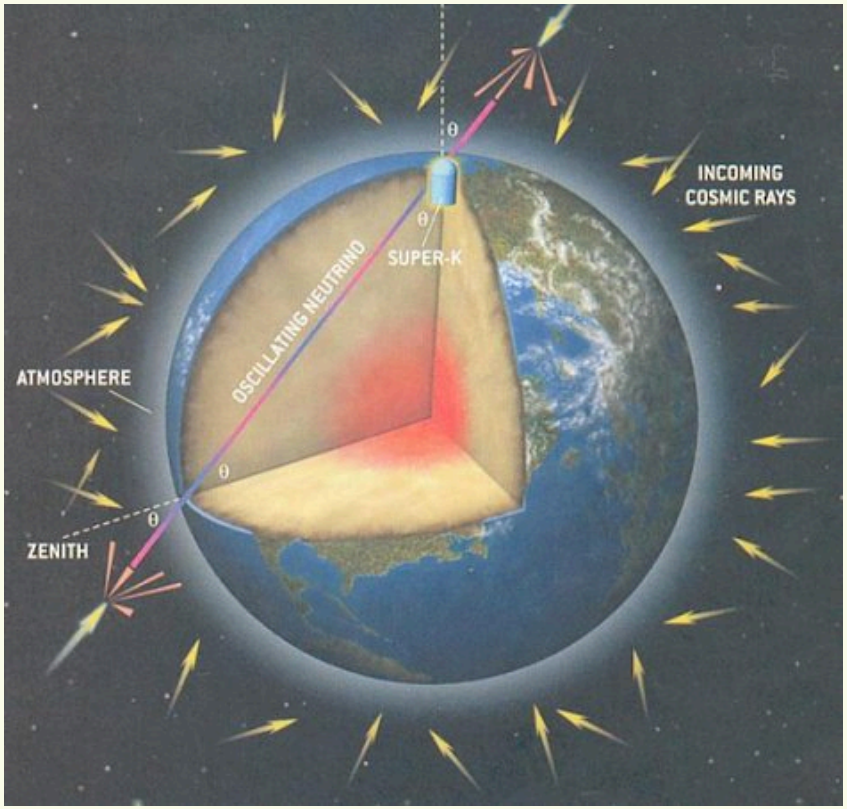
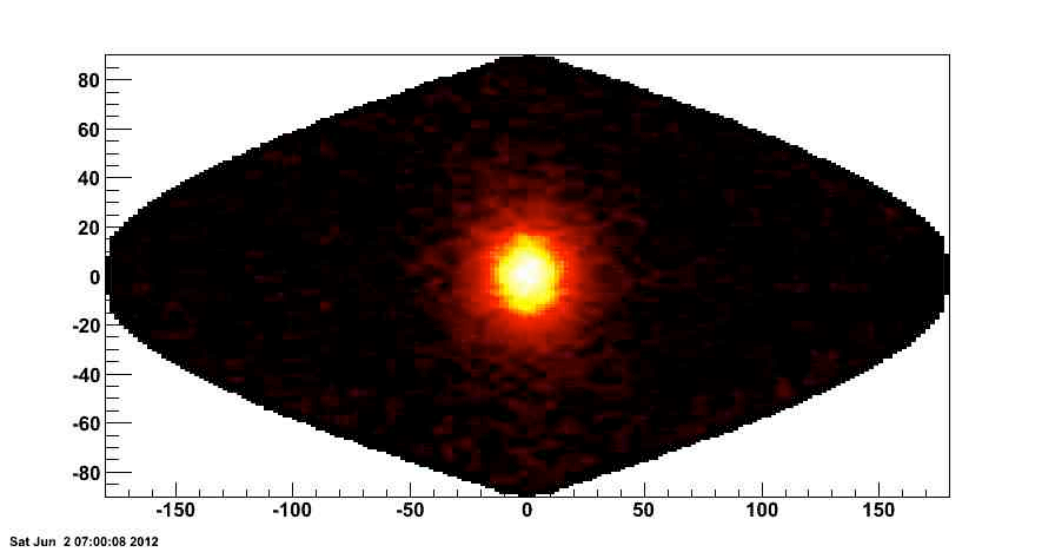
Results and Prospects from Atmospheric and Solar Neutrinos



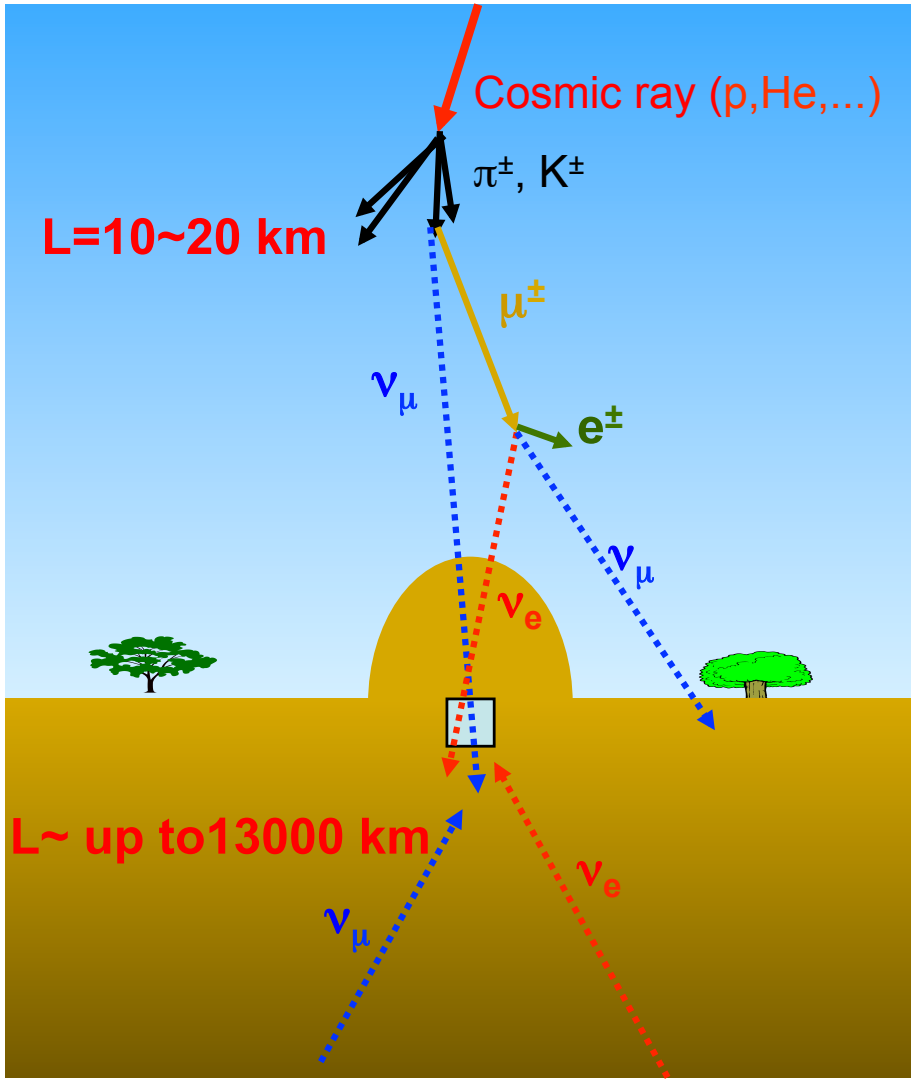


Yusuke Koshio
Okayama University

22nd International Workshop on Next Generation Nucleon Decay and Neutrino Detectors (NNN23)
11-13 October, 2023
Procida, Italy

Atmospheric neutrino

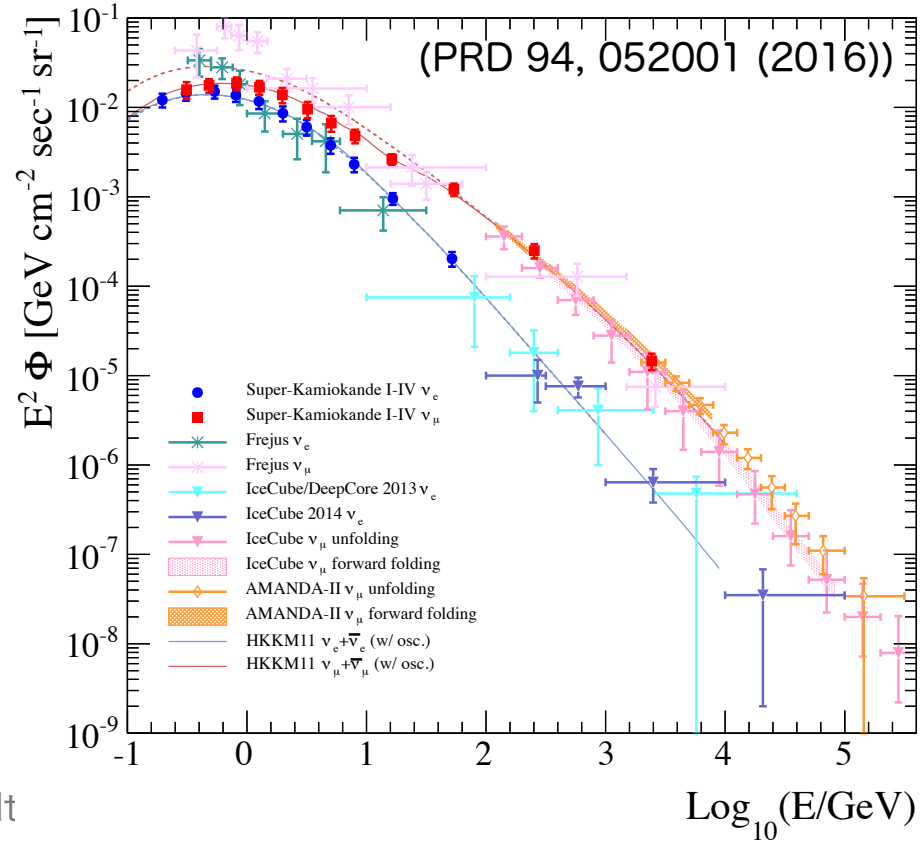
Atmospheric neutrino



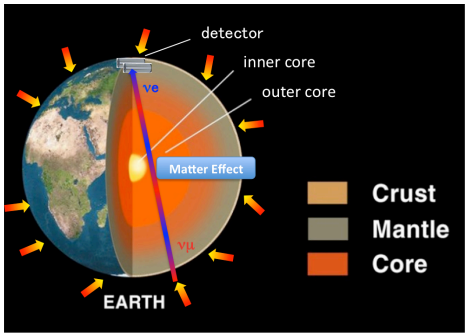
Cosmic rays strike air nuclei and the decay of the out-going hadrons gives neutrinos.

✓ Flux measurement by several experiments

✓ Model calculation is consistent with data.



