Neutrino mass hierarhy in the atmospheric sector: Earth matter effects

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ORCA Workshop

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θ_{13}-driven matter effects

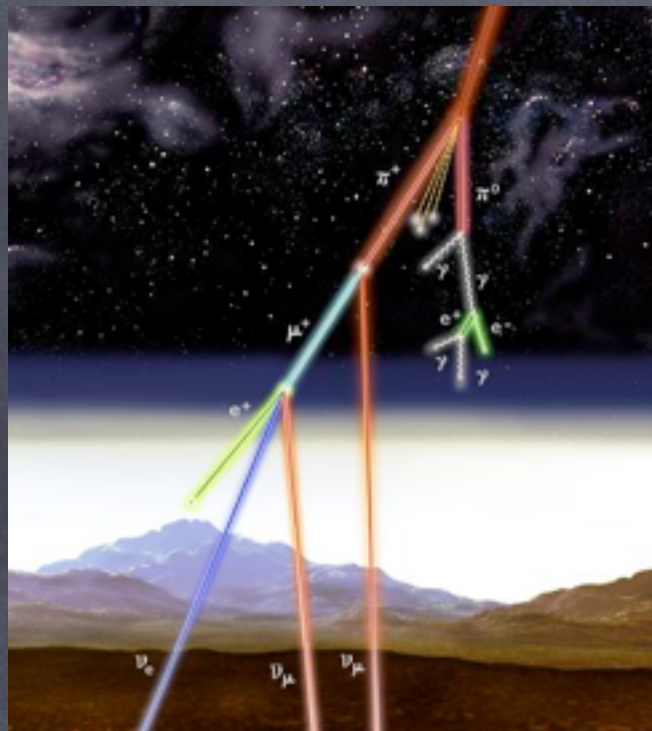
$$U_{PMNS} = \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix}$$

solar angle — reactor angle — atmospheric angle

If θ_{13} vanishes, all analysis get reduced to a 2x2 mixing problem

θ_{13} drives subleading $\nu_\mu \to \nu_e$ transitions:
crucial to determine CP violation and mass hierarchy
it helps to determine θ_{23} octant

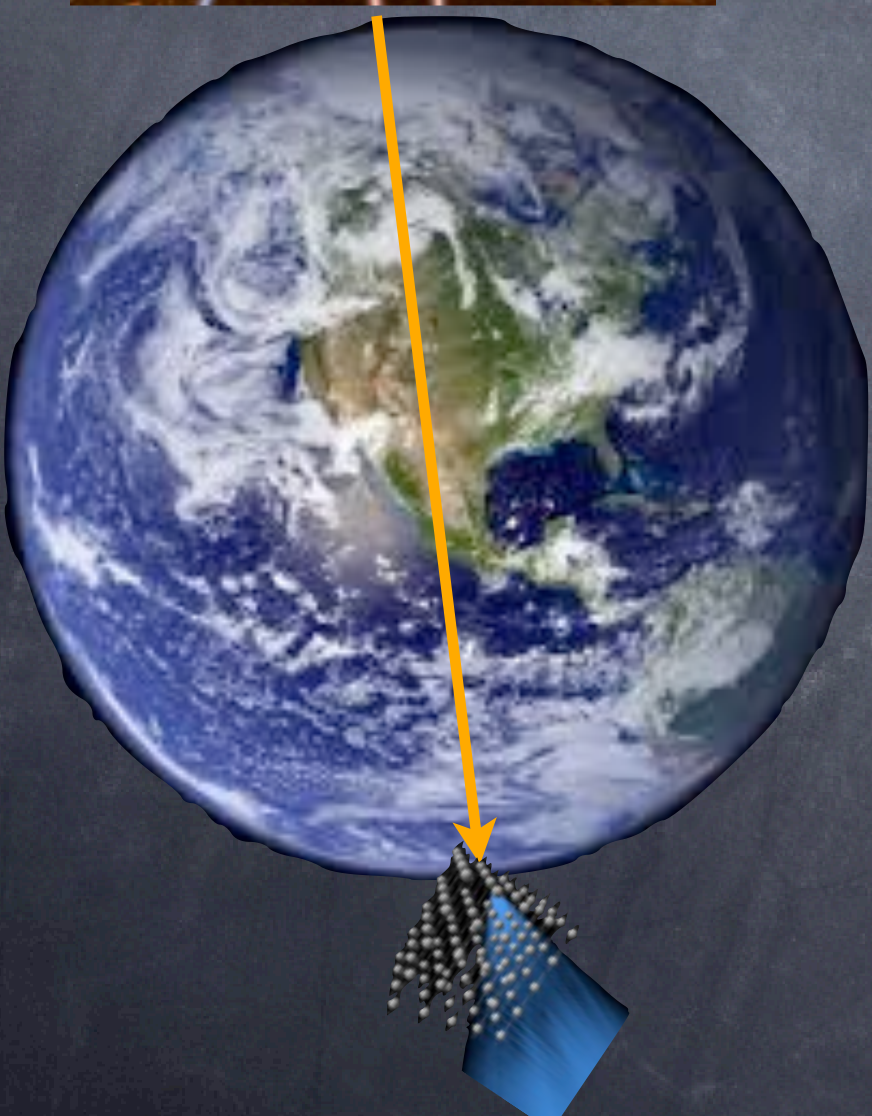
Atmospheric neutrinos

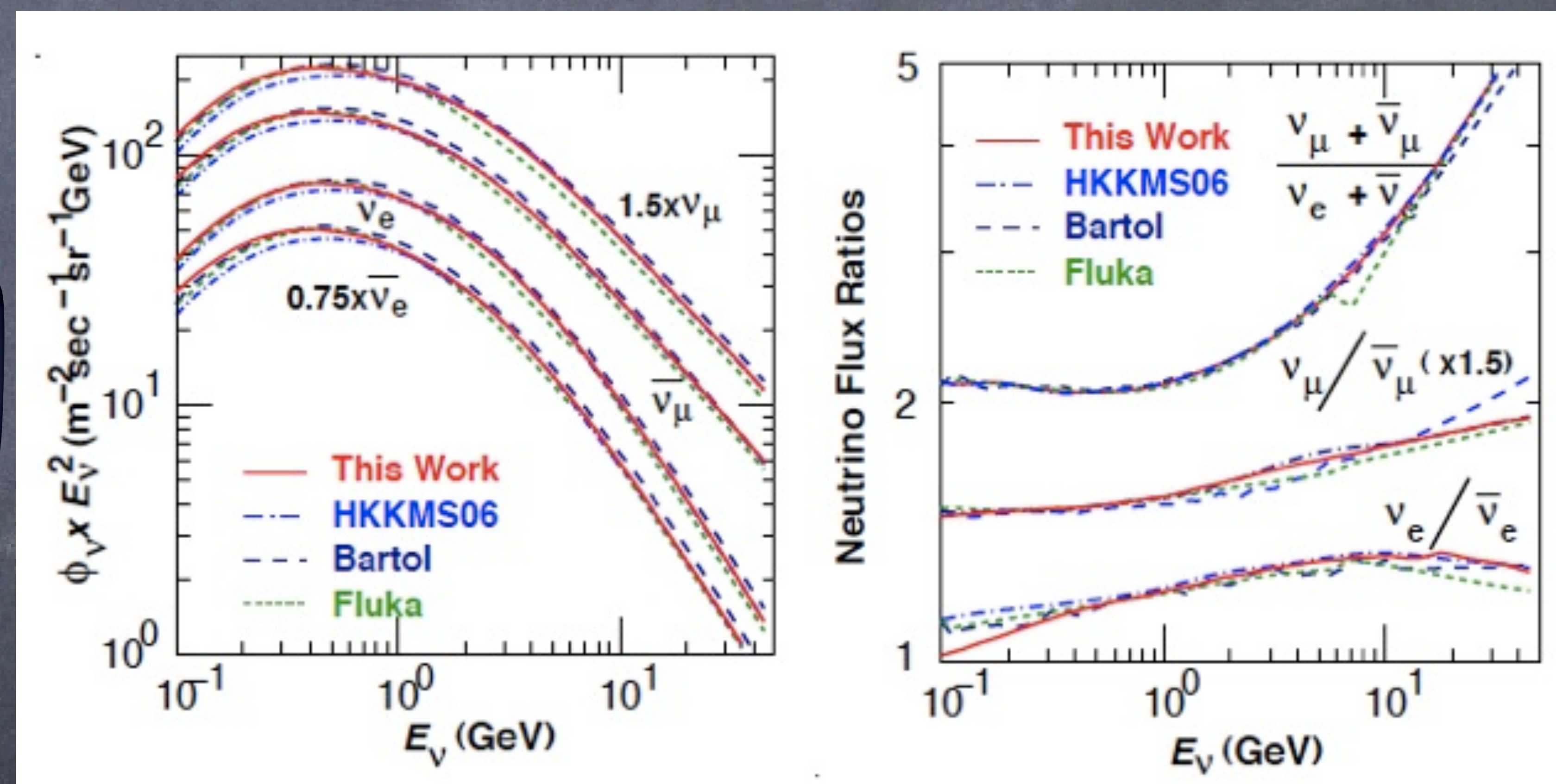


$$p + X \to \pi^{\pm} / K^{\pm} + Y$$

$$\mu^{\pm} + \nu_{\mu}(\bar{\nu}_{\mu})$$

$$e^{\pm} + \nu_{e}(\bar{\nu}_{e}) + \bar{\nu}_{\mu}(\nu_{\mu})$$



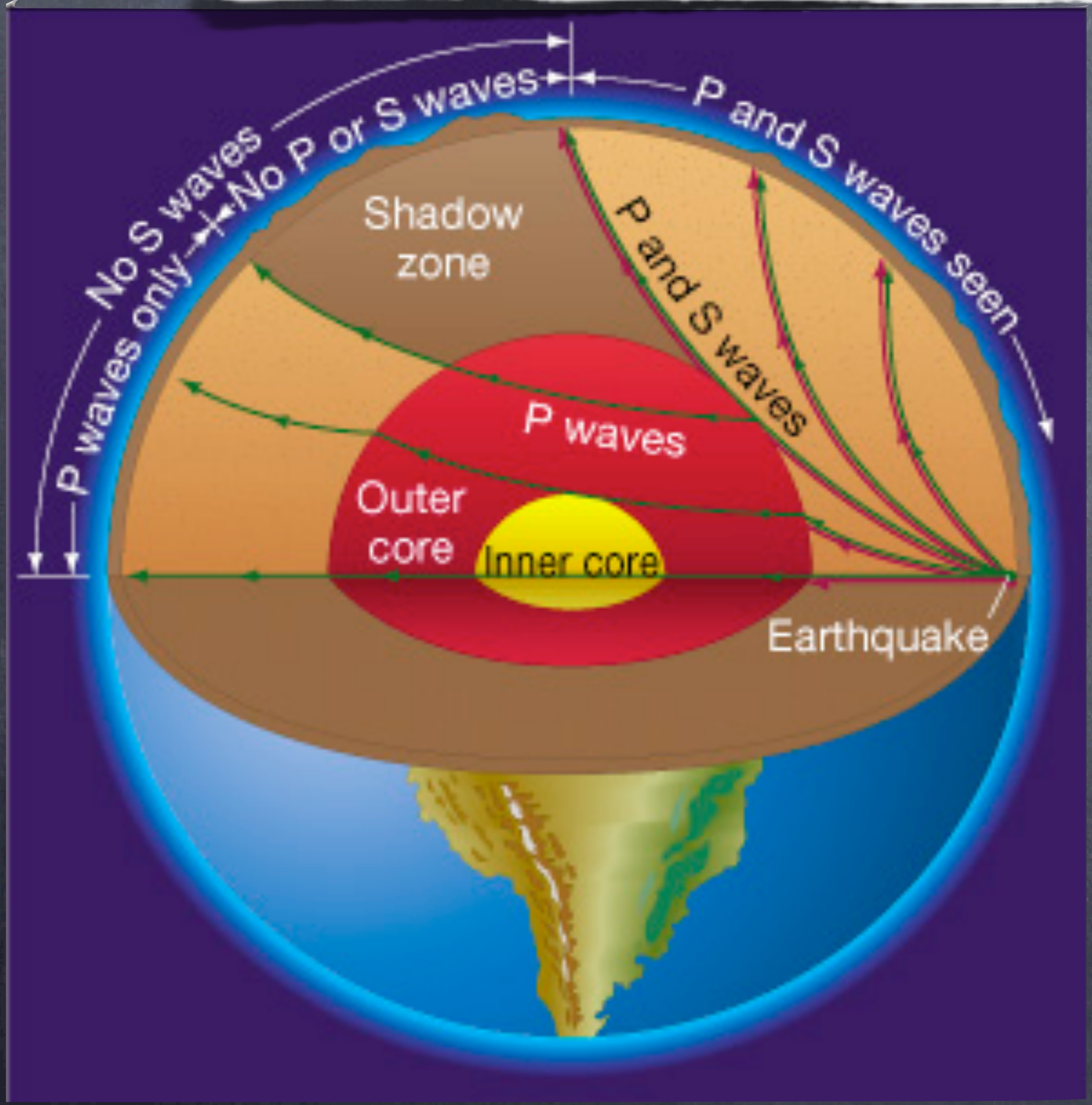


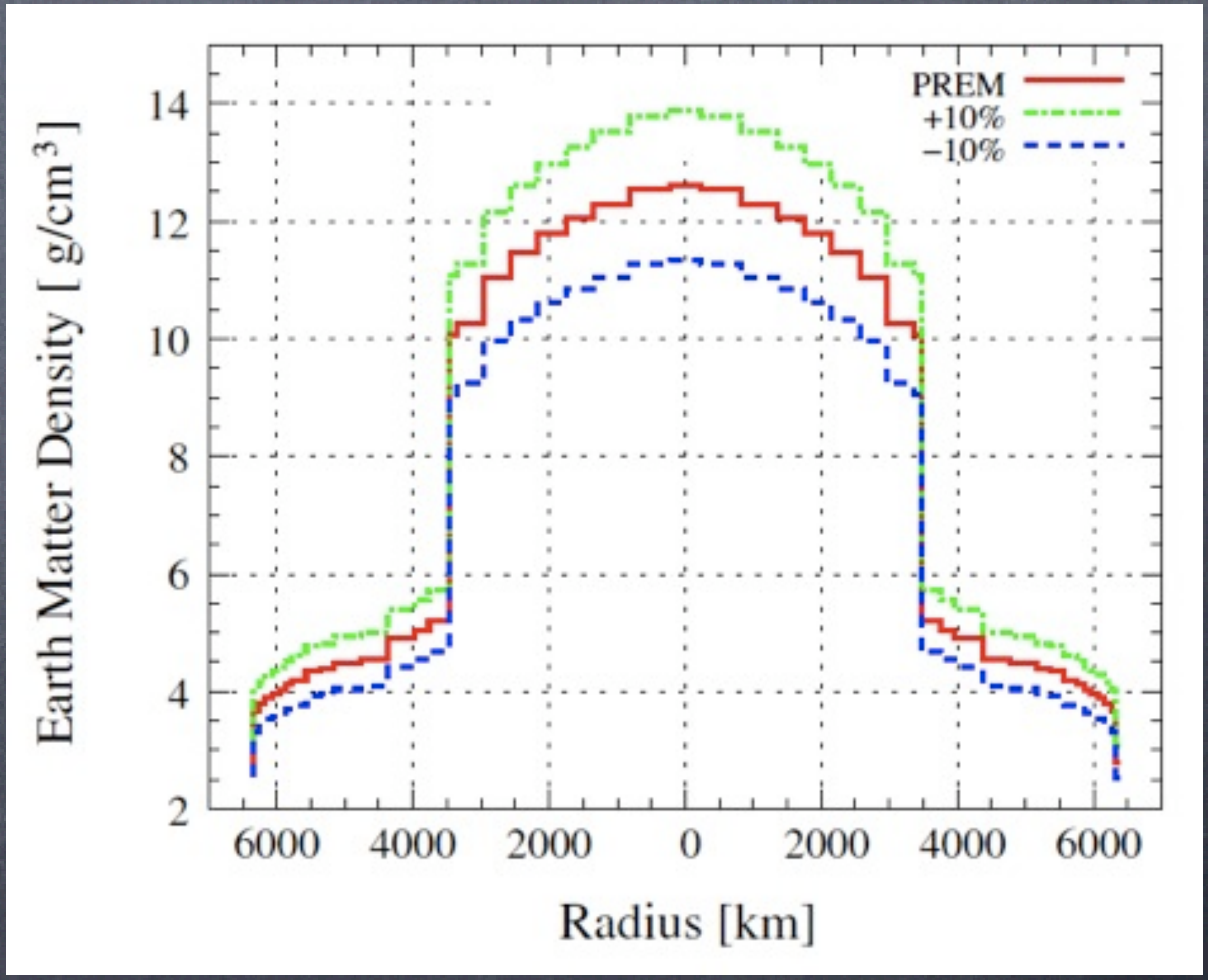
M. Honda, T. Kajita, K. Kasahara and S. Midorikawa, *Phys. Rev. D83:123001, 2011*

G. D. Barr, T. K. Gaisser, P. Lipari, S. Robbins and T. Stanev, *Phys. Rev. D70:023006, 2004*
G. Battistoni, A. Ferrari, T. Montarulli and P. R. Sala, *Astropart. Phys. 19:269, 2003*

Earth density profile

The most widely used radially symmetric model is the Preliminary Reference Earth Model (PREM):
it includes anisotropy in the upper mantle and it is a good fit to:
- free oscillation center frequency measurements,
- surface-wave dispersion observations,
- travel-time data for body-waves
- the Earth's radius, mass and moment of inertia





S. K. Agarwalla, T. Li, O. Mena and SPR, *arXiv:1212:2238*

Earth matter effect

$$\left|\Delta m^2_{31}\right| \gg \Delta m^2_{21}$$

Approximately a 2-neutrino problem

$$\nu_e \rightarrow s_{23}\nu_\mu + c_{23}\nu_\tau \equiv \nu_x$$

$$P_{3\nu}\left(\nu_e \rightarrow \nu_e\right) = 1 - P_{2\nu}\left(\nu_e \rightarrow \nu_x; \Delta m^2_{31}, \theta_{13}\right)$$

$$P_{3\nu}\left(\nu_e \rightarrow \nu_\mu\right) = s^2_{23} P_{2\nu}\left(\nu_e \rightarrow \nu_x; \Delta m^2_{31}, \theta_{13}\right)$$

