How long do neutrinos live and how much do they weigh?

F.Pompa, O.Mena (Eur.Phys.J.C 84 2, 134, 2024)

PLANCK2024 — 06/06/2024

Federica Pompa - fpompa@ific.uv.es

Neutrinos in the Standard Model

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1 Weakly interacting particles

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2 Appearing in three flavors, determined by the outgoing lepton produced by their interactions

ν_e ν_μ ν_τ

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3. Electrically neutral

Neutrinos in the Standard Model

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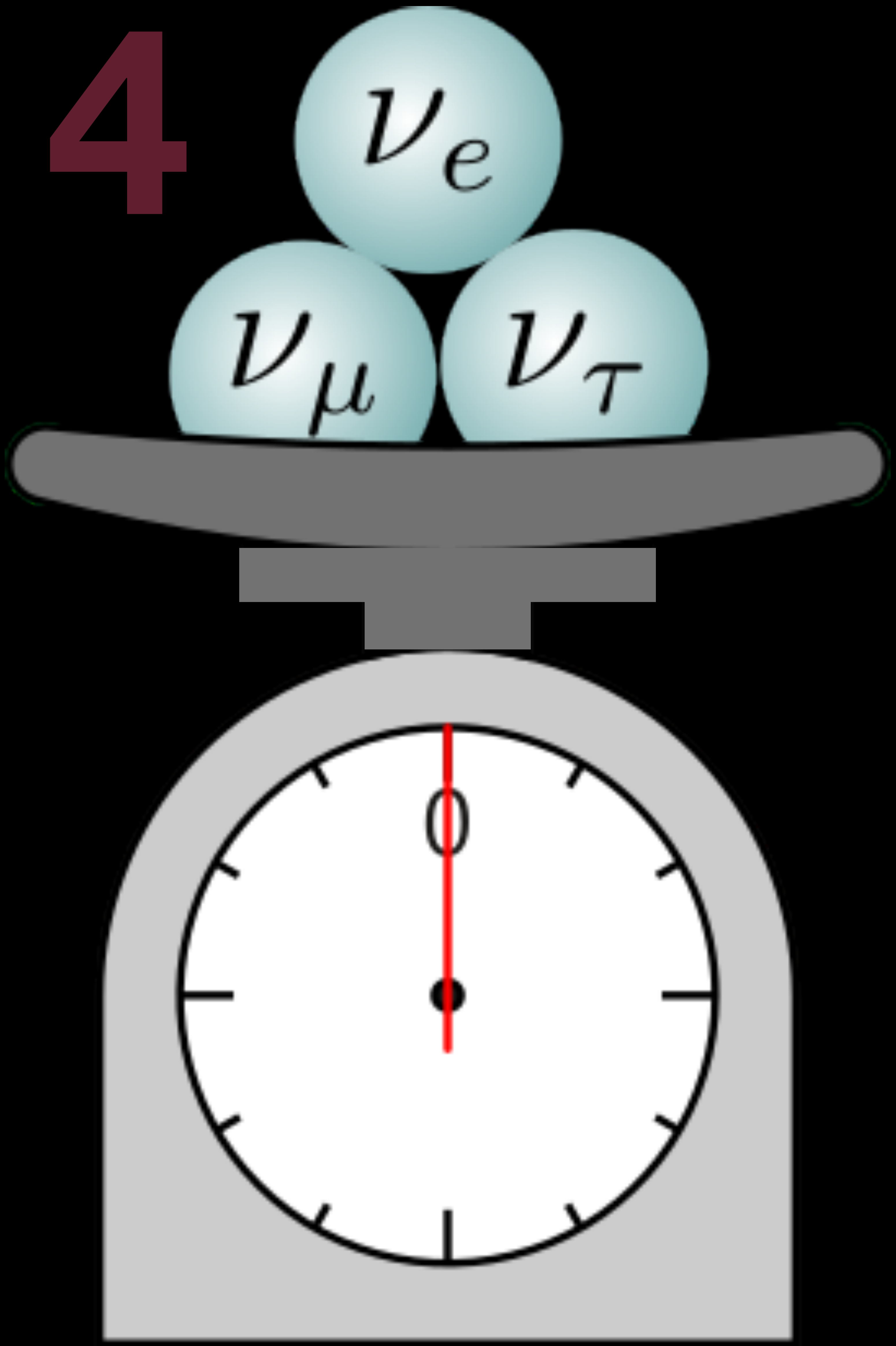
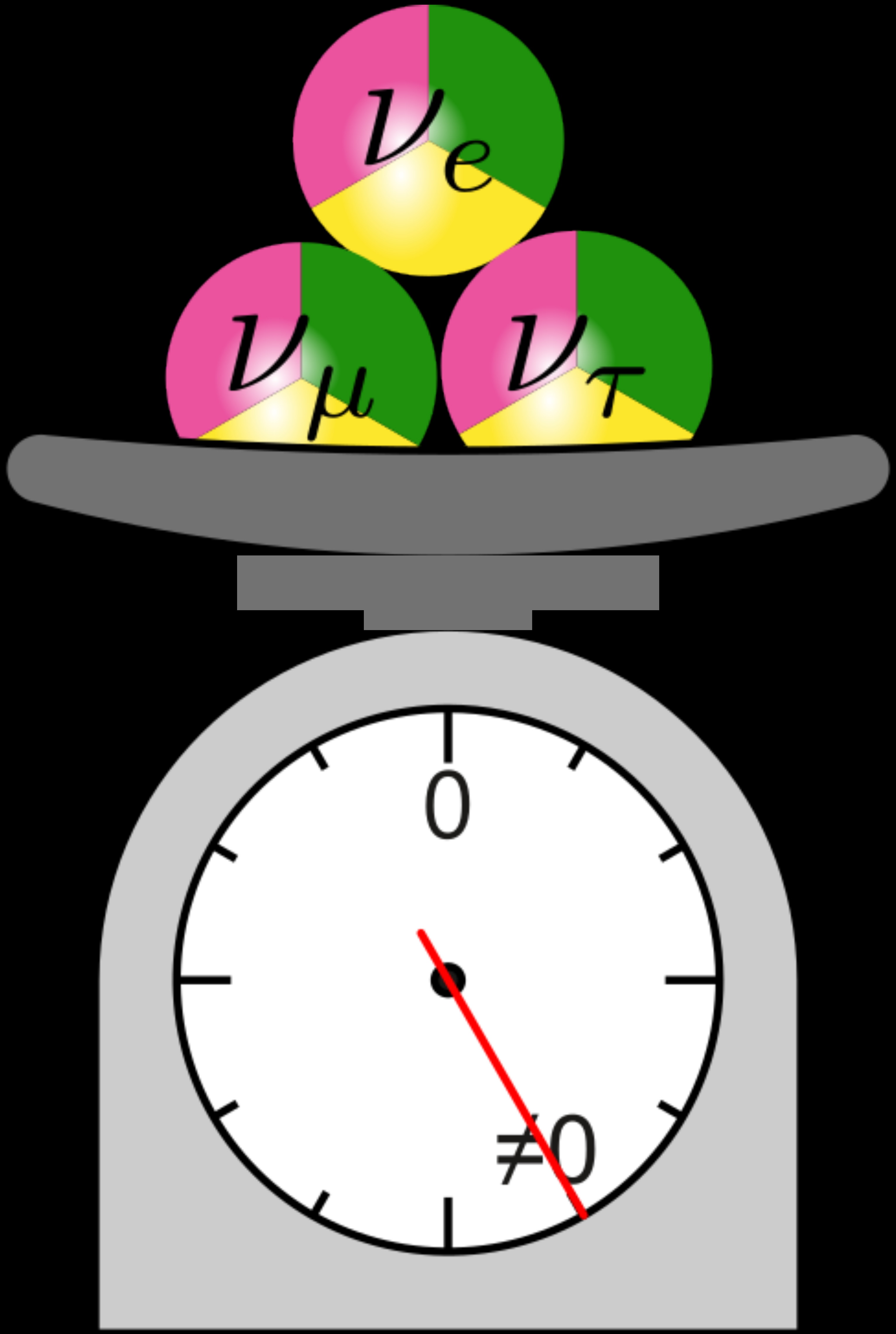
2 Appearing in three flavors, determined by the outgoing lepton produced by their interactions

3 Electrically neutral

4



Neutrinos have mass!



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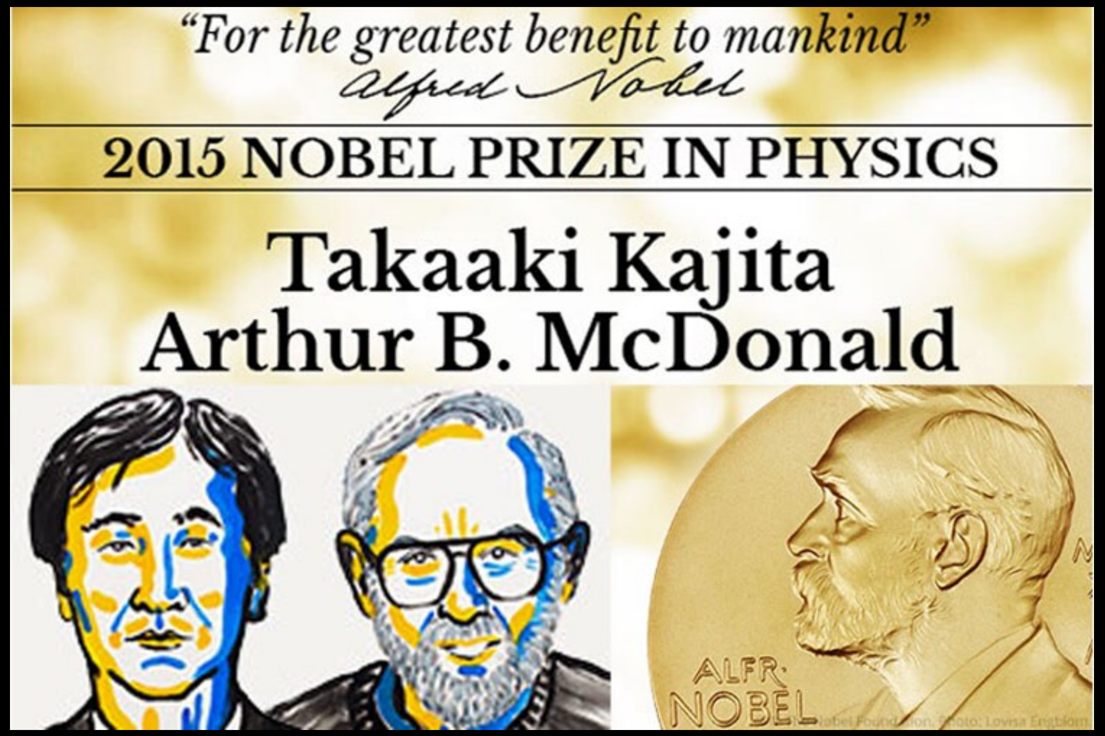


"For the greatest benefit to mankind"
Alfred Nobel

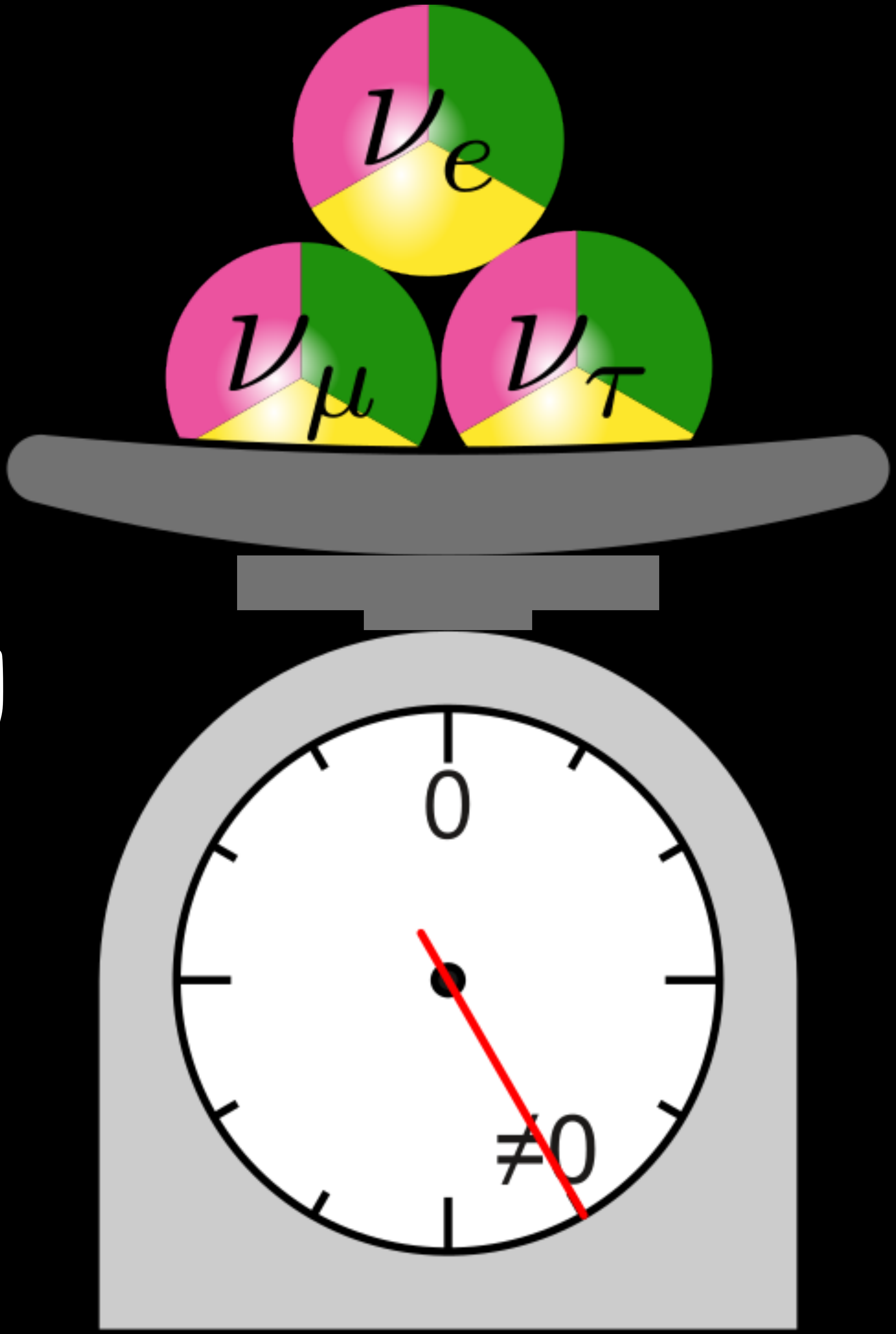
2015 NOBEL PRIZE IN PHYSICS

Takaaki Kajita
Arthur B. McDonald

"For the discovery of neutrino oscillations, which shows that neutrinos have mass"

$$\nu_\alpha = \sum_{i=1}^{3} U_{\alpha i}\, \nu_i$$

$$P_{\nu_\alpha \to \nu_\beta} = \sin^2(2\vartheta)\, \sin^2\!\left(\frac{\Delta m^2 L}{4E}\right)$$



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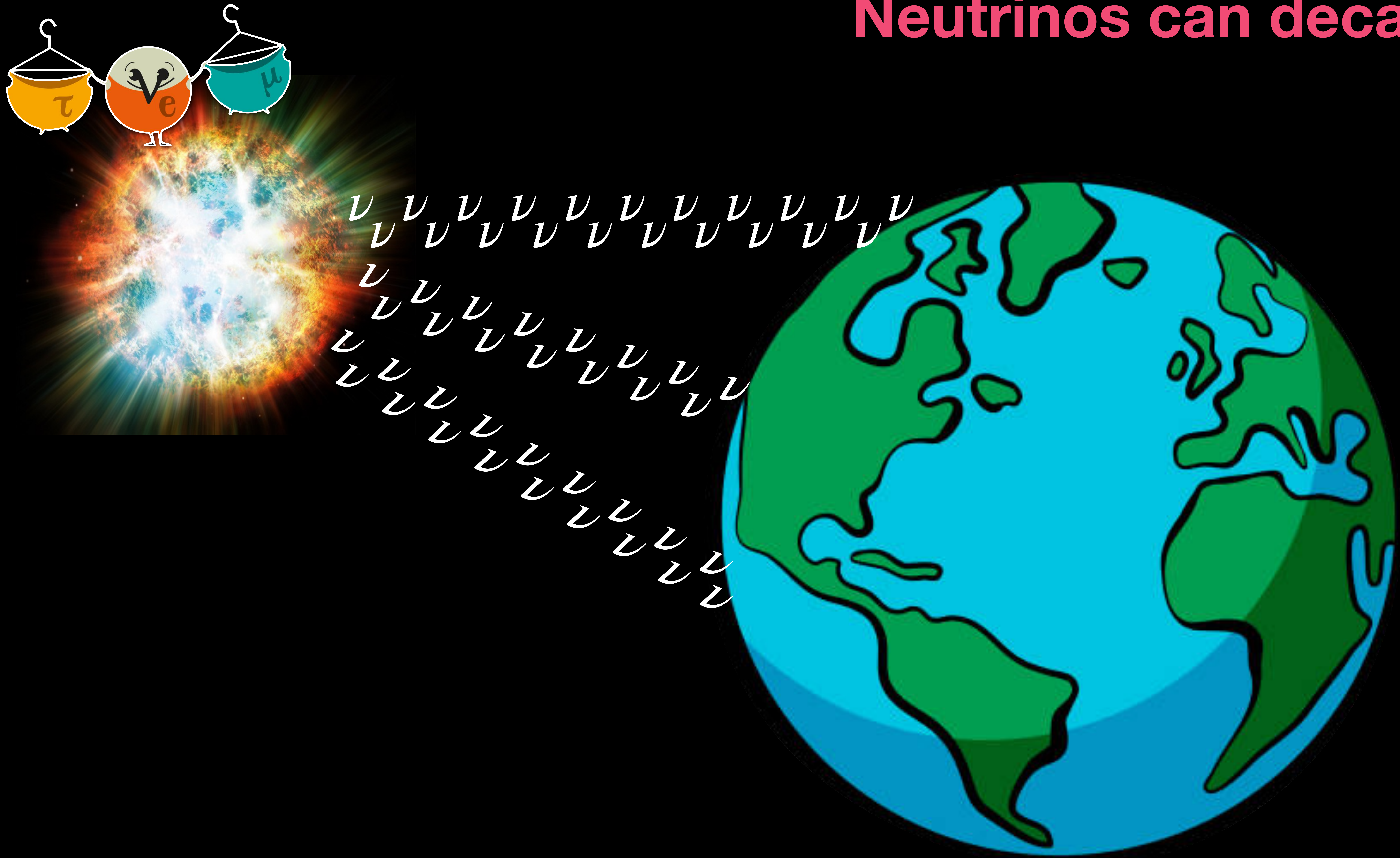

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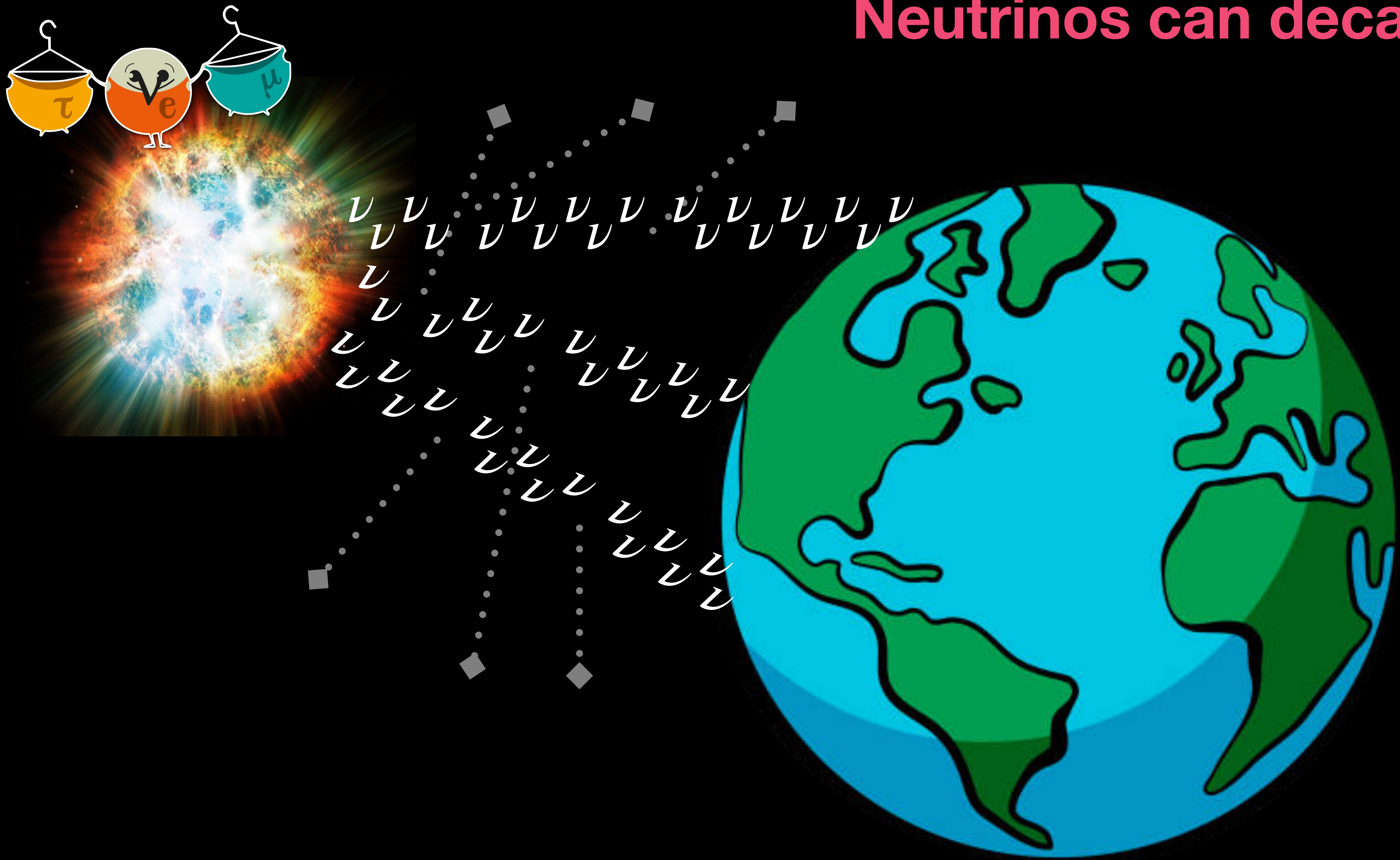


Neutrino mass

From cosmology:

DESI Collaboration (2024)

$\sum m_\nu < 0.072$ eV (95% C.L.)

