Determination of the neutrino mass ordering

Invisibles 14 workshop, 14-18 July 2014, Paris

Thomas Schwetz

Stockholms universitet

Oskar Klein centre

invisibles neutrinos, dark matter & dark energy physics

MARIE CURIE ACTIONS

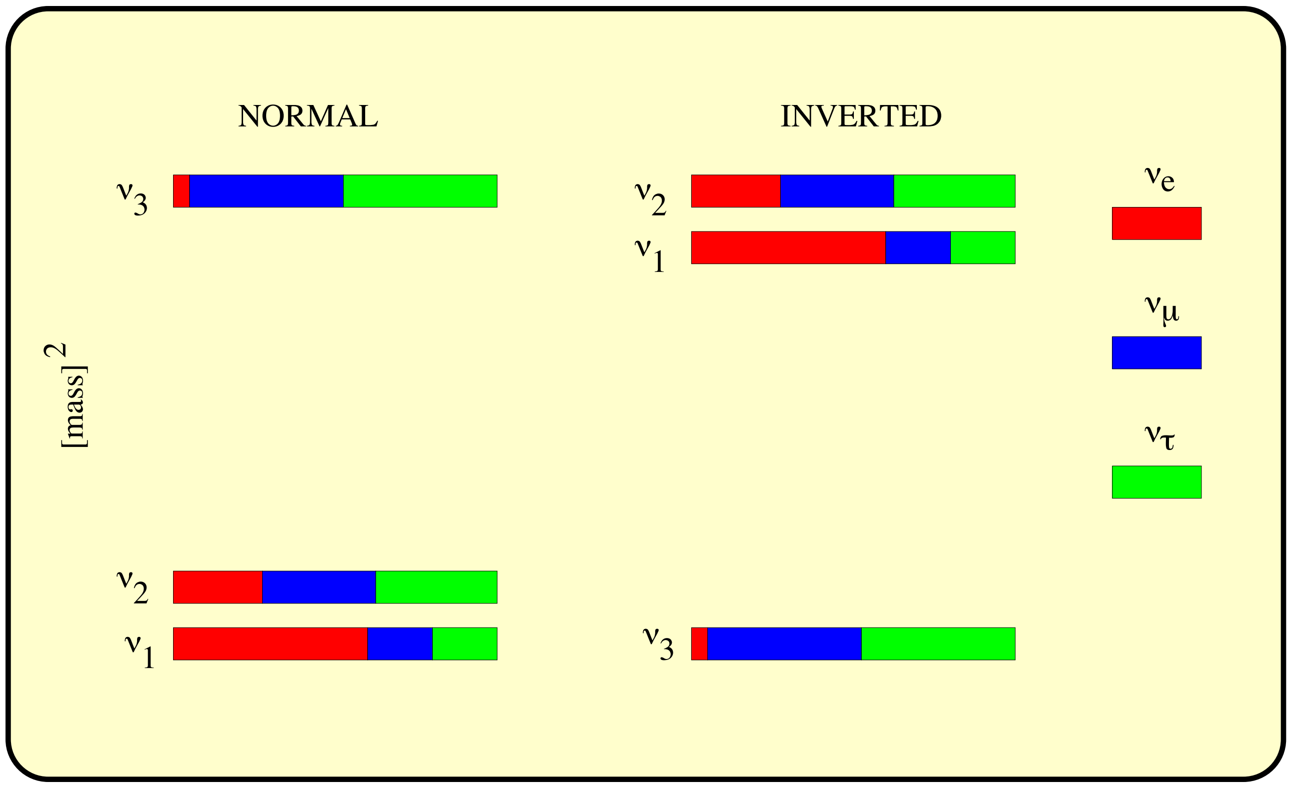
PEOPLE

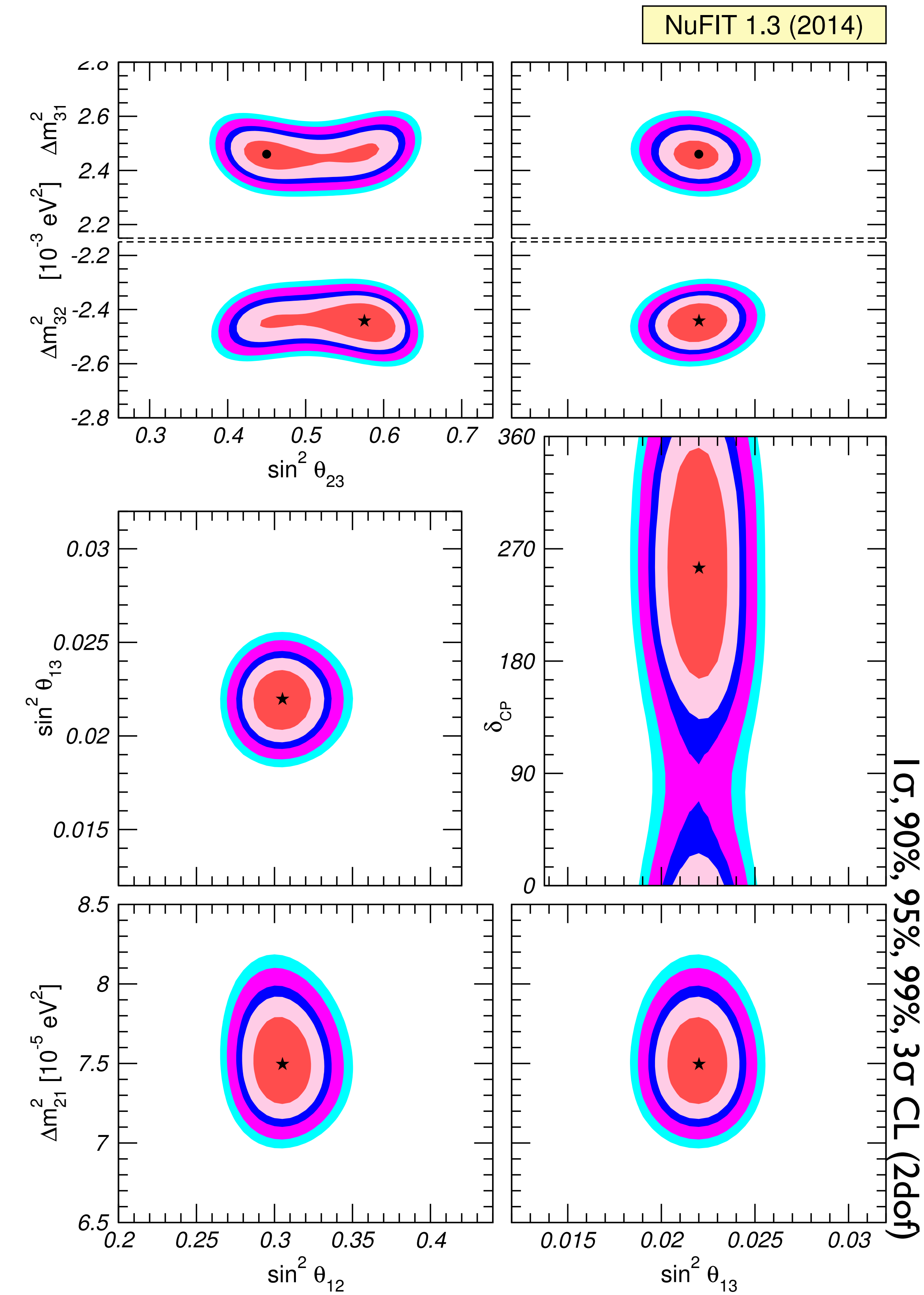
Blennow, Coloma, Huber, Schwetz, arXiv:1311.1822
Blennow, Schwetz, arXiv:1306.3988
Blennow, Schwetz, arXiv:1203.3388

3-flavour global fit to oscillation data

www.nu-fit.org

with C. Gonzalez-Garcia, M. Maltoni





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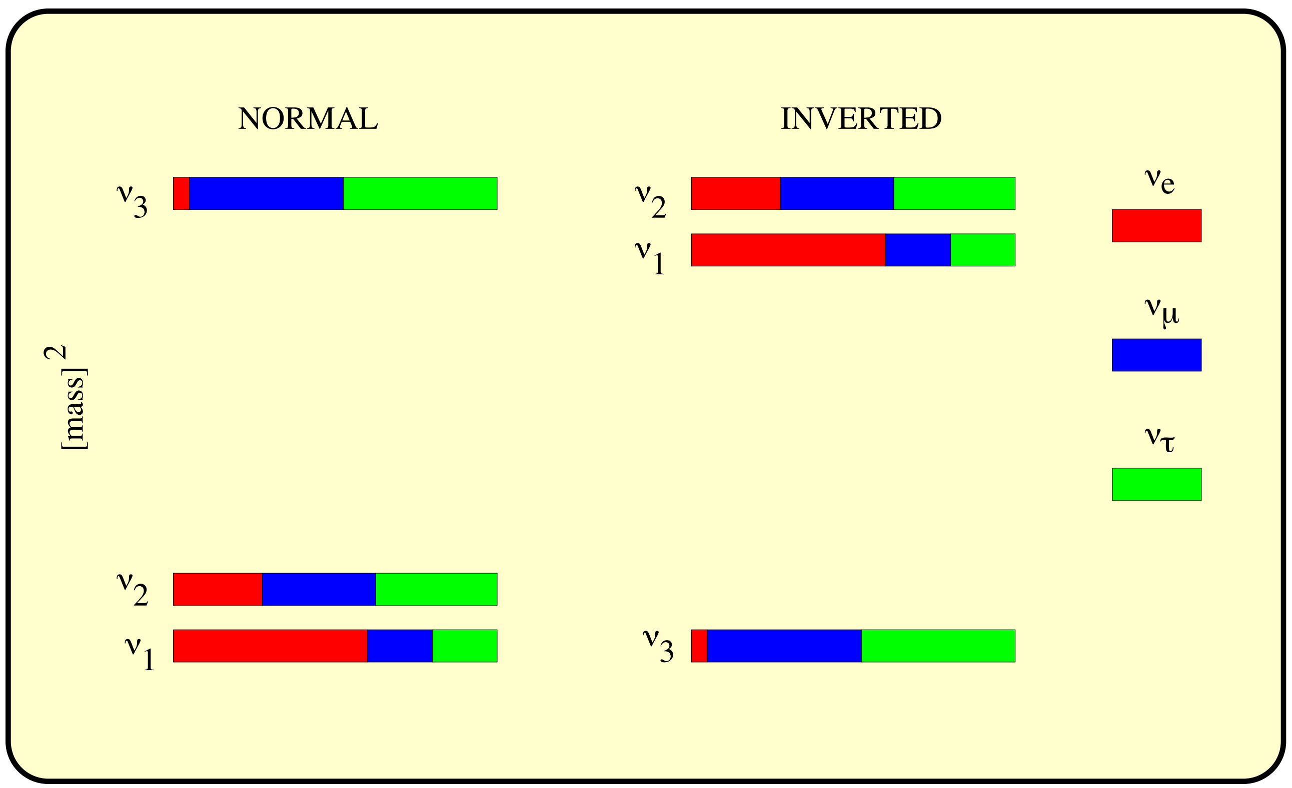
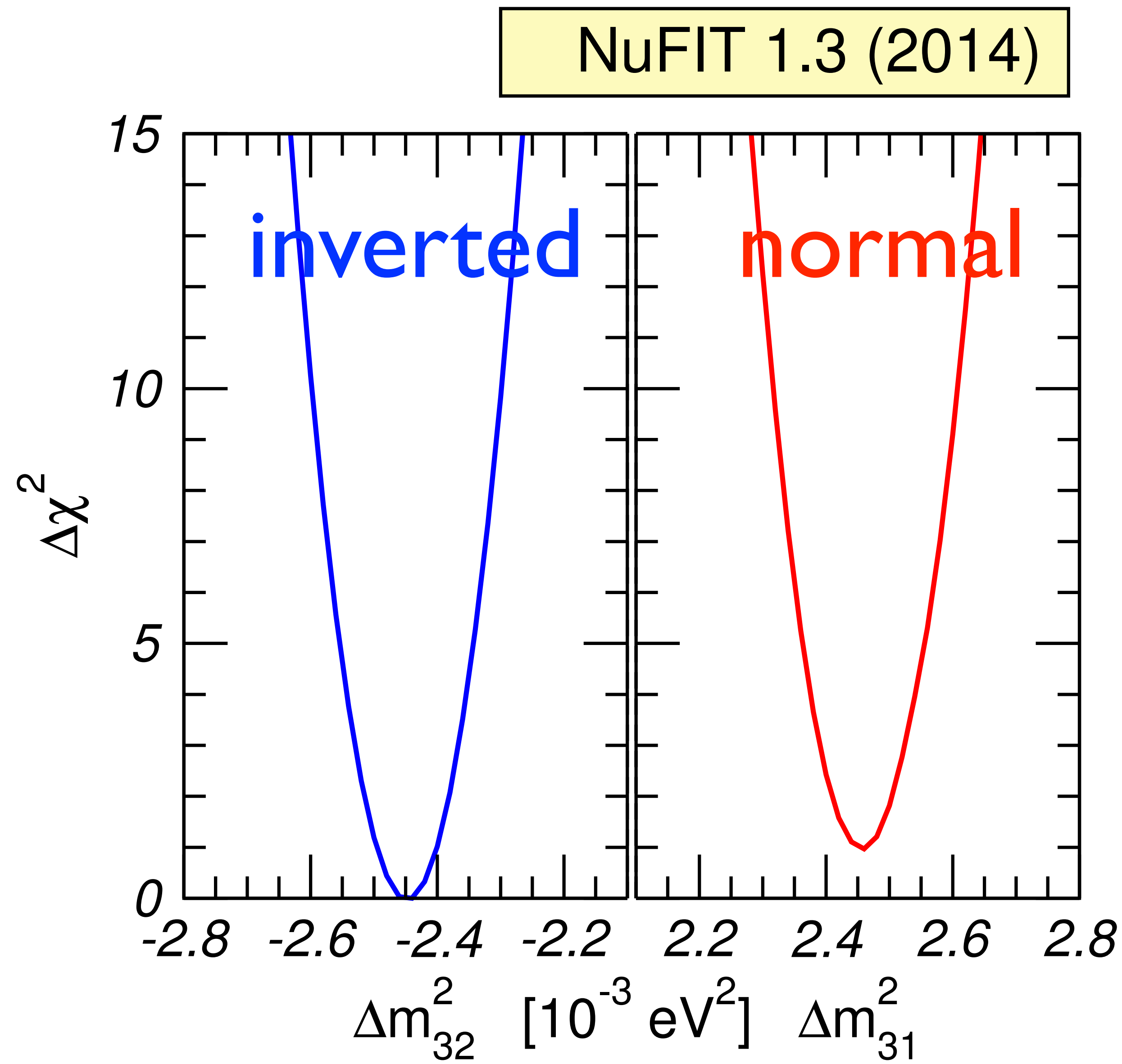
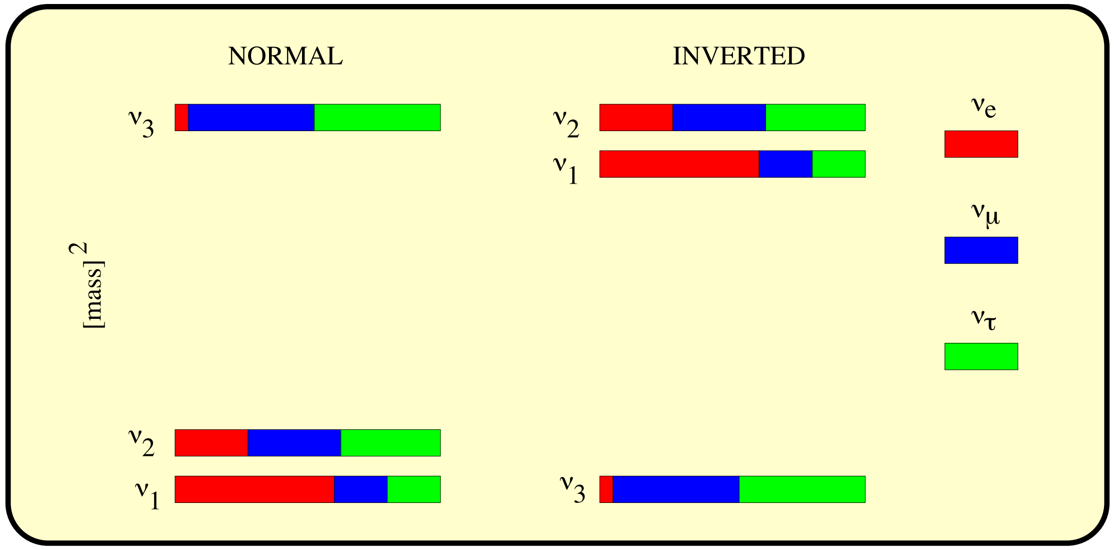




