Interacting Neutrinos in Cosmology

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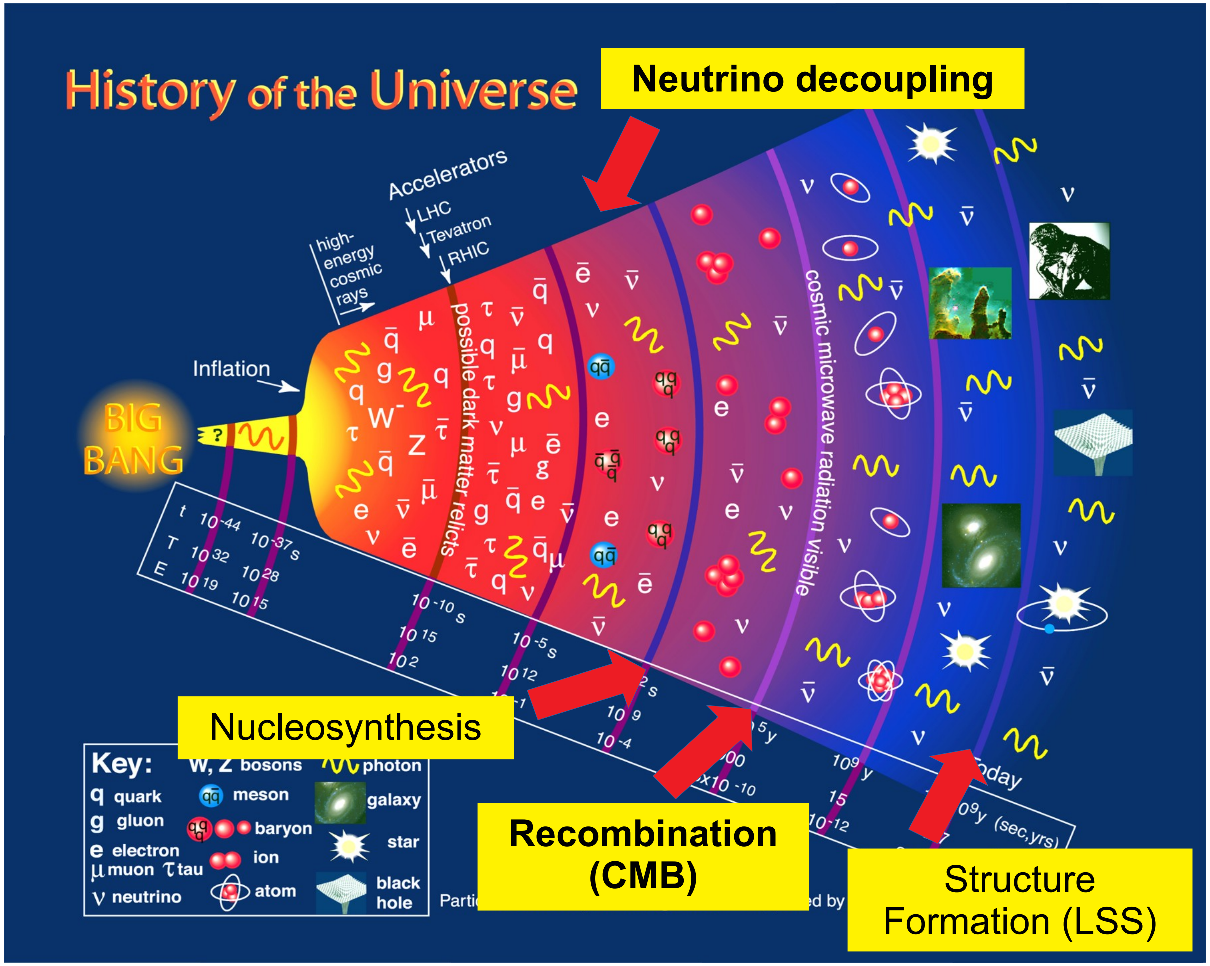
YOUNGST@RS - Interacting dark sectors in astrophysics, cosmology, and the lab



