Non-standard neutrino interactions in cosmology

Isabel M. Oldengott (University of Valencia and IFIC)

with G. Barenboim, P. Denton, C. Rampf, T. Tram, Y. Y. Y. Wong

arXiv: 1903.02036, arXiv: 1706.02123, arXiv:1409.1577

Neutrino sector: Clear hint for physics beyond the standard model

Non-standard neutrino interactions

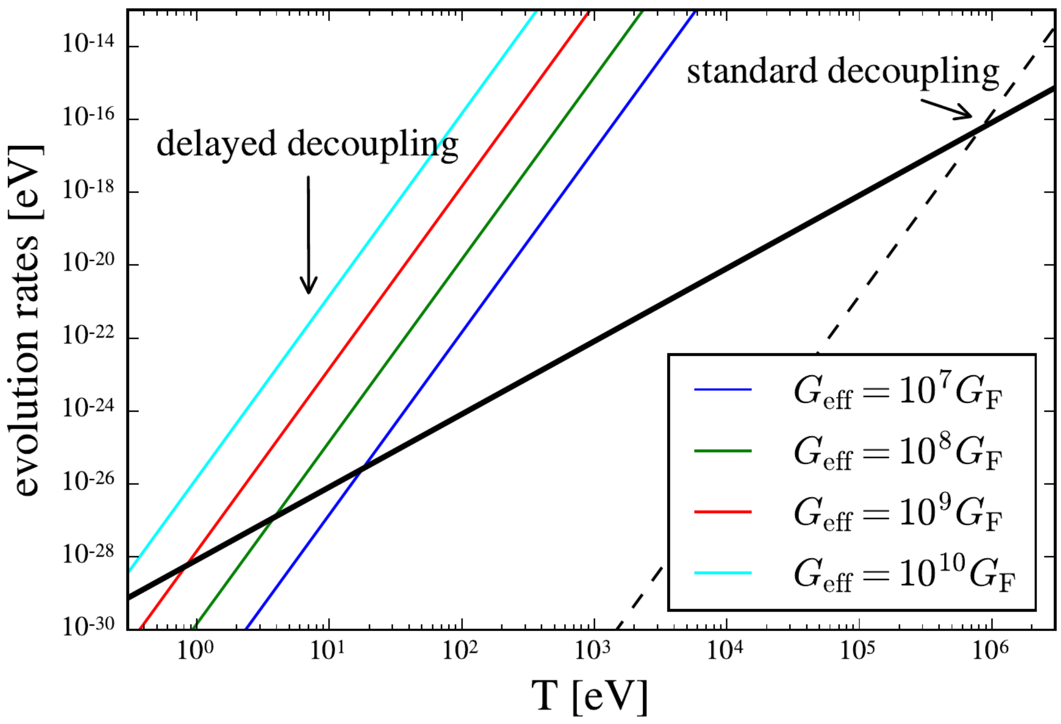
$$\mathcal{L}_{\rm int} = \mathfrak{g}_{ij}\bar{\nu}_i\nu_j\phi + \mathfrak{h}_{ij}\bar{\nu}_i\gamma_5\nu_j\phi$$

Neutrino sector: Clear hint for physics beyond the standard model

Non-standard neutrino interactions

$$\mathcal{L}_{\text{int}} = \mathfrak{g}_{ij}\bar{\nu}_i\nu_j\phi + \mathfrak{h}_{ij}\bar{\nu}_i\gamma_5\nu_j\phi$$

massive scalar limit: $\Gamma_{\text{new}} \sim G_{\text{eff}}^2 T^5$



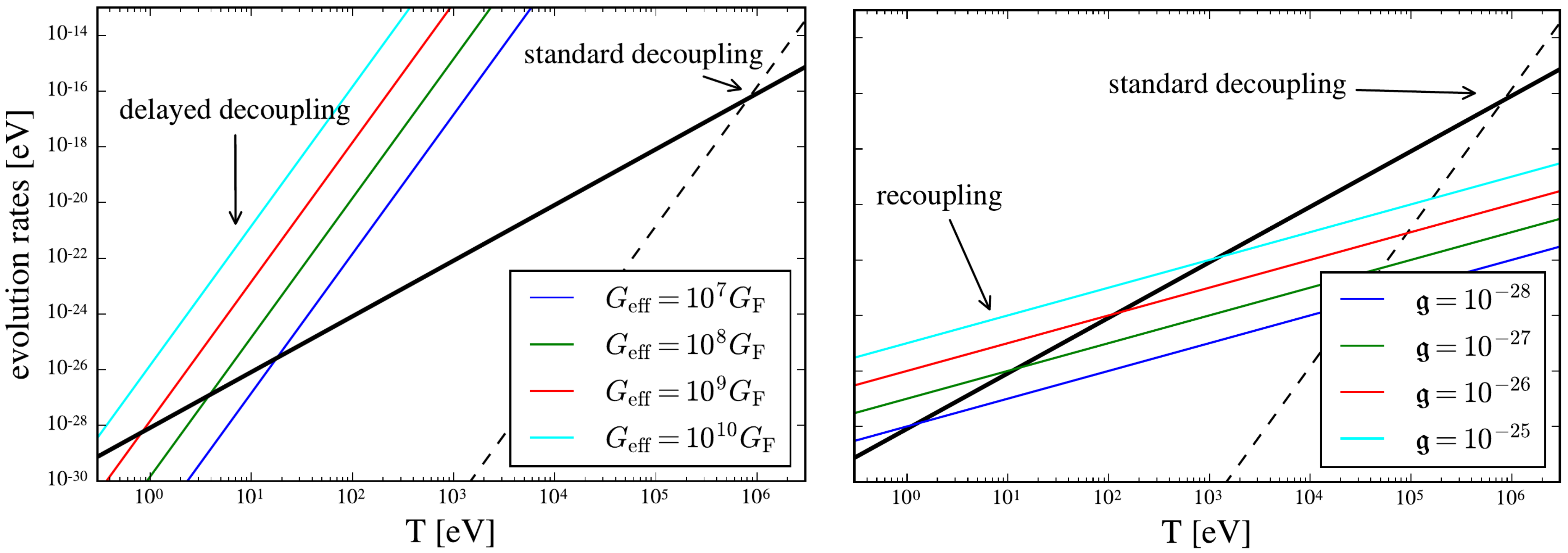
Neutrino sector: Clear hint for physics beyond the standard model

Non-standard neutrino interactions

$$\mathcal{L}_{\rm int} = \mathfrak{g}_{ij}\bar{\nu}_i\nu_j\phi + \mathfrak{h}_{ij}\bar{\nu}_i\gamma_5\nu_j\phi$$

