Future options for neutrino oscillations

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Outline

- Neutrino oscillation
- Need for new facilities
- Superbeam
- Beta beam
- Neutrino factory
- Summary

What we want to learn

In the context of long baseline neutrino experiments

- $\sin^2 2\theta_{13}$
- δ_{CP}
- mass hierarchy
- $\theta_{23} = \pi/4$, $\theta_{23} < \pi/4$ or $\theta_{23} > \pi/4$?

It is very difficult to rank those measurements in their relative importance, with exception of $\sin^2 2\theta_{13}$ since its size has practical implications beyond theory.

Given the current state of the theory of neutrinos we can not say with confidence that any one quantity is more fundamental than any other.

CP violation

Like in the quark sector mixing can cause CP violation

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

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.

Matter effects

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

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

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

Matter effects

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

$$\Delta m^2 \simeq A \quad \Leftrightarrow \quad E_{\rm res}^{\rm Earth} = 6 - 8\,\mathrm{GeV}$$

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

$P_{\mu e}$

Two-neutrino limit – $\Delta m^2_{21} = 0$

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

$P_{\mu e}$

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

$$\begin{aligned}
&\approx \quad \sin^2 2\theta_{13} \quad \sin^2\theta_{23} \quad \frac{\sin^2((\hat{A}-1)\Delta)}{(\hat{A}-1)^2}\\
&\pm \quad \alpha \sin 2\theta_{13} \quad \sin\delta \sin 2\theta_{12} \sin 2\theta_{23} \quad \frac{\sin(\Delta)\sin(\hat{A}\Delta)\sin((1-\hat{A})\Delta)}{\hat{A}(1-\hat{A})}\\
&+ \quad \alpha \sin 2\theta_{13} \quad \cos\delta \sin 2\theta_{12} \sin 2\theta_{23} \quad \frac{\cos(\Delta)\sin(\hat{A}\Delta)\sin((1-\hat{A})\Delta)}{\hat{A}(1-\hat{A})}\\
&+ \quad \alpha^2 \quad \cos^2\theta_{23} \sin^2 2\theta_{12} \quad \frac{\sin^2(\hat{A}\Delta)}{\hat{A}^2}
\end{aligned}$$

$P_{\mu e}$

Small quantities – $\alpha := \Delta m^2_{21}/\Delta m^2_{31}$ and $\sin 2\theta_{13}$

$$
\begin{array}{llll}
\approx & \sin^2 2\theta_{13} & \sin^2\theta_{23} & \dfrac{\sin^2((\hat{A}-1)\Delta)}{(\hat{A}-1)^2} \\
\pm & \alpha \sin 2\theta_{13} & \sin\delta \sin 2\theta_{12} \sin 2\theta_{23} & \dfrac{\sin(\Delta)\sin(\hat{A}\Delta)\sin((1-\hat{A})\Delta)}{\hat{A}(1-\hat{A})} \\
+ & \alpha \sin 2\theta_{13} & \cos\delta \sin 2\theta_{12} \sin 2\theta_{23} & \dfrac{\cos(\Delta)\sin(\hat{A}\Delta)\sin((1-\hat{A})\Delta)}{\hat{A}(1-\hat{A})} \\
+ & \alpha^2 & \cos^2\theta_{23}\sin^2 2\theta_{12} & \dfrac{\sin^2(\hat{A}\Delta)}{\hat{A}^2}
\end{array}
$$

Eight-fold degeneracy

By measuring only two numbers n_ν and $n_{\bar{\nu}}$, the following solutions remain

- intrinsic ambiguity for fixed α
- Disappearance determines only $|\Delta m^2_{31}| \Rightarrow$ $\mathcal{T}_s := \Delta m^2_{31} \longrightarrow -\Delta m^2_{31}$
- Disappearance determines only $\sin^2 2\theta_{23} \Rightarrow$ $\mathcal{T}_t := \theta_{23} \longrightarrow \pi/2 - \theta_{23}$
- Both transformations $\mathcal{T}_{st} := \mathcal{T}_s \oplus \mathcal{T}_t$

For studies of CP violation the sign ambiguity $\mathcal{T}_s$ poses the most severe problems.

Magic baseline

$$\sin \hat{A}\Delta = 0 \Leftrightarrow \sqrt{2} G_f n_e L = 2\pi$$

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

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

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

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

Magic baseline

For $L \simeq 7\,500\,\mathrm{km}$, we have $\sin \hat{A}\Delta = 0$

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

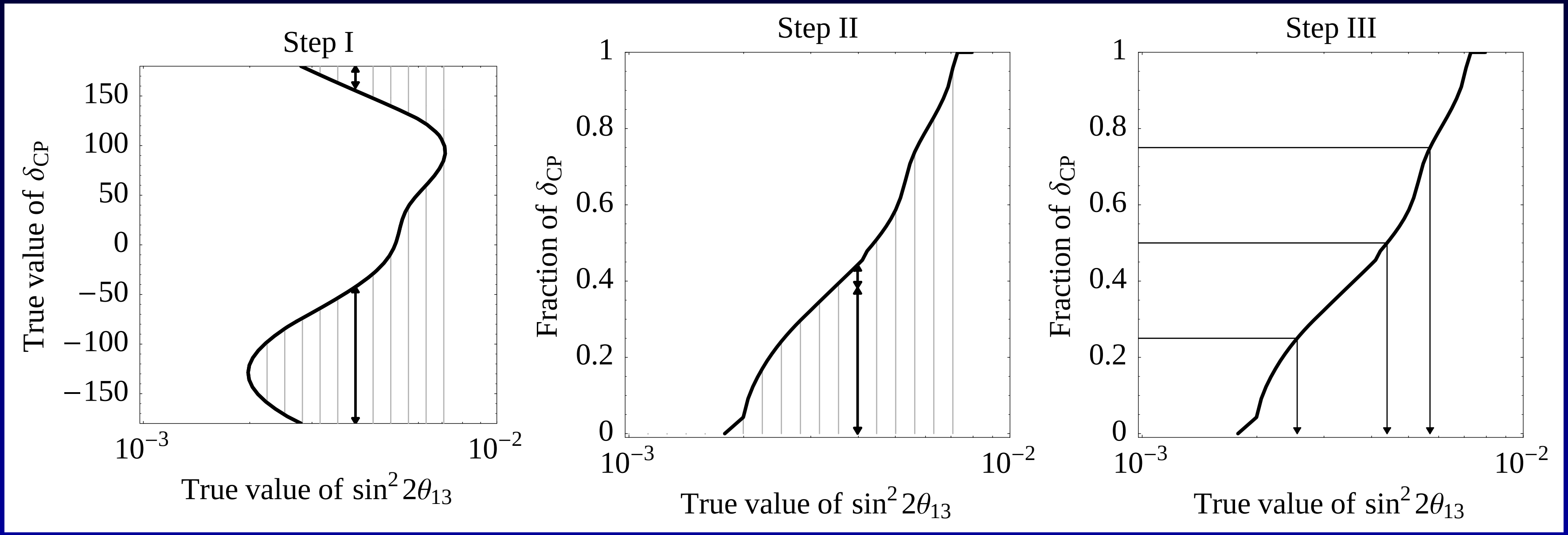
Magic baseline restores effective two-flavor oscillation, while maintaining full sensitivity to mass hierarchy.

