Optimization of the Two-Baseline β-Beam

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Based on the collaboration:
S. Choubey, P. Coloma, A. Donini and E. Fernández-Martínez; arXiv:0907.2379 [hep-ph]

Outline

- Leptonic mixing
- Proposed solutions
  - Neutrino Factory
  - β-Beams
- The two-baseline β-Beam
  - The far detector as a degeneracy solver
  - The Li/B alternative
- The ultimate β-beam
  - Our proposal
  - Storage rings: design and feasibility
  - Results & comparison with other facilities
- Conclusions

Leptonic mixing

$$\mathcal{L}_\nu = \frac{g}{\sqrt{2}} U^*_{\alpha i}(\theta_{12}, \theta_{23}, \theta_{13}; \delta) \left(\overline{l_{\alpha L}} \, \gamma^\mu \, \nu_{iL} W^-_\mu + h.c. \right) + \mathcal{L}_{\text{mass}}(m_{\nu_i}; \, m_{l_\alpha})$$

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What we know:

$\theta_{12},\ \Delta m^2_{12}$

$\theta_{23},\ |\Delta m^2_{23}|$

Uncertainties
~$\mathcal{O}$(10%), though...

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Shopping list:

θ_{13}

δ

$\text{sign}(\Delta m^2_{23})$

$\delta\theta_{23} = \left| \theta_{23} - \frac{\pi}{4} \right|$

Physics BSM??

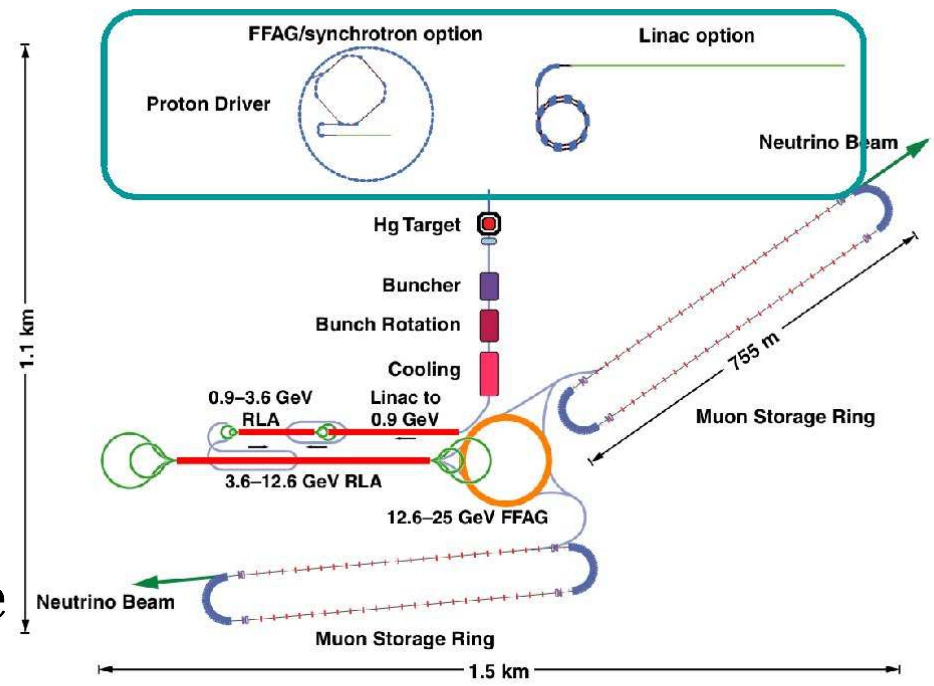
Future proposed facilities

- The Neutrino Factory:

$$\mu^+ \to e^+ + \bar{\nu}_\mu + \nu_e$$

$$\rightarrow \begin{cases} E_\mu = 25\,\text{GeV} \\ E_\nu \in [1.5,\ 25]\,\text{GeV} \end{cases}$$

  - 5 years/polarity
  - $5 \cdot 10^{20}$ useful muons/baseline per year
  - 2 baselines: 4000, 7500 Km
  - 50 Kton MIND detectors



Future proposed facilities

- The β-Beam:

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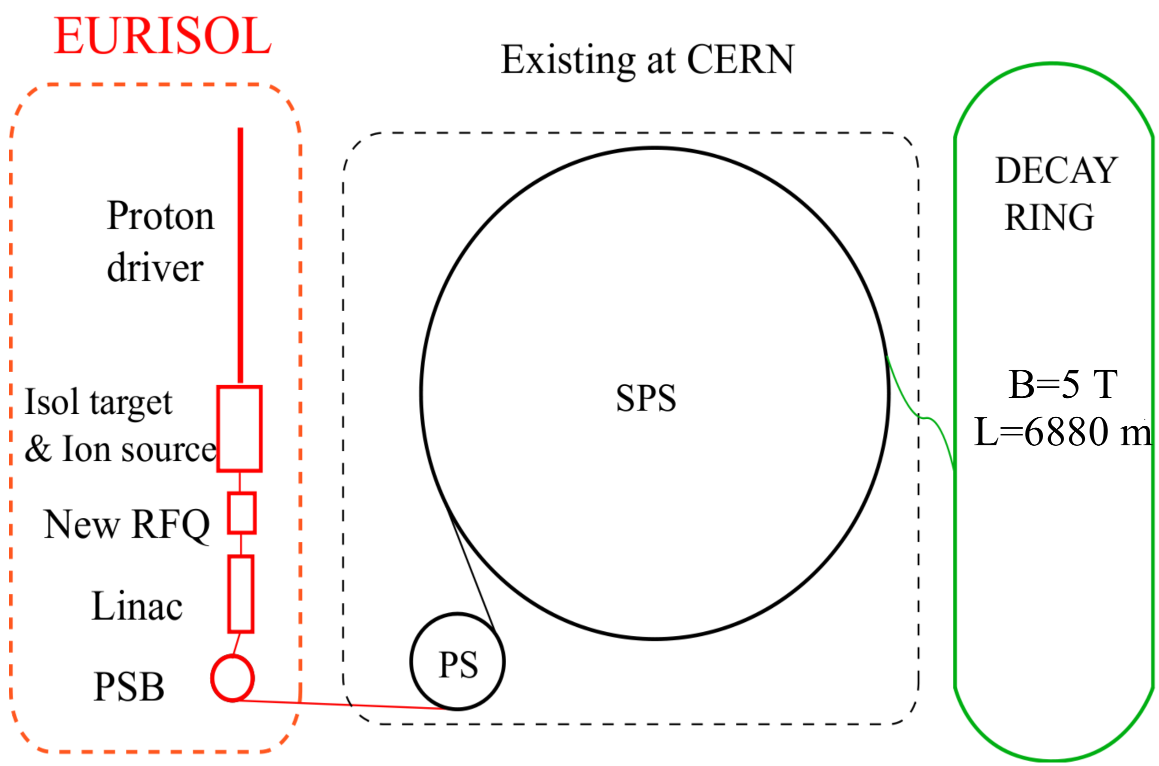
$$N(A,Z) \rightarrow N(A,Z-1) + e^+ + \bar{\nu}_e$$



- ➔ $<E> \sim \gamma E_0$
- ➔ $N_{events}^{on-peak} \propto N_\beta \left(\frac{\Delta m^2}{2n-1}\right)^2 \frac{\gamma}{E_0}$
- ➔ $^6\mathrm{He}/^{18}\mathrm{Ne}: \; \gamma = 100 \Rightarrow L_{\text{first-peak}} = 130\,\mathrm{Km}$ (CERN-Fréjus)

P. Zucchelli, hep-ph/0107006

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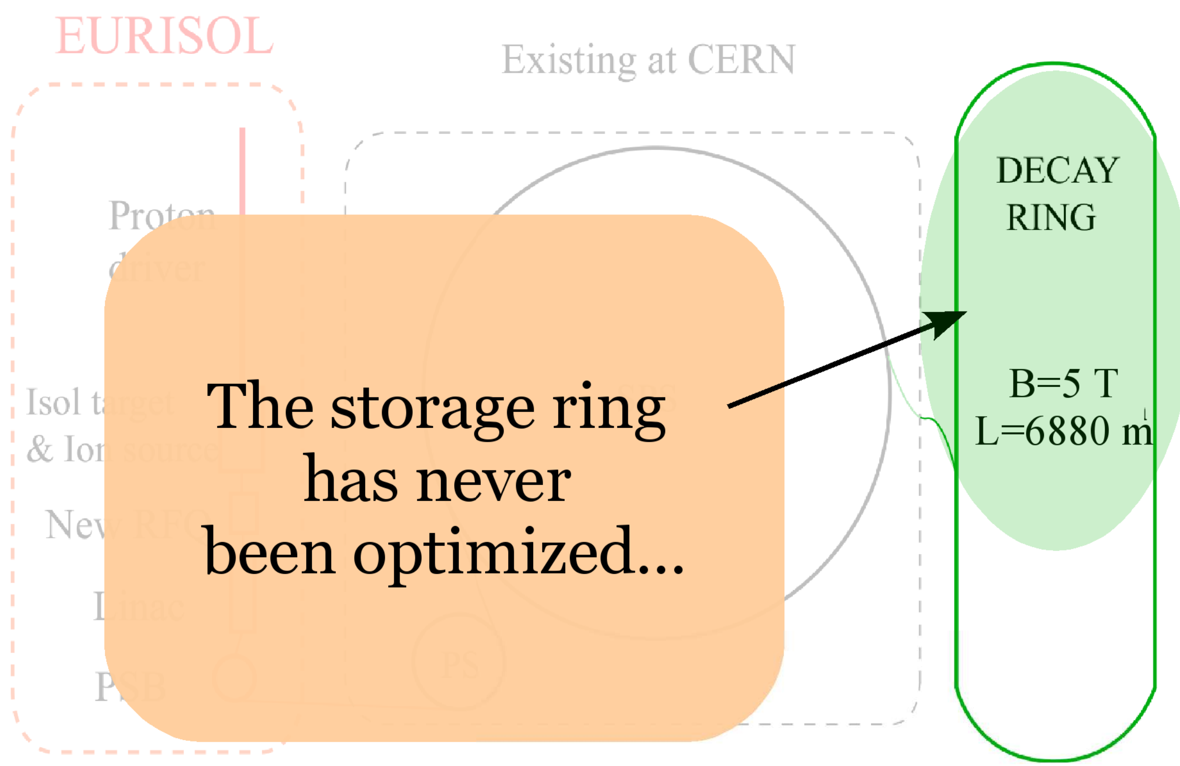

The storage ring has never been optimized...

