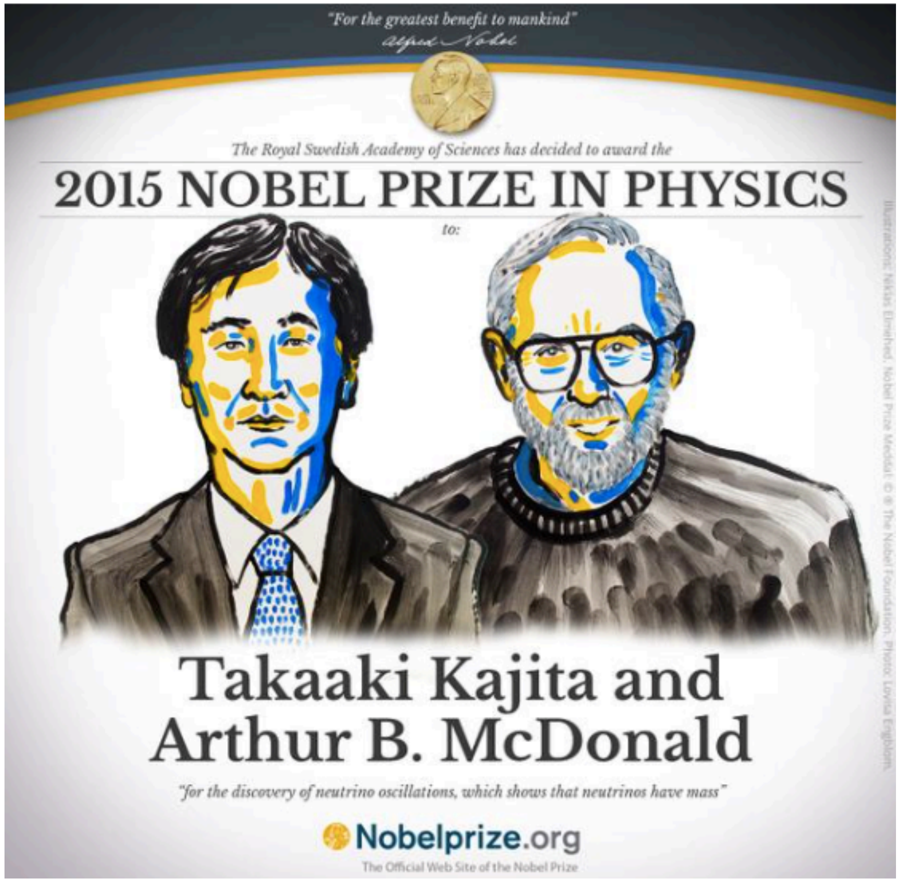
Neutrino Experiment Overview

Kate Scholberg, Duke University

HEP 2016, Valparaiso, Chile, January 2016

Neutrinos are on a roll: a brand new Nobel Prize!



The fourth Nobel
for neutrinos:

1988: neutrino flavor
1995: discovery of the neutrino
2002: solar and supernova neutrinos
2015: neutrino oscillations (and mass)

And also: the Breakthrough Prize

Neutrinos Win Again: More Than 1,300 Physicists Share Breakthrough Prize for Particle Experiments

In October two discoverers of neutrino oscillations won the Nobel Prize. Now their full teams and those of several other experiments on the strange particles share a $3-million award

Recognized also 1300 scientists from 6 collaborations!

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:

MO and CP δ

Beyond 3-flavor?

The mass pattern and mixing matrix

Absolute Mass

βdk endpoint, cosmology

The mass scale

Majorana vs Dirac?

Neutrinoless ββdk

The mass nature

also of interest! but will skip for lack of time

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

The three-flavor paradigm

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

Parameterize mixing matrix U as

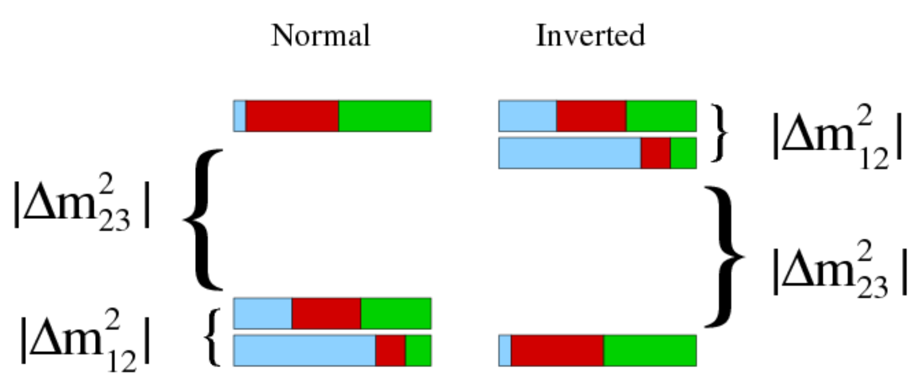
$$U = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{bmatrix} \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

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

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

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

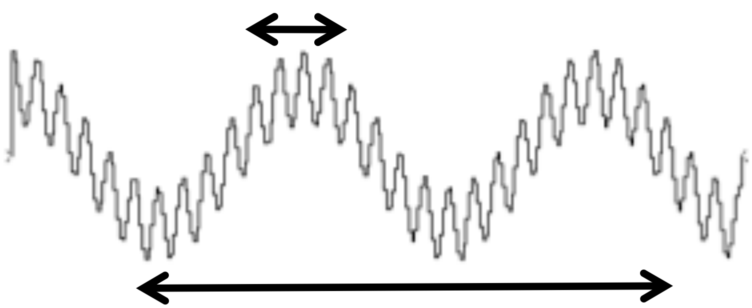
$$|\nu_f\rangle = \sum_{i=1}^{N} U_{fi}^{*}|\nu_i\rangle$$

$\Delta m_{ij}^2 \equiv m_i^2 - m_j^2$ (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



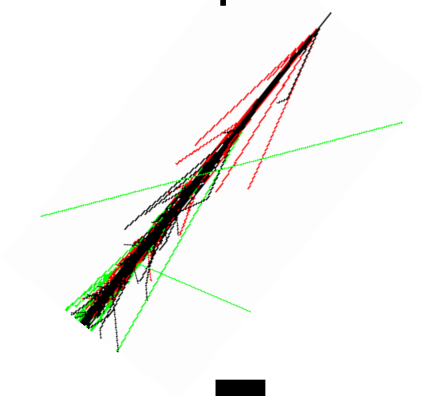
$|\Delta m_{23}^2| >> |\Delta m_{12}^2|$ ➔ two frequency scales

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

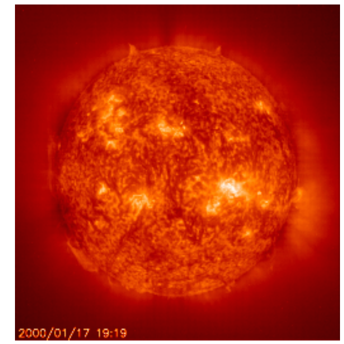
$$P(\nu_f \to \nu_g) = \sin^2 2\theta \sin^2\left(\frac{1.27\Delta m^2 L}{E}\right)$$

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

atmospheric

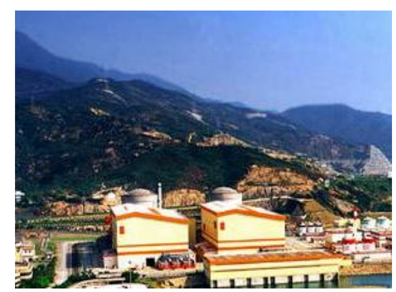


solar



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

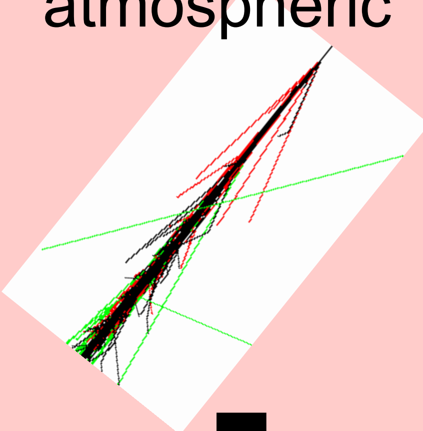
beams



reactor

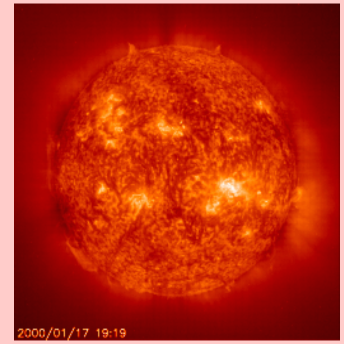
We now have clean flavor-transition signals in two 2-flavor sectors

atmospheric



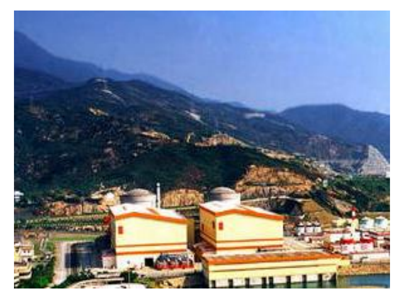
signal with
“wild” neutrinos...

solar



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

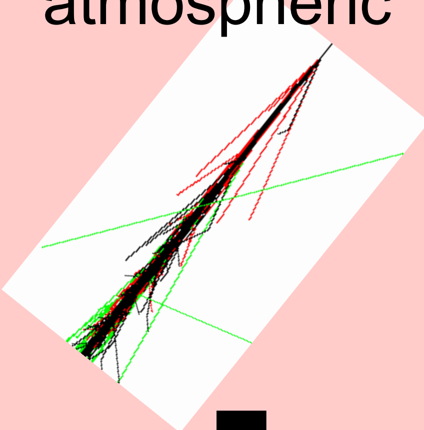
beams



reactor

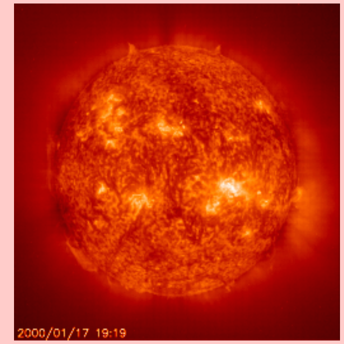
We now have clean flavor-transition signals in two 2-flavor sectors

atmospheric



signal with
"wild" neutrinos...

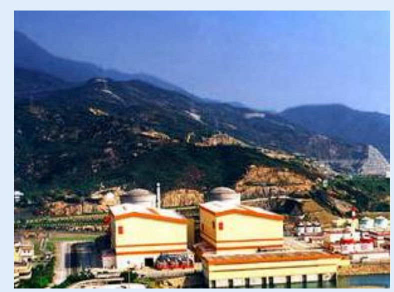
solar



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

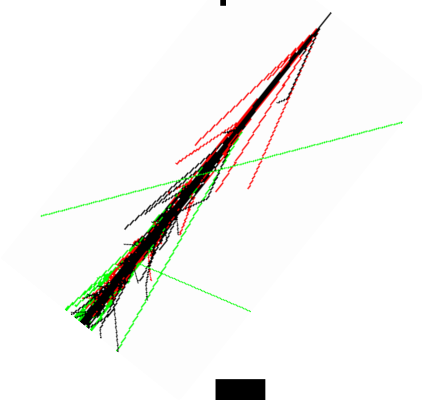
beams

confirmed with
"tame" ones...

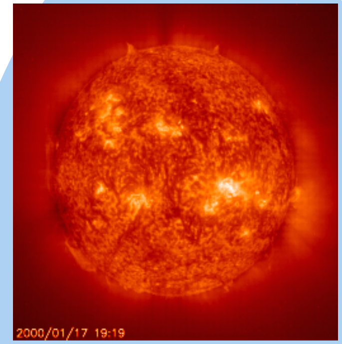


reactor

atmospheric



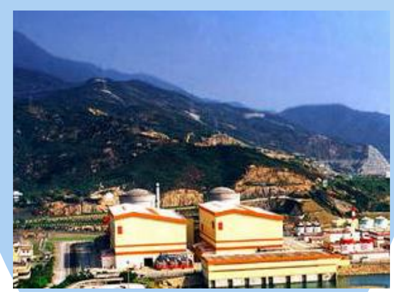
solar



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

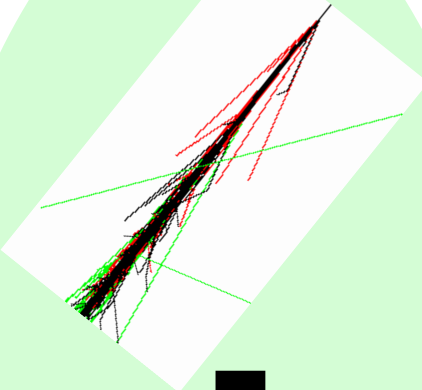
beams

“Solar” sector: solar ν oscillations confirmed with reactors

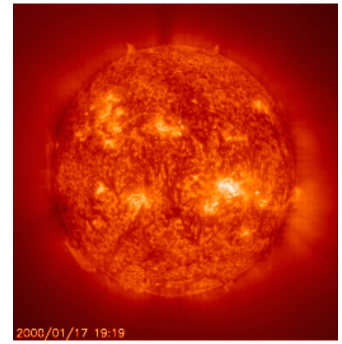


reactor

atmospheric



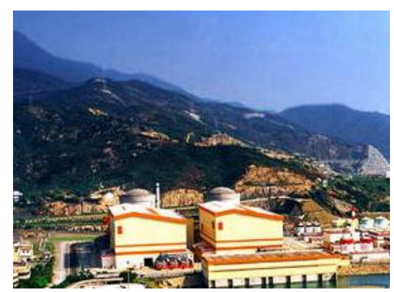
solar



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

beams

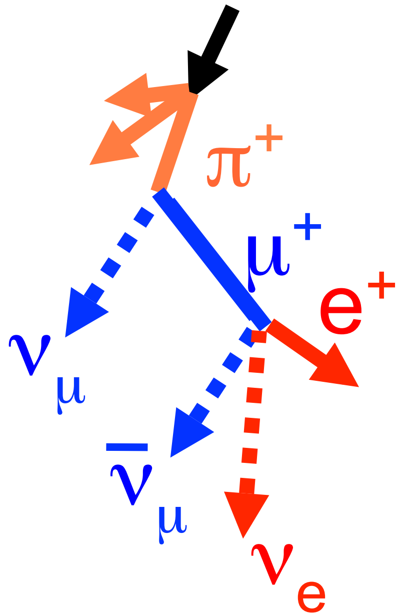
I will focus on the “atmospheric” sector

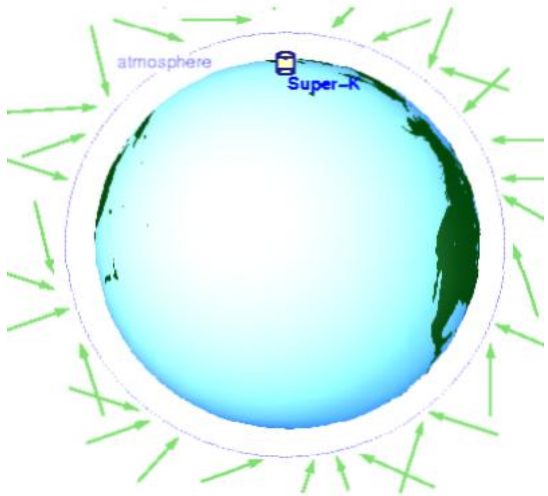


reactor

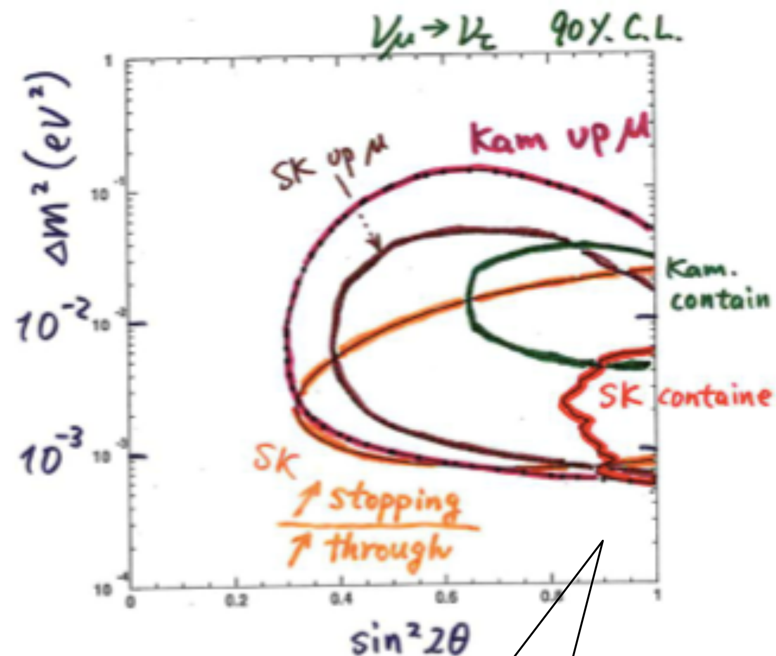
Atmospheric neutrinos

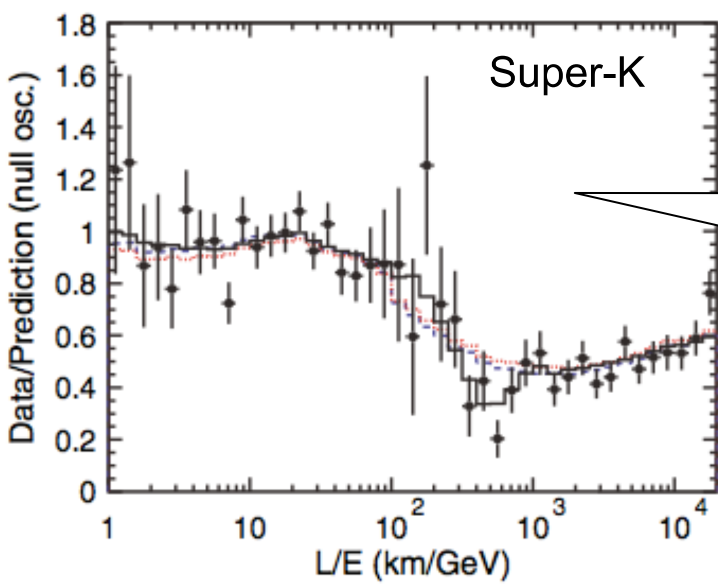
The neutrinos are free, and have a range of baselines & energies





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





Clear ν_μ disappearance

Well described by
23 oscillation parameters:
$|\Delta m^2_{32}|$ ~ 2 x 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

K2K
KEK to Kamioka
250 km, 5 kW

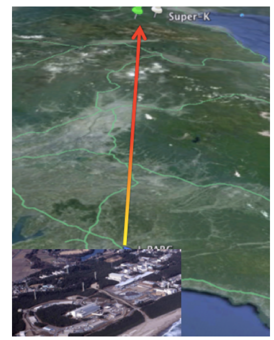
MINOS (+)
FNAL to Soudan
734 km, 400 kW

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

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
KEK to Kamioka
250 km, 5 kW

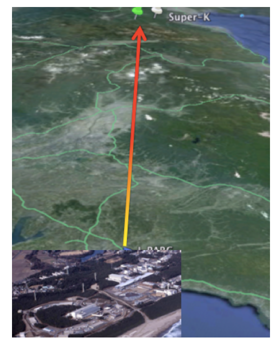
MINOS (+)
FNAL to Soudan
734 km, 400 kW

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

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



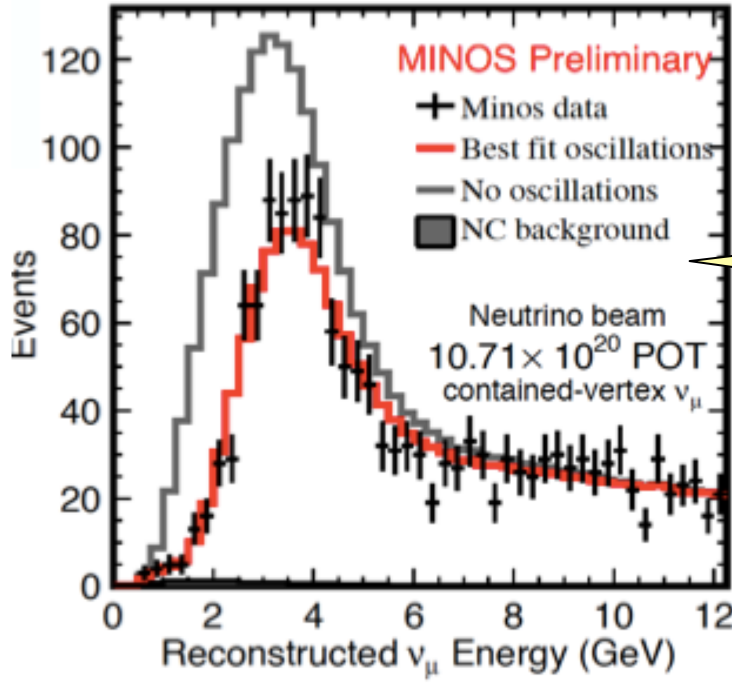
Hyper-K
J-PARC to Kamioka
295 km, 750 kW
(➔..)

And beyond...
ESSnuB,
neutrino factories...

MINOS (now +)

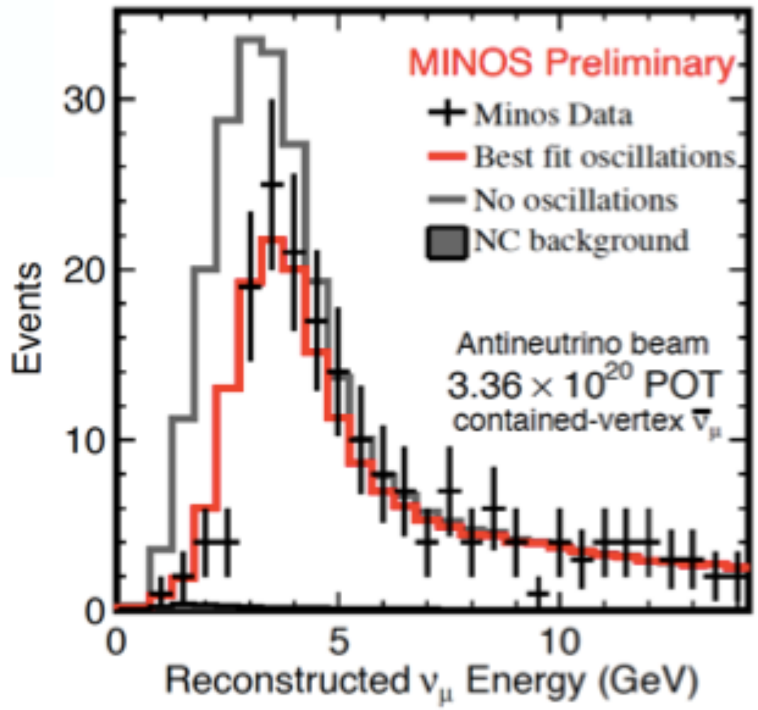
in US made precision measurements of ν_μ disappearance

Neutrinos



suppression of μ-like events

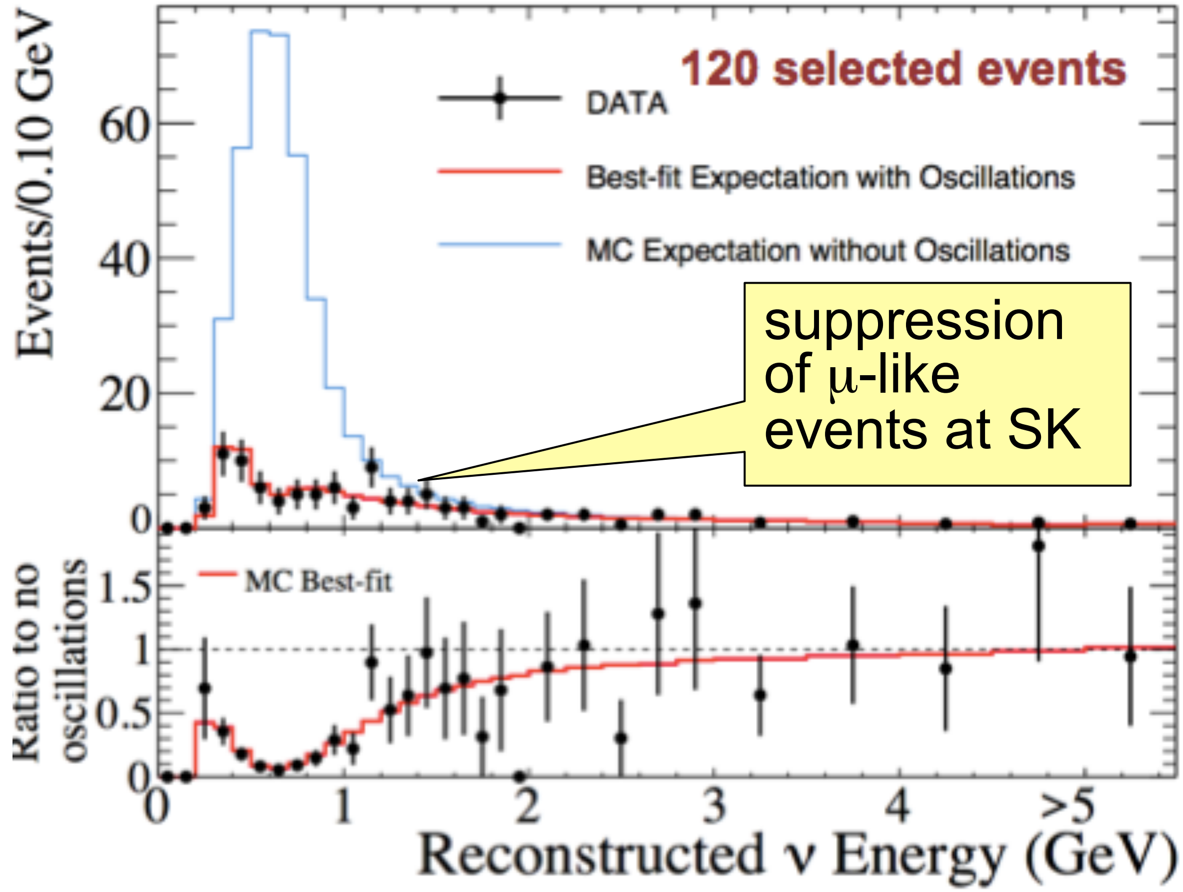
Antineutrinos



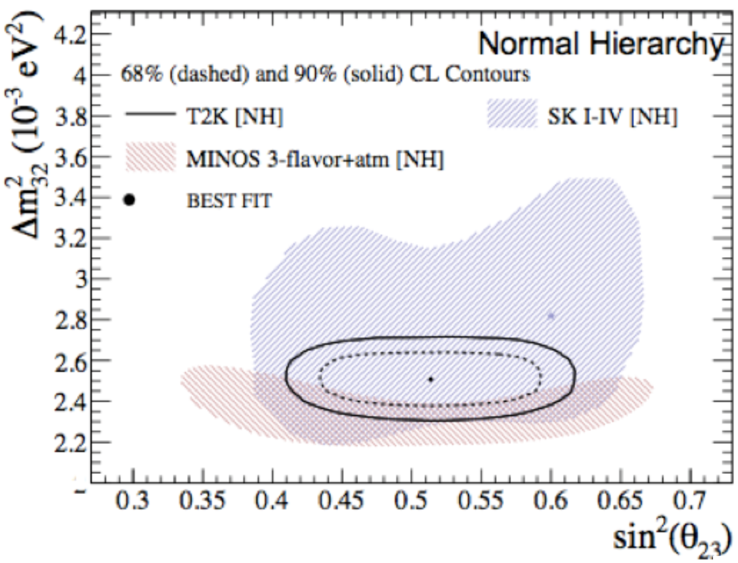
Magnetized iron tracker enables sign selection and event-by-event antineutrino selection

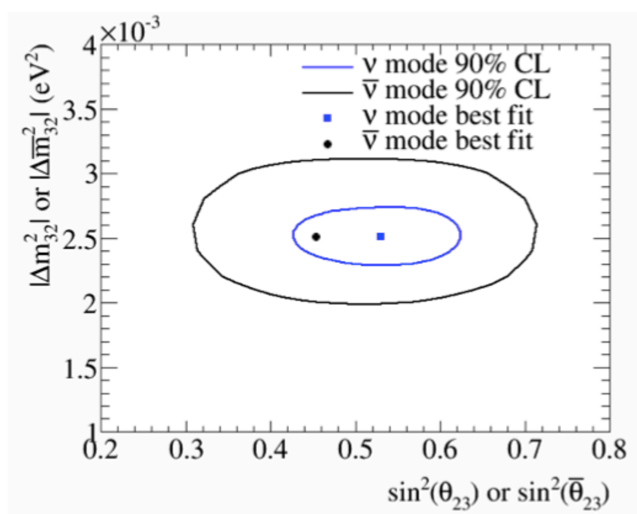
ν_μ disappearance results from T2K

current best measurement of θ_{23}



suppression of μ-like events at SK





NEW

T2K
anti-ν_μ result

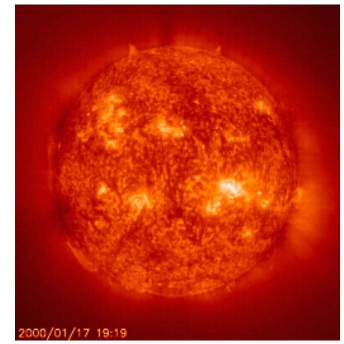
See talk by P. Przewlocki on Monday

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

atmospheric

θ_{13}, the "twist in the middle"

