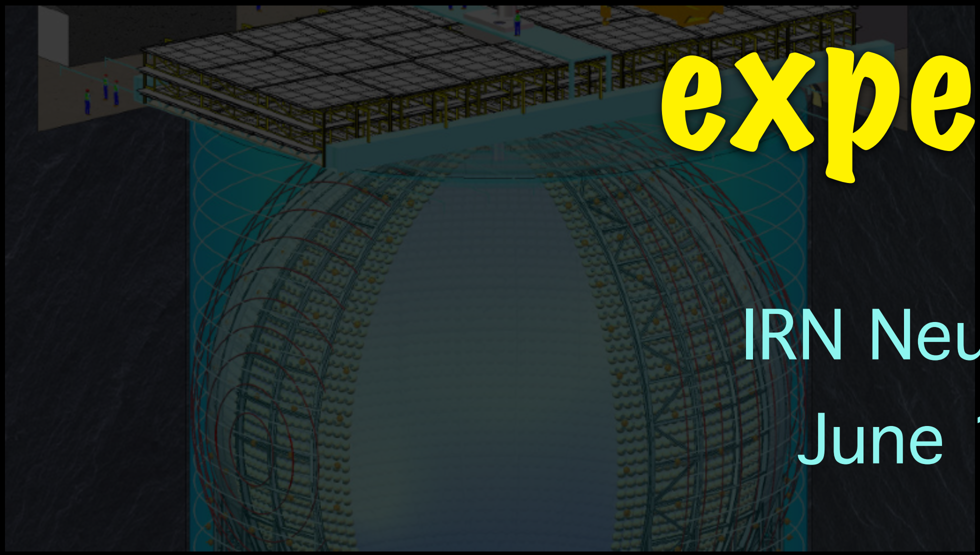
Valentina De Romeri

(IFIC Valencia - UV/CSIC)

Neutrino quantum decoherence at reactor experiments



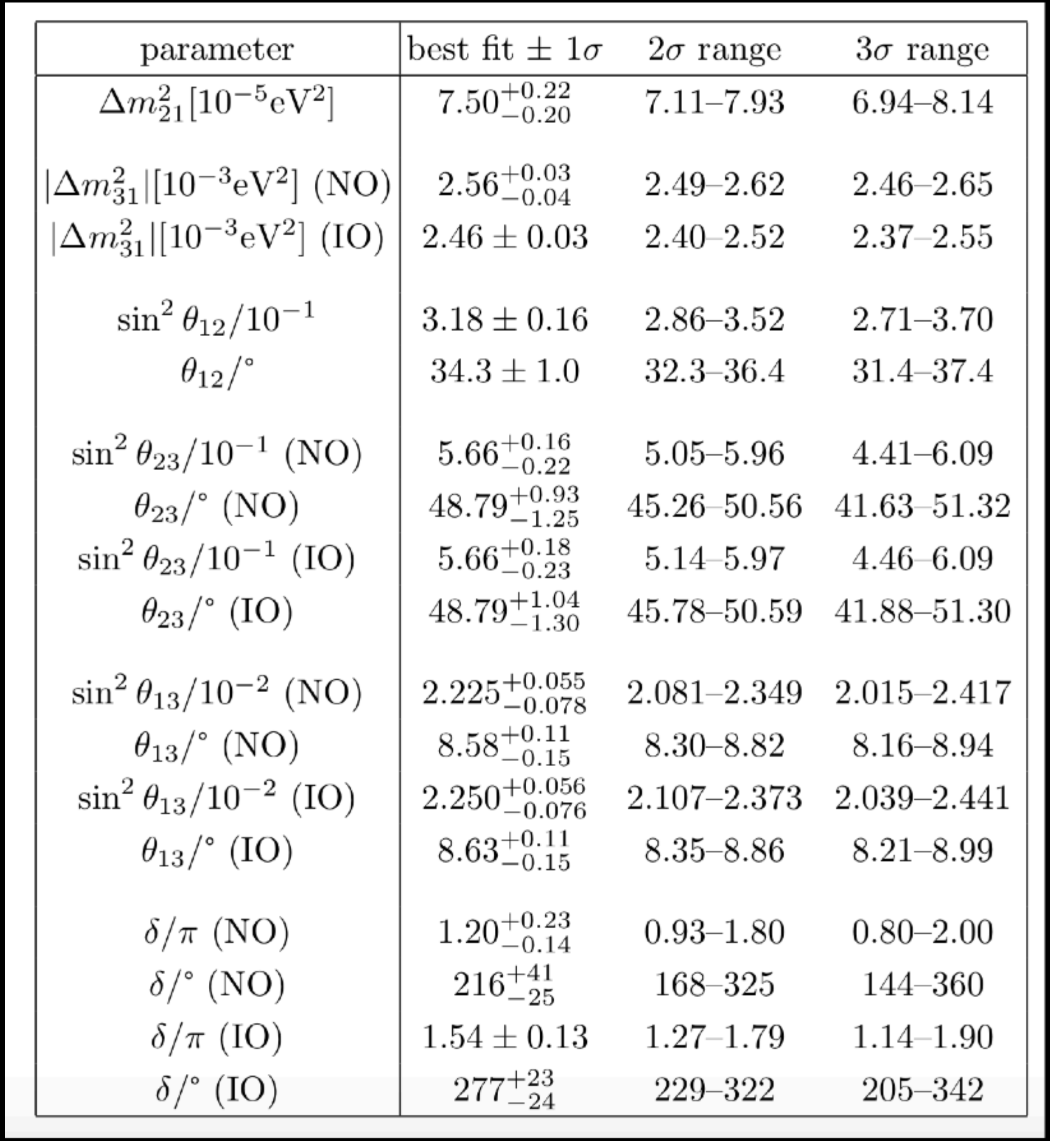
IRN Neutrino meeting

June 10-11 2021

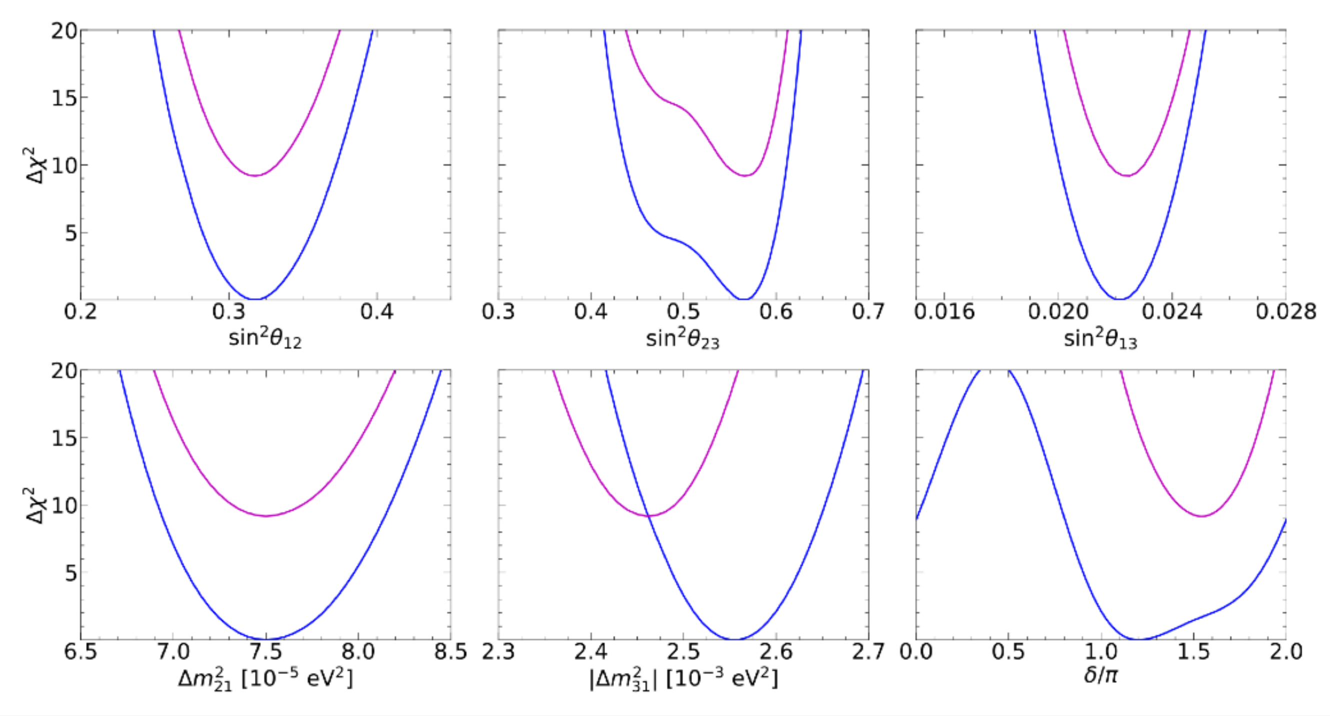
Based on JHEP 08 (2020) 018 and JHEP 06 (2021) 042 in collaboration with André de Gouvêa and Christoph Ternes

Lepton mixing and neutrino physics

- As of today, data favour a three-active neutrinos oscillation framework.
- Neutrino oscillation parameters have been inferred by detecting neutrinos coming from the Sun, the Earth's atmosphere, nuclear reactors and accelerator beams.