3 flavor neutrino oscillation analysis

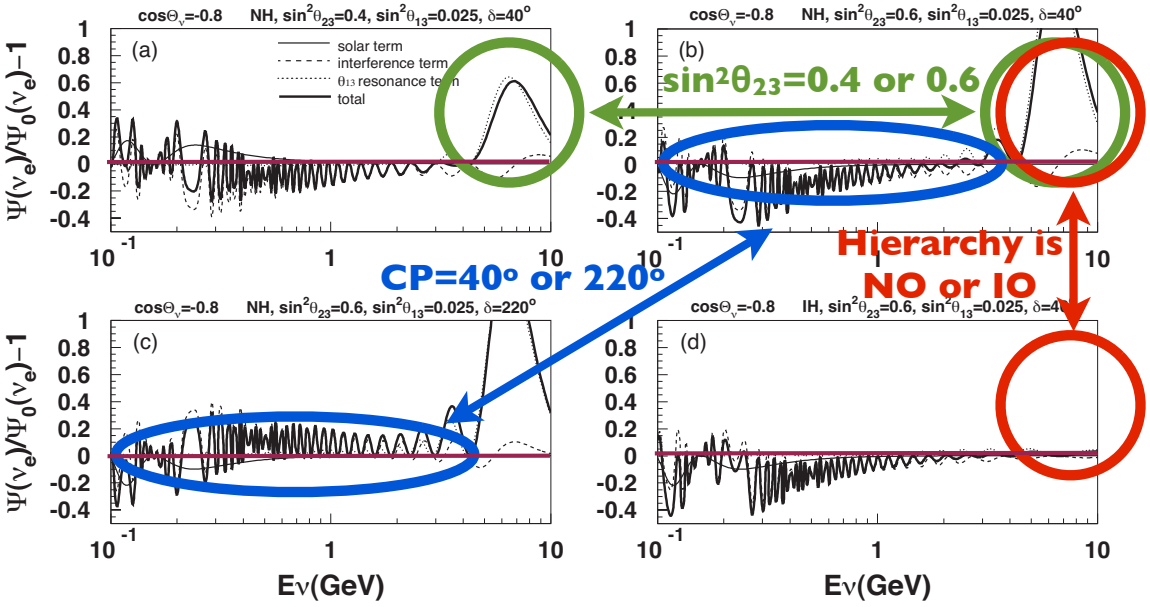


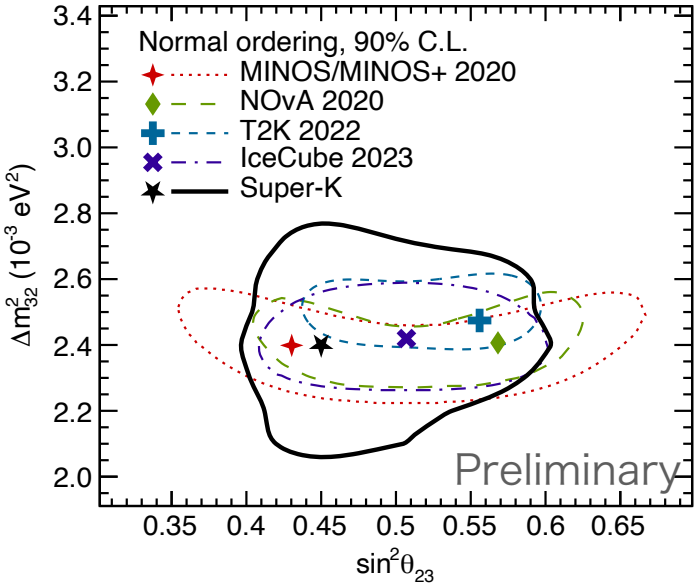
Consider all the sub-leading effects (Δm^2_{21}, matter)

- Mass ordering : resonance in multi-GeV ν_e or $\bar{\nu}_e$
- Octant θ_{23} : magnitude of the resonance
- δ_{CP} : interference btw two Δm^2 driven oscillation

Super-K atmospheric neutrinos

Fractional change of upward ν_e flux ($\cos\theta_{zenith} = -0.8$)

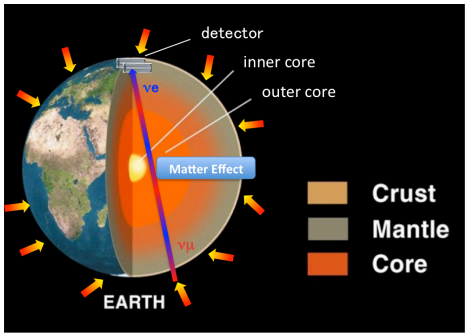




Data favors:

- maximal mixing
- δCP ~ $-\pi/2$
- Normal mass ordering

3 flavor neutrino oscillation analysis



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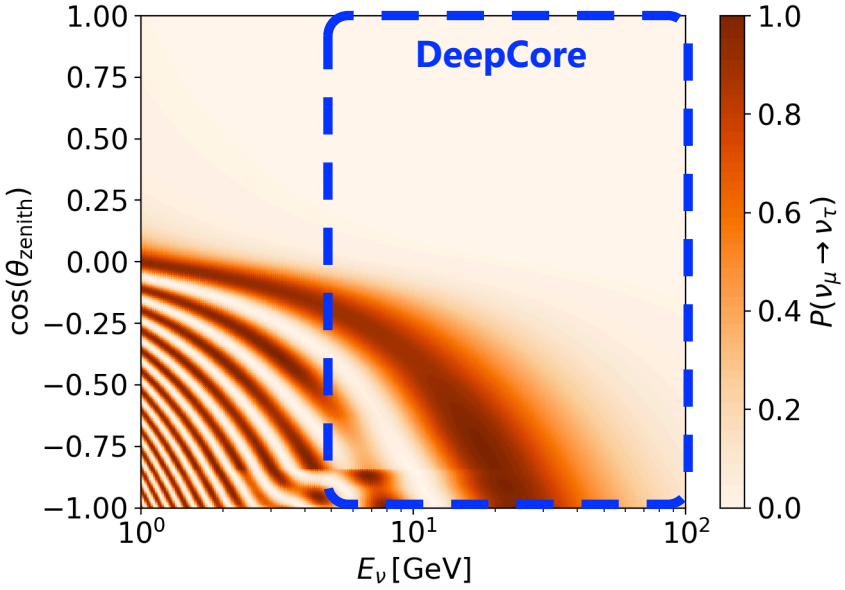
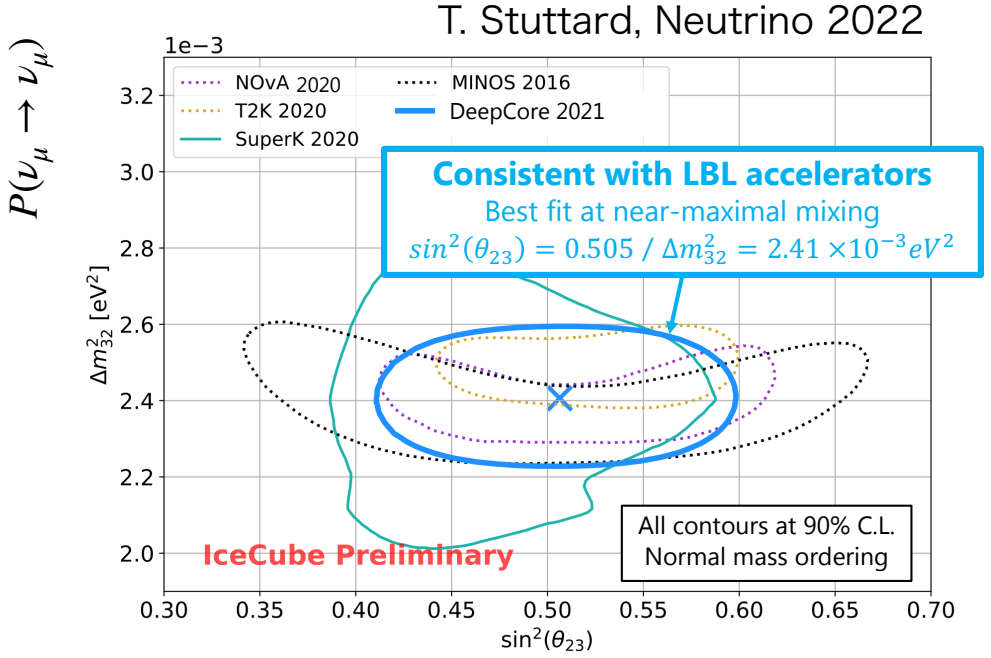
IceCube atmospheric neutrinos



T. Stuttard, Neutrino 2022



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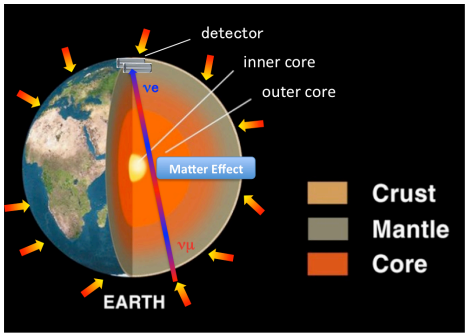

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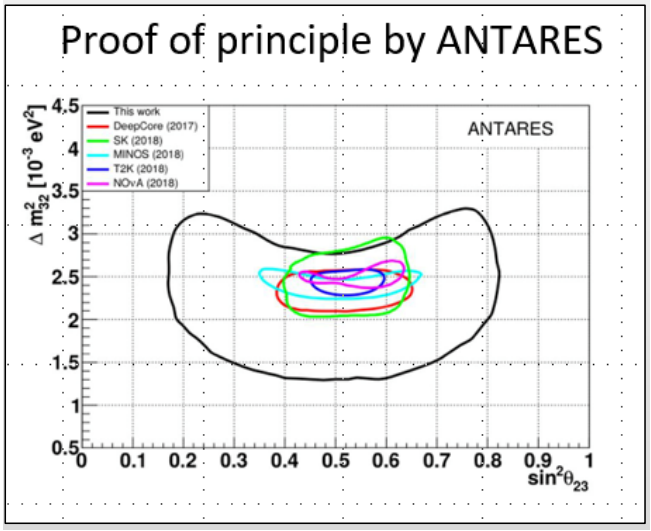
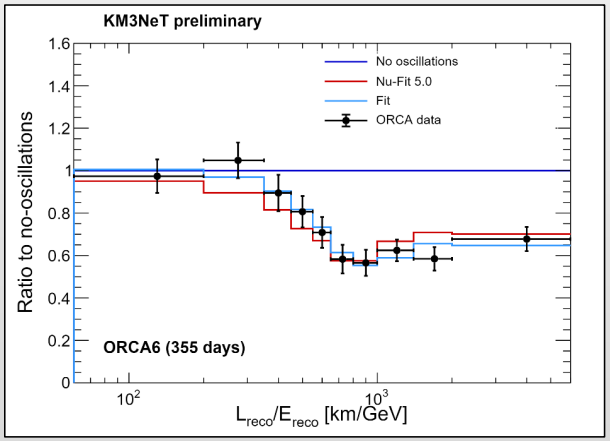
ANTARES / KM3NeT (ORCA) atmospheric neutrinos

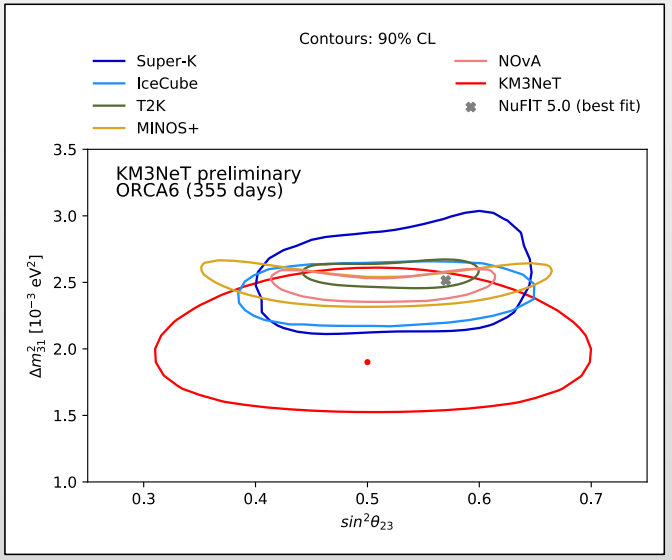
A. Heijboer, Neutrino 2022



JHEP, 2019, 6., 113

1 year of data with 6 lines of ORCA
≈1 kton-year.

