Prospect for Sensitivity of some Prominent Experiments to Neutrino Mass Ordering

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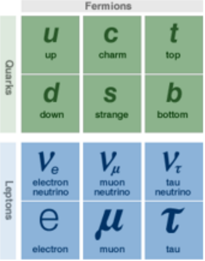
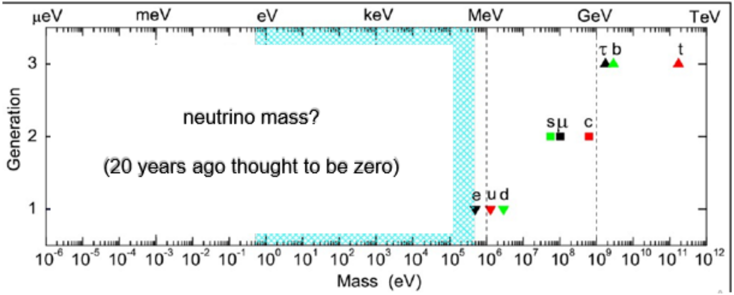
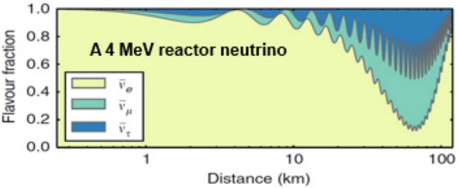
Introduction

- 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 Oscillation



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

$$\downarrow$$

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

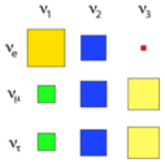
Atmospheric /
Long baseline accelerator

Short baseline reactor /
Long baseline accelerator

Solar /
Long baseline reactor r

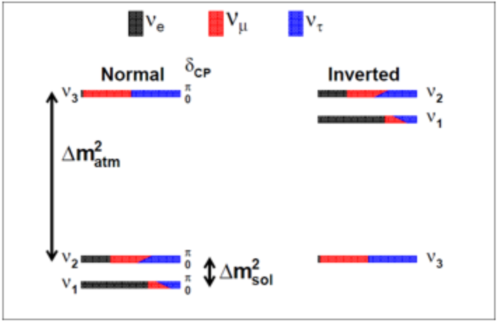
Neutrinoless
double beta decay

- ☐ 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



Knowledge about MO

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



- 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): $\nu_3 > \nu_2 > \nu_1$ (ν_e is lighter)
  - Inverted Hierarchy (IH): $\nu_2 > \nu_1 > \nu_3$ (ν_e is heavier)

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

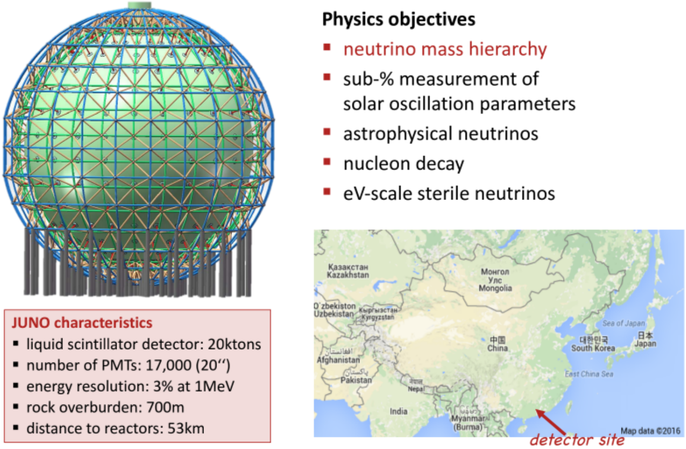
Prominent experiments to detect MO

1. **Medium Baseline Reactor based experiment (JUNO)**
2. **Long Baseline Accelerator based experiment (T2K, NOvA, HK, DUNE)**
3. **Summary**

- **Experimental Overview**
- **Method of determining MO**
- **Challenges/Requirements**
- **Key designs to meet the requirements**

Medium Baseline Reactor based experiments (JUNO)

1.1. Experimental Overview



Physics objectives

- neutrino mass hierarchy
- sub-% measurement of solar oscillation parameters
- astrophysical neutrinos
- nucleon decay
- eV-scale sterile neutrinos

JUNO characteristics

- liquid scintillator detector: 20ktons
- number of PMTs: 17,000 (20'')
- energy resolution: 3% at 1MeV
- rock overburden: 700m
- distance to reactors: 53km

