Neutrino Mass Hierarchy

Chao Zhang

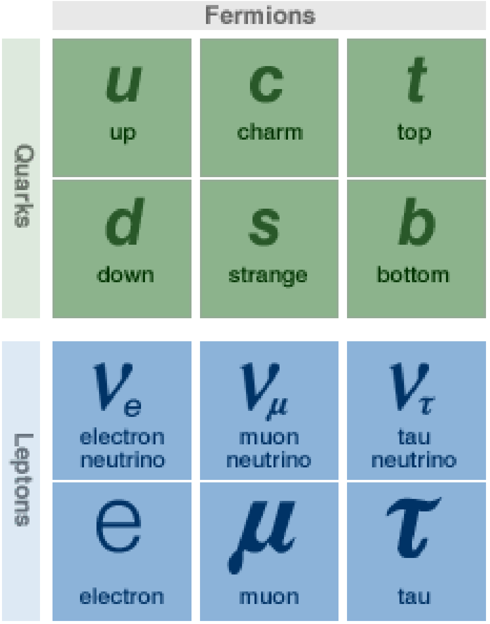
BROOKHAVEN
NATIONAL LABORATORY

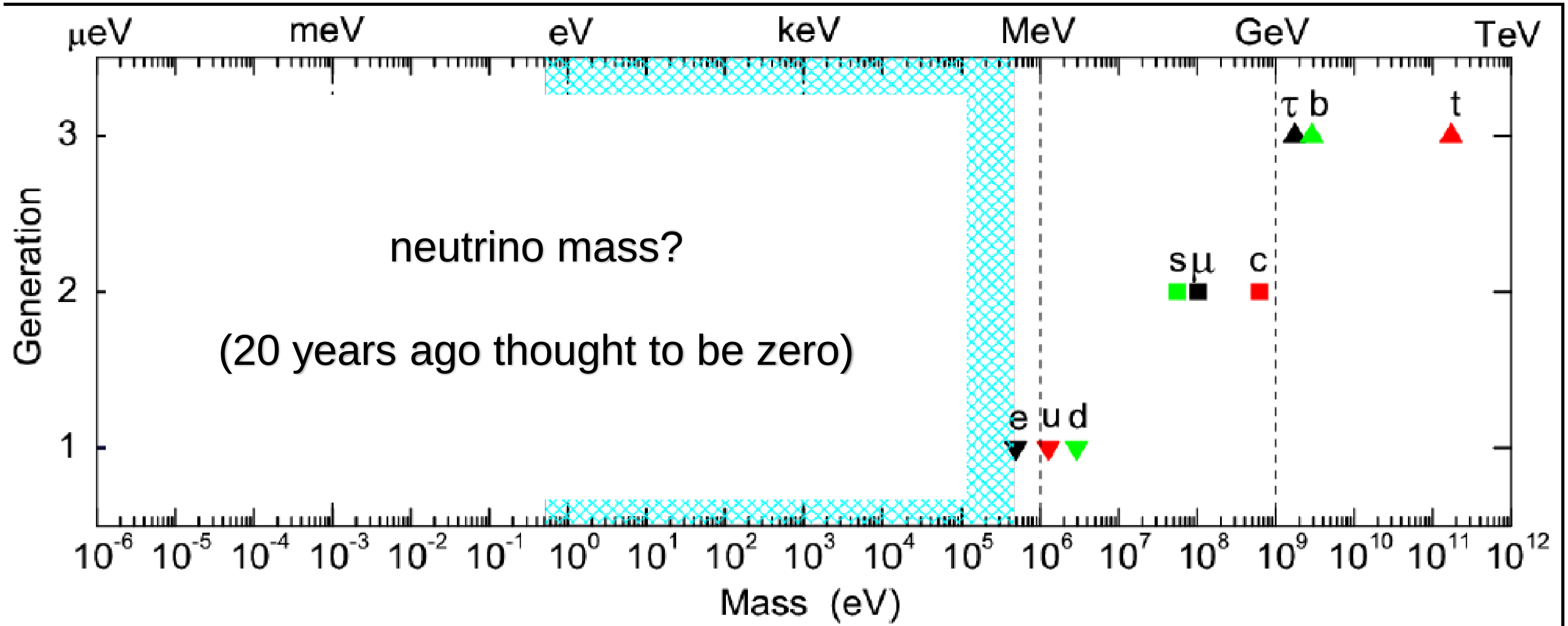
Outline

- What is “Neutrino Mass Hierarchy (MH)”?
    - Recently more popularly (and accurately) known as “Neutrino Mass Ordering (MO)”
- Various methods to determine MH
- Status of current and future experiments

- Disclaimer:
    - Selected overview of topics
    - Focus more on experimental particle physics

- Standard Model has three generations of fundamental matter particles (fermions)
- The quark and charged lepton mass show a hierarchical structure (Gen III > Gen II > Gen I)
- Does neutrino mass show the same hierarchy?

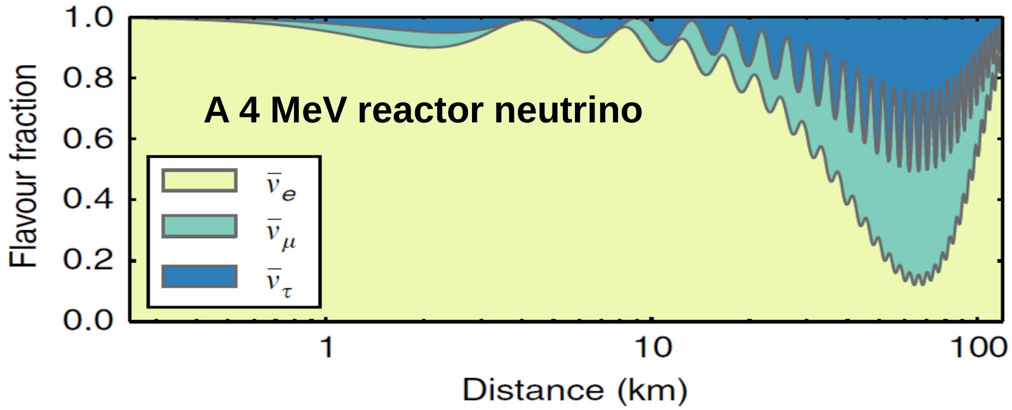




neutrino mass?

(20 years ago thought to be zero)

Discovery of Neutrino Oscillations



$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = U_{\mathrm{PMNS}}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

$$\begin{pmatrix}1 & 0 & 0\\ 0 & \cos\theta_{23} & \sin\theta_{23}\\ 0 & -\sin\theta_{23} & \cos\theta_{23}\end{pmatrix}\begin{pmatrix}\cos\theta_{13} & 0 & \sin\theta_{13}e^{-i\delta}\\ 0 & 1 & 0\\ -\sin\theta_{13}e^{i\delta} & 0 & \cos\theta_{13}\end{pmatrix}\begin{pmatrix}\cos\theta_{12} & \sin\theta_{12} & 0\\ -\sin\theta_{12} & \cos\theta_{12} & 0\\ 0 & 0 & 1\end{pmatrix}\begin{pmatrix}1 & 0 & 0\\ 0 & e^{-i\alpha_1/2} & 0\\ 0 & 0 & e^{-i\alpha_2/2}\end{pmatrix}$$

Atmospheric / Long baseline accelerator

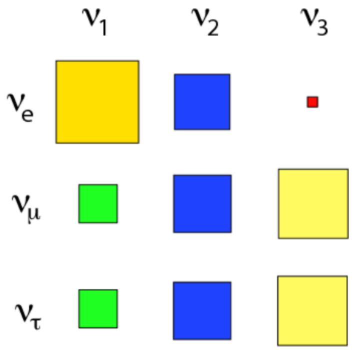
Short baseline reactor / Long baseline accelerator

Solar / Long baseline reactor

Neutrinoless double beta decay

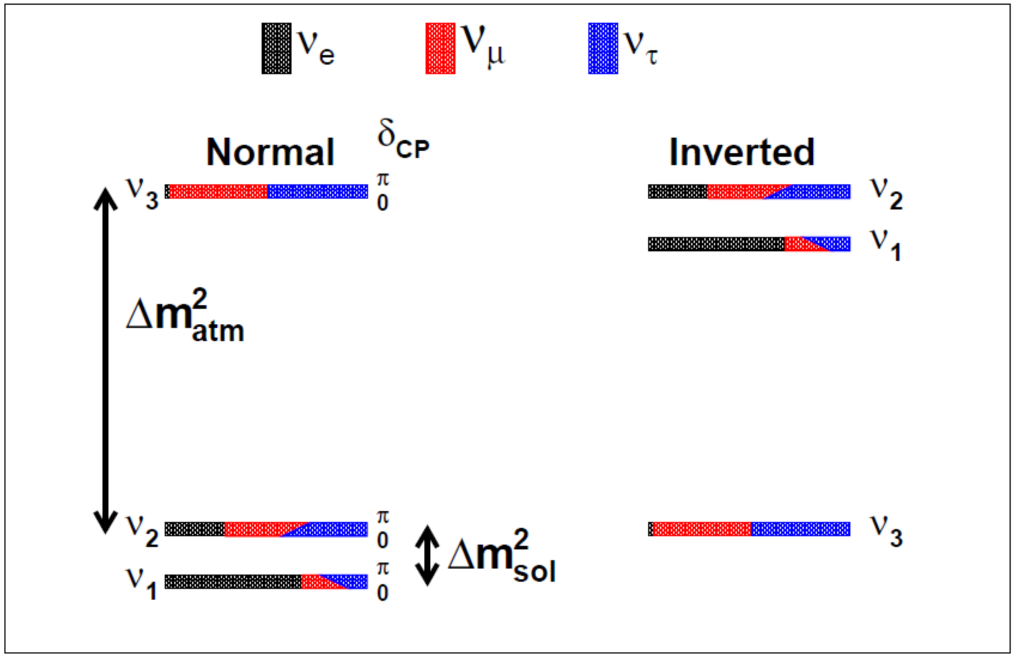
- Neutrino oscillation indicates:
  - Neutrinos have mass
  - Neutrino flavor eigenstates (ν_e, ν_μ, ν_τ) are mixtures of mass eigenstates (ν_1, ν_2, ν_3).
  - Neutrino mixing is large

