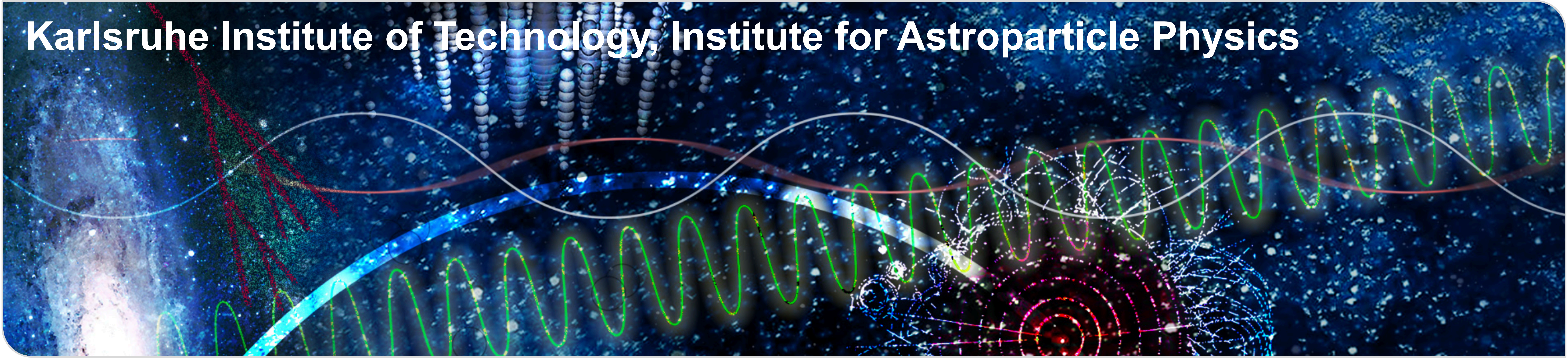
Karlsruher Institut für Technologie

HIDDeν
Hunting Invisibles: Dark sectors, Dark matter and Neutrinos

The gallium anomaly and quantum decoherence

Thomas Schwetz — IRN Neutrino meeting, Nantes, France — 19 June 2023

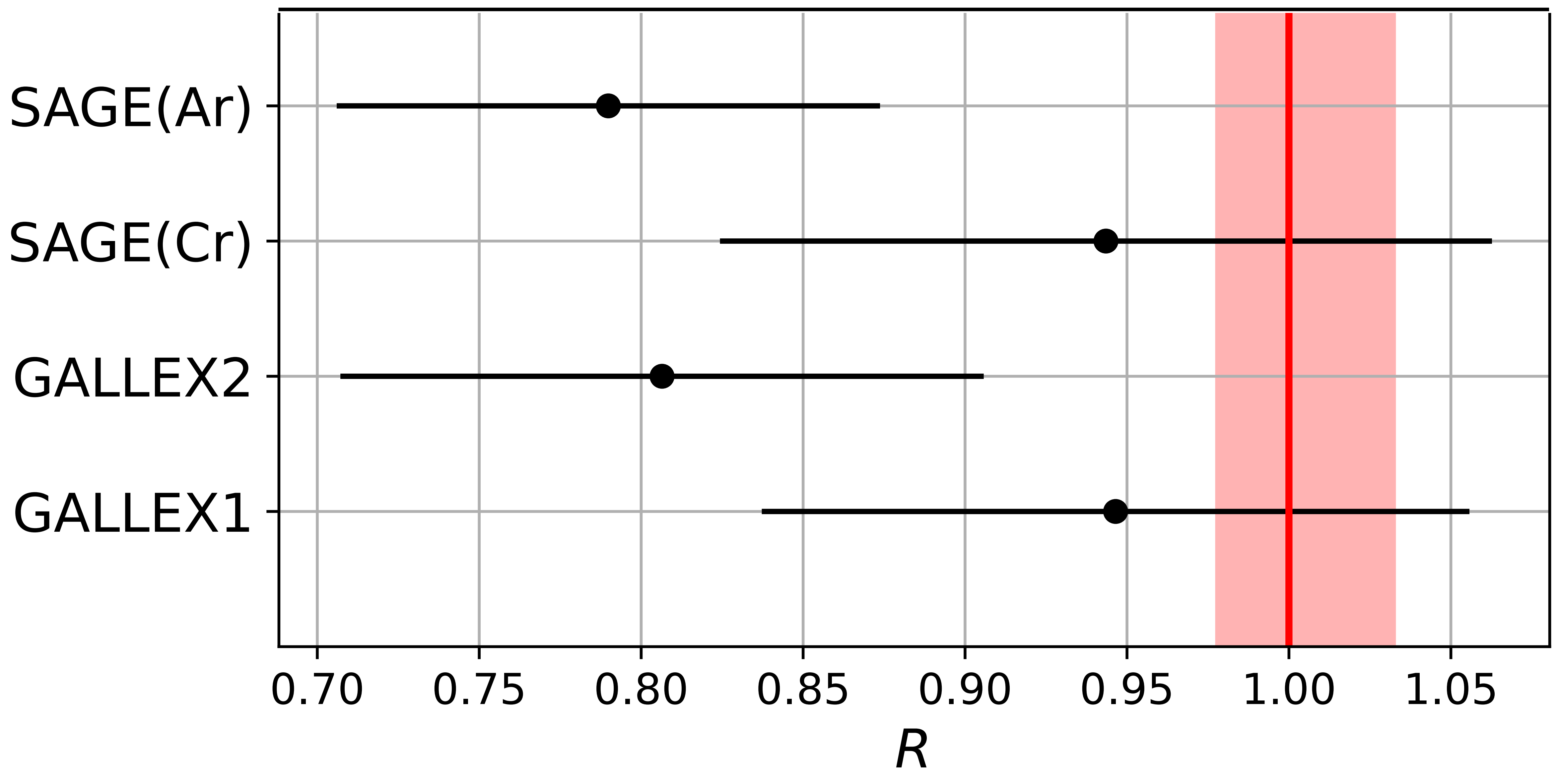


Outline

- The gallium anomaly and why sterile neutrinos are problematic
- A QFT calculation of standard decoherence effects in reactor and radioactive source experiments
  w. Raphael Krüger, arXiv:2303.15524 (EPJC to appear)
- An explanation of the gallium anomaly in terms of new physics quantum decoherence without sterile neutrinos
  w. Yasaman Farzan, arXiv:2306.09422 (today)

The gallium anomaly

- Measurements of gallium solar neutrino experiments GALLEX and SAGE with radioactive ^{51}Cr or ^{37}Ar sources lead to rates lower than expected ($\sim 2\sigma$) e.g. Giunti, Laveder, 2011
- possible explanation due to eV sterile neutrino oscillations?