Figure: JUNO experiment overview

Medium Baseline Reactor based experiments (JUNO)

1.2. Method of determining MO
Precision vaccum oscillation measurement

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

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

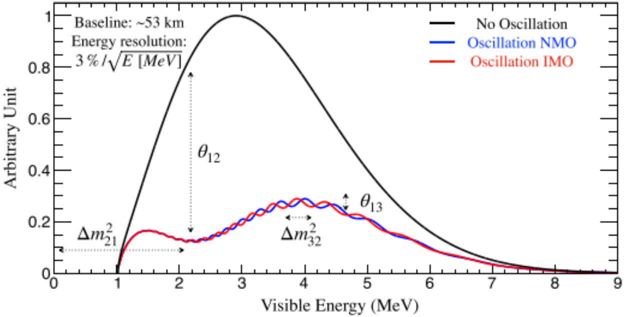


Figure: JUNO neutrino bi-oscillation spectral distorsion

Medium Baseline Reactor based experiment (JUNO)

1.3. Challenges/Requirements

- High statistics (10^5 events in 6 years)
- High Energy resolution ($\tilde{3}\%$ at 1MeV)
- Low Energy scale uncertainty ($< 1\%$)

1.4. Key designs to satisfy the requirements

- Large liquid scintillator volume (20kton)
- High liquid scintillator light yield and transparency
- High PMT coverage and efficiency
- Double (stereo-) calorimetry
- Complementary calibration system
- Using JUNO+TAO

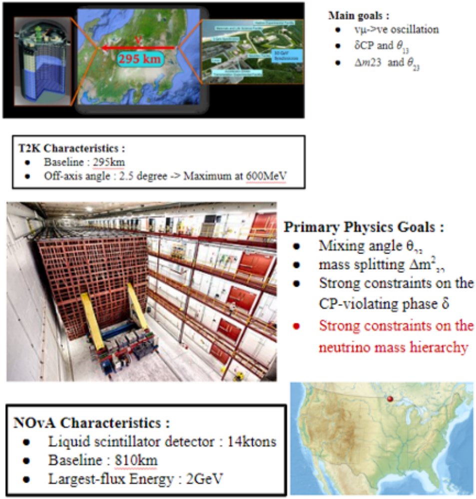
Long Baseline Accelerator Based Experiment

2.1. Experimental Overview

Basically 3 generations :

- First generation : K2K, MINOS, OPERA
- **Second generation : NOvA, T2K**
- **Third generation : DUNE, Hyper-Kamiokande (HK)**

Long Baseline Accelerator Based Experiment (Gen. 2)



Main goals :
- $\nu_\mu \to \nu_e$ oscillation
- δCP and θ_{13}
- $\Delta m23$ and θ_{23}

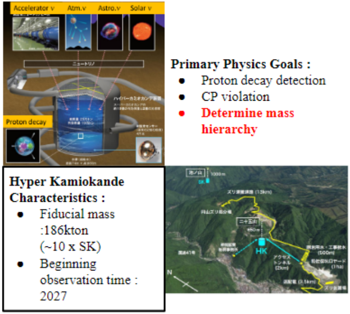
T2K Characteristics :
- Baseline : 295km
- Off-axis angle : 2.5 degree -> Maximum at 600MeV

Primary Physics Goals :
- Mixing angle θ_{23}
- mass splitting Δm^2_{23}
- Strong constraints on the CP-violating phase δ
- Strong constraints on the neutrino mass hierarchy

NOvA Characteristics :
- Liquid scintillator detector : 14ktons
- Baseline : 810km
- Largest-flux Energy : 2GeV

Figure: T2K (Upper) and NOνA (Lower) experiment overview

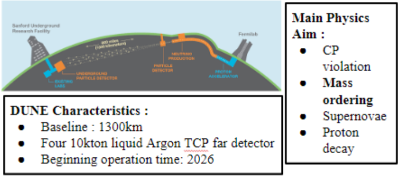
Long Baseline Accelerator Based Experiment (Gen.3)



Primary Physics Goals :
- Proton decay detection
- CP violation
- **Determine mass hierarchy**

Hyper Kamiokande Characteristics :
- Fiducial mass :186kton (~10 x SK)
- Beginning observation time : 2027

