Magic Baseline Beta Beam

Sanjib Kumar Agarwalla

sanjib@mri.ernet.in

Harish-Chandra Research Institute, Allahabad, India

work done in collaboration with

S. Choubey, A. Raychaudhuri and A. Samanta

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PLAN

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- **Present Status & Missing Links**
- **"Golden Channel", $P_{e\mu}$**

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- “Magic Baseline”
- CERN based β-beam source
- India-Based Neutrino Observatory (INO)
- Results
- Conclusions

Then and Now

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Now (2004): APS Neutrino Study Group

Much of what we know about neutrinos we have learned in the last six years. . . . . We have so many new questions, . . . We are most certain of one thing : neutrinos will continue to surprise us . . . .

Past and Present

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Next generation experiments have been planned/proposed world-wide to further pin down the values of the oscillation parameters

Present Status

⇒ **ATM + K2K + MINOS :**
$|\Delta m^2_{31}| \simeq 2.5^{+0.7}_{-0.5} \times 10^{-3}\textbf{eV}^2$, $\theta_{23} \simeq 45.0^{\circ}{}^{+9.22^{\circ}}_{-9.22^{\circ}}$ (3σ)

⇒ **Solar Neutrino Experiments + KamLAND :**
$\Delta m^2_{21} \simeq 8.0^{+1.2}_{-0.8} \times 10^{-5}\textbf{eV}^2$, $\theta_{12} \simeq 33.83^{\circ}{}^{+4.82^{\circ}}_{-3.83^{\circ}}$ (3σ)

(Our convention : $\Delta m^2_{ij} = m^2_i - m^2_j$**)**

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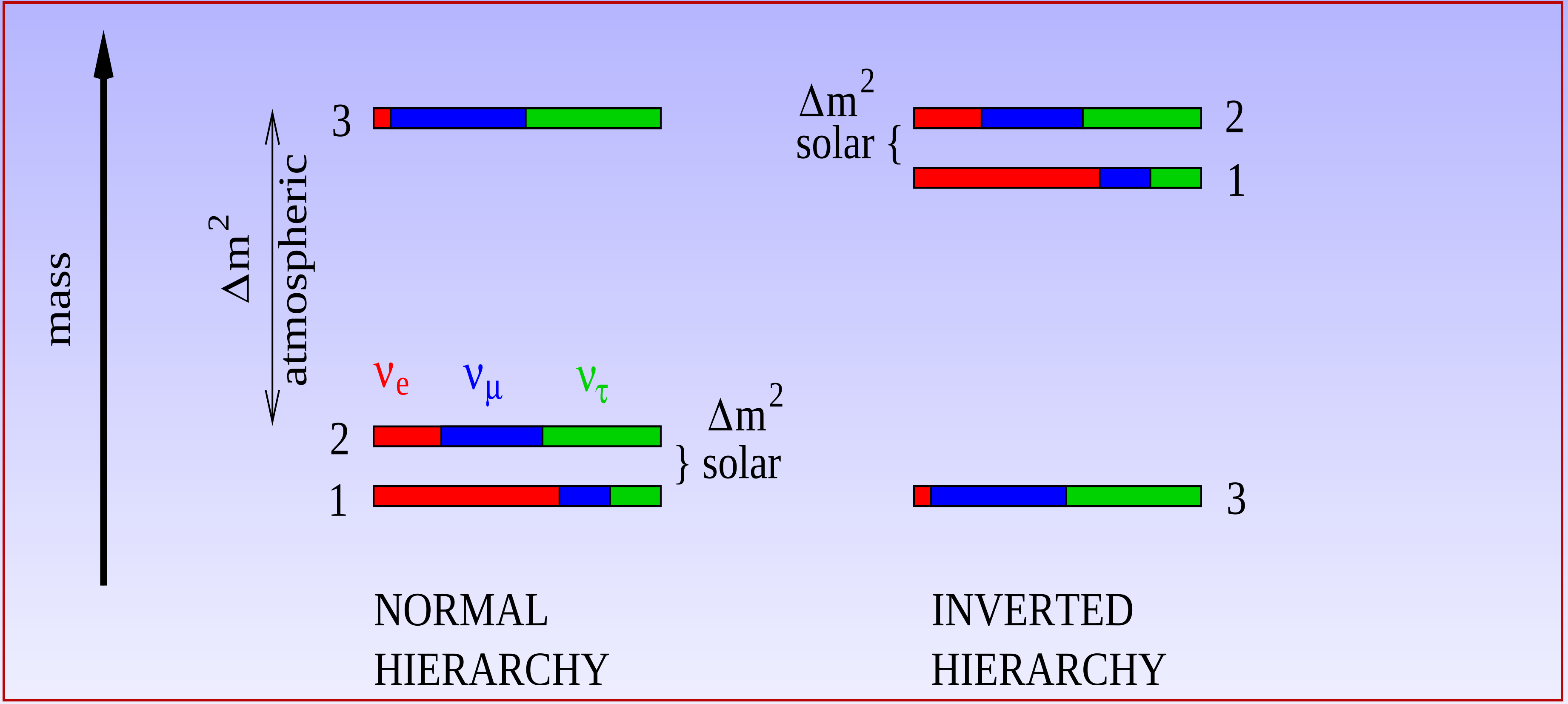
⇒ **Chooz + Palo Verde :**
$\sin^2 2\theta_{13} < \mathbf{0.17}$ **(3**σ**)**

⇒ **Two large mixing angles and the relative oscillation frequencies open the possibility to test CP violation in the neutrino sector, if** θ_{13} **and** δ_{CP} **are not vanishingly small**

Unsolved Issues

- **The sign of Δm^2_{31} $(m^2_3 - m^2_1)$ is not known.** **Neutrino mass spectrum can be normal or inverted hierarchical**



Continued..

- **Only an upper limit on** $\sin^2 2\theta_{13}$ (< 0.17 **at** 3σ) **exists**

- **The Dirac CP phase** (δ_{CP}) **is unconstrained**

We will focus on the first two issues. . .

Golden Channel ($P_{e\mu}$)

The appearance probability $(\nu_e \to \nu_\mu)$ **in matter, upto second order in the small parameters** $\alpha \equiv \Delta m^2_{21}/\Delta m^2_{31}$ **and** $\sin 2\theta_{13}$**,**

$$
\begin{aligned}
P_{e\mu} \quad \simeq \quad & \sin^2 2\theta_{13} \, \sin^2\theta_{23} \frac{\sin^2[(1-\hat{A})\Delta]}{(1-\hat{A})^2} \\
+ \quad & \alpha \, \sin 2\theta_{13} \, \xi \, \sin\delta_{CP} \sin(\Delta) \frac{\sin(\hat{A}\Delta)}{\hat{A}} \frac{\sin[(1-\hat{A})\Delta]}{(1-\hat{A})} \\
+ \quad & \alpha \, \sin 2\theta_{13} \, \xi \, \cos\delta_{CP} \cos(\Delta) \frac{\sin(\hat{A}\Delta)}{\hat{A}} \frac{\sin[(1-\hat{A})\Delta]}{(1-\hat{A})} \\
+ \quad & \alpha^2 \, \cos^2\theta_{23} \sin^2 2\theta_{12} \frac{\sin^2(\hat{A}\Delta)}{\hat{A}^2};
\end{aligned}
$$

where $\Delta \equiv \Delta m^2_{31} L/(4E)$**,** $\xi \equiv \cos\theta_{13} \, \sin 2\theta_{21} \, \sin 2\theta_{23}$**,**
and $\hat{A} \equiv \pm(2\sqrt{2} G_F n_e E)/\Delta m^2_{31}$

Cervera *et al.*, hep-ph/0002108

Freund, Huber, Lindner, hep-ph/0105071

Eight-fold Degeneracy

- $(\theta_{13},\ \delta_{CP})$ **intrinsic degeneracy**

  Burguet-Castell, Gavela, Gomez-Cadenas, Hernandez, Mena, hep-ph/0103258

- $(sgn(\Delta m^2_{31}),\ \delta_{CP})$ **degeneracy**

  Minakata, Nunokawa, hep-ph/0108085

- $(\theta_{23}, \pi/2 - \theta_{23})$ **degeneracy**

  Fogli, Lisi, hep-ph/9604415

Severely deteriorates the sensitivity

Problem & Solution

Degeneracies create "Clone" Solutions

Barger, Marfatia, Whisnant, hep-ph/0112119

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Barger, Marfatia, Whisnant, hep-ph/0112119

Kill the "Clones" at the "Magic" Baseline

Huber, Winter, hep-ph/0301257

Smirnov, hep-ph/0610198

Magic Baseline

Magic Baseline

If one chooses : $\sin(\hat{A}\Delta) = 0$

- **The** δ_{CP} **dependence disappears from** $P_{e\mu}$
- **Golden channel enables a clean determination of** θ_{13} **and** $sgn(\Delta m^2_{31})$

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First non-trivial solution: $\sqrt{2} G_F n_e L = 2\pi$ **(indep of E)**

- **Isoscalar medium of constant density ρ :**
  $L_{\rm magic}[{\rm km}] \approx 32725/\rho[{\rm gm/cm}^3]$
- **According to PREM, the "Magic Baseline"**

