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CONSEJO SUPERIOR DE INVESTIGACIONES CIENTÍFICAS

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Neutrino quantum decoherence at reactor experiments

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Based on JHEP 08 (2020) 018 and JHEP 06 (2021) 042 in collaboration with André de Gouvêa and Christoph Ternes

Neutrino quantum decoherence

- ▶ Neutrino oscillations are an example of flavour oscillations, which arise when the particles produced and detected in an experiment are superpositions of different mass eigenstates.
- ▶ Consequence of the fact that the charged-current weak interactions are not diagonal in the basis of the mass eigenstates for both the charged leptons and the neutrinos.
- ▶ The QM uncertainty principle implies that when neutrinos are produced at some source they must be in a superposition of different momentum states. The neutrino wave function must be a wave packet.
- ▶ Coherence is essential for neutrino oscillations!



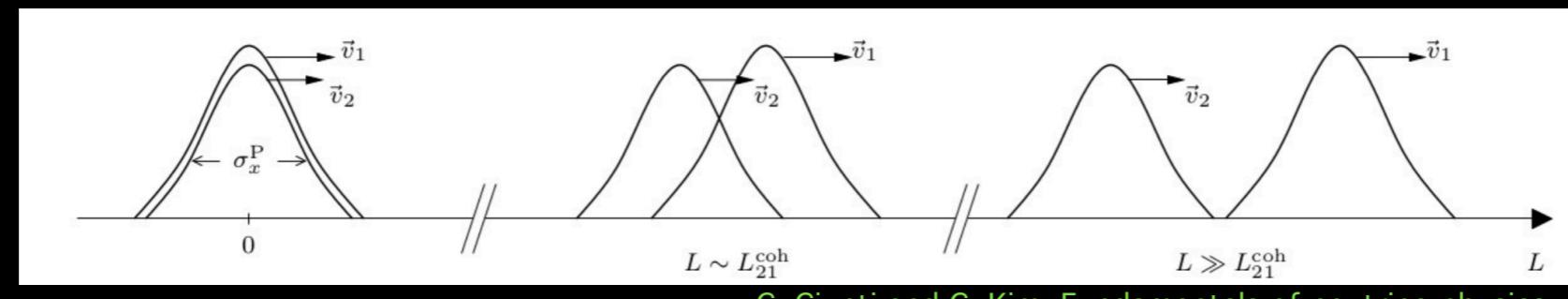
Illustration: © Johan Jarnestad/The Royal Swedish Academy of Sciences

S. Nussinov, Phys. Lett. B 63 (1976) 201–203.
B. Kayser,, Phys. Rev. D 24 (1981) 110.
C. Giunti, C. Kim, and U. Lee, Phys. Rev. D 44 (1991) 3635–3640.
C. Giunti, C. Kim, and U. Lee, Phys. Lett. B 274 (1992) 87–94.
K. Kiers and N. Weiss, Phys. Rev. D 57 (1998) 3091–3105

C. Giunti and C. Kim, Phys. Rev. D 58 (1998) 017301,
W. Grimus, P. Stockinger, and S. Mohanty, Phys.
E. K. Akhmedov and J. Kopp, JHEP 04 (2010) 008
D. Naumov and V. Naumov, J. Phys. G 37 (2010) 105014
E. Akhmedov, D. Hernandez, and A. Smirnov, JHEP 04 (2012) 052

Neutrino quantum decoherence

- To date there is no experimental evidence of distance-dependent loss of coherence for propagating neutrinos.
- Physics that leads to this type of decoherence: the wave packets corresponding to different neutrino mass eigenstates propagate with different speeds and, given enough time, the wave-packets ultimately separate.



- Eventually, the wave packets of two different mass eigenstates will have no significant overlap any more and their coherence will be lost, leading to a suppression of neutrino oscillations.
- Nuclear reactors are excellent laboratories to study neutrino coherence.

S. Nussinov, Phys. Lett. B 63 (1976) 201–203.

B. Kayser,, Phys. Rev. D 24 (1981) 110.

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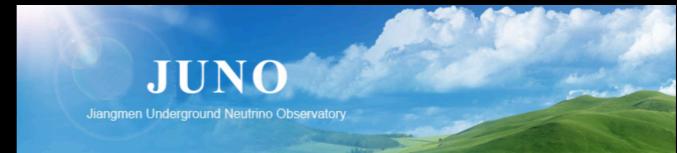
D. Naumov and V. Naumov, J. Phys. G 37 (2010) 105014

E. Akhmedov, D. Hernandez, and A. Smirnov, JHEP 04 (2012) 052

Decoherence and reactor experiments

► Jiangmen Underground Neutrino Observatory (JUNO)

- 10 reactors
- 1 far detector (+ 1 near detector under consideration)
- $L \sim 50$ km
- JUNO will measure the solar parameters and the atmospheric mass splitting at below 1%



► Reactor Experiment for Neutrino Oscillation (RENO)

- 6 power plants
- 2 identical detectors
- $L \sim 100$ m



► Daya Bay reactor experiment

- 6 power plants
- 8 identical detectors at 3 experimental halls
- $L \sim 1000$ m



► Kamioka Liquid Scintillator Antineutrino Detector (KamLAND)

- more than 50 reactor cores
- distances ranging from ~ 100 km to ~ 1000 km



Neutrino oscillations with decoherence

The survival probability of electron antineutrinos including decoherence effects is:

$$P^{\text{dec}}(\bar{\nu}_e \rightarrow \bar{\nu}_e) = \sum_{j,k} |U_{ej}|^2 |U_{ek}|^2 \exp[-i\Delta_{jk} - \xi_{jk}]$$

where $\Delta_{jk} \equiv 2\pi \frac{L}{L_{jk}^{\text{osc}}} \equiv \frac{\Delta m_{jk}^2 L}{2E}$

Giunti, Kim, Lee, PLB274 (1992)
M. Beuthe, PRD66 (2002)
Kayser, Kopp, arXiv:1005.4081

and $\xi_{jk}(L, E) = \xi_{kj}(L, E)$ quantify the loss of coherence as a function of the neutrino energy and the baseline.