almost complete degeneracy in present data

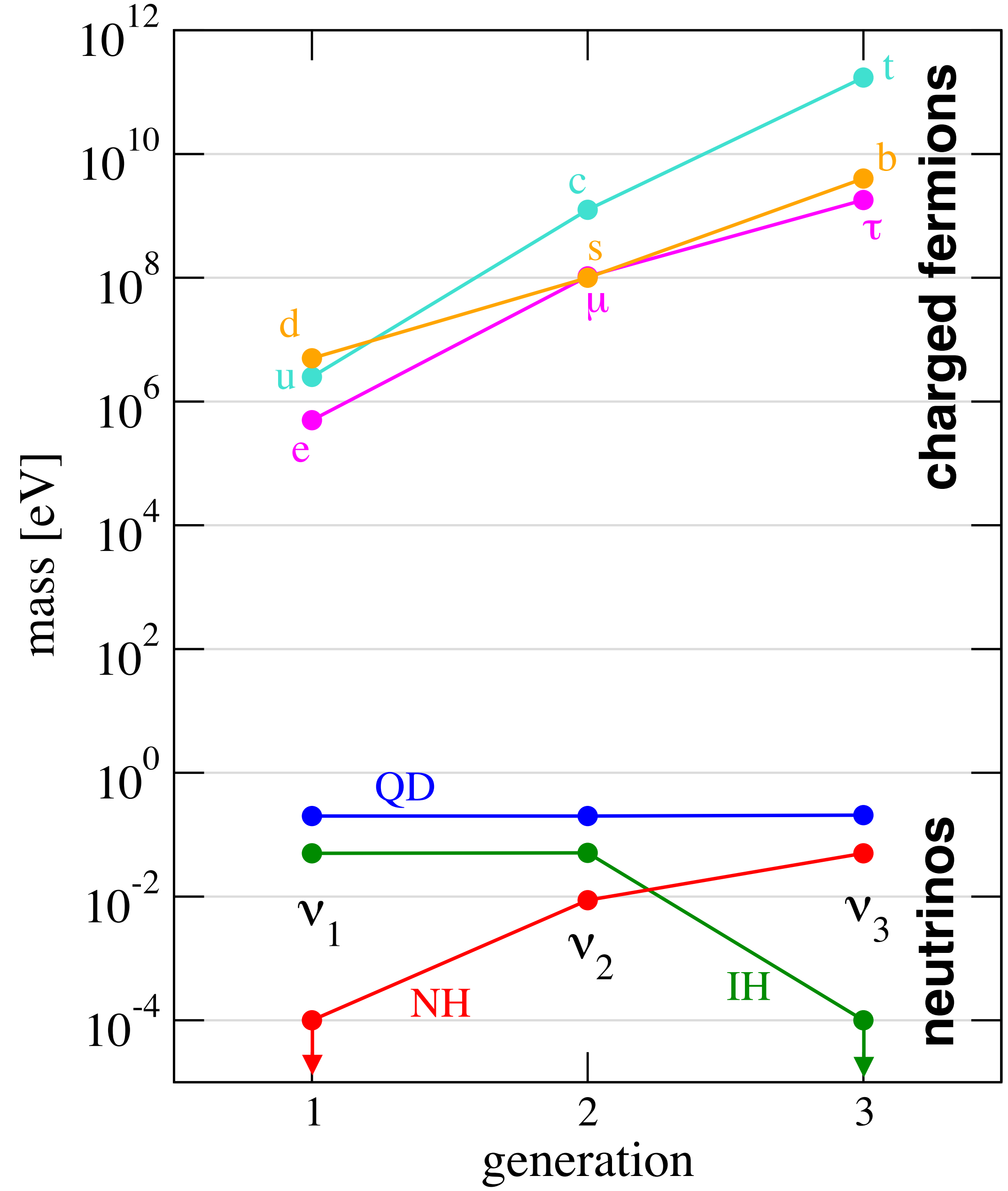
On parameterization and conventions



- *We know that the mass state with a dominant ν_e component ("ν_1") is the lighter of the (ν_1 ν_2) pair ($m_1 < m_2$)*
- *We do not know whether the mass state with the smallest ν_e component ("ν_3") is lighter or heavier than the (ν_1 ν_2) pair* (sign of Δm^2_{31})

normal versus abnormal

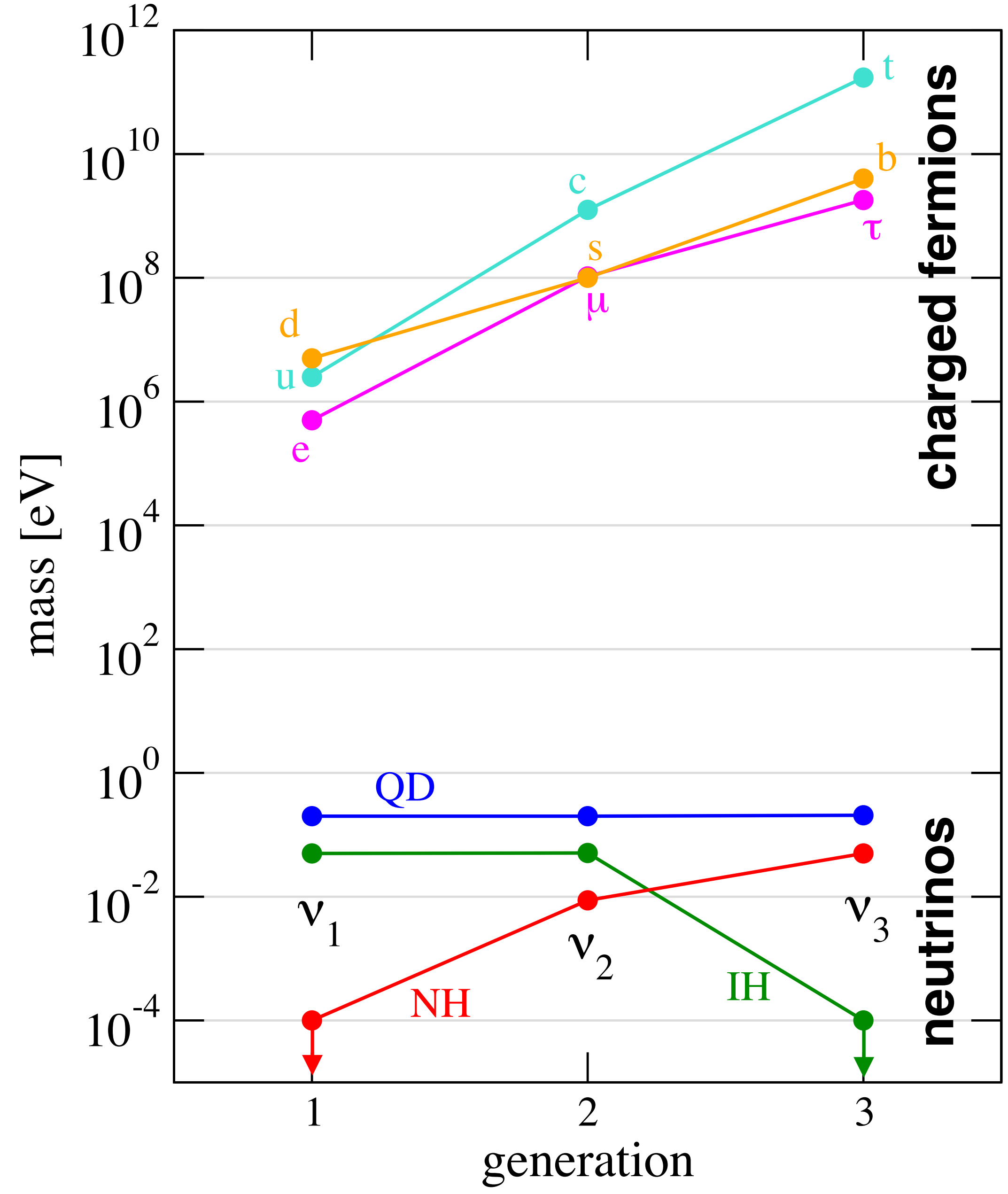
for inverted ordering lepton mixing is very different from quarks:



normal versus abnormal

for inverted ordering lepton mixing is very different from quarks:

- *the neutrino mass state mostly related to the 1st generation is not the lightest*



normal versus abnormal

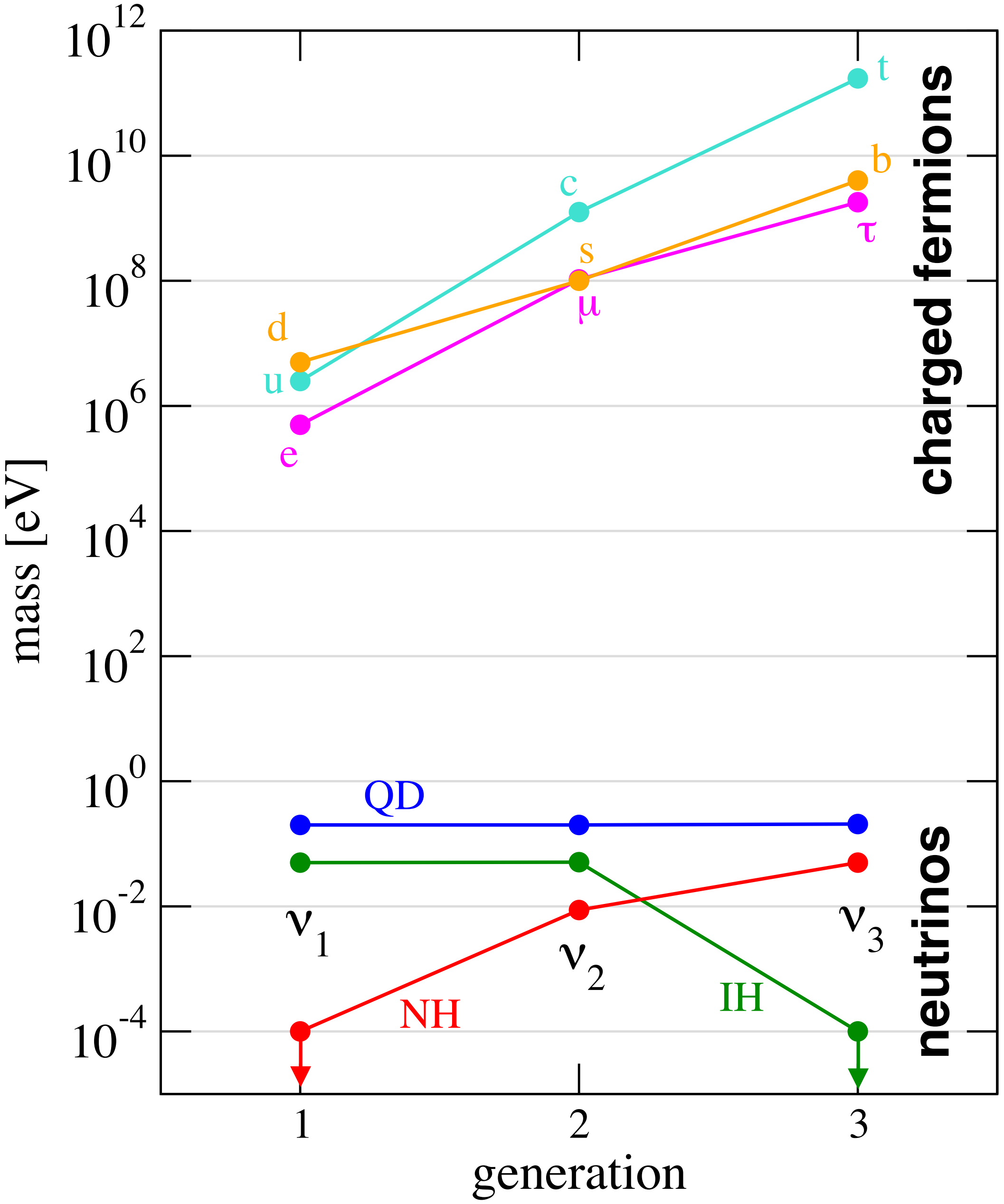
for inverted ordering lepton mixing is very different from quarks:

- *the neutrino mass state mostly related to the 1st generation is not the lightest*
- *there is strong degeneracy between at least two mass states*

$$deg \equiv \frac{m_2 - m_1}{\overline{m}} = 2\frac{\Delta m^2_{21}}{(m_1 + m_2)^2}$$

$$\approx \frac{1}{2}\frac{\Delta m^2_{21}}{|\Delta m^2_{31}| + m^2_3} \leq \frac{1}{2}\frac{\Delta m^2_{21}}{|\Delta m^2_{31}|}$$

$$1.3 \times 10^{-3} \left(\frac{\sum m_i}{0.5\,\mathrm{eV}}\right)^{-2} \leq deg \leq 1.8 \times 10^{-2}$$



How to determine the mass ordering?

- *Matter effect in the 1-3 sector*
- *Interference of (vacuum) oscillations with Δm^2_{21} and Δm^2_{31}*

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Both methods depend on θ_{13}

- *many experimental options are open, thanks to "large" value of θ_{13}*

How to determine the mass ordering?

