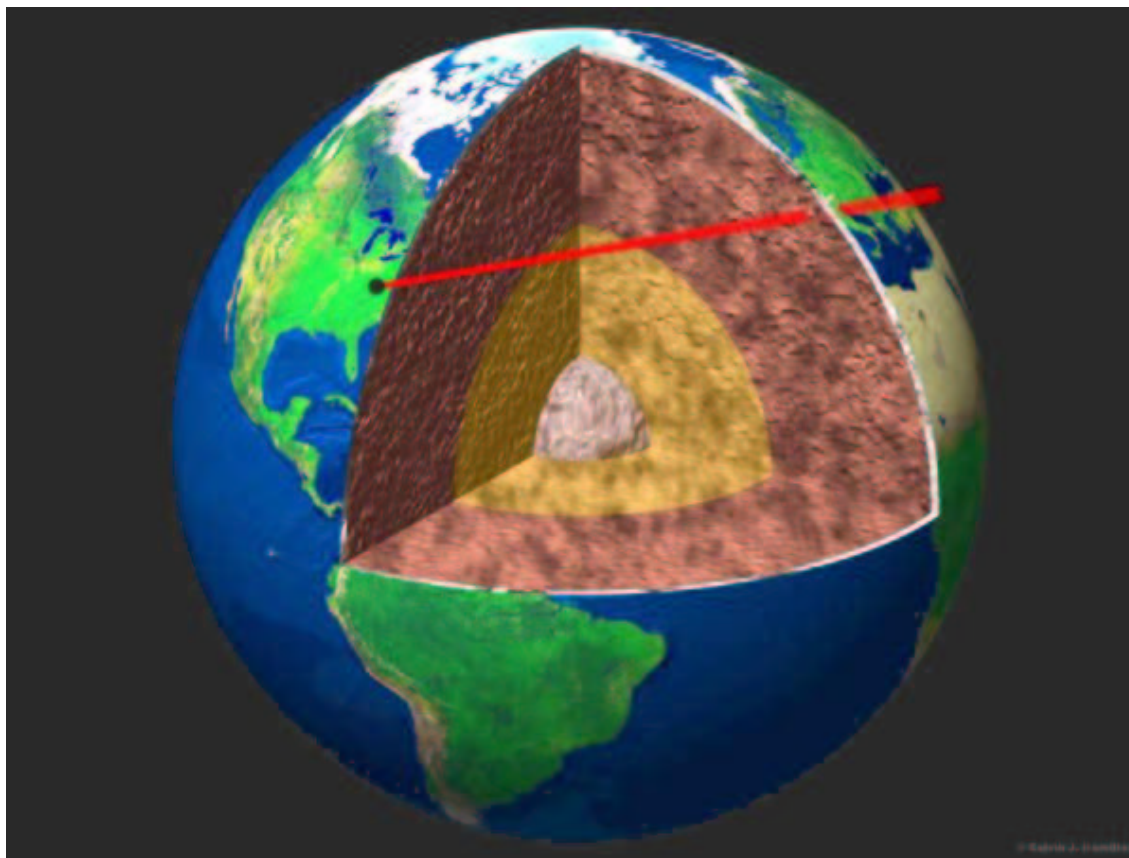


Precision Oscillation Tests with Superbeams and Neutrino Factories

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Precision!

Source



Oscillation



Detector

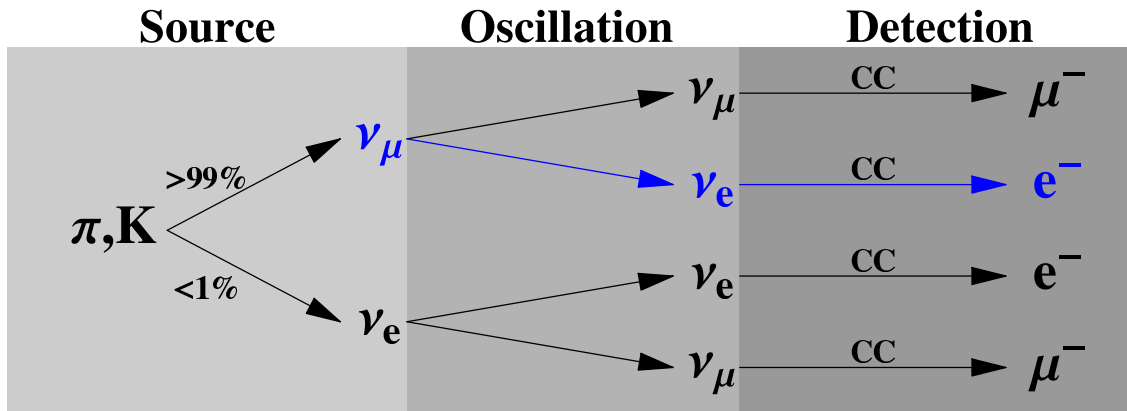
- neutrino energy E
- flux and spectrum
- flavour composition
- contamination
- symmetric $\nu/\bar{\nu}$ operation

- oscillation channels
- realistic baselines
- MSW matter profile

- effective mass, material
- threshold, resolution
- particle ID (flavour, charge, event reconstruction, ...)
- backgrounds
- x-sections (at low E)

