HIDDeν
Hunting Invisibles: Dark sectors, Dark matter and Neutrinos

Core-collapse Supernovae to constraint neutrino mass with future neutrino detectors

Pompa, Capozzi, Mena, Sorel (PRL 129, 2022)

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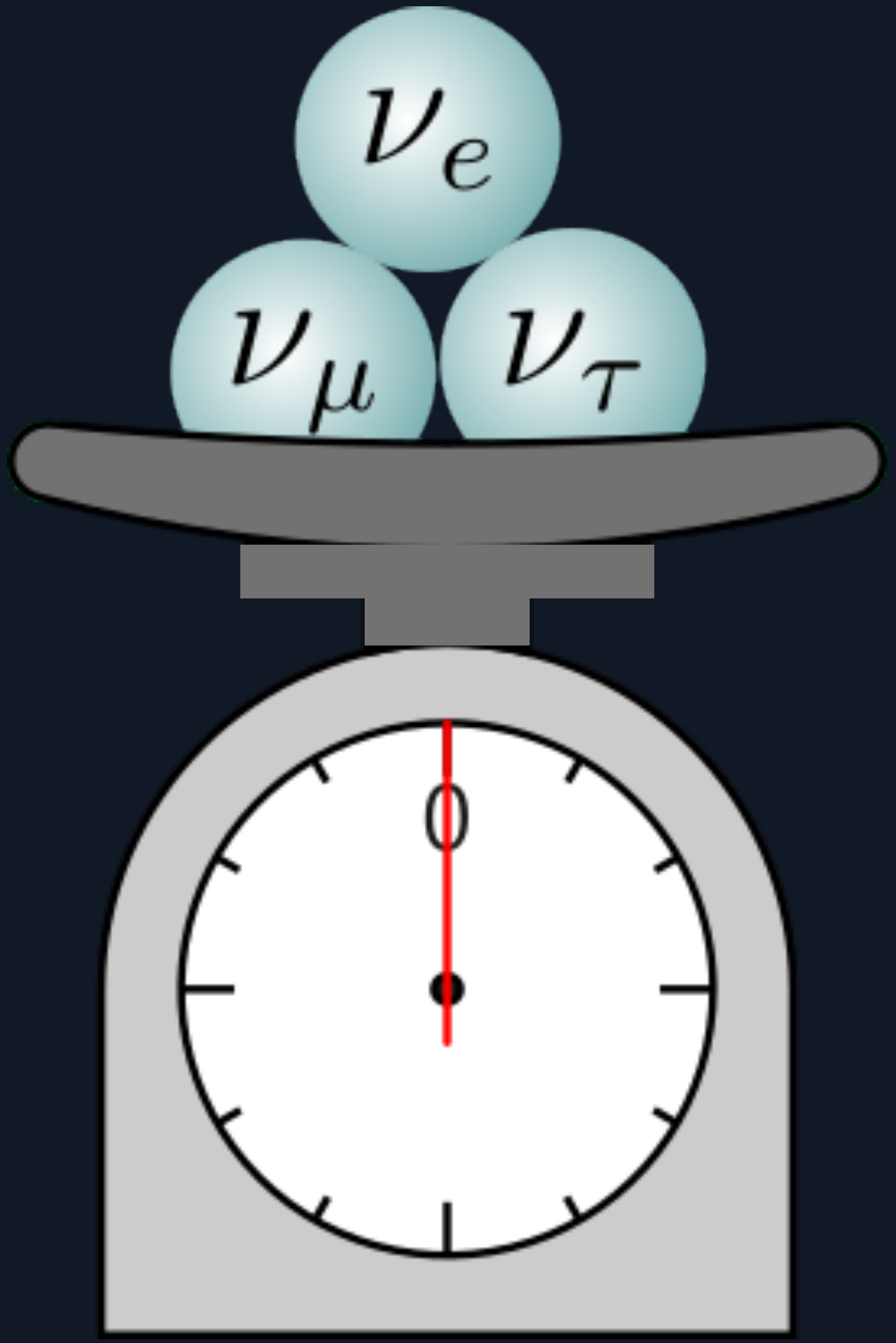
Institut de Física Corpuscular

Neutrino mass



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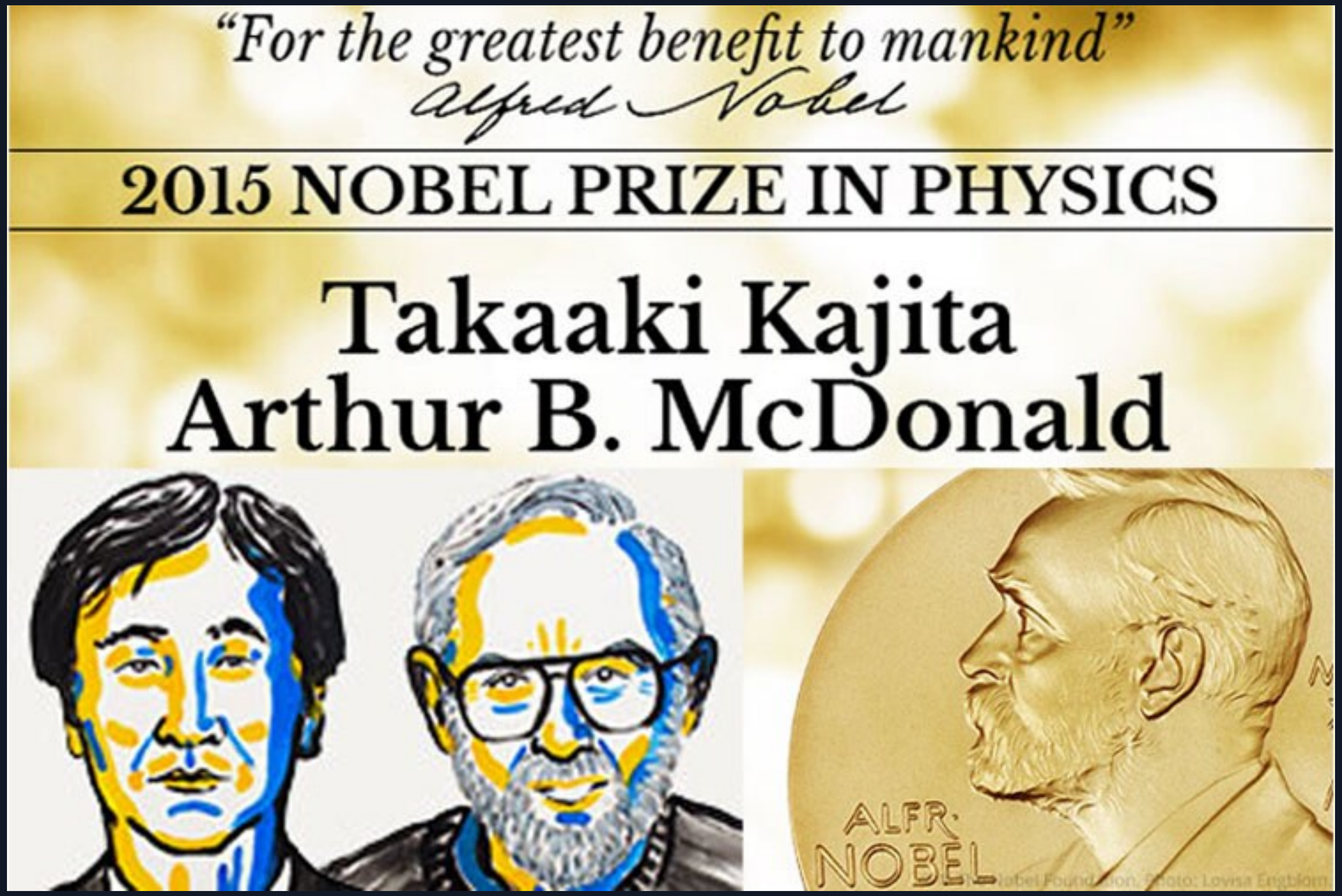

$$\nu_\alpha = \sum_{i=1}^{3} U_{\alpha i}\, \nu_i$$

Neutrino mass

From cosmology:

Di Valentino,Gariazzo,Mena (PRD 104, 2021)

(CMB+BAO) $\Rightarrow \sum m_\nu < 0.12$ eV (95% CL)

From kinematic measurements:

KATRIN Collaboration (2021)

KATRIN $\Rightarrow m_\beta < 0.8$ eV (90% CL)

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

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

Time-of-flight constraints:

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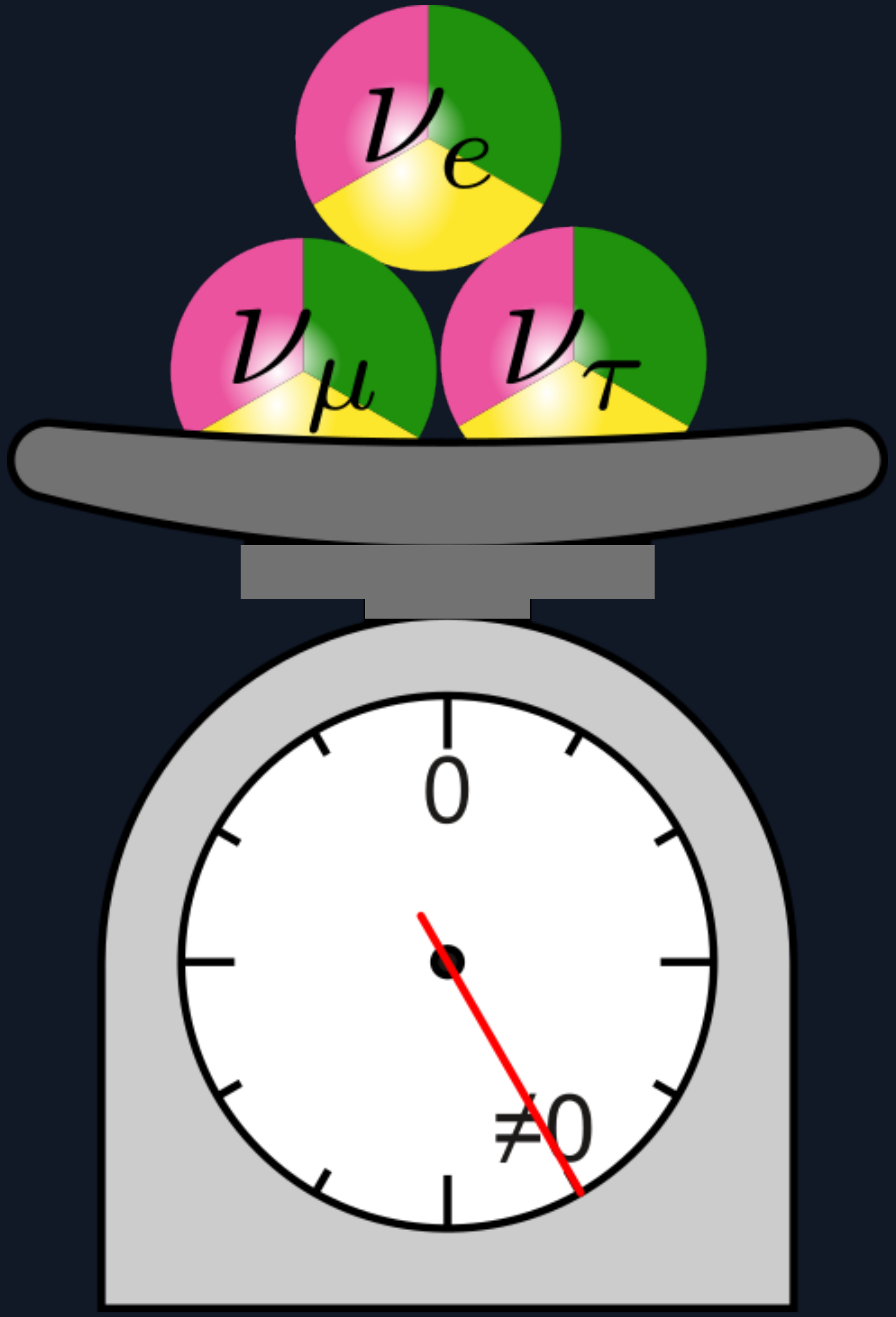

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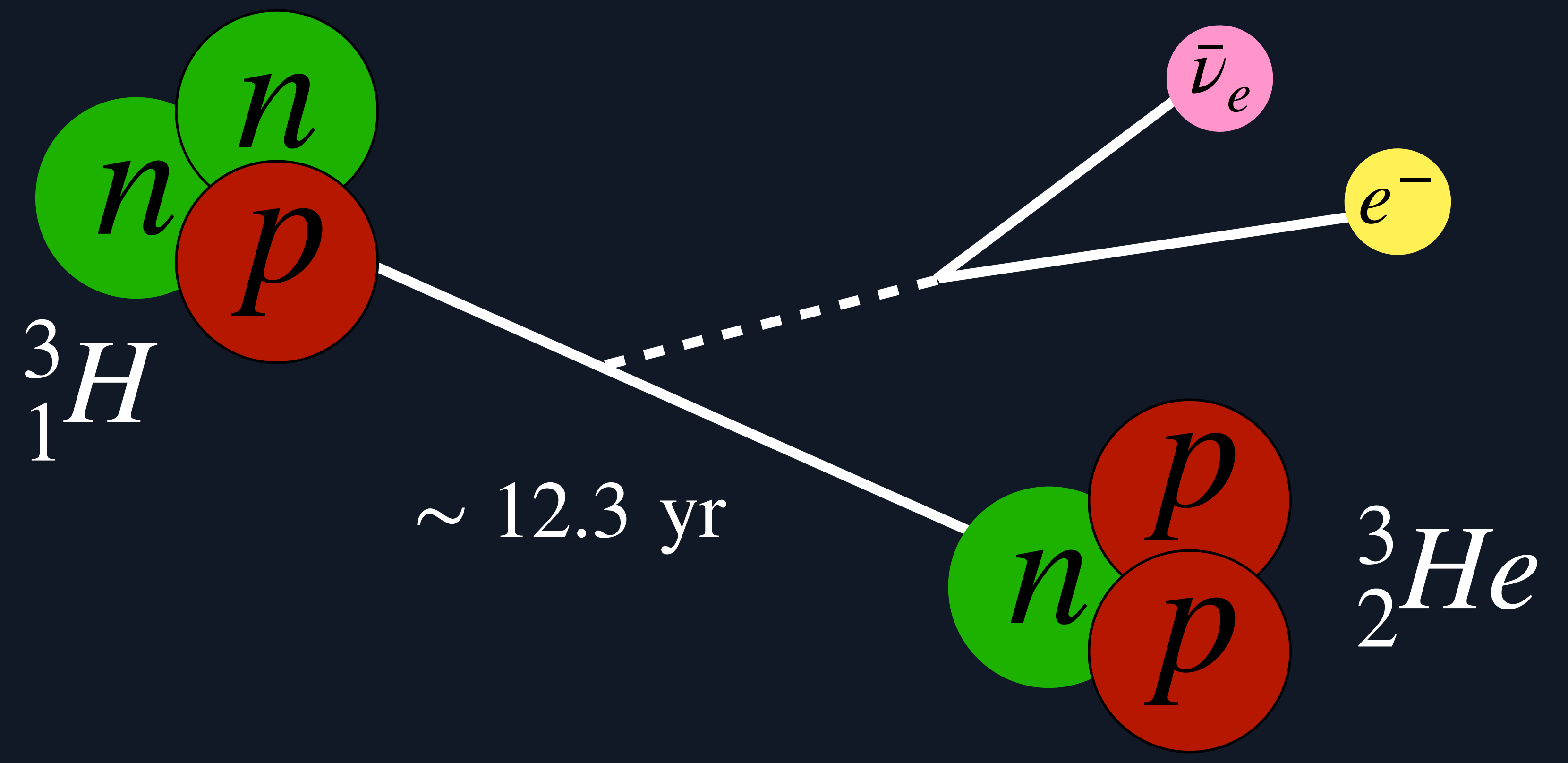
Planck+lensing +Pantheon	Σm_ν [eV]
+ DR12 *BAO only*	< 0.116
+ DR12 *BAO+RSD*	< 0.118
+ DR16 *BAO only*	< 0.158
+DR16 *BAO+RSD*	< 0.101
+DR12 *BAO only* + DR16 *BAO only*	< 0.121
+DR12 *BAO only* + DR16 *BAO+RSD*	< 0.0866
+DR12 *BAO+RSD* + DR16 *BAO only*	< 0.125
+DR12 *BAO+RSD* + DR16 *BAO+RSD*	< 0.0934

Neutrino mass



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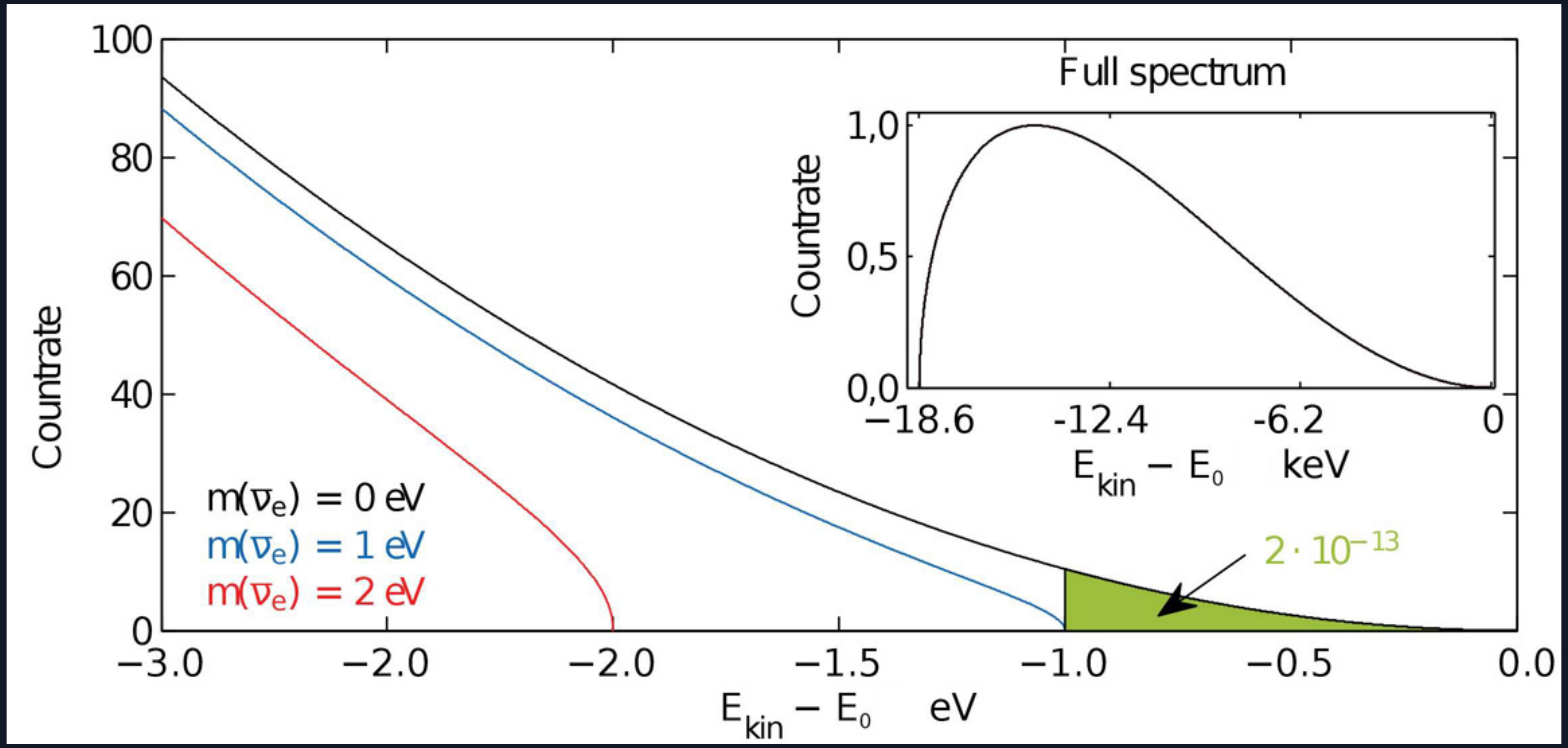