- *Matter effect in the 1-3 sector*
- *Interference of (vacuum) oscillations with Δm^2_{21} and Δm^2_{31}*

not discussed here:

- *Supernova: need to get lucky (to have a SN explode + have detector)*
- *neutrino mass from cosmology*
- *other ideas....*

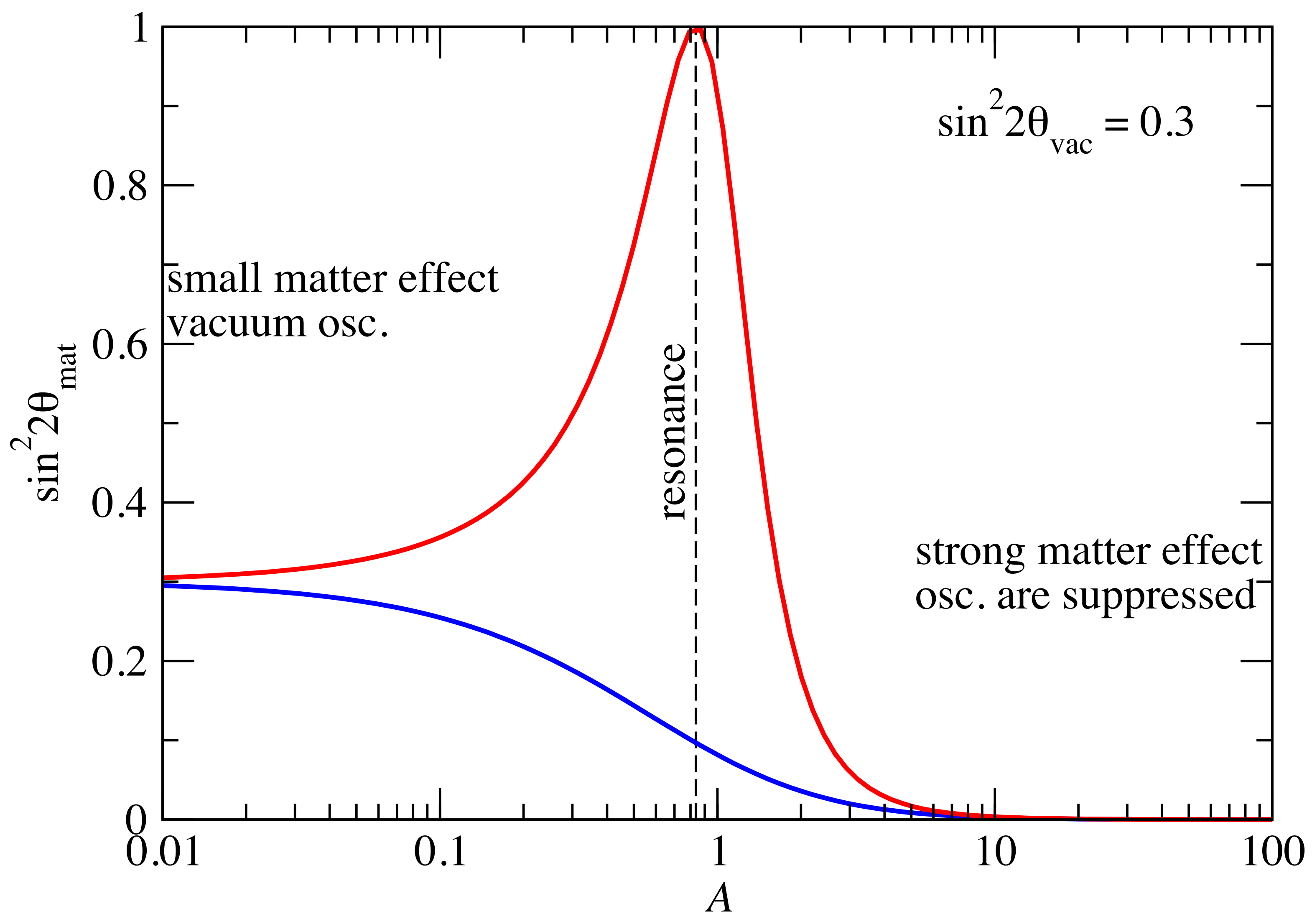
How to determine the mass ordering?

- Matter effect in the 1-3 sector
  - long-baseline accelerator experiments
    NOvA, LBNE, LBNO, ESS-SB, NuFact
  - atmospheric neutrinos INO, PINGU, ORCA, HyperK
- Interference of oscillations with Δm^2_{21} and Δm^2_{31}
  - Reactor experiment at ~60 km JUNO, RENO50

Matter effect - MSW resonance

$$\sin^2 2\theta_{\text{mat}} = \frac{\sin^2 2\theta}{\sin^2 2\theta + (\cos 2\theta - A)^2} \qquad A \equiv \pm \frac{2EV}{\Delta m^2}$$

resonance for $\cos 2\theta = A$



Long-baseline experiments

look for matter effect in $\nu_\mu \rightarrow \nu_e$ transitions

$$
\begin{aligned}
P_{\mu e} \simeq\ & \sin^2 2\theta_{13} \sin^2\theta_{23} \frac{\sin^2(1-A)\Delta}{(1-A)^2} \\
+\ & \sin 2\theta_{13}\ \hat{\alpha}\ \sin 2\theta_{23} \frac{\sin(1-A)\Delta}{1-A} \frac{\sin A\Delta}{A} \cos(\Delta + \delta_{\rm CP}) \\
+\ & \hat{\alpha}^2\ \cos^2\theta_{23} \frac{\sin^2 A\Delta}{A^2}
\end{aligned}
$$

with

$$
\Delta \equiv \frac{\Delta m^2_{31} L}{4E_\nu}, \quad \hat{\alpha} \equiv \frac{\Delta m^2_{21}}{\Delta m^2_{31}} \sin 2\theta_{12}, \quad A \equiv \frac{2E_\nu V}{\Delta m^2_{31}}
$$

- *correlation with CP phase important - "sign degeneracy"*

Long-baseline experiments

look for matter effect in $\nu_\mu \to \nu_e$ transitions

- *In vaccum, $P_{\mu e}$ for neutrinos and antineutrinos are invariant under* *Minakata, Nunokawa, JHEP 01*

$$\Delta m^2_{31} \to -\Delta m^2_{31}\,, \quad \delta_{\rm CP} = \pi - \delta_{\rm CP}$$

- *Leading order in A << 1 cannot break the degeneracy* *TS, hep-ph/0703279*
- *need to observe "strong" matter effect*

Long-baseline experiments

look for matter effect in $\nu_\mu \to \nu_e$ transitions

size of the matter effect:

$$A \simeq 0.09 \left(\frac{E}{\mathrm{GeV}}\right)\left(\frac{|\Delta m^2_{31}|}{2.5\times 10^{-3}\,\mathrm{eV}^2}\right)^{-1}$$

for experiments at the 1st osc. max, $|\Delta m^2_{31}|L/2E \simeq \pi$, and

$$A \simeq 0.02 \left(\frac{L}{100\,\mathrm{km}}\right)$$

need $L \gtrsim 2000$ km and $E_\nu \gtrsim 5$ GeV in order to reach the regime of strong matter effect $A \gtrsim 0.5$.

Long-baseline experiments

- NOvA: Fermilab → 820 km
  have seen already few neutrinos!
- LBNE: Fermilab → Homestake, 1300 km
  LAr detector (10 - 34 kt)
- LBNO: CERN → ? (Finnland 2300 km)
  LAr detector (20 - ? kt)
- ESS-SB: Lund → ? (360 / 540 km)
  WC detector
- Neutrino Factory: ?

On the sensitivity statistics

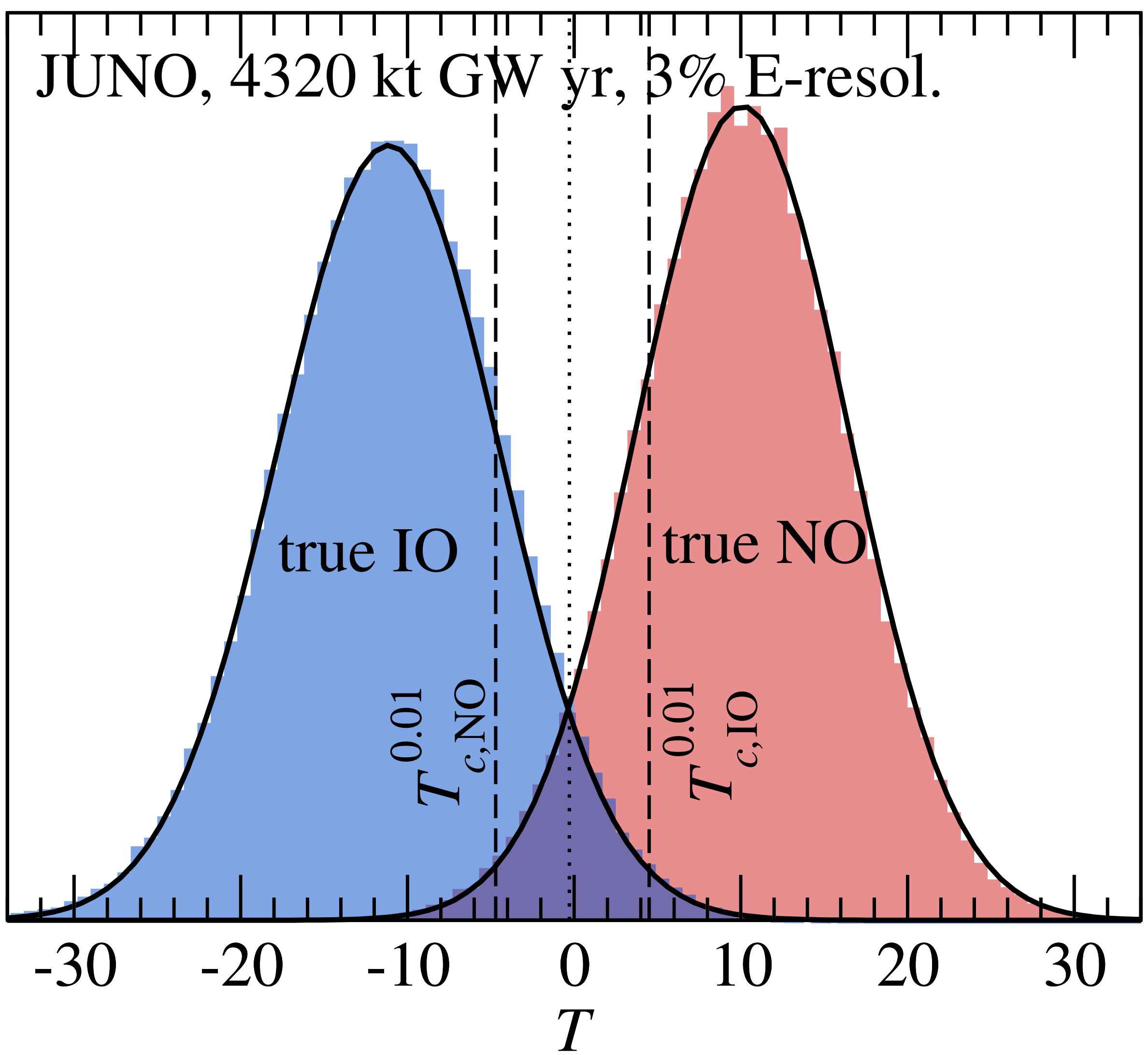
To quantify the sensitivity of an experiment we need to specify two numbers (errors of first and second kind):

- *Decide on a CL at which you want to exclude a certain hypothesis.*
- *Determine how likely it is that a given experiment will exclude the hypothesis at that CL.*

On the sensitivity statistics

define a test statistics and find out its distribution

$$T = \min_{\theta \in \mathrm{IO}} \chi^2(\theta) - \min_{\theta \in \mathrm{NO}} \chi^2(\theta)$$



On the sensitivity statistics

Under certain conditions T is normal distributed:

$$T = \mathcal{N}(\pm T_0, 2\sqrt{T_0})$$

Qian et al, 1210.3651
Blennow et al, 1311.1822

with

$$T_0^{\rm NO}(\theta_0) = \min_{\theta\in{\rm IO}} \sum_i \frac{[\mu_i^{\rm NO}(\theta_0) - \mu_i^{\rm IO}(\theta)]^2}{\sigma_i^2}$$

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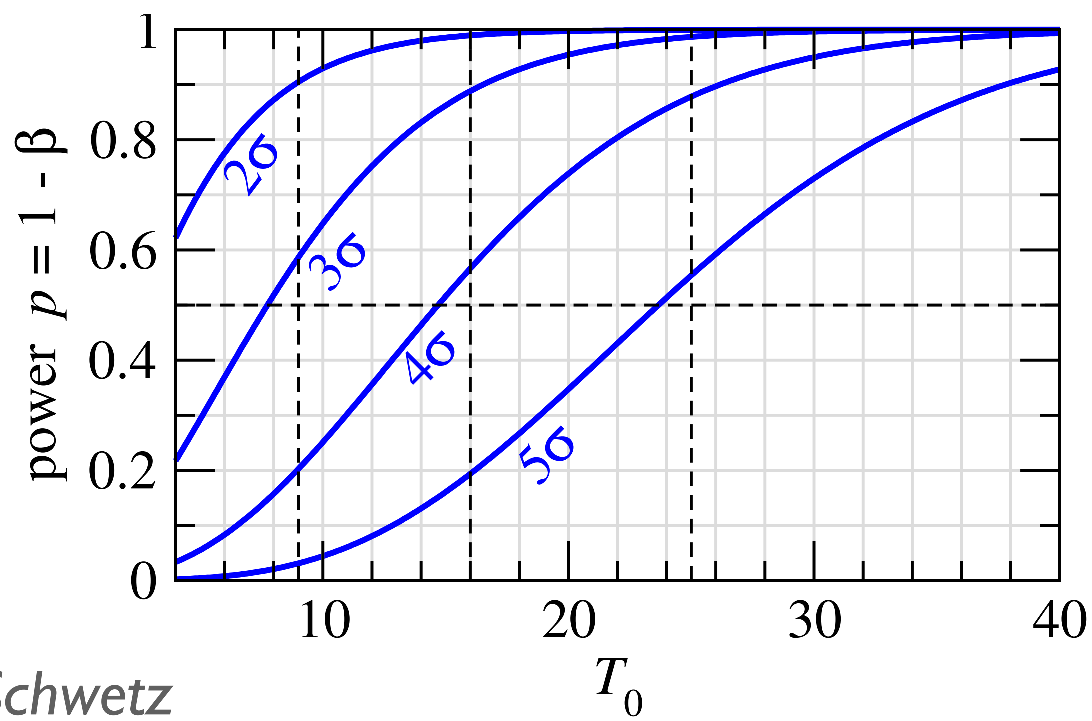

