Quantum Decoherence in Supernova Neutrinos

Consequences and future phenomenological limits

SNvD 2023@LNGS

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GEFAN
Grupo de Estudos em Física e Astrofísica de Neutrinos

- Sources of decoherence:

Quantum Decoherence hypothesis: neutrino spontaneously loses coherence by non-standard mixing effects (new physics, e.g. candidate theories of quantum gravity)

-S. W. Hawking, “Particle creation by black holes”, in “Euclidean quantum gravity”, pp. 167–188. World Scientific, 1975.
-J. D. Bekenstein, “Statistical black-hole thermodynamics”, *Physical Review D* **12** (1975), no. 10, 3077.
-J. Ellis, J. S. Hagelin, D. V. Nanopoulos, and M. Srednicki, “Search for violations of quantum mechanics”, *N.P. B* **241** (1984).

- Largely tested in neutrino physics
- Framework to phenomenologically describe it: open quantum systems with Lindblad (or GKSL) equation

$$\frac{d\rho}{dt} = -i[H,\rho] + \mathcal{D}(\rho) \qquad \mathcal{D}(\rho) = \sum_p^{N^2-1} \left(V_p \rho V_p^\dagger - \frac{1}{2}\{V_p^\dagger V_p, \rho\}\right)$$

ρ: Reduced density matrix for a N-level system

V_p: Jumping operator

- Subsystem in contact to environment
- Trace preserving evolution
- Ensures positivity

Expansion in SU(N) generators:

$$\mathcal{D}(\rho) = \mathcal{D}(\rho)_\mu \lambda^\mu = D_{\mu\nu}\rho^\nu \lambda^\mu$$

$$\dot{\rho} = (\mathcal{H} + D)\rho$$

ρ : 9 x 1 vector for N = 3

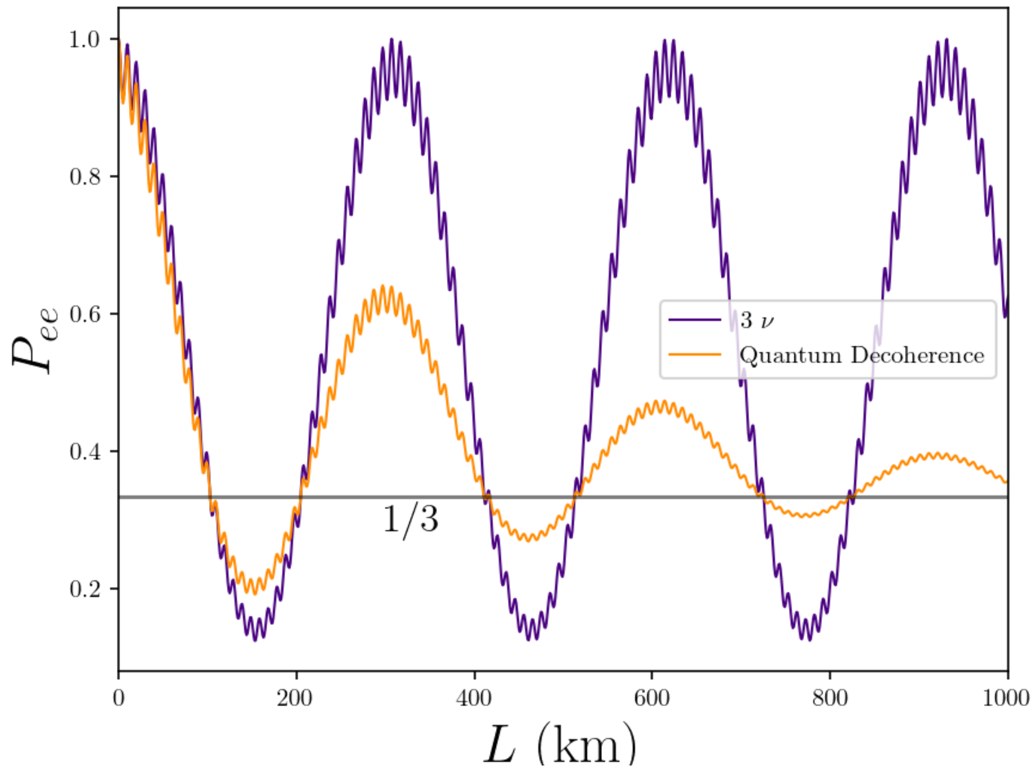
-V. Gorini, A. Kossakowski, and E. C. G. Sudarshan, “Completely positive dynamical semigroups of n-level systems”, J. of Math. P.17 (1976), no. 5, 821–825.
-G. Lindblad, “On the generators of quantum dynamical semigroups”, Communications in Mathematical Physics 48 (1976), no. 2, 119–130.

- Assumption: $V_p = V_p^\dagger$ (increase of von Neumann entropy)

$$D = \begin{pmatrix} 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & -\gamma_1 & \beta_{12} & \beta_{13} & \beta_{14} & \beta_{15} & \beta_{16} & \beta_{17} & \beta_{18} \\ 0 & \beta_{12} & -\gamma_2 & \beta_{23} & \beta_{24} & \beta_{25} & \beta_{26} & \beta_{27} & \beta_{28} \\ 0 & \beta_{13} & \beta_{23} & -\gamma_3 & \beta_{34} & \beta_{35} & \beta_{36} & \beta_{37} & \beta_{38} \\ 0 & \beta_{14} & \beta_{24} & \beta_{34} & -\gamma_4 & \beta_{45} & \beta_{46} & \beta_{47} & \beta_{48} \\ 0 & \beta_{15} & \beta_{25} & \beta_{35} & \beta_{45} & -\gamma_5 & \beta_{56} & \beta_{57} & \beta_{58} \\ 0 & \beta_{16} & \beta_{26} & \beta_{36} & \beta_{46} & \beta_{56} & -\gamma_6 & \beta_{67} & \beta_{68} \\ 0 & \beta_{17} & \beta_{27} & \beta_{37} & \beta_{47} & \beta_{57} & \beta_{67} & -\gamma_7 & \beta_{78} \\ 0 & \beta_{18} & \beta_{28} & \beta_{38} & \beta_{48} & \beta_{58} & \beta_{68} & \beta_{78} & -\gamma_8 \end{pmatrix}$$