From kinematic measurements:

KATRIN Collaboration (2021)

KATRIN $\Rightarrow m_\beta < 0.8$ eV (90% C.L.)

From $0\nu\beta\beta$ measurements:

KamLAND-Zen Collaboration (2022)

KamLAND-Zen $\Rightarrow m_{\beta\beta} < 0.16$ eV (90% C.L.)

Time-of-flight constraints with Supernovae:

G.Pagliaroli,F.Rossi-Torres,F.Vissani (Astropart.Phys.Vol33,2010)

Kamiokande-II (SN1987A) $\Rightarrow m_\nu < 5.8$ eV (95% C.L.)

Neutrino lifetime

From atmospheric and long-baseline data:

M.C.Gonzalez-Garcia, M.Maltoni (Phys.Lett.B 663, 2008)

$\tau_{\nu_3}/m_{\nu_3} > 10^{-10}$ s/eV (90% CL)

From Big Bang Nucleosynthesis:

M.Escudero, M.Fairbairn (Phys.Rev.D 100, 2019)

$\tau_\nu/m_\nu > 3 \times 10^{-3}$ s/eV (95% CL)

From high-energy astrophysical IceCUBE data:

M.Bustamante, J.F.Beacom, K.Murase (Phys.Rev.D 95, 2017)

$\tau_\nu/m_\nu > 10$ s/eV (90% CL)

From Supernovae:

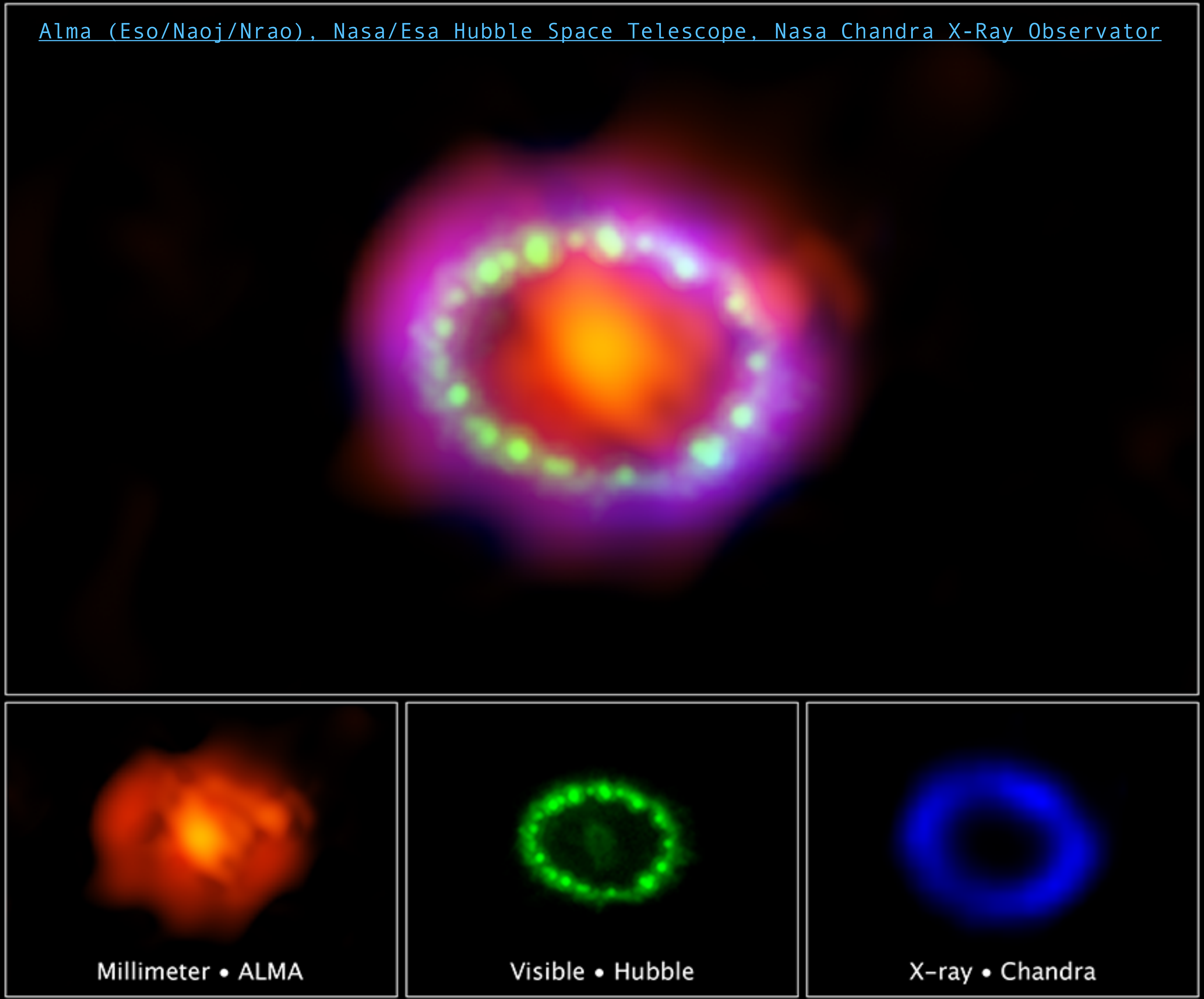
A.de Gouvea, I.Martinez-Soler, M.Sen (Phys.Rev.D 101, 2020)

Neutronization peak : $\tau_\nu/m_\nu \lesssim 10^6 - 10^7$ s/eV

J.A.Frieman, H.E.Haber, K.Freese (Phys.Lett.B 200, 1988)

SN1987A : $\tau_\nu/m_\nu > 5.7 \times 10^5$ s/eV (90% CL)

Neutrino etime


Alma (Eso/Naoj/Nrao), Nasa/Esa Hubble Space Telescope, Nasa Chandra X-Ray Observator

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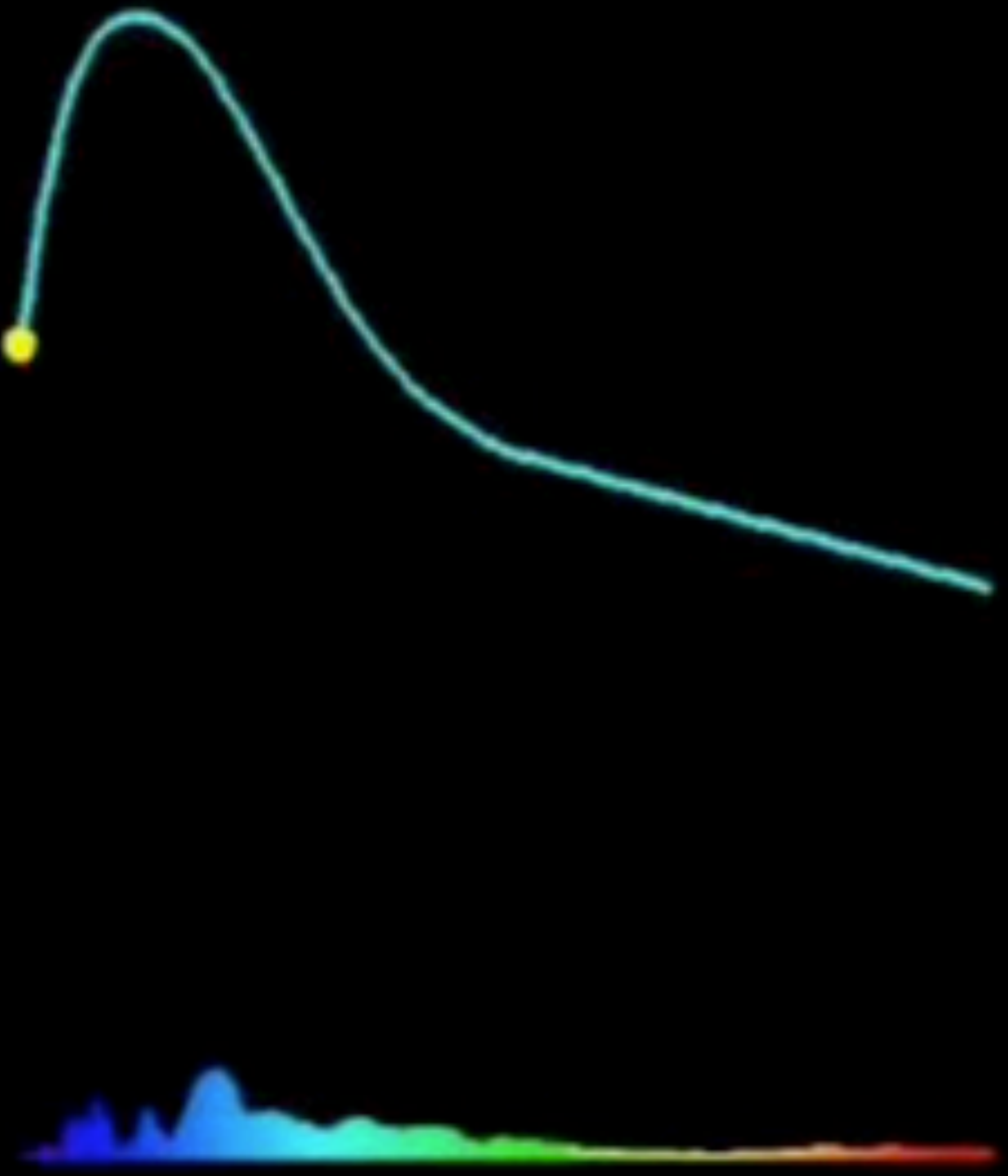
Why Supernovae?

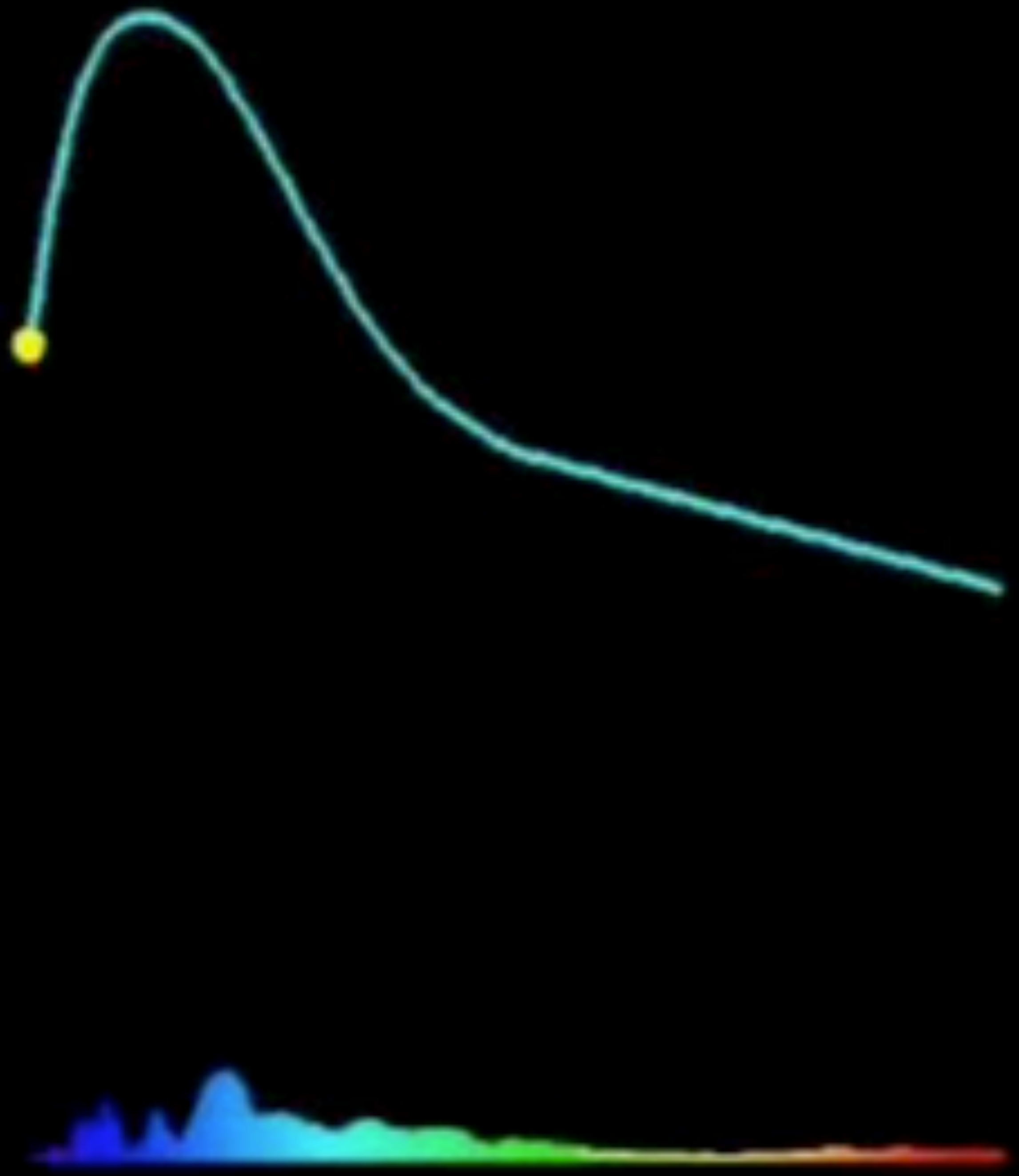


Why Supernovae?

1

Already observed!

Neutrino signal from SN1987A



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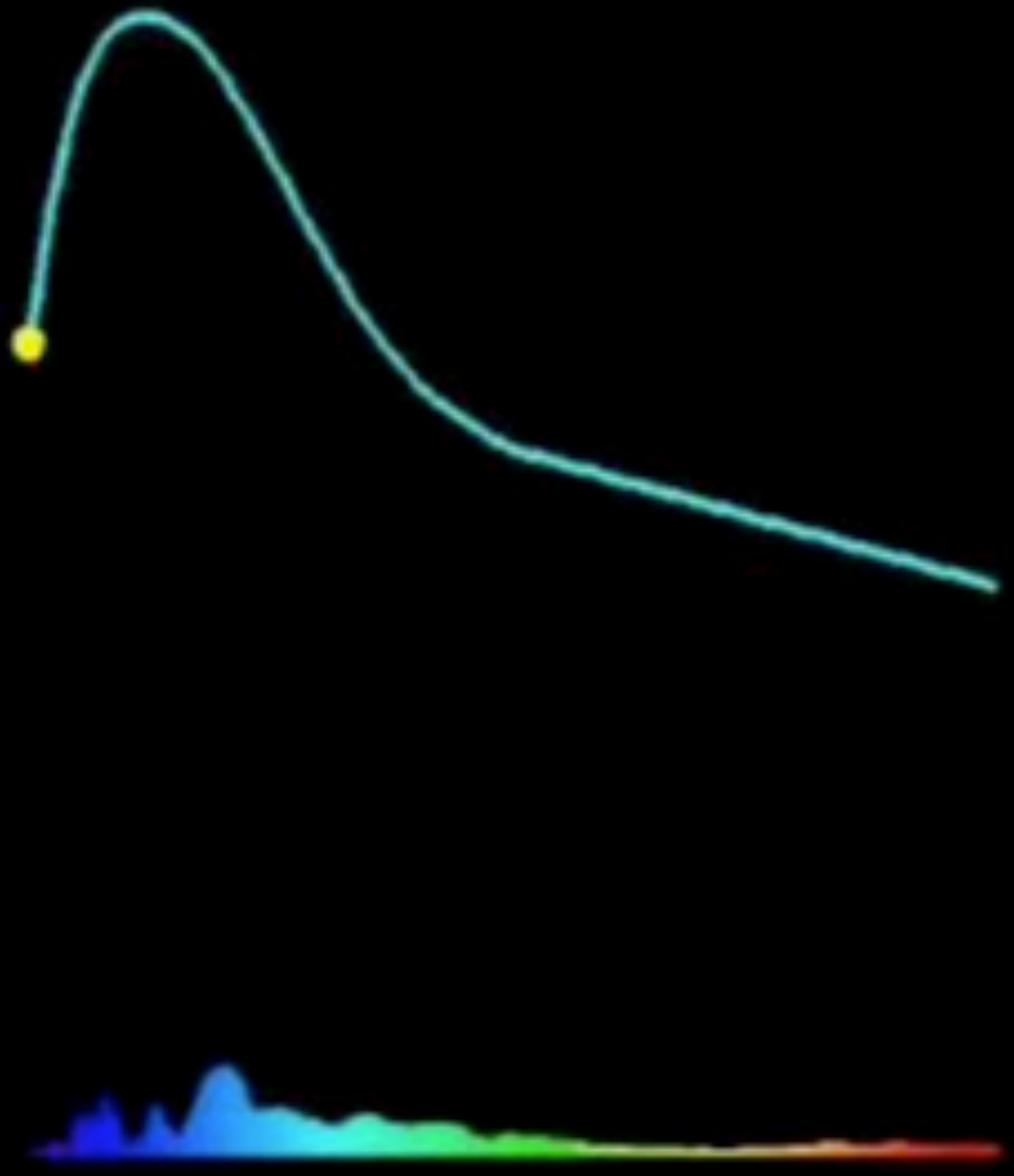
Neutrinos factories…

~99% energy released through neutrinos fluxes

… and not only!



