Decaying Neutrinos In Cosmology

Isabel M. Oldengott,

Gabriela Barenboim, Joe Zhiyu Chen, Steen Hannestad,
Giovanni Pierobon, Thomas Tram, Yvonne Y. Y. Wong

***CP3, Université catholique de Louvain**

arXiv: 2203.09075, 2011.01502

I) Why neutrino decay?

I) Why neutrino decay?

Neutrino oscillations

→ Standard model of particle physics has to be extended

→ new particles/new interactions naturally appear

I) Why neutrino decay?

Neutrino oscillations

→ Standard model of particle physics has to be extended

→ new particles/new interactions naturally appear

Here: Effective Lagrangian

$$\boxed{\mathcal{L}_{\text{int}} = \mathfrak{g}_{ij}\bar{\nu}_i\nu_j\phi}$$

here: assume massless ϕ

I) Why neutrino decay?

Neutrino oscillations

→ Standard model of particle physics has to be extended

→ new particles/new interactions naturally appear

Here: Effective Lagrangian

$$\boxed{\mathcal{L}_{\text{int}} = \mathfrak{g}_{ij}\bar{\nu}_i\nu_j\phi}$$

here: assume massless ϕ

Universal coupling:

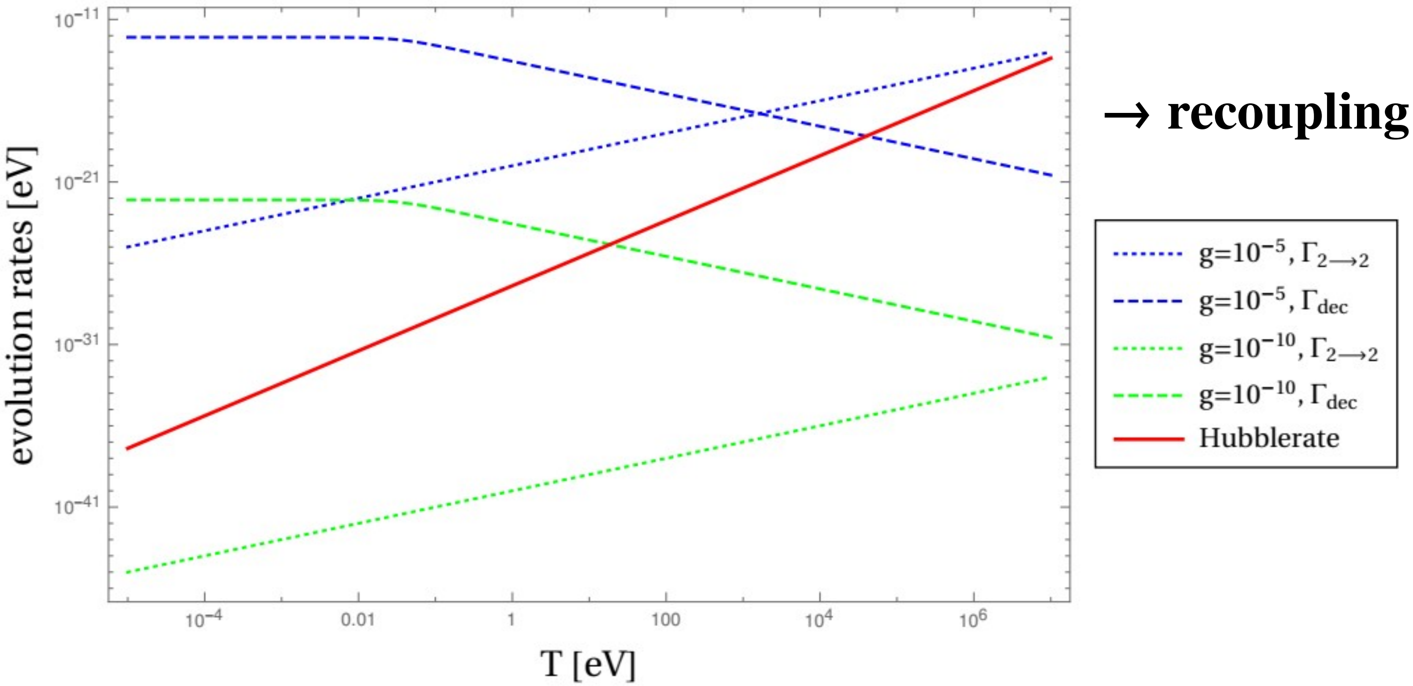
$$\mathfrak{g}_{ij} = \mathfrak{g}\begin{pmatrix} 1 & 1 & 1 \\ 1 & 1 & 1 \\ 1 & 1 & 1 \end{pmatrix}$$

New interactions:

- **Invisible neutrino decay**

$$\nu_H \to \nu_l + \phi$$

- 2 ↔ 2 processes



→ recoupling

I) Why neutrino decay?

Neutrino oscillations

→ Standard model of particle physics has to be extended

→ new particles/new interactions naturally appear

Here: Effective Lagrangian

$$\boxed{\mathcal{L}_{\rm int} = \mathfrak{g}_{ij}\bar{\nu}_i\nu_j\phi}$$

here: assume massless ϕ

Universal coupling:

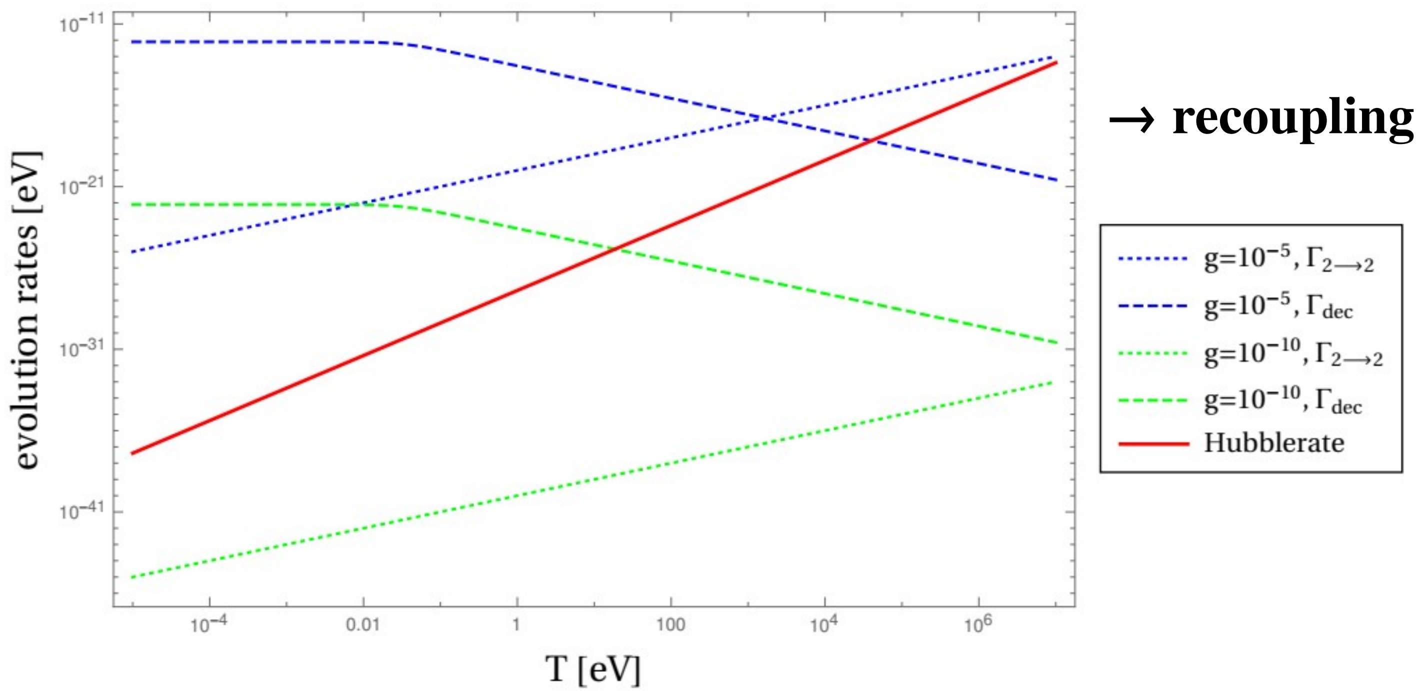
$$\mathfrak{g}_{ij} = \mathfrak{g}\begin{pmatrix} 1 & 1 & 1 \\ 1 & 1 & 1 \\ 1 & 1 & 1 \end{pmatrix}$$