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The high-γ β-Beam

- $\left.\begin{array}{c} ^6\mathrm{He}/^{18}\mathrm{Ne} \\ \text{SPS+:}\ \gamma = 100 \rightarrow 350 \end{array}\right\} \Rightarrow E_\nu \in [0,\ 2.5]\ \mathrm{GeV}$
- $L_{\text{first-peak}} \sim 600 - 700\ \mathrm{Km}$ (CERN-Canfranc)
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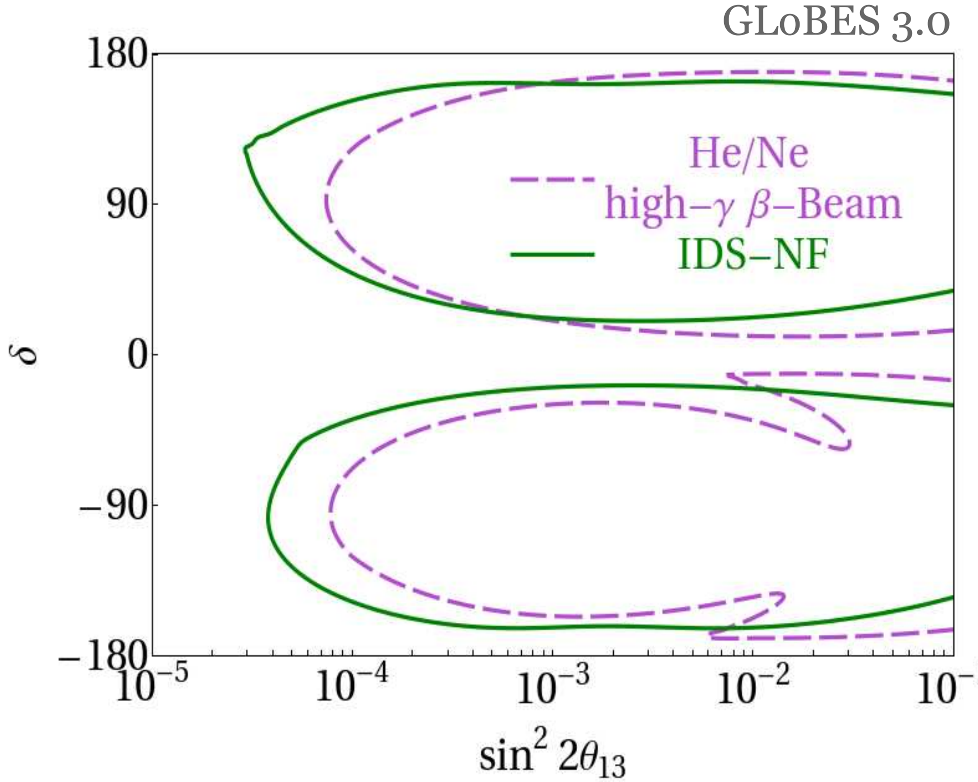
- 10^{19} total ion decays/year ($\sim 3{\cdot}10^{18}$ useful)

CP discovery reach (1 d.o.f 3σ C.L.)



J. Burguet Castell *et al*, hep-ph/0312068
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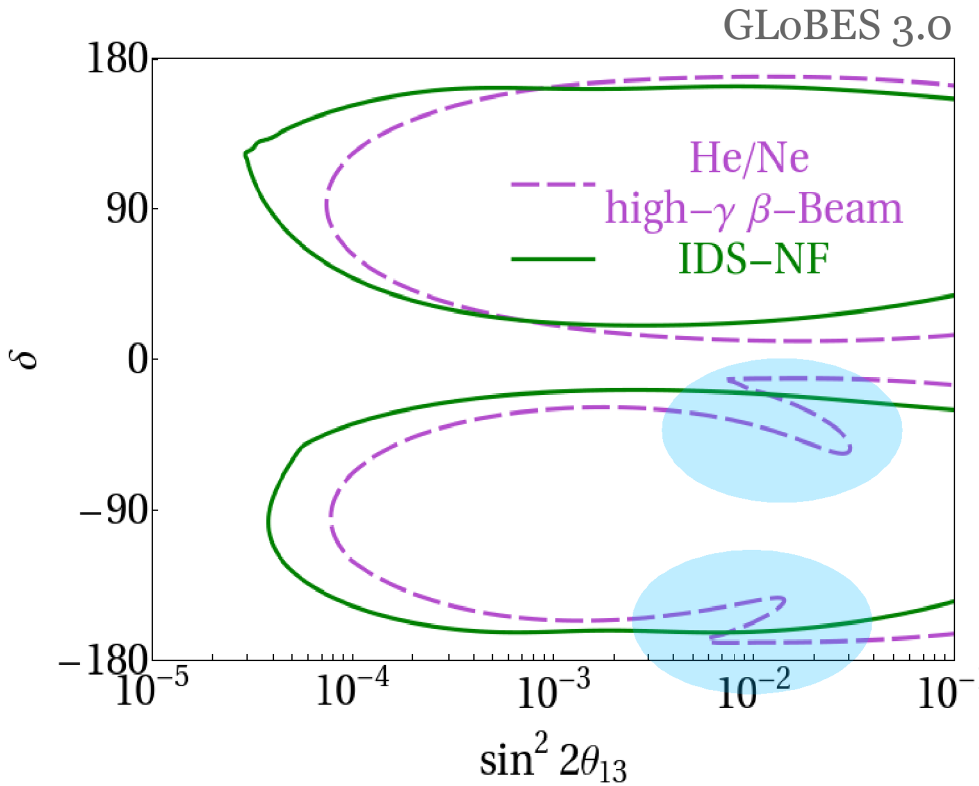

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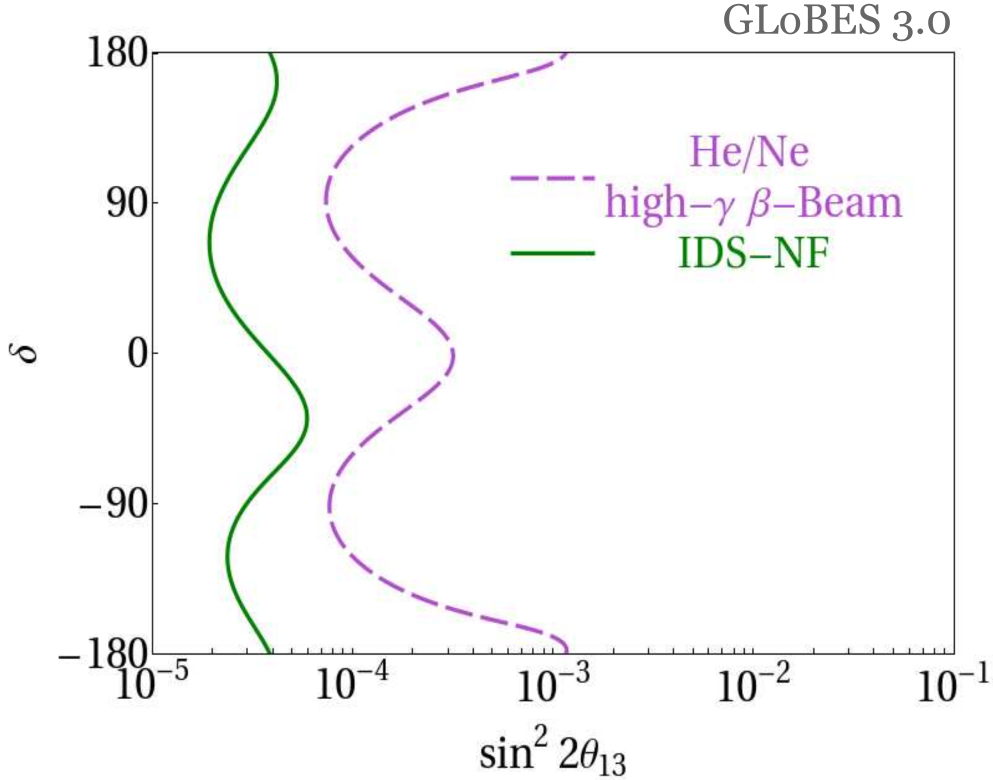

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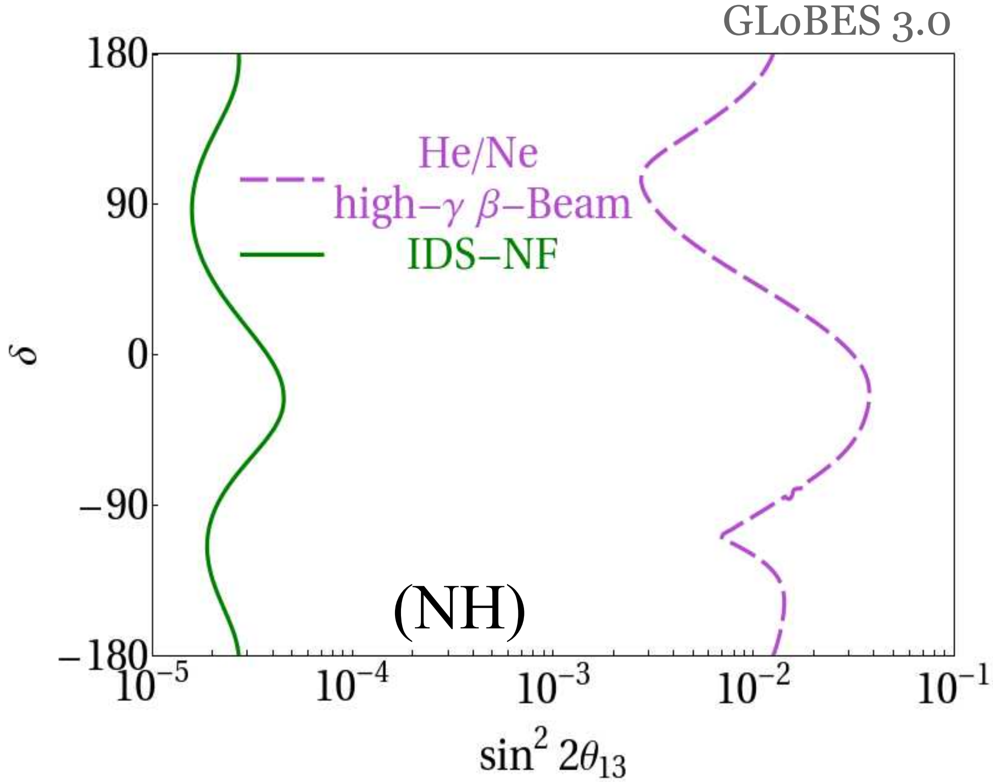
➔ Major drawback: poor sensitivity to mass hierarchy

$sgn(\Delta m^2_{31})$ reach in $\sin^2 2\theta_{13}$ (3σ)