massive scalar limit: $\Gamma_{\rm new} \sim G_{\rm eff}^2 T^5$

massless scalar limit: $\Gamma_{\rm new} \sim gT$

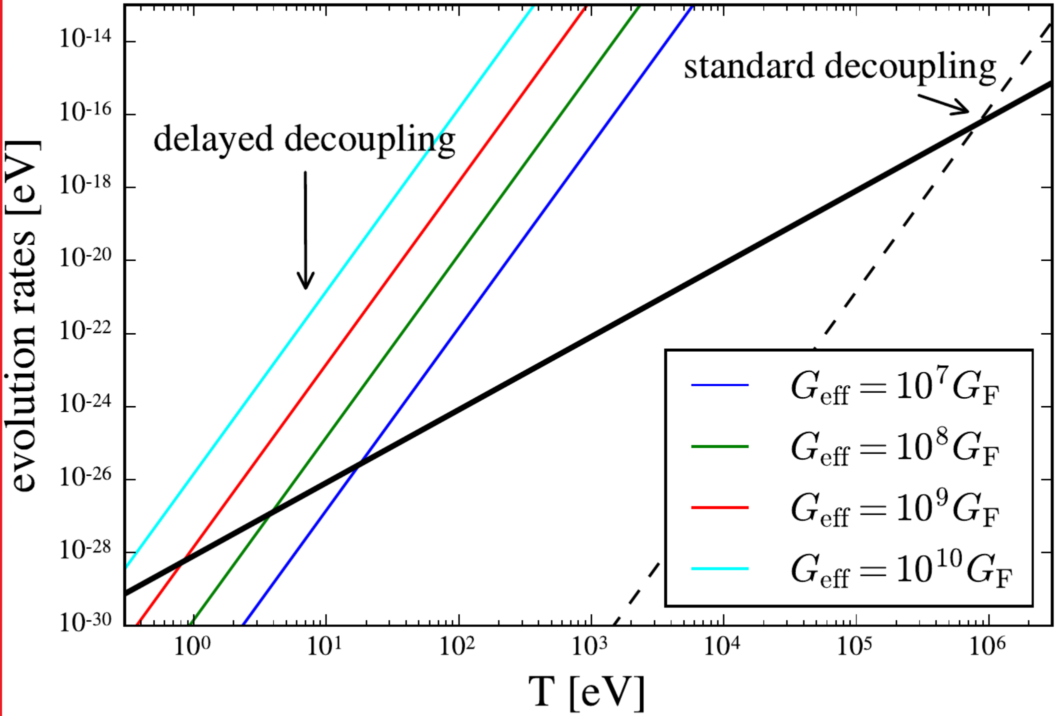


Neutrino sector: Clear hint for physics beyond the standard model

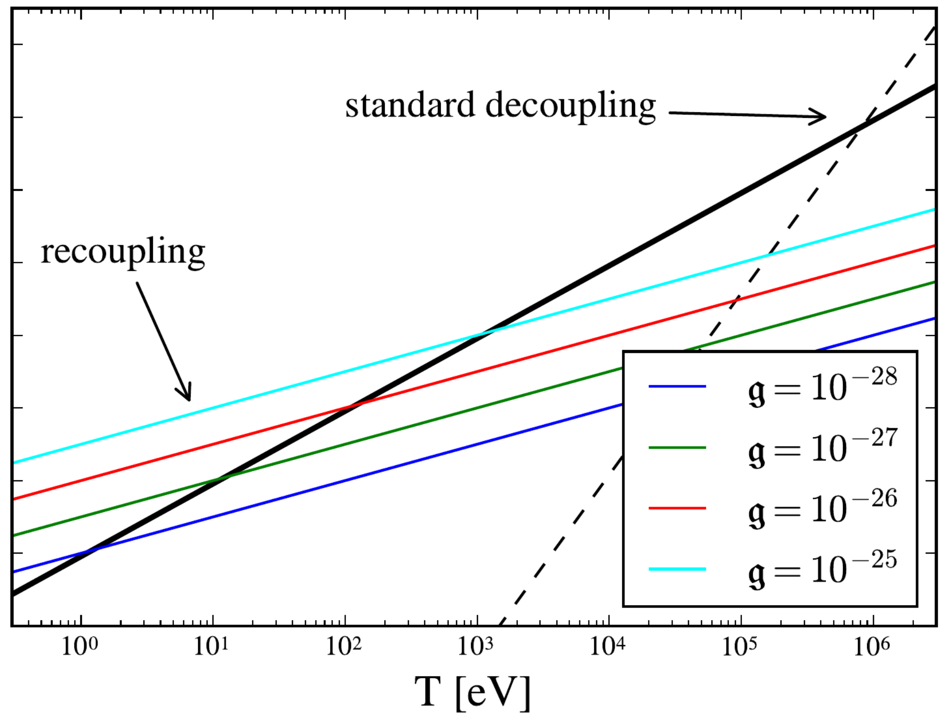
Non-standard neutrino interactions

$$\mathcal{L}_{\rm int} = \mathfrak{g}_{ij}\bar{\nu}_i\nu_j\phi + \mathfrak{h}_{ij}\bar{\nu}_i\gamma_5\nu_j\phi$$

massive scalar limit: $\Gamma_{\rm new} \sim G_{\rm eff}^2 T^5$



massless scalar limit: $\Gamma_{\rm new} \sim gT$



→ cosmological signature?

→ see: *Archidiacono et al. 2013, Forastieri et al. 2019, Forastieri et al. 2015*

→ *see: 0.1 eV – 1 MeV range: Escudero & Witte 2019*

Impact on the CMB described by **Boltzmann hierarchy for interacting neutrinos**

What's that...?

→ **Cosmic perturbation theory**

Small fluctuations from inflation are the seeds for the structures observed today

1.) Perturbed Einstein equation: $\bar{G}_{\mu\nu} + \delta G_{\mu\nu} = 8\pi G(\bar{T}_{\mu\nu} + \delta T_{\mu\nu})$ *Lifshitz, 1946*

2.) Perturbed Boltzmann equations: *Peebles & Yu 1970*

Perturbed phase-space density: $f(\mathbf{k}, \mathbf{q}, \eta) = \bar{f}(q)\,(1 + \Psi(\mathbf{k}, \mathbf{q}, \eta))$

$$\dot{\Psi}_i(\mathbf{k}, \mathbf{q}, \eta) + \mathrm{i}\frac{|\mathbf{q}||\mathbf{k}|}{\epsilon}(\hat{k}\cdot\hat{q})\,\Psi_i(\mathbf{k}, \mathbf{q}, \eta) + \frac{\partial \ln \bar{f}_i(|\mathbf{q}|, \eta)}{\partial \ln |\mathbf{q}|}\left[\dot{\tilde{\eta}} - (\hat{k}\cdot\hat{q})^2\,\frac{\dot{h} + 6\dot{\tilde{\eta}}}{2}\right] = \left(\frac{\partial f_i}{\partial \eta}\right)^{(1)}_{\mathrm{coll}}$$

Apply on all relevant particle species:

	interacting	non-interacting
relativistic	photons	**neutrinos?**
non-relativistic	baryons	CDM

Decompose phase-space perturbation into Legendre polynomials:

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

Apply on all relevant particle species:

	interacting	non-interacting
relativistic	photons	**neutrinos?**
non-relativistic	baryons	CDM

Decompose phase-space perturbation into Legendre polynomials:

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

→ Taking moments: $\int_{-1}^{1} \mathrm{d}(\hat{k}\cdot\hat{q})P_{\ell}(\hat{k}\cdot\hat{q})\,[\text{Boltzmann eq.}]$

<u>→ Neutrino Boltzmann hierarchy:</u> *Stewart 1970*

$$\dot{\delta}_{\nu} = -\frac{4}{3}\theta - \frac{2}{3}\dot{h},$$

$$\dot{\theta} = k^2\left(\frac{1}{4}\delta - \sigma\right),$$

$$\dot{F}_2 = 2\dot{\sigma} = \frac{8}{15}\theta - \frac{3}{5}kF_3 + \frac{4}{15}\dot{h} + \frac{8}{5}\dot{\eta},$$

$$\dot{F}_{\ell\geq 3} = \frac{k}{2\ell+1}\left[lF_{\ell-1} - (\ell+1)F_{\ell+1}\right]$$

→ analogously for all other particle species

How to include neutrino interactions?

1.) Relaxation time approximation:

$$\dot{\mathcal{F}}_{\nu 2} = \frac{8}{15}\theta_\nu - \frac{3}{5}k\mathcal{F}_{\nu 3} + \frac{4}{15}\dot{h} + \frac{8}{5}\dot{\tilde{\eta}} + \alpha_2\dot{\tau}_\nu\mathcal{F}_{\nu 2} \ ,$$

$$\dot{\mathcal{F}}_{\nu\ell} = \frac{k}{2\ell+1}\left[\ell\mathcal{F}_{\nu(\ell-1)} - (\ell+1)\mathcal{F}_{\nu(\ell+1)}\right] + \alpha_\ell\dot{\tau}_\nu\mathcal{F}_{\nu\ell} \ , \quad \ell \geq 3 \ ,$$

→ motivated from the photon hierachy

F. Cyr-Racine, K. Sigurdson, arXiv:1306.1536

How to include neutrino interactions?