New interactions:

- **Invisible neutrino decay**

$$\nu_H \to \nu_l + \phi$$

- 2 ↔ 2 processes



→ recoupling

for small couplings → invisible **decay dominant process**

II) Why cosmology?

II) Why cosmology?

Neutrino mass:

$m_\nu < \mathcal{O}(1\,\mathrm{eV})$

$$\Gamma_{\mathrm{dec}} = \frac{1}{\gamma\tau_0}$$
$$= \frac{\mathfrak{g}^2}{4\pi} m_{\nu H} \boxed{\left(\frac{m_{\nu H}}{E_{\nu H}}\right)}$$

Life time gets time dilated,
decay rate contracted

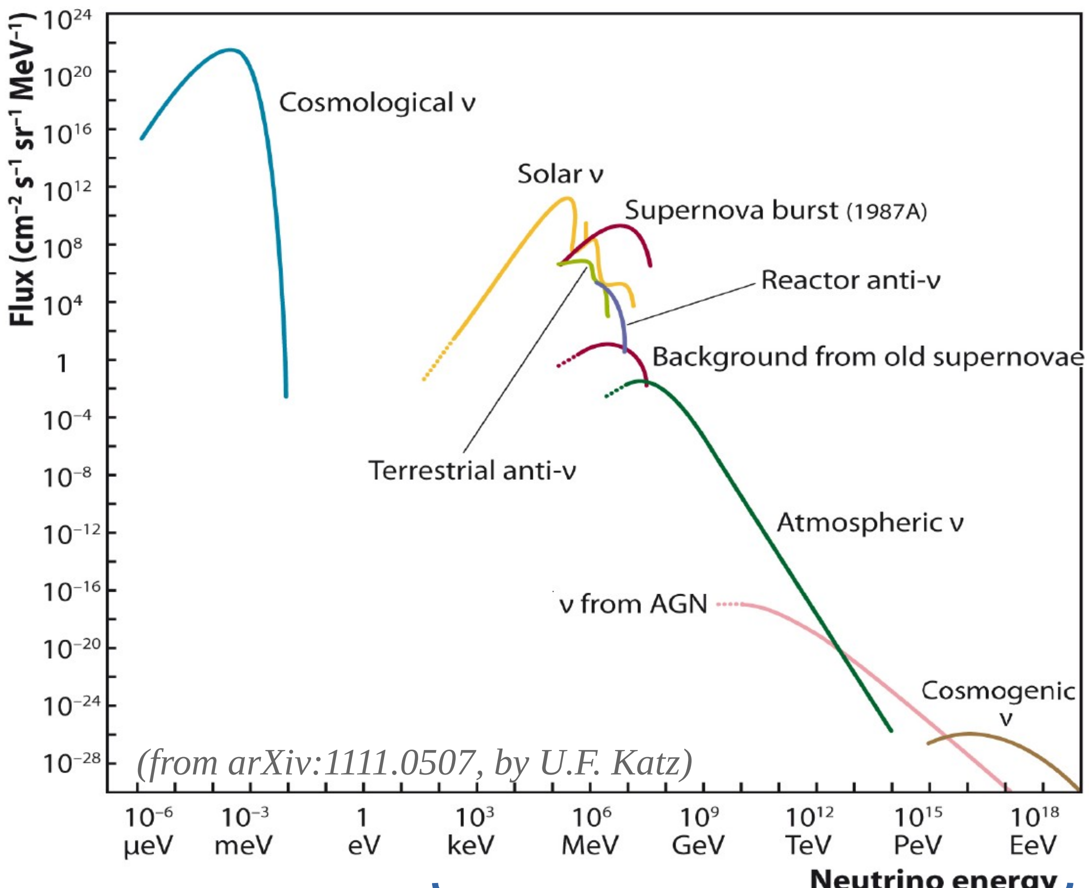
II) Why cosmology?

Neutrino mass:

$$m_\nu < \mathcal{O}(1\,\mathrm{eV})$$

$$\Gamma_{\rm dec} = \frac{1}{\gamma \tau_0} = \frac{\mathfrak{g}^2}{4\pi} m_{\nu H} \boxed{\left(\frac{m_{\nu H}}{E_{\nu H}}\right)}$$

Life time gets time dilated, decay rate contracted



$\underbrace{\hspace{5cm}}$

γ-factor: $10^3 - 10^{17}$

→ **strongly suppressed**

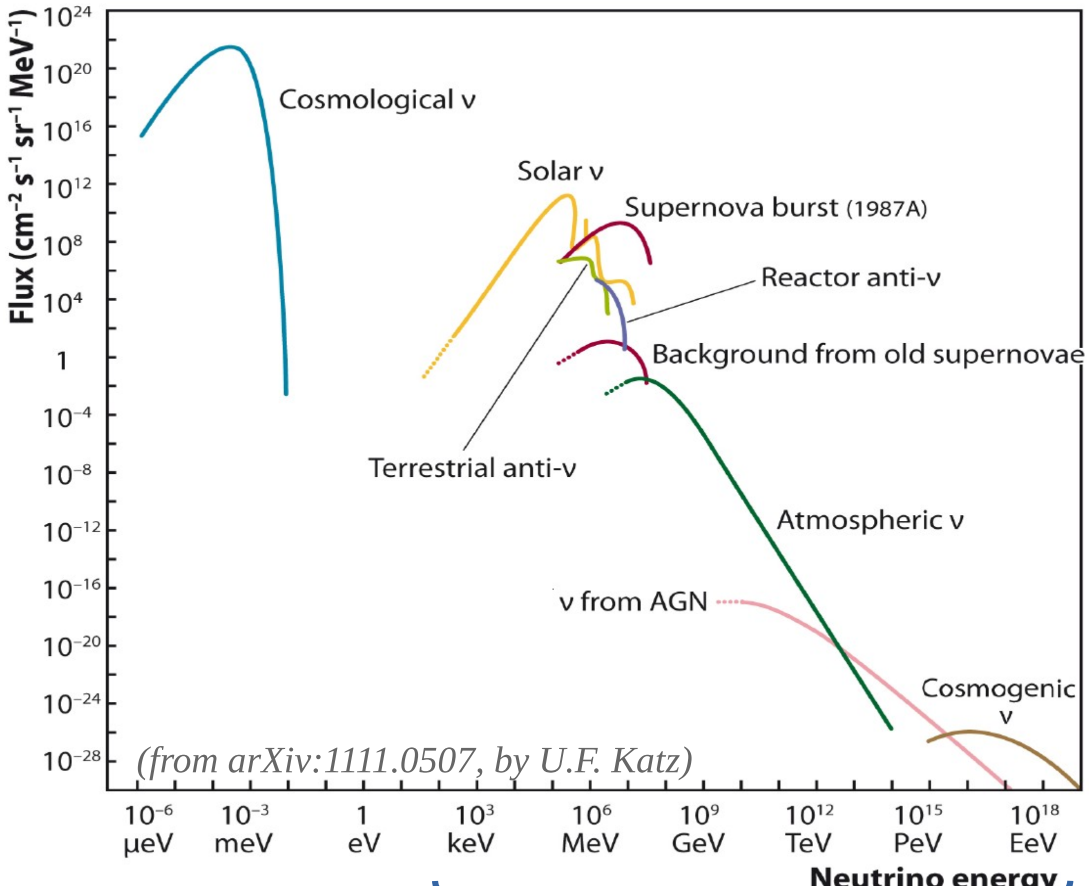
II) Why cosmology?