sensitivity of the median experiment (in sigma) is given approximately by

$$n(\sigma) \approx \sqrt{T_0}$$

On the sensitivity statistics

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Qian et al, 1210.3651
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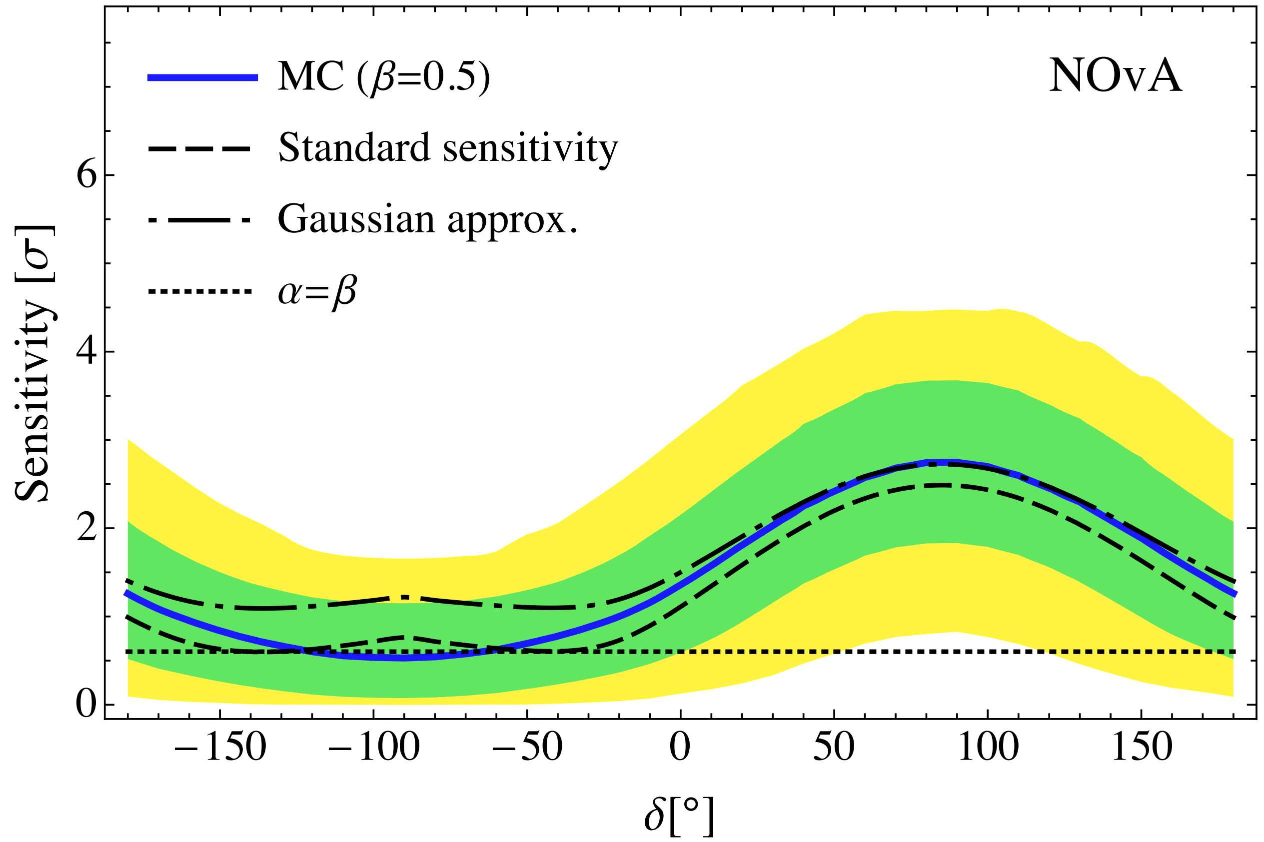
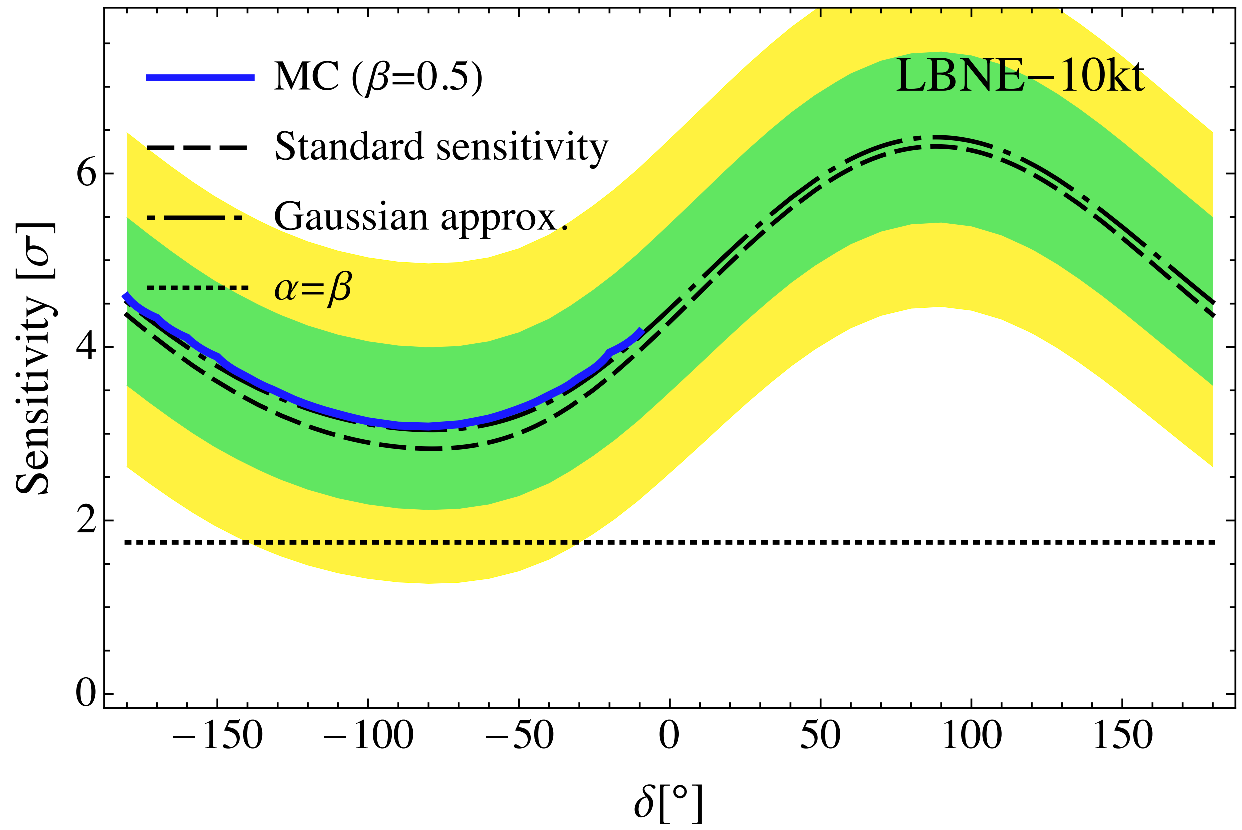
$$T_0^{\rm NO}(\theta_0) = \min_{\theta \in {\rm IO}} \sum_i \frac{[\mu_i^{\rm NO}(\theta_0) - \mu_i^{\rm IO}(\theta)]^2}{\sigma_i^2}$$

- *For most experiments we simulated the Gaussian approximation is good (to excellent)*
- *largest deviations found for NOvA*

