Phenomenology of future neutrino oscillation measurements

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Neutrino Horizons in the 21st Century

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Outline

- Neutrino oscillation
- Experimental strategies
- Next steps
- Superbeams
- Neutrino factories & β-beams
- Summary & Outlook

Neutrino oscillations

The mass eigenstates are related to flavor eigenstates by U_ν, thus a neutrino which is produced as flavor eigenstate is a superposition of mass eigenstates. These mass eigenstates propagate with different velocity and a phase difference is generated. This phase difference gives rise to a finite transition probability

$$P_{\nu_\alpha \to \nu_\beta} = \sum_{ij} U_{\alpha j} U^*_{\beta j} U^*_{\alpha i} U_{\beta i} e^{-i\frac{\Delta m^2_{ij} L}{2E}} \sim \sin^2 2\theta \sin^2 \frac{\Delta m^2_{ij} L}{4E}$$

Neutrino oscillation is a quantum mechanical interference phenomenon and therefore it is uniquely sensitive to extremely tiny effects.

Neutrino oscillations – CP viol.

Like in the quark sector mixing can cause CP violation

$$P(\nu_\alpha \rightarrow \nu_\beta) - P(\bar{\nu}_\alpha \rightarrow \bar{\nu}_\beta) \neq 0$$

The size of this effect is proportional to

$$J_{CP} = \frac{1}{8} \cos \theta_{13} \sin 2\theta_{13} \sin 2\theta_{23} \sin 2\theta_{12} \sin \delta$$

The experimentally most suitable transition to study CP violation is $\nu_e \leftrightarrow \nu_\mu$, which is only available in beam experiments.

Neutrino oscillation – matter

The charged current interaction of ν_e with the electrons creates a potential for ν_e

$$A = \pm 2\sqrt{2} G_F \cdot E \cdot n_e$$

where $+$ is for ν and $-$ for $\bar{\nu}$.
This potential gives rise to an additional phase for ν_e and thus changes the oscillation probability. This has two consequences

$$P(\nu_\alpha \rightarrow \nu_\beta) - P(\bar{\nu}_\alpha \rightarrow \bar{\nu}_\beta) \neq 0$$

even if $\delta = 0$, since the potential distinguishes neutrinos from anti-neutrinos.

Neutrino oscillation – matter

The second consequence of the matter potential is that there can be a resonant conversion – the MSW effect. The condition for the resonance is

$$\Delta m^2 \simeq A$$

Obviously the occurrence of this resonance depends on the signs of both sides in this equation. Thus oscillation becomes sensitive to the mass ordering

	ν	$\bar{\nu}$
$\Delta m^2 > 0$	MSW	-
$\Delta m^2 < 0$	-	MSW

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

Two-neutrino limit $- \Delta m_{21}^2 = 0$

$$\approx \quad \sin^2 2\theta_{13} \qquad \sin^2 \theta_{23} \qquad \frac{\sin^2((\hat{A}-1)\Delta)}{(\hat{A}-1)^2}$$

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

Three flavors $- \Delta m^2_{21} \neq 0$

$$\approx \quad \sin^2 2\theta_{13} \qquad \sin^2 \theta_{23} \qquad\qquad \frac{\sin^2((\hat{A}-1)\Delta)}{(\hat{A}-1)^2}$$

$$\pm \quad \alpha \sin 2\theta_{13} \quad \sin \delta \sin 2\theta_{12} \sin 2\theta_{23} \quad \frac{\sin(\Delta) \sin(\hat{A}\Delta) \sin((1-\hat{A})\Delta)}{\hat{A}(1-\hat{A})}$$

$$+ \quad \alpha \sin 2\theta_{13} \quad \cos \delta \sin 2\theta_{12} \sin 2\theta_{23} \quad \frac{\cos(\Delta) \sin(\hat{A}\Delta) \sin((1-\hat{A})\Delta)}{\hat{A}(1-\hat{A})}$$

$$+ \quad \alpha^2 \qquad \cos^2 \theta_{23} \sin^2 2\theta_{12} \qquad \frac{\sin^2(\hat{A}\Delta)}{\hat{A}^2}$$

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

Small quantities $-\alpha := \Delta m_{21}^2 / \Delta m_{31}^2$ and $\sin 2\theta_{13}$

$$\approx \quad \sin^2 2\theta_{13} \qquad \sin^2 \theta_{23} \qquad \frac{\sin^2((\hat{A}-1)\Delta)}{(\hat{A}-1)^2}$$

$$\pm \quad \alpha \sin 2\theta_{13} \quad \sin \delta \sin 2\theta_{12} \sin 2\theta_{23} \quad \frac{\sin(\Delta) \sin(\hat{A}\Delta) \sin((1-\hat{A})\Delta)}{\hat{A}(1-\hat{A})}$$

$$+ \quad \alpha \sin 2\theta_{13} \quad \cos \delta \sin 2\theta_{12} \sin 2\theta_{23} \quad \frac{\cos(\Delta) \sin(\hat{A}\Delta) \sin((1-\hat{A})\Delta)}{\hat{A}(1-\hat{A})}$$

$$+ \quad \alpha^2 \qquad \cos^2 \theta_{23} \sin^2 2\theta_{12} \qquad \frac{\sin^2(\hat{A}\Delta)}{\hat{A}^2}$$

