# Measuring the Neutrino Mass Hierarchy

Report by the LBNL Neutrino Mass Hierarchy Task Force

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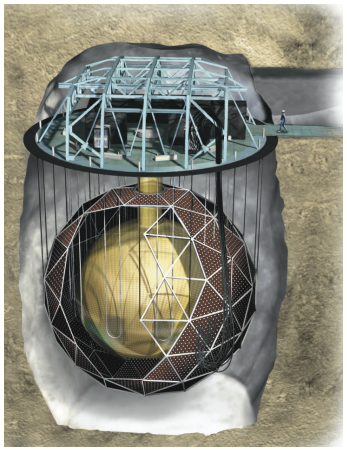
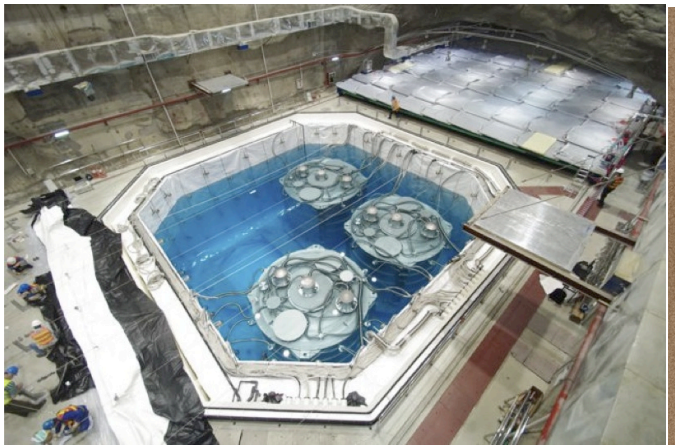
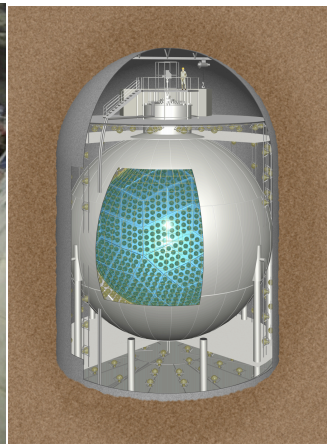
arXiv:1307.5487 and SNOW13-00069


Nuclear Science Division
Physics Division

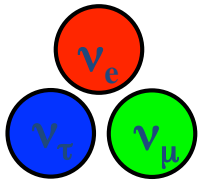
# Motivation: Role of the National Lab

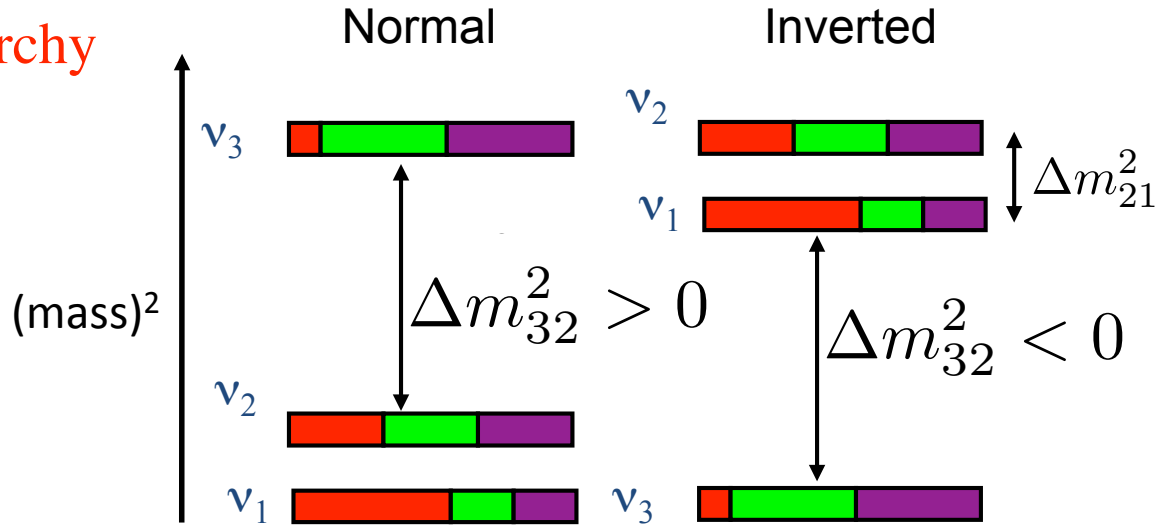
- Critically address issues facing the community at large
- Provide leadership, guidance, and technical expertise
  - Long history of achievement in neutrino experiments in both Physics and Nuclear Science Divisions
- While we have involvement in some projects described below, we have attempted to survey the field independently and pedagogically
  - Rely (mostly) on existing literature and presentations

# Neutrino Mass Hierarchy

- Open questions in Neutrino Physics:
  - The very nature of the neutrino: Majorana vs Dirac
  - Absolute mass scale
    - ☞ Sensitivity to GUT mass scales
  - Neutrinos as a probe
  - Structure of neutrino mixing
  - Neutrino mass hierarchy



# Measurements Sensitive to MH

(1) Solar neutrinos
(2) Supernova neutrinos
(3) Direct mass measurements
(4) Neutrinoless double beta decay
(5) Long-baseline experiments
(6) Reactor neutrinos
(7) Atmospheric neutrinos
(8) Cosmology

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Very limited scope for definitive measurement

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Some potential...

