Neutrino mass from Astro- to Particle Physics

Neutrino Frontiers @GGI - Focus Week - 03/07/2024

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GENERALITAT VALENCIANA
CIDEGENT/2018/019
HIDDeν
Hunting Invisibles: Dark sectors, Dark matter and Neutrinos

Neutrinos in the Standard Model

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1. Weakly interacting particles

Neutrinos in the Standard Model

1 Weakly interacting particles

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

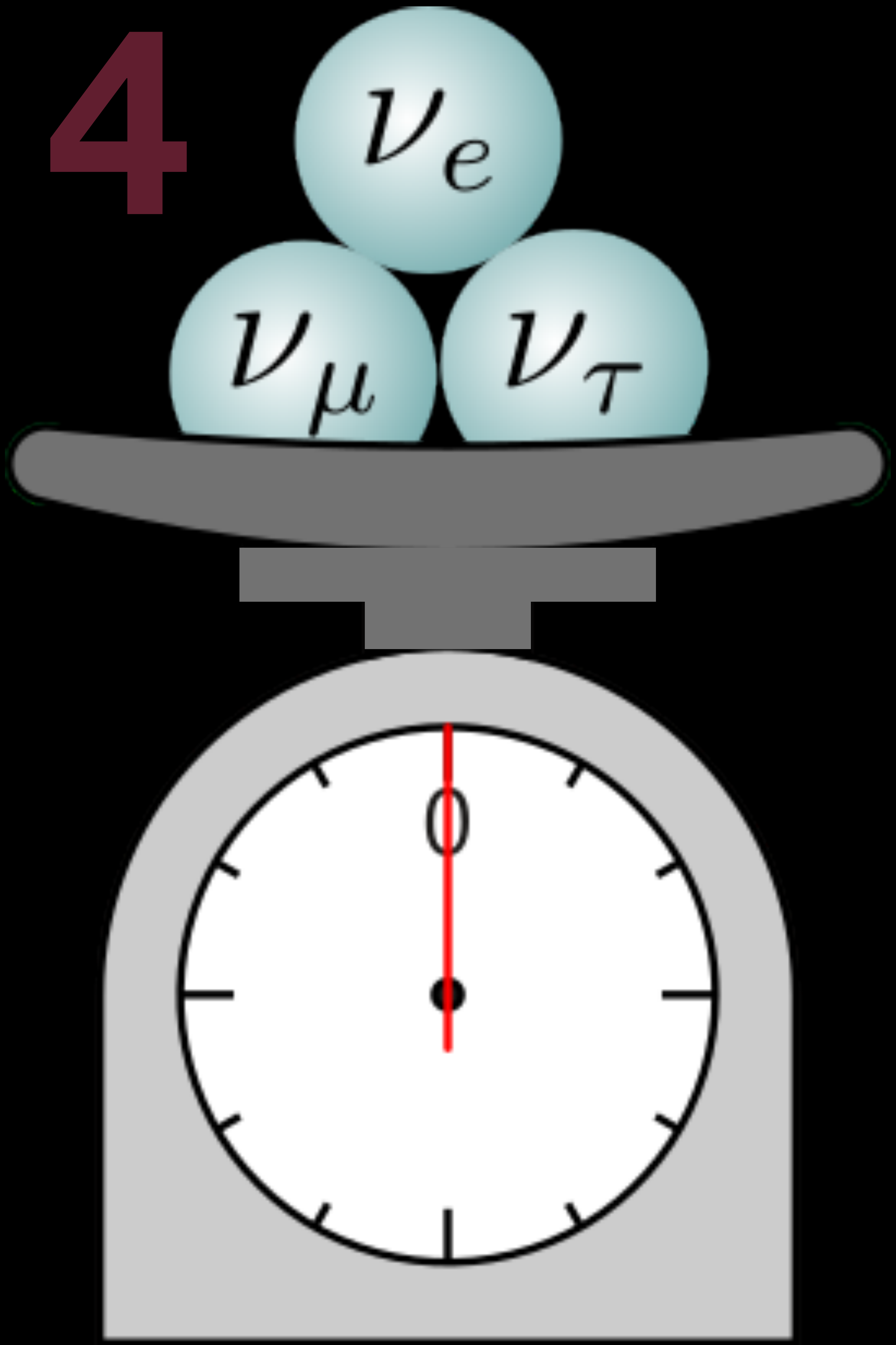
Neutrinos in the Standard Model

1 Weakly interacting particles

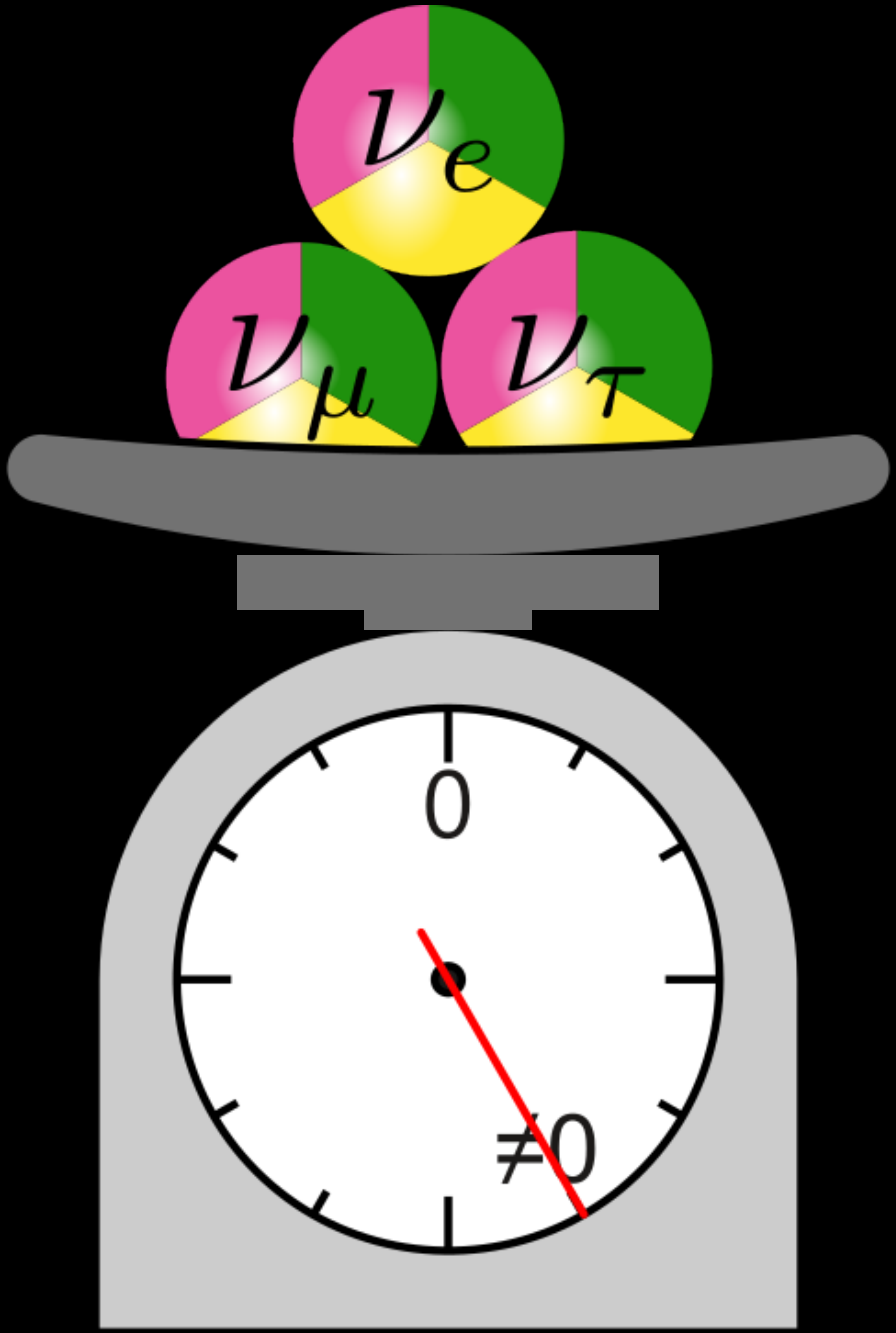
2 Appearing in three flavors, determined by the outgoing lepton produced by their interactions

3 Electrically neutral

4



Neutrinos have mass!



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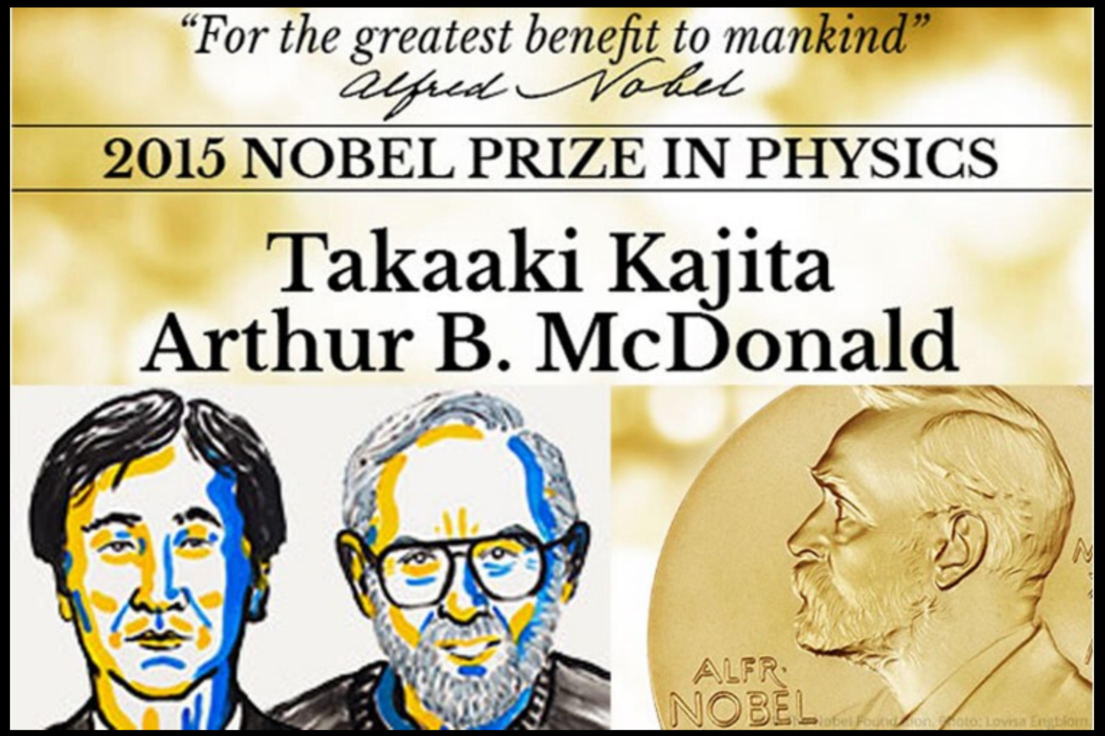
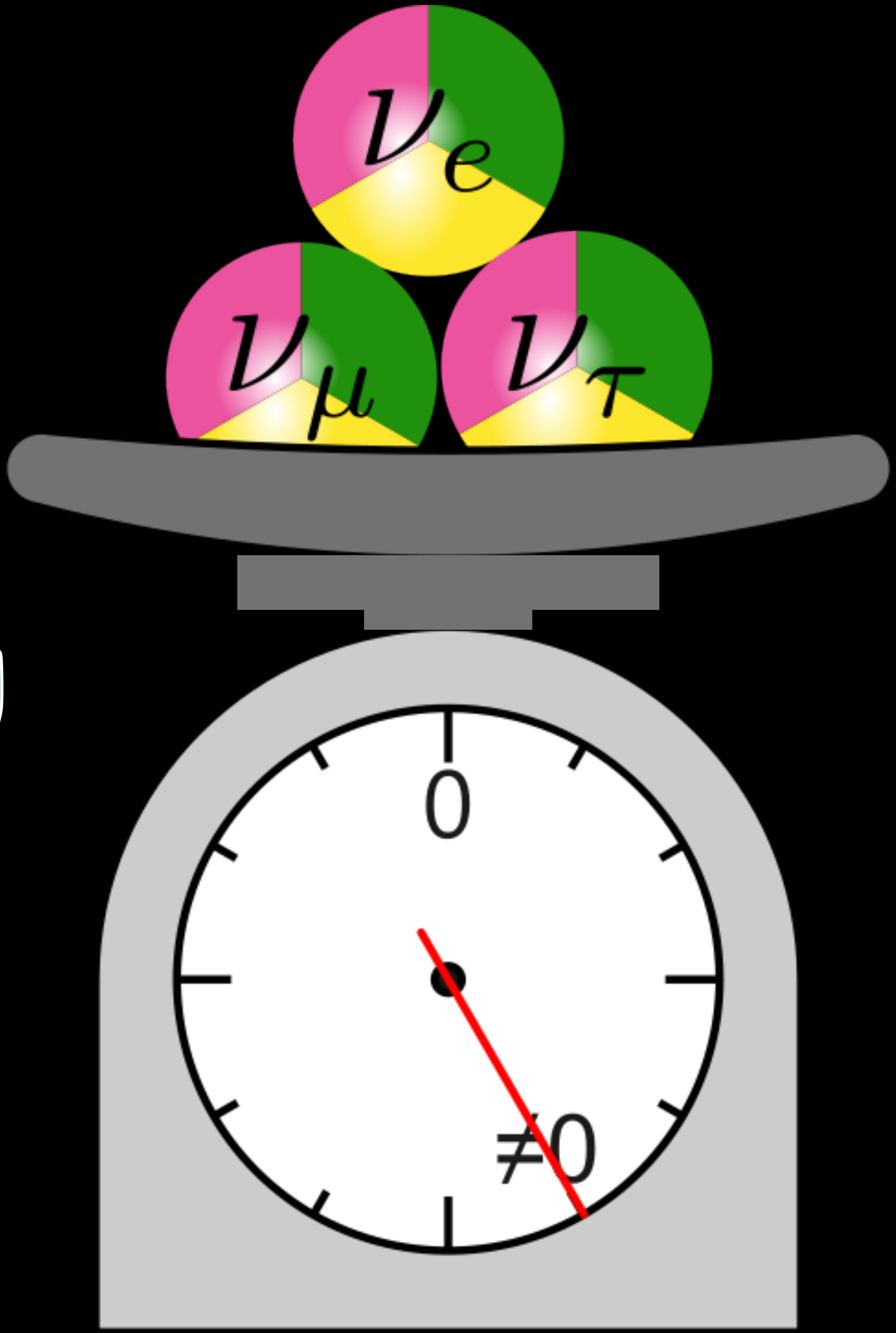


"For the discovery of neutrino oscillations, which shows that neutrinos have mass"

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

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



Neutrinos have mass!

From cosmology:

DESI Collaboration (2024)

$\sum m_\nu < 0.072$ eV (95% CL)

From kinematic measurements:

KATRIN Collaboration (2024)

KATRIN $\Rightarrow m_\beta < 0.45$ eV (90% CL)

Time-of-flight constraints with Supernovae:

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

SN1987A $\Rightarrow m_\nu < 5.8$ eV (95% CL)

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

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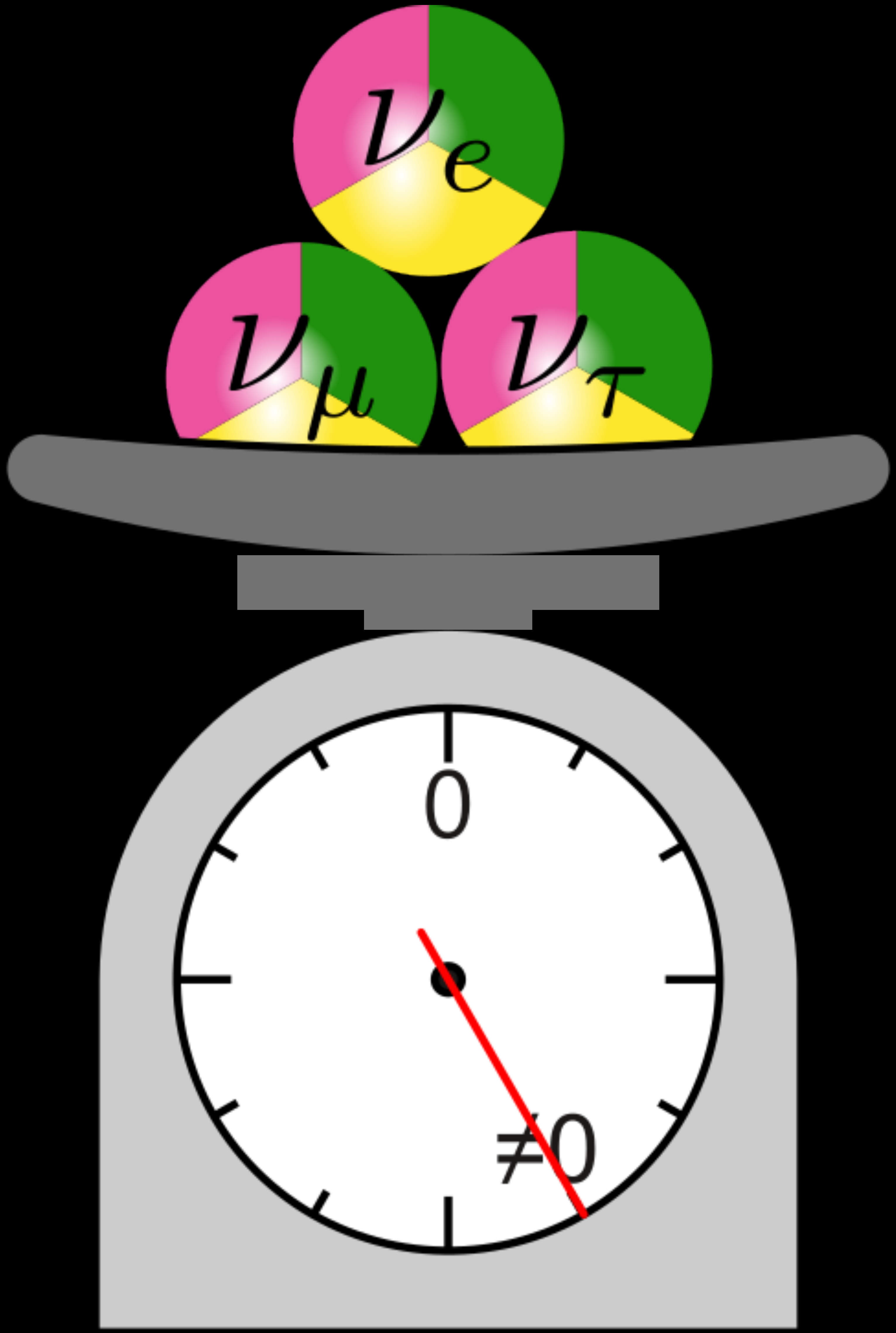
KamLAND-Zen $\Rightarrow m_{\beta\beta} < 0.16$ eV (90% CL)