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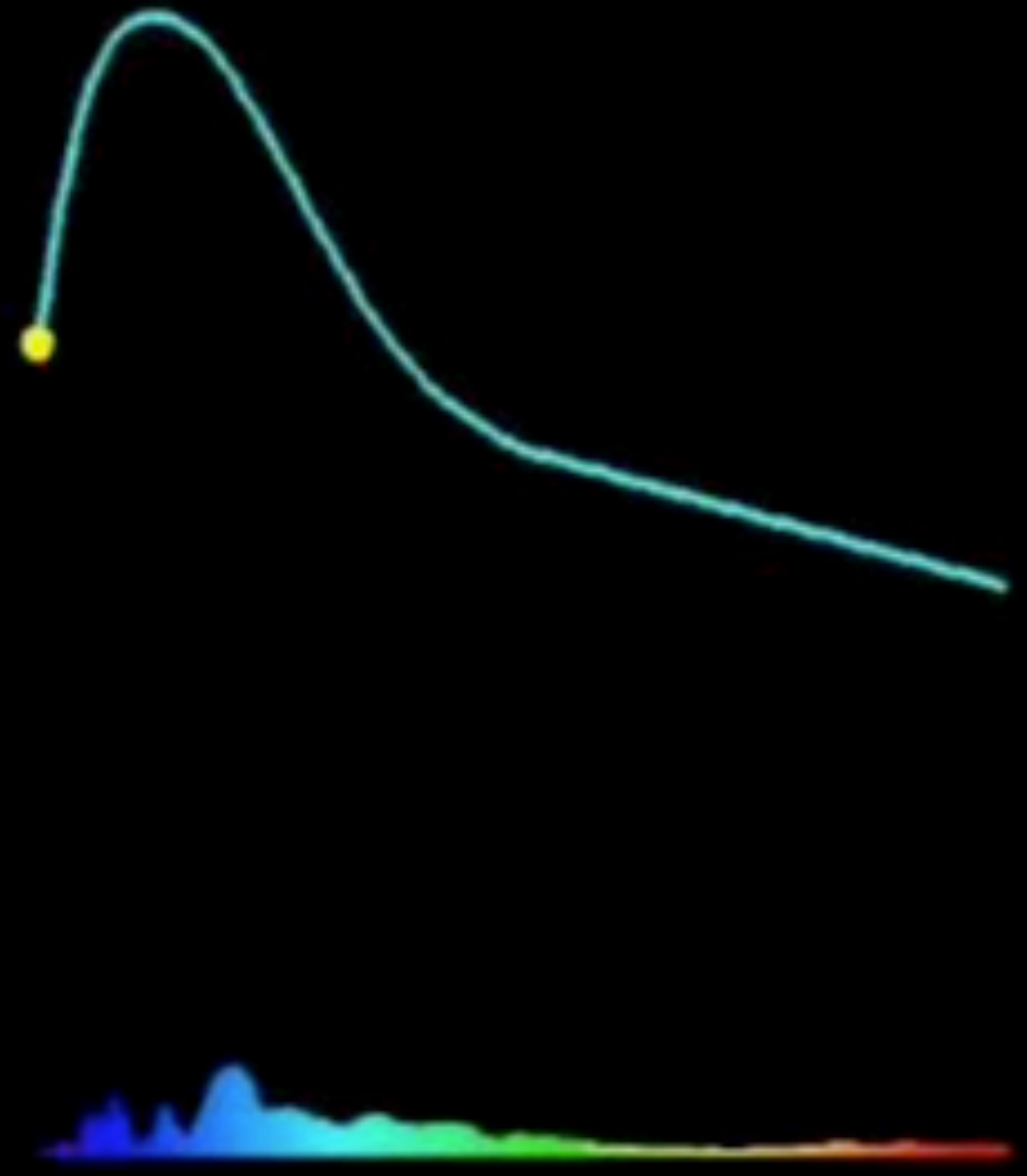

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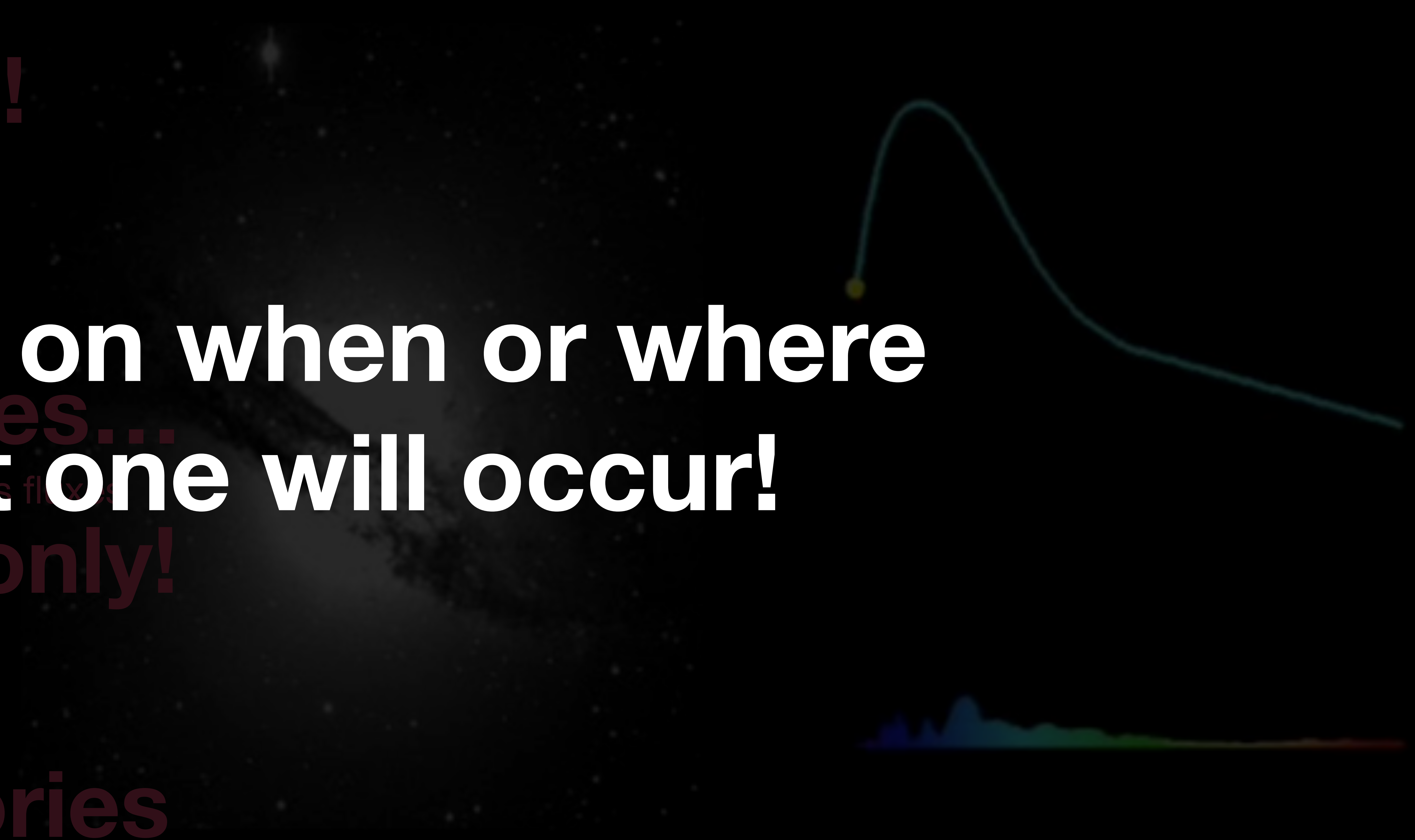
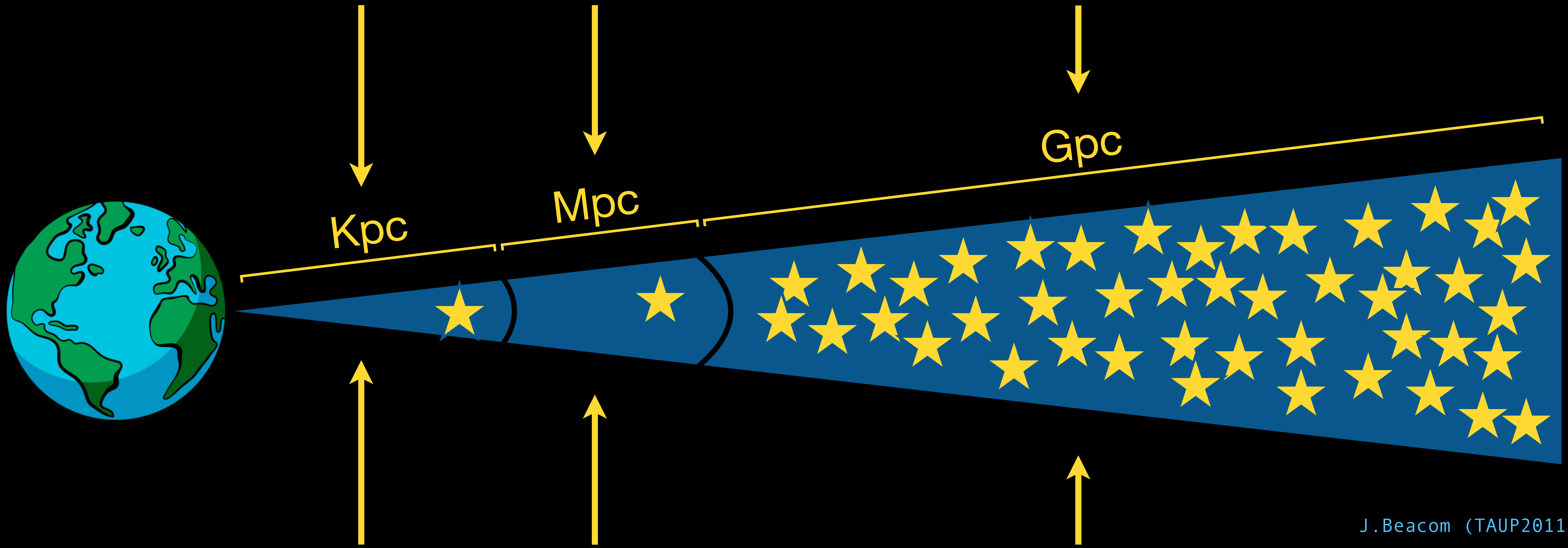


No control on when or where the next one will occur!

Supernova bursts in galaxies

Diffuse Supernova Neutrino Background

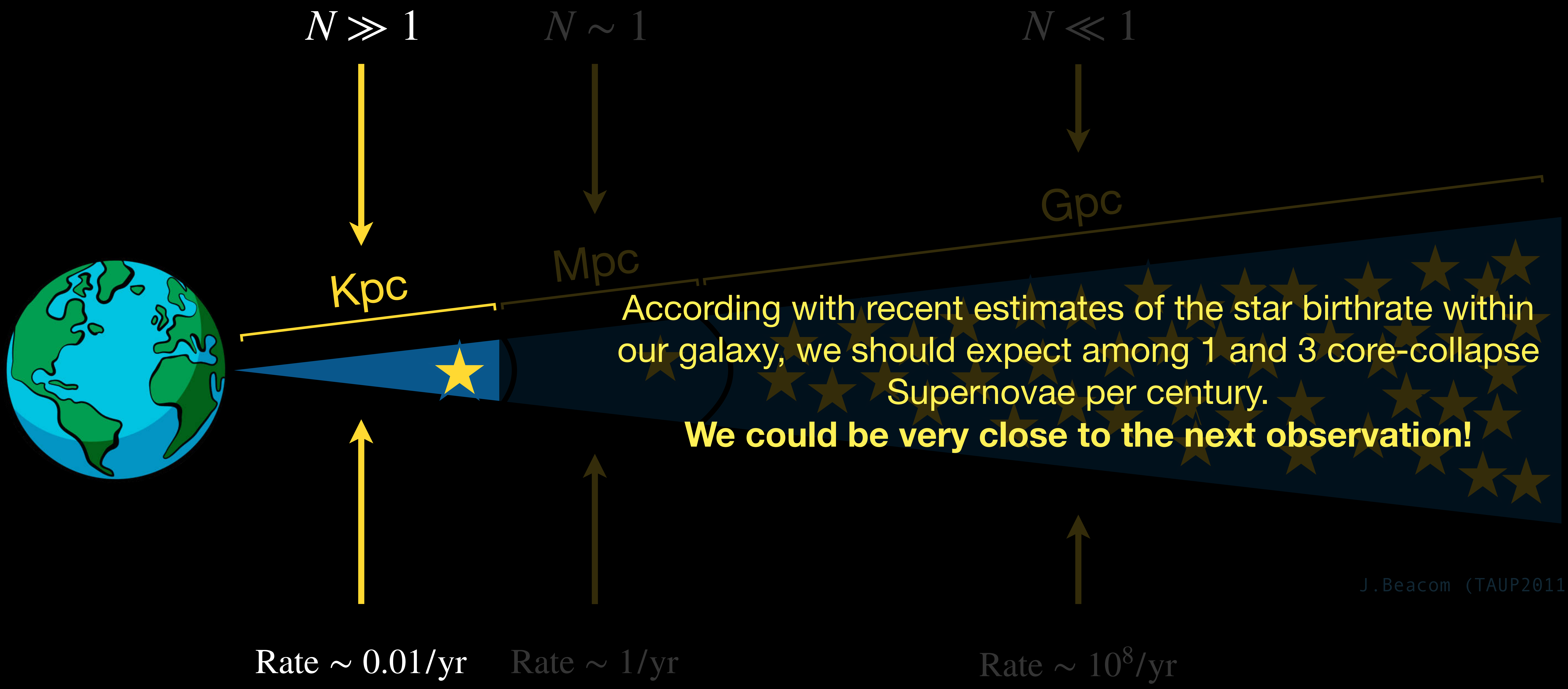
$N \gg 1$ $N \sim 1$ $N \ll 1$



Rate $\sim 0.01/\mathrm{yr}$ Rate $\sim 1/\mathrm{yr}$ Rate $\sim 10^8/\mathrm{yr}$

J.Beacom (TAUP2011)

Supernova bursts in **near** galaxies Diffuse Supernova Neutrino Background



$N \gg 1$ $N \sim 1$ $N \ll 1$

Kpc

Mpc

Gpc

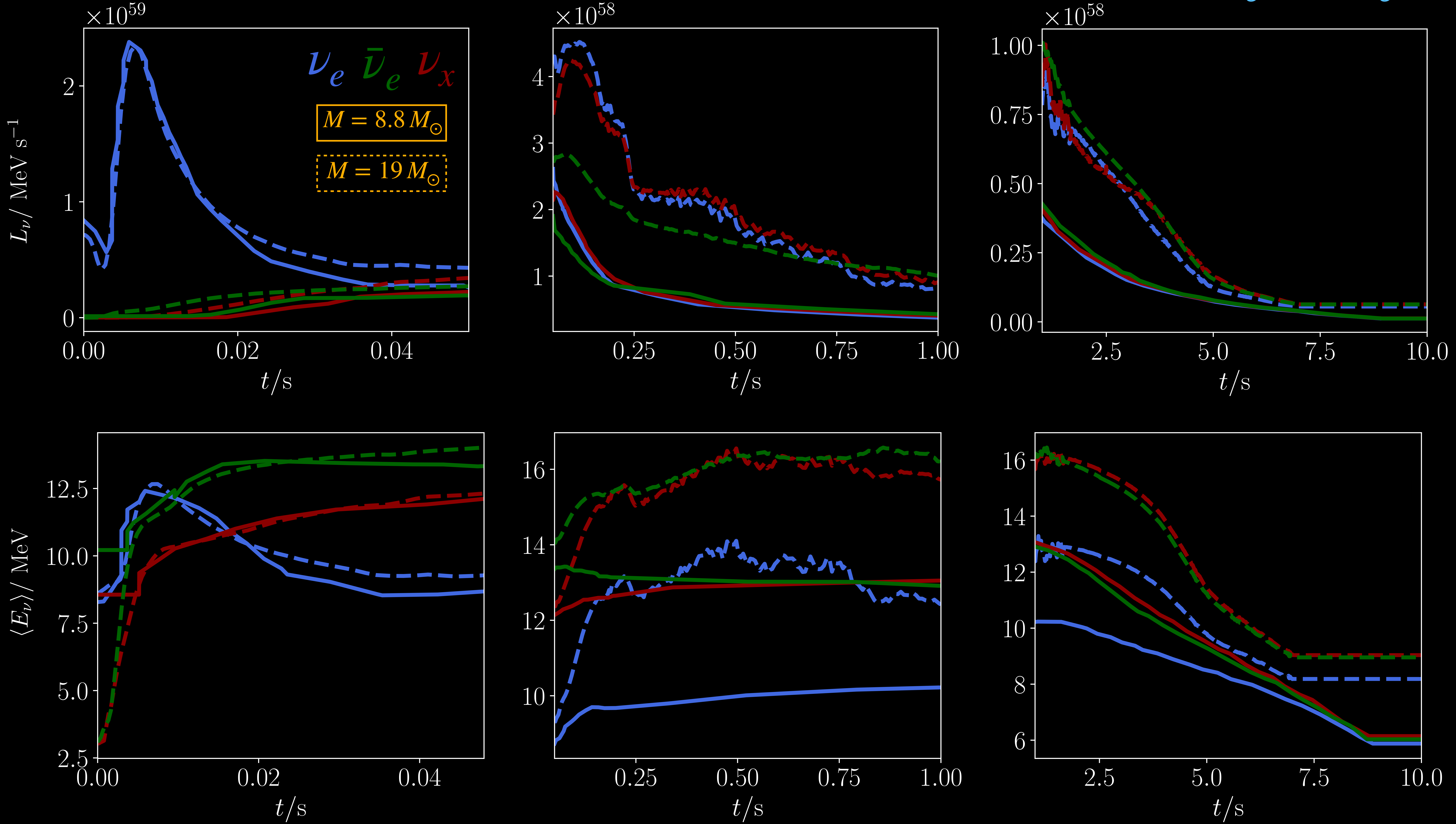
According with recent estimates of the star birthrate within our galaxy, we should expect among 1 and 3 core-collapse Supernovae per century.

We could be very close to the next observation!

Rate $\sim 0.01/\mathrm{yr}$ Rate $\sim 1/\mathrm{yr}$ Rate $\sim 10^8/\mathrm{yr}$

J.Beacom (TAUP2011)

Garching Modeling Group

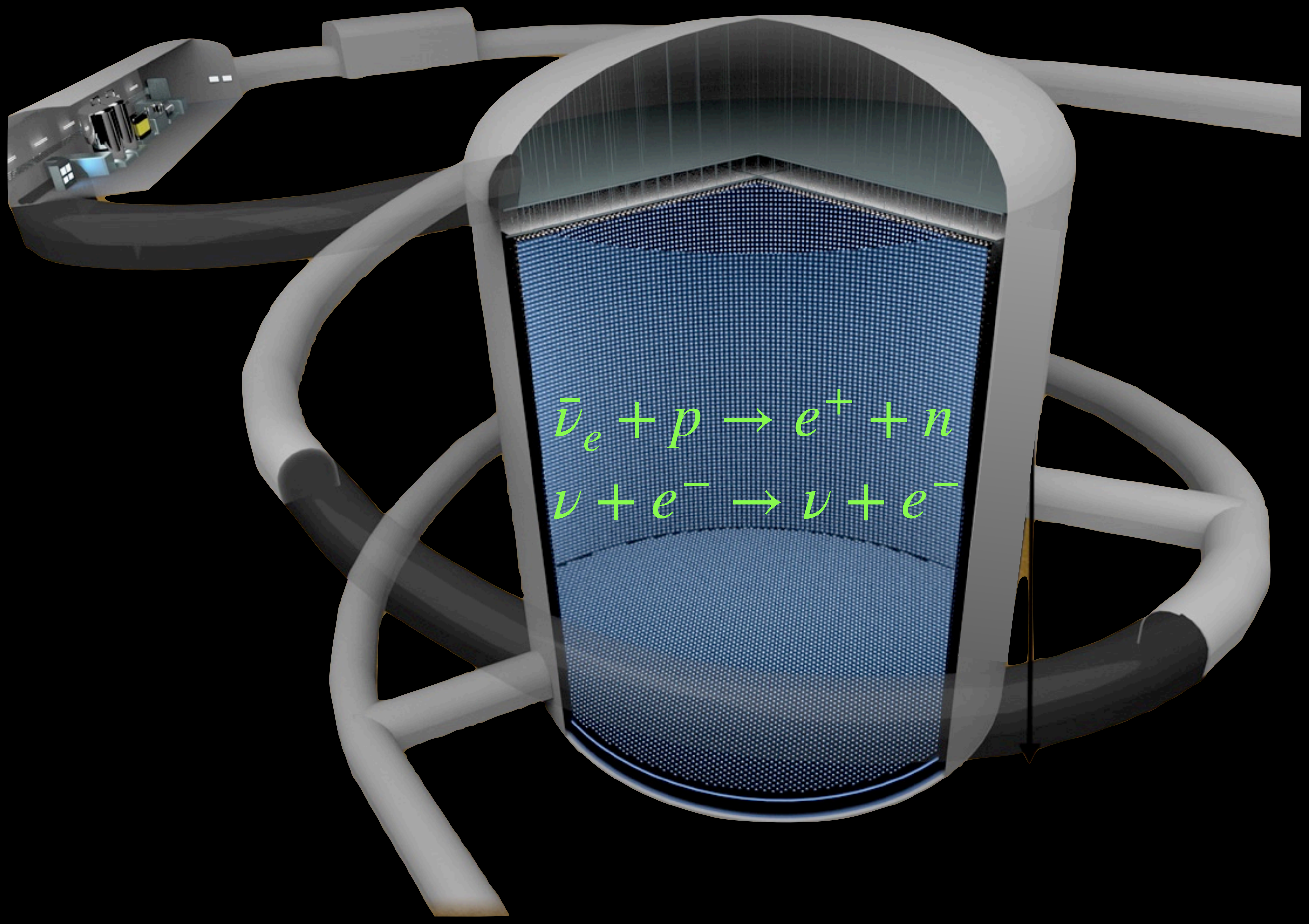


$$R(t,E) = \quad N_{\text{target}}\ \epsilon(E) \quad \sigma_{\text{sec}}(E) \quad \Phi_{\nu}(t,E)$$

$$R(t,E) = \boxed{N_{\mathrm{target}}\ \epsilon(E)}\ \boxed{\sigma_{\mathrm{sec}}(E)}\ \ \Phi_{\nu}(t,E)$$