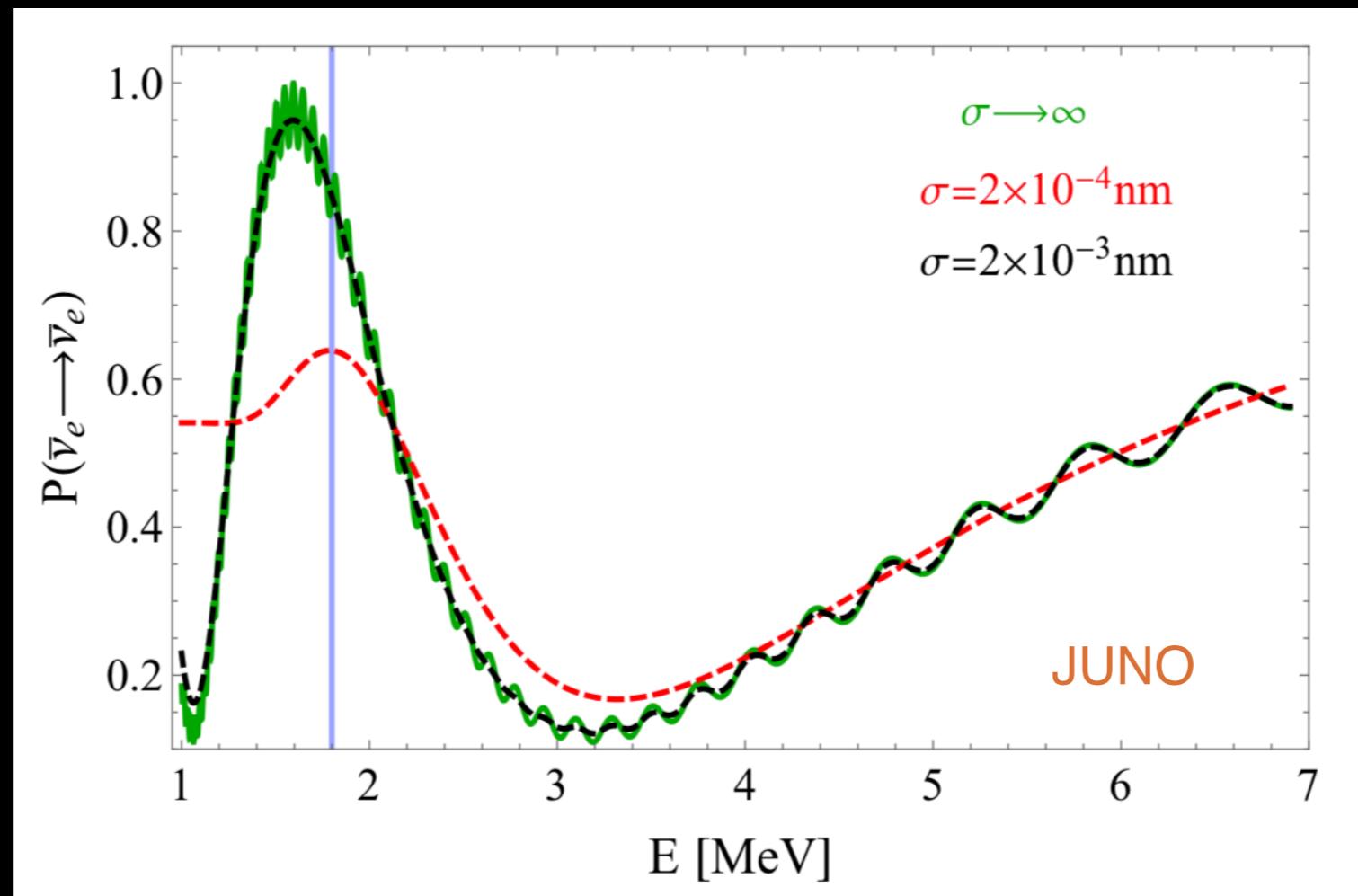
$$\xi_{jk}(L, E) = \left(\frac{L}{L_{jk}^{\text{coh}}} \right)^2$$

$$L_{jk}^{\text{coh}} = \frac{4\sqrt{2}E^2}{|\Delta m_{jk}^2|} \sigma$$

σ is the effective width of the neutrino wave-packet and depends on the properties of the neutrino source and of the detector.

Decoherence effects at reactor experiments

Decoherence effects in reactor experiments grow with the baseline and decrease with the neutrino energy.

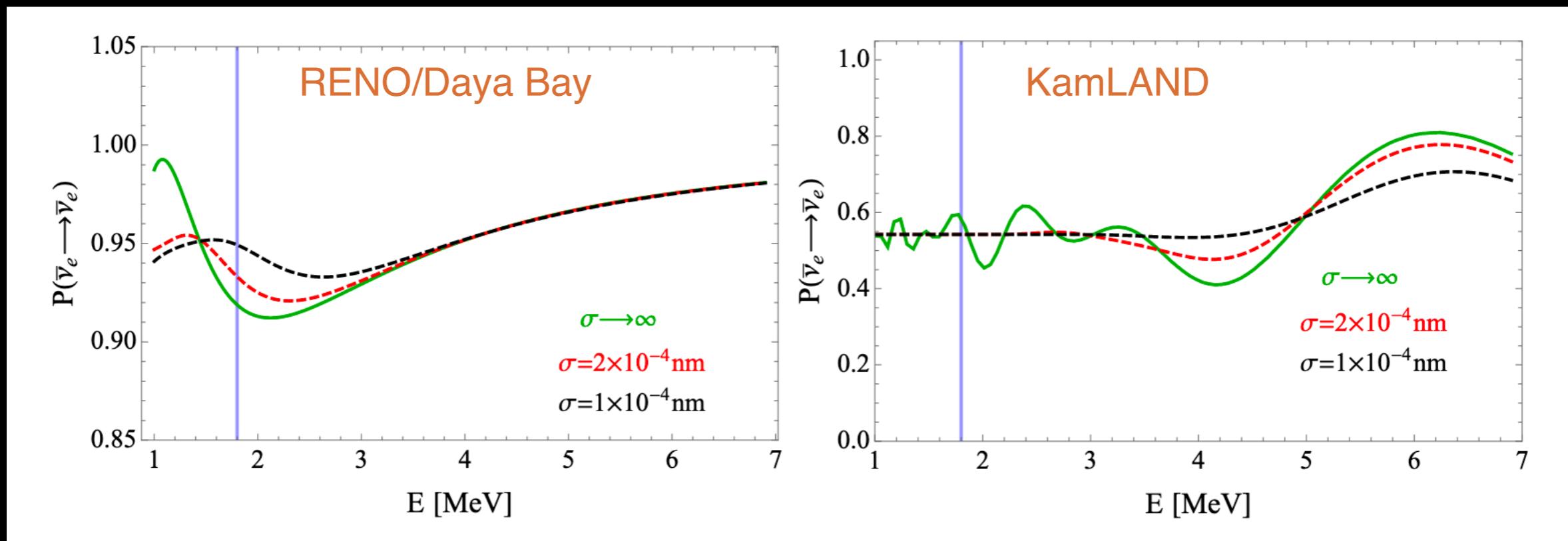


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The fast oscillations “disappear” first and that the effect is more pronounced at smaller neutrino energies.