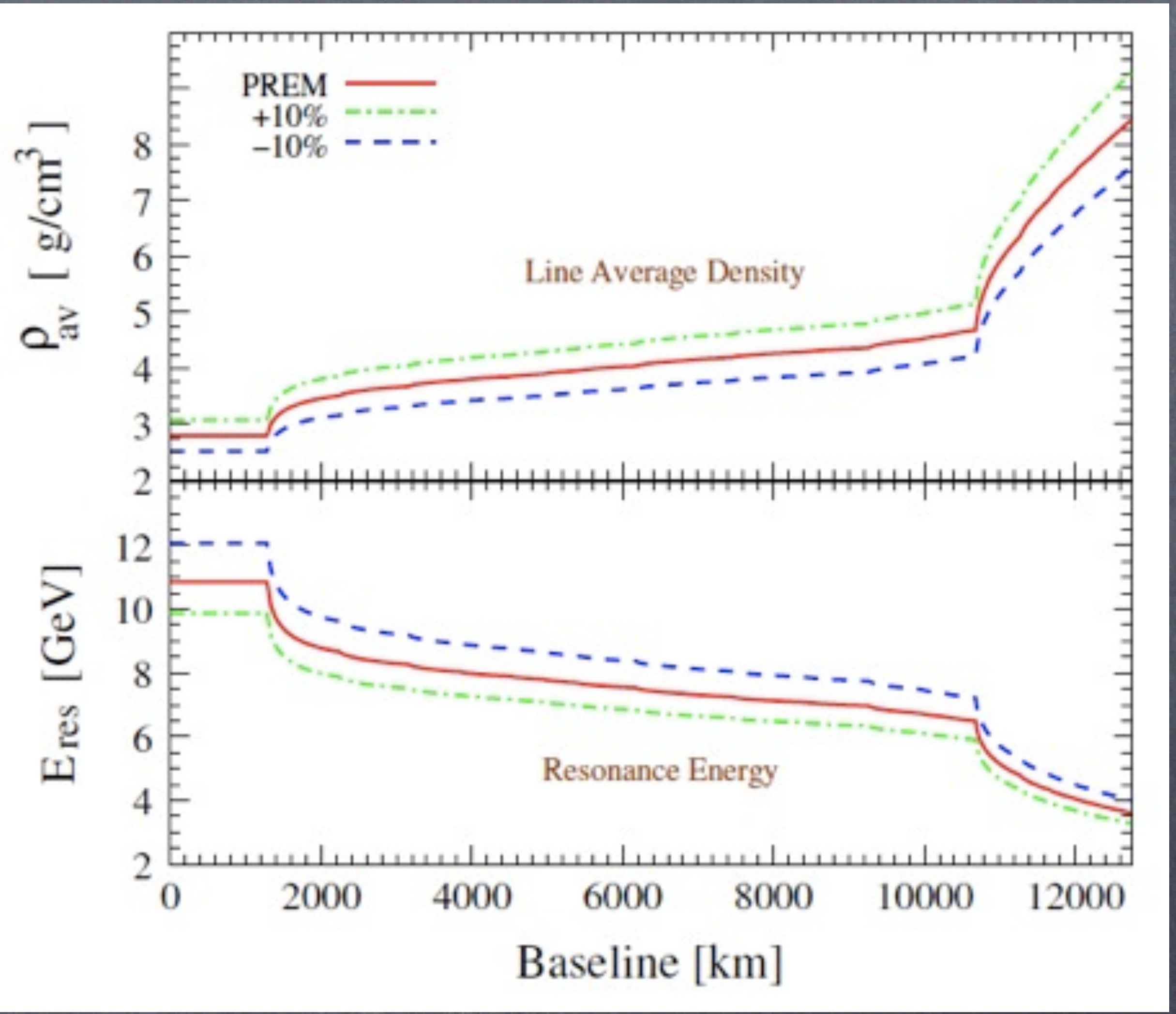
$$P_{3\nu}\left(\nu_e \rightarrow \nu_\tau\right) = c^2_{23} P_{2\nu}\left(\nu_e \rightarrow \nu_x; \Delta m^2_{31}, \theta_{13}\right)$$

For constant density and neglecting the solar sector

$$P_{3\nu}(\nu_e \to \nu_\tau) = 1 - s_{23}^4 P_{2\nu}(\Delta m_{31}^2, \theta_{13}) + \frac{1}{2}\sin^2 2\theta_{23}\left[\cos\left(\frac{L}{4E}(\Delta m_{31}^2 - A)\right)\cos\left(\frac{\Delta_{31}^m L}{4E}\right) - \cos 2\theta_{13}^m \sin\left(\frac{L}{4E}(\Delta m_{31}^2 - A)\right)\sin\left(\frac{\Delta_{31}^m L}{4E}\right) - 1\right]$$

$$P_{3\nu}(\nu_e \to \nu_e) = 1 - P_{2\nu}(\Delta m_{31}^2, \theta_{13})$$

$$P_{3\nu}(\nu_e \to \nu_\mu) = s_{23}^2 P_{2\nu}(\Delta m_{31}^2, \theta_{13})$$



S. K. Agarwalla, T. Li, O. Mena and SPR, *arXiv:1212:2238*

$$P_{2\nu}(\nu_e \to \nu_x) = \sin^2 2\theta_{13}^m \sin^2\left(\frac{\Delta_{31}^m L}{4E}\right)$$

$$\Delta_{31}^m = \sqrt{(\Delta m_{31}^2 \cos 2\theta_{13} \mp A)^2 + (\Delta m_{31}^2 \sin 2\theta_{13})^2}$$

$$\sin^2 2\theta_{13}^m = \sin^2 2\theta_{13}\left(\frac{\Delta m_{31}^2}{\Delta_{31}^m}\right)^2$$

$$E_{res} = \frac{\Delta m_{31}^2 \cos 2\theta_{13}}{2\sqrt{2}G_F n_e} \simeq 7\ \text{GeV}\left(\frac{4.5\ \text{g/cm}^3}{\rho}\right)\left(\frac{\Delta m_{31}^2}{2.4\times 10^{-3}\ \text{eV}^2}\right)\cos 2\theta_{13}$$

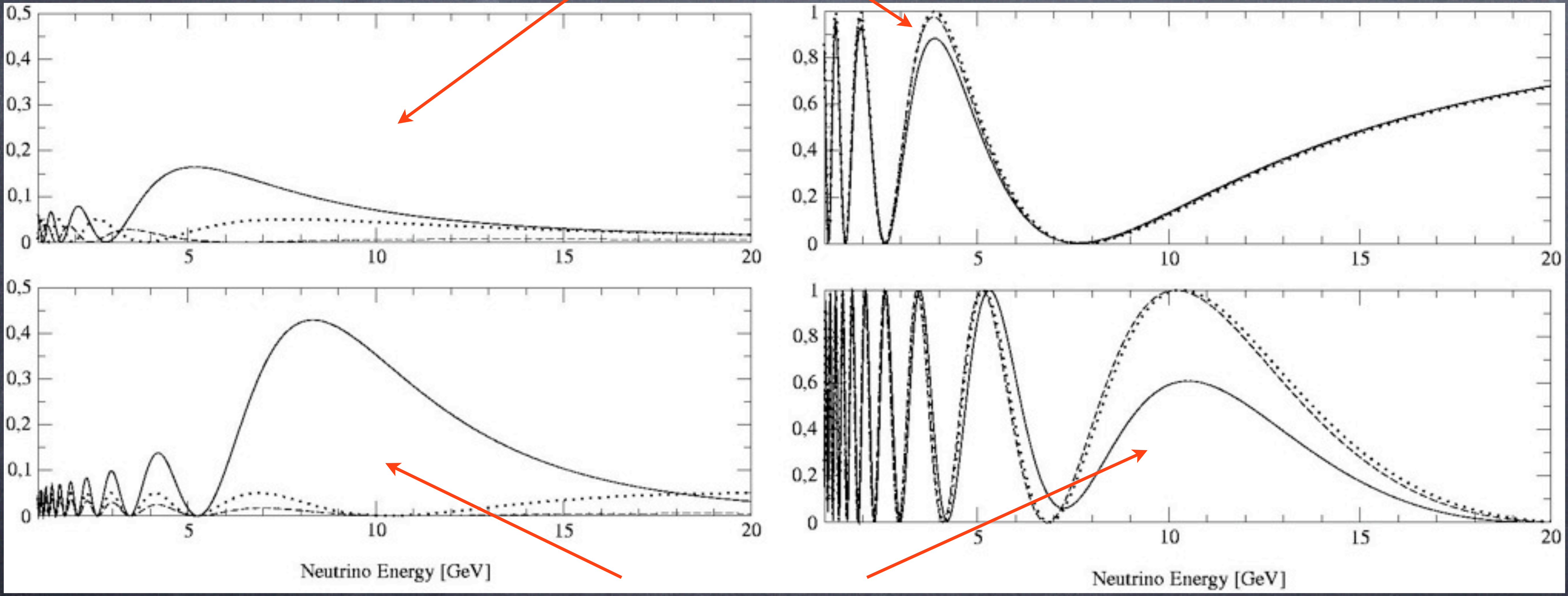
$$L_{max} = \frac{\pi}{\sqrt{2}G_F n_e \tan 2\theta_{13}} \simeq 1.1\times 10^4\ \text{km}\left(\frac{4.5\ \text{g/cm}^3}{\rho}\right)\left(\frac{1/3}{\tan 2\theta_{13}}\right)$$

Propagation through the mantle

M. C. Bañuls, G. Barenboim and J. Bernabeu, *Phys. Lett. B513:391, 2001*

Non-resonant effects

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



Resonant effects

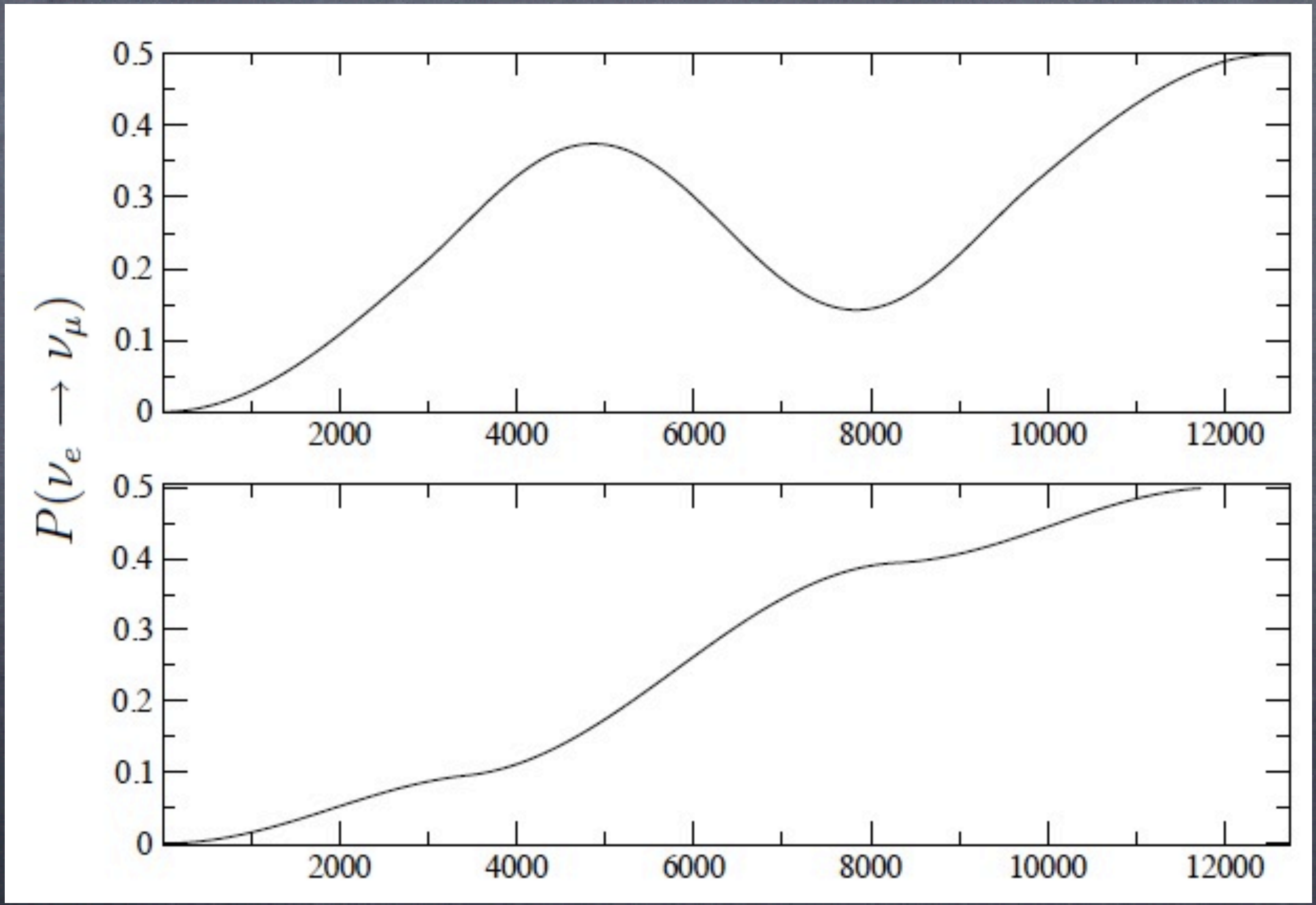
J. Bernabeu and SPR, adapted from Proc. EPS conference, 2001, *arXiv: hep-ph/0112002*

Mantle-core effect

Approximately three layers of constant density

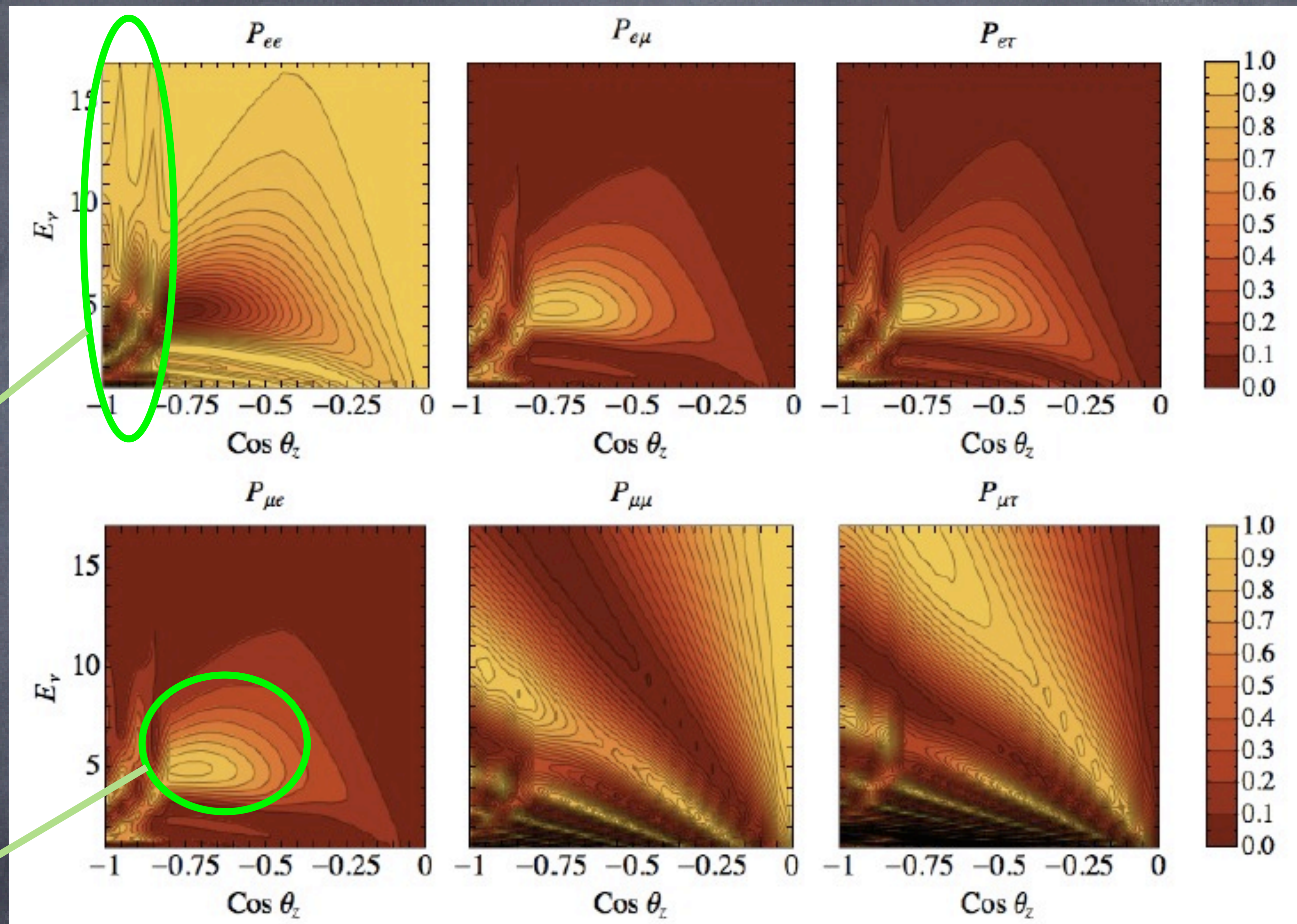
Non-trivial resonant effects

$$E_c < E_{res} < E_m$$



J. Bernabeu, SPR, A. Perez and S. T. Petcov, *Phys. Lett. B531:90, 2002*

Neutrino oscillograms



Mantle-core effect

Mantle effect

E. Kh. Akhmedov, S. Razzaque and A. Yu. Smirnov, *JHEP 1302:082, 2013*

See also:
E. Kh. Akhmedov, M. Maltoni and A. Yu. Smirnov,
Phys. Rev. Lett. 95:211801, 2005; JHEP 0705:077, 2007; JHEP 0806:072, 2008

Multi-GeV events

$$\Phi_{\nu_e}(E,\theta) \simeq \Phi^0_{\nu_e}\left(1+\left(r\sin^2\theta_{23}-1\right)P_{2\nu}\right)$$

$$r \equiv \frac{\Phi^0_{\nu_\mu}(E,\theta)}{\Phi^0_{\nu_e}(E,\theta)}$$

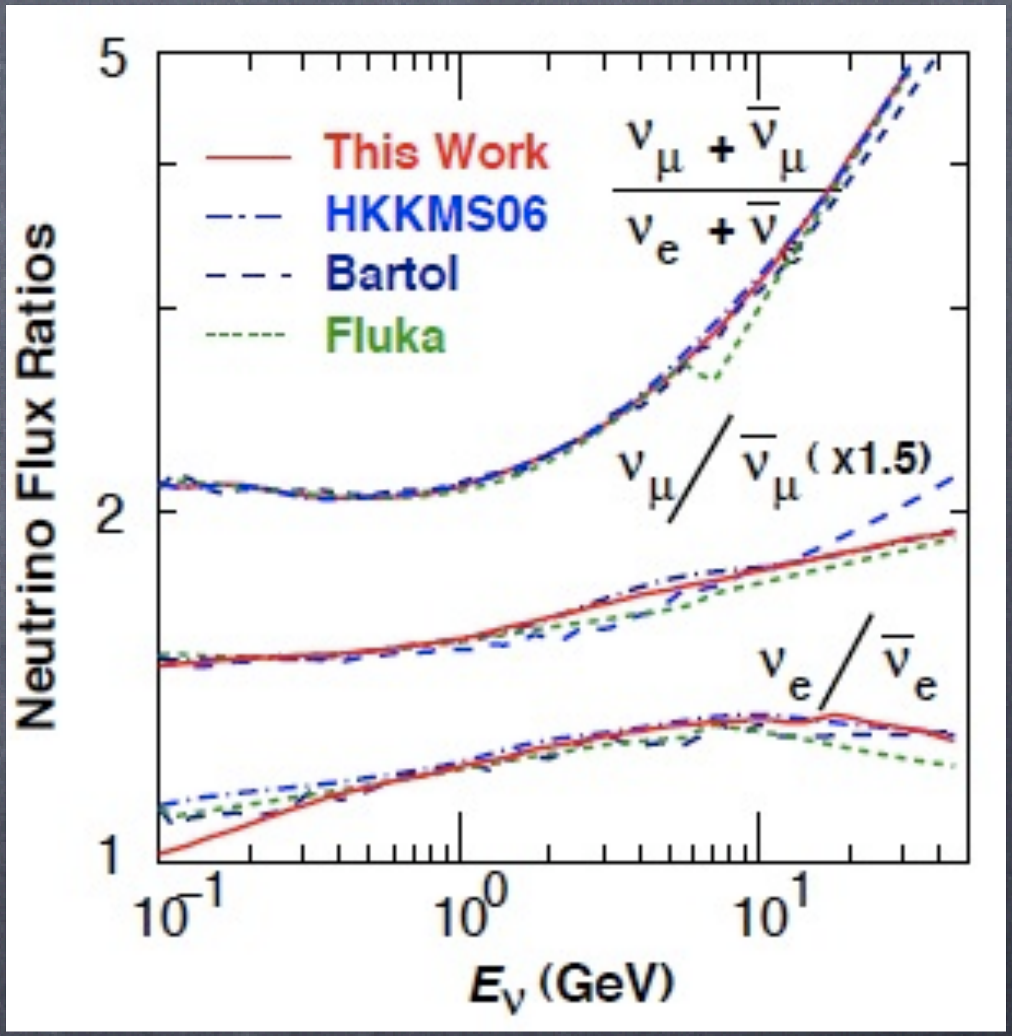
Enhanced for second octant

Sub-GeV events:

r = 2.0-2.2 (2.1-2.6)

Multi-GeV events:

r = 2.1-5.6 (2.4-7.2)



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How to determine the mass hierarchy?