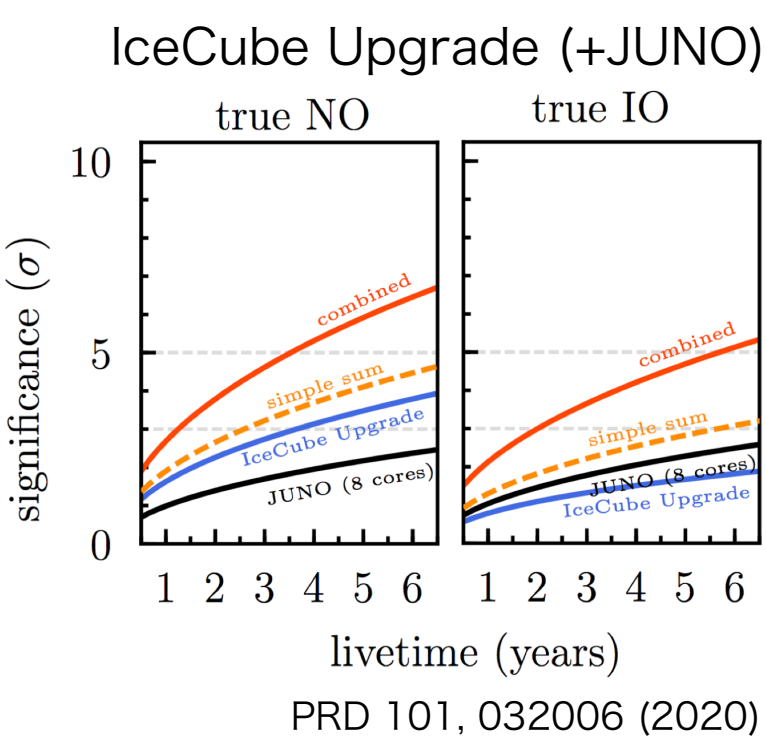




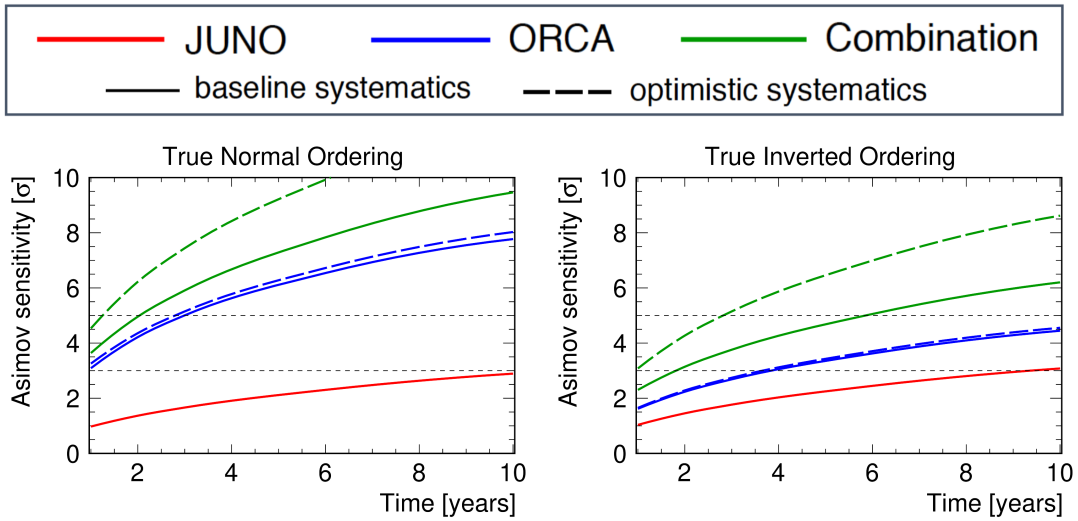
Prospects for neutrino oscillation

Mass Ordering

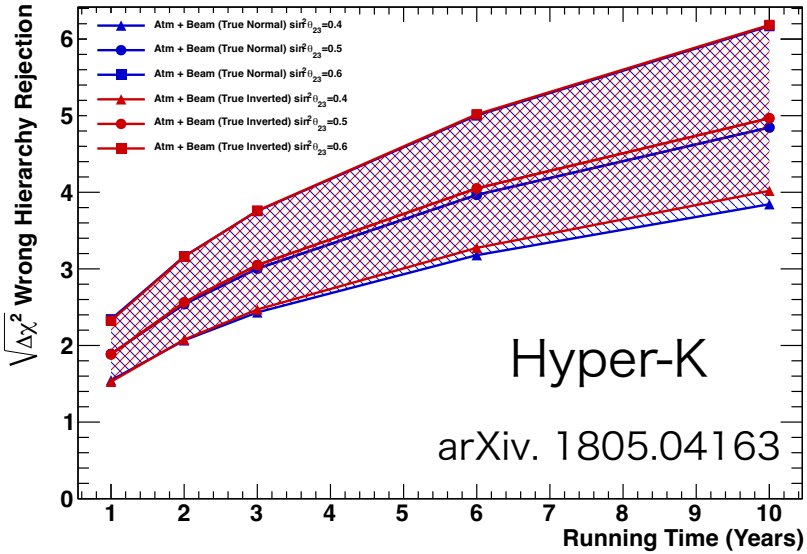
JHEP, 2022, 03., 055



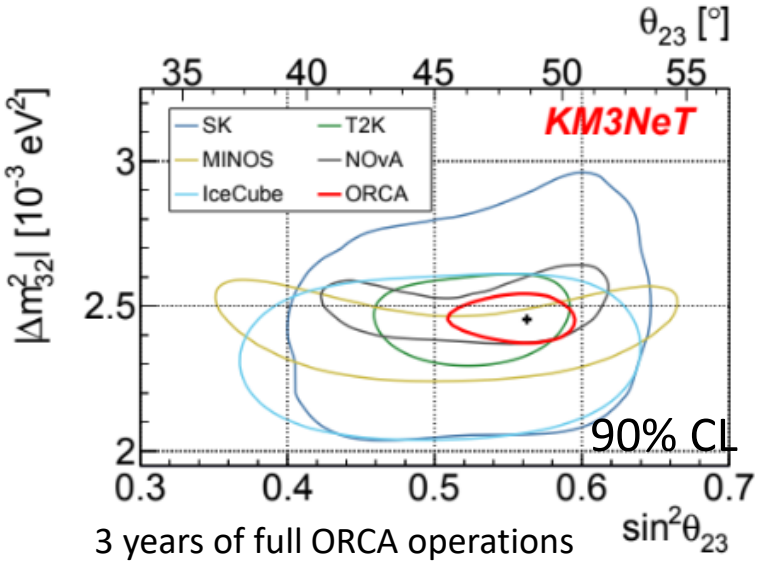
PRD 101, 032006 (2020)



