# An absolute $\nu$-mass measurement at the DUNE detector

07 July 2022

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*In collaboration with:*

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Dr. Michel Sorel
Dr. Francesco Capozzi

$\nu$

- The most elusive of the known fermions
- Evidence that “new physics” is required

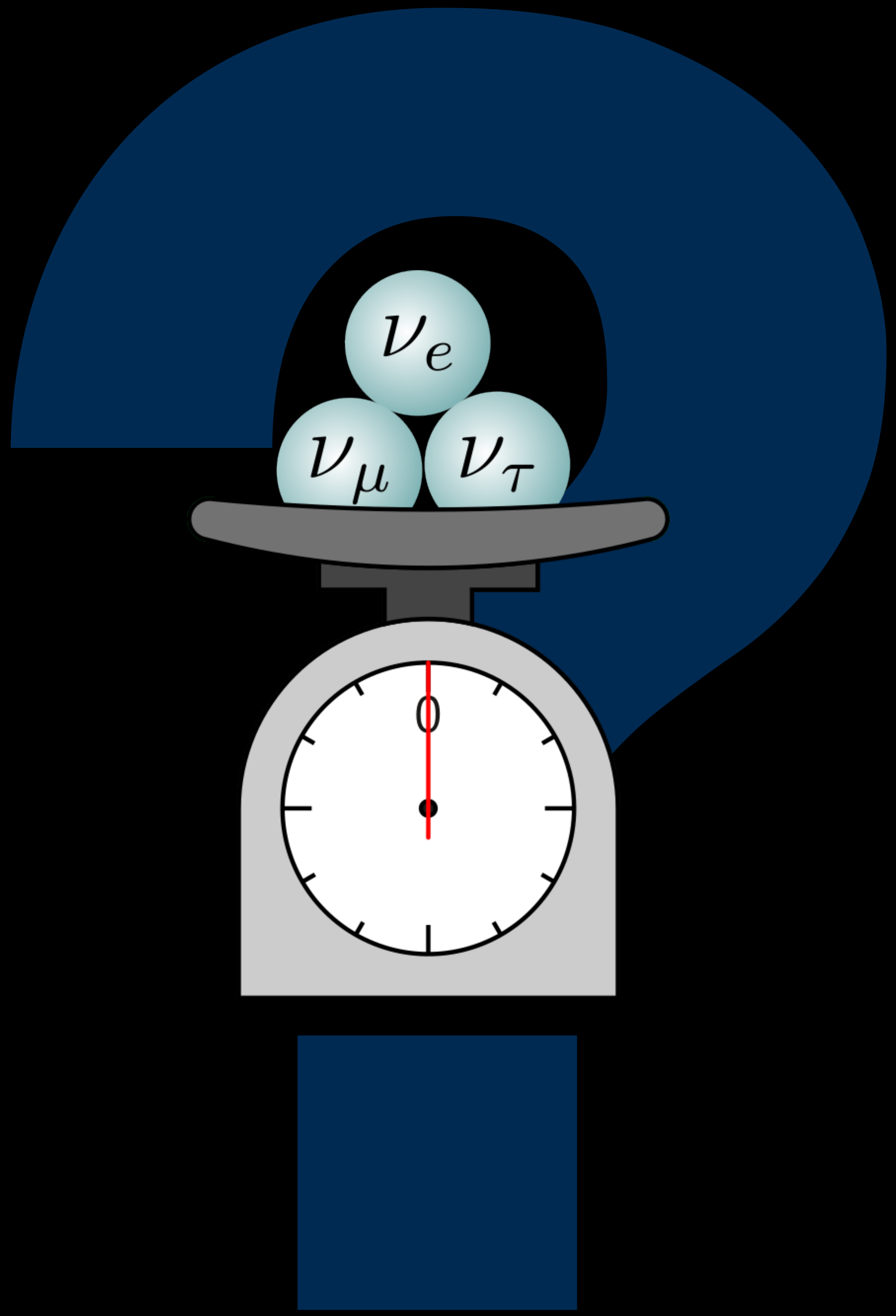
?

# $\nu$ mass

IN THE STANDARD MODEL

$$\nu_\alpha\,,\, \alpha = e, \mu, \tau$$

$$m_\nu = 0$$



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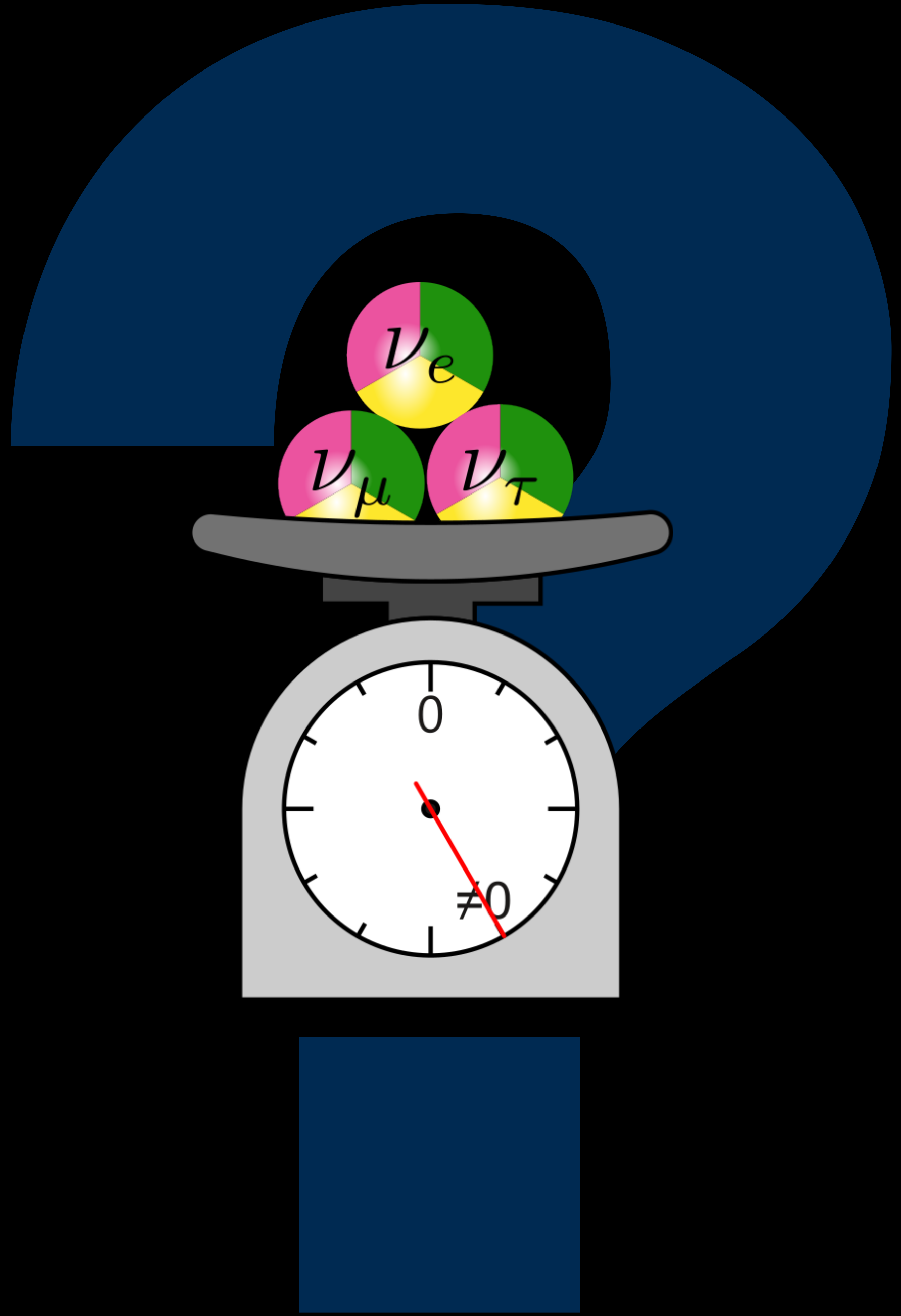


$\nu$ FLAVOUR OSCILLATIONS

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

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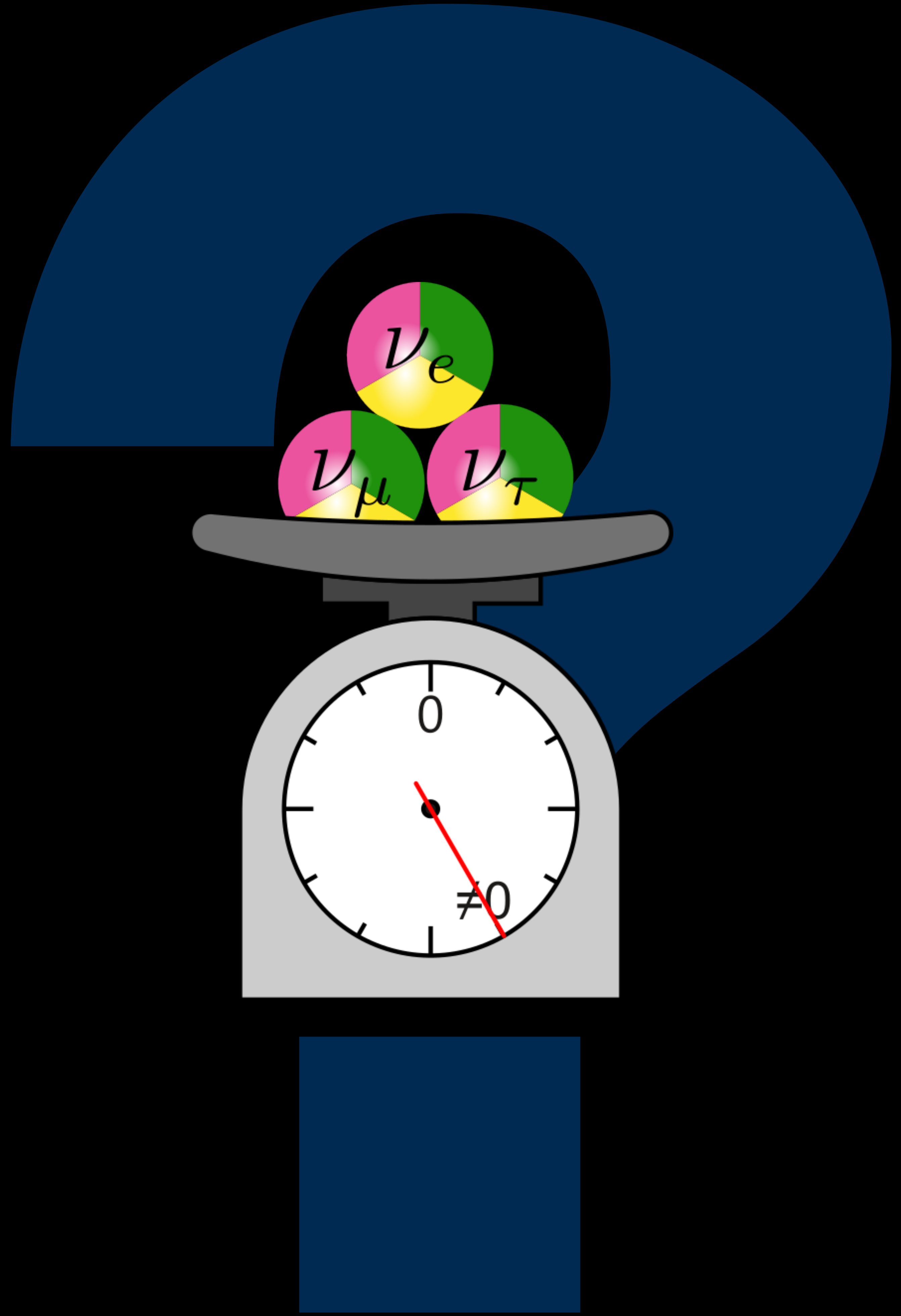


$\nu$ FLAVOUR OSCILLATIONS

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$$m_\nu \neq 0$$

From cosmology:
(CMB+BAO)

$\sum m_\nu < 0.12$ eV (95% CL)

arXiv:2106.15267

From $0\nu\beta\beta$ measurements:
KamLAND-Zen

$m_{\beta\beta} \in [36, 156]$ meV (90% CL)

arXiv:2203.02139

From kinematic measurements:
KATRIN

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

arXiv:2105.08533

Time-of-flight constraints:
Kamiokande-II (SN1987A)

$m_\nu < 5.7$ eV (95% CL)

arXiv:1002.3349

# Supernova $\nu$

## Copiously produced during the Supernova explosion

99% of the released energy emitted through $\nu$ and $\bar{\nu}$ of all flavors with mean energies of $\mathcal{O}(10)$ MeV

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Already detected!