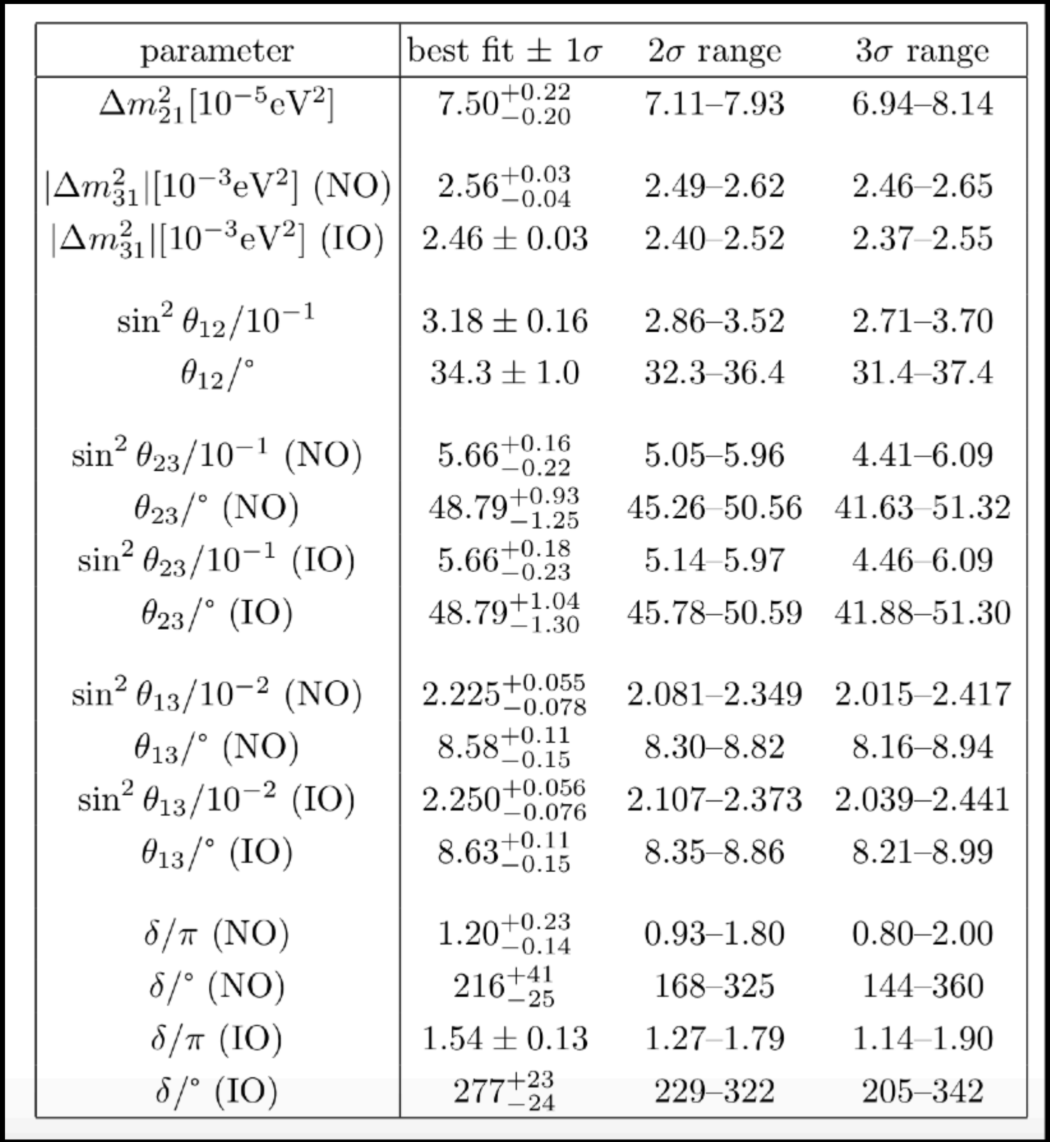
parameter	best fit ± 1σ	2σ range	3σ range
$\Delta m^2_{21} [10^{-5}\mathrm{eV}^2]$	$7.50^{+0.22}_{-0.20}$	7.11–7.93	6.94–8.14
$\lvert\Delta m^2_{31}\rvert [10^{-3}\mathrm{eV}^2]$ (NO)	$2.56^{+0.03}_{-0.04}$	2.49–2.62	2.46–2.65
$\lvert\Delta m^2_{31}\rvert [10^{-3}\mathrm{eV}^2]$ (IO)	2.46 ± 0.03	2.40–2.52	2.37–2.55
$\sin^2\theta_{12}/10^{-1}$	3.18 ± 0.16	2.86–3.52	2.71–3.70
$\theta_{12}/^\circ$	34.3 ± 1.0	32.3–36.4	31.4–37.4
$\sin^2\theta_{23}/10^{-1}$ (NO)	$5.66^{+0.16}_{-0.22}$	5.05–5.96	4.41–6.09
$\theta_{23}/^\circ$ (NO)	$48.79^{+0.93}_{-1.25}$	45.26–50.56	41.63–51.32
$\sin^2\theta_{23}/10^{-1}$ (IO)	$5.66^{+0.18}_{-0.23}$	5.14–5.97	4.46–6.09
$\theta_{23}/^\circ$ (IO)	$48.79^{+1.04}_{-1.30}$	45.78–50.59	41.88–51.30
$\sin^2\theta_{13}/10^{-2}$ (NO)	$2.225^{+0.055}_{-0.078}$	2.081–2.349	2.015–2.417
$\theta_{13}/^\circ$ (NO)	$8.58^{+0.11}_{-0.15}$	8.30–8.82	8.16–8.94
$\sin^2\theta_{13}/10^{-2}$ (IO)	$2.250^{+0.056}_{-0.076}$	2.107–2.373	2.039–2.441
$\theta_{13}/^\circ$ (IO)	$8.63^{+0.11}_{-0.15}$	8.35–8.86	8.21–8.99
δ/π (NO)	$1.20^{+0.23}_{-0.14}$	0.93–1.80	0.80–2.00
$\delta/^\circ$ (NO)	216^{+41}_{-25}	168–325	144–360
δ/π (IO)	1.54 ± 0.13	1.27–1.79	1.14–1.90
$\delta/^\circ$ (IO)	277^{+23}_{-24}	229–322	205–342



arXiv:2006.11237 P.F. de Salas et al.,
https://globalfit.astroparticles.es/

Lepton mixing and neutrino physics

- very precise and robust determination for most of the mixing parameters
- slight preference for θ_{23} at the 2nd octant
- preference for $\pi < \delta < 2\pi$; CP conservation allowed at 1.4σ (3.9σ) for NO (IO)
- ~3σ hint in favour of NO from atmospheric, LBL and reactor data