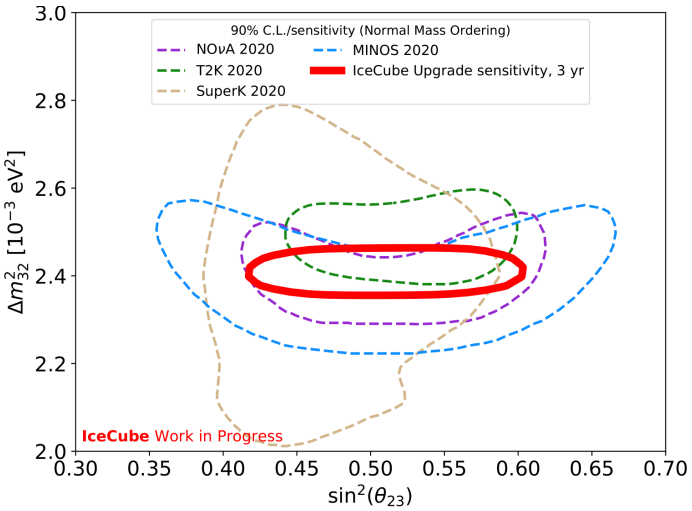
Expect to be determined



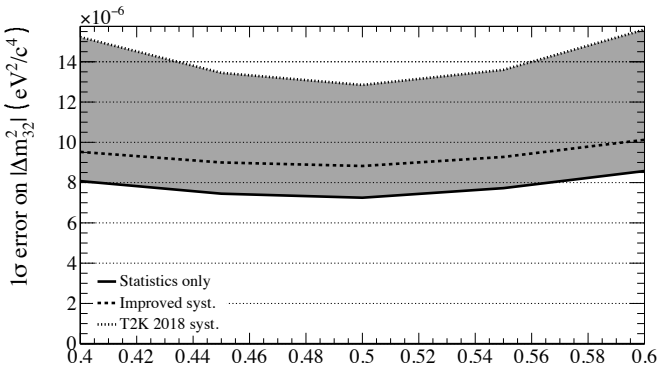
Prospects for neutrino oscillation

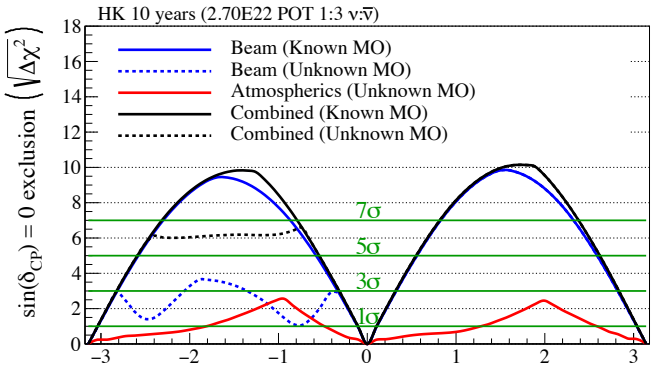


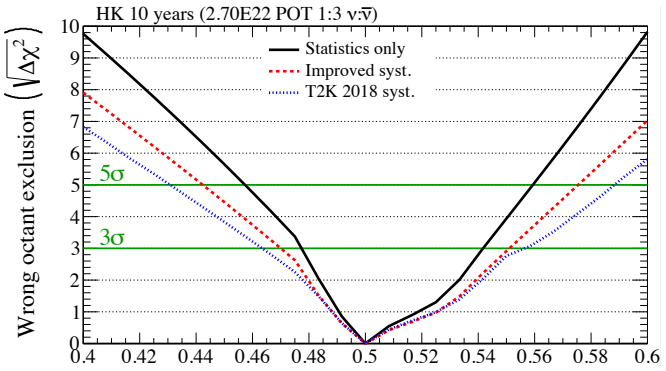
3 years of full ORCA operations

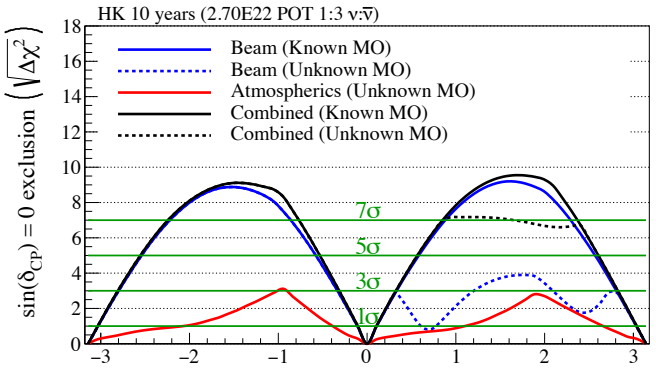


Hyper-K 10 years





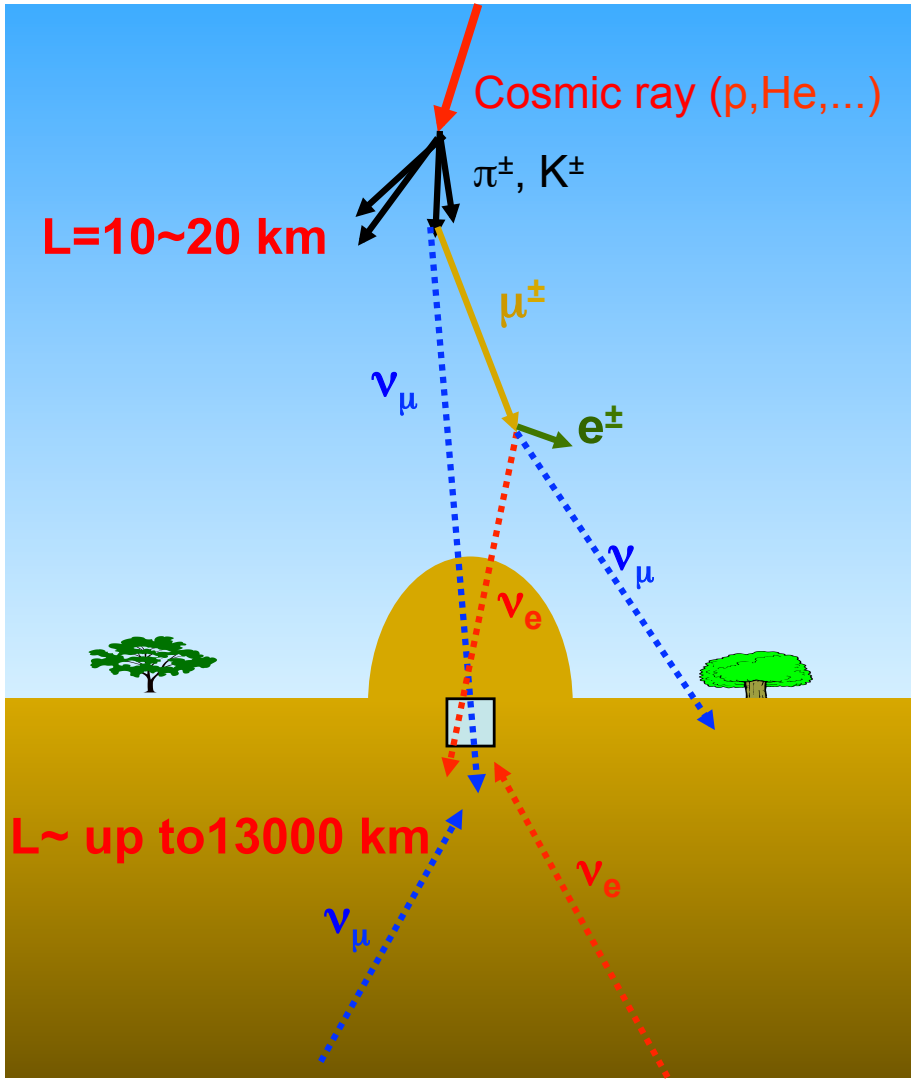




J. Wilson, Neutrino 2022

Precise measurements with several experiments

Atmospheric neutrino



Physics targets other than neutrino oscillation

✓ Foreground for studying astrophysical neutrinos such as DSNB.

✓ Probes of very forward particle production phase space.

Flux prediction is important

- Energy region up to ~100GeV
  - 3D Monte Carlo -> Honda, Bartol
- Higher energy region
  - Solve cascade equation -> MCEq

Geomagnetic field and atmosphere

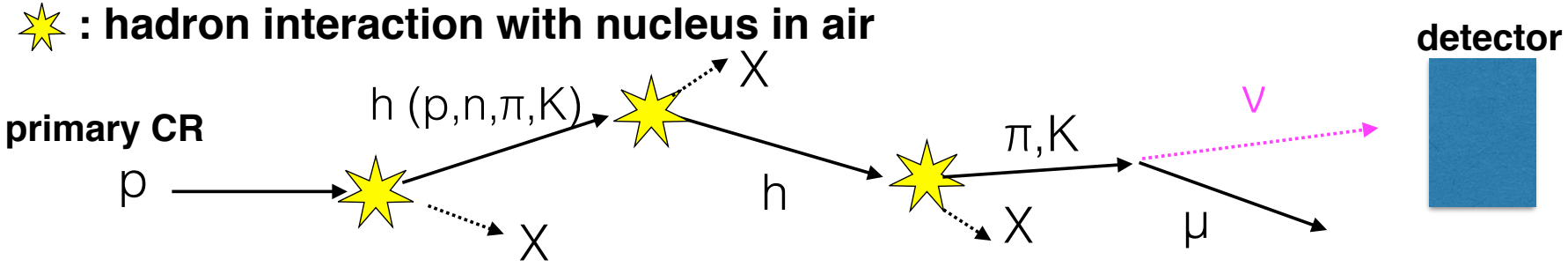
$$\phi_{\nu_i} = \sum_A \phi_A \otimes R \otimes Y_{A\to\nu_i}$$

Primary cosmic-ray flux **Hadron interactions**

(dominant uncertainties)

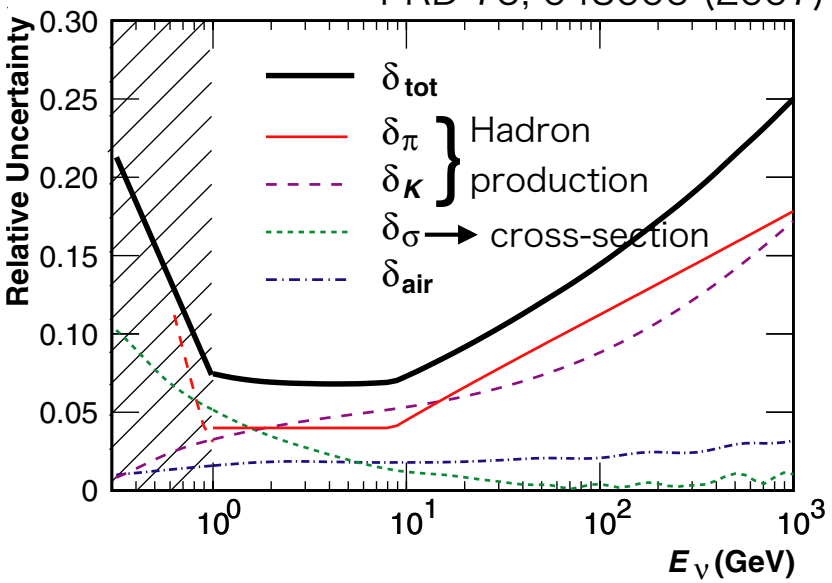
K. Sato, A. Fedynitch, Neutrino 2022

Improvement of hadron interaction error



uncertainty of each source

PRD 75, 043006 (2007)



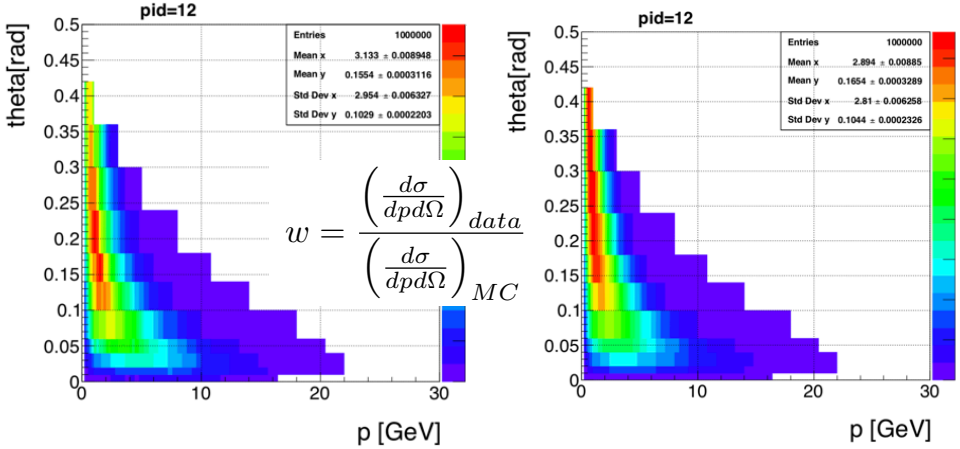
Arising from model uncertainty

Accelerator-data-driven tuning

e.g.) p (31GeV) + Air → π^++ X

differential cross-seciton of outgoing π^+

NA61/SHINE **ATMNC**



Promising reduction in error

New data is also planed (NA61, EMPHATIC, ..)

Summary of atmospheric ν

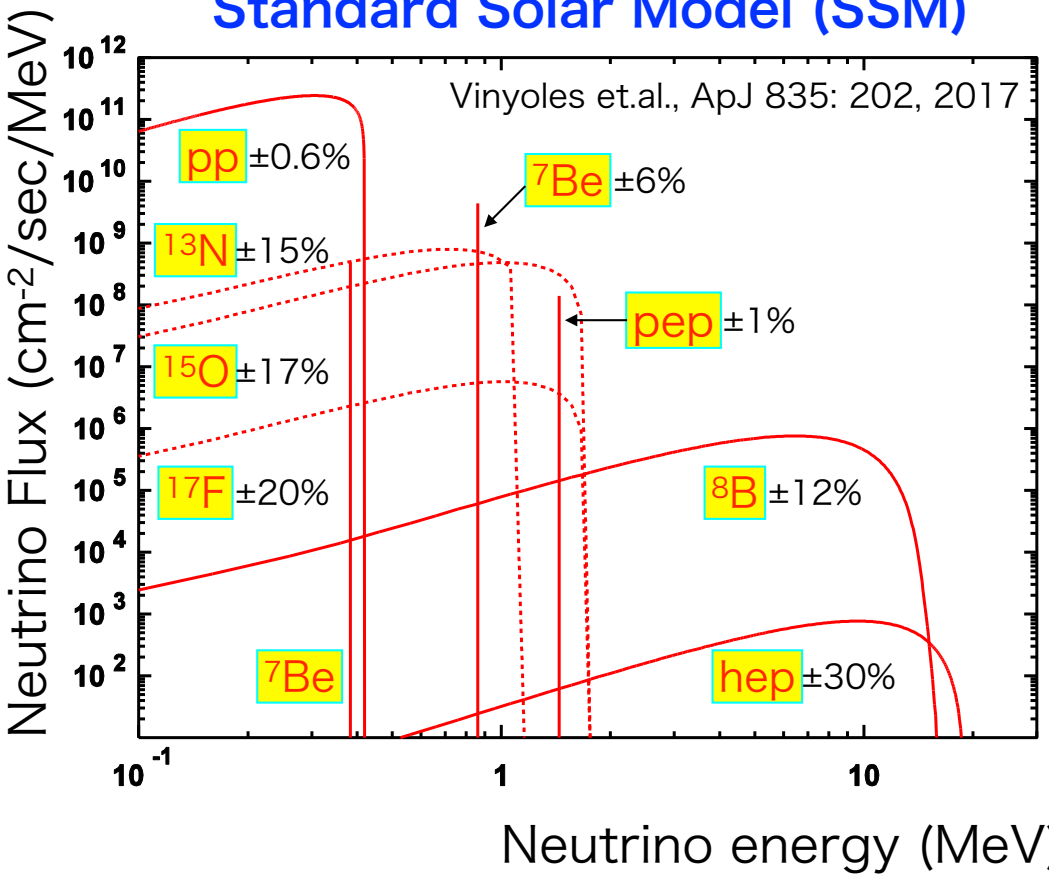
- Three flavor oscillation analysis are performed to extract the neutrino oscillation parameters by atmospheric neutrino data.
- Current unknown parameters are expected to be determined by the atmospheric neutrino measurements in the next generation detectors.
- The flux uncertainty is important also for other physics, and will be reduced in near future.

