How Neutrino Measurements Fit Together: Past, Present, and Future

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Fermilab

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Division of Particles and Fields
Fermi National Accelerator Laboratory
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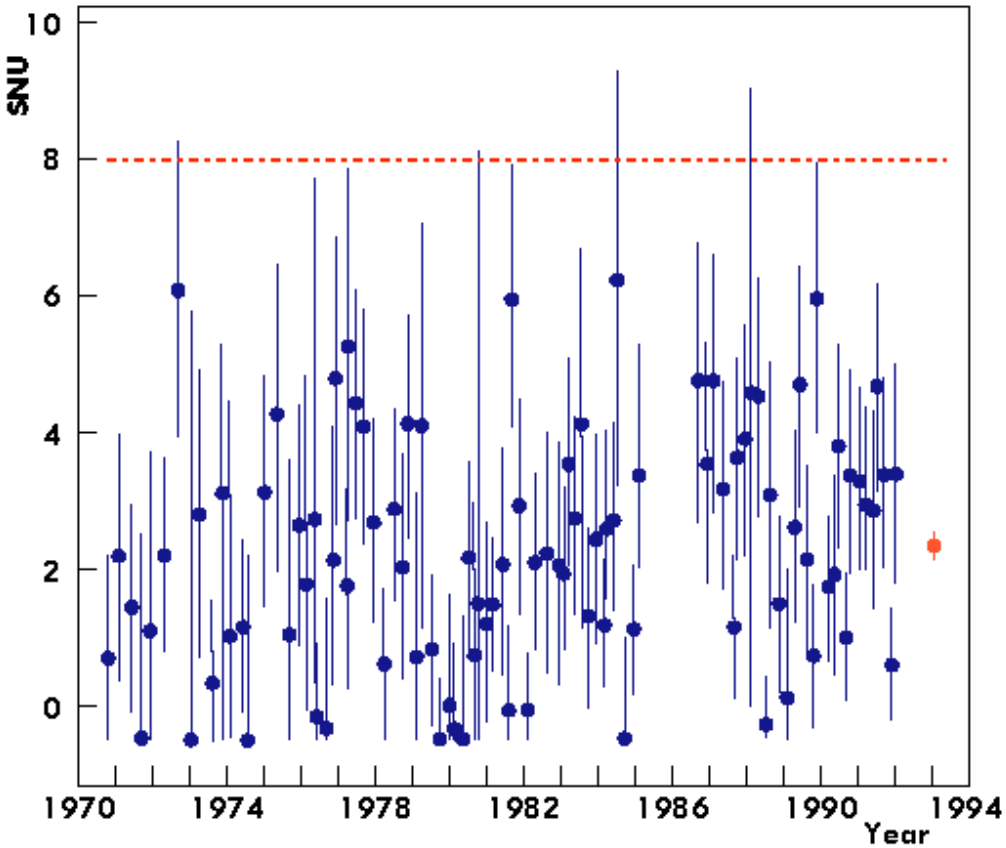
Introduction

- "How all neutrino experiments fit together" is a *really* broad topic, and we only have 20 minutes.
- This talk will focus just on some examples of fitting together neutrino oscillation experiments.
- Some other things this talk could have been about:
  - Cross-section + oscillation measurements
  - Oscillation experiments + 0νββ
  - N_ν from cosmology + sterile neutrino searches
  - $m_{\nu e}$ vs. $m_{\beta\beta}$ vs. Σm
    - Beta decay vs. 0νββ vs. cosmology

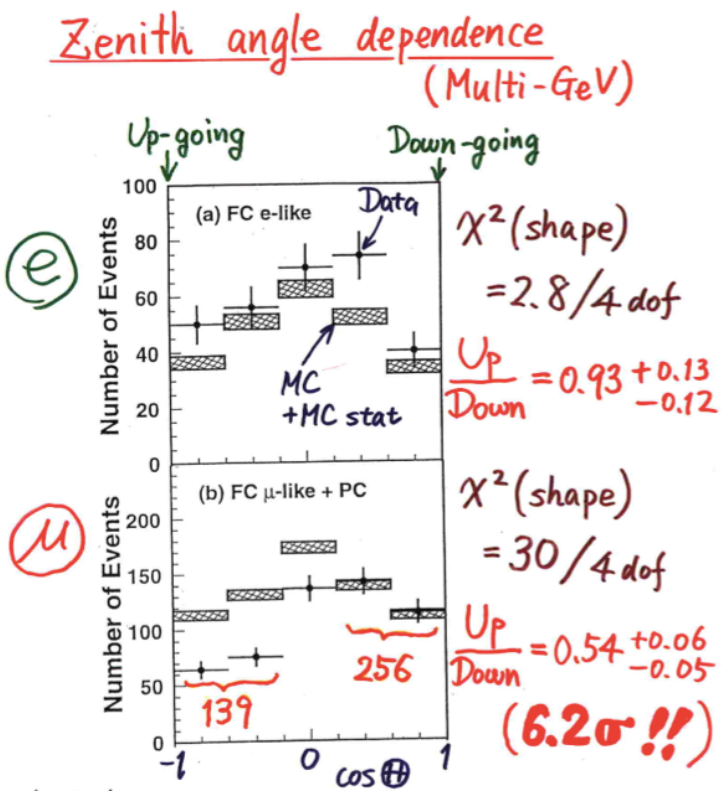
The Past: The Solar Neutrino Problem

- The start of neutrino oscillation physics.



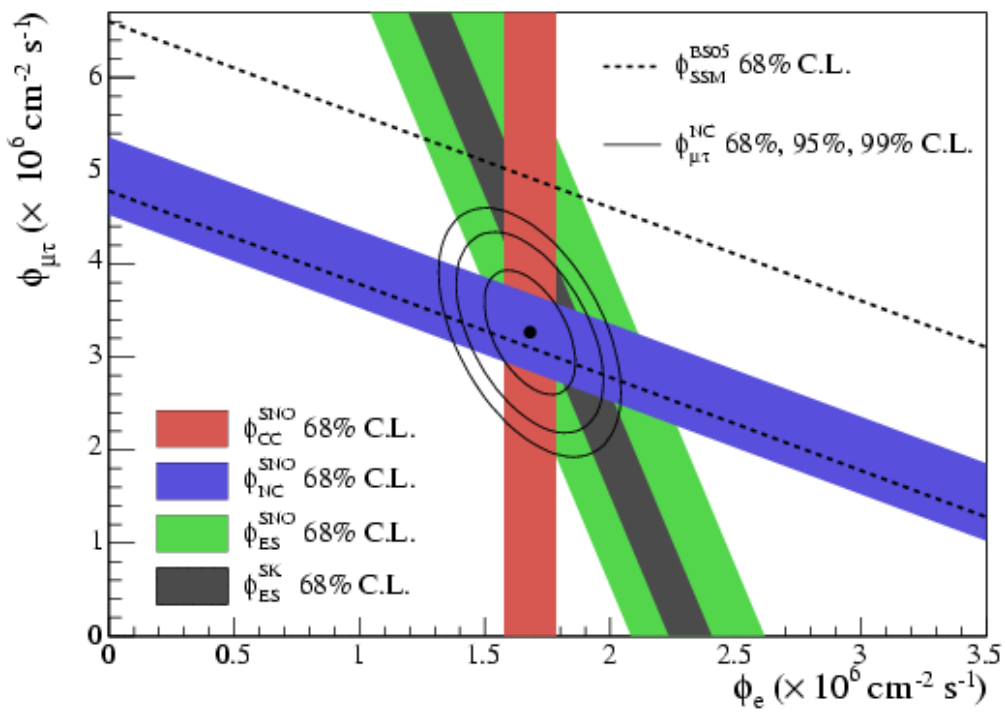
- Super-Kamiokande shows that neutrinos oscillate
- SNO shows that only the ν_e flux is depleted in solar neutrinos

Super-Kamiokande



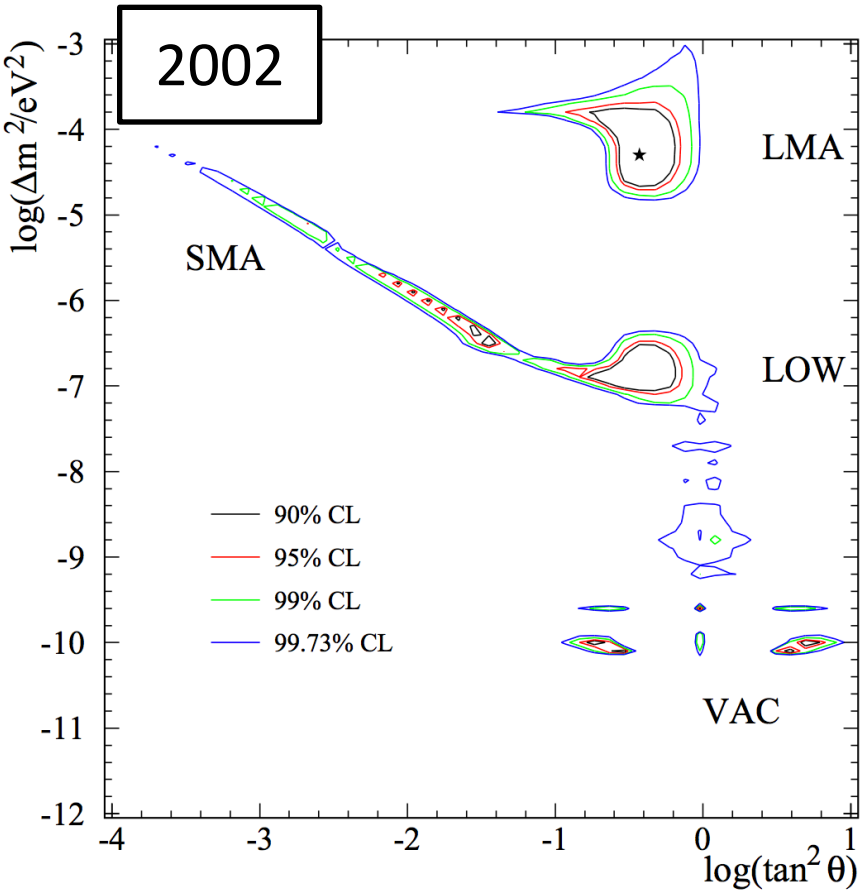
T. Kajita, NEUTRINO 1998

SNO



SNO Collaboration, PRL **89** (2002), p. 011301

- The initial observation still allowed *very* different regions of parameter space.
- But, even the latest paper from SNO alone cannot determine the oscillation parameters unambiguously.



SNO Collaboration, PRL **89** (2002), p. 011302

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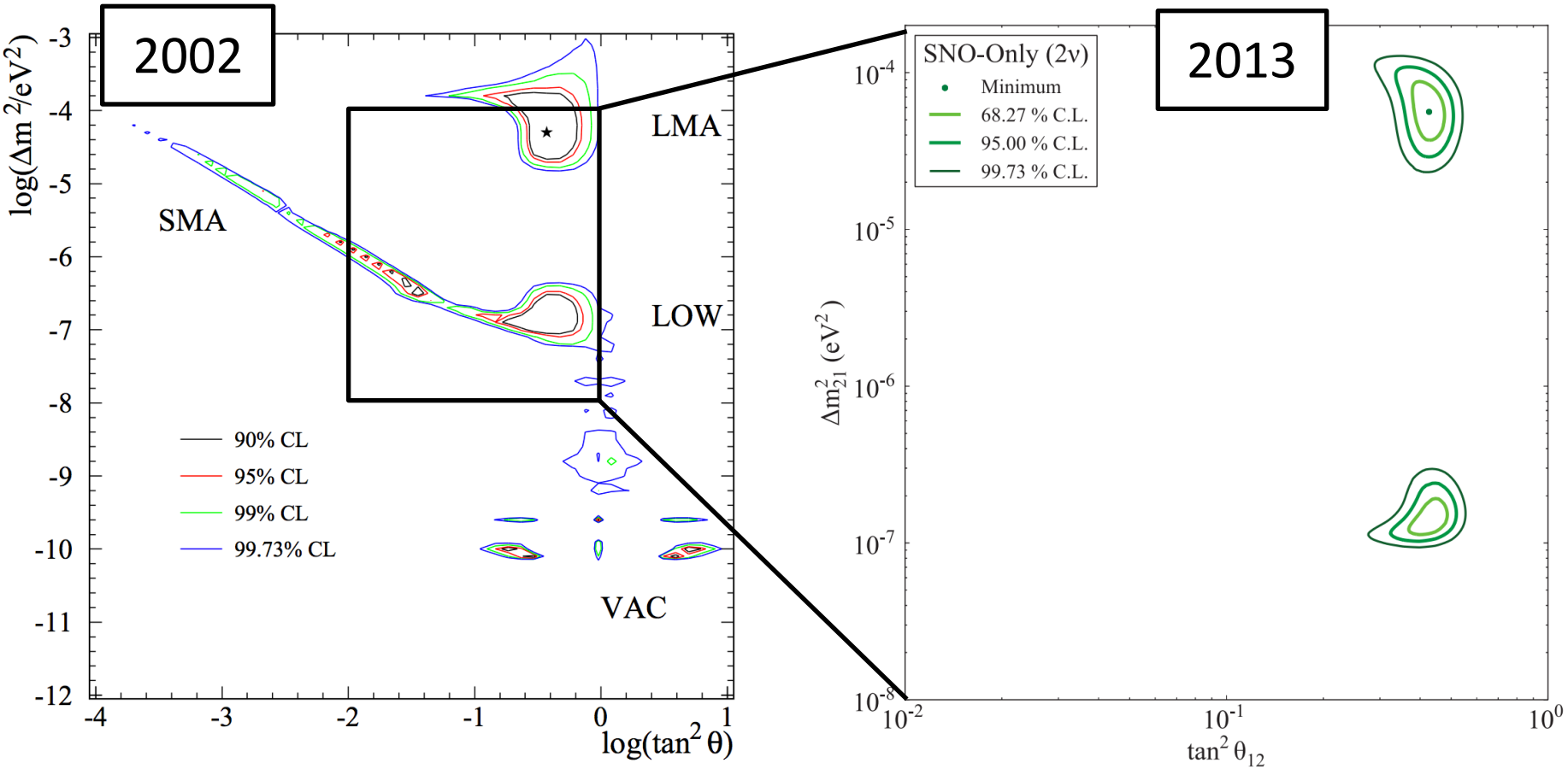
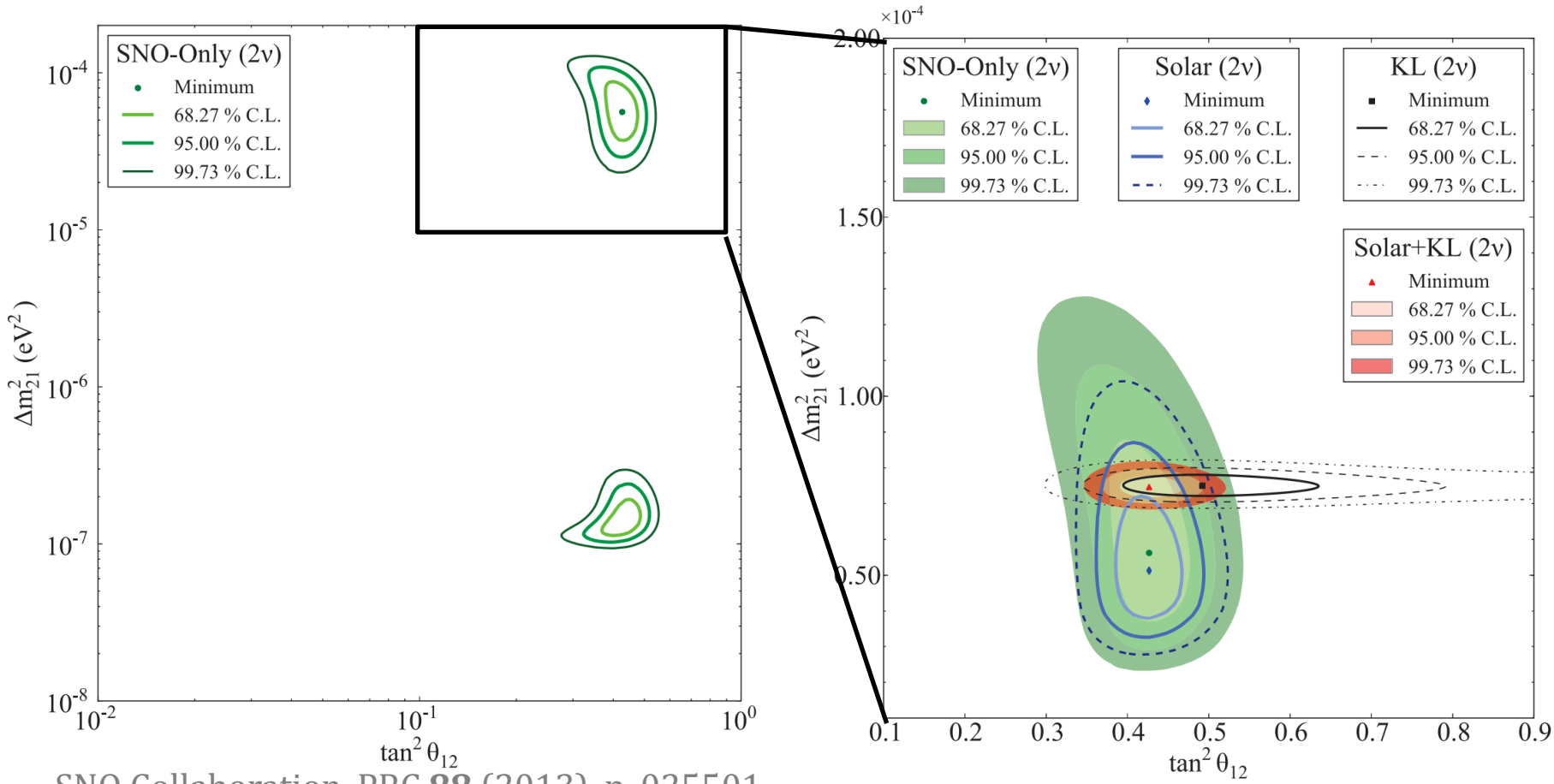