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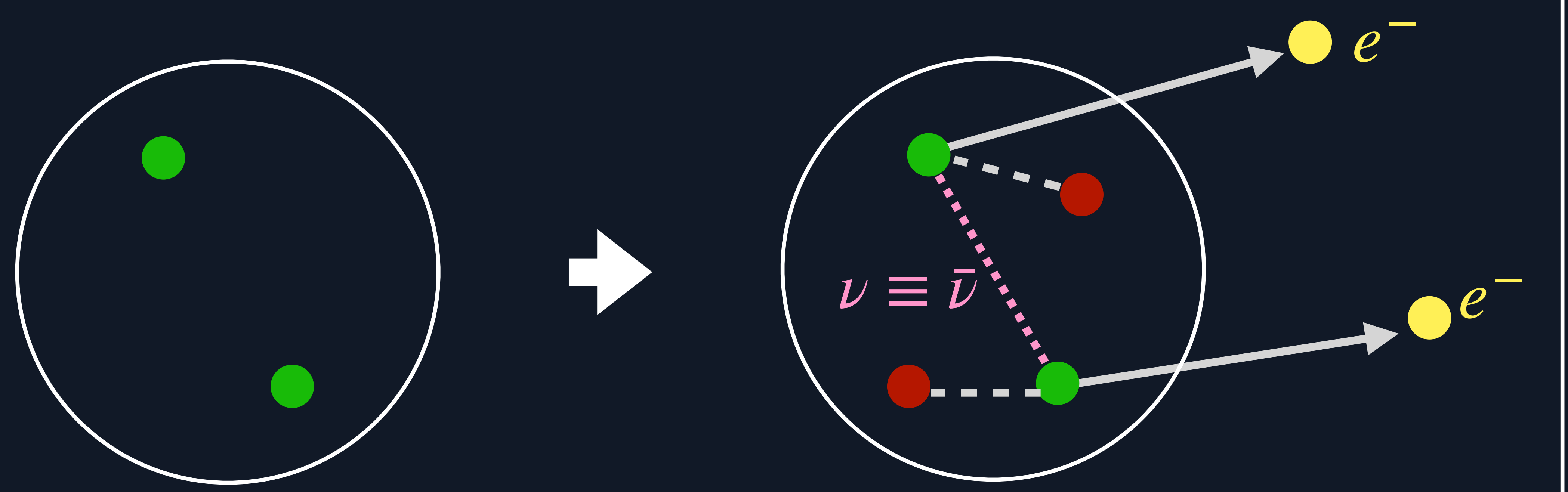

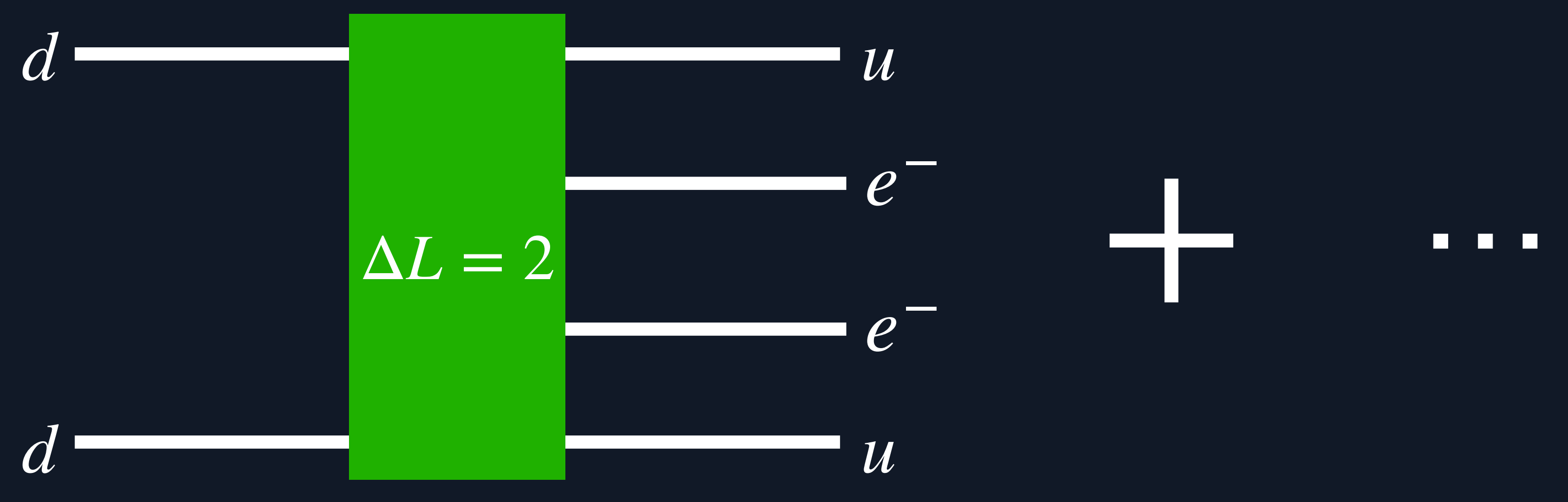

$$\Gamma = G_{0\nu} M_{0\nu}^2 \varepsilon(\Delta L = 2)$$

$$m_{\beta\beta} = \sum_i |U_{ei}|^2 m_i$$

Nuclear Models dependence!
Majorana neutrino assumption!

Neutrino mass

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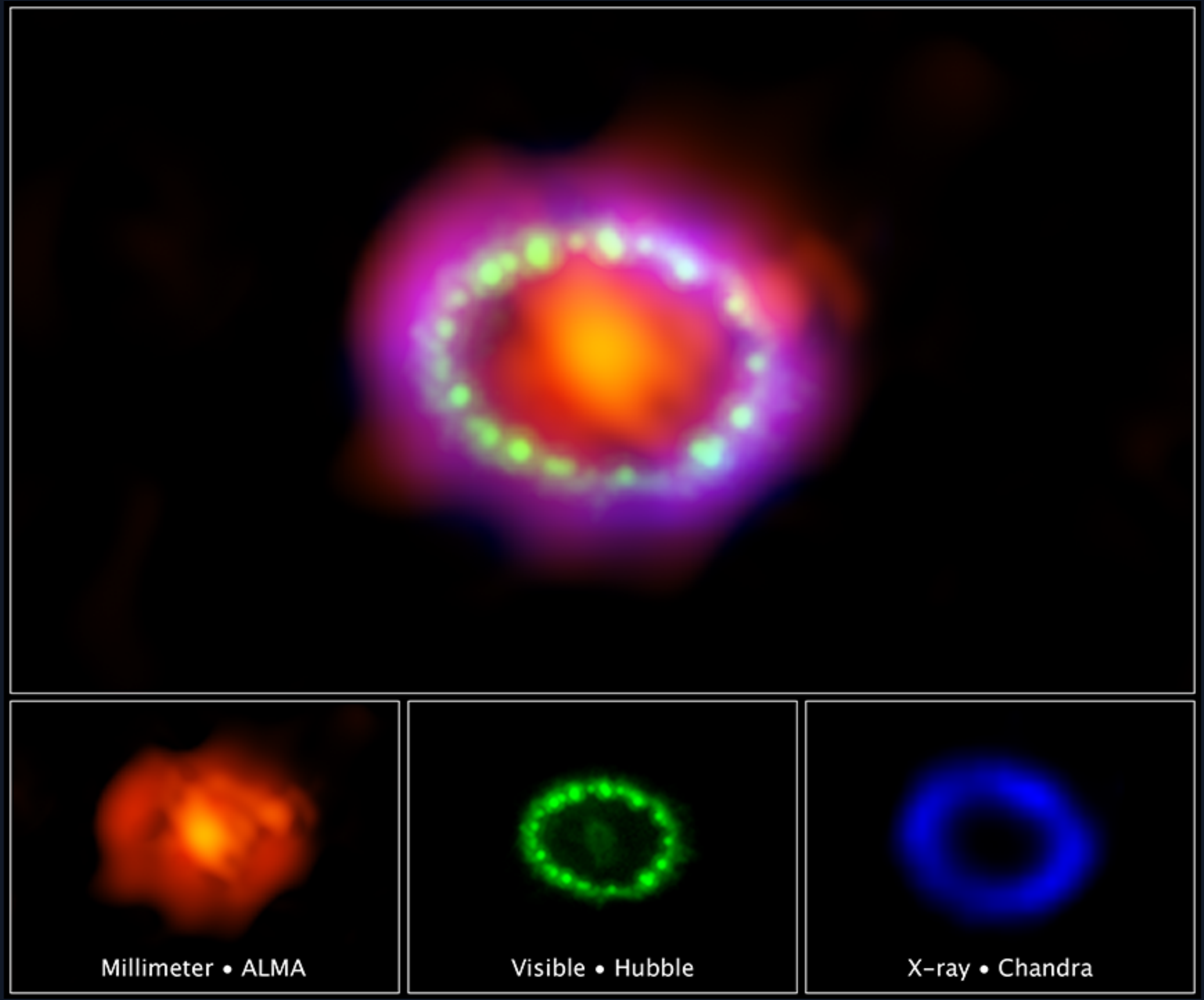
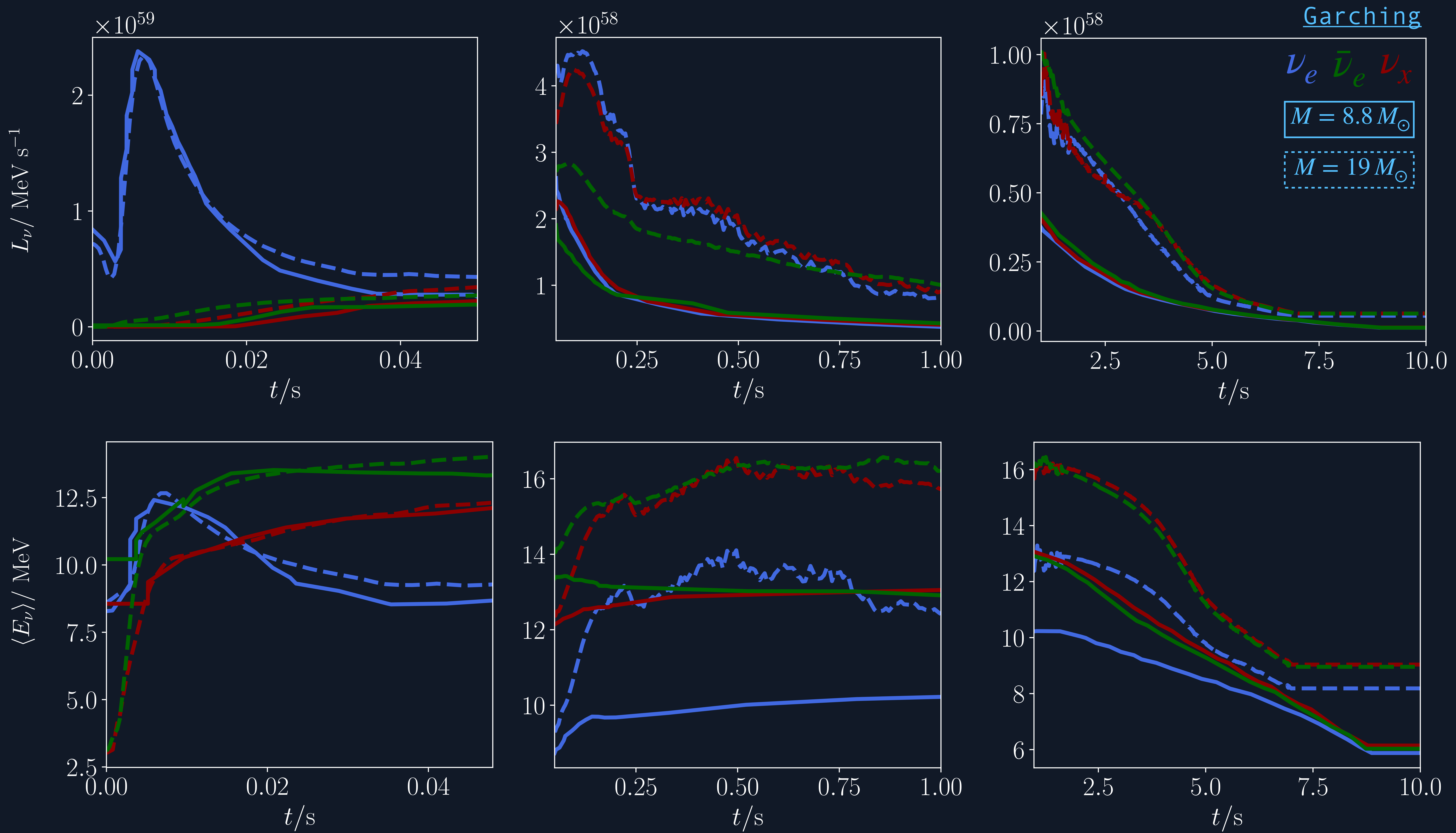
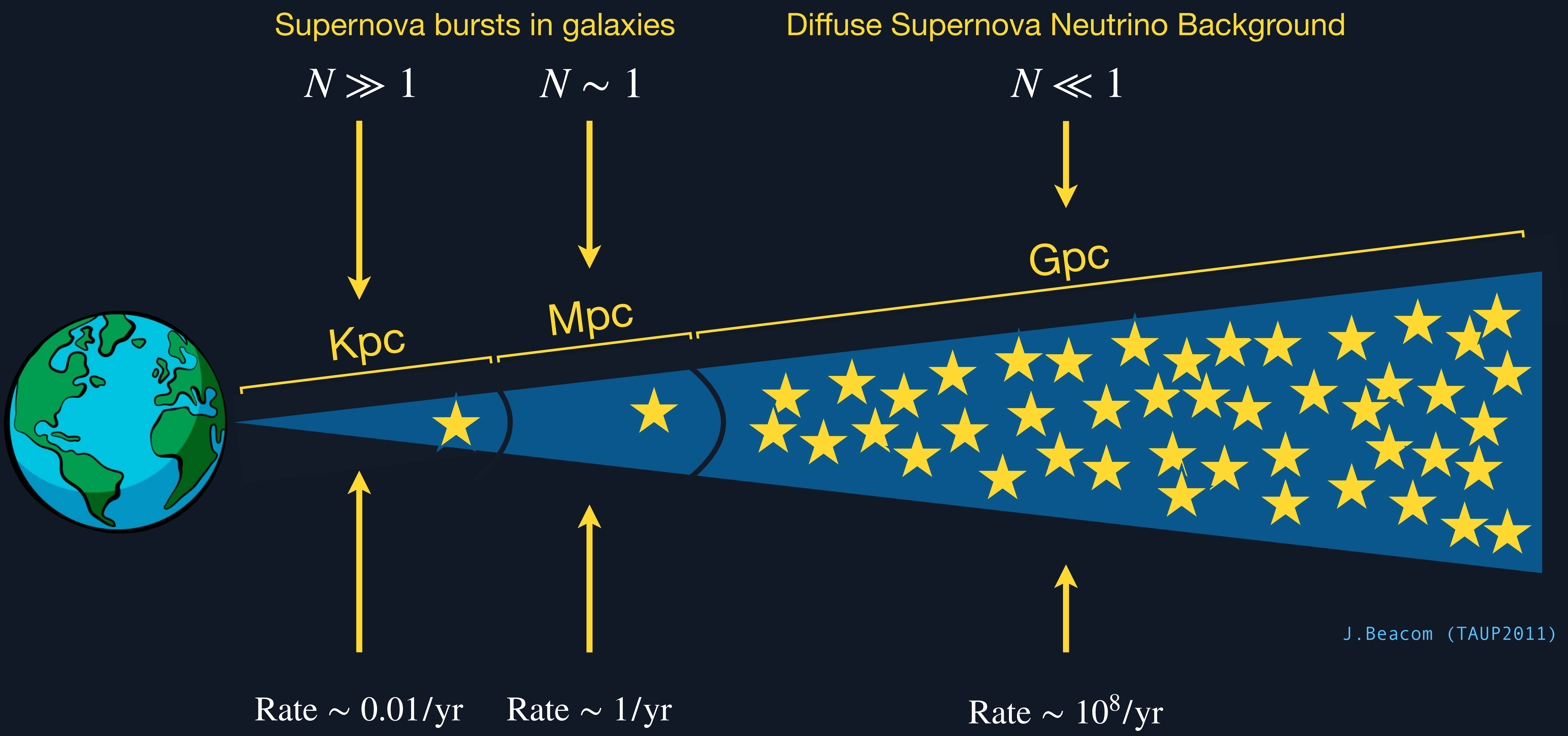


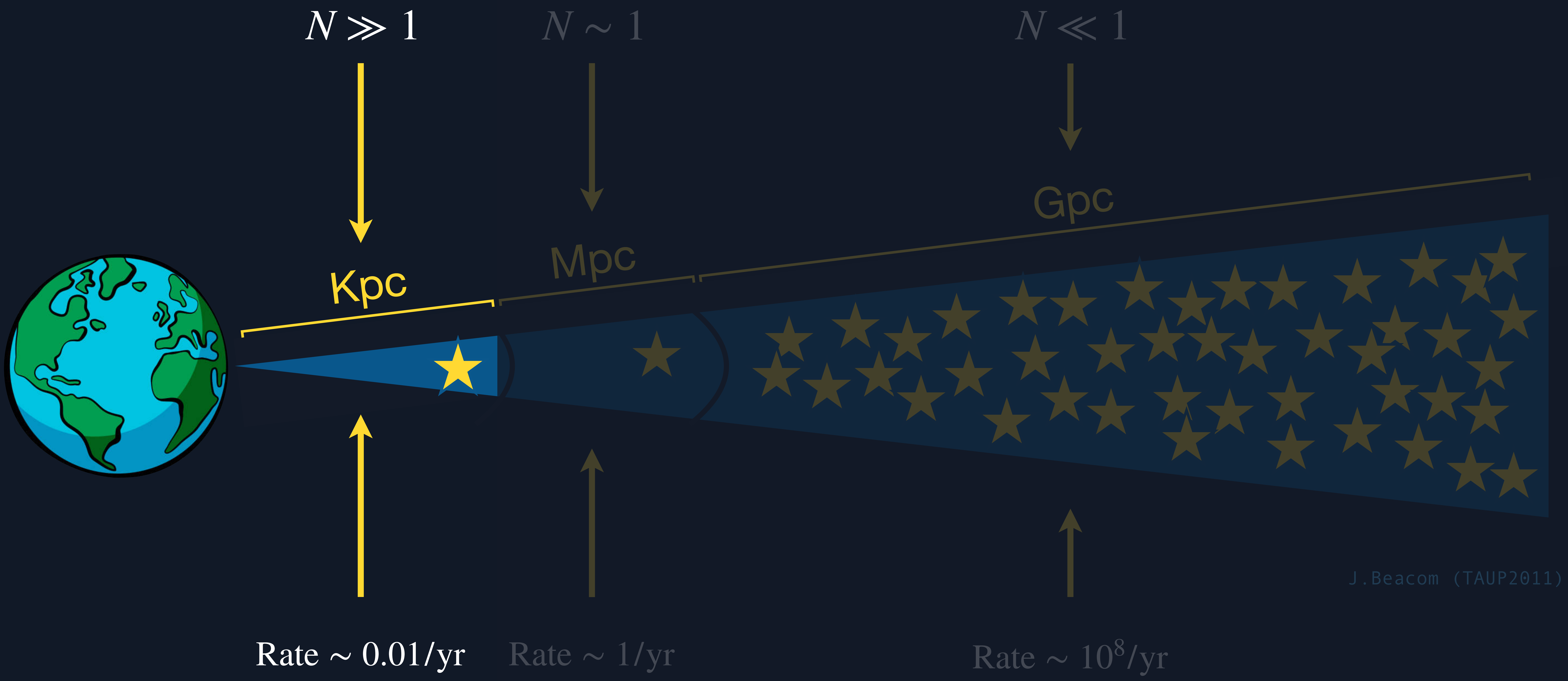
Alma (Eso/Naoj/Nrao), Nasa/Esa Hubble Space Telescope, Nasa Chandra X-Ray Observator


