# Neutrino mass constraints in next-generation experiments with Supernovae

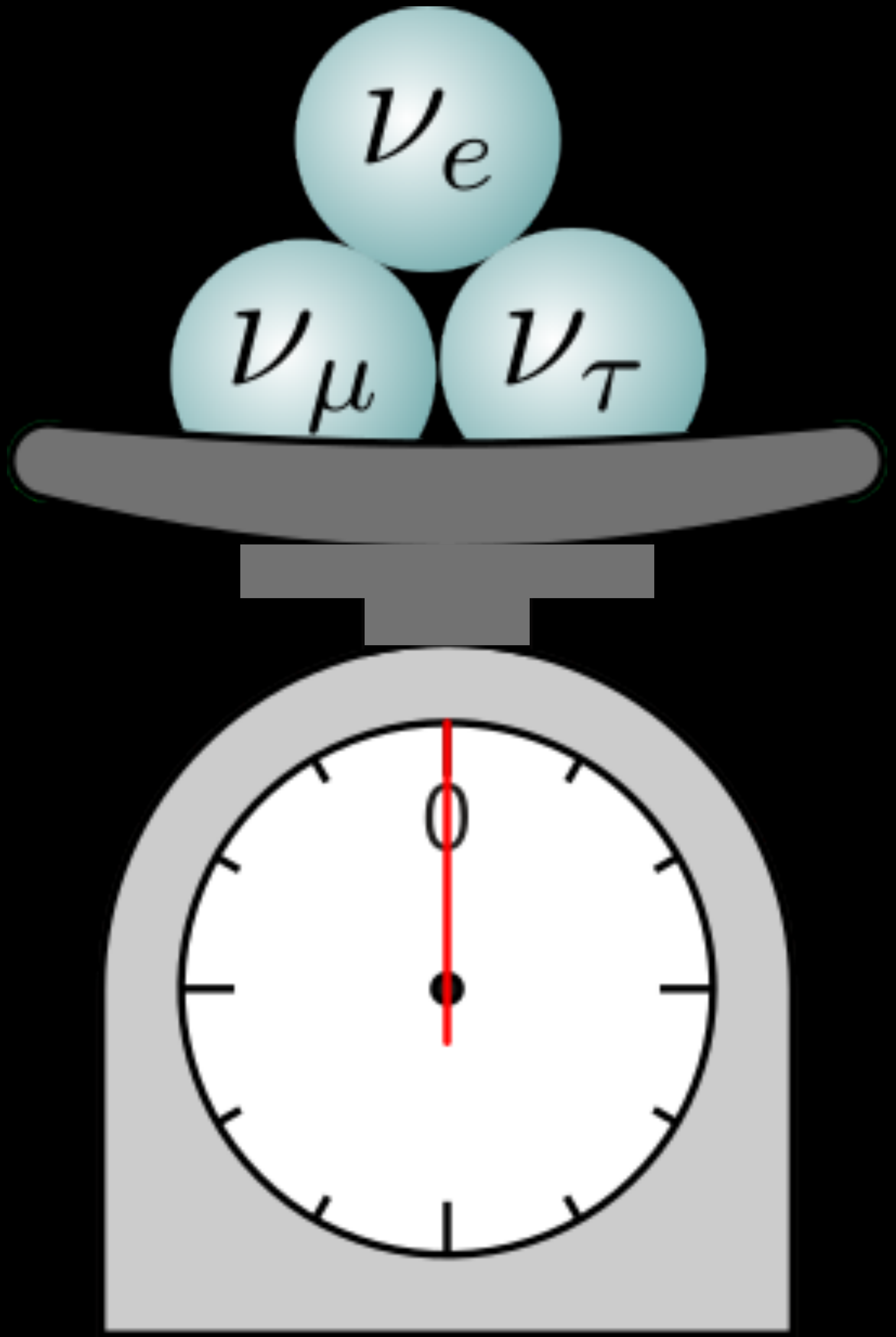
Pompa, Capozzi, Mena, Sorel (PRL 129, 2022)

SN$\nu$D-2023@LNGS

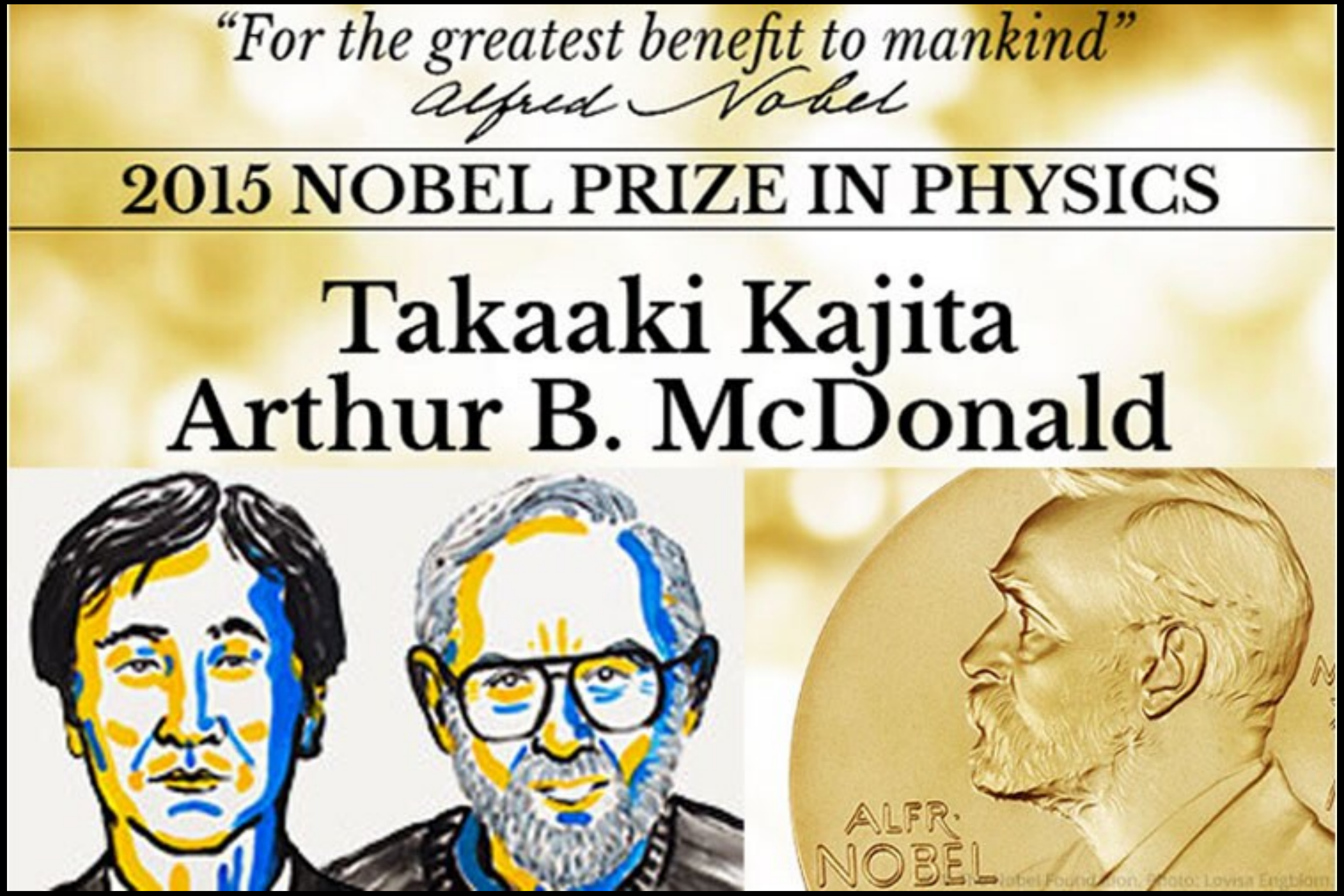
01/06/2023

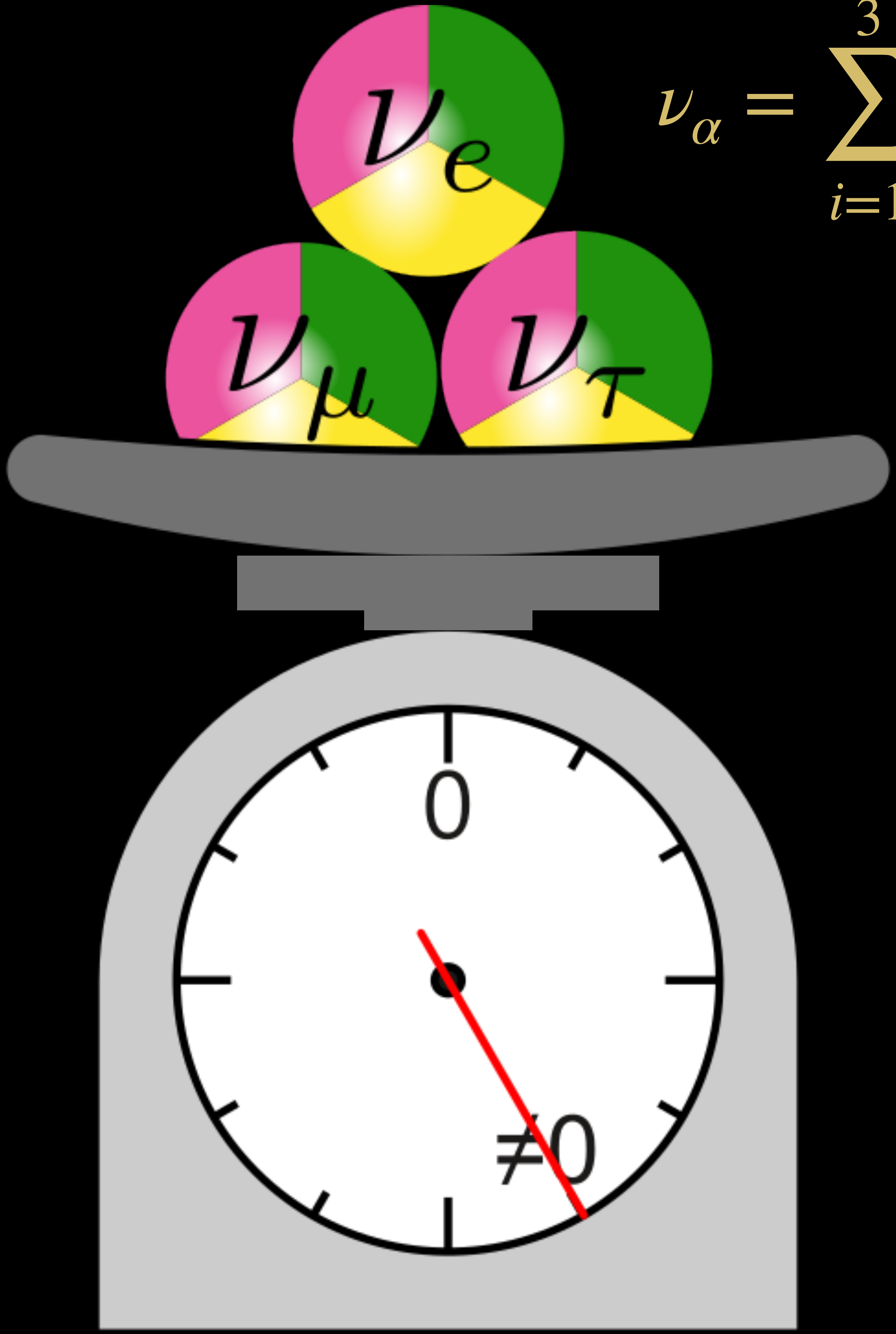
**Federica Pompa** - fpompa@ific.uv.es

# Neutrino mass



# Neutrino mass




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

# 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:

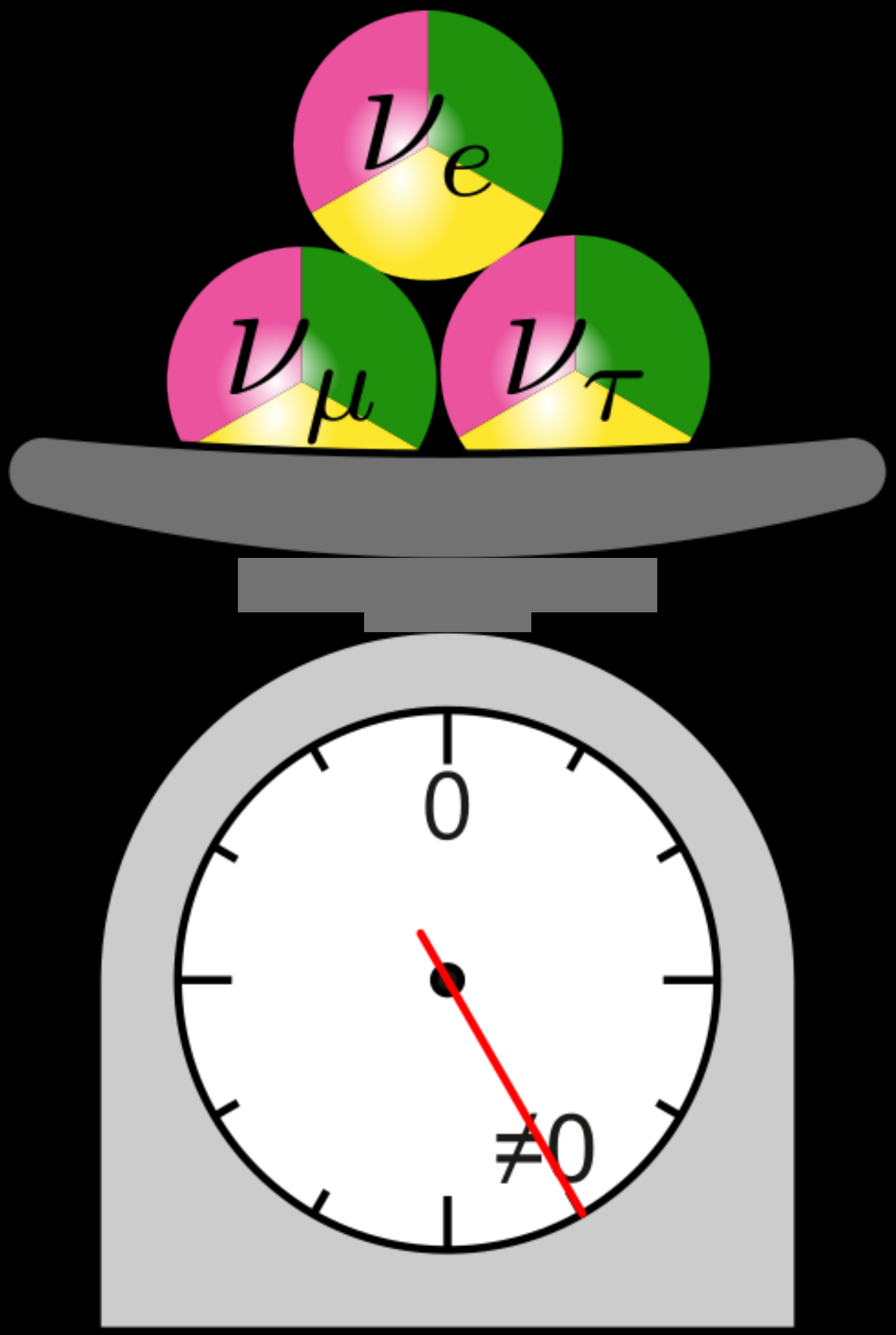
KamLAND-Zen Collaboration (PRL 130, 2022)

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

Time-of-flight constraints:

Pagliaroli,Rossi-Torres,Vissani(Astropart.Phys.V33,2010)

Kamiokande-II (SN1987A) $\Rightarrow m_\nu < 5.7$ eV (95% CL)



# Neutrino mass

$$\boxed{\begin{array}{l}\text{From cosmology:}\\ \text{Di Valentino, Gariazzo, Mena (PRD 104, 2021)}\\ \text{(CMB+BAO)} \Rightarrow \sum m_\nu < 0.12 \text{ eV (95\% CL)}\end{array}}$$

From kinematic measurements:

KATRIN Collaboration (2021)

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

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

KamLAND-Zen Collaboration (PRL 130, 2022)

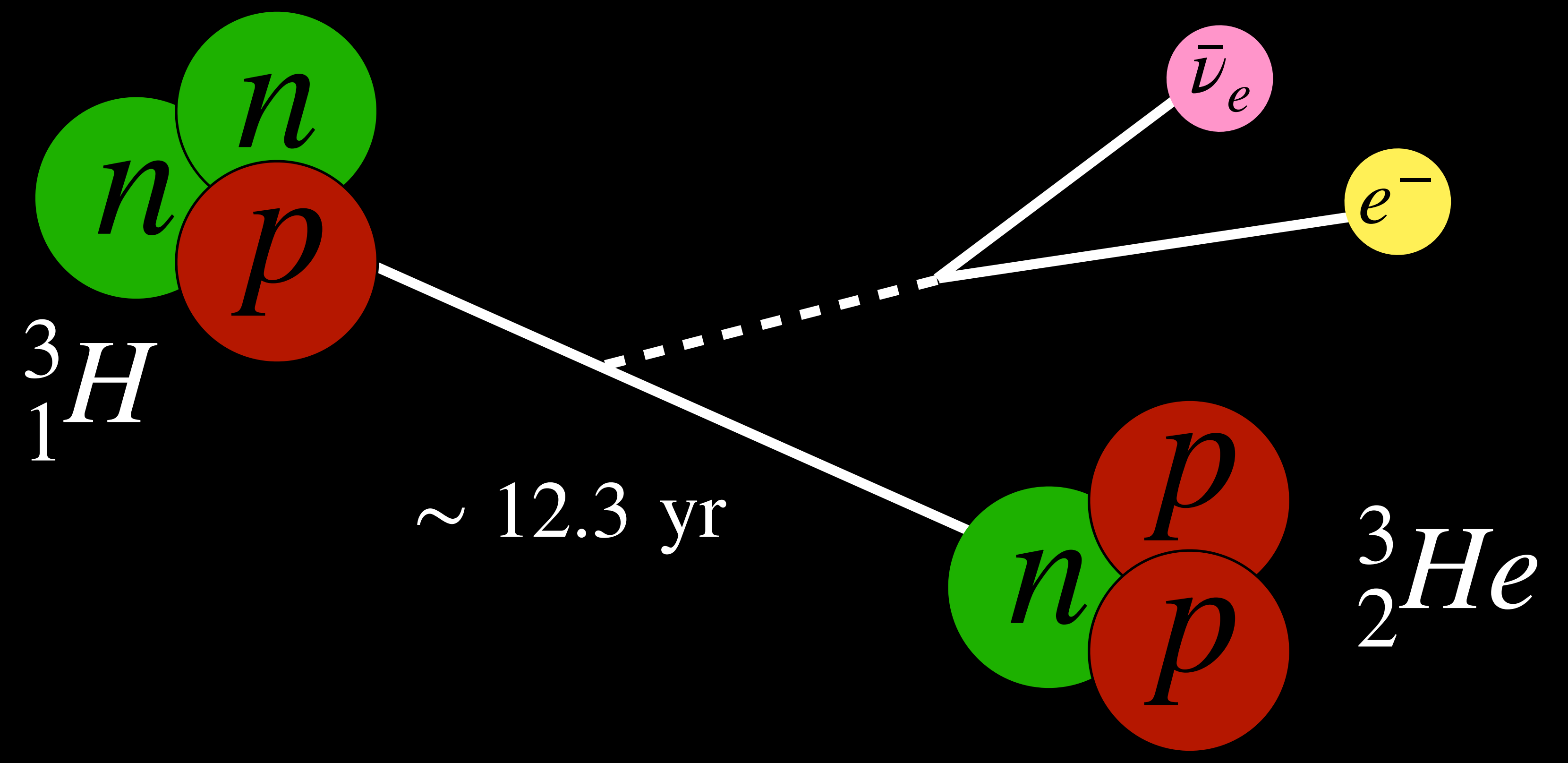
KamLAND-Zen $\Rightarrow m_{\beta\beta} < 0.16$ eV (90% CL)

Time-of-flight constraints:

Pagliaroli, Rossi-Torres, Vissani (Astropart. Phys. V33, 2010)

Kamiokande-II (SN1987A) $\Rightarrow m_\nu < 5.7$ eV (95% CL)