Need of matter effects:

Long-baseline experiments
Supernova neutrinos
Atmospheric neutrinos

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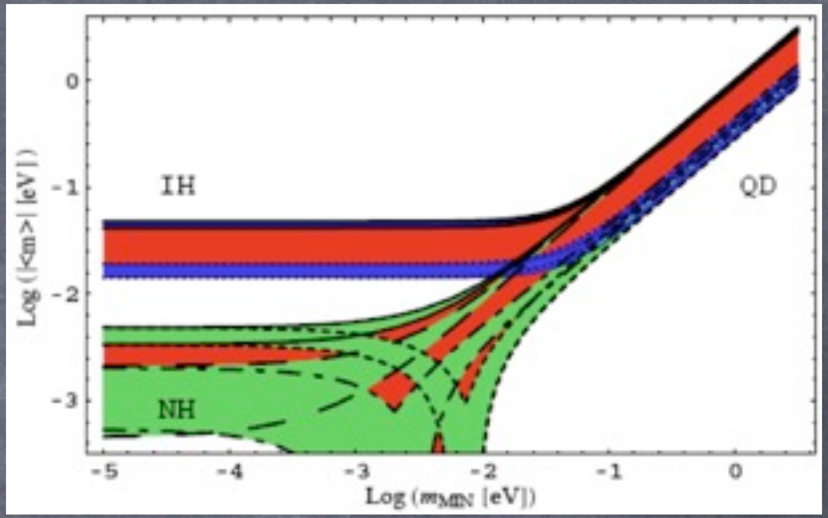
or...

neutrino-less double beta decay
+ absolute mass scale



S. Pascoli, S. T. Petcov and T. Schwetz, *Nucl. Phys. B734:24, 2006*

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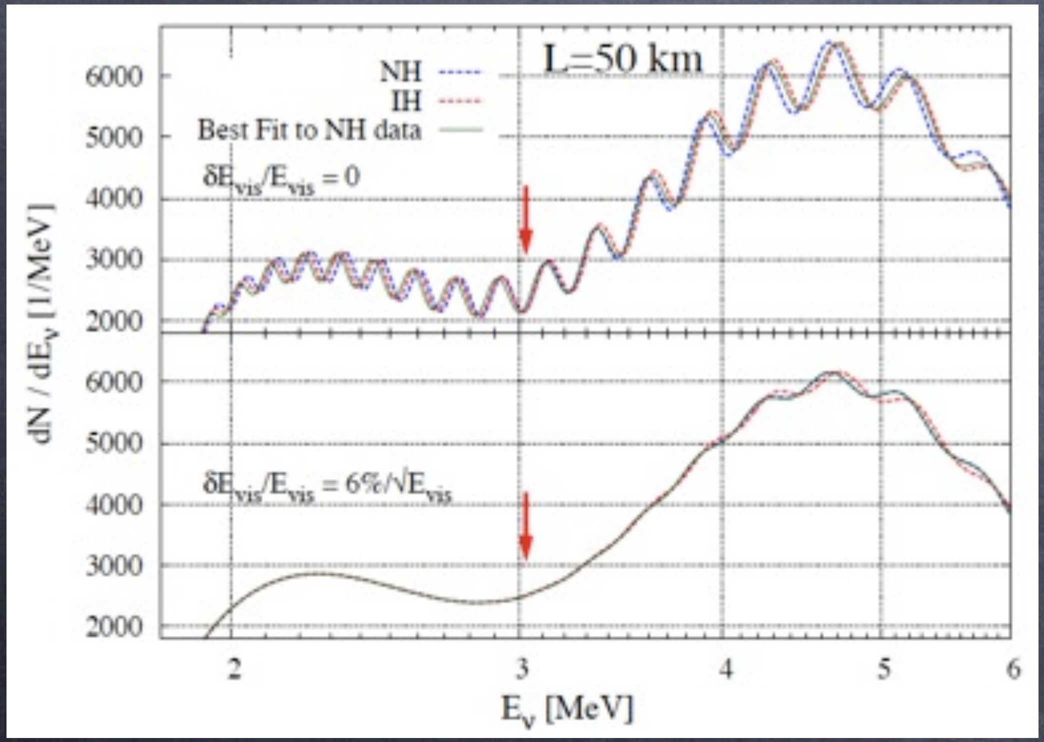

S.-F. Ge, K. Hagiwara, N. Okamura and Y. Takaesu, *arXiv:1210.8141*

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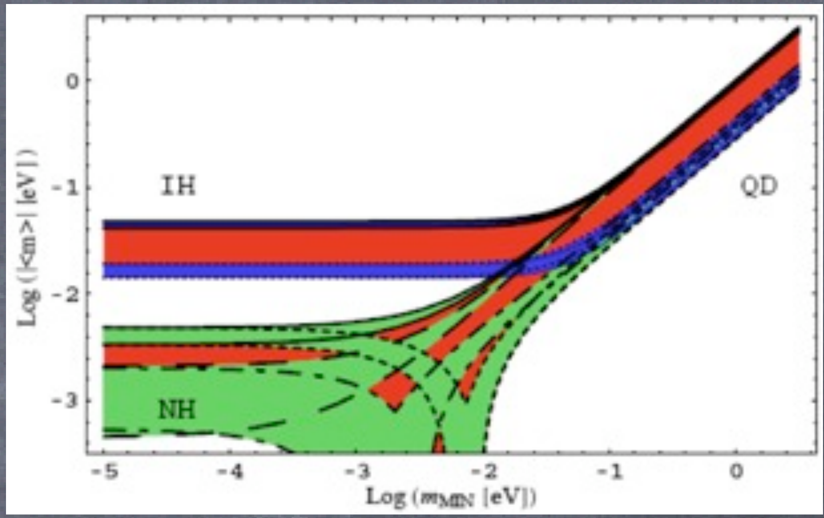

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reactor neutrinos at a intermediate baseline

S. Choubey, S. T. Petcov and M. Piai, *Phys. Rev. D68:113006, 2003*

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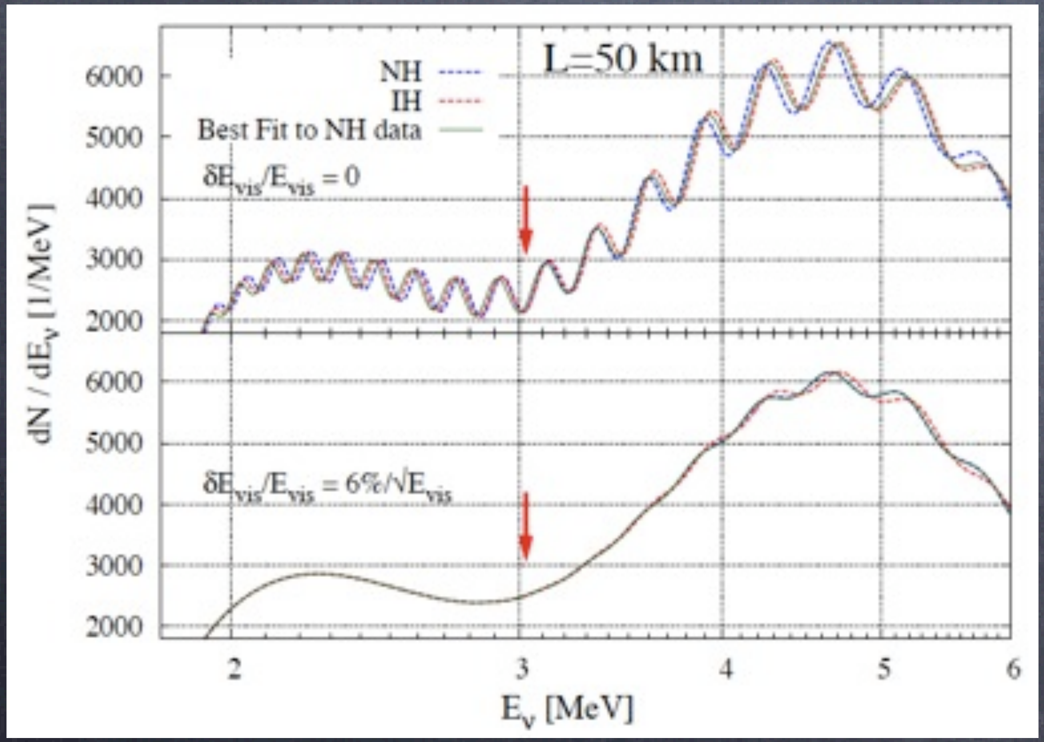

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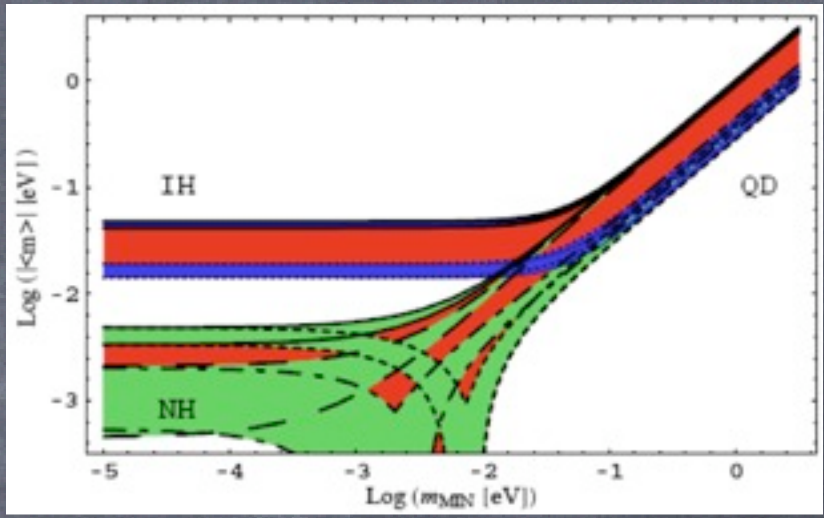

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Mass hierarchy determination with atmospheric neutrinos: Extensive literature

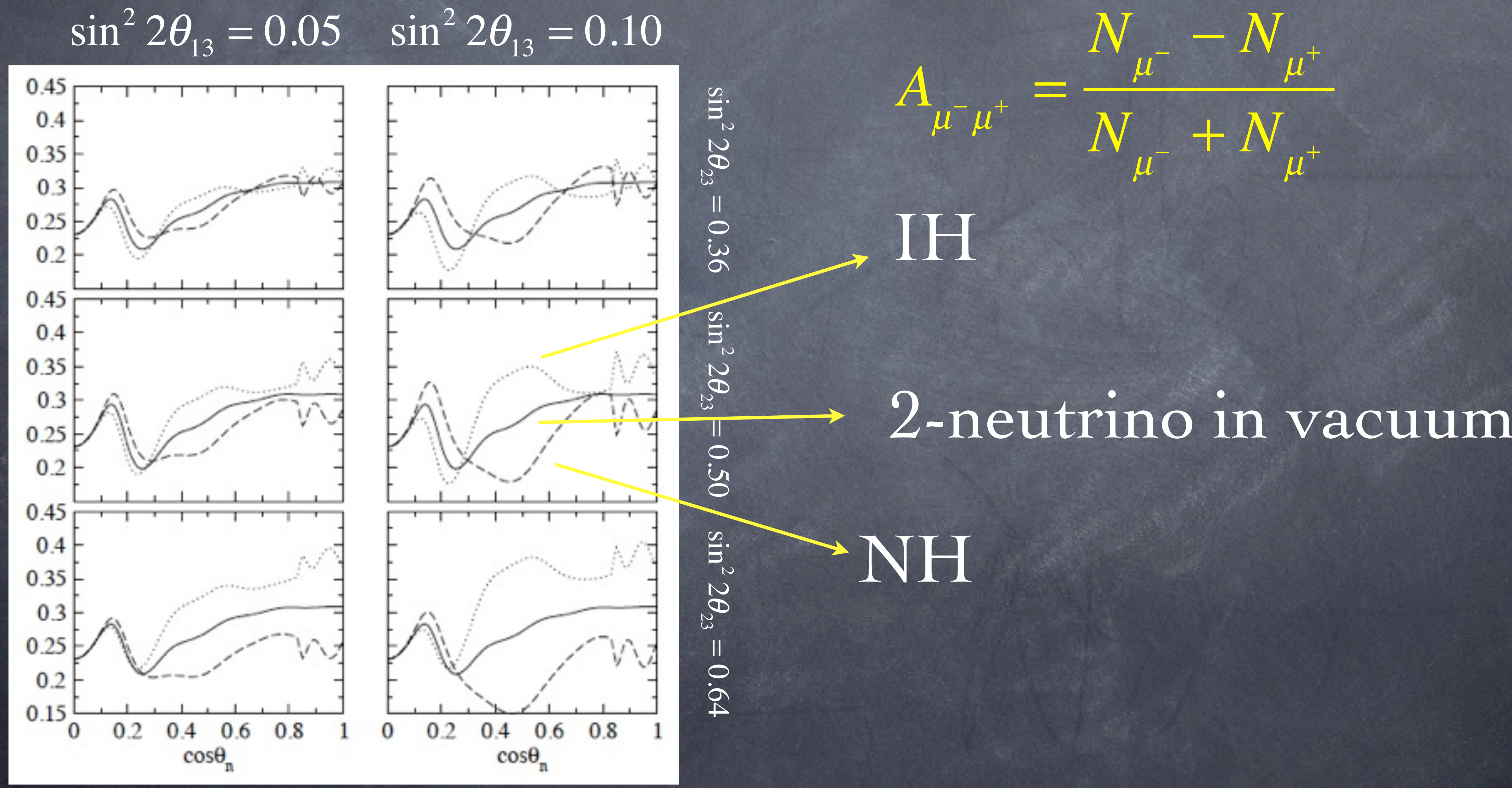
Probably incomplete list:

Petcov 98; Akhmedov 98; Akhmedov, Dighe, Lipari and Smirnov 98; Chizov, Maris and Petcov 98; Chizhov and Petcov 99,00,01; Bañuls, Barenboim and Bernabéu 01; Bernabéu, Pérez, SPR and Petcov 01; González-García and Maltoni 03; Bernabéu, SPR and Petcov 03; SPR and Petcov 04; Indumathi and Murthy 04; González-García, Maltoni and Smirnov 04; Gandhi, Ghosal, Goswami, Mehta and Sankar 04; Huber, Maltoni and Schwetz 05; Akhmedov, Maltoni and Smirnov 05, 06, 08; Choubey and Roy 05; Petcov and Schwetz 06; Indumathi, Murthy, Rajasekaran and Sinha 06; Samanta 06, 09; Gandhi, Ghoshal, Goswami, Mehta, Sankar and Shalgar 07; Mena, Mocioiu and Razzaque 08; Gandhi, Ghoshal, Goswami and Sankar 08; Giordano, Mena and Mocioiu 10; Fernández-Martínez, Giordano, Mena and Mocioiu 10; Samanta and Smirnov 10; González-García, Maltoni and Salvado 11; Blennow and Schwetz 12; Barger, Gandhi, Ghoshal, Goswami, Marfatia, Prakash, Raut and Sankar 12; Akhmedov, Razzaque and Smirnov 12; Ghosh, Thakore and Choubey 12; Agarwalla, Li, Mena and SPR 12, Franco, Joliet, Kouchner, Kulikovskiy, Meregaglia, Perasso, Pradier, Tonazzo and Van Elewyck 13, Ribordy and Smirnov 13...

Mass hierarchy with magnetized detectors

Charge discrimination:

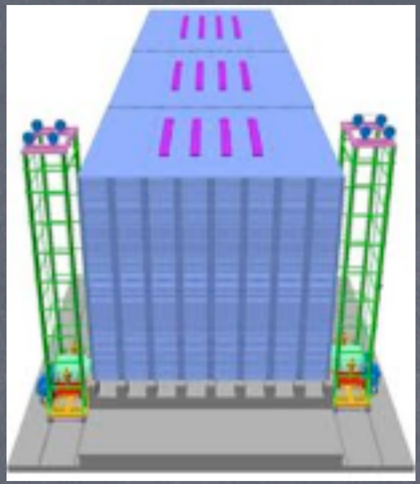
distinction between neutrinos and antineutrinos



$$A_{\mu^-\mu^+} = \frac{N_{\mu^-} - N_{\mu^+}}{N_{\mu^-} + N_{\mu^+}}$$

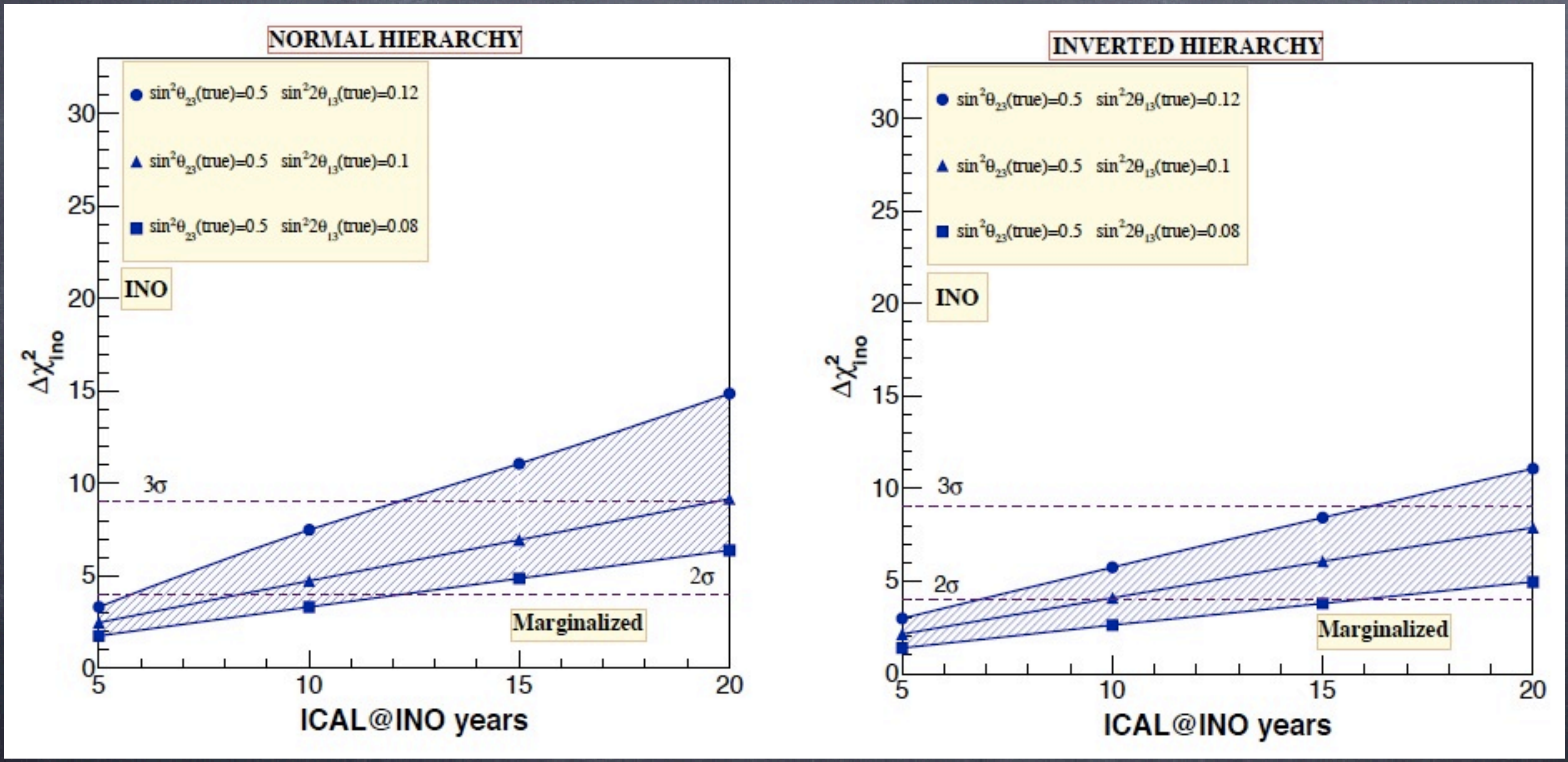
SPR and S. T. Petcov, *Nucl. Phys. B712:392, 2005*

