中国科学院高能物理研究所
Institute of High Energy Physics, Chinese Academy of Sciences

TAUP XICHANG

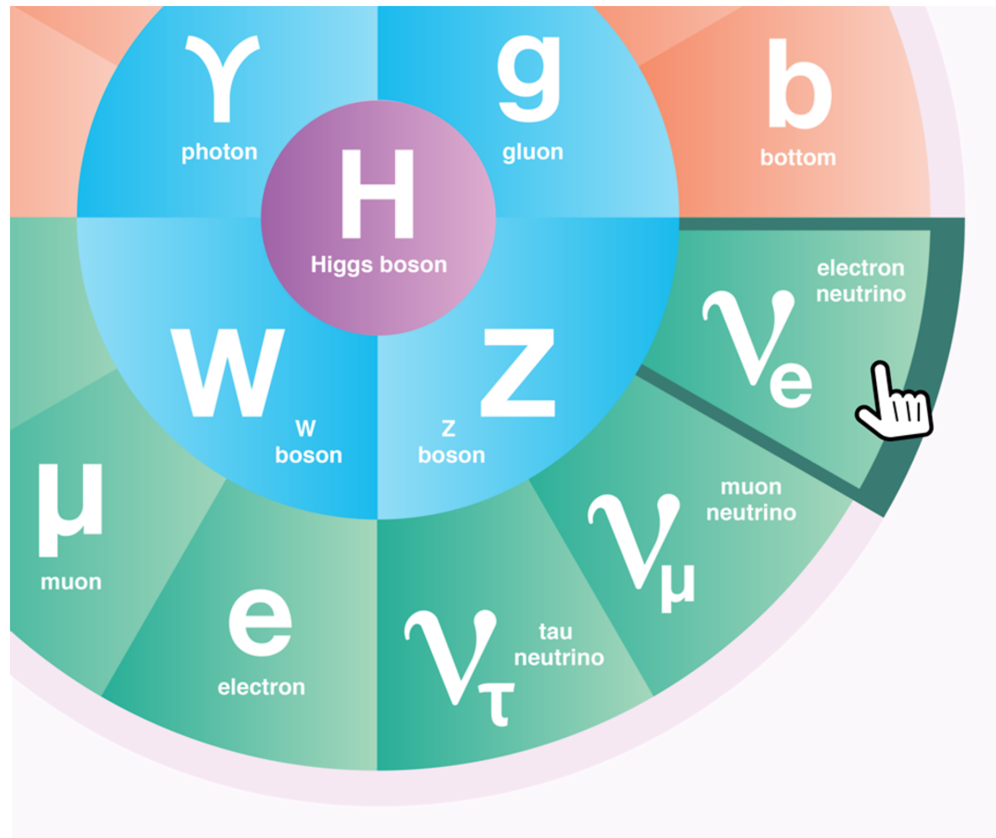
Helicity-changing Decays of Relic Neutrinos and Detections in PTOLEMY-like Experiments

Jihong Huang 黄吉鸿
Institute of High Energy Physics (IHEP)

Based on: JH & Shun Zhou, *JCAP 09 (2024) 067*

The XIX International Conference on Topics in Astroparticle and Underground Physics (TAUP2025)
Xichang, 2025/08/24-30

Neutrino Properties



- ✓ Neutrino oscillation: **massive neutrinos** & **significant leptonic flavor mixing**
- ✳ ***Neutrino mass ordering***: normal mass ordering (NO, $m_1 < m_2 < m_3$) or inverted mass ordering (IO, $m_3 < m_1 < m_2$)?
- ✳ The ***absolute neutrino mass scale*** is still unknown. Neutrino mass origin?
- ✳ ***Dirac** or **Majorana** particles*? Lepton number/flavor violation? (New physics!)

Neutrino Properties

See related reviews:

Neutrino Properties PDF

Sum of Neutrino Masses PDF

$\bar{\nu}$ MASS (electron based)	< 0.8 eV CL=90%
$\bar{\nu}$ MASS SQUARED (electron based)	0.08 ± 0.30 eV^2
ν MASS (electron based)	
ν MASS (muon based)	<0.19 MeV CL=90%
ν MASS (tau based)	<18.2 MeV CL=95%
SUM OF THE NEUTRINO MASSES, m_{tot}	
Limits on MASSES of Light Stable Right-Handed ν (with necessarily suppressed interaction strengths)	
Limits on MASSES of Heavy Stable Right-Handed ν (with necessarily suppressed interaction strengths)	
ν CHARGE	
ν (MEAN LIFE) / MASS	
ν MAGNETIC MOMENT	$\times 10^{-12}$ μ_B CL=90%
NEUTRINO CHARGE RADIUS SQUARED	-2.10×10^{-32} to 3.30×10^{-32} cm^2 CL=90%

upper bound...

neutrino mean life

μ $J = 1/2$

very precise!

μ MASS (atomic mass units u)		$0.1134289259 \pm 0.0000000025$ u
μ MASS	[1]	$105.6583755 \pm 0.0000023$ MeV
μ MEAN LIFE τ		$(2.1969811 \pm 0.0000022) \times 10^{-6}$ s
$\tau_{\mu^+}/\tau_{\mu^-}$ MEAN LIFE RATIO		1.00002 ± 0.00008
$(\tau_{\mu^+} - \tau_{\mu^-})/\tau_{\text{average}}$		$(2 \pm 8) \times 10^{-5}$
μ/p MAGNETIC MOMENT RATIO		$3.18334514 \pm 0.00000007$
▸ μ MAGNETIC MOMENT ANOMALY		
$(g_{\mu^+} - g_{\mu^-})/g_{\text{average}}$		$(-1.1 \pm 1.2) \times 10^{-9}$
μ ELECTRIC DIPOLE MOMENT (d)		$< 1.8 \times 10^{-19}$ e cm CL=95%
MUON-ELECTRON CHARGE RATIO ANOMALY $q_{\mu^+}/q_{e^-} + 1$		$(1.1 \pm 2.1) \times 10^{-9}$

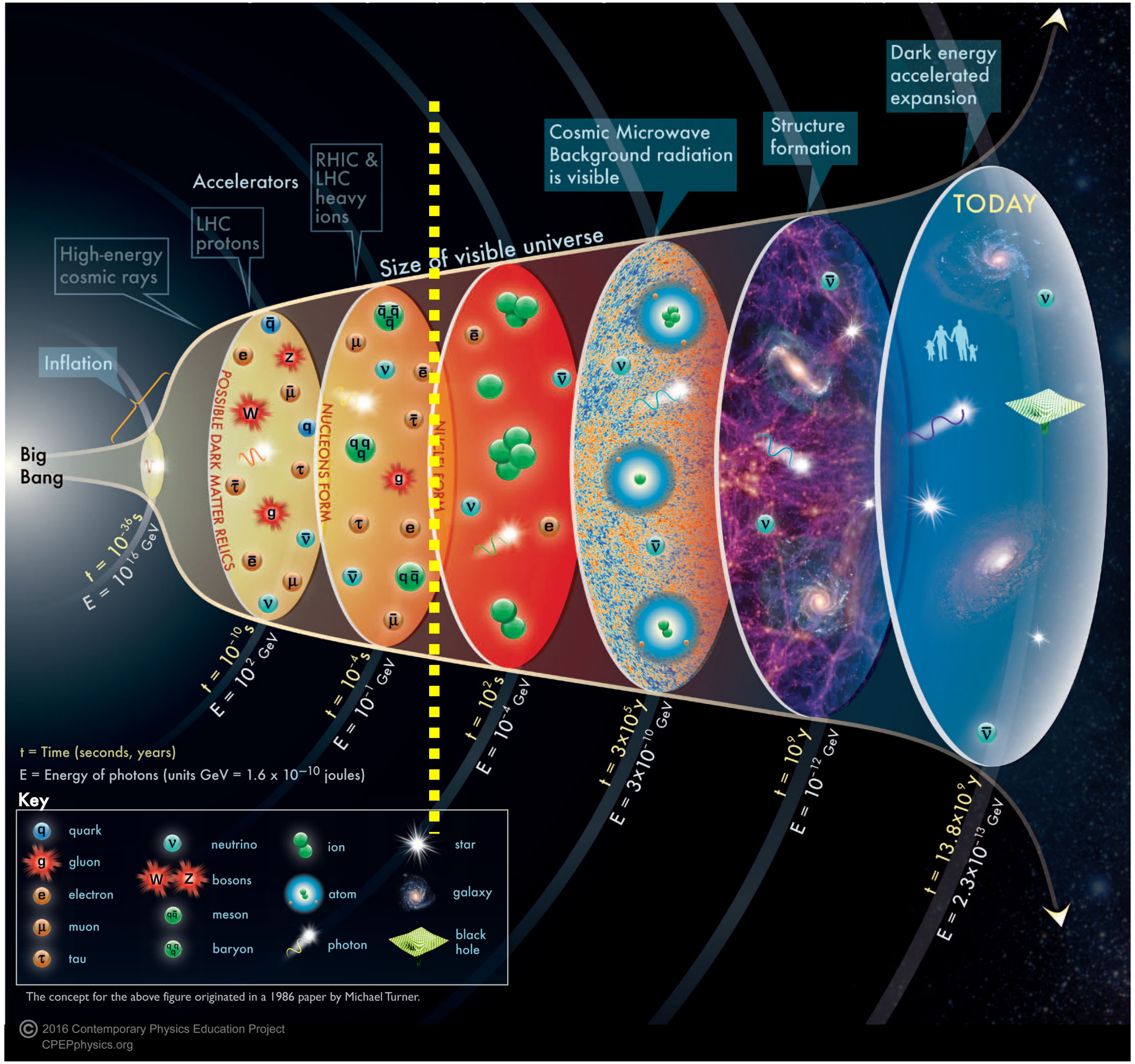
μ^- DECAY MODES

μ^+ modes are charge conjugates of the modes below.

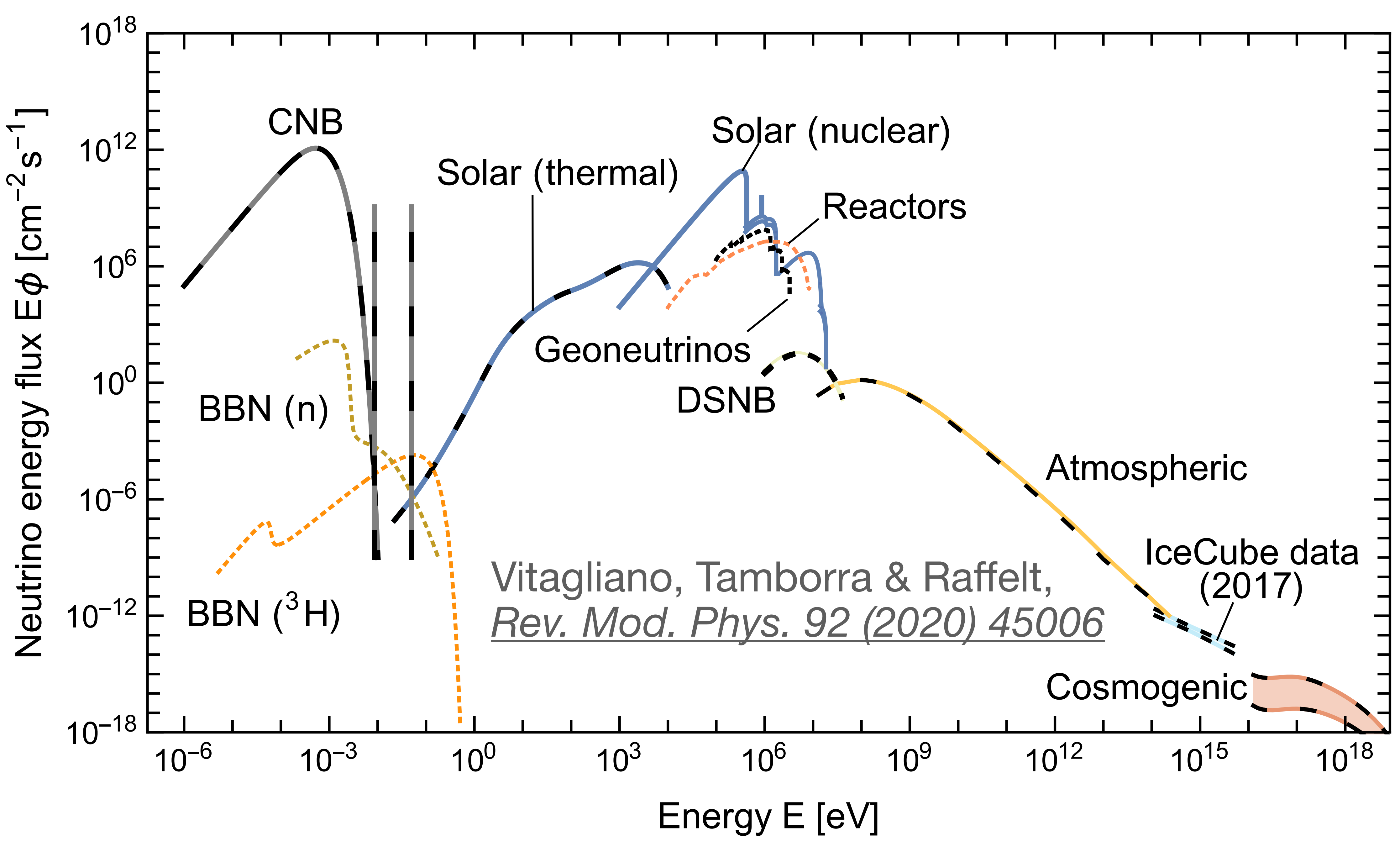
	Mode		Fraction (Γ_i/Γ)	Scale Factor/ Conf. Level	P(MeV/c)
Γ_1	$e^-\bar{\nu}_e\nu_\mu$		~ 100 %		53
Γ_2	$e^-\bar{\nu}_e\nu_\mu\gamma$	[3]	$(6.0 \pm 0.5) \times 10^{-8}$		53
Γ_3	$e^-\bar{\nu}_e\nu_\mu e^+ e^-$	[4]	$(3.4 \pm 0.4) \times 10^{-5}$		53

▸ Lepton Family number (LF) violating modes

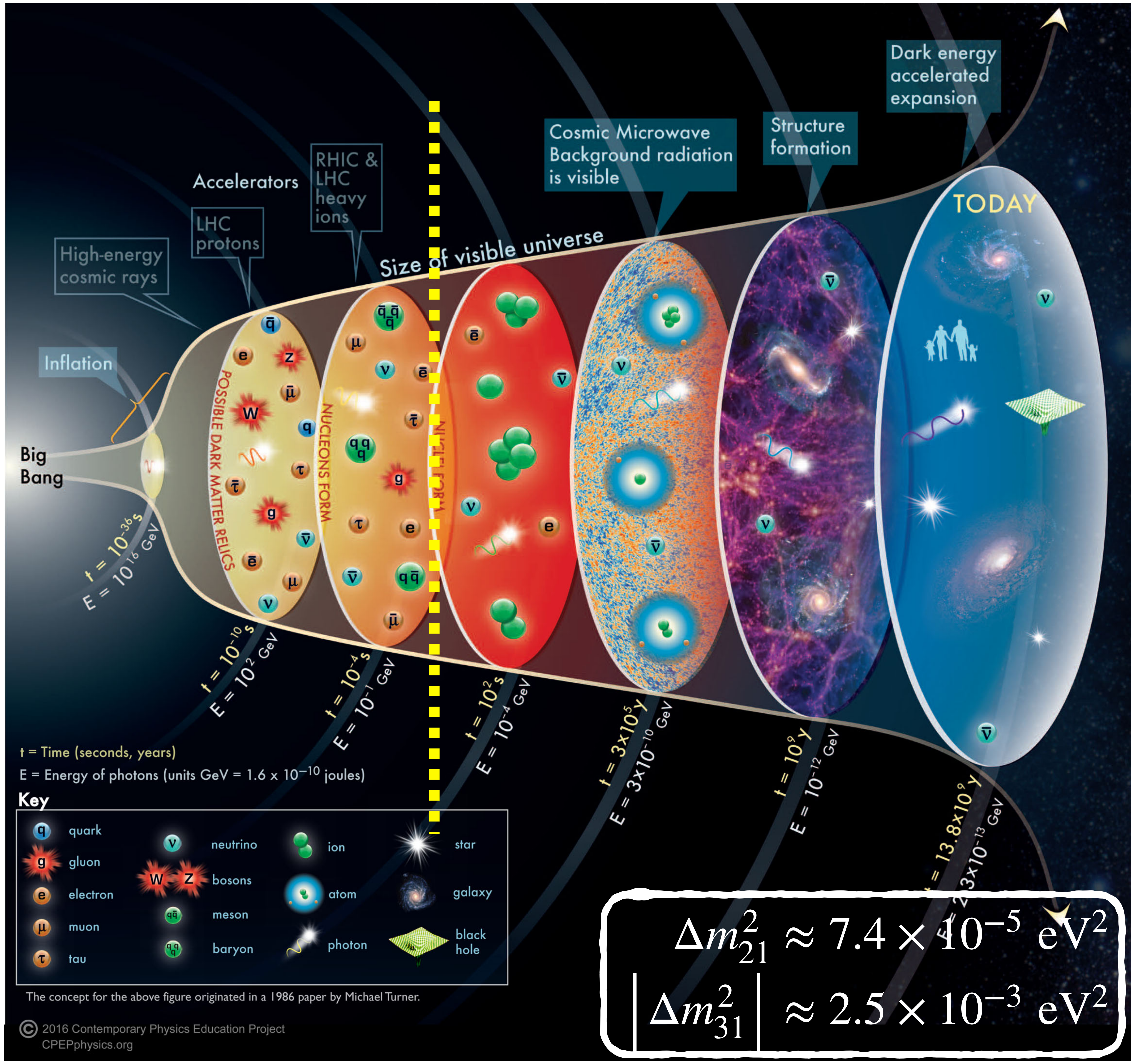
Relic Neutrinos



- ✓ Neutrinos decoupled @ the **1st** sec.
- ✓ A **non-relativistic** neutrino source
- ✓ Reveal neutrinos' intrinsic properties



Relic Neutrinos



$$\Delta m^2_{21} \approx 7.4\times10^{-5}\ \text{eV}^2$$
$$\left|\Delta m^2_{31}\right| \approx 2.5\times10^{-3}\ \text{eV}^2$$

✓ Neutrinos decoupled @ the **1st** sec.