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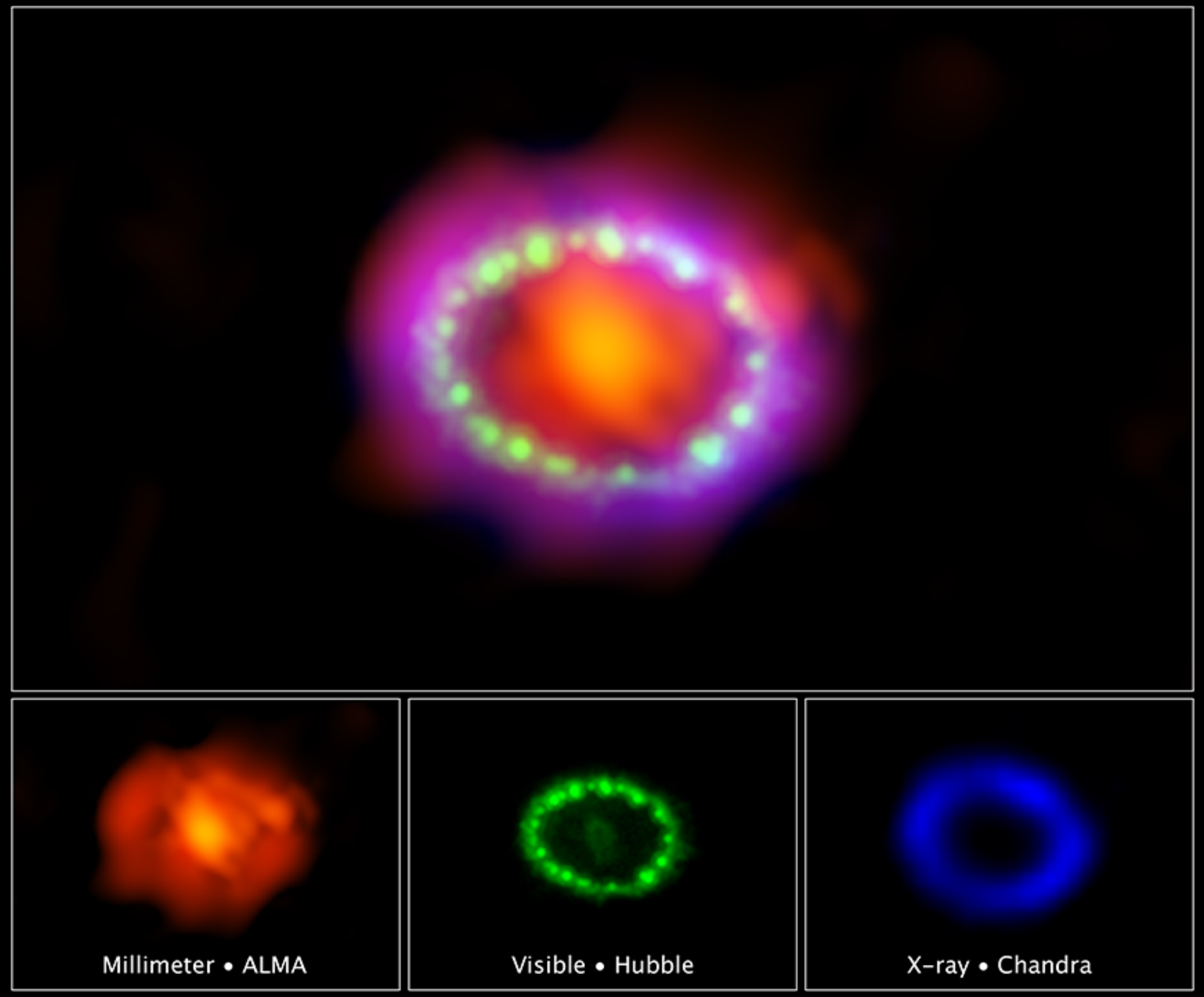
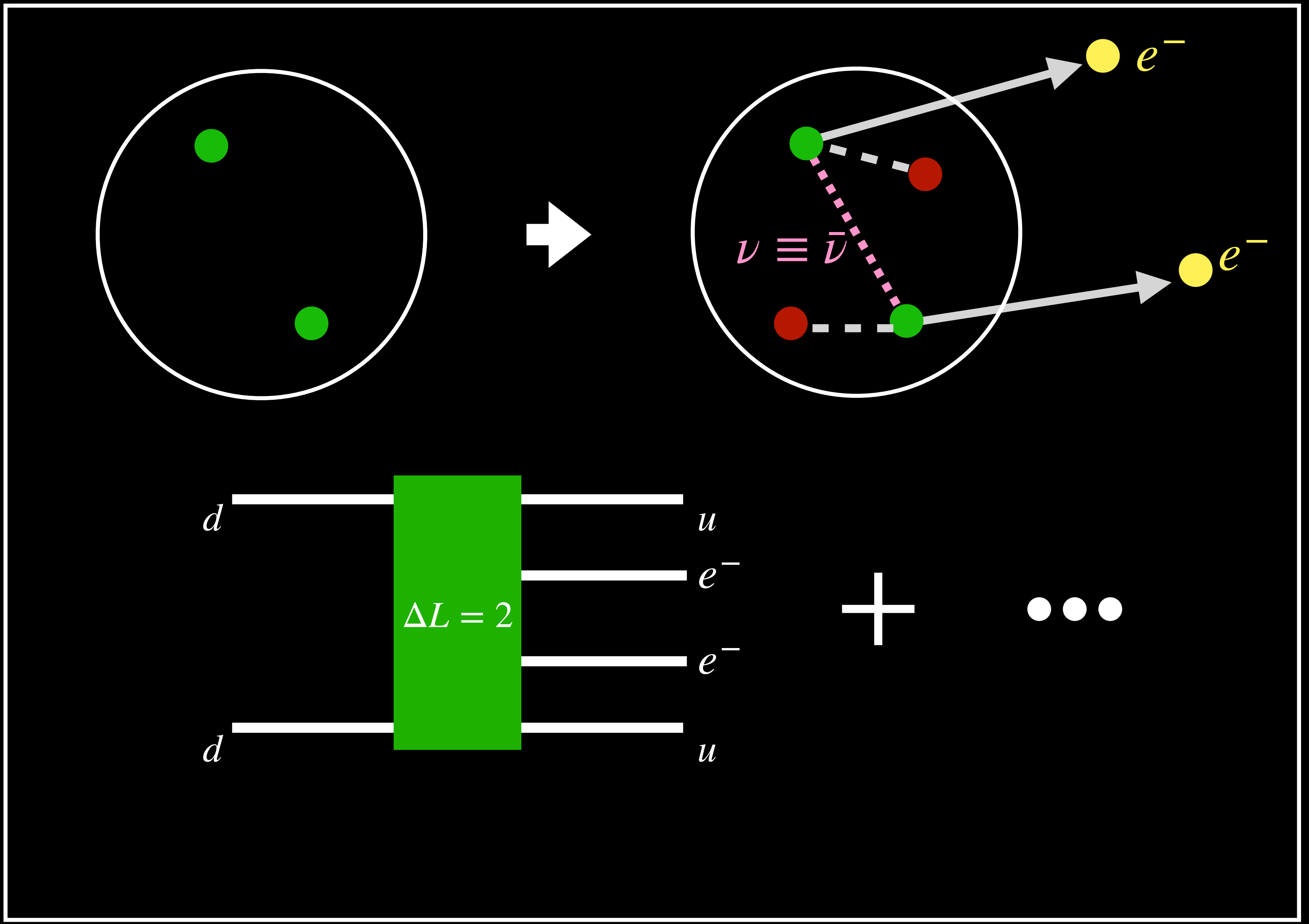
Alma (Eso/Naoj/Nrao), Nasa/Esa Hubble Space Telescope, Nasa Chandra X-Ray Observator





Core-collapse Supernovae

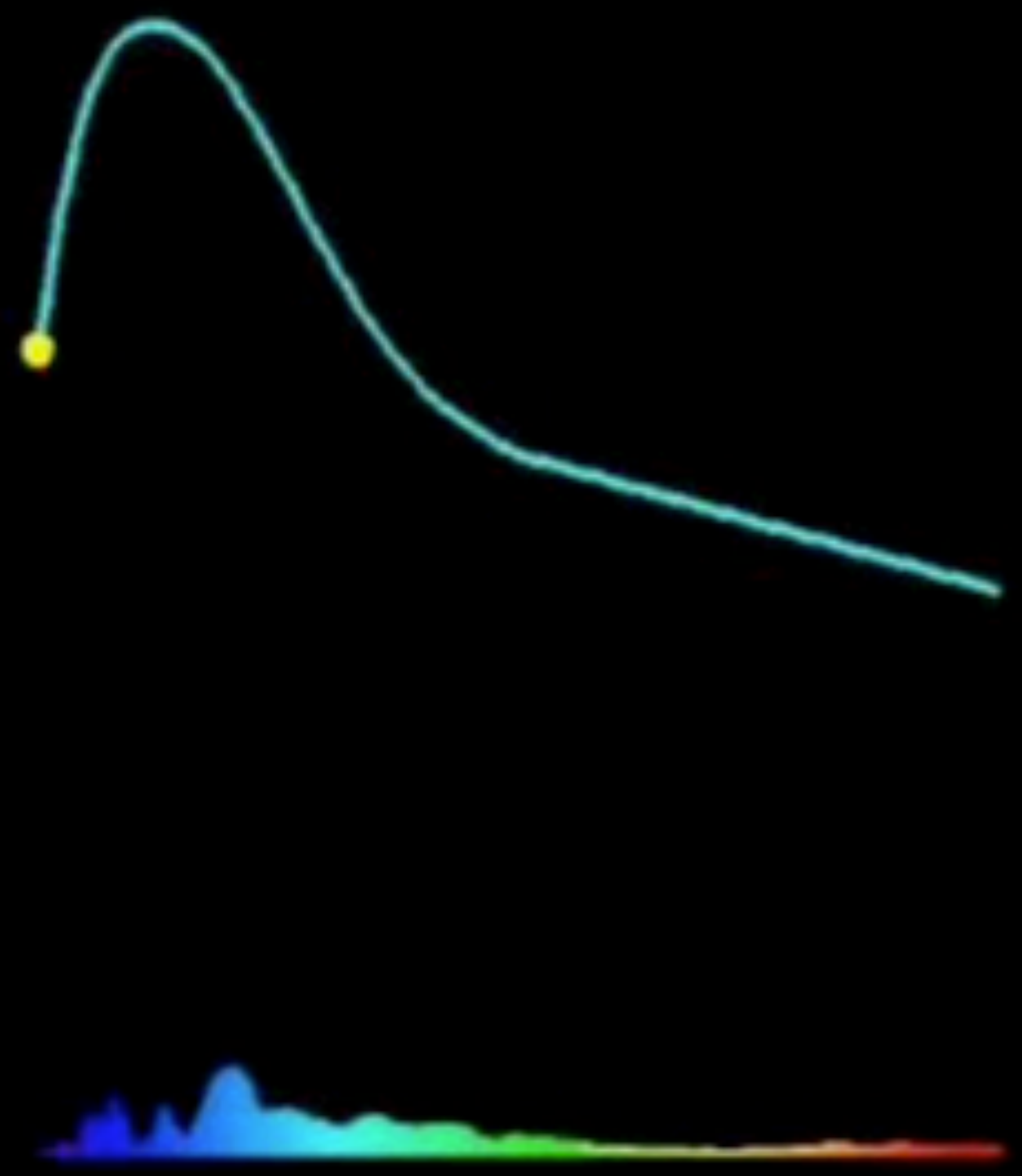
Why Supernovae?

Why Supernovae?

1

Already observed!

Neutrino signal from SN1987A



Why Supernovae?

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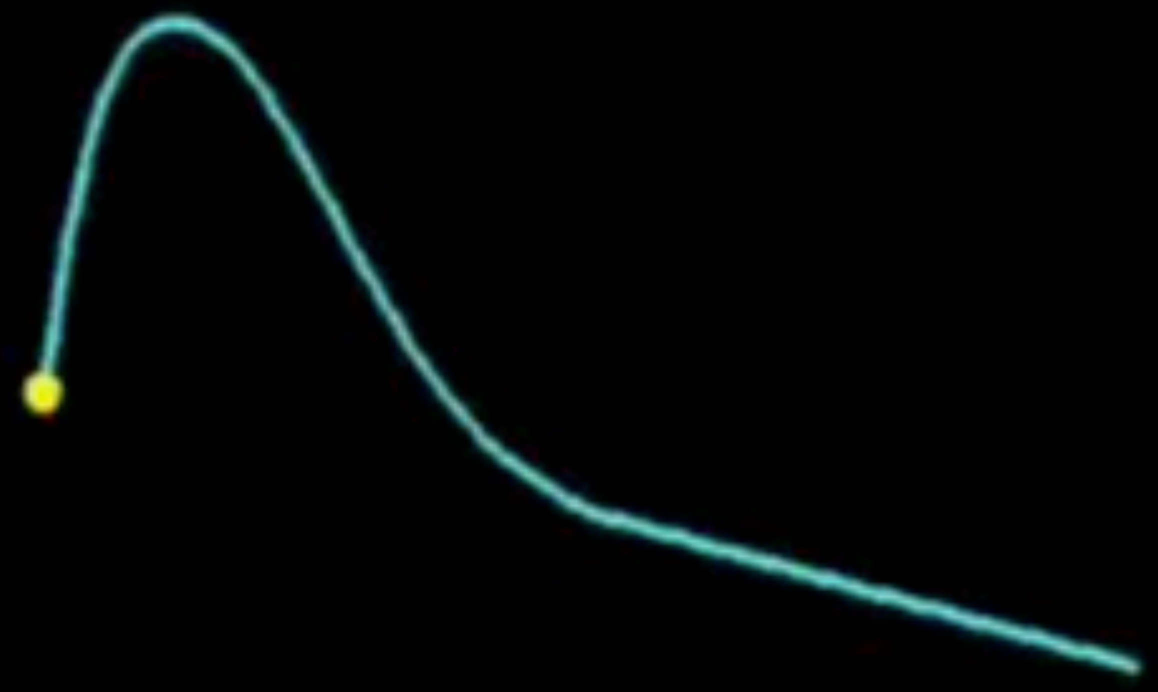
Neutrino signal from SN1987A

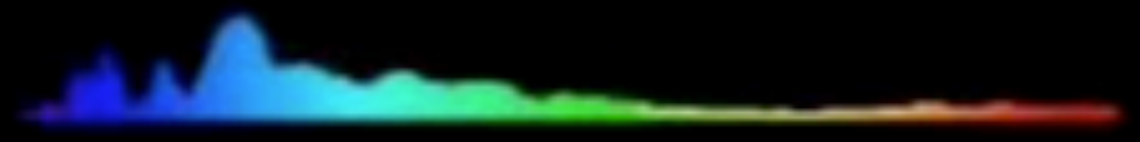
2

Neutrinos factories…

~99% energy released through neutrinos fluxes

… and not only!





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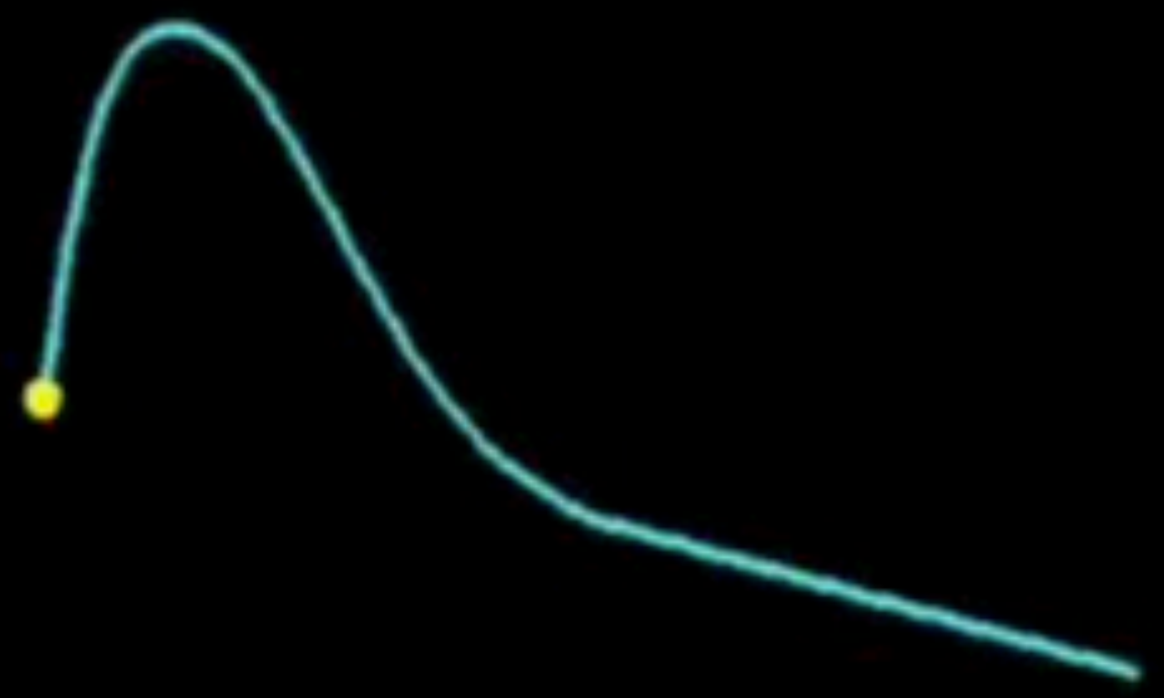

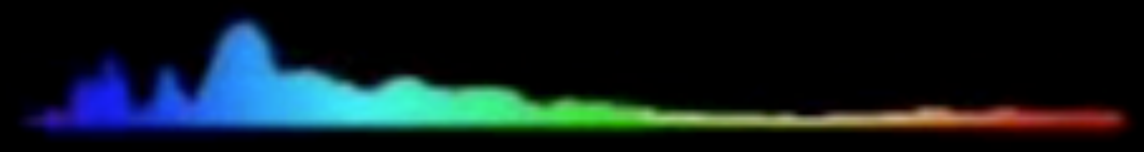

3

Cosmic Laboratories

unique opportunity to study interactions of elementary particles where new physics may be present

Why Supernovae?

1 **Already observed!**

Neutrino signal from SN1987A

2 **Neutrinos factories…**

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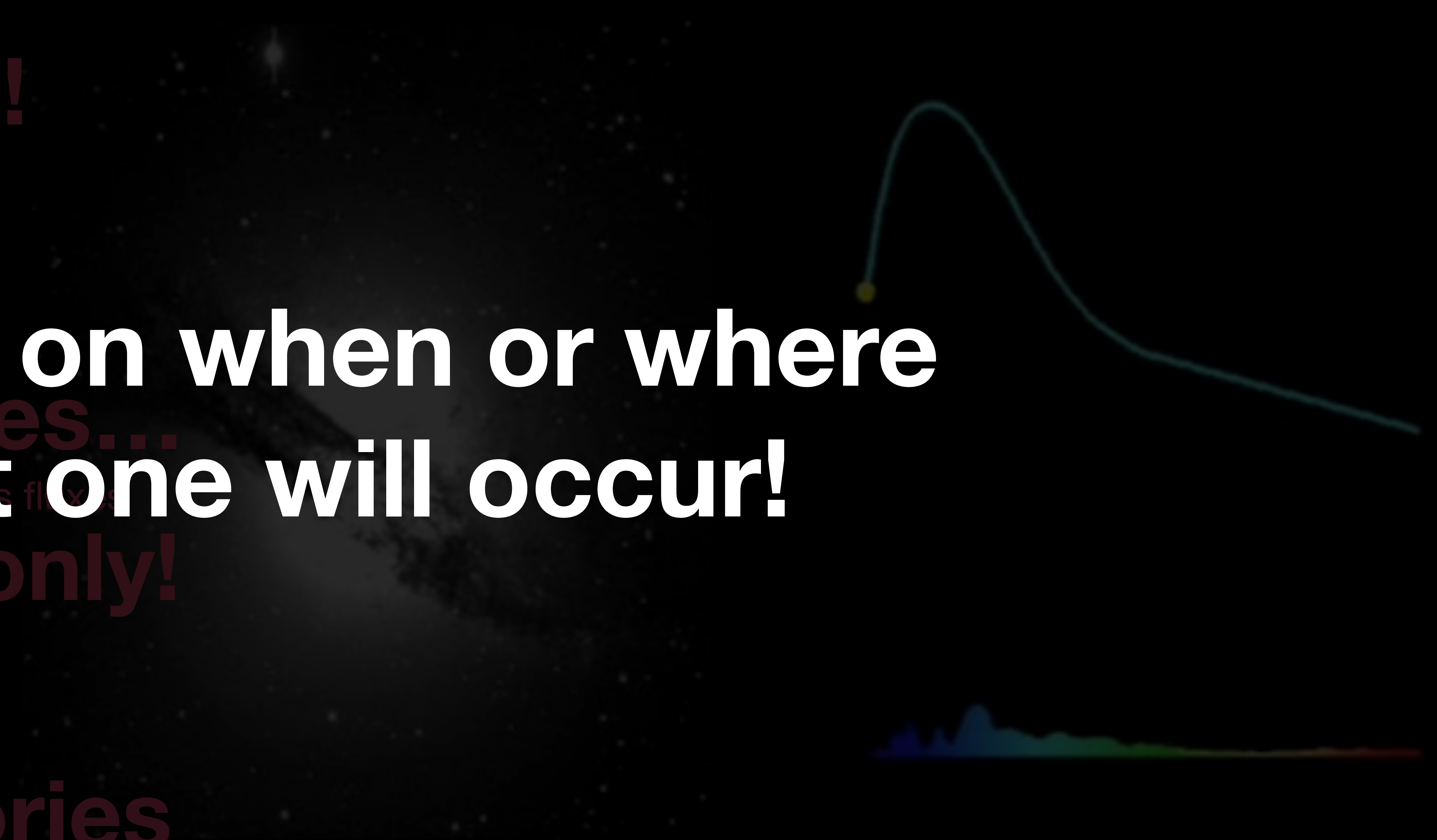
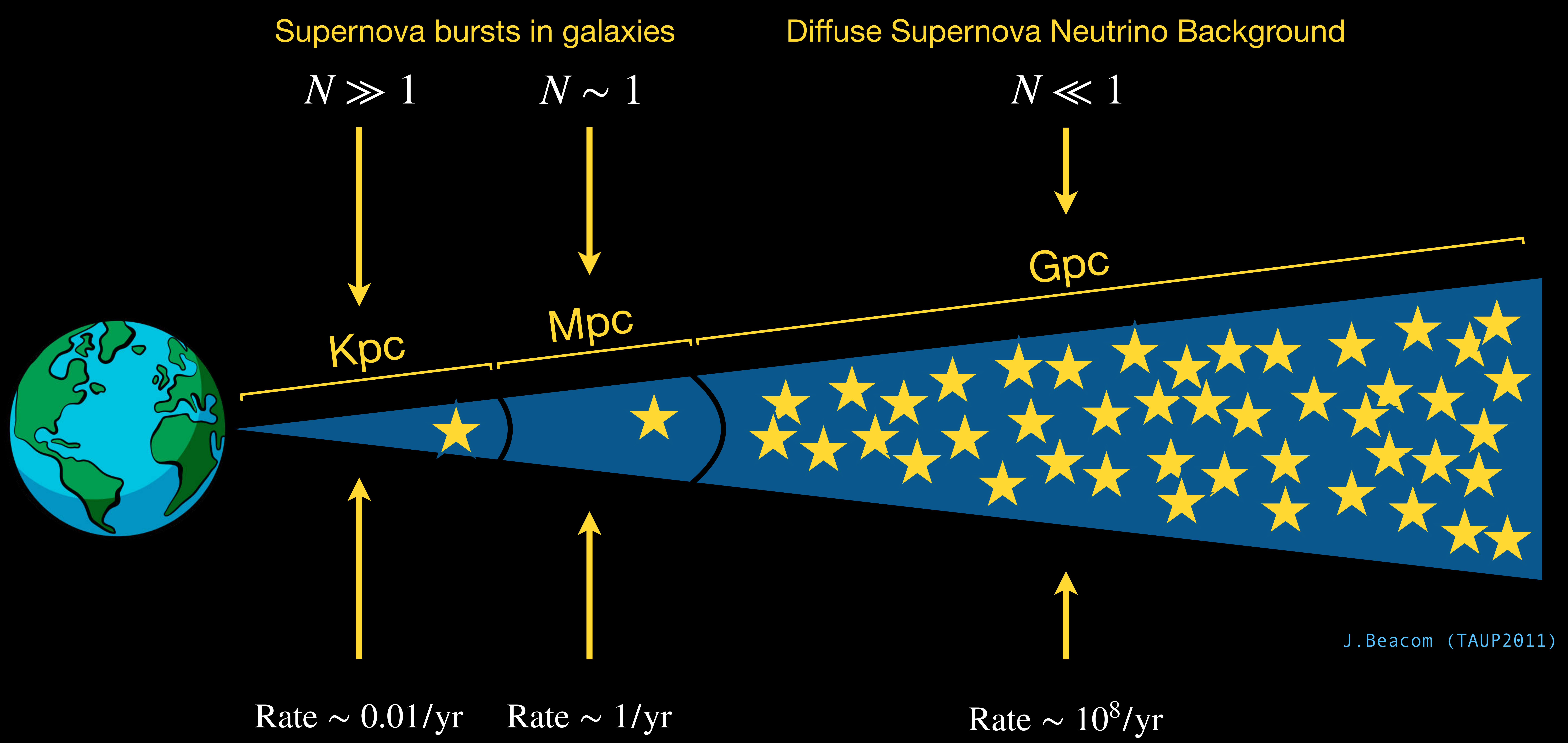
3 **Cosmic Laboratories**

