Reactor and Solar Tension and Measurements

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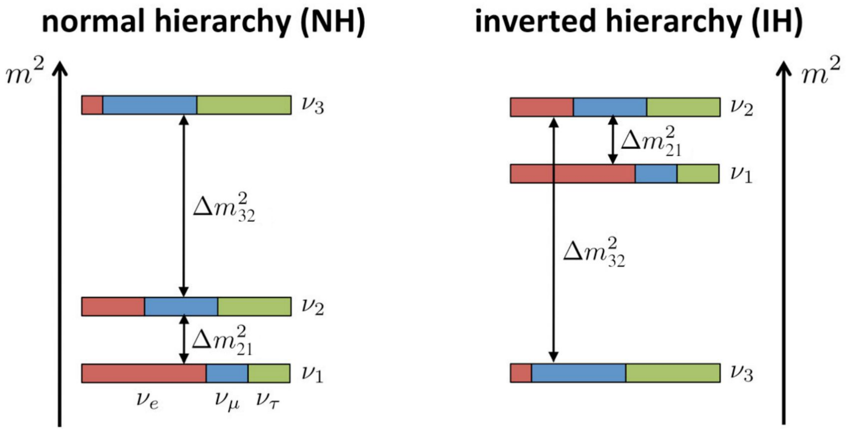
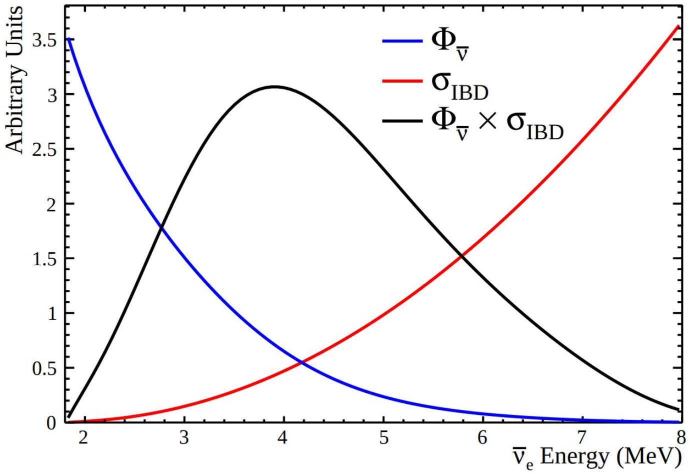
Neutrino Oscillations

- Neutrinos produced as one flavor later detected as another flavor
- Relationship between mass and flavor eigenstates described by PMNS Matrix
  - Parameterized by three mixing angles: $\boldsymbol{\theta_{12}}$, θ_{13},θ_{23}
  - Also a CP-violating phase $\boldsymbol{\delta}_{CP}$
- Oscillations also depend on squared mass differences: $\boldsymbol{\Delta m^2_{21}}$, $\Delta m^2_{32} \approx \Delta m^2_{31}$
- Focus on 2 parameters accessible by both Solar and Reactor Experiments
  - Δm^2_{21} & θ_{12}



Measuring Δm^2_{21} & θ_{12} (Reactor)

- Pure $\bar{\nu}_e$ source
- Produced in □ decays of nuclear fission products
- Energies up to ~10 MeV
- Detected via IBD
- More precise measurement of Δm^2_{21}
- Less precise measurement of θ_{12} (for now)
- Measure oscillations via distortion of energy spectrum
- $$P_{\bar{\nu}_e \to \bar{\nu}_e}(L,E) = 1 - \cos^4(\theta_{13})\sin^2(2\theta_{12})\sin^2\left(\frac{\Delta m^2_{21} L}{4E}\right) - \sin^2(2\theta_{13})\left(\cos^2(\theta_{12})\sin^2\left(\frac{\Delta m^2_{31} L}{4E}\right) + \sin^2(\theta_{12})\sin^2\left(\frac{\Delta m^2_{32} L}{4E}\right)\right)$$



