Physics with a very long neutrino factory baseline

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Introduction . . .

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- Over the past few years, goals in neutrino oscillation physics have been redefined and become increasingly focussed.
- A major and comprehensive goal is to determine with precision, the elements of the leptonic mixing matrix and neutrino mass-squared differences.
- Contained within this overall goal are several very important questions:
  Is there CP violation in the lepton sector?
  What is the ordering of neutrino masses?
  Is θ_{13} zero? Is θ_{23} maximal?.

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- A large number of experiments are thus planned or currently under way to achieve these goals. Among these, in the near future, are neutrino beam experiments *MINOS, NOνVA, T2K..* reactor experiments *D-Chooz, Daya Bay,....*, atmospheric neutrino experiments *SK, INO..* etc

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- The progress made by these experiments towards the goals depends crucially on the requirement that $\sin^2\theta_{13}$ be close to its current global bound, $\sin^2\theta_{13} \leq 0.047$. In particular, determination of the mass hierarchy, δ_{CP}, the maximality (or otherwise) of θ_{23}, all may be compromised if this is not the case.

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- A ν factory provides a largely *uncontaminated, high luminousity and high energy neutrino beam* which allows for unprecedented precision and sensitivity for crucial parameters like θ_{13}, θ_{23} and δ_{CP}.

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- It is important to ask: How precisely do we need to know the important parameters?
- Answer: It depends on what we find in the near future, *e.g*, if prelimnary measurements indicate θ_{13} is tiny, it could be exactly zero at high scales, signalling a symmetry relevant for unification.
- In this case its (small) low energy value, modified by corrections needs to be measured with a precision significantly higher than if θ_{13} is close to its present upper bound. Similar considerations apply to $\theta_{23} = \pi/4$.

Some consequences of high precision . . .

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We examine these issues in more detail in the rest of the talk.

Summary of previous Nufac Physics and Optimization Studies

- Physics and optimization studies have revealed:

  (Barger et al,hep-ph9906487, Cervera at al, hep-ph 0002108, Burguet-Castell et al,hep-ph0103256, Freund et al, hep-ph0105071, Huber et al, hep-ph 0606119....)

  If $\sin^2\theta_{13}$ is small,

  - High Sensitivity to CP violation for range $3000 - 5000$ km.
  - High sensitivity to Mass hierarchy for $L \geq 6000$ km.
  - Sensitivity to $\sin^2\theta_{13}$ only at or around L_{magic} *i.e* ~ 7500 km.

  If $\sin^2\theta_{13}$ is close to its present upper bound,

  - The present/near future round of experiments may resolve the important questions listed above, except for *CP violation*.

Importance of the Magic Baseline . . .

- Given that L_{magic}, small θ_{13} and high precision are interlinked,it is relevant to examine the following:
  - Since L_{magic} is decided by the (constant) density, what is the optimal value one must use to determine it? Is ρ_{av} good enough?
  - How sensitive is the value of the magic length to uncertainties the density and its profile?
  - Given the conflicting requirements for δ_{CP} and small θ_{13}, what are the physics possibilities and ramifications of having a 2 detector set-up, one between $3000-5000$ km and the other between $6000-9000$ km?

The magic baseline and the optimal constant density

- We recall that

$$P_{e\mu} \simeq \sin^2 2\theta_{13}\ \sin^2\theta_{23} \frac{\sin^2[(1-\hat{A})\Delta]}{(1-\hat{A})^2}$$
$$\pm\ \alpha \sin 2\theta_{13}\ \sin 2\theta_{12}\ \sin 2\theta_{23}\ \sin\delta_{\rm CP}\ \sin(\Delta)[\frac{\sin(\hat{A}\Delta)}{\hat{A}} \frac{\sin[(1-\hat{A})\Delta]}{(1-\hat{A})}]$$
$$+\ \alpha \sin 2\theta_{13}\ \sin 2\theta_{12}\ \sin 2\theta_{23}\ cos\delta_{\rm CP}\ \cos(\Delta)[\frac{\sin(\hat{A}\Delta)}{\hat{A}} \frac{\sin[(1-\hat{A})\Delta]}{(1-\hat{A})}]$$
$$+\ \alpha^2\ \cos^2\theta_{23}\sin^2 2\theta_{12}\frac{\sin^2(\hat{A}\Delta)}{\hat{A}^2}. \quad (1)$$