SNO Collaboration, PRL **89** (2002), p. 011302

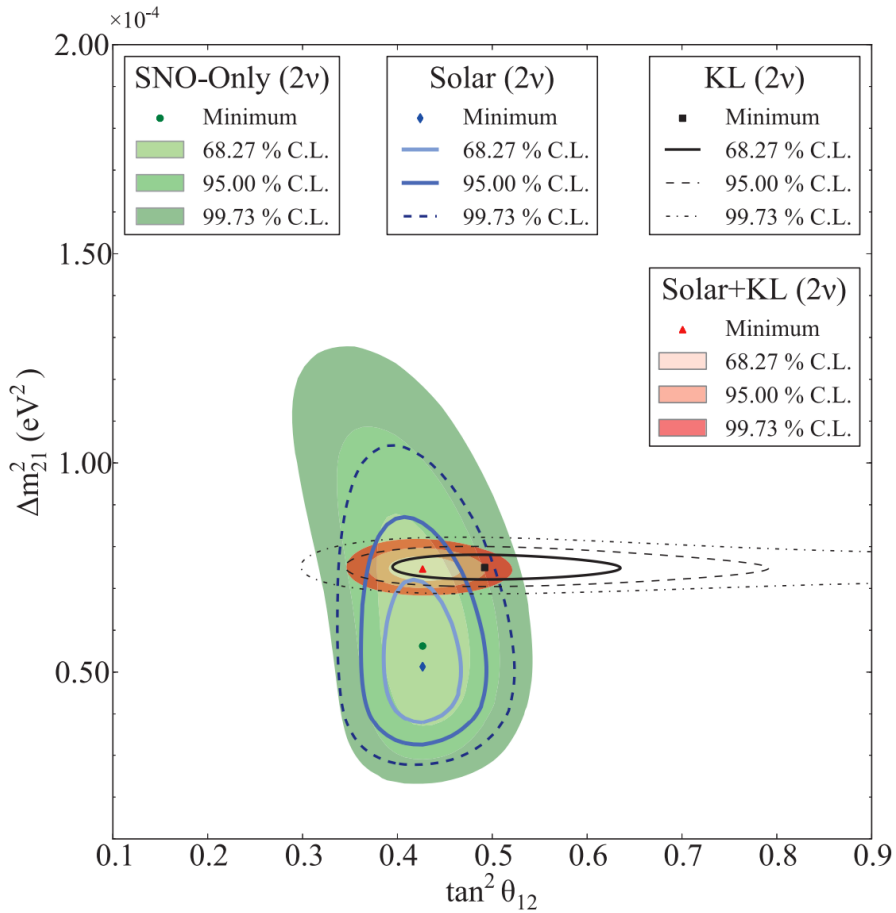
SNO Collaboration, PRC **88** (2013), p. 025501

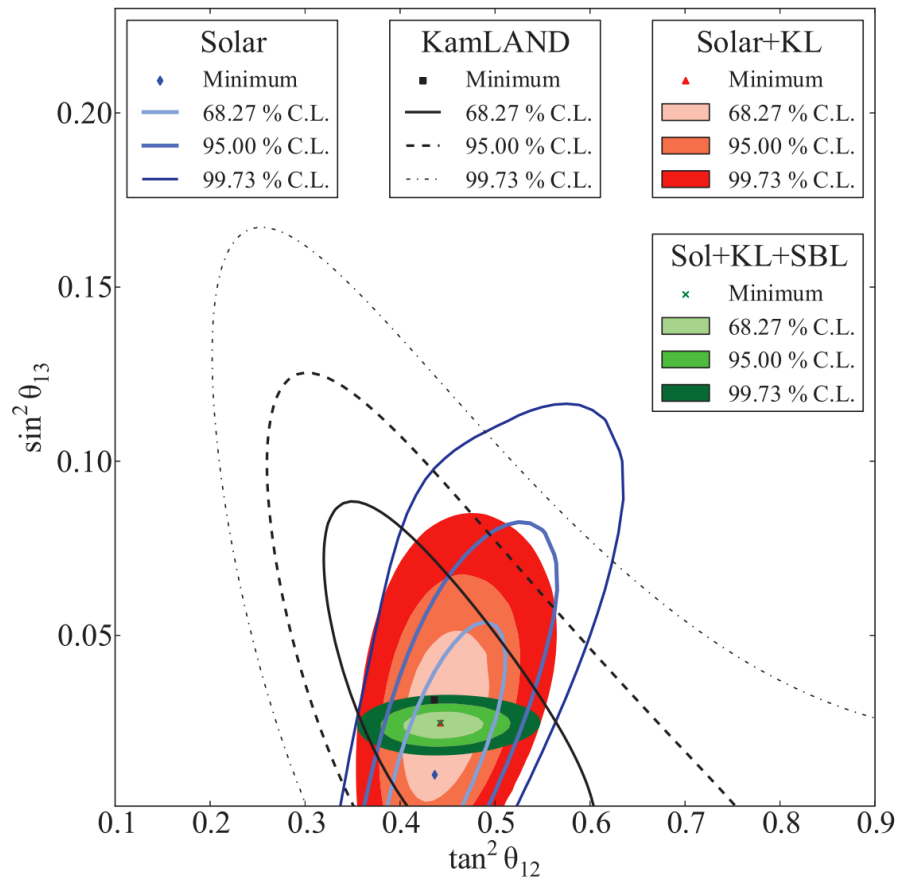
- Including the results from *other* solar experiments resolves the ambiguities.
- Bringing in the KamLAND reactor measurement demonstrates consistency between solar ν_e and reactor anti-ν_e and significantly increases precision.



SNO Collaboration, PRC **88** (2013), p. 025501

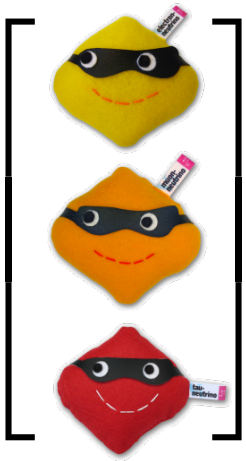
- The small tension between the two measurements in θ_{12} was, in fact, evidence of 3-flavor oscillations (e.g. $\theta_{13} > 0$).



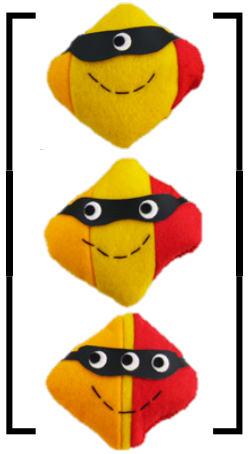


SNO Collaboration, PRC **88** (2013), p. 025501

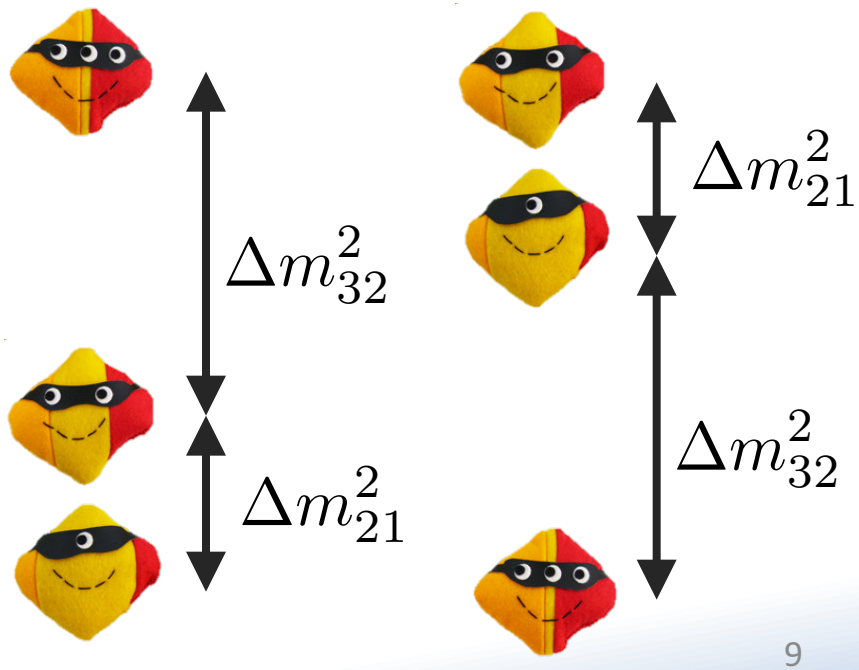
The Present: What we know now



$$= R(\theta_{23}) \cdot R(\theta_{13}, \delta_{CP}) \cdot R(\theta_{12})$$



- Oscillations among the three neutrino flavors depend on:
  - The mixing matrix
    - θ_{23}, θ_{13}, δ_{CP}, θ_{12}
  - The mass differences
    - $\Delta m^2{}_{32}$, $\Delta m^2{}_{21}$
  - The mass hierarchy
    - The sign of $\Delta m^2{}_{32}$



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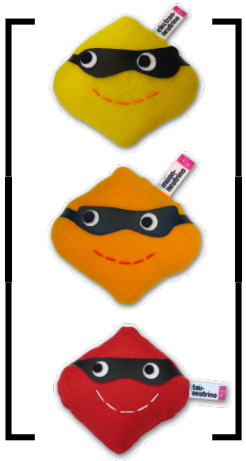

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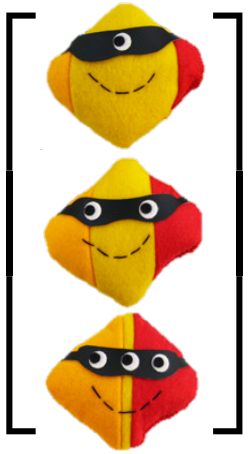
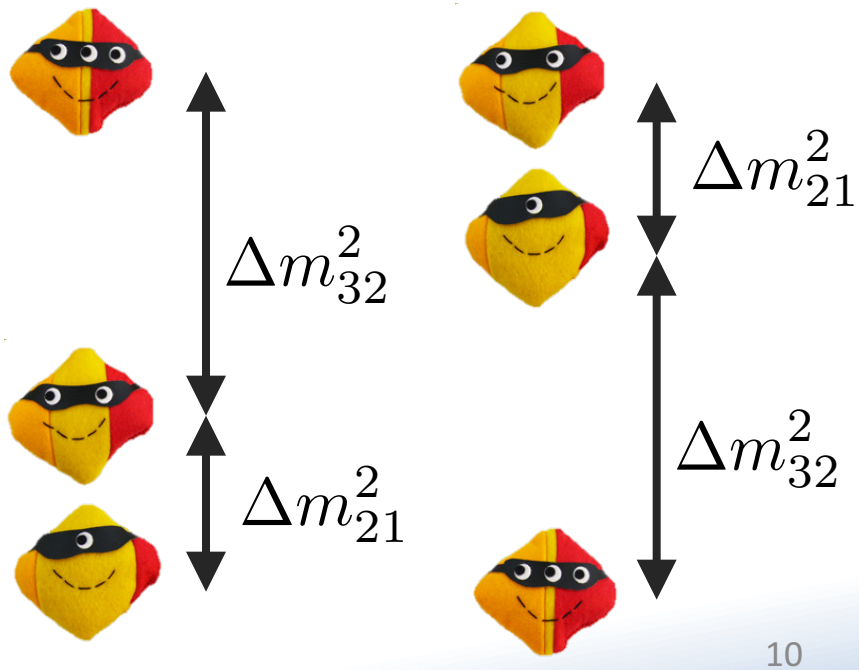
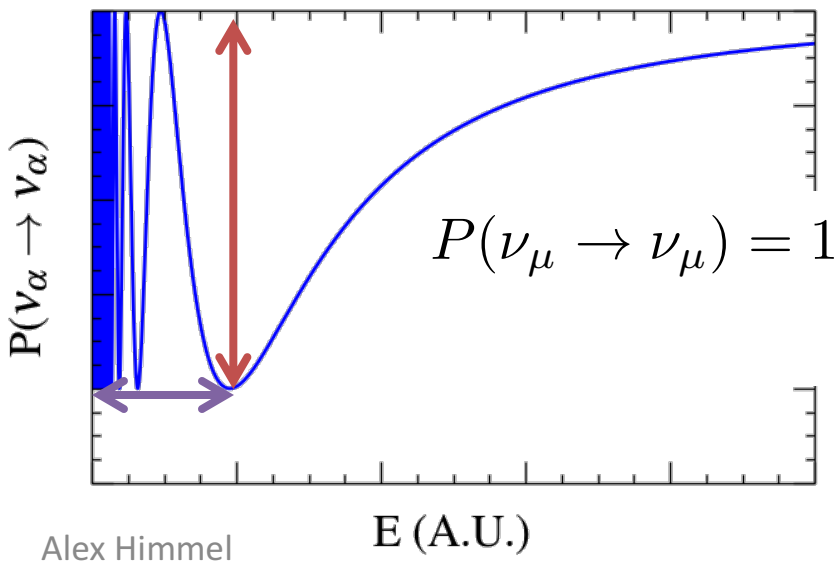


