Neutrino mass hierarchy at large detectors

Sergio Palomares-Ruiz

IFIC, CSIC-U. Valencia, Valencia

CFTP-IST, Lisboa

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La Thuile, March 5, 2013

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

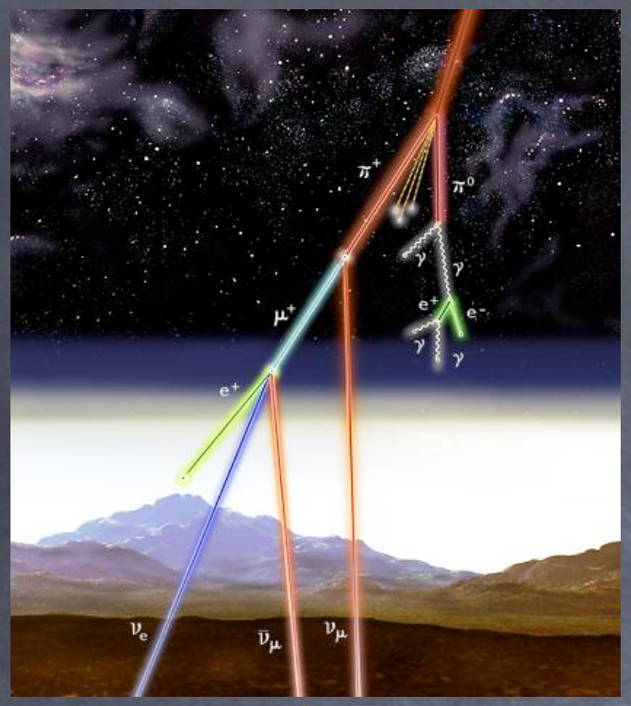
solar angle reactor angle atmospheric angle

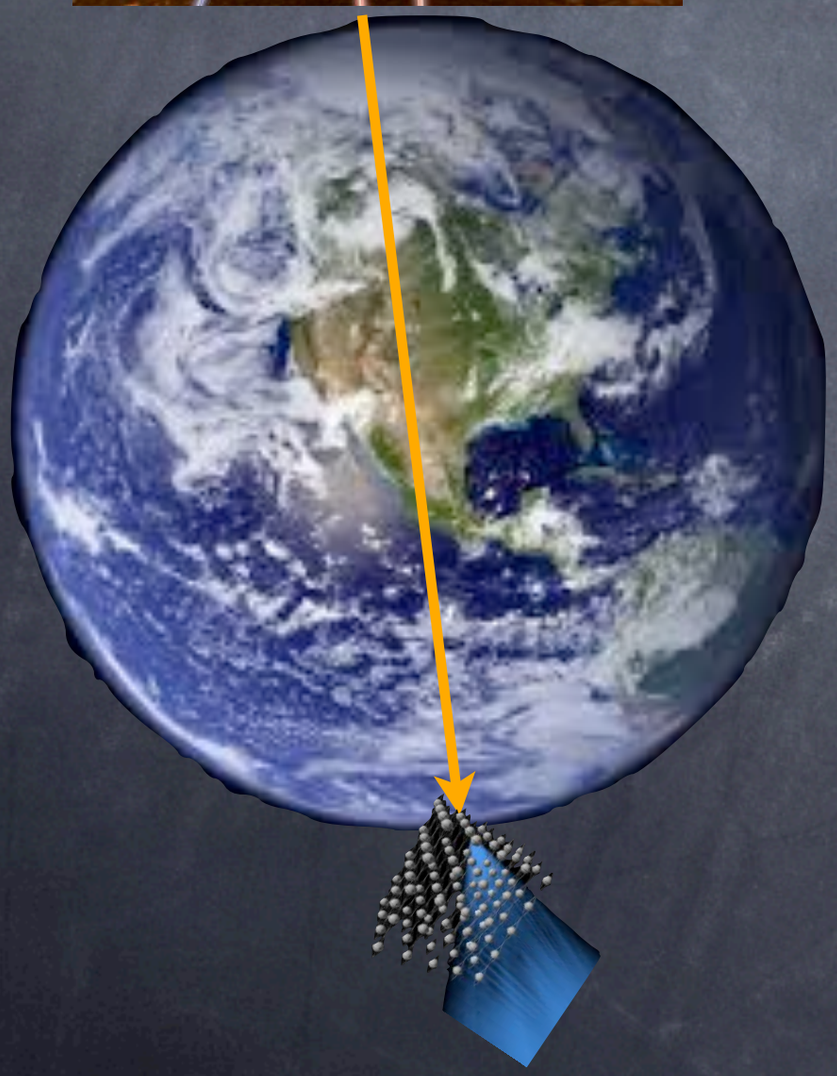
If θ_{13} vanishes, all analysis get reduced to a 2x2 mixing problem

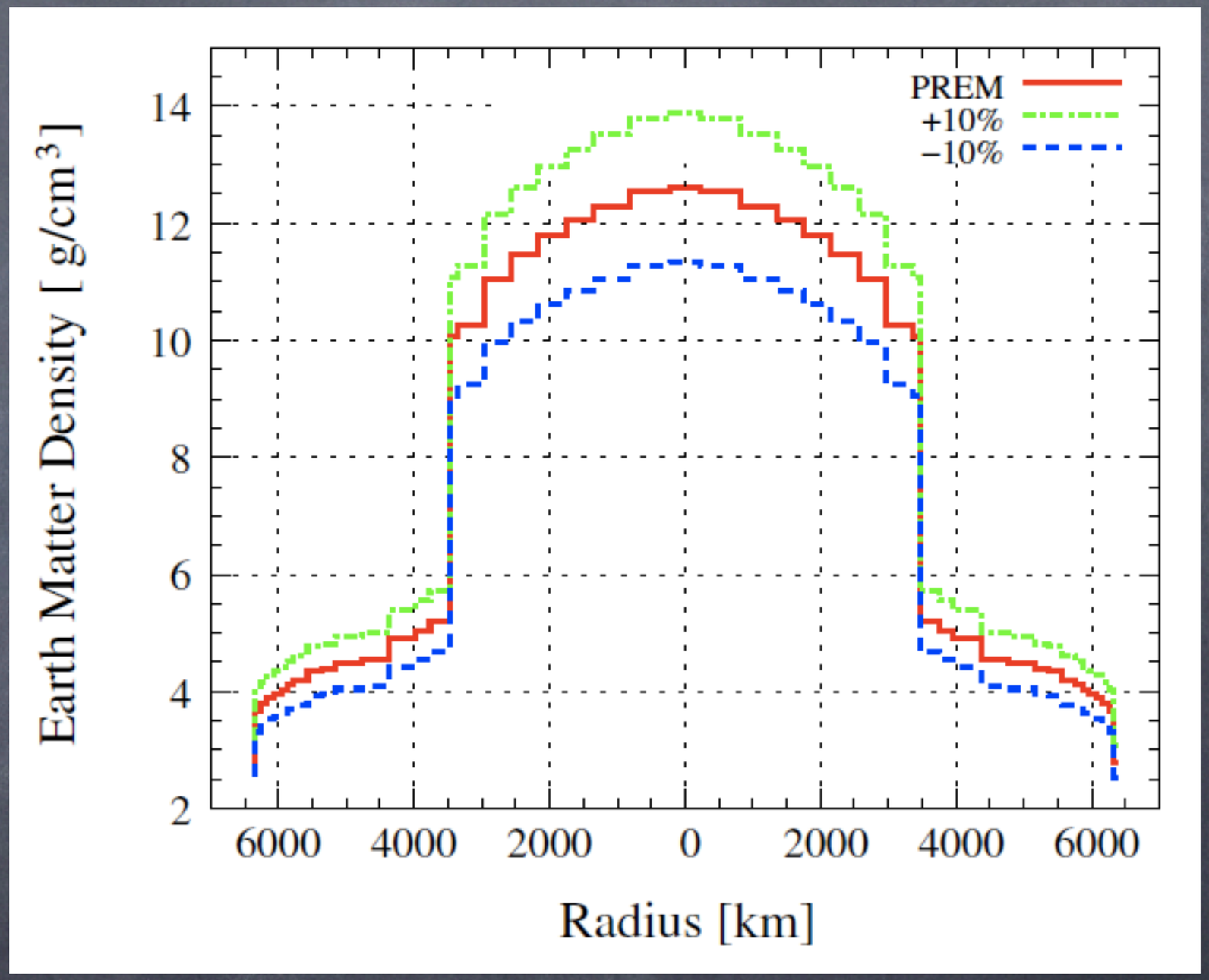
θ_{13} drives subleading $\nu_\mu \to \nu_e$ transitions:
crucial to determine CP violation and mass hierarchy

Mass hierarchy: help for model discrimination, important for neutrinoless double beta decay, neutrinos in cosmology...