- The defi ning condition for the magic baseline is:

$$\sin(\hat{A}\Delta) = 0 \quad \Rightarrow \quad \frac{G_F n_e L}{\sqrt{2}} = \pi \quad (2)$$

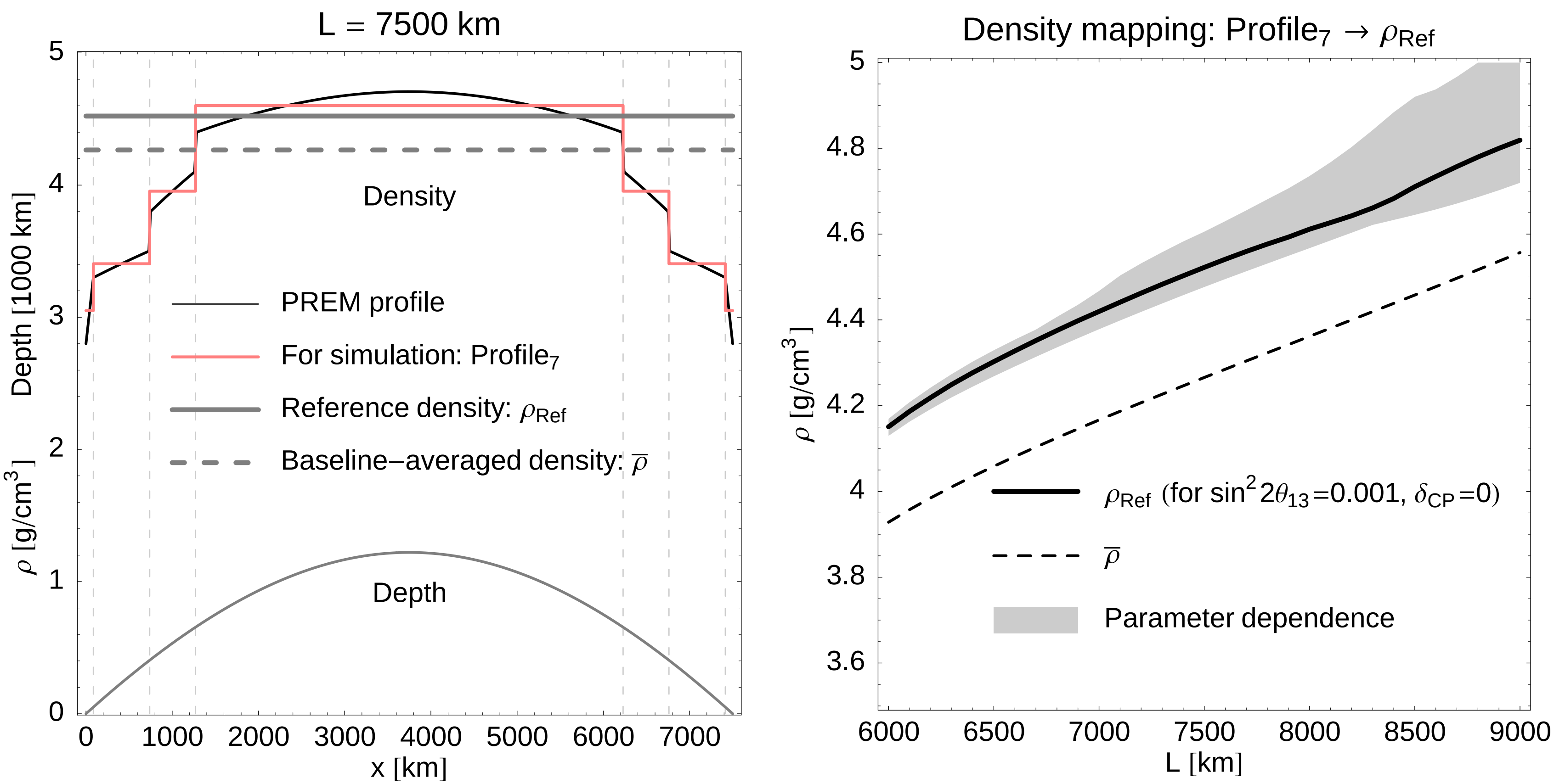
The magic baseline and the optimal constant density

- It is important to note:
  - The dependence of L_m on ρ alone makes it an optimal baseline for Earth density measurements. Also, $\sin(\hat{A}\Delta) = 0$ implies maximal sensitivity to any change in the assumed constant density.
  - It may not be possible to situate a detector very close to L_{magic}. What are the consequences of this?