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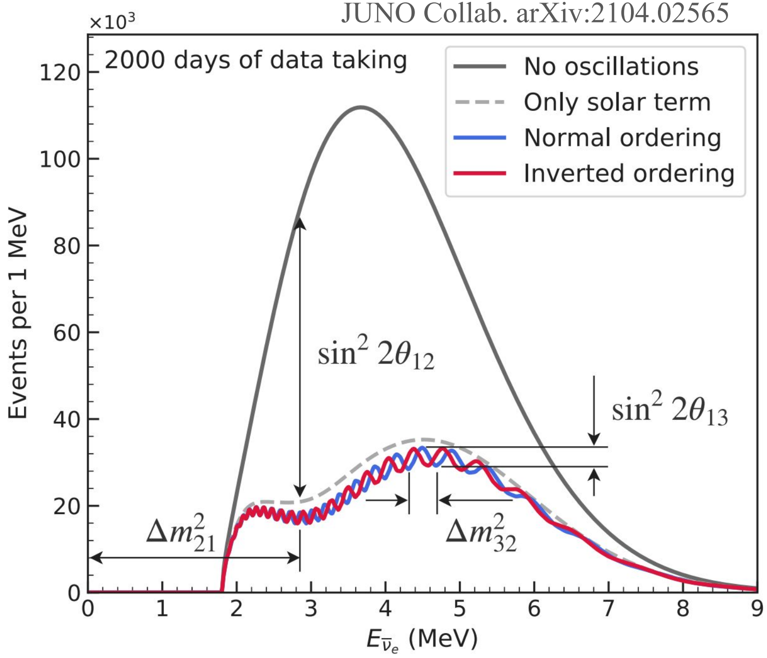
JUNO Collab. arXiv:2104.02565

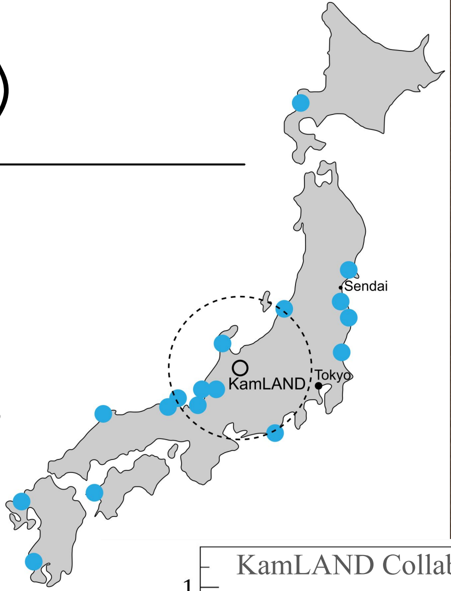


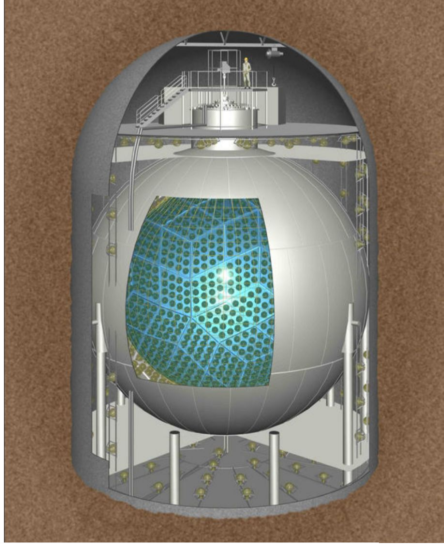
Δm^2_{21} & θ_{12} Results (Reactor)

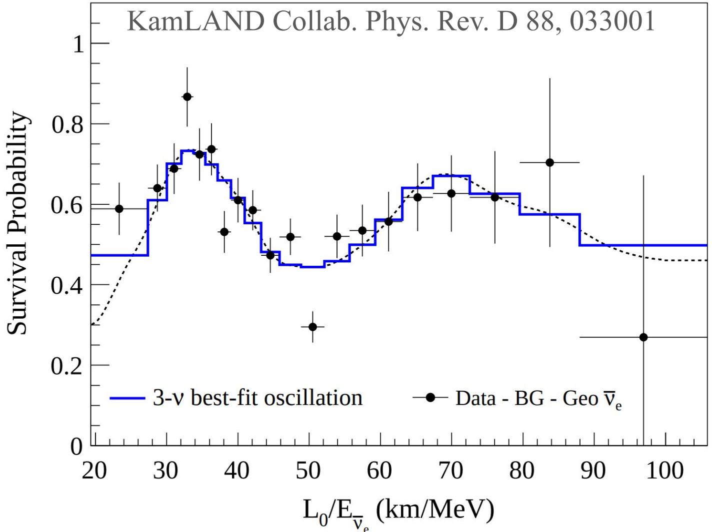
- KamLAND
  - Located 1km under Mt. Ikenoyama at Kamioka Observatory in Kamioka, Japan
  - 1 kton liquid scintillator target w/ ~1.3k PMTs
  - ~50 nearby Japanese reactors
  - Flux-weighted average baseline of 180 km
- ~7 years of livetime detecting reactor antineutrinos
- Best fit result of:

$$\Delta m^2_{21} = 7.53^{+0.18}_{-0.18} \times 10^{-5}\,\mathrm{eV}^2$$

$$\tan^2\theta_{12} = 0.436^{+0.029}_{-0.025}$$



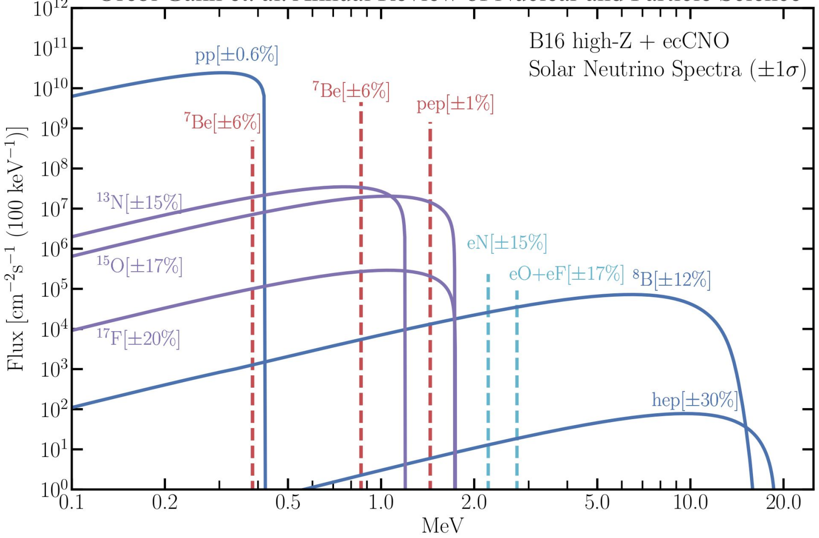




Measuring Δm^2_{21} & θ_{12} (Solar)

- Pure ν_e source
- Produced by several nuclear fusion processes in the sun
- Up to ~15 MeV
- Multiple effects due to oscillation
  - MSW Effect at high energies
  - Vacuum oscillation at low energies
  - Transition region between MSW & Vacuum
  - Day-Night Effect
- Less precise measurement of Δm^2_{21}
- More precise measurement of θ_{12} (for now)

Orebi Gann et. al. Annual Review of Nuclear and Particle Science



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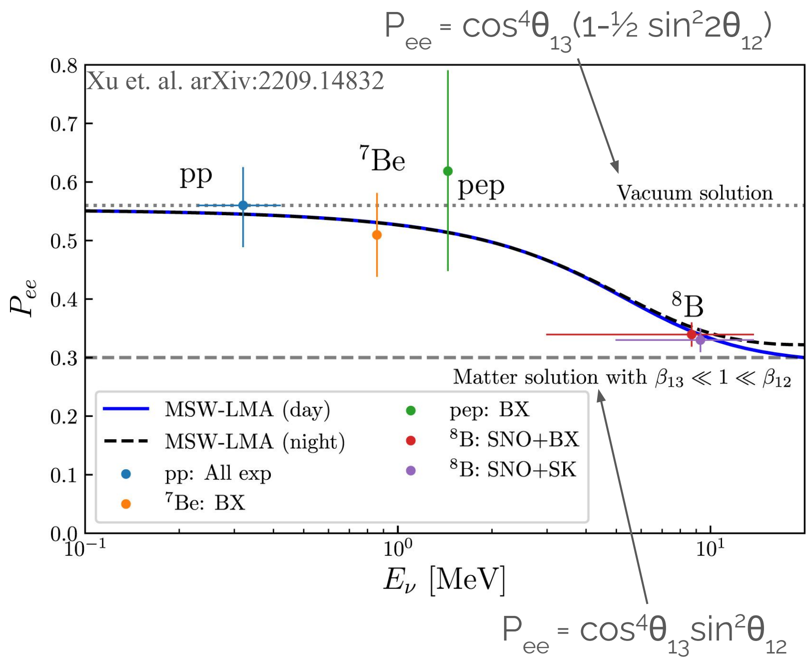
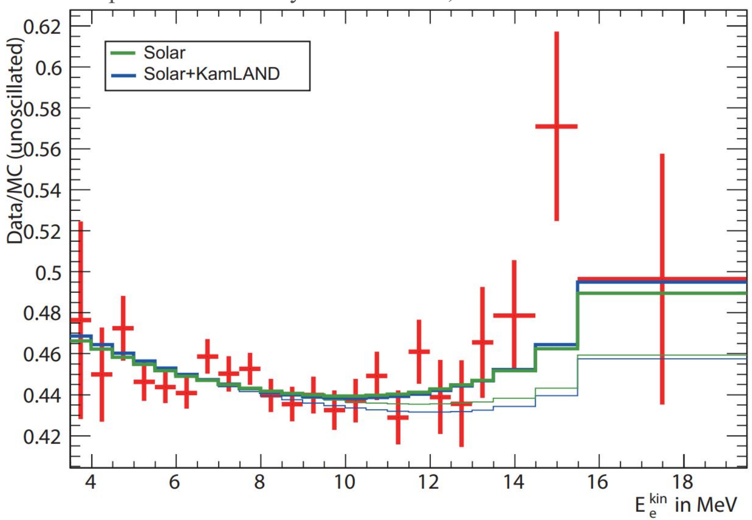