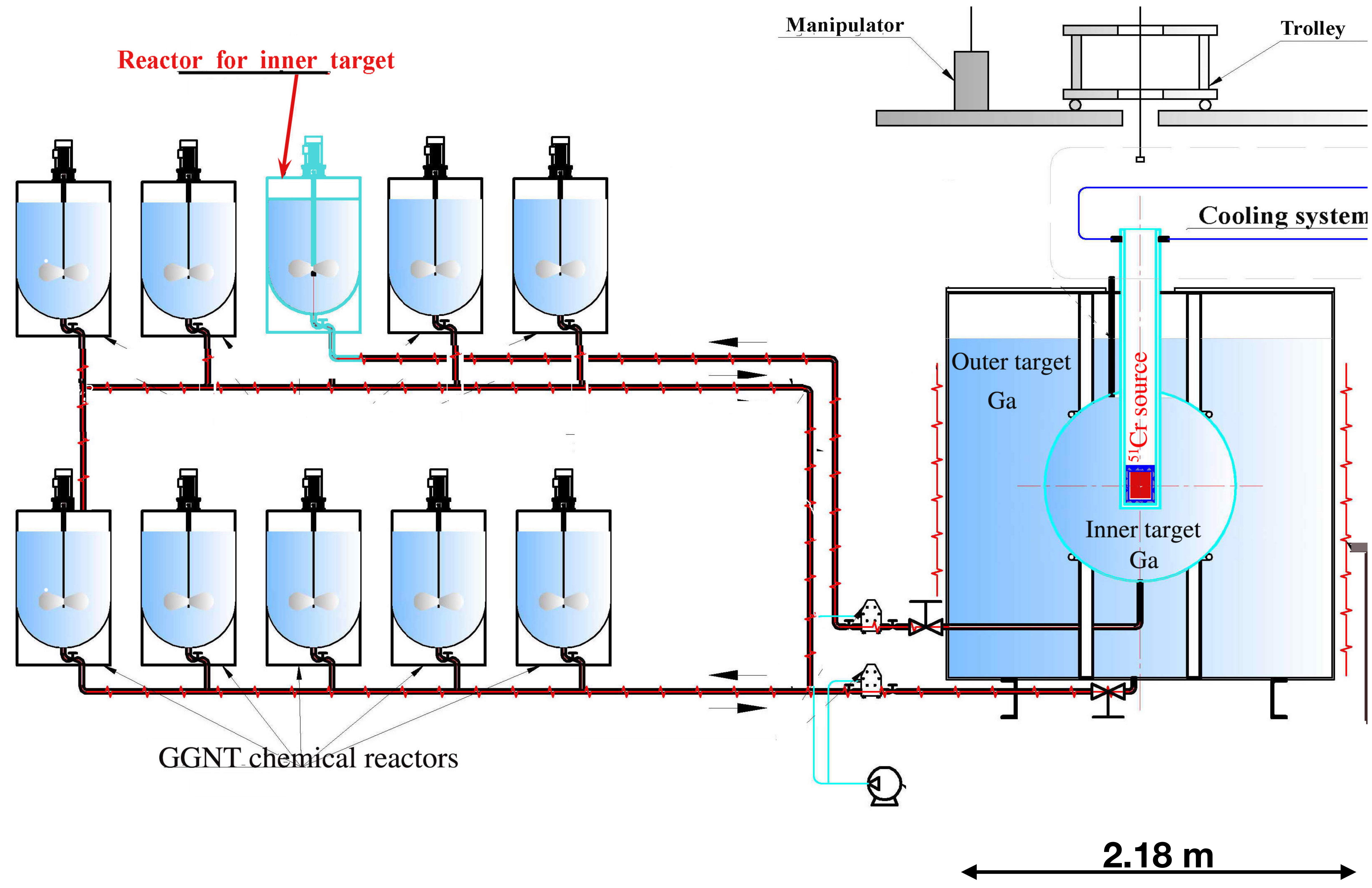


The BEST experiment

V. V. Barinov et al., Phys. Rev. Lett. 128 (2022), no. 23 232501;
Phys. Rev. C 105 (2022), no. 6 065502

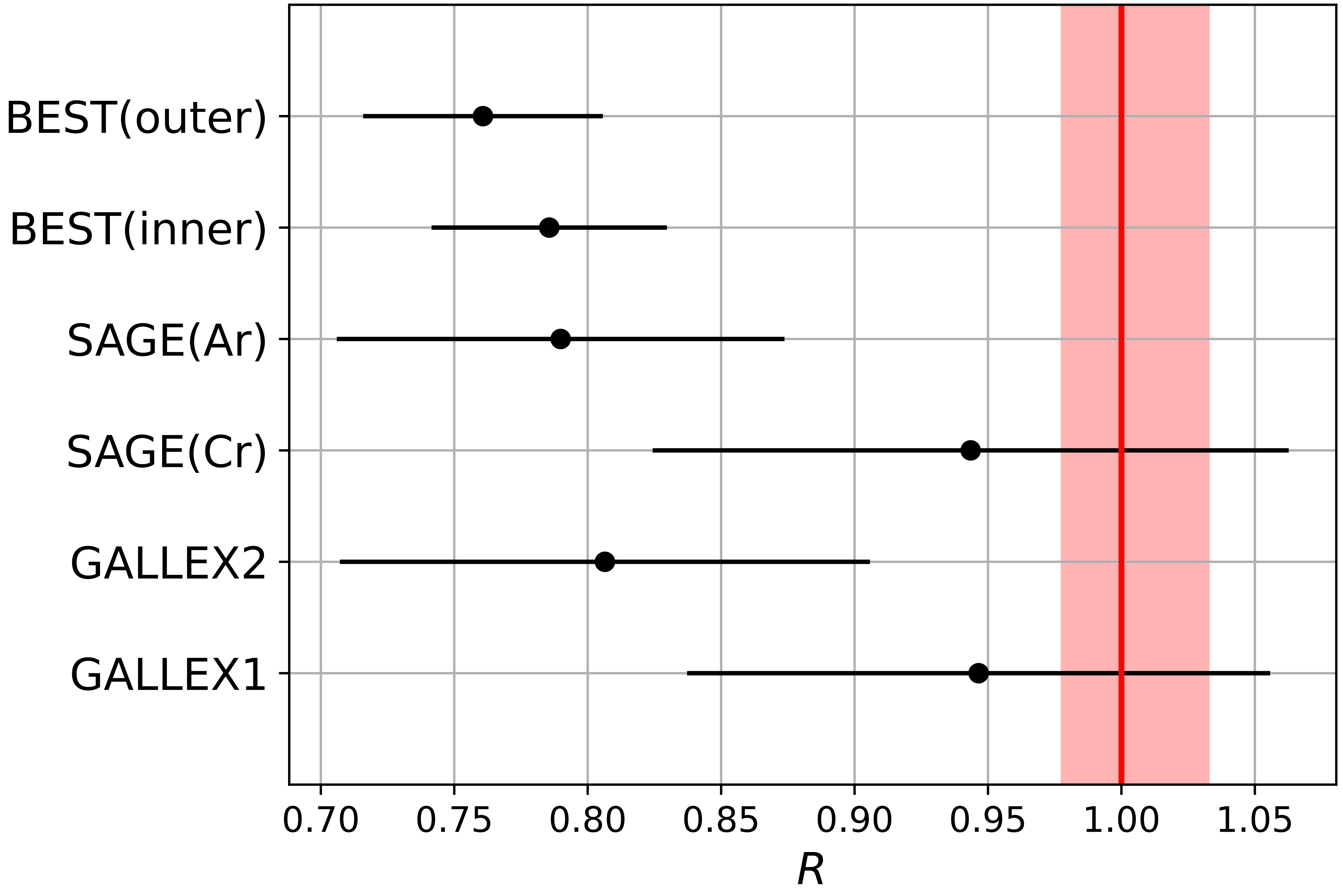
$$R_{in} = 0.79 \pm 0.05$$

$$R_{out} = 0.77 \pm 0.05$$



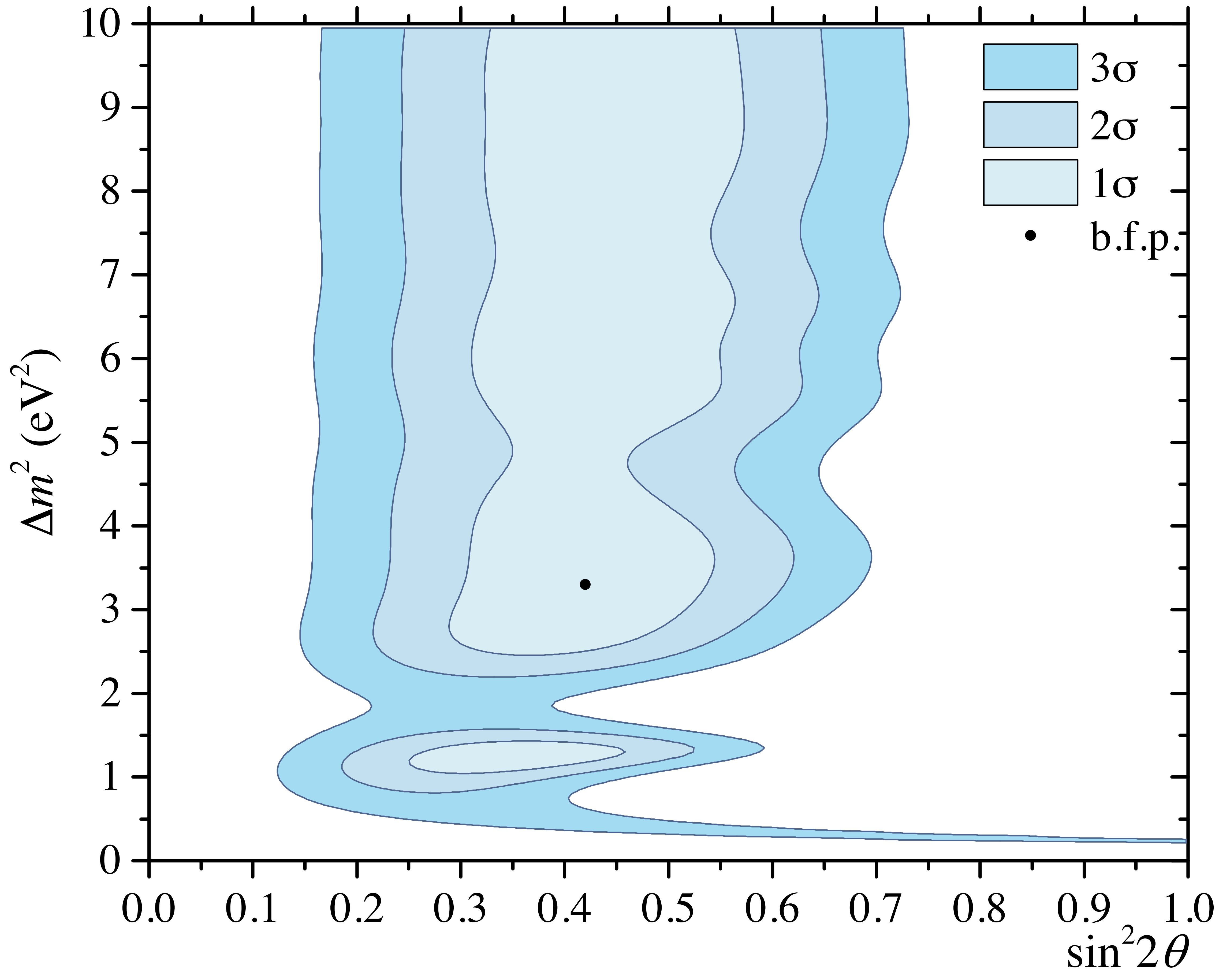
The gallium anomaly

	$\chi^2_{\text{null}}/\text{dof}$	p-value
CS1, BEST	$32.1/2$	1.1×10^{-7} (5.3σ)
CS1, all	$36.3/6$	2.4×10^{-6} (4.7σ)