$\theta_{12} \sim 33^{\circ}$
$\theta_{23} \sim 45^{\circ}$
$\theta_{13} \sim 9^{\circ}$



Neutrino mass: known and unknowns

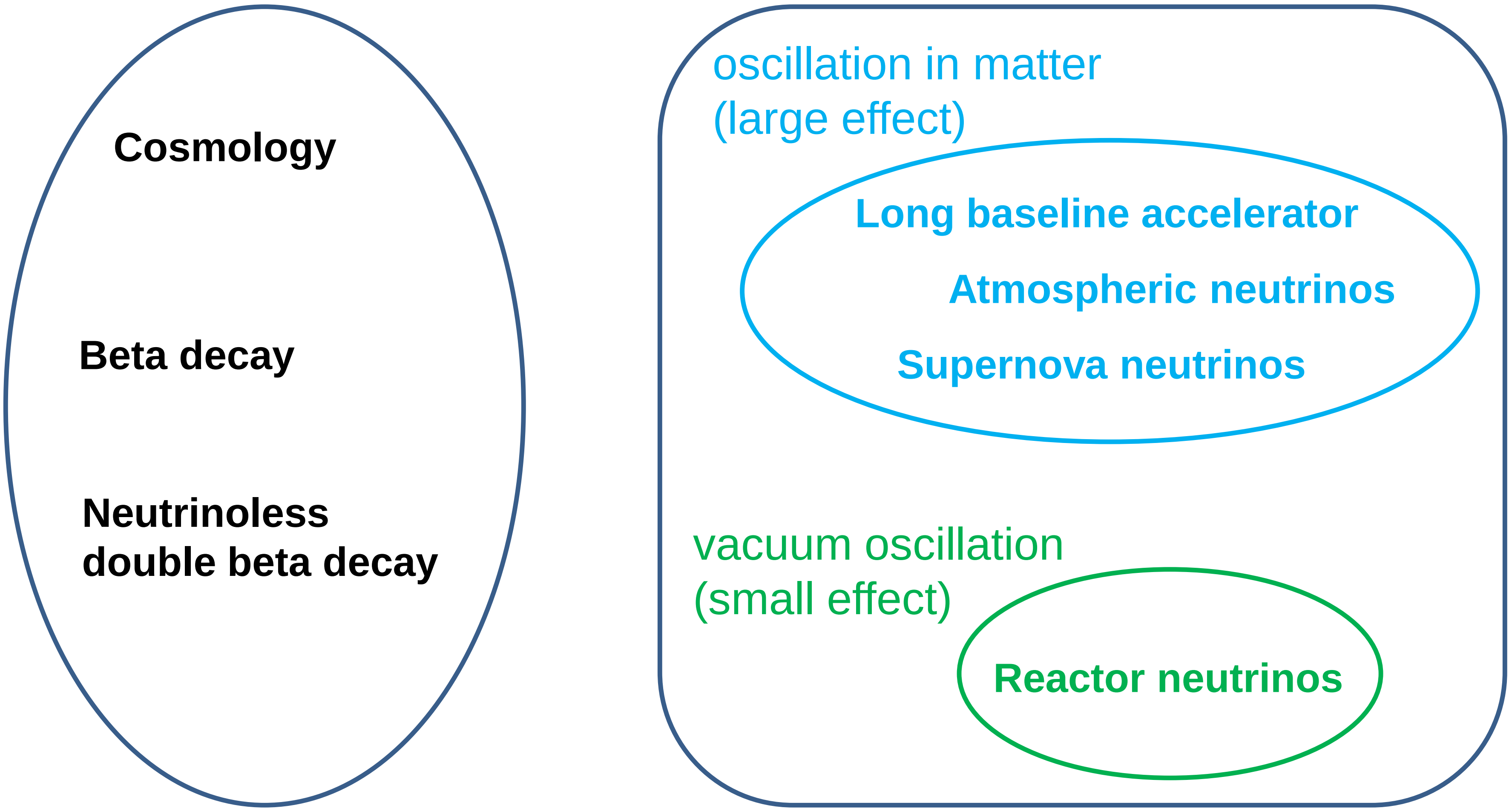
$$P(\nu_l \to \nu_{l'}) = \sin^2 2\theta \cdot \sin^2\left(1.27 \cdot \frac{\Delta m^2(\mathrm{eV}^2)\cdot L(\mathrm{m})}{E(\mathrm{MeV})}\right)$$



- We know the two mass-squared differences from neutrino oscillations:
  - $|\Delta m^2_{atm}| \sim 2.5 \times 10^{-3}$ eV^2
  - $\Delta m^2_{sol} \sim 7.5 \times 10^{-5}$ eV^2
- We don't know the sign of the Δm^2_{atm} since the leading order vacuum oscillation formula is only sensitive to $\sin^2(\Delta m^2)$
  - Normal Hierarchy (NH): $v_3 > v_2 > v_1$ (ν_e is lighter)
  - Inverted Hierarchy (IH): $v_2 > v_1 > v_3$ (ν_e is heavier)

We also don't know the absolute neutrino mass, δ_{CP}, or if neutrino is its own anti-particle

Methods Sensitive to Neutrino MH



Measure neutrino mass

Cosmology

Beta decay

Neutrinoless double beta decay

Measure neutrino oscillation

oscillation in matter
(large effect)

Long baseline accelerator

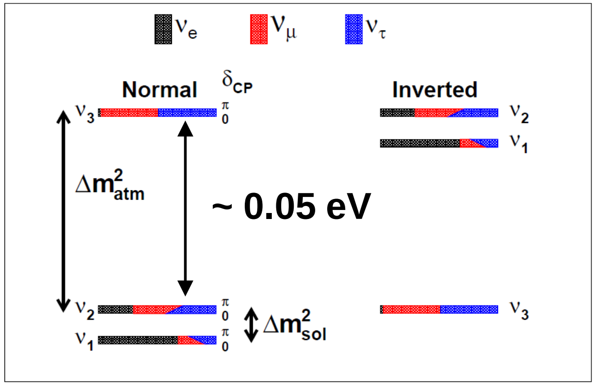
Atmospheric neutrinos

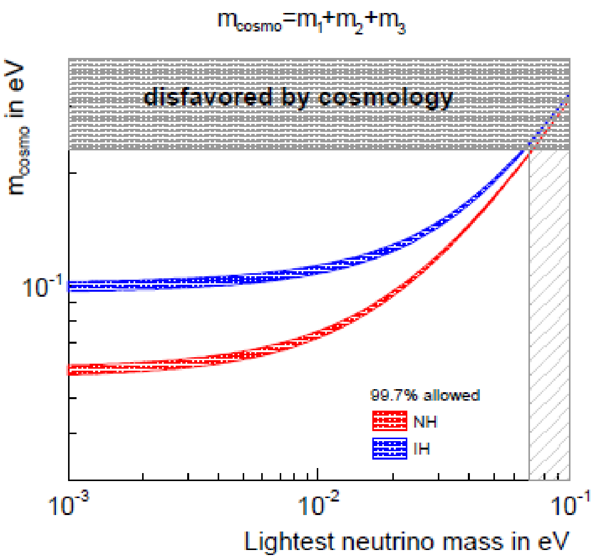
Supernova neutrinos

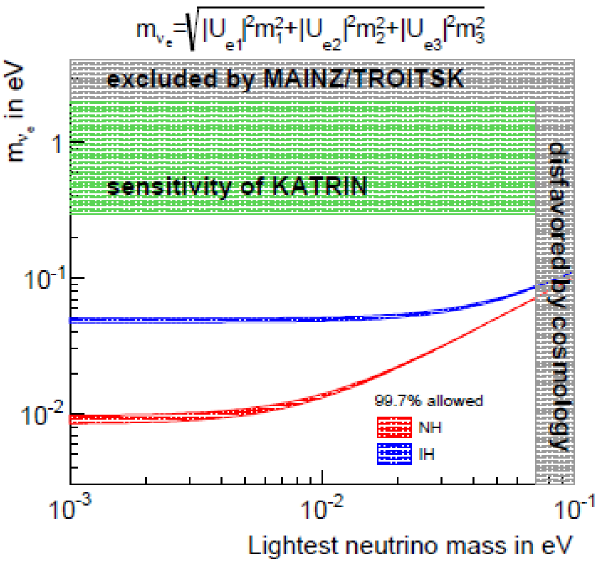
vacuum oscillation
(small effect)