Energy density:

$$\rho^{rad} \equiv \left[1 + \frac{7}{8}\left(\frac{4}{11}\right)^{4/3} N_{\rm eff}\right]\rho_\gamma$$

N_{eff} = 3.040 *(Bennet et al. 2020)*, **N_{eff} = 3.043** *(Cielo et al. 2023)*

$$N_{\rm eff} = 2.92^{+0.36}_{-0.37}\,(95\%\ {\rm CL})$$

(Planck 2018)

$$\sum m_\nu < 0.257\,{\rm eV}\,(95\%\ {\rm CL})$$

(Planck 2018)

Assumptions about neutrinos made in ΛCDM

- Neutrinos are free-streaming after 1 MeV (i.e. they are stable and have no interactions)
- Neutrinos follow a relativistic Fermi-Dirac spectrum
- They have a temperature of $$T_\nu = \left(\frac{4}{11}\right)^{1/3} T_\gamma$$
- There are as many neutrinos as anti-neutrinos (negligible lepton asymmetry)

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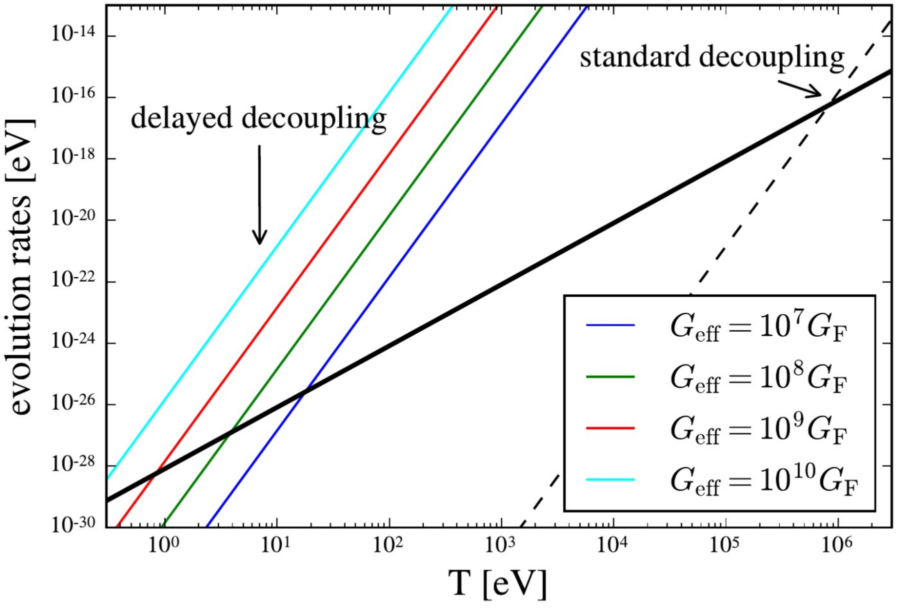
Modified by non-standard interactions

Neutrino sector: Clear hint for physics beyond the standard model

Non-standard neutrino interactions

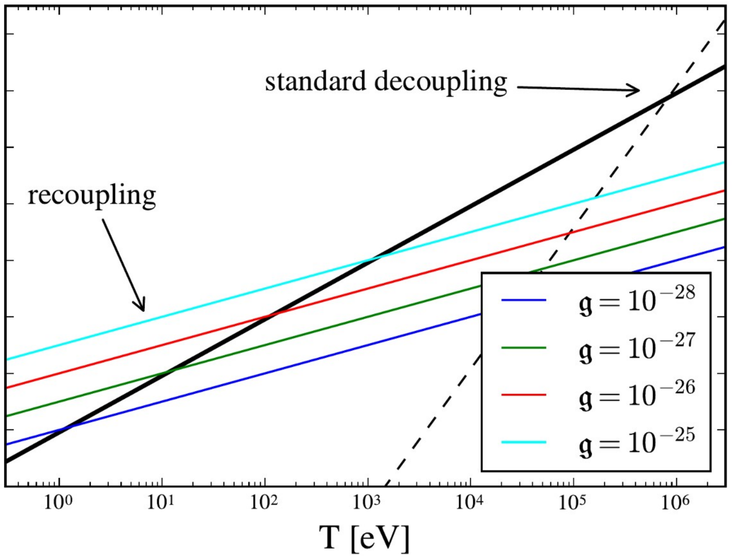
$$\mathcal{L}_{\text{int}} = \mathfrak{g}_{ij}\bar{\nu}_i\nu_j\phi$$ ← strongly constrained

