Learning from current facilities: mass ordering and CPV

NuTURN2012, 9 May 2012, LNGS, Italy

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θ_{13} is large!

with SBL data:

$$\sin^2\theta_{13} = 0.022^{+0.0033}_{-0.0030}$$
$$\sin^2 2\theta_{13} = 0.086 \pm 0.012$$
$$\theta_{13} = (8.5^{+0.62}_{-0.61})^\circ$$

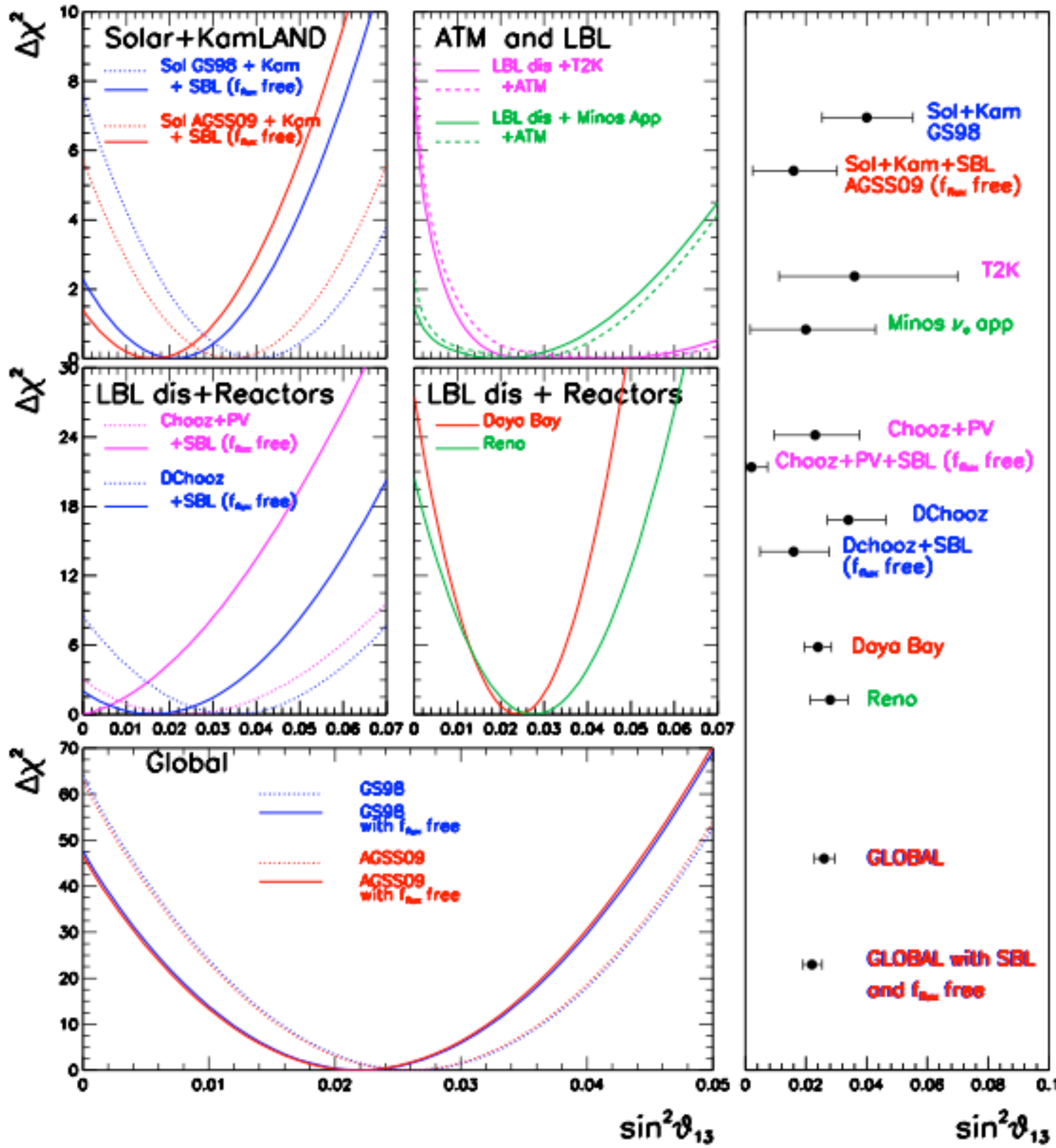
6.9σ significance

without SBL data using 2011 flux pred.:

$$\sin^2\theta_{13} = 0.026^{+0.0034}_{-0.0032}$$
$$\sin^2 2\theta_{13} = 0.101^{+0.013}_{-0.012}$$
$$\theta_{13} = (9.3 \pm 0.59)^\circ$$

8.0σ significance

Gonzalez-Garcia, Maltoni, Salvado, TS, in prep.



θ_{13} is large!

"Be careful what you wish for, because it may become true!"

Konfuzius

θ_{13} is large!

- *Is there a "fast track" to CPV and/or the mass ordering (MO)?*
- *What can we do with "current facilities"?*
- *Are there ways to say something within ~10 years?*

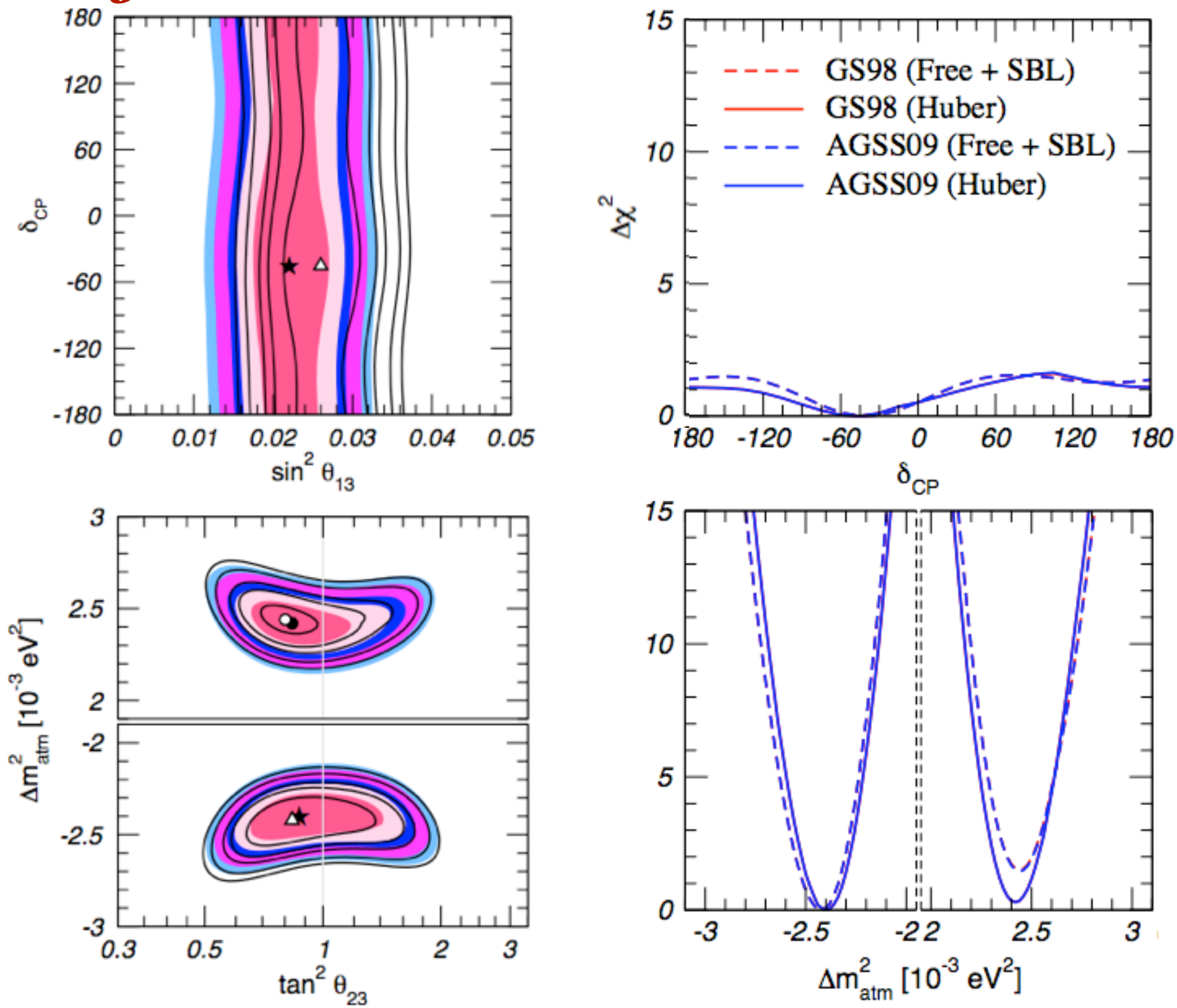
Outline

- *What can be done with T2K+NOvA+reactor?*
- *Can atmospheric neutrinos help (INO, PINGU)*
- *Mass ordering from a reactor experiment?*

What can be done with T2K+NOvA+reactors?

Global fit 2012

Gonzalez-Garcia, Maltoni, Salvado, TS, in prep.
see also talk by G. Fogli

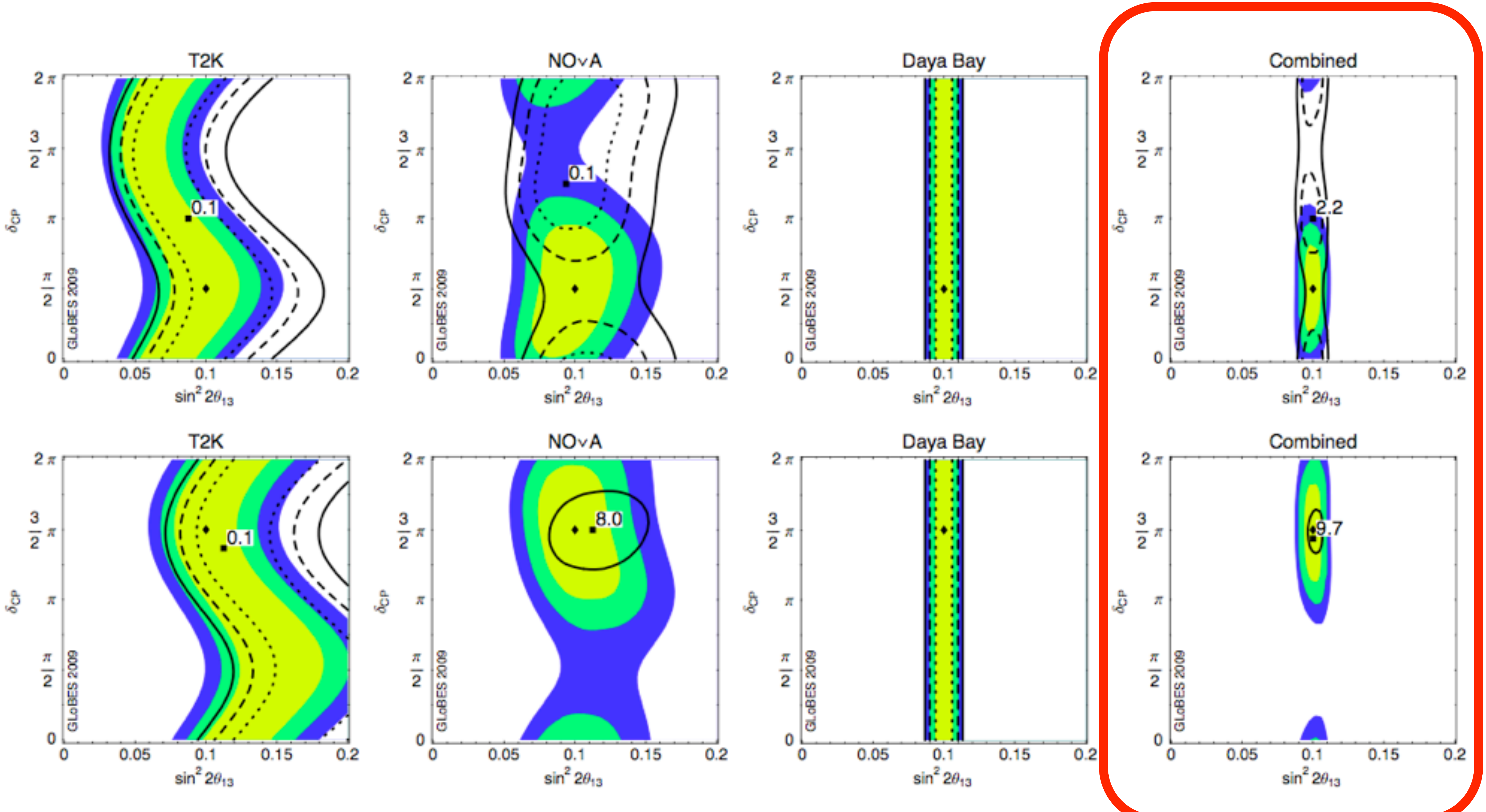


Global fit ~2020?