$L_{\rm magic}$ **= 7690 km**

Best-fit values

$$|\Delta m^2_{31}| = 2.5 \times 10^{-3} \text{ eV}^2$$

$$\sin^2 2\theta_{23} = 1.0$$

$$\Delta m^2_{21} = 8.0 \times 10^{-5} \text{ eV}^2$$

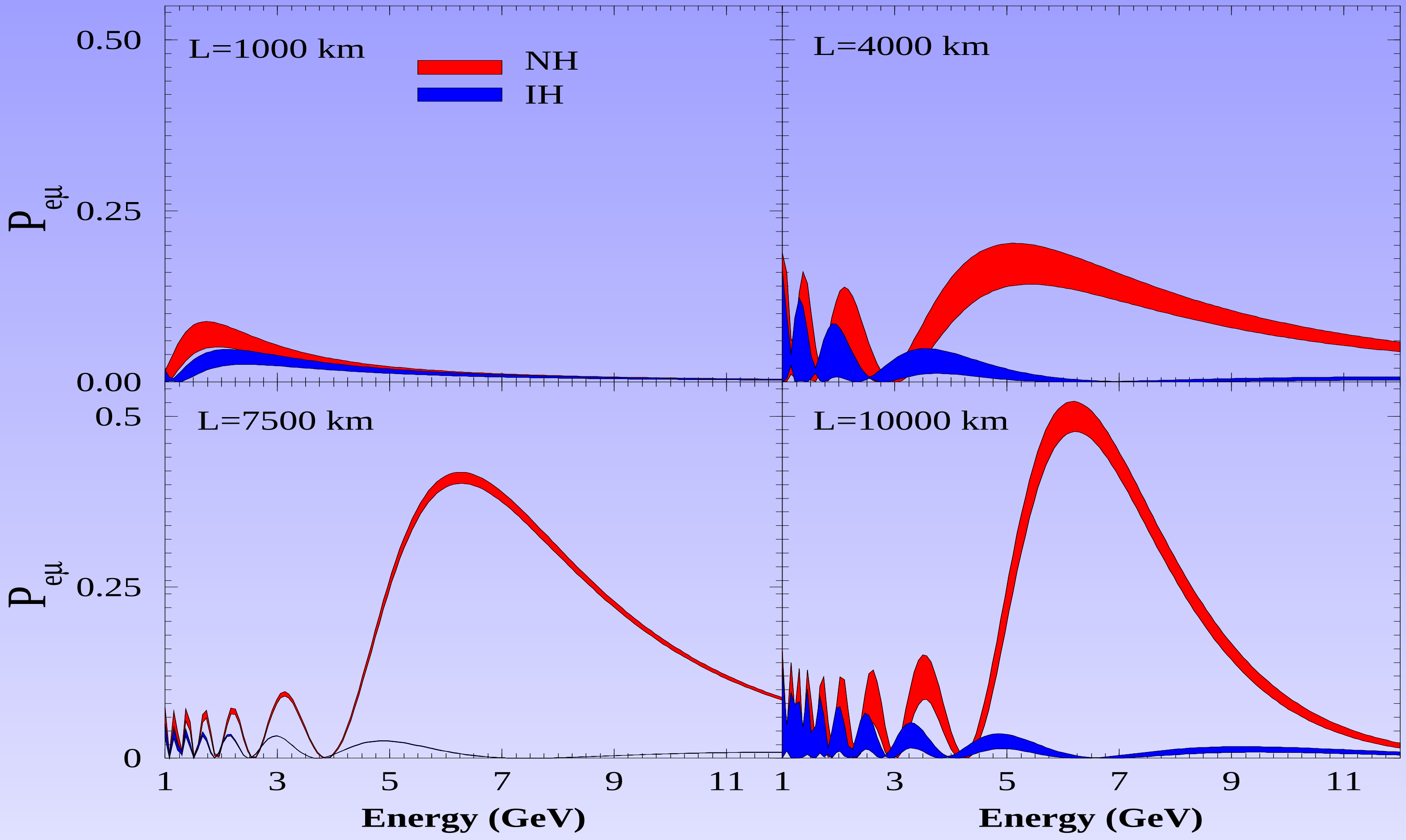
$$\sin^2 \theta_{12} = 0.31$$

$$\delta_{CP} = 0$$

Chosen benchmark values of oscillation parameters, except $\sin^2 2\theta_{13}$

Exact 3-flav osc. prob using PERM profile

Transition Probability $P_{e\mu}$



Agarwalla, Choubey, Raychaudhuri, hep-ph/0610333

Normal .vs. Inverted hierarchy $\sin^2 2\theta_{13} = 0.1$

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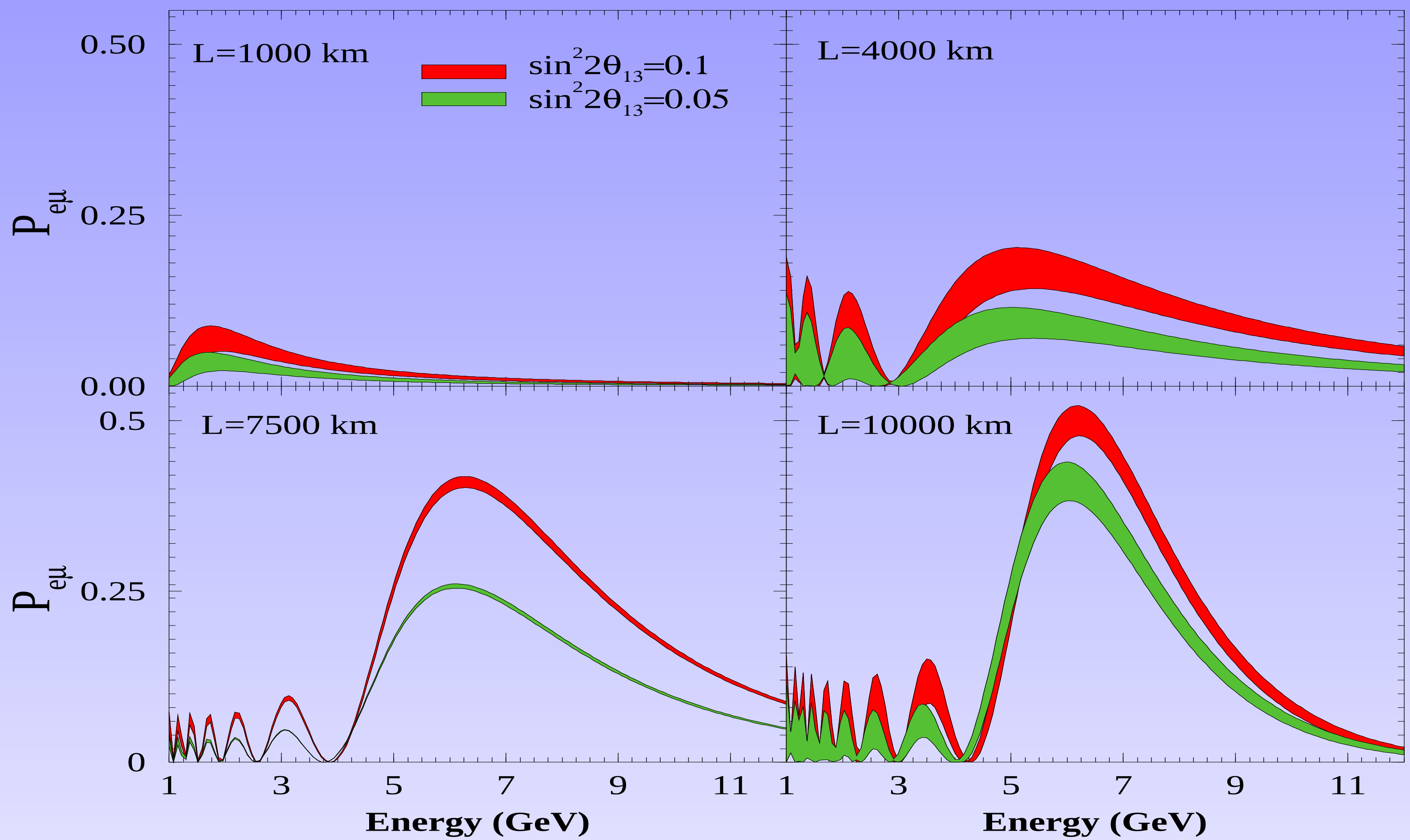
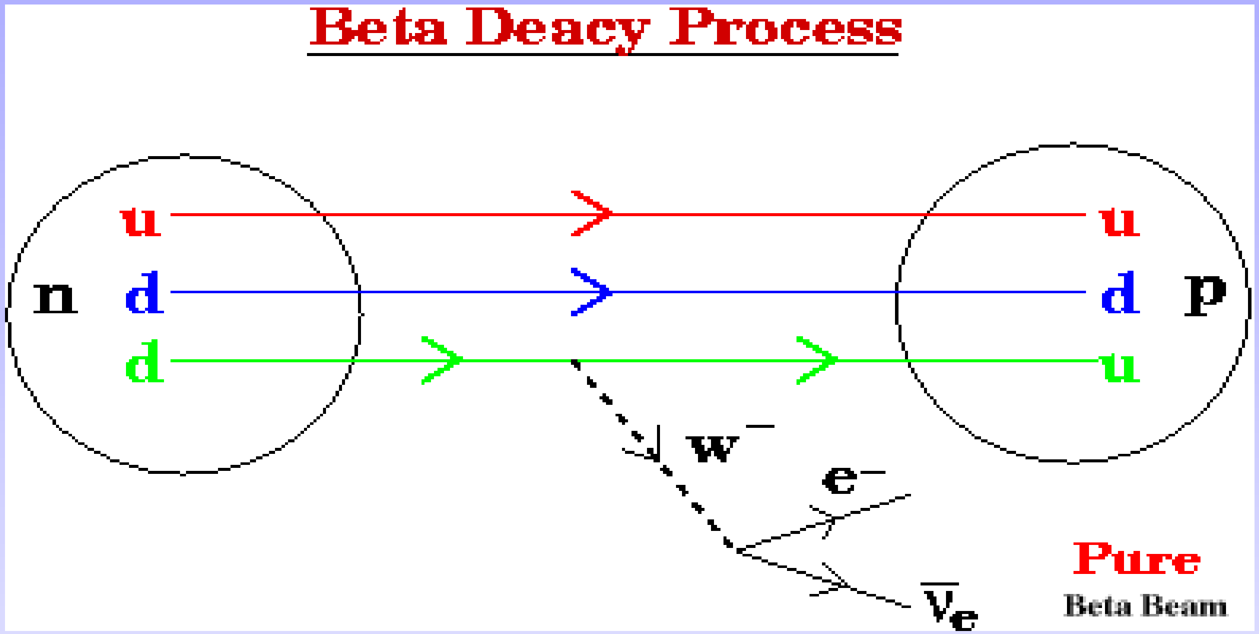


Agarwalla, Choubey, Raychaudhuri, hep-ph/0610333

Two different values of $\sin^2 2\theta_{13}$ **Normal hierarchy**

What is Beta Beam?