Figure: HK experiment overview



DUNE Characteristics :
- Baseline : 1300km
- Four 10kton liquid Argon TCP far detector
- Beginning operation time: 2026

Main Physics Aim :
- CP violation
- **Mass ordering**
- Supernovae
- Proton decay

Figure: DUNE experiment overview

Long Baseline Accelerator Based Experiment

2.2. Method of determining MO

Matter Effect

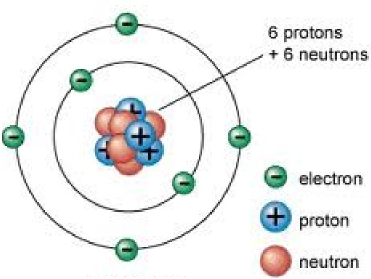


Figure: Atomic structure of Matter

Long Baseline Accelerator Based Experiment

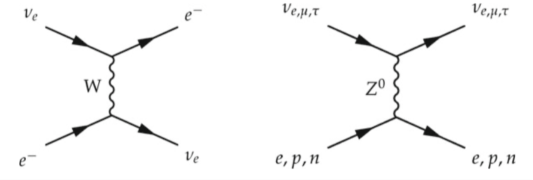


Figure: Feymann diagrams for charged current (left) and neutral current (right) in matter

Charged Current Interaction

- Giving additional effective potential (or "drag") to neutrino
- Only for electron neutrino

Neutral Current Interaction

- Giving additional potential (or "drag") to neutrino
- Affecting all flavors equally

$\Rightarrow$ **Induce an effect that depends on** Δm^2_{21}

Long Baseline Accelerator Based Experiment

Matter Effect

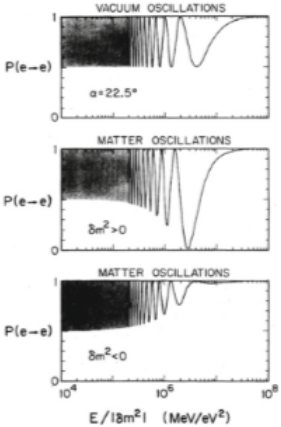


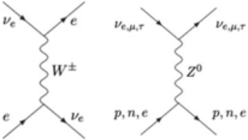
Figure: Survival probability of electron neutrino at baseline L=5x10^3 km

Long Baseline Accelerator Based Experiments

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_c)

$$V_C = \sqrt{2} G_F N_e$$



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

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

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

- ☐ (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 Based Experiments

2.3. Challenges

- Largely dependent on θ_{23}
- Coupled with size of CP phase
- Require precise estimation of matter density
- Require sufficiently long baseline

Summary

Long baseline Accelerator

T2K, NOvA,

HK, DUNE

Via Matter Effect due to Long Baseline

Reactor Experiment

JUNO

Via Oscillation in Vacuum

Sensitivity of Prominent Experiments to MO

Event Rate ≈ Prob. × Flux × Cross Section × Detection Efficiency

Expts.	Baseline(km)	Matter Density(gm/cc)	Matter Potential(eV)
HK	295	2.6	0.94×10^{-13}
T2K	295	2.6	0.94×10^{-13}
NOνA	810	2.8	1.01×10^{-13}
DUNE	1300	3	1.08×10^{-13}

Table: Matter potential and baseline for Experiments

Matter effect in Long Baseline Accelerator Based Experiment

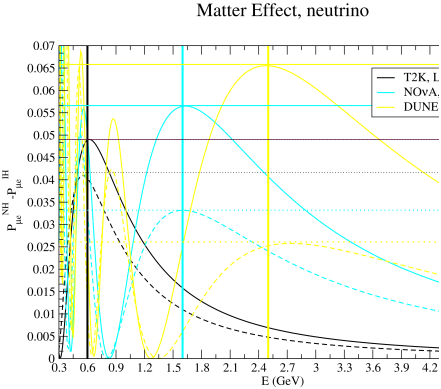
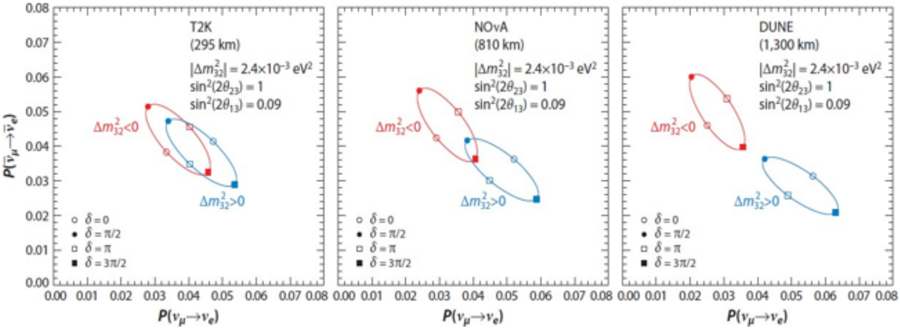


