Accelerator-Based Neutrino Oscillation Experiments

Kate Scholberg, Duke University

Windows on the Universe, ICISE, August 2013

OUTLINE

The three-flavor paradigm

Where are we now?

Results from accelerator-based experiments

Where do we still need to go (and why)?

Remaining 3-flavor parameters

Mass hierarchy strategies

CP δ strategies

Hunting down anomalies...

Overall summary

Neutrino oscillations in the three-flavor paradigm

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

Parameterize mixing matrix U as

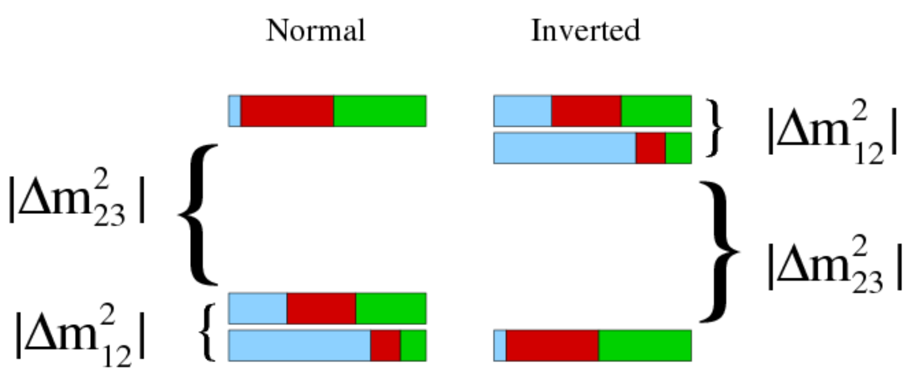
$$U = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{bmatrix} \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

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

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

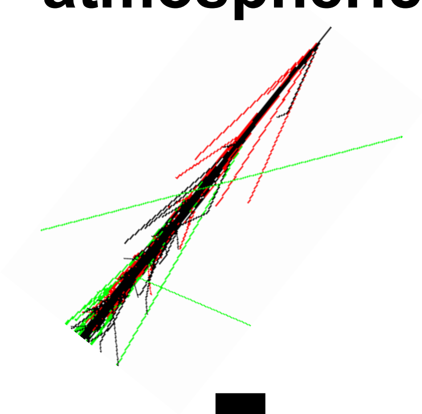
3 masses	m_1, m_2, m_3 (2 mass differences + absolute scale)
3 mixing angles	$\theta_{23}, \theta_{12}, \theta_{13}$
1 CP phase	δ
(2 Majorana phases)	α_1, α_2

signs of the mass differences matter

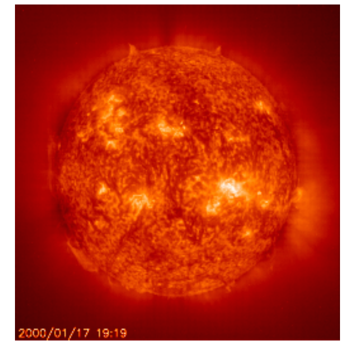


We now have clean flavor-transition signals in two 2-flavor sectors

atmospheric



solar



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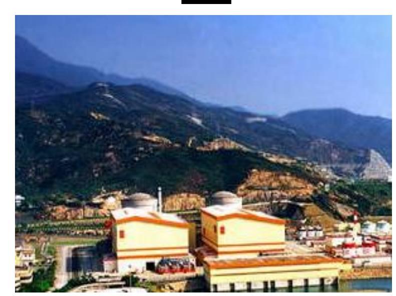
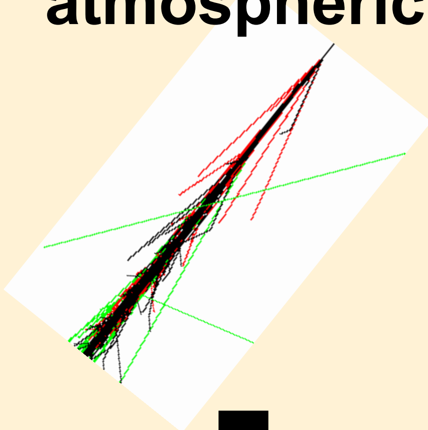
beams



reactor

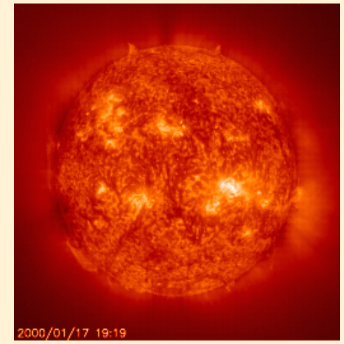
We now have clean flavor-transition signals in two 2-flavor sectors

atmospheric



signal with
“wild” neutrinos...

solar



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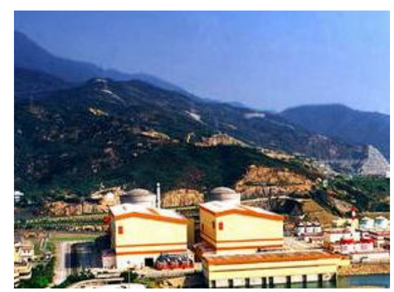
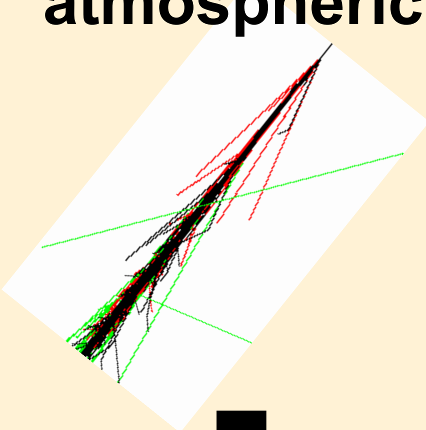
beams



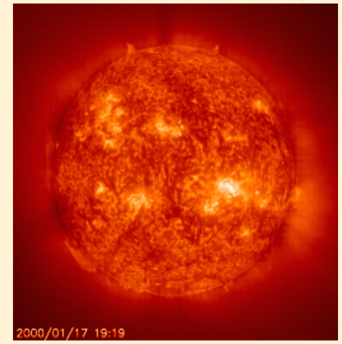
reactor

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

atmospheric



solar



signal with “wild” neutrinos...

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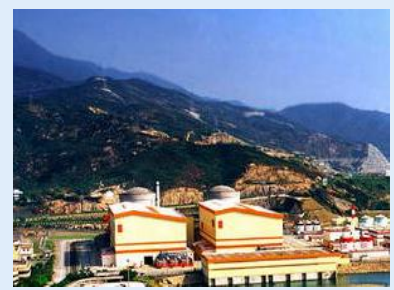
confirmed with “tame” ones...

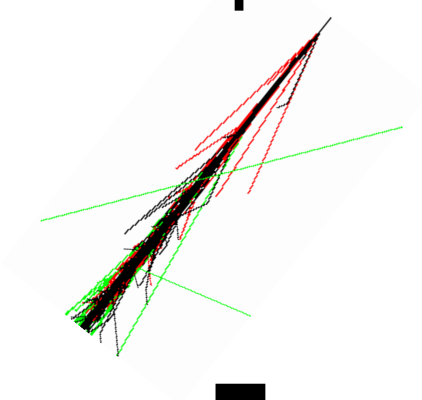
beams



reactor

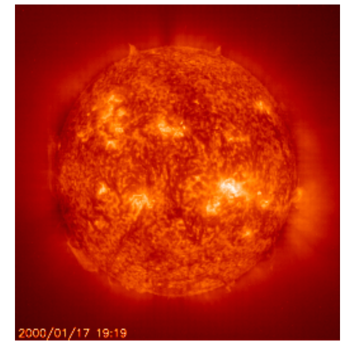
And now more information from beams and burns!

atmospheric



θ_{13} now known to be large!

solar



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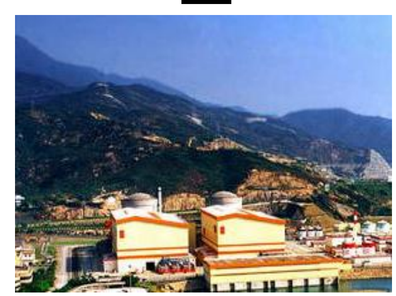
beams



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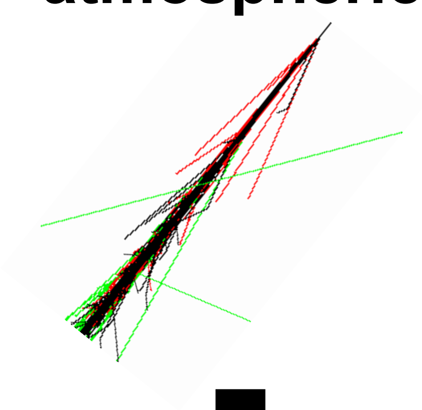

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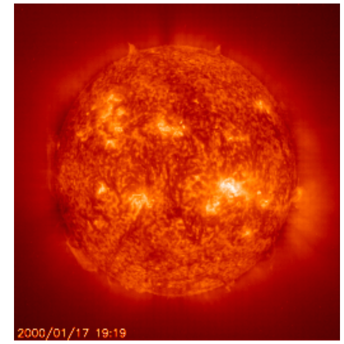

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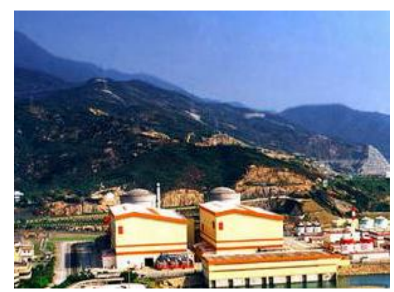
beams



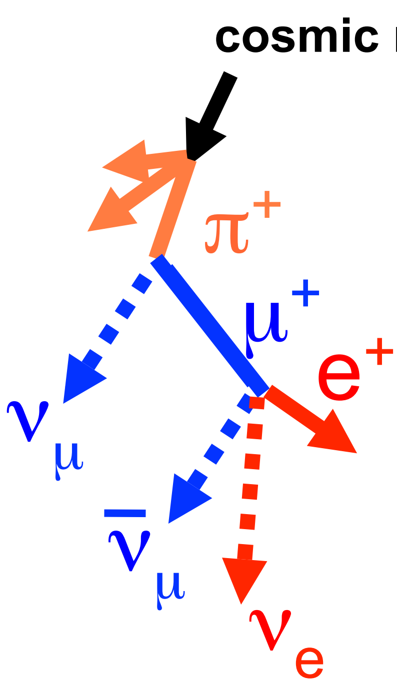
reactor

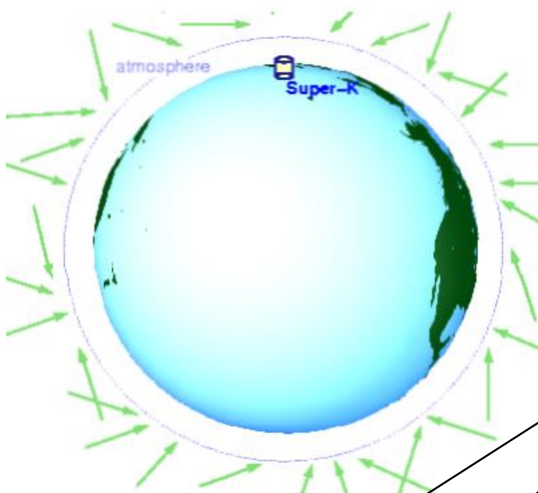
In this talk, will zoom in here

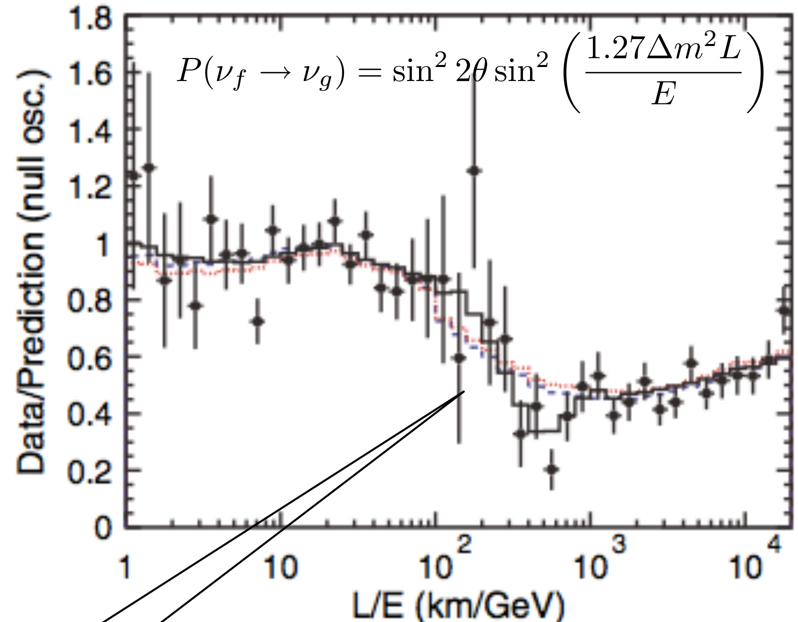
Atmospheric neutrinos

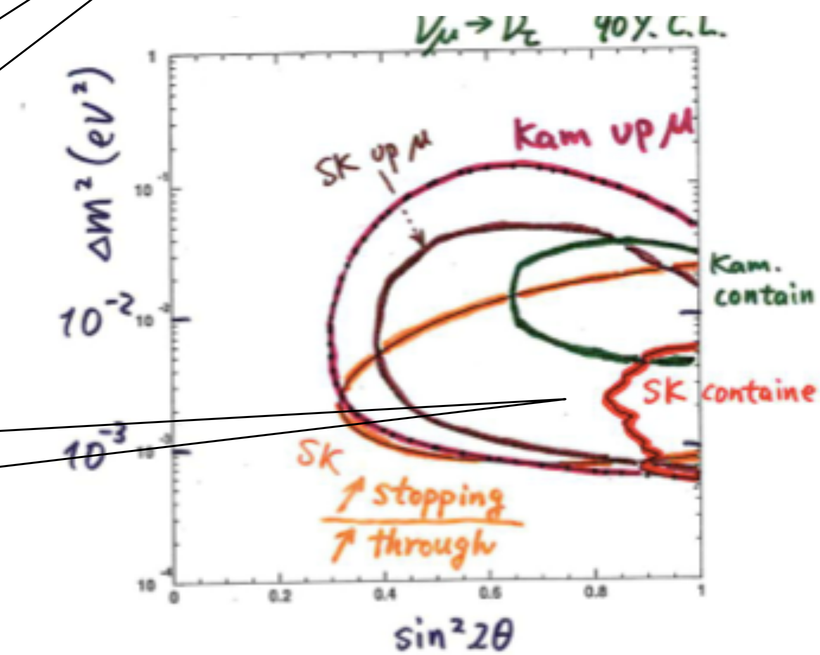
The neutrinos are free, and have a range of baselines & energies

.... but they do what they damn well please









Clear ν_μ disappearance

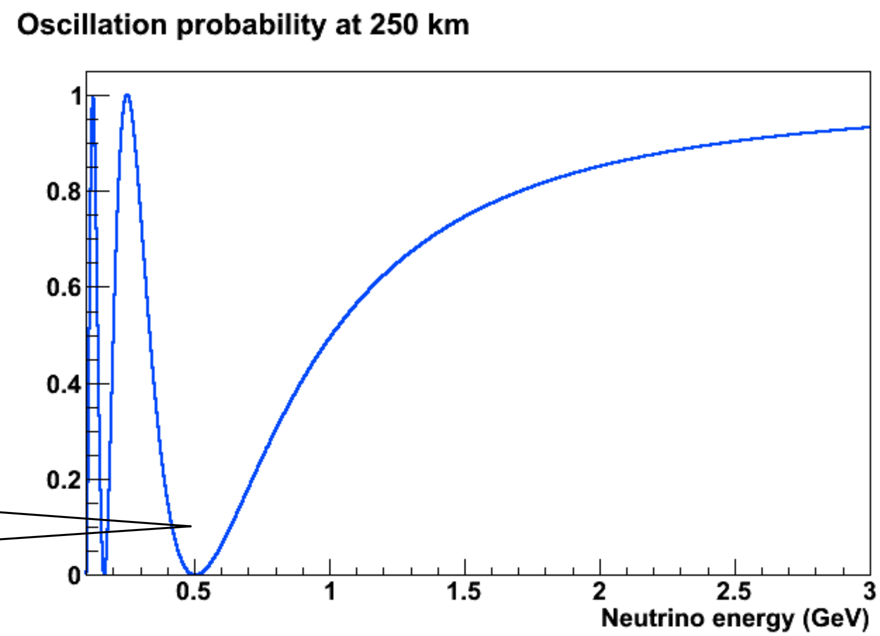
Well described by 23 oscillation parameters:
$|\Delta m^2_{32}| \sim 2 \times 10^{-3}$ eV^2,
~ maximal mixing

Taming the source to confirm & study oscillations with long-baseline beam experiments

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

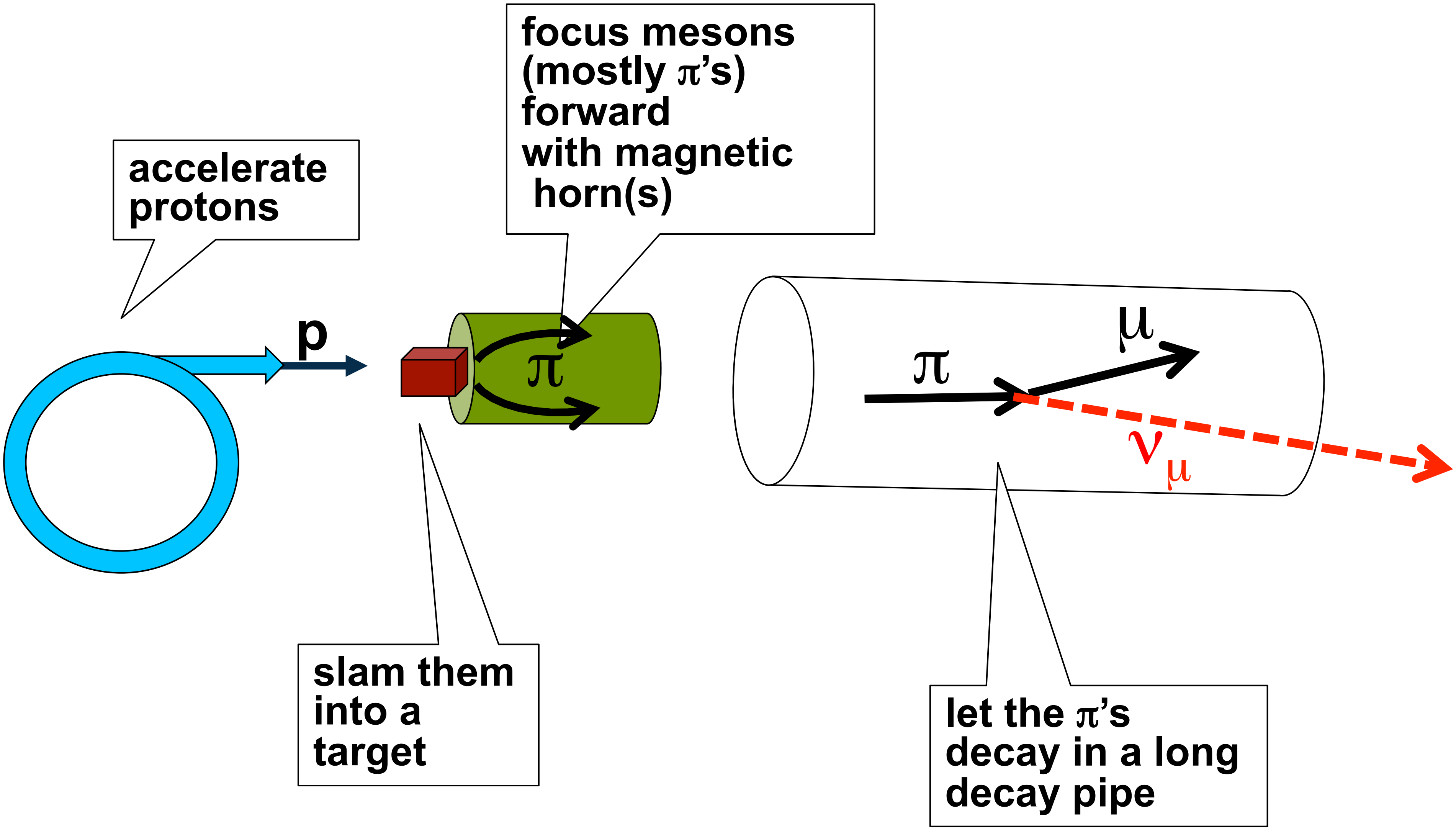
E_ν~ GeV, L~ 100's of km for same L/E

Compare flux, flavor and energy spectrum at near and far detectors



Design your beam at given baseline to cover oscillation peaks

How To Make Tame Neutrinos



Long-baseline beam experiments

Past — Current — Future

K2K

KEK to Kamioka
250 km, 5 kW

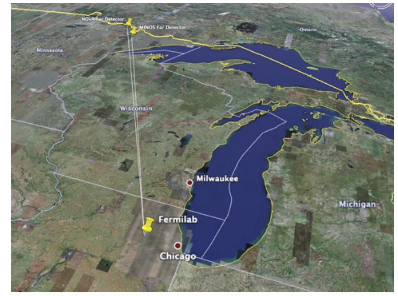
Long-baseline beam experiments

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, 750 kW



Long-baseline beam experiments

Past — Current — Future

K2K
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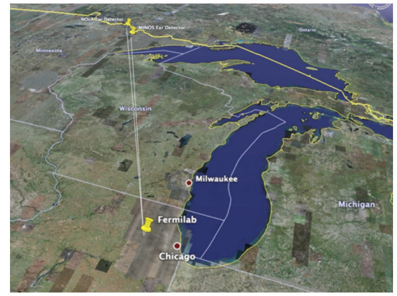

NOνA
FNAL to Ash River
810 km, 700 kW

T2K
J-PARC to Kamioka
295 km, 750 kW

LBNE
FNAL to Homestake
1300 km, 700 kW

T2HK
J-PARC to Kamioka
295 km, 700 kW

Long-baseline beam experiments

Past — Current — Future

K2K
KEK to Kamioka
250 km, 5 kW

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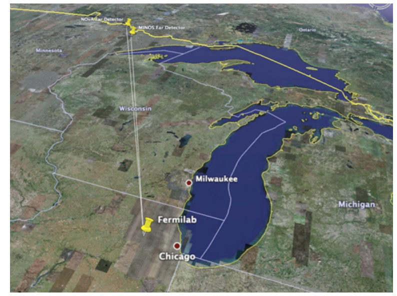
CERN to LNGS
730 km, 400 kW



NOνA
FNAL to Ash River
810 km, 700 kW

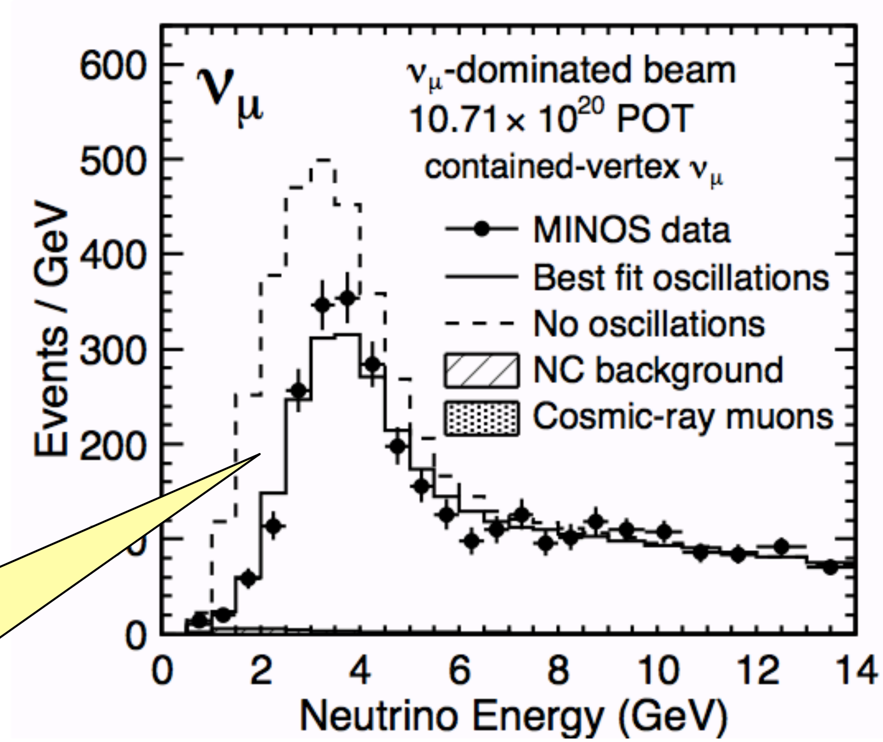
T2K
J-PARC to Kamioka
295 km, 750 kW

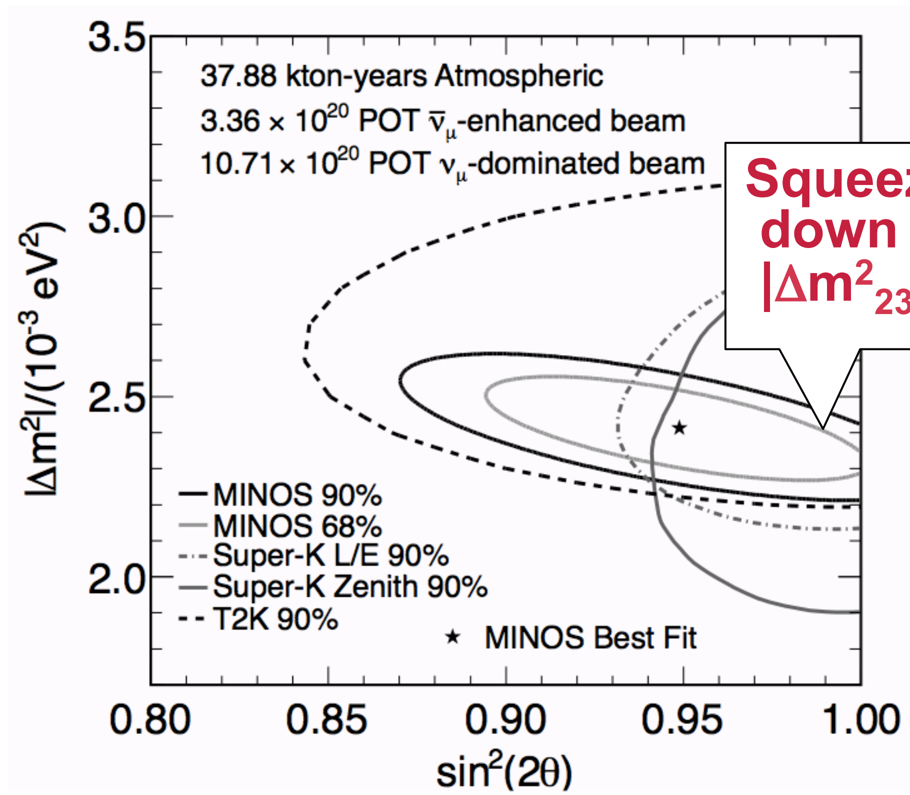
LBNE (➔Project X)
FNAL to Homestake
1300 km, 700 kW (➔2.3 MW)

T2HK
J-PARC to Kamioka
295 km, 700 kW (➔..)

MINOS
in US making precision measurements of ν_μ disappearance

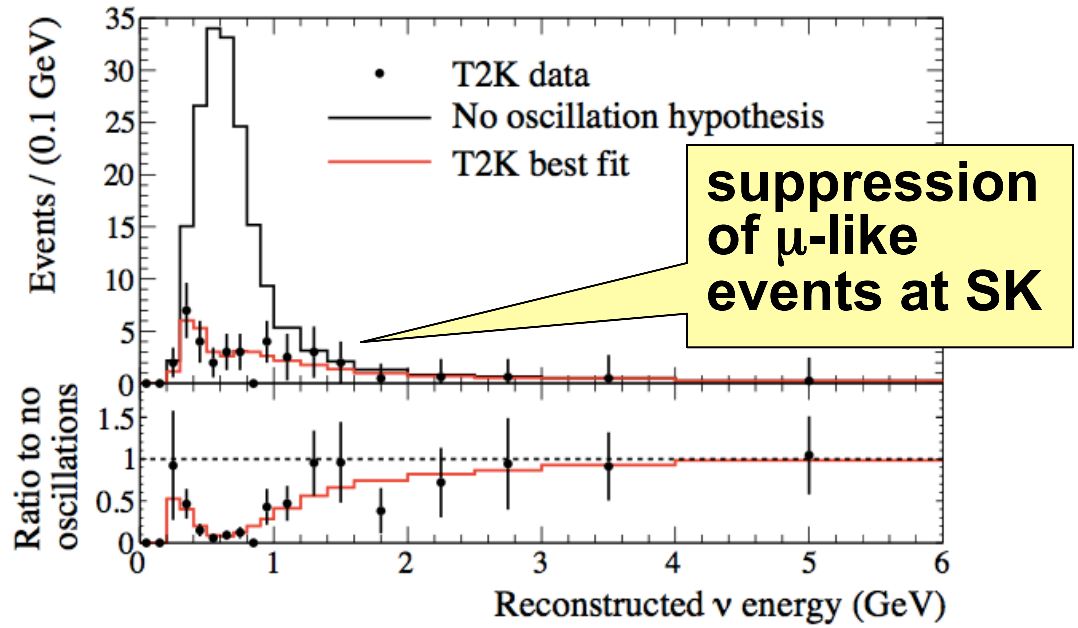
suppression of μ-like events at iron-tracker far detector

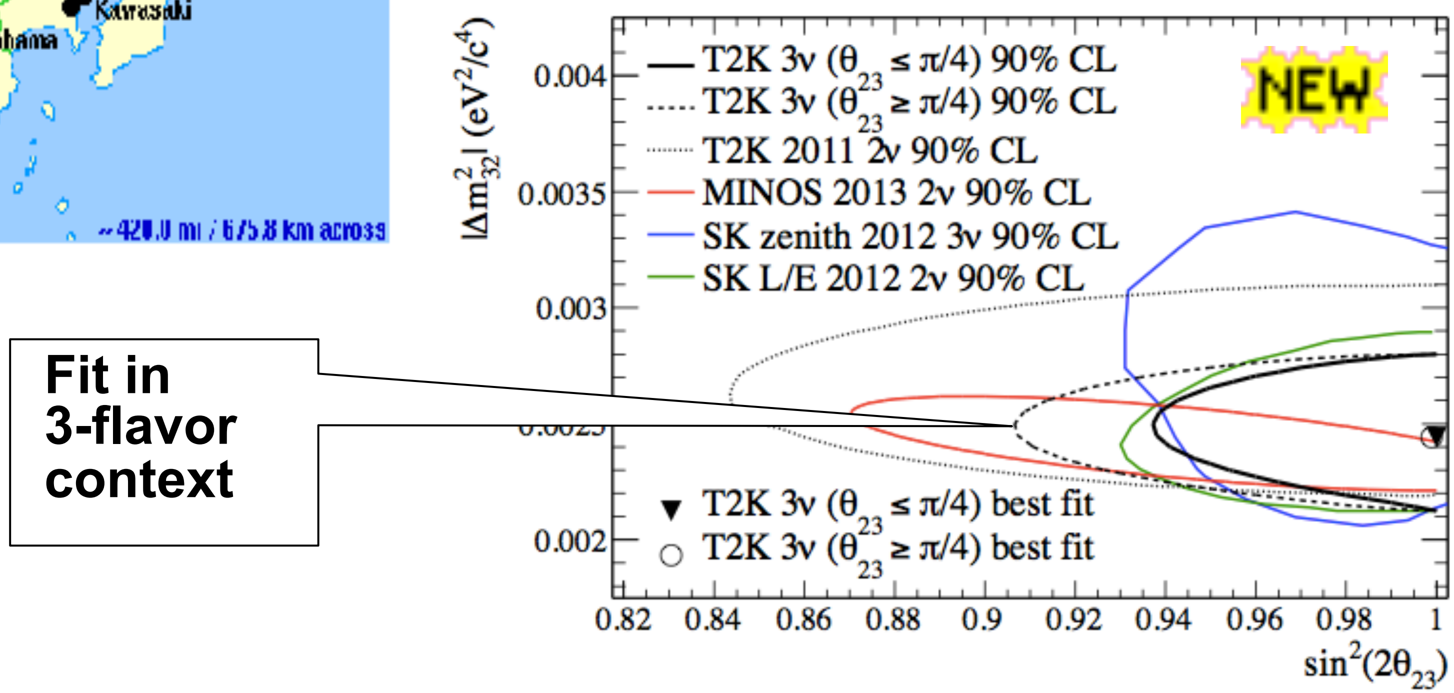




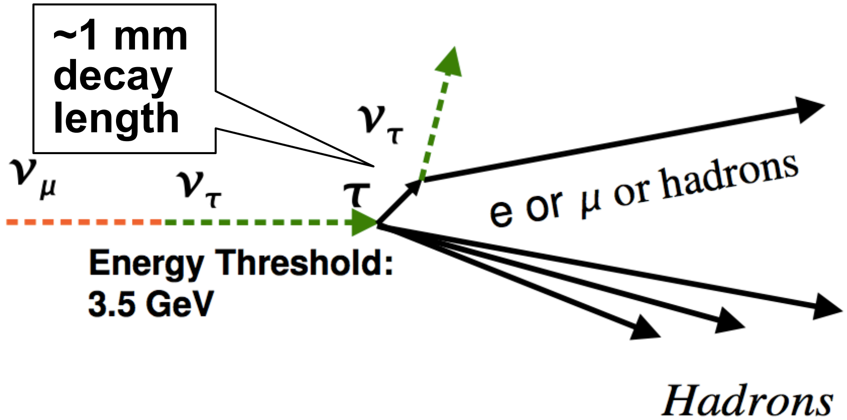
Squeezing down $|\Delta m^2_{23}|$!

And new ν_μ disappearance results from T2K



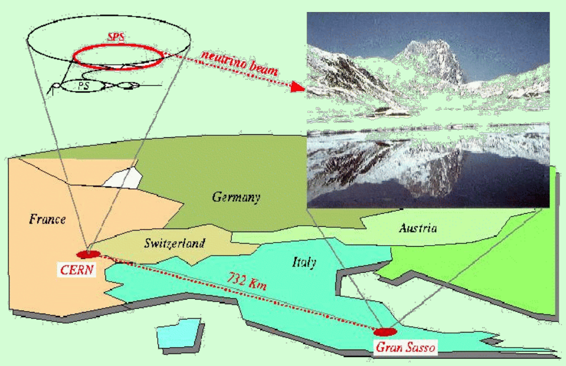


Is the disappearance $\nu_\mu \rightarrow \nu_\tau$?