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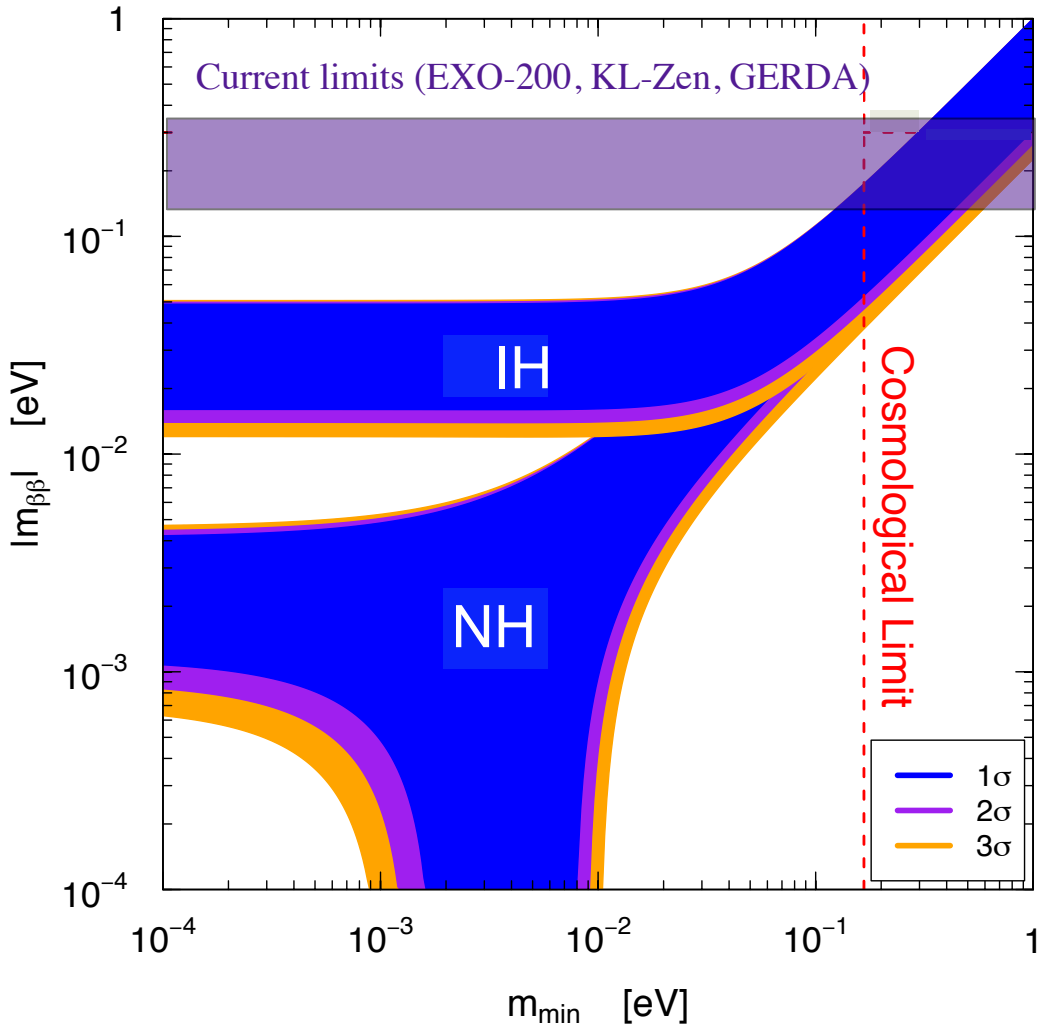
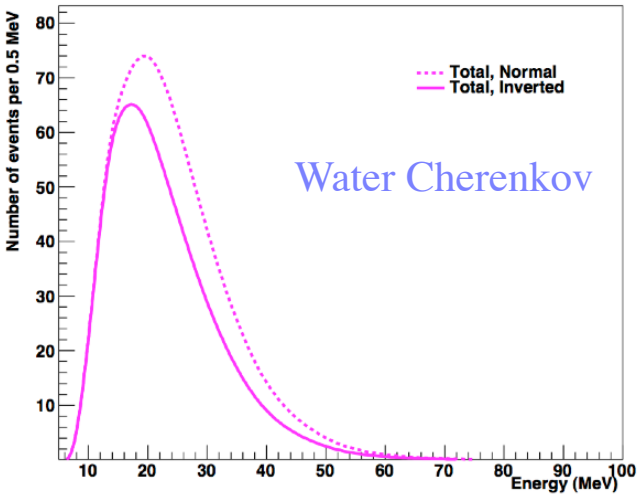
# 0νββ and Cosmology