Detector

Interaction

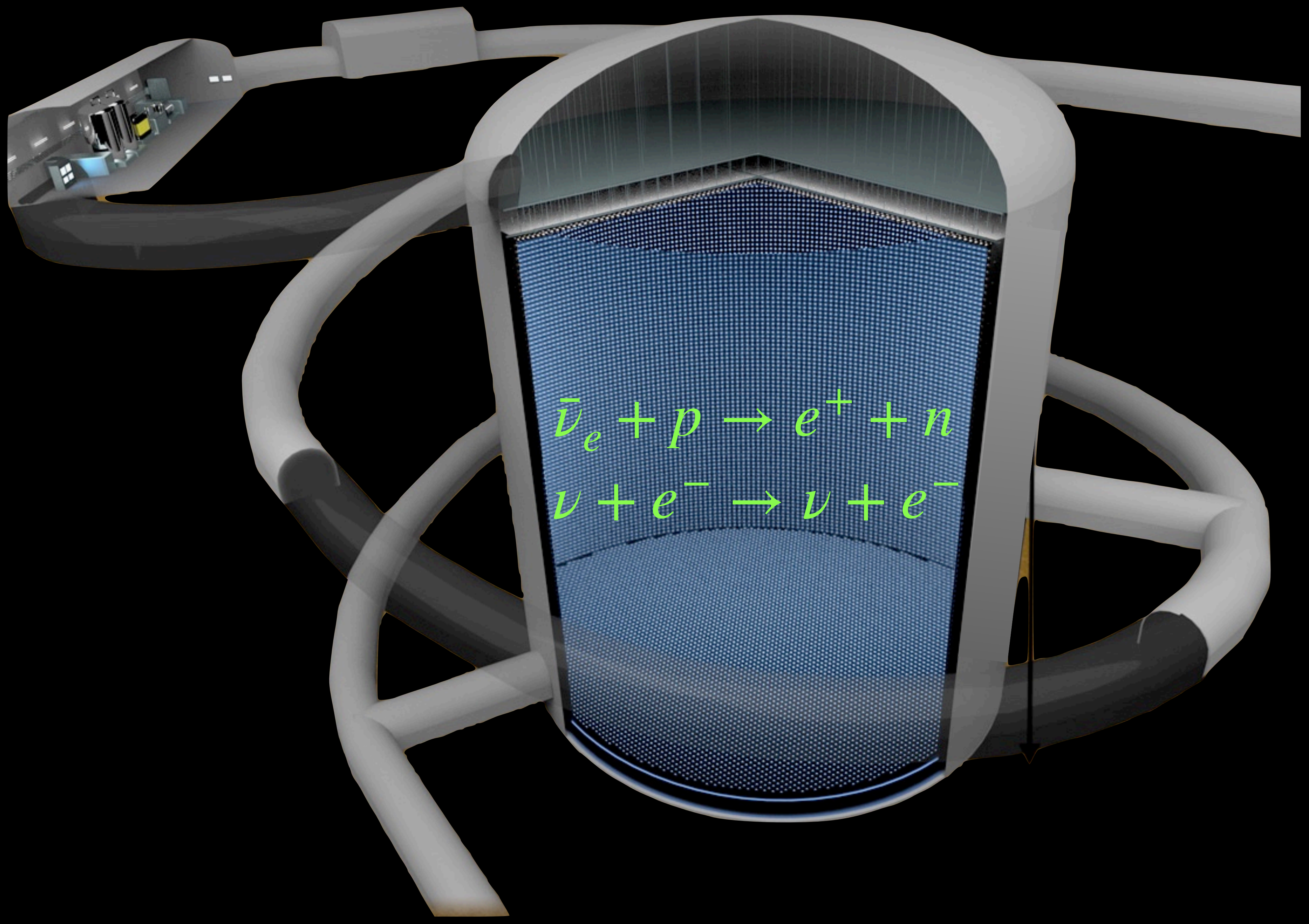


$$\bar{\nu}_e + p \rightarrow e^+ + n$$

$$\nu + e^- \rightarrow \nu + e^-$$

$$R(t,E) = \boxed{N_{\text{target}}\ \epsilon(E)}\ \boxed{\sigma_{\text{sec}}(E)}\ \boxed{\Phi_\nu(t,E)}$$

Detector **Interaction** **Source (and propagation!)**



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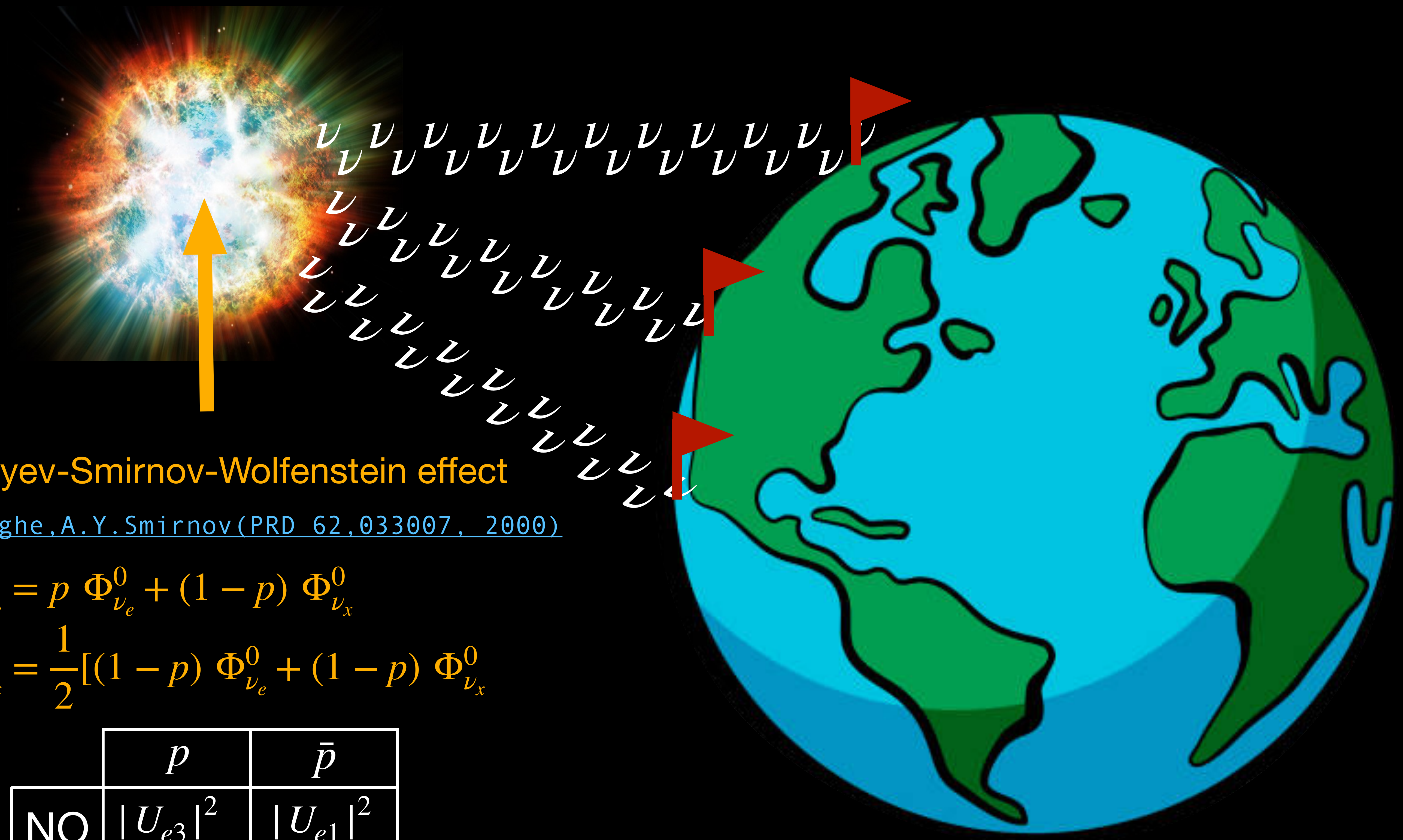


Mikheyev-Smirnov-Wolfenstein effect

A.S.Dighe,A.Y.Smirnov(PRD 62,033007, 2000)

$$\Phi_{\nu_e} = p\ \Phi^0_{\nu_e} + (1-p)\ \Phi^0_{\nu_x}$$

$$\Phi_{\nu_x} = \frac{1}{2}[(1-p)\ \Phi^0_{\nu_e} + (1-p)\ \Phi^0_{\nu_x}$$

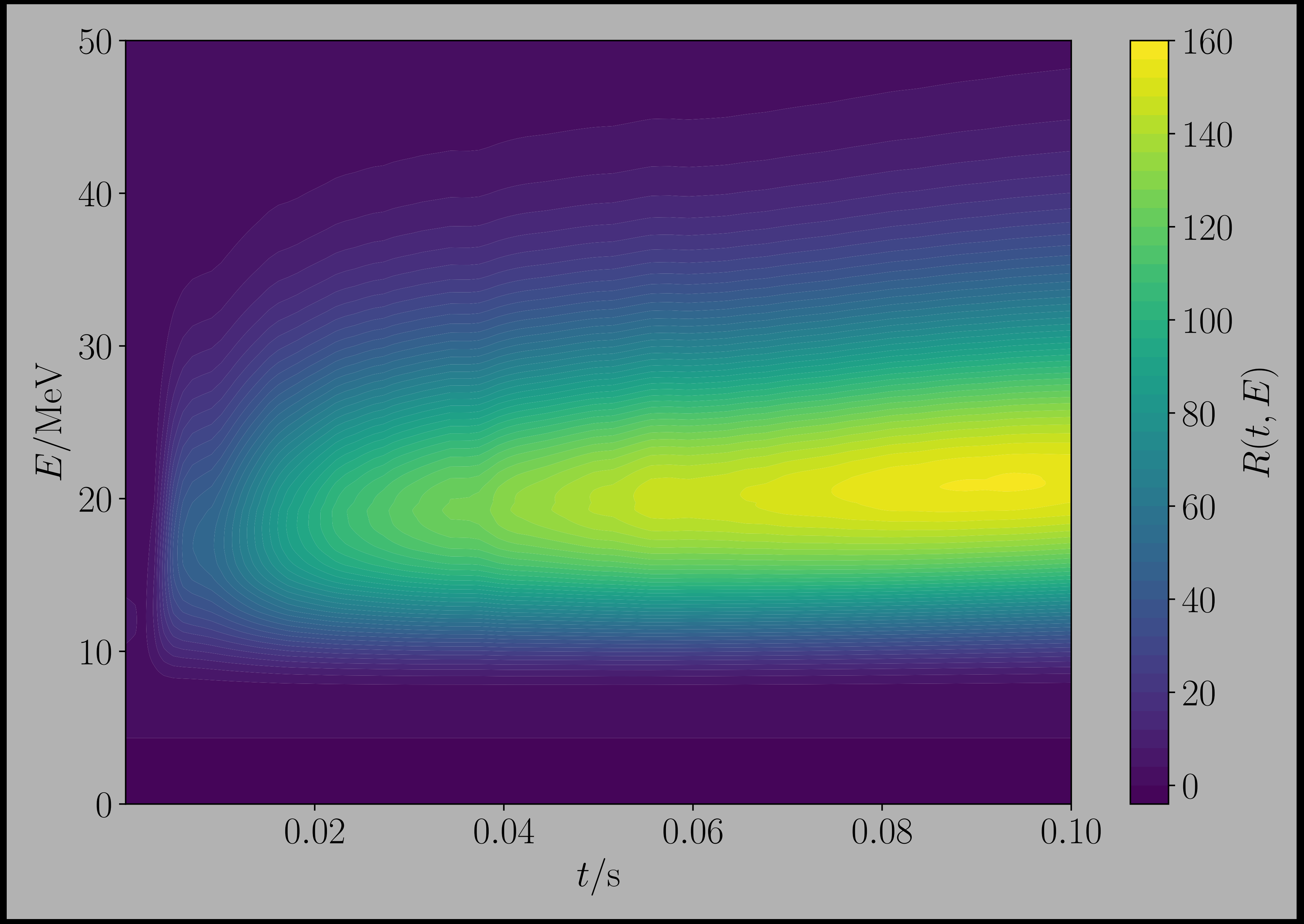
	p	$\bar{p}$
NO	$\lvert U_{e3}\rvert^2$	$\lvert U_{e1}\rvert^2$
IO	$\lvert U_{e2}\rvert^2$	$\lvert U_{e3}\rvert^2$

Effect of m_ν

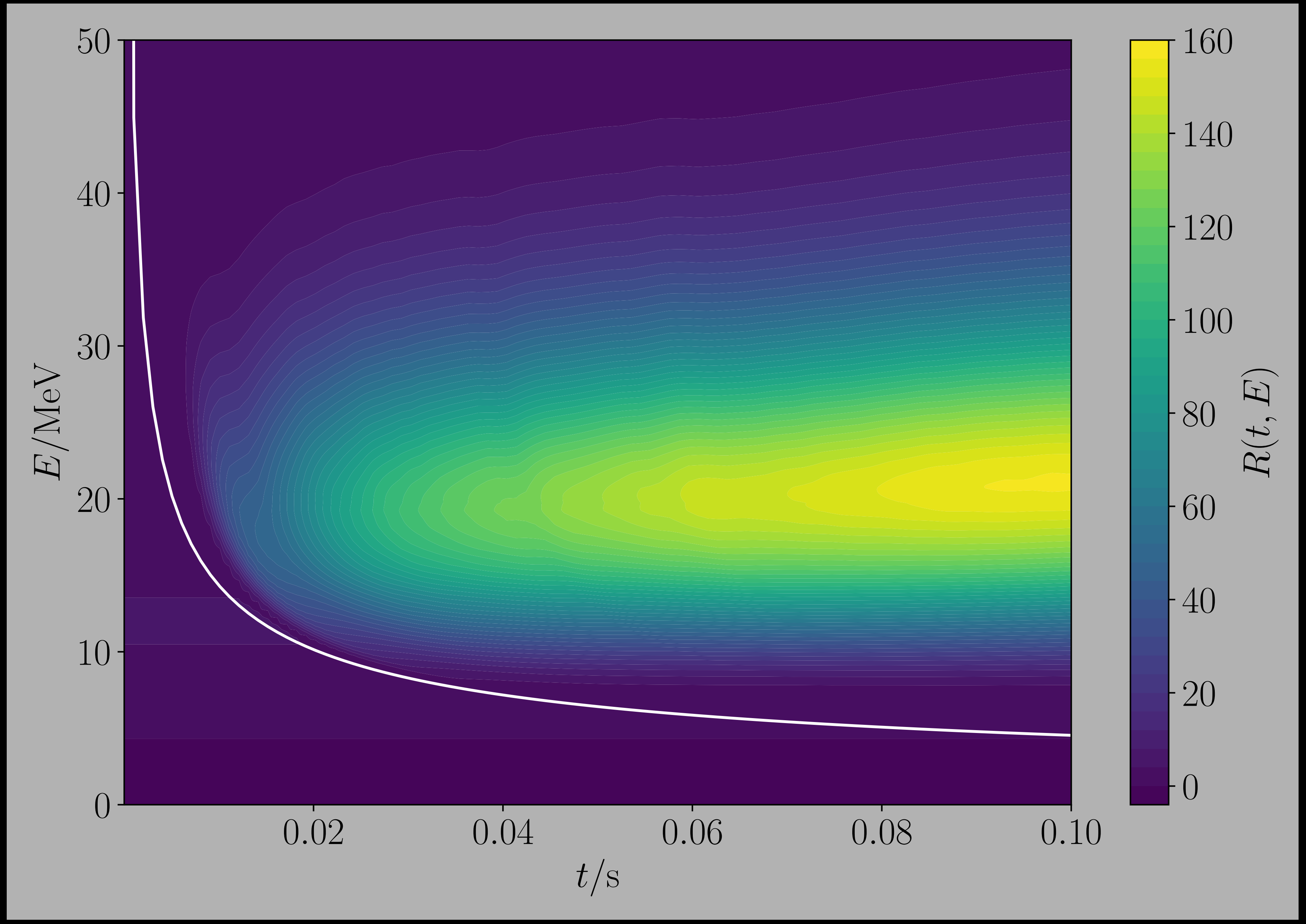
$$\Delta t_i(m_\nu) = \frac{D}{2c}\left(\frac{m_\nu}{E_i}\right)^2$$

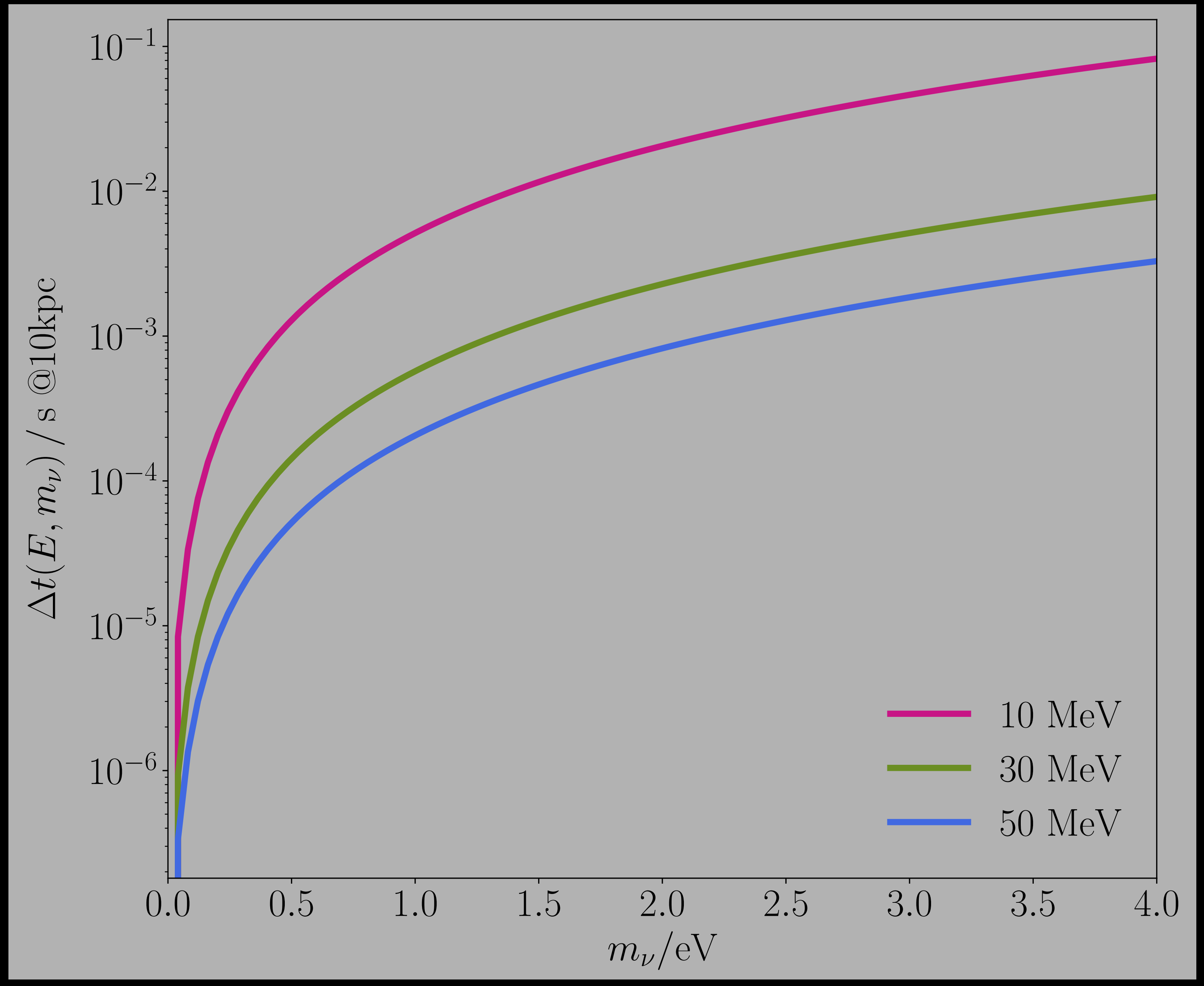
$$t_i = \delta t_i + t_{\mathrm{off}} - \Delta t_i(m_\nu)$$