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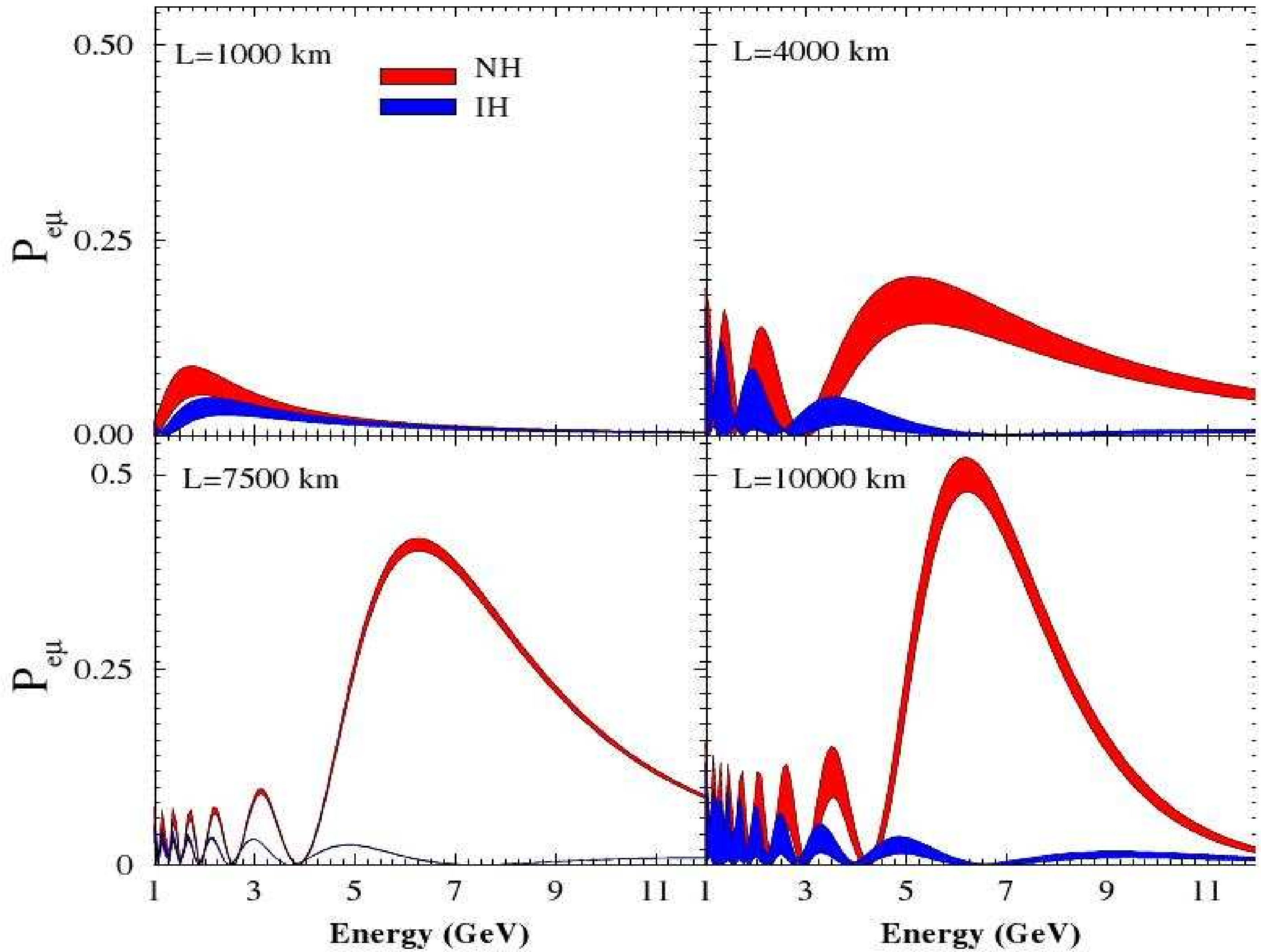
How can we improve this?

Matter effects at the magic baseline



S.K. Agarwalla, S. Choubey and A. Raychaudhuri, hep-ph/0610333

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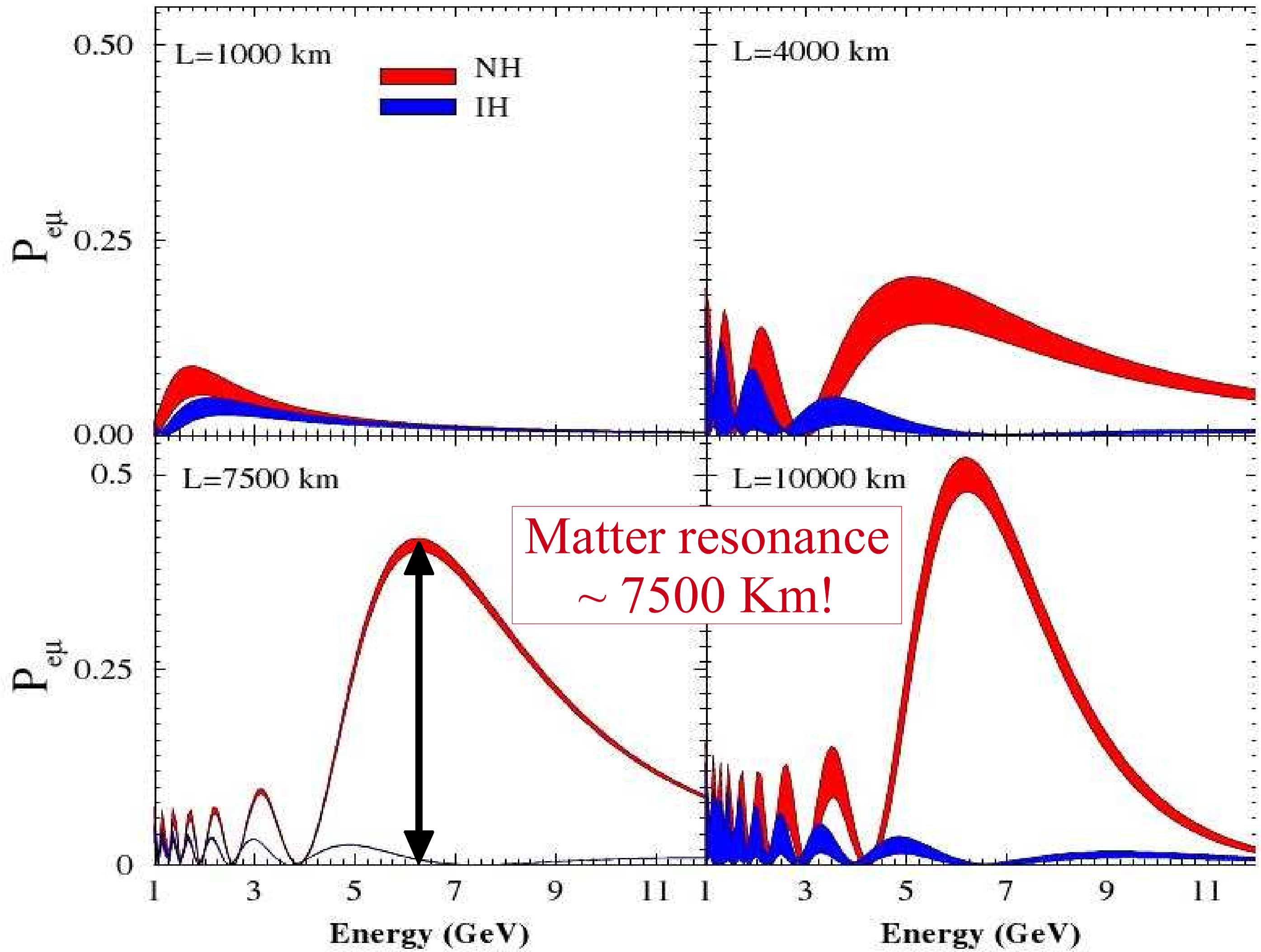

