Credit: Sandbox

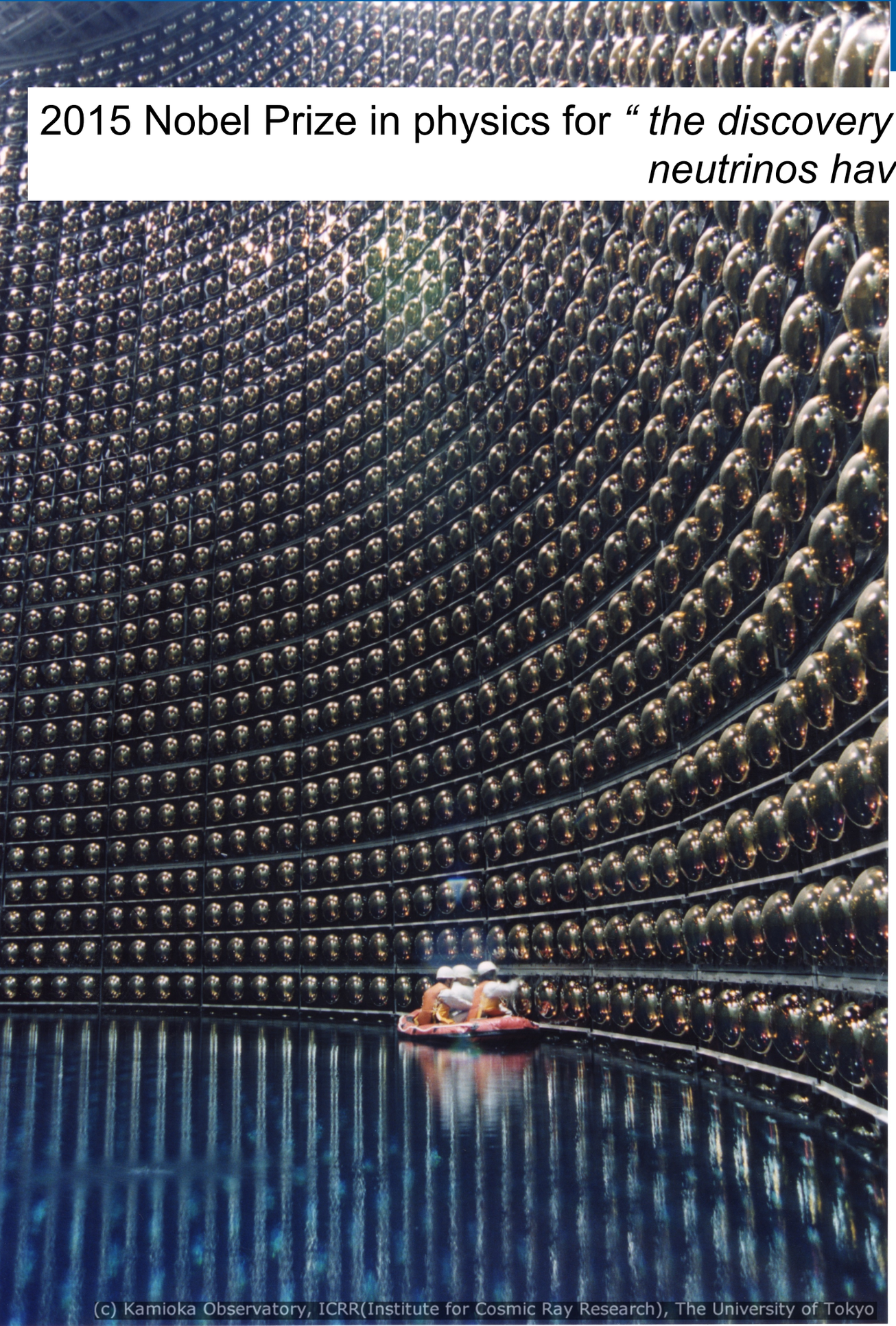
Neutrino Mixing

Louise Suter, Fermilab

Cosmic Neutrino Workshop

10th October 2019

2015 Nobel Prize in physics for *" the discovery of neutrino oscillations, which shows that neutrinos have mass"*



- Takaaki Kajita for "the first measurement of ν_μ disappearance in atmosphere ν using Super-Kamiokande"
- Arthur McDonald for "leading SNO, who demonstrated that solar ν were not disappearing on their way to Earth, instead they arrived at SNO with a different ν flavor"

Proved that neutrinos must have mass

New York Times, June 5th 1998

Mass Found in Elusive Particle; Universe May Never Be the Same

Discovery on Neutrino Rattles Basic Theory About All Matter

By MALCOLM W. BROWNE

TAKAYAMA, Japan, June 5 — In what colleagues hailed as a historic

Detecting Neutrinos

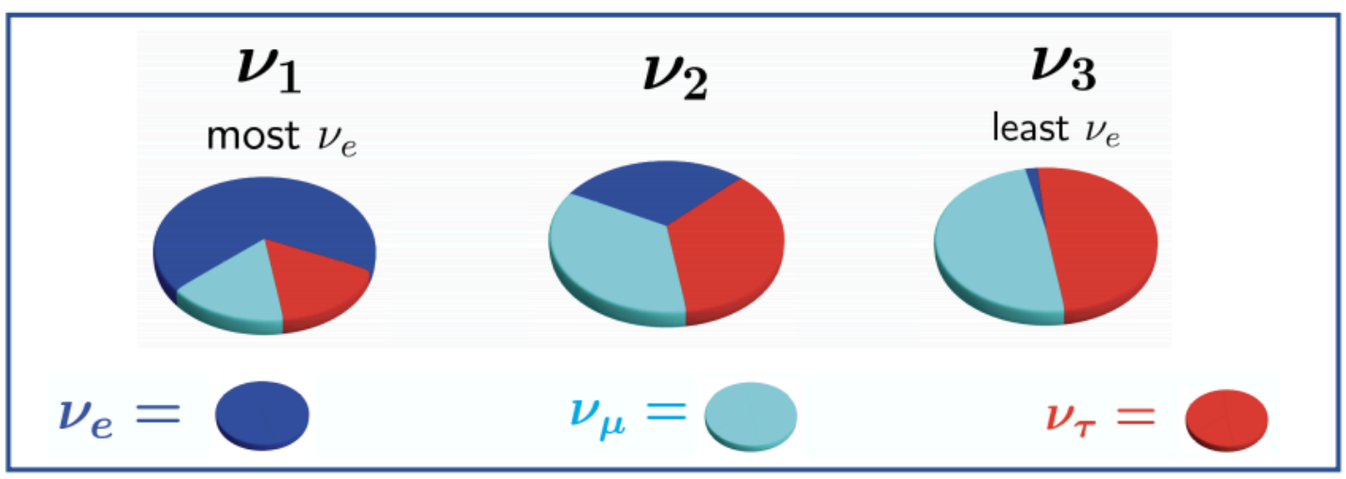
Neutrinos pass through the Earth's surface to a tank filled with 12.5 million gallons of ultra-pure water . . .

They are very light (m_ν < a few eV), electrically neutral, and only interact via weak force (and gravity)

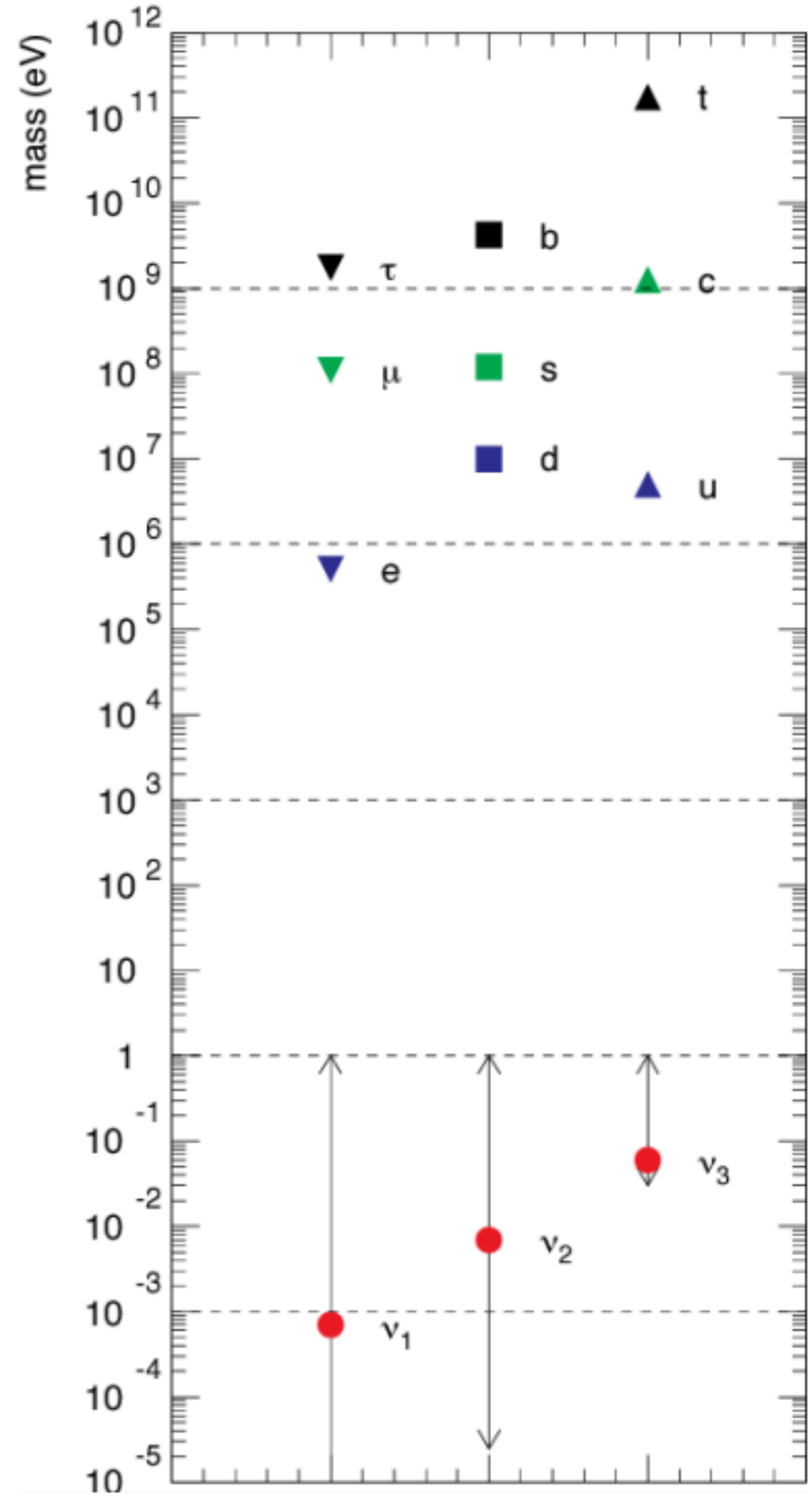
There are 3 types known to interact via the weak force

Interact in three flavor states, which are not the same as their mass states. Rotation from mass to flavor states described by the PMNS mixing matrix

$$\begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

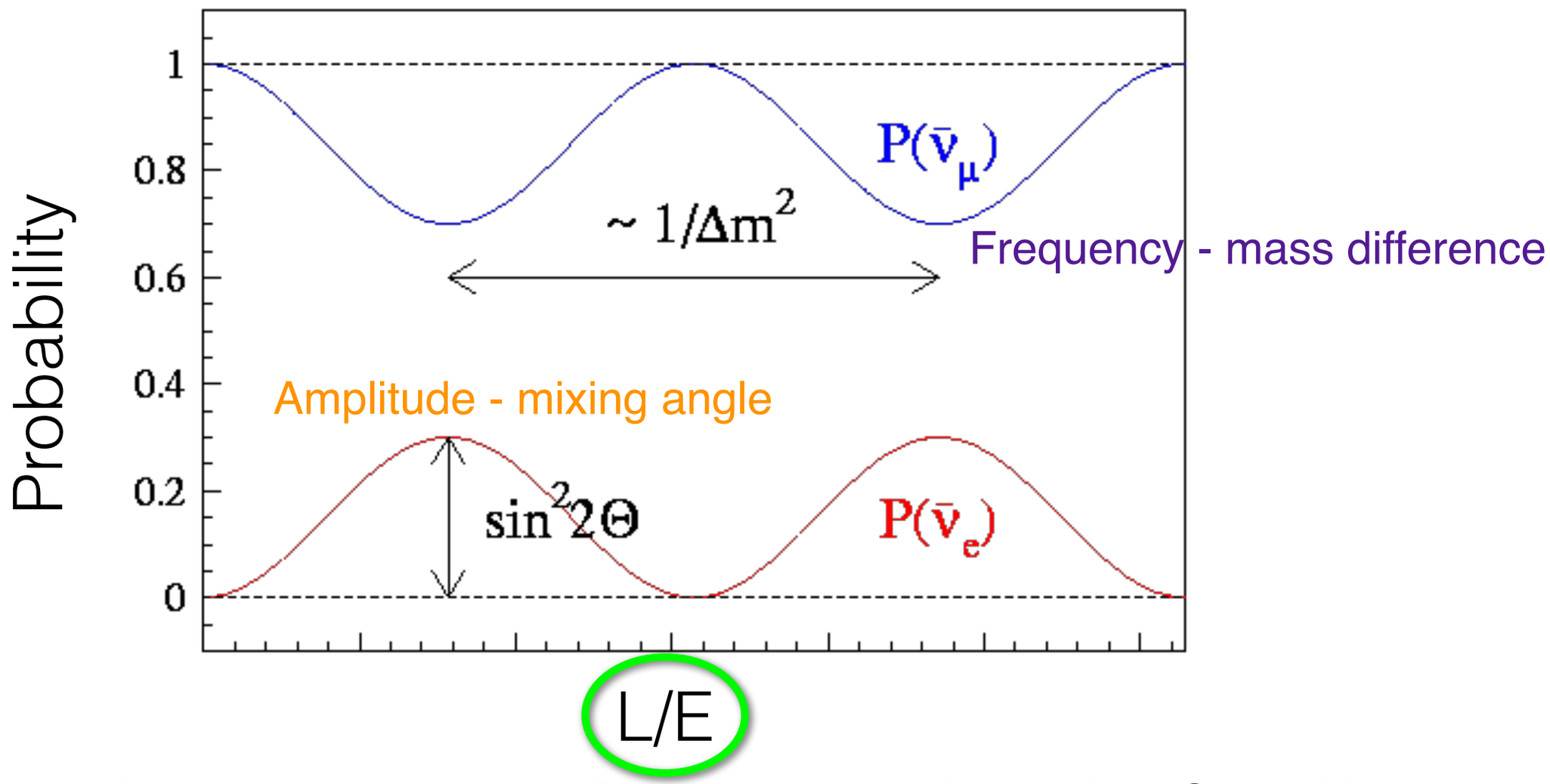


Mixing angles θ_{12}, θ_{13}, θ_{23} determine the flavor content of the mass eigenstate



2-flavor Oscillation Probability

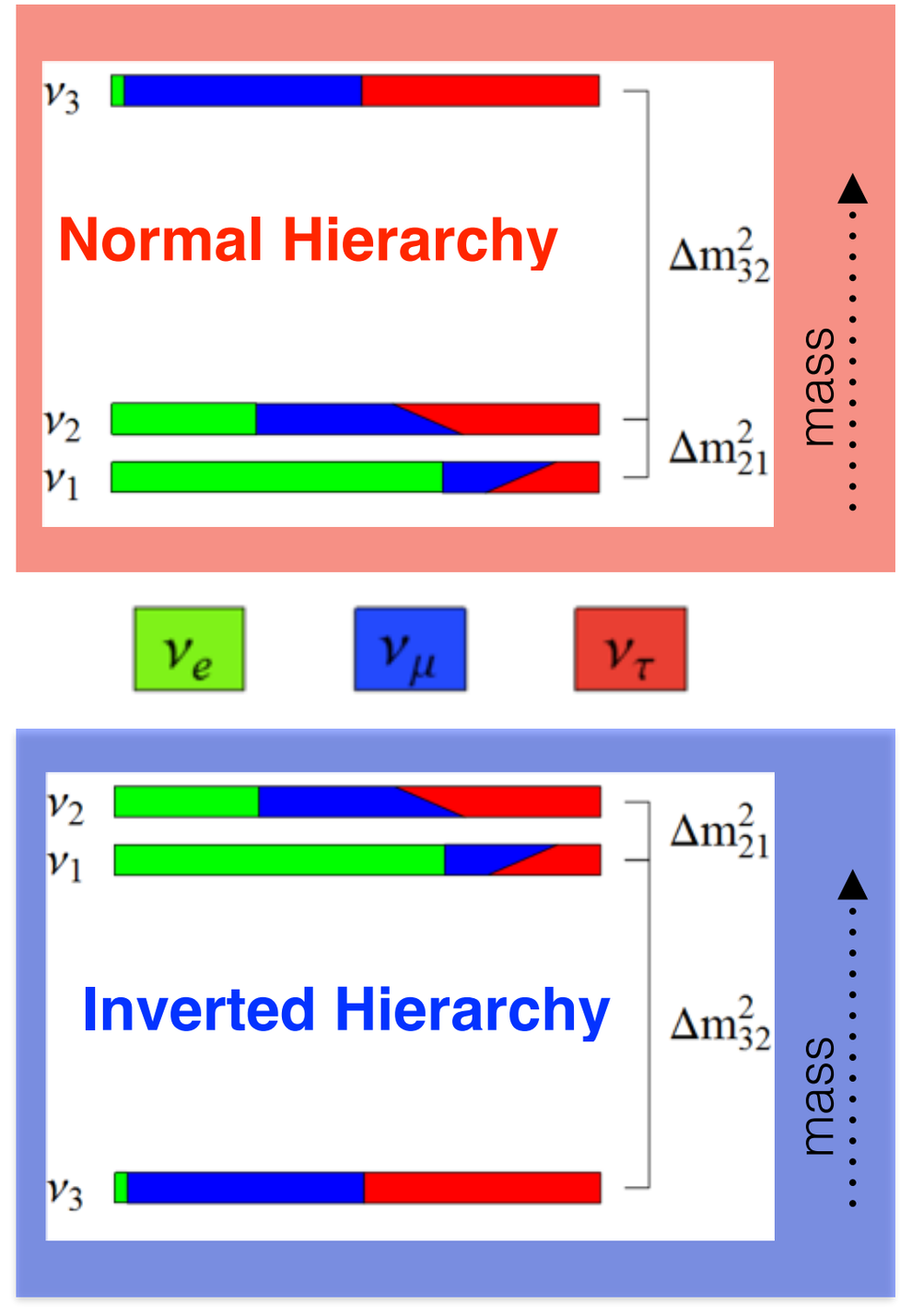
$$P\left(\nu_\alpha \to \nu_\beta\right) = \sin^2 2\theta_{ij} \times \sin^2\left(1.27\Delta m^2_{ij}\frac{L}{E}\right)$$



Neutrino experiments nominally work on a simple premise: Start with a source of neutrinos with a known flavor composition and measure it after some distance to see how it changes

Neutrino Mass Hierarchy/Ordering

- Since we have three neutrino flavors we would need two mass splittings to separate these states
  - Δm^2 Atmospheric = $\Delta m^2_{32} \simeq 2 \times 10^{-3} \mathrm{eV}^2$
  - Δm^2 Solar = $\Delta m^2_{21} \simeq 8 \times 10^{-5} \mathrm{eV}^2$
- We have only measured the absolute value of the atmospheric mass splitting, meaning we don't which of ν_1 or ν_3 is the heaviest
- Two possible orderings: Normal and Inverted



Neutrino mixing matrix, PMNS matrix, can be factorized into three terms

$$\left|\begin{matrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{matrix}\right\rangle = \begin{pmatrix}1 & & \\ & c_{23} & s_{23}\\ & -s_{23} & c_{23}\end{pmatrix}\begin{pmatrix}c_{13} & & s_{13}e^{-i\delta}\\ & 1 & \\ -s_{13}e^{i\delta} & & c_{13}\end{pmatrix}\begin{pmatrix}c_{12} & s_{12} & \\ -s_{12} & c_{12} & \\ & & 1\end{pmatrix}\left|\begin{matrix}\nu_1\\ \nu_2\\ \nu_3\end{matrix}\right\rangle$$

$\Delta m^2_{32} \simeq 2\times 10^{-3}\mathrm{eV}^2$
$L/E = 500\ \mathrm{km/GeV}$

$\Delta m^2_{31} \approx \Delta m^2_{32}$

$\Delta m^2_{21} \simeq 8\times 10^{-5}\mathrm{eV}^2$
$L/E = 15{,}000\ \mathrm{km/GeV}$

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

atmospheric and long baseline

$\nu_e \longrightarrow \nu_e$
$\nu_\mu \longrightarrow \nu_e$

reactor and long baseline

$\nu_e \longrightarrow \nu_e$
$\nu_e \longrightarrow \nu_\mu + \nu_\tau$

solar and reactor

$c_{\alpha\beta} = \cos_{\alpha\beta} \quad s_{\alpha\beta} = \sin_{\alpha\beta}$

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$$P_{\alpha\alpha} \approx 1 - \sin^2(2\theta)\sin^2\left(\frac{1.27\Delta m^2[\mathrm{eV}^2]L_\nu[\mathrm{km}]}{E_\nu[\mathrm{GeV}]}\right)$$

Extending to full three flavors

$$\sin^2(2\theta) = 4\sin^2\theta_{23}\cos^2\theta_{13}(1-\sin^2\theta_{23}\cos^2\theta_{13})$$

$$\Delta m^2 = \Delta m^2_{32} + \Delta m^2_{21}\sin^2\theta_{12} + \Delta m^2_{21}\cos\delta_{CP}\sin\theta_{13}\tan\theta_{23}\sin 2\theta_{12}$$

Oscillations in Matter: MSW = Mikheyev–Smirnov–Wolfenstein effect

$$\left|\begin{matrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{matrix}\right\rangle = \begin{pmatrix}1 & & \\ & c_{23} & s_{23}\\ & -s_{23} & c_{23}\end{pmatrix}\begin{pmatrix}c_{13} & & s_{13}e^{-i\delta}\\ & 1 & \\ -s_{13}e^{i\delta} & & c_{13}\end{pmatrix}\begin{pmatrix}c_{12} & s_{12} & \\ -s_{12} & c_{12} & \\ & & 1\end{pmatrix}\left|\begin{matrix}\nu_1\\ \nu_2\\ \nu_3\end{matrix}\right\rangle$$

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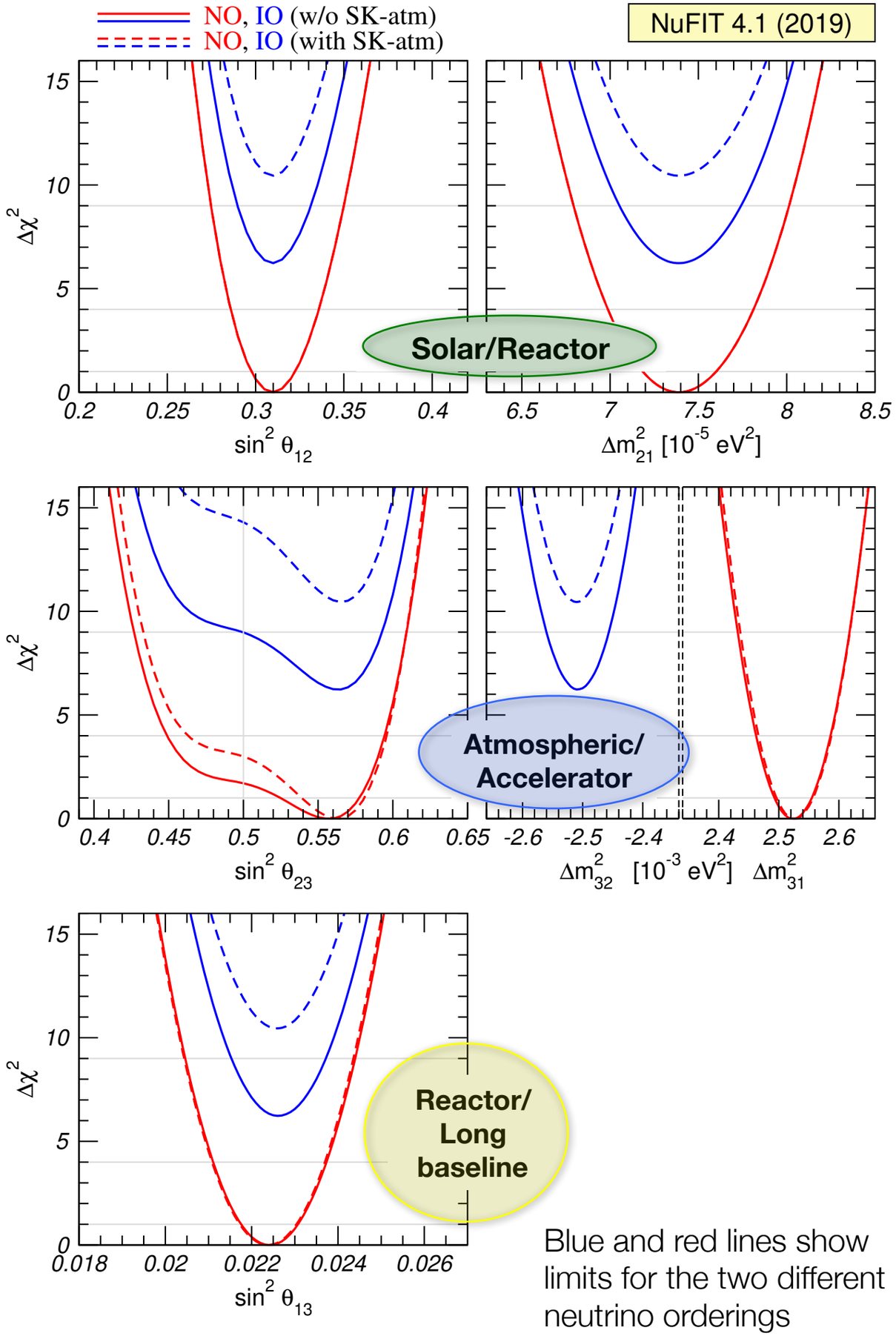
Still not the whole story, this is for oscillations in vacuum.
Probability is modified as neutrinos travel through matter.
Need to modify θ_{13} to θ_M, where

$$\sin^2 2\theta_M = \frac{\sin^2 2\theta_{13}}{\sin^2 2\theta_{13} + (A - \cos 2\theta_{13})^2}$$

$$A = \pm 2\sqrt{2} G_F n_e E_\nu / \Delta m^2_{13}$$

- Electron neutrinos experience additional interactions with the electrons in matter
- Big effect when traveling through dense mediums, i.e the Sun
- Matter effects allow accelerator and atmospheric experiments to probe the neutrino mass ordering