Neutrino mass:

$$m_\nu < \mathcal{O}(1\,\mathrm{eV})$$

$$\Gamma_{\mathrm{dec}} = \frac{1}{\gamma\tau_0} = \frac{\mathfrak{g}^2}{4\pi} m_{\nu H} \boxed{\left(\frac{m_{\nu H}}{E_{\nu H}}\right)}$$

Life time gets time dilated,
decay rate contracted



γ-factor: $10^3 - 10^{17}$

→ **strongly suppressed**

CMB: T_ν~0.1 eV → Cosmological probes can potentially give the strongest constraints

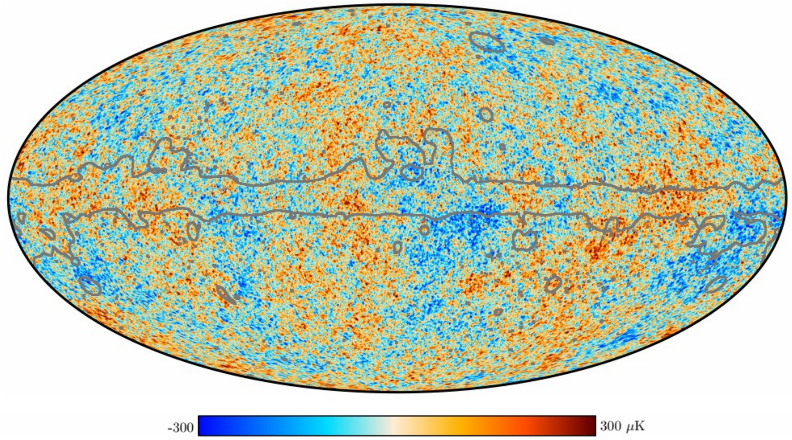
How does neutrino decay impact the Cosmic Microwave Background (CMB)?

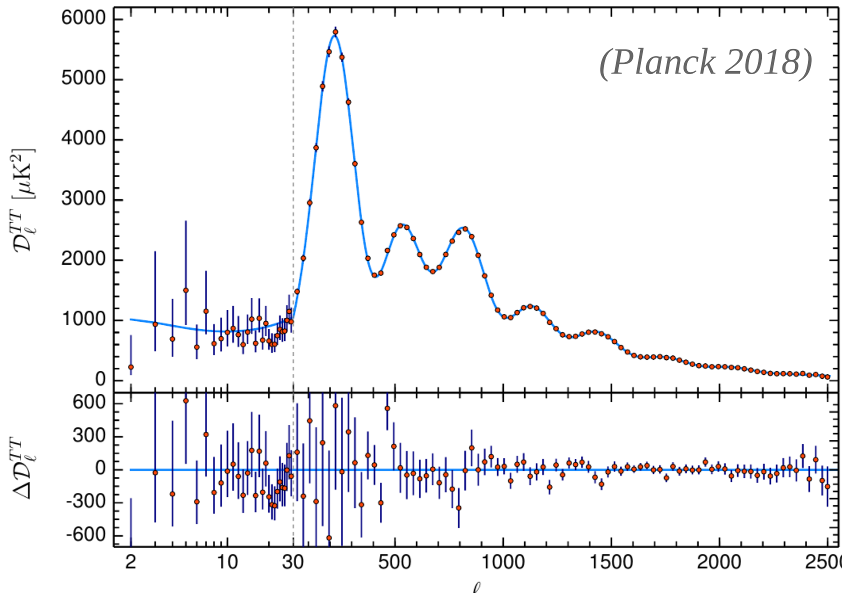
Recombination (~ 0.3 eV) → Universe gets transparent to photons

How does neutrino decay impact the Cosmic Microwave Background (CMB)?

Recombination (~ 0.3 eV) → Universe gets transparent to photons

(Redshifted) photo of the early Universe

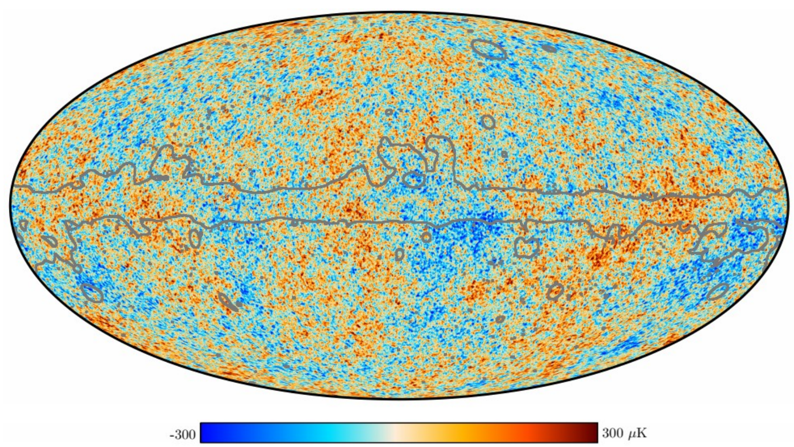


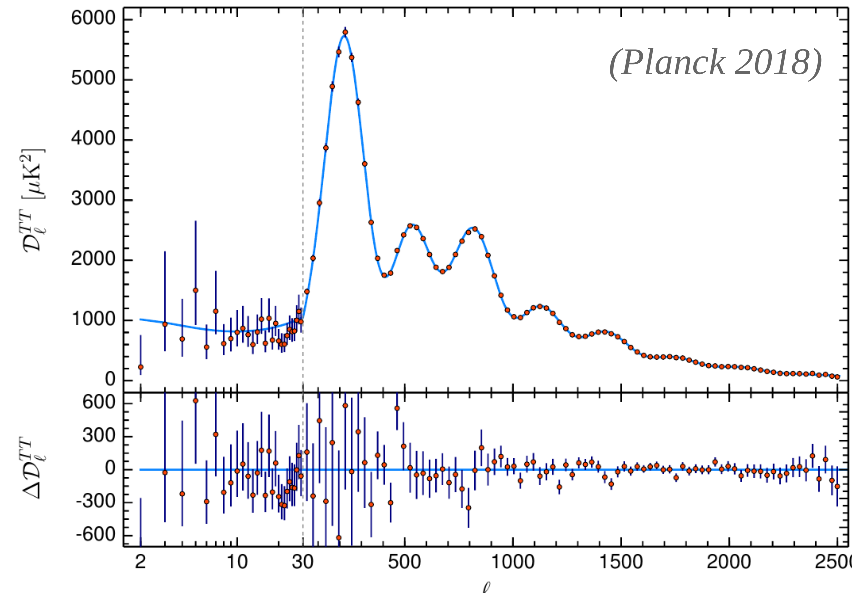


How does neutrino decay impact the Cosmic Microwave Background (CMB)?