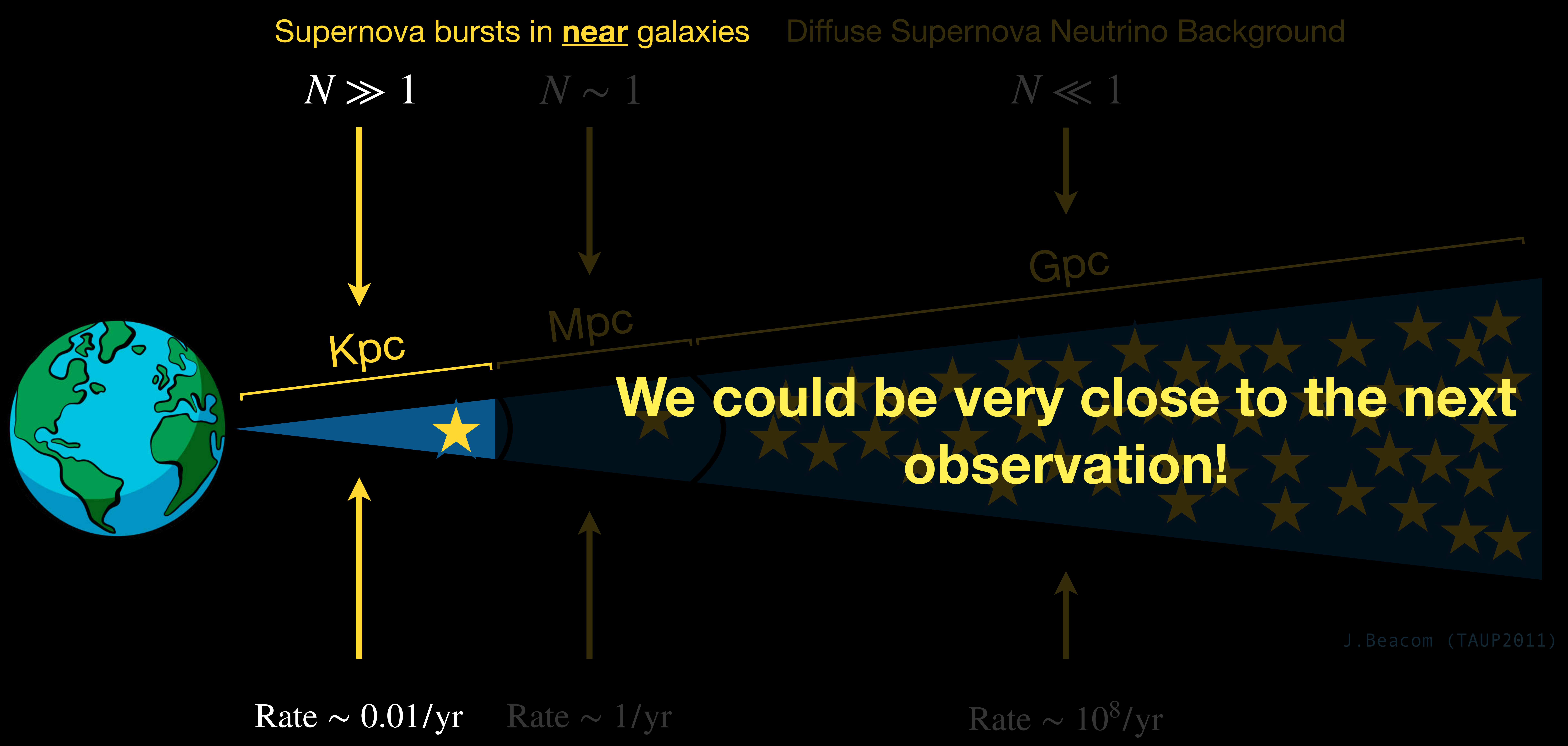
unique opportunity to study interactions of elementary particles where new physics may be present



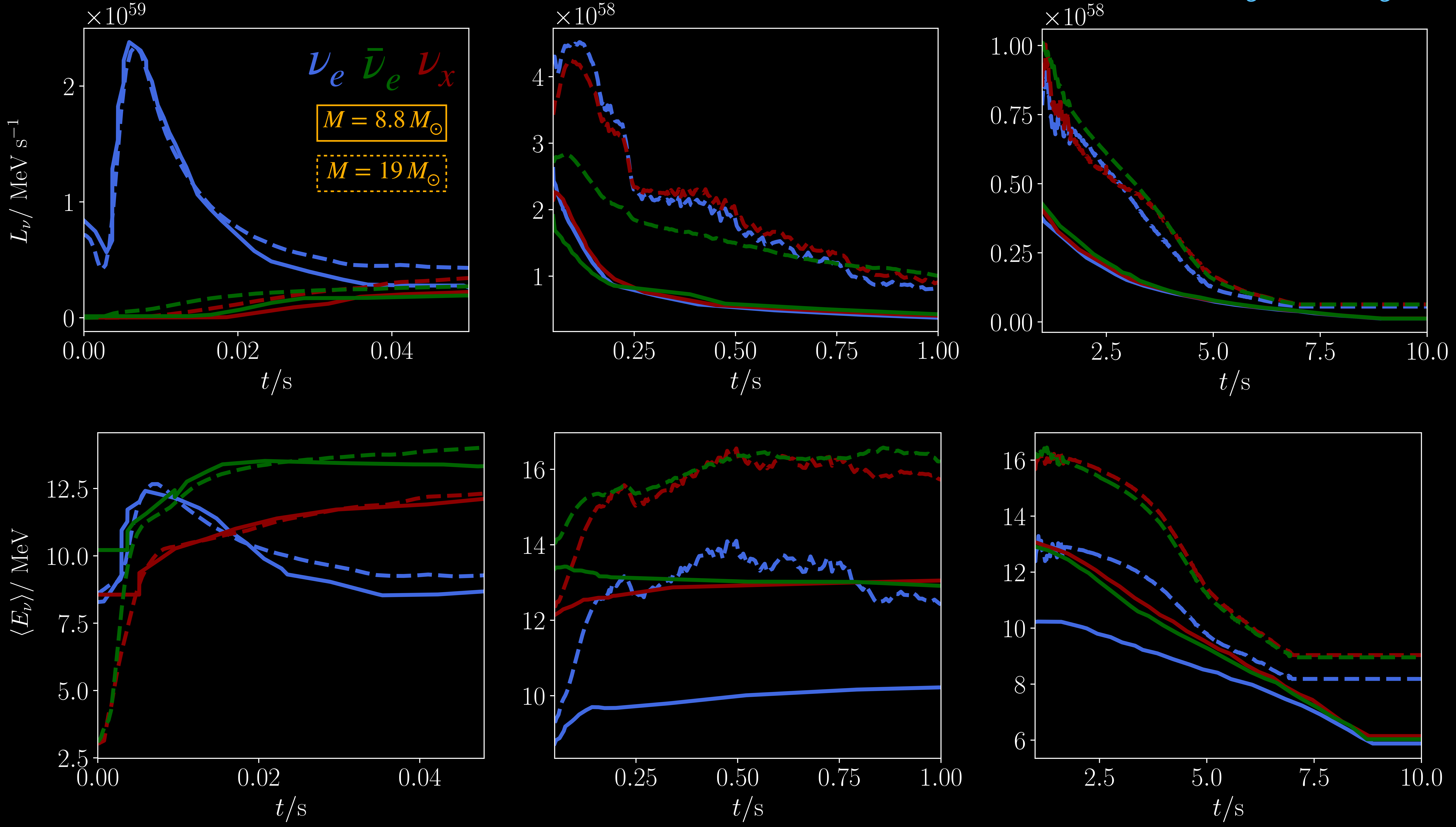
No control on when or where the next one will occur!



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



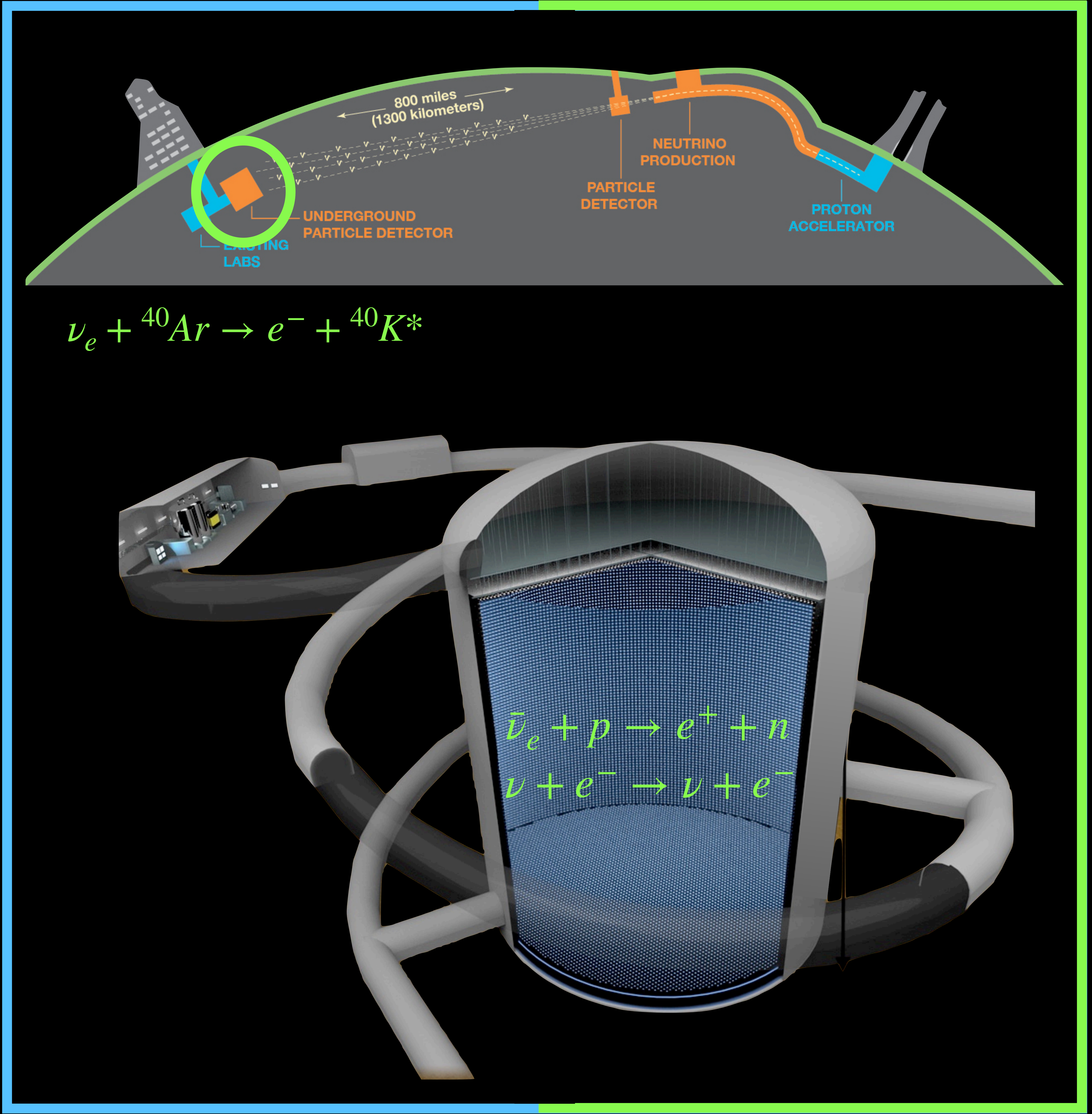
Supernova bursts in near galaxies
Diffuse Supernova Neutrino Background
$N \gg 1$
$N \sim 1$
$N \ll 1$
Kpc
Mpc
Gpc
We could be very close to the next observation!
J.Beacom (TAUP2011)
Rate $\sim$ 0.01/yr
Rate $\sim$ 1/yr
Rate $\sim 10^8$/yr


ν_e $\bar{\nu}_e$ ν_x
$M = 8.8\,M_\odot$
$M = 19\,M_\odot$
$\times 10^{59}$
$\times 10^{58}$
$\times 10^{58}$
L_ν/ MeV s^{-1}
$\langle E_\nu \rangle$/ MeV
t/s
0.00
0.02
0.04
0.25
0.50
0.75
1.00
2.5
5.0
7.5
10.0

$$R(t, E) =$$

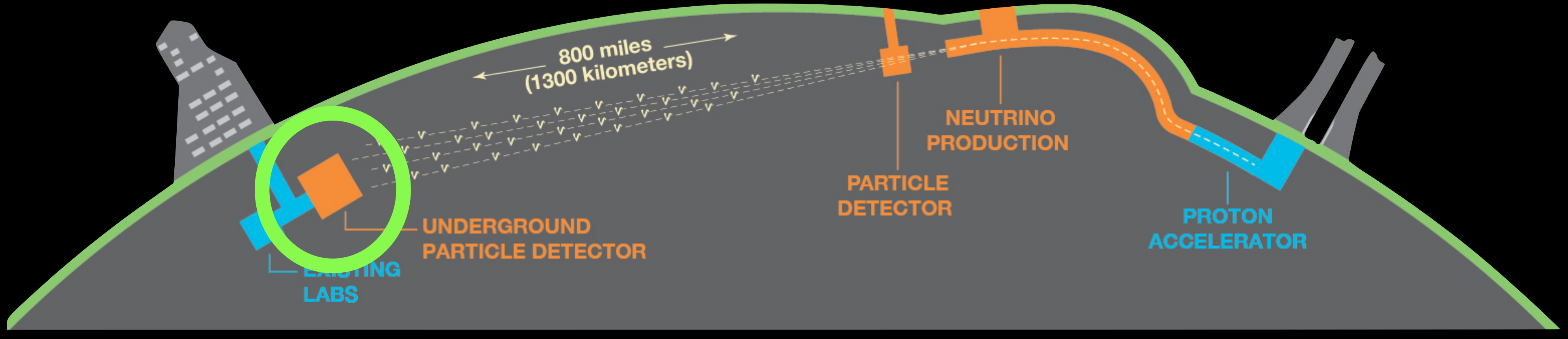
$$R(t, E) = N_{\text{target}}\ \epsilon(E)\ \sigma_{\text{sec}}(E)$$

Detector **Interaction**

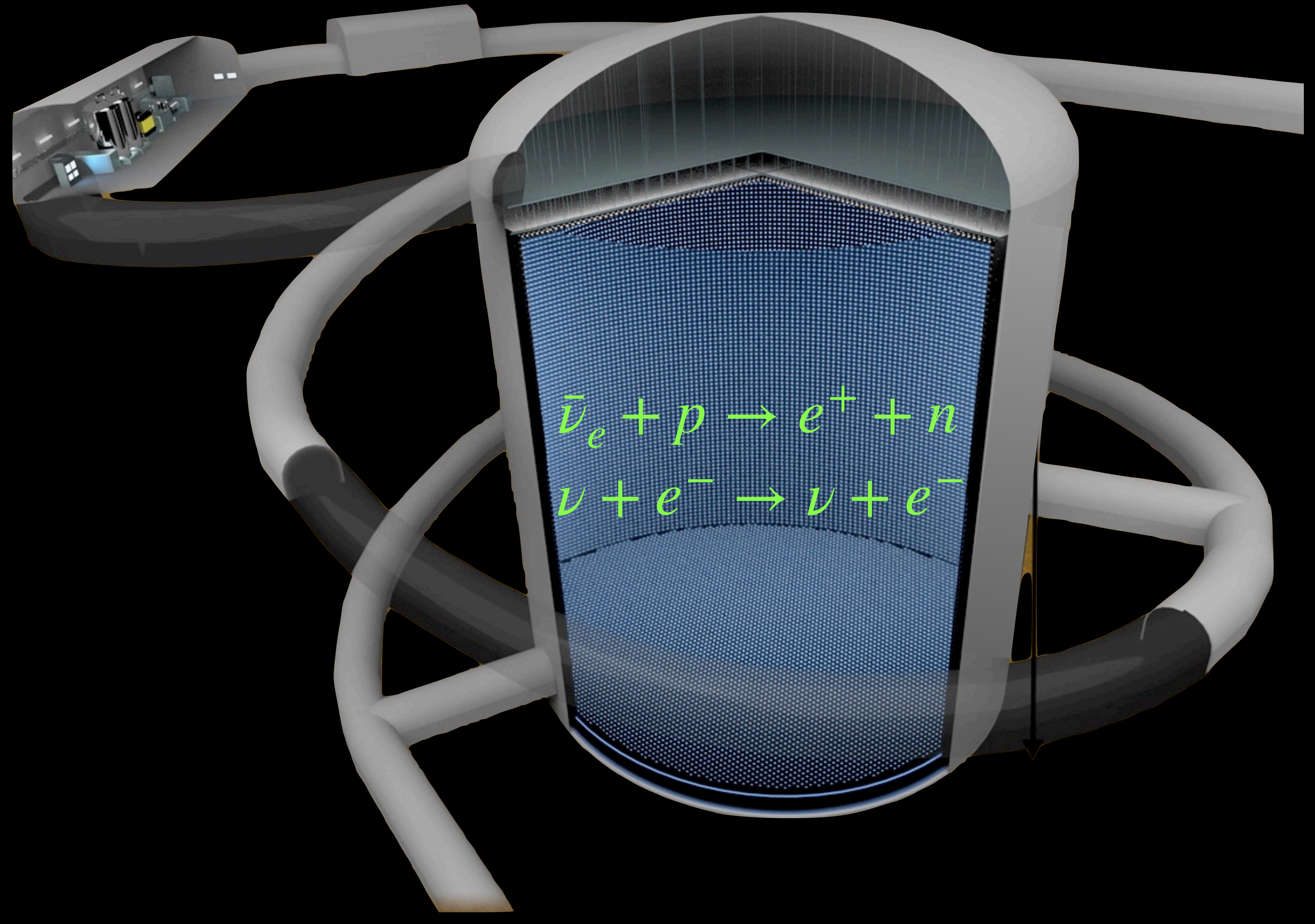


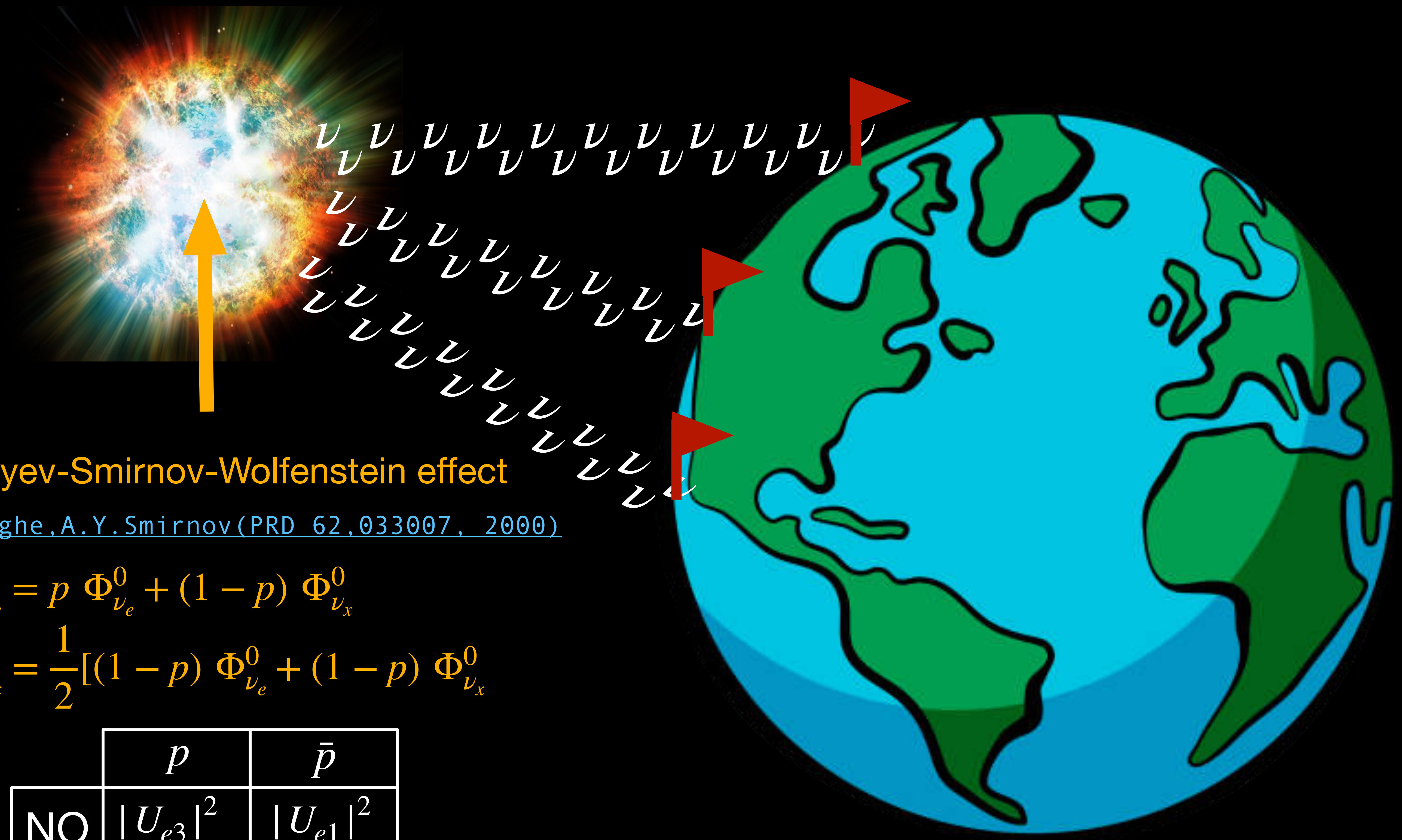
$$R(t,E) = \boxed{N_{\text{target}}\ \epsilon(E)}\ \boxed{\sigma_{\text{sec}}(E)}\ \boxed{\Phi_\nu(t,E)}$$

