# Neutrino mass hierarchy and $\theta_{13}$ with a magic baseline Beta Beam experiment

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**Phys. Lett. B629 (2005) 33-40 & hep-ph/0610333**

# PLAN

- Unsolved Issues
- “Golden Channel”, $P_{e\mu}$
- “Eight-fold” degeneracy
- “Magic Baseline”
- CERN based $\beta$-beam source
- India-Based Neutrino Observatory (INO)
- Results
- Conclusions

# Missing Links

- **The sign of $\Delta m^2_{31}$ $(m_3^2 - m_1^2)$ is not known. Neutrino mass spectrum can be direct or inverted hierarchical**

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

- **The CP phase $(\delta_{CP})$ is unconstrained**

# 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 $\sin 2\theta_{13}$,**

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

**where $\Delta \equiv \Delta m^2_{31} L/(4E)$, $\xi \equiv \cos\theta_{13}\, \sin 2\theta_{21}\, \sin 2\theta_{23}$,**

**and $\hat{A} \equiv \pm(2\sqrt{2} G_F n_e E)/\Delta m^2_{31}$.**

# Eight-fold Degeneracy

- $(\theta_{13}, \delta_{CP})$ **intrinsic degeneracy**
- $(sgn(\Delta m^2_{31}), \delta_{CP})$ **degeneracy**
- $(\theta_{23}, \pi/2 - \theta_{23})$ **degeneracy**

$\Rightarrow$ **severely deteriorates the sensitivity**

# Magic Baseline

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

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

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

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

$$\boxed{L_{\rm magic} = \mathbf{7690\ km}}$$

# CERN - INO Long Baseline

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

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

# Resonance in matter effect

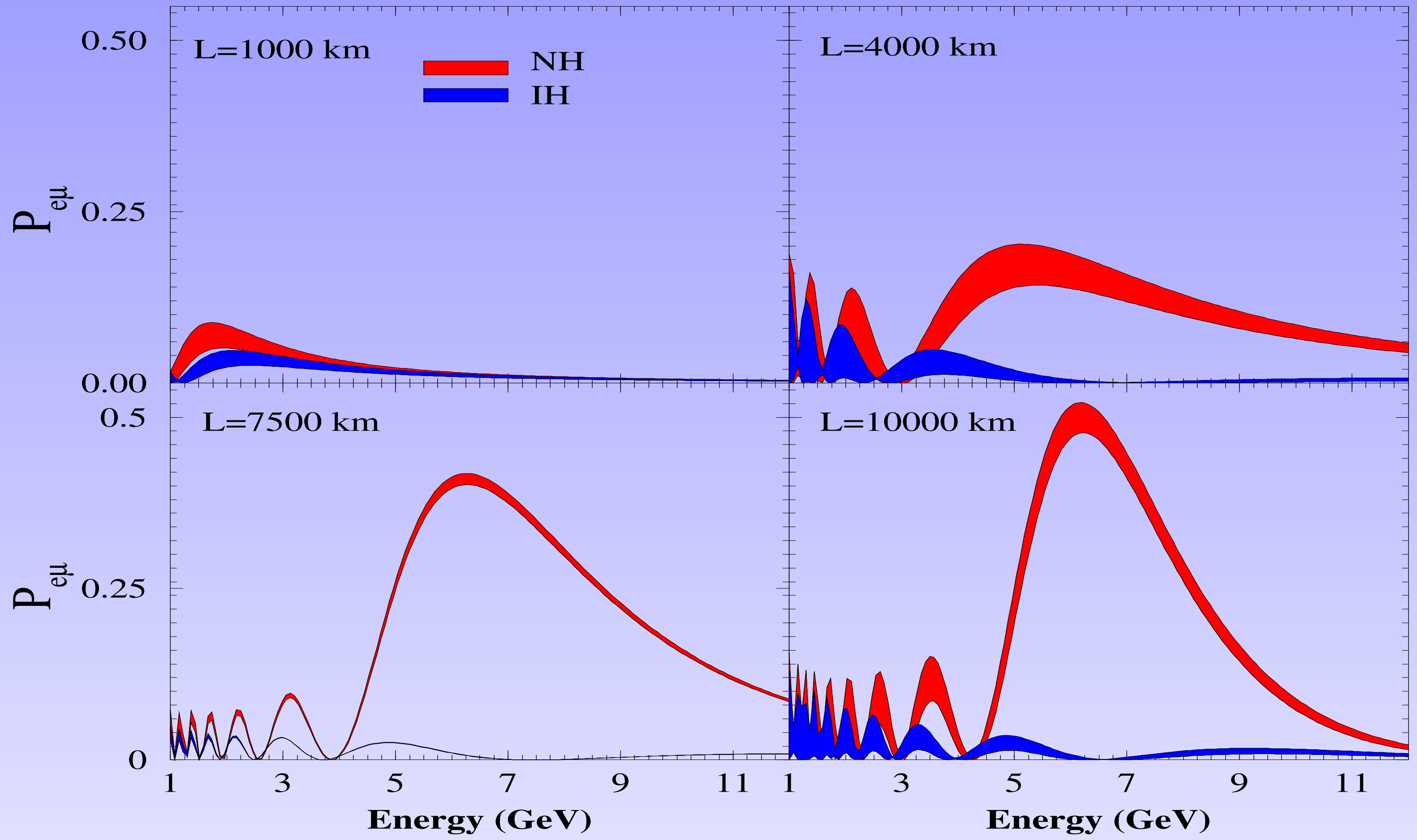
- The very long CERN - INO baseline provides an excellent avenue to pin-down matter induced contributions
- In particular, a resonance occurs at

