SN1987A bounds for gravitationally induced neutrino quantum decoherence in the presence of dark fermions

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What is quantum gravity decoherence?

- Neutrino flavour eigenstate is a coherent mixture of mass eigenstates: $|\nu_e\rangle = \sum_i U_{ei}|\nu_i\rangle$
- For a neutrino quantum system, there are two phenomena reducing the coherence:

Wave-packet decoherence	Environment-induced decoherence

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- Quantum Gravity (QG): spacetime itself could be subject to quantum fluctuations → *spacetime foam*
- Neutrinos interact with gravitational degrees of freedom → QG decoherence!

Building a model for QG decoherence

- Open quantum system approach: **Lindblad formalism**

$$\frac{\partial \rho}{\partial \mathrm{t}} = -i\,[H\,, \rho] + D(\rho)$$

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5. We assume the existence of new fermions that share the same quantum numbers as neutrinos under the unbroken SM gauge group (n_f = total number of fermions).

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6. Simplicity

Building a model for QG decoherence

- The model is fully described by: [Hellmann, Päs, Rani, 2022]

$$H = H_{\text{vacuum}} \left(+ H_{\text{matter}} \right) \qquad \text{with} \qquad H_{\text{vacuum}} = \frac{1}{2\left|\vec{p}\right|} \text{diag}\left(0, \Delta m_{21}^2, \ldots, \Delta m_{n_\text{f}1}^2\right)$$

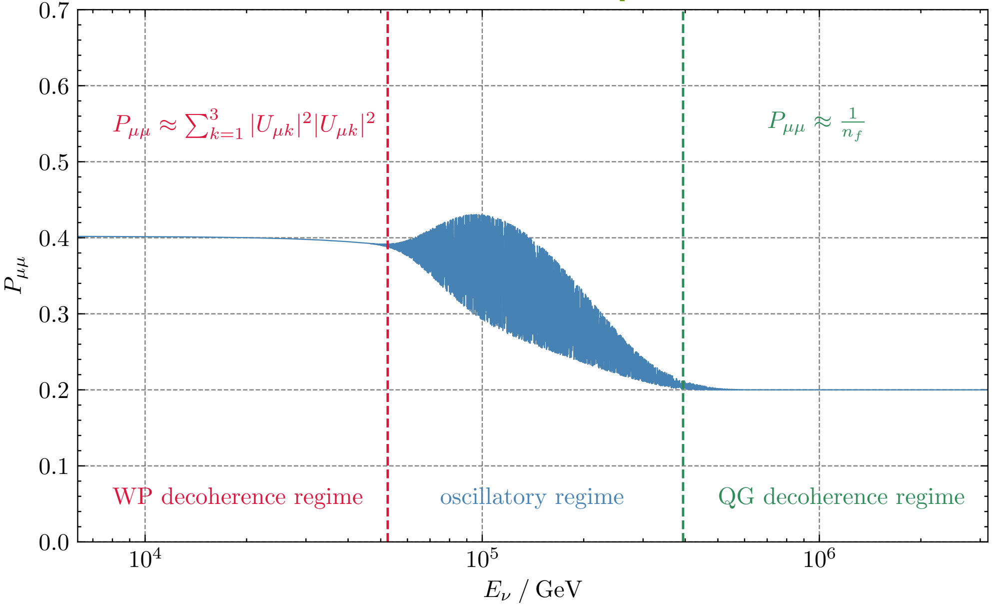
$$D_{\text{QG}}(\rho) = \sum_{i,j=0}^{n_\text{f}^2-1} \left((\mathscr{D}_{\text{QG}})_{ij} \rho_j \right) \lambda_i \qquad \text{with} \qquad \mathscr{D}_{\text{QG}} = \text{diag}\left(0, \Gamma, \ldots, \Gamma\right)$$

$$\Gamma(E) = \gamma_0 \left(\frac{E}{E_0} \right)^n$$

- Determine altered neutrino oscillation probability:

solve Lindblad equation $\rho(0) \to \rho(L)$	$\rightarrow$	determine osc. prob. $P_{\alpha\beta} = \text{Tr}\left(\rho_\beta \rho(L)\right)$	$\rightarrow$	model fully encoded in $P_{\alpha\beta}(E, L)$

[Domi, Eberl, Hellmann, Krieg, Päs, 2025]