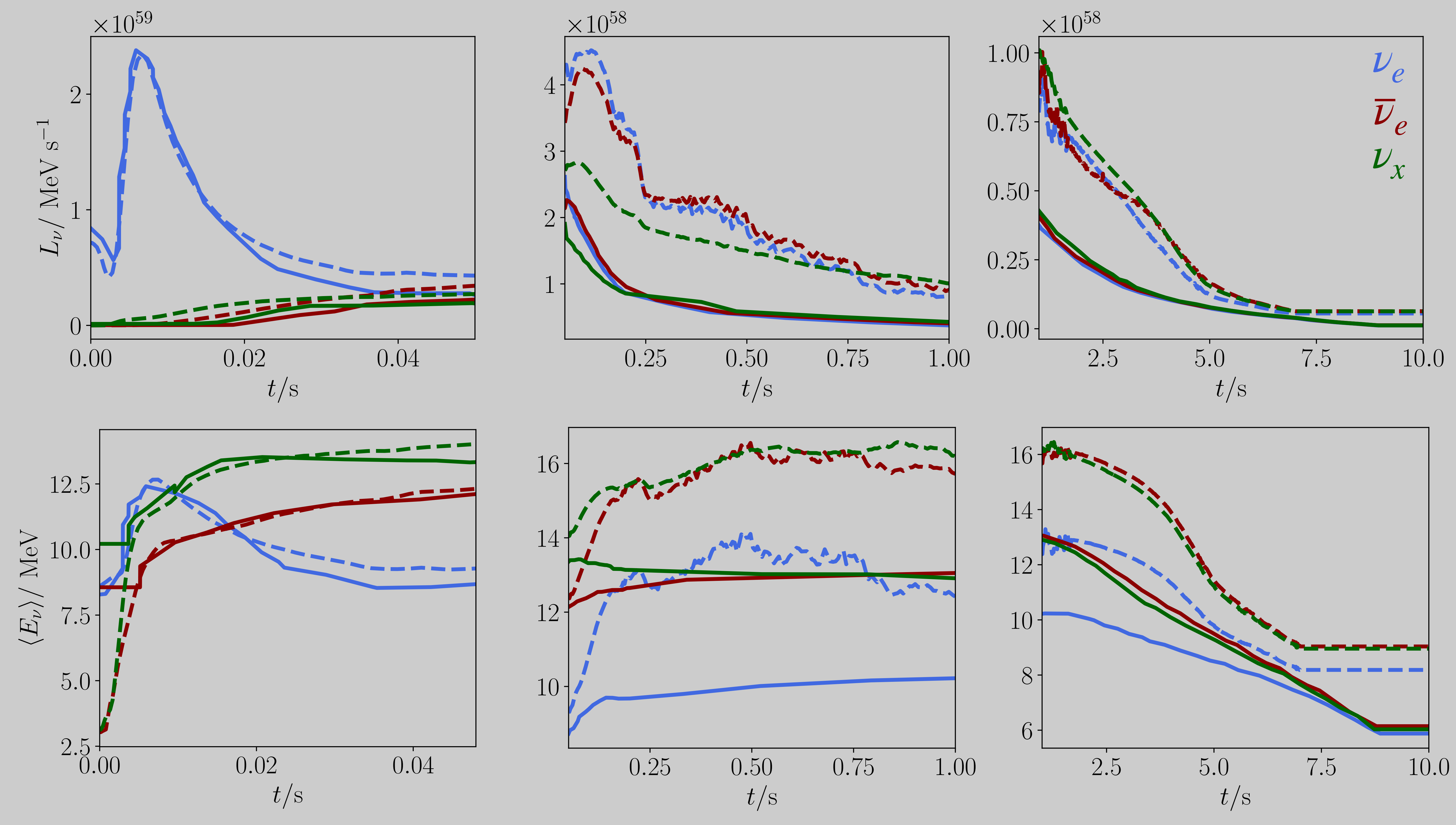
SN1987A

$M \approx 20 M_\odot$

@ $\sim 50$ kpc

Kamiokande-II: Phys. Rev. Lett. 58, 1490

Garching Models : $M = 8.8\,M_\odot$ $M = 19\,M_\odot$



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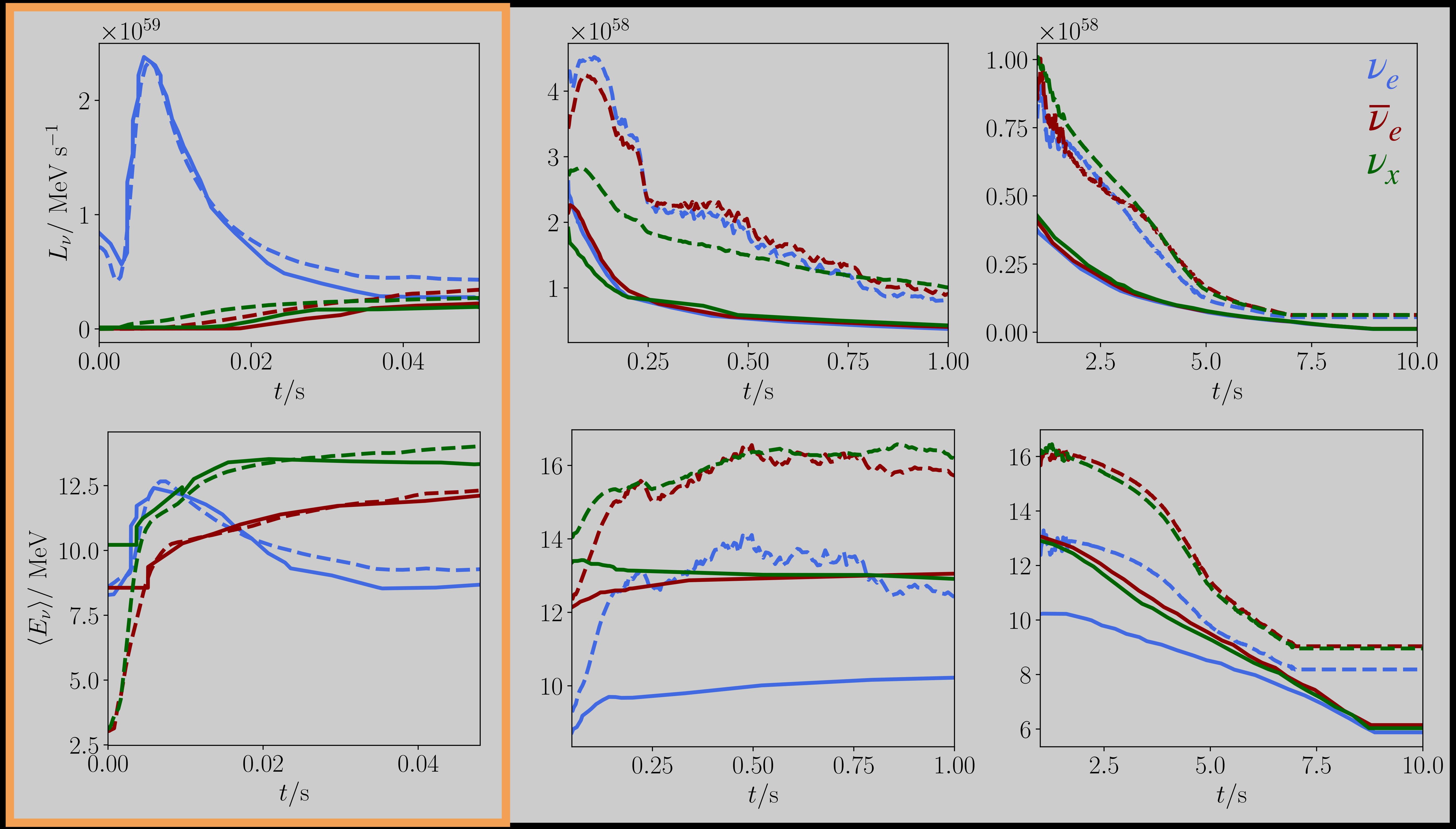
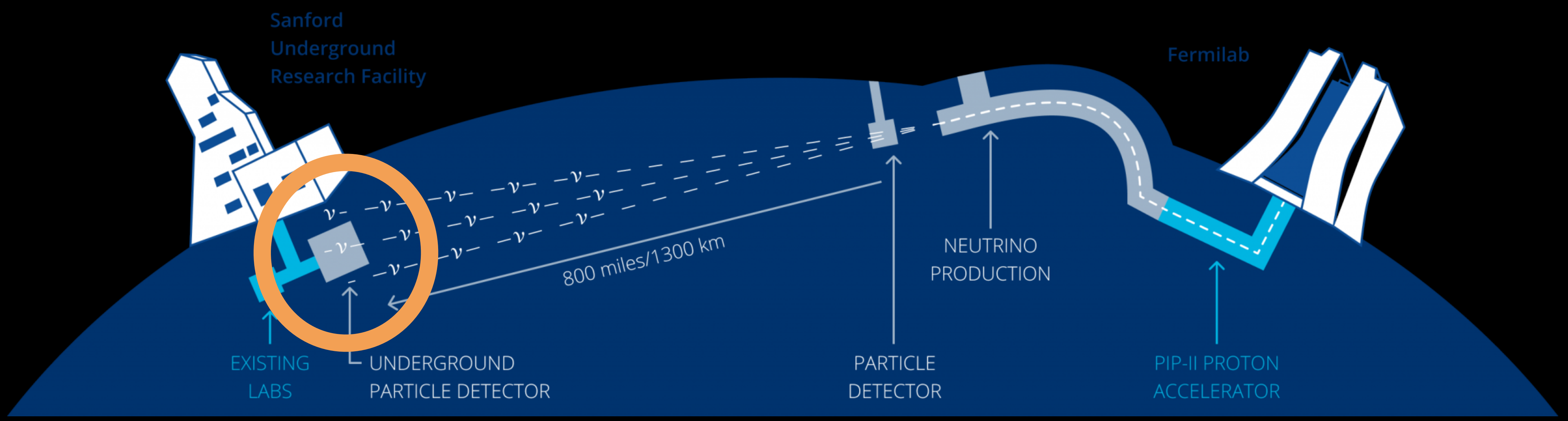



**Neutronization burst**

first 50 ms of the explosion

$$p + e^- \rightarrow n + \nu_e$$



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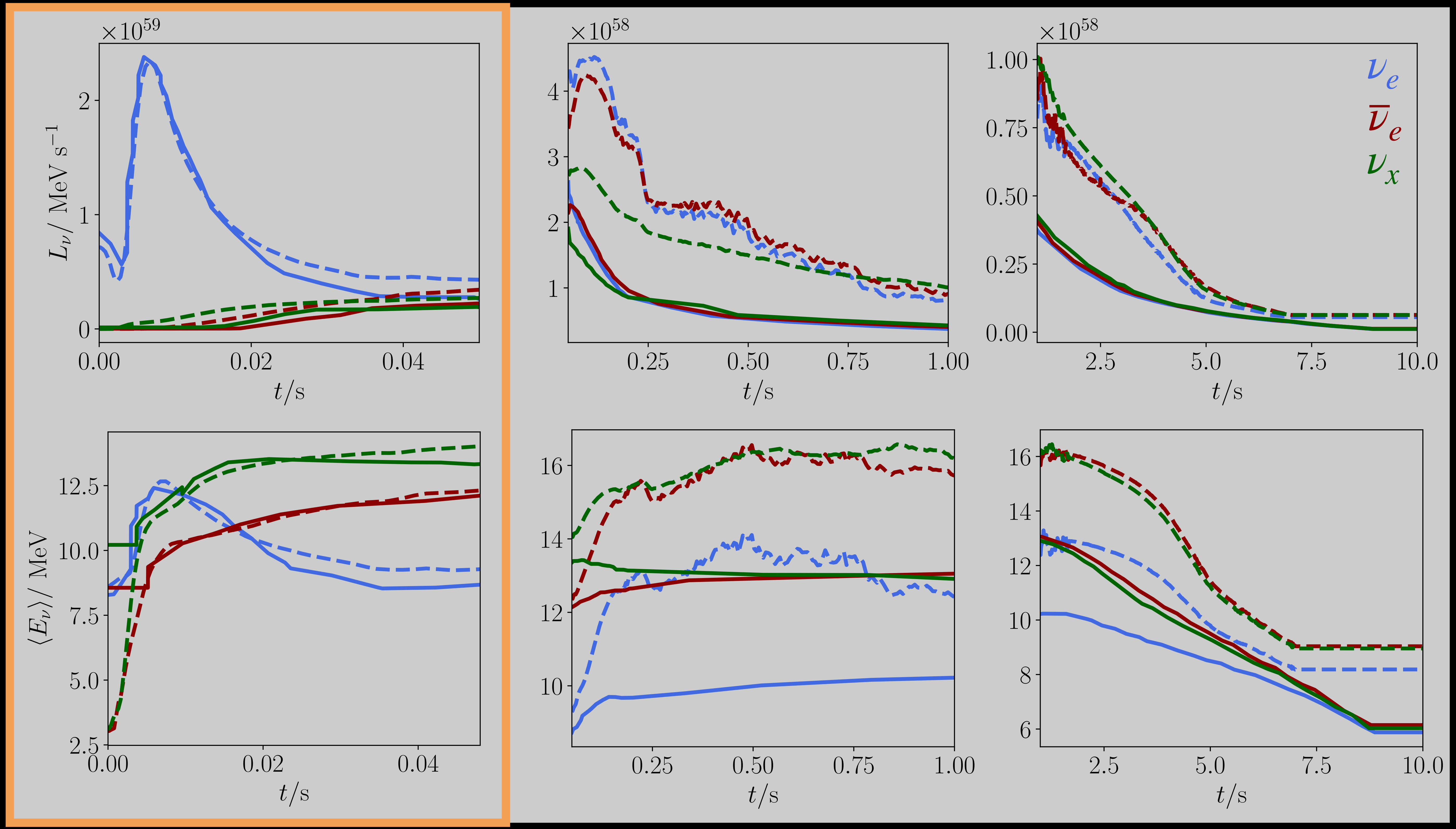