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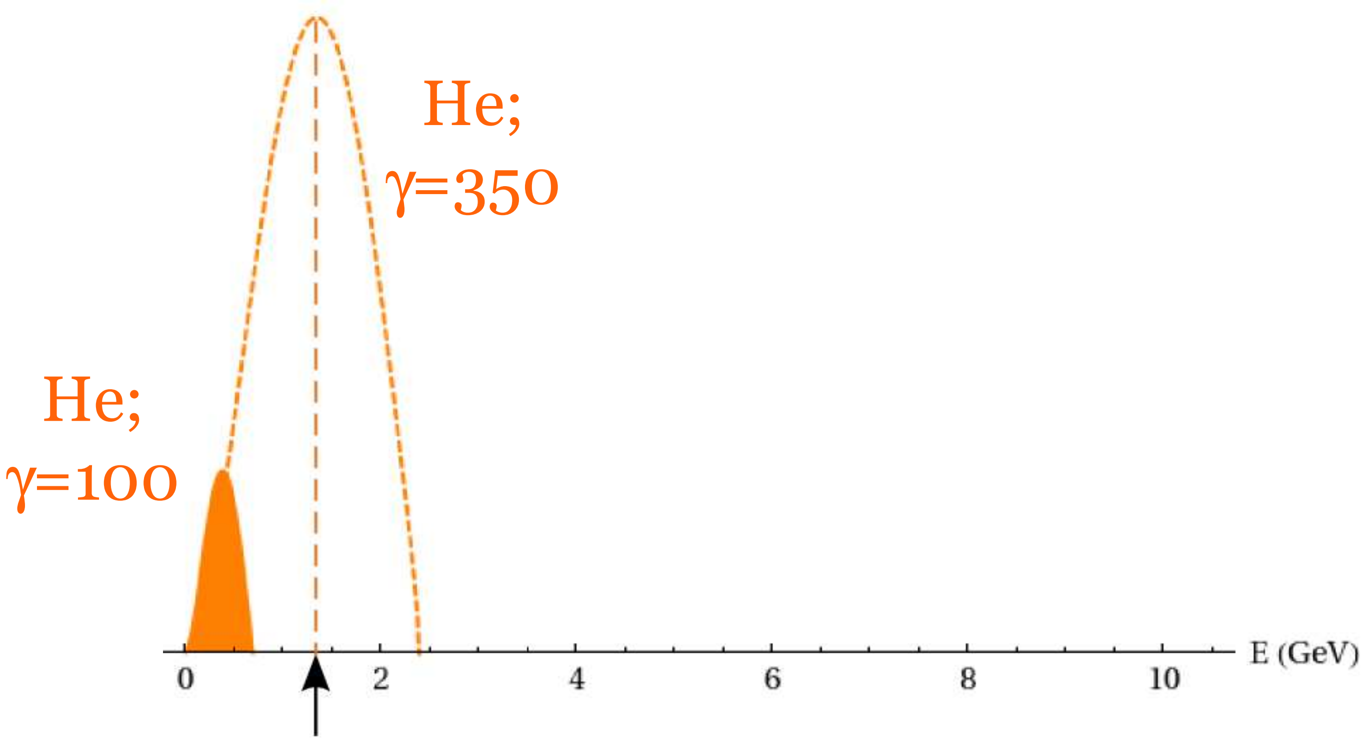
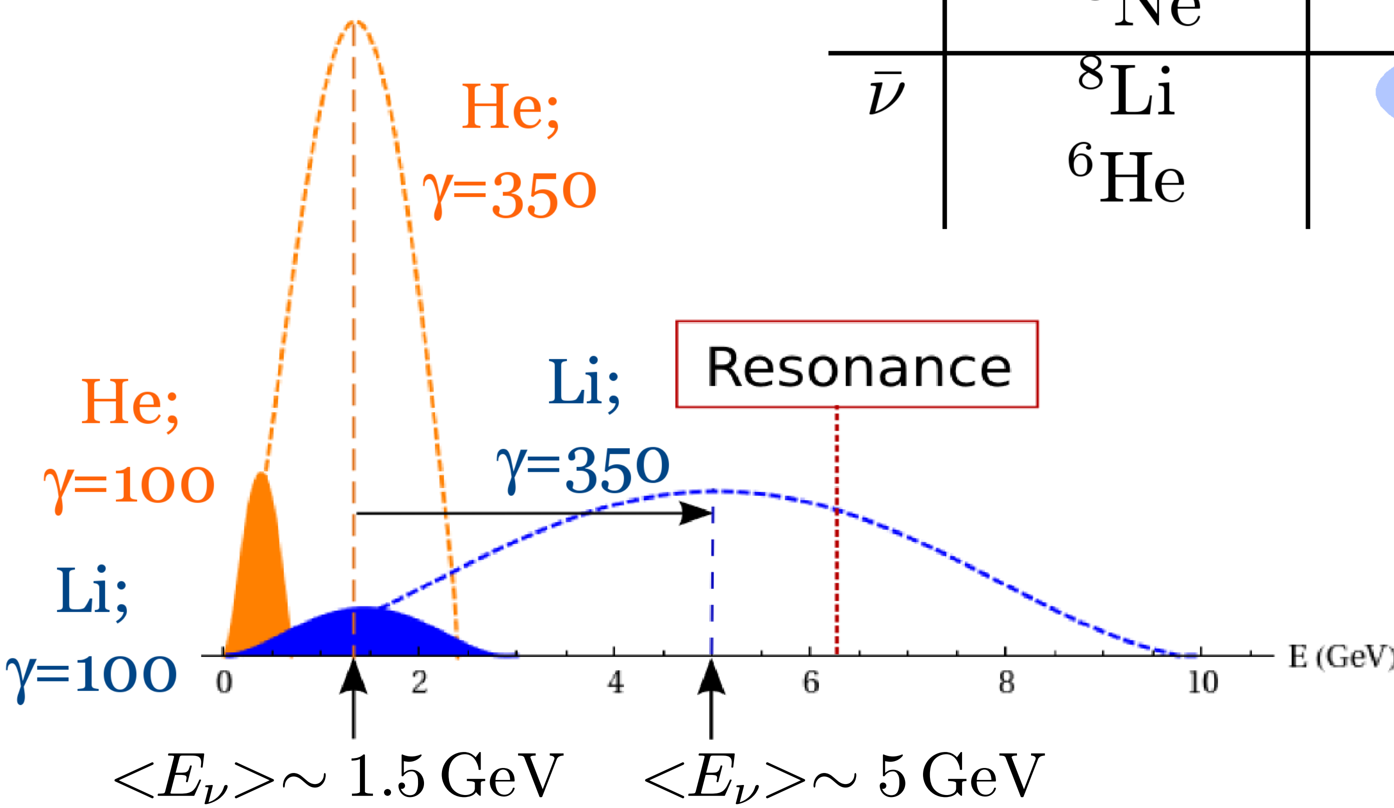


$$<E_\nu>\sim 1.5\,\mathrm{GeV}$$

Matter effects at the magic baseline

$^{6}\mathrm{He}/^{18}\mathrm{Ne} \rightarrow {}^{8}\mathrm{Li}/^{8}\mathrm{B}$

	Element	E_0(MeV)
ν	$^{8}\mathrm{B}$	13.92
	$^{18}\mathrm{Ne}$	3.41
$\bar{\nu}$	$^{8}\mathrm{Li}$	12.96
	$^{6}\mathrm{He}$	3.51



The Two-Baseline β-Beam: old proposals

P. Coloma, A. Donini, E. Fernández-Martínez and J. López-Pavón,

arXiv: 0712.0796

- Li/B at 2000 Km:
  $\gamma = 350$
  50 Kton-MIND detector

- Li/B at 7000 Km:
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- He/Ne at 730 Km:
  $250 < \gamma < 650$
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- Li/B at 7150 Km:
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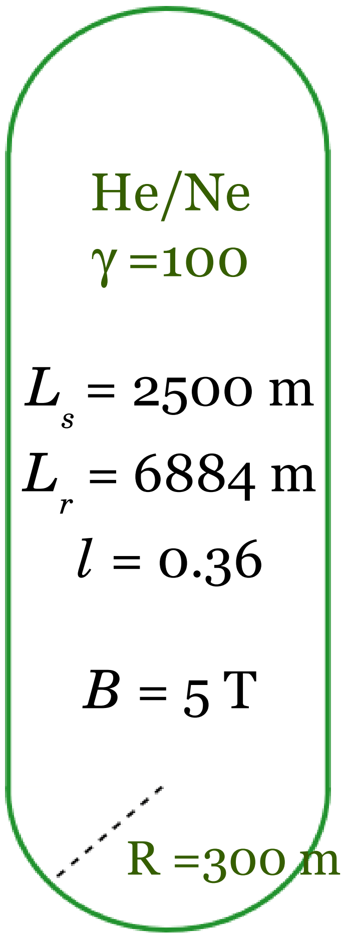
The storage ring for He/Ne: the Long Ring



$$l = \frac{L_s}{L_r}$$

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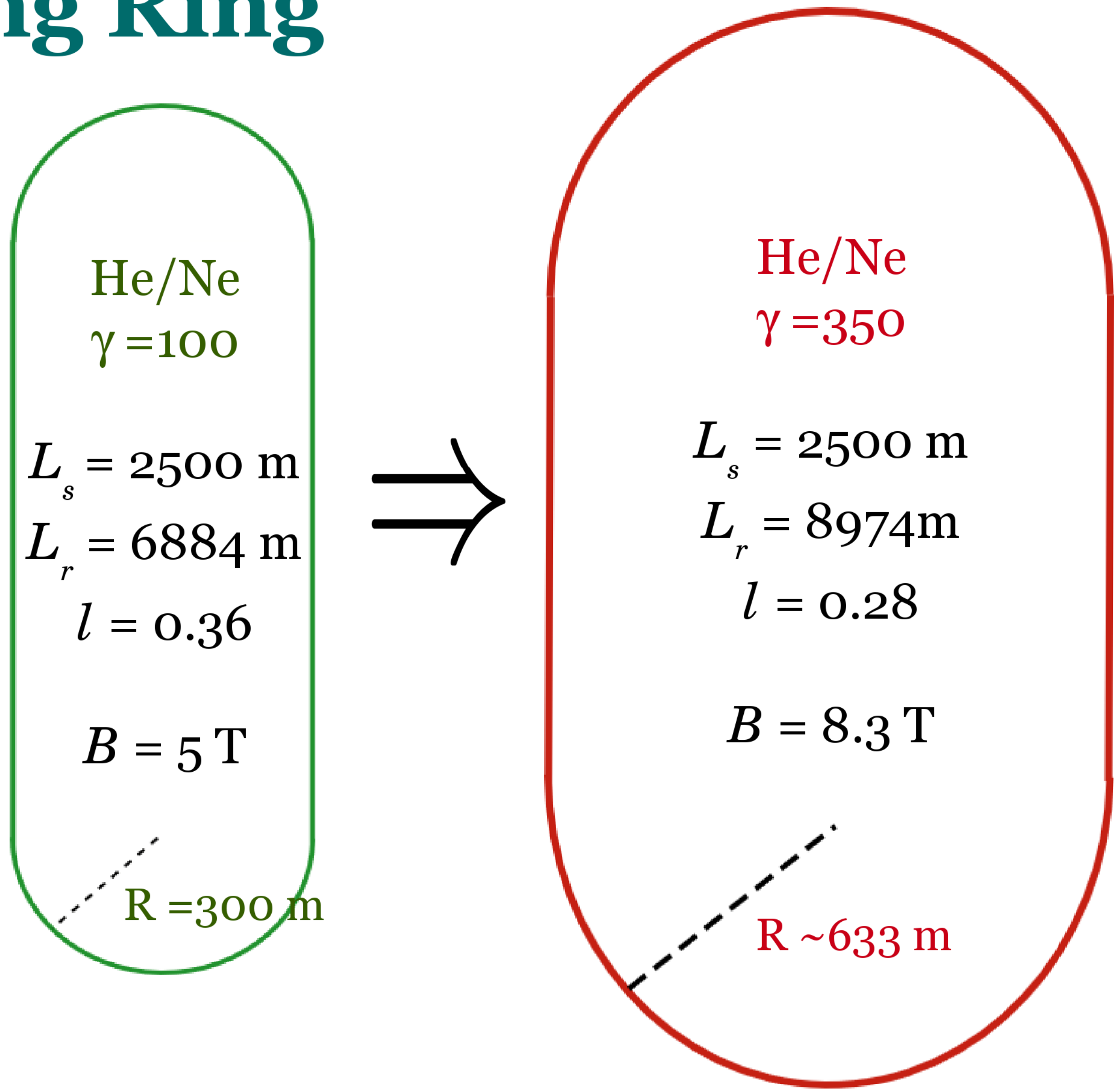