Analysing the SN1987A data

- Our data analysis is close to [Ternes, Pagliaroli, Villante, 2025]

Compute Likelihood
$\mathscr{L}(\gamma_0, E_{\text{tot}}, \langle E_\nu \rangle)$

$\downarrow$

Determine best-fit, i.e. minimise $\chi^2 = -2 \ln \left(\mathscr{L}(\gamma_0, E_{\text{tot}}, \langle E_\nu \rangle) \right)$
w.r.t. the parameters $\gamma_0, E_{\text{tot}}, \langle E_\nu \rangle \implies \chi^2_{\text{min}}$

$\downarrow$

Profile out the parameters $E_{\text{tot}}, \langle E_\nu \rangle$, i.e. minimise $\chi^2 = -2 \ln \left(\mathscr{L}(\gamma_0^{\text{fix}}, E_{\text{tot}}, \langle E_\nu \rangle) \right)$
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Analysing the SN1987A data

$$\boxed{\text{Profile out the parameters } E_{\text{tot}}, \langle E_\nu \rangle, \text{ i.e. minimise } \chi^2 = -2\ln\left(\mathscr{L}(\gamma_0^{\text{fix}}, E_{\text{tot}}, \langle E_\nu\rangle)\right) \text{ w.r.t. } E_{\text{tot}}, \langle E_\nu \rangle \implies \chi^2_{\text{profile}}}$$

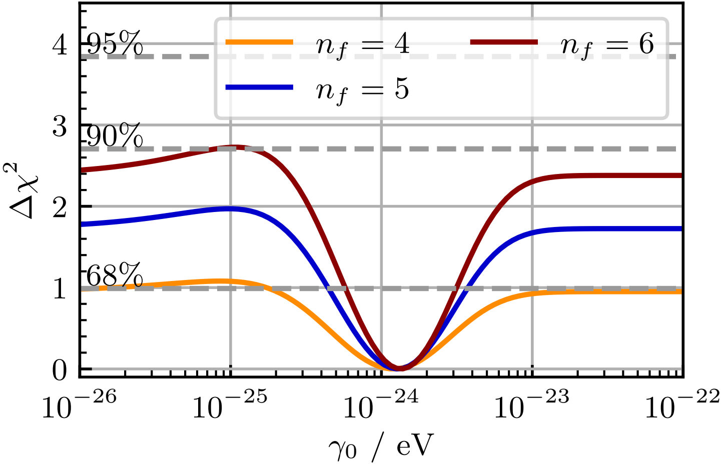
$$\downarrow$$

$$\boxed{\text{Plot } \Delta\chi^2(\gamma_0) \text{ against } \gamma_0 \text{, where } \Delta\chi^2(\gamma_0) = \chi^2_{\text{profile}} - \chi^2_{\text{min}}}$$

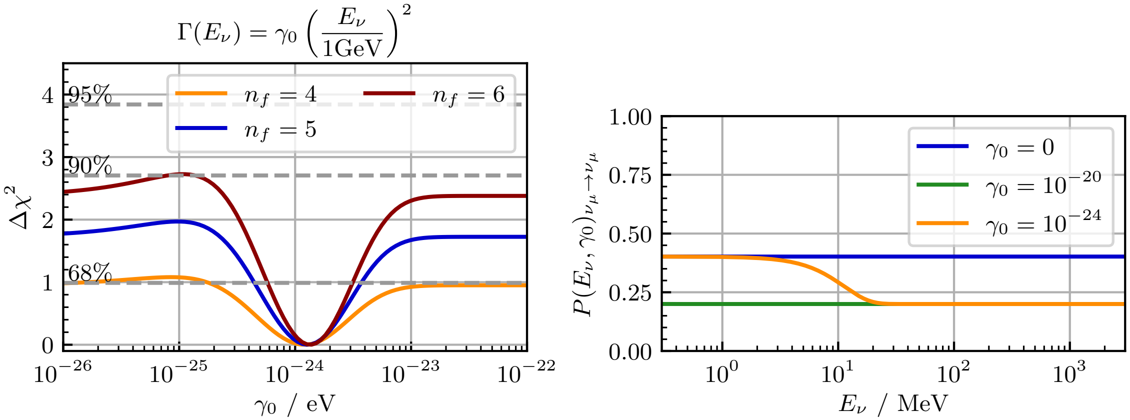
- SN1987A neutrino events were measured by Kamiokande-II, Baksan, and Irvine–Michigan–Brookhaven experiment