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



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





Mikheyev-Smirnov-Wolfenstein effect

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

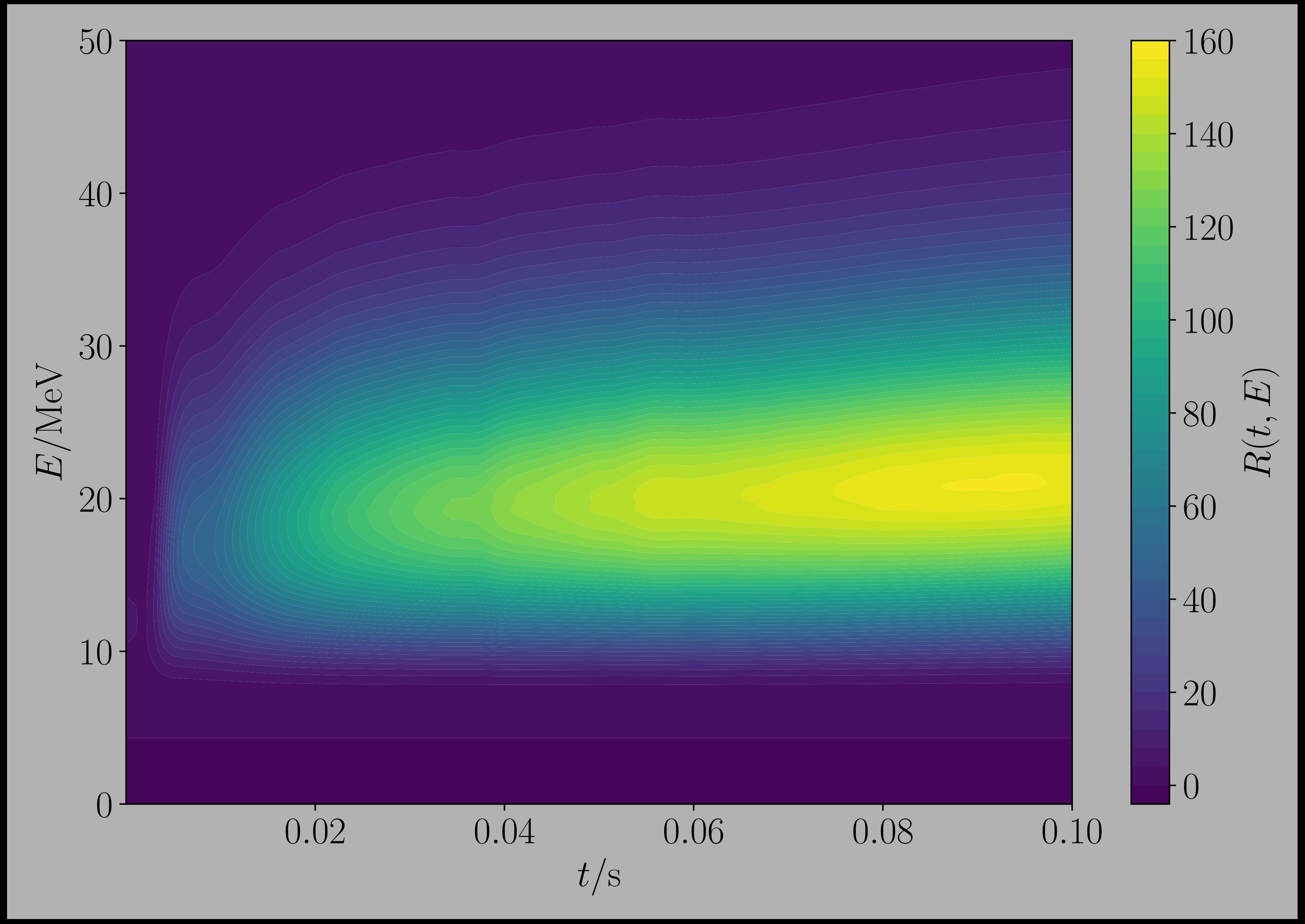
$$\Phi_{\nu_e} = p\ \Phi^0_{\nu_e} + (1-p)\ \Phi^0_{\nu_x}$$

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

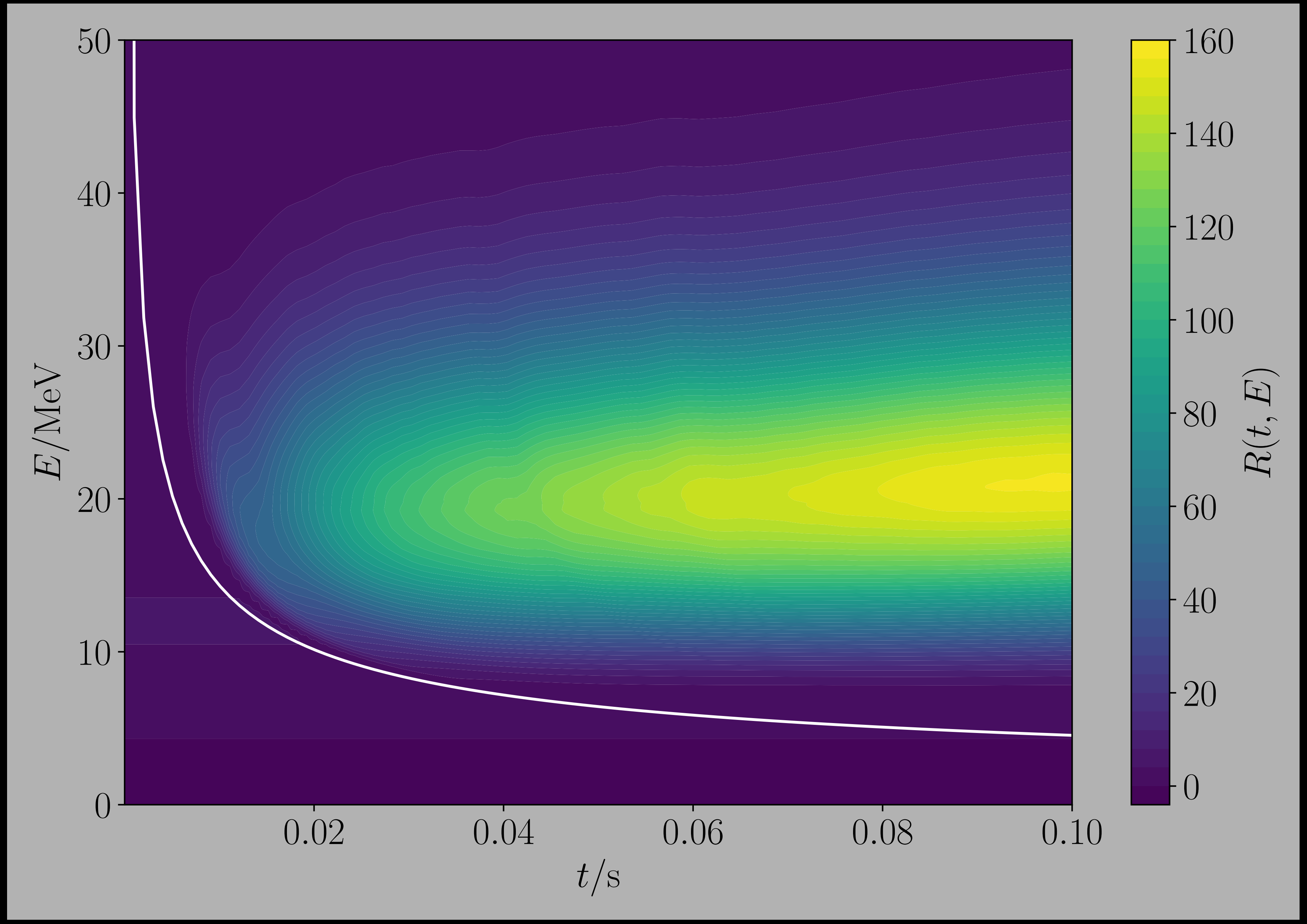
	p	$\bar{p}$
NO	$\lvert U_{e3}\rvert^2$	$\lvert U_{e1}\rvert^2$
IO	$\lvert U_{e2}\rvert^2$	$\lvert U_{e3}\rvert^2$