Decoherence effects at reactor experiments

Decoherence “erases” the oscillatory behaviour of the survival probability and its impact is more pronounced at relatively smaller energies. KamLAND observes oscillation minimum and maximum.

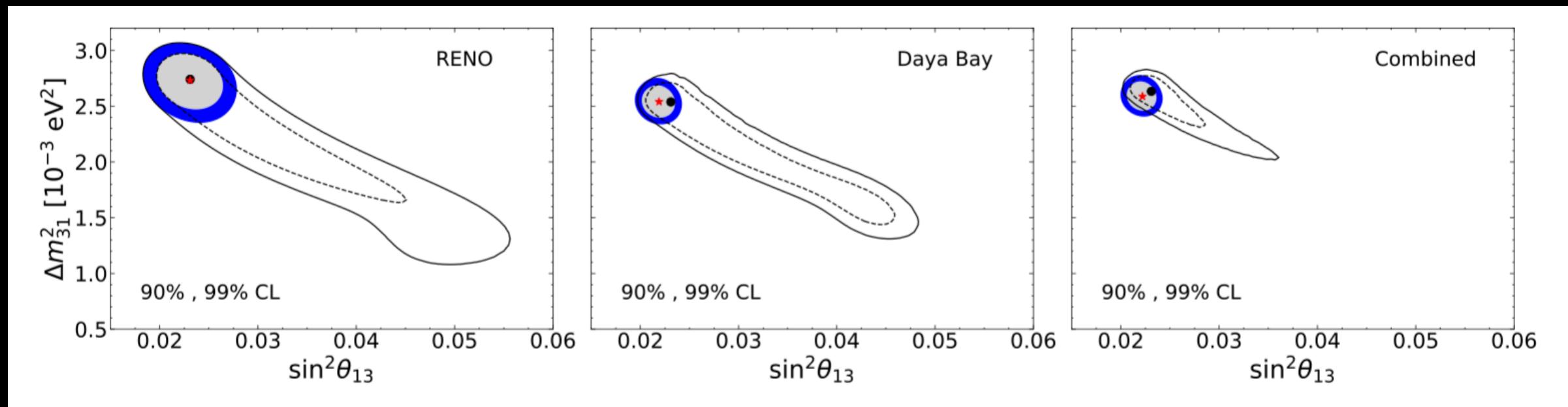


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Bounds from RENO and Daya Bay

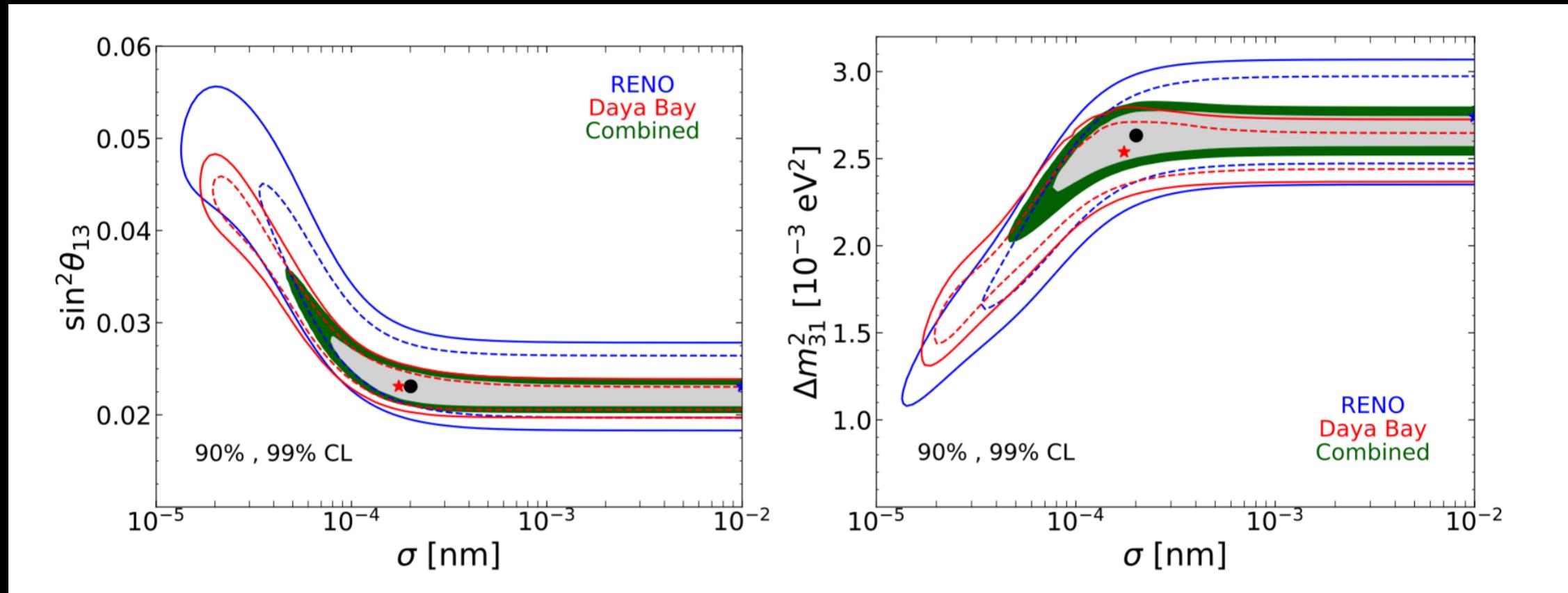
Compare results assuming a perfectly coherent source (filled regions) with the case in which allow finite values of σ .

Sensitivity is reduced when including the wave packet width in the analysis.