Solar neutrino

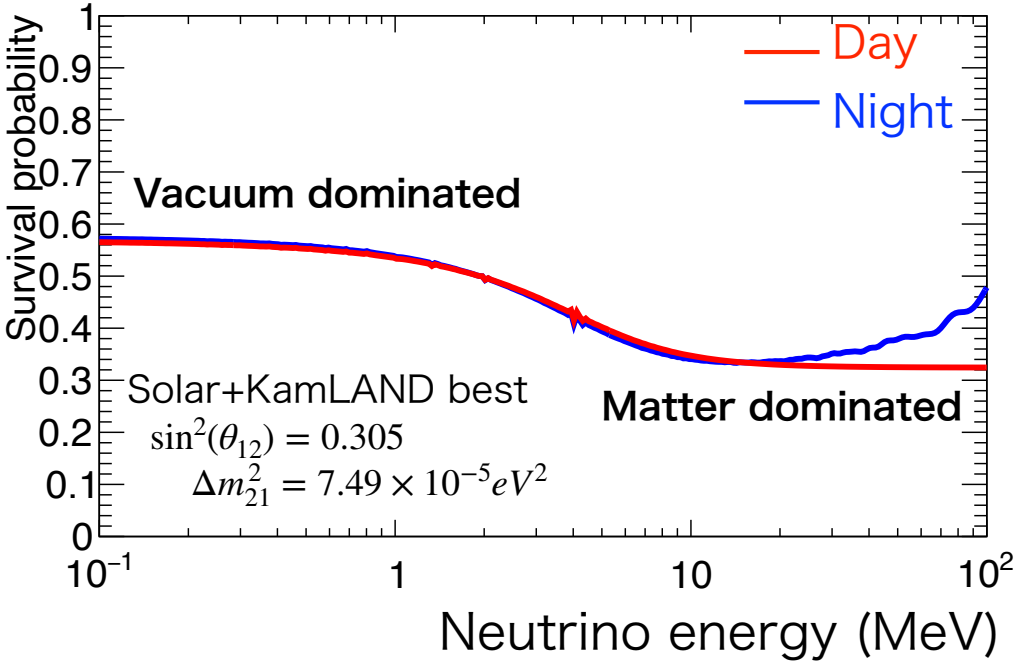
Solar neutrinos

Standard scenario

Standard Solar Model (SSM)



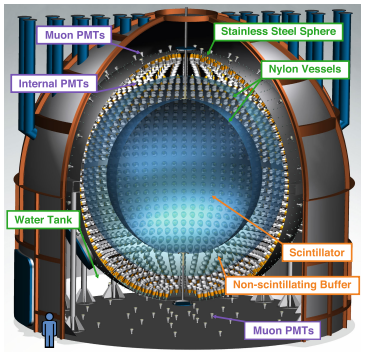
Neutrino oscillation (MSW-LMA)

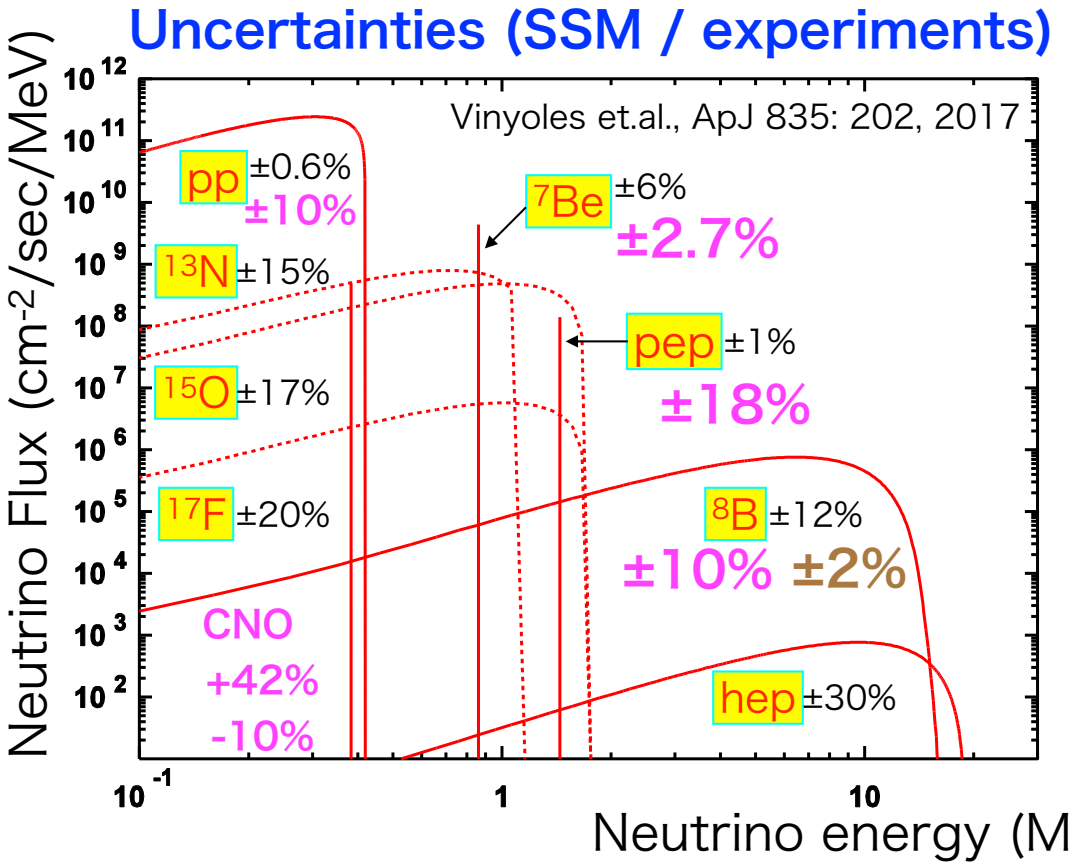


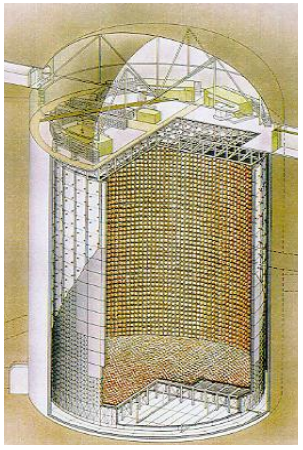
Solar neutrinos

Recent results

Borexino





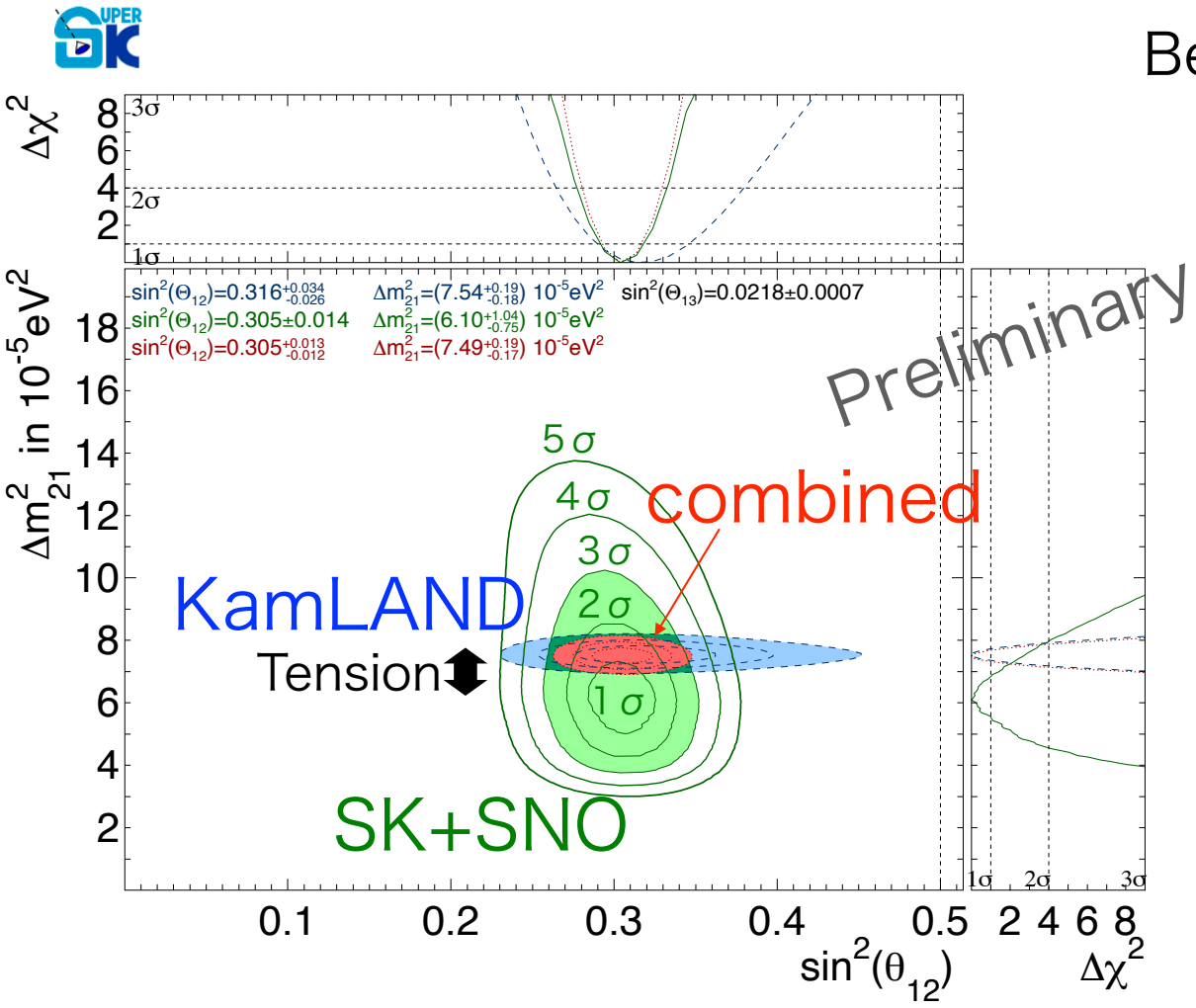


Super-K

Precision of the measurements becomes better and better.