# 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:

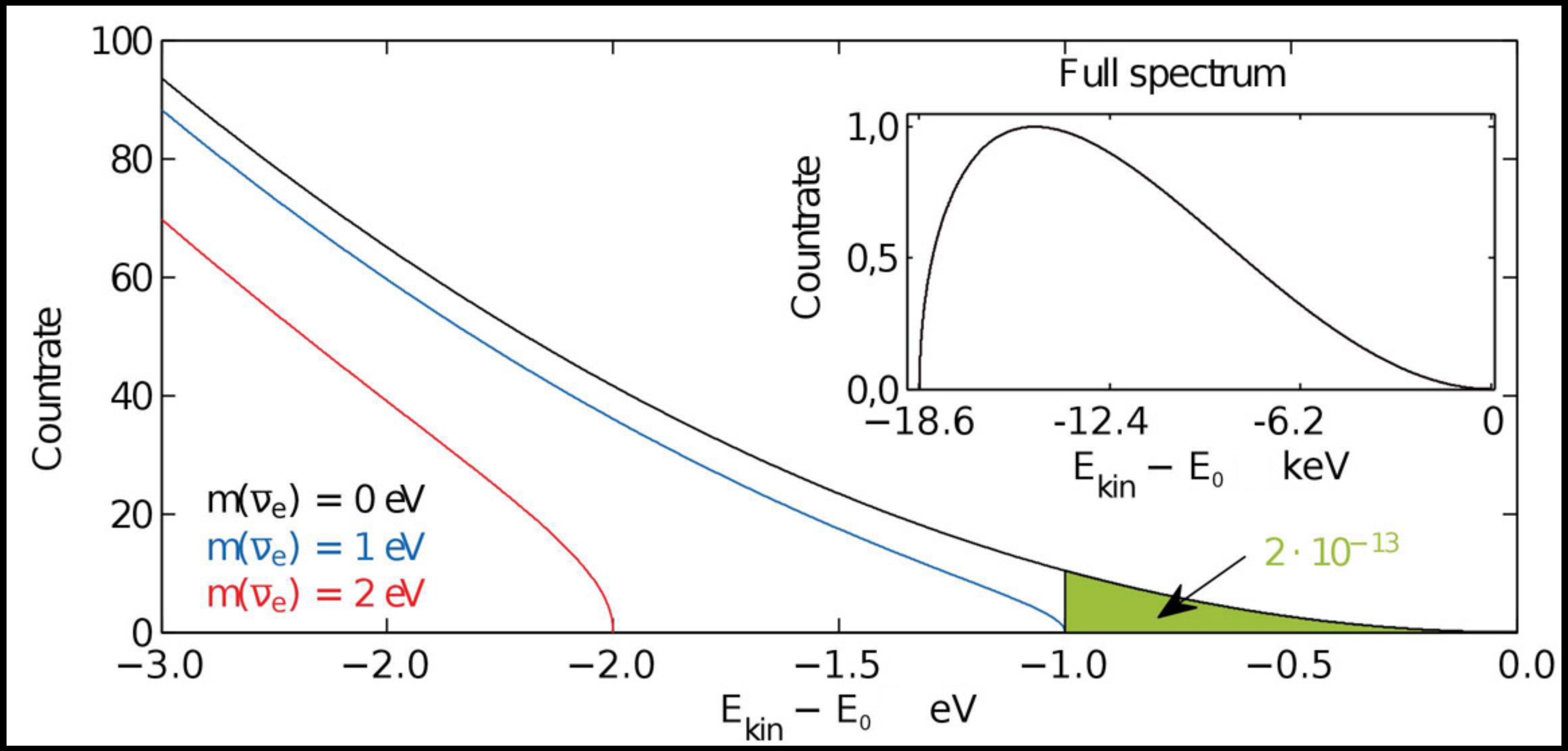
KamLAND-Zen Collaboration (PRL 130, 2022)

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

Time-of-flight constraints:

Pagliaroli,Rossi-Torres,Vissani(Astropart.Phys.V33,2010)

Kamiokande-II (SN1987A) $\Rightarrow m_\nu < 5.7$ eV (95% CL)



# 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:

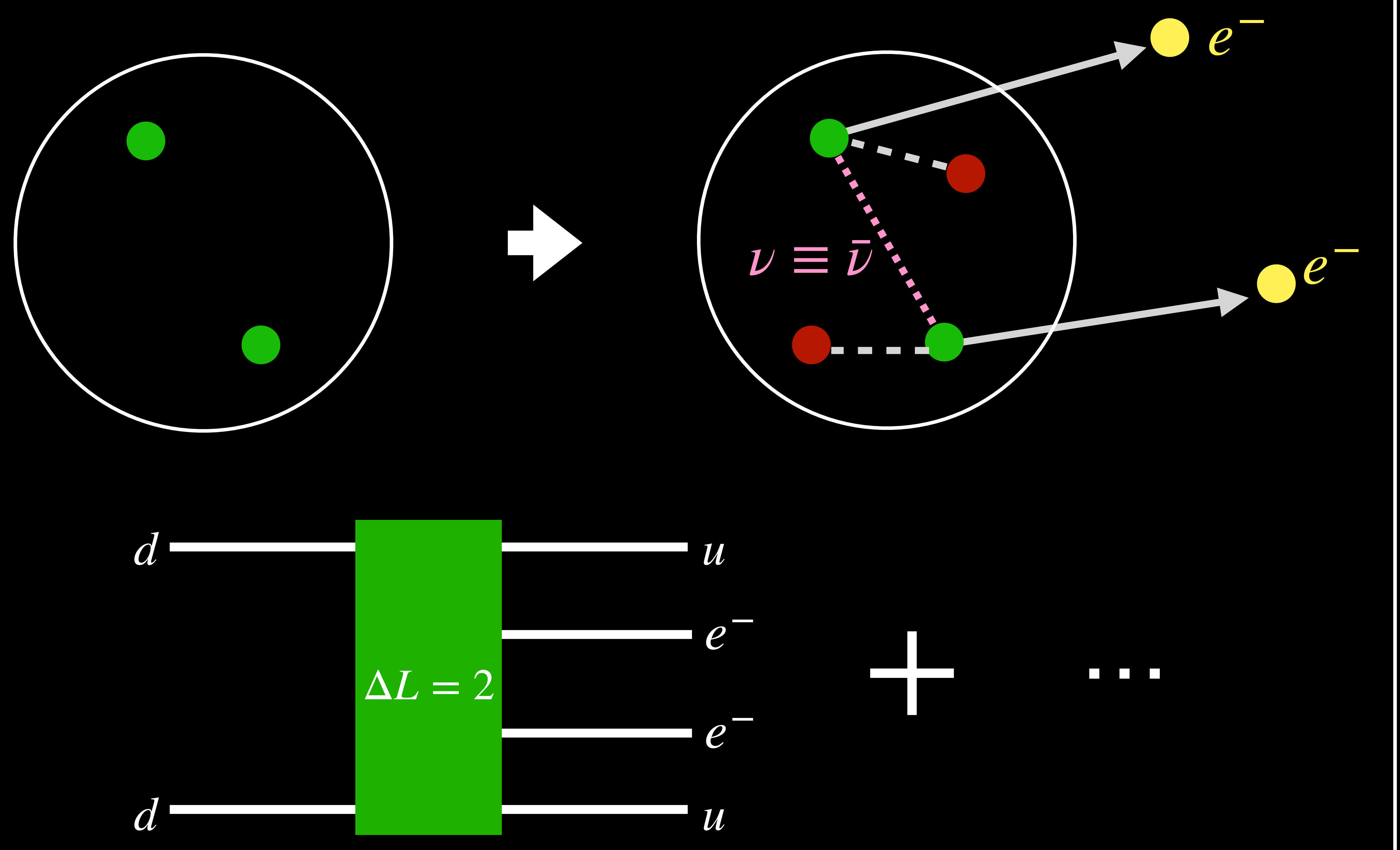
KamLAND-Zen Collaboration (PRL 130, 2022)

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

Time-of-flight constraints:

Pagliaroli,Rossi-Torres,Vissani(Astropart.Phys.V33,2010)

Kamiokande-II (SN1987A) $\Rightarrow m_\nu < 5.7$ eV (95% CL)




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

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

**Nuclear Models dependence!**
**Majorana neutrino assumption!**

# Neutrino mass

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:

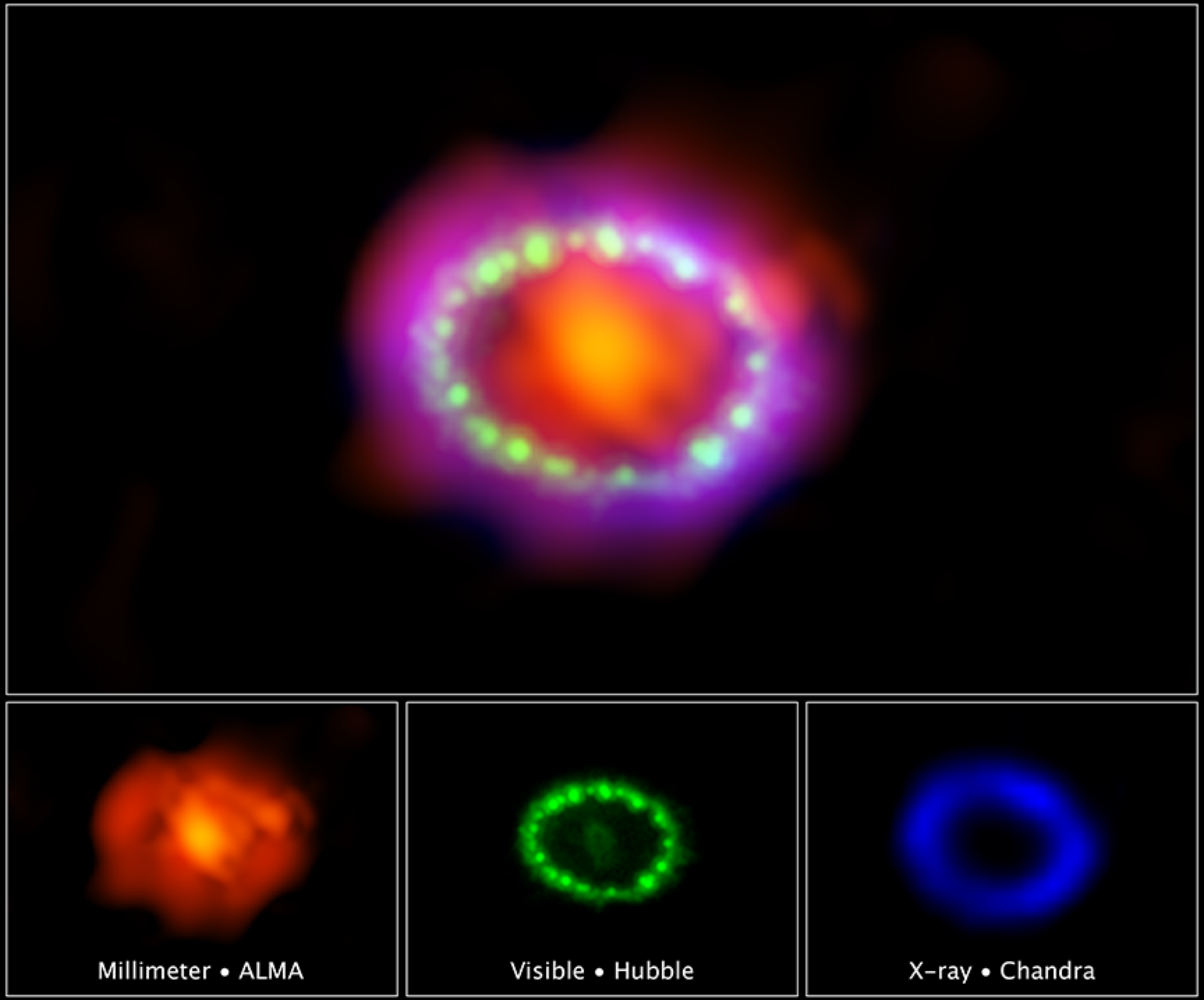
KamLAND-Zen Collaboration (PRL 130, 2022)

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

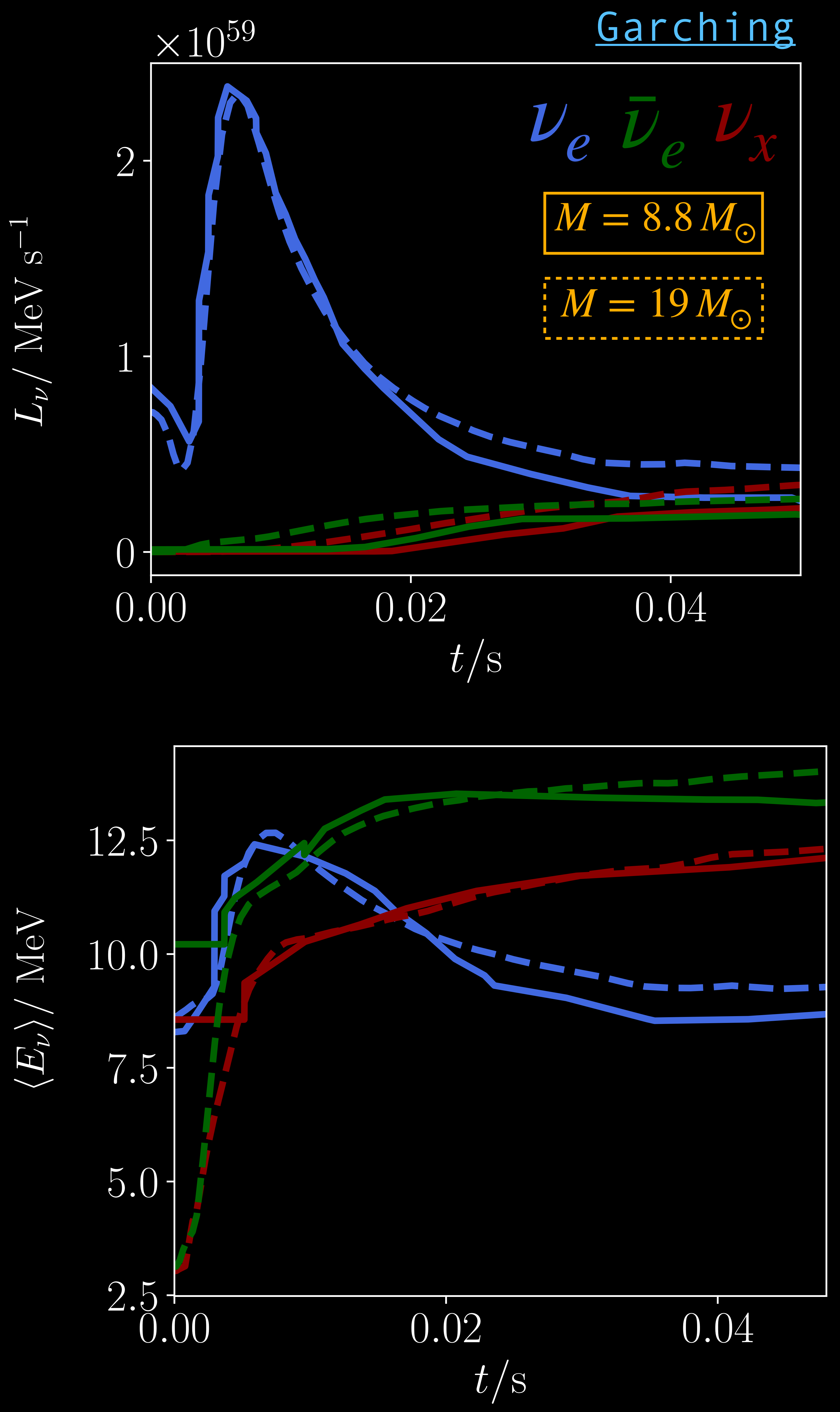
Time-of-flight constraints:

Pagliaroli,Rossi-Torres,Vissani(Astropart.Phys.V33,2010)

Kamiokande-II (SN1987A) $\Rightarrow m_\nu < 5.7$ eV (95% CL)




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

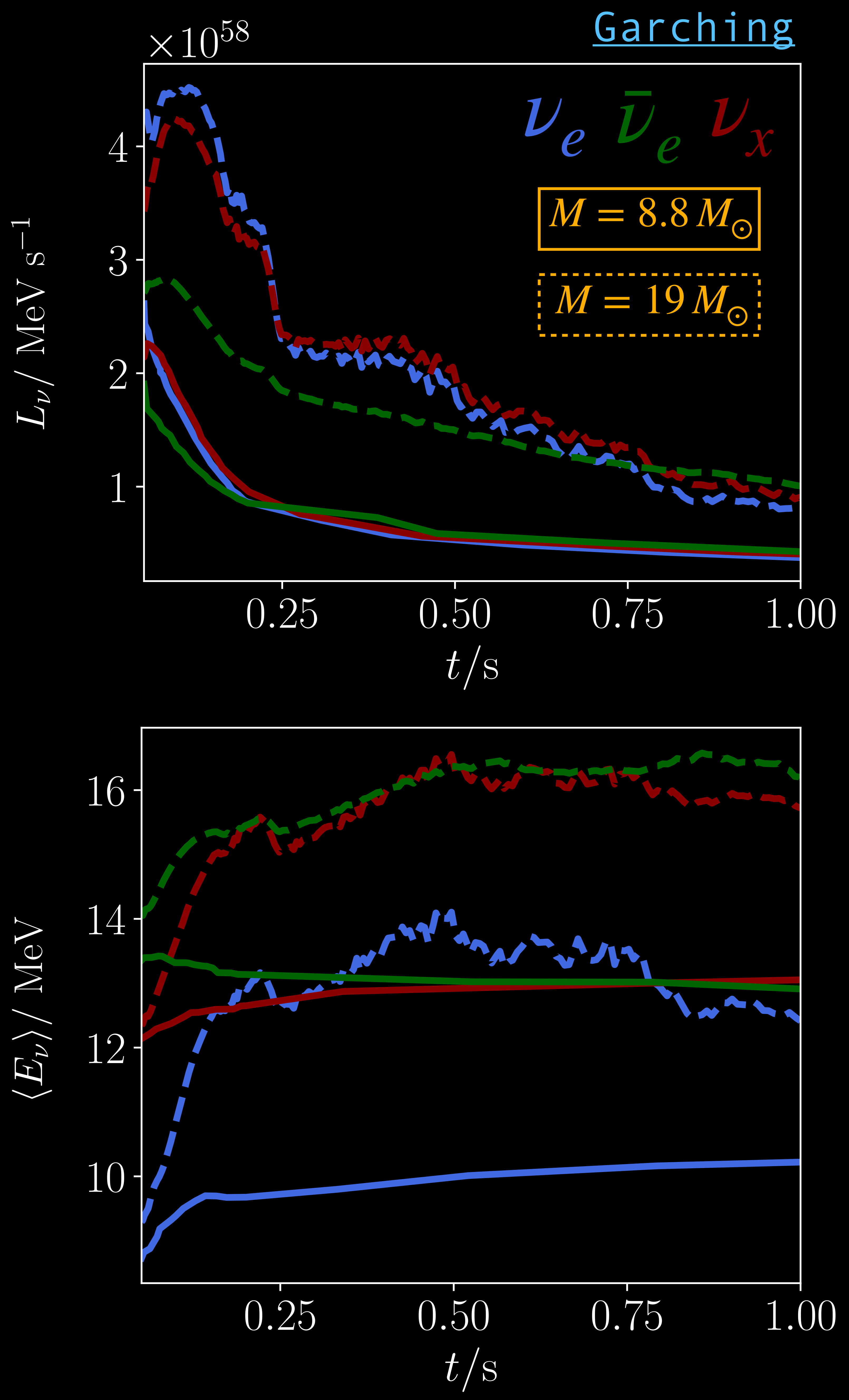



NEUTRONIZATION BURST

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

**Progenitor independent!**

ACCRETION PHASE




## Progenitor dependence!

Higher mass $M$

↓

More binding energy released

↓

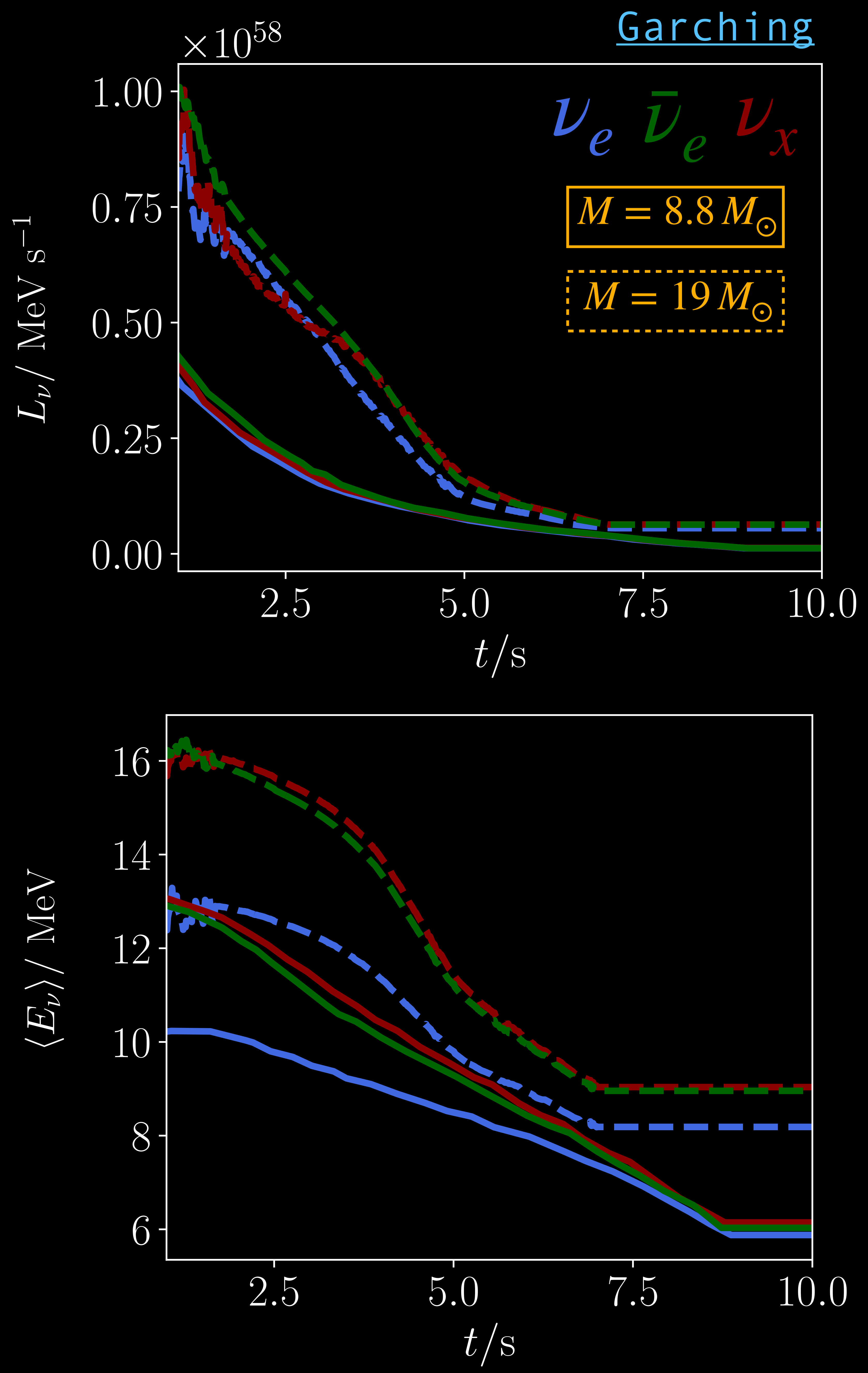
Higher $L_\nu$ (rates)