✓ A **non-relativistic** neutrino source

✓ Reveal neutrinos' intrinsic properties

- ***Number density*** *per flavor per helicity*

$$n_{C\nu B} \approx 56\left(\frac{T_\gamma}{2.726\ \text{K}}\right)\ \text{cm}^{-3}$$

- ***Temperature*** *today*

$$T_{C\nu B} \approx 1.95\ \text{K} \sim 0.168\ \text{meV}$$

- *Average momentum* $\langle p_\nu \rangle \approx 0.5\ \text{meV}$

At least two mass states are non-relativistic!

Detection CνB with Tritium

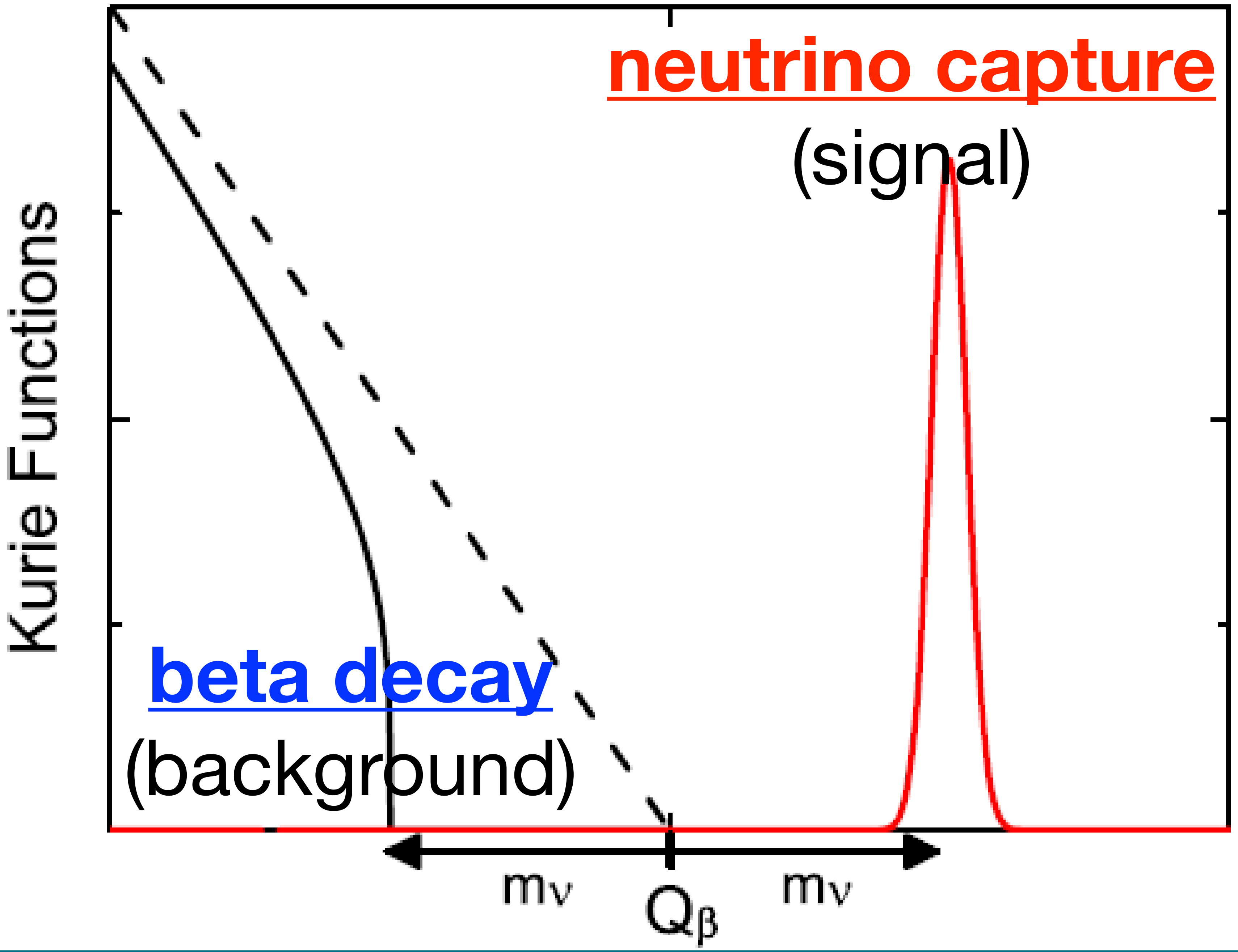
PHYSICAL REVIEW VOLUME 128, NUMBER 3 NOVEMBER 1, 1962

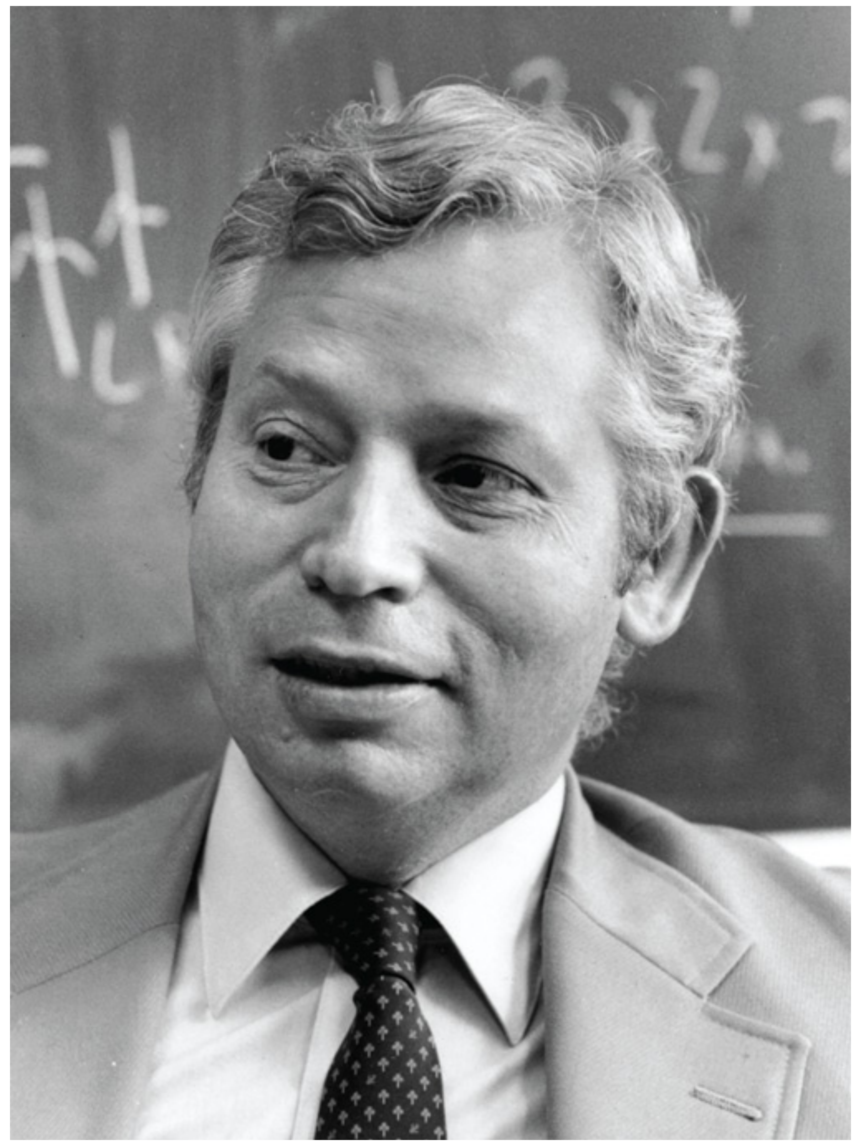
Universal Neutrino Degeneracy

STEVEN WEINBERG*
Imperial College of Science and Technology, London, England
(Received March 22, 1962)

200+ citations

It would evidently be very worthwhile to do a counter experiment specifically designed to look for electrons with energies just above the end point in a β^- decay. Tritium might be preferable because of background problems and because it has an accurately known end point; a decay process with a higher Q value would give more counts above the end point, though a smaller proportion. For tritium $Q=17.95$ keV and the half-life is 12.5 yr, so (using 144) the number of events above the end point per gram of tritium is 76/sec if $E_F=1$ eV. It varies as $E_F{}^3$ (and for other decays roughly as Q^2). The limiting factor on such an experiment is energy resolution and our imperfect knowledge of β^- end points rather than the rarity of absorption events. Probably it

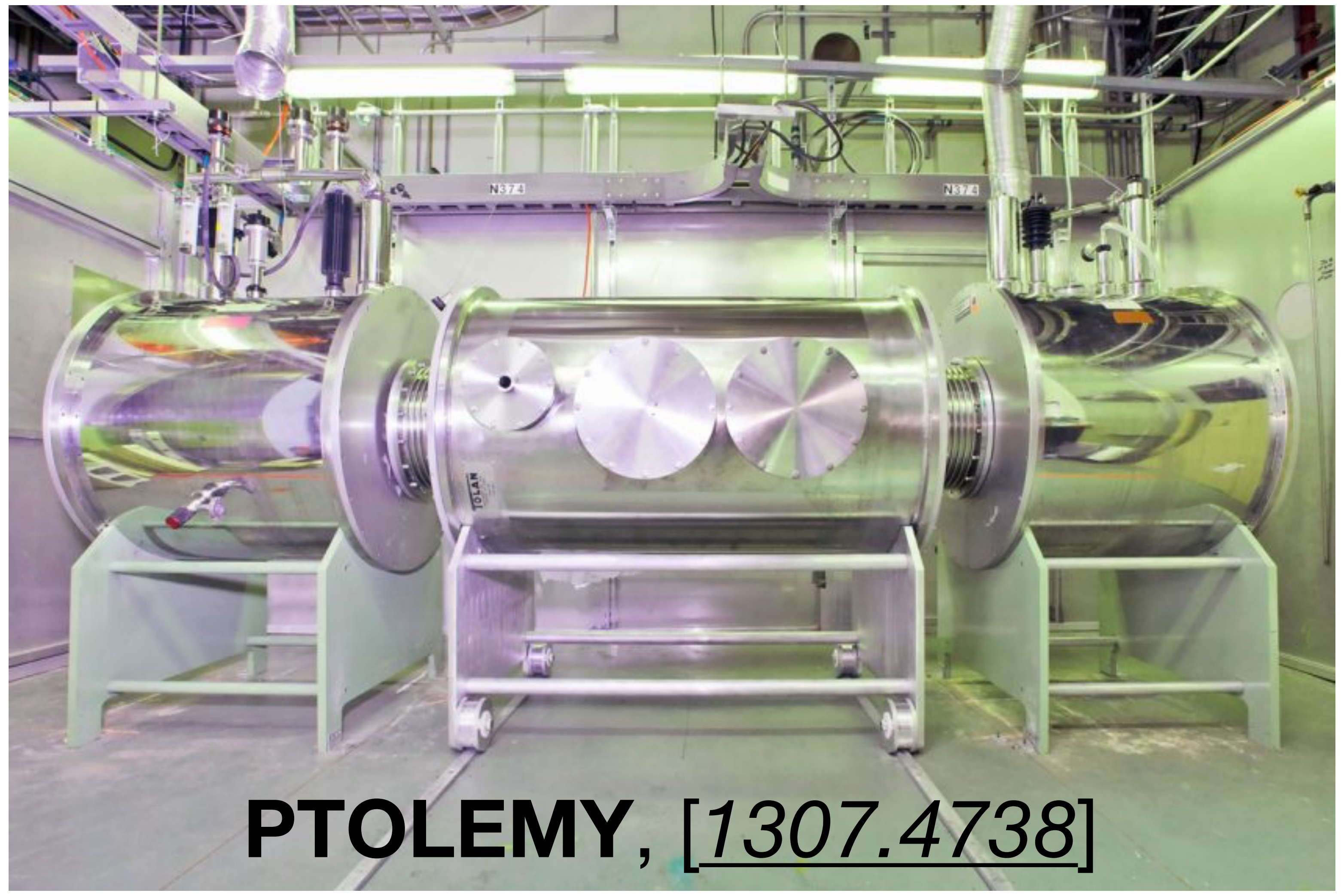




Steven Weinberg
(1933~2021)

- ✤ Measuring ***neutrino absolute mass scale*** from tritium decay $^3H \rightarrow {}^3He + e^- + \bar{\nu}_e$
- ★ ***Detecting cosmic relic neutrinos*** through the tritium capture $\nu_e + {}^3H \rightarrow {}^3He + e^-$
- ✓ ***No energy threshold*** (vs 1.8 MeV for IBD), suitable for non-relativistic neutrino case

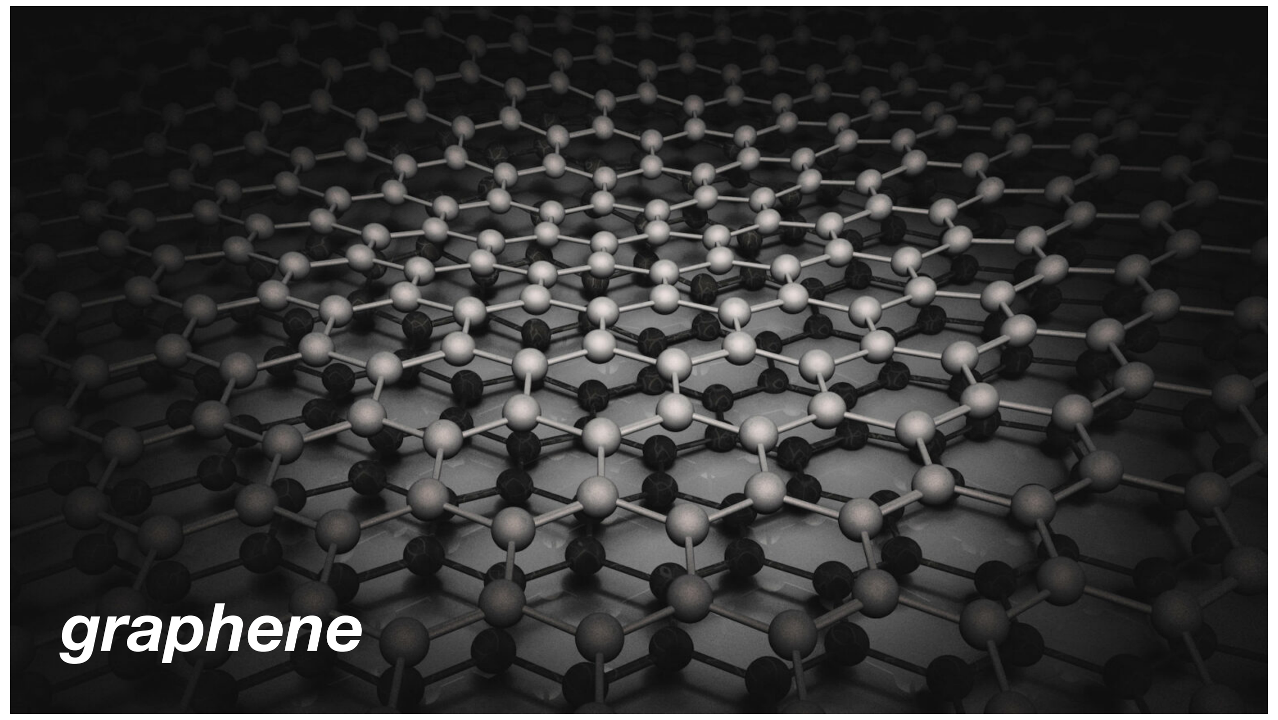
Capture Rates of CνB



Princeton **T**ritium **O**bservatory for **L**ight, **E**arly-Universe, **M**assive-Neutrino **Y**ield (**PTOLEMY**)

- *Capture Rates:* Long, Lunardini & Sabancilar, *JCAP 08 (2014) 038*

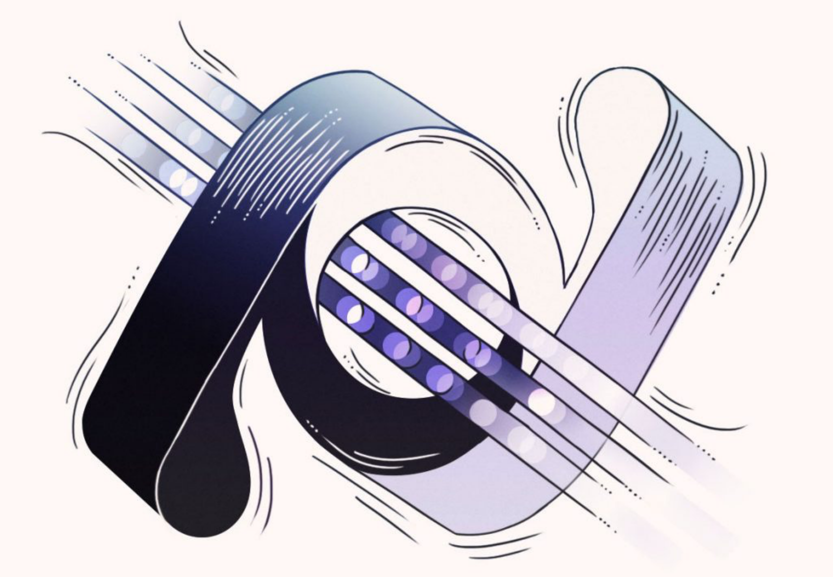
$$\Gamma_{\mathrm{C}\nu\mathrm{B}} = N_{\mathrm{T}} \bar{\sigma} \sum_{s_i = \pm 1/2} \sum_{i=1}^{3} \left| U_{ei} \right|^2 n_i(s_i) \mathscr{A}(s_i)$$



- *Number of tritium nuclei* in the target (100 g tritium) $N_{\mathrm{T}} \approx 2 \times 10^{25}$
- *Cross section* $\bar{\sigma} \approx 3.8 \times 10^{-45}\ \mathrm{cm}^2$
- $\mathscr{A}(s_i) \equiv 1 - 2 s_i \beta_i = \begin{cases} 1 - \beta_i & s_i = +1/2 \\ 1 + \beta_i & s_i = -1/2 \end{cases}$

✓ ***Helicity ?!***

✓ ***Velocity ?!***



$\Gamma^{\mathrm{D}}_{\mathrm{C}\nu\mathrm{B}} \approx 4\ \mathrm{yr}^{-1}$

$\Gamma^{\mathrm{M}}_{\mathrm{C}\nu\mathrm{B}} \approx 8\ \mathrm{yr}^{-1}$

A factor of 2 !