Atmospheric neutrinos







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

Mass hierarchy determination with atmospheric neutrinos: Extensive literature

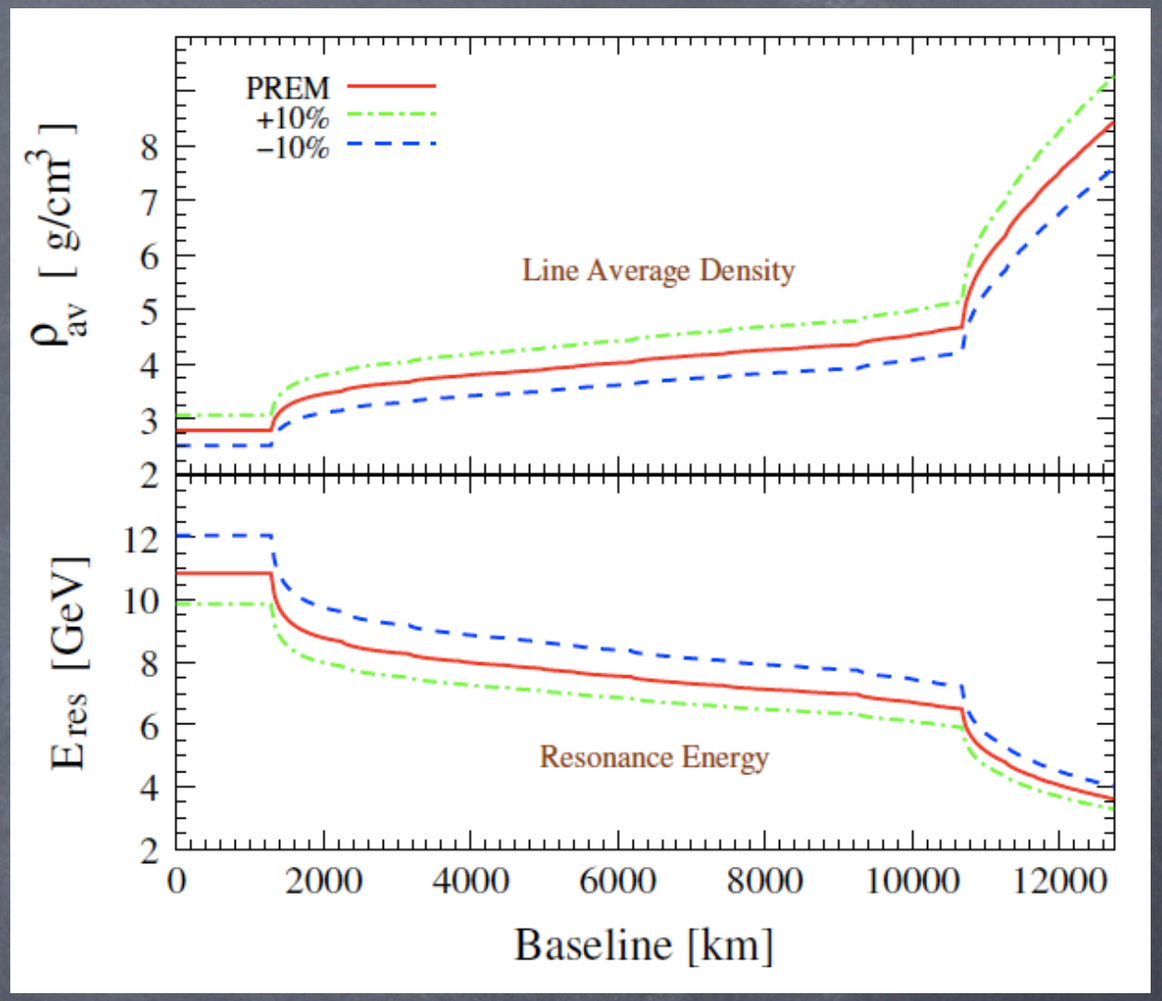
Probably incomplete list:

Petcov 98; Akhmedov 98; Chizhov and Petcov 99,00,01; Akhmedov, Dighe, Lipari and Smirnov 98; Chizov, Maris and Petcov 98; 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...

For constant density and neglecting the solar sector

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

$$
\begin{aligned}
\Delta_{31} &\equiv \frac{\Delta m_{31}^2}{2E_\nu}, \\
\Delta_{31}^m &\equiv \frac{1}{2E_\nu}\sqrt{(\Delta m_{31}^2 \cos 2\theta_{13} - A)^2 + (\Delta m_{31}^2 \sin 2\theta_{13})^2}, \\
\sin^2 2\theta_{13}^m &\equiv \sin^2 2\theta_{13}\left(\frac{\Delta_{31}}{\Delta_{31}^m}\right)^2,
\end{aligned}
$$