Garching
ν_e $\bar{\nu}_e$ ν_x
$M = 8.8\,M_\odot$
$M = 19\,M_\odot$
L_ν/ MeV s^{-1}
$\langle E_\nu \rangle$/ MeV
t/s
$\times 10^{59}$
$\times 10^{58}$
$\times 10^{58}$


Supernova bursts in galaxies
Diffuse Supernova Neutrino Background
$N \gg 1$
$N \sim 1$
$N \ll 1$
Kpc
Mpc
Gpc
J.Beacom (TAUP2011)
Rate $\sim 0.01/\mathrm{yr}$
Rate $\sim 1/\mathrm{yr}$
Rate $\sim 10^8/\mathrm{yr}$

Supernova bursts in near galaxies

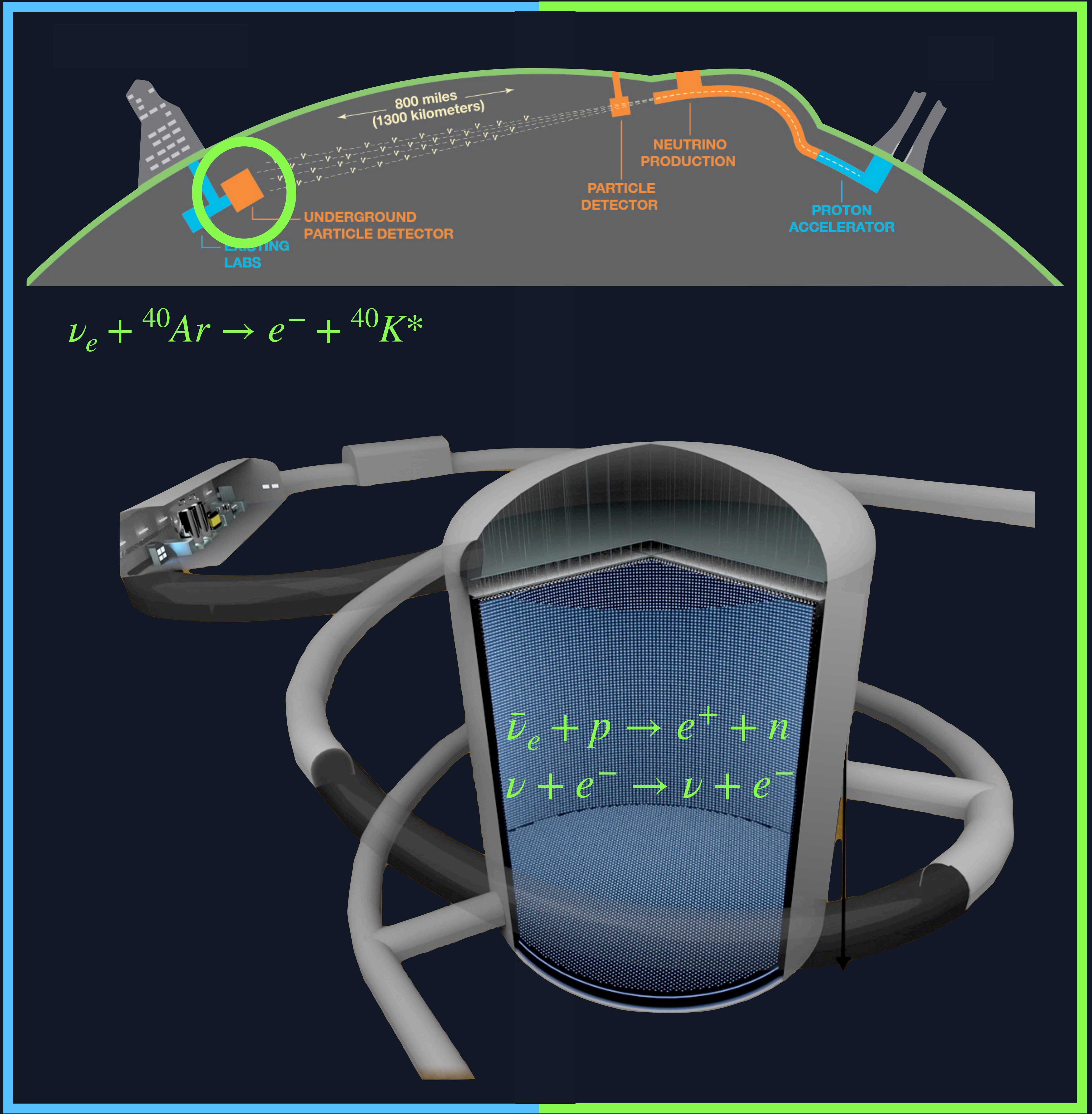
Diffuse Supernova Neutrino Background



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

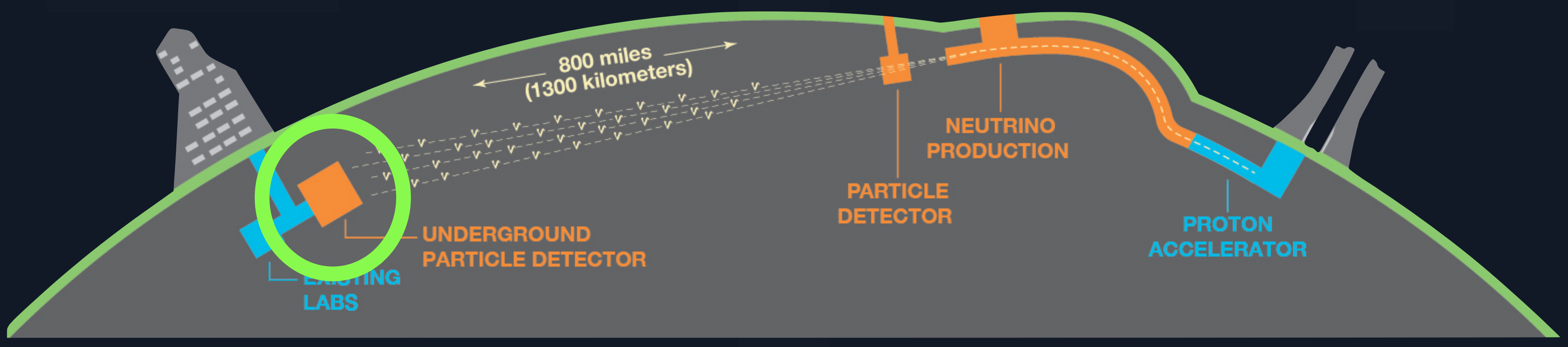
$$R(t,E) = \boxed{N_{\text{target}}\ \epsilon(E)}\ \boxed{\sigma_{\text{sec}}(E)}\ \Phi_\nu(t,E)$$

Detector **Interaction**

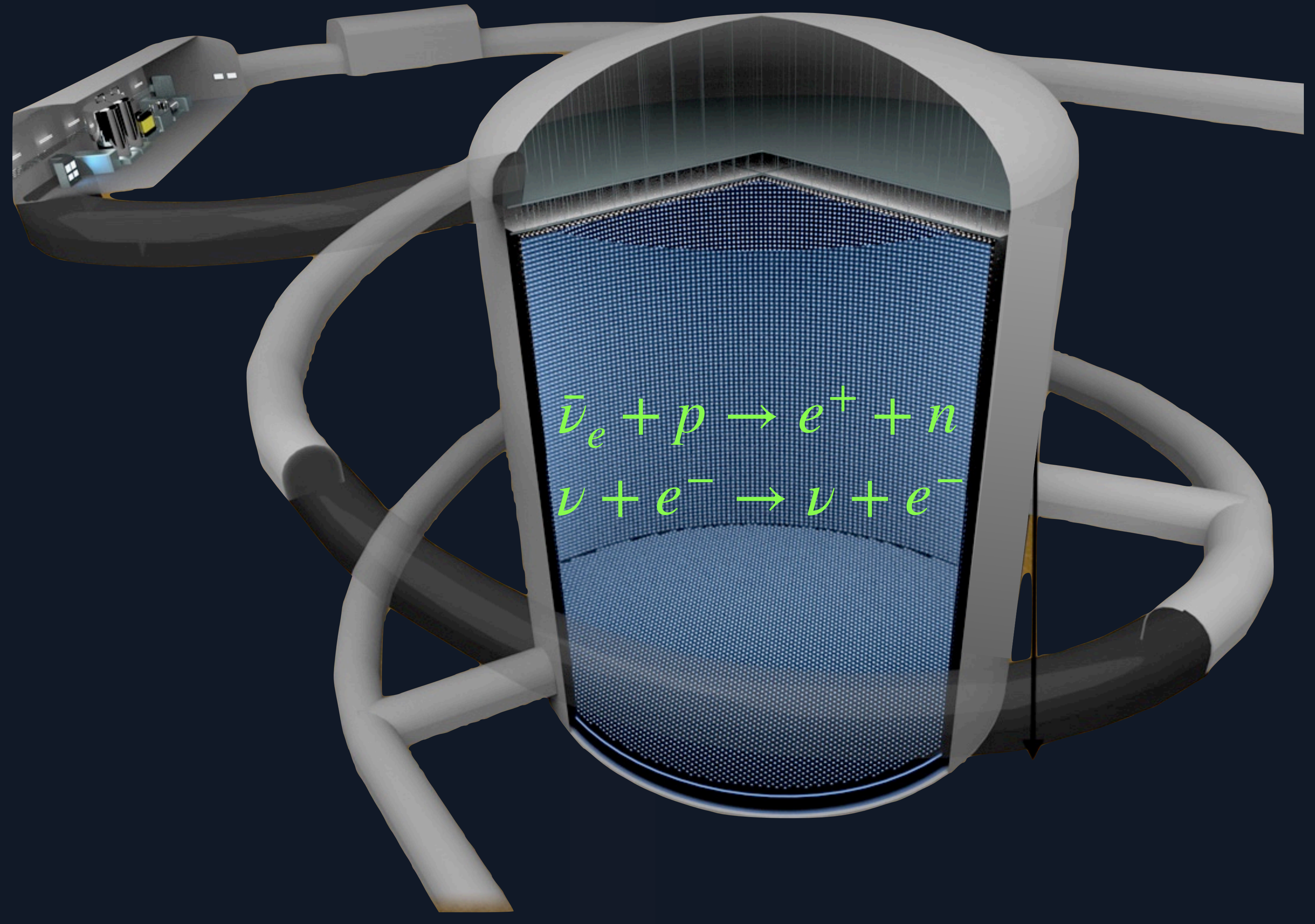


$$R(t, E) = \boxed{N_{\text{target}}\ \epsilon(E)}\ \boxed{\sigma_{\text{sec}}(E)}\ \boxed{\Phi_\nu(t, E)}$$

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

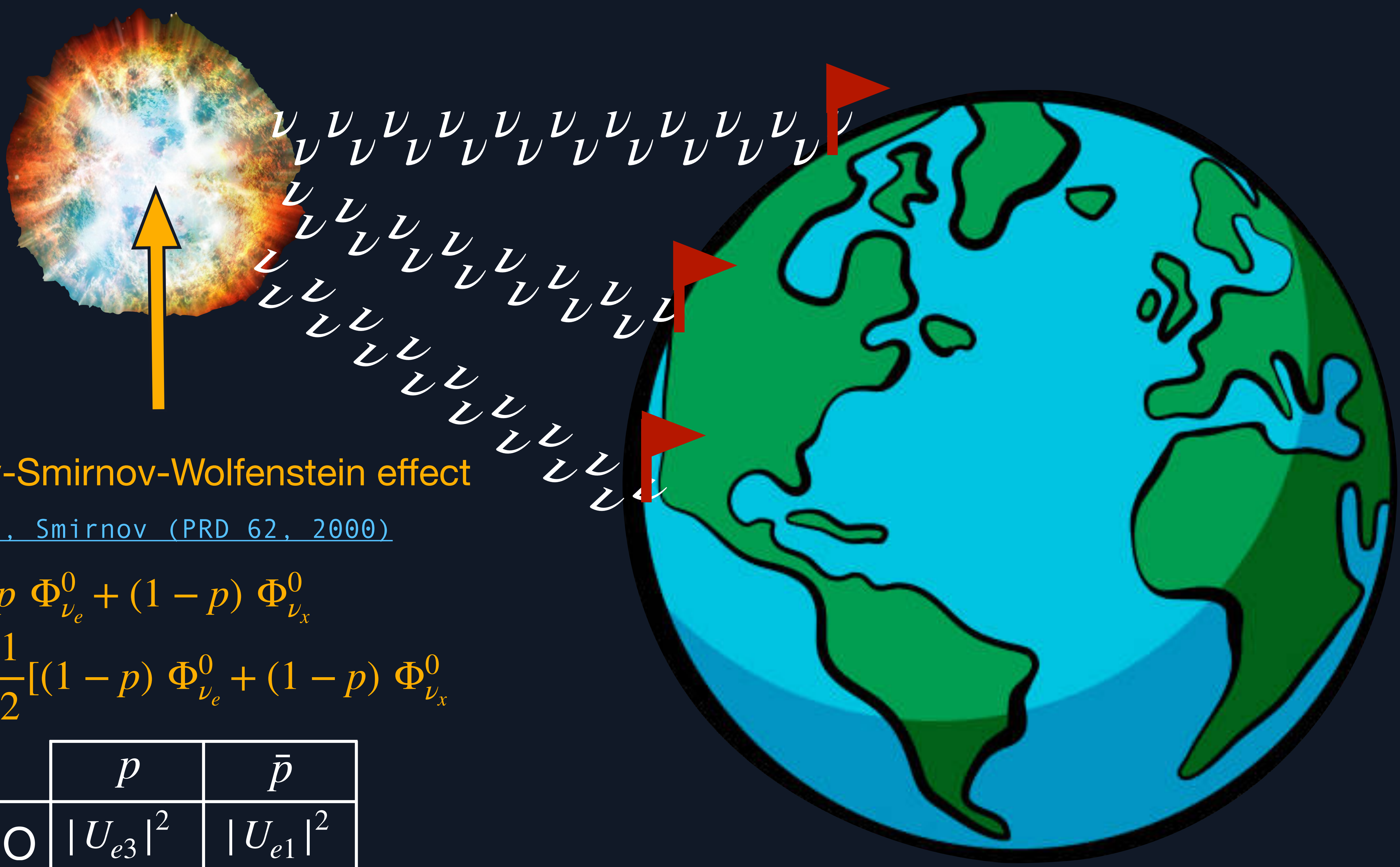


$\nu_e + {}^{40}Ar \rightarrow e^- + {}^{40}K^*$



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

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



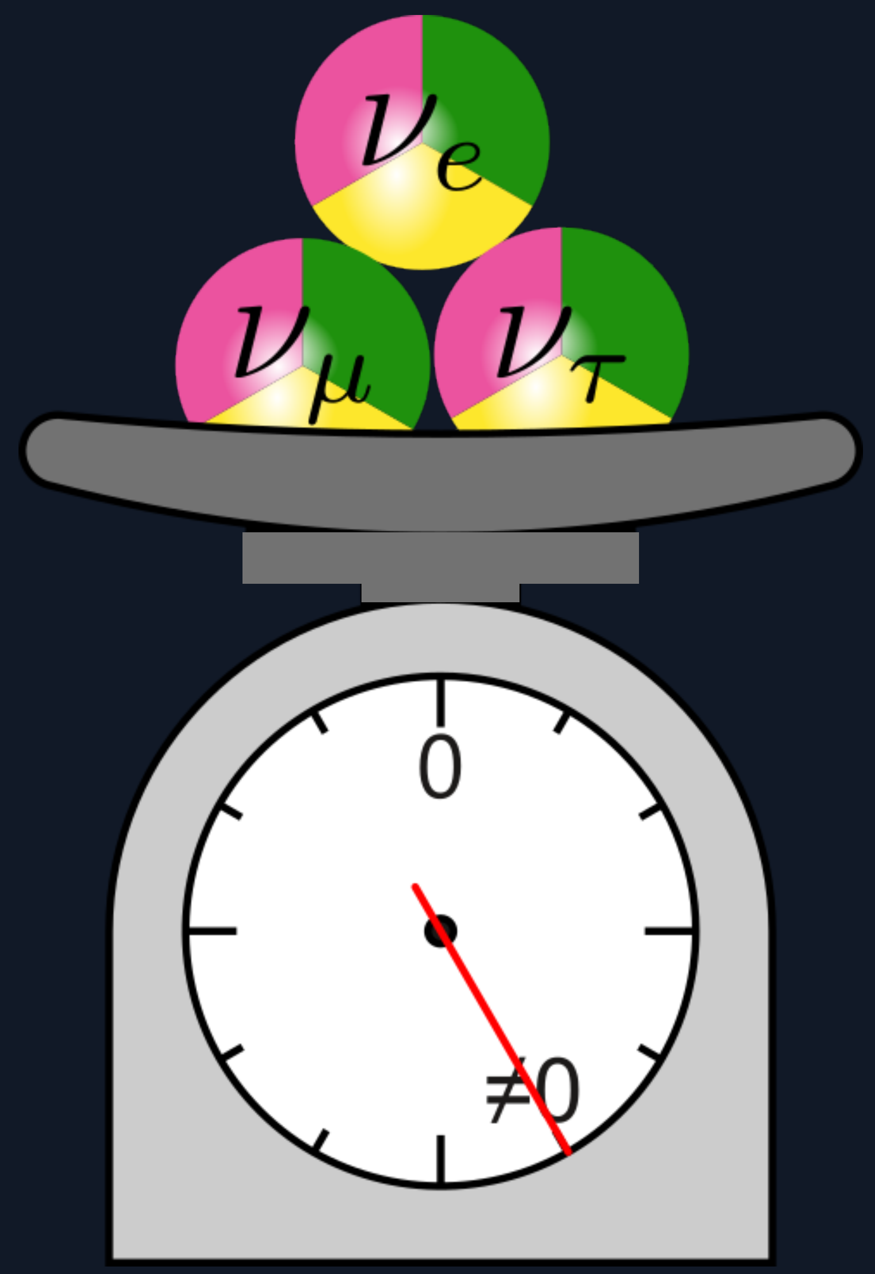
Mikheyev-Smirnov-Wolfenstein effect

Dighe, Smirnov (PRD 62, 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	$\lvert U_{e2}\rvert^2$	$\lvert U_{e3}\rvert^2$