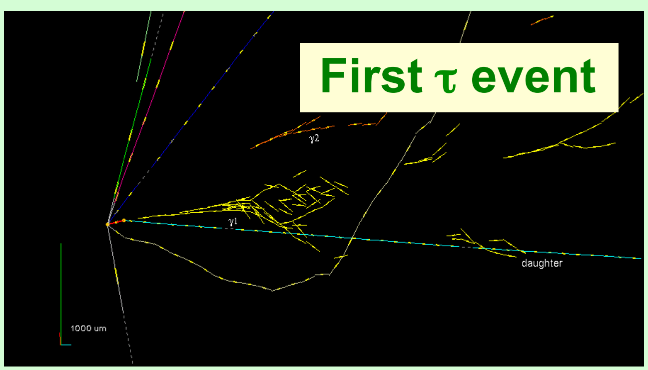


Hard to see τ's explicitly: require >3.5 GeV, multiple decay modes

OPERA @ CNGS



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

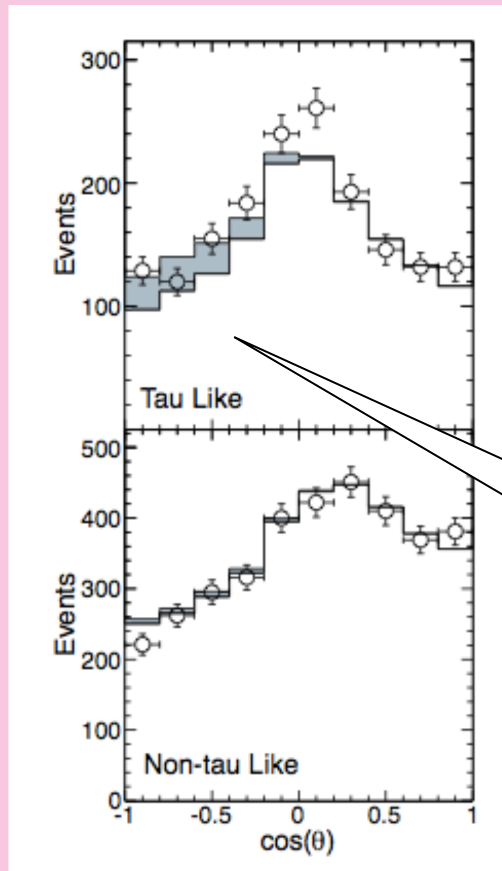


NEW

2 τ candidates, expect 0.18 ± 0.02 bg (2.4σ)

arXiv:1308.2553

Super-K atmospheric ν's



Upgoing excess of tau-like topologies

New 3.8σ appearance result

The “last” mixing angle θ_{13}:

'the twist in the middle'

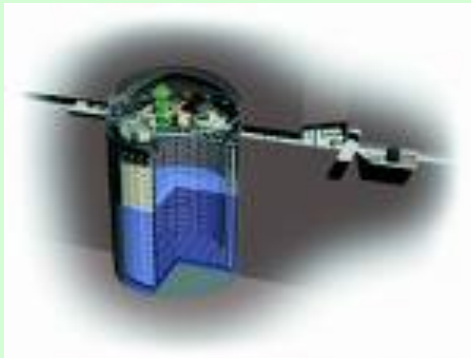
$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

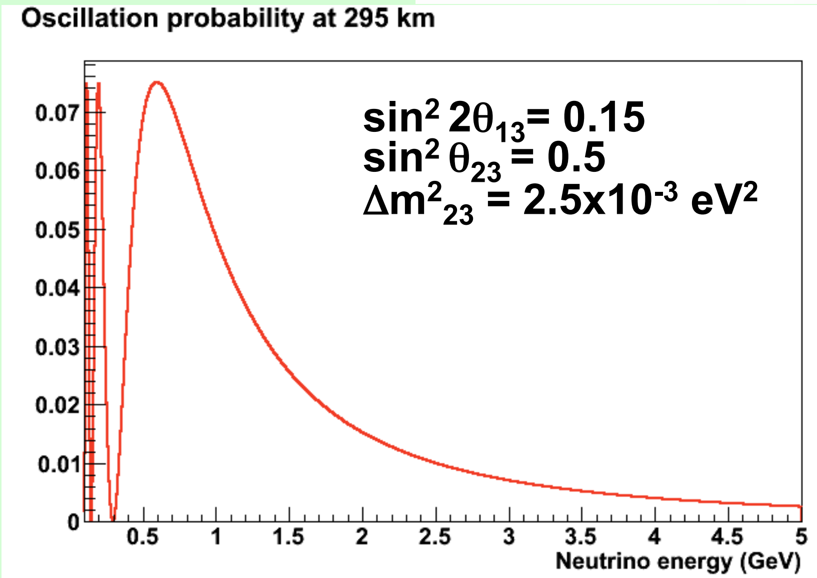
atmospheric

solar

Strategies for going after θ_{13}

Beams

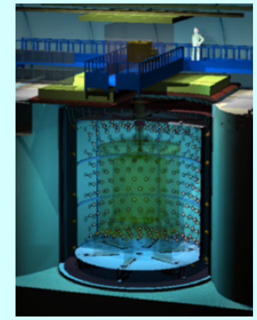


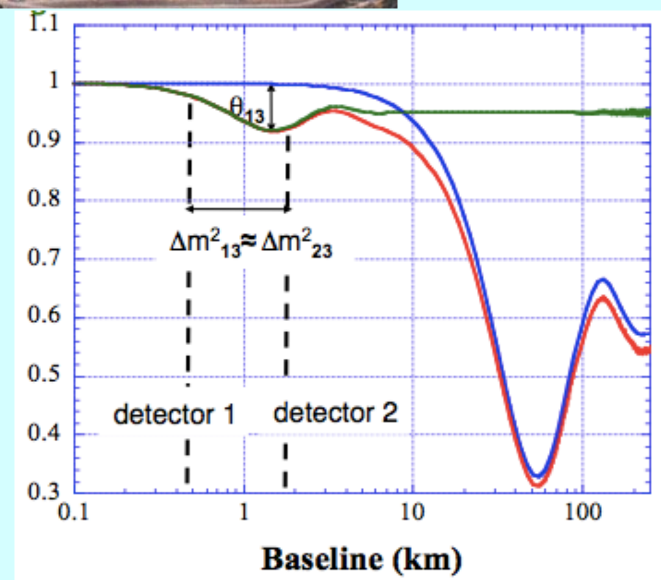


Look for *appearance* of ~GeV ν_e in ν_μ beam on ~300 km distance scale

K2K, MINOS, T2K, NOνA

Reactors





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

CHOOZ, Double Chooz, Daya Bay, RENO

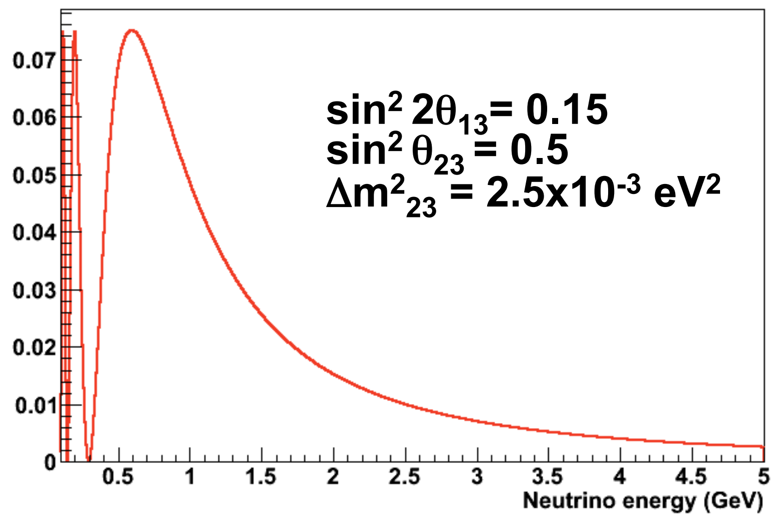
The long-baseline beam approach:

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

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

ν_e

Oscillation probability at 295 km



atmospheric-like wiggling

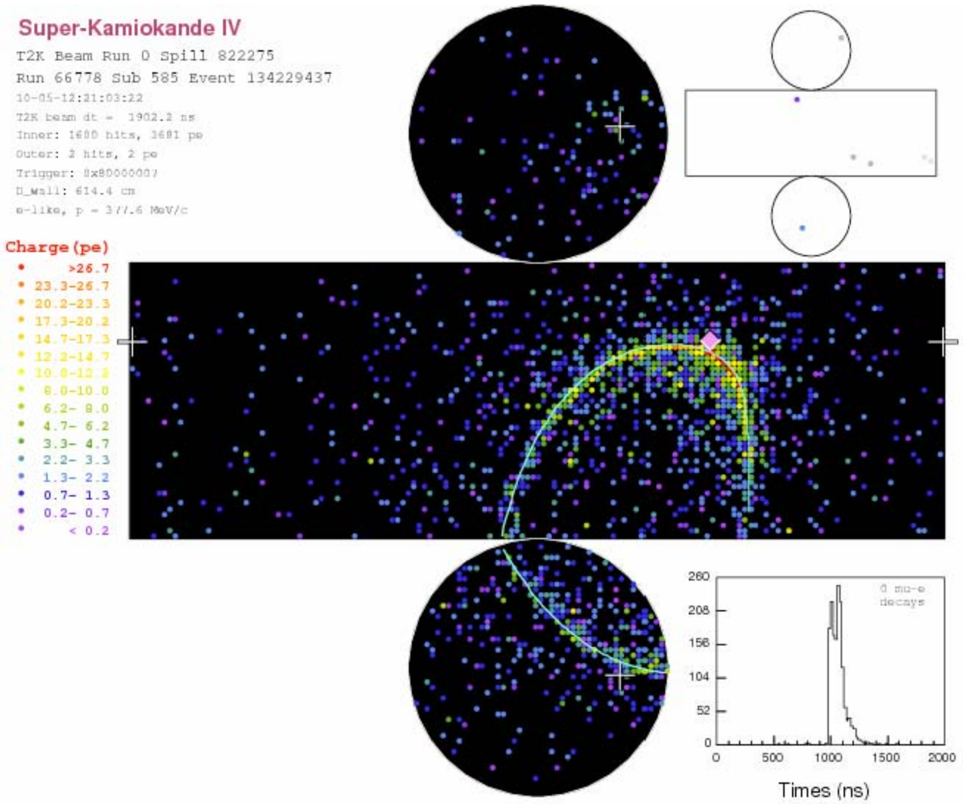
$$P(\nu_\mu \rightarrow \nu_e) = \sin^2 2\theta_{13} \sin^2 \theta_{23} \sin^2 \left(\frac{\Delta m^2_{23} L}{4E} \right)$$

small modulation **~ 1/2**

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

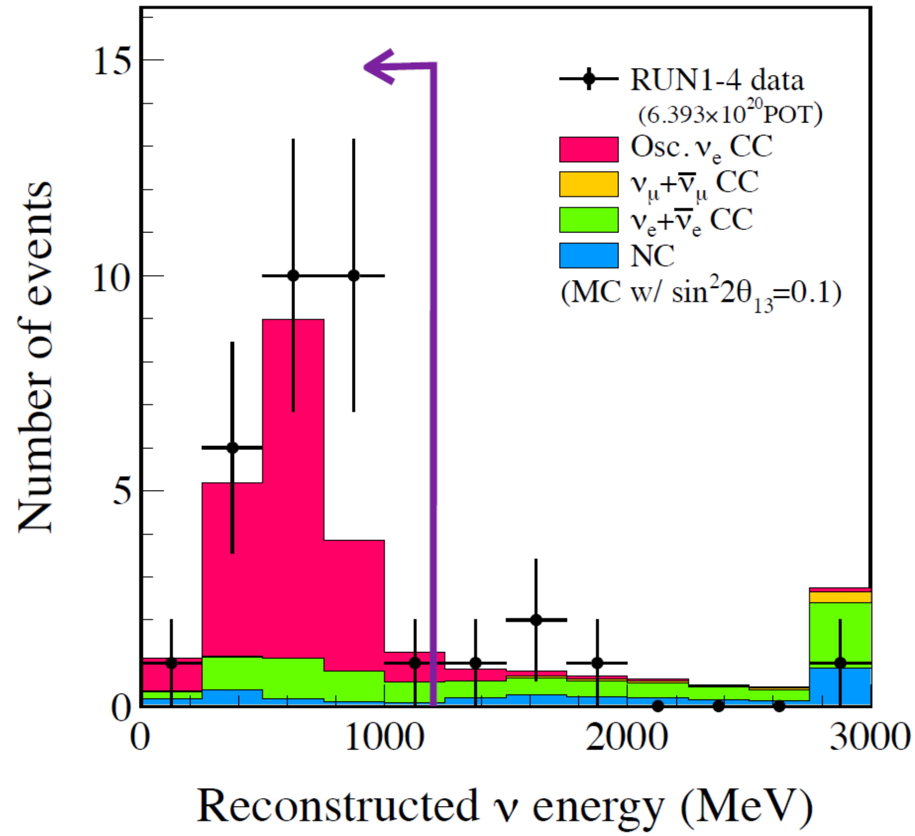
Hard to measure... known from the CHOOZ reactor experiment that it's a *small* modulation!
Need good statistics, clean sample

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



28 ν_e candidate e-like rings seen, 4.64 ± 0.52 bg expected

Reconstructed events after all ν_e cuts



NEW

T2K allowed region in $\sin^2 2\theta_{13}$ and CP δ

Best fit w/ 68% C.L. error @ $\delta_{CP}=0$

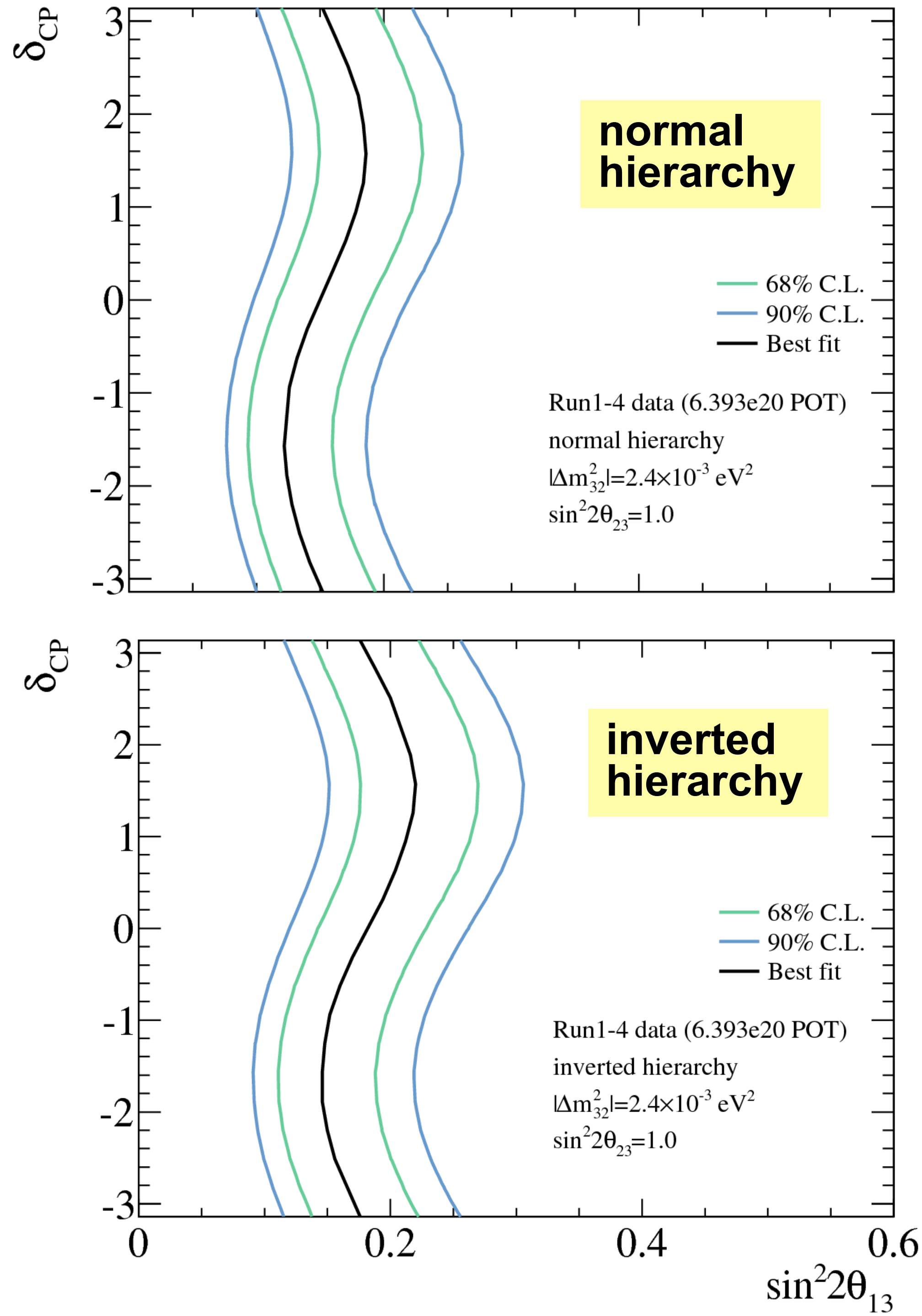
normal hierarchy

$$\sin^2 2\theta_{13} = 0.150^{+0.039}_{-0.034}$$

inverted hierarchy:

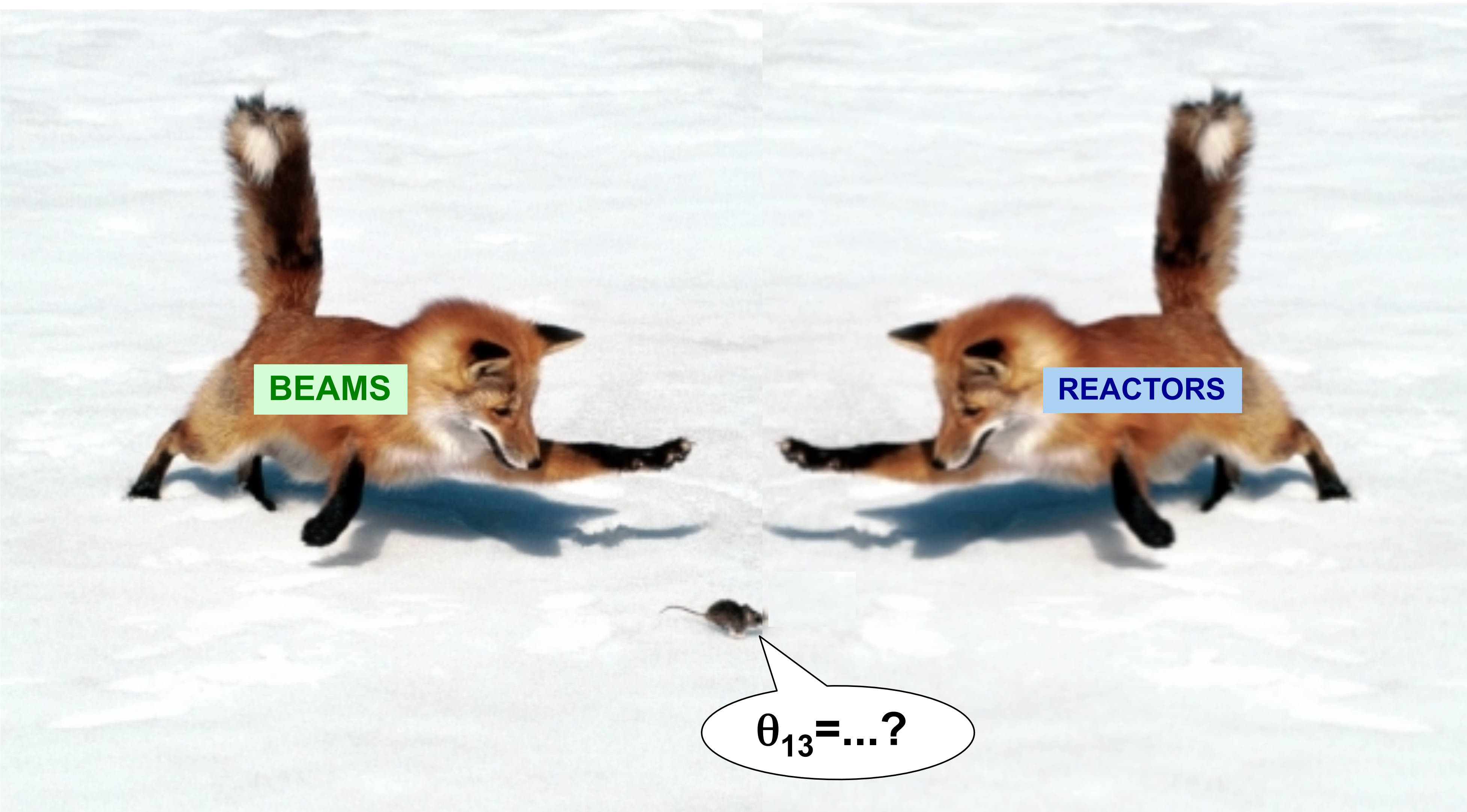
$$\sin^2 2\theta_{13} = 0.182^{+0.046}_{-0.040}$$

Assuming
$|\Delta m^2_{32}|=2.4\times10^{-3}$ eV^2
$\sin^2 2\theta_{23}=1.0$

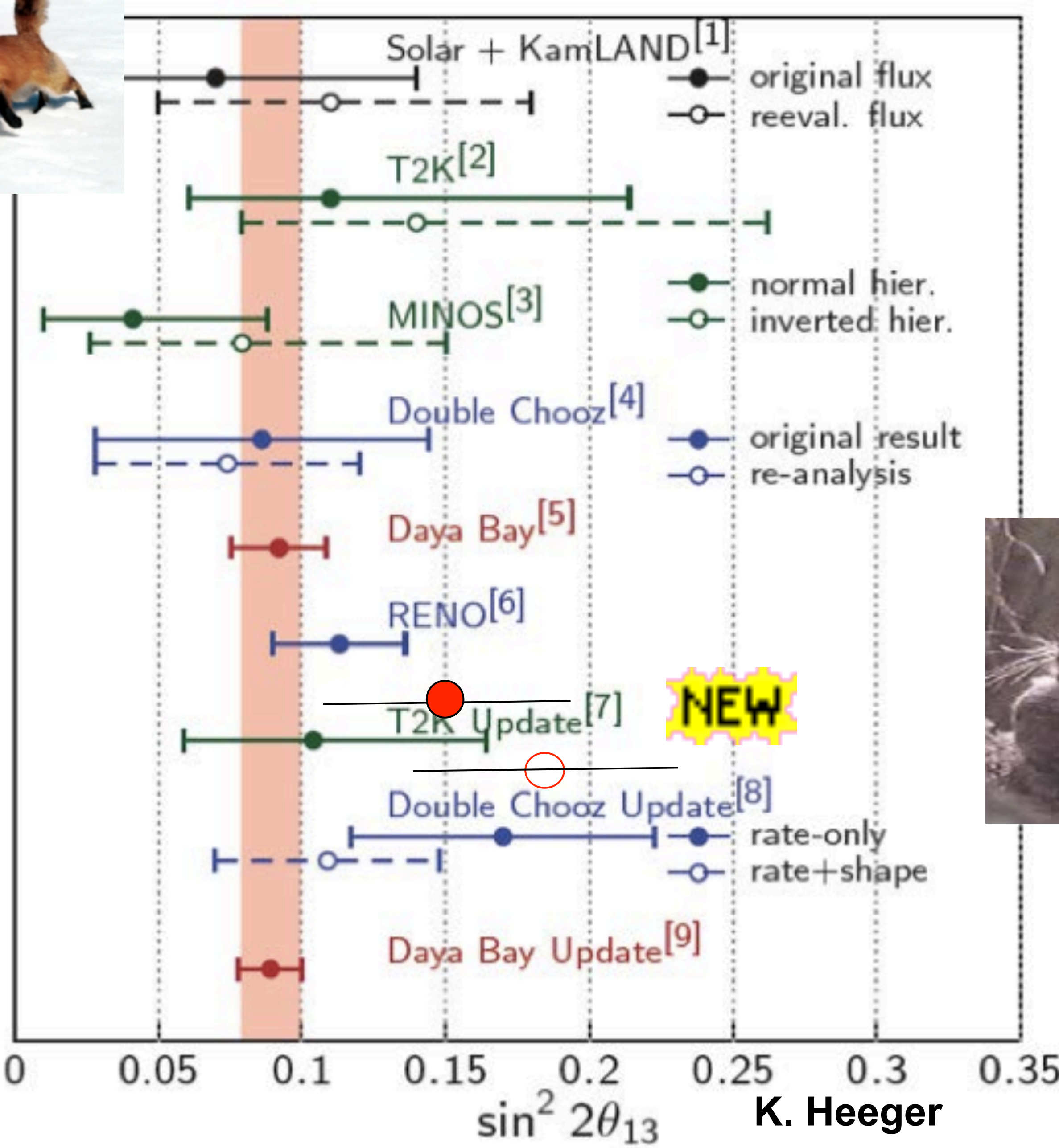


A slide from December 2011:

We're closing in on the answer...



We now know that θ_{13} is large!



K. Heeger

The three-flavor picture fits well

Global three-flavor fits to all data

	Free Fluxes + RSBL		3σ knowledge
	bfp $\pm 1\sigma$	3σ range	
$\sin^2\theta_{12}$	$0.302^{+0.013}_{-0.012}$	$0.267 \to 0.344$	~14%
$\theta_{12}/^\circ$	$33.36^{+0.81}_{-0.78}$	$31.09 \to 35.89$	
$\sin^2\theta_{23}$	$0.413^{+0.037}_{-0.025} \oplus 0.594^{+0.021}_{-0.022}$	$0.342 \to 0.667$	~42%
$\theta_{23}/^\circ$	$40.0^{+2.1}_{-1.5} \oplus 50.4^{+1.3}_{-1.3}$	$35.8 \to 54.8$	
$\sin^2\theta_{13}$	$0.0227^{+0.0023}_{-0.0024}$	$0.0156 \to 0.0299$	~32%
$\theta_{13}/^\circ$	$8.66^{+0.44}_{-0.46}$	$7.19 \to 9.96$	
$\delta_{CP}/^\circ$	300^{+66}_{-138}	$0 \to 360$	~no info
$\frac{\Delta m^2_{21}}{10^{-5}\ \mathrm{eV}^2}$	$7.50^{+0.18}_{-0.19}$	$7.00 \to 8.09$	~14%
$\frac{\Delta m^2_{31}}{10^{-3}\ \mathrm{eV}^2}$ (N)	$+2.473^{+0.070}_{-0.067}$	$+2.276 \to +2.695$	~17%
$\frac{\Delta m^2_{32}}{10^{-3}\ \mathrm{eV}^2}$ (I)	$-2.427^{+0.042}_{-0.065}$	$-2.649 \to -2.242$	

M. C. Gonzalez-Garcia, M. Maltoni, J. Salvado, T. Schwetz, 10.1007/JHEP12(2012)123

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

	Free Fluxes + RSBL	
	bfp $\pm 1\sigma$	3σ range
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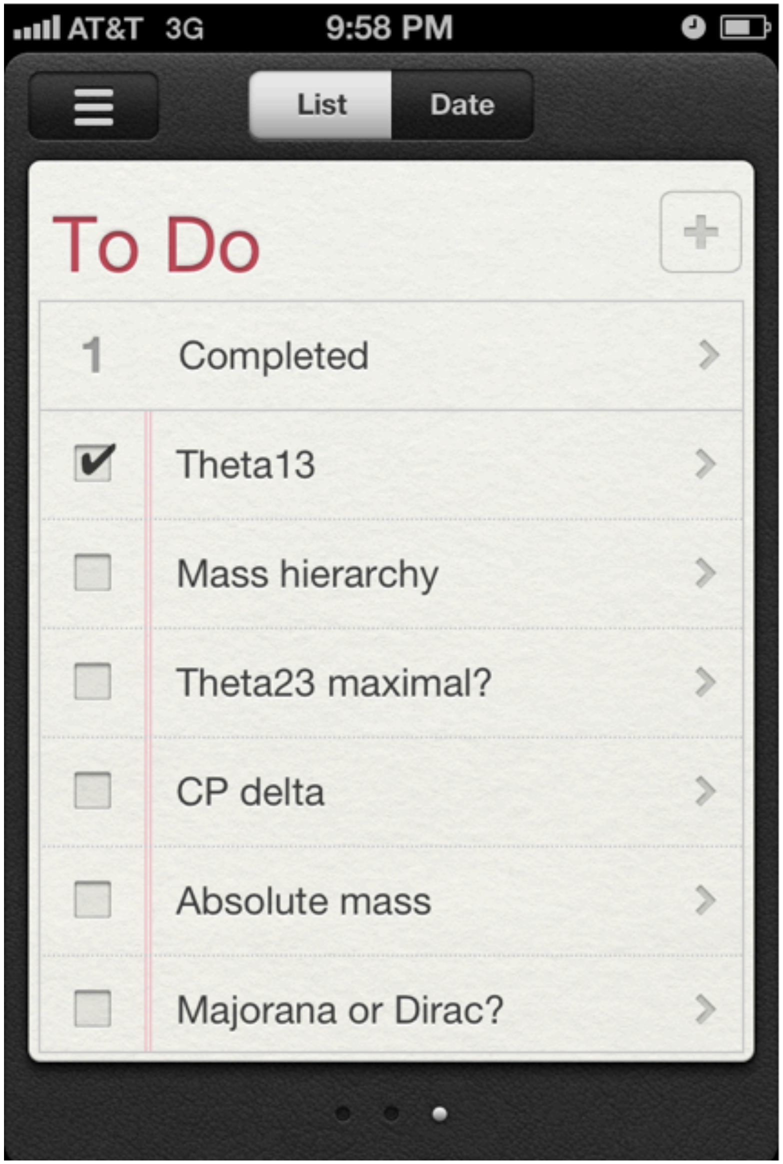
$\sin^2\theta_{23}$	$0.413^{+0.037}_{-0.025} \oplus 0.594^{+0.021}_{-0.022}$	$0.342 \to 0.667$
$\theta_{23}/^\circ$	$40.0^{+2.1}_{-1.5} \oplus 50.4^{+1.3}_{-1.3}$	$35.8 \to 54.8$
$\sin^2\theta_{13}$	$0.0227^{+0.0023}_{-0.0024}$	$0.0156 \to 0.0299$
$\theta_{13}/^\circ$	$8.66^{+0.44}_{-0.46}$	$7.19 \to 9.96$
$\delta_{CP}/^\circ$	300^{+66}_{-138}	$0 \to 360$
$\frac{\Delta m^2_{21}}{10^{-5}\ \text{eV}^2}$	$7.50^{+0.18}_{-0.19}$	$7.00 \to 8.09$
$\frac{\Delta m^2_{31}}{10^{-3}\ \text{eV}^2}$ (N)	$+2.473^{+0.070}_{-0.067}$	$+2.276 \to +2.695$
$\frac{\Delta m^2_{32}}{10^{-3}\ \text{eV}^2}$ (I)	$-2.427^{+0.042}_{-0.065}$	$-2.649 \to -2.242$

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

basically unknown

sign of Δm^2 unknown (ordering of masses)

Why do we care about these parameters?
Is it just a checklist?
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?

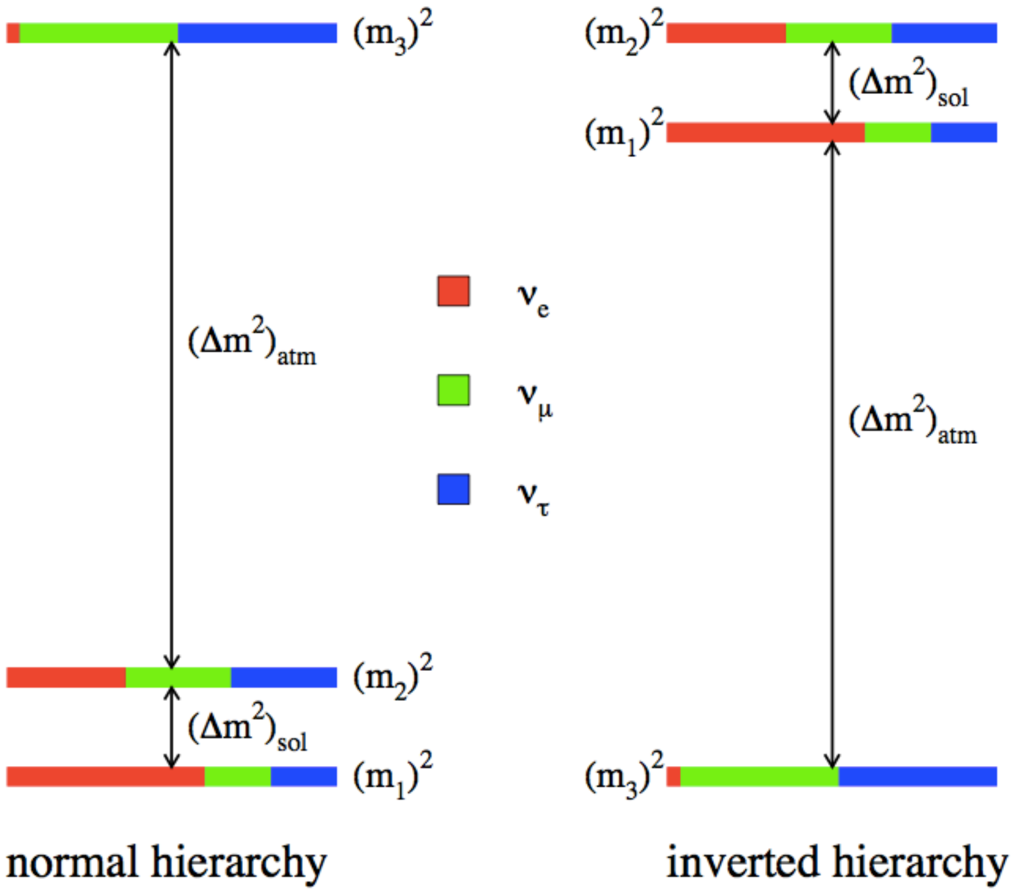
But what it's really about is
testing the paradigm**...**

We need not only to fill in the missing parameters,
but make precision measurements of *all* the parameters

Next on the list to go after experimentally:

mass hierarchy

(sign of Δm^2_{32})



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

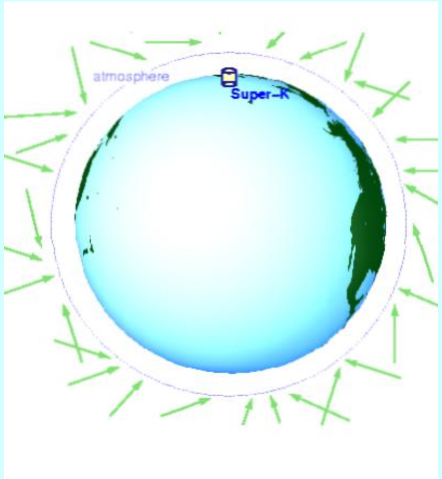
There are many ways to measure the mass hierarchy

They are all challenging...