Reactor neutrinos

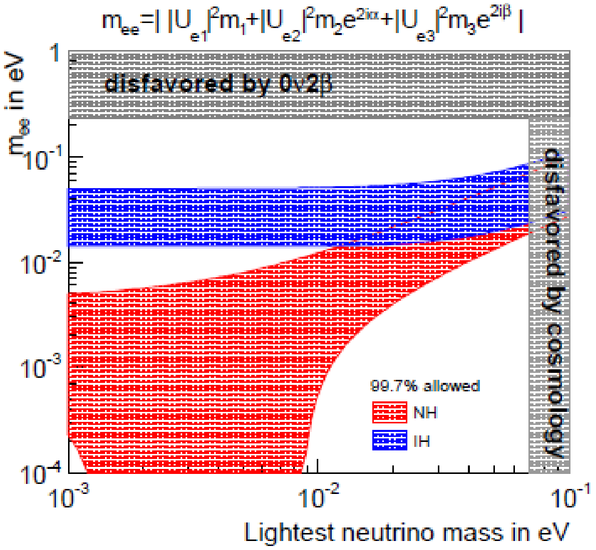
MH through neutrino mass







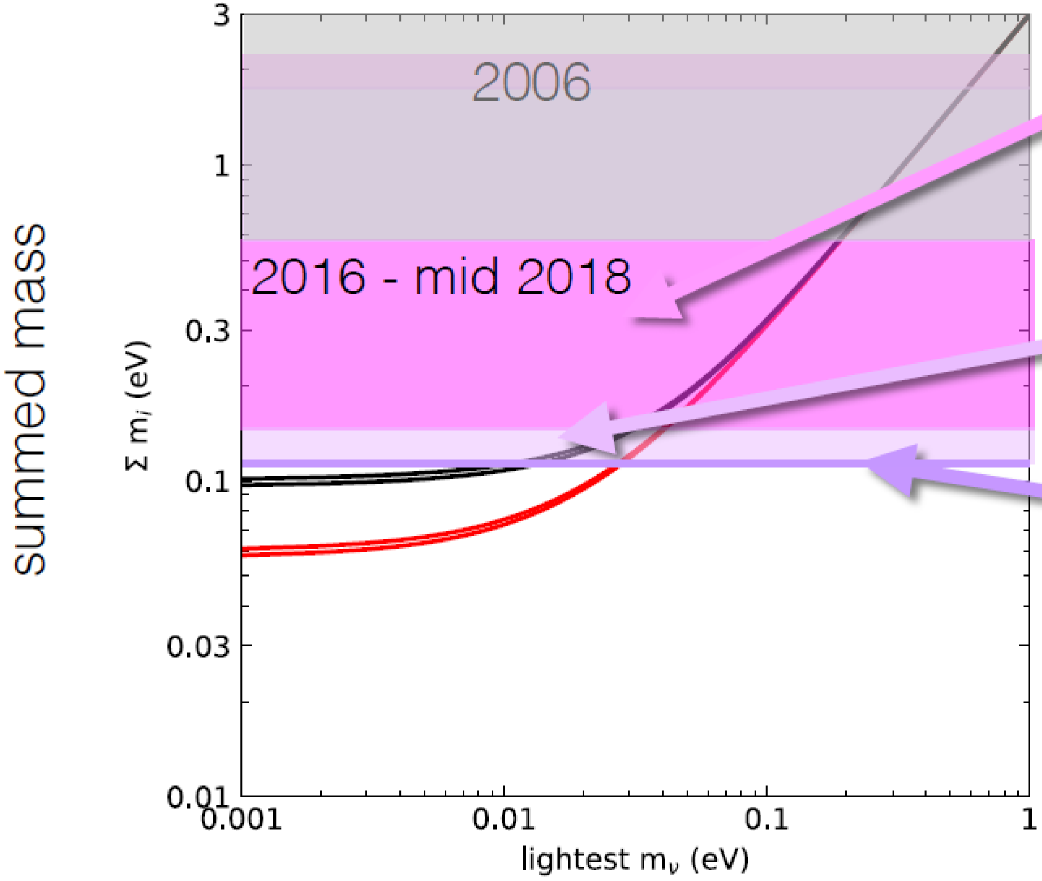
X. Qian and P. Vogel, Prog. Part. Nucl. Phys 83, 1 (2015).



- Cosmology, beta-decay, and double beta-decay experiments measure different combination of the total mass of neutrinos
- Sensitive to MH:
  - NH: at least one mass eigenstate ~0.05 eV
  - IH: at least two mass eigenstates ~0.05 eV
- MH could have large impact on the future neutrinoless double beta decay experiments

Cosmology is pushing the limit

95%CL upper bounds on $\Sigma_i m_i$ for 7 parameters



CMB only: Planck,
w/o high-l polarisation and lensing…
$\Sigma_i m_i < 590$ to 140 meV (95%CL)

CMB + conservative LSS :

- Planck 2016 {TT+SIMLow+lensing} + BAO: $\Sigma_i m_i <$ **170 meV** (95%CL)
- Planck 2016 {TTTEEE+SIMLow} + BAO: $\Sigma_i m_i <$ **120 meV** (95%CL)

- Planck 2015 + Lyman-α: $\Sigma_i m_i <$ **120 meV** (95%CL)

[Planck col.] 1605.02985; Cuesta et al. 2016;
Palanque-Delabrouille et al. 1506.05976;
Vagnozzi et al. 1701.08172;
PDG "Neutrino Cosmology" [JL & Verde]

… harder to avoid bounds with simple cosmological model extensions

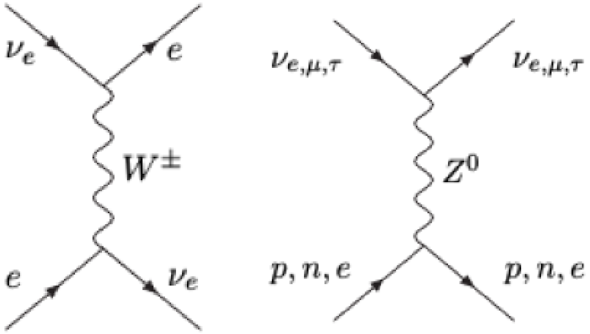
harder to avoid bounds with simple cosmological model extensions

Julien Lesgourgues, Neutrino 2018

MH through neutrino oscillation (I)

$V_C = \sqrt{2} G_F N_e$

- Beyond vacuum oscillation: matter effect (MSW effect)
  - Neutrino forward scatter with electron when travelling in matter, gaining an additional effective potential ±V_C (minus for antineutrino), causing a phase shift in oscillation that is dependent on MH
  - Neutral current scattering doesn't contribute (same phase shift for ν_e, ν_μ, ν_τ)
- Usually exploited by measuring ν_μ ($\bar{\nu}_\mu$) to ν_e ($\bar{\nu}_e$) appearance probability



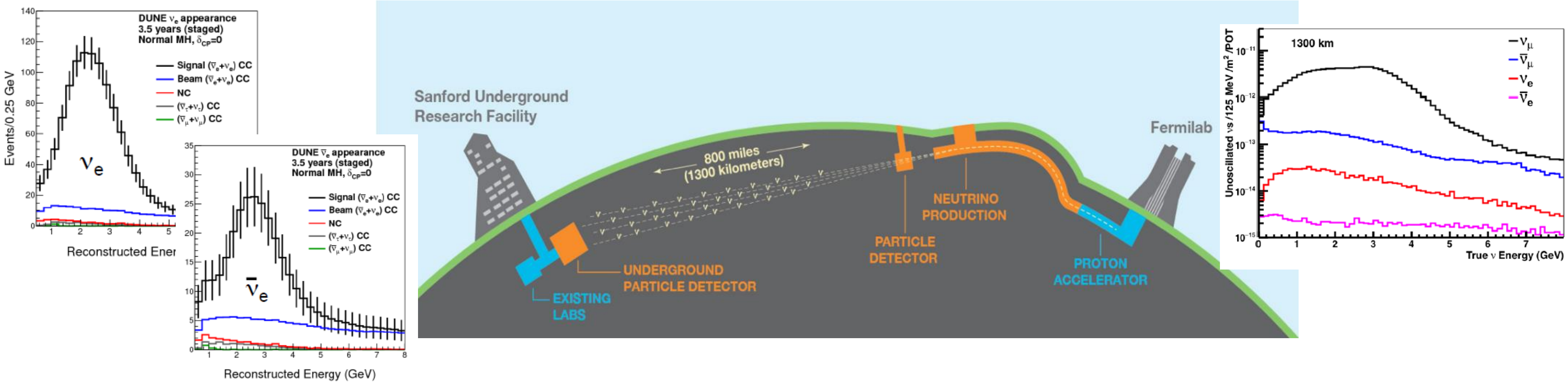
$$P(\nu_\mu \to \nu_e) \approx \sin^2\theta_{23}\sin^2 2\theta_{13}\frac{\sin^2[\Delta(1-x)]}{(1-x)^2} + \alpha J\cos(\Delta \pm \delta)\frac{\sin(\Delta x)\sin[\Delta(1-x)]}{x(1-x)} + \alpha^2\cos^2\theta_{23}\sin^2 2\theta_{12}\frac{\sin^2(\Delta x)}{x^2},$$

$$\Delta \equiv \Delta m^2_{32} L/(4E) \qquad x \equiv \pm 2\sqrt{2} G_F n_e E/\Delta m^2_{32}$$