$m_\nu = 0$

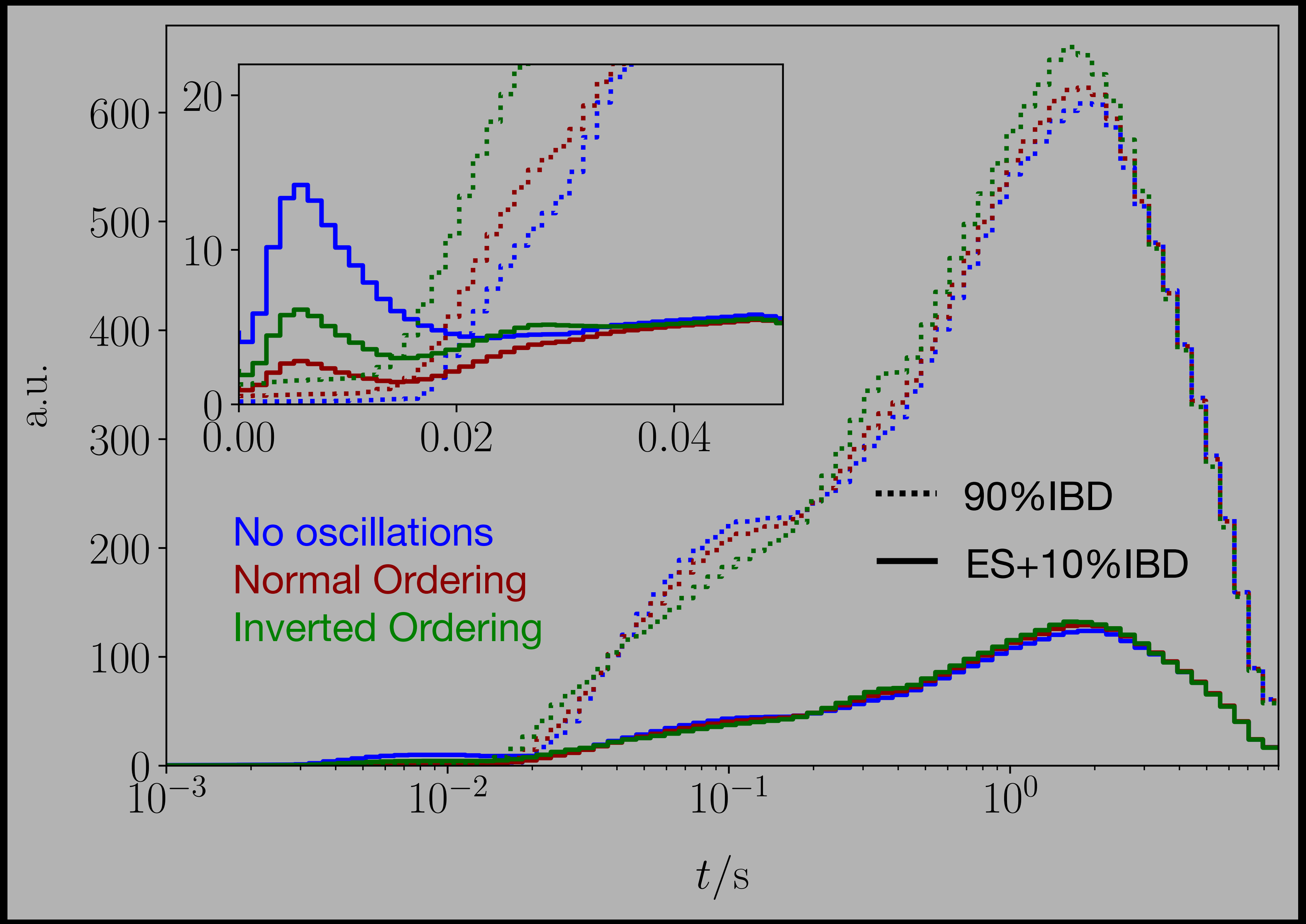


$m_\nu = 2\,\mathrm{eV}$

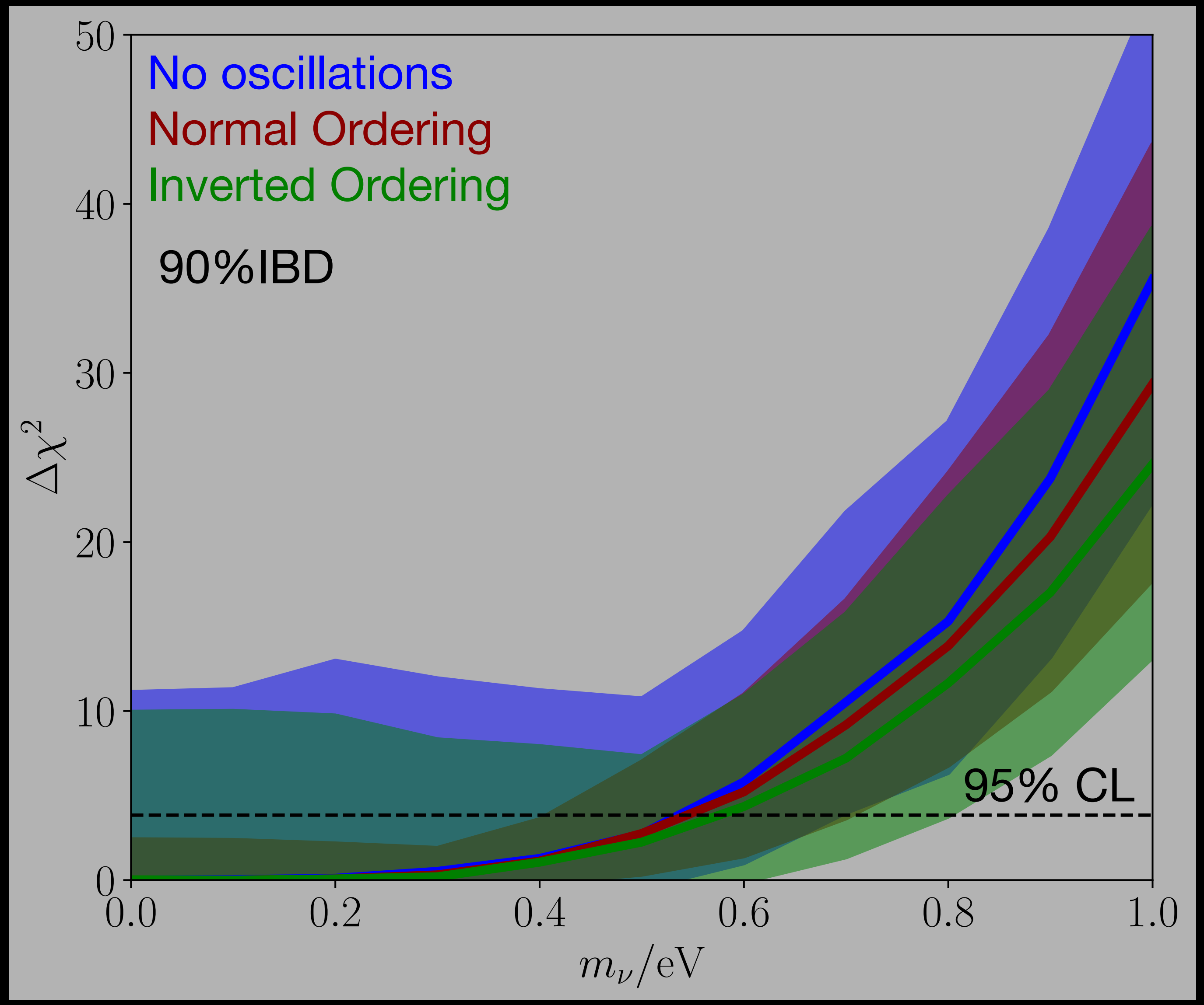




$D = 10$ kpc



$M = 8.8\,M_\odot$	10 s	50 ms
90%IBD	16003	414
ES+10%IBD	3462	249
90%IBD	16223	466
ES+10%IBD	3419	130
90%IBD	16678	573
ES+10%IBD	3491	178



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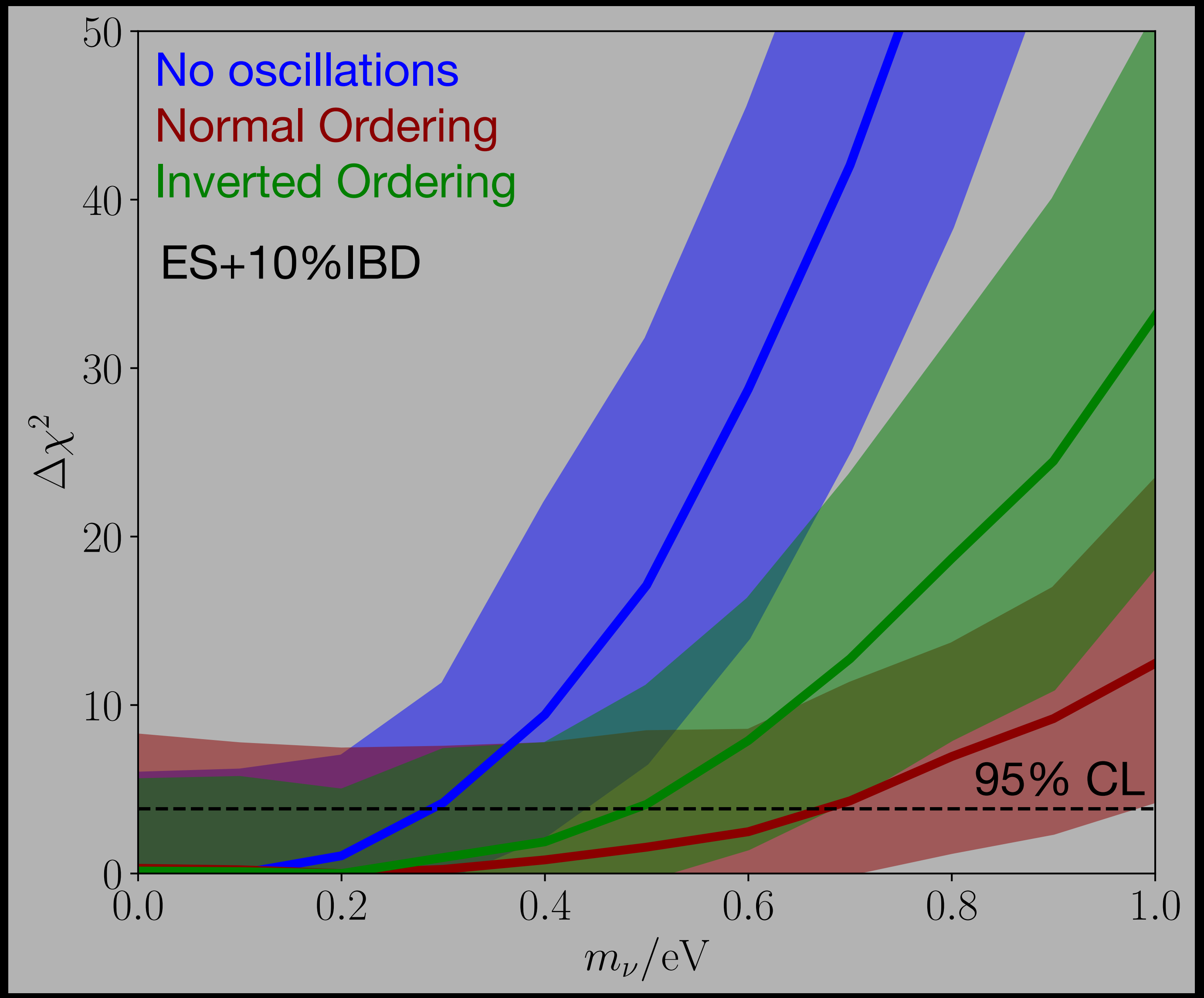

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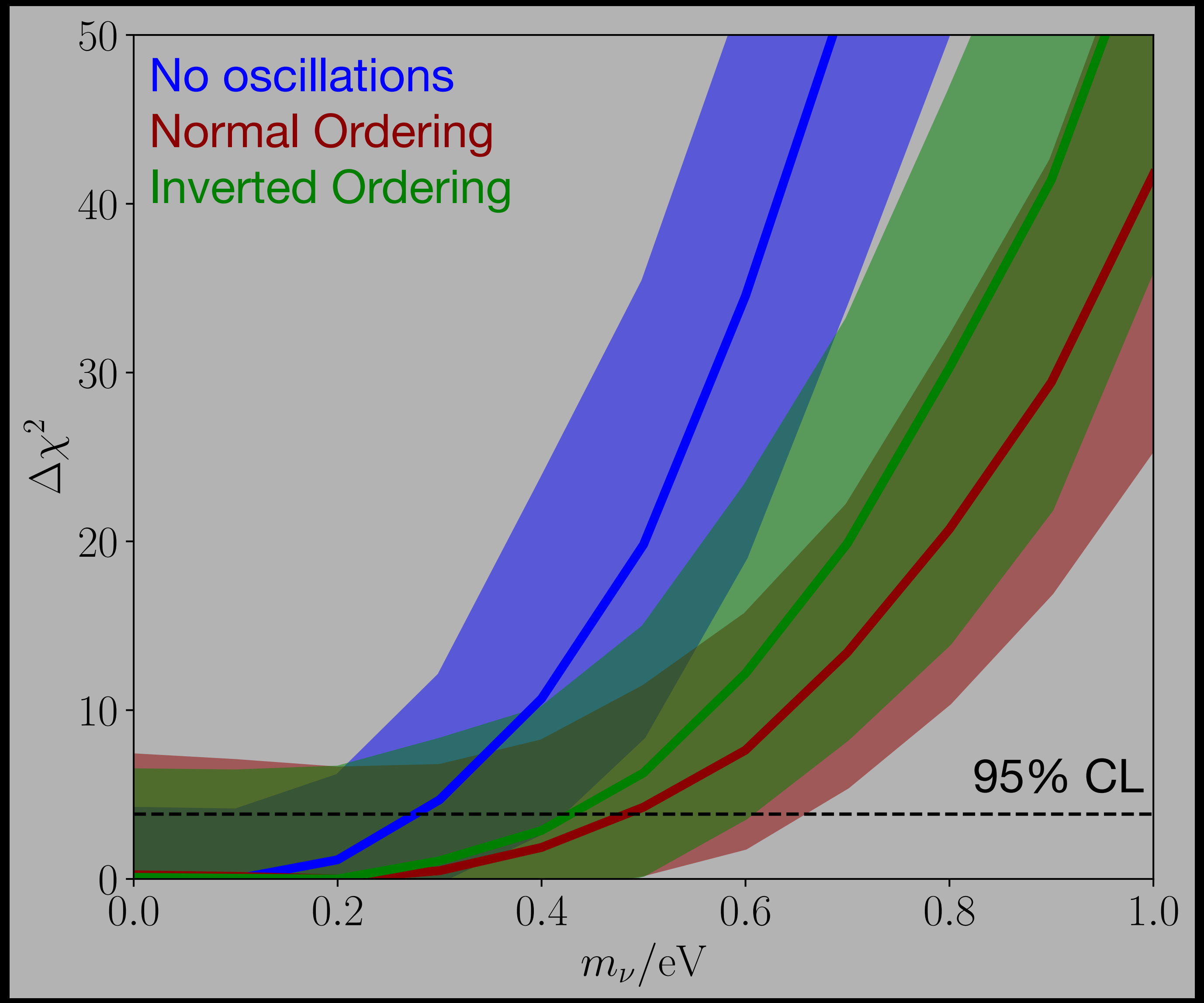
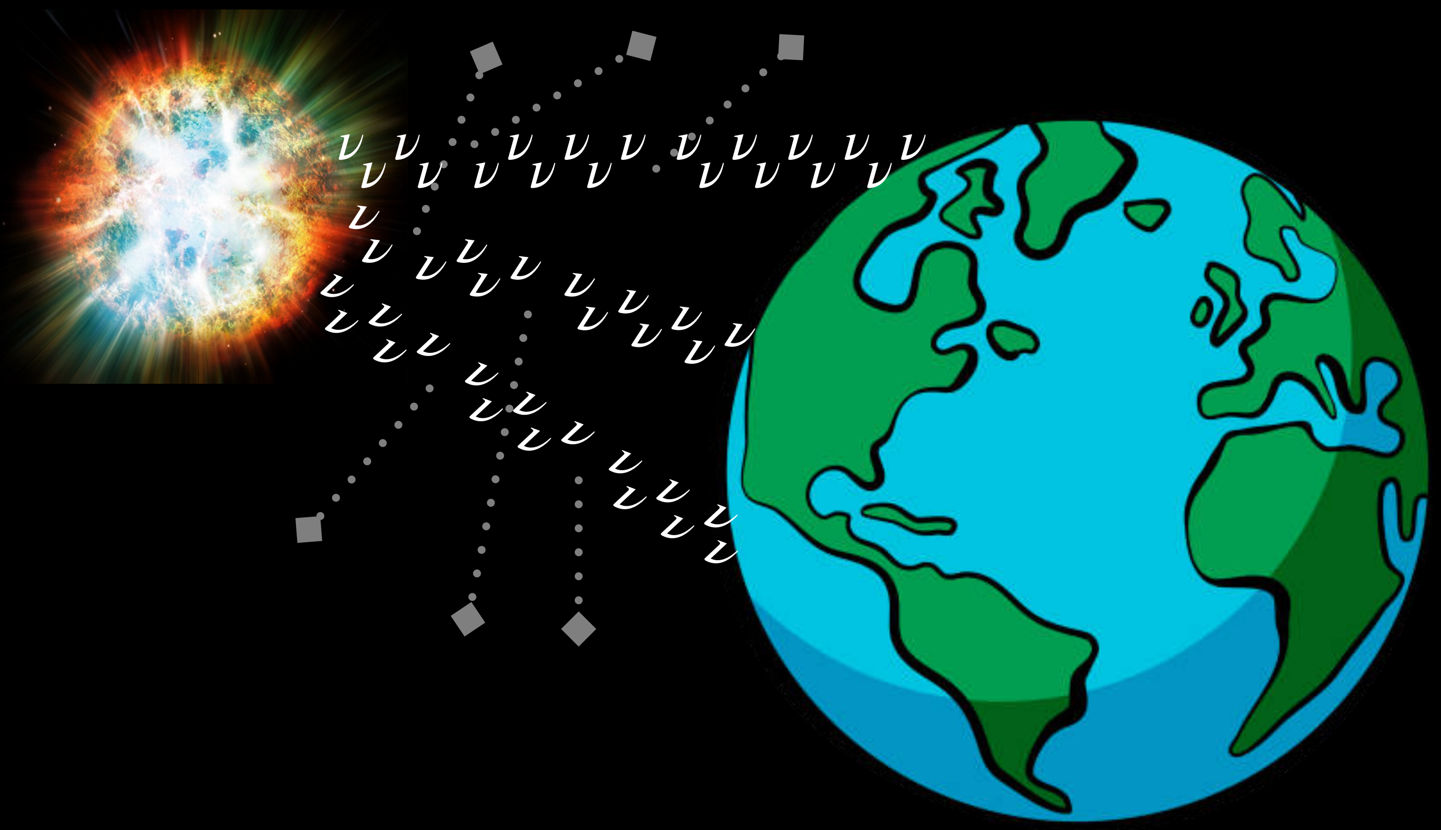


ν invisible decay

$$\Phi(E,t) \sim \boxed{\exp\left(-\frac{D\ m_{\nu_i}}{E_\nu\ \tau_{\nu_i}}\right)}\Phi_0(E,t)$$



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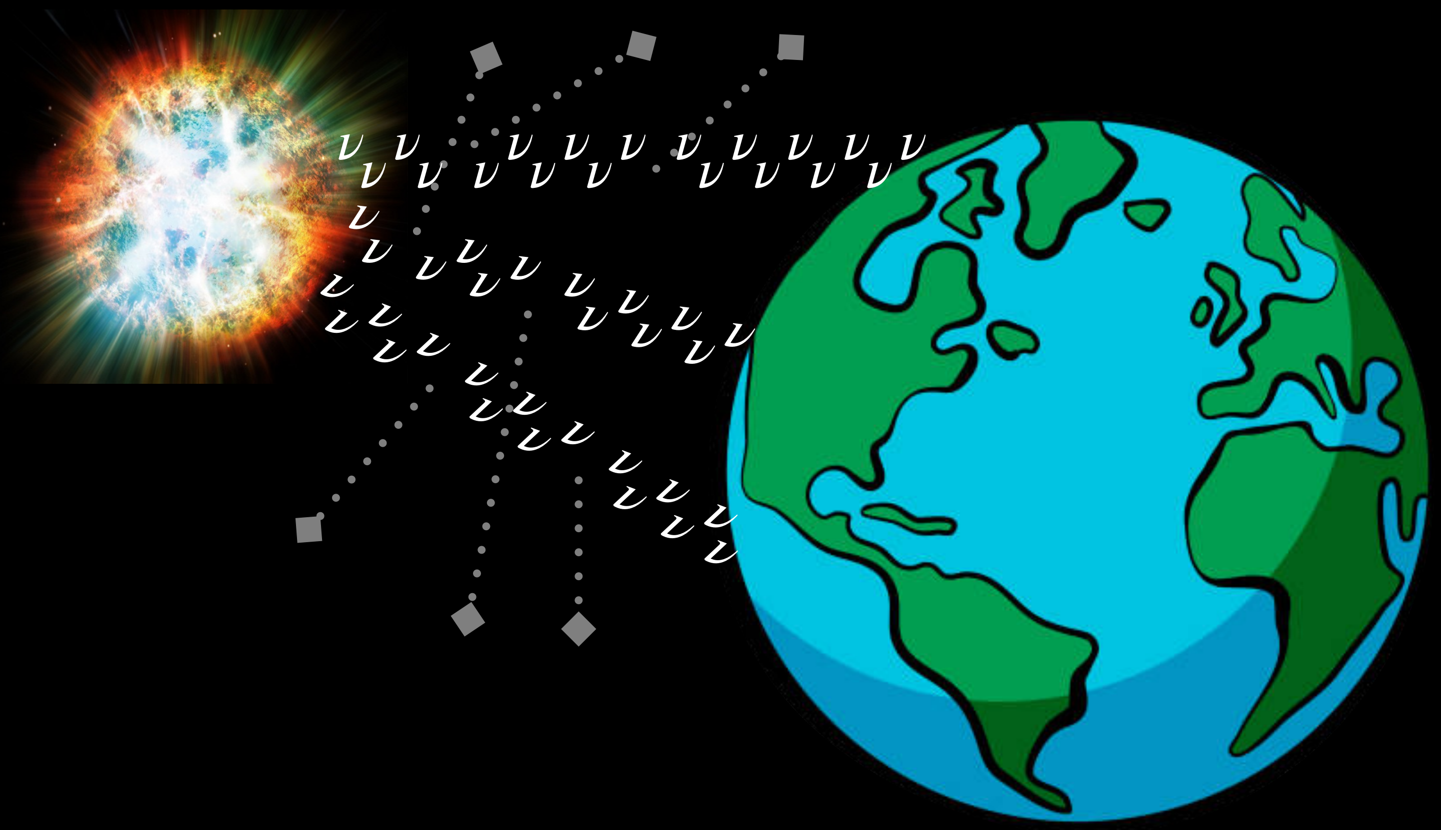