The magic baseline and the optimal constant density

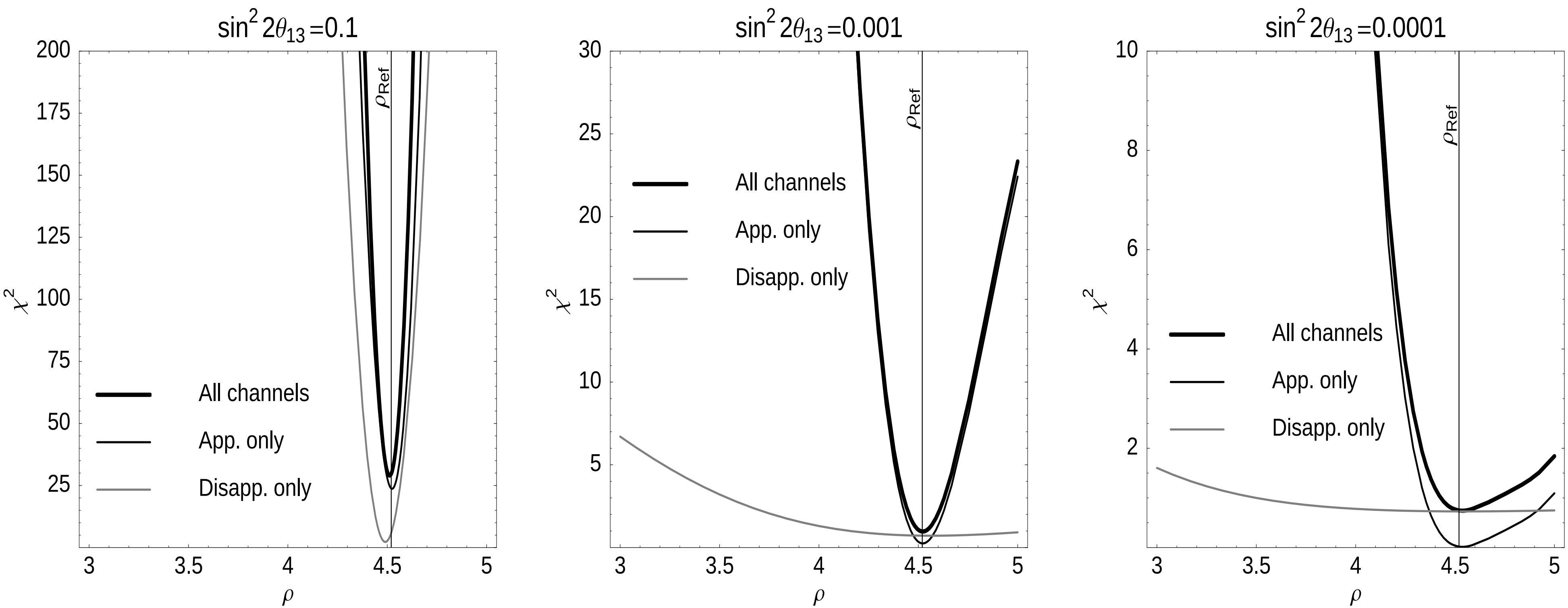
- For our calculations we use:
  - A $E_\mu = 50$ GeV factory beam and a 50 kT (INO-like) magnetized iron calorimeter.
  - Luminousity of 4.24×10^{21} useful muon decays over 4 years.
  - The GLOBES package for simulation.
  - Include appropriate correlations, parameter degeneracies and marginalizations. Treat density like any other oscillation parameter.
  - Where appropriate, we study and compare the performance of combination of2 detectors of 50 kT, one at 4000 km and the other between 6000-9000 km.