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Ruling out decoherence



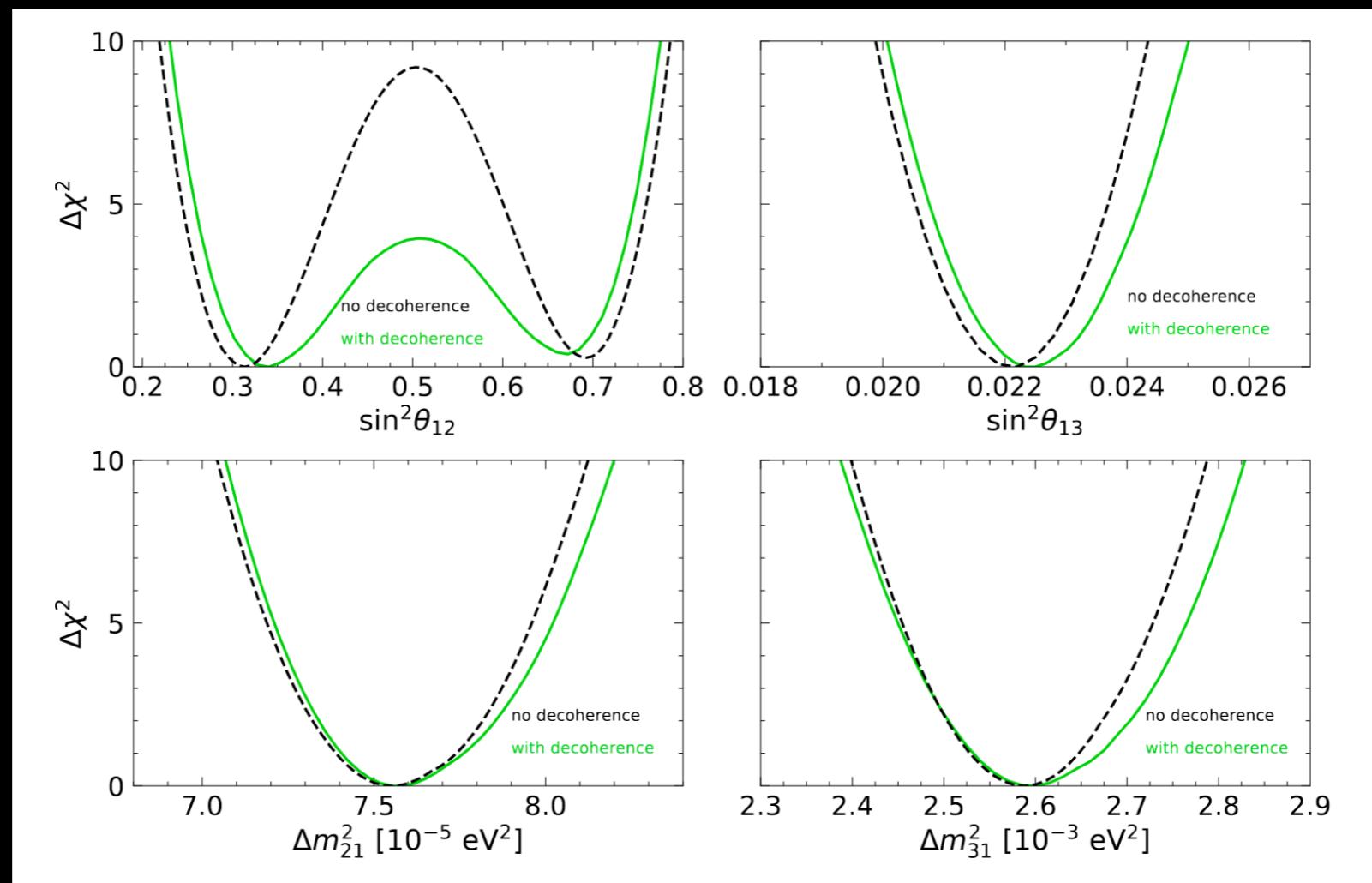
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The reduction of sensitivity is due to a new correlation between the standard parameters and the wave packet width.

Small values of sigma are correlated with large (small) values of the mixing angle (mass splitting).

Bounds from RENO and Daya Bay + KamLAND

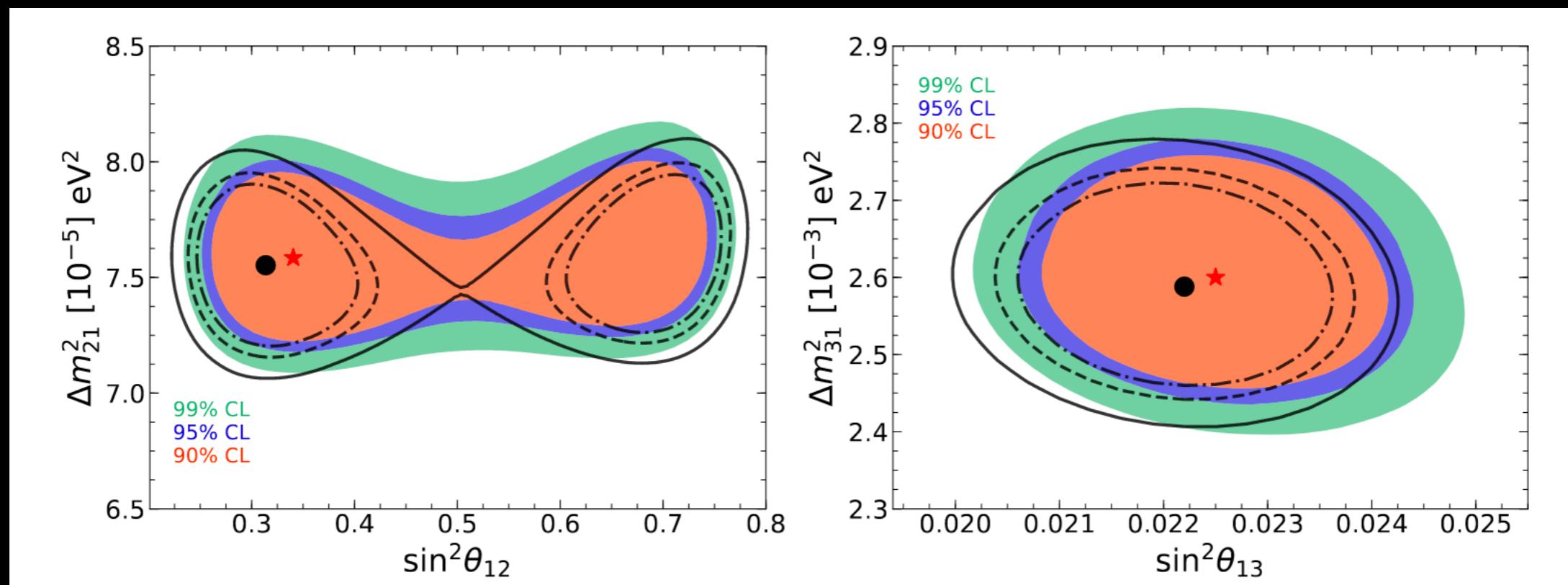
The determination of the standard oscillation parameters is not substantially impacted by the possible loss of coherence of neutrino oscillations due to neutrino wave-packet separation.