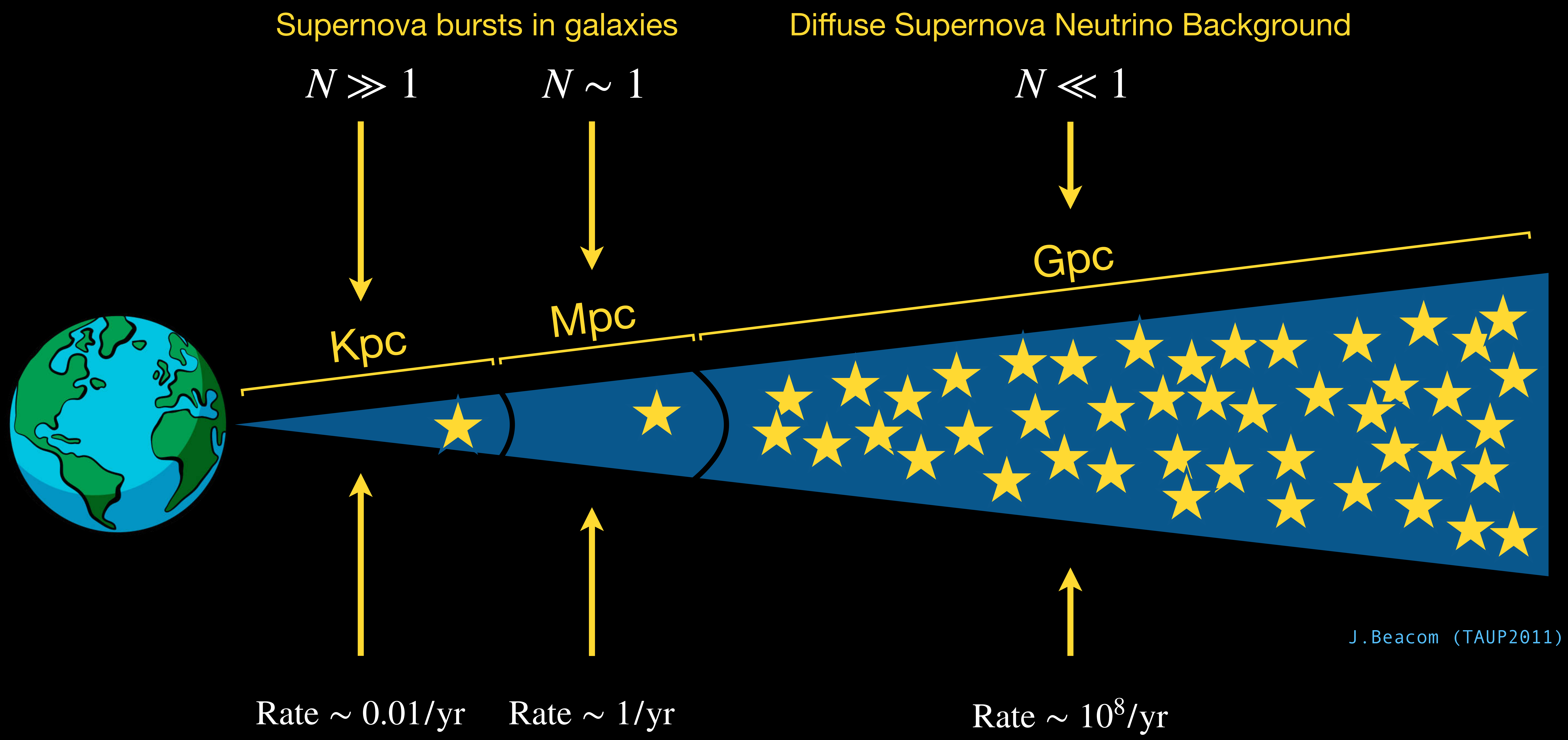
Final stage of the core collapse.

Emission of $\nu$ and $\bar{\nu}$ of all flavors.

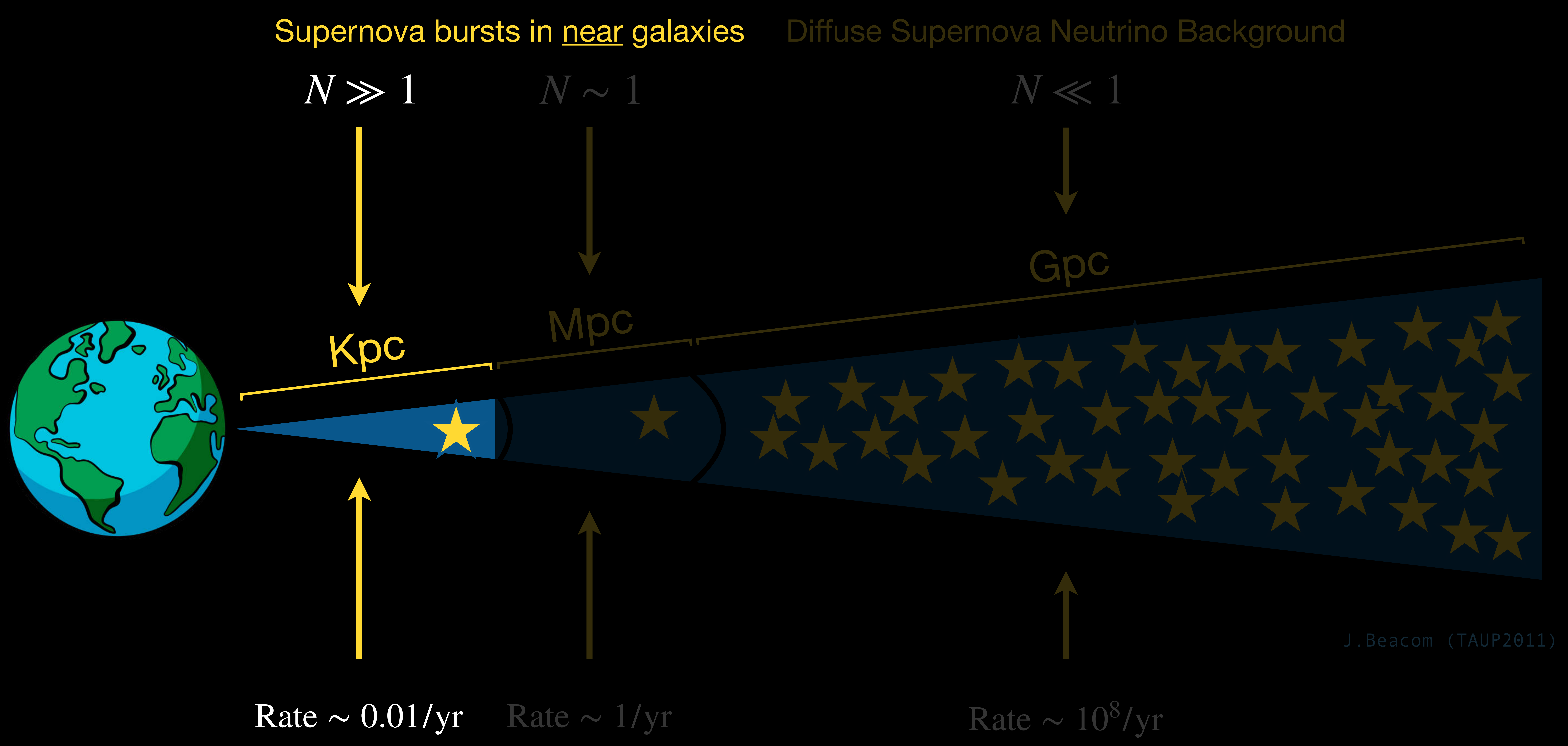
Mean energies: $\mathcal{O}(10)$ MeV

**COOLING PHASE**





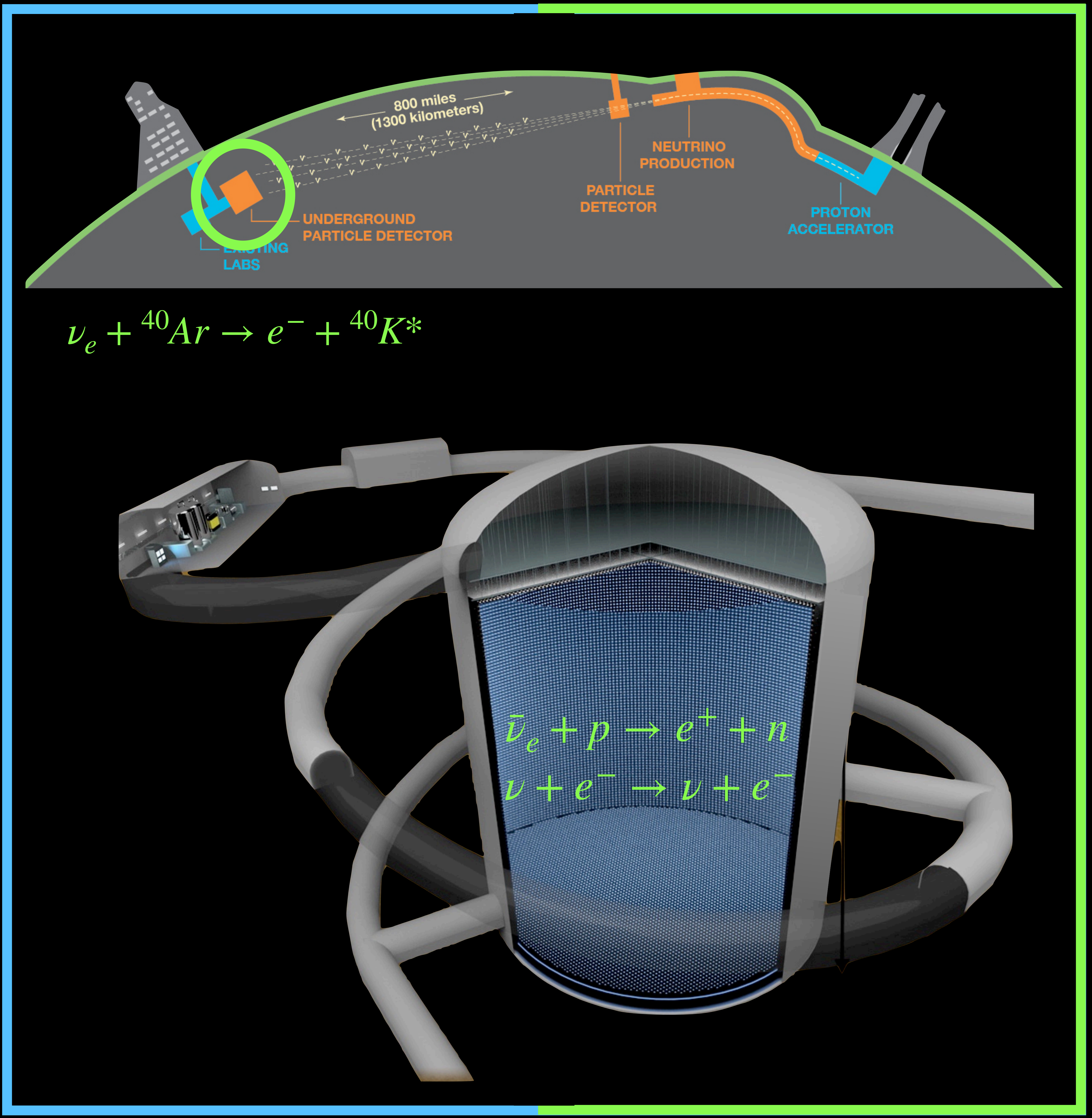
Supernova bursts in galaxies
Diffuse Supernova Neutrino Background
$N \gg 1$
$N \sim 1$
$N \ll 1$
Kpc
Mpc
Gpc
J.Beacom (TAUP2011)
Rate $\sim 0.01/\mathrm{yr}$
Rate $\sim 1/\mathrm{yr}$
Rate $\sim 10^8/\mathrm{yr}$


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

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

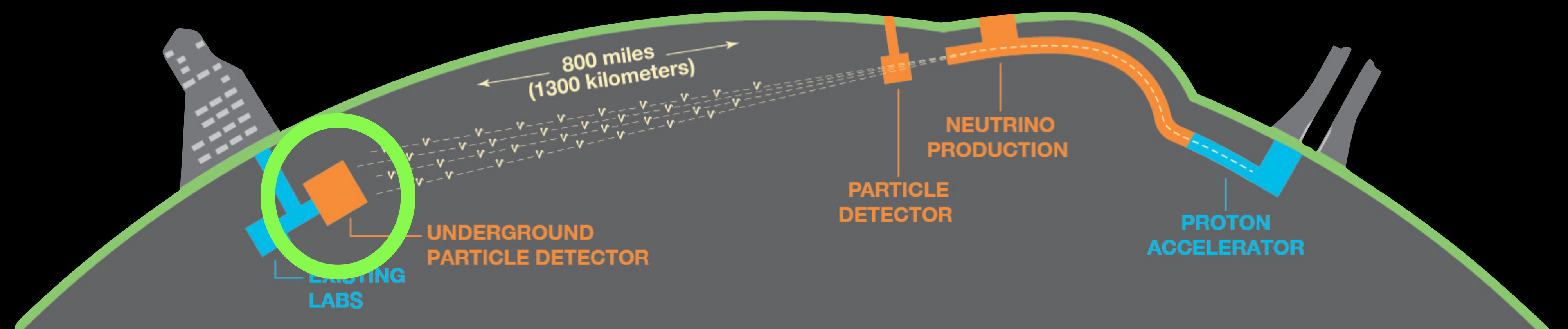
$$R(t,E) = \boxed{N_{\rm target}\ \epsilon(E)}\ \boxed{\sigma_{\rm sec}(E)}\ \ \Phi_\nu(t,E)$$

**Detector** **Interaction**

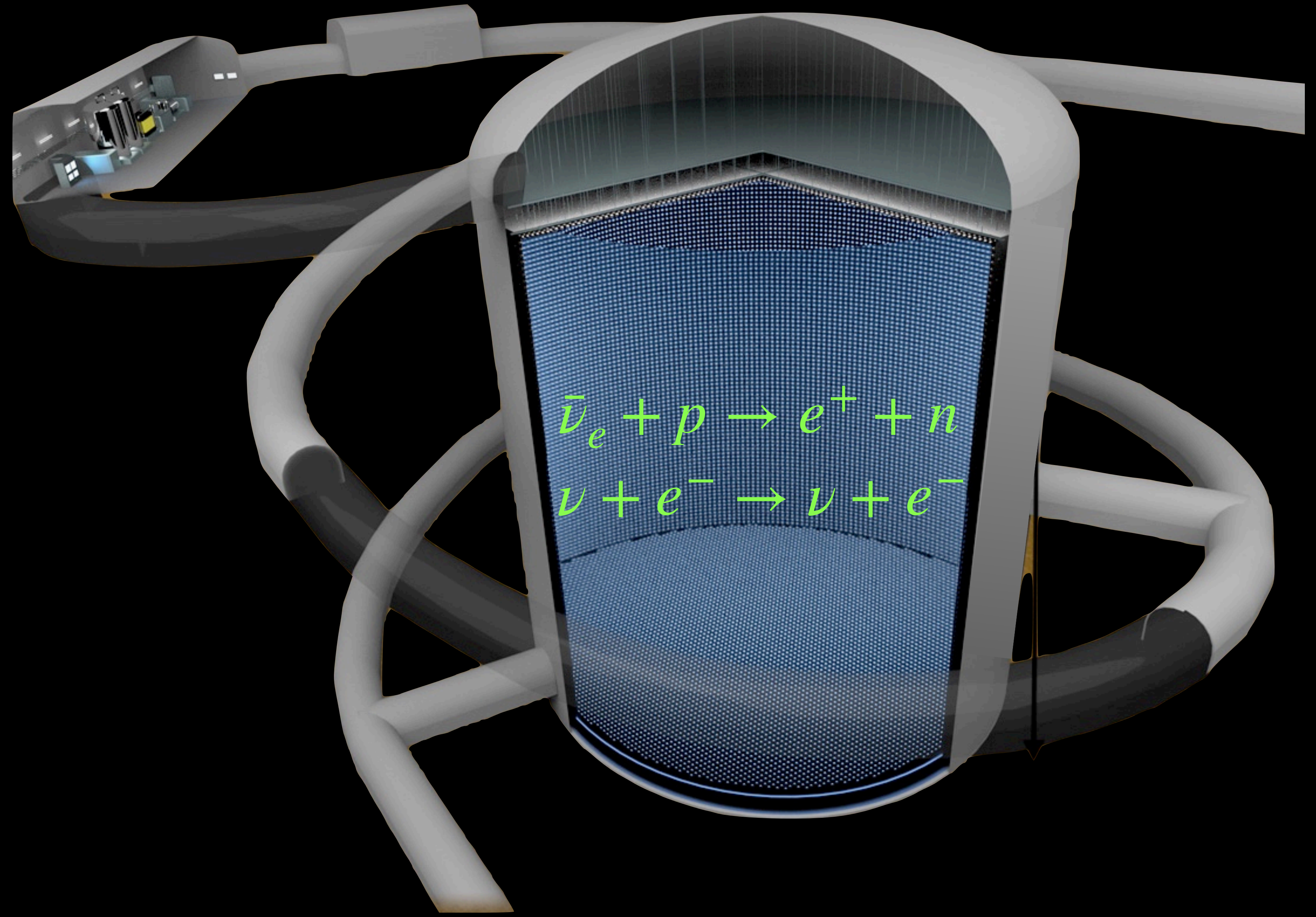


$$R(t,E) = \boxed{N_{\text{target}}\ \epsilon(E)}\ \boxed{\sigma_{\text{sec}}(E)}\ \boxed{\Phi_\nu(t,E)}$$