The Magic baseline and the optimal constant density



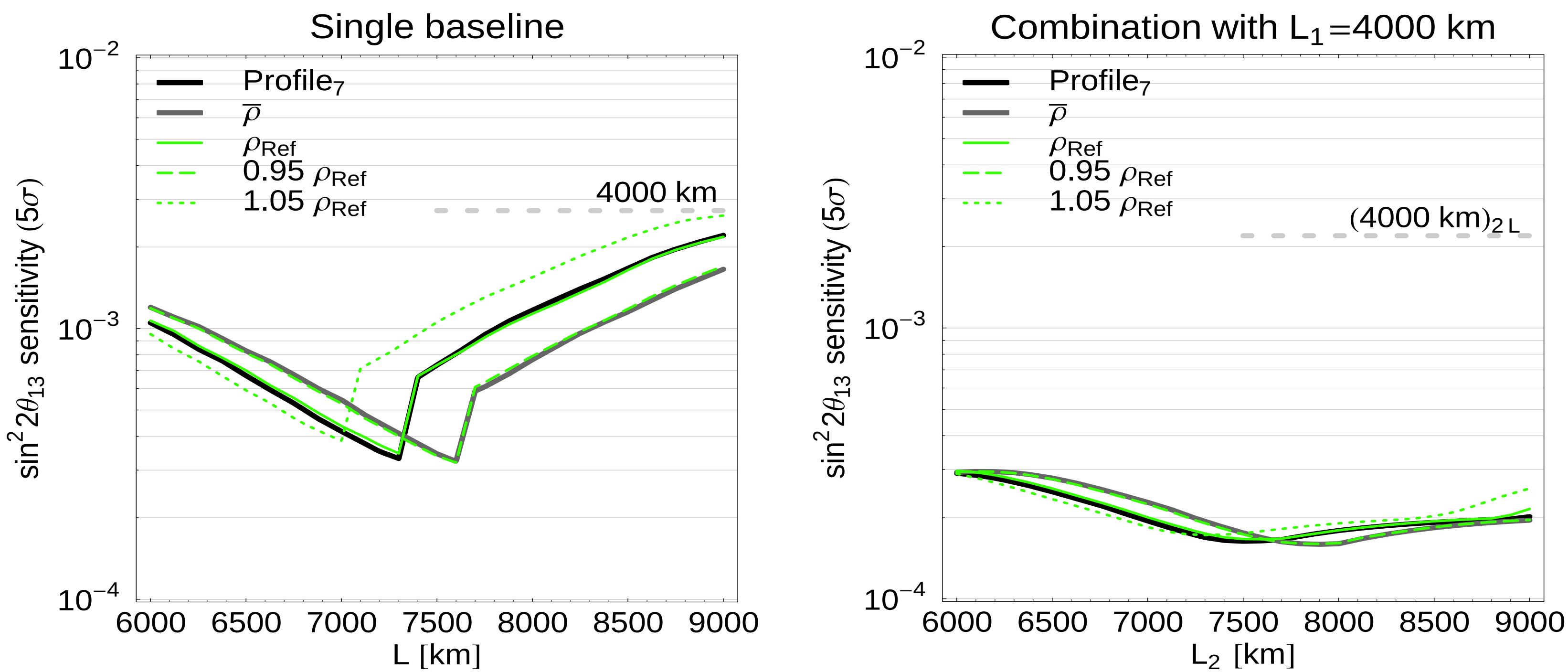
- ρ_{ref} is the constant density which best reproduces results of PREM profi le for full neutrino factory simulation for a given set of osscillation parameters.
- Gray band represents effect of varying osscillation parameters over allowed ranges.
- Magic baseline determination with ρ_{ref} lowers it by 300-400 km.