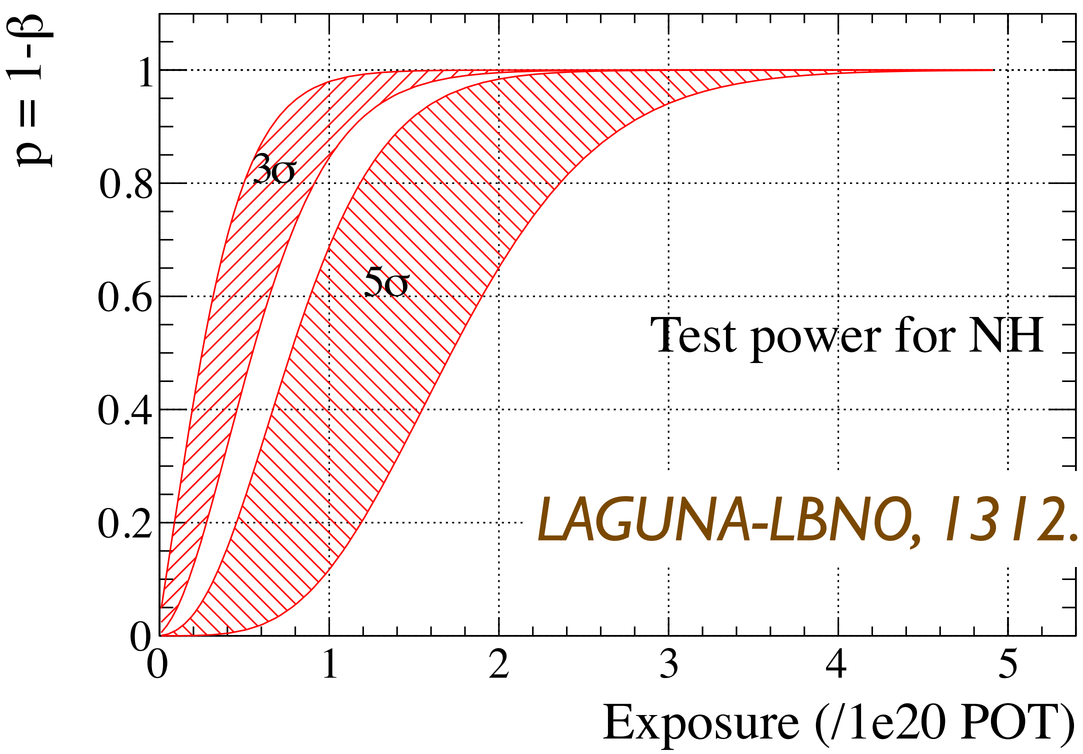
NOvA and LBNE





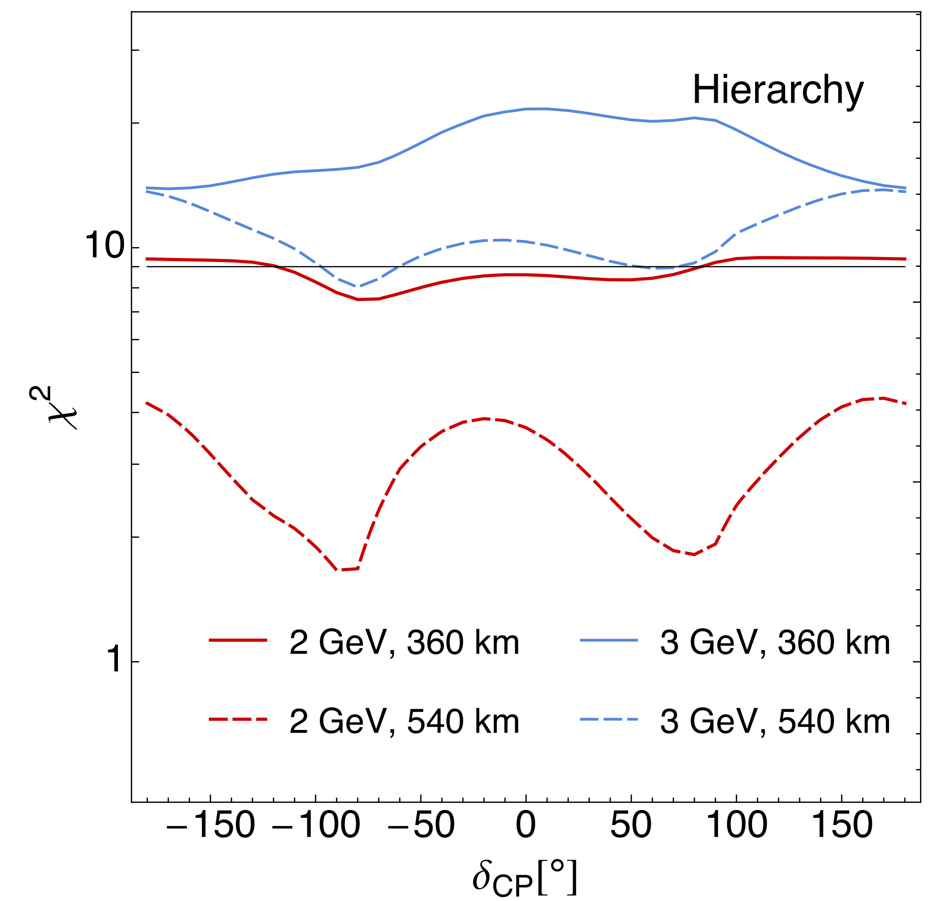
Blennow, Coloma, Huber, TS, 1311.1822

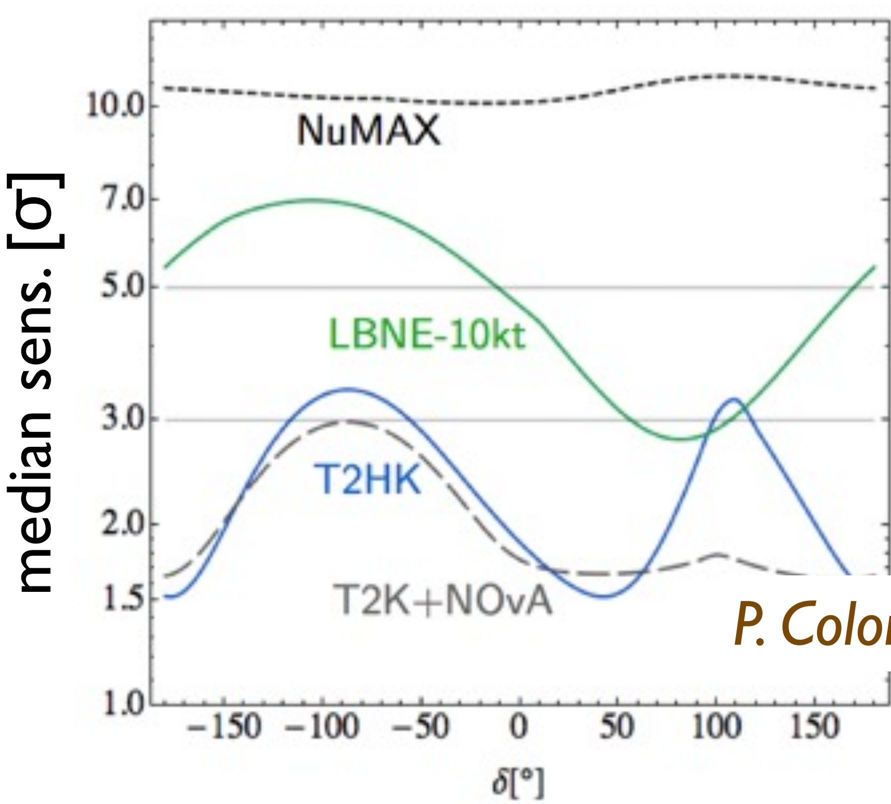
Other LBL sensitivities



LAGUNA-LBNO, 1312.6520

ESS-SB, 1309.7022



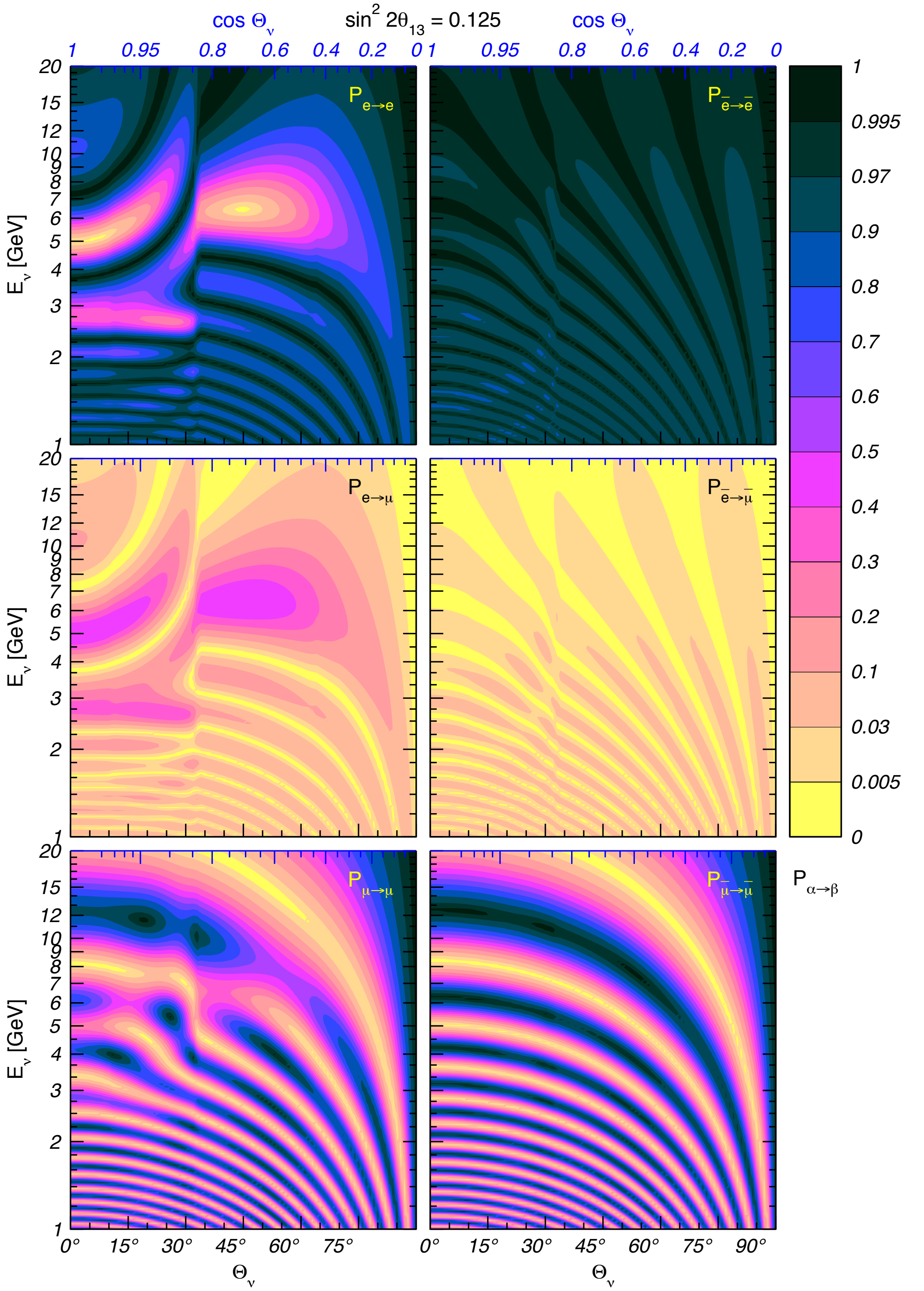


P. Coloma, '14

Atmospheric neutrinos

atmospheric neutrino fluxes

$$\phi_{\nu_\mu},\ \phi_{\nu_e},\ \phi_{\bar\nu_\mu},\ \phi_{\bar\nu_e}$$



Akhmedov, Maltoni, Smirnov 06

Atmospheric neutrinos

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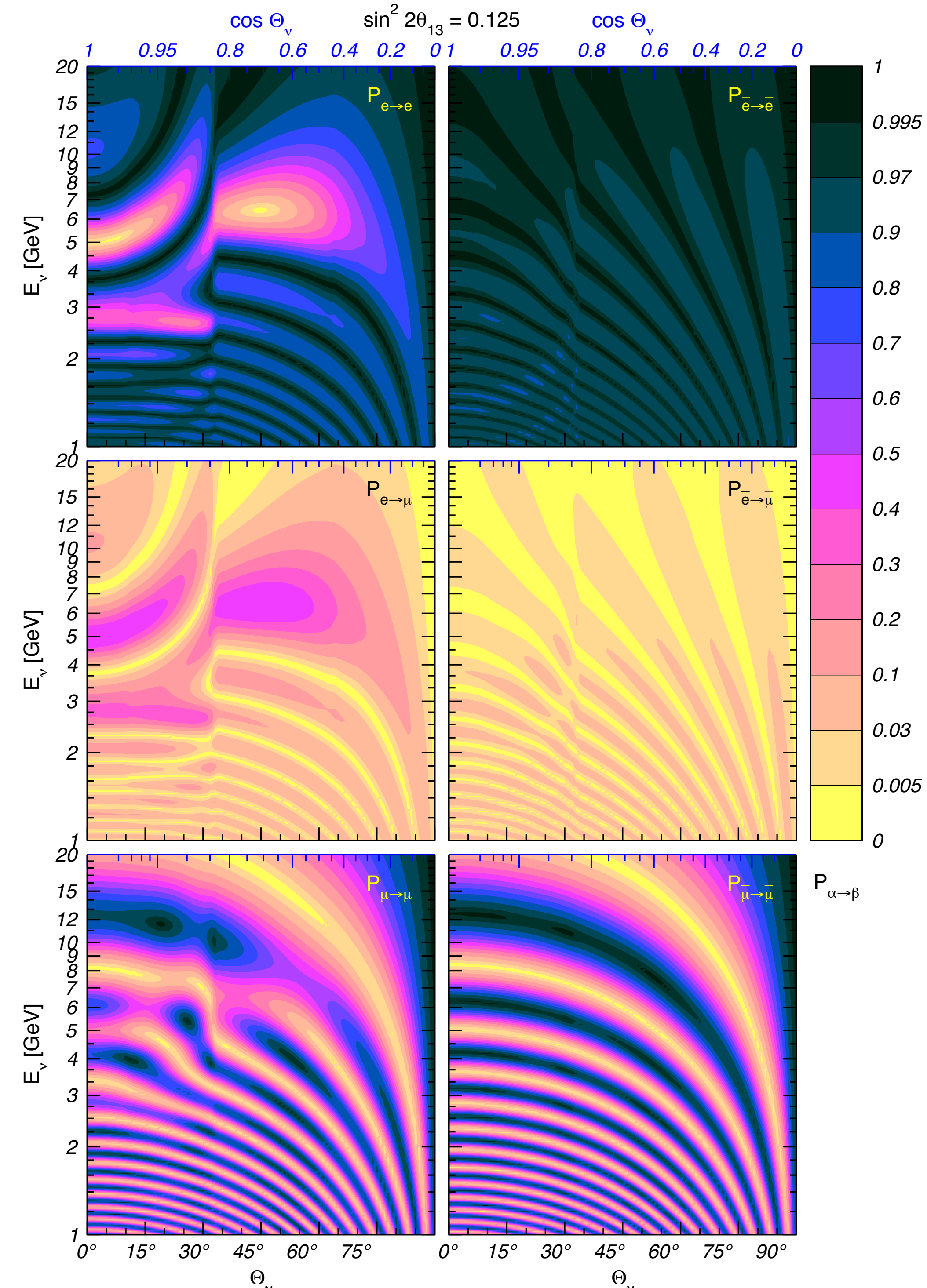
$$\phi_{\nu_\mu},\ \phi_{\nu_e},\ \phi_{\bar{\nu}_\mu},\ \phi_{\bar{\nu}_e}$$

ex.: μ-like events

$$N_\mu \sim [\phi_{\nu_\mu} P_{\nu_\mu\to\nu_\mu} + \phi_{\nu_e} P_{\nu_e\to\nu_\mu}]\sigma_{\nu_\mu}$$



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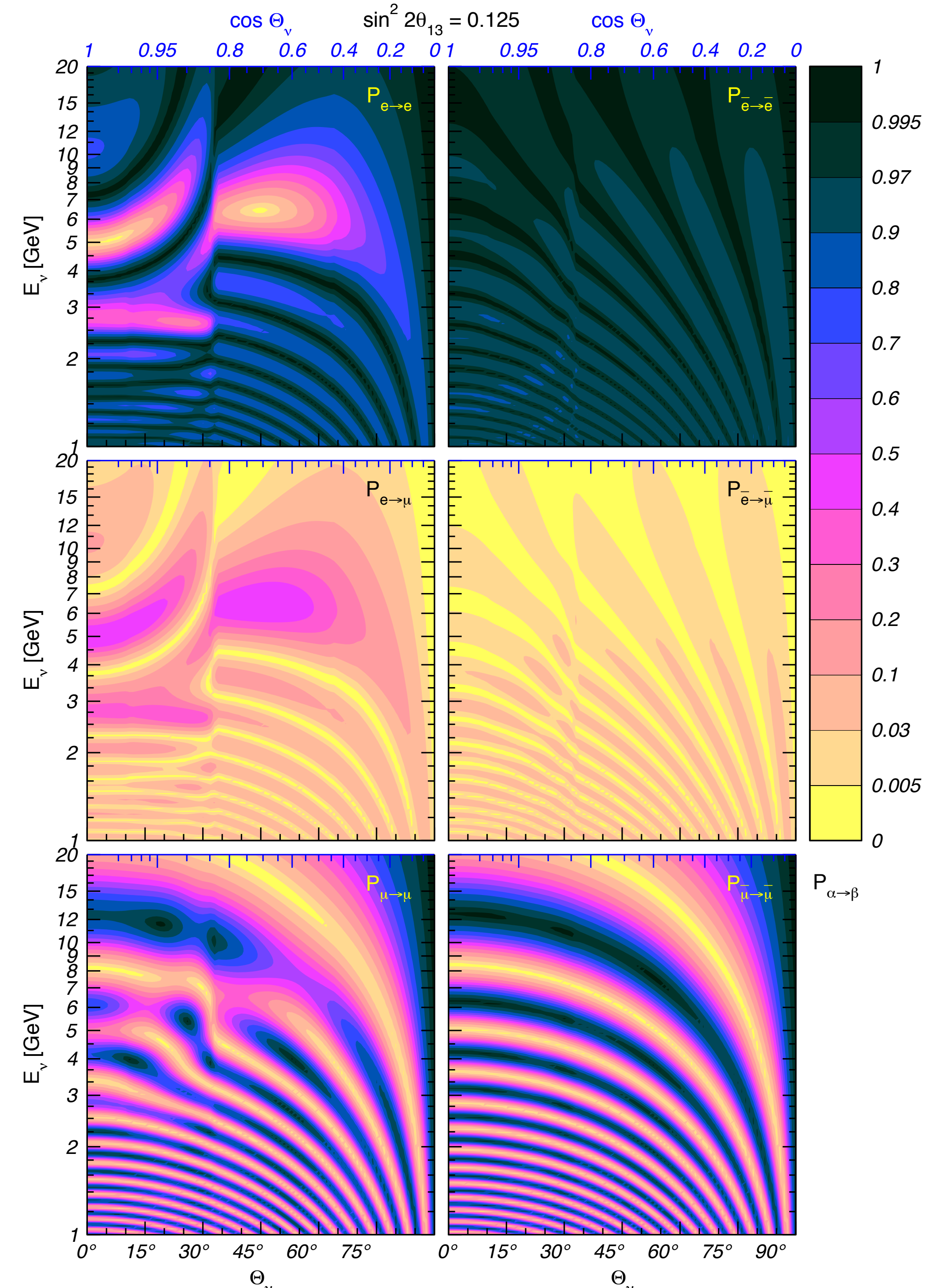

Akhmedov, Maltoni, Smirnov 06

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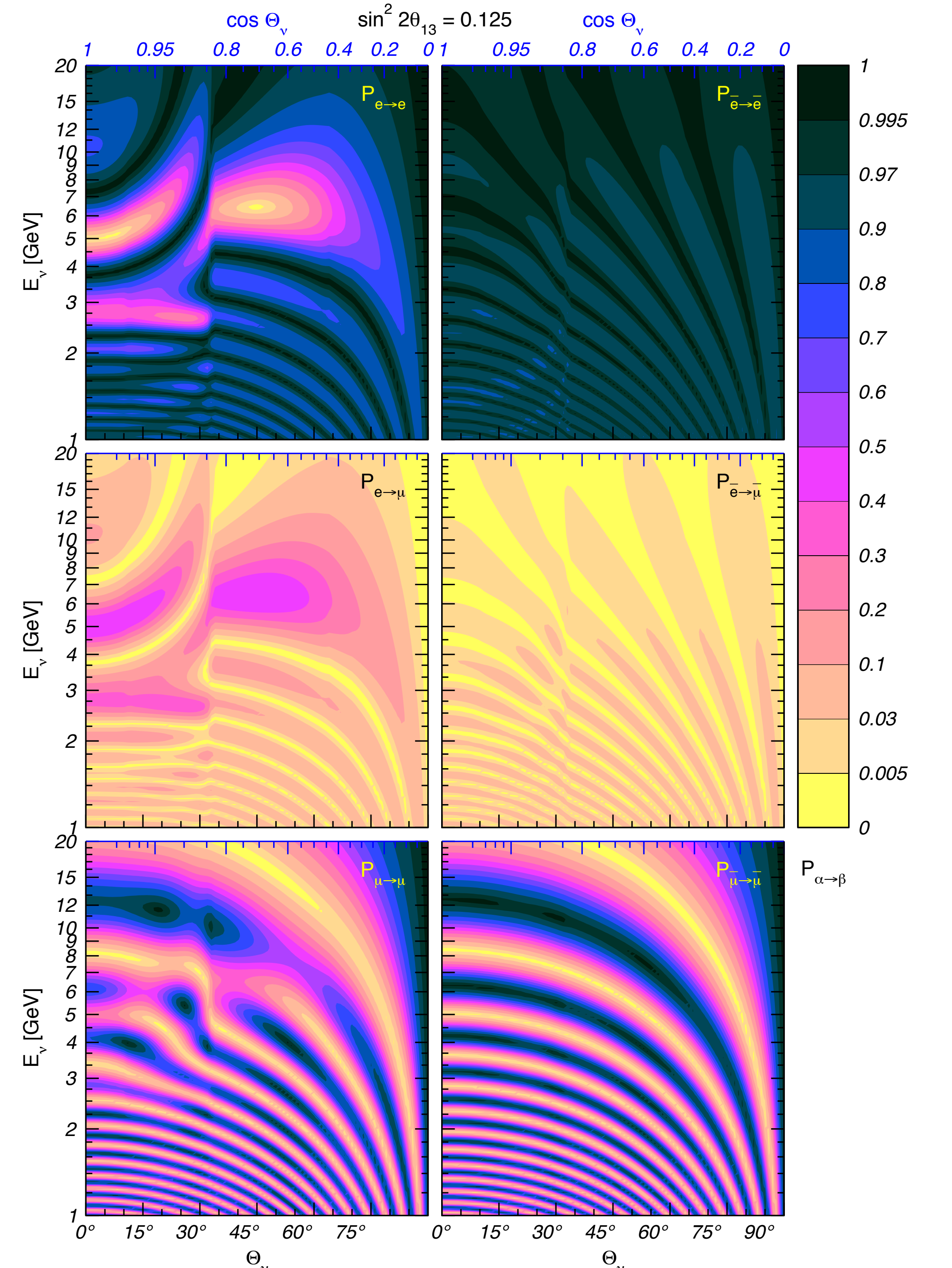
energy and angular reconstruction is crucial!