CS2, BEST	$34.7/2$	2.9×10^{-8} (5.5σ)
CS2, all	$38.4/6$	9.4×10^{-7} (4.9σ)



Farzan, TS, 2306.09422
cross sections CS1, CS2 from
Haxton et al., 2303.13623

Can it be explained by eV sterile neutrino oscillations?

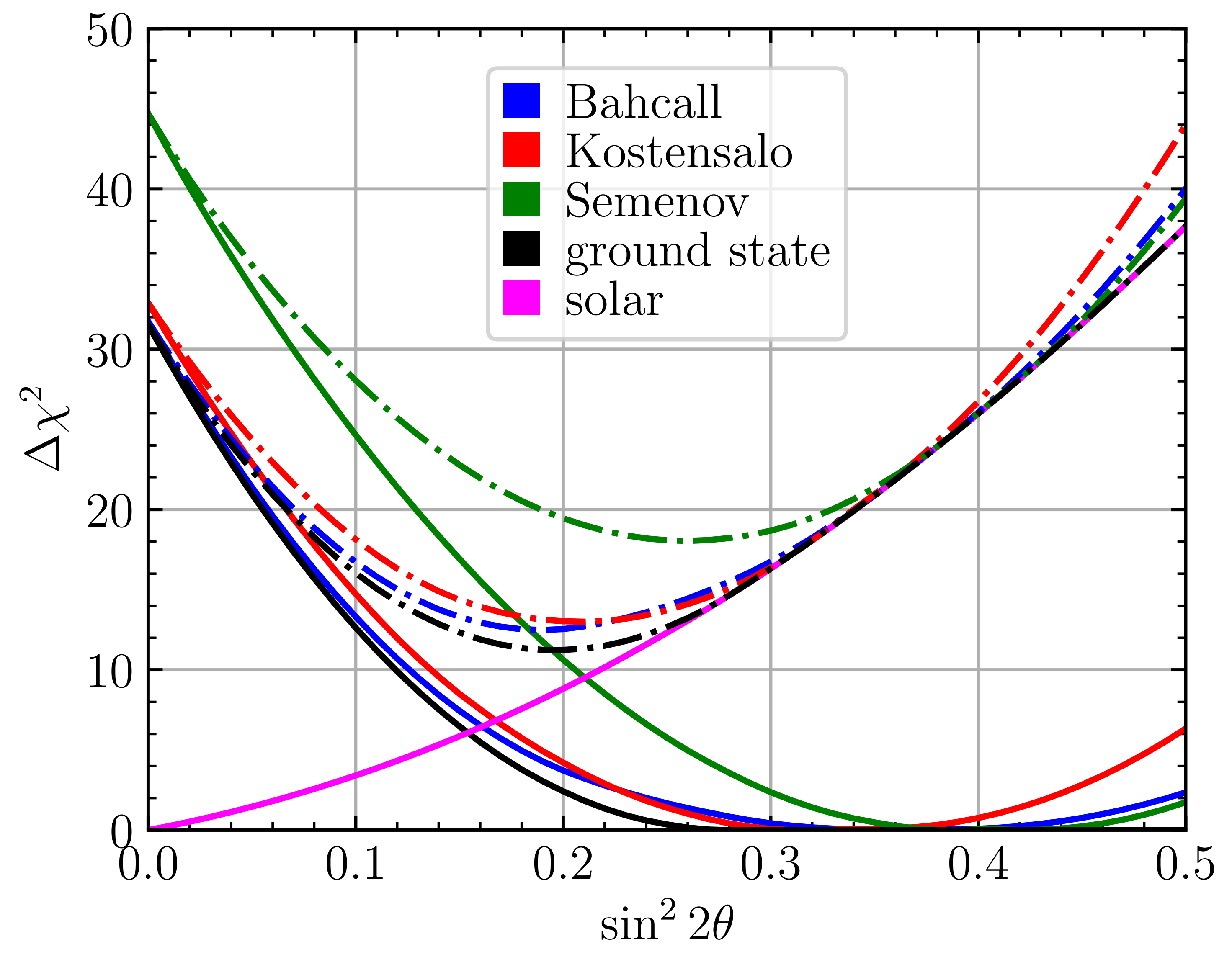


Barinov et al., PRL(2022)

Can it be explained by eV sterile neutrino oscillations?

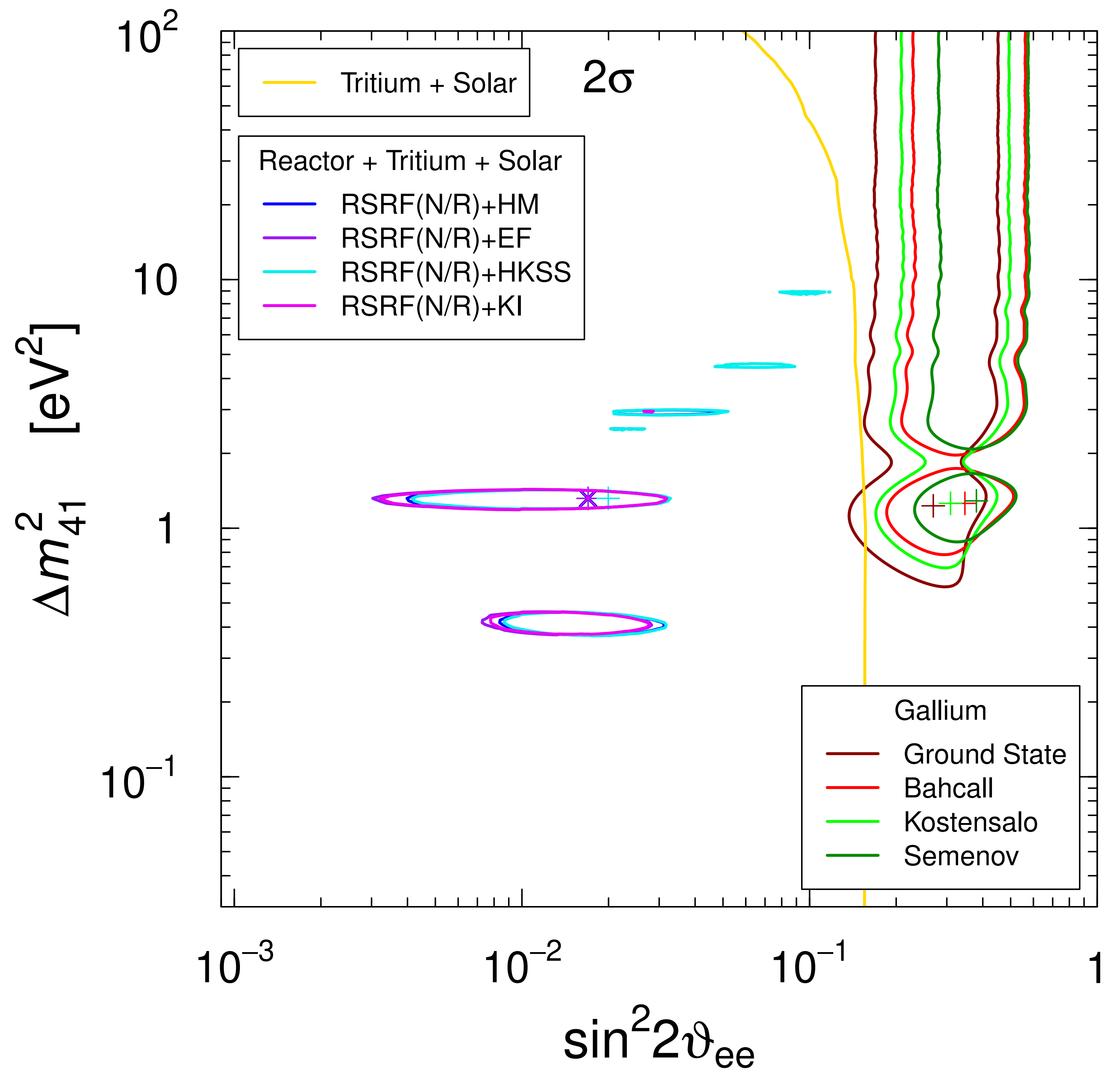
- in tension with solar neutrinos and reactor experiments