PRELIMINARY

$$\Gamma(E_\nu) = \gamma_0 \left(\frac{E_\nu}{1\mathrm{GeV}}\right)^2$$



PRELIMINARY

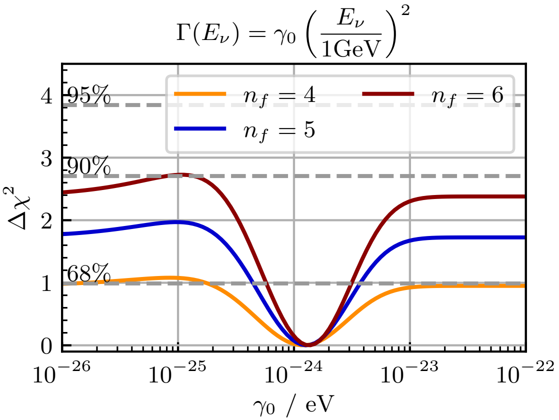


Outlook

- Different power law dependencies
- Time dependent analysis of the data [Ternes, Pagliaroli, Villante, 2025]
- Matter effects?
- Inverse neutrino mass ordering?
- Neutrino flux from supernova simulations?
- Sensitivity tests of future detectors?

Takeaway messages

- Spacetime fluctuations may act as an environment for propagating neutrinos, thus, inducing decoherence.
- If dark fermion species being singlets w.r.t the unbroken SM gauge group exist, this could induce transitions between neutrinos and these dark fermions.
- Analysing the SN1987A neutrino data, we find a statistically non-significant, but still interesting, preference for our model.



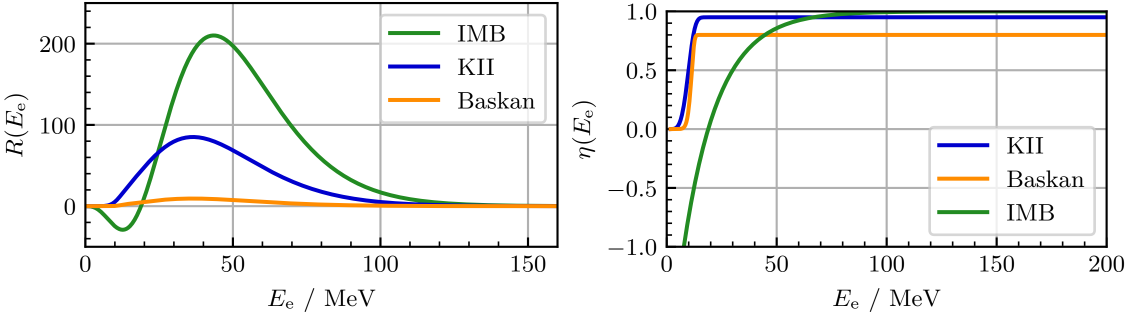
Backup

Formulae

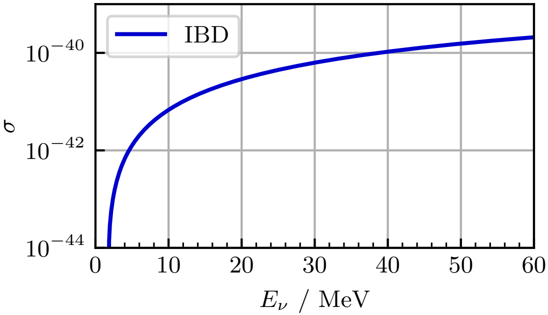
- χ^2 definition: $\chi^2 = -2\sum_{d=K,I,B} \ln\left(\mathscr{L}_d\right)$
- Event rate: $R(E_e) = N_p \sigma_{\bar{\nu}_e p}(E_\nu) F_{\bar{\nu}_e}(E_\nu)\eta(E_e)$
- Time integrated neutrino flux: $F^{\mathrm{SN}}_{\bar{\nu}_e}(E_\nu) = \frac{1}{4\pi D^2}\frac{E^{\bar{\nu}_e}_{\mathrm{tot}}}{\langle E_{\bar{\nu}_e}\rangle}\frac{(1+\alpha)^{(1+\alpha)}}{\Gamma[1+\alpha]}\left(\frac{E_\nu}{\langle E_{\bar{\nu}_e}\rangle}\right)^2 e^{-\frac{(1+\alpha)E_\nu}{\langle E_{\bar{\nu}_e}\rangle}}$
- Time integrated neutrino flux at the detector: $F^{\mathrm{dec}}_{\bar{\nu}_e}(E_\nu) = \left(P_{ee} + P_{\mu e} + P_{\tau e}\right) F^{\mathrm{SN}}_{\bar{\nu}_e}(E_\nu)$
- Likelihood: $\overline{\mathscr{L}}_d = e^{-R}\prod_{i=1}^{N^*_d}\left[\int R(E_e)G(E_e, E_i)dE_e\right]$
- Smearing function: $G(E_e, E_i) = \frac{1}{\sqrt{2\pi}\delta E_i}\exp\left(-\frac{(E_e - E_i)^2}{2\delta E_i^2}\right)$