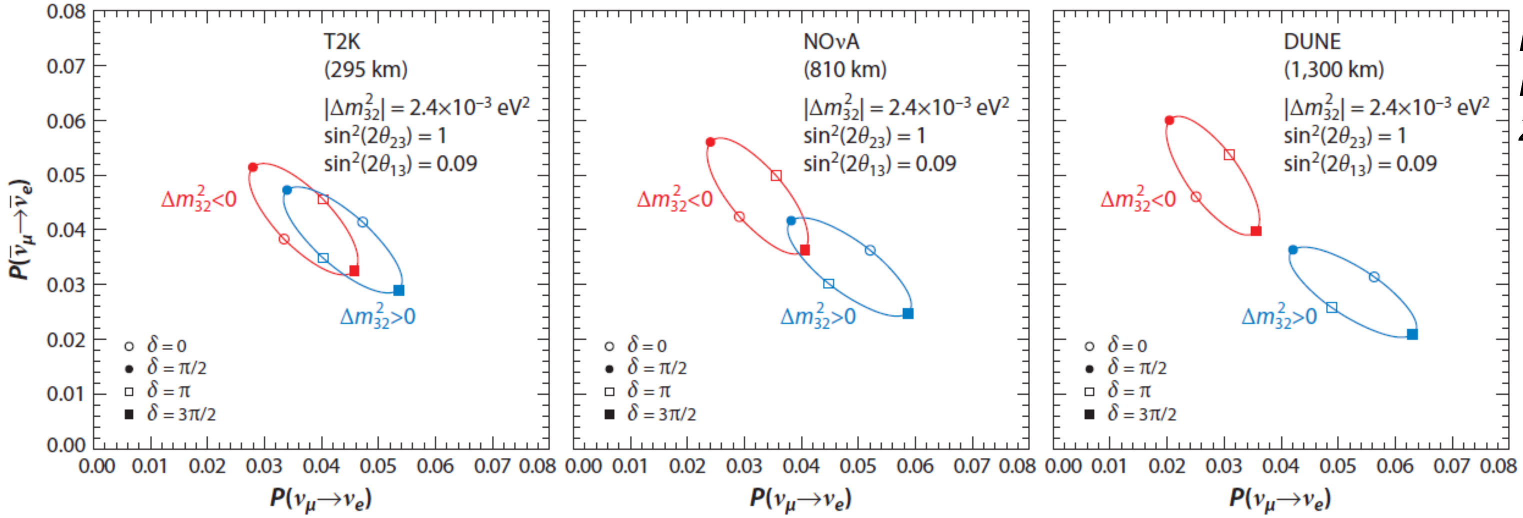
$$J \equiv \cos\theta_{13}\sin 2\theta_{13}\sin 2\theta_{12}\sin 2\theta_{23}$$

- (1-x) term carries the MH information through matter effect
- Effect is usually opposite for neutrino vs. antineutrino
- Effect is usually larger for higher energy and longer distance
- Effect is largely dependent on θ_{23} (due to octant ambiguity)
- Effect is coupled with size of CP phase

Long Baseline Accelerator Neutrinos



NH: enhance v, suppress anti-v IH: enhance anti-v, suppress v

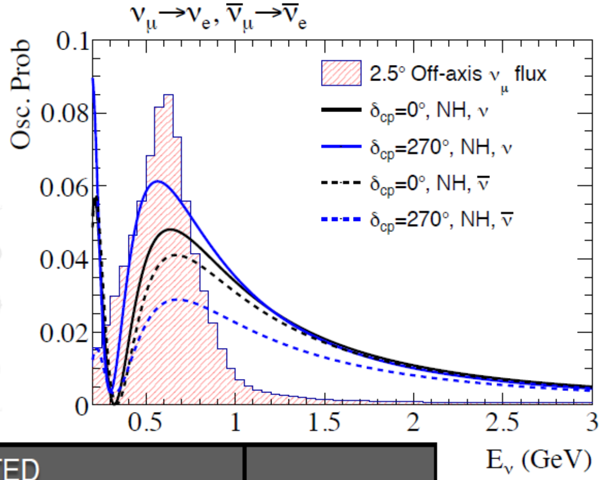


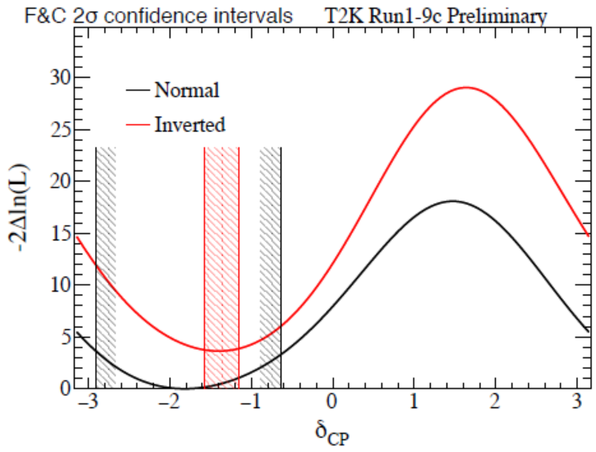
R.B. Patterson, Annu. Rev. Nucl. Part. Sci. 2015. 65:177

For illustration only: Also strong dependence on theta23, E, etc.

T2K

- Long-baseline neutrino experiment (295 km) in Japan from J-PARK (Tokai) to Super-Kamiokande
- Off axis beam peaked at ~600 MeV
  - ν: 1.5e21 POT
  - anti-ν: 1.1e21 POT
- Observed enhanced ν_e event rate
  - Best-fit: NH, -π/2
- Bayesian posterior favors NH:
  - NH:IH = 0.888: 0.112 ($\Delta\chi^2$~4, ~2σ)



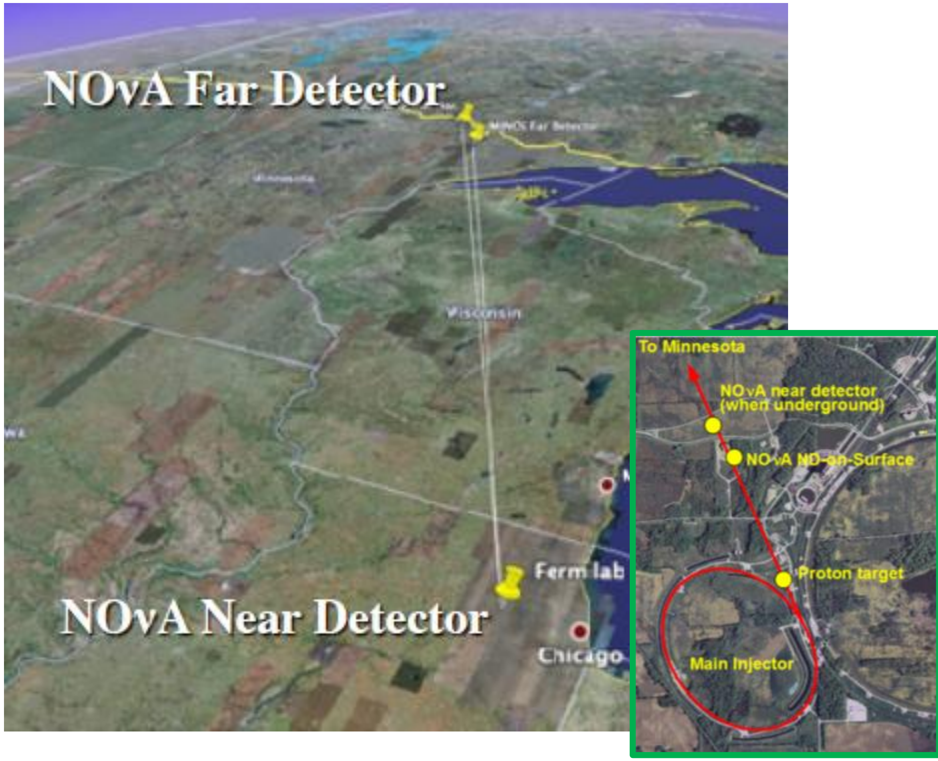


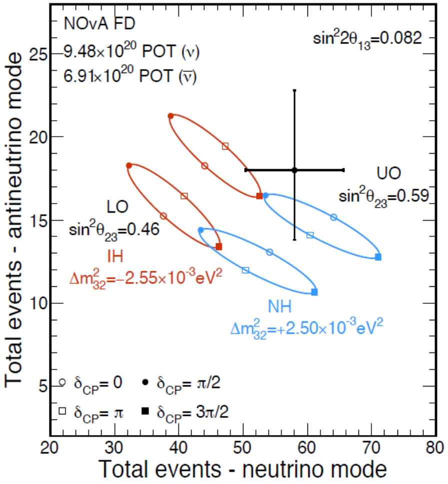
SAMPLE	PREDICTED				OBSERVED
	δ_{CP}=−π/2	δ_{CP}=0	δ_{CP}=+π/2	δ_{CP}=π	
FHC 1Re 0 decay-e	73.8	61.6	50.0	62.2	75