Effect of m_ν

$m_\nu = 0$

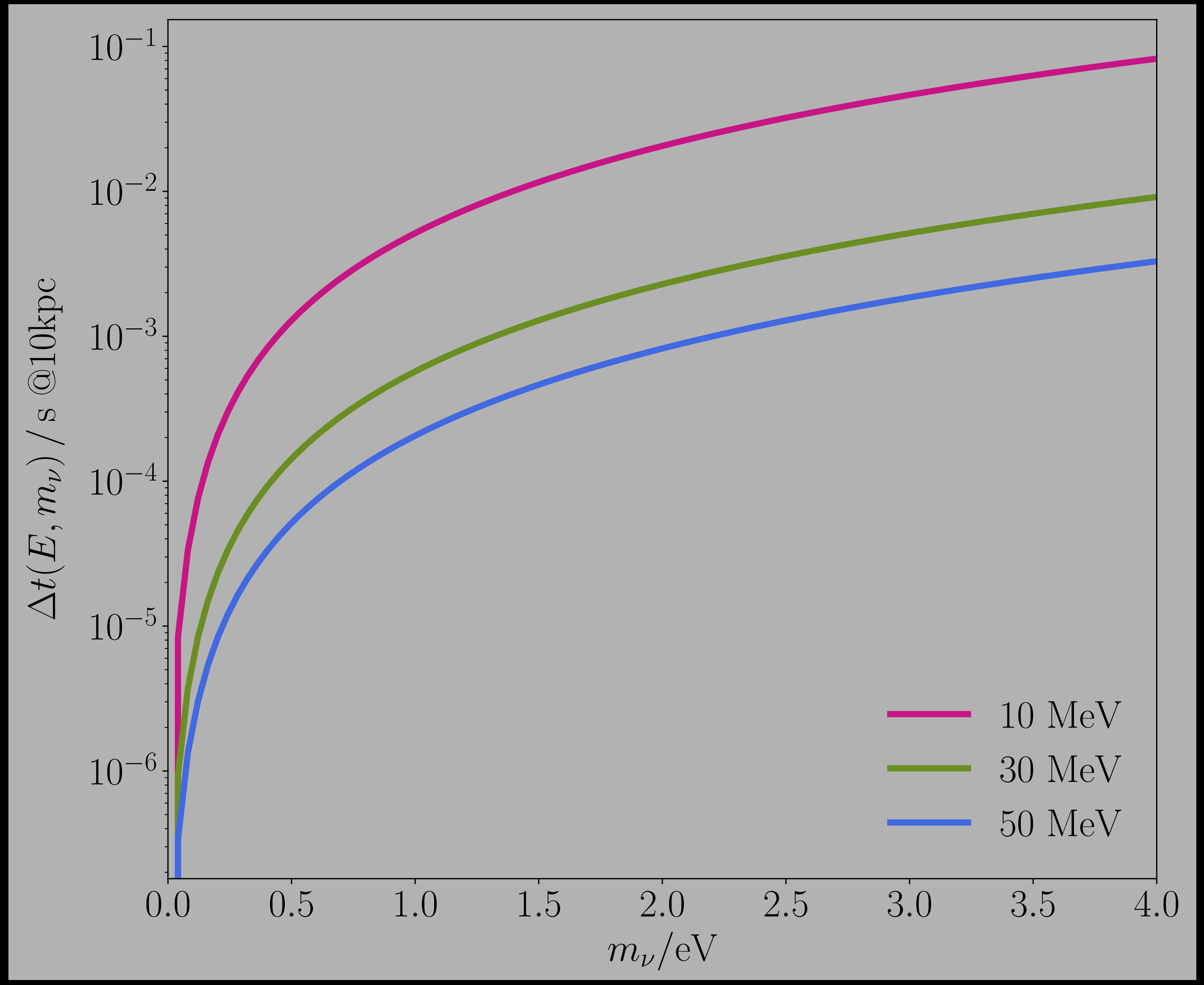


$m_\nu = 2\,\mathrm{eV}$

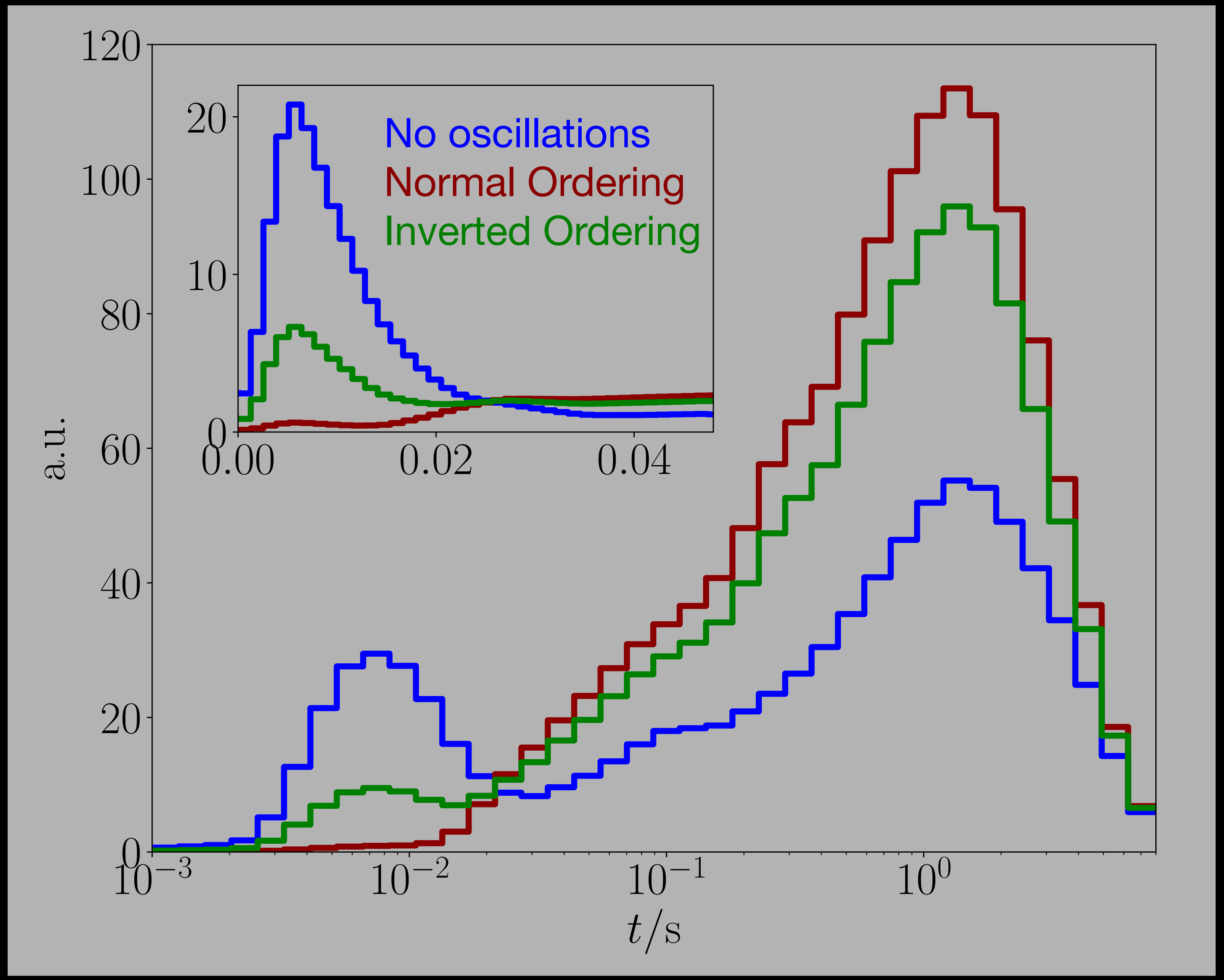


$$\Delta t_i(m_\nu) = \frac{D}{2c}\left(\frac{m_\nu}{E_i}\right)^2$$

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

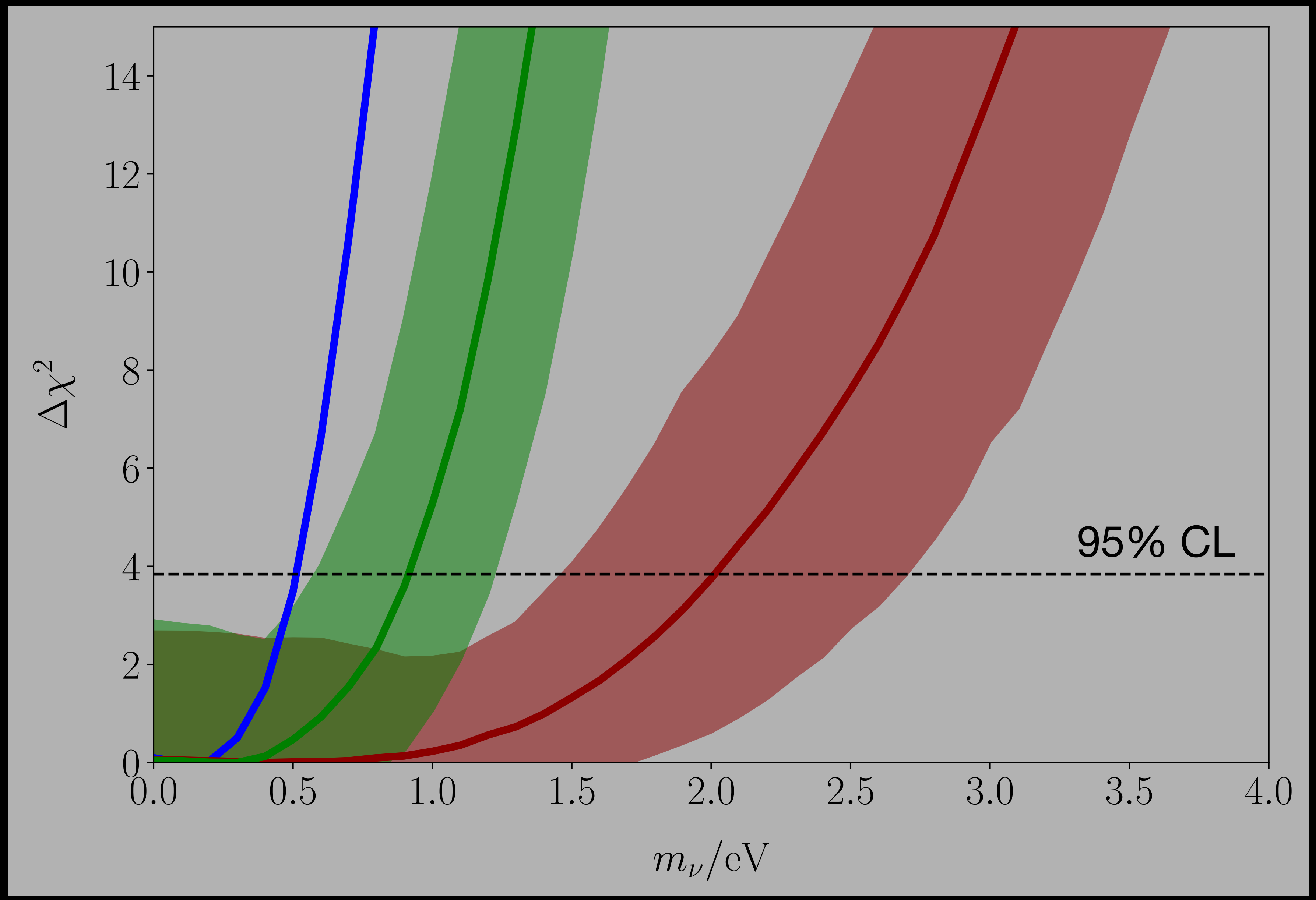


DUNE: D = 10 kpc



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

$M = 8.8\,M_\odot$



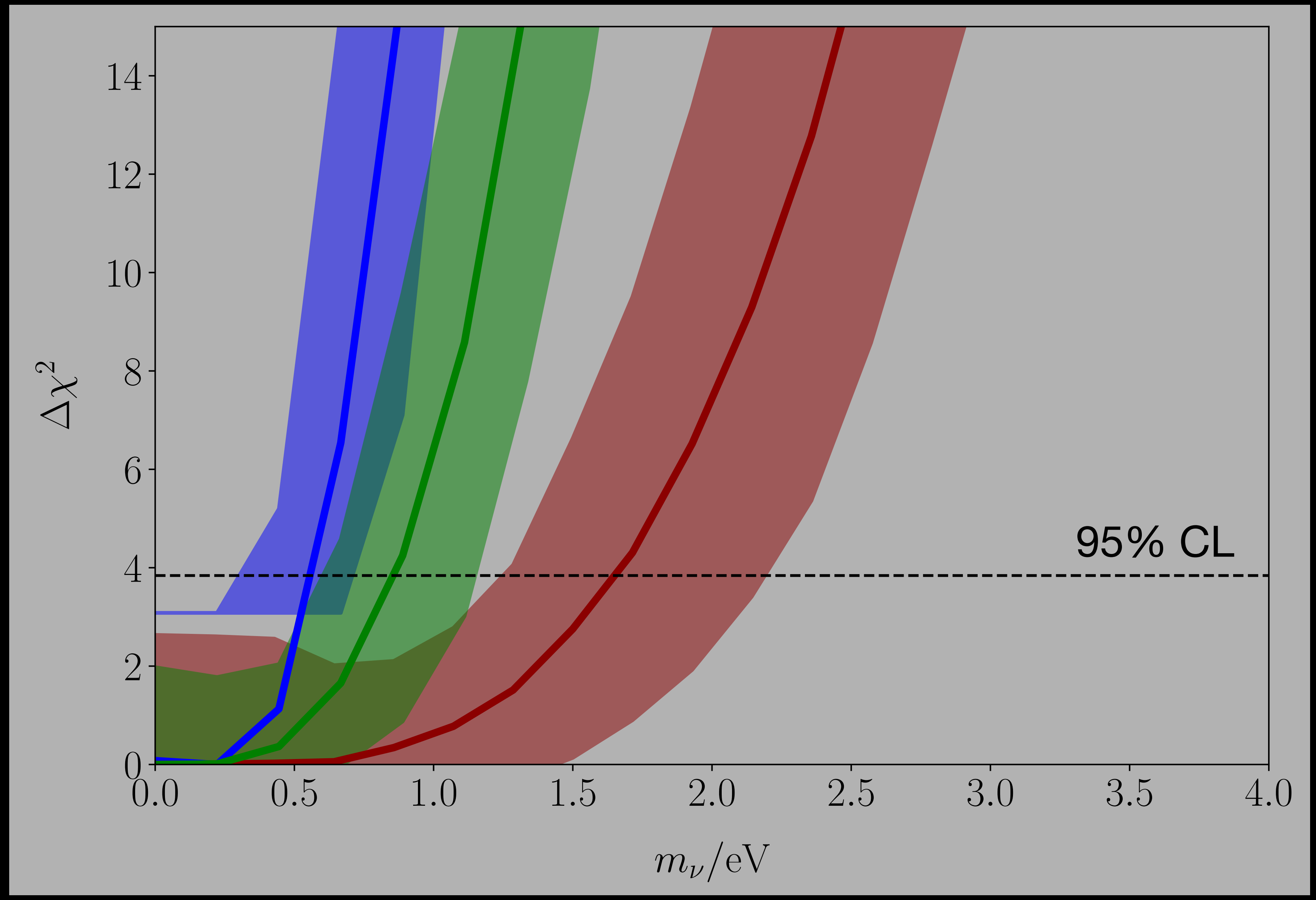
$m_\nu \leq 0.51^{+0.20}_{-0.19}$ eV

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

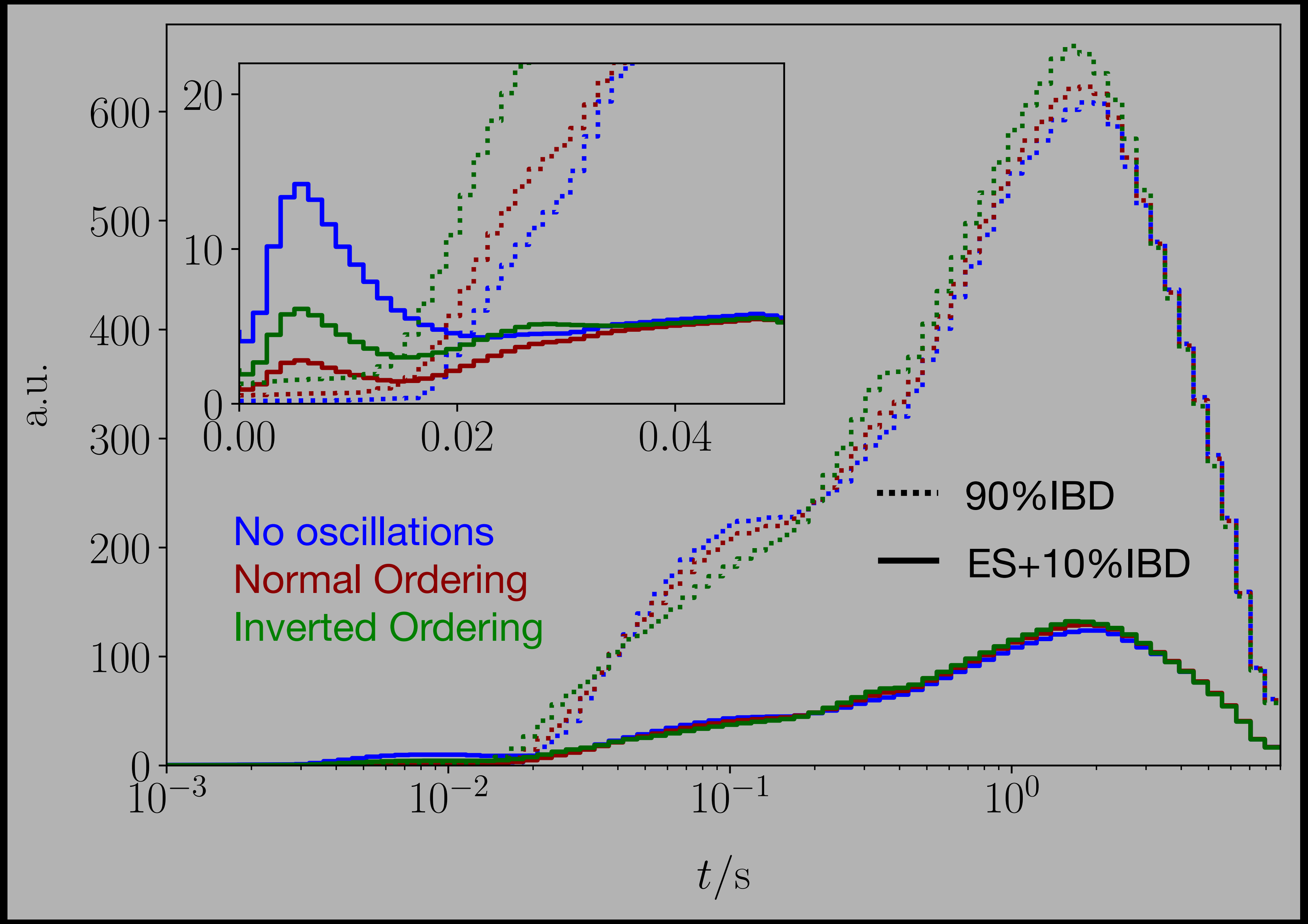


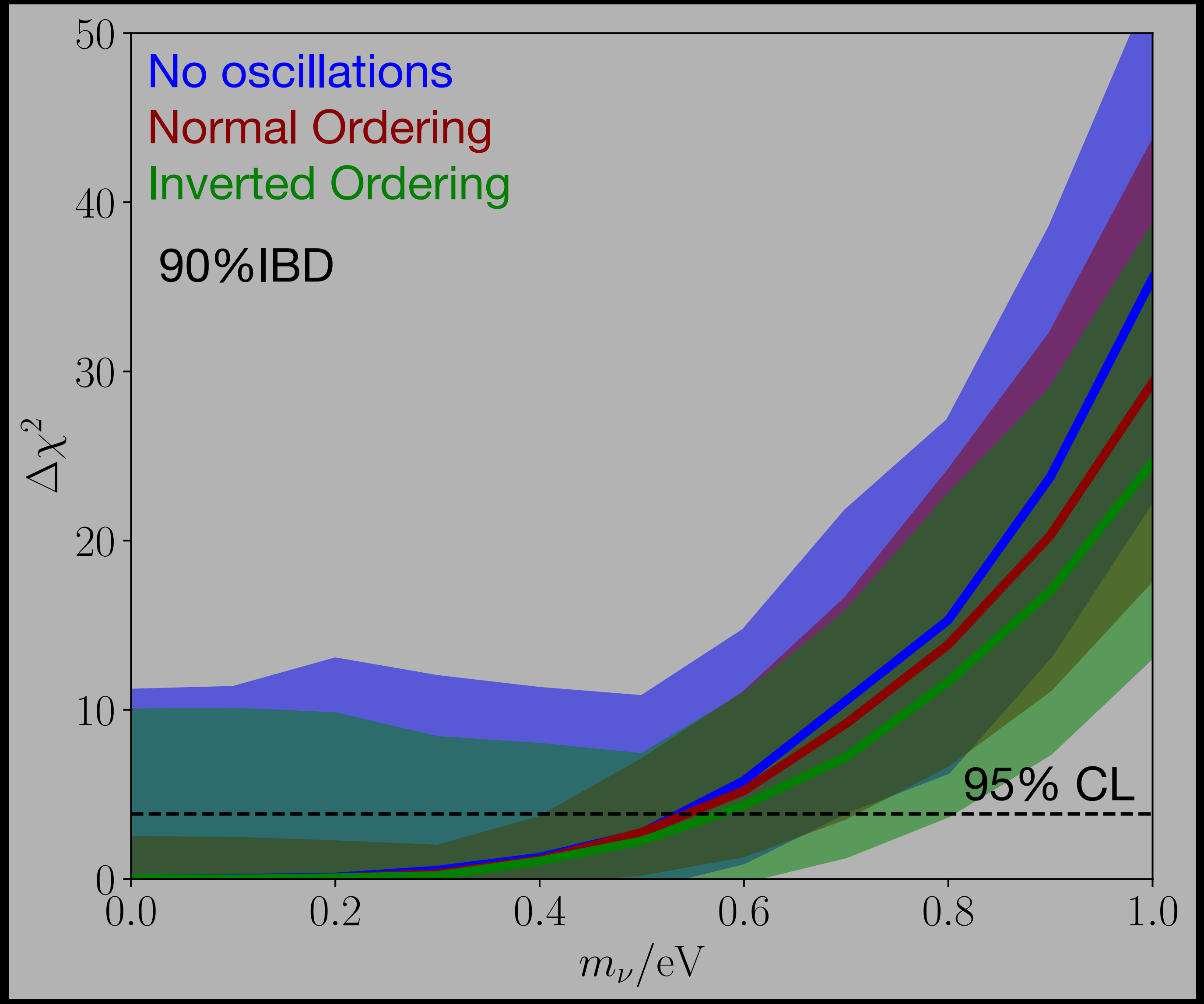
$m_\nu \leq 0.56^{+0.20}_{-0.21}$ eV

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

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

HK: D = 10 kpc





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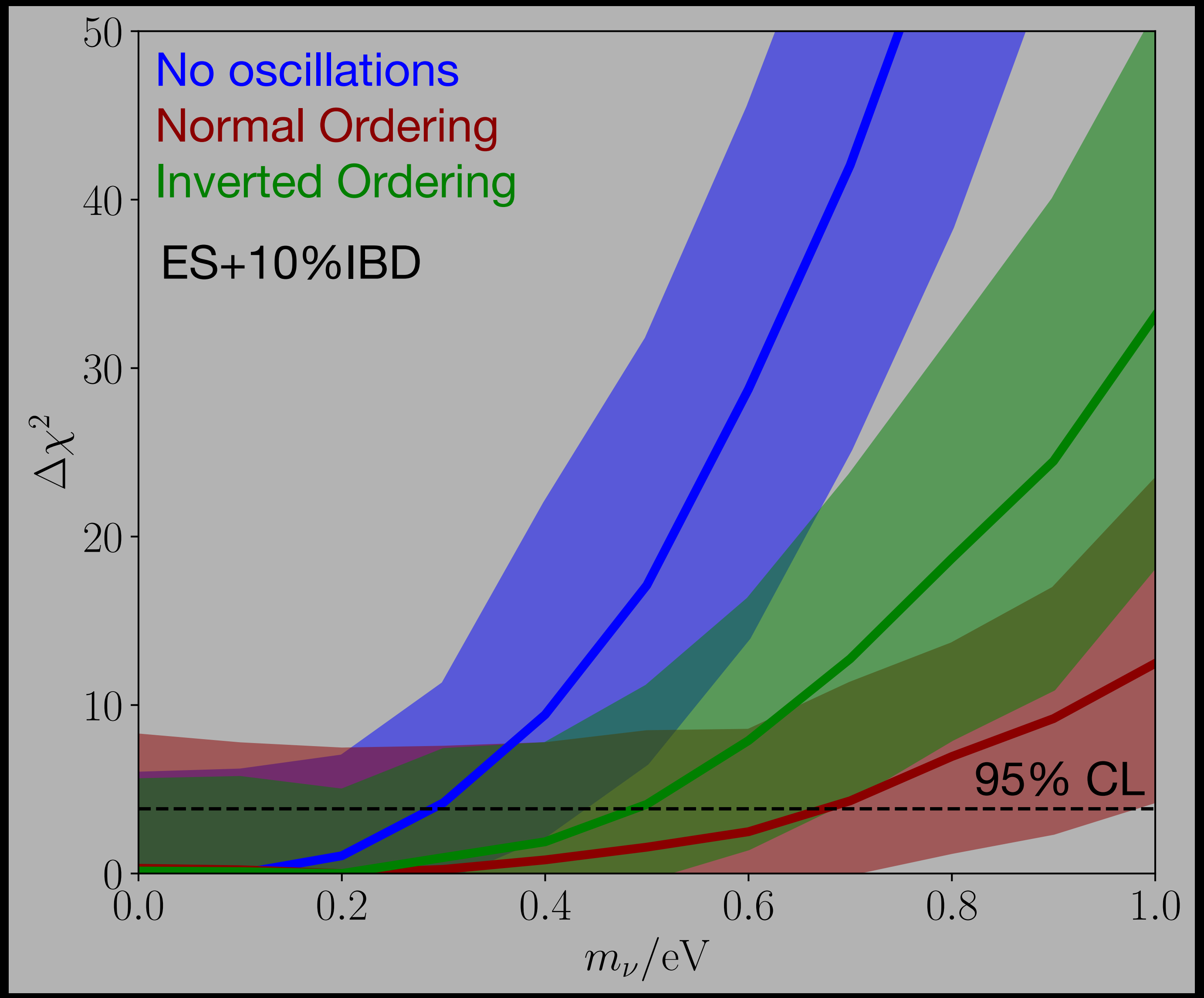

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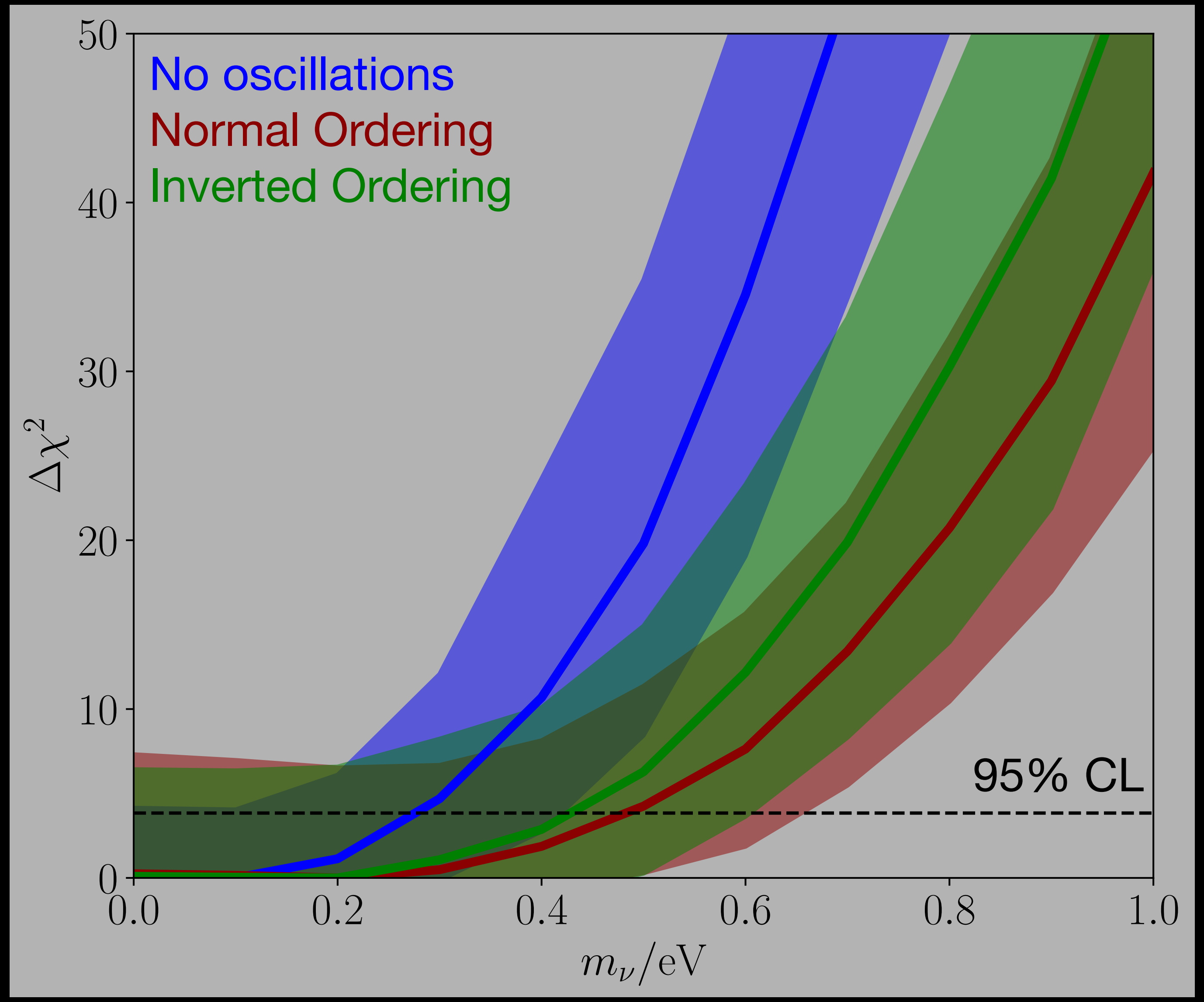
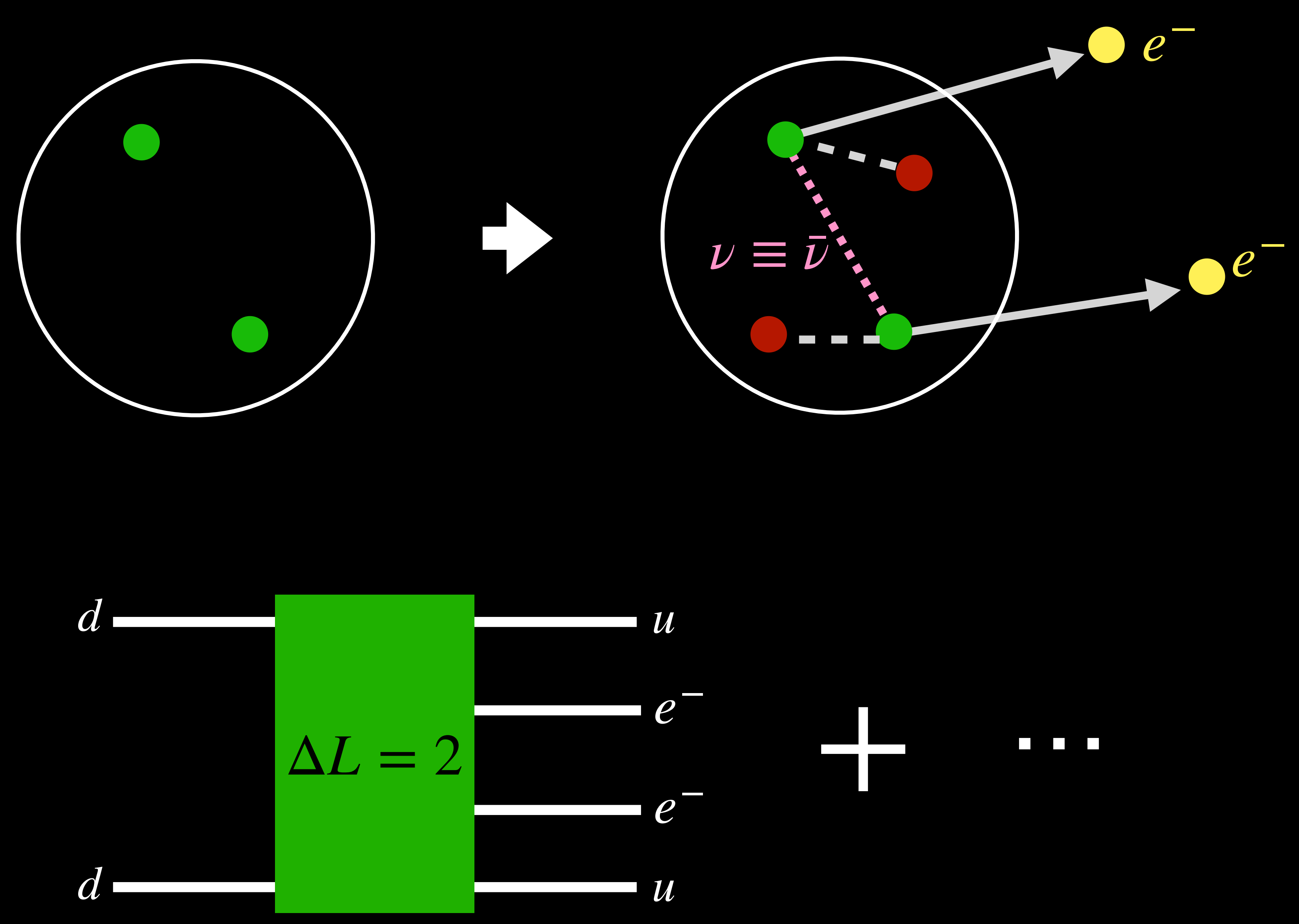


$M = 8.8\,M_\odot$	10 s	50 ms
90%IBD	16003	414
ES+10%IBD	3462	249
90%IBD	16223	466
ES+10%IBD	3419	130
90%IBD	16678	573
ES+10%IBD	3491	178

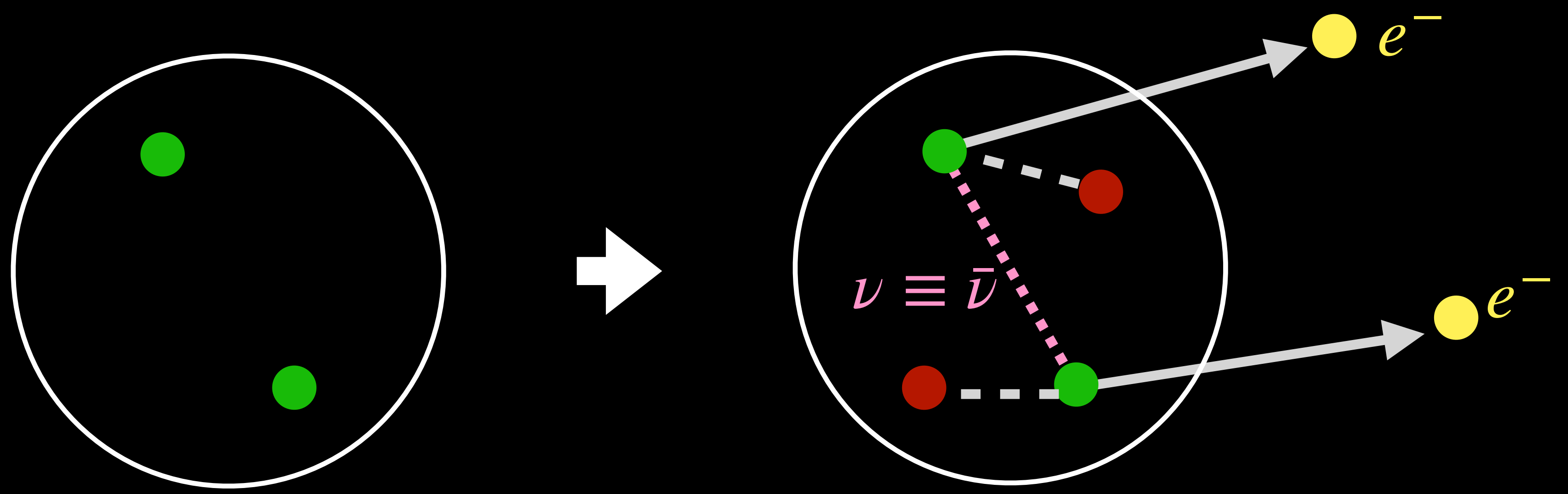
$0\nu\beta\beta$

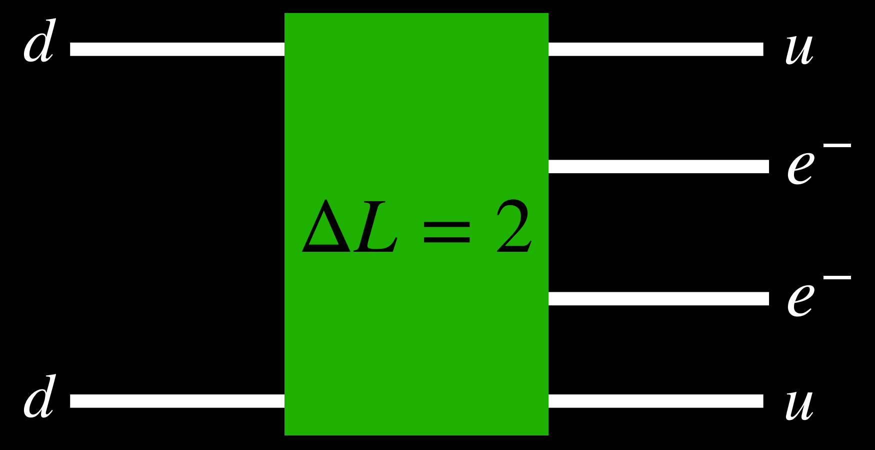
$0\nu\beta\beta$



- Hypothetical $(A, Z) \longrightarrow (A, Z+2) + 2e^-$
- Forbidden in the Standard Model : $\Delta L = 2$
- The only known feasible way to prove the Majorana nature of ν

