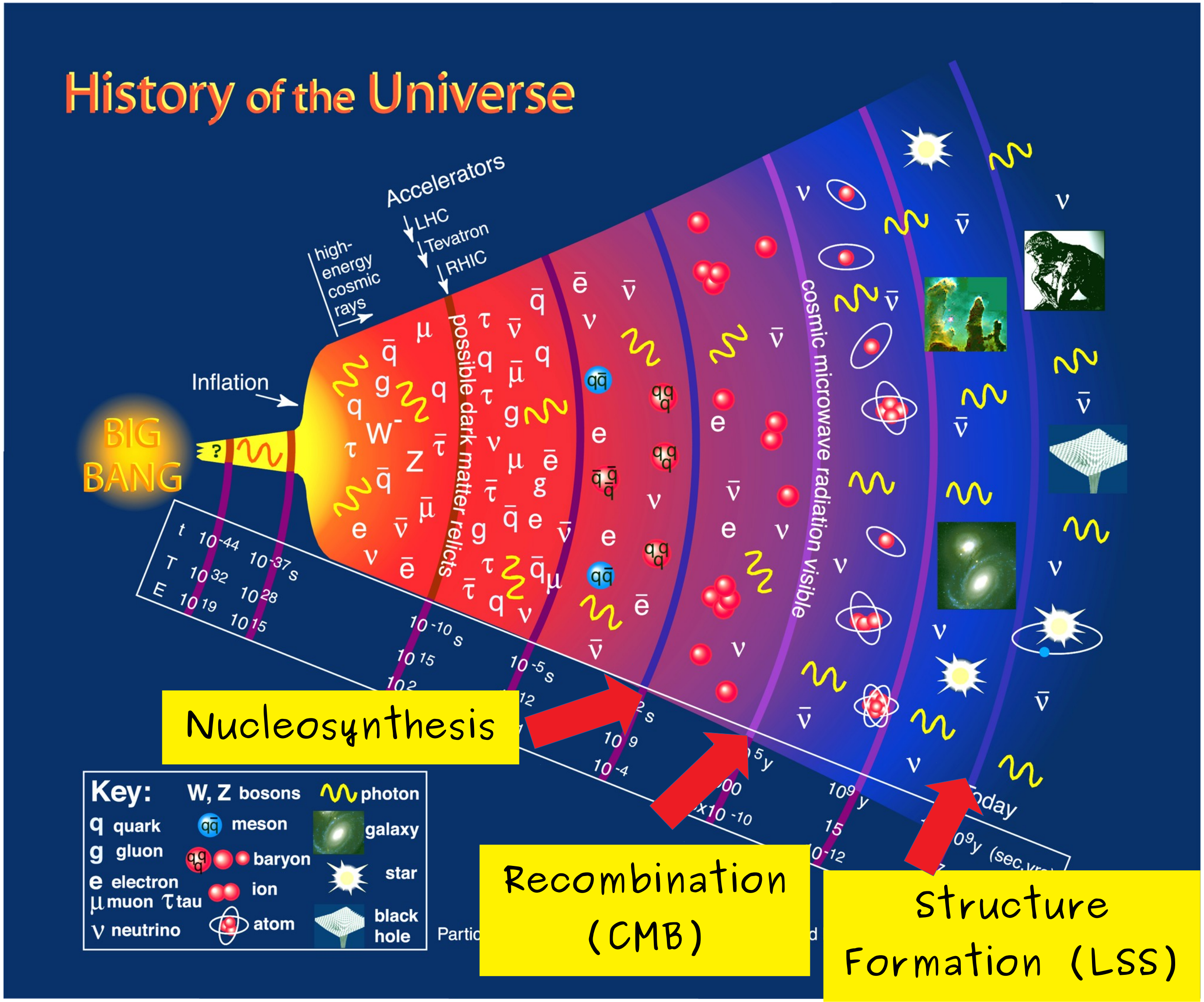
Neutrinos in Cosmology

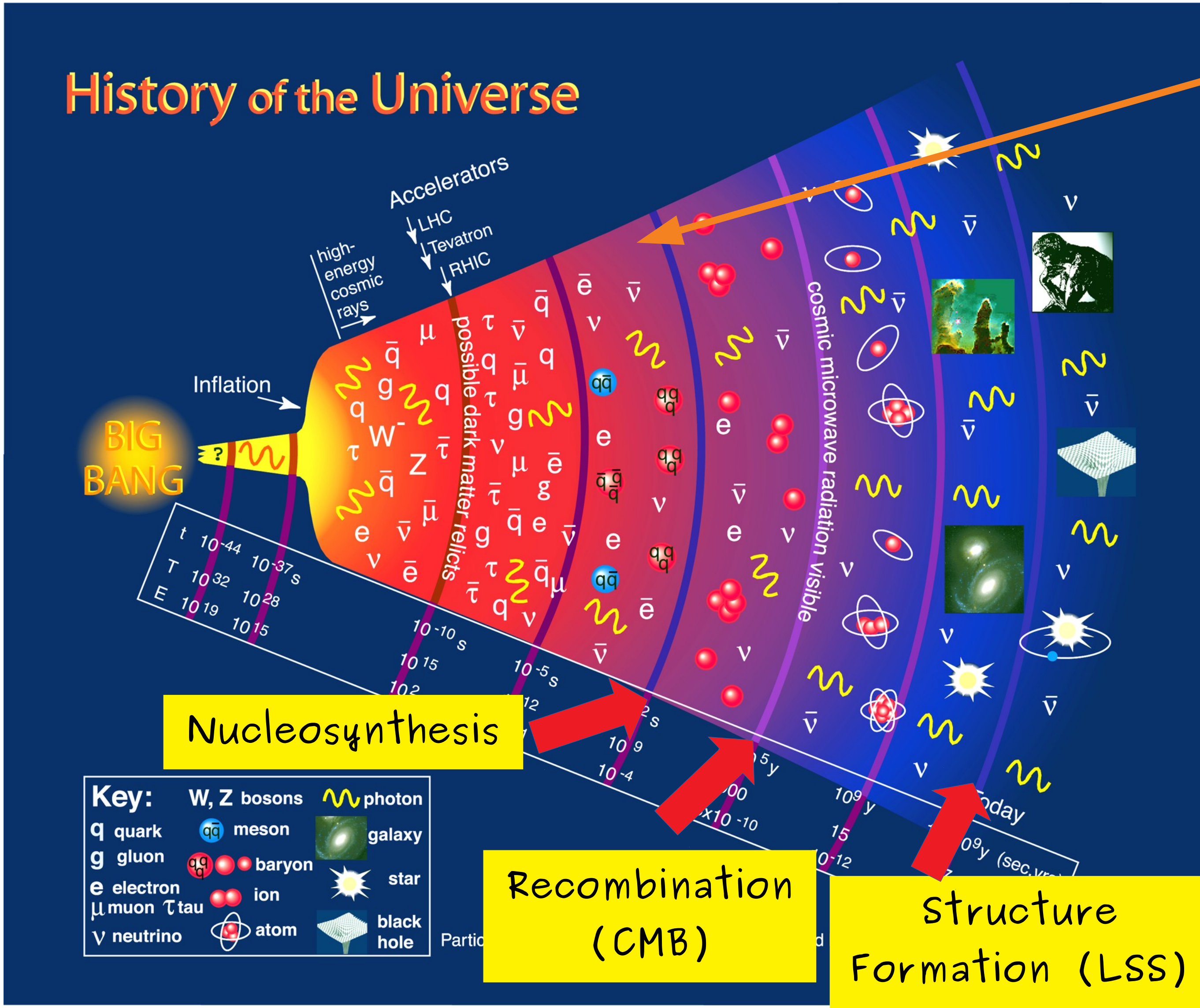
Isabel M. Oldengott

University of Valencia and IFIC

7-11 October 2019, Geneva

Neutrino Platform Week 2019: Hot Topics in Neutrino Physics


History of the Universe
BIG BANG
Inflation
high-energy cosmic rays
Accelerators
LHC
Tevatron
RHIC
possible dark matter relicts
cosmic microwave radiation visible
t 10^-44 10^-37 s
T 10^32 10^28
E 10^19 10^15
10^-10 s
10^-5 s
10^9 y
today
Key:
W, Z bosons
photon
q quark
meson
galaxy
g gluon
baryon
star
e electron
ion
μ muon τ tau
atom
black hole
ν neutrino
Nucleosynthesis
Recombination (CMB)
Structure Formation (LSS)



~ 1 MeV:

neutrino decoupling

→ cosmic neutrino background:

Temperature:

$$T_\nu^0 = \left(\frac{4}{11}\right)^{1/3} T_\gamma^0$$

$$= 1.95\,\mathrm{K}$$

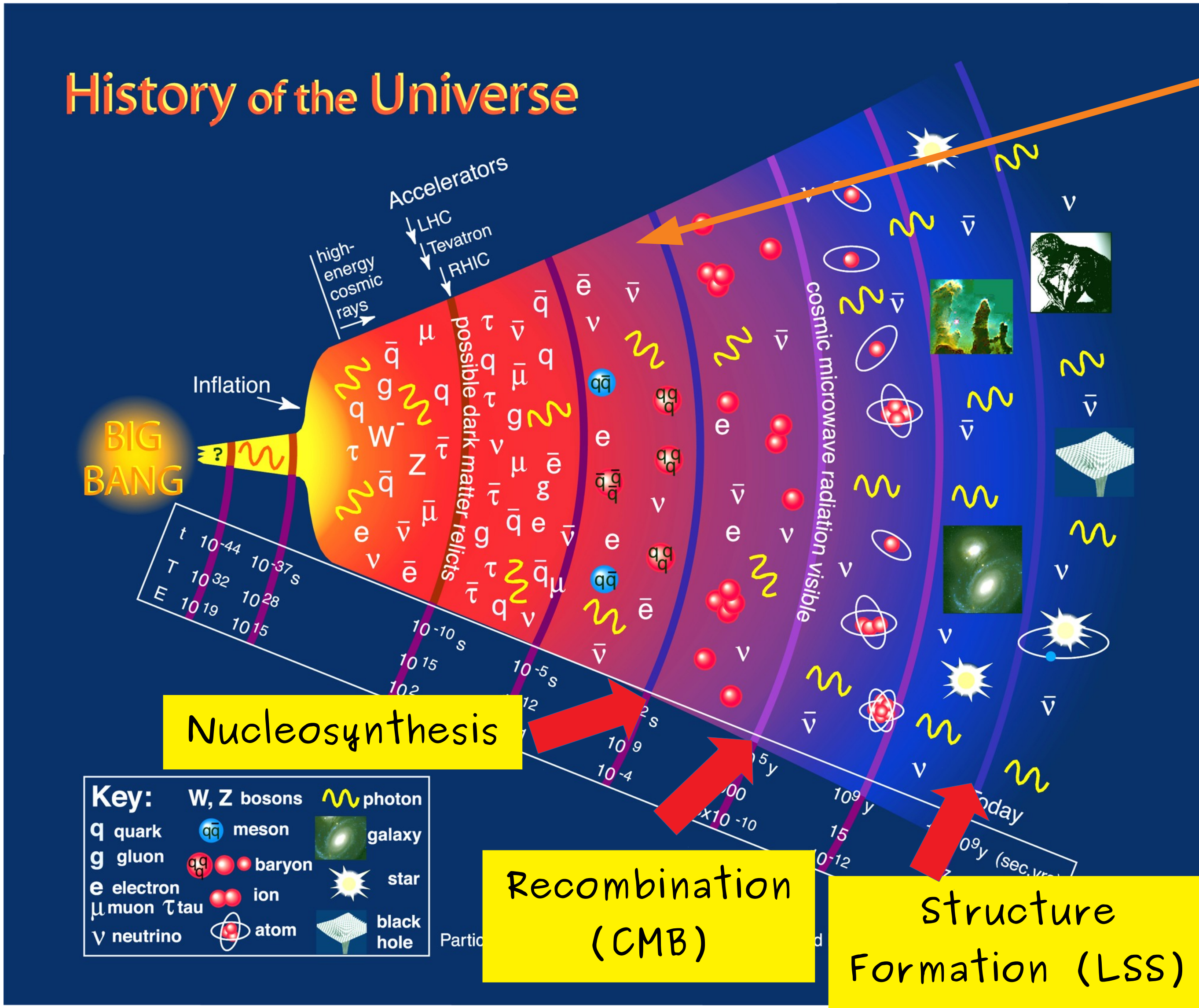
Number density:

$$n_\nu^0 \approx 112\,\mathrm{cm}^{-3}$$

Energy density:

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

Standard: **N_{eff} = 3.045** *(de Salas & Pastor 2016)*



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Ways to enhance N_{eff}:
non-standard temperature, number of species, chemical potentials, distribution, etc.

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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
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What can cosmology teach us about neutrinos?

→ Let's first look at N_{eff} and Σm_ν

Big Bang Nucleosynthesis

Early times: weak interactions

$$p + \bar{\nu}_e \leftrightarrow n + e^+$$

$$p + e^- \leftrightarrow n + \nu_e$$

$$n \leftrightarrow p + e^- + \bar{\nu}_e$$

Big Bang Nucleosynthesis

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freeze-out

$$\left(\frac{n}{p}\right)_{\mathrm{eq}} \approx e^{-(m_\mathrm{n} - m_\mathrm{p})/T}$$

Big Bang Nucleosynthesis

Early times: weak interactions → $\mathcal{O}(1\,\mathrm{MeV})$ → $\mathcal{O}(0.1\,\mathrm{MeV})$

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Onset of nuclear reactions

$$\left(\frac{n}{p}\right)_{\mathrm{BBN}} \approx \frac{1}{7}$$

→ ^{2}H, ^{3}H, ^{3}He, ^{4}He etc.