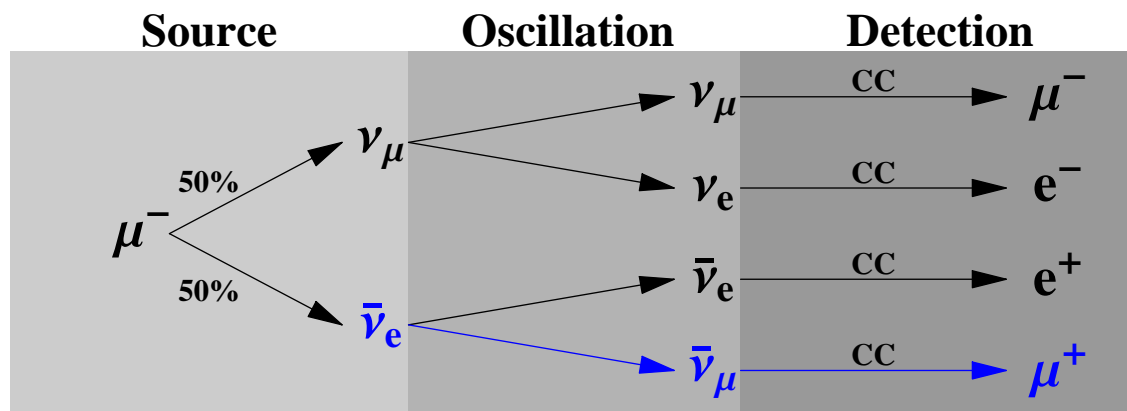
Sources, Oscillation and Detection

A) Conventional ν -Beams from Beam Dumps \Rightarrow Superbeams



$\nu_\mu \rightarrow \nu_e$ oscillation most interesting
 ν_e contamination \Leftrightarrow off-axis
 good electron detection efficiency
 good NC background rejection
 near detector
 $\bar{\nu}$ -beam \simeq different experiment

B) Neutrino Factories



$\bar{\nu}_e \rightarrow \bar{\nu}_\mu$ oscillation most interesting
 excellent beam properties
 very good charge ID required
 good NC background rejection
 μ^+ mode very symmetric

C) Radioactive Beams ? Pure ν_e or $\bar{\nu}_e$ beam from β decay, $\gamma \simeq 100$

Qualitative Analytic Understanding

- full numerical simulation
- $\Delta = \Delta m_{31}^2 L/4E$
- qualitative understanding \Rightarrow expand in $\alpha = \Delta m_{21}^2/\Delta m_{31}^2$ and $\sin^2 2\theta_{13}$
- matter effects $\hat{A} = A/\Delta m_{31}^2 = 2VE/\Delta m_{31}^2$; $V = \sqrt{2}G_F n_e$

$$P(\nu_\mu \rightarrow \nu_\mu) \approx 1 - \cos^2 \theta_{13} \sin^2 2\theta_{23} \sin^2 \Delta + 2 \alpha \cos^2 \theta_{13} \cos^2 \theta_{12} \sin^2 2\theta_{23} \Delta \cos \Delta$$

$$\begin{aligned}
 P(\nu_e \rightarrow \nu_\mu) &\approx \sin^2 2\theta_{13} \sin^2 \theta_{23} \frac{\sin^2((1-\hat{A})\Delta)}{(1-\hat{A})^2} \\
 &\pm \sin \delta_{\text{CP}} \alpha \sin 2\theta_{12} \cos \theta_{13} \sin 2\theta_{13} \sin 2\theta_{23} \sin(\Delta) \frac{\sin(\hat{A}\Delta) \sin((1-\hat{A})\Delta)}{\hat{A}(1-\hat{A})} \\
 &+ \cos \delta_{\text{CP}} \alpha \sin 2\theta_{12} \cos \theta_{13} \sin 2\theta_{13} \sin 2\theta_{23} \cos(\Delta) \frac{\sin(\hat{A}\Delta) \sin((1-\hat{A})\Delta)}{\hat{A}(1-\hat{A})} \\
 &+ \alpha^2 \sin^2 2\theta_{12} \cos^2 \theta_{23} \frac{\sin^2(\hat{A}\Delta)}{\hat{A}^2}
 \end{aligned}$$

Freund

Cervera & Donini & Gavela & Gomez Cadenas & Hernandez & Mena & Rigolin

Freund & Huber & ML

The Importance of θ_{13}

CHOOZ \Rightarrow $\sin^2 2\theta_{13} < 0.1$ \Rightarrow effects depend crucially on θ_{13} :

- the total transition rate, matter effects
- effects due to the sign of Δm_{31}^2 , CP violating effects

The magic Baseline

- $\sin \delta_{CP}$ and $\cos \delta_{CP}$ terms proportional to $\sin(\hat{A}\Delta)$
 - α^2 term proportional to $\sin^2(\hat{A}\Delta)$
- \Rightarrow For $\sin^2(\hat{A}\Delta) = 0$: **Only the first term survives!**

Magic Baseline: $L_{magic} = \pi/4V \simeq 8100$ km

Errors, Degeneracies and Correlations

Look at expansion in powers of $\alpha = \Delta m_{21}^2 / \Delta m_{31}^2$ and $\sin \theta_{13}$; $\Delta = \Delta m_{31}^2 L / 4E$; $V = 0$

$$\begin{aligned}
 P(\nu_e \rightarrow \nu_\mu) &\approx \sin^2 2\theta_{13} \sin^2 \theta_{23} \sin^2(\Delta) \\
 &\pm \sin \delta_{CP} \alpha \sin 2\theta_{12} \cos \theta_{13} \sin 2\theta_{13} \sin 2\theta_{23} \sin^3(\Delta) \\
 &+ \cos \delta_{CP} \alpha \sin 2\theta_{12} \cos \theta_{13} \sin 2\theta_{13} \sin 2\theta_{23} \cos(\Delta) \sin^2(\Delta) \\
 &+ \alpha^2 \sin^2 2\theta_{12} \cos^2 \theta_{23} \sin^2(\Delta)
 \end{aligned}$$