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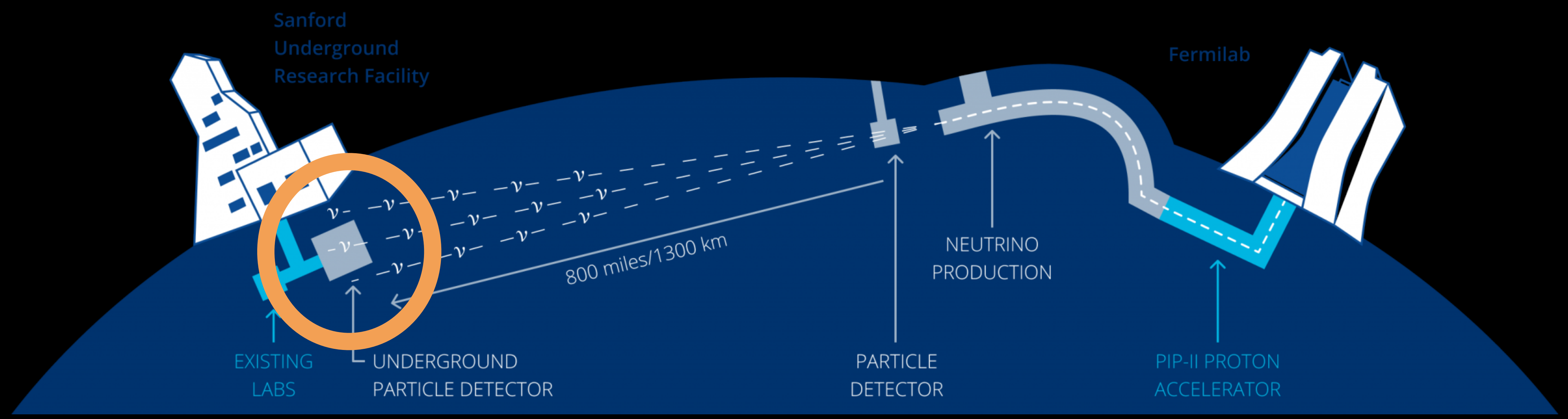


# Why DUNE?

**Liquid Argon Time Projection Chamber**

Charged-current electron neutrino interactions on Ar nuclei

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

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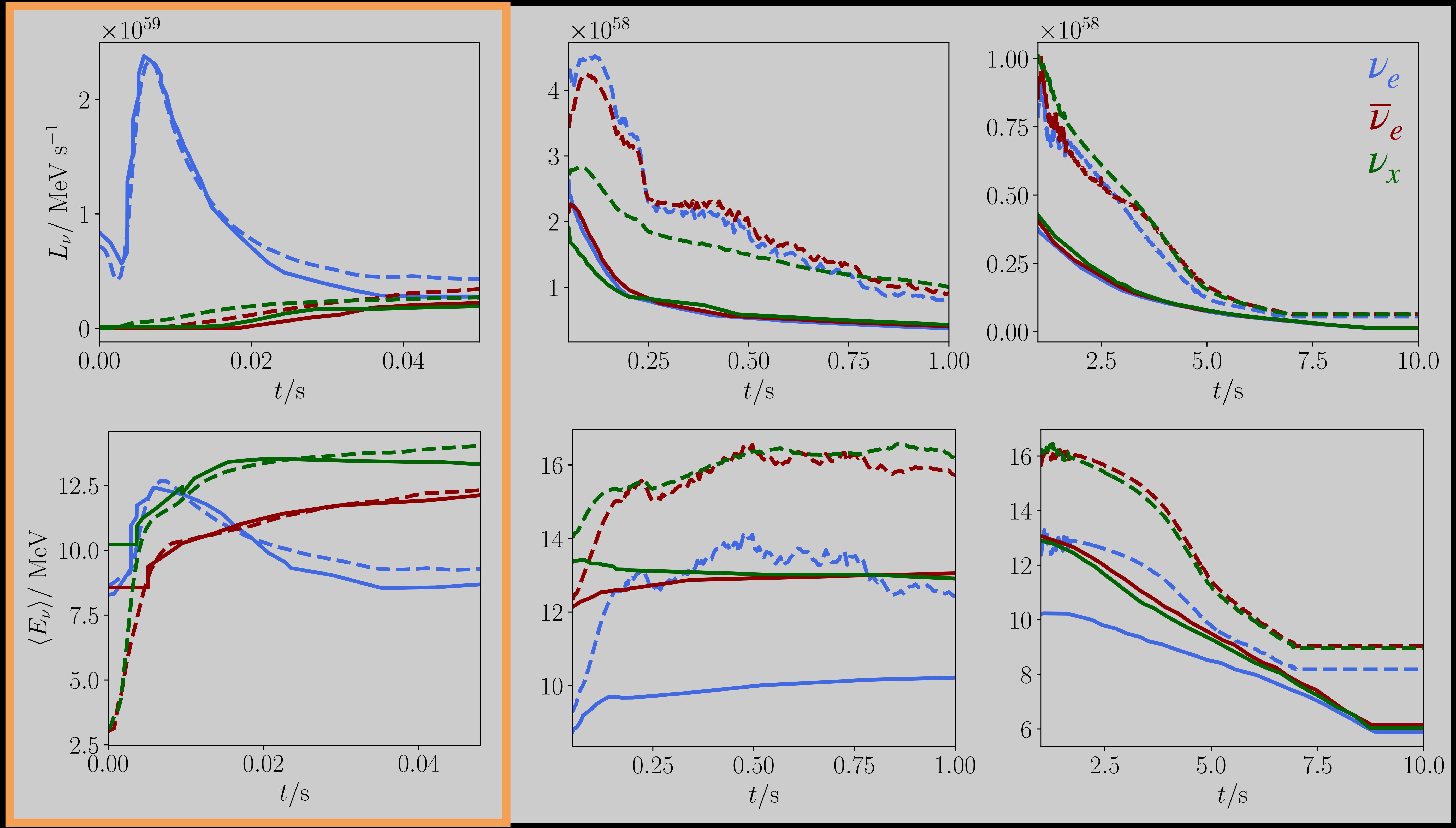