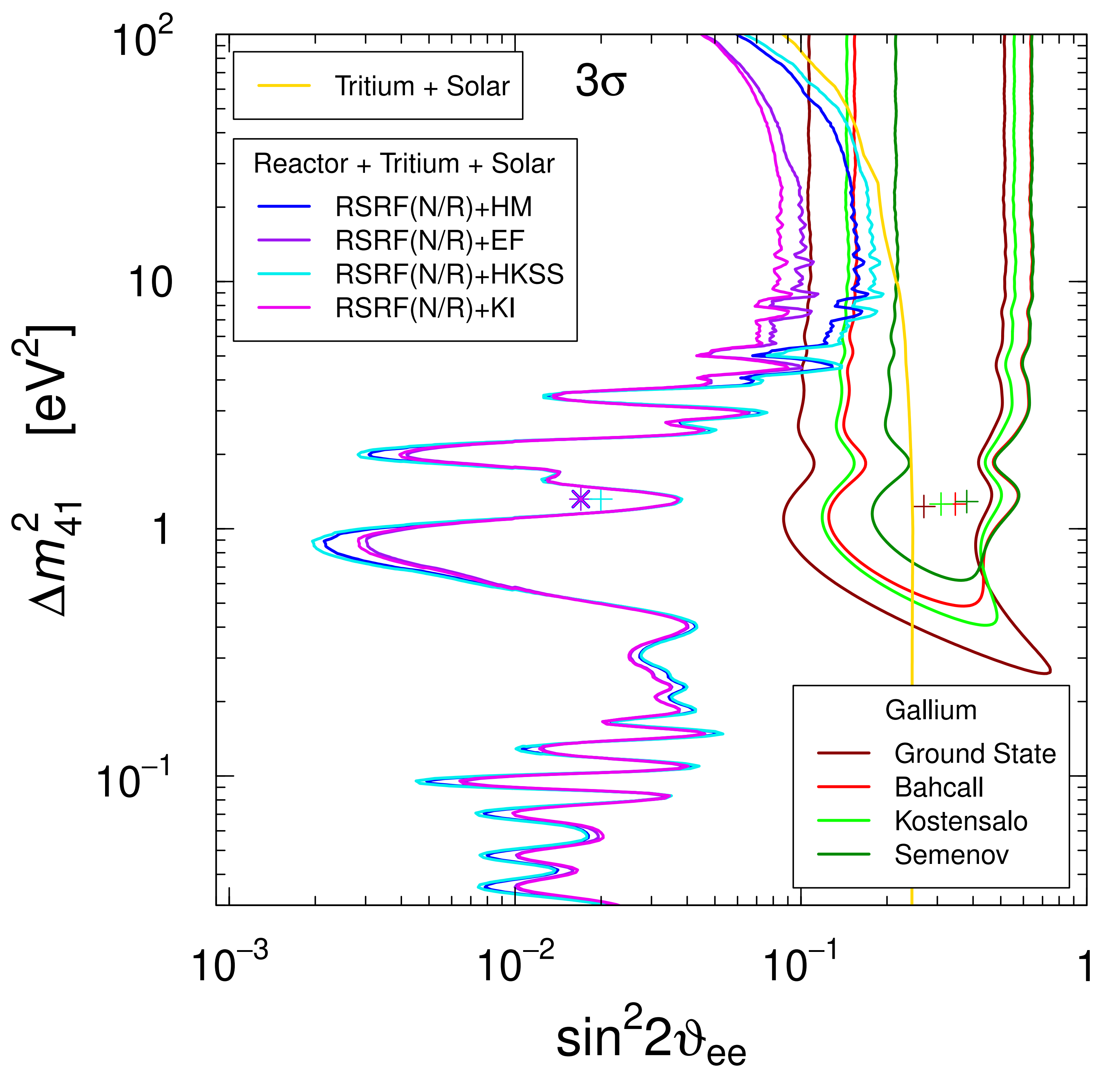
Berryman, Coloma, Huber, TS, Zhou, 2111.12530
Goldhagen, Maltoni, Reichard, TS, 2109.14898



tension $\gtrsim 3\sigma$

Giunti, Li, Ternes, Tyagi, Xin, 2209.00916





see also Brdar, Gehrlein, Kopp, 2303.05528

Can quantum decoherence have an effect on the gallium/reactor tension?

- Arguelles, Bertolez-Martinez, Salvado, Impact of Wave Packet Separation in Low-Energy Sterile Neutrino Searches [2201.05108]
- Arguelles, Conrad et al., New Clues About Light Sterile Neutrinos: Preference for Models with Damping Effects in Global Fits [2211.02610]

- Akhmedov, Smirnov, Damping of neutrino oscillations, decoherence and the lengths of neutrino wave packets, [2208.03736]; Jones, Comment on... [2209.00561], Akhmedov, Smirnov, Reply to comment... [2210.01547]

- Jones, Marzec, Spitz, The Width of a Beta-decay-induced Antineutrino Wavepacket [2211.00026]

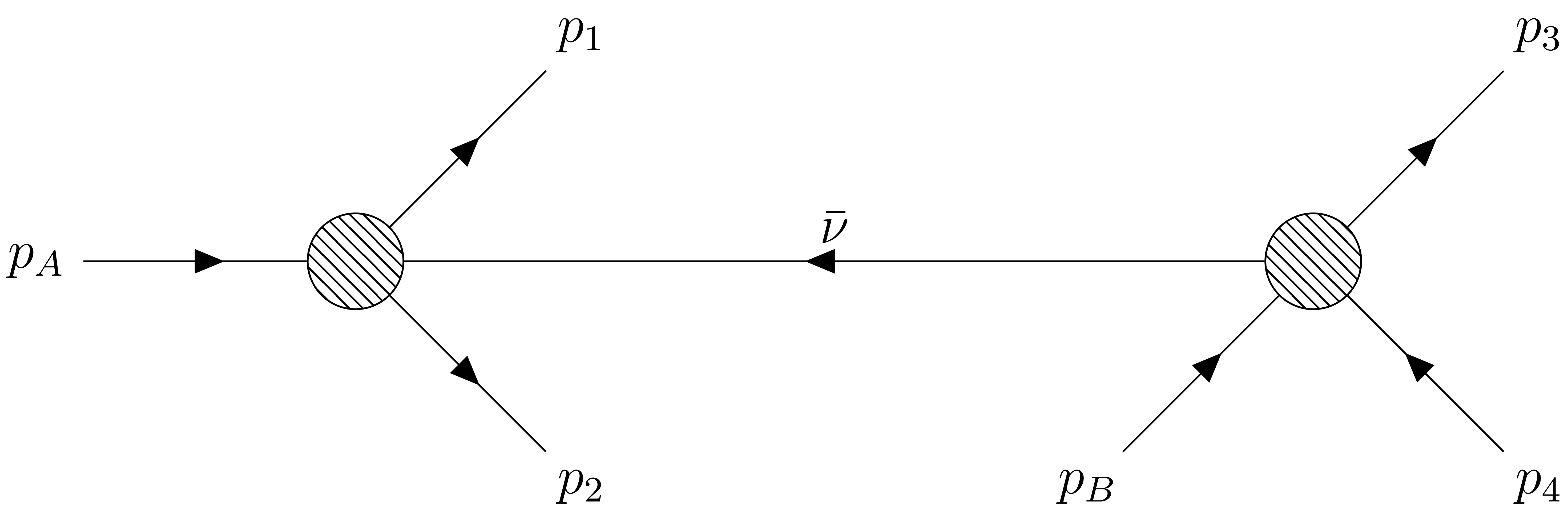
Can quantum decoherence have an effect on the gallium/reactor tension?