- depends on solar parameters only via the product $\Delta m_{21}^2 \cdot \sin 2\theta_{12}$
- most interesting: $\sin^2 2\theta_{13} \simeq \alpha \cdot \sin^2 2\theta_{12} = \sin^2 2\theta_{12} \Delta m_{21}^2 / \Delta m_{31}^2$
- **degeneracies**: $(\delta_{CP} - \theta_{13})$, $(\delta_{CP} - \text{sign}(\Delta m_{31}^2))$, $(\theta_{23} - \frac{\pi}{2} - \theta_{23})$
- $\alpha^2 = (\Delta m_{21}^2)^2 / (\Delta m_{31}^2)^2$ term dominates **for tiny $\sin^2 2\theta_{13}$** \Leftrightarrow error of Δm_{21}^2

- 1,2,3, ... baselines and/or beam energies
- total rates \Leftrightarrow spectral distributions

The Potential of Future LBL Setups

Physis input:

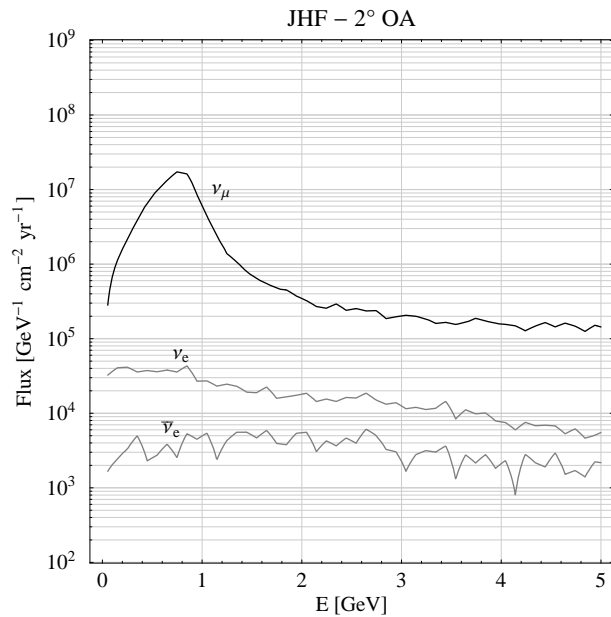
- **full numerical 3- ν simulation** and analytic understanding
- **matter density profile** and errors taken into account
- **error correlations included** (no fixed unknown parameters)

Analysis:

- **MC for all possible input parameters**
 - **combined fit of appearance and disappearance channels for both polarities**
 - **fit spectral information and/or total rates**
 - **adequate statistical methods** (small event rates/bin):
 - ⇒ Poissonian statistics
 - ⇒ parameterization of systematical uncertainties
 - ⇒ integrating out the nuisance parameters
 - ⇒ projection on the parameter of interest
 - ⇒ external information from KamLand (=LMA) and geophysics
 - ⇒ 6 remaining parameters
- ⇒ Extract parameters and (correlated) errors \Leftrightarrow **sensitivity**

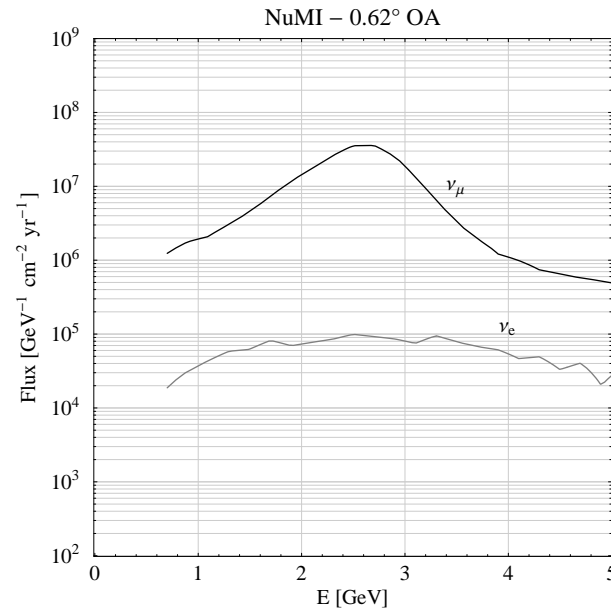
The Sources

JHF



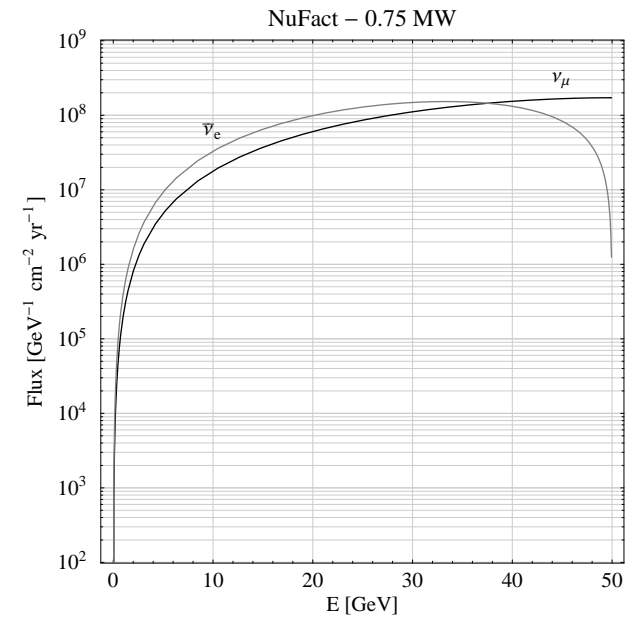
- mean energy 0.51 GeV
- peak intensity $1.7 \cdot 10^7 \text{ GeV}^{-1} \text{ cm}^{-2} \text{ yr}^{-1}$ at 0.78 GeV
- ν_μ/ν_e -ratio at peak 0.2%

NuMI off-axis



- mean energy 2.78 GeV
- peak intensity $3.6 \cdot 10^7 \text{ GeV}^{-1} \text{ cm}^{-2} \text{ yr}^{-1}$ at 2.18 GeV
- ν_μ/ν_e -ratio at peak 0.2%

NuFact



- mean energy 30 GeV
- peak intensity $1.5 \cdot 10^8 \text{ GeV}^{-1} \text{ cm}^{-2} \text{ yr}^{-1}$ at 33.33 GeV
- ν_μ/ν_e -ratio at peak 83%

Uncertainties in flux and ν_e -background

Uncertainties in flux

Itow et al.