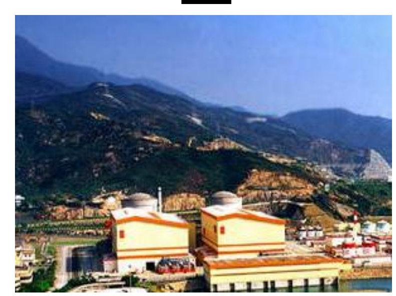
solar



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

beams

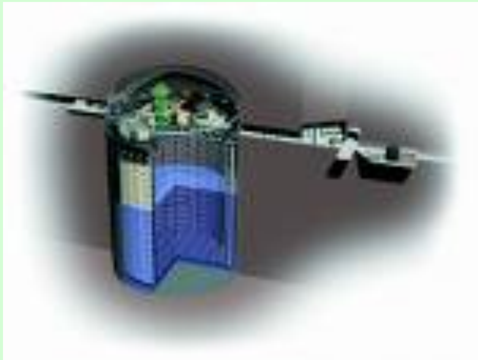
Before 2011, known to be small

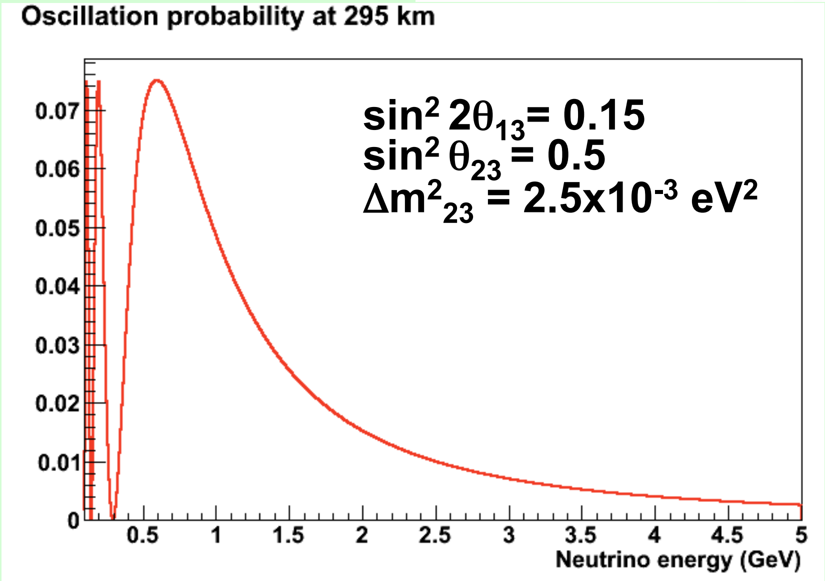


reactor

How to measure θ_{13}

Beams

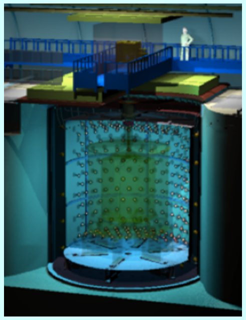


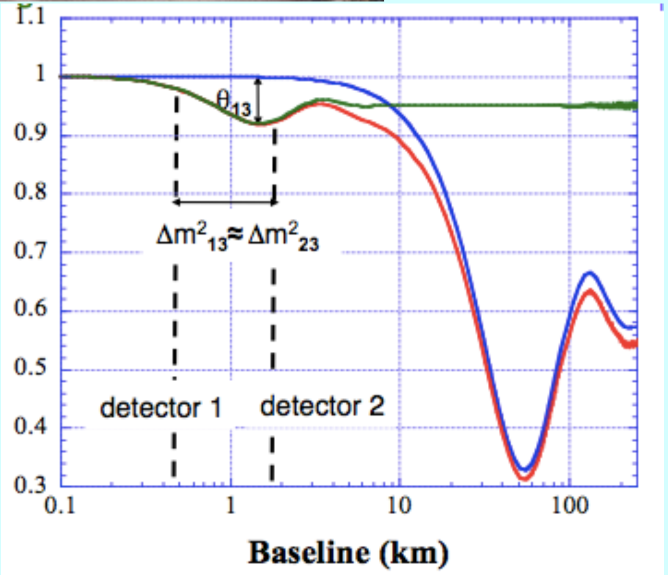


Look for *appearance* of ~GeV ν_e in ν_μ beam on ~300 km distance scale

K2K, MINOS, T2K, NOνA

Reactors



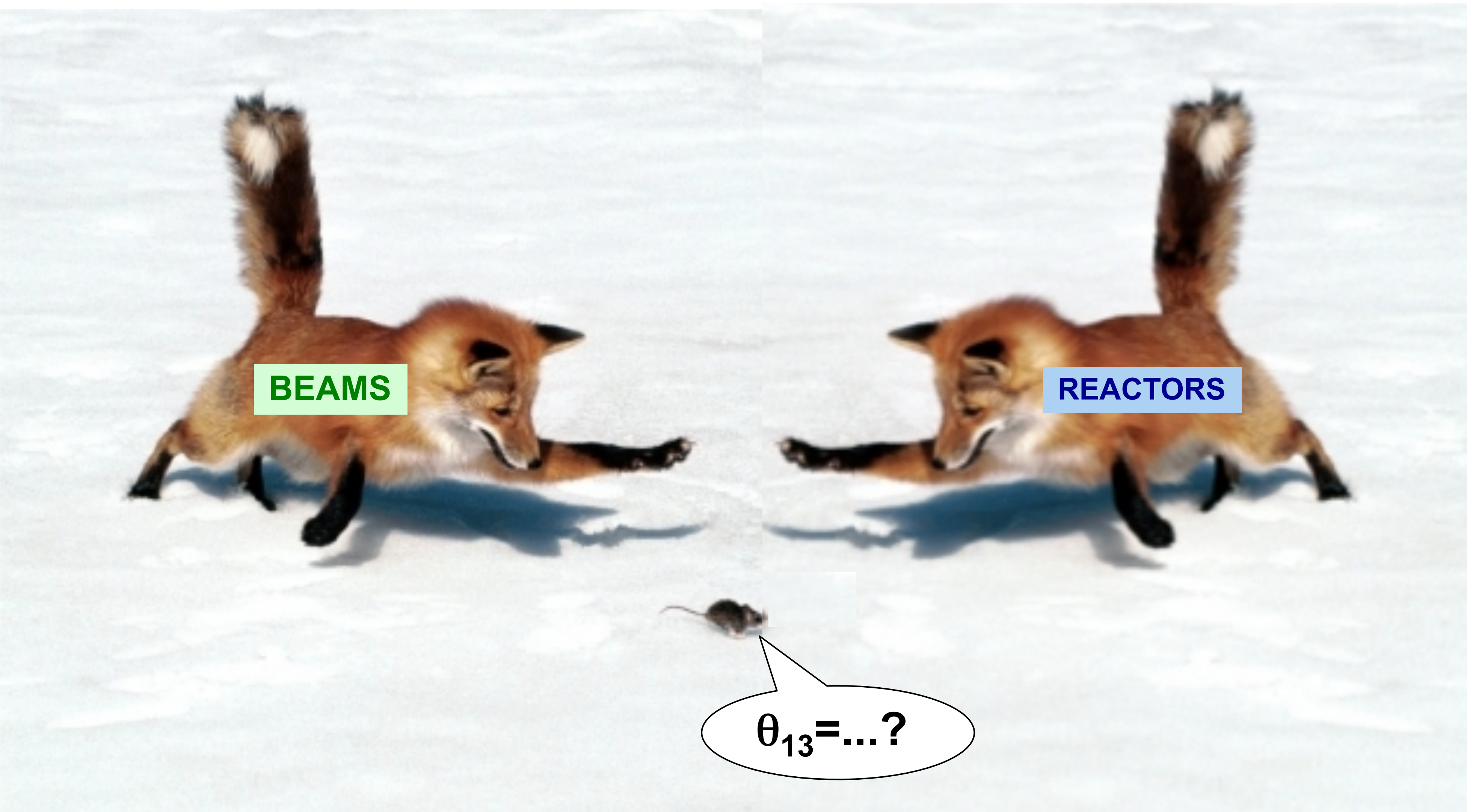


Look for *disappearance* of ~few MeV $\bar{\nu}_e$ on ~km distance scale

CHOOZ, Double Chooz, Daya Bay, RENO

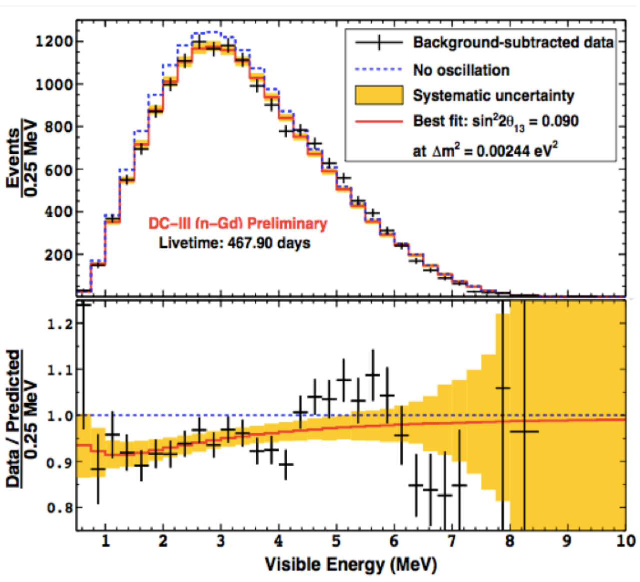
A slide from December 2011:

We're closing in on the answer...



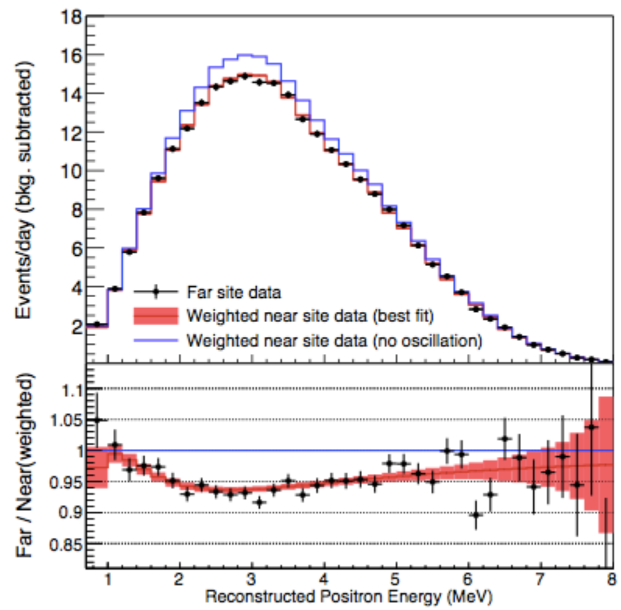
Tour-de-force reactor θ_{13} measurements

Double Chooz



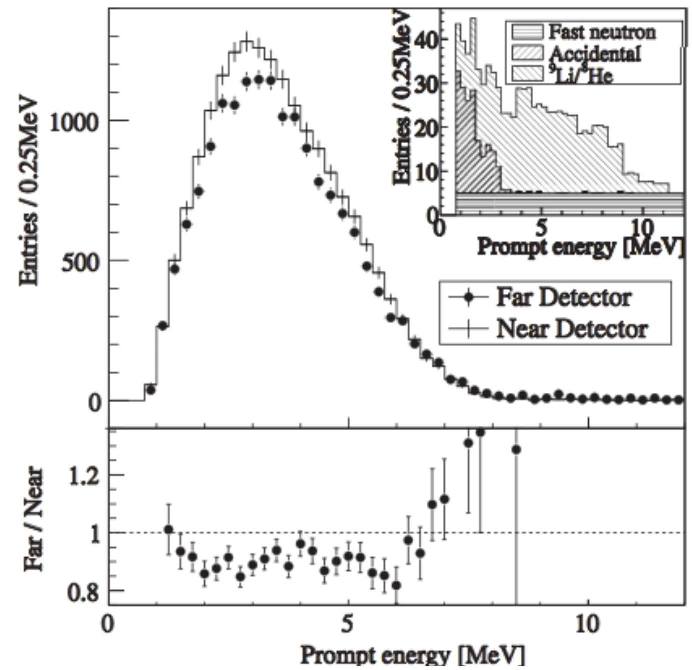
$\sin^2(2\theta_{13})=(0.09\pm0.03)$

Daya Bay



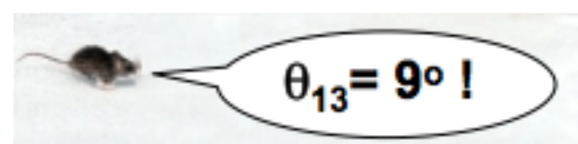
$$\sin^2 2\theta_{13} = 0.084^{+0.005}_{-0.005}$$

RENO



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

Disappearance of reactor antineutrinos with characteristic spectral distortion

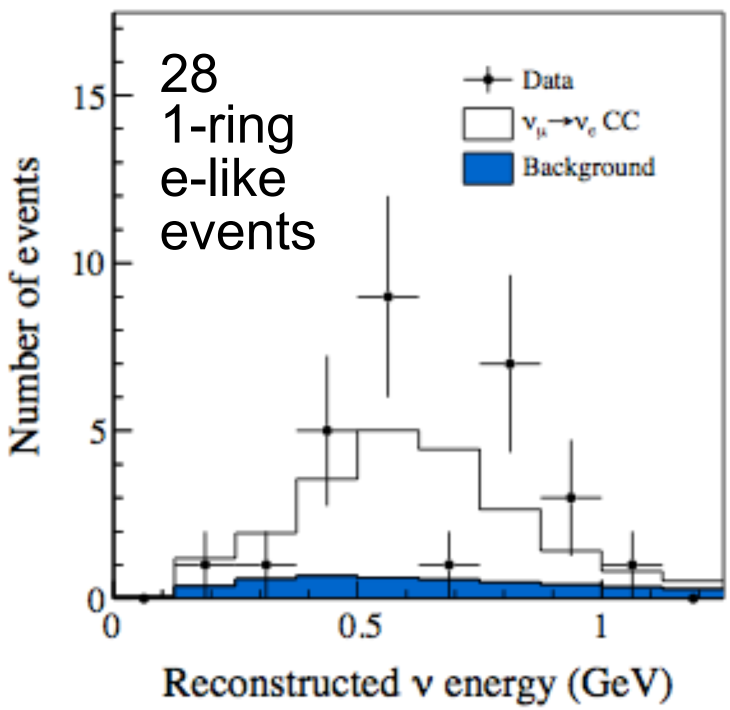


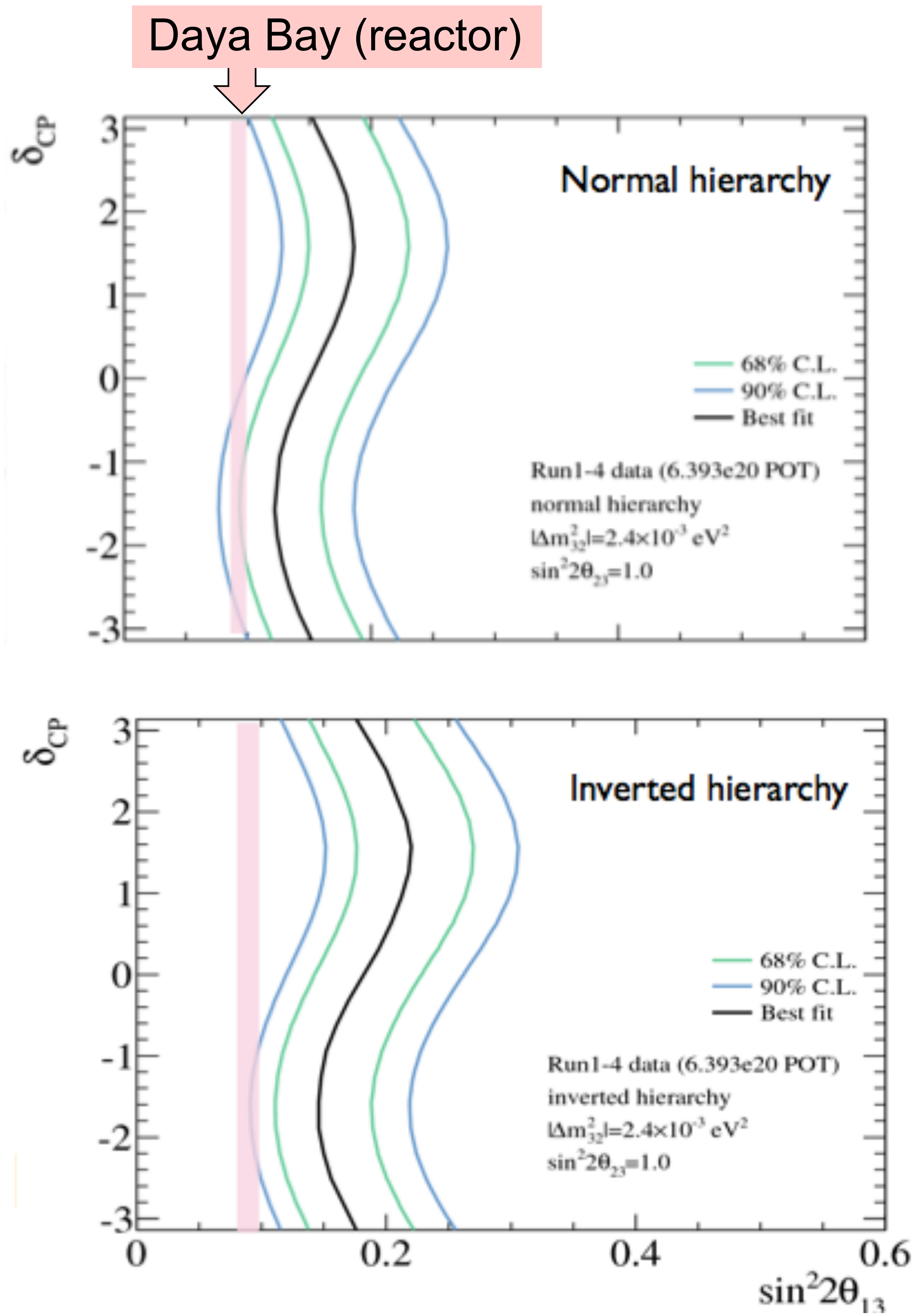
See talk by N. Viaux on Monday for latest DB details

T2K result for ν_e appearance

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

Reconstructed events after all ν_e cuts

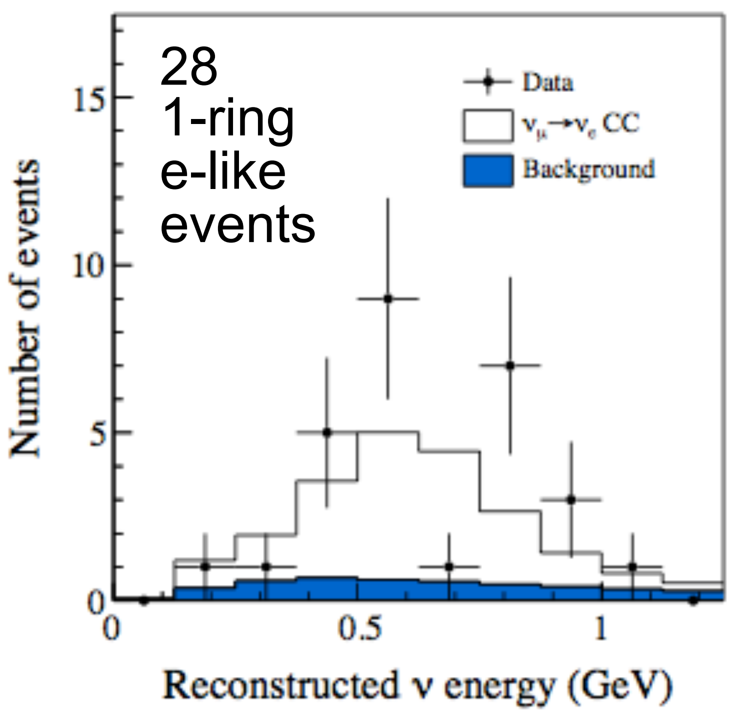


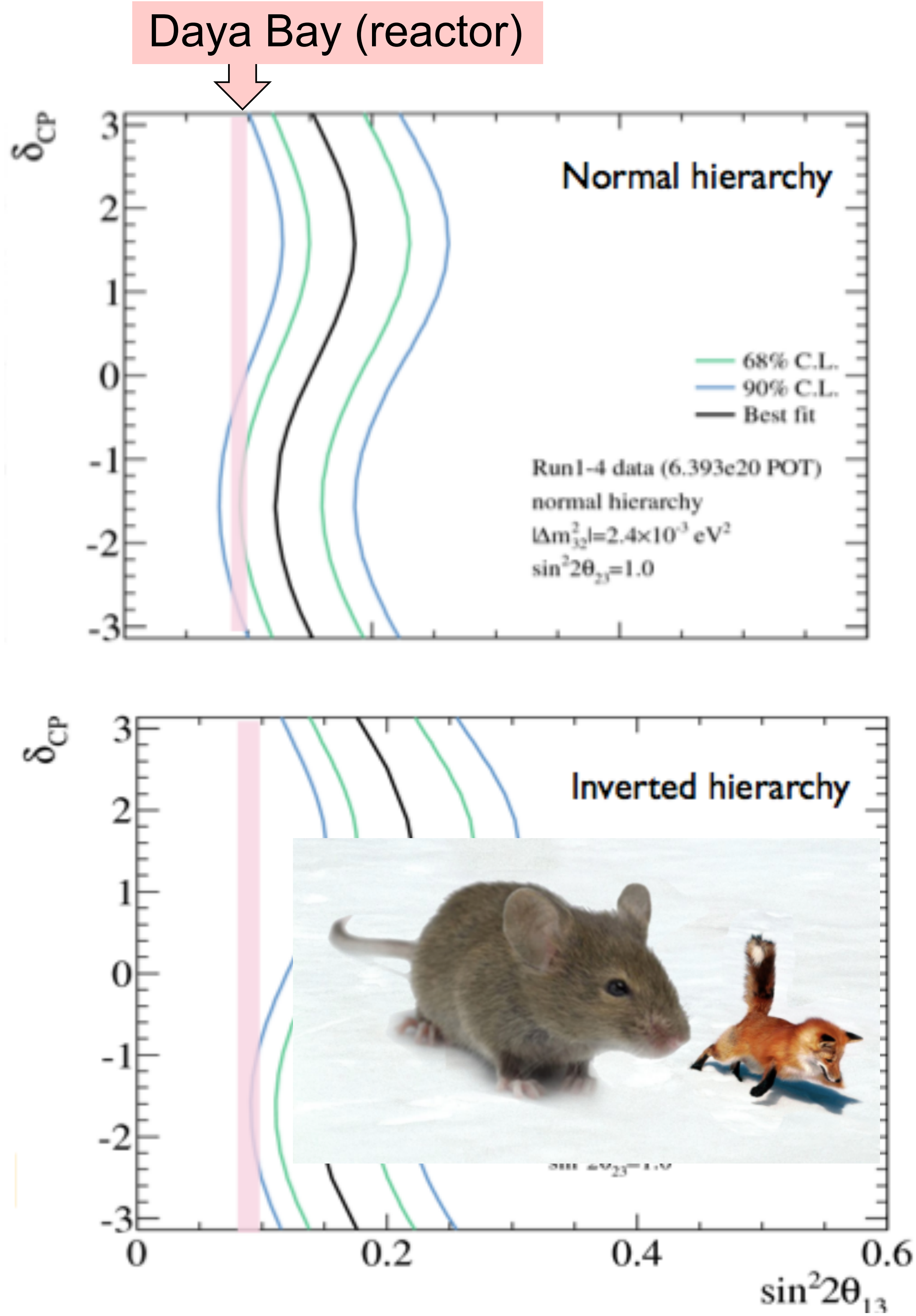


T2K result for ν_e appearance

$$\nu_\mu \to \nu_e$$

Reconstructed events after all ν_e cuts

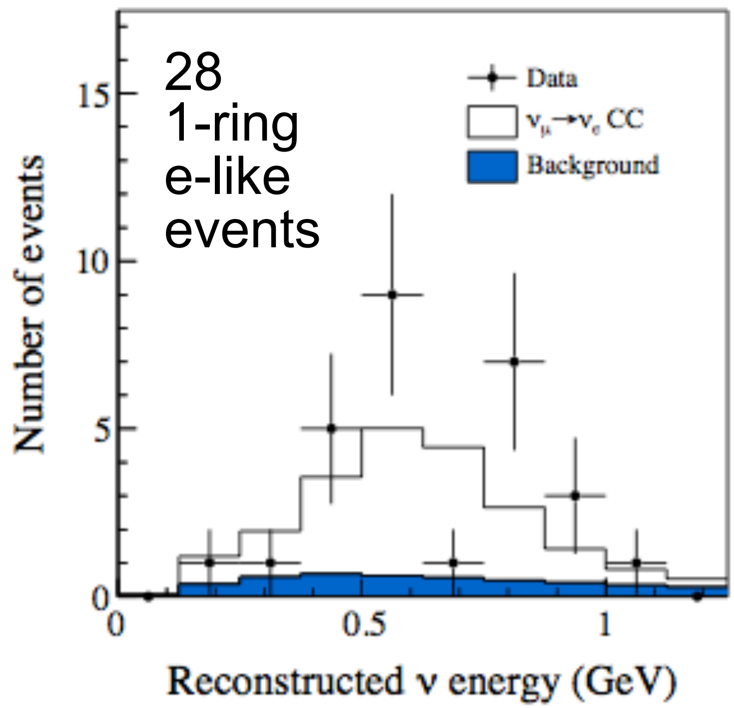




T2K result for ν_e appearance

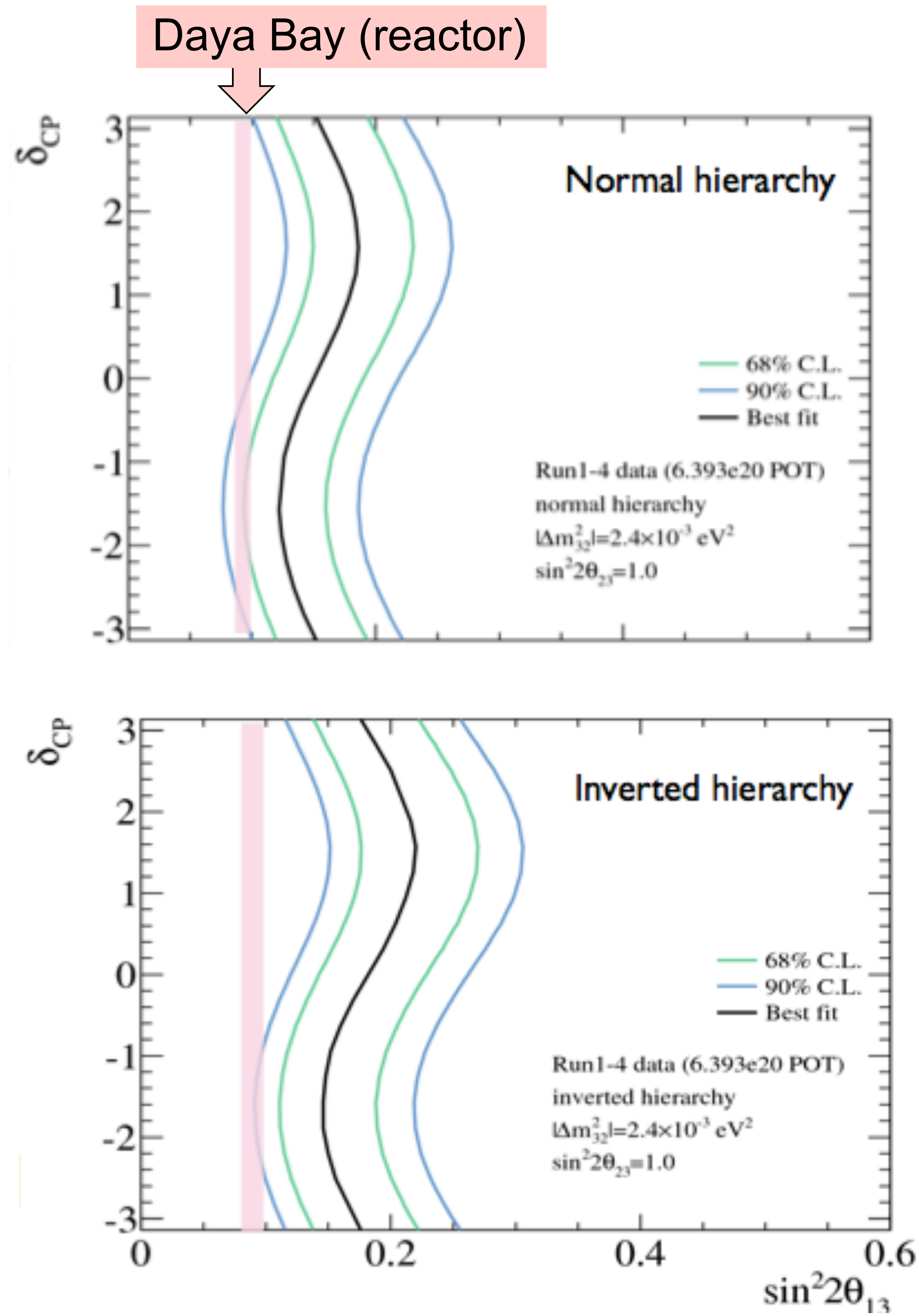
$$\nu_\mu \rightarrow \nu_e$$

Reconstructed events after all ν_e cuts



NEW : **antineutrinos**

See talk by P. Przewlocki on Monday



The three-flavor picture fits the data well

Global three-flavor fits to all data

	3σ range	<u>3σ knowledge</u>
$\sin^2\theta_{12}$	$0.270 \to 0.344$	
$\theta_{12}/^\circ$	$31.29 \to 35.91$	~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%
$\delta_{CP}/^\circ$	$0 \to 360$	~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, T. Schwetz, arXiv:1512.06856