1.) Relaxation time approximation:

$$\dot{\mathcal{F}}_{\nu 2} = \frac{8}{15}\theta_\nu - \frac{3}{5}k\mathcal{F}_{\nu 3} + \frac{4}{15}\dot{h} + \frac{8}{5}\dot{\tilde{\eta}} + \alpha_2 \dot{\tau}_\nu \mathcal{F}_{\nu 2} \ ,$$

$$\dot{\mathcal{F}}_{\nu \ell} = \frac{k}{2\ell+1}\left[\ell \mathcal{F}_{\nu(\ell-1)} - (\ell+1)\mathcal{F}_{\nu(\ell+1)}\right] + \alpha_\ell \dot{\tau}_\nu \mathcal{F}_{\nu\ell} \ , \quad \ell \geq 3 \ ,$$

→ motivated from the photon hierachy

F. Cyr-Racine, K. Sigurdson, arXiv:1306.1536

2.) Parameterisation used to fit cosmological data:

$$\dot{\delta}_\nu = -\frac{4}{3}\theta_\nu - \frac{2}{3}\dot{h} + \frac{\dot{a}}{a}(1-3c_{\rm eff}^2)\left(\delta_\nu + 4\frac{\dot{a}}{a}\frac{\theta_\nu}{k^2}\right),$$

$$\dot{\theta}_\nu = k^2\left(\frac{1}{4}\delta_\nu - \sigma_\nu\right) - \frac{k^2}{4}(1-3c_{\rm eff}^2)\left(\delta_\nu + 4\frac{\dot{a}}{a}\frac{\theta_\nu}{k^2}\right),$$

$$\dot{\mathcal{F}}_{\nu 2} = 2\dot{\sigma}_\nu = \frac{8}{15}\theta_\nu - \frac{3}{5}k\mathcal{F}_{\nu 3} + \frac{4}{15}\dot{h} + \frac{8}{5}\dot{\tilde{\eta}} - (1-3c_{\rm vis}^2)\left(\frac{8}{15}\theta_\nu + \frac{4}{15}\dot{h} + \frac{8}{5}\dot{\tilde{\eta}}\right),$$

$$\dot{\mathcal{F}}_{\nu \ell} = \frac{k}{2\ell+1}\left[\ell \mathcal{F}_{\nu(\ell-1)} - (\ell+1)\mathcal{F}_{\nu(\ell+1)}\right], \quad \ell \geq 3$$

$$(c_{\rm eff}^2, c_{\rm vis}^2) = \left(\frac{1}{3}, \frac{1}{3}\right)$$

→ standard case

$$(c_{\rm eff}^2, c_{\rm vis}^2) = \left(\frac{1}{3}, 0\right)$$

→ tightly coupled limit

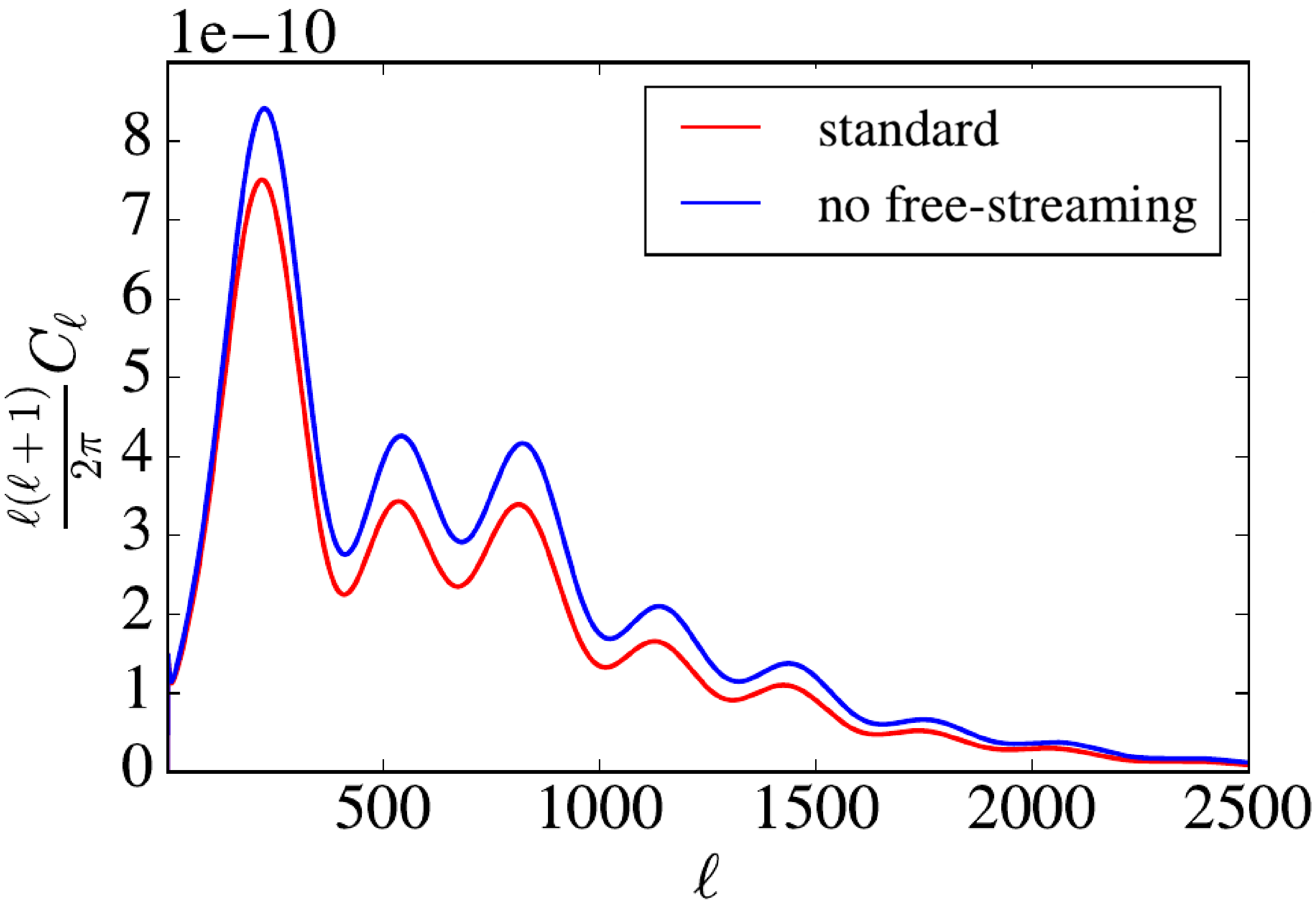
e.g. A. Melchiorri, arXiv:1109.2767, ...

General expected signal

suppression of free-streaming

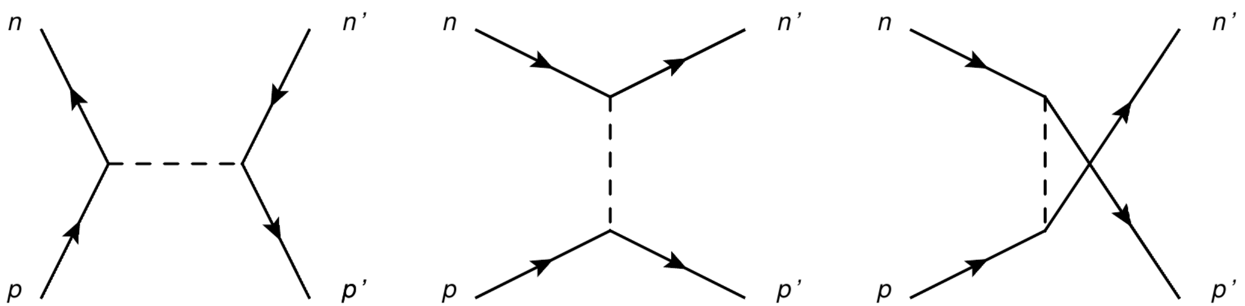
$\rightarrow$ enhancement of neutrino monopole/energy density