Akhmedov, Maltoni, Smirnov 06

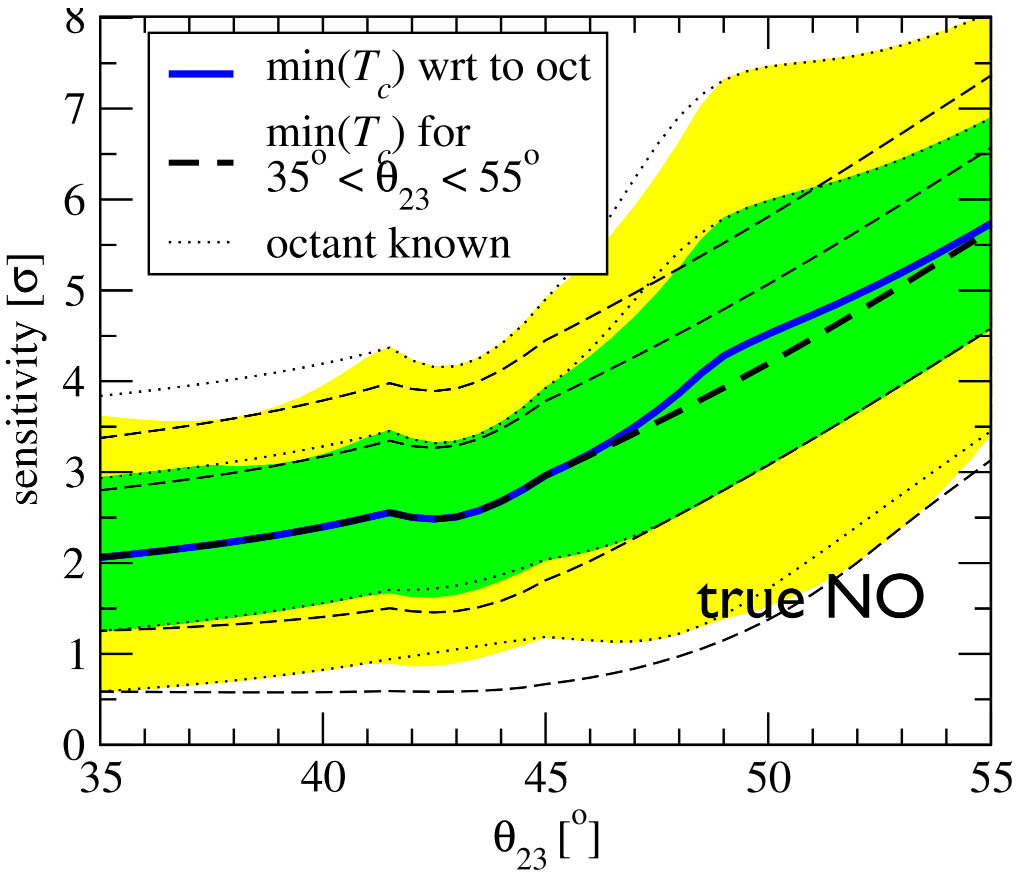
Atmospheric neutrino experiments

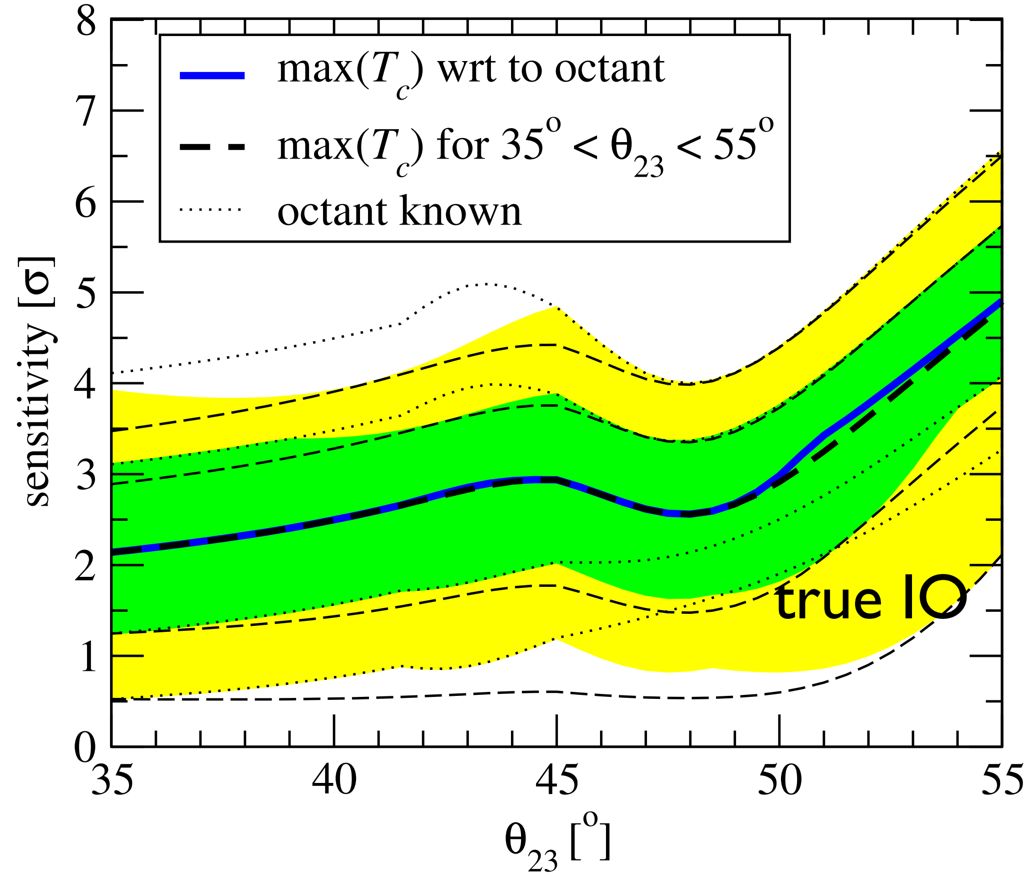
- *INO: magnetized iron, 50-100 kt*
  μ-like events with charge ID
- *PINGU / ORCA: ice/water, multi-Mt*
  μ-like (+shower) events, no charge ID
- *Hyper-K: water, sub-Mt*
  μ-like and e-like events,
  no charge ID (maybe statistically)

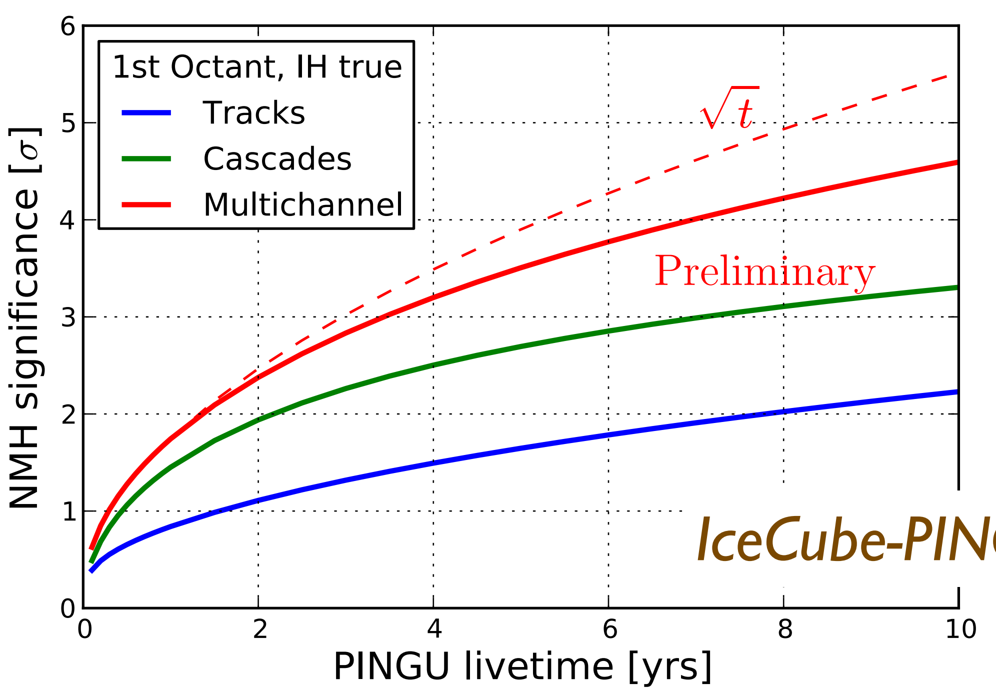
PINGU

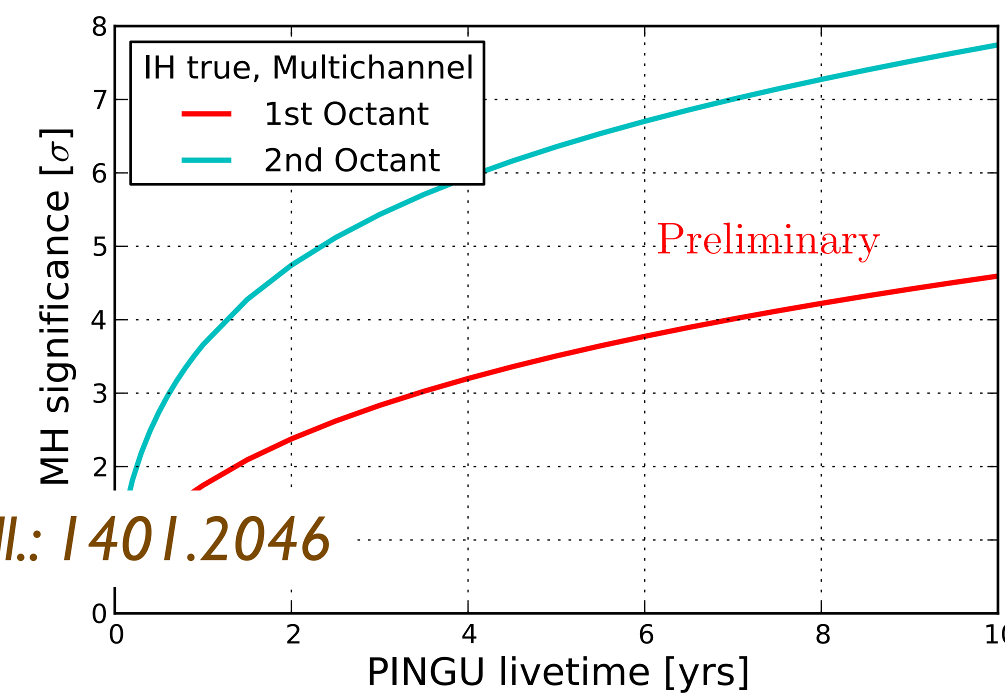
Blennow, Coloma, Huber, TS, 1311.1822

median sensitivity (3 yrs)