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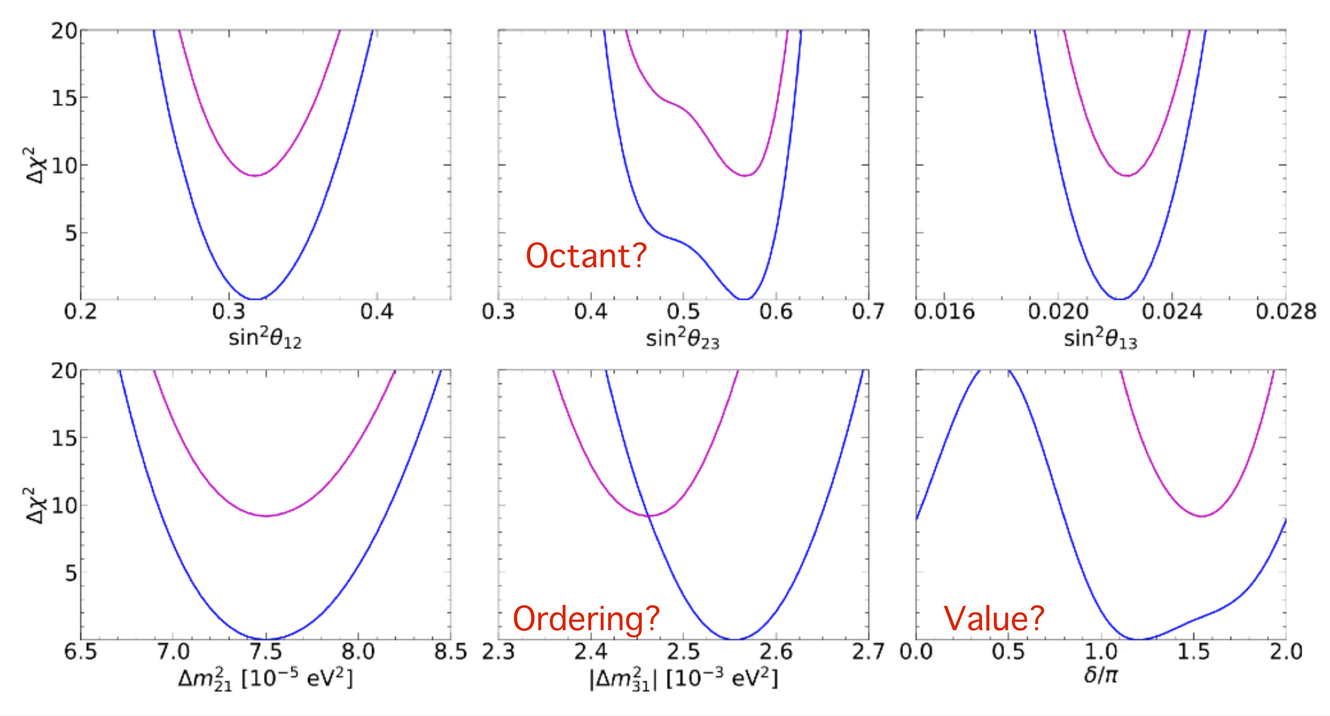


arXiv:2006.11237 P.F. de Salas et al.,
https://globalfit.astroparticles.es/

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

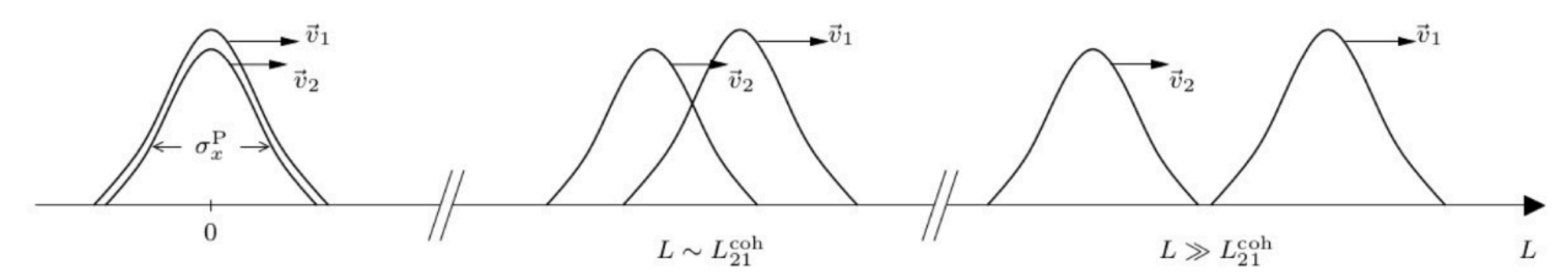
S. Nussinov, Phys. Lett. B 63 (1976) 201–203.
B. Kayser,, Phys. Rev. D 24 (1981) 110.
C. Giunti, C. Kim, and U. Lee, Phys. Rev. D 44 (1991) 3635–3640.
C. Giunti, C. Kim, and U. Lee, Phys. Lett. B 274 (1992) 87–94.
K. Kiers and N. Weiss, Phys. Rev. D 57 (1998) 3091–3105

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.



C. Giunti and C. Kim, Fundamentals of neutrino physics

- 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.
C. Giunti, C. Kim, and U. Lee, Phys. Rev. D 44 (1991) 3635–3640.
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Neutrino quantum decoherence

- Oscillation experiments can be used to constrain how coherent neutrino sources are.

- We want to answer the following questions:
  1. Are the existing reactor neutrino experiments consistent with the hypothesis that nuclear reactors are a source of perfectly coherent antineutrinos?
  2. If the decoherence parameters of all antineutrinos from reactors are the same, how well can they be constrained by current data?
  3. If one allows for nontrivial values of the decoherence parameters, how much is the measurement of the standard oscillation parameters affected?
  4. How well future reactor experiments can improve current bounds or even discover decoherence?

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

Decoherence and reactor experiments

- Jiangmen Underground Neutrino Observatory (JUNO)
  - 12 reactors
  - 1 far detector (+ 1 near detector under consideration)
  - L ~ 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 ~ 100 m

- Daya Bay reactor experiment
  - 6 power plants
  - 8 identical detectors at 3 experimental halls
  - L ~ 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:

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

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

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

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

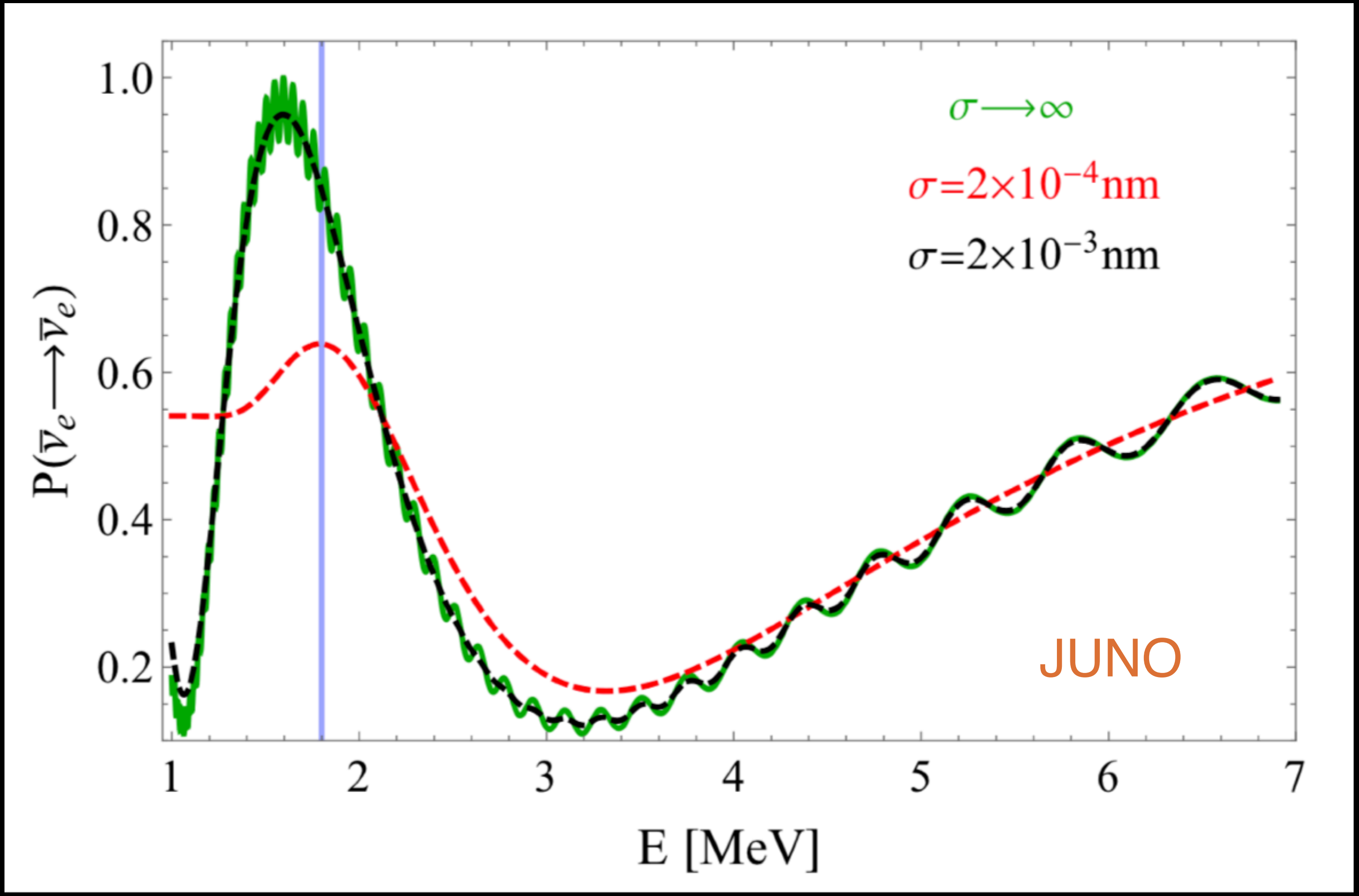
$$\xi_{jk}(L,E) = \left(\frac{L}{L_{jk}^{\rm coh}}\right)^2$$

