Resolving degeneracies for different values of θ_{13}

NuFact 03 Workshop, Columbia University, New York

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- Impact factors to the measurement
- General properties of the appearance channels
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Introduction: neutrino oscillations

$$P_{\alpha\beta} = \underbrace{\delta_{\alpha\beta} - 4 \sum_{\substack{i=1 \\ i>j}}^{3} \sum_{j=1}^{3} \mathrm{Re}\, J_{ij}^{\alpha\beta} \sin^2 \Delta_{ij}}_{\mathrm{CP-conserving}} - \underbrace{2 \sum_{\substack{i=1 \\ i>j}}^{3} \sum_{j=1}^{3} \mathrm{Im}\, J_{ij}^{\alpha\beta} \sin 2\Delta_{ij}}_{\mathrm{CP-violating}}$$

with

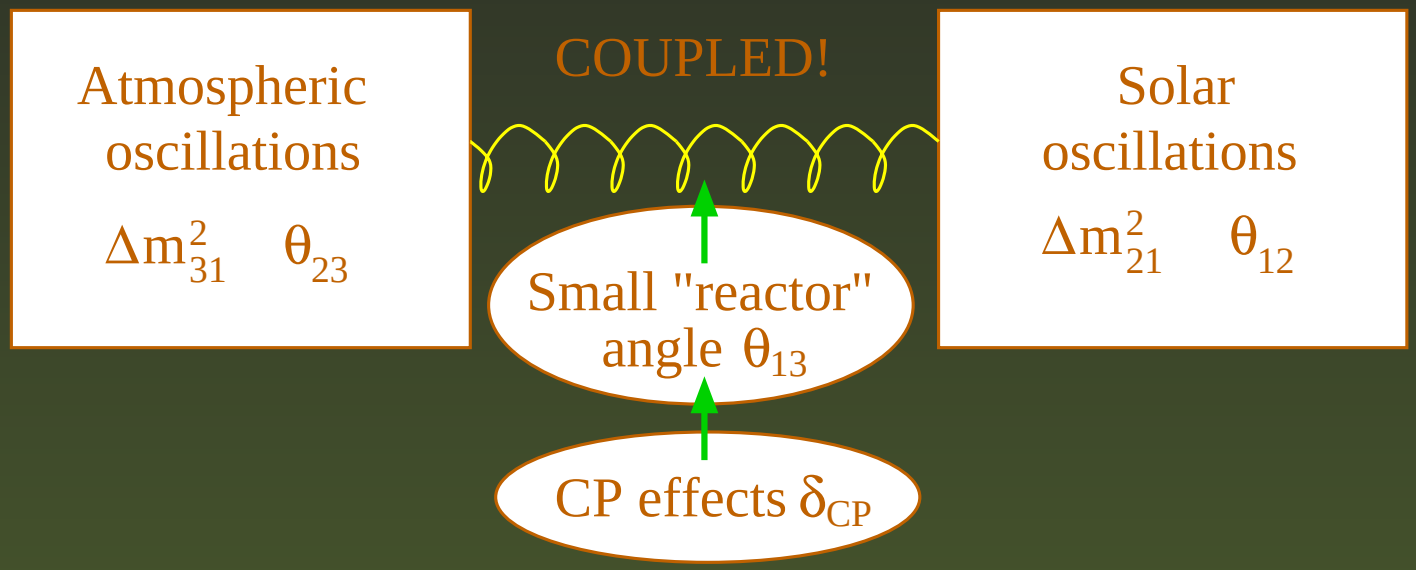
$$J_{ij}^{\alpha\beta} \equiv U_{\alpha i} U_{\alpha j}^* U_{\beta i}^* U_{\beta j}, \qquad \Delta_{ij} \equiv \frac{\Delta m_{ij}^2 L}{4E} \equiv \frac{\left(m_i^2 - m_j^2\right) L}{4E},$$

$$U = \begin{pmatrix} c_{12} c_{13} & s_{12} c_{13} & s_{13} e^{-i\delta} \\ -s_{12} c_{23} - c_{12} s_{23} s_{13} e^{i\delta} & c_{12} c_{23} - s_{12} s_{23} s_{13} e^{i\delta} & s_{23} c_{13} \\ s_{12} s_{23} - c_{12} c_{23} s_{13} e^{i\delta} & -c_{12} s_{23} - s_{12} c_{23} s_{13} e^{i\delta} & c_{23} c_{13} \end{pmatrix}.$$

$\rightarrow$ Six parameters: Δm_{31}^2, Δm_{21}^2, θ_{23}, θ_{12}, θ_{13}, δ_{CP}

Classification of oscillation parameters

... with mass hierarchy $|\Delta m^2_{21}| \ll |\Delta m^2_{31}|$ and $\sin^2 2\theta_{13} \lesssim 0.1$:



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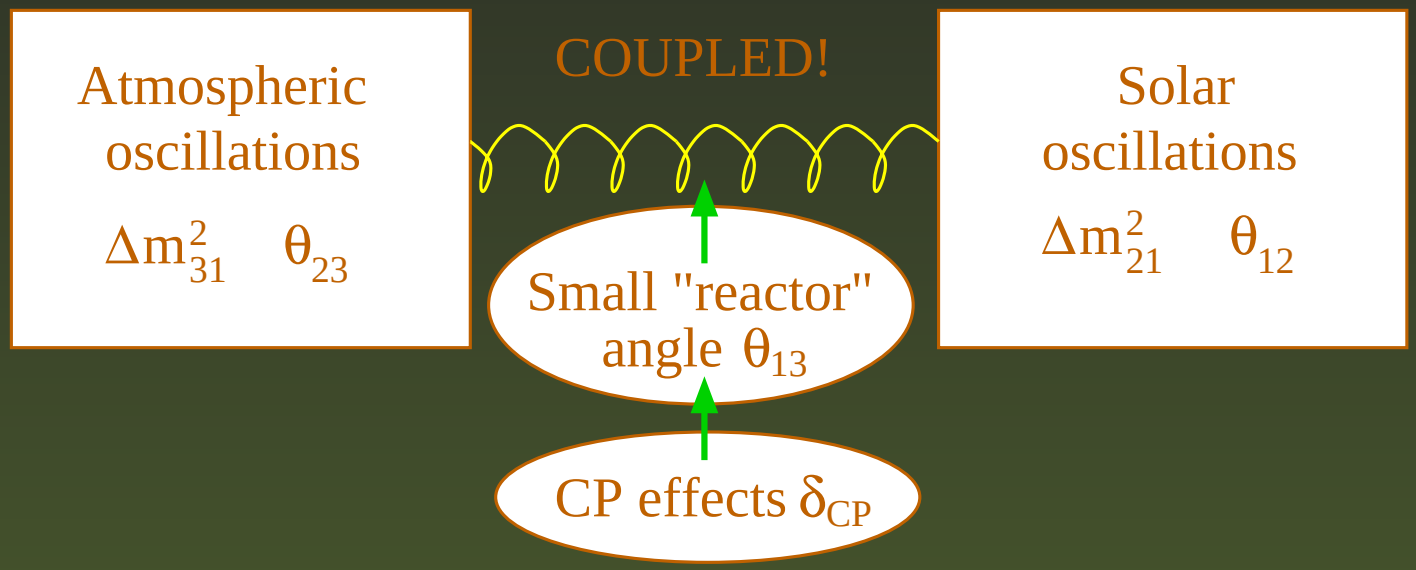

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- Superbeams
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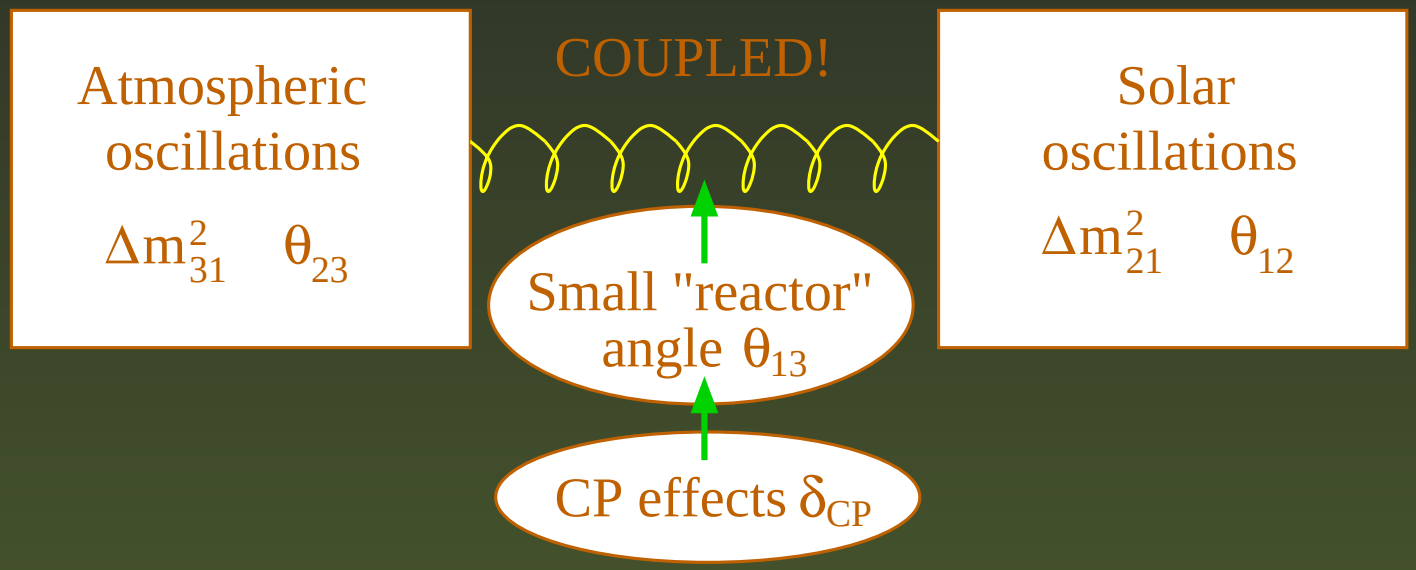