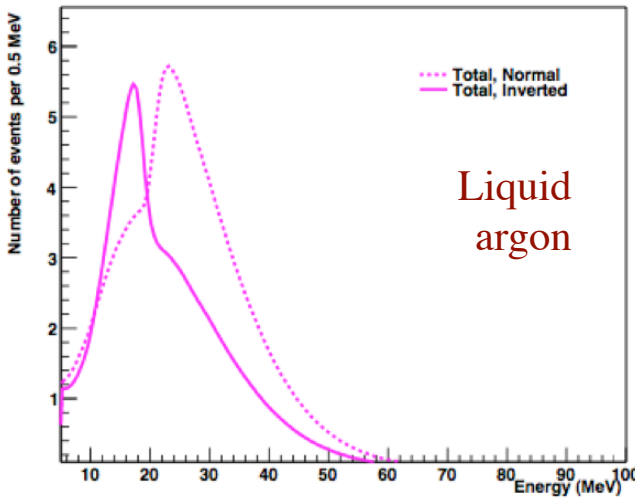



- Mass hierarchy defines the scope for future 0νββ experiments
- Current and future cosmological measurements of Σm in combination with MH determine the absolute mass scale of each ν scale

S. M. Bilenky & C. Giunti
Mod. Phys. Lett. A27, 1230015 (2012)

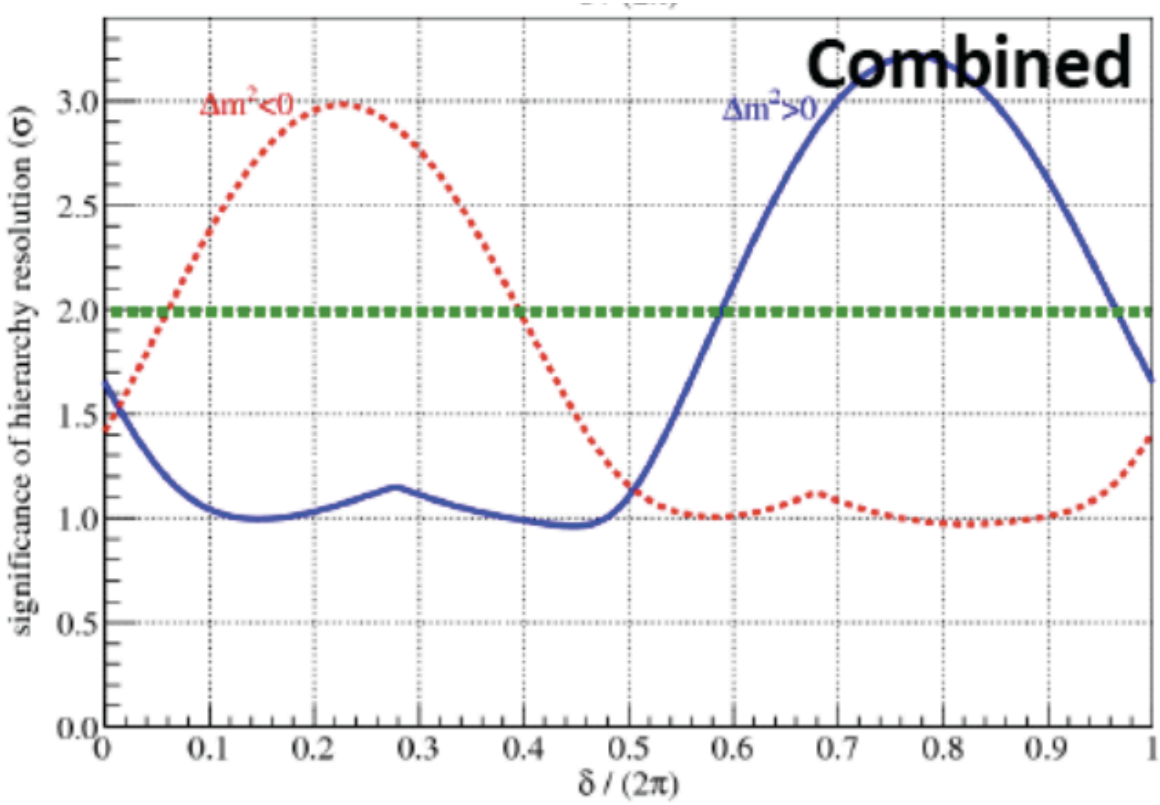
# Supernova




- Robust MSW signal but very complicated dynamics
- Possible signal for a specific S/N model
- Model uncertainties too large to guarantee a definitive measurement
- Hierarchy measurement is a very useful input for S/N models!