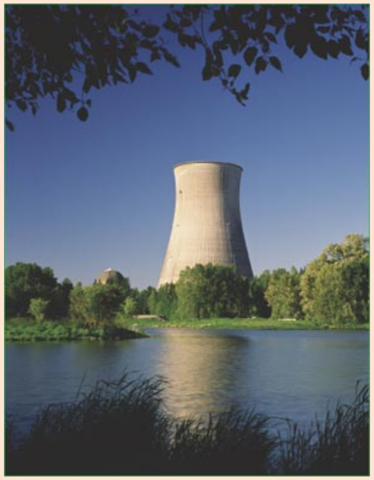
Four of the possible ways to get MH

Long-baseline beams

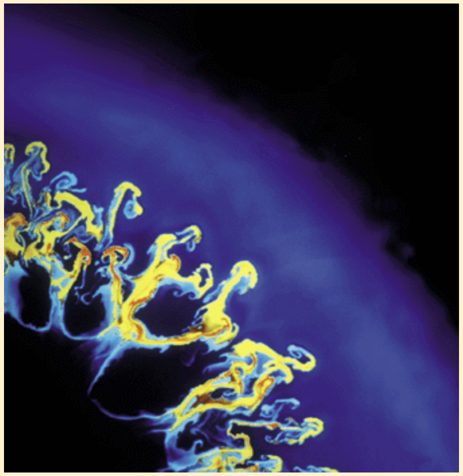
Atmospheric neutrinos



Reactors



Supernovae



Long-baseline beams

Other methods
(PINGU, JUNO, supernova, cosmology...)
are very promising,
but the long-baseline method
is the only one that's *guaranteed* with
sufficient exposure at long baseline

Determining the MH with long-baseline beams

The basic strategy

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)

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

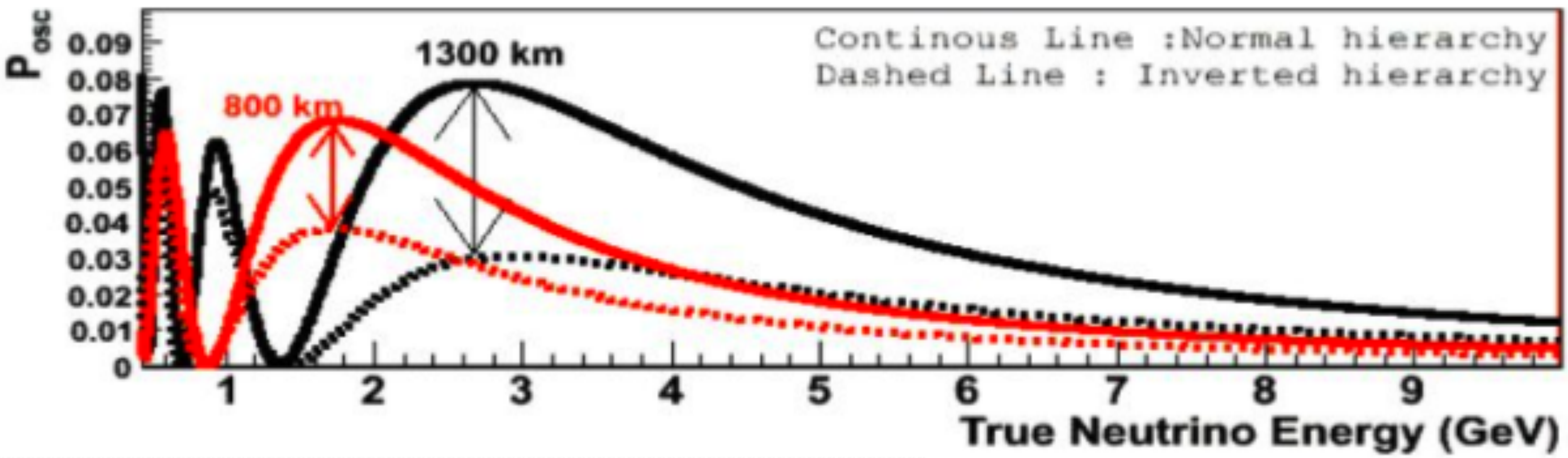
$\Delta_{ij} \equiv \frac{\Delta m_{ij}^2}{2E_\nu}$, $\tilde{B}_\mp \equiv |A \mp \Delta_{13}|$, $A = \sqrt{2} G_F N_e$

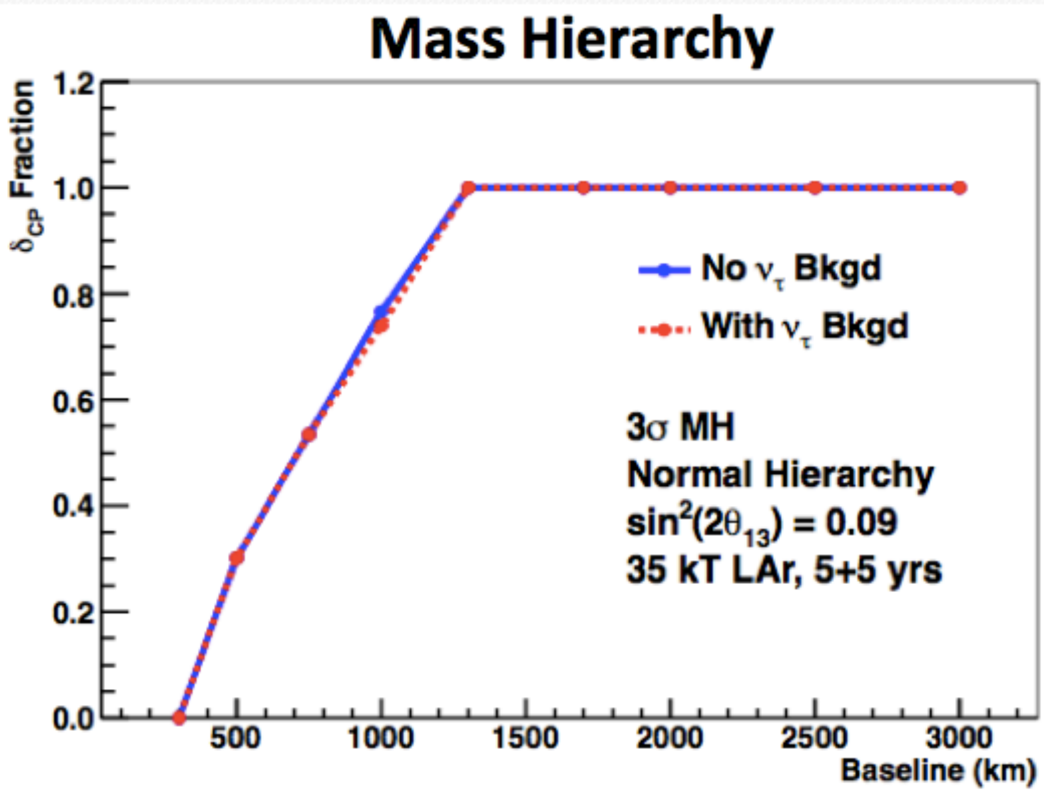
$\theta_{13}, \Delta_{12}L, \Delta_{12}/\Delta_{13}$ are small

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

- **CP δ (more later on that)**
- **matter density (Earth has electrons, not positrons)**

The baseline matters:





easier to separate MH from CP effects at long baseline

New U.S. long-baseline experiments

NOνA

14 kt scintillator
700 kW off-axis FNAL beam
810 km baseline
operations start this year

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Long-Baseline Neutrino Experiment

34 kton LArTPC in SD @ 4850 ft
1300 km baseline
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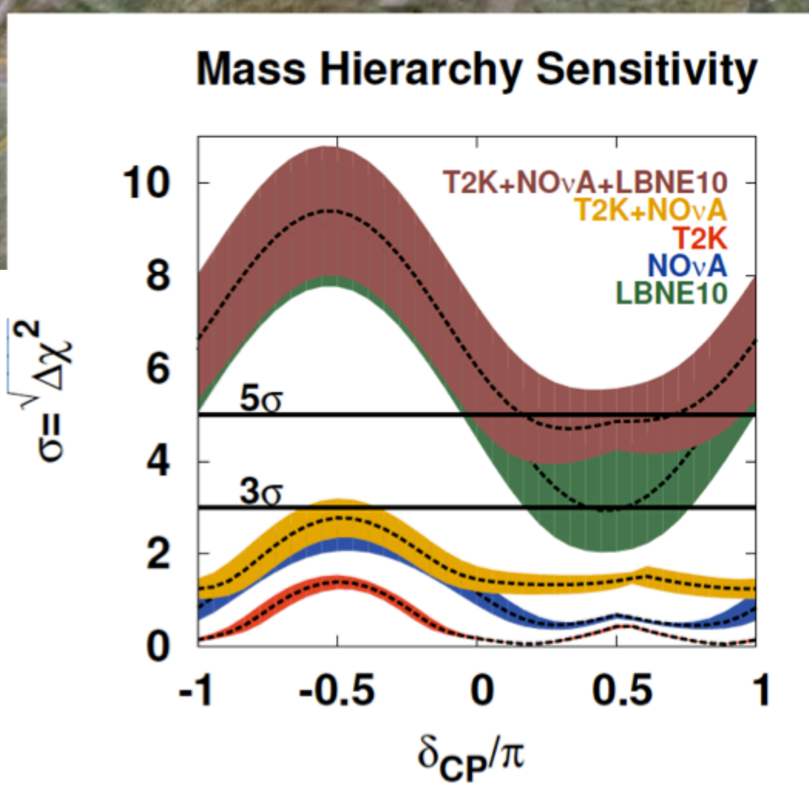

good MH reach, and
improvement with more mass
& combination w/ others

Next: CP violation

Measure transition probabilities for

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

(matter effects understood, or absent)

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

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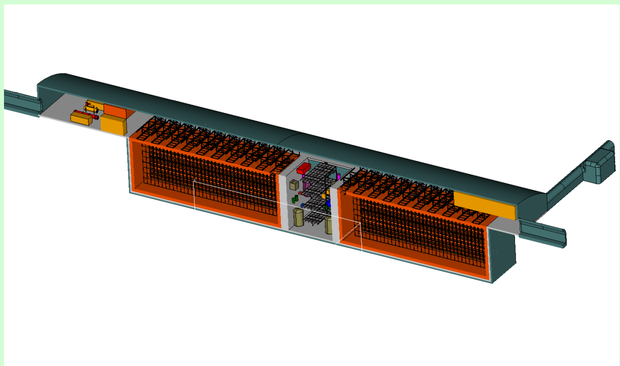
$\theta_{13}, \Delta_{12}L, \Delta_{12}/\Delta_{13}$ are small

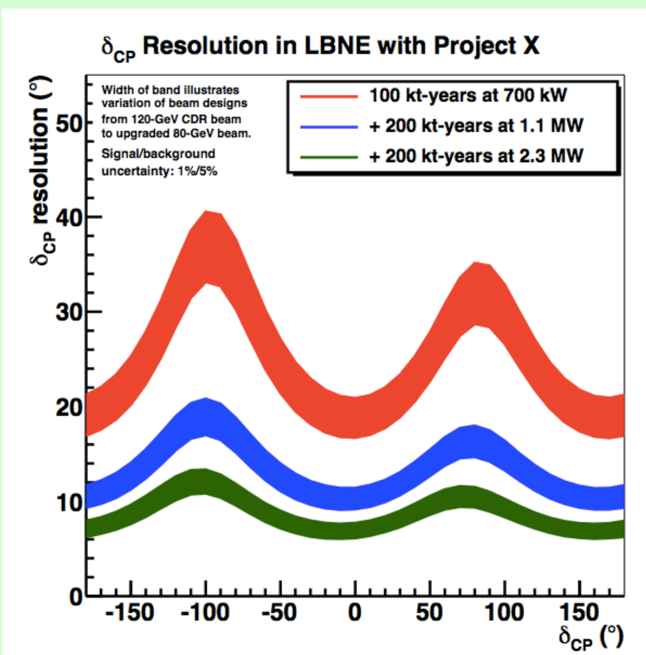
A. Cervera et al., Nuclear Physics B 579 (2000)

The Next Generation of CP Searches

LBNE (U.S.)

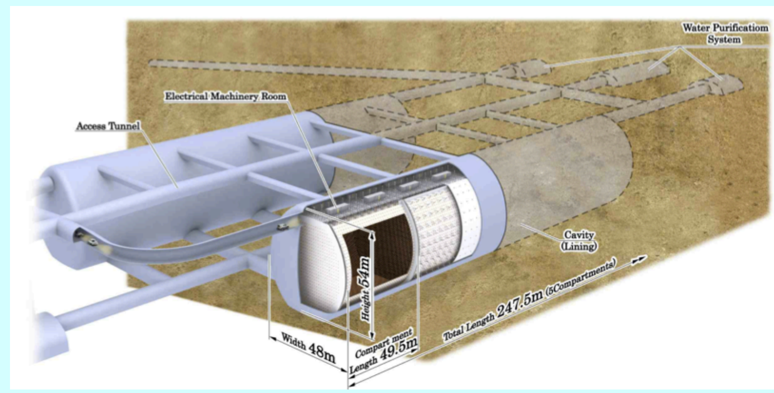
new FNAL 700 kW beam + eventual PX (1300 km)

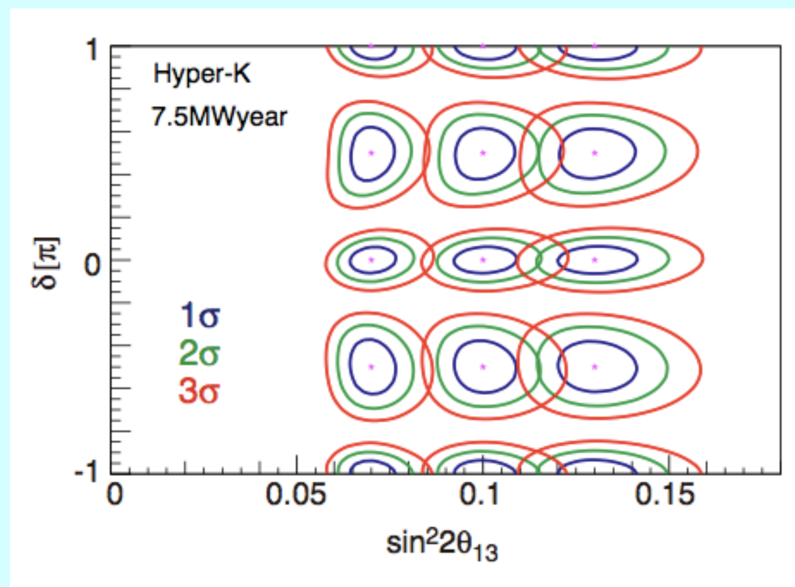




Hyper-K (Japan)

upgraded T2K beam from J-PARC (300 km), 560 kton water Cherenkov





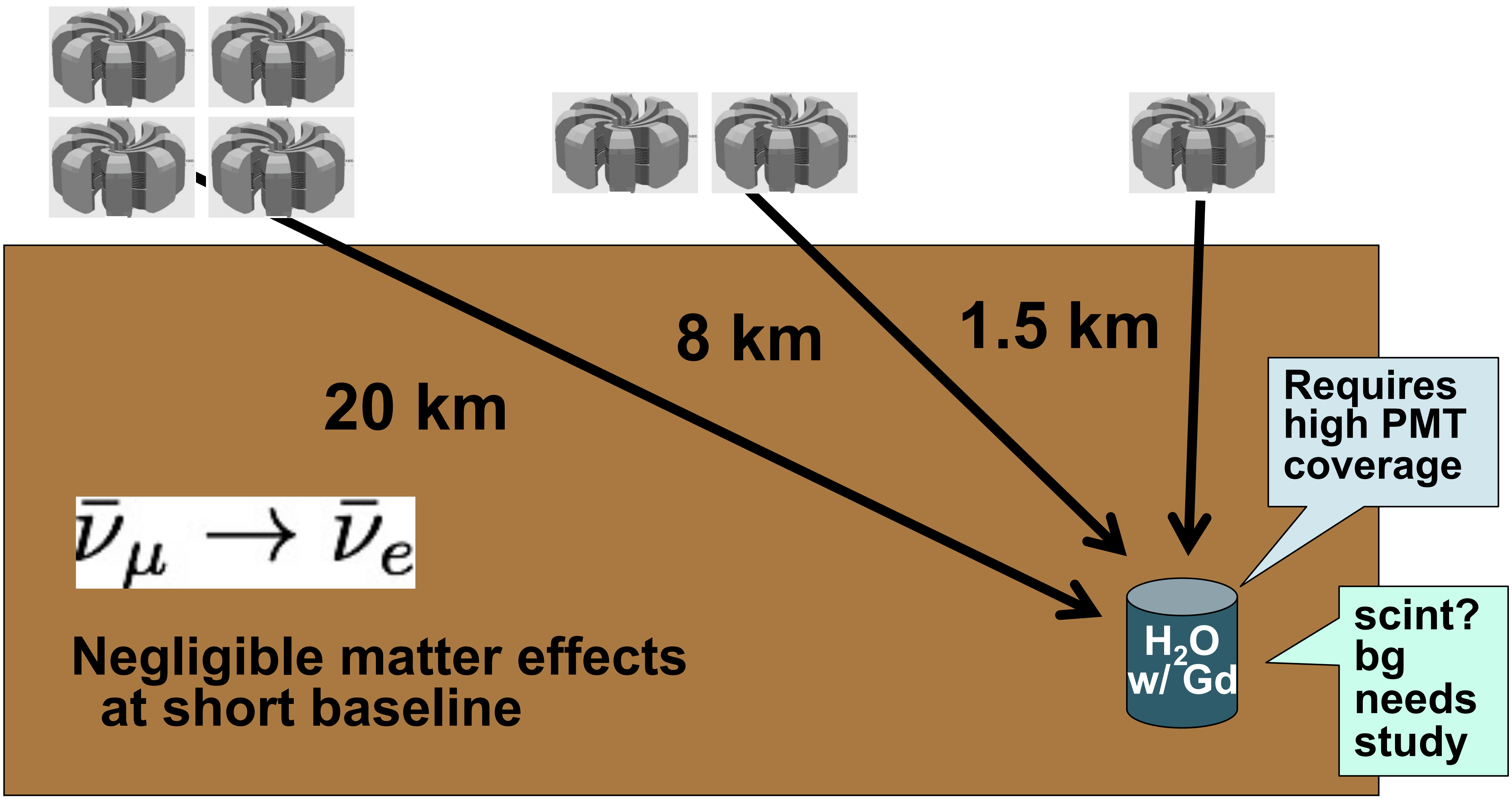
A different approach for ν CPV: DAEδALUS

Multiple stopped-pion neutrino sources:

L ~1.5-20 km

E ~10-50 MeV

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



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

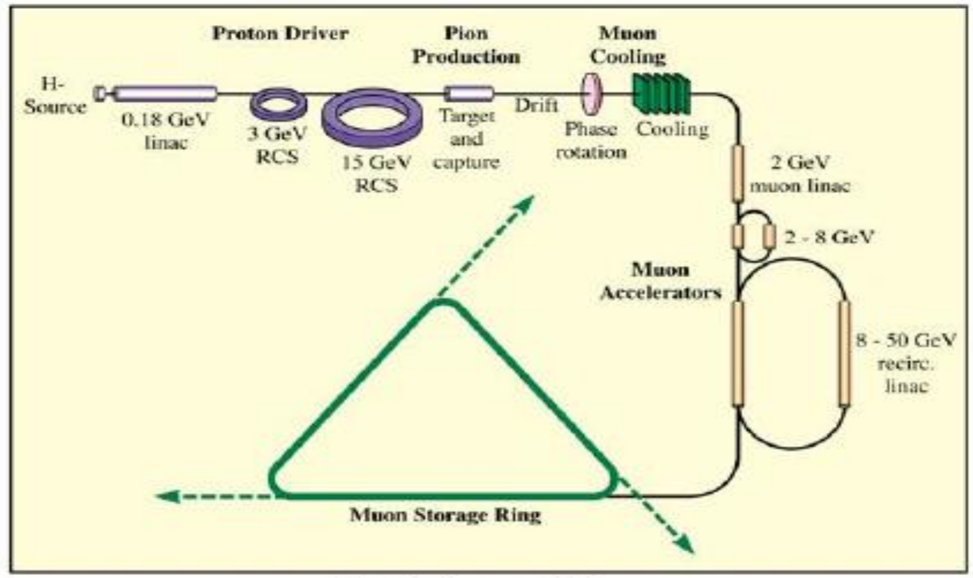
And thinking further ahead:

eventually limited by systematics... need well-understood beams

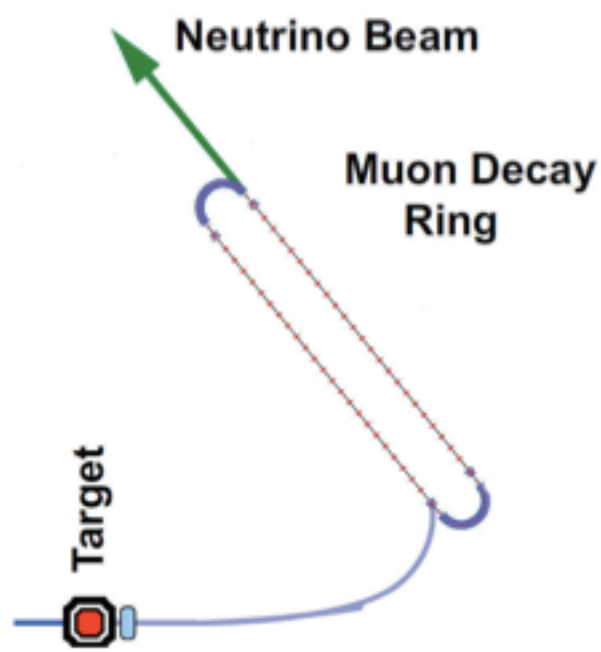
Neutrino factories

storage ring of
muons decaying
to neutrinos

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



Neutrino Factory at RAL

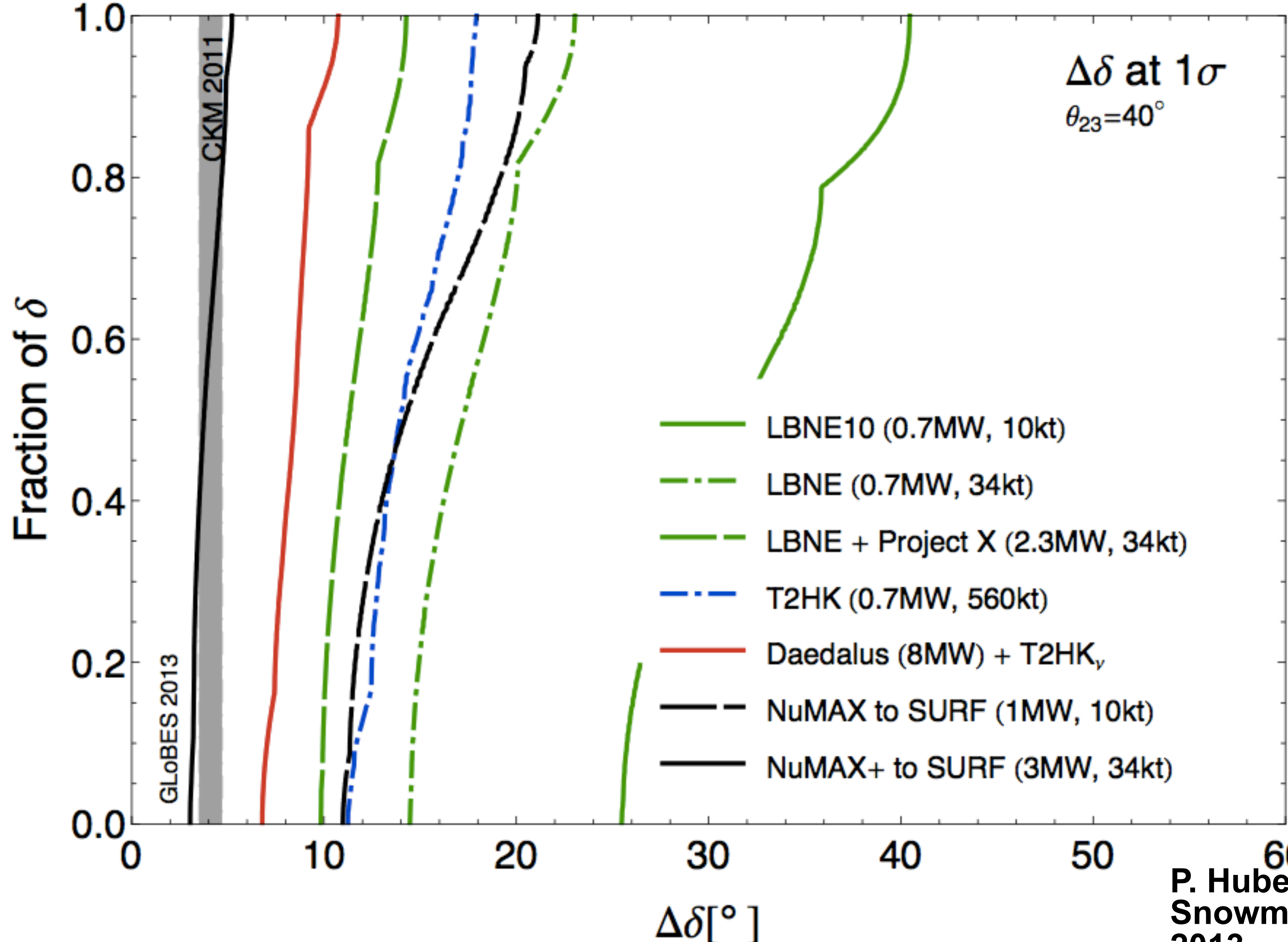


NuStorm:

a possible first phase

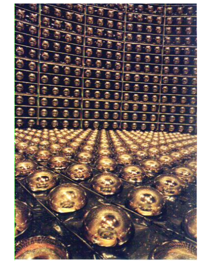
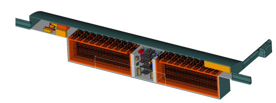
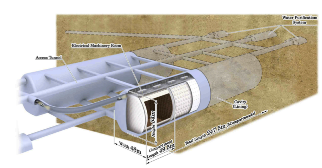
arXiv:1206.0294

Long-term CP reach



P. Huber, Snowmass 2013

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*	 
CPV	ν & anti-ν oscillation	**Long-baseline beams; cyclotron-based beams; neutrino factories**	

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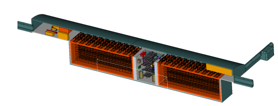
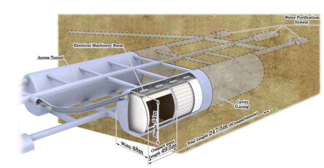
Mass hierarchy	Matter-induced ν/ anti-ν asymmetry; anti-ν_e oscillation pattern; (cosmology, 0nbbdk,...)	**Long-baseline beams;** reactor experiments; atmospheric neutrinos*	 
CPV	ν & anti-ν oscillation	**Long-baseline beams; cyclotron-based beams; neutrino factories**	

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Observable	**Signature**	**Next steps**	
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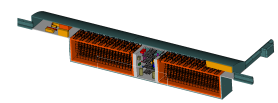
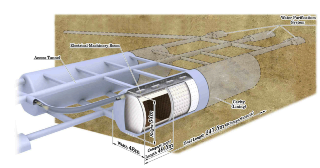
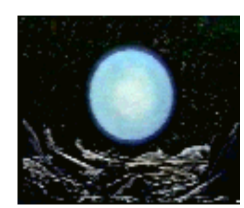
Mass hierarchy	Matter-induced ν/ anti-ν asymmetry; anti-ν_e oscillation pattern; (cosmology, 0nbbdk,...)	**Long-baseline beams;** reactor experiments; atmospheric neutrinos*	 
CPV	ν & anti-ν oscillation	**Long-baseline beams; cyclotron-based beams; neutrino factories**	

*Super nova



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...

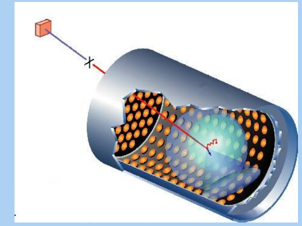
Open a parenthesis:

(

Outstanding 'anomalies'

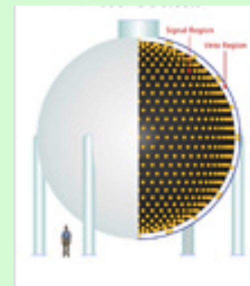
LSND @ LANL (~30 MeV, 30 m)

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 (ν,$\overline{\nu}$ ~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

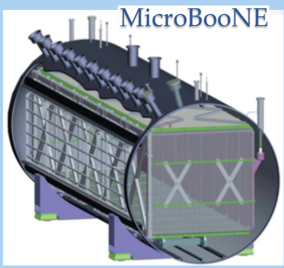
????

more data needed

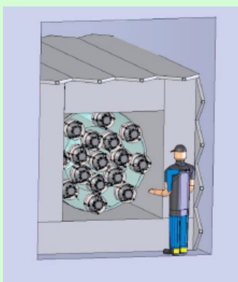
Also: possible deficits of reactor $\overline{\nu}_e$ ('reactor anomaly')
and source ν_e ('gallium anomaly')

Sterile neutrinos?? (i.e. no normal weak interactions)
Some theoretical motivations for this, both from particle physics & astrophysics. Or some other new physics??

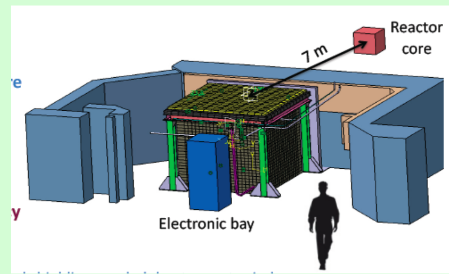
Ideas to address these anomalies...

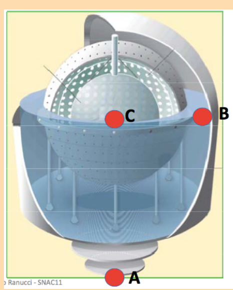


Experiments with beams (meson decay in flight and at rest)

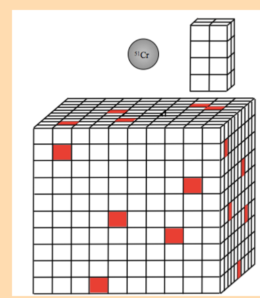


Experiments at reactors





Experiments with radioactive sources



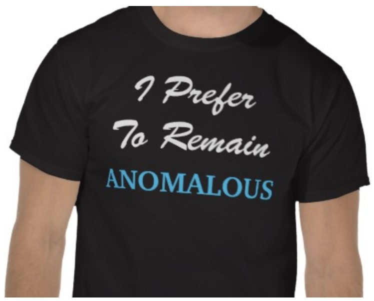
Many more! see e.g. `arXiv:1204.5379`

Parenthesis is not closed...

Possible futures

exciting new world to explore!

anomalies confirmed



fill in the 3-flavor parameters and keep pushing on the paradigm

anomalies go away

Summary

We now have a pretty robust, simple 3-flavor neutrino paradigm, describing most of the data

Still a few unknown parameters in this picture, notably MH and CP δ, but clear steps to take

- **MH: multiple approaches (all challenging but conceivable)**
- **CP δ: standard LBL approach is promising**

and plenty of long-term ideas....

➔need to push on the paradigm w/ precision measurements

Anomalies are still out there... they may or may not go away...