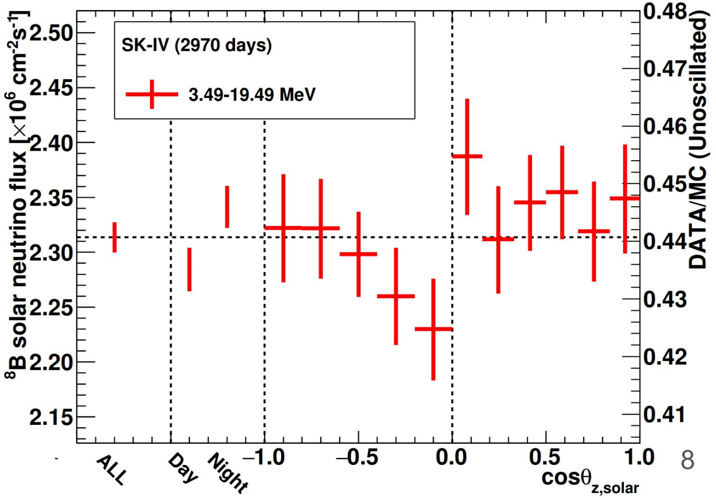
Δm^2_{21} & θ_{12} Results (Solar)

- Super K analysis of all available solar data
- Evidence of both low energy upturn and Day-Night Effect (3.2 σ)
- Best Fit Results:

$$\sin^2\theta_{12,\text{solar}} = 0.306 \pm 0.013,$$
$$\Delta m^2_{21,\text{solar}} = (6.10^{+0.95}_{-0.81}) \times 10^{-5}\ \text{eV}^2.$$

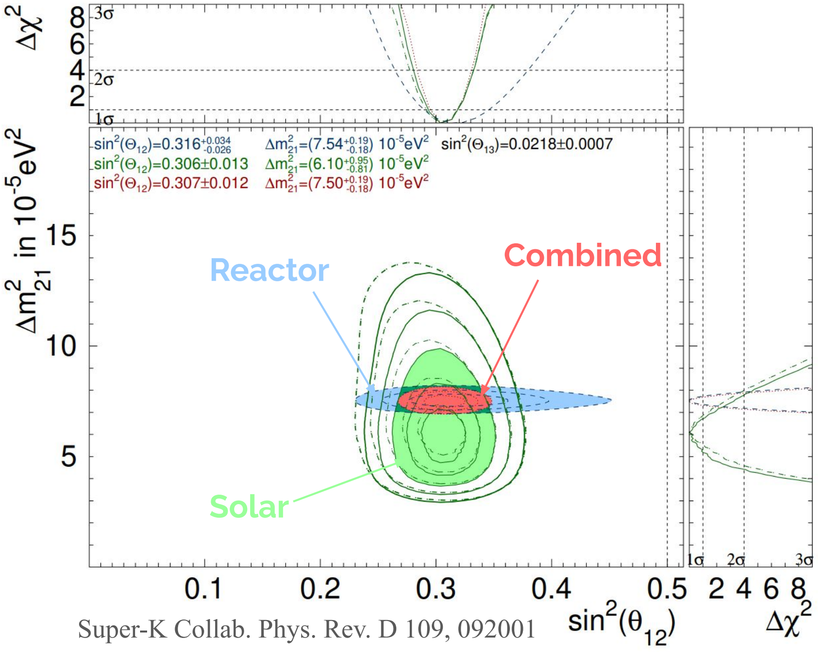
Super-K Collab. Phys. Rev. D 109, 092001





Current Tensions

- Measurements of θ_{12} in good agreement
- Measurements of Δm^2_{21} in ~1.5 σ tension
- Why?