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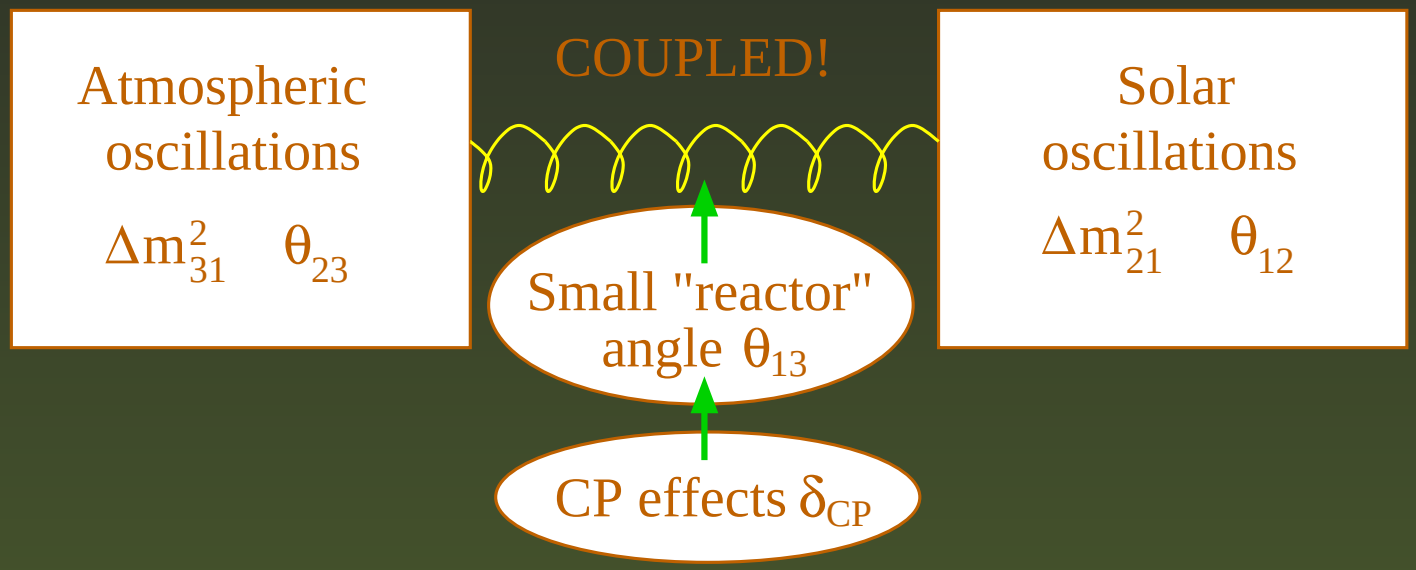

Future important experiments: (examples)	- Beams (K2K, MINOS, CNGS) - Superbeams - ν-Factories	- Beams? - Reactor (θ_{13}) - Superbeams - ν-Factories	- KamLAND - Solar exp.

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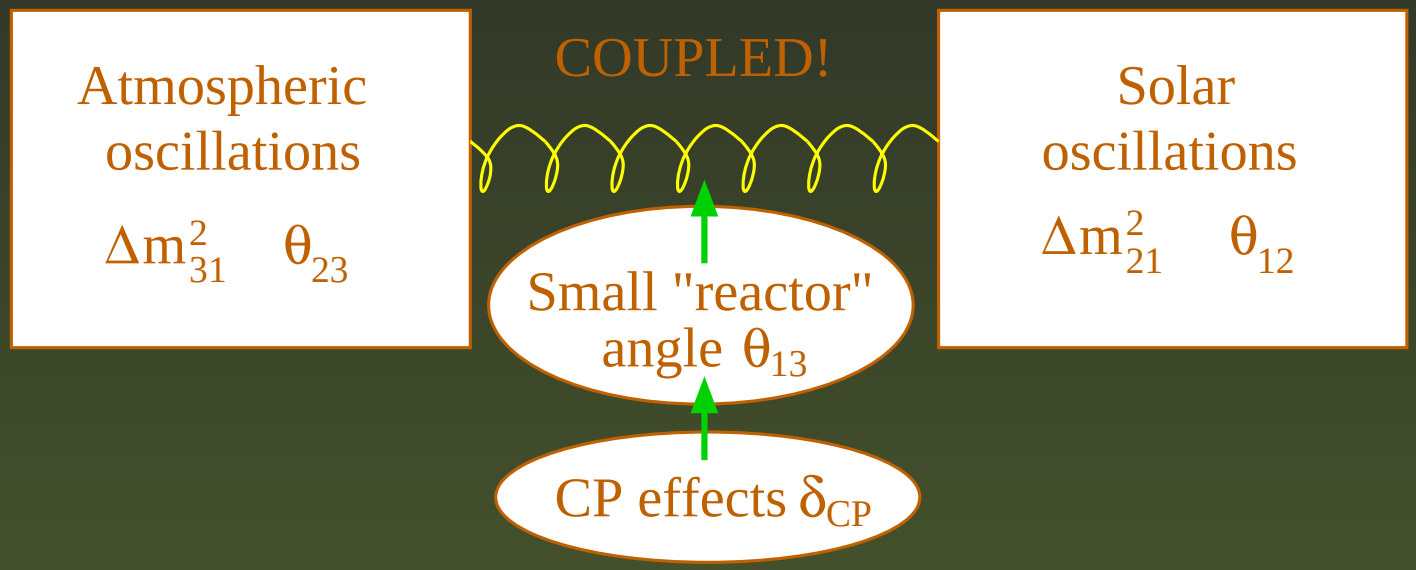
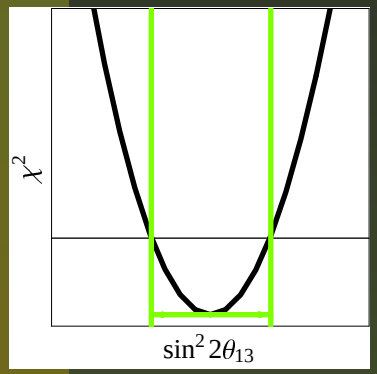


Future important experiments: (examples)	- Beams (K2K, MINOS, CNGS) - Superbeams - ν-Factories	- Beams? - Reactor (θ_{13}) - Superbeams - ν-Factories	- KamLAND - Solar exp.

Most interesting for future LBL: θ_{13}, $\mathrm{sgn}(\Delta m^2_{31})$, δ_{CP}

Impact factors to the measurement

1. Statistical errors



For a more detailed discussion: see Secs. 3 and 5 of hep-ph/0204352

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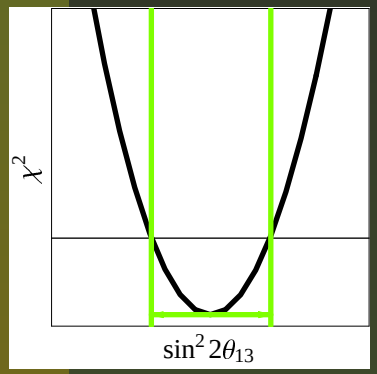

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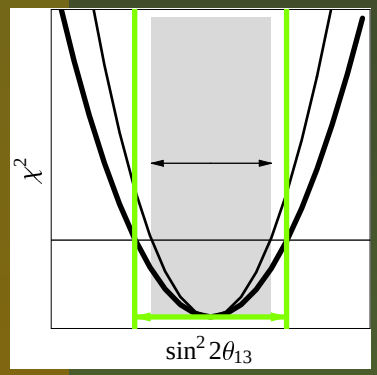

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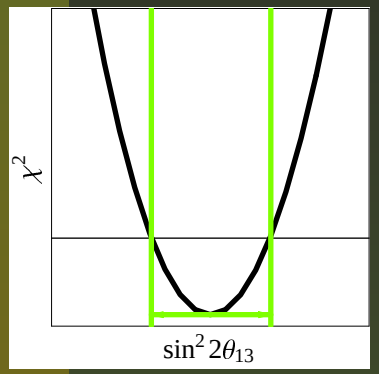

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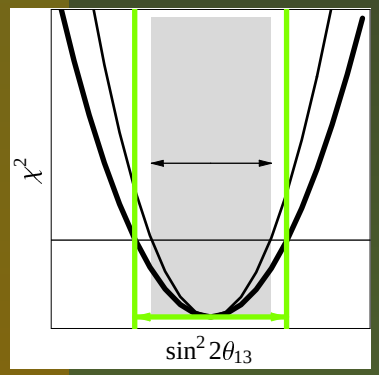

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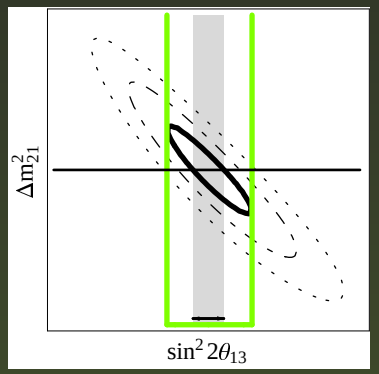

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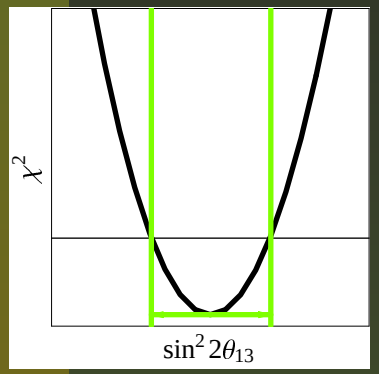