- Let's look at a combined analysis of all available neutrino data: **NuFit 3.0**
  - I. Esteban, M. C. Gonzalez-Garcia, M. Maltoni, I. Martinez-Soler, T. Schwetz JHEP **01** (2017) 087



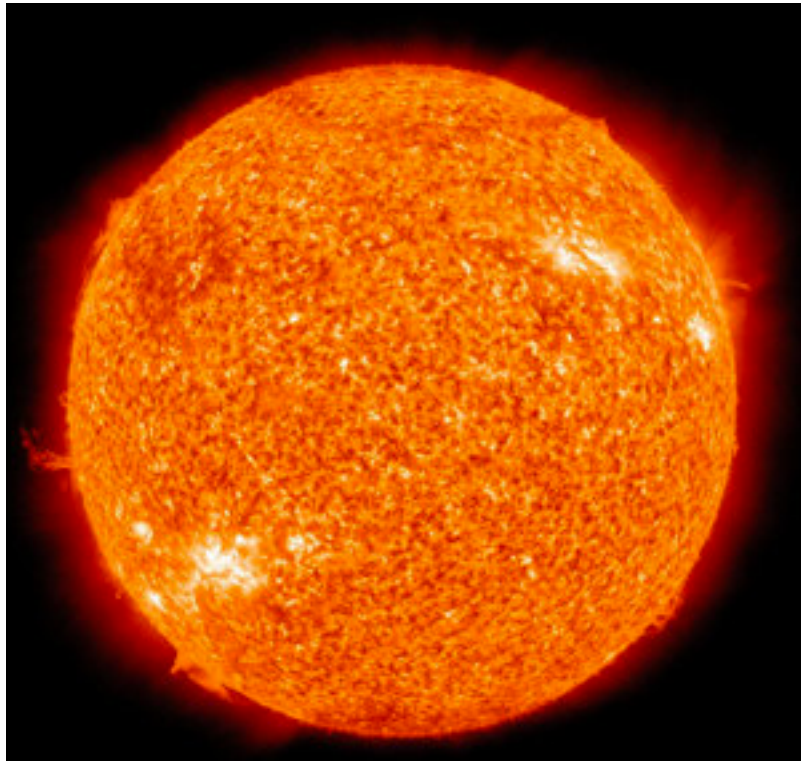
Available measurements

- Neutrinos are hard to work with
  - Can only access a certain subset of flavor transitions
  - Certainly cannot see them all in the same experiment.
- Remember – oscillations depend on distance and energy.
  - Vacuum oscillations depend on L/E
  - Matter effects depend on L, too.
- Disappearance ($\nu_\alpha \to \nu_\alpha$) and appearance ($\nu_\alpha \to \nu_\beta$) probe different things.



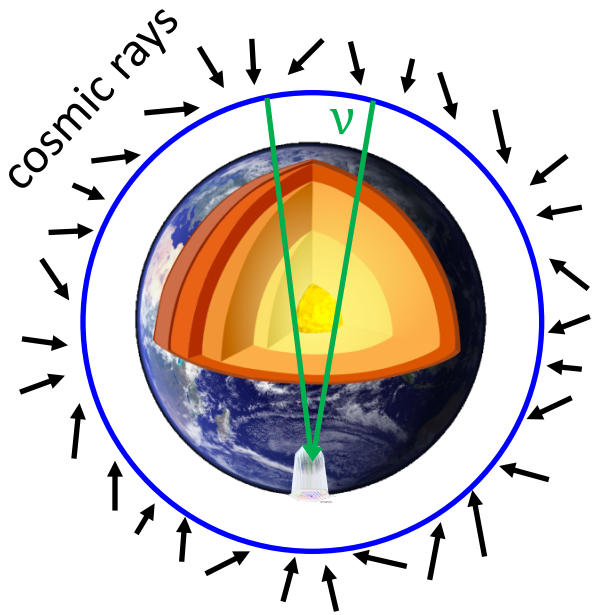
$$P(\nu_\mu \to \nu_\mu) = 1 - \left(\sin^2(2\theta_{13}) \sin^2(\theta_{23}) + \cos^4(\theta_{13}) \sin^2(2\theta_{23}) \right) \sin^2\left(\frac{\Delta m^2 L}{4E} \right)$$

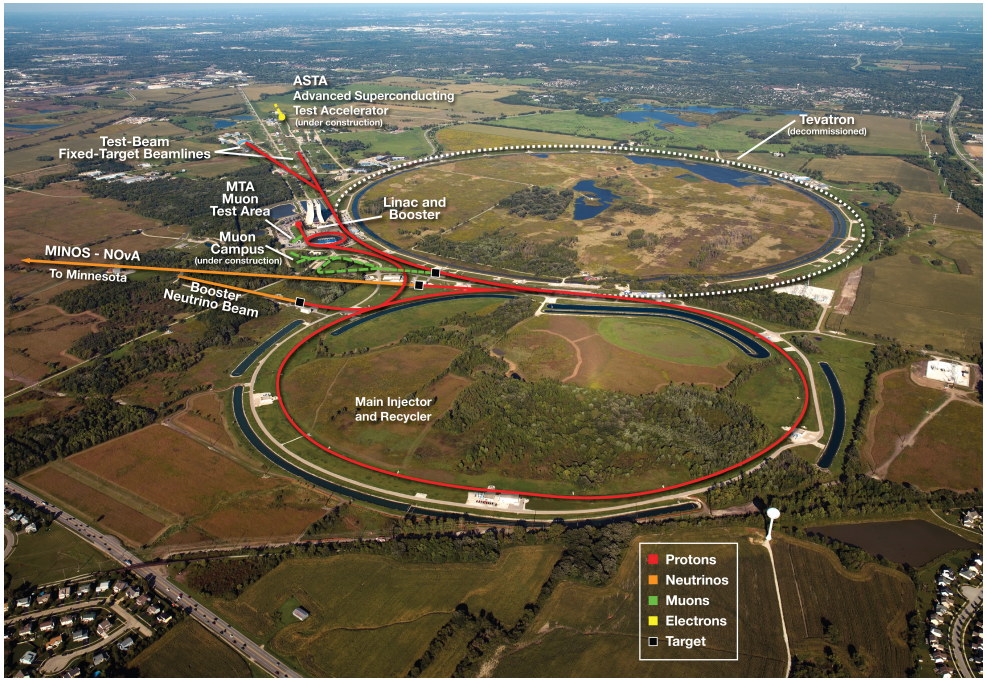
- $\nu_e \rightarrow \nu_e, \nu_x$
  - Source: **the Sun**
  - No choice of distance – all the oscillations happen in the Sun.
  - Only probes $\Delta m^2{}_{21}$
  - At this energy, can only tag CC ν_e or NC events.

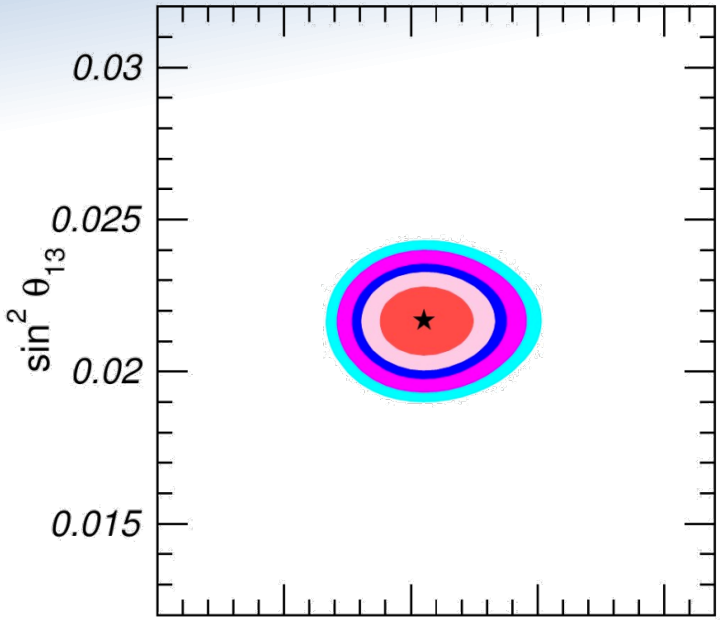


- anti-$\nu_e \rightarrow$ anti-ν_e
  - **Nuclear reactors** produce copious anti-ν_e's
  - No choice of energy, but can choose baseline to match either mass splitting.

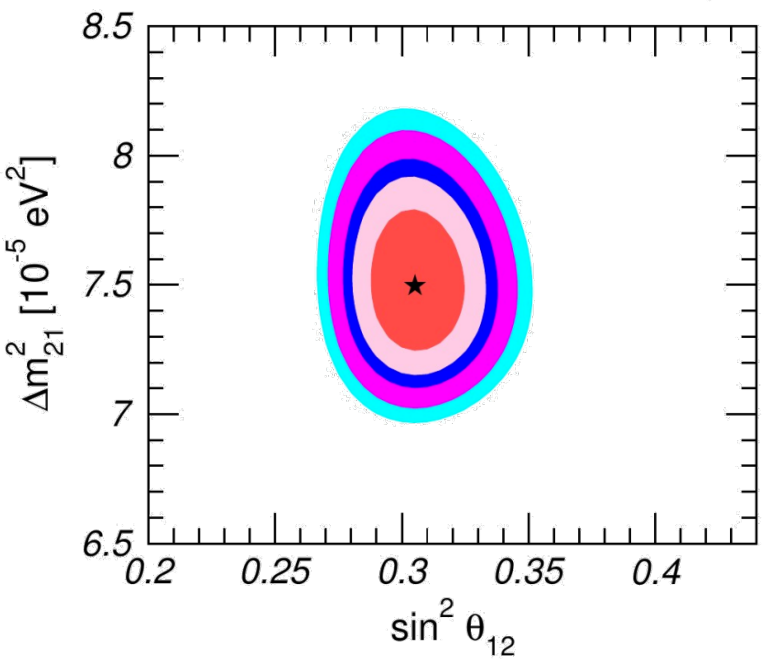
- $\nu_\mu \rightarrow \nu_\mu, \nu_e, \nu_\tau$
  - Antineutrinos, too
  - **Atmospheric neutrinos** give wide range of energies, baselines, but they are all mixed together.
  - **Accelerators** give well-controlled sources at particular energies, but we need to pay for the neutrinos.

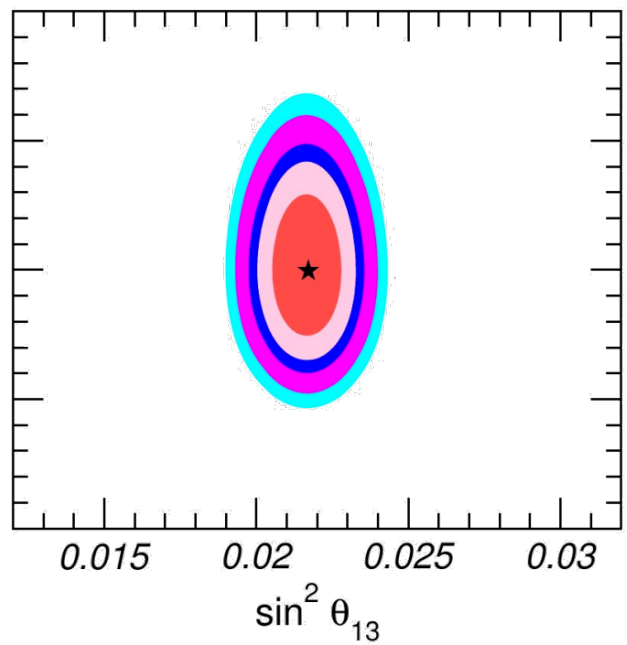


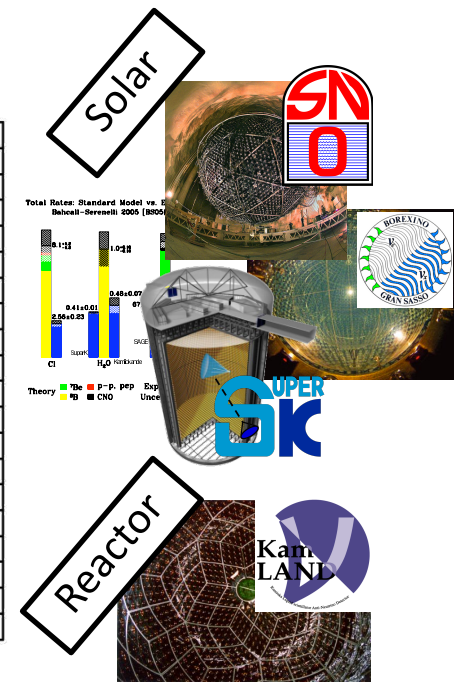




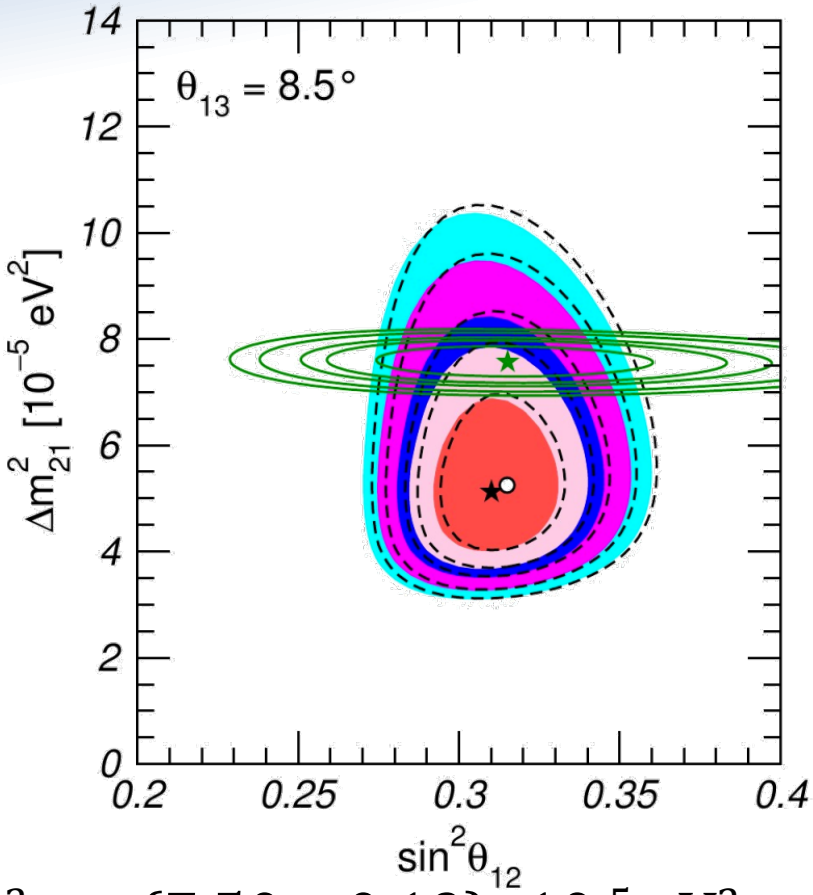
- $\theta_{13} = 8.46° \pm 0.15°$
  - Went rapidly from unknown to the most precisely known mixing angle.
- $\theta_{12} = 33.56° \pm 0.77°$
  - Allowing non-zero θ_{13} resolves reactor-solar tension in this parameter.