- R. Krüger, T. Schwetz, 2303.15524 (EPJC to appear):

  perform a QFT calculation of the oscillation amplitude, taking into account localization of external particles for reactor and gallium experiments

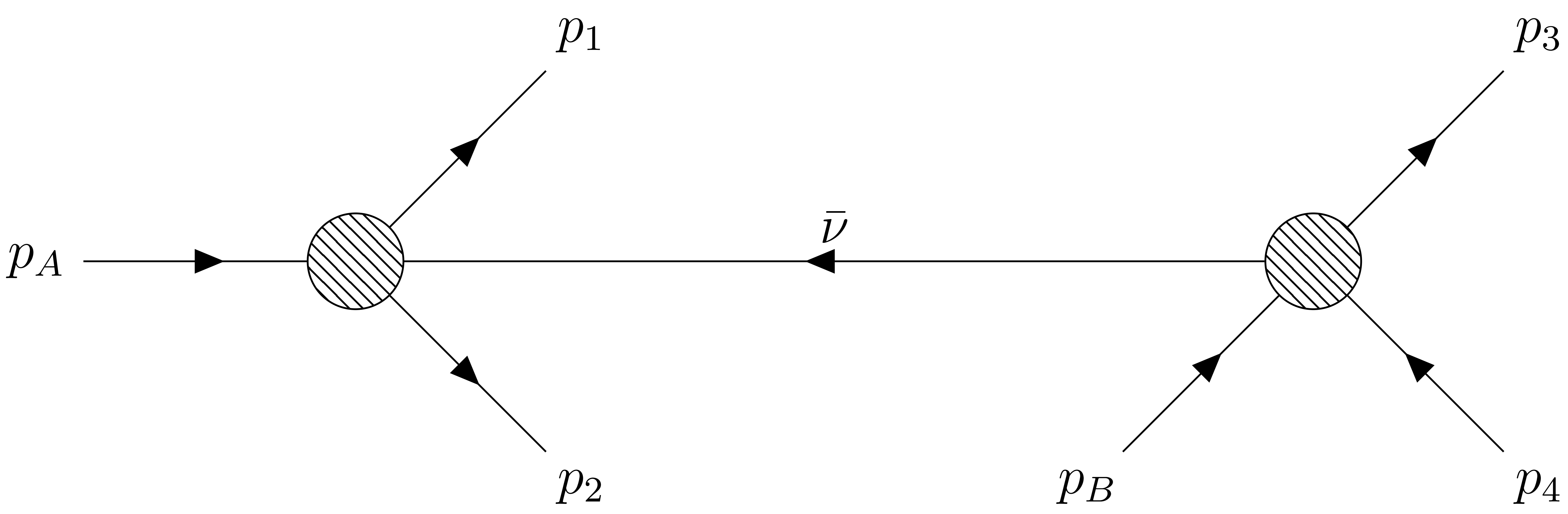
  „first principle“ calculation of decoherence effects

QFT approach to neutrino oscillations



- Feynman diagram for joint process of production, propagation, detection macroscopic separation of the two vertices
- early papers: Rich,1993; Giunti,Kim,Lee,Lee,1993; Grimus,Stockinger,1996; Kiers,Weiss,1998
- review paper: M. Beuthe, Phys. Rept. 375 (2003) 105 [hep-ph/0109119]

QFT approach to neutrino oscillations



reactor experiments:

- production: $A \to A' + e^- + \bar{\nu}_e$
- detection: $\bar{\nu}_e + p \to n + e^+$
- $\Rightarrow A + p \to A' + n + e^- + e^+$

Gallium source experiments:

- production: $\mathrm{Cr} \to \mathrm{V} + \nu_e$
- detection: $\mathrm{Ga} + \nu_e \to \mathrm{Ge} + e^-$
- $\Rightarrow \mathrm{Cr} + \mathrm{Ga} \to \mathrm{V} + \mathrm{Ge} + e^-$

QFT approach to neutrino oscillations

- coherence properties of oscillation amplitude is determined by localization of external particles and their velocities
- assume Gaussian wave packets in momentum space:

$$|\phi\rangle = \int d\tilde{\mathbf{k}} \phi(\mathbf{k}) |\mathbf{k}\rangle \qquad \phi(\mathbf{k}) = \left(\frac{2\pi}{\sigma^2}\right)^{3/4} e^{-\frac{(\mathbf{k}-\mathbf{p})^2}{4\sigma^2}}$$

The transition amplitude

$$i\mathcal{A}_{\alpha\beta} \propto \sum_j U_{\alpha j} U^*_{\beta j} \int \frac{d^4p}{(2\pi)^4} i\tilde{\mathcal{M}}_P \frac{\not{p} - m_j}{p^2 - m_j^2 + i\epsilon} i\tilde{\mathcal{M}}_D \, e^{-ip(x_D - x_P)}$$

$$\times \prod_{I=P,D} \frac{\pi^2}{\sigma_{pI}^3 \sigma_{EI}} \exp\left[-\frac{(\mathbf{p} - \mathbf{p}_I)^2}{4\sigma_{pI}^2} - \frac{(p^0 - E_I - \mathbf{v}_I(\mathbf{p} - \mathbf{p}_I))^2}{4\sigma_{EI}^2} \right]$$

and effective momentum and energy spreads:

$$\sigma_p^2 \equiv \sum_{i,f} \sigma_{i,f}^2 \,, \qquad \sigma_e^2 \equiv \sigma_p^2 (\Sigma - \mathbf{v}^2)$$

and a weighted velocity and velocity-squared:

$$\mathbf{v} \equiv \frac{1}{\sigma_p^2} \sum_{i,f} \sigma_{i,f}^2 \mathbf{v}_{i,f} \,, \qquad \Sigma \equiv \frac{1}{\sigma_p^2} \sum_{i,f} \sigma_{i,f}^2 \mathbf{v}_{i,f}^2 \,, \qquad \mathbf{v_i} \equiv \left. \frac{\partial E_i}{\partial \mathbf{k}_i} \right|_{\mathbf{k}_i = \mathbf{p}_i}$$

generalizations:

- finite life-time of decaying particles
- interactions with environment (effect in analogy to collisional line broadening)

…after some algebra:

$$\overline{|\mathcal{A}_{\alpha\beta}|^2} \propto \exp\left[i\frac{\Delta m^2 L}{2E_0}\right]$$ standard oscillation phase

$$\times \exp\left[-\frac{1}{2}\left(\frac{\Delta m^2}{4E_0\sigma_m}\right)^2\right]$$ localization decoherence $\xi_{\rm loc}$

$$\times \exp\left[-\frac{1}{2}\left(\frac{\Delta m^2 L\sigma_{\rm en}}{2E_0^2}\right)^2\right]$$ energy decoherence $\xi_{\rm en}$

$\sigma_m, \sigma_{\rm en}$ are calculable from localization properties of initial and final state particles

- Localization decoherence:

$$\xi_{\mathrm{loc}} = \exp\left[-\frac{1}{2}\left(\frac{\Delta m^2}{4E_\nu\sigma_m}\right)^2\right] = \exp\left[-2\pi^2\left(\frac{\delta_{\mathrm{loc}}}{L_{\mathrm{osc}}}\right)^2\right] \quad \text{with} \quad \sigma_m\delta_{\mathrm{loc}} = \frac{1}{2}$$