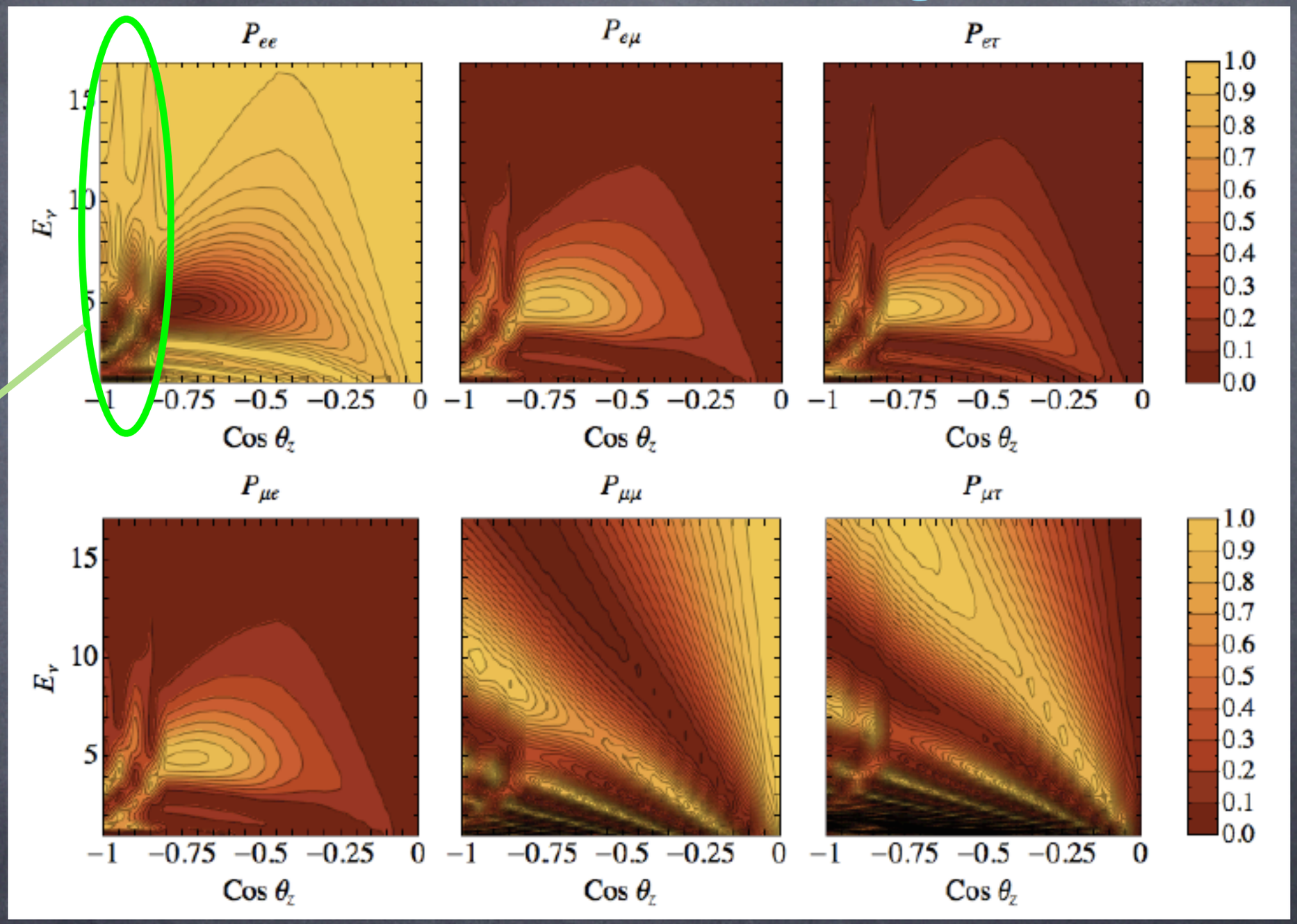


S. K. Agarwalla, T. Li, O. Mena and SPR, *arXiv:1212:2238*

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

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

Neutrino oscillograms

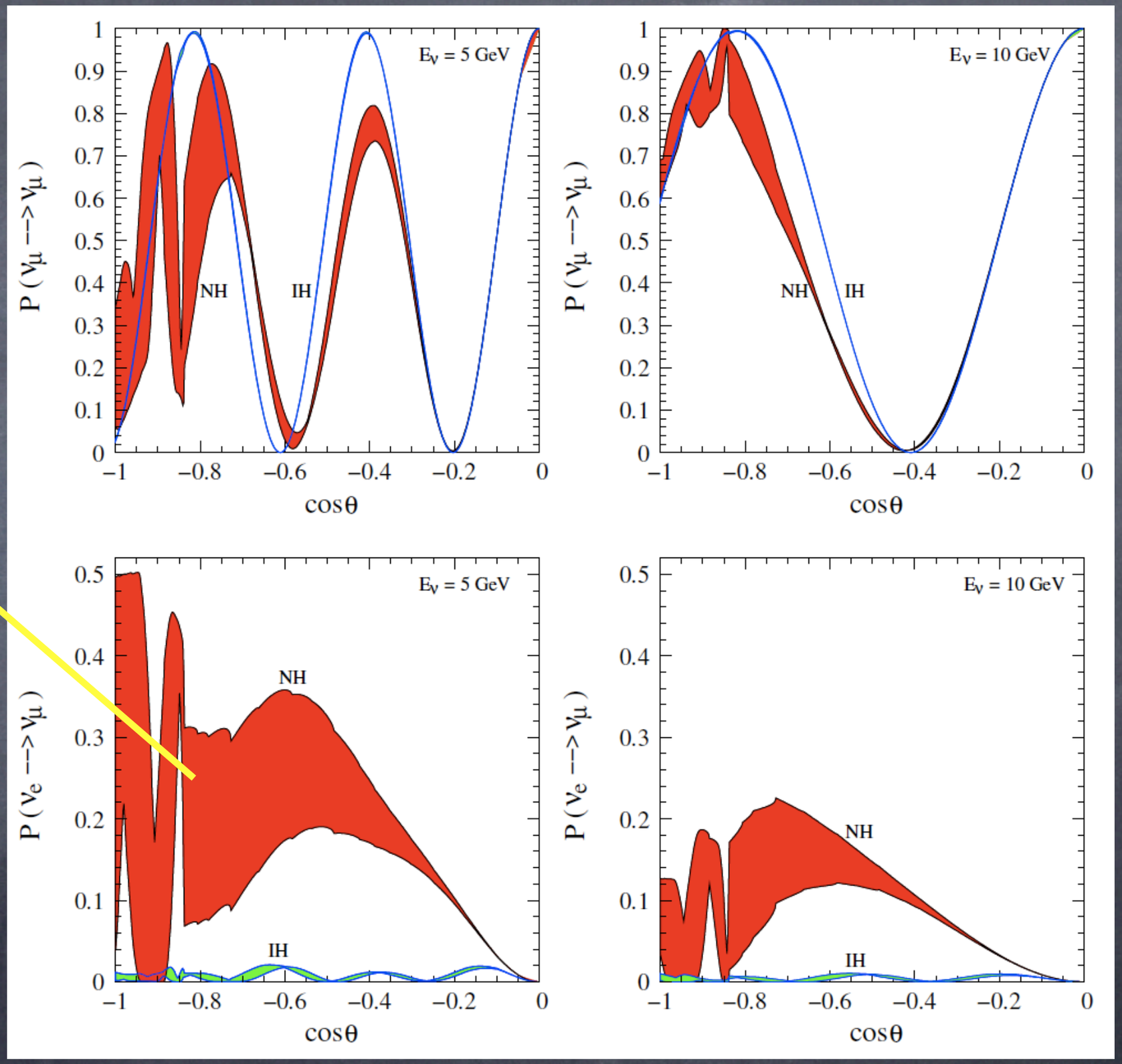


Mantle-core effect

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

Large sensitivity to variations in the density



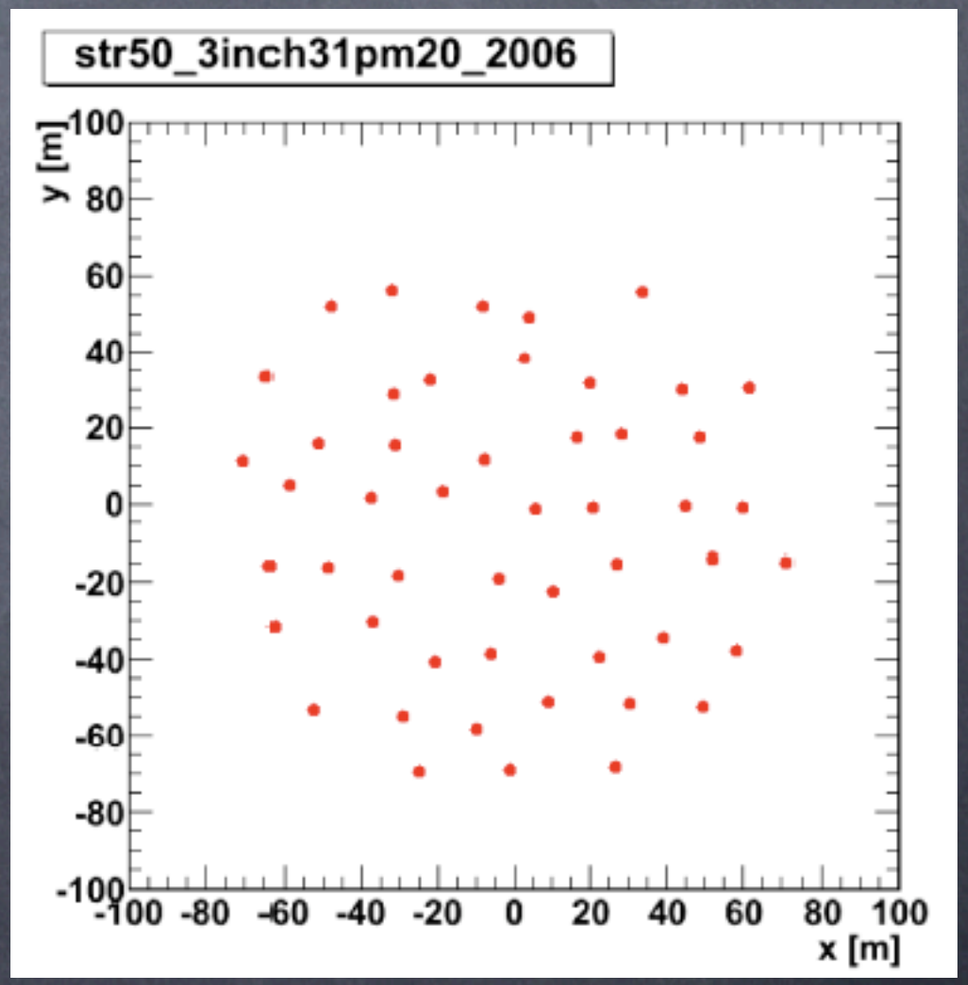
S. K. Agarwalla, T. Li, O. Mena and SPR, *arXiv:1212:2238*

ORCA: mediterranean sea

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

Instrumented volume = 1.75 Mton

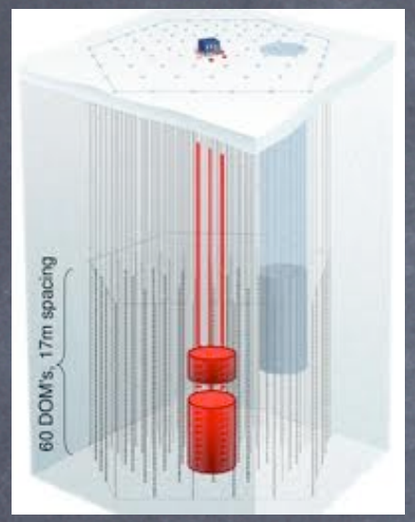
*50 strings
*OM=31 3" PMTs
*20 OM in each string
*6m vertical distance between OMs
*20m average distance between strings