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Bounds from RENO and Daya Bay + KamLAND

Combining all data restores the sensitivity to standard oscillation parameters.



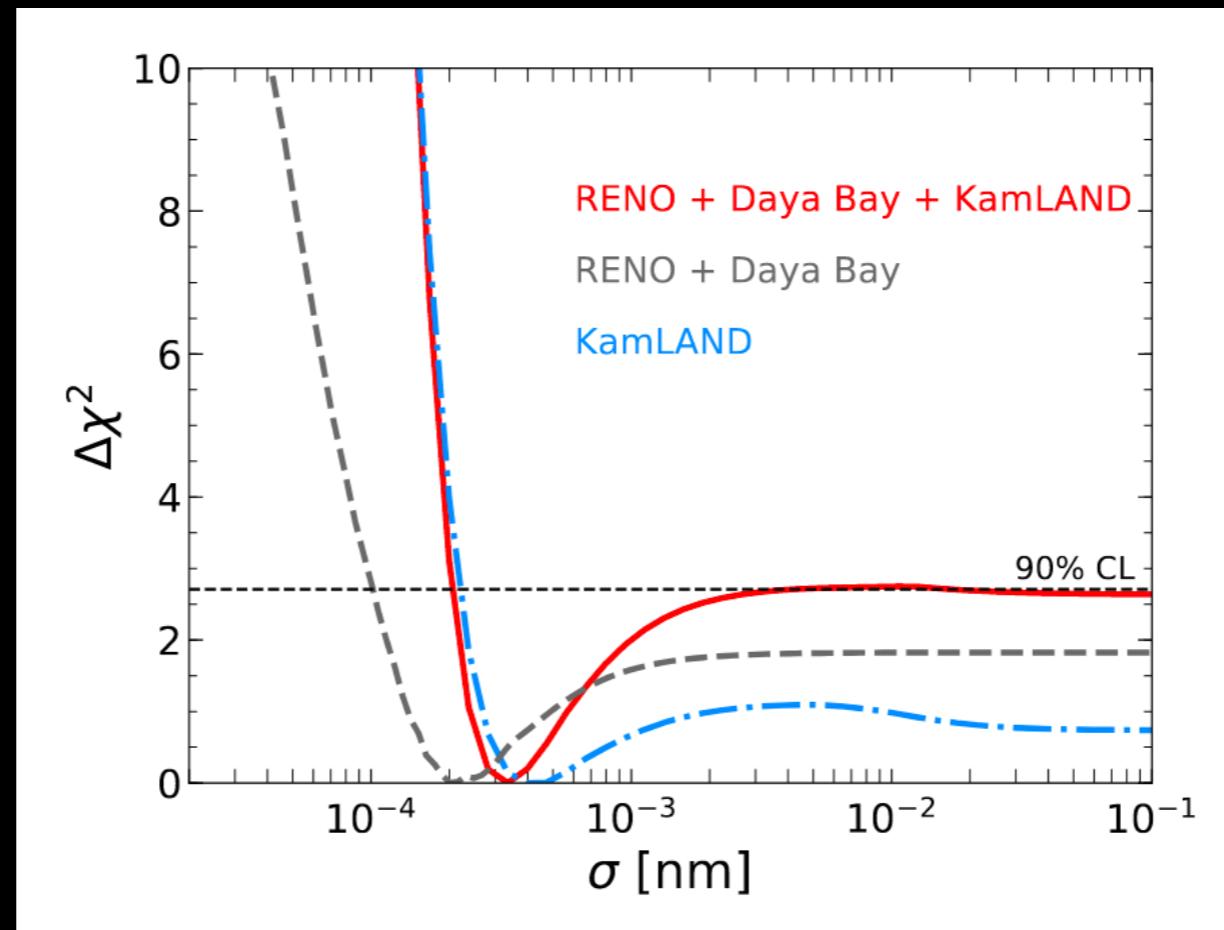
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Bounds from RENO and Daya Bay + KamLAND

Reduced $\chi^2(\sigma)$:

From the combined analysis we obtain a lower bound (driven by KL)
 $\sigma > 2.1 \times 10^{-4}$ nm at 90% CL.