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

	3σ range
$\sin^2\theta_{12}$	$0.270 \to 0.344$
$\theta_{12}/^\circ$	$31.29 \to 35.91$
$\sin^2\theta_{23}$	$0.385 \to 0.644$
$\theta_{23}/^\circ$	$38.3 \to 53.3$
$\sin^2\theta_{13}$	$0.0188 \to 0.0251$
$\theta_{13}/^\circ$	$7.87 \to 9.11$
$\delta_{\rm CP}/^\circ$	$0 \to 360$
$\frac{\Delta m^2_{21}}{10^{-5}\ {\rm eV}^2}$	$7.02 \to 8.09$
$\frac{\Delta m^2_{3\ell}}{10^{-3}\ {\rm eV}^2}$	$\begin{bmatrix} +2.325 \to +2.599 \\ -2.590 \to -2.307 \end{bmatrix}$

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

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

	3σ range
$\sin^2\theta_{12}$	$0.270 \to 0.344$
$\theta_{12}/^\circ$	$31.29 \to 35.91$
$\sin^2\theta_{23}$	$0.385 \to 0.644$
$\theta_{23}/^\circ$	$38.3 \to 53.3$
$\sin^2\theta_{13}$	$0.0188 \to 0.0251$
$\theta_{13}/^\circ$	$7.87 \to 9.11$
$\delta_{\rm CP}/^\circ$	$0 \to 360$
$\frac{\Delta m^2_{21}}{10^{-5}\ {\rm eV}^2}$	$7.02 \to 8.09$
$\frac{\Delta m^2_{3\ell}}{10^{-3}\ {\rm eV}^2}$	$\begin{bmatrix} +2.325 \to +2.599 \\ -2.590 \to -2.307 \end{bmatrix}$

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
$\sin^2\theta_{12}$	$0.270 \to 0.344$
$\theta_{12}/^\circ$	$31.29 \to 35.91$
$\sin^2\theta_{23}$	$0.385 \to 0.644$
$\theta_{23}/^\circ$	$38.3 \to 53.3$
$\sin^2\theta_{13}$	$0.0188 \to 0.0251$
$\theta_{13}/^\circ$	$7.87 \to 9.11$
$\delta_{\mathrm{CP}}/^\circ$	$0 \to 360$
$\dfrac{\Delta m^2_{21}}{10^{-5}\ \mathrm{eV}^2}$	$7.02 \to 8.09$
$\dfrac{\Delta m^2_{3\ell}}{10^{-3}\ \mathrm{eV}^2}$	$\begin{bmatrix} +2.325 \to +2.599 \\ -2.590 \to -2.307 \end{bmatrix}$

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

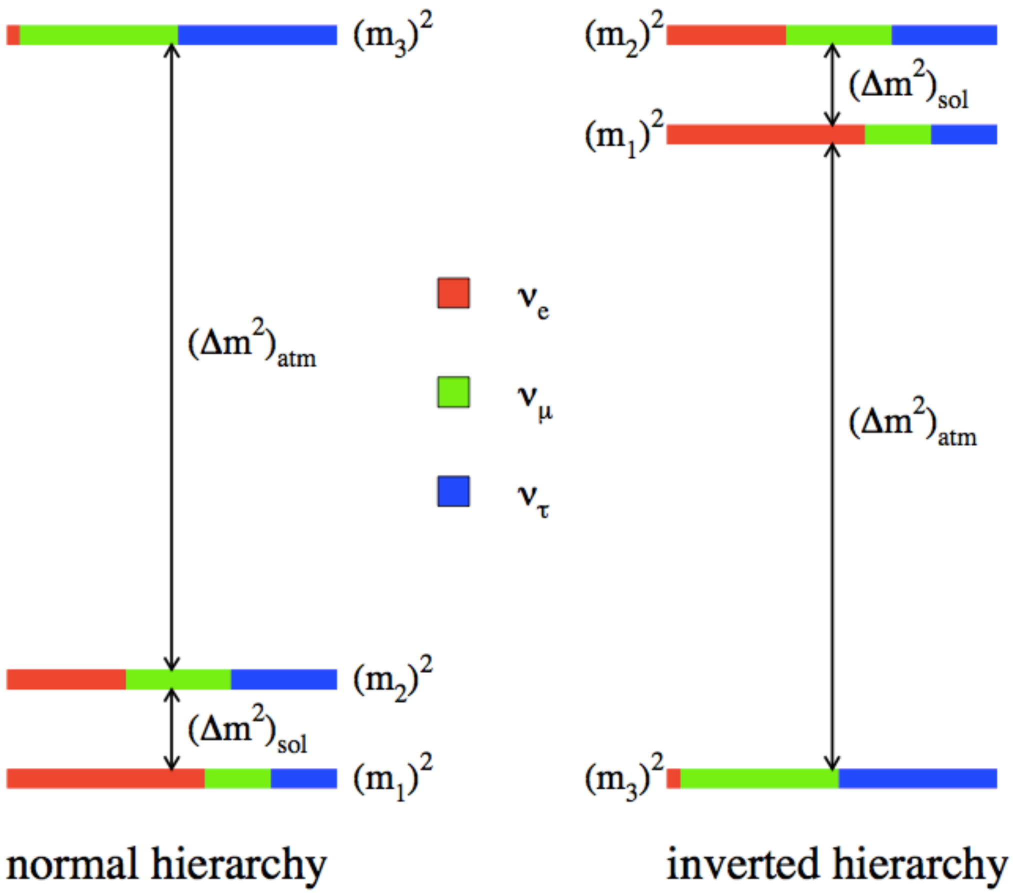
almost unknown

sign of Δm^2 unknown (ordering of masses)

Next on the list to go after experimentally:

mass ordering (sign of Δm^2_{32})

[Note: “mass hierarchy” is now uncool to say, as masses may be quasi-degenerate]



$$\Delta m^2_{ij} \equiv m_i^2 - m_j^2$$

There are many ways to determine the mass ordering

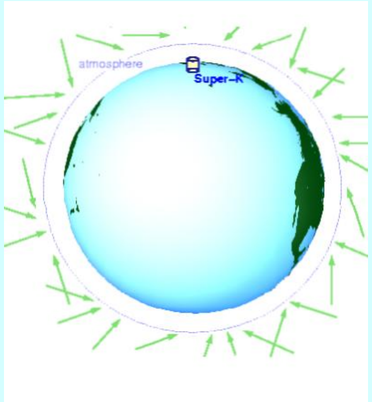
They are all challenging...

Four of the possible ways to get MH

Long-baseline beams

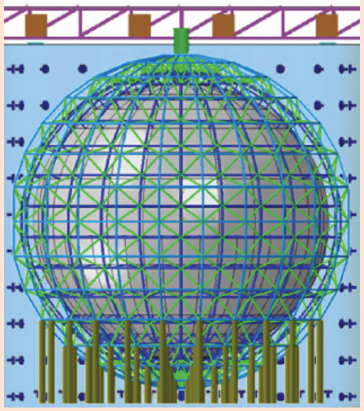
Hyper-K, LBNF/DUNE

Atmospheric neutrinos



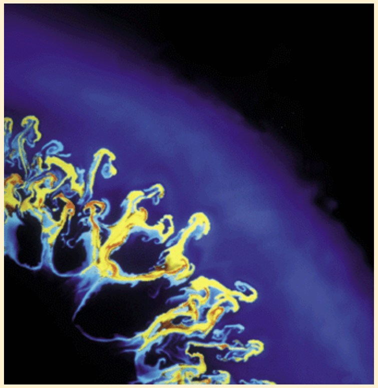
Super-K, Hyper-K, PINGU, DUNE,INO

Reactors



JUNO, RENO-50

Supernovae



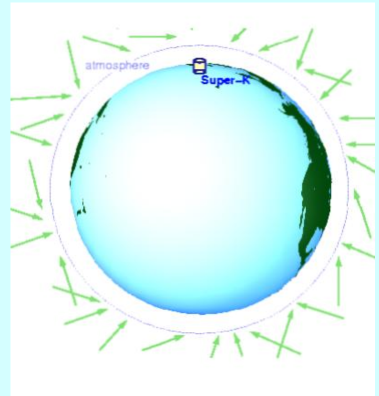
Many existing & future detectors

Four of the possible ways to get MO

Long-baseline beams

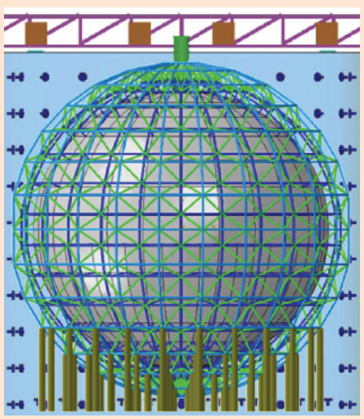
Hyper-K, LBNF/DUNE

Atmospheric neutrinos



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

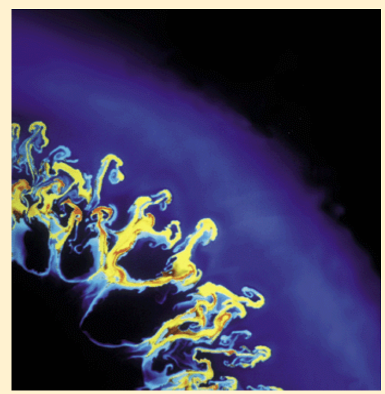
Reactors



See talk by
Y. Malyshkin
on Saturday

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

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

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

Change of sign for antineutrinos

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

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

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

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

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

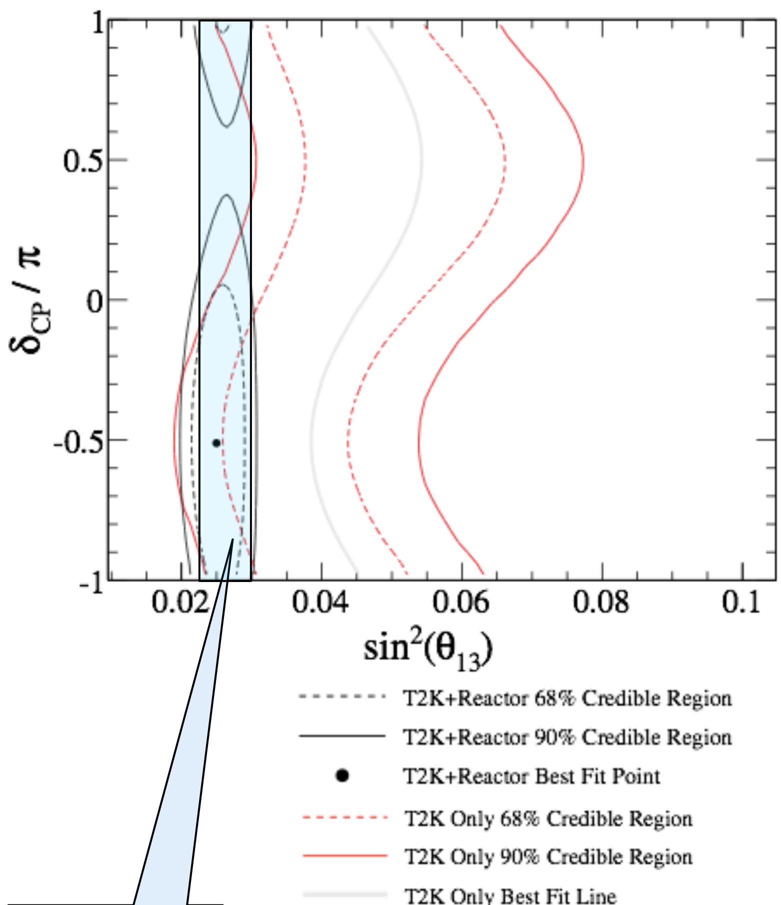
Different probabilities as a function of L& E for neutrinos and antineutrinos, depending on:

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

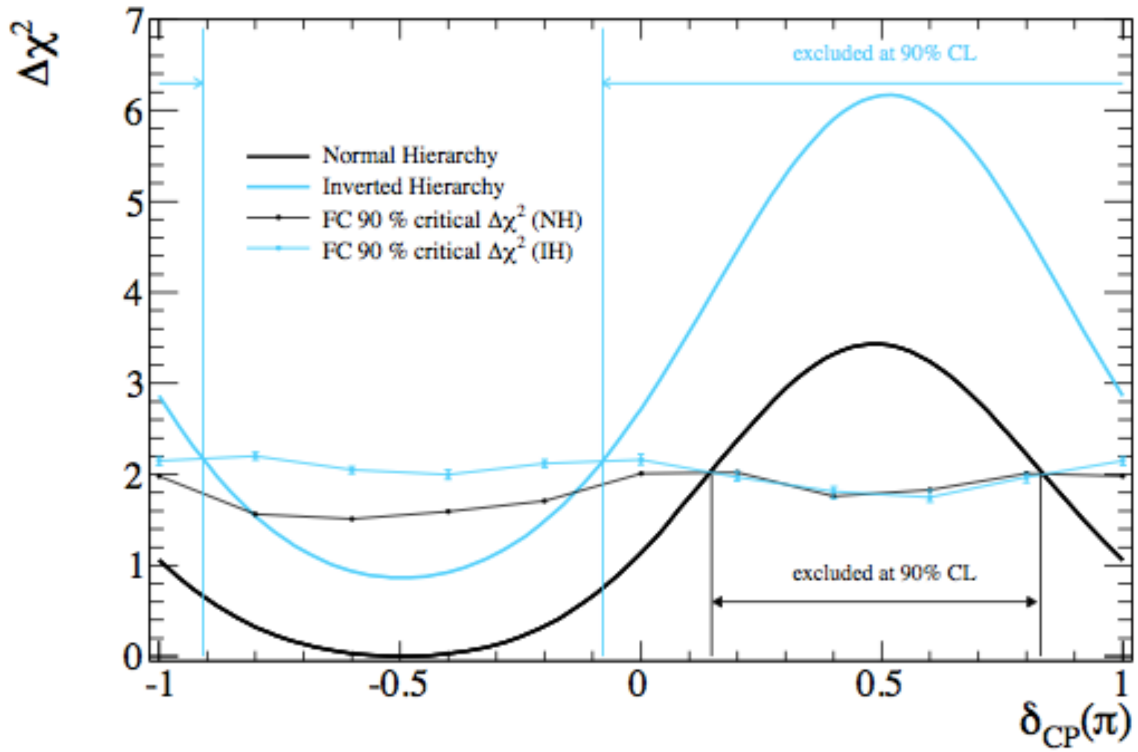
CP Information from T2K (+ reactors)

Joint ν_μ, ν_e three-flavor fit,

including reactor constraint on θ_{13} $\sin^2 2\theta_{13} = 0.095 \pm 0.010$

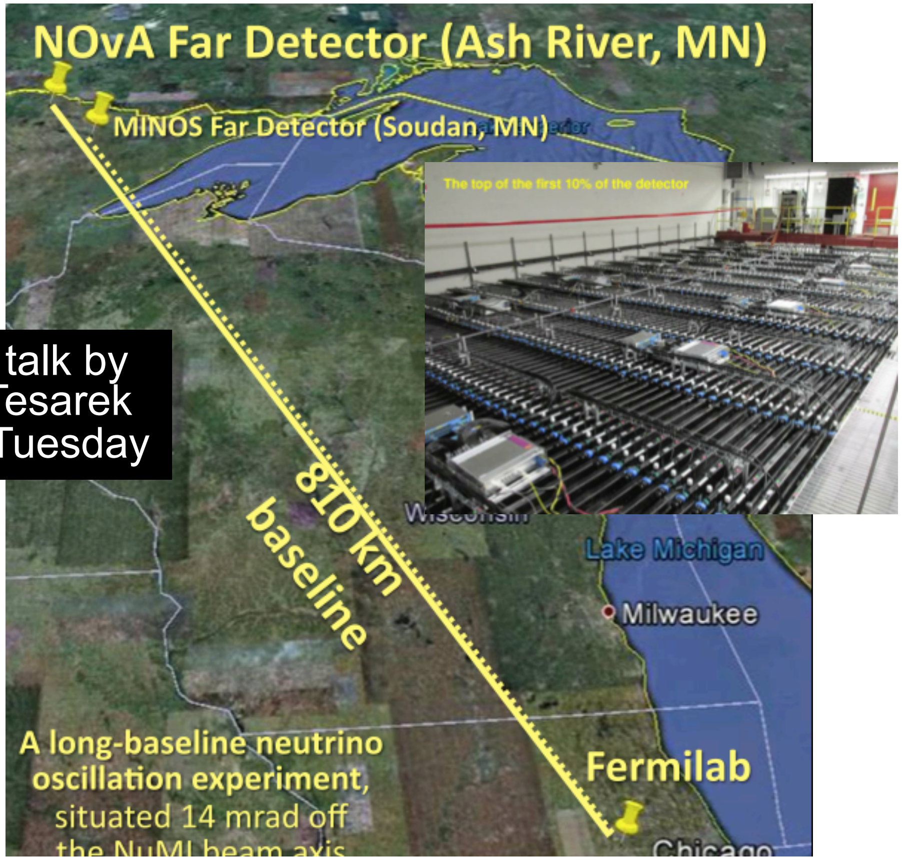


this region favored

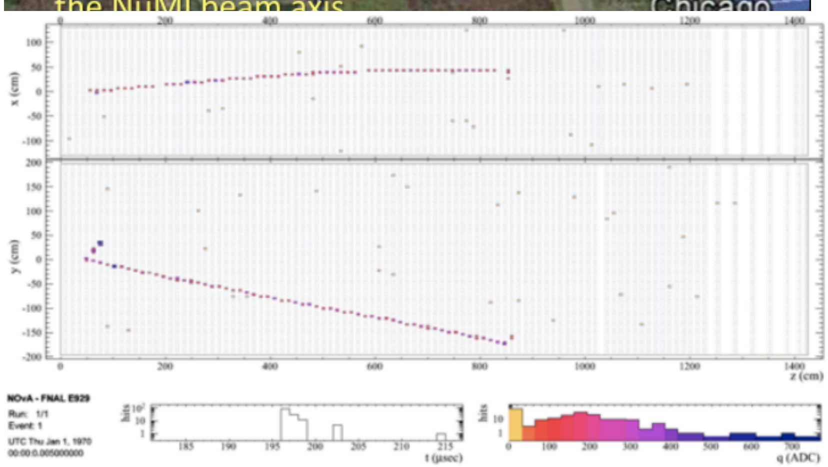


Mild preference for $\delta \sim -\pi/2$

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

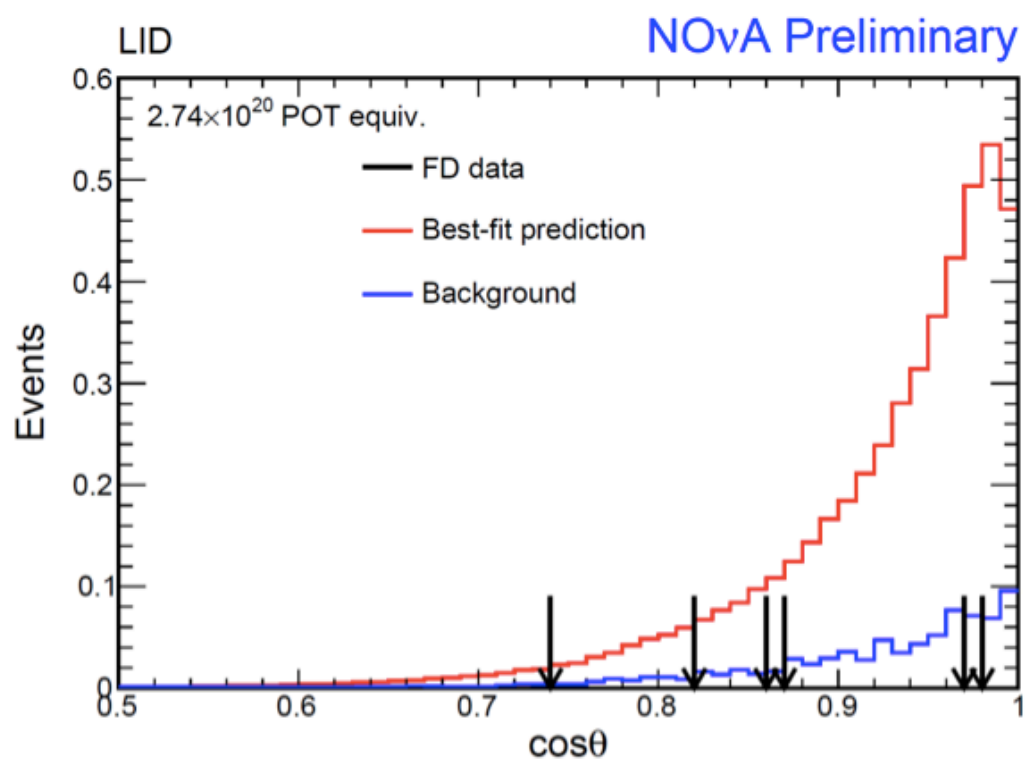


See talk by R. Tesarek on Tuesday

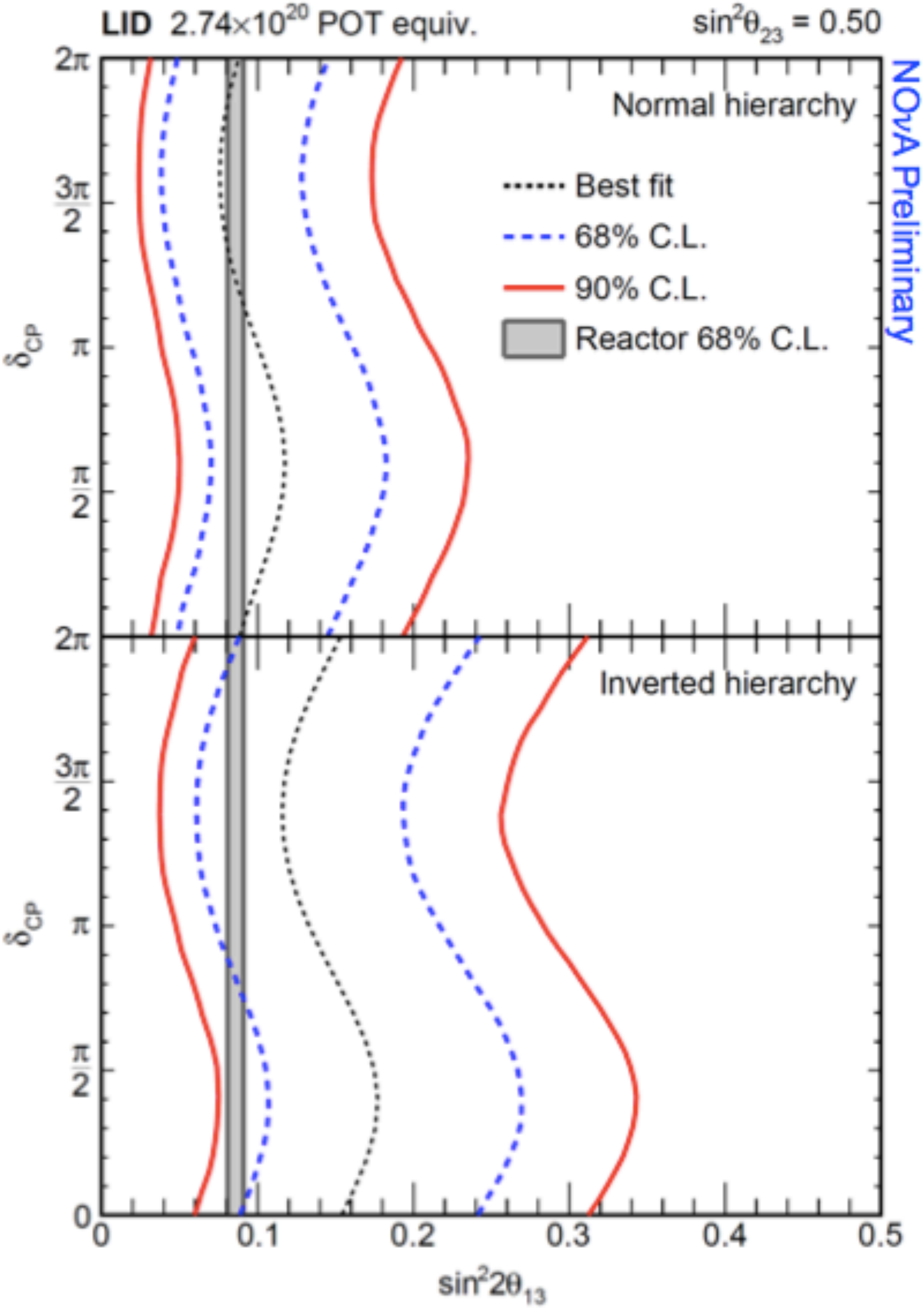


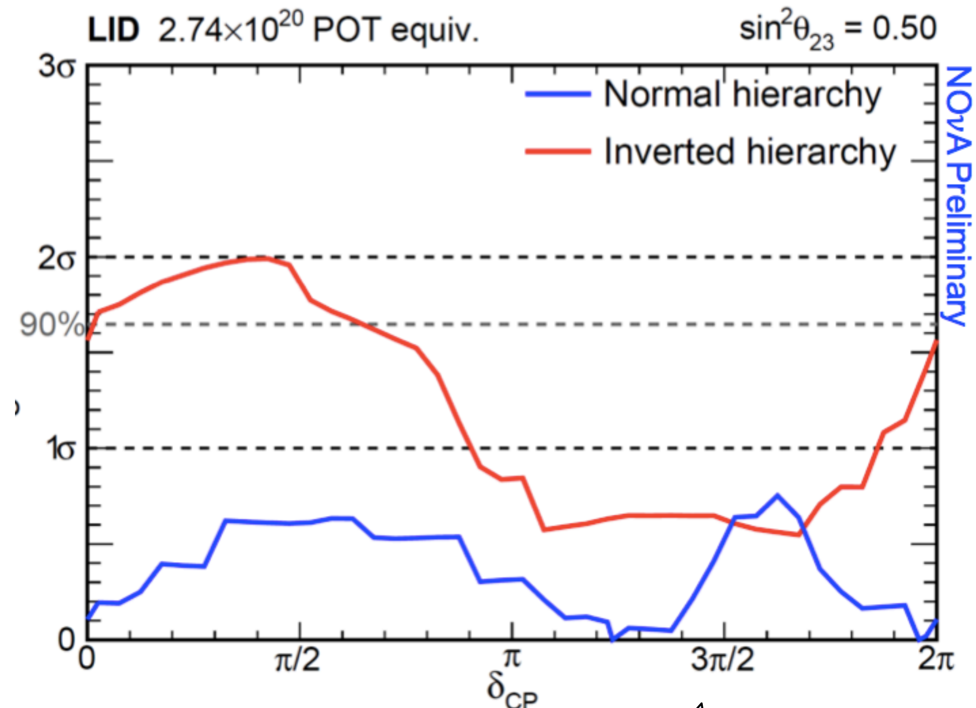
14 kt scintillator
700 kW off-axis FNAL beam
810 km baseline

Search for ν_e **appearance:**
6 events in one analysis,
expect 0.94±0.09 bg
(and another consistent analysis)