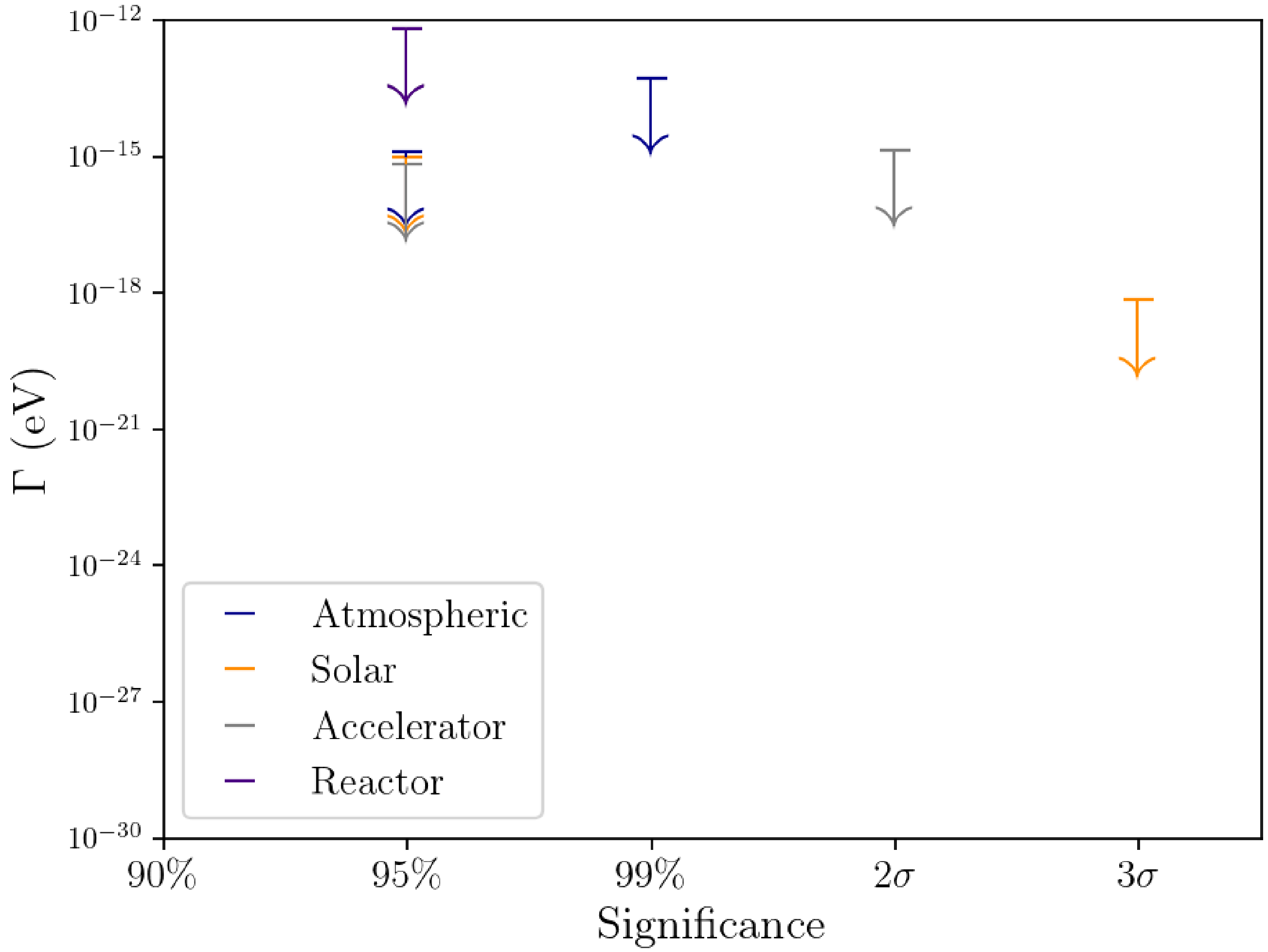
- Coefficients are not independent to ensure complete positivity
- # of parameters is unmanageable: diagonal format

- Initial ν_e in **vacuum**:
  - Damping
  - Maximal mixing



-F. Benatti and H. Narnhofer, "Entropy behaviour under completely positive maps", *letters in mathematical physics* **15** (1988), no. 4, 325–334.
-J. Carrasco, F. Díaz, and A. Gago, "Probing cpt breaking induced by quantum decoherence at dune", Physical Review D 99 (2019), no. 7, 075022.

- Only upper limits:



-E. Lisi, A. Marrone, and D. Montanino, "Probing possible decoherence effects in atmospheric neutrino oscillations", *Physical Review Letters* **85** (2000), no. 6, 1166.
-P. Coloma, J. Lopez-P., I. Martinez-S., and H. Nunokawa, "Decoherence in neutrino propagation through matter, and bounds from icecube/deepcore", *The Eur. P. J. C,* 2018.
-R. Oliveira, M. Guzzo, and P. de Holanda, "Quantum dissipation and c p violation in minos", *Physical Review D* **89** (2014), no. 5, 053002.
-J. A. Coelho, W. A. Mann, and S. S. Bashar, "Nonmaximal θ 23 mixing at nova from neutrino decoherence", *Physical Review Letters* **118** (2017), no. 22, 221801.
-J. Carpio, E. Massoni, and A. Gago, "Testing quantum decoherence at dune", *Physical Review D* **100** (2019), no. 1, 015035.
-G. B. Gomes, M. Guzzo, P. De Holanda, and R. Oliveira, "Parameter limits for neutrino oscillation with decoherence in kamland", *Physical Review D* **95** (2017), no. 11, 113005.
-P. C. de Holanda, "Solar neutrino limits on decoherence", *Journal of Cosmology and Astroparticle Physics* **2020** (2020), no. 03, 012.