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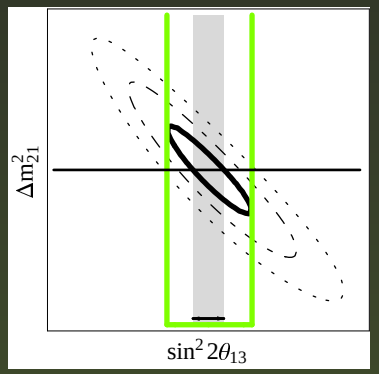

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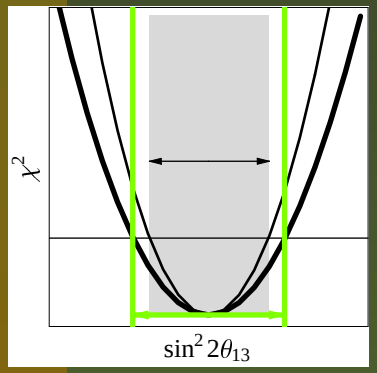

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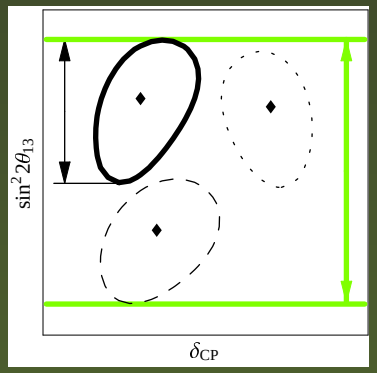

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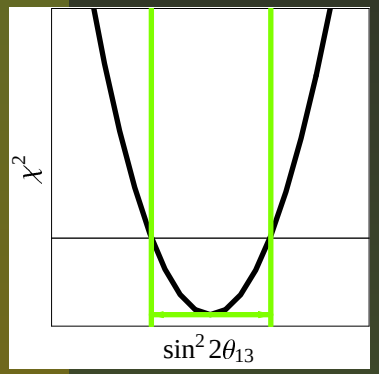

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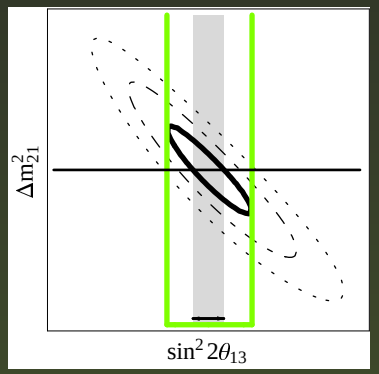

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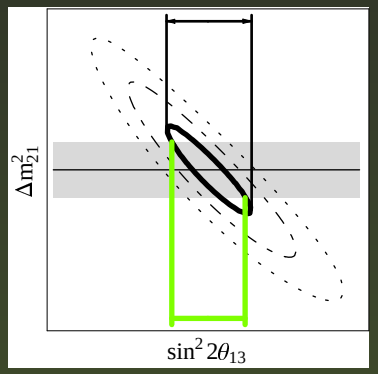

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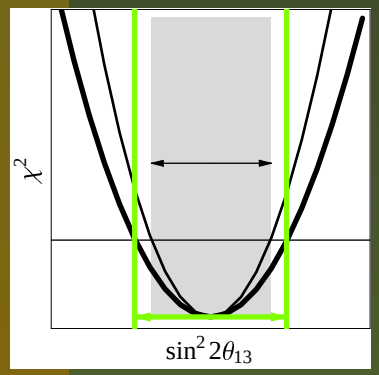

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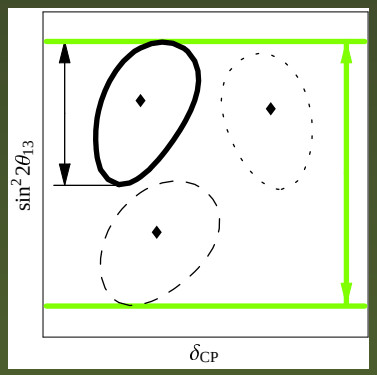

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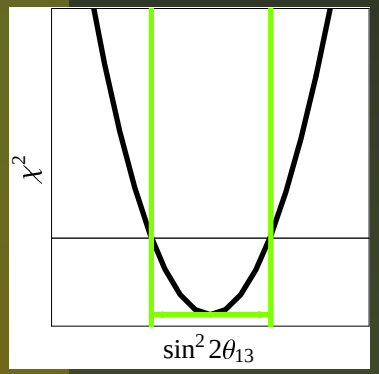

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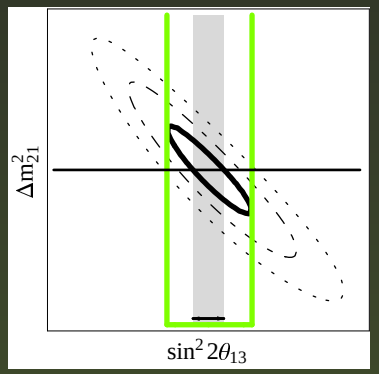

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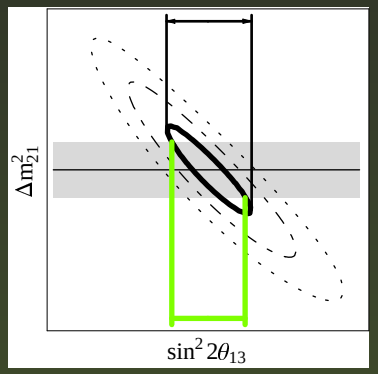

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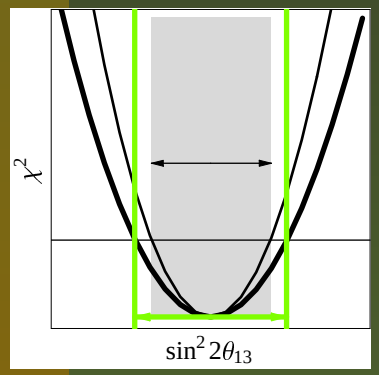

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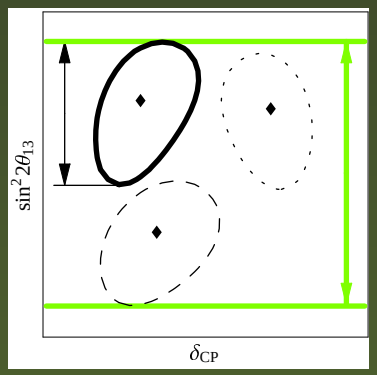

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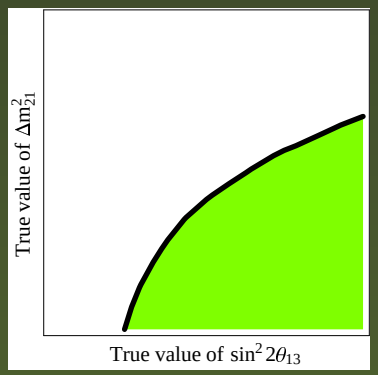

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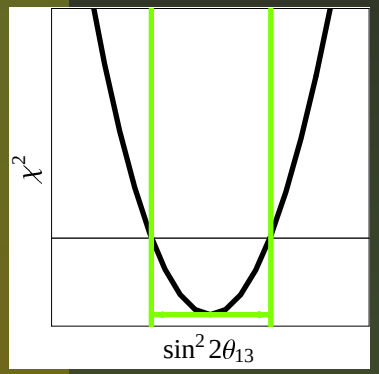

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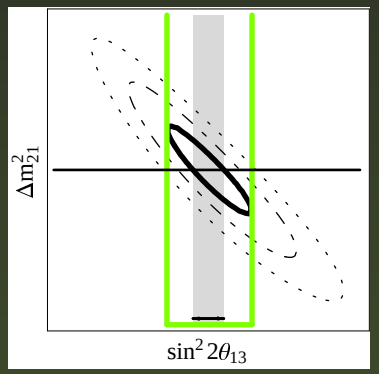

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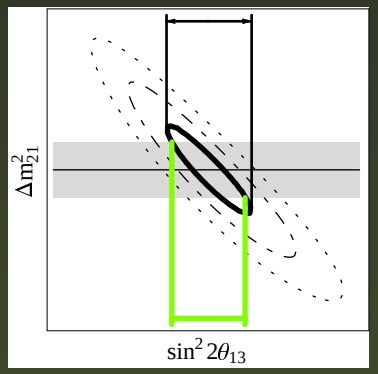

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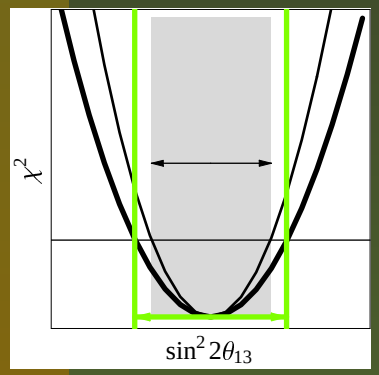

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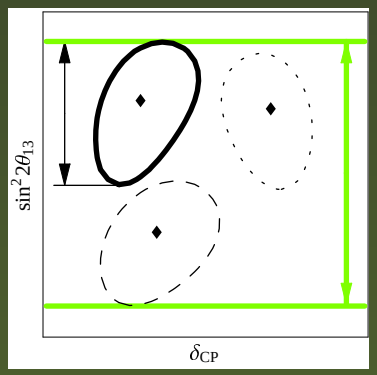