Interpretation in terms of oscillation parameters



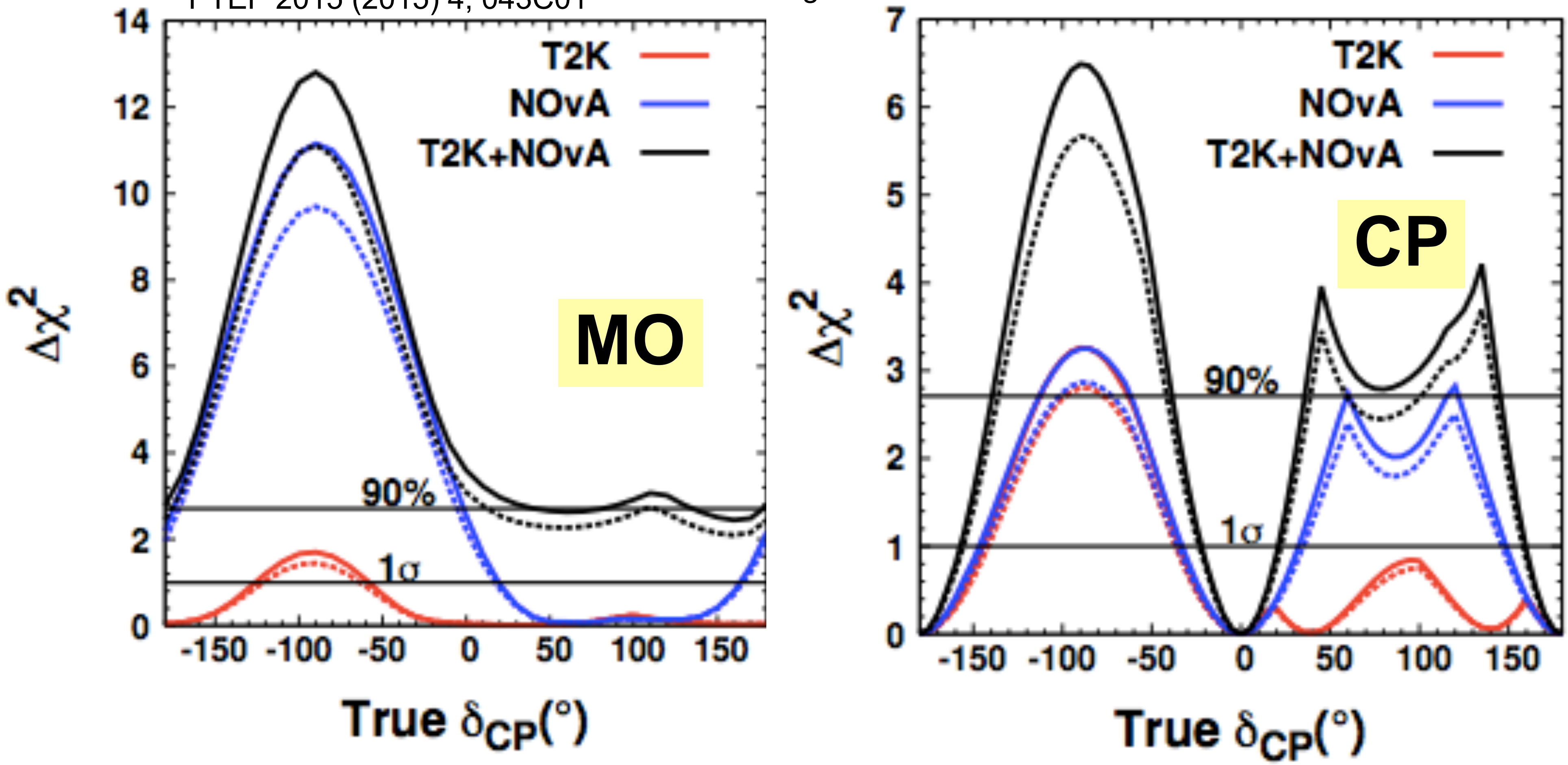


Also favors (weakly) δ_{CP} ~$3\pi/2$, NH

More data to come from both T2K and NOνA...
(so far: T2K ~14%, NOνA ~8%) **...how far will that take us?**

PTEP 2015 (2015) 4, 043C01

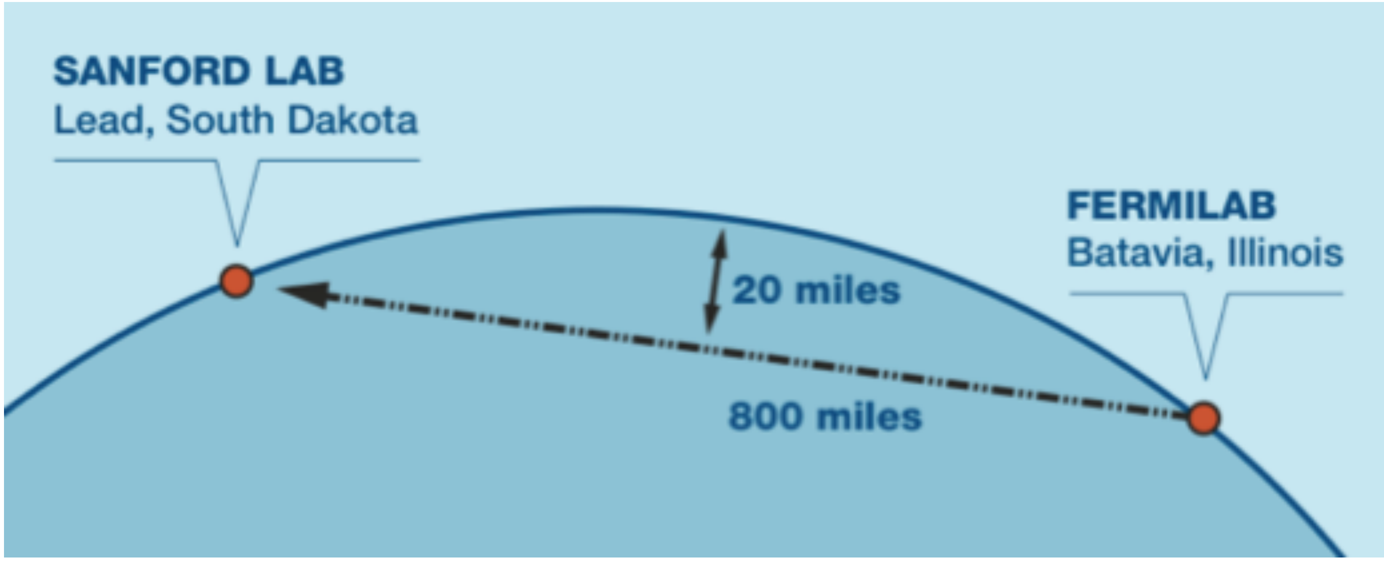
Assuming NH is true



Expected sensitivities for T2K+NOνA
(MO sensitivity driven by NOνA thanks to longer baseline)

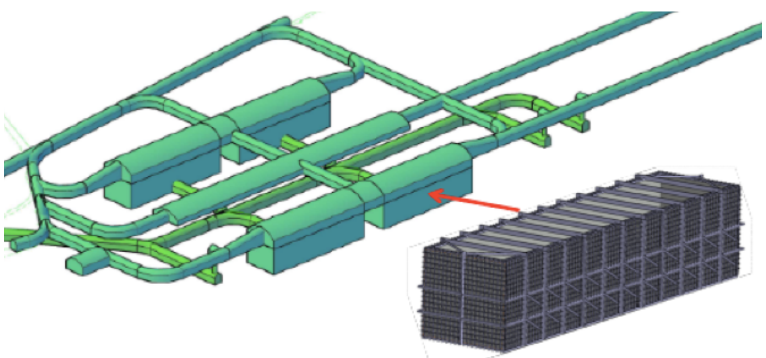
➔ Possible "indications" within ~5 years if parameters are lucky (hints so far are in the right direction!)

To go beyond, yet longer baseline is favorable



DEEP UNDERGROUND NEUTRINO EXPERIMENT

reformulated international collaboration

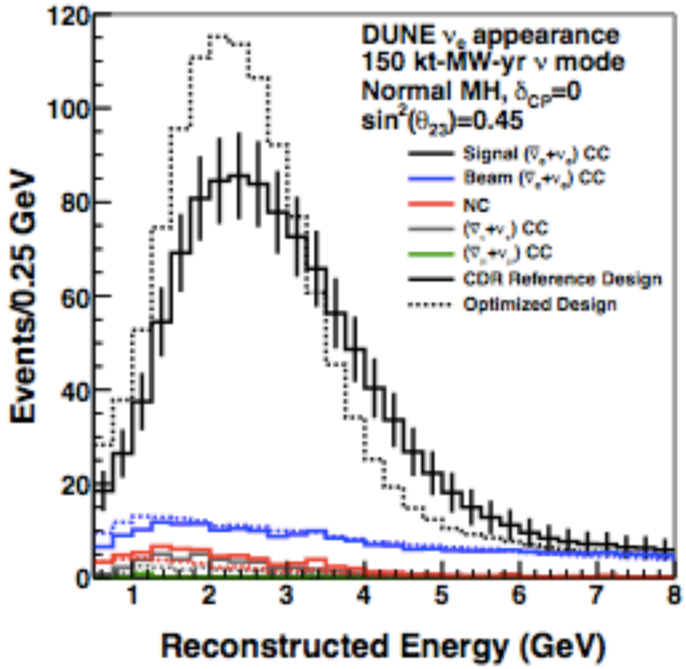


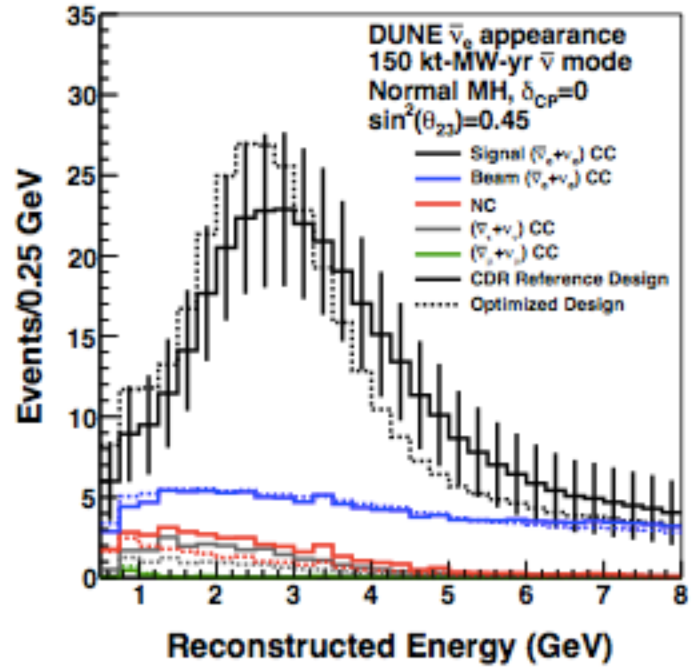
Long-Baseline Neutrino Facility/Deep Underground Neutrino Experiment

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

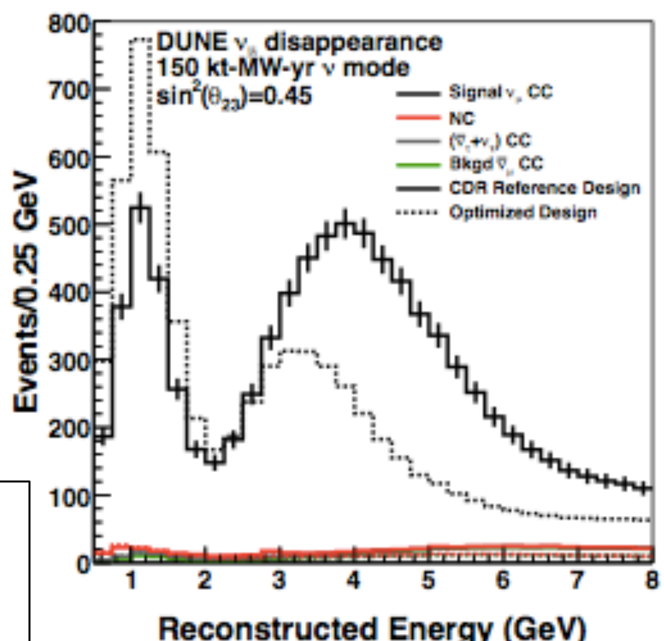
highest intermediate term priority in U.S.

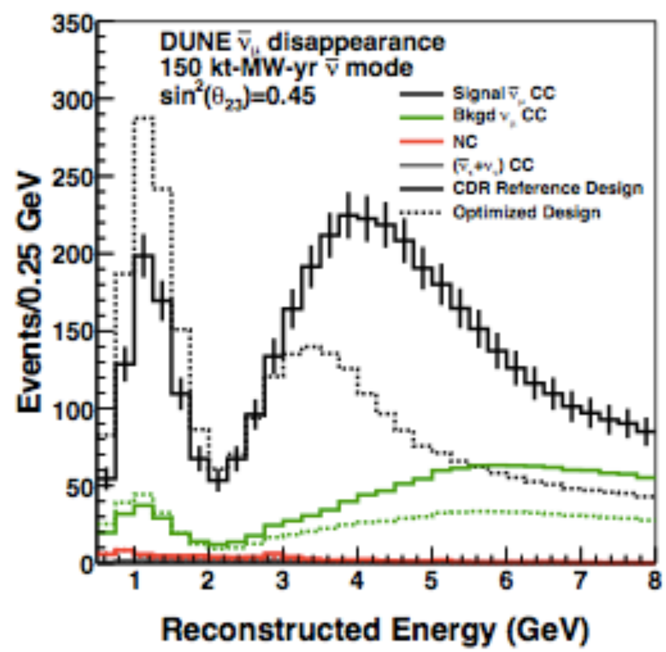
Electron (+anti) neutrino appearance





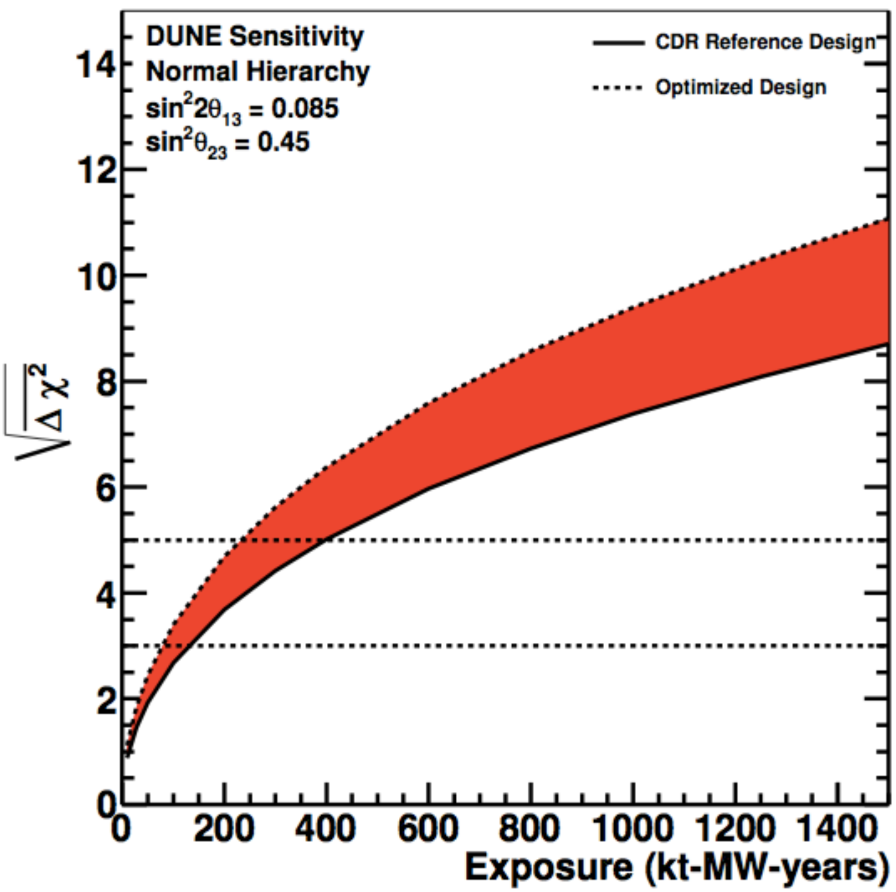
Muon (+anti)neutrino disappearance

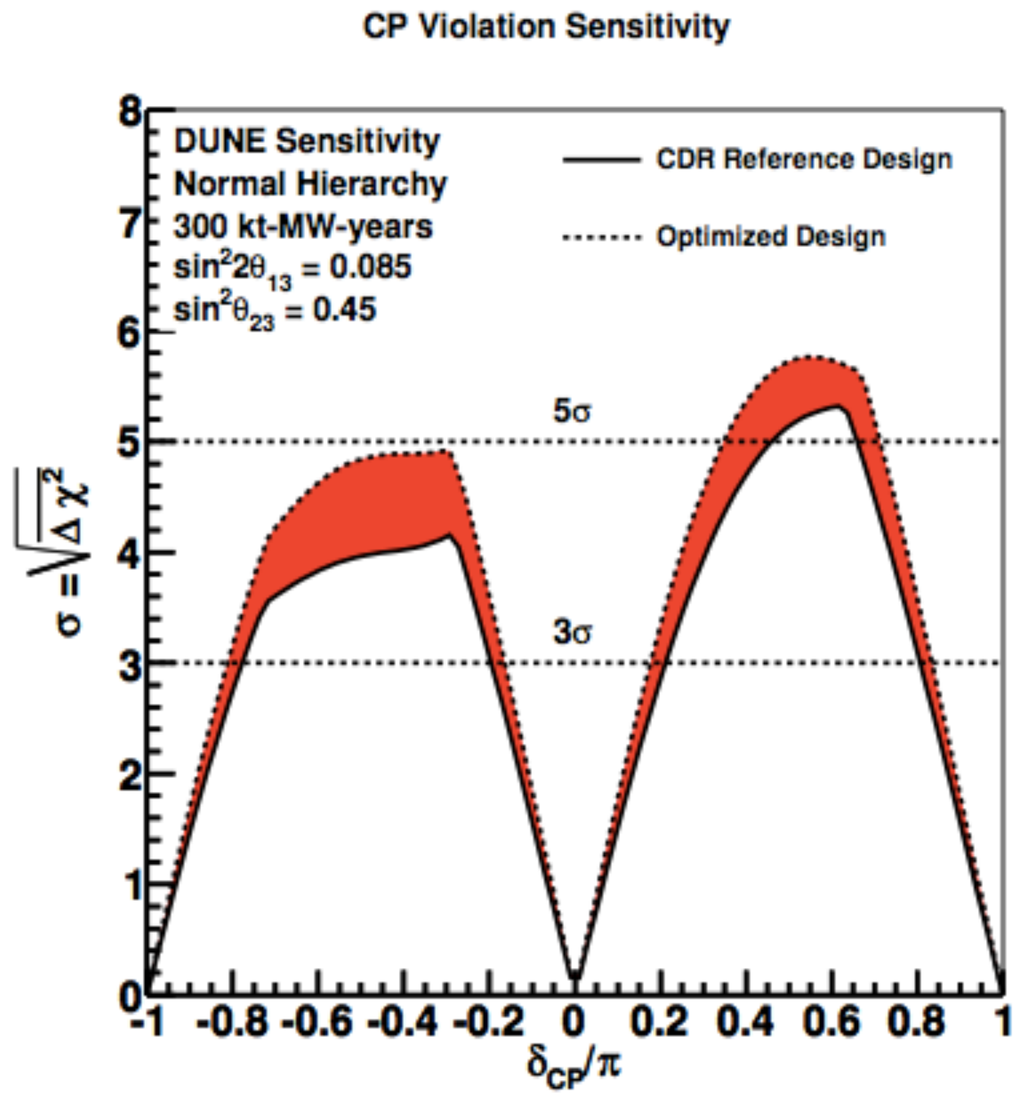




Nominal exposure:
300 kt-MW-yr:
~7 yrs of data
(3.5 nu, 3.5 antinu) w/40 kt,
1.07-MW 80-GeV beam

DUNE sensitivity

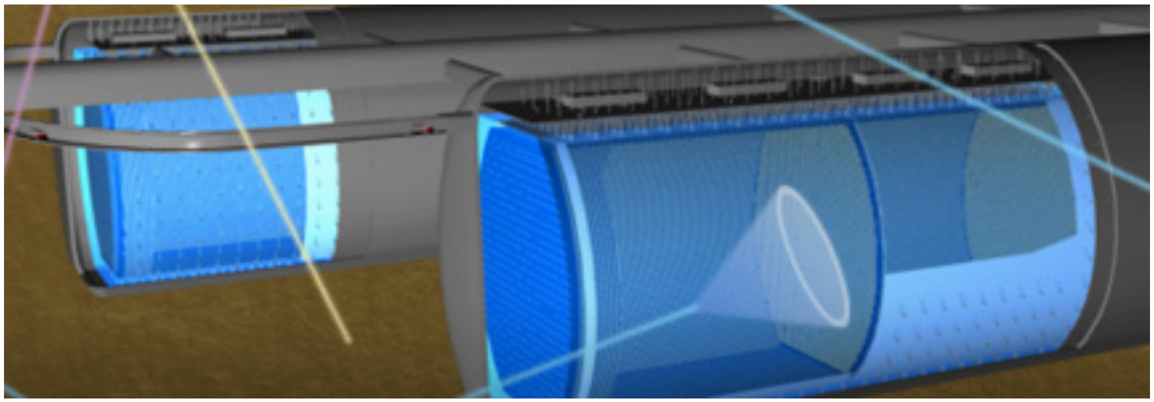




Excellent mass hierarchy reach for all CP values

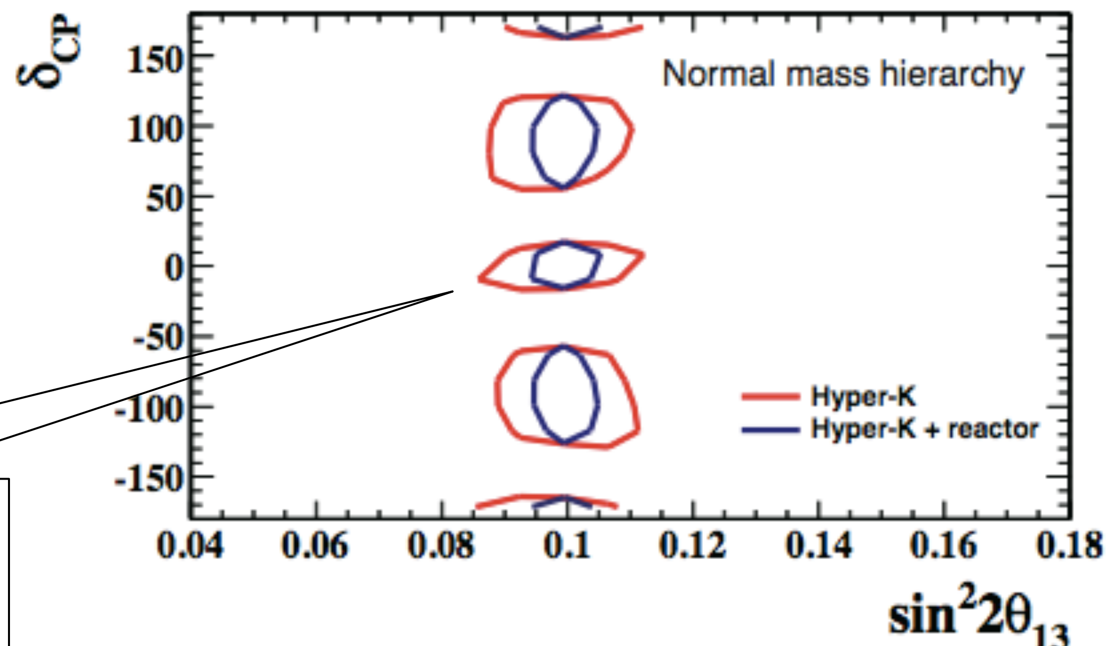
Decent chance to measure CPV

Another proposal: Hyper-K in Japan



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

arXiv:1502.05199

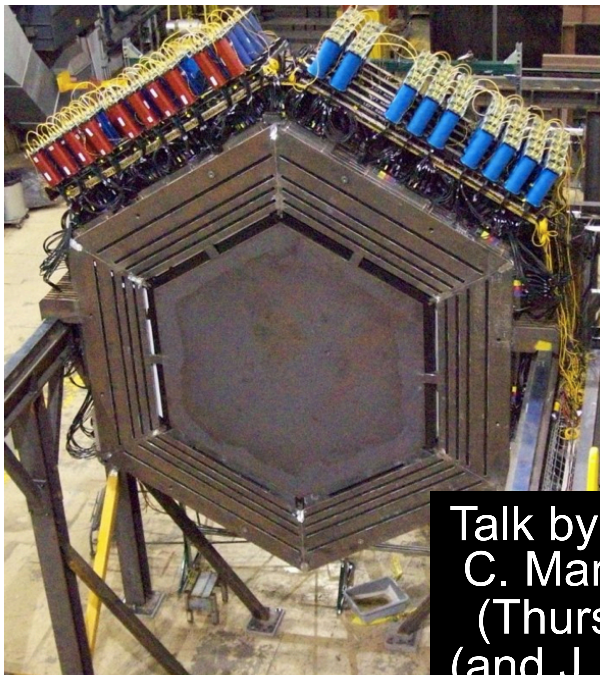


shorter baseline,
so less good at MH,
but good CP sensitivity

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

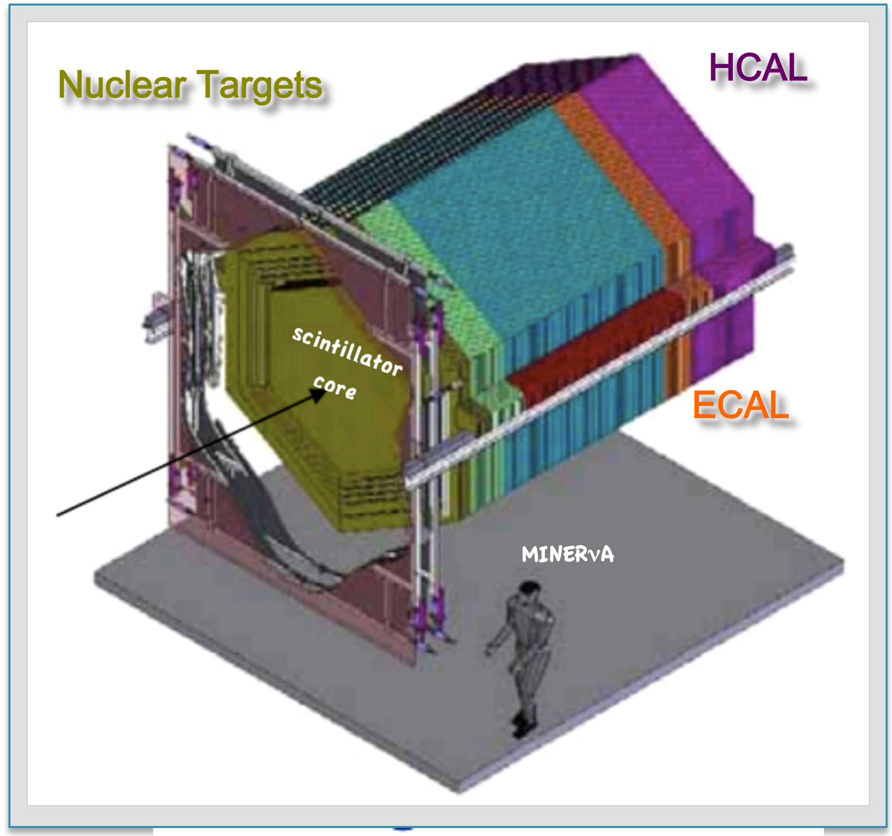
MINERνA

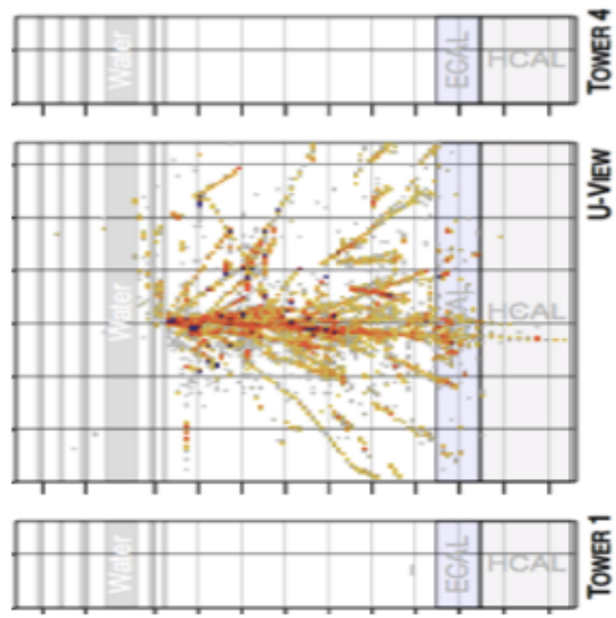
Detector at NuMI (Fermilab)
to measure cross-sections of
~GeV neutrinos on nuclear targets
(finely-segmented scintillator
+ em& hadronic calorimeters)



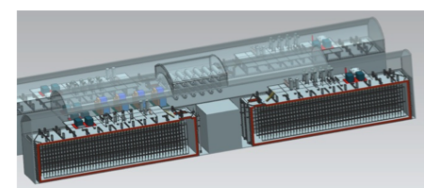
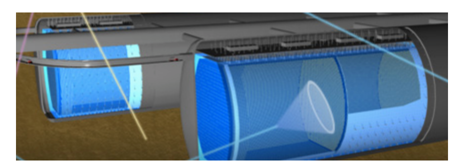
Talk by
C. Marshall
(Thursday)
(and J. Morfin's
on Wednesday)

Critical to understand interactions for interpretation of long-baseline oscillation experiment backgrounds & systematics!