[Ternes, Pagliaroli, Villante, 2025]

Event Rates and Detector Efficiencies



Inverse Beta Decay Cross Section



Data

[Ternes, Pagliaroli, Villante, 2025]

TABLE III. The Baskan data set. No information on the angle was provided and it is assumed to be 90° for all events.

δt_i	$E_i \pm \delta E_i$	$\theta_i \pm \delta\theta_i$	B_i
0.0	12.0 ± 2.4	90 ± 0	8.4×10^{-4}
0.435	17.9 ± 3.6	90 ± 0	1.3×10^{-3}
1.710	23.5 ± 4.7	90 ± 0	1.2×10^{-3}
7.687	17.5 ± 3.5	90 ± 0	1.3×10^{-3}
9.099	20.3 ± 4.1	90 ± 0	1.3×10^{-3}

TABLE IV. The IMB data set. The background is assumed to be negligible.

δt_i	$E_i \pm \delta E_i$	$\theta_i \pm \delta\theta_i$	B_i
0.0	38.0 ± 7.0	80 ± 10	0
0.412	37.0 ± 7.0	44 ± 15	0
0.650	28.0 ± 6.0	56 ± 20	0
1.141	39.0 ± 7.0	65 ± 20	0
1.562	36.0 ± 9.0	33 ± 15	0
2.684	36.0 ± 6.0	52 ± 10	0
5.010	19.0 ± 5.0	42 ± 20	0
5.582	22.0 ± 5.0	105 ± 20	0

TABLE II. The Kamiokande-II data set. For the TI data analysis only the data indicated with a * are considered, while in the TD analysis we include the entire data set. Energies are given in MeV and times are relative times with respect to the bounce in seconds.

δt_i	$E_i \pm \delta E_i$	$\theta_i \pm \delta\theta_i$	B_i
0.0^*	20.0 ± 2.9	18 ± 18	1.0×10^{-5}
0.107^*	13.5 ± 3.2	40 ± 27	5.4×10^{-4}
0.303^*	7.5 ± 2.0	108 ± 32	3.1×10^{-2}
0.324^*	9.2 ± 2.7	70 ± 30	8.5×10^{-3}
0.507^*	12.8 ± 2.9	135 ± 23	5.3×10^{-4}
0.686	6.3 ± 1.7	68 ± 77	7.1×10^{-2}
1.541^*	35.4 ± 8.0	32 ± 16	5.0×10^{-6}
1.728^*	21.0 ± 4.2	30 ± 18	1.0×10^{-5}
1.915^*	19.8 ± 3.2	38 ± 22	1.0×10^{-5}
9.219^*	8.6 ± 2.7	122 ± 30	1.8×10^{-2}
10.433^*	13.0 ± 2.6	49 ± 26	4.0×10^{-4}
12.439^*	8.9 ± 1.9	91 ± 39	1.4×10^{-2}
17.641	6.5 ± 1.6	103 ± 50	7.2×10^{-3}
20.257	5.4 ± 1.4	110 ± 50	5.2×10^{-2}
21.355	4.6 ± 1.3	120 ± 50	1.8×10^{-2}
23.814	6.5 ± 1.6	112 ± 50	7.3×10^{-2}

More Technicalities...

arXiv:
2103.11984

[Hellmann, Päs, Rani, 2022]

arXiv:
2208.11754

[Hellmann, Päs, Rani, 2022]

More Technicalities...

arXiv: 2409.12633

[Domi, Eberl, Hellmann, Krieg, Päs, 2025]

arXiv: 2503.04573

[Ternes, Pagliaroli, Villante, 2025]