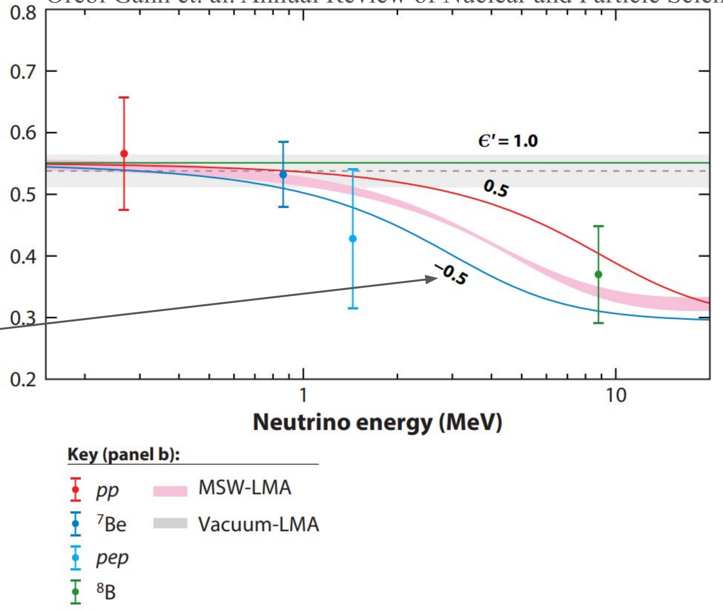


Super-K Collab. Phys. Rev. D 109, 092001

Possible Explanations

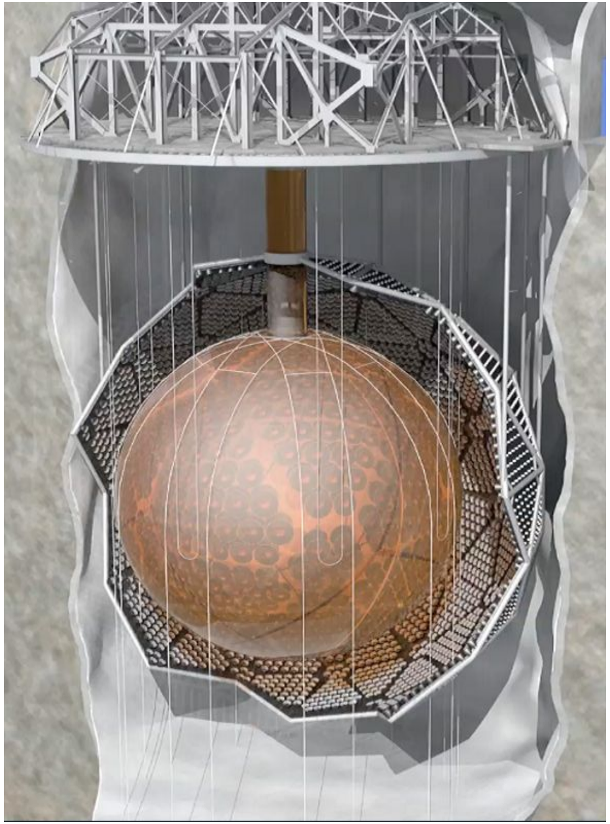
- Fluctuation / Underestimated Systematic (boring)
- Significant differences in measurements
  - ν_e vs. $\overline{\nu}_e$
  - Matter Effect + Vacuum vs. Low Density Matter
  - Distances travelled
- Many theories beyond 3 flavor framework
  - CPT Violation
  - Non Standard Interactions
  - MaVaNs
  - New Forces