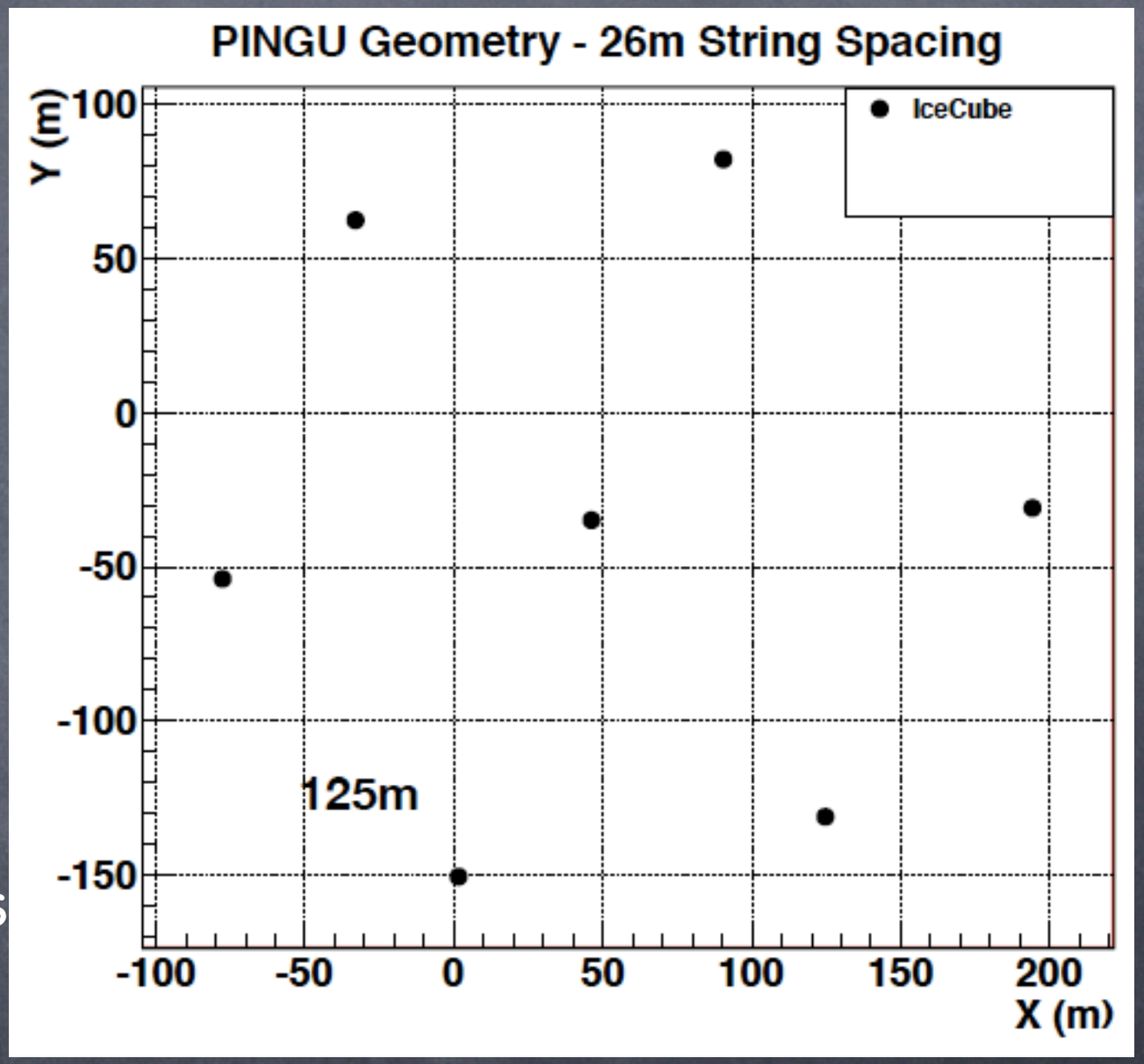


J. Brunner, Talk at New Directions in Neutrino Physics, Aspen, CO, February 2013

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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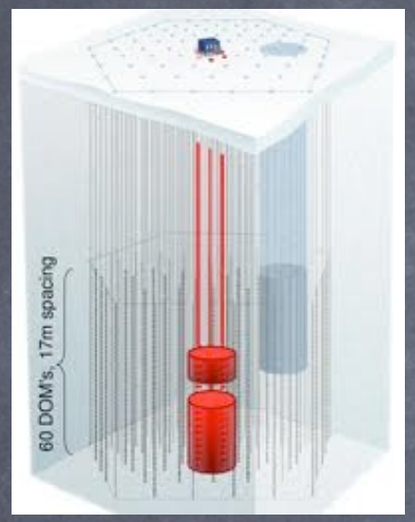

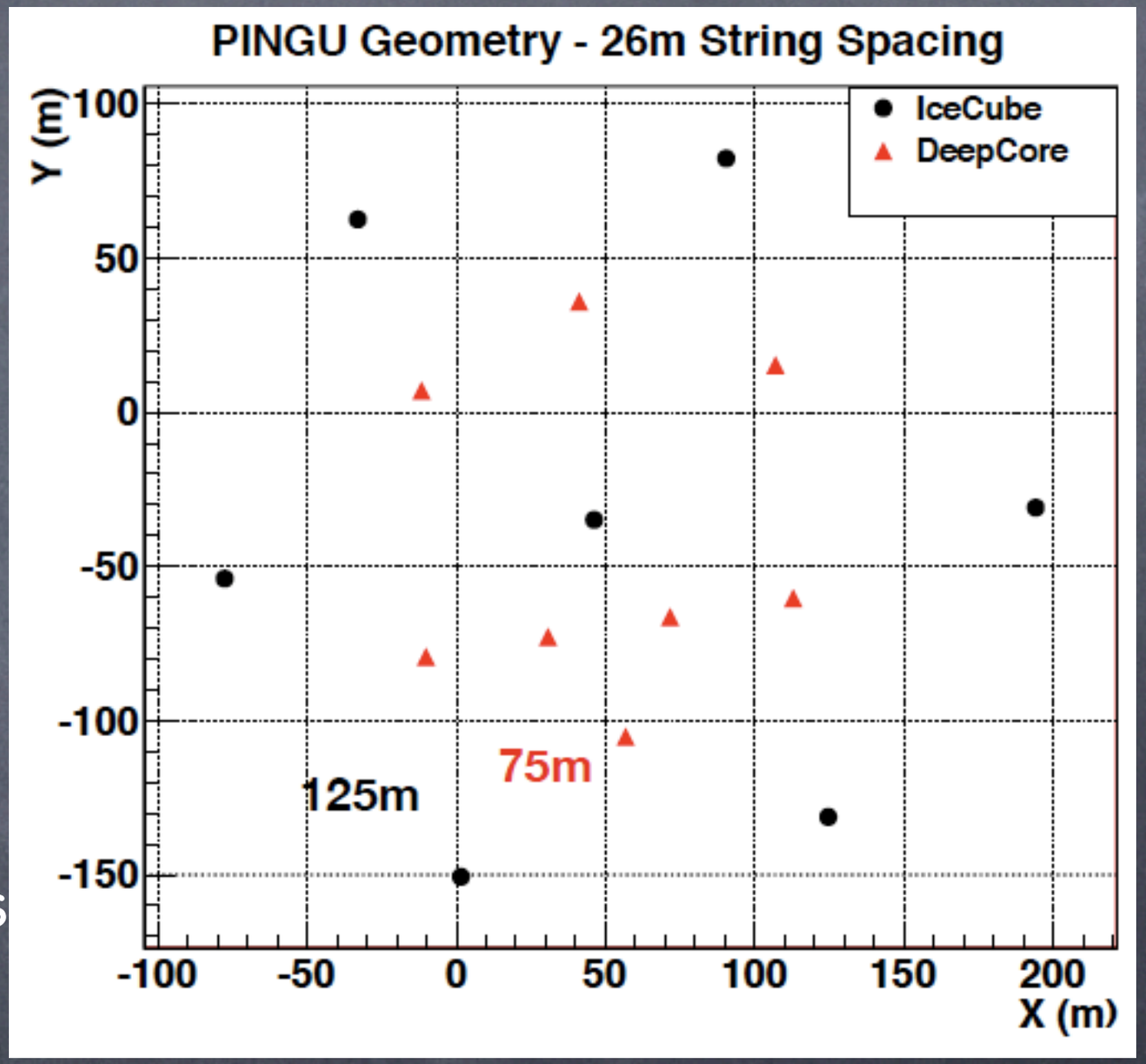

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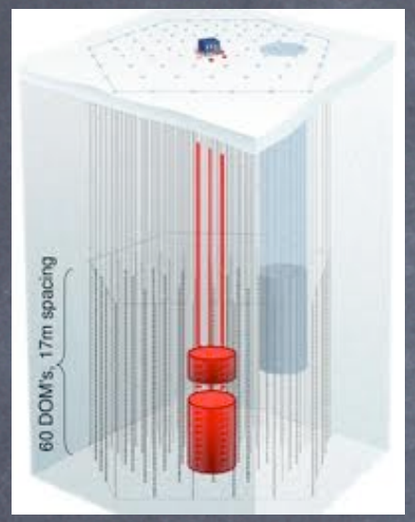