Eight-fold degeneracy

- intrinsic ambiguity for fixed α

- Disappearance determines only $|\Delta m_{31}^2| \Rightarrow$
$\mathcal{T}_s := \Delta m_{31}^2 \rightarrow -\Delta m_{31}^2$

- Disappearance determines only $\sin^2 2\theta_{23} \Rightarrow$
$\mathcal{T}_t := \theta_{23} \rightarrow \pi/2 - \theta_{23}$

- Both transformations $\mathcal{T}_{st} := \mathcal{T}_s \oplus \mathcal{T}_t$

Consequences for experiments

- need to measure 2 out of $P(\nu_\mu \to \nu_e)$, $P(\bar{\nu}_\mu \to \bar{\nu}_e)$, $P(\nu_e \to \nu_\mu)$ and $P(\bar{\nu}_e \to \bar{\nu}_e)$

- need more than 1 energy and 1 baseline

- matter resonance at $\sim 10\,\mathrm{GeV}$

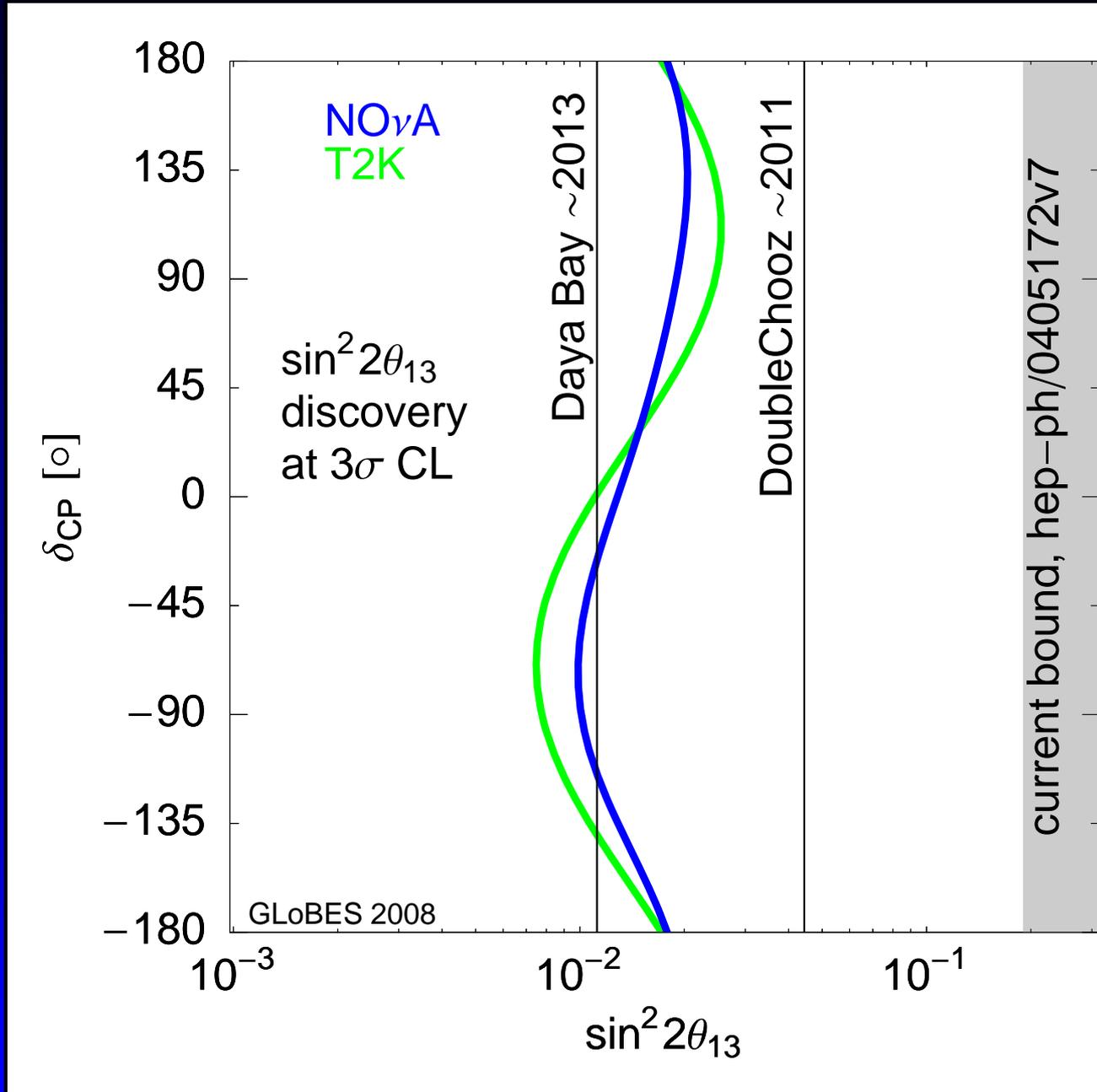- matter effects sizable for $L > 1\,000\,\mathrm{km}$
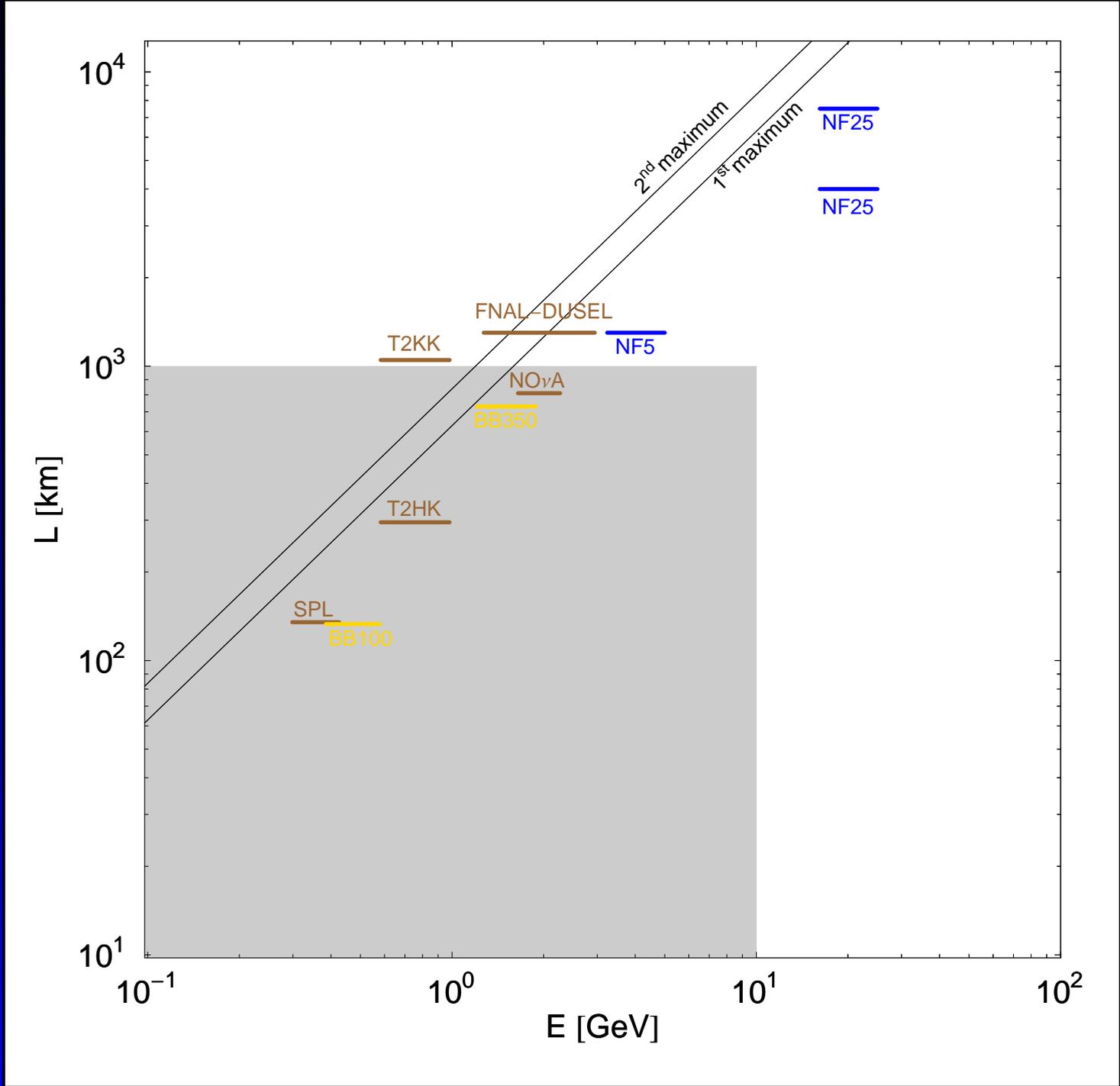
Next steps