Blue and red lines show limits for the two different neutrino orderings

Need precision measurements of the 5 parameters: 3 mixing angles and 2 mass splitting

Also two unknowns, CP phase and mass ordering - See P. Vahle's talk

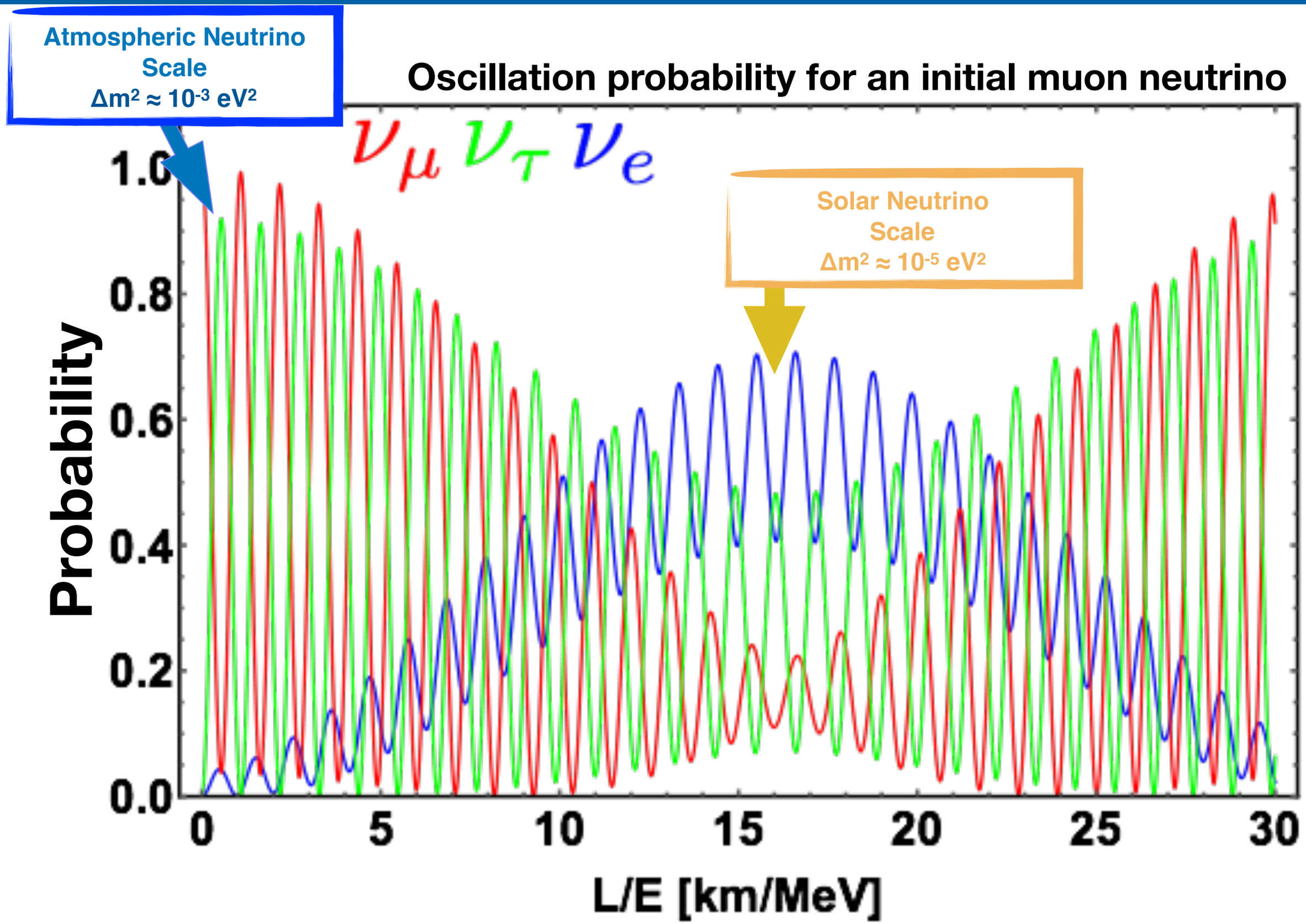
Further there are open questions about if our picture is complete:
Is there only three flavors?
Is it a unitary matrix ?

Most mixing angles and mass splittings known to a precision of about 3%

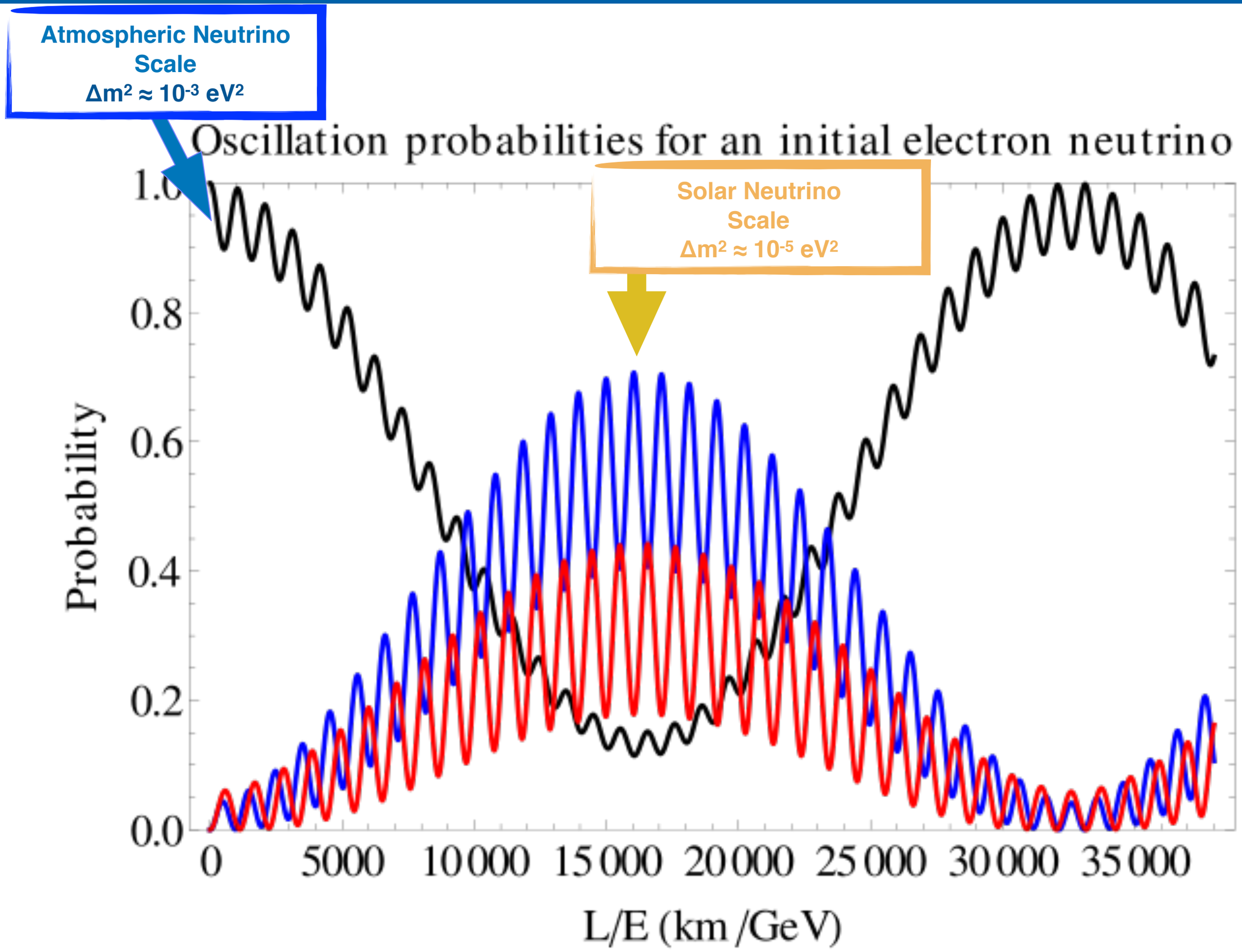
Mixing angle θ_{23} least well constrained and may indicate an additional symmetry

- θ_{23} ~45 degrees indicating possible maximal mixing between ν_μ and ν_τ in the ν_3 mass state
- If not maximal is it greater or less than 45 degrees (octant) ?

JHEP 01 (2019) 106 [arXiv:1811.05487], NuFIT 4.1 (2019), www.nu-fit.org



Probe angles and mass splitting by placing detectors at known L/E's


Atmospheric Neutrino Scale
Δm² ≈ 10⁻³ eV²
Solar Neutrino Scale
Δm² ≈ 10⁻⁵ eV²
Oscillation probabilities for an initial electron neutrino
Probability
1.0
0.8
0.6
0.4
0.2
0.0
0
5000
10000
15000
20000
25000
30000
35000
L/E (km /GeV)

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atmospheric and long baseline

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$\nu_\mu \to \nu_e$

reactor and long baseline

$\nu_e \to \nu_e$
$\nu_e \to \nu_\mu + \nu_\tau$

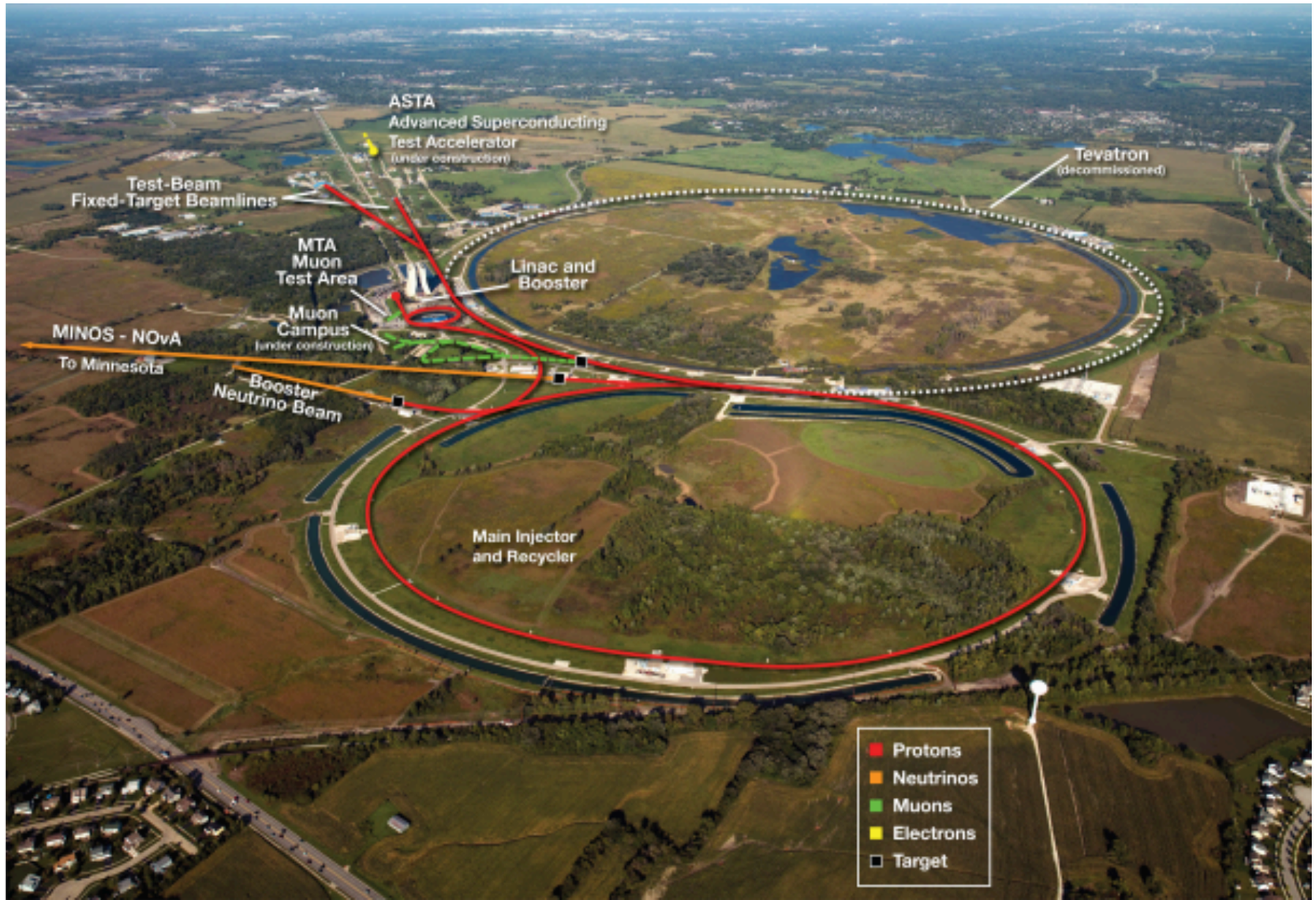
solar and reactor

Can be well approximated by 2-flavor oscillations in a vacuum

Long-Baseline accelerator and atmospheric experiments can probe

$c_{\alpha\beta} = \cos_{\alpha\beta}$
$s_{\alpha\beta} = \sin_{\alpha\beta}$

Long Baseline Accelerator Neutrinos

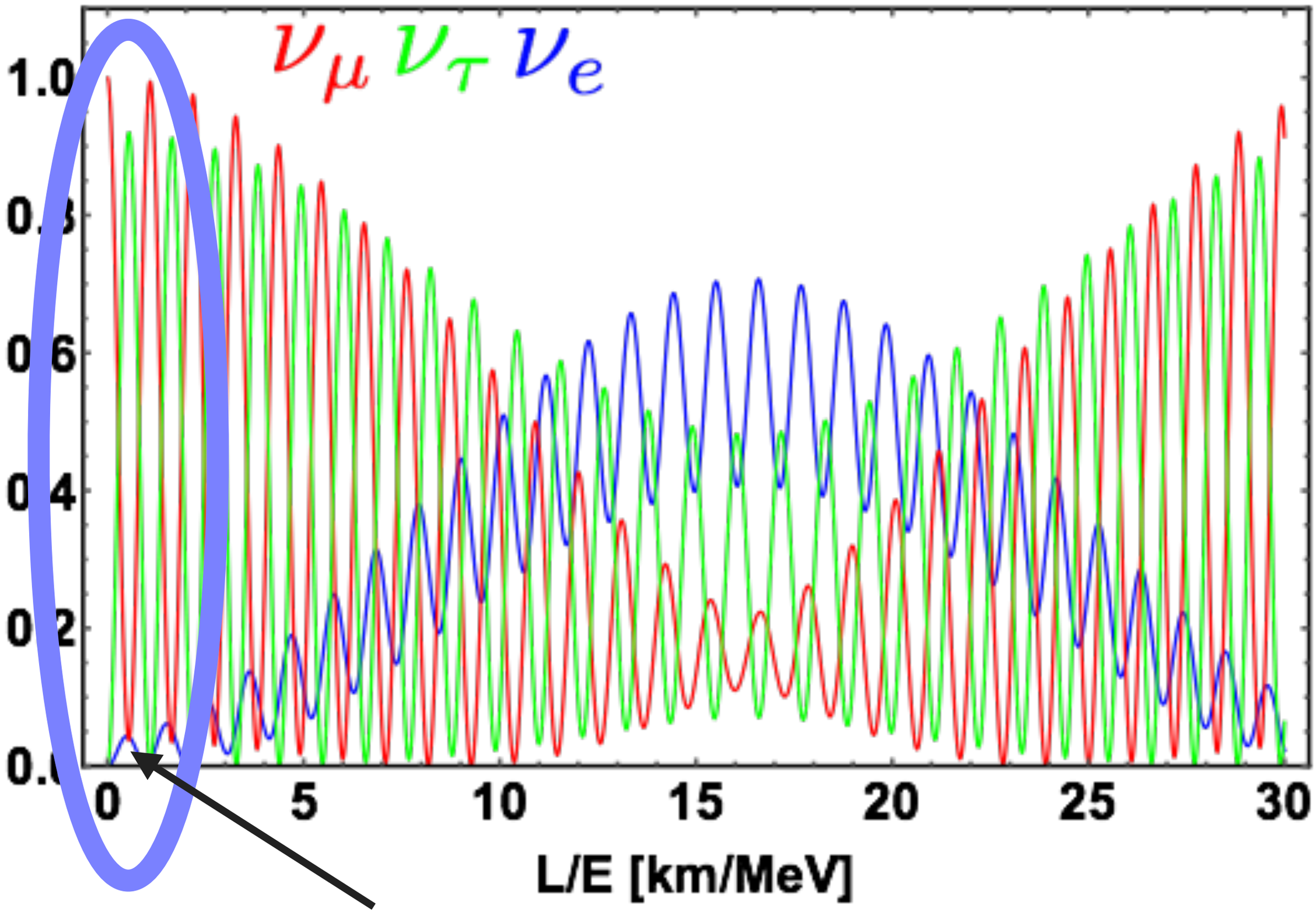


Produce beam of nearly pure muon neutrinos, in a relativity small range of known energies

Look at muon neutrino (or antineutrinos) oscillating
$\nu_\mu \rightarrow \nu_\mu, \nu_\tau, \nu_e$
(either ν_μ disappearing or other flavors appearing)

SK/T2K/MINOS ($\nu_\mu \rightarrow \nu_\mu$)	$4\lvert U_{\mu 3}\rvert^2 \left(1 - \lvert U_{\mu 3}\rvert^2\right) = 4\cos^2\theta_{13}\sin^2\theta_{23}\left(1 - \cos^2\theta_{13}\sin^2\theta_{23}\right)$
T2K/MINOS ($\nu_\mu \rightarrow \nu_e$)	$4\lvert U_{e3}\rvert^2\lvert U_{\mu 3}\rvert^2 = \sin^2 2\theta_{13}\sin^2\theta_{23}$

Oscillation probability for an initial muon neutrino



Measure % of muon neutrino oscillating into other flavors

ν_μ disappearance

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The two-flavor oscillation is a good approximation to measure the atmospheric parameter as the two mass splittings are very different

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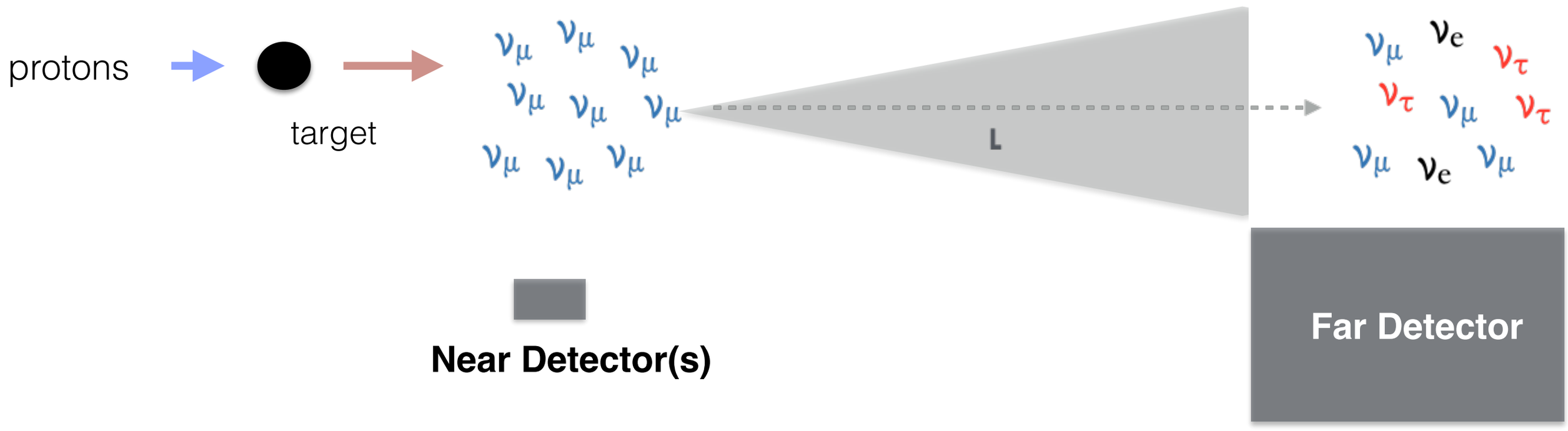
$$c_{\alpha\beta} = \cos_{\alpha\beta} \quad s_{\alpha\beta} = \sin_{\alpha\beta}$$

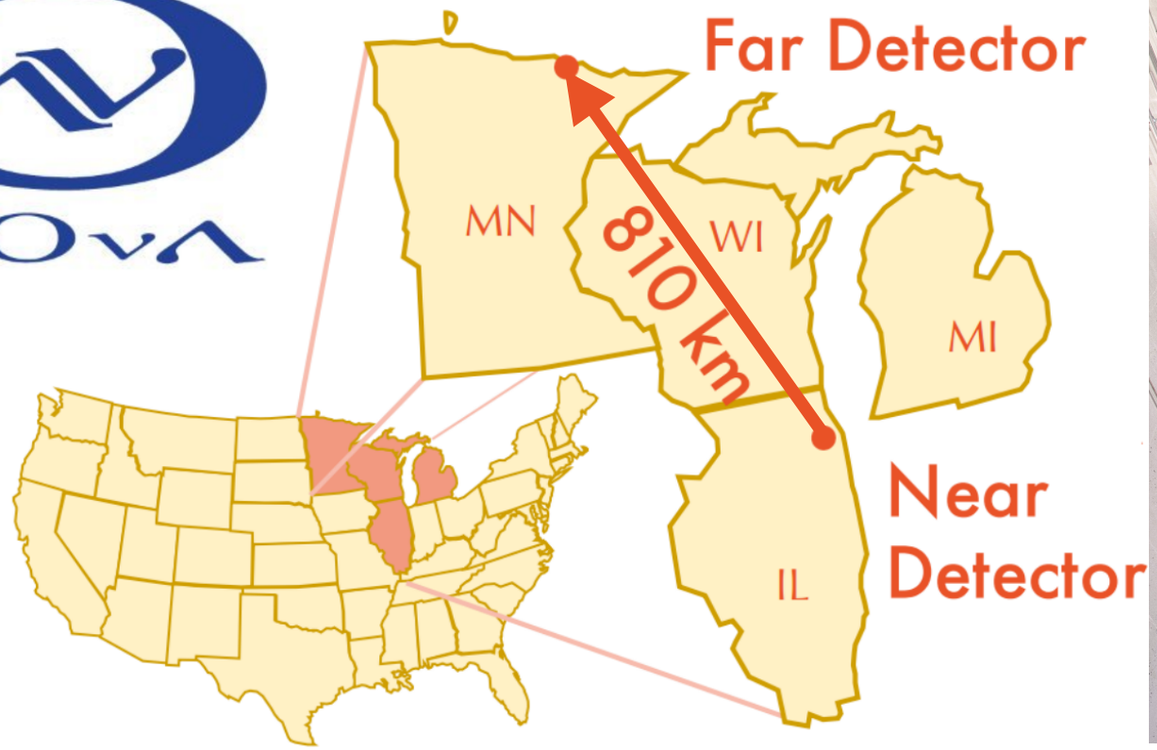
Long-baseline Accelerator Neutrino

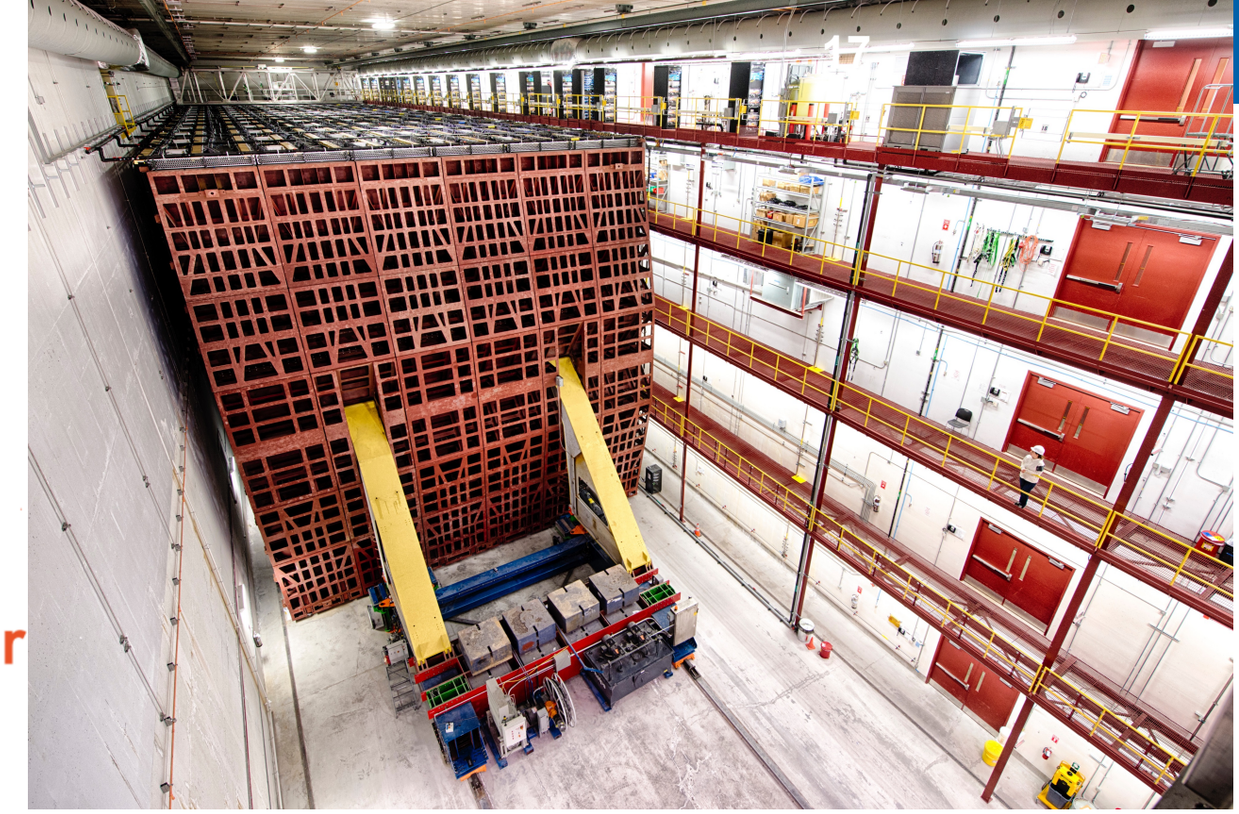
Create ~100% muon-neutrino beam (or anti-neutrino beam)