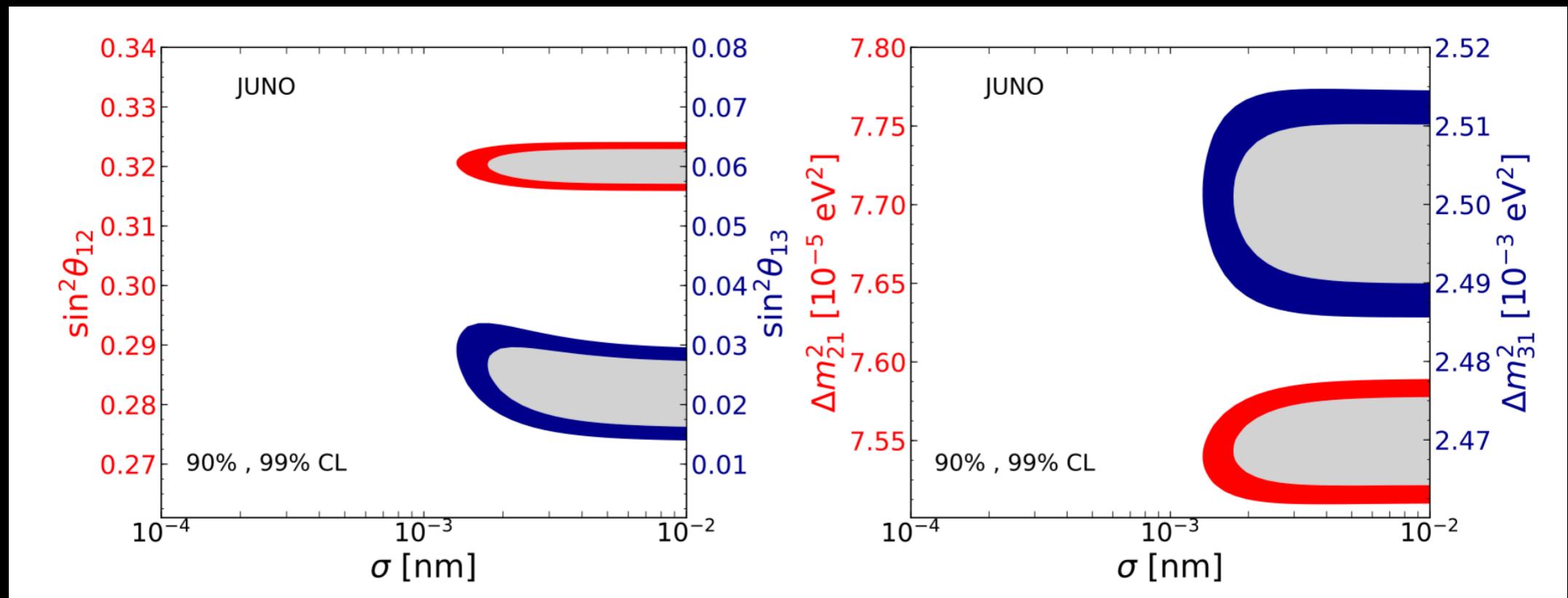
The fully coherent scenario is disfavored at 90% CL.



Sensitivity of JUNO

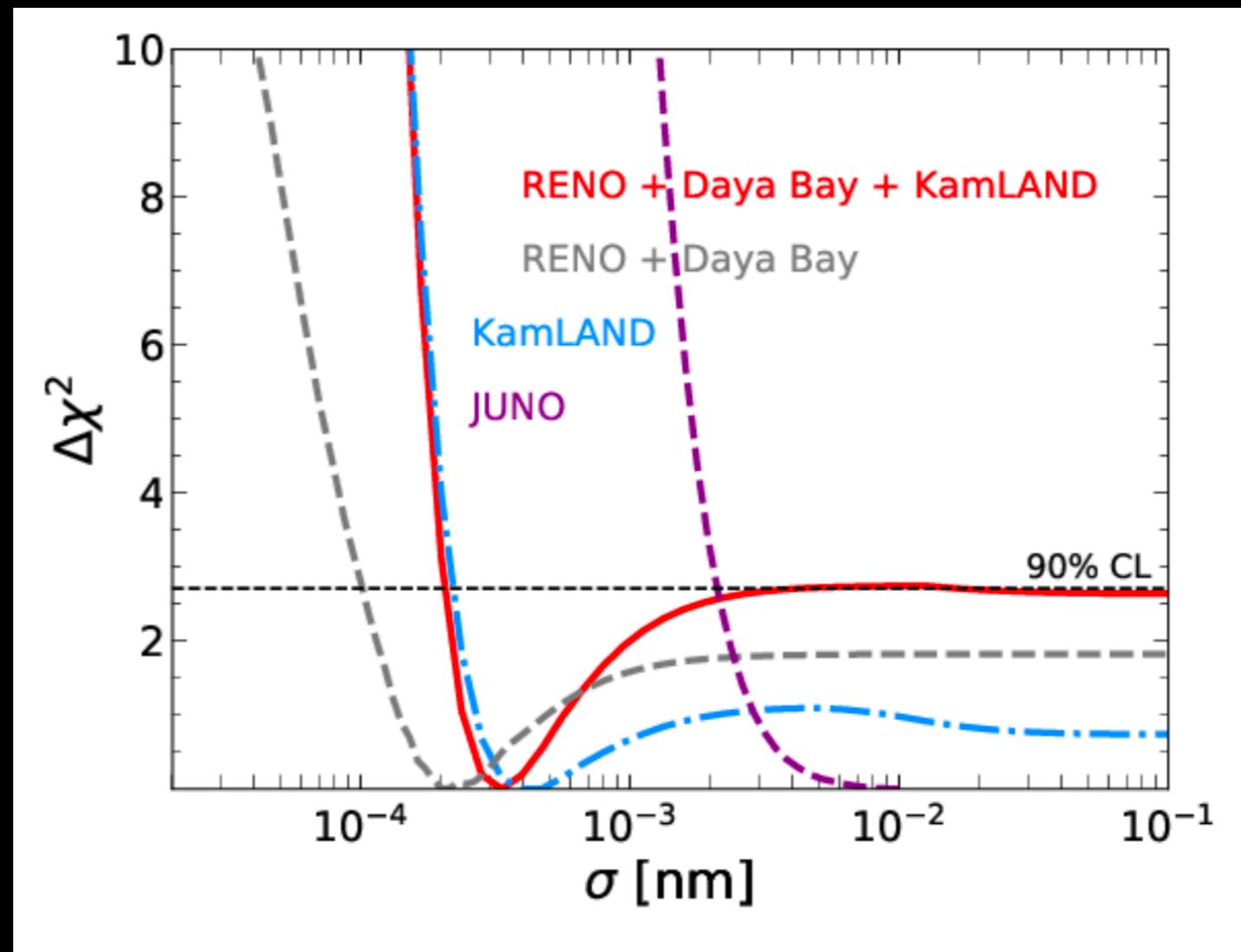
We assume the 10-reactor configuration, 6 years of data taking.
We first simulate data consistent with no decoherence ($\sigma \rightarrow \infty$).

The measurement of the standard neutrino oscillation parameters remains mostly unaffected when allowing for the possibility that σ is finite.