A pure, intense, collimated beam of ν_e or $\bar{\nu}_e$, essentially background free



P. Zucchelli, Phys. Lett. B 532 (2002) 166

Beta decay of completely ionized, radioactive ions circulating in a storage ring. No contamination of other types of neutrinos

Some positive features

- Known energy spectrum
- High intensity and low systematic errors
- High Lorentz boost of the parent ions $\Rightarrow$ better collimation and higher energy of beam

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- Known energy spectrum
- High intensity and low systematic errors
- High Lorentz boost of the parent ions $\Rightarrow$ better collimation and higher energy of beam
- Can be produced with existing CERN facilities or planned upgrades
- It can be operated simultaneously in the ν_e as well as $\bar{\nu}_e$ mode. The boost factors are fixed by the e/m ratio of the respective ions

Beta Beam : Ion sources

Ion	τ (s)	E_0 (MeV)	f	Decay fraction	Beam
$^{18}_{10}$Ne	2.41	3.92	820.37	92.1%	ν_e
$^{6}_{2}$He	1.17	4.02	934.53	100%	$\bar{\nu}_e$
$^{8}_{5}$B	1.11	14.43	600684.26	100%	ν_e
$^{8}_{3}$Li	1.20	13.47	425355.16	100%	$\bar{\nu}_e$

Comparison of different source ions

Low-γ design, useful decays in case of anti-neutrinos can be 2.9×10^{18}/year and for neutrinos 1.1×10^{18}/year

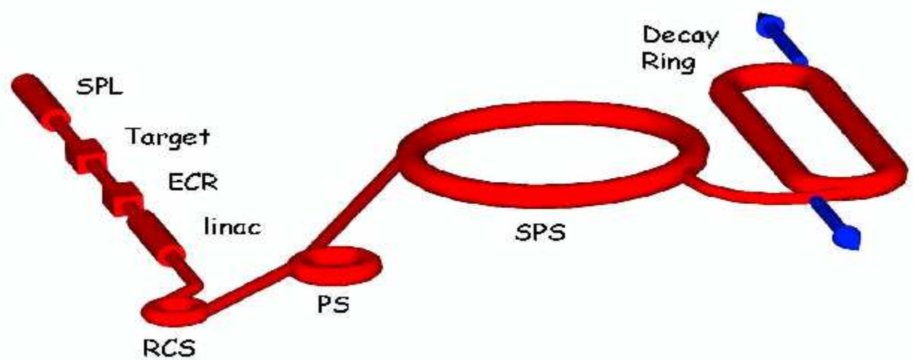
Larger total end-point energy, E_0 is preferred

Schematic Lay-out

- Baseline Beta Beam facility comprises these sections
  - Proton Driver
    - SPL (≈4 GeV)
  - ISOL Target
    - spallation neutrons or direct protons
  - Ion Source
    - pulsed ECR
  - Acceleration
    - linac, RCS, PS, SPS
  - Decay Ring
    - 7000 m; 2500 m straight

Baseline concept assumes CERN PS, SPS

Use of Tevatron also being considered



Proposed β-beam complex at CERN

Comparison with Nufact

ν-factory → proton $\xrightarrow{\text{target}}$ π^+ + ...

↳ $\mu^+ + \nu_\mu$ (super-beam)

↳ $e^+ + \nu_\mu + \bar{\nu}_e$

and charge conjugated

beta-beam → proton $\xrightarrow{\text{target}}$ isotope

↳ isotope* + $e^+ + \nu_e$

ν-factory uses beam of 4th generation.
Beta-beam uses 3rd generation beam.
Beta-beam is technically closer to existing/used accelerator technology.

Ion source ⇒ Acceleration ⇒ Storage ⇒ Neutrino beam

Ultimate choice depends on future R&D

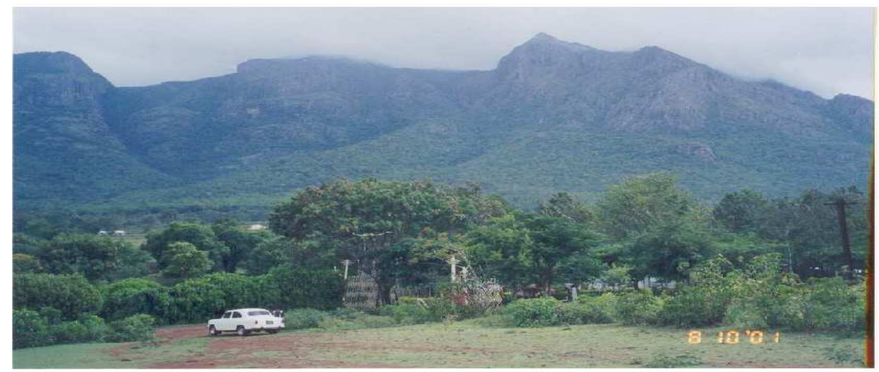
INO

The India-based Neutrino Observatory

The INO/ICAL will be the world's first magnetized large mass iron calorimeter with interleaved Glass RPC detectors

Funding considerations in final stage

Location of INO

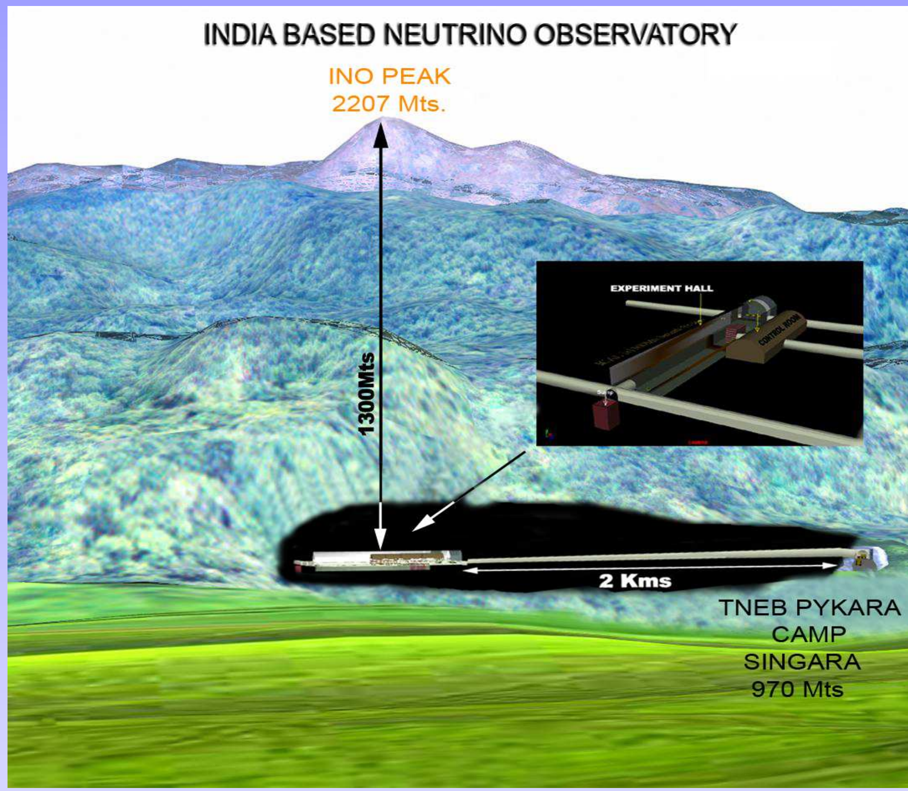


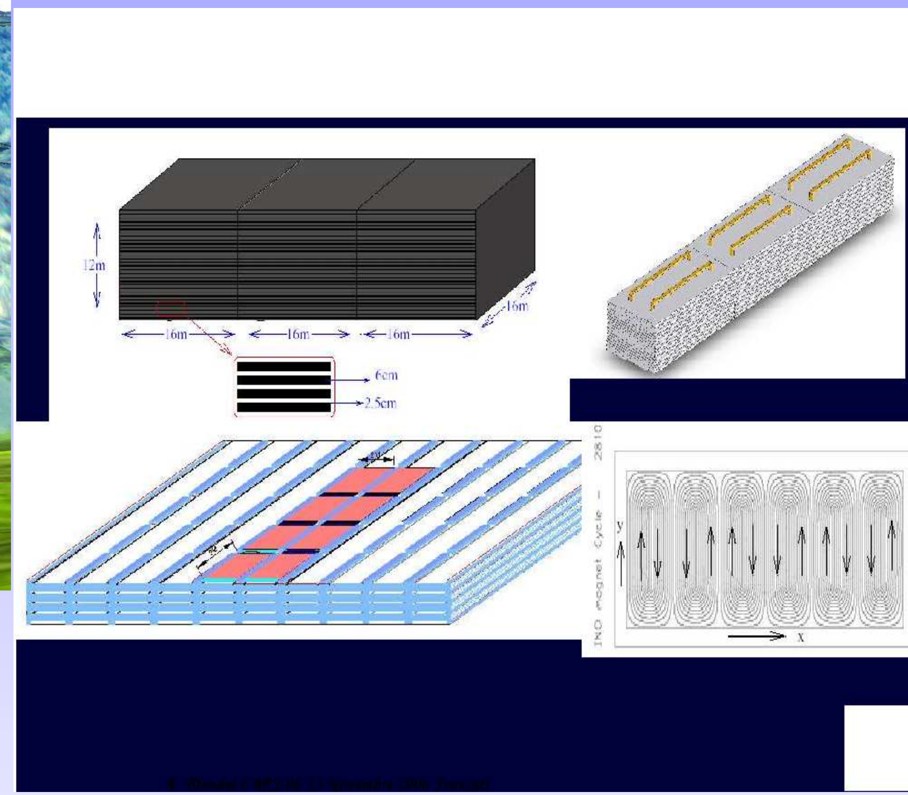
PUSHEP Site (Lat: N11.5°, Long: E76.6°)