ICAL@INO: 50kton



Good energy and angular resolution

1-2 GeV threshold



A. Ghosh, T. Thakore and S. Choubey, *arXiv:1212.1305*

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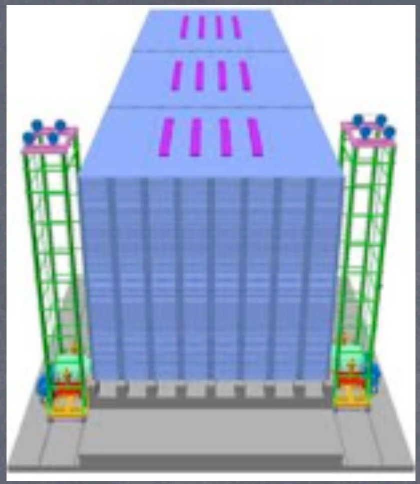

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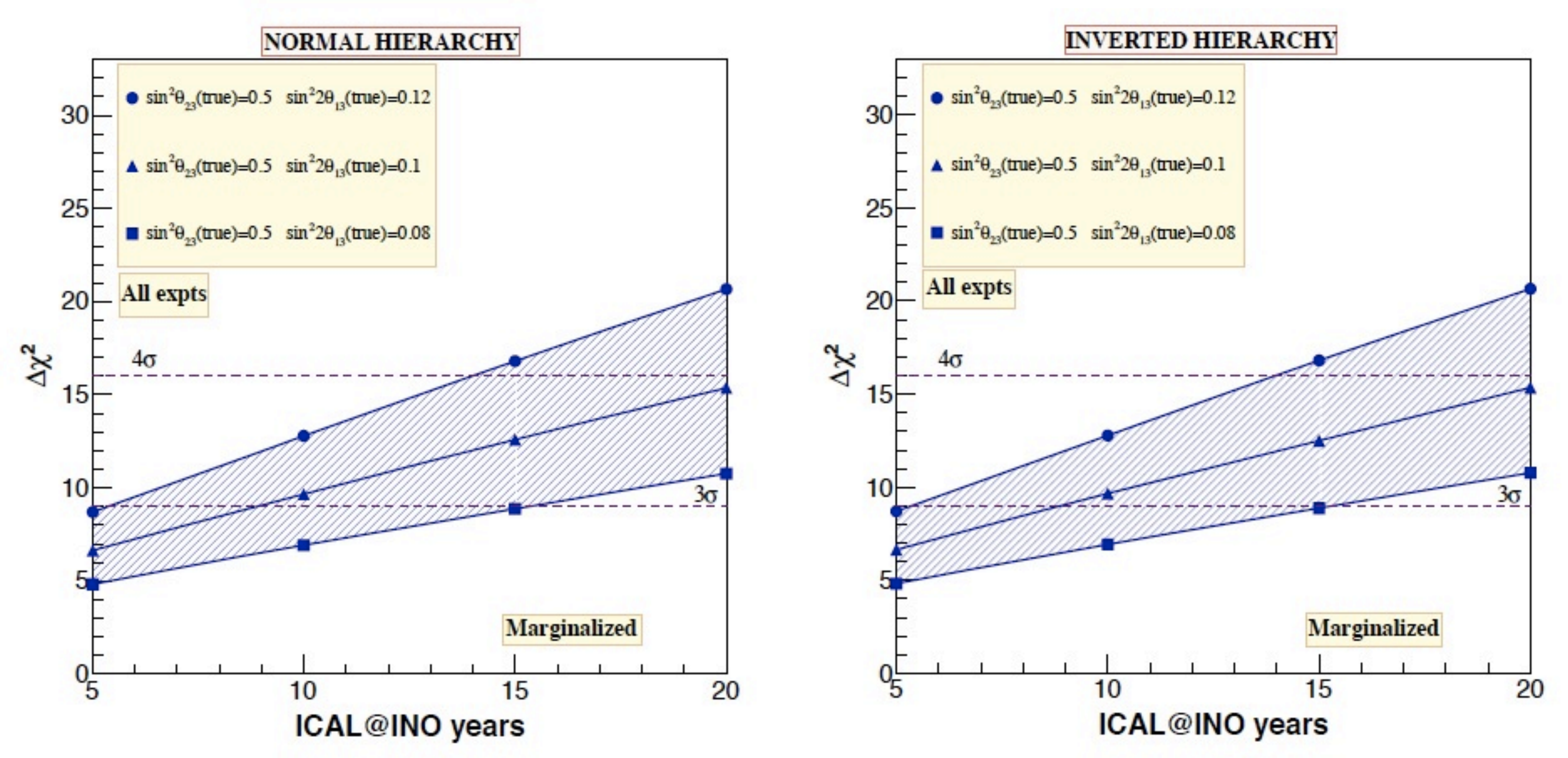

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Mass hierarchy with Cherenkov detectors

No charge discrimination is possible:
no distinction between neutrinos and antineutrinos

In the limit the solar sector can be neglected
(few GeV and 1000's km):

$$P^{NH} = \overline{P}^{IH}$$

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Then... how can we tell the hierarchy?

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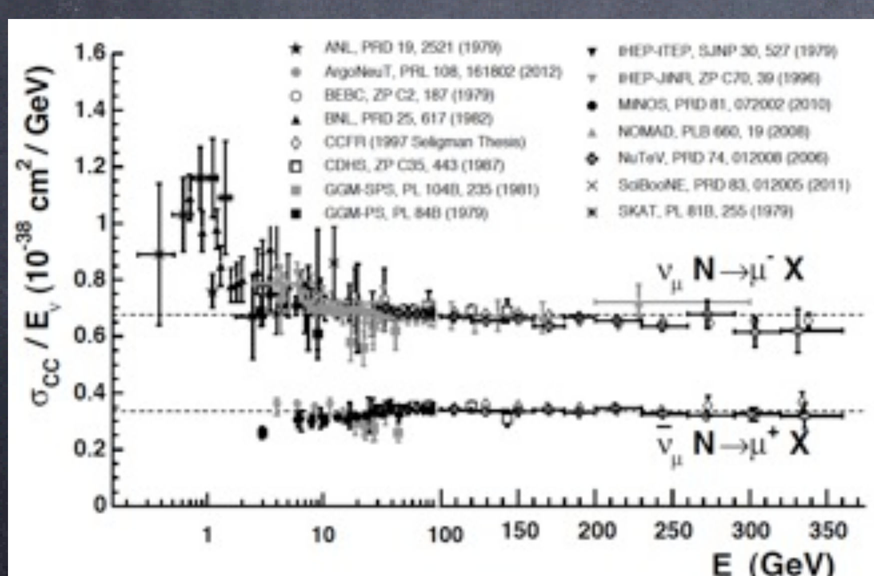
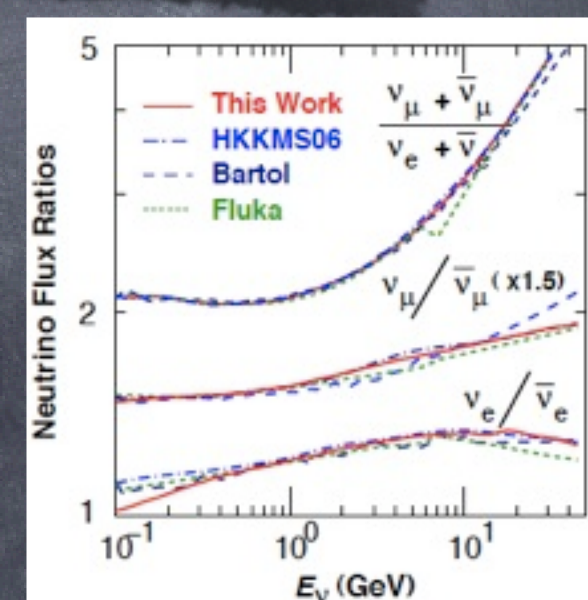


J. Beringer *et al.* (PDG), *Phys. Rev. D86:010001, 2012*

Different cross sections

Different fluxes



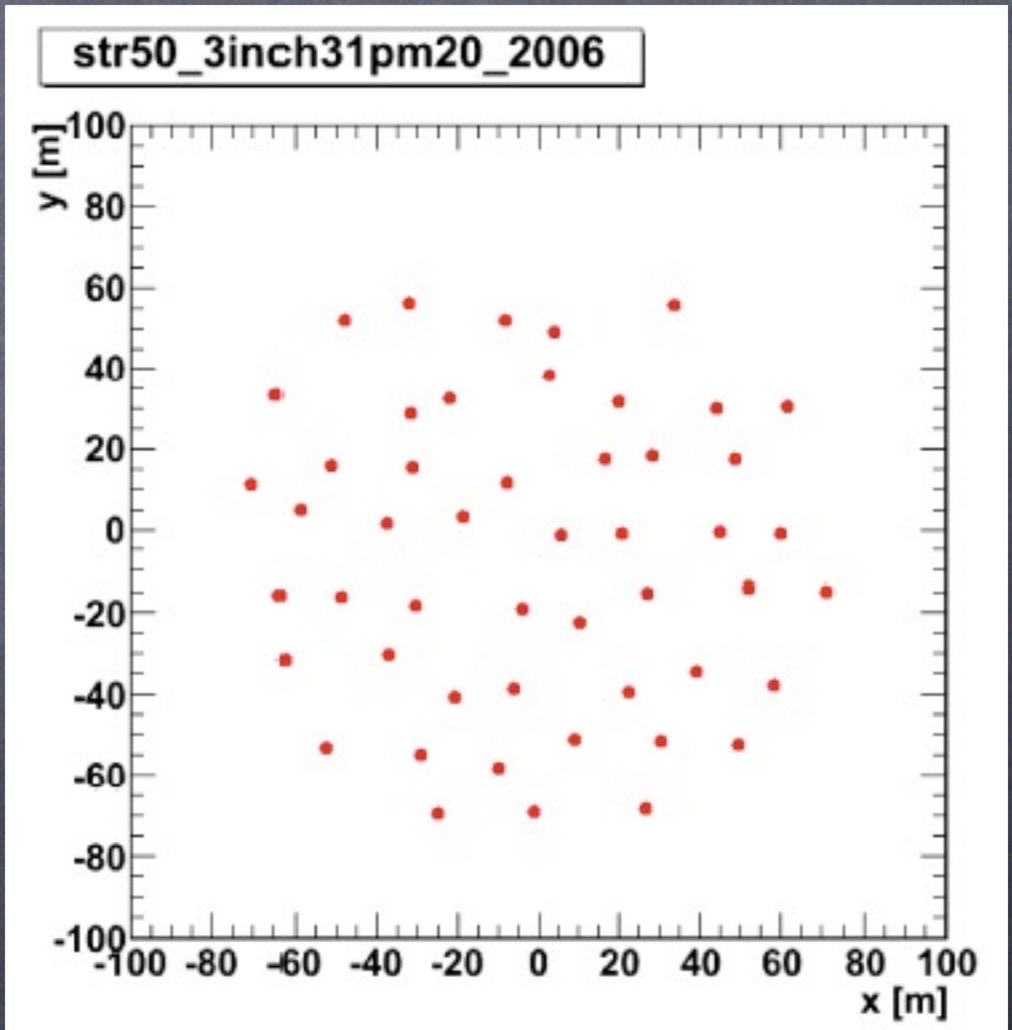
M. Honda, T. Kajita, K. Kasahara and S. Midorikawa, *Phys. Rev. D83:123001, 2011*

ORCA: mediterranean sea

Possible phase 1 of KM3NeT to reduce the energy threshold down to ~GeV

Instrumented volume = 1.75 Mton

*50 strings
*OM=31 3” PMTs
*20 OM in each string
*6m vertical distance between OMs
*20m average distance between strings



J. Brunner, Talk at New Directions in Neutrino Physics, Aspen, CO, February 2013

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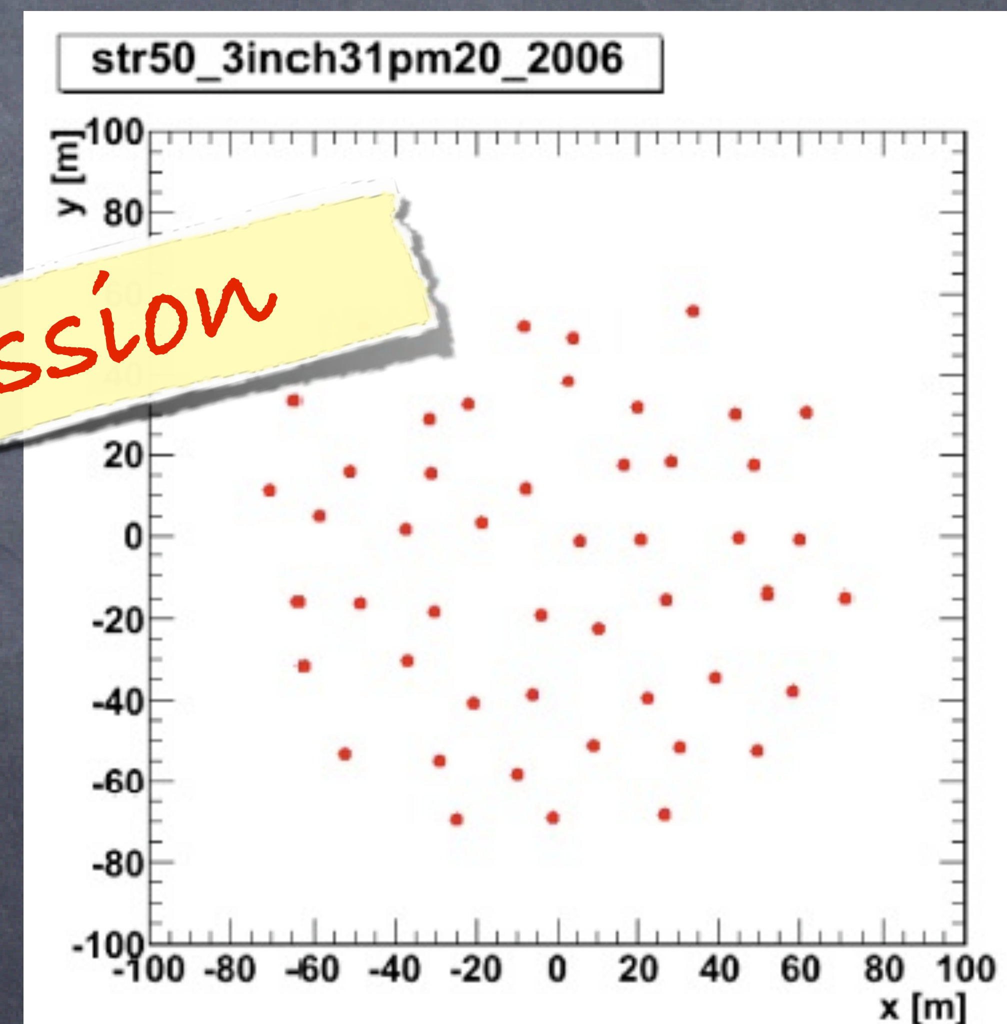
See tomorrow’s session



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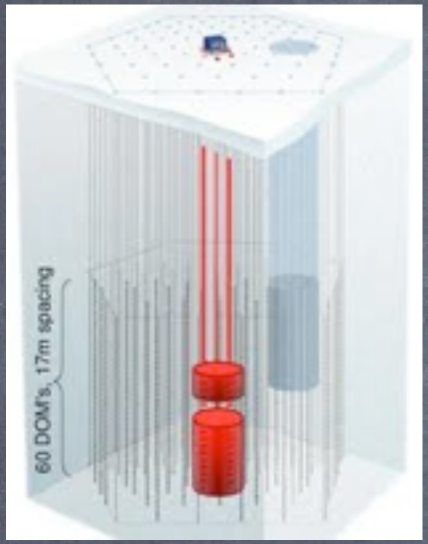
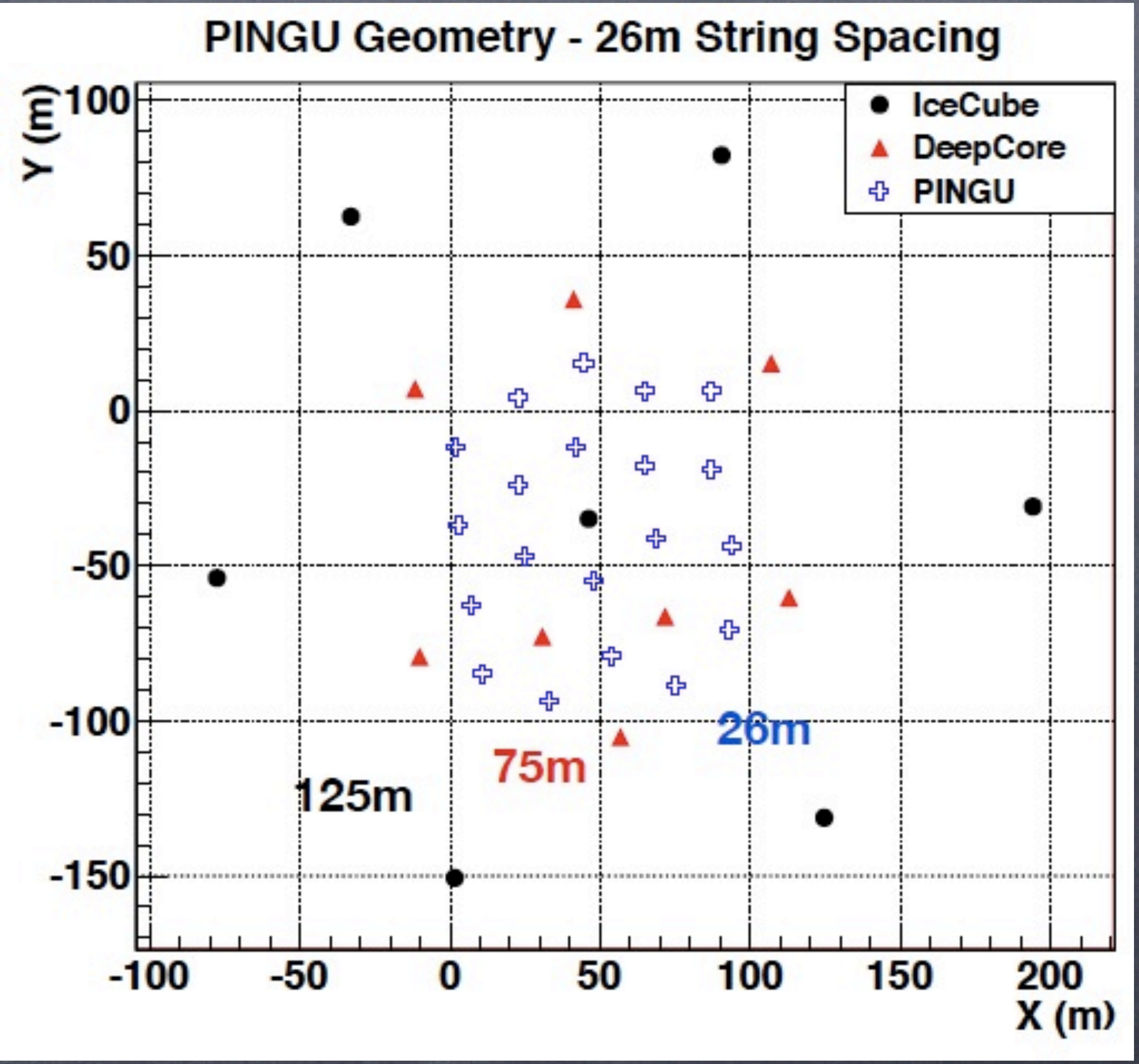
PINGU: south pole