At the same time the 1st oscillation maximum of Δm^2_{31} is close to the MSW resonance energy $\rightarrow$ large enhancement of $P_{\mu e}$

Consequences for experiments

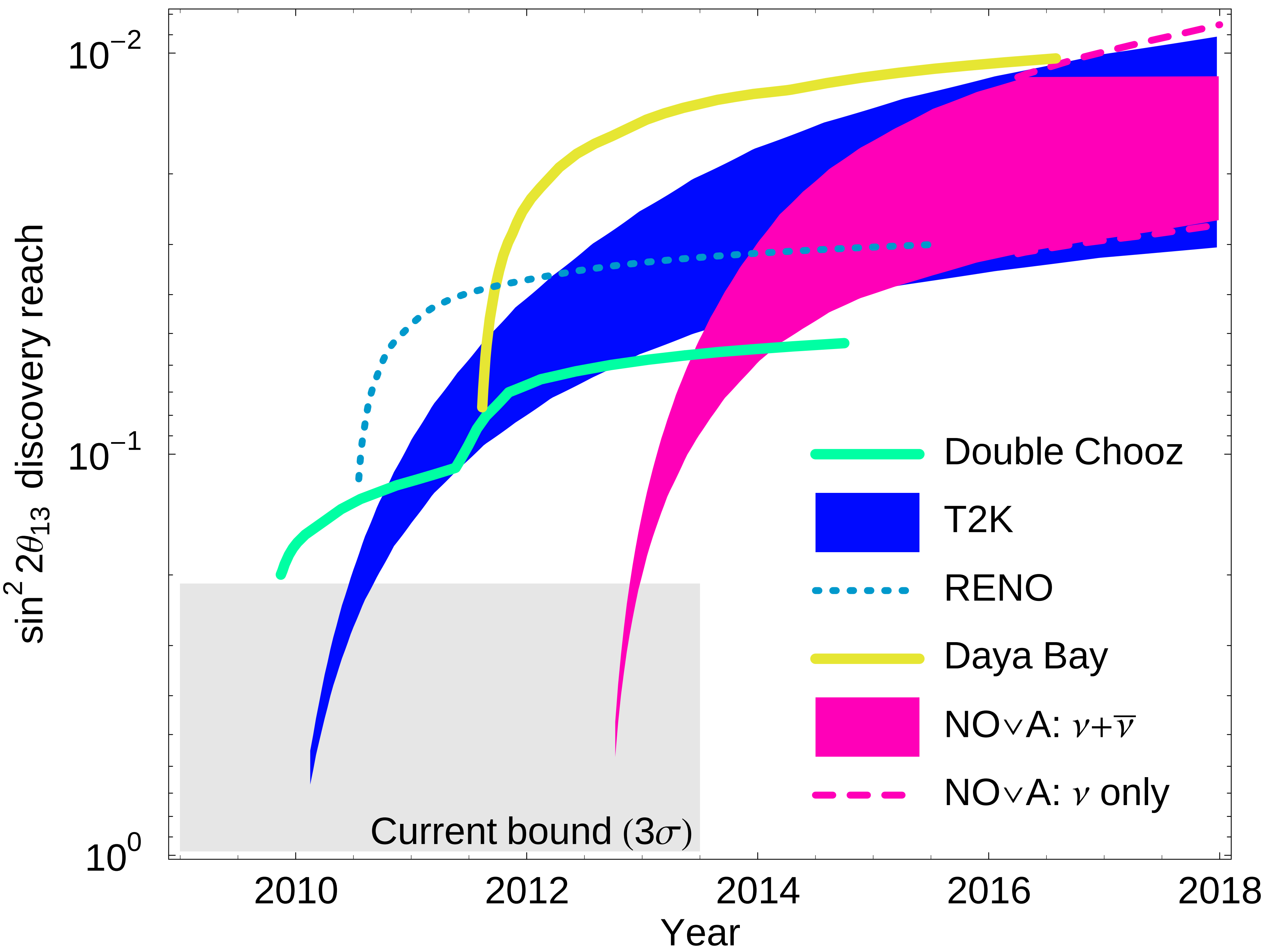
- need to measure 2 out of $P(\nu_\mu \to \nu_e)$, $P(\bar{\nu}_\mu \to \bar{\nu}_e)$, $P(\nu_e \to \nu_\mu)$ and $P(\bar{\nu}_e \to \bar{\nu}_\mu)$
- need more than 1 energy and 1 baseline
- matter resonance at $6 - 8\,\mathrm{GeV}$
- matter effects sizable for $L > 1\,000\,\mathrm{km}$
- magic baseline allows for a clean measurement of the mass hierarchy

CP fraction



- reduces 2D plot to 3 points
- allows unbiased comparison
- allows risk assessment
- CPF = 1, worst case – guaranteed sensitivity
- CPF =0, best case

$\sin^2 2\theta_{13}$ discovery potential (NH, 3σ CL)

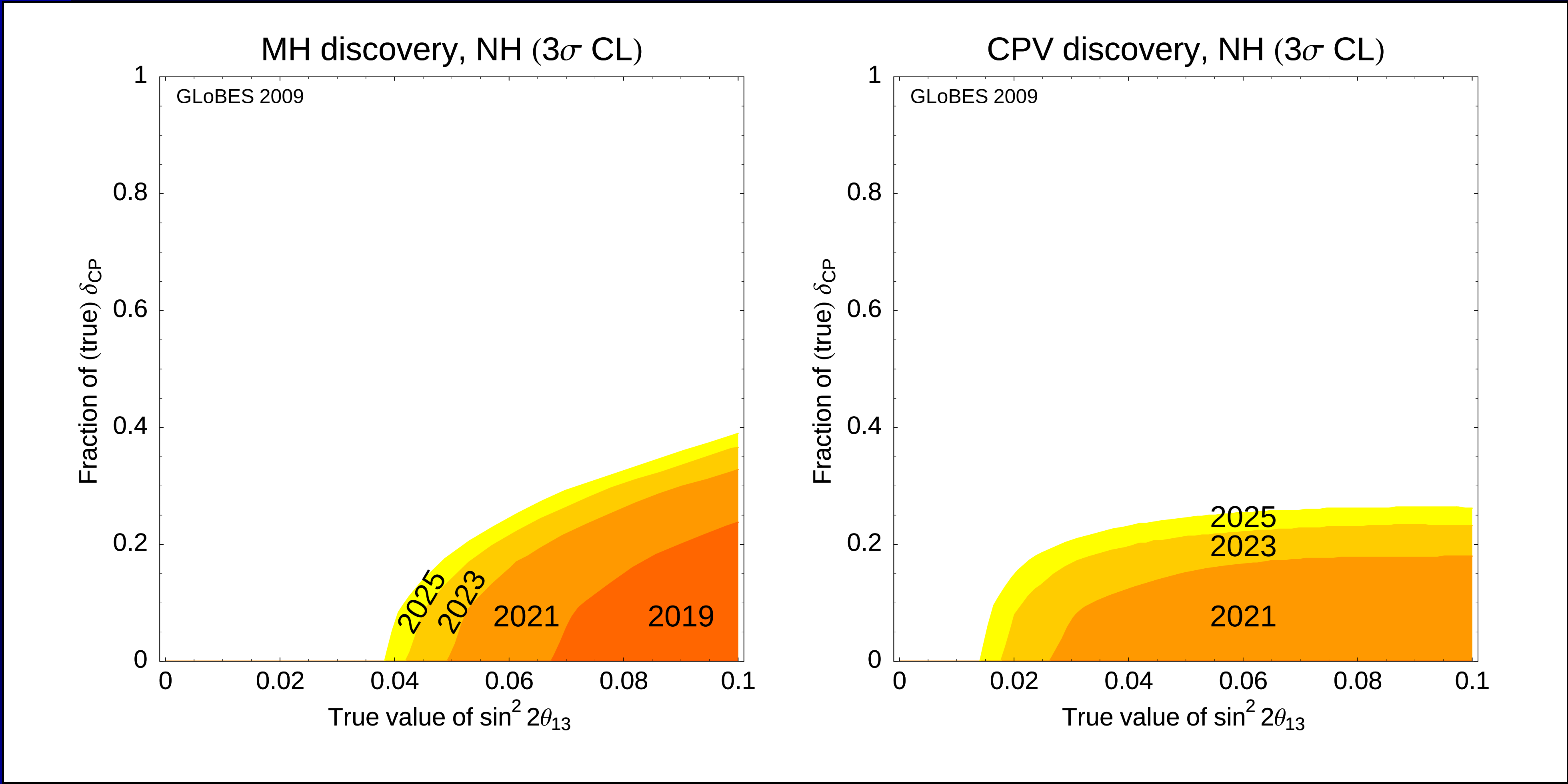


PH, M. Lindner, T. Schwetz, W. Winter, arXiv:0907.1896.