  - energy/momentum uncertainty be large enough that individual mass states cannot be identified: $\sigma_m \gg \Delta m^2/E_\nu$
  - production/detection regions be localized better than oscillation length: $\delta_{\mathrm{loc}} \ll L_{\mathrm{osc}}$

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  - energy/momentum uncertainty be large enough that individual mass states cannot be identified: $\sigma_m \gg \Delta m^2 / E_\nu$
  - production/detection regions be localized better than oscillation length: $\delta_{\rm loc} \ll L_{\rm osc}$

- Energy decoherence:

$$\xi_{\rm en} = \exp\left[-\frac{1}{2}\left(\frac{\Delta m^2 L \sigma_{\rm en}}{2E_\nu^2}\right)^2\right] = \exp\left[-2\pi^2\left(\frac{L}{L_{\rm osc}}\frac{\sigma_{\rm en}}{E_\nu}\right)^2\right]$$

  - the neutrino energy needs to be well defined $\sigma_{\rm en} \ll E_\nu$
  - can be interpreted as neutrino wave packet separation ($v_j \approx 1 - m_j^2/2E_\nu^2$)

Classical averaging

$$\overline{|\mathcal{A}_{\alpha\beta}|^2} \propto \exp\left[i\frac{\Delta m^2 L}{2E_0}\right] \exp\left[-2\pi^2\left(\frac{\delta_{\rm loc}}{L_{\rm osc}}\right)^2\right] \times \exp\left[-\frac{1}{2}\left(\frac{\Delta m^2 L \sigma_{\rm en}}{2E_0^2}\right)^2\right]$$

- Classical averaging of $|\mathcal{A}_{\alpha\beta}|^2$ over space and energy have the same effect as intrinsic QM decoherence:

$$\delta^2_{\rm loc} \to \delta^2_{\rm loc} + \delta^2_{\rm clas}\,, \quad \sigma^2_{\rm en} \to \sigma^2_{\rm en} + \sigma^2_{\rm clas}$$

- indistinguishable phenomenologically
  Kiers, Nussinov, Weiss, 1996; Stodolsky, 1998; Ohlsson, 2001
- quantum mechanical uncertainties provide a fundamental lower bound on the uncertainty
- to observe QM decoherence, classical averaging effects have to be suppressed down to the quantum level

Numerical estimates for gallium and reactors

R. Krüger, TS, 2303.15524

- nuclei localization: inter-atomic distances in cristal lattice or fluid
- velocities: either thermal velocities or velocities for typical kin. energies of outgoing particles
- electron/positron localization: distance the particle travels until it deposits one mean excitation energy (integrating $\langle dE/dx \rangle$ Bethe equation)

	Particle	δ_x [nm]	σ [eV]	v
Reactor (P)	N	0.24	410	1×10^{-6}
$N \to N' + e^- + \overline{\nu}_e$	N'	0.24	410	4×10^{-5}
	e^-	260	0.38	0.99
Reactor (D)	p	0.1	990	5×10^{-6}
$p + \overline{\nu}_e \to n + e^+$	n	5×10^6	2×10^{-5}	5×10^{-3}
	e^+	320	0.3	0.99
Gallium (P)	Cr	0.20	480	7×10^{-7}
$\mathrm{Cr} \to \mathrm{V} + \nu_e$	V	0.20	480	2×10^{-5}
Gallium (D)	Ga	0.27	370	6×10^{-7}
$\mathrm{Ga} + \nu_e \to \mathrm{Ge} + e^-$	Ge	0.27	370	1×10^{-5}
	e^-	310	0.32	0.83

Numerical estimates for gallium and reactors

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- localization decoherence:

for reactor and gallium experiments dominated by hadronic particles

$$\sigma_m \simeq (400 - 500)\,\mathrm{eV}\,, \qquad \delta_{\mathrm{loc}} = \frac{1}{2\sigma_m} \simeq 0.2\,\mathrm{nm}$$

$$-\ln \xi_{\mathrm{loc}} = \frac{1}{2}\left(\frac{\Delta m^2}{4E_\nu \sigma_m}\right)^2 \approx 1.3 \times 10^{-19} \left(\frac{\Delta m^2}{1\,\mathrm{eV}^2}\right)^2 \left(\frac{1\,\mathrm{MeV}}{E_\nu}\right)^2 \left(\frac{500\,\mathrm{eV}}{\sigma_m}\right)^2$$

$\Rightarrow$ QM localization decoherence irrelevant for all practical purposes: $\xi_{\mathrm{loc}} = 1$

Note: classical spatial averaging is relevant and needs to be taken into account

Numerical estimates for gallium and reactors

R. Krüger, TS, 2303.15524

- energy decoherence:

including phase space integration and Doppler broadening:

$$\sigma_{\rm en} \approx 0.5\,{\rm eV}\,, \qquad \delta_{\rm en} \approx 200\,{\rm nm}$$

$$-\ln \xi_{\rm en} = 2\pi^2 \left(\frac{L}{L_{\rm osc}} \frac{\sigma_{\rm en}}{E_\nu}\right)^2 \approx 4.9 \times 10^{-12} \left(\frac{L}{L_{\rm osc}}\right)^2 \left(\frac{1\,{\rm MeV}}{E_\nu}\right)^2 \left(\frac{\sigma_{\rm en}}{0.5\,{\rm eV}}\right)^2$$

$\Rightarrow$ QM energy decoherence (“wave packet separation”) irrelevant for all practical purposes: $\xi_{\rm en} = 1$

Note: classical energy averaging is relevant and needs to be taken into account

Summary energy decoherence

R. Krüger, TS, 2303.15524

s. also Akhmedov, Smirnov, 2208.03736

- our result: $\sigma_{\rm en} \approx 0.5\,\mathrm{eV}\,, \quad \delta_{\rm en} \approx 200\,\mathrm{nm}$

- energy resolution of typical reactor neutrino detectors:

$$(0.03 - 0.06)\,\mathrm{MeV}\sqrt{E/\mathrm{MeV}} \quad \Rightarrow \quad \sigma_{\rm clas} \simeq 0.1\ \mathrm{MeV}$$

about 6 orders of magnitude larger than $\sigma_{\rm en}$!

- QM decoherence negligible — dominated by classical averaging (holds also for JUNO)

- phenomenological constraint is dominated by classical energy resolution:
  $\sigma < 0.47\,\mathrm{MeV}, \delta > 2.1 \times 10^{-4}\,\mathrm{nm}$ [Gouvea,Romeri,Ternes, 2005.03022, 2104.05806]

Any decoherence effect on top of classical averaging will point towards new physics!

Barenboim, Mavromatos, Sarkar, Waldron-Lauda, 2006
Fogli, Lisi, Marrone, Montanino, Palazzo, 2007
Farzan, TS, Smirnov, 2008; Bakhti, Farzan, TS, 2015
Guzzo, de Holanda, Oliveira, 2014
Hellmann, Pas, Rani, 2022
Banks, Kelly, McCullough, 2023
…

Decoherence explanation of the gallium anomaly

Y. Farzan, TS, 2306.09422

- three SM neutrinos (no steriles)
- modified QM evolution:

$$H = \frac{1}{2E_\nu}\mathrm{diag}(m_1^2, m_2^2, m_3^2)\,,$$

$$\frac{d\rho}{dt} = i[\rho, H] - \{\rho, D^2\} + 2D\rho D$$

$$D = \mathrm{diag}(d_1, d_2, d_3)\,,$$

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- damping of interference terms:

$$P_{ee} = \sum_{i=1}^{3} |U_{ei}|^4 + \sum_{i\neq j} |U_{ei}|^2 |U_{ej}|^2 e^{-\gamma_{ij} L} e^{-i\phi_{ij}}$$

$$\gamma_{ij} = (d_i - d_j)^2 = \frac{1}{\lambda_{ij}}\left(\frac{E_{\mathrm{ref}}}{E_\nu}\right)^r$$