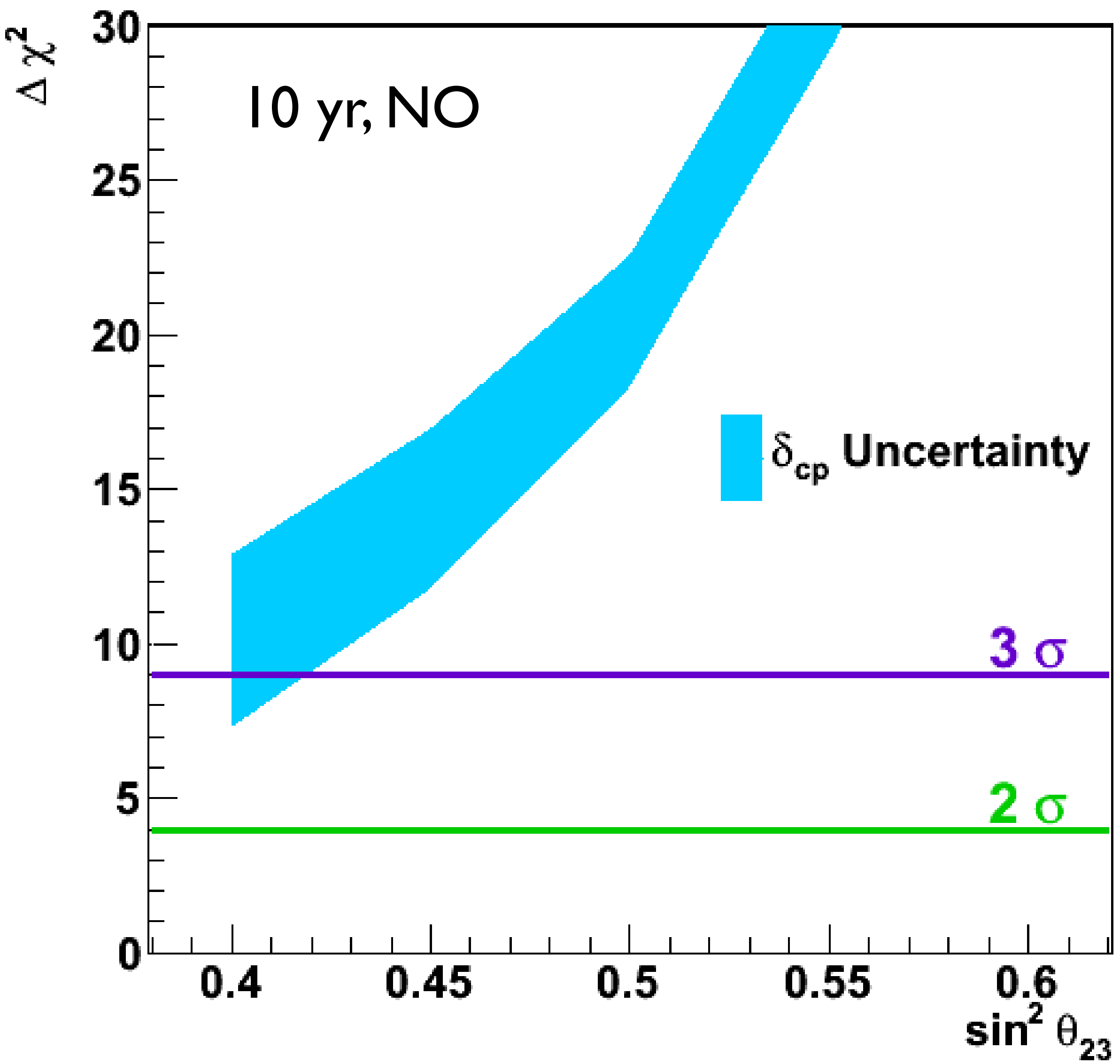




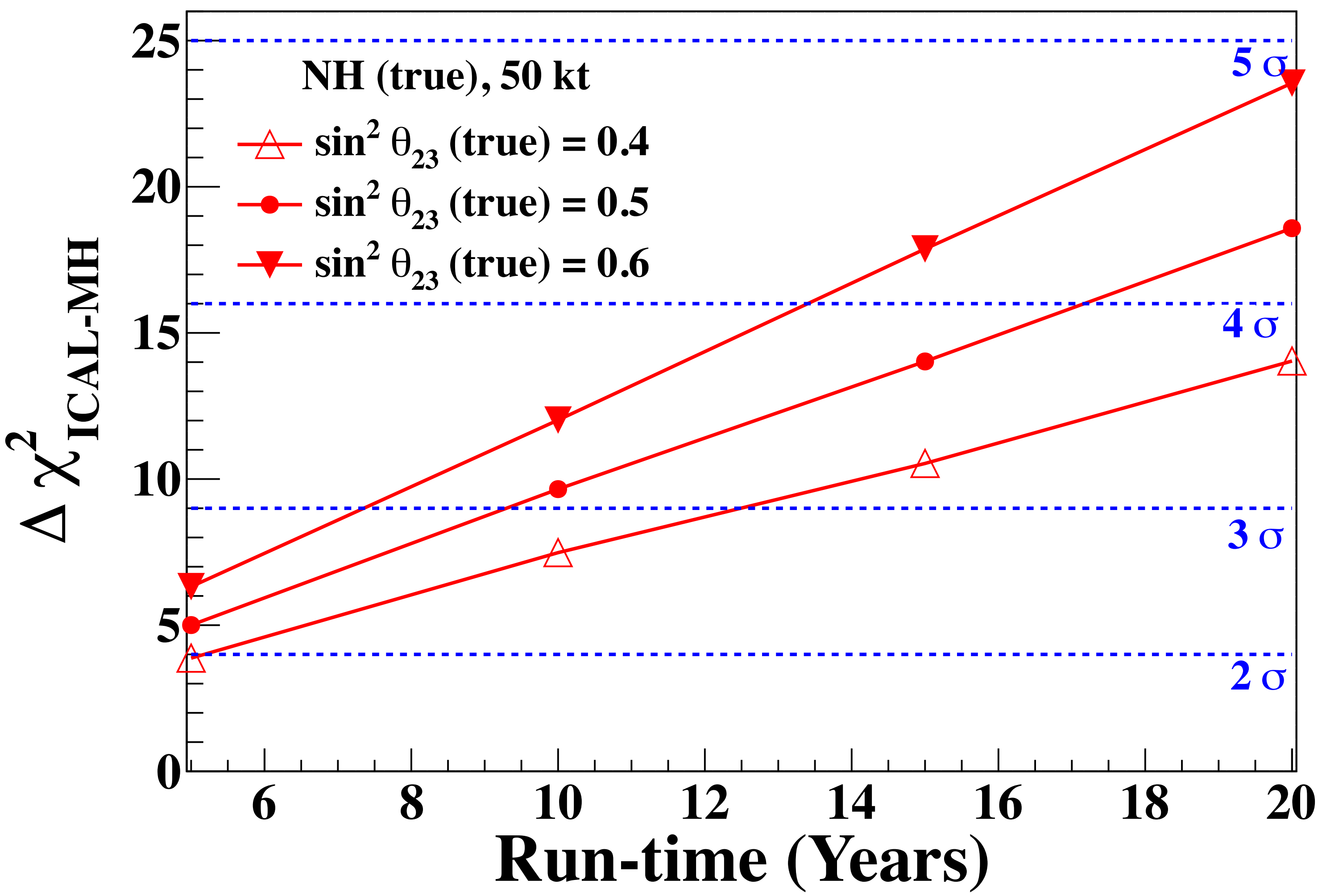
IceCube-PINGU Coll.: 1401.2046

HyperK *INO*

E. Kearns et al, 1309.0184

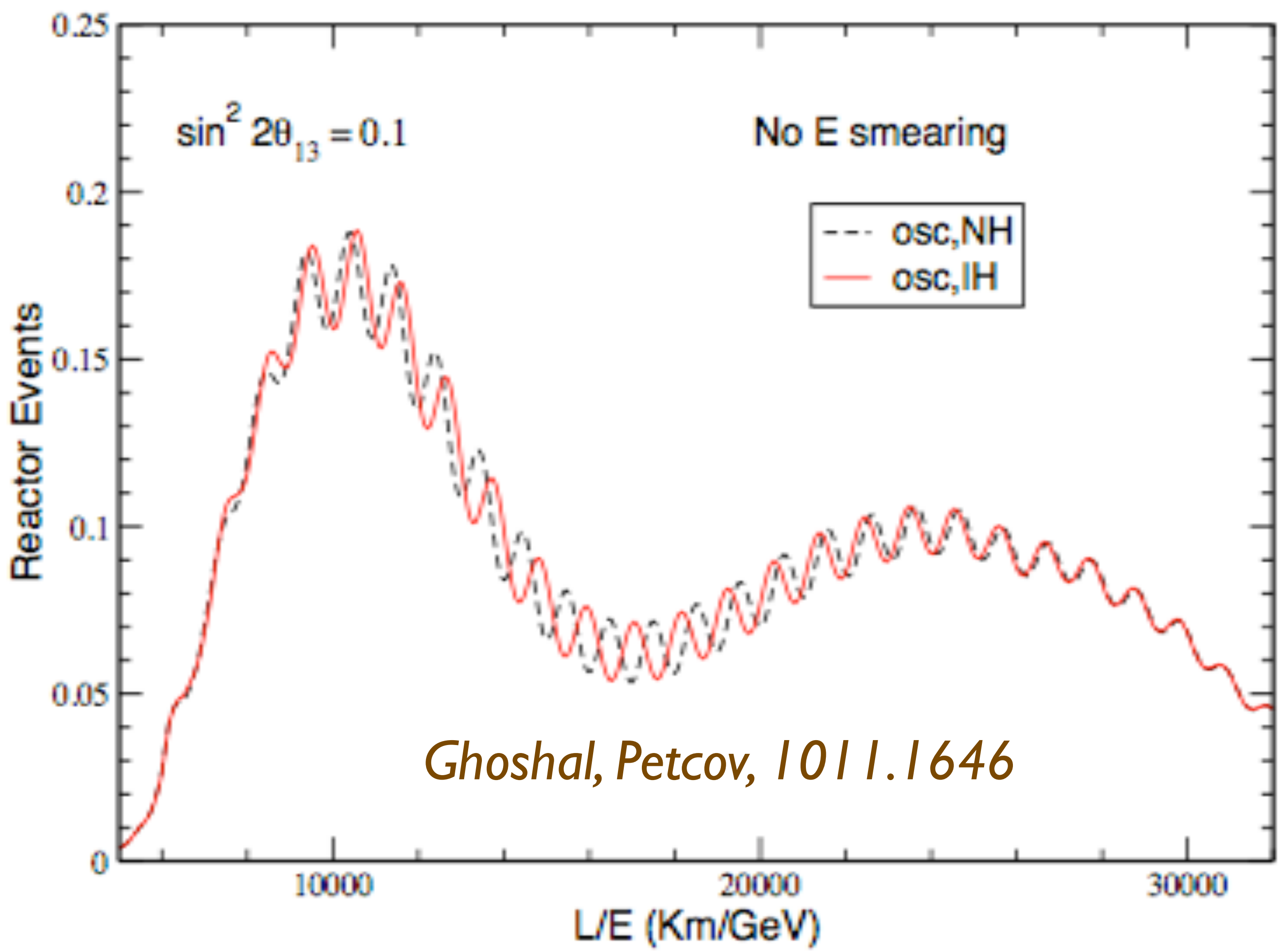


Agarwalla, Devi, Dighe, Thakore, 1406.3689



Mass ordering from a reactor experiment

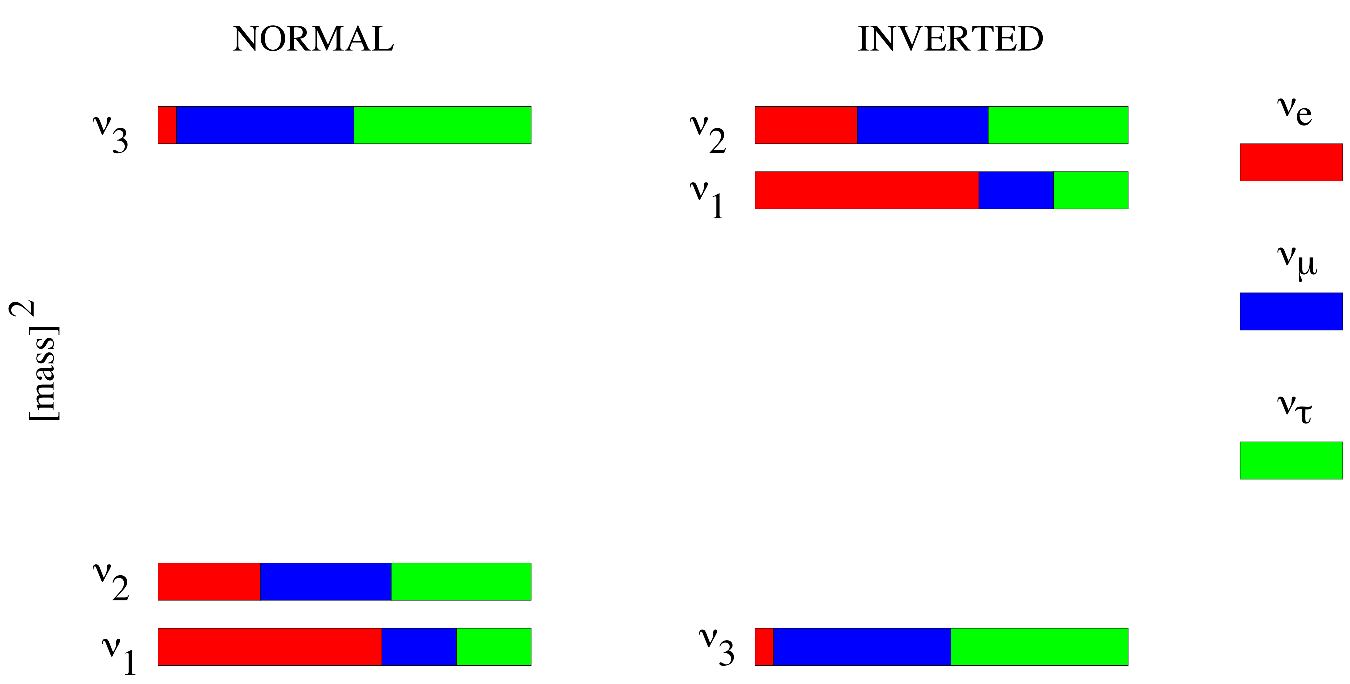
$$P_{ee}^{\rm vac} = 1 - c_{13}^4 \sin^2 2\theta_{12} \sin^2\left(\frac{\Delta m_{21}^2 L}{4E}\right) - \sin^2 2\theta_{13}\left[c_{12}^2 \sin^2\left(\frac{\Delta m_{31}^2 L}{4E}\right) + s_{12}^2 \sin^2\left(\frac{\Delta m_{32}^2 L}{4E}\right)\right]$$

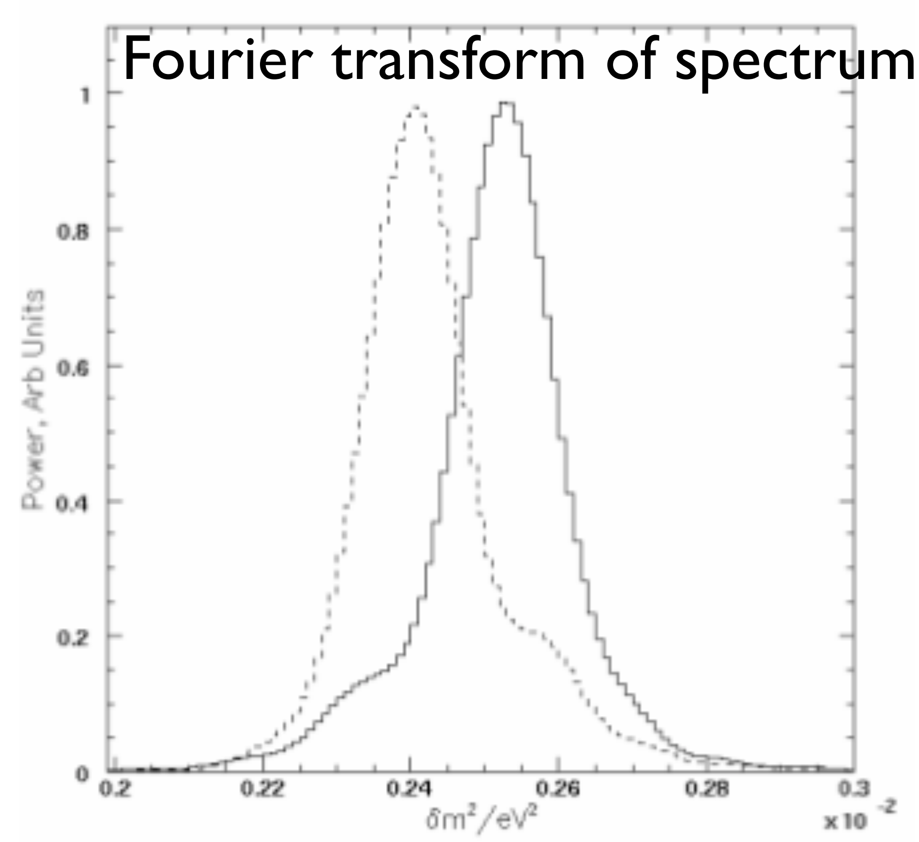


Petcov, Piai, hep-ph/0112074

$\bar{\nu}_e$ disappearance at intermediate baseline (40~60 km)

Mass ordering from a reactor experiment





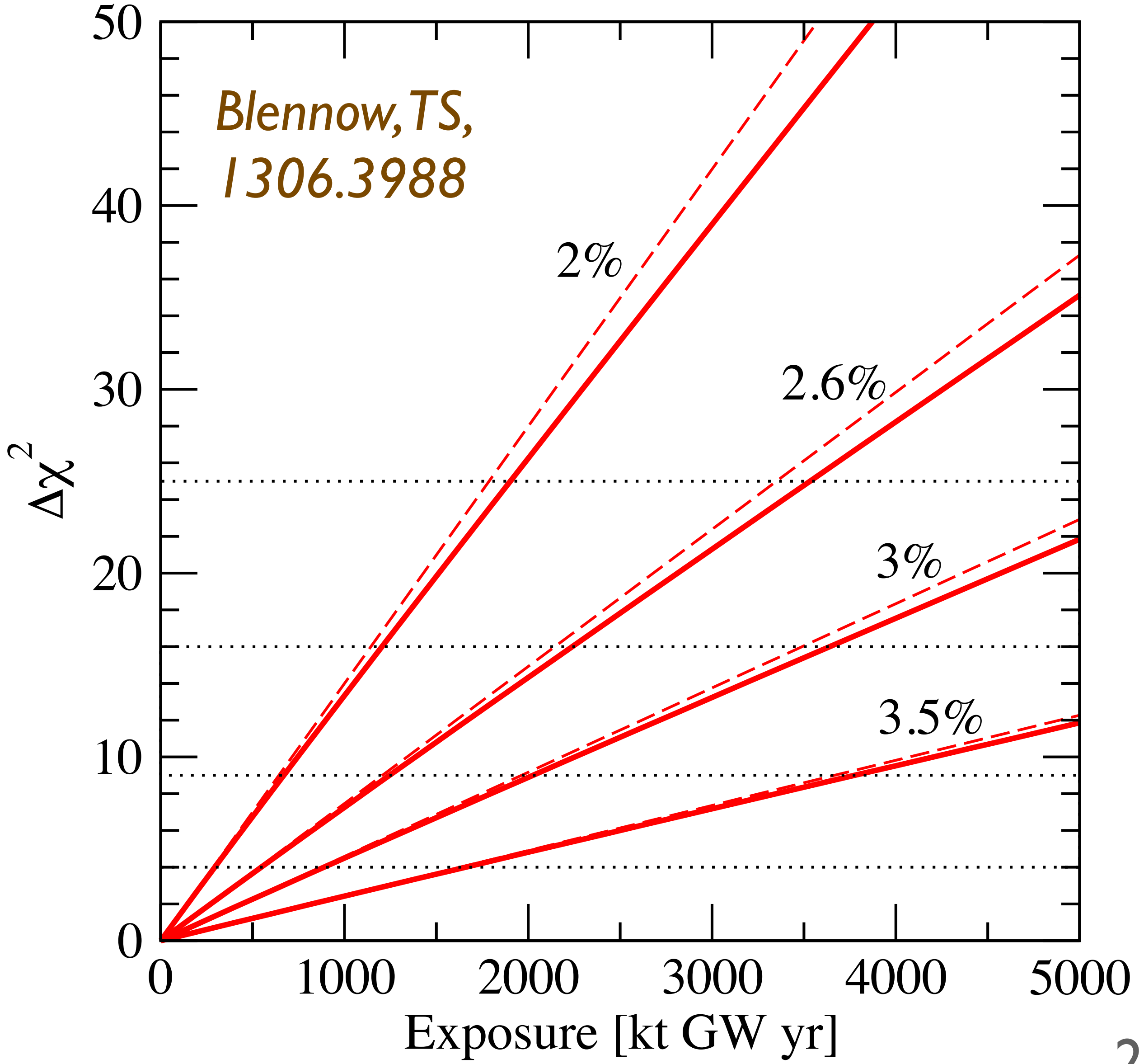
Learned, Dye, Pakvasa, Svoboda, 06
Zhan, Wang, Cao, Wen, 08

- *there are two large frequencies: Δm^2_{31} and Δm^2_{32}*
- *θ_{12} is non-maximal and we know the sign of Δm^2_{21}*
- *for NO (IO) the larger (smaller) frequency dominates*

Mass ordering from a reactor experiment

Dwyer, McKeown, Qian, Vogel, Wang, Zhang, 1208.1551, Capozzi, Lisi, Marrone, 1309.1638 many more