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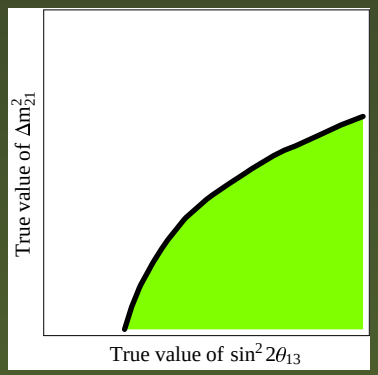

Determined by R&D of experiment

For a more detailed discussion: see Secs. 3 and 5 of hep-ph/0204352

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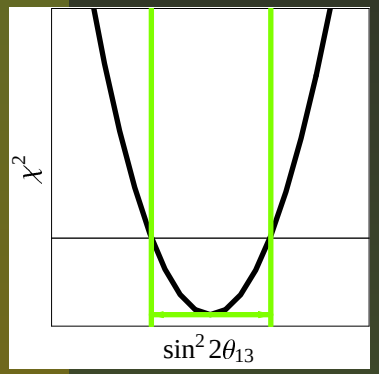

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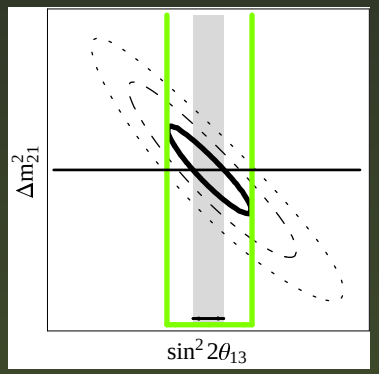

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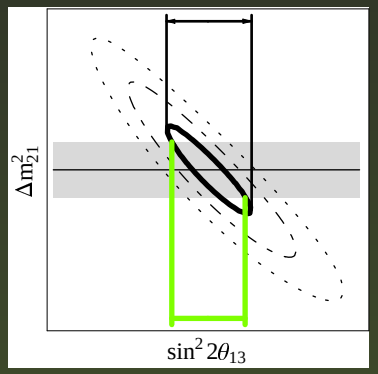

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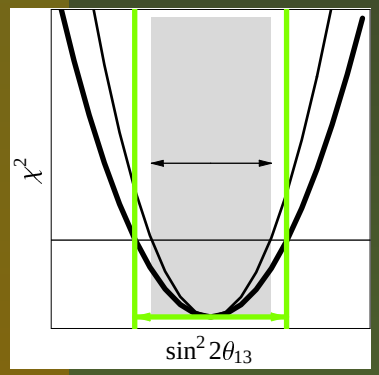

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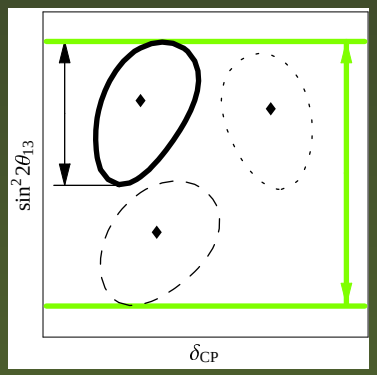

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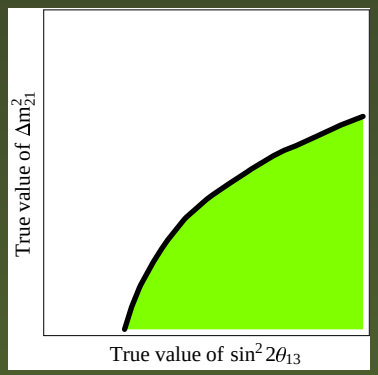

Determined by R&D of experiment

Controllable by L, E, combinations, ...

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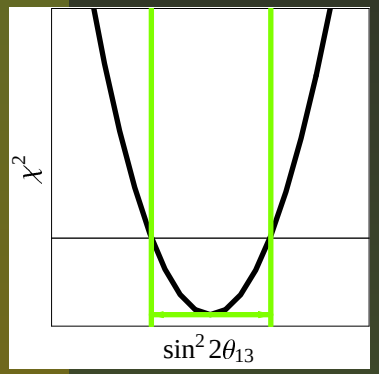

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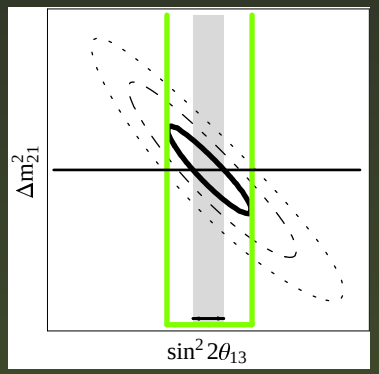

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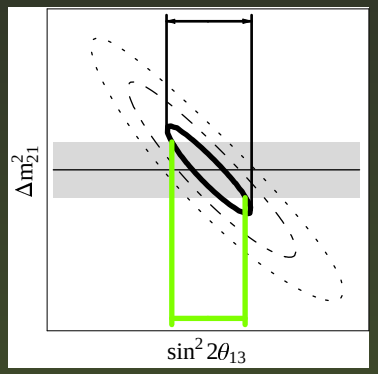

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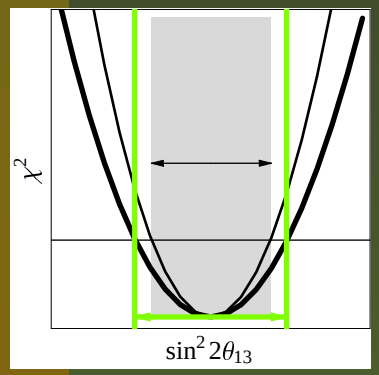

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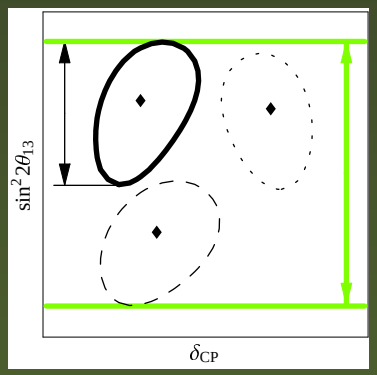

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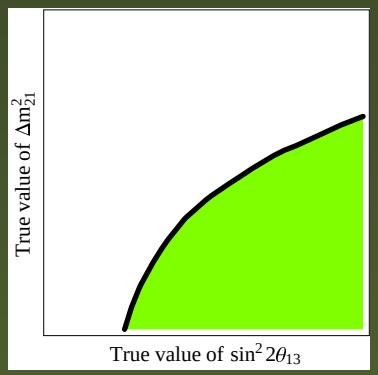


Determined by R&D of experiment

Controllable by L, E, combinations, ...

No influence by experiment

For a more detailed discussion: see Secs. 3 and 5 of hep-ph/0204352

Example: $\sin^2 2\theta_{13}$-sensitivity limit

Statistical errors

$\Downarrow$

Systematics

$\Downarrow$

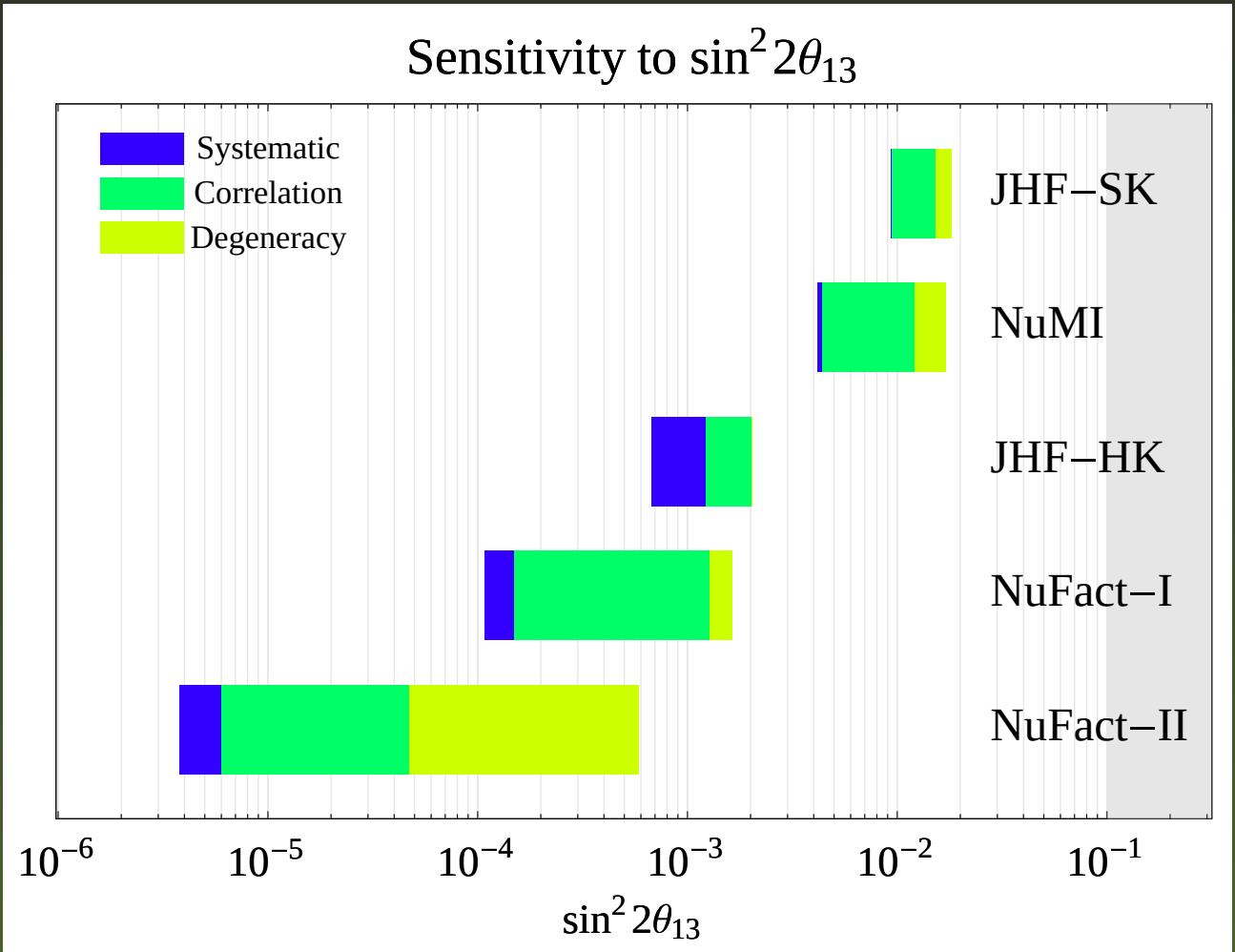
Correlations

$\Downarrow$

Degeneracies

$\Downarrow$

Final result



$\rightarrow$ Correlations and degeneracies to be reduced by clever combinations!