Characterize beam with ND

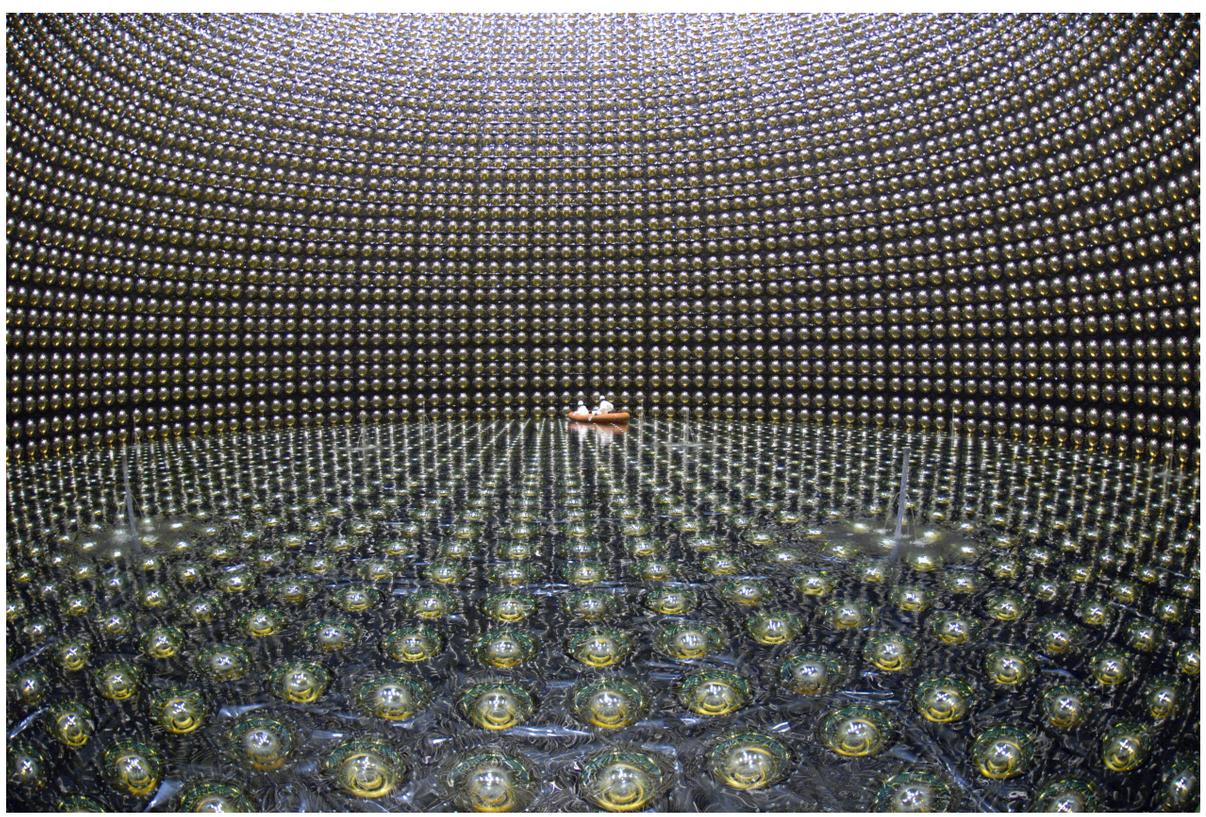
Measure beam content after oscillation,
ν_e appearance ($\nu_\mu \longrightarrow \nu_e$)
ν_μ survival (disappearance) ($\nu_\mu \longrightarrow \nu_\mu$)

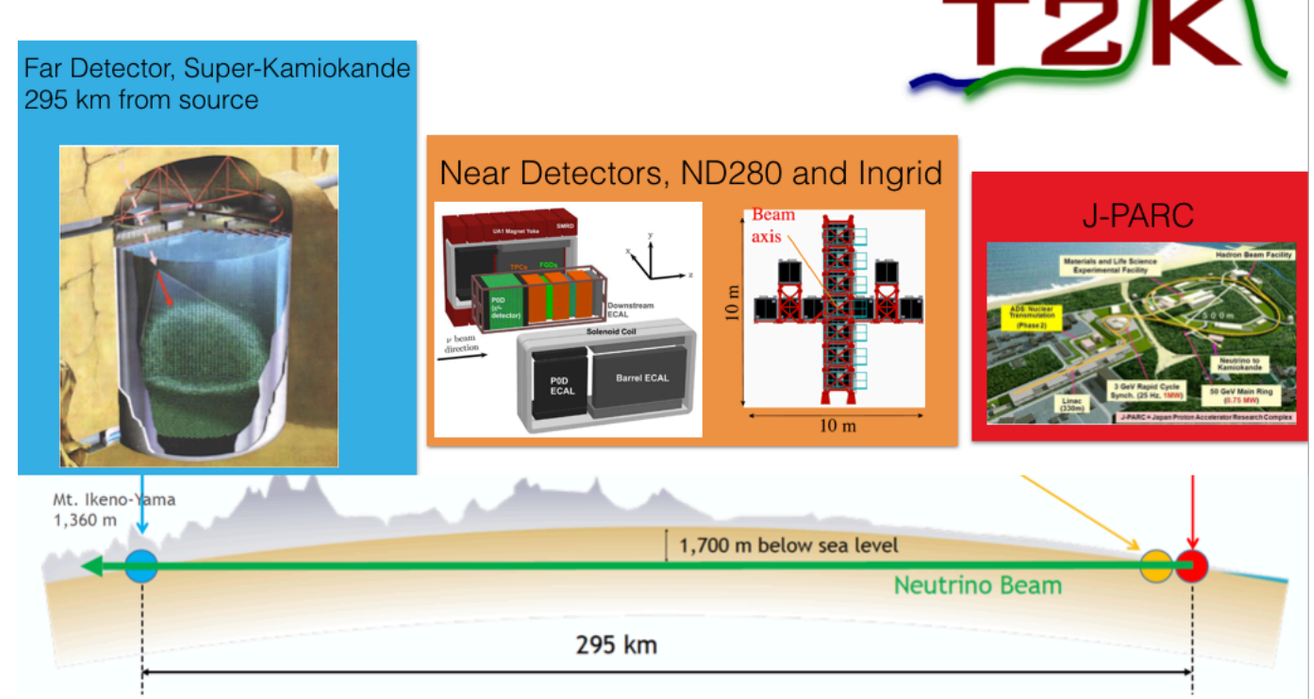






Currently running long baseline accelerator neutrino experiments

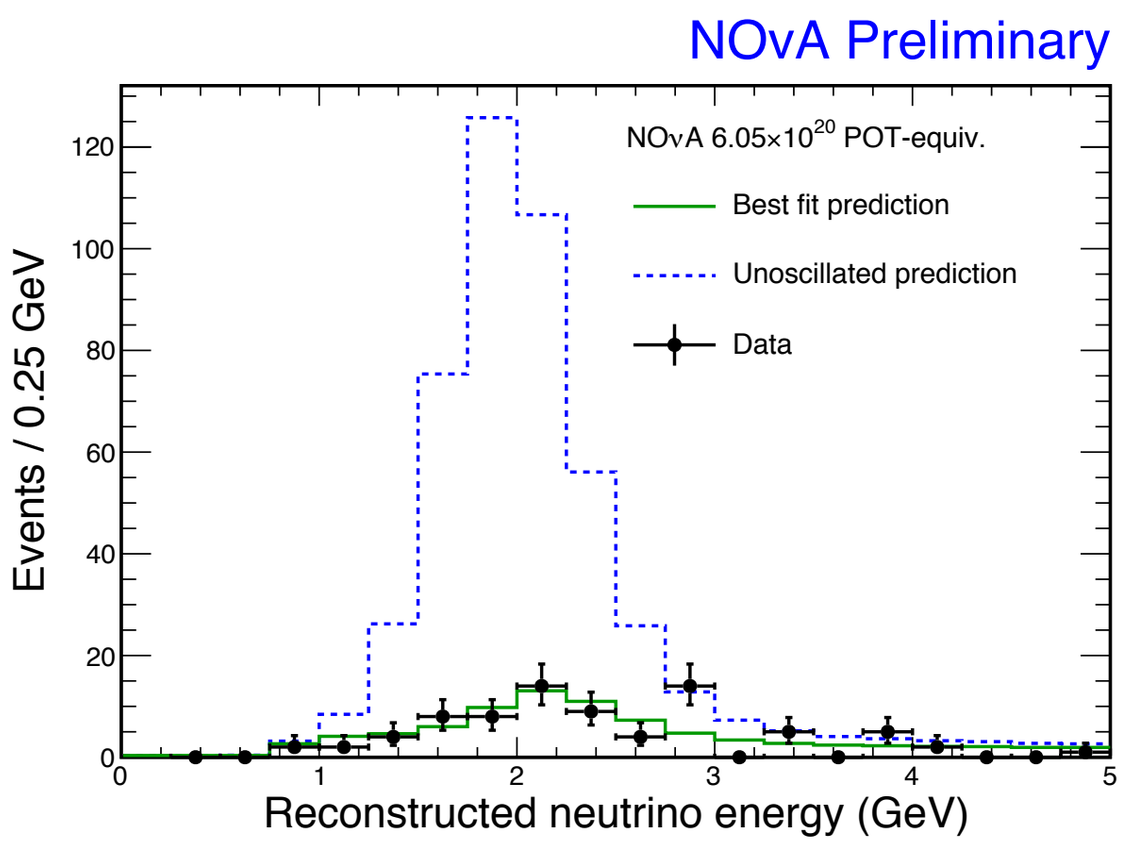


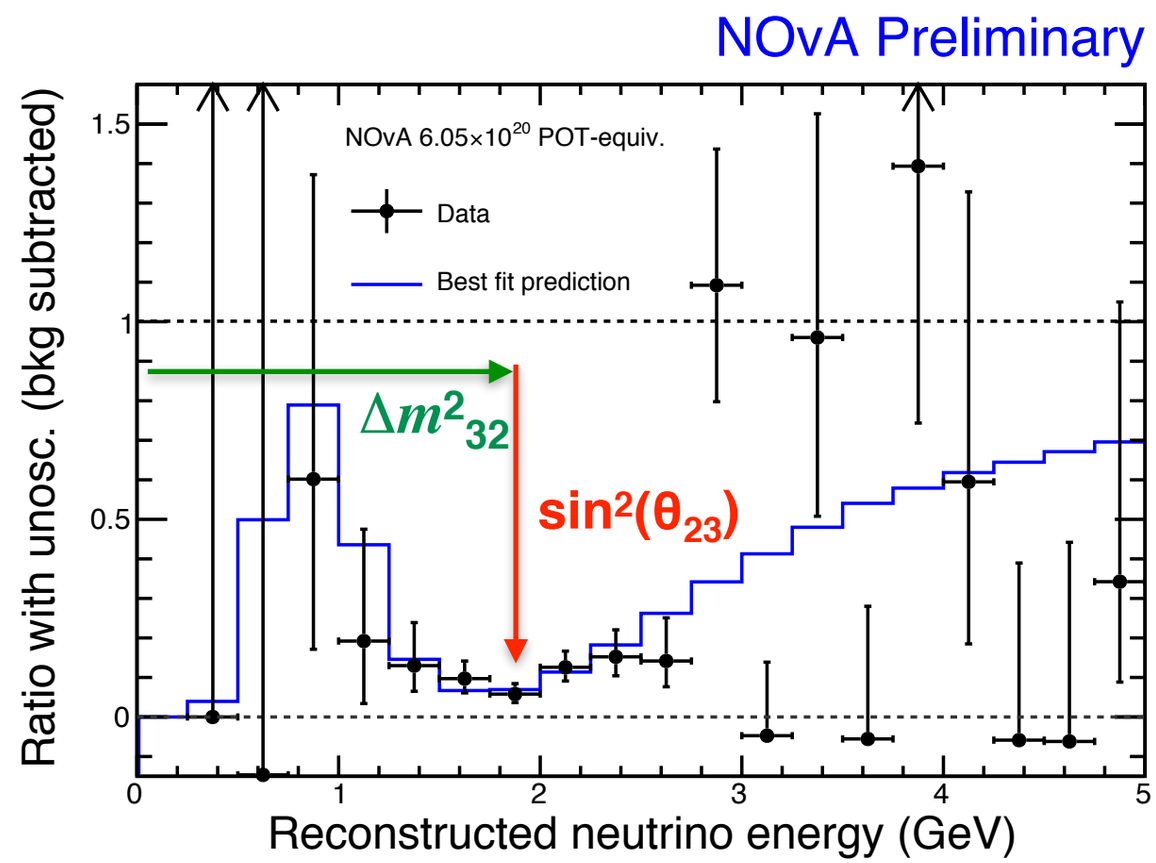


$\nu_\mu \rightarrow \nu_\mu$, ν_μ disappearance in a ν_μ beam

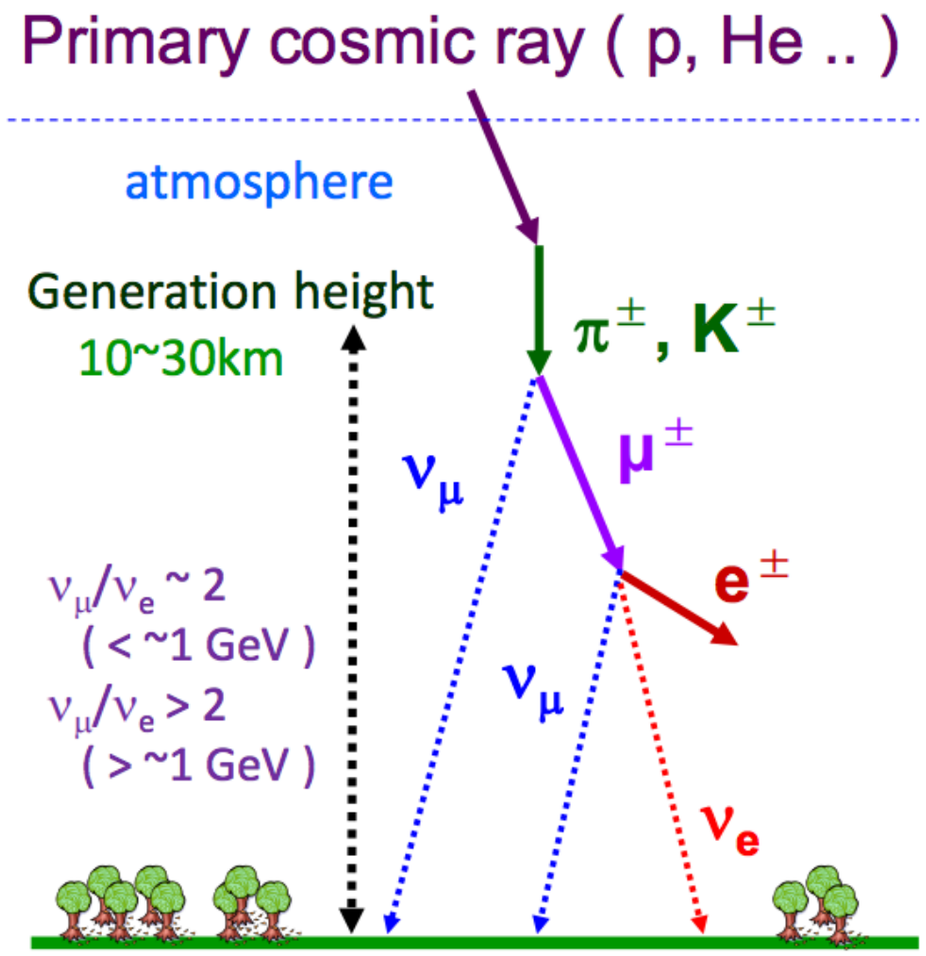
Compare predicted number of events in Near and Far Detectors, looks to see what percent of muons neutrinos have oscillation to other flavors

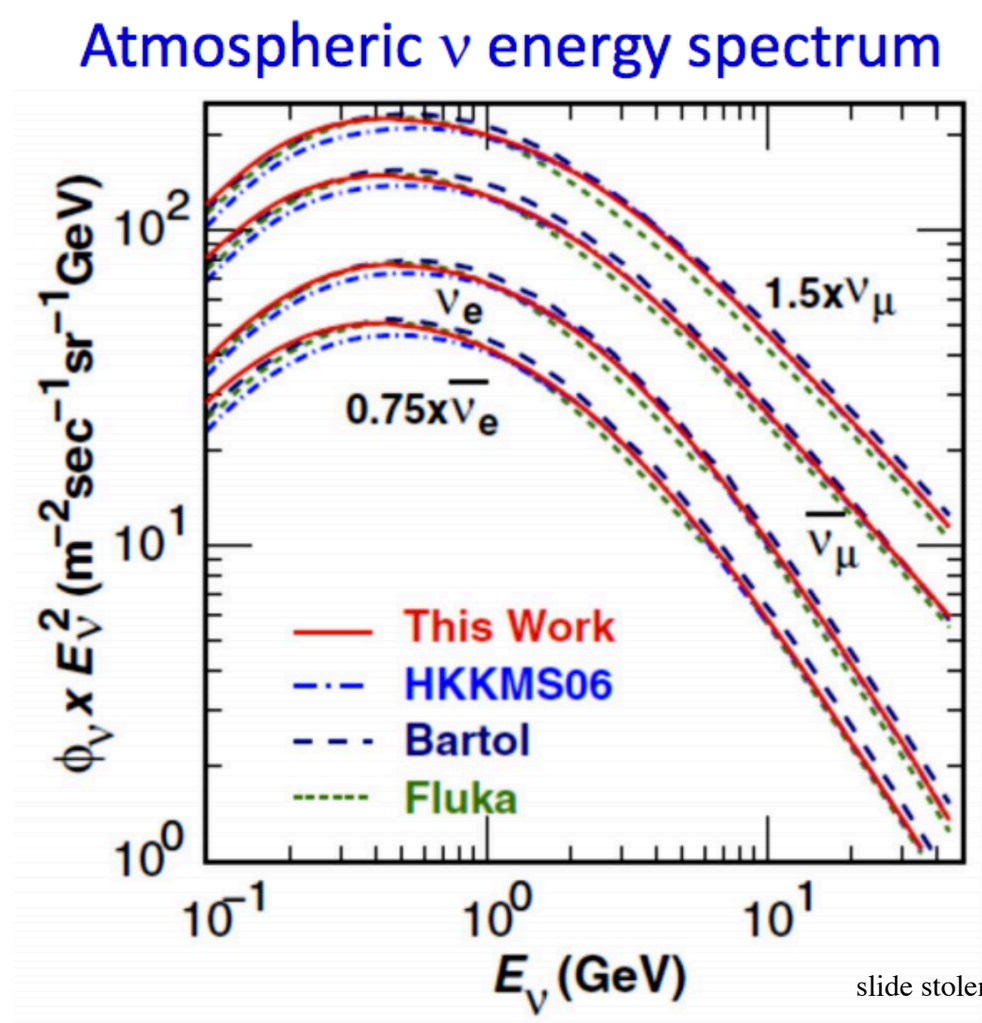
$$P(\nu_\mu \rightarrow \nu_\mu) \approx 1 - \sin^2(2\theta_{23}) \sin^2\left(\frac{1.27\Delta m^2_{32}[\mathrm{eV}^2] L_\nu[\mathrm{km}]}{E_\nu[\mathrm{GeV}]}\right)$$





Atmospheric Neutrinos





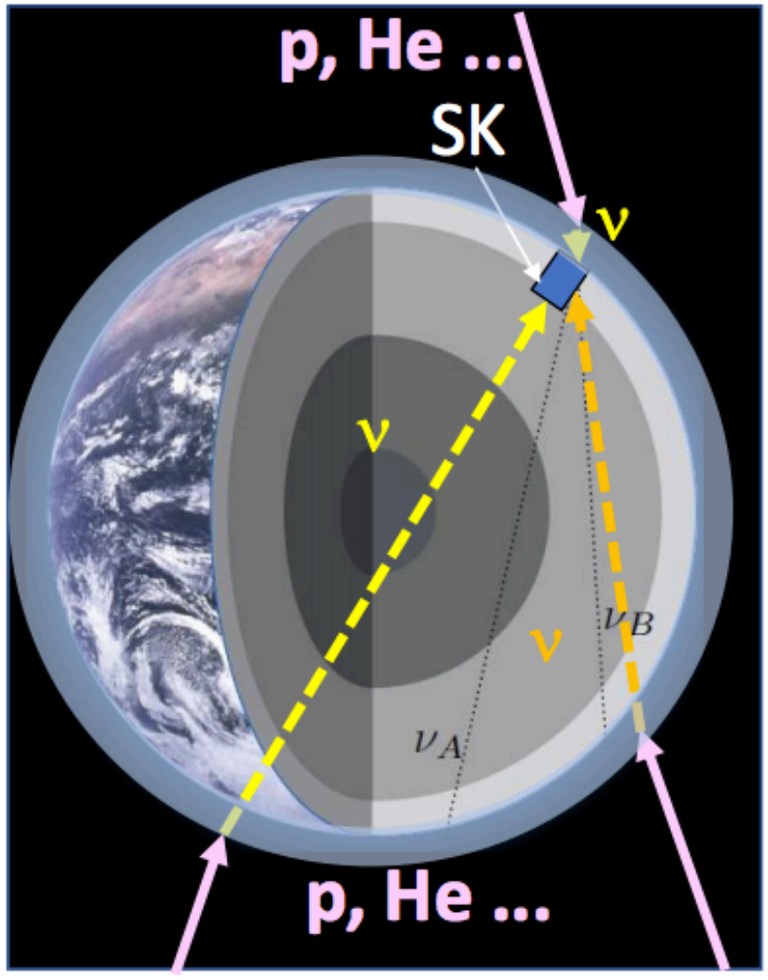
slide stolen from Yoshinari Hayato

Atmospheric neutrino energy spectrum
Peaked at ~ ***several hundreds of MeV, Extended > TeV***

Free abundant source of neutrinos, but in wide range of energies and baselines mixing together

Look at muon neutrino (or antineutrinos) oscillating
$\nu_\mu \rightarrow \nu_\mu, \nu_\tau, \nu_e$
(either ν_μ disappearing or other flavors appearing)

Atmospheric Neutrinos

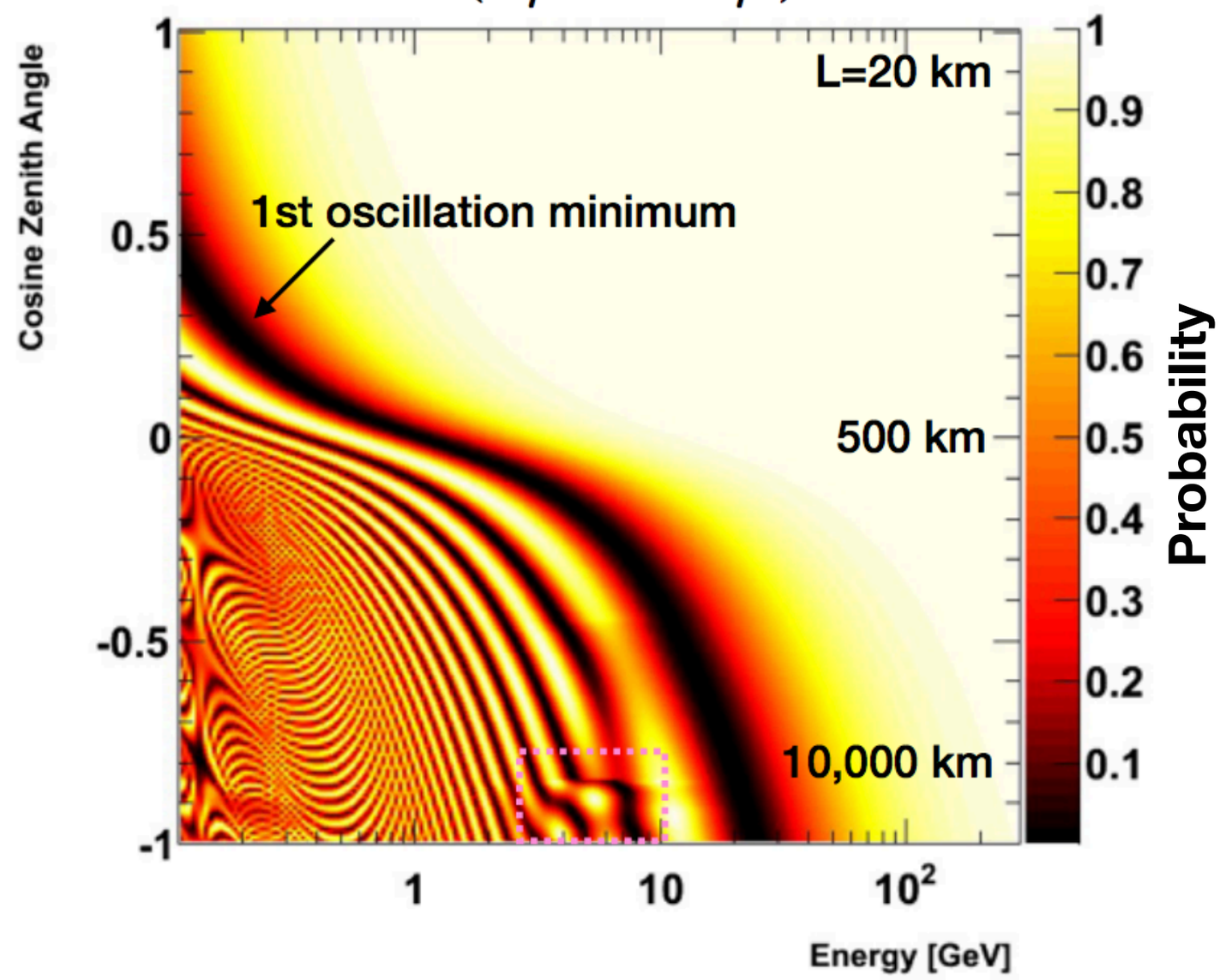


Minimum travel distance ~ thickness of the air -> 10 ~ 30 km

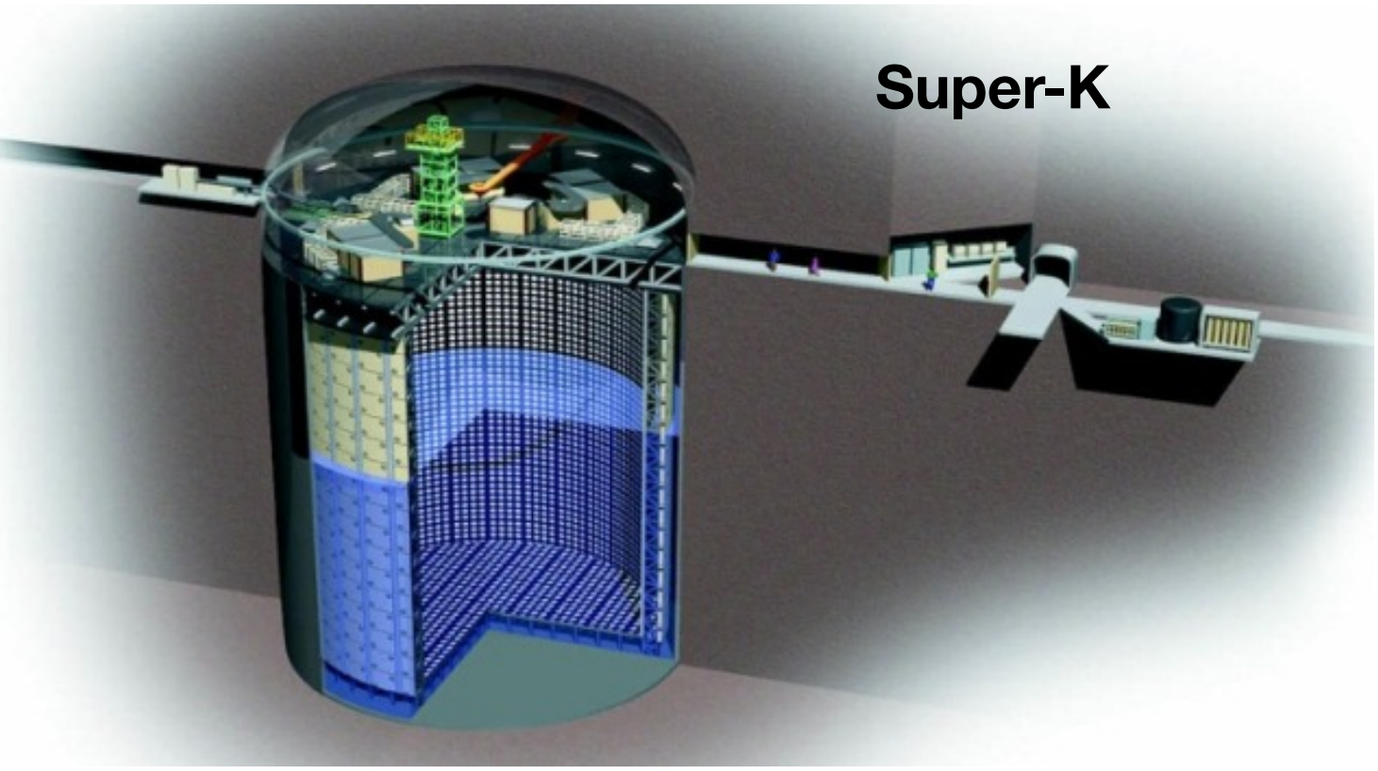
Maximum travel distance ~ diameter of the earth -> 13,000 km