Extras/Backups

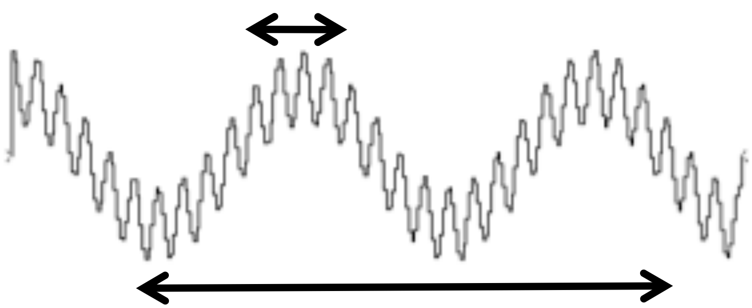
Oscillation probabilities in a 3-flavor context

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

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

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

oscillatory behavior in L and E



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

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

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

In 2-flavor approximation:

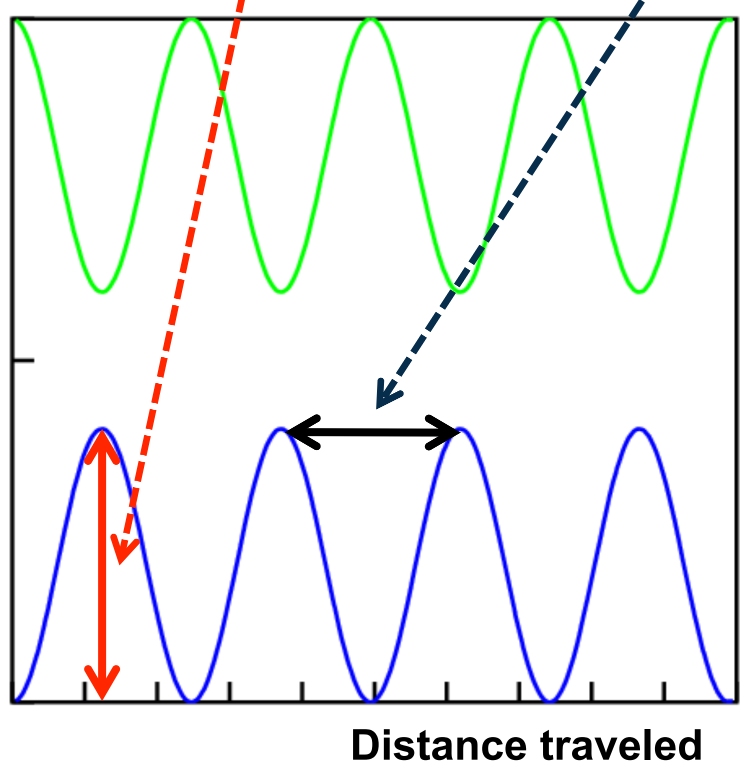
$$P(\nu_f \rightarrow \nu_g) = \sin^2 2\theta \sin^2\left(\frac{1.27\Delta m^2 L}{E}\right)$$

amplitude

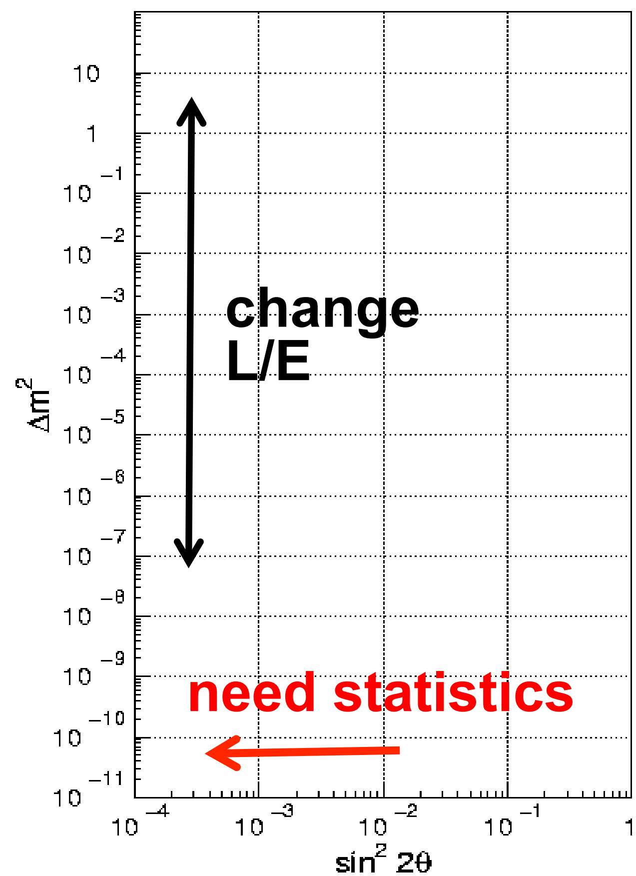
wavelength= $\pi E/(1.27\Delta m^2)$

$P(\nu_f \rightarrow \nu_f)$

$P(\nu_f \rightarrow \nu_g)$



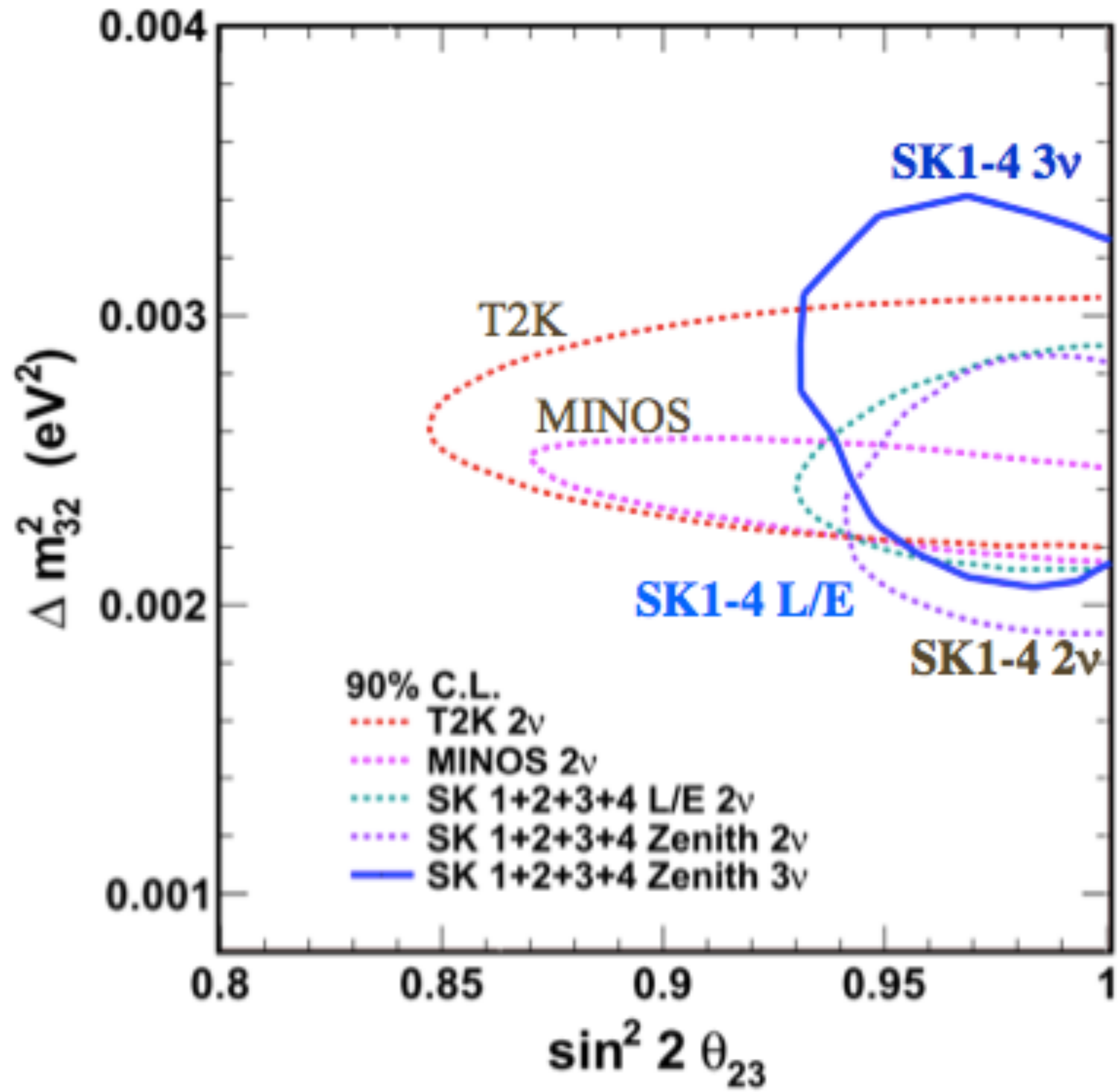
Parameter space



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

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

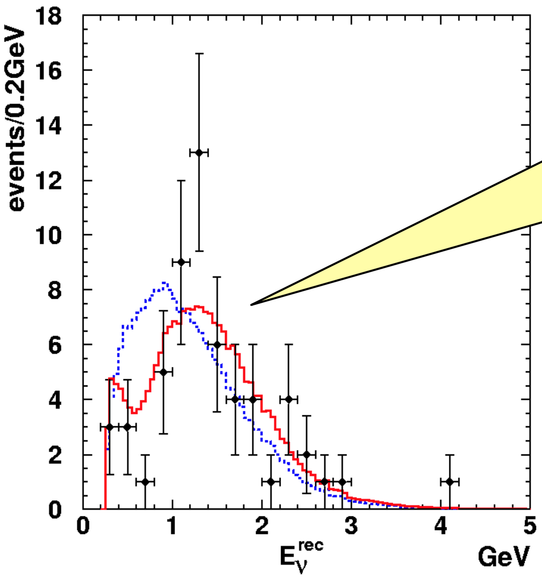
e.g. $\nu_\mu \rightarrow \nu_\tau$ at ~GeV



0.004
0.003
0.002
0.001
Δ m²₃₂ (eV²)
0.8
0.85
0.9
0.95
1
sin² 2 θ₂₃
SK1-4 3ν
T2K
MINOS
SK1-4 L/E
SK1-4 2ν
90% C.L.
T2K 2ν
MINOS 2ν
SK 1+2+3+4 L/E 2ν
SK 1+2+3+4 Zenith 2ν
SK 1+2+3+4 Zenith 3ν

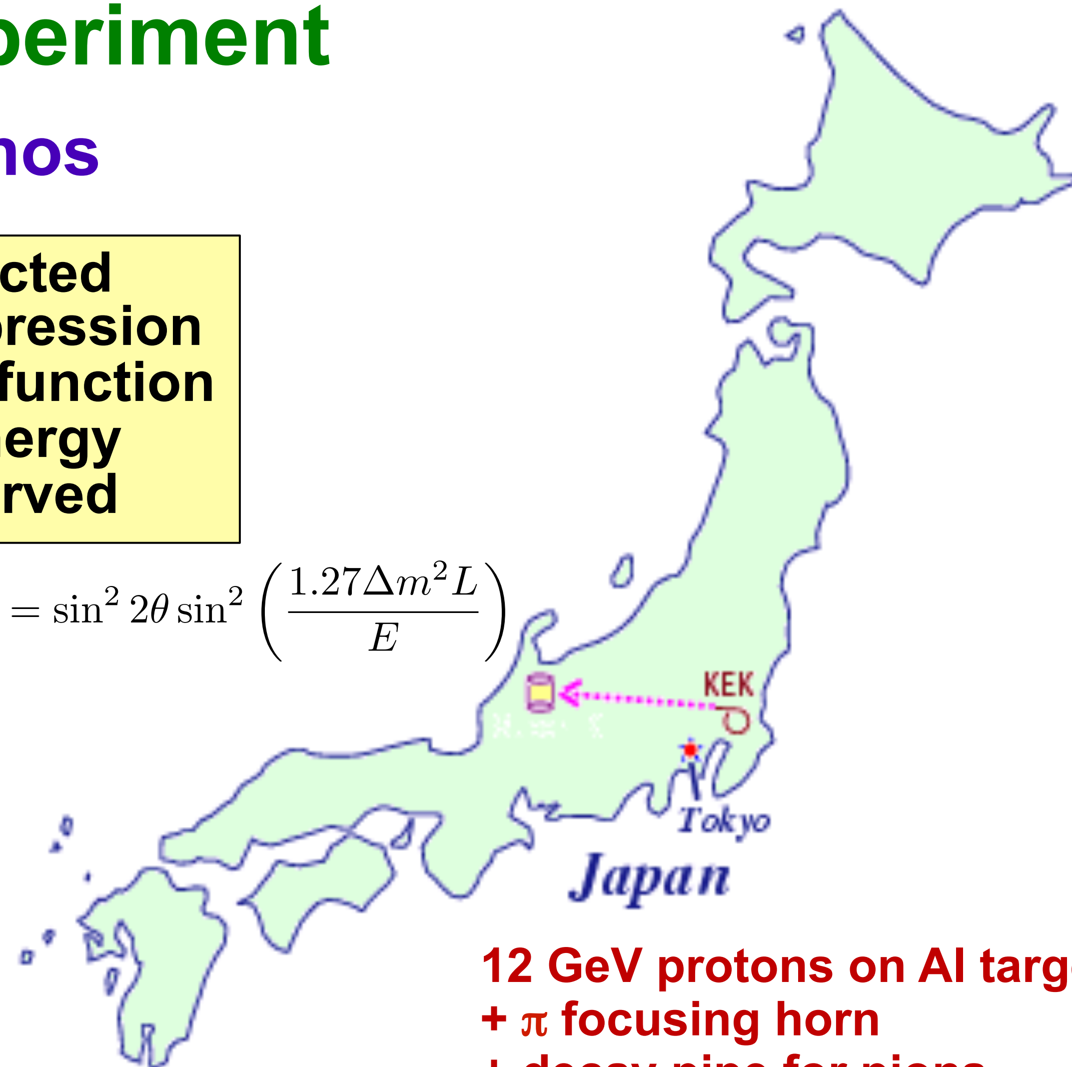
K2K (KEK to Kamioka): the first Long-Baseline Experiment

~ 1 GeV muon neutrinos



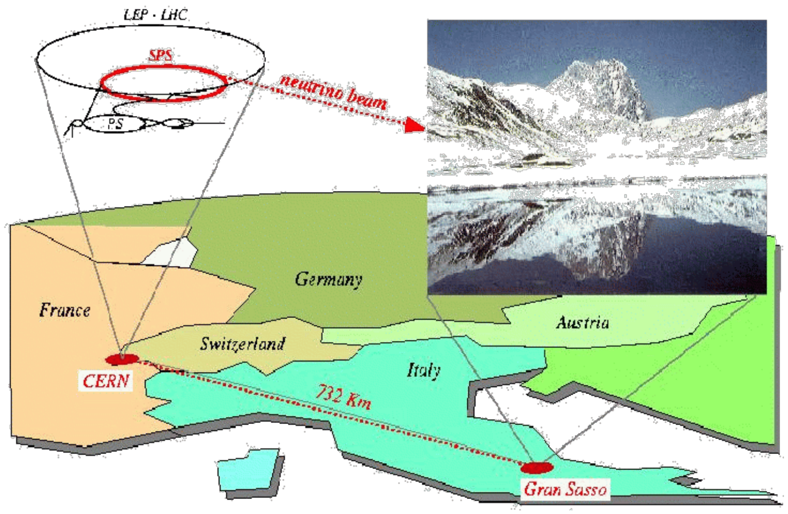
expected suppression as a function of energy observed

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



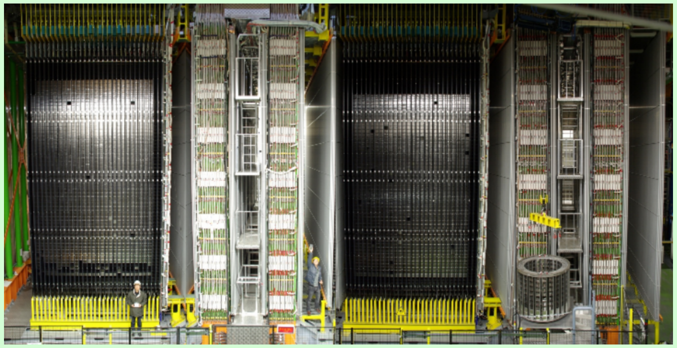
12 GeV protons on Al target
+ π focusing horn
+ decay pipe for pions

CERN Neutrinos to Gran Sasso

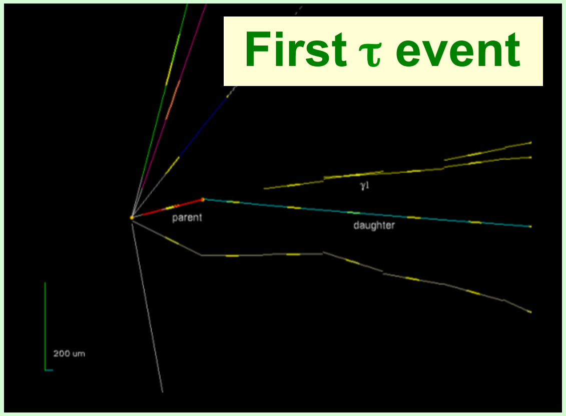


higher energy beam
(~17 GeV,
above τ threshold),
fine-grained
tracking detectors

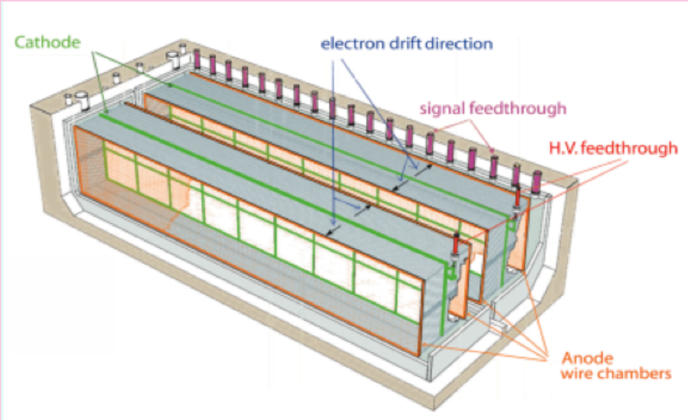
OPERA



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

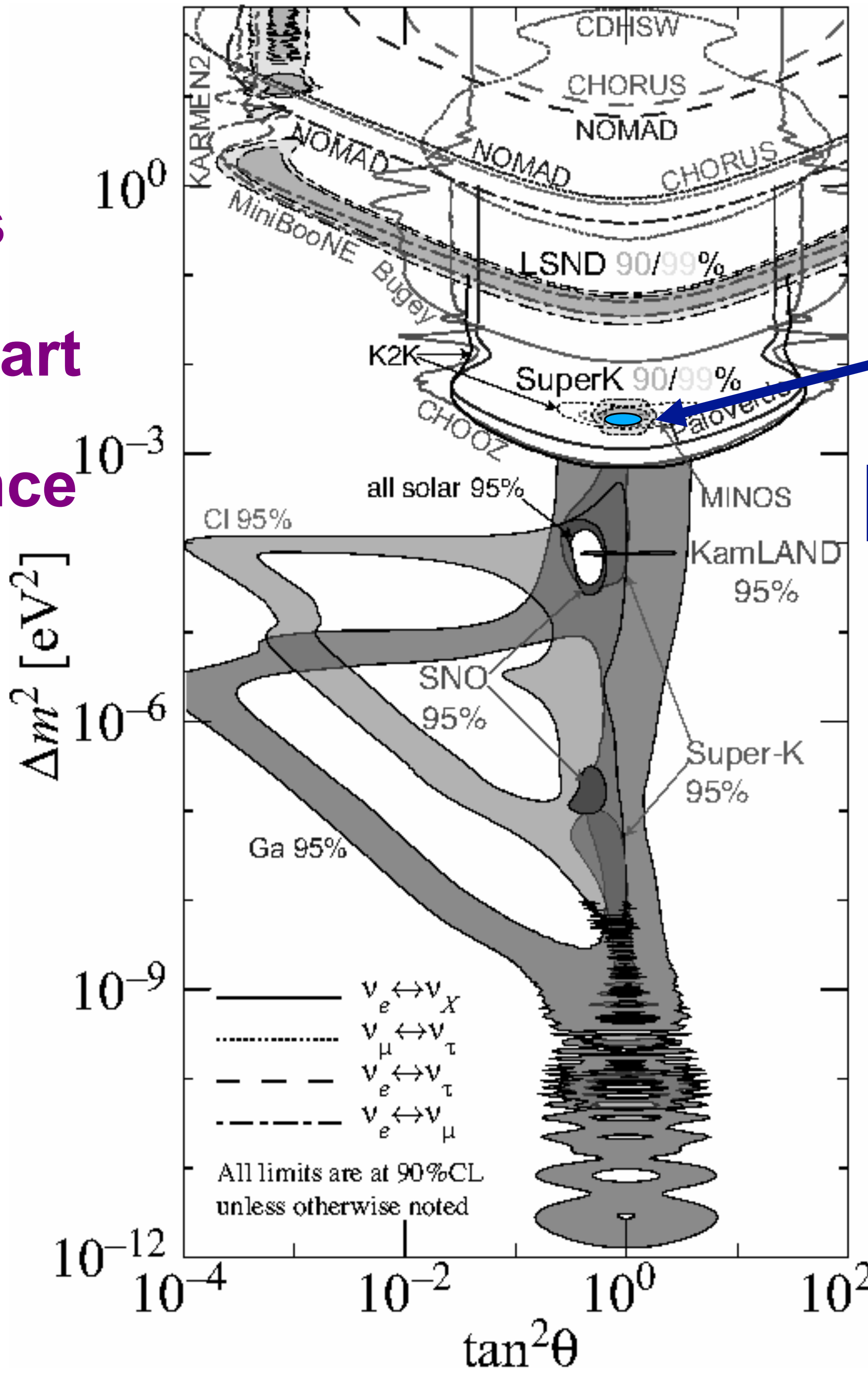


ICARUS



600 ton liquid argon TPC

Accelerator experiments are state-of-the-art for ν_μ disappearance

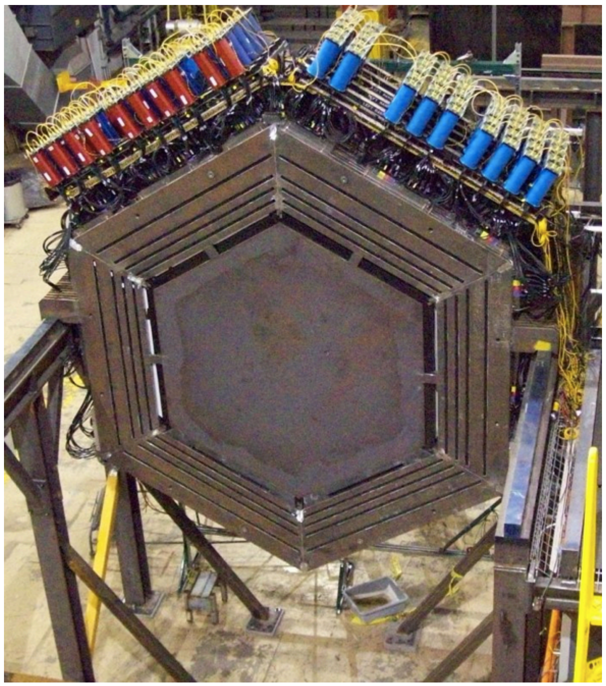


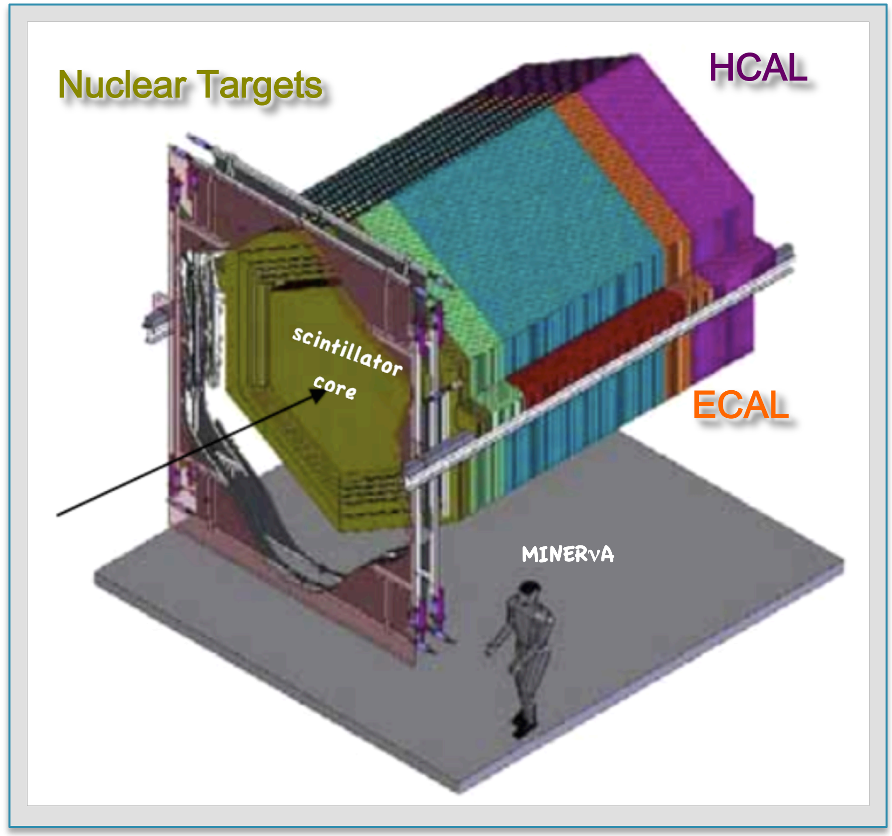
atmospheric/ beam neutrinos

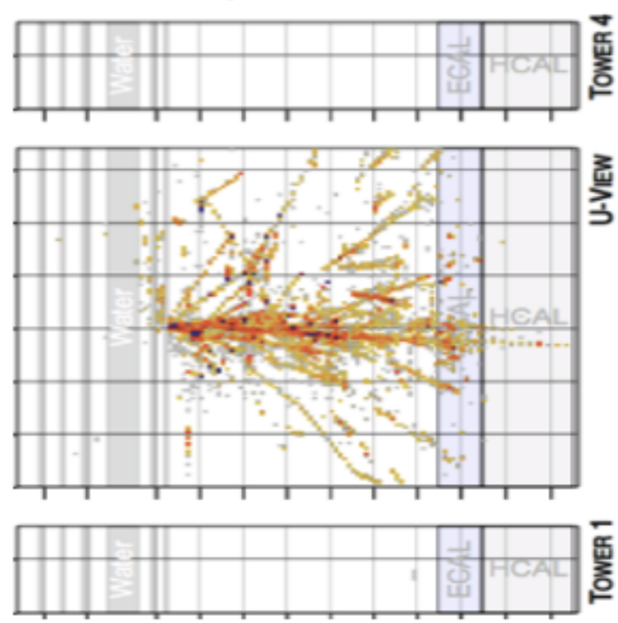
Described by θ_{23}, Δm^2_{23}

Side note: MINERνA

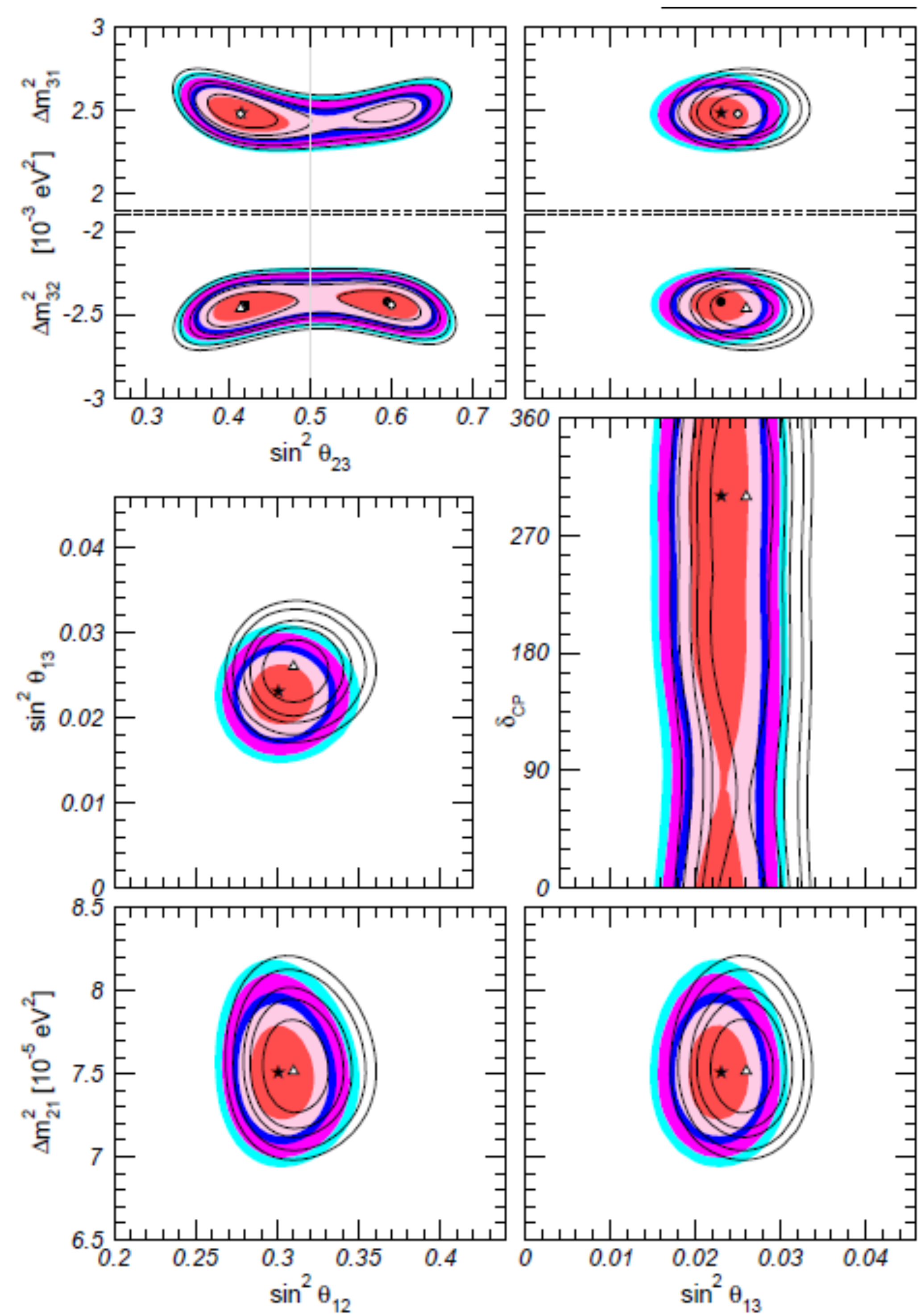
Detector at NuMI (Fermilab) to measure cross-sections of ~GeV neutrinos on nuclear targets
(finely-segmented scintillator + em& hadronic calorimeters)







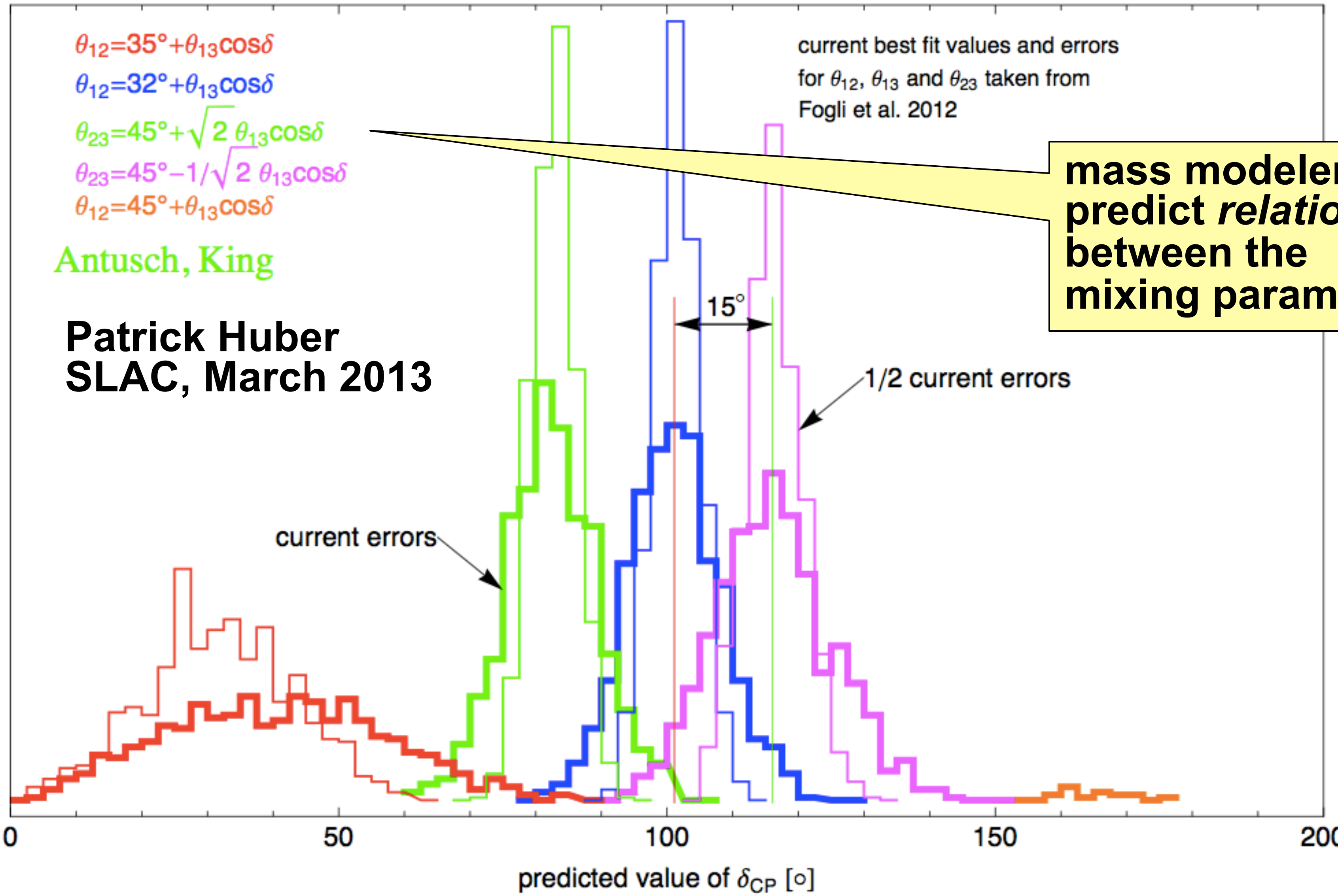
Vital to understand interactions for interpretation of long baseline oscillation experiment backgrounds & systematics!



Δm^2_{31} $[10^{-3}$ eV$^2]$ Δm^2_{32}
$\sin^2\theta_{23}$
$\sin^2\theta_{13}$
δ_{CP}
Δm^2_{21} $[10^{-5}$ eV$^2]$
$\sin^2\theta_{12}$
$\sin^2\theta_{13}$

But what it's really about is *testing the paradigm*...

How well do we need to know the parameters?