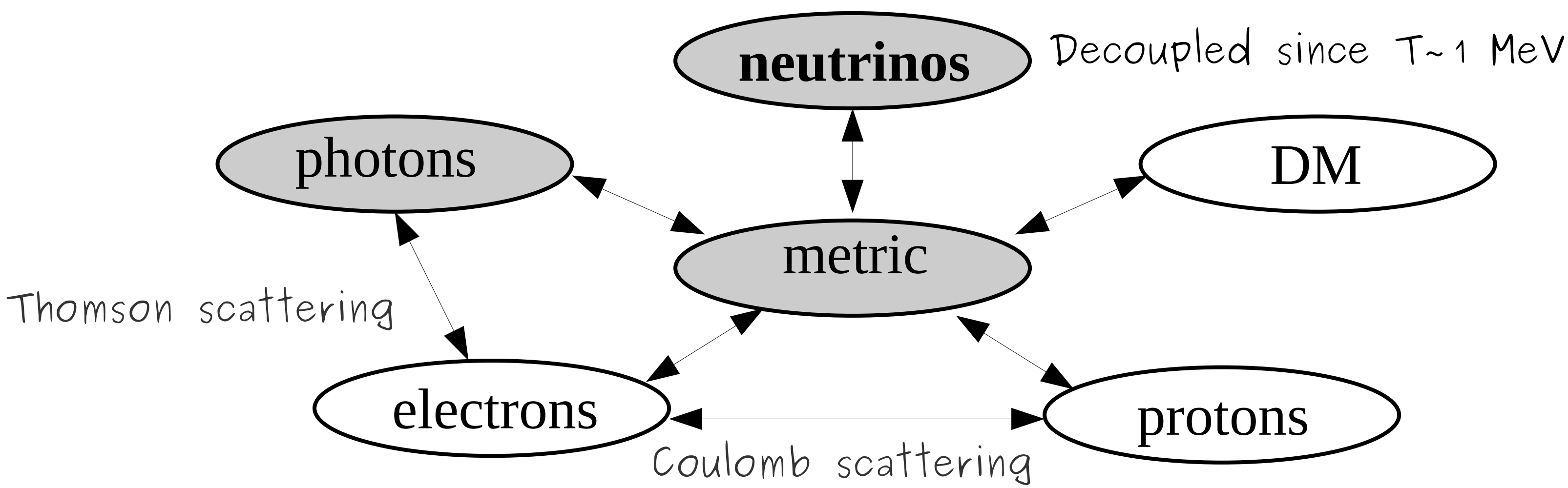
Recombination (~ 0.3 eV) → Universe gets transparent to photons

(Redshifted) photo of the early Universe





→ Fluctuations in the photon temperature/density:



Let's be more technical... → **Cosmic perturbation theory:**

1) Perturbed Einstein equation: $\bar{G}_{\mu\nu} + \delta G_{\mu\nu} = 8\pi G(\bar{T}_{\mu\nu} + \delta T_{\mu\nu})$

2) Perturbed phase-space distribution $f(\mathbf{k}, \mathbf{q}, \tau) = \bar{f}(q, \tau)\,(1 + \Psi(\mathbf{k}, \mathbf{q}, \tau))$

Perturbed Boltzmann equation:

$$\boxed{\dot{\Psi}(\mathbf{k}, \mathbf{q}, \tau) + \mathrm{i}\frac{|\mathbf{q}||\mathbf{k}|}{\epsilon}(\hat{k}\cdot\hat{q})\,\Psi(\mathbf{k}, \mathbf{q}, \tau) + \frac{\partial \ln \bar{f}_i(|\mathbf{q}|, \tau)}{\partial \ln |\mathbf{q}|}\left[\dot{\tilde{\eta}} - (\hat{k}\cdot\hat{q})^2\,\frac{\dot{h} + 6\dot{\tilde{\eta}}}{2}\right] = \mathcal{C}[\Psi]}$$

Let's be more technical... → **Cosmic perturbation theory:**

1) Perturbed Einstein equation: $$\bar{G}_{\mu\nu} + \delta G_{\mu\nu} = 8\pi G(\bar{T}_{\mu\nu} + \delta T_{\mu\nu})$$

2) Perturbed phase-space distribution $$f(\mathbf{k}, \mathbf{q}, \tau) = \bar{f}(q, \tau)\,(1 + \Psi(\mathbf{k}, \mathbf{q}, \tau))$$

Perturbed Boltzmann equation:

standard free-streaming case

$$\boxed{\dot{\Psi}(\mathbf{k}, \mathbf{q}, \tau) + \mathrm{i}\,\frac{|\mathbf{q}||\mathbf{k}|}{\epsilon}(\hat{k}\cdot\hat{q})\,\Psi(\mathbf{k}, \mathbf{q}, \tau) + \frac{\partial \ln \bar{f}_i(|\mathbf{q}|, \tau)}{\partial \ln |\mathbf{q}|}\left[\dot{\tilde{\eta}} - (\hat{k}\cdot\hat{q})^2\,\frac{\dot{h} + 6\dot{\tilde{\eta}}}{2}\right] = \cancel{C[\Psi]}}$$

Let's be more technical... → **Cosmic perturbation theory:**

1) Perturbed Einstein equation: $\bar{G}_{\mu\nu} + \delta G_{\mu\nu} = 8\pi G(\bar{T}_{\mu\nu} + \delta T_{\mu\nu})$

2) Perturbed phase-space distribution $f(\mathbf{k}, \mathbf{q}, \tau) = \bar{f}(q, \tau)\,(1 + \Psi(\mathbf{k}, \mathbf{q}, \tau))$

Perturbed Boltzmann equation:

standard free-streaming case

$$\boxed{\dot{\Psi}(\mathbf{k}, \mathbf{q}, \tau) + \mathrm{i}\frac{|\mathbf{q}||\mathbf{k}|}{\epsilon}(\hat{k}\cdot\hat{q})\,\Psi(\mathbf{k}, \mathbf{q}, \tau) + \frac{\partial \ln \bar{f}_i(|\mathbf{q}|, \tau)}{\partial \ln |\mathbf{q}|}\left[\dot{\tilde{\eta}} - (\hat{k}\cdot\hat{q})^2\,\frac{\dot{h} + 6\dot{\tilde{\eta}}}{2}\right] = \cancel{\mathcal{C}[\Psi]}}$$

Decompose phase-space perturbation into Legendre polynomials:

$$\Psi(|\mathbf{k}|, |\mathbf{q}|, \hat{k}\cdot\hat{q}) = \sum_{\ell=0}(-i)^{\ell}(2\ell+1)\Psi_{\ell}(|\mathbf{k}|, |\mathbf{q}|)P_{\ell}(\hat{k}\cdot\hat{q})$$

→ Neutrino Boltzmann hierarchy:

$$\dot{\Psi}_0 = -\frac{qk}{\epsilon}\Psi_1 + \frac{1}{6}\dot{h}\frac{d\ln f_0}{d\ln q} + \cancel{\mathcal{C}[\Psi_0]},$$

free-streaming

$$\dot{\Psi}_1 = \frac{qk}{3\epsilon}(\Psi_0 - 2\Psi_2) + \cancel{\mathcal{C}[\Psi_1]},$$

$$\dot{\Psi}_2 = \frac{qk}{5\epsilon}(2\Psi_1 - 3\Psi_3) - \left(\frac{1}{15}\dot{h} + \frac{2}{5}\dot{\eta}\right)\frac{d\ln f_0}{d\ln q} + \cancel{\mathcal{C}[\Psi_2]},$$

$$\dot{\Psi}_{\ell\geq 3} = \frac{qk}{(2\ell+1)\epsilon}\left[\ell\Psi_{\ell-1} - (\ell+1)\Psi_{\ell+1}\right] + \cancel{\mathcal{C}[\Psi_\ell]}$$