Beam upgrades

- T2K: 2015 - 2016: 0.75 MW - 1.66 MW linear
  Talk by K. Hasegawa, NNN 2008
- NOvA: 03/2018-03/2019: 0.7 MW - 2.33 MW linear, Project X Project X: resource loaded schedule

Optimal sensitivities



PH, M. Lindner, T. Schwetz, W. Winter, arXiv:0907.1896.

2025

Knowledge in 2025 without new facilities at $3\,\sigma$ CL

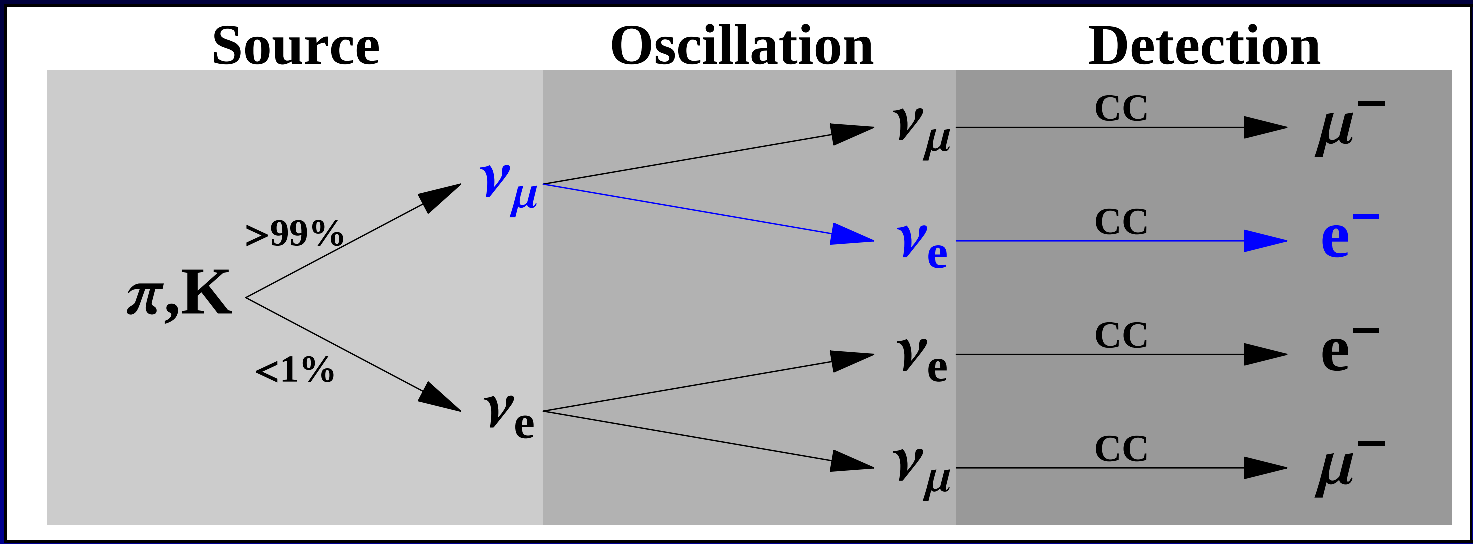
- $\theta_{23} = \pi/4$ – for maximal mixing $45^\circ \pm 4^\circ$
- size of θ_{13} – if $\sin^2 2\theta_{13} > 0.01$
- mass hierarchy – if $\sin^2 2\theta_{13} > 0.04$ for at most 30% of all CP phases
- CP violation in leptons – if $\sin^2 2\theta_{13} > 0.02$ for at most 20% of all CP phases

Even for the largest currently allowed θ_{13} more than 70% of parameter space are not accessible.

Superbeams

Superbeams

Neutrino beam from π-decay



They are called 'super'

- beam power $\sim 1\,\mathrm{MW}$
- detectors mass $\sim 100\,\mathrm{kt}$
- running time of the experiment $\sim$ 10 years
- price

Setups

- T2KK – beam from JAERI, $P = 4\,\mathrm{MW}$, two water Cherenkov detectors at $L = 295\,\mathrm{km}$ and $L = 1050\,\mathrm{km}$ with a fiducial mass of $270\,\mathrm{kt}$, off-axis
- WBB-WC – beam from FNAL, $P = 1.1\,\mathrm{MW}$, one water Cherenkov detector at $L = 1300\,\mathrm{km}$ with a fiducial mass of $300\,\mathrm{kt}$, on-axis
- WBB-LAr – same as WBB-WC, but with $100\,\mathrm{kt}$ liquid Argon instead

Note, WBB-XXX with lower luminosity (20kt/100kt @ 0.7MW) is now called Long Baseline Neutrino Experiment (LBNE).