Additional strings within the IceCube/DeepCore volume



*20 strings
*60 DOM in each string
*5m vertical distance between DOMs
*26m average distance between strings



Other configurations are under investigation

J. Koskinen, Talk at New Directions in Neutrino Physics, Aspen, CO, February 2013

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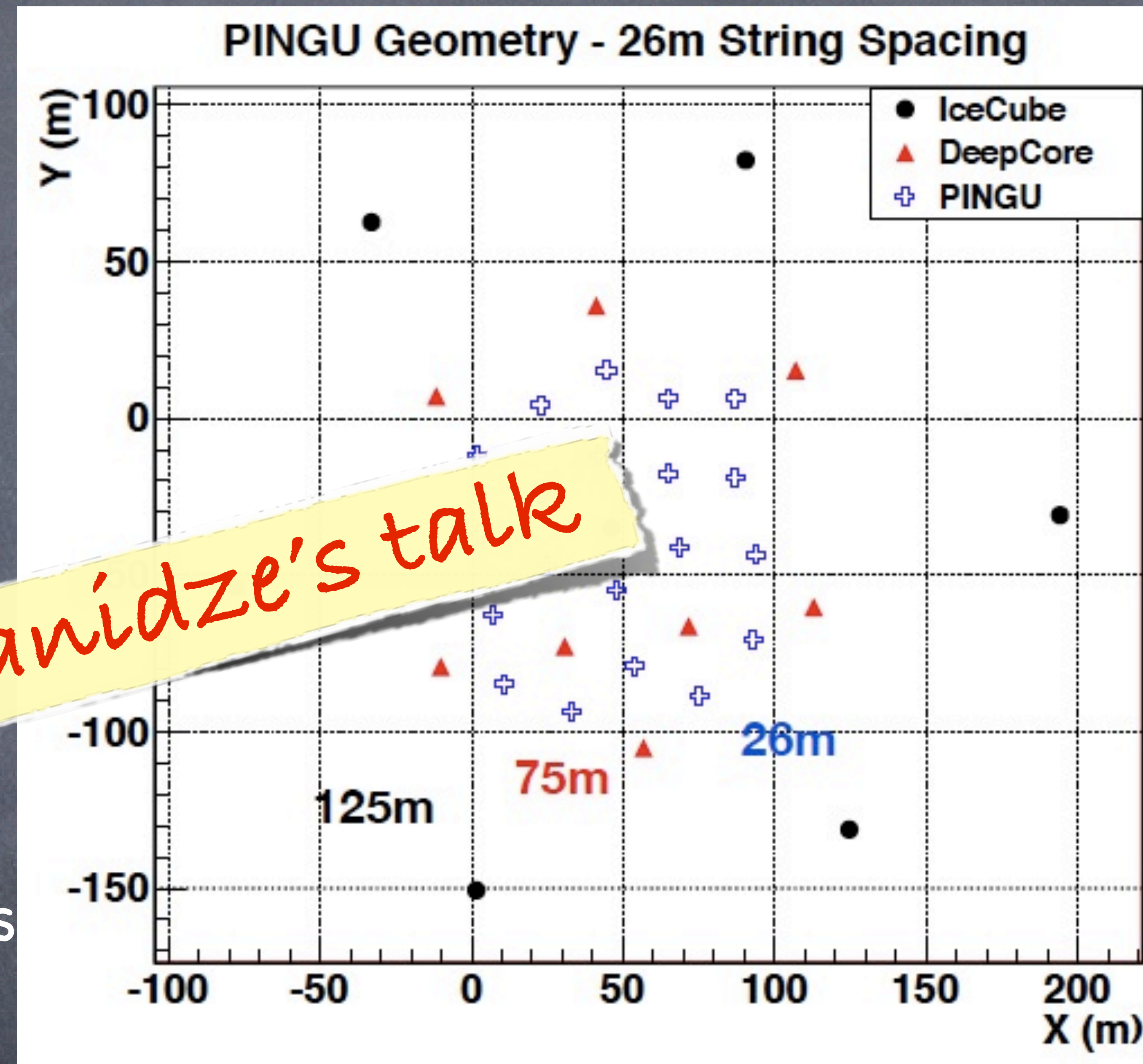
See Rezo Shanidze's talk



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Setups

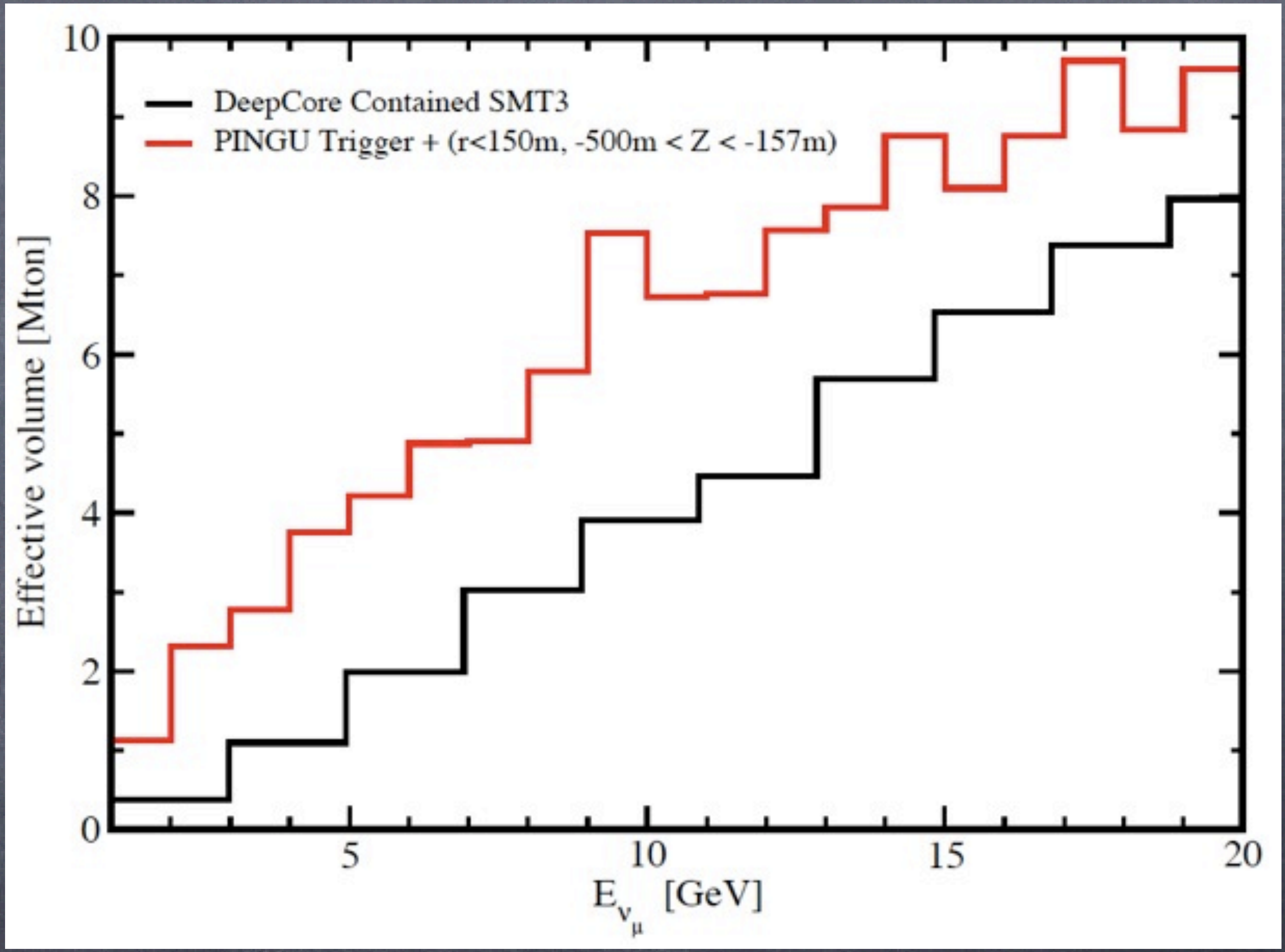
We assume 50% post-trigger efficiency

DeepCore: 1 energy bin
10-15 GeV

PINGU-0: 2 energy bins
5-10 and 10-15 GeV

PINGU-I: 4 energy bins
5-7.5, 7.5-10,
10-12.5, 12.5-15 GeV

10 angular bins
$\Delta\cos\theta=0.1$ for $\cos\theta=[-1,0]$



Thanks to Jason Koskinen and Ty DeYoung

Mixing parameters and priors

Future error:
Reactors & LBL

True Values	Marginalization Range	External 1σ error
$\sin^2\theta_{13}^{\rm true} = 0.025$	$[0.019,\ 0.030]$	$\sigma(\sin^2 2\theta_{13}) = 5\%$
$\sin^2\theta_{23}^{\rm true} = 0.5$	$[0.38,\ \ 0.66]$	$\sigma(\sin^2 2\theta_{23}) = 2\%$
$(\Delta m^2_{\rm eff})^{\rm true} = \pm 2.4 \times 10^{-3}\ {\rm eV}^2$	$[2.2,\ 2.6] \times 10^{-3}\ {\rm eV}^2$ (NH) $-[2.6,\ 2.2] \times 10^{-3}\ {\rm eV}^2$ (IH)	$\sigma(\lvert\Delta m^2_{\rm eff}\rvert) = 4\%$
$(\Delta m^2_{21})^{\rm true} = 7.62 \times 10^{-5}\ {\rm eV}^2$	–	–
$\sin^2\theta_{12}^{\rm true} = 0.32$	–	–
$\delta_{\rm CP}^{\rm true} = 0°$	–	–
$\Delta\rho^{\rm true} = 0$	[-0.1, 0.1]	–
$\xi_{\rm norm}^{\rm true} = 0$	[-1, 1]	$\sigma_{\rm norm} = 20\%$

Correlated error: normalization of the atmospheric neutrino flux, detector effective mass, efficiency, cross sections

Statistical analysis

$$\vec{\lambda}_{\pm} = \left\{\theta_{13},\theta_{23},\left|\Delta m^2_{eff}\right|,\pm,\Delta\rho;\theta_{12}^{true},\left(\Delta m^2_{21}\right)^{true},\delta_{CP}^{true}\right\}$$

$$\chi^2_{\pm}(\Delta\rho) = \min_{\left(\xi_{norm},\xi_{\sin^2 2\theta_{13}},\xi_{\sin^2 2\theta_{23}},\xi_{\left|\Delta m^2_{eff}\right|}\right)} \left\{\chi^2_{MH\pm}\left(\vec{\lambda}_{\mp},\xi_{norm}\right) + \left(\frac{\xi_{norm}}{\sigma_{norm}}\right)^2 + \chi^2_{prior}\right\}$$

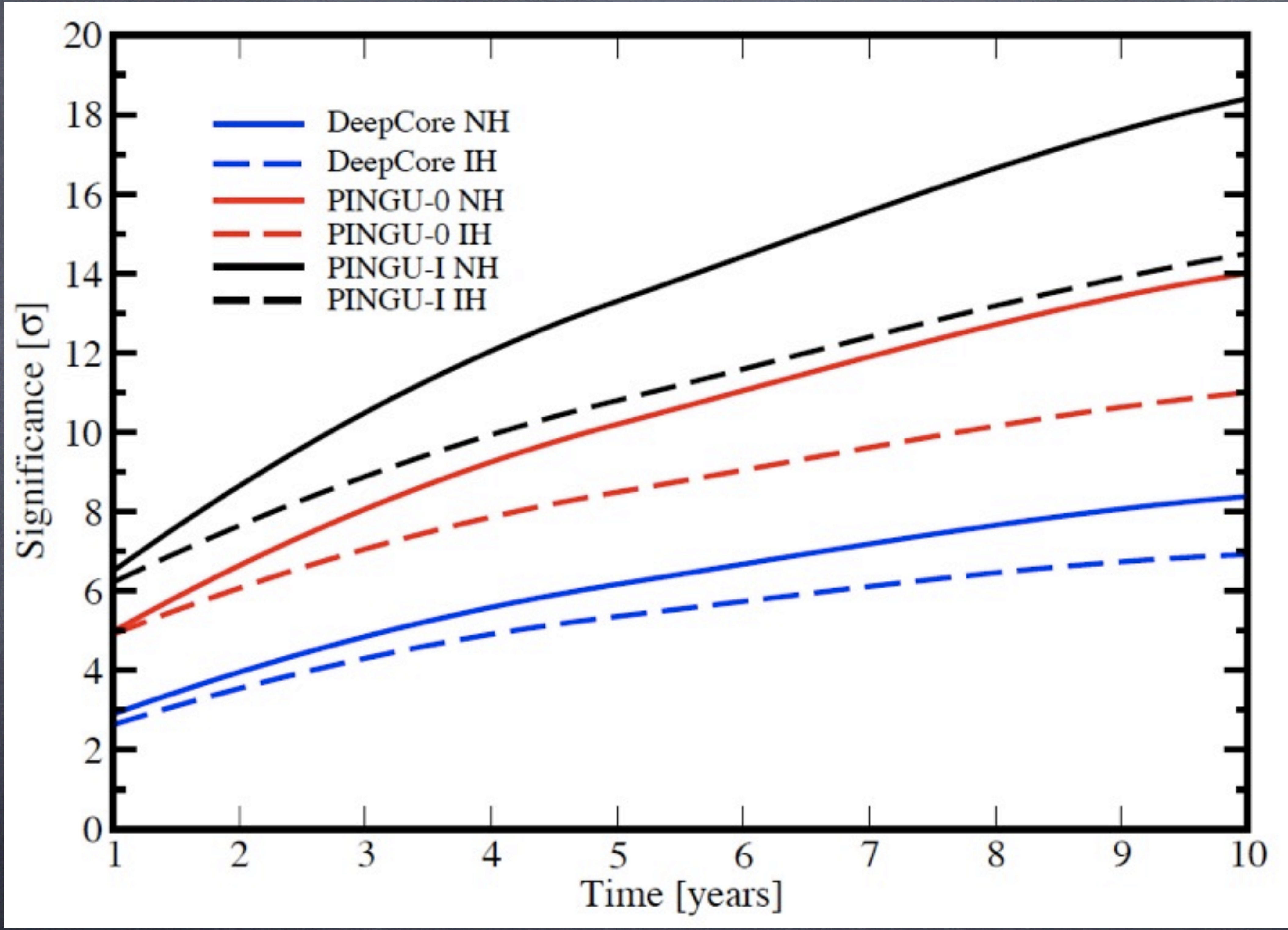
Marginalized parameters

$$\chi^2_{MH\pm}\left(\vec{\lambda}_{\mp},\xi_{norm}\right) = \sum_{(\cos\theta)_i}\sum_{(E_\nu)_j} \frac{\left[N_{ij}^{th}\left(\vec{\lambda}_{\pm}^{true}\right) - N_{ij}^{th}\left(\vec{\lambda}_{\mp}\right)\left(1+\xi_{norm}\right)\right]^2}{N_{ij}^{th}\left(\vec{\lambda}_{\pm}^{true}\right)}$$

$$\chi^2_{prior} = \left(\frac{\xi_{\sin^2 2\theta_{13}}}{\sigma\left(\sin^2 2\theta_{13}\right)}\right)^2 + \left(\frac{\xi_{\sin^2 2\theta_{23}}}{\sigma\left(\sin^2 2\theta_{23}\right)}\right)^2 + \left(\frac{\xi_{\left|\Delta m^2_{eff}\right|}}{\sigma\left(\left|\Delta m^2_{eff}\right|\right)}\right)^2$$