Orebi Gann et. al. Annual Review of Nuclear and Particle Science



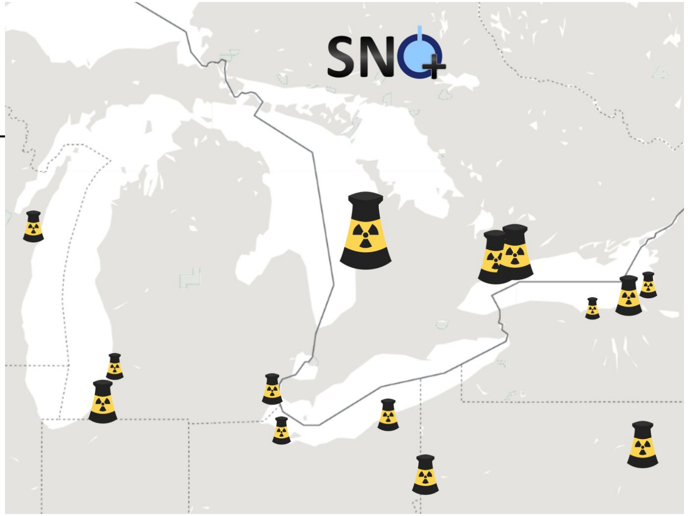
SNO+ Experiment

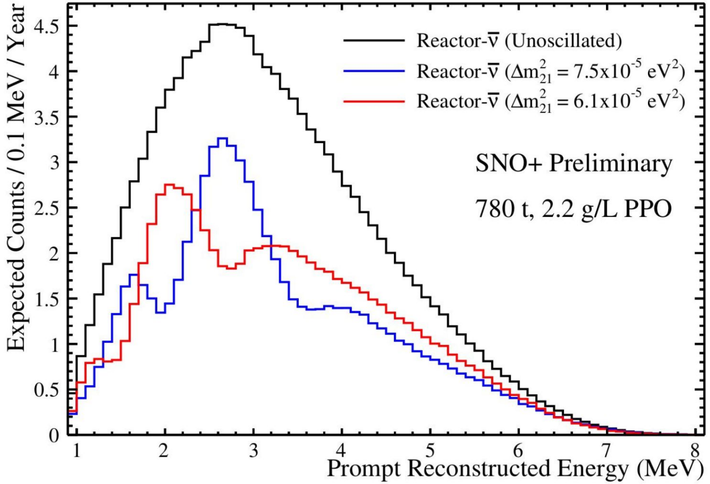
- SNO+
  - Located 2km underground at SNOLAB in Subury, Ontario, Canada
  - Muon rate ~3 / hr
  - Class-2000 clean room
  - 780 ton liquid scintillator target
  - ~10k PMTs
- Inherits most of its infrastructure from the SNO experiment
- Broad physics program with primary goal to search for $0\nu\beta\beta$ in ^{130}Te



SNO+ Measurement

- Expect ~100 reactor antineutrino interactions per year
- ~60% of reactor antineutrino flux comes from 3 Canadian reactors
  - **Bruce: Baseline of 240 km, ~40% of flux**
  - Pickering, Darlington: Baseline of 350 km, ~10% of flux each
- Spectral features of oscillation are well preserved





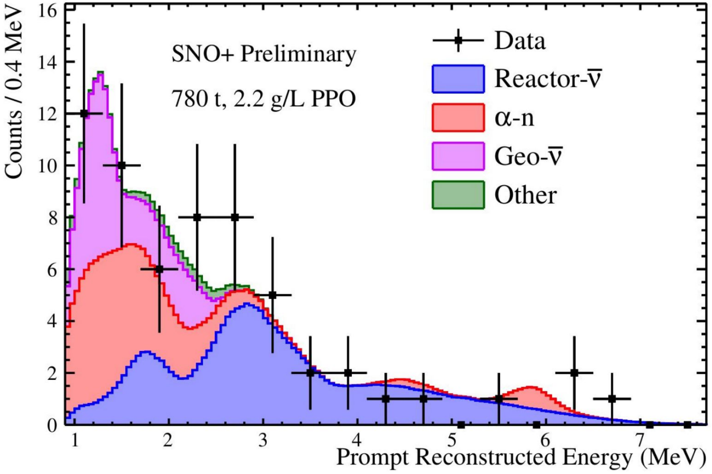
SNO+ Result

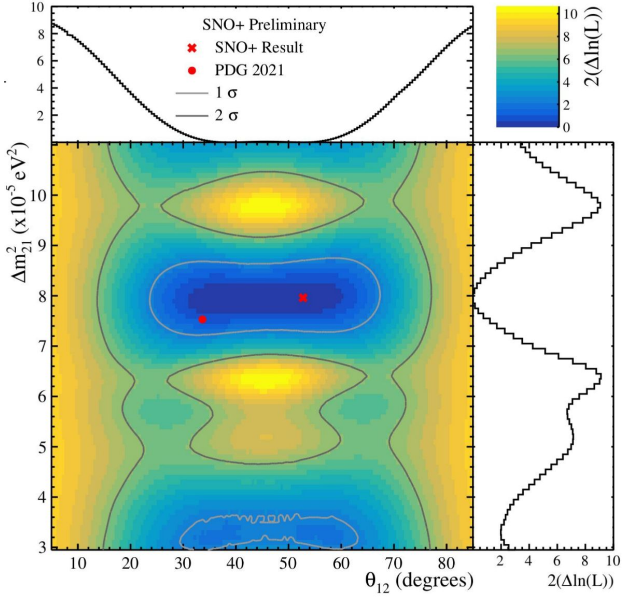
- Preliminary best fit result:

$$\Delta m^2_{21} = 7.96^{+0.48}_{-0.41} \times 10^{-5}\ \mathrm{eV}^2$$

$$\theta_{12} = 53^{\circ}{}^{+9^{\circ}}_{-25^{\circ}}$$

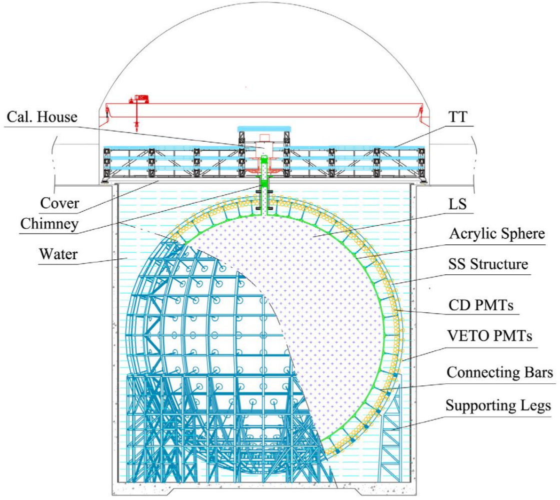
- Second ever measurement of Δm^2_{21} & θ_{12} using reactor neutrinos
- In good agreement with previous KamLAND result
- In similar tension with solar result
- ~2-3 years livetime in these conditions will achieve similar sensitivity to KamLAND
- Sensitivity unaffected by Te loading



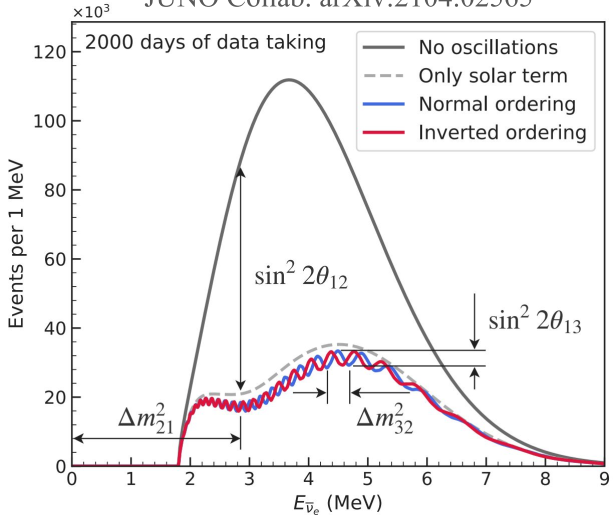


Future Prospects (Reactor)

- JUNO
  - 700m underground
  - 20 kton liquid scintillator target
  - ~40k PMTs
  - 2 reactor complexes at 52 km produce >90% of flux
  - ~80 IBD interactions / day
- Aim to measure Δm^2_{21} & $\sin^2\theta_{12}$ with percent level precision