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

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

CP violation

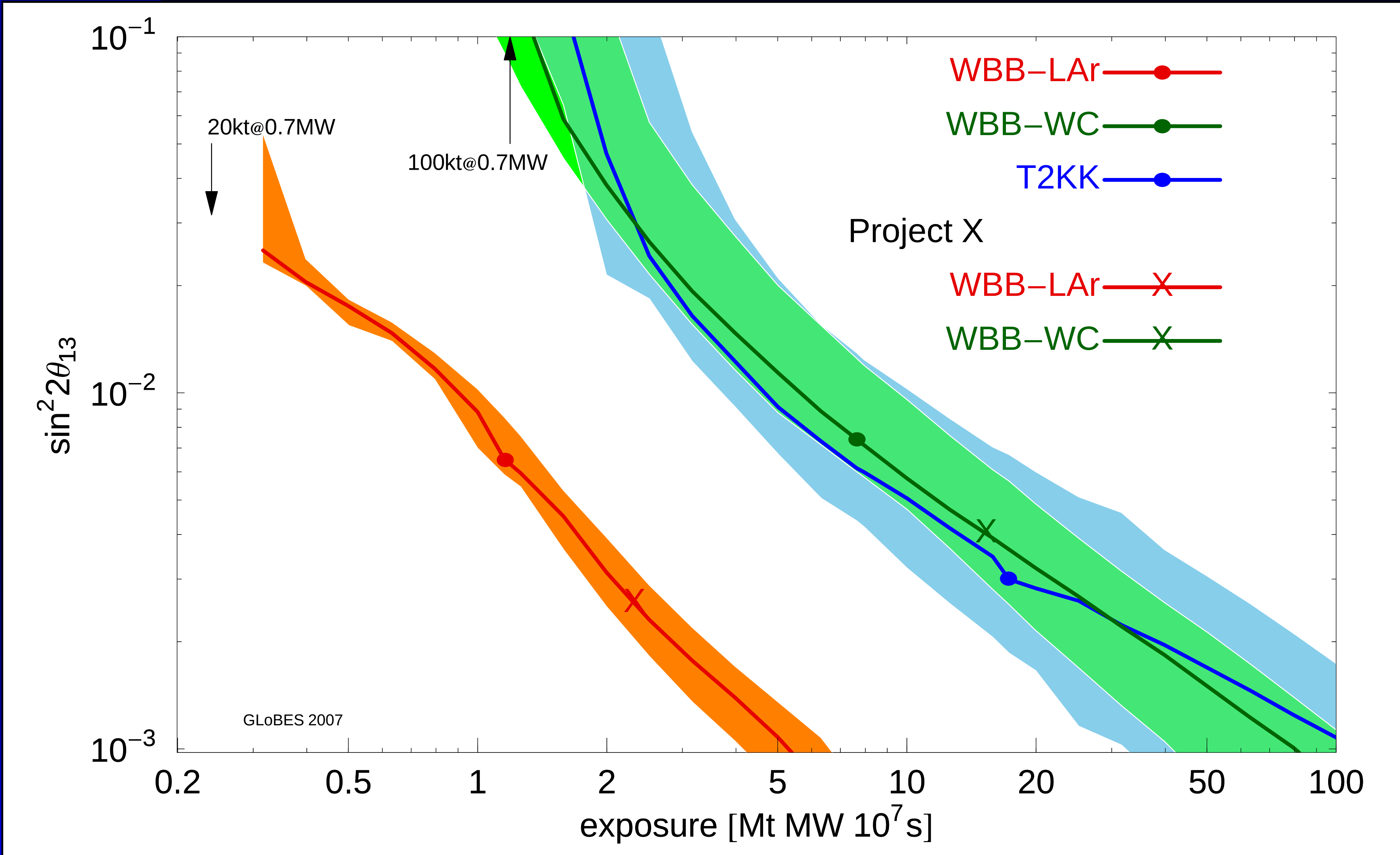


figure adapted from Barger, PH, Marfatia, Winter, Phys.Rev. D76 (2007) 053005

Mass hierarchy

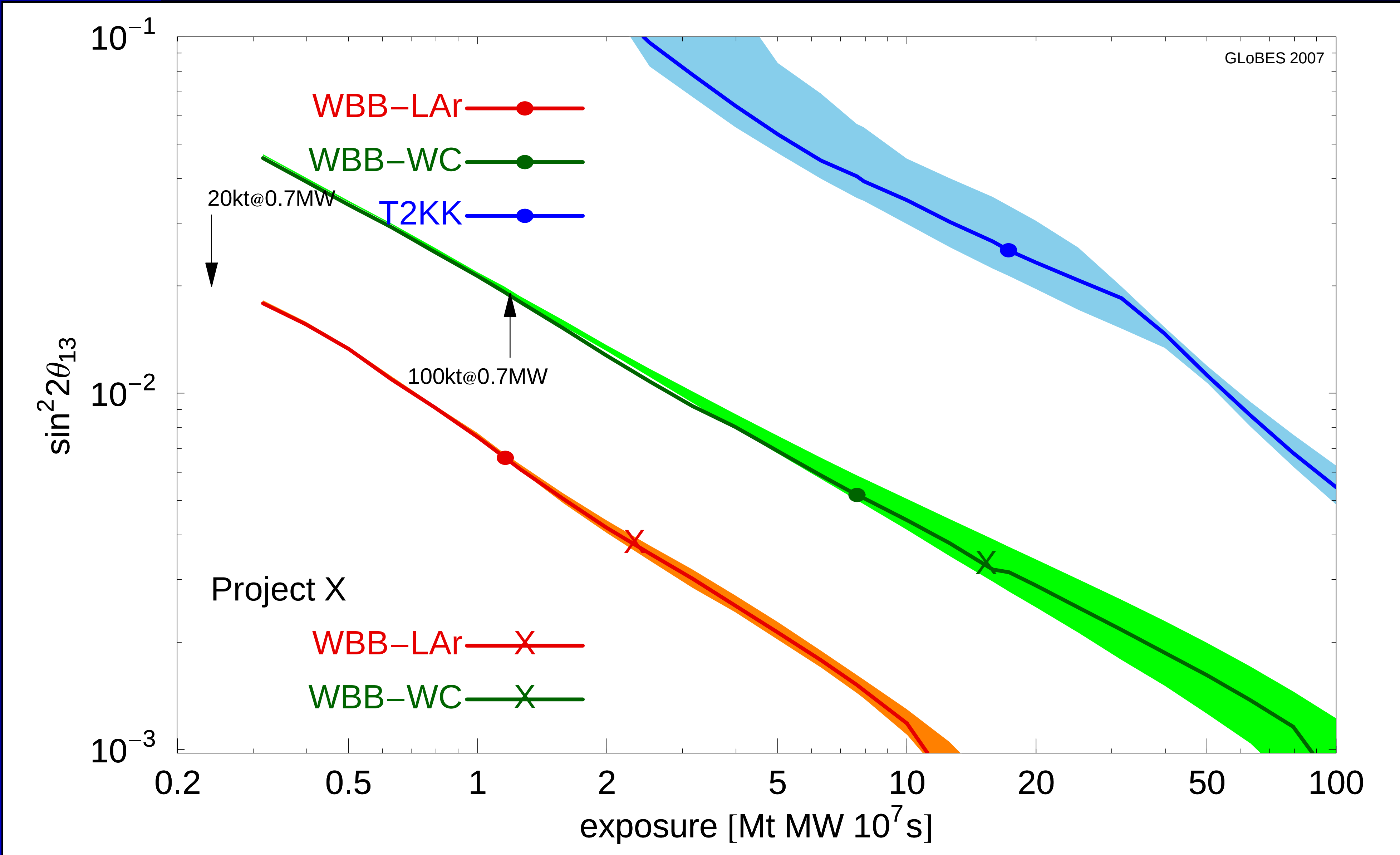
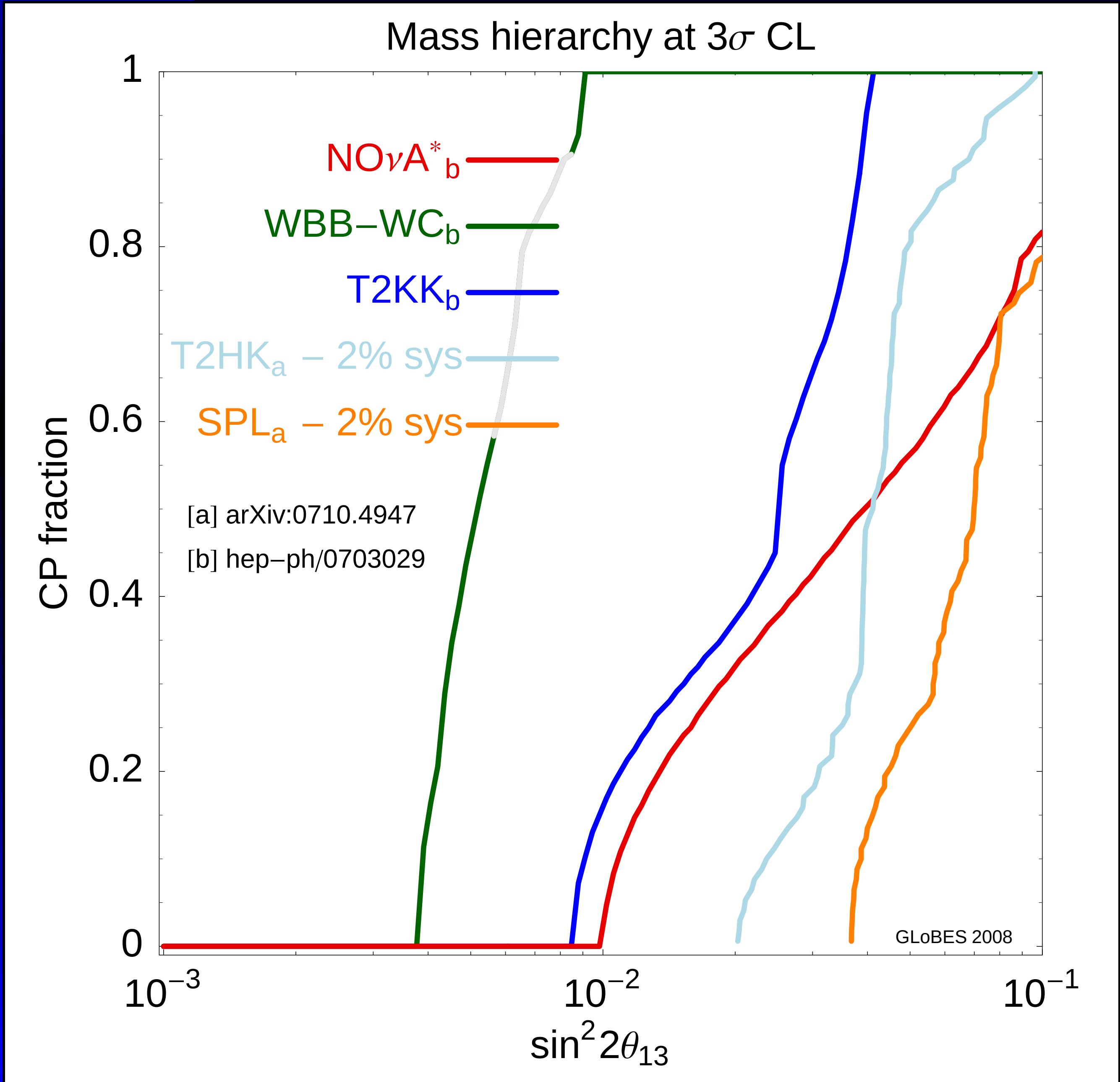


figure adapted from Barger, PH, Marfatia, Winter, Phys.Rev. D76 (2007) 053005

Alternatives?