Finally, we marginalize over the density

Sensitivity to the mass hierarchy



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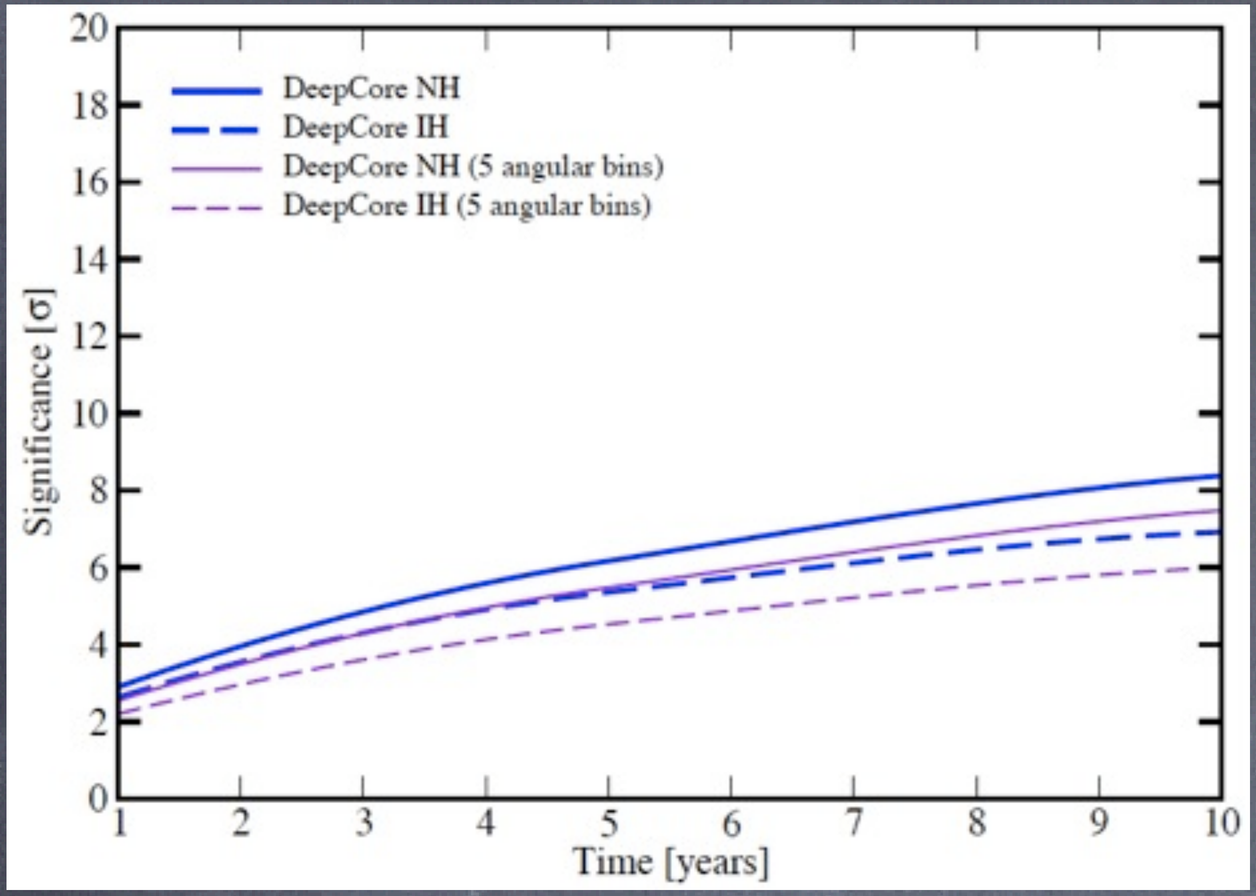
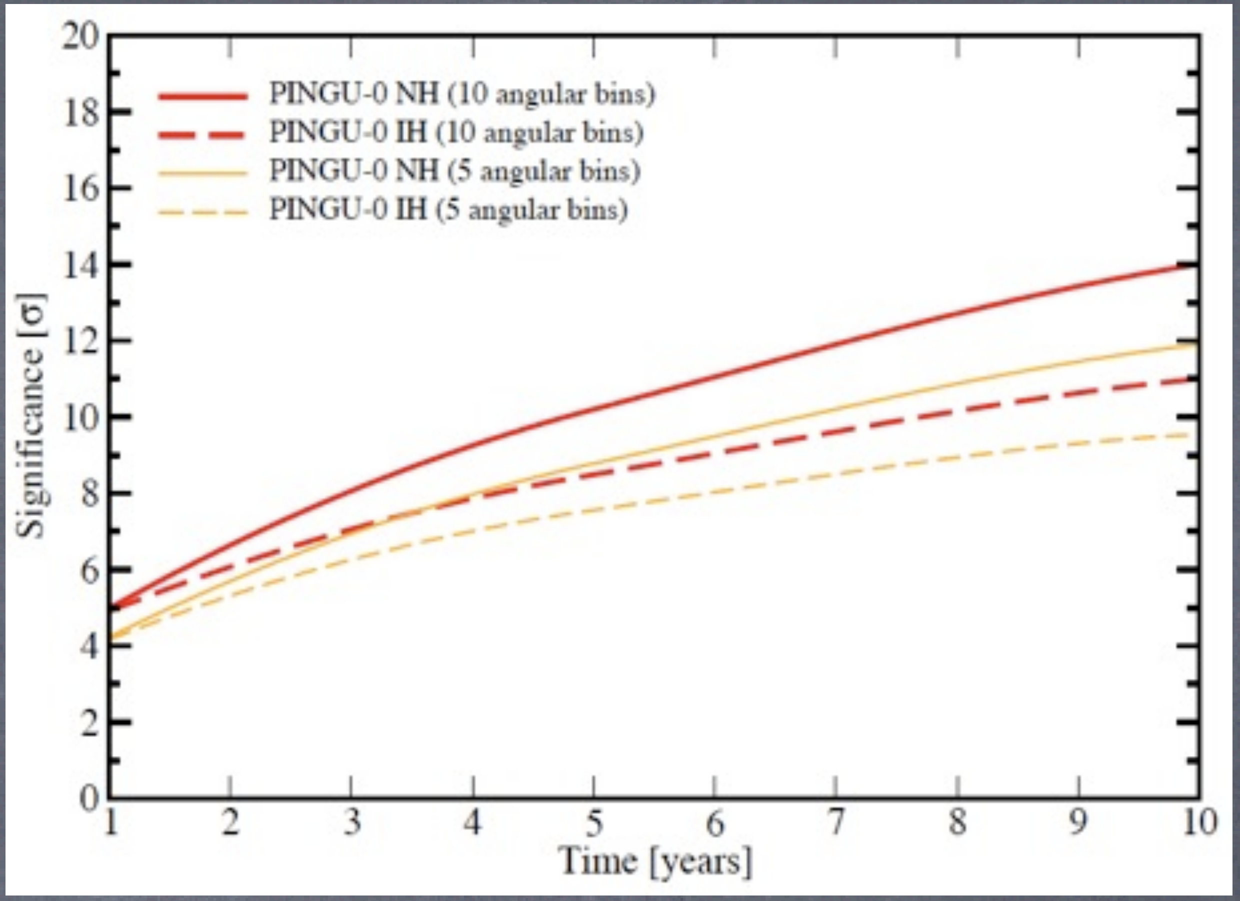
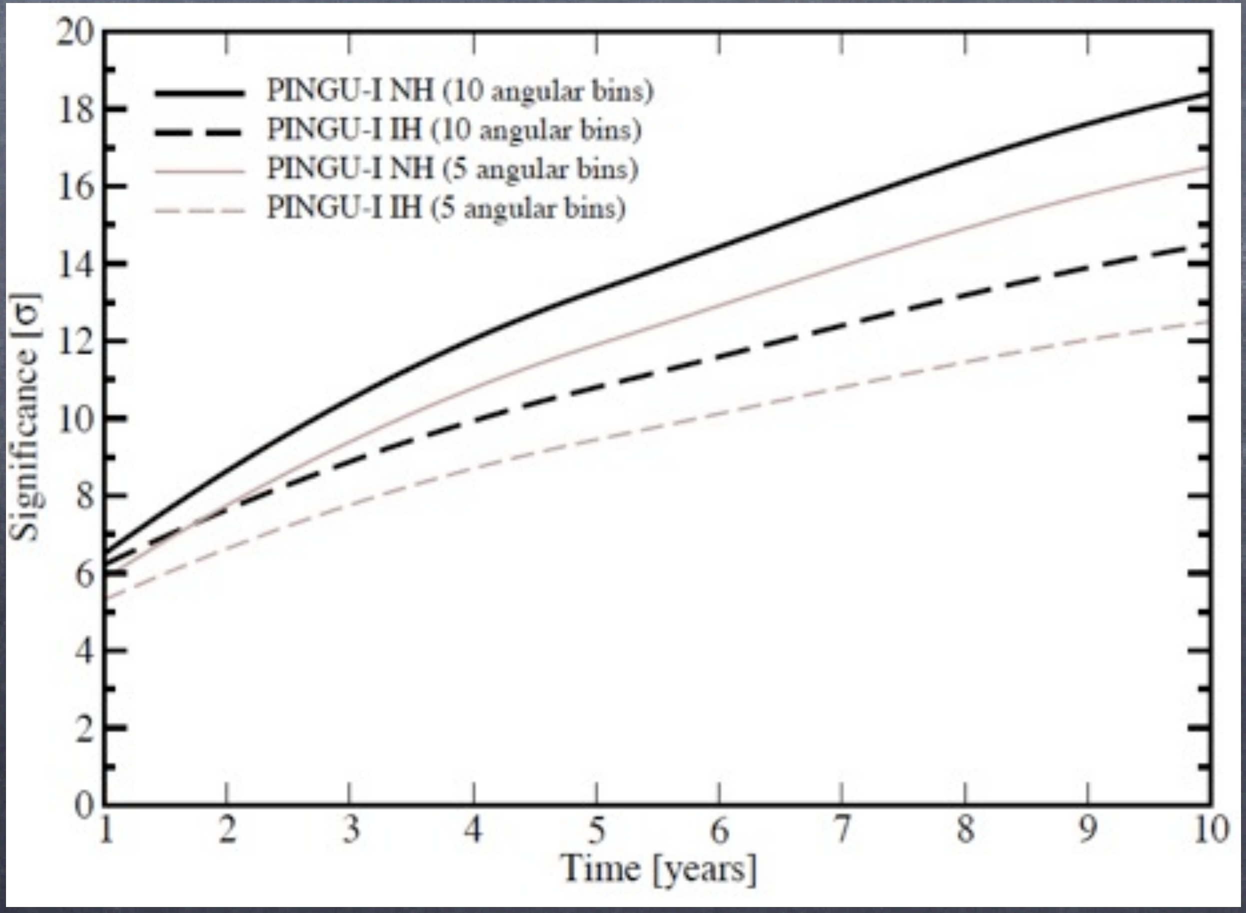




Effect of angular binning



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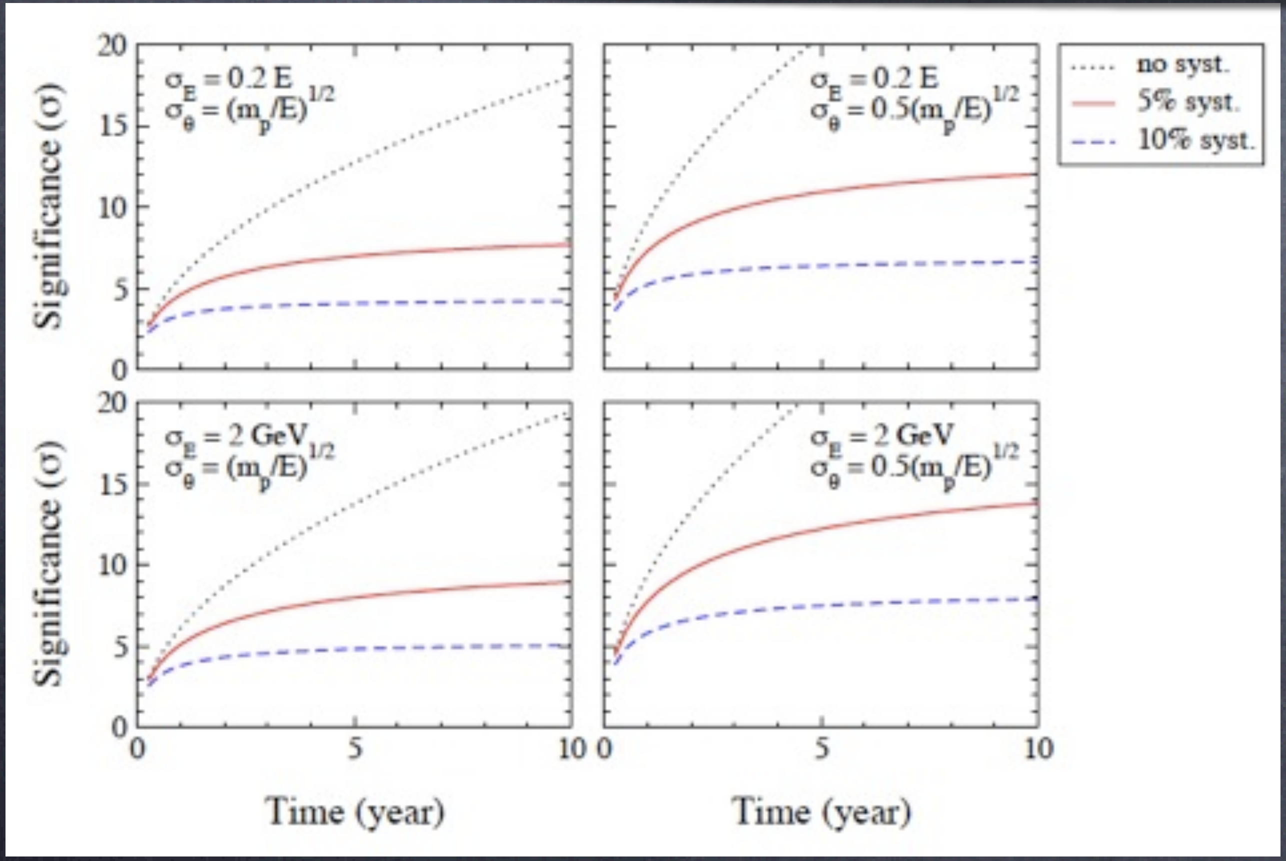
Note of caution:

-We include marginalization over relevant parameters, take large energy bins and add the impact of correlated errors, but...

-a more accurate account of the resolutions is needed, likely to decrease the sensitivity by ~2/3
-effect of uncorrelated systematic errors: 5% error would decrease the sensitivity by ~2/3
-kinematical smearing would also reduce the sensitivity



E. Kh. Akhmedov, S. Razzaque and A. Yu. Smirnov, *JHEP 1302:082, 2013*

Using inelasticity:

partial separation of neutrino and antineutrino
help in neutrino direction reconstruction
reduction of neutrino parameters degeneracy
reduce systematic uncertainties

Improvement of 5%-15%, depending on resolutions

M. Ribordy and A. Yu. Smirnov, *arXiv:1303.0758*

<u>Note of caution:</u>

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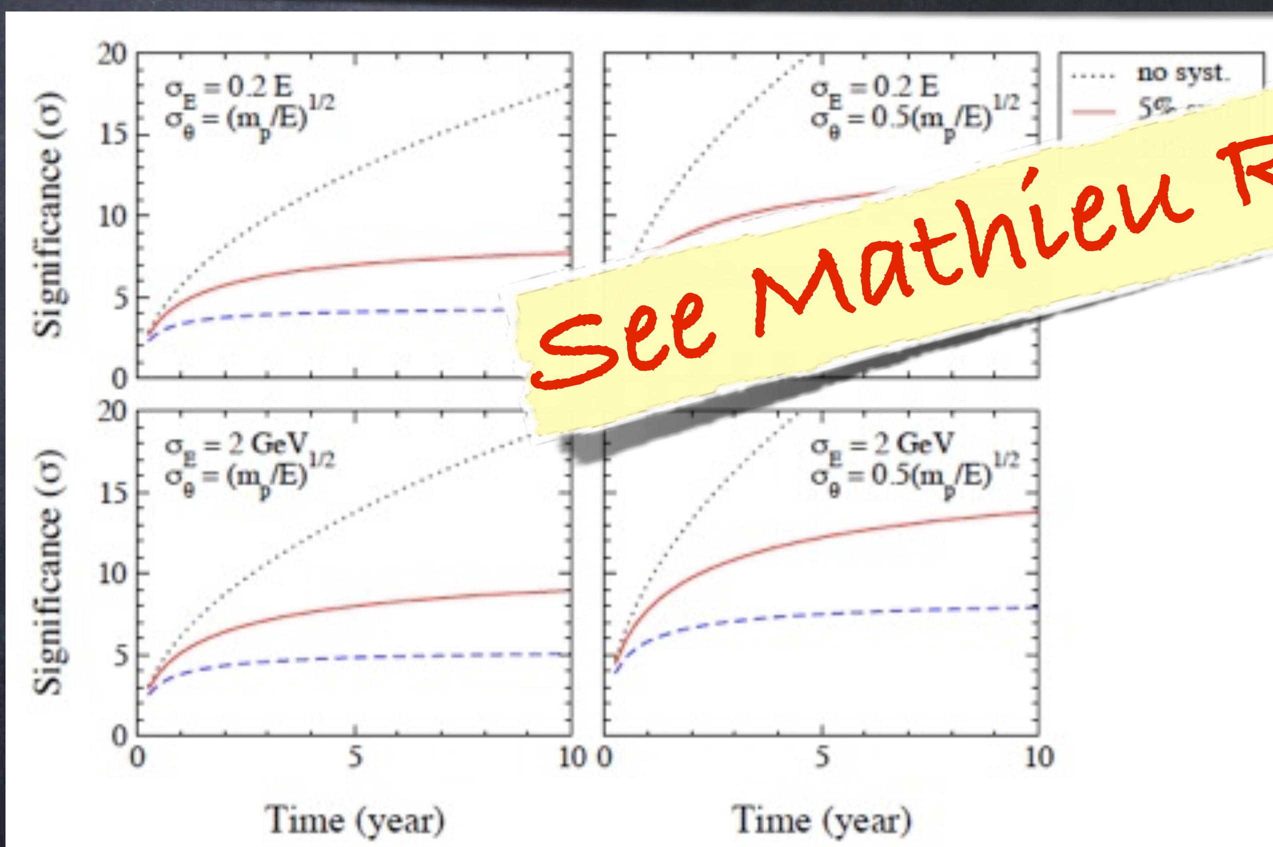
See Mathieu Ribordy's talk



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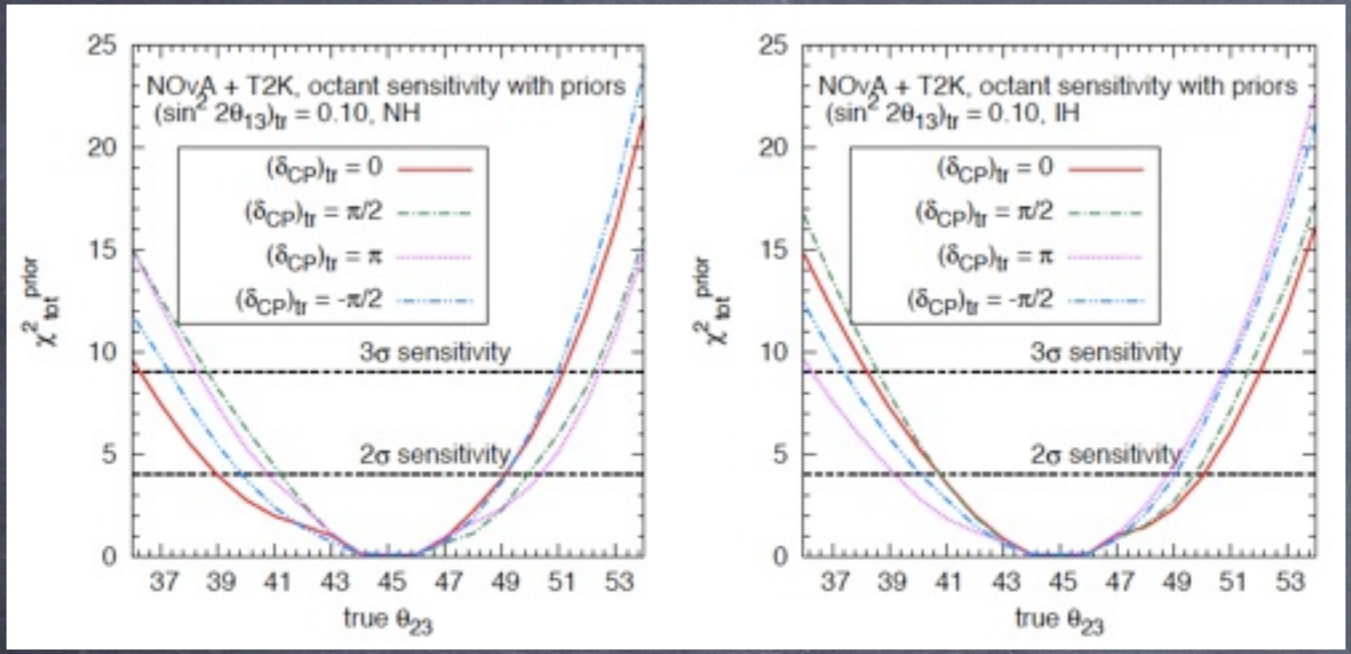
Determination of the θ_{23} octant

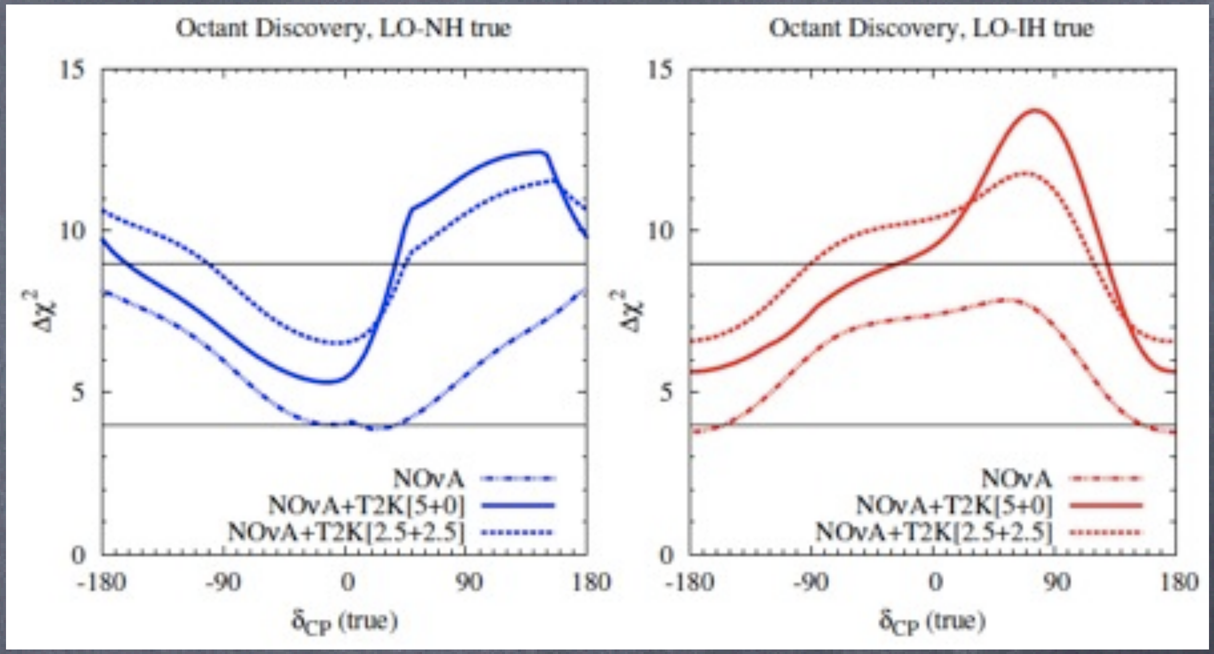
Problem: octant degeneracy

G. L. Fogli and E. Lisi, *Phys. Rev. D54:3667, 1996*

Long-baseline experiments: it depends on the CP phase



A. Chatterjee, P. Ghoshal, S. Goswami and S. K. Raut, *arXiv:1302.1370*



S. K. Agarwalla, S. Prakash and S. U. Sankar, *arXiv:1301.2574*

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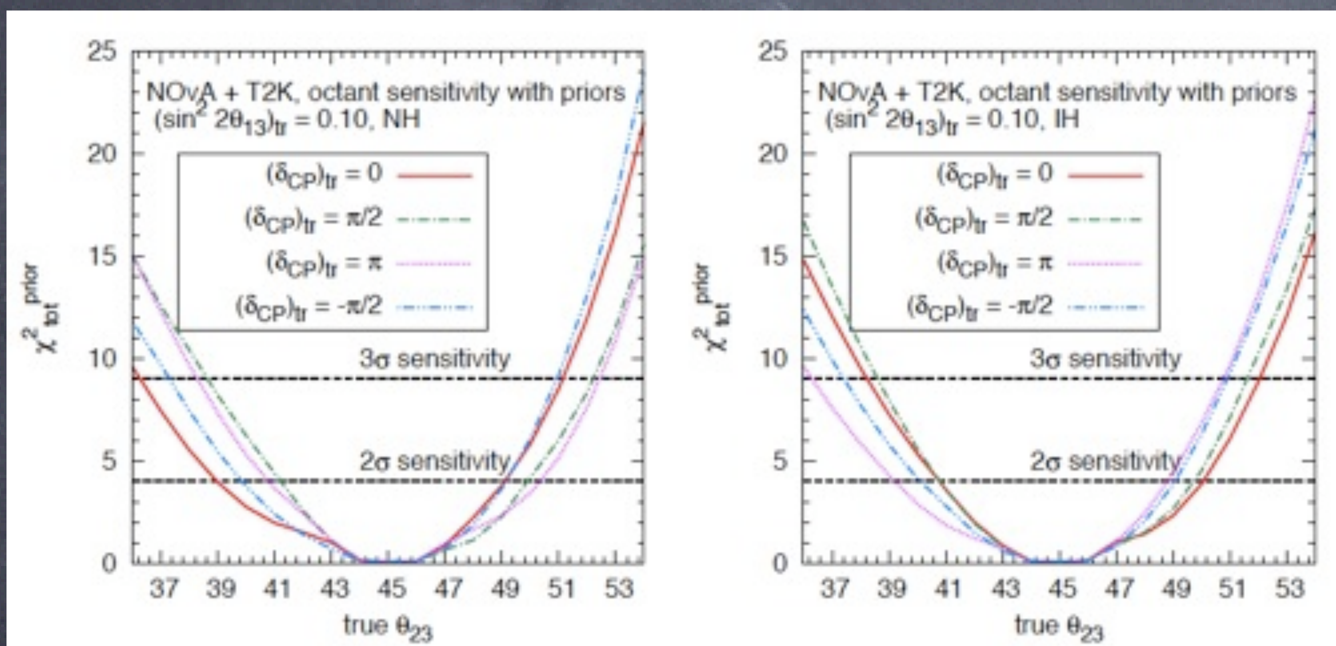