Neutrino decay → Calculate collision integral

*G. Barenboim, J. Chen, S. Hannestad, **IMO**, T. Tram, Y. Wong arXiv: 2011.01502*

Background Boltzmann:

$$\frac{\partial \bar{f}_{\nu H}}{\partial \tau} = \frac{a^2(m_{\nu H}+m_{\nu l})}{\tau_0\,\epsilon_1\,q_1}\left[\underbrace{-q_1\frac{(m_{\nu H}^2-m_{\nu l}^2)}{m_{\nu H}^2}\bar{f}_{\nu H}(q_1)}_{\text{dec}}+\underbrace{\int_{q_{2,-}}^{q_{2,+}}\mathrm{d}q_2\,\frac{q_2}{\epsilon_2}\,\bar{f}_{\nu l}(q_2)\,\bar{f}_\phi(\epsilon_1-\epsilon_2)}_{\text{inv}}+\underbrace{\bar{f}_{\nu H}(q_1)\left(\int_{q_{2,-}}^{q_{2,+}}\mathrm{d}q_2\,\frac{q_2}{\epsilon_2}\,\bar{f}_{\nu l}(q_2)-\int_{q_{3,-}}^{q_{3,+}}\mathrm{d}q_3\,\bar{f}_\phi(q_3)\right)}_{\text{qs}}\right]$$

$$\frac{\partial \bar{f}_{\nu l}}{\partial \tau} = \frac{a^2(m_{\nu H}+m_{\nu l})}{\tau_0\epsilon_2 q_2}\left[\underbrace{\int_{q_{1,-}}^{q_{1,+}}\mathrm{d}q_1\,\frac{q_1}{\epsilon_1}\,\bar{f}_{\nu H}(q_1)}_{\text{dec}}-\underbrace{\bar{f}_{\nu l}(q_2)\int_{q_{3,-}}^{q_{3,+}}\mathrm{d}q_3\,\bar{f}_\phi(q_3)}_{\text{inv}}+\underbrace{\int_{q_{1,-}}^{q_{1,+}}\mathrm{d}q_1\,\frac{q_1}{\epsilon_1}\,\left(\bar{f}_{\nu H}(q_1)\,\bar{f}_\phi(\epsilon_1-\epsilon_2)-\bar{f}_{\nu H}(q_1)\,\bar{f}_{\nu l}(q_2)\right)}_{\text{qs}}\right]$$

$$\frac{\partial \bar{f}_{\phi}}{\partial \tau} = \frac{2a^2(m_{\nu H}+m_{\nu l})}{\tau_0 q_3^2}\left[\underbrace{\int_{\bar{q}_1}\mathrm{d}q_1\,\frac{q_1}{\epsilon_1}\,\bar{f}_{\nu H}(q_1)}_{\text{dec}}-\underbrace{\bar{f}_\phi(q_3)\int_{\bar{q}_2}\mathrm{d}q_2\,\frac{q_2}{\epsilon_2}\,\bar{f}_{\nu l}(q_2)}_{\text{inv}}+\underbrace{\int_{\bar{q}_1}\mathrm{d}q_1\,\frac{q_1}{\epsilon_1}\,\left(\bar{f}_{\nu H}(q_1)\,\bar{f}_\phi(q_3)-\bar{f}_{\nu H}(q_1)\,\bar{f}_{\nu l}\left(\sqrt{(\epsilon_1-q_3)^2-a^2m_{\nu l}^2}\right)\right)}_{\text{qs}}\right]$$

Perturbation equations:

$$\mathcal{C}^1[\Psi_{\nu H,\ell}(q_1)] = \frac{a^2(m_{\nu H}+m_{\nu l})}{\tau_0 \epsilon_1 q_1 \bar{f}_{\nu H}} \Bigg[\underbrace{\int_{q_{2,-}}^{q_{2,+}} \mathrm{d}q_2 \frac{q_2}{\epsilon_2} \left(K_\ell(q_1,q_2)\Psi_{\nu l,\ell} - \bar{f}_{\nu H}\Psi_{\nu H,\ell}\right) \bar{f}_{\nu l}(q_2) \bar{f}_\phi\left(\epsilon_1 - \epsilon_2\right)}_{\text{inv}}$$

$$+ \underbrace{\int_{\bar{q}_{3,-}}^{\bar{q}_{3,+}} \mathrm{d}q_3 L_\ell(q_1,q_3)\Psi_{\phi,\ell}\bar{f}_\phi(q_3)\bar{f}_{\nu l}\left(\sqrt{(\epsilon_1-q_3)^2 - a^2 m_{\nu l}^2}\right)}_{\text{inv}}$$

$$+ \underbrace{\bar{f}_{\nu H}(q_1)\left(\int_{q_{2,-}}^{q_{2,+}} \mathrm{d}q_2 \frac{q_2}{\epsilon_2} K_\ell(q_1,q_2)\Psi_{\nu l,\ell}\bar{f}_{\nu l}(q_2) - \int_{\bar{q}_{3,-}}^{\bar{q}_{3,+}} \mathrm{d}q_3 L_\ell(q_1,q_3)\Psi_{\phi,\ell}\bar{f}_\phi(q_3)\right)}_{\text{qs}} \Bigg]$$

$$\mathcal{C}^1[\Psi_{\nu l,\ell}(q_2)] = \frac{a^2(m_{\nu H}+m_{\nu l})}{\tau_0 \epsilon_2 q_2 \bar{f}_{\nu l}} \Bigg[\underbrace{\int_{q_{1,-}}^{q_{1,+}} \mathrm{d}q_1 \frac{q_1}{\epsilon_1} \left(K_\ell(q_2,q_1)\Psi_{\nu H,\ell} - \bar{f}_{\nu l}(q_2)\Psi_{\nu l,\ell}\right) \bar{f}_{\nu H}(q_1)}_{\text{dec}}$$

$$\underbrace{- \bar{f}_{\nu l}(q_2)\int_{q_{3,-}}^{q_{3,+}} \mathrm{d}q_3 L_\ell(q_2,q_3)\bar{f}_\phi(q_3)\Psi_{\phi,\ell}}_{\text{inv}}$$

$$+ \underbrace{\int_{q_{1,-}}^{q_{1,+}} \mathrm{d}q_1 \frac{q_1}{\epsilon_1} K_\ell(q_2, q_1 \bar{f}_{\nu H}(q_1)\Psi_{\nu H,\ell}\left(\bar{f}_\phi(\epsilon_1-\epsilon_2) - \bar{f}_{\nu l}(q_2)\right)}_{\text{qs}}$$

$$+ \underbrace{\int_{q_{3,-}}^{q_{3,+}} \mathrm{d}q_3 \left(L_\ell(q_2,q_3)\Psi_{\phi,\ell} - \Psi_{\nu l,\ell}\right)\bar{f}_\phi(q_3)\bar{f}_{\nu H}\left(\sqrt{(\epsilon_2+q_3)^2 - a^2 m_{\nu H}^2}\right)}_{\text{qs}} \Bigg]$$

+ similar for ϕ

haven't solved yet...

In principle: Implement equations in linear Einstein-Boltzmann solver

In practice: This is <u>extremely</u> hard...