PUSHEP-Bangalore: 250km

http://www.imsc.res.in/∼ino/

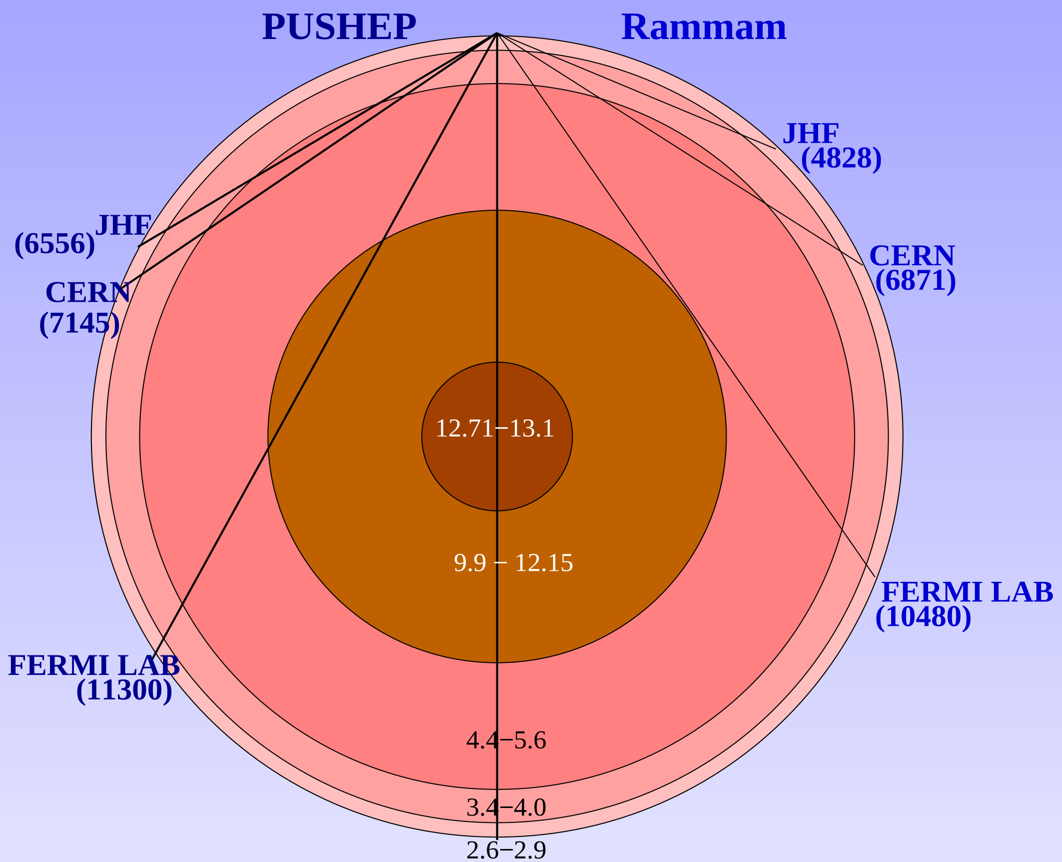
ICAL Design





Spokesperson: Prof. N.K. Mondal, TIFR

INO : 2nd Phase



Artificial Source

Beta Beam ?

Neutrino Factory ?

$L_{\text{magic}} = \mathbf{7690\ km}$

INO

- A magnetized Iron calorimeter (ICAL) detector with excellent efficiency of charge identification ($\sim 95\%$) and good energy determination

- Preferred location is Singara (PUSHEP) in the Nilgiris (near Bangalore), 7152 km from CERN

- A (50+50) Kton Iron detector

- Oscillation signal is the muon track ($\nu_e \rightarrow \nu_\mu$ channel)

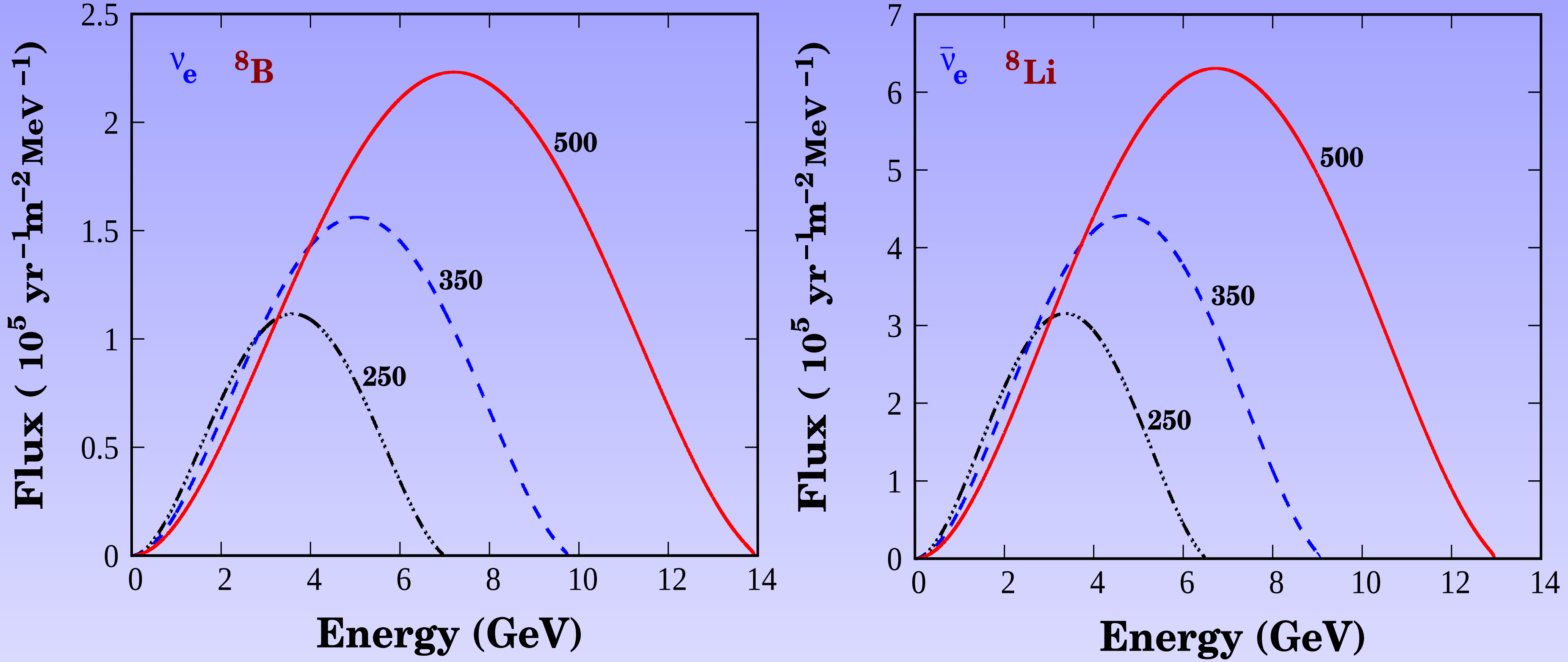
Detector assumptions

Total Mass	50 kton
Energy threshold	1.5 GeV
Detection Efficiency (ϵ)	60%
Charge Identification Efficiency (f_{ID})	95%

Detector characteristics used in the simulations

We assume a Gaussian energy resolution function with $\sigma = 0.15E$

β-beam flux at INO-ICAL



Agarwalla, Choubey, Raychaudhuri, hep-ph/0610333

Boosted on-axis spectrum of ν_e and $\bar{\nu}_e$
at the far detector assuming no oscillation

CERN - INO Long Baseline

$L_{\mathrm{CERN-INO}} = \mathbf{7152\ km}$

- **The longer baseline captures a matter-induced contribution to the neutrino parameters, essential for probing the sign of Δm^2_{31}**

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$L_{\text{CERN-INO}}$ **= 7152 km**

- **The longer baseline captures a matter-induced contribution to the neutrino parameters, essential for probing the sign of Δm^2_{31}**
- **The CERN - INO baseline, close to the 'Magic' value, ensures essentially no dependence of the final results on δ_{CP}. This 'Magic' value is independent of E**
- **This permits a clean measurement of θ_{13} avoiding the degeneracy issues which plague other baselines**

Resonance in matter effect

- **The very long CERN - INO baseline provides an excellent avenue to pin-down matter induced contributions**