Huber, Lindner, TS, Winter, 0907.1896

Setup	t_ν [yr]	$t_{\bar{\nu}}$ [yr]	P_{Th} or P_{Target}	L [km]	Detector technology	m_{Det}
Double Chooz	-	3	8.6 GW	1.05	Liquid scintillator	8.3 t
Daya Bay	-	3	17.4 GW	1.7	Liquid scintillator	80 t
RENO	-	3	16.4 GW	1.4	Liquid scintillator	15.4 t
T2K	5	-	0.75 MW	295	Water Cerenkov	22.5 kt
NOνA	3	3	0.7 MW	810	TASD	15 kt

Global fit ~2020



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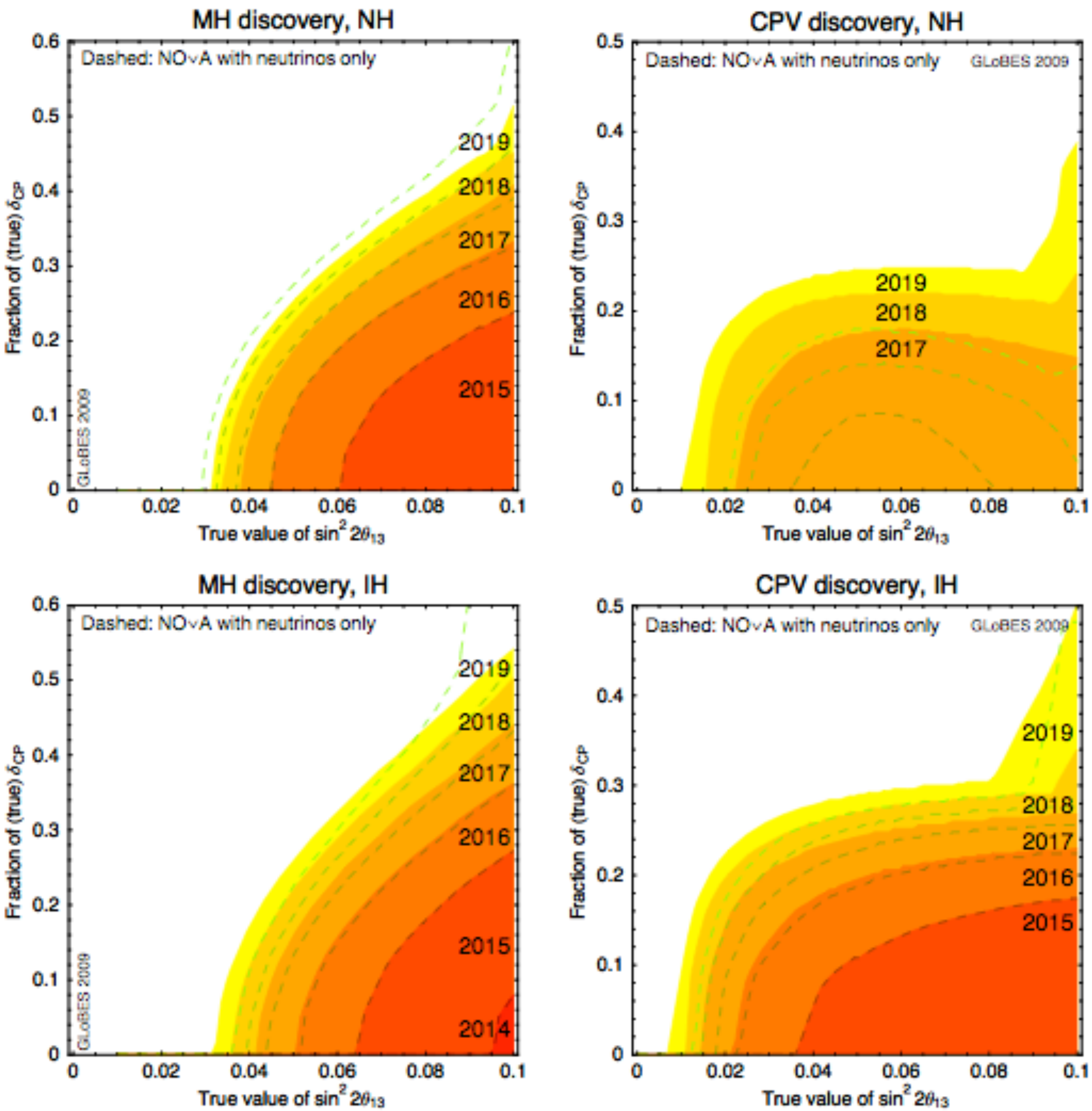

Huber, Lindner, TS, Winter, 0907.1896

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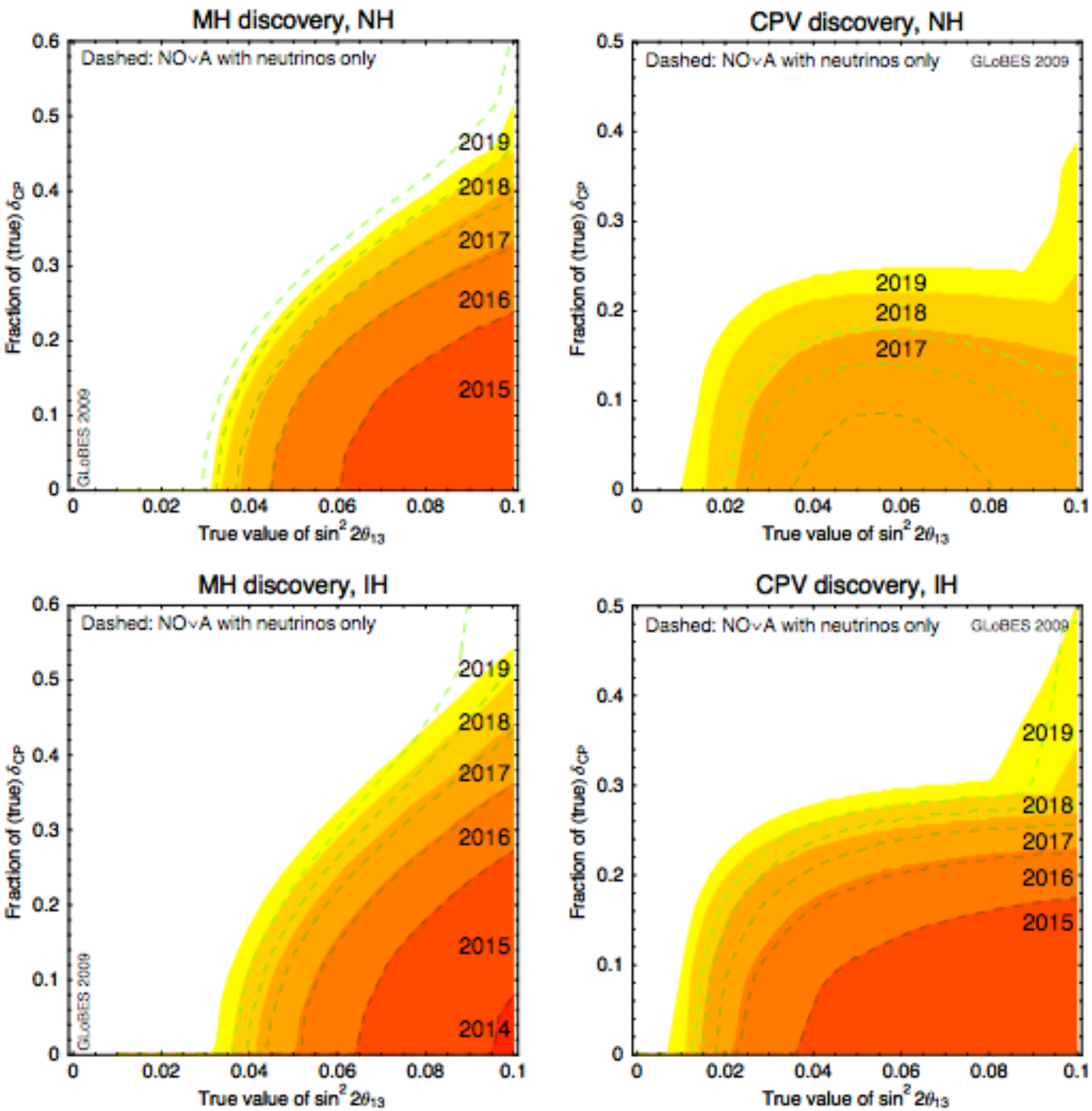
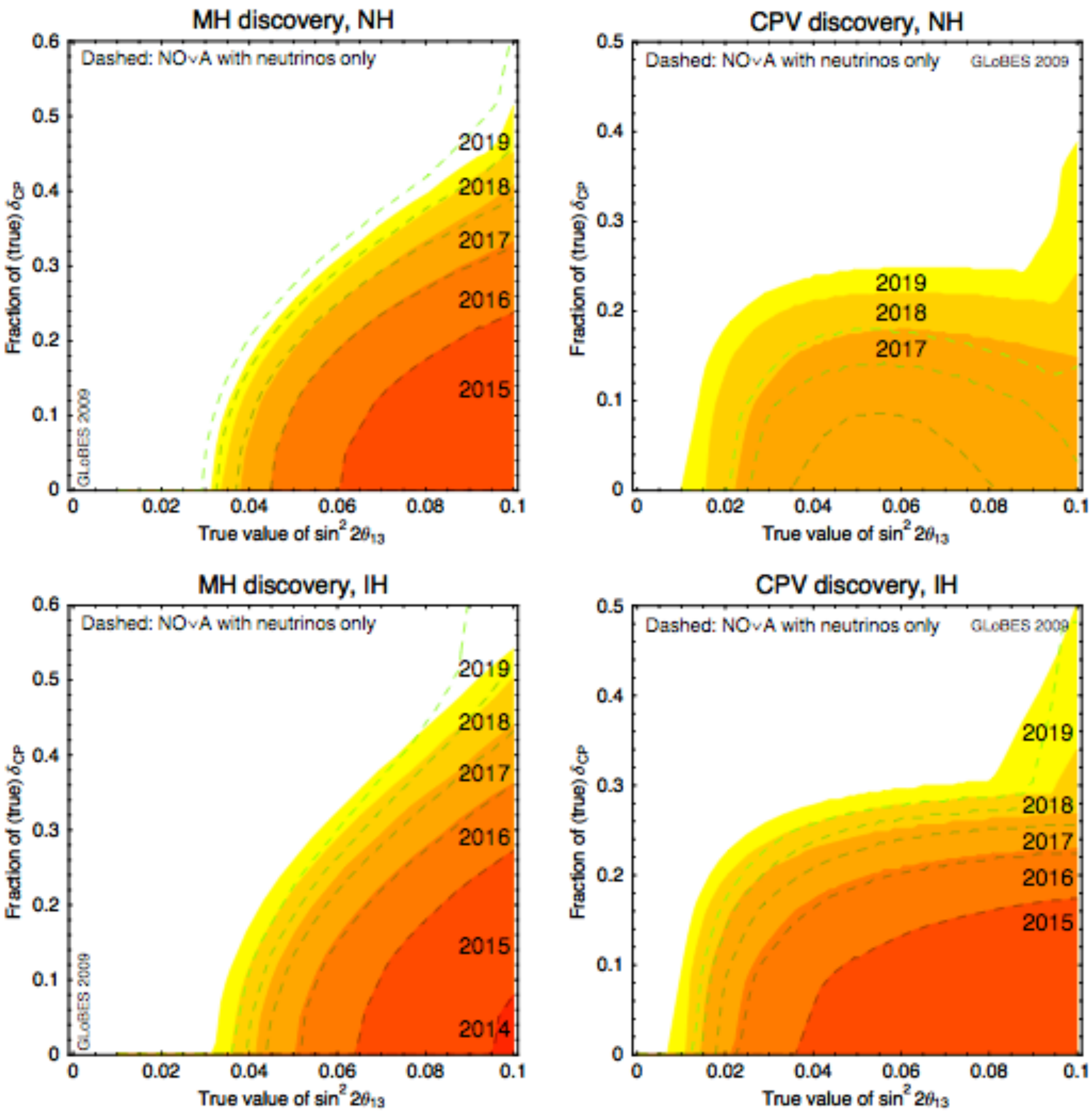


BUT: 90% CL
note scale on y axis

Huber, Lindner, TS, Winter, 0907.1896

Global fit ~2020



BUT: 90% CL
note scale on y axis

at 3σ those
plots are empty!

Huber, Lindner, TS, Winter, 0907.1896

How well can we do in θ_{23}?

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

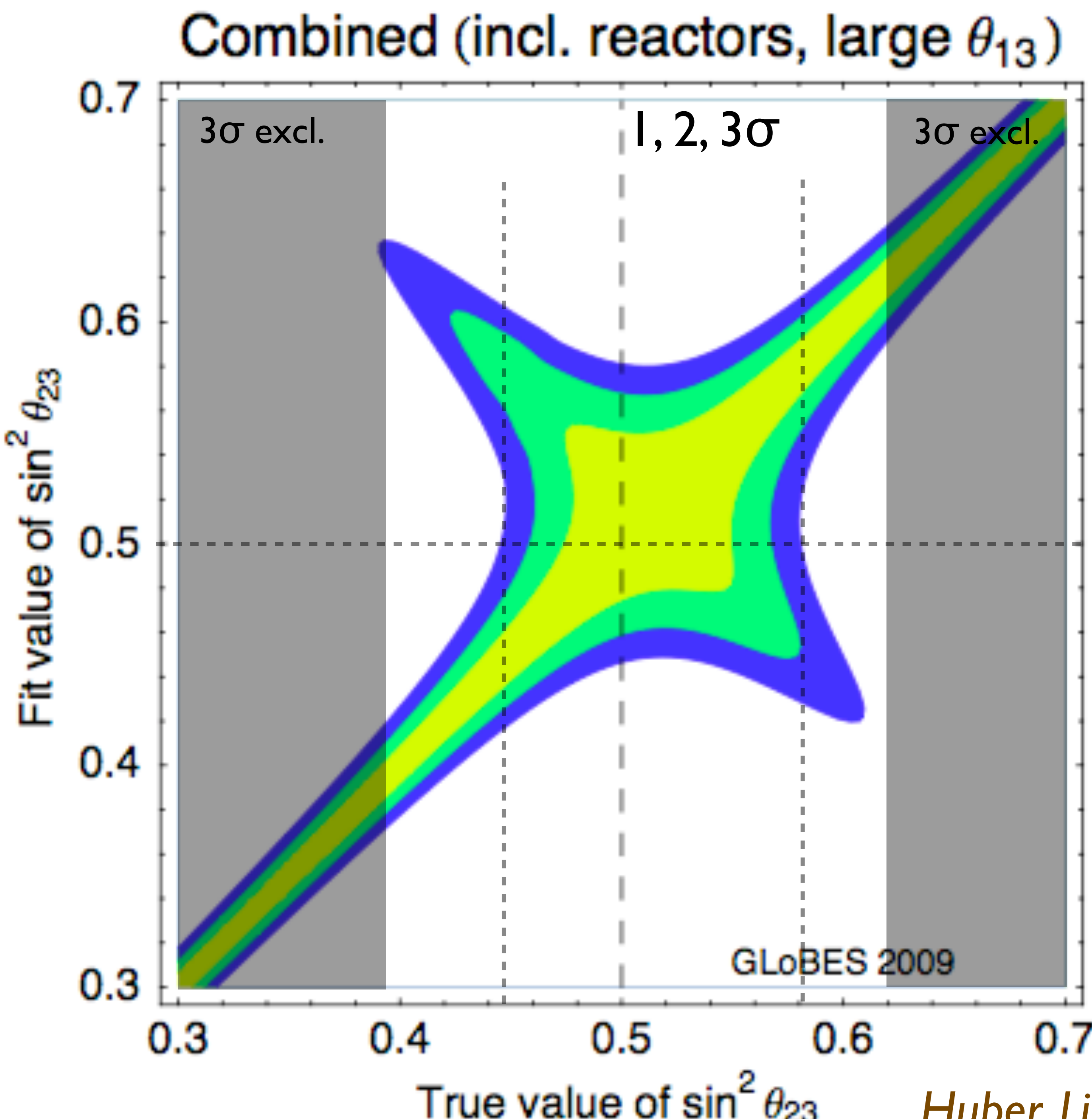
with

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

- *for large θ_{13} the leading term depends on octant*
- *beam+reactor combination may be sensitive to octant*