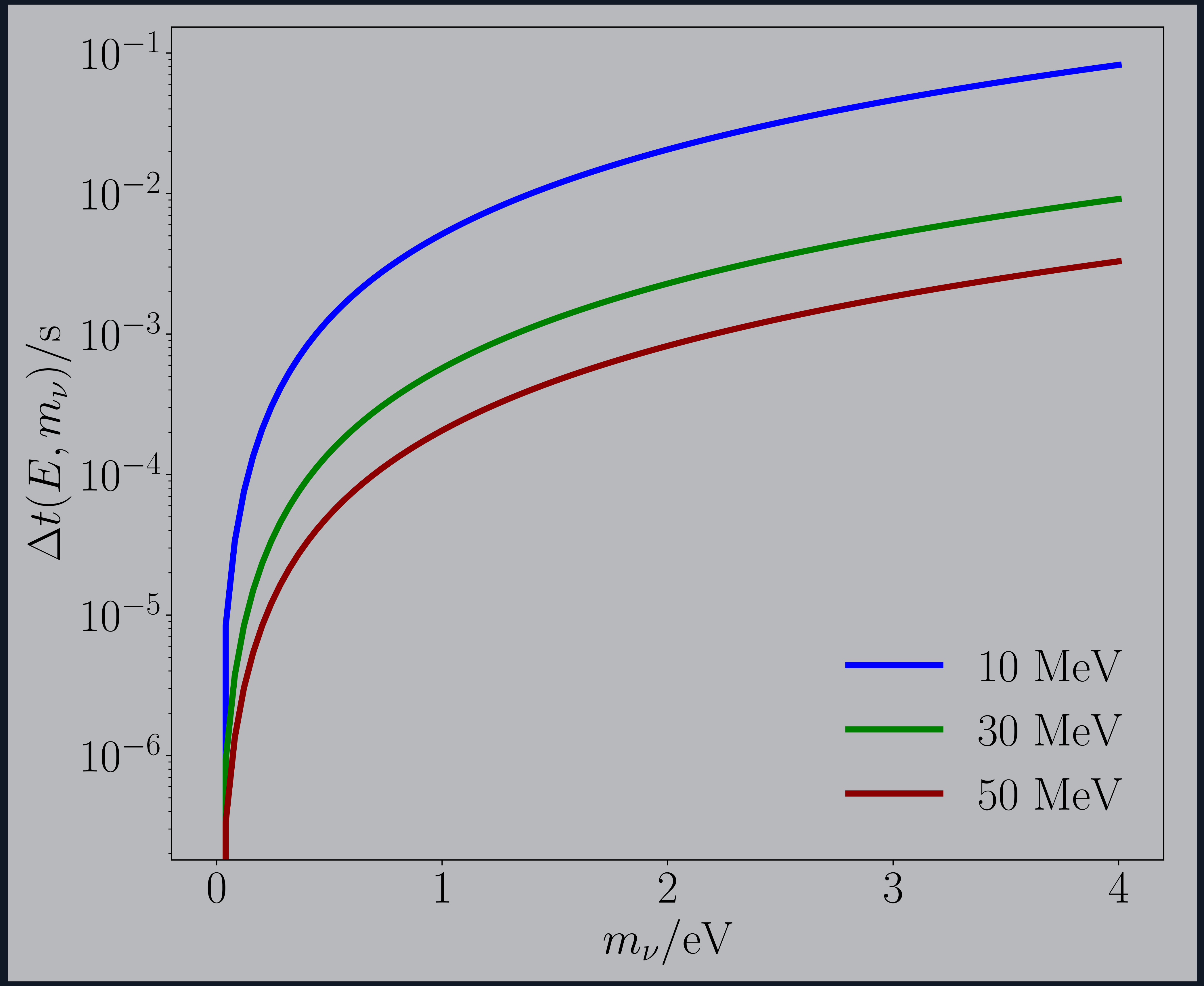
$$\Delta t_i(m_\nu) = \frac{D}{2c}\left(\frac{m_\nu}{E_i}\right)^2$$

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

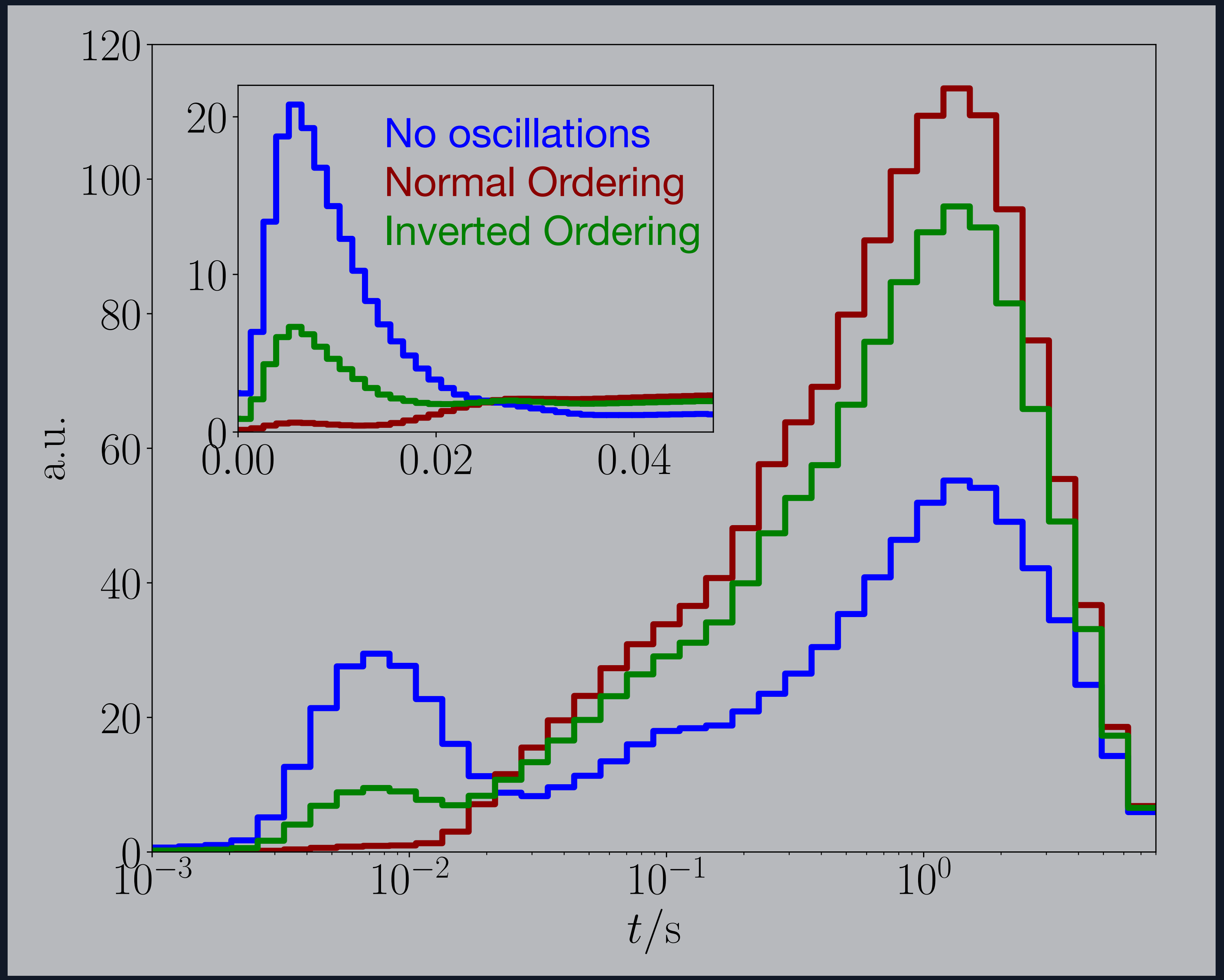
@the detector

@the source

offset time (detector)

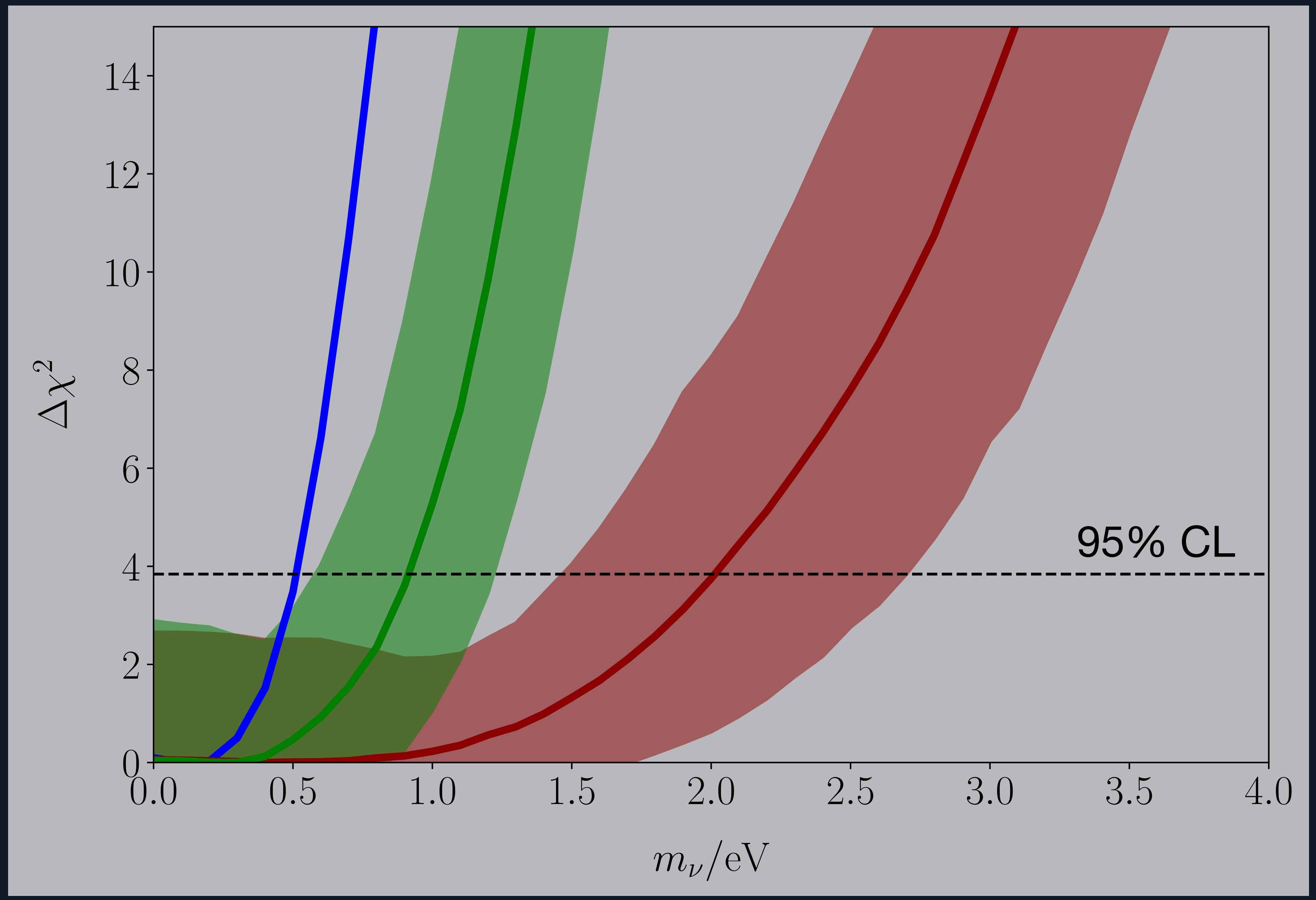


DUNE: D = 10 kpc



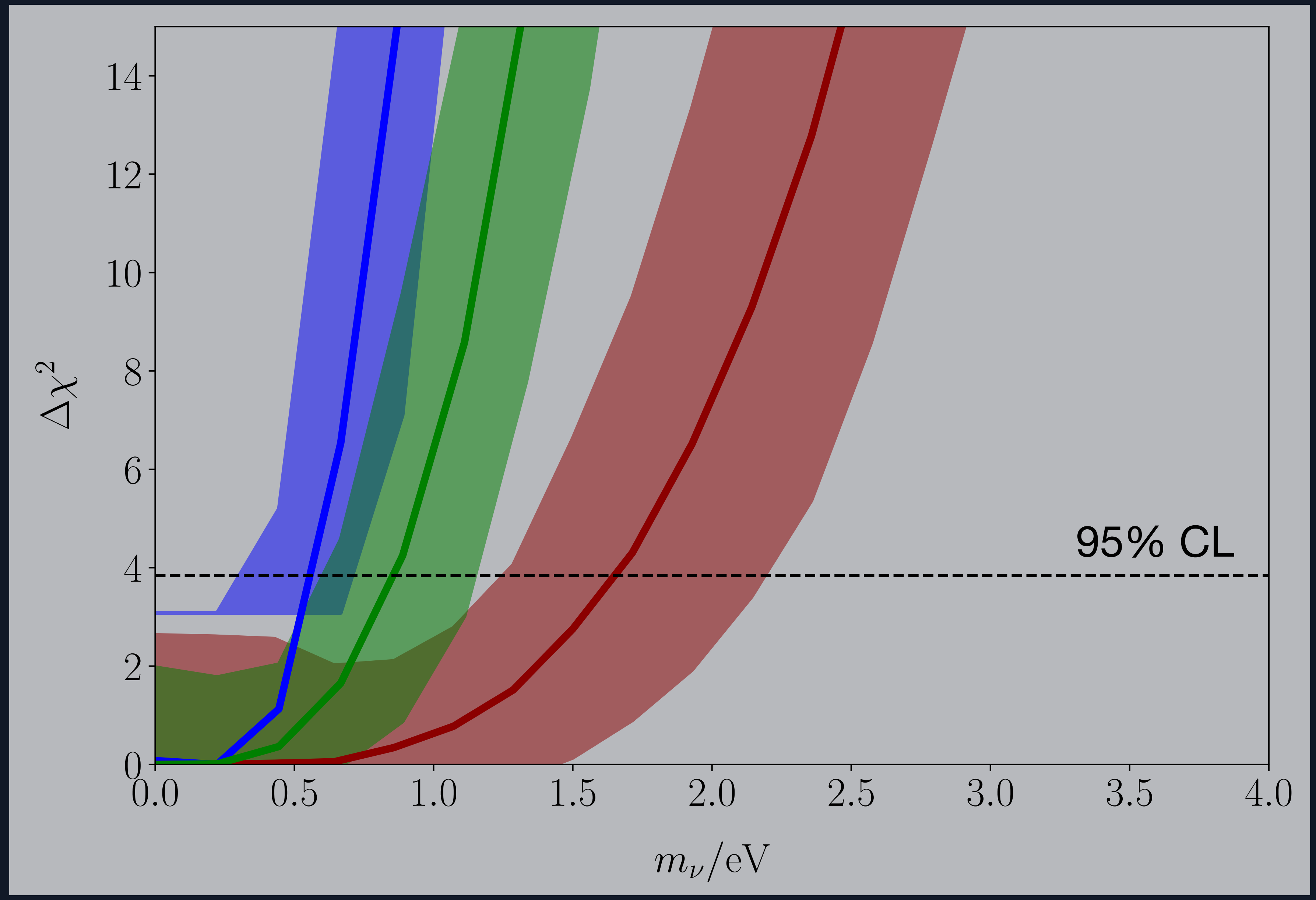
10 s	50 ms
~ 845	~ 201
~ 1372	~ 54
~ 1222	~ 95

$M = 8.8\,M_\odot$



10 s	50 ms
~ 3644	~ 200
~ 5441	~ 88
~ 4936	~ 120

$M = 19\,M_\odot$



UPPER BOUNDS ON

$$m_\nu = \sqrt{\sum_{i=1}^{3} |U_{ei}|^2 m_i^2}$$

$m_\nu \leq 0.51^{+0.20}_{-0.19}$ eV

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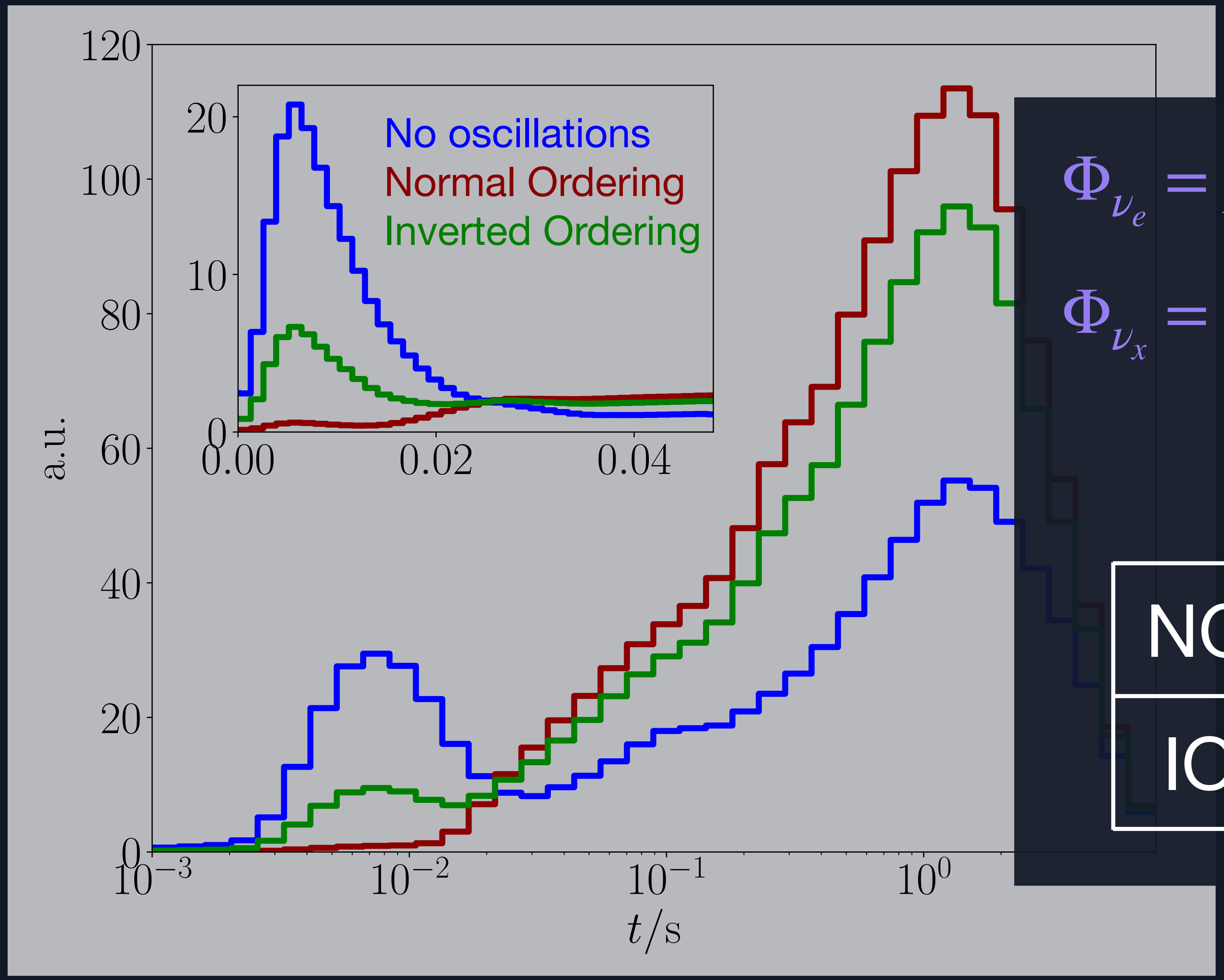
DUNE: *D* = 10 kpc