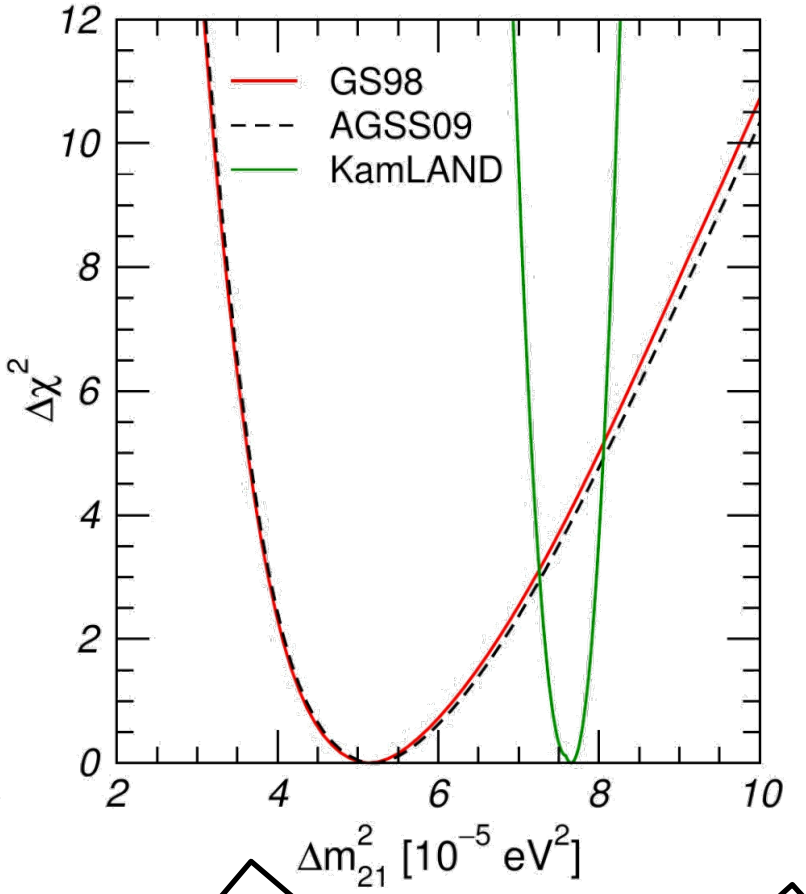




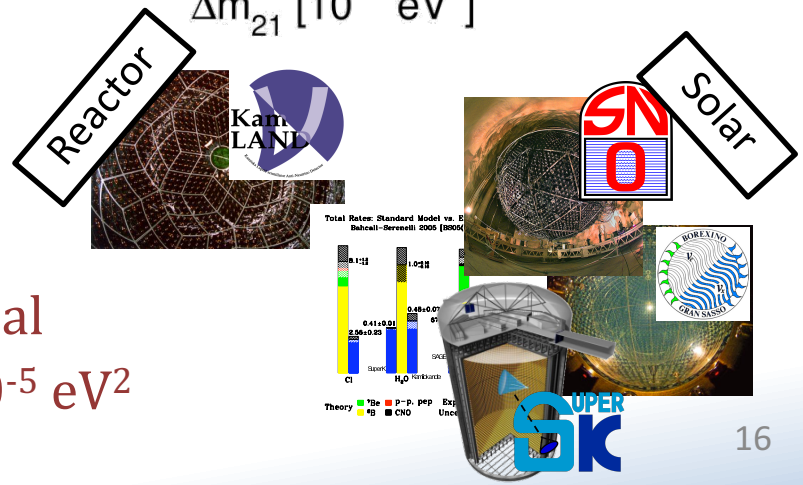


NuFIT 3.0 (2016)

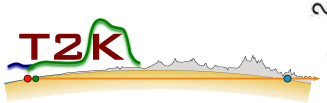


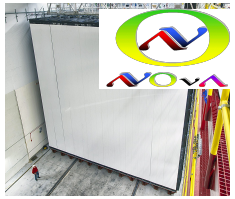


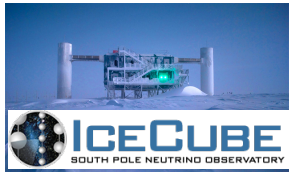
- $\Delta m^2_{21} = (7.50 \pm 0.19)\times10^{-5}$ eV^2
  - This measurement is dominated by KamLAND.
  - Some interesting tension with the global solar experiments which prefer $\sim5\times10^{-5}$ eV^2



Accelerator and Atmospheric







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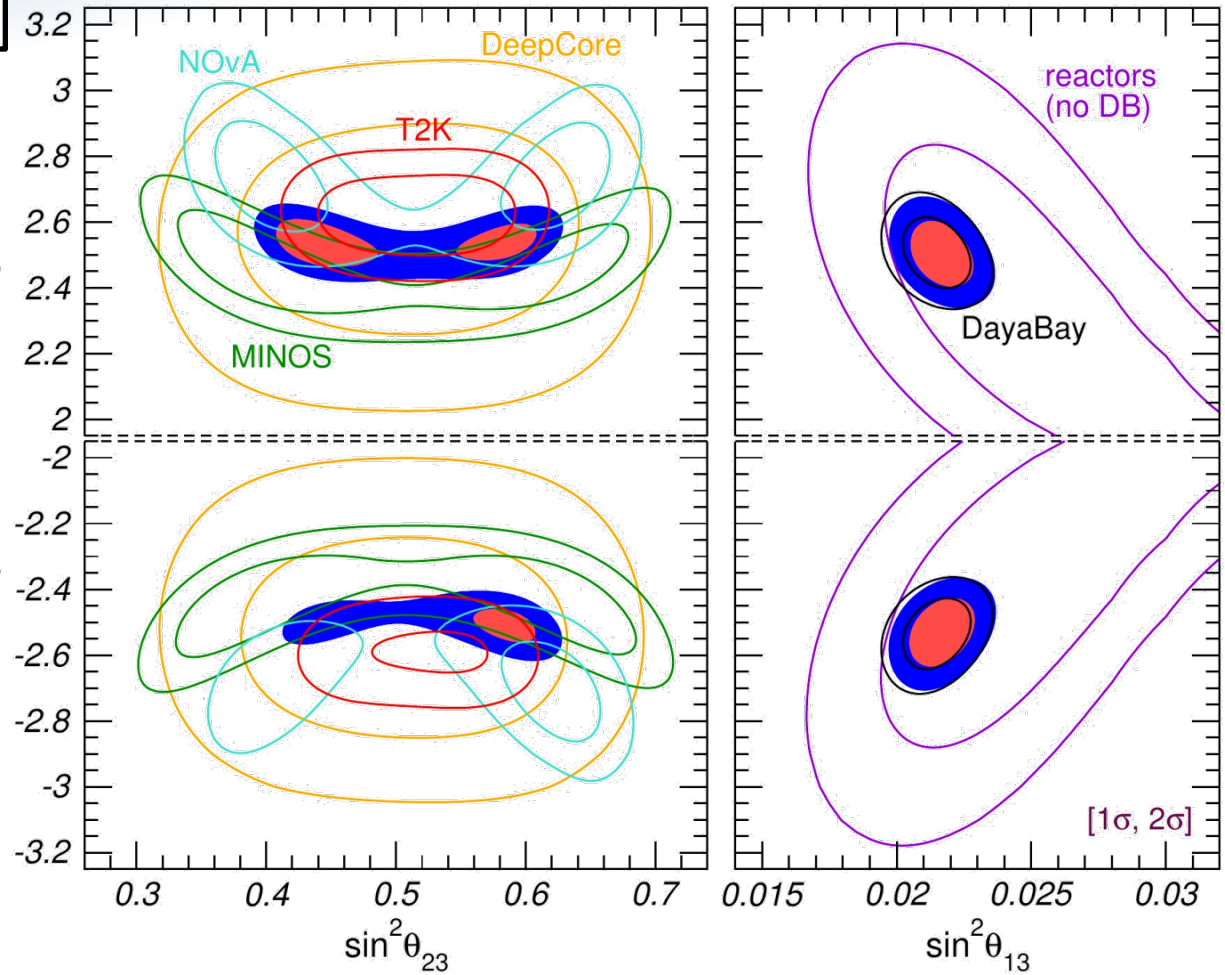
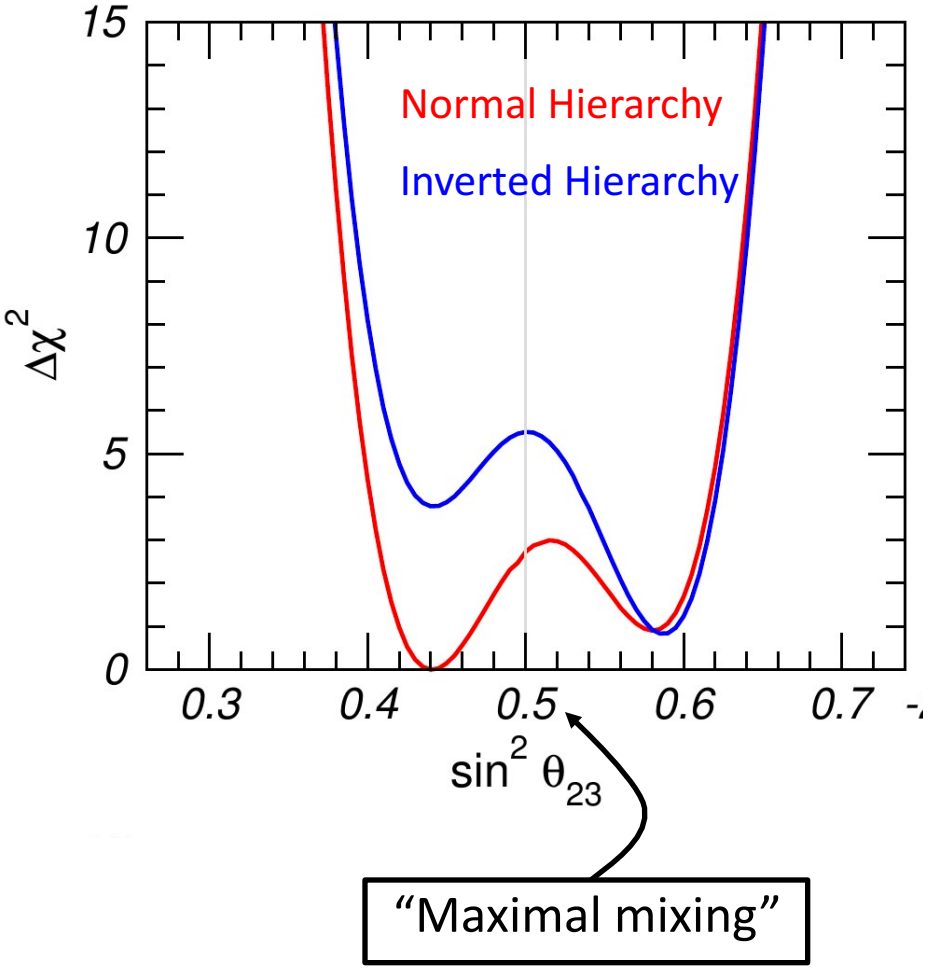


Reactor

- $\Delta m^2_{31} = (2.52 \pm 0.04)\times10^{-3}$ eV^2 or
  $\Delta m^2_{32} = (-2.51 \pm 0.04)\times10^{-3}$ eV^2
  - ν_μ disappearance in accelerator, atmospheric experiments
  - ν_e disappearance in reactor experiments

- $\theta_{23} = 41.6° \pm 0.15°$ in NH
  $\theta_{23} = 50.6° \pm 0.15°$ in IH
  - Primarily constrained by ν_μ disappearance, but influences ν_e appearance.
- "Maximal mixing" allowed at about the 90% C.L.
  - $\sin^2 \theta_{23} = 0.5$
  - $\theta_{23} = 45°$ or
  - ν_3 is equal parts ν_μ and ν_τ