The Magic baseline and the optimal constant density



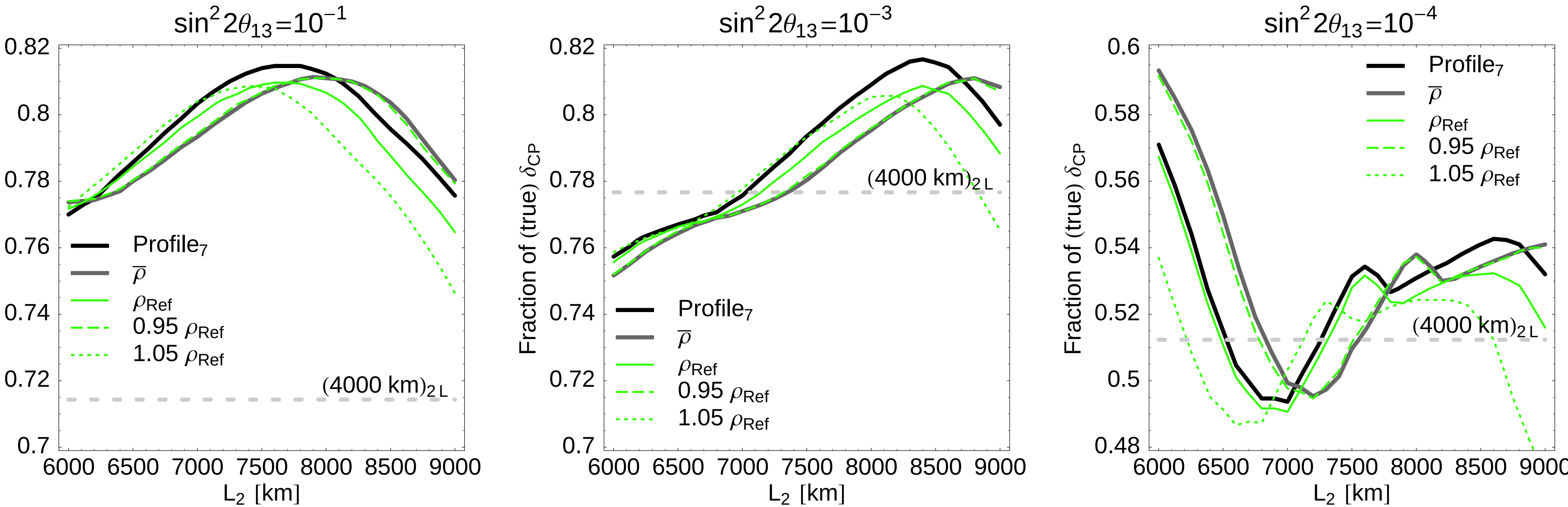
- ρ_{ref} chosen by minimizing χ^2. Note steep dependance when matter effects large.
- Note softer dependance of disappearance channel compared to matter sensitive appearance channel.