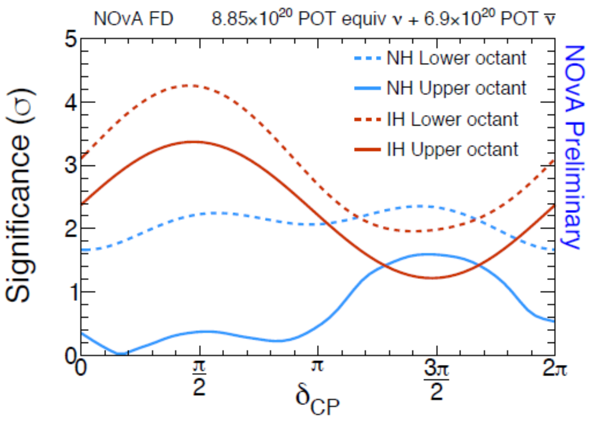
M. Wascko, Neutrino 2018

NOVA

- Long-baseline neutrino experiment (810 km) in US from Fermilab to Ash River (Minnesota)
    - 14 kton segmented liquid scintillator far detector
- Off-axis NUMI beam peaked at ~2 GeV
    - V: 9.5e20 POT
    - Anti-v: 6.9e20 POT
- Observed 58 ν_e in v-mode and 18 $\bar{\nu}_e$ in anti-v mode
    - Best fit: NH, 0.2π
- Feldman-Cousins approach: prefers NH by 1.8 σ

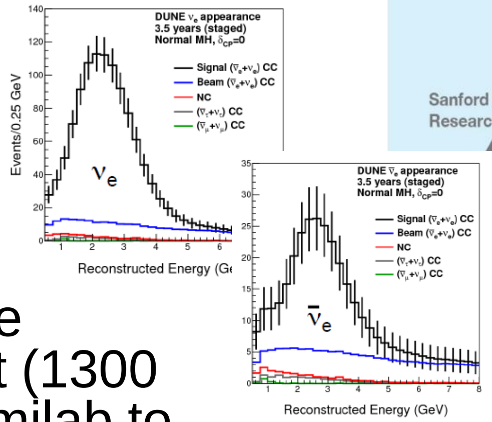


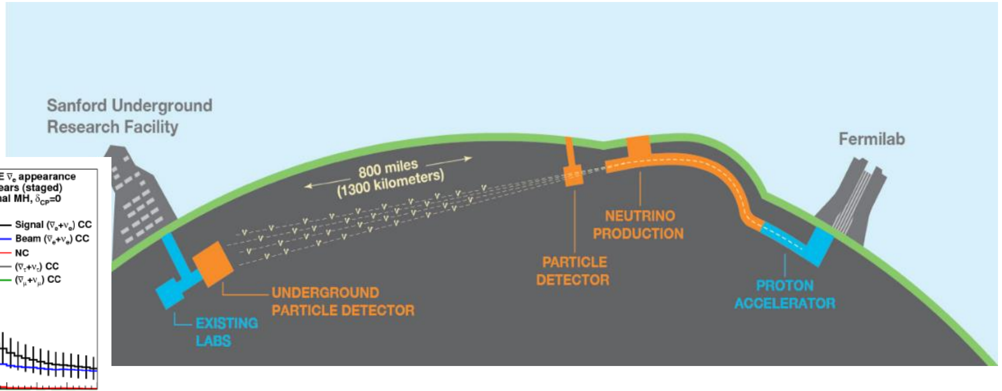




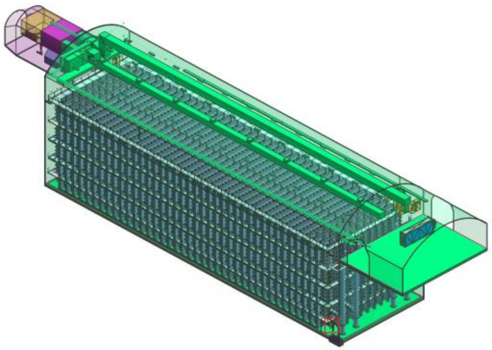
M. Sanchez, Neutrino 2018

DUNE



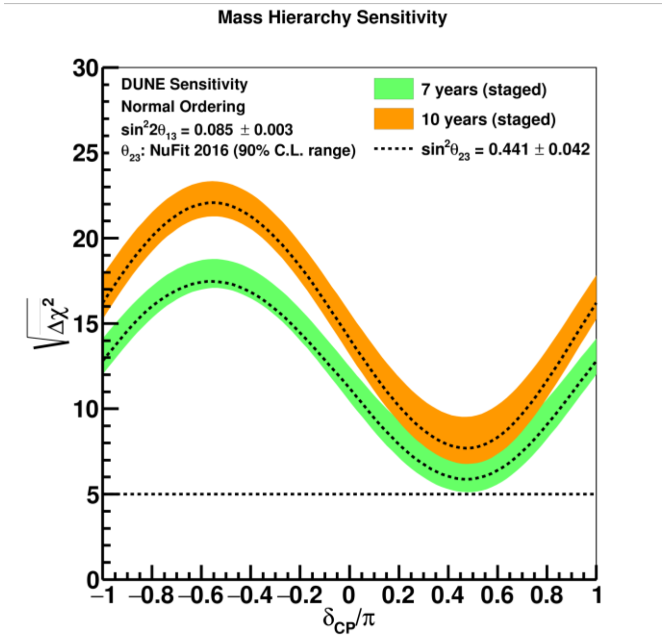


- Future long-baseline neutrino experiment (1300 km) in US from Fermilab to SURF (South Dakota)
  - Four 10 kton liquid argon TPC far detectors
- On-axis wide band beam
  - 1.2 MW upgradable to 2.4 MW
- 2022: installation begins 2026: neutrino beam available
- Order 1000 ν_e appearance events in ~7 years of equal running in neutrino and antineutrino mode
- More than 5σ sensitivity to MH for all possible CP phase and θ_{23} values in 7 years



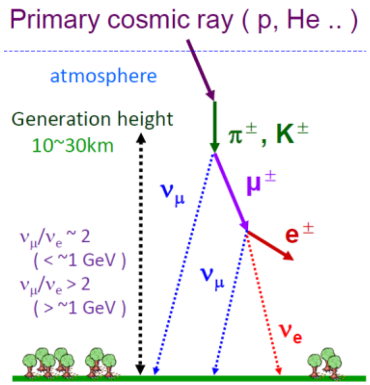
Single phase: 10 kt module

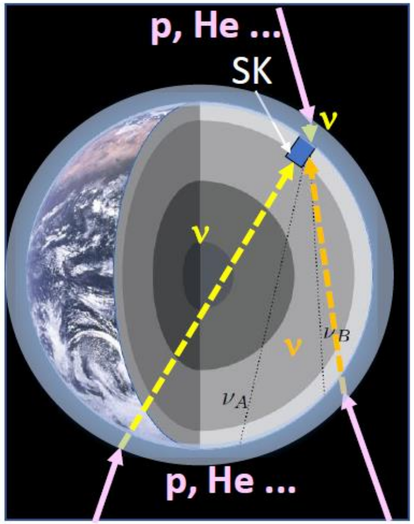
384,000 readout wires
150 “APAs” (2.3 m x 6 m)
12 m high
15.5 m wide
58 m long