## Neutronization burst

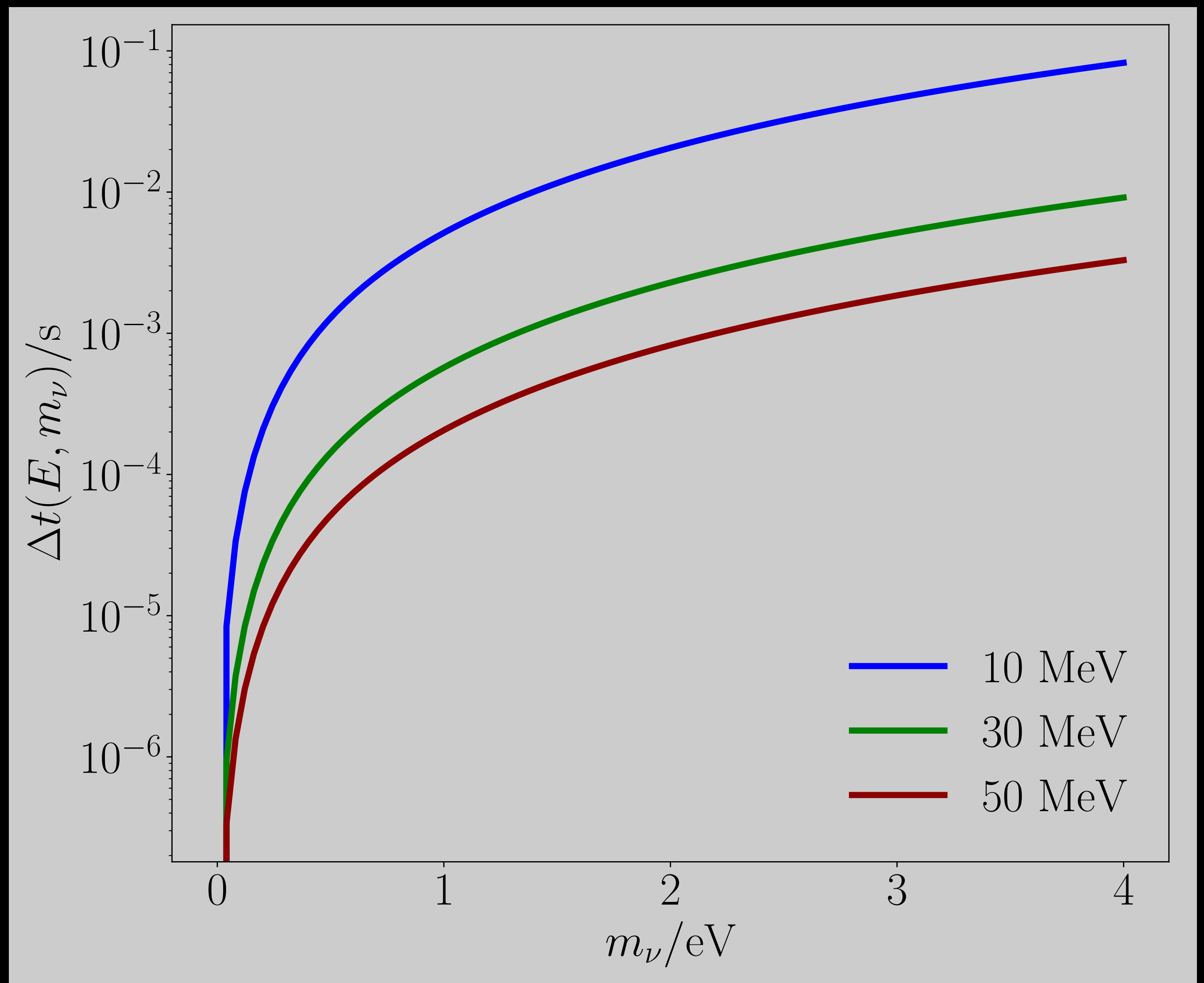
first 50 ms of the explosion

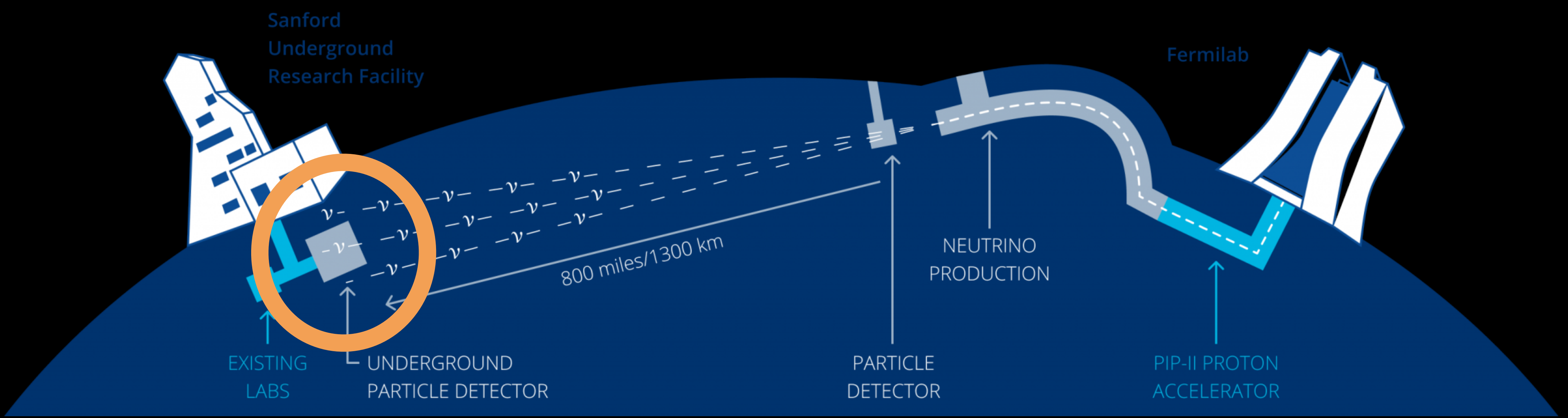
$$p + e^- \rightarrow n + \nu_e$$

## Effects of non-zero neutrino mass:

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

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

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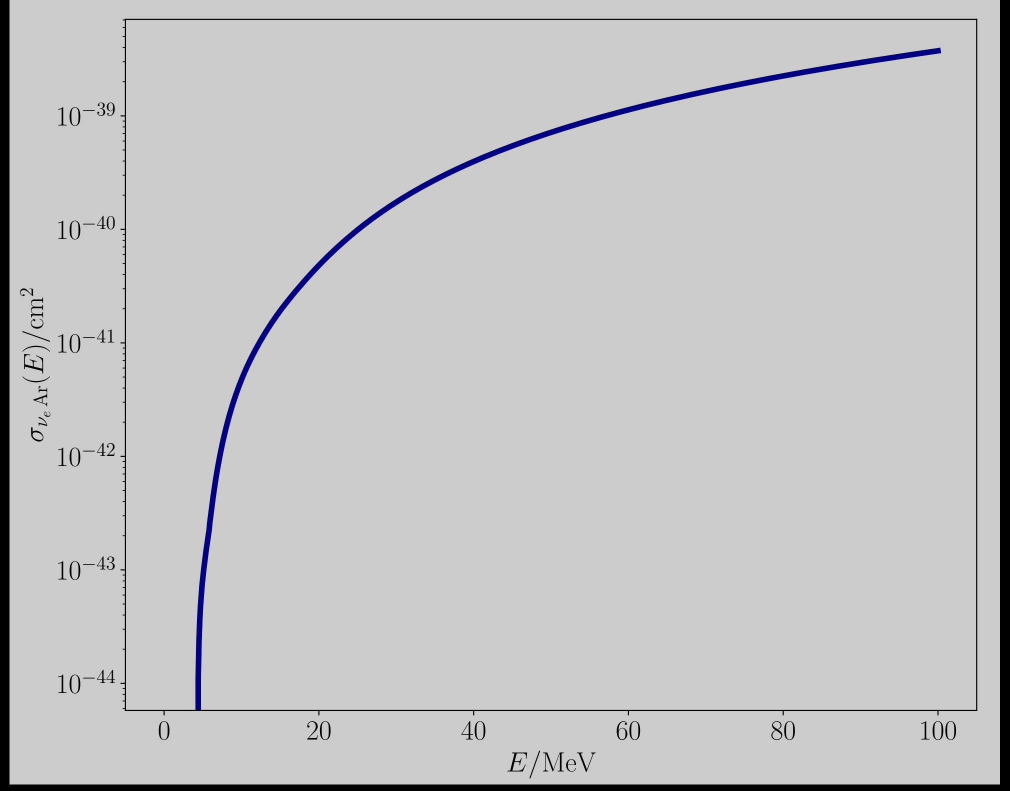
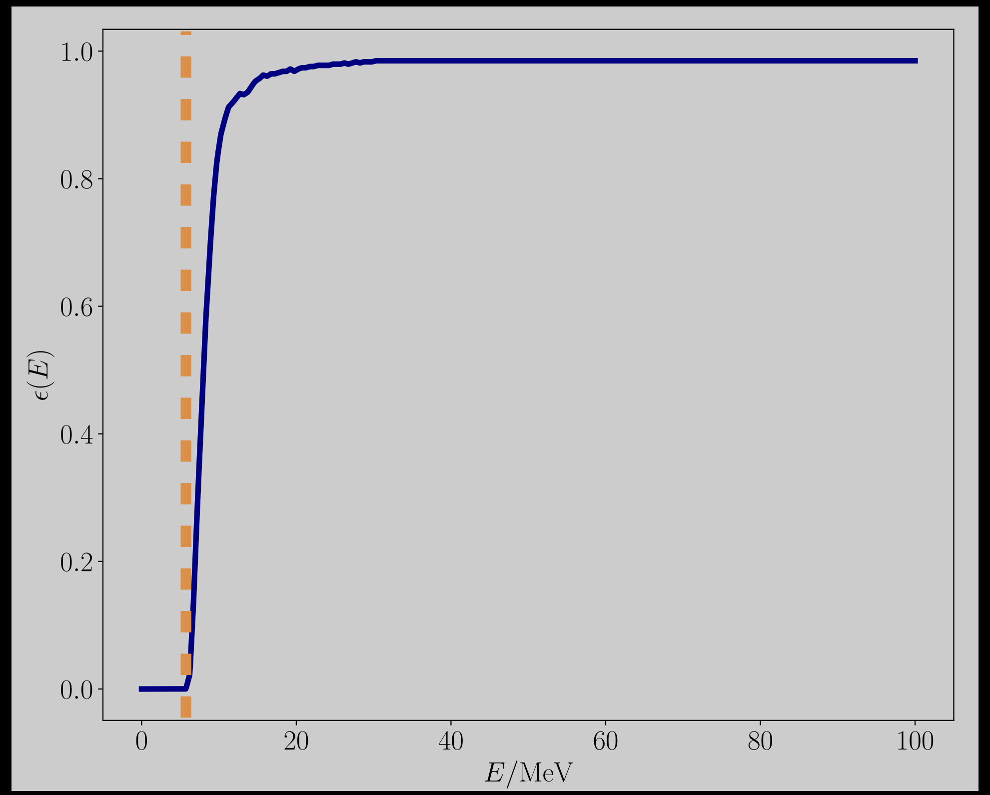



SNOwGLoBES

arXiv:2008.06647




$E_{th} \approx 5.8$ MeV

$$R(t,E) = N_{target}\, \sigma_{CC}(E)\, \Phi_{\nu_e}(t,E)\, \epsilon(E)$$

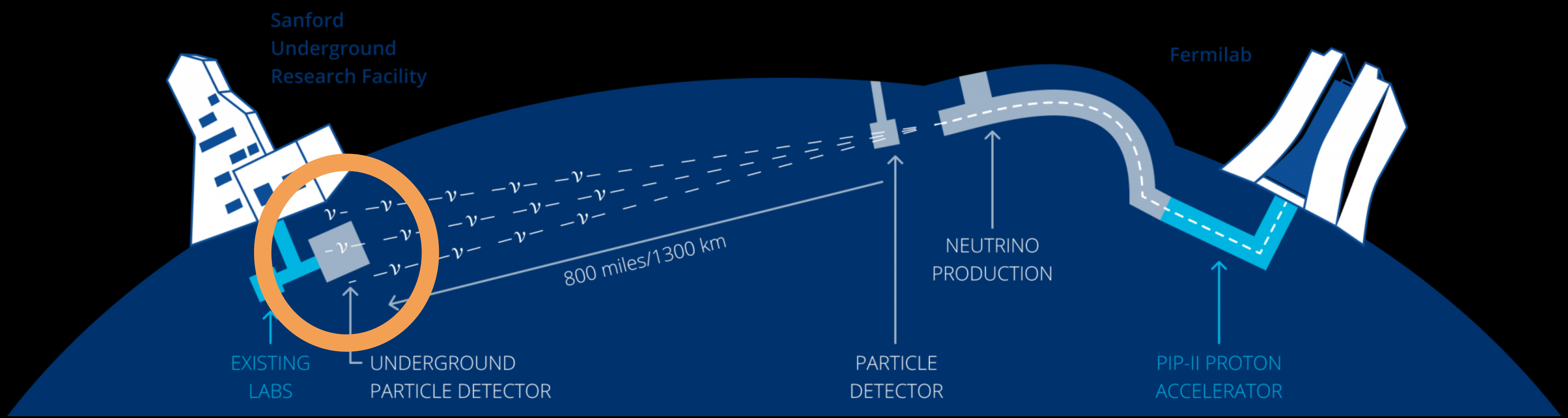
DUNE far-detector fiducial mass: 40 kton of LAr

Non oscillated and oscillated fluxes (Large Mixing Angle MSW)

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

Normal mass Ordering : $p = |U_{e3}|^2$

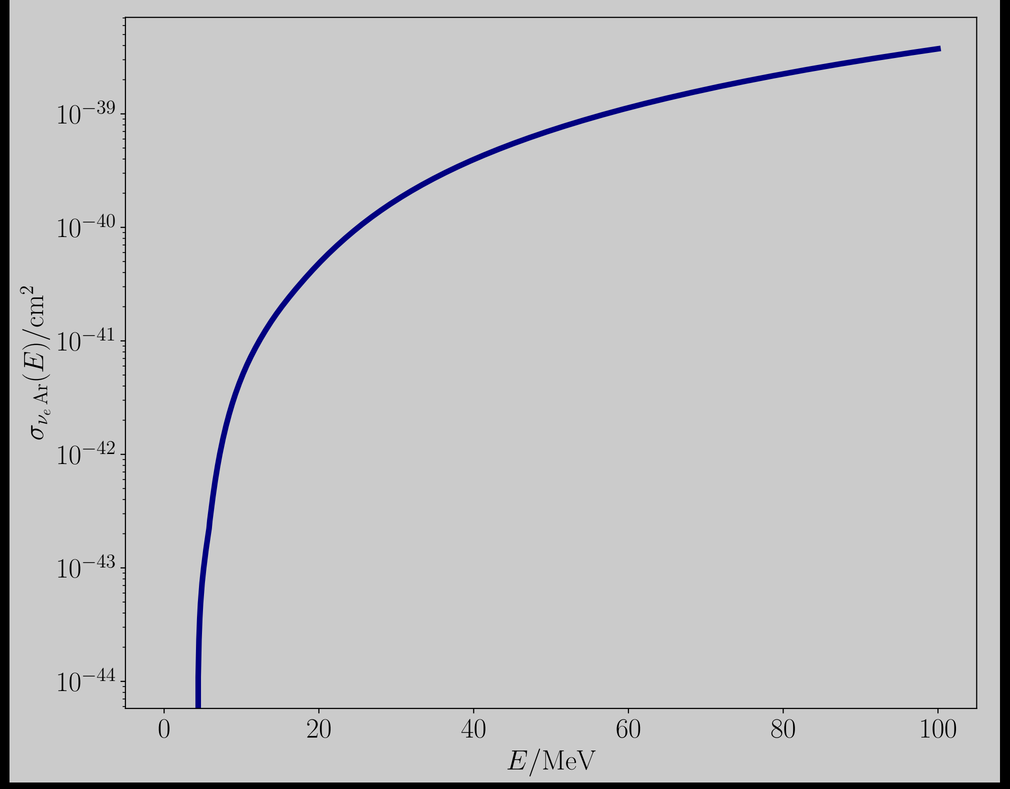
Inverted mass Ordering : $p = |U_{e2}|^2$



# Likelihood analysis

- $(\delta t_i, E_i)$ generation by fixing $D$
- $L(t, m_\nu) = \prod_{i=1}^{R} \int R(t_i, E_i)\ G_i(E, 0.1E)\ dE$
- $\chi^2(t_i, m_\nu) = -2\log(L)$
- $\Delta\chi^2(m_\nu) = \chi^2(m_\nu) - \chi^2_{min}(m_\nu)$