θ_{13} *Sensitivity at very long baselines*



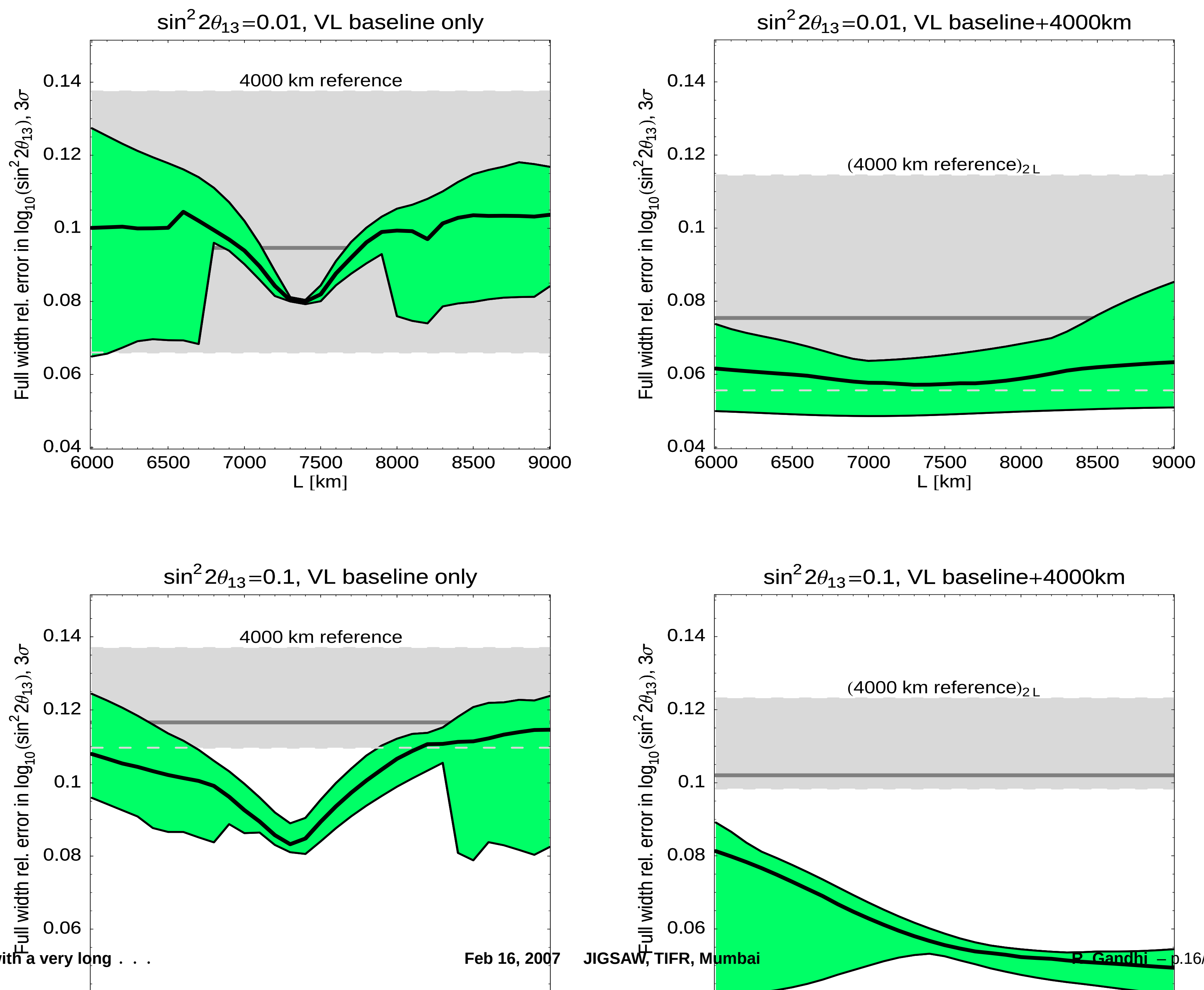
- Note sensitivity to density variations for very long baseline when used by itself.
- This softens considerably when combination of 2 baselines is used..