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

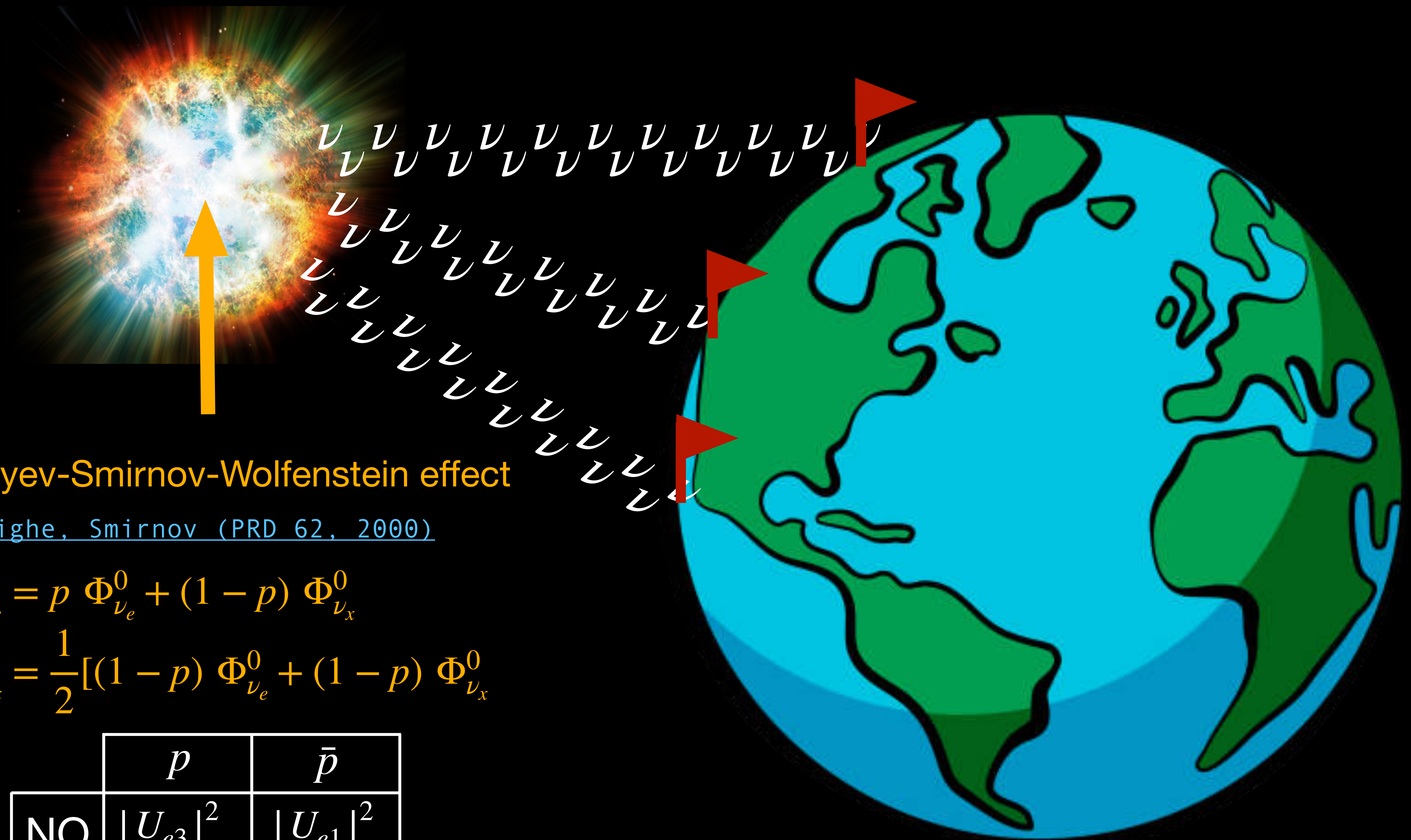



$\nu_e + {}^{40}Ar \rightarrow e^- + {}^{40}K^*$



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

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



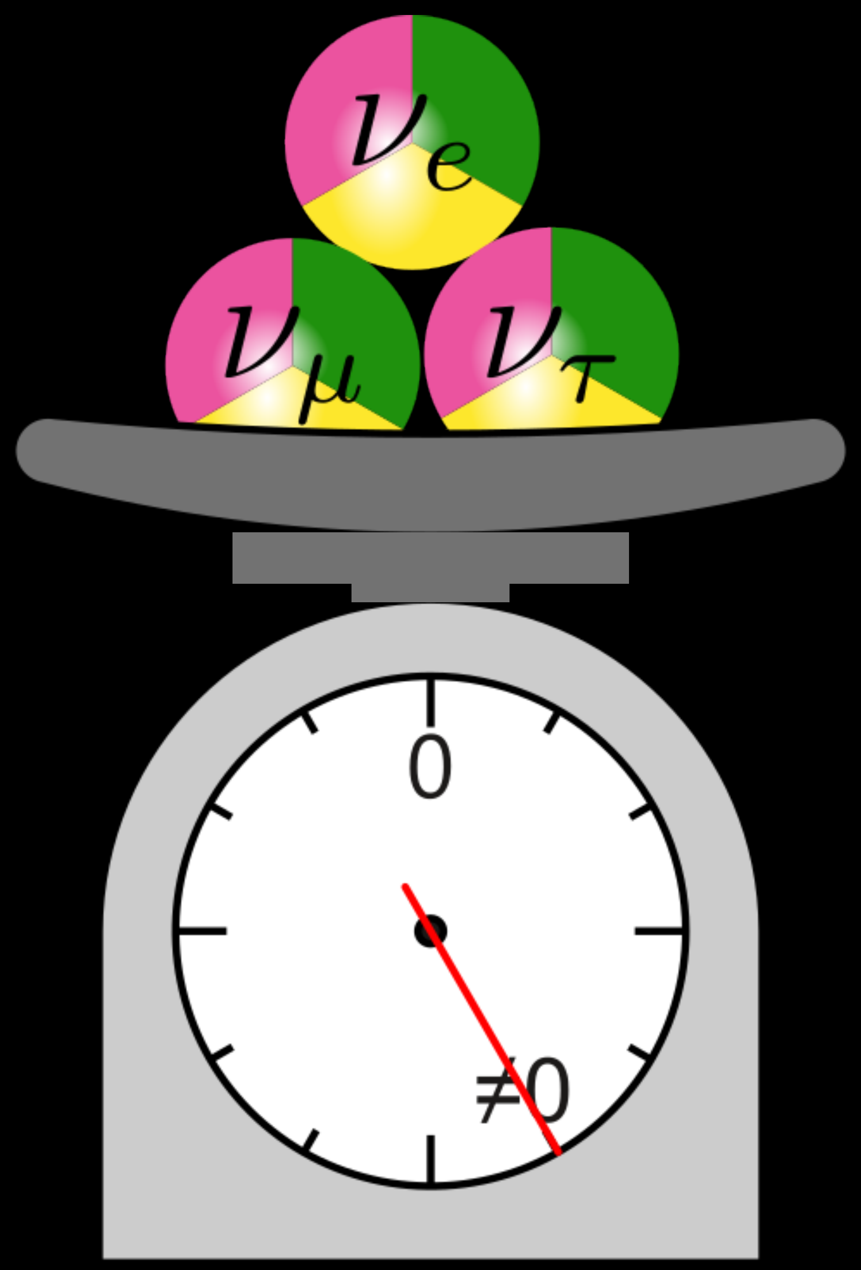
Mikheyev-Smirnov-Wolfenstein effect

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 | $\lvert U_{e2}\rvert^2$ | $\lvert U_{e3}\rvert^2$ |



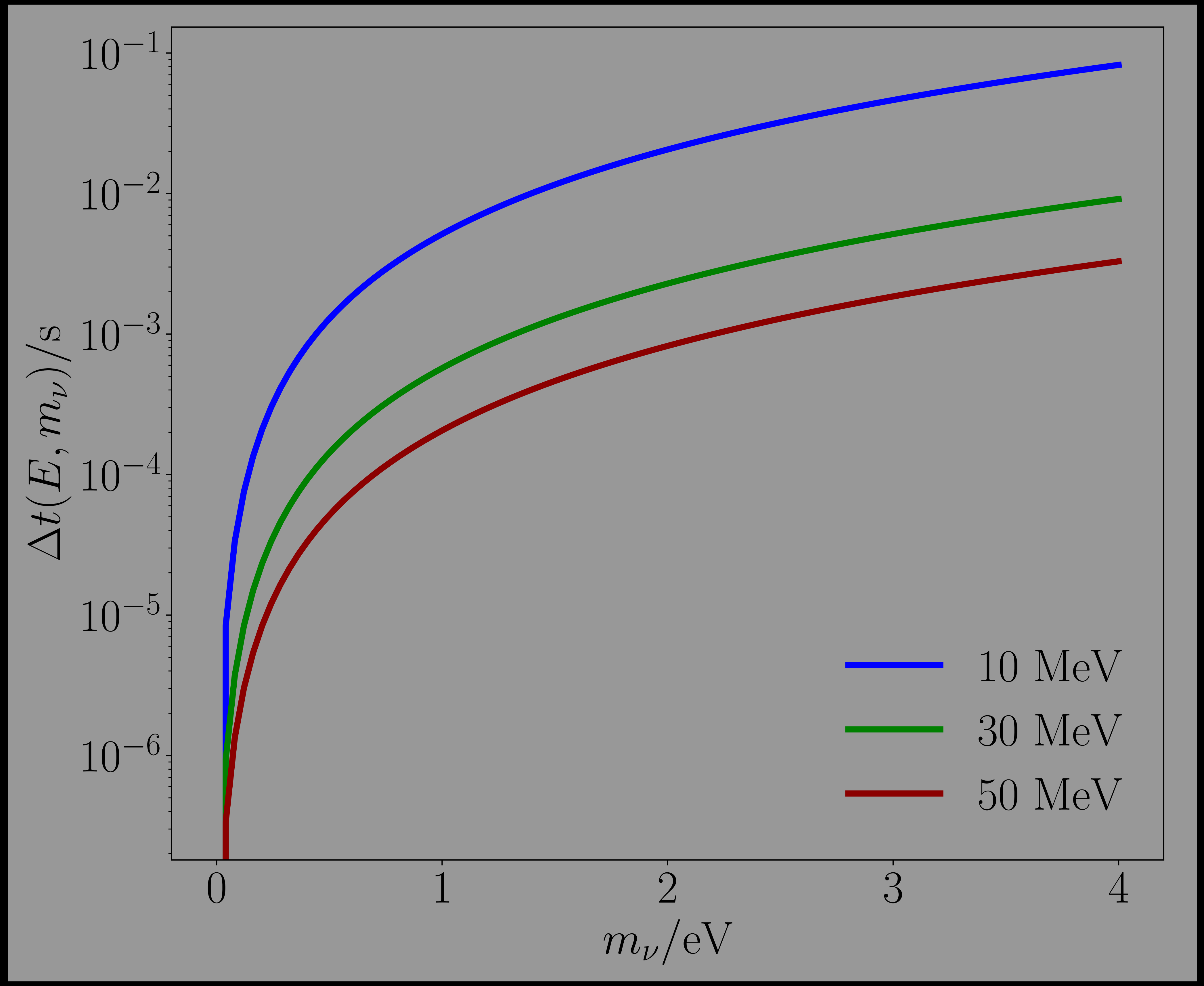

$$\Delta t_i(m_\nu) = \frac{D}{2c}\left(\frac{m_\nu}{E_i}\right)^2$$

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

@the detector

@the source

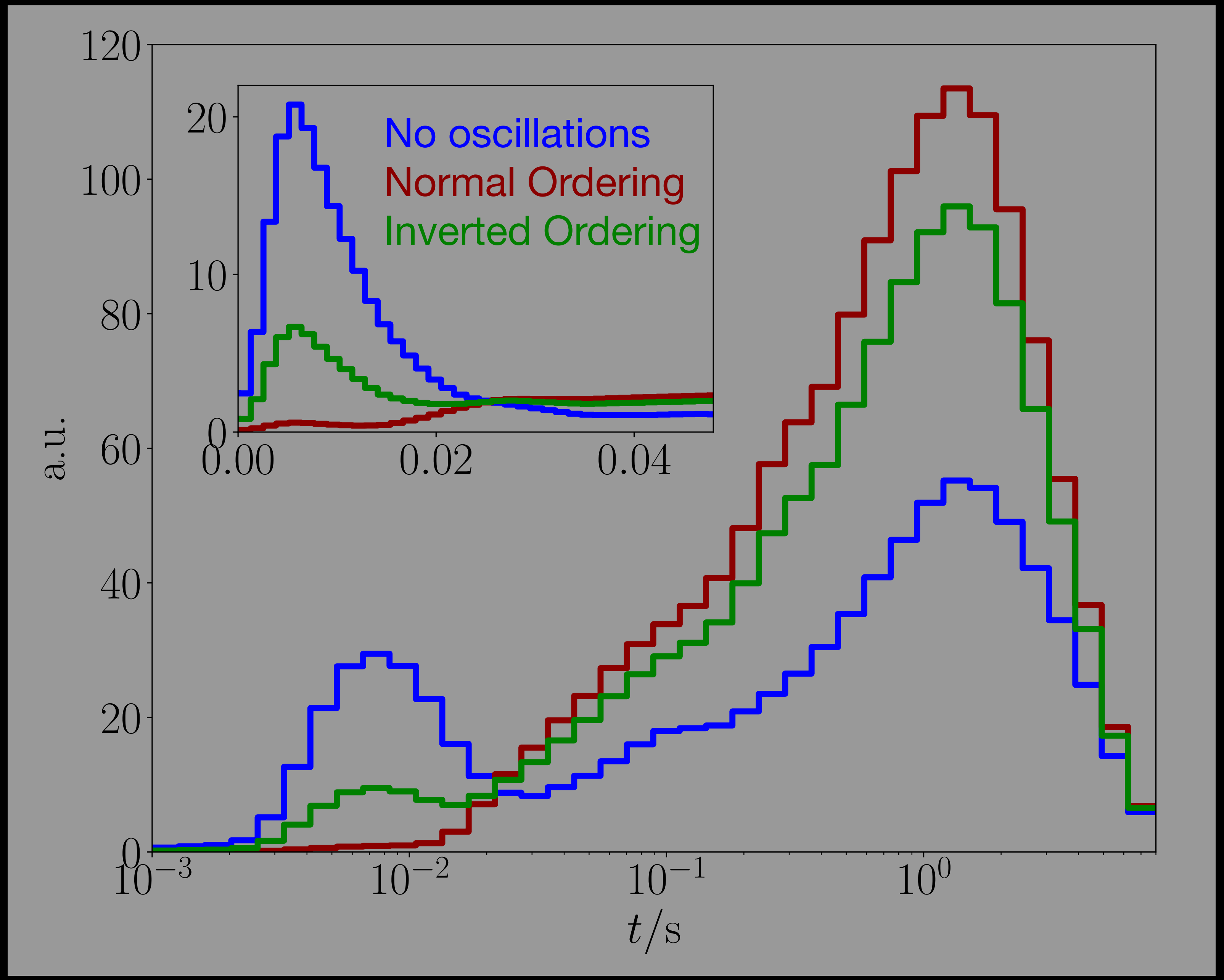
offset time (detector)