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

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.



de Gouvêa, VDR, Ternes JHEP 08 (2020) 018

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

Decoherence with matter effects

The survival probability of electron antineutrinos including decoherence effects is:

$$P^{\mathrm{dec}}(\overline{\nu}_e \to \overline{\nu}_e) = \sum_{j,k} |\tilde{U}_{ej}|^2 |\tilde{U}_{ek}|^2 \, \exp[-i\tilde{\Delta}_{jk} - \tilde{\xi}_{jk}]$$

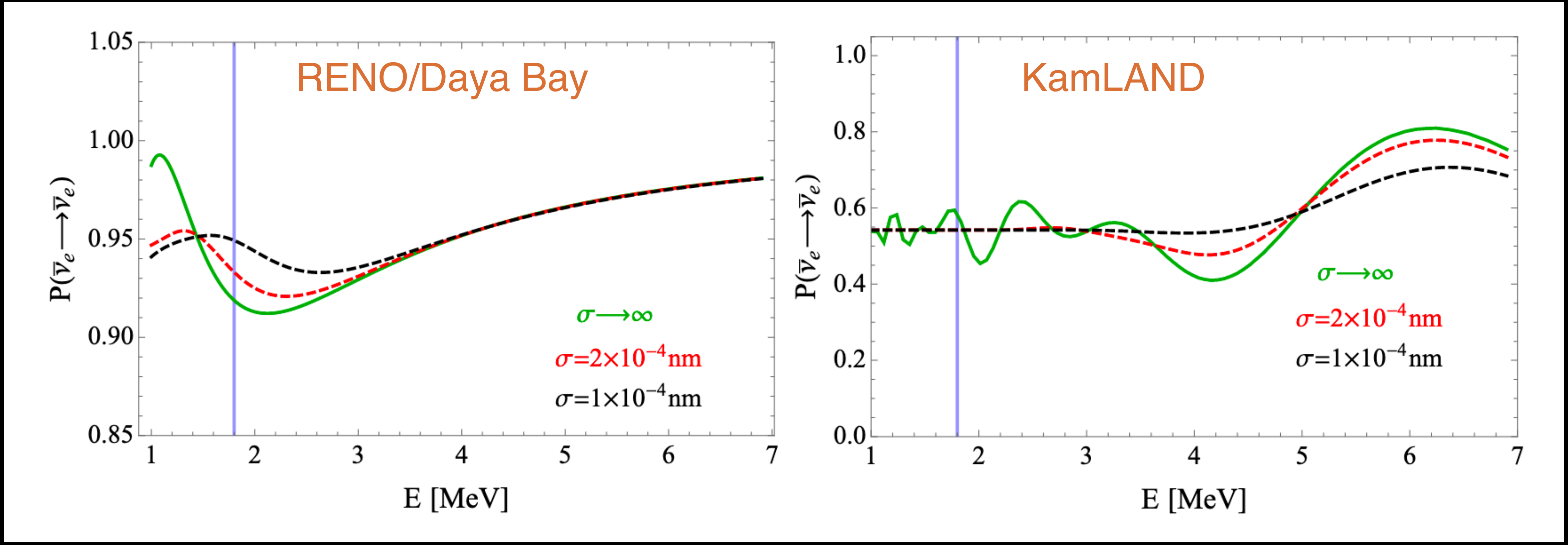
where

$$\tilde{\Delta}_{jk} \equiv 2\pi \frac{L}{\tilde{L}^{\mathrm{osc}}_{jk}} \equiv \frac{\Delta\tilde{m}^2_{jk} L}{2E}$$

we include matter effects (assuming the antineutrinos propagate through a medium with constant density) by substituting all the quantities in vacuum with the corresponding effective matter-quantities.

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.

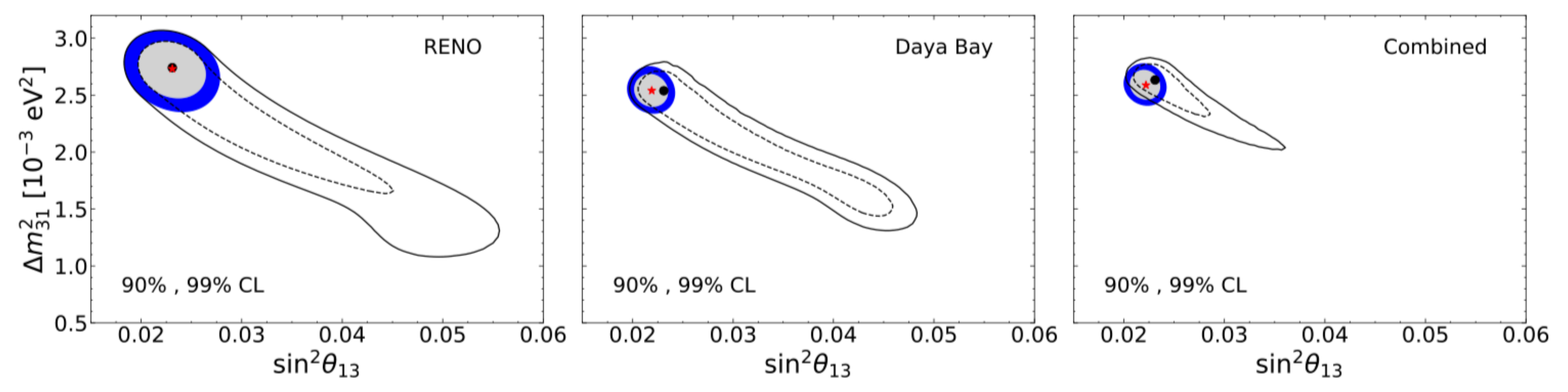


de Gouvêa, VDR, Ternes JHEP 06 (2021) 042

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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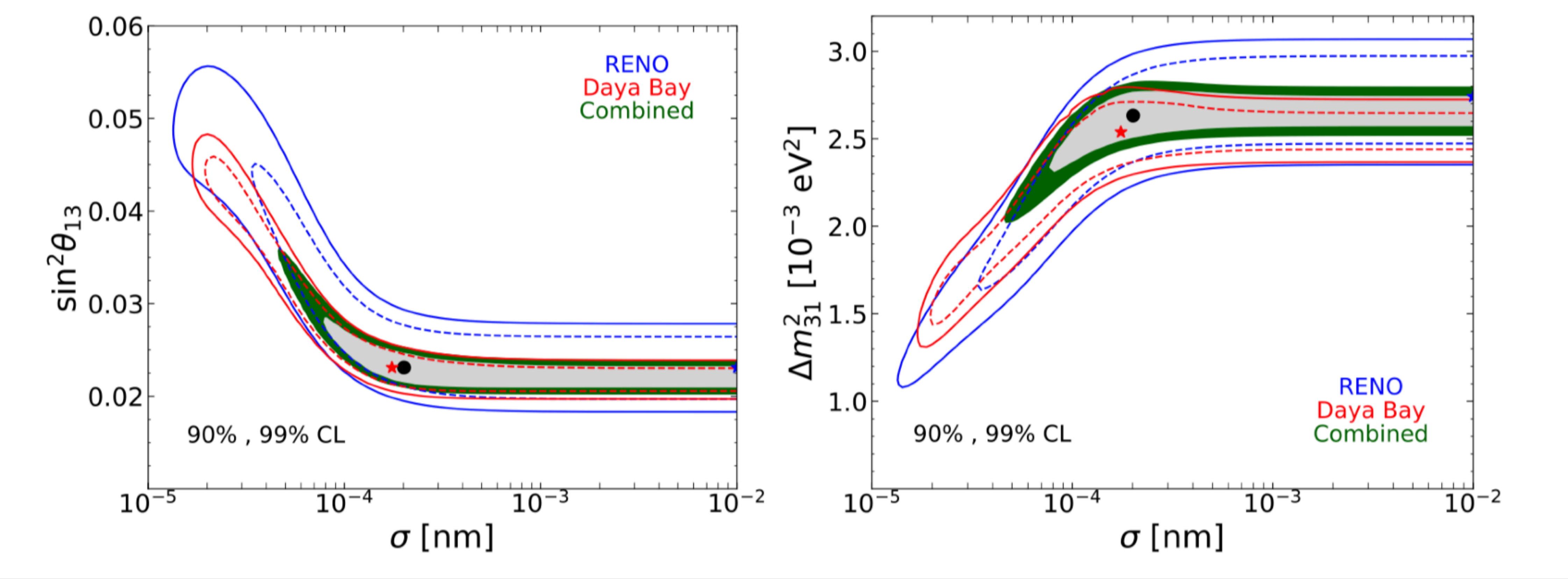
Ruling out decoherence