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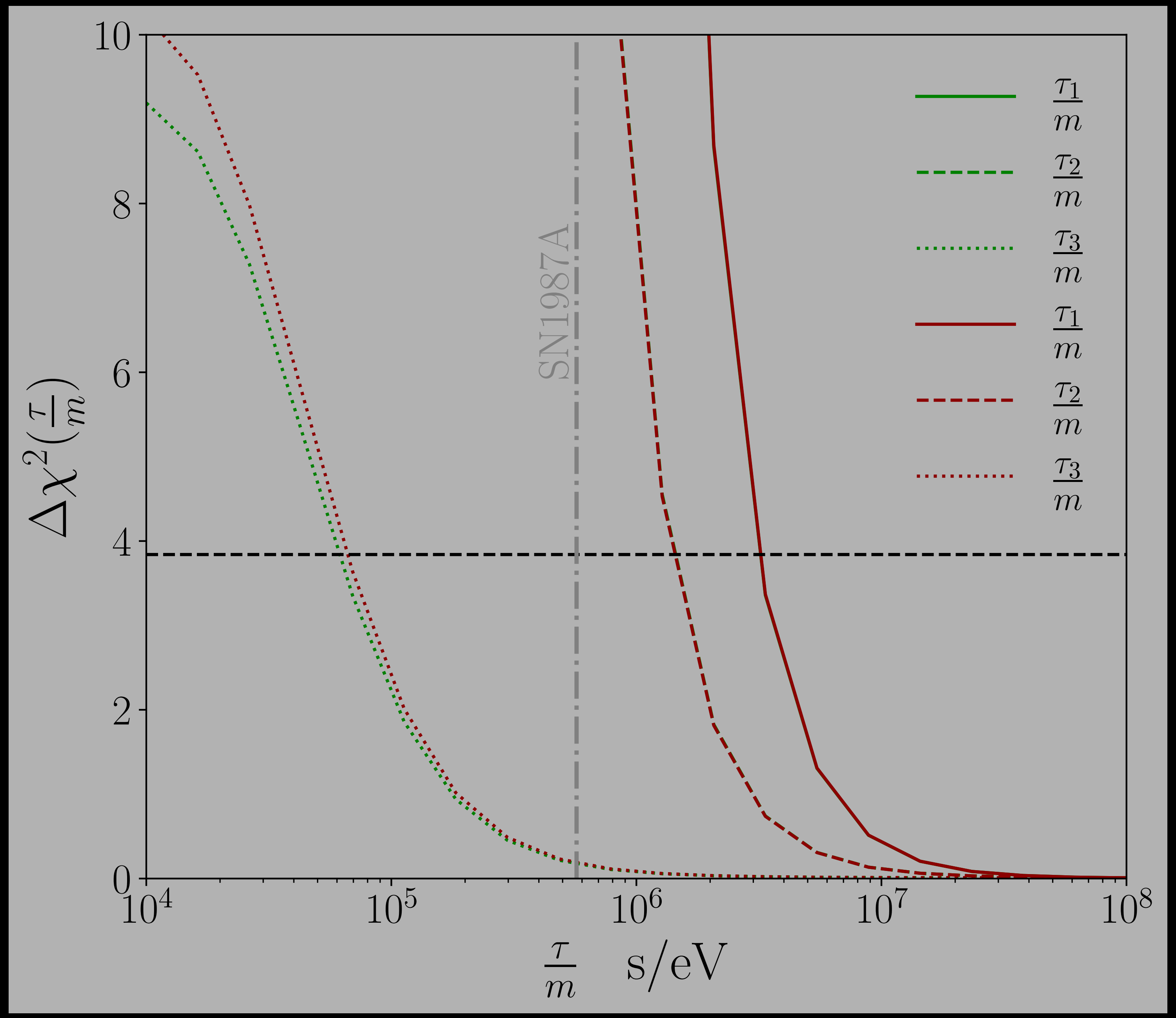
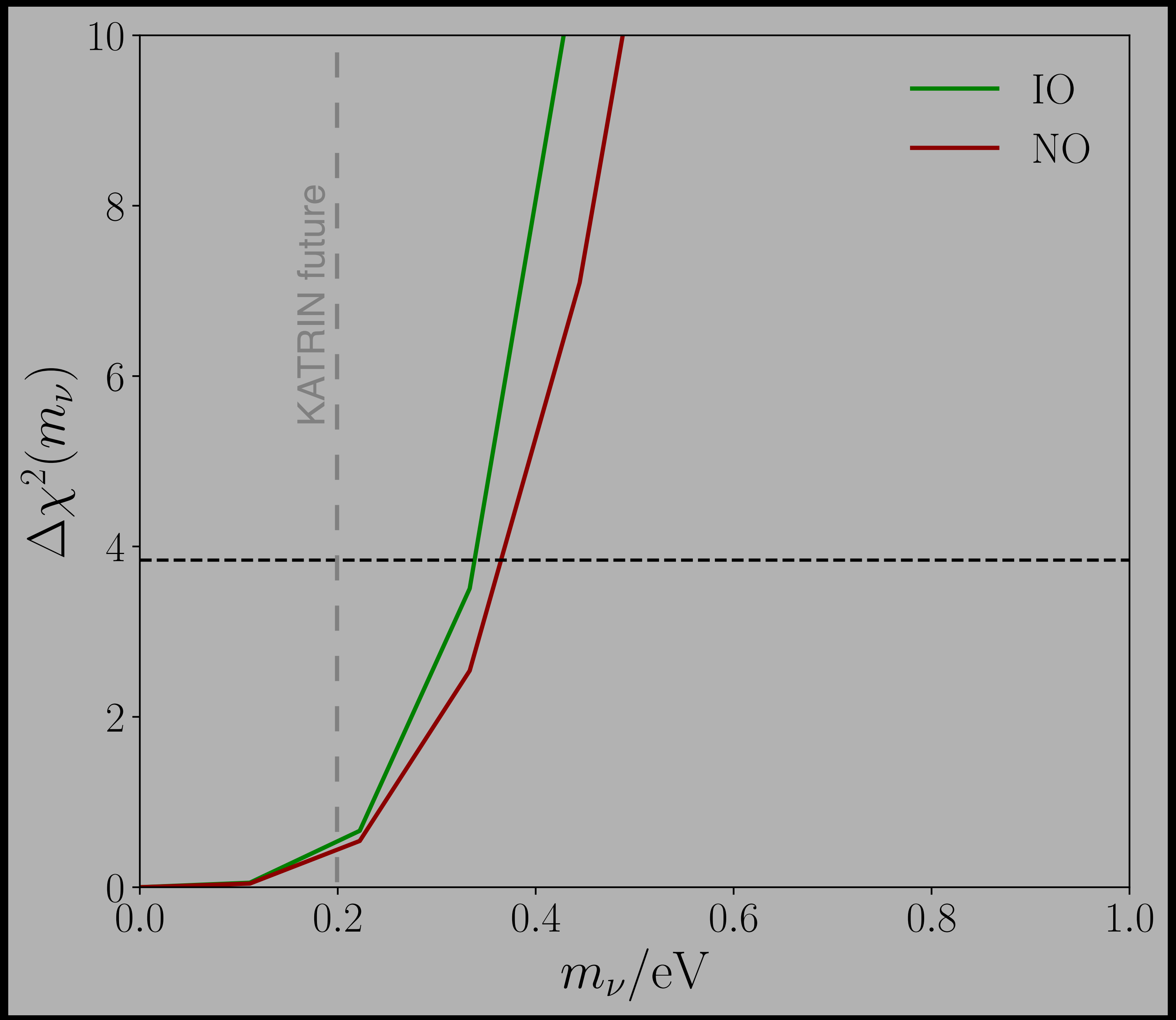
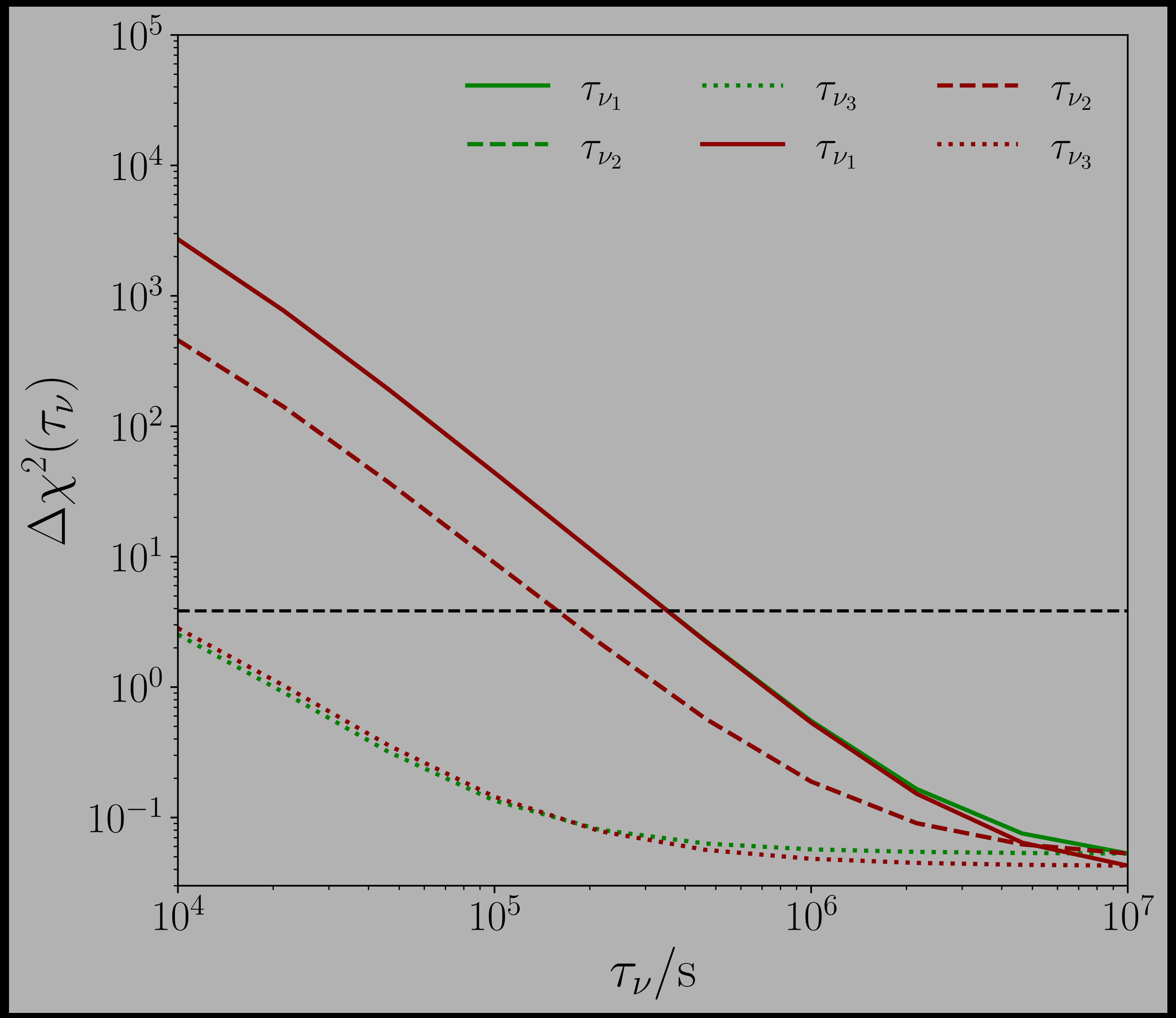


$\tau_1/m_1 \gtrsim 3\times10^6$ s/eV



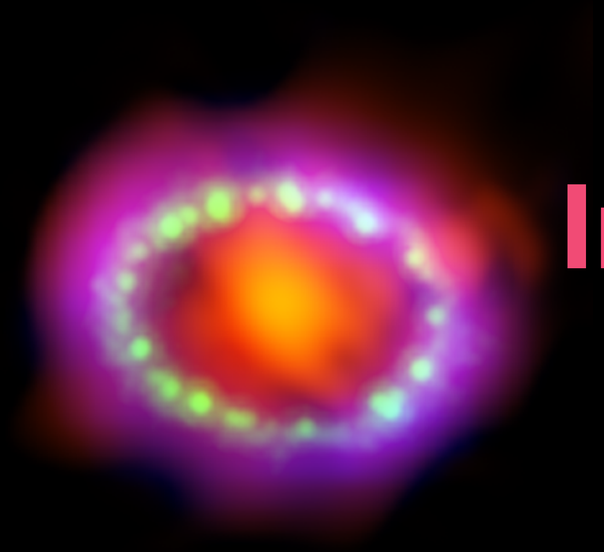
$m_\nu < 0.35$ eV



$\tau_1 \gtrsim 4\times10^5$ s

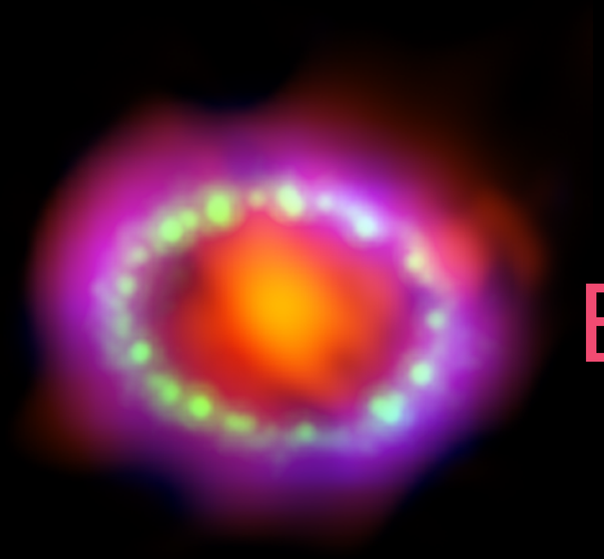
Take-home message

With future Supernova neutrino observatories:



Impact of neutronization peak detection on neutrino mass constraints

complementary (and independent) measurement to laboratory and cosmology



Exploring neutrino invisible decays

Bounds improved and independent on mass ordering

Simultaneous mass and lifetime constraints

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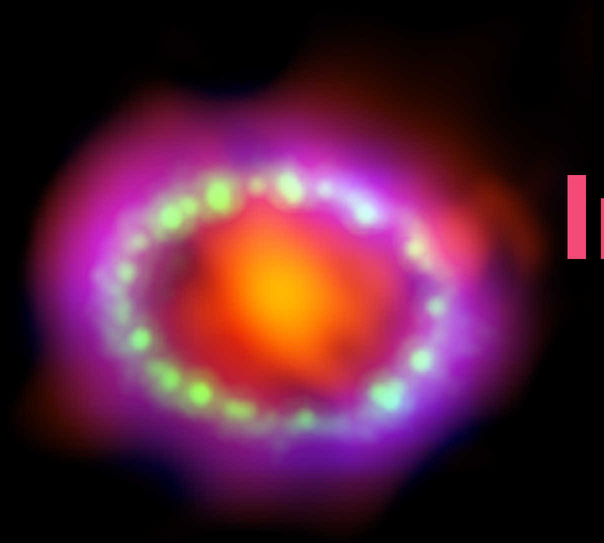

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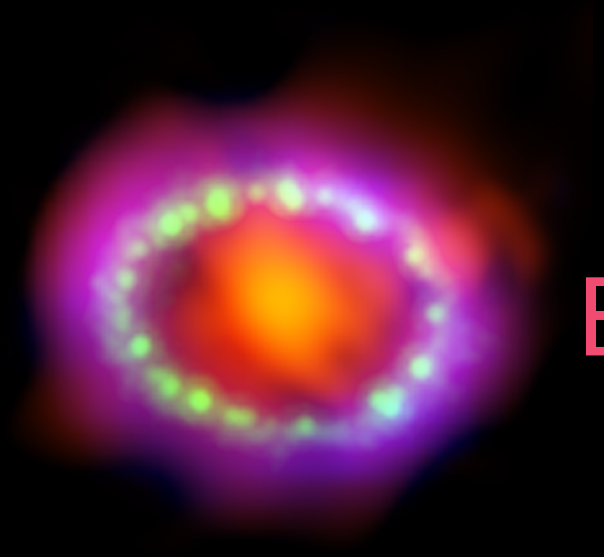
Be prepared and wait for SN20….



Exploring neutrino invisible decays

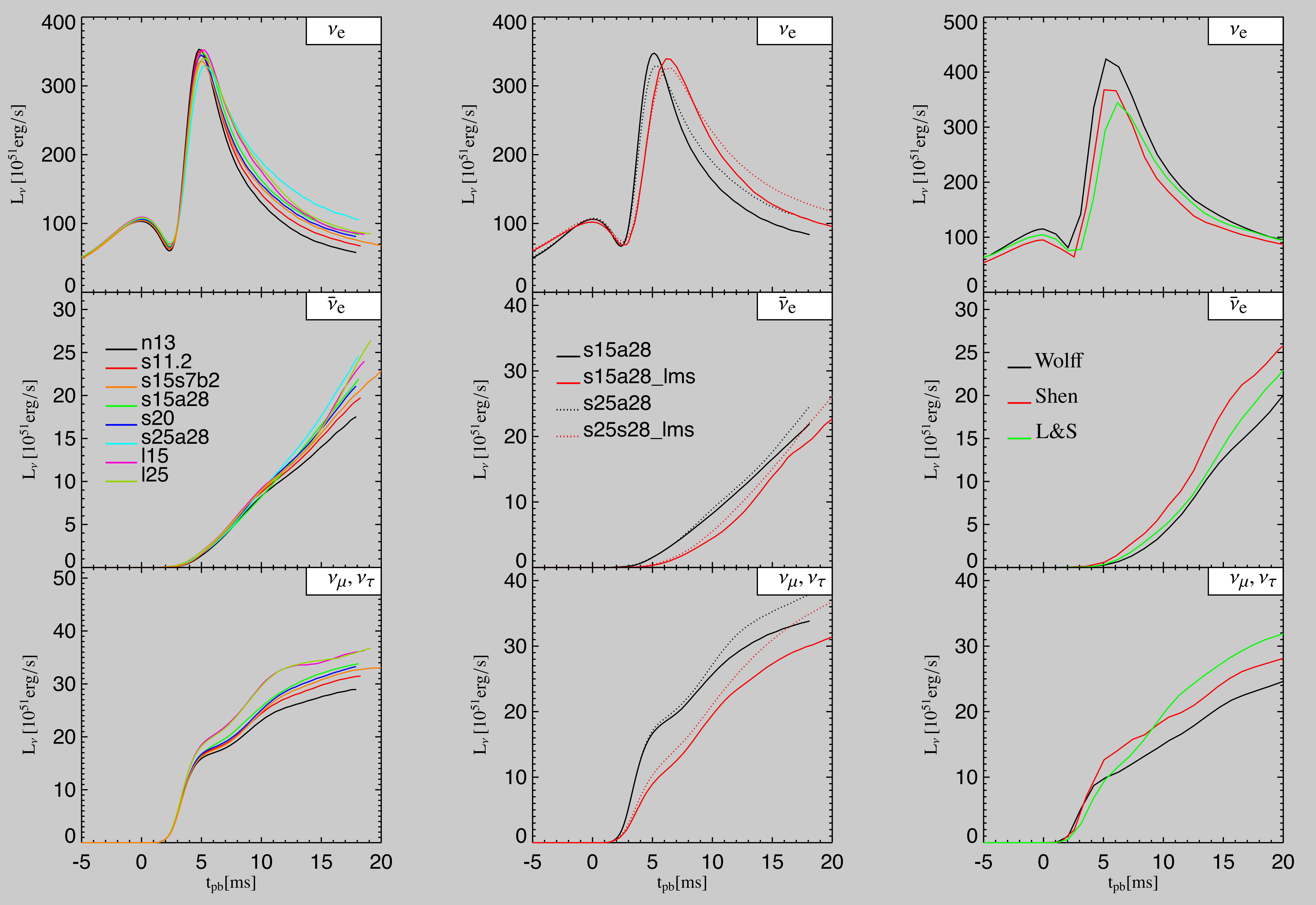
Bounds improved and independent on mass ordering

Simultaneous mass and lifetime constraints

Backup

Supernova parameters uncertainties: luminosity

M.Kachelriess, R.Tomas, R.Buras, H.-Th.Janka, A.Marek, M.Rampp (PRD 71,063003, 2005)



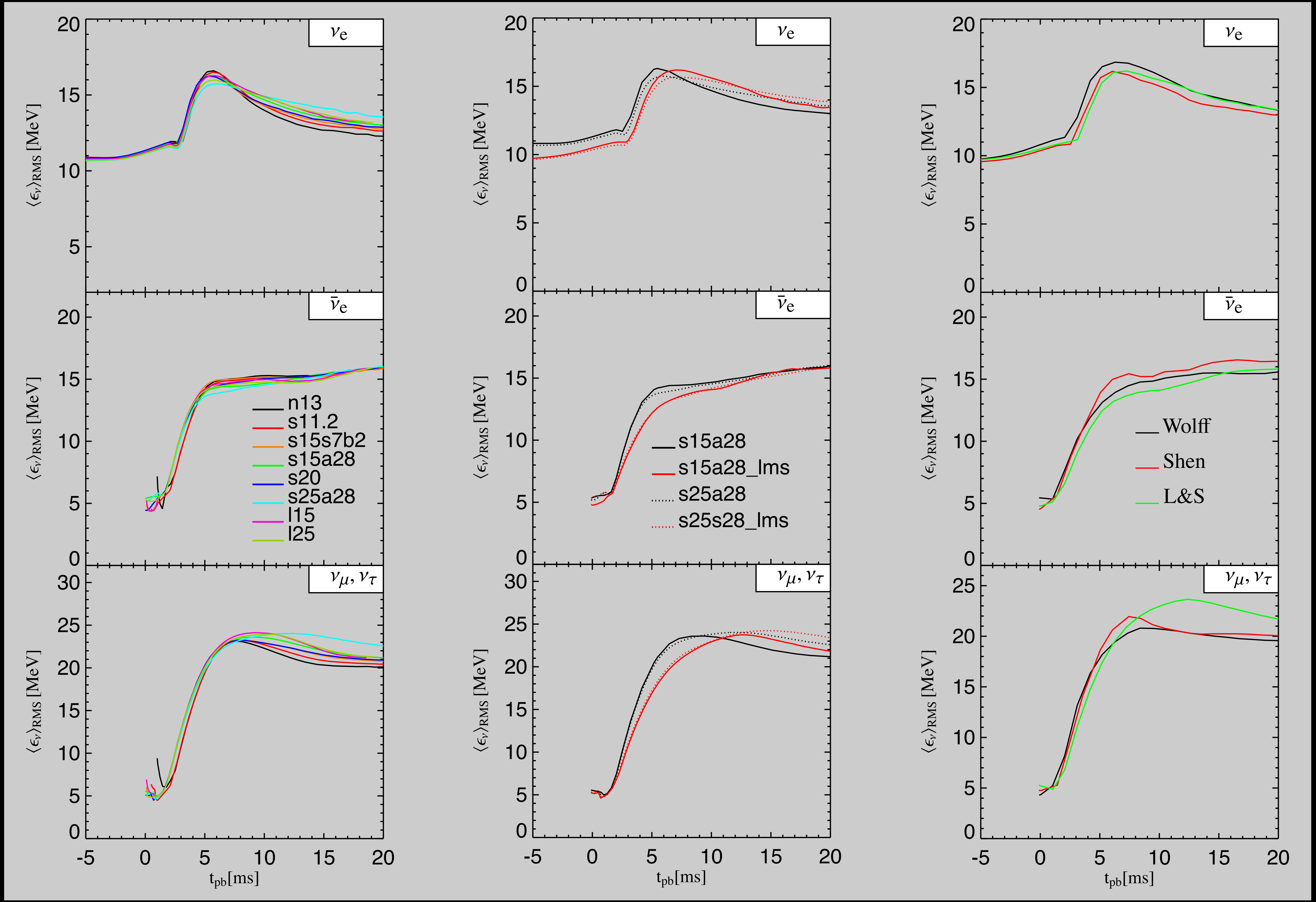
The neutronization burst results to be a robust, **model independent** prediction of the Supernova models.