Super-K Oscillation probabilities vs. zenith angle and energy

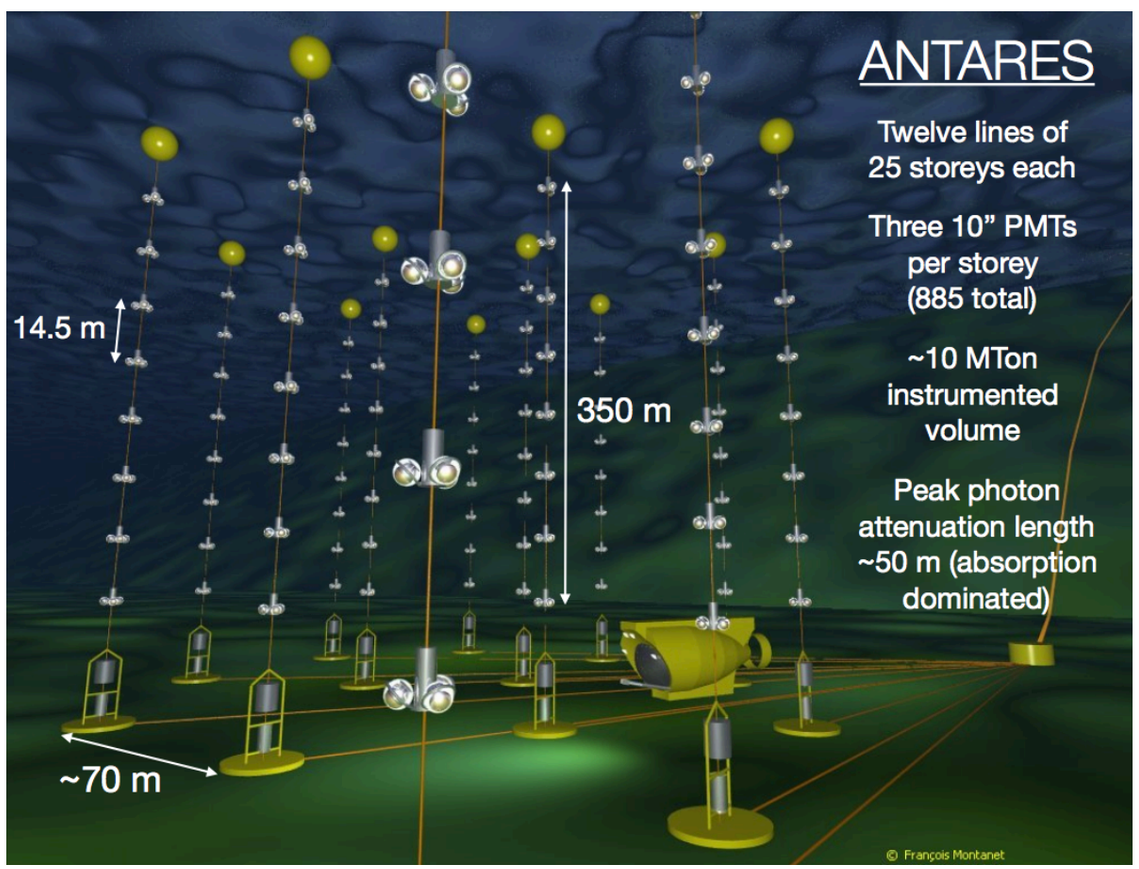
$$P(\nu_\mu \to \nu_\mu)$$

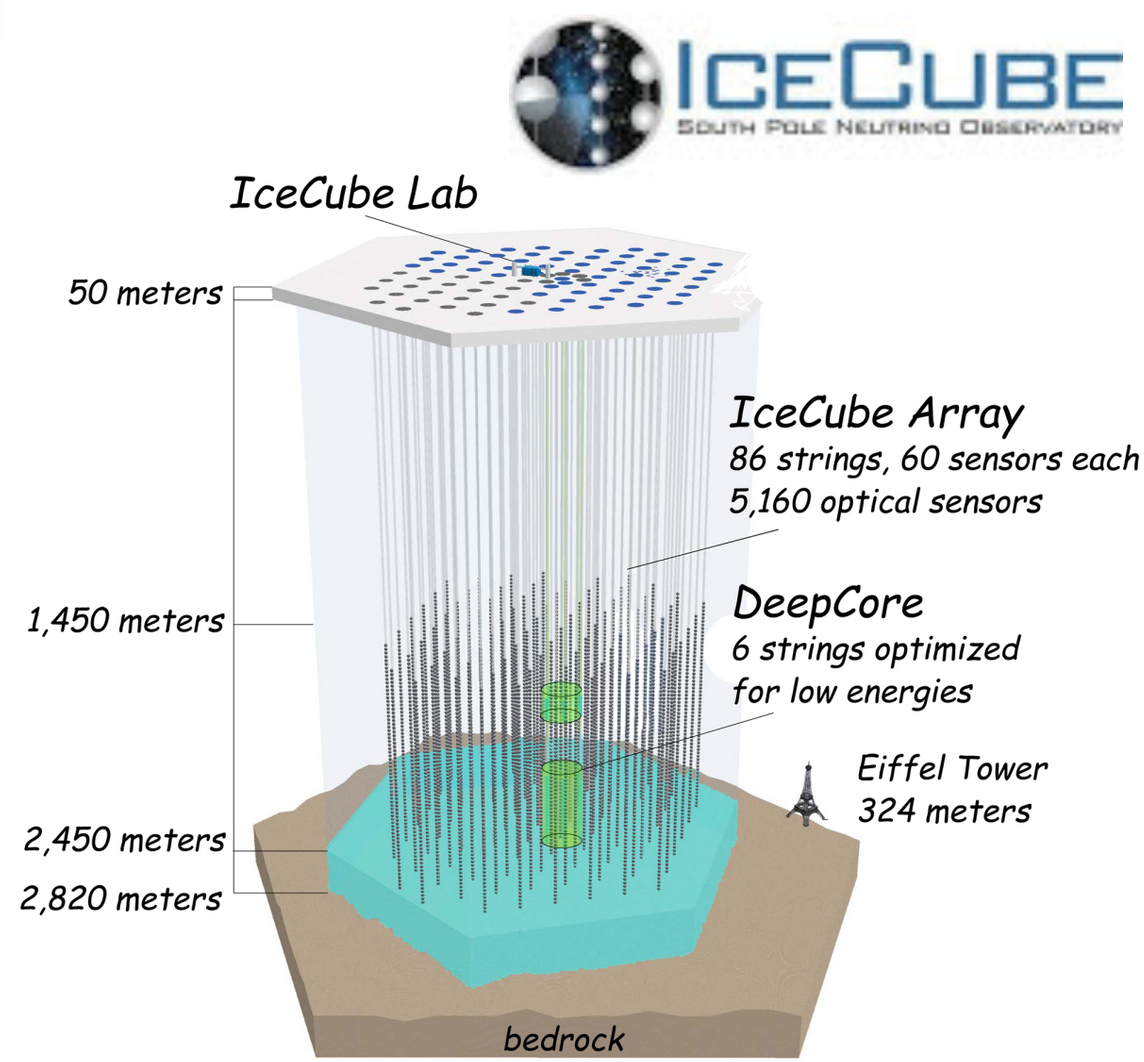


Travel distance of neutrino has good correlation with its zenith angle. Possible to study neutrino oscillation with observed energy (momentum) and zenith angle.

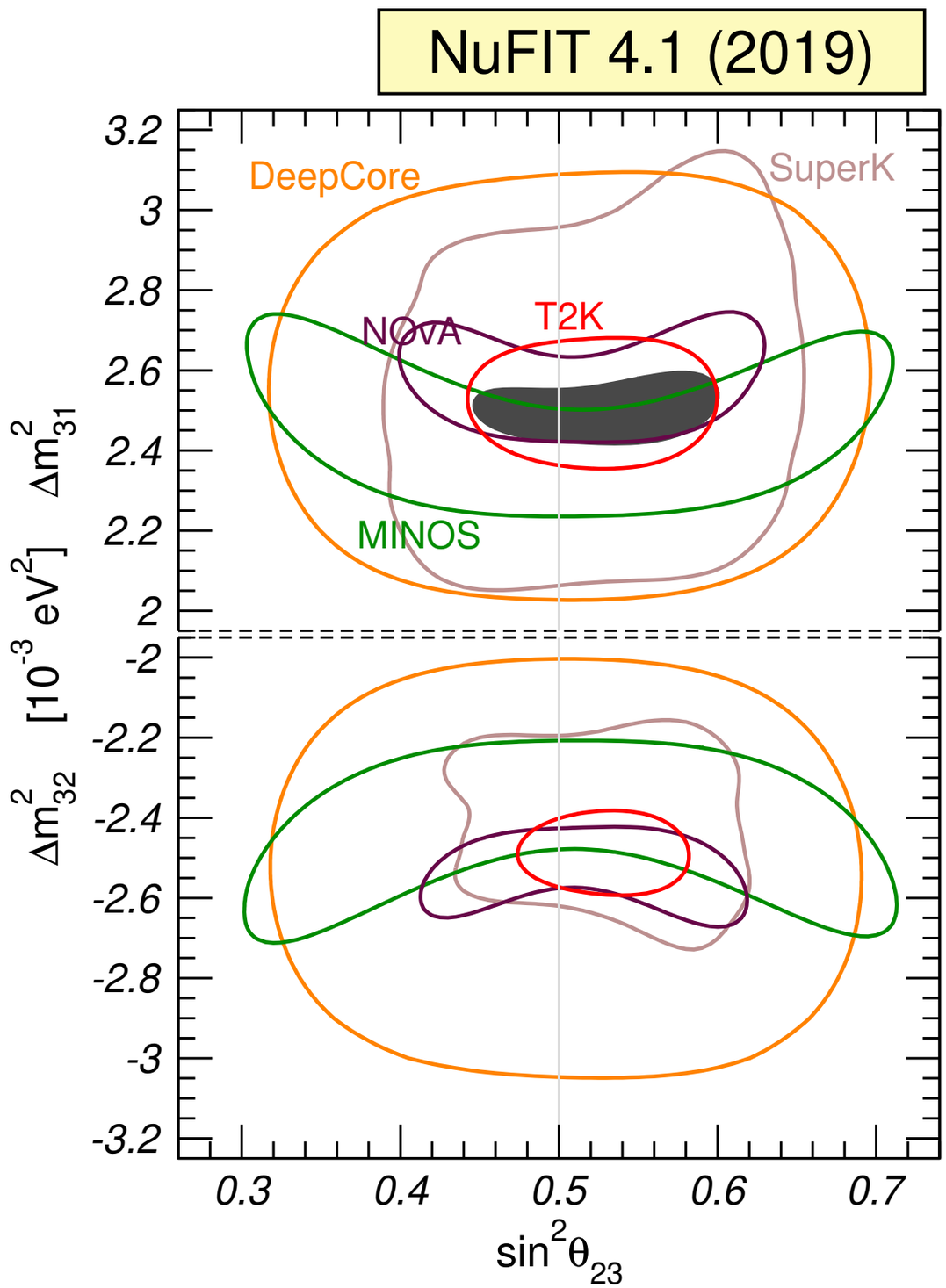


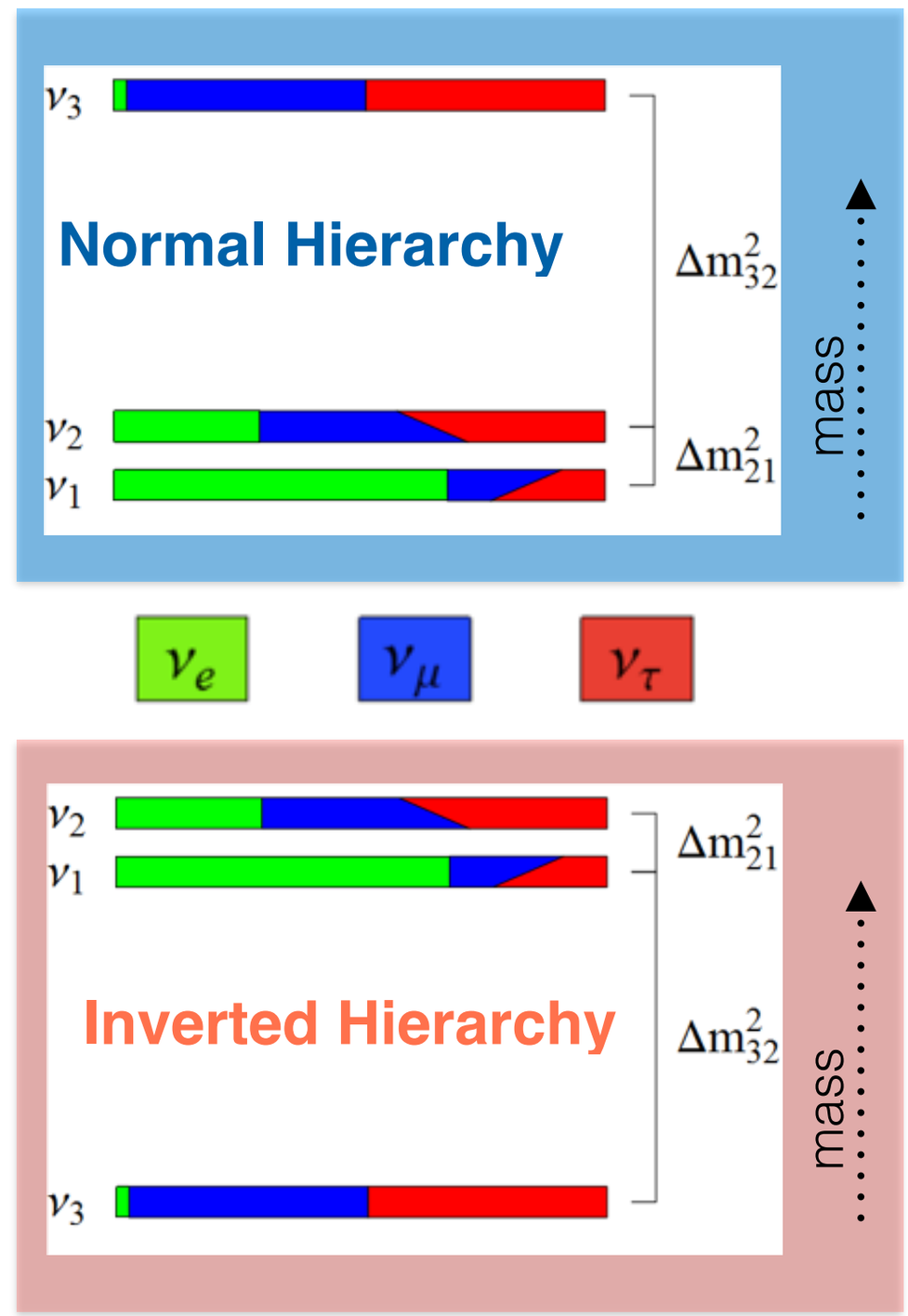
Generally large Cherenkov detectors, often using naturally occurring medium





Global Comparison of Atmospheric Fits





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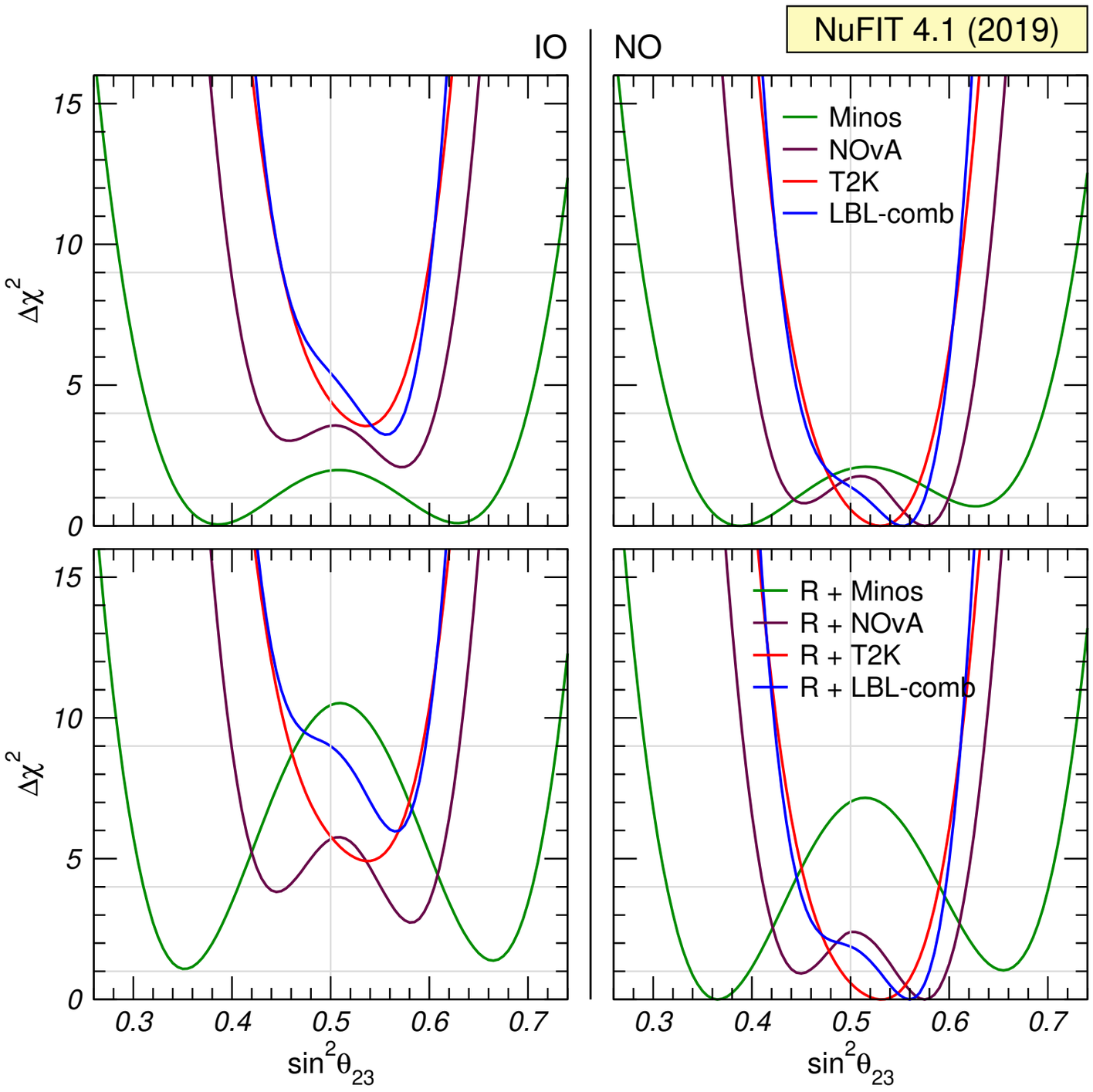

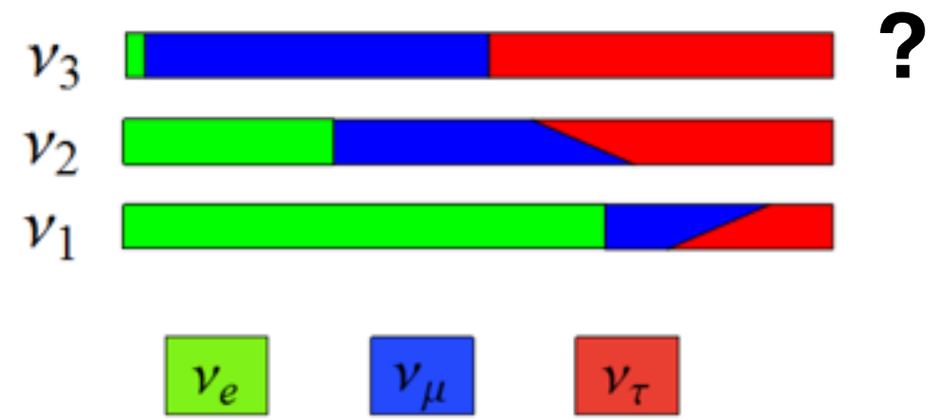

NOvA and MINOS slightly prefer non maximal mixing, best fit very slightly in upper octant.

Top: Long baseline
Bottom: Long baseline + reactors

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$\nu_\mu \to \nu_\mu$
$\nu_\mu \to \nu_\tau$

atmospheric and long baseline

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

reactor and long baseline

$\nu_e \to \nu_e$
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solar and reactor

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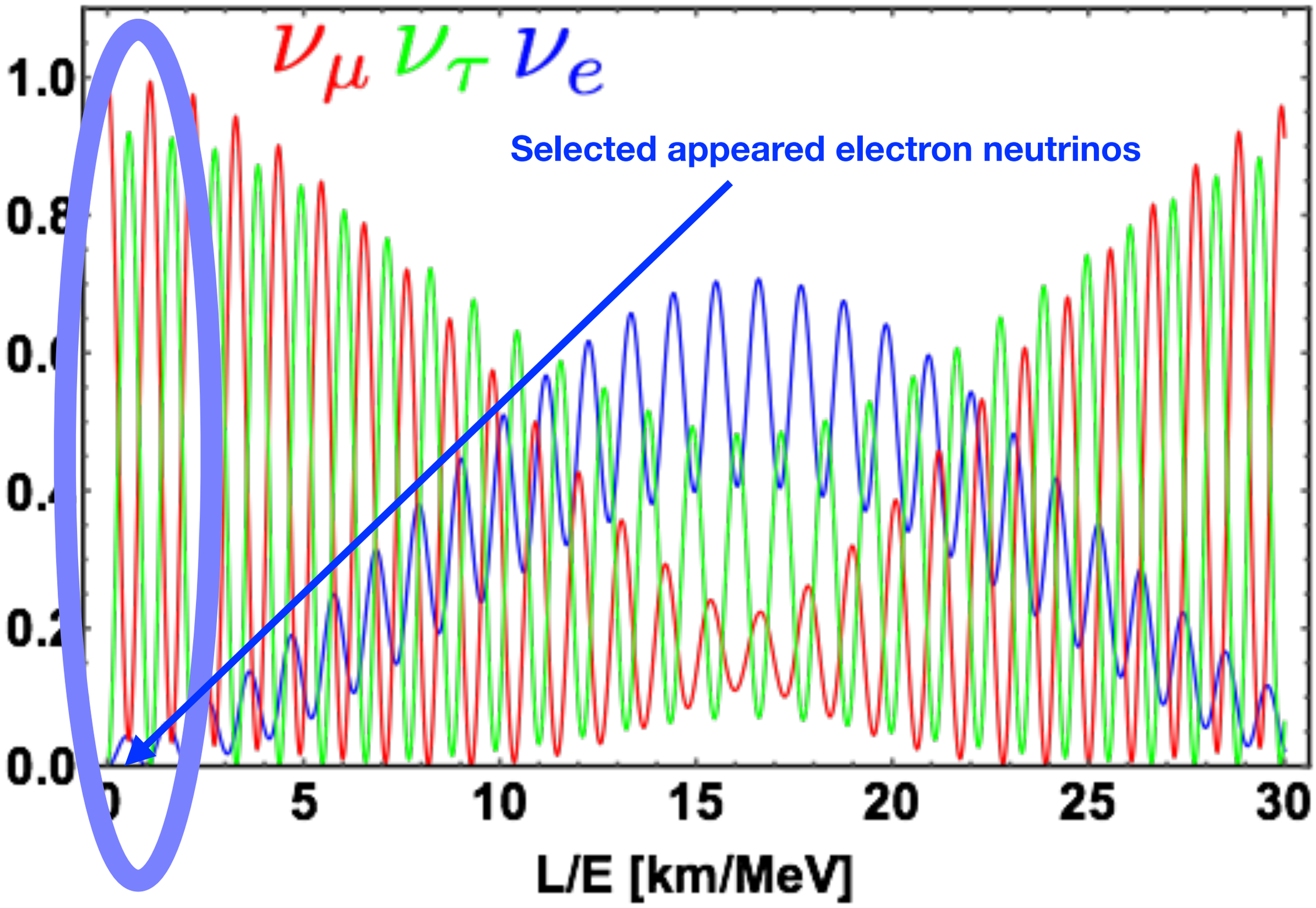
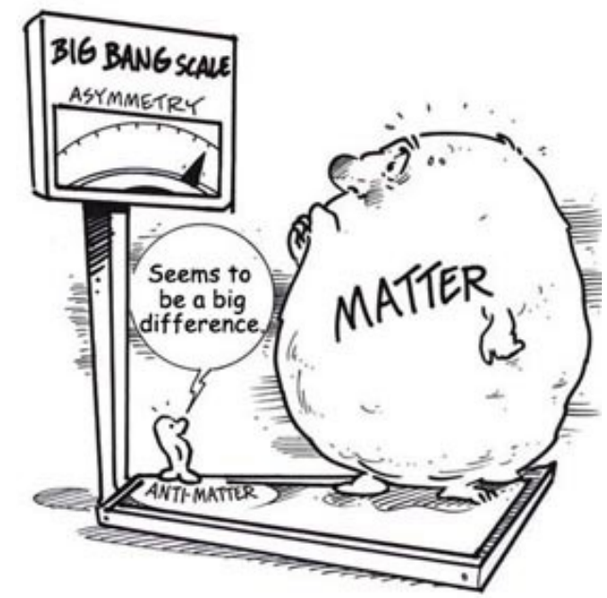
Oscillation probability for a muon neutrino