Reactor experiments

- DoubleChooz – start data taking 2008/2009

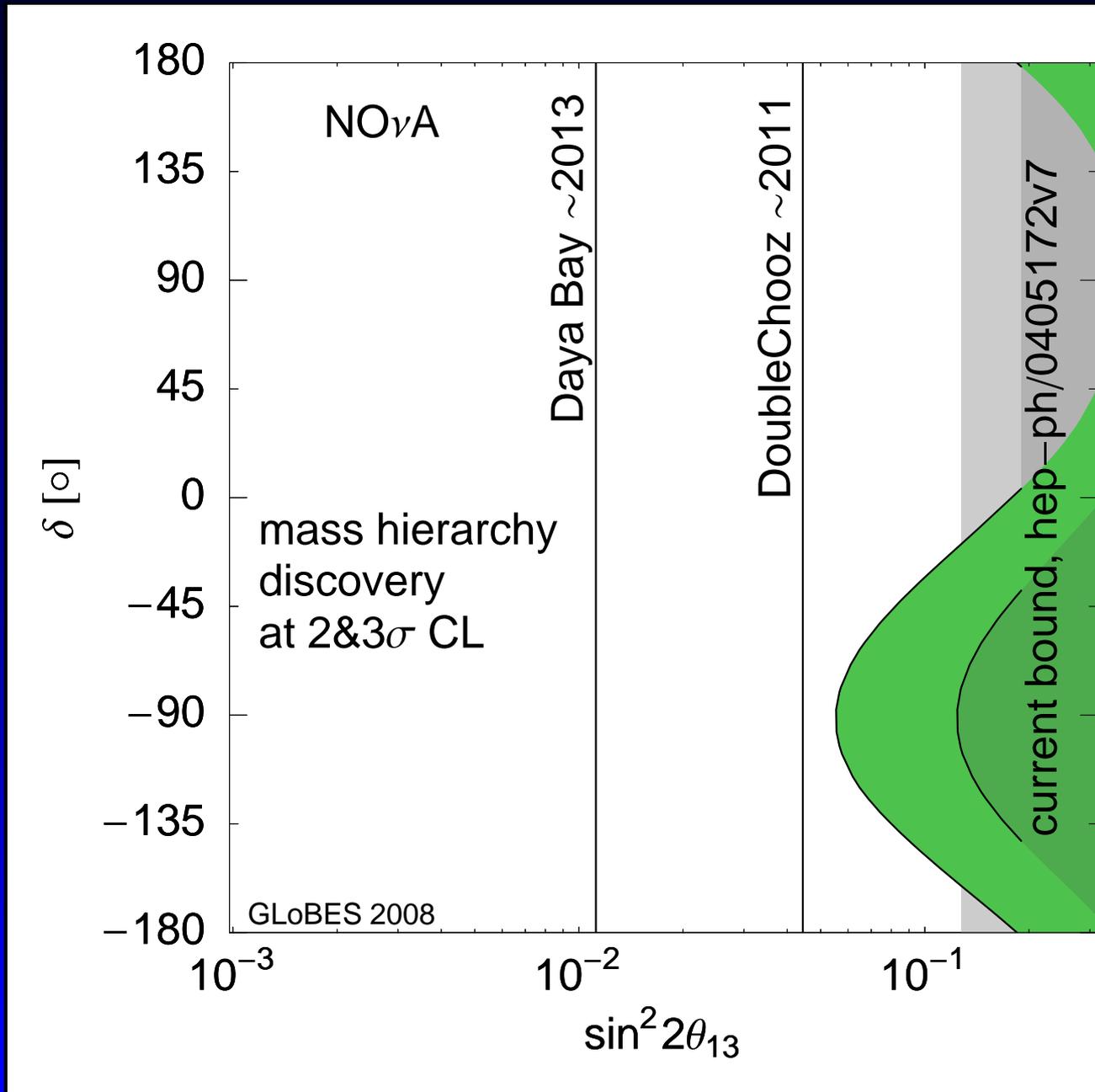- Daya Bay – start data taking middle 2010

- Reno – not approved yet

Long baseline experiments

- T2K – start data taking mid 2009

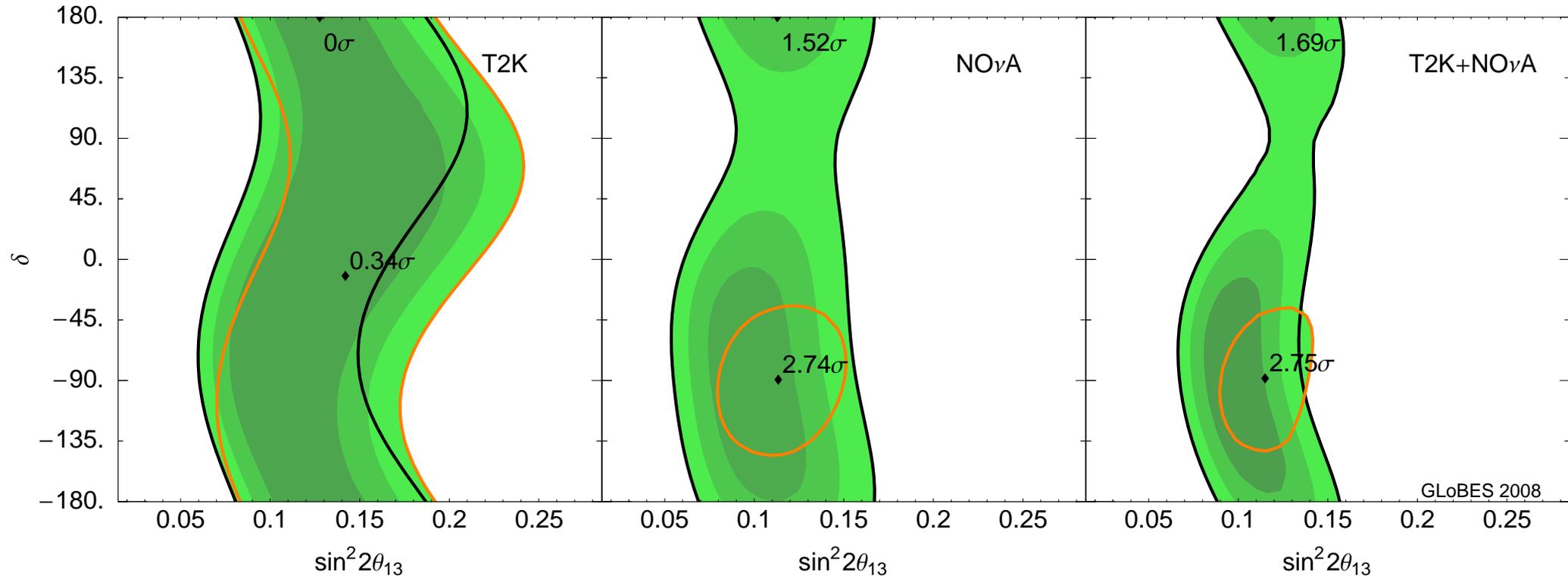- NOνA – start data taking 2010 (US budget woes moved that to 2011)