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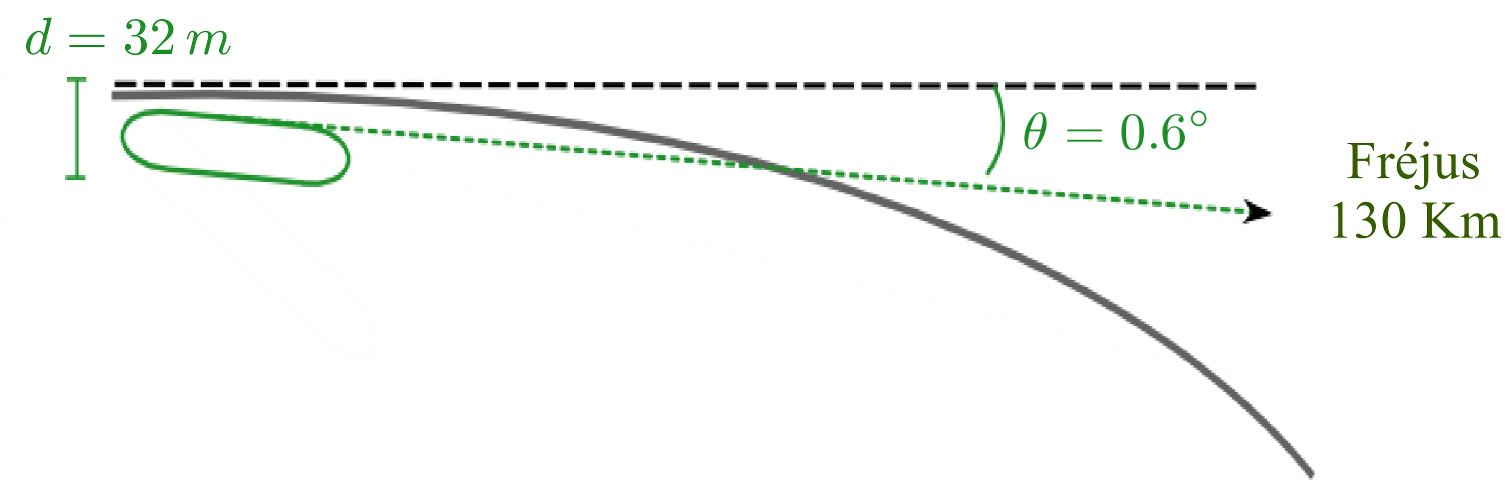
The storage ring: is it feasible?



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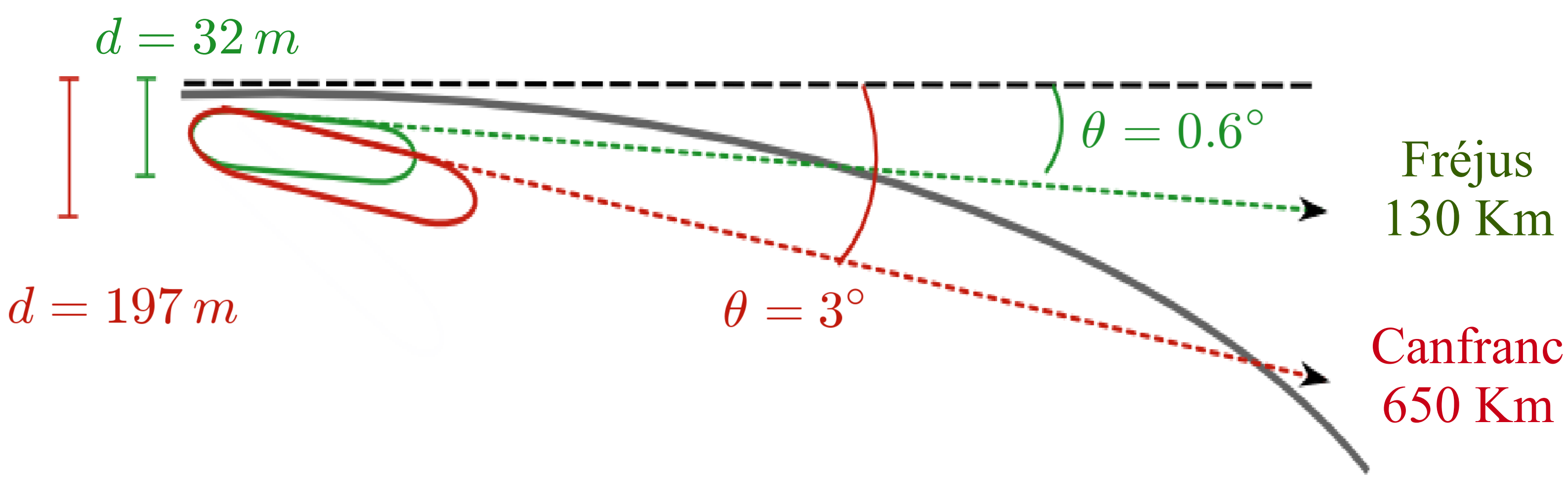

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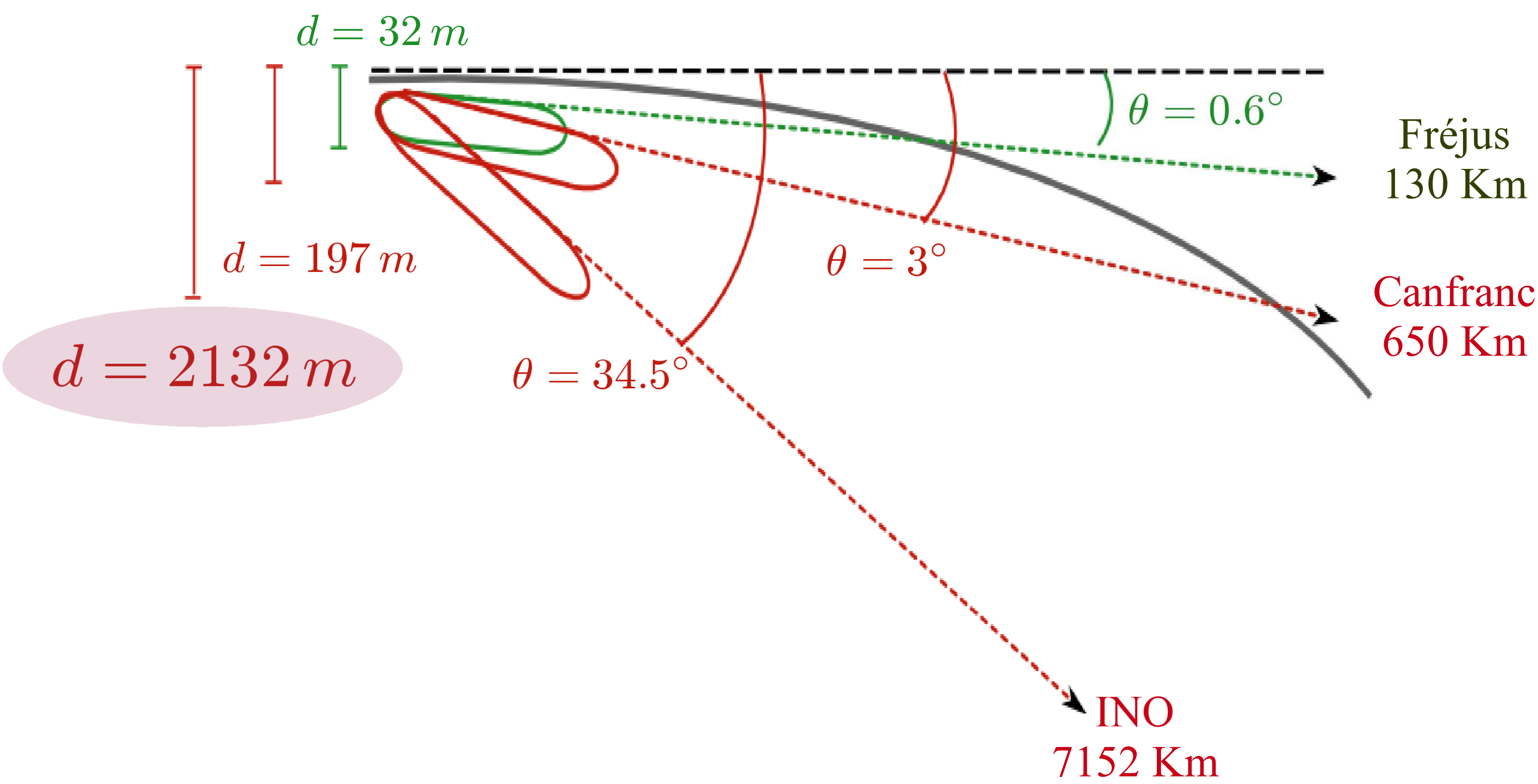