$\nu_\mu \rightarrow \nu_e$, ($\nu_e$ appearance)

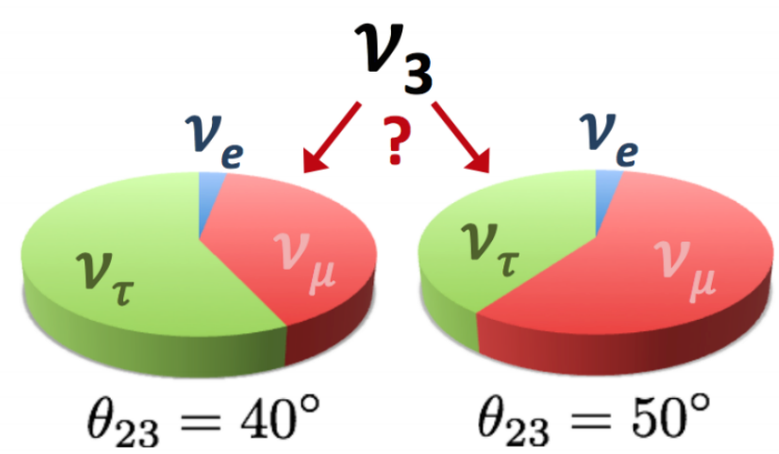
To describe ν_e appearance must use full 3-flavor description and include effects of interaction of neutrinos with matter and any CP violating phase

$$P(\nu_\mu \rightarrow \nu_e) \propto \theta_{23}, \Delta m^2_{13}, \theta_{13}, \delta_{cp}$$



Has sensitivity to some of the biggest questions in the field - See talk by Patricia Vahle

- Matter effect gives sensitivity to neutrino mass ordering
- Sensitivity to charge-parity in the neutrino sector
- Can measure octant of θ_{23} .Unlike in muon neutrino disappearance which is only sensitive to the square of mixing angle

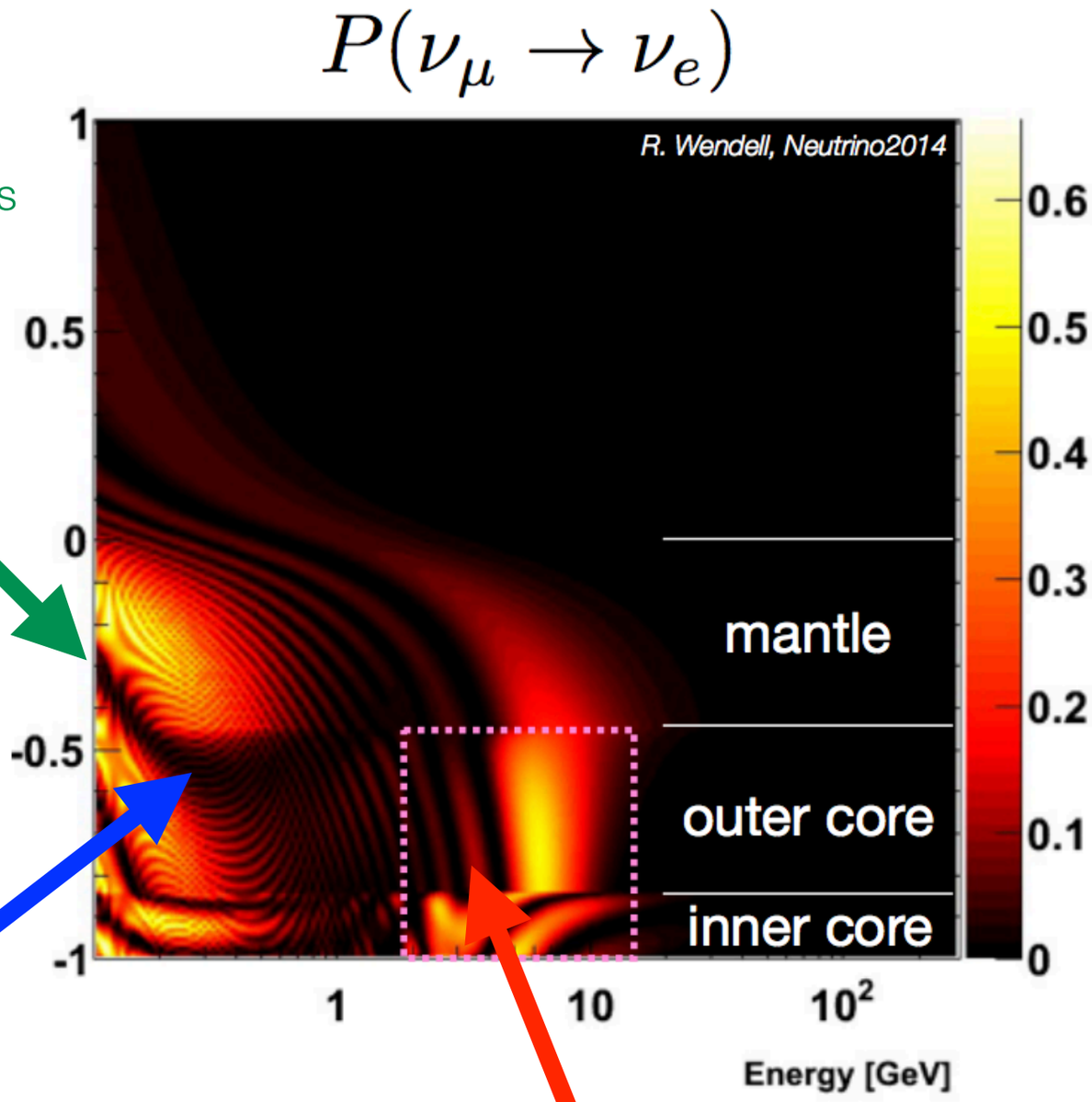


See talk by Patricia Vahle

Atmospheric $\nu_\mu \rightarrow \nu_e$, ($\nu_e$ appearance)

Super-K Oscillation probabilities vs. zenith angle and energy

Presence of Δm^2_{21}: gives sensitivity to the octant θ_{23}
Increase in ν_e for $\theta_{23} < 45$ degrees

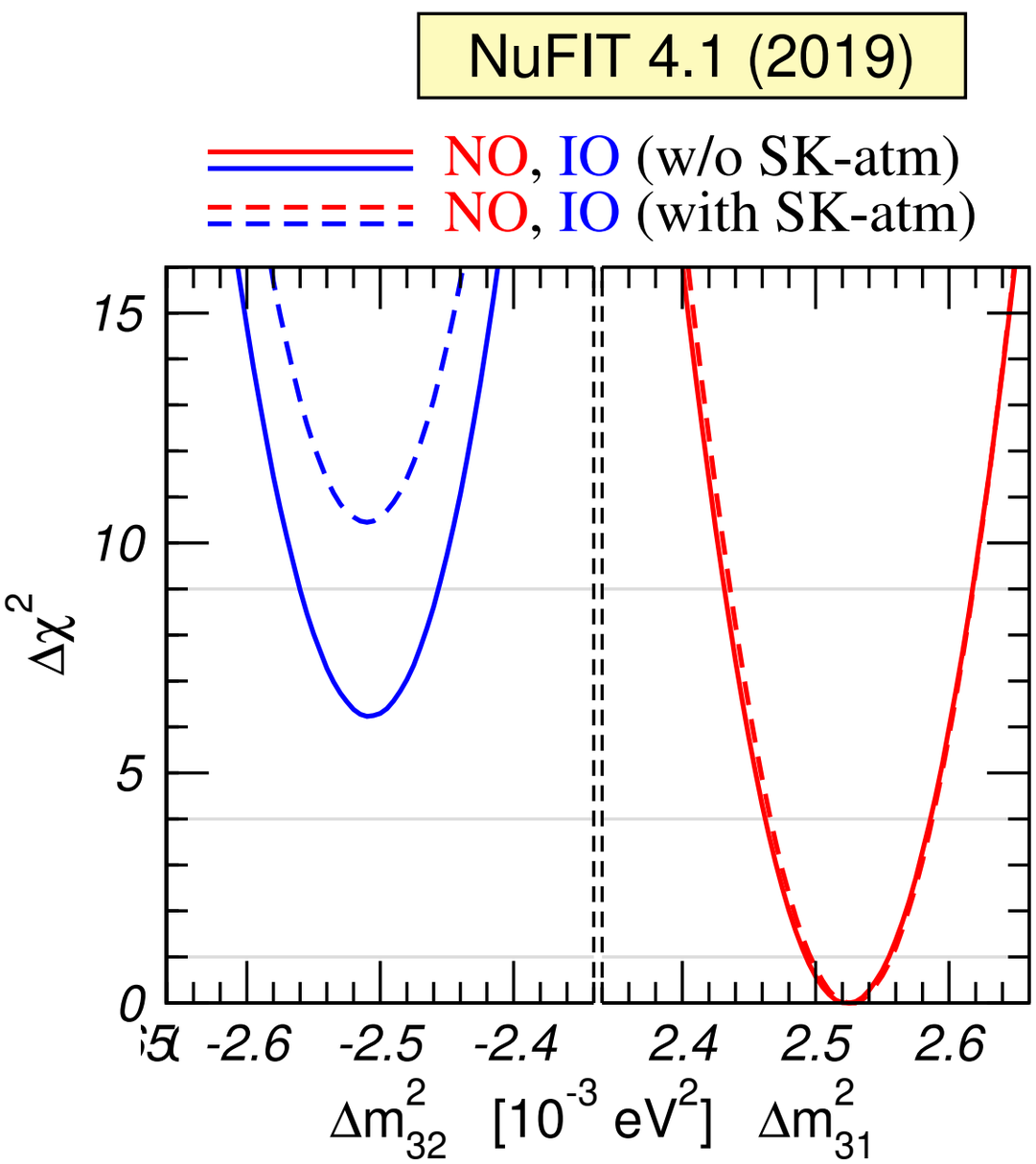


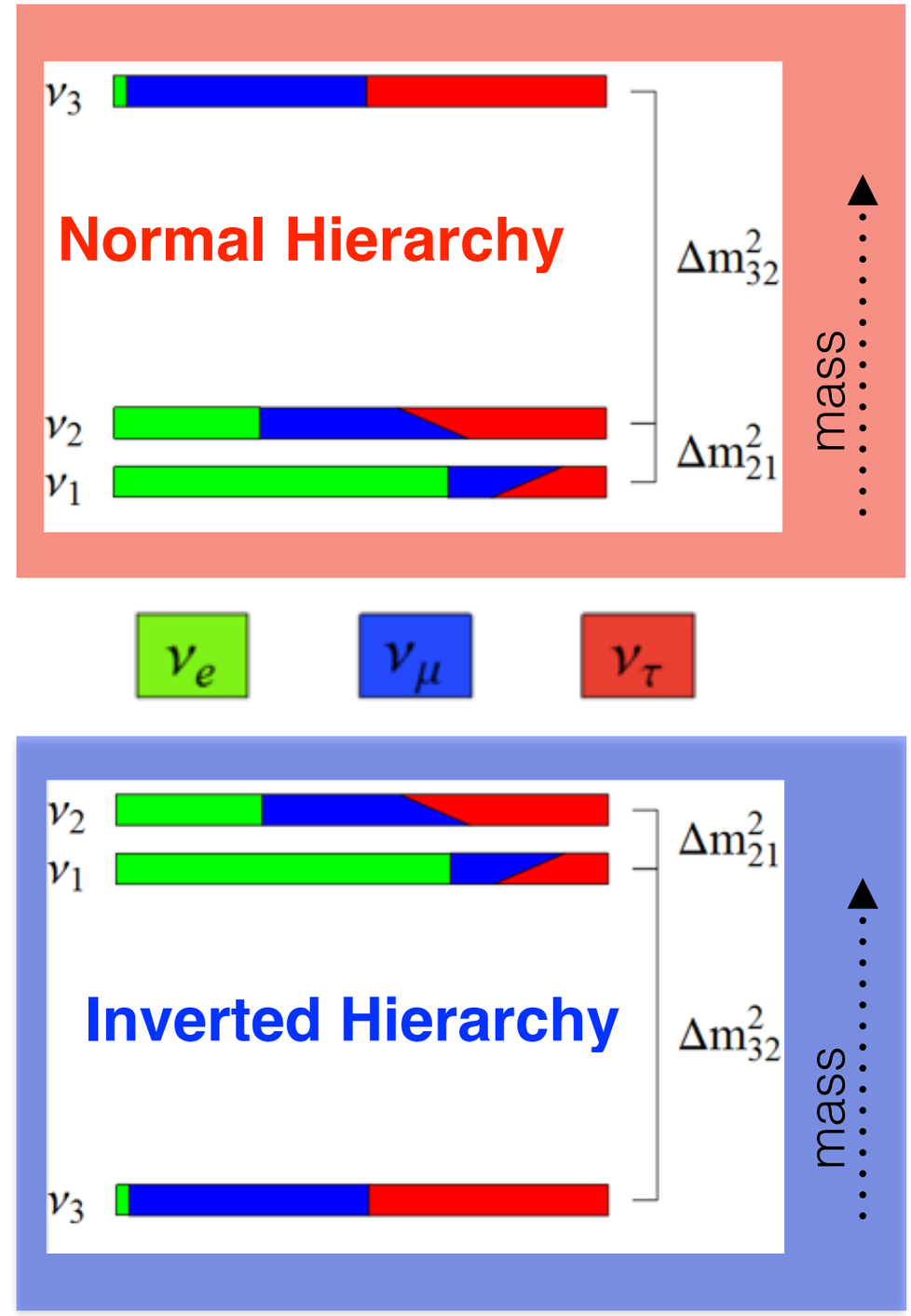
Presence of interference gives sensitivity to the CP violating phase
More ν_e for $\pi < \delta_{cp} < \pi$

Presence of matter: matter effect on θ_{13} gives sensitivity to the mass hierarchy

Resonance conversion: Suppression flips to enhancement with Hierarchy flip

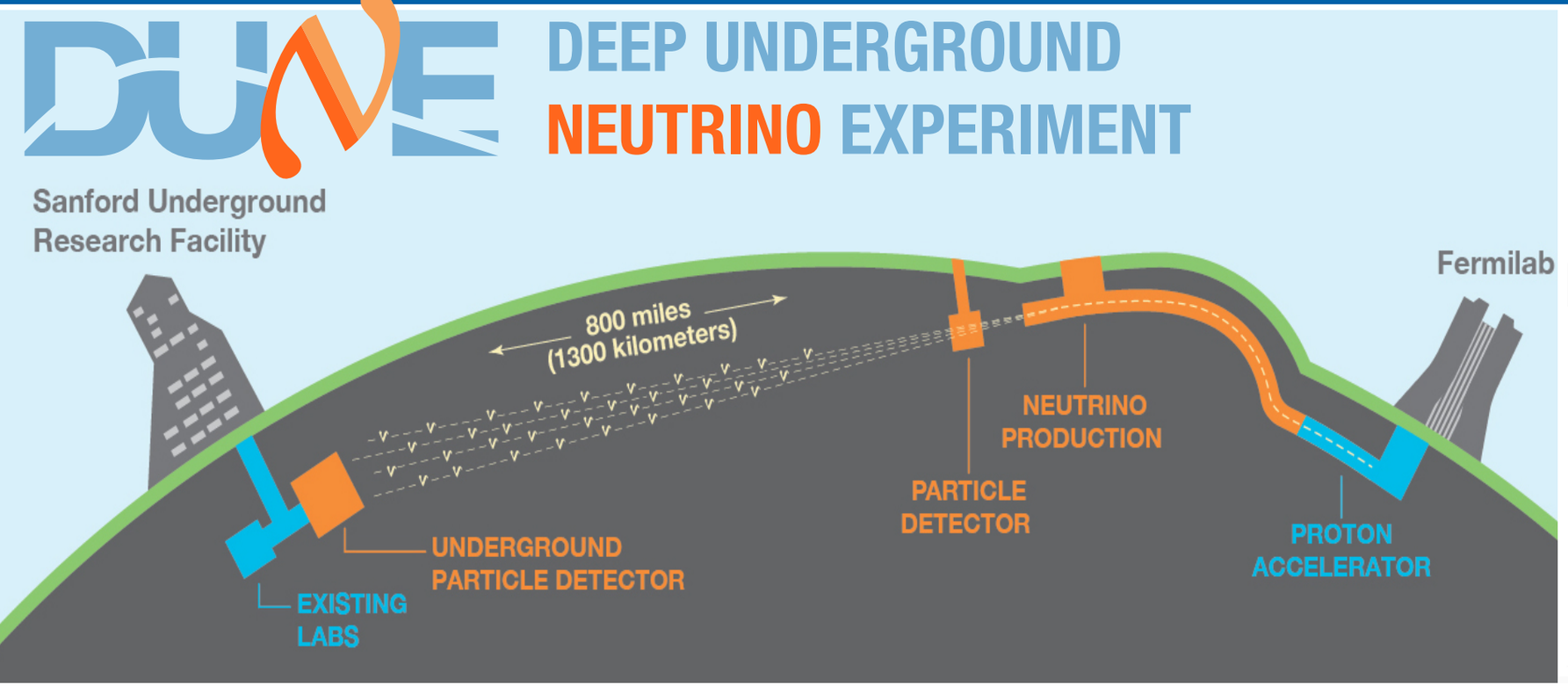
Neutrino mass ordering

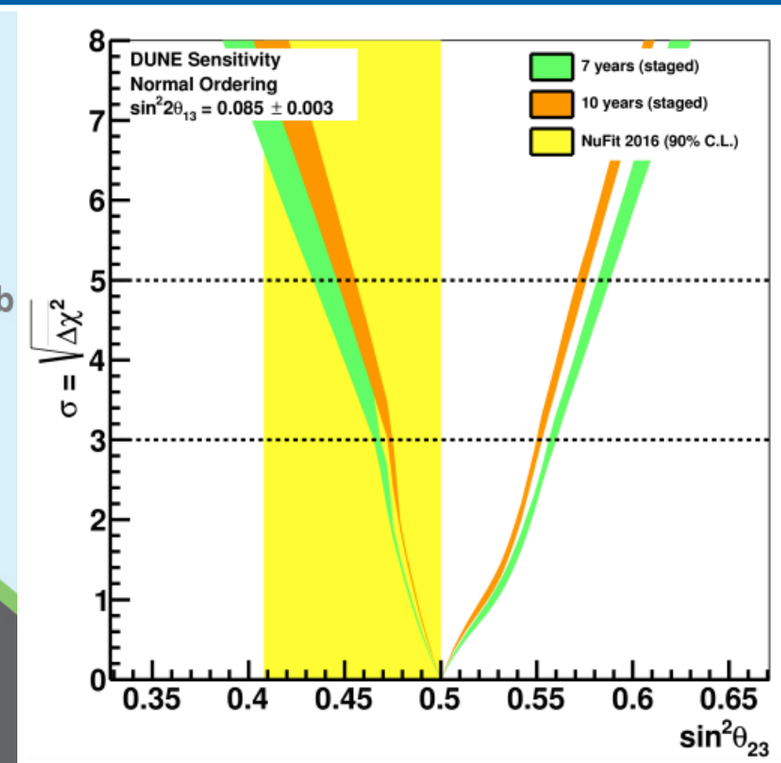




Hints of preference for the normal ordering/hierarchy, $m_{\nu 1} < m_{\nu 2} < m_{\nu 3}$

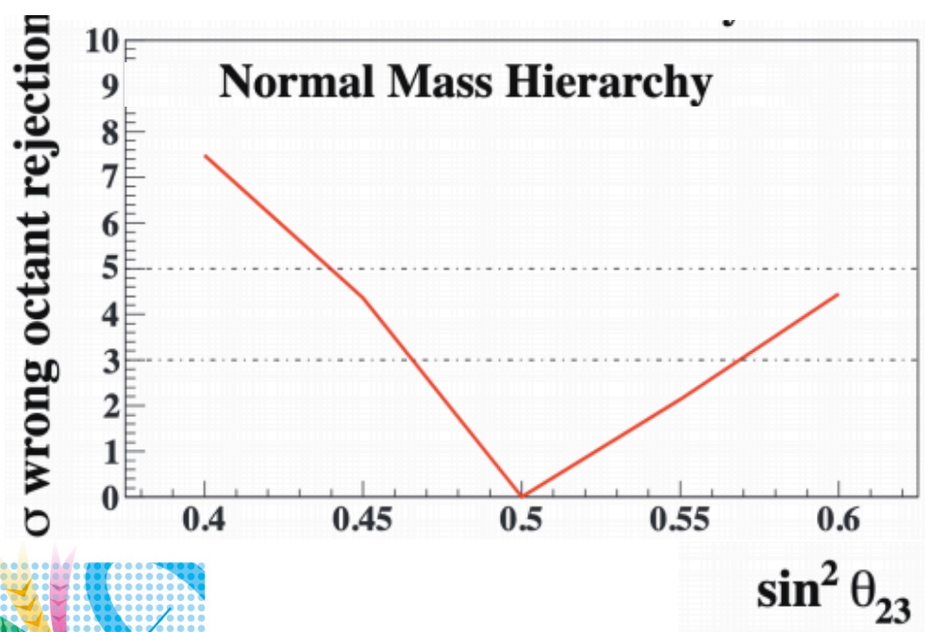
NOvA and future JUNO experiment sensitivity at > 3σ

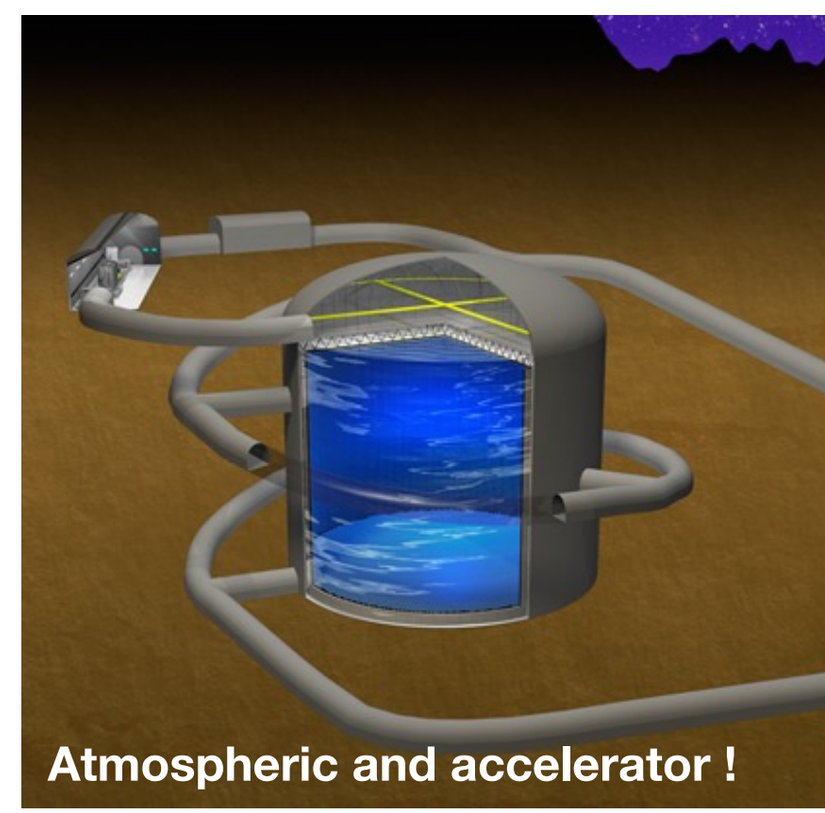




Future accelerator neutrino experiments.