$0\nu\beta\beta$





$+ \cdots$

- Hypothetical $(A, Z) \longrightarrow (A, Z+2) + 2e^-$
- Forbidden in the Standard Model : $\Delta L = 2$
- The only known feasible way to prove the Majorana nature of ν

$$\Gamma_\alpha(m_{\beta\beta}, M_{\alpha i}) = G_{0\nu} \times (\, g_A^2 \, | \, M_{\alpha i} \, | \,)^2 \times \varepsilon_{\mathrm{BMS}}$$

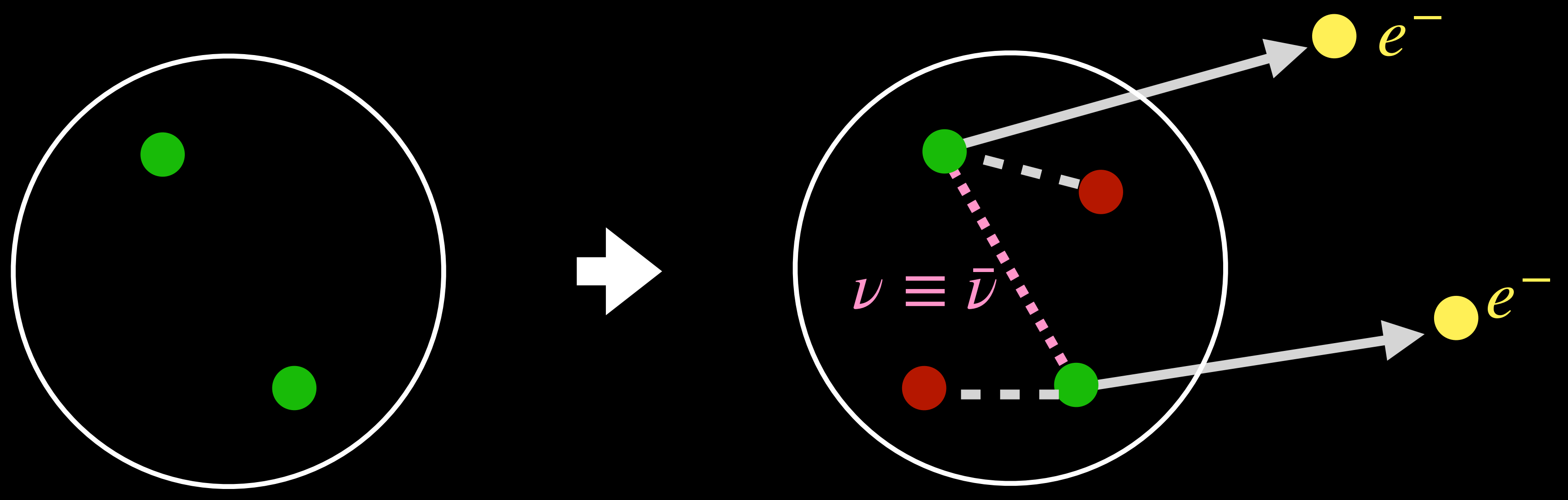
Phase Space Factor (PSF)
(kinematic)

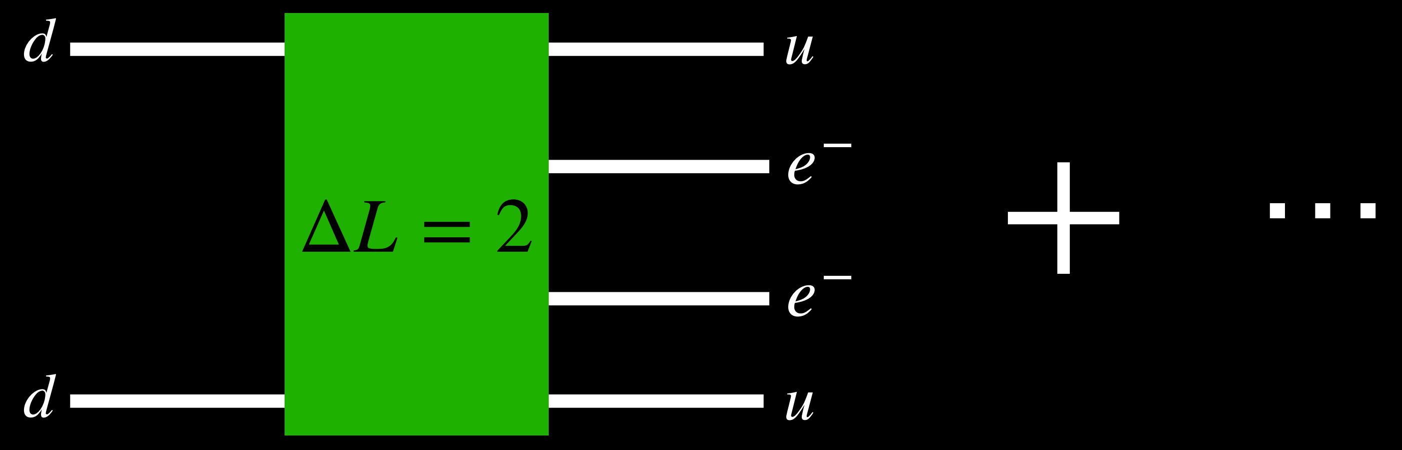
$M_{\alpha i}$ **Nuclear Matrix Element (NME)**

$g_{\mathrm{A}} = q \, g_{\mathrm{A}}^{\mathrm{bare}}$

New Physics

$0\nu\beta\beta$





- Hypothetical $(A, Z) \longrightarrow (A, Z+2) + 2e^-$
- Forbidden in the Standard Model : $\Delta L = 2$
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If $0\nu\beta\beta$ mediated by the exchange of a light Majorana ν :

$$\Gamma_\alpha(m_{\beta\beta}, M_{\alpha i}) = G_{0\nu} \times (\, g_A^2 \,|\, M_{\alpha i} \,|\,)^2 \times m_{\beta\beta}^2$$

Phase Space Factor (PSF)
(kinematic)

$M_{\alpha i}$ **Nuclear Matrix Element (NME)**

$$g_A = q\, g_A^{\text{bare}}$$

Effective Majorana mass

$$\left| \sum_j U_{ej}^2 m_j \right|$$

Nuclear Models and Nuclear Matrix Elements

M.Agostini et all. - Rev.Mod.Phys. 95 (2023) 2, 025002

$M_{0\nu} = M_{0\nu}^{long}$ Long-range contribution to the decay rate induced by the exchange of light Majorana ν

- Calculations performed by different groups by assuming $g_A^{bare} = 1.27$
- Data not available for all the isotopes
- Variation in $M_{0\nu}^{long}$ of a factor ~ 3

		^{76}Ge	^{82}Se	^{100}Mo	^{130}Te	^{136}Xe
Nuclear Shell Model	N1	2.89	2.73	-	2.76	2.28
	N2	3.07	2.90	-	2.96	2.45
	N3	3.37	3.19	-	1.79	1.63
	N4	3.57	3.39	-	1.93	1.76
	N5	2.66	2.72	-	3.16	2.39
Quasiparticle Random Phase Approximation	Q1	5.09	-	-	1.37	1.55
	Q2	5.26	3.73	3.90	4.00	2.91
	Q3	4.85	4.61	5.87	4.67	2.72
	Q4	3.12	2.86	-	2.90	1.11
	Q5	3.40	3.13	-	3.22	1.18
	Q6	-	-	-	4.05	3.38
Energy-Density Functional theory	E1	4.60	4.22	5.08	5.13	4.20
	E2	5.55	4.67	6.59	6.41	4.77
	E3	6.04	5.30	6.48	4.89	4.24
Interacting Boson Model	I1	5.14	4.19	3.84	3.96	3.25
	I2	6.34	5.21	5.08	4.15	3.40

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M.Agostini et all. - Rev.Mod.Phys. 95 (2023) 2, 025002

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Long-range contribution to the decay rate induced by the exchange of light Majorana ν

- Calculations performed by different groups by assuming $g_{\mathrm{A}}^{\mathrm{bare}} = 1.27$
- Data not available for all the isotopes
- Variation in $M_{0\nu}^{\mathrm{long}}$ of a factor ~ 3

Large theoretical uncertainties!

		^{76}Ge	^{82}Se	^{100}Mo	^{130}Te	^{136}Xe
Nuclear Shell Model	N1	2.89	2.73	-	2.76	2.28
	N2	3.07	2.90	-	2.96	2.45
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Short-range contribution

V.Cirigliano et al, Phys.Rev.Lett.120,202001

To renormalize the $0\nu\beta\beta$ amplitude due to light Majorana ν exchange

$$M_{\alpha i} = M_{\alpha i}^{\text{long}} + M_{\alpha i}^{\text{short}} = M_{\alpha i}^{\text{long}}(1 + n_{\alpha i})$$

↓

Unknown value and sign leading either to an enhancement or suppression of the expected decay rate ← $n_{\alpha i} = \dfrac{M_{\alpha i}^{\text{short}}}{M_{\alpha i}^{\text{long}}}$ → $|n_{\alpha i}| \in$

(Hints for + sign = best scenario)

M.Agostini et all. - Rev.Mod.Phys. 95 (2023) 2, 025002

	Nuclear Shell Model %	Quasiparticle Random Phase Approximation %
^{76}Ge	$15 \div 42$	$32 \div 73$
^{82}Se	$15 \div 42$	$30 \div 70$
^{100}Mo	-	$49 \div 108$
^{130}Te	$17 \div 47$	$34 \div 77$
^{136}Xe	$17 \div 47$	$30 \div 70$

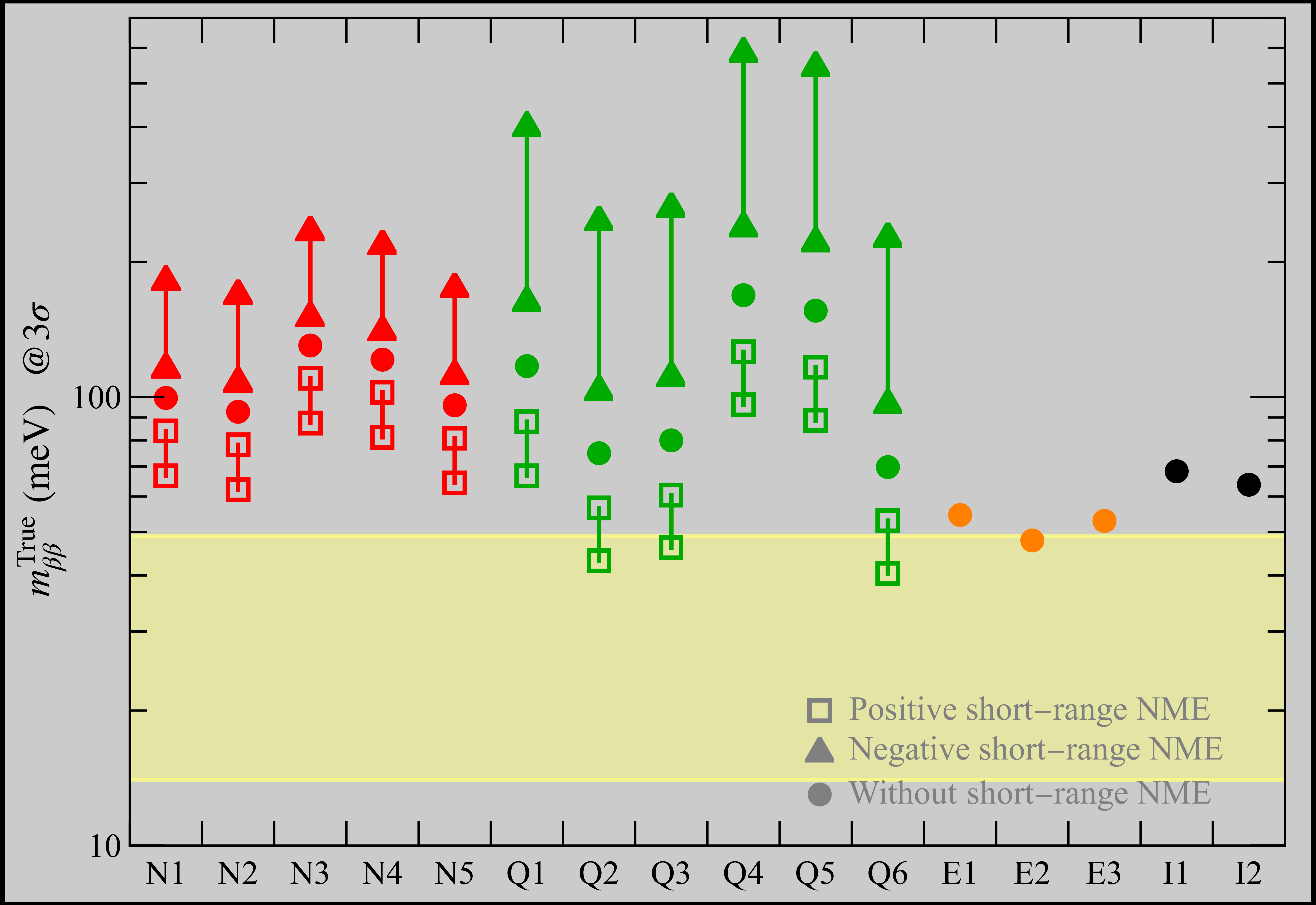
L.Jokiniemi et all. - Phys.Lett.B 823 (2021) 136720

Current picture…

- Impact of the short-range term
- Uncertainties on both the size and sign of $|n_{\alpha i}|$

(In some cases) already touching the IMO region!

$@\,3\sigma\ \ (\Delta\chi^2_{\rm tot} = 9)$



… and future prospect

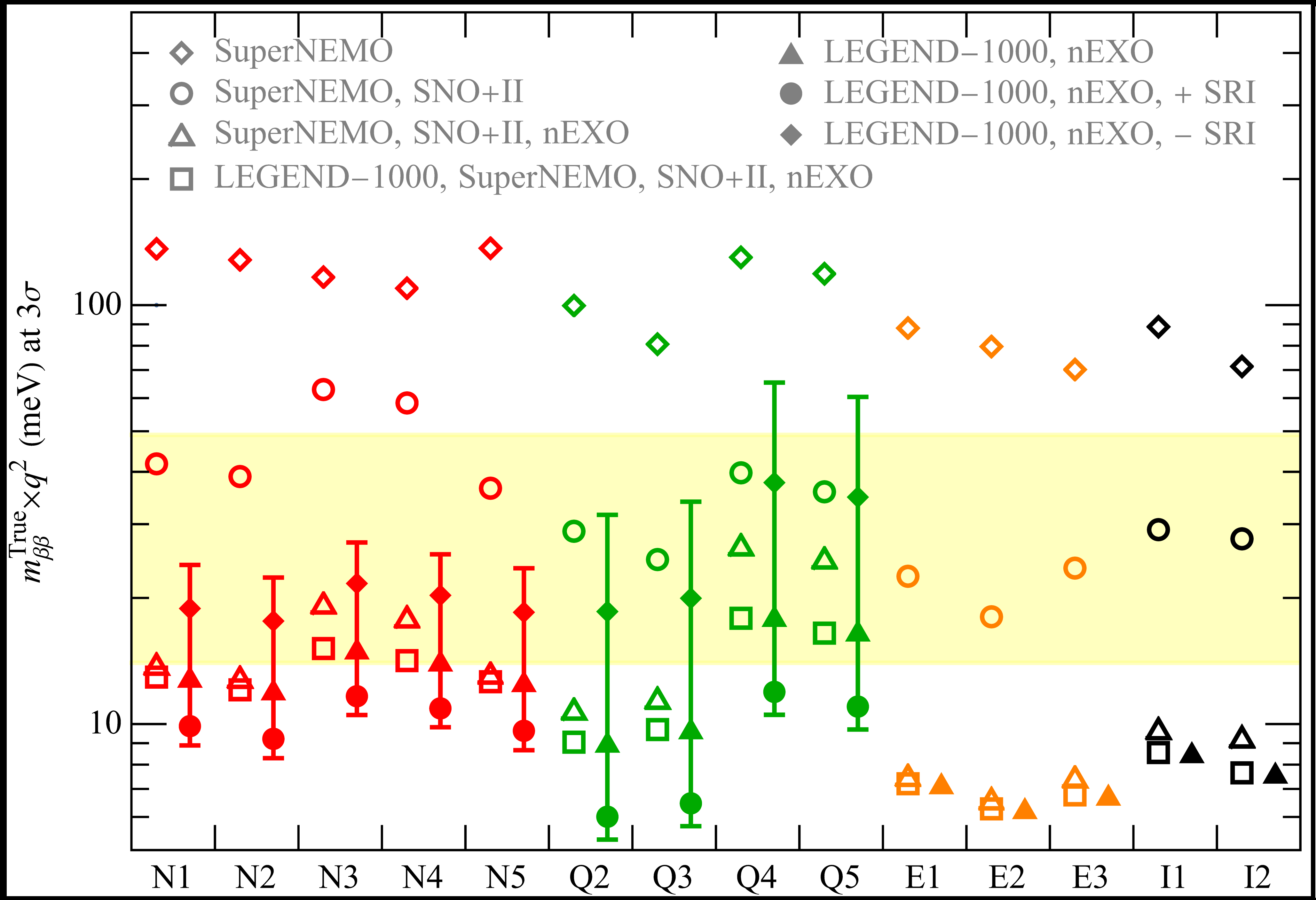
M.Agostini et all. - Rev.Mod.Phys. 95 (2023) 2, 025002

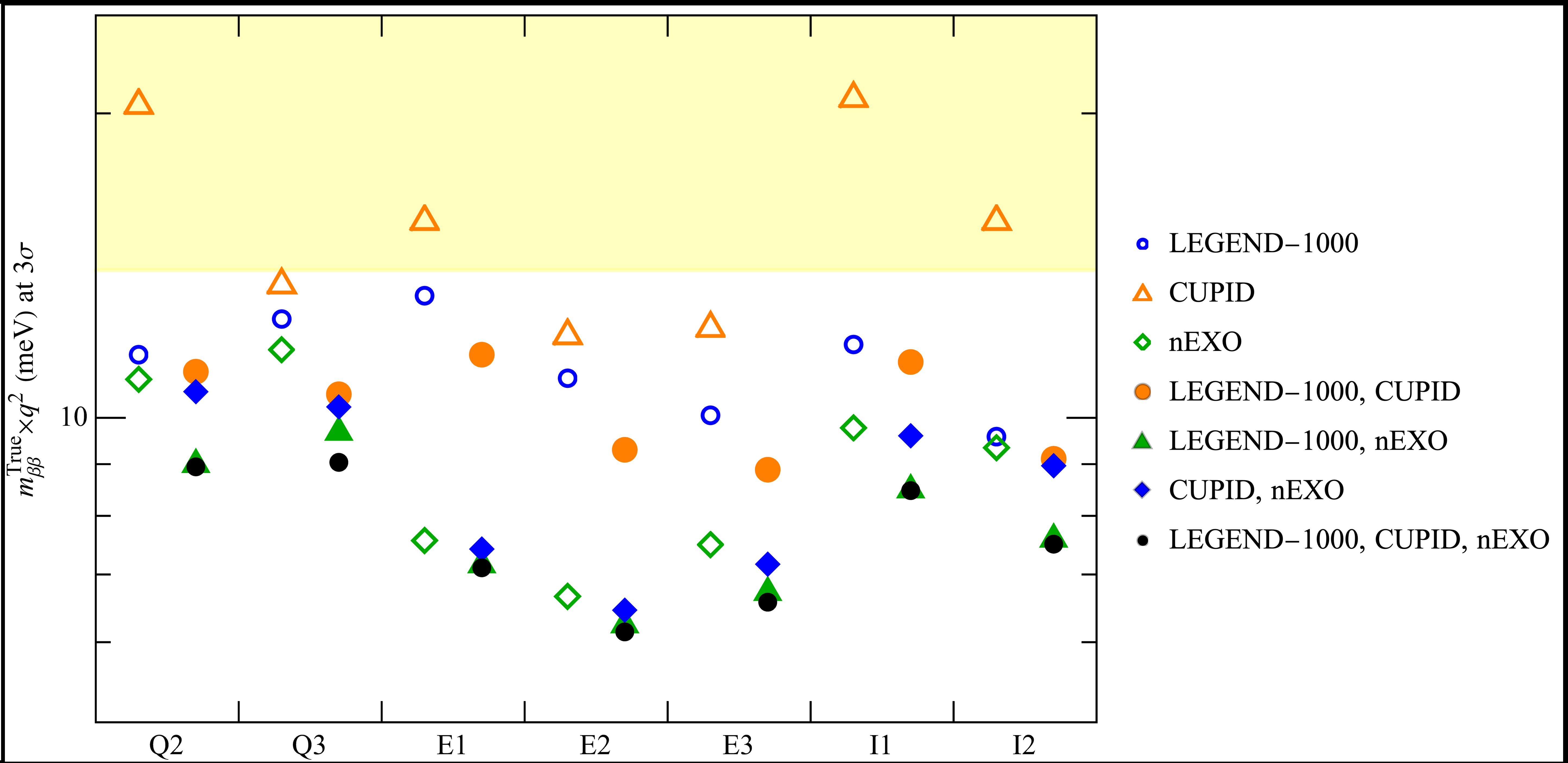
IMO completely explored!