(distinguish D or M)

$\Gamma^{\mathrm{D}}_{\mathrm{C}\nu\mathrm{B}} \approx 7\ \mathrm{yr}^{-1}$ for NO

considering velocity distribution

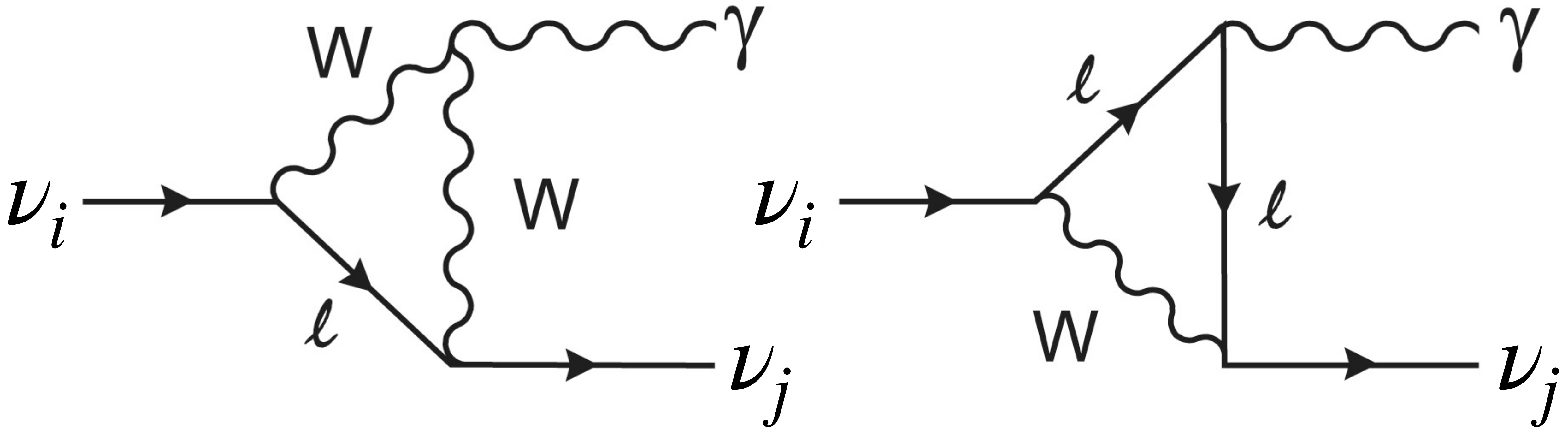
Roulet & Vissani, *JCAP 10 (2018) 049*

Neutrino Decays

It is interesting to investigate whether ***a heavier neutrino*** *can* ***decay*** *into* ***a lighter one*** *and other elementary particles within or beyond the SM.*

Radiative decays: $\nu_i \to \nu_j + \gamma$

$$\Gamma\left(\nu_i \to \nu_j + \gamma\right) = 5.3\ \mathrm{s}^{-1}\left(1-\frac{m_j^2}{m_i^2}\right)^3\left(\frac{m_i}{1\ \mathrm{eV}}\right)^3\left(\frac{\mu_{\mathrm{eff}}}{\mu_{\mathrm{B}}}\right)^2$$



- ***Effective magnetic dipole moment***

$$\mu_{\mathrm{eff}} \approx 10^{-23}\mu_{\mathrm{B}}$$

➡ Neutrino lifetime $\tau_\nu \approx 10^{49}$ s, ***MUCH LONGER*** than the age of the Universe $t_0 \approx 4 \times 10^{17}$ s

Direct decays: $\nu_i \to \nu_j + \phi$

Neutrinos can interact with the Nambu-Goldstone boson, the **Majoron**, to explain the neutrino mass origin (***Majoron model***).

$$\mathcal{L}_{\mathrm{M}} = \frac{1}{2}\sum_i \left(\overline{\nu_i}\mathrm{i}\partial\!\!\!/\nu_i - m_i\overline{\nu_i}\nu_i\right) + \frac{1}{2}\partial_\mu\phi\partial^\mu\phi - \left[\mathrm{i}\phi\sum_{i,j} g_{ij}\overline{\nu_i}\gamma^5\nu_j + \mathrm{h.c.}\right]$$

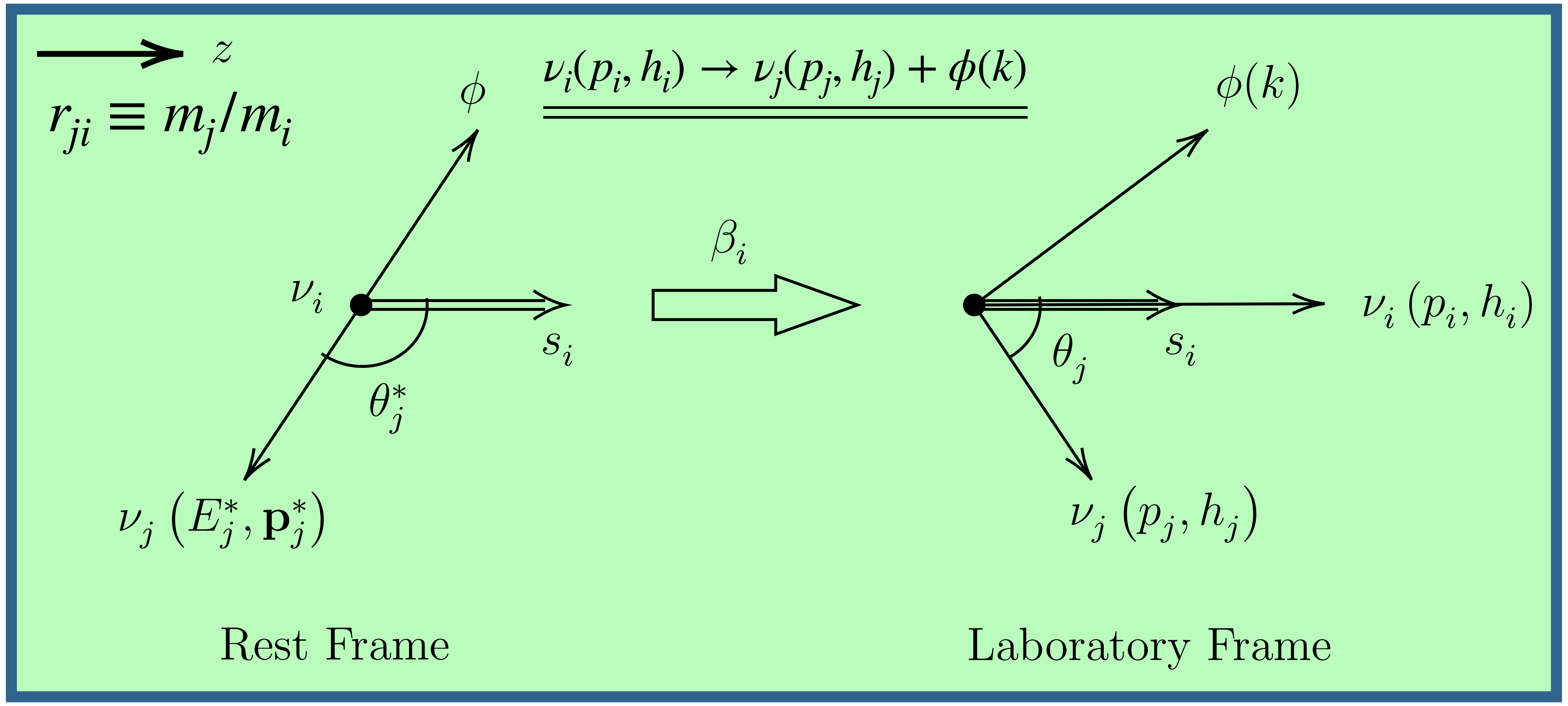
- **Dirac case**: $\nu_i \to \nu_j + \phi$ and $\overline{\nu}_i \to \overline{\nu}_j + \phi$
- The decay *amplitudes* for Majorana neutrinos are ***twice*** that for Dirac ones.

Neutrino Invisible Decays

Direct decays: $\nu_i \to \nu_j + \phi$

Neutrinos can interact with the Nambu-Goldstone boson, the **Majoron**, to explain the neutrino mass origin (***Majoron model***).

$$\mathcal{L}_{\mathrm{M}} = \frac{1}{2}\sum_i \left(\overline{\nu_i}\mathrm{i}\partial\!\!\!/\nu_i - m_i\overline{\nu_i}\nu_i\right) + \frac{1}{2}\partial_\mu\phi\partial^\mu\phi - \left[\mathrm{i}\phi\sum_{i,j} g_{ij}\overline{\nu_i}\gamma^5\nu_j + \mathrm{h.c.}\right]$$



Modern Physics Letters A Vol. 5, No. 5 (1990) 297–299

SOME REMARKS ON NEUTRINO DECAY VIA A NAMBU-GOLDSTONE BOSON

C. W. KIM and W. P. LAM
Department of Physics and Astronomy, Johns Hopkins University, Baltimore, MD 21218, USA

Received 30 August 1989

$$\Gamma(\nu_2 \to \nu_1) = \frac{m_1 m_2}{16\pi E_2}\left[g_1^2\left(\frac{x}{2} + 2 + \frac{2}{x}\log x - \frac{2}{x^2} - \frac{1}{2x^3}\right)\right.$$

$$\left. + g_2^2\left(\frac{x}{2} - 2 + \frac{2}{x}\log x + \frac{2}{x^2} - \frac{1}{2x^3}\right)\right]$$

relativistic limit
$E \gg m$

$$\Gamma(\nu_2 \to \overline{\nu}_1) = \frac{m_1 m_2}{16\pi E_2}\left[(g_1^2 + g_2^2)\left(\frac{x}{2} - \frac{2}{x}\log x - \frac{1}{2x^3}\right)\right] \qquad \left(x = \frac{m_2}{m_1}\right).$$

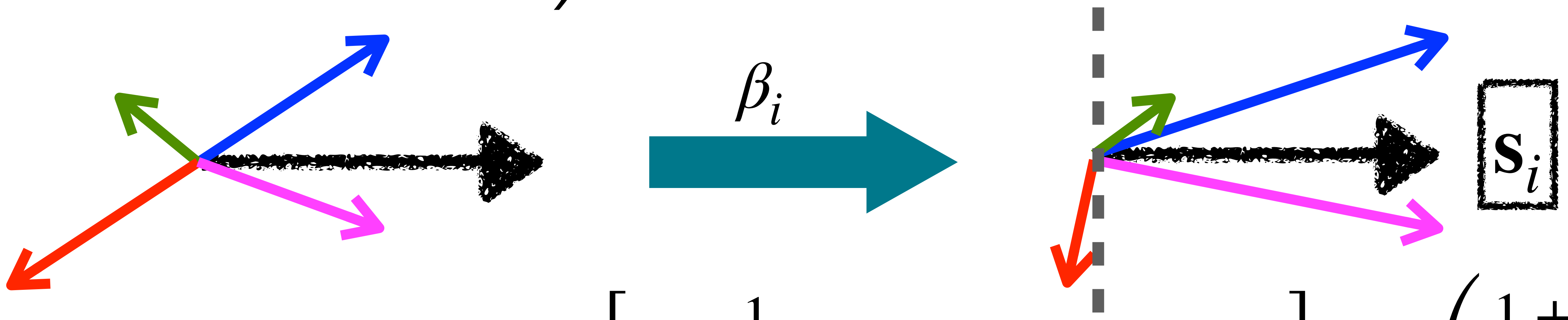
also see: Funcke, Raffelt & Vitagliano, *PRD 101 (2020) 1, 015025*

Decay amplitudes (with specific helicities) $\Longrightarrow$ ***Amplitude squared*** $\Longrightarrow$ ***Decay rates***

Total Decay Rates

Total decay rates *(the most general* ***for the first time****)*

① *For* $\beta_i \leqslant \beta_{ji}^* \equiv (1 - r_{ji}^2)/(1 + r_{ji}^2)$



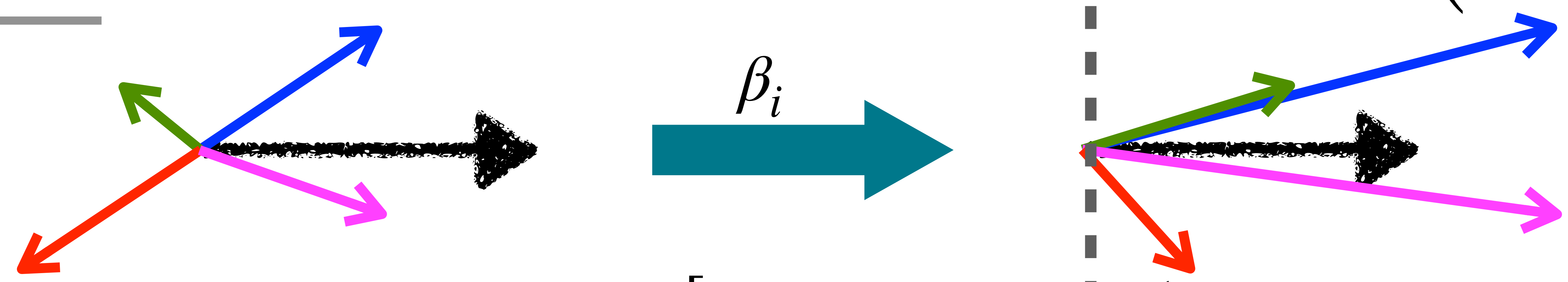
- *Helicity-preserving:*

$$\Gamma^{\rm M}_{\pm\pm,ij} = \frac{g_{ij}^2 m_i}{4\pi}\sqrt{1-\beta_i^2}\left\{\frac{1}{2}\left(1-r_{ji}^2\right)(1-r_{ji})^2 - (1+r_{ji}+r_{ji}^2)r_{ji}\beta_i^{-1} + \left[r_{ji} + \frac{1}{2}(\beta_i^{-2}-1)(1+r_{ji}+r_{ji}^2)\right] r_{ji}\ln\left(\frac{1+\beta_i}{1-\beta_i}\right)\right\}$$

- *Helicity-changing:*

$$\Gamma^{\rm M}_{\pm\mp,ij} = \frac{g_{ij}^2 m_i}{4\pi}\sqrt{1-\beta_i^2}\left\{\frac{1}{2}\left(1-r_{ji}^2\right)(1-r_{ji})^2 + (1+r_{ji}+r_{ji}^2)r_{ji}\beta_i^{-1} - \left[r_{ji} + \frac{1}{2}(\beta_i^{-2}-1)(1+r_{ji}+r_{ji}^2)\right] r_{ji}\ln\left(\frac{1+\beta_i}{1-\beta_i}\right)\right\}$$

② *For* $\beta_i > \beta_{ji}^* \equiv (1 - r_{ji}^2)/(1 + r_{ji}^2)$



- *Helicity-preserving:*

$$\Gamma^{\rm M}_{\pm\pm,ij} = \frac{g_{ij}^2 m_i}{4\pi}\sqrt{1-\beta_i^2}\left\{\frac{1}{2}\left(1-r_{ji}^2\right)(1-r_{ji})^2 - r_{ji}(1-r_{ji}^2) - 2r_{ji}^2\ln r_{ji} - (\beta_i^{-2}-1)\left[(1+r_{ji}+r_{ji}^2)r_{ji}\ln r_{ji} + \frac{1}{4}(1-r_{ji}^2)(1+4r_{ji}+r_{ji}^2)\right]\right\}$$

- *Helicity-changing:*

Consistent with previous results in the relativistic limit, i.e., $\beta_i \to 1$

$$\Gamma^{\rm M}_{\pm\mp,ij} = \frac{g_{ij}^2 m_i}{4\pi}\sqrt{1-\beta_i^2}\left\{\frac{1}{2}\left(1-r_{ji}^2\right)(1-r_{ji})^2 + r_{ji}(1-r_{ji}^2) + 2r_{ji}^2\ln r_{ji} + (\beta_i^{-2}-1)\left[(1+r_{ji}+r_{ji}^2)r_{ji}\ln r_{ji} + \frac{1}{4}(1-r_{ji}^2)(1+4r_{ji}+r_{ji}^2)\right]\right\}$$

Decay-rate Asymmetries

✓ For $\beta_i \leqslant \beta^*_{ji} \equiv (1 - r^2_{ji})/(1 + r^2_{ji})$

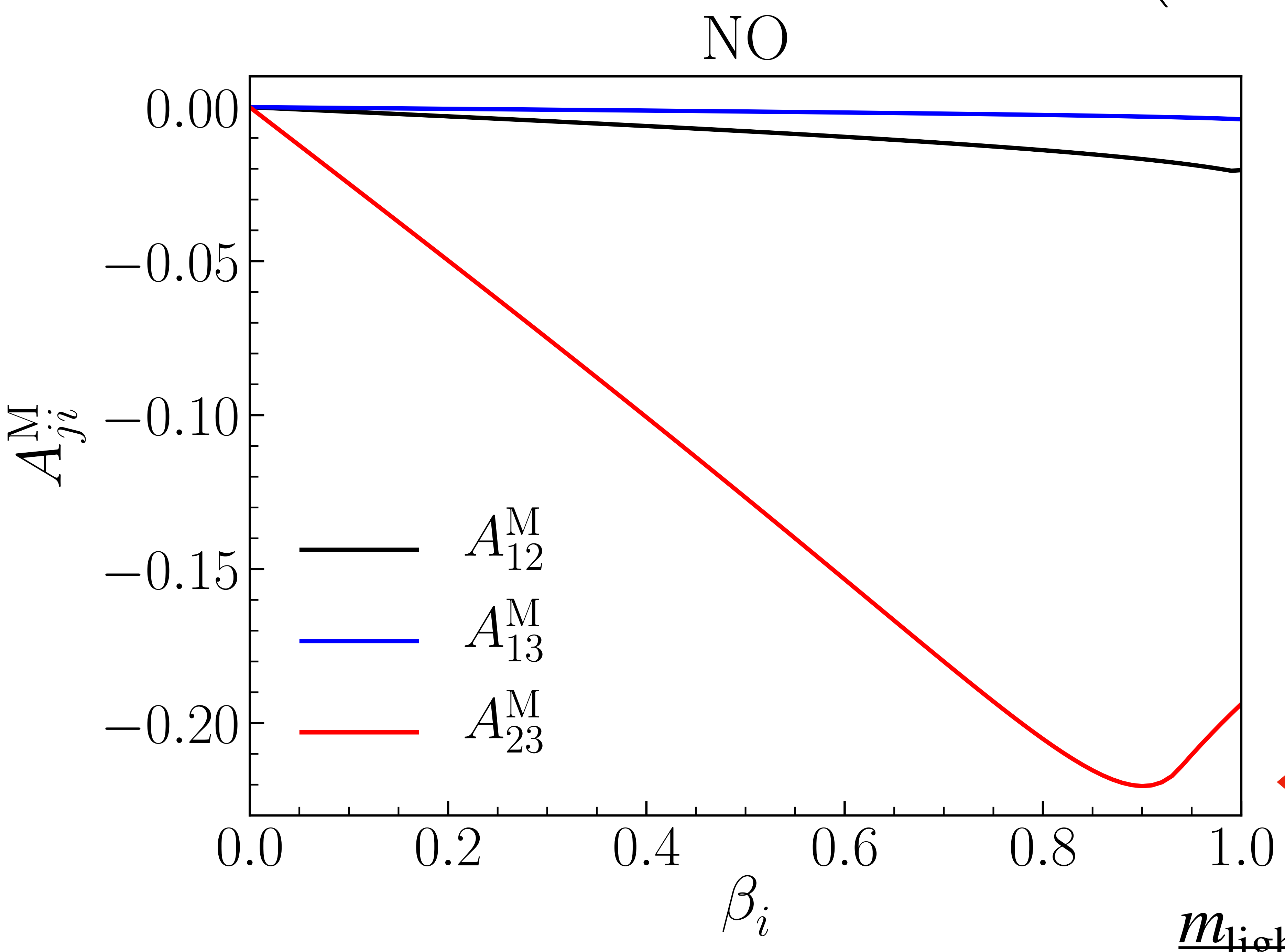
$$\Gamma^{\rm M}_{\pm\pm,ij} = \frac{g^2_{ij} m_i}{4\pi}\sqrt{1-\beta_i^2}\left\{\frac{1}{2}\left(1-r^2_{ji}\right)(1-r_{ji})^2 - (1+r_{ji}+r^2_{ji})r_{ji}\beta_i^{-1} + \left[r_{ji} + \frac{1}{2}(\beta_i^{-2}-1)(1+r_{ji}+r^2_{ji})\right] r_{ji}\ln\left(\frac{1+\beta_i}{1-\beta_i}\right)\right\},$$

$$\Gamma^{\rm M}_{\pm\mp,ij} = \frac{g^2_{ij} m_i}{4\pi}\sqrt{1-\beta_i^2}\left\{\frac{1}{2}\left(1-r^2_{ji}\right)(1-r_{ji})^2 + (1+r_{ji}+r^2_{ji})r_{ji}\beta_i^{-1} - \left[r_{ji} + \frac{1}{2}(\beta_i^{-2}-1)(1+r_{ji}+r^2_{ji})\right] r_{ji}\ln\left(\frac{1+\beta_i}{1-\beta_i}\right)\right\},$$