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 ordering	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

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**...

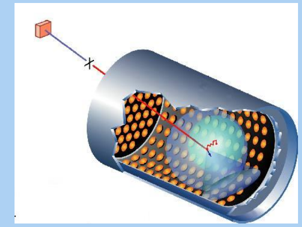
Open a parenthesis:

(

Outstanding ‘anomalies’

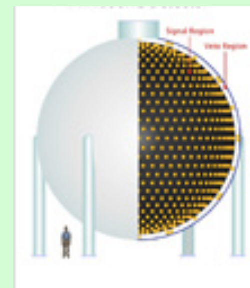
LSND @ LANL (~30 MeV, 30 m)

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)



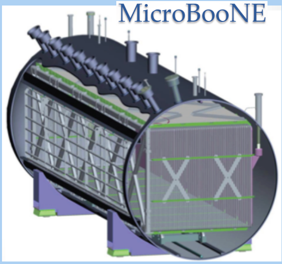
- unexplained >3 σ excess for E < 475 MeV in neutrinos
  (inconsistent w/ LSND oscillation)
- no excess for E > 475 MeV in neutrinos
  (inconsistent w/ LSND oscillation)
- small excess for E < 475 MeV in antineutrinos
  (~consistent with neutrinos)
- small excess for E > 475 MeV in antineutrinos
  (consistent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

????
more data needed

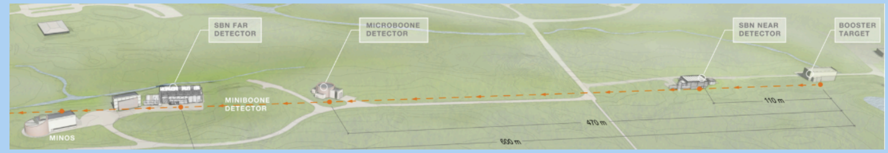
Also: possible deficits of reactor $\overline{\nu}_e$ (‘reactor anomaly’) and source ν_e (‘gallium anomaly’)

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??

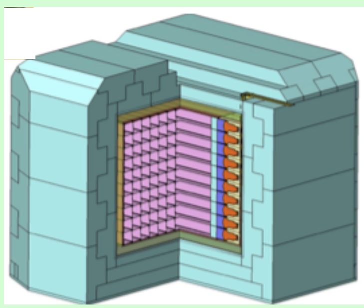
Experimental ideas to address these anomalies...



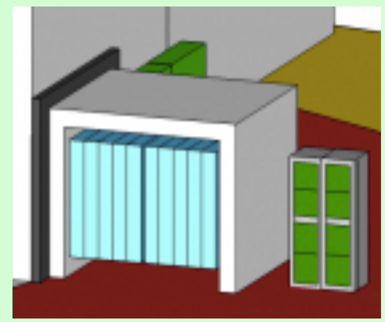
Experiments with beams
(meson decay in flight and at rest)



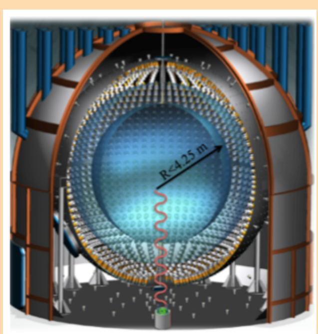
MINOS+, FNAL SBN, OscSNS, J-PARC MLF, ...



Experiments at reactors

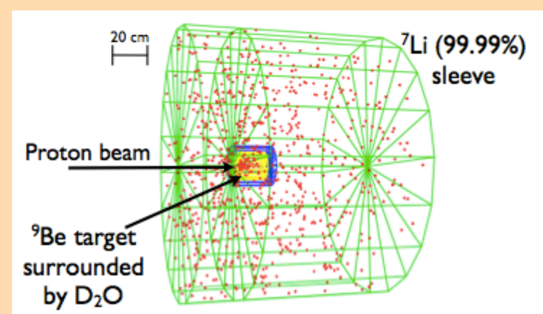


PROSPECT, SoLid, NuLAT, STEREO, DANNS, Neutrino4, Hanaro,..



Experiments with radioactive sources

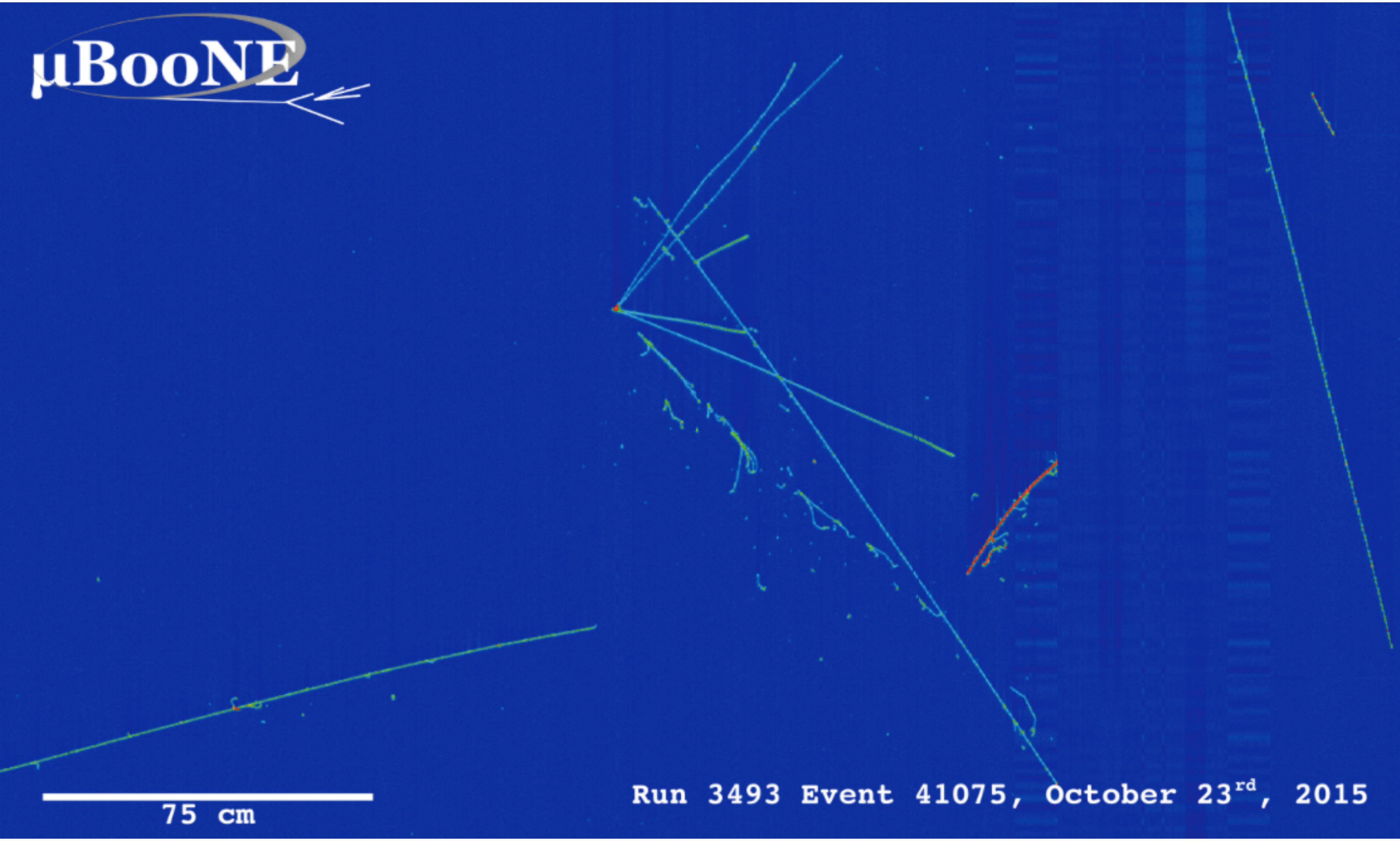
SOX, CeSOX, IsoDAR, ...



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

... parenthesis not closed...

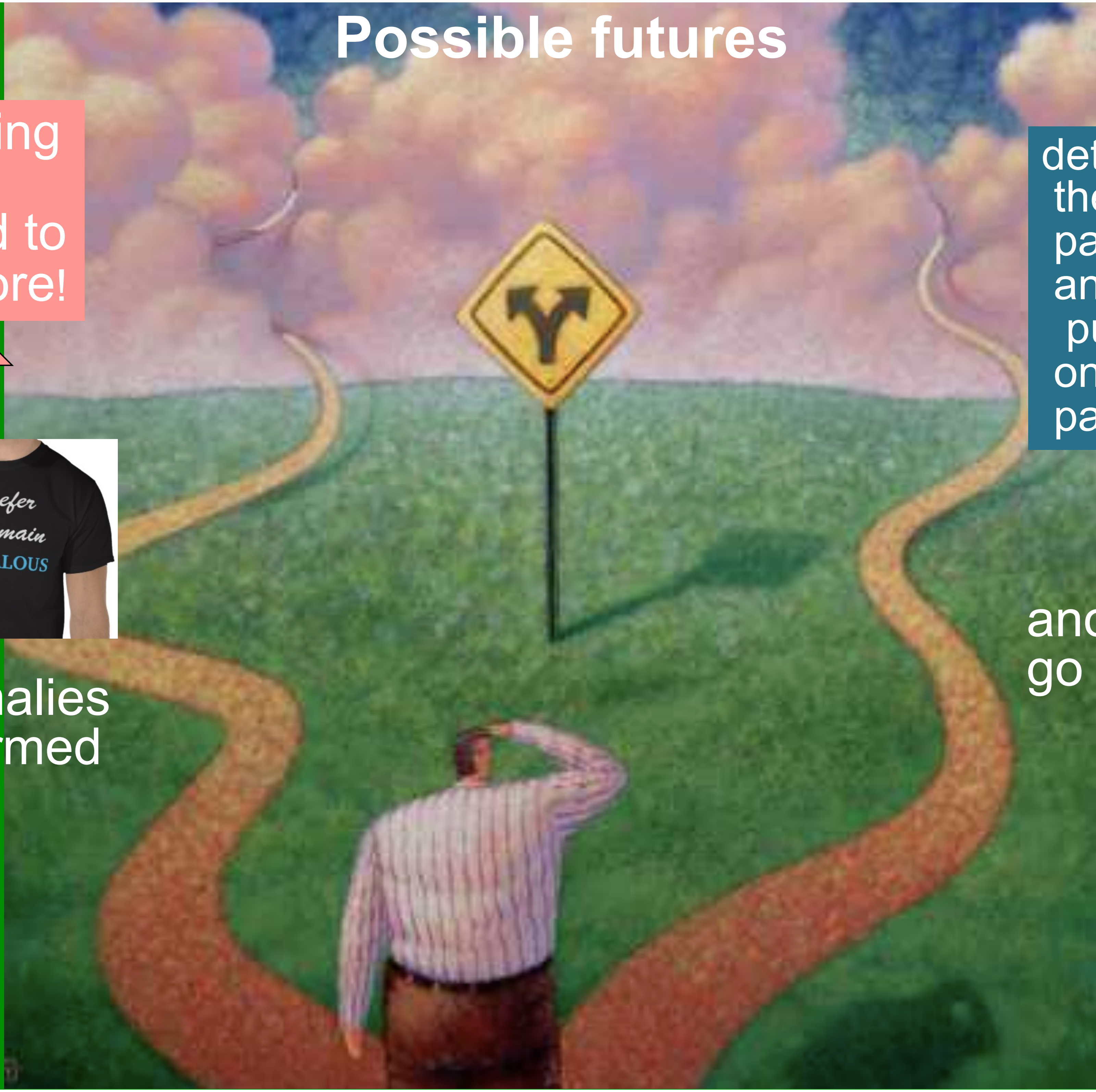
NEW MicroBooNE @ FNAL now seeing beam events!



Possible futures

exciting new world to explore!

anomalies confirmed

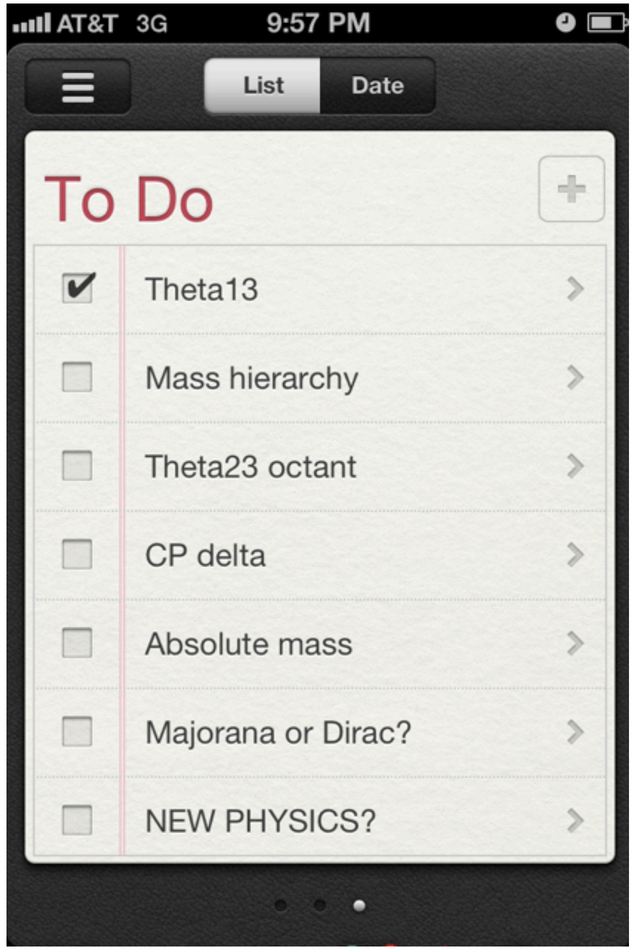


determine the 3-flavor parameters and keep pushing on the paradigm

anomalies go away

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? ...

Still exciting years ahead!

Jorge S. Diaz @jsdiaz_ 90d

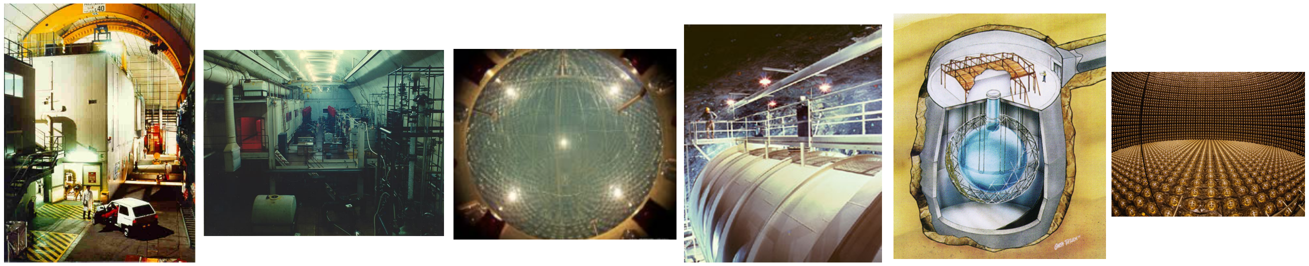
#neutrino #neutrino #neutrino #neutrino #neutrino #neutrino #neutrino #neutrino #neutrino #neutrino #neutrino #neutrino #neutrino #neutrino

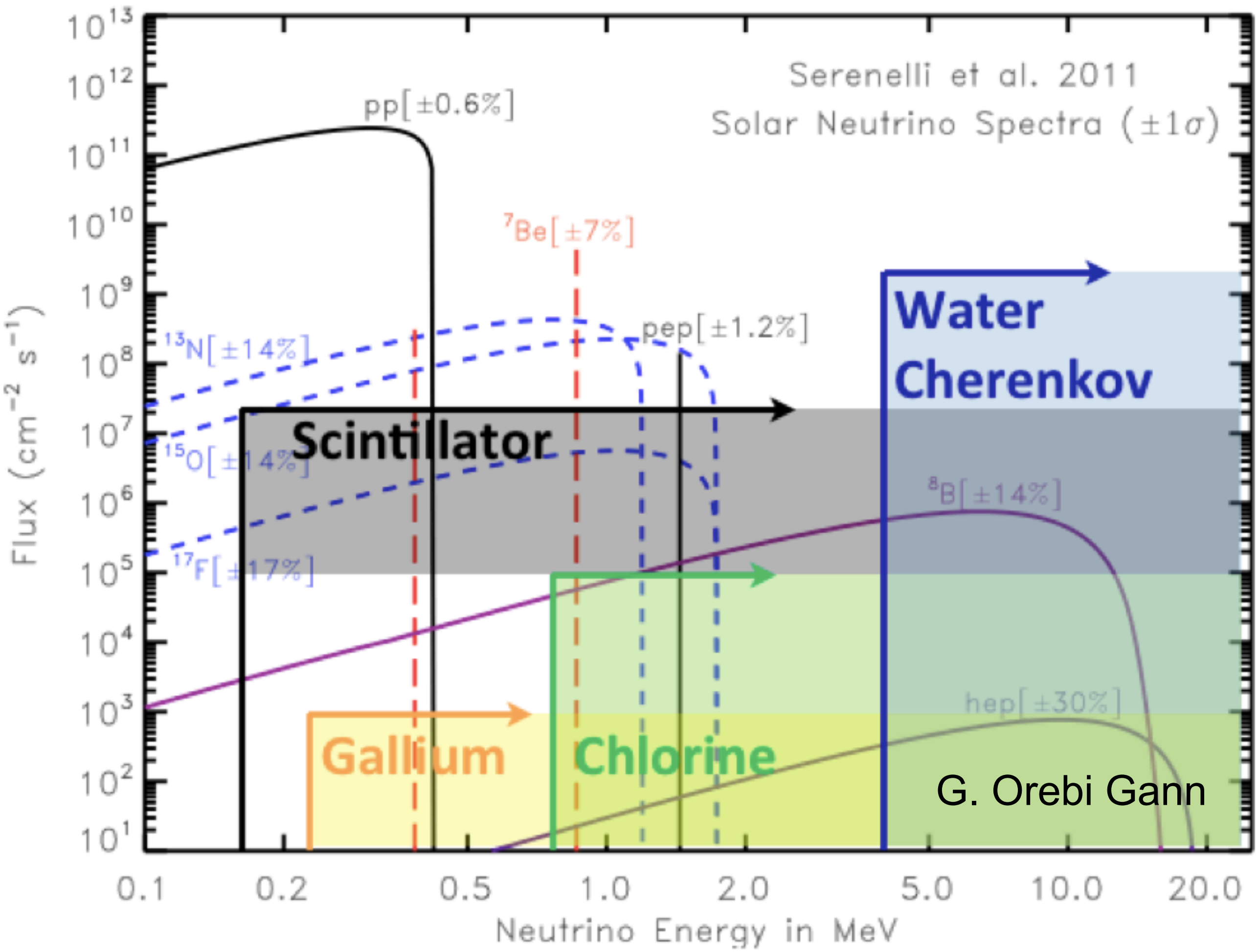
Details

Extras/backups

Solar and reactor neutrinos

Multiple measurements over ~5 decades



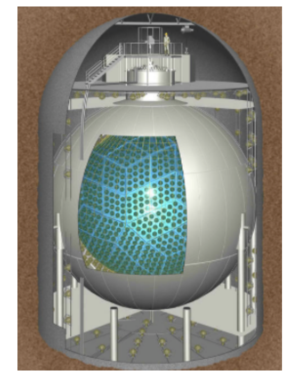


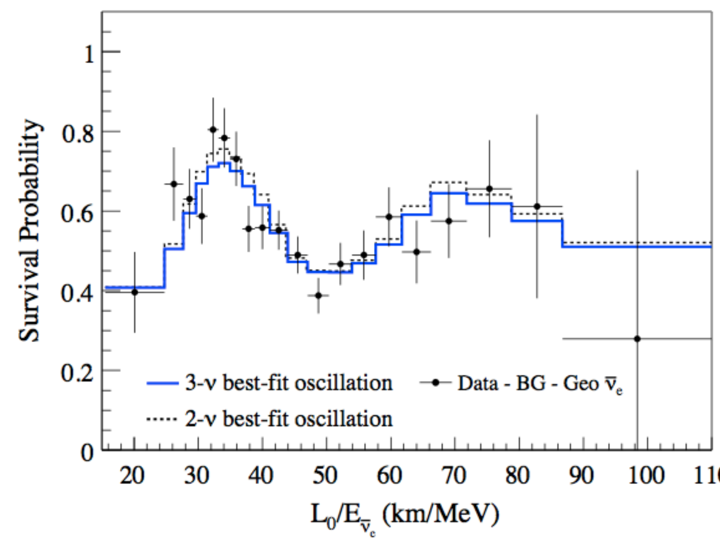
ν_e disappearance, confirmed directly as

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

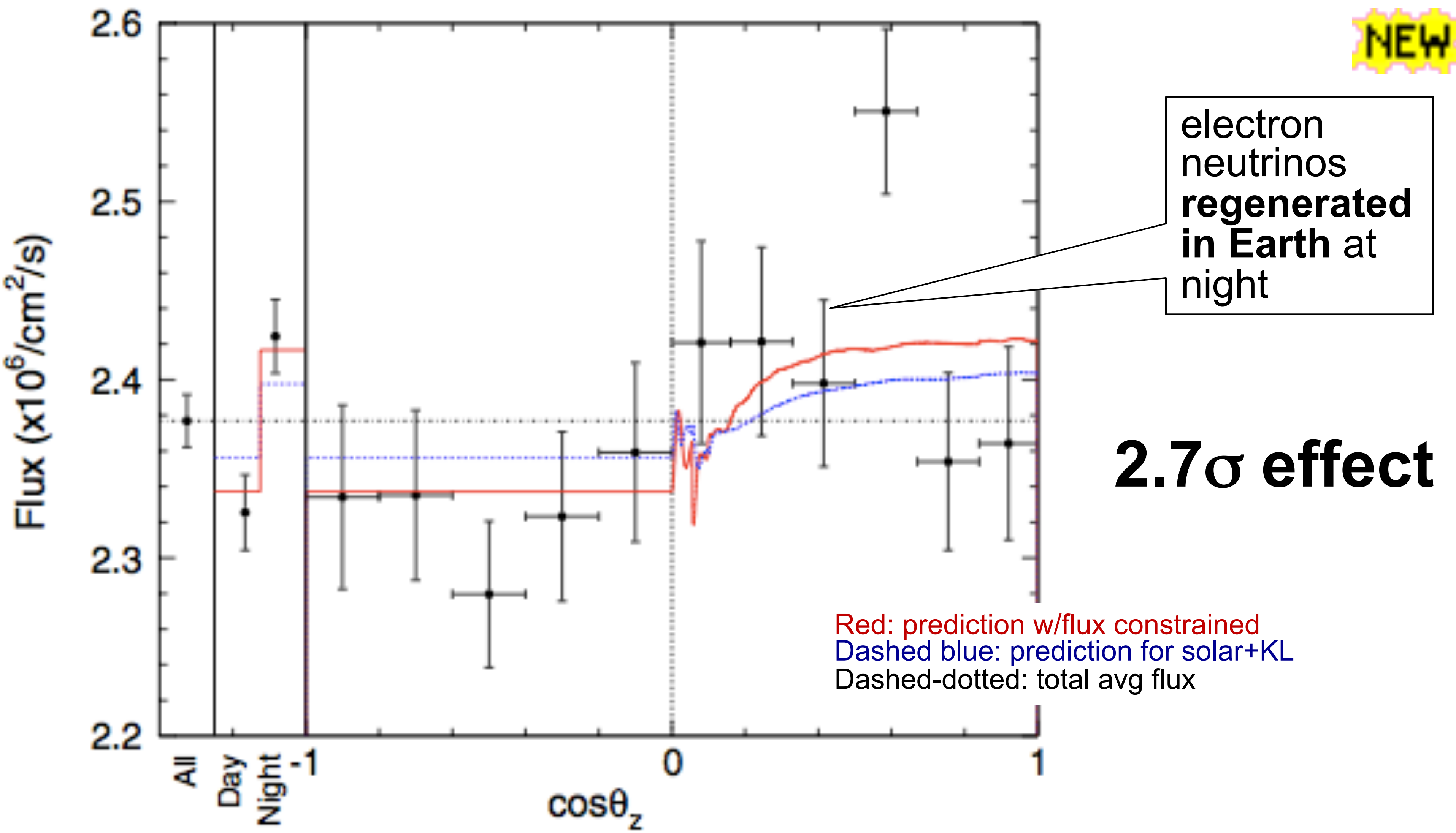
by SNO....