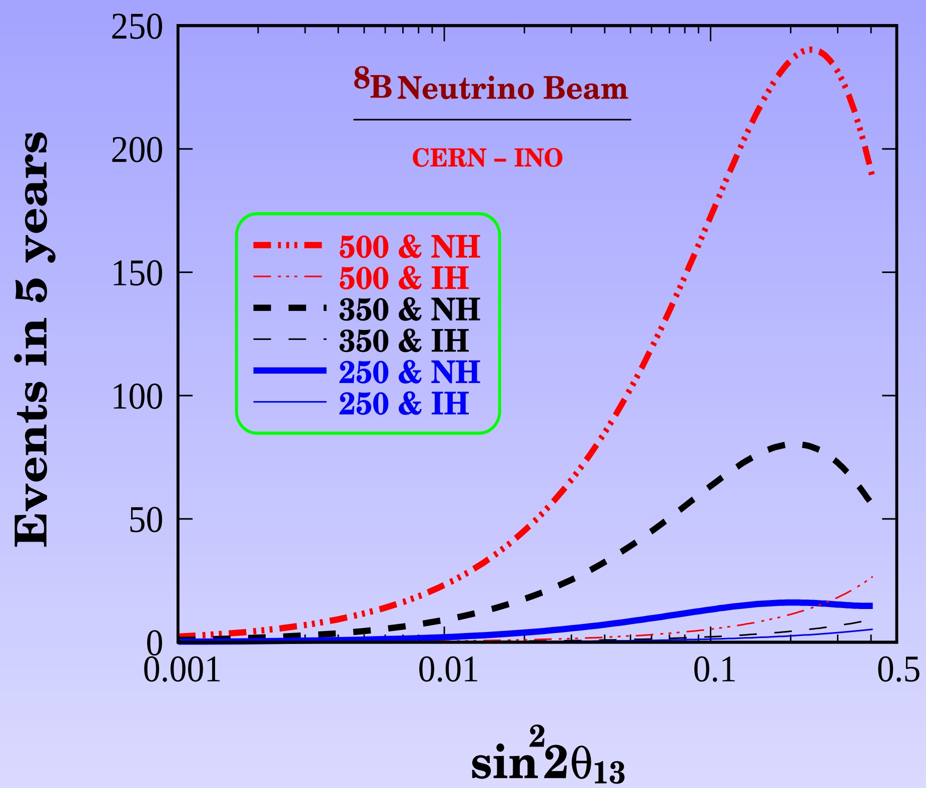
- **In particular, a resonance occurs at**

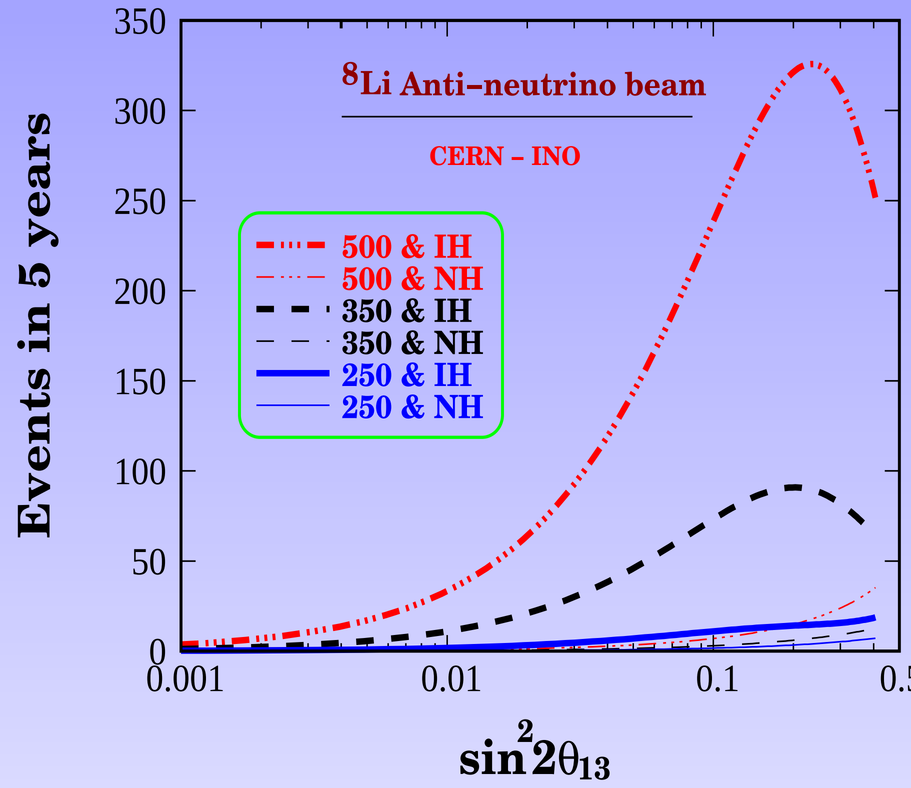
$$E_{res} \equiv \frac{|\Delta m^2_{31}| \cos 2\theta_{13}}{2\sqrt{2} G_F N_e}$$

$$= \mathbf{6.1\ GeV}$$

with $|\Delta m^2_{31}| = 2.5 \times 10^{-3}$ **eV^2,** $\sin^2 2\theta_{13} = 0.1$ **and** $\rho_{av} = 4.13$ **gm/cc (PREM) for the baseline of 7152 km**

Event Rates in INO-ICAL





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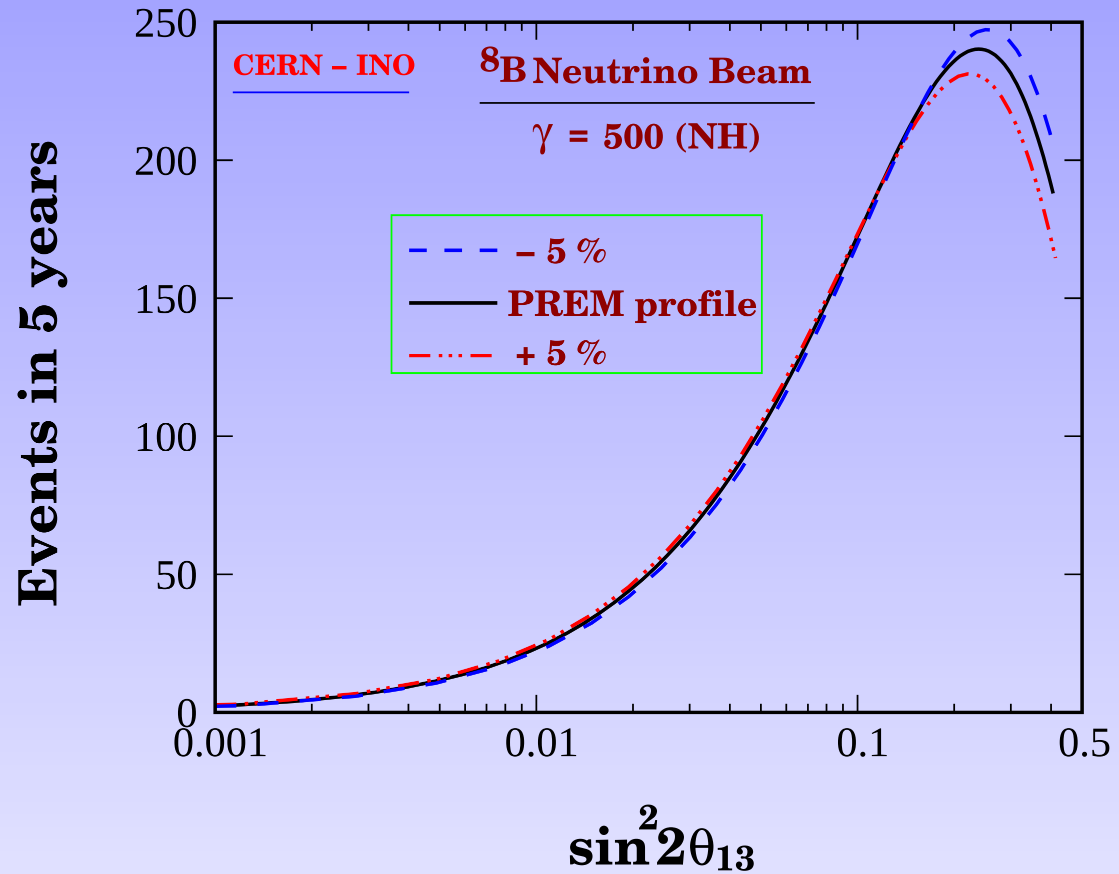
Event rates sharply depend on mass ordering and θ_{13}

Event Rates (contd..)



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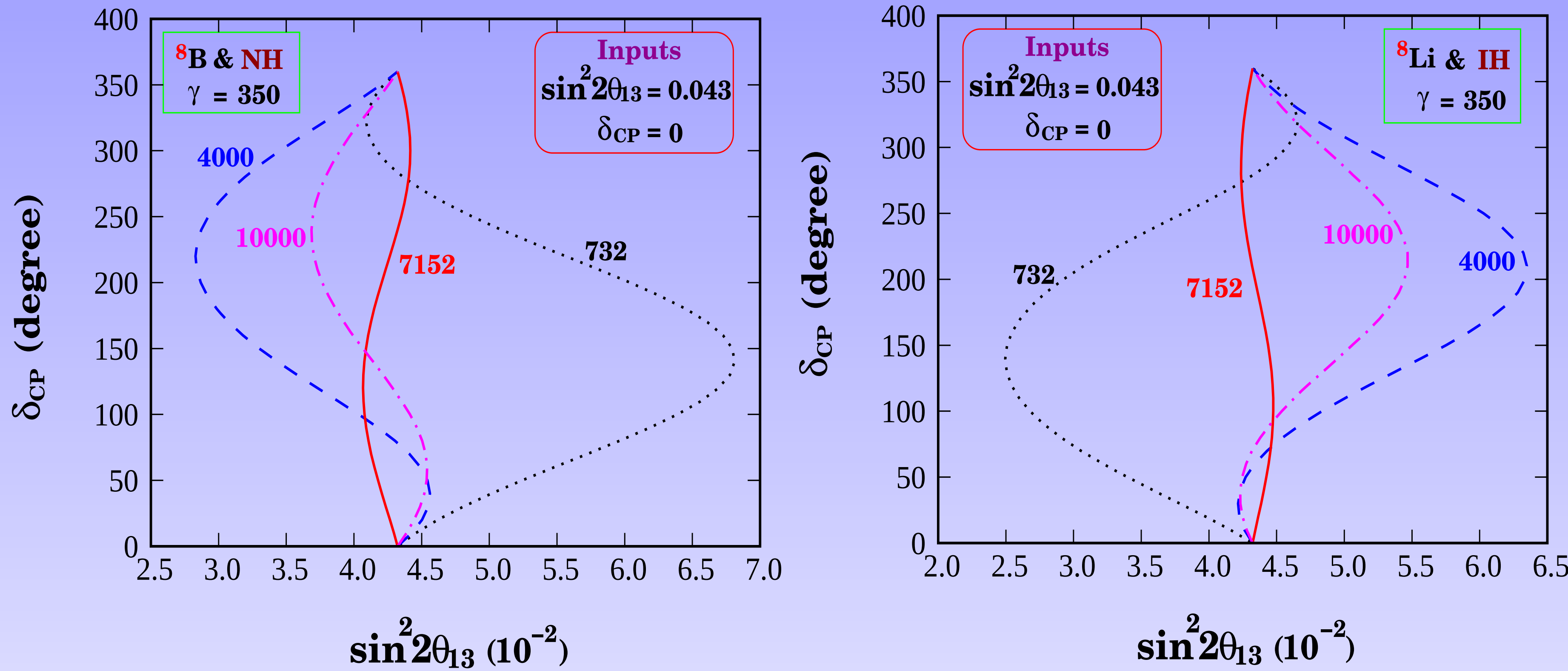
Sensitivity to matter profile