In principle: Implement equations in linear Einstein-Boltzmann solver

In practice: This is extremely hard...

Study equations in limiting regimes:

Non-relativistic decay

relativistic decay

G. F. Abellán et al, arXiv: 2112.13862; Z. Chacko et al. arXiv:1909.05275; Z. Chacko et al. ArXiv:2002.08401; M. Kaplinghat et al. arXiv:9907388

In principle: Implement equations in linear Einstein-Boltzmann solver

In practice: This is extremely hard...

Study equations in limiting regimes:

NON-RELATIVISTIC DECAY

RELATIVISTIC DECAY

G. F. Abellán et al, arXiv: 2112.13862; Z. Chacko et al. arXiv:1909.05275; Z. Chacko et al. ArXiv:2002.08401; M. Kaplinghat et al. arXiv:9907388

In a nutshell

- We found an **inconsistency in the perturbation equations** in previous literature (→ violation of momentum conservation) *(arXiv: 2011.01502)*

In principle: Implement equations in linear Einstein-Boltzmann solver

In practice: This is extremely hard...

Study equations in limiting regimes:

NON-RELATIVISTIC DECAY

RELATIVISTIC DECAY

G. F. Abellán et al, arXiv: 2112.13862; Z. Chacko et al. arXiv:1909.05275; Z. Chacko et al. ArXiv:2002.08401; M. Kaplinghat et al. arXiv:9907388

In a nutshell

- We found an **inconsistency in the perturbation equations** in previous literature (→ violation of momentum conservation) *(arXiv: 2011.01502)*
- However, the main effect comes from the background equations:

G. F. Abellán et al, arXiv: 2112.13862 → missing term in perturbation eqs. not that important

→ Former findings remain valid: Transfer of energy from matter to radiation sector

→ strong degeneracy between τ_0 and m_ν

→ **relaxation of cosmological neutrino mass bound**

RELATIVISTIC DECAY

At background level: Transfer energy from one relativistic species to another

→ no impact

RELATIVISTIC DECAY

At background level: Transfer energy from one relativistic species to another

→ no impact

At perturbation level, expect: decay and inverse decay isotropize ν-ϕ fluid

→ suppression of anisotropic stress and higher multipoles

→ enhancement of neutrino monopole/perturbed energy density

RELATIVISTIC DECAY

At background level: Transfer energy from one relativistic species to another

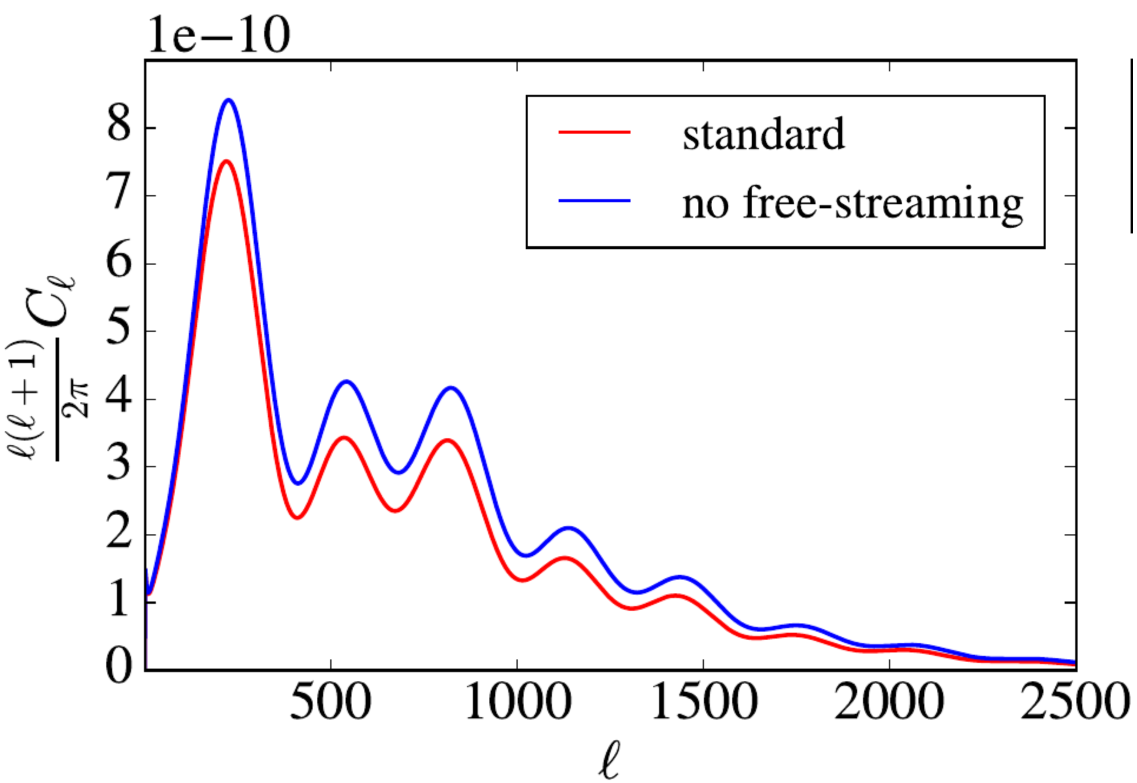
$\rightarrow$ no impact

At perturbation level, expect: decay and inverse decay isotropize ν-ϕ fluid

$\rightarrow$ suppression of anisotropic stress and higher multipoles

$\rightarrow$ enhancement of neutrino monopole/perturbed energy density

$\rightarrow$ enhancement of temperature anisotropies



What's the rate of supression of the anisotropic stress?

$$\dot{\Psi}_{2,\nu\phi} = ... - a\Gamma_T \Psi_{2,\nu\phi} \qquad \Rightarrow \qquad \Gamma_T = ???$$

What's the rate of supression of the anisotropic stress?

$$\dot{\Psi}_{2,\nu\phi} = ... - a\Gamma_T \Psi_{2,\nu\phi} \qquad \Rightarrow \qquad \Gamma_T = ???$$

Former works:

S. Hannestad and G. Raffelt arXiv:hep-ph/0509278, M. Escudero and M. Fairbairn arXiv:1907.05425 [hep-ph], M. Archidiacono and S. Hannestad arXiv:1311.3873

$$\Gamma_{\mathrm{T}} \simeq \Gamma^0_{\mathrm{dec}} \left(\frac{m_{\nu H}}{E_{\nu H}} \right)^3 \qquad \Rightarrow \qquad \tau_0 \geq \mathcal{O}\left(10^9\right)\ \mathrm{s} \left(\frac{m_\nu}{50\,\mathrm{meV}} \right)^3$$

Extra γ^{-2} suppression due to co-linear decay products.