Solar neutrinos

Recent results of neutrino oscillation by Super-K



Best fit oscillation parameters

$$\sin^2(\theta_{12}) = 0.316^{+0.034}_{-0.026}$$

$$\Delta m^2_{21} = 7.54^{+0.19}_{-0.18} \times 10^{-5} eV^2$$

$$\sin^2(\theta_{12}) = 0.305 \pm 0.014$$

$$\Delta m^2_{21} = 6.10^{+1.04}_{-0.75} \times 10^{-5} eV^2$$

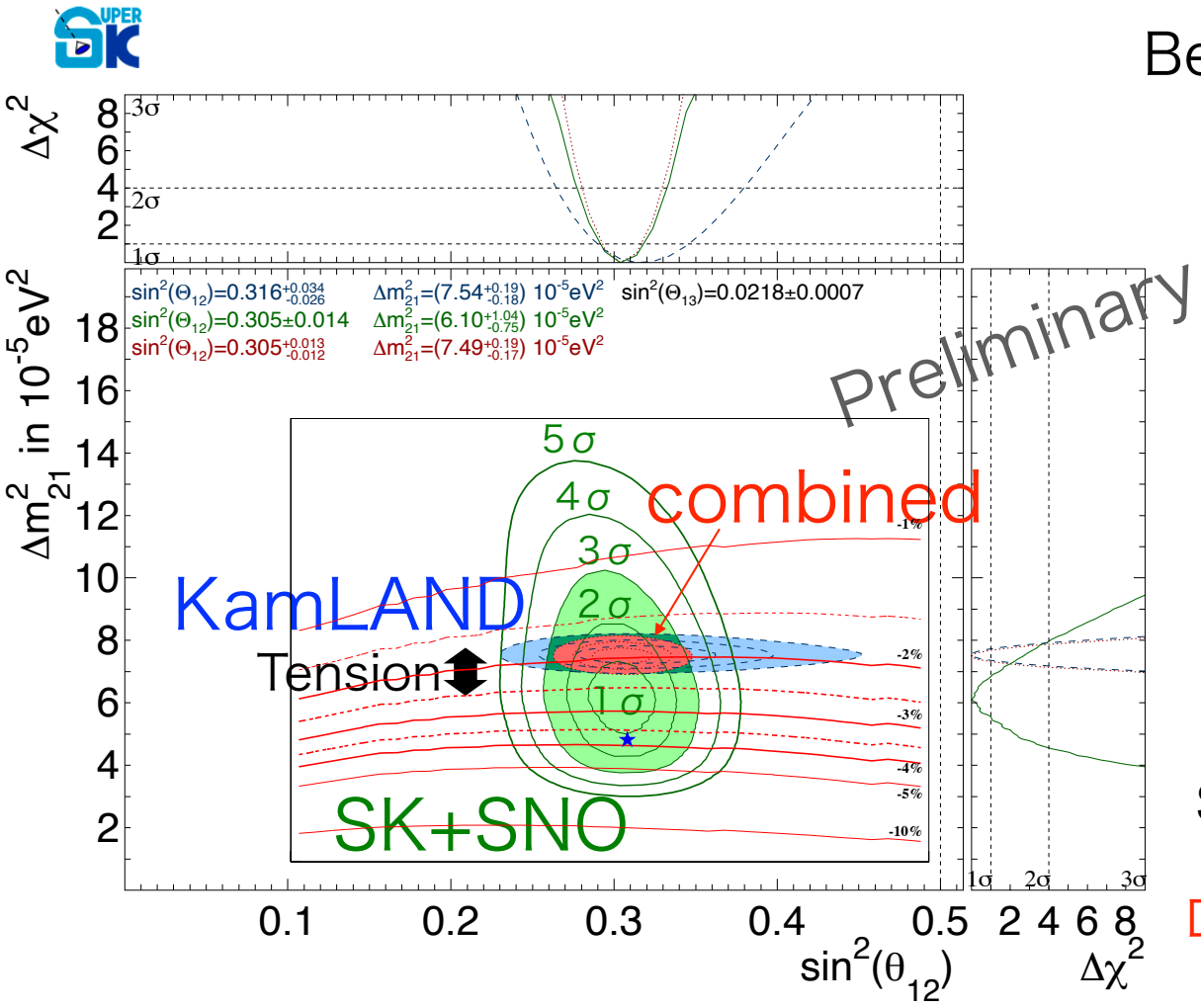
$$\sin^2(\theta_{12}) = 0.305^{+0.013}_{-0.012}$$

$$\Delta m^2_{21} = 7.49^{+0.19}_{-0.17} \times 10^{-5} eV^2$$

There is ~1.5 σ tension between SK+SNO and KamLAND in Δm^2_{21}

Solar neutrinos

Recent results of neutrino oscillation by Super-K



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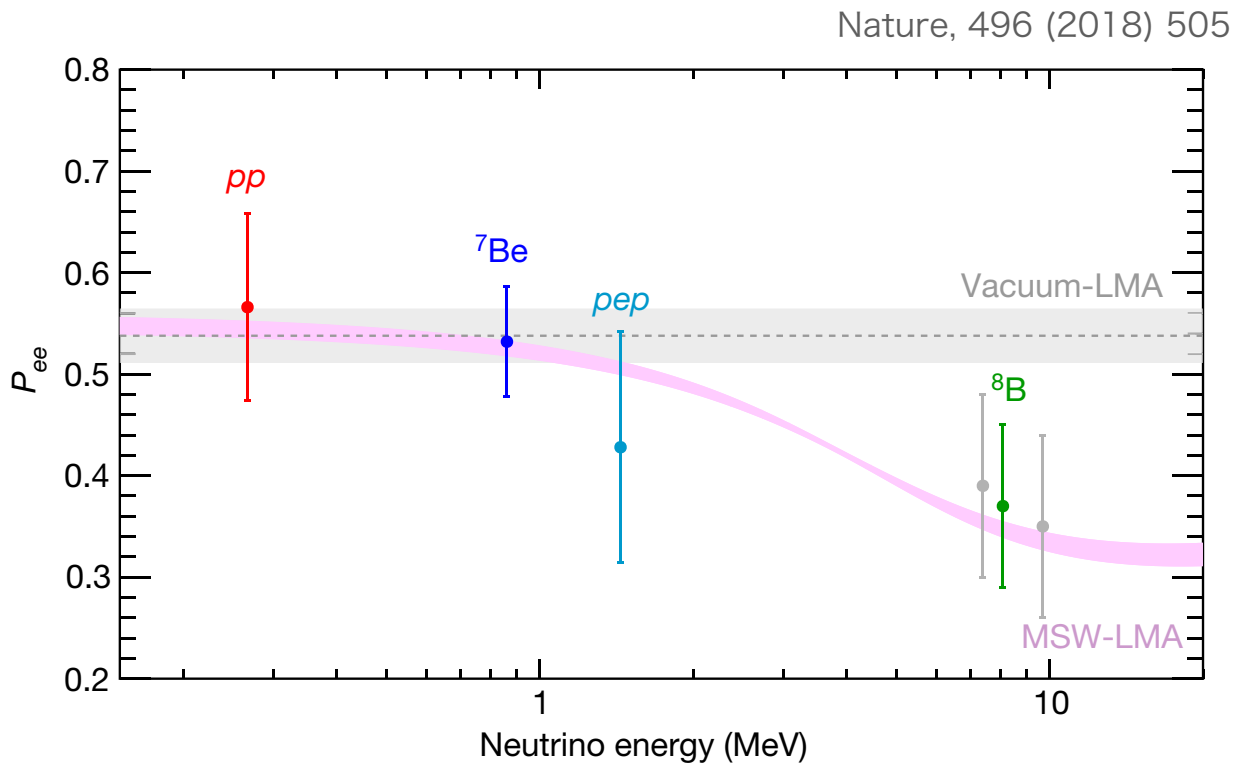
Day-Night asymmetry is important
SK see more than 3 σ effect

Solar neutrinos

Recent results of neutrino oscillation by Borexino

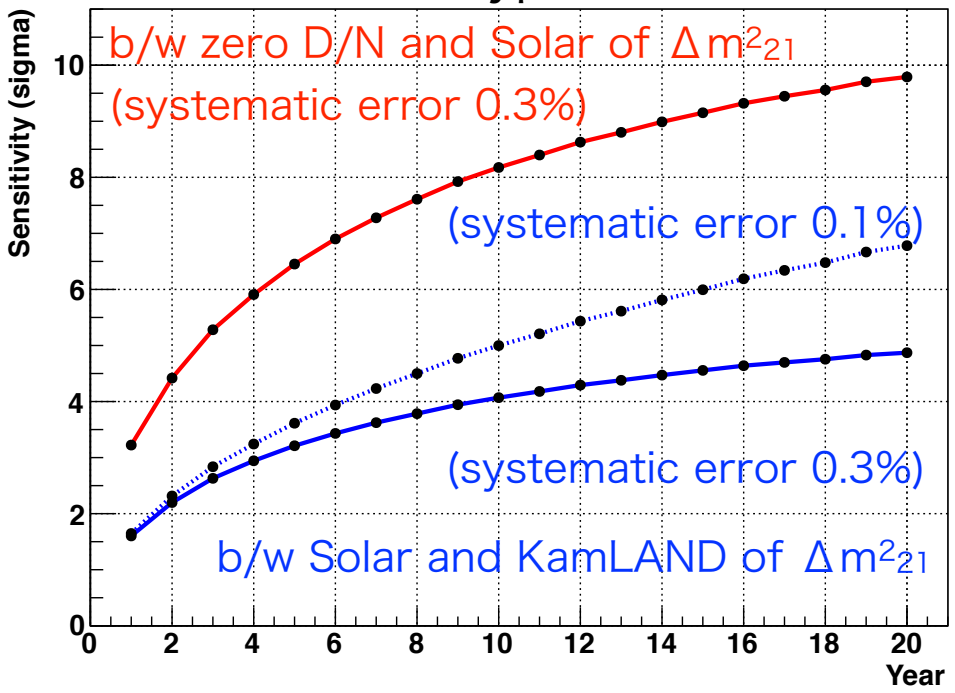


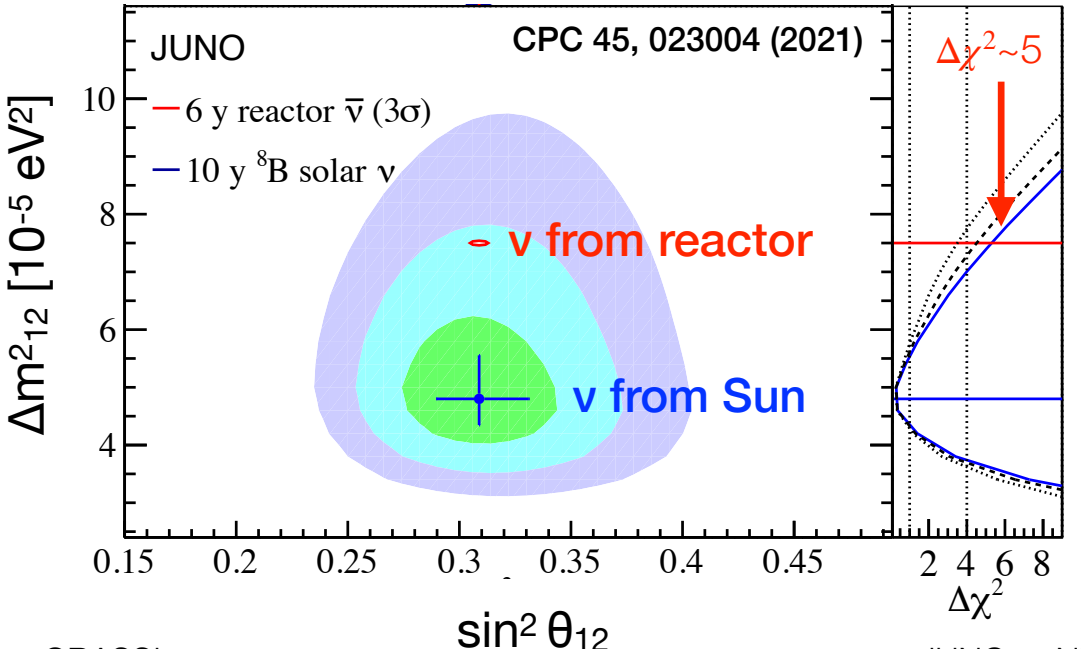
Consistent with the expectation from standard scenario (MSW-LMA).