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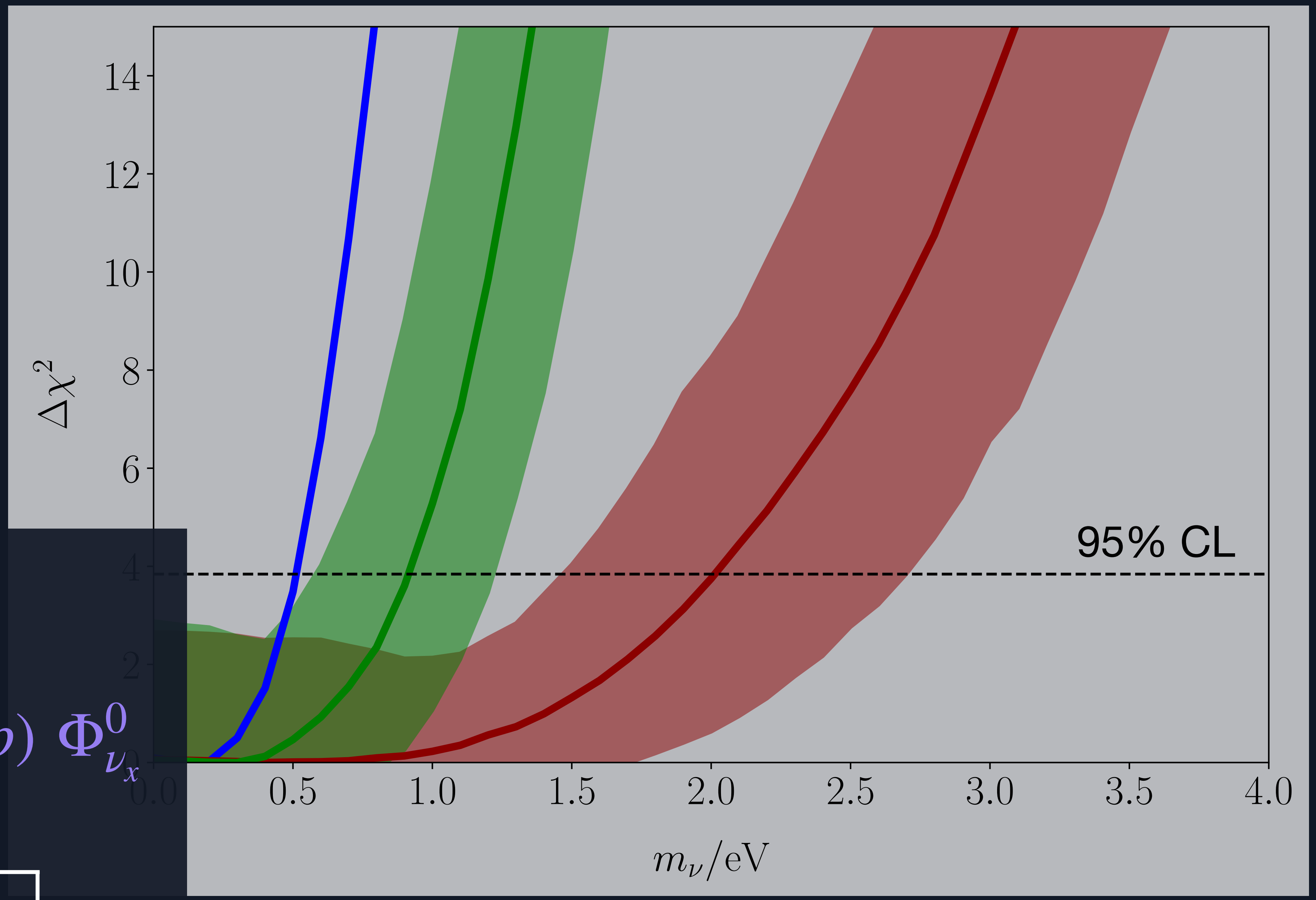

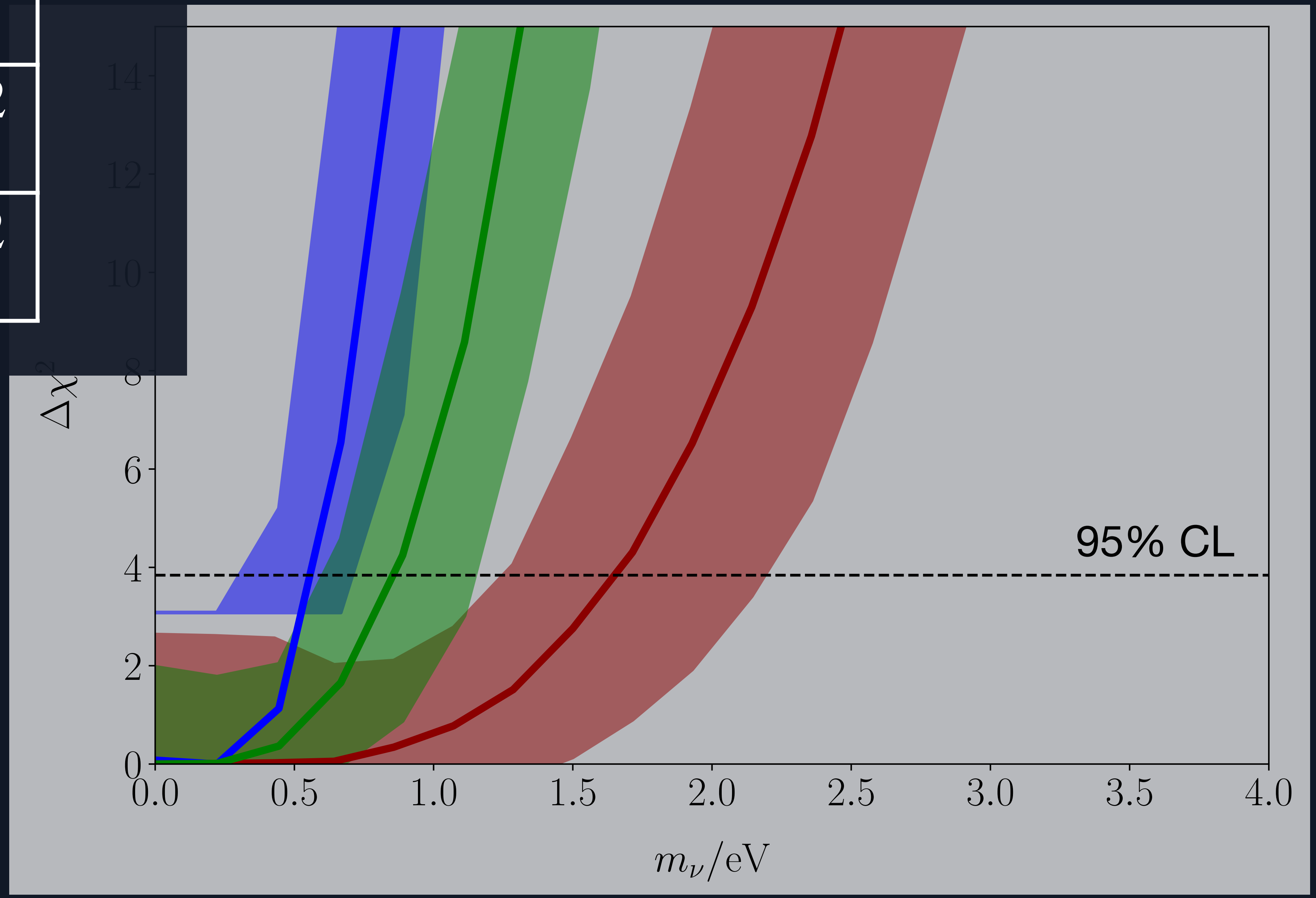

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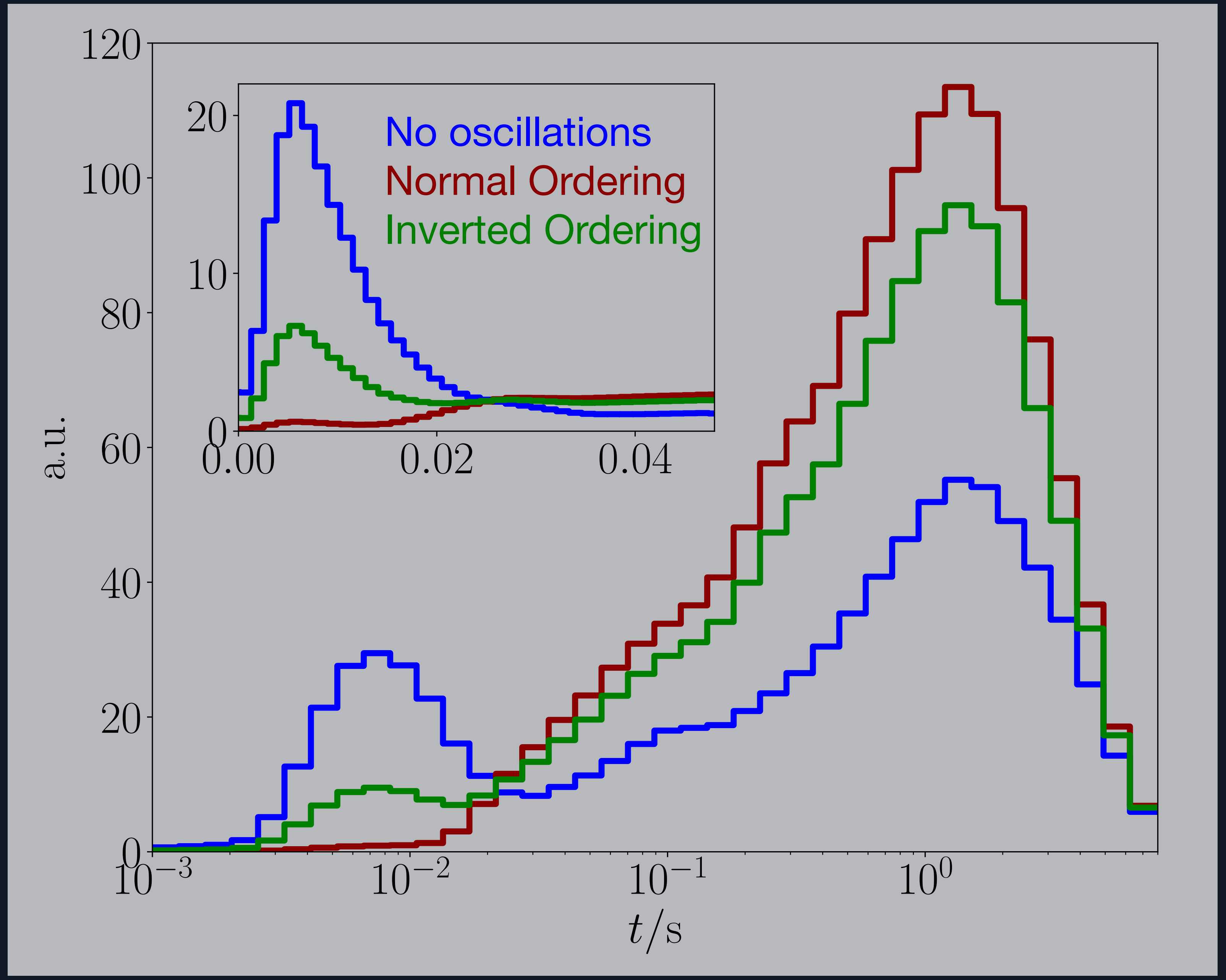

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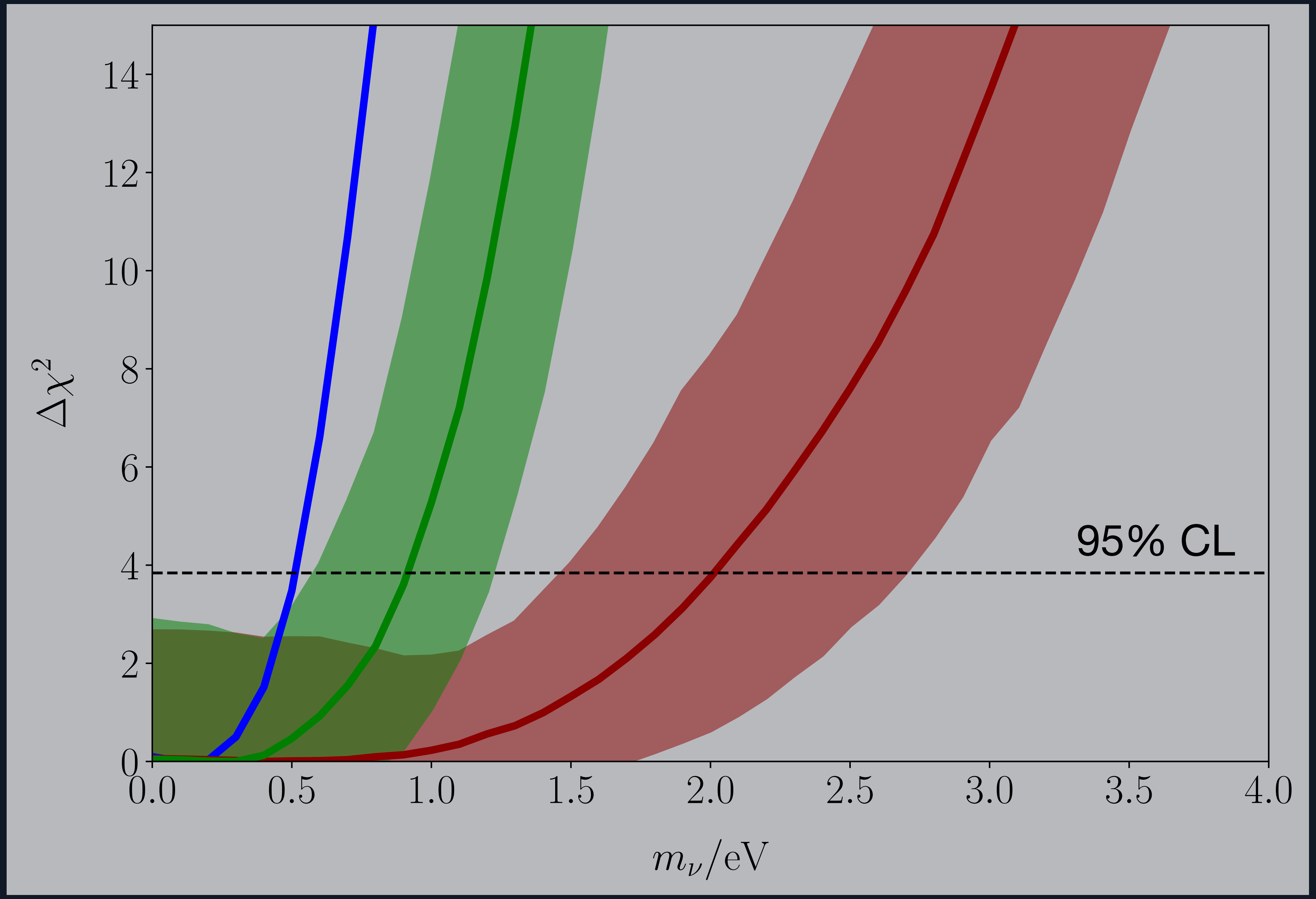

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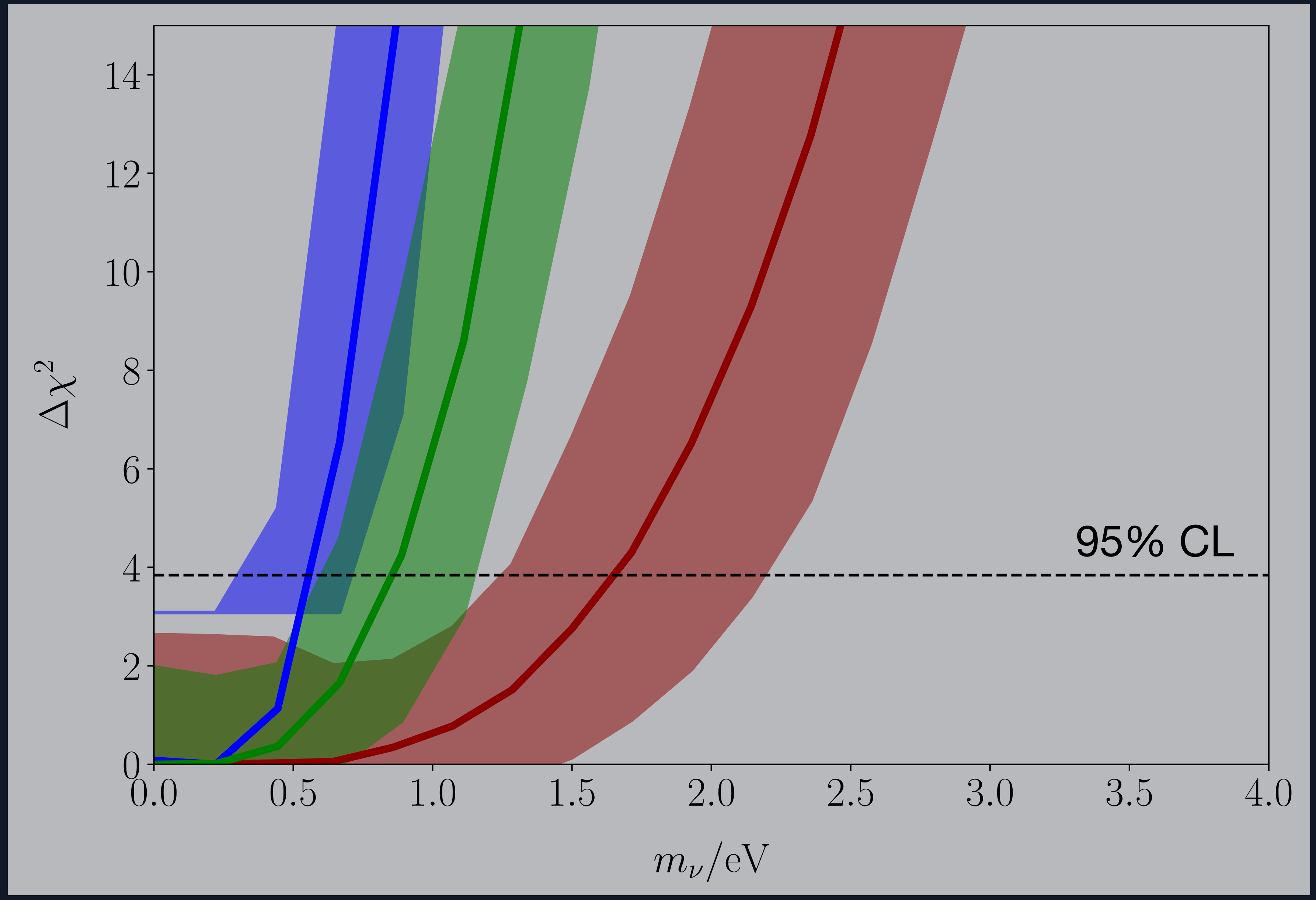

