Neutrino

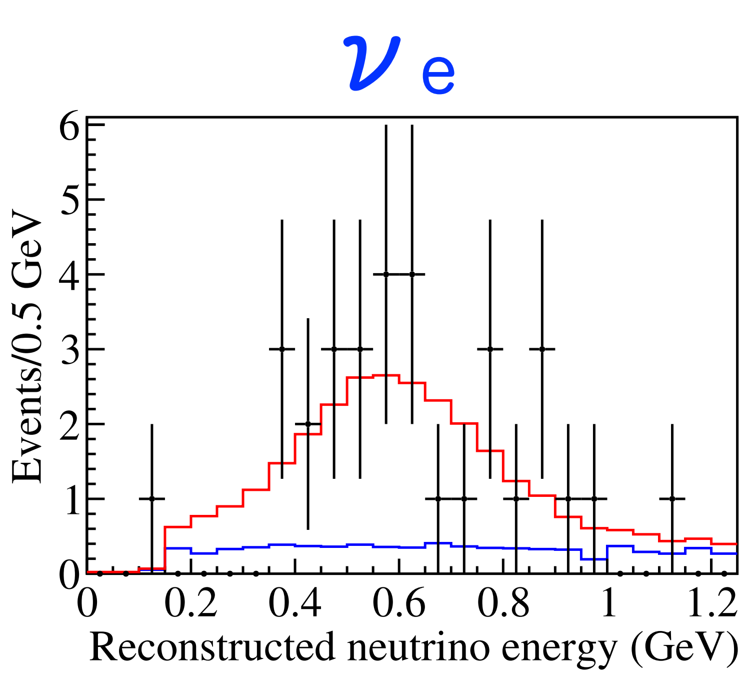
Experimental approaches and Asian experiments

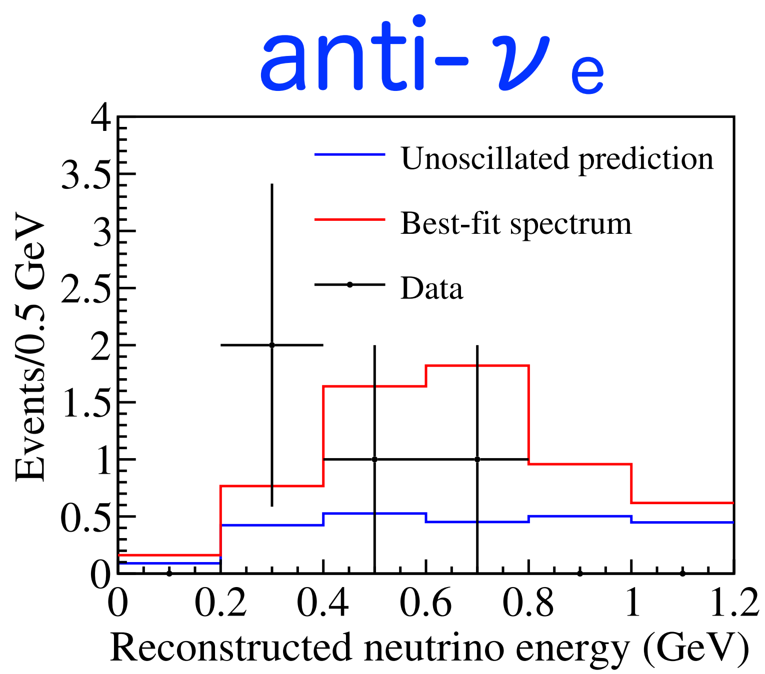
- Accelerator neutrino:
  T2K, T2K-II, T2HK (Japan), T2HKK (+Korea)
- Reactor neutrino:
  RENO (Korea), Daya Bay, JUNO (China)
- Atmospheric neutrino:
  Super-K, SK-Gd, Hyper-K (Japan), INO (India)
- Not covered here: Astro. ν (Solar, SN, ...), KamLAND

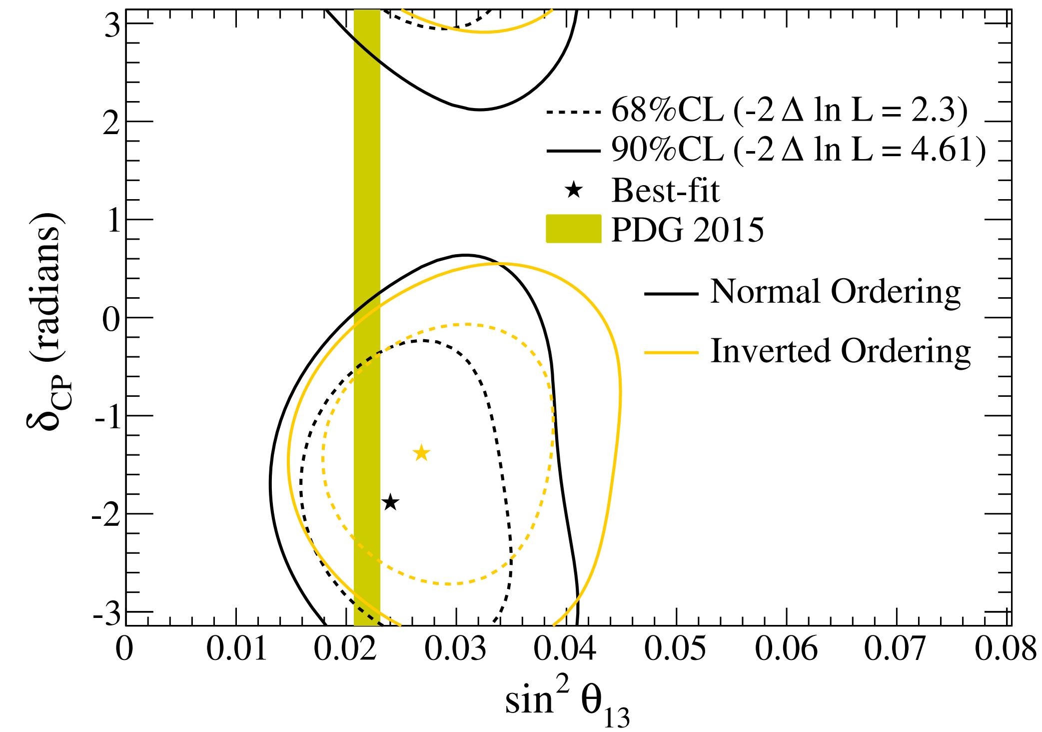
Kuze

T2K results on δ CP

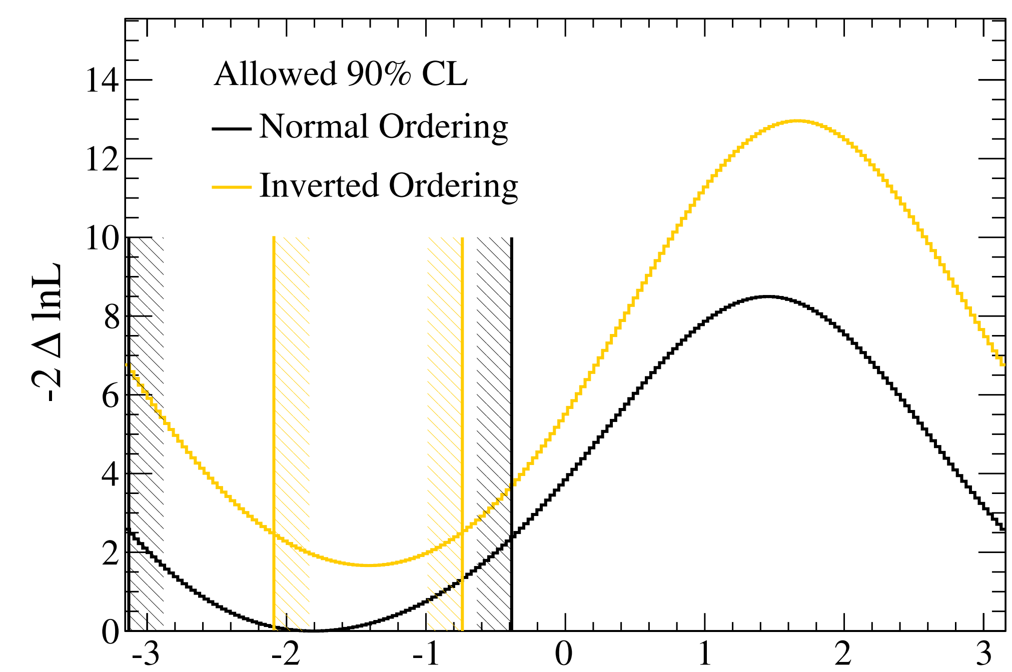
- Compare $\nu_\mu \rightarrow \nu_e$ appearance between ν and anti-ν
- Using reactor θ_{13} constraint,
  δ=0 or π excluded at 90% C.L.







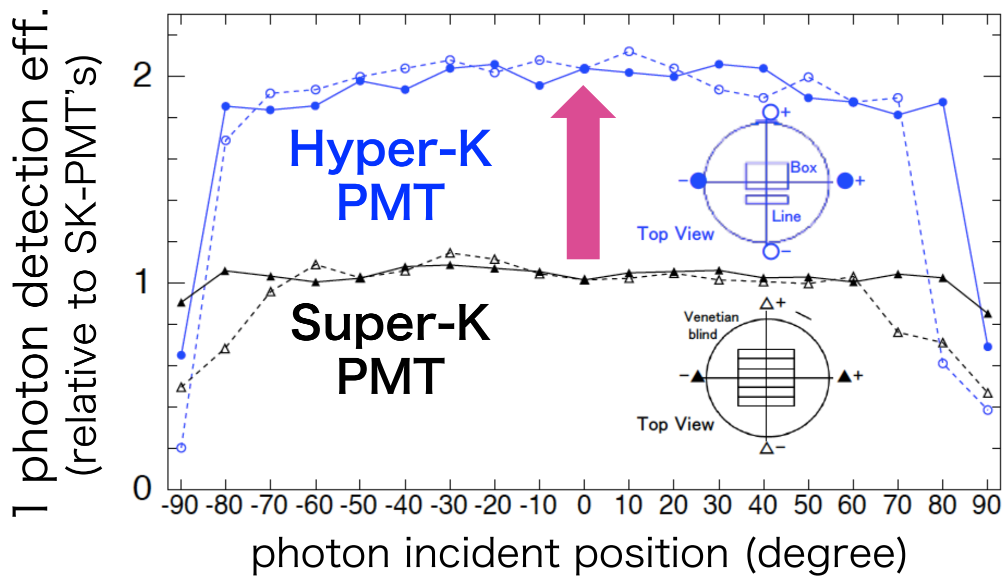
PRL118, 151801 (2017)

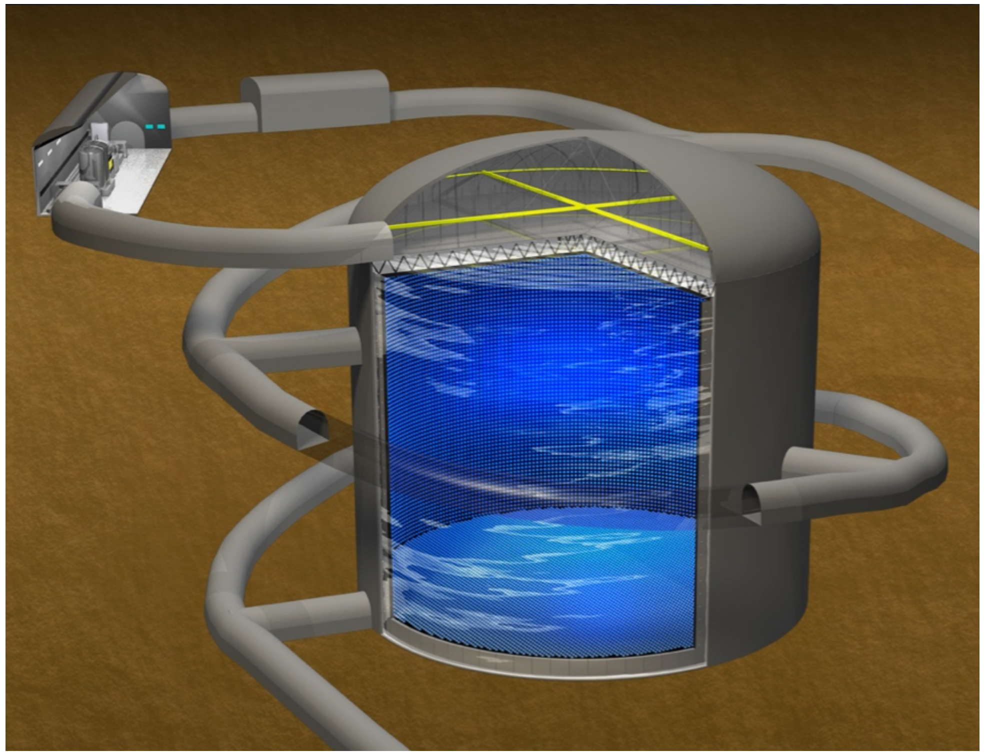


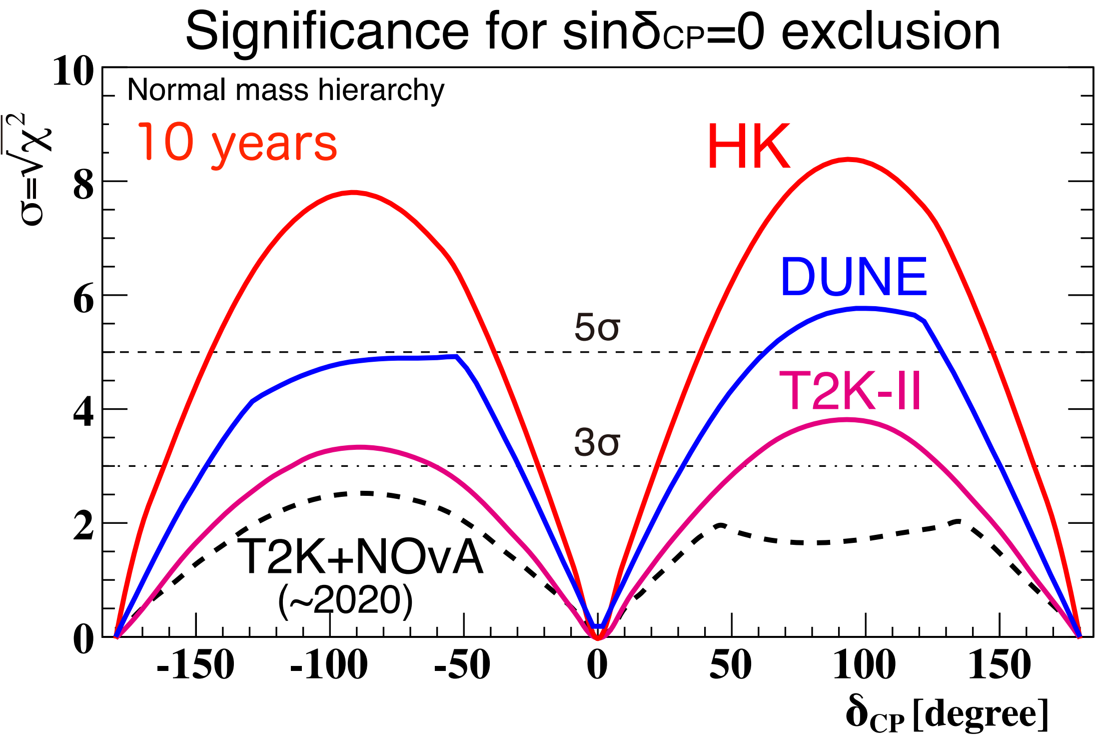
Normal	$\delta_{CP} = -\pi/2$	$\delta_{CP} = 0$	$\delta_{CP} = \pi/2$	$\delta_{CP} = \pi$	Observed
ν_e	28.7	24.2	19.6	24.1	32
$\bar{\nu}_e$	6.0	6.9	7.7	6.8	4
Inverted	$\delta_{CP} = -\pi/2$	$\delta_{CP} = 0$	$\delta_{CP} = \pi/2$	$\delta_{CP} = \pi$	Observed
ν_e	25.4	21.3	17.1	21.3	32
$\bar{\nu}_e$	6.5	7.4	8.4	7.4	4