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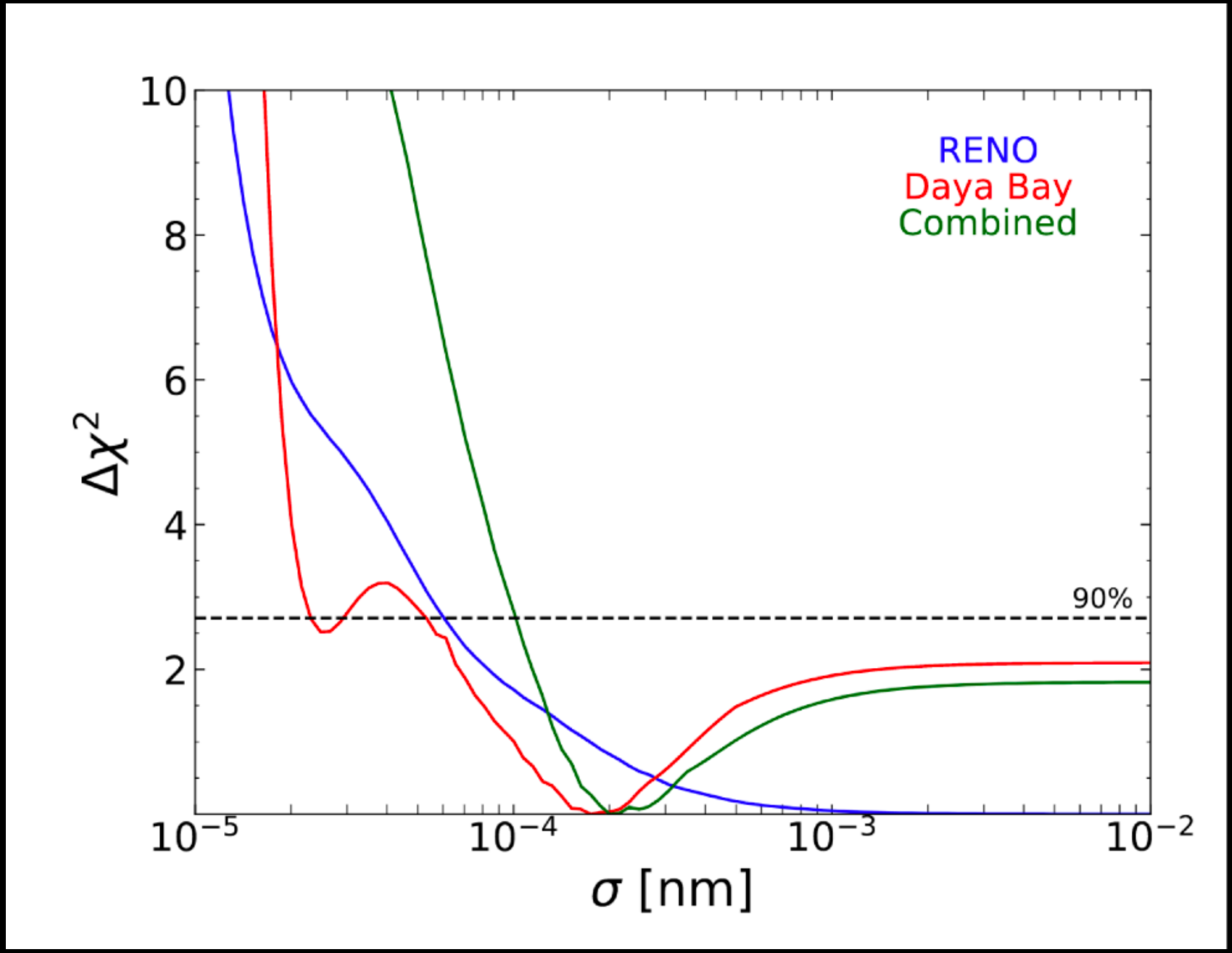
The reduction of sensitivity is due to a new correlation between the standard parameters and the wave packet width.
Small values of sigma are correlated with large (small) values of the mixing angle (mass splitting).

Bounds from RENO and Daya Bay

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

Arbitrarily large values of σ are allowed at better than the 90% CL and translate into the lower bound $\sigma > 1.02 \times 10^{-4}$ nm at 90% CL (RENO + DB).
The lines extend to infinity.

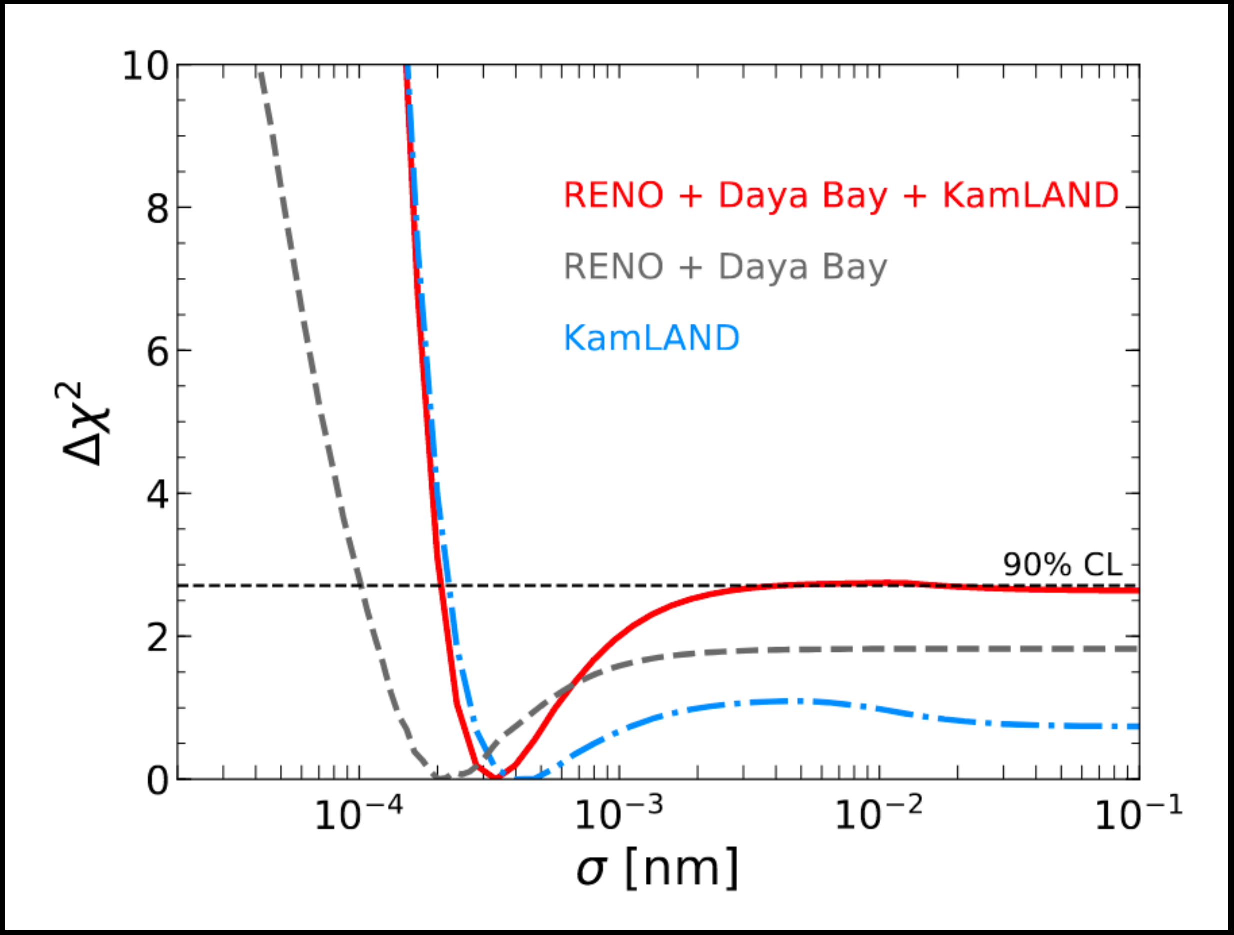


de Gouvêa, VDR, Ternes JHEP 08 (2020) 018

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.