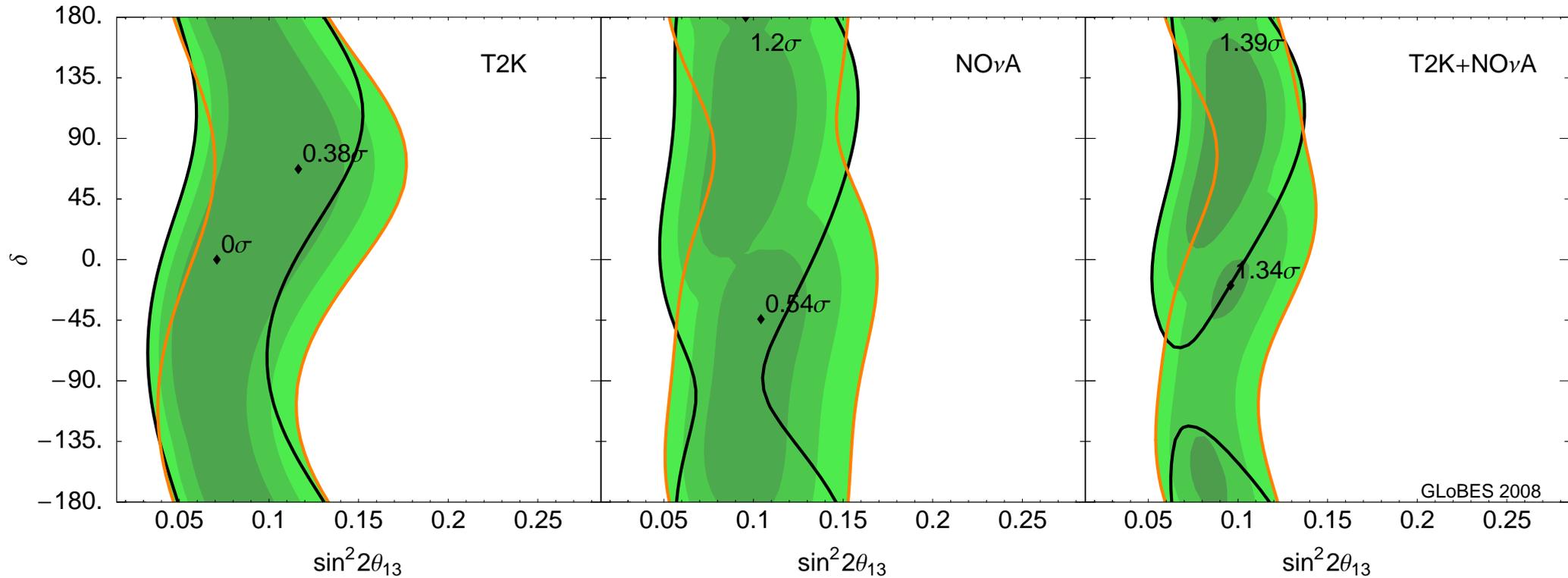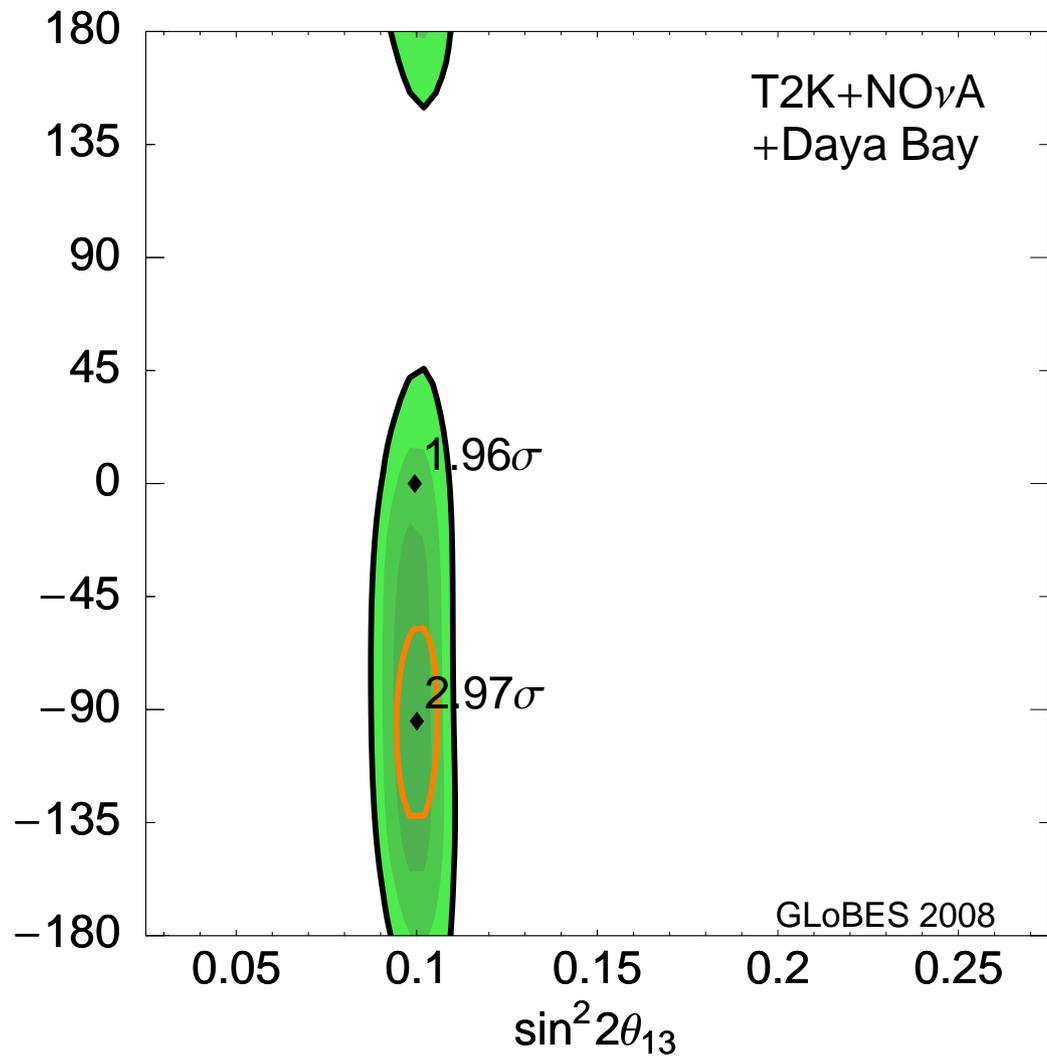# $\sin^2 2\theta_{13}$ **reach**