δ_{CP} Sensitivity at very long baselines

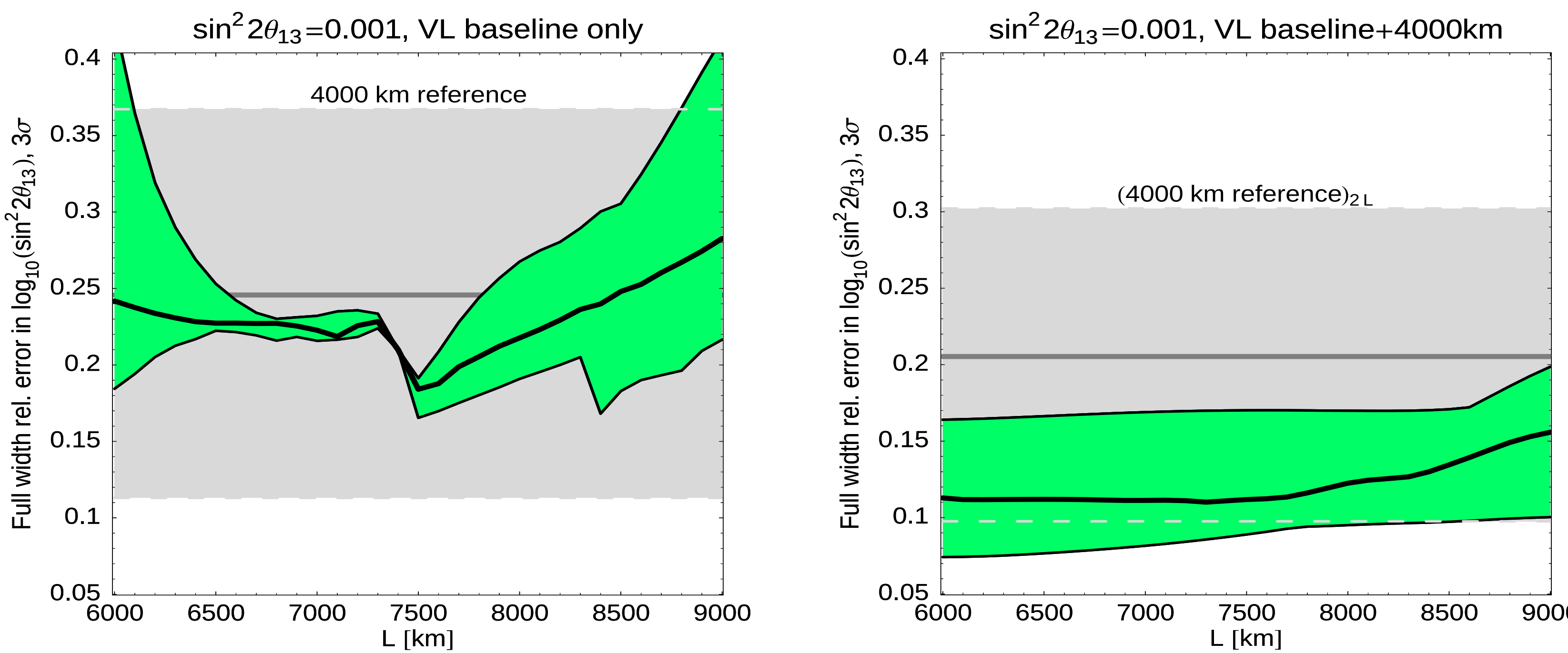


- Fraction of δ_{CP} is fraction of full range for which CPV detectable at 3σ.
- Note degeneracy resolving power of very long baseline..

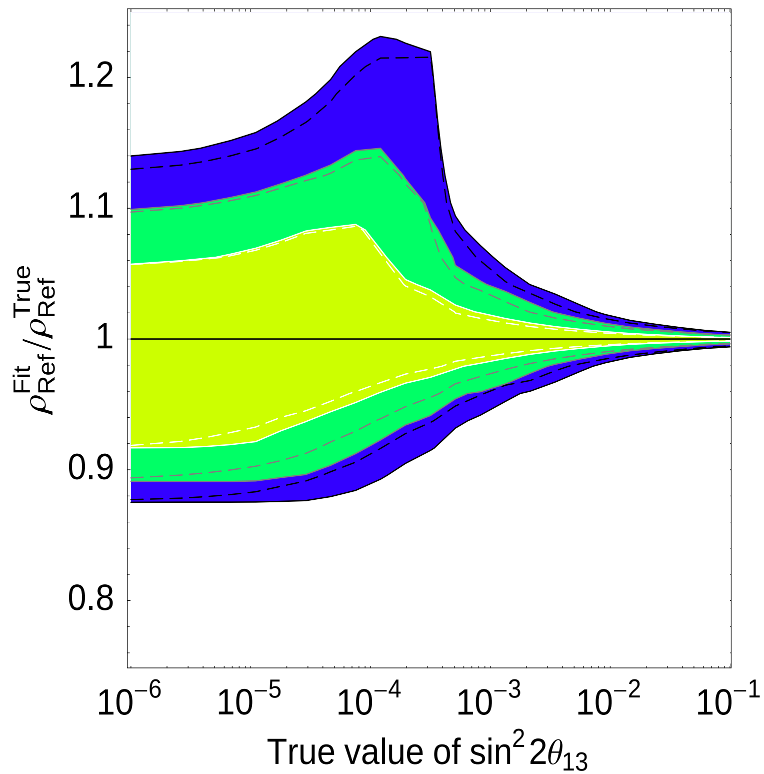
θ_{13} *Precision at very long baselines*