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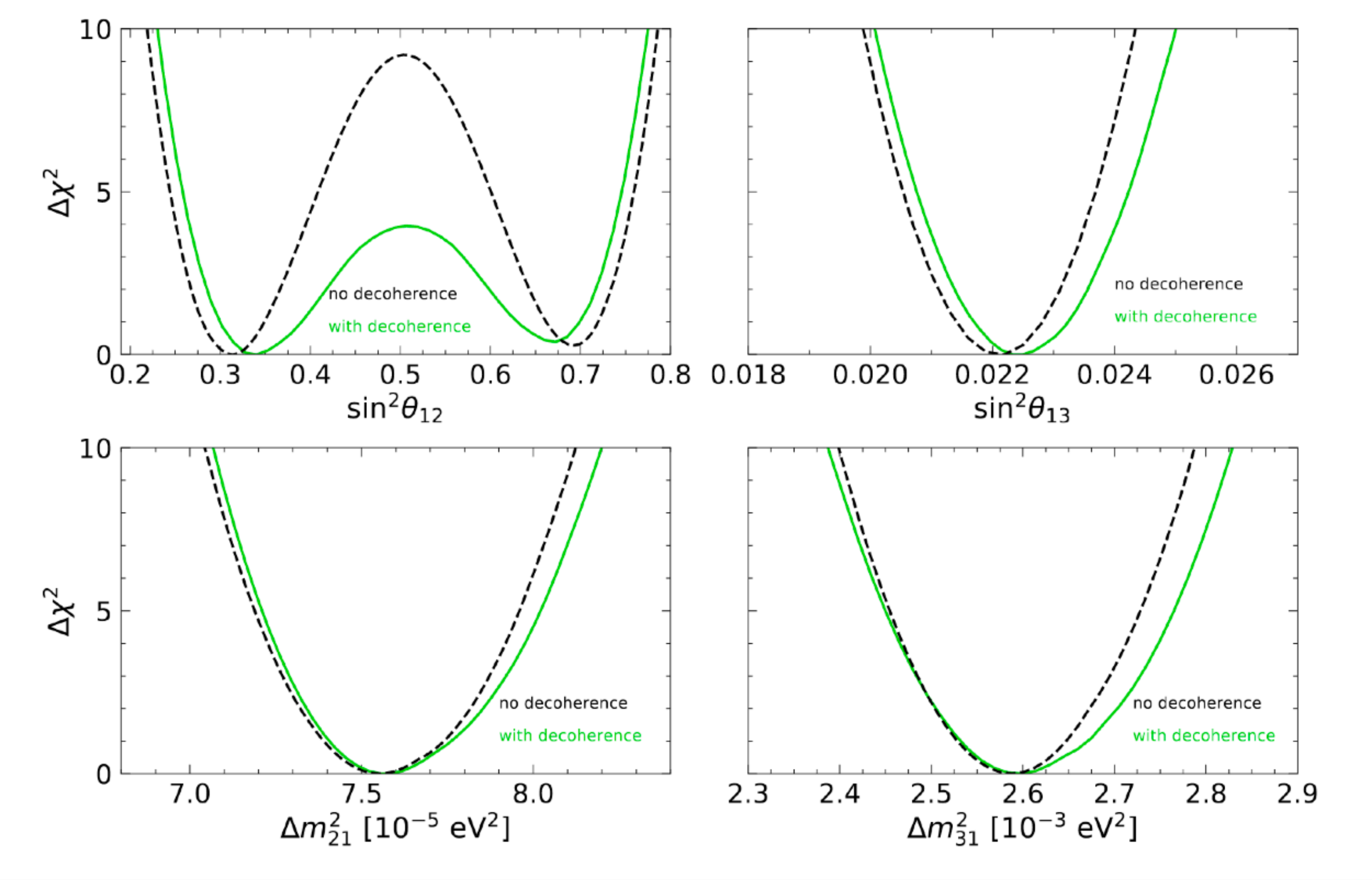
Bounds from RENO and Daya Bay + KamLAND

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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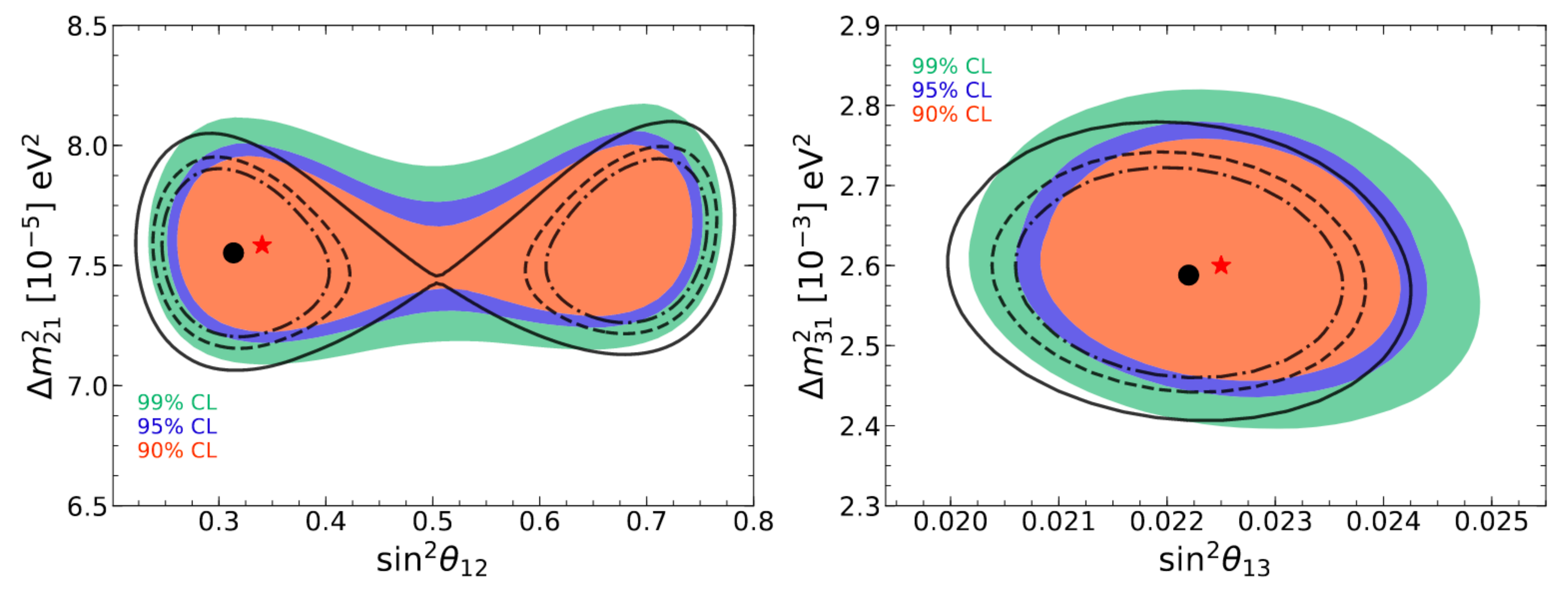
Bounds from RENO and Daya Bay + KamLAND

Combining all data restores the sensitivity to standard oscillation parameters.