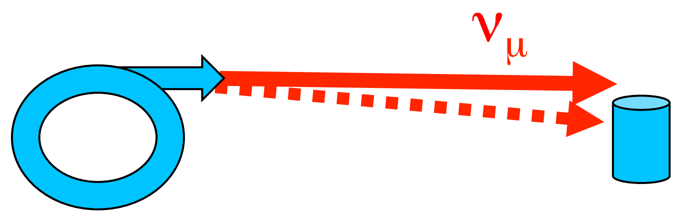


Patrick Huber
SLAC, March 2013

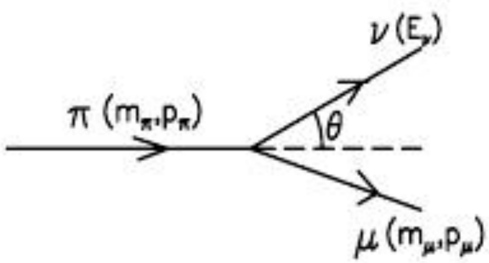
mass modelers predict *relations* between the mixing parameters

We need not only to fill in the missing parameters, but make precision measurements of *all* the parameters

The off-axis trick



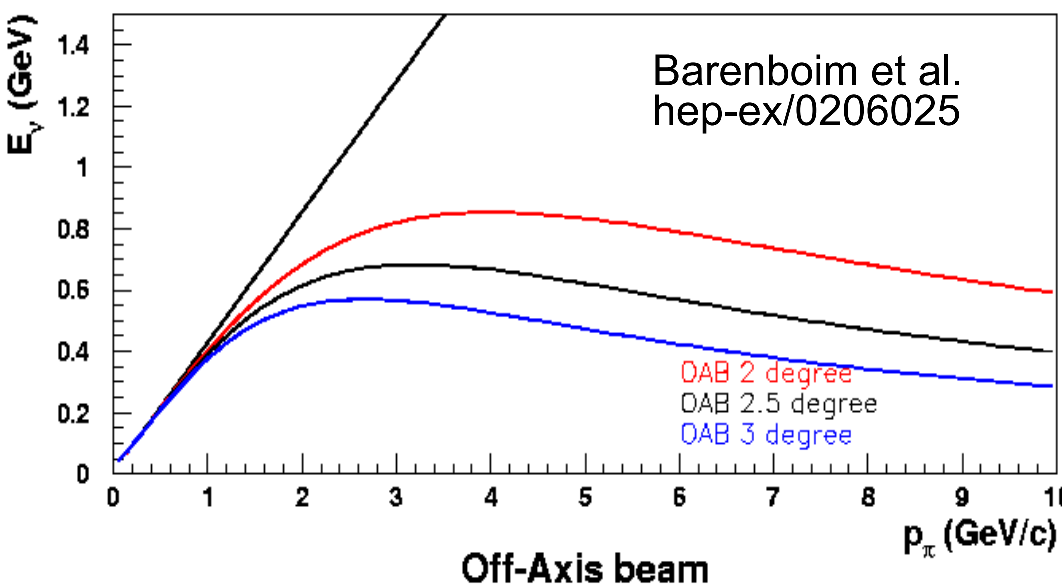
2-body pion decay kinematics

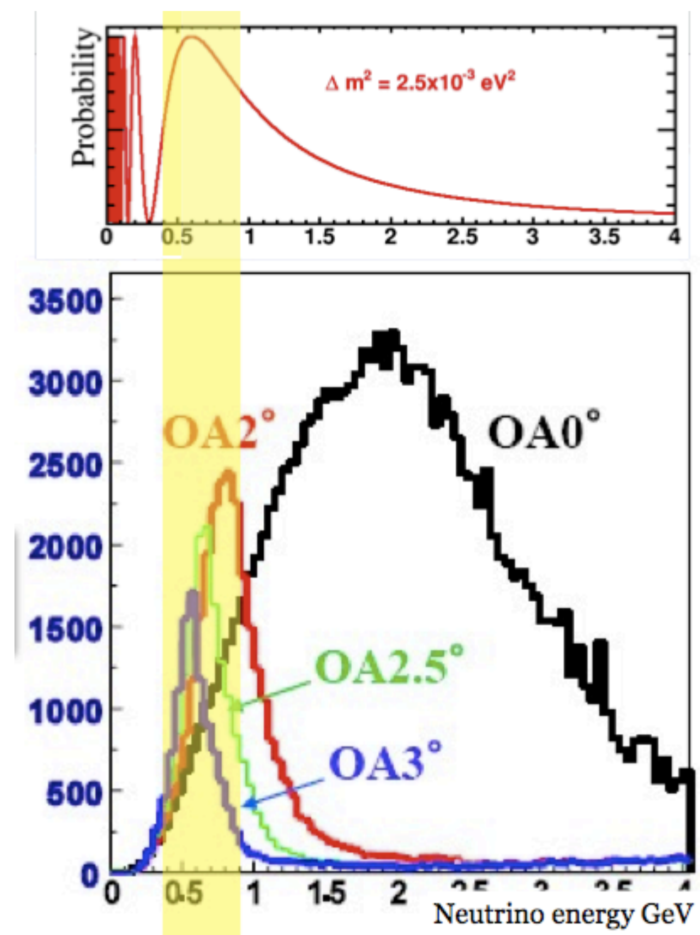


$$E_\nu = \frac{m_\pi^2 - m_\mu^2}{2(E_\pi - p_\pi \cos\theta)}$$

Off-axis, ν energy becomes relatively independent of π energy

Get *more sharply peaked* ν energies, and more flux at the oscillation minimum
➔ good for background reduction and oscillation fits

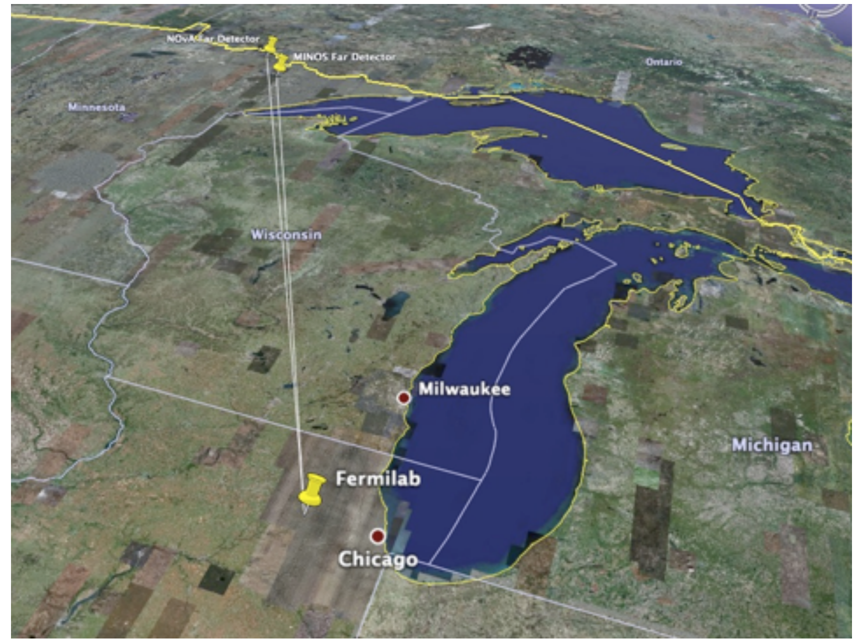




Current off-axis long-baseline experiments

T2K: "Tokai to Kamioka"

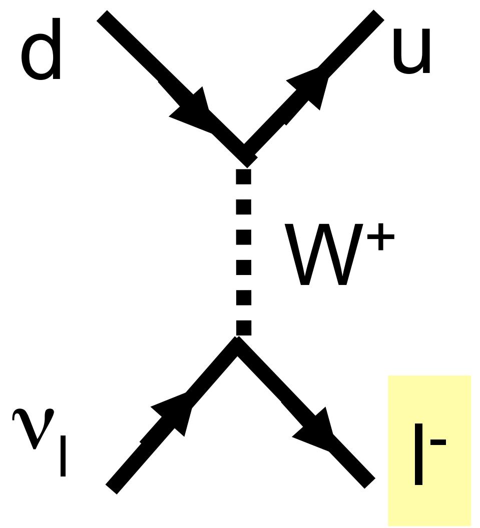
NOνA at NuMi



Pre-existing detector: Super-K
New beam from J-PARC
295 km baseline
Water Cherenkov detector

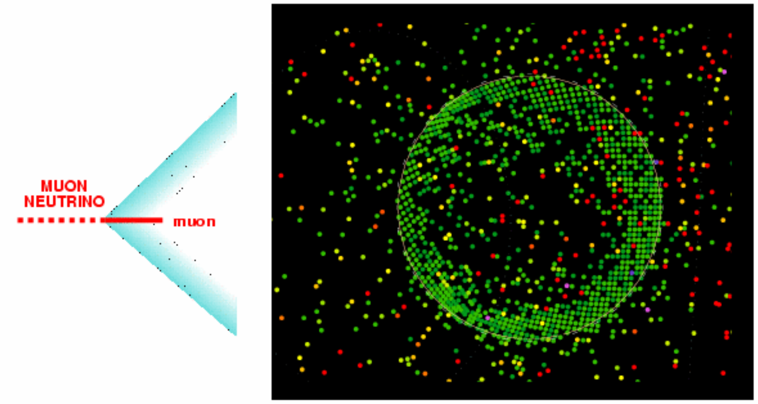
Pre-existing beam:
Fermilab NuMi upgrade
810 km baseline
Scintillator detector

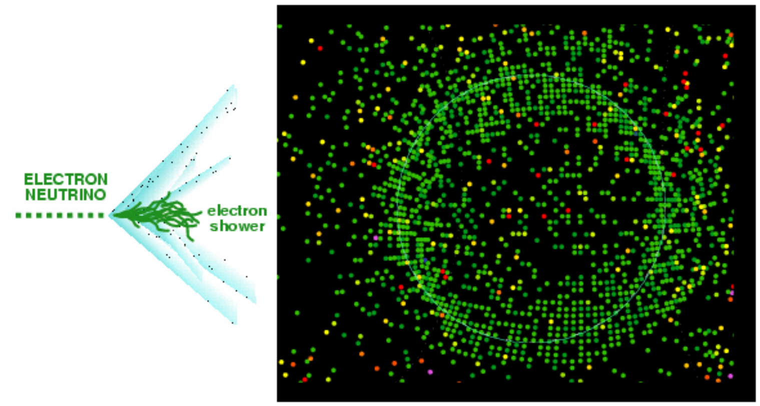
Signature of non-zero θ_{13} at far detector

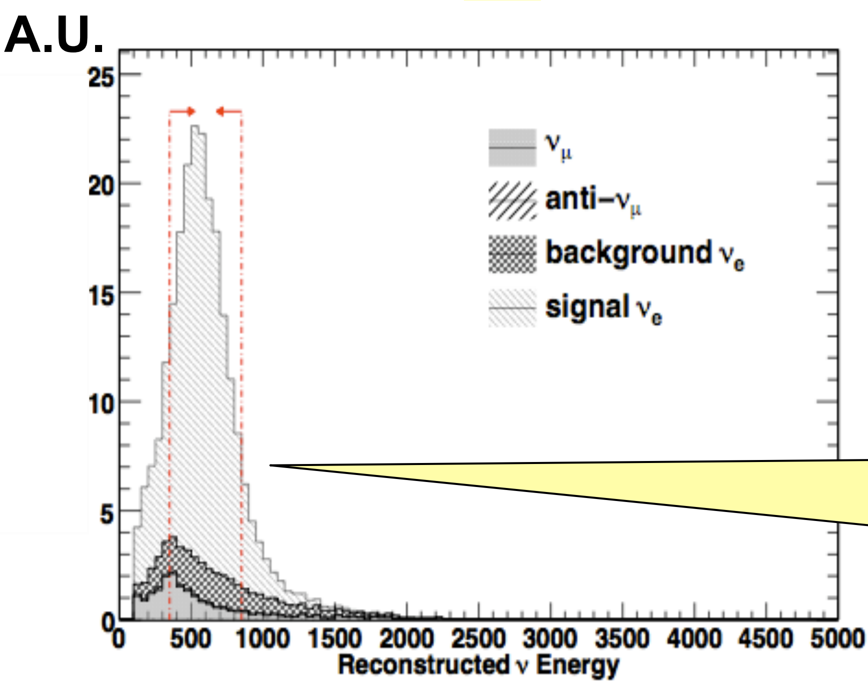


$\nu_l + N \rightarrow l^{\pm} + N'$

select charged-current quasi-elastic events (~single ring);
vertex, energy, direction from Cherenkov light



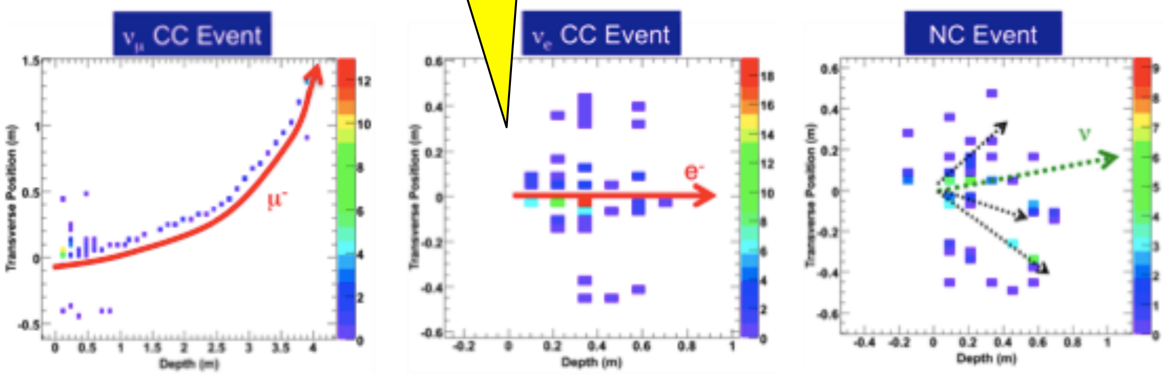




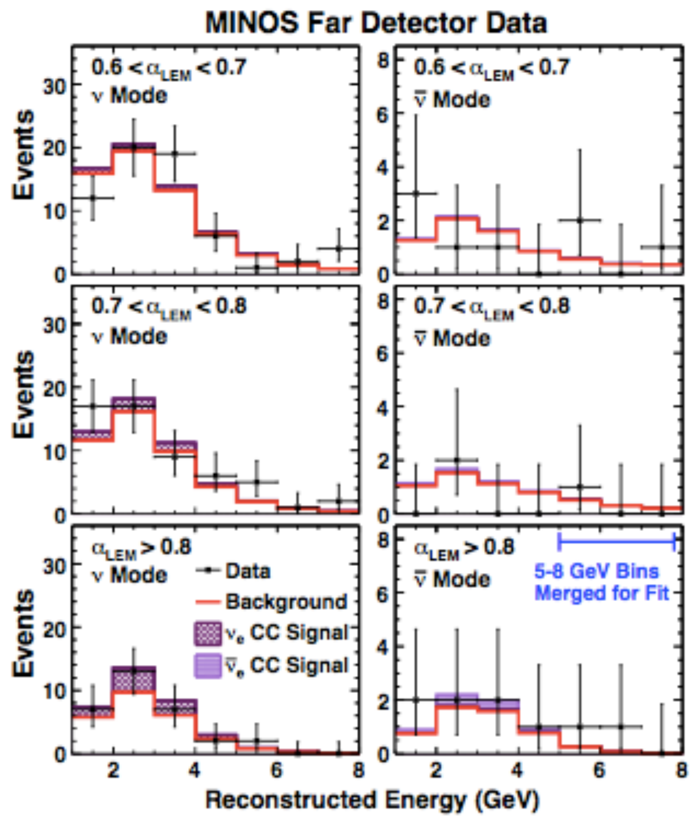
Look for electron appearance: single fuzzy rings excess on top of background, with expected spectrum

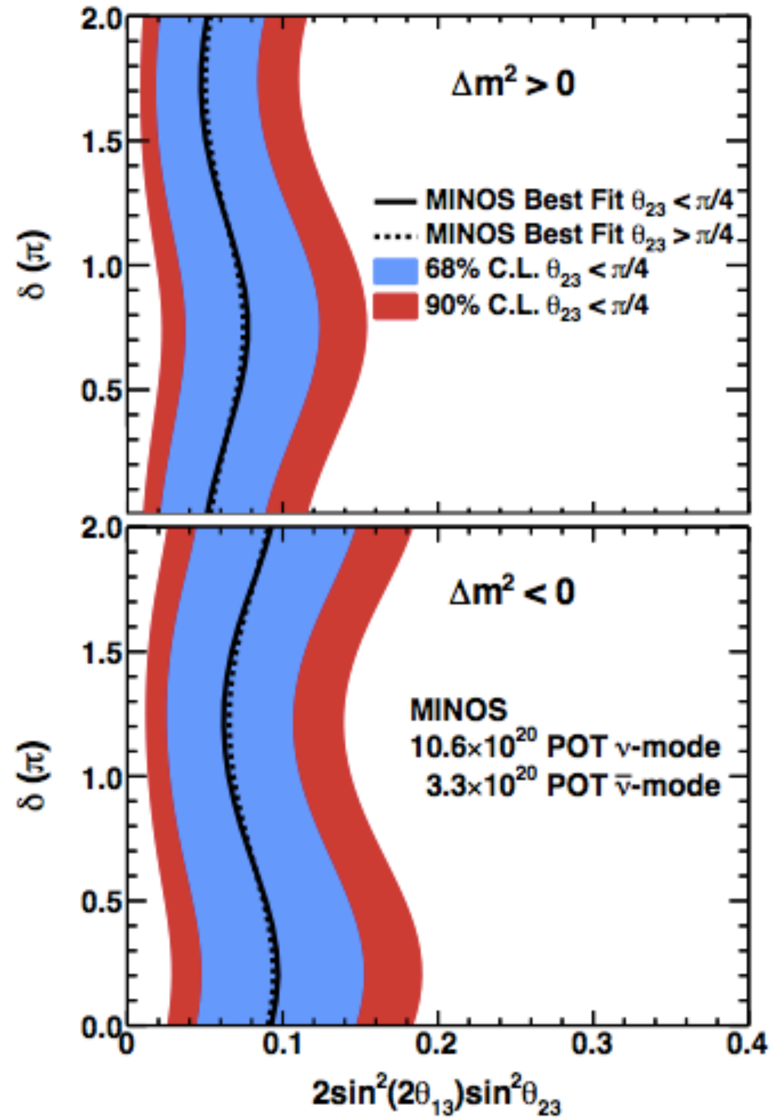
ν_e appearance results from MINOS are consistent

look for these



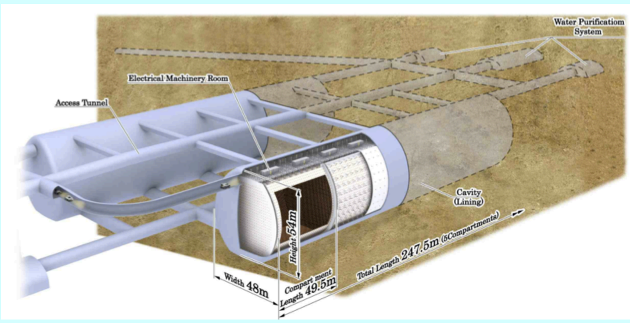
Spectrum of electron –like events

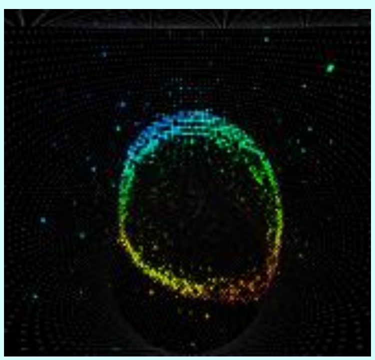




Possible large (multi-kton) detector technologies

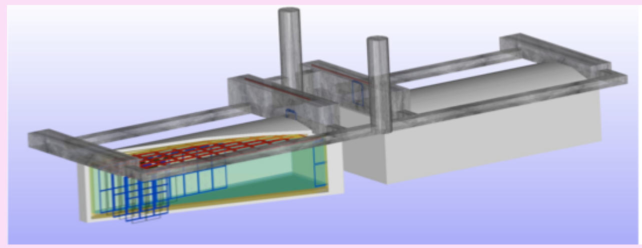
Water Cherenkov

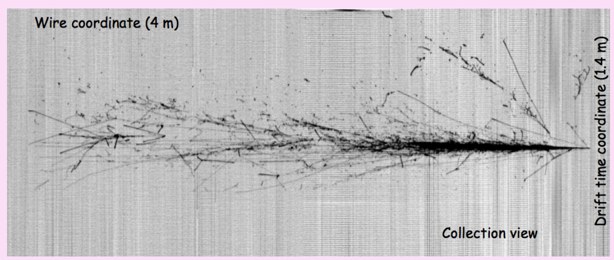




Cheap material, proven at very large scale

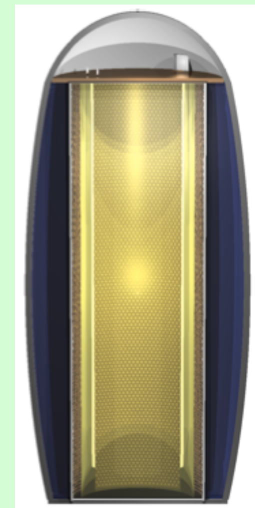
Liquid Argon

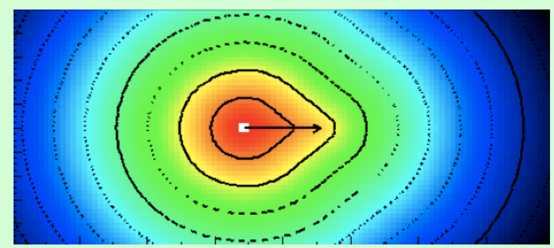




Excellent particle reconstruction, high efficiency

Liquid Scintillator

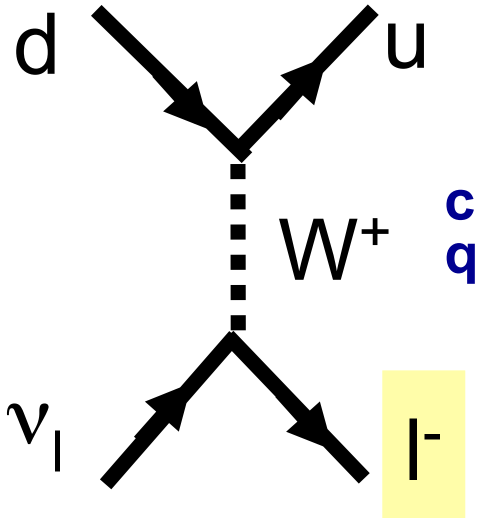




Low energy thresh, good resolution
(but: high energy particle reconstruction difficult for LBL)

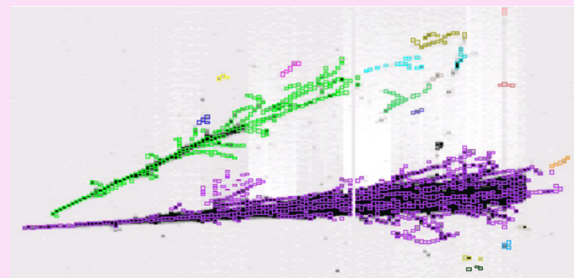
What you're looking for experimentally:

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

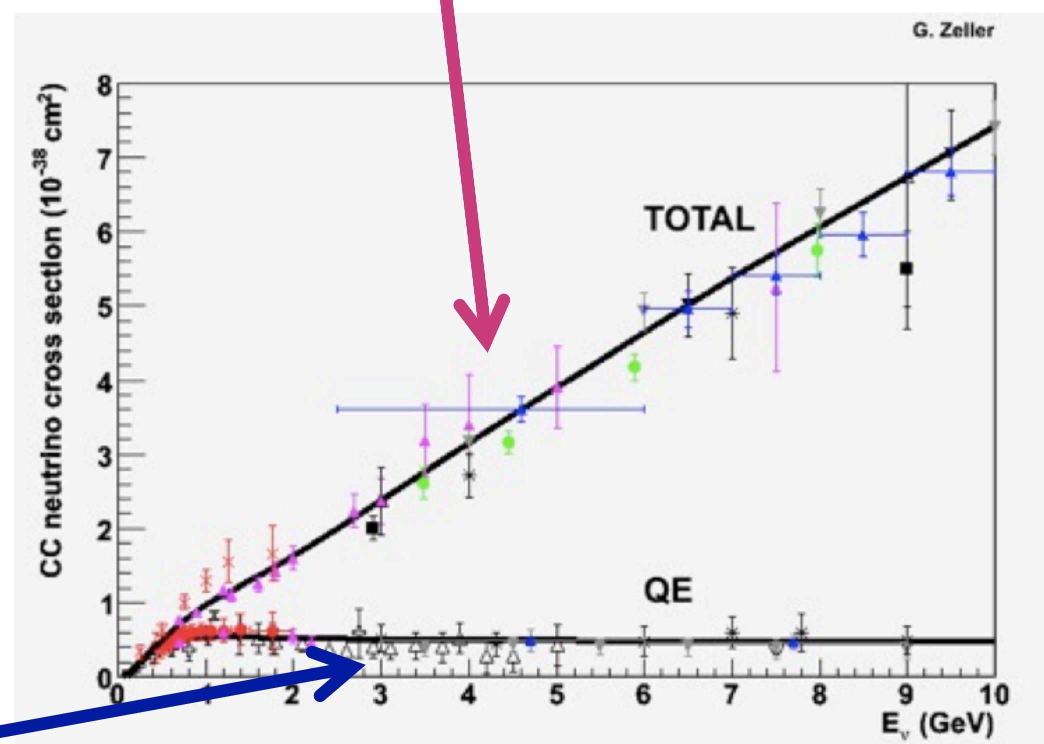


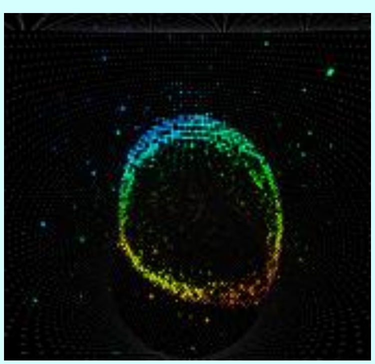
charged-current quasi-elastic

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



A LAr detector (in principle) reconstructs everything

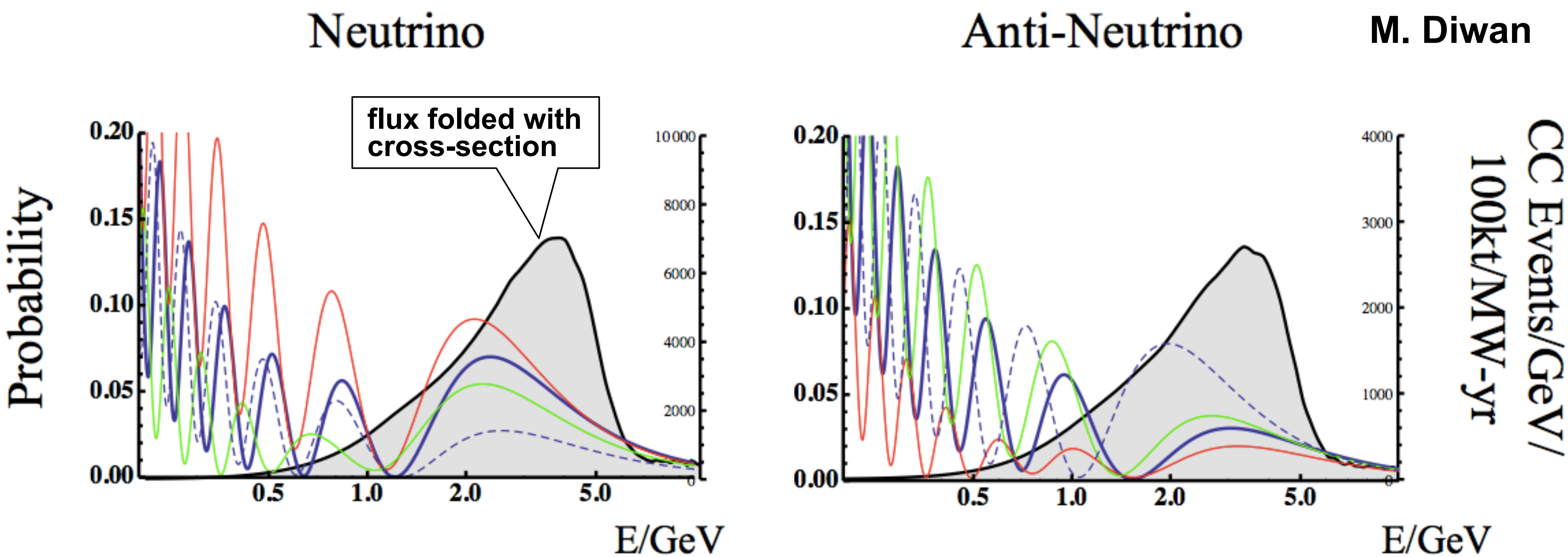




A WCh detector needs to cut hard to select clean QE events

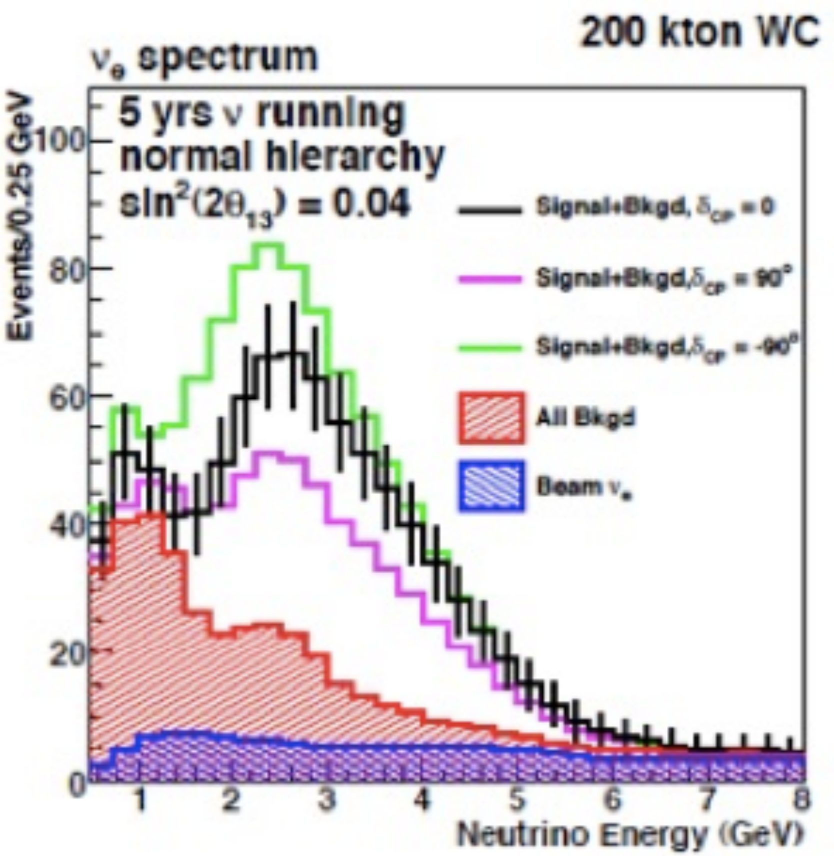
A long-baseline beam works well

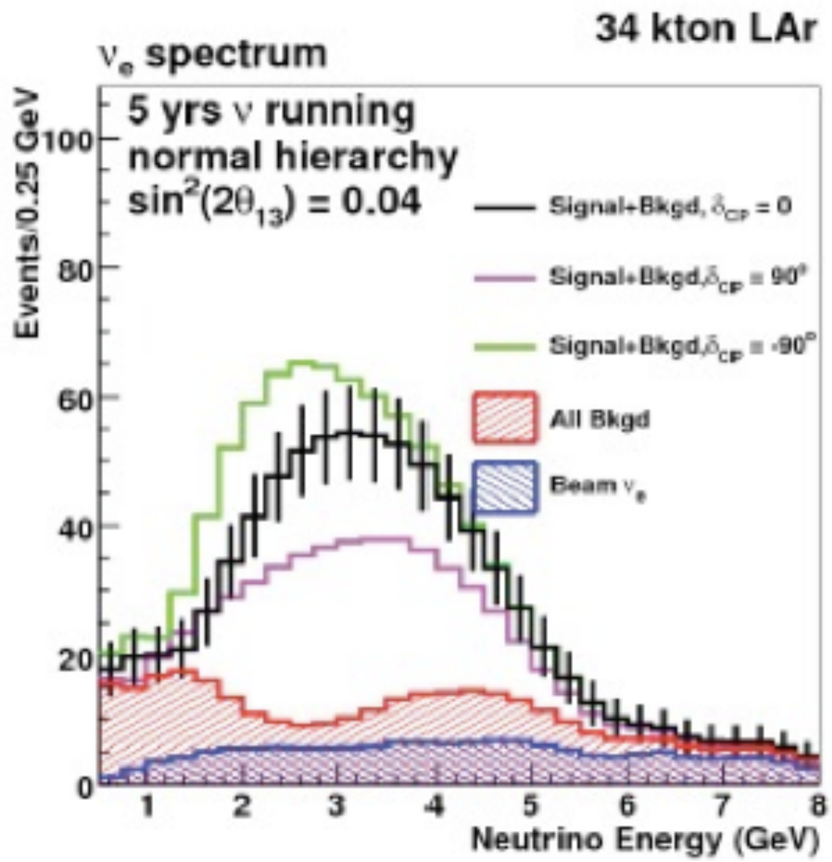
LBNE events at 1300 km w/ oscillation probabilities



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

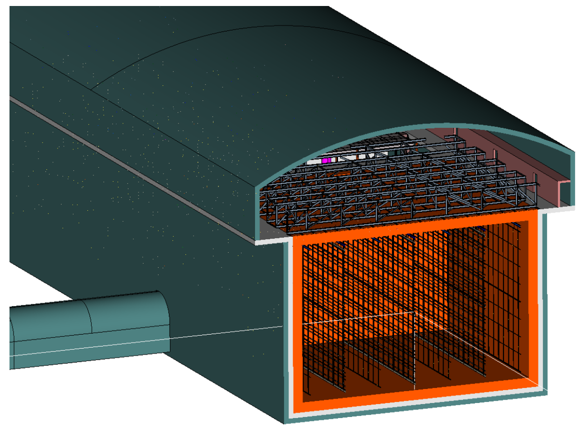
34 kton LAr ~ 200 kt WCD because of better LAr efficiency: detector sizes for technology choice set for ~ equal oscillation sensitivity