# NOvA+T2K

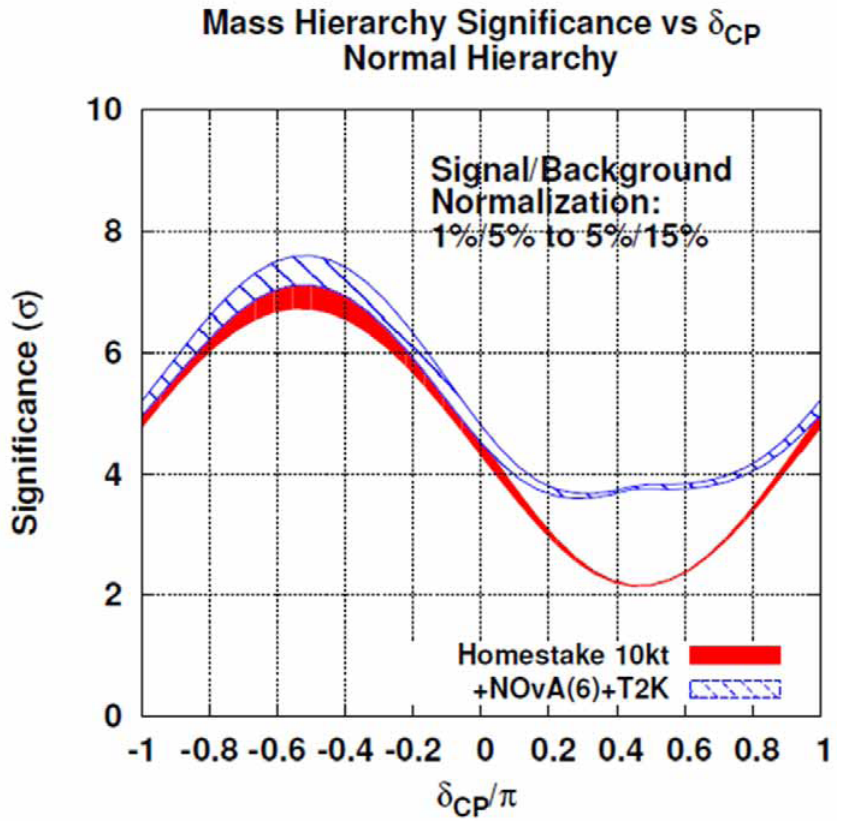



Complementary baselines: T2K measures CP asymmetries, NOvA can then subtract them off from matter effects

Good chance (~40%) to have an indication of the hierarchy before LBNE/HyperK turn on