Prospects for solar neutrino

Neutrino oscillation

Sensitivity of day-Night asymmetry in Hyper-K

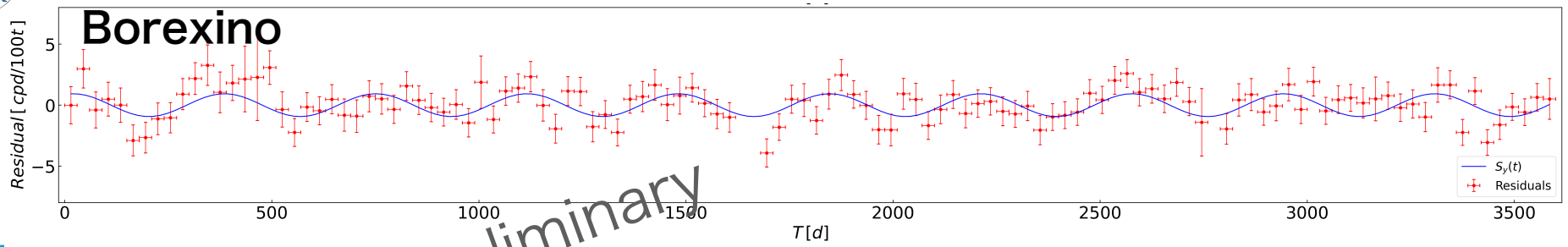




Expect to solve the puzzle

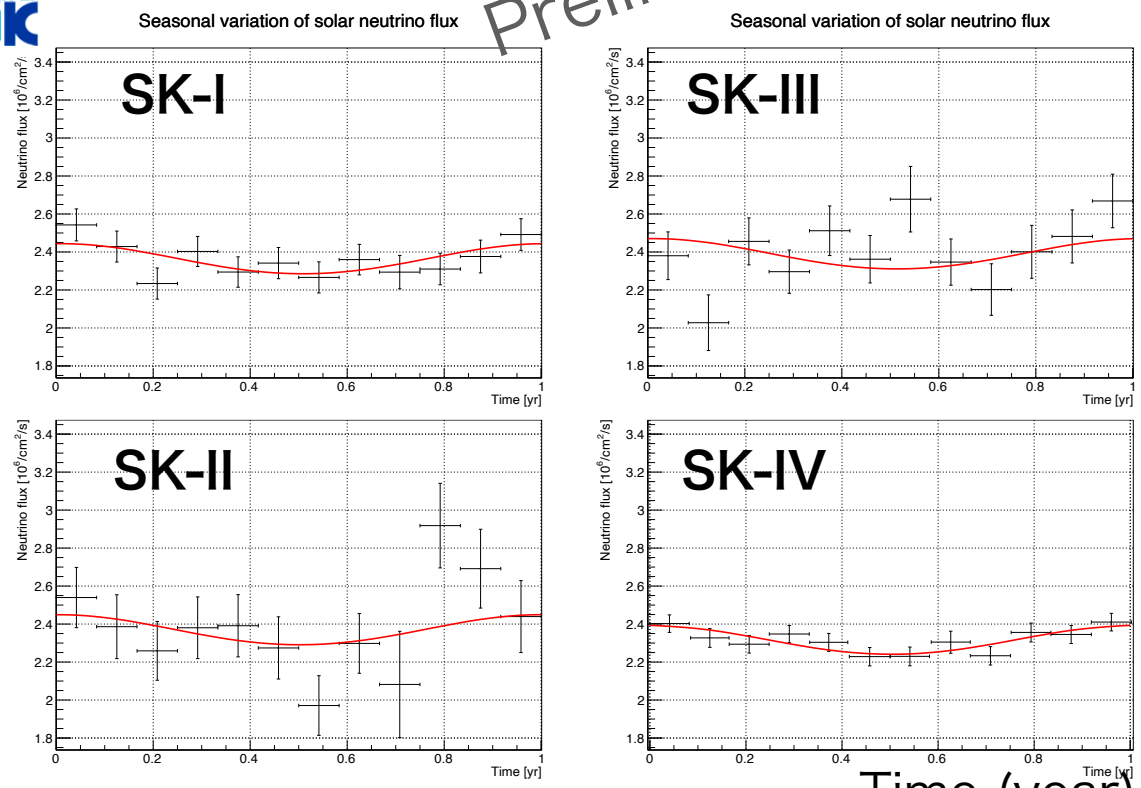
Solar neutrinos

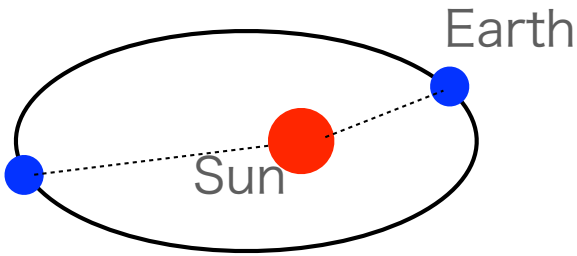
Seasonal variation



Preliminary

Solar neutrino flux





Observed seasonal variation is consistent with the expectation by the Earth's orbital eccentricity.

Time (year)

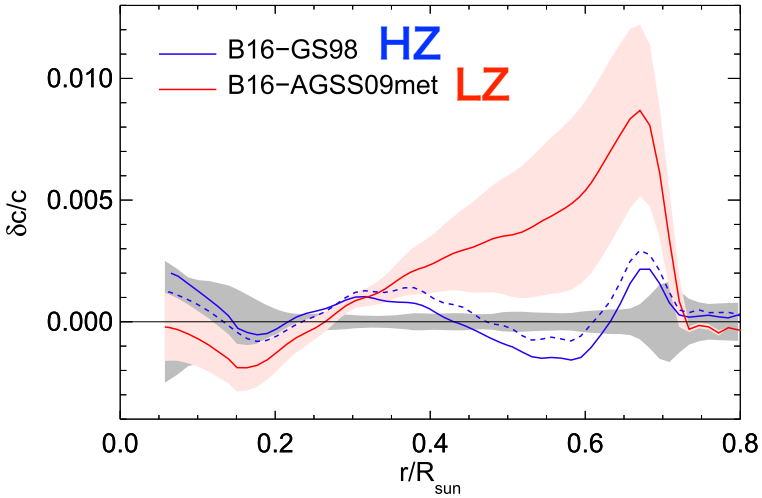
Solar neutrinos

Metallicity problem

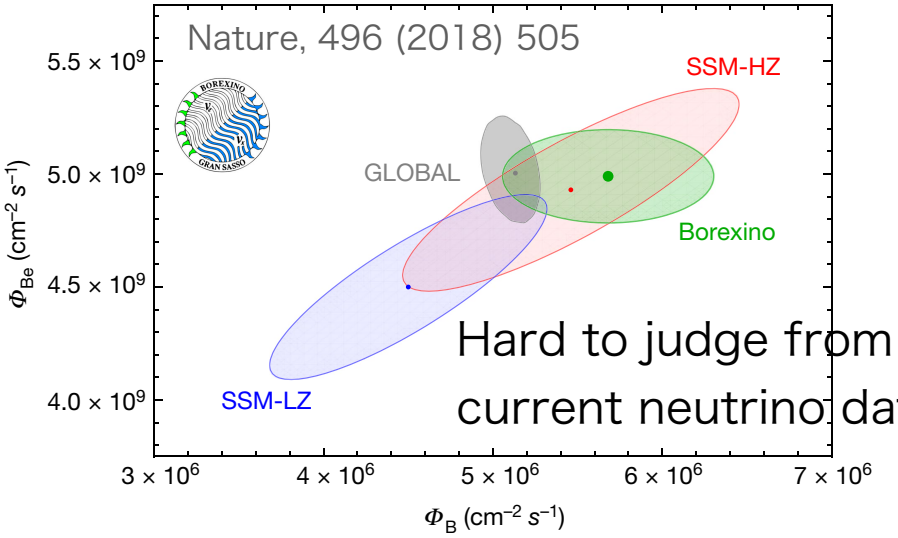
Heavy element abundance:

Z/X=0.02292 (GS98) -> HZ model

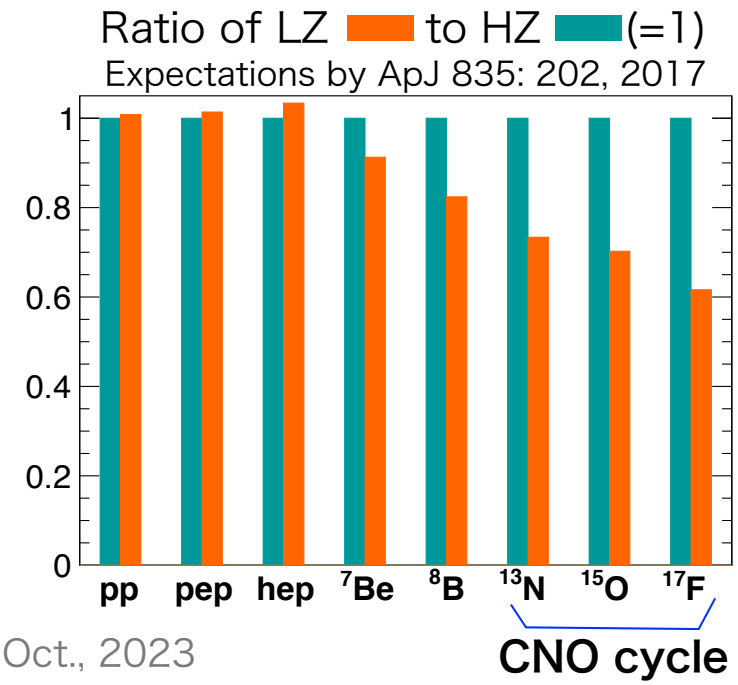
Z/X=0.01780 (AGSS09) -> LZ model



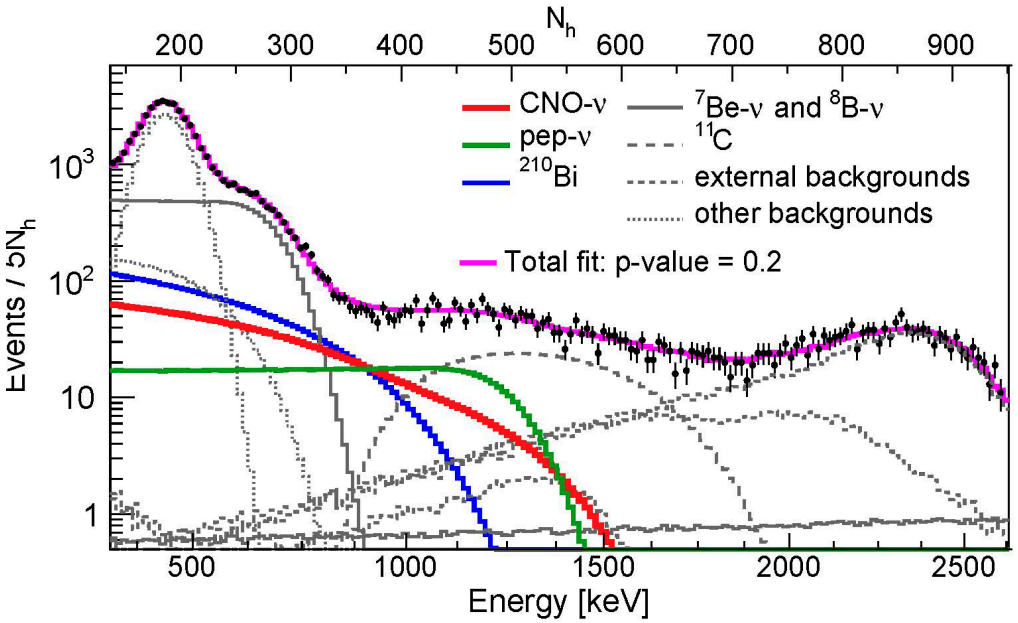
HZ model seems to be better from helioseismology

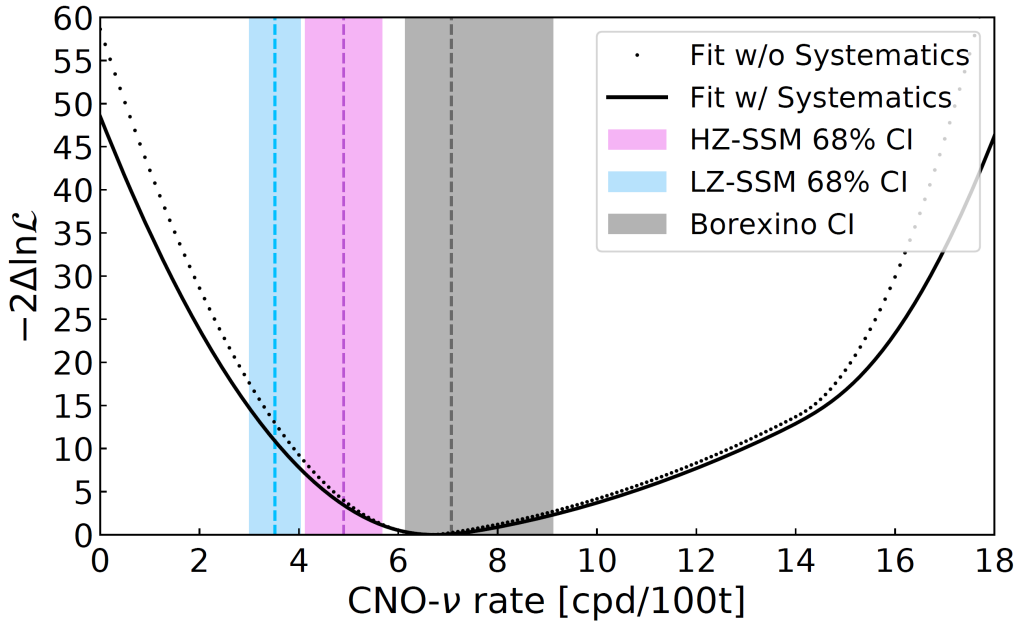


Hard to judge from current neutrino data..