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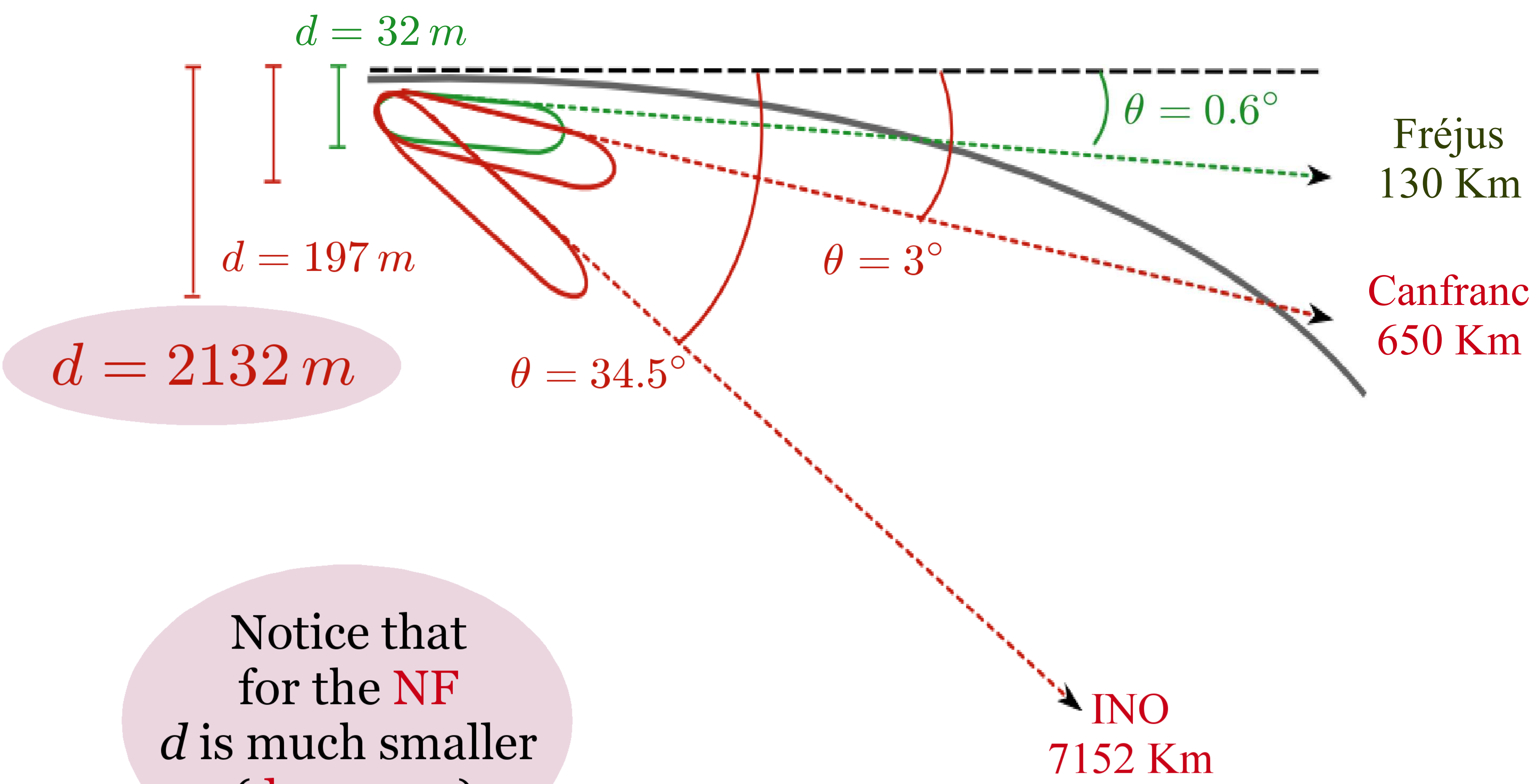
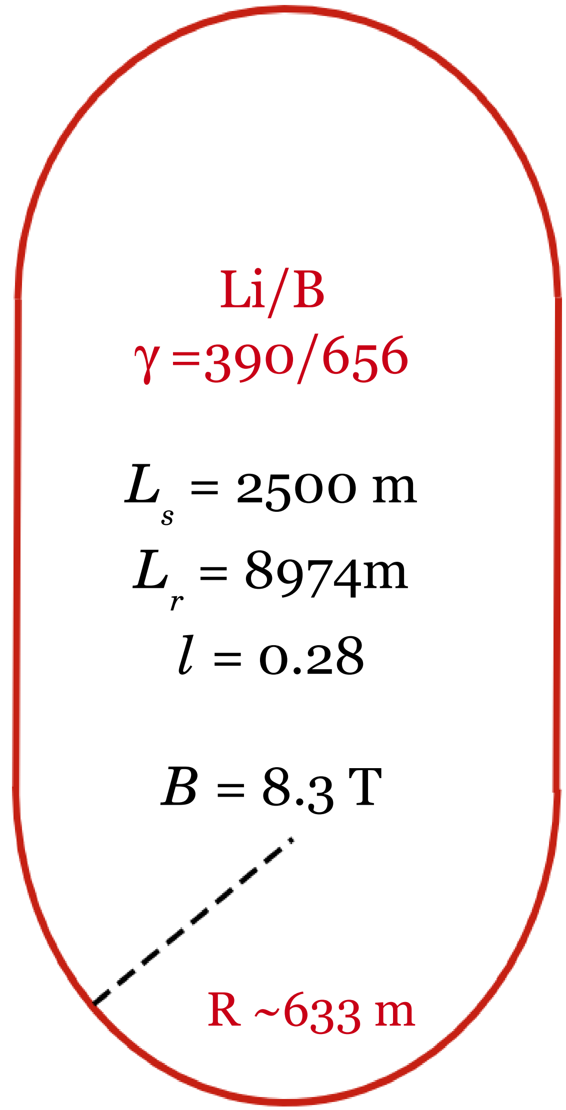


Notice that
for the NF
d is much smaller
(d= 423 m)

The storage ring for Li/B

- Due to a different A/Z, we can reach higher boost factors for Li/B in the LR:

$$\gamma_{max}^{Li/B}\Big|_{Long\ Ring} = 390/656$$



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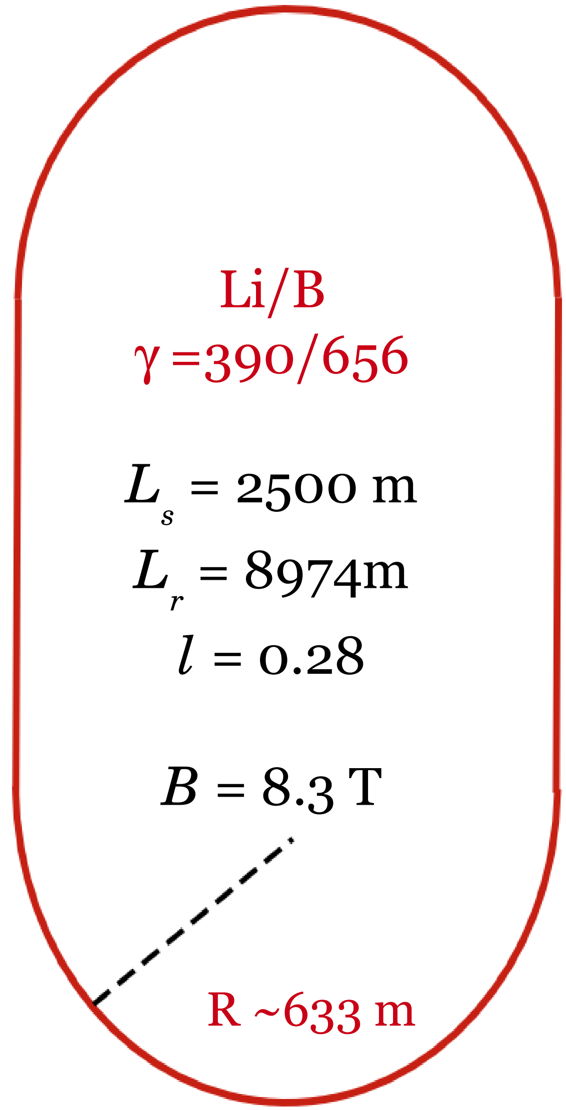
$$N_{ev}^{Li}(390) = N_{ev}^{Li}(350) \times 1.5$$



The storage ring for Li/B: the Short Ring

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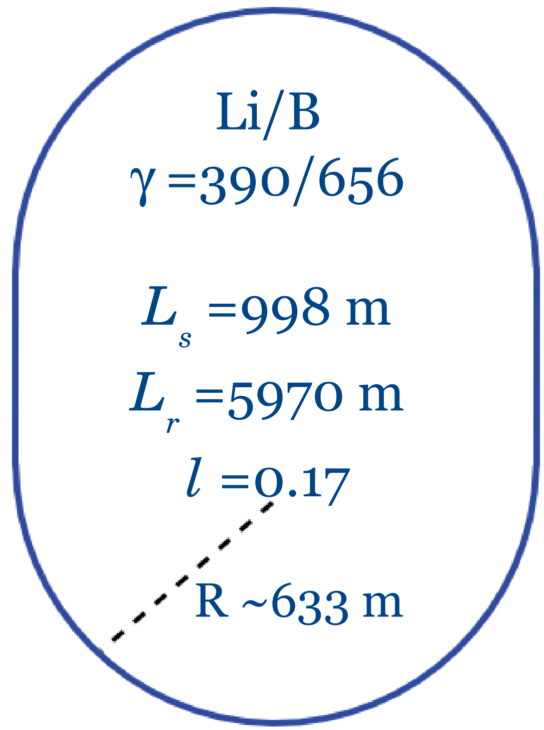
- We can use this to reduce the ring size:

$$l = 0.6 \times 0.28 \sim 0.17 \Rightarrow \begin{cases} L_s = 998\, m \\ d = 1282\, m \end{cases}$$



Our proposal

He/Ne @ WC

- $E_0 \sim 3$ MeV;
- $\gamma = 350$;
- 500 Kton fiducial mass;
- 650 Km (first osc.peak);
- 2.5 years/ion;
- 10^{19} total $\Longrightarrow 3 \cdot 10^{18}$ useful decays/year;
- 6 energy bins with $\Delta E = 0.25$ GeV ;
  last bin with $\Delta E = 0.5$ GeV ;
  $E_\nu \in [0.5, 2.5]$ GeV ;
- Migration matrices from hep-ph/0503021;
- Uncorrelated systematic errors: 2.5% and 5%.

Li/B @ MIND

- $E_0 \sim 13$ MeV;
- $\gamma = 350 \cdot (A/Z)$;
- 50 Kton;
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- 10^{19} total $\Longrightarrow 1.7 \cdot 10^{18}$ useful decays/ year;
- $E_\nu \in [1.0, 18.55]$ GeV ;
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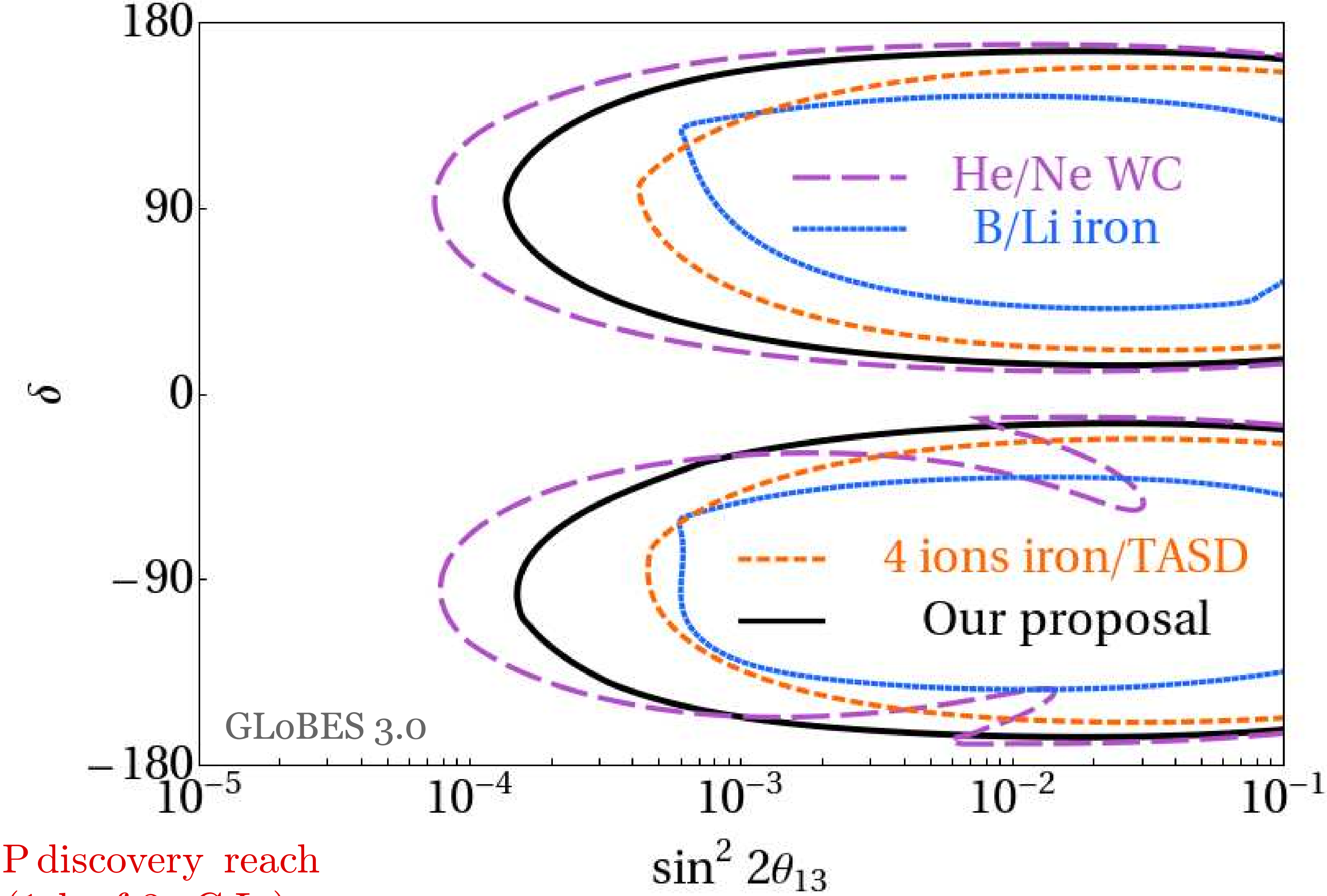
Comparative sensitivity reach