θ_{13} *Precision at very long baselines*

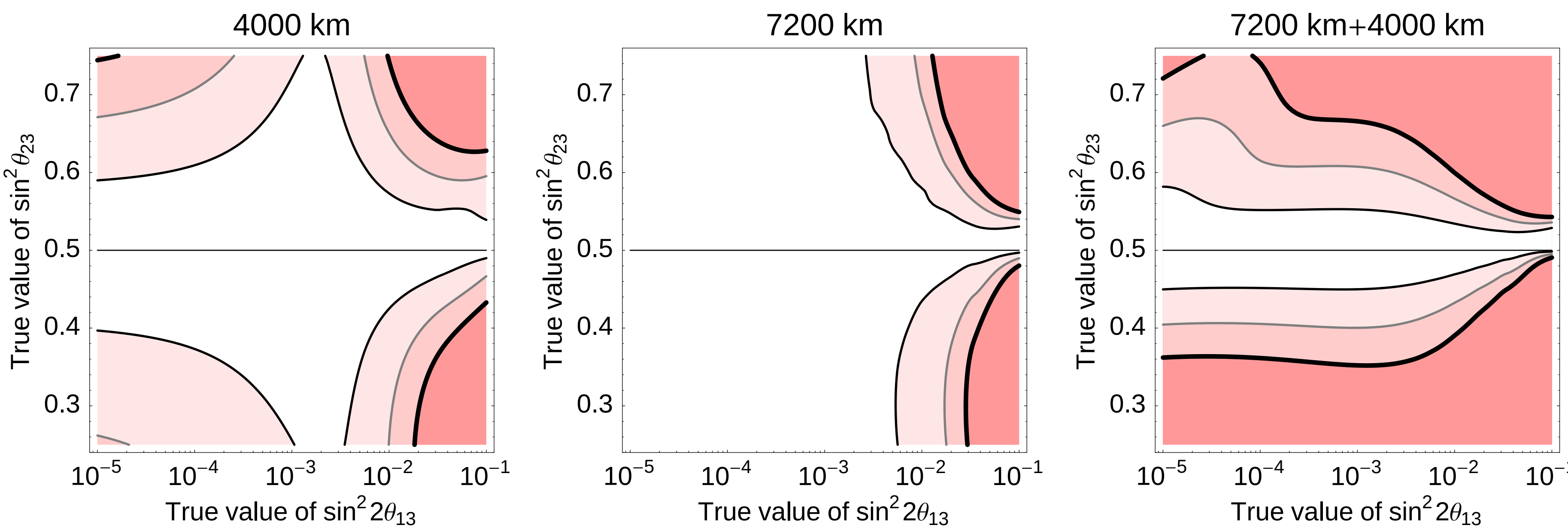


Sensitivity to density measurements at very long baselines



- Sensitivity to density measurements of 2 detector combination. Excellent for large θ_{13}.
- Worst sensitivity for intermediate values of $\sin^2 2\theta_{13}$.

Resolving the θ_{23} degeneracy at very long baselines



- Degeneracy considered to be resolved if no value in “other” octant fi ts original solution at chosen CL..
- Very long baseline on its own has sensitivity only for large $\sin^2 2\theta_{13}$. Shorter baseline reasonably sensitive to all but intermediate value of $\sin^2 2\theta_{13}$.
- Combination of the two performs better for almost all possible values of $\sin^2 2\theta_{13}$.

The magic baseline and the optimal constant density

- We recall that

$$
\begin{aligned}
P_{e\mu} \quad &\simeq \quad \sin^2 2\theta_{13}\ \sin^2\theta_{23} \frac{\sin^2[(1-\hat{A})\Delta]}{(1-\hat{A})^2} \\
&\pm \quad \alpha \sin 2\theta_{13}\ \sin 2\theta_{12}\ \sin 2\theta_{23}\ \sin\delta_{\rm CP}\ \sin(\Delta)[\\
&\quad\quad \frac{\sin(\hat{A}\Delta)}{\hat{A}} \frac{\sin[(1-\hat{A})\Delta]}{(1-\hat{A})}] \\
&+ \quad \alpha \sin 2\theta_{13}\ \sin 2\theta_{12}\ \sin 2\theta_{23}\ cos\delta_{\rm CP}\ \cos(\Delta)[\\
&\quad\quad \frac{\sin(\hat{A}\Delta)}{\hat{A}} \frac{\sin[(1-\hat{A})\Delta]}{(1-\hat{A})}] \\
&+ \quad \alpha^2\ \cos^2\theta_{23} \sin^2 2\theta_{12} \frac{\sin^2(\hat{A}\Delta)}{\hat{A}^2}. \qquad (3)
\end{aligned}
$$

- The defi ning condition for the magic baseline is:

$$
\sin(\hat{A}\Delta) = 0 \quad \Rightarrow \quad \frac{G_F n_e L}{\sqrt{2}} = \pi \qquad (4)
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Conclusions . . .

- The optimal constant density is different from ρ_{av} and lowers the value of L_{magic} by 300-400 km.

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- An INO-like detector, positioned anywhere between 6000-9000 km, in combination with a intermediate baseline detector fed from a neutrino factory would lead to significant progress towards resolving almost all important questions in the physics of neutrino oscillation for a very wide range of δ_{CP} and θ_{13}

Conclusions . . .

- The combination of a 4000 km and VL baseline detector also has significantly reduced sensitivity to errors/uncertainty in the profile and density. This consideration can be important if high precision is required.

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- The combination of a 4000 km and VL baseline detector also has significantly reduced sensitivity to errors/uncertainty in the profile and density. This consideration can be important if high precision is required.

- If θ_{13} is very small, and if a δ_{CP} is crucial to understanding the BAU via leptogenesis, this combination may be one of the very few options to determining both.