Para, Szleper

Geer

Baseline & MSW Matter Effects

Beams in Earth Matter:

⇒ electron density profile
as function of radius **Stacy**
density errors **Geller & Hara**

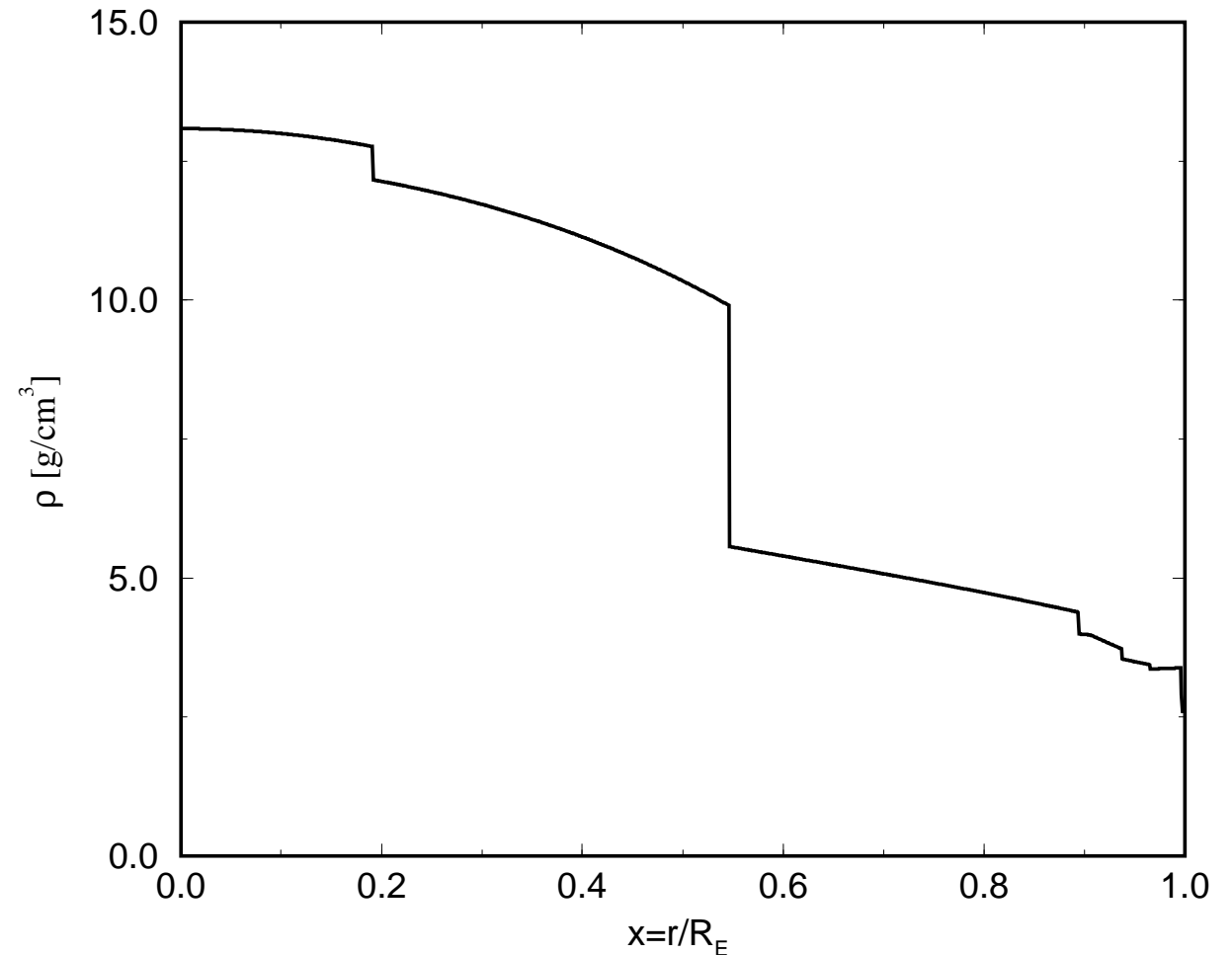
Large L ⇒ steep angles

$L = 2800$ km ⇔ 13°

$L = 7300$ km ⇔ 35°

$L = 12750$ km ⇔ 90°

$L \leq \mathcal{O}(10\,000$ km) ⇔ **mantle**



- $E_{\text{resonance}} \simeq 10 - 15$ GeV, matter effects grow with distance L
- Average density profile uncertainties decrease with L ⇒ $\simeq 5\%$ error

Detectors

	water Cherenkov = SK (HK)	low-Z calorimeter	magnetized iron calorimeter
fiducial mass	22.5 kt (1 000 kt)	20 kt	10 kt (50 kt)
energy range	0.4 – 1.2 GeV	1 – 5 GeV	4 – 50 GeV
energy resolution	5%	10%	20%
signal efficiency	0.5	0.5	0.45
NC rejection	0.01	0.001	$< 10^{-5}$
CID	–	–	$< 10^{-5}$
background uncertainty	5%	5%	5%

- **threshold effects** for the magnetized iron calorimeter
linear rise of the **efficiency** between 4 GeV and 20 GeV
- **liquid Argon TPC ?**