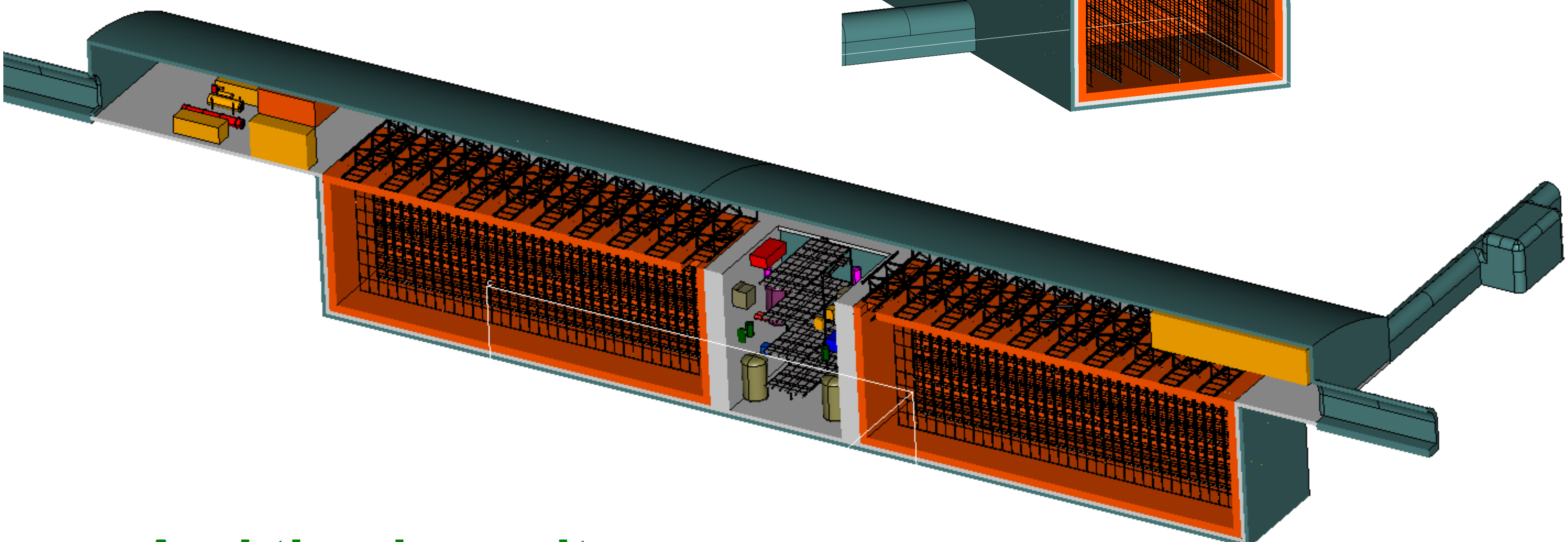




After long decision-making process for LBNE... it's Liquid Argon

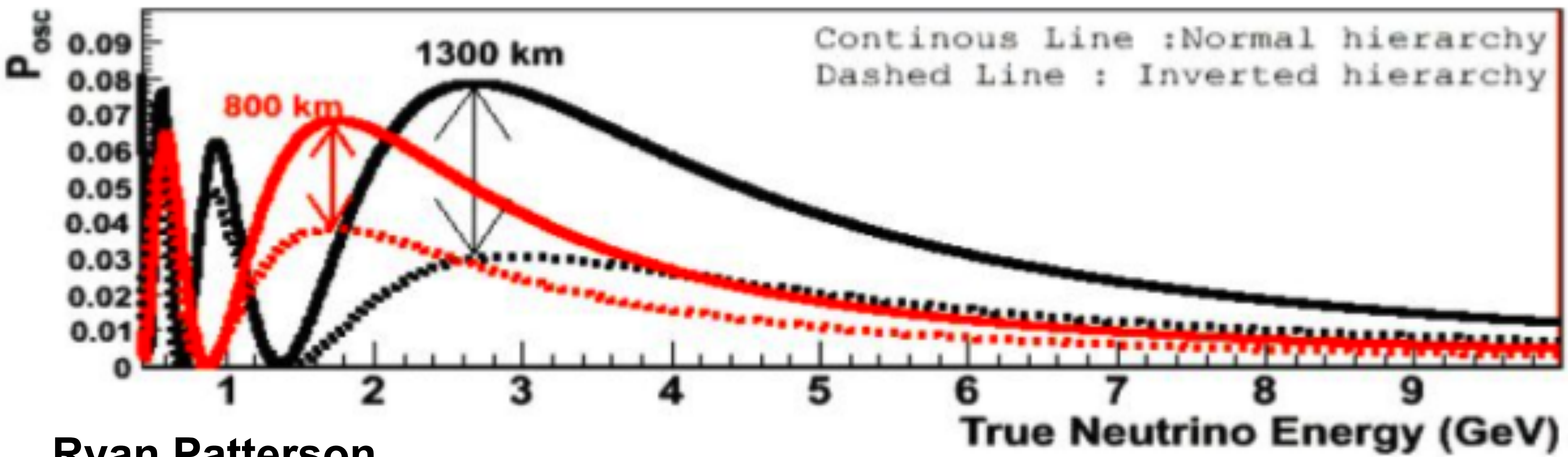
(waiting for FNAL/DOE concurrence)



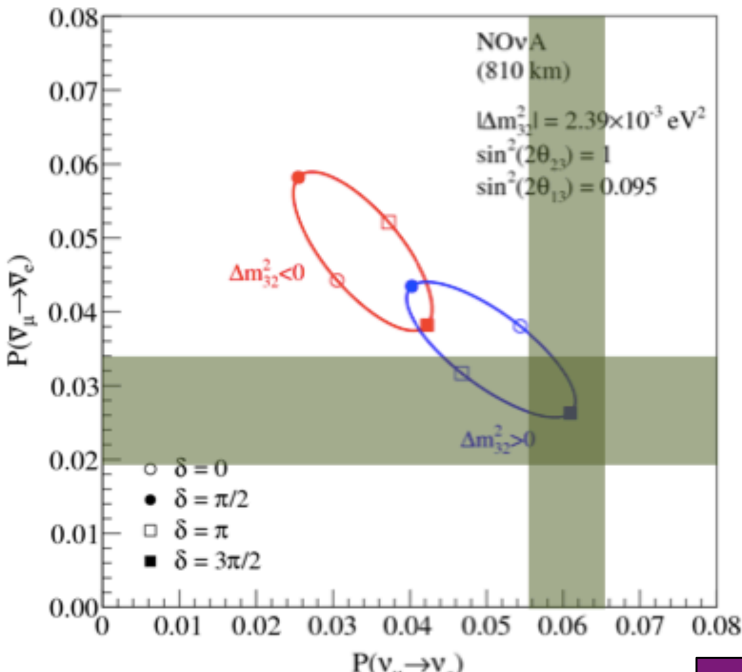


And the deep site (4850 ft at Homestake) is favored

The baseline matters:



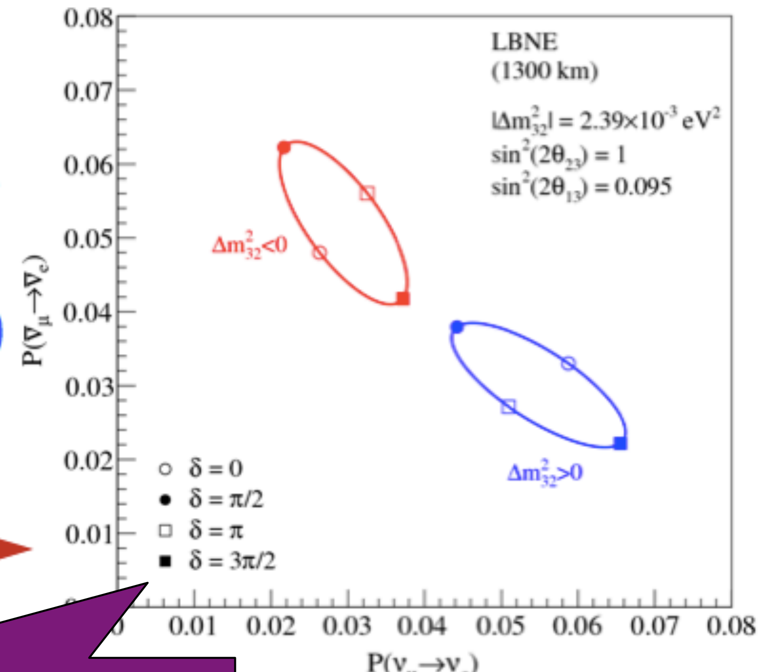
Ryan Patterson



$P(\bar{\nu}_\mu\to\bar{\nu}_e)$ vs. $P(\nu_\mu\to\nu_e)$

shown at a particular *L/E*
for
both choices of sign(Δm^2)
and for full range of δ_{CP}

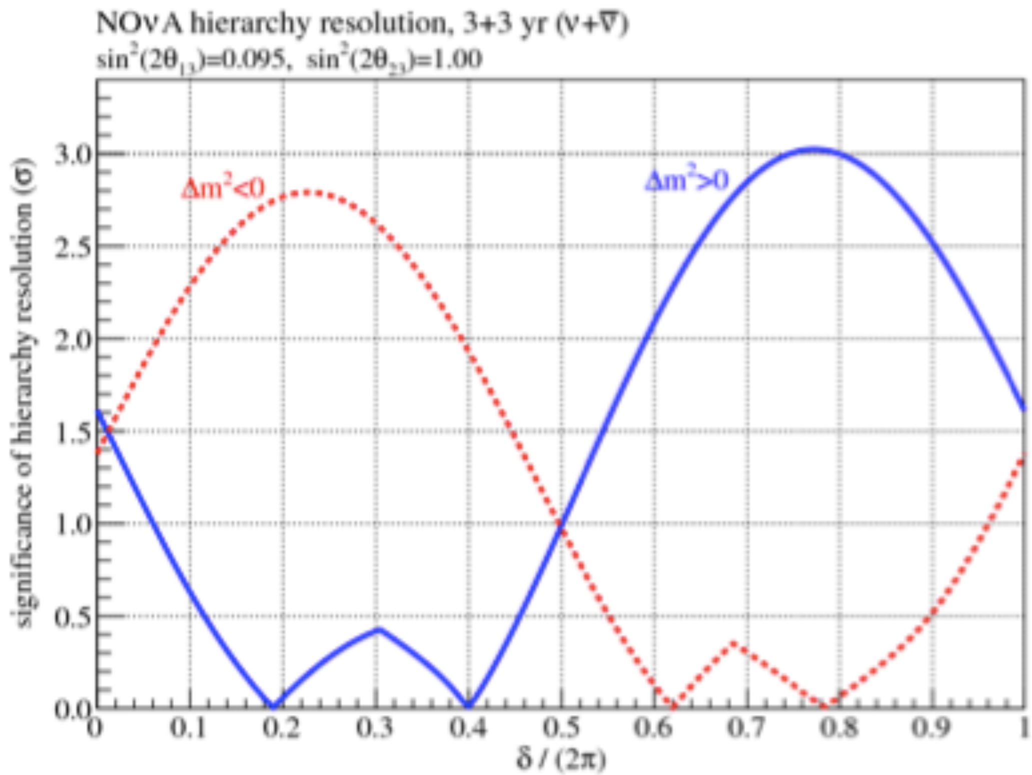
810 km ← → *1300 km*



easier to separate MH from CP effects at long baseline

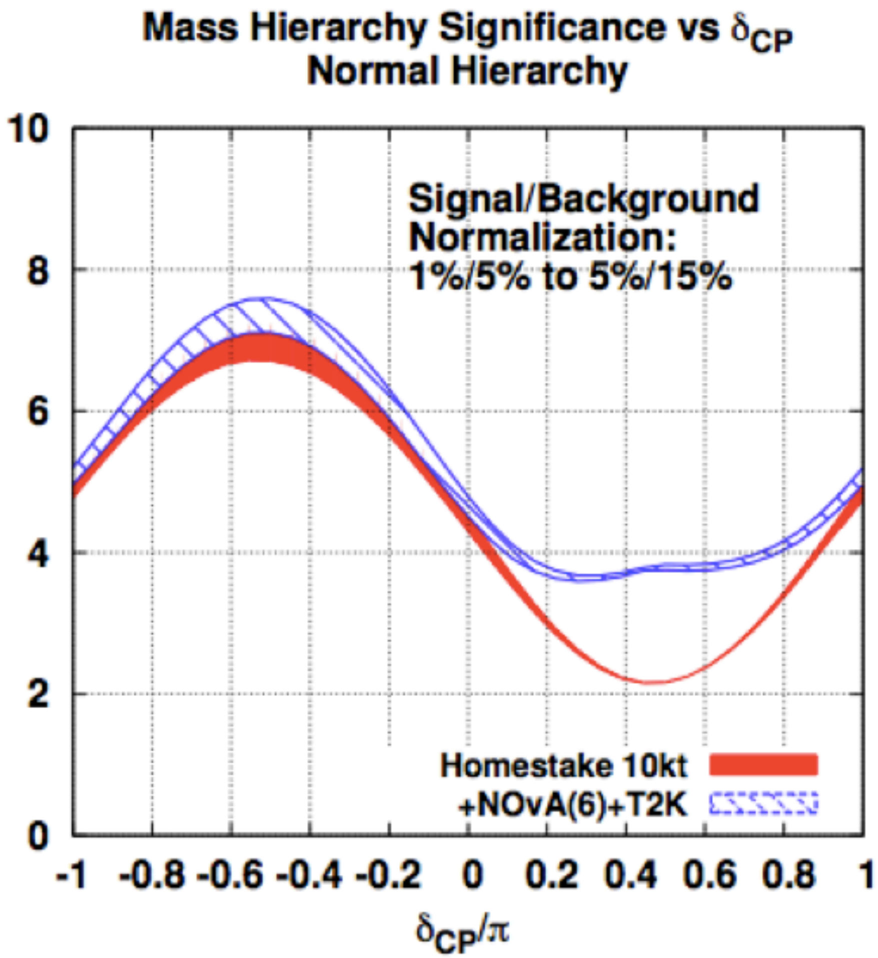
The NOvA experiment MH reach

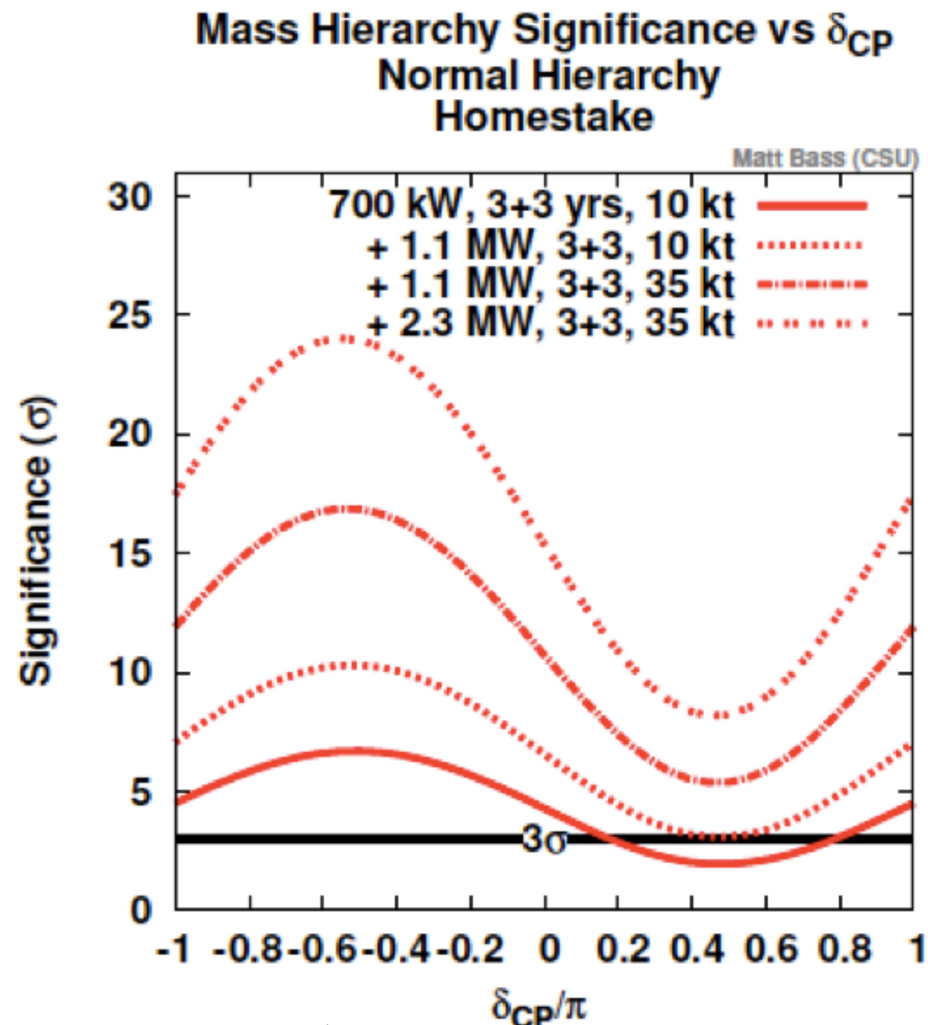
- 14 kt scintillator
- 700 kW off-axis FNAL beam
- 810 km baseline
- operations start this year



6 year run ➔>2σ MH determination for 35% of δ range

LBNE Sensitivity to mass hierarchy





M. Diwan, Venice, Mar 2013

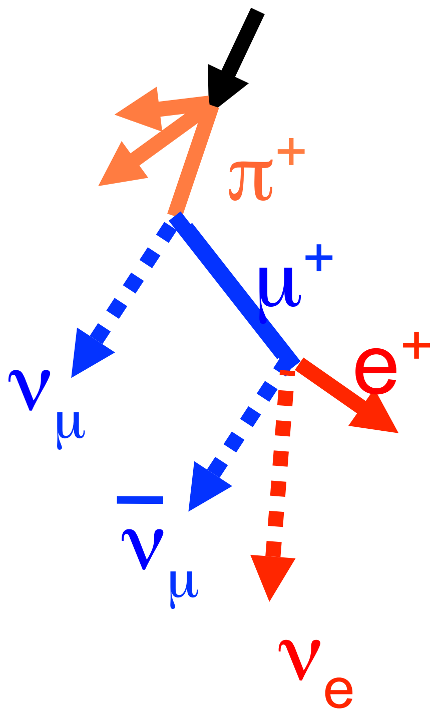
improvement with more mass or beam (e.g. Project X at FNAL)

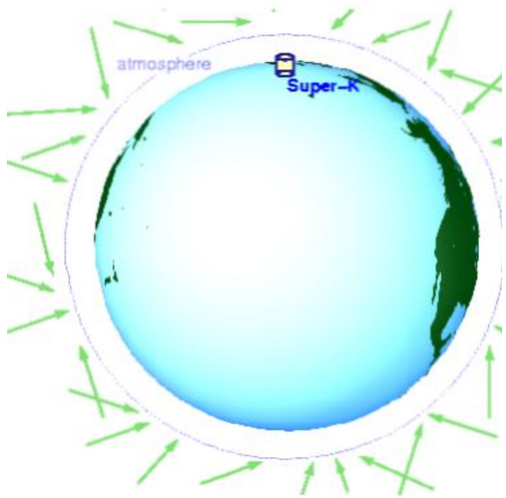
Atmospheric neutrinos: back into the wild

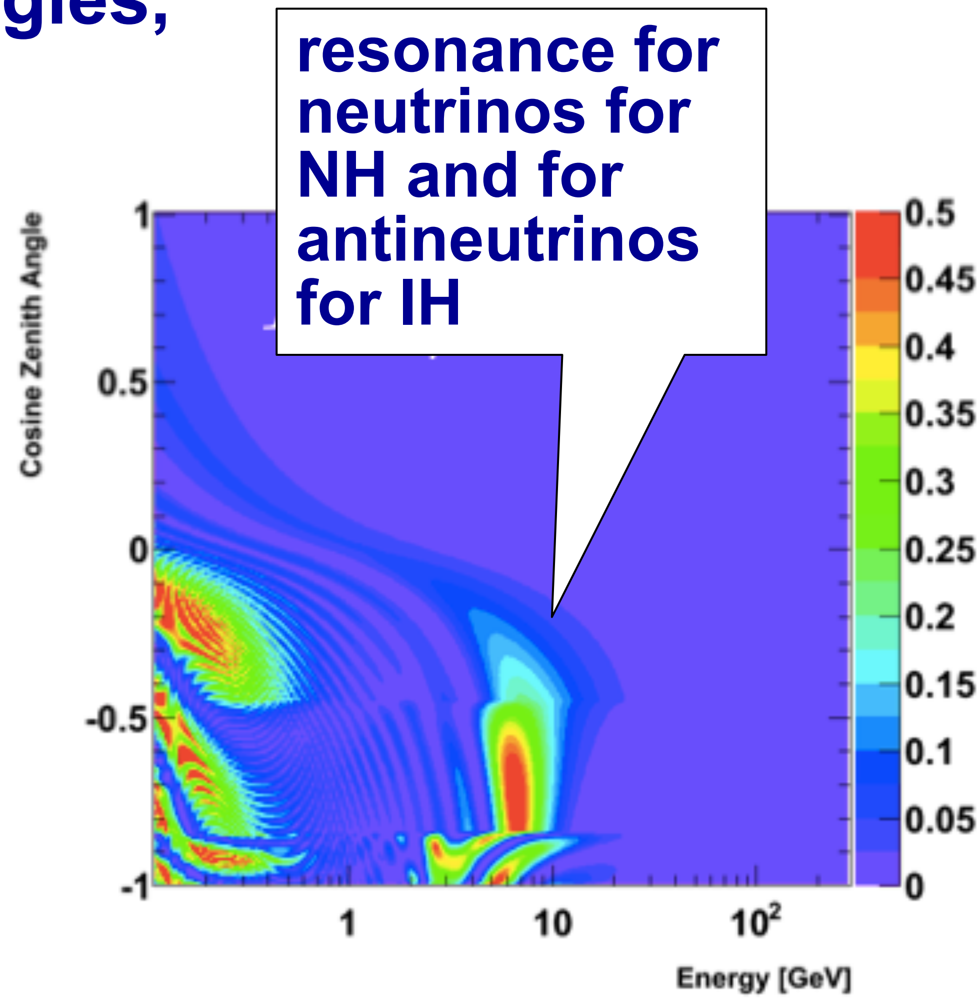
The neutrinos are free, and have a range of baselines & energies,

.... but they do what they damn well please

cosmic ray (p)



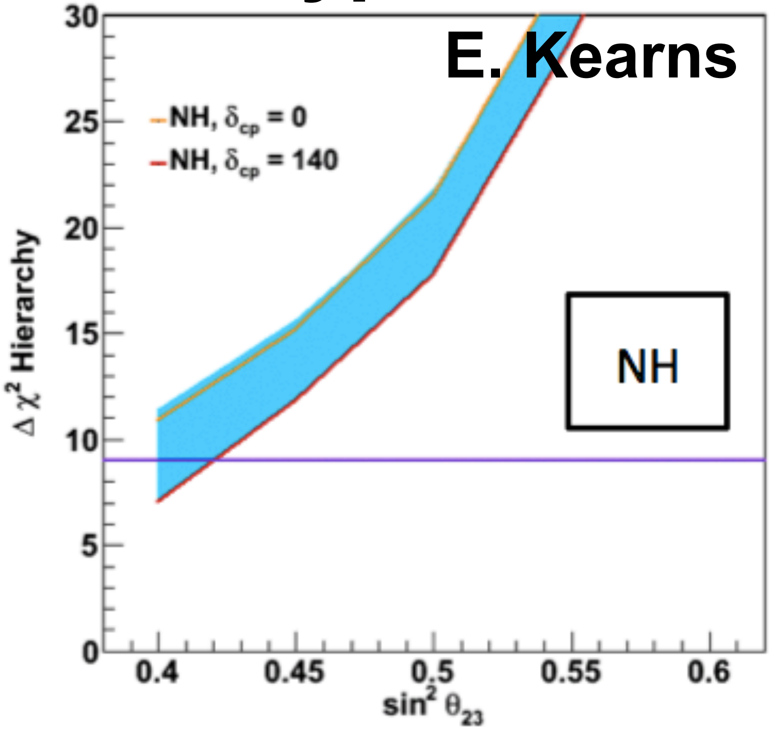


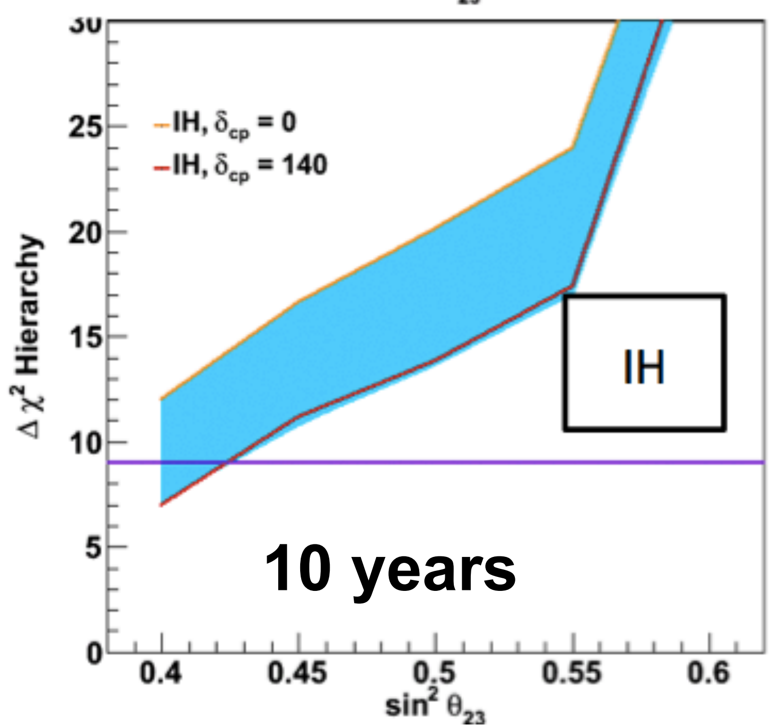


$$P(\nu_\mu \to \nu_e)$$

Need both statistics and ability to reconstruct ν energy & direction

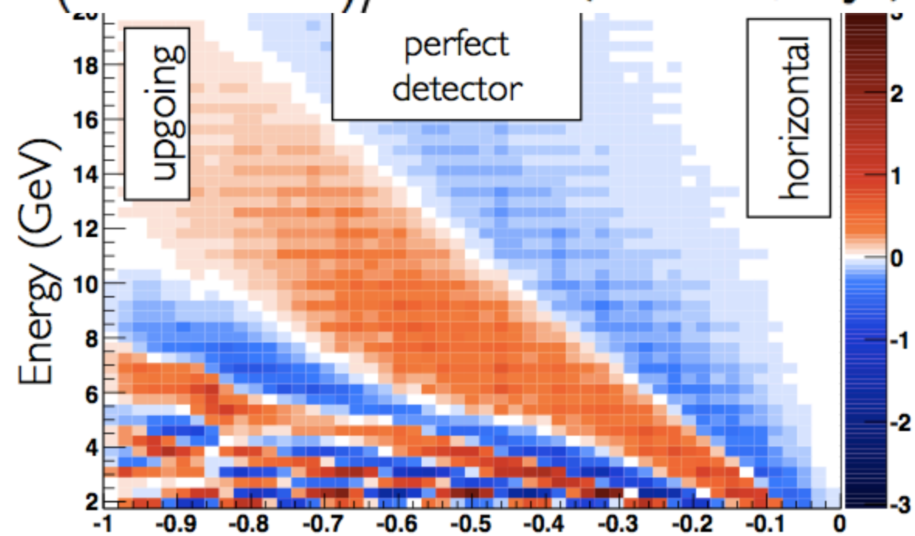
Hyper-K

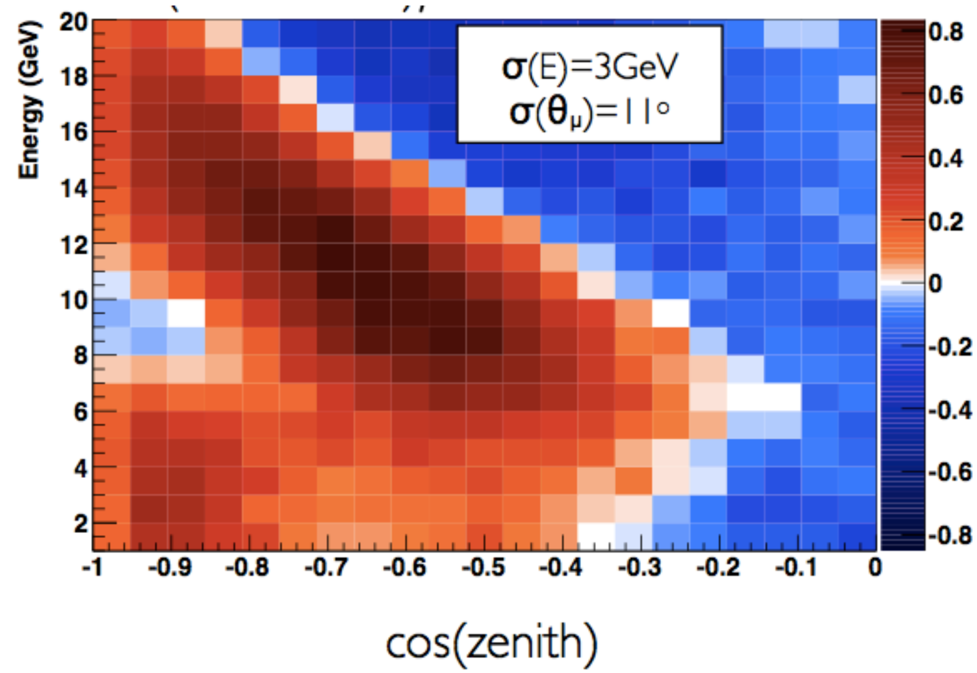




PINGU

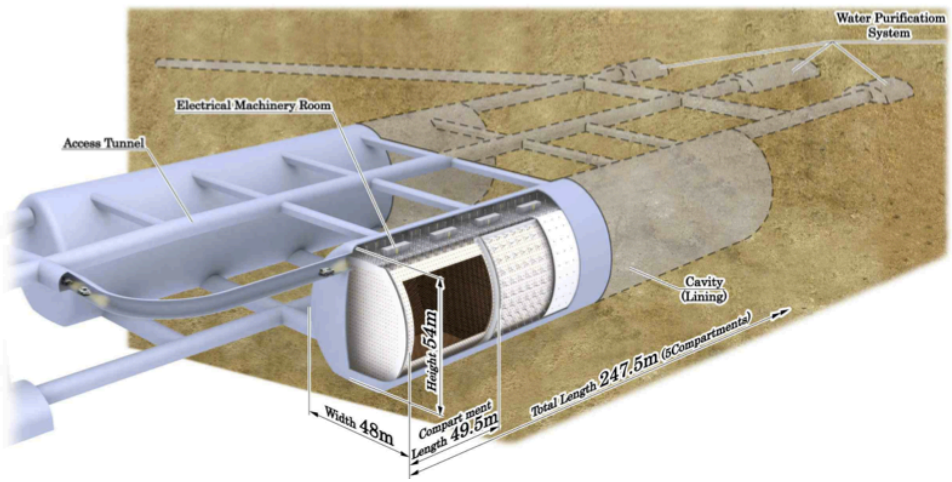
$$\left(N^{IH} - N^{NH}\right)/\sqrt{N^{NH}} \text{ (PINGU, 1 yr)}$$





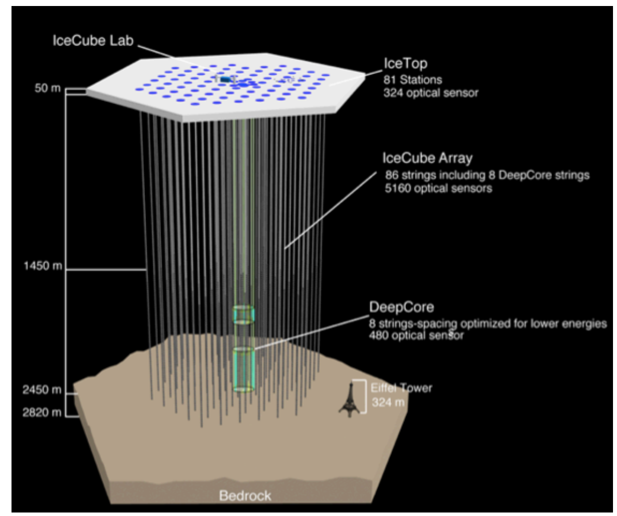
Akhmedov, Razzaque, and Smirnov 1205.7071

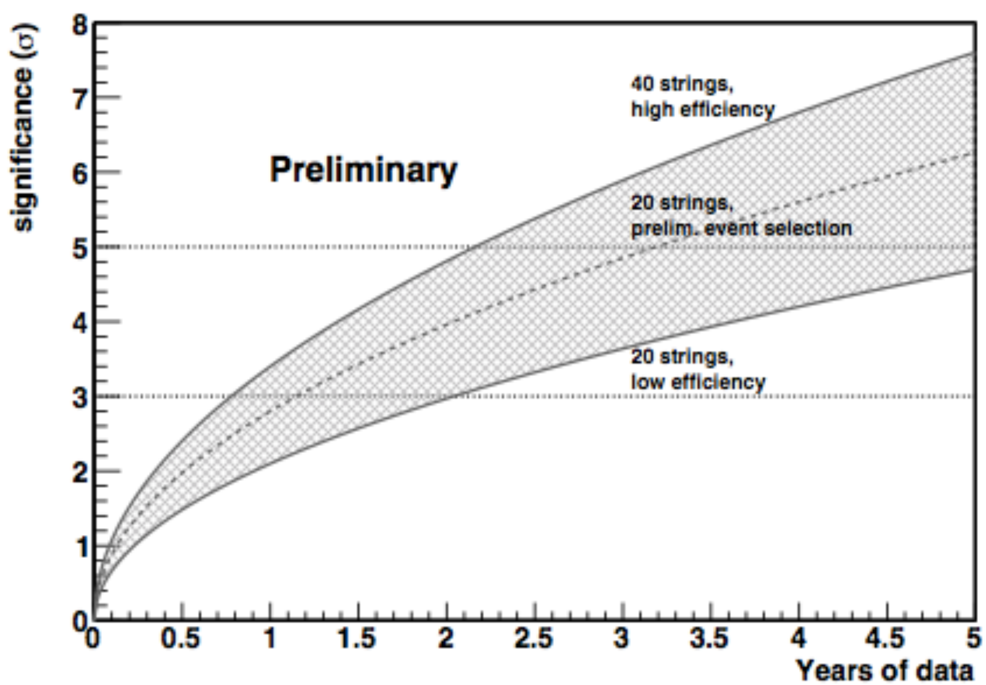
Examples: Hyper-K



- Tochibora mine, near Kamioka;
  (1500-1750 mwe)
- 560 ktons (25 x SK)
- LOI on arXiv:1109.3262

IceCube DeepCore/PINGU





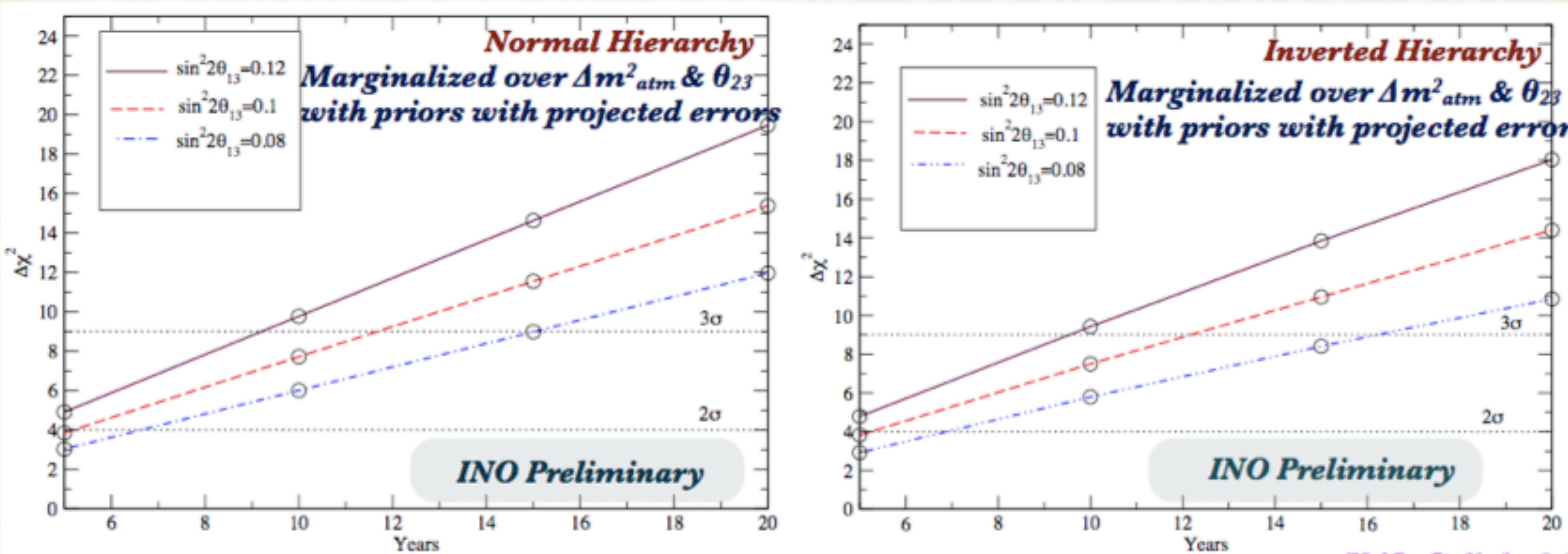
- enormous detector volume & atmnu statistics
- sparse PMTs, so poor reconstruction