What a future supernovae could contribute to this picture

- Turning off collective oscillations
- Only **MSW** effect

NH	IH
$\nu_e \rightarrow \nu_3$	$\nu_e \rightarrow \nu_2$
$\bar{\nu}_e \rightarrow \nu_1$	$\bar{\nu}_e \rightarrow \nu_3$
$\nu_x \rightarrow \nu_1, \nu_2, \nu_3$	$\nu_x \rightarrow \nu_1, \nu_2, \nu_3$

Already incoherent flavor states!

- No **damping** in SN (only MSW)

- Would it be possible the **maximal mixing**?

- Solve the equation of motion in **mass basis in vacuum** for:

$$V_p = V_p^\dagger$$

$$D = -\mathrm{diag}(0, \gamma_1, \gamma_2, \gamma_3, \gamma_4, \gamma_5, \gamma_6, \gamma_7, \gamma_8)$$

- Evaluate equation of motion in mass basis in vacuum

Transition of mass states (in vacuum)

$$D = -\mathrm{diag}(0, \gamma_1, \gamma_2, \gamma_3, \gamma_4, \gamma_5, \gamma_6, \gamma_7, \gamma_8)$$

$$P_{11} = \frac{1}{3} + \frac{1}{2}e^{-\left(\Gamma_3+\frac{\Gamma_8}{3}\right)x} + \frac{1}{6}e^{-\Gamma_8 x}$$

$$P_{12} = \frac{1}{3} - \frac{1}{2}e^{-\left(\Gamma_3+\frac{\Gamma_8}{3}\right)x} + \frac{1}{6}e^{-\Gamma_8 x}$$

$$P_{13} = \frac{1}{3} - \frac{1}{3}e^{-\Gamma_8 x}$$

$$P_{33} = \frac{1}{3} + \frac{2}{3}e^{-\Gamma_8 x}$$

$$P_{22} = P_{11}$$

$$P_{23} = P_{13}$$

Change of variables (to independent ones):

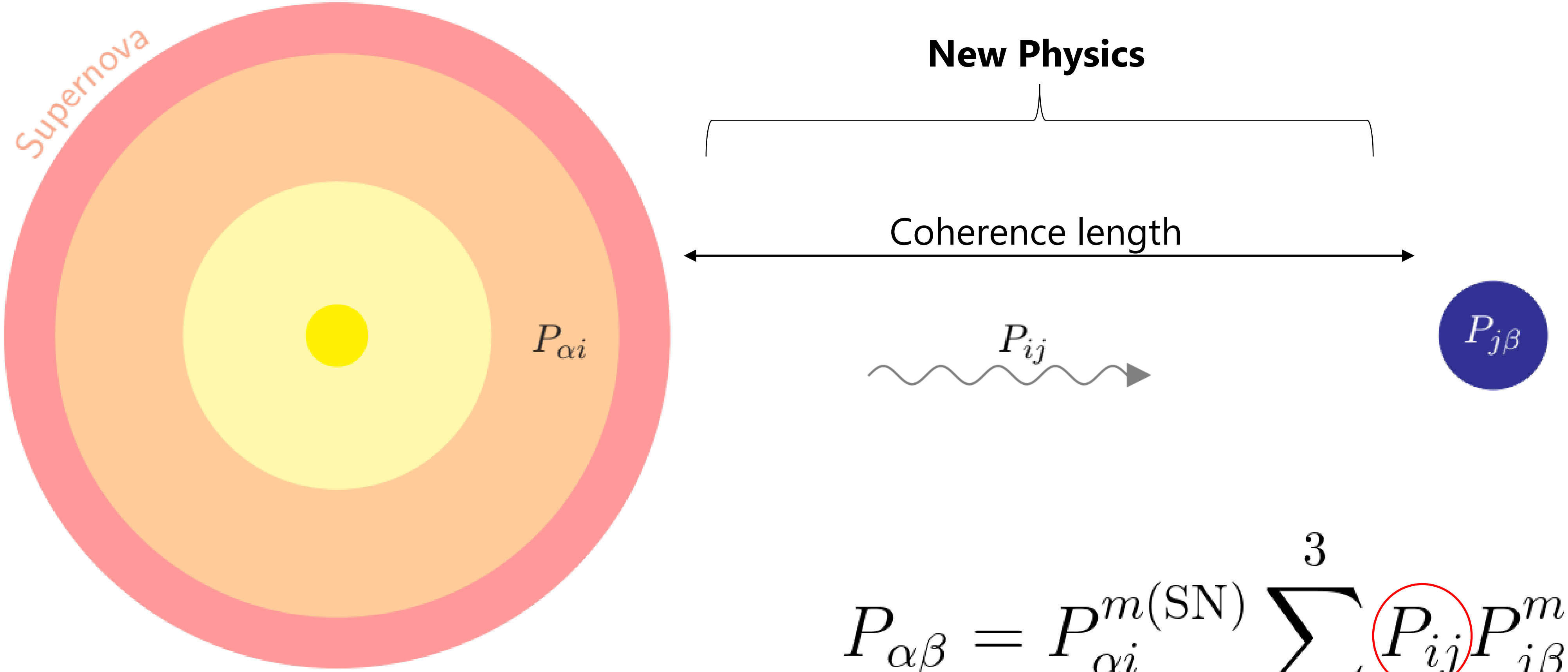
$$\gamma_3 = \Gamma_3 + \frac{\Gamma_8}{3}$$