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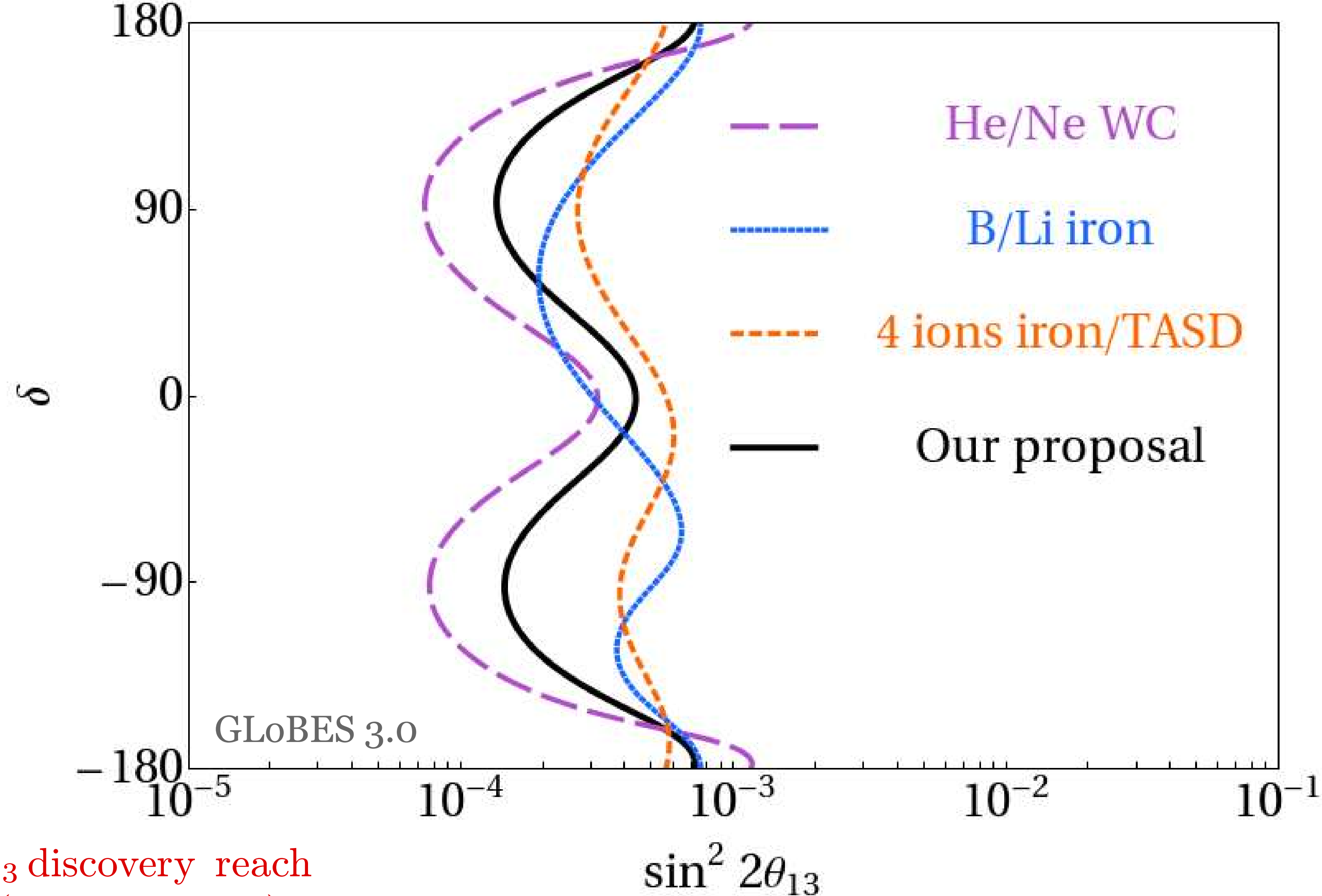

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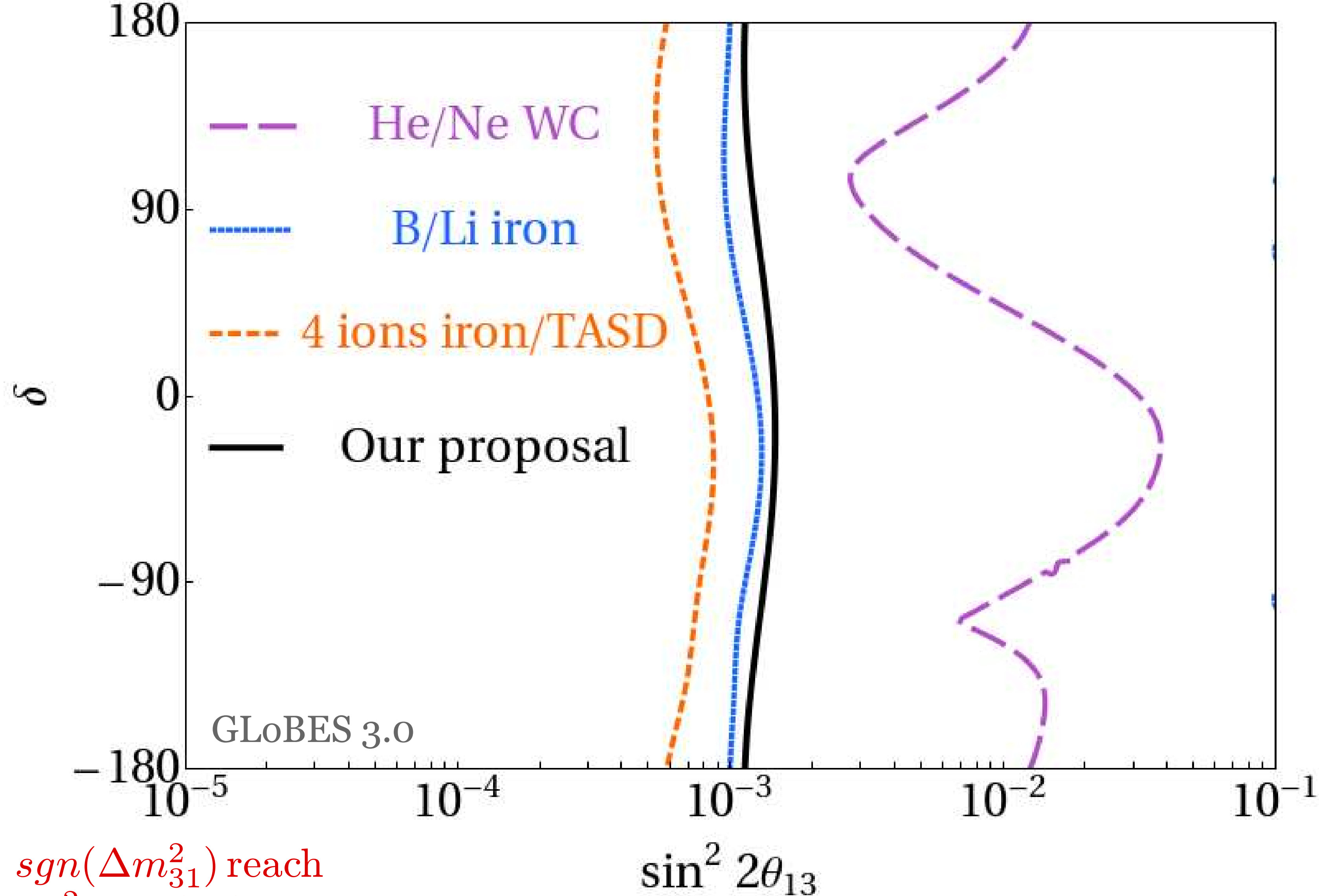
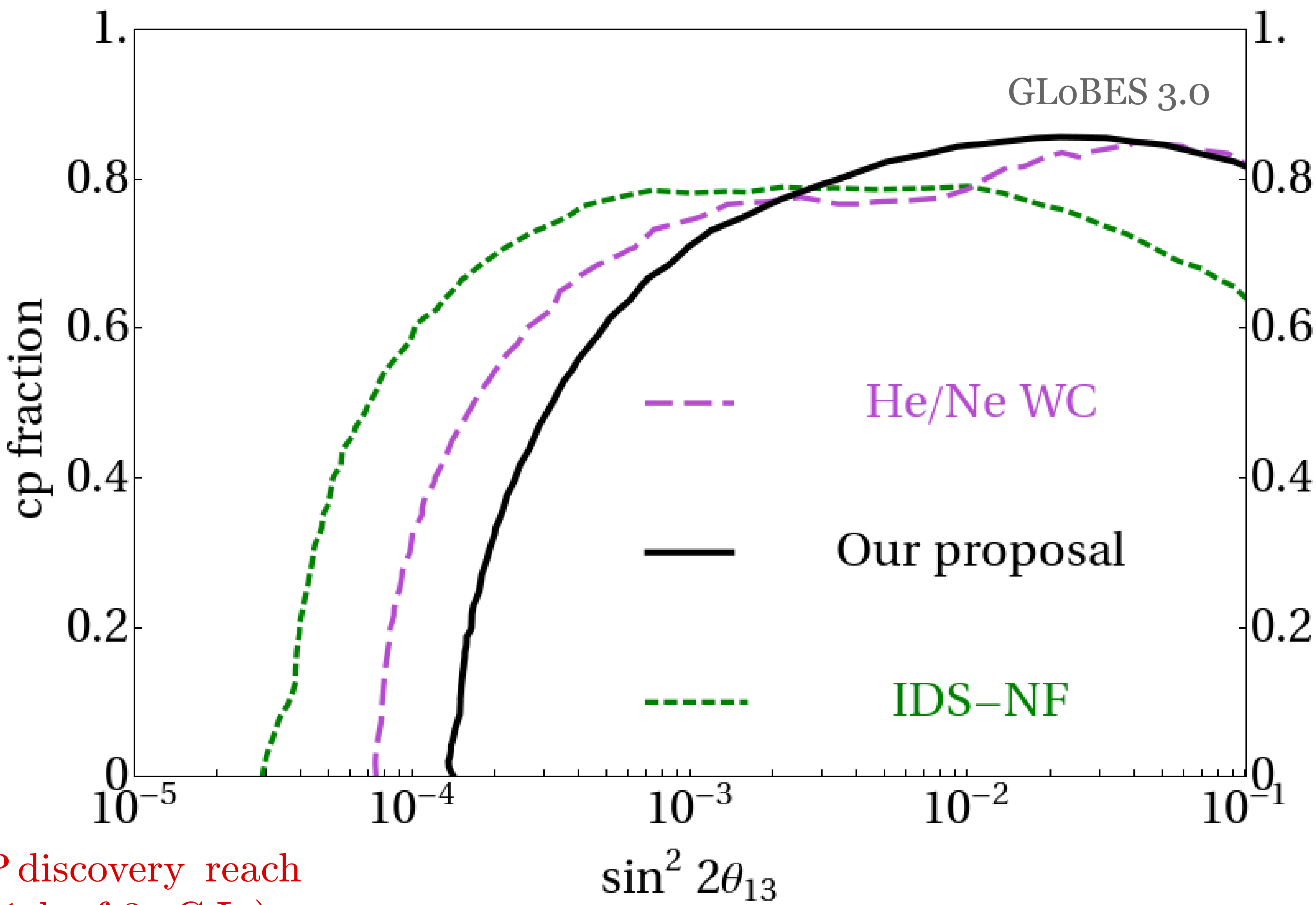