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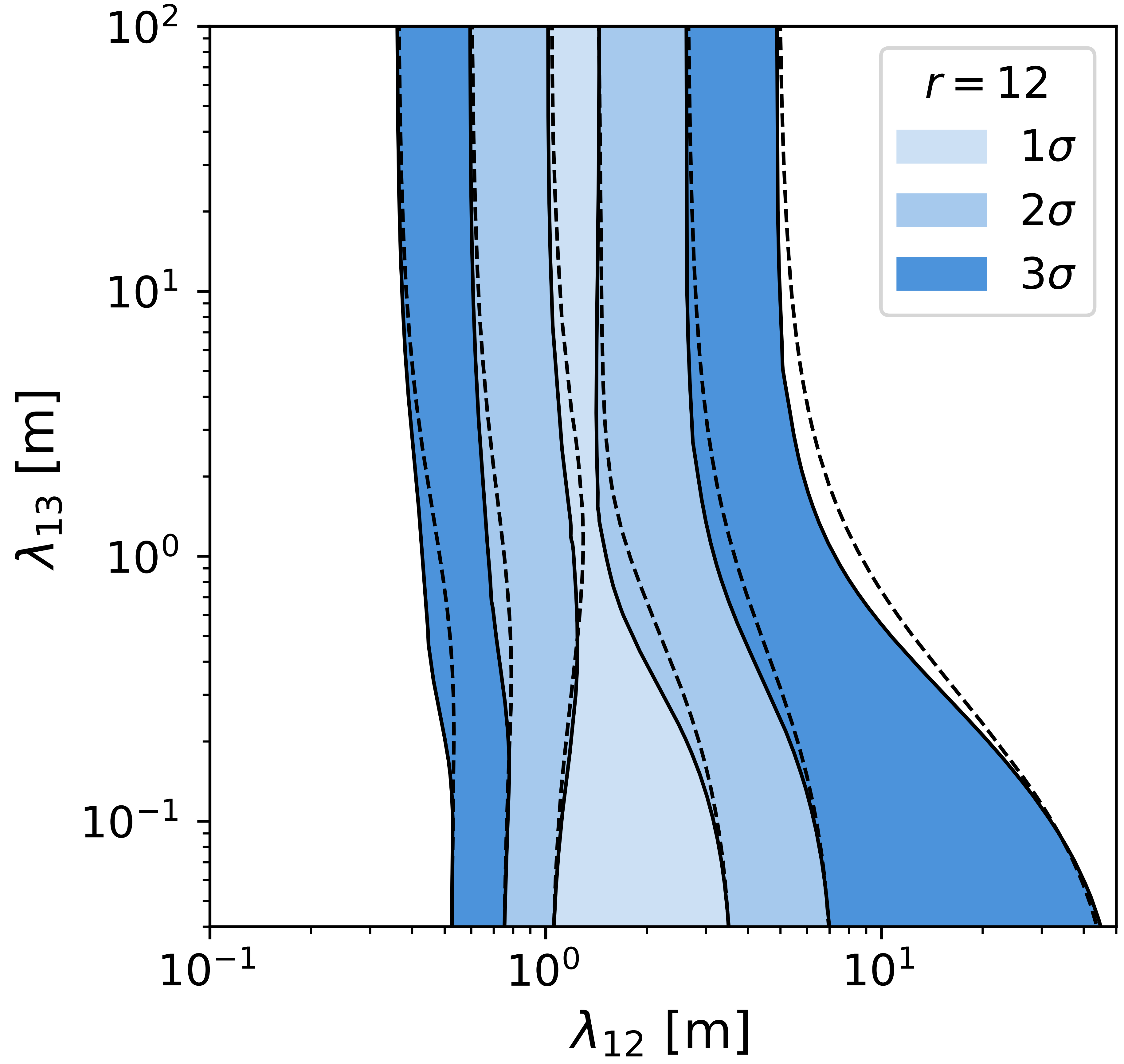
	$r = 12$				
	$\chi^2_{\rm min}$/dof	p-val.	$\Delta\chi^2$	$\#\sigma$	λ_{12} [m]
BEST	2.2/1	0.14	32.5	5.4	1.44
all	9.2/5	0.10	29.2	5.0	1.74



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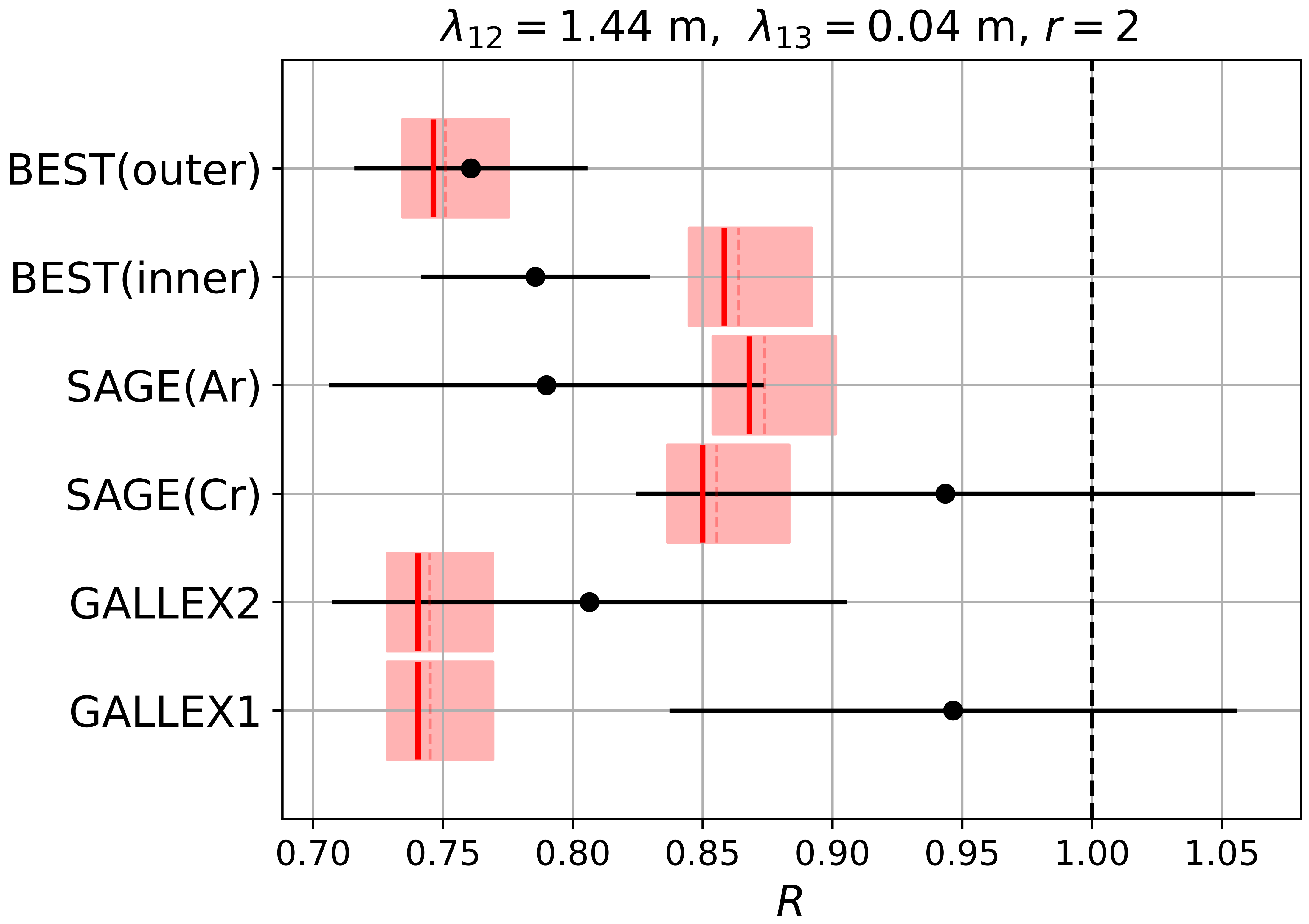
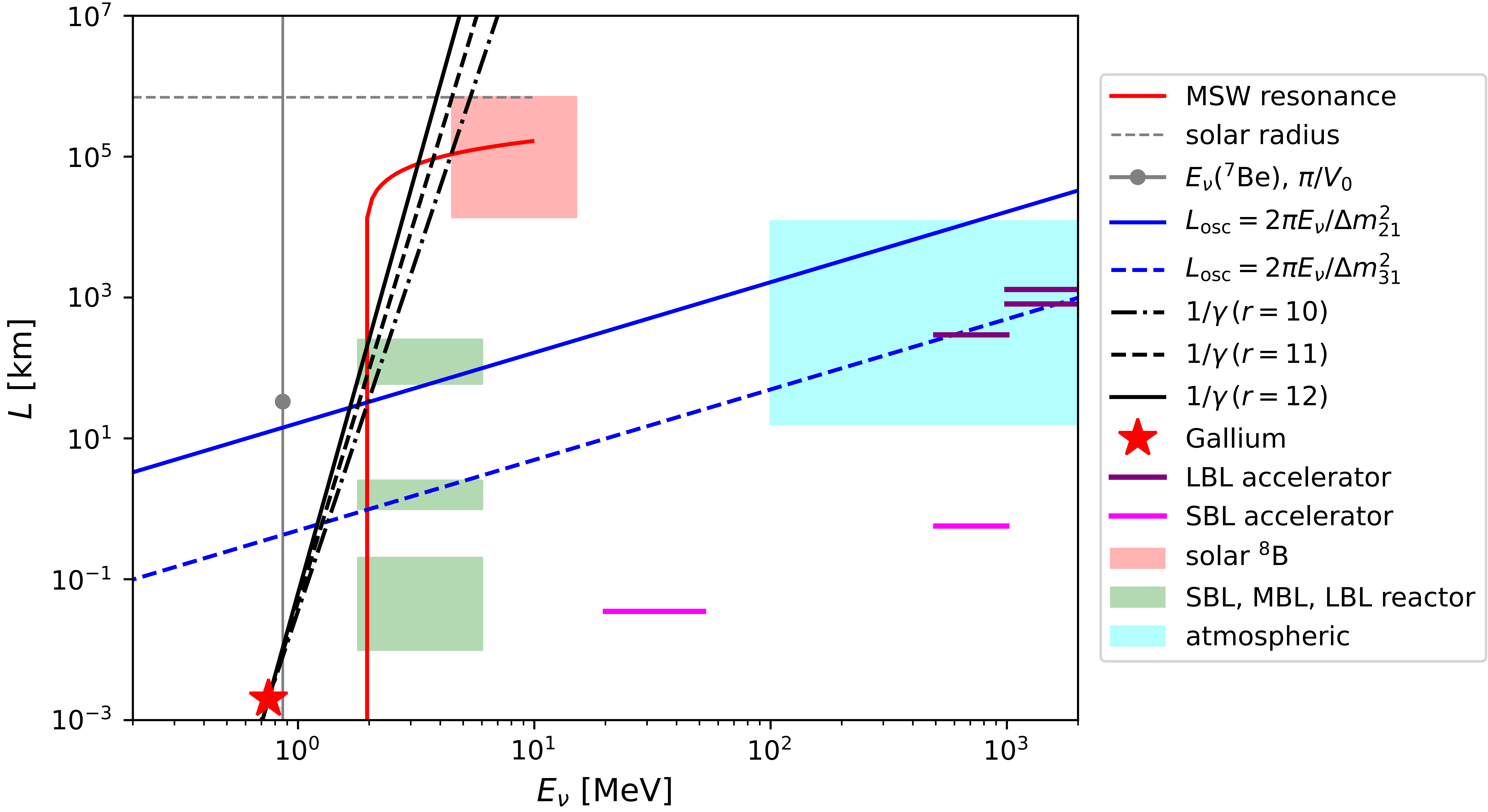
$$P_{ee}^{\rm gal} \approx 1 - \frac{1}{2}\sin^2 2\theta_{13} - \frac{1}{2}\cos^4\theta_{13}\sin^2 2\theta_{12}\left(1 - e^{-\gamma_{12}L}\right)$$