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



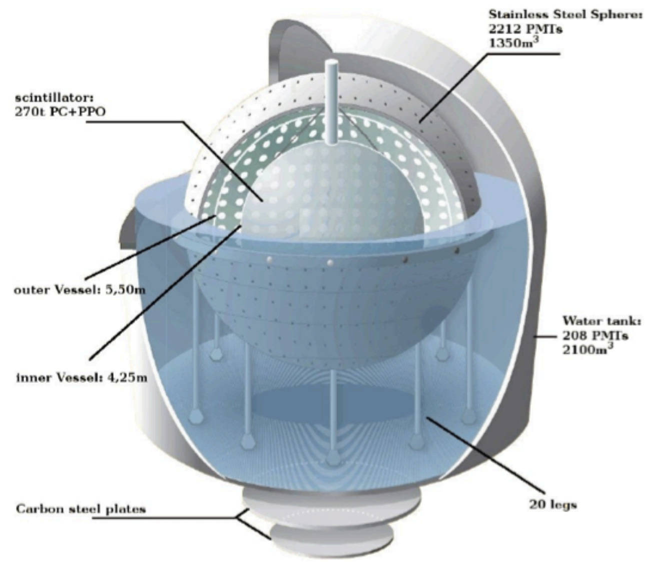


From Super-K: day/night asymmetry observed; first direct observation of matter effects

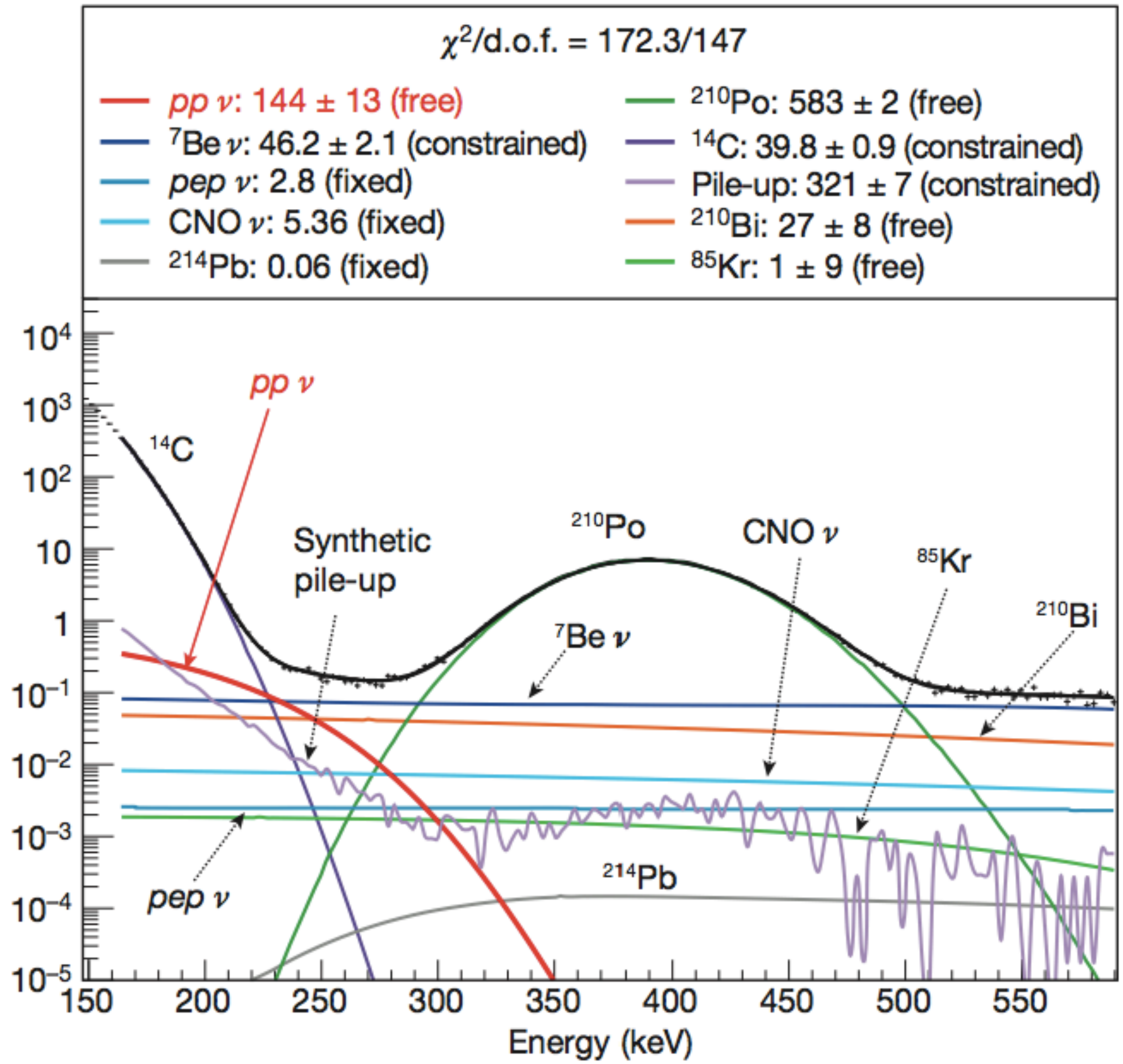


2.7σ effect

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



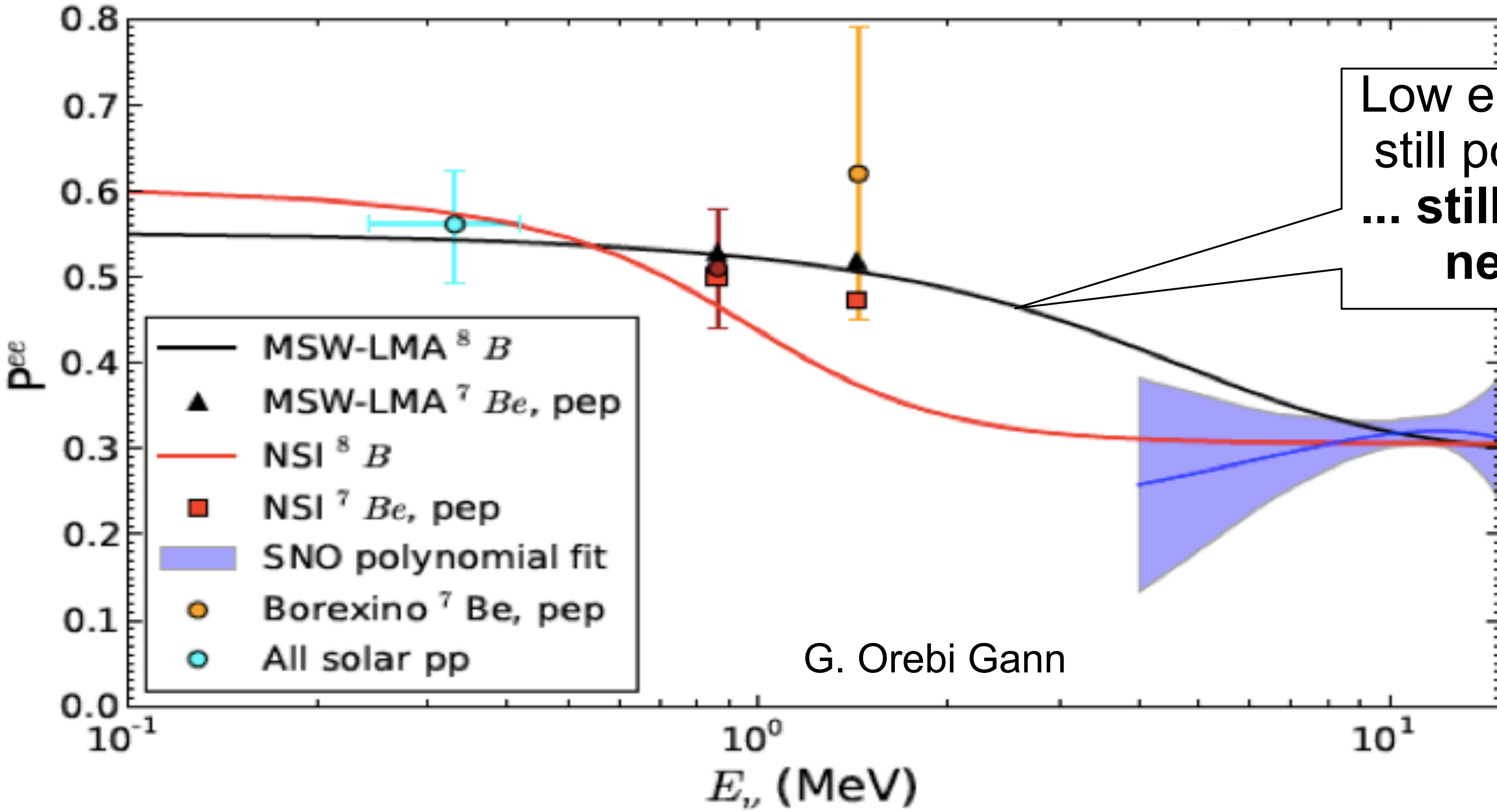
$$\nu_{e,x} + e^- \rightarrow \nu_{e,x} + e^-$$



Nature 512 (2014) 385

What's next for solar neutrinos?

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

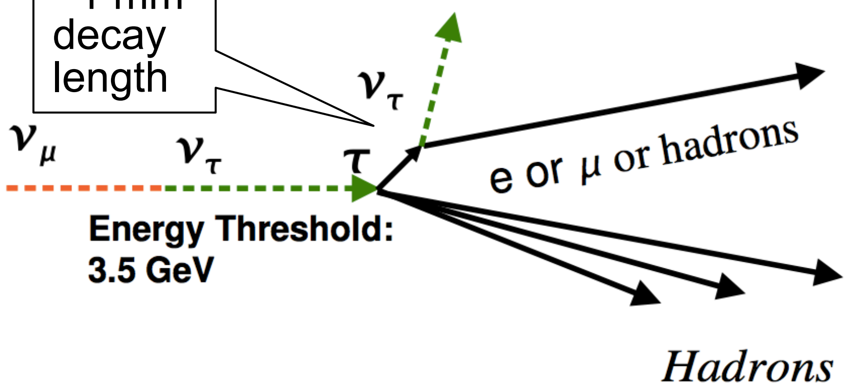


Low energy region
still poorly measured
... still room for
new physics?

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

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

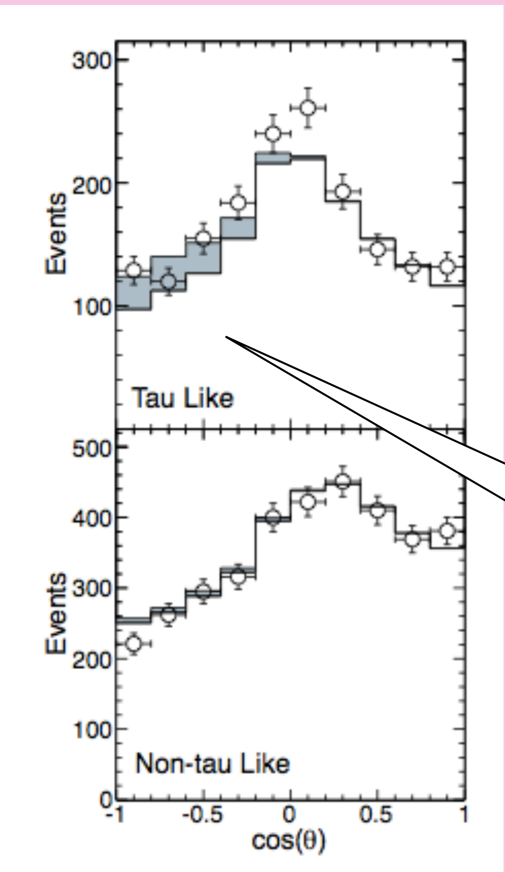
Is the disappearance $\nu_\mu \rightarrow \nu_\tau$?



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

Super-K atmospheric ν's

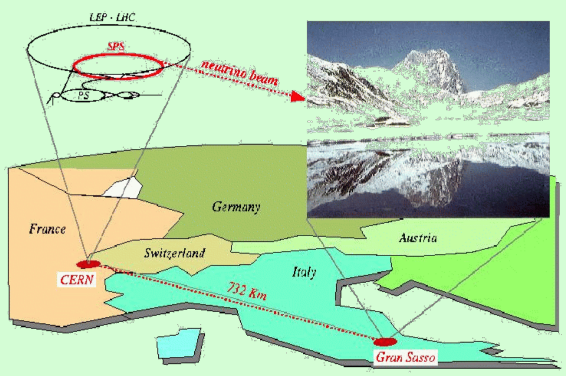
Phys.Rev.Lett. 110 (2013) 18, 181802



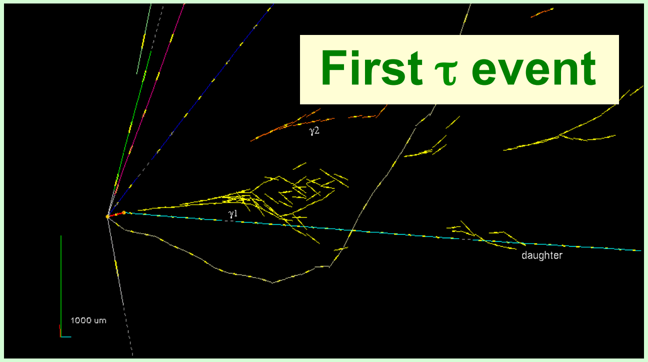
3.8σ appearance result

OPERA @ CNGS

PTEP 2014 (2014) 10, 101C01

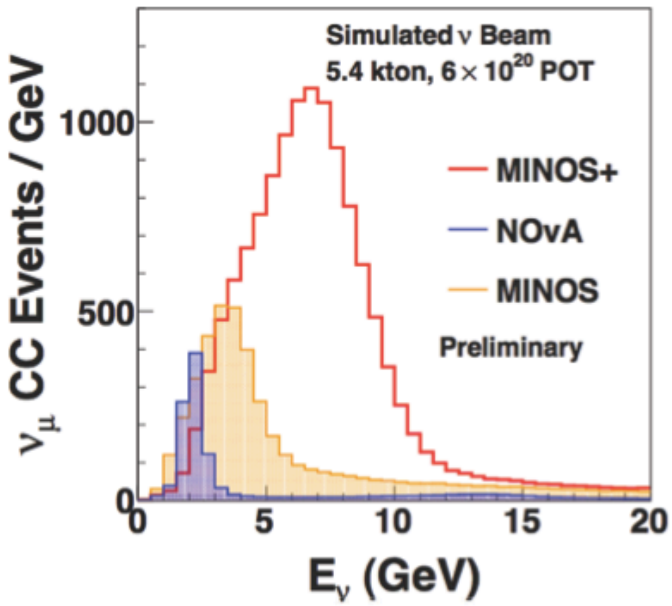


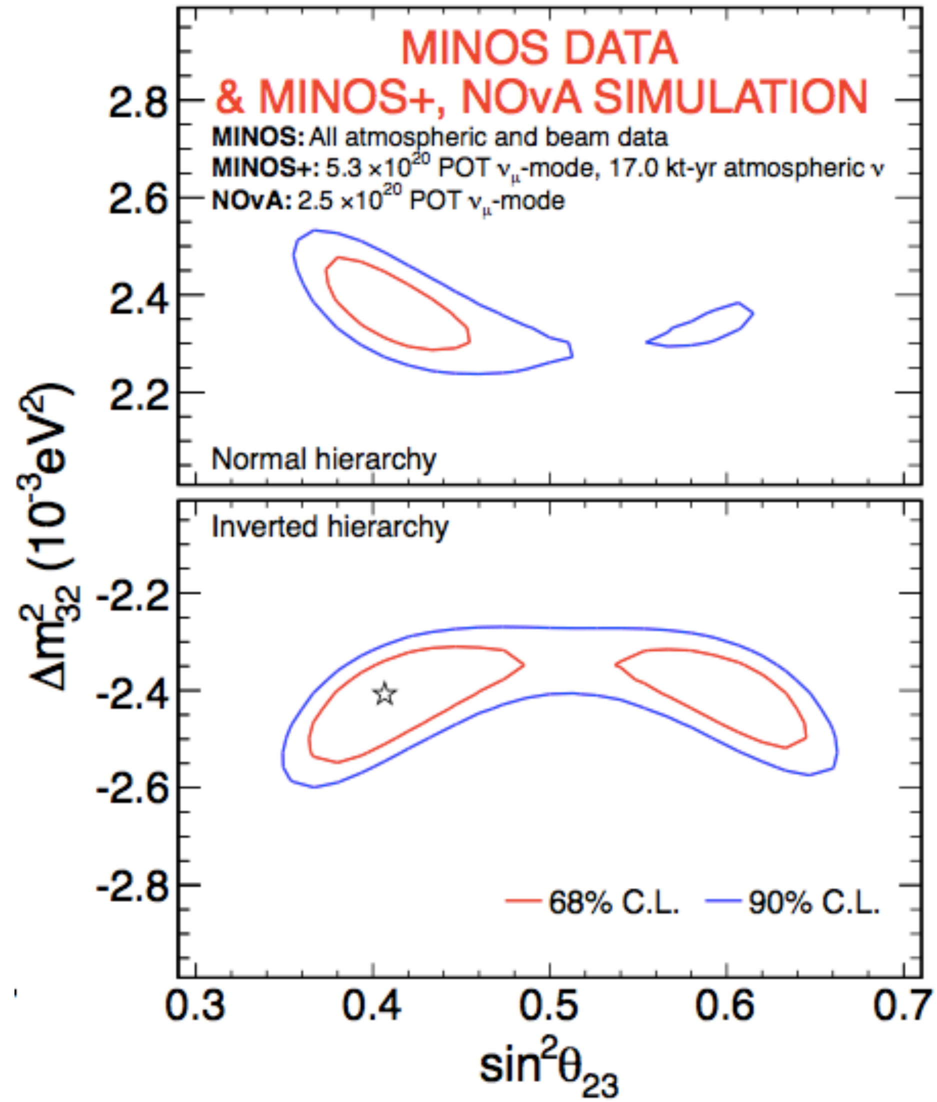
lead/emulsion sandwich + active scint. strip planes + magnetic spectrometer, ~17 GeV beam

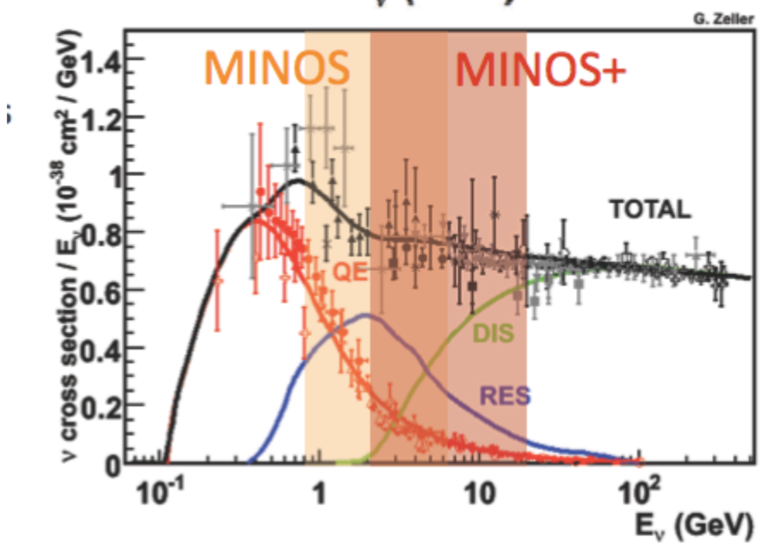


NEW

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







upgraded NuMi beam since 2013
@higher energy

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

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

Measuring CP violation in neutrinos

B. Kayser, PDG

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

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

Flavor transition probability is:

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

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

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

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

From this expression:

$$P(\nu_g \to \nu_f; U) = P(\nu_f \to \nu_g; U^*)$$

Now if CPT holds,

$$P(\bar{\nu}_f \to \bar{\nu}_g) = P(\nu_g \to \nu_f)$$

Putting this together with the above expression:

$$P(\bar{\nu}_f \to \bar{\nu}_g; U) = P(\nu_f \to \nu_g; U^*)$$

Probability for antinus same as for nus, but with U^*

If U is complex, the 2nd term has opposite sign for antinus, and probabilities differ for nus and antinus

Observation of

$$P(\bar{\nu}_f \to \bar{\nu}_g) \neq P(\nu_f \to \nu_g)$$

is a signature of *intrinsic* CP violation (complex U)

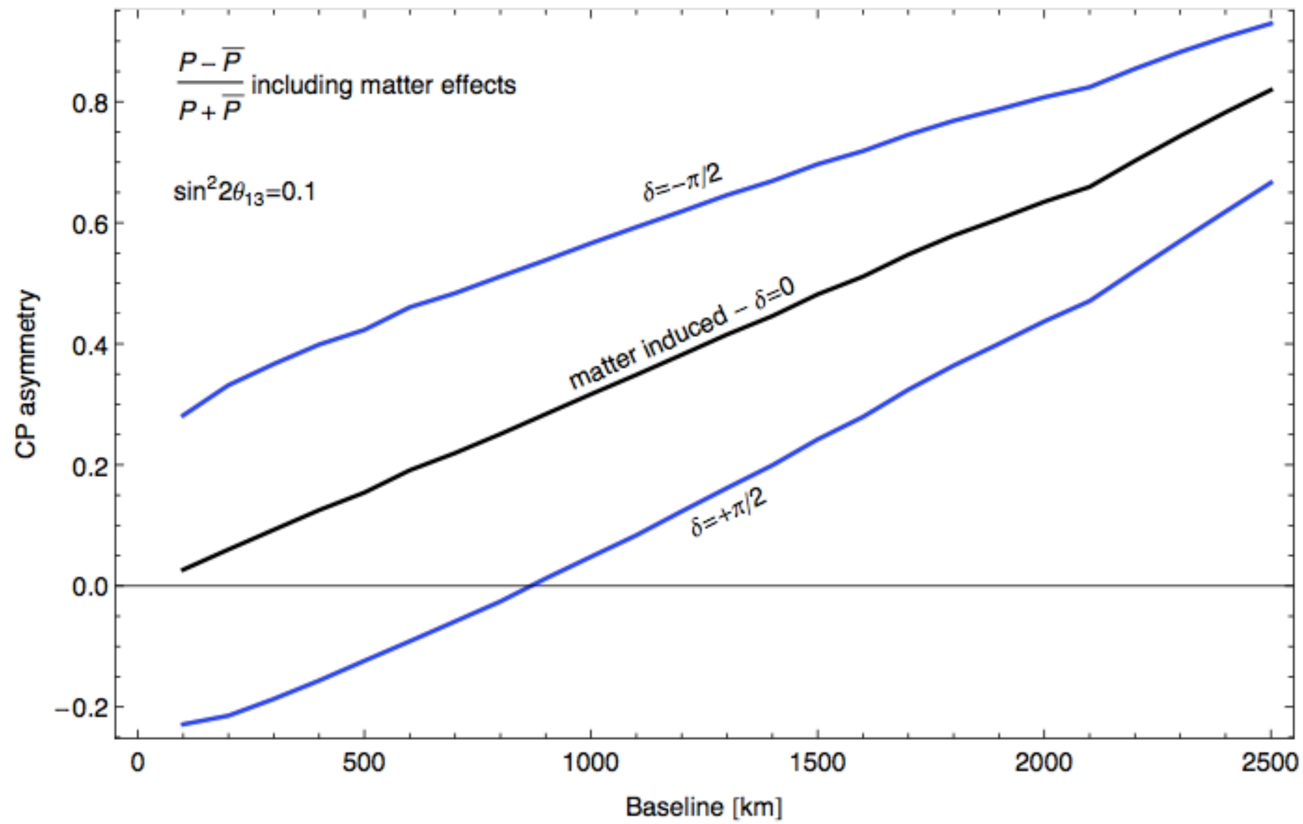
But measurement of CP violation is tangled up with matter effects (depending on MH)...

Matter potential $\nu_\mu \rightarrow \nu_e$ $$V_{\mathrm{mat}} = \pm 2\sqrt{2} G_F N_e E$$

+ for neutrinos, - for antineutrinos

Earth has electrons, not positrons!

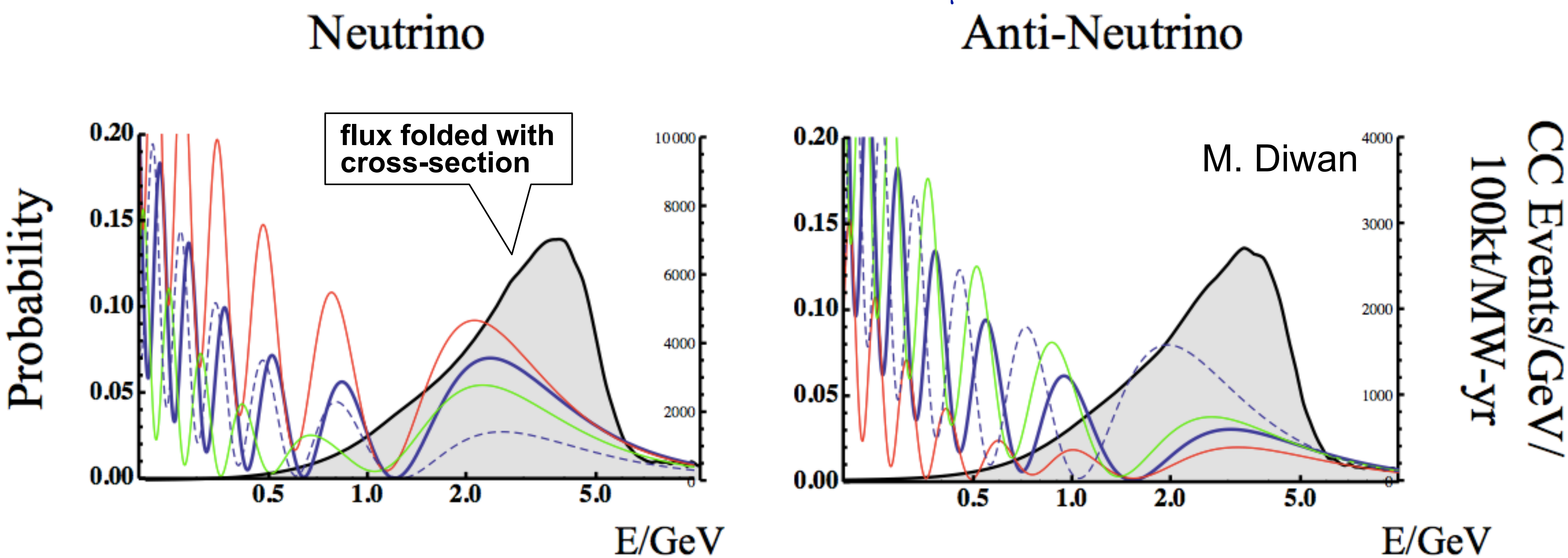
Matter-induced CP asymmetry competes with intrinsic CP asymmetry



P. Huber, NuFact 2013

The information about CP δ and mass hierarchy is in the spectrum of ν_e (and ν_μ) events you measure after long-distance propagation

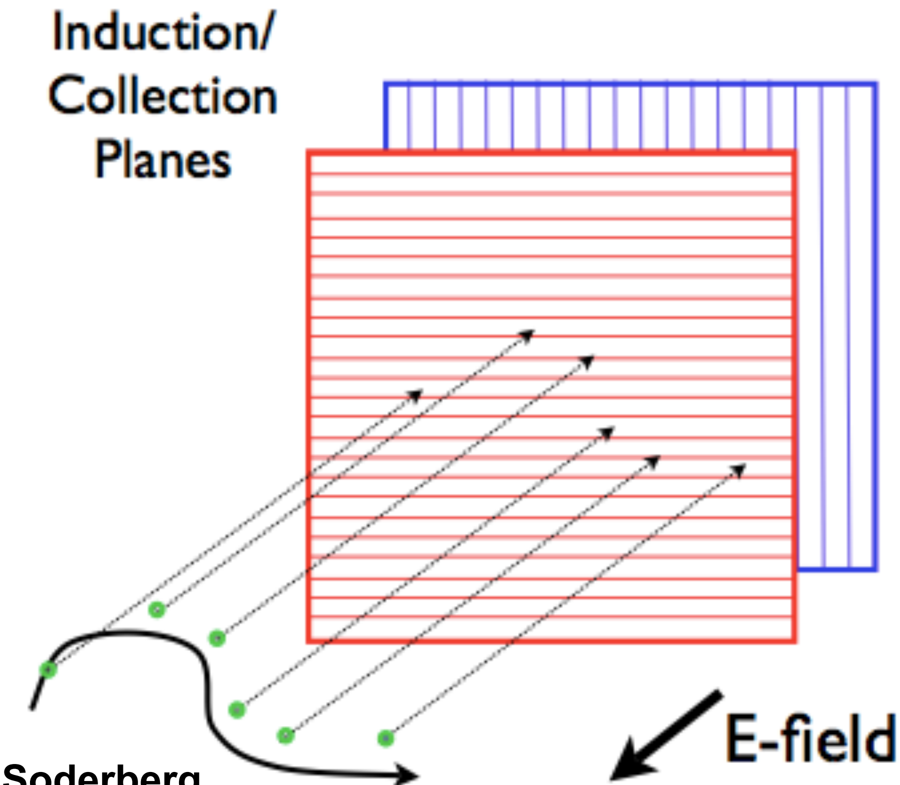
Few-GeV beam events at 1300 km w/ $\nu_\mu \rightarrow \nu_e$ oscillation probabilities



θ_{13}= 9°, δ_{CP} r:+90, b: 0, g: -90, dashed: Inverted Hierarchy, L: 1300 km

Different parameters produce different observed ν & anti-ν spectra

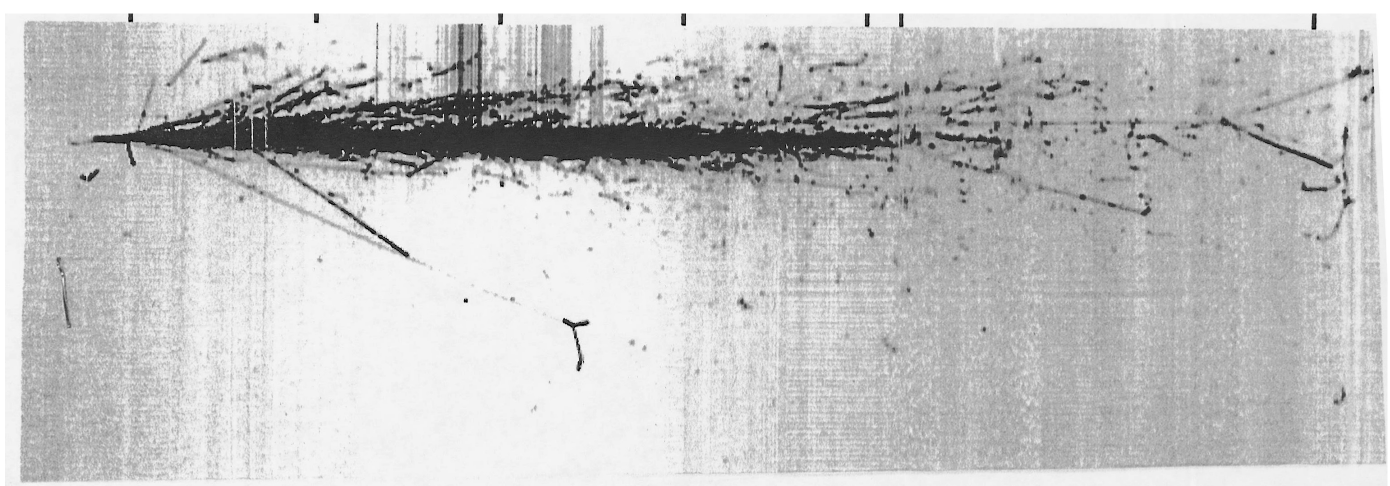
Liquid argon time projection chambers



M. Soderberg

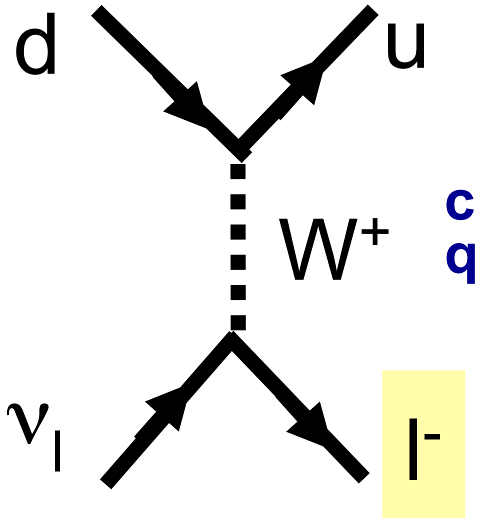
Ionization charge
drifted and collected;
3D track using time info