5 Considered Scenarios

	JHF-SK	NuMI	NuFact-I
detector	water cherenkov	low-Z calorimeter	10kt magnetized iron calorimeter
baseline	295 km	735 km	3 000 km
matter density	2.8 g cm^{-3}	2.8 g cm^{-3}	3.5 g cm^{-3}
L/E_{peak}	378 km GeV^{-1}	337 km GeV^{-1}	90 km GeV^{-1}

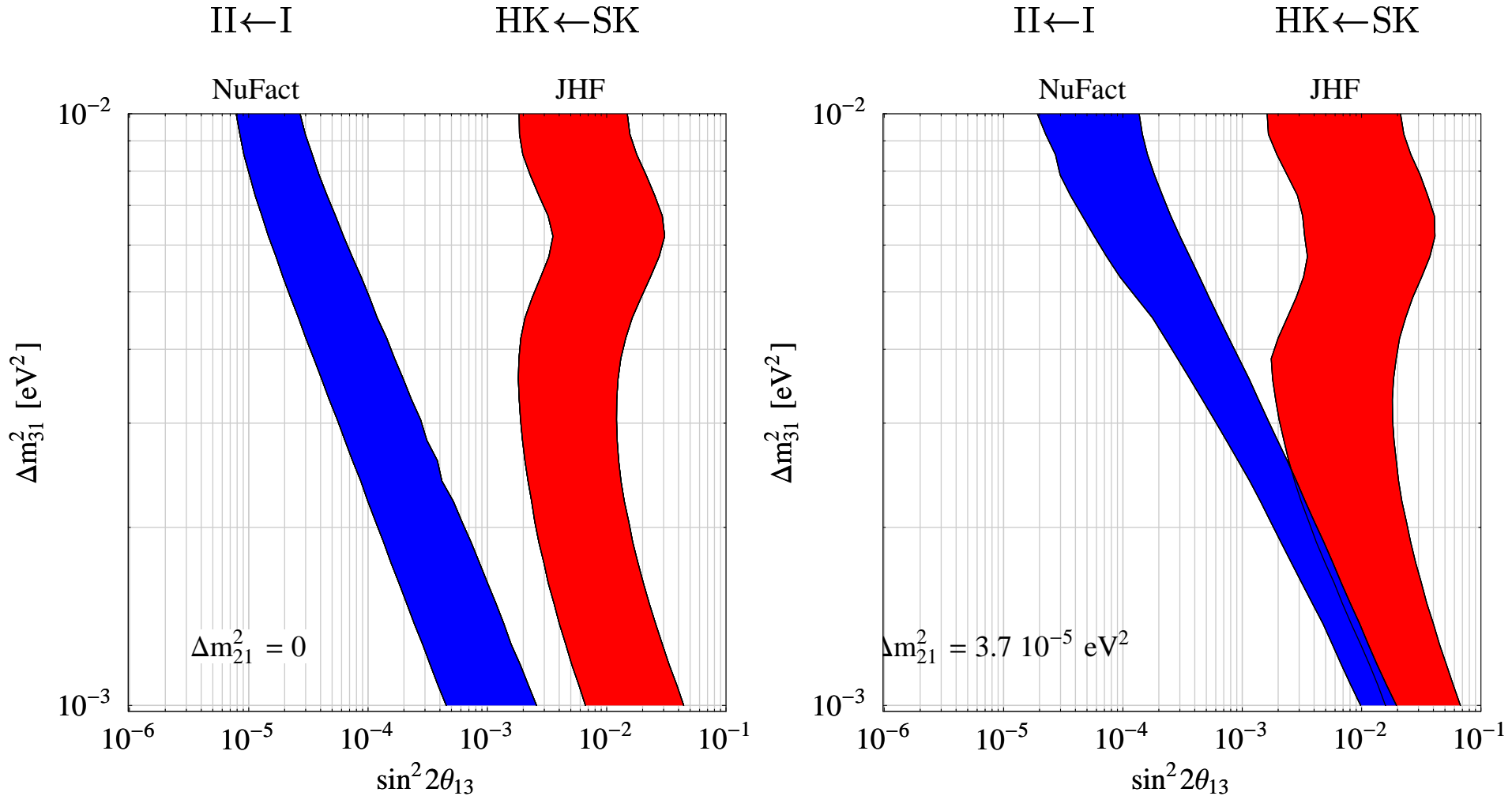
- **JHF-HK** \Rightarrow $\simeq 95$ times more luminosity than JHF-SK
 - plus anti-neutrino running
- **NuFact-II** \Rightarrow $\simeq 42$ times more luminosity than NuFact-I

Itow et al., A. Para, A. Blondel et al.

	JHF-SK	NuMI	JHF-HK	NuFact-I	NuFact-II
signal	139.0	387.5	13 180.0	1 522.8	64 932.6
background	23.3	53.3	2 204.6	4.2	180.3
S/N	6	6	6	360	360