- *good energy resolution <3% (KamLAND ~6%)*
- *energy scale has to be under control at % level*
- *it has to be **BIG** : ~4000 GW kt yr → 20 kt detector (KamLAND: 1 kt)*



Sensitivity comparison

Blennow, Coloma, Huber, TS, 1311.1822

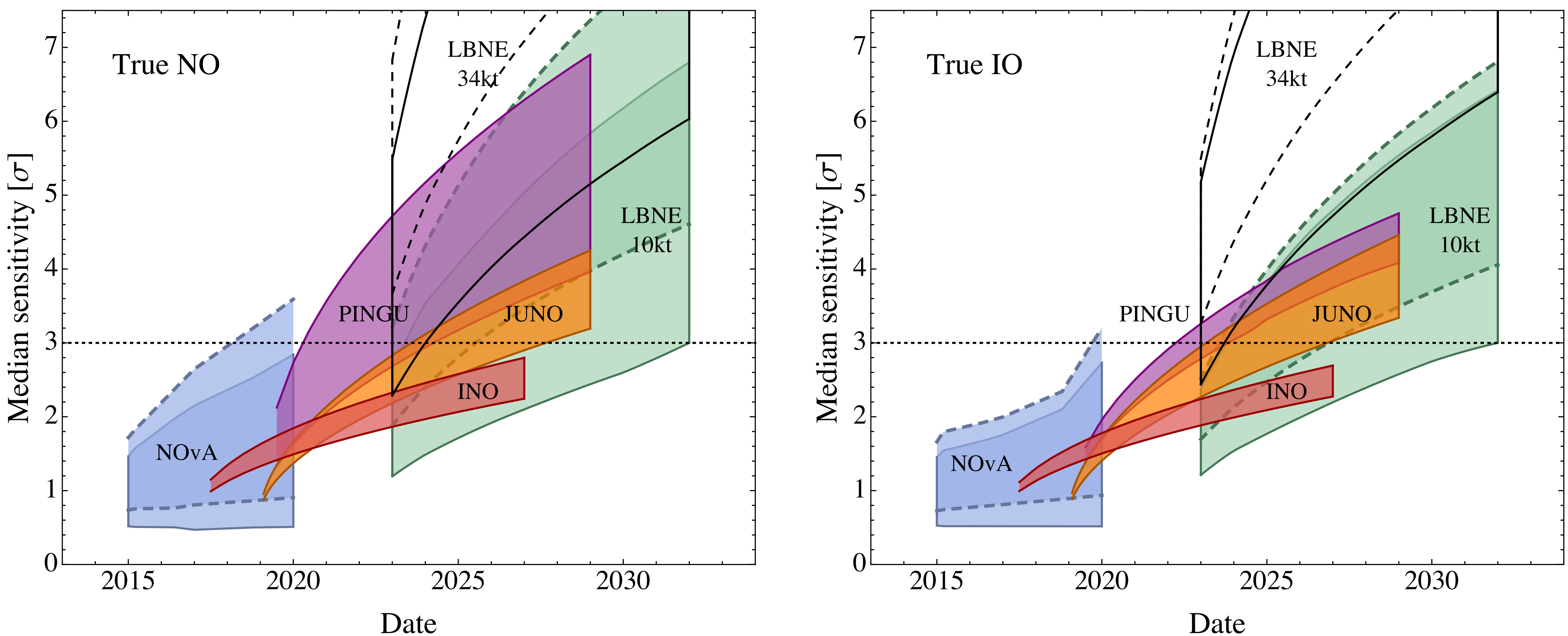
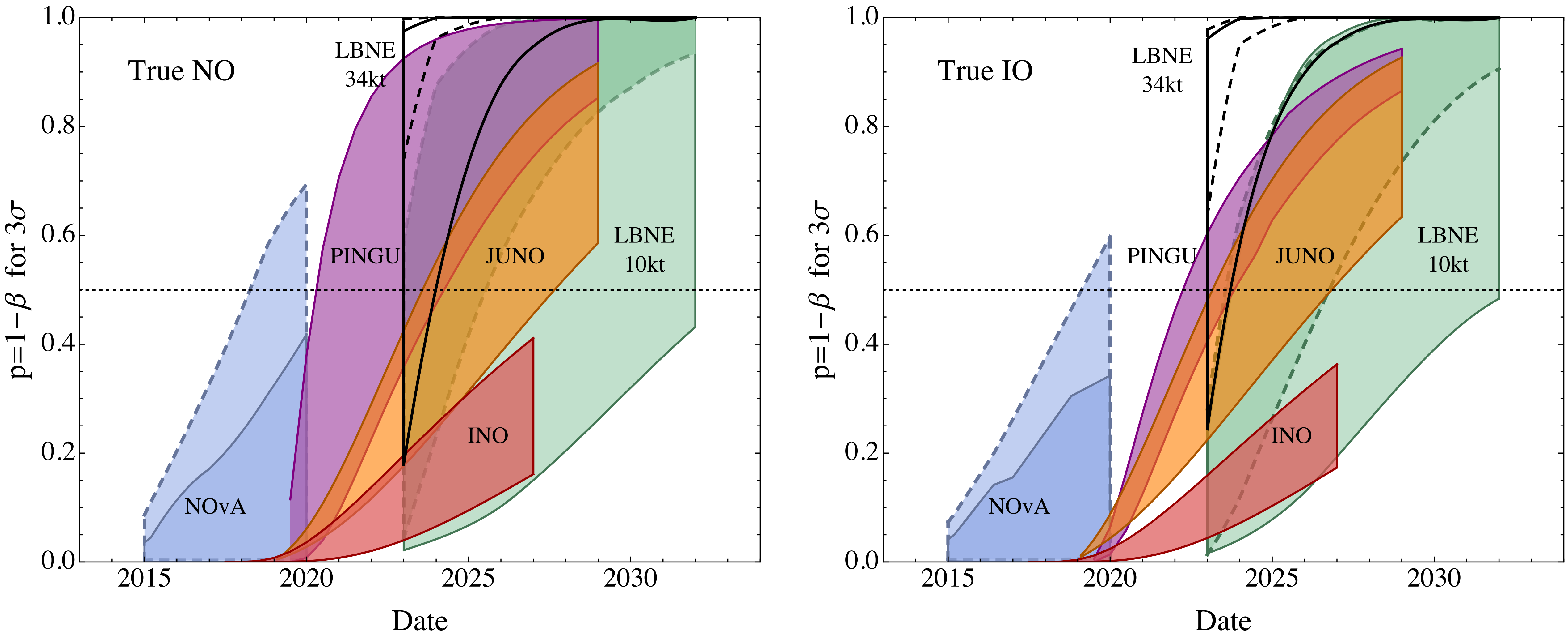


FIG. 12: The left (right) panel shows the median sensitivity in number of sigmas for rejecting the IO (NO) if the NO (IO) is true for different facilities as a function of the date. The width of the bands correspond to different true values of the CP phase δ for NOνA and LBNE, different true values of θ_{23} between 40° and 50° for INO and PINGU, and energy resolution between $3\%\sqrt{1\ \mathrm{MeV}/E}$ and $3.5\%\sqrt{1\ \mathrm{MeV}/E}$ for JUNO. For the long baseline experiments, the bands with solid (dashed) contours correspond to a true value for θ_{23} of 40° (50°). In all cases, octant degeneracies are fully searched for.

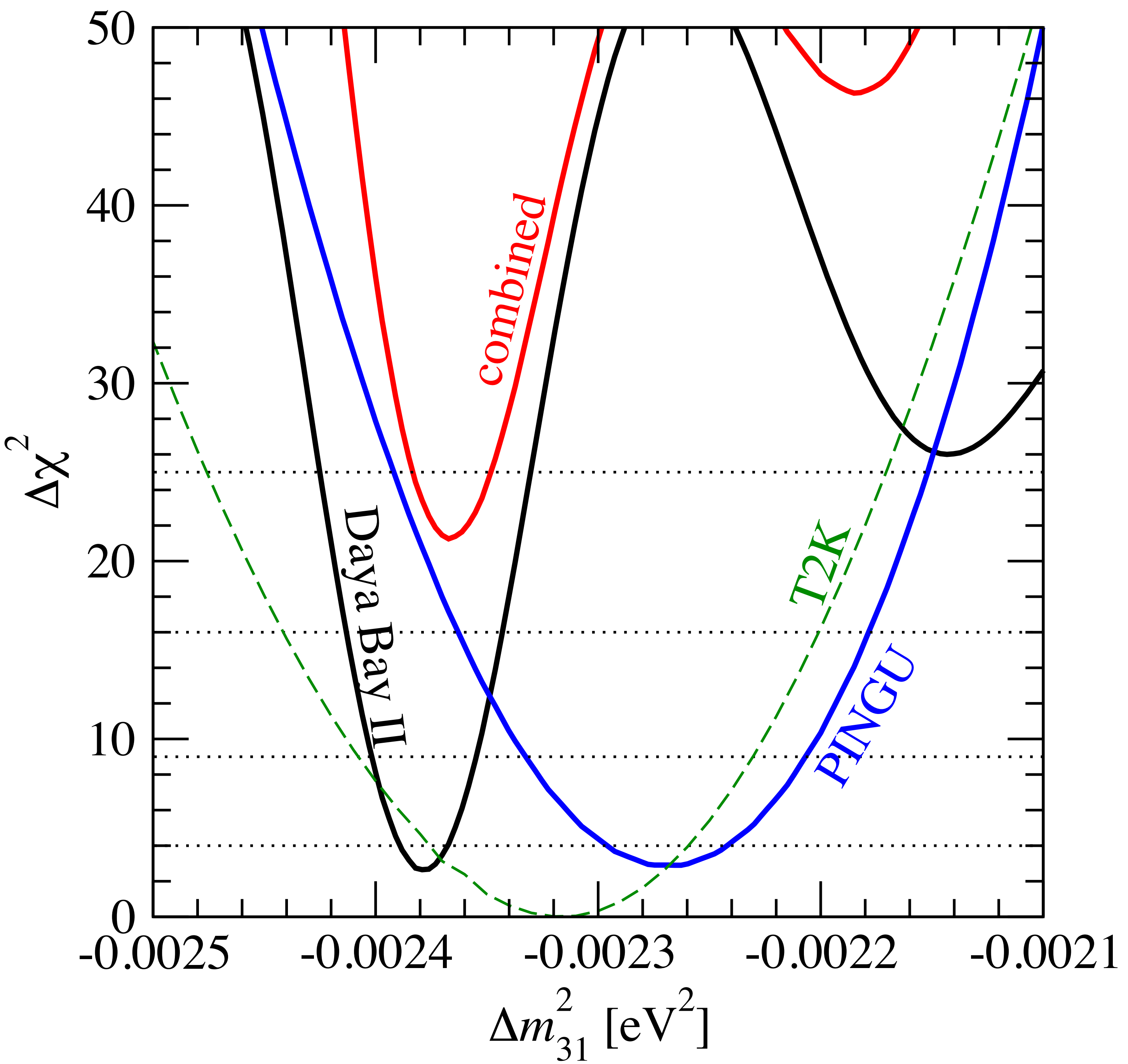
Sensitivity comparison

Blennow, Coloma, Huber, TS, 1311.1822

probability to exclude wrong ordering at 3σ



Explore synergy between different experiments



combine measurements of $|\Delta m^2_{31}|$ from PINGU and JUNO

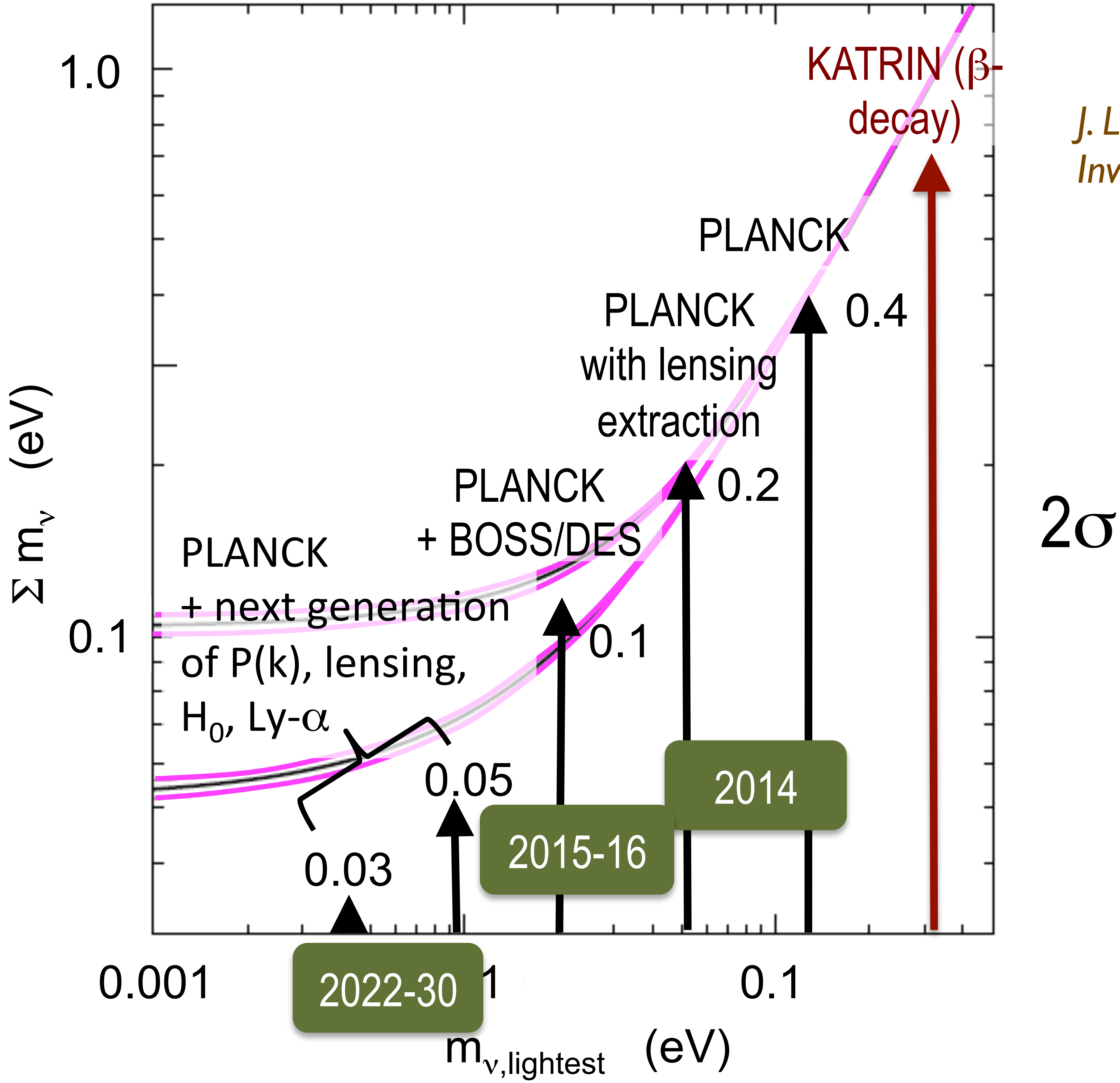
Blennow, Schwetz, arXiv:1306.3988

requires more careful investigations wrt to energy scale uncertainties - both for JUNO and PINGU!

Summary

- *thanks to large θ_{13} several options are open to determine the neutrino mass ordering*
- *3σ determination likely within 5-10 years*
- *combined fit to several experiments may be usefull*
- *more significant determination will most likely require a large-scale experiment*

Cosmology sensitivity to neutrino mass



J. Lesgourgues, Invisibles 2014 school