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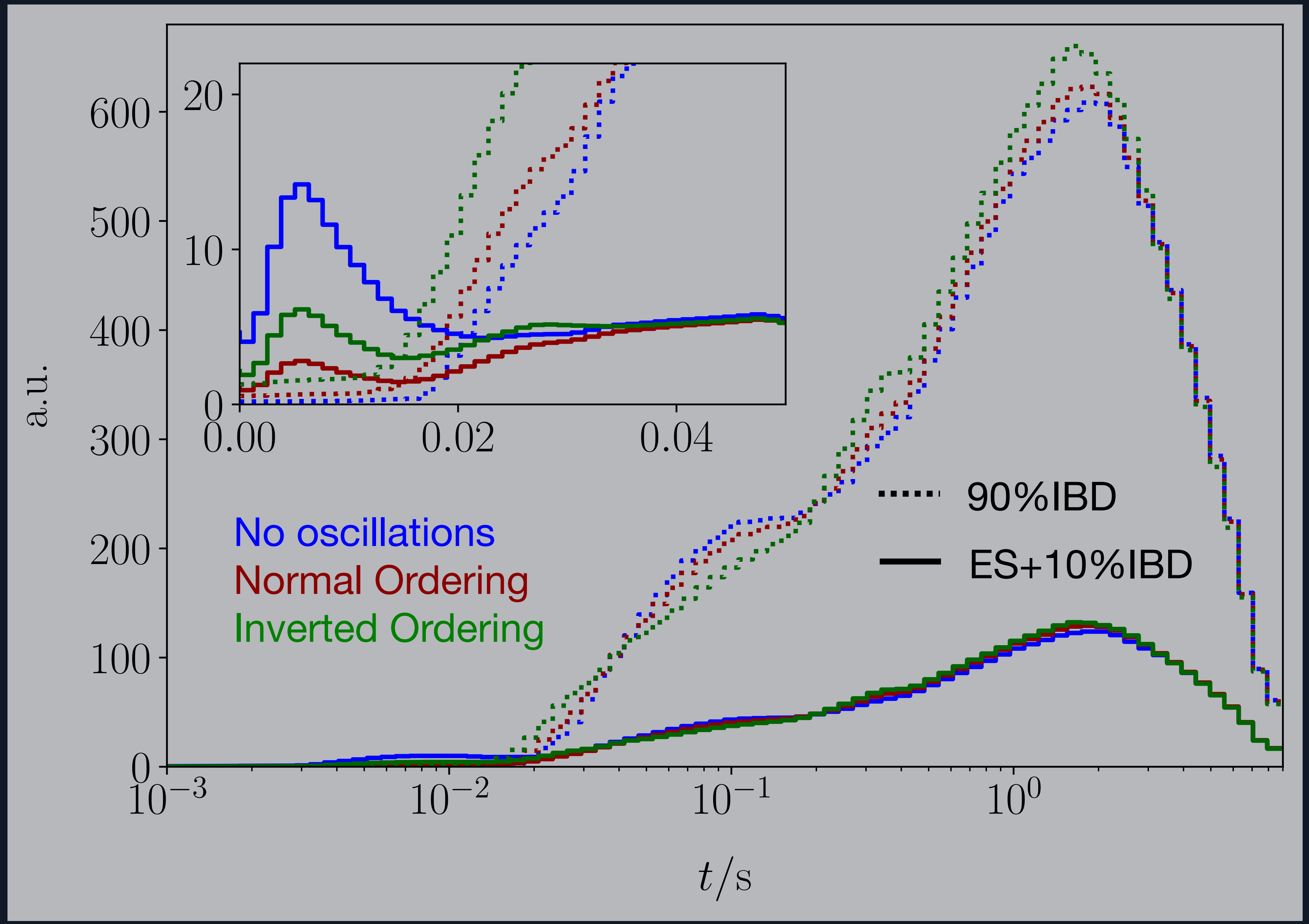
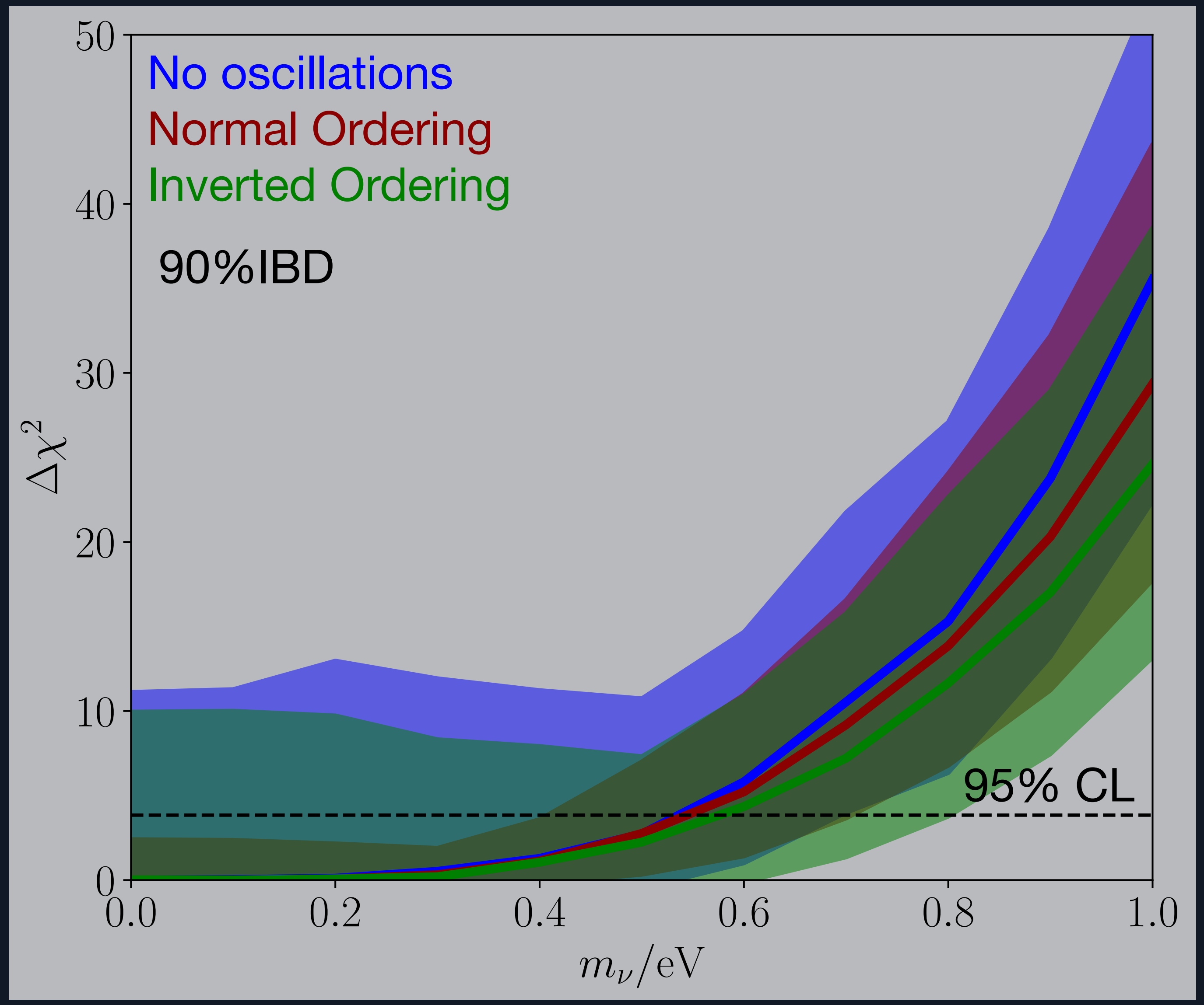
HK: D = 10 kpc





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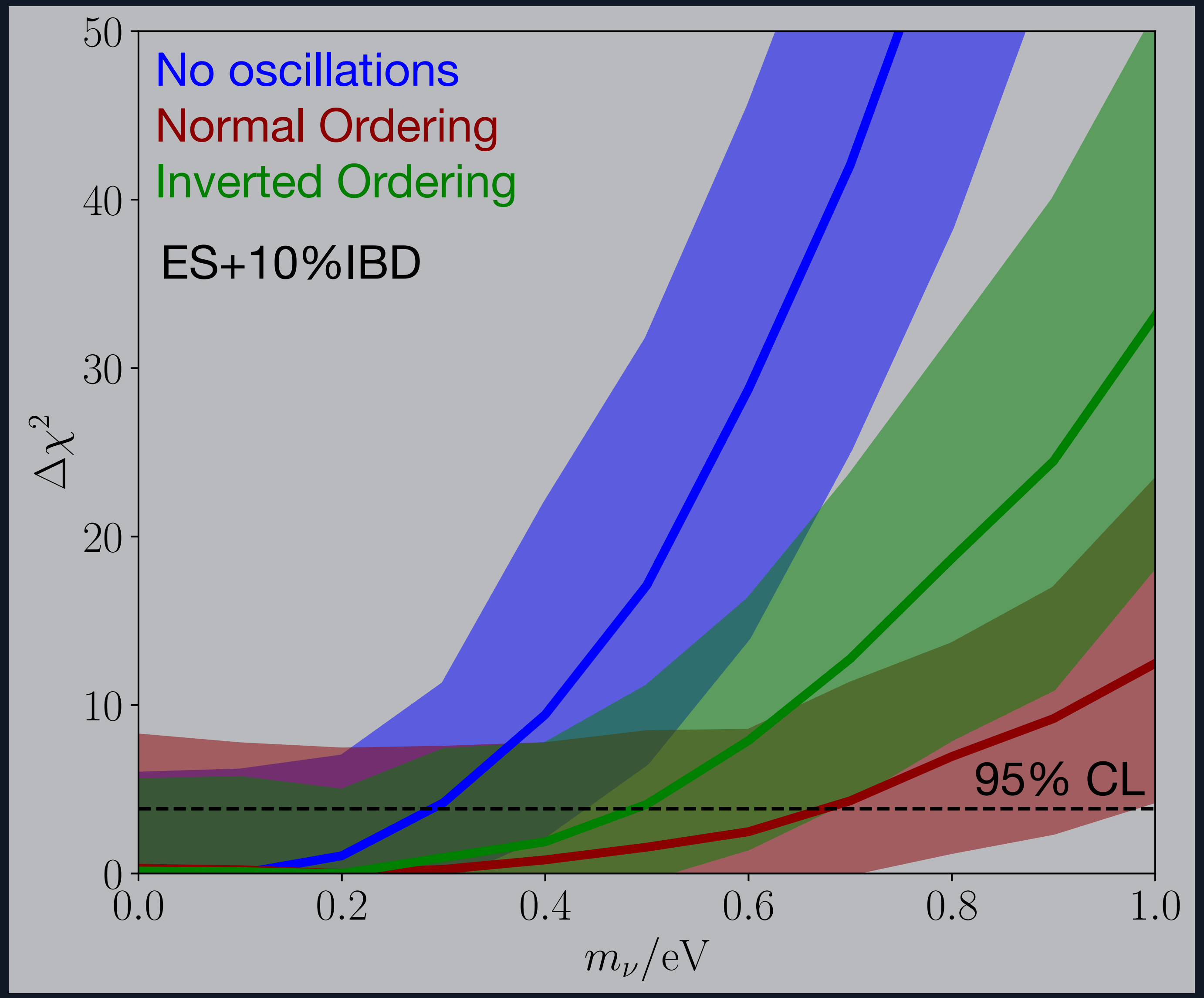
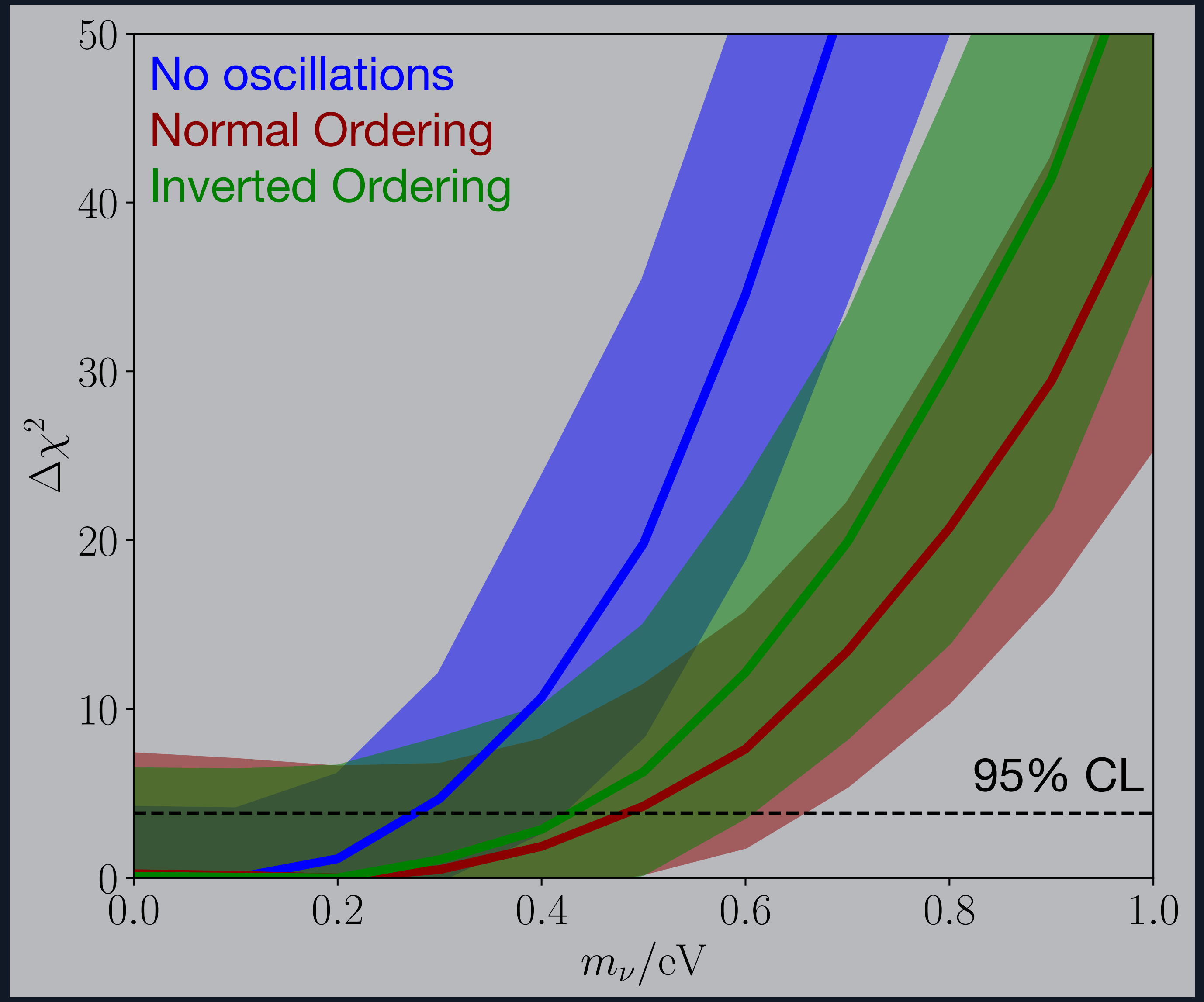


$M = 8.8\,M_\odot$	10 s	50 ms
90%IBD	16003	414
ES+10%IBD	3462	249
90%IBD	16223	466
ES+10%IBD	3419	130
90%IBD	16678	573
ES+10%IBD	3491	178

=



Preliminary!

Take-home message

The neutrino signal coming from the Supernova neutronization burst, visible only in the ν_e spectrum, constitutes an important tool to constrain the absolute value of the neutrino mass and it can give a complementary (and independent) measurement to β-decays and cosmology.

This project has received funding and support from the European Union's Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement No 860881-HIDDeN

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Waiting for SN20XXX…

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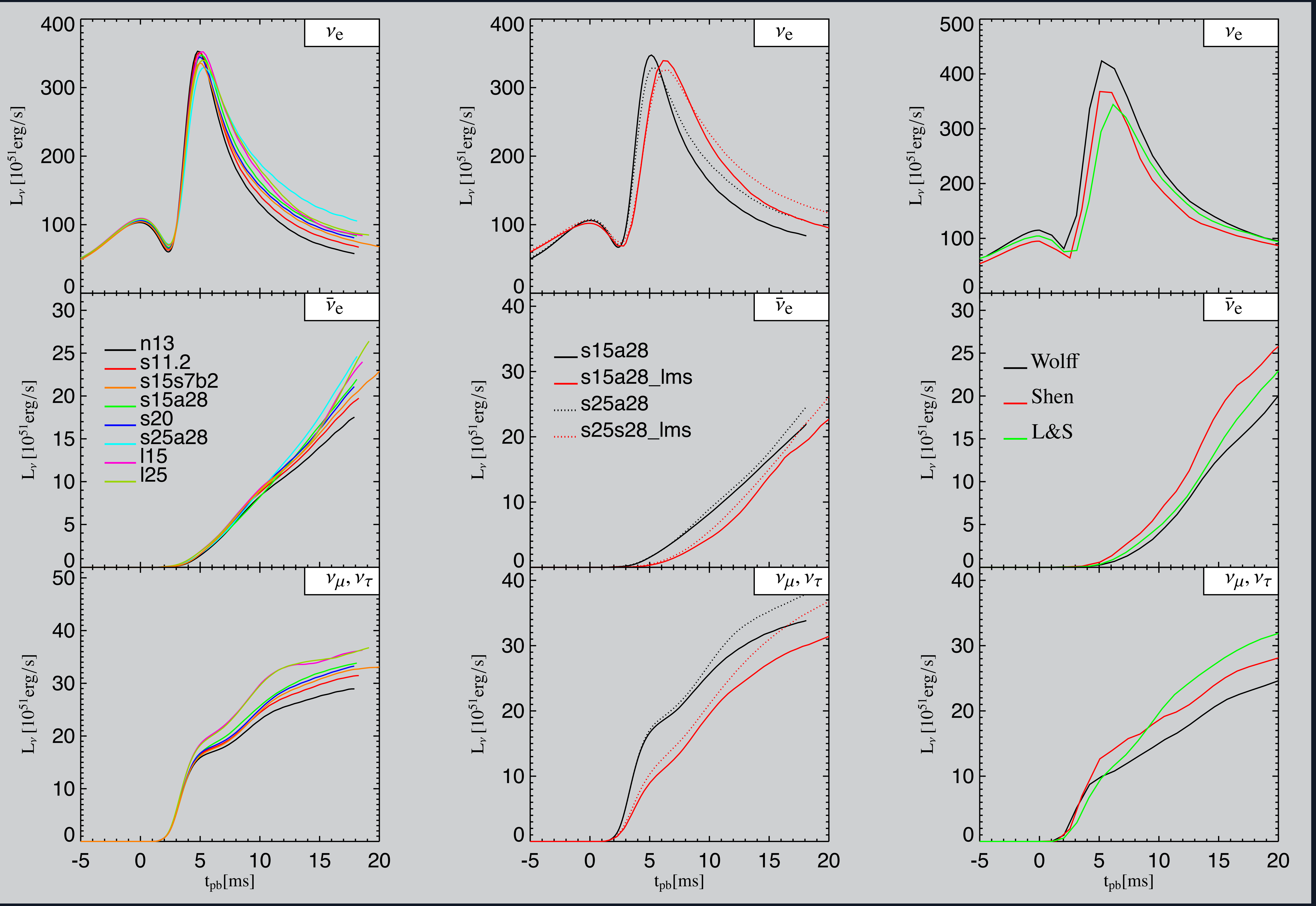
Backup