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



→ CMB signature?

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



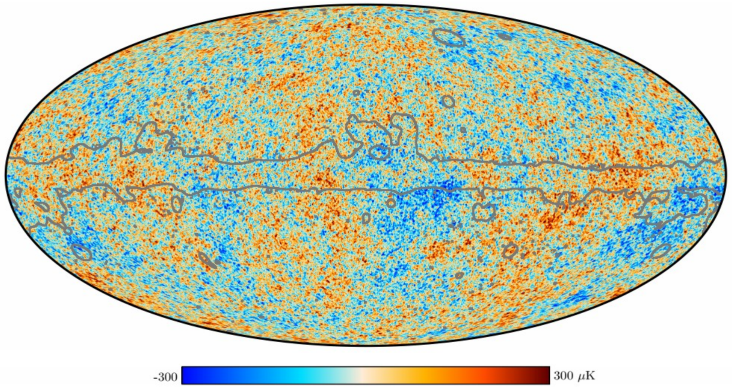
→ massless: see e.g. *Brinckmann et al. 2023, Venzor et al. 2022, Forastieri et al. 2019, Forastieri et al. 2015, Archidiacono et al. 2013*

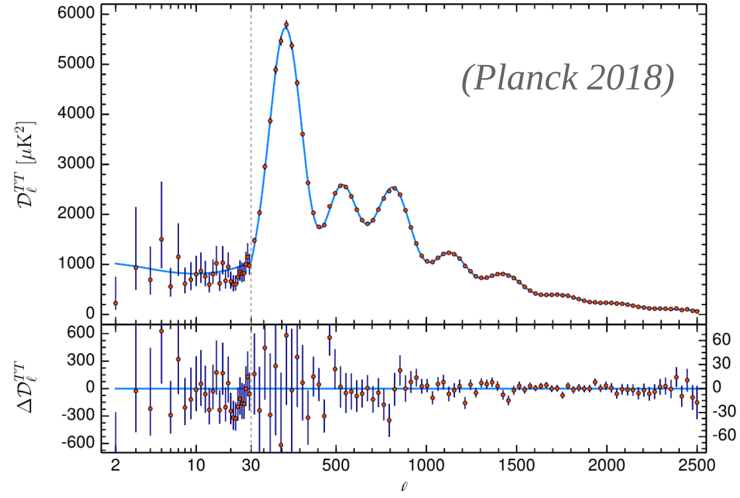
→ *0.1 eV – 1 MeV range: see e.g. Sandner et al. 2023, Venzor et al. 2023, Escudero & 2019*