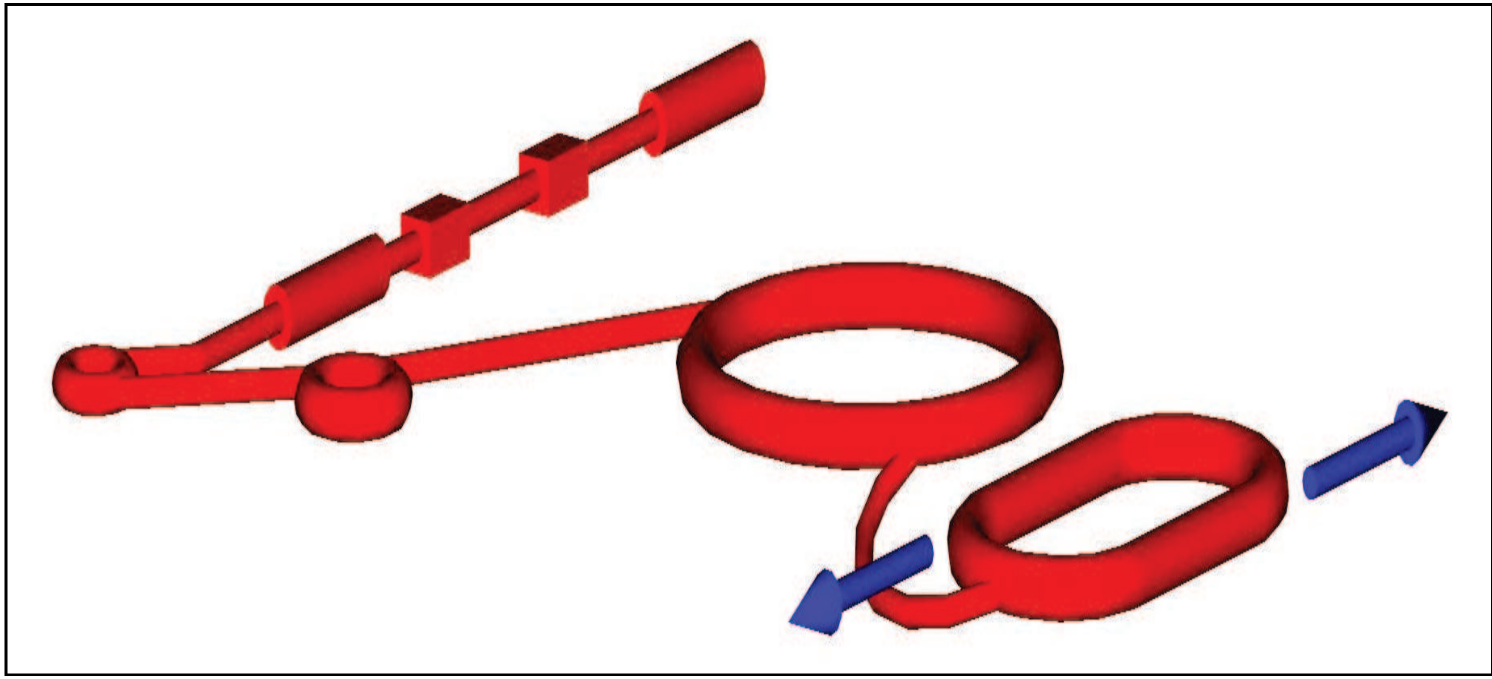


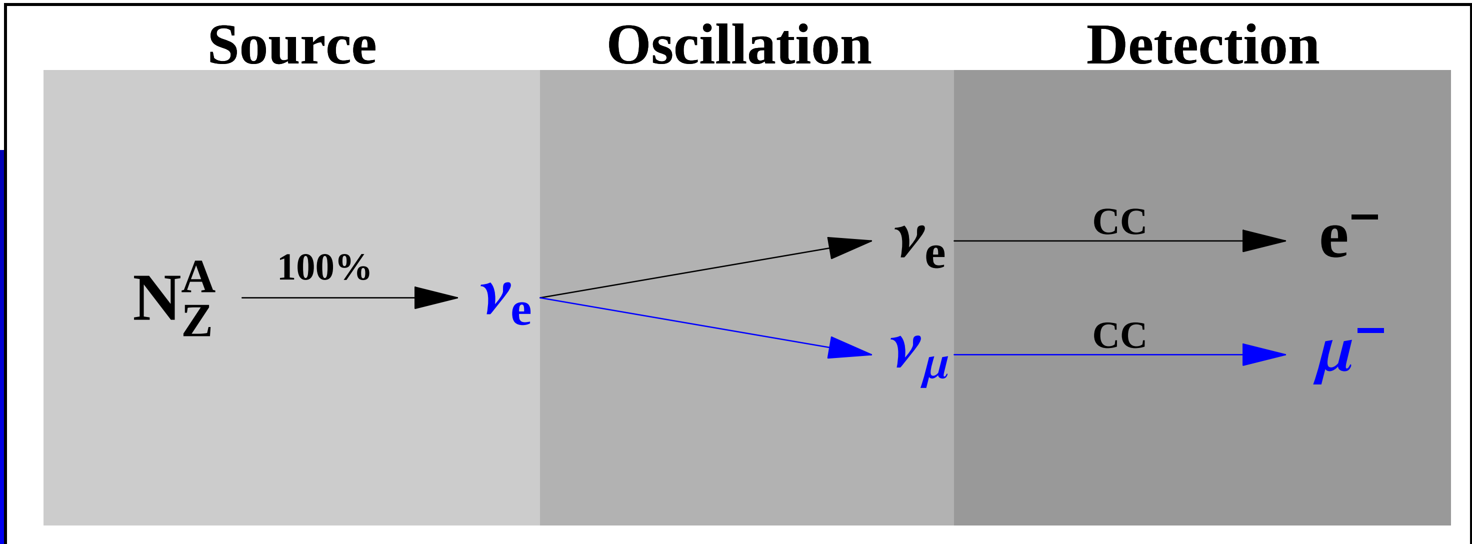
1st maximum at longer L
$\rightarrow$ higher E_ν:
- WBB-WC

2nd maximum
$\rightarrow$ second detector:
- NOνA*
- T2KK

Beta beam

β-beams





Candidate ions

	A/Z	half life [s]	Q value [MeV]	production rate
^{6}He	3.0	0.8	3.5	OK
^{8}Li	2.7	0.8	13.0	OK?
^{18}Ne	1.8	1.7	3.4	unsolved
^{8}B	1.6	0.8	13.9	OK?

For a beam peak energy of 1 GeV, Lorentz boosts of $\gamma \sim 150$ (^{8}Li and ^{8}B) or of $\gamma \sim 570$ (^{6}He and ^{18}Ne) are required.

Detector choice depends on neutrino energy: water Cerenkov and liquid Argon for low energy, iron calorimeter for high energy

Lorentz boost

^{6}He is the most difficult isotope since $A/Z = 3$.

size of storage ring			
γ	rigidity [Tm]	ring length [m] B=5 T & f=36%	dipole field [T] L=7 km
100	938	4916	3.1
150	1404	6421	4.7
200	1867	7917	6.2
350	3277	12474	10.9
500	4678	17000	15.6

Optimized beta beam

In view of the difficulties associated with large values of γ, an optimized, 2 baseline, four isotope setup has been proposed:

- upgraded CERN SPS as accelerator
- He/Ne at $\gamma = 350$ aimed at 500kt water Cerenkov, baseline 650km
- Li/B at $\gamma = 656/390$ aimed at 50kt iron detector, baseline 7000km
- 2.5 years running for each isotope
- shortened decay ring, 8.3 T dipole field , 3-4km long and dips 700m below ground,