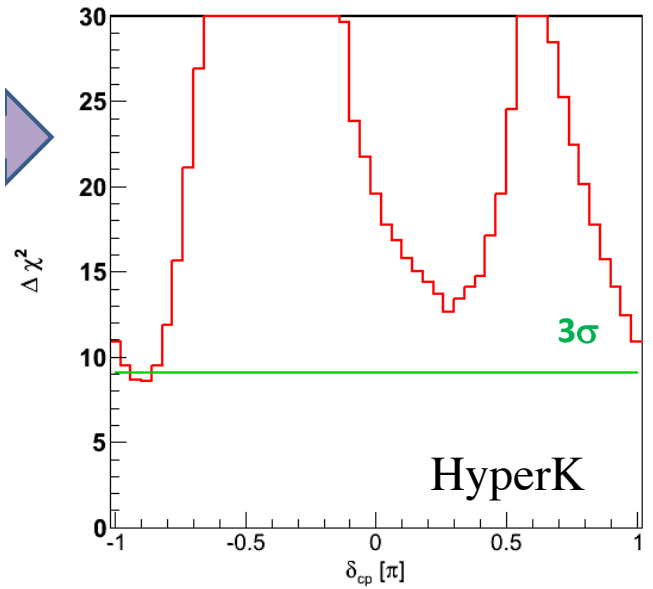
# LBNE

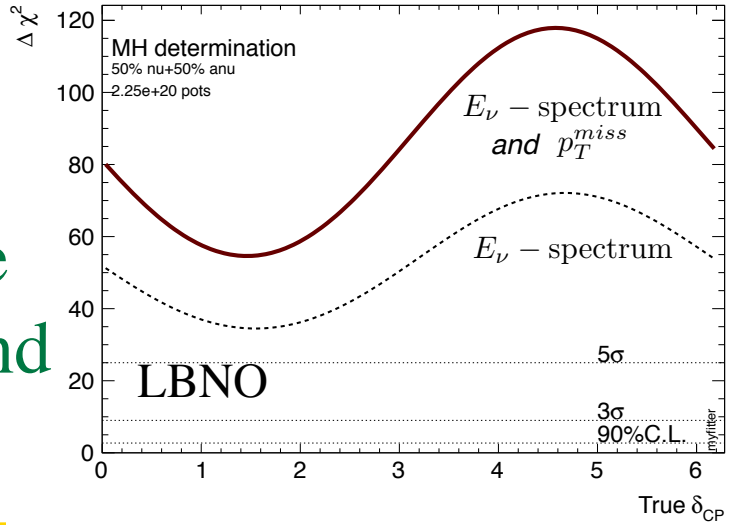
- >3σ stat significance for determination of MH in (in combination with NOvA +T2K) independently of $\delta_{CP}$
  - Major part of US program
- However:
  - Timescale & cost, may not be the first measurement of MH
  - Limited scope (MH, $\delta_{CP}$)
  - Poorly understood nuclear effects



# HyperK and LBNO

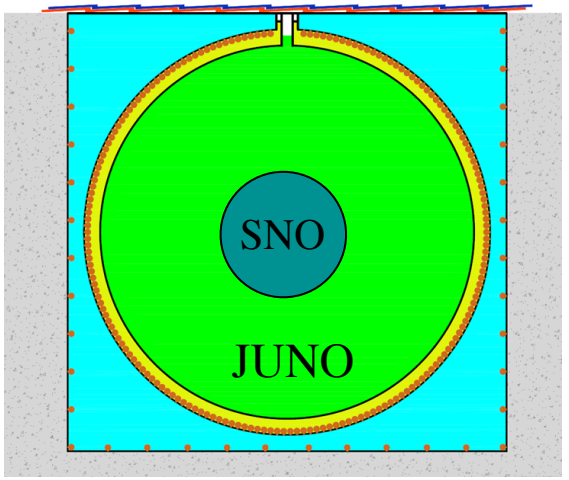
- HyperK: focus on CP and proton decay
  - Large WC detector, short baseline: sensitivity to MH primarily from atmospheric νs
  - Very complementary to LBNE
  - Concerns: costs
- LBNO-LAGUNA
  - Excellent sensitivity to MH due to long baseline CERN→Finland
  - Concern: costs, likelihood

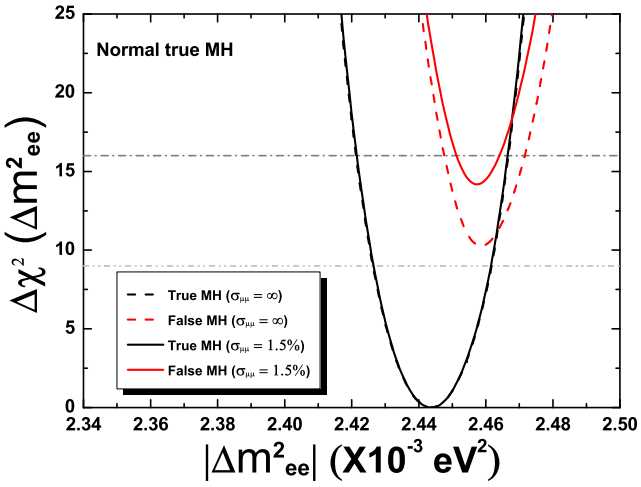


# Reactor Neutrinos (JUNO)

- Statistical sensitivity to MH
- Major project in China (already funded)
- Very challenging measurement
  - Requires major improvements in detector technology (multiple factors of 2)
  - Energy resolution and scale are of paramount importance
  - Improves with percent-level precision on $\Delta m^2_{23}$