Supernova parameters uncertainties: luminosity

Kachelriess, Tomas, Buras, Janka, Marek, Rampp (PRD 71, 2005)



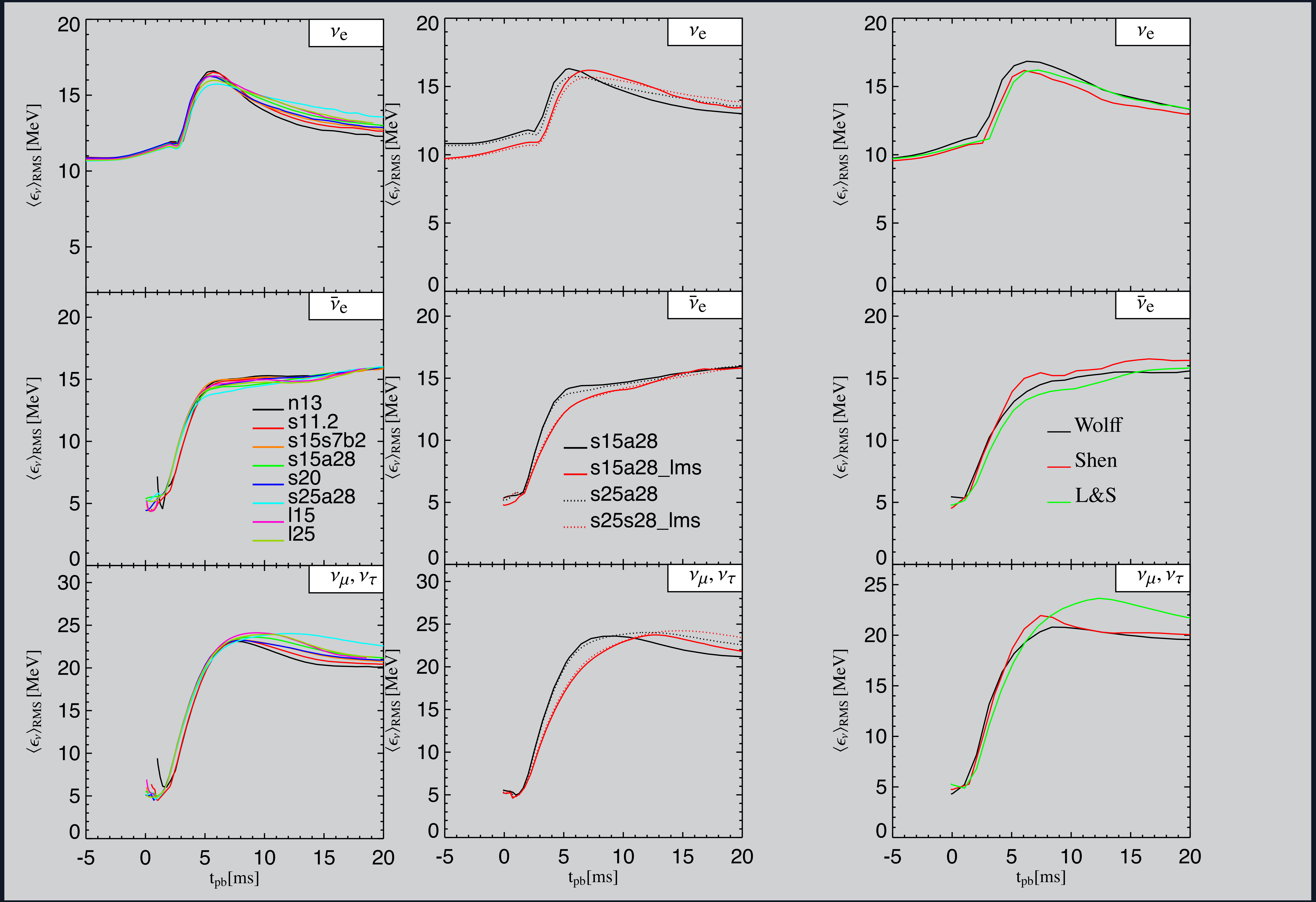
The neutronization burst results to be a robust, **model independent** prediction of the Supernova models.

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

Kachelriess, Tomas, Buras, Janka, Marek, Rampp (PRD 71, 2005)



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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 neutrinos emission: details

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

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

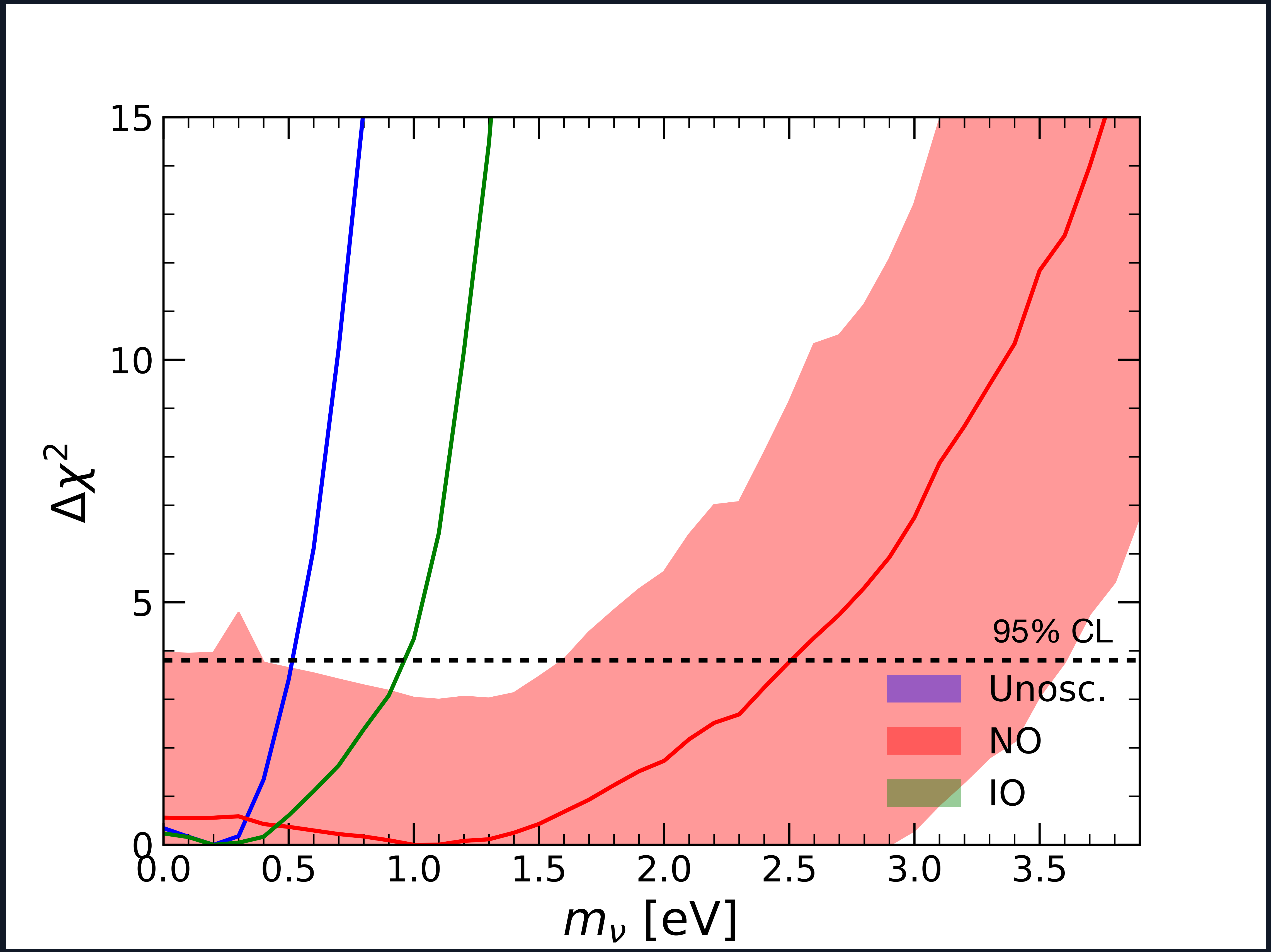
$$\alpha_\beta(t) = \frac{2\langle E_{\nu_\beta}(t)\rangle^2 - \langle E^2_{\nu_\beta}(t)\rangle}{\langle E^2_{\nu_\beta}(t)\rangle - \langle E_{\nu_\beta}(t)\rangle^2}$$

Backup

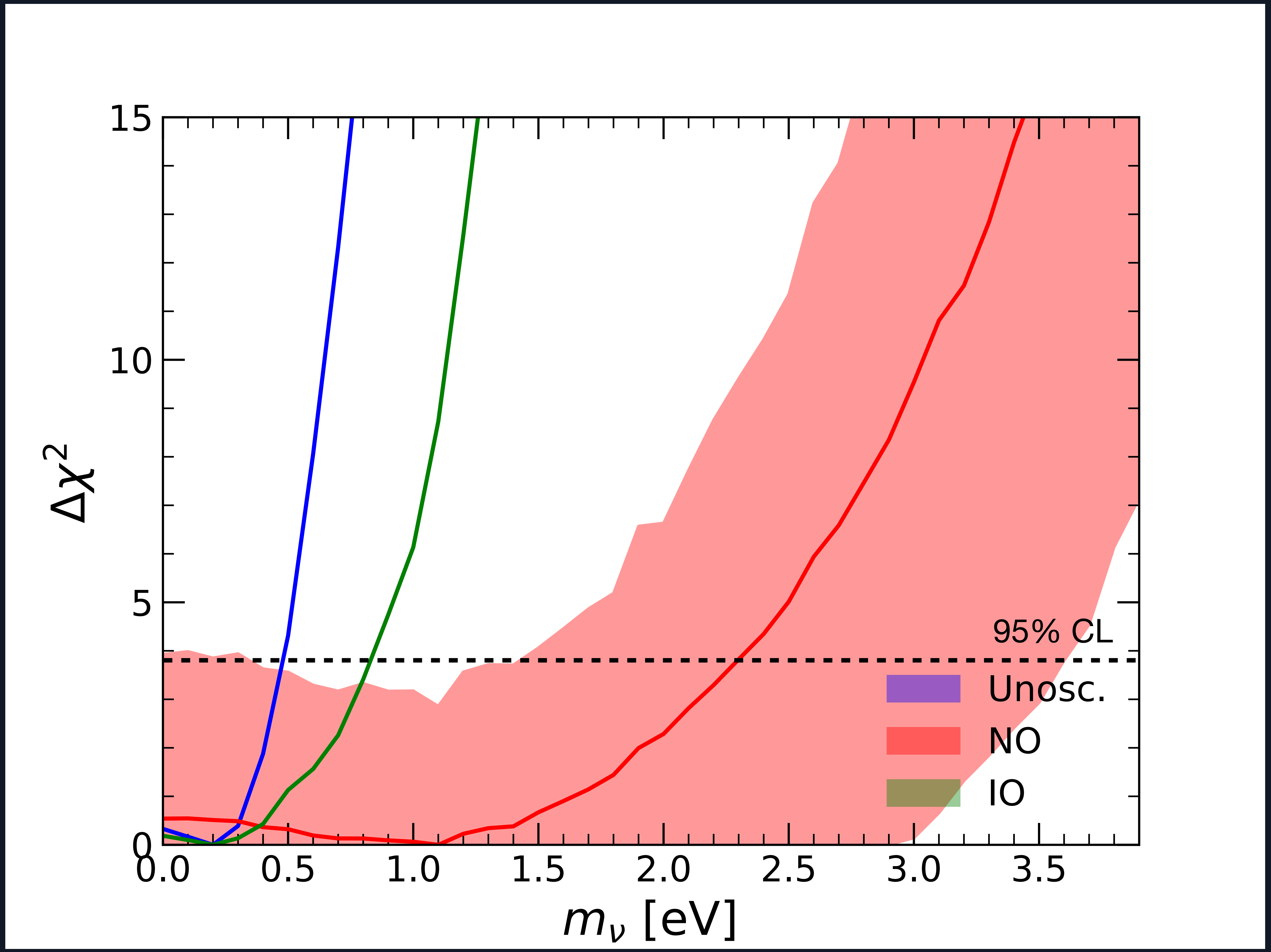
Dependency on SN parameters

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

$$\alpha_{\nu_\beta} = (1 + f^2_{\nu_\beta})\ \alpha^0_{\nu_\beta}$$



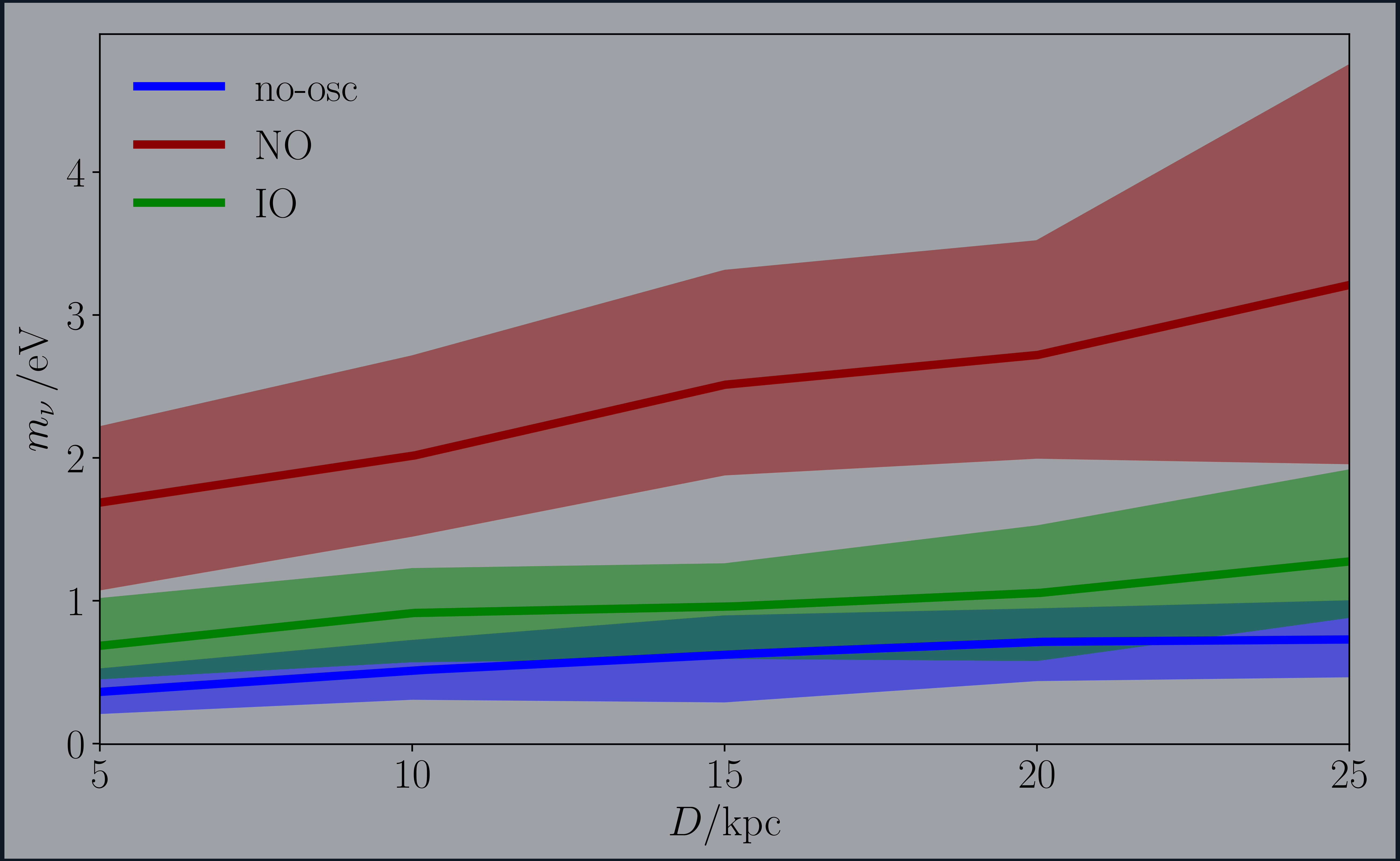
One time-windows: [0, 10] s



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

Backup

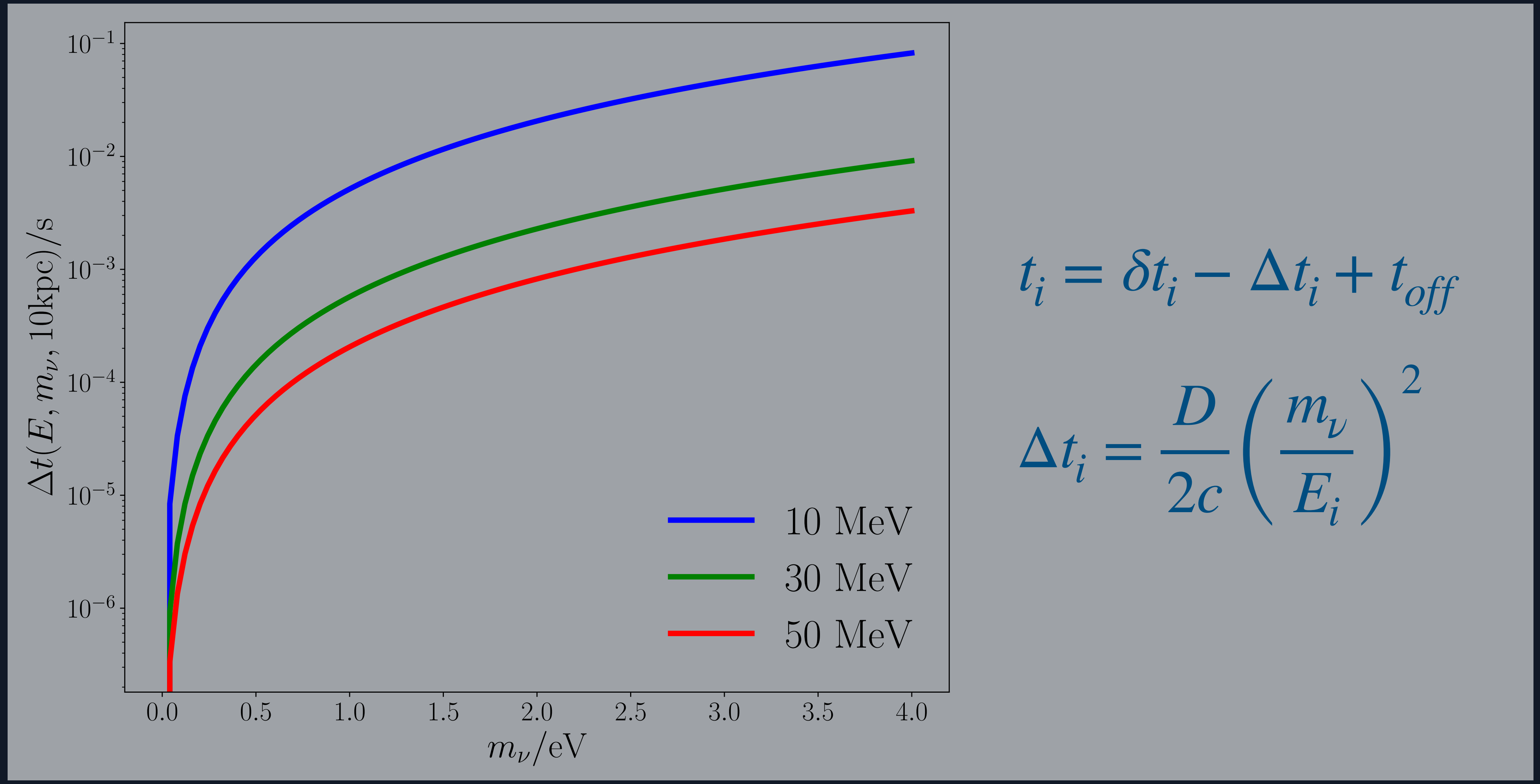
Dependency on SN distance



Backup

Likelihood analysis

Pagliaroli, Vissani, Costantini, Ianni (Astropart. Phys. V31, 2009)