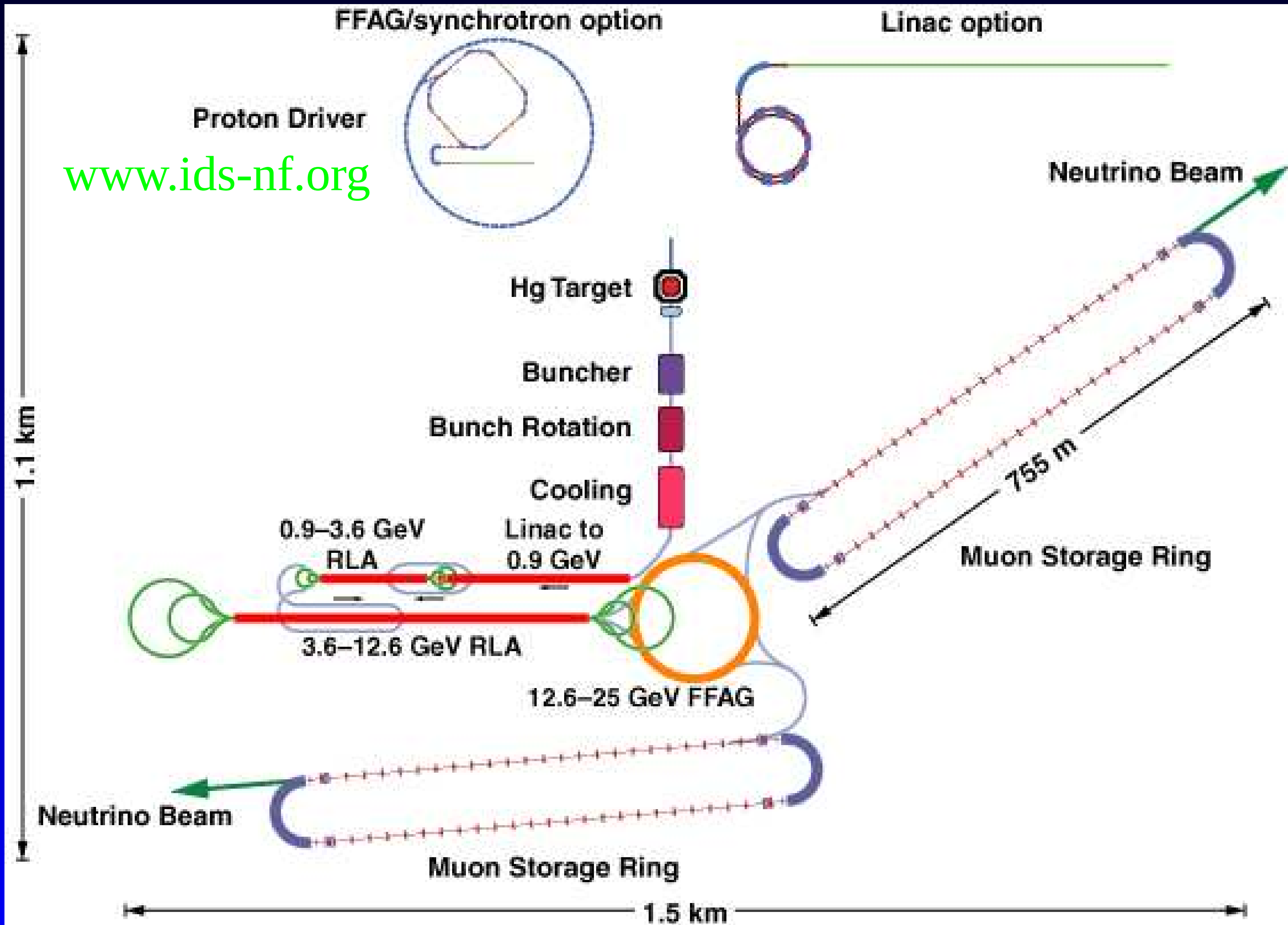
Choubey, Coloma, Donini, Fernandez-Martinez, arXiv:0907.2379

Challenges

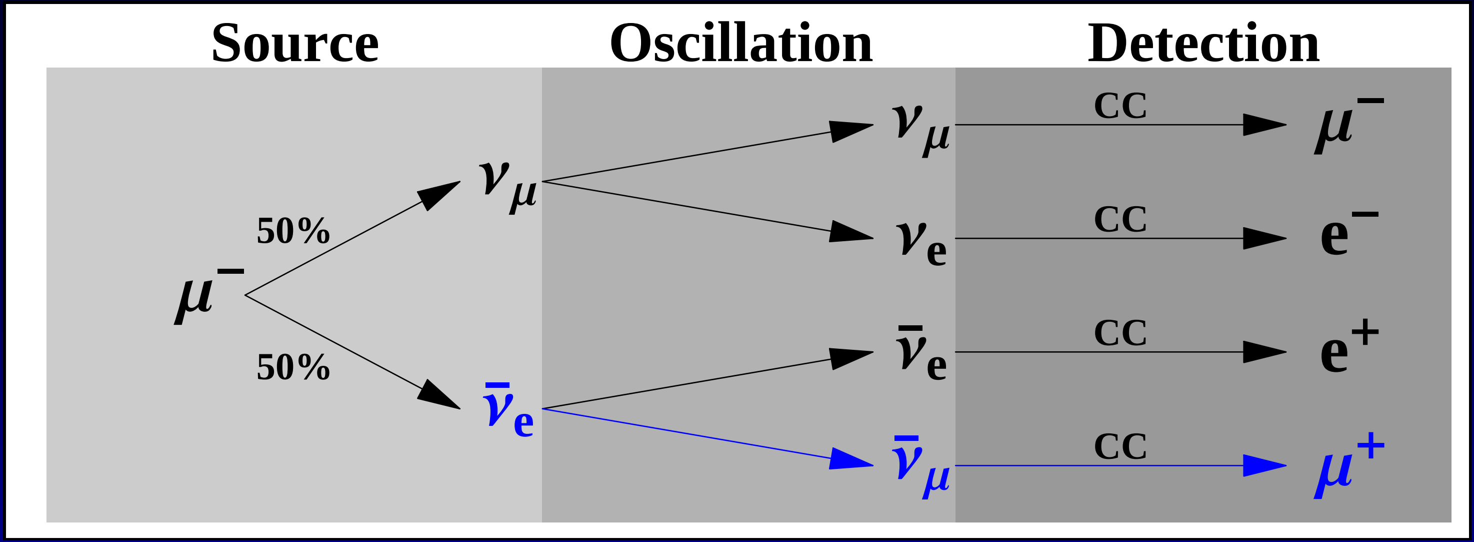
- isotope production
- acceleration – sufficiently high neutrino energies
- radioactive beams – activation of equipment
- storage ring – high ion densities, size
- no ν_μ disappearance, thus no θ_{23} measurement

Neutrino factory

Neutrino Factory



Signal



This requires a detector which can distinguish μ^+ from μ^- $\Rightarrow$ magnetic field of around 1T

- above 3 GeV – iron calorimeter like MINOS
- below 3 GeV – magnetized, totally active, fine grained scintillator