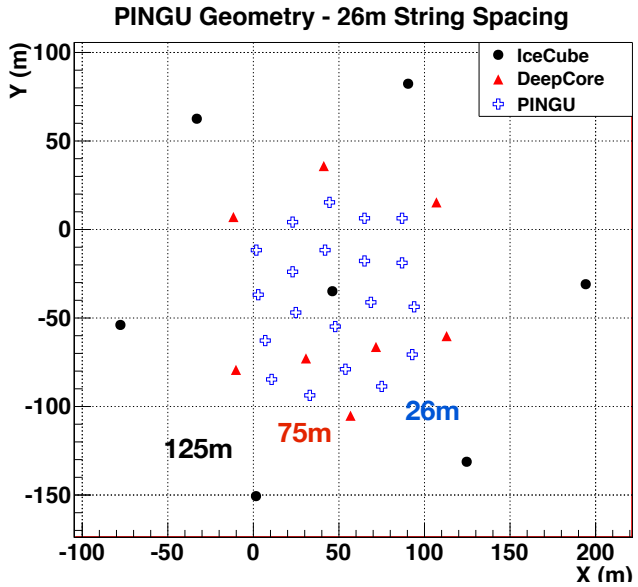


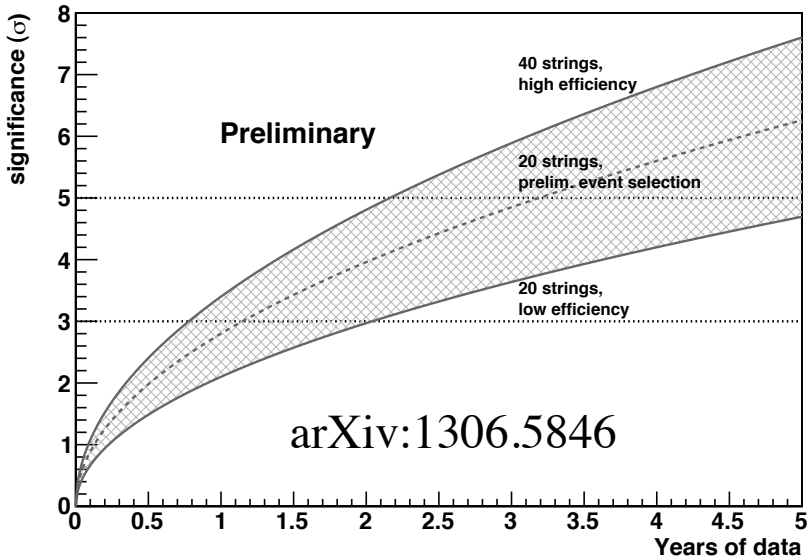




arXiv:1303.6733

# Atmospheric Neutrinos (PINGU)

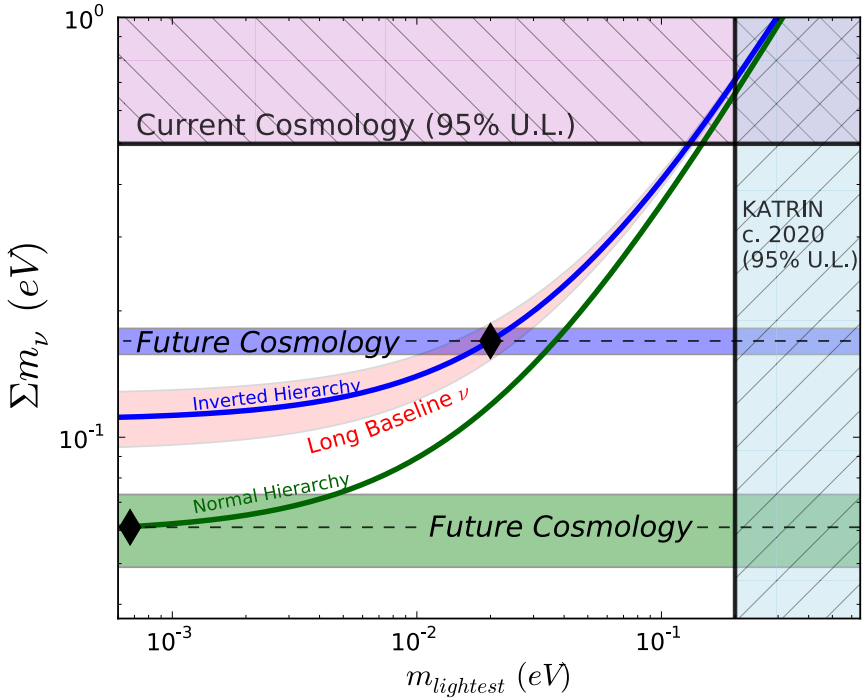
- Excellent statistical sensitivity to MH
  - Modest cost, timescale
- Issues
  - Energy resolution and scale
    - ☞ Impact on sensitivity
    - ☞ Practical calibration techniques
  - Rapid recent progress; disagreement with an independent evaluation of sensitivity needs to be resolved