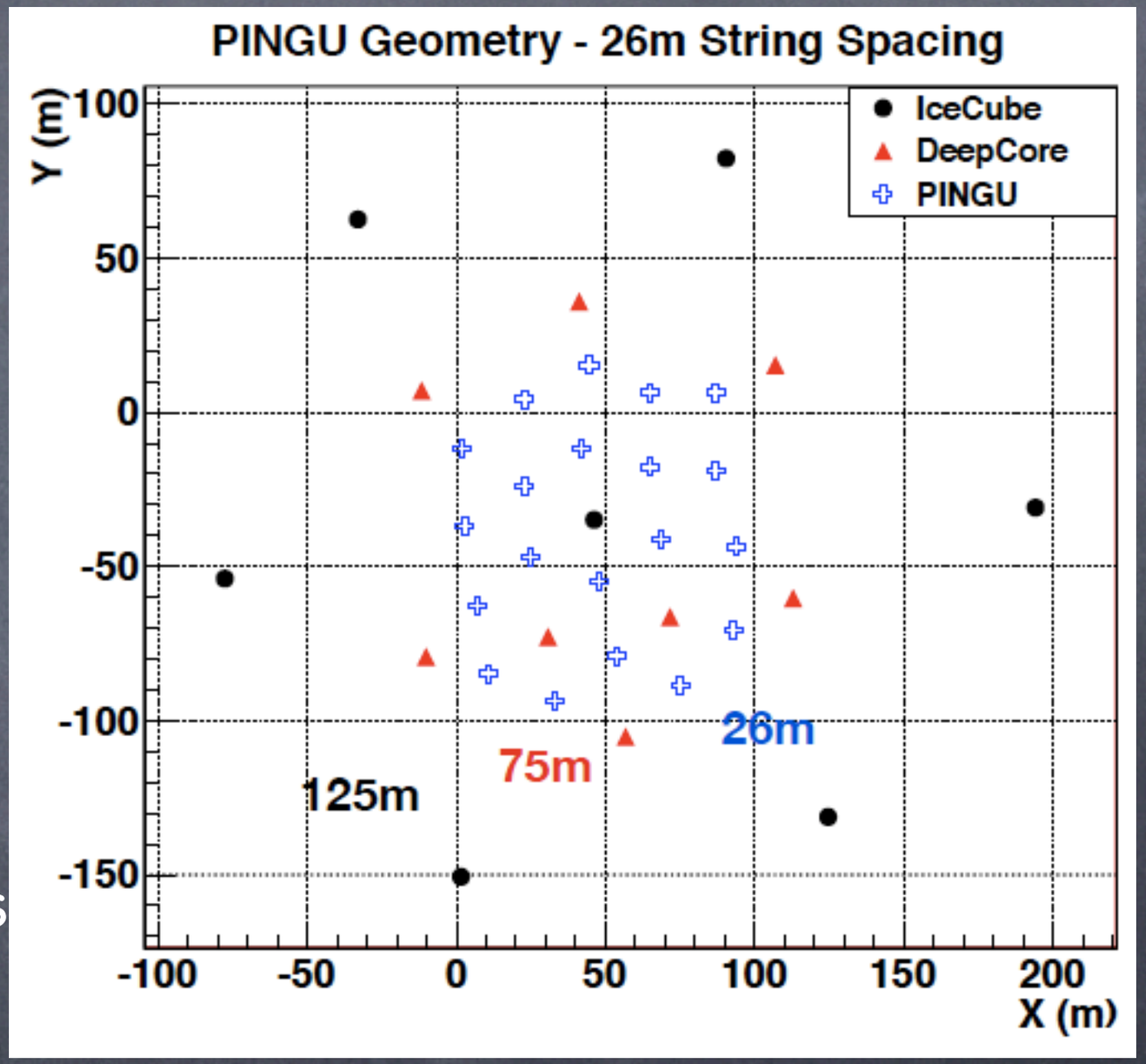

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Mass hierarchy with Cherenkov detectors

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

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

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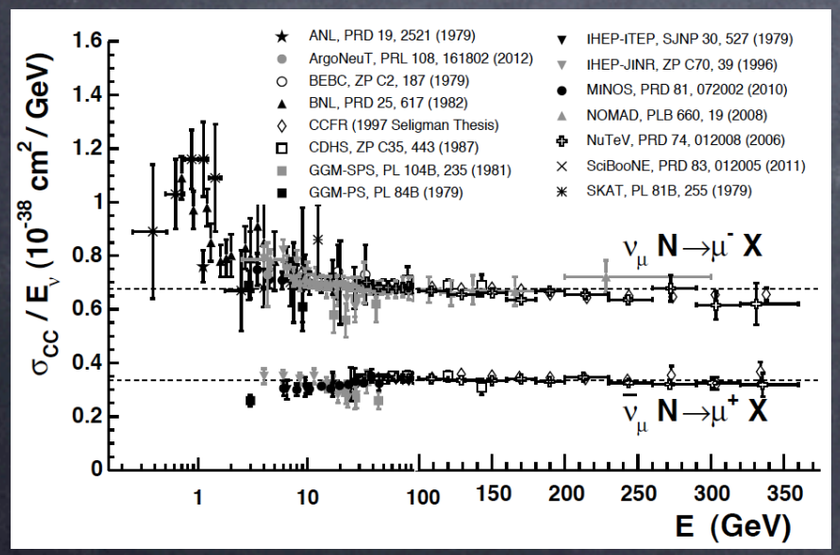
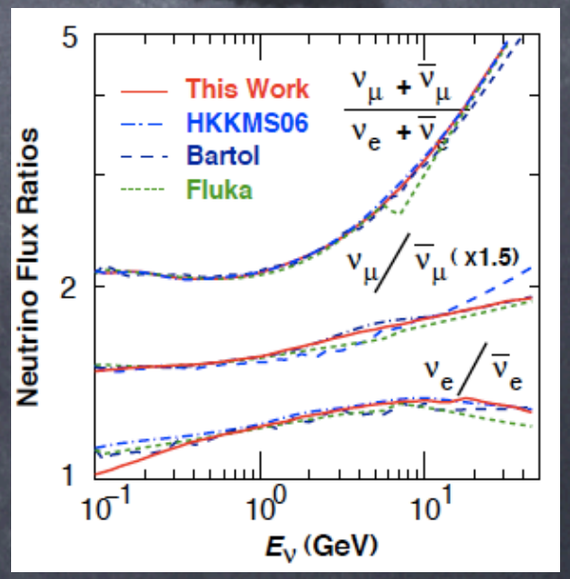