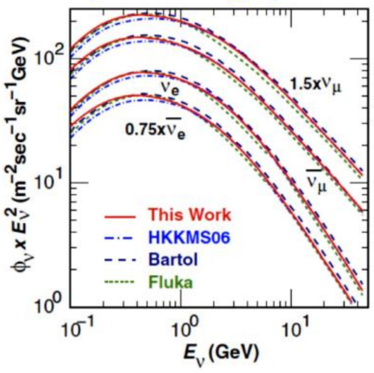
E. Worcester, Neutrino 2018

Atmospheric Neutrinos



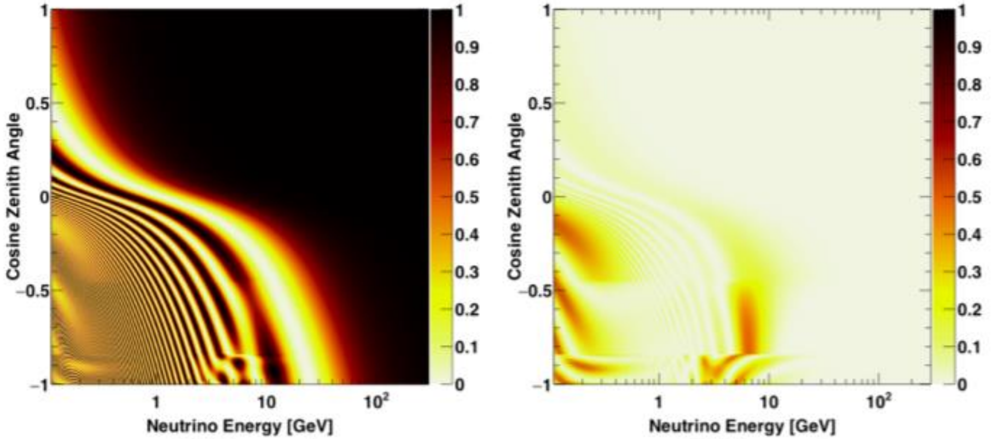


Atmospheric ν energy spectrum

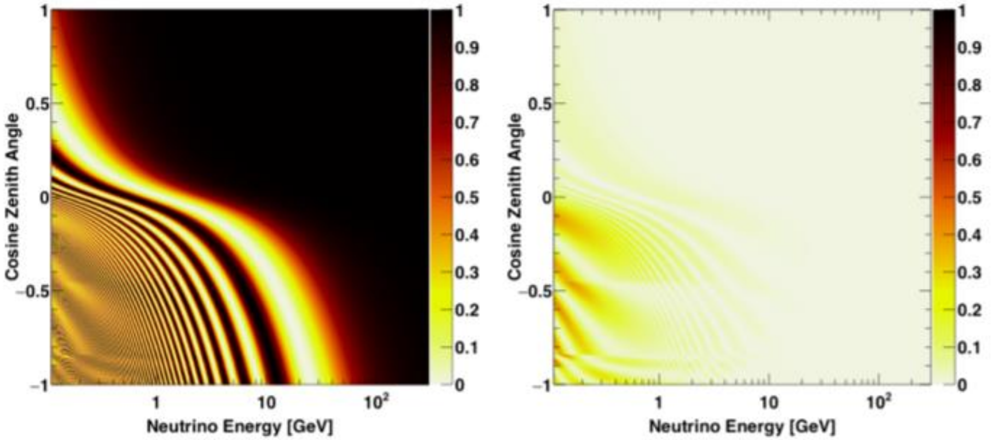


- Earth matter effect for upgoing atmospheric ν traveling in the mantle or core
- Energy and zenith angle dependent oscillation probabilities
- Matter effect features in both ν_μ disappearance and ν_e appearance
- NH: Resonance features in ν
  IH: Resonance features in anti-ν

Normal Hierarchy



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

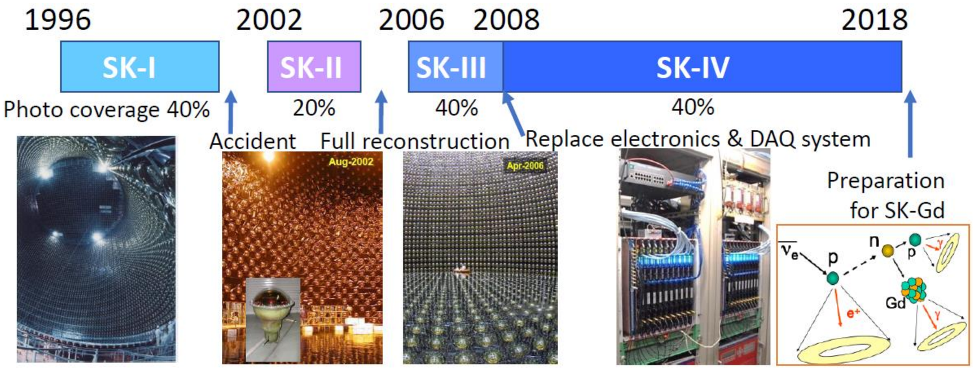


(c) $P(\bar{\nu}_\mu \to \bar{\nu}_\mu)$ (d) $P(\bar{\nu}_\mu \to \bar{\nu}_e)$

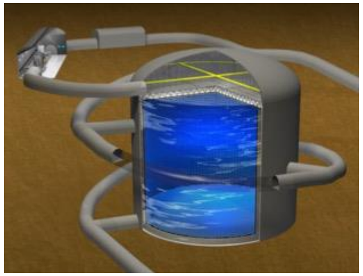
For IH the resonance features appear in anti-ν

Super-K, PRD 97, 072001 (2018)

Super-K, Hyper-K

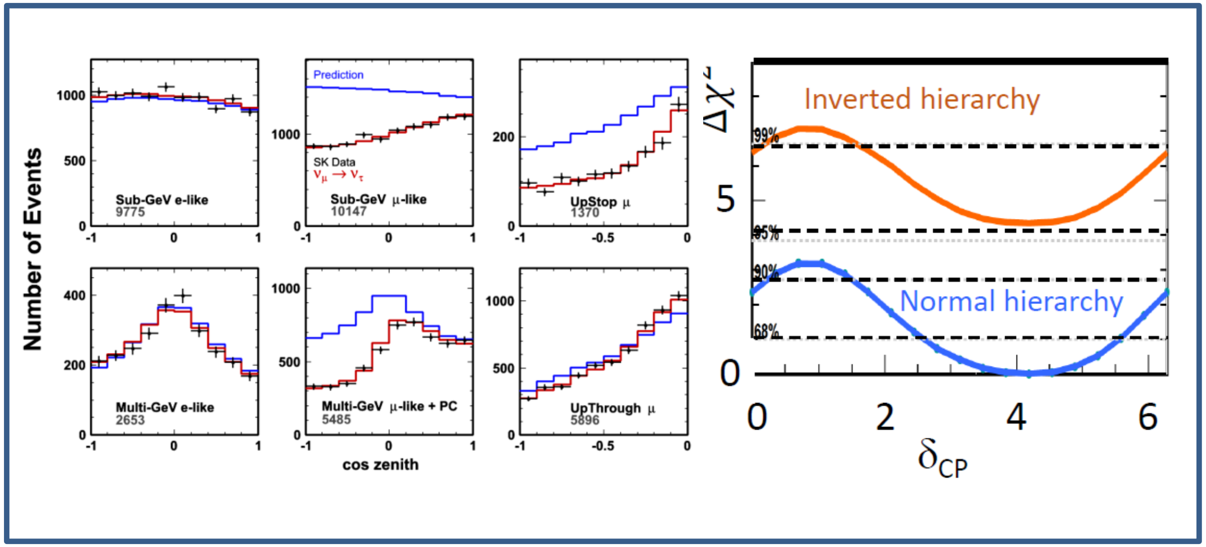


- ❑ Super-K operating since 1996
  - 20 kt fiducial water Cerenkov detector
  - 4-generation upgrades
- ❑ Rich atmospheric ν samples
  - 19 samples in final analysis
- ❑ Prefers NH by ~2σ

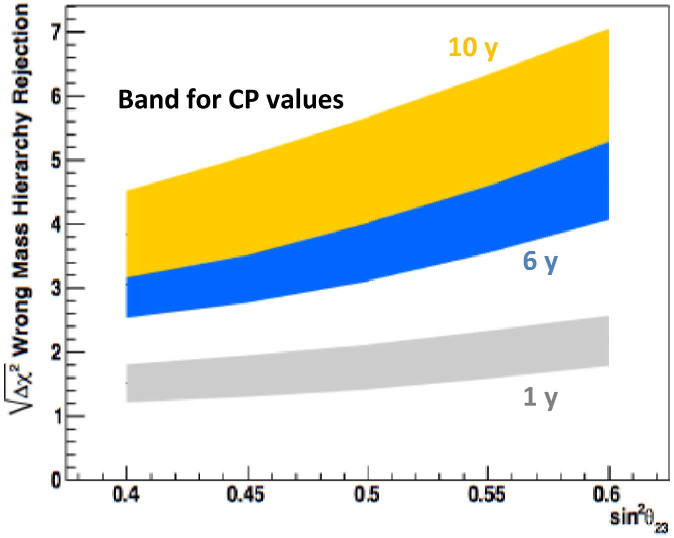


Hyper-K: 186 kton fiducial mass (~10 x Super-K)
Aiming to start construction in FY2019
Operation in FY2026

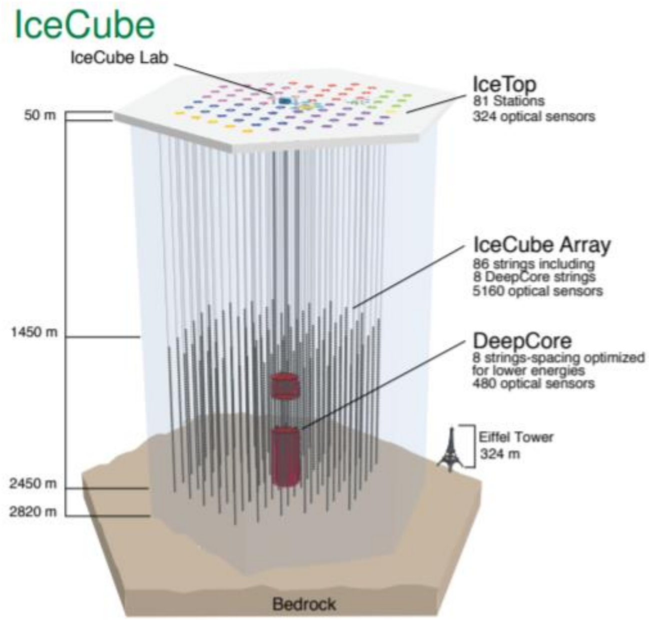
Super-K, PRD 97, 072001 (2018)