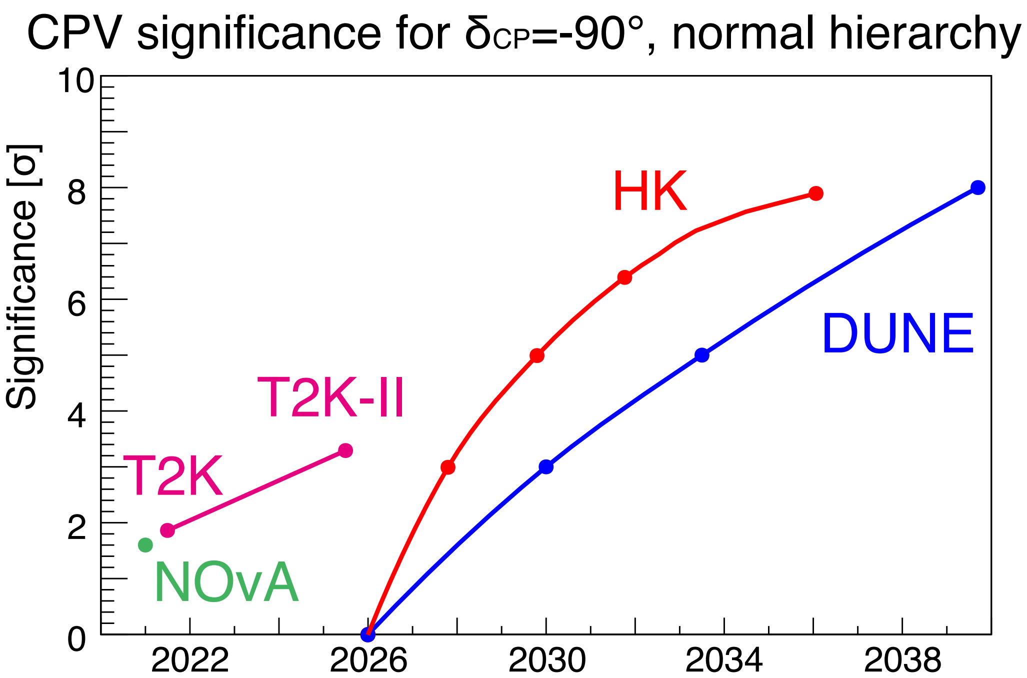
Hyper-Kamiokande

- 260kton tank (D74m×H60m)
- 190kton fiducial mass (~×10 of Super-K)
- 40,000 PMTs with 2x eff.
- >5σ discovery in wide δ_{CP} range





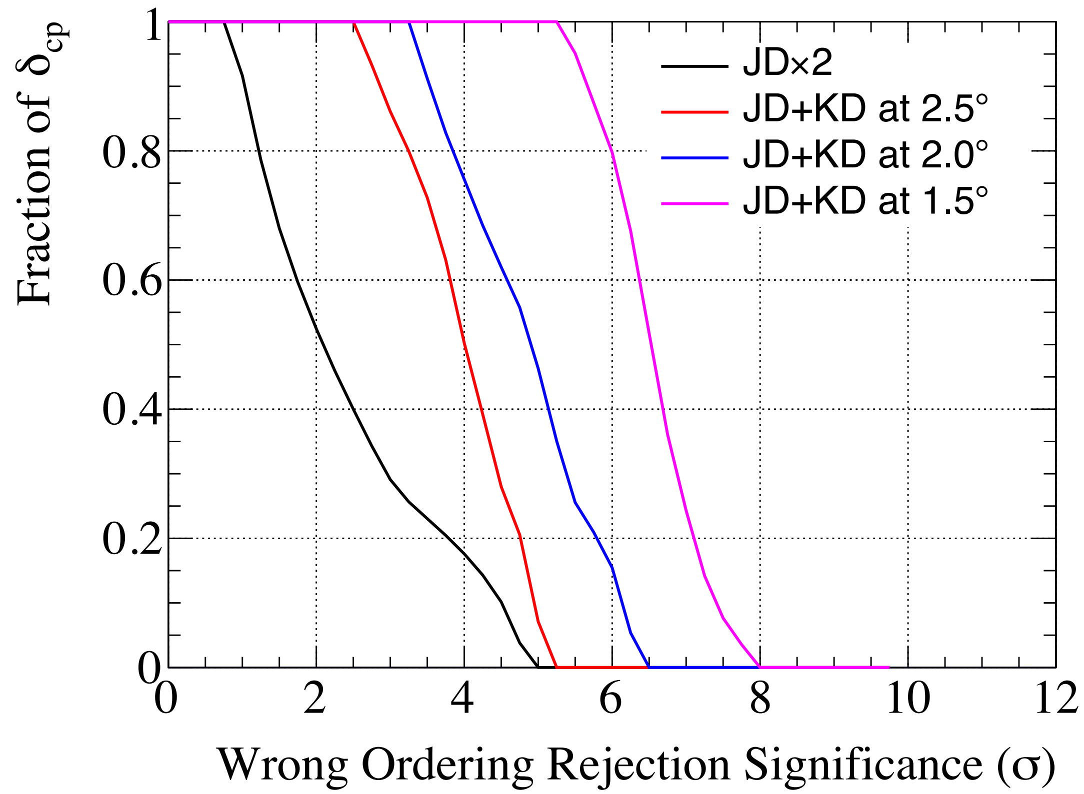




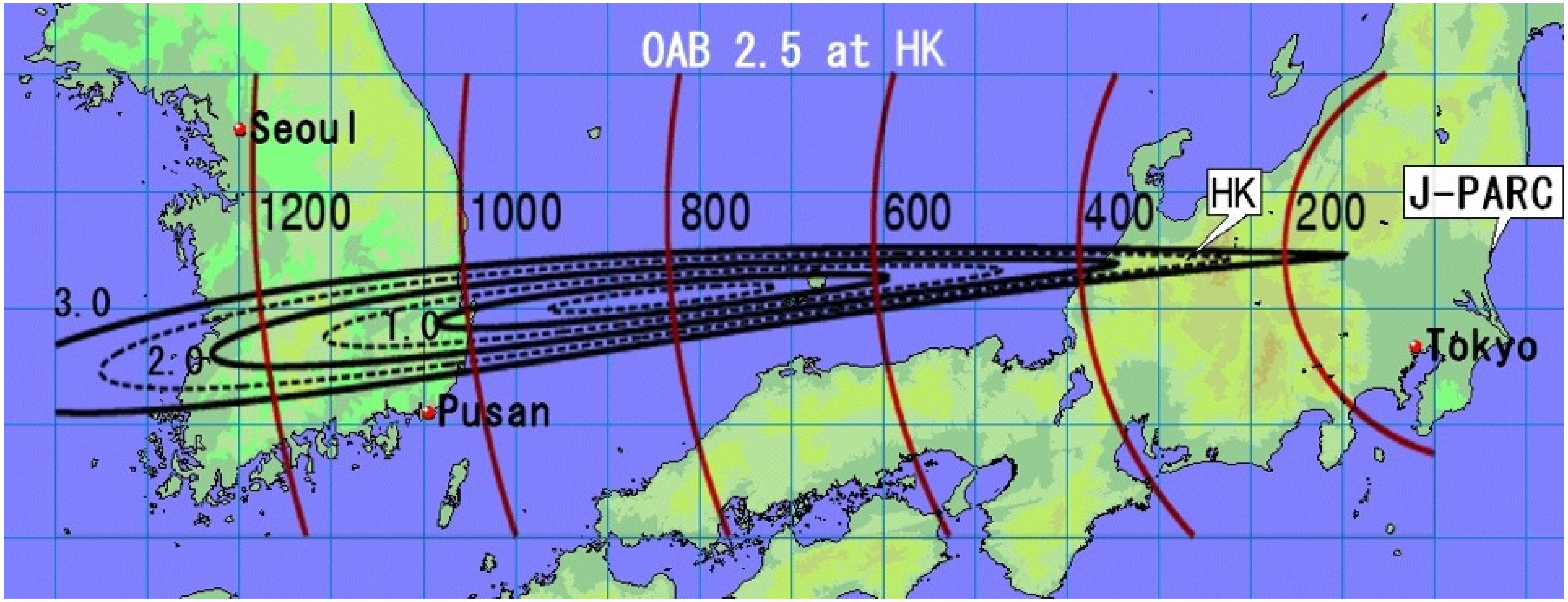
Kuze

T2HKK (Tokai 2 HK & Korea)

- Idea to build a 2nd tank in Korea (“lower” Off-Axis beam reaches Earth surface in Korea)
- L~1100km → large matter effect
  → Mass Hierarchy sensitivity
- > 5σ for any δ_{CP} value
- Also δ_{CP} precision improves

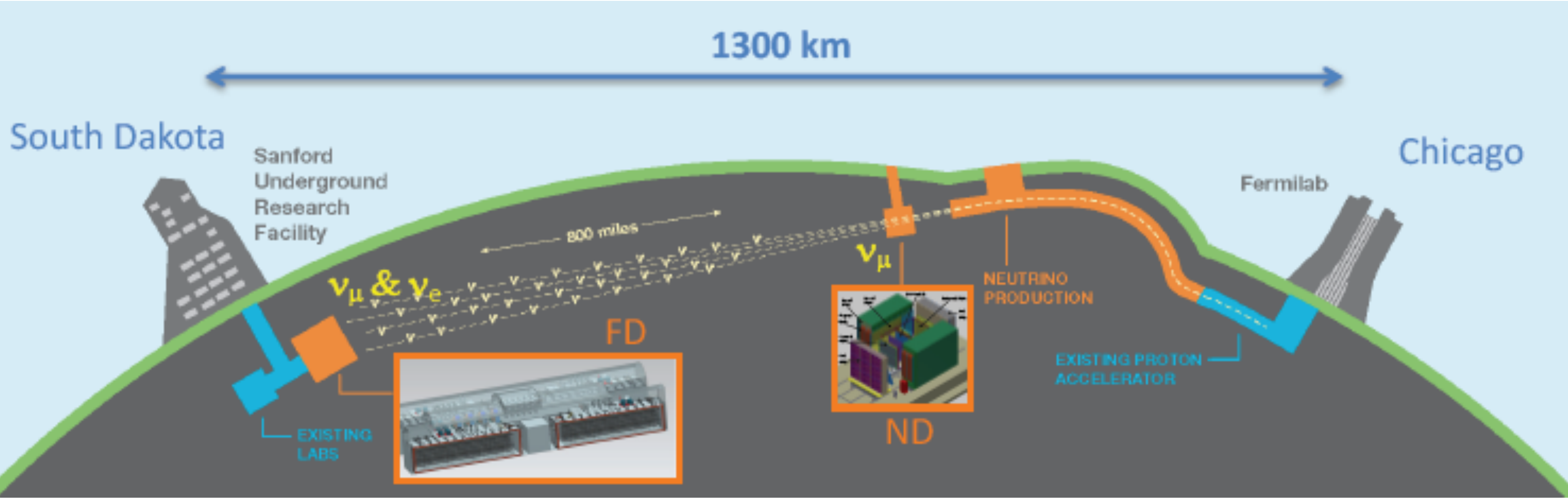


T2HKK White Paper
1611.06118



PLB 637(2006)266
PRD 76(2007)093002

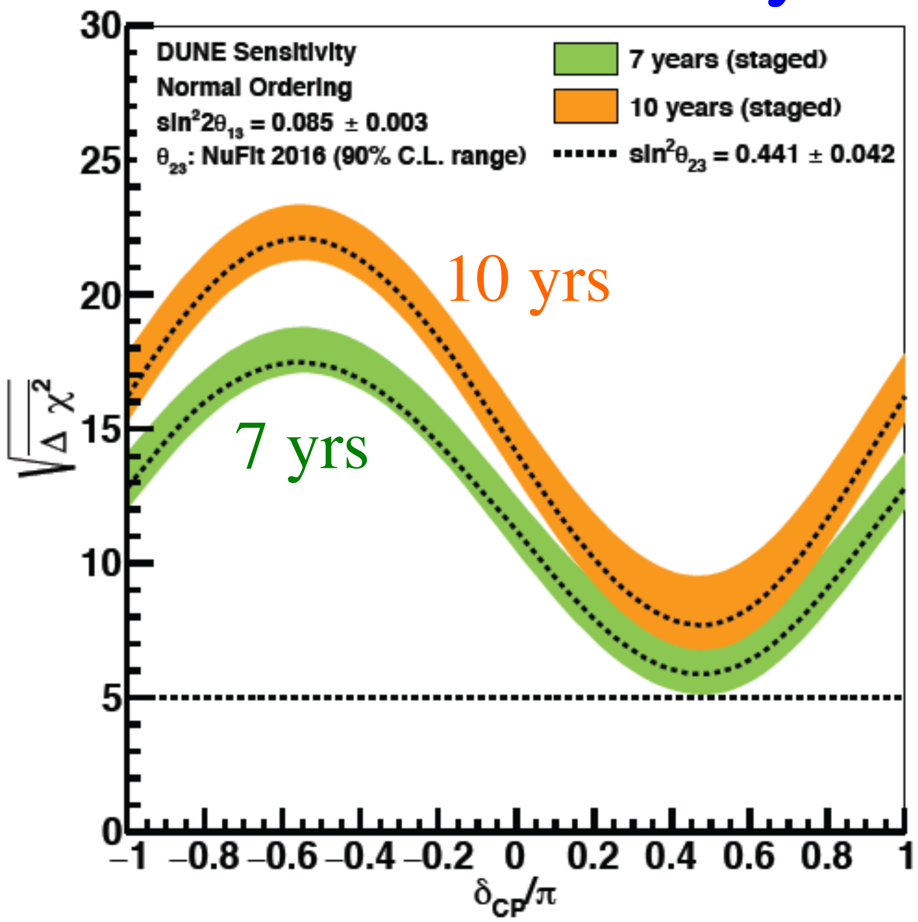
DUNE

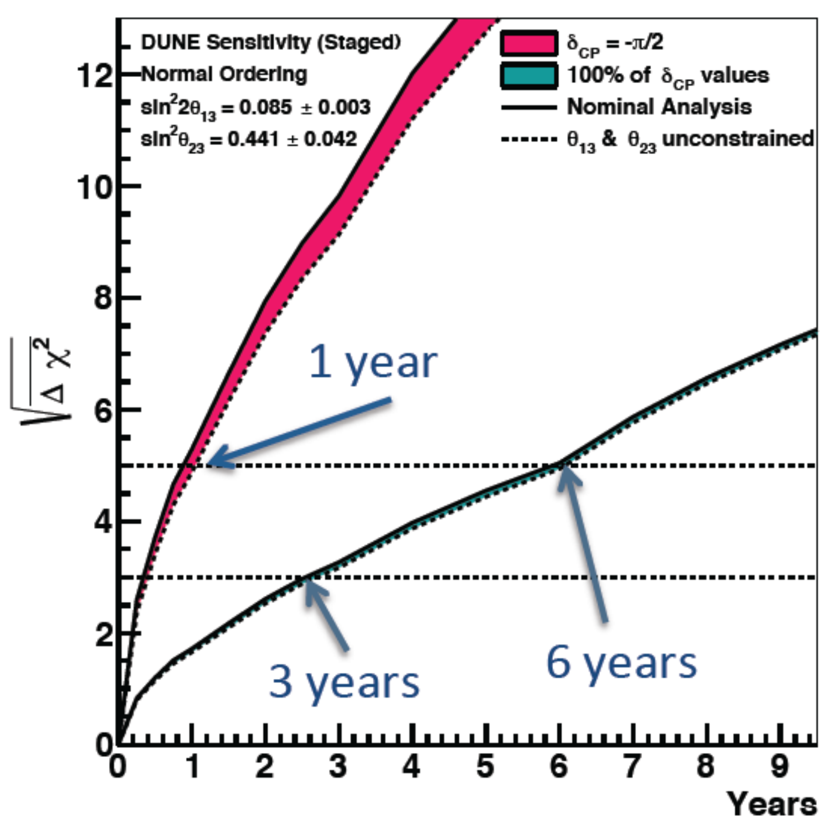


- A long-baseline neutrino experiment designed for studying
  - CP violation in neutrino oscillation
    - Study ν_e appearance
  - Neutrino mass-hierarchy problem
  - Precise measurement of mixing angle θ_{23} and mass splitting Δm^2_{32}
  - Nucleon decay
  - Other physics