➔ PINGU infill for be reconstruction & lower threshold

- arXiv:1306.5846

MASS HIERARCHY @ INO

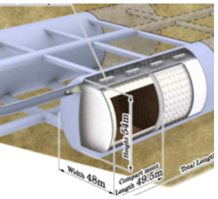
- *Events generated using Nuance and ICAL resoln in E and cosθ_{zenith}*

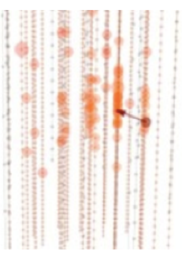


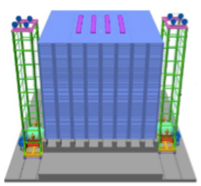
INO Collab, 2012

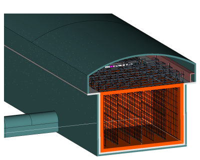
- *~2σ sensitivity for $\sin^2\theta_{23}$=0.5, $\sin^2 2\theta_{13}$=0.1 by 2022 (5 yrs)*
- *~2.7σ sensitivity for $\sin^2\theta_{23}$=0.5, $\sin^2 2\theta_{13}$=0.1 by 2027 (10 yrs)*

Experiments going after MH with atmnus







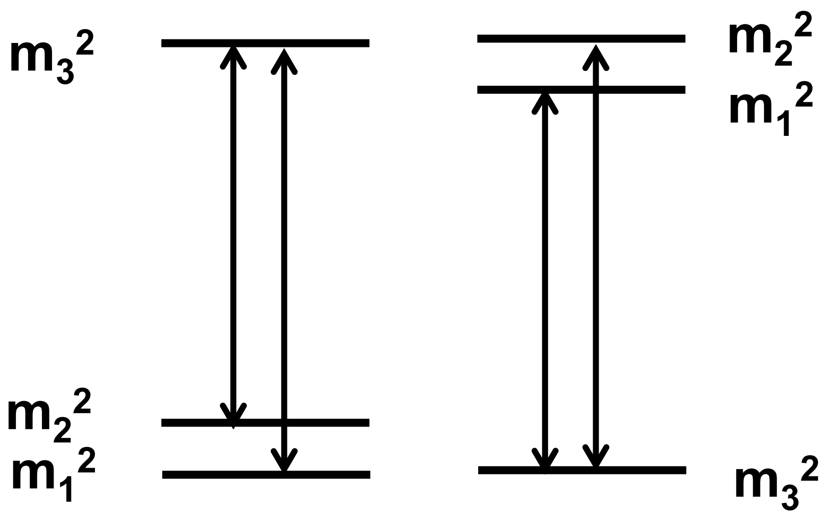


Experiment	Type	Location	Reconstruction	Mass (kt)	Notes
Super-K	Water Cherenkov	Japan	Good	22.5	Good reconstruction, low stats
Hyper-K	Water Cherenkov	Japan	Good	560	Good reconstruction and stats
IceCube DeepCore	Long String Water Ch.	South Pole	Poor	Mton	Systematics under study, huge stats
PINGU	Long String Water Ch.	South Pole	Improved	Mton	Systematics under study, huge stats
ORCA	Long String Water Ch.	Europe	Poor	Mton	Systematics under study, huge stats
ICAL@INO	Iron Calorimeter	India	Good	50	Magnetized➔ lepton sign selection
LBNE	LArTPC	USA	Excellent	10-34	Excellent reconstruction
GLACIER	LArTPC	Europe	Excellent	20-100	Excellent reconstruction

The Reactor MH Method

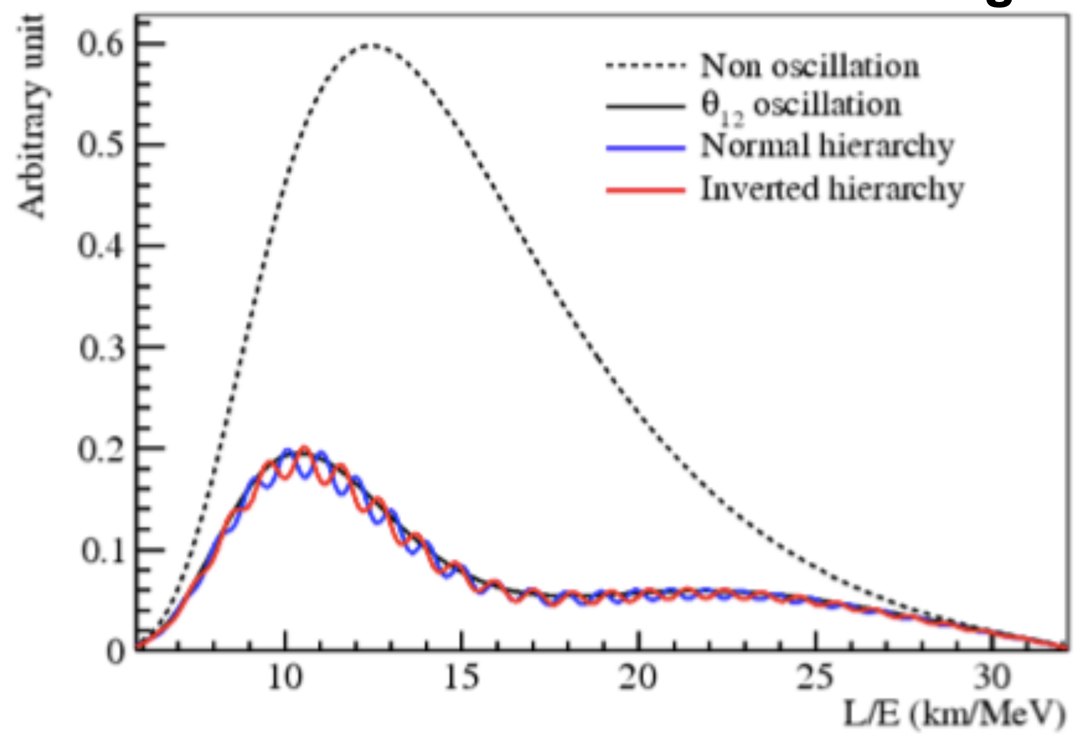
Vacuum oscillation frequencies depend on $\Delta m^2/E_\nu$

Different MH ➔ slightly different frequencies at reactor energies



$$\text{NH}: \ |\Delta m^2_{31}| = |\Delta m^2_{32}| + |\Delta m^2_{21}|$$
$$\text{IH}: \ |\Delta m^2_{31}| = |\Delta m^2_{32}| - |\Delta m^2_{21}|$$

Y. Wang

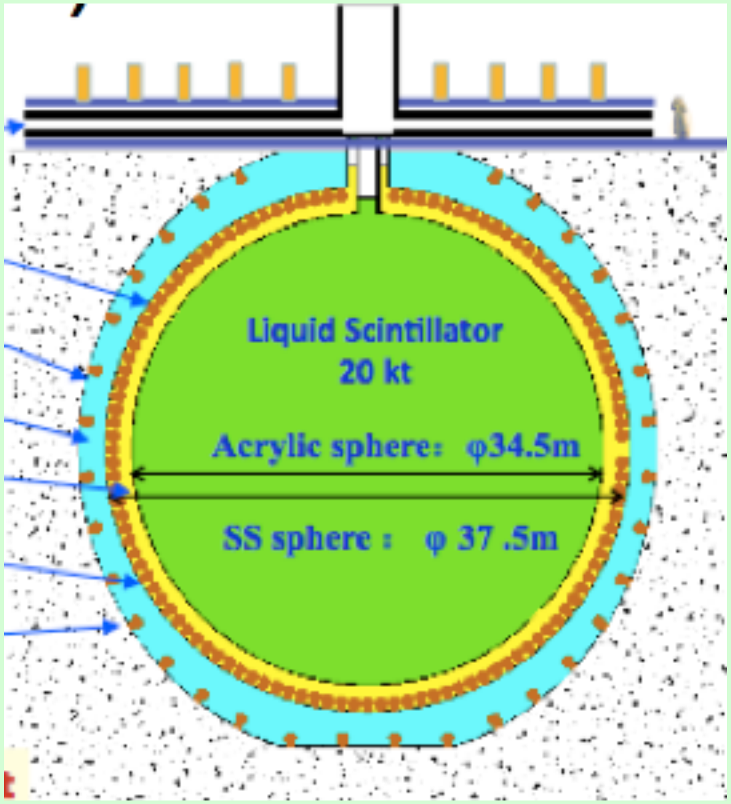


Requires:

- **good energy resolution** (~3%)
- **excellent understanding of energy scale** (fraction of a percent)

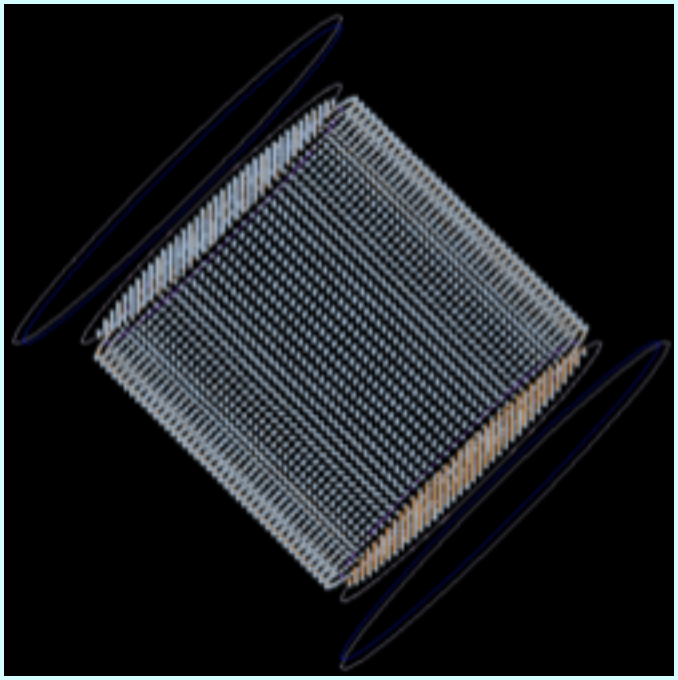
Proposed reactor experiments going after MH

Daya Bay II (China)



- 20 kt detector at 55-60 km
- ~ 40 GW_{th} power
- ~700 m underground
- < 3% resolution @ 1 MeV
- ~0.2% energy calibration

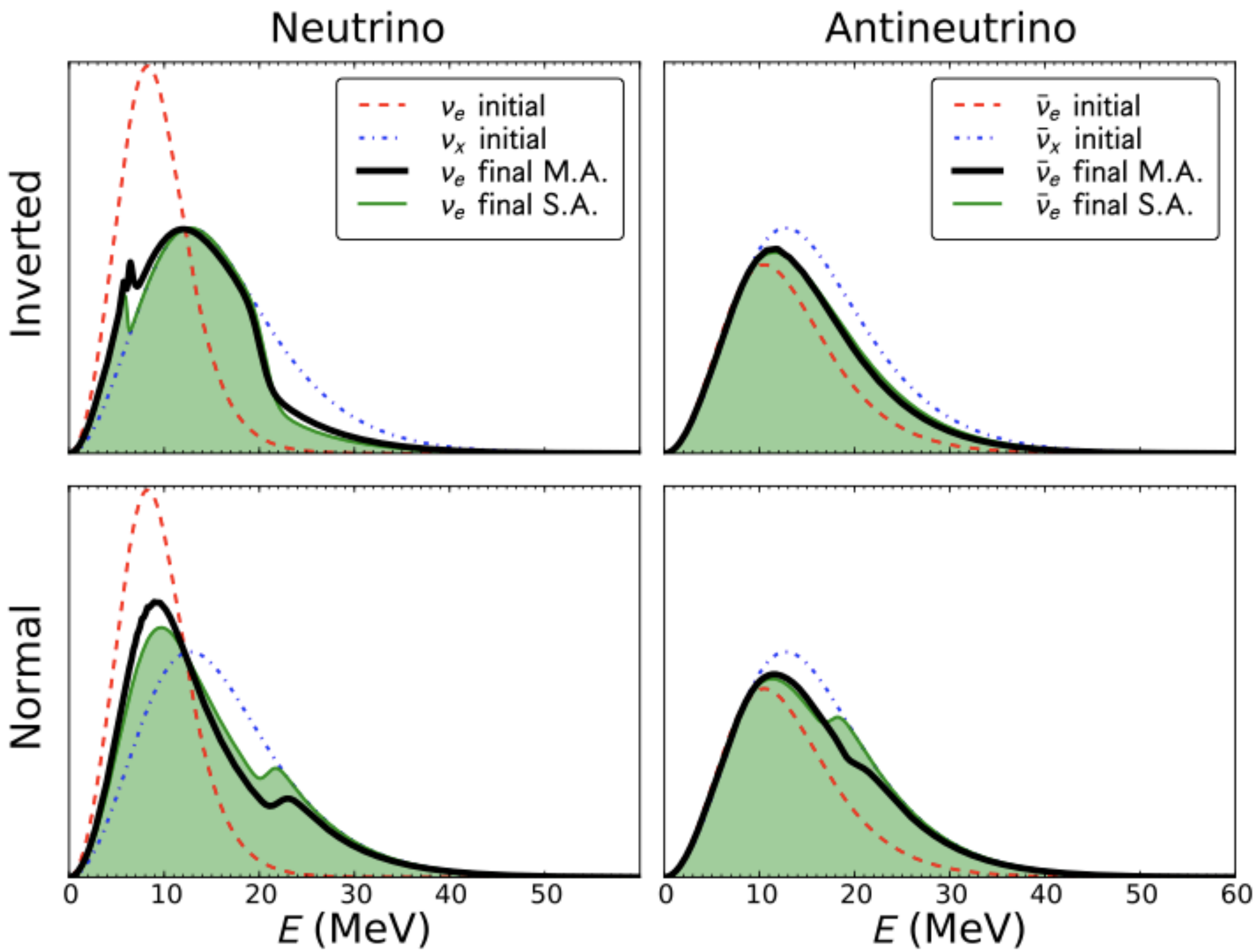
RENO-50 (South Korea)



- 18 kt detector at 47 km
- 16.8 GW power (Yonggwang)
- >500 m underground
- similar detector requirements

One more way of going after MH: supernova neutrinos

Core collapse burst neutrinos: all flavors, few 10's of MeV



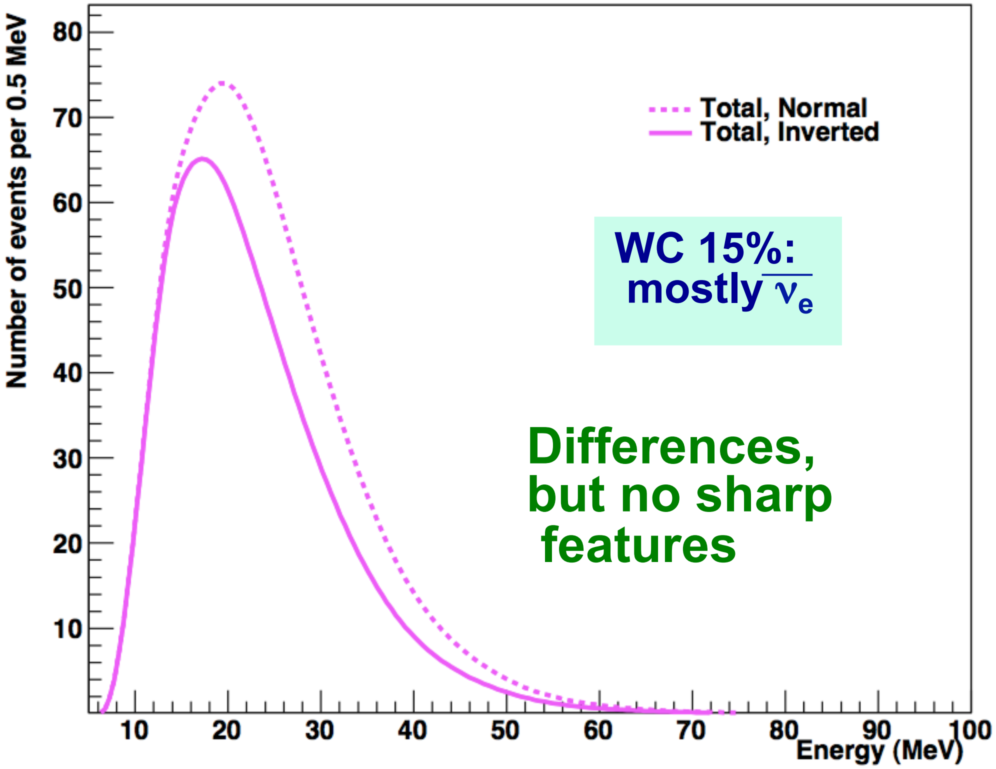
***Distinctive spectral swap features depend on neutrino mass hierarchy*, for neutrinos vs antineutrinos**

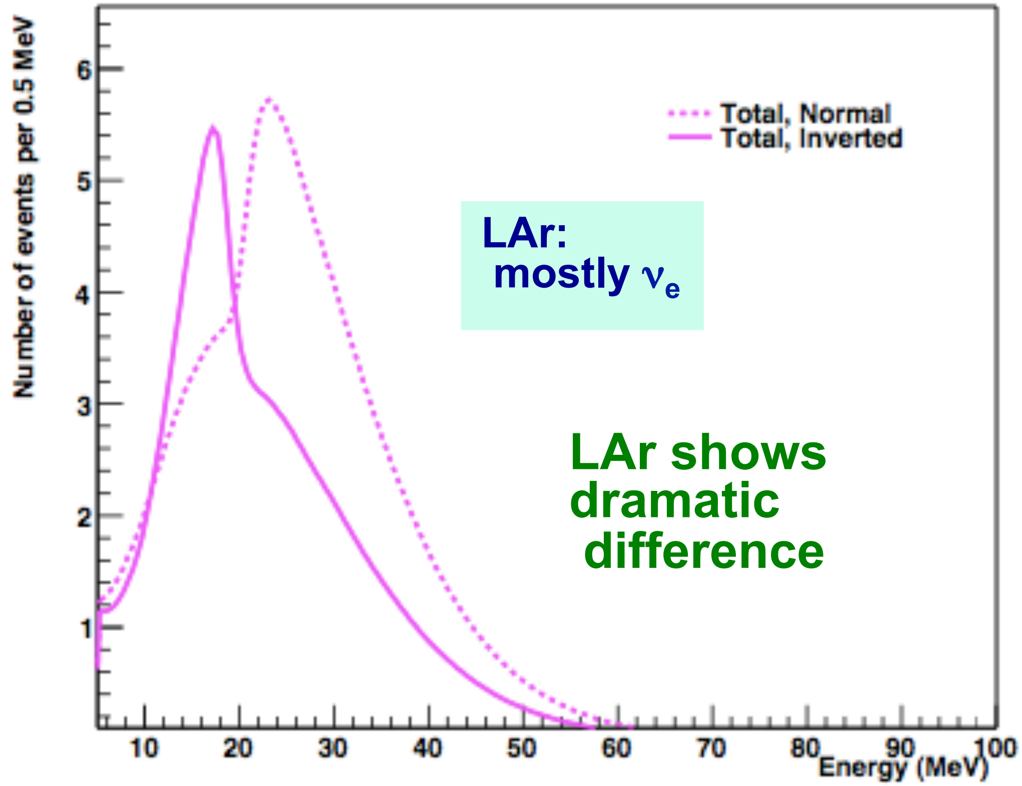
(also: matter effects in Earth)

Duan & Friedland, arXiv:1006.2359

An anecdotal example

(1 second late time slice, flux from H. Duan w/collective effects)





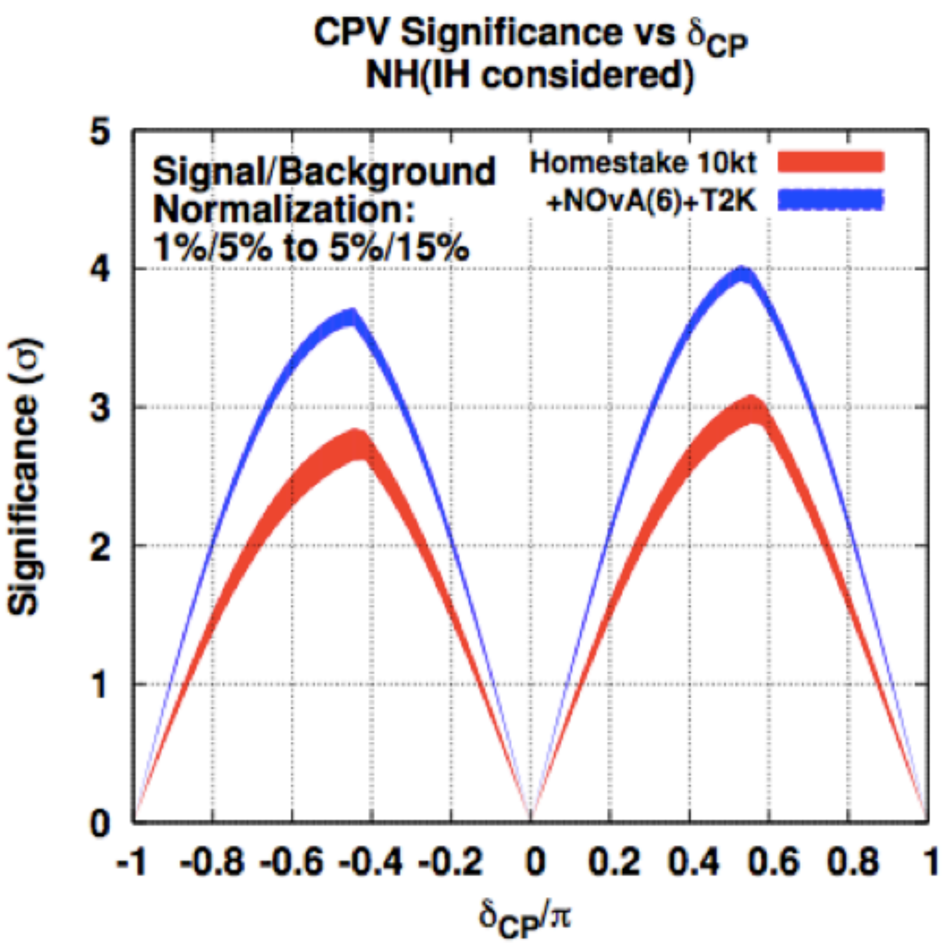
There will be very rich information in the observed flavor, time, energy spectra

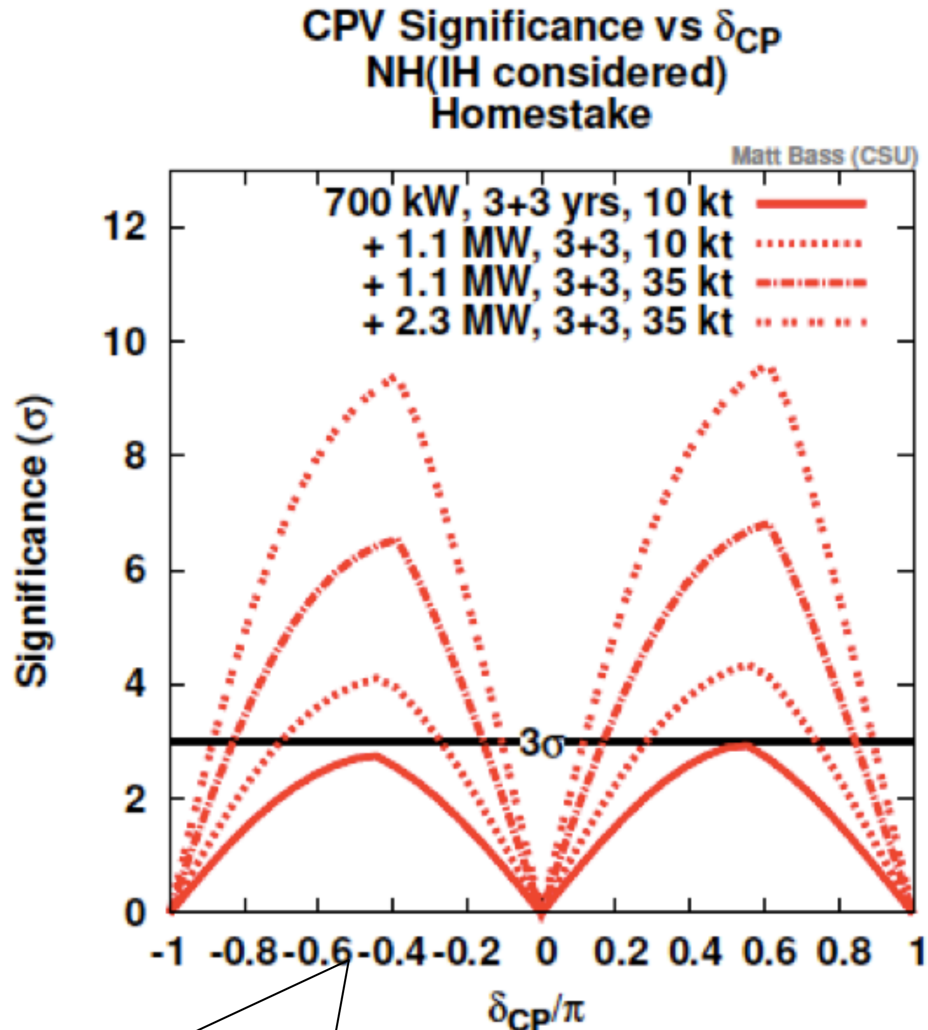
Worldwide sensitivity to multiple flavors is key: different detection technologies are highly complementary

LBNE CP sensitivity

M. Diwan

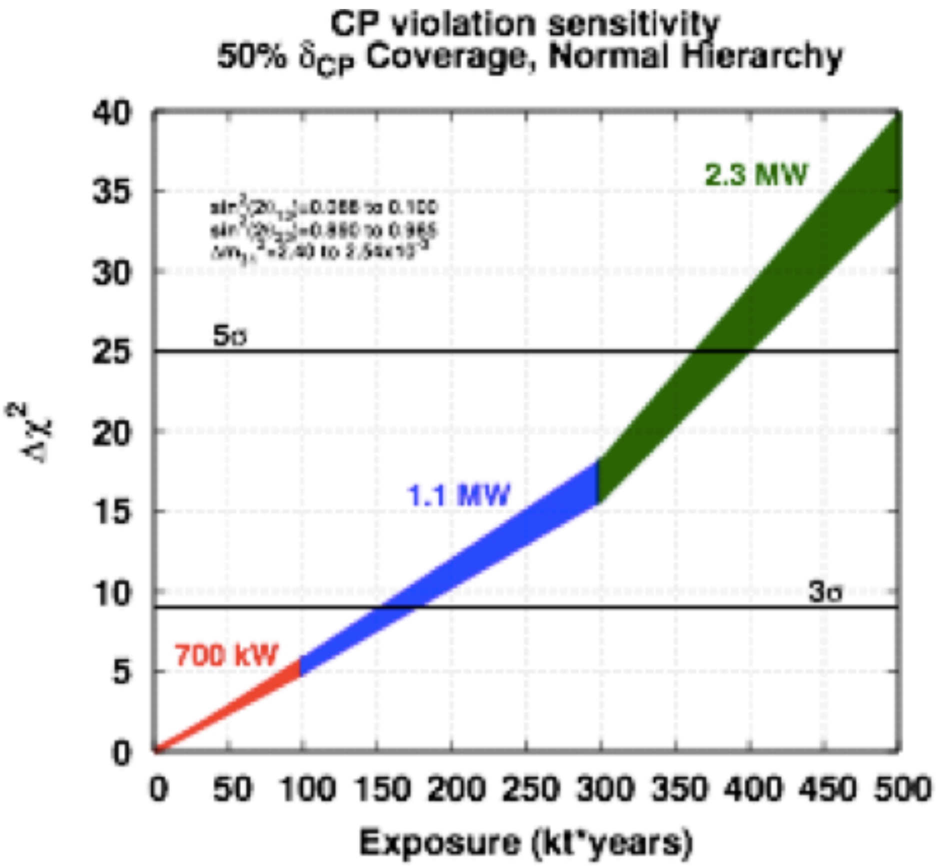
LBNE events at 1300 km w/ oscillation probabilities

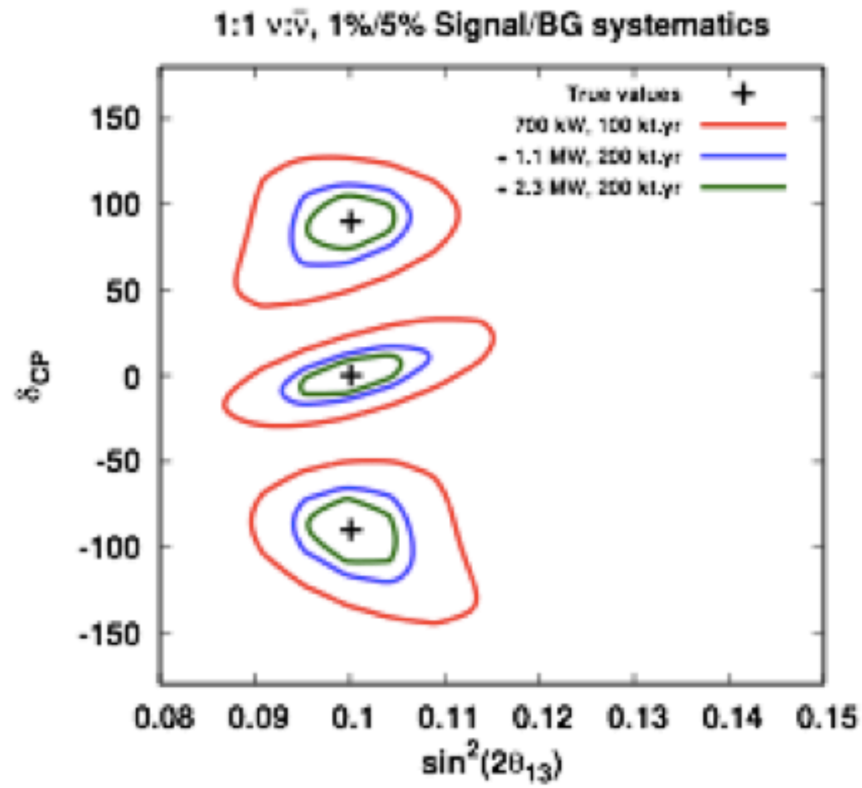




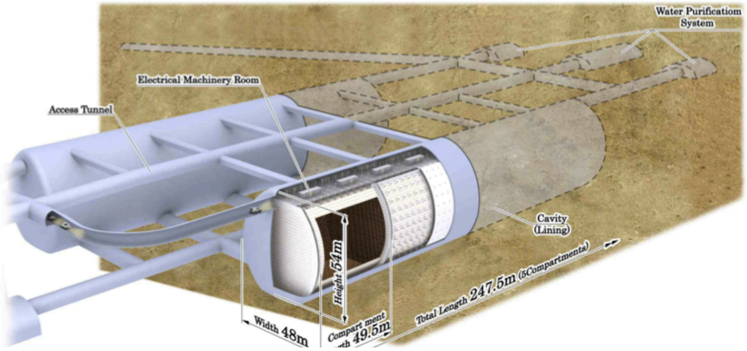
improvement with more mass
or beam (e.g. Project X at FNAL)

Long range plan for LBNE

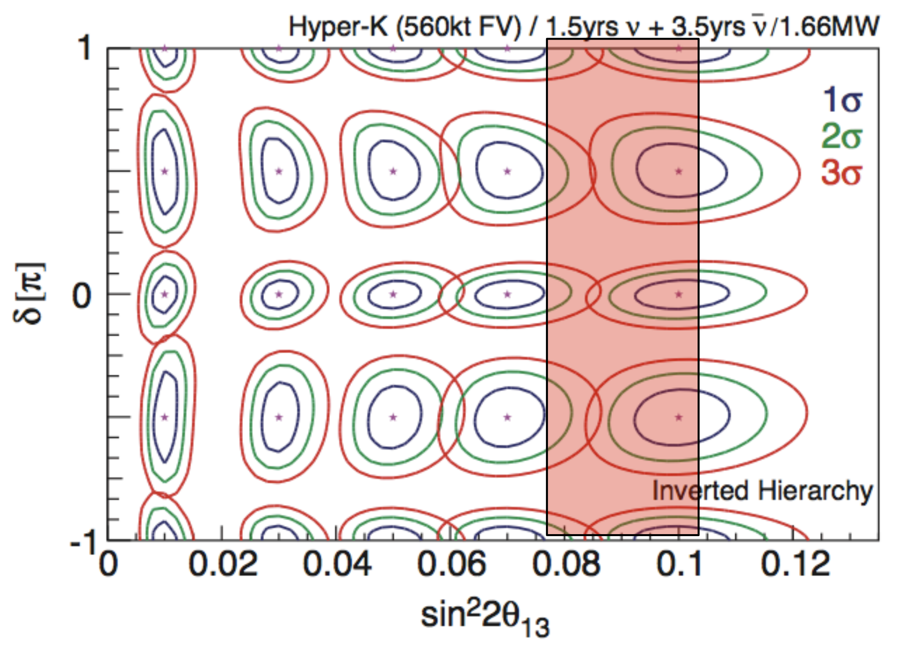




Other long-baseline programs: Hyper-K in Japan



M. Yokoyama

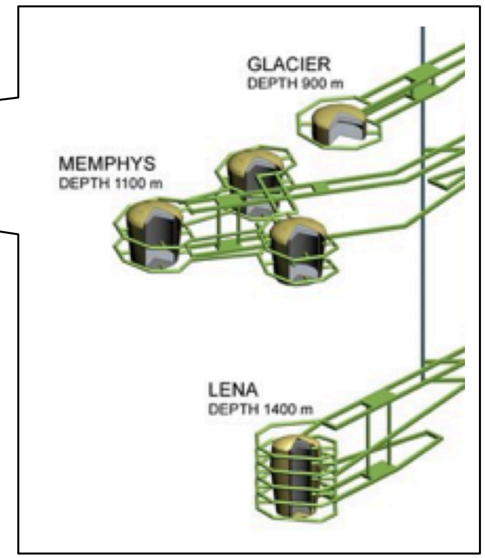


Large detector and long-baseline programs in Europe

LAGUNA-LBNO

MEMPHYS: 0.5 Mt water
GLACIER: 100 kt LAr
LENA: 50 kt scintillator

Pyhäsalmi (2300 km)