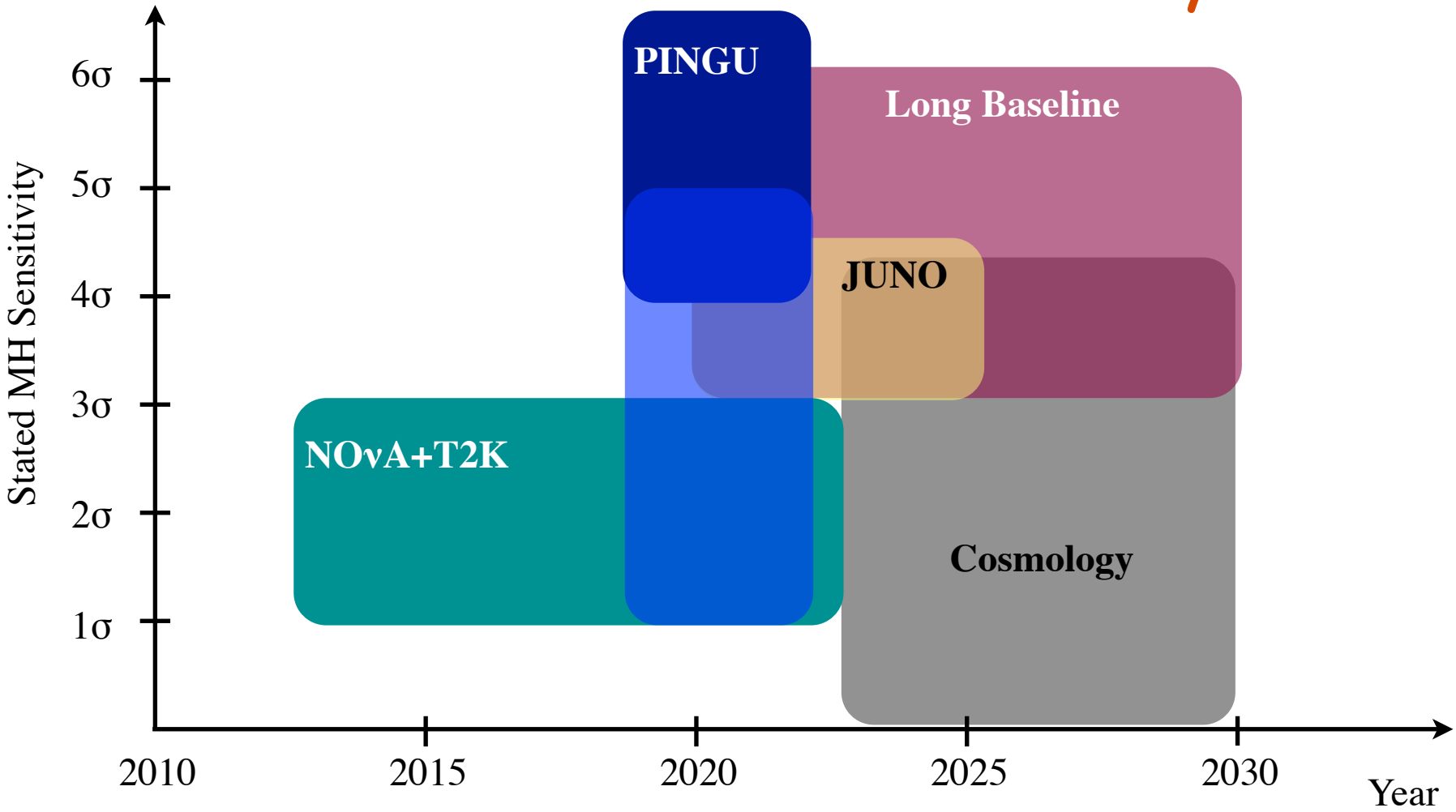
# Cosmological Constraints

- Cosmological fits are sensitive to the *sum* of neutrino masses
  - Direct determination of MH is possible iff MH is normal (sum of masses is small)
    - ☞ Complementarity to terrestrial measurements
    - ☞ 10-15 meV precision on Σm on timescale of 2030
    - ☞ Also will measure the number of (relativistic) neutrinos $N_{eff}$




CF5 report:
K.N. Abazajian, J.E. Carlstrom, A.T. Lee, et. al: http://is.gd/AnSecR
Also K. Abazajian's CF plenary talk on Thu

# Timescale and Sensitivity

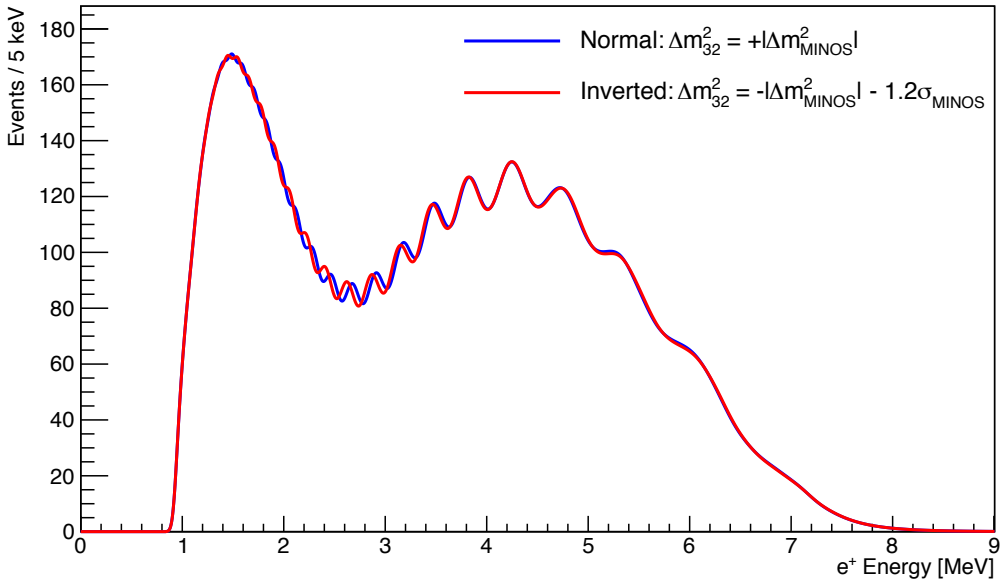



Current projections of sensitivity and schedule. Complementarity of techniques can improve sensitivity of a combined measurement (c.f. arXiv:1306.3988)