- **very high quality particle reconstruction** possible
- need scintillation light (photosensors) for absolute time
- require very high purity, cryogenic liquid



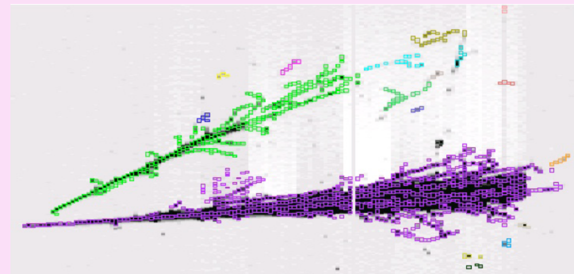
What you're looking for experimentally:

electron flavor appearance on top of background
(NC, beam ν_e, mis-ids)

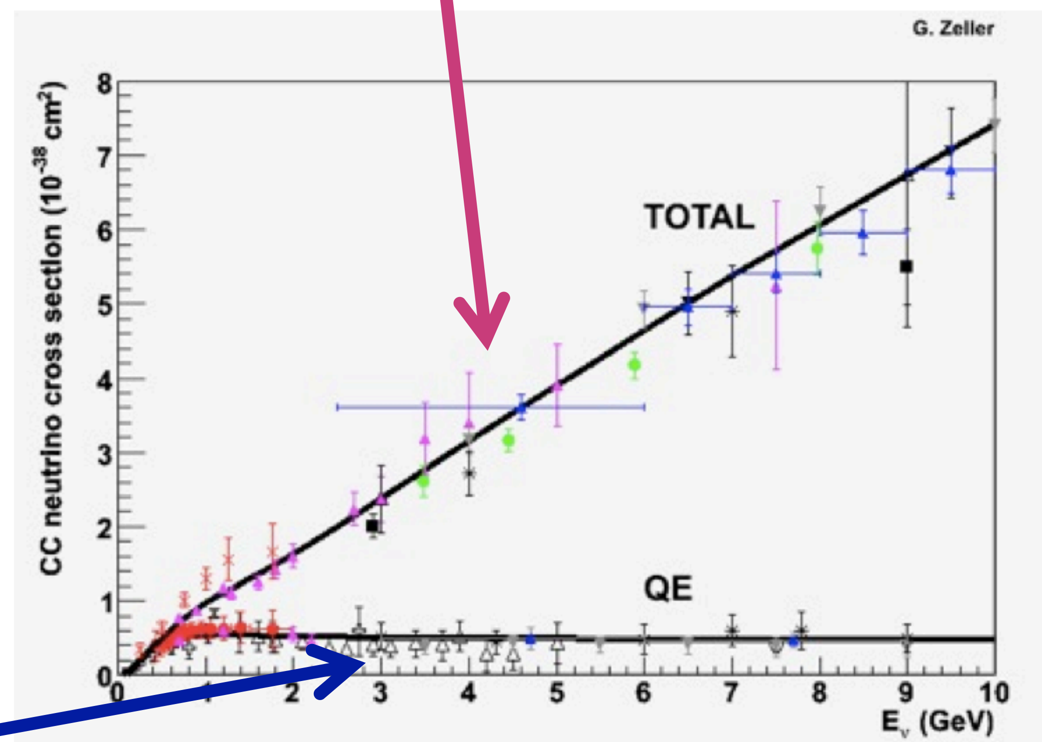


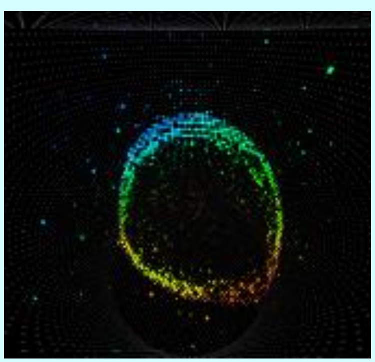
charged-current quasi-elastic

$$\nu_l + N \rightarrow l^{\pm} + N'$$



A LAr detector (in principle) reconstructs everything

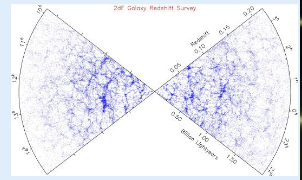
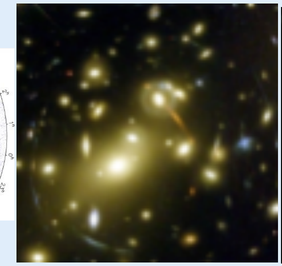
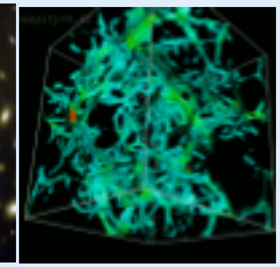
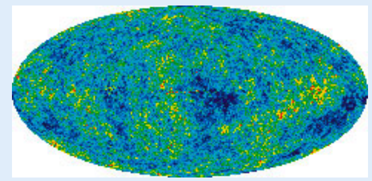
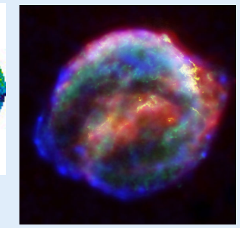




A WCh detector needs to cut hard to select clean QE events

Information on absolute neutrino mass from cosmology

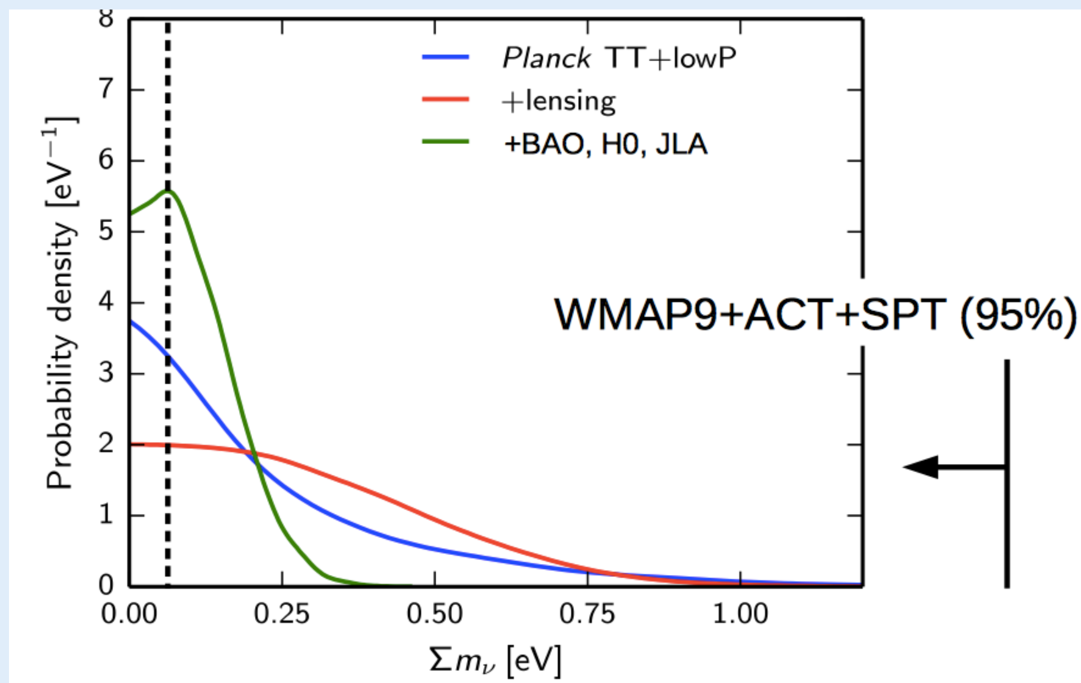
Fits to cosmological data:
CMB, large scale structure,
high Z supernovae,
weak lensing,...

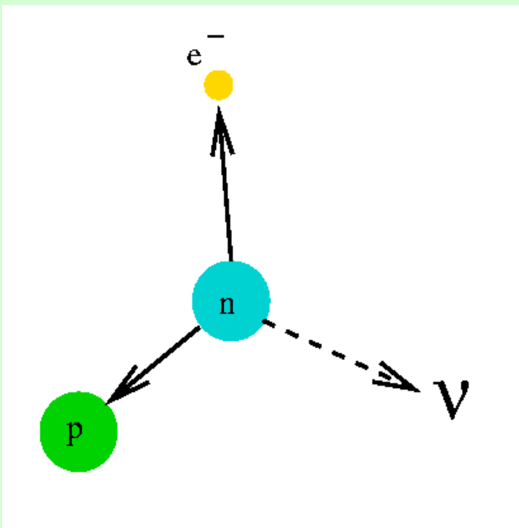
(model-dependent)

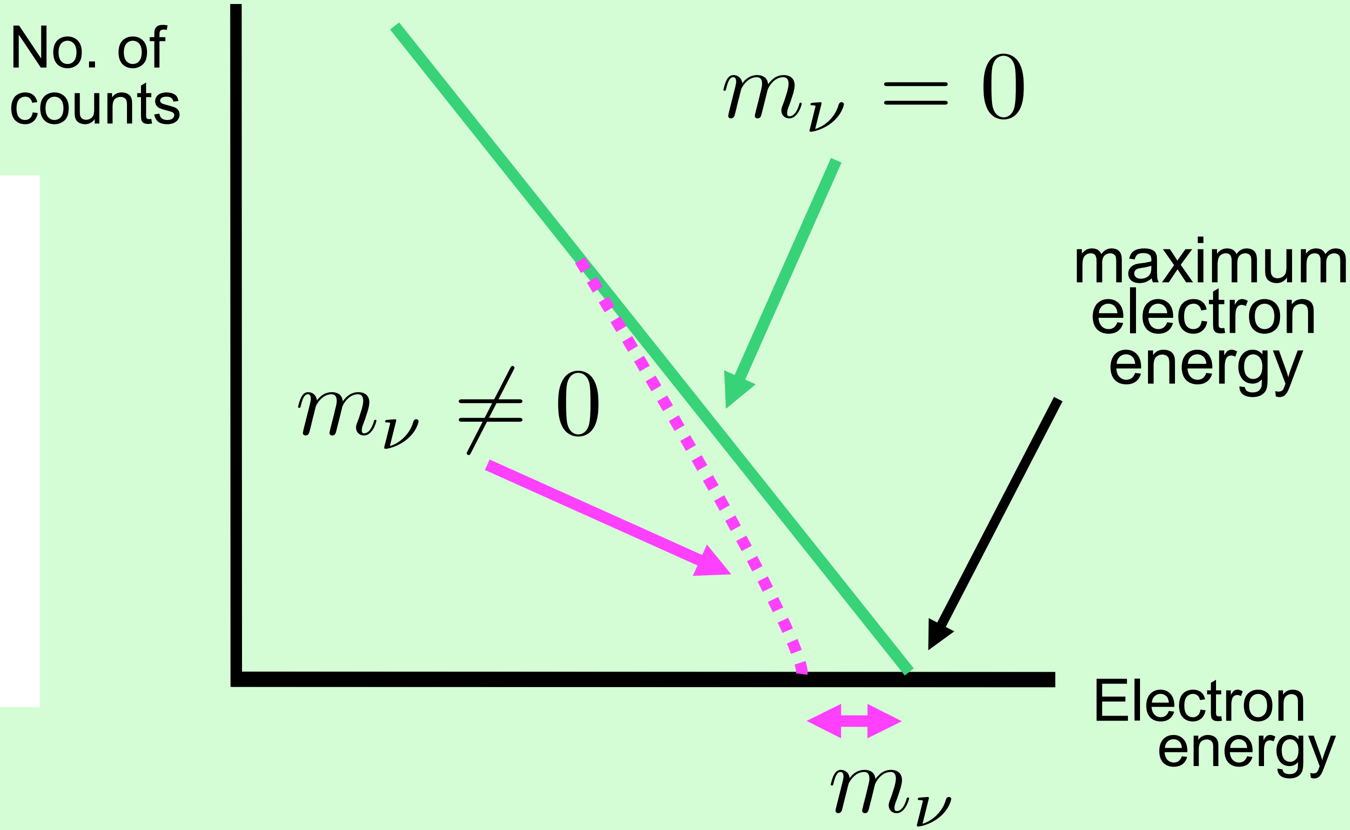
Information
on **sum** of
neutrino masses

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



Kinematic experiments for absolute neutrino mass





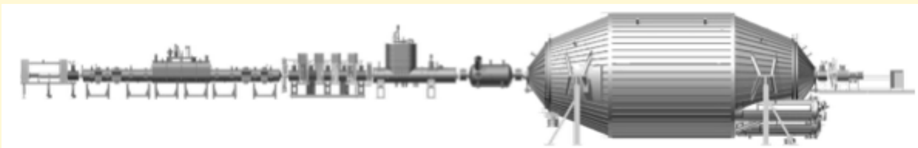
Look for distortion of β-decay spectrum near endpoint

Kinematic neutrino mass approaches

Tritium spectrometer: KATRIN

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

18.6 keV endpoint

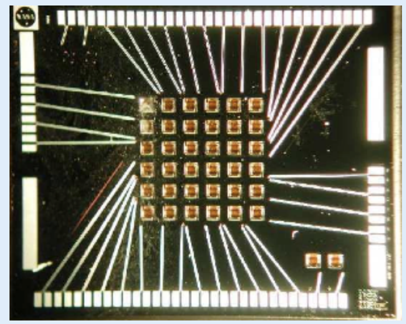


Sensitivity to ~0.2 eV
Data in 2016?

turning on soon

Thermal calorimetry

e.g., **MANU, MIBETA, MARE**



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

2.5 keV endpoint

Hard to scale up...

R&D...

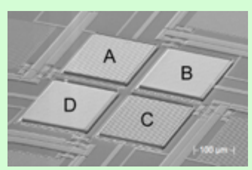
Holmium

e.g., **ECHo, HOLMES,NuMECs**

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

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

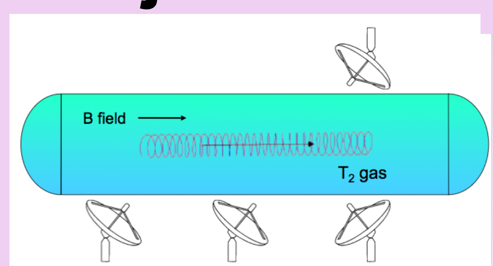
metallic magnetic calorimeters

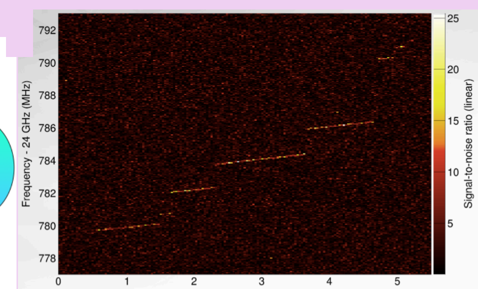


electron capture decay,
ν mass affects deexcitation spectrum
R&D in progress

R&D

Cyclotron radiation tritium spectrometer: Project 8





First single electrons seen!

R&D

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

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

Essential for ν mass understanding....

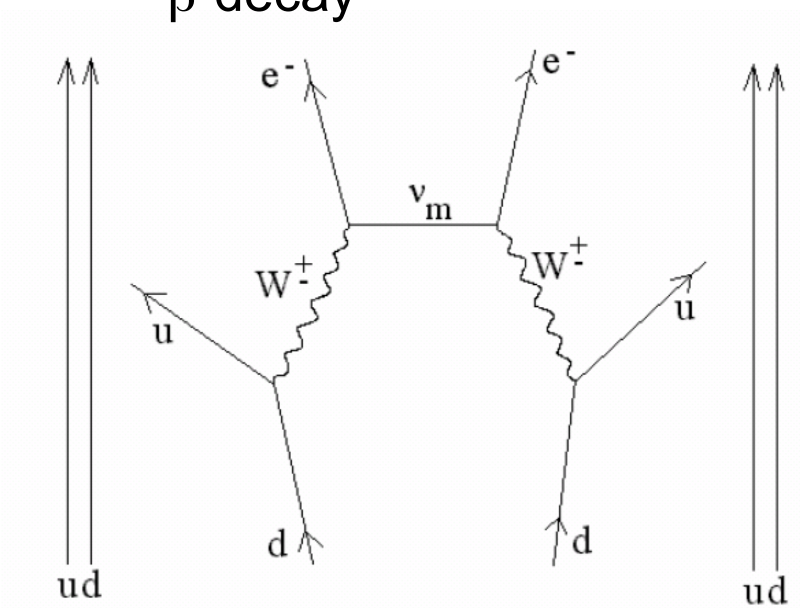
$$\mathcal{L}_m \sim m_D \, [\, \bar{\psi}_L \psi_R + \ldots] + \, [m_L \bar{\psi}_L^c \, \psi_L + m_R \bar{\psi}_R^c \, \psi_R + h.c.]$$

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

... may be helpful for leptogenesis...

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

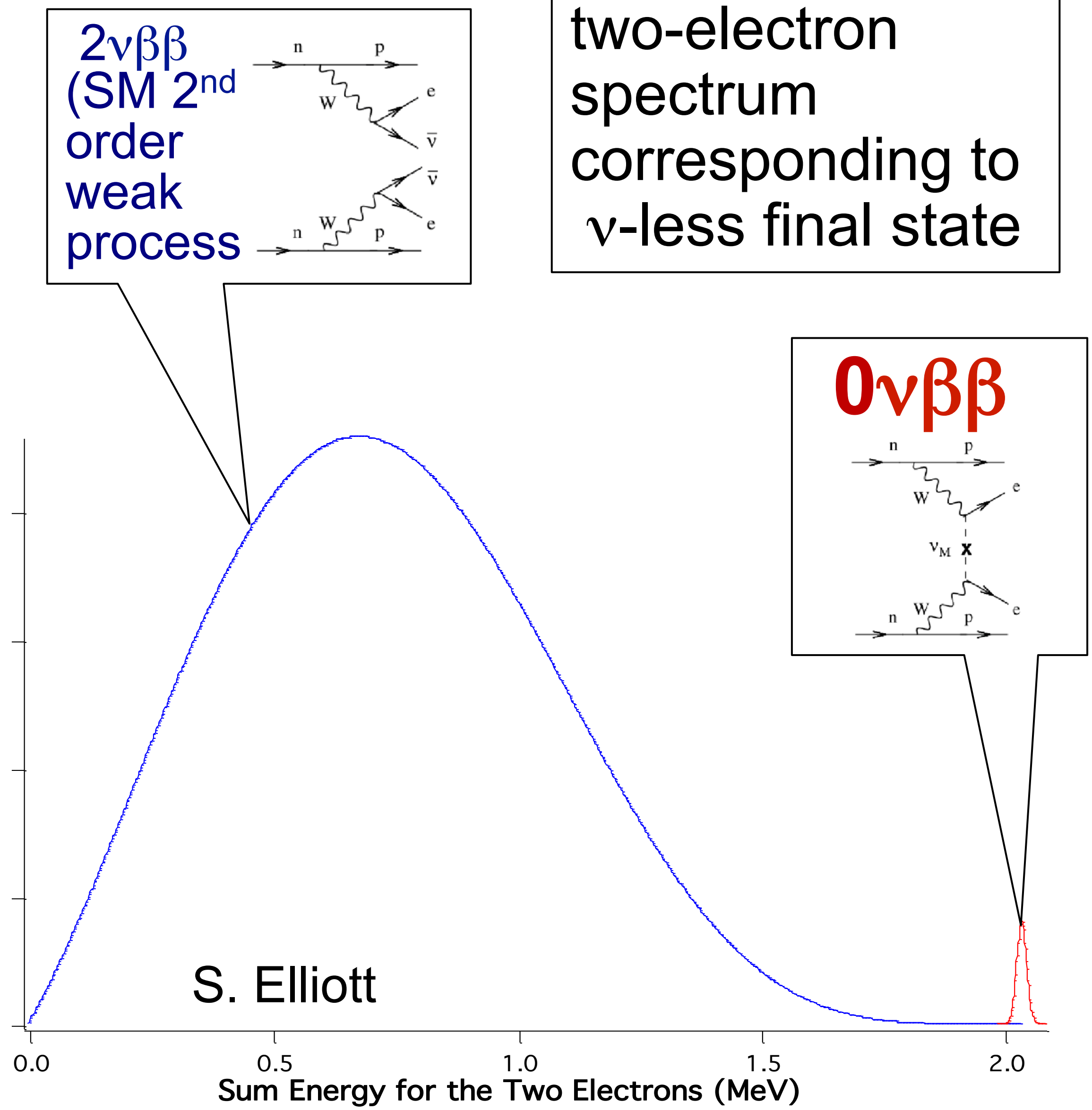
in isotopes for
which it is energetically
possible
and which don't single
β-decay



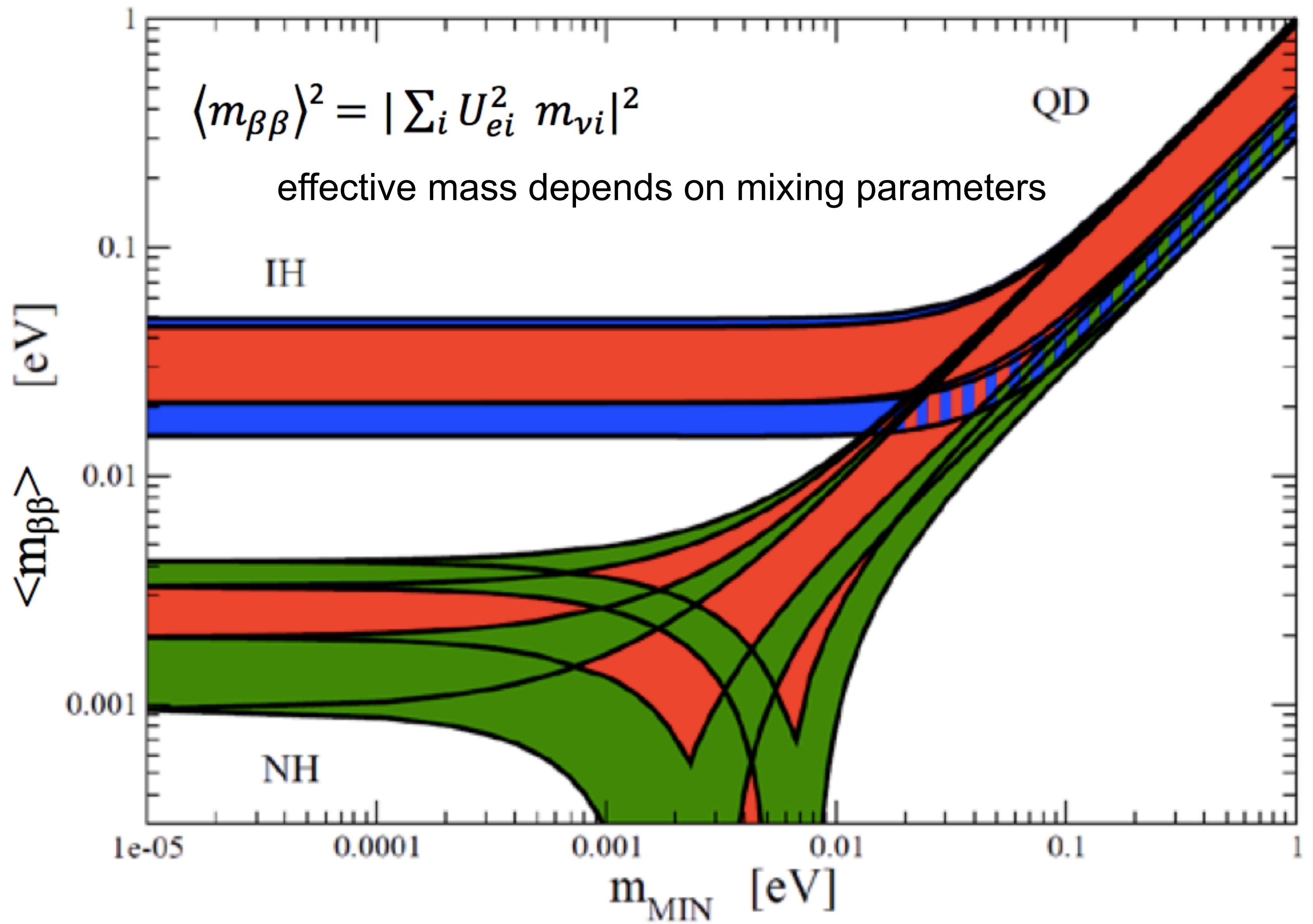
Only possible
for Majorana ν
(...or exotic physics)