Mass hierarchy

CP violation

- input values $\sin^2 2\theta_{13} = 0.1$ and $\delta = -90°$
- at most a $1.7\,\sigma$ hint for CPV
- no value of δ excluded at $3\,\sigma$
- this is already the best case

CP violation

- input values $\sin^2 2\theta_{13} = 0.1$ and $\delta = +90°$
- even at $2\,\sigma$ CL no value of δ excluded

Reactors help

T2K+NOνA
+Daya Bay

1.96σ

2.97σ

GLoBES 2008

δ

$\sin^2 2\theta_{13}$

2016

- input values $\sin^2 2\theta_{13} = 0.1$ and $\delta = -90°$

- about $130°$ of δ excluded at $3\,\sigma$, 36% of parameter space
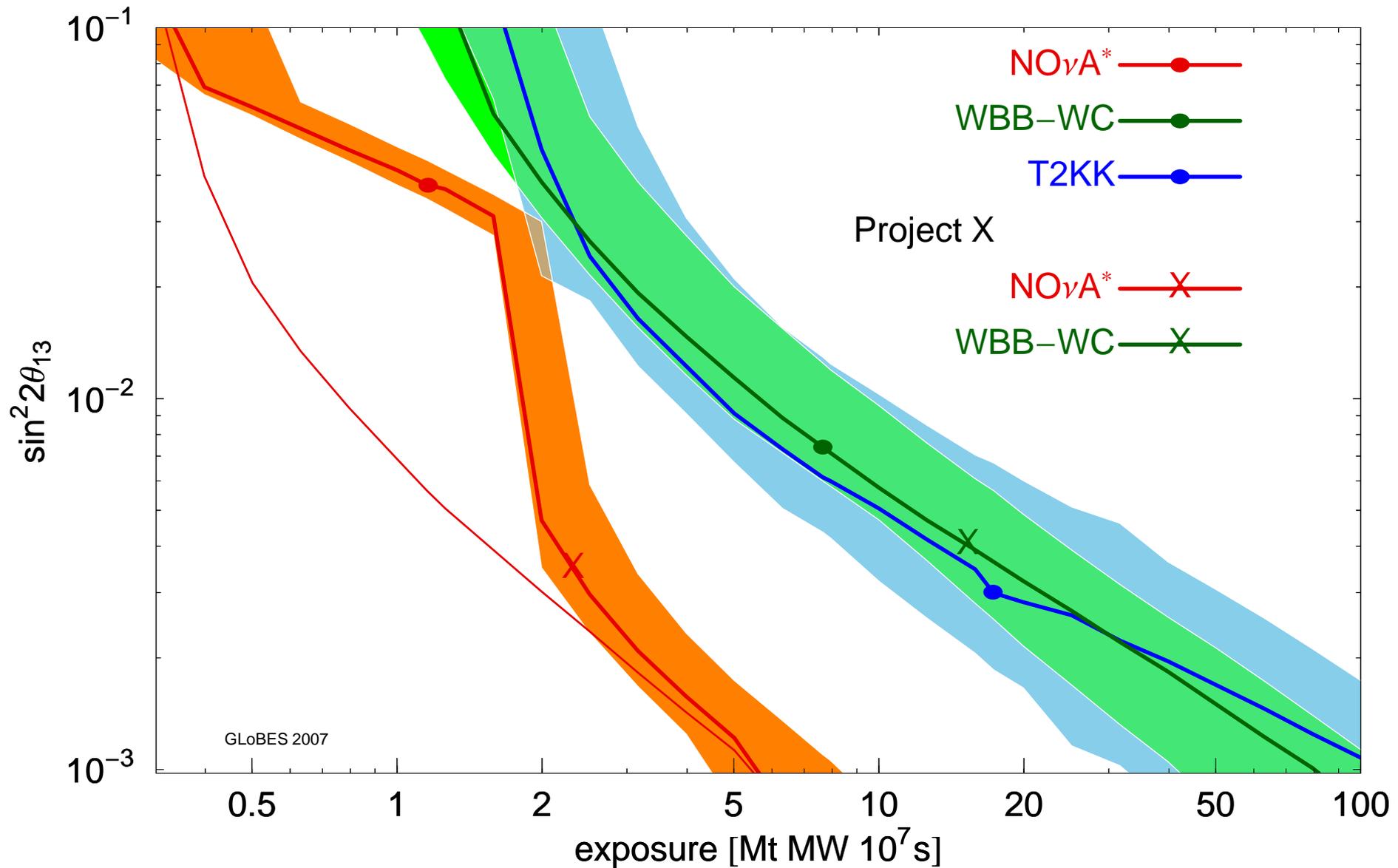
Exposure