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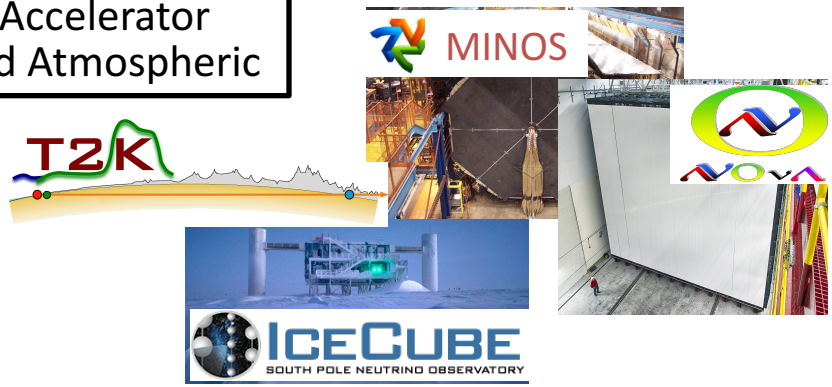
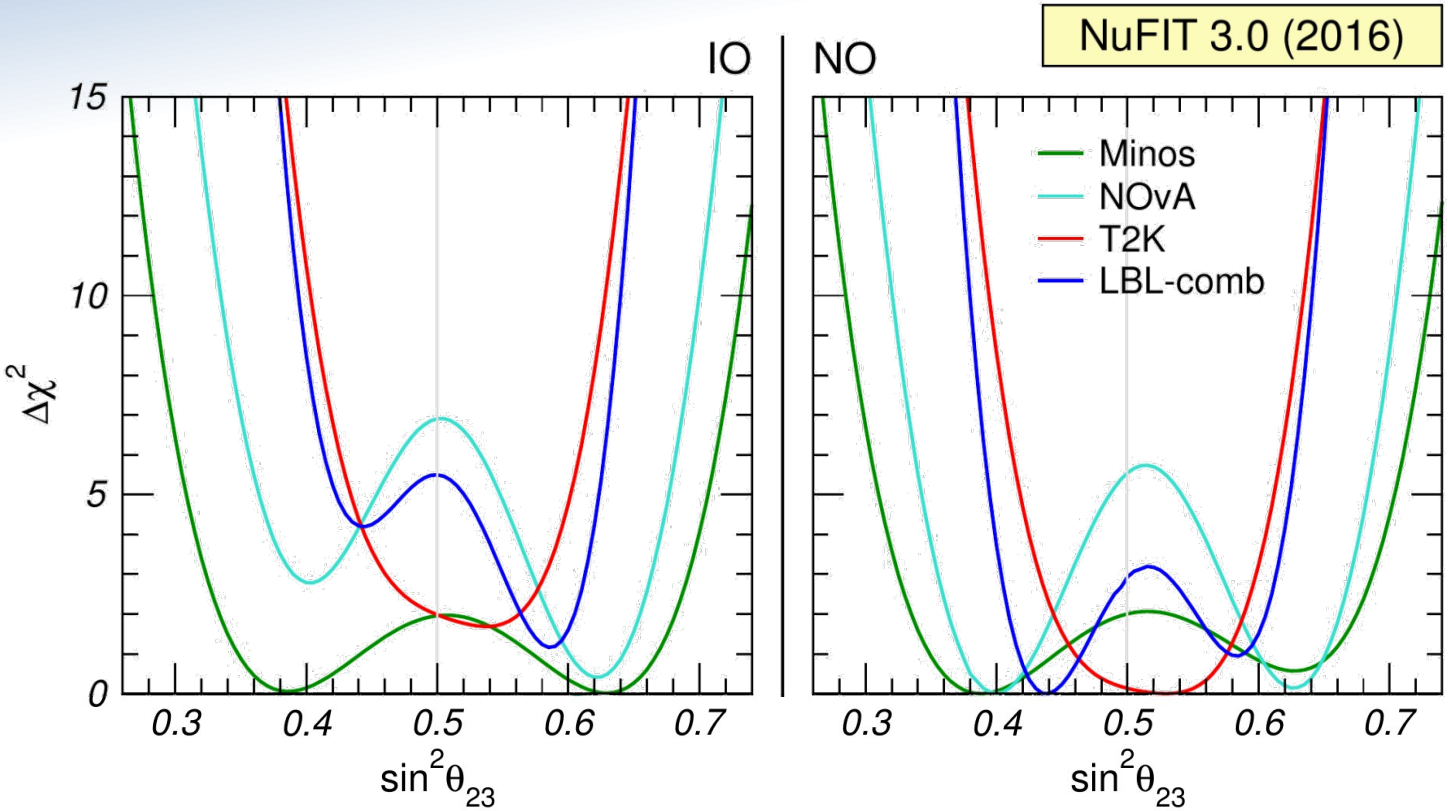
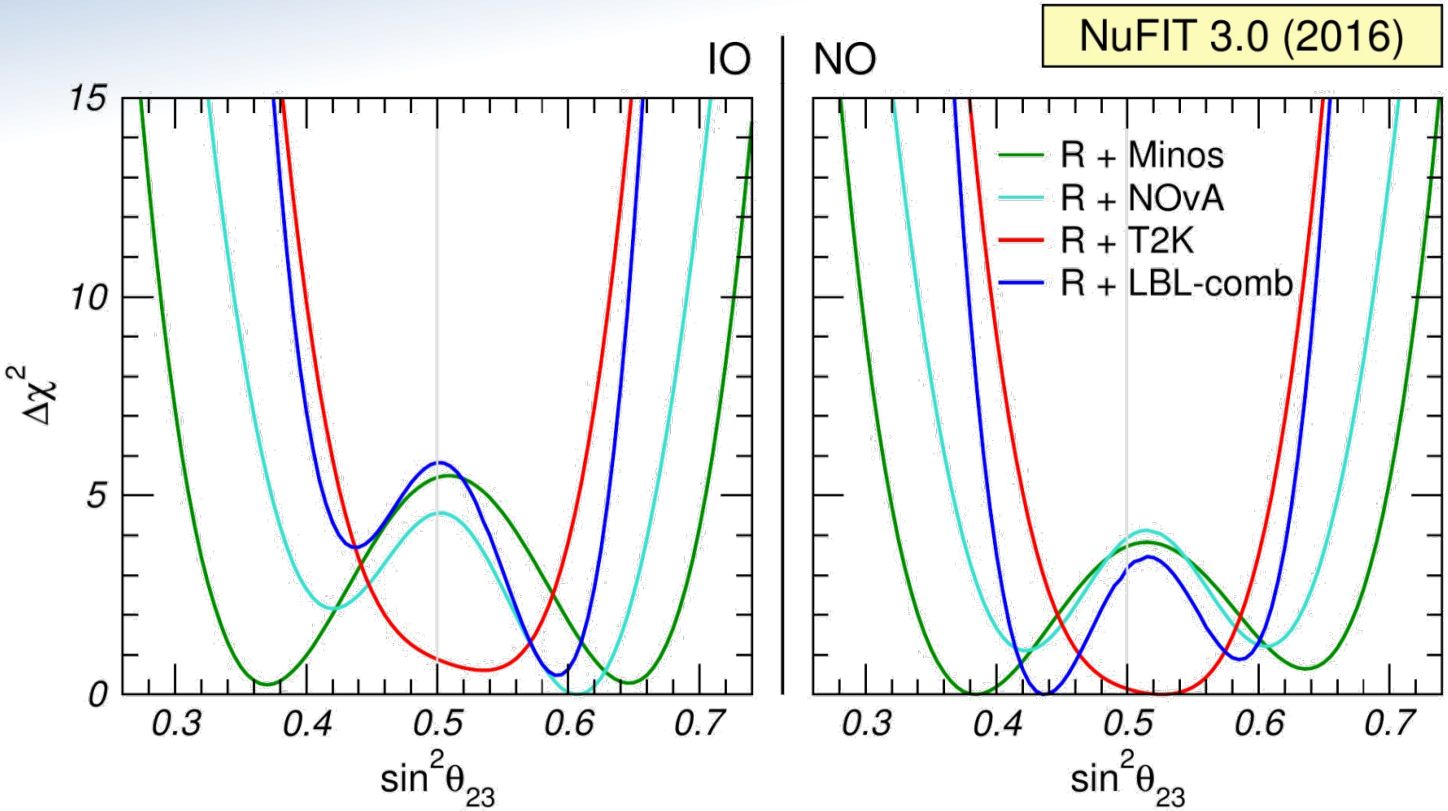




- Some interesting tensions under the hood
  - MINOS, NOvA, Super-K favor non-maximal
  - T2K, IceCube (not shown) favor maximal
- Introducing the Daya Bay constraint on $\Delta m^2{}_{32}$ makes the story on maximal mixing (more) consistent.
  - This is because accelerator experiments have significant correlations between $\Delta m^2{}_{32}$ and θ_{23}



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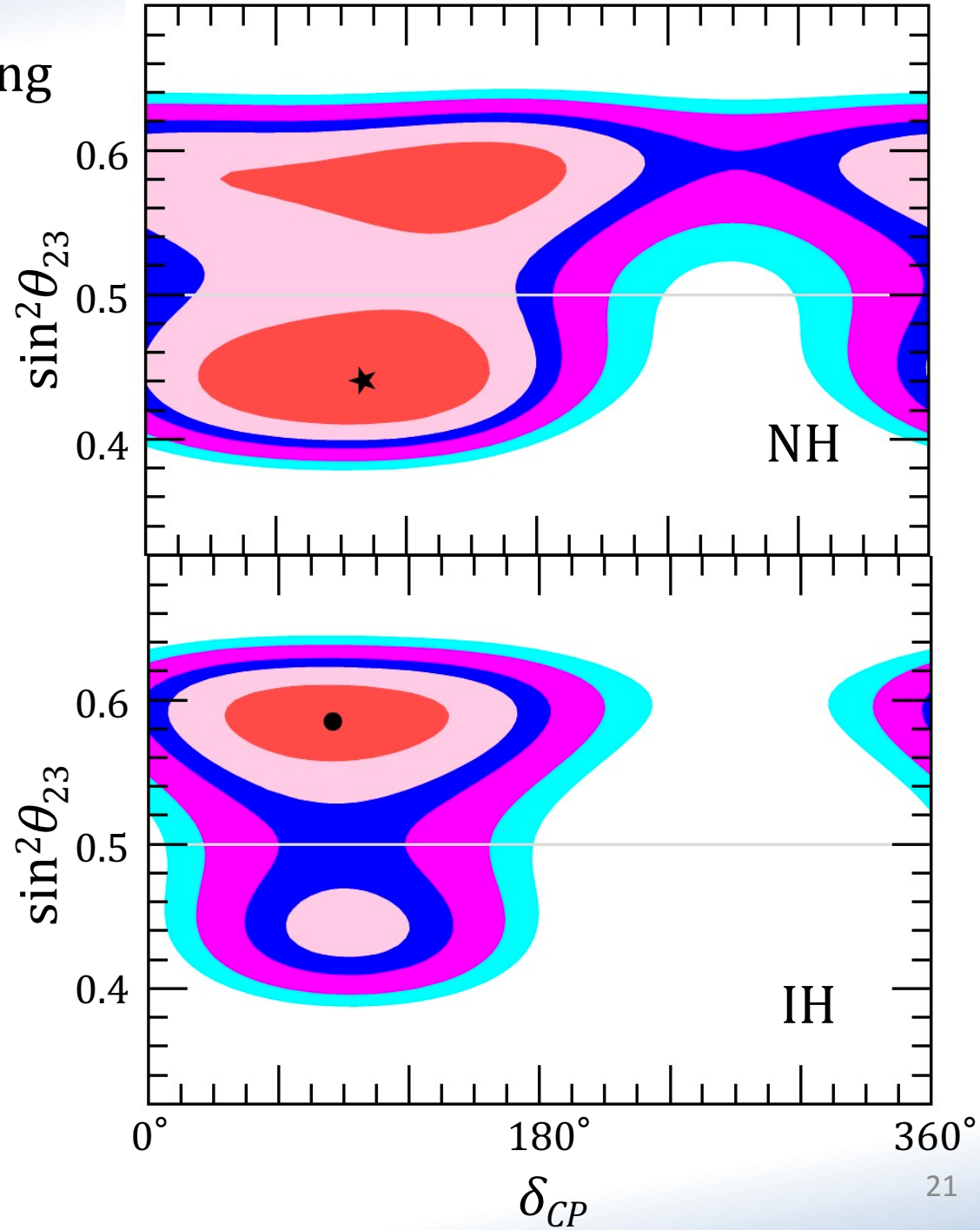
- What about the remaining open questions:
  - Is *CP* violated?
  - Mass hierarchy
  - Maximal μ-τ mixing?
- Not much yet due to degeneracies
  - The normal hierarchy is favored by $\Delta\chi^2$ of 0.83.



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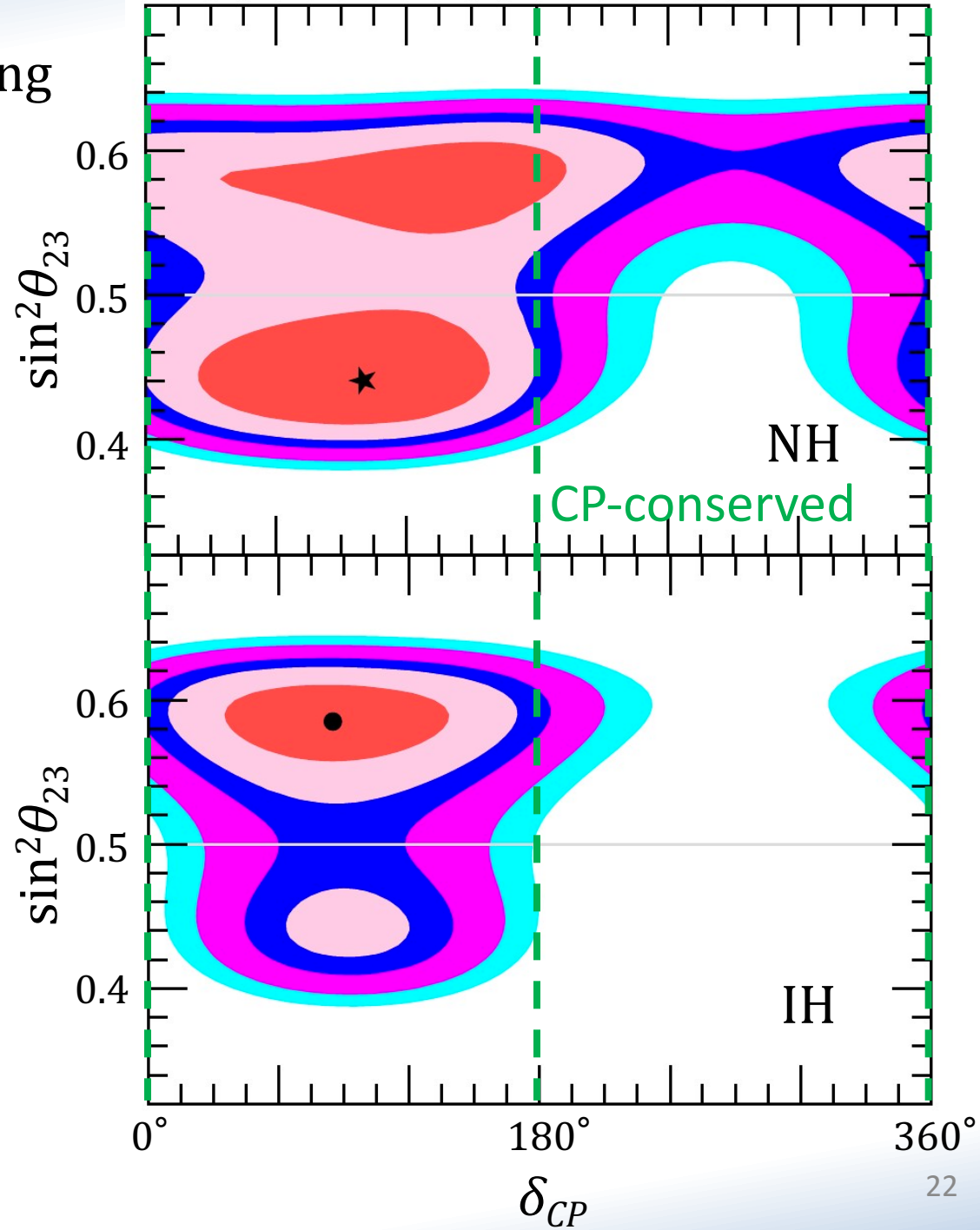