(Huber, Lindner, Winter, NPB 645/3, 2002, hep-ph/0204352)

The appearance channels

LBL exp: interesting information in $P_{\rm app} = P_{e\mu}$, $P_{\mu e}$, $P_{\bar{e}\bar{\mu}}$, or $P_{\bar{\mu}\bar{e}}$

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To second order in $\sin 2\theta_{13}$ and the hierarchy parameter $\alpha \equiv \frac{\Delta m^2_{21}}{\Delta m^2_{31}}$:

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

$\Delta \equiv \frac{\Delta m^2_{31} L}{4E}$, $\xi \equiv \cos\theta_{13} \sin 2\theta_{12} \sin 2\theta_{23}$, $\hat{A} \equiv \pm \frac{2\sqrt{2} G_F n_e E}{\Delta m^2_{31}}$.

(Cervera et al., 2000; Freund, Huber, Lindner, 2000; Freund, 2001)

The appearance channels

LBL exp: interesting information in $P_{\rm app} = P_{e\mu}$, $P_{\mu e}$, $P_{\bar{e}\bar{\mu}}$, or $P_{\bar{\mu}\bar{e}}$

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

$\Delta \equiv \frac{\Delta m^2_{31} L}{4E}$, $\xi \equiv \cos\theta_{13} \sin 2\theta_{12} \sin 2\theta_{23}$, $\hat{A} \equiv \pm \frac{2\sqrt{2} G_F n_e E}{\Delta m^2_{31}}$.

$\rightarrow$ The true values of $\sin^2 2\theta_{13}$ and Δm^2_{21} change the relative weights!

(Cervera et al., 2000; Freund, Huber, Lindner, 2000; Freund, 2001)

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Especially for large α and $\sin 2\theta_{13}$ all terms act simultaneously

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3) $\underline{(\delta, \theta_{13})}$-degeneracy (Burguet-Castell, Gavela, Gomez-Cadenas, Hernandez, Mena, 2001)

Important for neutrino factories because of good energy resolution and statistics

The parameters of interest (illustrated)

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

- Main information in first term
- First term enhanced by matter effects (Resonance: $\hat{A} \to 1$)
- Spoilt by degeneracies for large α
- Insufficient Δm^2_{21} $\to$ correlations with α/α^2-terms

$$
\begin{aligned}
P_{\rm app} \simeq\ & \sin^2 2\theta_{13}\, \sin^2\theta_{23} \frac{\sin^2[(1-\hat{A})\Delta]}{(1-\hat{A})^2} \\
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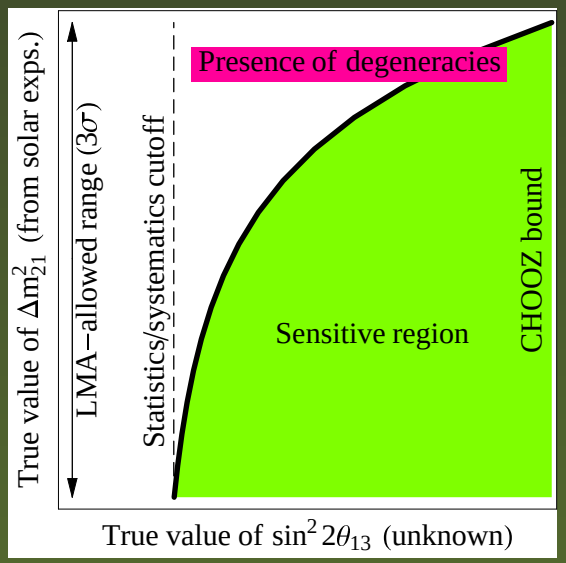
\end{aligned}
$$



The parameters of interest (illustrated)

$\mathrm{sgn}(\Delta m^2_{31})$

- Main information in first term through matter effects
- Biggest influence at resonance $\hat{A} \to 1$
- Spoilt by $\mathrm{sgn}(\Delta m^2_{31})$-degeneracy for large α
- True value of δ_{CP} relevant!

$$
\begin{aligned}
P_{\mathrm{app}} \simeq\ & \sin^2 2\theta_{13}\, \sin^2\theta_{23} \frac{\sin^2[(1-\hat{A})\Delta]}{(1-\hat{A})^2} \\
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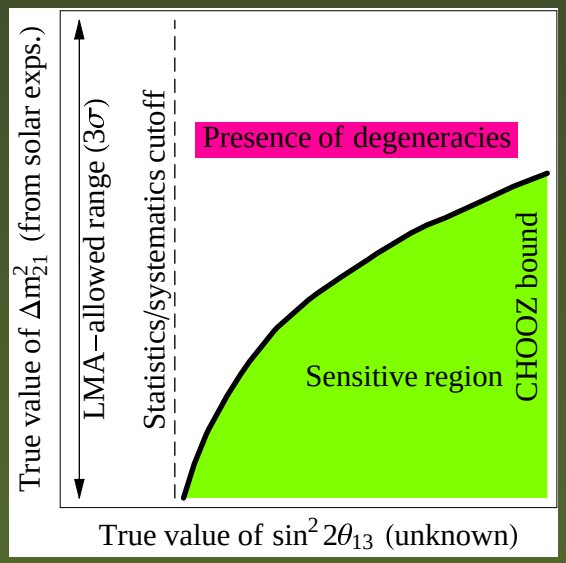

The parameters of interest (illustrated)

$\delta_{\rm CP}$

- Main information in second and third terms
- Other terms act as background
- Large $\sin 2\theta_{13}$ <u>and</u> Δm^2_{21} required

$$
\begin{aligned}
P_{\rm app} \simeq\ & \sin^2 2\theta_{13}\ \sin^2\theta_{23}\,\frac{\sin^2[(1-\hat{A})\Delta]}{(1-\hat{A})^2} \\
\pm\ & \alpha\ \sin 2\theta_{13}\,\xi \sin\delta_{\rm CP}\,\sin(\Delta)\,\frac{\sin(\hat{A}\Delta)}{\hat{A}}\,\frac{\sin[(1-\hat{A})\Delta]}{(1-\hat{A})} \\
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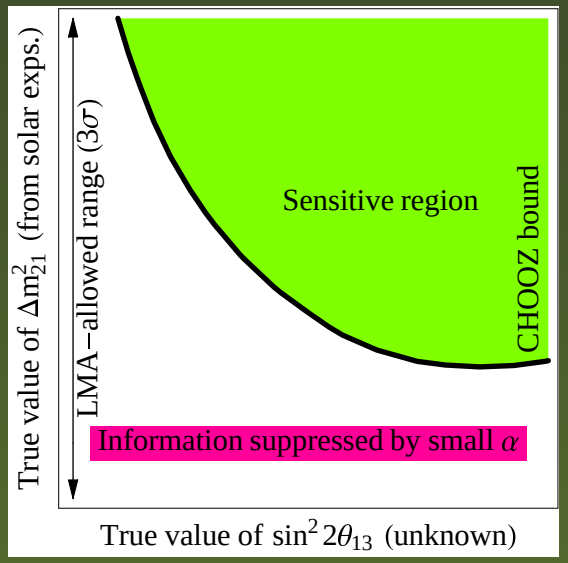

Different scales of $\sin^2 2\theta_{13}$

True value of $\sin^2 2\theta_{13}$:

Timescale???

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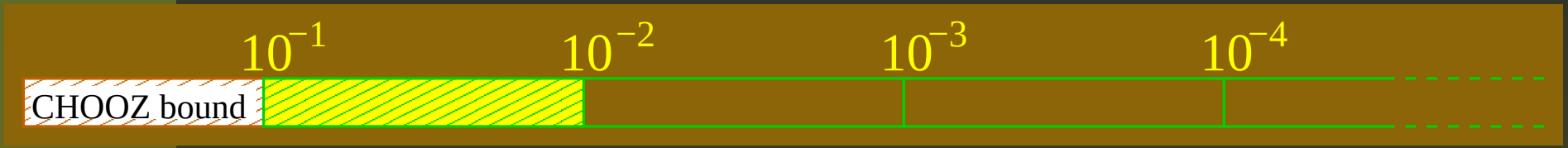
$\rightarrow$ Experiments to resolve degs. "selected" by true value of $\sin^2 2\theta_{13}$

$\rightarrow$ Combinations of experiments with similar capabilities!