Everyone has different assumptions about

- seconds in a year

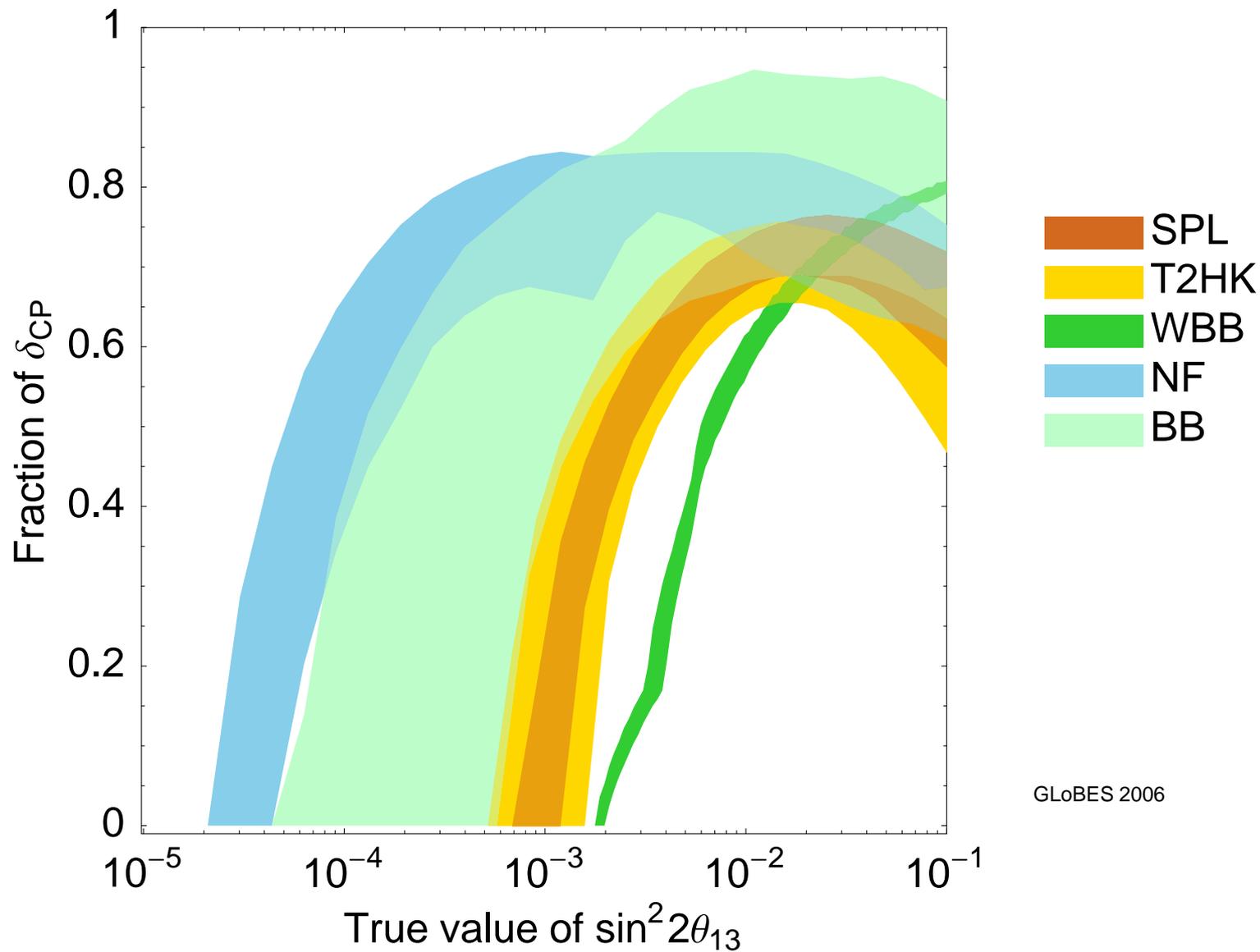- number of years

- detector size

- beam power (or pot)

Therefore we introduce the concept of exposure

$$\text{detector mass}\,[\text{Mt}] \times \text{target power}\,[\text{MW}] \times \text{running time}\,[10^7\,\text{s}]\,.$$