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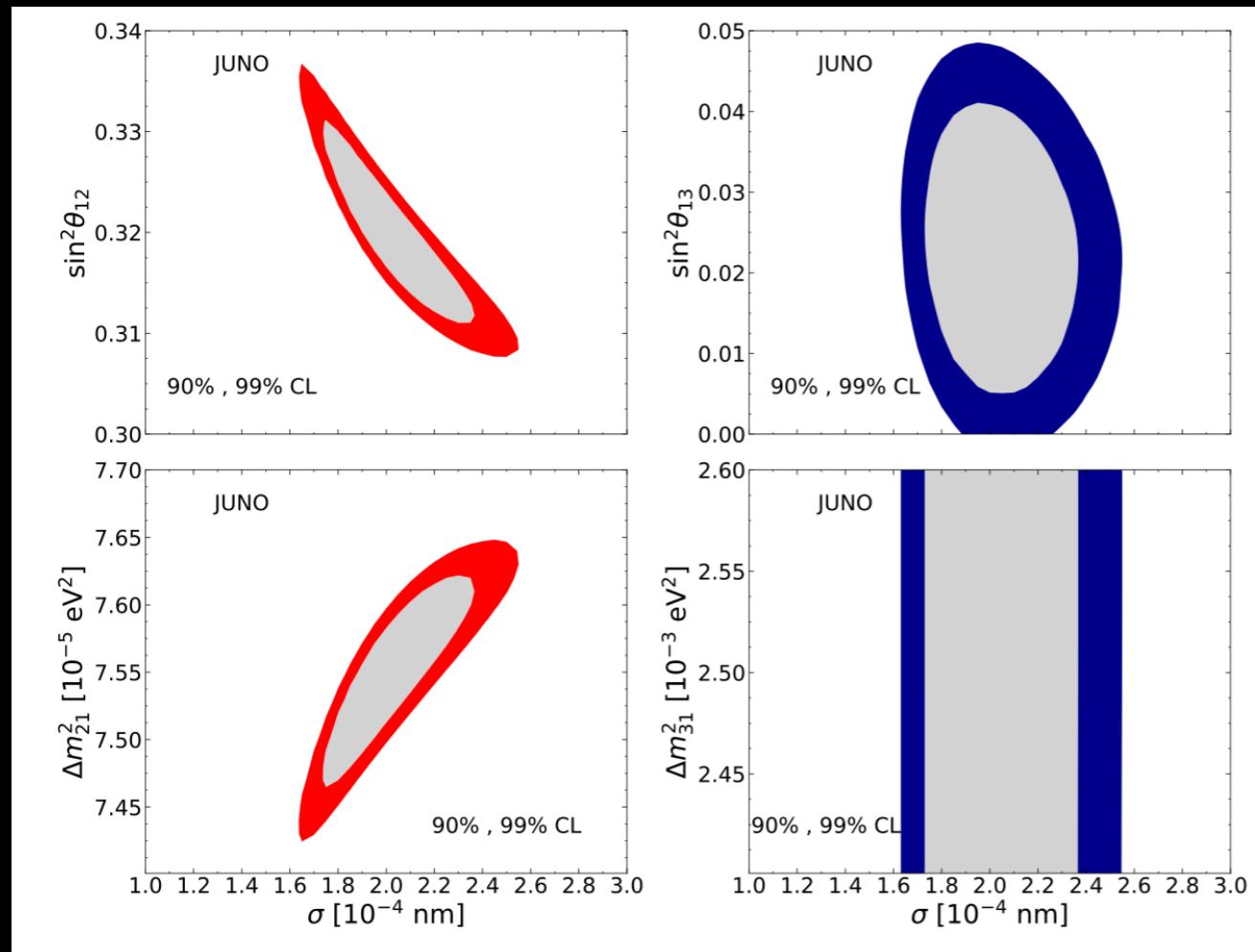
Sensitivity of JUNO



Reduced $\chi^2(\sigma)$:

lower bound $\sigma > 2.11 \times 10^{-3}$ nm at the 90% CL. This is more than a factor of 10 stronger than the current bound from RENO, Daya Bay and KamLAND.

Observing and measuring decoherence at JUNO



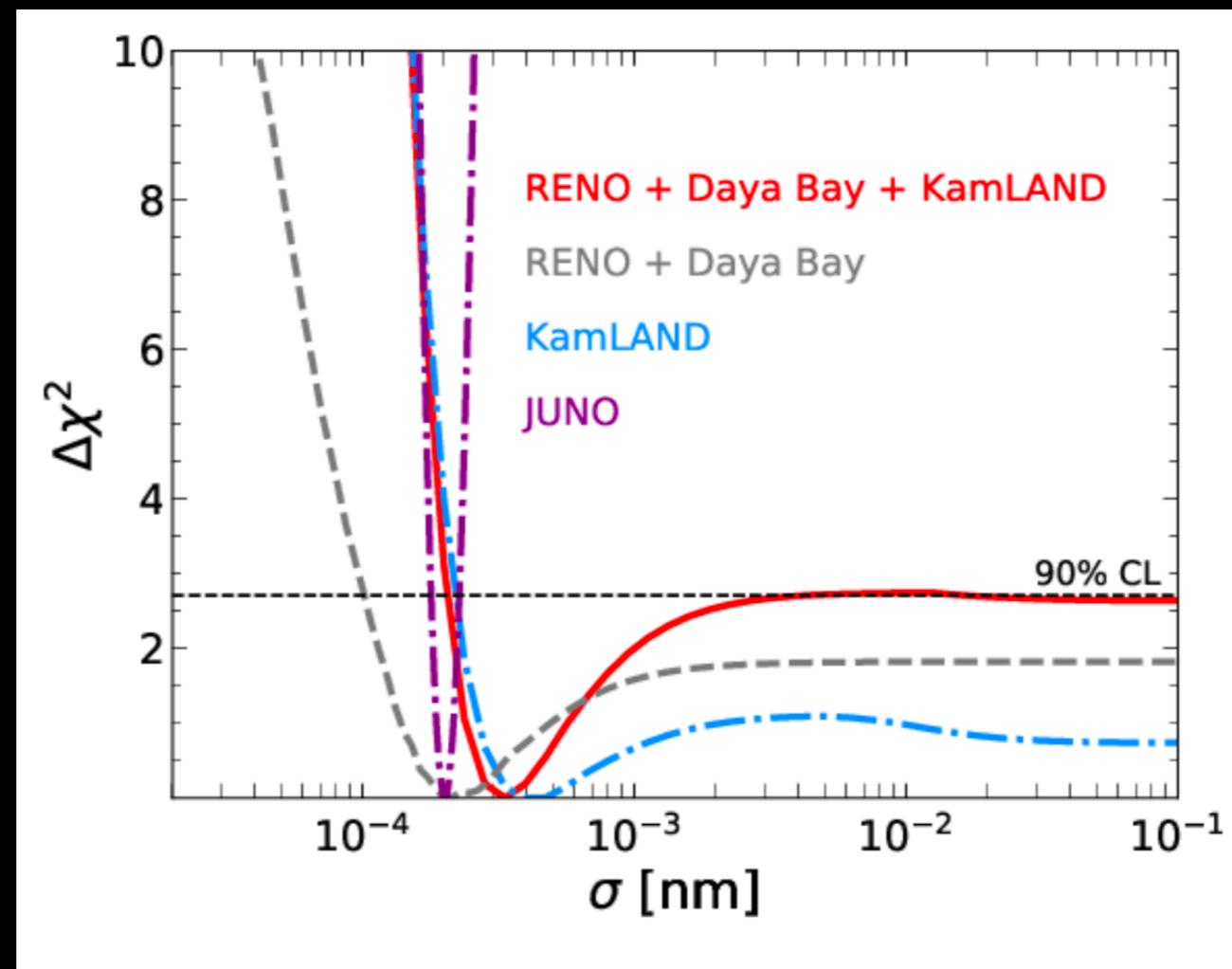
No sensitivity to Δm_{31}^2 .