✓ For $\beta_i > \beta^*_{ji} \equiv (1 - r^2_{ji})/(1 + r^2_{ji})$

$$\Gamma^{\rm M}_{\pm\pm,ij} = \frac{g^2_{ij} m_i}{4\pi}\sqrt{1-\beta_i^2}\left\{\frac{1}{2}\left(1-r^2_{ji}\right)(1-r_{ji})^2 - r_{ji}(1-r^2_{ji}) - 2r^2_{ji}\ln r_{ji} - (\beta_i^{-2}-1)\left[(1+r_{ji}+r^2_{ji})r_{ji}\ln r_{ji} + \frac{1}{4}(1-r^2_{ji})(1+4r_{ji}+r^2_{ji})\right]\right\},$$

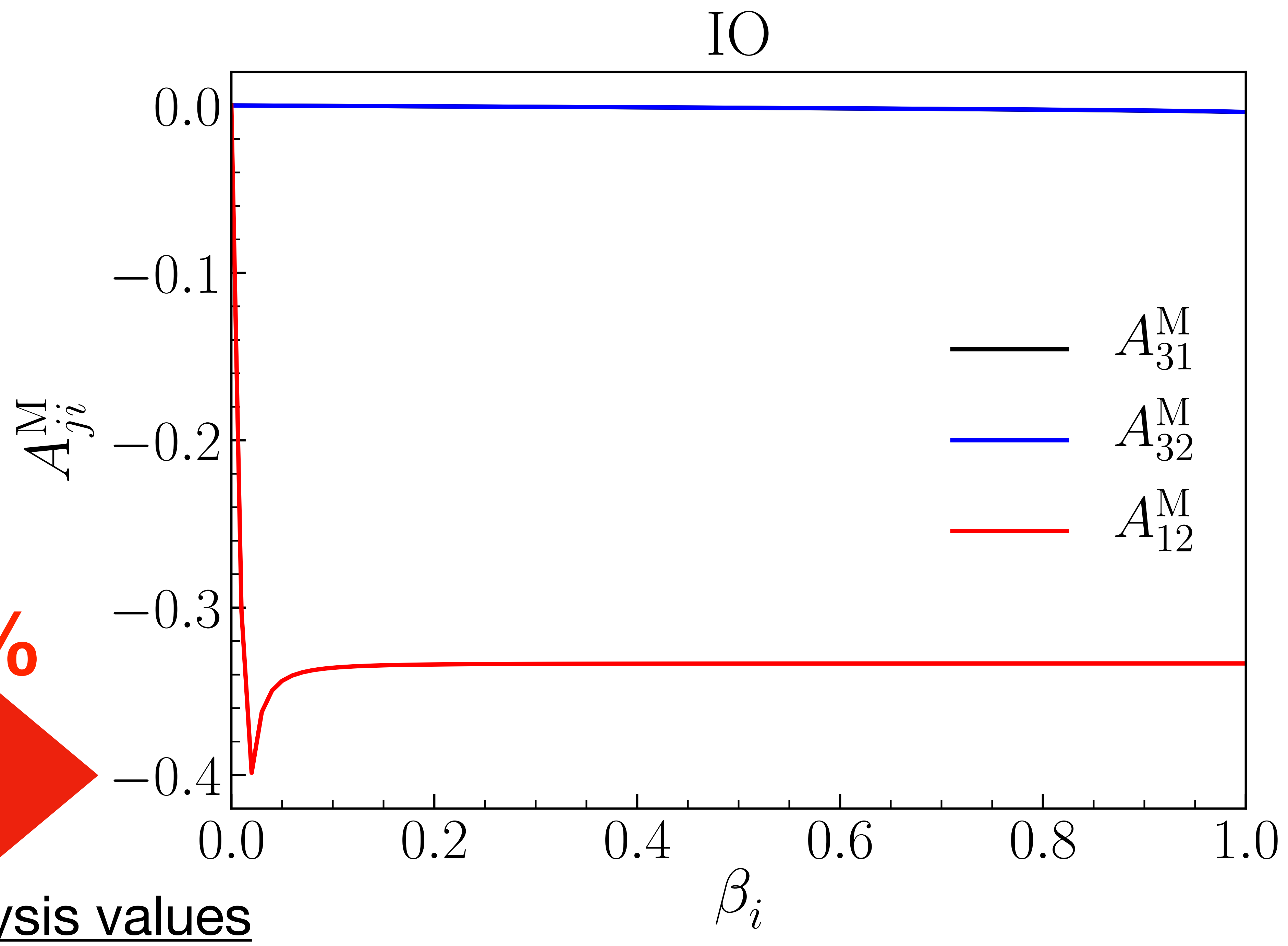
$$\Gamma^{\rm M}_{\pm\mp,ij} = \frac{g^2_{ij} m_i}{4\pi}\sqrt{1-\beta_i^2}\left\{\frac{1}{2}\left(1-r^2_{ji}\right)(1-r_{ji})^2 + r_{ji}(1-r^2_{ji}) + 2r^2_{ji}\ln r_{ji} + (\beta_i^{-2}-1)\left[(1+r_{ji}+r^2_{ji})r_{ji}\ln r_{ji} + \frac{1}{4}(1-r^2_{ji})(1+4r_{ji}+r^2_{ji})\right]\right\},$$



$$A^{\rm M}_{ji} \equiv \frac{\Gamma^{\rm M}_{\pm\pm,ij} - \Gamma^{\rm M}_{\pm\mp,ij}}{\Gamma^{\rm M}_{\pm\pm,ij} + \Gamma^{\rm M}_{\pm\mp,ij}}$$

Asymmetry *between helicity-preserving and -changing decay rates*

20% ← → **40%**



$m_{\rm lightest} = 0.1$ meV and global analysis values

Experimental Constraints on g

✓ Set all couplings to be equal $g_{ij} = g$

✓ The massless ϕ serves as an extra radiation affecting the **BBN** and the **CMB** power spectrum through decays $\nu_i \to \nu_j + \phi$ and scatterings $\nu_i + \nu_j \to \phi + \phi$

✴ For $g \lesssim 10^{-7}$ the scalar ϕ will never be in thermal equilibrium via scatterings before the CMB formation

see, Hannestad & Raffelt, *Phys. Rev. D 72 (2005) 103514*

✓ The lower bound on τ_i (ultra-relativistic):

Barenboim et al., *JCAP 03 (2021) 087*

$$\tau_i \gtrsim 4 \times 10^{(5\cdots6)}\ \mathrm{s} \left(\frac{m_\nu}{50\ \mathrm{meV}}\right)^5$$

*Daughter neutrino masses may **weaken** the lifetime constraint up to a factor of 50*

i.e. (for NO), $g \lesssim (1.6\cdots5.0) \times 10^{-10}$ (for ν_3) , $g \lesssim (0.4\cdots1.3) \times 10^{-7}$ (for ν_2)

We choose $10^{-16} \lesssim g \lesssim 10^{-10}$ in this work (a benchmark value: $g = 10^{-12}$)

Experimental Constraints on g

✓ Set all couplings to be equal $g_{ij} = g$ $\mathscr{L} \supset -\frac{1}{2}\overline{N^c_R}\mathbf{y}_N N_R S + \mathrm{h.c.} \Rightarrow \frac{i\phi}{2f}\sum_{i=1}^{3} m_i \overline{\nu}_i \gamma^5 \nu_i$ $[S \equiv (f+\rho+i\phi)/\sqrt{2}]$

✓ The massless ϕ serves as an extra radiation affecting the **BBN** and the **CMB** power spectrum through decays $\nu_i \to \nu_j + \phi$ and scatterings $\nu_i + \nu_j \to \phi + \phi$

- ✳ For $g \lesssim 10^{-7}$ the scalar ϕ will never be in thermal equilibrium via scatterings before the CMB formation — see, Hannestad & Raffelt, *Phys. Rev. D 72 (2005) 103514*

✓ The lower bound on τ_i (ultra-relativistic): Barenboim et al., *JCAP 03 (2021) 087*

$$\tau_i \gtrsim 4 \times 10^{(5\cdots6)}\ \mathrm{s} \left(\frac{m_\nu}{50\ \mathrm{meV}}\right)^5$$

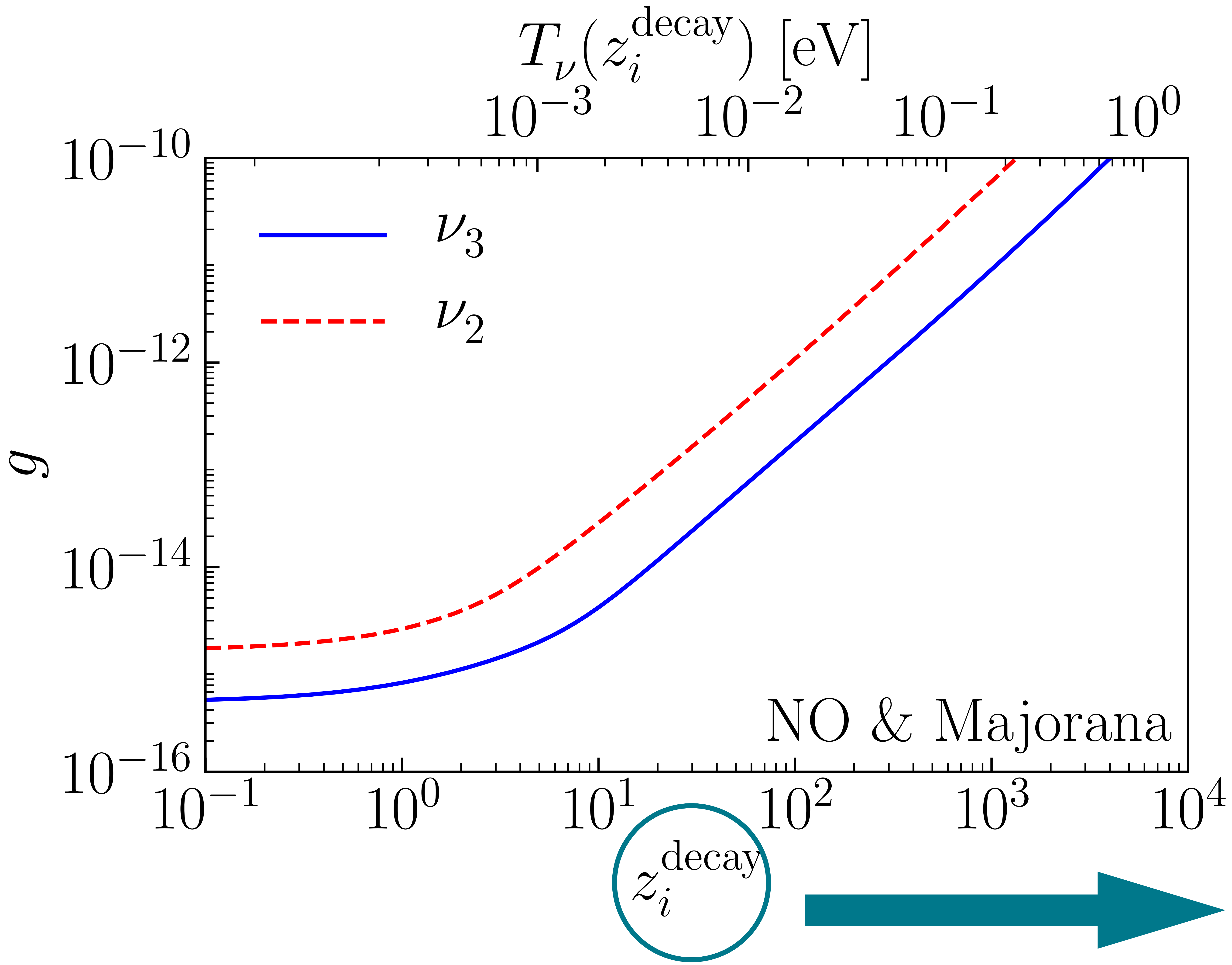
*Daughter neutrino masses may **weaken** the lifetime constraint up to a factor of 50*

i.e. (for NO), $g \lesssim (1.6\cdots5.0) \times 10^{-10}$ (for ν_3) , $g \lesssim (0.4\cdots1.3) \times 10^{-7}$ (for ν_2)

We choose $10^{-16} \lesssim g \lesssim 10^{-10}$ in this work (a benchmark value: $g = 10^{-12}$)

CvB Decays and Evolutions

- *Modified number density* $n_i(z) = \bar{n}_i(z) a(z)^3$



- Estimate $z_i^{\rm decay}$ from

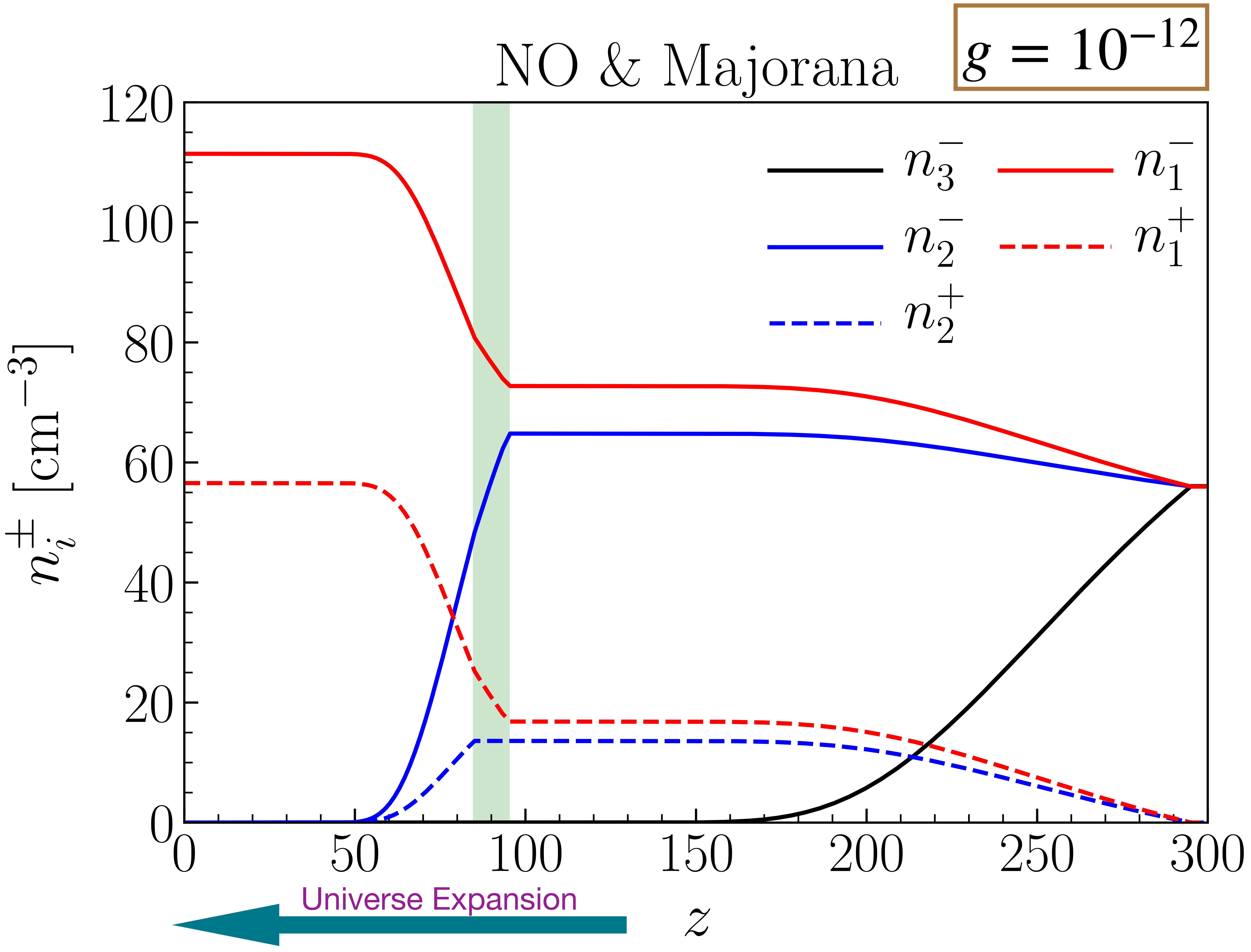
$$\frac{\int_0^\infty e^{-\widetilde{\lambda}_i(z_i^{\rm decay})} f_{\rm FD}\left[|\mathbf{p}|, T_\nu(z_i^{\rm decay})\right] |\mathbf{p}|^2 \, {\rm d}|\mathbf{p}|}{\int_0^\infty f_{\rm FD}\left[|\mathbf{p}|, T_\nu(z_i^{\rm decay})\right] |\mathbf{p}|^2 \, {\rm d}|\mathbf{p}|} = e^{-1}$$

where the ***suppression factor***

$$\widetilde{\lambda}_i(z_i^{\rm decay}) \equiv \int_{z_i^{\rm decay}}^\infty \frac{{\rm d}z \, \Gamma^{\rm M*}_{\pm,i}}{(1+z)H(z)\gamma_i(z)}$$