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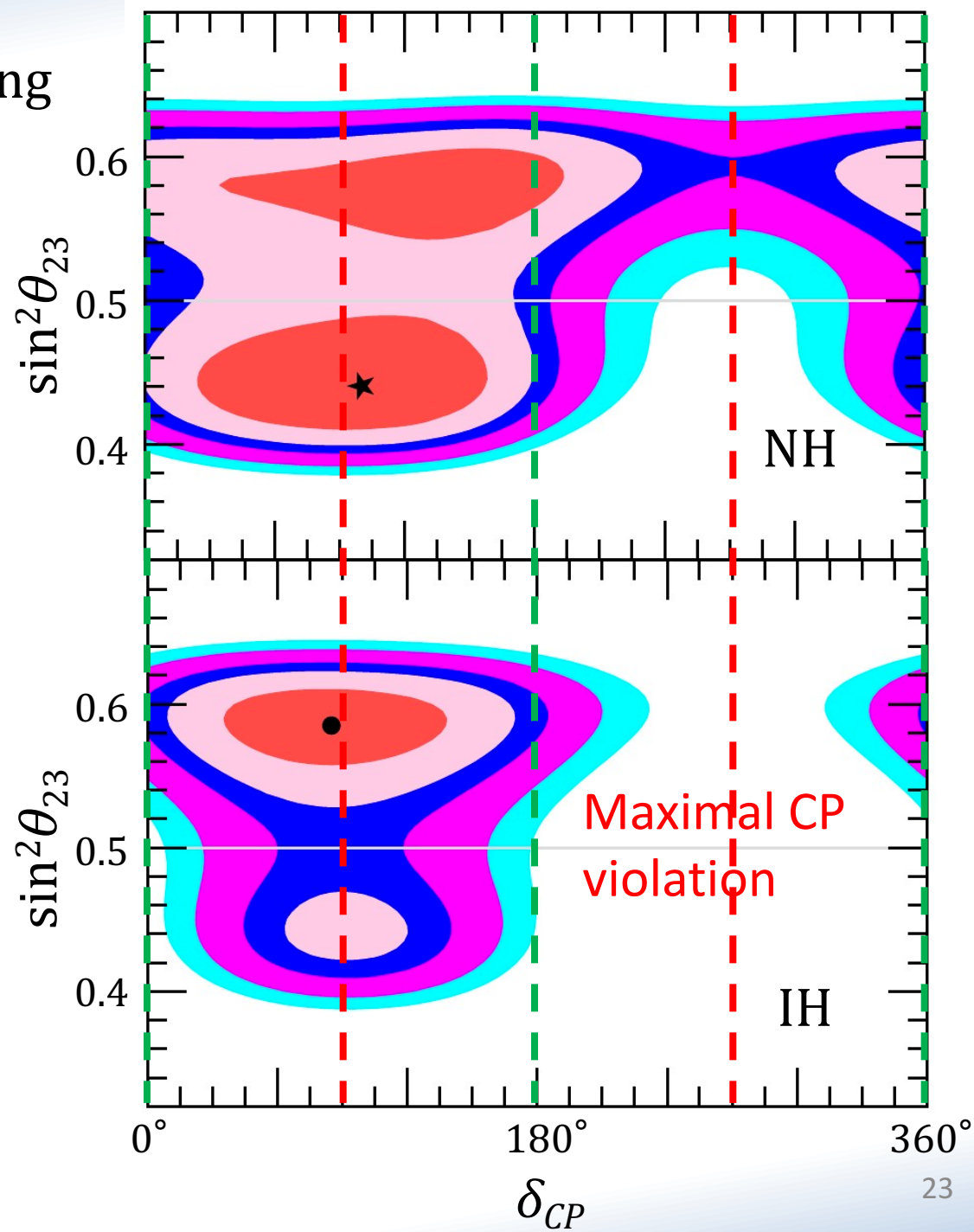
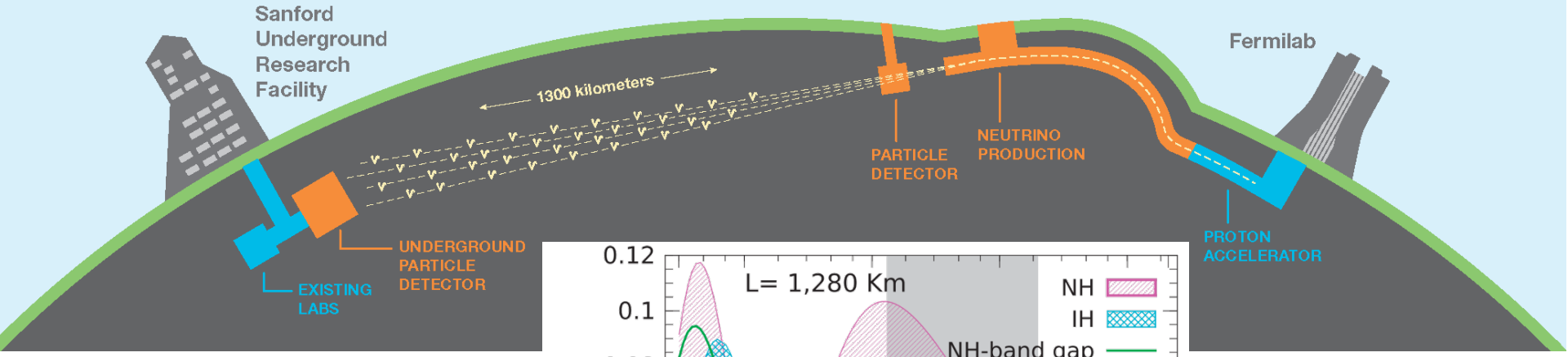
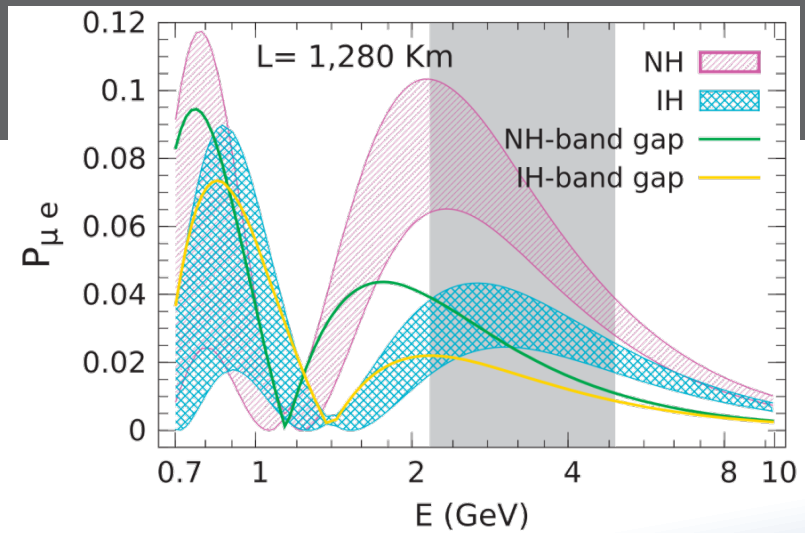


The Future: Mass hierarchy, three ways

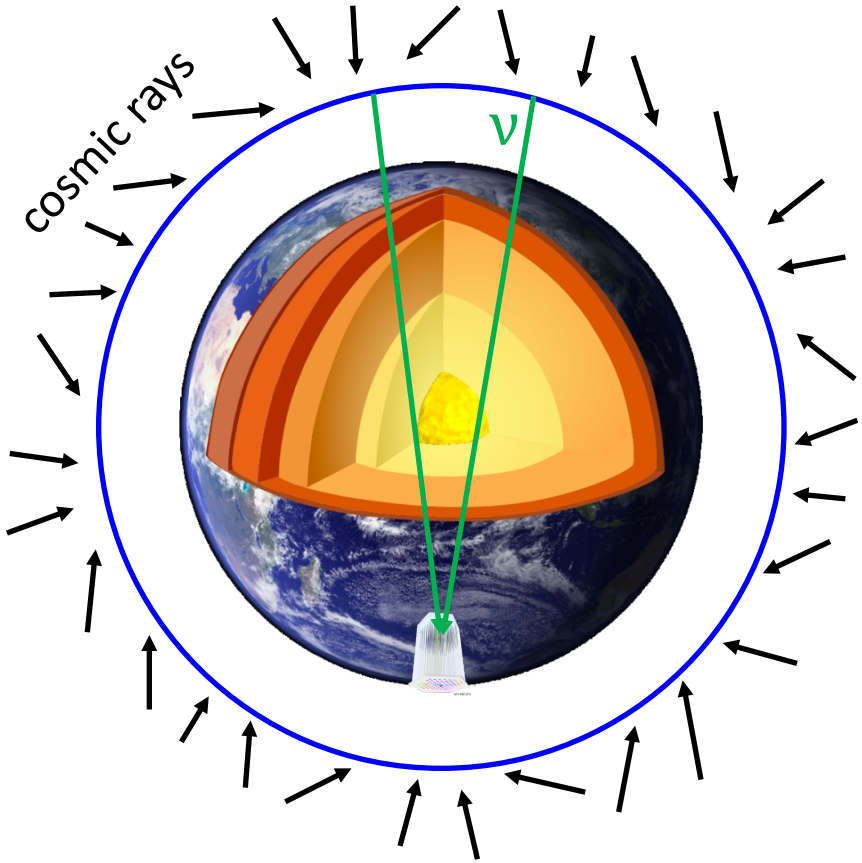
- **DUNE**: matter effects in the Earth's crust
  - Subtle effect, but with a well-understood neutrino source

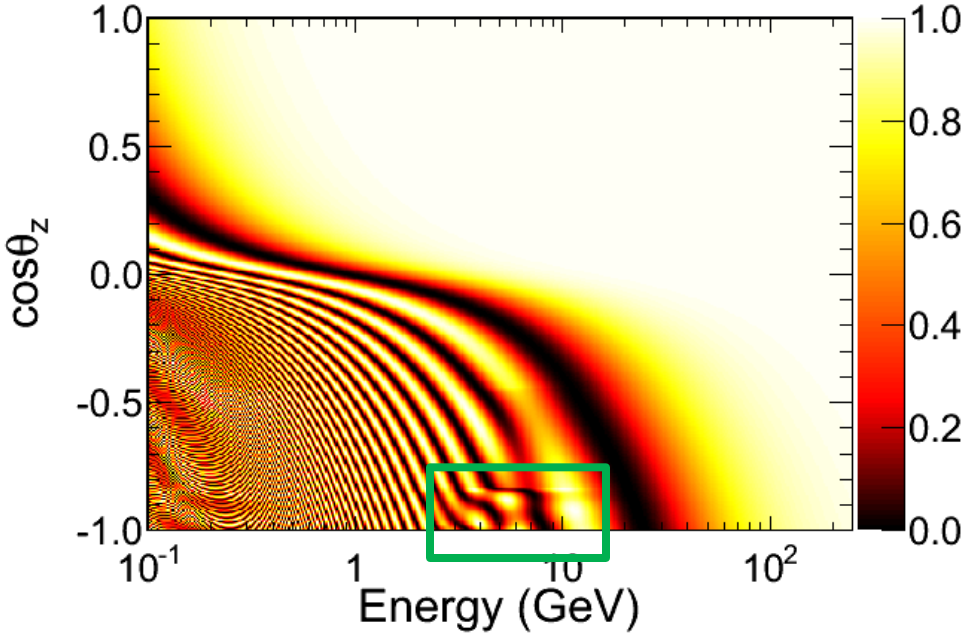




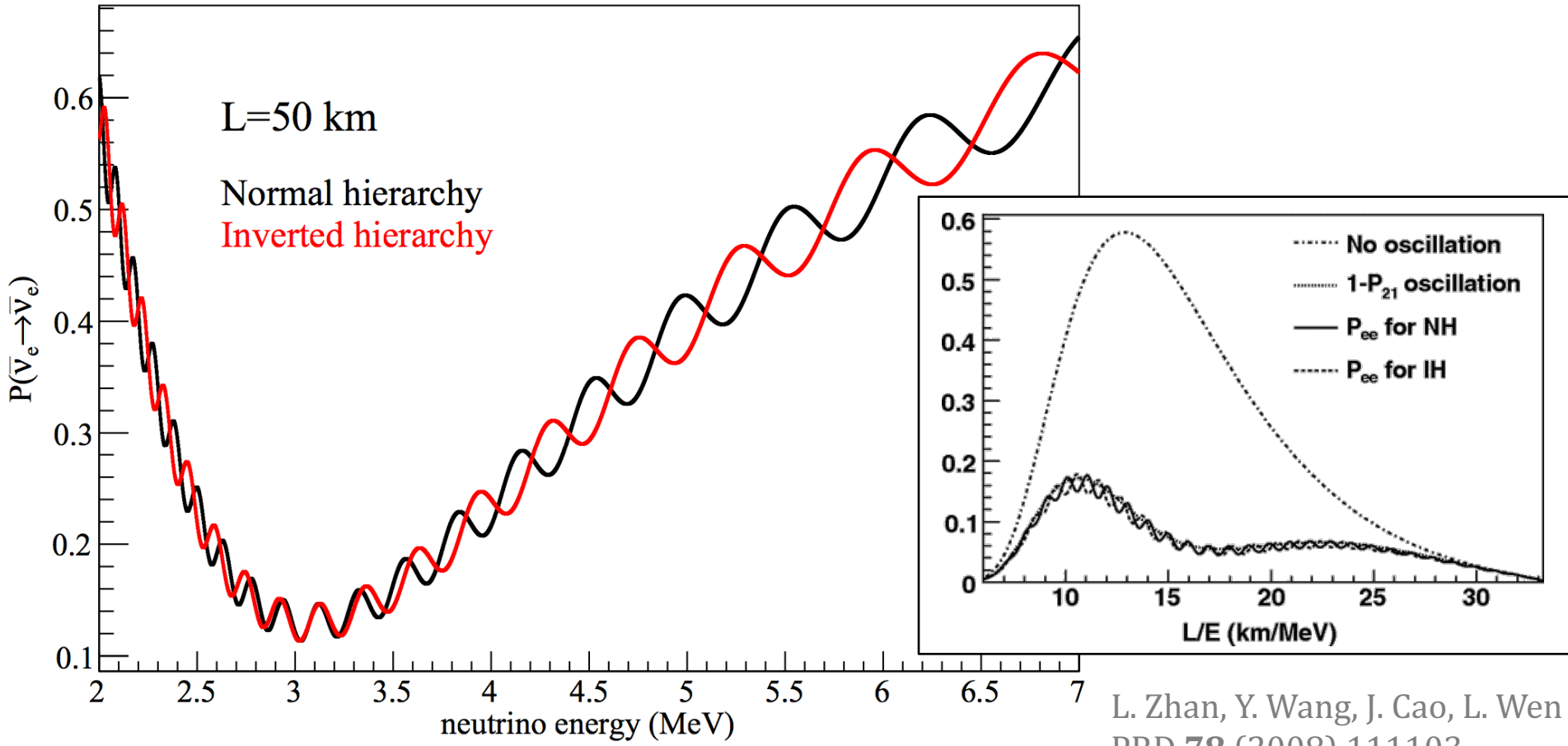
M. Singh, PTEP**10** (2016) 103B03.

- Resonant matter effect in the Earth's core in atmospheric neutrinos
  - A strong effect, but with a challenging natural neutrino source.
- **IceCube**: using ν_μ disappearance (and very high statistics)
- **Hyper-Kamiokande**: using ν_e appearance





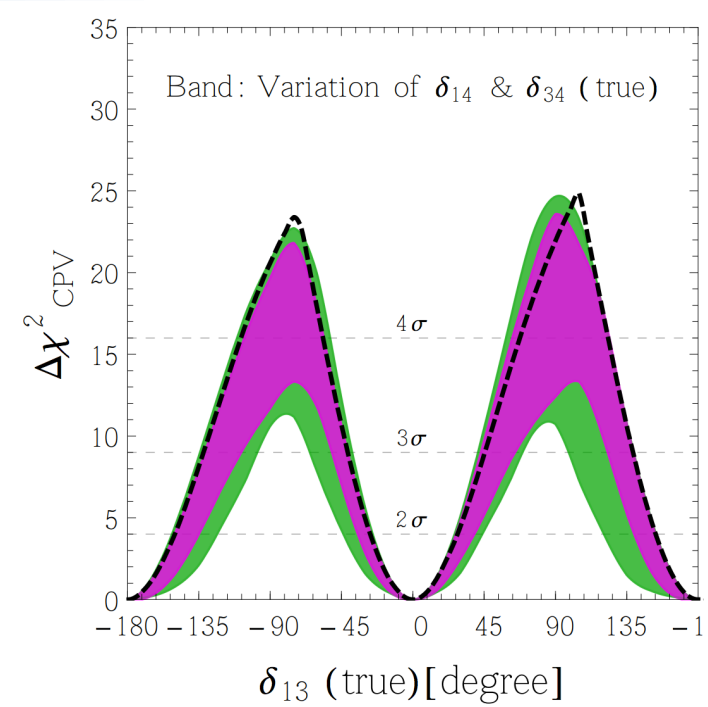
- JUNO: Direct measurement of both $\Delta m^2{}_{21}$ and $\Delta m^2{}_{32}$ at the same time.
  - This method is completely independent of matter effects.