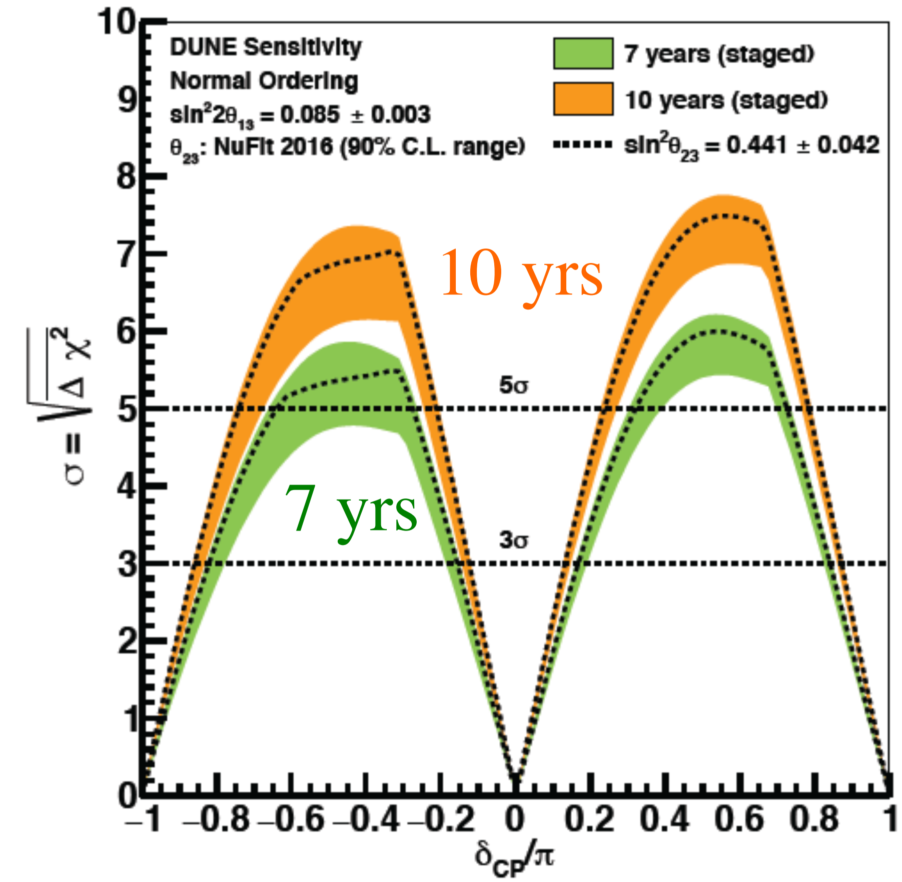
DUNE: Scientific Reach

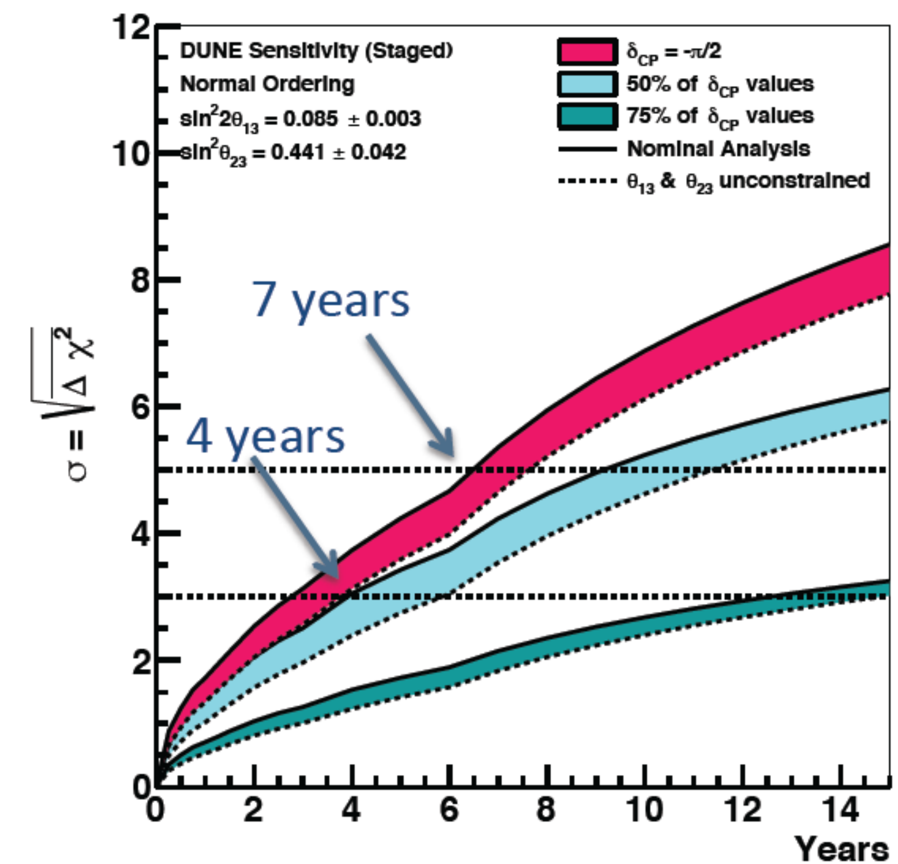
Mass Hierarchy





CP Violation

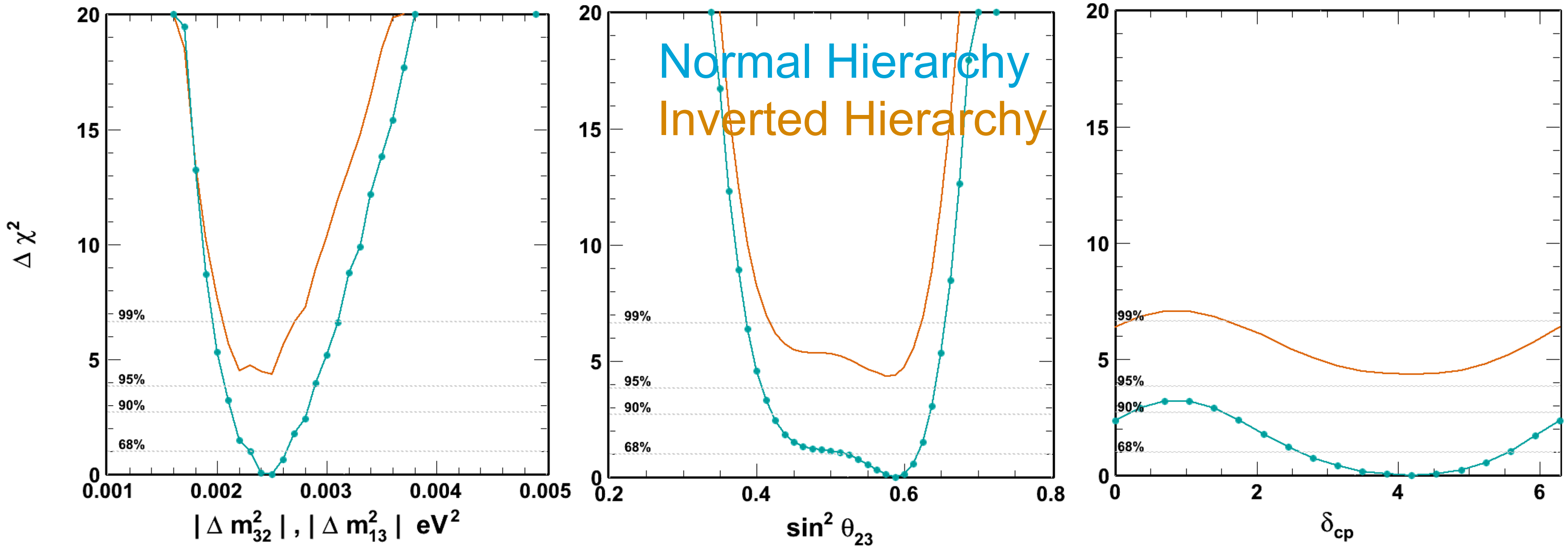




Moderate preference on NH

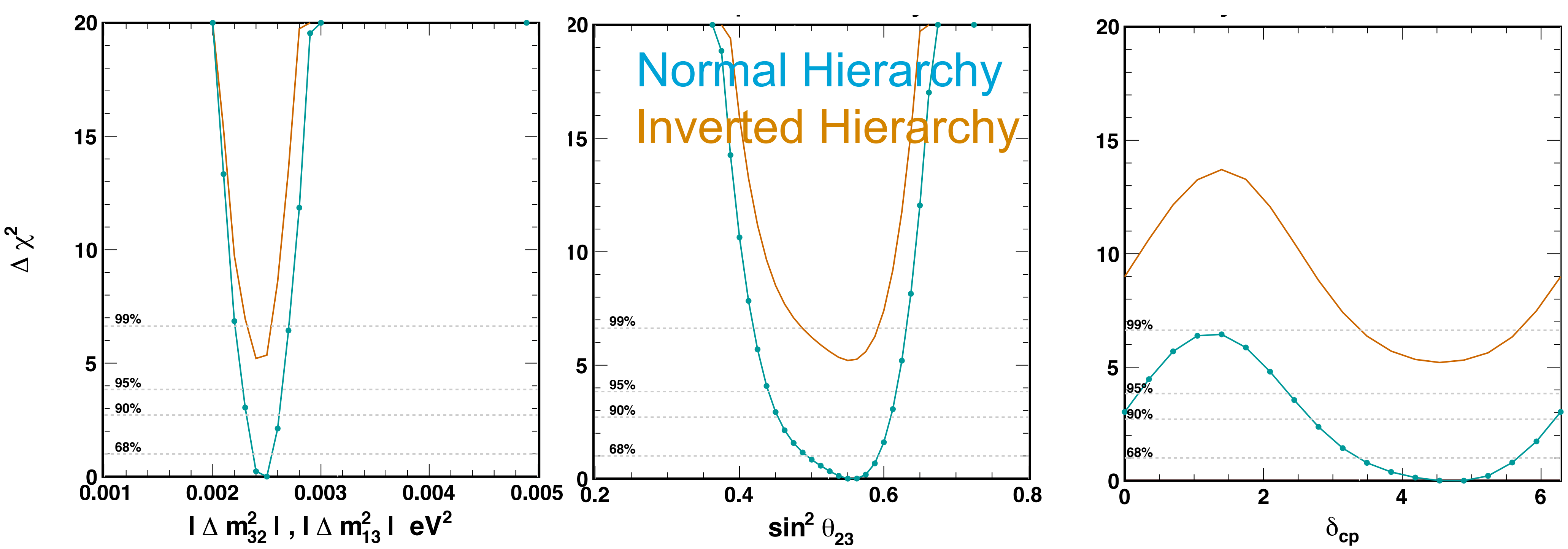
Kuze

- SK Atm-ν + fixed θ_{13}



$\Delta\chi^2$=-4.3

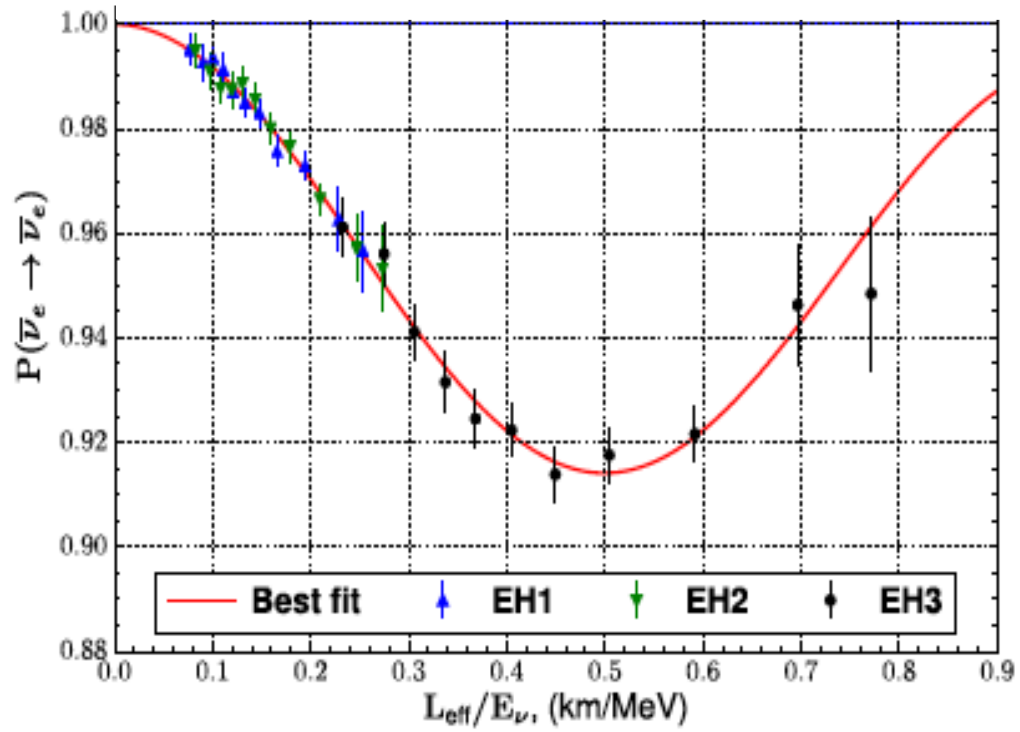
- + T2K θ_{23} and Δm^2_{32}



$\Delta\chi^2$=-5.2

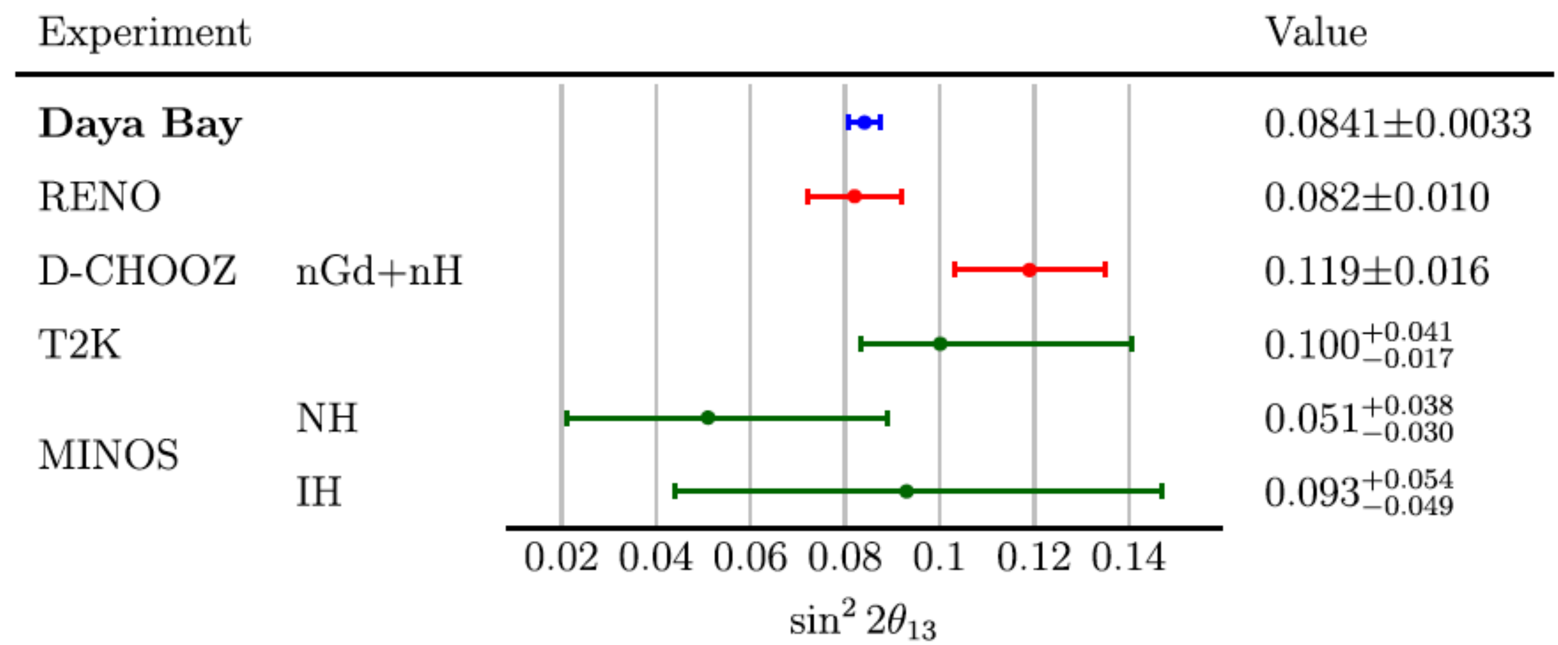
Daya Bay: Most Precise θ_{13}

1230 days: PRD **95** (2017) 072006



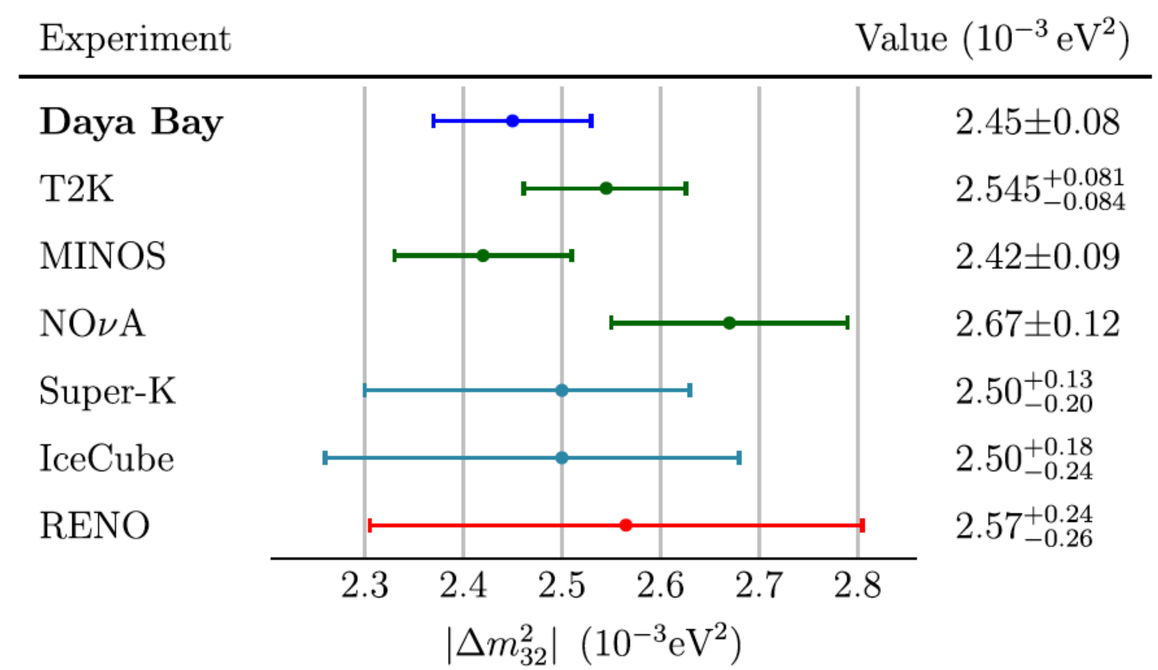