$$\gamma_8 = \Gamma_8$$

Maximal mixing: 1/3

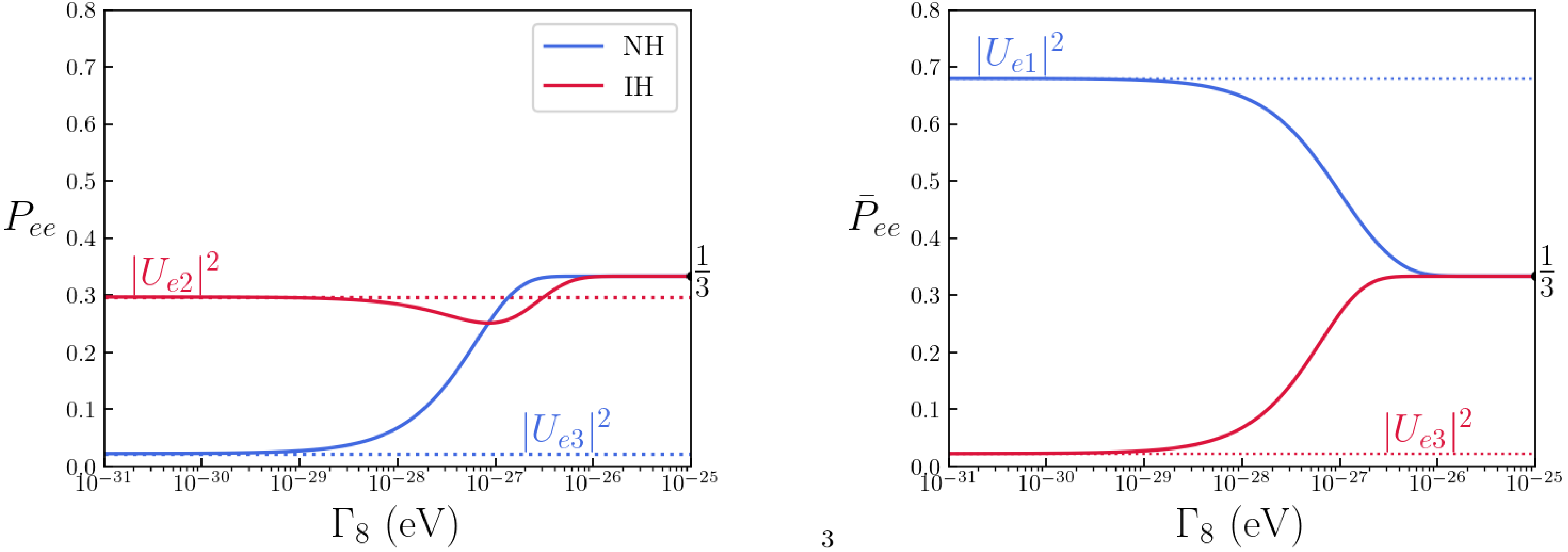
-P. C. de Holanda, "Solar neutrino limits on decoherence", Journal of Cosmology and Astroparticle Physics (2020), no. 03, 012.

- Factorize probability for supernova neutrinos



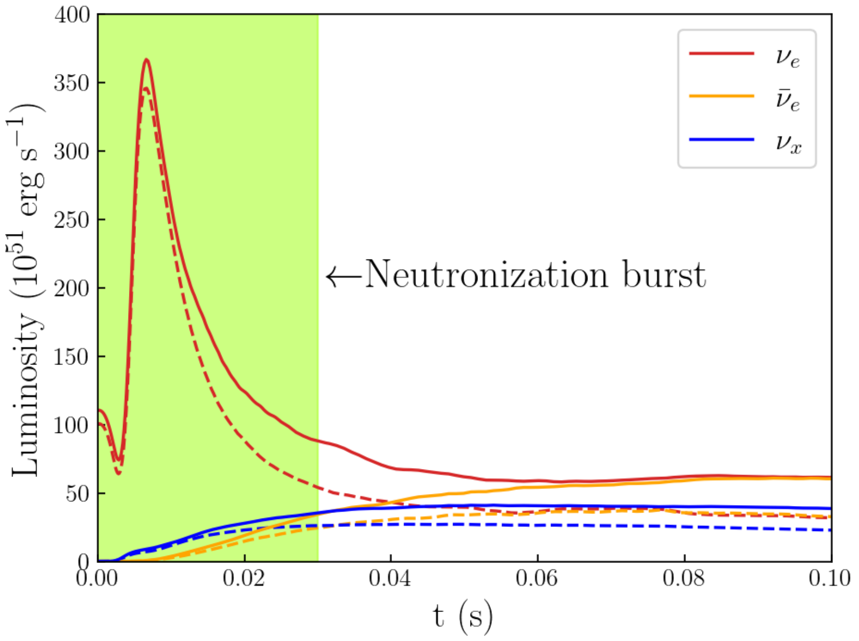
$$P_{\alpha\beta} = P_{\alpha i}^{m(\mathrm{SN})} \sum_{j=1}^{3} P_{ij} P_{j\beta}^{m(\mathrm{Earth})}$$

- Survival probabilities for a **10 kpc SN** (adiabatic propagation)



$$P_{\alpha\beta} = P_{\alpha i}^{m(\mathrm{SN})} \sum_{j=1}^{3} P_{ij} P_{j\beta}^{m(\mathrm{Earth})}$$

- How to test maximal mixing in Supernova neutrinos?
  - Simulated data (from Garching group, thank you!)
  - Collective oscillations are uncertain in the current scenario: **neutronization burst**



$$\phi_{\nu_e} = \phi^0_{\nu_e} P_{ee} + \phi^0_{\nu_x}(1 - P_{ee})$$
$$\phi_{\bar{\nu}_e} = \phi^0_{\bar{\nu}_e} \bar{P}_{ee} + \phi^0_{\nu_x}(1 - \bar{P}_{ee})$$
$$\phi_{\nu_x} = \phi^0_{\nu_e}(1 - P_{ee}) + \phi^0_{\nu_x}(2 + P_{ee} + \bar{P}_{ee}) + \phi^0_{\bar{\nu}_e}(1 - \bar{P}_{ee})$$

$27\ M_\odot$ progenitor

- Future generation experiments: **DUNE**, **Hyper-K**, **JUNO**

- How to test maximal mixing in Supernova neutrinos?
  - Spectrum of events for each detector

$$N_j = n_d^c \int_0^\infty dt \int_0^\infty dE_\nu \frac{d\phi_\nu^2}{dtdE_\nu} \eta(E_\nu) \int_{E_i}^{E_f} d\bar{E}_\nu R_j(\bar{E}_\nu, E_\nu) \sigma(E_\nu, \bar{E}_\nu)$$