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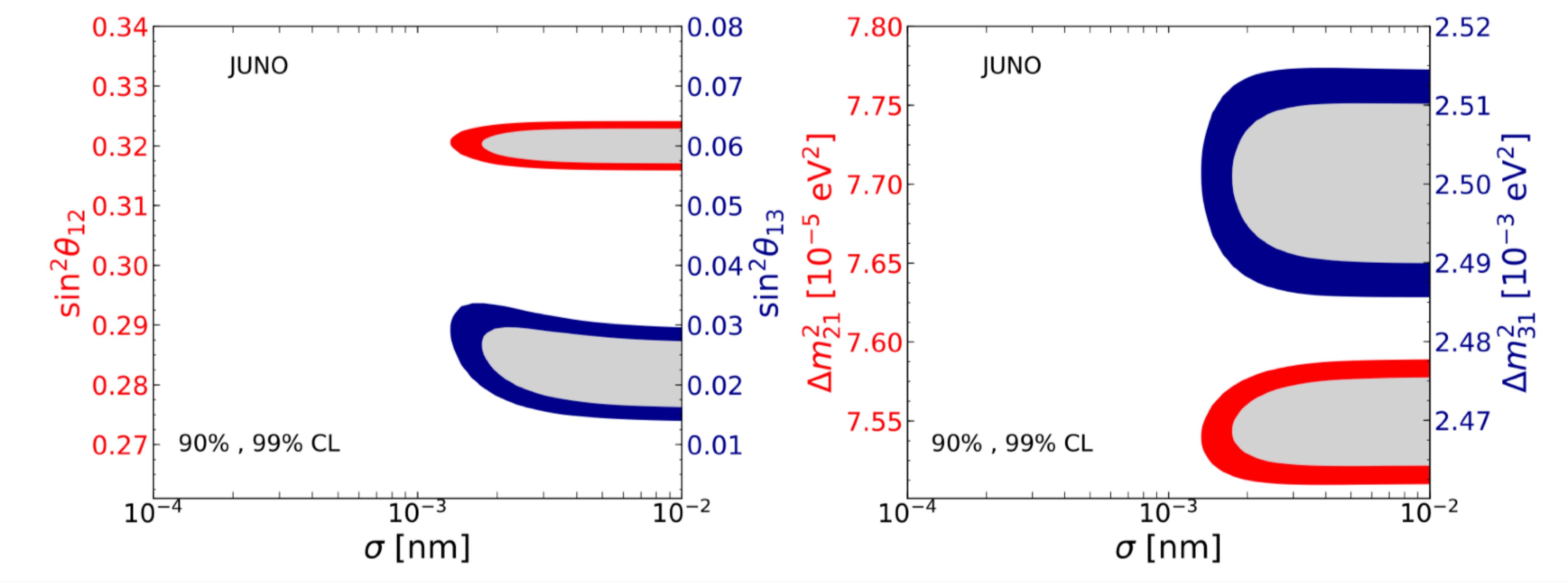
Sensitivity of JUNO

We assume the 10-reactor configuration, 6 years of data taking.
We first simulate data consistent with no decoherence (σ → ∞).

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



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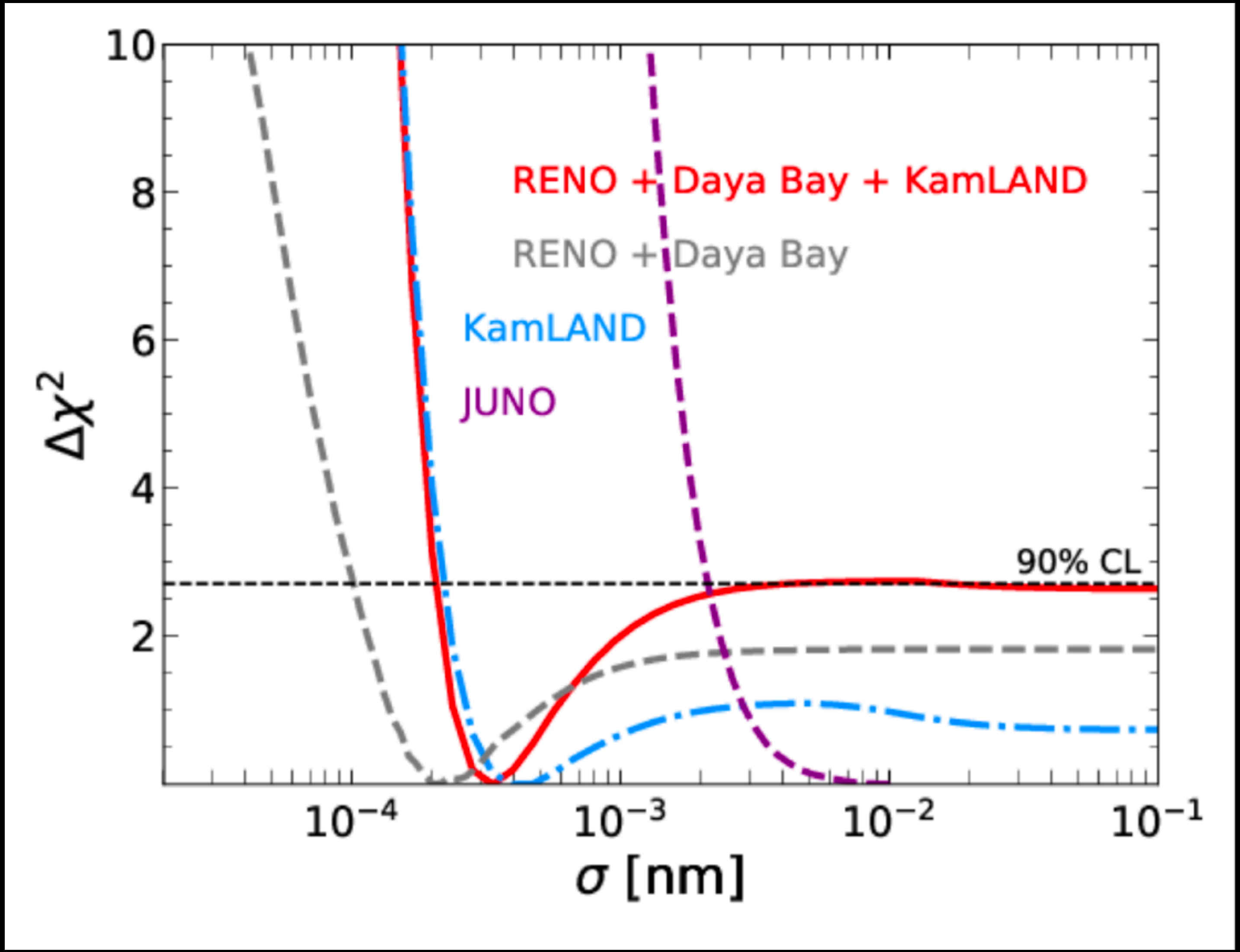
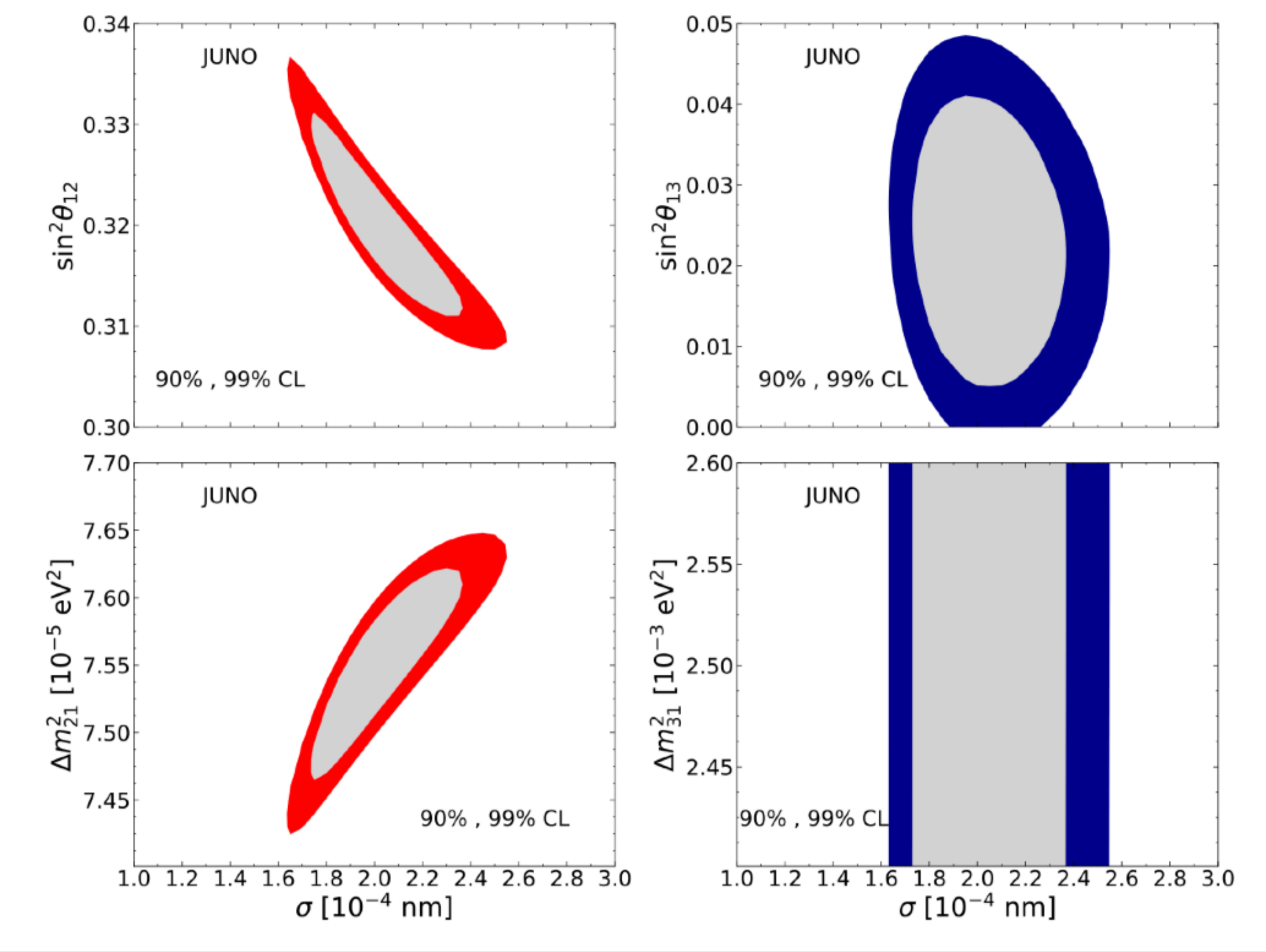