$\sin^2 2\theta_{13} = 0.0841 \pm 0.0027 \pm 0.0019$

- Ultimate precision ≈ 0.0025, the best in the foreseeable future.

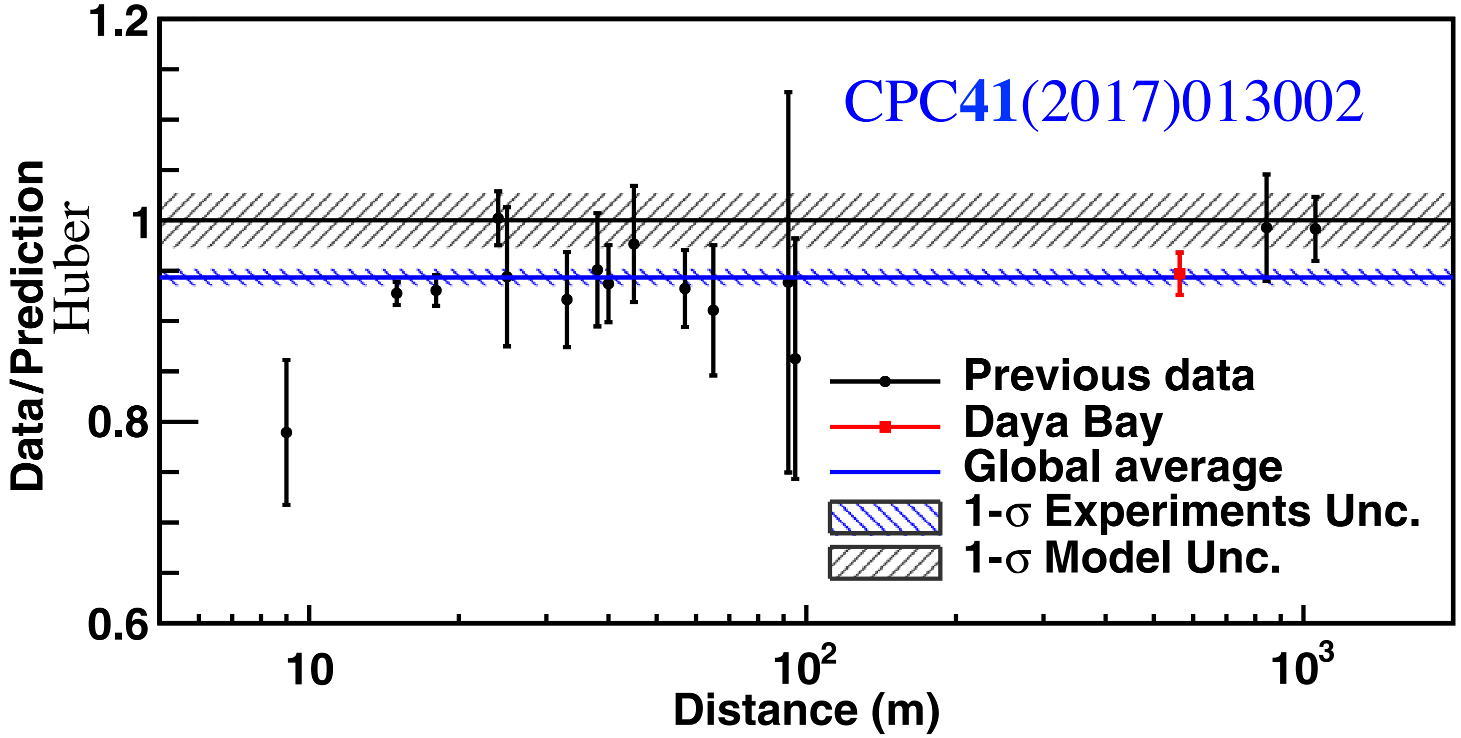


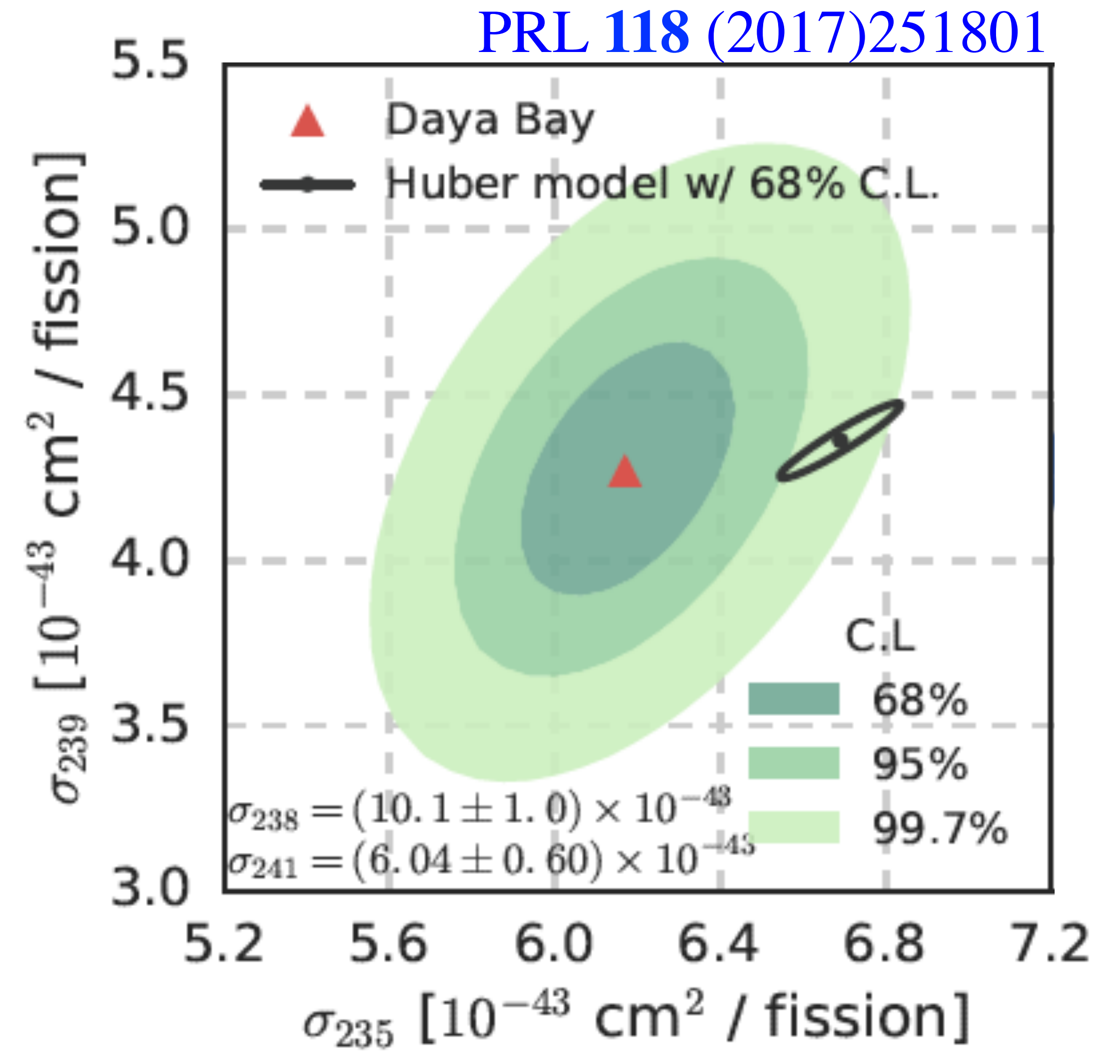
$\Delta m^2_{32} = (+2.45 \pm 0.06 \pm 0.06) \times 10^{-3}\ eV^2$ (NH)
$\Delta m^2_{32} = (-2.56 \pm 0.06 \pm 0.06) \times 10^{-3}\ eV^2$ (IH)

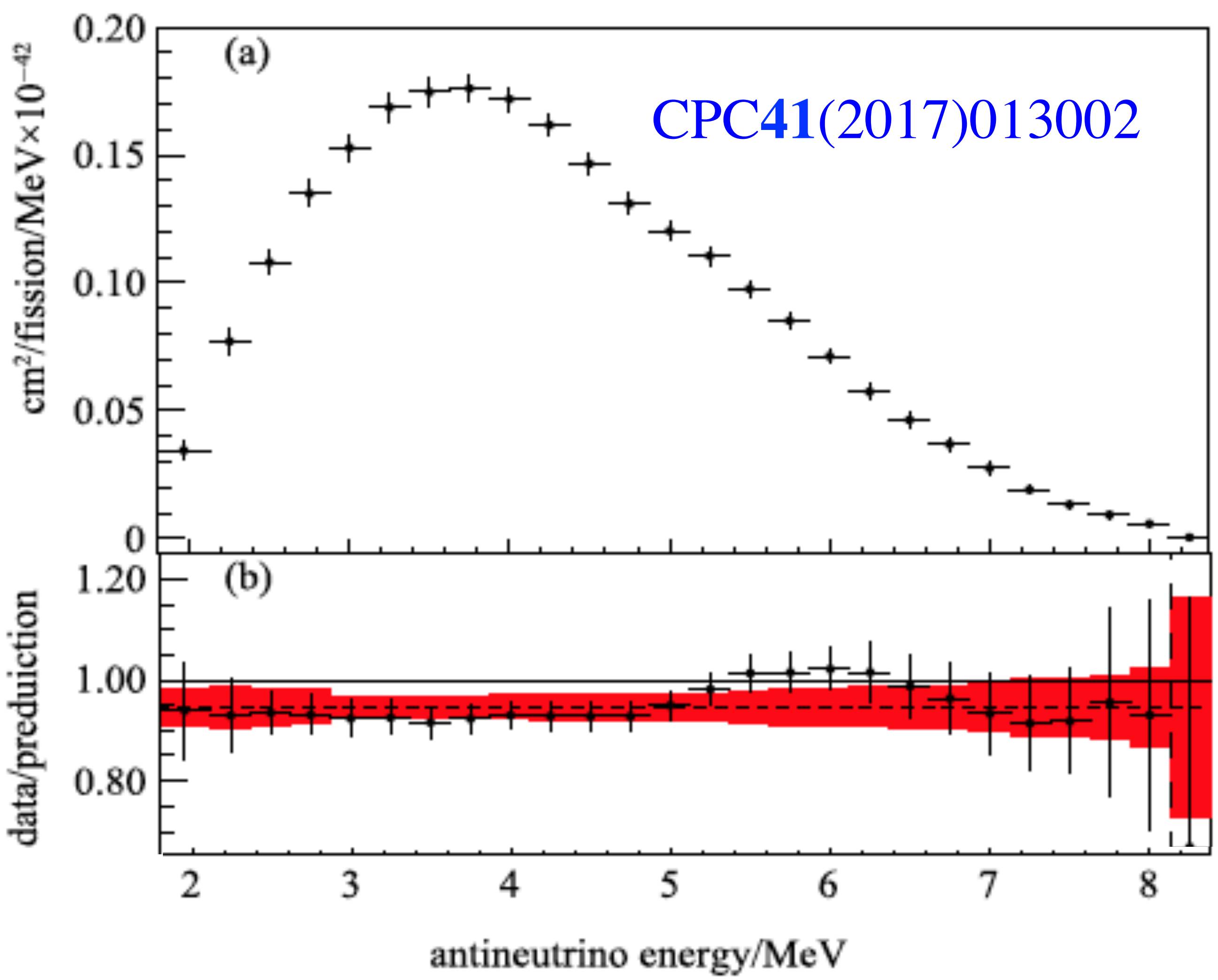
- Final precision ≈ $0.06 \times 10^{-3}\ eV^2$
- Agreement between the ν_e and ν_μ experiments strongly supports 3-flavor mixing.