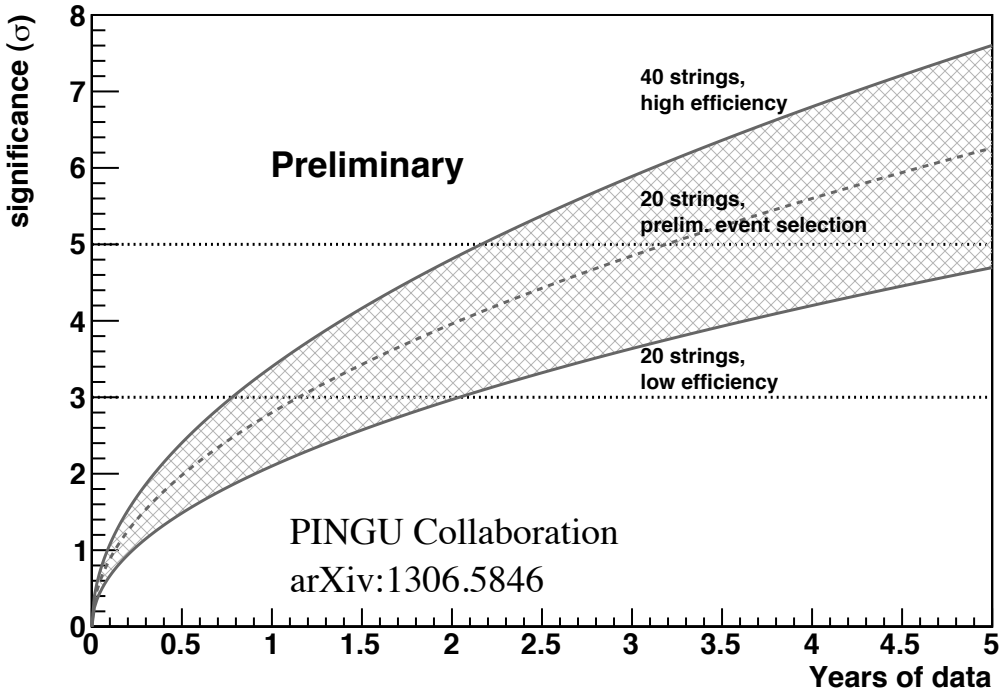
# Backup

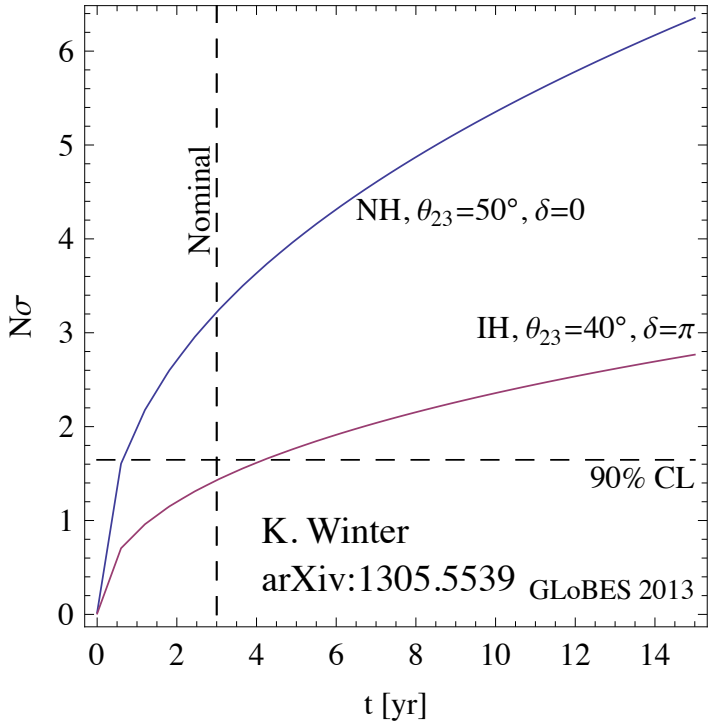
# JUNO

- Very challenging measurement; requires detector technology improvements beyond current state of the art
- Energy resolution critical
- No complete independent verification of sensitivity so far



# PINGU Sensitivity: Two Evaluations




Much recent progress from collaboration

Sensitivity very sensitive to the choice of experimental parameters (efficiency, energy and angular resolution, systematics) and oscillation parameters (in particular, $\Delta m^2_{23}$ )

Needs to be resolved