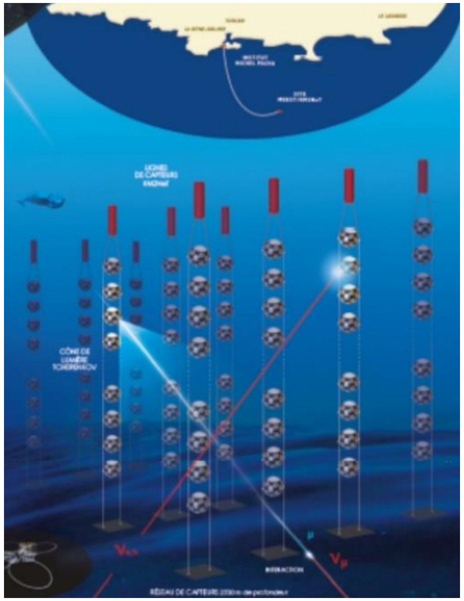


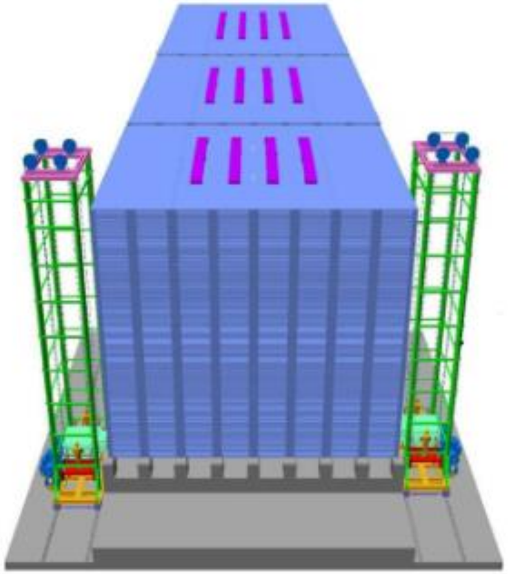
Hyper-K MH sensitivity

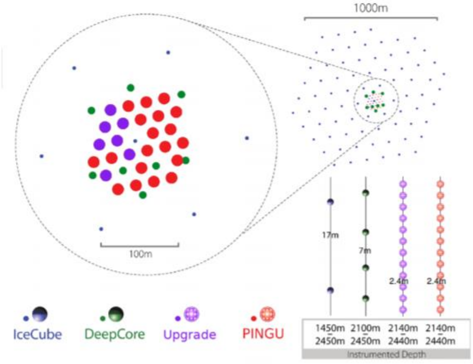


PINGU, KM3NeT / ORCA, INO





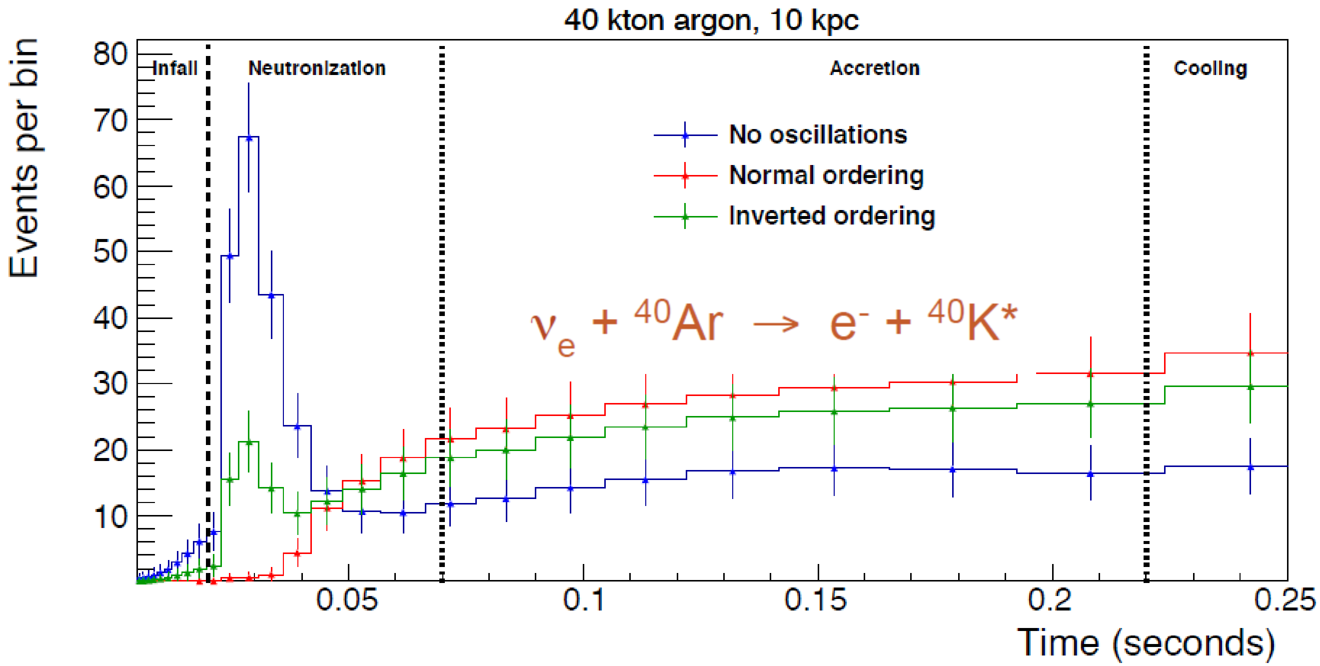




- PINGU will be a low-energy extension (~ a few GeV) of IceCube at the South Pole with high-density arrays of optical modules. ORCA is a similar project in the Mediterranean sea. Both have multi mega-ton mass (ice or water) instrumented.
- INO will be a 50 kton magnetized Iron calorimeter (ICAL) with RPC as the active detector in Southern India
  - Able to identify neutrinos vs. antineutrinos from curvature
- Aiming for 3-5σ sensitivity to MH in 3-5 years (dependent on θ_{23}) with atmospheric neutrinos

Supernova Neutrinos

- ❑ Supernova neutrino oscillation is also sensitive to MH through matter effect
  - Neutronization phase: MSW effect, ν_e strongly suppressed in NH
  - Accretion phase: collective effect (self-interaction), rich time-dependent spectral features
- ❑ Many detectors in the world, sensitive to different flavors



DUNE (LArTPC): ν_e

Hyper-K (Water): $\bar{\nu}_e$

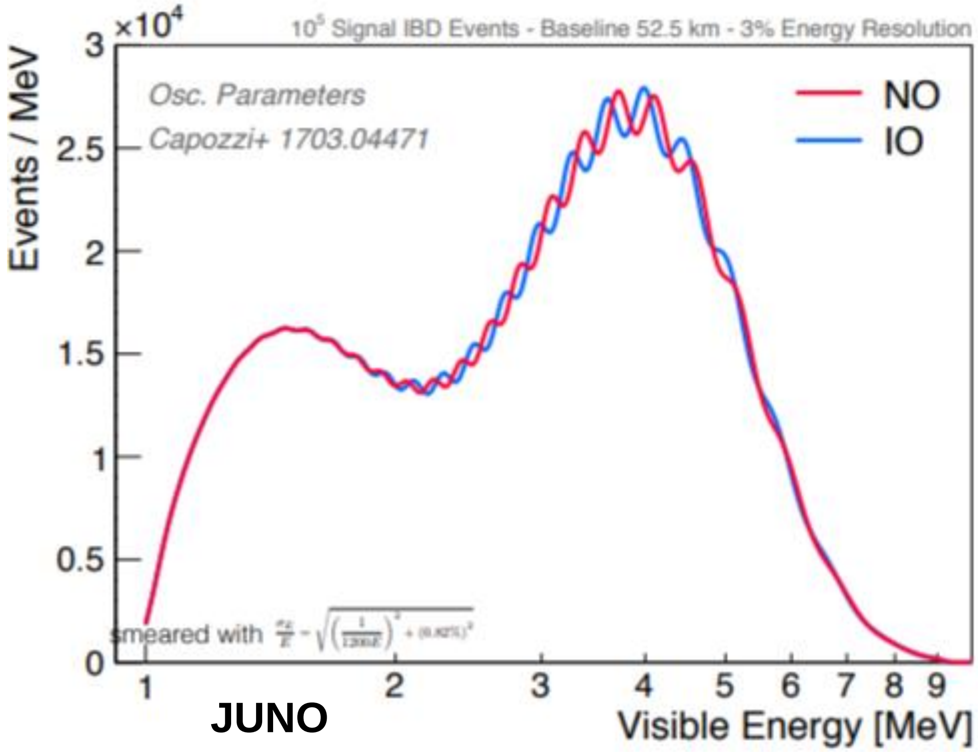
JUNO (LS): $\bar{\nu}_e$, ν_x

MH through neutrino oscillation (II)