Minakata et al. hep-ph/0211111; McConnel, Shaevitz, hep-ex/0409028; see also talk by G. Fogli

Global fit ~2020 - θ_{23} octant



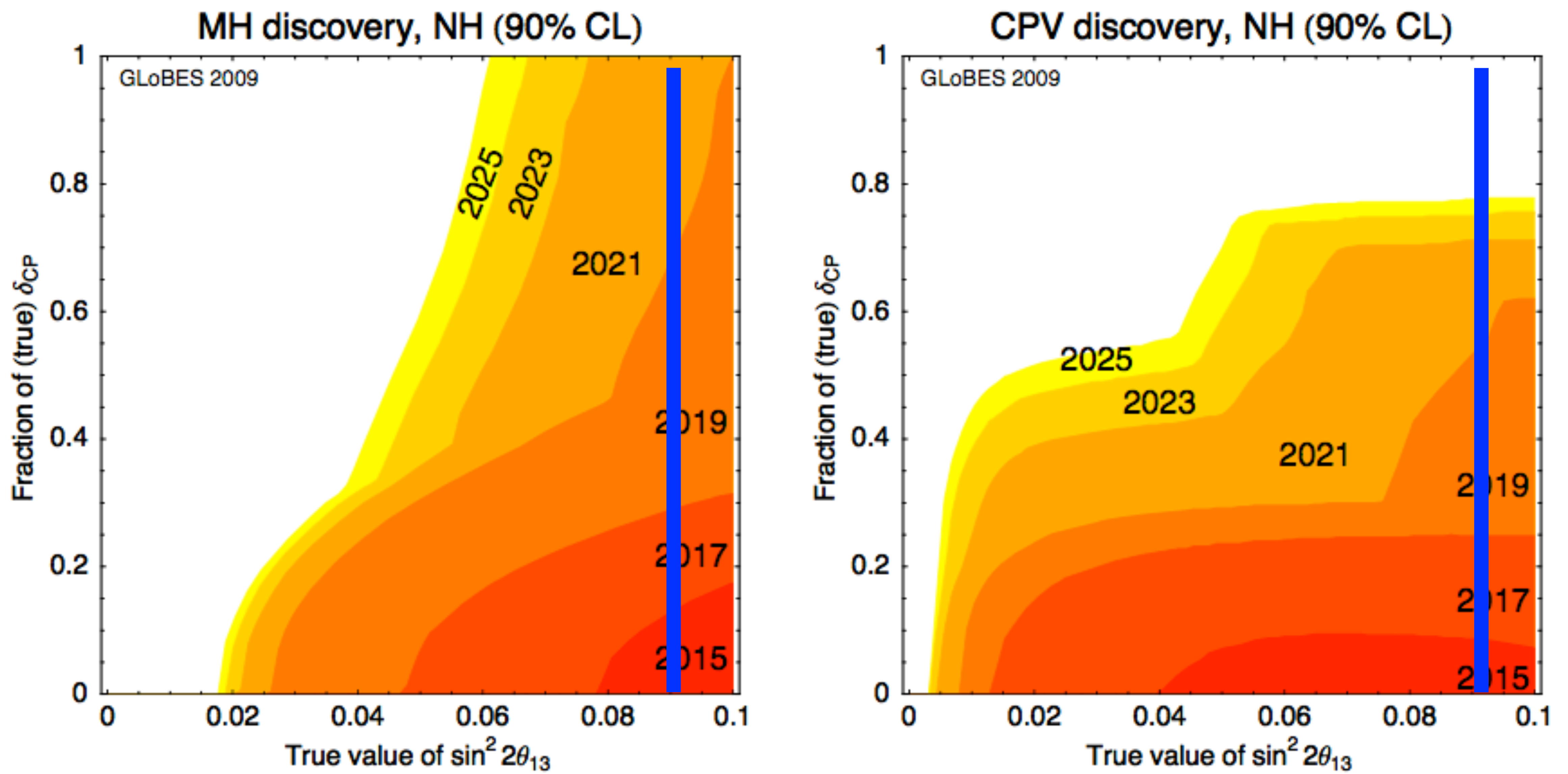
Huber, Lindner, TS, Winter, 0907.1896

T2K + NOvA upgrades

- *T2K: proton driver, increase power from 0.57 to 1.66 MW linearly from 2015 to 2016*
- *NOvA: project X, increase power from 0.2 to 2.3 MW linearly from 2018 to 2019*
- *continue running till 2025*
- *use mutually optimized neutrino/antineutrino running times in NOvA and T2K*

T2K + NOvA upgrades

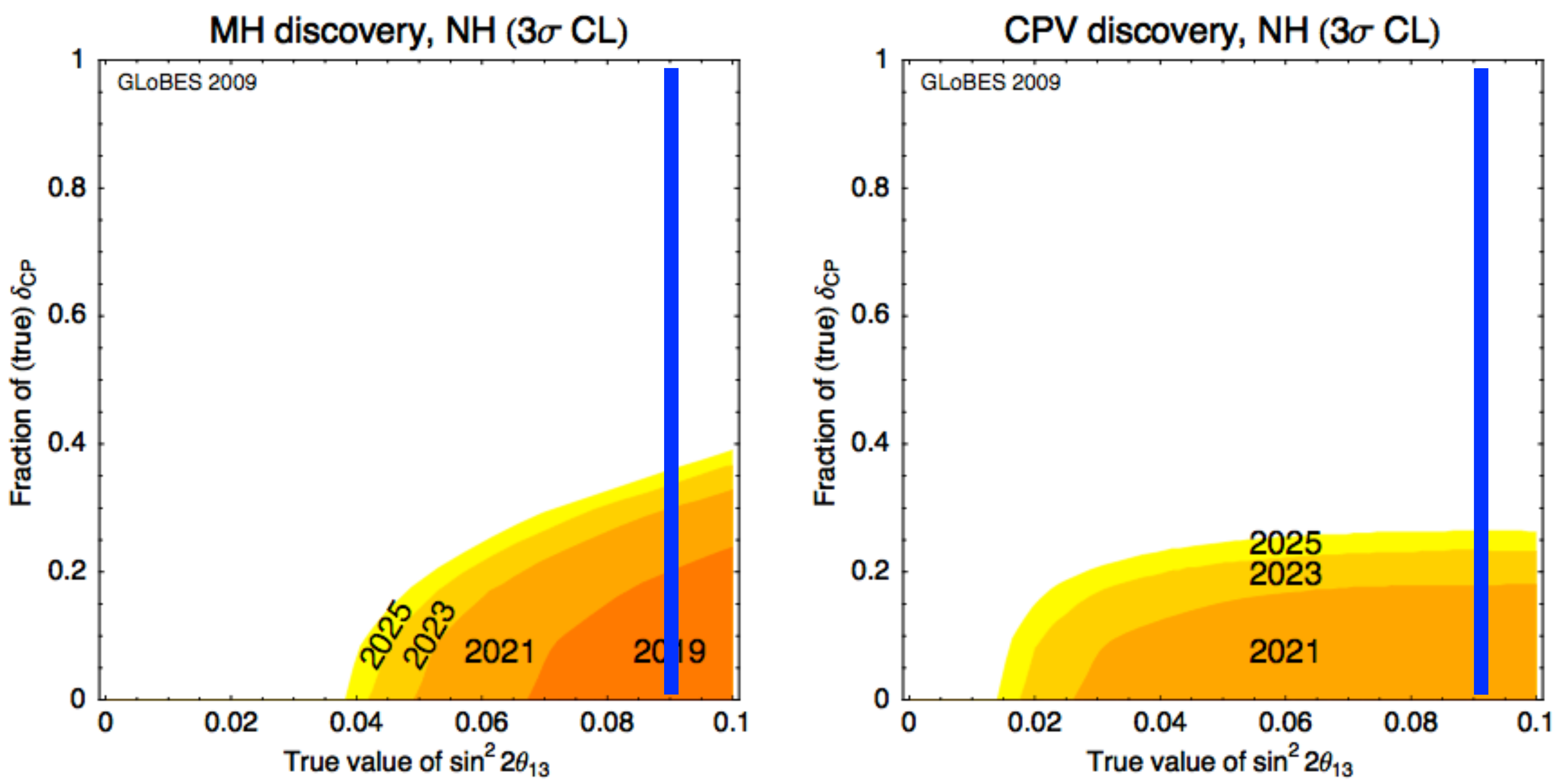
Huber, Lindner, TS, Winter, 0907.1896



see also talk by J.Thomas

T2K + NOvA upgrades

Huber, Lindner, TS, Winter, 0907.1896



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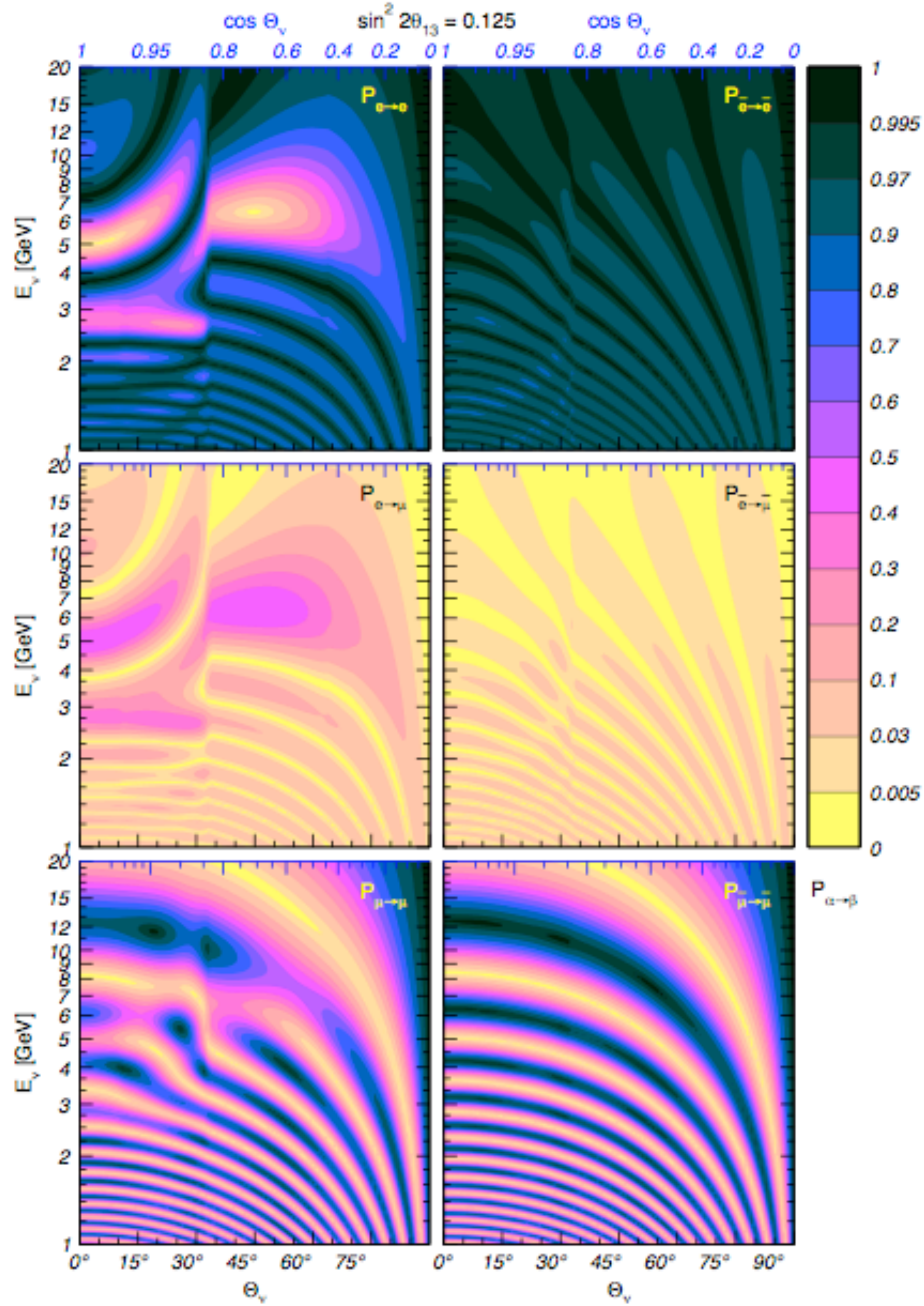
Atmospheric neutrino data