Cosmic Microwave Background $\mathcal{O}(0.3\,\mathrm{eV})$

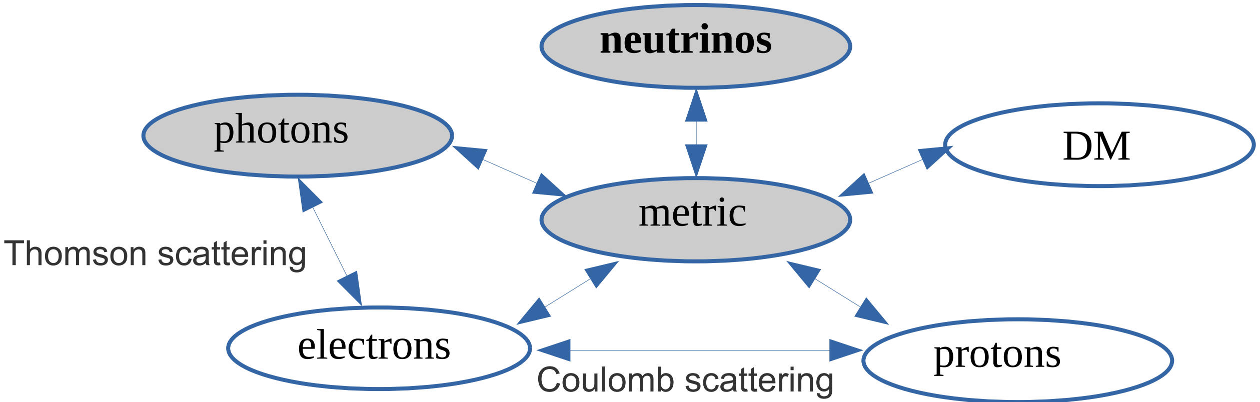
Recombination → Universe gets transparent to photons

(Redshifted) photo of the early Universe





→ <u>Fluctuations in the photon temperature/density:</u>



<u>Cosmic (linear) perturbation theory =</u>

Boltzmann equations +
Einstein equations

→ e.g. CLASS *(Lesgourgues, Tram)*
CAMB *(A. Lewis)*

→ 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

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

→ Neutrino Boltzmann hierarchy:

Decompose phase-space perturbation

into Legendre polynomials:

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

free-streaming

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

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

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

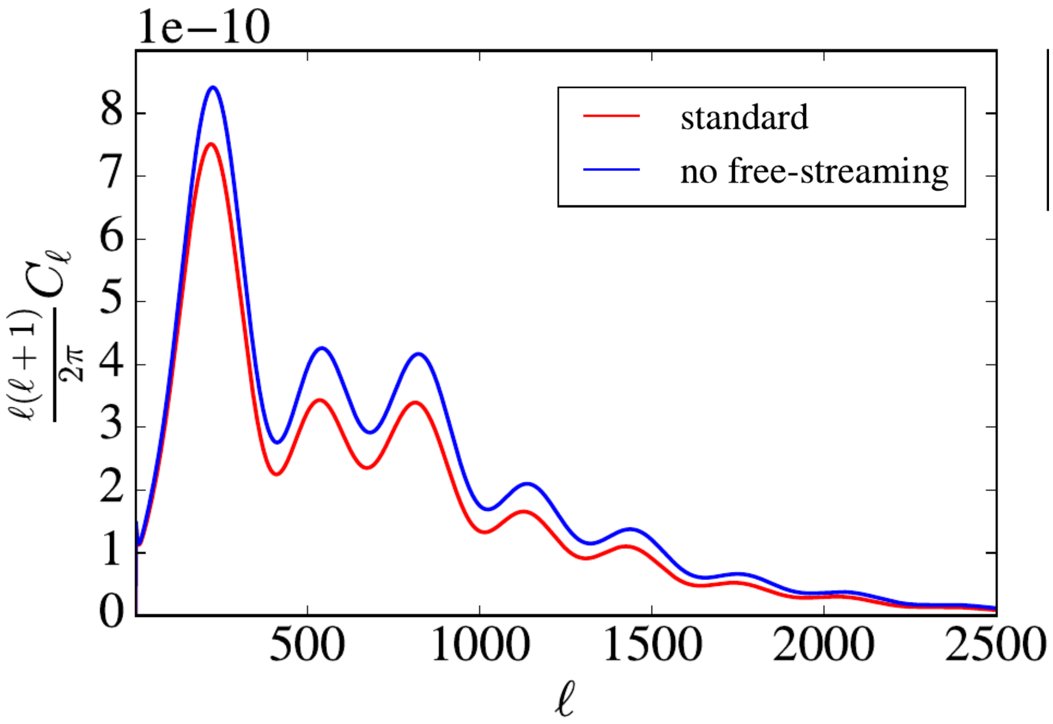
$$\dot{\Psi}_{\ell\geq 3} = \frac{qk}{(2\ell+1)\epsilon}\left[\ell\Psi_{\ell-1} - (\ell+1)\Psi_{\ell+1}\right] + \cancel{C[\Psi_\ell]}$$