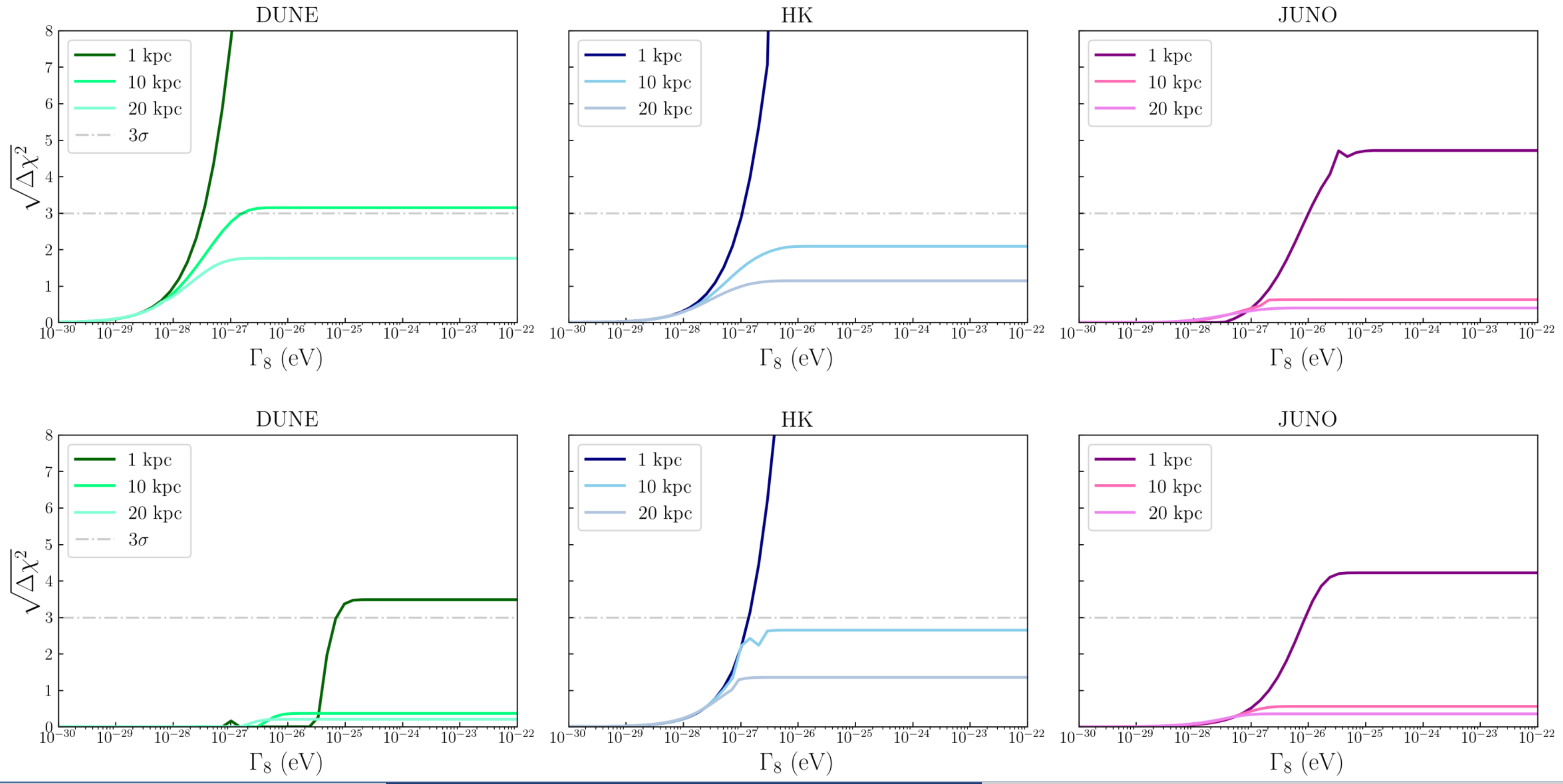
  - Statistical analysis

$$\chi^2(\Gamma_8, \Gamma_3) = \sum_d \sum_{j=1}^{m} \frac{(N_{j,d}^{\text{std}} - (1+a) N_{j,d}^{\text{th}})^2}{N_{j,d}^{\text{th}}} + \frac{a^2}{\sigma_a^2}$$

• Future limits (no Earth regeneration):