$\rightarrow$ enhancement of temperature anisotropies



Exact description of interacting neutrinos needs calculation of the **collision integral**.

$$\Rightarrow \dot{\Psi}_i(\mathbf{k},\mathbf{q},\tau) + \mathrm{i}\frac{|\mathbf{q}||\mathbf{k}|}{\epsilon}(\hat{k}\cdot\hat{q})\,\Psi_i(\mathbf{k},\mathbf{q},\tau) + \frac{\partial \ln \bar{f}_i(|\mathbf{q}|)}{\partial \ln |\mathbf{q}|}\left[\dot{\eta} - (\hat{k}\cdot\hat{q})^2\,\frac{\dot{h}+6\dot{\eta}}{2}\right] = \boxed{\left(\frac{\partial f_i}{\partial \tau}\right)^{(1)}_{\mathrm{coll}}}$$



$$\left(\frac{\partial f_i}{\partial \tau}\right)^{(1)}_{ij\leftrightarrow kl}(\boldsymbol{k},\boldsymbol{q},\tau) = \frac{g_j g_k g_l}{2|\boldsymbol{q}|(2\pi)^5}\int\frac{\mathrm{d}^3\boldsymbol{q}'}{2|\boldsymbol{q}'|}\int\frac{\mathrm{d}^3\boldsymbol{l}}{2|\boldsymbol{l}|}\int\frac{\mathrm{d}^3\boldsymbol{l}'}{2|\boldsymbol{l}'|}\,\delta^4_{\mathrm{D}}(q+l-q'-l')$$
$$\times\,|\mathcal{M}_{ij\leftrightarrow kl}|^2\Big(\bar{f}_k(|\boldsymbol{q}'|)\,\bar{f}_k(|\boldsymbol{l}'|)\,\Psi_l(\boldsymbol{k},\boldsymbol{l}') + \bar{f}_l(|\boldsymbol{l}'|)\,\bar{f}_l(|\boldsymbol{q}'|)\,\Psi_k(\boldsymbol{k},\boldsymbol{q}')$$
$$-\,\bar{f}_i(|\boldsymbol{q}|)\,\bar{f}_i(|\boldsymbol{l}|)\,\Psi_j(\boldsymbol{k},\boldsymbol{l}) - \bar{f}_j(|\boldsymbol{l}|)\,\bar{f}_j(|\boldsymbol{q}|)\,\Psi_i(\boldsymbol{k},\boldsymbol{q})\Big)$$

$$\dot{\Psi}_0(q) = -\,k\Psi_1(q) + \frac{1}{6}\frac{\partial \ln \bar{f}}{\partial \ln q}\dot{h} - \frac{40}{3}G^{\rm m} q\, T_{\nu,0}^4\, \Psi_0(q)$$
$$+\, G^{\rm m}\int {\rm d}q'\, \frac{q'}{q\bar{f}(q)}\left[2K_0^{\rm m}(q,q') - \frac{20}{9}q^2\, {q'}^2 e^{-q/T_{\nu,0}}\right]\, \bar{f}_\nu(q')\, \Psi_0(q')\,,$$

$$\dot{\Psi}_1(q) = -\,\frac{2}{3}k\Psi_2(q) + \frac{1}{3}k\Psi_0(q) - \frac{40}{3}G^{\rm m} q\, T_{\nu,0}^4\, \Psi_1(q)$$
$$+\, G^{\rm m}\int {\rm d}q'\, \frac{q'}{q\bar{f}(q)}\left[2K_1^{\rm m}(q,q') + \frac{10}{9}q^2\, {q'}^2 e^{-q/T_{\nu,0}}\right]\, \bar{f}(q')\, \Psi_1(q')\,,$$

$$\dot{\Psi}_2(q) = -\,\frac{3}{5}k\Psi_3(q) + \frac{2}{5}k\Psi_1(q) - \frac{\partial \ln \bar{f}}{\partial \ln q}\left(\frac{2}{5}\dot{\tilde{\eta}} + \frac{1}{15}\dot{h}\right) - \frac{40}{3}G^{\rm m} q\, T_{\nu,0}^4\, \Psi_2(q)$$
$$+\, G^{\rm m}\int {\rm d}q'\, \frac{q'}{q\bar{f}(q)}\left[2K_2^{\rm m}(q,q') - \frac{2}{9}q^2\, {q'}^2 e^{-q/T_{\nu,0}}\right]\, \bar{f}(q')\, \Psi_2(q')\,,$$

$$\dot{\Psi}_{\ell>2}(q) = \frac{k}{2\ell+1}\left[\ell\Psi_{\ell-1}(q) - (\ell+1)\Psi_{\ell+1}(q)\right] - \frac{40}{3}G^{\rm m} q\, T_{\nu,0}^4\, \Psi_\ell(q)$$
$$+\, G^{\rm m}\int {\rm d}q'\, 2\frac{q'}{q\bar{f}(q)}K_\ell^{\rm m}(q,q')\, \bar{f}(q')\, \Psi_\ell(q')$$

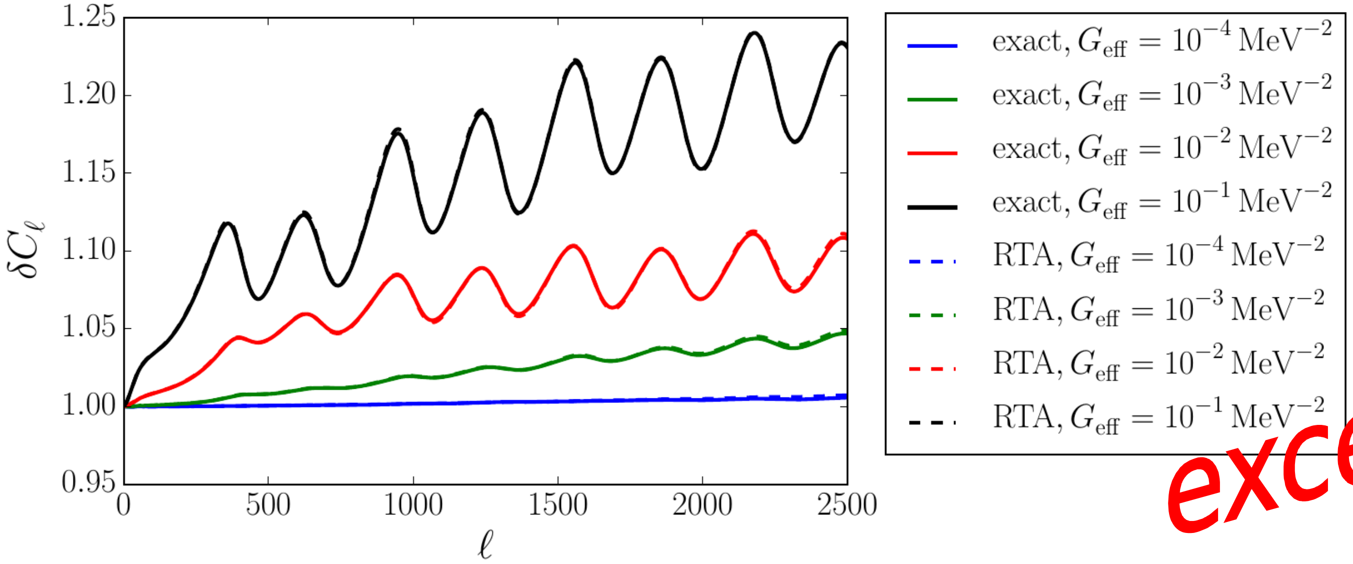
IMO et al. arXiv:1409.1577

- **momentum-dependence reflects non-negligible energy transfer**
- formally very different from other approaches → implement in Boltzmann code CLASS *(J. Lesgourgues, et al.)*