Atmospheric neutrino data

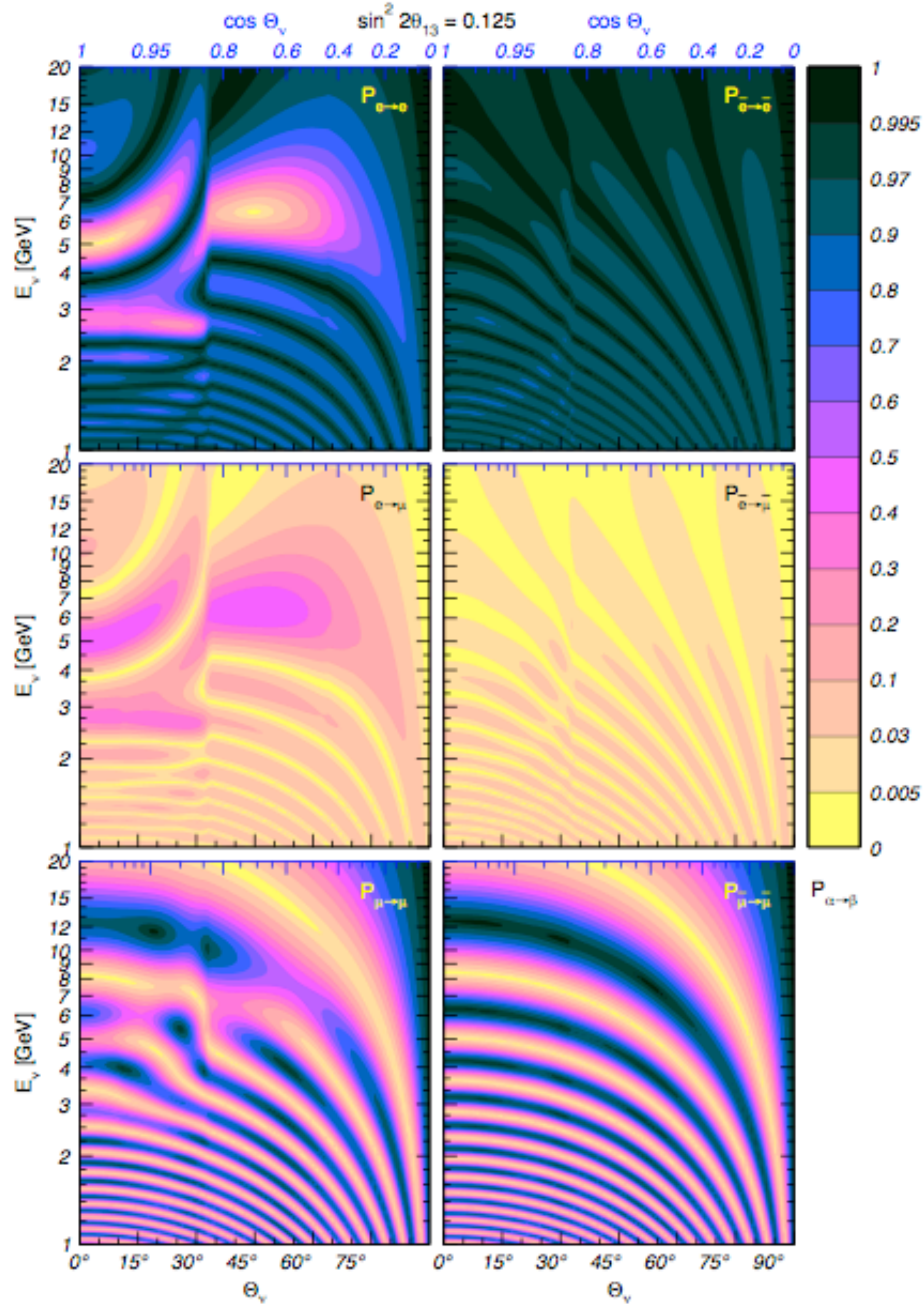


Akhmedov, Maltoni, Smirnov, hep-ph/0612285

Atmospheric neutrino data

The ideal detector should be able to

- observe muons and electrons
- distinguish the charge (of both)
- reconstruct neutrino energy and direction



Akhmedov, Maltoni, Smirnov, hep-ph/0612285

Which atmospheric neutrino detector?

- *Water Cerenkov?*
  no charge-ID → dilution of effect
  → huge detectors (> Mt yr)
  statistical neutrino/antineutrino separation?
- *Liquid Argon?*
  same as above - magnetize it?
- *Magnetized iron calorimeter?*
  no electrons
- *Ice? no charge ID, E-reconstruction hard,*
  no electrons (maybe sum of e, τ, NC), but VERY BIG

3-flavor effects in atmospheric neutrinos

excess in electron-like events:

$$\frac{N_e}{N_e^0} - 1 \simeq (r\, s_{23}^2 - 1)\, P_{2\nu}(\Delta m_{31}^2, \theta_{13}) \qquad \theta_{13}\text{-effects}$$

$$+ (r\, c_{23}^2 - 1)\, P_{2\nu}(\Delta m_{21}^2, \theta_{12}) \qquad \Delta m_{21}^2\text{-effects}$$

$$- 2 s_{13} s_{23} c_{23}\, r\, \mathrm{Re}(A_{ee}^* A_{\mu e}) \qquad \text{interference: } \delta_{\rm CP}$$

$$r = r(E_\nu) \equiv \frac{F_\mu^0(E_\nu)}{F_e^0(E_\nu)}$$

$r \approx 2$ (sub-GeV)

$r \approx 2.6 - 4.5$ (multi-GeV)

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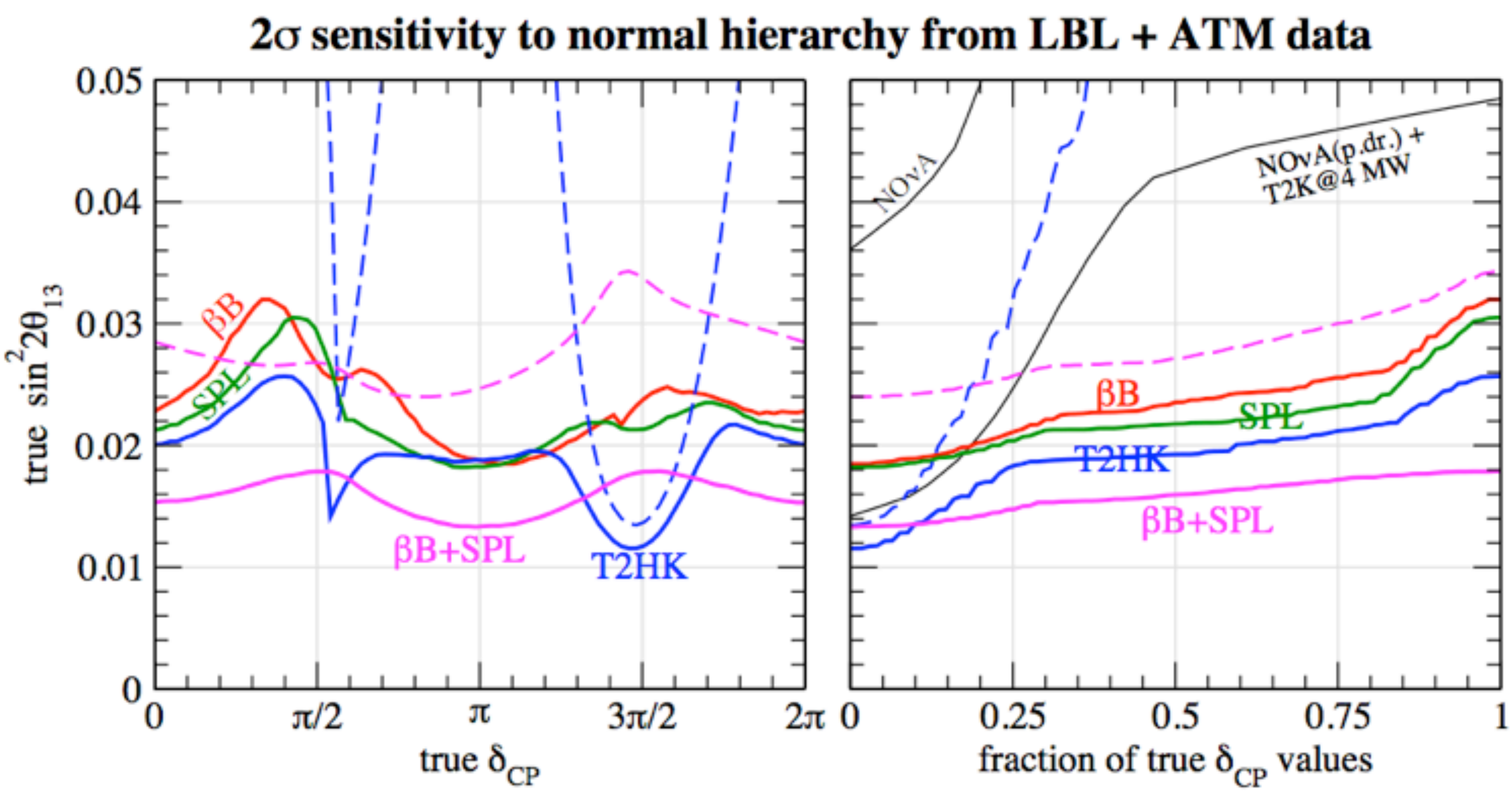
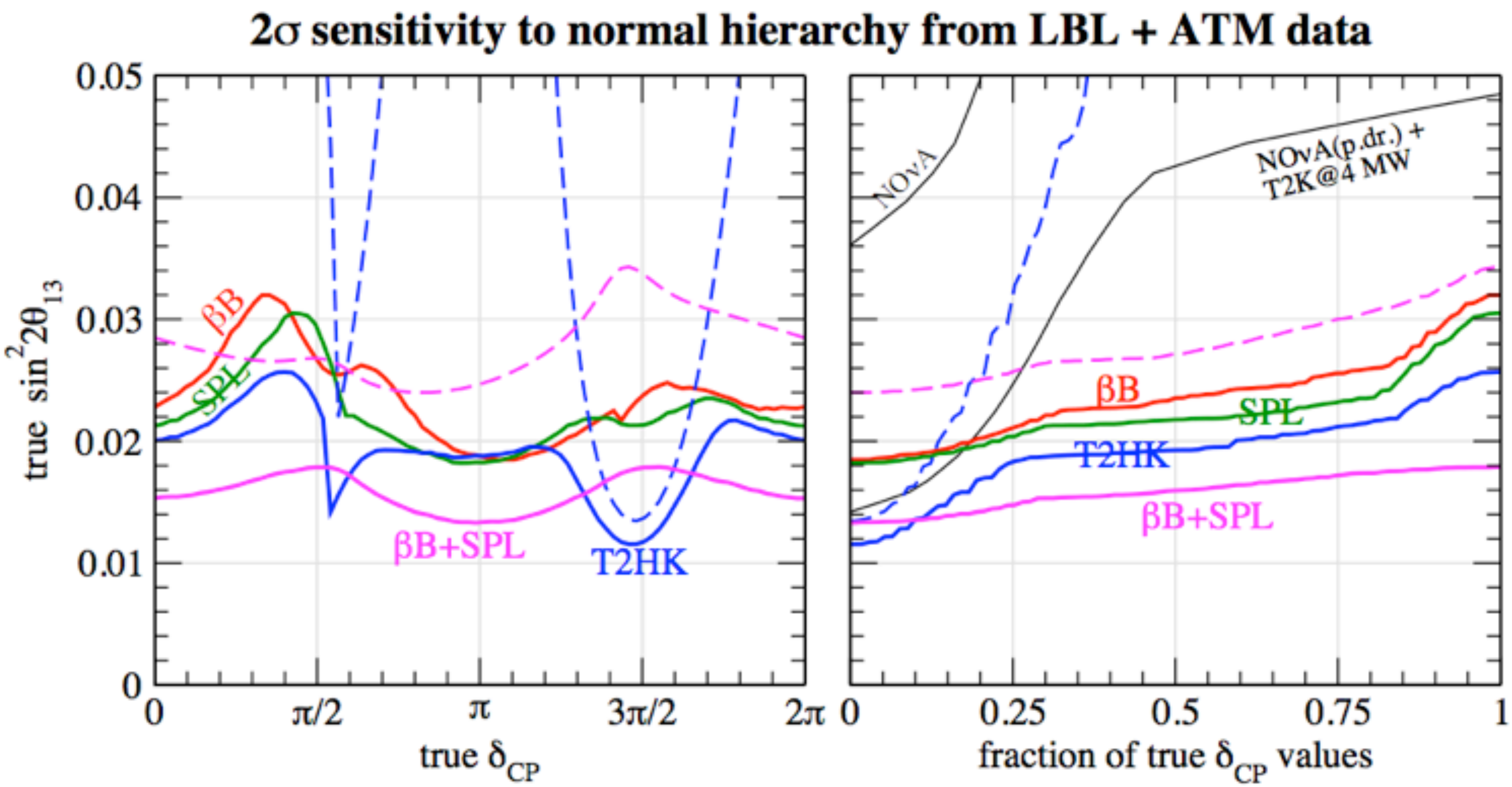
Hierarchy with a 400kt WC detector



Campagne, Maltoni, Mezzetto, TS, 06

For $\sin^2 2\theta_{13}$ = 0.1, it is quite likely that with ~Mt yr atm neutrino data from a WC or LAr detector we will determine the hierarchy

Hierarchy with a 400kt WC detector



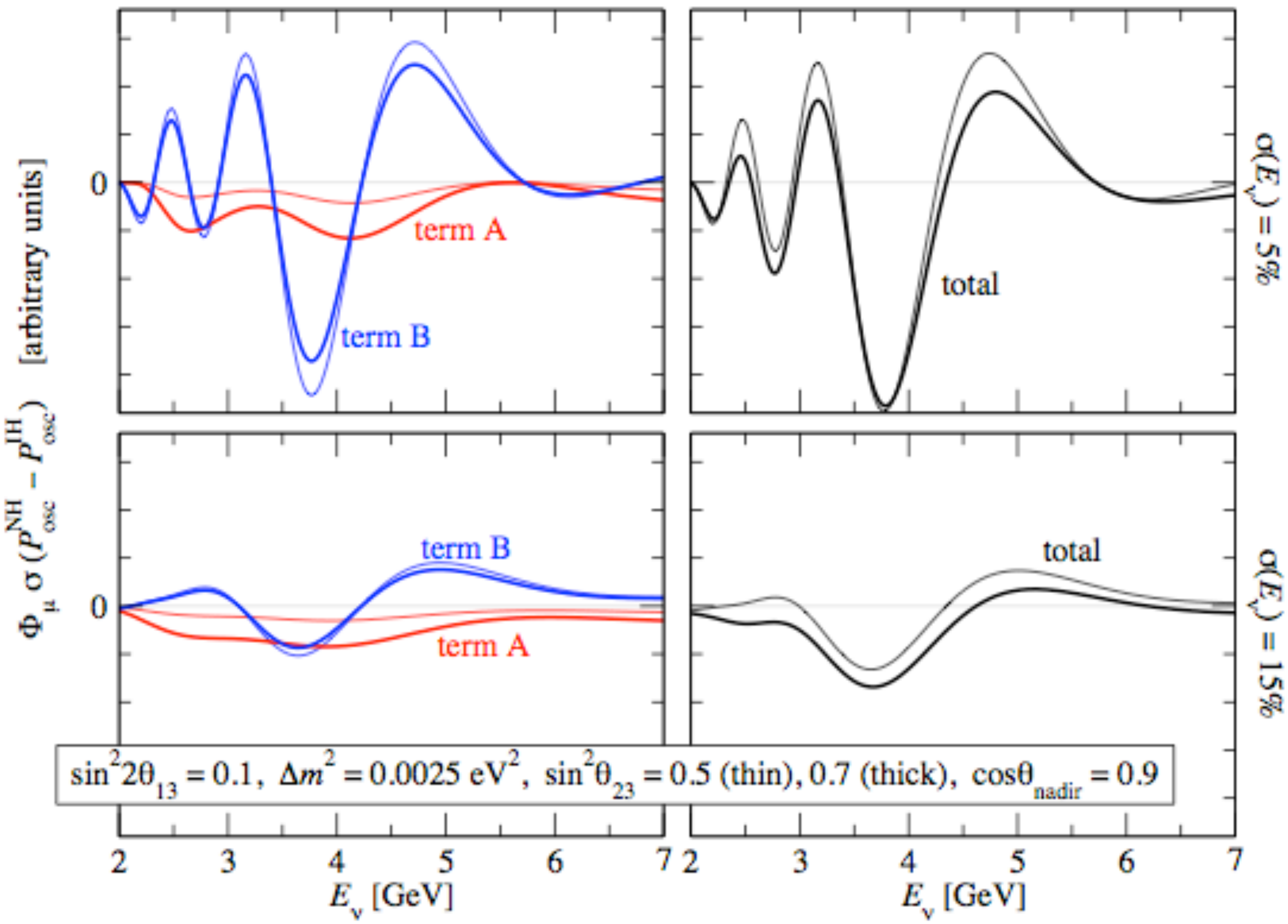
Campagne, Maltoni, Mezzetto, TS, 06

For $\sin^2 2\theta_{13}$ = 0.1, it is quite likely that with ~Mt yr atm neutrino data from a WC or LAr detector we will determine the hierarchy

Can we do something before that?