Precise measurements of θ_{23}, Δm^2_{13}, θ_{13}, δ_{cp} and mass ordering





Hyper-Kamiokande

$$\left|\begin{matrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{matrix}\right\rangle = \begin{pmatrix}1 & & \\ & c_{23} & s_{23}\\ & -s_{23} & c_{23}\end{pmatrix}\begin{pmatrix}c_{13} & & s_{13}e^{-i\delta}\\ & 1 & \\ -s_{13}e^{i\delta} & & c_{13}\end{pmatrix}\begin{pmatrix}c_{12} & s_{12} & \\ -s_{12} & c_{12} & \\ & & 1\end{pmatrix}\left|\begin{matrix}\nu_1\\ \nu_2\\ \nu_3\end{matrix}\right\rangle$$

$\Delta m^2_{32} \simeq 2\times 10^{-3}\mathrm{eV}^2$
$L/E = 500\ \mathrm{km/GeV}$

$\Delta m^2_{31} \approx \Delta m^2_{32}$

$\Delta m^2_{21} \simeq 8\times 10^{-5}\mathrm{eV}^2$
$L/E = 15,000\ \mathrm{km/GeV}$

$\nu_\mu \to \nu_\mu$
$\nu_\mu \to \nu_\tau$
atmospheric and long baseline

$\nu_e \to \nu_e$
$\nu_\mu \to \nu_e$
reactor and long baseline

$\nu_e \to \nu_e$
$\nu_e \to \nu_\mu + \nu_\tau$
solar and reactor

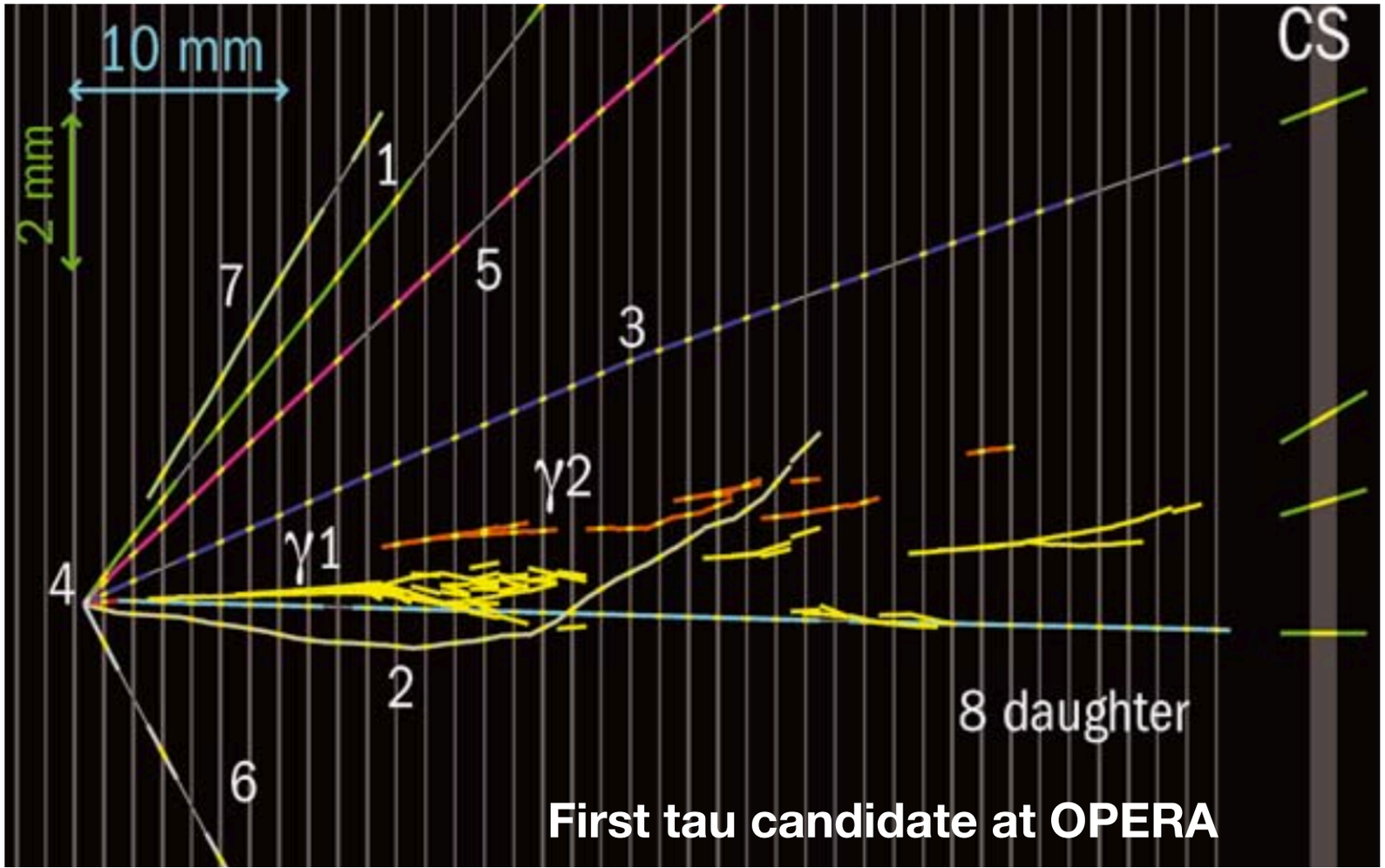
Can be well approximated by 2-flavor oscillation in a vacuum

Long-Baseline accelerator and atmospheric experiments can probe

$c_{\alpha\beta} = \cos_{\alpha\beta}$
$s_{\alpha\beta} = \sin_{\alpha\beta}$

$\nu_\mu \rightarrow \nu_\tau$, tau neutrino appearance

- Tau leptons are hard and tau neutrinos no exception. ν_τ oscillation is poorly constrained
  - Tau neutrinos discovered in 1997 by DONUT at Fermilab
  - Tau lepton production threshold general above neutrino beam energy
  - Taus leptons will decay almost instantaneously and neutrino experiments don't normally have resolution to see tau leptons before decay.



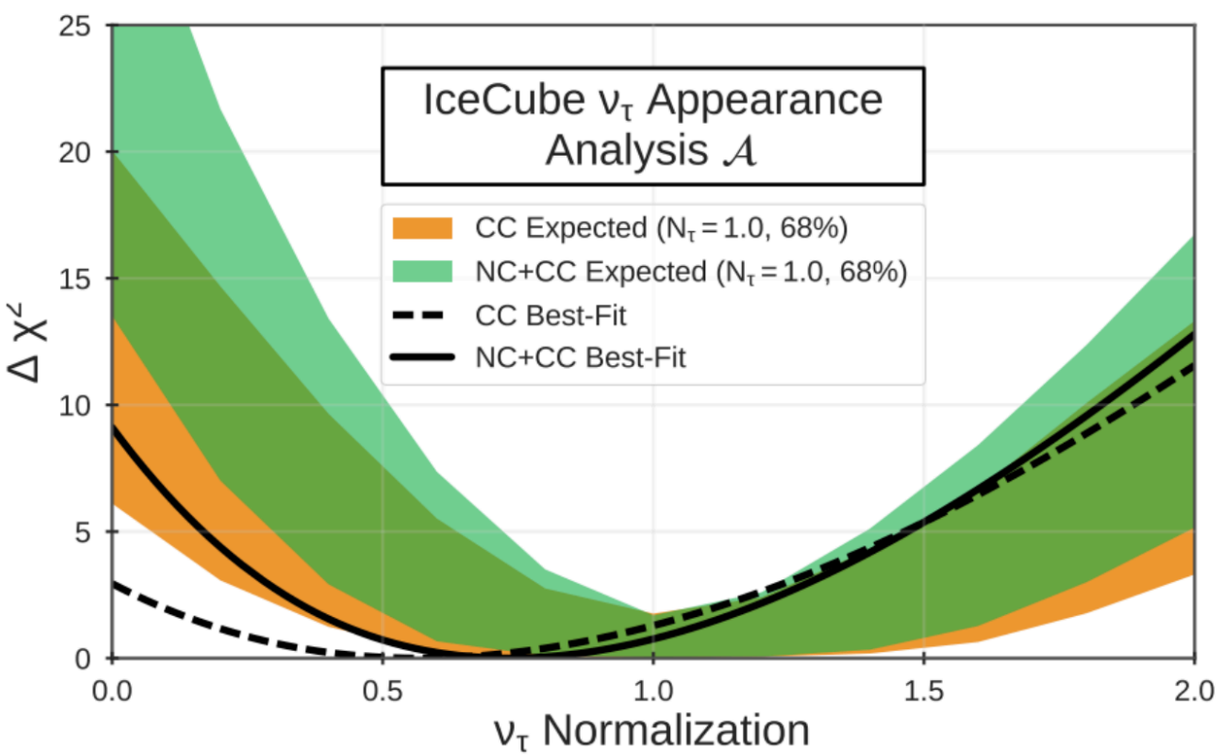
First tau candidate at OPERA

SK/OPERA ($\nu_\mu \rightarrow \nu_\tau$)	$4\lvert U_{\mu 3}\rvert^2 \lvert U_{\tau 3}\rvert^2 = \sin^2 2\theta_{23} \cos^4 \theta_{13}$

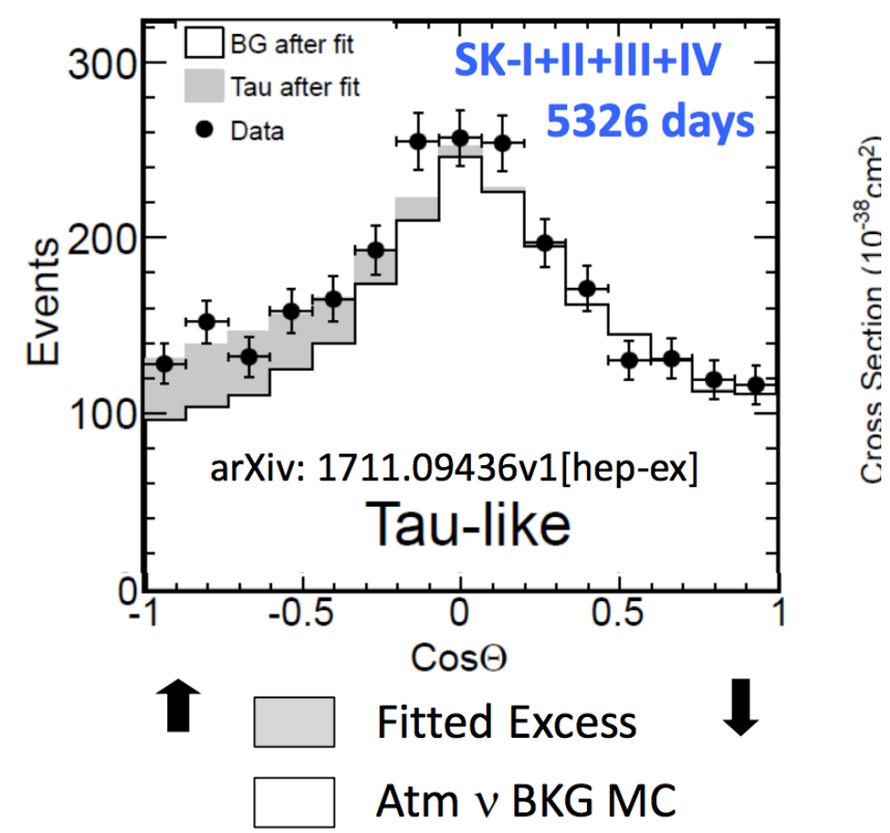
$\nu_\mu \rightarrow \nu_t$, tau neutrino appearance

ν_τ have been observed statistically at atmospheric experiments or at low numbers by dedicated beam experiments

- **Opera** -Using CNGS beam from CERN and emulsion based detector, observed ten ν_τ candidate events
- **IceCube** - Excluding the absence of oscillations into ν_τ at 3.2σ
- **Super-K** - Using distribution of events as a function of angle.
  Reject no-ν_τ-appearance @ 4.6σ. (Expected significance is 3.3σ)



Zenith angle distribution



$$\left|\begin{matrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{matrix}\right\rangle = \begin{pmatrix}1 & & \\ & c_{23} & s_{23}\\ & -s_{23} & c_{23}\end{pmatrix}\begin{pmatrix}c_{13} & & s_{13}e^{-i\delta}\\ & 1 & \\ -s_{13}e^{i\delta} & & c_{13}\end{pmatrix}\begin{pmatrix}c_{12} & s_{12} & \\ -s_{12} & c_{12} & \\ & & 1\end{pmatrix}\left|\begin{matrix}\nu_1\\ \nu_2\\ \nu_3\end{matrix}\right\rangle$$

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$L/E = 500\ \mathrm{km/GeV}$

$\Delta m^2_{31} \approx \Delta m^2_{32}$

$\Delta m^2_{21} \simeq 8\times 10^{-5}\mathrm{eV}^2$
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$\nu_\mu \to \nu_\mu$
$\nu_\mu \to \nu_\tau$

atmospheric and long baseline

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

reactor and long baseline

$\nu_e \to \nu_e$
$\nu_e \to \nu_\mu + \nu_\tau$

solar and reactor

Can be well approximated by 2-flavor oscillation in a vacuum

The sun and reactors are ν_e (or anti-ν_e) sources

$c_{\alpha\beta} = \cos_{\alpha\beta} \quad s_{\alpha\beta} = \sin_{\alpha\beta}$

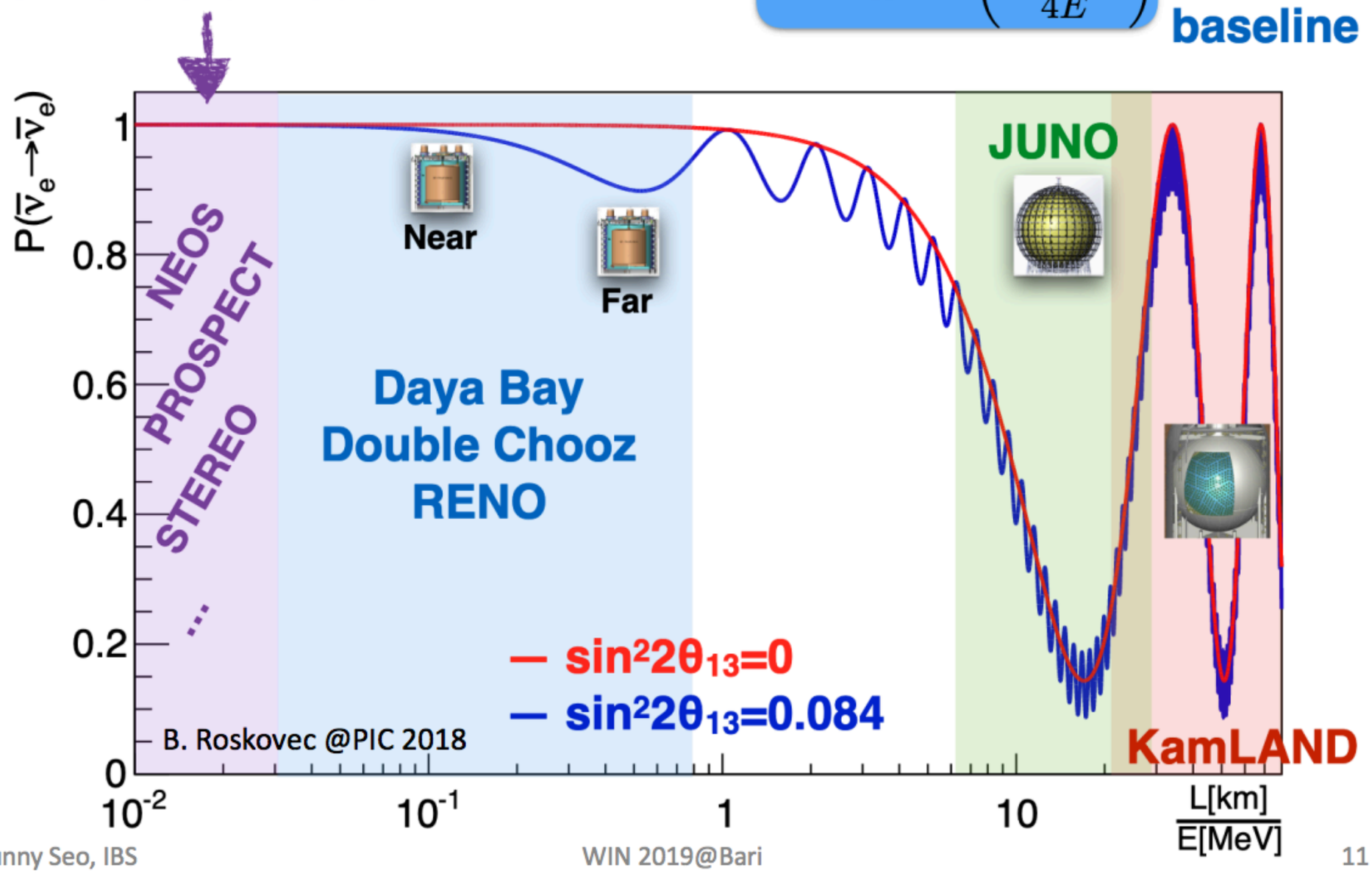
Reactor based experiments

Two modes of oscillations: $P(\bar{\nu}_e \to \bar{\nu}_e) = 1 - \sin^2 2\theta_{12} \cos^4 \theta_{13} \sin^2\left(\frac{\Delta m^2_{21} L}{4E}\right) - \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta m^2_{ee} L}{4E}\right)$

Medium baseline

Short baseline

Is there 3rd mode?!?



Sunny Seo, IBS WIN 2019@Bari 11

Short baseline lets us probe θ_{13} and atmosphere mass term

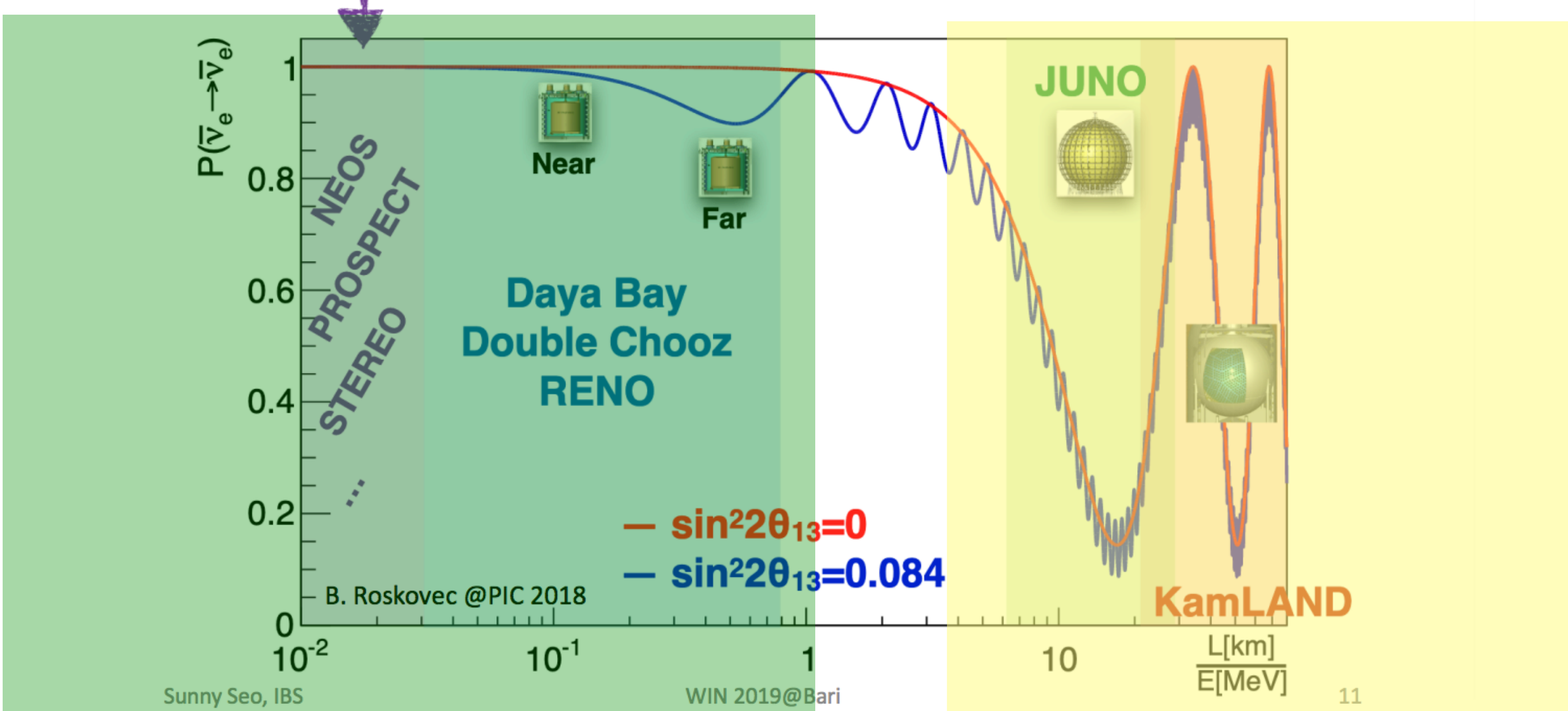
Medium baseline or solar term lets you probe θ_{12} and solar mass term

Reactor based experiments

Two modes of oscillations: $P(\bar{\nu}_e \to \bar{\nu}_e) = 1 - \sin^2 2\theta_{12} \cos^4 \theta_{13} \sin^2\left(\frac{\Delta m^2_{21} L}{4E}\right)$ **Medium baseline**

$- \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta m^2_{ee} L}{4E}\right)$ **Short baseline**

Is there 3rd mode?!?



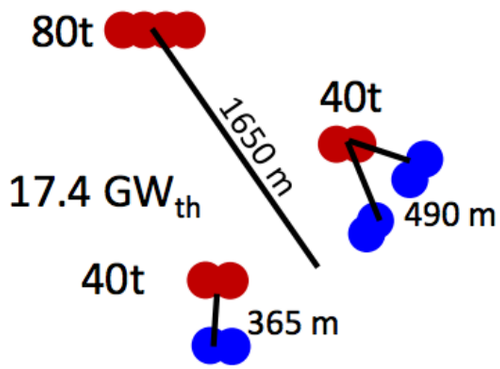
Short baseline reactor: lets us probe θ_{13} and atmosphere mass term

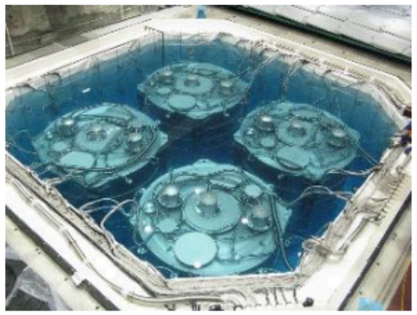
Medium baseline: lets you probe θ_{12} and solar mass term

Short baseline reactor, anti-$\nu_e \rightarrow$ anti-ν_e

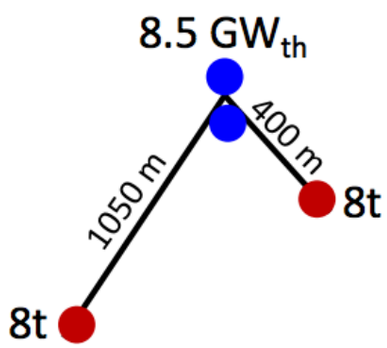
Nuclear reactors produce copious anti-ν_e's detectors placed close are at an optimal position to measure θ_{13}.

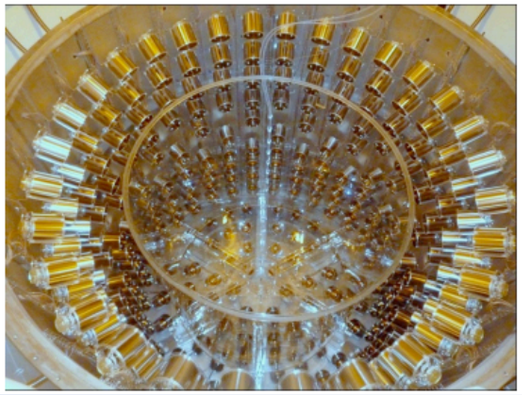
Daya Bay



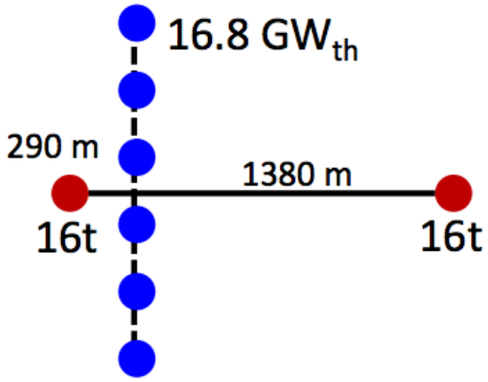


Double Chooz





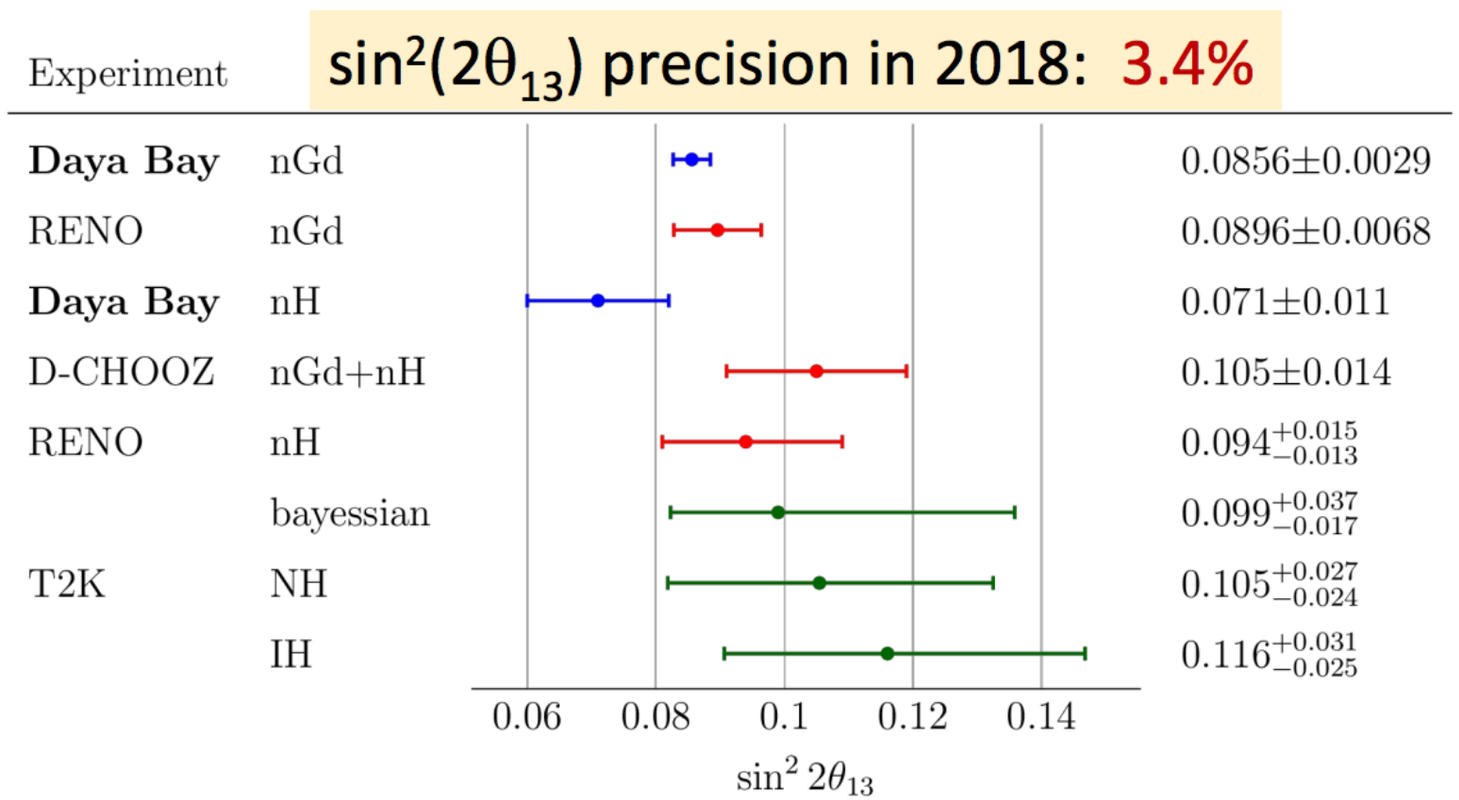
RENO

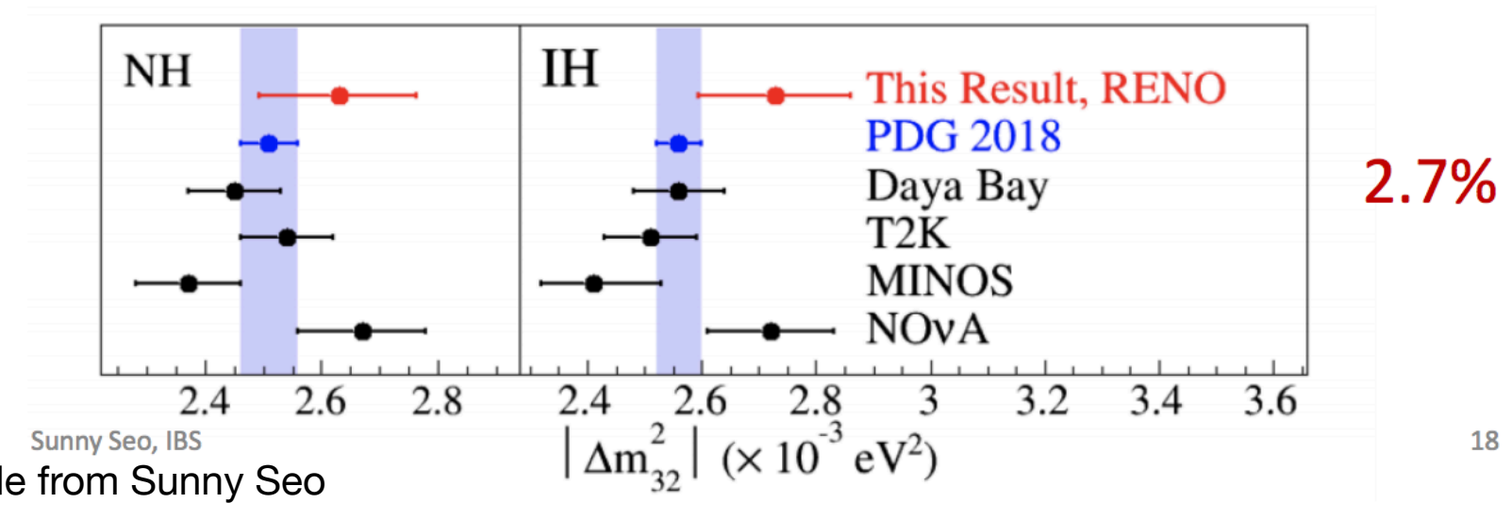


slide from Sunny Seo

Reactor SBL ($\overline{\nu}_e \rightarrow \overline{\nu}_e$)	$4\lvert U_{e3}\rvert^2 \left(1 - \lvert U_{e3}\rvert^2\right) = \sin^2 2\theta_{13}$