Averaged-out effects of the short-wavelength oscillations remain and $\sin^2 \theta_{13}$ can be measured (poorer precision).

Long-wavelength effects are still present: both Δm_{21}^2 and $\sin^2 \theta_{12}$ can be measured.

Similar to RENO + DB, measurements of the **oscillation frequency and amplitude are strongly correlated with those of σ** . These degeneracies lead to a less precise determination of the solar parameters.

Observing and measuring decoherence at JUNO



If decoherence effects are within JUNO range a very good measurement of the wave packet width is possible.

The no-decoherence hypothesis would be excluded at more than 10 sigma.

Summary of decoherence effects

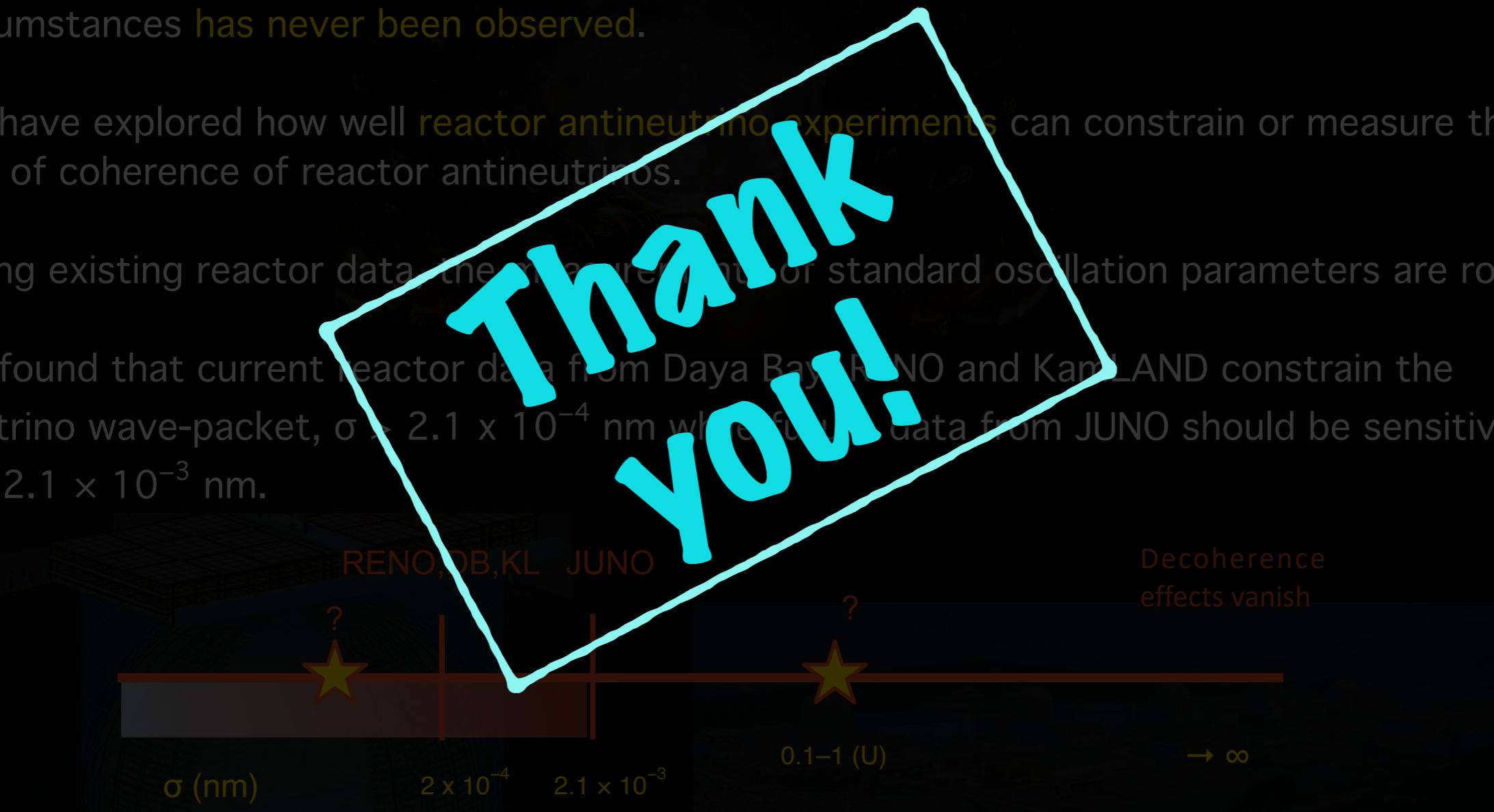
- The position-dependent loss of coherence of neutrinos produced and detected under any circumstances has never been observed.
- We have explored how well reactor antineutrino experiments can constrain or measure the loss of coherence of reactor antineutrinos.
- Given existing reactor data, the measurements of standard oscillation parameters are robust.
- We found that current reactor data from Daya Bay, RENO and KamLAND constrain the neutrino wave-packet, $\sigma > 2.1 \times 10^{-4}$ nm while future data from JUNO should be sensitive to $\sigma < 2.1 \times 10^{-3}$ nm.



- The discovery of nontrivial decoherence effects in JUNO would indicate that our understanding of the coherence of neutrino sources is, at least, incomplete.

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