General expected signal from interactions:

suppression of free-streaming

→ enhancement of neutrino monopole/perturbed energy density

→ enhancement of temperature anisotropies



Neutrino Boltzmann hierarchy

*(**IMO**, C. Rampf, Y. Y. Y. Wong 2014)*

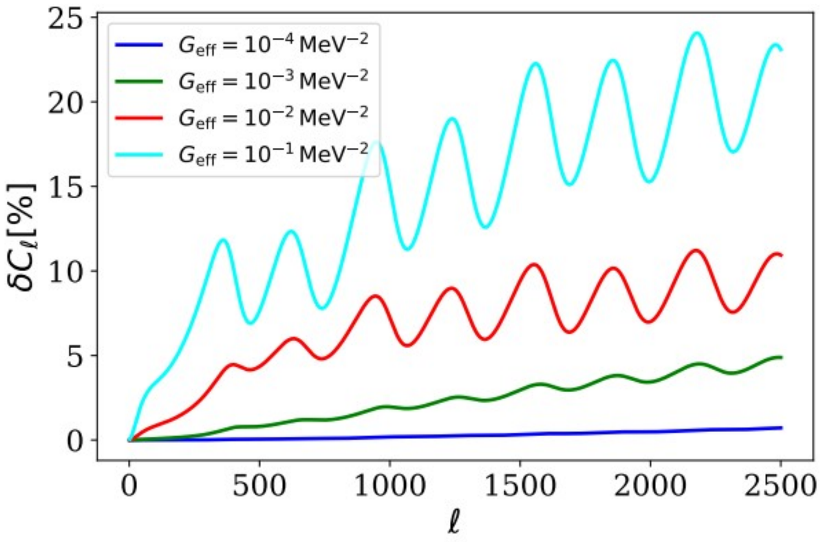
$$\dot{\Psi}_0(q) = -\,k\Psi_1(q) + \frac{1}{6}\frac{\partial \ln \bar{f}}{\partial \ln q}\dot{h} - \frac{40}{3}G^{\mathrm{m}} q\, T_{\nu,0}^4\, \Psi_0(q)$$
$$+\, G^{\mathrm{m}} \int \mathrm{d}q'\, \frac{q'}{q\bar{f}(q)} \left[2K_0^{\mathrm{m}}(q,q') - \frac{20}{9}q^2\, {q'}^2 e^{-q/T_{\nu,0}}\right] \bar{f}_\nu(q')\, \Psi_0(q')\,,$$
$$\dot{\Psi}_1(q) = -\,\frac{2}{3}k\Psi_2(q) + \frac{1}{3}k\Psi_0(q) - \frac{40}{3}G^{\mathrm{m}} q\, T_{\nu,0}^4\, \Psi_1(q)$$
$$+\, G^{\mathrm{m}} \int \mathrm{d}q'\, \frac{q'}{q\bar{f}(q)} \left[2K_1^{\mathrm{m}}(q,q') + \frac{10}{9}q^2\, {q'}^2 e^{-q/T_{\nu,0}}\right] \bar{f}(q')\, \Psi_1(q')\,,$$
$$\dot{\Psi}_2(q) = -\,\frac{3}{5}k\Psi_3(q) + \frac{2}{5}k\Psi_1(q) - \frac{\partial \ln \bar{f}}{\partial \ln q}\left(\frac{2}{5}\dot{\tilde{\eta}} + \frac{1}{15}\dot{h}\right) - \frac{40}{3}G^{\mathrm{m}} q\, T_{\nu,0}^4\, \Psi_2(q)$$
$$+\, G^{\mathrm{m}} \int \mathrm{d}q'\, \frac{q'}{q\bar{f}(q)} \left[2K_2^{\mathrm{m}}(q,q') - \frac{2}{9}q^2\, {q'}^2 e^{-q/T_{\nu,0}}\right] \bar{f}(q')\, \Psi_2(q')\,,$$
$$\dot{\Psi}_{\ell>2}(q) = \frac{k}{2\ell+1}\left[\ell\Psi_{\ell-1}(q) - (\ell+1)\Psi_{\ell+1}(q)\right] - \frac{40}{3}G^{\mathrm{m}} q\, T_{\nu,0}^4\, \Psi_\ell(q)$$
$$+\, G^{\mathrm{m}} \int \mathrm{d}q'\, 2\frac{q'}{q\bar{f}(q)} K_\ell^{\mathrm{m}}(q,q')\, \bar{f}(q')\, \Psi_\ell(q')$$