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

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

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**

# Transition Probability $P_{e\mu}$

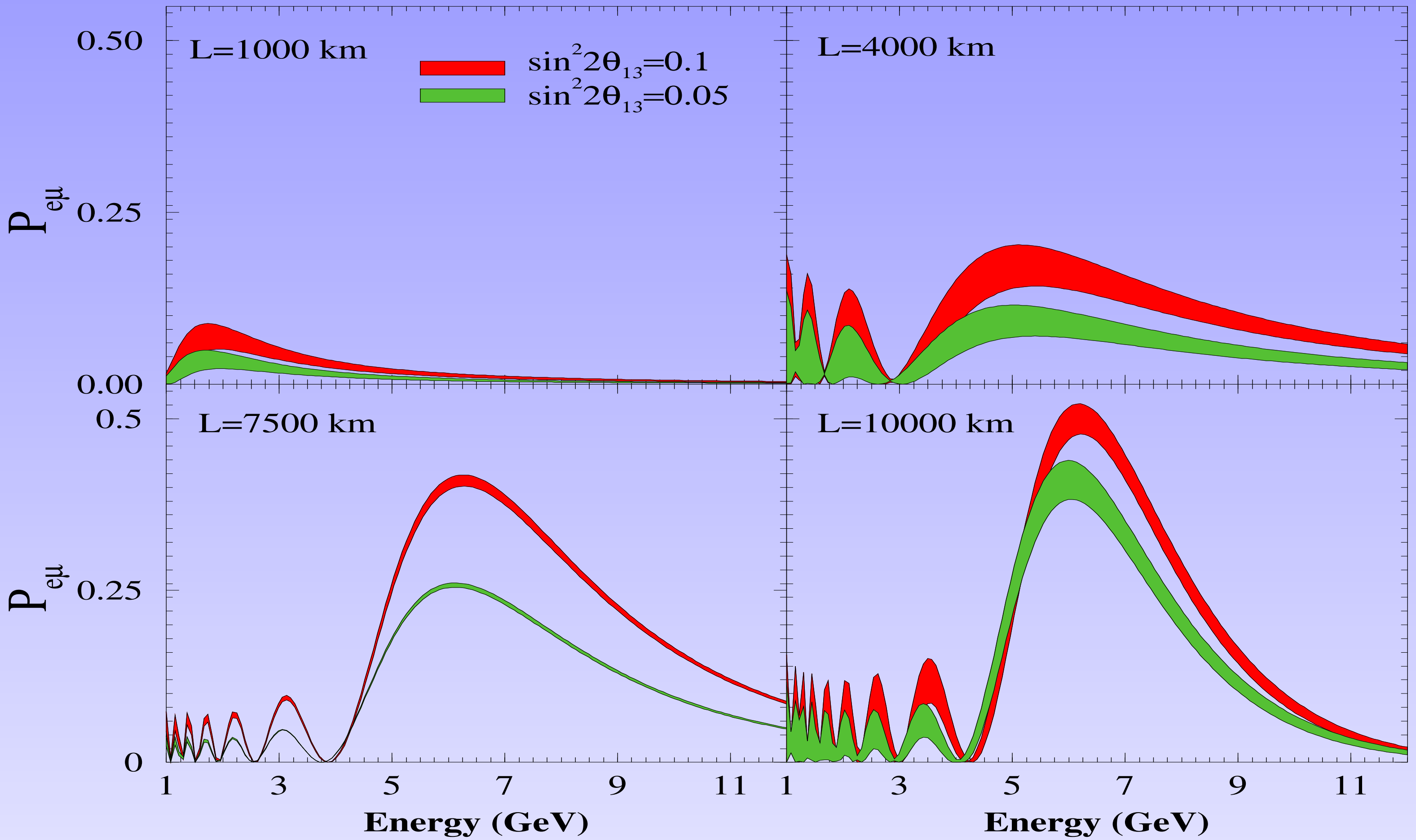


Transition probability for different baselines

Normal .vs. Inverted hierarchy

$\sin^2 2\theta_{13} = 0.1$ & all other osc. param. are fixed to their best-fit

# Transition Probability $P_{e\mu}$



Transition probability for different baselines

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

Normal hierarchy & all other osc. param. are fixed to their best-fit

# What is Beta Beam?

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

- **$\nu_e$ and $\bar{\nu}_e$ beams may also be produced at the same time in the set-up**

- **Origin : 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 ⇒ better collimation and higher energy of beam
- Can be produced with existing CERN facilities or planned upgrades
- Both $\nu_e$ and $\bar{\nu}_e$ beams can run simultaneously in the storage ring. The boost factors are fixed by their e/m ratio