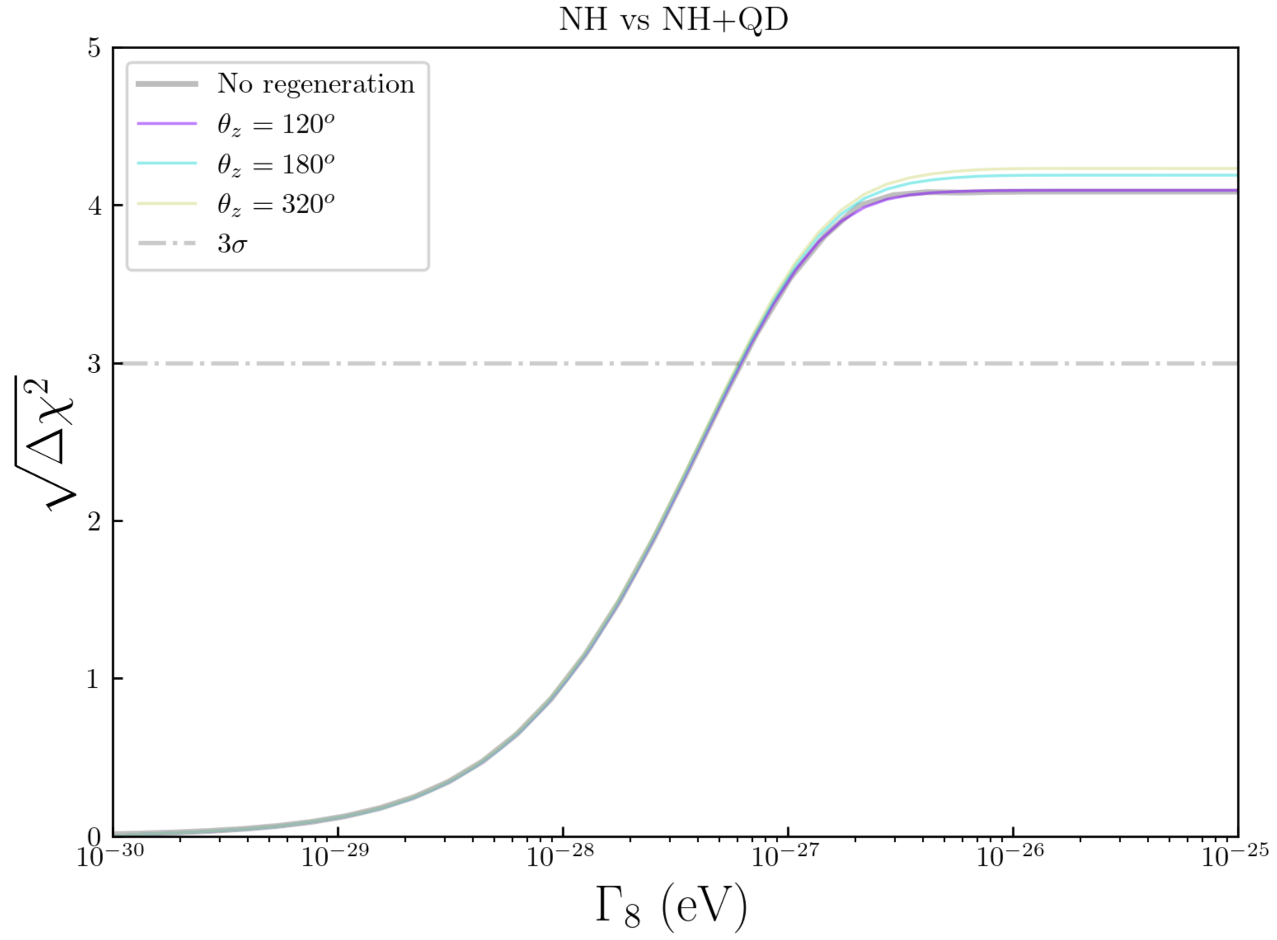
NH

IH



• Future limits (with Earth regeneration) for a **10 kpc** SN:

DUNE+HK+JUNO



- Future limits (with Earth regeneration) for a **10 kpc** SN:

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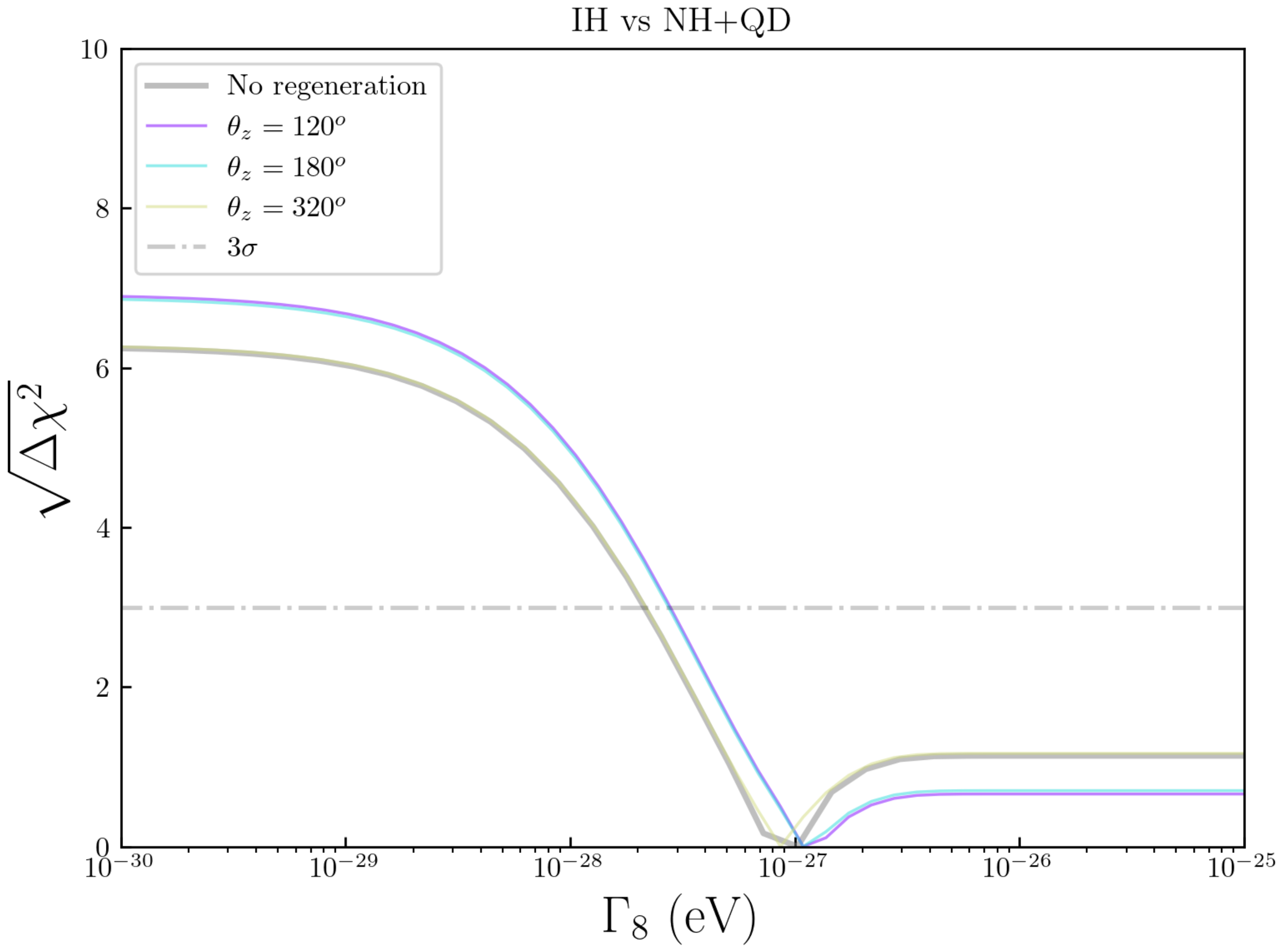
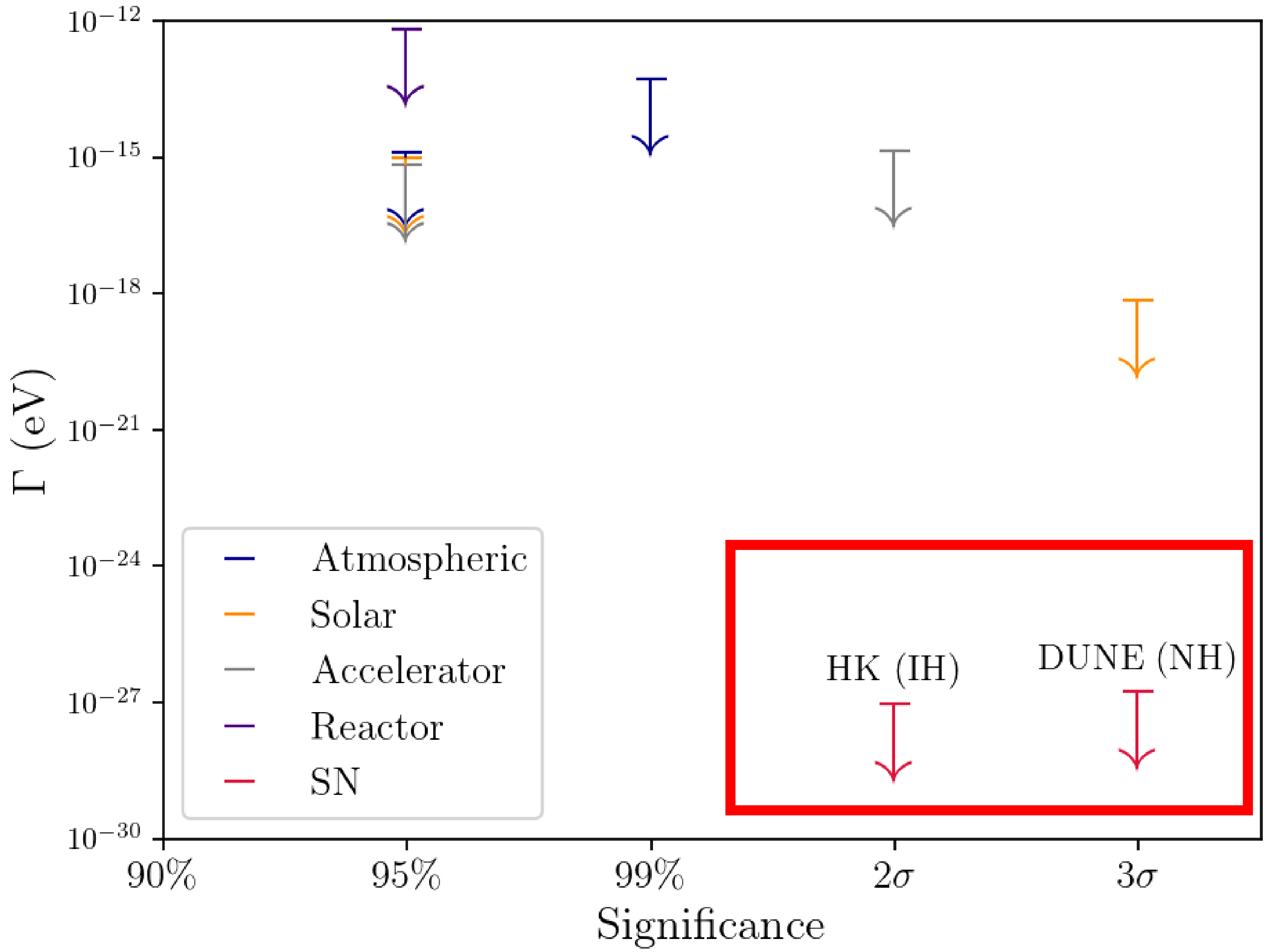