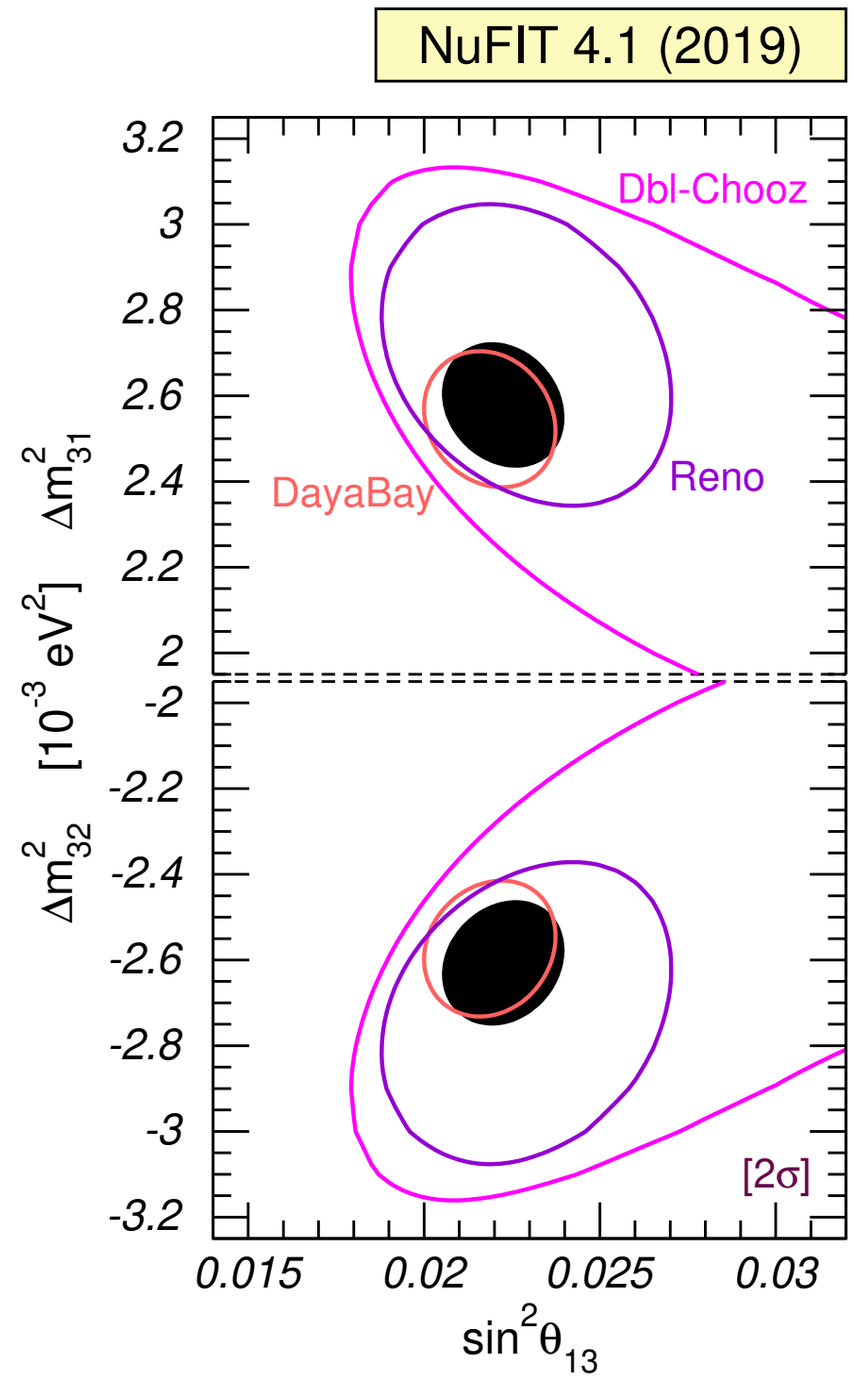
Reactor θ_{13} results



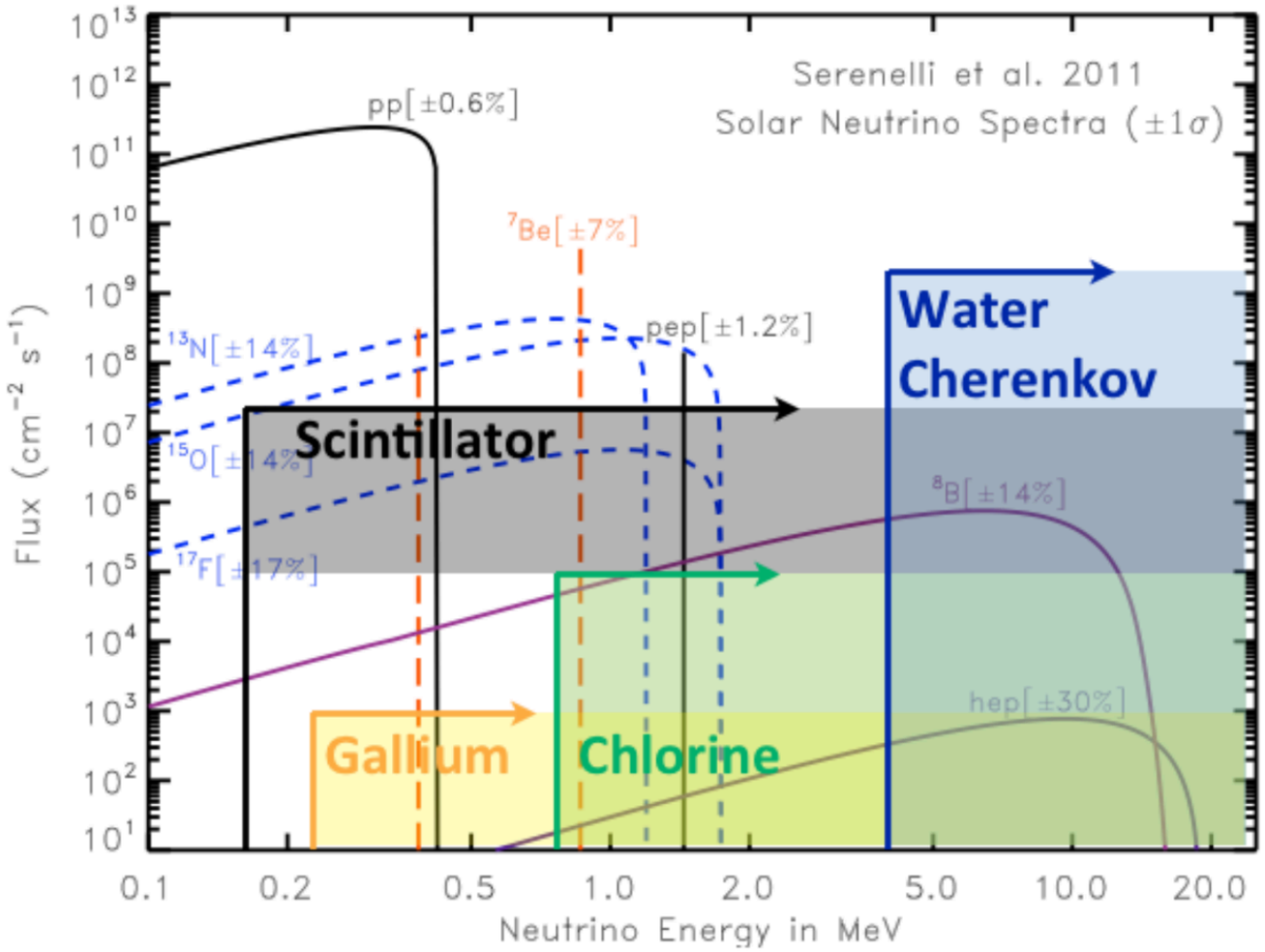


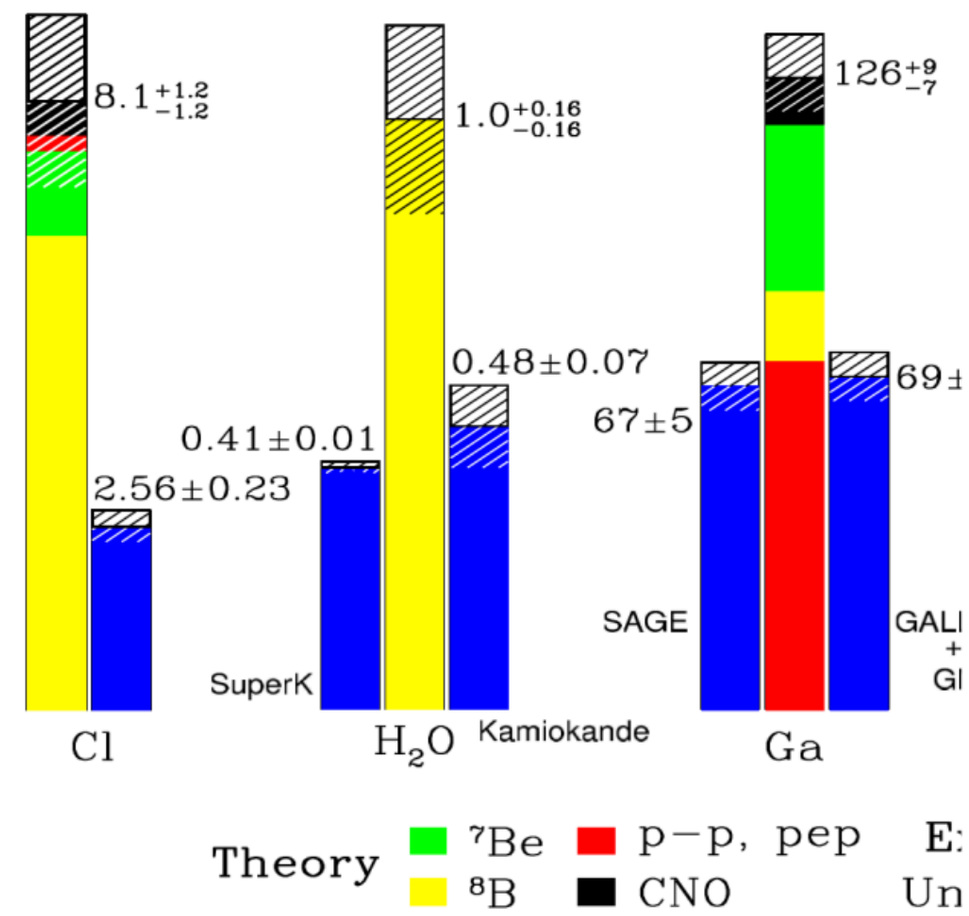
2.7%

slide from Sunny Seo



Solar measurements





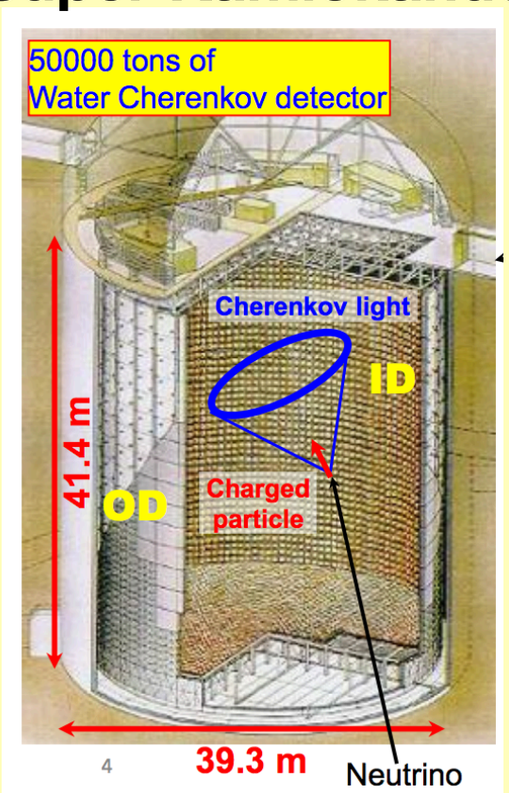
- Early measurements of solar neutrinos, only sensitivity to nue, only saw about 1/3 of expected rate of neutrinos coming from the sun. Called '*Solar Neutrino Problem*'
- First evidence of neutrino oscillation, in matter!
- SNO experiment designed to see neutral current interactions, which are insensitive to neutrino flavors, as well as interactions which only involve the electron.

Solar experiments

Reactor LBL ($\overline{\nu}_e \to \overline{\nu}_e$)	$4\|U_{e1}\|^2\|U_{e2}\|^2 = \sin^2 2\theta_{12}\cos^4\theta_{13}$
SNO (ϕ_{CC}/ϕ_{NC} Ratio)	$\|U_{e2}\|^2 = \cos^2\theta_{13}\sin^2\theta_{12}$

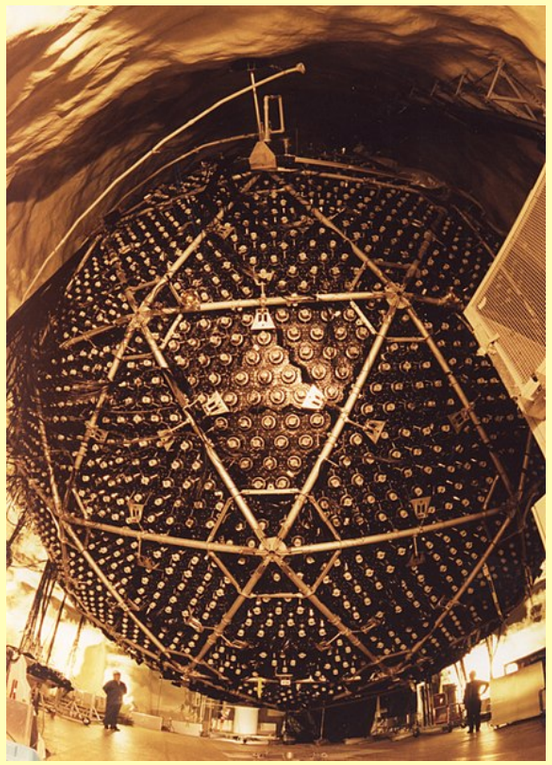
- Solar neutrinos as source: large number of low energy neutrinos. **Probes Δm^2_{21} and θ12 and matter (MSW) effects**
- ν_e can interact via both CC and NC interaction with the electrons in the earth (where as the other flavors only interact via NC) —> increases the effective mass of the ν_e
- Effect is energy dependance:
  - Sub-MeV energies vacuum oscillation dominates, P ~1/2
  - Above about 5 GeV Matter effects become significant, P ~1/3

Super Kamiokande

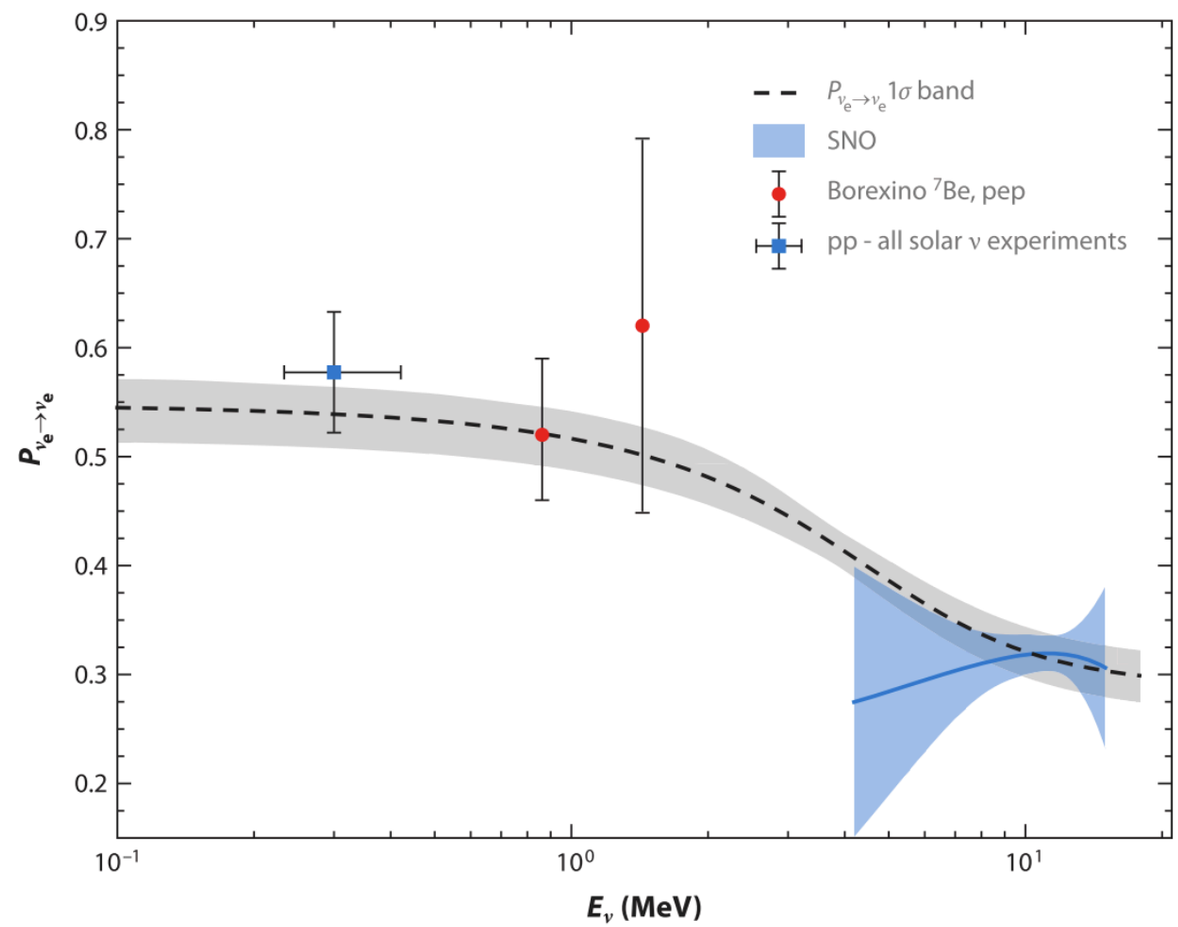


50 kton water Cherenkov

SNO

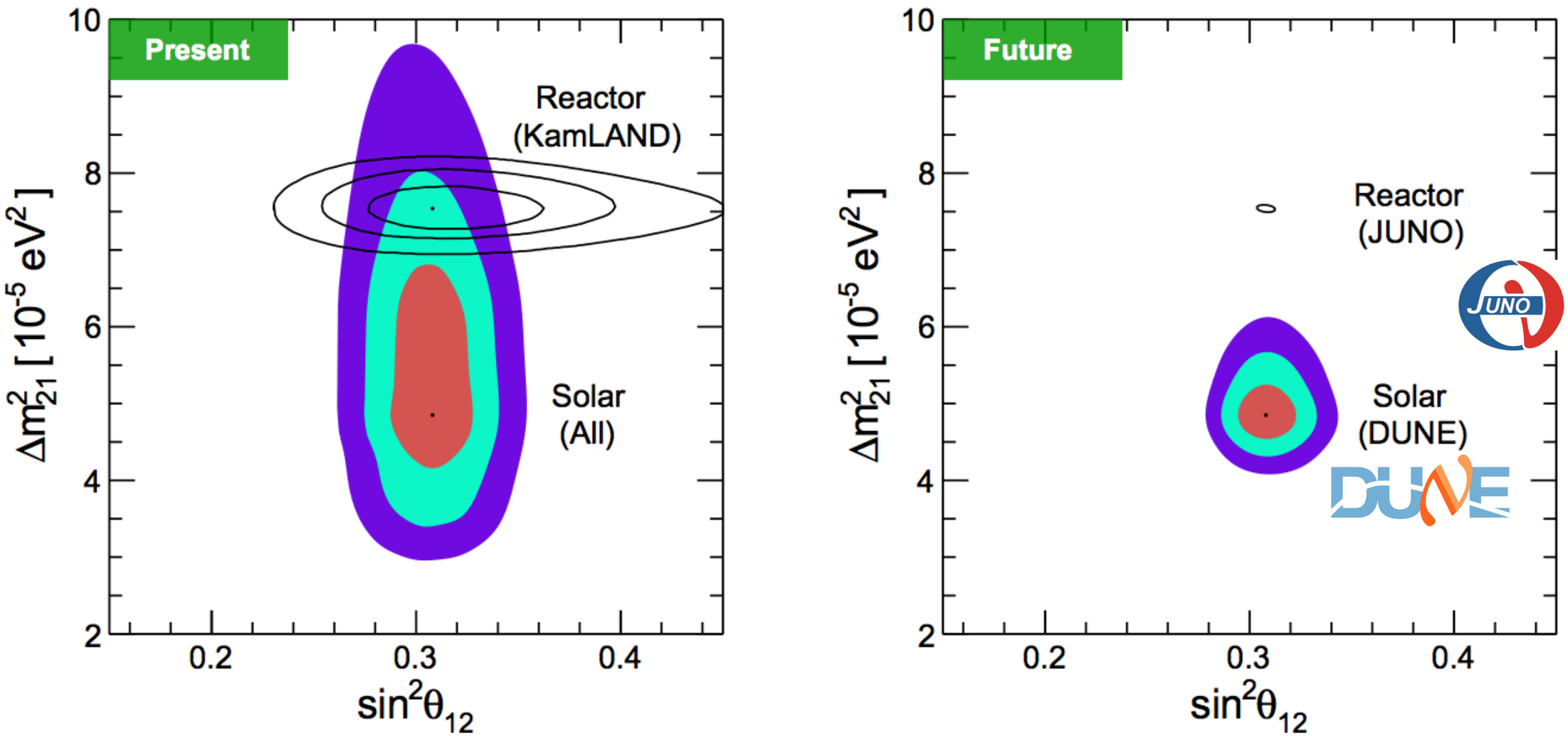


1 kton heavy-water Cherenkov



- There is tension in the results from KamLAND (reactor) and the solar measurements
  - SK spectrum and SNO data favor a lower θ_{21} value than KamLAND's by more than 2σ and mostly determine this parameter in the solar neutrino oscillation fit

arXiv:1808.08232, F. Capozzi, S Weishi Li, G. Zhu, J. F. Beacom

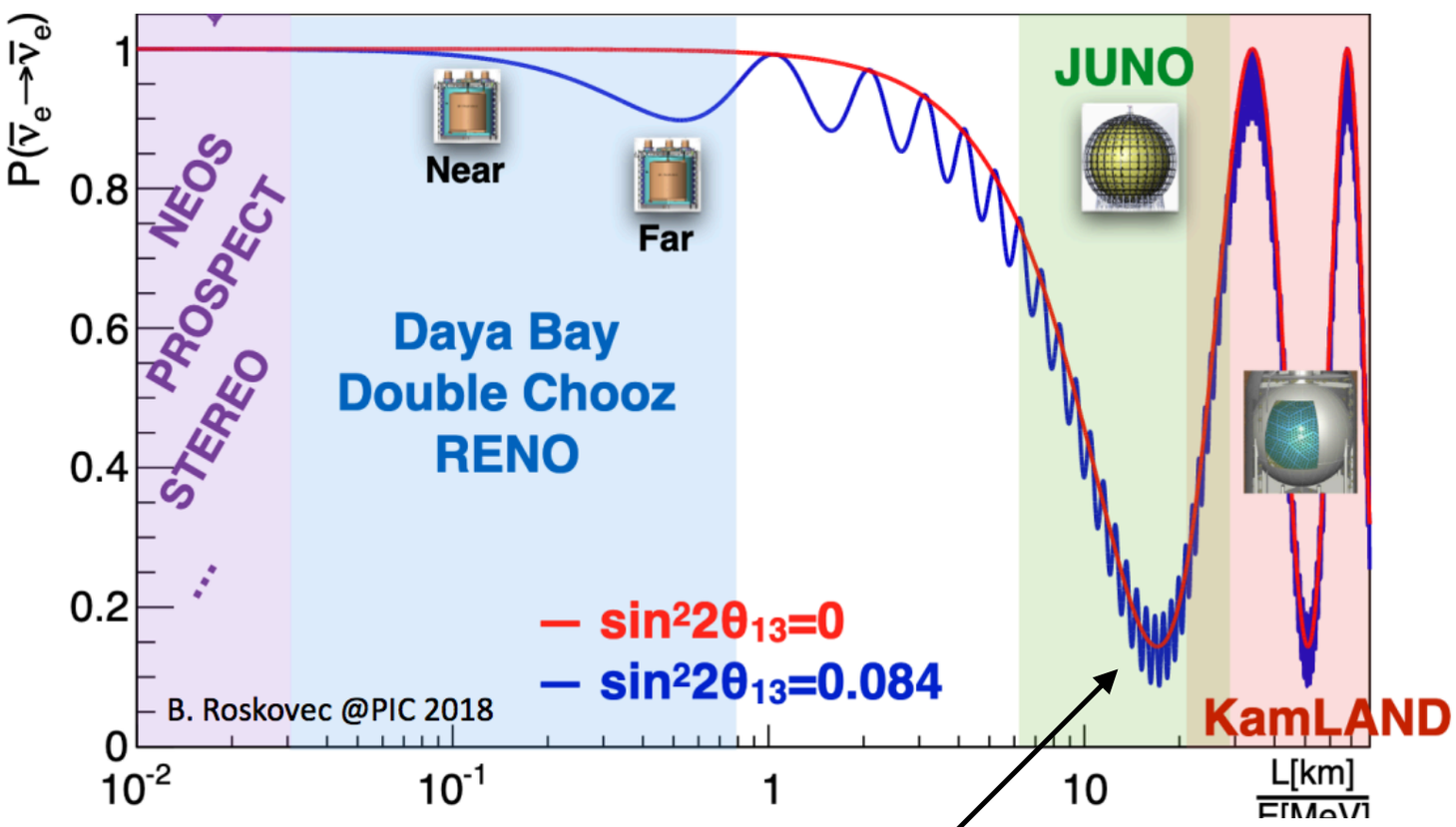


JUNO reactor experiment planned for 2021 will make very high precise measurements of the solar sector