- $z_i^{\rm decay}$ characterizes the redshift when *a substantial fraction* of ν_i starts to decay for a given g after taking account of its *momentum distribution*

CvB Decays and Evolutions



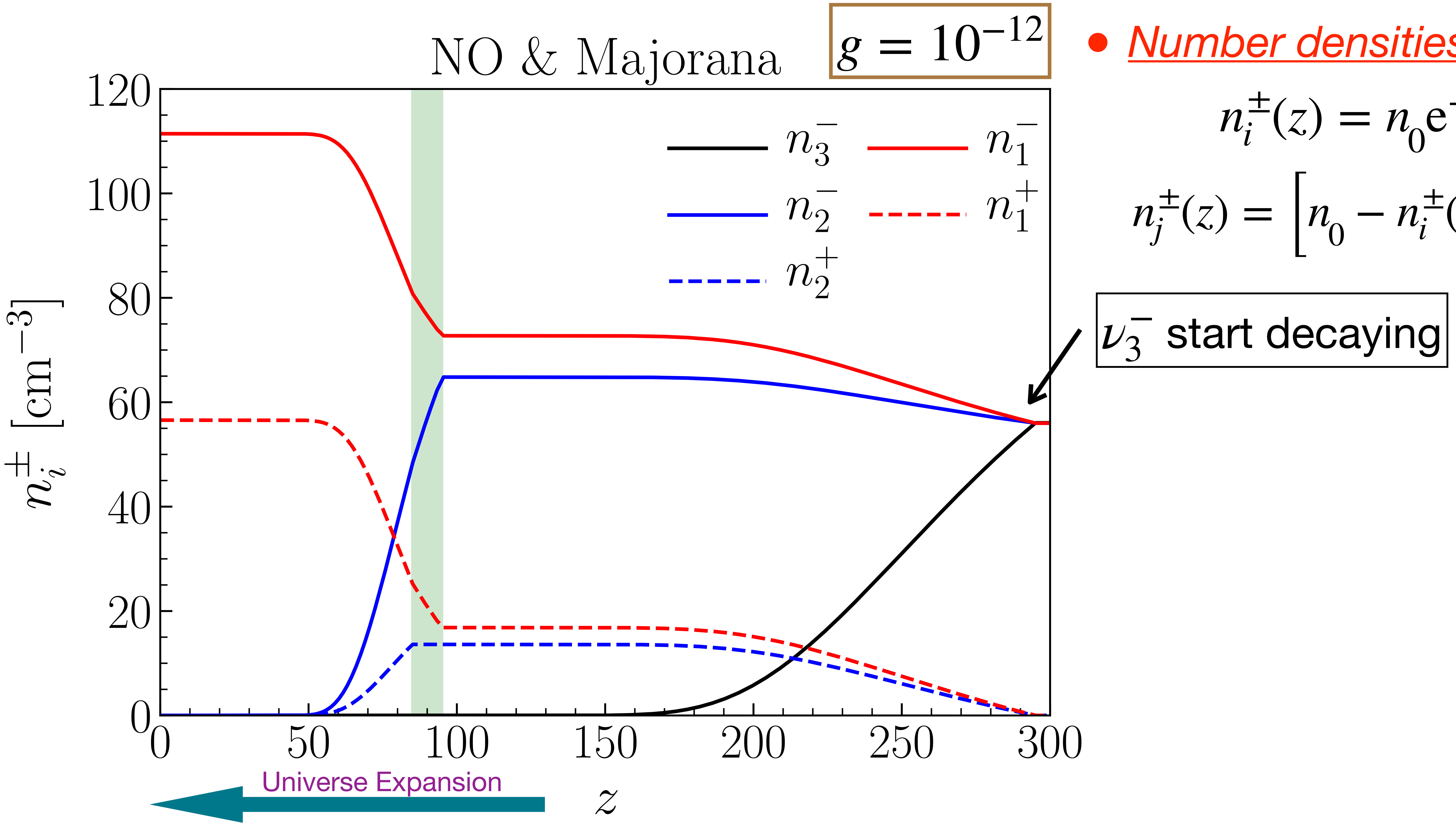
- *Number densities*

$$n_i^\pm(z) = n_0 e^{-\lambda_i(z)}$$

$$n_j^\pm(z) = \left[n_0 - n_i^\pm(z)\right] \mathscr{B}_{ij}^{\mathrm{M}+}$$

branching ratio of helicity-preserving decays

CvB Decays and Evolutions

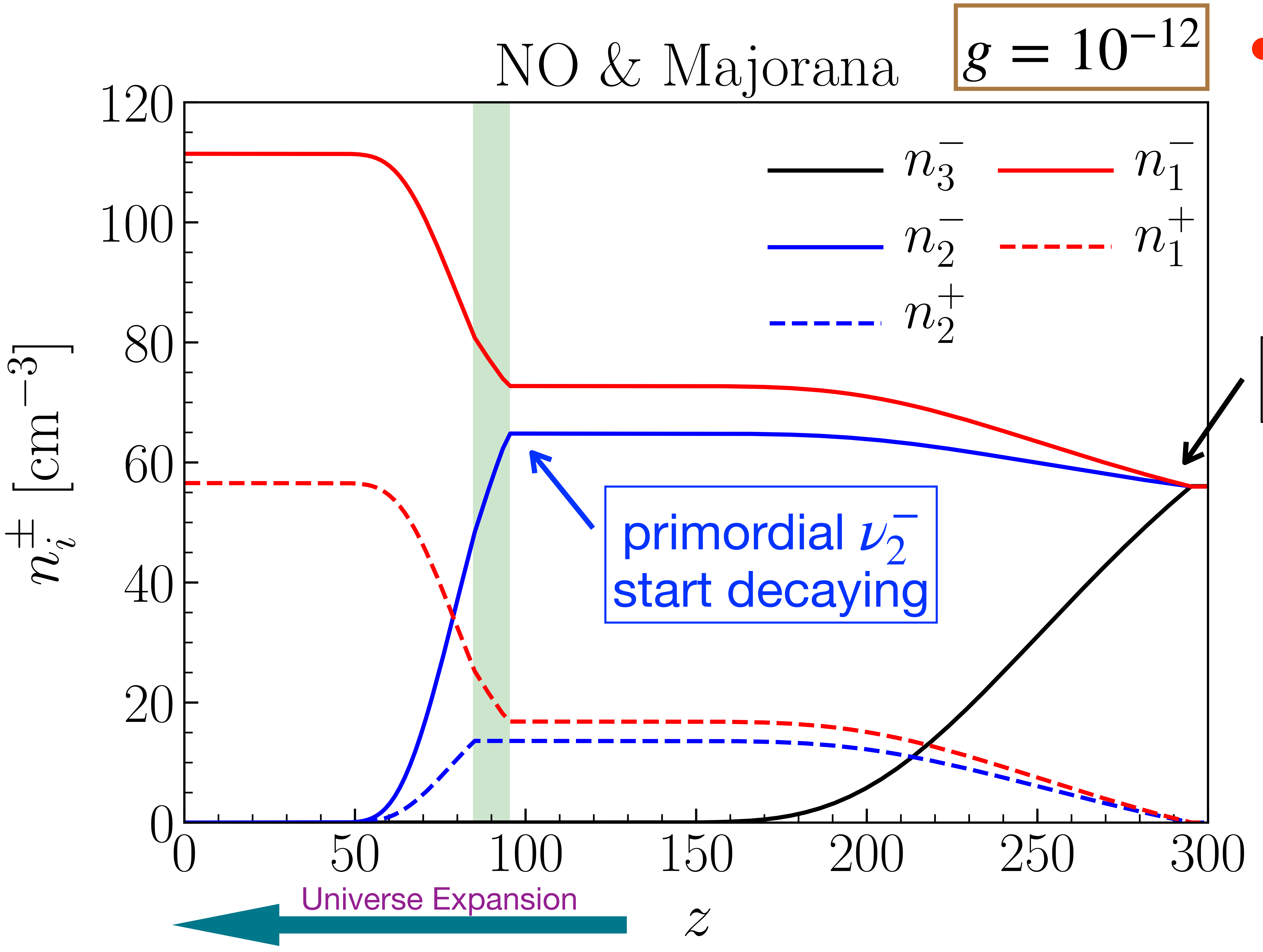


- *Number densities*

$$n_i^\pm(z) = n_0 e^{-\lambda_i(z)}$$

$$n_j^\pm(z) = \left[n_0 - n_i^\pm(z) \right] \mathscr{B}_{ij}^{\mathrm{M}+}$$

CvB Decays and Evolutions



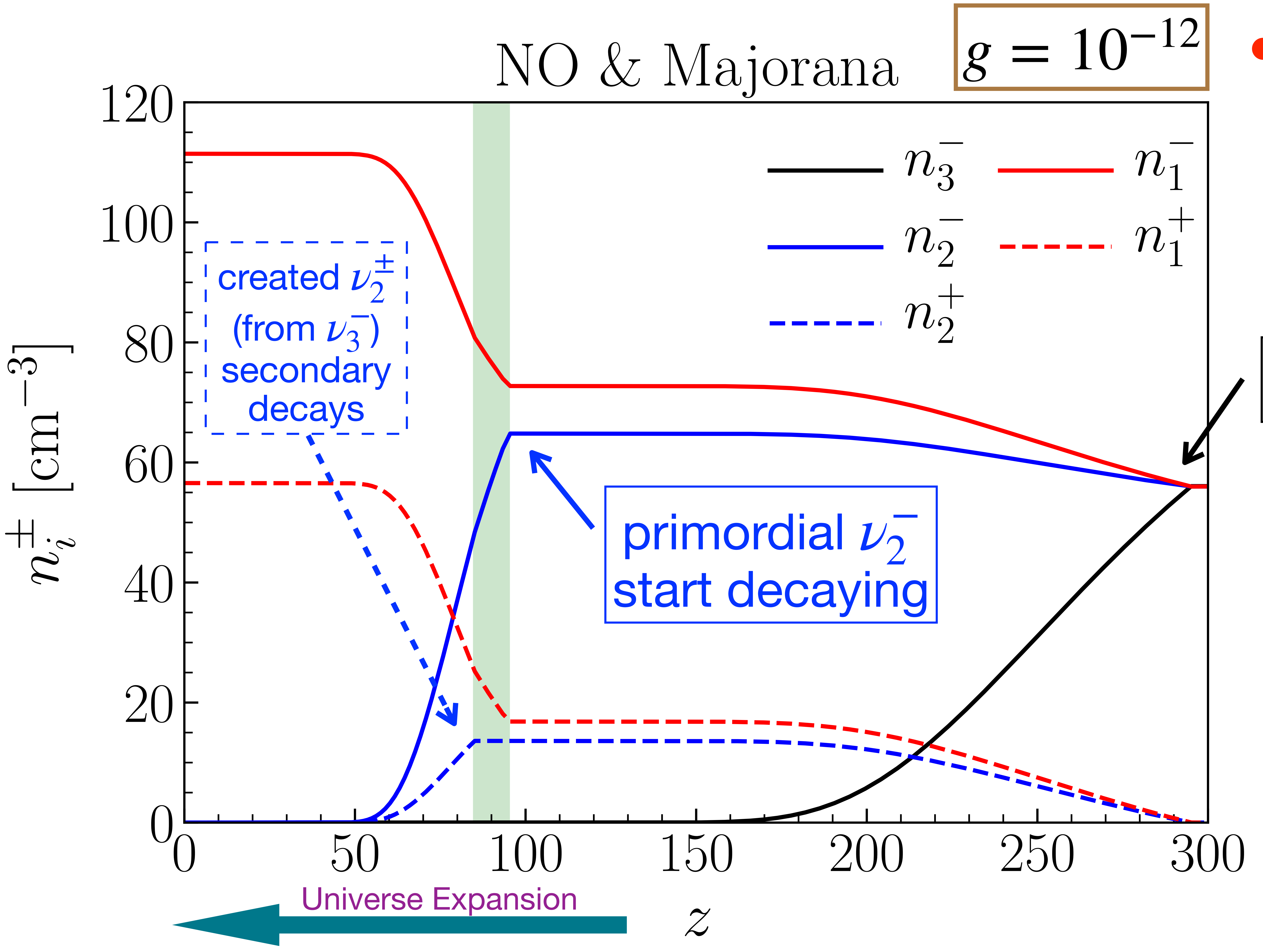
ν_3^- start decaying

- *Number densities*

$$n_i^\pm(z) = n_0 e^{-\lambda_i(z)}$$

$$n_j^\pm(z) = \left[n_0 - n_i^\pm(z)\right] \mathscr{B}_{ij}^{\mathrm{M}+}$$

CvB Decays and Evolutions

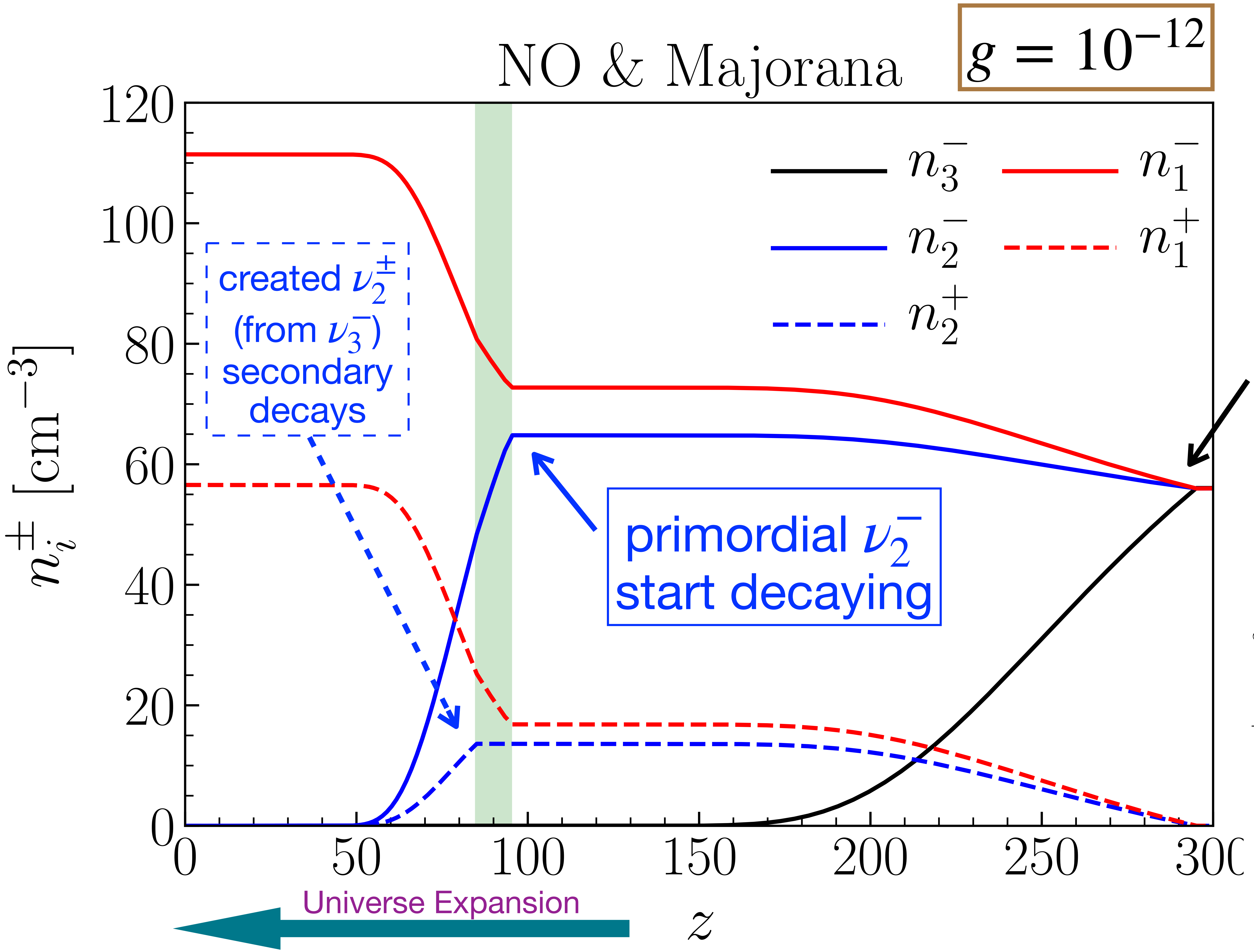


- *Number densities*

$$n_i^\pm(z) = n_0 e^{-\lambda_i(z)}$$

$$n_j^\pm(z) = \left[n_0 - n_i^\pm(z)\right] \mathscr{B}_{ij}^{M+}$$

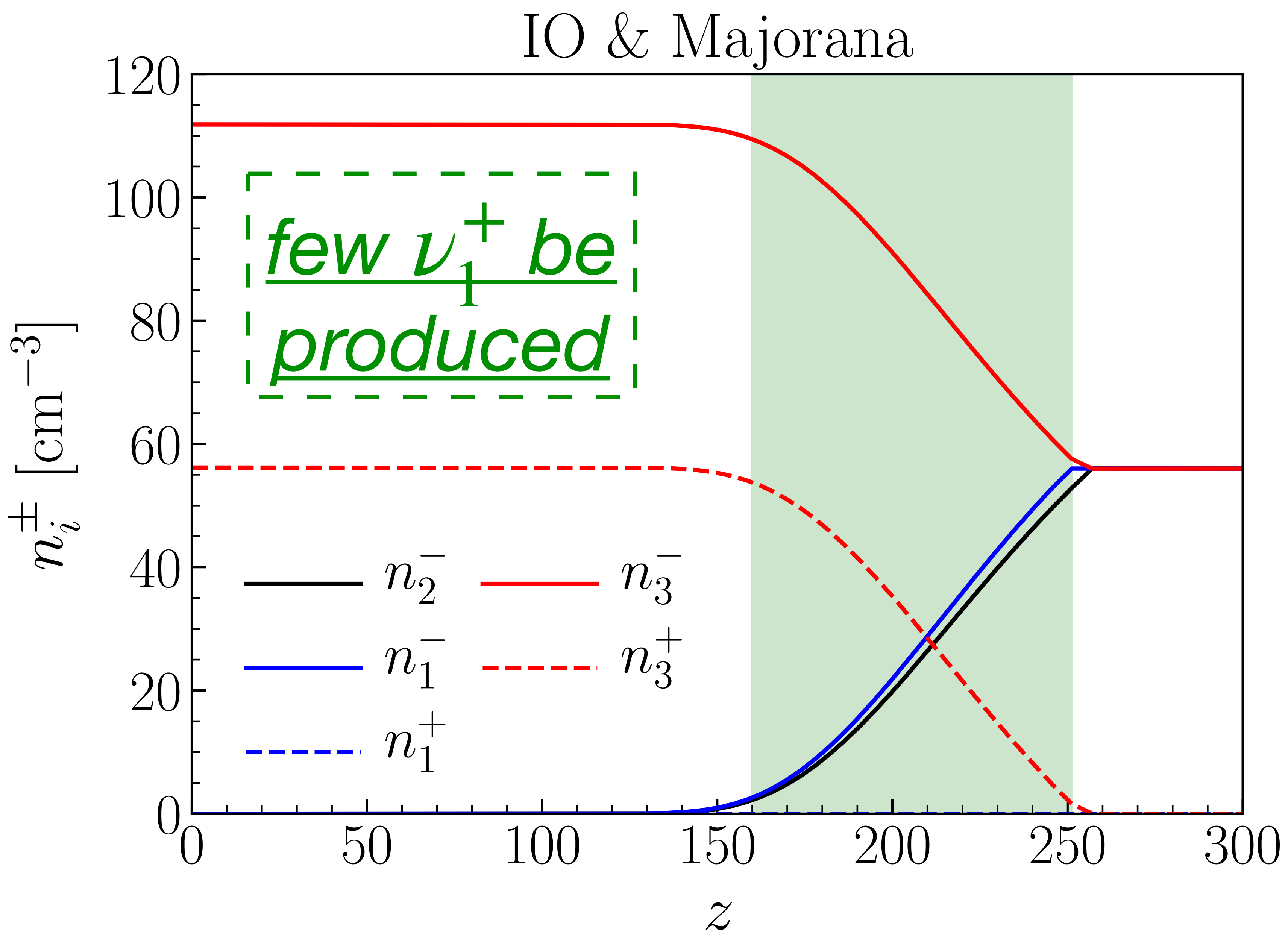
CvB Decays and Evolutions



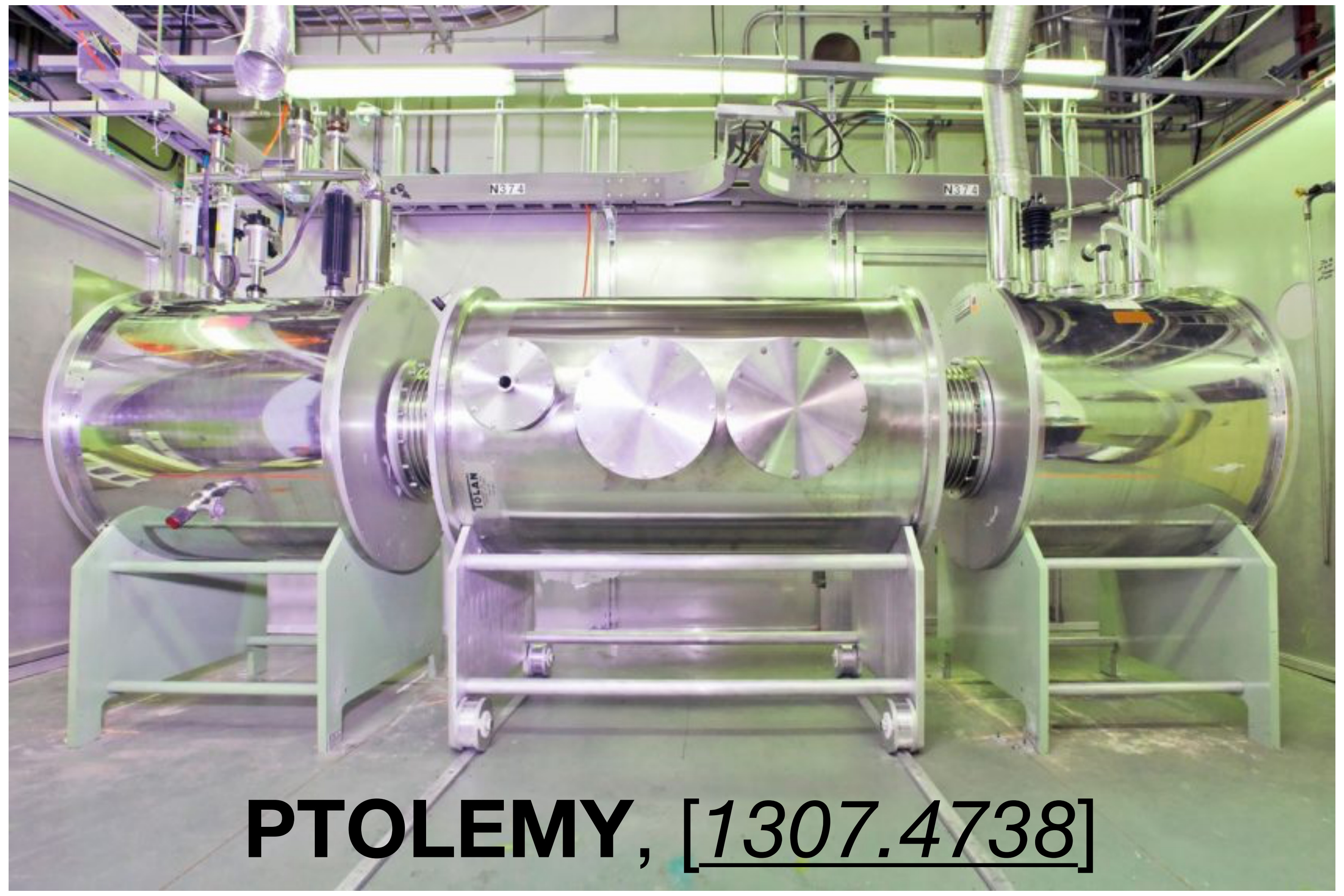
- ***Number densities***

$$n_i^{\pm}(z) = n_0 \mathrm{e}^{-\lambda_i(z)}$$

$$n_j^{\pm}(z) = \left[n_0 - n_i^{\pm}(z) \right] \mathscr{B}_{ij}^{\mathrm{M}+}$$



CνB Capture Rates