Comparison with other approaches

IMO et al., arXiv: 1706.02123

1.) Relaxation time approximation

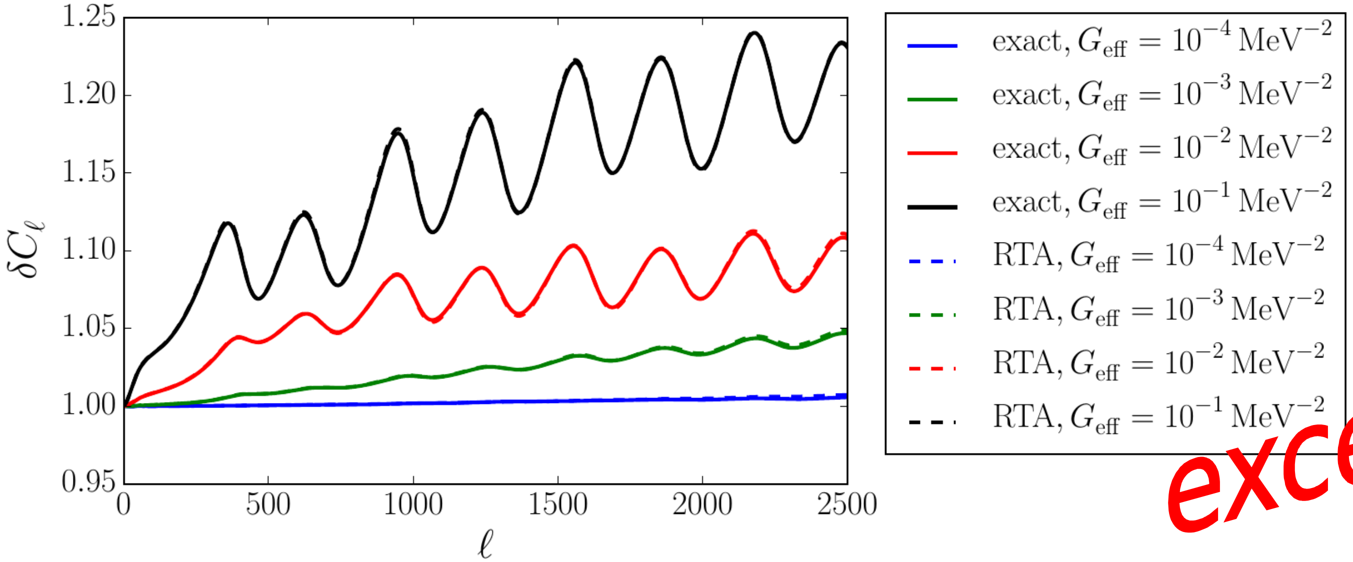


excellent

Comparison with other approaches

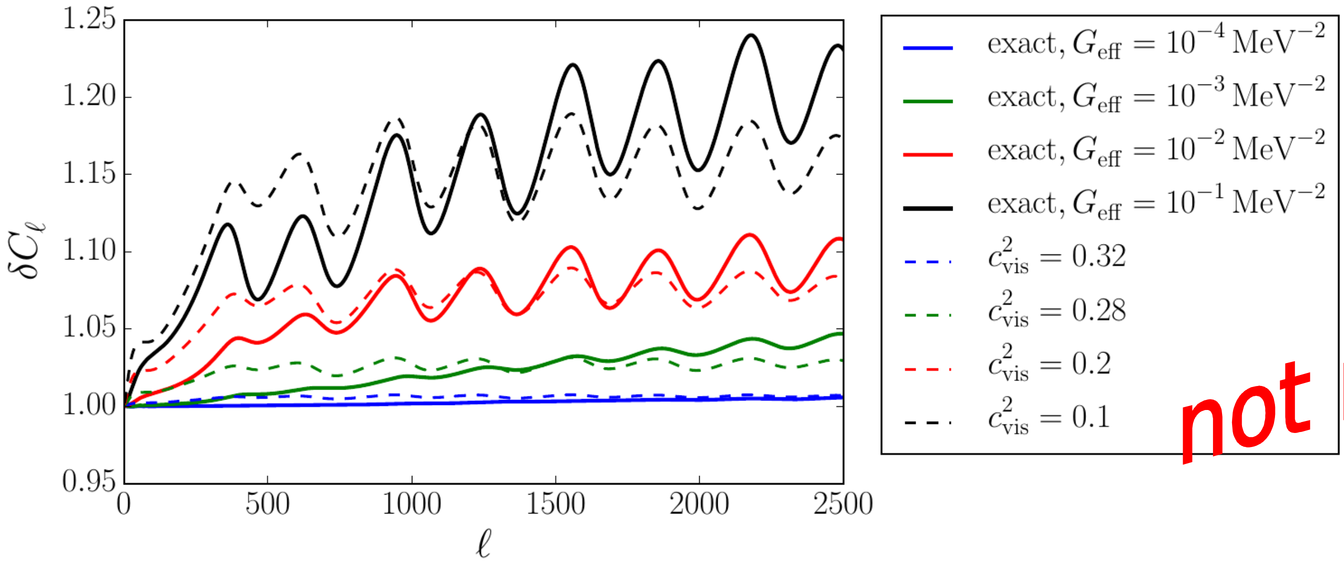
IMO et al., arXiv: 1706.02123

1.) Relaxation time approximation



excellent

2.) $(c^2_{\rm eff}, c^2_{\rm vis})$

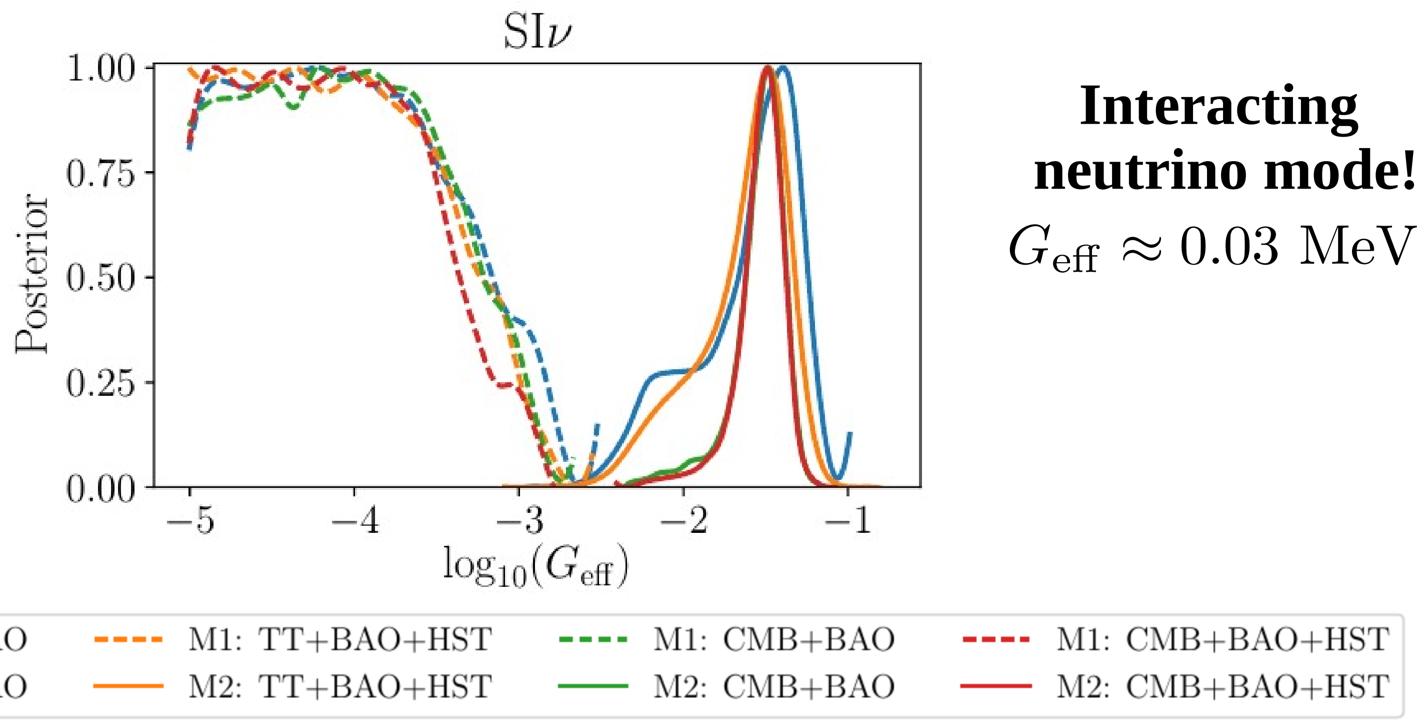


not really...