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

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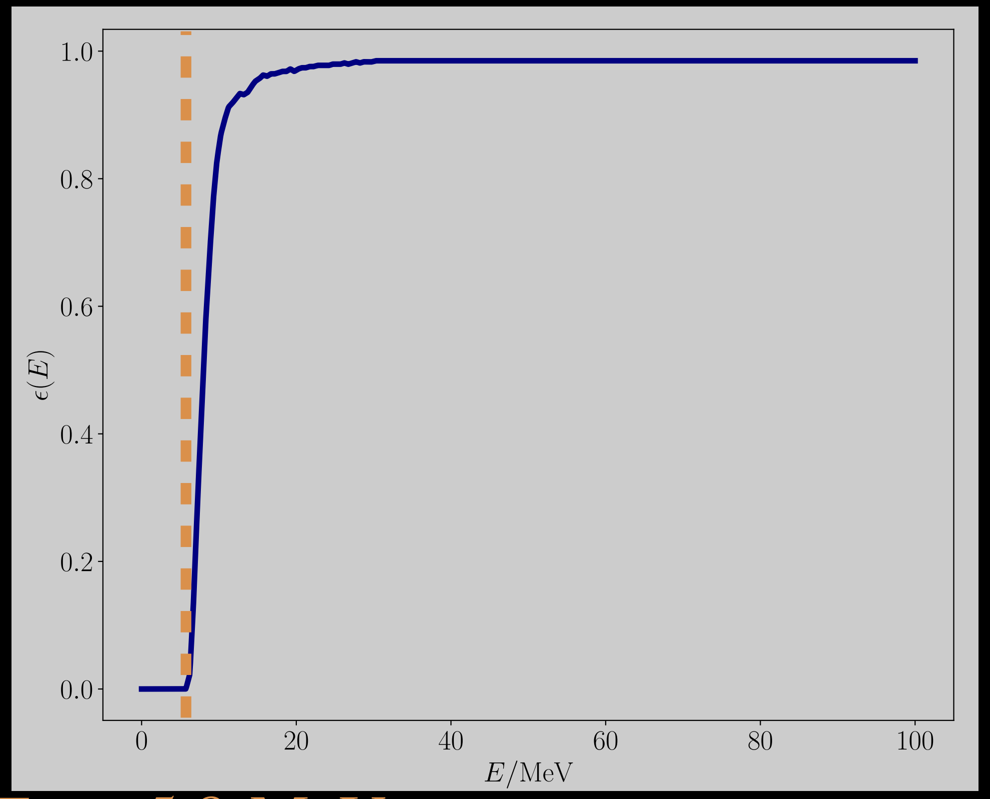


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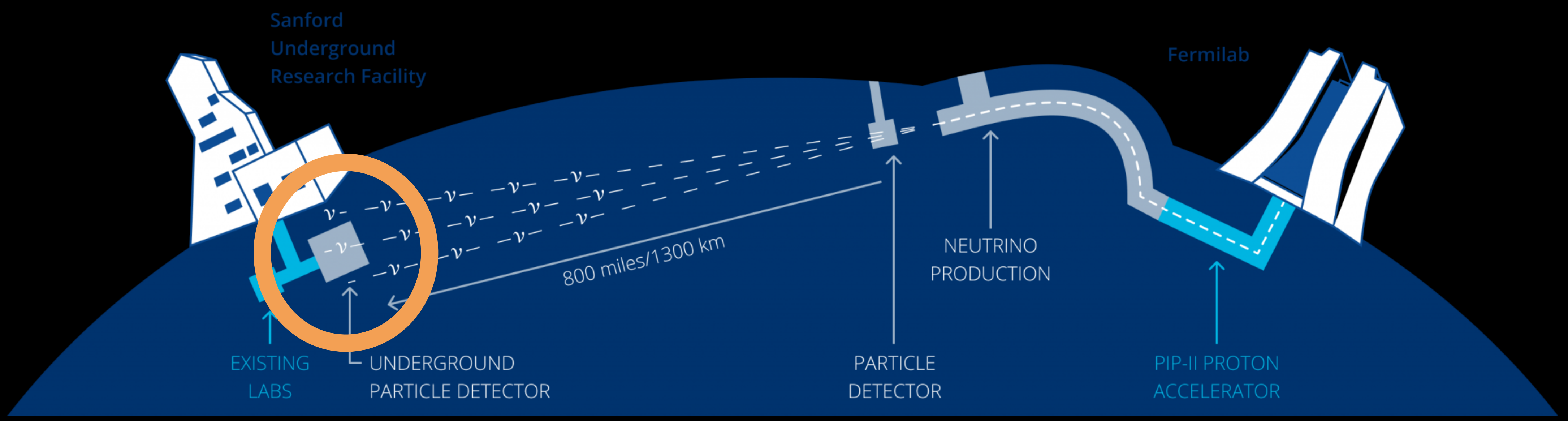
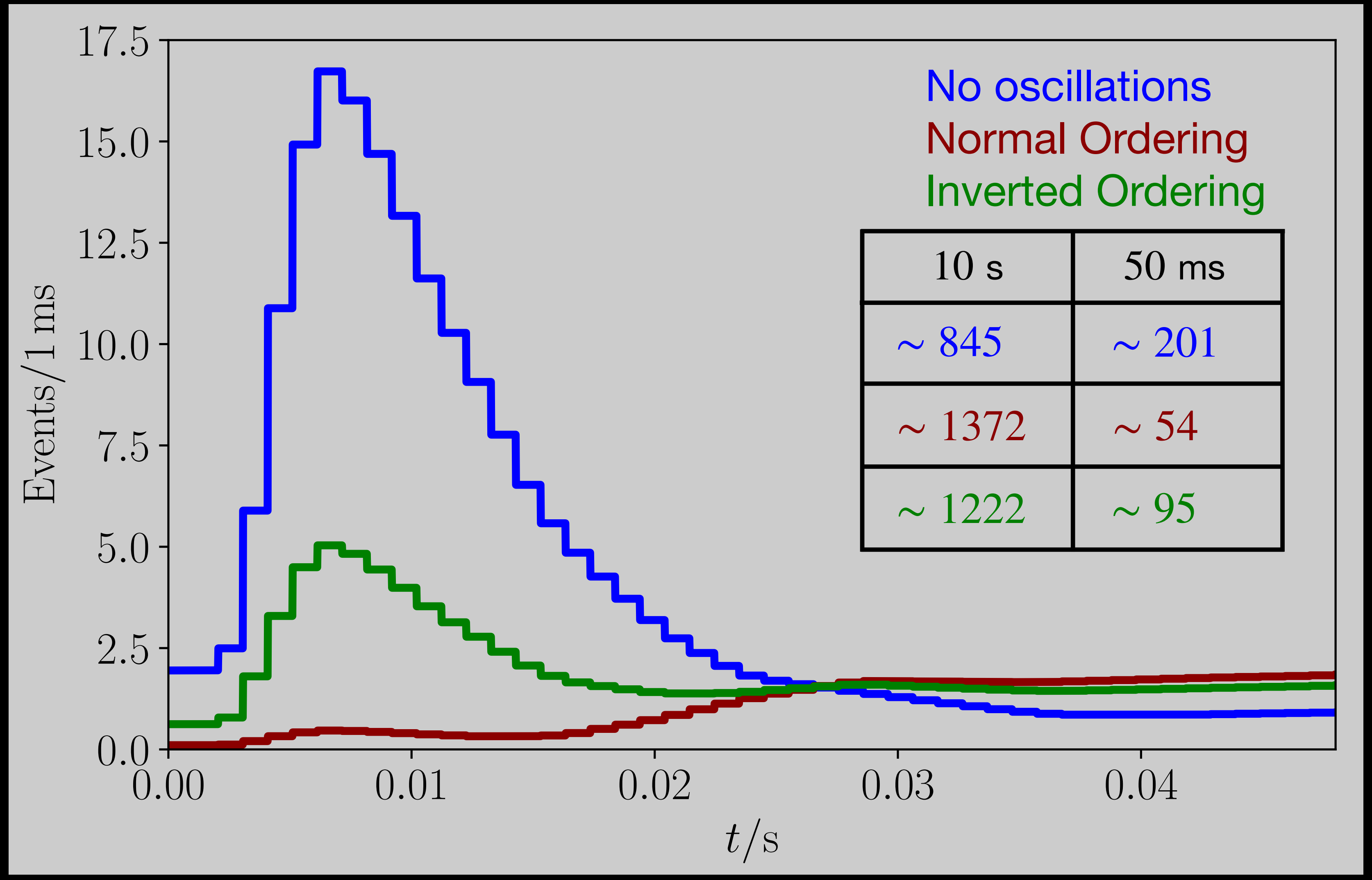