- Future limits for a **10 kpc SN**:



$$\Gamma \lesssim 10^{-28} \text{ eV}$$

- Final remarks:

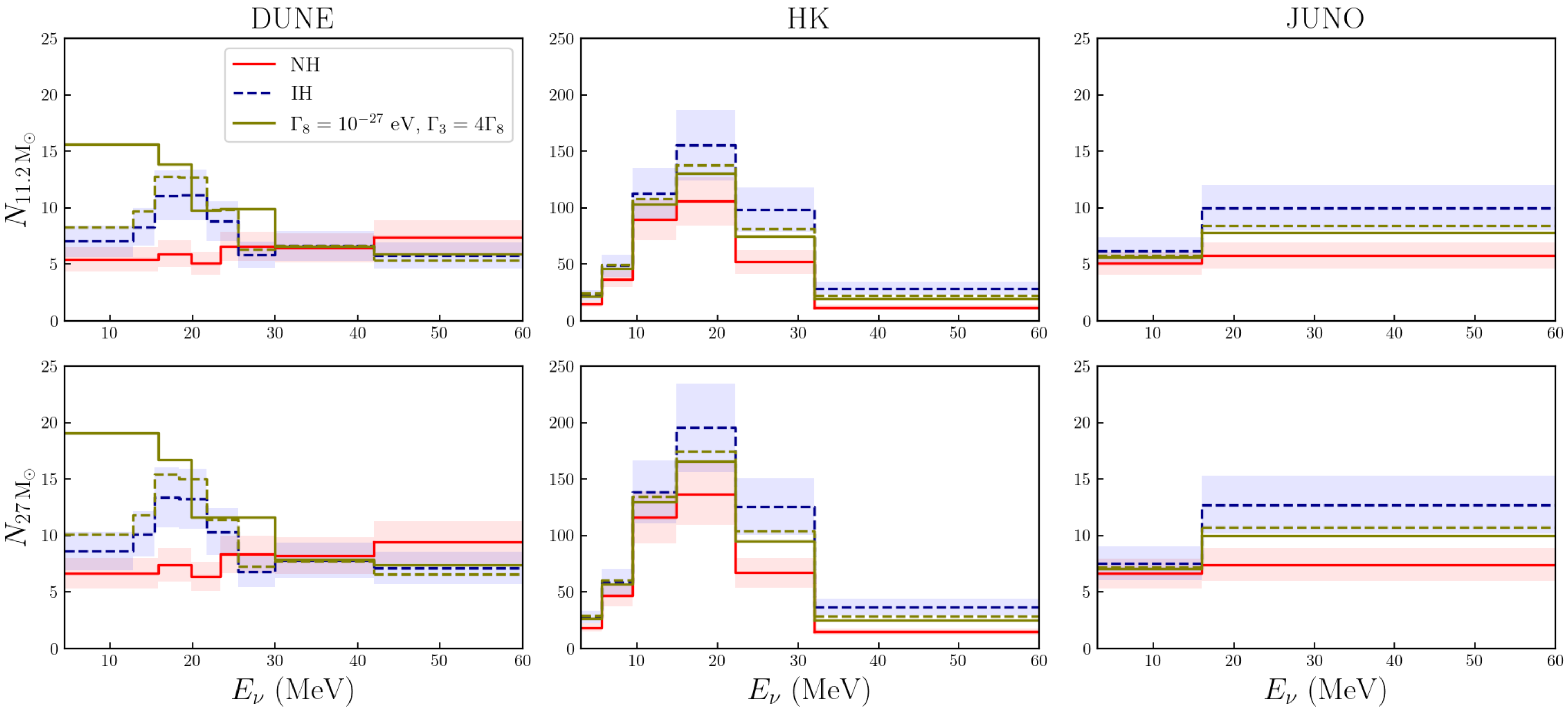
  - Quantum decoherence can be highly constrained
  - Demonstrates the powerfull capabilities of next generation detectors
  - In arxiv soon: MVS, P. Dedin Neto, P. C. de Holanda, Ernesto Kemp. **On the Effects of Quantum Decoherence in a Future Supernova Neutrino Detection**, 2023.