Hierarchy with a magn. iron calorimeter

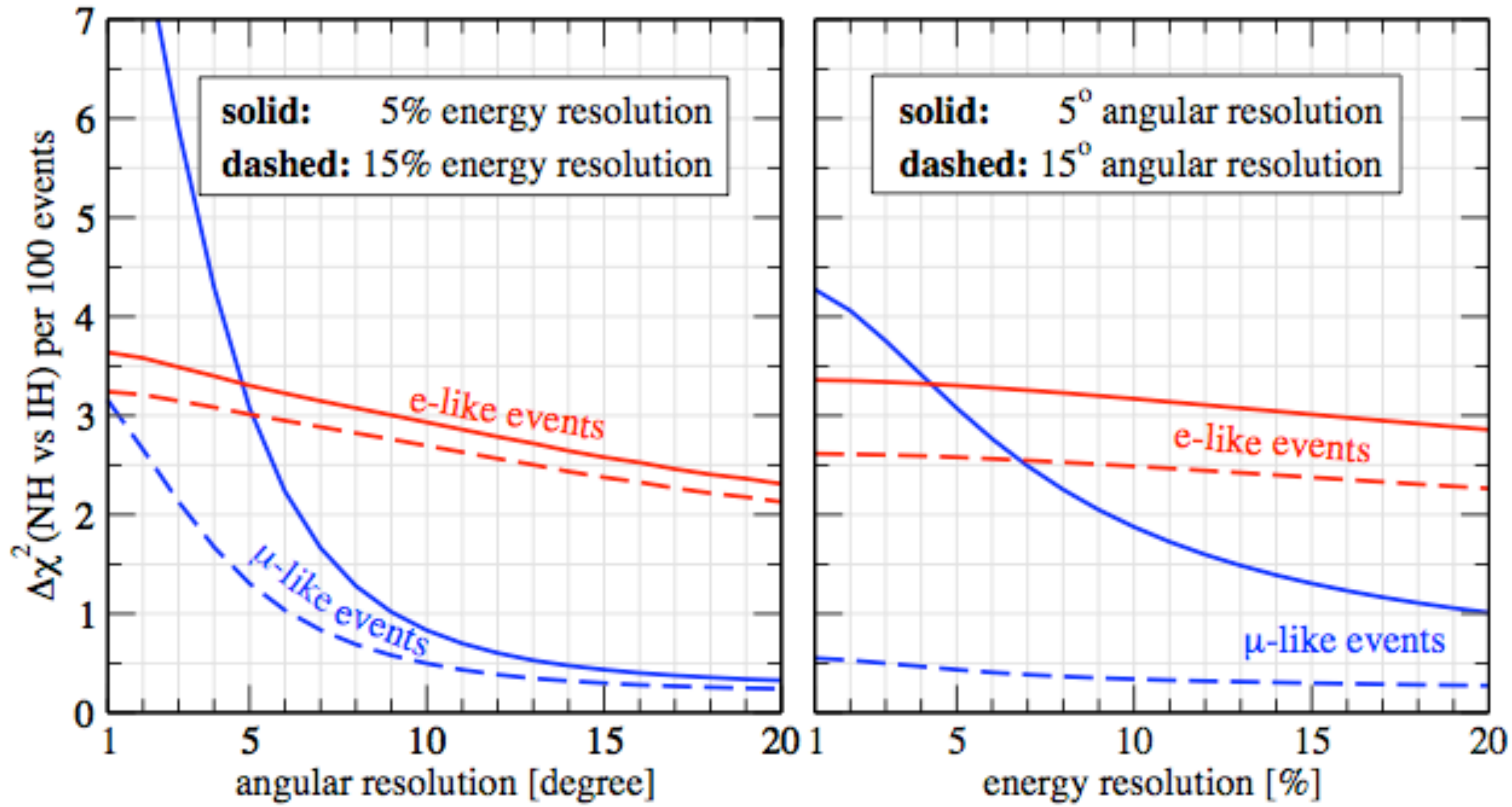
difference of the μ-like event spectra for NH and IH



$$\Delta S_\mu \propto \underbrace{\Phi_\mu \sigma \sin^2\theta_{23}\left(\frac{1}{r} - \sin^2\theta_{23}\right)\Delta P_{2\nu}}_{\text{term A}} + \underbrace{\Phi_\mu \sigma \frac{1}{2}\sin^2 2\theta_{23}\Delta\mathrm{Re}\,(A'_{33})}_{\text{term B}}$$

Hierarchy with a magn. iron calorimeter

Ability to reconstruct neutrino energy and direction is crucial



Petcov, TS, hep-ph/0511277; Indumathi, Murthy, hep-ph/0407336

INO (Identifying the Neutrino mass Ordering)

How does the global situation improve if atmospheric data from the India-based Neutrino Observatory (INO) is combined with NOvA+T2K+reactors? Blennow, TS, 1203.3388

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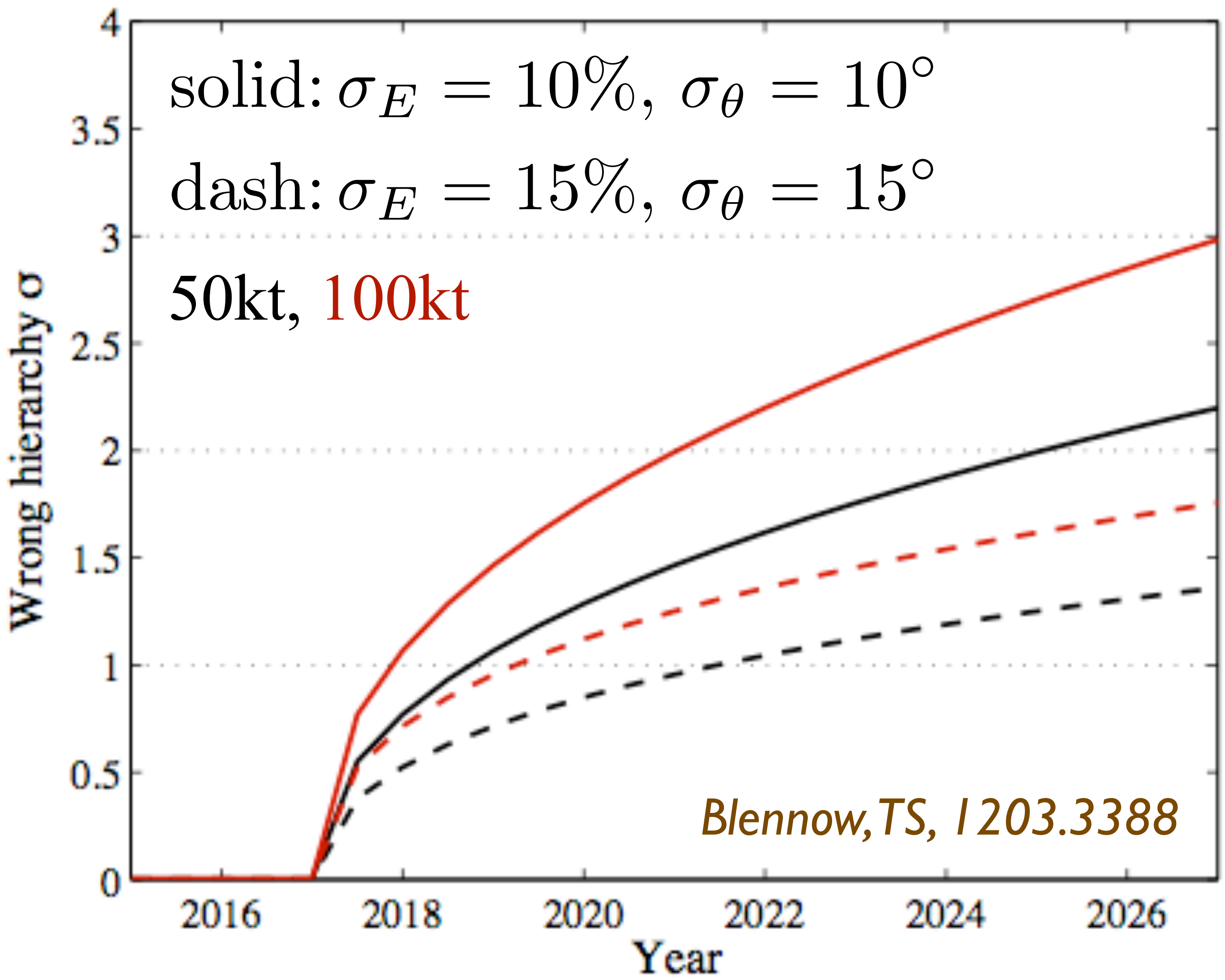
- *INO starts 2017 with 50kt or 100kt*
- *muon threshold of 2 GeV*
- *zenith angle region $-1 < \cos\theta < -0.1$*
- *~230 (neutrino+antineutrino) events per 50 kt yr (no osc)*
- *for energy and direction reconstruction consider "low" (15%, 15°) and "high" (10%, 10°) resolution scenario*
- *assume $\sin^2 2\theta_{13} = 0.09 \pm 0.017$*

INO *(Identifying the Neutrino mass Ordering)*



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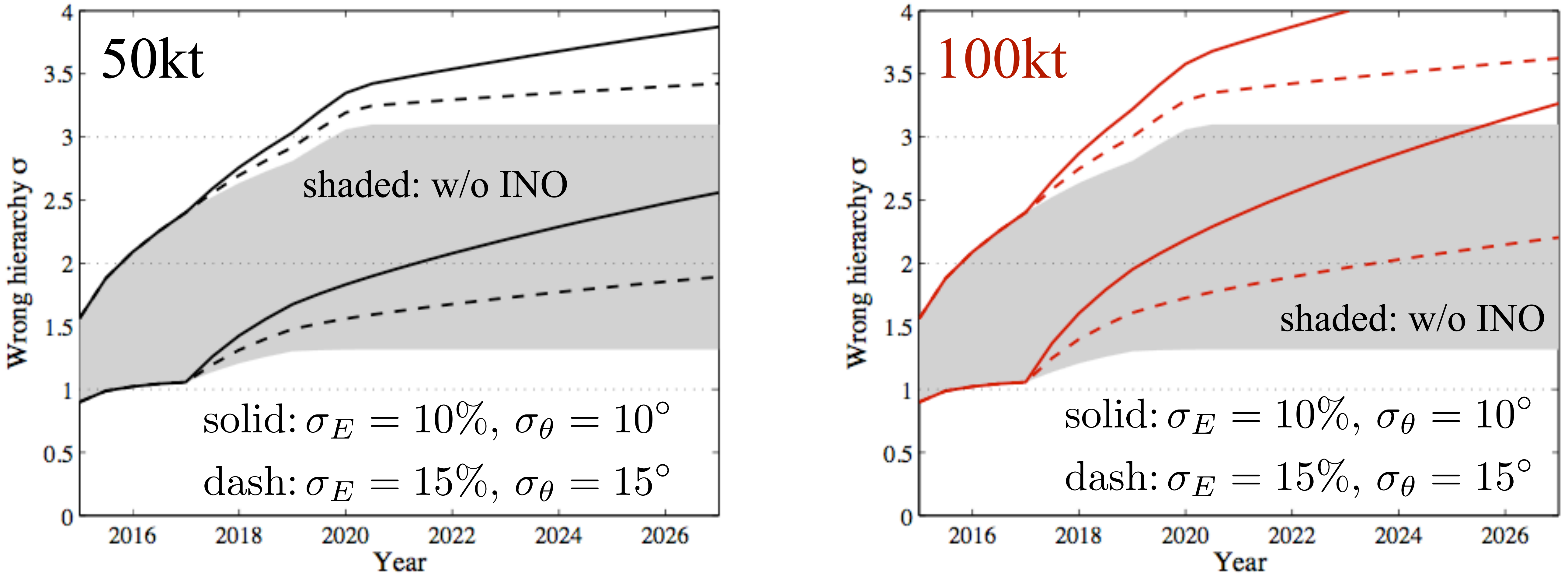