J. Beringer *et al.* (PDG), *Phys. Rev. D86:010001, 2012*

Different cross sections

Different fluxes



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

Setups

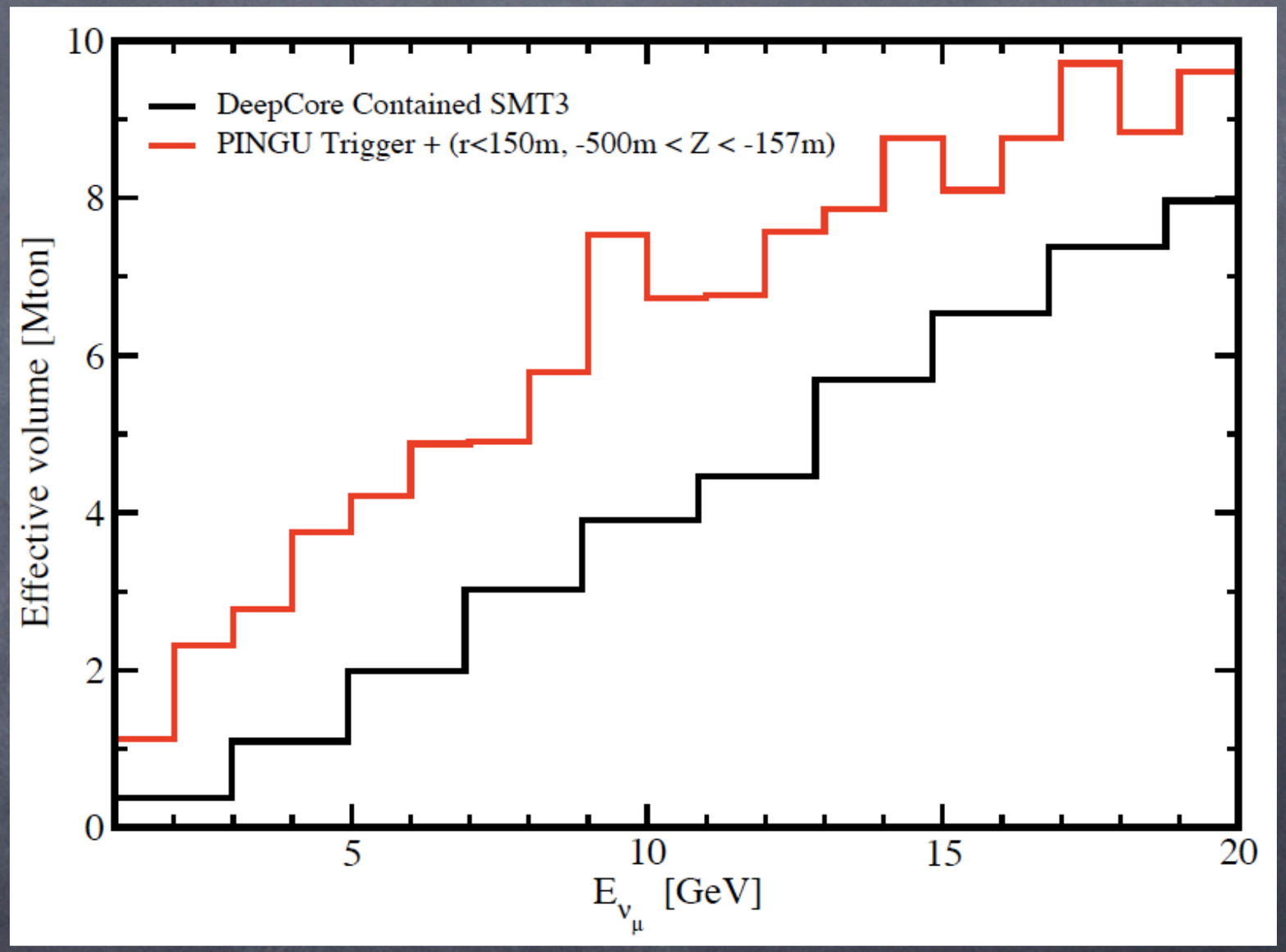
We assume 50% post-trigger efficiency

DeepCore: 1 energy bin
10-15 GeV

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

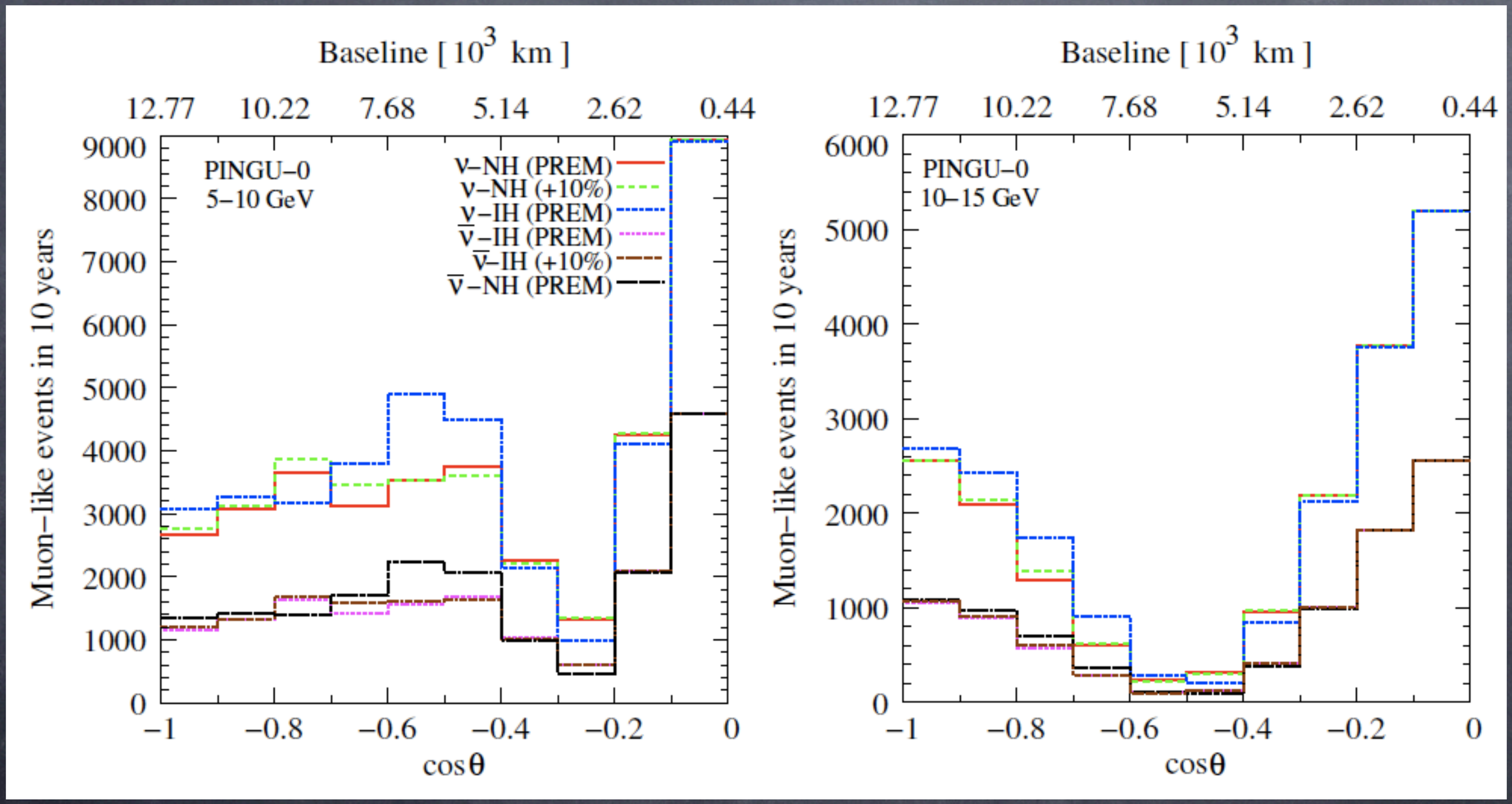
PINGU-I: 4 energy bins
5-7.5, 7.5-10,
10-12.5, 12.5-15 GeV

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



Thanks to Jason Koskinen

Events after 10 years



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

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]	$\sigma(\sin^2 2\theta_{23}) = 2\%$
$(\Delta m^2_{\rm eff})^{\rm true} = \pm 2.4\times 10^{-3}$ eV^2	$[2.2, 2.6]\times 10^{-3}$ eV^2 (NH) $-[2.6, 2.2]\times 10^{-3}$ eV^2 (IH)	$\sigma(\lvert\Delta m^2_{\rm eff}\rvert) = 4\%$
$(\Delta m^2_{21})^{\rm true} = 7.62\times 10^{-5}$ eV^2	–	–
$\sin^2\theta_{12}^{\rm true} = 0.32$	–	–
$\delta_{\rm CP}^{\rm true} = 0^\circ$	–	–
$\Delta\rho^{\rm true} = 0$	[-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