Iso-event curves



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At CERN-INO distance, the effect of δ_{CP} on the measurement of θ_{13} is less

The χ^2 function

Assume Poissonian distribution and define

$$\chi^2(\{\omega\}) = \min_{\xi_k}\left[2\left(\tilde{N}^{th} - N^{ex} - N^{ex}\ln\frac{\tilde{N}^{th}}{N^{ex}}\right) + \sum_k \xi_k^2\right]$$

$\{\omega\}$: oscillation parameters, $\{\xi_k\}$: "pulls", where k runs over systematic uncertainties

$$\tilde{N}^{th}(\{\omega\},\{\xi_k\}) = N^{th}(\{\omega\})\left[1 + \sum_{k=1}^{K}\pi^k\xi_k\right] + \mathcal{O}(\xi_k^2)$$

Minimize χ^2 with respect to the pulls $\{\xi_k\}$ and finally marginalize over oscillation parameters by minimizing $\chi^2_{total} = \chi^2 + \chi^2_{prior}$

The systematic errors

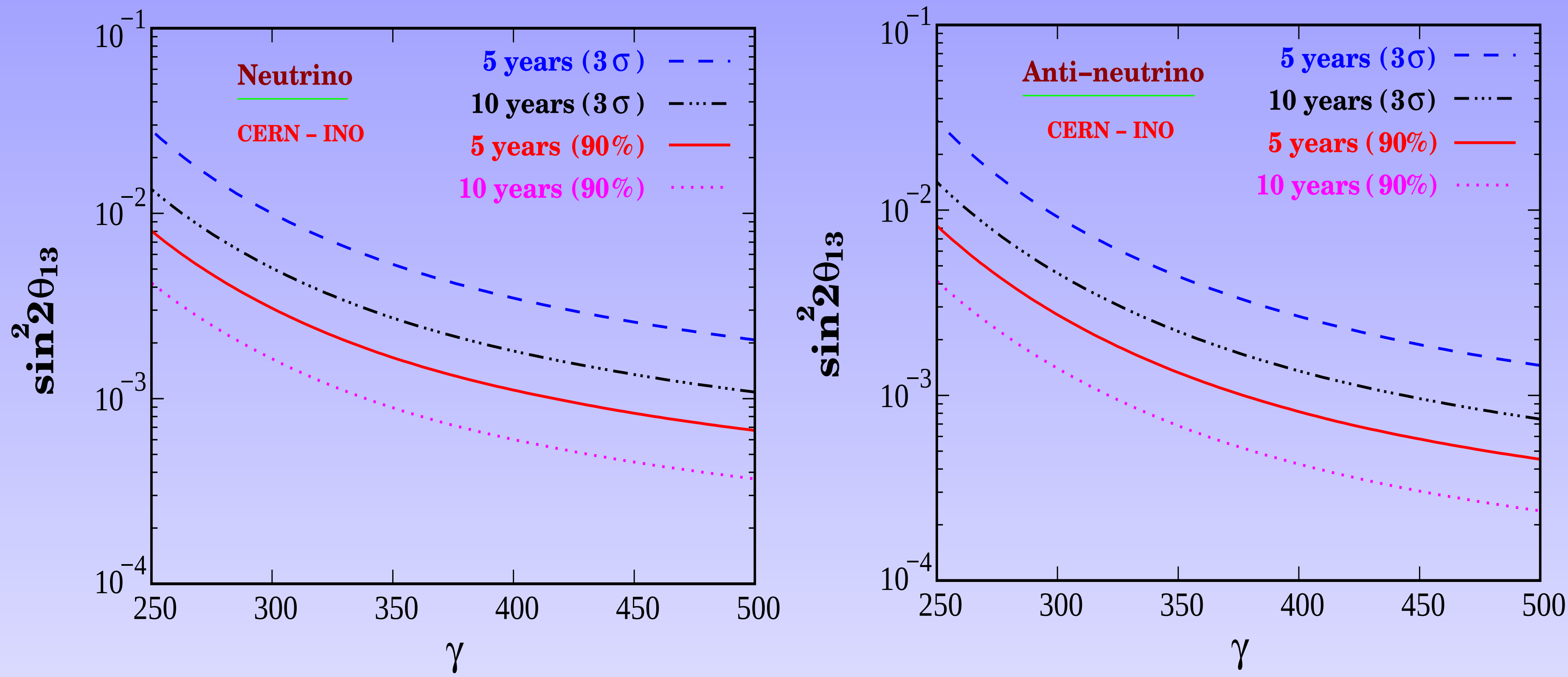
2% flux normalization error

10% error in the interaction cross section

Detector systematic uncertainty of 2%

No systematic error related to the shape of the energy spectrum. We work with the energy integrated total rates

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



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$\sin^2 2\theta_{13}$ **limit below which experiment is insensitive**

For ν_e ($\bar{\nu}_e$) true hierarchy is assumed normal (inverted)

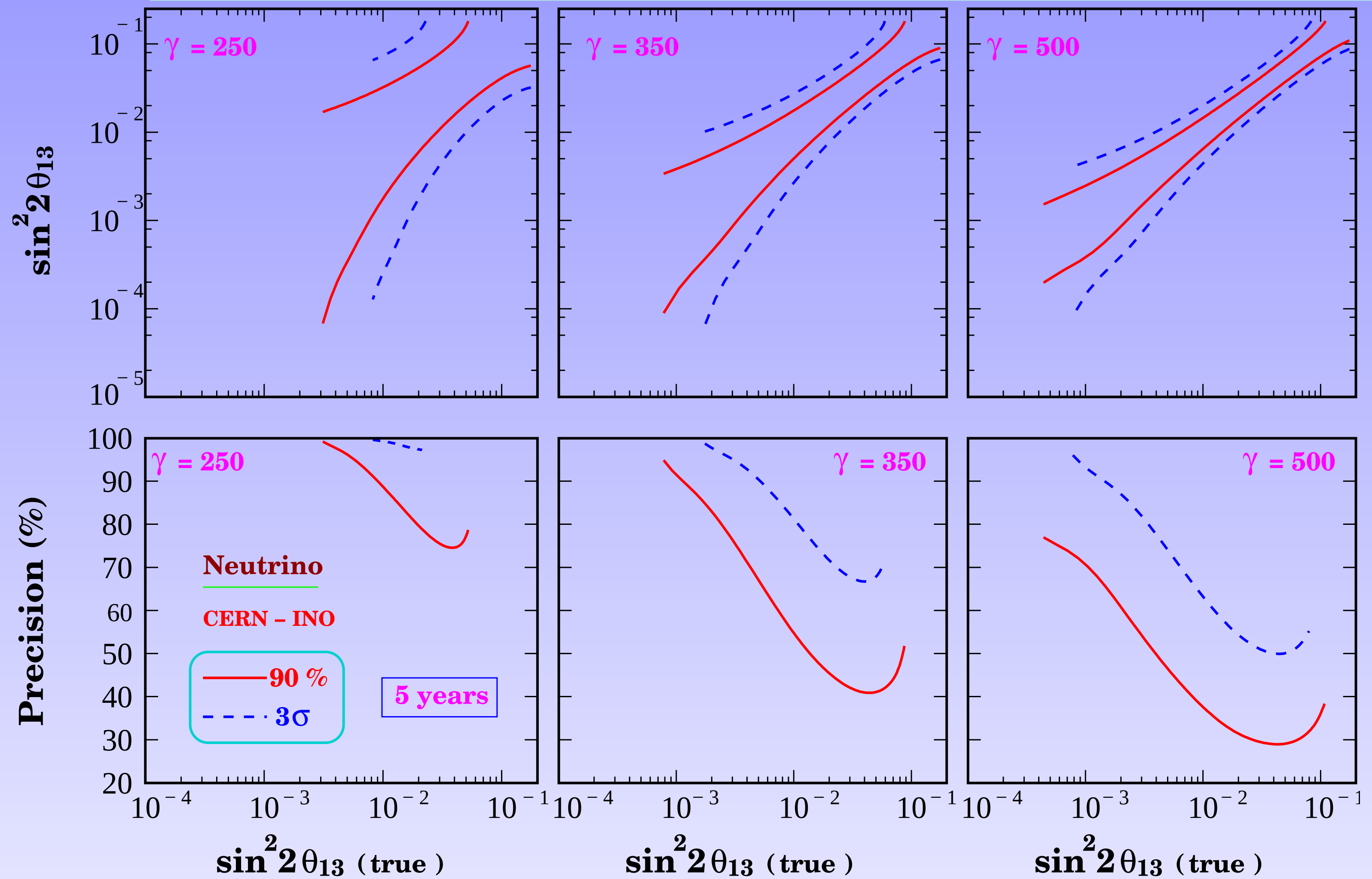
Marginalization over $|\Delta m^2_{31}|$, $\sin^2 2\theta_{23}$ and δ_{CP}