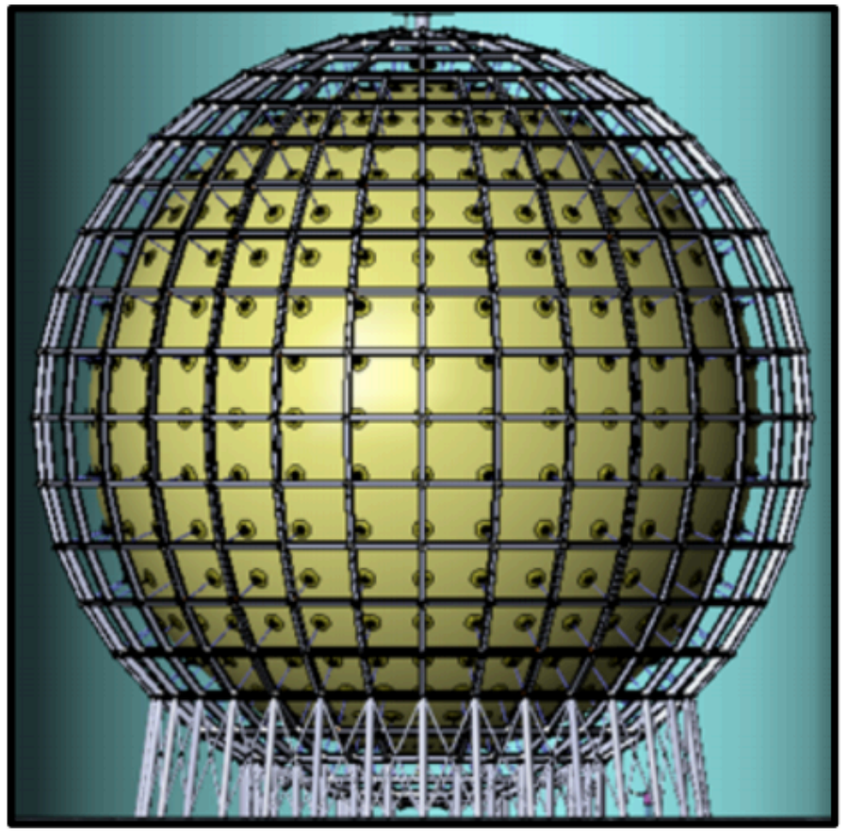
Future Reactor Experiment: JUNO

Primary physics goals:

- Probe medium and short baseline
- Mass ordering determination (>3σ)
- Measure $\sin^2\theta_{12}$, Δm^2_{21}, Δm^2_{ee} to better than 1%



JUNO (c. 2021)



Mass ordering, $\sin^2\theta_{12}$, Δm^2_{12}, Δm^2_{ee}
Supernova νs, solar νs geoneutrinos, baryon number violation, BSM

Designed with good enough energy resolution to resolve wiggles

Future Reactor Experiment: JUNO

Primary physics goals:

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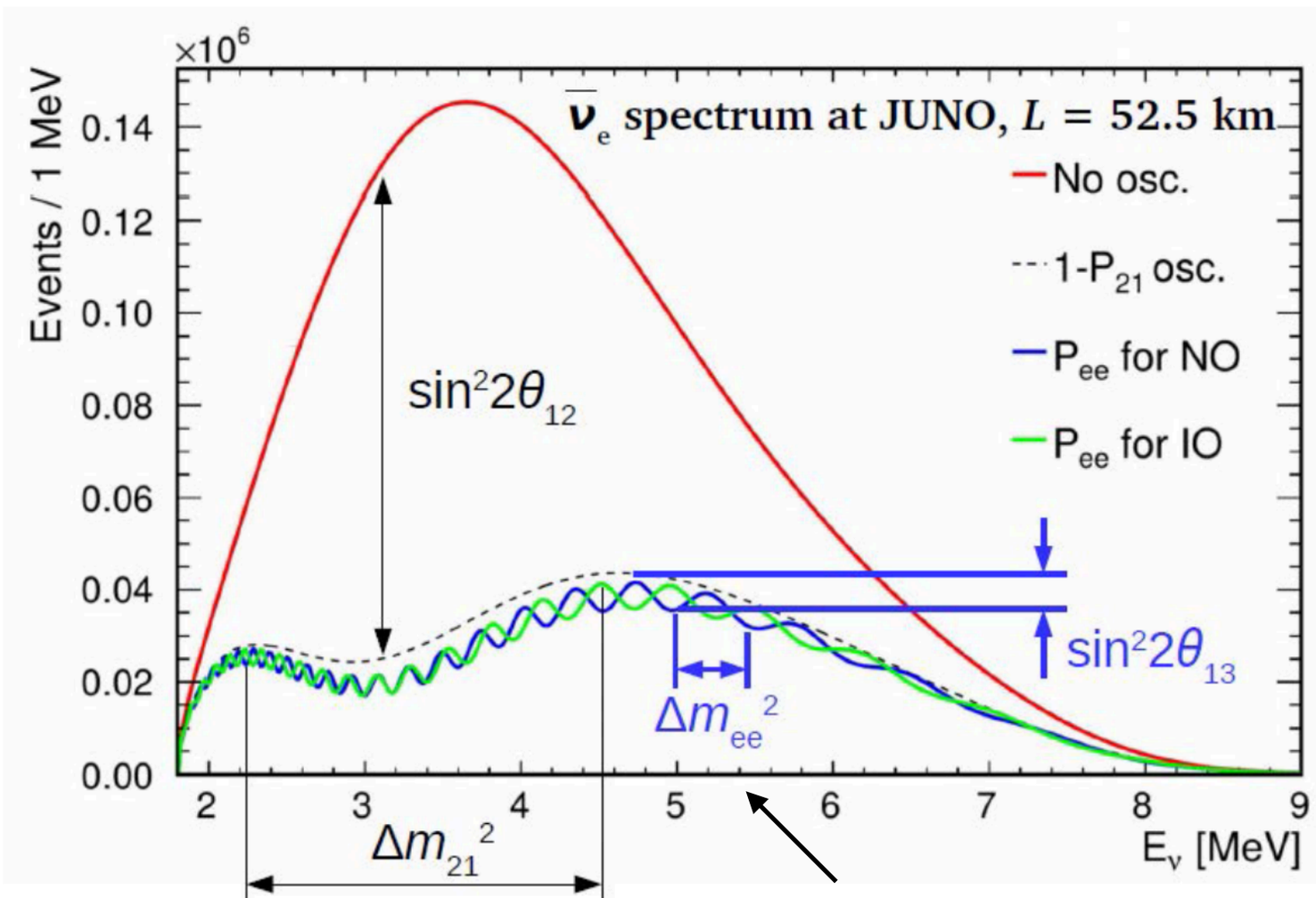
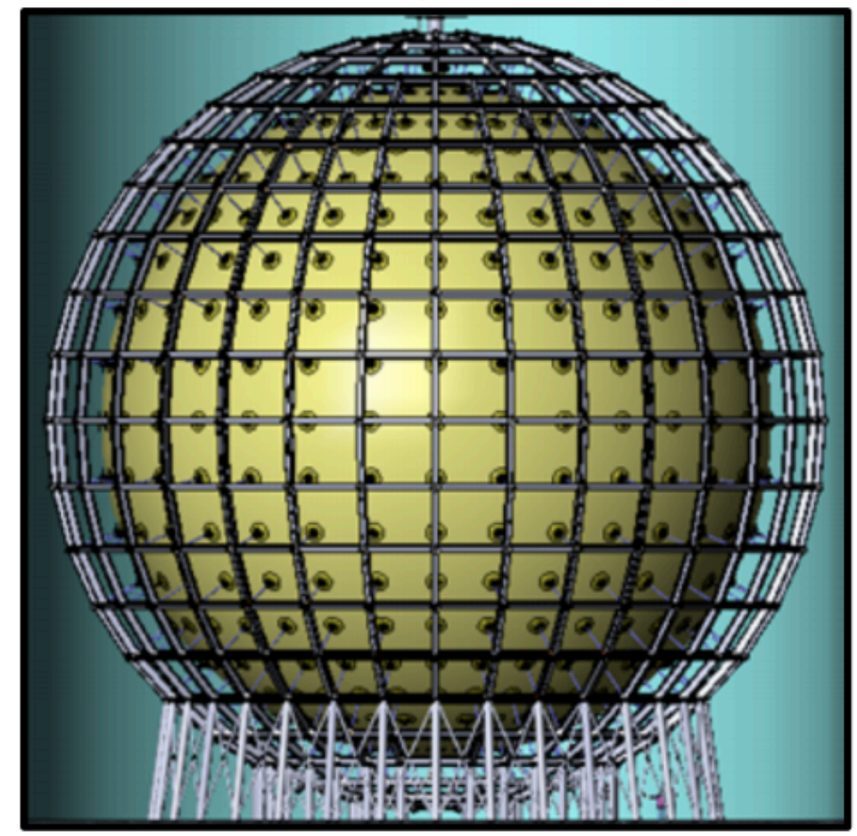


Designed with good enough energy resolution to resolve wiggles

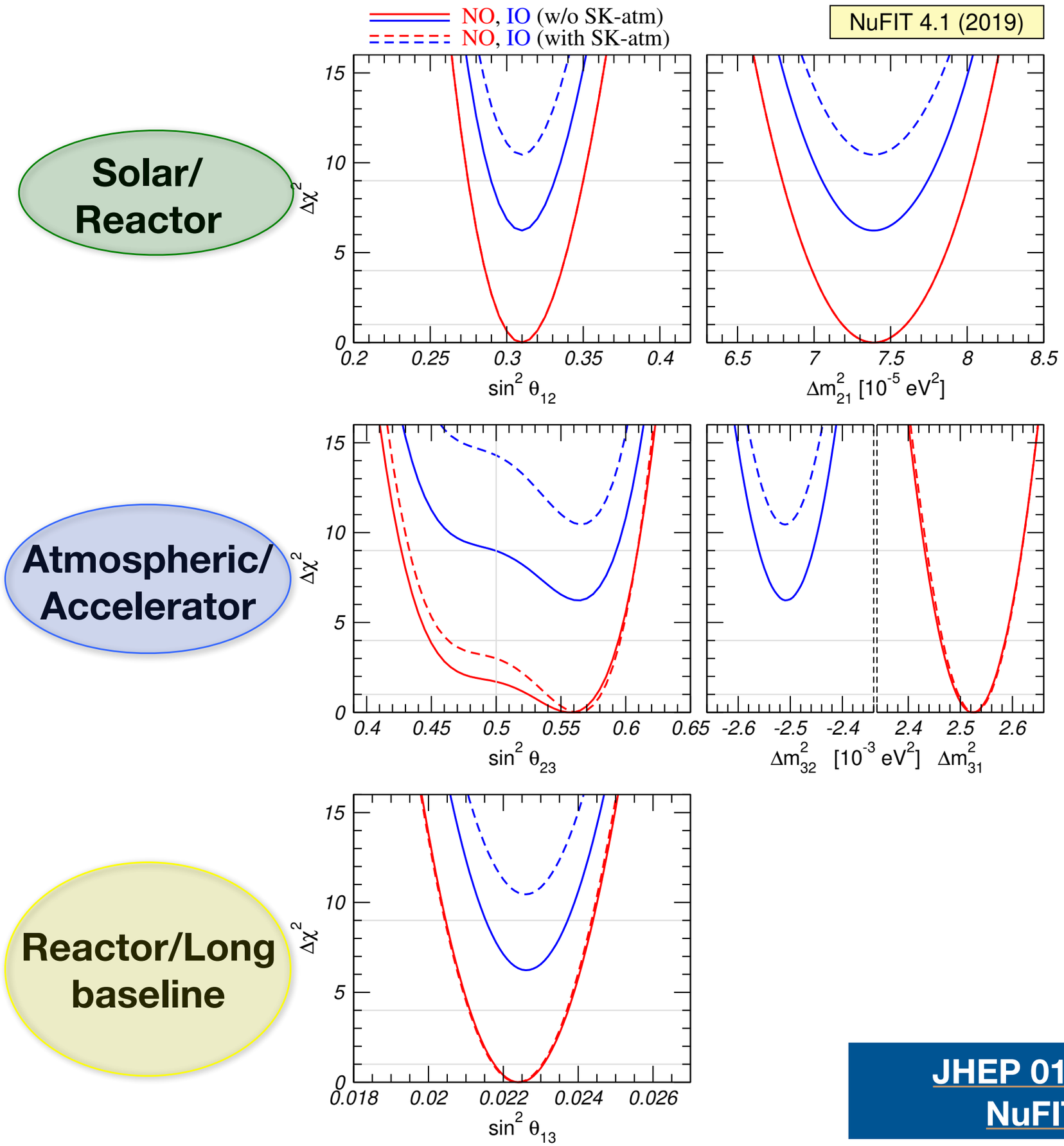
JUNO (c. 2021)



Mass ordering, $\sin^2\theta_{12}$, Δm^2_{12}, Δm^2_{ee}

Supernova νs, solar νs geoneutrinos, baryon number violation, BSM

image from E. Worcester



Suite of experiments to come

INO

DUNE

HYPER KO

ORCA

PINGU

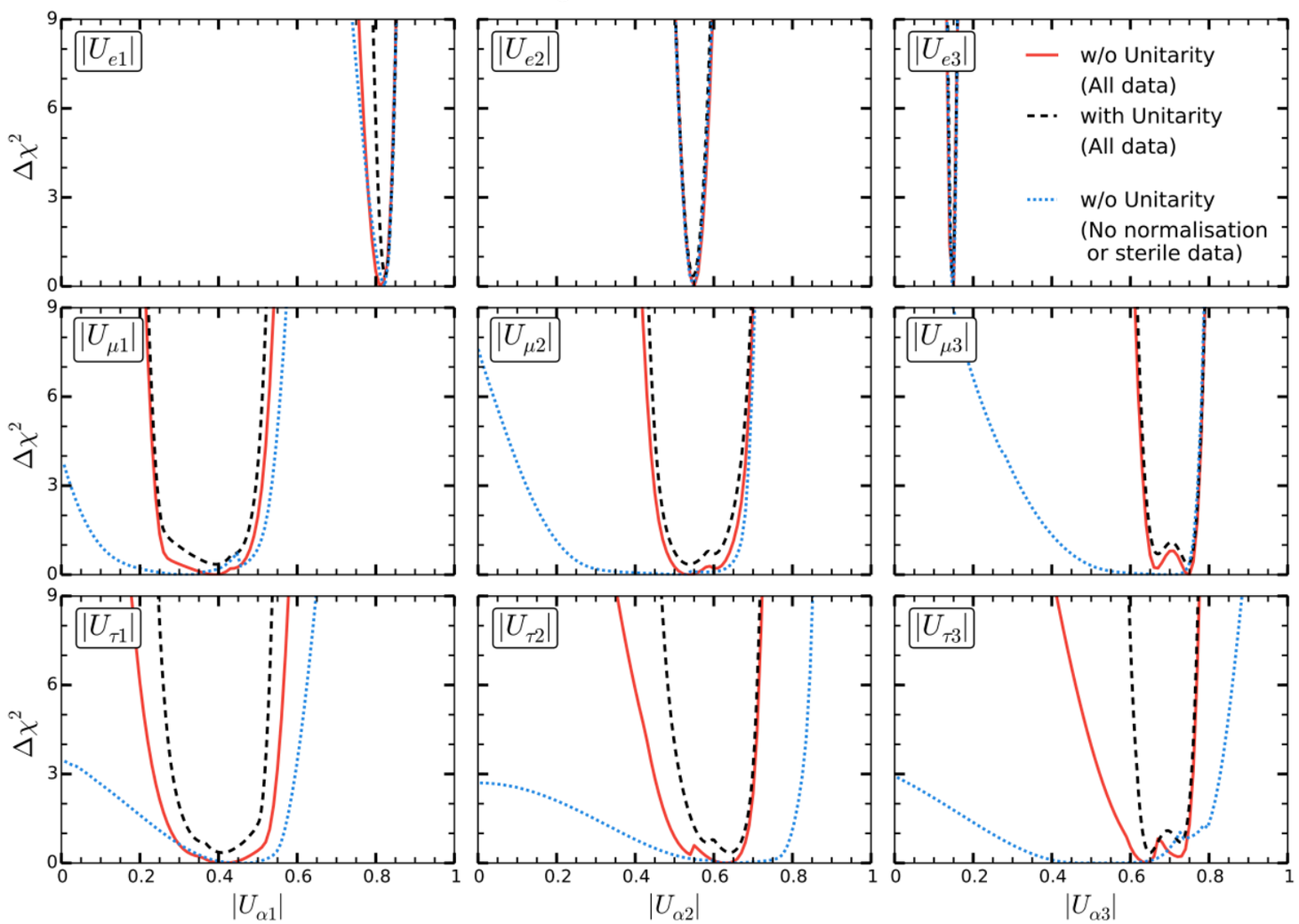
JUNO

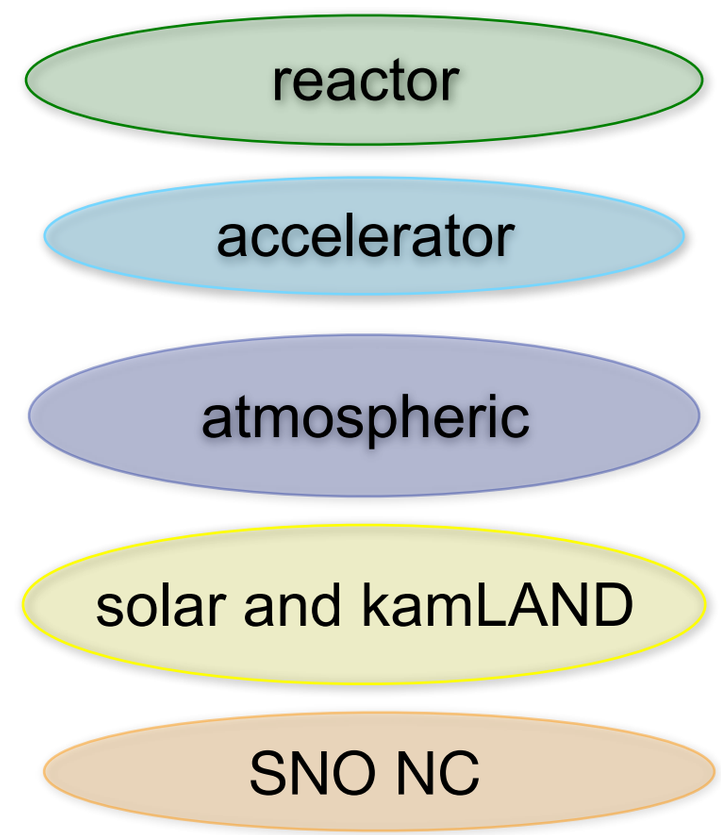
JHEP 01 (2019) 106 [arXiv:1811.05487], NuFIT 4.1 (2019), www.nu-fit.org

Although we have probed of the angles and mass splittings we have not probed all the matrix elements.

$$= \begin{bmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta_{CP}} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta_{CP}} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta_{CP}} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta_{CP}} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta_{CP}} & c_{23}c_{13} \end{bmatrix}$$

arXiv:1508.05095 S.Parke and M. Ross-Lonergan

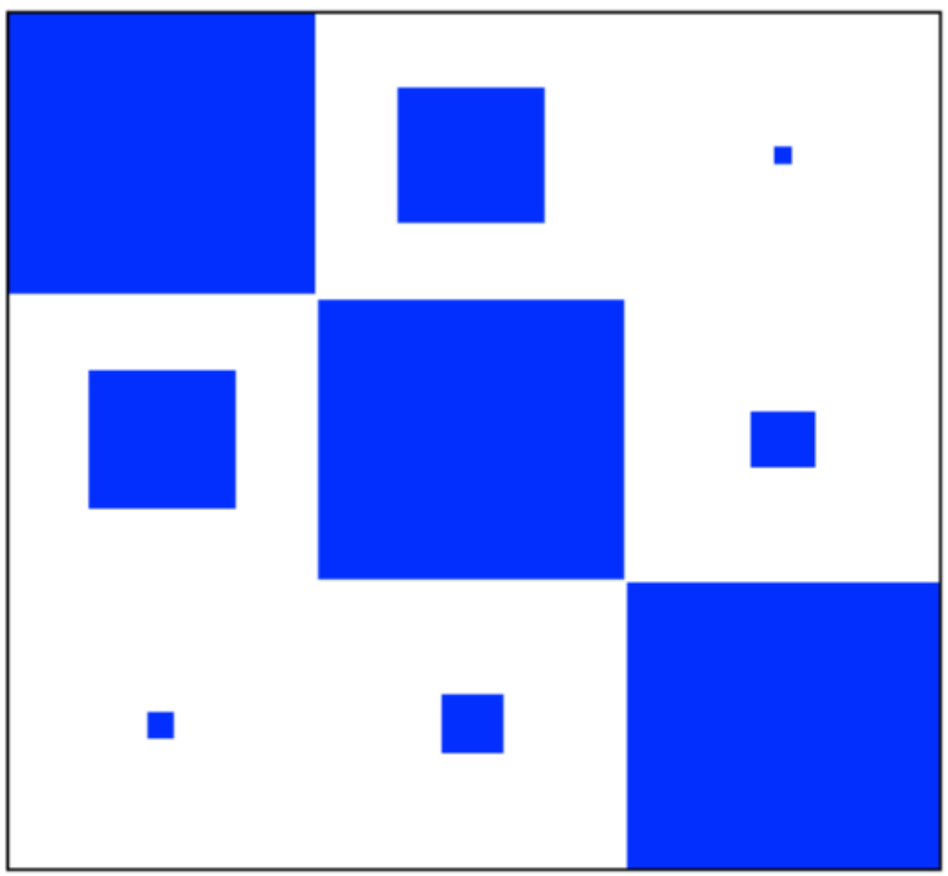




Lots of area for new physics specially in poorly constrained ν_τ sector

Many parts of PMNS matrix not well constrained and we do not understand the relative sizes of these values nor the relationship between quarks and neutrino mixing

Quark mixing



Neutrino mixing

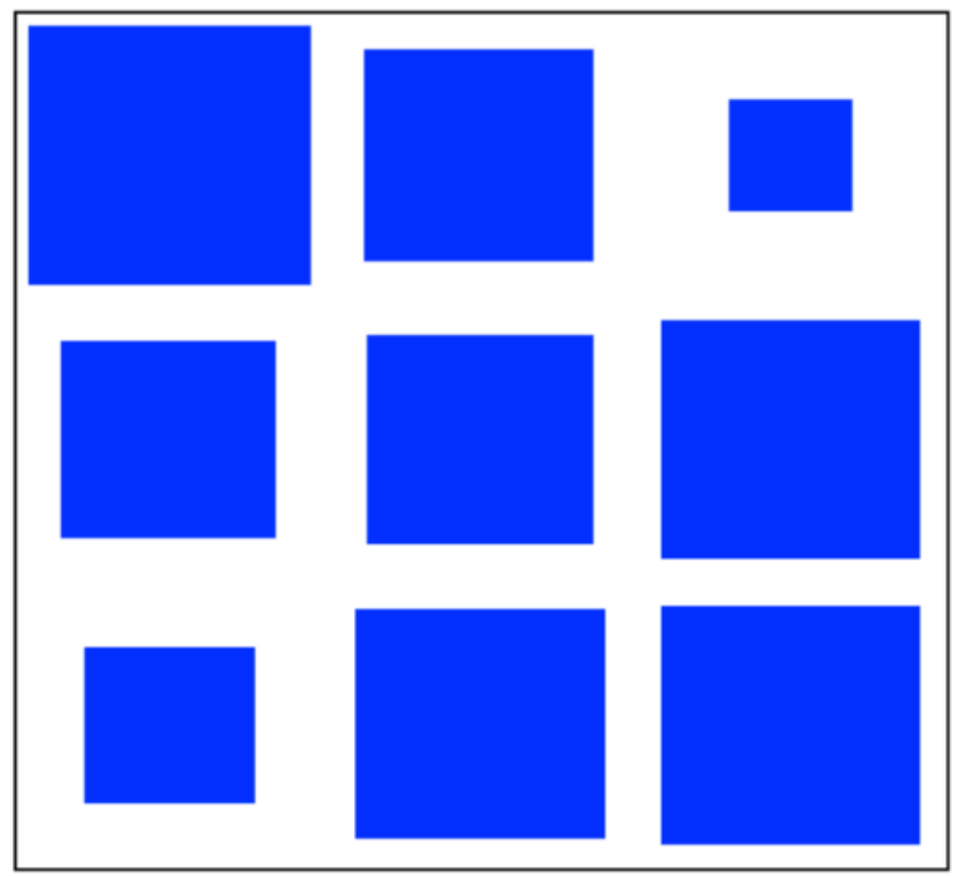


Image from Mark Messier

Conclusions

- Solar experiments study ν_e which originate in the sun, probe solar mass term and θ_{12}
- Reactor experiments look at anti-ν_e → anti-ν_e oscillations probe at both:
  - Short baseline experiments measure θ_{13} to high precision
  - Medium baseline experiments probe solar term
  - Future reactor experiment JUNO will provide very precise measurements of solar parameters and > 3σ mass ordering determination
- Atmospheric and accelerator experiments study ν_u disappearance and ν_e appearance.
  - Currently running accelerator experiments T2K and NOvA making precision measurements of mass splitting and mixing angle. θ_{23} and have potential to provide evidence, ~3σ level, on neutrino mass ordering and charge-parity violation.
  - Future T2HK and DUNE will enable precision measurements mixing angles and determination charge-parity violation.
- Still a long way to go to fully constrain the PMNS mixing matrix and lots of room for new physics!