# Beta Beam : Ion sources

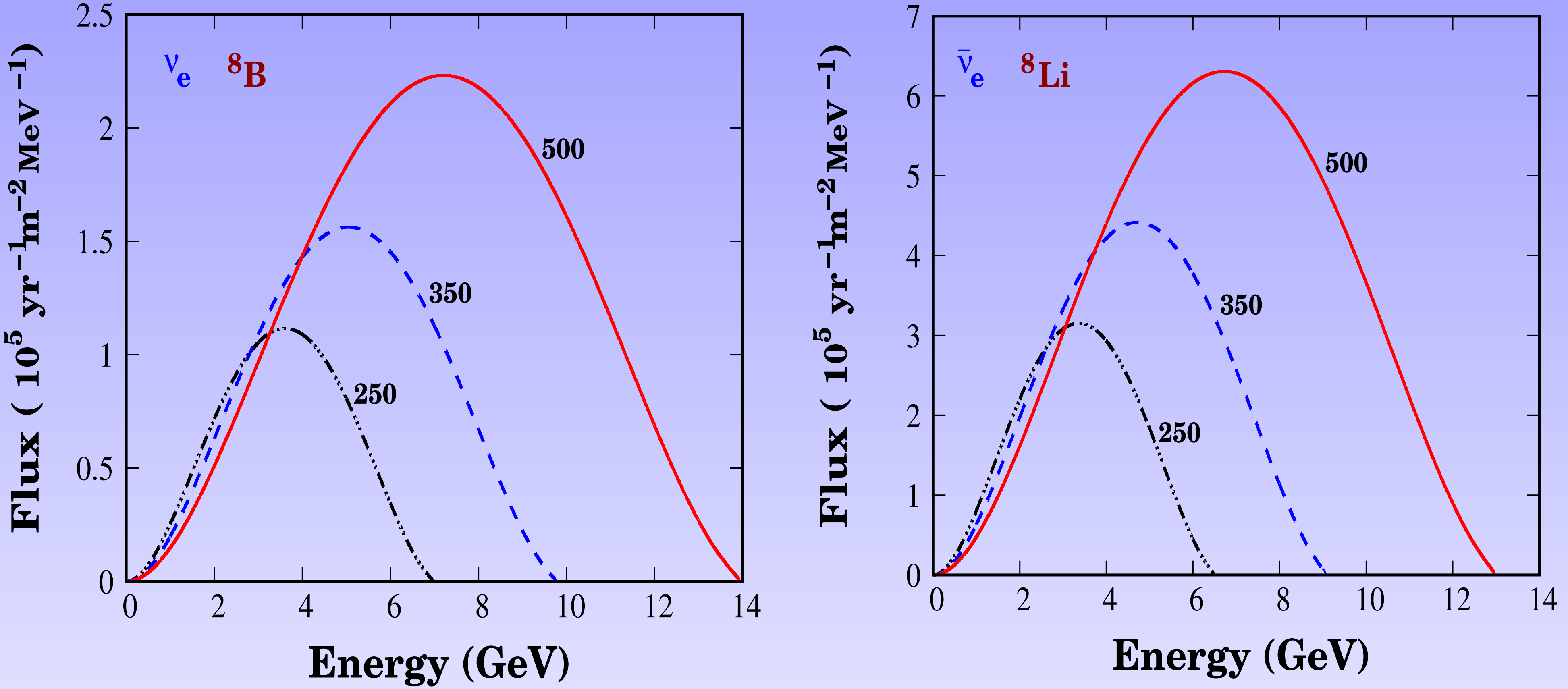
| Ion | $\tau$ (s) | $E_0$ (MeV) | $f$ | Decay fraction | Beam |
|---|---|---|---|---|---|
| $^{18}_{10}$Ne | 2.41 | 3.92 | 820.37 | 92.1% | $\nu_e$ |
| $^{6}_{2}$He | 1.17 | 4.02 | 934.53 | 100% | $\bar{\nu}_e$ |
| $^{8}_{5}$B | 1.11 | 14.43 | 600684.26 | 100% | $\nu_e$ |
| $^{8}_{3}$Li | 1.20 | 13.47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

**Comparison of different source ions**

**Low-$\gamma$ design, useful decays in case of anti-neutrinos can be $2.9 \times 10^{18}$/year and for neutrinos $1.1 \times 10^{18}$/year**

**Larger total end-point energy, $E_0$ is preferred**

# $\beta$-beam flux at INO-ICAL



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

# INO

- **A magnetized Iron calorimeter (ICAL) detector with excellent efficiency of charge identification (~ 95%) and good energy determination**
- **Preferred location is Singara (PUSHEP) in the Nilgiris (near Bangalore),** 7152 **km from CERN**
- **A 50 kton Iron detector**
- **Oscillation signal is the muon track ($\nu_e \rightarrow \nu_\mu$ channel)**
- **Energy threshold is around 800 MeV**