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

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



The NLDBD T-Shirt Plot

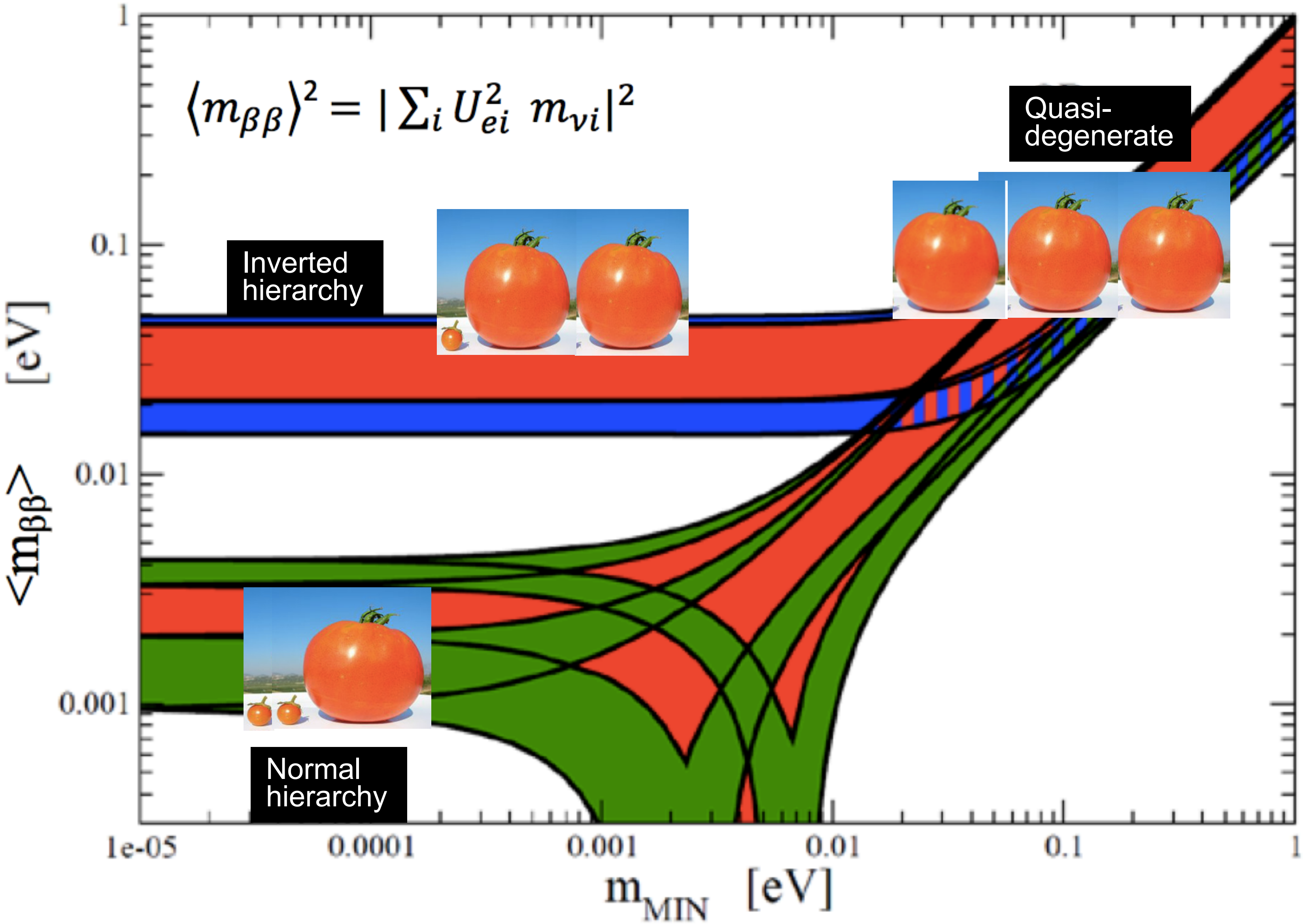


***If* neutrinos are Majorana*, experimental results must fall in the shaded regions**

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

*and standard 3-flavor picture

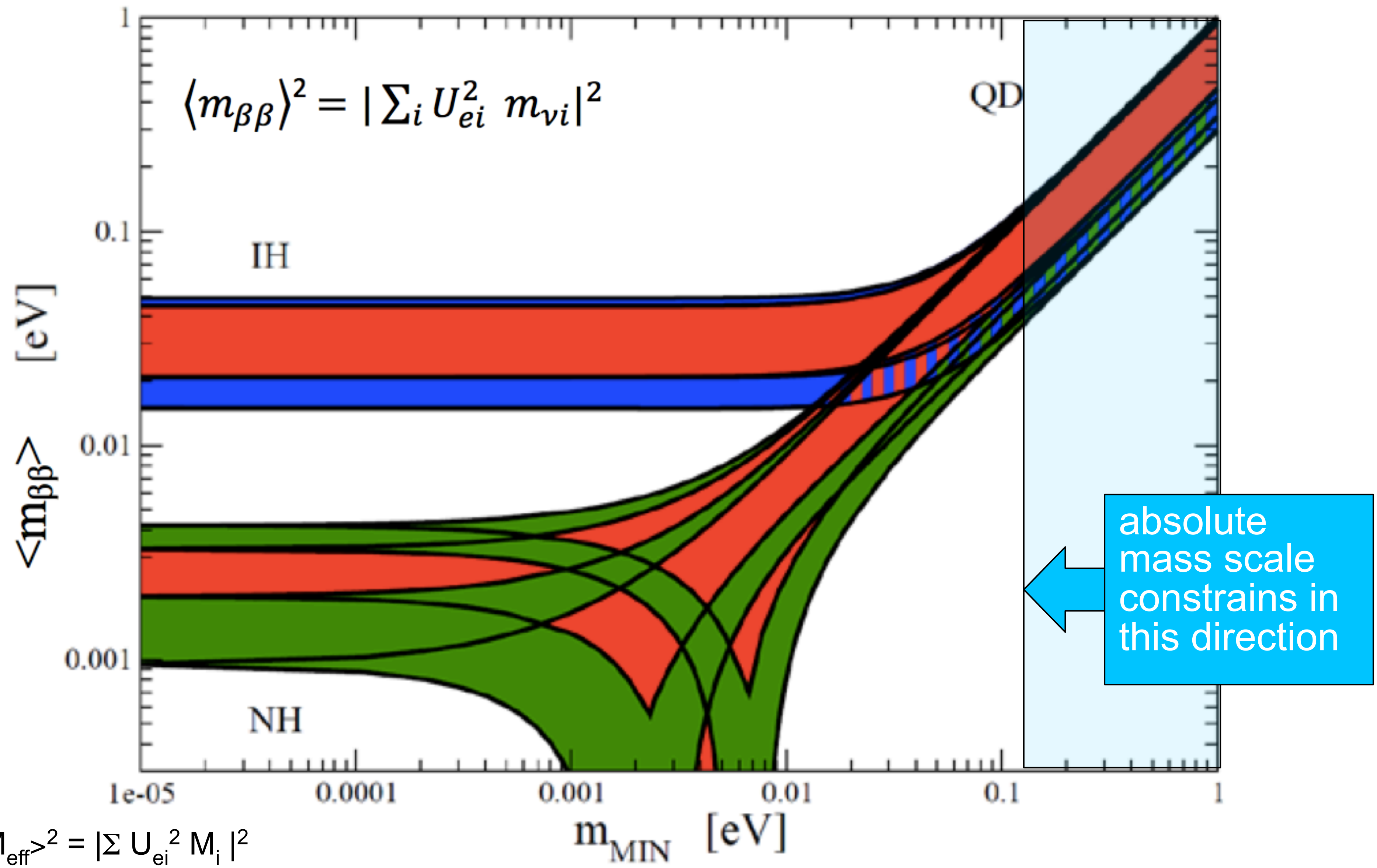
The NLDBD T-Shirt Plot



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

The NLDBD T-Shirt Plot

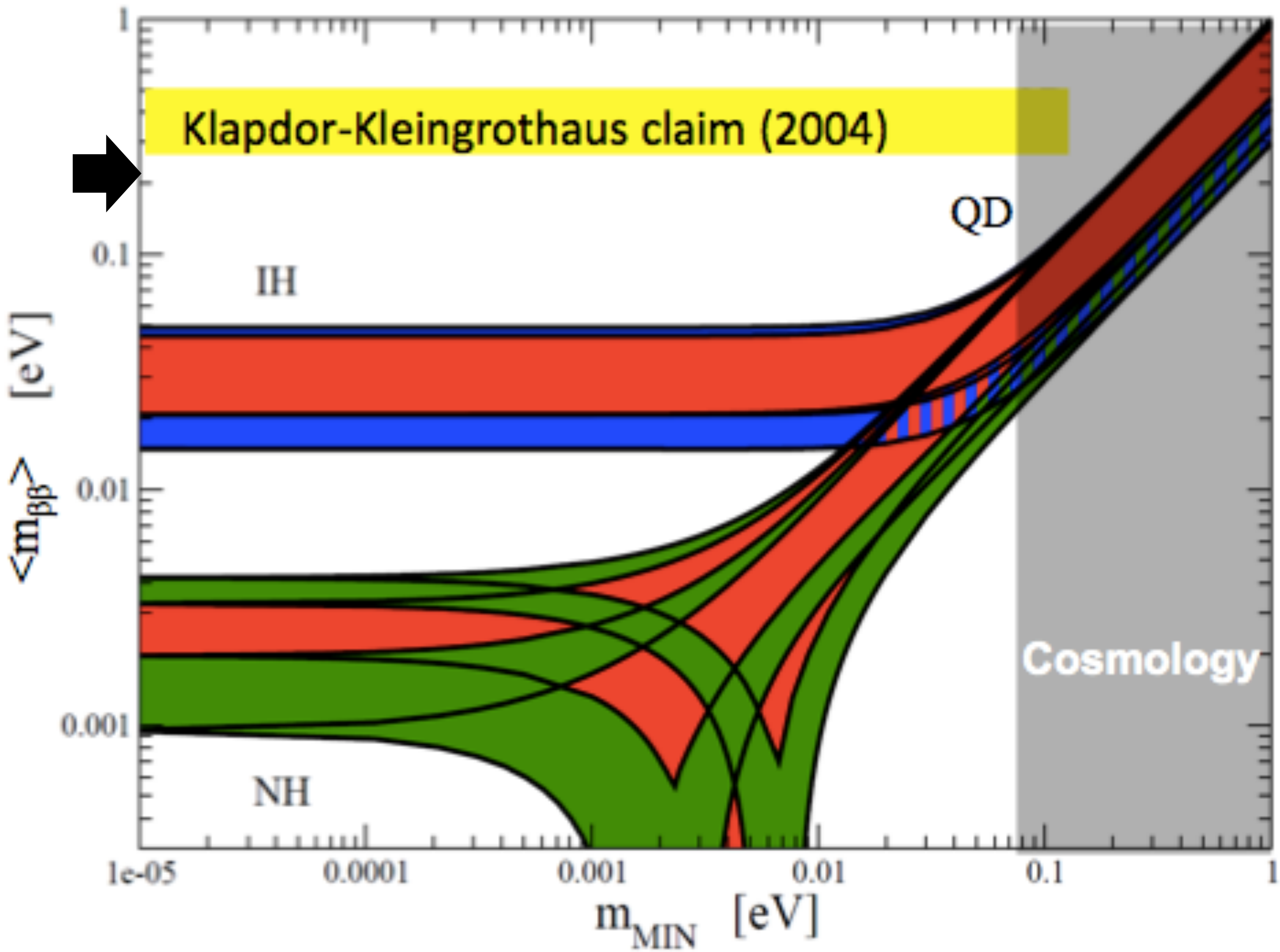


$<M_{eff}>^2 = |\Sigma\ U_{ei}^2\ M_i\ |^2$

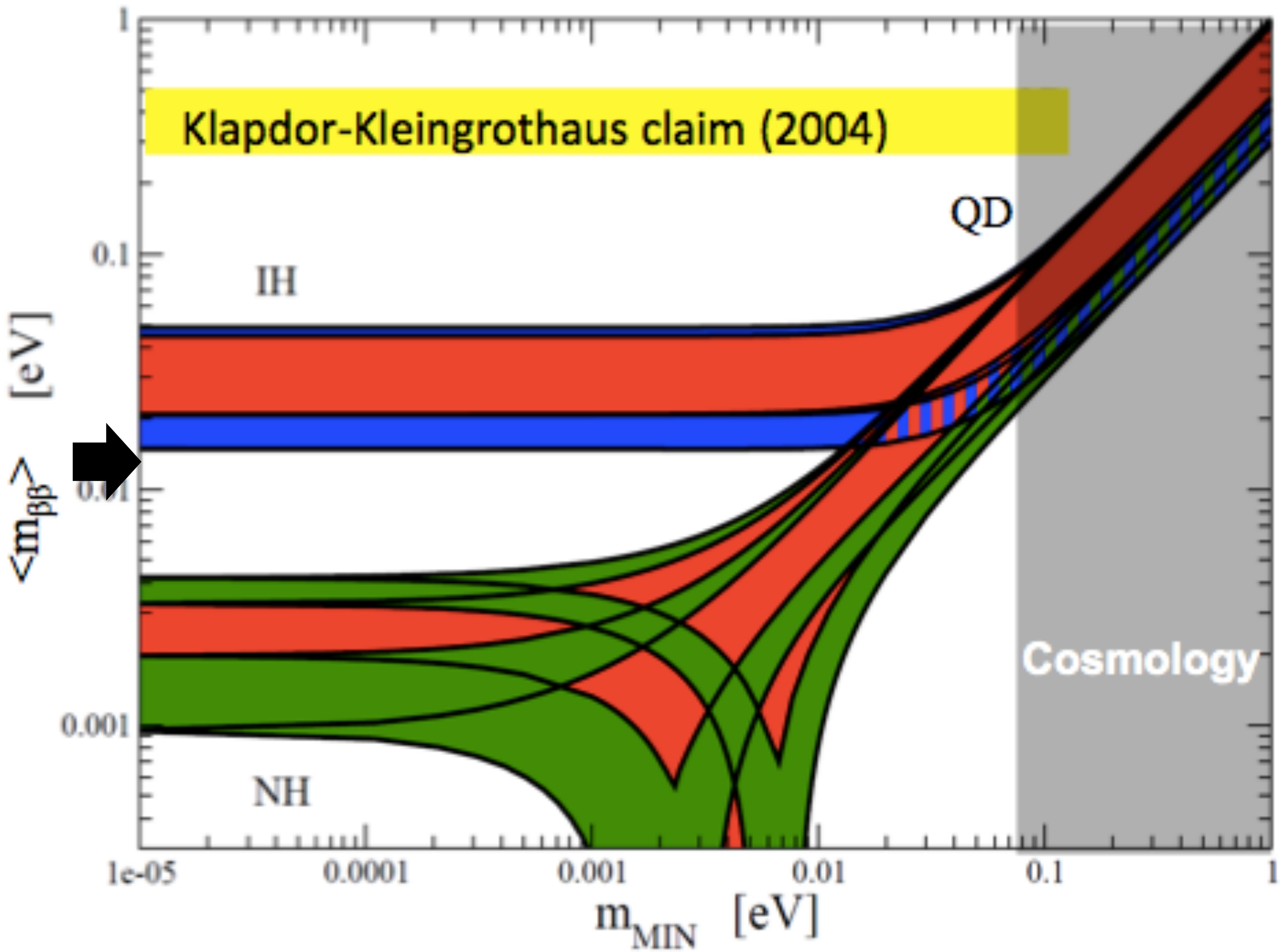
If **neutrinos are Majorana, experimental results must fall in the shaded regions**

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



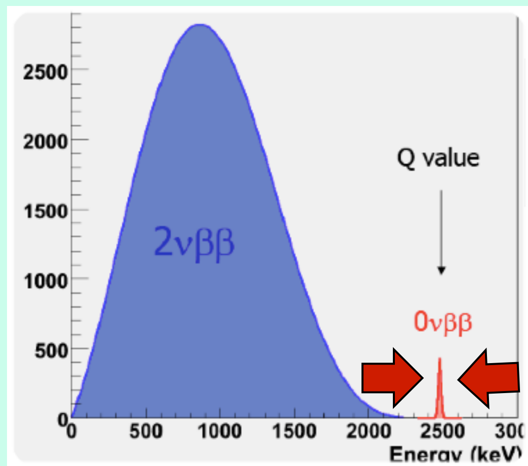
General NLDBD experiment strategies

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

The “Brute Force” Approach

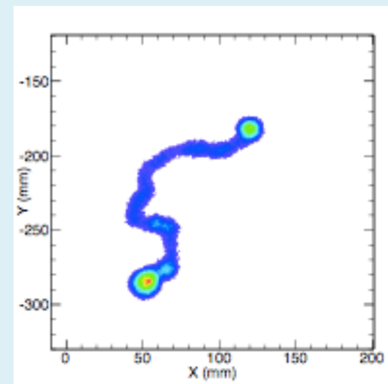
focus on the numerator with **a huge amount of material**
(often sacrificing resolution)

The “Peak-Squeezer” Approach



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

The “Final-State Judgement” Approach

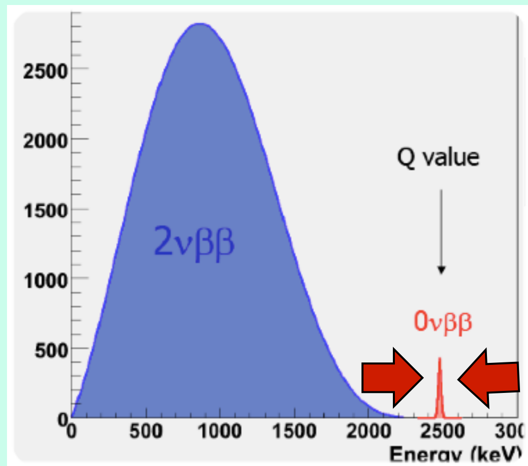
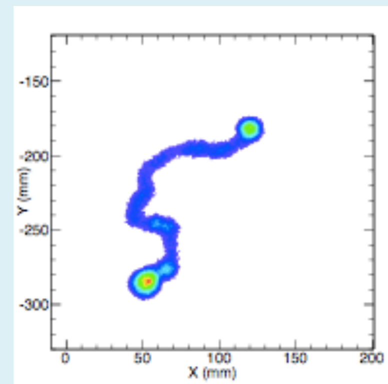


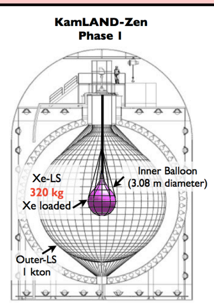
try to make the background zero by **tracking or tagging**

...some experiments take hybrid approaches...

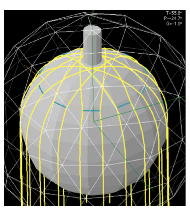
General NLDBD experiment strategies

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

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



KamLAND-Zen
(^{136}Xe)



SNO+
(^{130}Te)

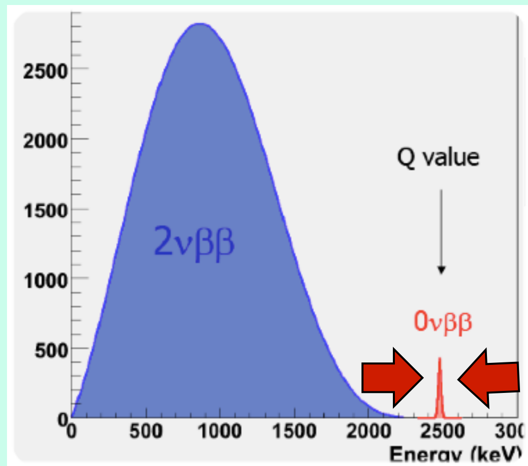
+more future ideas...

General NLDBD experiment strategies

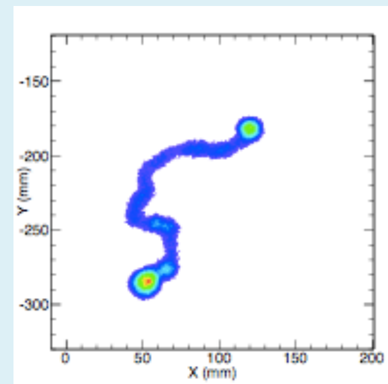
$$T_{1/2} > \frac{\ln 2 \;\; \varepsilon \cdot N_{source} \cdot T}{UL(B(T) \cdot \Delta E)}$$

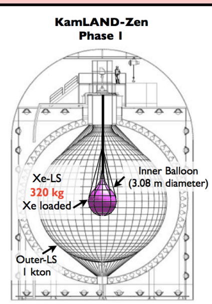
The “Brute Force” Approach

The “Peak-Squeezer” Approach

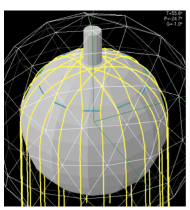


The “Final-State Judgement” Approach

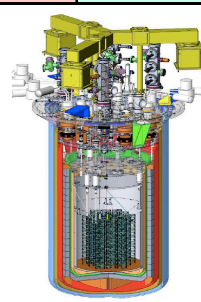




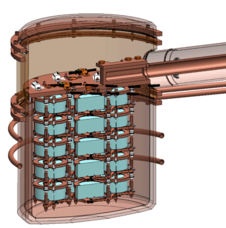
KamLAND-Zen (^{136}Xe)



SNO+ (^{130}Te)

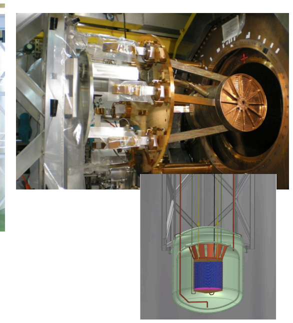


CUORICINO/ CUORE (^{130}Te)



MAJORANA (^{76}Ge)

GERDA (^{76}Ge)

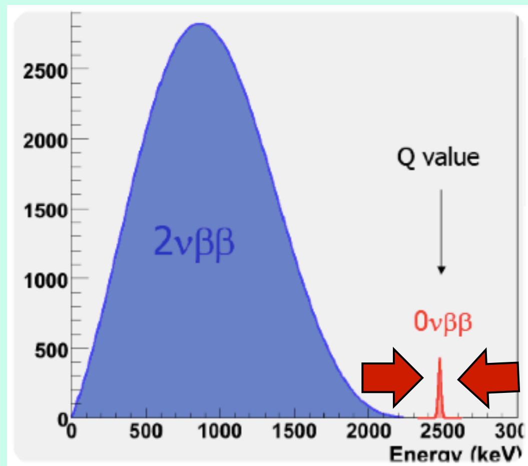
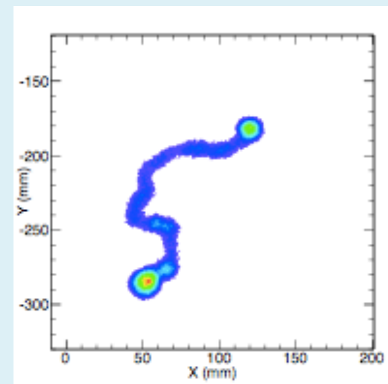


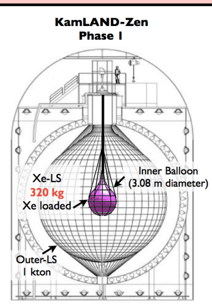
EXO/nEXO (^{136}Xe)

+more future ideas...

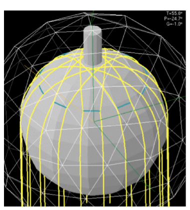
General NLDBD experiment strategies

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

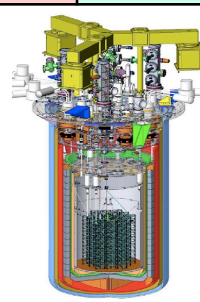
The "Brute Force" Approach	The "Peak-Squeezer" Approach	The "Final-State Judgement" Approach
		



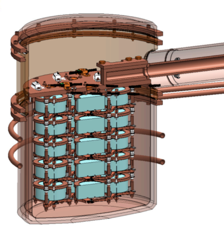
KamLAND-Zen
(^{136}Xe)



SNO+
(^{130}Te)

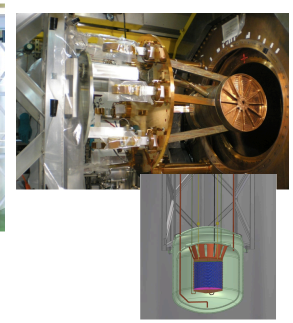


CUORICINO/
CUORE
(^{130}Te)

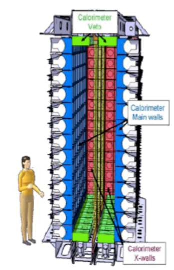


MAJORANA
(^{76}Ge)

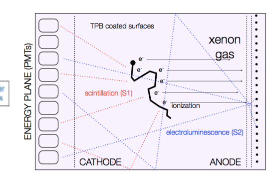
GERDA
(^{76}Ge)



EXO/nEXO
(^{136}Xe)



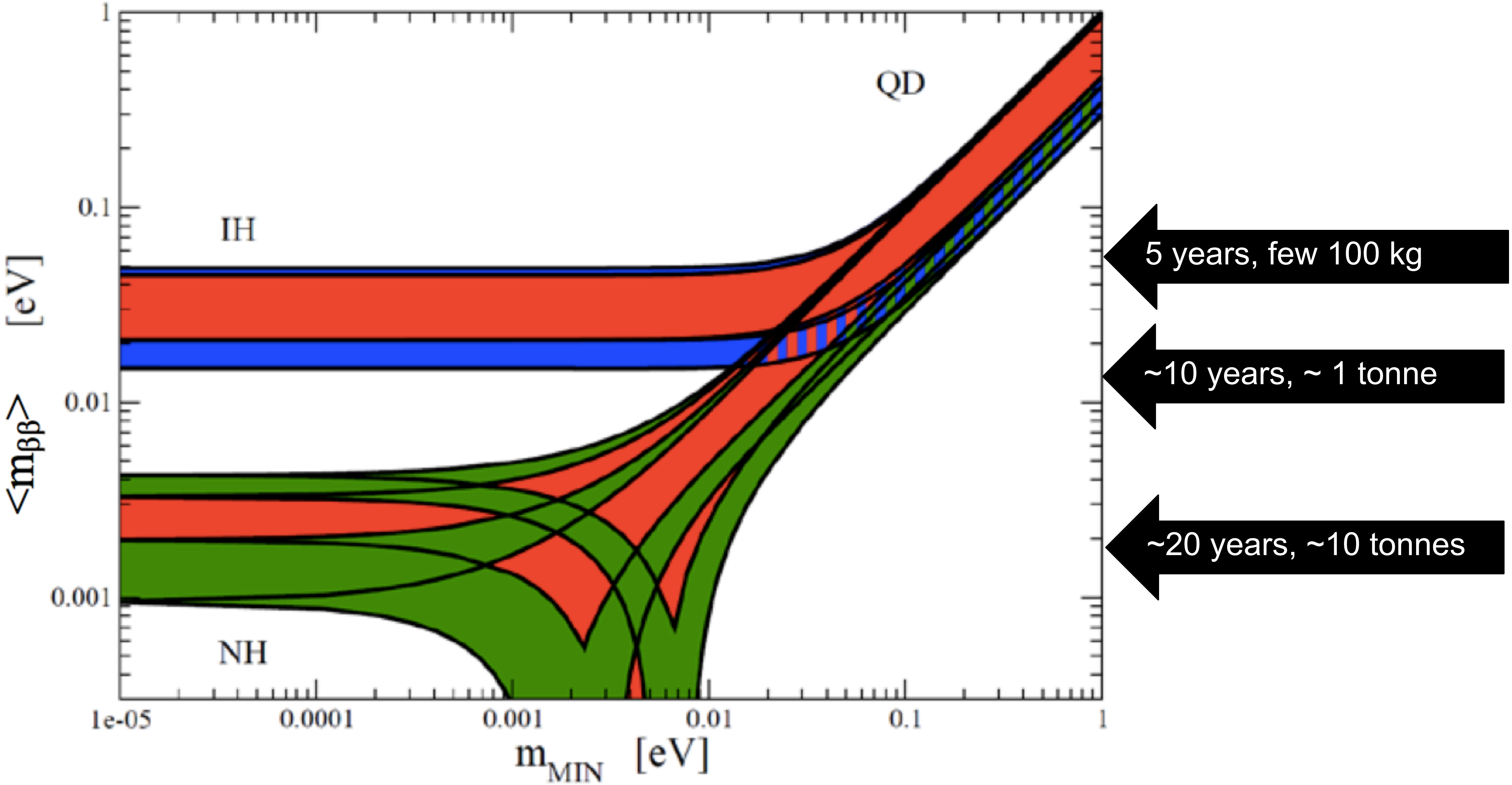
NEMO/
SuperNEMO
(various/^{82}Se)



NEXT
(^{136}Xe)

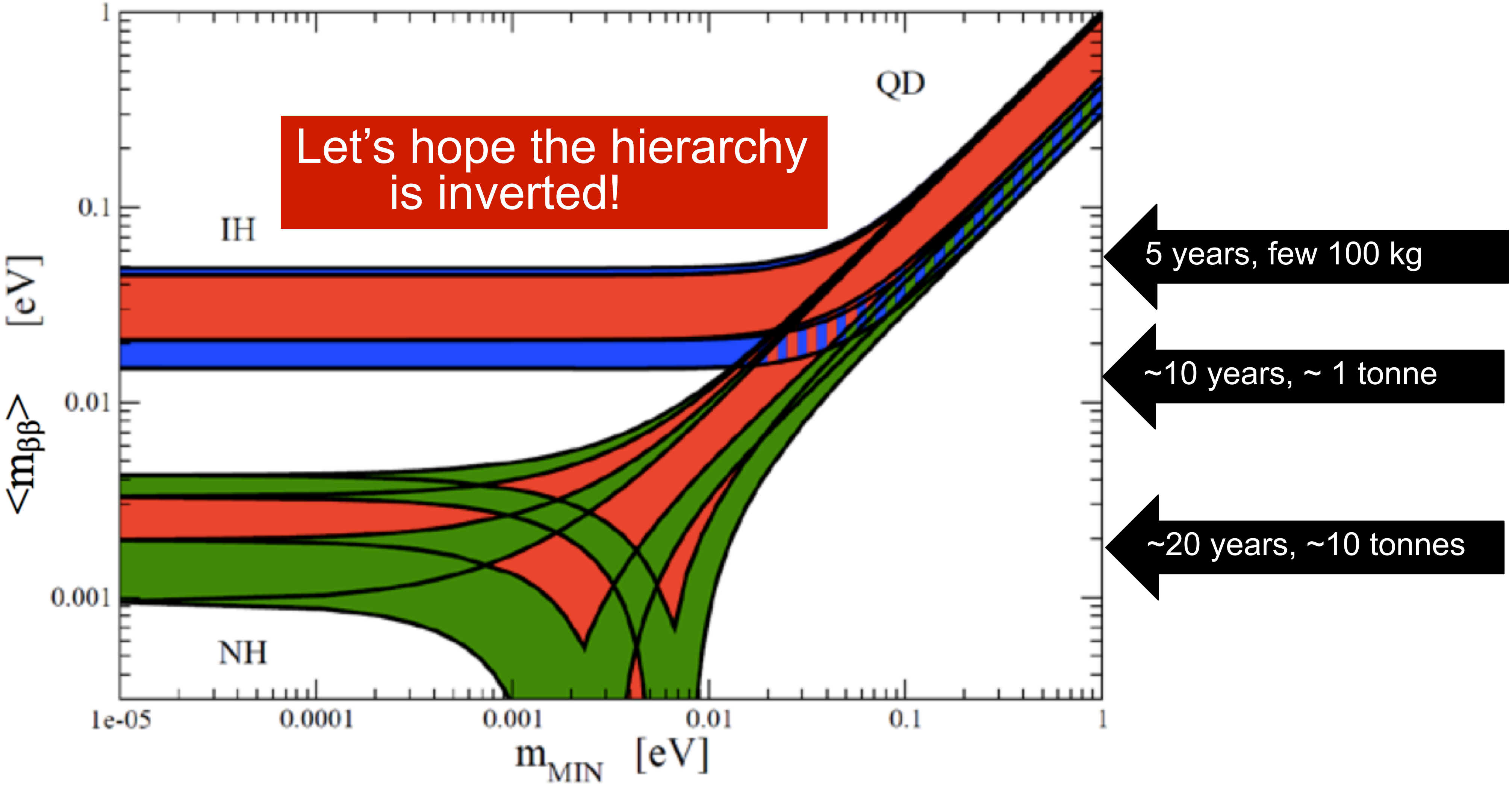
+more future ideas...

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!