$sgn(\Delta m^2_{31})$ reach
in $\sin^2 2\theta_{13}$ (3σ) for NH

Comparison with the Neutrino Factory



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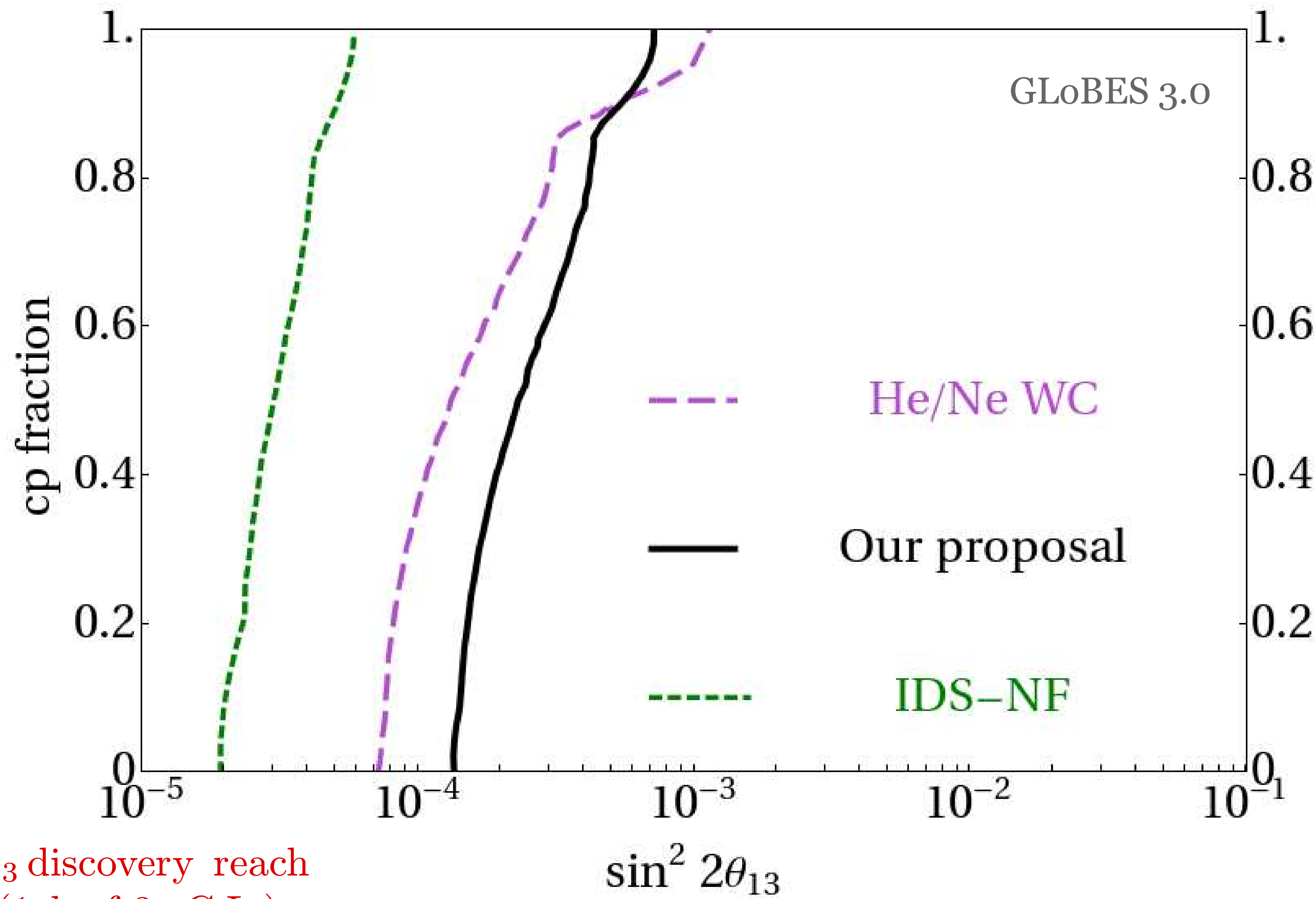

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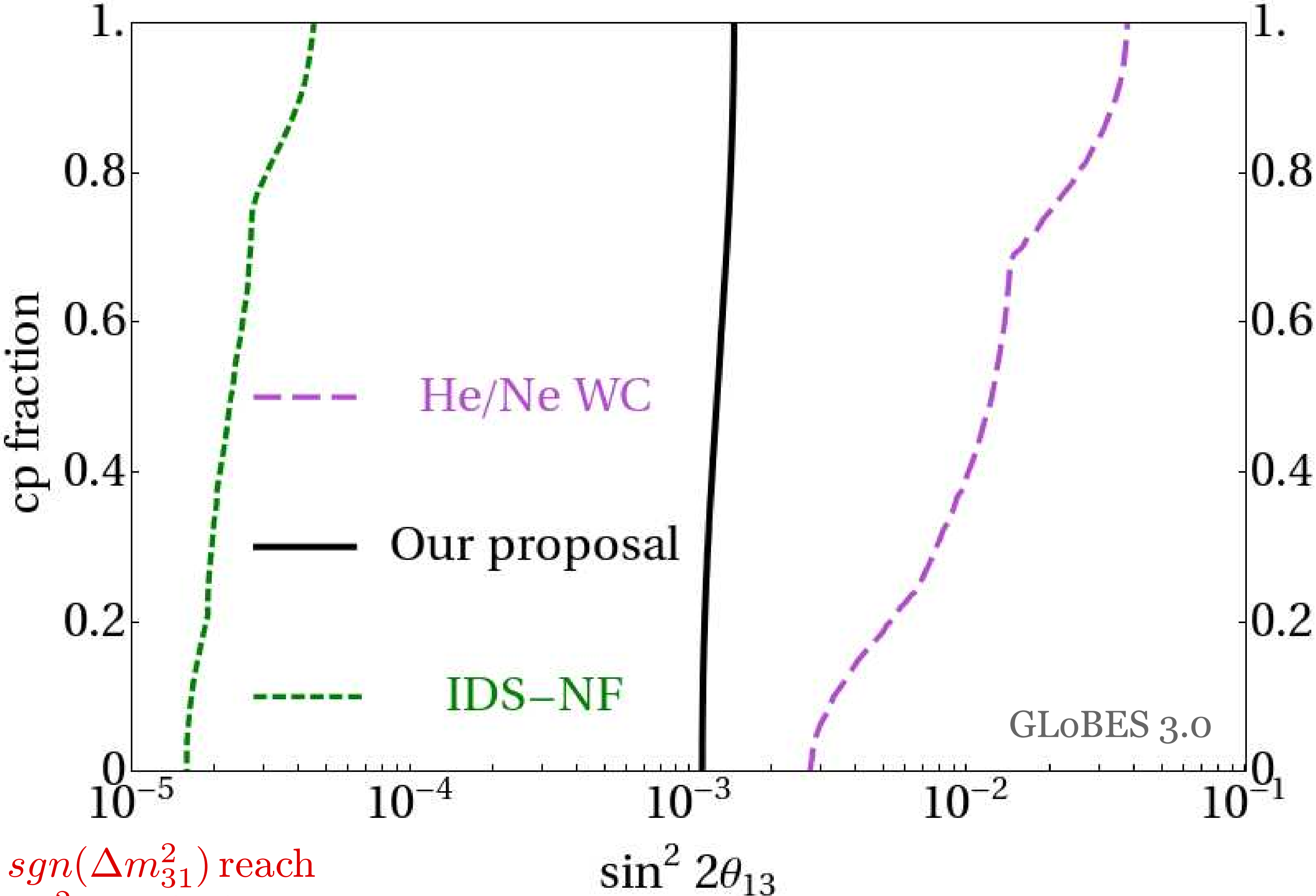

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Conclusions

- We believe that the β-Beam we propose here represents an optimal setup:
  - It has the advantages of the high-γ He/Ne β-Beam, but solving the degeneracies that affected this setup for $\sin^2(2\theta_{13}) \sim 10^{-2}$
  - It uses the magic baseline to achieve good sensitivity to the mass hierarchy
- We have addressed the issue of the storage ring for a β-Beam aimed at the magic baseline, proposing a realistic setup

Conclusions

- β-Beams still cannot compete with the NF for extremely small values of θ_{13}, but our proposal is better optimized for regions with $\sin^2(2\theta_{13}) > 10^{-3}$
  - The sensitivity is unaffected by the poor efficiencies for the lower energy bins
- However, we still are limited…
  - By the number of ions that can be produced: all the setups presented here are strongly limited by statistics
  - A study of the MIND detector performance when exposed to a β-Beam is lacking