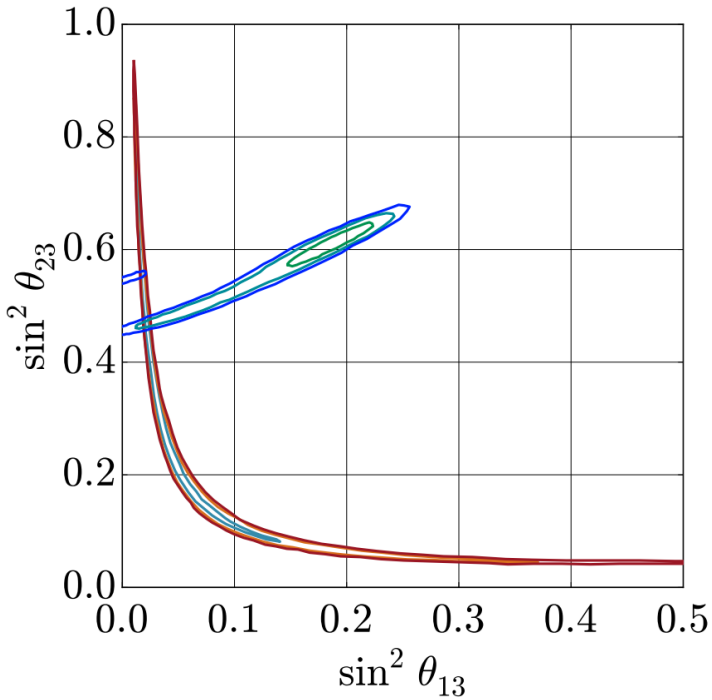


L. Zhan, Y. Wang, J. Cao, L. Wen
PRD **78** (2008) 111103

R.B. Patterson, Ann. Rev. Nucl. Part. Sci. **65** (2015) 177

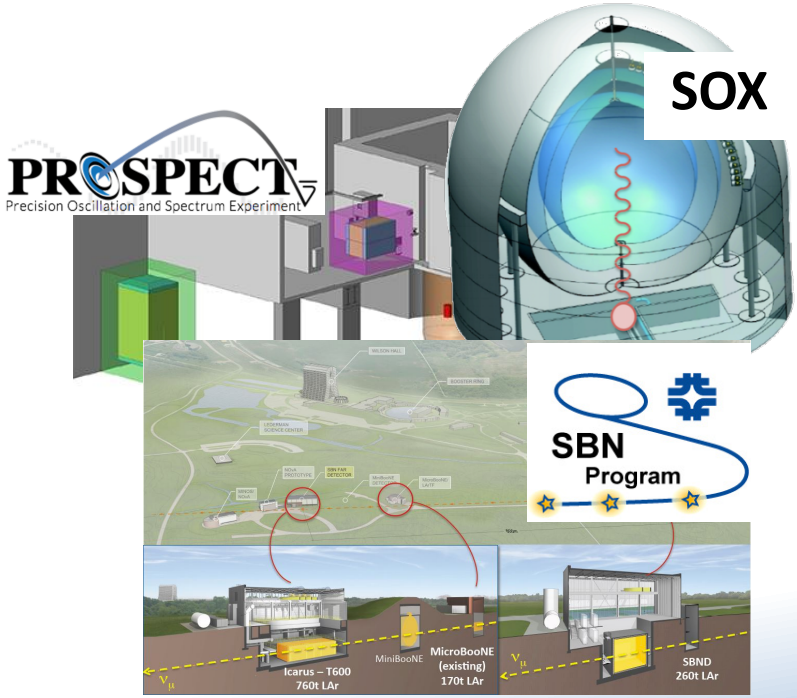
The Future: How do we know we are measuring δ_{CP}?



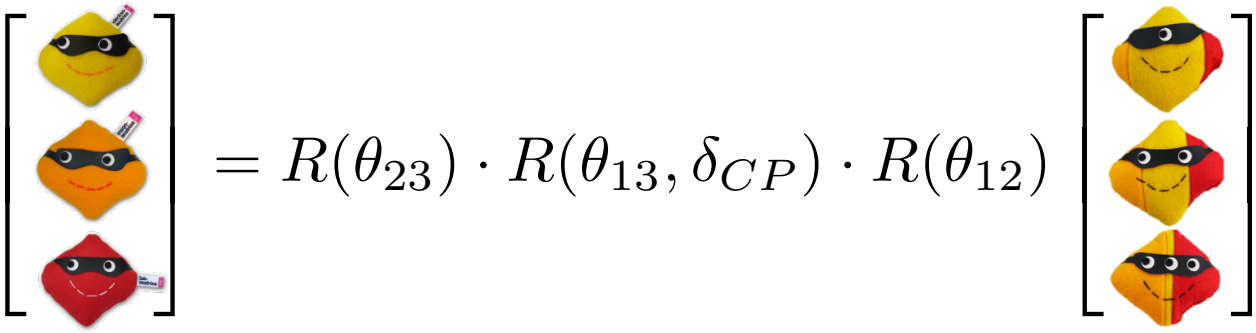


- 1 or more sterile neutrinos can strongly affect a measurement of CP-violation in long-baseline experiments like DUNE and Hyper-K.
  - R. Gandhi, B. Kayser, M. Masud, S. Prakash. JHEP **1511** (2015) 039
  - J. Berryman, A. de Gouvêa, K. Kelly, A. Kobach. Phys.Rev. D**92** (2015) 073012
  - S. Agarwalla, S. Chatterjee, A Palazzo. JHEP **1609** (2016) 016
  - …

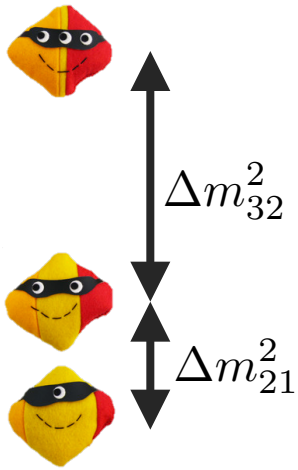
- The answer is to either confirm or refute the existence of sterile neutrinos as soon as we can.
  - An example of complementarity between current generation and next-generation experiments.
  - Includes measurements at existing experiments built for other goals and new dedicated experiments.



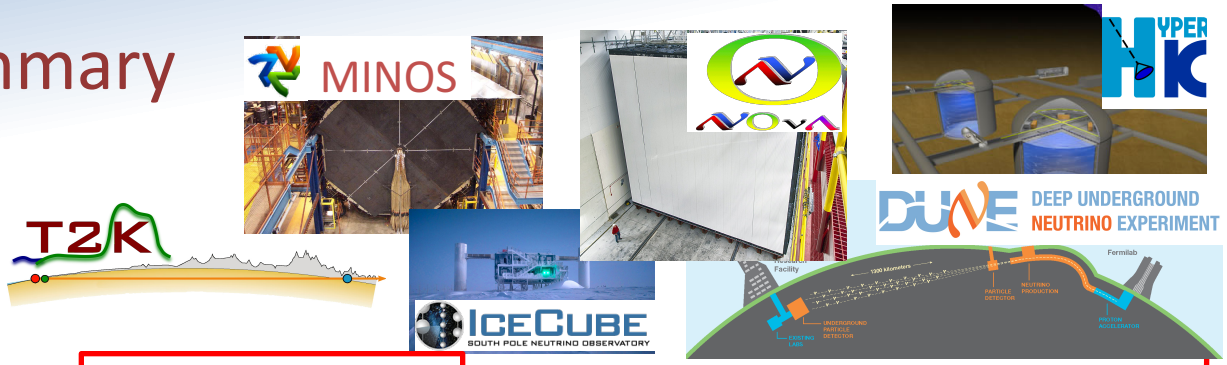
Summary



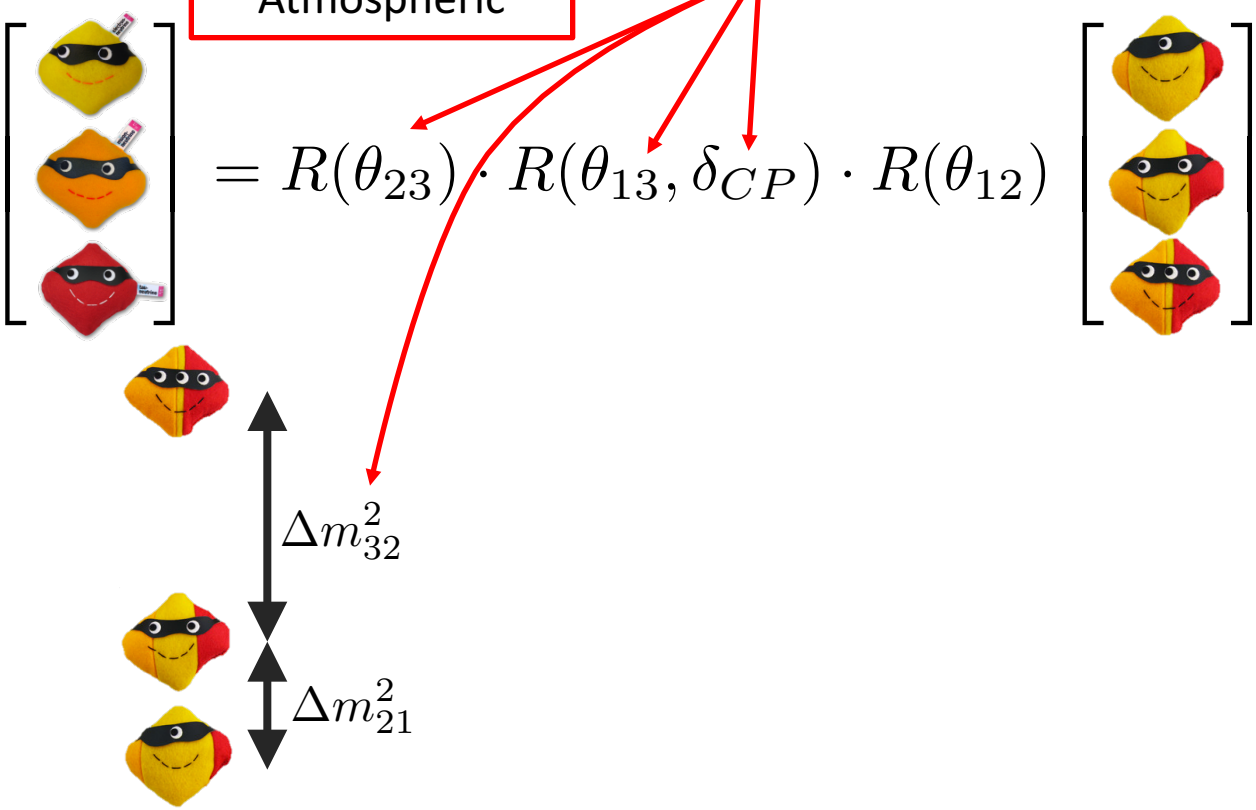
$$= R(\theta_{23}) \cdot R(\theta_{13}, \delta_{CP}) \cdot R(\theta_{12})$$