Upper limit on $\sin^2 2\theta_{13}$

At 3σ**,** $\sin^2 2\theta_{13} < 8.4 \times 10^{-4} (1.6 \times 10^{-3})$ **with** 80% **detection efficiency and 10(5) years data in the neutrino mode assuming normal hierarchy as true with** $\gamma = 500$

At 3σ**,** $\sin^2 2\theta_{13} < 1.1 \times 10^{-3} (2.1 \times 10^{-3})$ **with** 60% **detection efficiency and 10(5) years data in the neutrino mode assuming normal hierarchy as true with** $\gamma = 500$

$\sin^2 2\theta_{13}$ precision (5 yrs)



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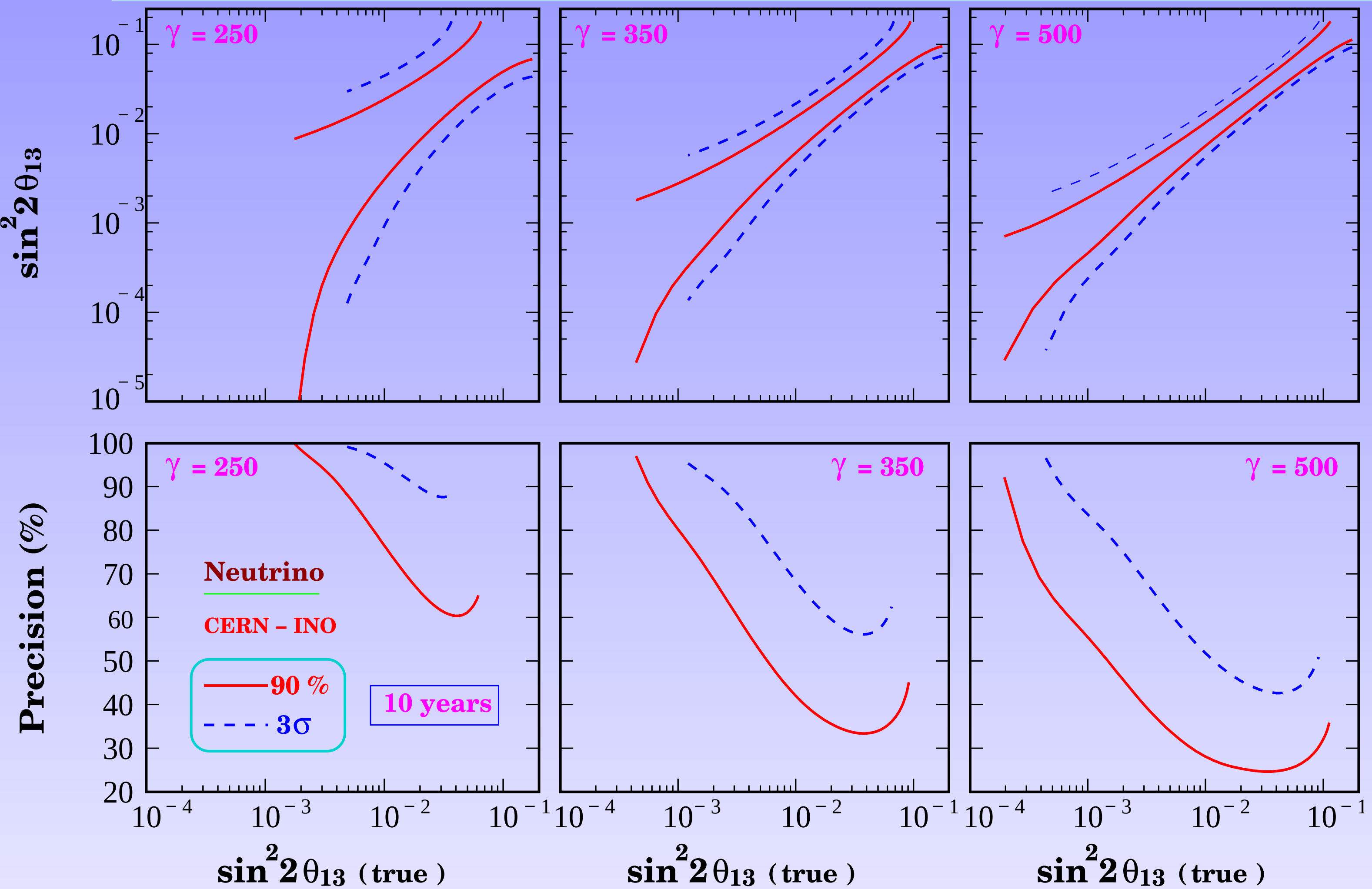
Upper panels show the band of “measured” values of $\sin^2 2\theta_{13}$ and lower ones depict the corresponding precision

$\sin^2 2\theta_{13}$ precision (10 yrs)



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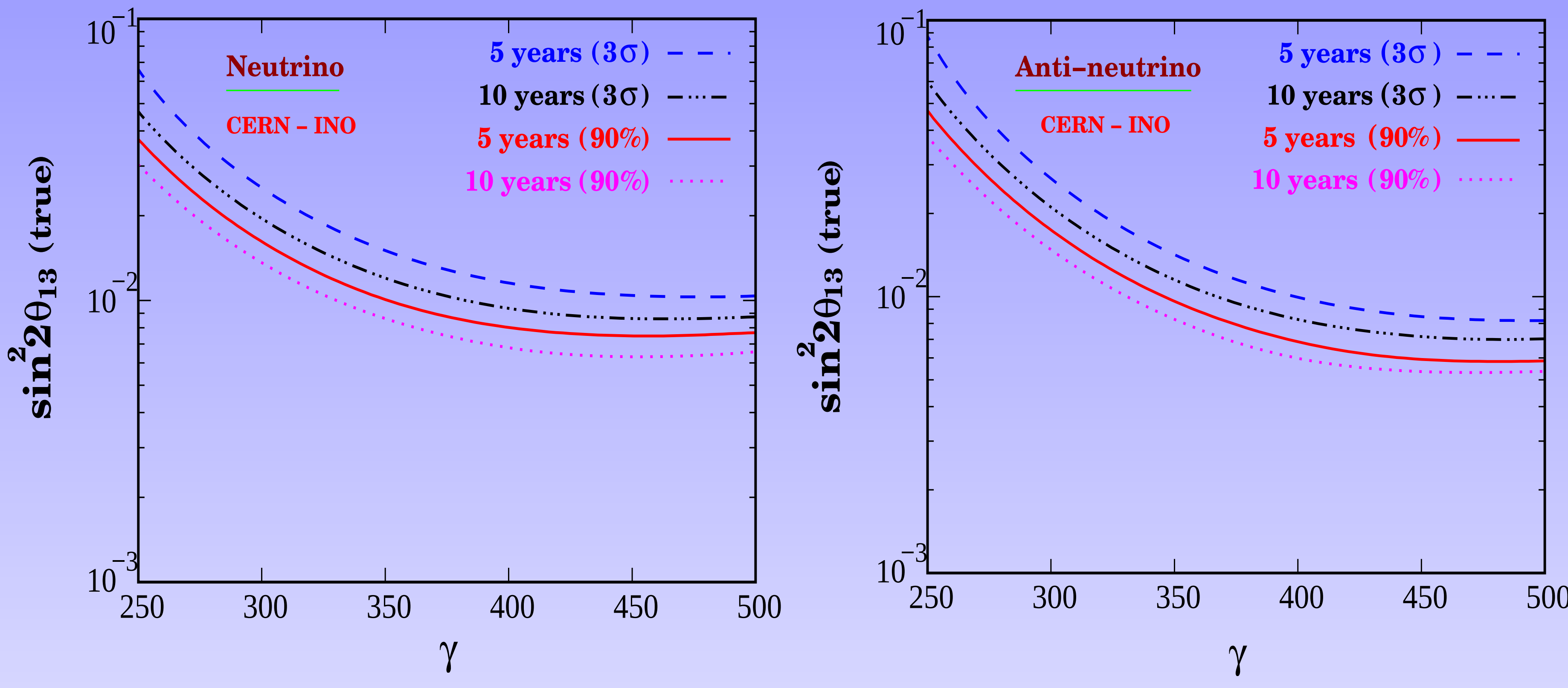
Upper panels show the band of "measured" values of $\sin^2 2\theta_{13}$ and lower ones depict the corresponding precision

Sensitivity to $Sgn(\Delta m^2_{31})$



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Min value of $\sin^2 2\theta_{13}$(true) as a function of γ to rule out wrong hierarchy. True hierarchy is normal (inverted) for ν_e ($\bar{\nu}_e$).