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

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

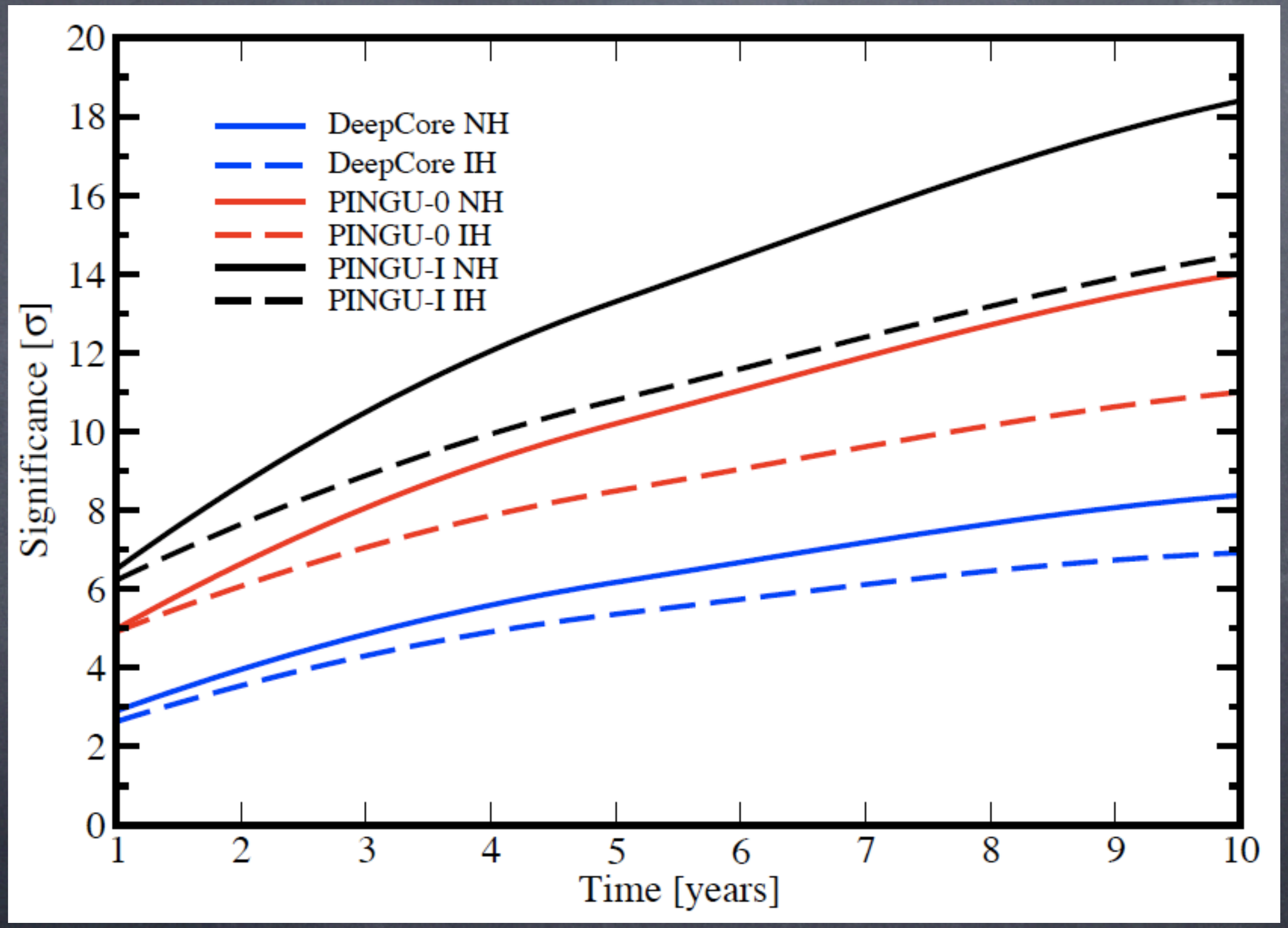
Marginalized parameters

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

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

Finally, we marginalize over the density

Sensitivity to the mass hierarchy



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

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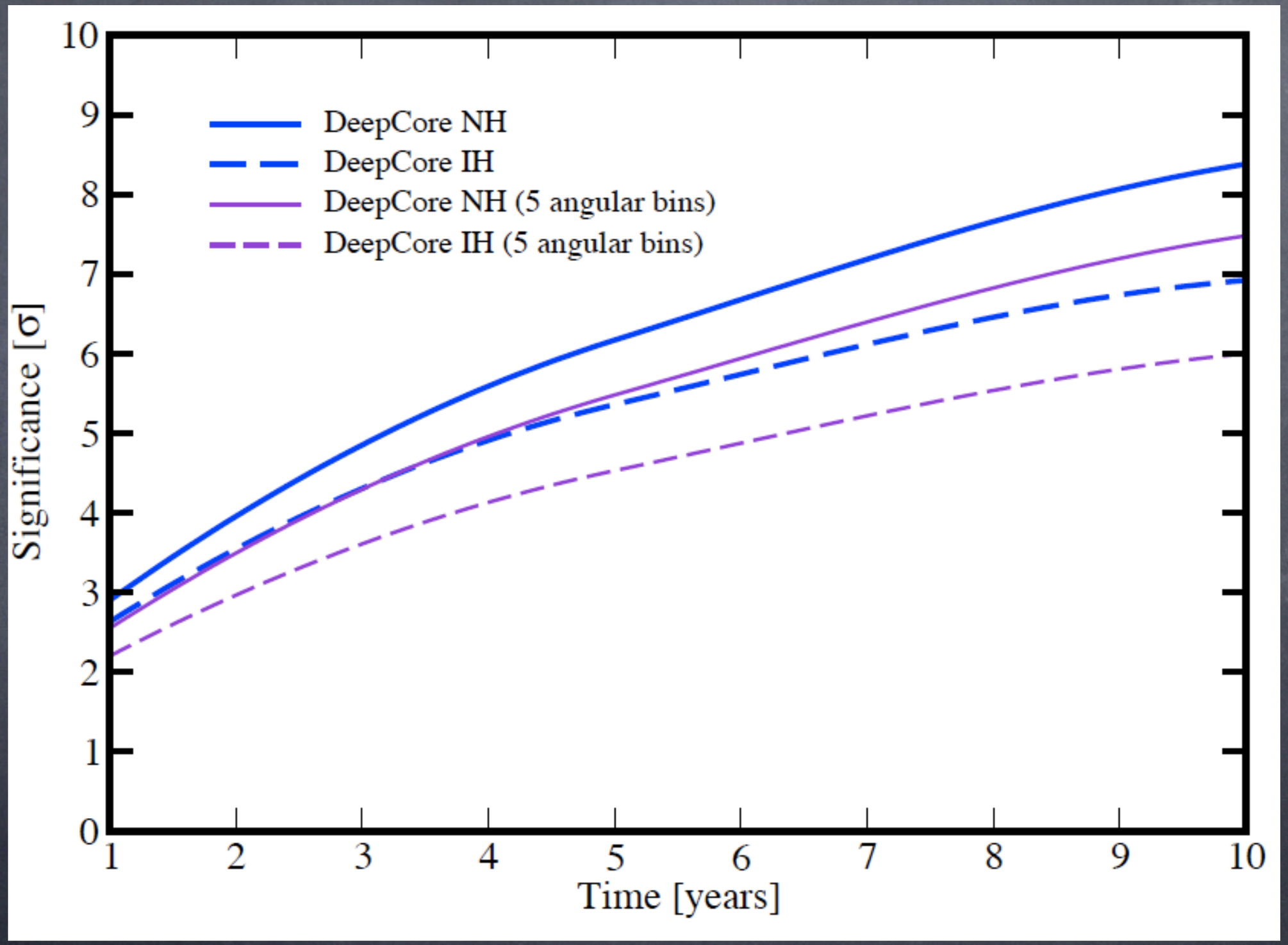

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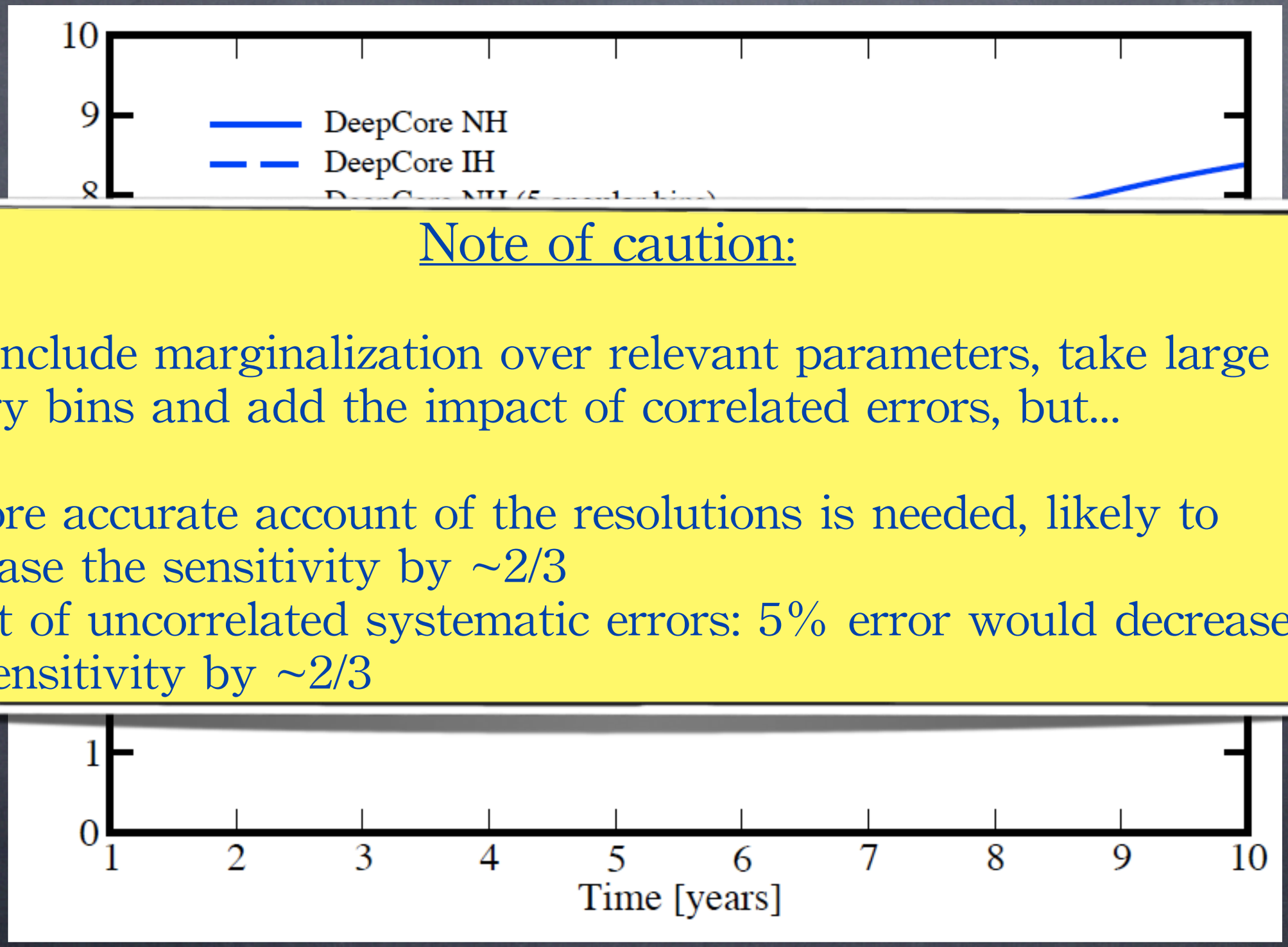