Consistency with other oscillation data



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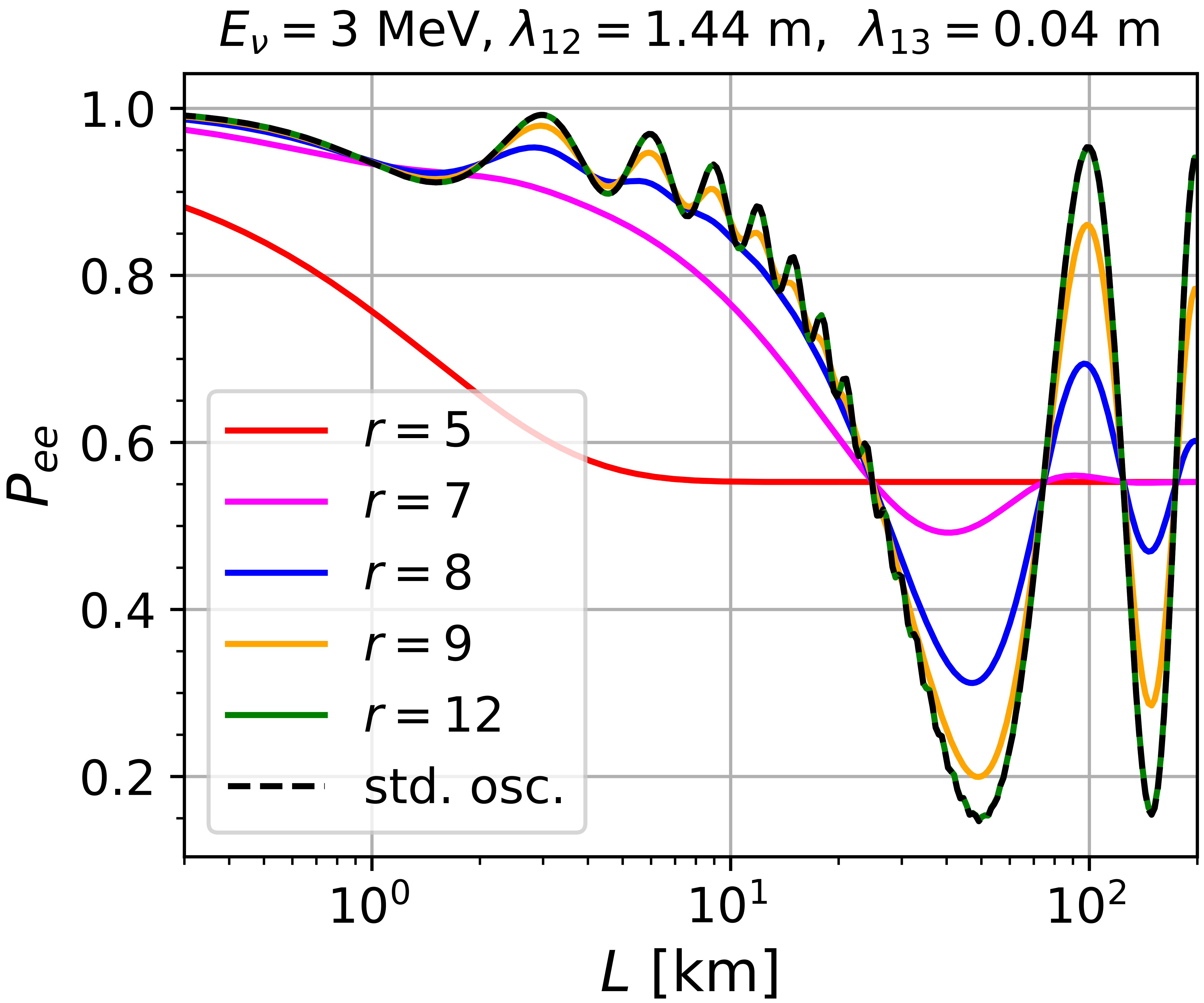

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Decoherence explanation of gallium — discussion

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- solar and reactor neutrinos require steep energy dependence of decoherence effects: $\gamma \propto E_\nu^{-r}, \; r \gtrsim 10-12$ $\Rightarrow$ other oscillation evidences not affected

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- can be made compatible with decoherence explanation of LSND Bakhti, Farzan, TS [1503.05374] either
  - different decoherence parameters for neutrinos and antineutrinos, or
  - play with energy dependence: $d_1 \approx 0$, d_2 peak @ 0.75 MeV, d_3 peak @ 30 MeV

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  - play with energy dependence: $d_1 \approx 0, d_2$ peak @ 0.75 MeV, d_3 peak @ 30 MeV

- no effect predicted in MiniBooNE or SBL reactors

Summary

- BEST results make gallium anomaly highly significant $\approx 5\sigma$
- sterile neutrino explanation in tension with reactors and solar neutrinos
- standard QM localization/wave packet effects are negligible
- presented an explanation in terms of new-physics decoherence, consistent with oscillation data, potentially compatible with an LSND explanation

Summary

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- sterile neutrino explanation in tension with reactors and solar neutrinos
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Thank you for your attention