IMO, C. Rampf, T. Tram, Y. Y. Y. Wong, 2017

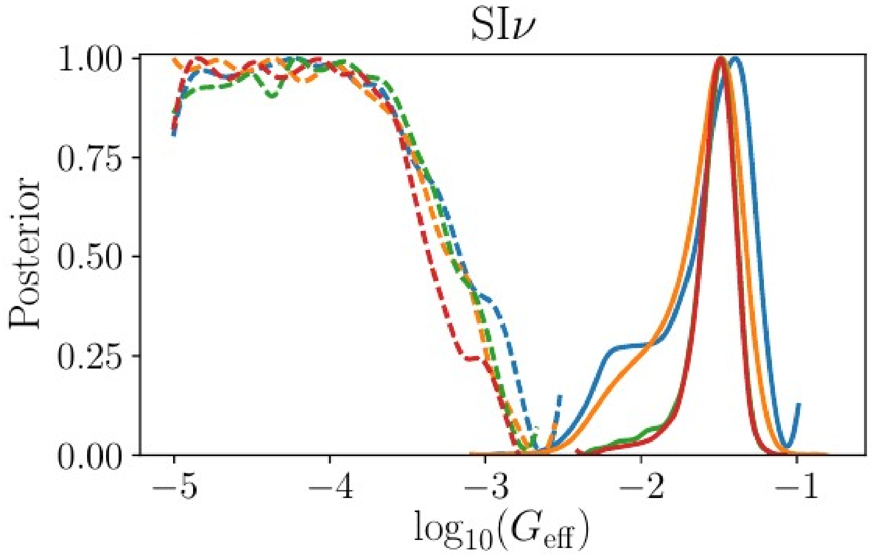
Complicated neutrino Boltzmann hierarchy → Well approximated by relaxation time approach (*Cyr-Racine, K. Sigurdson 2013*)

$$\dot{\mathcal{F}}_{\nu 2} = \frac{8}{15}\theta_\nu - \frac{3}{5}k\mathcal{F}_{\nu 3} + \frac{4}{15}\dot{h} + \frac{8}{5}\dot{\tilde{\eta}} + \frac{9}{10}\alpha_2\dot{\tau}_\nu\mathcal{F}_{\nu 2}\ ,$$