- Big impact of the short-range term
- Uncertainties on both the size and sign of $|n_{\alpha i}|$
- LEGEND-1000 (^{76}Ge) + nEXO (^{136}Xe)

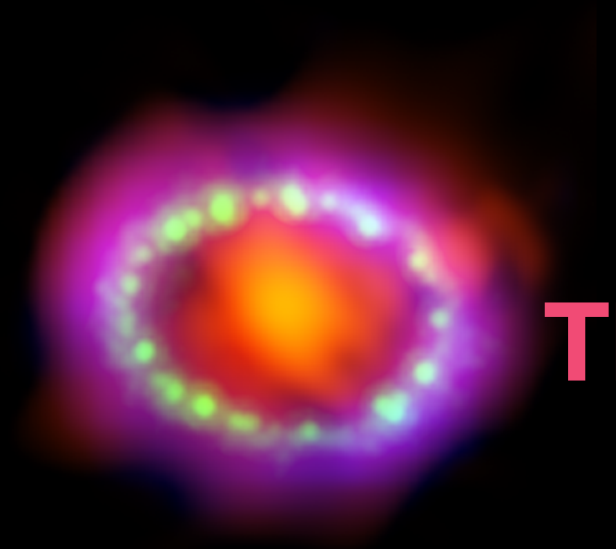
^{76}Ge	LEGEND-1000
^{136}Xe	nEXO
^{100}Mo	CUPID
^{130}Te	SNO+II
^{82}Se	SuperNEMO

Sensitivity @ 3σ $(\Delta\chi^2_{\rm tot} = 9)$

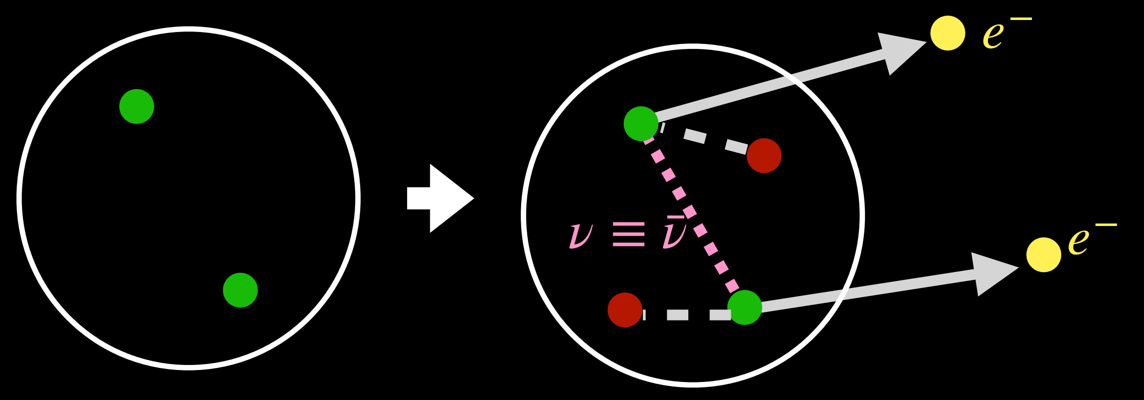




Take-home message



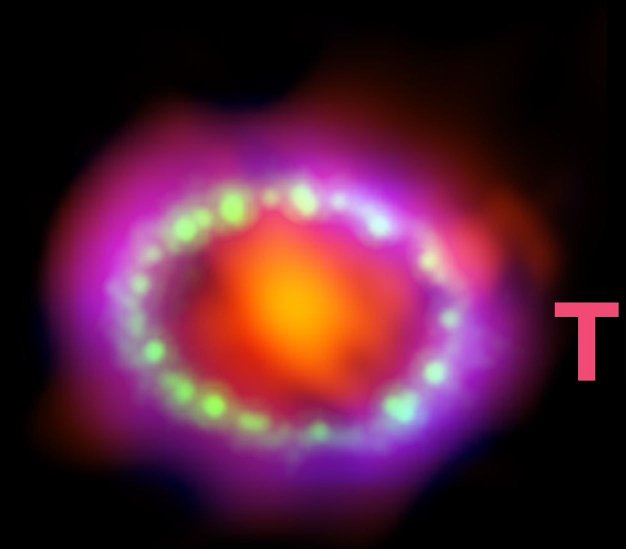
The neutrino signal coming from the Supernova neutronization burst, visible only in the ν_e spectrum, constitutes a fundamental tool to constrain the neutrino mass in a model-independent way.



Future $0\nu\beta\beta$ setups able to prove or rule out the inverted mass ordering region for many NME models in the light-Majorana neutrino exchange scenario.

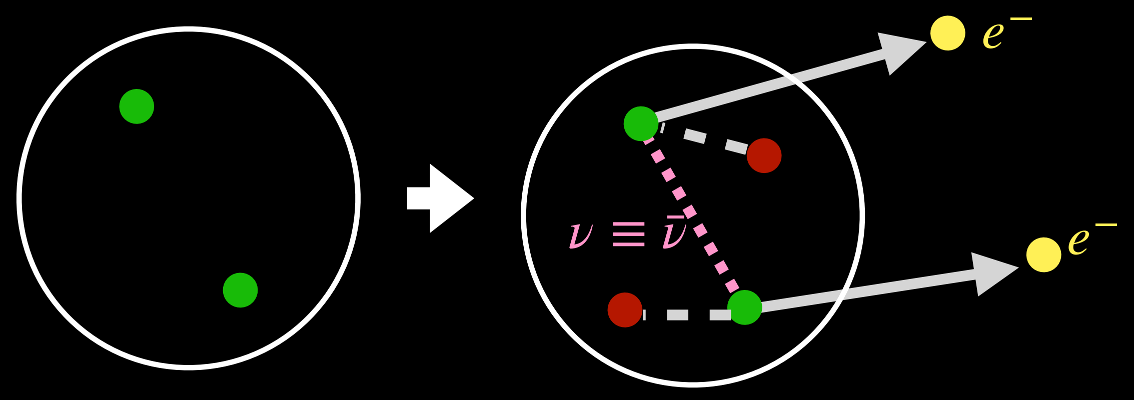
Short-range contribution and huge uncertainties from nuclear theory affect considerably the $m_{\beta\beta}$ sensitivities of next-generation experiments.

Take-home message



The neutrino signal coming from the Supernova neutronization burst, visible only in the ν_e spectrum, constitutes a fundamental tool to constrain the neutrino mass in a model-independent way.

Be prepared and wait for SN20….



Future $0\nu\beta\beta$ setups able to prove or rule out the inverted mass ordering region for many NME models in the light-Majorana neutrino exchange scenario.

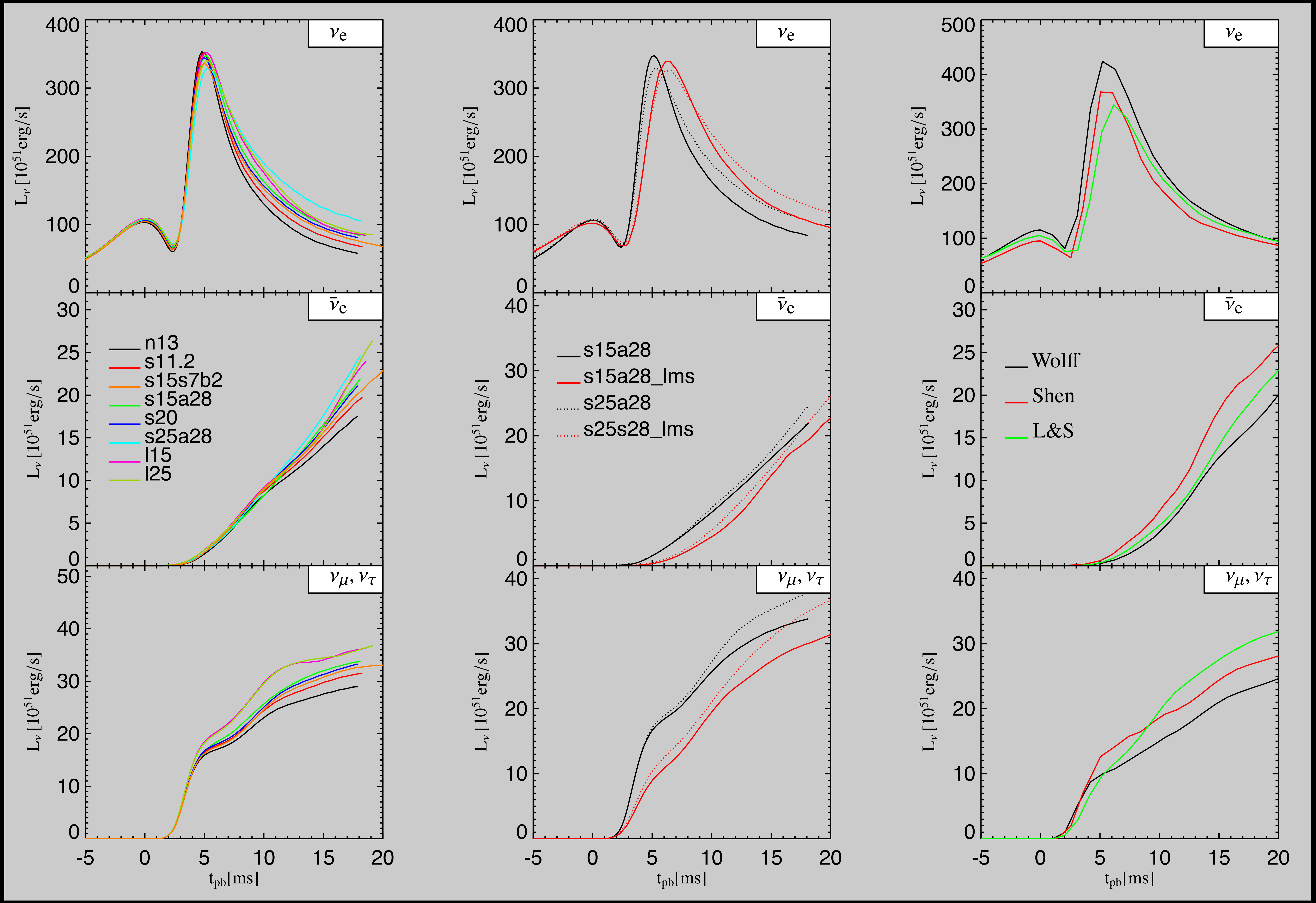
Short-range contribution and huge uncertainties from nuclear theory affect considerably the $m_{\beta\beta}$ sensitivities of next-generation experiments.

New hints from Nuclear Physics!

Backup

Supernova parameters uncertainties: luminosity

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



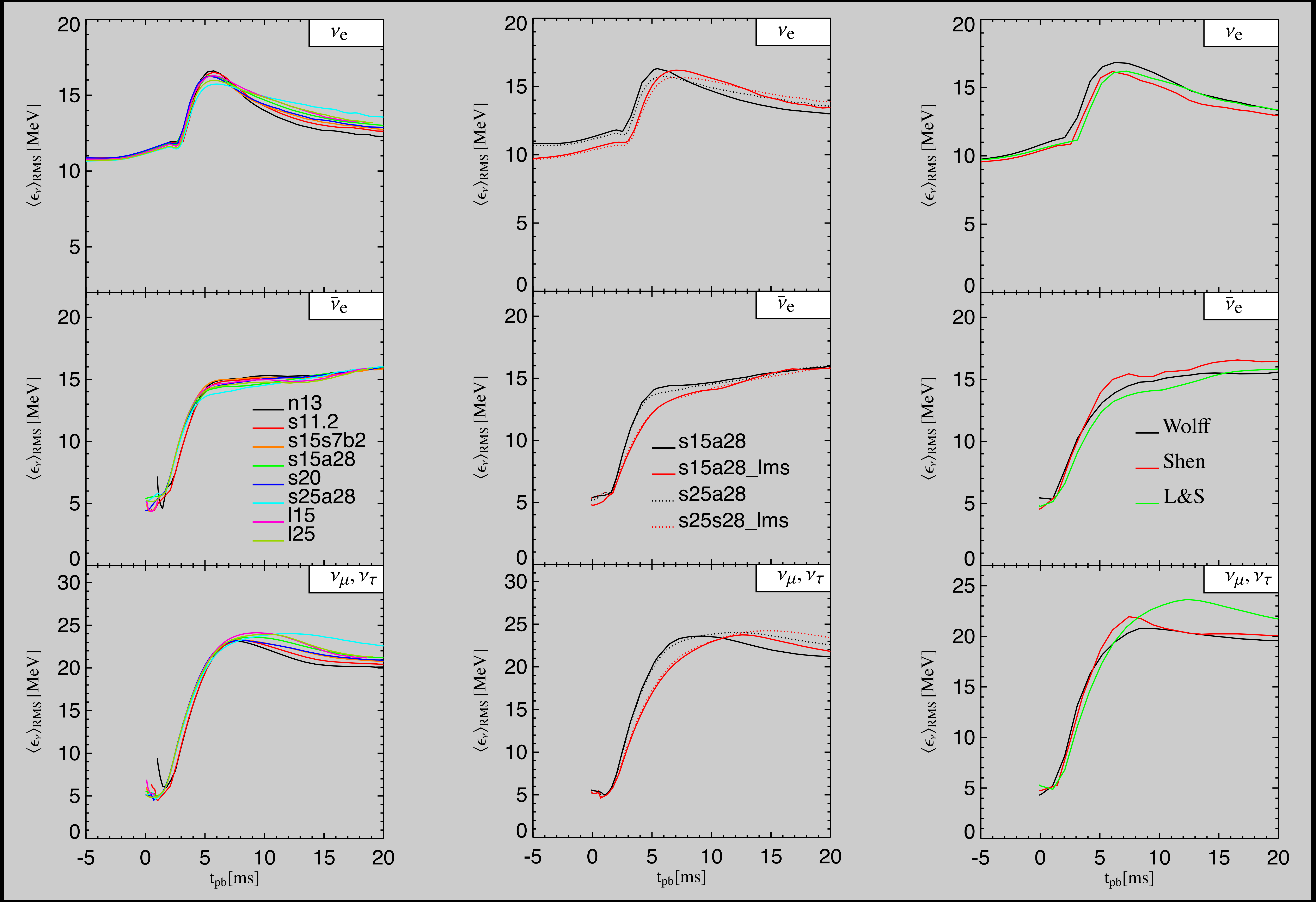
The neutronization burst results to be a robust, **model independent** prediction of the Supernova models.

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)

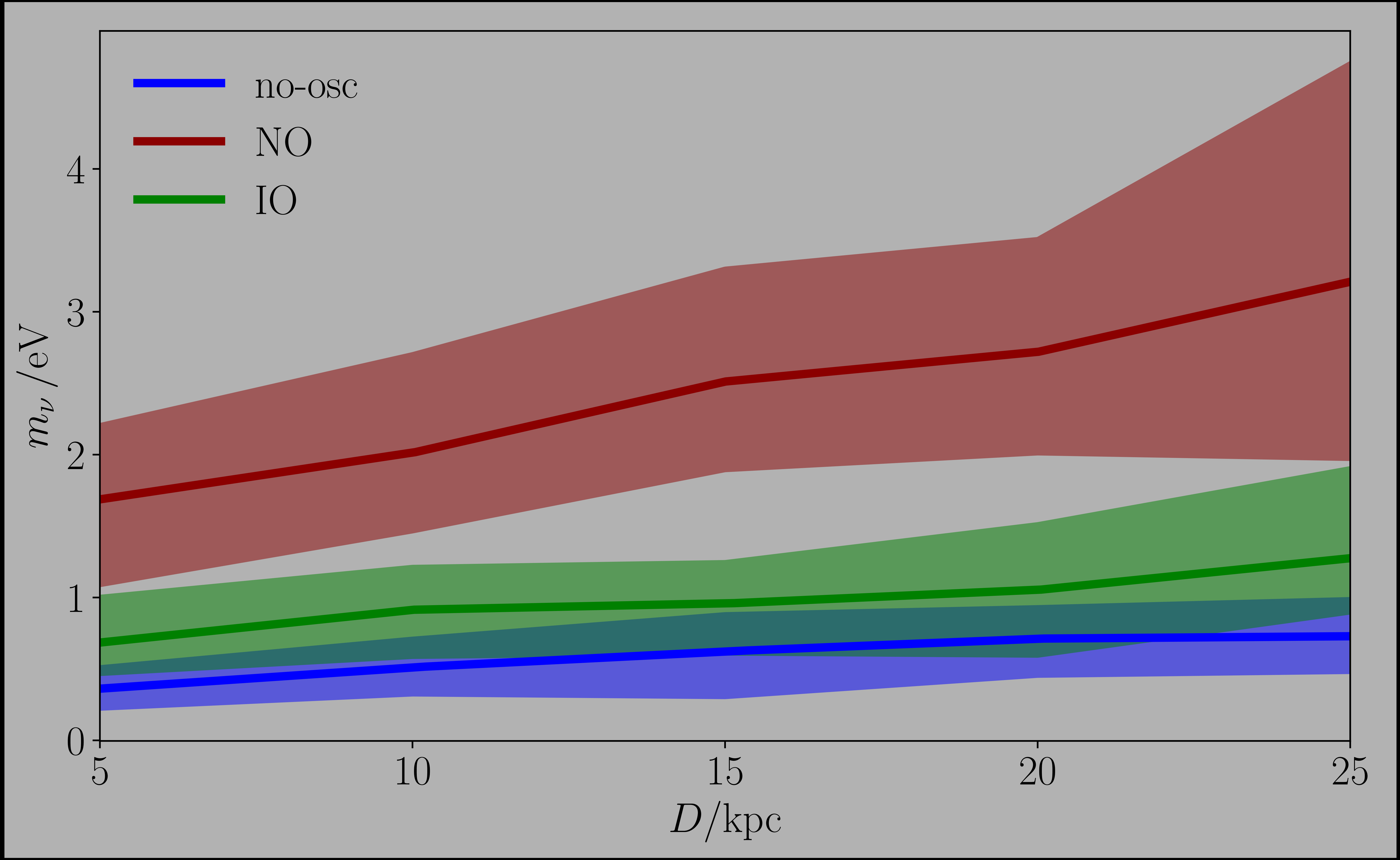


The neutronization burst results to be a robust, **model independent** prediction of the Supernova models.

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

Backup

Dependency on SN distance: $\sim \frac{1}{D^2}$



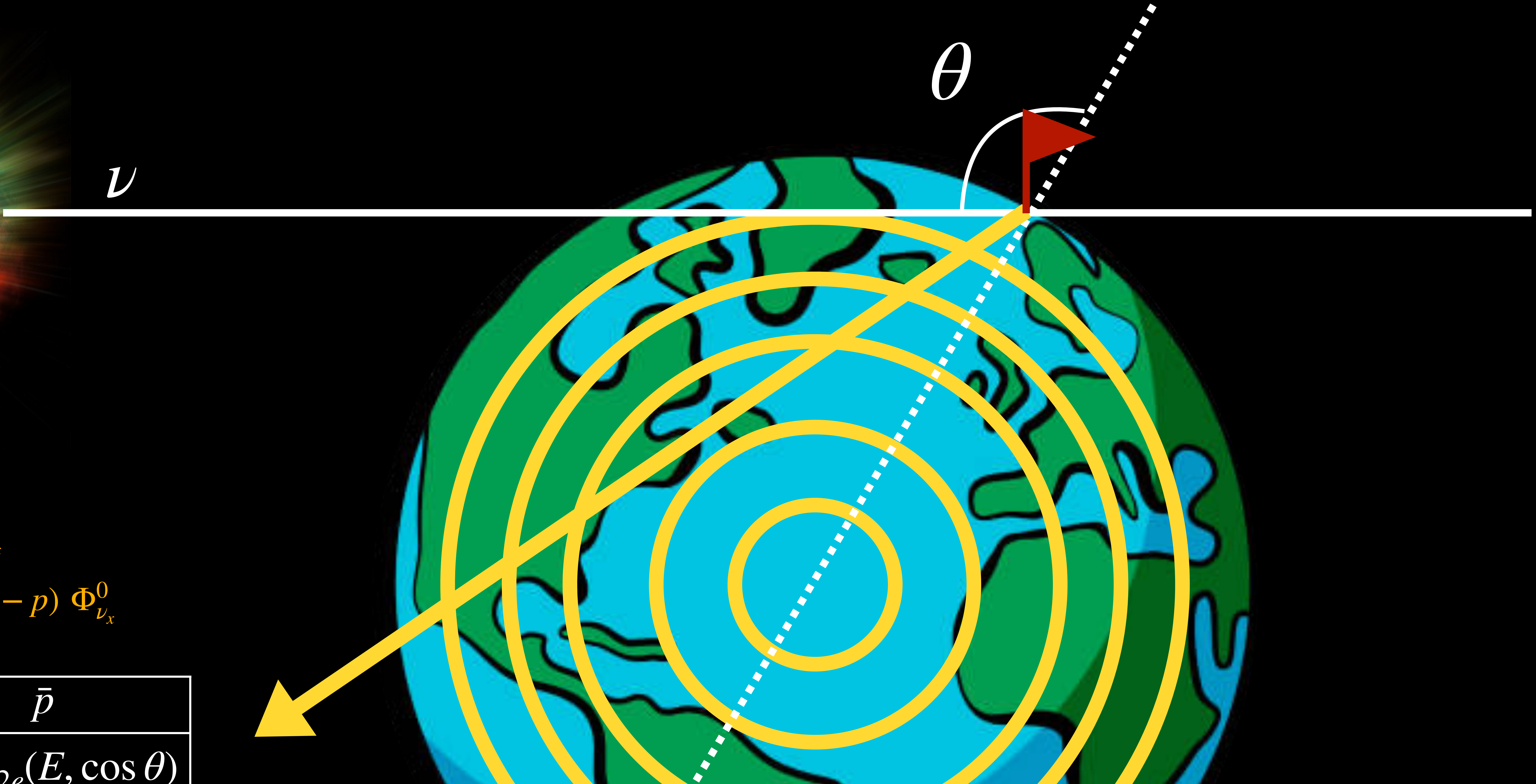
$$\Phi_{\nu_e} = p\ \Phi^0_{\nu_e} + (1-p)\ \Phi^0_{\nu_x}$$