CP violation

ISS results in a nutshell

GLoBES 2006

IDS-NF baseline
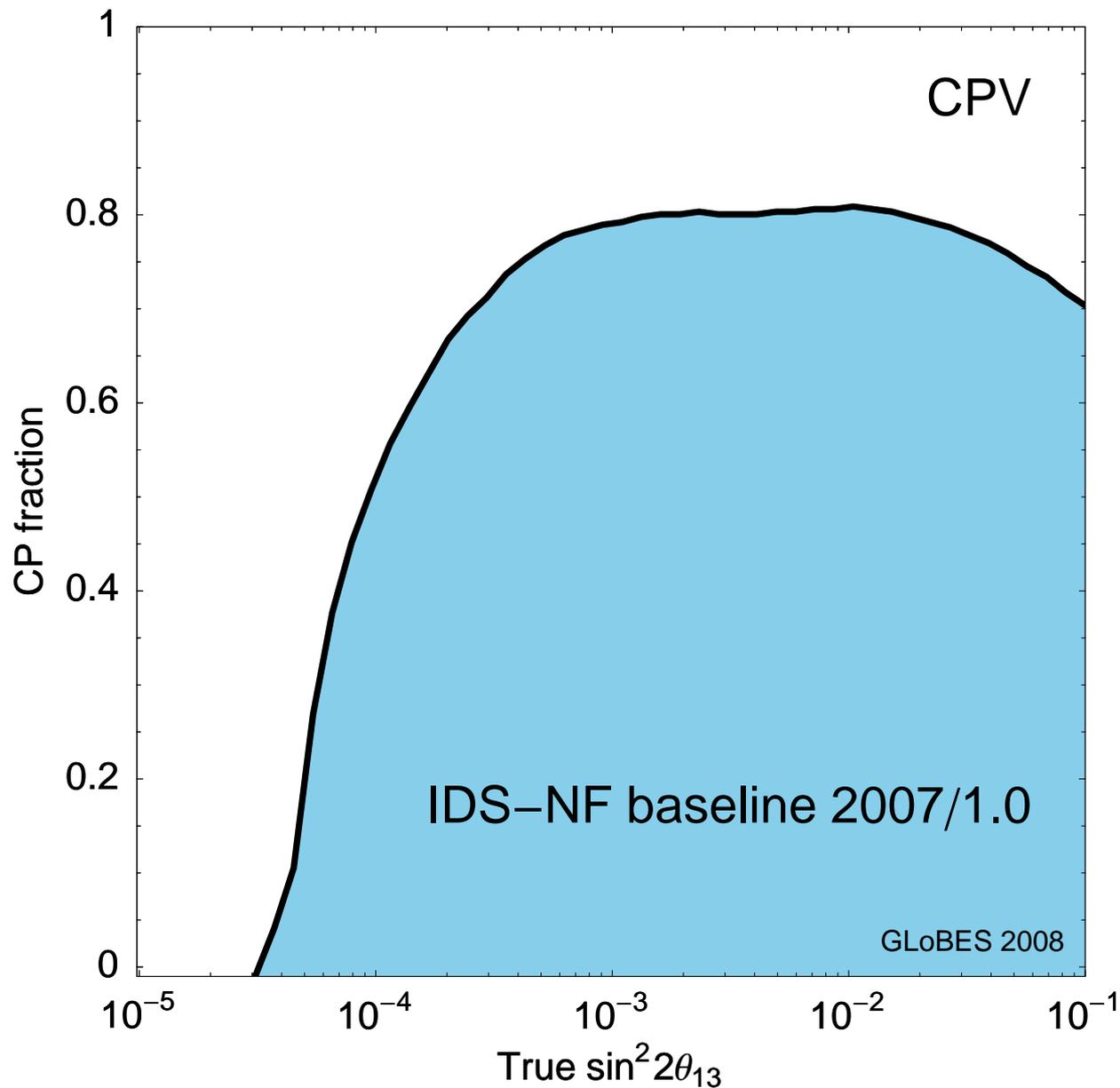
- $E_\mu = 25\,\mathrm{GeV}$
- 10^{21} useful muon decays per year
- 2 baselines: 4000 and 7500 km
- 2 mag. iron detector with $m_f = 50\,\mathrm{kt}$
- $10\,\mathrm{kt}$ OPERA-like detector at 4000km

Summary

Next steps

- $\sin^2 2\theta_{13}$ down to 0.045 by 2011 (Double Chooz)

- $\sin^2 2\theta_{13}$ down to 0.01 by 2013 (Daya Bay)

- T2K and NOνA have similar performances

- NOνA has a slim chance to test the mass hierarchy, if Double Chooz sees a signal within its first 6 month.

- In the best case a $\sim 3\,\sigma$ signal for CPV by combining all data by 2016

Outlook

Superbeams

- Exposure is the key factor – money and physics
- Detector technology plays a big role
- Off vs On-axis decision requires careful analysis
- Short distances ($< 500\,\mathrm{km}$) are disfavored
- Every strategy requires MW beams, 0.1 Mt detectors, 10 years of running

Neutrino factories and β-beams require considerable R&D and may be very difficult to justify if $\sin^2 2\theta_{13}$ is large.