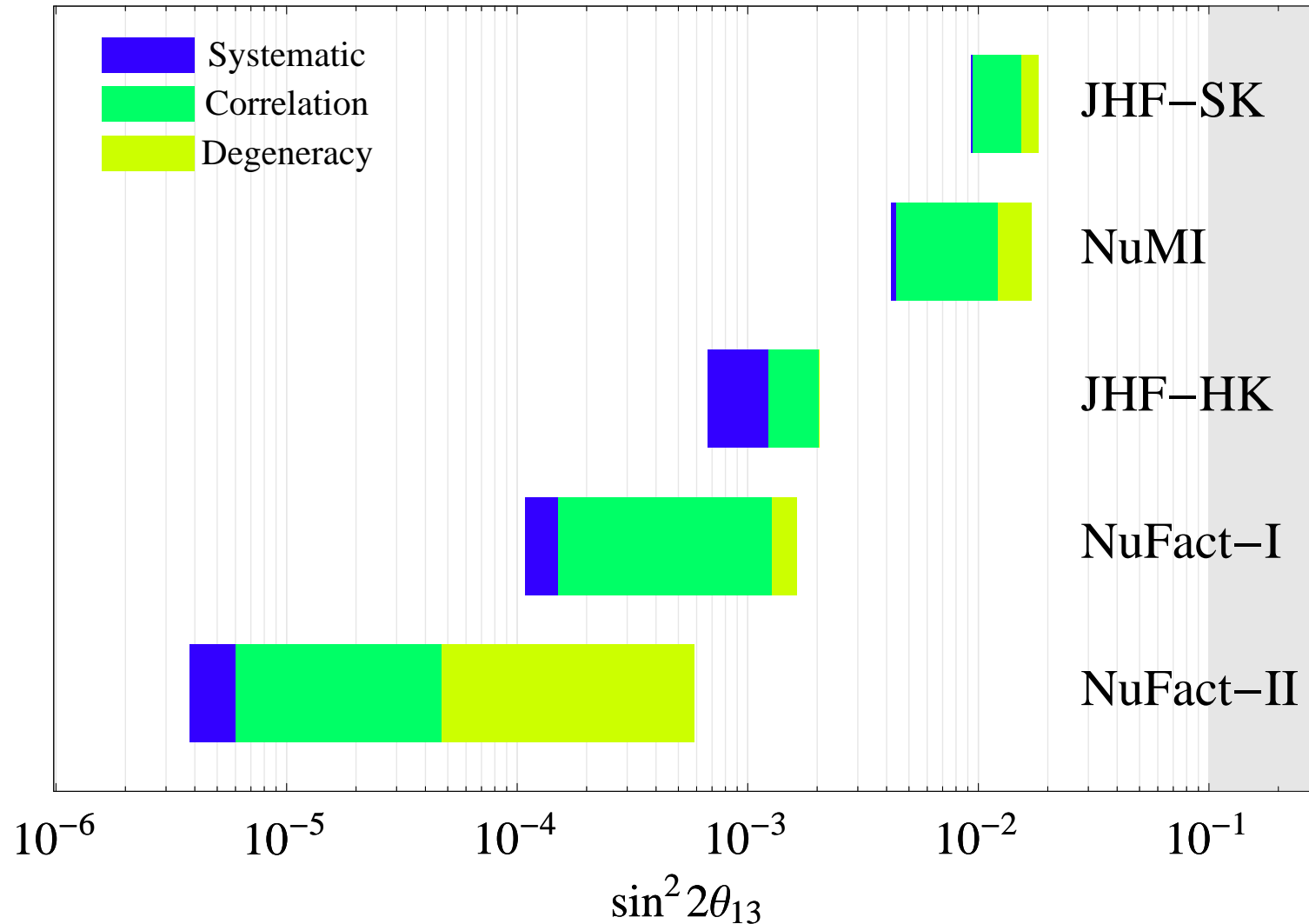
Sub-Leading Parameters: $\sin^2 2\theta_{13}$ Sensitivity

All parameter correlations must be taken into account



- sizable Δm_{31}^2 and Δm_{21}^2 dependence of sensitivity limits
- up to an order of magnitude difference
- effect strongest for short baselines