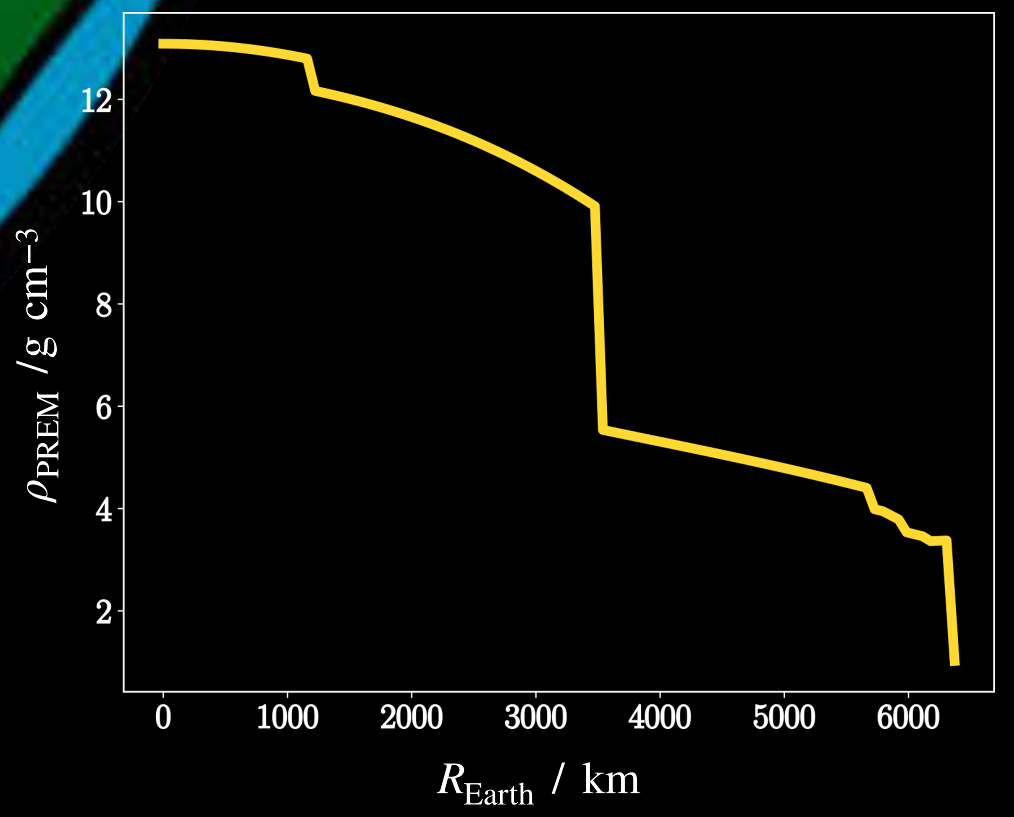
$$\Phi_{\nu_x} = \frac{1}{2}[(1-p)\ \Phi^0_{\nu_e} + (1-p)\ \Phi^0_{\nu_x}$$

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

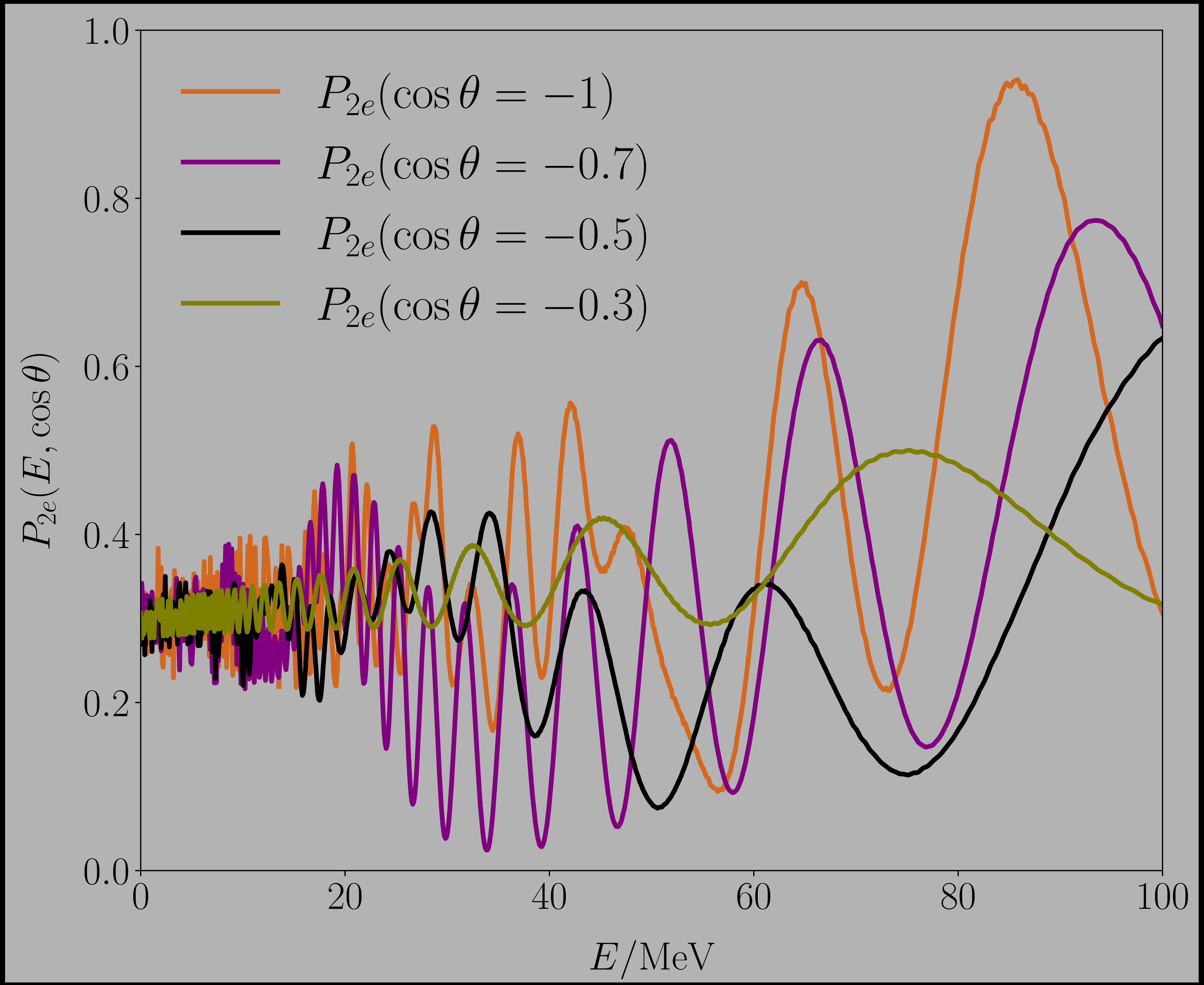
$$P_{2e}(E, \cos\theta) = \mathcal{T}_{e\beta} \cdot U_{e2}$$

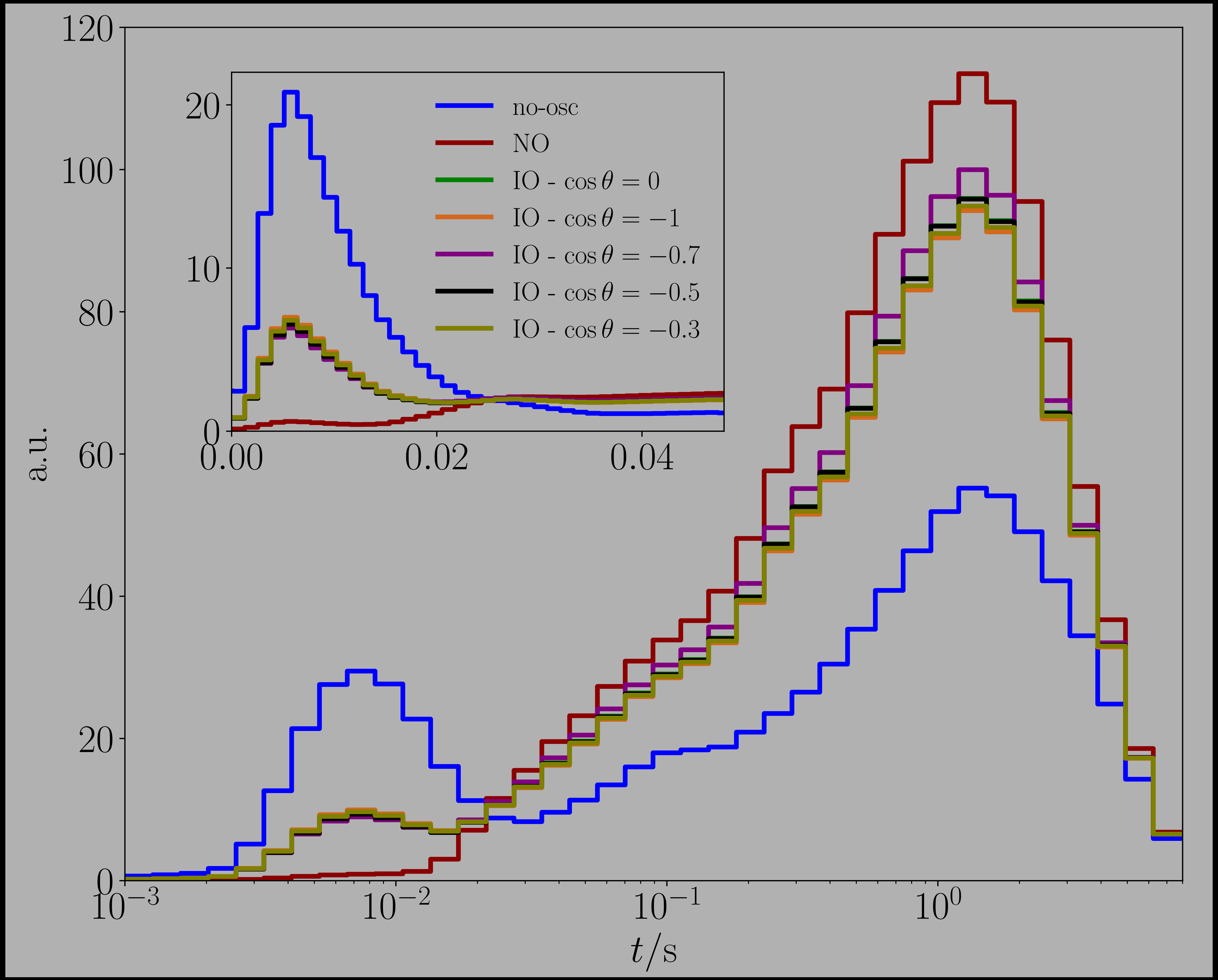
$$\mathcal{T}_{\alpha\beta} = \mathcal{T}(\overline{P_{det}\, P_1})\, \mathcal{T}(\overline{P_1\, P_2}) \cdots \mathcal{T}(\overline{P_M\, P_{prod}})$$





ν_e channel – IO





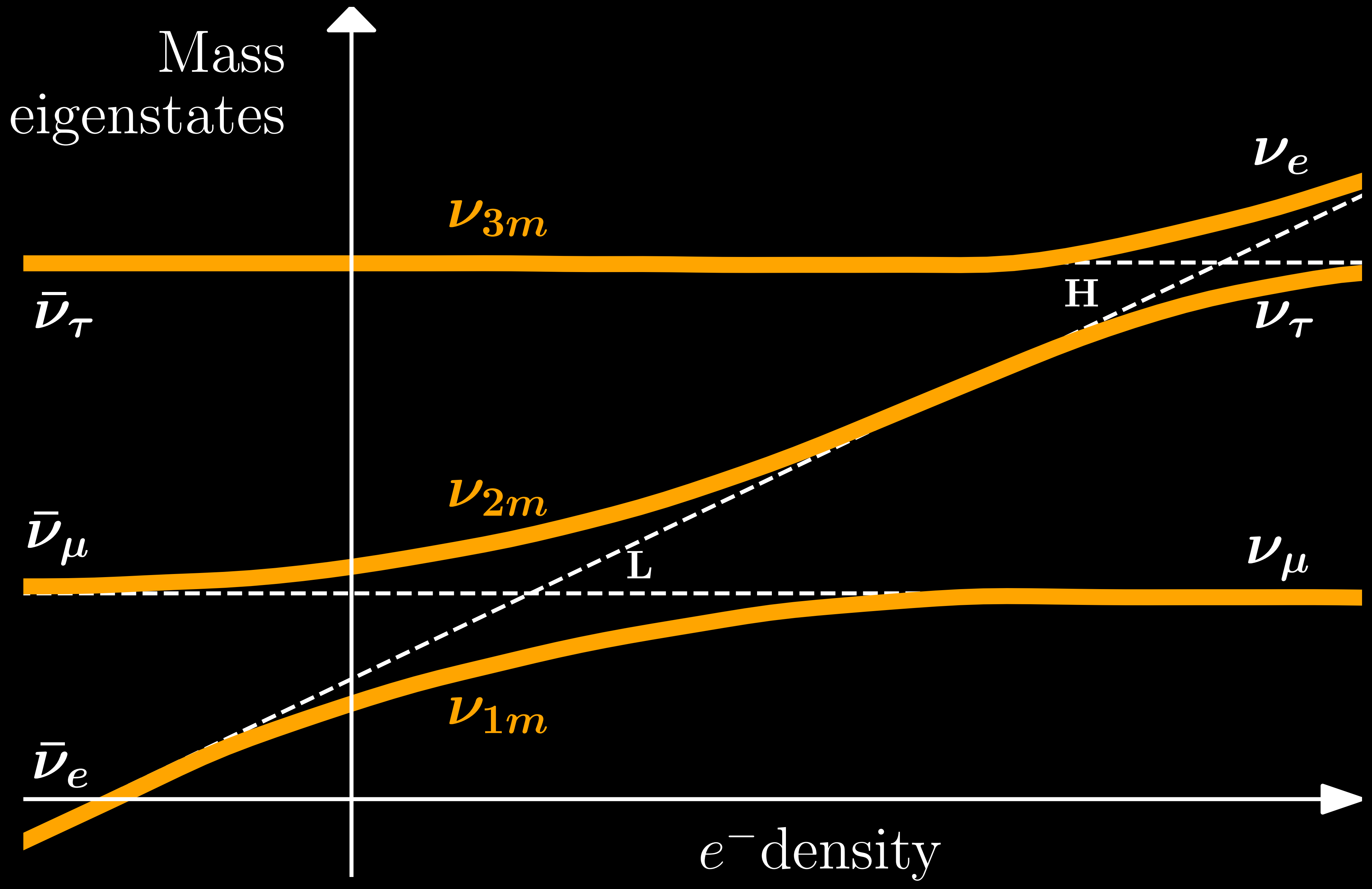
Backup

Mikheyev-Smirnov-Wolfenstein effect

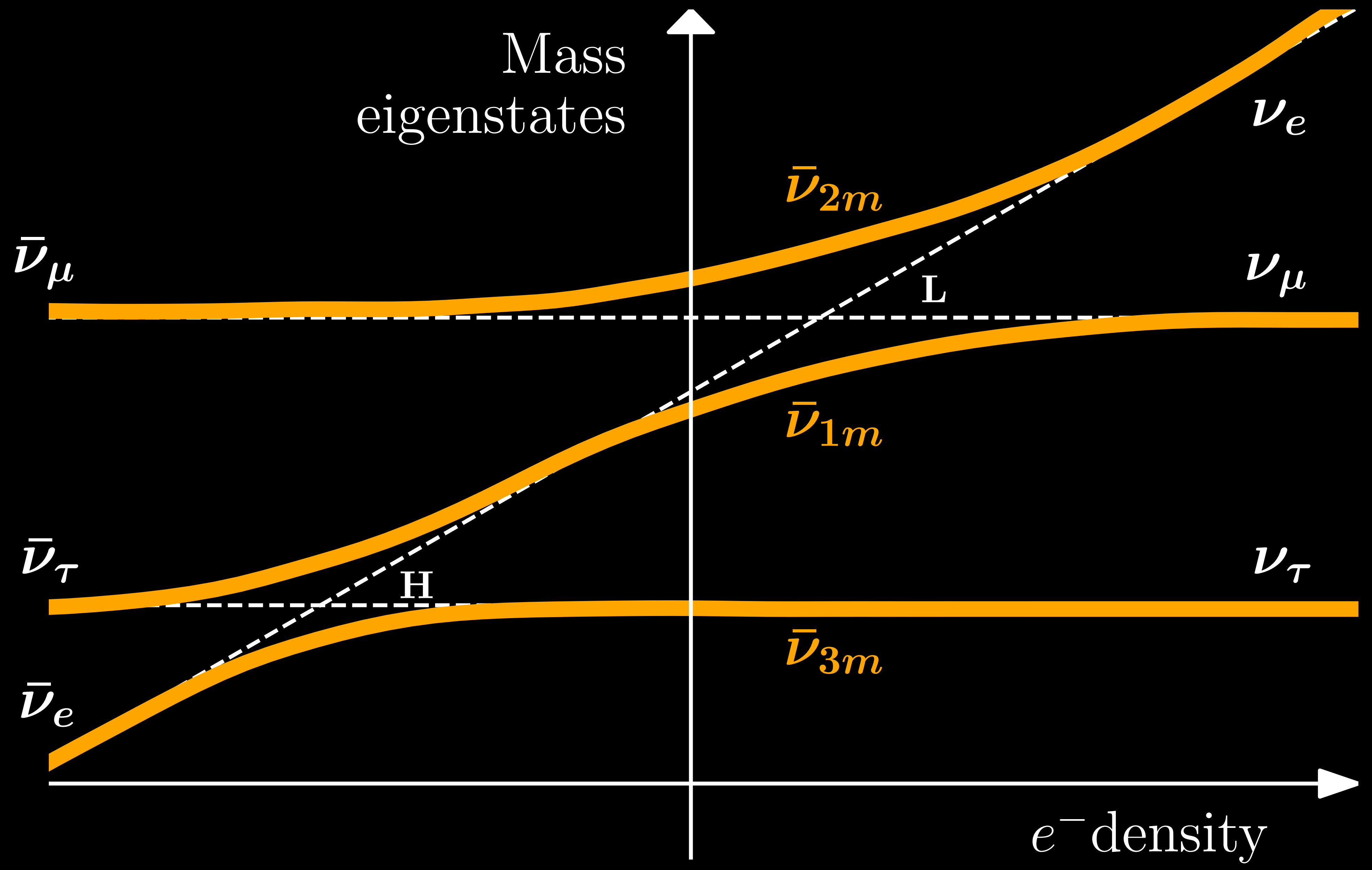
A.S.Dighe,A.Y.Smirnov (PRD 62,033007, 2000)

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

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



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



Current picture

E.Lisi, A.Marrone - Phys.Rev.D 106 (2022) 1, 013009

$$\Delta\chi^2_r(\Gamma_\alpha) = a_r\,(\Gamma_\alpha)^2 + b_r\,\Gamma_\alpha + c_r$$

$$\Gamma_\alpha(m_{\beta\beta}, M_{\alpha i}) = G_{0\nu}\,(\,g_A^2\,|\,M_{0\nu}\,|\,)^2\,m_{\beta\beta}^2$$

↓

$$\chi^2_{\mathrm{tot}}(m_{\beta\beta}) = \sum_r \Delta\chi^2_r(m_{\beta\beta})$$

$$\Delta\chi^2_{\mathrm{tot}}(m_{\beta\beta}) = \chi^2_{\mathrm{tot}}(m_{\beta\beta}) - \chi^2_{\mathrm{tot,min}}(m_{\beta\beta})$$

Future prospect

M.Agostini et all. - Rev.Mod.Phys. 95 (2023) 2, 025002

$$S_{\alpha i}(m_{\beta\beta}, M_{\alpha i}) = \ln 2 \cdot N_A \cdot \varepsilon_\alpha \cdot \left(\frac{T}{1\ \mathrm{yr}}\right) \cdot \widetilde{\Gamma}_\alpha(m_{\beta\beta}, M_{\alpha i})$$

$$B_\alpha = b_\alpha \cdot \varepsilon_\alpha \cdot \left(\frac{T}{1\ \mathrm{yr}}\right)$$

$$[\varepsilon] = \mathrm{mol}\cdot\mathrm{yr} \qquad [b] = \frac{\mathrm{events}}{\mathrm{mol}\cdot\mathrm{yr}} \qquad N_{\alpha i} = S_{\alpha i} + B_\alpha$$

↓

$$\Delta\chi^2_{ij}(m_{\beta\beta}, M_{\alpha j}\,;\,m_{\beta\beta}^{\mathrm{True}}, M_{\alpha i}^{\mathrm{True}}) = 2\sum_\alpha \left(N_{\alpha j} - N_{\alpha i}^{\mathrm{True}} + N_{\alpha i}^{\mathrm{True}} \ln\frac{N_{\alpha i}^{\mathrm{True}}}{N_{\alpha j}}\right)$$

Backup

$$\Delta\chi^2_r(\Gamma_\alpha) = a_r(\Gamma_\alpha)^2 + b_r\Gamma_\alpha + c_r$$

E.Lisi, A.Marrone - Phys.Rev.D 106 (2022) 1, 013009

Nuclide	Experiment	a_r	b_r	c_r	$T^{90}_{1/2}/10^{26}$yr
^{76}Ge	GERDA	0.000	4.871	0.000	1.8
	MAJORANA	0.000	2.246	0.000	0.83
^{130}Te	CUORE	0.257	−0.667	0.433	0.22
^{136}Xe	KamLAND-Zen	14.315	0.000	0.000	2.3
	EXO-200	0.443	−0.342	0.066	0.35

Updated with recent results

Backup

$$S_{\alpha i}(m_{\beta\beta}, M_{\alpha i}) = \ln 2 \cdot N_A \cdot \varepsilon_\alpha \cdot \left(\frac{T}{1\ \text{yr}}\right) \cdot \Gamma_\alpha(m_{\beta\beta}, M_{\alpha i})$$

$$B_\alpha = b_\alpha \cdot \varepsilon_\alpha \cdot \left(\frac{T}{1\ \text{yr}}\right)$$

M.Agostini et all. - Rev.Mod.Phys. 95 (2023) 2, 025002

Experiment	Isotope	ε [mol·yr]	b [events/(mol·y)]	PSF [yr^{-1} eV^{-2}]
LEGEND-1000	^{76}Ge	8736	$4.9 \cdot 10^{-6}$	$2.36 \cdot 10^{-26}$
SuperNEMO	^{82}Se	185	$5.4 \cdot 10^{-3}$	$10.19 \cdot 10^{-26}$
CUPID	^{100}Mo	1717	$2.3 \cdot 10^{-4}$	$15.91 \cdot 10^{-26}$
SNO+II	^{130}Te	8521	$5.7 \cdot 10^{-3}$	$14.2 \cdot 10^{-26}$
nEXO	^{136}Xe	13700	$4.0 \cdot 10^{-5}$	$14.56 \cdot 10^{-26}$