# Best-fit values

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

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

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

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

$$\delta_{CP} = 0$$

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

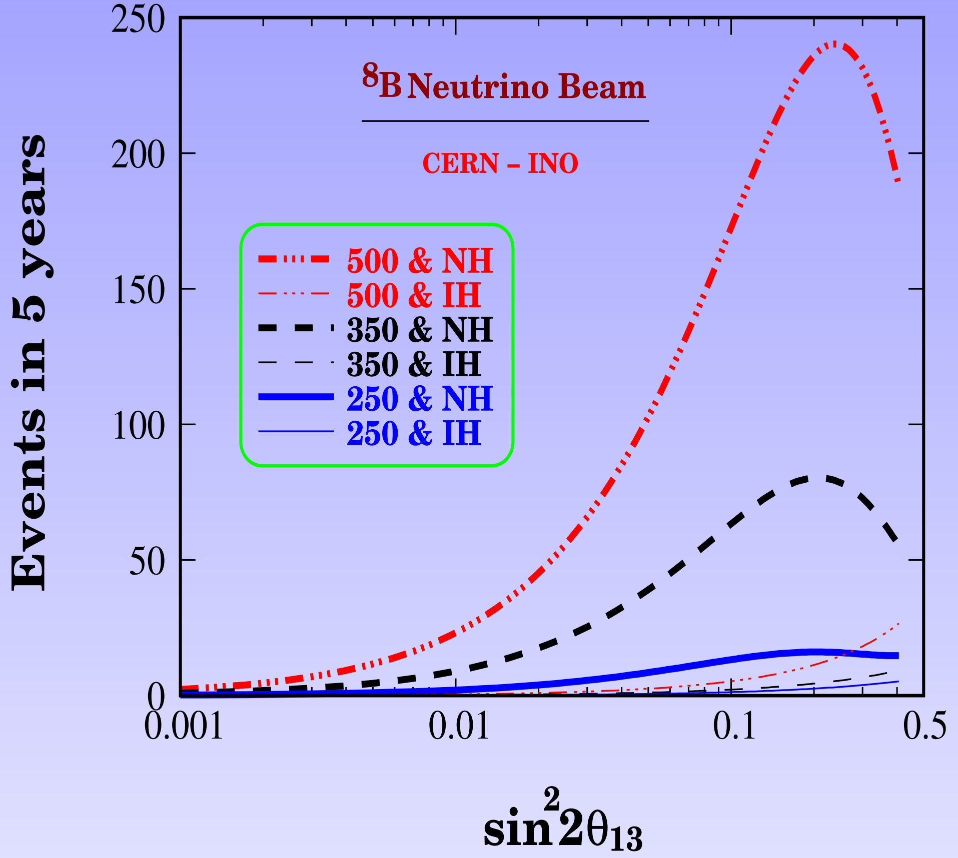
# Detector assumptions

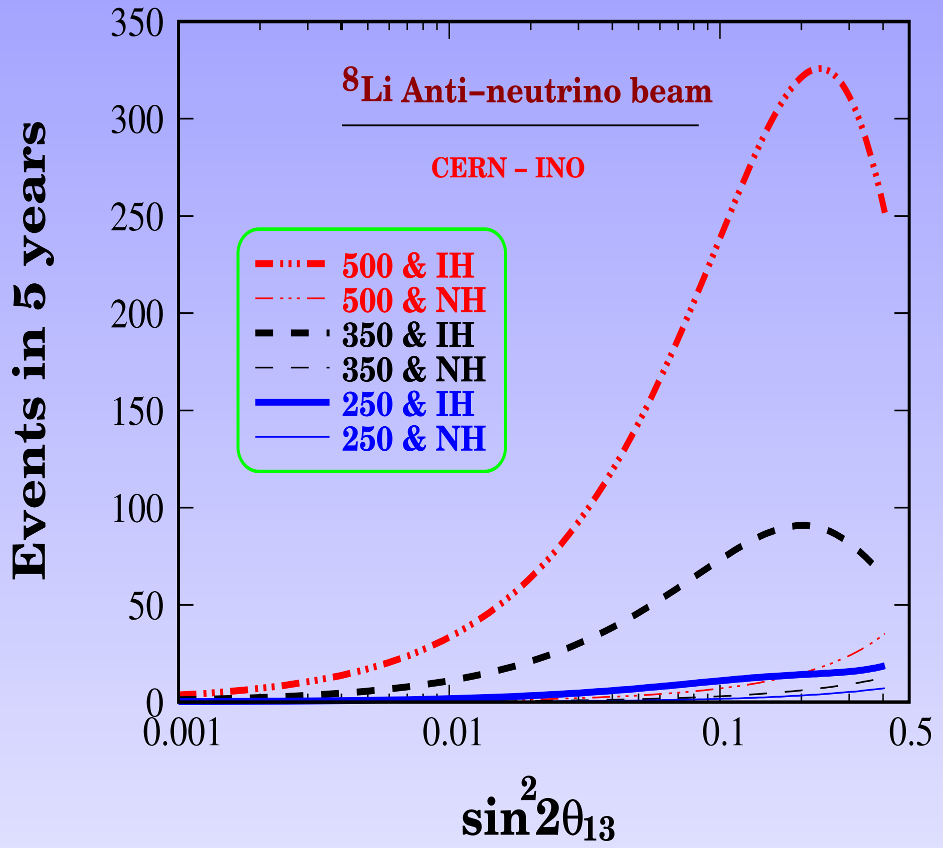
| | |
|---|---|
| Total Mass | 50 kton |
| Energy threshold | 1.5 GeV |
| Detection Efficiency ($\epsilon$) | 60% |
| Charge Identification Efficiency ($f_{ID}$) | 95% |