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



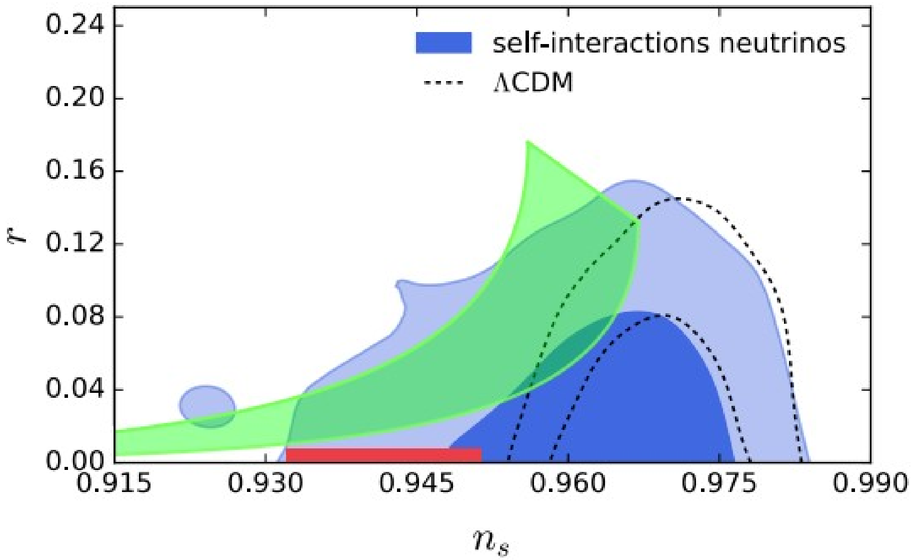
MCMC → Planck 2015



→ bimodal distribution: **strongly interacting neutrino mode**

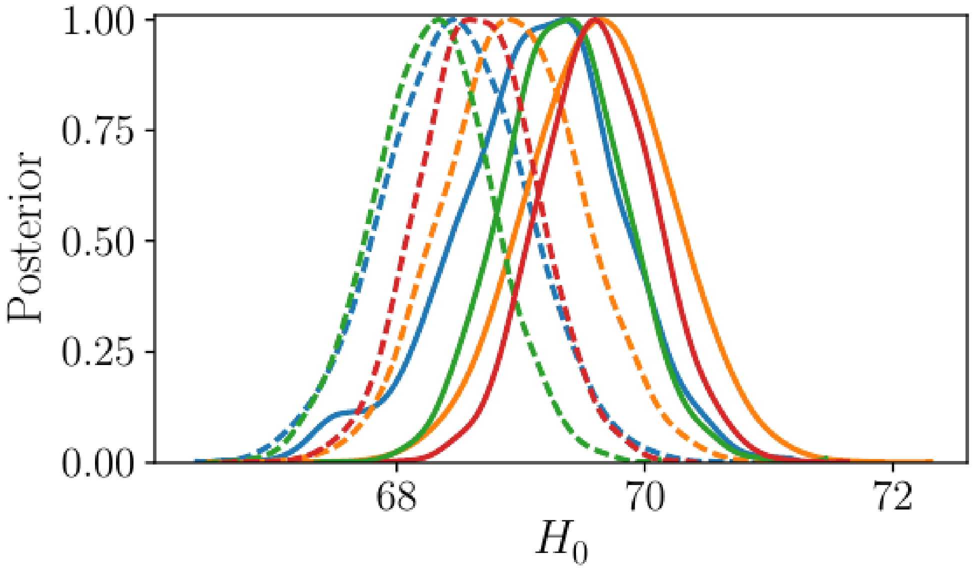
(compare e.g. with Cyr-Racine et. al. 2013, Lancaster 2017, Kreisch et al. 2019)

*G. Barenboim, P. Denton, **IMO**, 2019*



→ Interesting for inflationary model selection

***IMO**, C. Rampf, T. Tram, Y. Y. Y. Wong, 2017*



→ **Helps to weaken the Hubble tension**

"Solution of the Hubble tension"

(C. Kreisch, F.-Y. Cyr-Racine, O. Doré 2019)

Final remarks:

- **Strongly interacting mode in cosmological data is persistent.**

  (e.g. Kreisch et al. 2022, Camarena 2023)

- **CMB analysis with Planck-2018 data & different data combinations:**

  Does not solve the Hubble tension (alleviates it at most).

  (S. R. Choudhury at al. 2021 & 2022, A. Mazumdar et al. 2021, A. Das et al. 2021, T. Brinckmann et al. 2020 & 2021)

- **Strong constraints from BBN and laboratory experiments.** *(Blinov at al. 2019, K-F Lyu et al. 2020, Brdar at al. 2020)*