- Relaxation time approximation entirely sufficient.
- $(c_{\rm eff}{}^2\text{-}c_{\rm vis}{}^2)$-parameterisation should not be used.

MCMC results (using the relaxation time approximation)

Compare with *arXiv: 1704.06657 (Lancaster et al.) & arXiv:1306.1536 (Cyr-Racine, Sigurdson)*

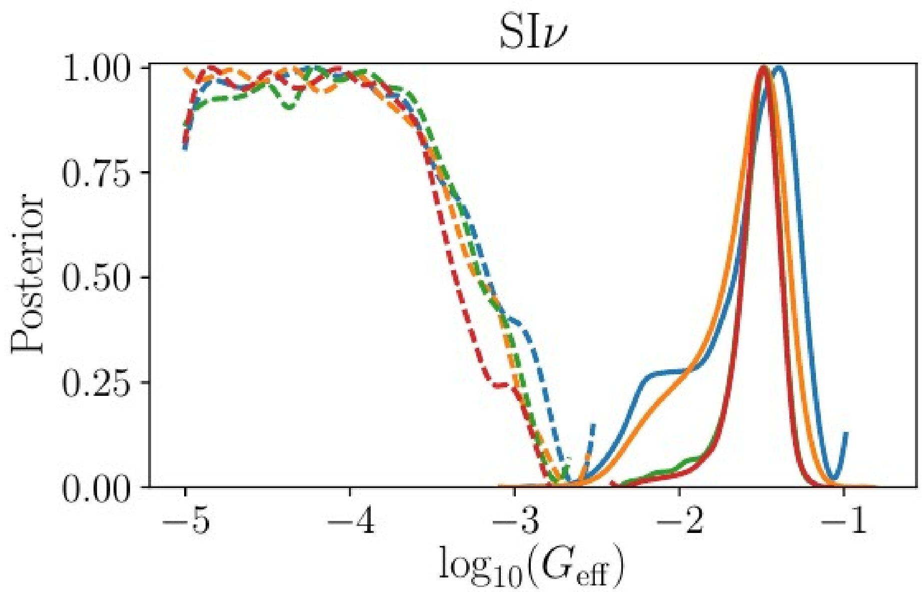


Interacting neutrino mode!

$G_{\rm eff} \approx 0.03\ {\rm MeV}^{-2}$

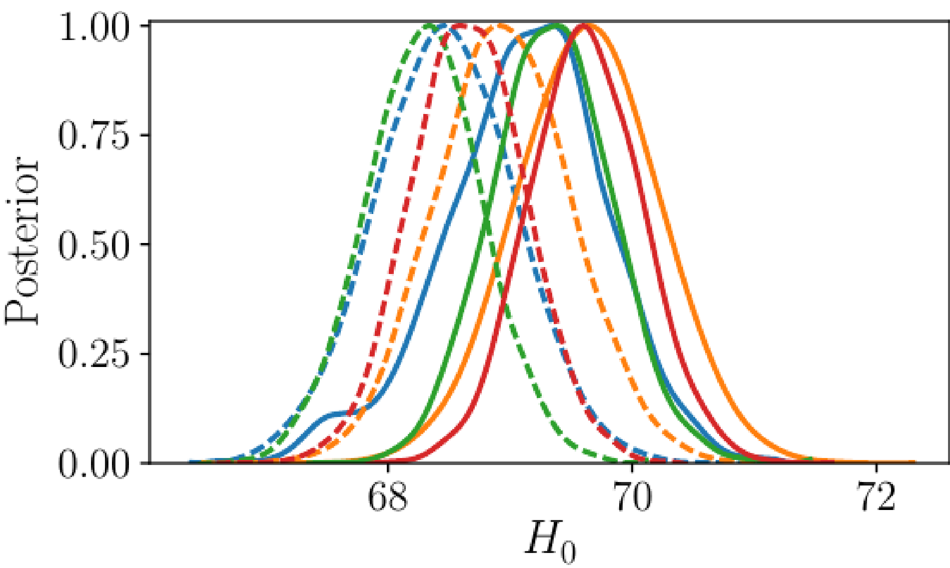
<u>MCMC results</u> (using the relaxation time approximation)

Compare with *arXiv: 1704.06657 (Lancaster et al.) & arXiv:1306.1536 (Cyr-Racine, Sigurdson)*



Interacting neutrino mode!

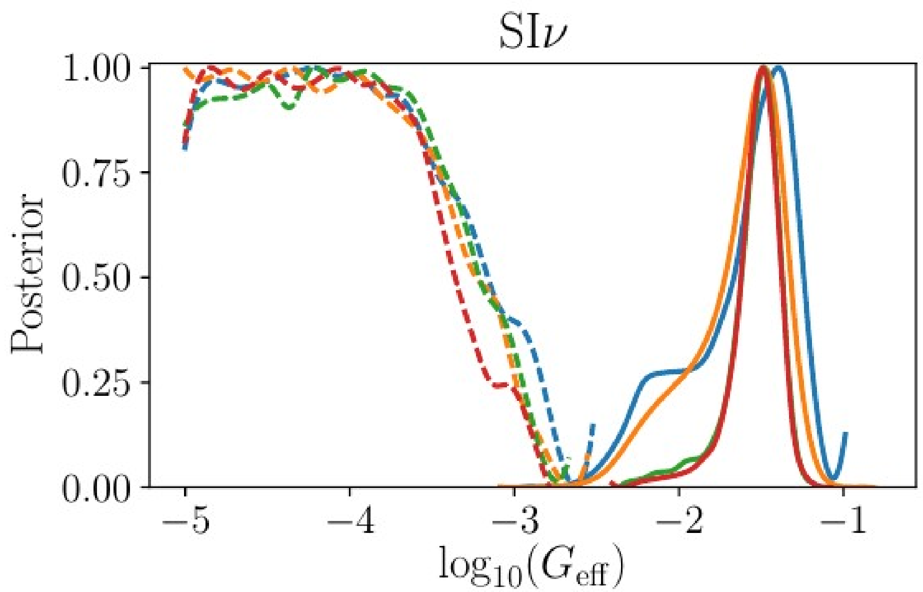
$G_{\rm eff} \approx 0.03\ \mathrm{MeV}^{-2}$



Possible solution to Hubble tension???

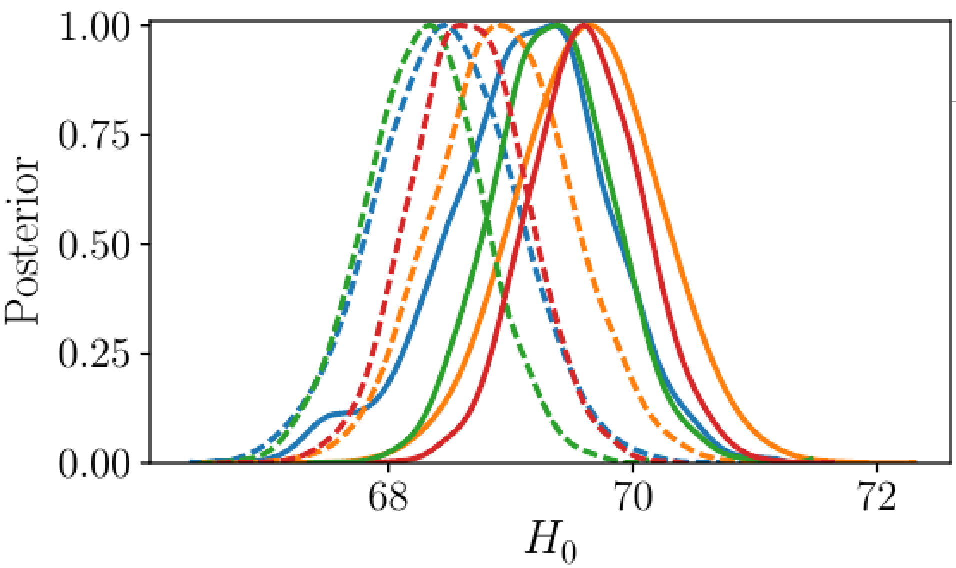
MCMC results (using the relaxation time approximation)

Compare with *arXiv: 1704.06657 (Lancaster et al.) & arXiv:1306.1536 (Cyr-Racine, Sigurdson)*



Interacting neutrino mode!