Daya Bay: Reactor Antineutrino







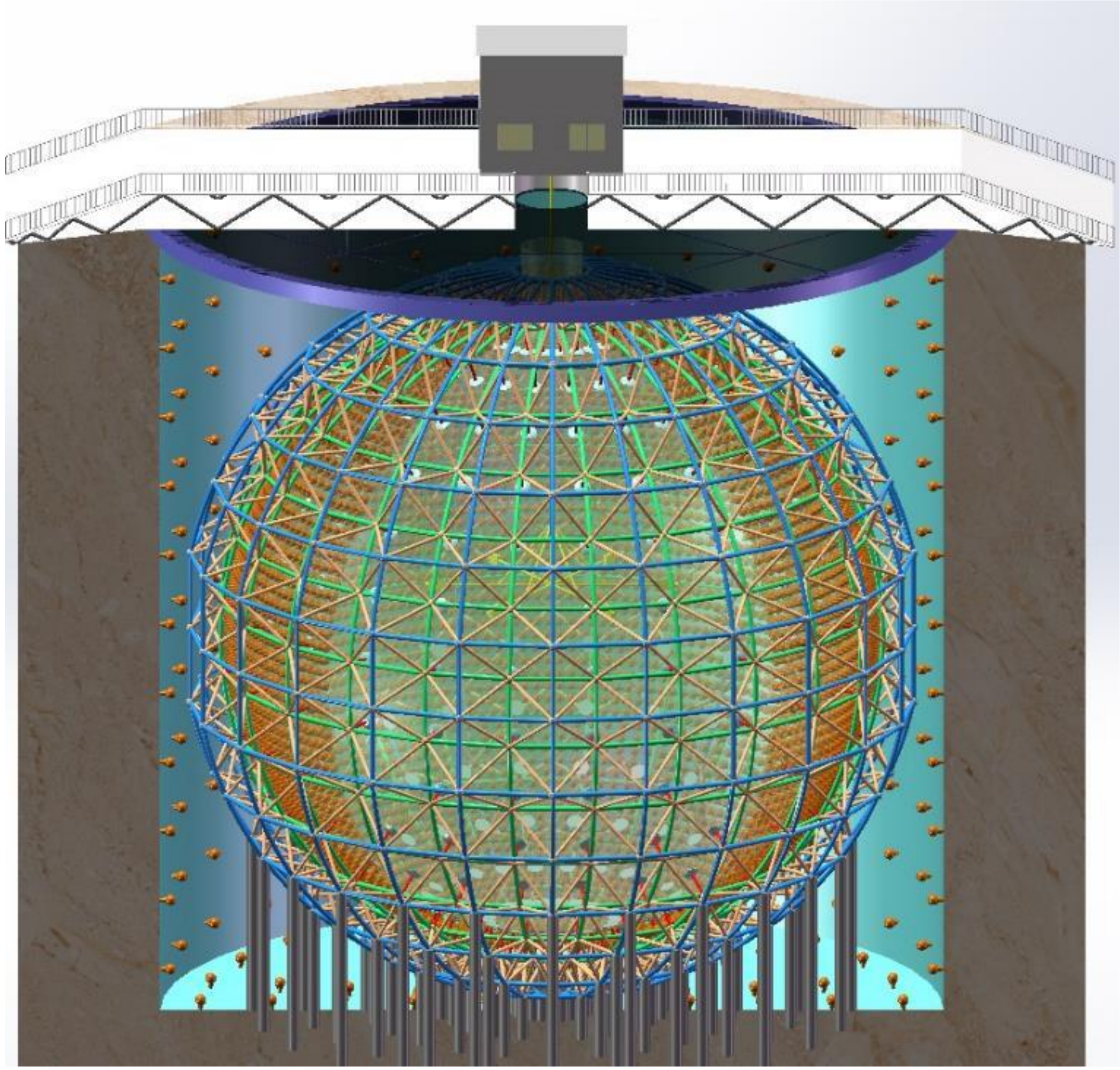
- Precise flux
  - consistent with previous results.
  - disagreed with Huber's model at 3.1σ.
  - yield from ^{235}U may be the key contributors to the reactor antineutrino anomaly.
- Most precise energy spectrum
  - Observed excess of events with $\overline{\nu}_e$ energy between 5 and 7 MeV.

Kuze

JUNO for Mass Hierarchy

The JUNO Experiment

- **Jiangmen Underground Neutrino Observatory, a multiple-purpose neutrino experiment, approved in Feb. 2013. ~ 300 M$.**



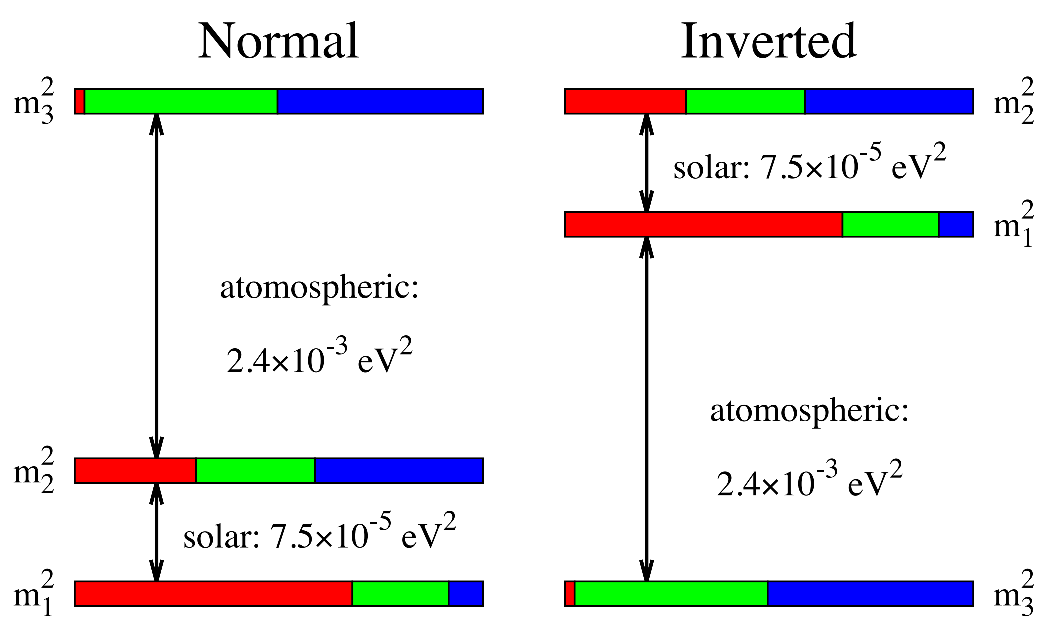
- **20 kton LS detector**
- **3% energy resolution**
- **700 m underground**
- **Rich physics possibilities**
  - ⇨ **Reactor neutrino for Mass hierarchy and precision measurement of oscillation parameters**
  - ⇨ **Supernovae neutrino**
  - ⇨ **Geoneutrino**
  - ⇨ **Solar neutrino**
  - ⇨ **Atmospheric neutrino**
  - ⇨ **Exotic searches**

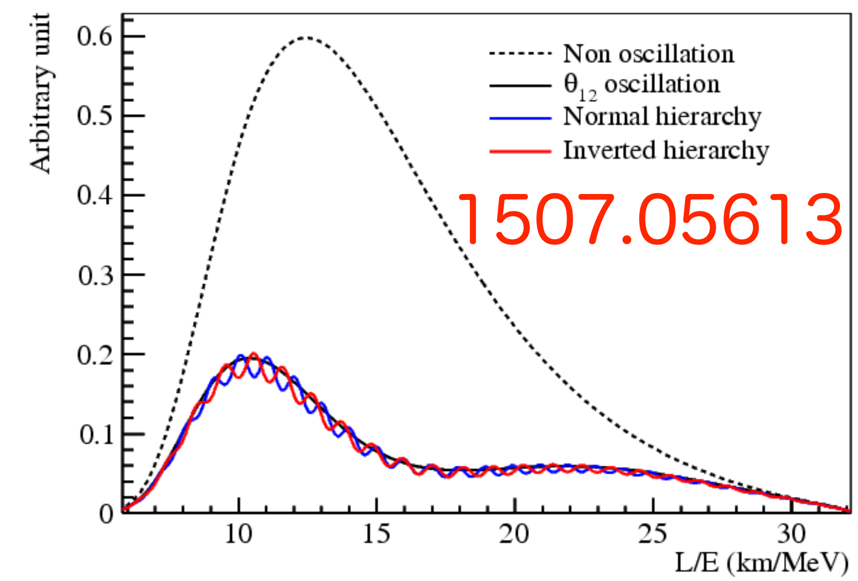
J. Cao, NuTel 2015

Kuze

How to access Mass H.?

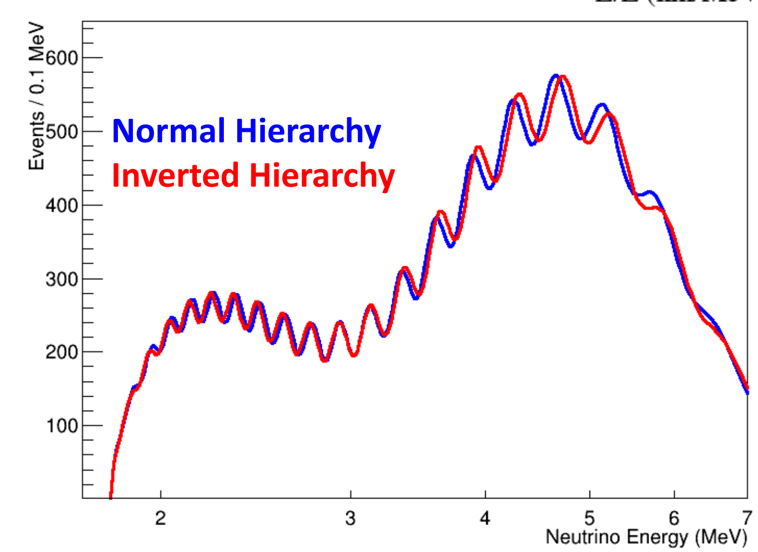
- Detect θ_{13} 'ripple' at θ_{12} osc. max. (53km)
- Energy resolution is the key (80% PMT coverage)





True energy

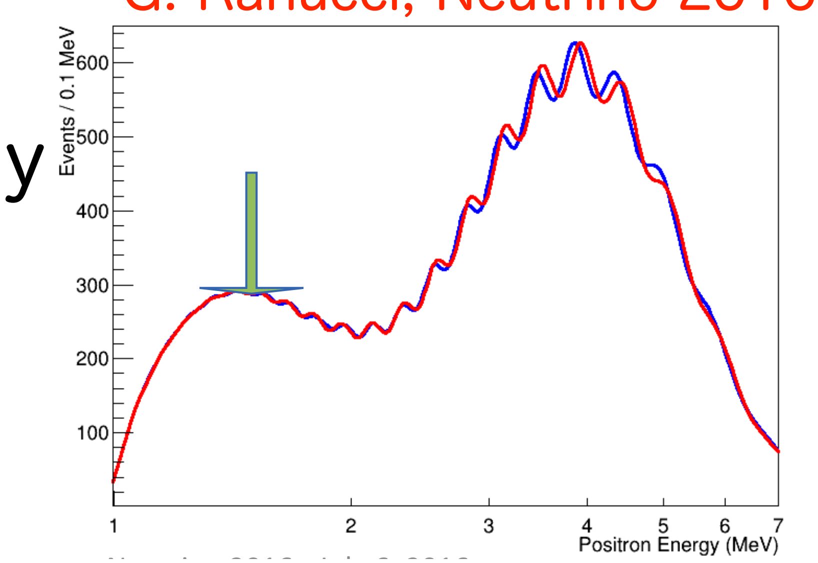
↓



G. Ranucci, Neutrino 2016

Visible energy

$\sigma(E)/E = 3\%/\sqrt{E(\mathrm{MeV})}$



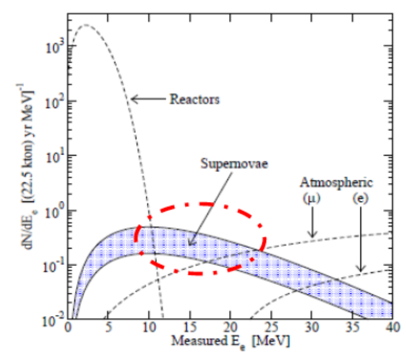
Near-future of SK: SK-Gd

- Main motivation: Supernova relic ν
- Also reduces p-decay BG

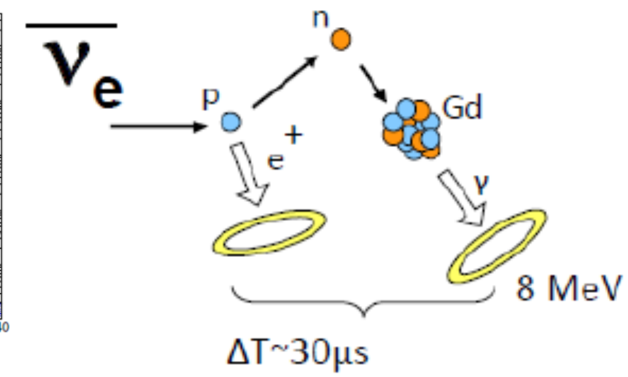
SK-Gd

•Discovery of relic SN neutrinos is expected by O(1) sensitivity improvement
•0.1% Gd loading to tag $\overline{\nu}$e+p→e+n, Gd+n→Gd+γs

•R&D in test tank and water system construction going on
•Start SK-Gd in a few yrs



Phys. Rev. Lett. 93 (2014) 171101.