CNO by Borexino



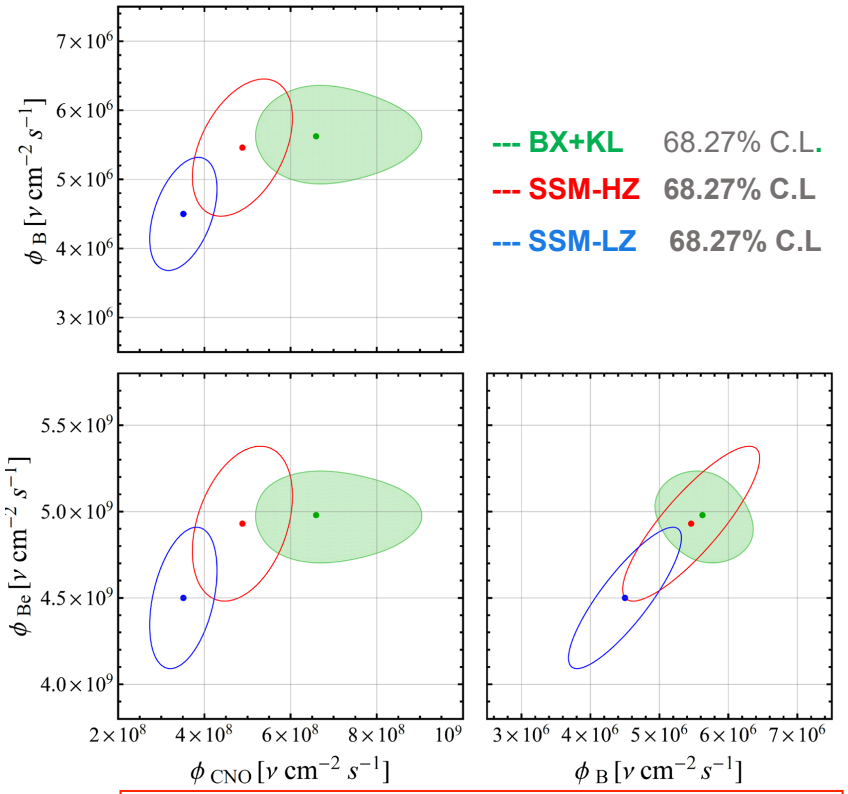


Latest results: B. Caccianiga, Neutrino 2022

Rate (CNO) = $6.7^{+2.0}_{-0.8}$ cpd/100t

ϕ(CNO) = $6.6^{+2.0}_{-0.9}$ x 10^8 ν cm^{-2}s^{-1}

Disfavor the CNO=0 hypothesis with ~7σ

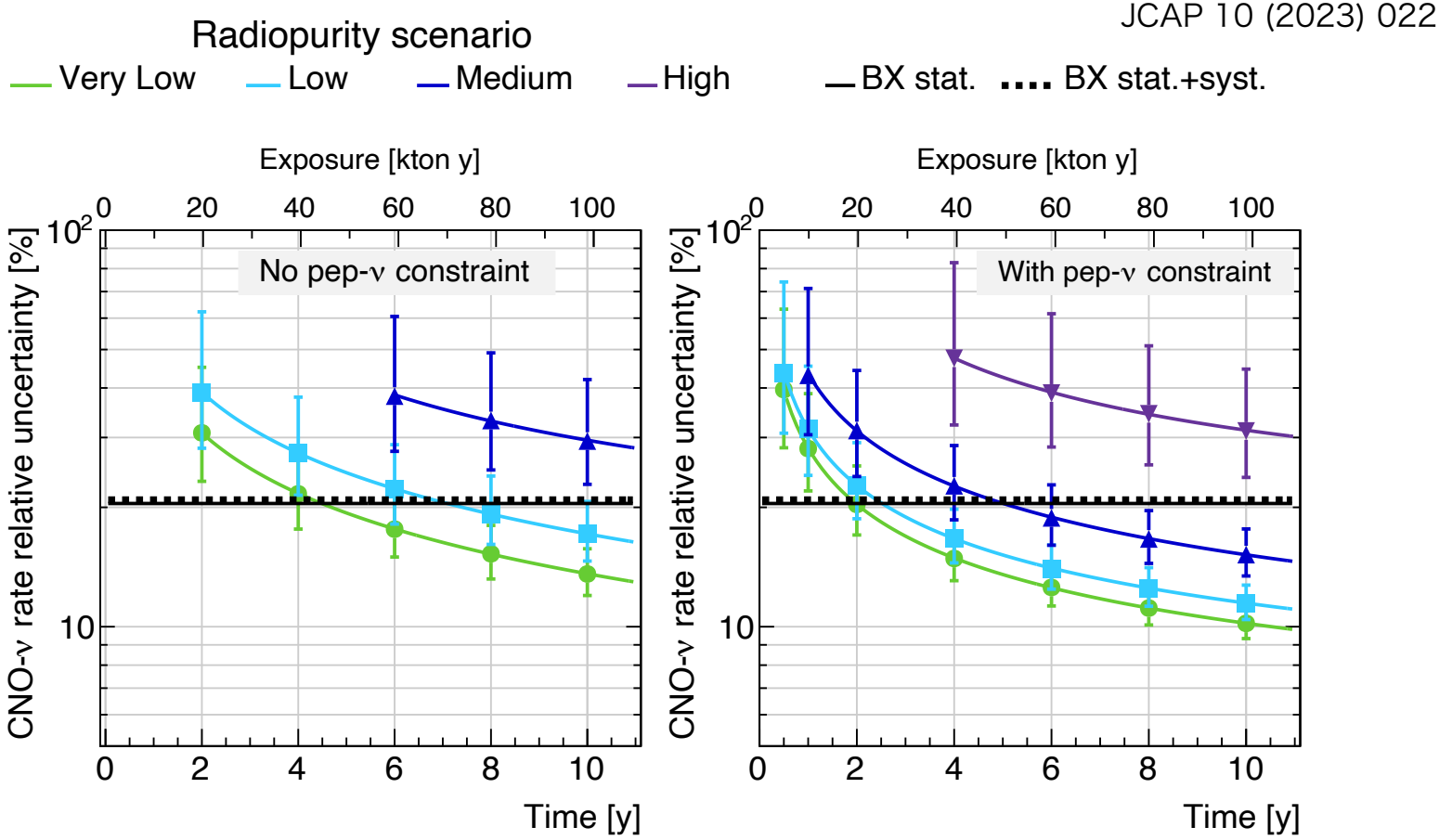


Disfavor the SSM-LZ at 3.1σ

Prospects for solar neutrino

CNO by JUNO

JCAP 10 (2023) 022

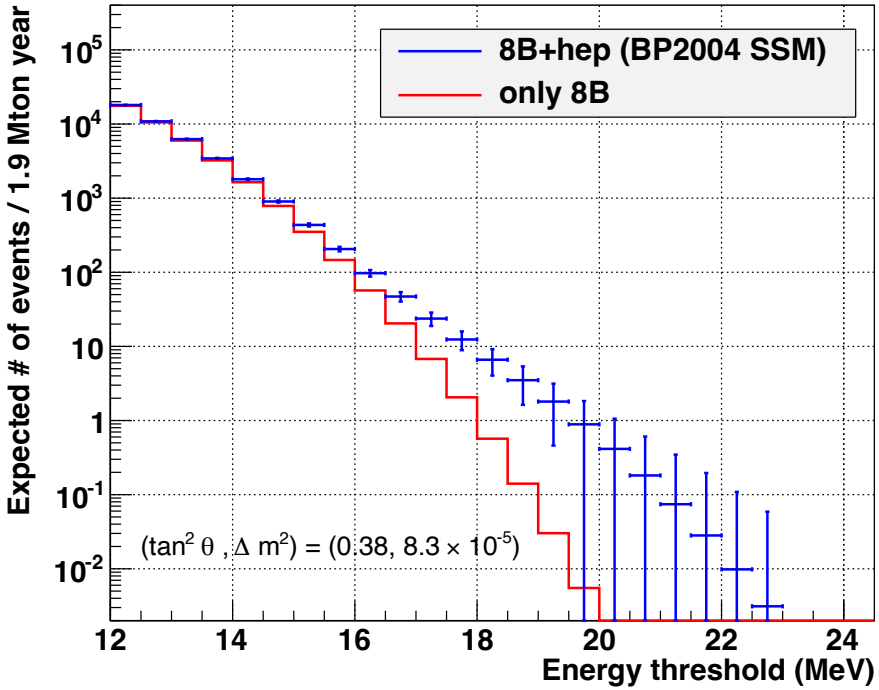


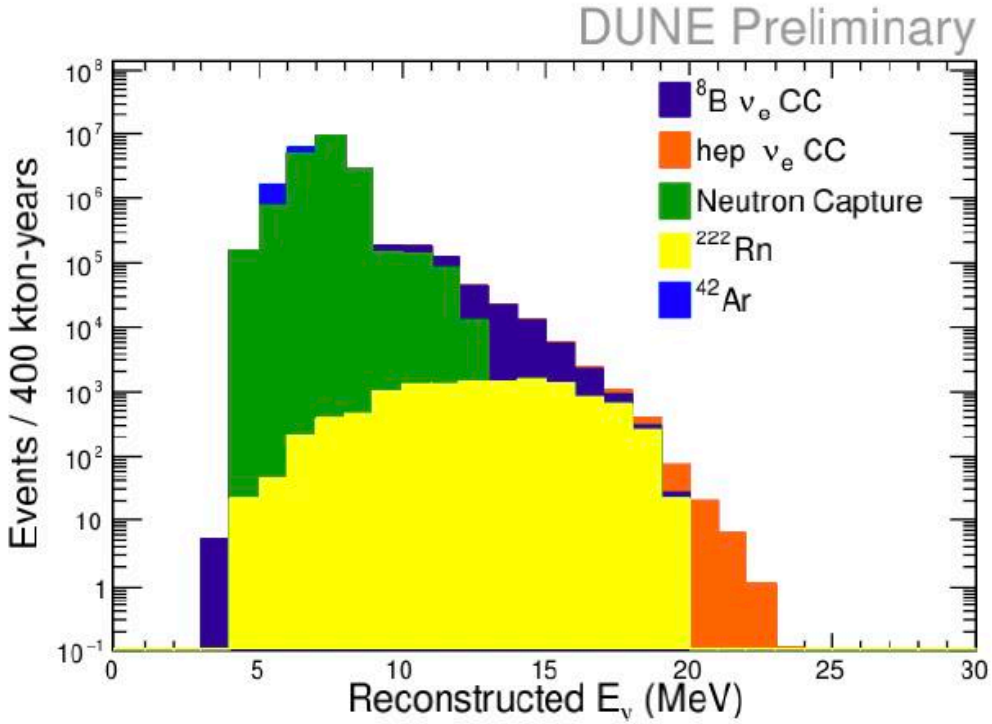
Expect more knowledge on metallicity problem

Prospects for solar neutrino

hep neutrino

Spectrum with/without hep neutrino in HK 10 years (~2σ)





Expect the first detection

Summary of solar ν

- Solar neutrinos except for hep were detected. Recent results provided good accuracy of each solar neutrino flux.
- There is a tension in Δm^2_{21} between Solar and KamLand. It will be solved in the next generation detectors.
- CNO neutrino is important for metallicity problem.

Thank you for your attention!