Resolving degs: $\sin^2 2\theta_{13} \sim 10^{-2} - 10^{-1}$

Options:

Resolving degs: $\sin^2 2\theta_{13} \sim 10^{-2} - 10^{-1}$



Options:

- Combinations of first-generation superbeams

  (Whisnant, Yang, Young, 2002)

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Example: Synergies JHF-SK + NuMI

... as in LOIs (Itow et al, 2001; Ayres et al, 2002), 5 years running time

Initial situation:

- No sensitivity to the mass hierarchy
- Both optimized for similar params
- Only marginal CP sensitivity

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Initial situation:

- No sensitivity to the mass hierarchy
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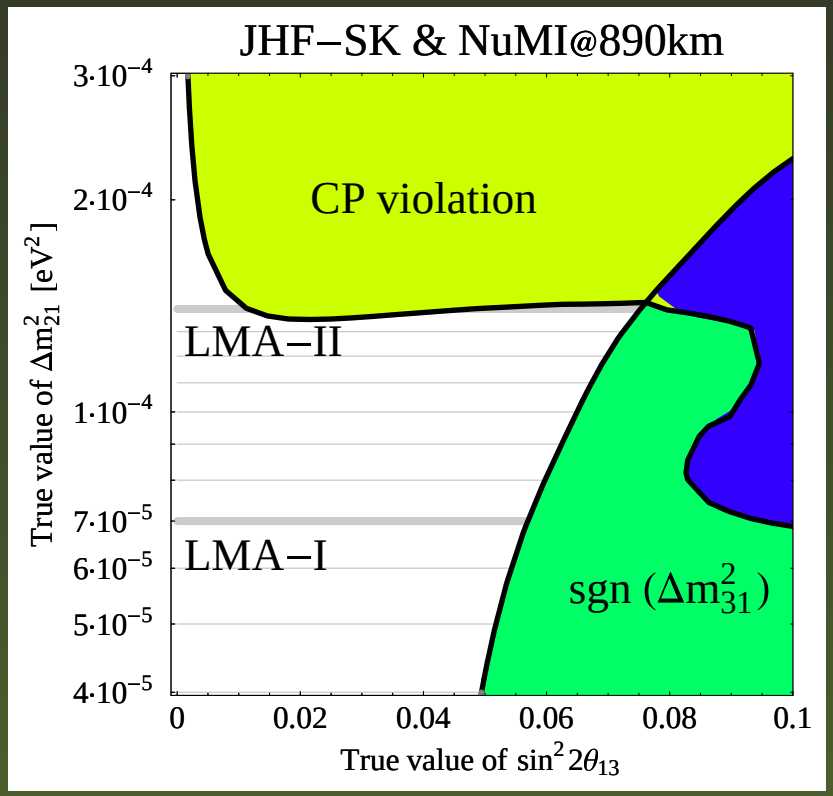
Possible modifications:

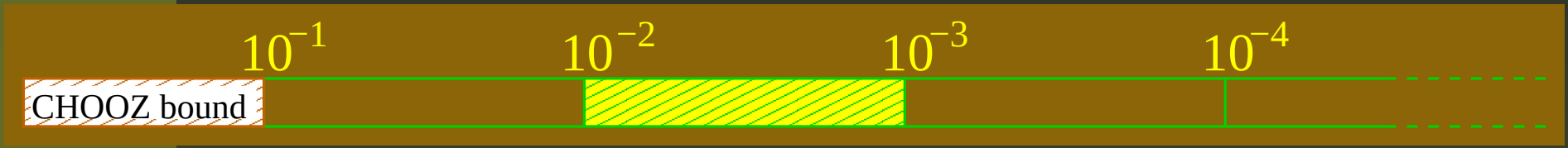
- For $\delta_{\rm CP}$: partial antineutrino running (especially JHF-SK!)
- For mass hierarchy: NuMI@longer baseline (here: $890\,\mathrm{km}$ for OA $0.72°$ alternatively: $950\,\mathrm{km}$ for OA $0.97°$)



90% CL

(Huber, Lindner, Winter, NPB 654/3, 2002, hep-ph/0211300)

Resolving degs: $\sin^2 2\theta_{13} \sim 10^{-3} - 10^{-2}$



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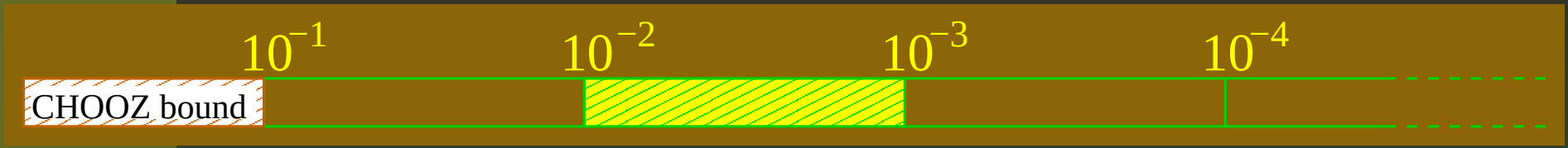

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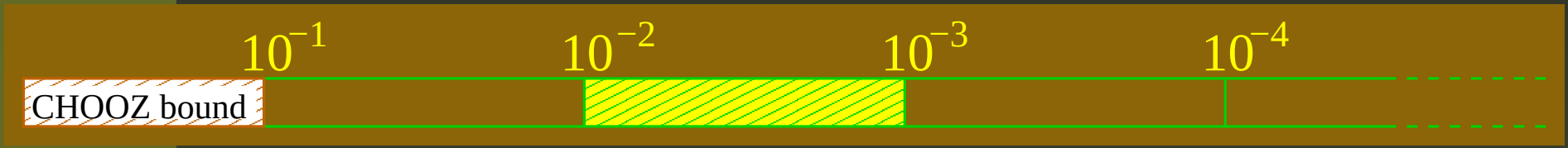

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- Superbeam upgrade and neutrino factory

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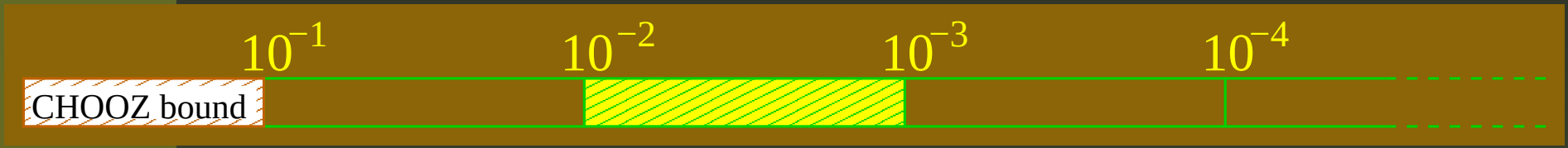

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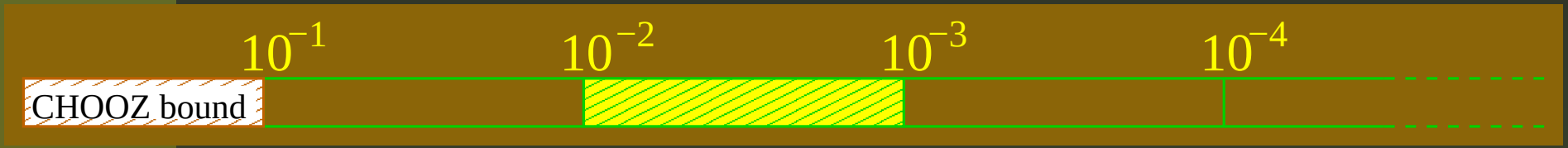

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(not $\hat{A} \to 1$ = Matter resonance!)

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$$
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$\to$ Correlations/degs. disappear

$\to$ Independent of E, osc. params

$\to$ Evaluates to $\sqrt{2} G_F n_e L = 2\pi$,

$L_{\text{magic}} \simeq 7\,630\,\text{km}$ (average density)

$L_{\text{magic}} \simeq 7\,250\,\text{km}$ (PREM profile)

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However: no CP at L_{magic}!

$$
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Example: NuFact-II

... as a “large” neutrino factory

- Detector: magnetized iron calorimeter
- Detector mass: $50\,\mathrm{kt}$
- Running time: $4\,\mathrm{y}$ neutrinos plus $4\,\mathrm{y}$ antineutrinos
- Standard baseline: $3\,000\,\mathrm{km}$ (to be varied)
- Target power: $4\,\mathrm{MW}$
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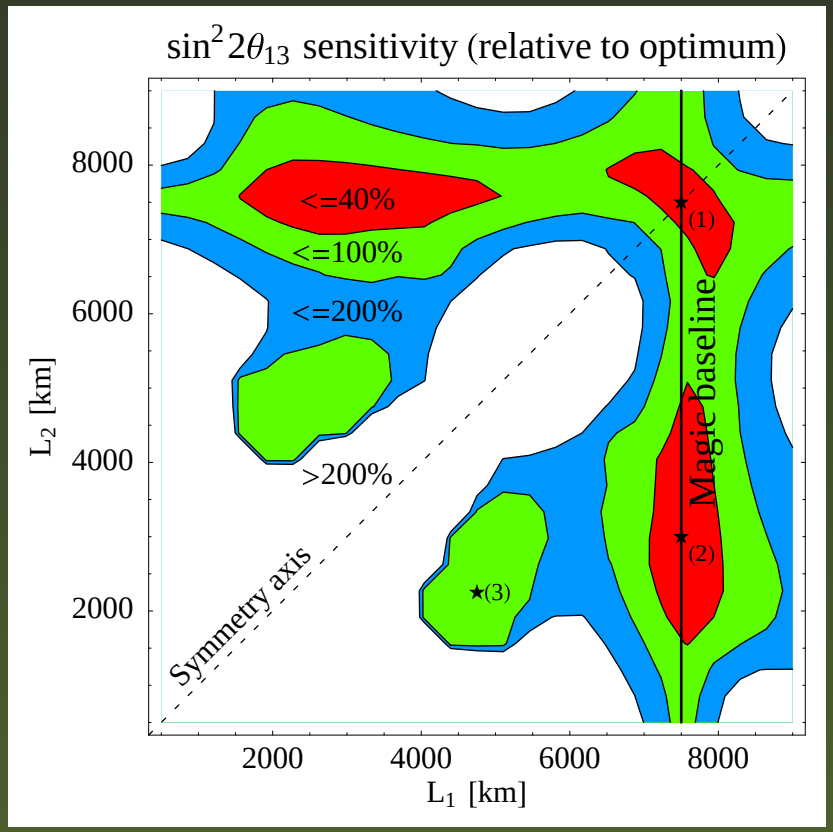
<u>Now:</u> split detector mass into two equal pieces of $25\,\mathrm{kt}$ placed at L_1 and L_2