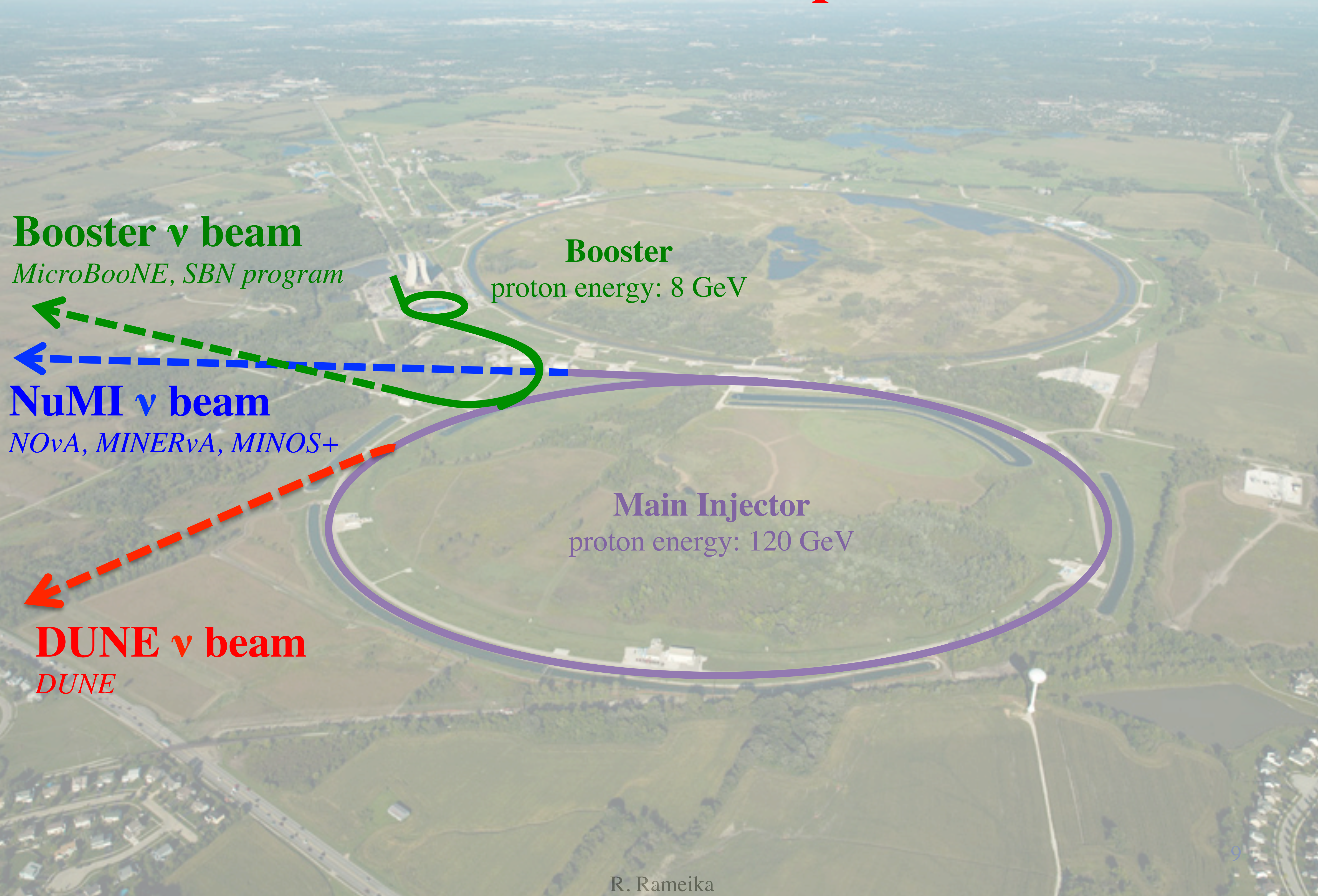


Model Tν	10-16MeV Eve/10yrs	16-28MeV Eve/10yrs	Total (10-28MeV)	Significance 2 energy bin
8 MeV	11.3	19.9	31.2	5.3σ
6 MeV	11.3	13.5	24.8	4.3σ
4 MeV	7.7	4.8	12.5	2.5σ
1987a	5.1	6.8	11.9	2.1σ
BG	10	24	34	---

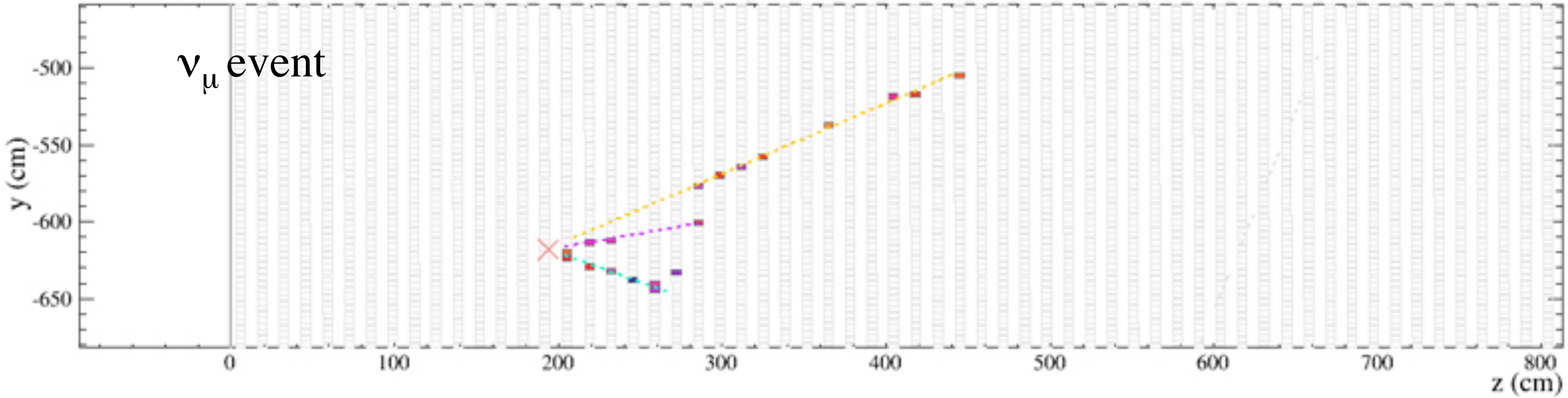
Model: Phys. Rev. D 79 (2009) 083013.

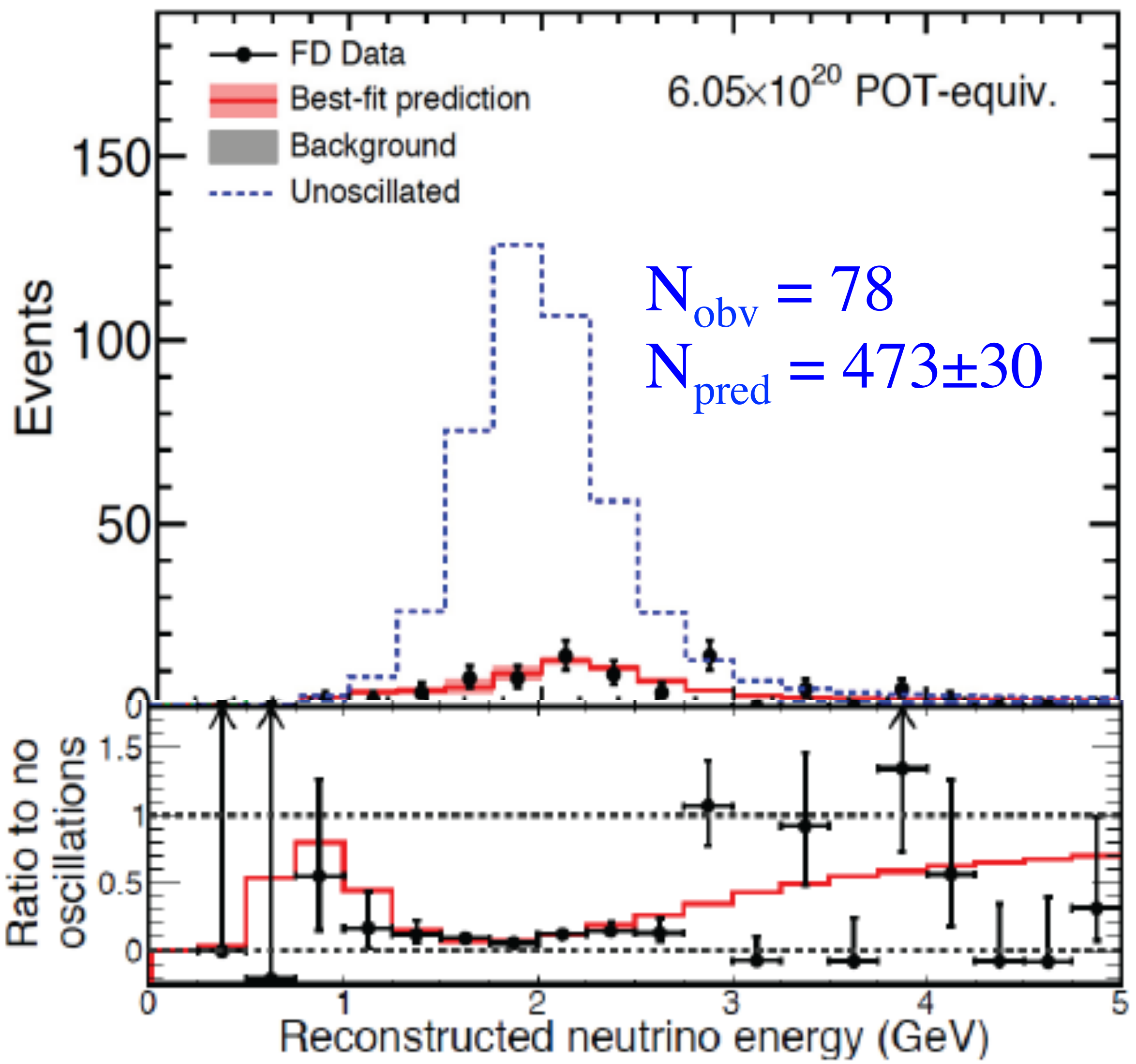
M. Shiozawa, NuTel 2017

Fermilab Neutrino Experiments

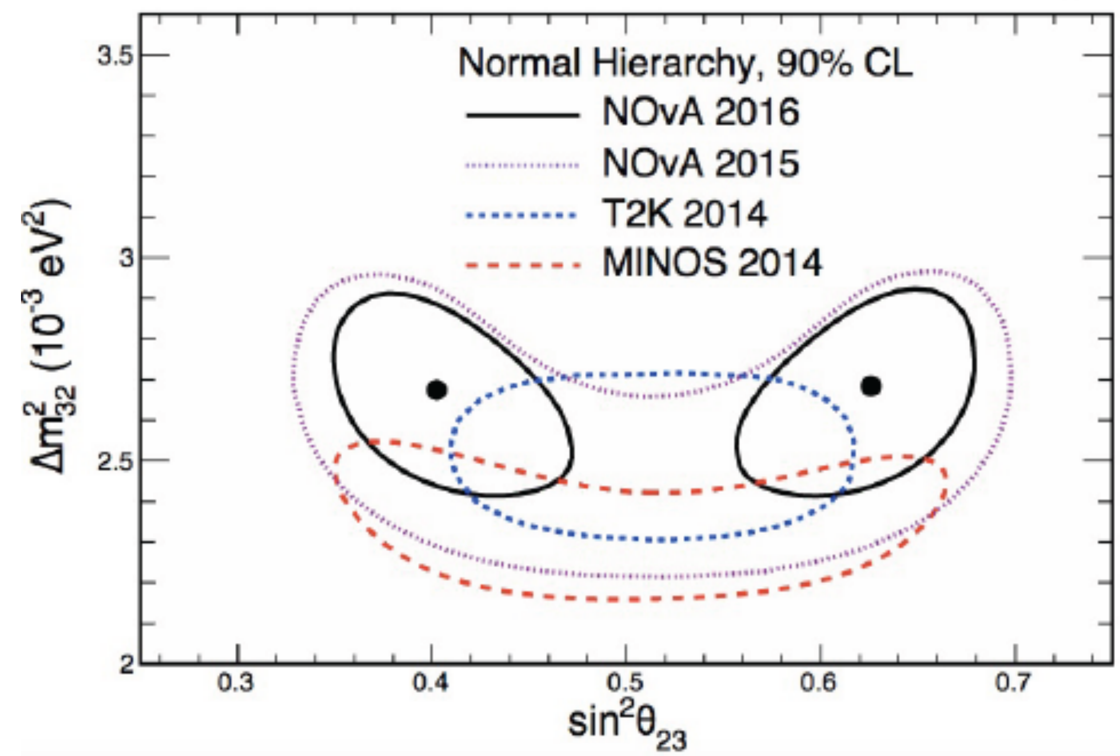


NOvA: ν_μ Disappearance





PRL **118** (2016)151802



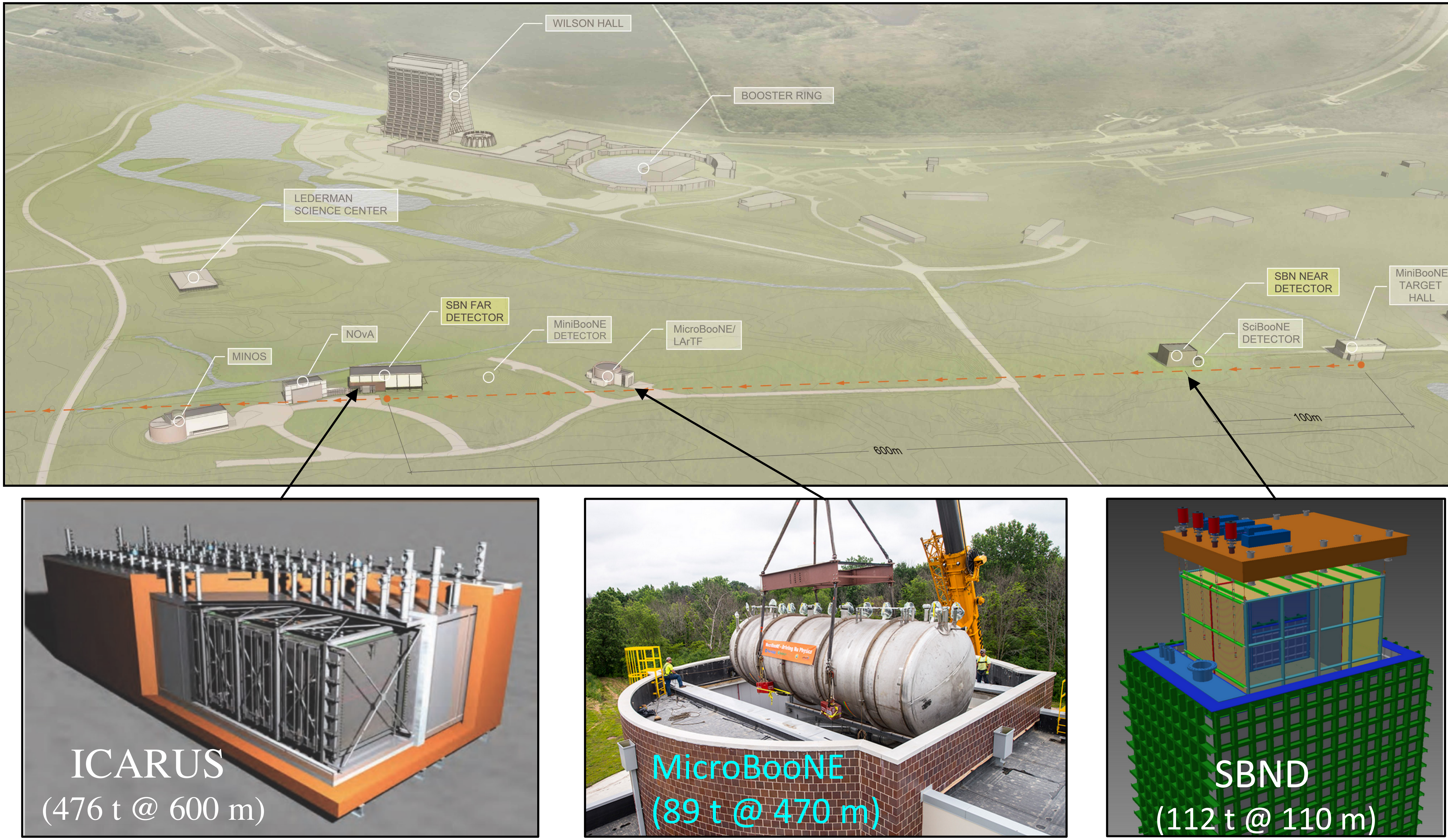
- $\sin^2\theta_{23} = 0.404^{+0.030}_{-0.022}$ or $0.624^{+0.022}_{-0.030}$ (NH)