PTOLEMY, [1307.4738]

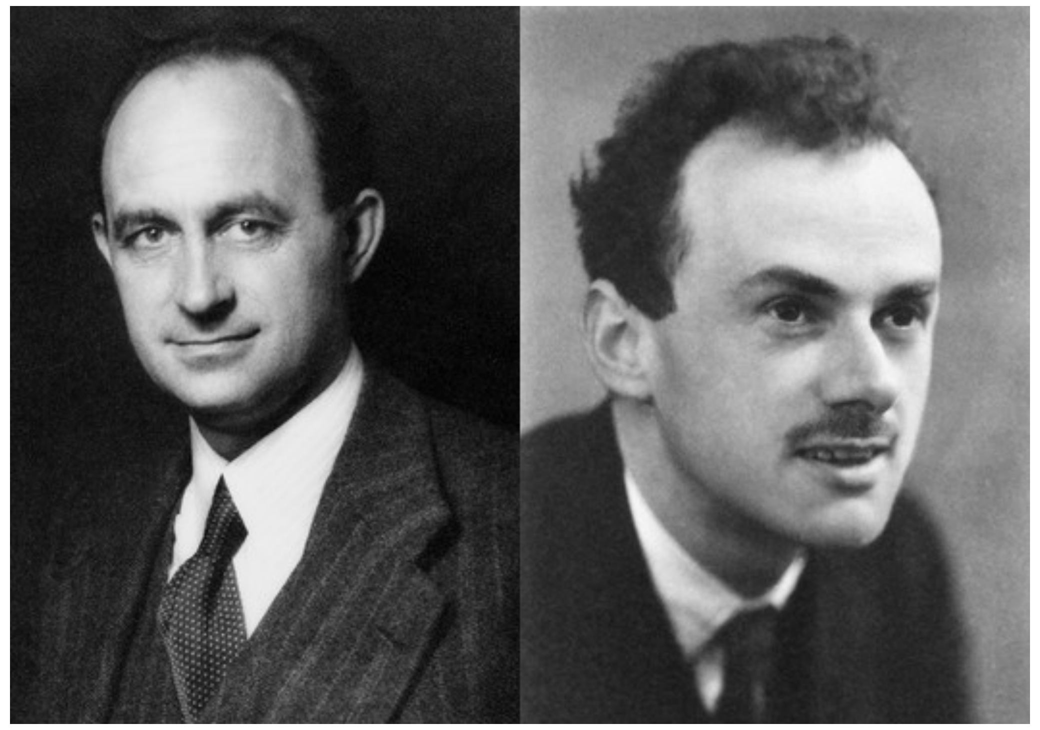
Princeton **T**ritium **O**bservatory for **L**ight, **E**arly-Universe, **M**assive-Neutrino **Y**ield (**PTOLEMY**)

- *Capture Rates:* Long, Lunardini & Sabancilar, *JCAP 08 (2014) 038*

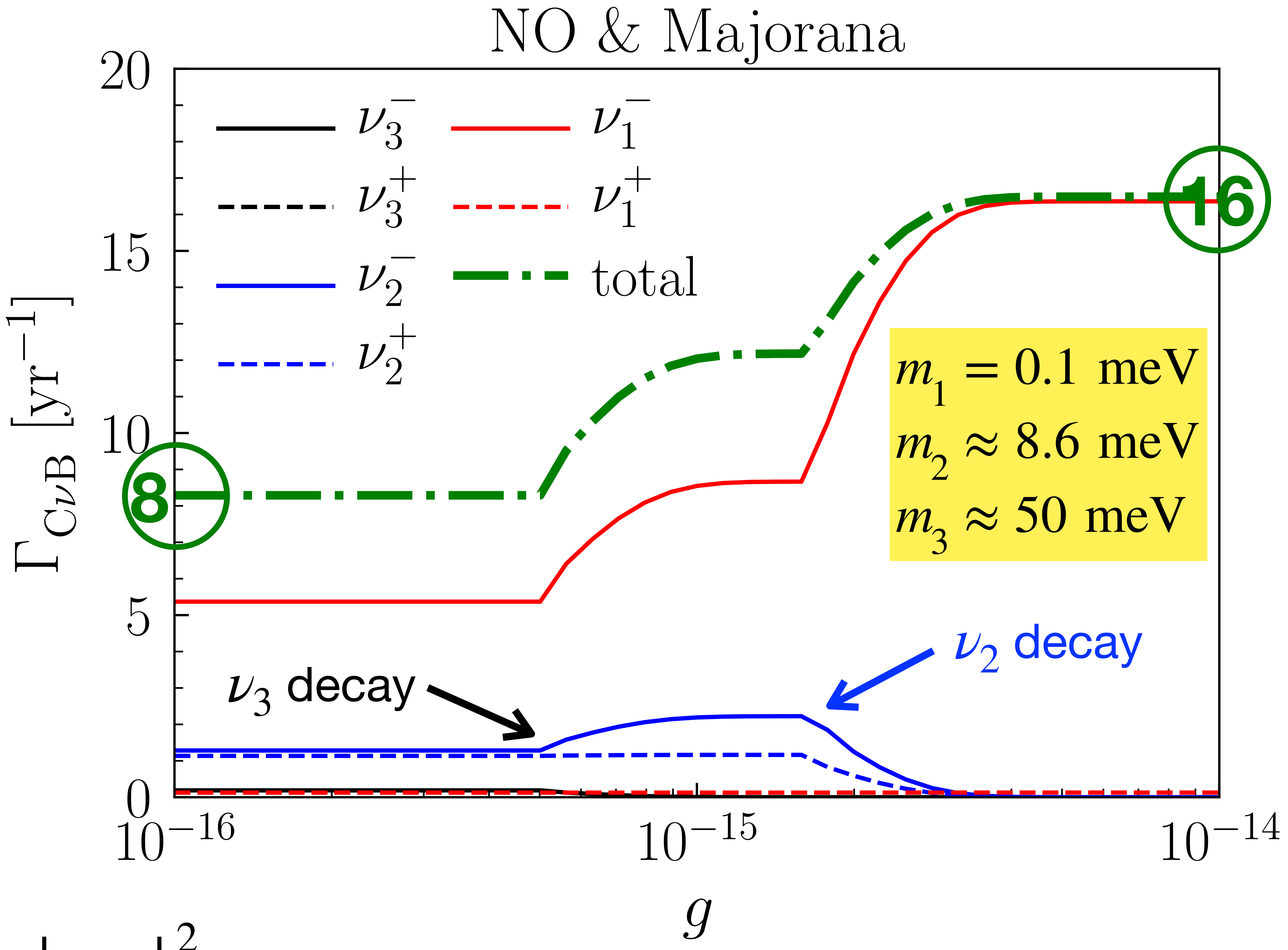
$$\Gamma_{\mathrm{C\nu B}} = N_{\mathrm{T}}\bar{\sigma} \sum_{s_i=\pm 1/2} \sum_{i=1}^{3} \left|U_{ei}\right|^2 n_i(s_i)\mathscr{A}(s_i)$$

- *Number of tritium nuclei* in the target (100 g tritium) $N_{\mathrm{T}} \approx 2 \times 10^{25}$
- *Cross section* $\bar{\sigma} \approx 3.8 \times 10^{-45}\ \mathrm{cm}^2$
- *Leptonic flavor mixing matrix* $\left|U_{e1}\right|^2 \approx 0.677\ ,\ \left|U_{e2}\right|^2 \approx 0.298\ ,\ \left|U_{e3}\right|^2 \approx 0.023$
- $\mathscr{A}(s_i) \equiv 1 - 2s_i \left\langle \beta_i \right\rangle$ with the momentum Fermi-Dirac distribution

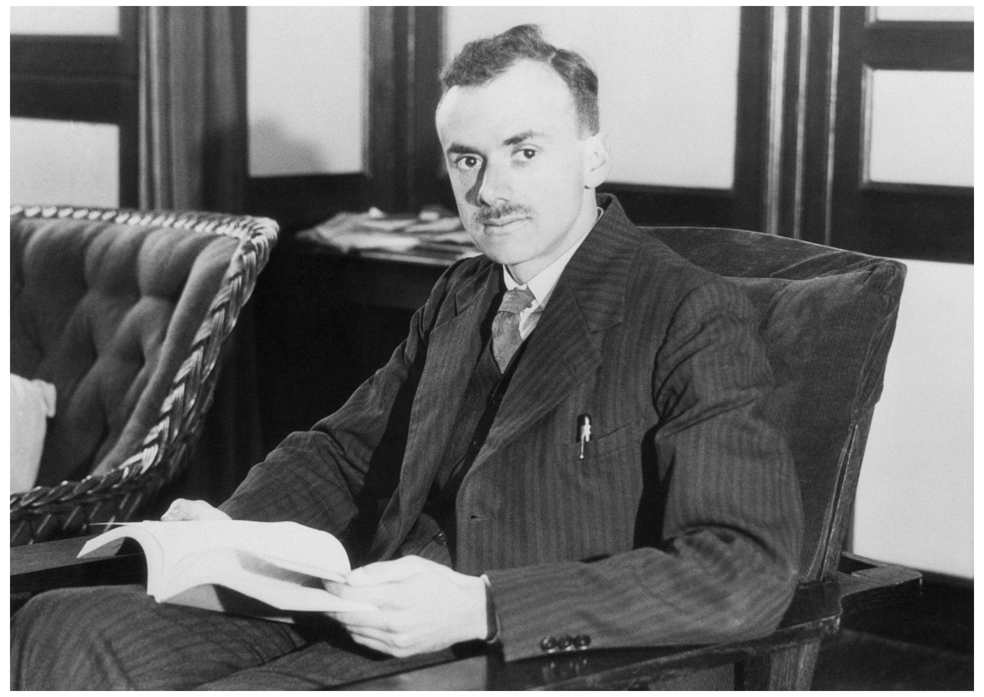
$$\left\langle \beta_i \right\rangle = \frac{\int_0^\infty \beta_i\, f_{\mathrm{FD}}\left(\left|\mathbf{p}_i\right|, T^0_{\nu_i}\right) |\mathbf{p}_i|^2\, \mathrm{d}|\mathbf{p}_i|}{\int_0^\infty f_{\mathrm{FD}}\left(|\mathbf{p}_i|, T^0_{\nu_i}\right) |\mathbf{p}_i|^2\, \mathrm{d}|\mathbf{p}_i|}$$



Capture Rates (NO)



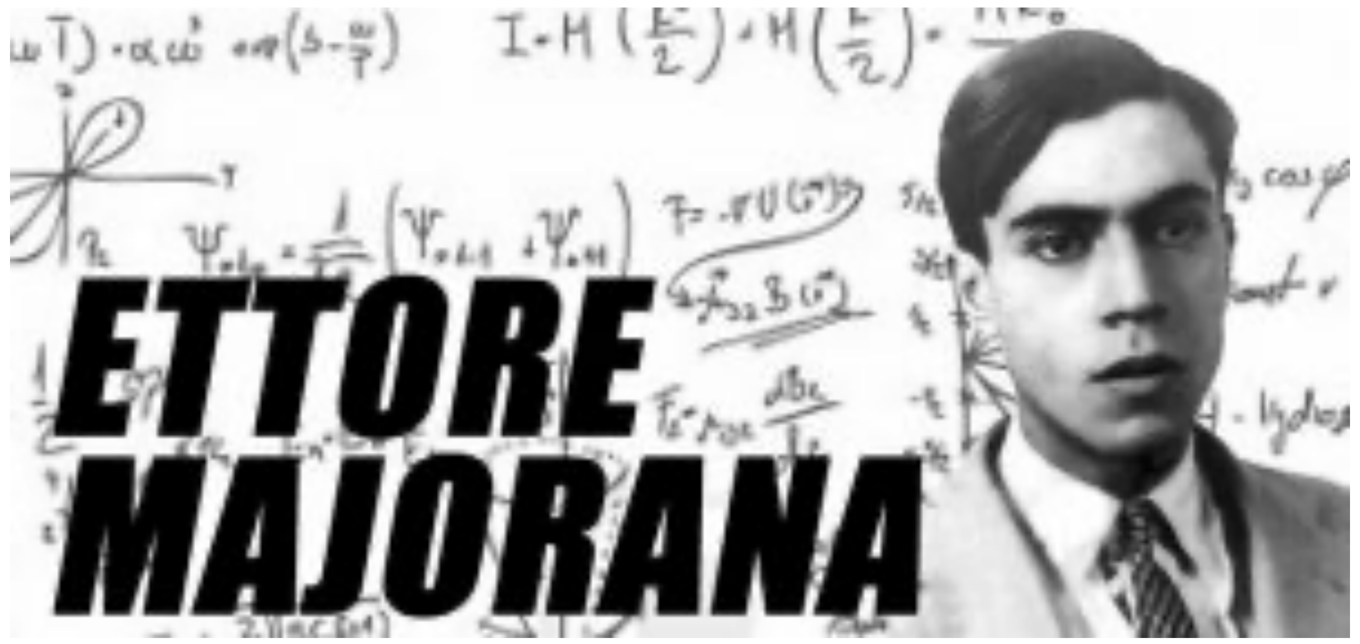
✓ The number density of left-helical states will be much larger **without helicity-changing decays**.