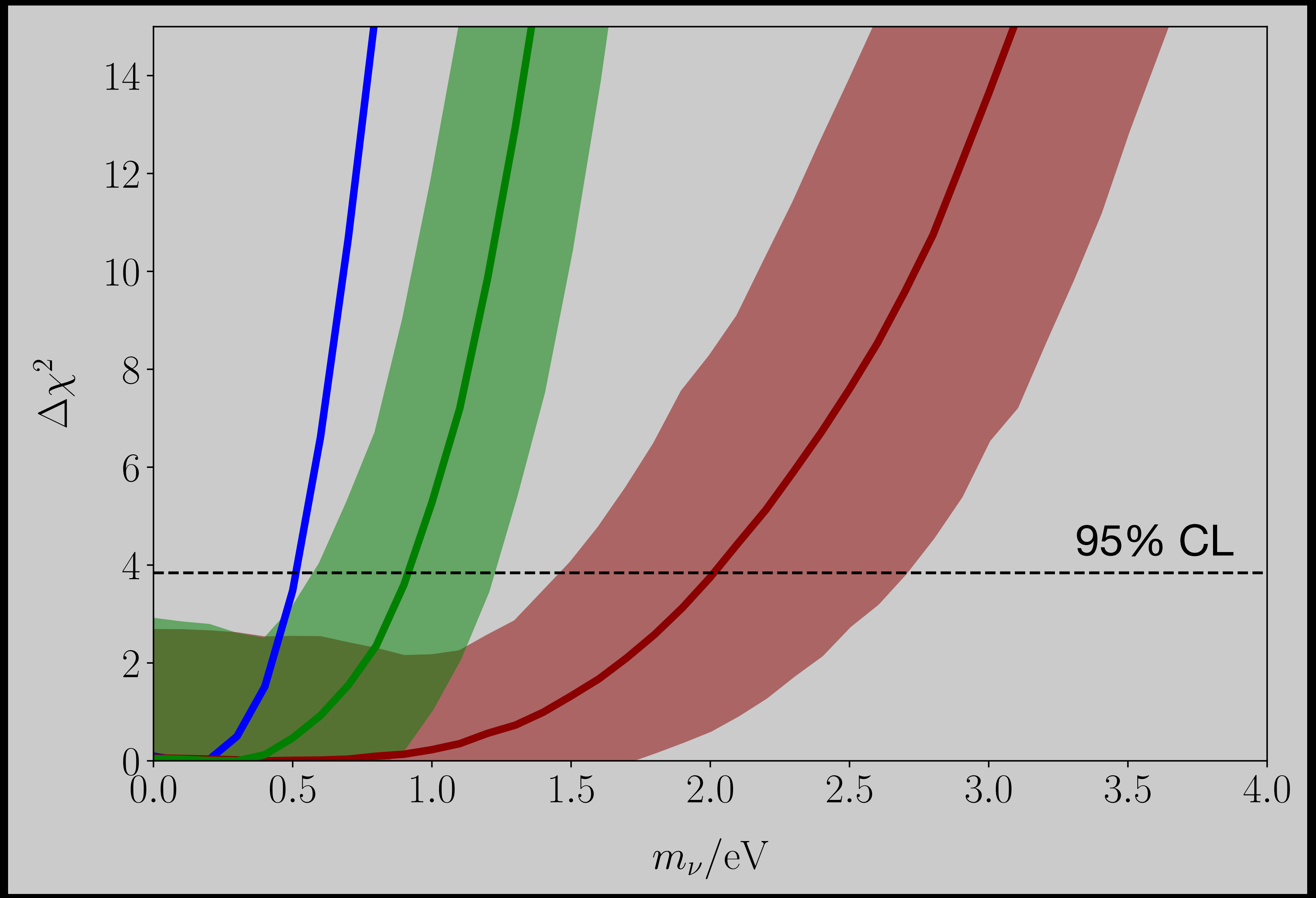
# Results: $D$ = 10 kpc

UPPER BOUNDS ON

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

$M = 8.8\, M_\odot$



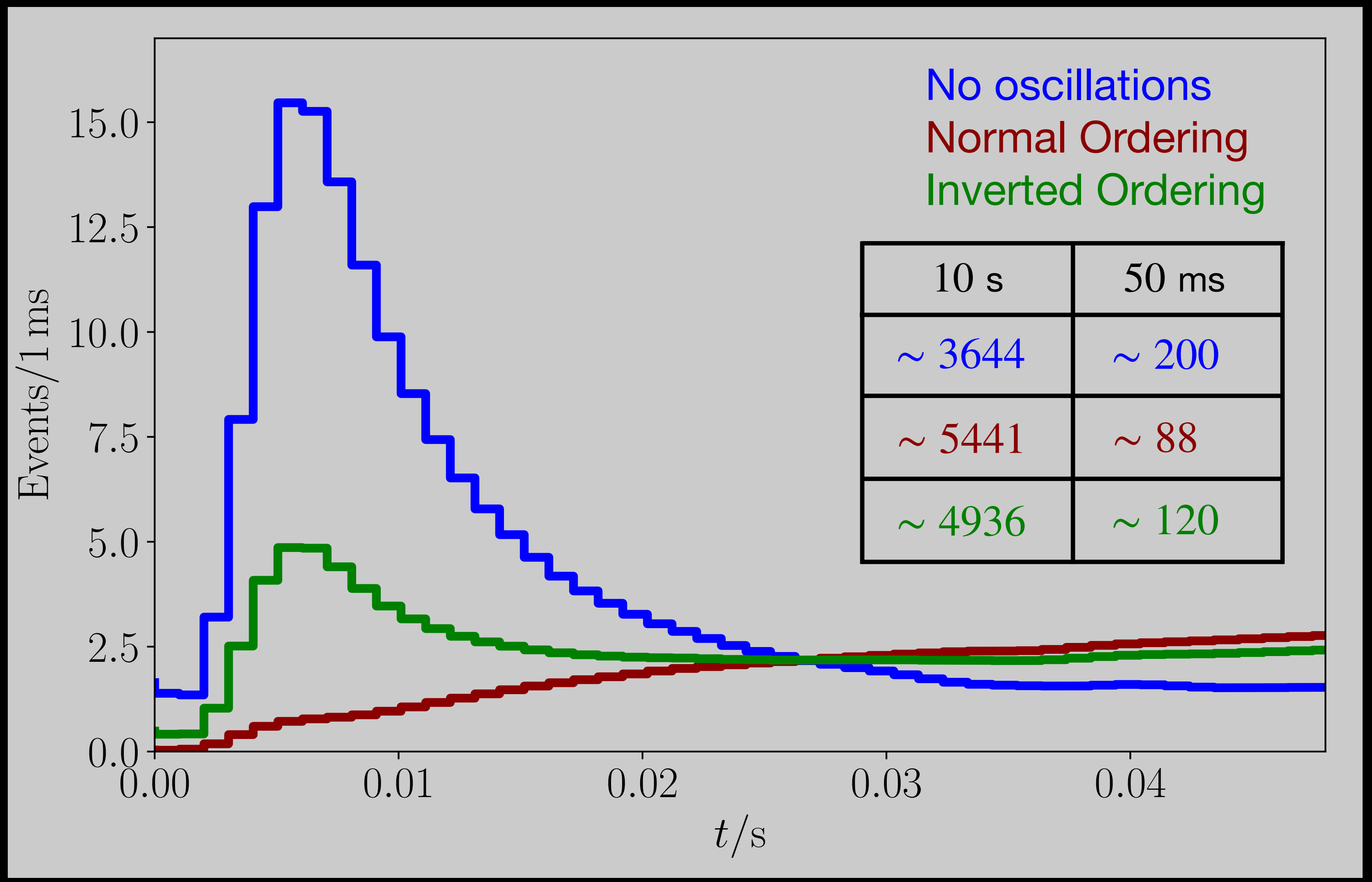



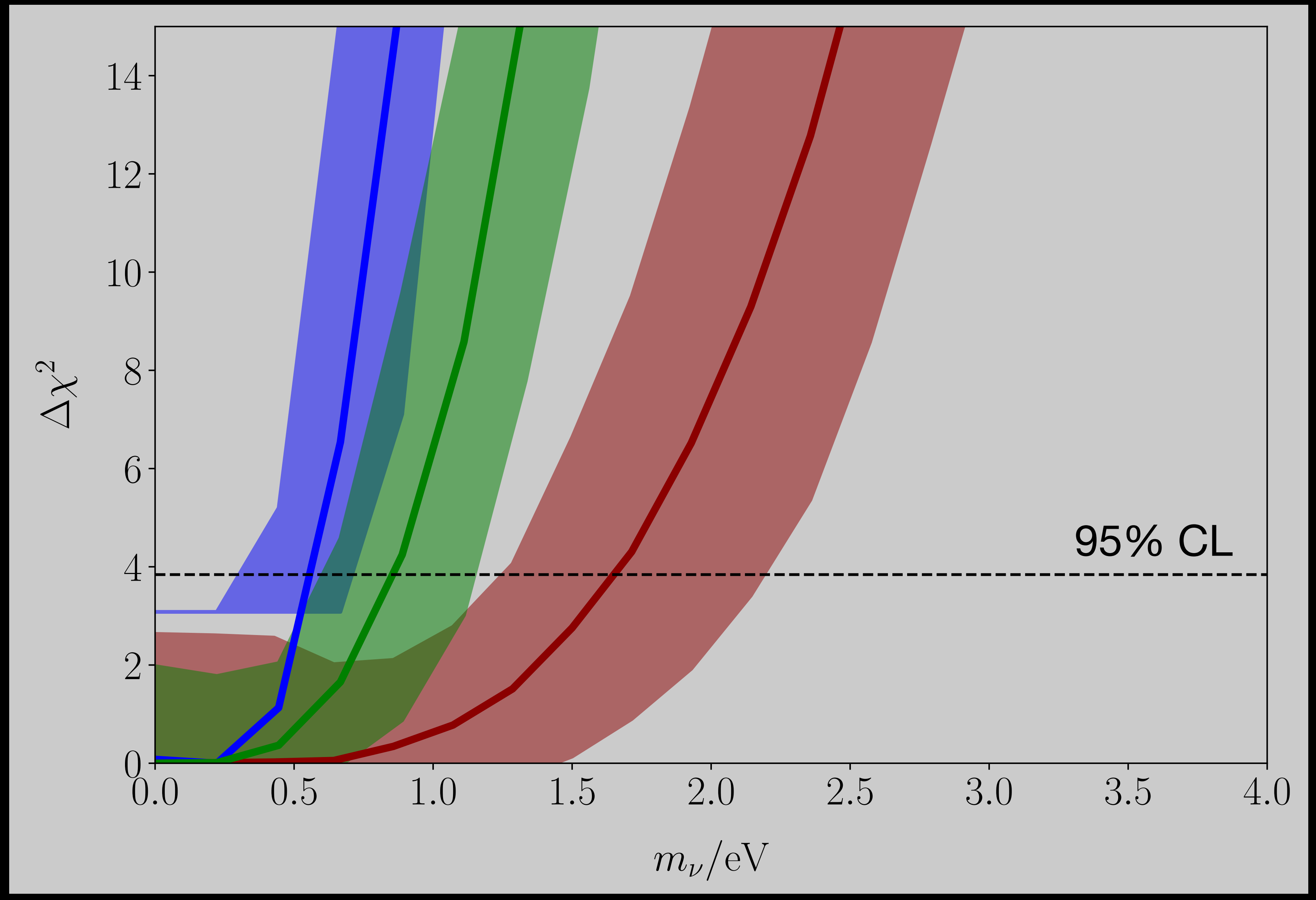

$m_\nu \leq 0.51^{+0.20}_{-0.19}$ eV

$m_\nu \leq 0.91^{+0.30}_{-0.33}$ eV

$m_\nu \leq 2.01^{+0.69}_{-0.55}$ eV

$M = 19\, M_\odot$




$m_\nu \leq 0.56^{+0.20}_{-0.21}$ eV

$m_\nu \leq 0.85^{+0.30}_{-0.25}$ eV

$m_\nu \leq 1.65^{+0.54}_{-0.40}$ eV

# Results: including Earth matter effects

arXiv:9702343

arXiv:1205.5254

Affect only the Inverted mass Ordering in the neutrino channel

$$\Phi_{\nu_e}^{\oplus\ NO}(t, E) = \Phi_{\nu_e}^{NO}(t, E)$$

$$\Phi_{\nu_e}^{\oplus\ IO}(t, E) = P_{2e}\,\Phi_{\nu_e}^{0}(t, E) + (1 - P_{2e})\Phi_{\nu_x}^{0}(t, E)$$

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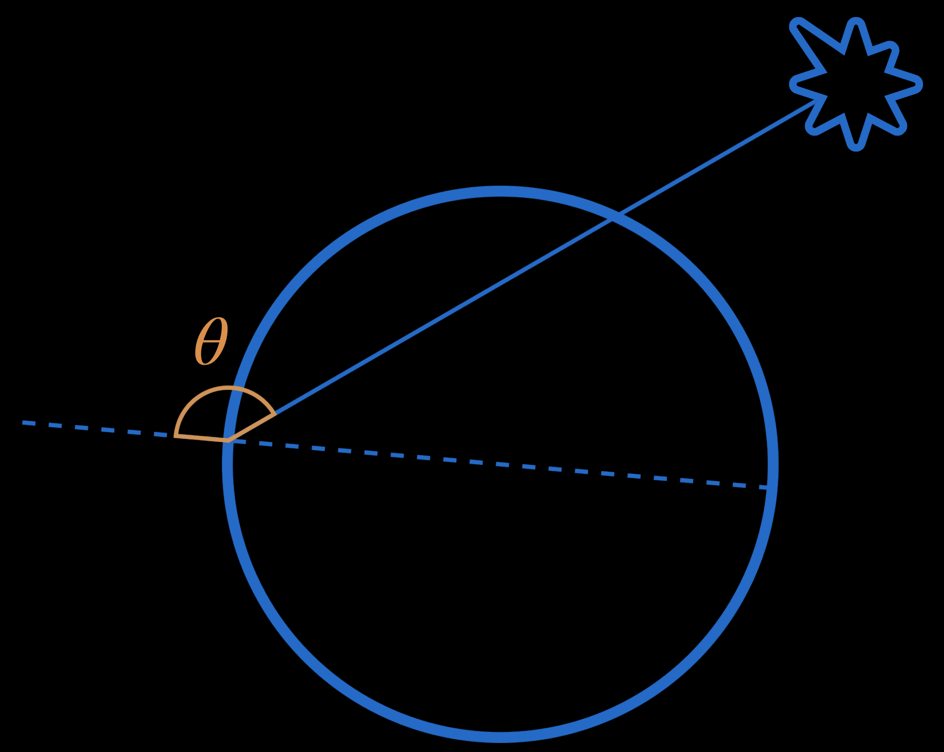


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$$\mathcal{T}_{\alpha\beta} = \mathcal{T}(\overline{P_{det}P_1})\,\mathcal{T}(\overline{P_1P_2})\cdots\mathcal{T}(\overline{P_MP_{prod}}) \quad \rightarrow \quad P_{2e}(E,\cos\theta) = \mathcal{T}_{e\beta}\cdot U_{PMNS,2}$$

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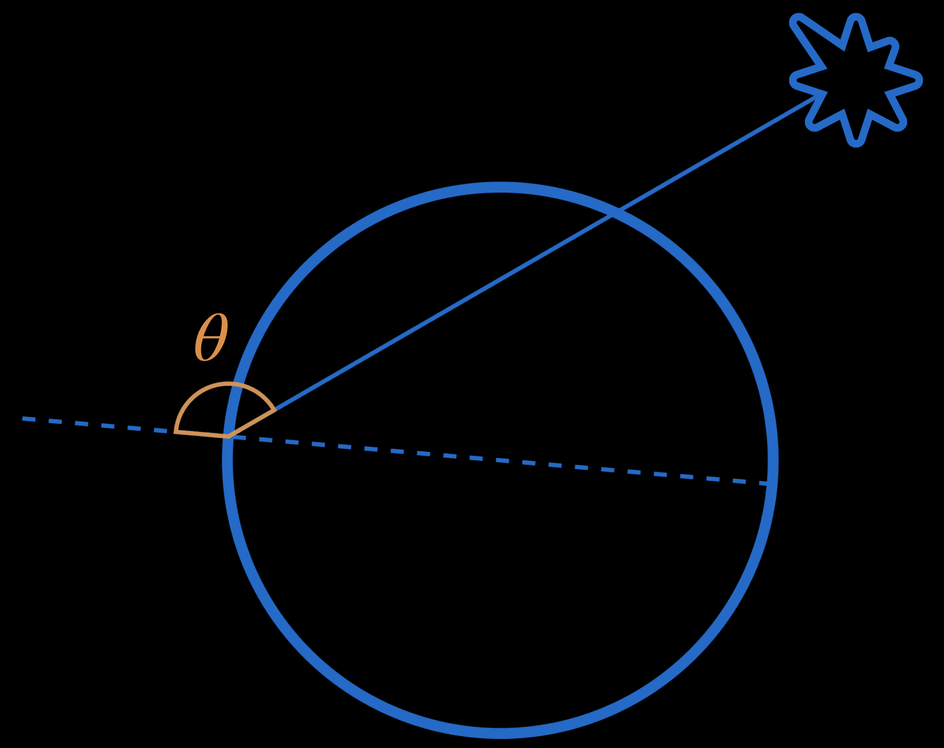