- Precision vacuum oscillation measurement
  - Usually exploited through $\bar{\nu}_e$ disappearance using reactor neutrinos

$$\Delta_{ij} \equiv \Delta m^2_{ij} L/4E$$

$$P_{\bar{\nu}_e \to \bar{\nu}_e} = 1 - \sin^2 2\theta_{13} (\cos^2 \theta_{12} \sin^2 \Delta_{31} + \sin^2 \theta_{12} \sin^2 \Delta_{32}) - \cos^4 \theta_{13} \sin^2 2\theta_{12} \sin^2 \Delta_{21}$$

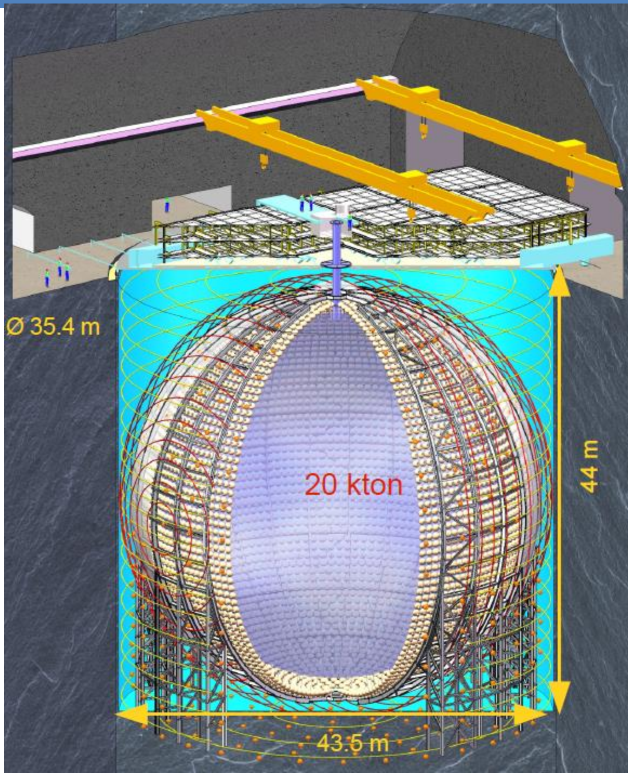


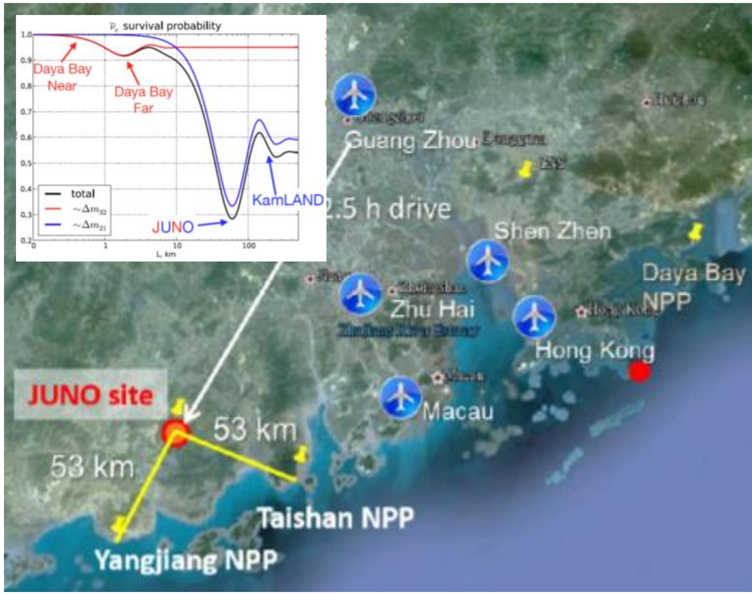
JUNO

- Simple Formula
  - No CP dependence
  - No θ_{23} dependence
- Small MH dependence
  - Interference of two slightly different oscillation frequencies
  - Need large statistics and excellent control of systematics -> precision reactor experiments

JUNO

- Reactor neutrino experiment in China
  - Optimized baseline at 53 km from two large Nuclear Power Plants (36 GW_{th} total)
  - 20 kt liquid scintillator detector
- Expect ~60 reactor ν/day, ~4 bkg/day
- Key detector features
  - ~3% energy resolution (~80% photo-coverage)
  - <1% energy scale calibration
- Expect data taking 2021
- >3σ sigma sensitivity to MH in 6 years.
  - Can reach >4σ with 1% constraint on $\Delta m^2_{\mu\mu}$ from future accelerator experiments



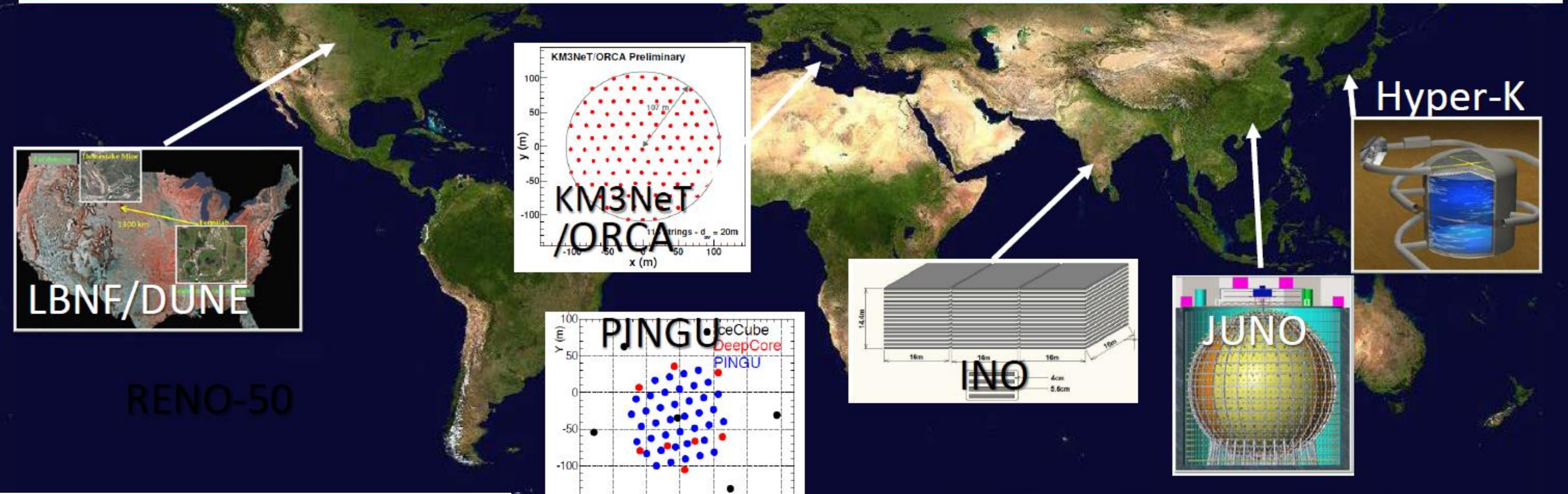


Summary

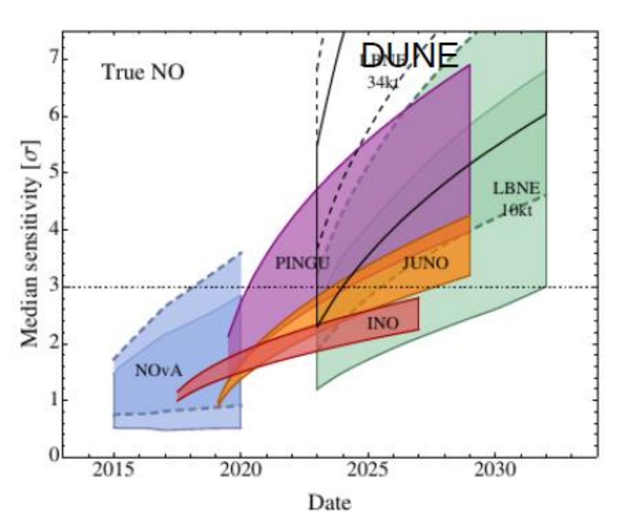
- Neutrino Mass Hierarchy is still a fundamental property that we don’t know
- Currently, there is ~2σ preference for Normal Hierarchy from individual experiment: T2K, NOVA, Super-K (combined with reactor θ_{13} measurement)
  - Global analysis can push to ~3σ hints for NH
- Next generation experiments aim to have >3σ sensitivity to MH in a single experiment (2025-2030)
  - Complementary technologies (long baseline accelerator, atmospheric neutrinos, reactor neutrinos)
- In addition to particle physics, cosmology and supernova neutrinos provide alternative opportunities to determine neutrino MH

Future experiments that will tell us the neutrino masses hierarchy

We would like to be convinced the neutrino mass ordering by consistent results from several different technologies/methods with > 3 σ CL from each exp.



Takaaki Kajita, Neutrino 2018



Blennow et al.
JHEP 03 028 (2014)

For illustration
assumptions in systematics and dates

Stay tuned!