Reduced $\chi^2(\sigma)$:
lower bound $\sigma > 2.11 \times 10^{-3}$ nm at the 90% CL. This is more than a factor of 10 stronger than the current bound from RENO, Daya Bay and KamLAND.

Observing and measuring decoherence at JUNO



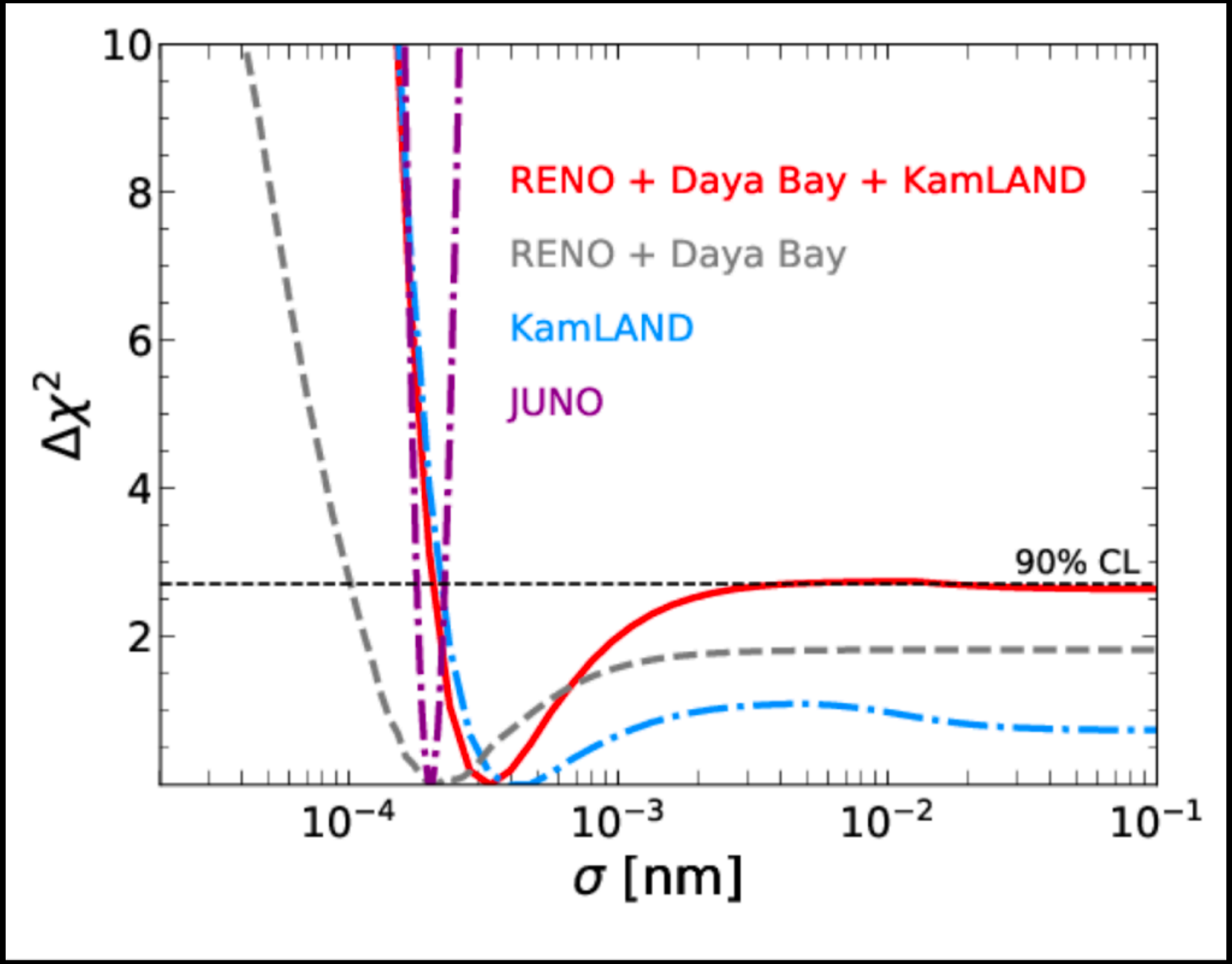
de Gouvêa, VDR, Ternes JHEP 08 (2020) 018

No sensitivity to Δm^2_{31}.
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^2_{21} 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.

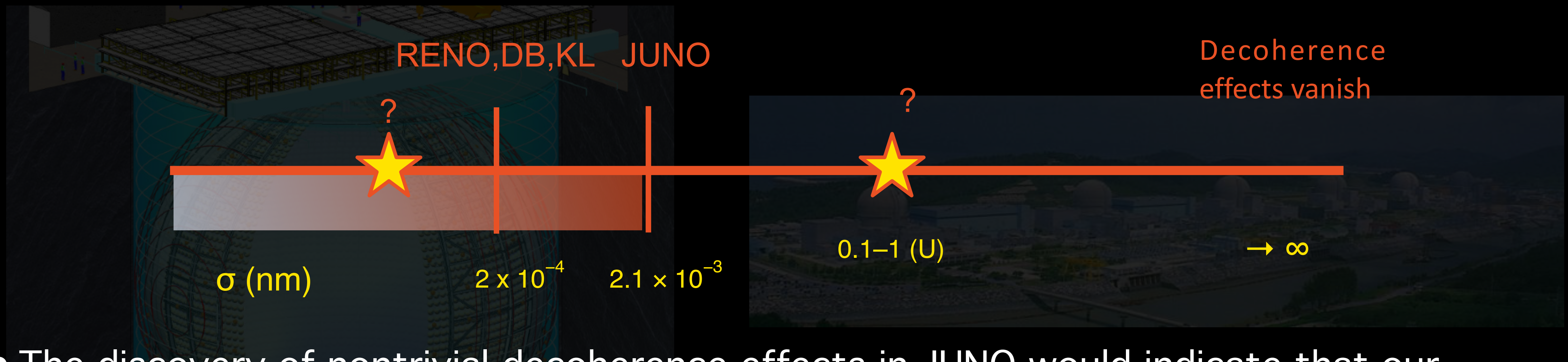
Observing and measuring decoherence at JUNO



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.
- Giving 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.

Thank you!