Very slight variations as a function of progenitor mass (left panel), microphysics of neutrino interactions (middle panel) and equation of state (right panel).

Backup

Supernova parameters uncertainties: mean energy

M.Kachelriess, R.Tomas, R.Buras, H.-Th.Janka, A.Marek, M.Rampp (PRD 71,063003, 2005)



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Backup

Supernova neutrinos emission: details

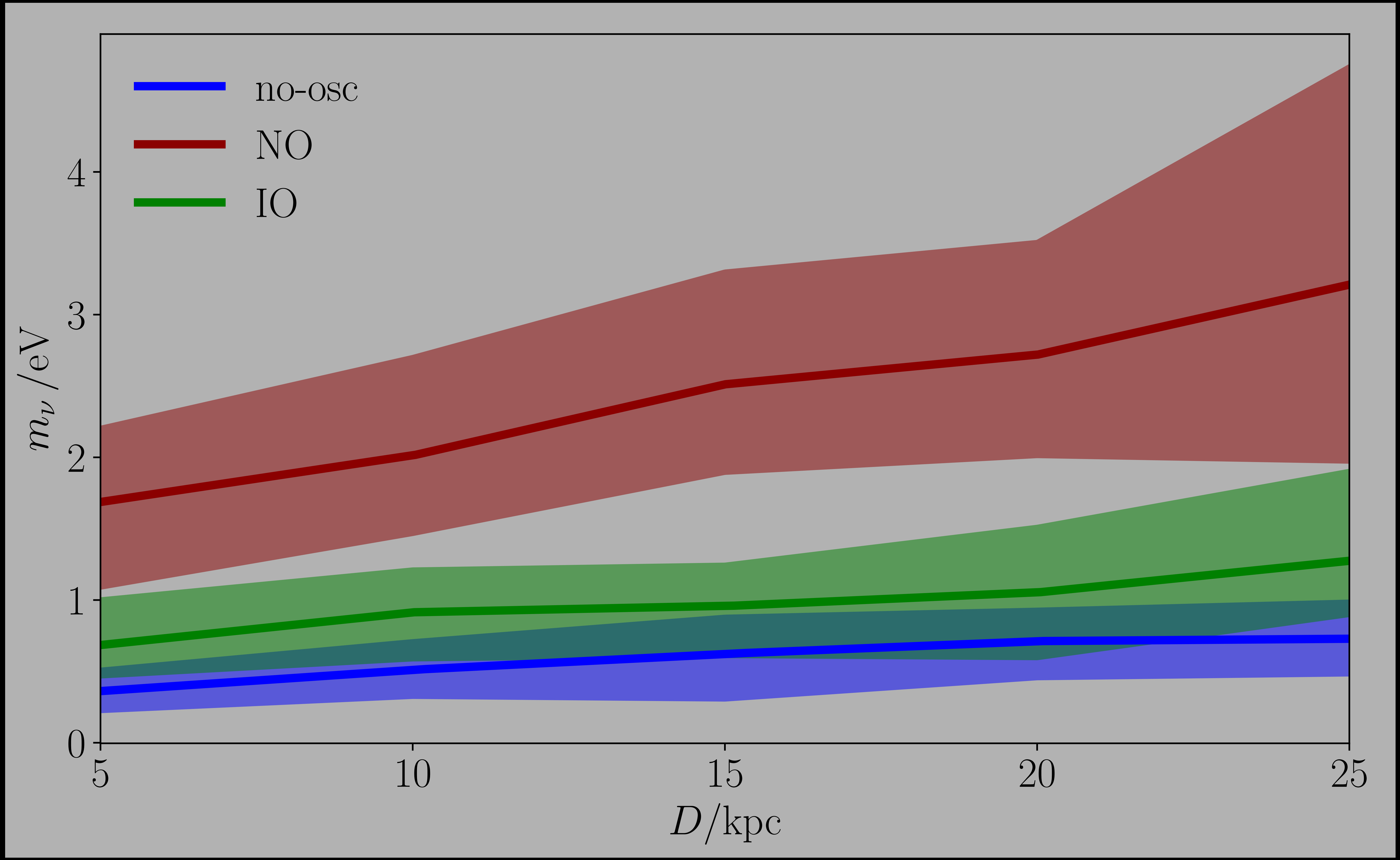
$$\Phi^0_{\nu_\beta}(E,t) = \frac{L_{\nu_\beta}(t)}{4\pi D^2}\frac{\varphi_{\nu_\beta}(E,t)}{\langle E_{\nu_\beta}(t)\rangle} \qquad \Phi^0_{\nu_\mu}, \Phi^0_{\nu_\tau} \equiv \Phi^0_{\nu_x}$$

$$\varphi_{\nu_\beta}(E,t) = \xi_\beta(t)\left(\frac{E}{\langle E_{\nu_\beta}(t)\rangle}\right)^{\alpha_\beta(t)} e^{\left\{\frac{-[\alpha_\beta(t)+1]\,E}{\langle E_{\nu_\beta}(t)\rangle}\right\}}$$

$$\alpha_\beta(t) = \frac{2\langle E_{\nu_\beta}(t)\rangle^2 - \langle E^2_{\nu_\beta}(t)\rangle}{\langle E^2_{\nu_\beta}(t)\rangle - \langle E_{\nu_\beta}(t)\rangle^2}$$

Backup

Dependency on SN distance

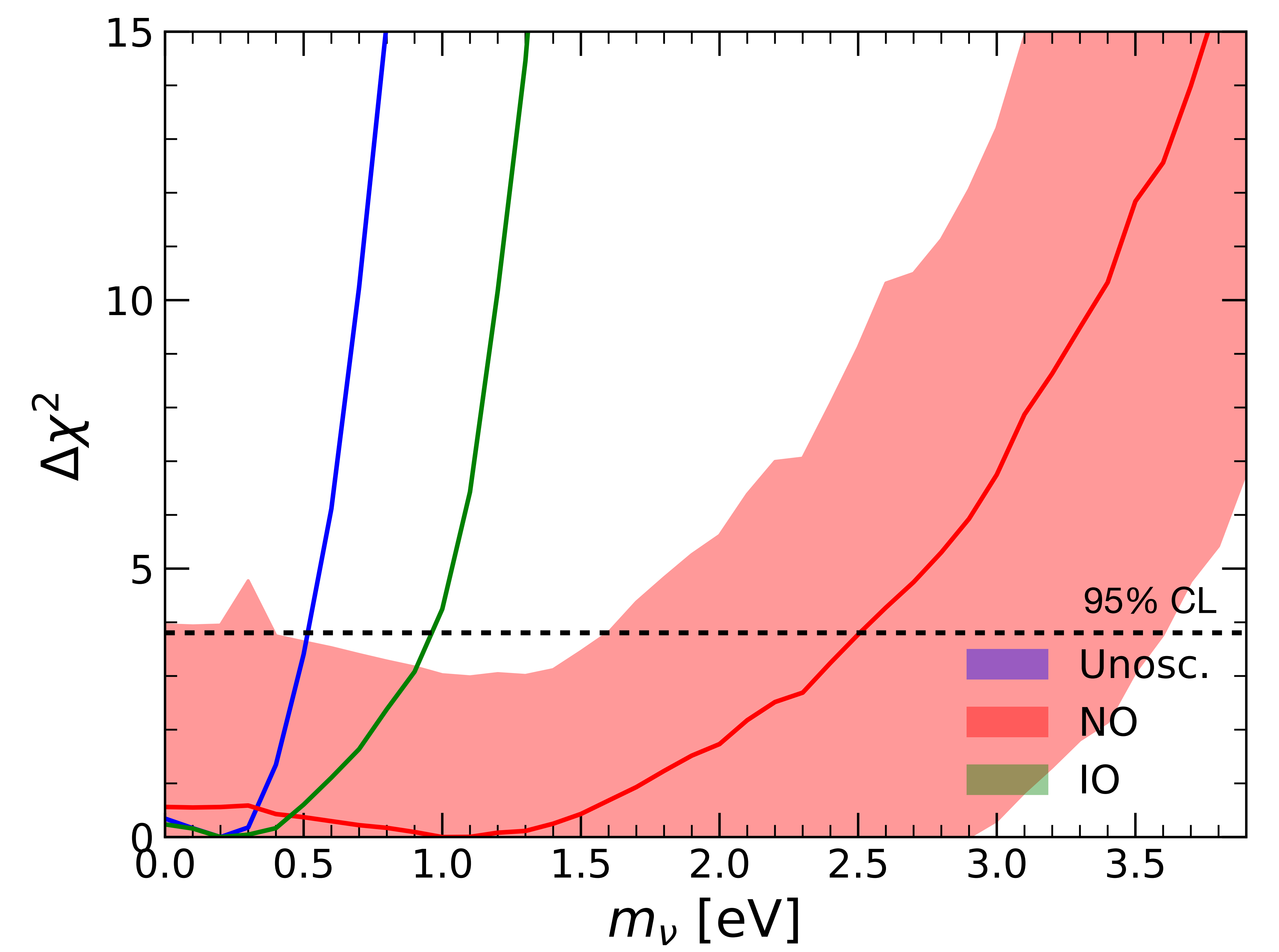


Backup

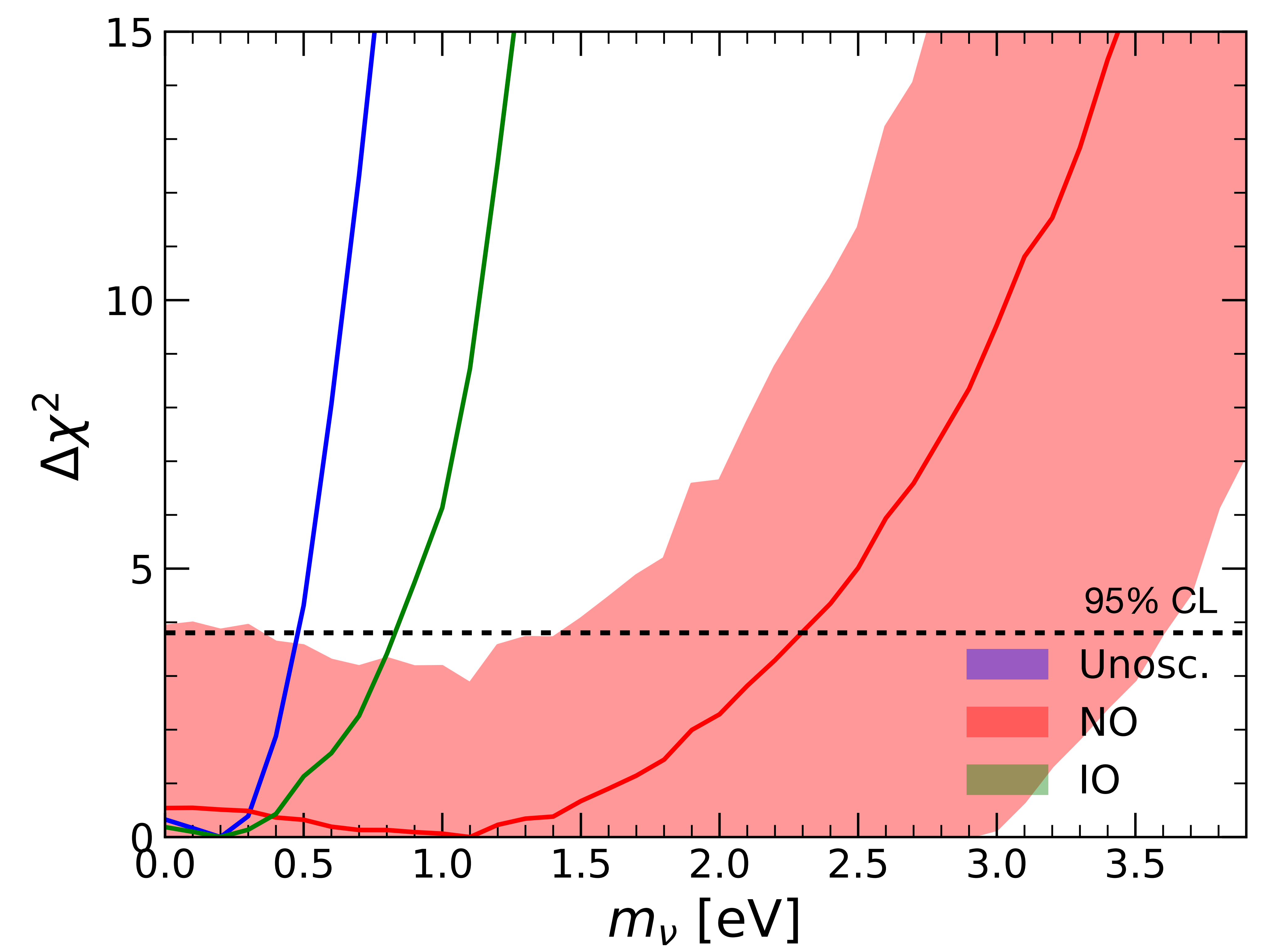
Dependency on SN parameters

$$\langle E_{\nu_\beta} \rangle = (1 + f^E_{\nu_\beta})\ \langle E_{\nu_\beta} \rangle^0$$

$$\alpha_{\nu_\beta} = (1 + f^\alpha_{\nu_\beta})\ \alpha^0_{\nu_\beta}$$



One time-windows: [0, 10] s

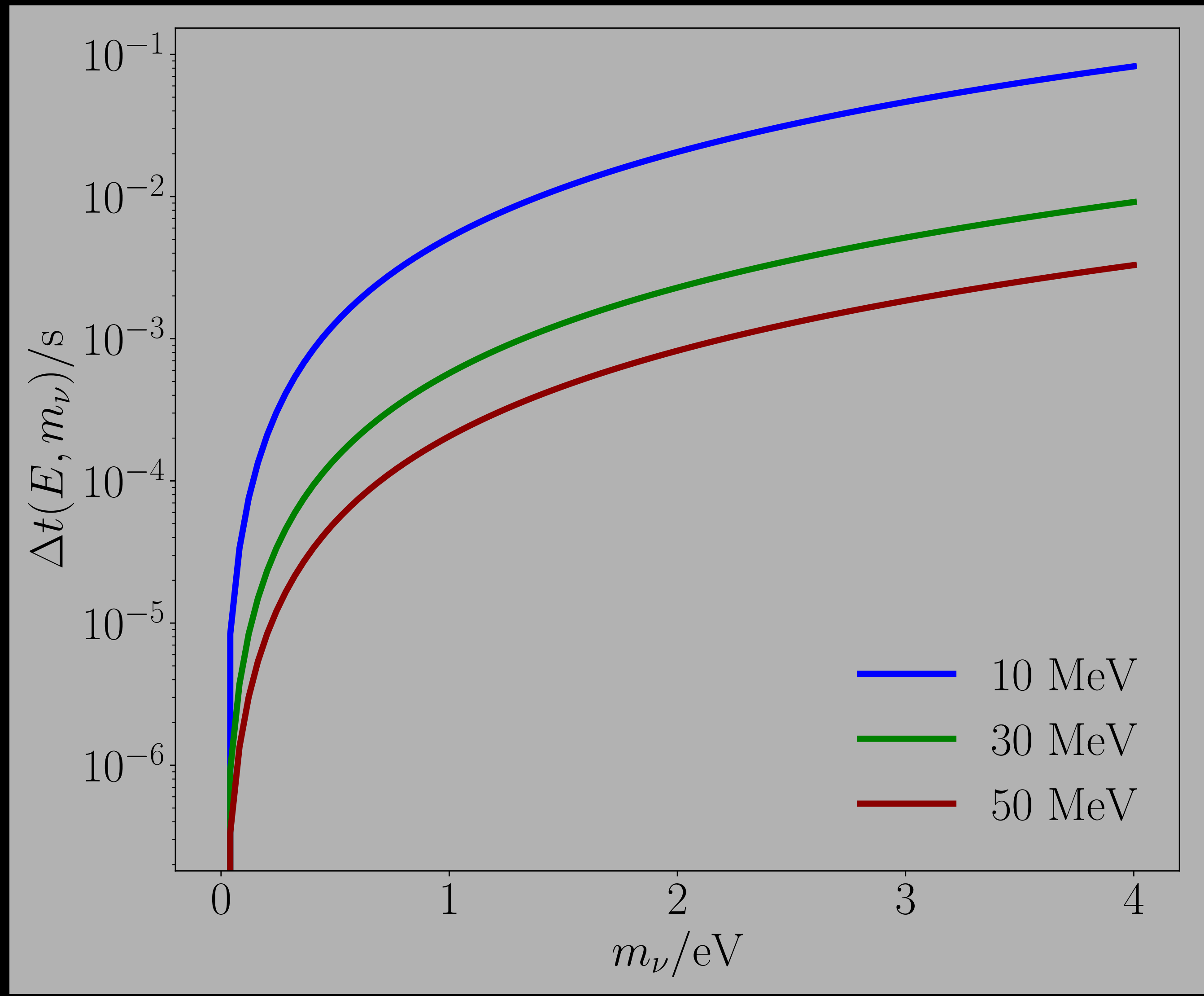


Two time-windows: [0, 0.5] s and [0.5, 10] s

Backup

Likelihood analysis

G.Pagliaroli,F.Vissani,M.L.Costantini,A.Ianni(Astropart. Phys. Vol 31, 2009)



$$t_i = \delta t_i - \Delta t_i + t_{off}$$

$$\Delta t_i = \frac{D}{2c}\left(\frac{m_\nu}{E_i}\right)^2$$

- Dataset generation

  $(\delta t_i\,, E_i\,)$ generation by fixing D

- Likelihood construction

  $$L(t_i\,, m_\nu) = \int R(t_i\,, E)\; G(E)\; dE$$

  $G(E)$: Gaussian smearing (10% energy resolution)