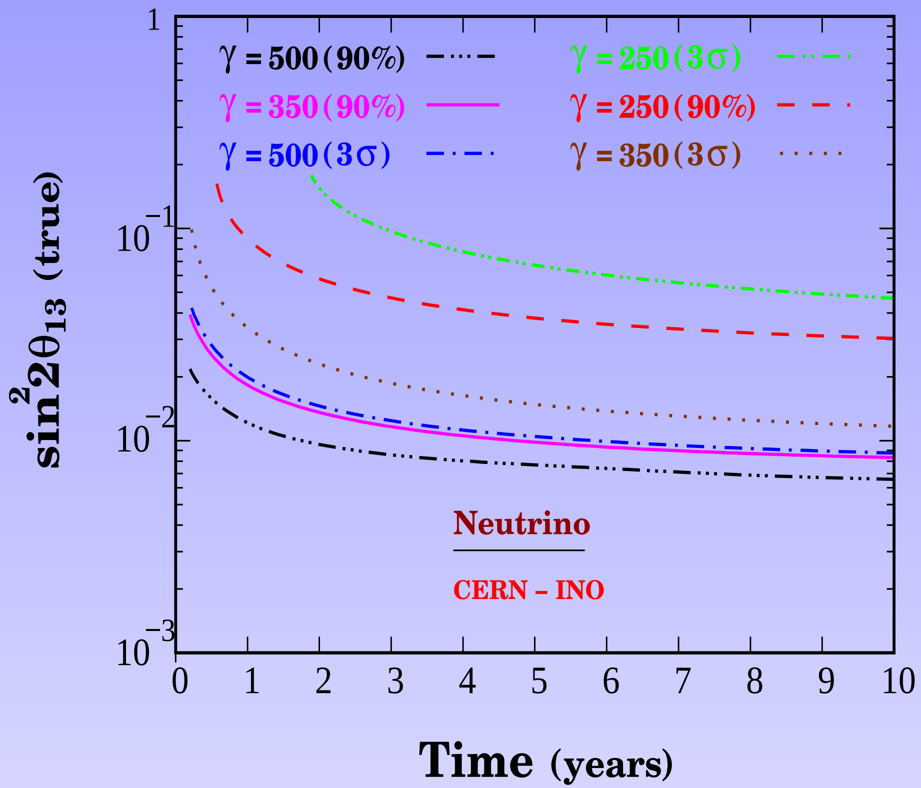
Marginalized over $|\Delta m^2_{31}|$, $\sin^2 2\theta_{23}$, δ_{CP} and $\sin^2 2\theta_{13}$

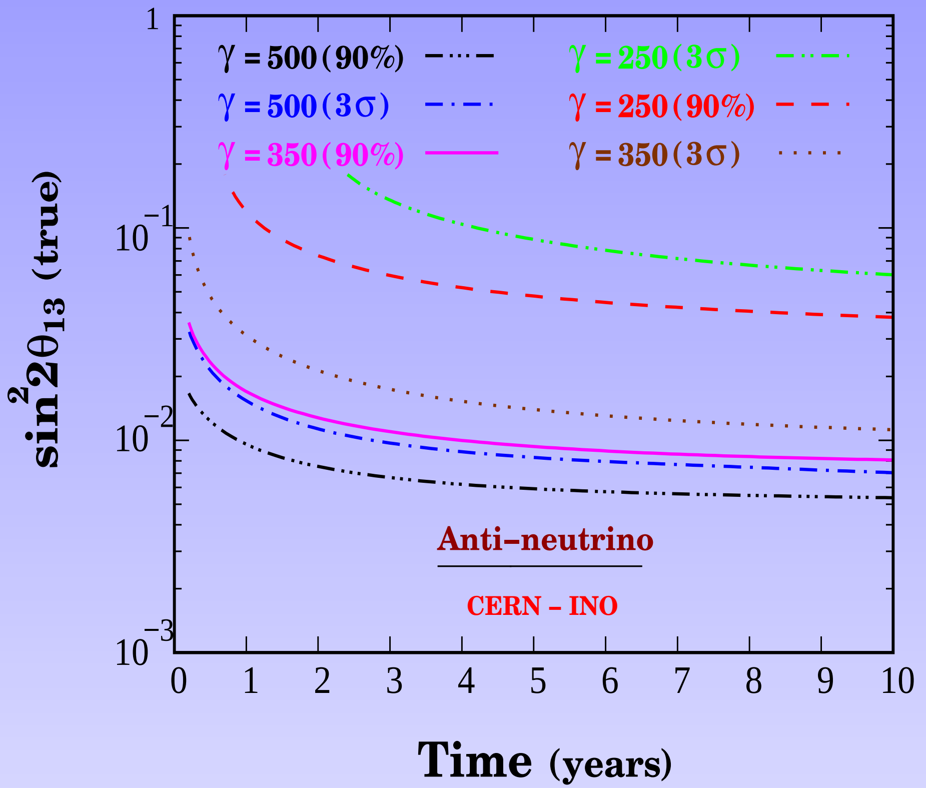
Sensitivity to mass ordering

Minimum value of $\sin^2 2\theta_{13} \rightarrow 8.5 \times 10^{-3} (9.8 \times 10^{-3})$ for which one can rule out inverted hierarchy at 3σ C.L. with 10(5) years of neutrino run assuming normal hierarchy as true hierarchy with $\gamma = 500$ and 80% detection efficiency

Minimum value of $\sin^2 2\theta_{13} \rightarrow 8.7 \times 10^{-3} (1.0 \times 10^{-2})$ for which one can rule out inverted hierarchy at 3σ C.L. with 10(5) years of neutrino run assuming normal hierarchy as true hierarchy with $\gamma = 500$ and 60% detection efficiency

How much time we need?





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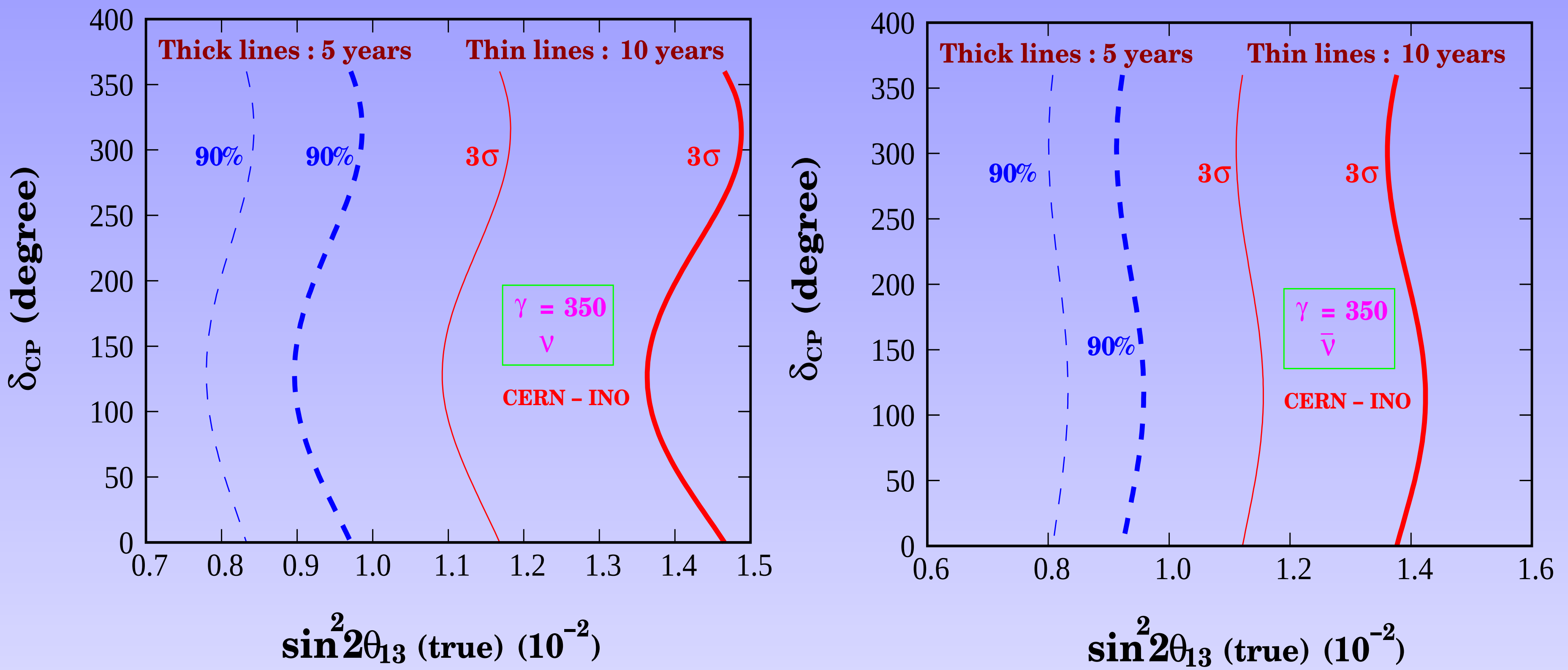
Just 9 months run in the ν_e mode to rule out the wrong inverted hierarchy at the 3σ C.L. with $\gamma = 500$ and 60% detection efficiency if $\sin^2 2\theta_{13}(\text{true}) = 5 \times 10^{-2}$ and the normal hierarchy is true

Impact of δ_{CP} on hierarchy



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The loss in hierarchy sensitivity due to the uncertainty in δ_{CP} is very marginal. Best sensitivity to hierarchy comes for $\delta_{CP} \simeq 125$ (300) in the ν ($\bar{\nu}$) mode

Conclusions

- Ical@INO → 50 Kt magnetized iron calorimeter
- CERN-INO baseline (7152 Km) - tantalizingly close to the magic baseline and hence will be free of the clone solutions

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- At this baseline we can get near-resonant matter effect for $E \approx 6\ GeV$ $\Rightarrow$ possible with ${}^8_5$B and ${}^8_3$Li
- Near-resonant matter effect gives largest possible $P_{e\mu}$ $\Rightarrow$ enough statistics

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- Near-resonant matter effect gives largest possible $P_{e\mu}$ $\Rightarrow$ enough statistics
- The CERN-INO Beta-Beam experiment is expected to give sensitivity to θ_{13} and $Sgn(\Delta m^2_{31})$ better than all other rival proposals, apart from a high performance neutrino factory

Wait for Magic

!! Thank You !!