$G_{\rm eff} \approx 0.03\ \mathrm{MeV}^{-2}$



→ Possible solution to Hubble tension???

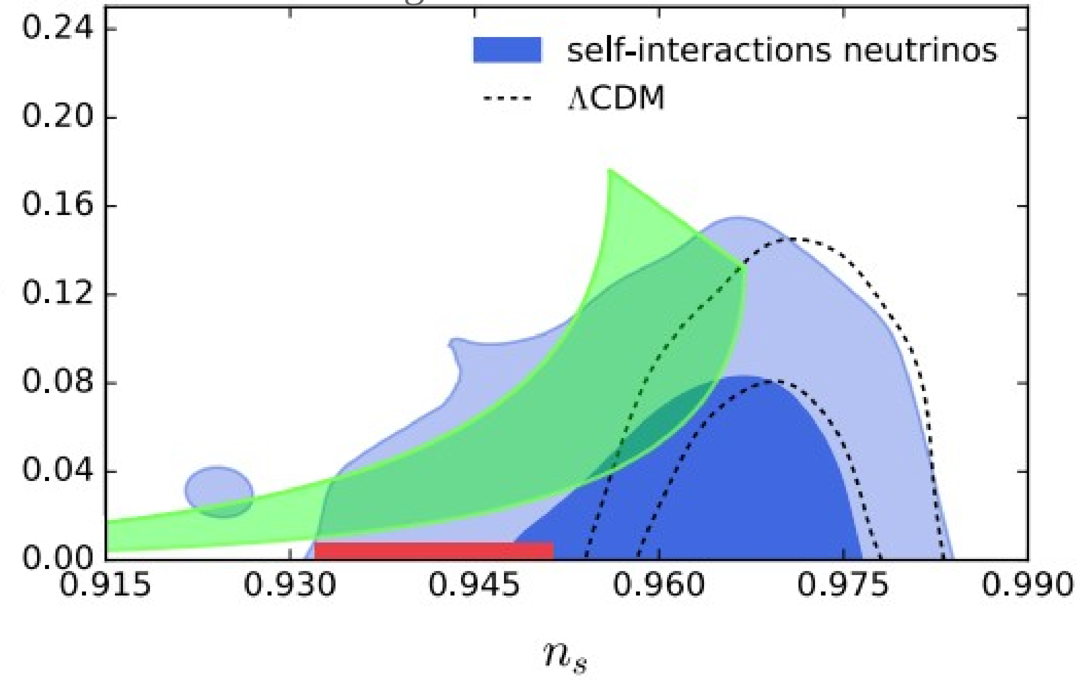
Interacting neutrino mode gets stronger when including Σm_ν and $N_{\rm eff}$

→ see Kreisch, Cyr-Racine, Doré, arXiv: 1902.00534

Barenboim, Denton, IMO, arXiv: 1903.02036

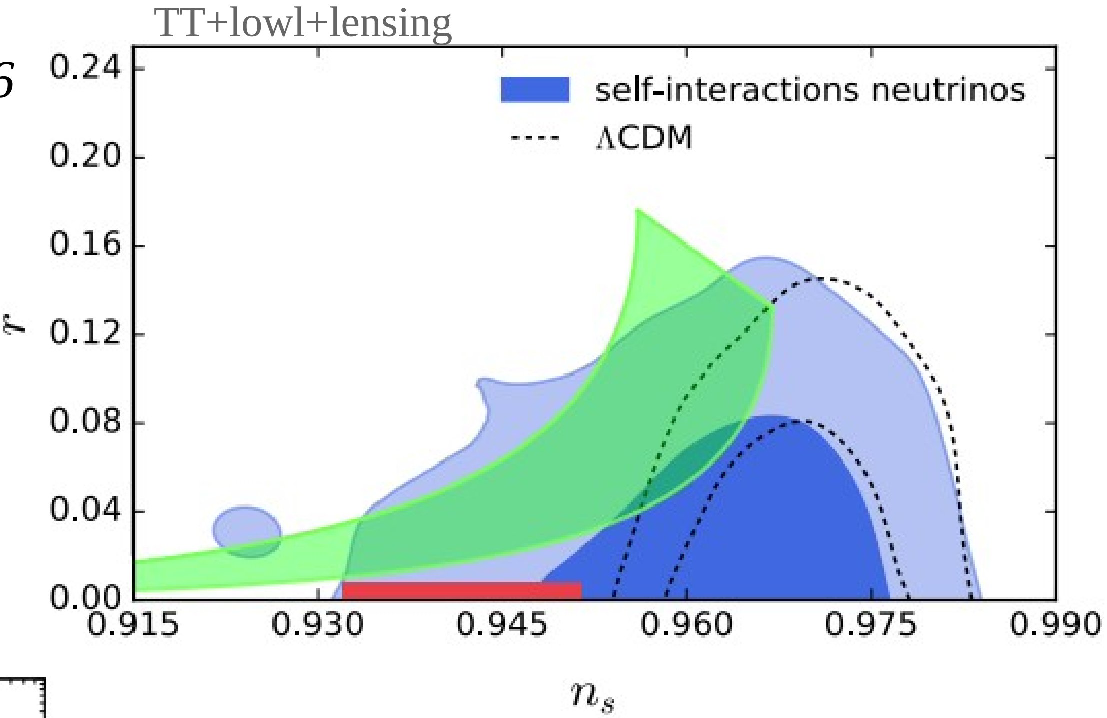
Consequences on inflationary model selection...

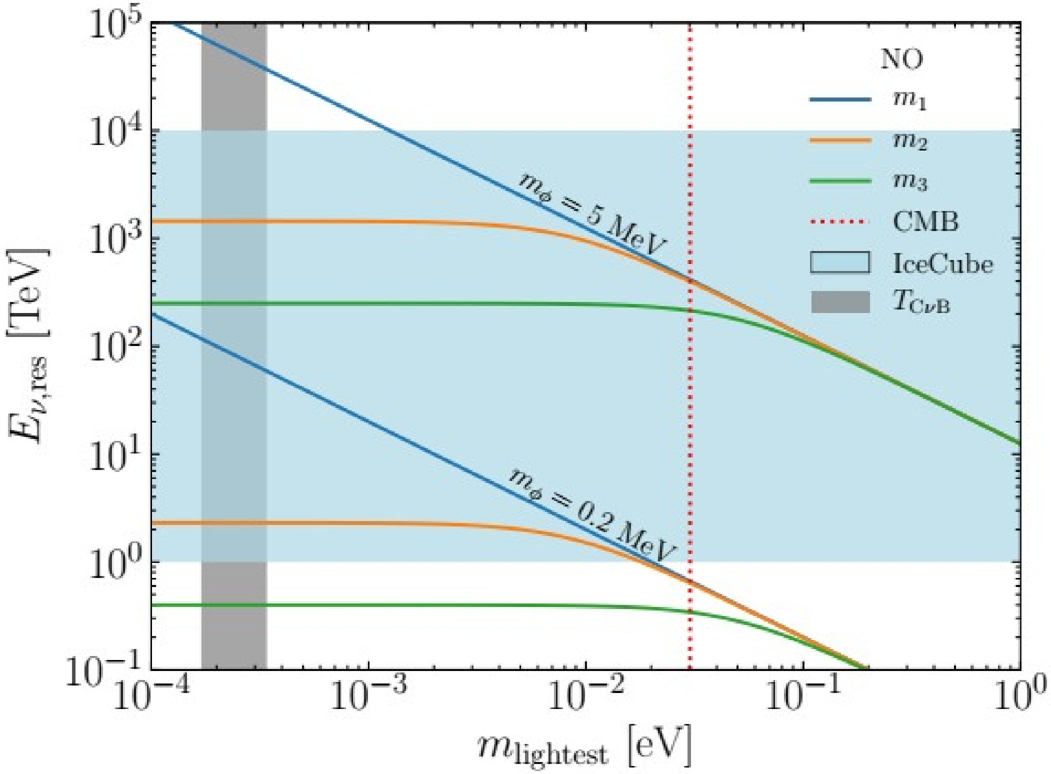
TT+lowl+lensing



Barenboim, Denton, IMO, arXiv: 1903.02036

Consequences on inflationary model selection...