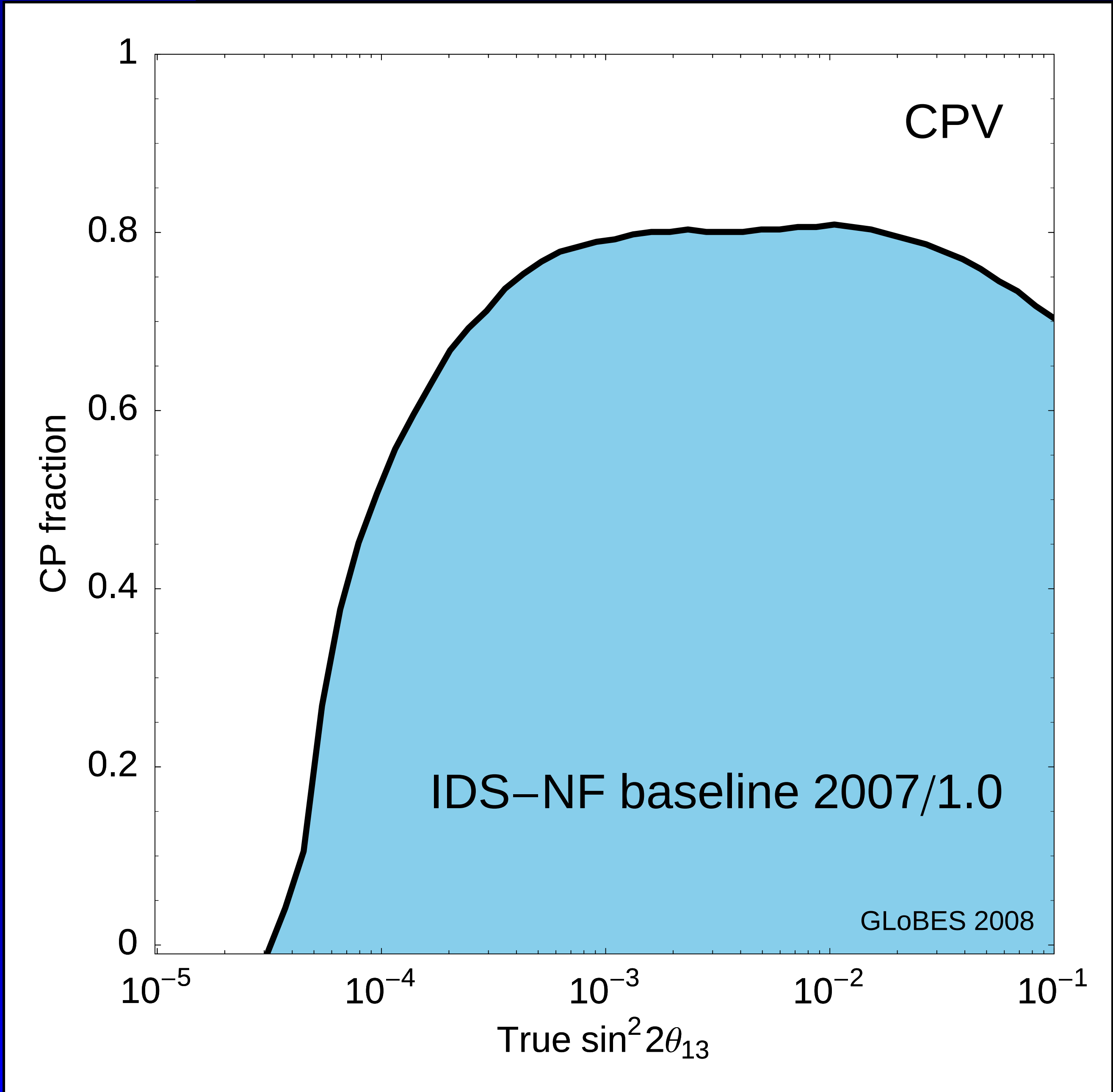
Challenges

- muon production (MERIT)
- muon cooling (MICE, MuCool)
- muon acceleration (EMMA)

All these step are necessary for a muon collider, too. Active R&D effort, which will yield a reference design report by 2012.

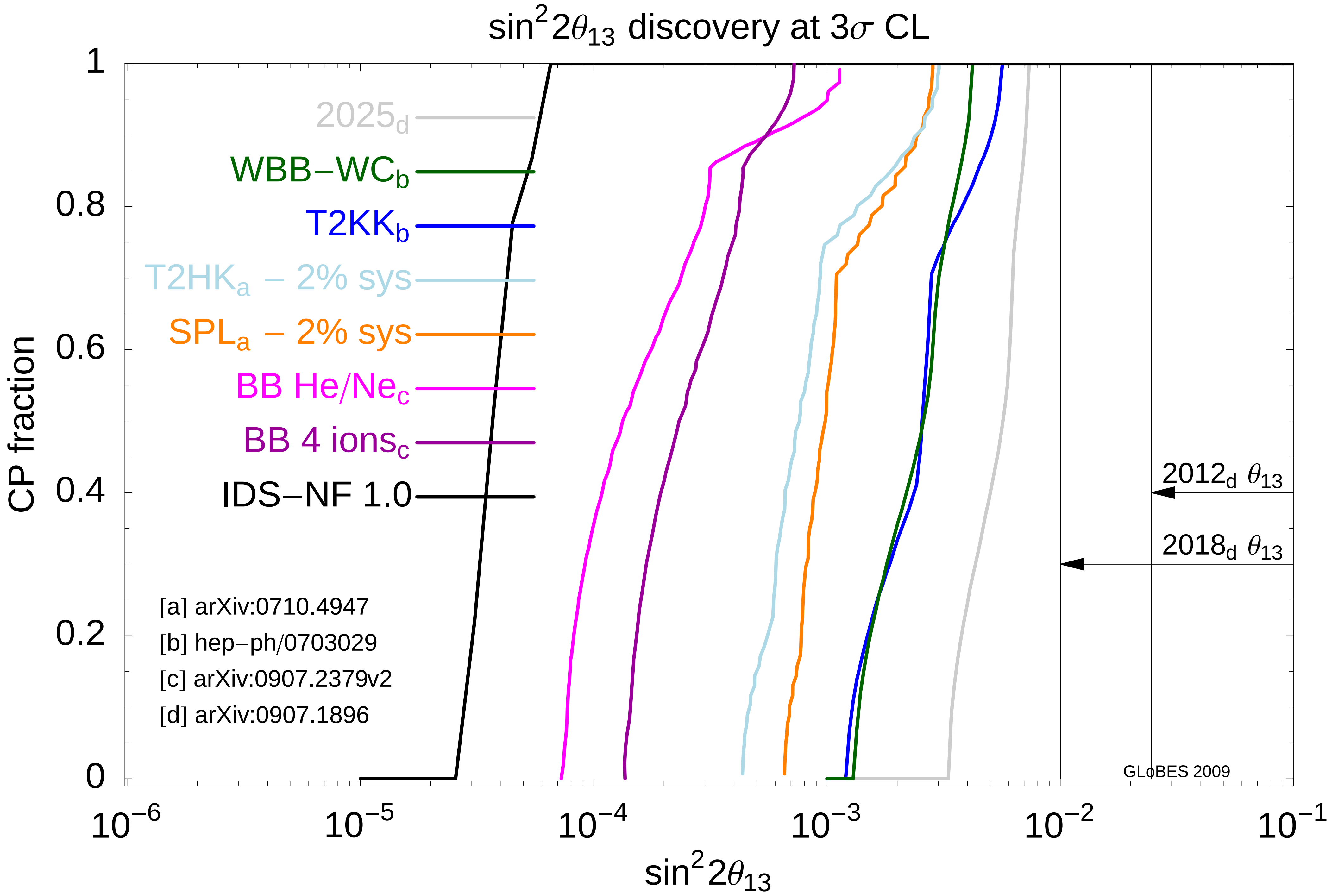
International Design Study for a Neutrino Factory (IDS-NF): www.ids-nf.org