Blennow, TS, 1203.3388

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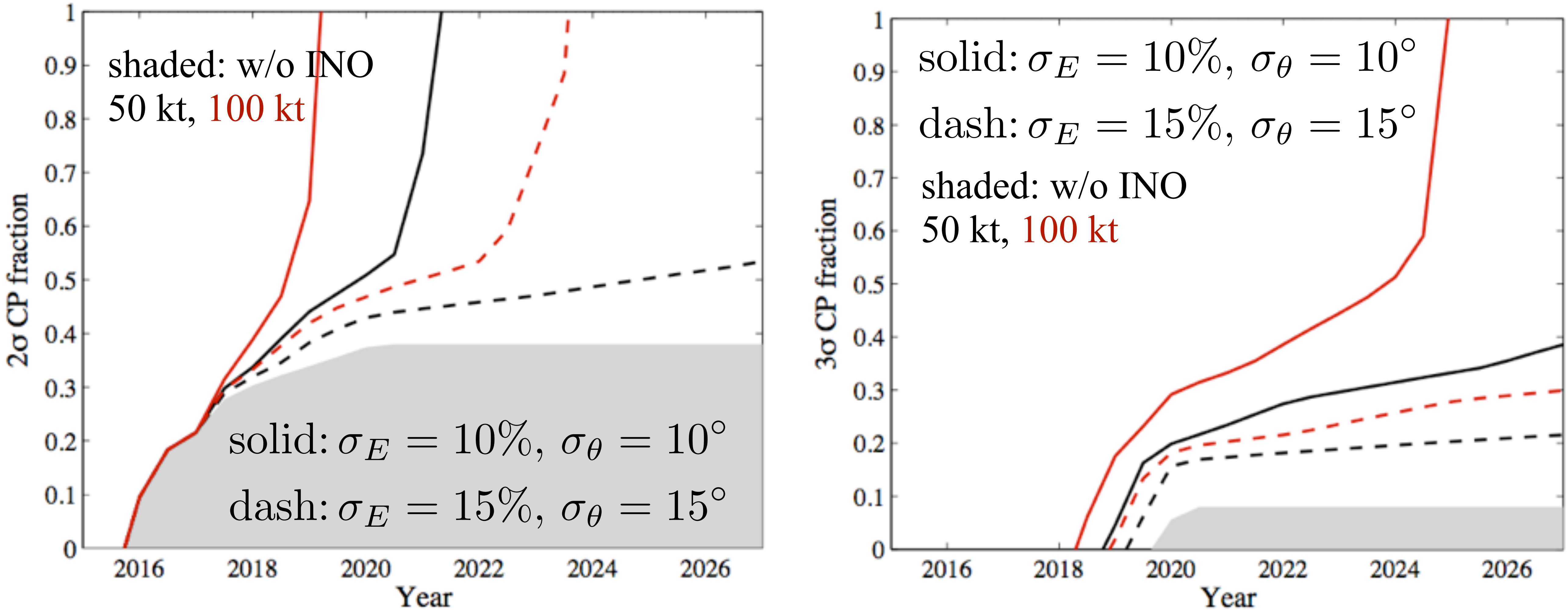
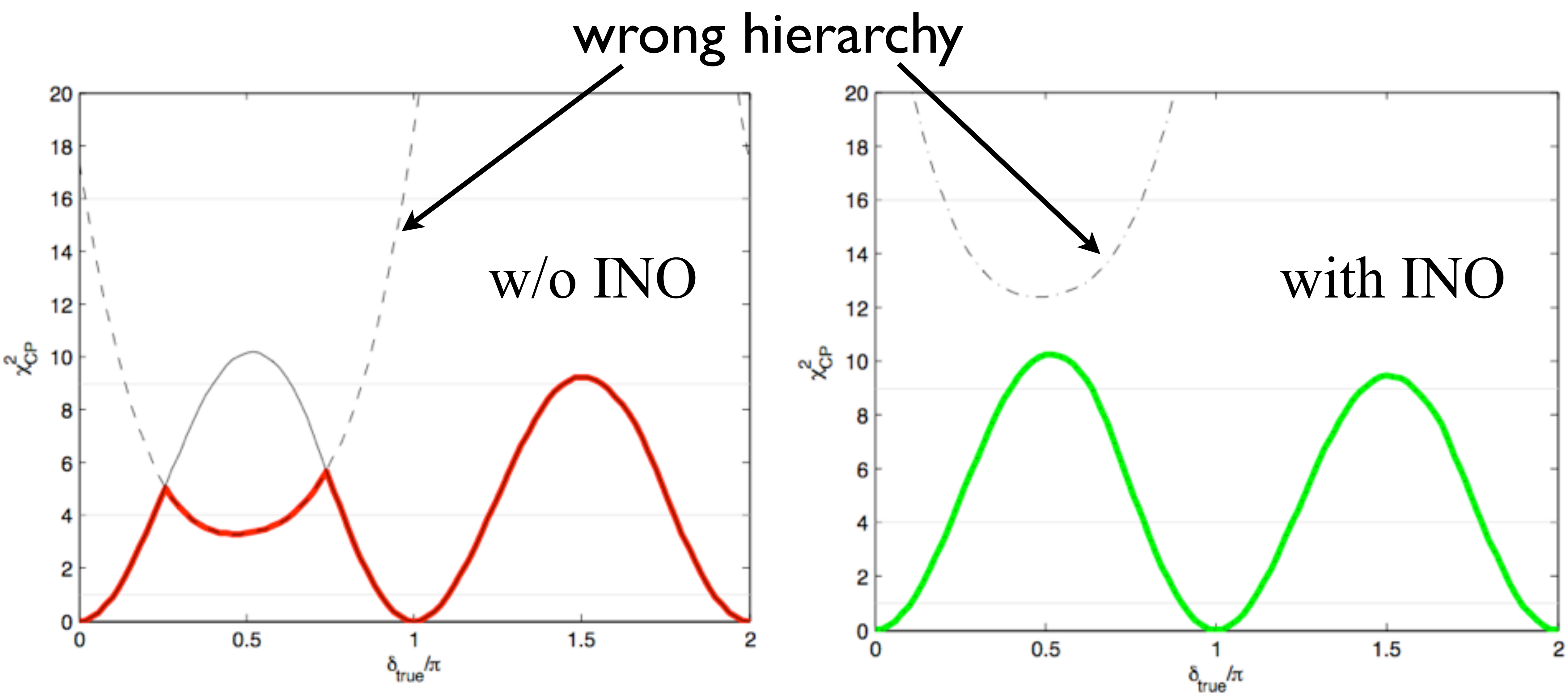


Blennow, TS, 1203.3388

Can INO improve the sensitivity to CPV?

Blennow, TS, preliminary

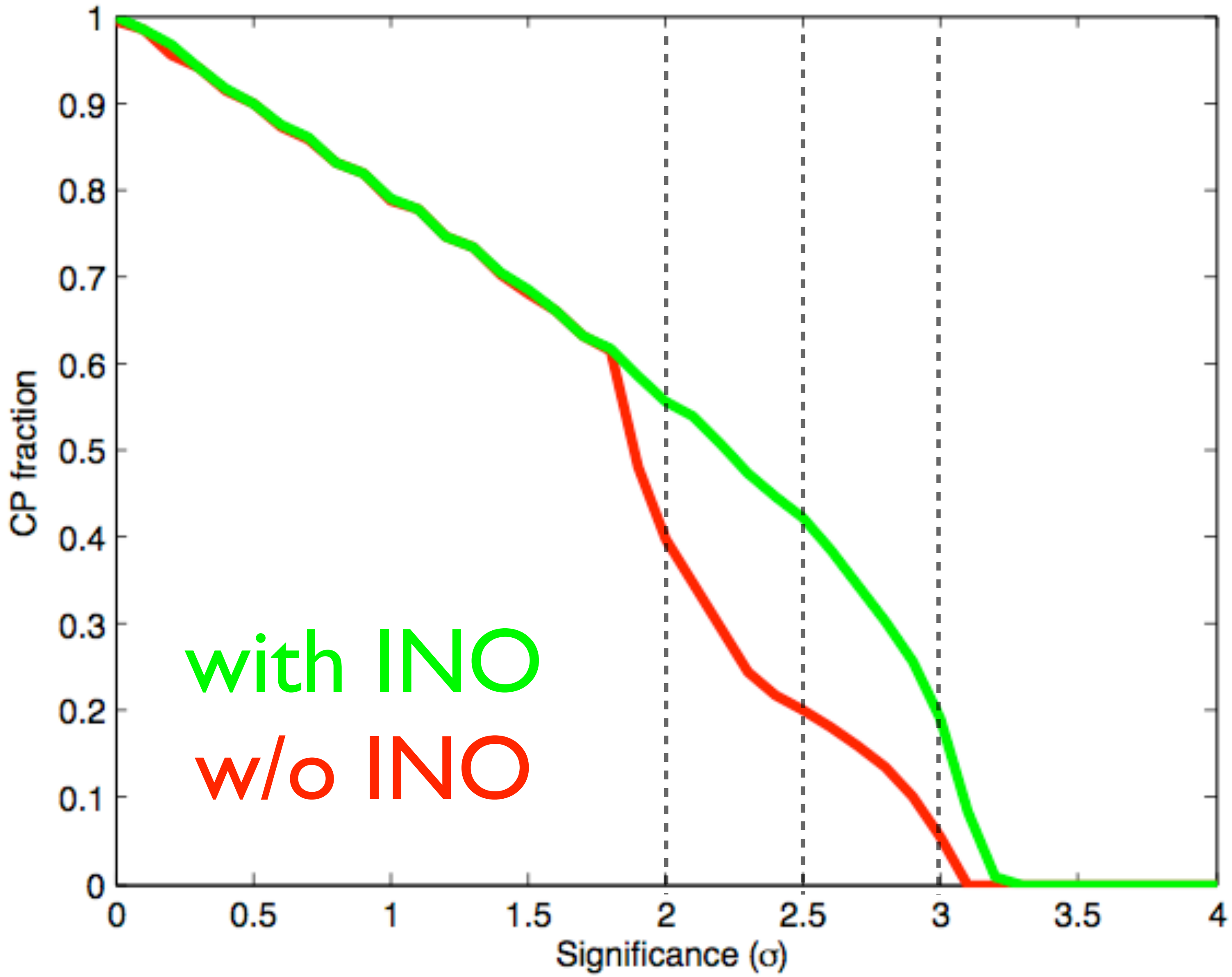


exclusion of CP conservation as function of true CP phase

T2K (5y ν+5y anti-ν) + NOvA (6y ν+6y anti-ν) + 1 Mt yr INO (high res.)

Can INO improve the sensitivity to CPV?

Blennow, TS, preliminary



T2K (5y ν+5y anti-ν) + NOvA (6y ν+6y anti-ν) + 1 Mt yr INO (high res.)

The mass hierarchy from the ice?

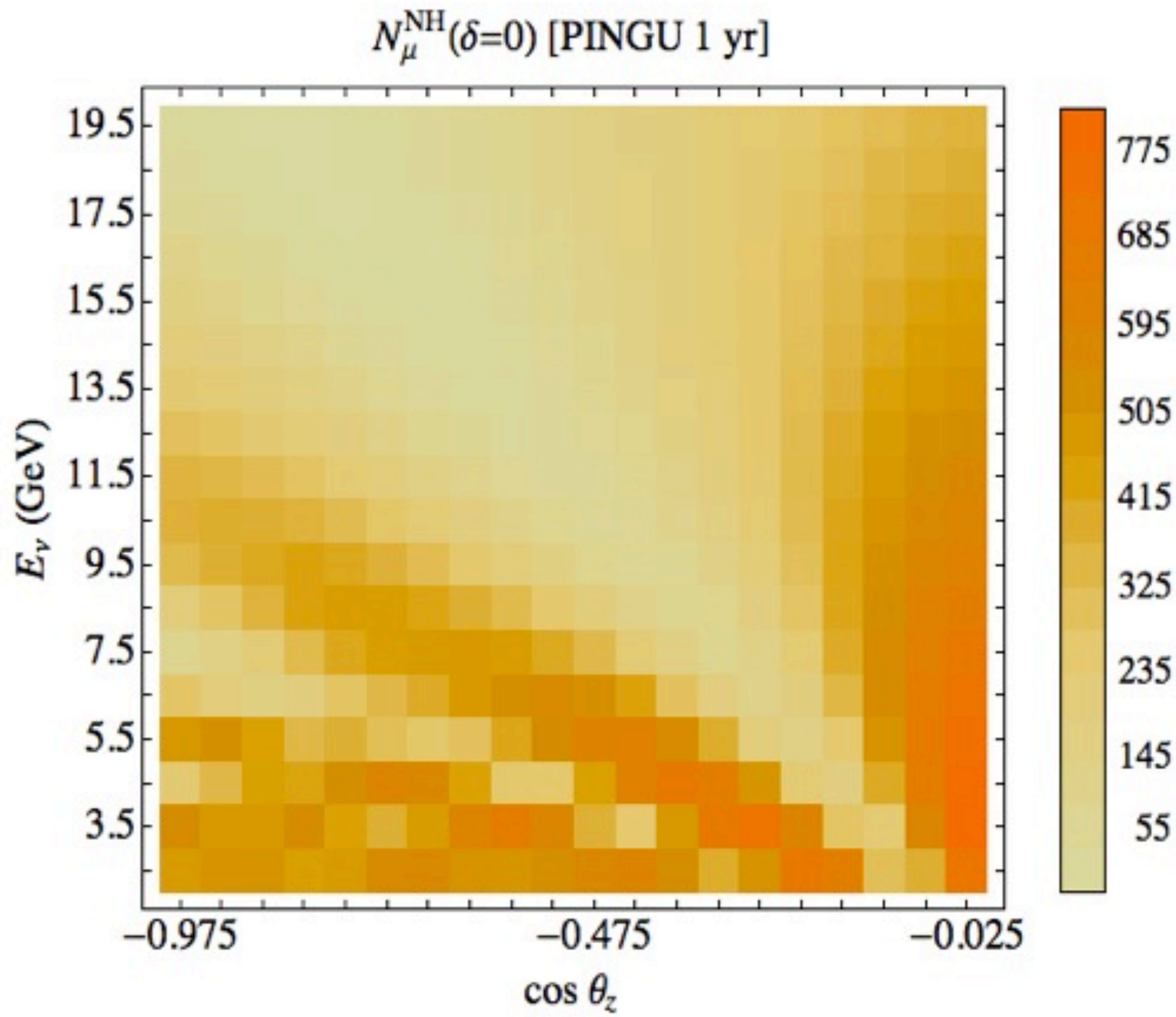
IceCube → DeepCore → **PINGU**

- ~20 additional strings within DeepCore
- lower threshold to few GeV
- ~10 Mt effective volume
- construction within 1 yr, ~$25 M