Figure: The plot shows the matter effect in $P_{\mu e}$ in different baselines. The horizontal solid lines represent the $P_{\mu e}$ for NH and the horizontal dashed lines for IH at the first oscillation peak of T2K/T2HK (*black*), NOνA (*cyan*) and DUNE (*yellow*) respectively. The difference $P_{\mu e}^{NH} - P_{\mu e}^{IH}$ represents the magnitude of matter effect in each experiments. $\delta = 0^\circ$ and $\theta_{23} = \pi/4$ is considered. Other parameter are taken from NuFIT 5.1.

Matter Effect in Long Baseline Accelerator Based Experiments

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

Depend on Mixing angle and other parameter also



Impact of θ_{23}

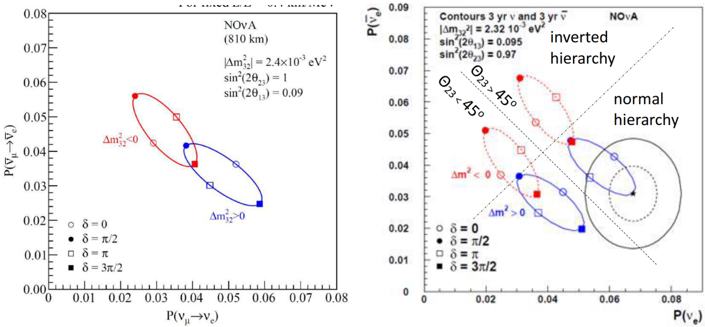


Figure: Left: Maximal θ_{23}. Right: Impact of Upper and Lower octant

T2K and NOνA Sensitivity to MO (2 Gen.)

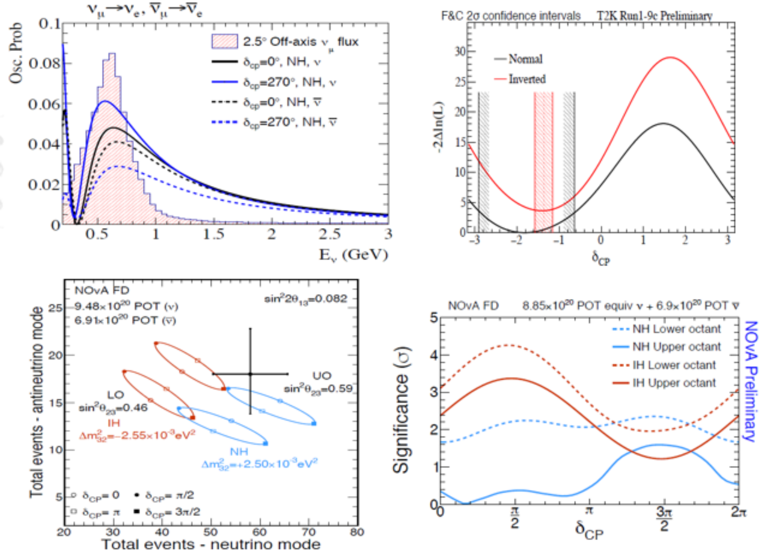


Figure: T2K (upper) and NOνA (lower)

HK and DUNE Sensitivity to MO (3 Gen.)