What's the rate of supression of the anisotropic stress?

$$\dot{\Psi}_{2,\nu\phi} = \ldots - a\Gamma_T \Psi_{2,\nu\phi} \quad \Rightarrow \quad \Gamma_T = ???$$

Former works:

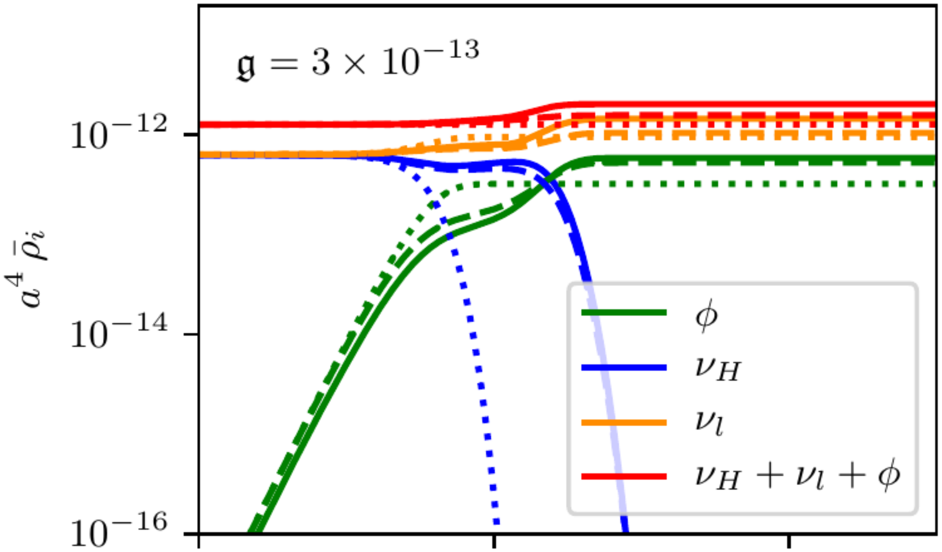
S. Hannestad and G. Raffelt arXiv:hep-ph/0509278, M. Escudero and M. Fairbairn arXiv:1907.05425 [hep-ph], M. Archidiacono and S. Hannestad arXiv:1311.3873

$$\Gamma_{\mathrm{T}} \simeq \Gamma^0_{\mathrm{dec}} \left(\frac{m_{\nu H}}{E_{\nu H}}\right)^3 \quad \Rightarrow \quad \tau_0 \geq \mathcal{O}\left(10^9\right)\ \mathrm{s} \left(\frac{m_\nu}{50\,\mathrm{meV}}\right)^3$$

Extra γ^{-2} suppression due to co-linear decay products.

Our critique: **Γ_T motivated from heuristic arguments, seems ad hoc**

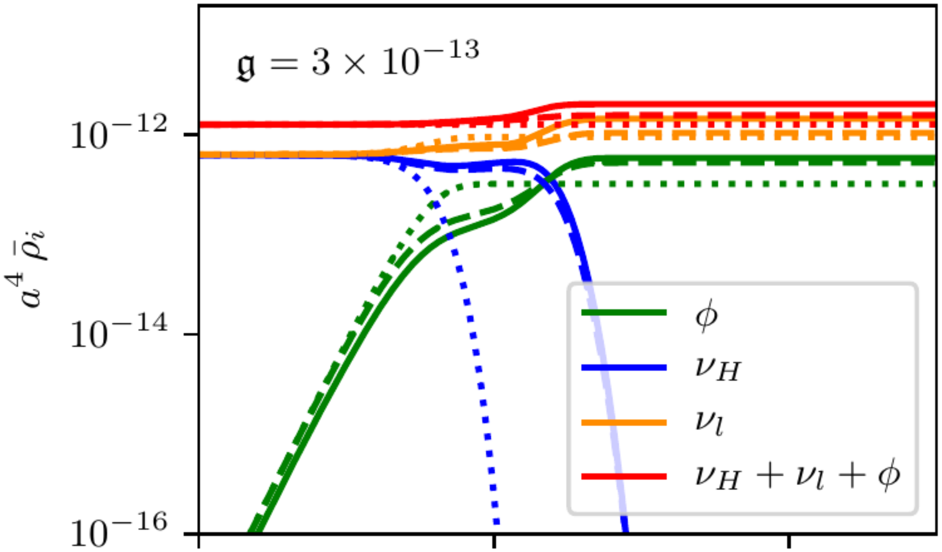
(doubts also in A. Basboll, O. E. Bjaelde et al. arXiv:0806.1735)



Solution of the background Boltzmann equations

Steady-state regime

(larger coupling means steady-state lasts longer)



Solution of the background Boltzmann equations

Steady-state regime

(larger coupling means steady-state lasts longer)

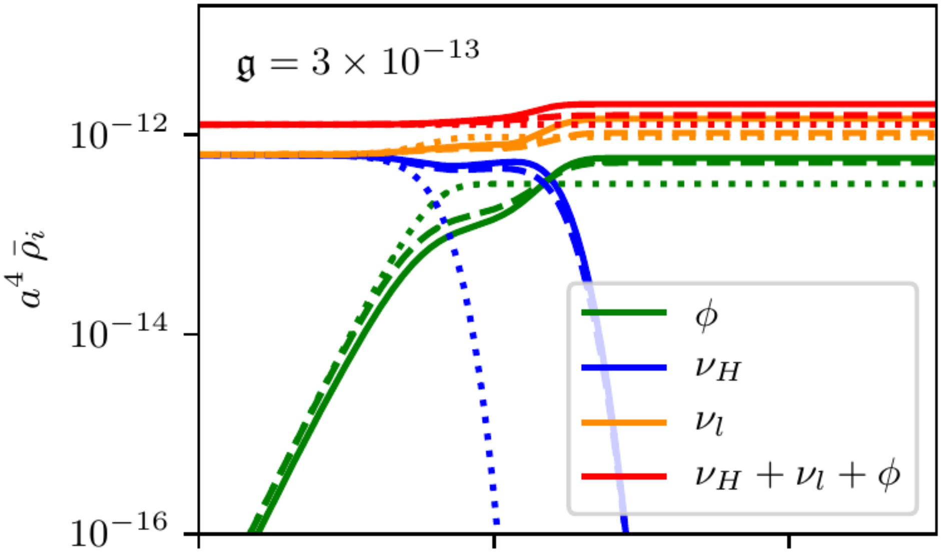
Motivated assumptions (to obtain a closed set of equations)

1) Equilibrium distribution in steady-state phase (Maxwell-Boltzmann)

2) Separable ansatz: $\Psi_{i,\ell}(|\mathbf{k}|, |\mathbf{q}|) \simeq -\frac{1}{4}\frac{\mathrm{d}\ln \bar{f}_i}{\mathrm{d}\ln |\mathbf{q}|}\,\mathcal{F}_{i,\ell}(|\mathbf{k}|)$

Validity in the context of ν-self-interactions demonstrated, IMO et al. arXiv: 1706.02123

3) Same perturbation contrast in all species: $\mathcal{F}_{\nu H,\ell} = \mathcal{F}_{\nu l,\ell} = \mathcal{F}_{\phi,\ell}$



Solution of the background Boltzmann equations

Steady-state regime
(larger coupling means steady-state lasts longer)

Motivated assumptions (to obtain a closed set of equations)

1) Equilibrium distribution in steady-state phase (Maxwell-Boltzmann)

2) Separable ansatz: $\Psi_{i,\ell}(|\mathbf{k}|, |\mathbf{q}|) \simeq -\frac{1}{4}\frac{\mathrm{d}\ln \bar{f}_i}{\mathrm{d}\ln|\mathbf{q}|}\,\mathcal{F}_{i,\ell}(|\mathbf{k}|)$

Validity in the context of ν-self-interactions demonstrated, IMO et al. arXiv: 1706.02123

3) Same perturbation contrast in all species: $\mathcal{F}_{\nu H,\ell} = \mathcal{F}_{\nu l,\ell} = \mathcal{F}_{\phi,\ell}$

massless ν_l

$$\Gamma_{\mathrm{T}} \simeq \Gamma^0_{\mathrm{dec}} \underbrace{\left(\frac{m_{\nu H}}{E_{\nu H}}\right)}_{\text{Extra } \gamma^{-2} \text{ suppression}}{}^{5}$$

Significantly weaker bounds expected (~10^3 weaker)

For realistic mass ordering: $\Gamma_{\rm T} \simeq \Gamma^0_{\rm dec} \left(\frac{\Delta m^2_\nu}{m^2_{\nu H}} \right)^2 \left(\frac{m_{\nu H}}{E_{\nu H}} \right)^5$ $\Rightarrow$ **Additional suppression**

For realistic mass ordering: $\Gamma_{\mathrm{T}} \simeq \Gamma^{0}_{\mathrm{dec}} \left(\frac{\Delta m_\nu^2}{m_{\nu H}^2} \right)^2 \left(\frac{m_{\nu H}}{E_{\nu H}} \right)^5$ $\Rightarrow$ **Additional suppression**

For realistic mass ordering: $\Gamma_{\mathrm{T}} \simeq \Gamma^0_{\mathrm{dec}} \left(\frac{\Delta m_\nu^2}{m_{\nu H}^2}\right)^2 \left(\frac{m_{\nu H}}{E_{\nu H}}\right)^5$ → **Additional suppression**

Which constraints on the neutrino life time from CMB?