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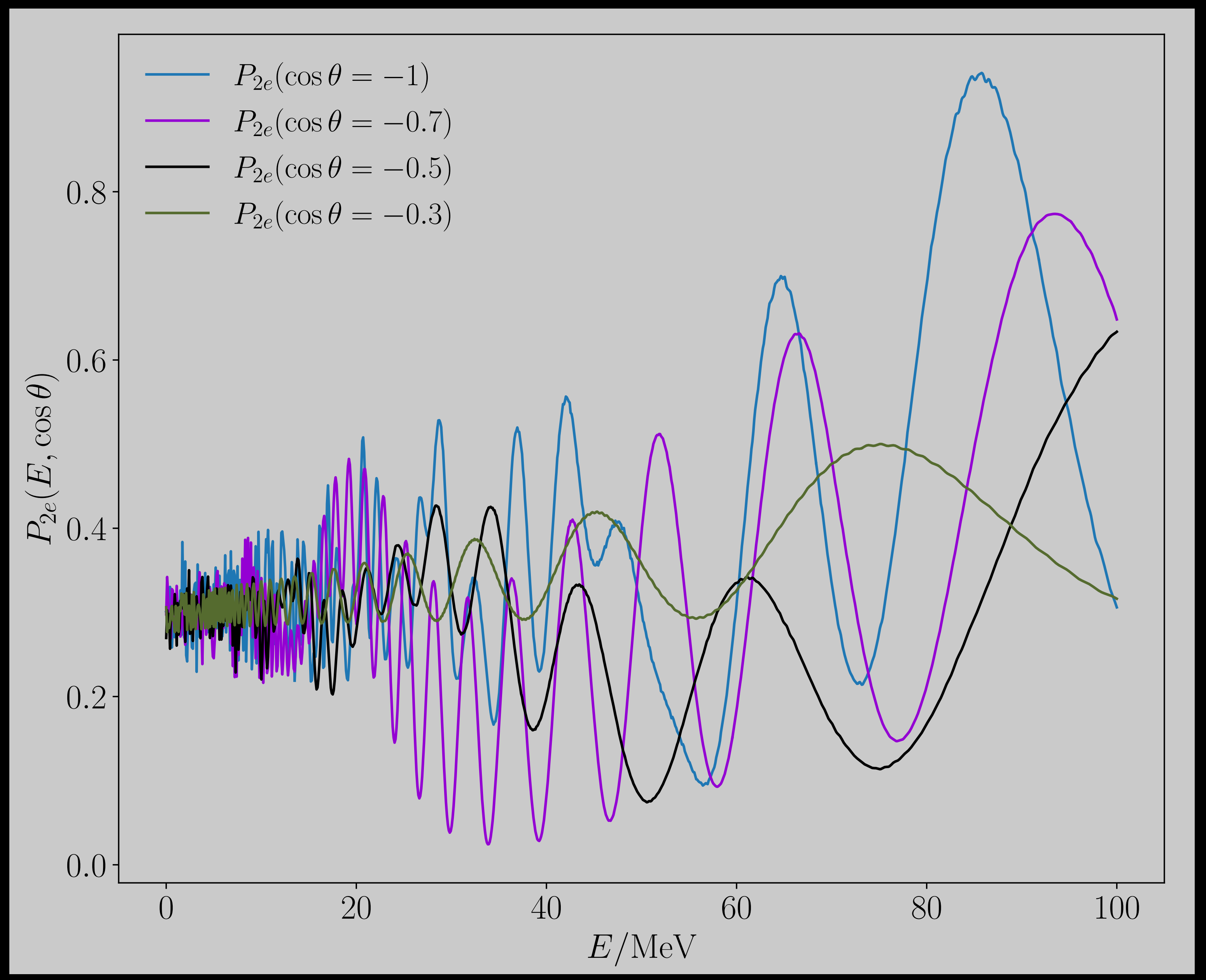
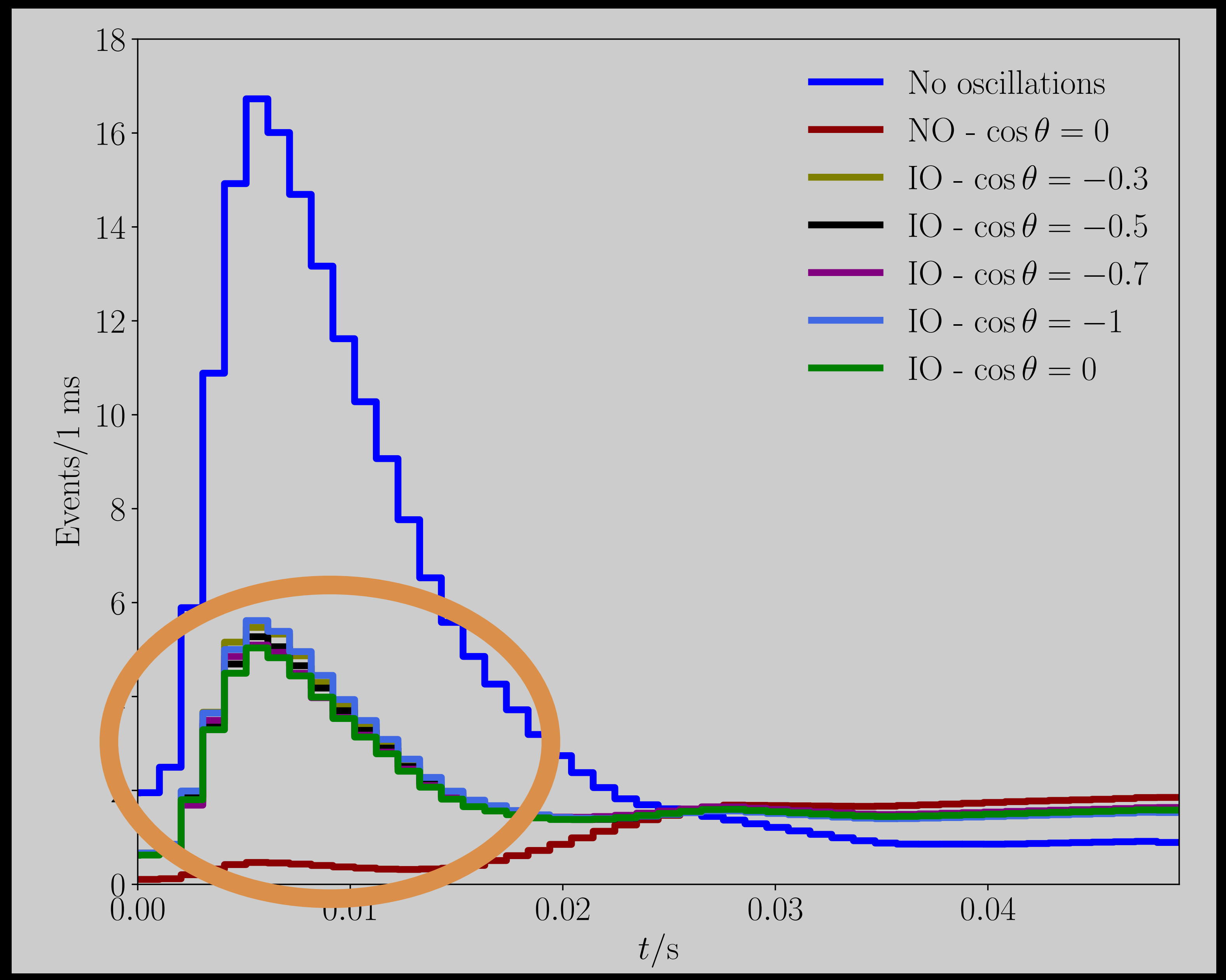



$D = 10$ kpc

$M = 8.8\,M_\odot$

**EFFECTS ON RATE**




Mild variation respect to the case of absence of Earth matter

# Summary

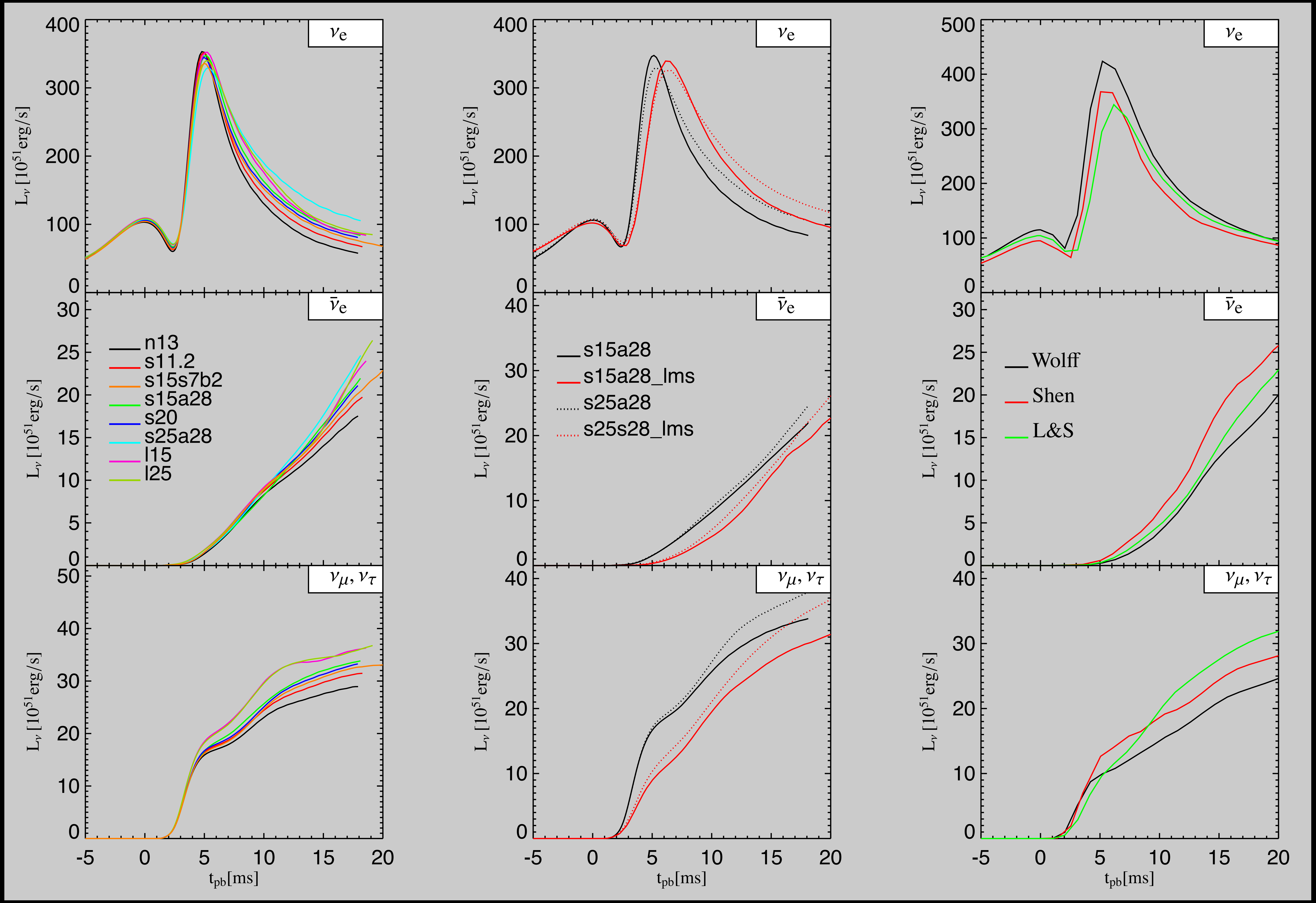
**The neutrino signal coming from the Supernova neutronization burst, visible only in the $\nu_e$ spectrum, constitutes an important tool to constrain the absolute value of the neutrino mass and it can give a complementary (and independent) measurement to $\beta$-decays and cosmology.**