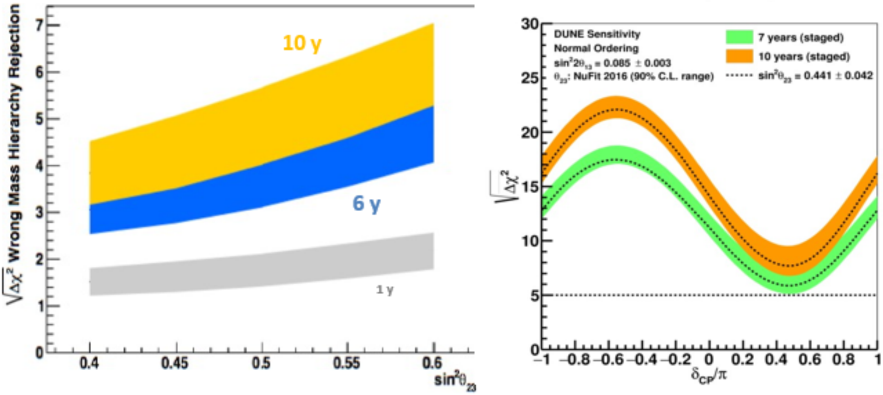
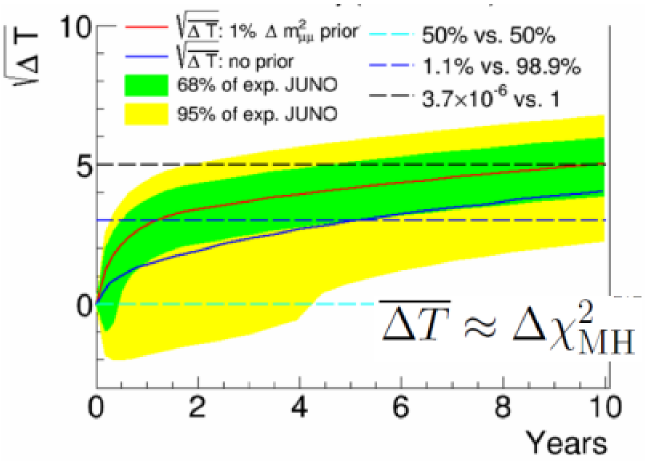
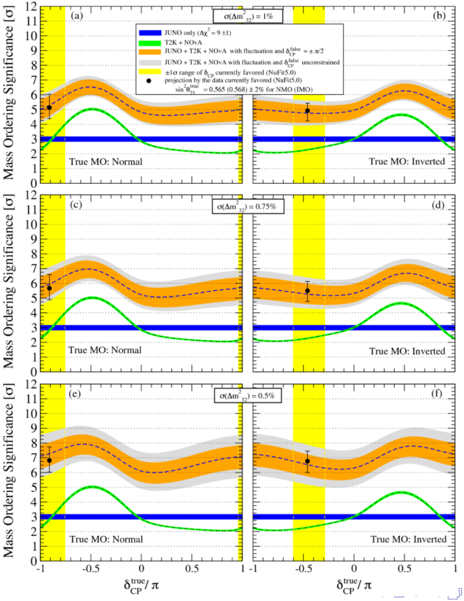


Figure: HK (left) and DUNE (right)

JUNO Sensitivity to MO



Combined Sensitivity to MO



Conclusion

- Neutrino Mass Hierarchy is still a fundamental property that we don't know
- Currently, there is 2σ preference for Normal Ordering from individual experiment: T2K, NOVA, combined with reactor θ_{13} measurement
- Next generation experiments aim to have greator than 3σ sensitivity to MO in a single experiment (2025-2030)
- JUNO is independent of $\delta_C P$ and $\theta_2 3$ but LBL acclerator depend on these parameter.So Two different techniques convering to same result can give a concrete evidence.
- Resolved MO can help to distinguish between different mass models and other aspects related to neutrino mass and CP violaion.

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- We are very grateful to all the Lecturers for their very informative talks and hands-on.
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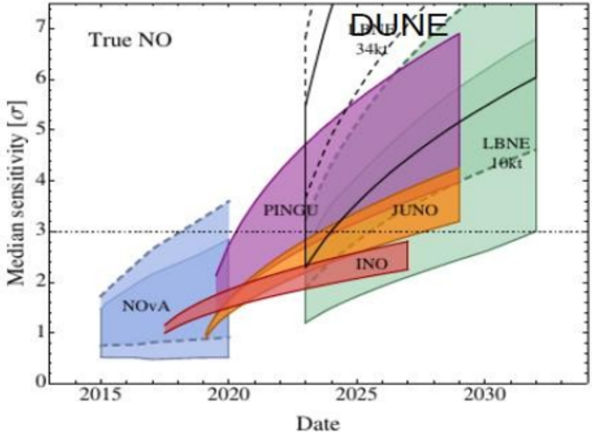

Blennow et al.
JHEP 03 028 (2014)

For illustration assumptions in systematics and dates

THANK YOU