Note of caution:

-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

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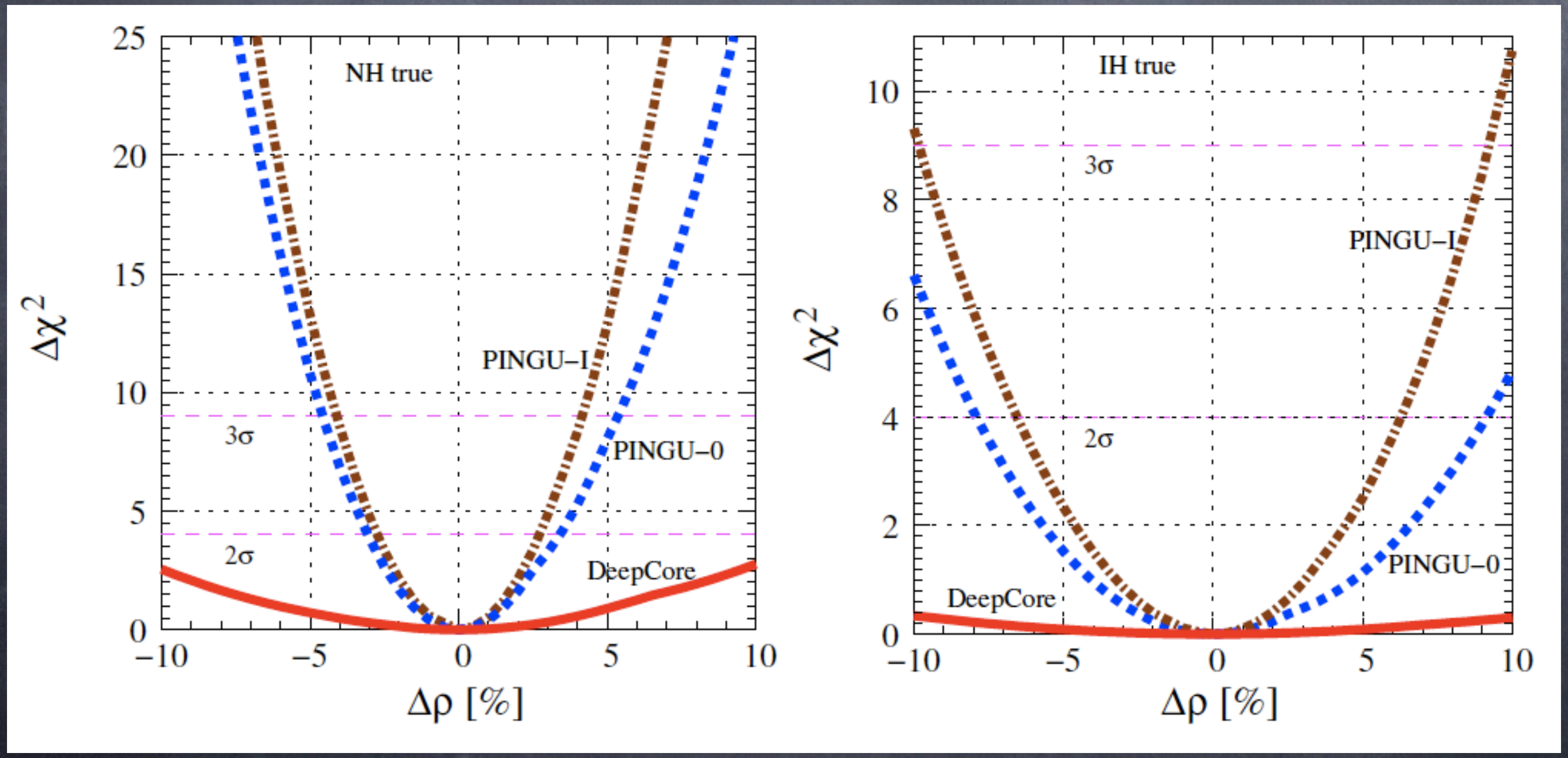
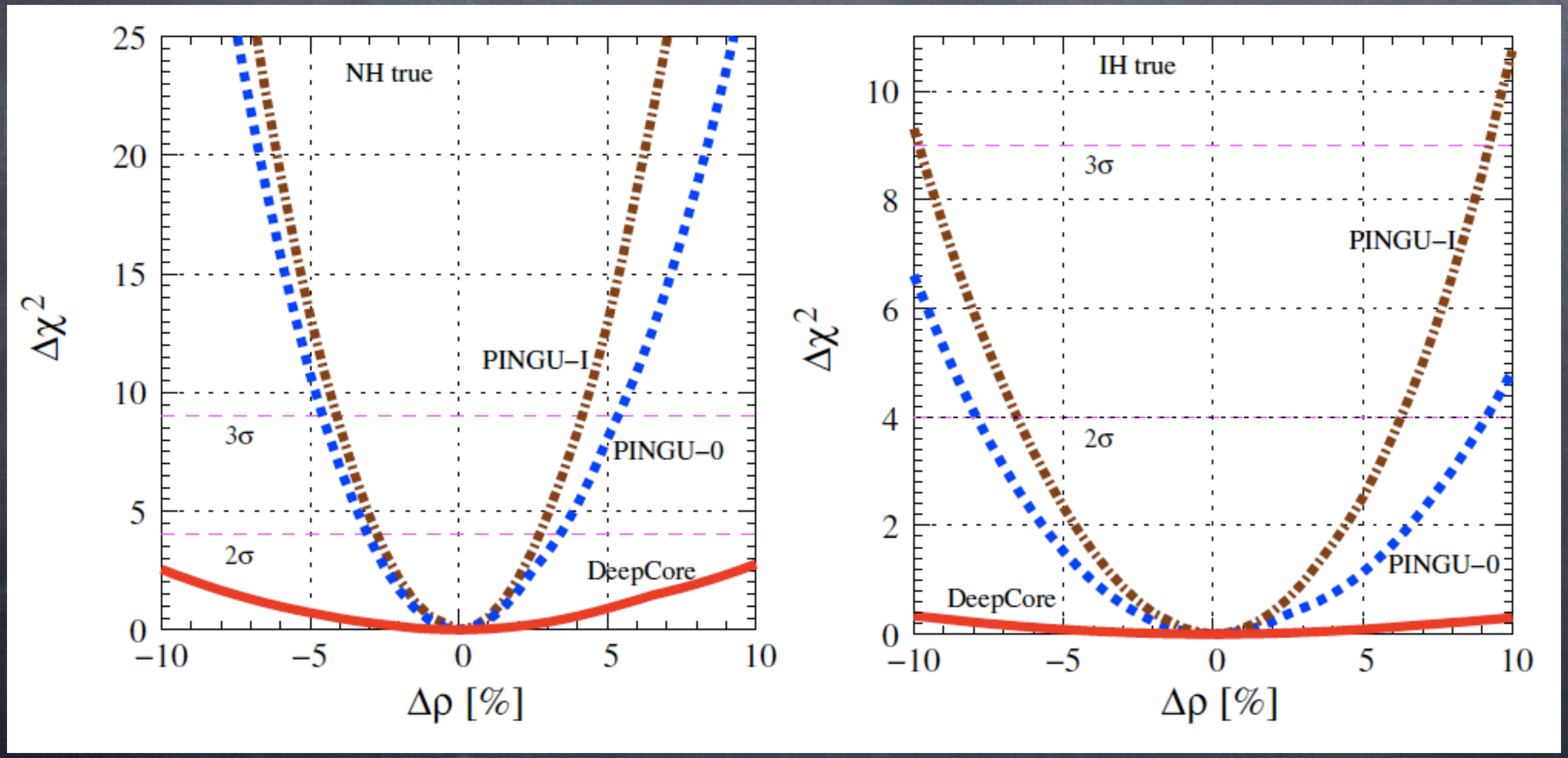
Sensitivity to the Earth density



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 (very preliminary) sensitivity of PINGU to the mass hierarchy and the Earth density
- This is just the first step! Studies on the achievable capabilities of such detectors are currently going on!