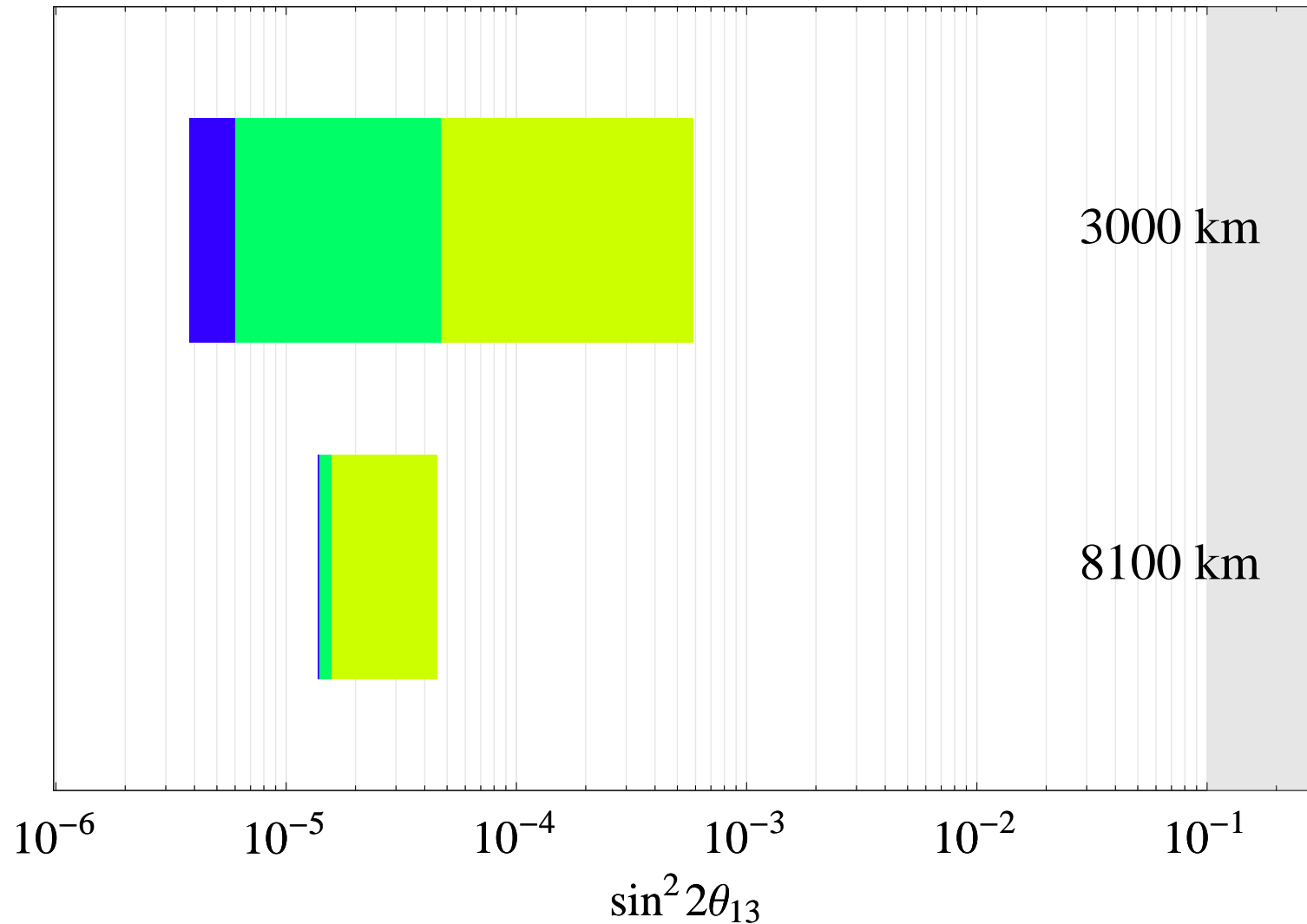
Sensitivity to $\sin^2 2\theta_{13}$



- Different sensitivity reductions by systematics
- Correlations & degeneracies lead to severe limitations
- Improvements by combining experiments

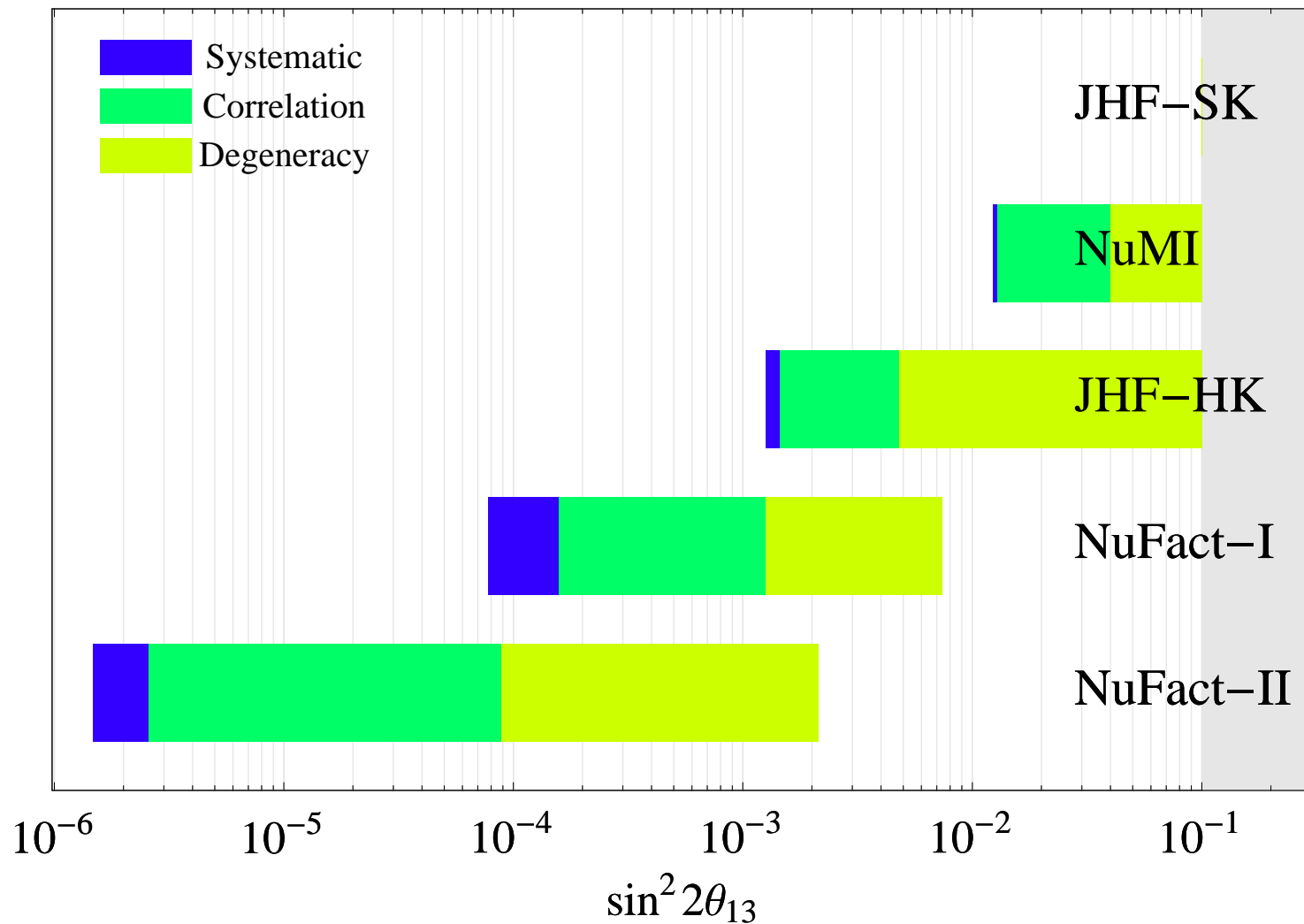
Comparing 3000 km with 8100 km

Sensitivity to $\sin^2 2\theta_{13}$ for NuFact-II



- Reduction of event rates rates
- Reduced correlations & degeneracies
- \Rightarrow better sensitivity!