Doug Cowen, NuSky, ICTP, June 2011

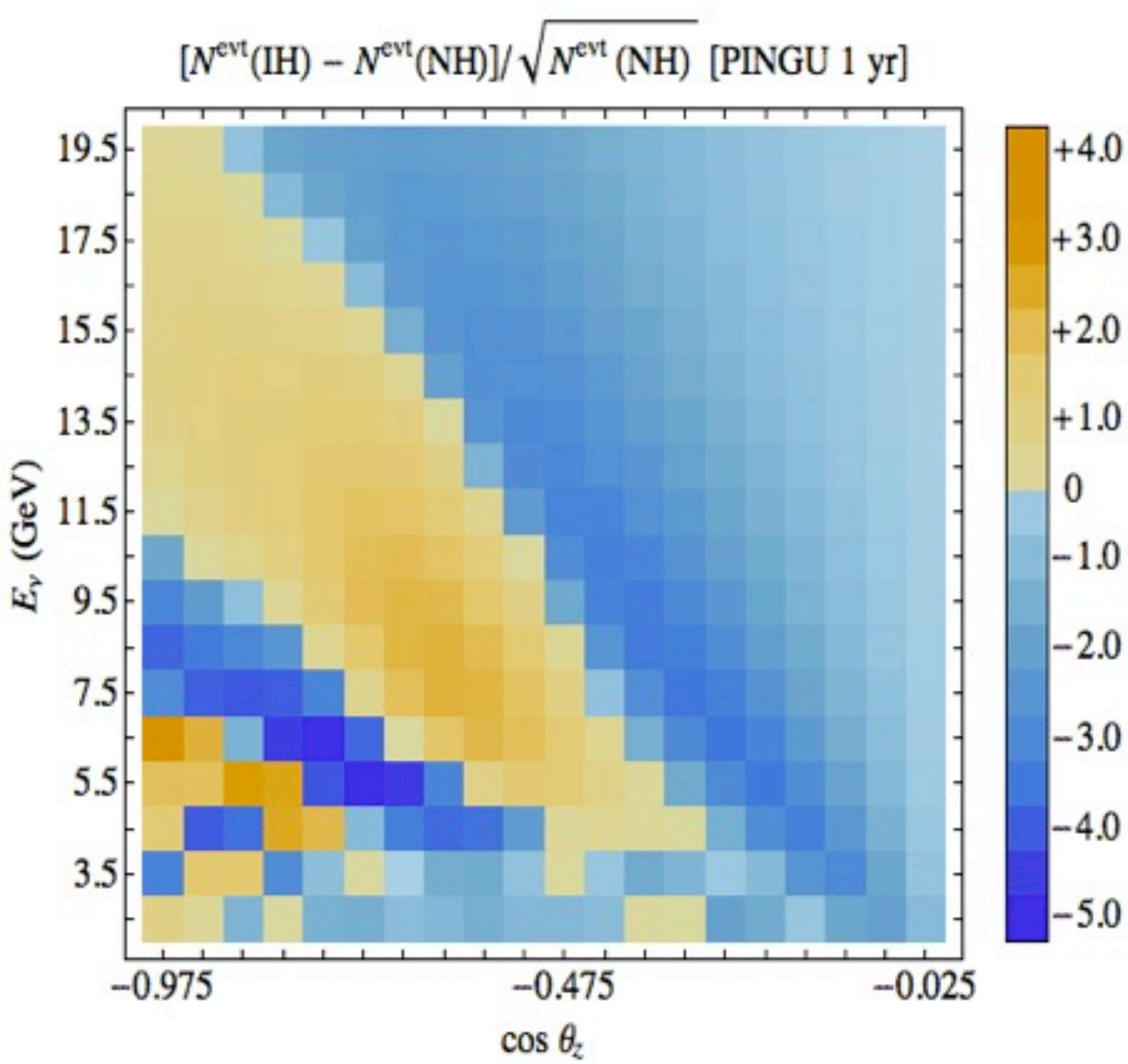
Atmospheric neutrinos (muons) in PINGU

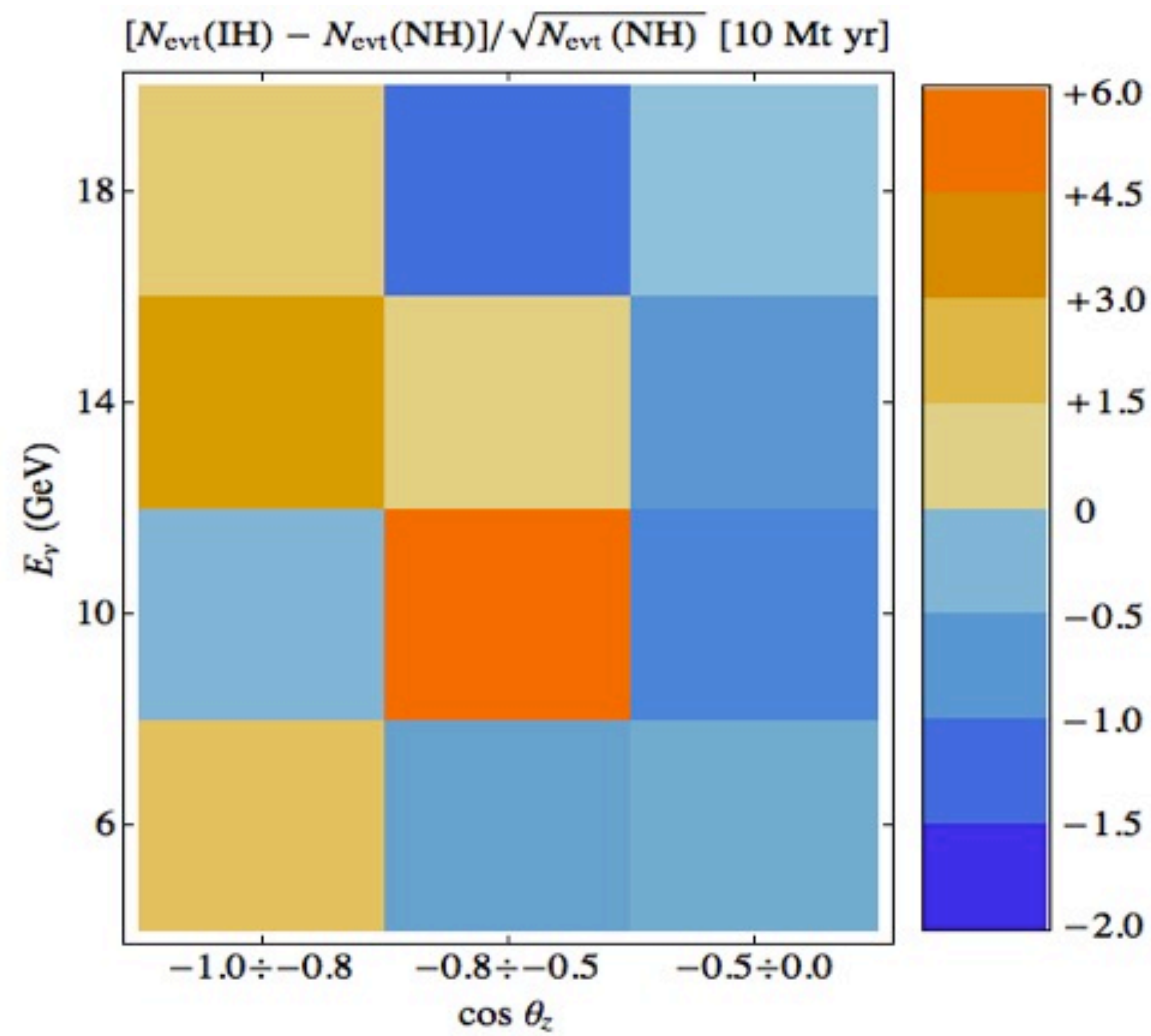
many events....



Akhmedov, Razzaque, Smirnov, in prep.

Mass hierarchy from PINGU





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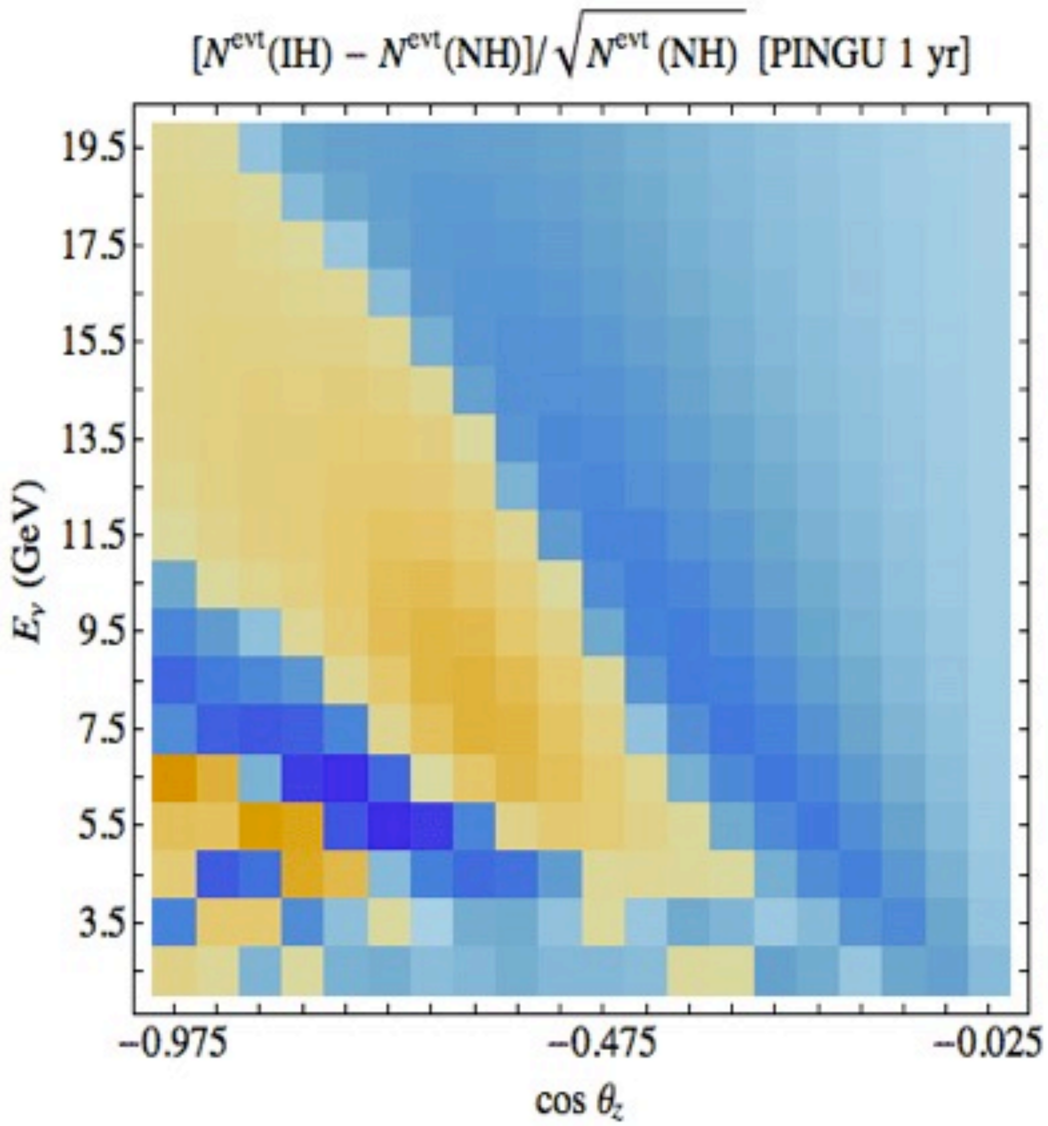
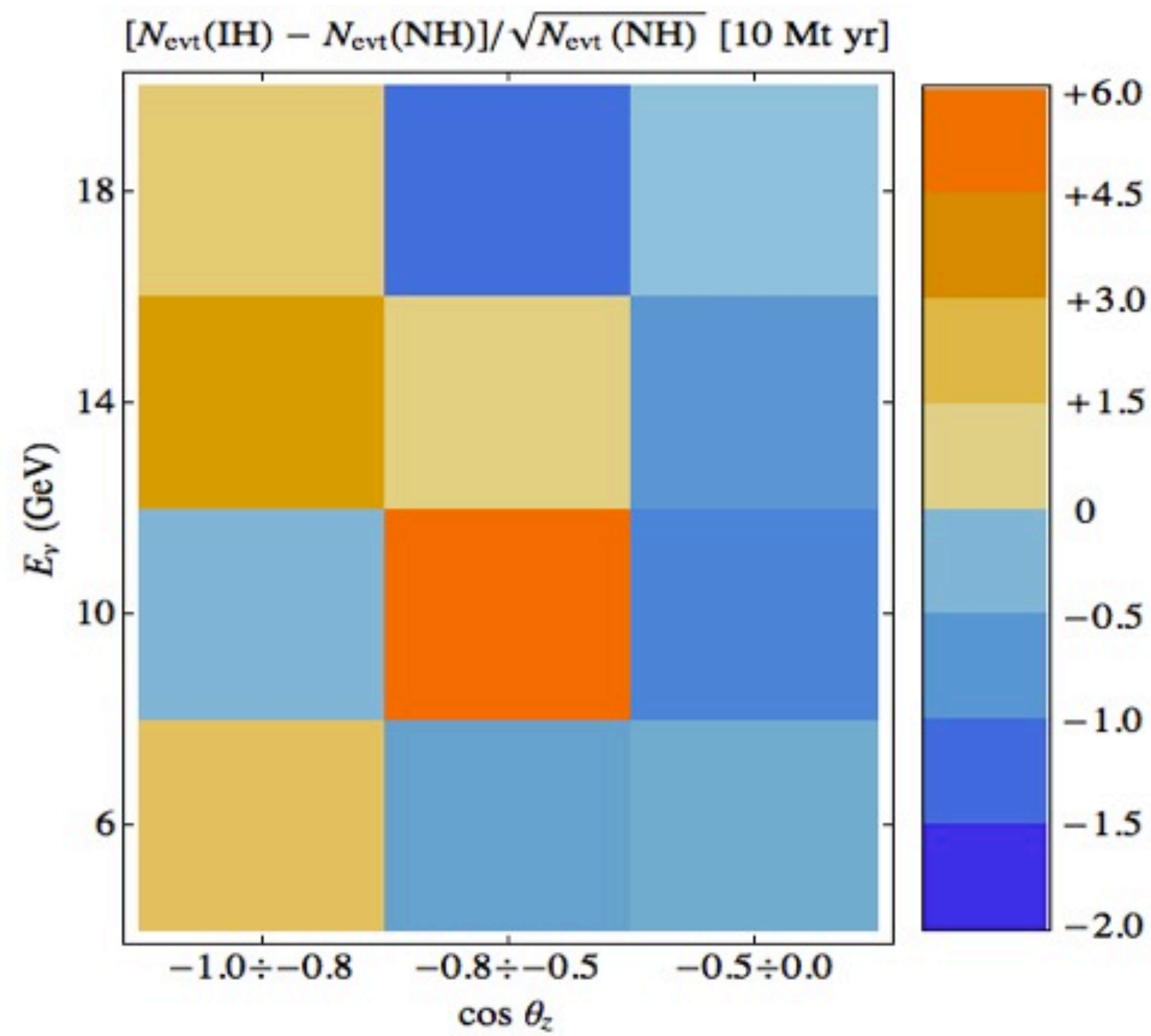