- 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

Evolution operator definition

Lisi, Montanino (PRD 56, 1997)

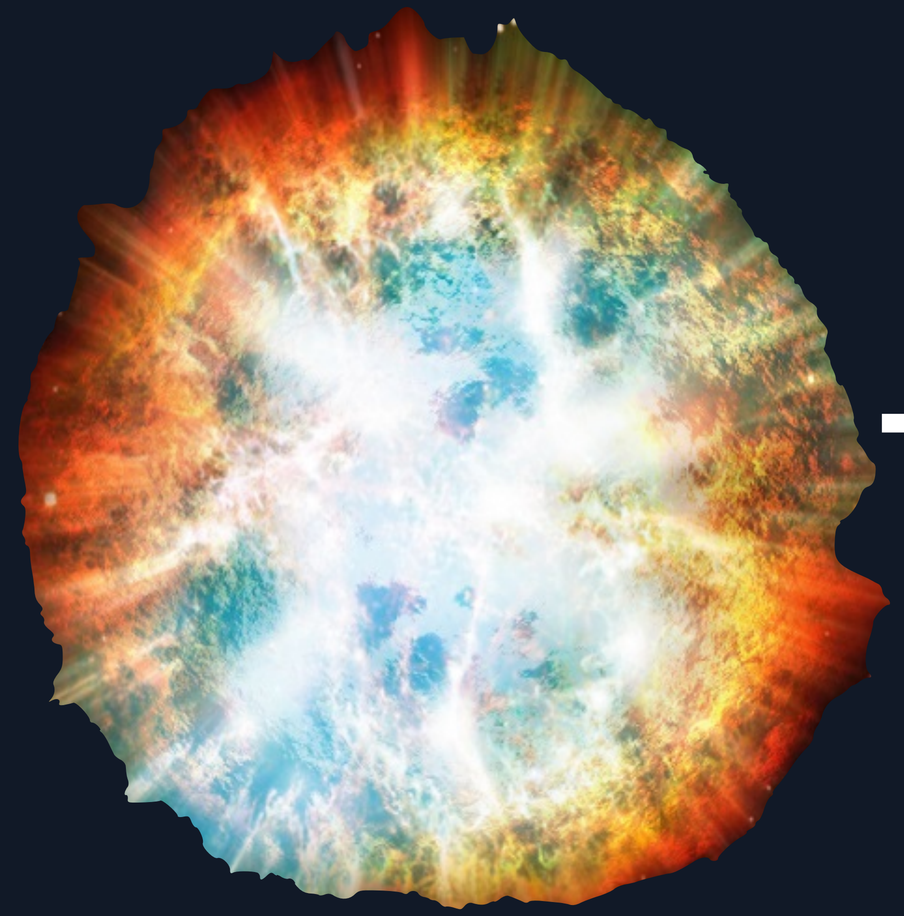
$$\mathcal{T}(\overline{P_{j-1}P_j}) = \exp\{-i(H_0 - V_{matter,j}) \cdot l_j\}$$

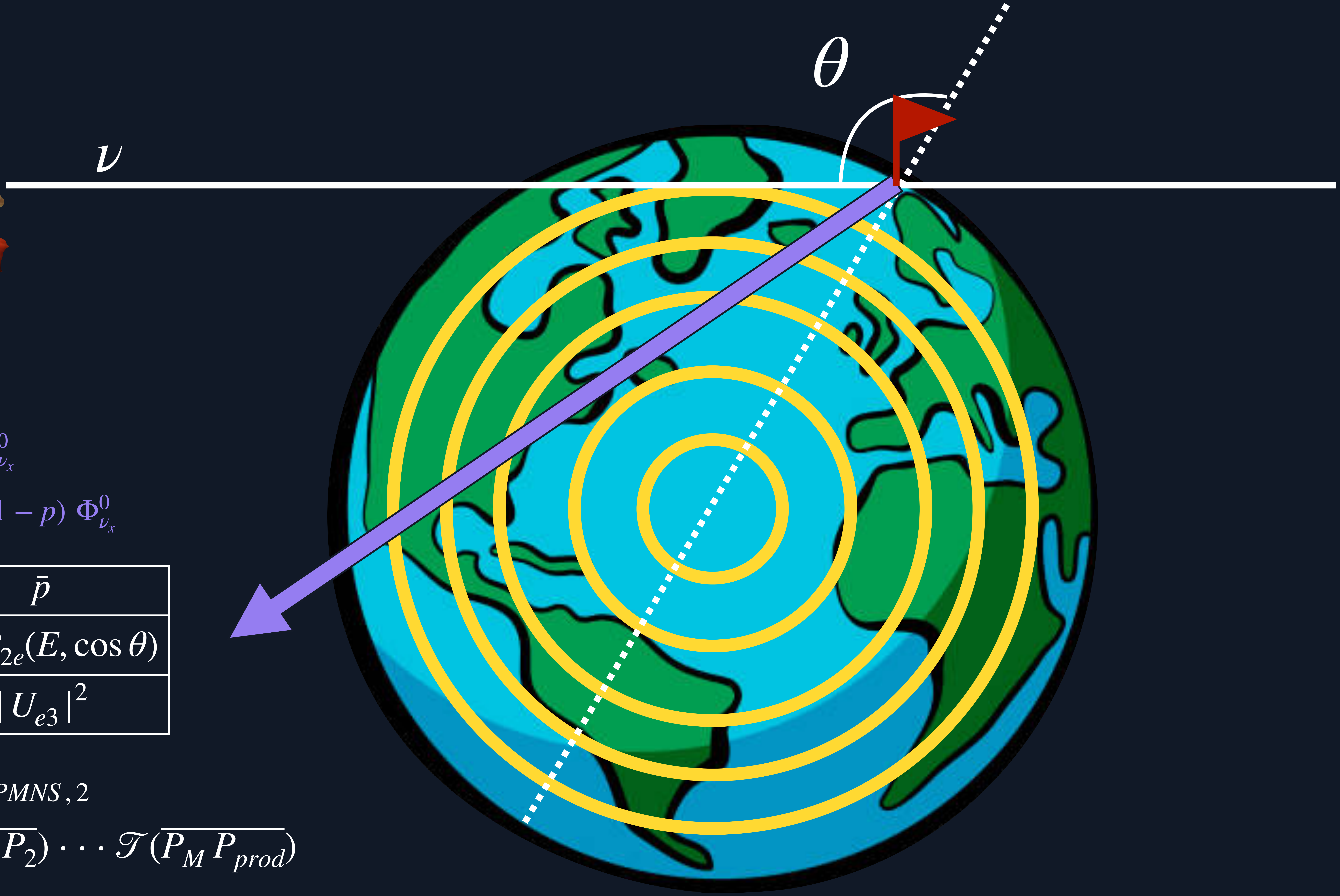
$$H_0 = \frac{U_{PMNS} M_{mass} U^{\dagger}_{PMNS}}{2E}$$

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

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

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





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

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

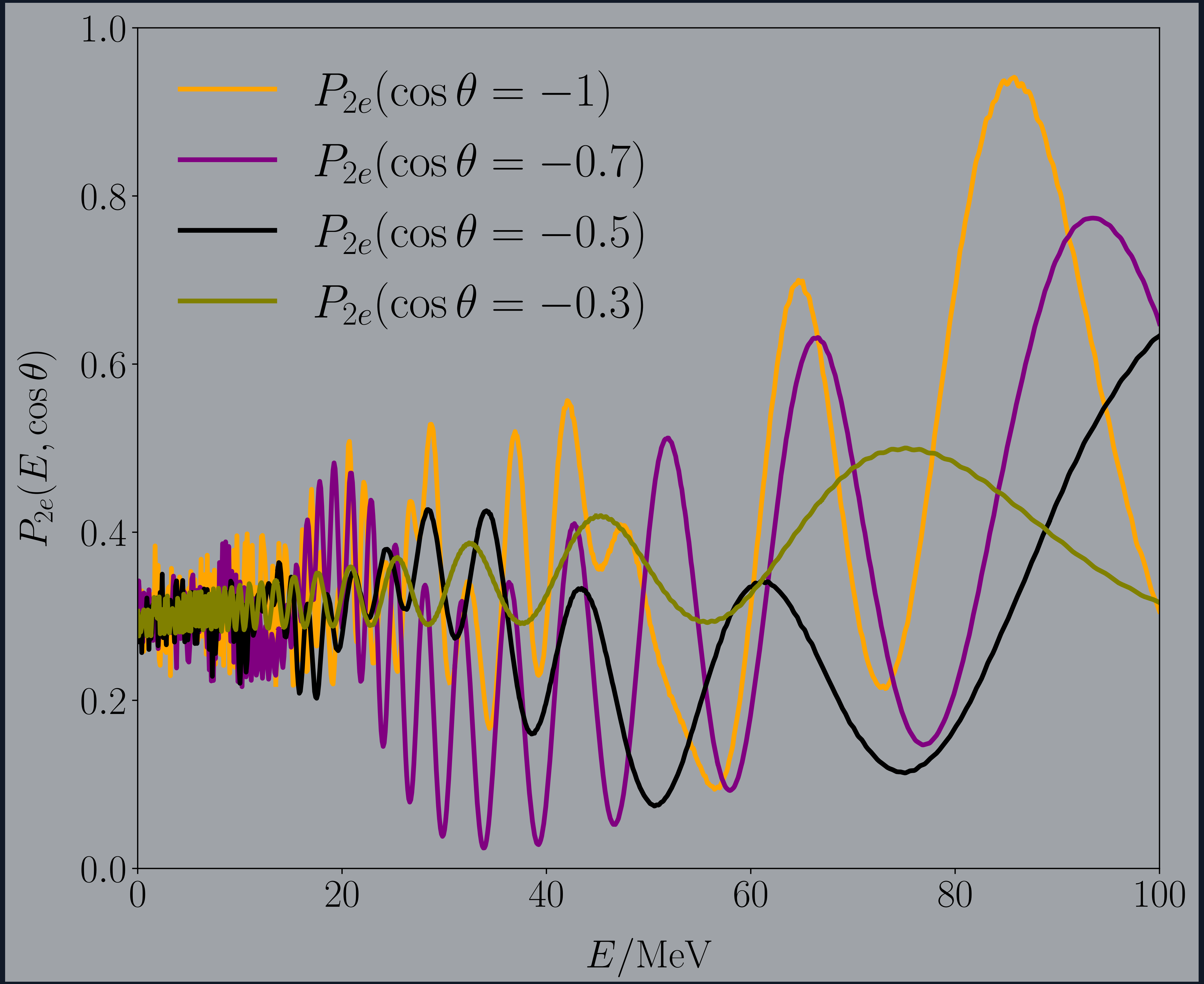
	p	$\bar{p}$
NO	$\lvert U_{e3} \rvert^2$	$1 - P_{2e}(E, \cos\theta)$
IO	$P_{2e}(E, \cos\theta)$	$\lvert U_{e3} \rvert^2$

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

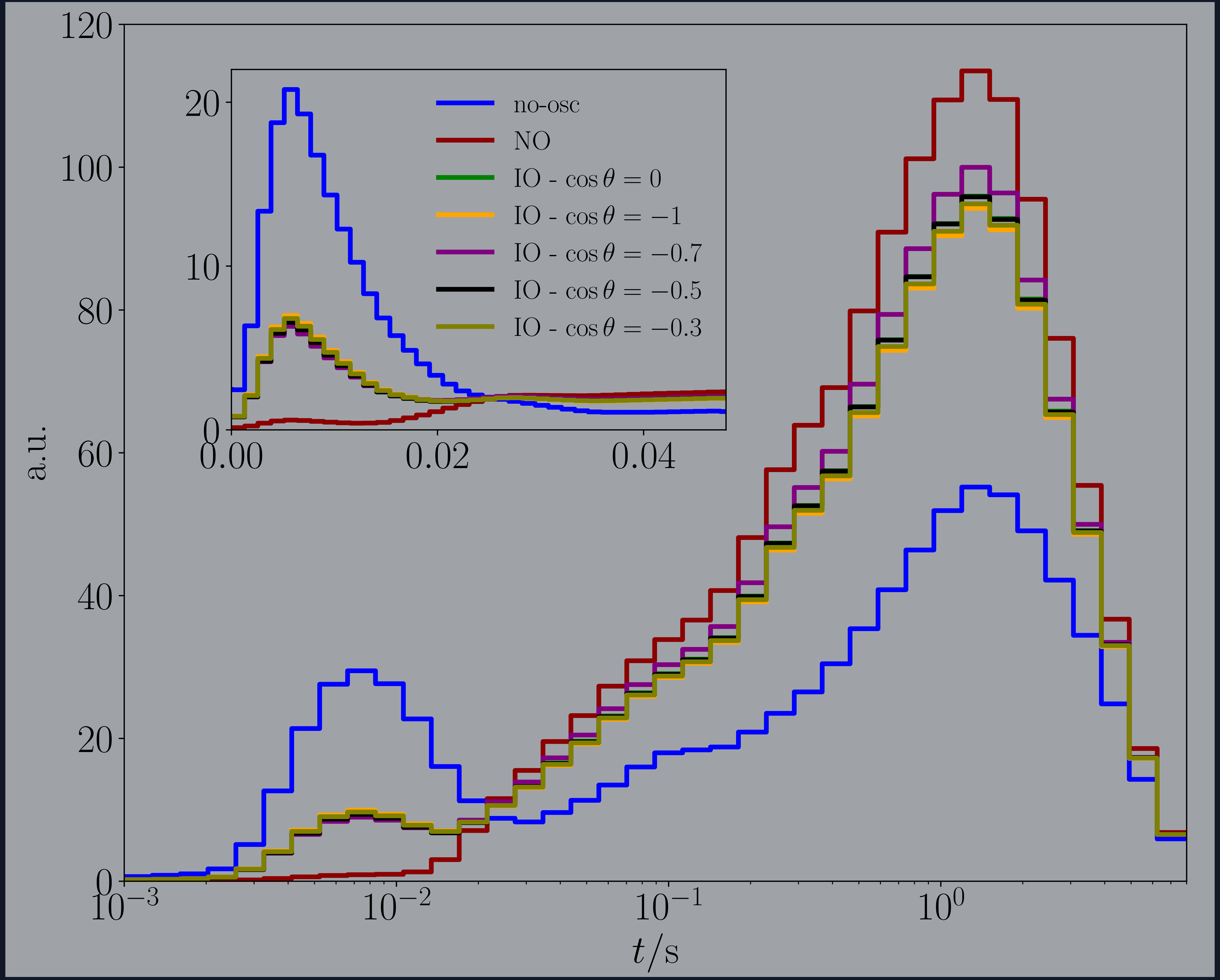
$$\mathcal{T}_{\alpha\beta} = \mathcal{T}(\overline{P_{det}\,P_1})\,\mathcal{T}(\overline{P_1\,P_2}) \cdots \mathcal{T}(\overline{P_M\,P_{prod}})$$

Lisi, Montanino (PRD 56, 1997)

Earth matter effects



ν_e channel – IO



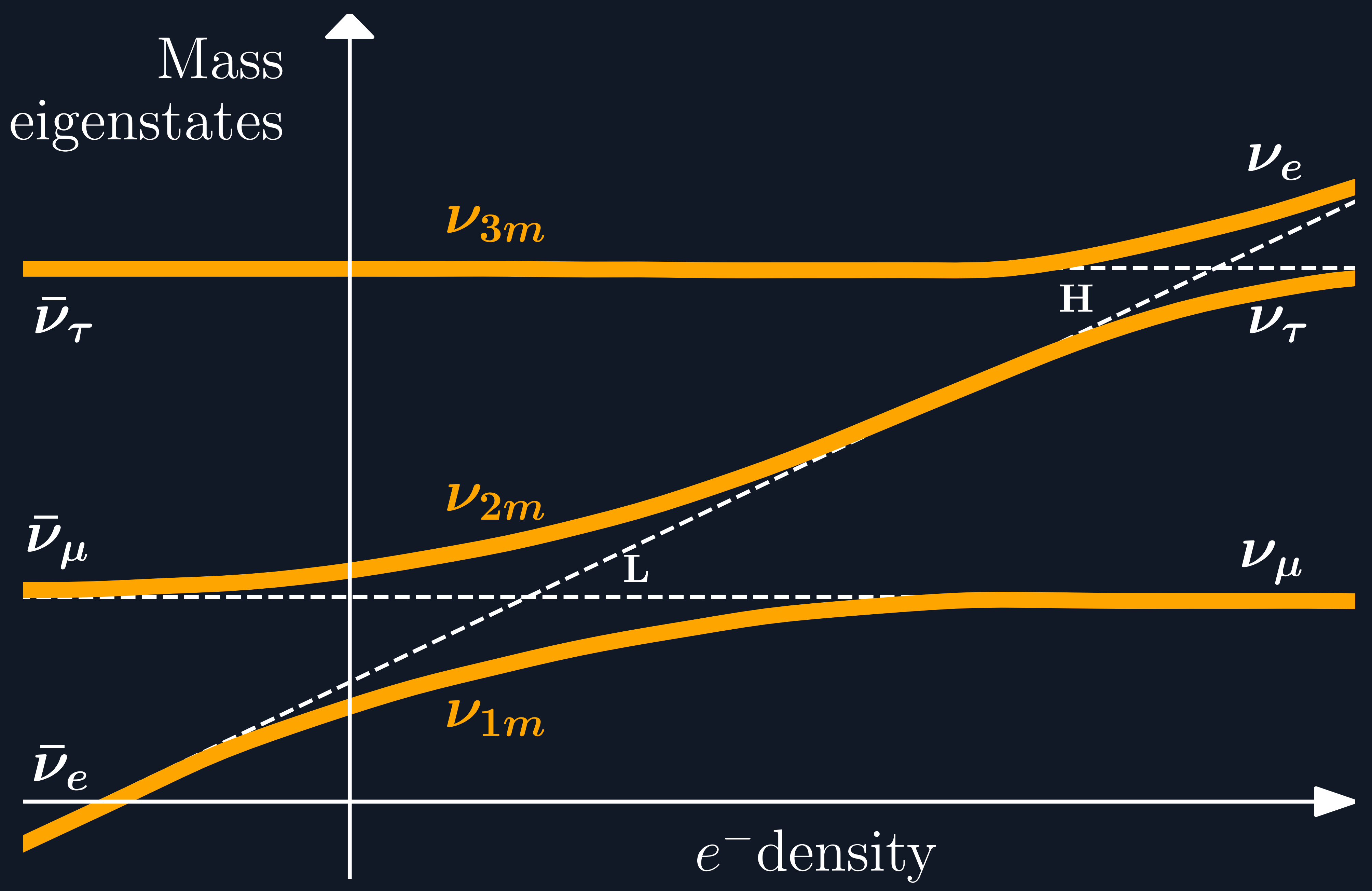
Backup

Mikheyev-Smirnov-Wolfenstein effect

Dighe, Smirnov (PRD 62, 2000)

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

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



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