Constraints from BBN and Z-decay:

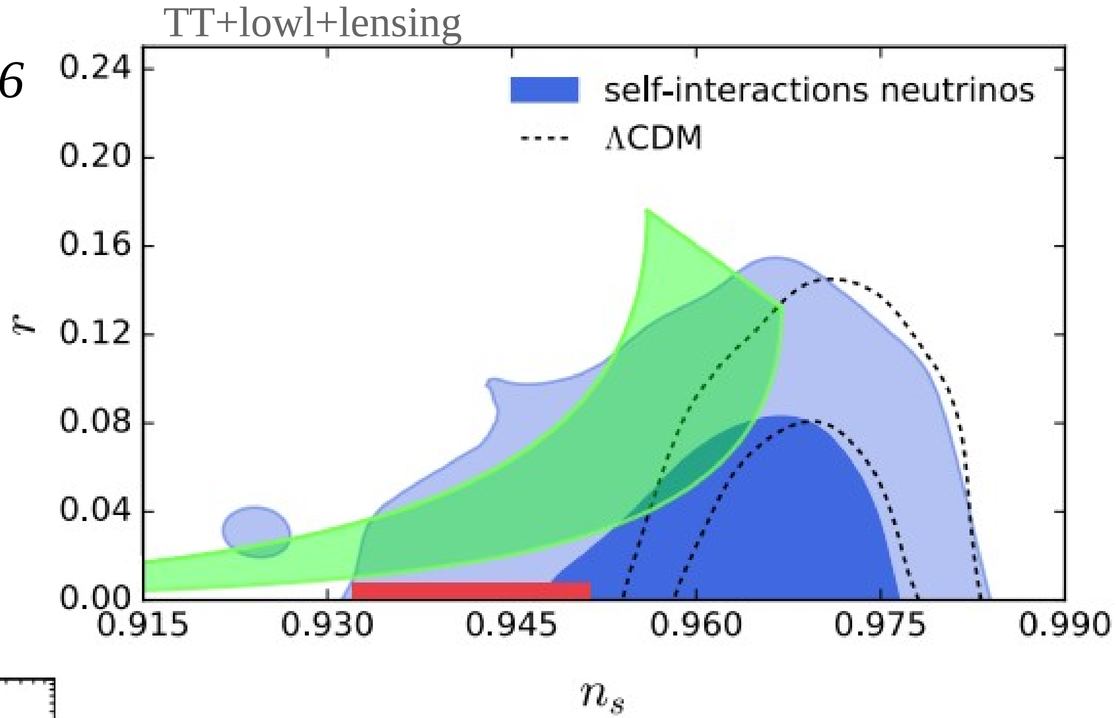
$$m_\phi = \mathcal{O}(0.2 - 5)\,\mathrm{MeV}$$

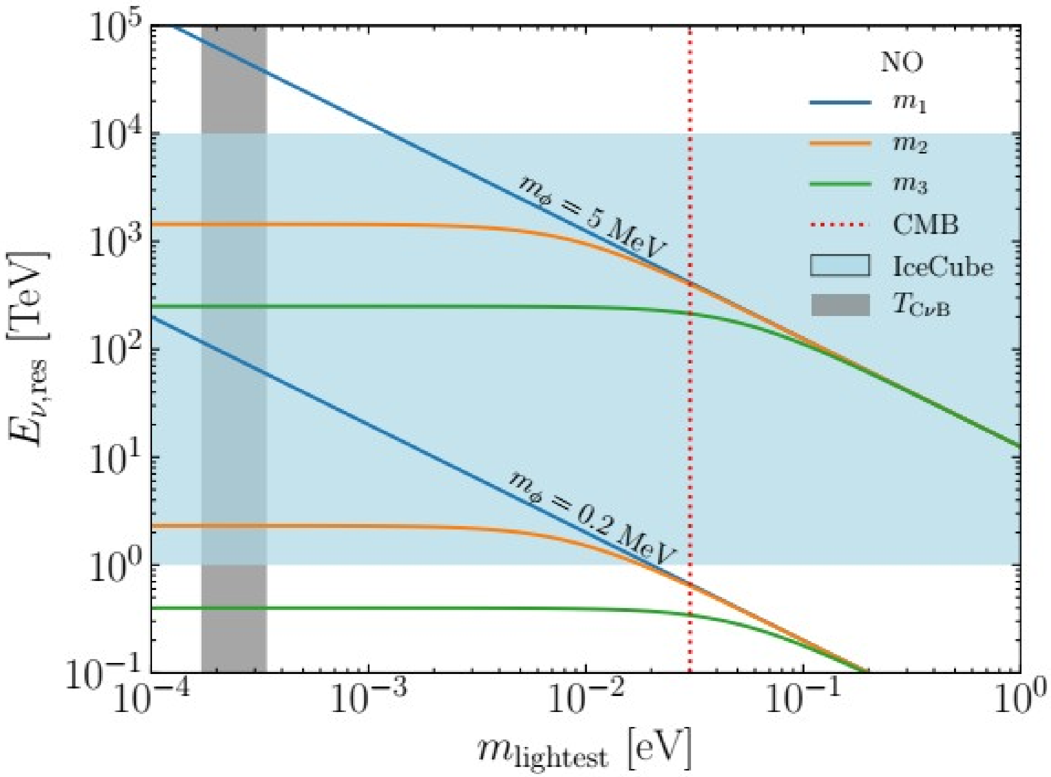
Can produce scalar on **resonance** by astrophysical neutrinos + relic neutrinos

→ dip in astrophysical neutrino flux
→ exactly in IceCubes window

Barenboim, Denton, IMO, arXiv: 1903.02036

Consequences on inflationary model selection...





Constraints from BBN and Z-decay:

$$m_\phi = \mathcal{O}(0.2 - 5)\,\mathrm{MeV}$$

Can produce scalar on **resonance** by astrophysical neutrinos + relic neutrinos

→ dip in astrophysical neutrino flux
→ exactly in IceCubes window

However double beta decay point out interactions must be in τ-sector only
→ see Blinov et al., arXiv:1905.02727

Conclusions:

- Boltzmann hierarchy has **formally** a much richer structure than approximations by others
- … but **relaxation time approximation** is an **excellent** effective description
- $(c_{eff}^2 - c_{vis}^2)$-parameterisation does not describe neutrino interactions
- MCMC: there is an **interacting neutrino mode**!

→ possible solution to the **Hubble tension**?

→ interesting for inflationary model selection

Conclusions:

- Boltzmann hierarchy has **formally** a much richer structure than approximations by others
- … but **relaxation time approximation** is an **excellent** effective description
- $(c_{eff}^2 - c_{vis}^2)$-parameterisation does not describe neutrino interactions
- MCMC: there is an **interacting neutrino mode**!

→ possible solution to the **Hubble tension**?

→ interesting for inflationary model selection

Thank you for your attention!