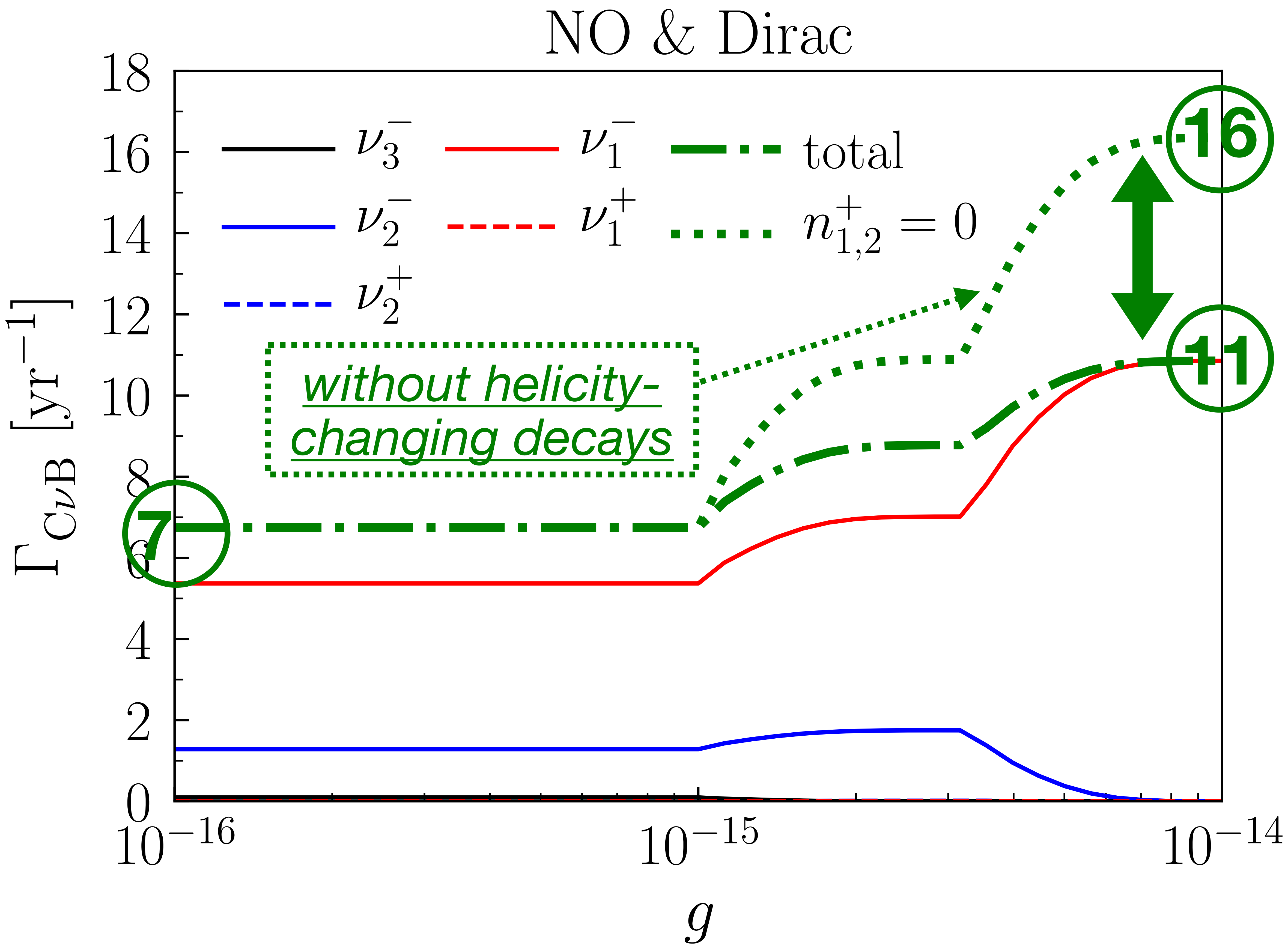


$|U_{e1}|^2 \approx 0.677$

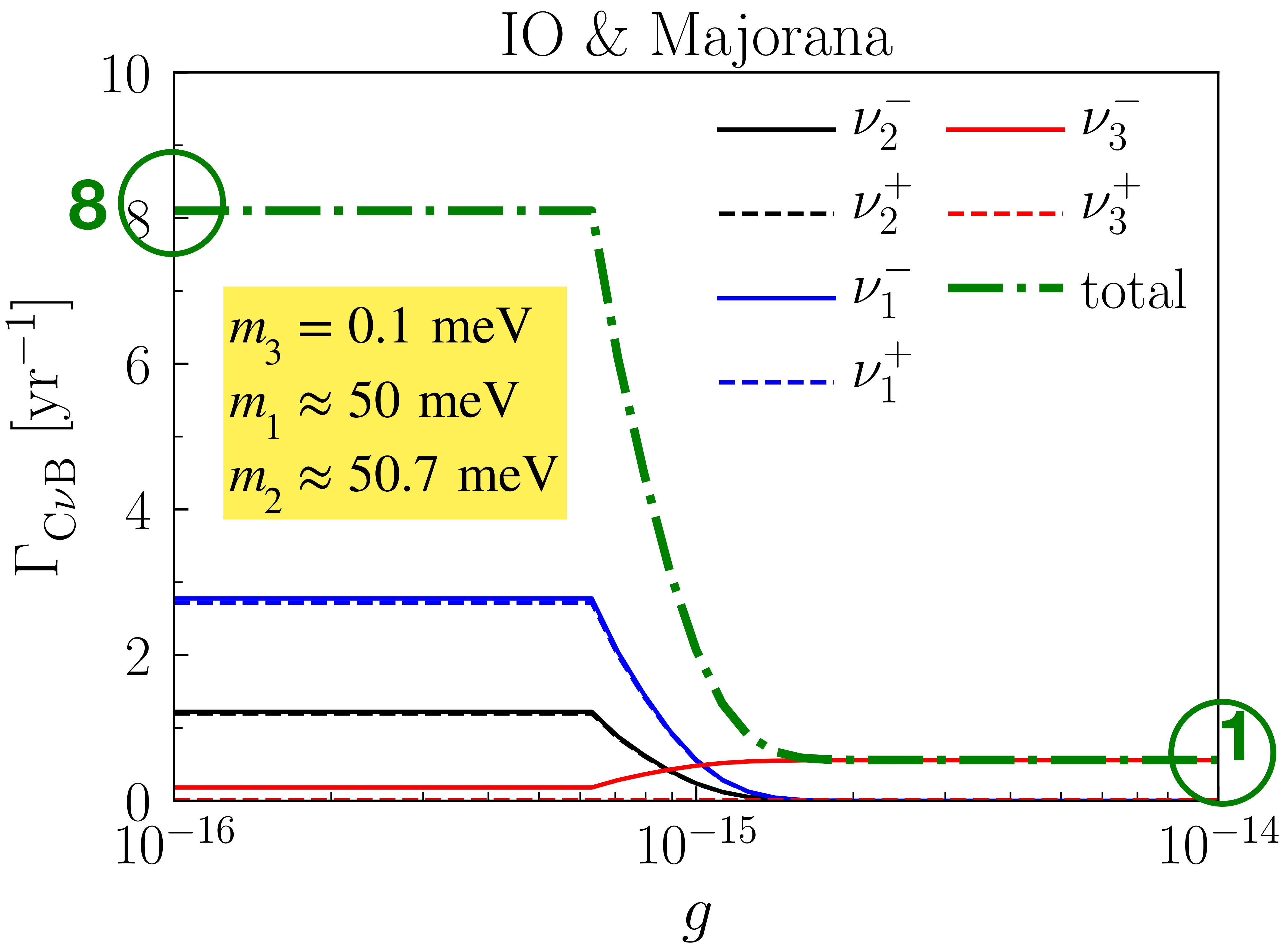
$|U_{e2}|^2 \approx 0.298$

$|U_{e3}|^2 \approx 0.023$

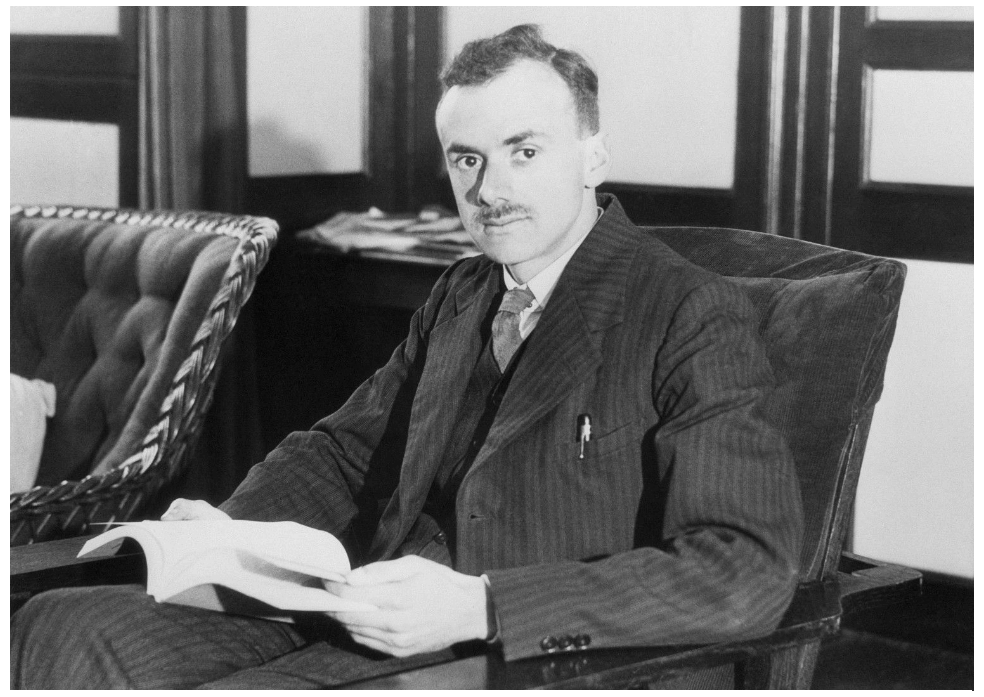


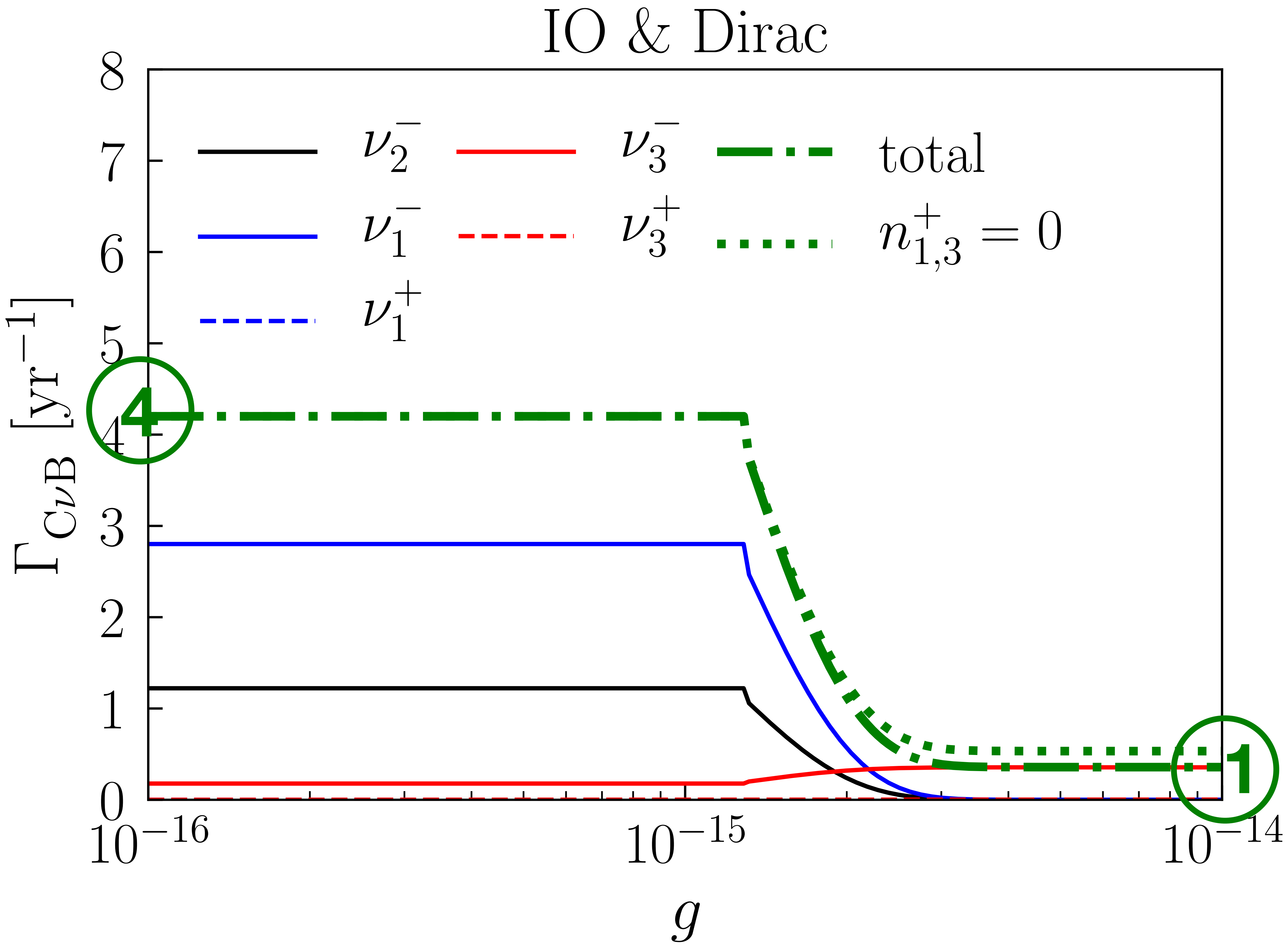


Capture Rates (IO)

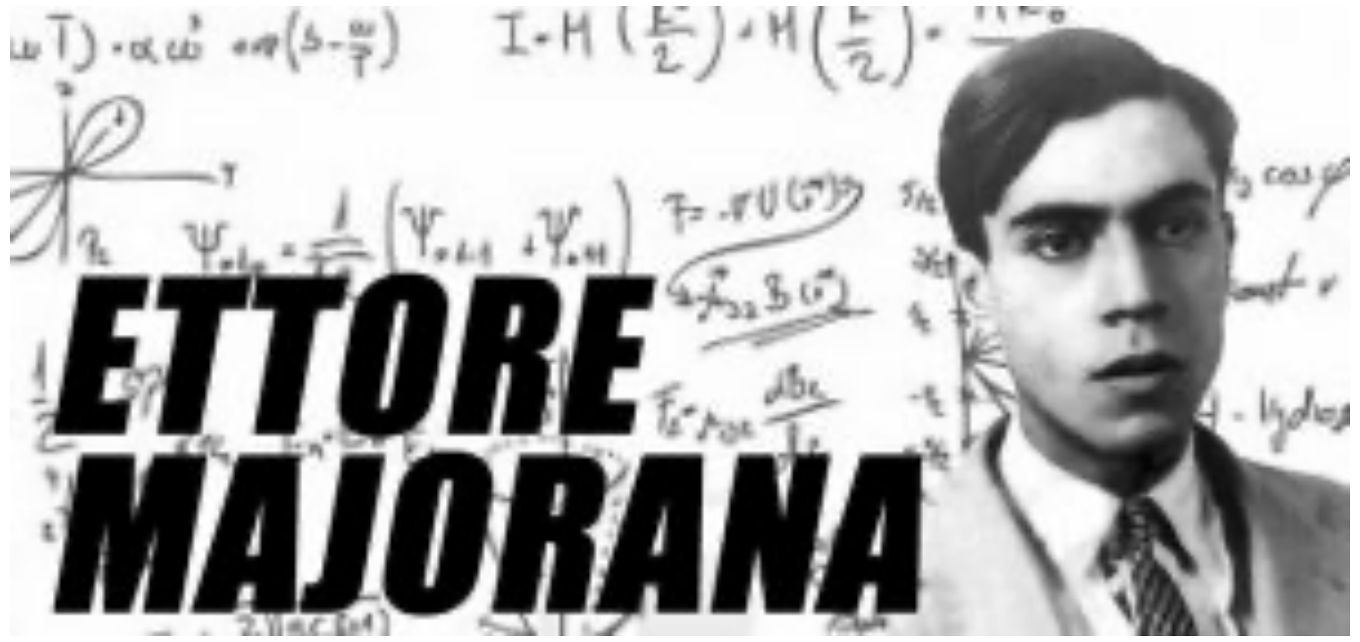


✓ The difference is negligible for **IO** ($\nu_2 \to \nu_1$ decays are suppressed).