Sensitivity to the sign of Δm_{31}^2

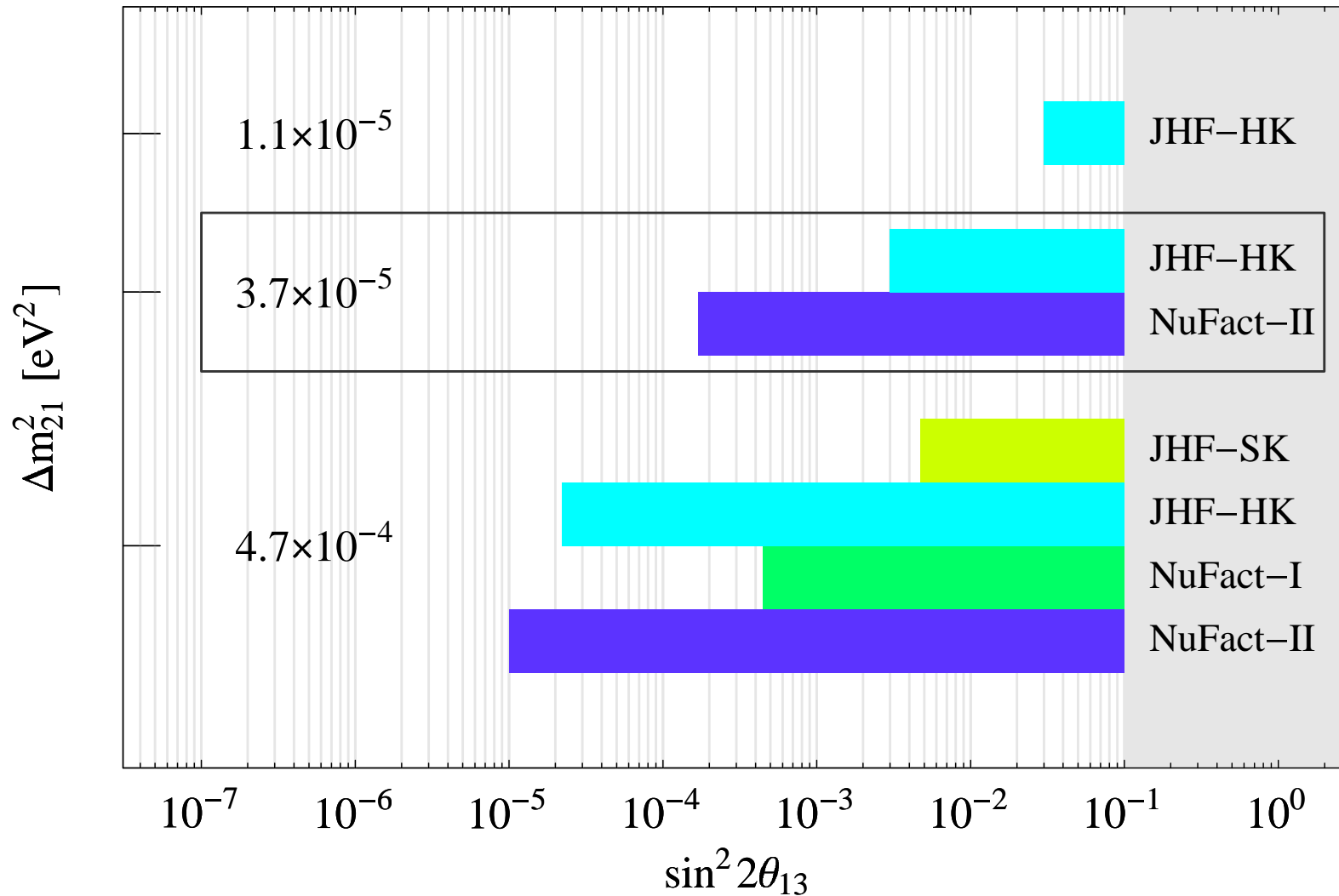


- $sign(\Delta m_{31}^2)$ very hard to determine with superbeams
 - degeneracies with δ_{CP} are the main problem
- ⇒ combine experiments!

Huber, ML, Winter, hep-ph/0204352

Measurements of CP-violation

Sensitivity to CP-Violation at $\delta_{CP} = +\pi/2$



- CP violation with high luminosity superbeams feasible
- sensitivity is δ_{CP} dependent

Huber, ML, Winter, hep-ph/0204352

Conclusions

Future LBL experiments \Rightarrow precision 3ν -Oscillation:

- requires very precise knowledge of the neutrino source
- in addition to detectors, oscillation framework (3ν , matter, ...)

\Rightarrow **“Laboratory” Sources:** Reactors, β -beams, **superbeams, neutrino factories**

- known Δm_{atm}^2 , $E_\nu \simeq 1 - 100 \text{ GeV} \Rightarrow$ baselines 100...10000km
- is very promising and possible in stages $\Rightarrow \Delta m_{31}^2, \theta_{23}, \theta_{13}, \delta_{CP}$
- Earth **matter effects** \Rightarrow complication & chance

Unique Impact on Physics:

- **precise masses and mixings** w/o hadronic uncertainties
- NSI, FCNC, $> 3\nu$, CPT, \Rightarrow very interesting limits
- very valuable flavour information \Leftrightarrow **models of masses and mixings**
- Dirac & Majorana masses \Leftrightarrow information on **see-saw scales**
- CP violation \Leftrightarrow leptogenesis: **baryon asymmetry of the universe**

\Rightarrow **Very Promising Future for LBL Neutrino Physics**