  Maximal mixing is disflavoured at 2.6 σ

  $\sin^2\theta_{23} = 0.398^{+0.030}_{-0.022}$ (IH)
- $\Delta m^2_{32} = (+2.67 \pm 0.11) \times 10^{-3}$ eV^2 (NH)

  $\Delta m^2_{32} = (-2.72 \pm 0.11) \times 10^{-3}$ eV^2 (IH)

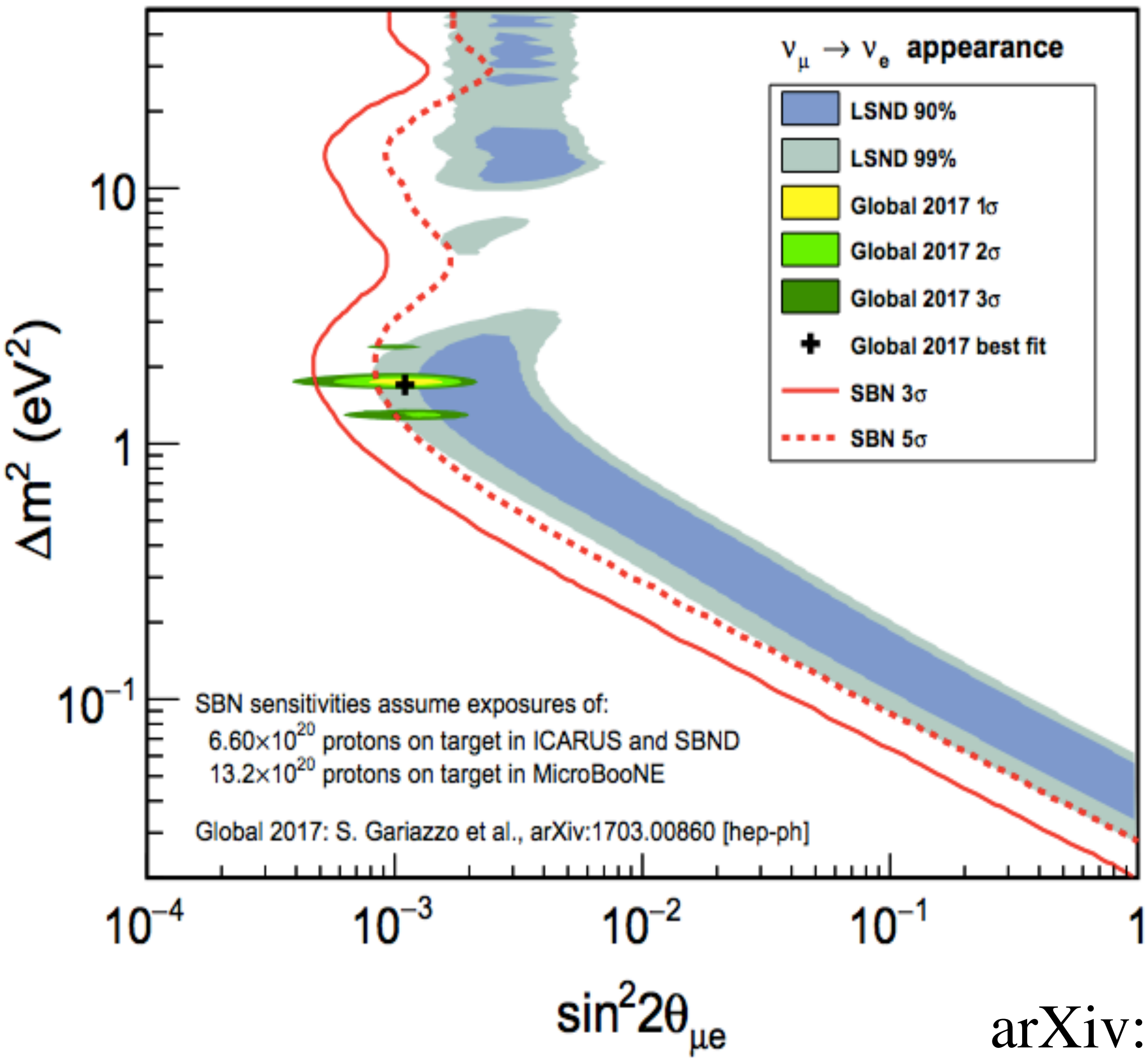
Short-Baseline Neutrino (SBN) Program



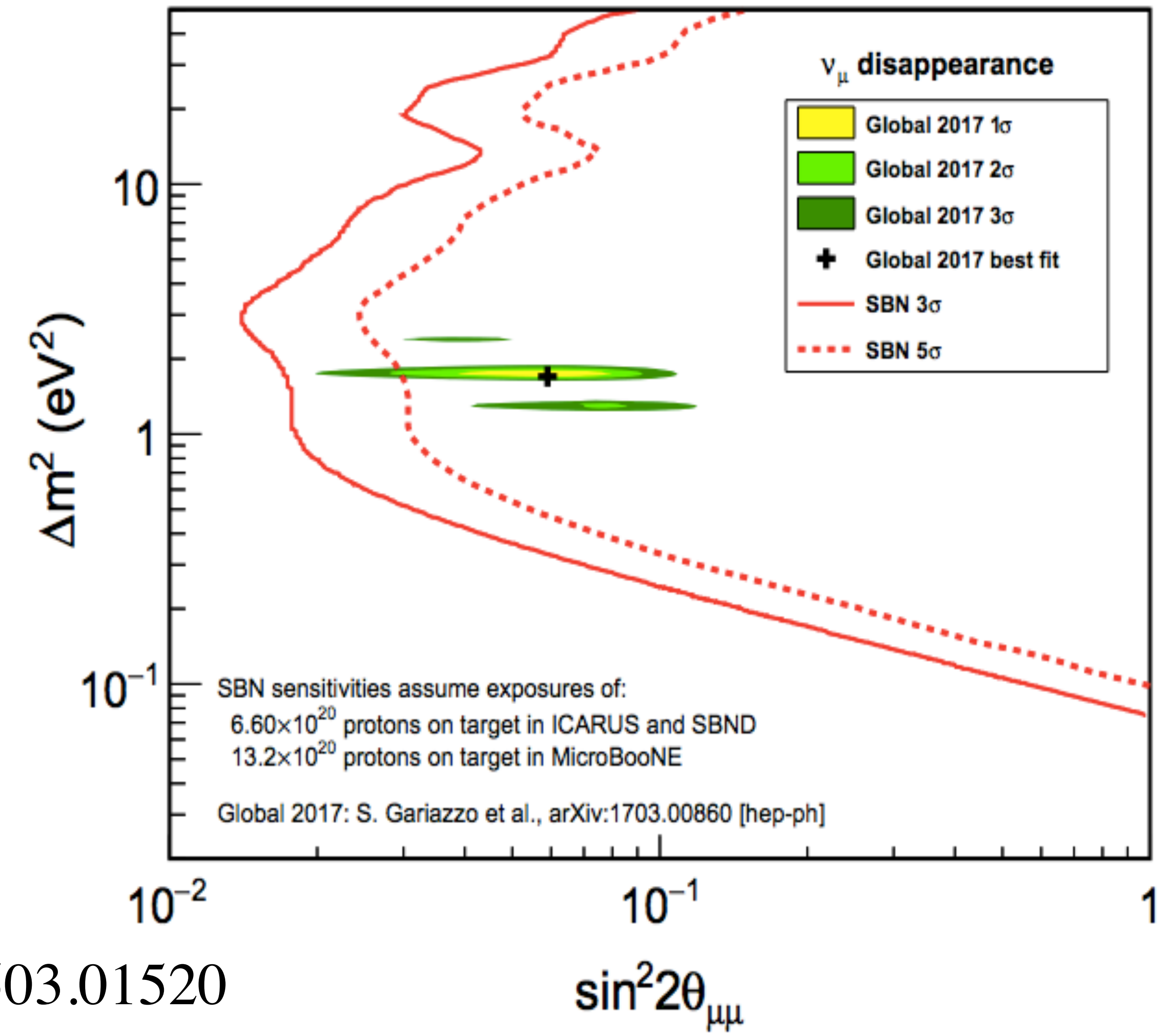
- All three detectors are liquid-argon TPCs
  - ICARUS and MicroBooNE exist
  - Build a DUNE-style detector: SBND

Sensitivities of the SBN Program

ν_e appearance



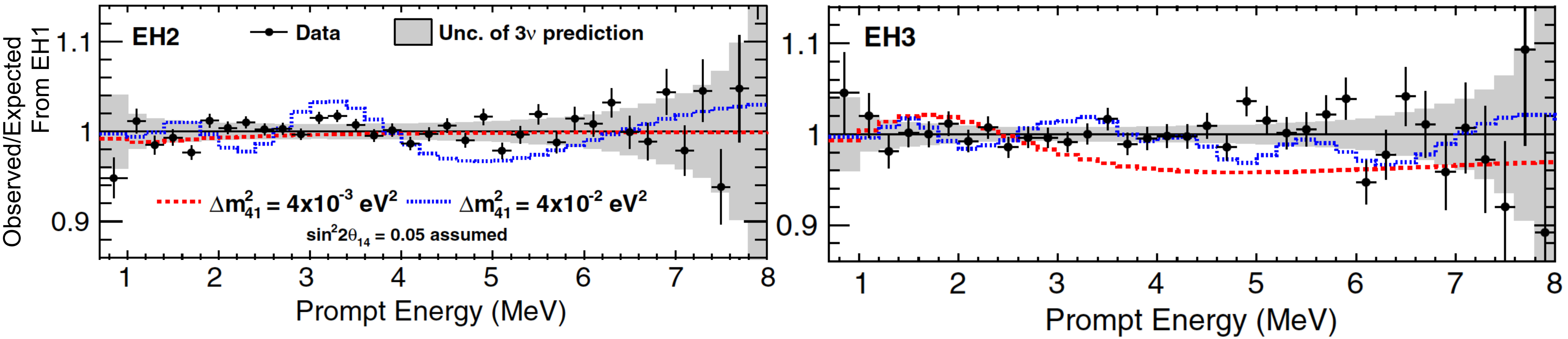
ν_μ disappearance



arXiv:1503.01520

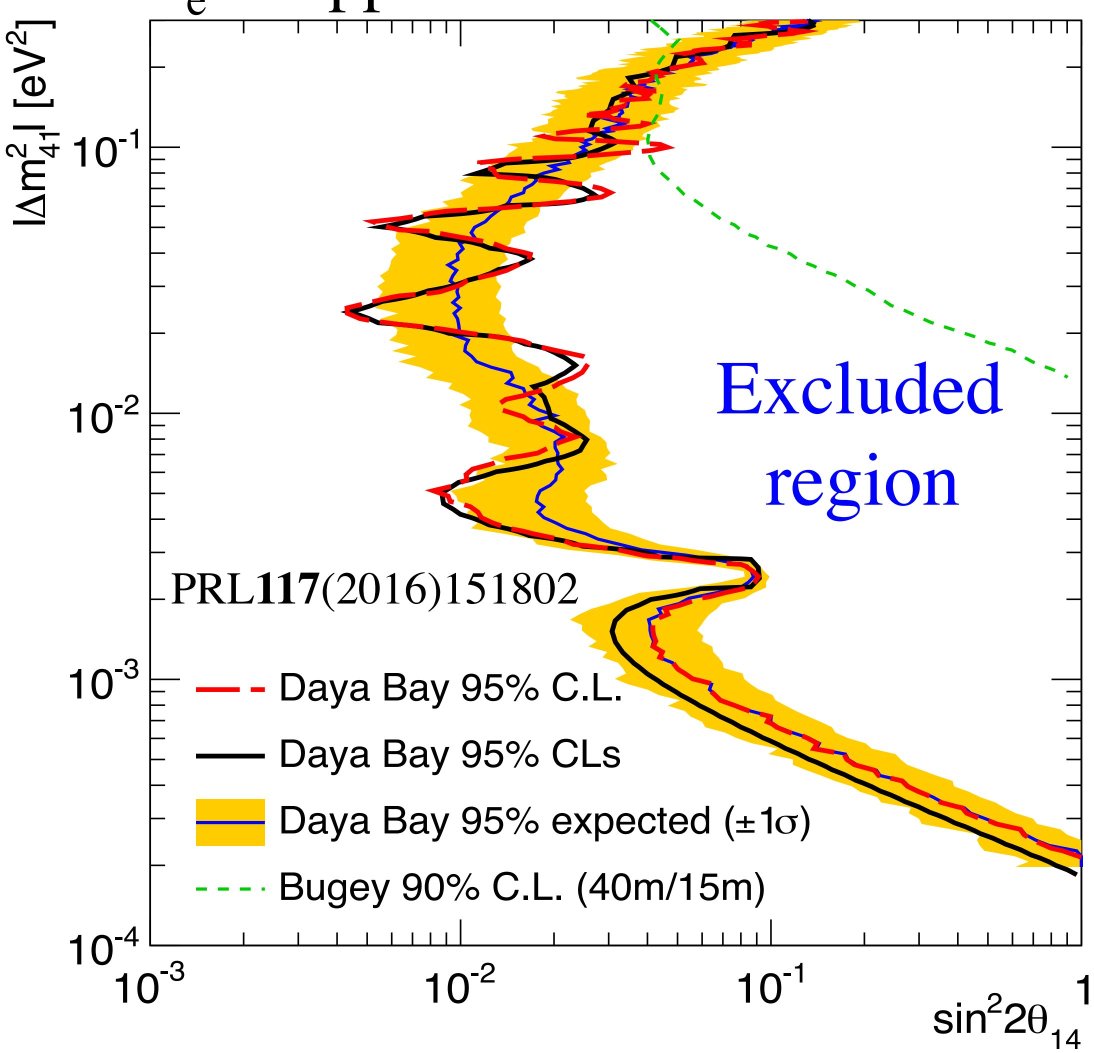
- Appearance and disappearance measurements with the same detectors
- SBN has the potential to cover the entire range of interest