no significant production of ν_1 from ν_2 decays



Summary

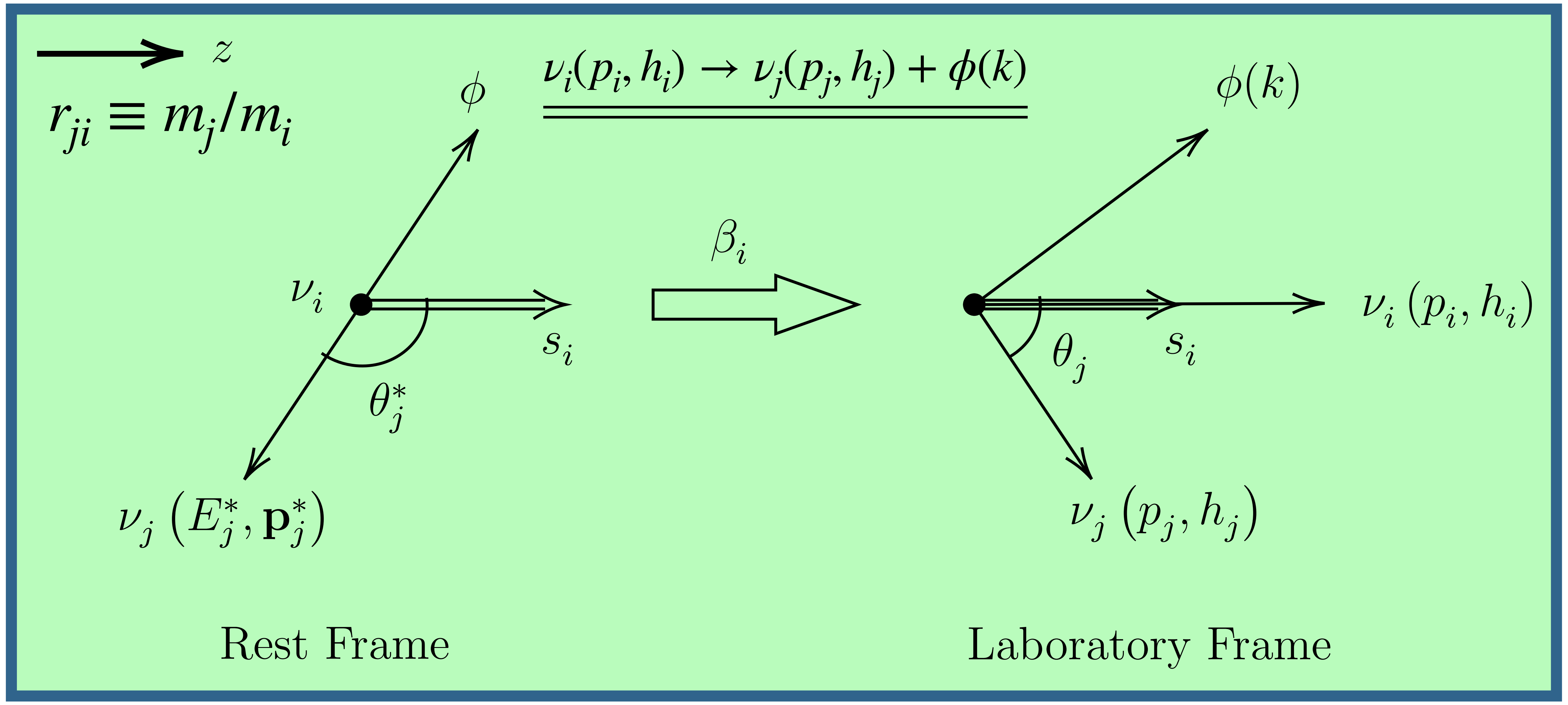
- We study the **invisible decays** of massive neutrinos and their implications for the **CνB detection**.
  1. The decay rates in the helicity-preserving and -changing decay channels are calculated and discussed in detail.
  2. The strategy to evaluate the cosmic neutrino number densities is explained by taking a benchmark value of the coupling between massive neutrinos and the Nambu-Goldstone boson.
  3. The capture rates of CνB in the PTOLEMY-like experiment are obtained when considering neutrino decays and the distribution function ($\Gamma^{\rm M}_{\rm C\nu B} \approx 16~{\rm yr}^{-1}$ and $\Gamma^{\rm D}_{\rm C\nu B} \approx 11~{\rm yr}^{-1}$ in the NO case, **1 event per year** in the IO case).
- It is important to probe the intrinsic properties of massive neutrinos (e.g., Dirac or Majorana nature, absolute mass scale, lifetimes, etc.). The PTOLEMY-like experiments have the capability to **measure the absolute neutrino mass** and **detect these relic neutrinos**. It also serve as an instructive platform to *test BSM theories* (Although the detection of CνB is definitely challenging…).

Thanks for your attention!

Backup Slides

Helicity-changing Decays

$$\mathcal{L}_{\rm M} = \frac{1}{2}\sum_i \left(\overline{\nu_i}\mathrm{i}\partial\!\!\!/\nu_i - m_i\overline{\nu_i}\nu_i\right) + \frac{1}{2}\partial_\mu\phi\partial^\mu\phi - \left[\mathrm{i}\phi\sum_{i,j} g_{ij}\overline{\nu_i}\gamma^5\nu_j + \mathrm{h.c.}\right]$$



- ***Helicity spinors*** with $h = \pm 1$

$$\chi^{(+)}(\theta,\phi) = \begin{pmatrix} \cos\frac{\theta}{2} \\ \mathrm{e}^{+\mathrm{i}\phi}\sin\frac{\theta}{2} \end{pmatrix}, \quad \chi^{(-)}(\theta,\phi) = \begin{pmatrix} -\sin\frac{\theta}{2} \\ \mathrm{e}^{+\mathrm{i}\phi}\cos\frac{\theta}{2} \end{pmatrix}$$

- ***Wave functions*** with $h = +1$ & -1

$$u(p, h=+1) = \cos\frac{\theta}{2}\begin{pmatrix} \sqrt{E-|\mathbf{p}|} \\ 0 \\ \sqrt{E+|\mathbf{p}|} \\ 0 \end{pmatrix} + \sin\frac{\theta}{2}\mathrm{e}^{\mathrm{i}\phi}\begin{pmatrix} 0 \\ \sqrt{E+|\mathbf{p}|} \\ 0 \\ \sqrt{E-|\mathbf{p}|} \end{pmatrix}$$

$$u(p, h=-1) = -\sin\frac{\theta}{2}\begin{pmatrix} \sqrt{E+|\mathbf{p}|} \\ 0 \\ \sqrt{E-|\mathbf{p}|} \\ 0 \end{pmatrix} + \cos\frac{\theta}{2}\mathrm{e}^{\mathrm{i}\phi}\begin{pmatrix} 0 \\ \sqrt{E-|\mathbf{p}|} \\ 0 \\ \sqrt{E+|\mathbf{p}|} \end{pmatrix}$$

E.g.

$$u_i(p_i, h_i = +1) = \begin{pmatrix} \sqrt{E_i-|\mathbf{p}_i|} \\ 0 \\ \sqrt{E_i+|\mathbf{p}_i|} \\ 0 \end{pmatrix}$$

✓ ***helicity-preserving:***

$h_j = +1 \Rightarrow \propto \cos(\theta/2)$

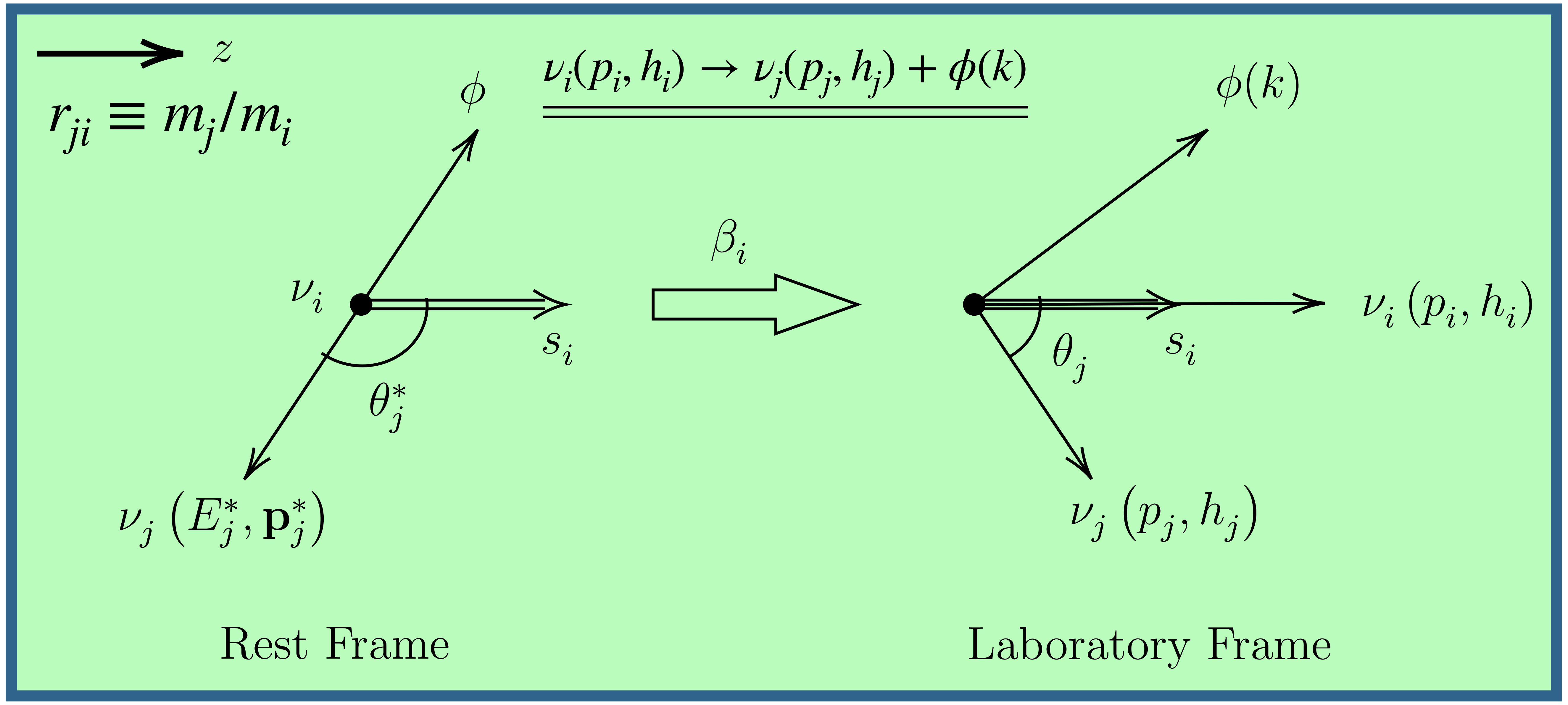
✓ ***helicity-changing***

$h_j = -1 \Rightarrow \propto \sin(\theta/2)$

*Both **positive**- and **negative**-helical states of daughter neutrinos can be produced!*

Decay Amplitudes and Decay Rates

$$\mathcal{L}_{\rm M} = \frac{1}{2}\sum_i \left(\overline{\nu_i} i\partial\!\!\!/ \nu_i - m_i \overline{\nu_i}\nu_i\right) + \frac{1}{2}\partial_\mu\phi\partial^\mu\phi - \left[i\phi \sum_{i,j} g_{ij}\overline{\nu_i}\gamma^5\nu_j + \text{h.c.}\right]$$



1. Decay amplitudes (Majorana ν)

$$i\mathcal{M}^{\rm M}_{h_i h_j, ij} = 2g_{ij}\overline{u_j}(p_j,h_j)\gamma^5 u_i(p_i,h_i)$$

2. Amplitude squared

$$|\mathcal{M}^{\rm M}_{h_i h_j, ij}|^2 = 4g_{ij}^2 \text{Tr}\left[u_i(p_i,h_i)\overline{u_i(p_i,h_i)}\gamma^5 u_j(p_j,h_j)\overline{u_j(p_j,h_j)}\gamma^5\right]$$

for a specific helicity

$$u(p,h)\overline{u(p,h)} = \frac{1}{2}(p\!\!\!/ + m)(1 + h\gamma^5 s\!\!\!/)$$

$$|\mathcal{M}^{\rm M}_{++,ij}|^2 = 8g_{ij}^2\left(E_iE_j - m_im_j - |\mathbf{p}_i||\mathbf{p}_j|\right)\cos^2\frac{\theta_j}{2}$$

$$|\mathcal{M}^{\rm M}_{+-,ij}|^2 = 8g_{ij}^2\left(E_iE_j - m_im_j + |\mathbf{p}_i||\mathbf{p}_j|\right)\sin^2\frac{\theta_j}{2}$$

✓ *These identities hold:*

$$|\mathcal{M}^{\rm M}_{++,ij}|^2 = |\mathcal{M}^{\rm M}_{--,ij}|^2, \quad |\mathcal{M}^{\rm M}_{+-,ij}|^2 = |\mathcal{M}^{\rm M}_{-+,ij}|^2$$

3. Differential decay rates

$$\frac{d\Gamma^{\rm M}_{\pm\pm,ij}}{dE_j} = \frac{g_{ij}^2 m_i^2}{4\pi E_i}\left[+\frac{E_i^2 r_{ji}^2 + E_j^2}{|\mathbf{p}_i|^2|\mathbf{p}_j|} - \frac{(1+r_{ji})^2}{2|\mathbf{p}_i|}\frac{E_iE_j}{|\mathbf{p}_i||\mathbf{p}_j|} + \frac{(1-r_{ji})^2}{2|\mathbf{p}_i|}\left(1 + \frac{m_i^2 r_{ji}}{|\mathbf{p}_i||\mathbf{p}_j|}\right)\right]$$

$$\frac{d\Gamma^{\rm M}_{\pm\mp,ij}}{dE_j} = \frac{g_{ij}^2 m_i^2}{4\pi E_i}\left[-\frac{E_i^2 r_{ji}^2 + E_j^2}{|\mathbf{p}_i|^2|\mathbf{p}_j|} + \frac{(1+r_{ji})^2}{2|\mathbf{p}_i|}\frac{E_iE_j}{|\mathbf{p}_i||\mathbf{p}_j|} + \frac{(1-r_{ji})^2}{2|\mathbf{p}_i|}\left(1 - \frac{m_i^2 r_{ji}}{|\mathbf{p}_i||\mathbf{p}_j|}\right)\right]$$

Cosmological Constraint

When converting this bound to that on the coupling constant, we have

$$g \lesssim (1.6 \cdots 5.0) \times 10^{-10} \text{ (for } \nu_3) , \quad g \lesssim (0.4 \cdots 1.3) \times 10^{-7} \text{ (for } \nu_2) , \qquad (2.39)$$

in the NO case. In the IO case, we get $g \lesssim (2 \cdots 6) \times 10^{-10}$ for both ν_1 and ν_2, since they are almost degenerate in mass. If the masses of daughter neutrinos are taken into account, a phase-space factor comes into play and the constraint on the lifetime will be weakened [43]. The revised bound on the coupling constant reads

$$g \lesssim 3.2 \times 10^{-10} \text{ (for } \nu_3) , \quad g \lesssim 5.0 \times 10^{-8} \text{ (for } \nu_2) \qquad (2.40)$$

in the NO case, while $g \lesssim 4 \times 10^{-10}$ in the IO case.

Chen, Oldengott, Pierobon & Wong, *EPJC 82 (2022) 7, 640*

$$\mathscr{L} = \frac{iJ}{2f} \sum_{i=1}^{3} m_i \bar{\nu}_i \gamma^5 \nu_i \qquad f \sim m_N$$

Other Constraints on *g*

- Other constraints on the coupling g come from **terrestrial experiments** and **astrophysical observations**.
- The interaction gives rise to the $0\nu\beta\beta$ decays with an extra scalar ϕ. The non-observation of such a signal in the EXO-200 experiment provides a constraint on the coupling constant $g \lesssim (0.4\cdots0.9)\times10^{-5}$ [Kharusi et al., *PRD 104 (2021) 11, 112002*]
- Astrophysical constraints on the coupling can also be derived from:
  - ✓ **BBN**: Ahlgren, Ohlsson & Zhou, *PRL 111 (2013) 19, 199001*; Huang, Ohlsson & Zhou, *PRD 97 (2018) 7, 075009*; Escudero & Witte, *EPJC 80 (2020) 4, 294*; Venzor, Pérez-Lorenzana & De-Santiago, *PRD 103 (2021) 4, 043534*
  - ✓ **SN1987A**: Kolb & Turner, *PRD 36 (1987) 2895*; Alekseev, Alekseeva, Krivosheina & Volchenko, *PLB 205 (1988) 209*; Farzan, *PRD 67 (2003) 073015*; Zhou, *PRD 84 (2011) 038701*; Shalgar, Tamborra & Bustamante, *PRD 103 (2021) 12, 123008*; Fiorillo, Raffelt & Vitagliano, *PRL 131 (2023) 2, 021001*; Fiorillo, Raffelt & Vitagliano, *PRL 132 (2024) 2, 021002*; Akita, Im, Masud & Yun, *JHEP 07 (2024) 057*; Martínez-Miravé, Tamborra & Tórtola, *JCAP 05 (2024) 002*
  - ✓ **Solar neutrinos**: Bahcall, Cabibbo & Yahil, *PRL 28 (1972) 316*; Berezhiani, Fiorentini, Moretti & Rossi, *ZPC 54 (1992) 581*; Cleveland et al., *Astrophys.J. 496 (1998) 505*; Beacom & Bell, *PRD 65 (2002) 113009*; SAGE collaboration, *PRC 80 (2009) 015807*; Bellini et al., *PRL 107 (2011) 141302*; KamLAND collaboration, *PRC 84 (2011) 035804*; *Phys.Rev.C 92 (2015) 5, 055808*; Super-Kamiokande collaboration, *PRD 94 (2016) 5, 052010*; Borexino collaboration, *PRD 101 (2020) 6, 062001*; SNO collaboration, *PRD 99 (2019) 3, 032013*; Huang & Zhou, *JCAP 02 (2019) 024*
  - ✓ **Atmospheric and long-baseline accelerator neutrinos**: Lipari & Lusignoli, *PRD 60 (1999) 013003*; Fogli, Lisi, Marrone & Scioscia, *PRD 59 (1999) 117303*; Gonzalez-Garcia & Maltoni, *PLB 663 (2008) 405*; Gomes, Gomes & Peres, *PLB 740 (2015) 345*; Choubey, Dutta & Pramanik, *JHEP 08 (2018) 141*
  - ✓ **High-energy astrophysical neutrinos**: Ng & Beacom, *PRD 90 (2014) 6, 065035*; Shoemaker & Murase, *PRD 93 (2016) 8, 085004*; Denton & Tamborra, *PRL 121 (2018) 12, 121802*; Salas et al., *PLB 789 (2019) 472*; Song et al., *JCAP 04 (2021) 054*; Valera, Fiorillo, Esteban & Bustamante, *PRD 110 (2024) 4, 043004*

Secondary distribution

The distribution function of the final-state ν_j in helicity-changing decay $\nu_i(p_i, \pm) \to \nu_j(p_j, \mp) + \phi$ is

$$f_j(E_j) = \int_{l(E_j)}^{\infty} \mathrm{d}E_i \; f_i(E_i) \times \frac{1}{\Gamma^{\mathrm{M}}_{\pm,i}} \frac{\mathrm{d}\Gamma^{\mathrm{M}}_{\pm\mp,ij}}{\mathrm{d}E_j}$$

Lipari, Lusignoli & Meloni, *PRD 75 (2007) 123005*

Here $f_i(E_i)$ is the energy distribution function of parent neutrinos and $l(E_j) = \frac{E_j}{2}\left(1 + \frac{1}{r_{ji}^2}\right) + \frac{|\mathbf{p}_j|}{2}\left(1 - \frac{1}{r_{ji}^2}\right)$