# DUNE: $D$ = 10 kpc

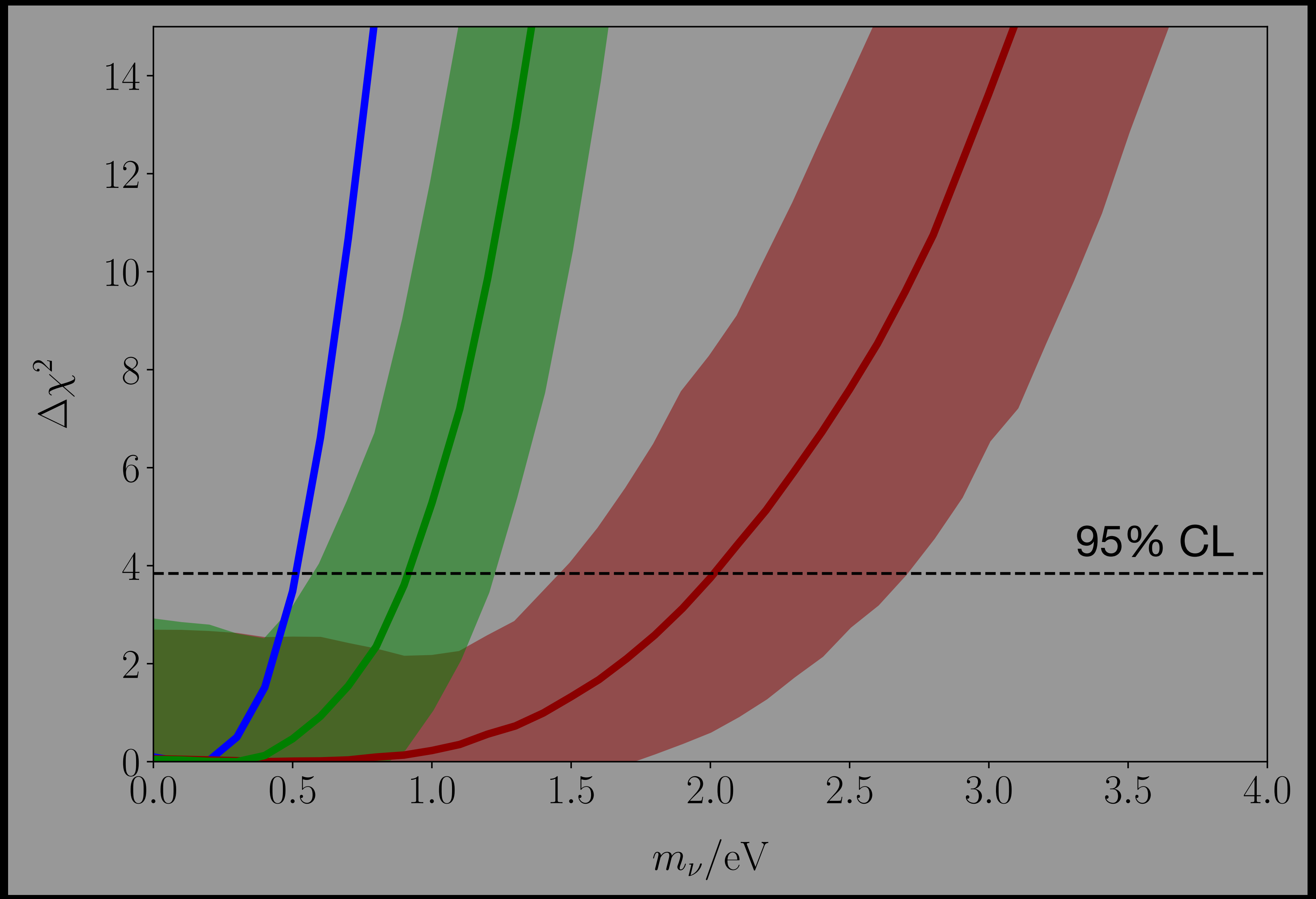
UPPER BOUNDS ON

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




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

$M = 8.8\, M_\odot$



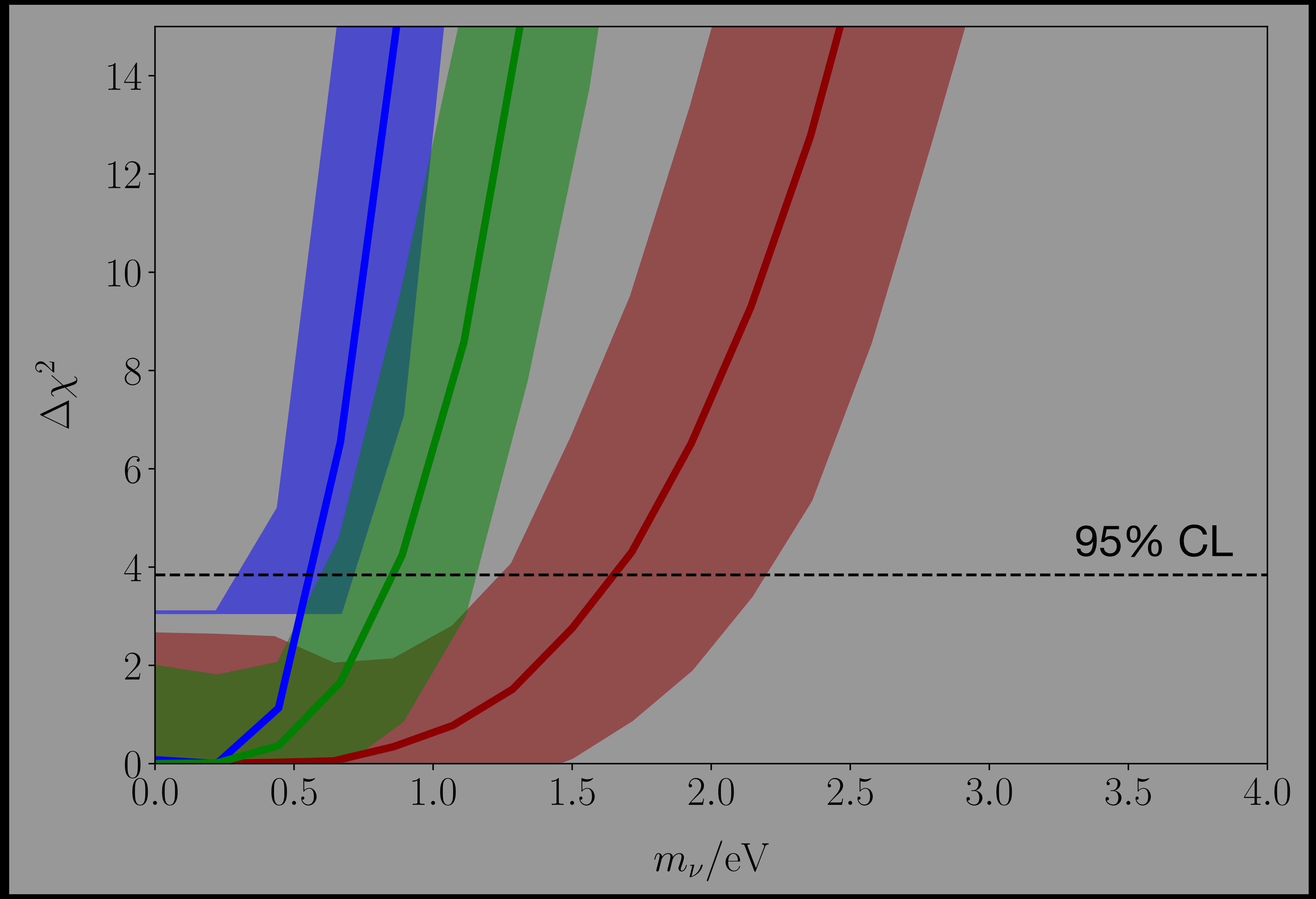

$m_\nu \leq 0.51^{+0.20}_{-0.19}$ eV

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

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

$M = 19\, M_\odot$

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

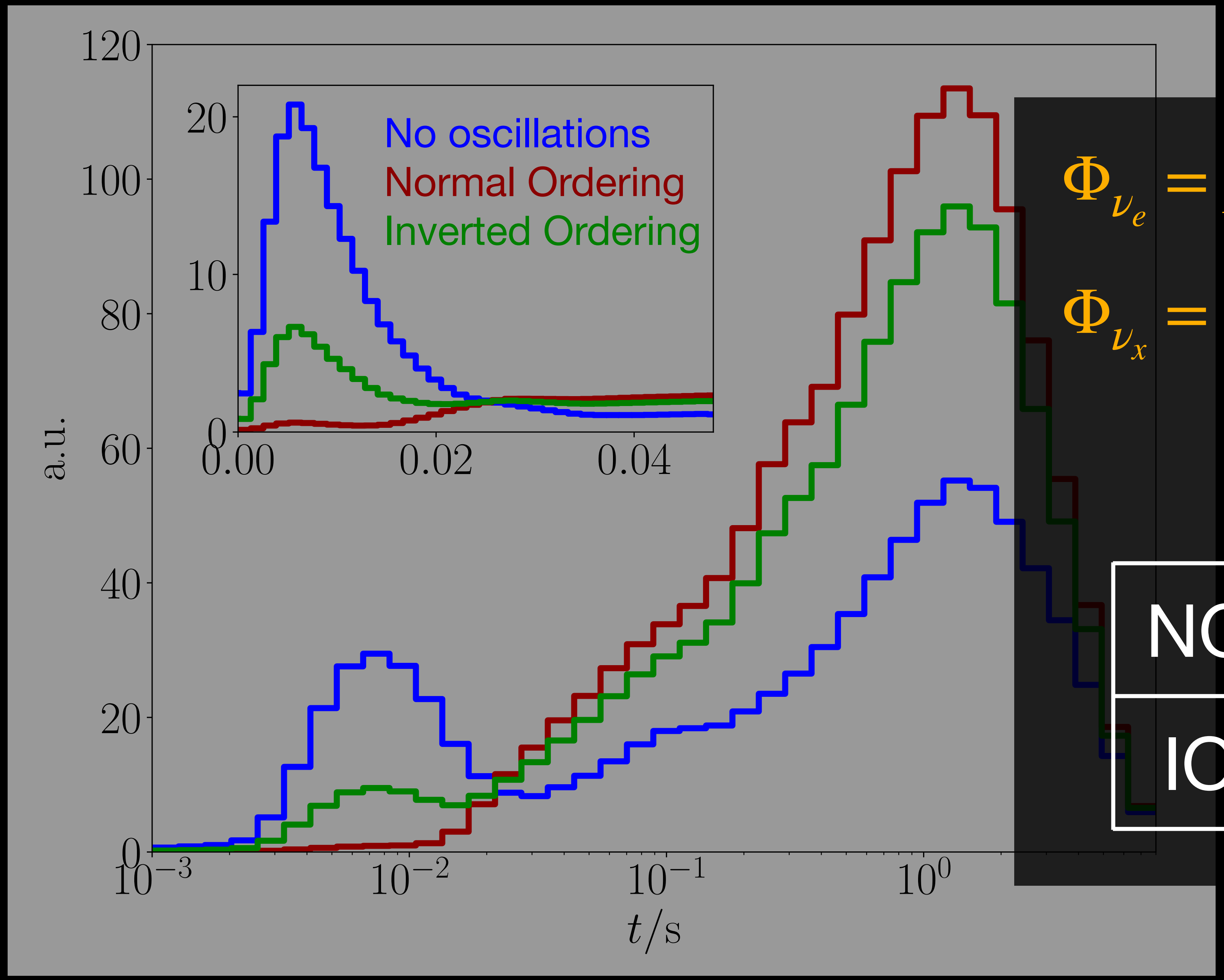



$m_\nu \leq 0.56^{+0.20}_{-0.21}$ eV

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

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

# DUNE: *D* = 10 kpc



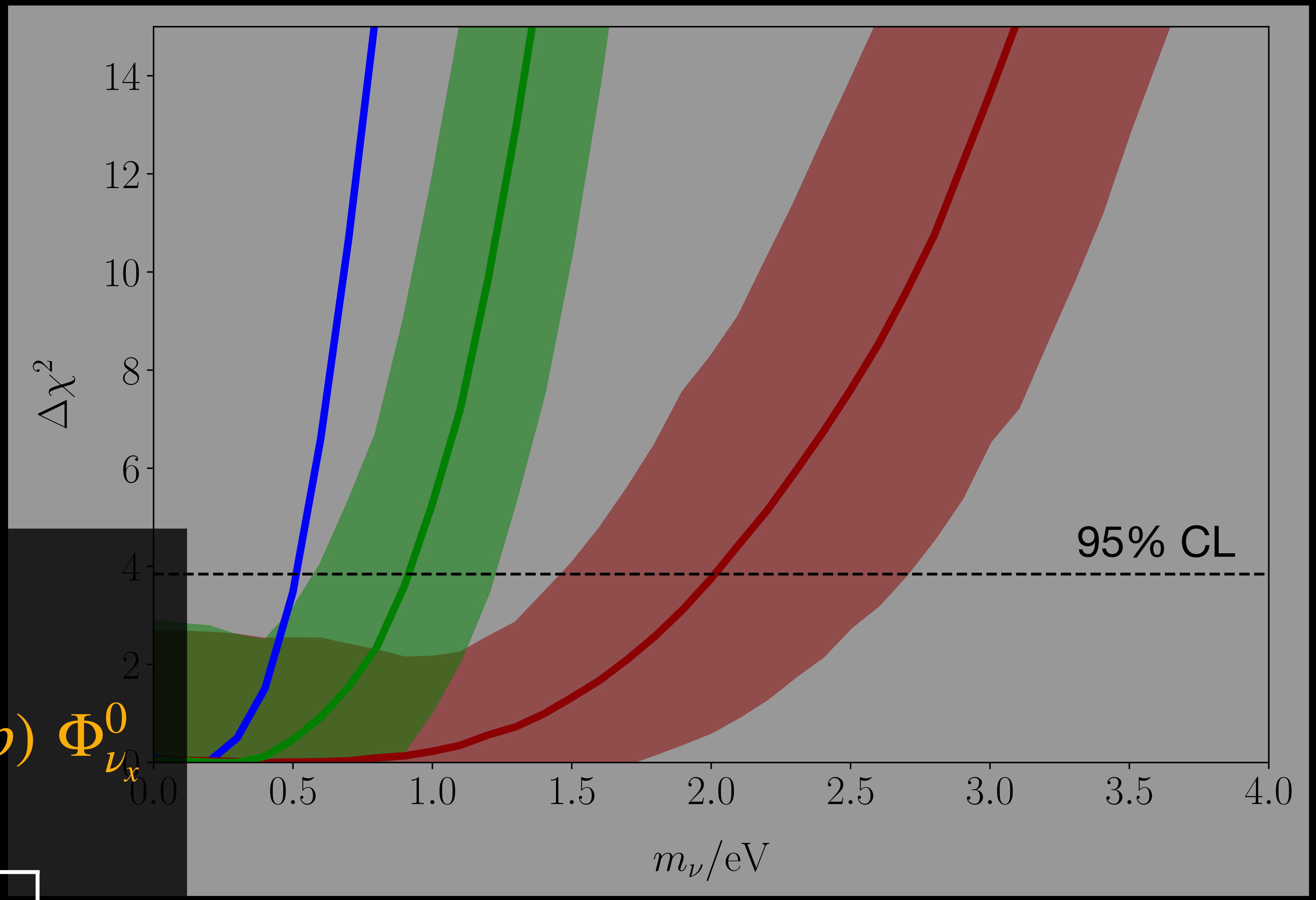

| 10 s | 50 ms |
|---|---|
| ~ 845 | ~ 201 |
| ~ 1372 | ~ 54 |
| ~ 1222 | ~ 95 |

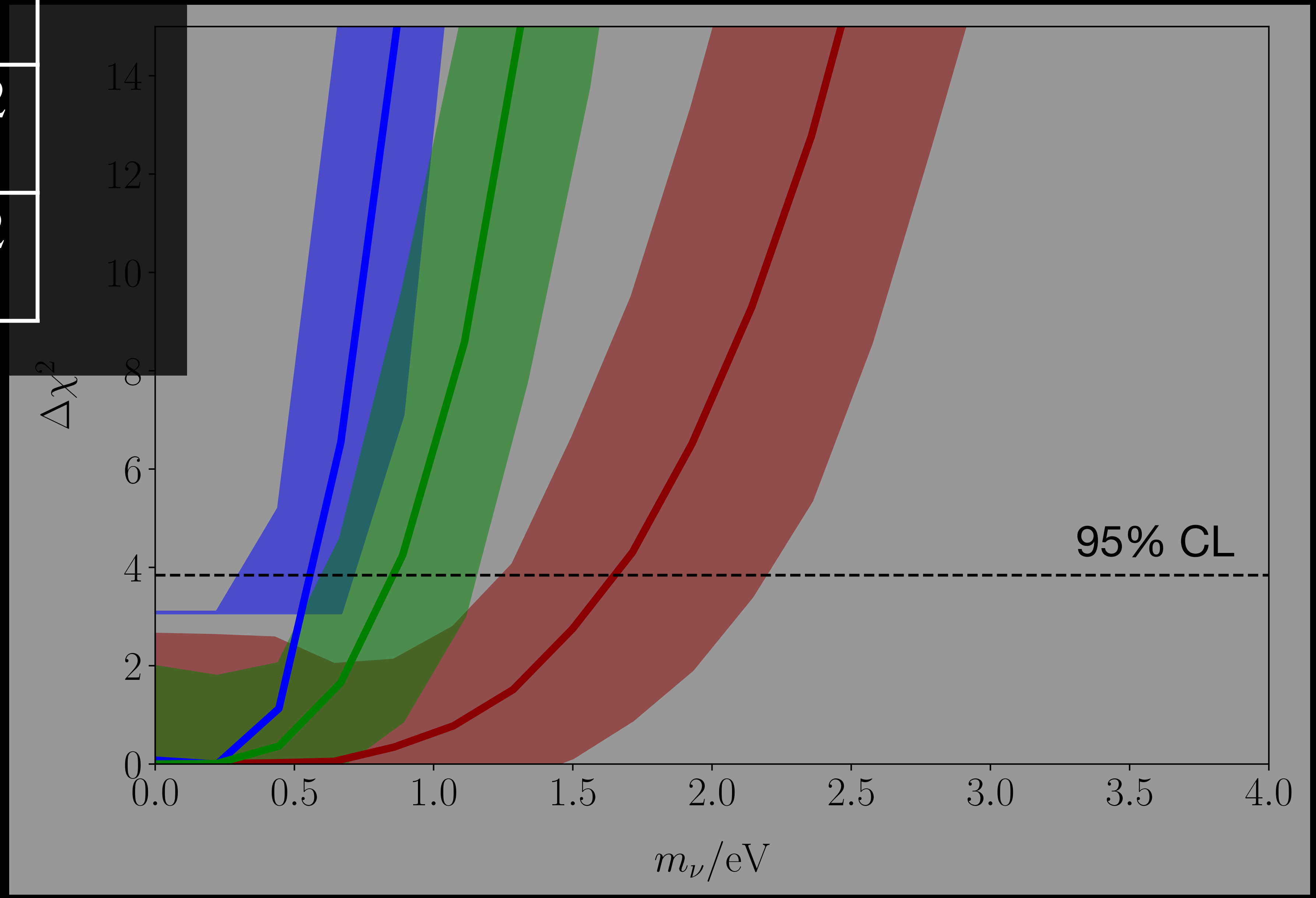
$$\Phi_{\nu_e} = p\ \Phi^0_{\nu_e} + (1-p)\ \Phi^0_{\nu_x}$$