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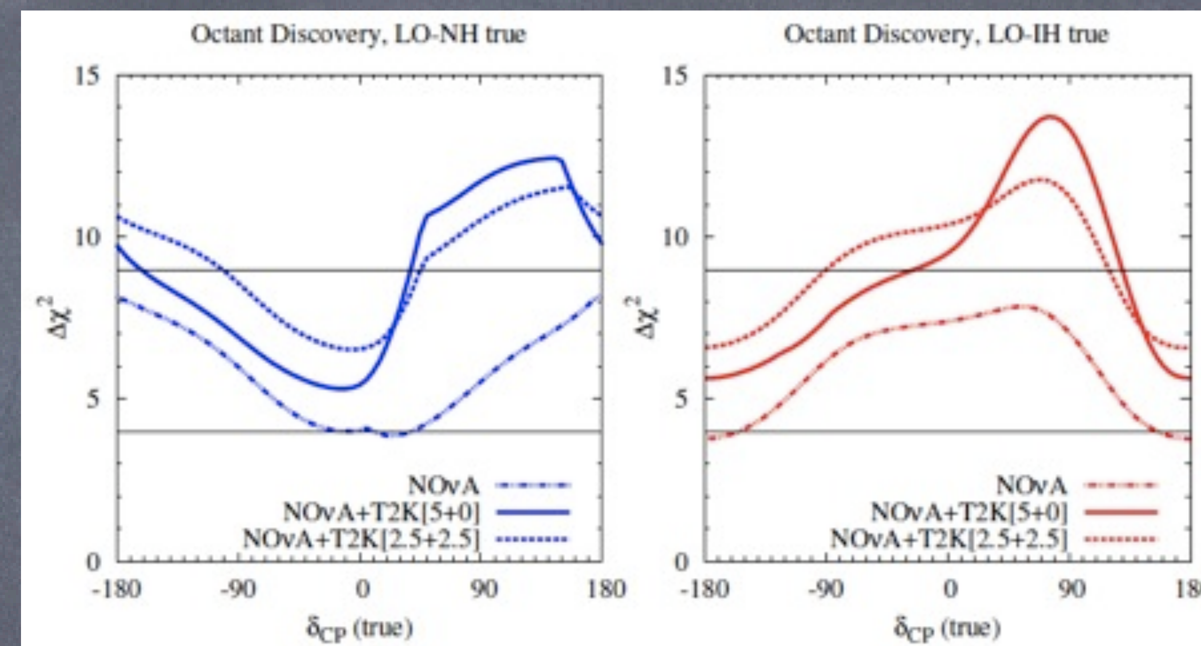

S. K. Agarwalla, S. Prakash and S. U. Sankar, *arXiv:1301.2574*

Atmospheric neutrinos:

sub-GeV events: solar term

multi-GeV events: matter effect

Octant determination with atmospheric neutrinos

Probably incomplete list:

Peres and Smirnov 03;

Gonzalez-Garcia, Maltoni and Smirnov 04;

Huber, Maltoni and Schwetz 05;

Choubey and Roy 05;

Campagne, Maltoni, Mezzetto and Schwetz 06;

Indumathi, Murthy, Rajasekaran and Sinha 06;

Samanta 08;

Fernandez-Martinez, Giordano, Mena and Mocioiu 10;

Samanta and Smirnov 10;

Barger, Gandhi, Ghoshal, Goswami, Marfatia, Prakash, Raut and Sankar 12;

Chatterjee, Ghoshal, Goswami and Raut 13;

Thakore, Ghosh, Choubey and Dighe 13

Determination of the θ_{23} octant: atmospheric neutrinos

$$\Phi_{\nu_\mu}(E,\theta) = \Phi^0_{\nu_\mu}\left(P_{3\nu}(\nu_\mu \to \nu_\mu) + \frac{1}{r} P_{3\nu}(\nu_e \to \nu_\mu)\right)$$

$$\Phi_{\nu_\mu}(E,\theta) \simeq \Phi^0_{\nu_\mu}\left(1 - \left(s^4_{23} - \frac{s^2_{23}}{r}\right)P_{2\nu} - \left(c^4_{23} - \frac{c^2_{23}}{r}\right)P^S_{2\nu} + f(\sin^2 2\theta_{23})\right)$$

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multi-GeV

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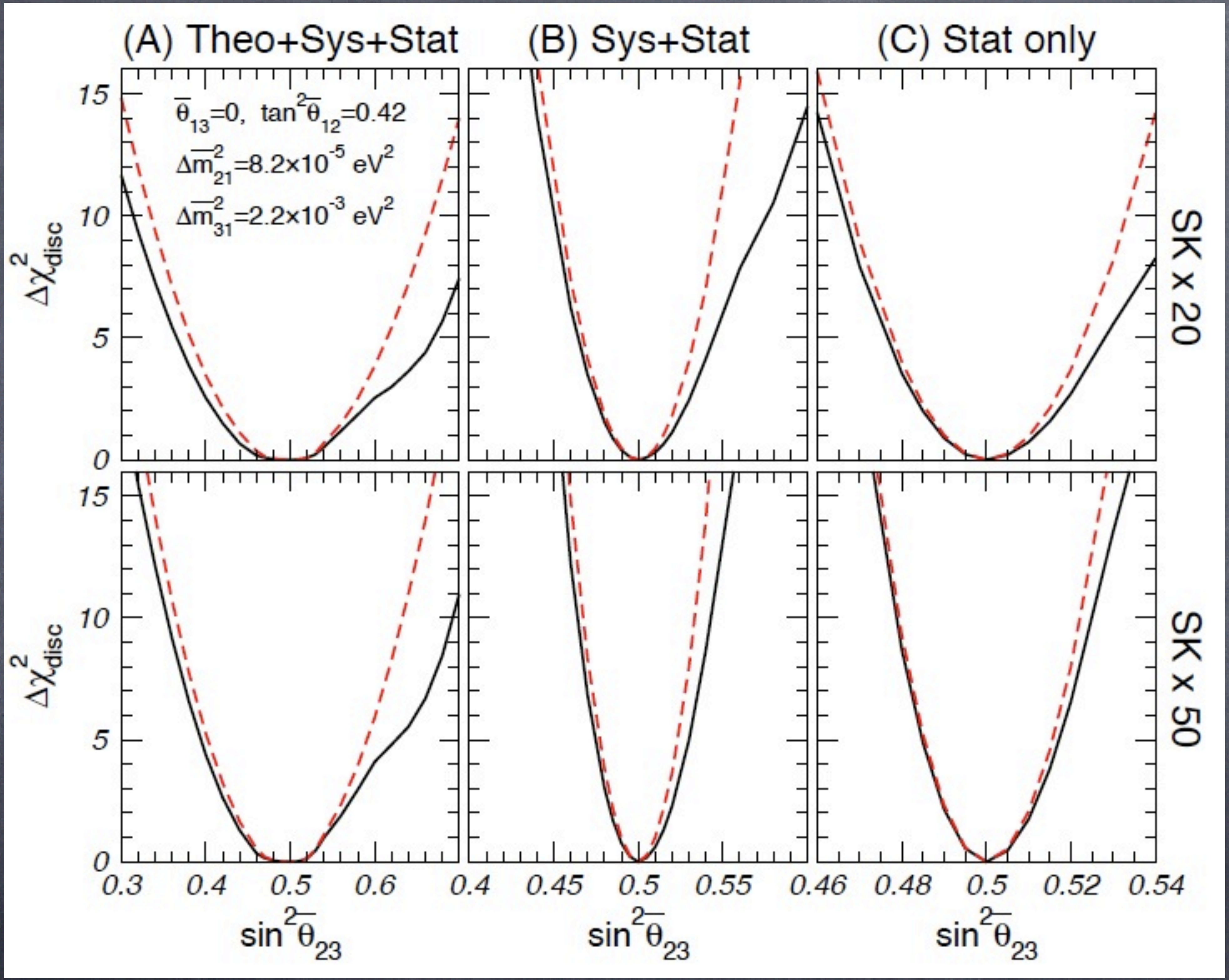
multi-GeV

sub-GeV

These terms break the symmetry around 45 degrees

Sensitivity to octant

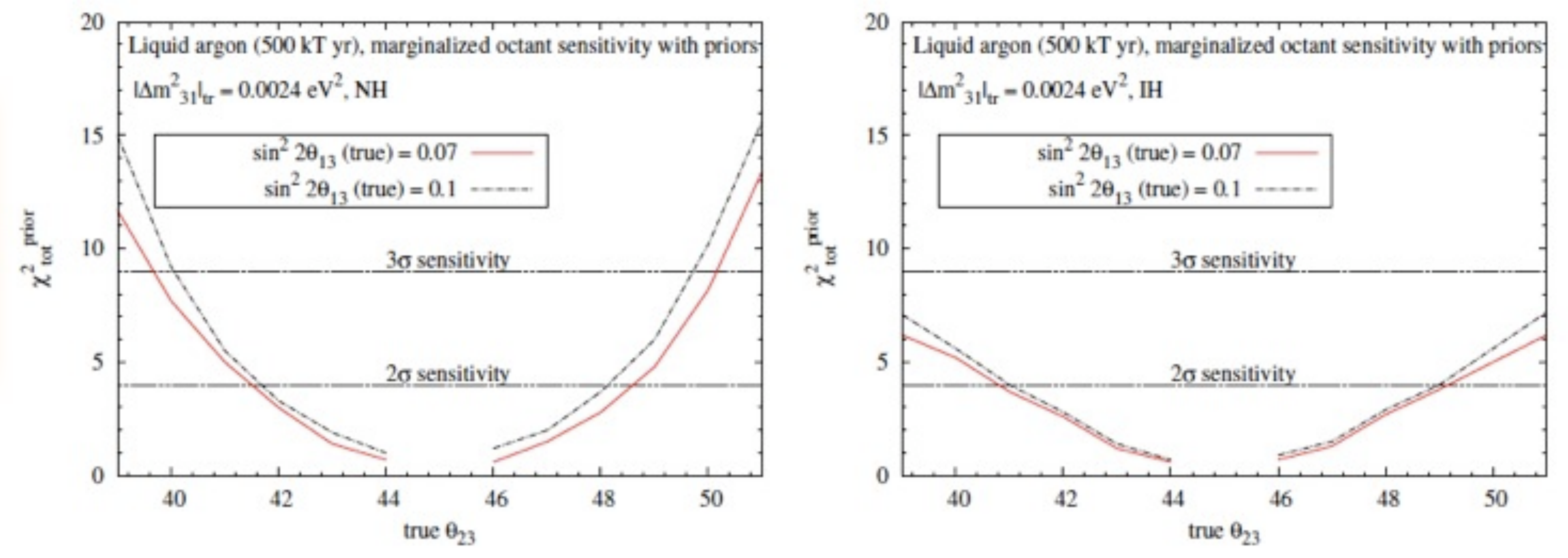
sub-GeV events



M. C. Gonzalez-Garcia, M. Maltoni, A. Yu. Smirnov, *Phys. Rev. D70:113012, 2004*

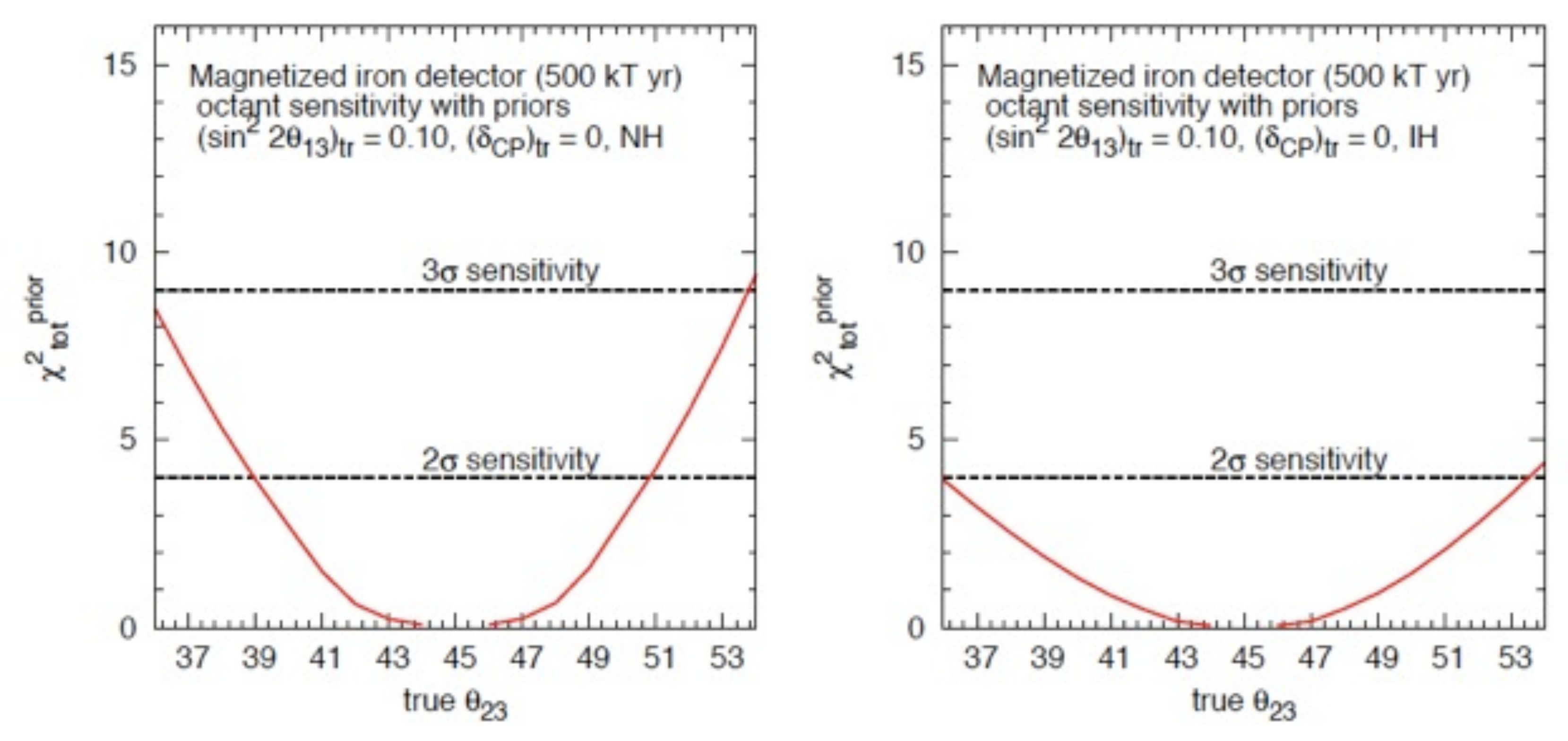
multi-GeV events: magnetized detectors

Magnetized LAr: very good angular resolution



V. Barger, R. Gandhi, P. Ghoshal, S. Goswami, D. Marfatia, S. Prakash, S. K. Raut and S. U. Sankar *Phys. Rev. Lett 109:091801, 2012*

ICAL: worse angular resolution than LAr



A. Chatterjee, P. Ghoshal, S. Goswami and S. K. Raut, *arXiv:1302.1370*

multi-GeV events: results for PINGU

$$\vec{\lambda} = \left\{\theta_{13,} \left|\Delta m^2_{eff}\right|, h, \Delta\rho; \theta_{12}^{true}, \left(\Delta m^2_{21}\right)^{true}, \delta_{CP}^{true}\right\}$$

$$\chi^2(\theta_{23}, \Delta\rho) = \min_{\left(\xi_{norm}, \xi_{\sin^2 2\theta_{13}}, \xi_{\left|\Delta m^2_{eff}\right|}, h\right)} \left\{\chi^2_{oct}\left(\vec{\lambda}, \theta_{23}, \xi_{norm}\right) + \left(\frac{\xi_{norm}}{\sigma_{norm}}\right)^2 + \chi^2_{prior}\right\}$$