Daya Bay: Search For Light Sterile Neutrino



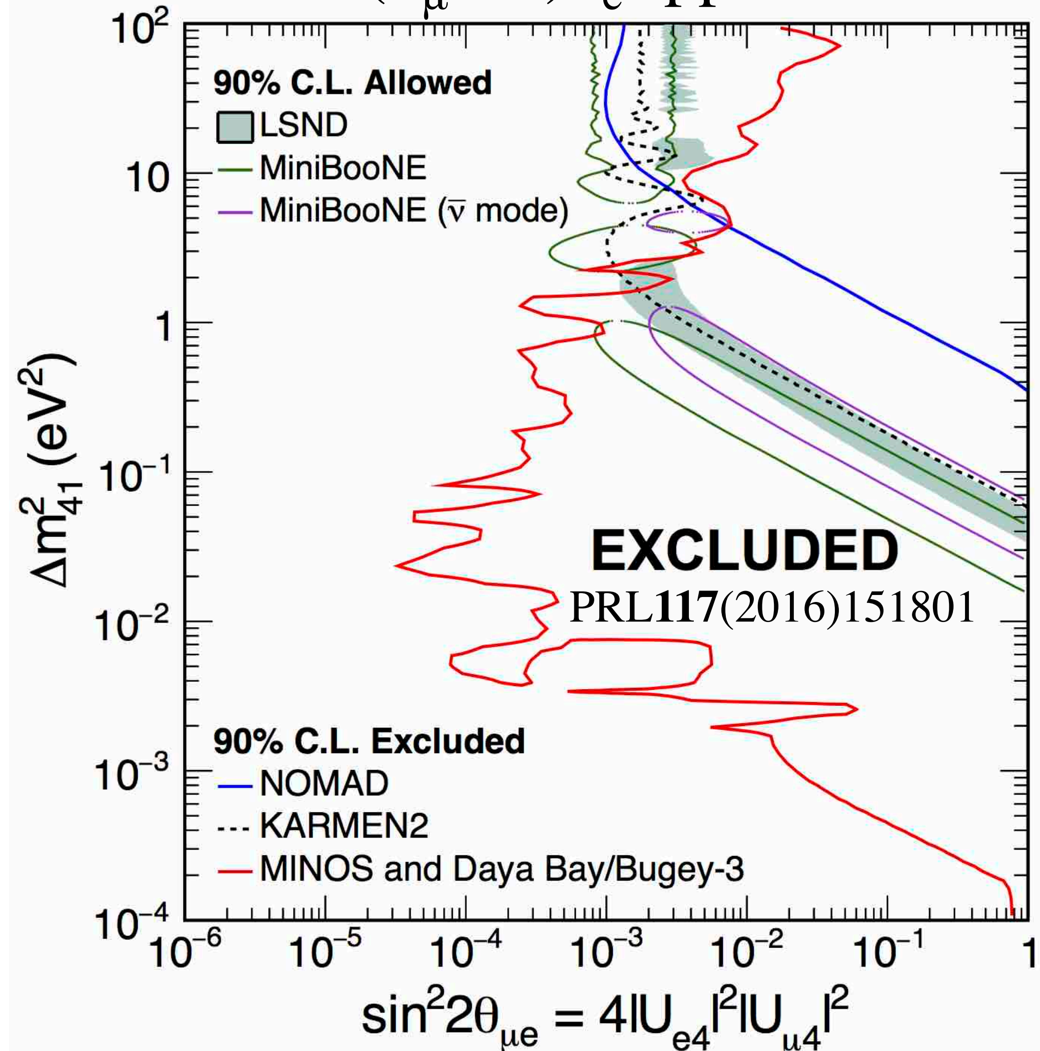
No evidence of a light sterile neutrino

$\overline{\nu}_e$ disappearance



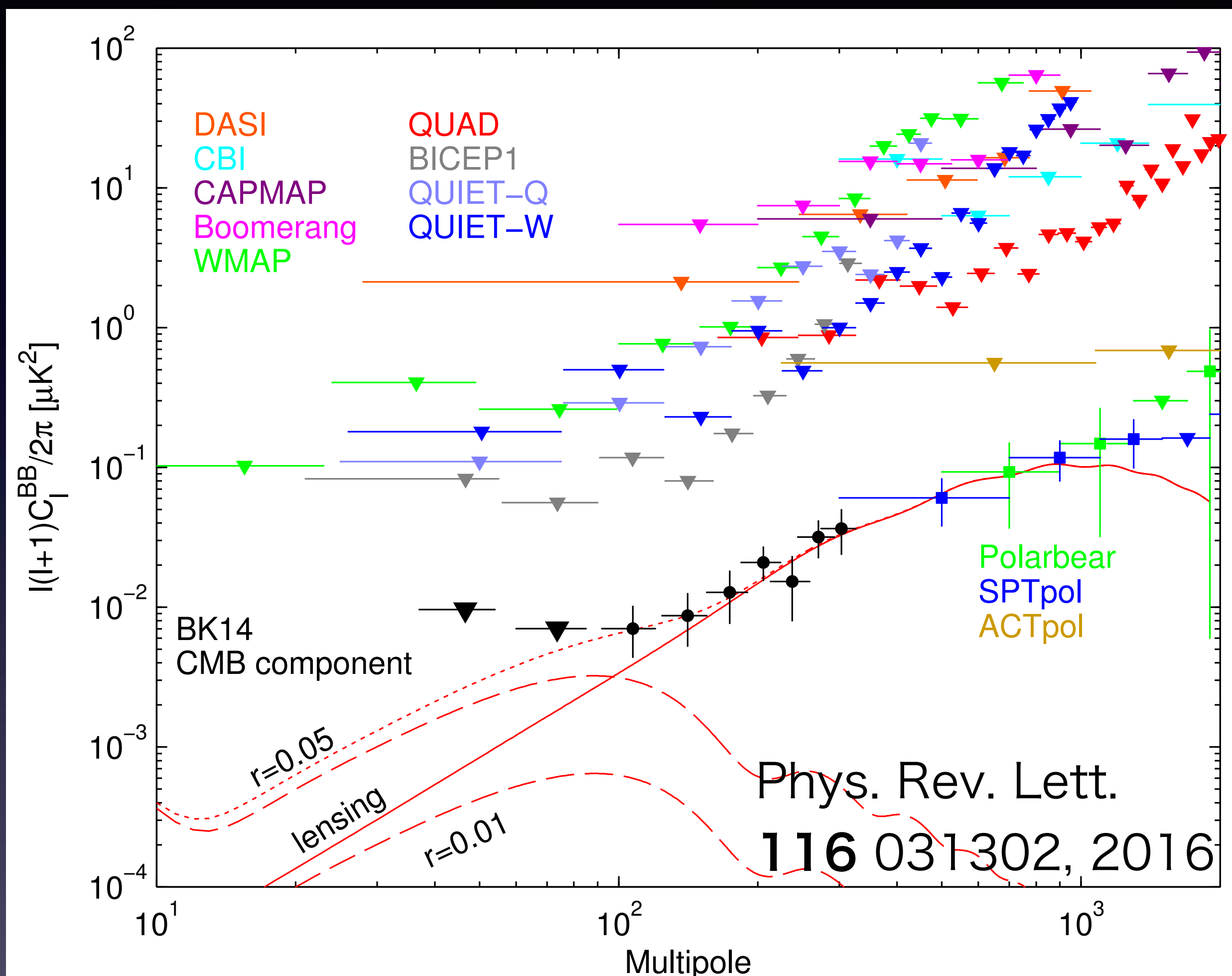
The best limit in this mass range.

(ν_μ-to-)ν_e appearance

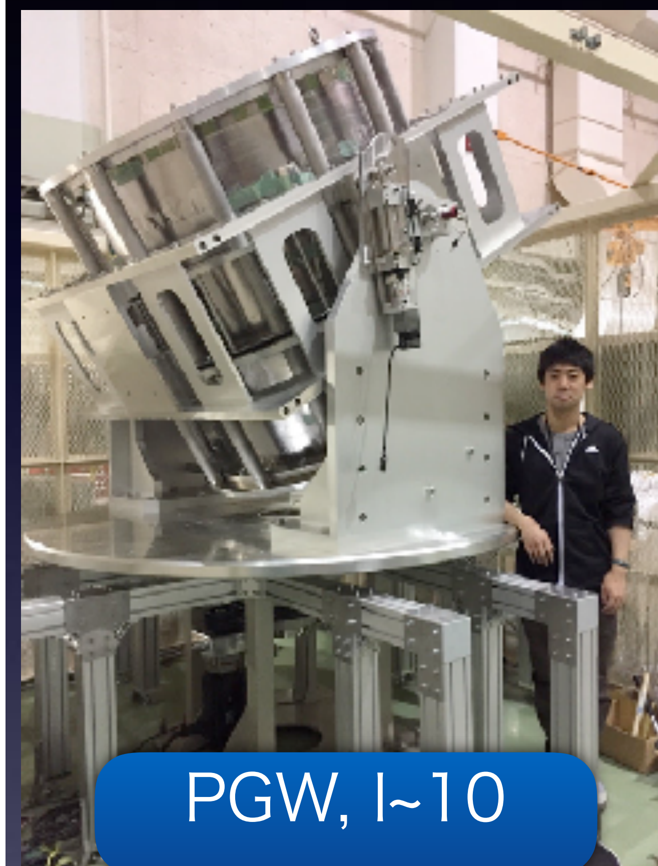


Ruled out a good fraction of the LSND and MiniBooNE's allowed regions

Ground-based telescopes



GroundBIRD

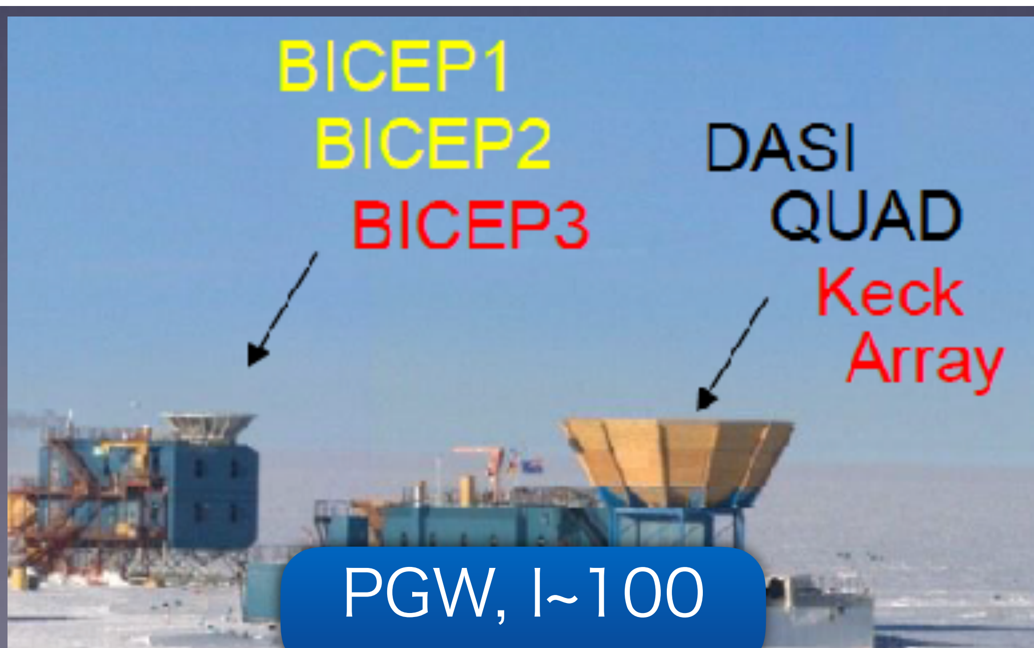


All of them employ

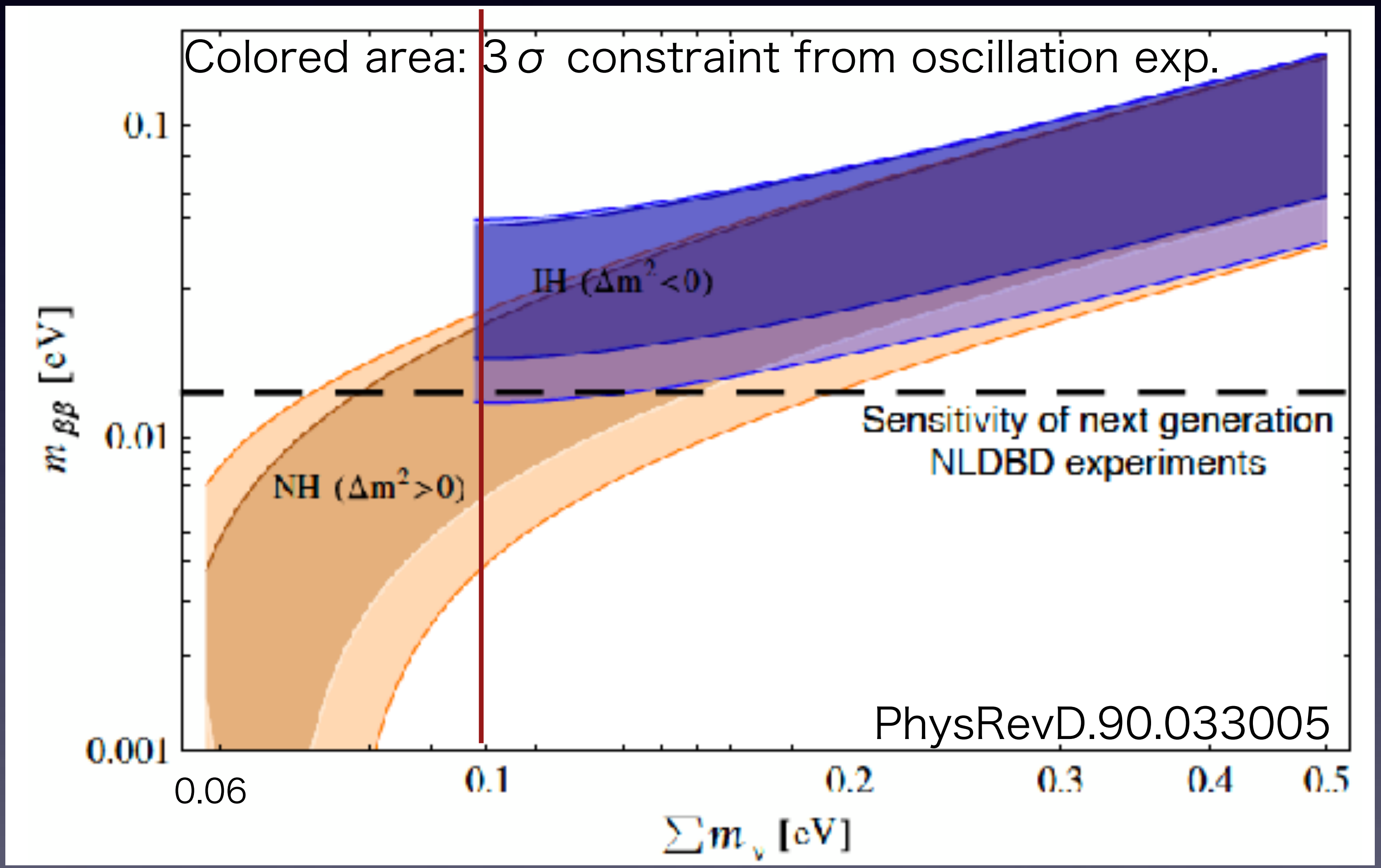
- Superconducting sensor array ~1000pix

Difference

- Target angular scale (Primordial or lensing)
  => scan area
  => telescope size



Future experiments and expected results



CMB-S4 (U.S.)

- 2020 ~
- Telescope array
  - Combination of existing experiments
- 100,000 sensors !
- Expected sensitivity

$$\sigma\left(\Sigma m_\nu\right) = 16\ \mathrm{meV}$$
$$\sigma\left(\mathrm{N}_{eff}\right) = 0.020$$

If CMB exp. observe the high mass(>0.1eV) neutrino
Neutrino less double beta decay exp.
Observe at same mass -> Majorana !
Reject that mass point -> Dirac !!
CMB cannot observe -> Normal !!!