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

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

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




UPPER BOUNDS ON

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

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

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

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

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

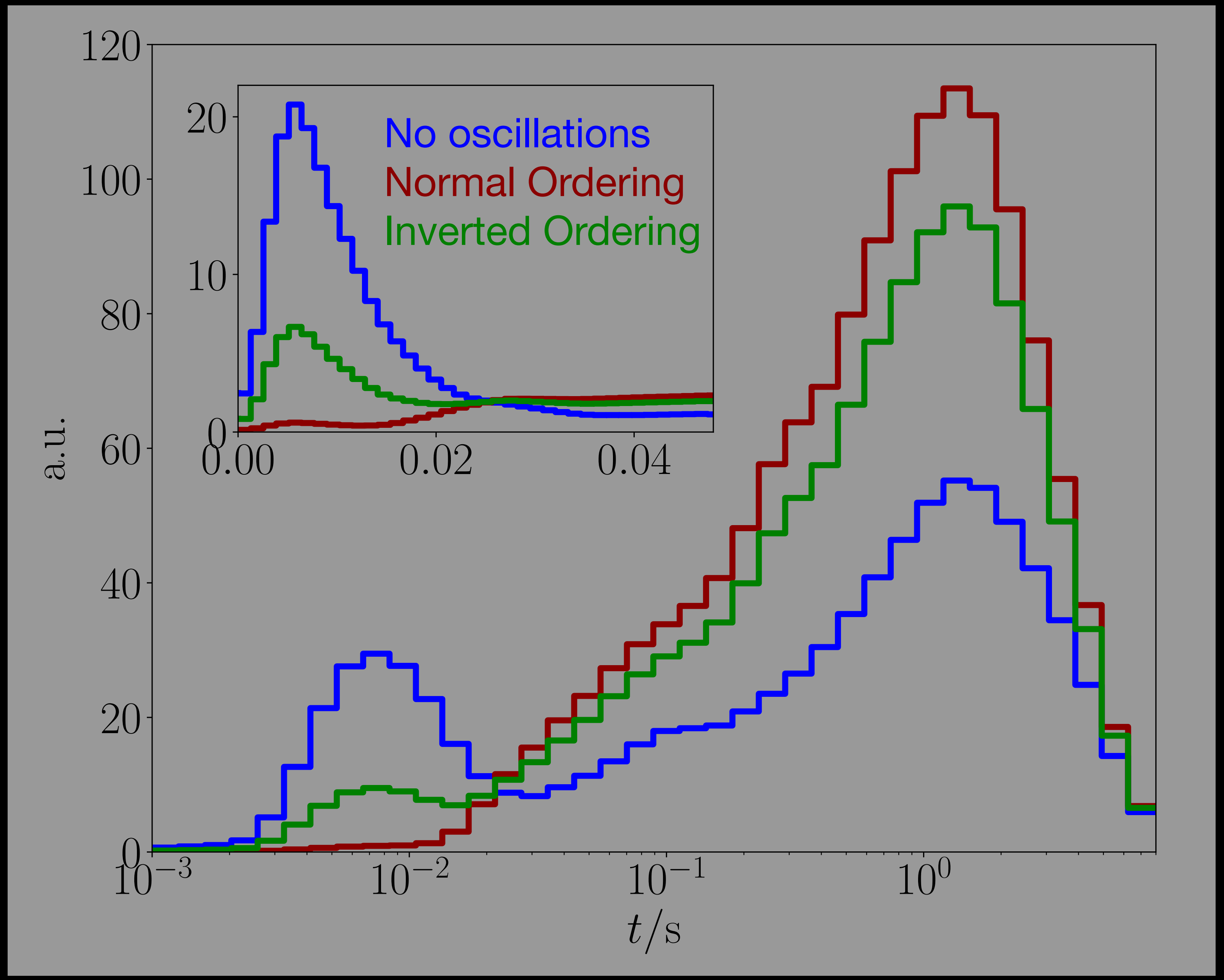
$m_\nu \leq 0.85^{+0.30}_{-0.25}$ eV

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

# DUNE: $D$ = 10 kpc

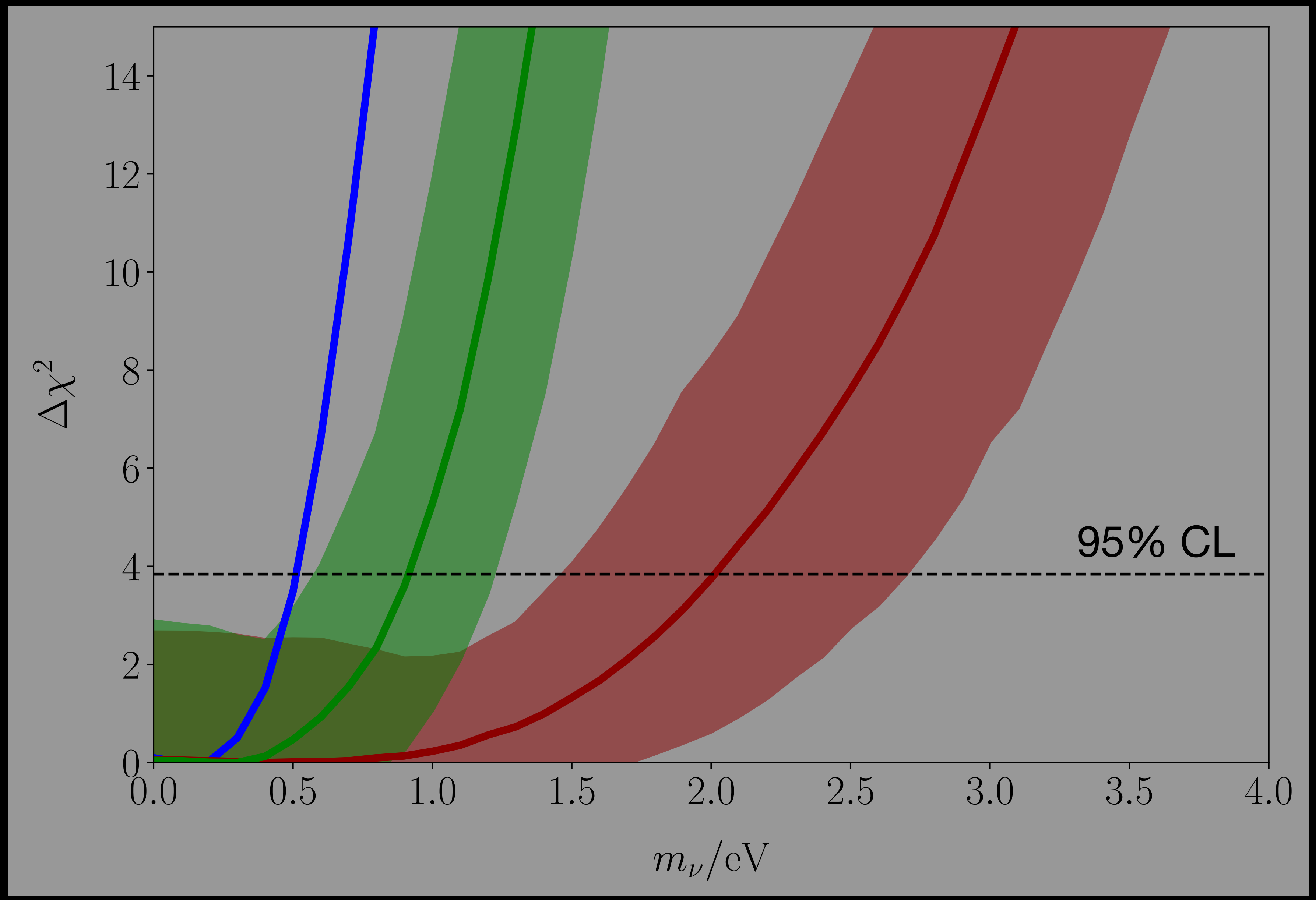
UPPER BOUNDS ON

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




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

$M = 8.8\, M_\odot$



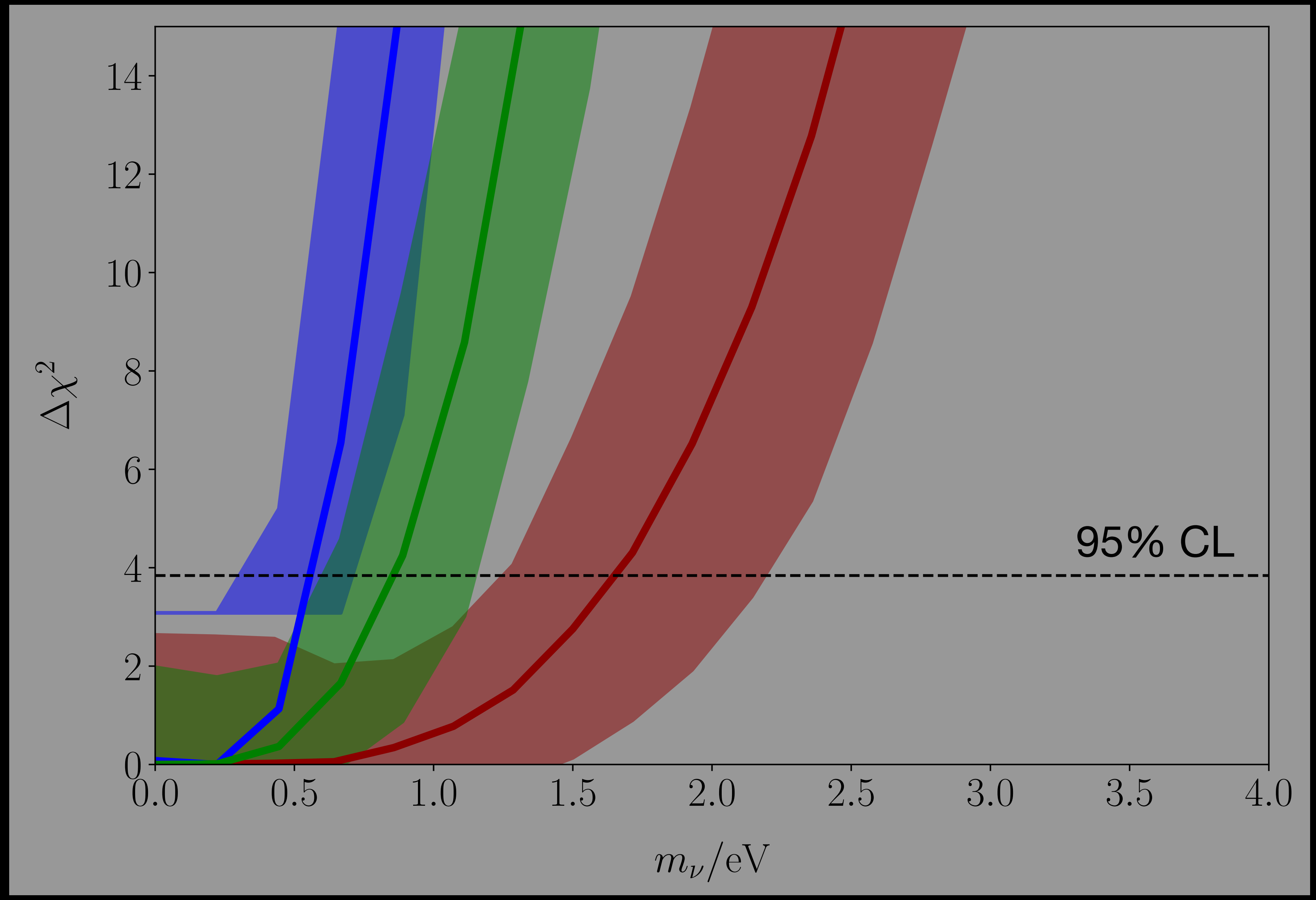

$m_\nu \leq 0.51^{+0.20}_{-0.19}$ eV

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

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

$M = 19\, M_\odot$

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

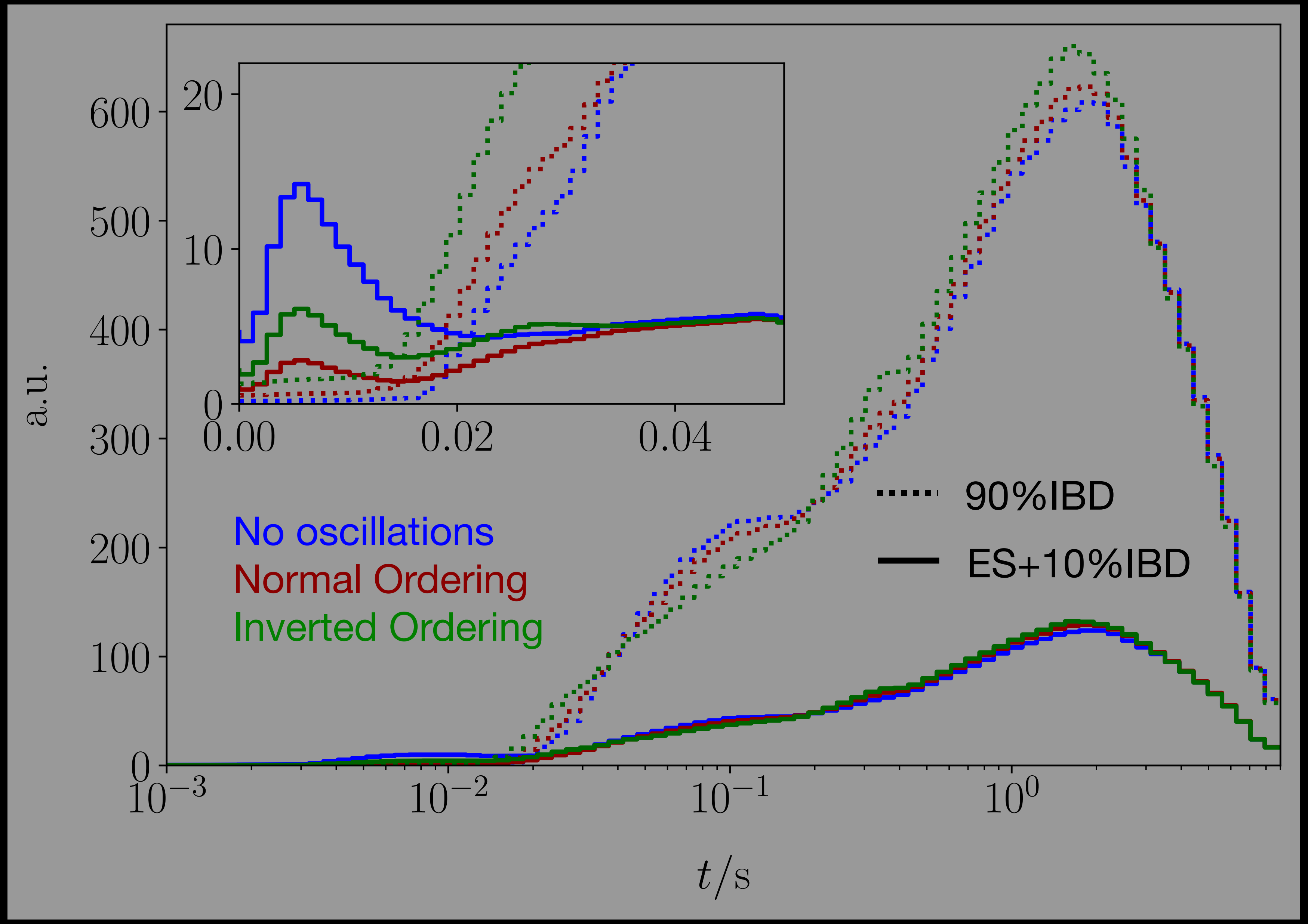



$m_\nu \leq 0.56^{+0.20}_{-0.21}$ eV

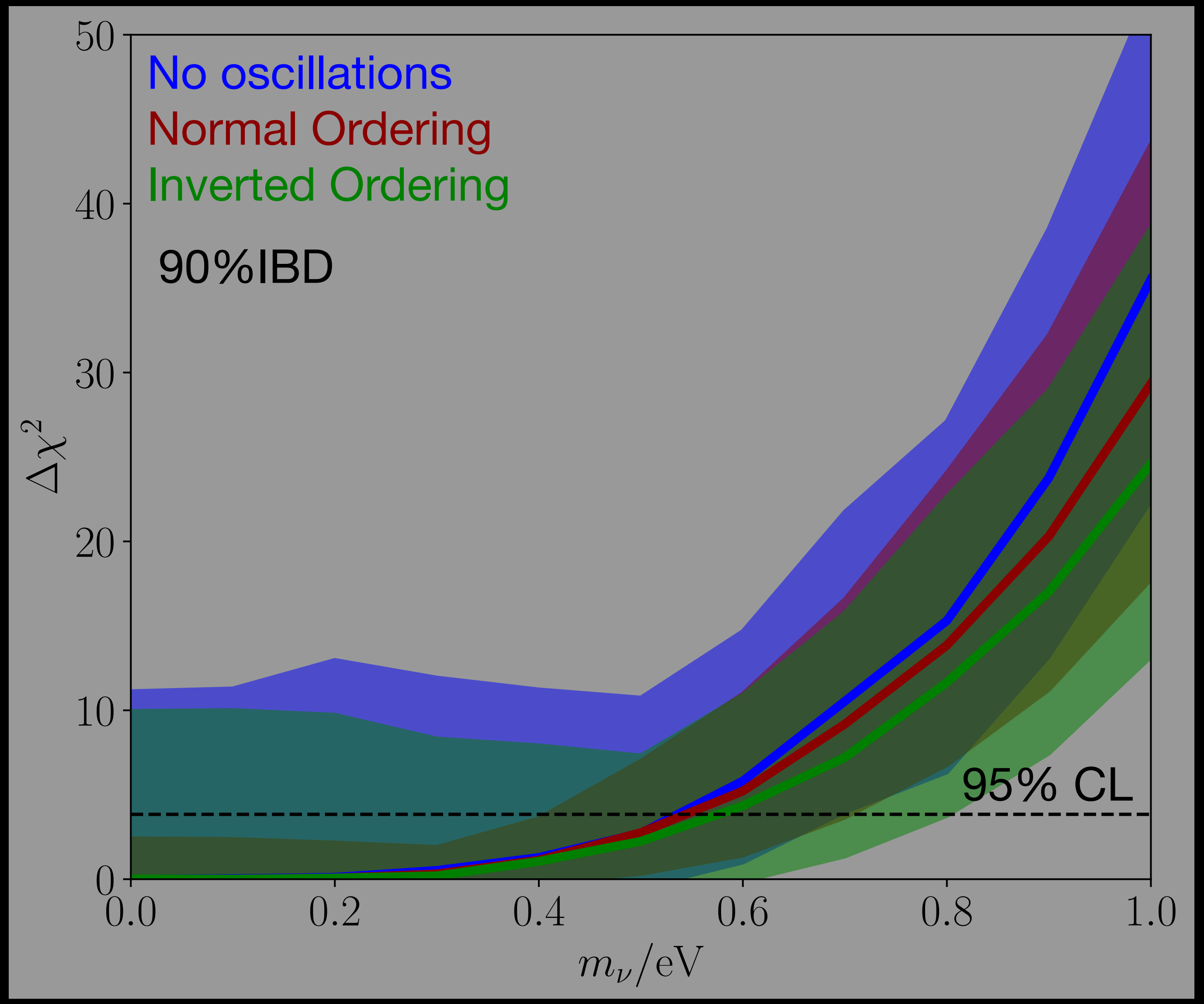
$m_\nu \leq 0.85^{+0.30}_{-0.25}$ eV

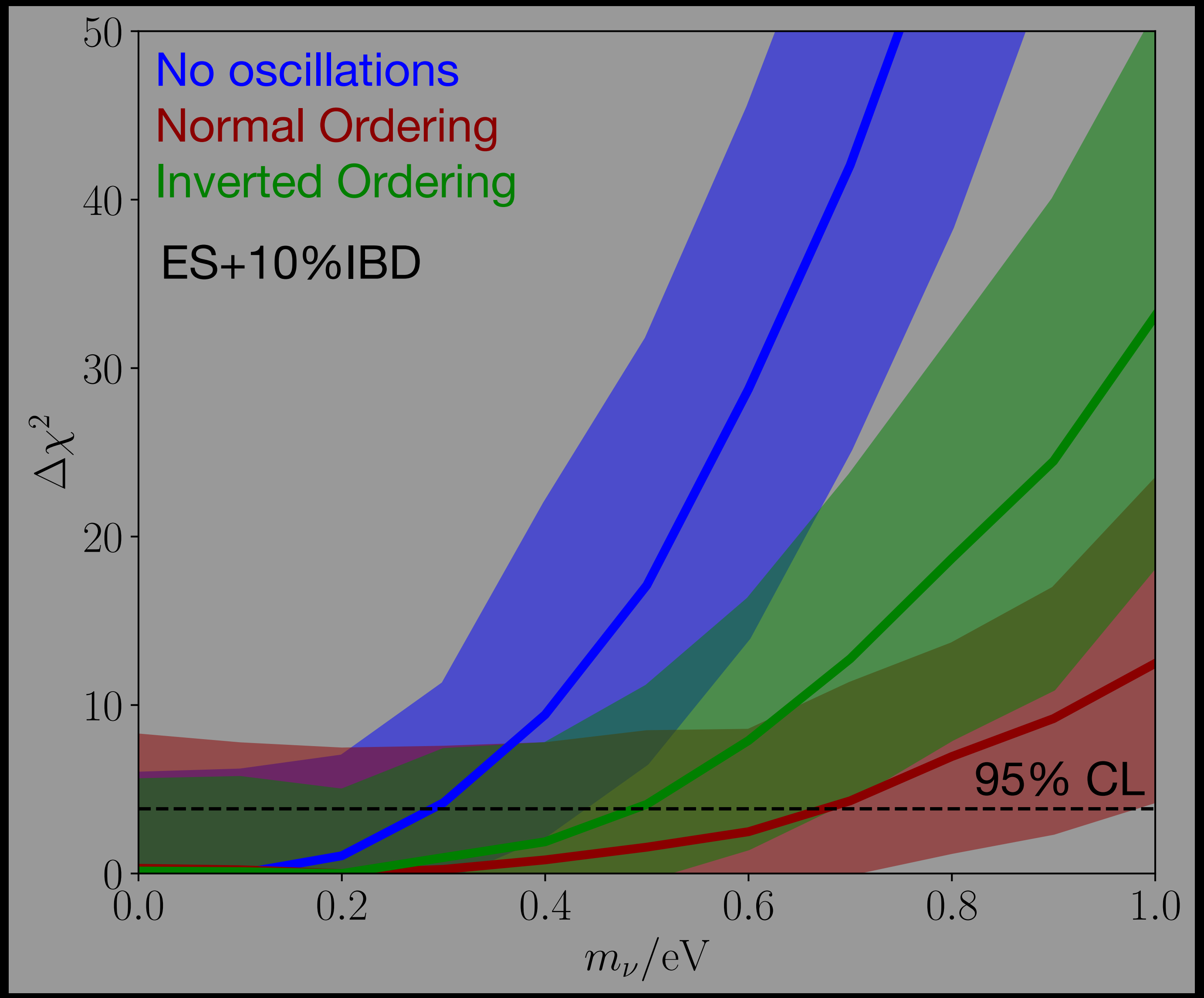
$m_\nu \leq 1.65^{+0.54}_{-0.40}$ eV

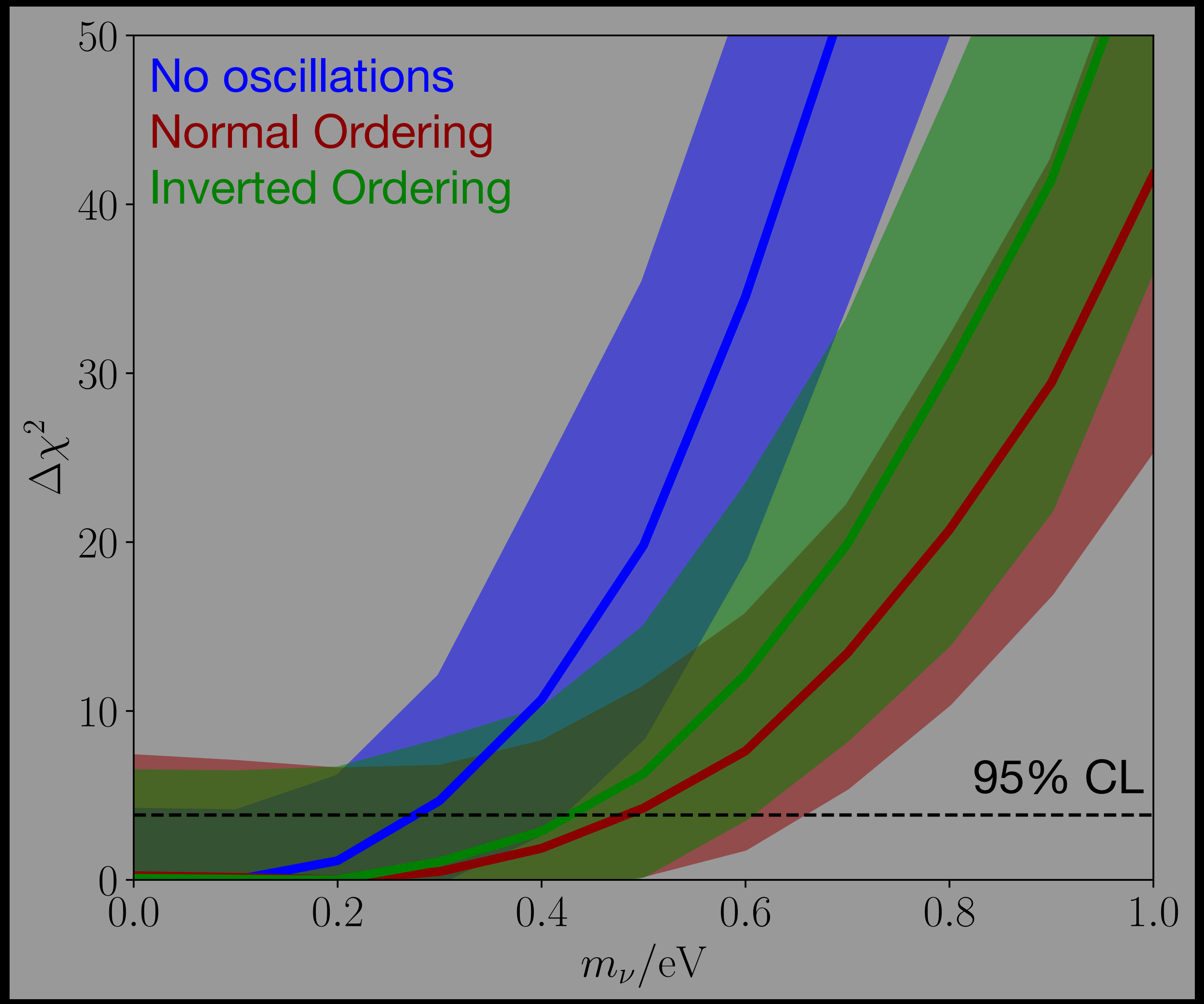
# HK: $D$ = 10 kpc




| $M = 8.8\,M_\odot$ | 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 |




**Work in progress!**

Mikheyev-Smirnov-Wolfenstein effect

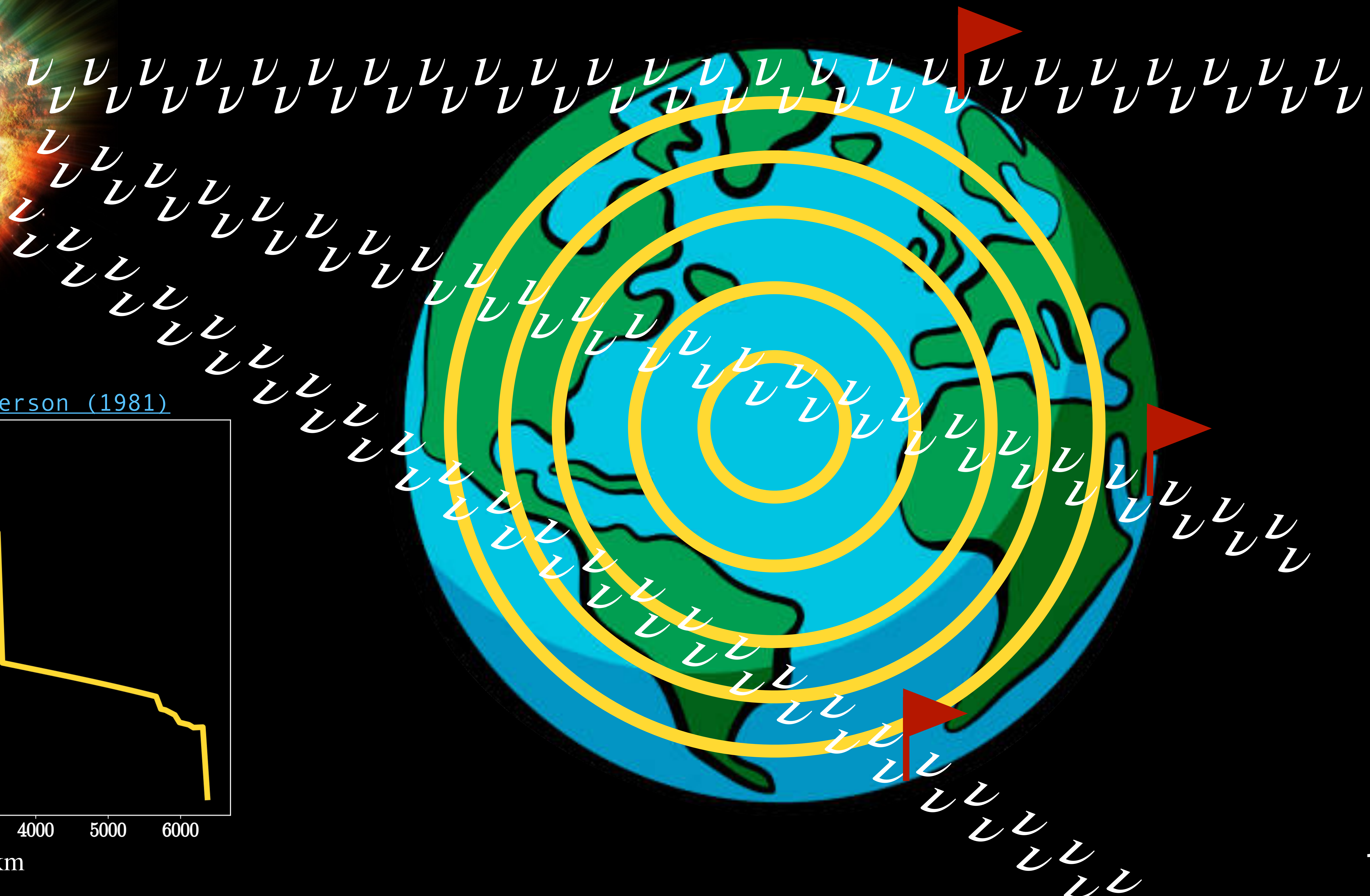
[Dighe, Smirnov (PRD 62, 2000)]