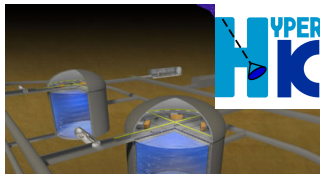
Summary

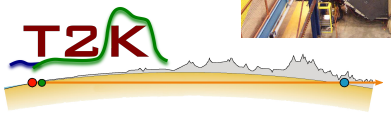


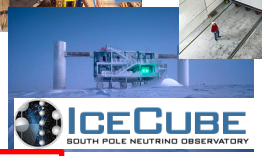
Accelerator and Atmospheric

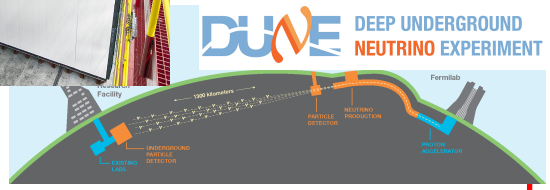


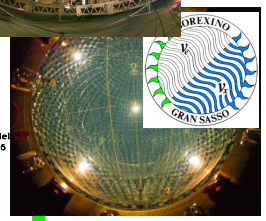
Summary



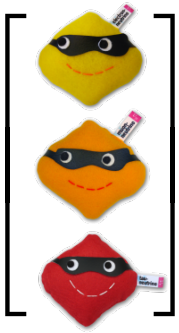




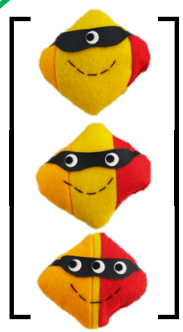




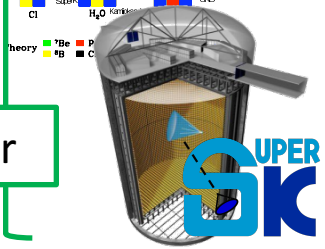
Accelerator and Atmospheric



$$= R(\theta_{23}) \cdot R(\theta_{13}, \delta_{CP}) \cdot R(\theta_{12})$$



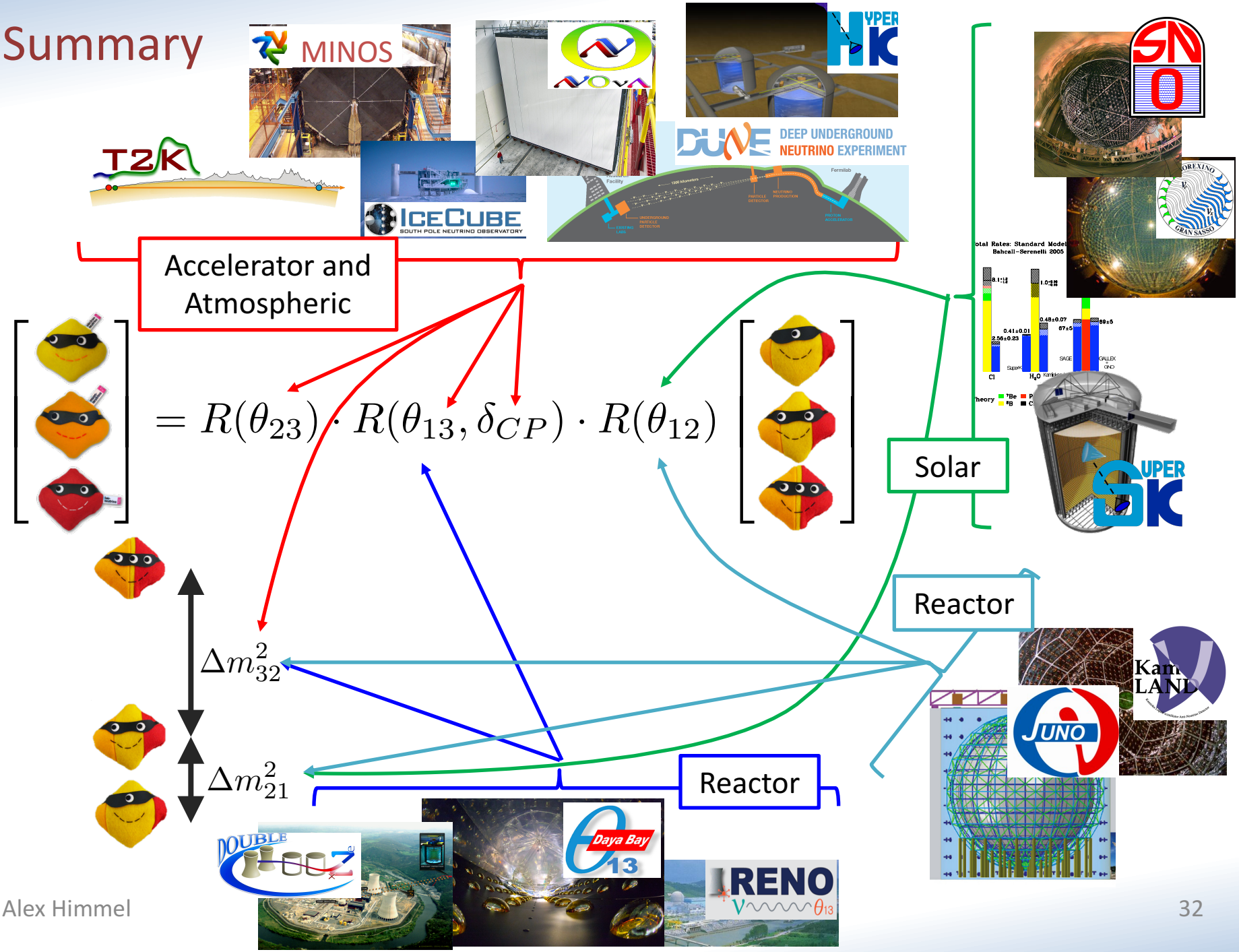
Solar



Δm^2_{32}

Δm^2_{21}

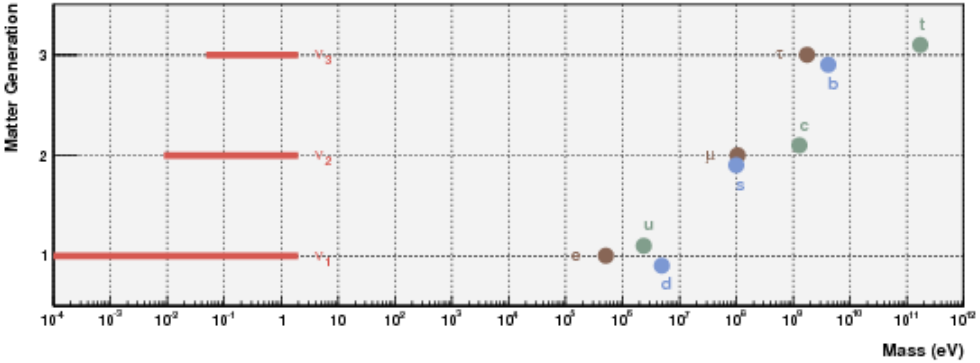
Summary

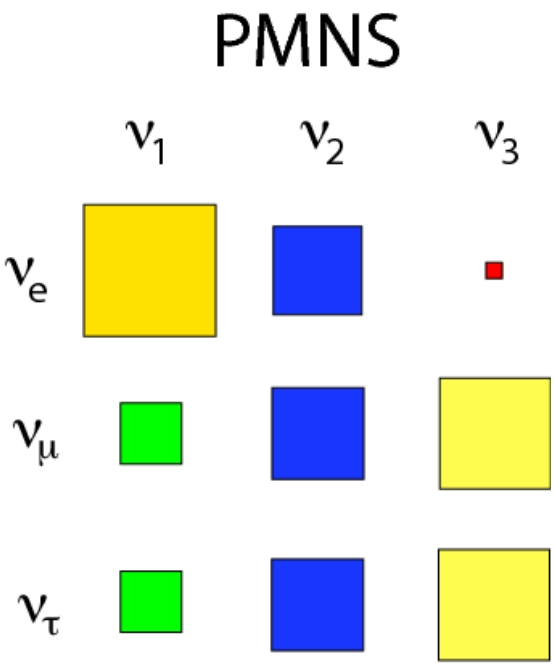

MINOS
NOvA
HYPER HK
T2K
DUNE DEEP UNDERGROUND NEUTRINO EXPERIMENT
ICECUBE SOUTH POLE NEUTRINO OBSERVATORY
SNO
BOREXINO GRAN SASSO
Accelerator and Atmospheric
$= R(\theta_{23}) \cdot R(\theta_{13}, \delta_{CP}) \cdot R(\theta_{12})$
Solar
SUPER K
Reactor
Δm^2_{32}
Δm^2_{21}
Reactor
KamLAND
JUNO
DOUBLE CHOOZ
Daya Bay
RENO

Backups

Open Questions in Neutrino Physics

- Pattern of neutrino masses:
  - What is their absolute mass?
  - Is the pattern normal, inverted, or degenerate?
- Are neutrinos Dirac or Majorana?
- Pattern of neutrino mixing:
  - Is ν_3 equal parts ν_μ and ν_τ?
    - Is the mixing maximal?
  - Do neutrino oscillations violate CP symmetry?
- Are there sterile neutrinos?





Neutrino Oscillations

- Create in one flavor (ν_μ), but detect in another (ν_e)

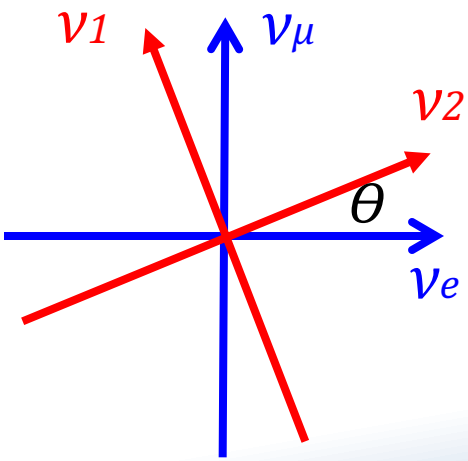
Neutrino Oscillations

- Create in one flavor (ν_μ), but detect in another (ν_e)

- Each flavor (e, μ) is a superposition of different masses (1, 2)

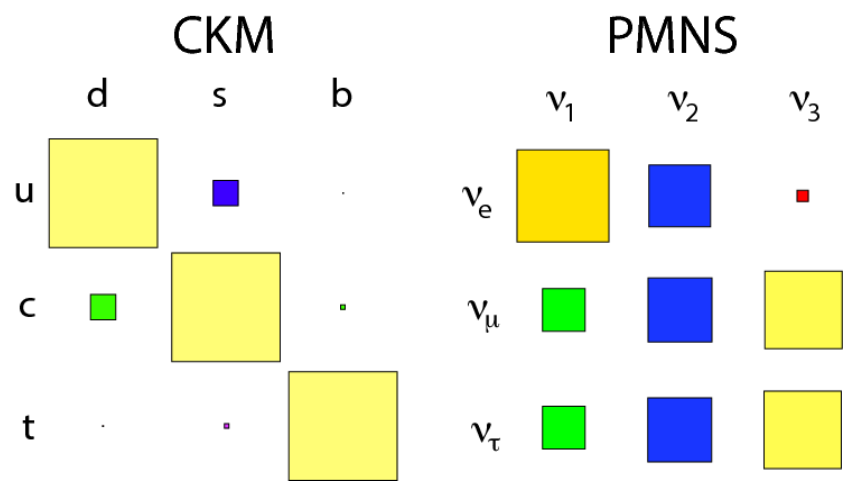
$$\begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

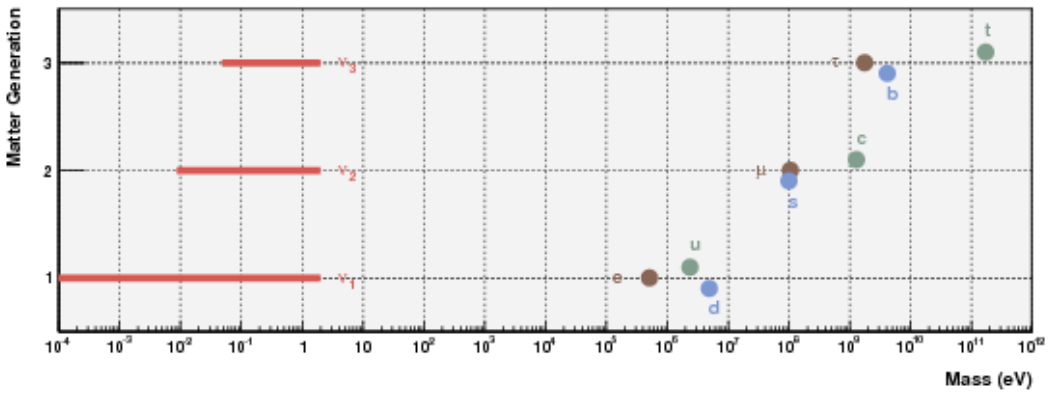
"Mixing Matrix"



Why study neutrino oscillations?

- Neutrinos are "weird":
  - Neutrino mixing looks very different from CKM.
  - Neutrino masses are *really* small compared to the rest of the SM.
- Potentially *CP*-violating
  - Might be a window into matter-antimatter asymmetry.
- Physics beyond the standard model!
  - Oscillations are an interferometric effect – gives access to high-scale physics.

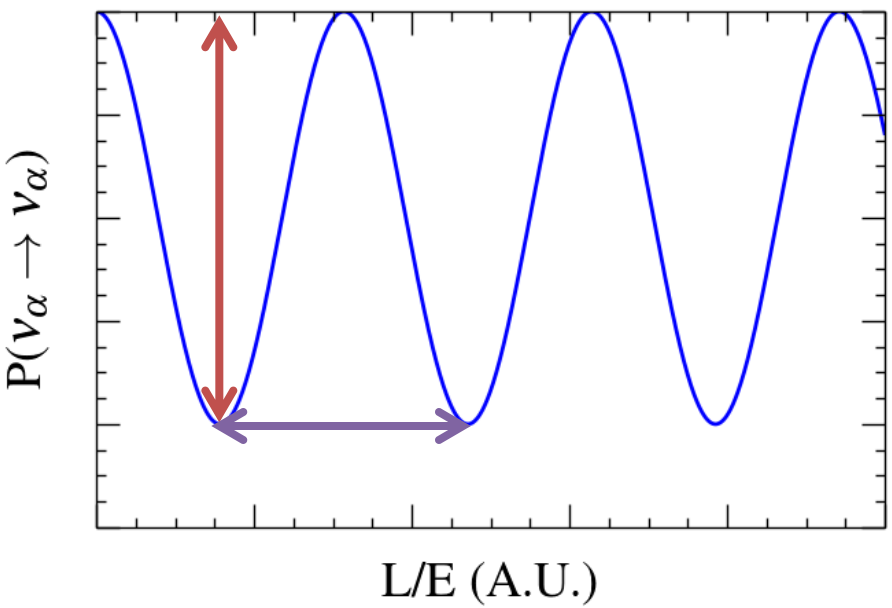


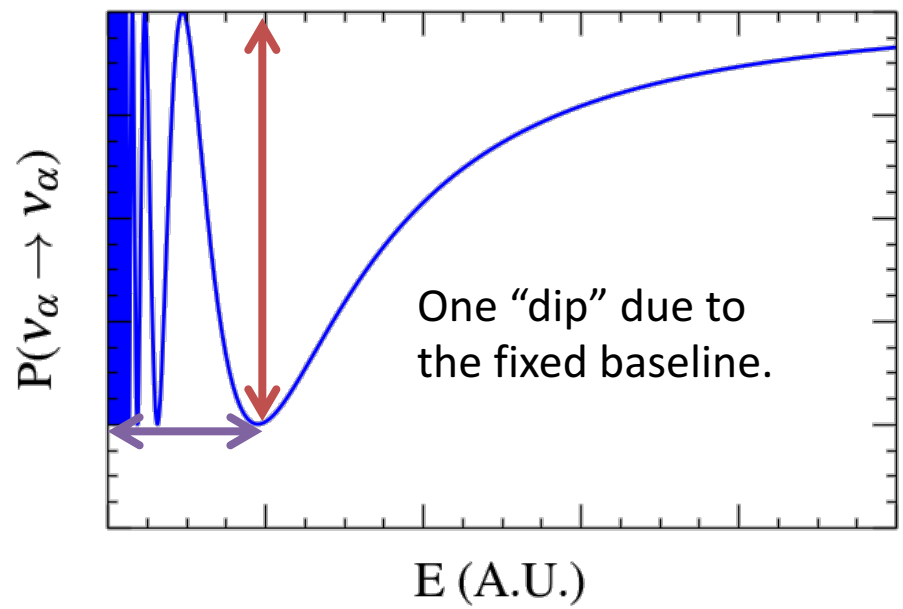


ν_μ Disappearance

Sub-dominant term due to small θ_{13}

$$P(\nu_\mu \to \nu_\mu) = 1 - \Big(\sin^2(2\theta_{13}) \sin^2(\theta_{23}) + \cos^4(\theta_{13}) \boxed{\sin^2(2\theta_{23})} \Big) \sin^2\left(\frac{\boxed{\Delta m^2} L}{4E} \right)$$





Nunokawa, Parke, Valle, in "CP Violation and Neutrino Oscillations", Prog.Part.Nucl.Phys. 60 (2008) 338-402.

ν_e Appearance

$$P(\nu_\mu \to \nu_e) \approx \left| \sqrt{P_{\rm atm}} e^{-e(\Delta_{32}+\delta_{CP})} + \sqrt{P_{\rm sol}} \right|^2$$

$$\approx P_{\rm atm} + P_{\rm sol} + 2\sqrt{P_{\rm atm} P_{\rm sol}} \left(\cos\Delta_{32} \boxed{\cos\delta_{CP}} \mp \sin\Delta_{32} \boxed{\sin\delta_{CP}}\right)$$

~1% at NOvA

From reactor measurements

$$\sqrt{P_{\rm atm}} = \boxed{\sin(\theta_{23})} \sin(2\theta_{13}) \boxed{\frac{\sin(\Delta_{31} - aL)}{\Delta_{31} - aL}} \Delta_{31}$$

- NOvA Measures:
  - *CP*-violating phase Phase
  - θ_{23} octant
  - Sign of Δm^2_{32} – "Mass Hierarchy"

Nunokawa, Parke, Valle, in "CP Violation and Neutrino Oscillations", Prog.Part.Nucl.Phys. **60** (2008) 338-402.