Full analysis and the magic baseline

... for $\sin^2 2\theta_{13}$-sensitivity limit in two baseline space (L_1, L_2) (incl. correlations and degeneracies)

<u>Three local minima:</u>



3σ CL, LMA-I

(Huber, Winter, 2003, PRD, to be published, hep-ph/0301257)

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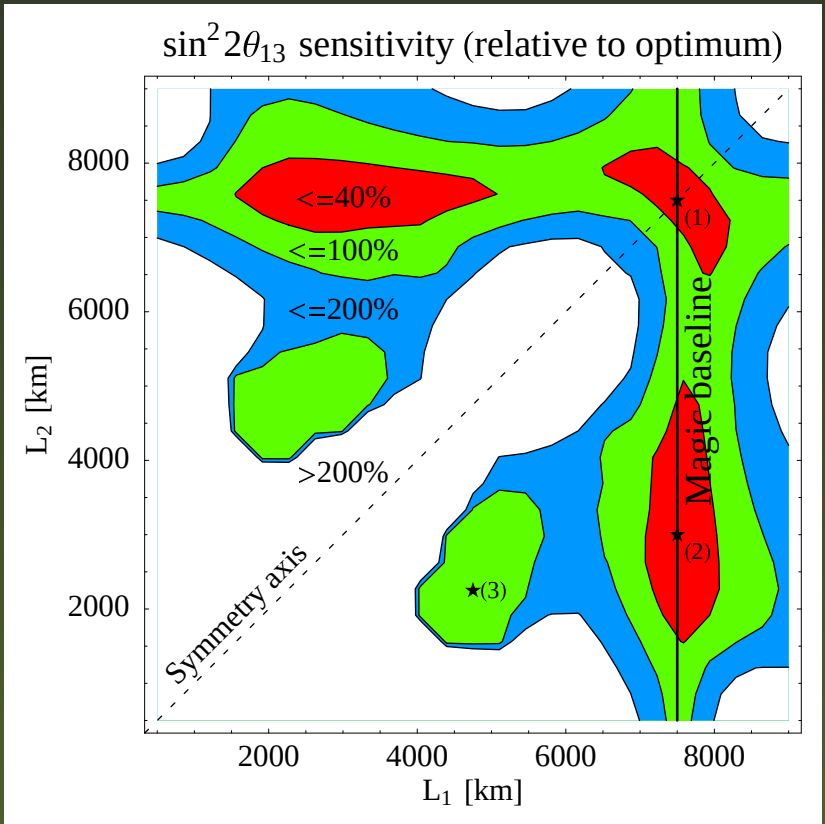
$\rightarrow$ No CP measurement possible!



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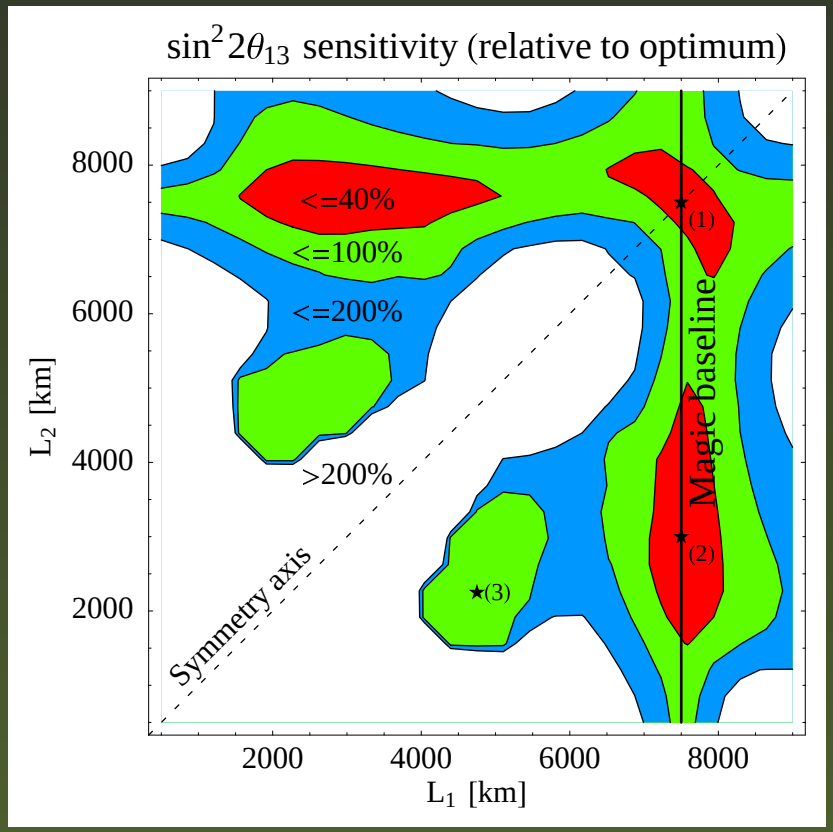

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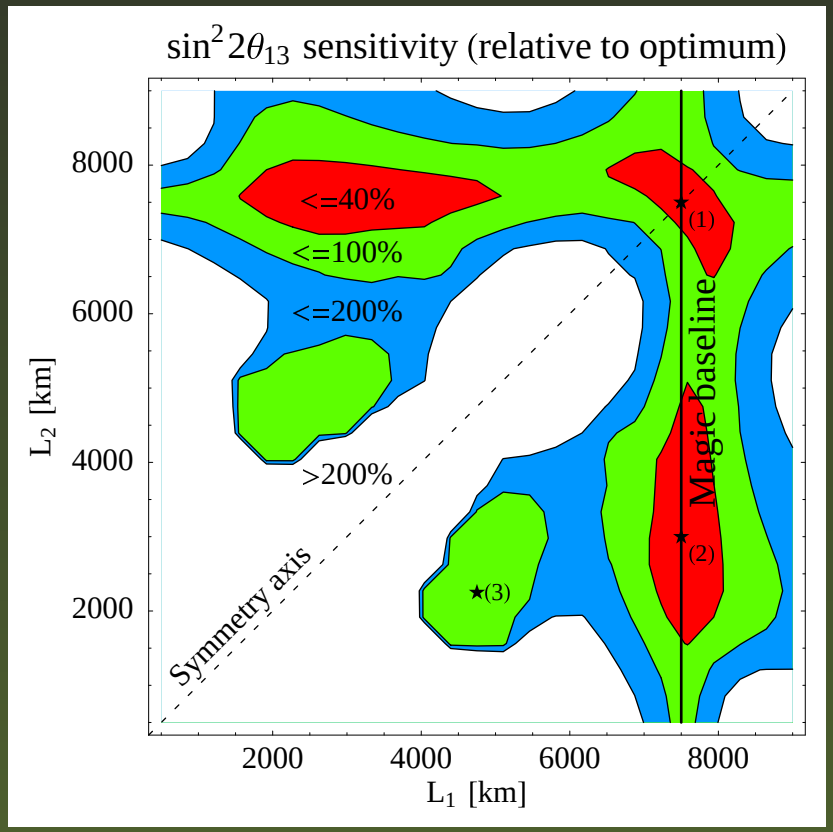
(3) $L_1 \simeq 4\,750\,\mathrm{km}$, $L_2 \simeq 2\,250\,\mathrm{km}$:

$\rightarrow$ Preferred by statistics

$\rightarrow$ Depends on osc. parameters

$\rightarrow$ Unstable $(\delta_{\mathrm{CP}}, \theta_{13})$-degeneracy

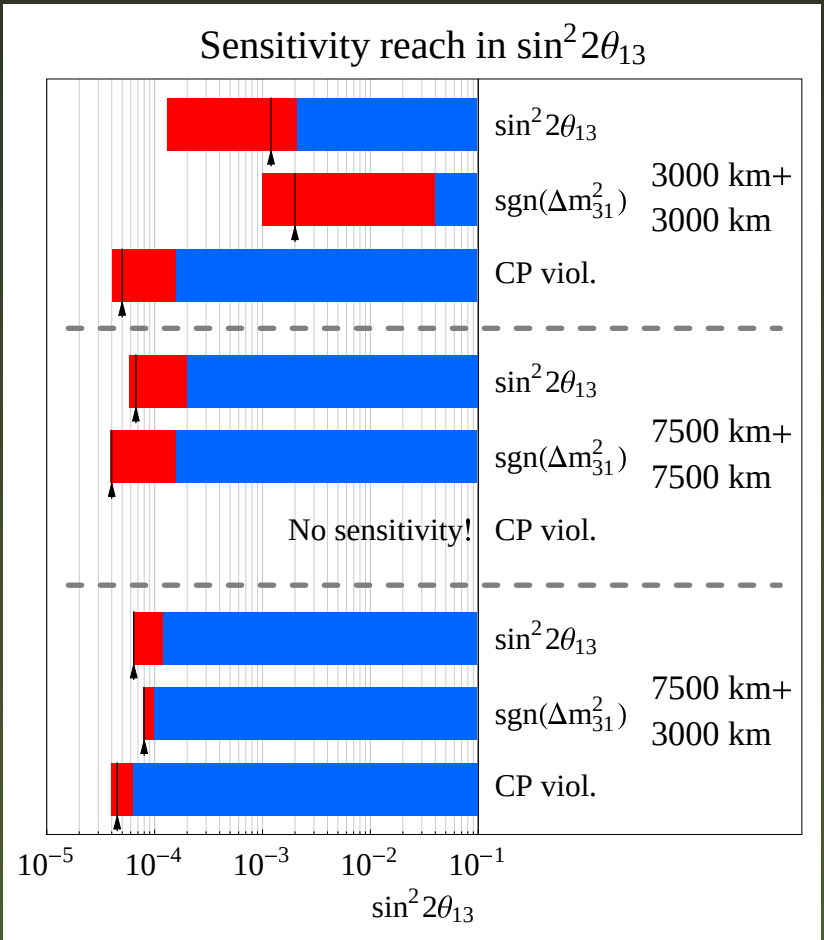


3σ CL, LMA-I

(Huber, Winter, 2003, PRD, to be published, hep-ph/0301257)