Marginalized parameters

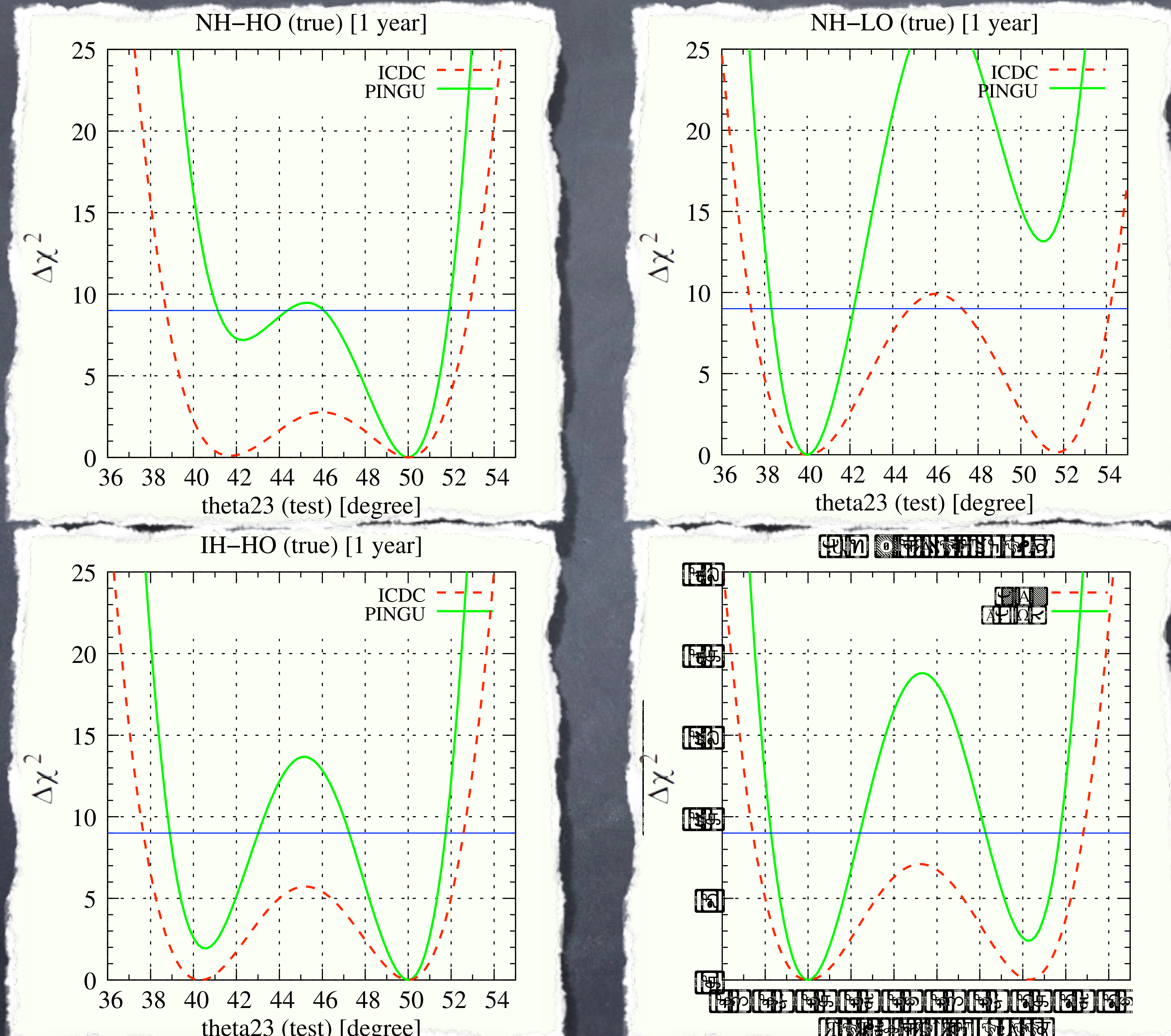
$$\chi^2_{oct}\left(\vec{\lambda}, \theta_{23}, \xi_{norm}\right) = \sum_{(\cos\theta)_i} \sum_{(E_\nu)_j} \frac{\left[N^{th}_{ij}\left(\vec{\lambda}^{true}, \theta_{23}^{true}\right) - N^{th}_{ij}\left(\vec{\lambda}, \theta_{23}\right)\left(1 + \xi_{norm}\right)\right]^2}{N^{th}_{ij}\left(\vec{\lambda}^{true}, \theta_{23}^{true}\right)}$$

$$\chi^2_{prior} = \left(\frac{\xi_{\sin^2 2\theta_{13}}}{\sigma\left(\sin^2 2\theta_{13}\right)}\right)^2 + \left(\frac{\xi_{\left|\Delta m^2_{eff}\right|}}{\sigma\left(\left|\Delta m^2_{eff}\right|\right)}\right)^2$$

Finally, we marginalize over the density

HO:

$\theta_{23}=50^\circ$

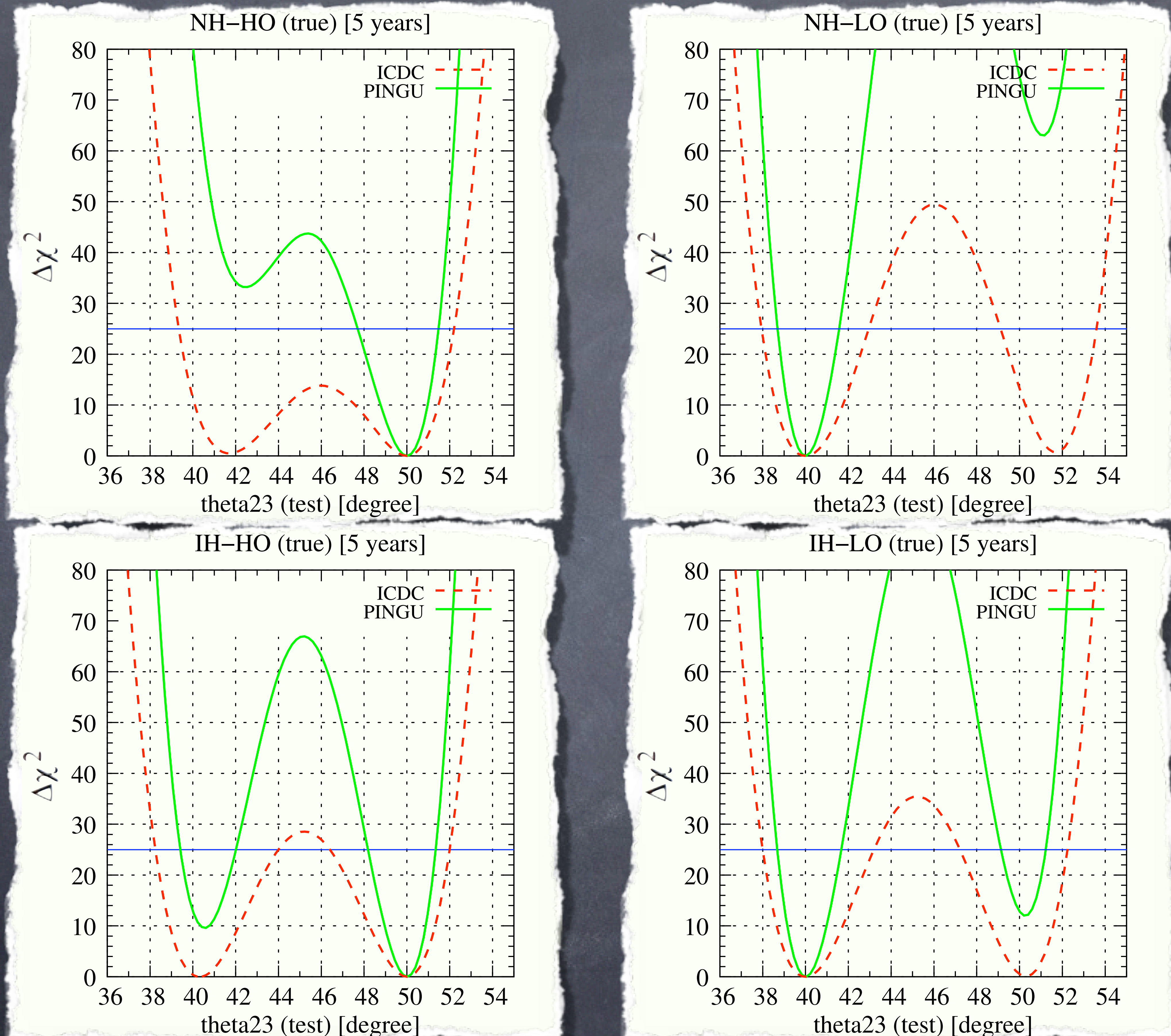


LO:

$\theta_{23}=40^\circ$

S. K. Agarwalla, O. Mena and SPR, *in preparation*

HO: $\theta_{23}=50^\circ$



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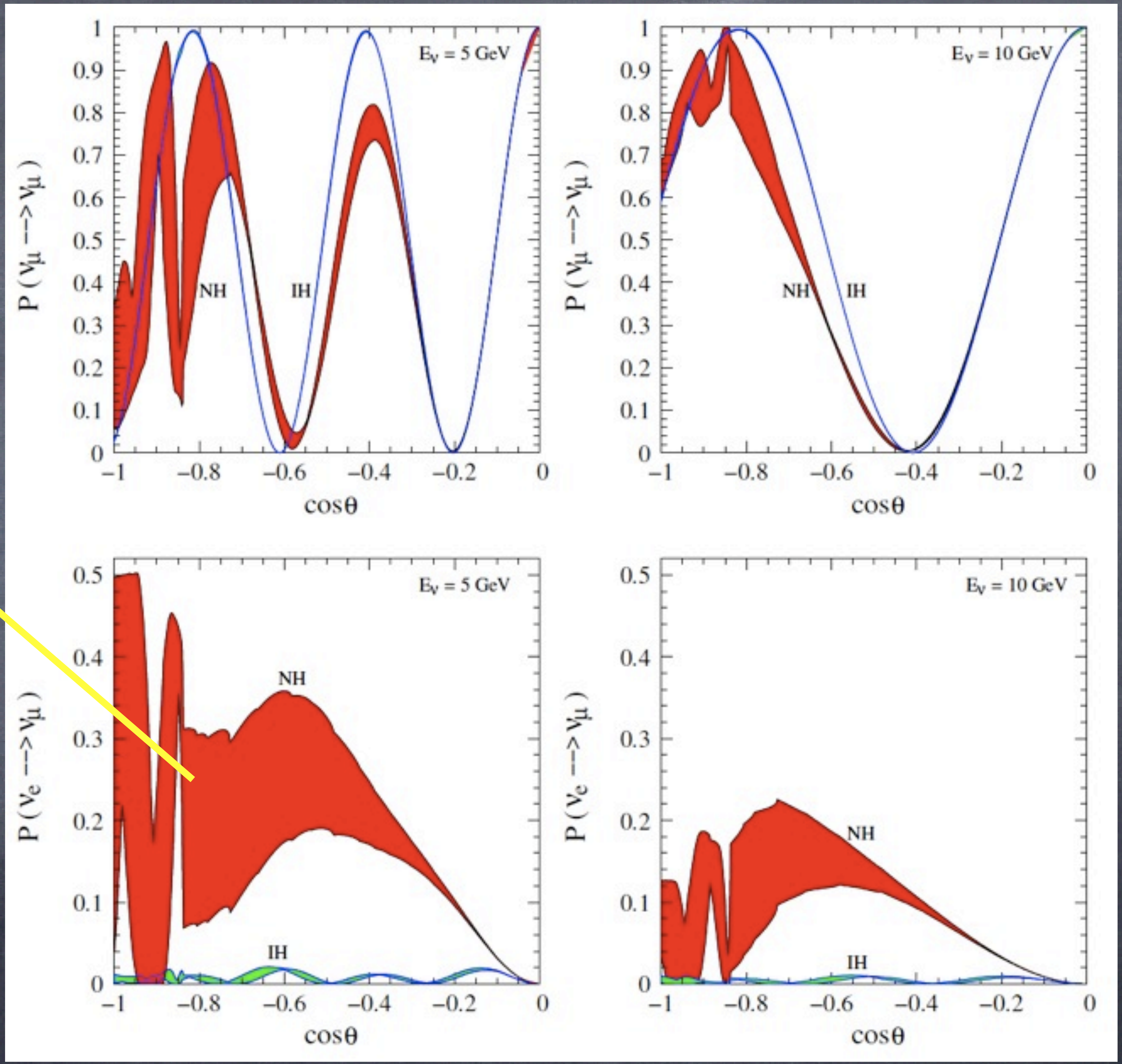
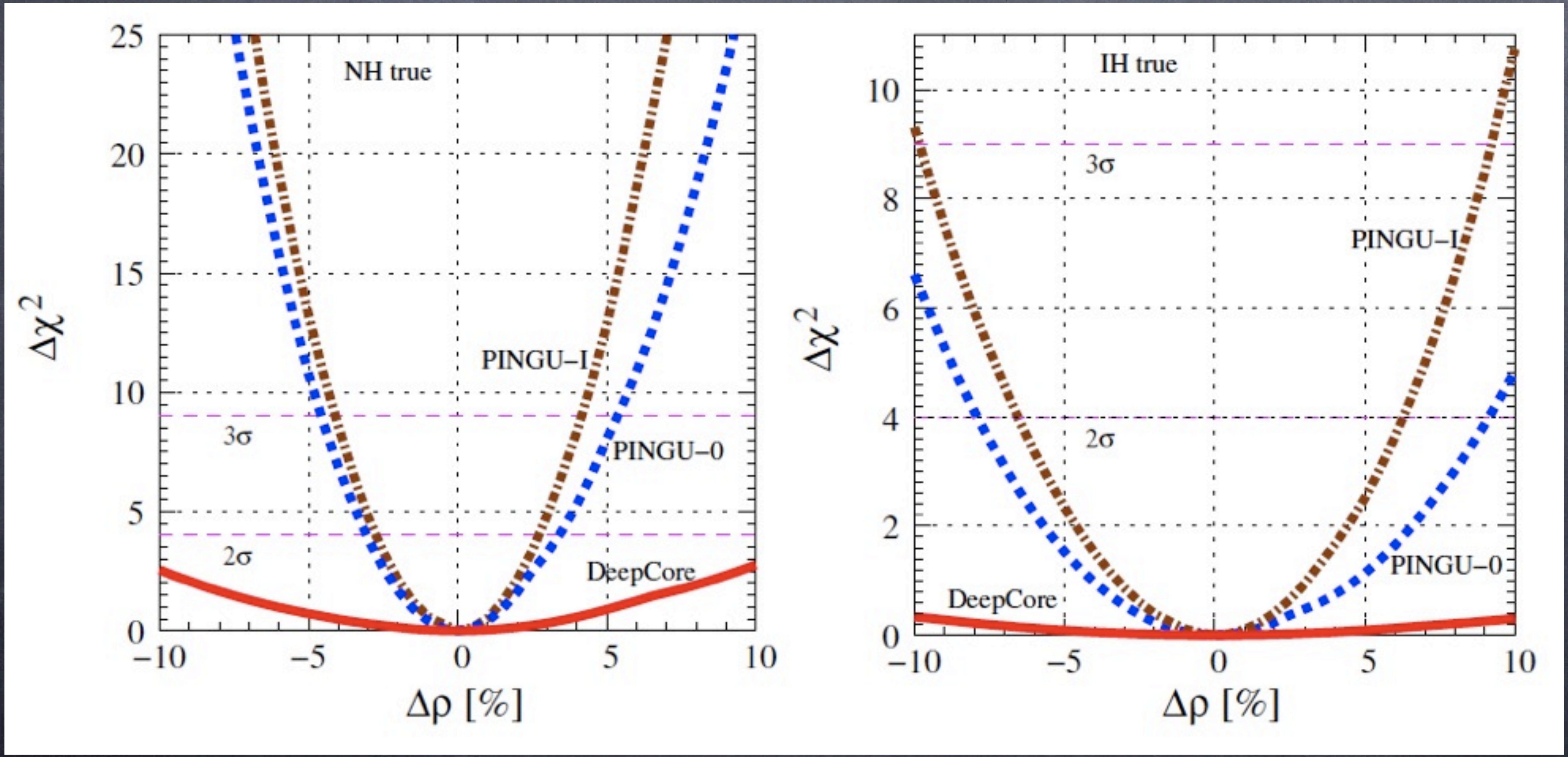
Large sensitivity to variations in the density



S. K. Agarwalla, T. Li, O. Mena and SPR, *arXiv:1212:2238*

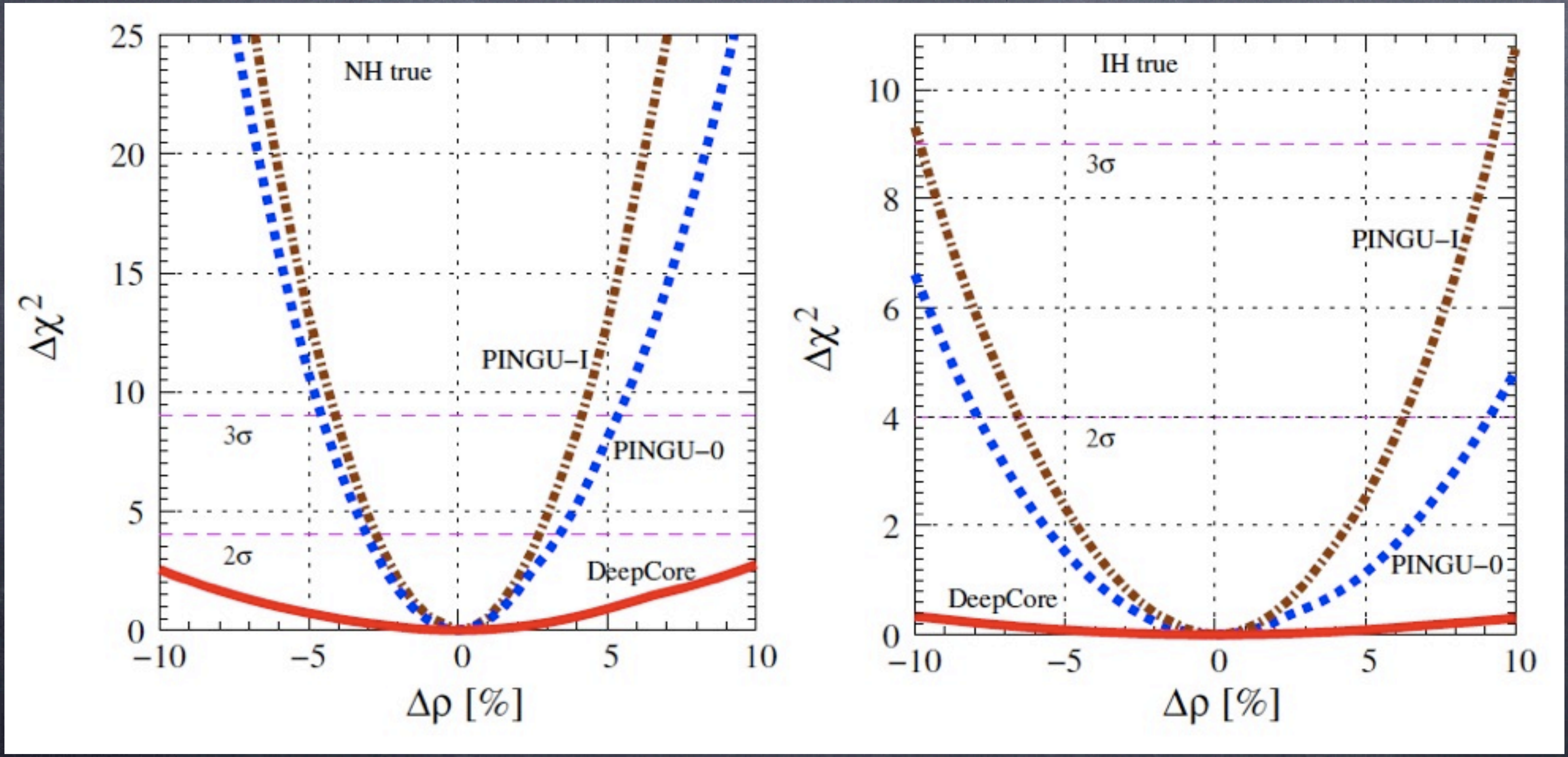
Sensitivity to the Earth density



S. K. Agarwalla, T. Li, O. Mena and SPR, *arXiv:1212:2238*

Sensitivity to the Earth density

Geophysicists determine the density distribution of the Earth by perturbation inversion using seismic data: averaged values over ~100 km known at the level of few per cent at all depths, but density gradients less known.
On the other hand, **linear integral constraints** known at the level of **0.01-0.1%**



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Summary

- Large θ_{13} opens the possibility to study leptonic CP violation and determine the neutrino mass hierarchy
- Future multi-Mton extensions of current neutrino telescopes, PINGU and ORCA, are proposed to lower the energy threshold down to a few GeV: quite a challenge!
- Atmospheric neutrinos experience resonant matter effects in the few GeV range
- We have studied the (preliminary) sensitivity of PINGU to the the θ_{23} octant, to the mass hierarchy and to the Earth density
- This is just the first step! Studies on the achievable capabilities of such detectors are currently going on!