*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*

HIDDeν
Hunting Invisibles: Dark sectors, Dark matter and Neutrinos

# Backup

## Supernova parameters uncertainties: luminosity

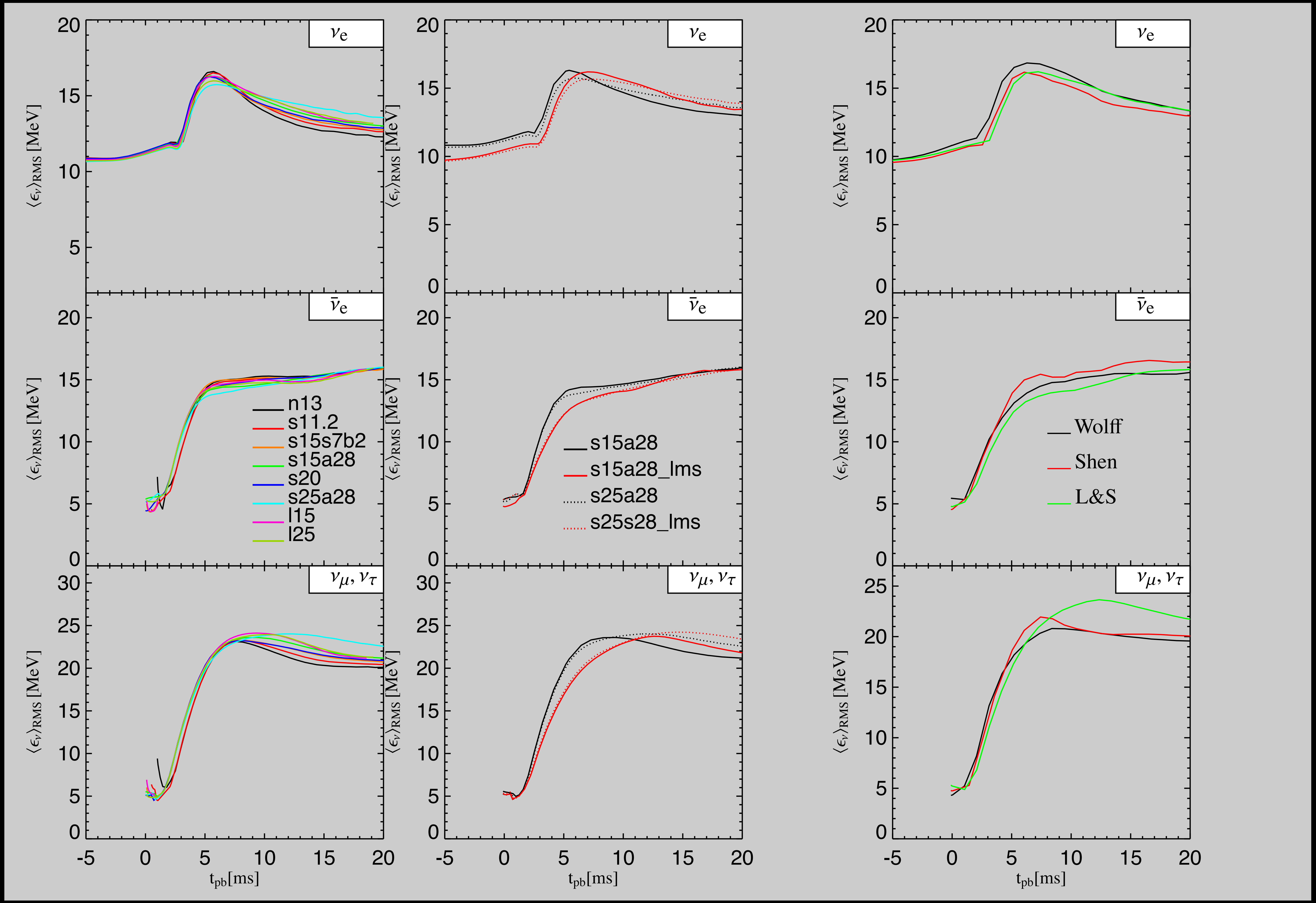



The neutronization burst results to be a robust, **model independent** prediction of the Supernova models.

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

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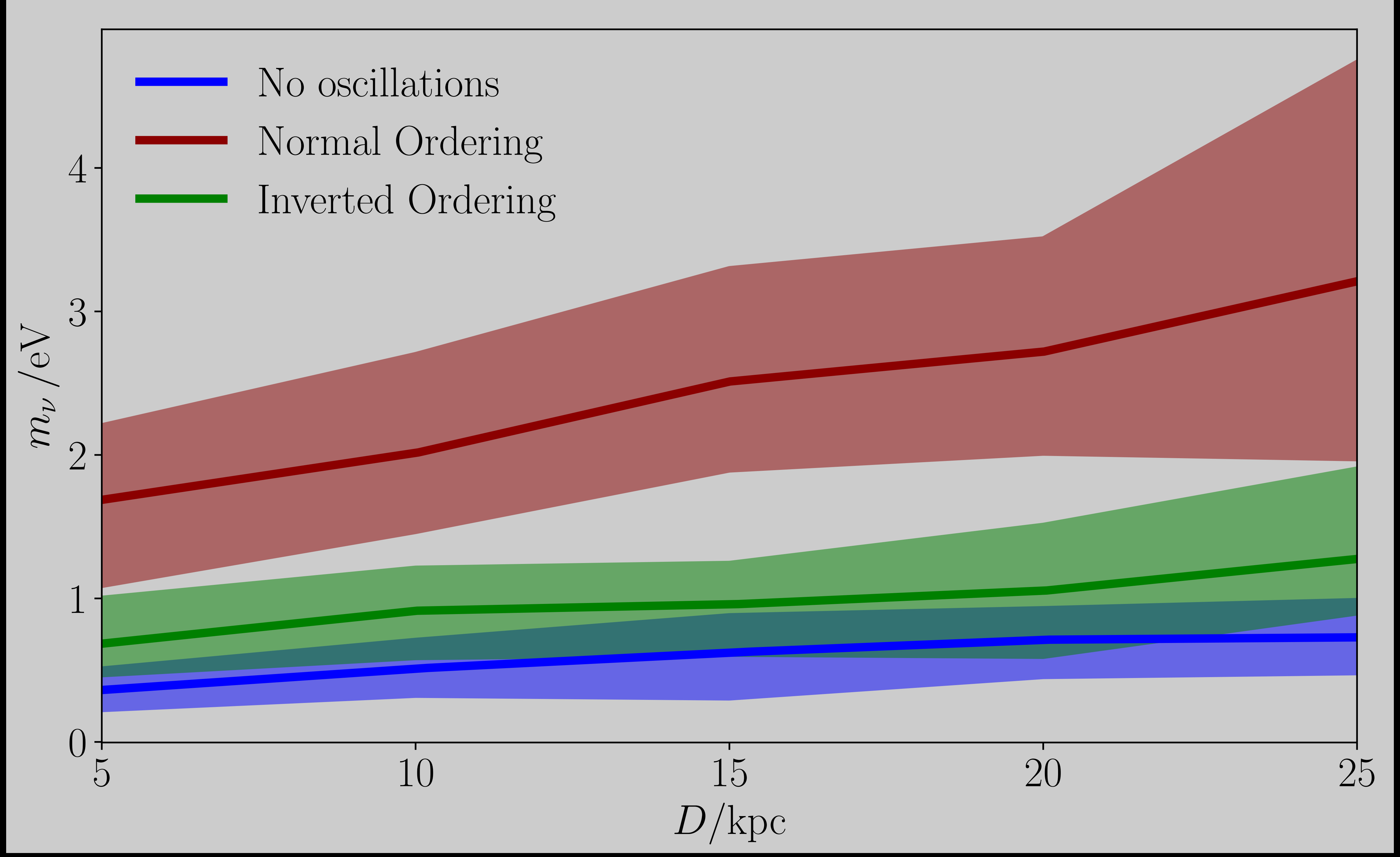
## Dependence on the Supernova distance from the detector

How the 95% CL upper bounds on $m_\nu$ shift with the Supernova distance $D$ from the detector

$M = 8.8\, M_\odot$



# 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

## Evolution operator definition

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

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

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

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

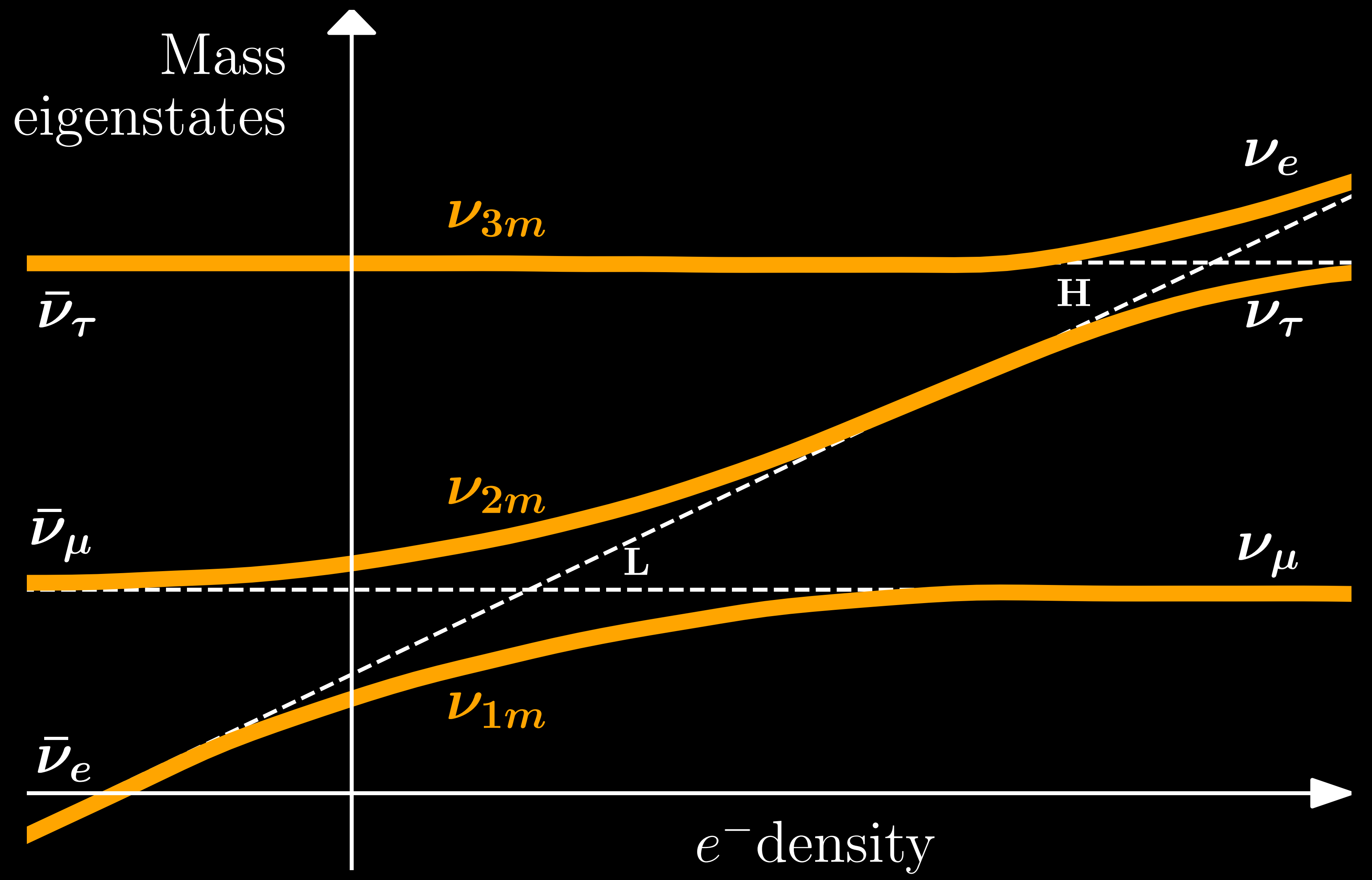
$$N_j(x) = \alpha_j + \beta_j x^2 + \gamma_j x^4$$

# Backup

## Mikheyev-Smirnov-Wolfenstein effect

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

$\Delta m_{13}^2 > 0$

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