Magic baseline: Main results

Magic baseline $L \sim 7\,500\,\mathrm{km}$ compared to $L = 3\,000\,\mathrm{km}$:



(Figure: 3σ CL; Red bars by variation of Δm^2_{21} in KamLAND-allowed 3σ-range; Arrows: LMA-I best-fit)

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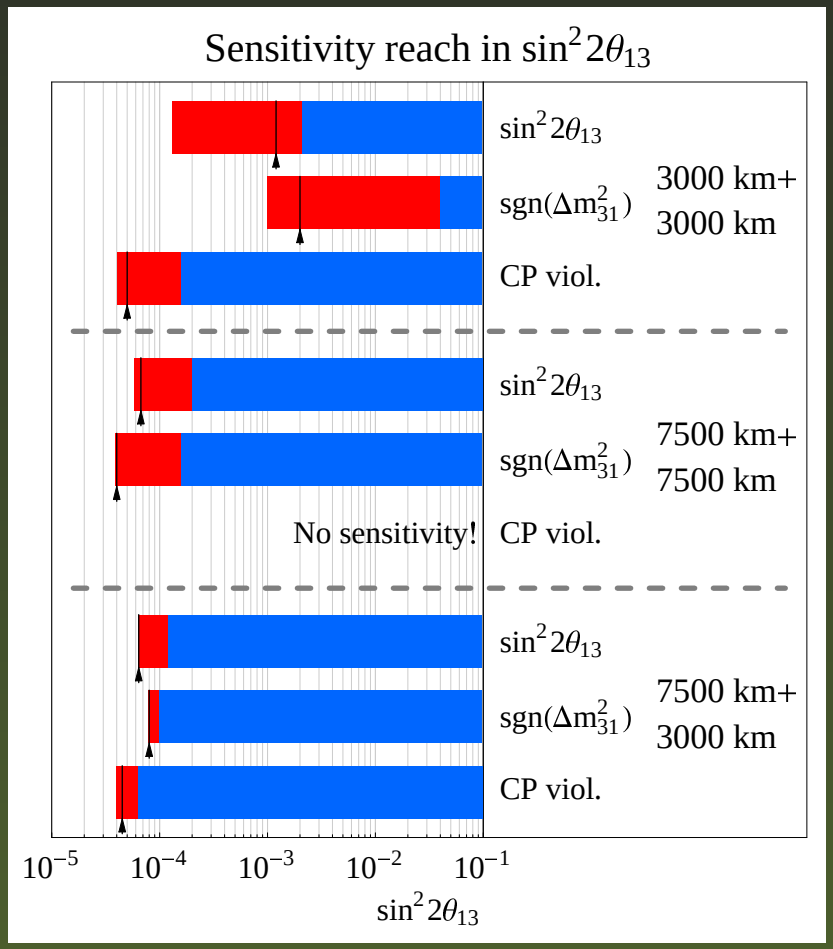

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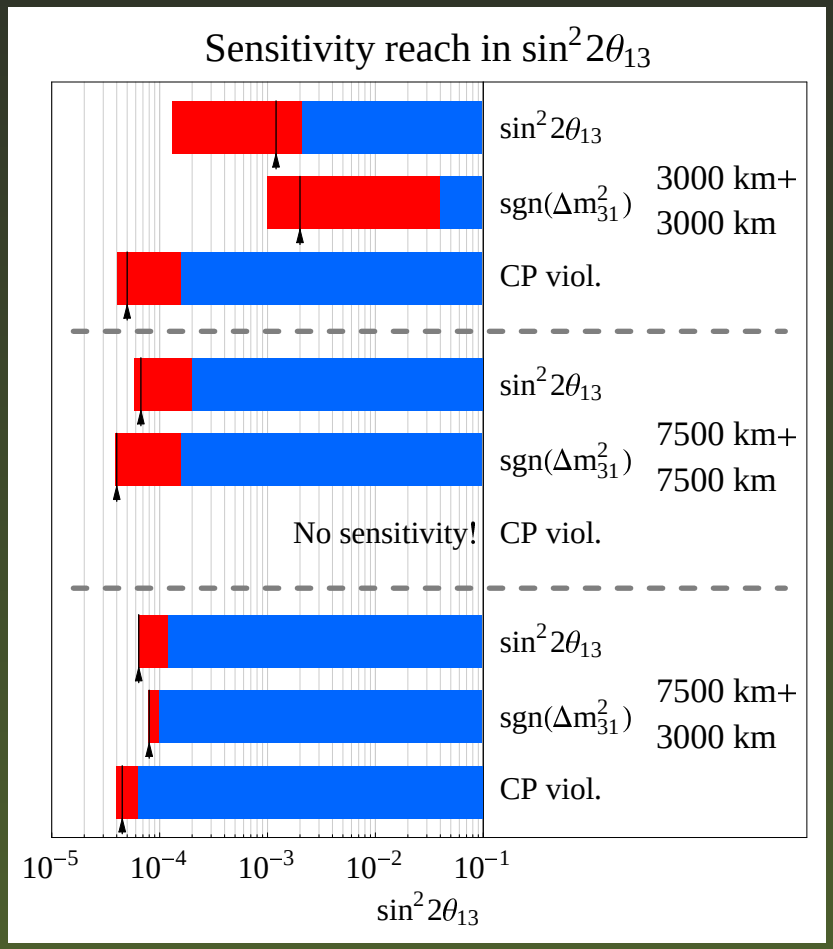

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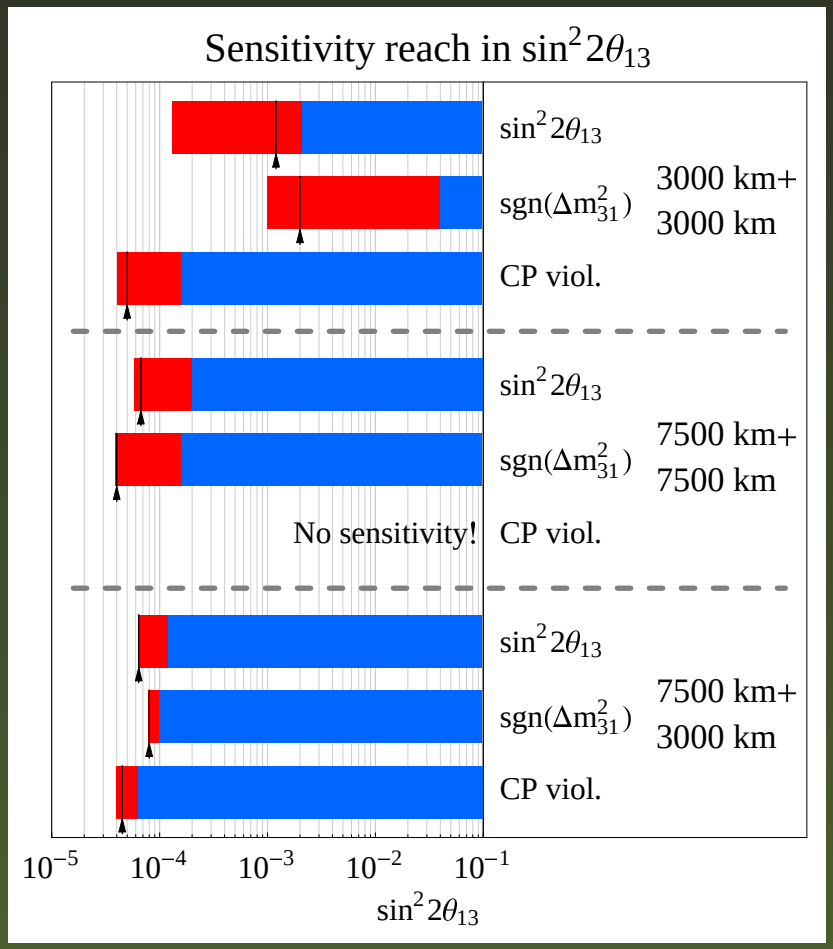
c) $L_1 = 7\,500\,\mathrm{km}$, $L_2 \simeq 3\,000\,\mathrm{km}$:

$\rightarrow$ Excellent for all parameters

esp. between $\sin^2 2\theta_{13} \sim 10^{-4} - 10^{-3}$



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However: If $\sin^2 2\theta_{13} = 0.07 \not\Rightarrow$ JHF-SK finds it (HLMA, LOW-ATM)
$\rightarrow$ Reactor experiments to test this range for sure!

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- We discussed a logarithmic scale of $\sin^2 2\theta_{13}$
  $\rightarrow$ Is this an appropriate representation?
  $\rightarrow$ Linear scale from linear mass models in flavor space?