**Detector characteristics used in the simulations**

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

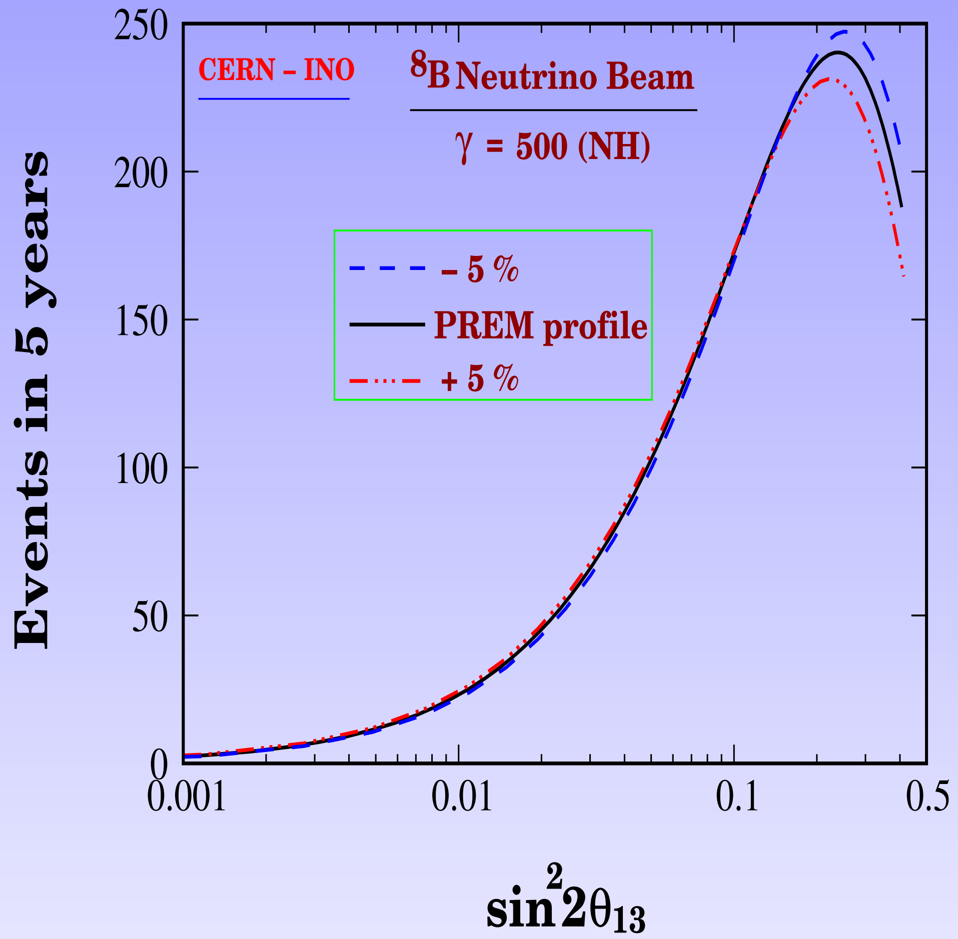
# Event Rates in INO-ICAL





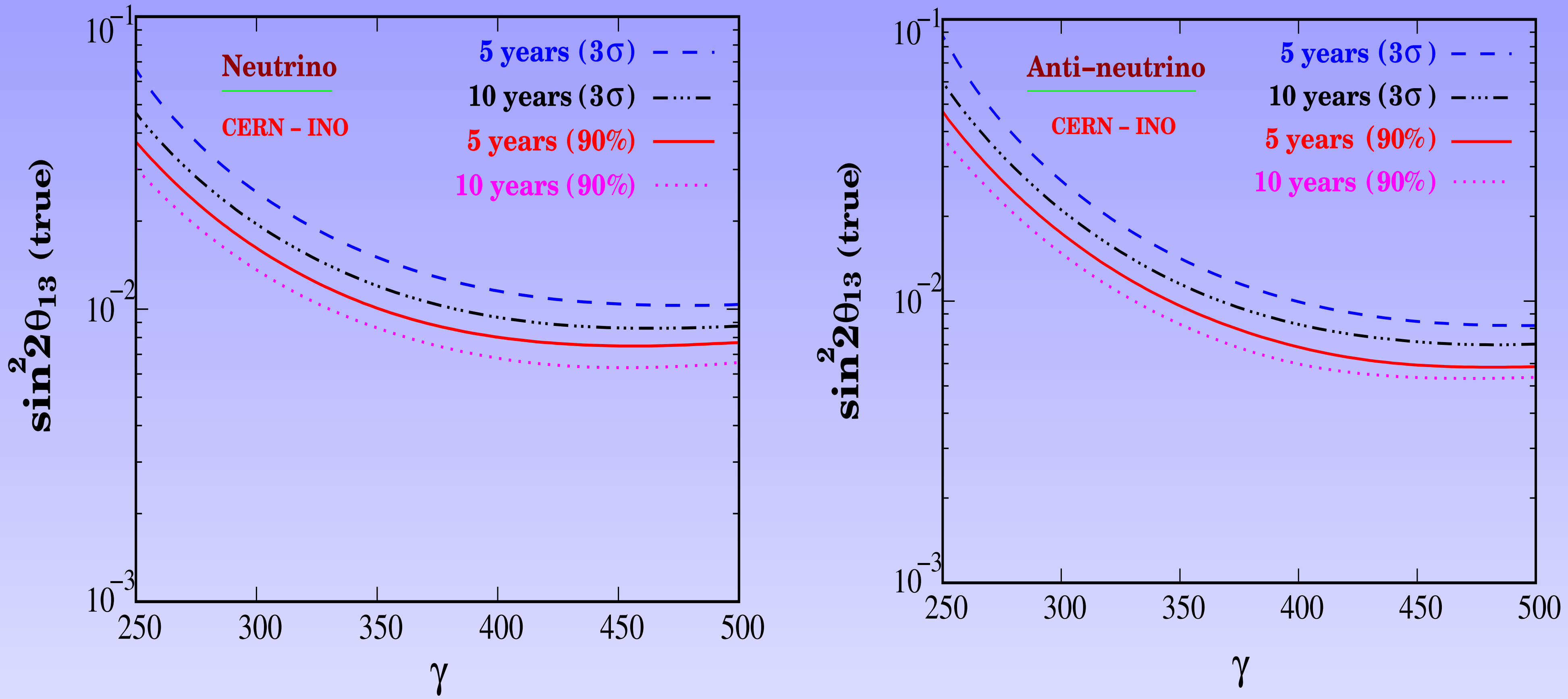
Event rates

# Event Rates (contd.)



Sensitivity to matter profile

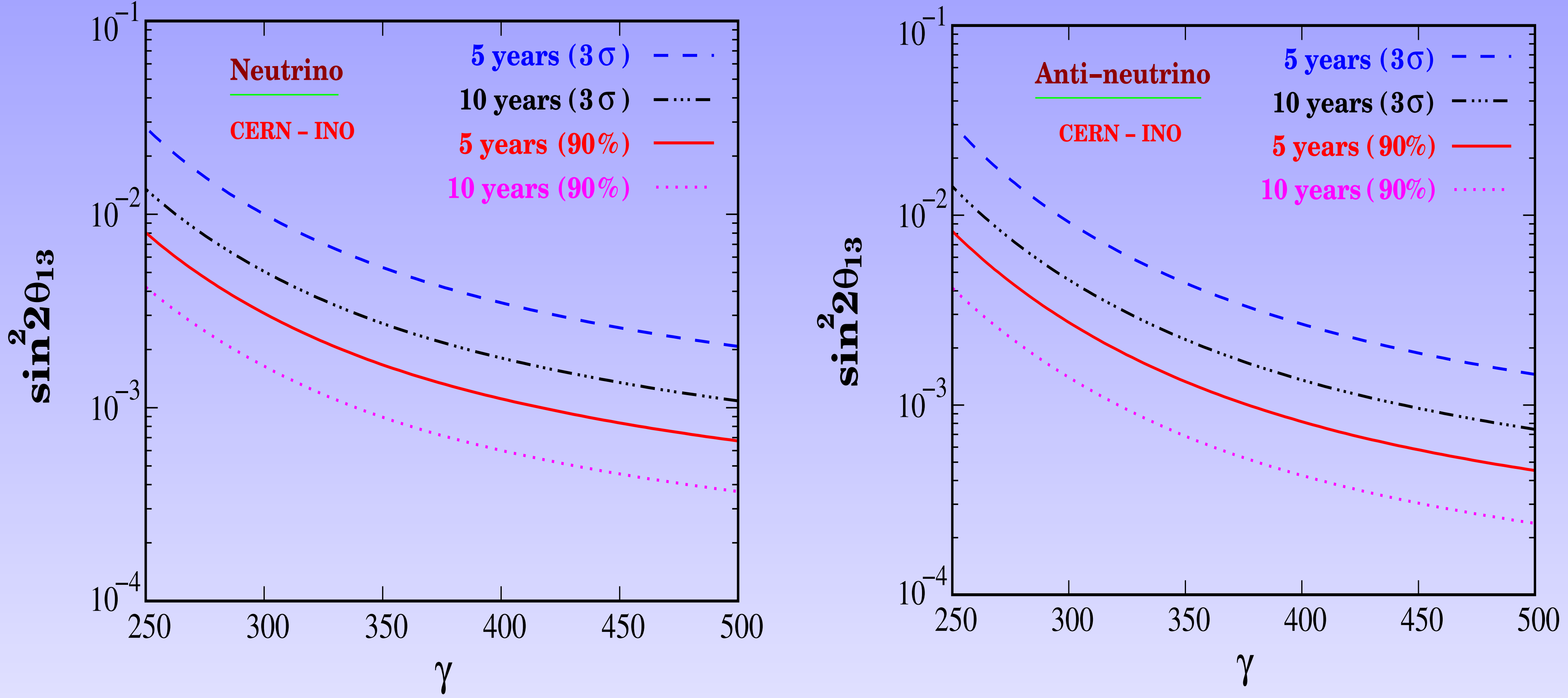
# Sensitivity to $Sgn(\Delta m^2_{31})$



Minimum value of $\sin^2 2\theta_{13}$(true) as a function of $\gamma$ at which the wrong hierarchy can be disfavored at the 90% and $3\sigma$ C.L. For $\nu_e$ ($\bar{\nu}_e$) true hierarchy is assumed normal (inverted)

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

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



$\sin^2 2\theta_{13}$ limit below which experiment is insensitive. For $\nu_e$ ($\bar{\nu}_e$) true hierarchy is assumed normal (inverted)

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

# Conclusions

- We have discussed the prospects of obtaining information on the mixing angle $\theta_{13}$ and the sign of $\Delta m^2_{31}$ using the proposed ICAL detector at INO with a Beta beam source at CERN
- The performance of the CERN - INO baseline is quite significant in comparison with other baselines avoiding the issue of degeneracy
- It appears that such a combination of a high intensity $\nu_e, \bar{\nu}_e$ source and a magnetized iron detector is well-suited for this purpose