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

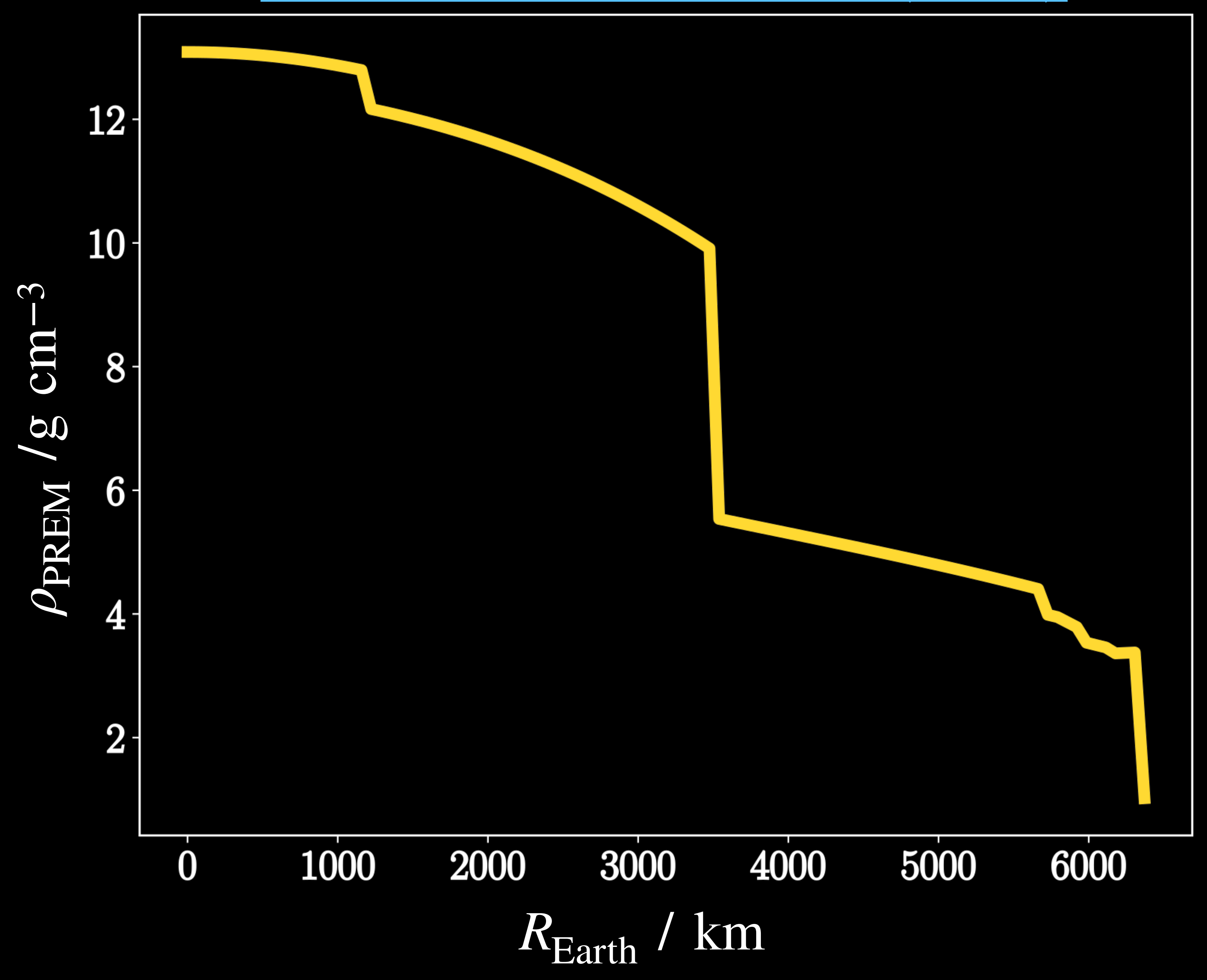
$$\Phi_{\nu_x} = \frac{1}{2}[(1-p)\ \Phi^0_{\nu_e} + (1-p)\ \Phi^0_{\nu_x}$$

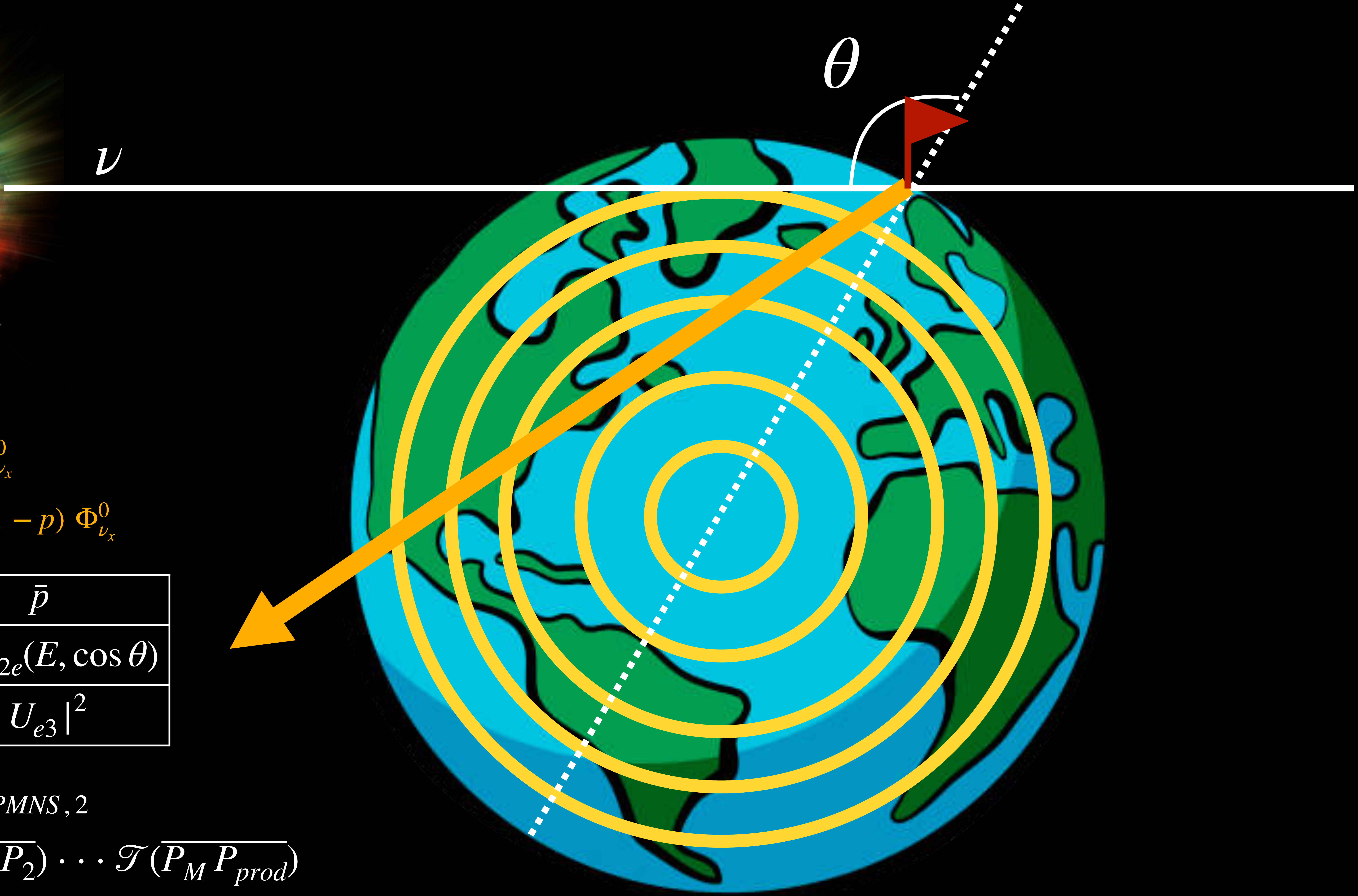
| | $p$ | $\bar{p}$ |
|---|---|---|
| NO | $\vert U_{e3}\vert^2$ | $\vert U_{e1}\vert^2$ |
| IO | $\vert U_{e2}\vert^2$ | $\vert U_{e3}\vert^2$ |

# Earth matter effects




Dziewonski, Anderson (1981)






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

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

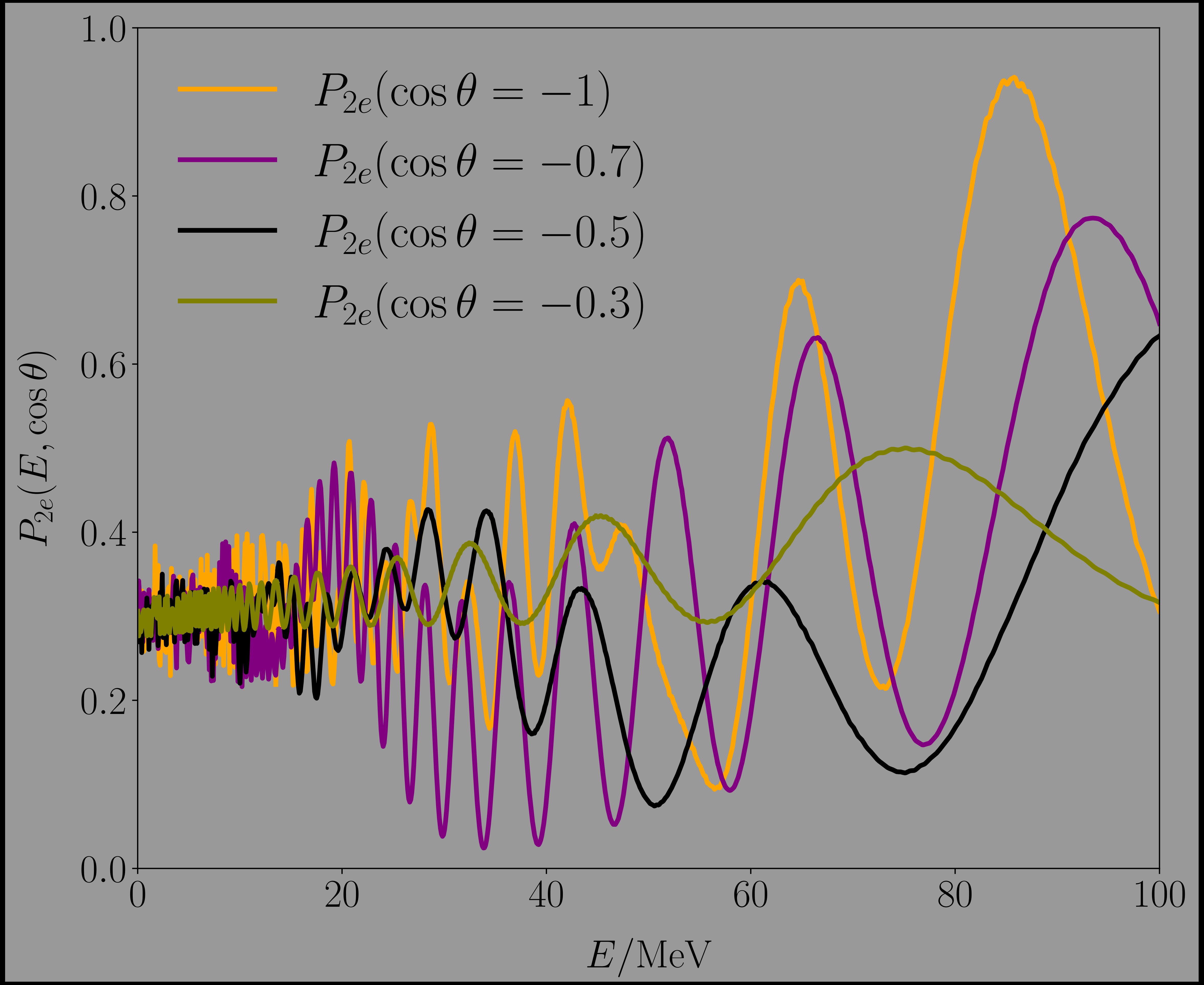
| | $p$ | $\bar{p}$ |
|---|---|---|
| NO | $\lvert U_{e3}\rvert^2$ | $1 - P_{2e}(E, \cos\theta)$ |
| IO | $P_{2e}(E, \cos\theta)$ | $\lvert U_{e3}\rvert^2$ |

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

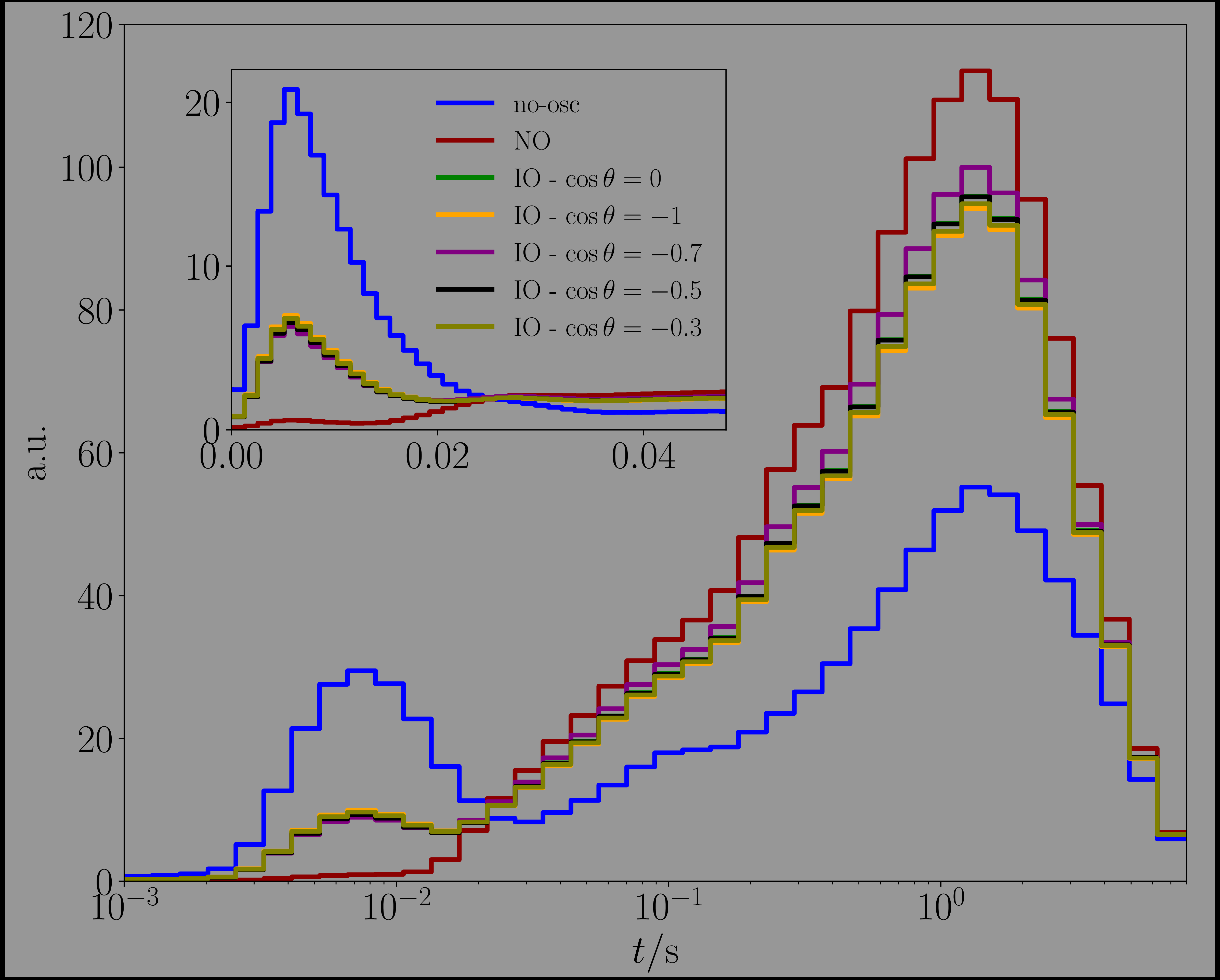
$$\mathcal{T}_{\alpha\beta} = \mathcal{T}(\overline{P_{det}\, P_1})\,\mathcal{T}(\overline{P_1\, P_2}) \cdots \mathcal{T}(\overline{P_M\, P_{prod}})$$

Lisi, Montanino (PRD 56, 1997)

# Earth matter effects




$\nu_e$ channel – IO



# Take-home message

**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

HIDDeN
Hunting Invisibles: Dark sectors, Dark matter and Neutrinos

# Take-home message

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.

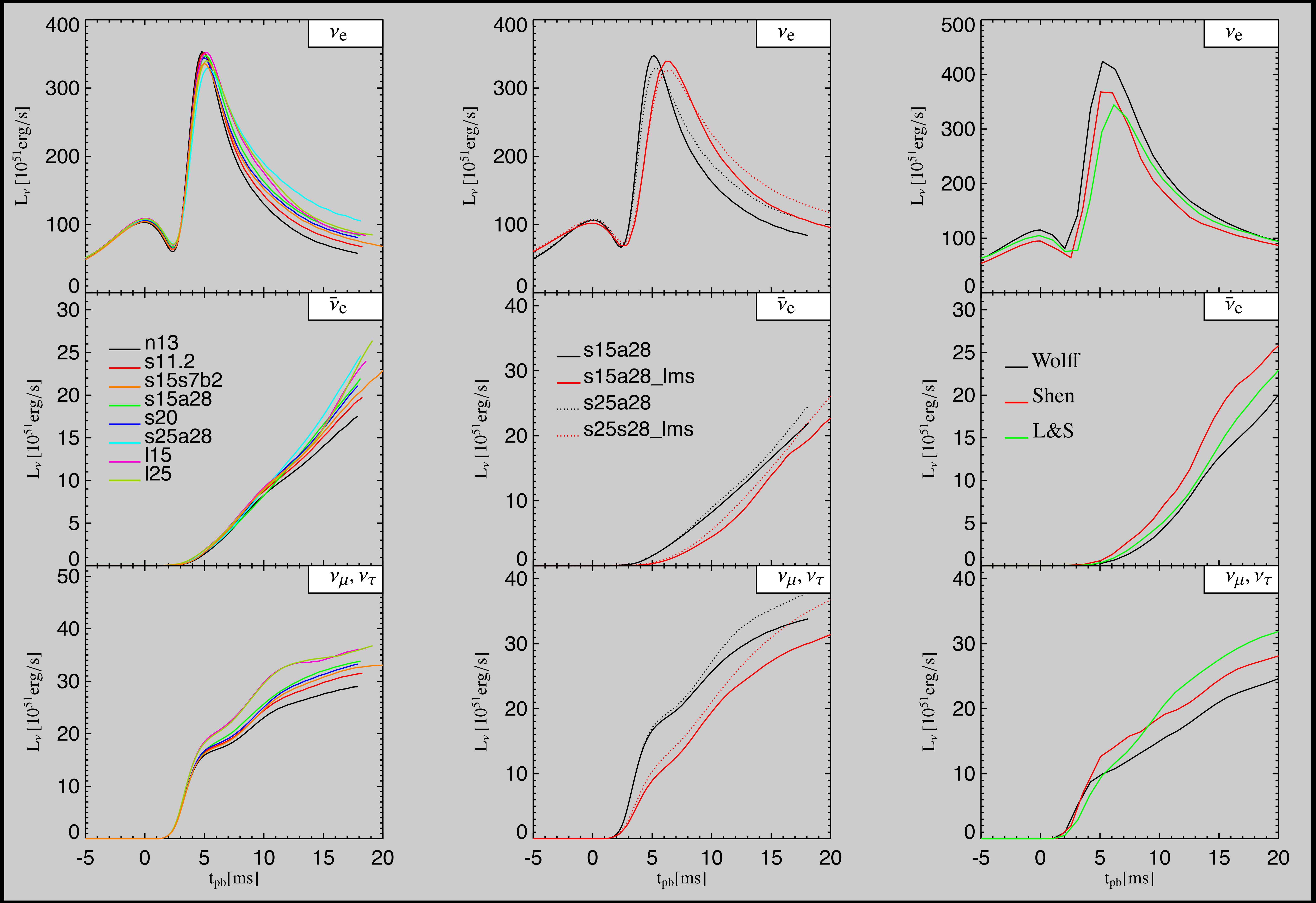
Waiting for SN20XXX…

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

# Backup

## Supernova parameters uncertainties: luminosity

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



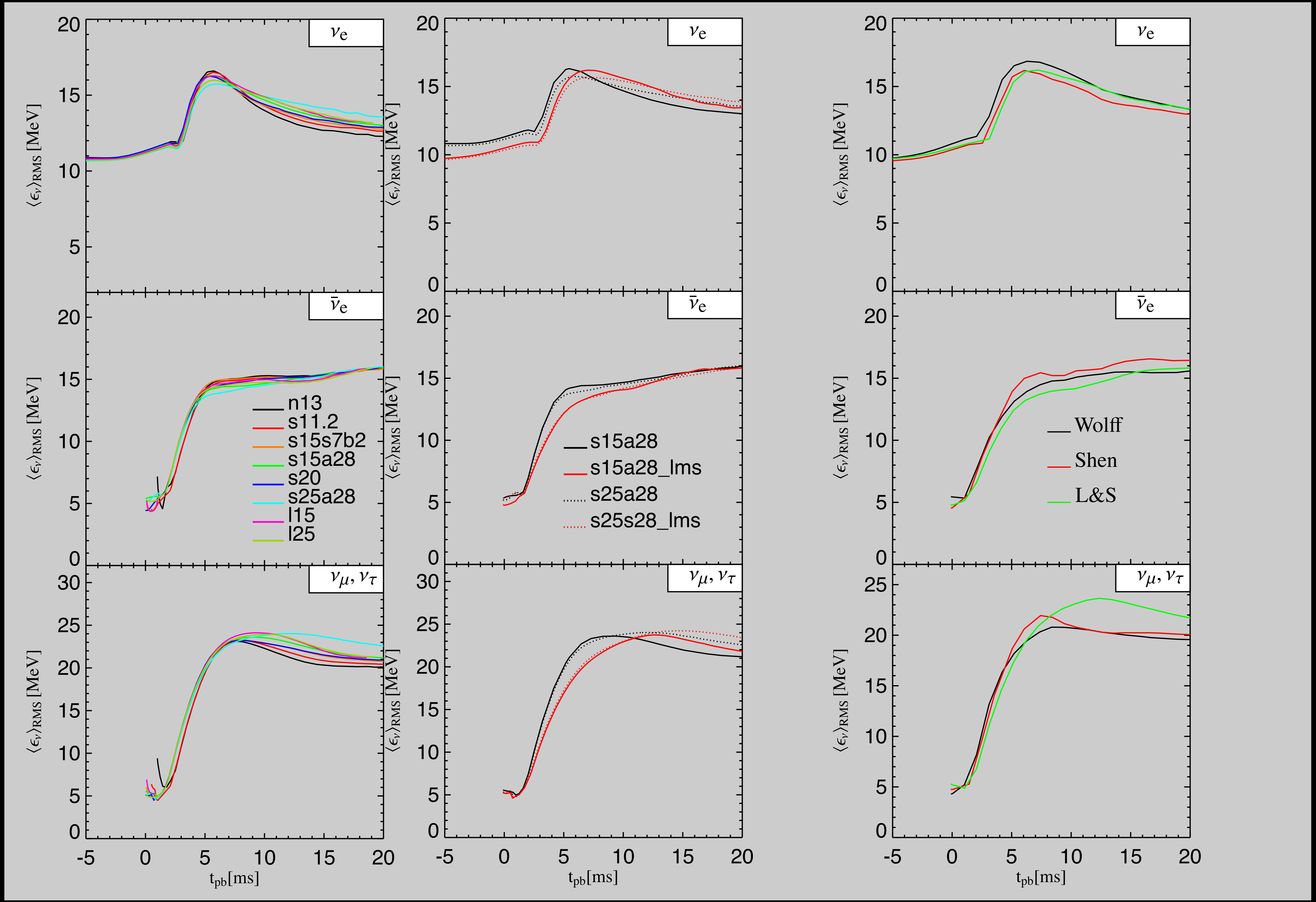

The neutronization burst results to be a robust, **model independent** prediction of the Supernova models.