Neutrinos in the proposed CERN Strategy

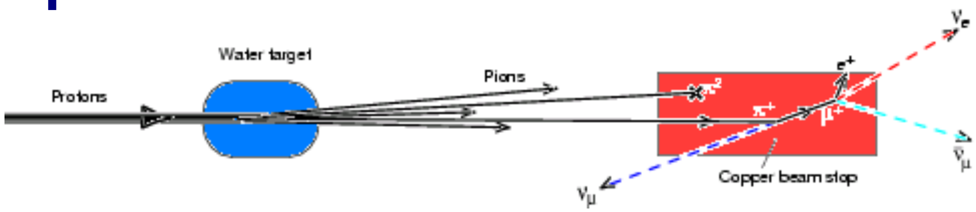
f) Rapid progress in neutrino oscillation physics, with significant European involvement, has established a strong scientific case for a long-baseline neutrino programme exploring CP violation and the mass hierarchy in the neutrino sector. *CERN should develop a neutrino programme to pave the way for a substantial European role in future long-baseline experiments. Europe should explore the possibility of major participation in leading neutrino projects in the US and Japan.*

Under discussion: collaboration on LBNE, HK; LBNO demonstrator @CERN, CENF, νStorm

(Parenthesis 1

LSND at Los Alamos

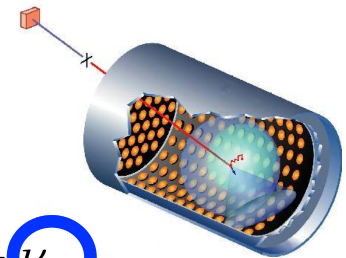
Liquid Scintillator Neutrino Detector



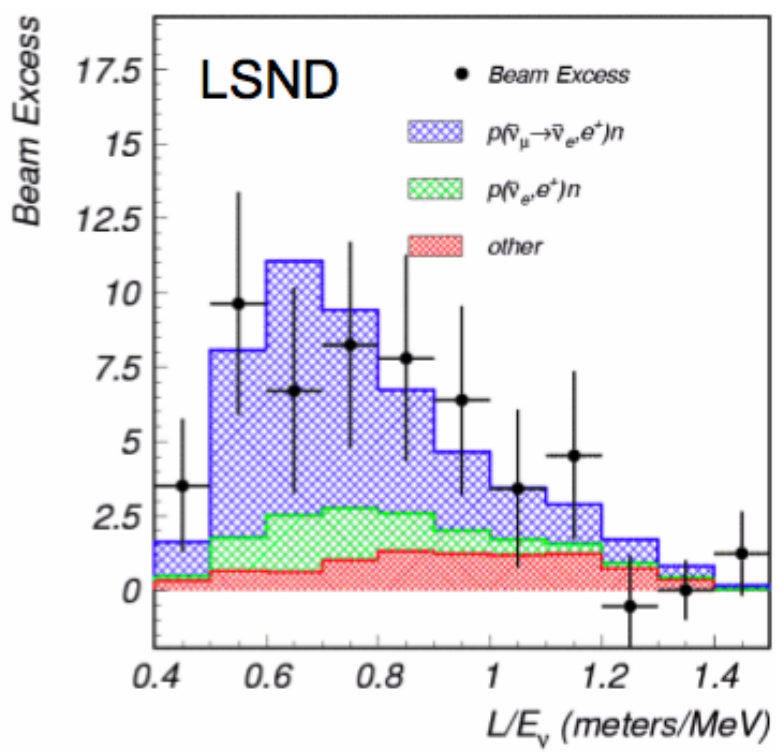
$\pi^+ \rightarrow \mu^+ + \nu_\mu$

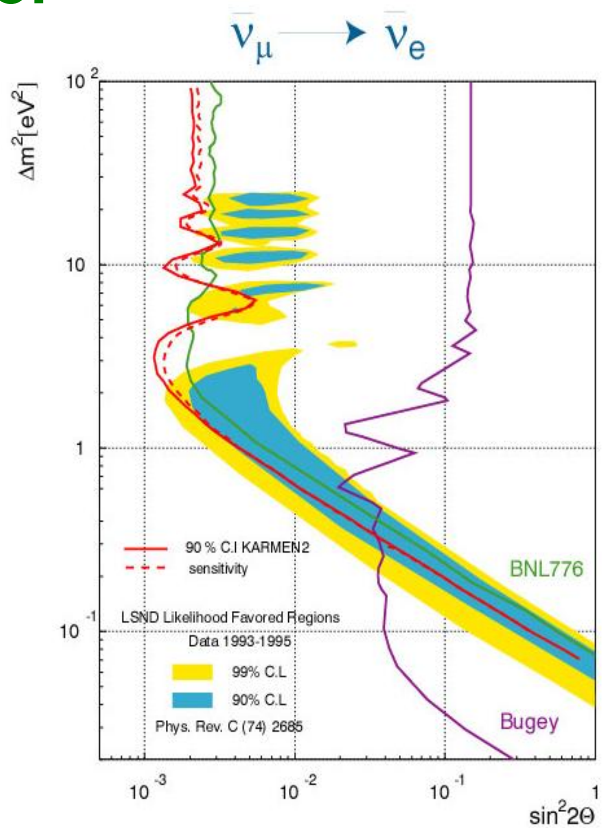
$\downarrow$

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



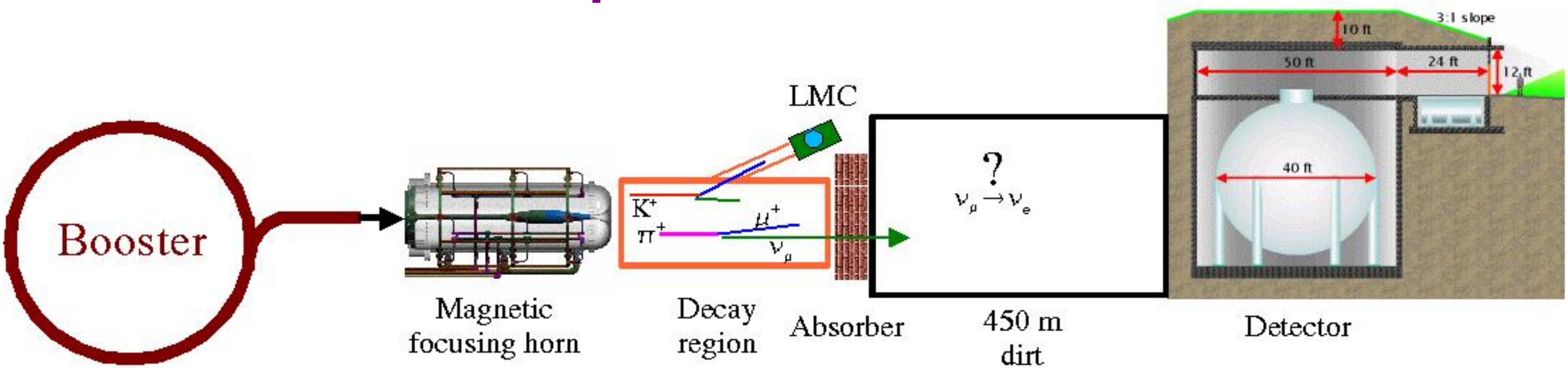
- 30 m baseline, 167 tons scintillator
- stopped pion source





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

MiniBooNE
Booster Neutrino Experiment at Fermilab



L~ 500 m

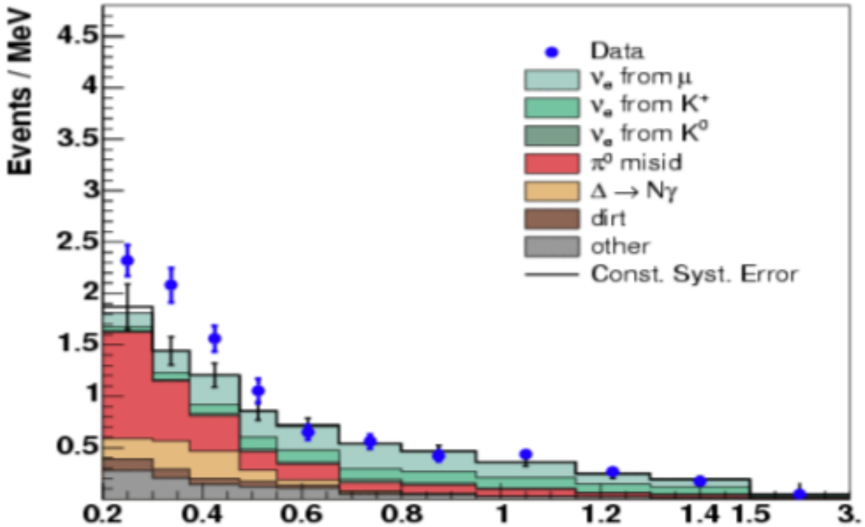
E_ν~ 1 GeV from 8 GeV booster

0.8 kton of mineral oil

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

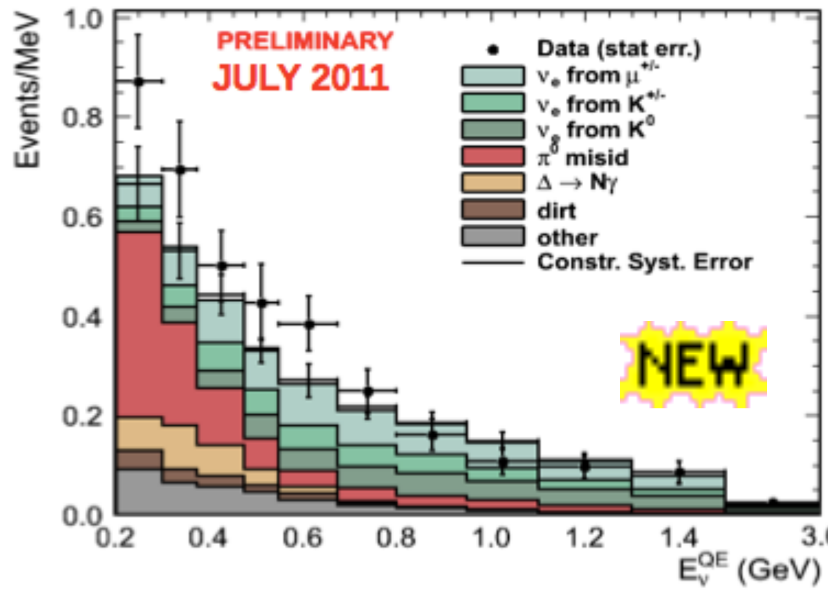
L↑, E↑ : different systematics

Neutrinos



R. Van de Water, Nu2010

Antineutrinos



Neutrinos:

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

????

Antineutrinos:

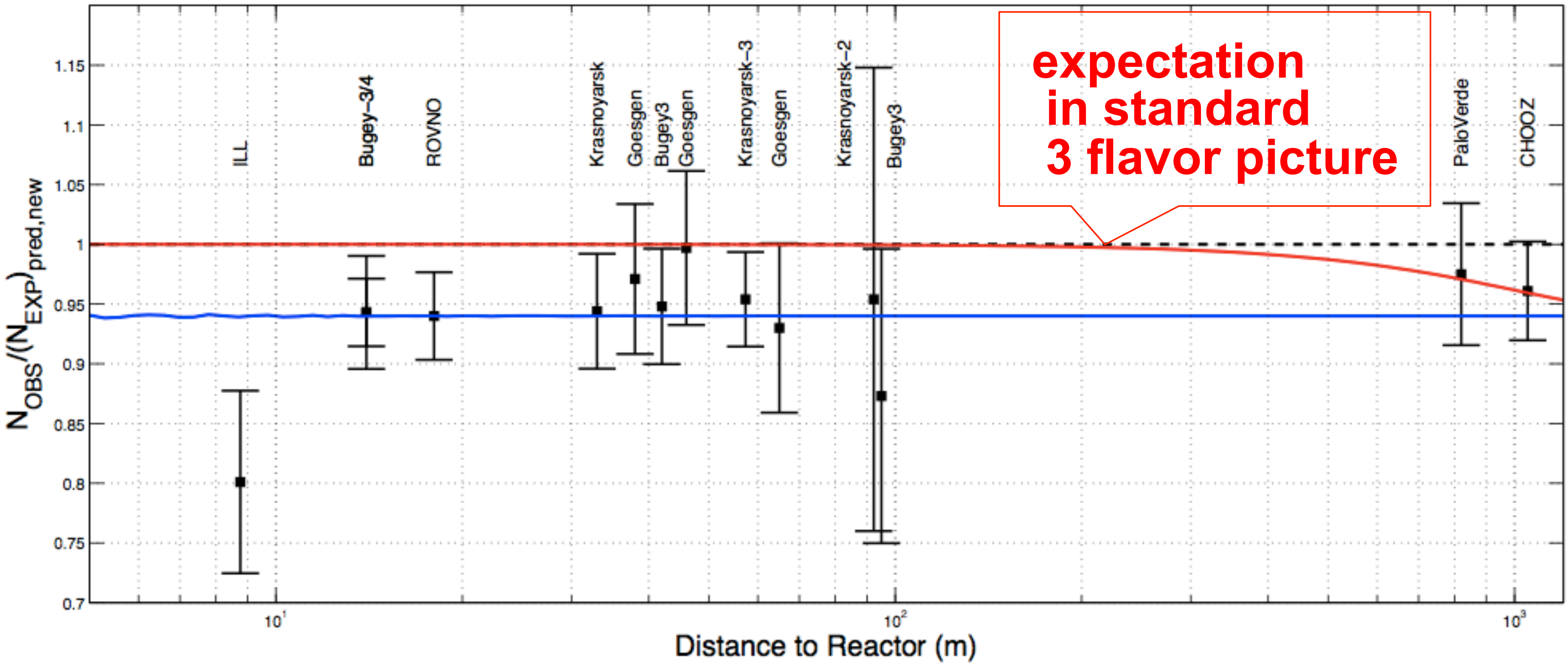
- small excess for E < 475 MeV, ~consistent with neutrinos
- small excess for E > 475 MeV (less than before)
  (consistent w/ LSND, 15% consistent w/ no osc)

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

Parenthesis 1)

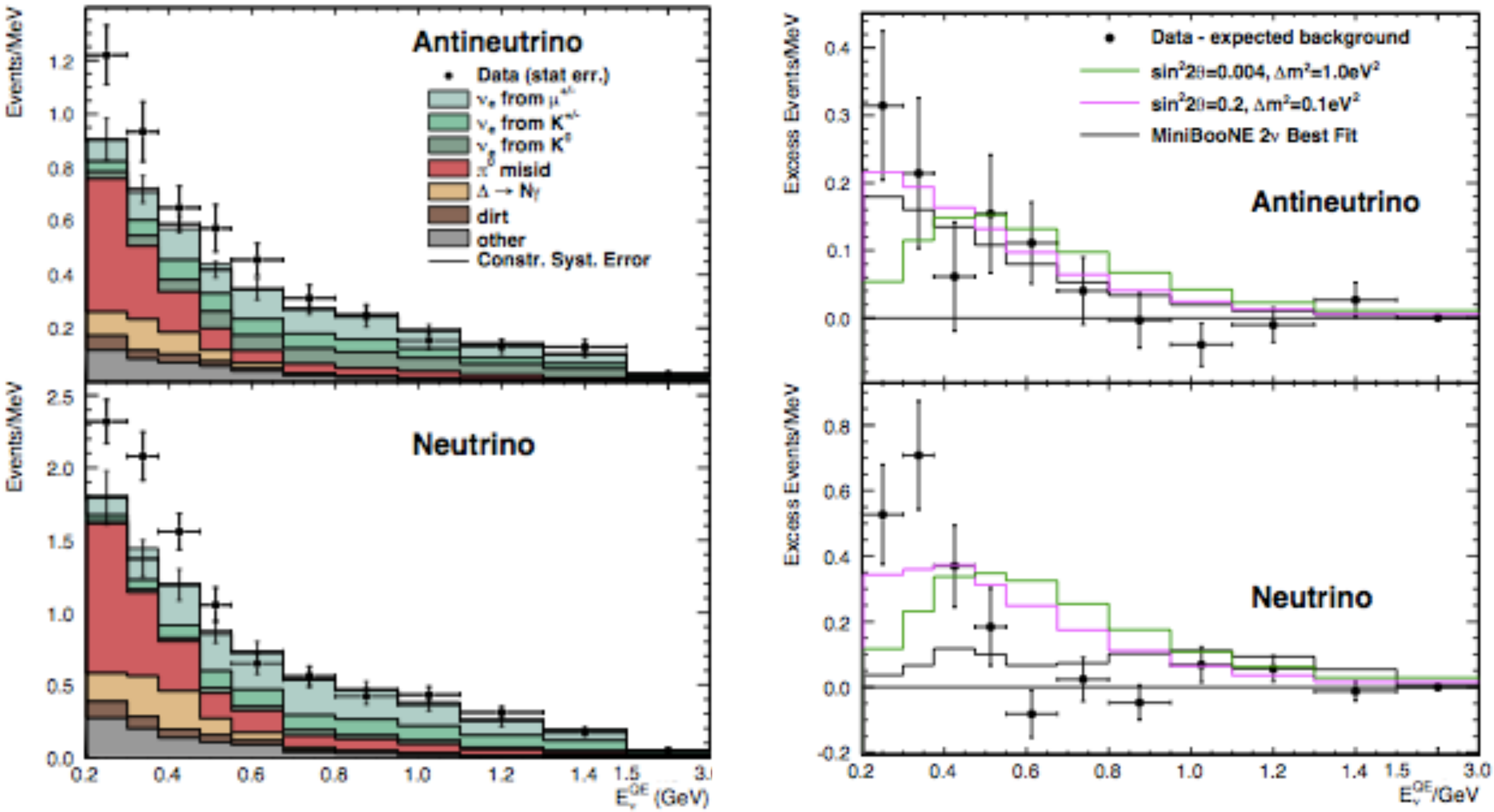
“Reactor neutrino anomaly”

arXiv:1101.2755

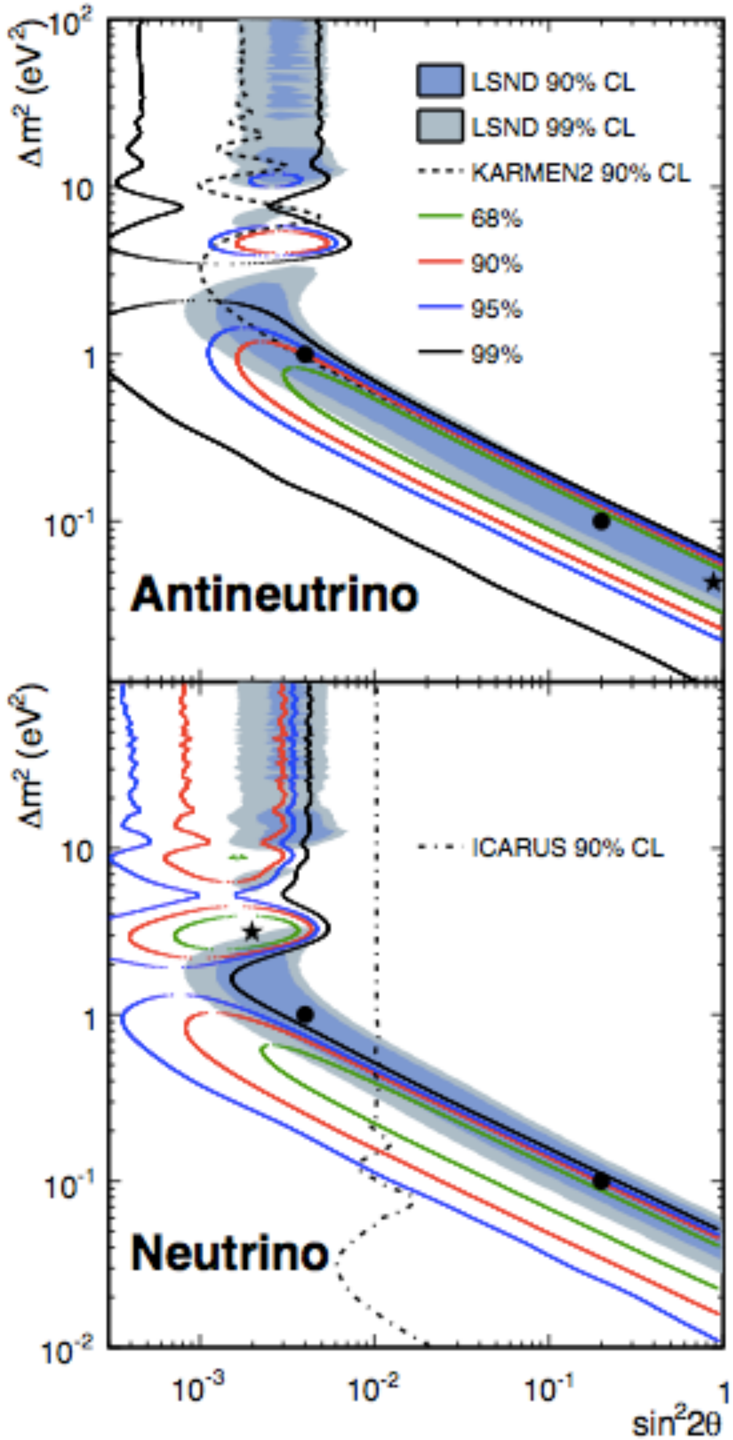


- Reactor neutrino flux calculations recently reevaluated (+3%, smaller uncertainty)
- Now historical data show deficit, <2% consistent w/expectation
- Sterile neutrino hint?

Latest MiniBooNE results



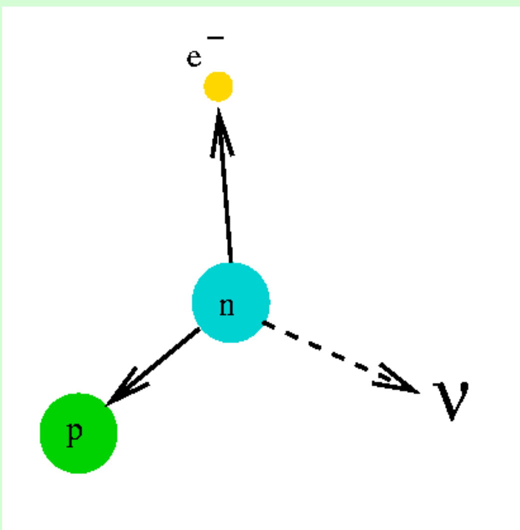
arXiv:1303.2588

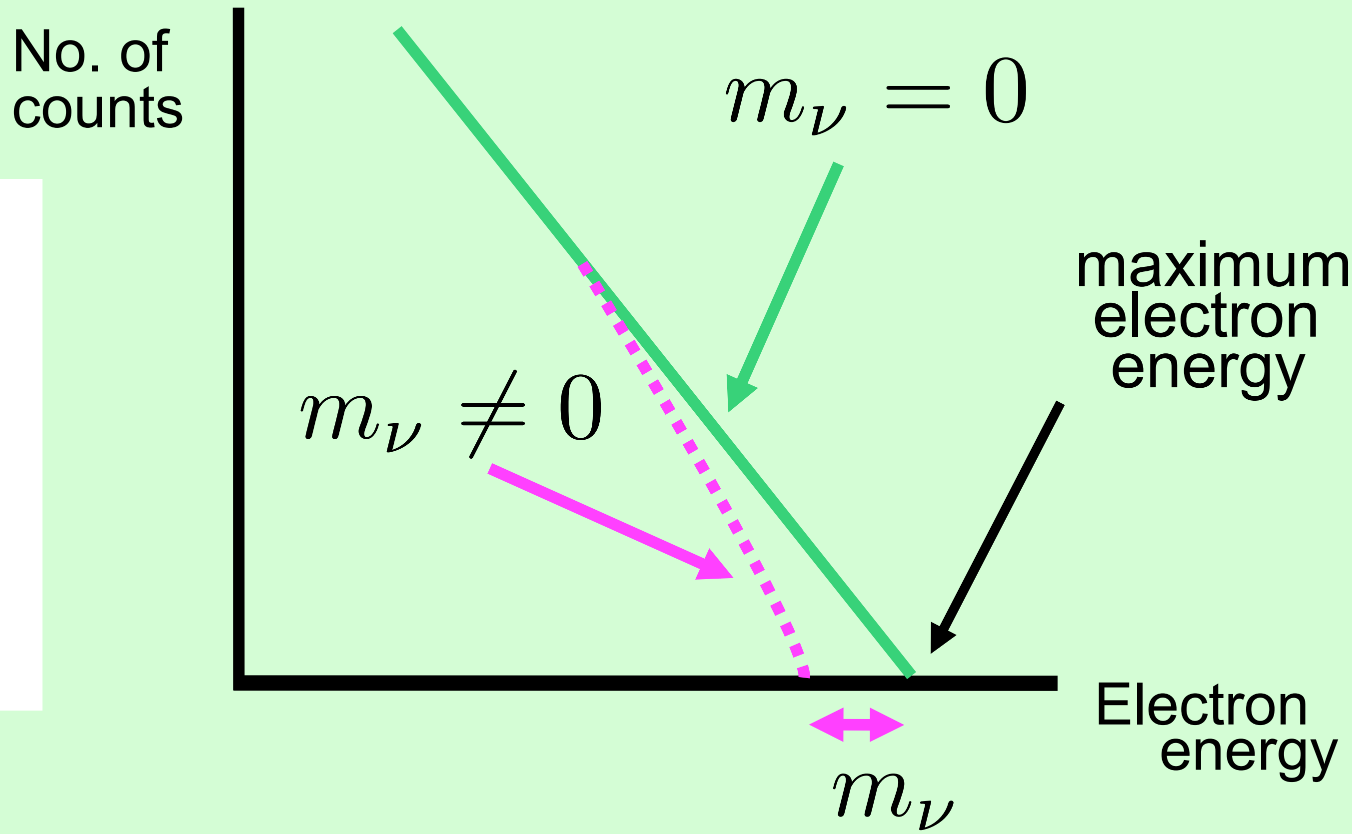


E_{ν}^{QE}>200 MeV

What about the absolute neutrino mass scale?

Kinematic experiments for absolute neutrino mass
(oscillation experiments only inform on mass *differences*)





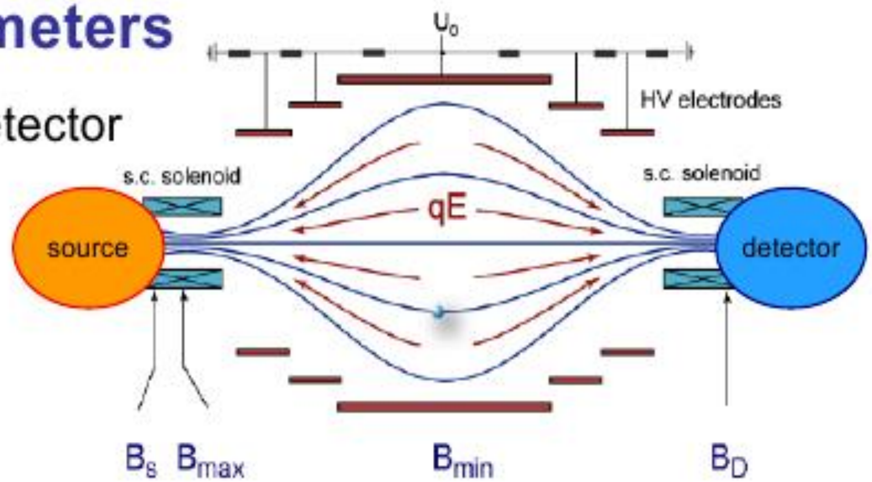
Look for distortion of β-decay spectrum near endpoint

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

Experimental approaches: aiming for sub-eV sensitivity

Spectrometers

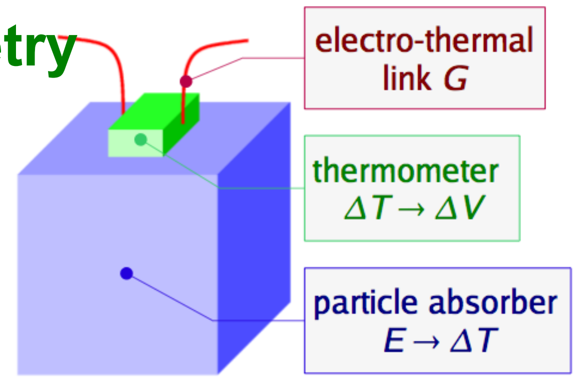
Source≠Detector



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

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

Thermal calorimetry

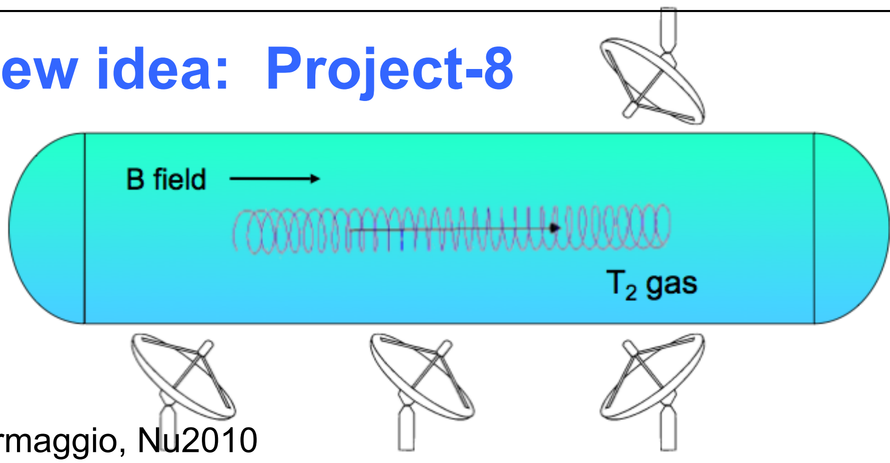


A. Nucciotti, Nu2010

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

2.5 keV endpoint
MARE

New idea: Project-8



J. Formaggio, Nu2010

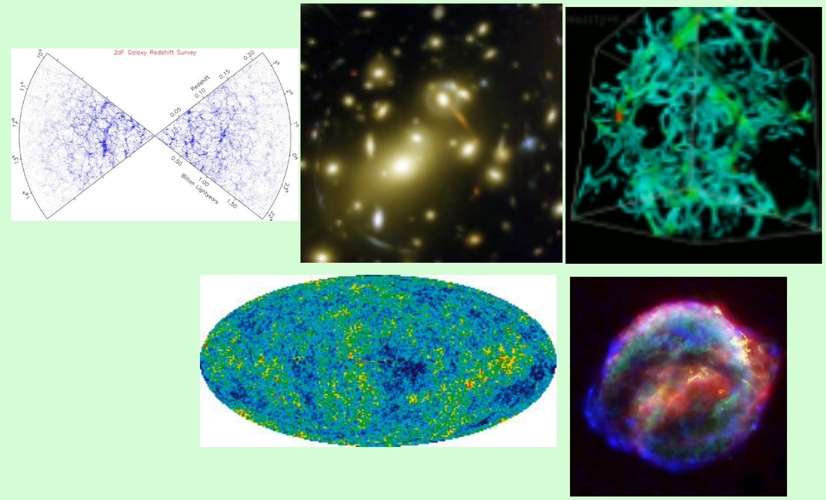
$$^3\mathrm{H} \rightarrow ^3\mathrm{He} + e^- + \bar{\nu}_e$$

Measure energy via
cyclotron frequency

Another way of getting at absolute neutrino mass

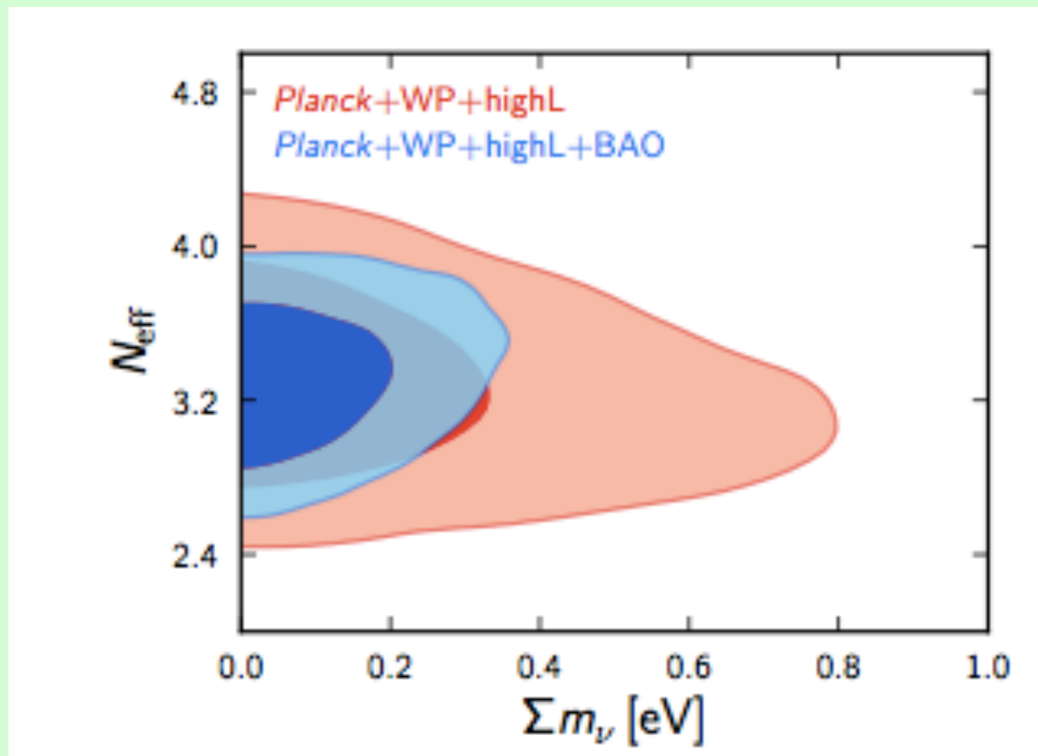
Fits to cosmological data:
CMB, large scale structure,
high Z supernovae,
weak lensing,...

(model-dependent)



from Planck

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



And some giant questions I will omit...

How do we add the masses to the SM?

Are neutrinos Majorana or Dirac?

Neutrinoless Double Beta Decay

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