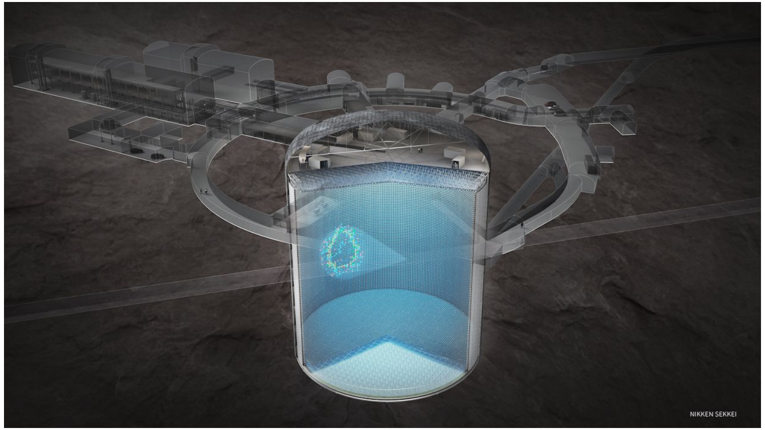


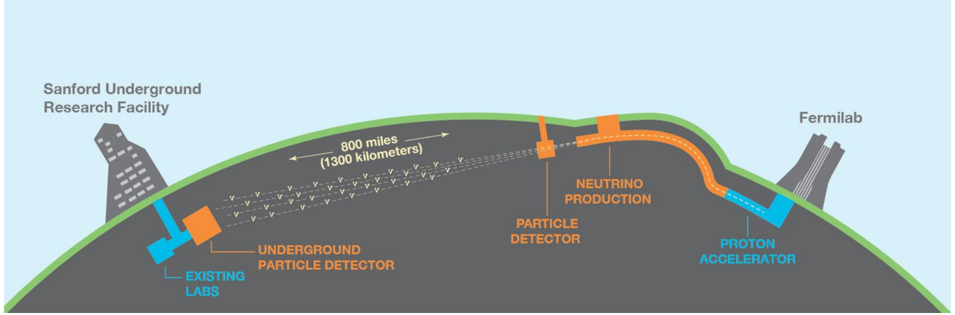
JUNO Collab. arXiv:2104.02565



Future Prospects (Solar)

- Hyper K
  - Similar to Super K but with 10x more volume, and better PMTs
- DUNE
  - Liquid Argon TPC
  - 40 kton
  - Allows CC interaction:
    $\nu_e + {}^{40}\mathrm{Ar} \rightarrow e^- + {}^{40}\mathrm{K}$
  - Larger cross section, and better estimate of neutrino energy
  - Significant day-night effect

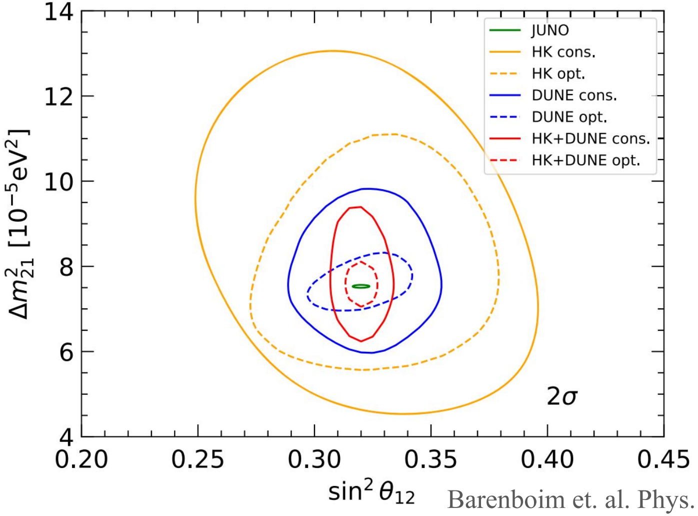




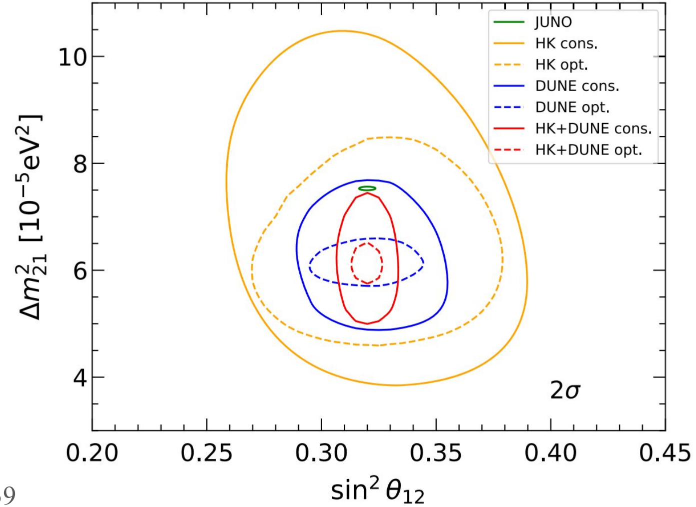
Potential Effect on Tension

- JUNO, Hyper K, and DUNE will significantly improve on oscillation measurements
- Could result in > 5σ tension if solar Δm^2_{21} remains unchanged

Solar Δm^2_{21} = Reactor Δm^2_{21}



Solar Δm^2_{21} ≠ Reactor Δm^2_{21}



Barenboim et. al. Phys. Rev. D 108, 035039

Conclusions

- Solar and Reactor experiments both have sensitivity to Δm^2_{21} & θ_{12}
- Measurements of Δm^2_{21} are in mild tension
- Potential new physics could explain
- SNO+ preliminary measurement of Δm^2_{21} is in good agreement with KamLAND result
- JUNO, Hyper-K, and DUNE will make significantly more precise measurements potentially resolving or amplifying tension