→ **performed MCMC analysis with Planck 2018 data**

For realistic mass ordering: $\Gamma_{\rm T} \simeq \Gamma^0_{\rm dec} \left(\frac{\Delta m^2_\nu}{m^2_{\nu H}}\right)^2 \left(\frac{m_{\nu H}}{E_{\nu H}}\right)^5$ → **Additional suppression**

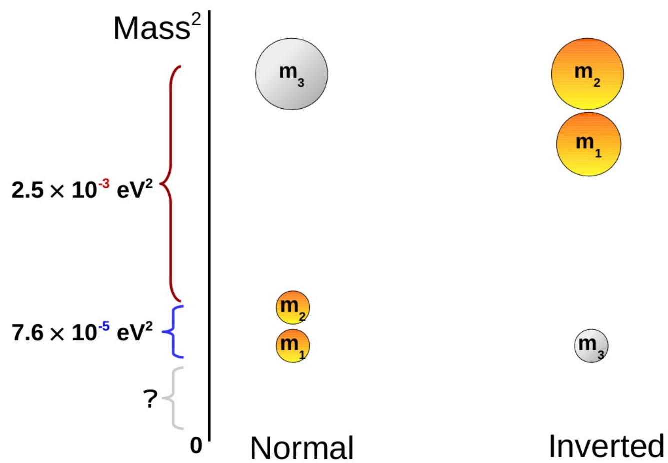
Which constraints on the neutrino life time from CMB?

→ **performed MCMC analysis with Planck 2018 data**

For realistic mass ordering: $\Gamma_{\mathrm{T}} \simeq \Gamma^0_{\mathrm{dec}} \left(\frac{\Delta m_\nu^2}{m_{\nu H}^2}\right)^2 \left(\frac{m_{\nu H}}{E_{\nu H}}\right)^5$ → **Additional suppression**

Which constraints on the neutrino life time from CMB?

→ performed MCMC analysis with Planck 2018 data



- Uniform coupling (→ 2-state approximation):

  $\boldsymbol{\tau_0 \geq (2 \to 6) \times 10^7}$ **s**

- $g_{23} \neq 0$ or $g_{13} \neq 0$ (athmospheric mass gap):

  $\boldsymbol{\tau_0 \geq (6 \to 10) \times 10^5}$ **s**

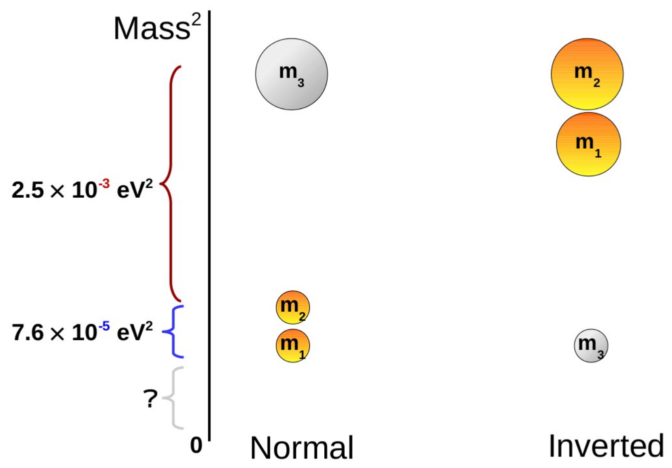
- $g_{12} \neq 0$ (solar mass gap):

  $\boldsymbol{\tau_0 \geq (400 \to 500)}$ **s**

For realistic mass ordering: $$\Gamma_{\mathrm{T}} \simeq \Gamma^0_{\mathrm{dec}} \left(\frac{\Delta m^2_\nu}{m^2_{\nu H}}\right)^2 \left(\frac{m_{\nu H}}{E_{\nu H}}\right)^5$$ → **Additional suppression**

Which constraints on the neutrino life time from CMB?

→ performed MCMC analysis with Planck 2018 data



- Uniform coupling (→ 2-state approximation):

  $\tau_0 \geq (2 \to 6) \times 10^7$ s

- $g_{23} \neq 0$ or $g_{13} \neq 0$ (athmospheric mass gap):

  $\tau_0 \geq (6 \to 10) \times 10^5$ s

- $g_{12} \neq 0$ (solar mass gap):

  $\tau_0 \geq (400 \to 500)$ s

Warning:

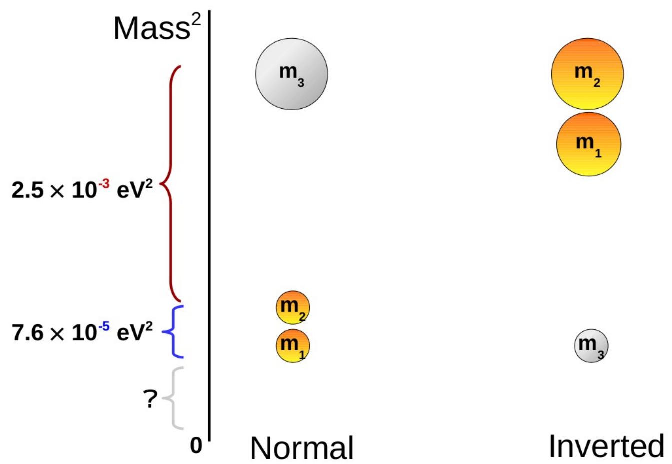
Only valid for relativistic limit

$m_{\nu H} < 0.1$ eV

For realistic mass ordering: $\Gamma_{\mathrm{T}} \simeq \Gamma^0_{\mathrm{dec}} \left(\frac{\Delta m^2_\nu}{m^2_{\nu H}}\right)^2 \left(\frac{m_{\nu H}}{E_{\nu H}}\right)^5$ → **Additional suppression**

Which constraints on the neutrino life time from CMB?

→ **performed MCMC analysis with Planck 2018 data**



- Uniform coupling (→ 2-state approximation):

  $\boldsymbol{\tau_0 \geq (2 \to 6) \times 10^7}$ **s**

- $g_{23} \neq 0$ or $g_{13} \neq 0$ (athmospheric mass gap):

  $\boldsymbol{\tau_0 \geq (6 \to 10) \times 10^5}$ **s**

- $g_{12} \neq 0$ (solar mass gap):

  $\boldsymbol{\tau_0 \geq (400 \to 500)}$ **s**

Warning:

Only valid for relativistic limit

$\boldsymbol{m_{\nu H} < 0.1}$ **eV**

Cosmology bounds significantly weaker than previously stated.

However, globally still the most stringent bounds.