Thank you!

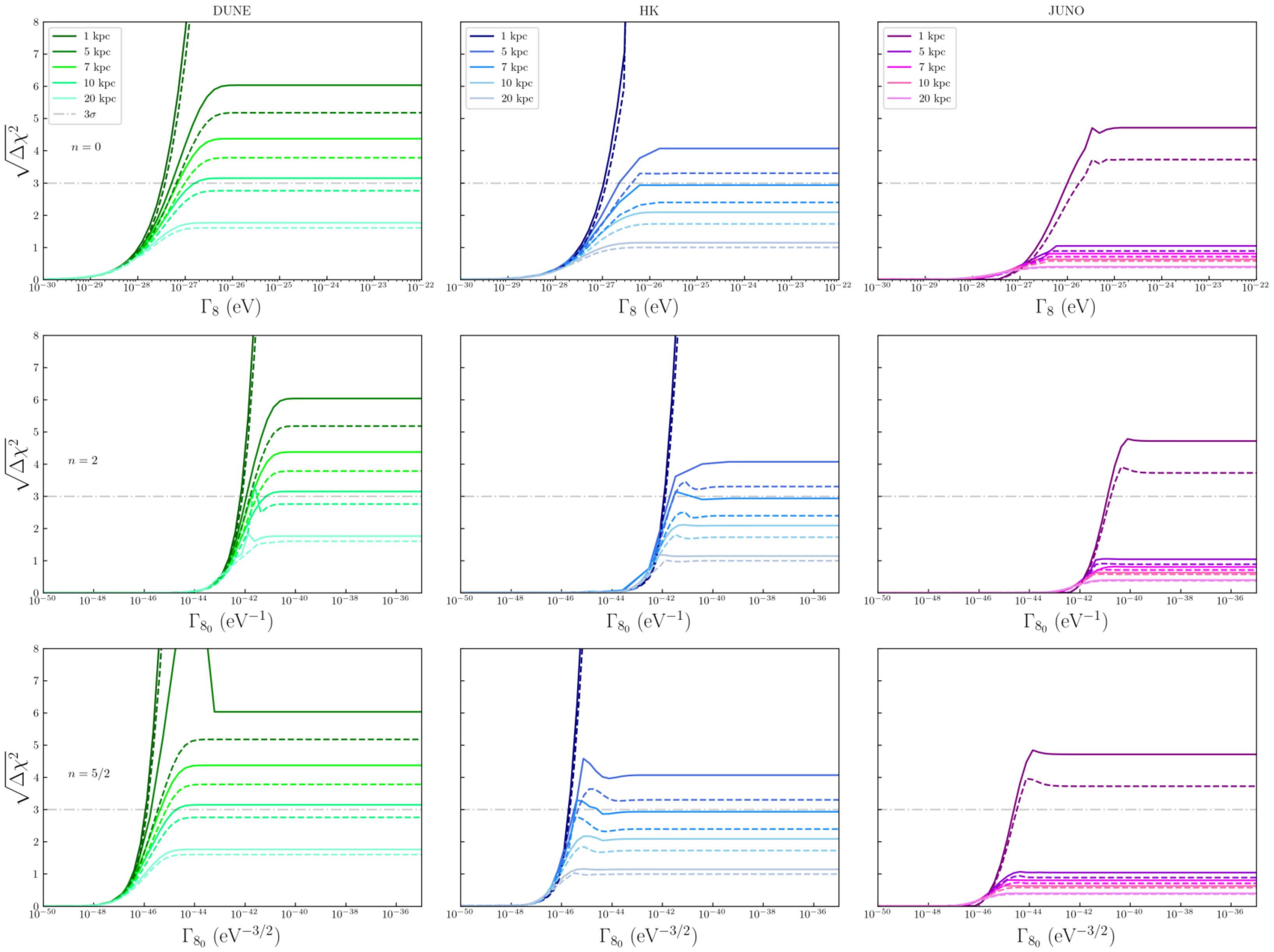
Grazie mille!

CAPES

Backup


DUNE
HK
JUNO
NH
IH
$\Gamma_8 = 10^{-27}$ eV, $\Gamma_3 = 4\Gamma_8$
$N_{11.2\,M_\odot}$
$N_{27\,M_\odot}$
E_ν (MeV)
E_ν (MeV)
E_ν (MeV)

NH


DUNE
HK
JUNO
1 kpc
5 kpc
7 kpc
10 kpc
20 kpc
3σ
n = 0
n = 2
n = 5/2
√Δχ²
Γ8 (eV)
Γ8₀ (eV⁻¹)
Γ8₀ (eV⁻³/²)