  $$\chi^2(t_i\,, m_\nu) = -\,2\log(L)$$

- Sensitivity to m_ν

  $$\Delta\chi^2(m_\nu) = \chi^2(m_\nu) - \chi^2_{min}(m_\nu)$$

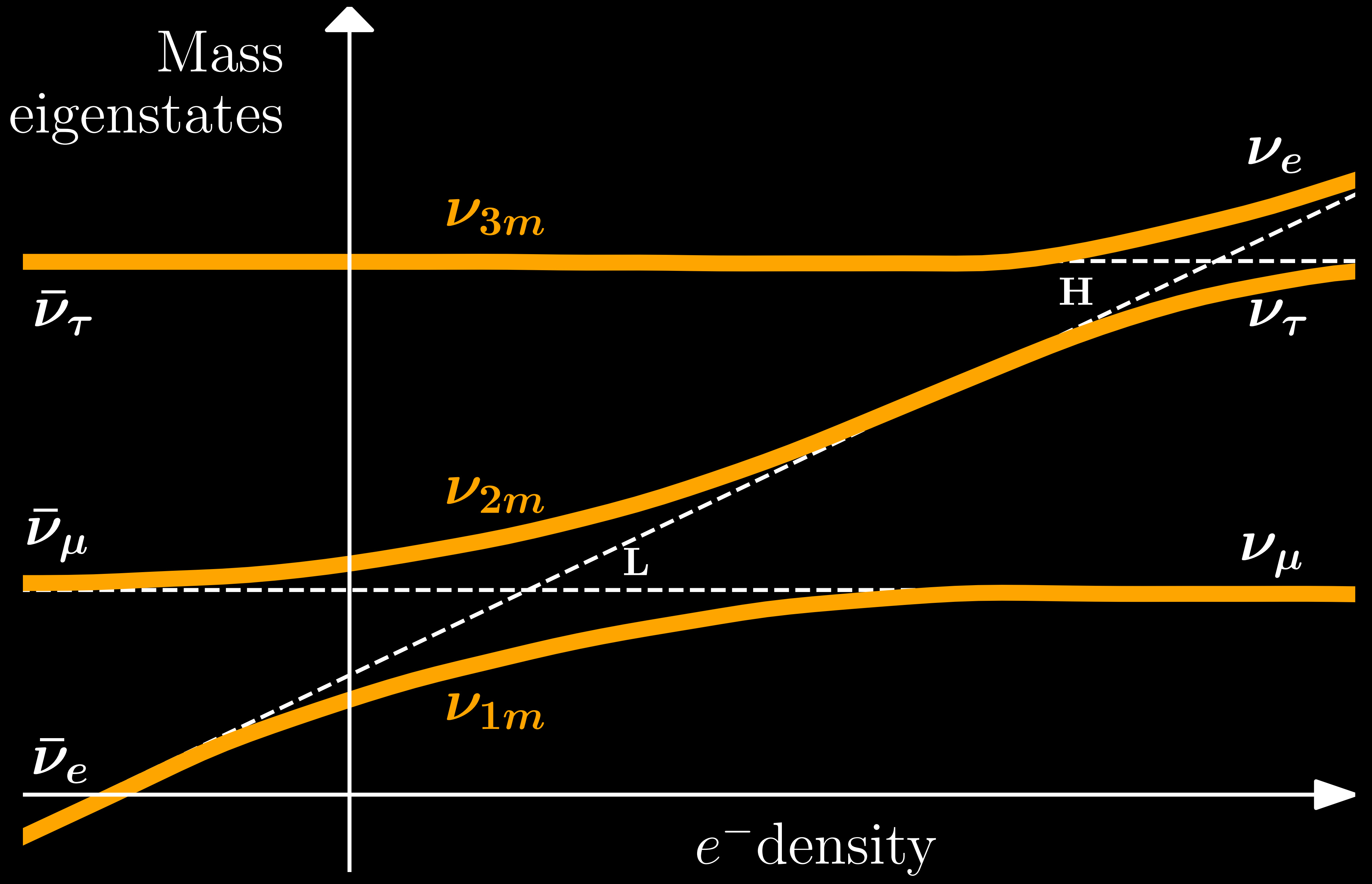
Backup

Mikheyev-Smirnov-Wolfenstein effect

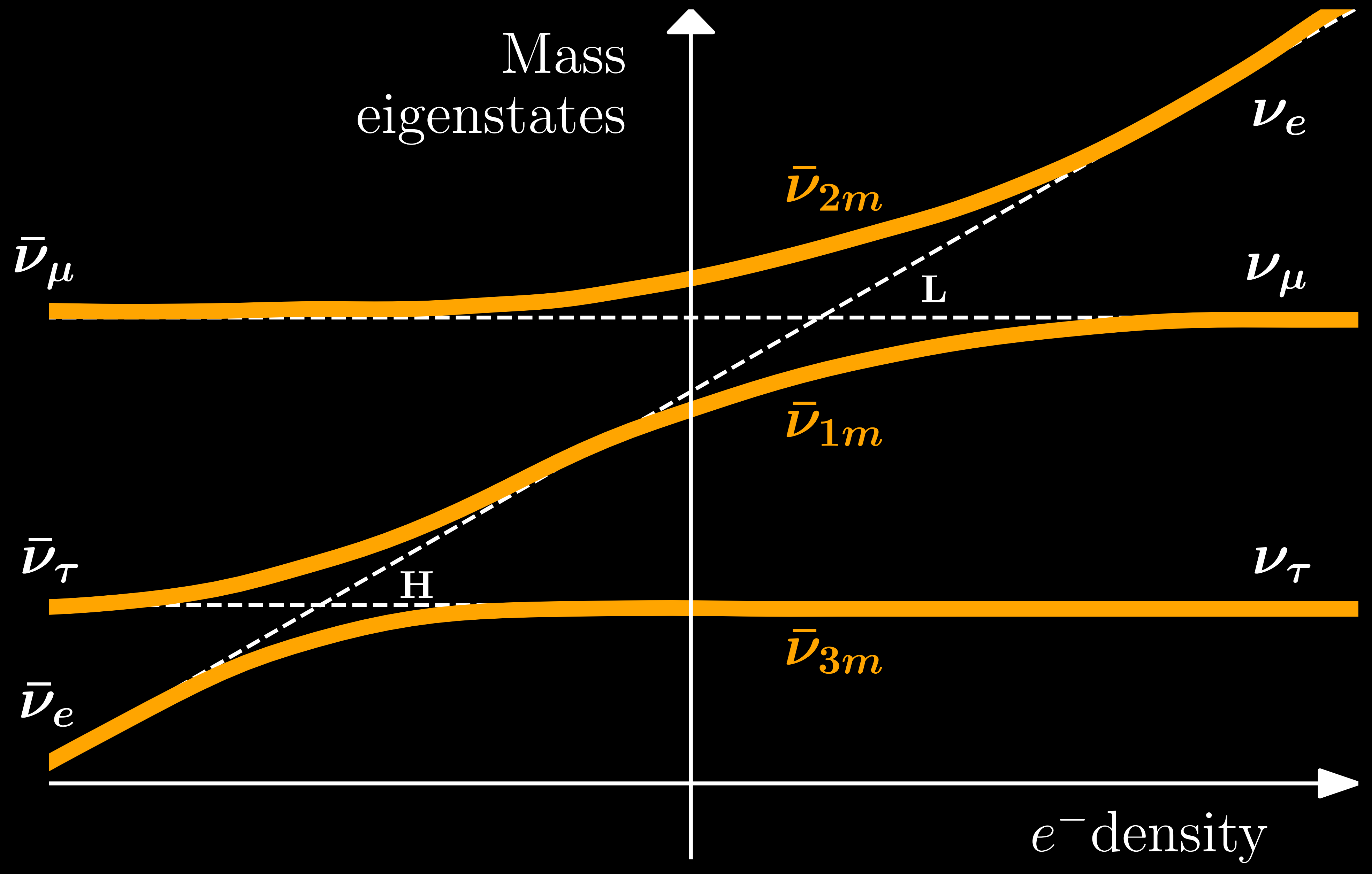
A.S.Dighe,A.Y.Smirnov (PRD 62,033007, 2000)

Adiabatic or partially adiabatic neutrino flavor conversion in medium with varying density

$\Delta m^2_{13} > 0$



$\Delta m^2_{13} < 0$



Backup

Evolution operator definition

E.Lisi, D.Montanino (PRD 56,1792,1997)

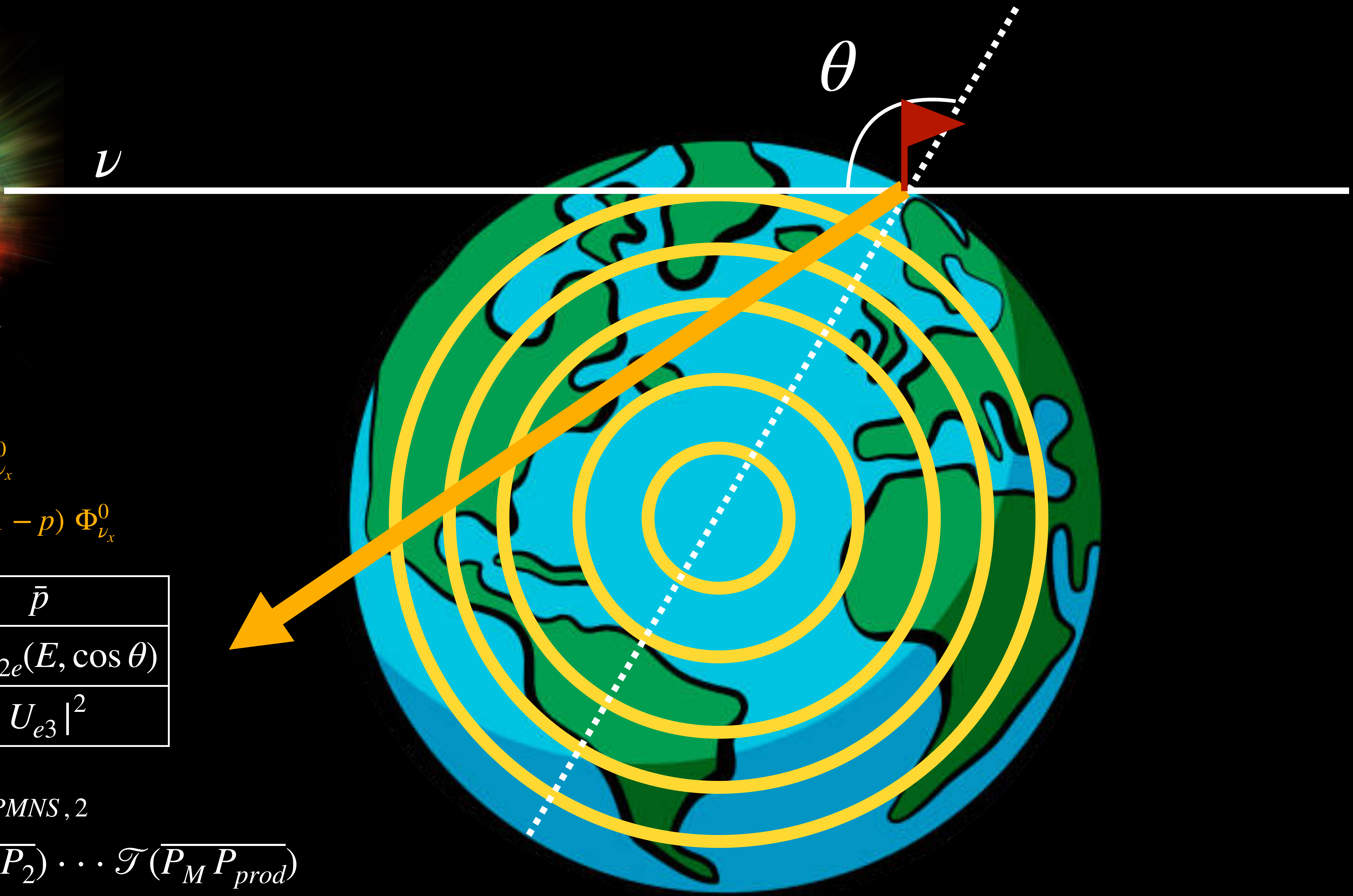
$$\mathcal{T}(\overline{P_{j-1}P_j}) = \exp\{-i(H_0 - V_{matter,j}) \cdot l_j\}$$

$$H_0 = \frac{U_{PMNS}\, M_{mass}\, U^\dagger_{PMNS}}{2E}$$

$$V_{matter,j} = \mathrm{diag}\left(\sqrt{2}\, G_F\, \overline{N_j}(x)\right)$$

$$\overline{N_j}(x) = \frac{1}{l_j}\int_{x_{j-1}}^{x_j} N_j(x)\, dx$$

$$N_j(x) = \alpha_j + \beta_j x^2 + \gamma_j x^4$$



$$\Phi_{\nu_e} = p\ \Phi^0_{\nu_e} + (1-p)\ \Phi^0_{\nu_x}$$

$$\Phi_{\nu_x} = \frac{1}{2}[(1-p)\ \Phi^0_{\nu_e} + (1-p)\ \Phi^0_{\nu_x}$$

	p	$\bar{p}$
NO	$\lvert U_{e3} \rvert^2$	$1 - P_{2e}(E, \cos\theta)$
IO	$P_{2e}(E, \cos\theta)$	$\lvert U_{e3} \rvert^2$

$$P_{2e}(E, \cos\theta) = \mathscr{T}_{e\beta} \cdot U_{PMNS,2}$$

$$\mathscr{T}_{\alpha\beta} = \mathscr{T}(\overline{P_{det} P_1})\, \mathscr{T}(\overline{P_1 P_2}) \cdots \mathscr{T}(\overline{P_M P_{prod}})$$

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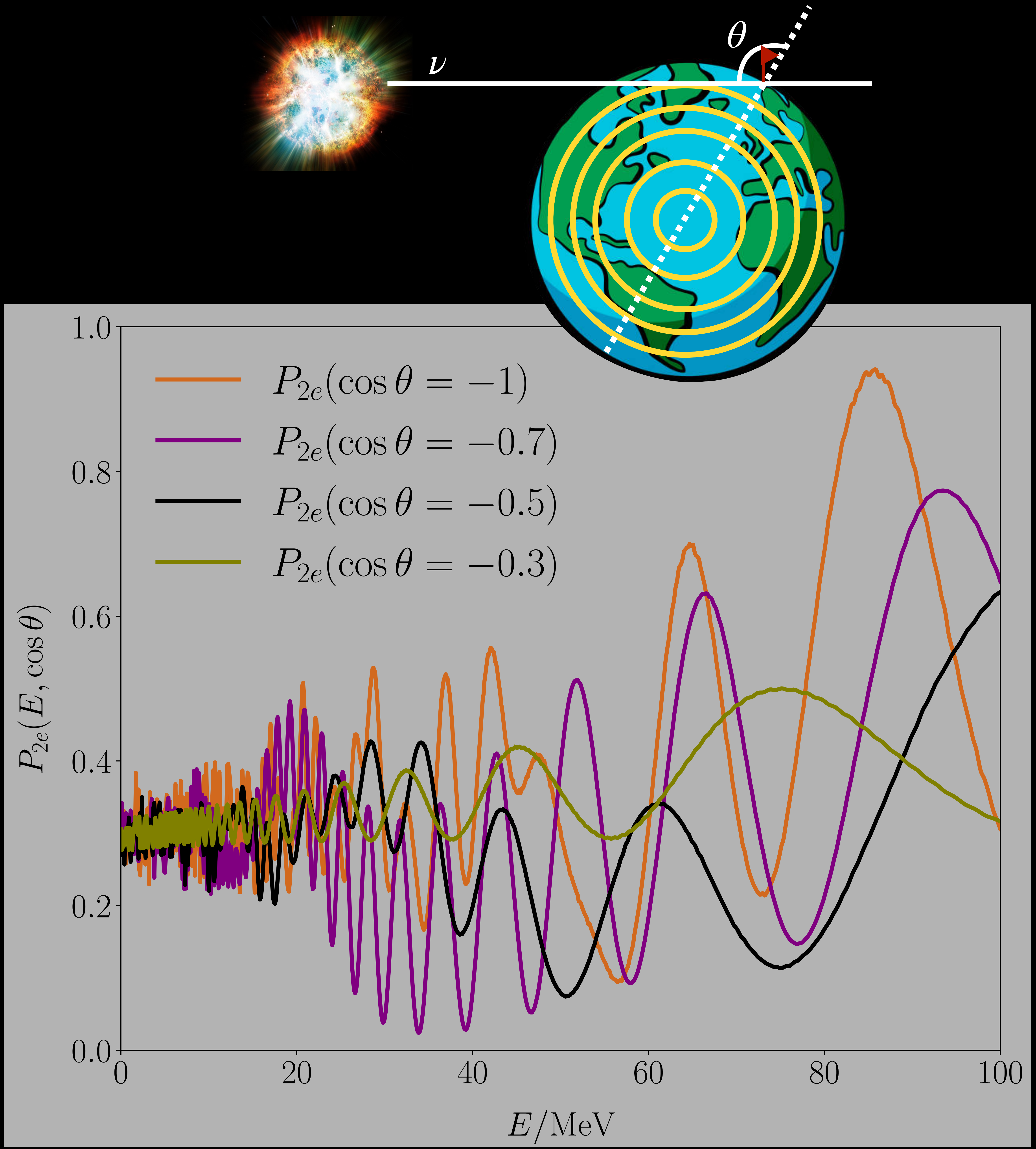
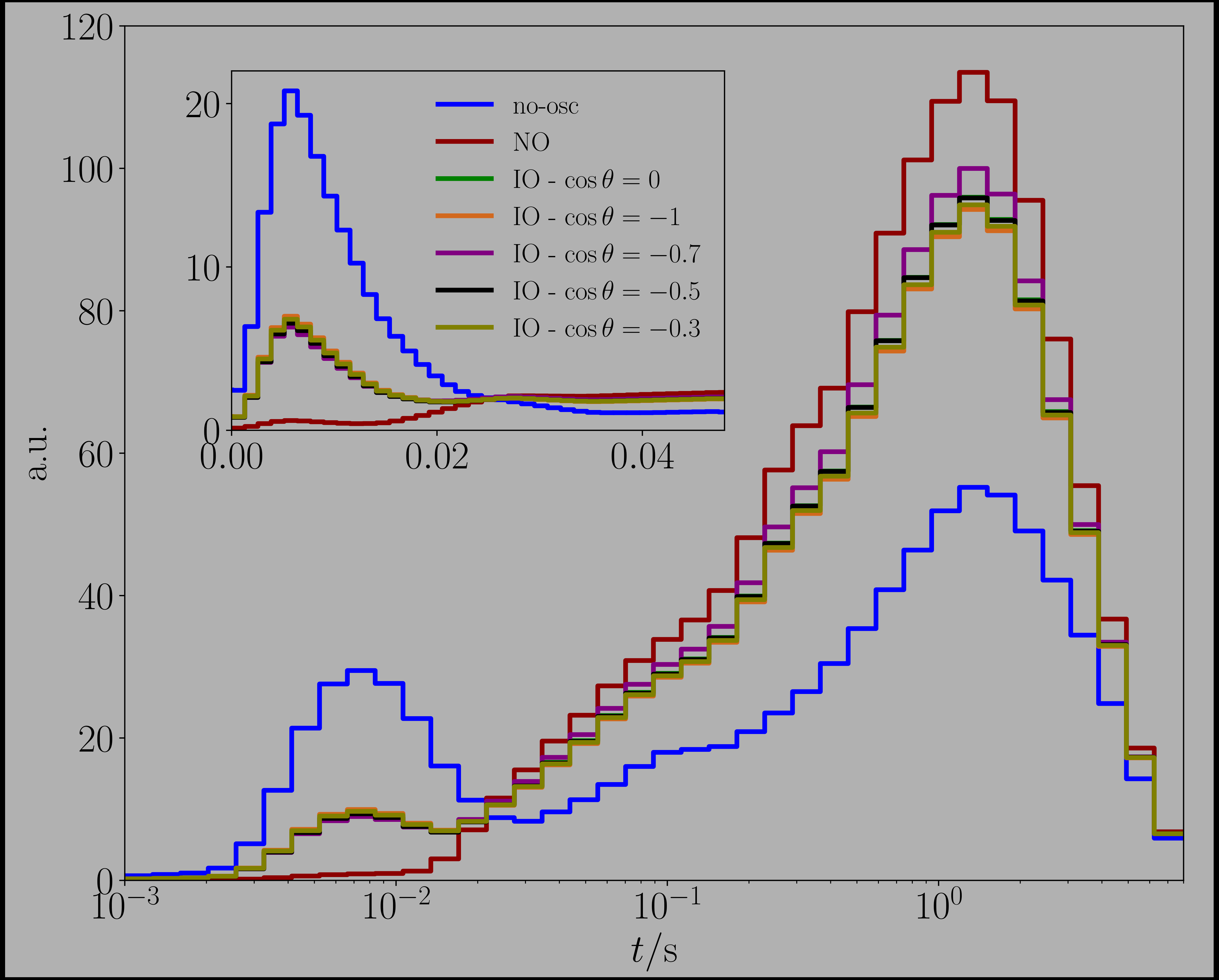
Earth matter effects



ν_e channel – IO



Backup

Dependency on SN parameters

$$\langle E_{\nu_\beta} \rangle = (1 + f^E_{\nu_\beta})\ \langle E_{\nu_\beta} \rangle^0$$

$$\alpha_{\nu_\beta} = (1 + f^\alpha_{\nu_\beta})\ \alpha^0_{\nu_\beta}$$