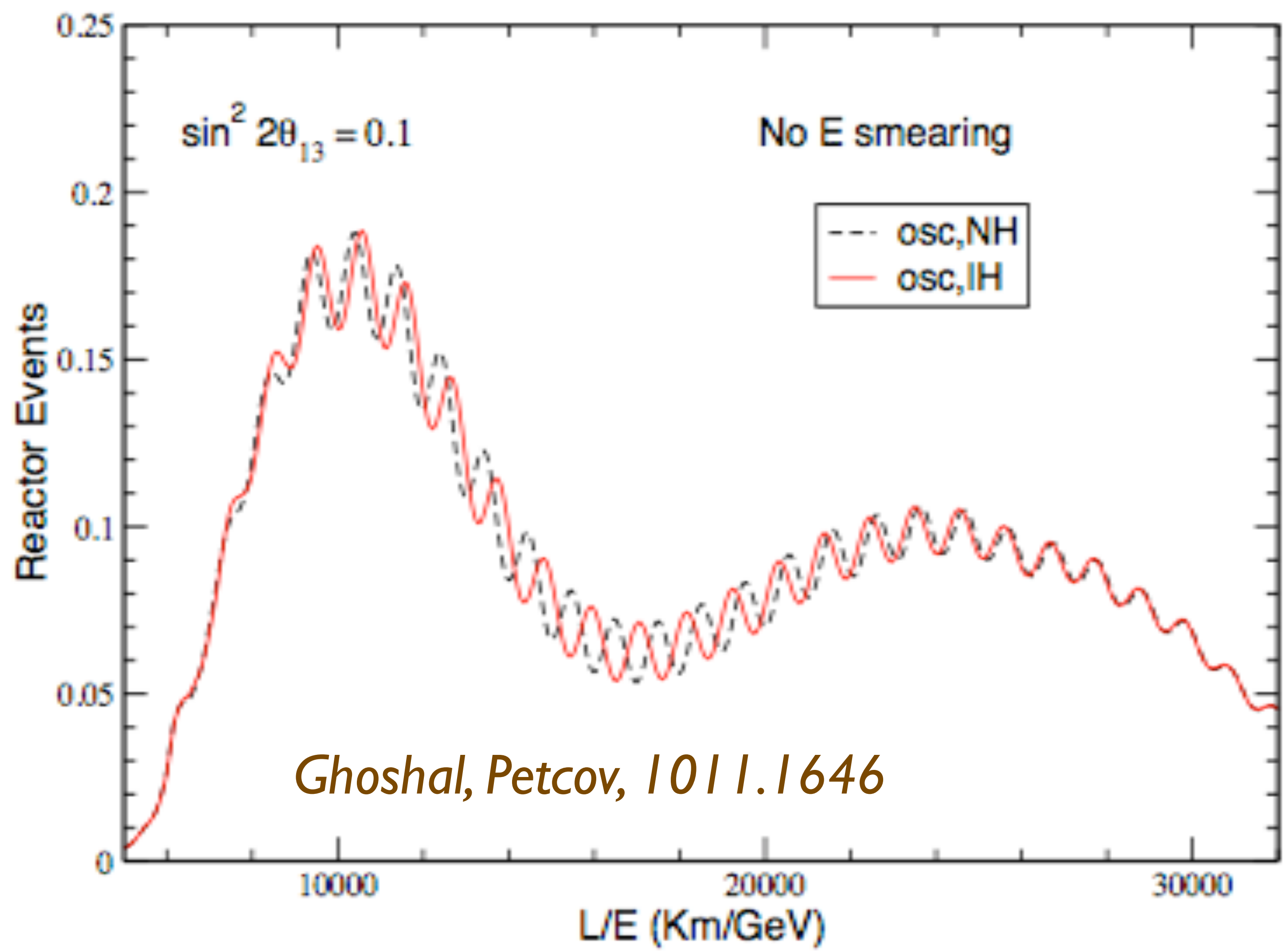
Akhmedov, Razzaque, Smirnov, in prep.

Very promising! Reconstruction abilities still to be studied

Hierarchy from a reactor experiment

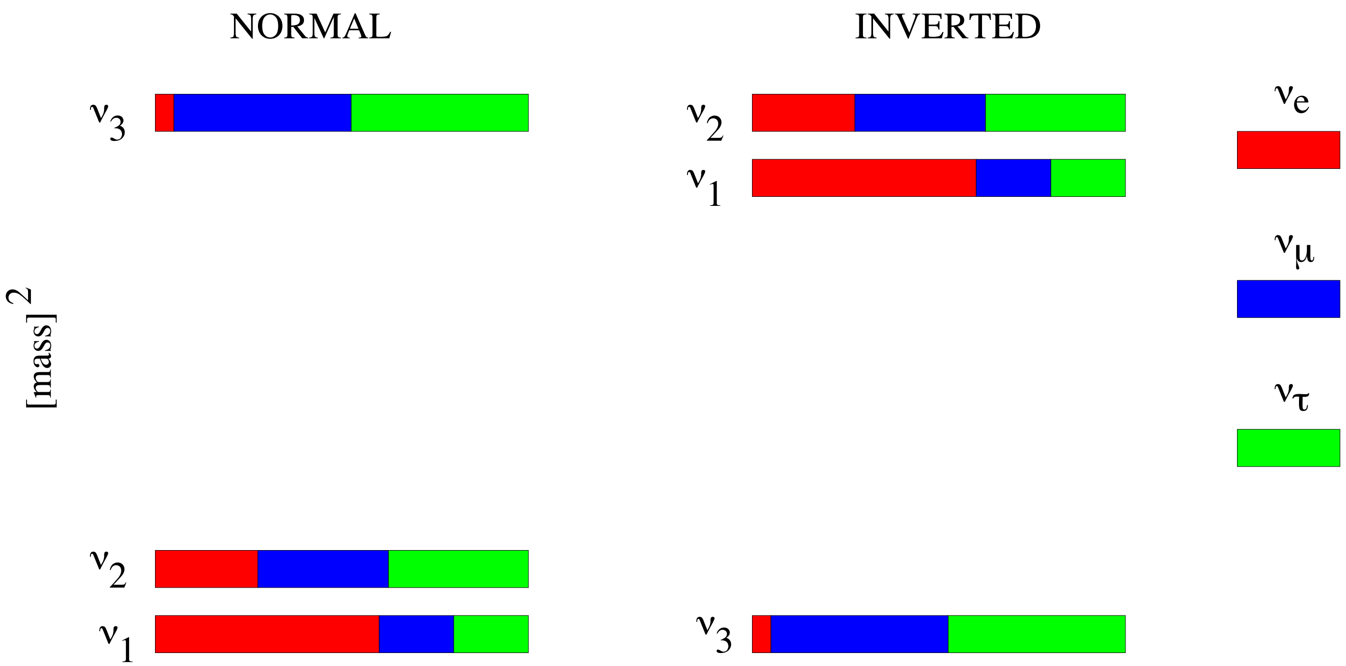
Petcov, Piai, hep-ph/0112074

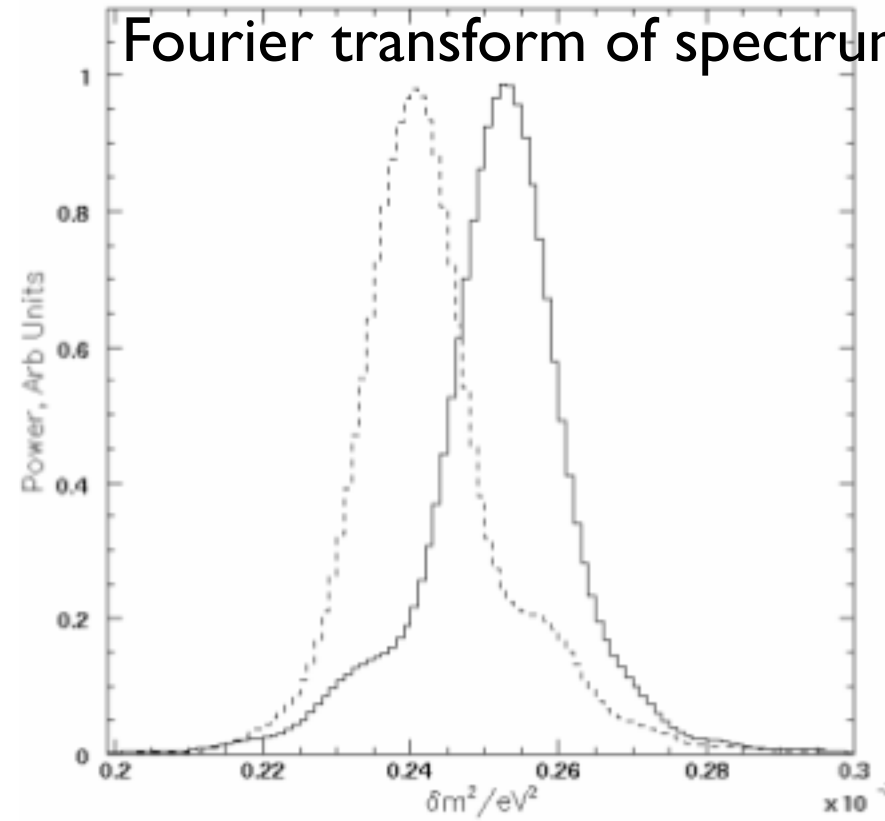
$\bar{\nu}_e$ disappearance at intermediate baseline (40~60 km)
interference term between solar and atmospheric oscillations



Ghoshal, Petcov, 1011.1646

Hierarchy 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 NH (IH) the larger (smaller) frequency dominates*

Hierarchy from a reactor experiment

$(\chi^2)^{min}_{stat}$	$\sin^2 2\theta_{13}^{\rm true} = 0.07$			$\sin^2 2\theta_{13}^{\rm true} = 0.1$		
Detector exposure, kT GW yr	Energy resolution					
	2%	3%	4%	2%	3%	4%
200	6.21	4.99	3.81	12.91	10.41	7.90
400	12.40	9.98	7.60	25.80	20.80	15.78
600	18.61	14.95	11.71	38.70	31.20	23.50

Ghoshal, Petcov, 1011.1646

- *energy resolution is crucial, and*
- *it has to be* **BIG** *(KamLAND: 1 kT, LENA: 50 kT)*

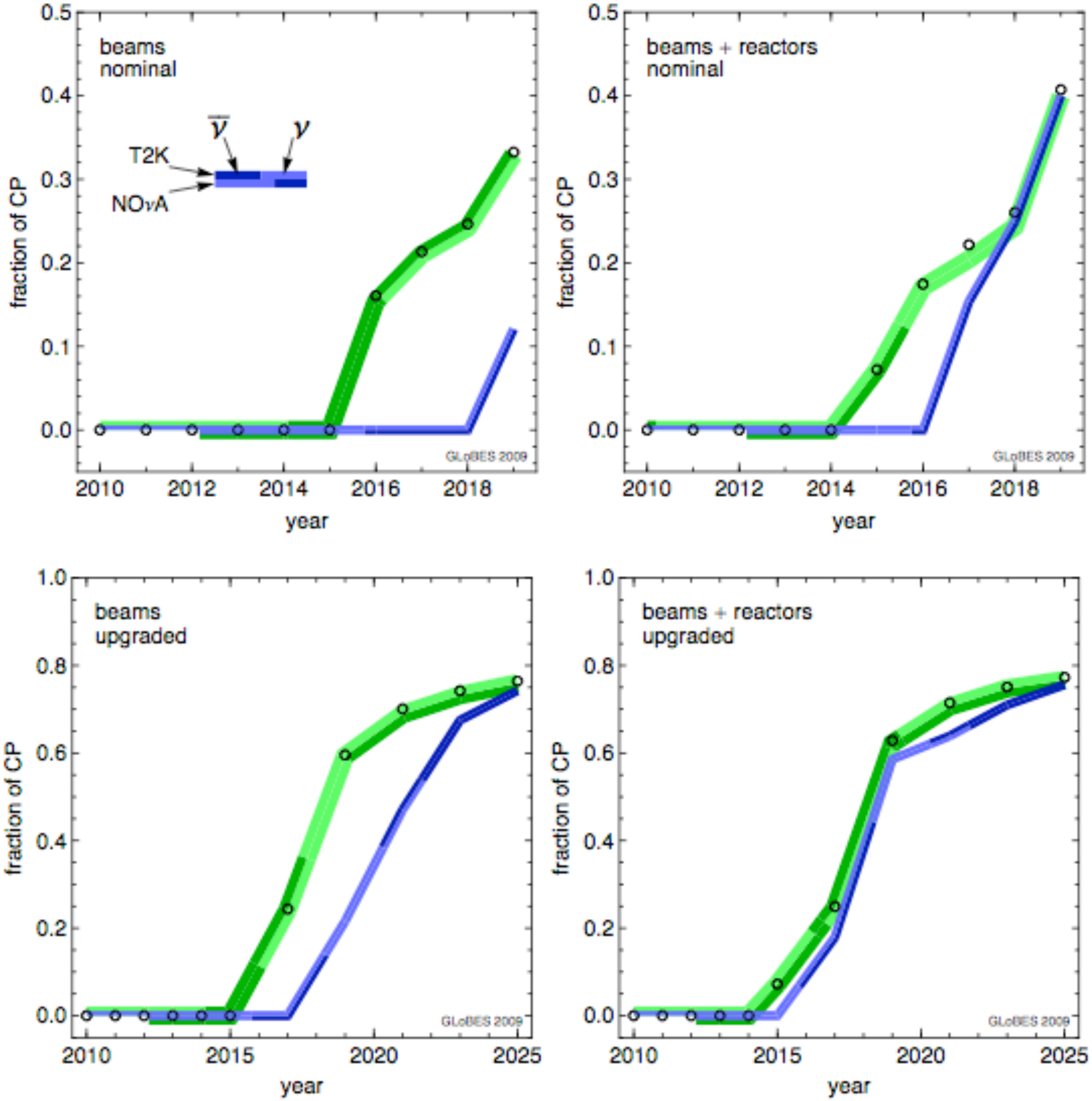
see talk by J. Cao

Conclusions

- *With a global fit of T2K+NOvA+reactor around 2020 it will be very hard to obtain information on MO and CPV (low significance hints - if lucky)*
- *also with beam power/detector upgrades it will be hard (but we could be lucky: CP-fraction around 30%)*
- *Adding atmospheric neutrino data from INO may help with MO (and indirectly for CPV)* ***BUT****: reconstruction abilities, schedule, and detector mass is crucial*
- *atmospheric data in PINGU is very promising for MO fast - reconstruction abilities to be studied*
- *MO from a reactor experiment at ~60 km: requires huge exposure (LENA-type) with good energy resolution*

Backup slides

T2K/NOvA neutrino/antineutrino optimization



Huber, Lindner, TS, Winter, 0907.1896

blue: nominal
green: optimized

INO - θ_{13} and θ_{23} dependence