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)




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 neutrinos emission: details

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

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

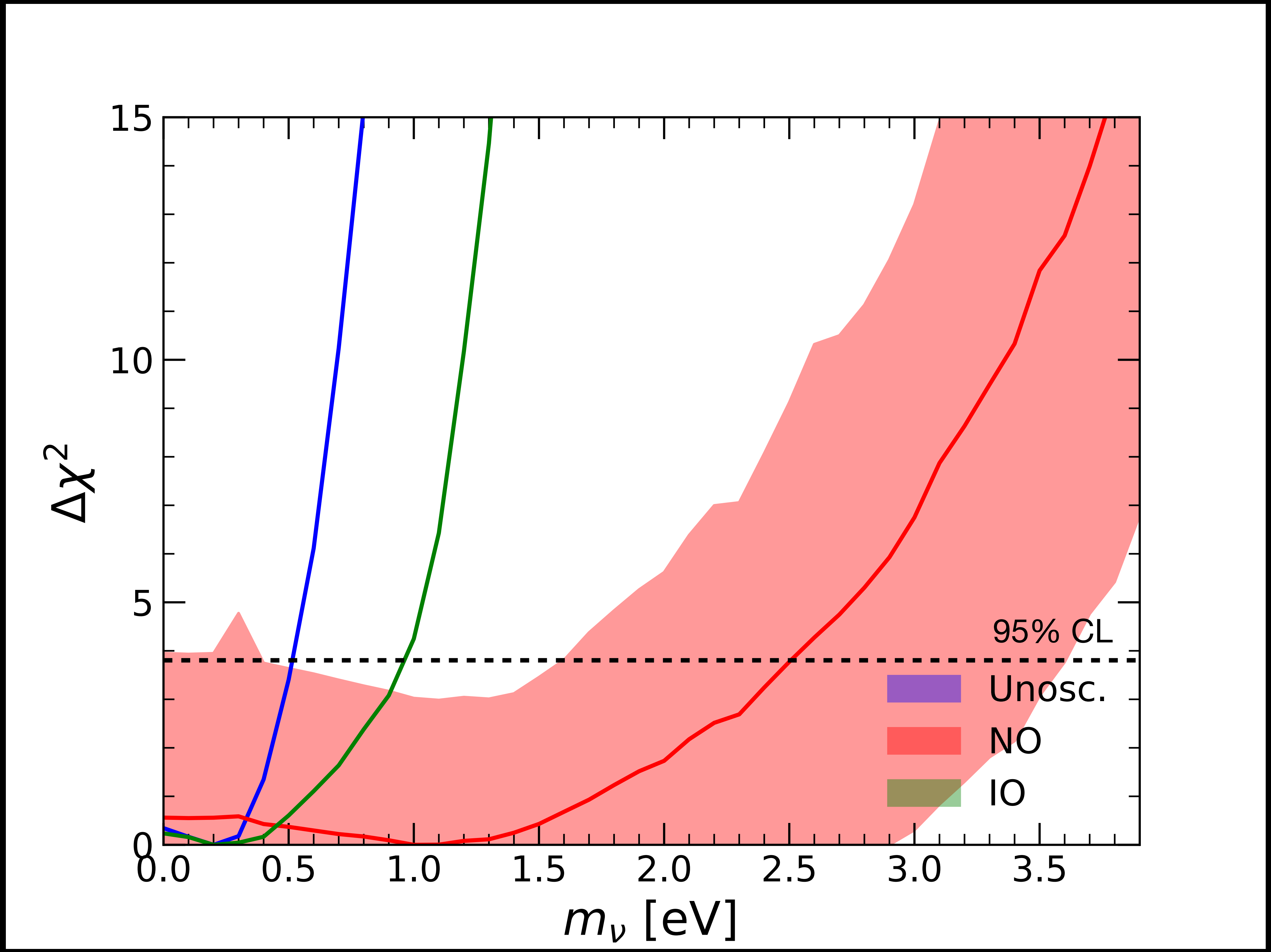
$$\alpha_\beta(t) = \frac{2\langle E_{\nu_\beta}(t)\rangle^2 - \langle E^2_{\nu_\beta}(t)\rangle}{\langle E^2_{\nu_\beta}(t)\rangle - \langle E_{\nu_\beta}(t)\rangle^2}$$

# Backup

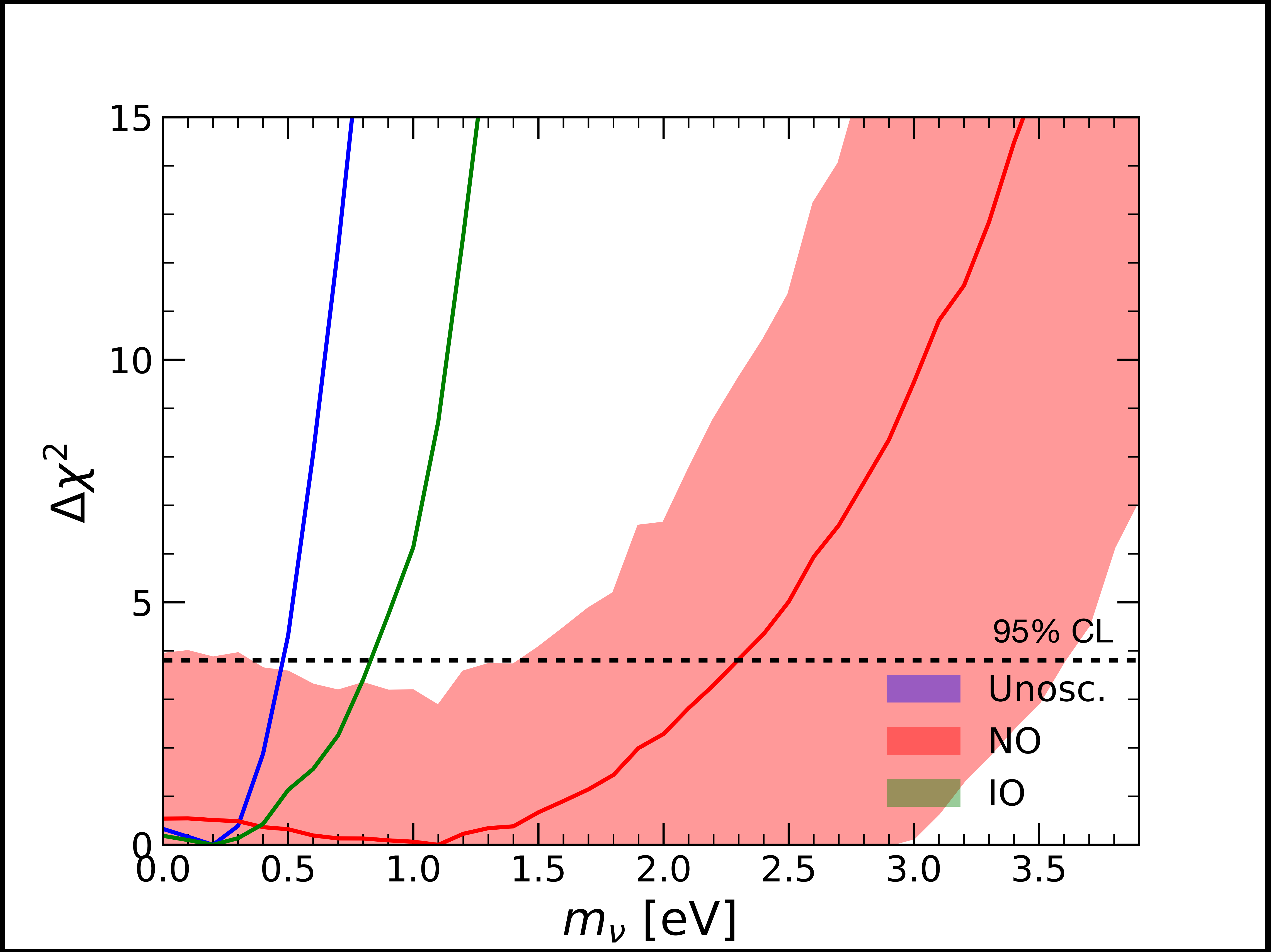
## Dependency on SN parameters

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

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



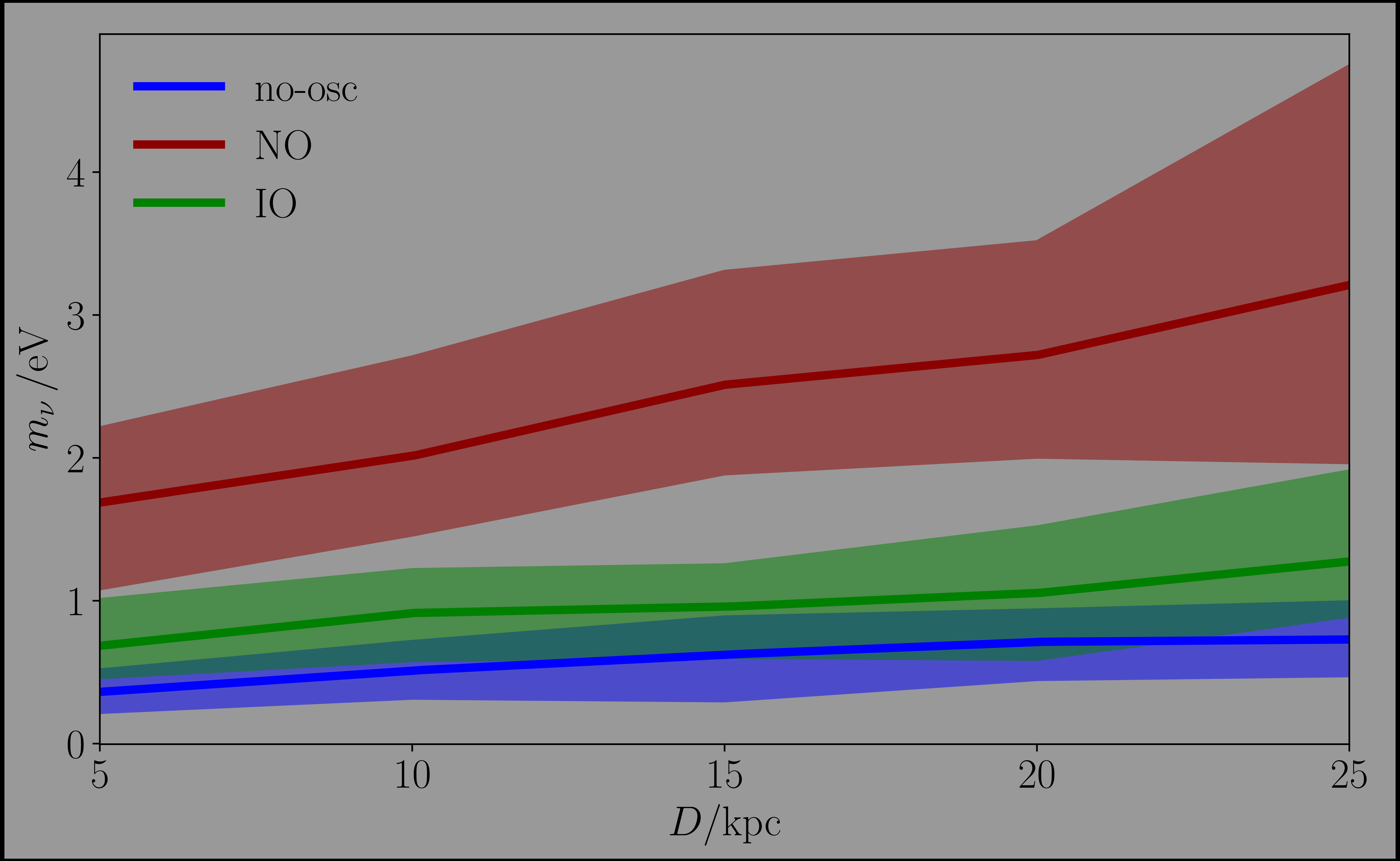

One time-windows: [0, 10] s




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

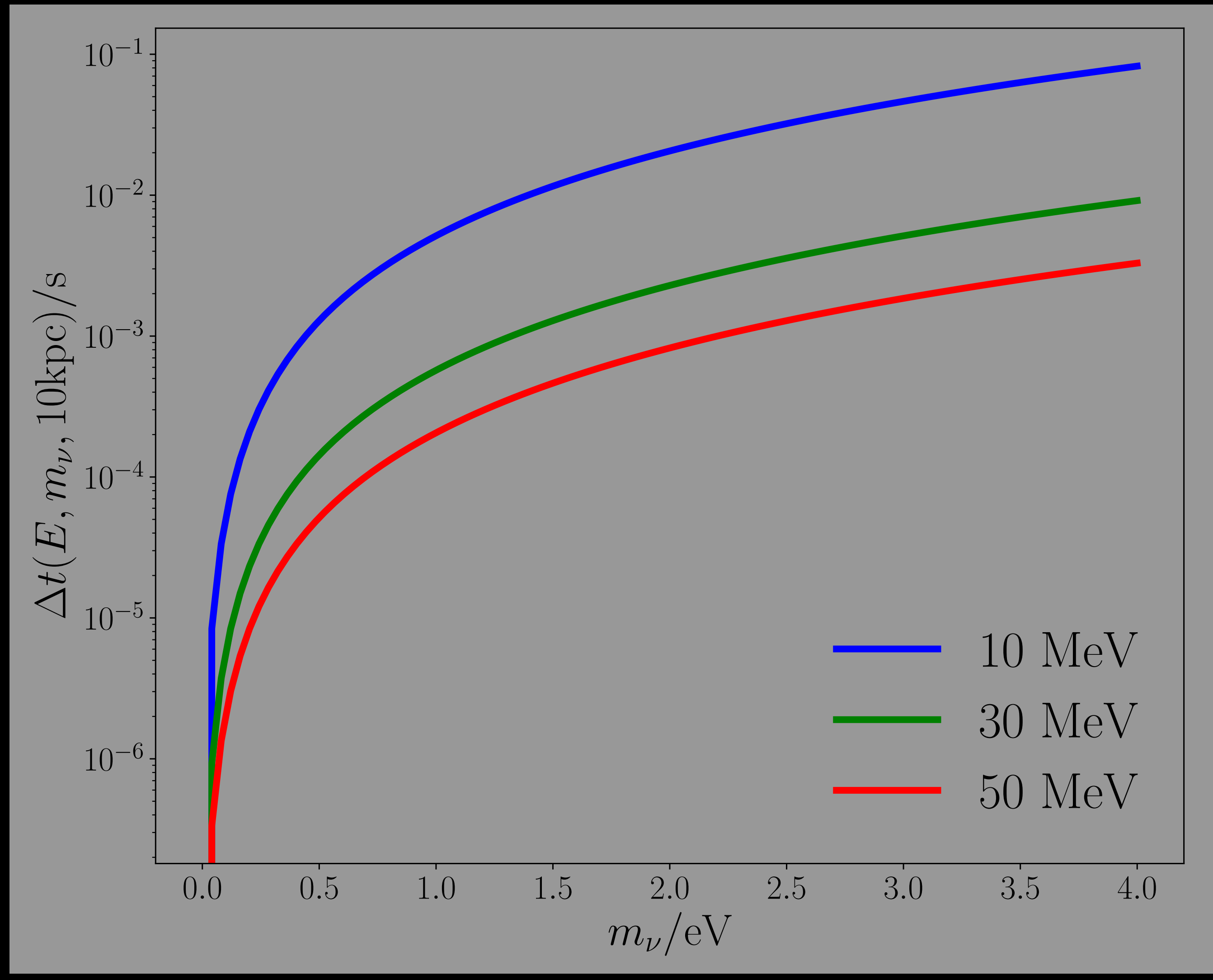
# Backup

## Dependency on SN distance



# Backup

## Likelihood analysis




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

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

→

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 $m_\nu$

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

# Backup

## Evolution operator definition

Lisi, Montanino (PRD 56, 1997)

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

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

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

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

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

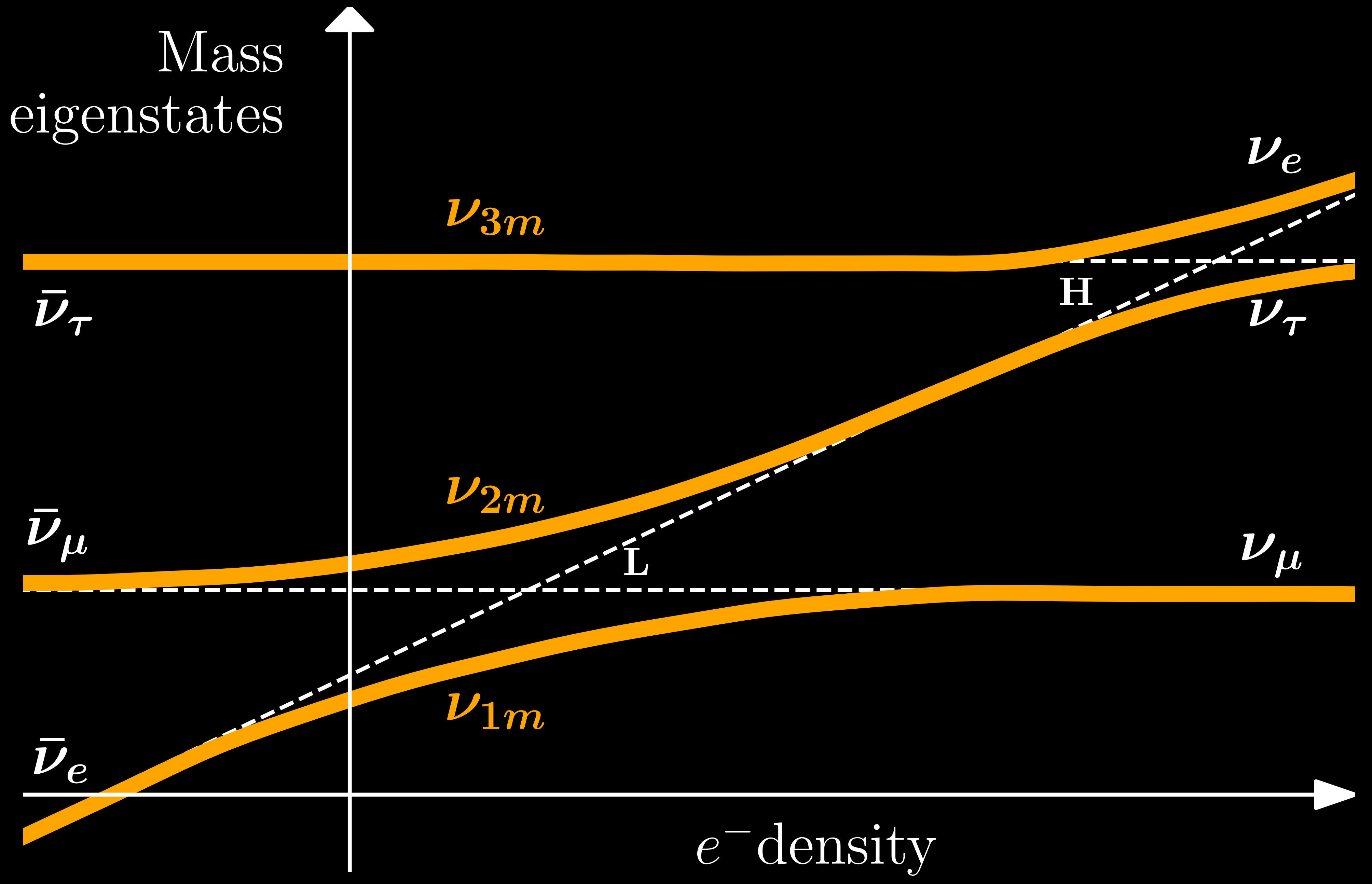
# Backup

## Mikheyev-Smirnov-Wolfenstein effect

Dighe, Smirnov (PRD 62, 2000)

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

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




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