IDS-NF baseline



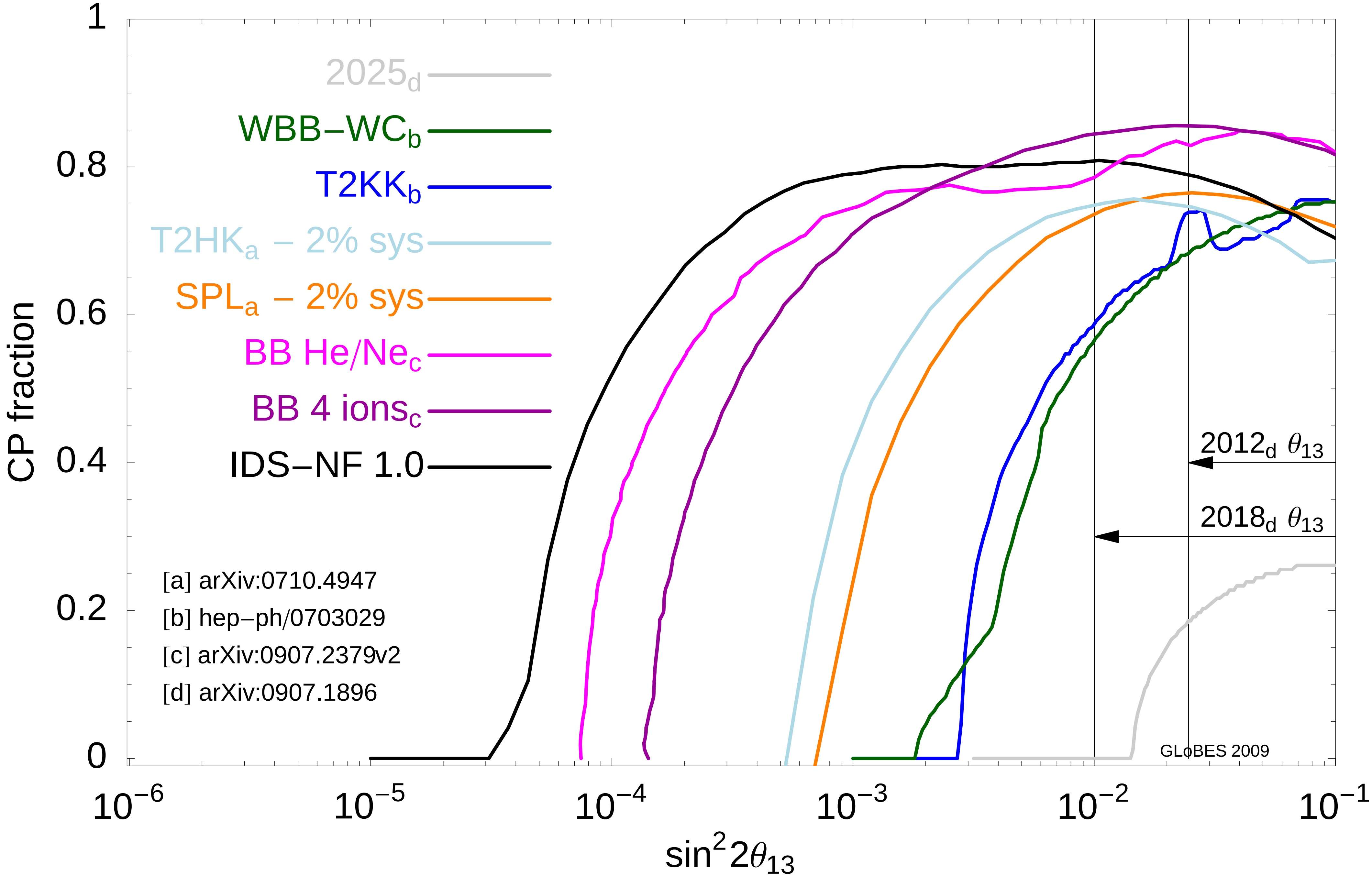
- $E_\mu = 25\,\mathrm{GeV}$
- 10^{21} useful muon decays per year
- 2 baselines: 4000 and 7500 km
- 2 mag. iron detector with $m_f = 50\,\mathrm{kt}$
- $10\,\mathrm{kt}$ OPERA-like detector at 4000km

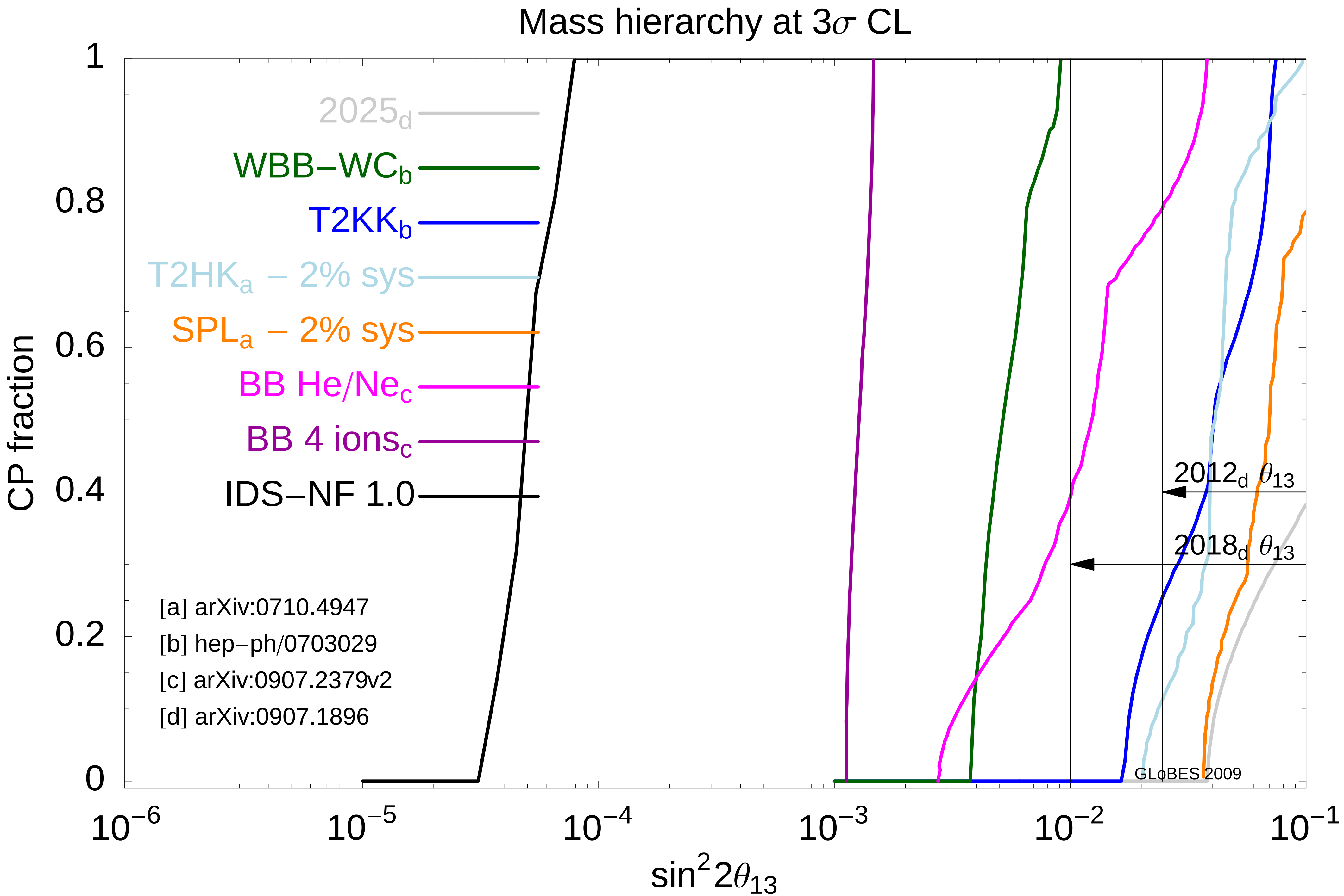
Summary



sin²2θ₁₃ discovery at 3σ CL
2025d
WBB−WCb
T2KKb
T2HKa − 2% sys
SPLa − 2% sys
BB He/Nec
BB 4 ionsc
IDS−NF 1.0
[a] arXiv:0710.4947
[b] hep−ph/0703029
[c] arXiv:0907.2379v2
[d] arXiv:0907.1896
2012d θ13
2018d θ13
GLoBES 2009
CP fraction
sin²2θ13
0
0.2
0.4
0.6
0.8
1
10−6
10−5
10−4
10−3
10−2
10−1

CP violation at 3σ CL





Mass hierarchy at 3σ CL
CP fraction
1
0.8
0.6
0.4
0.2
0
2025d
WBB−WCb
T2KKb
T2HKa − 2% sys
SPLa − 2% sys
BB He/Nec
BB 4 ionsc
IDS−NF 1.0
[a] arXiv:0710.4947
[b] hep−ph/0703029
[c] arXiv:0907.2379v2
[d] arXiv:0907.1896
2012d θ13
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GLoBES 2009
10−6
10−5
10−4
10−3
10−2
10−1
sin²2θ13

Three technologies

- Superbeams – for large $\sin^2 2\theta_{13} > 0.01$, require true MW beams and Mt detectors
- Beta beams – large experiments, with somewhat limited physics: no ν_μ disappearance, difficulties with mass hierarchy
- Neutrino factories – the ultimate tool, technologically moderately more difficult, can be built in steps (low energy option), gateway to muon collider

Summary

- New facilities are indispensable to fully exploit the discovery of neutrino oscillation
- CP violation is never easy to measure – even for the largest values of θ_{13}
- Mass hierarchy needs long baseline and multi-GeV beams

All options require a considerable, $> 10^9$€, and sustained, > 10 years, effort!