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Expansion rate (N_{eff}), distribution function (only ν_e)

Neutrinos

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↑

Neutrinos

$$Y_\mathrm{p} = 0.2449 \pm 0.004$$ *(Aver et al. 2015)*

$$y_\mathrm{DP} = 2.527 \pm 0.030$$ *(Cooke et al. 2018)*

$$N_{\mathrm{eff}} = 2.92 \pm 0.2\,(68\%\,\mathrm{CL})$$

(Pitrou et al. 2018, PRIMAT code)

$$N_{\mathrm{eff}} = 2.87^{+0.24}_{-0.21}\,(68\%\,\mathrm{CL})$$

(Consiglio et al. 2018, PArthENoPE code)

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

Recombination → Universe gets transparent to photons

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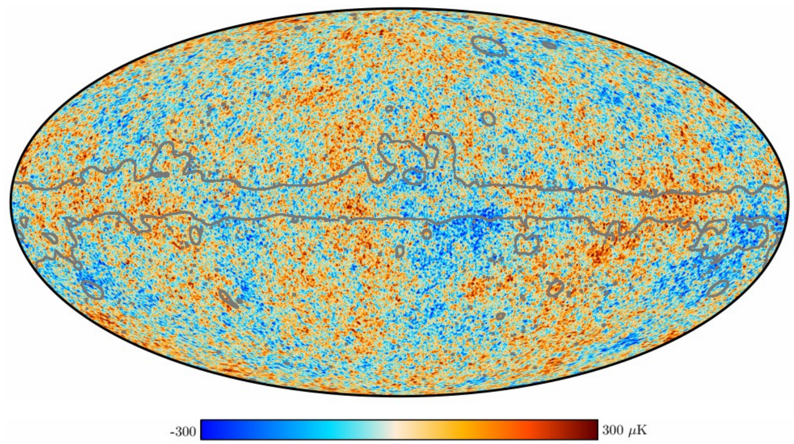
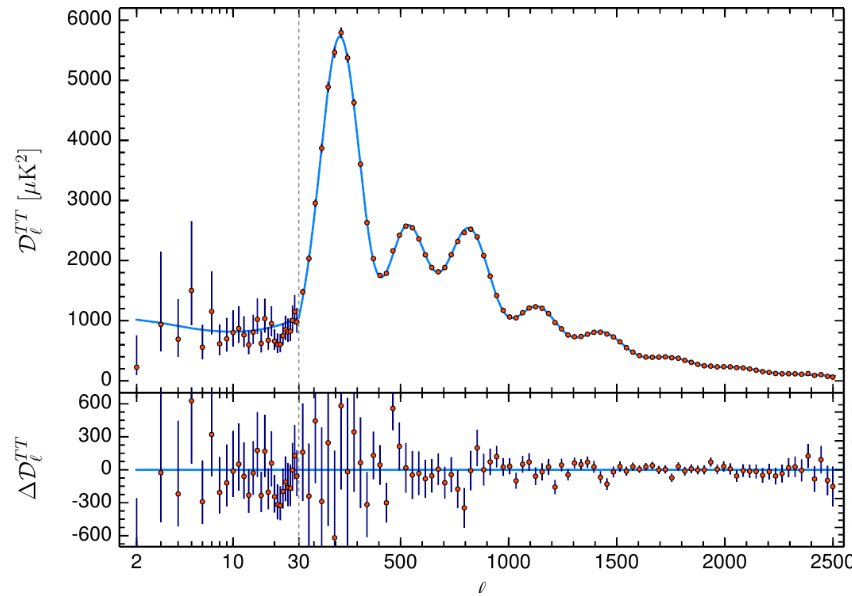
(Redshifted) photo of the early Universe





(Planck 2018)

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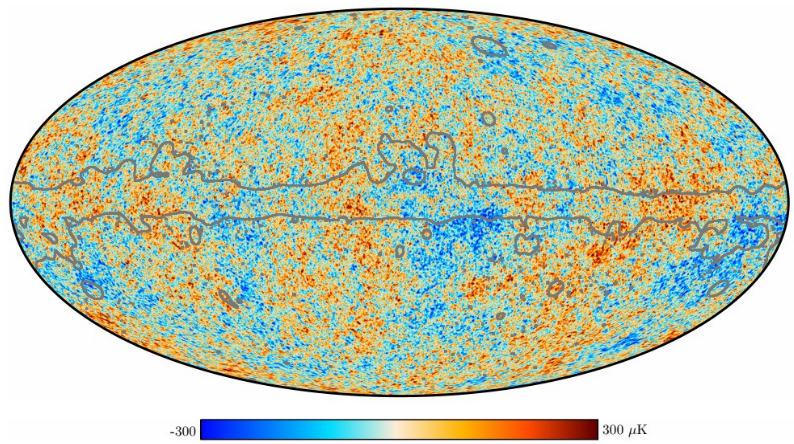
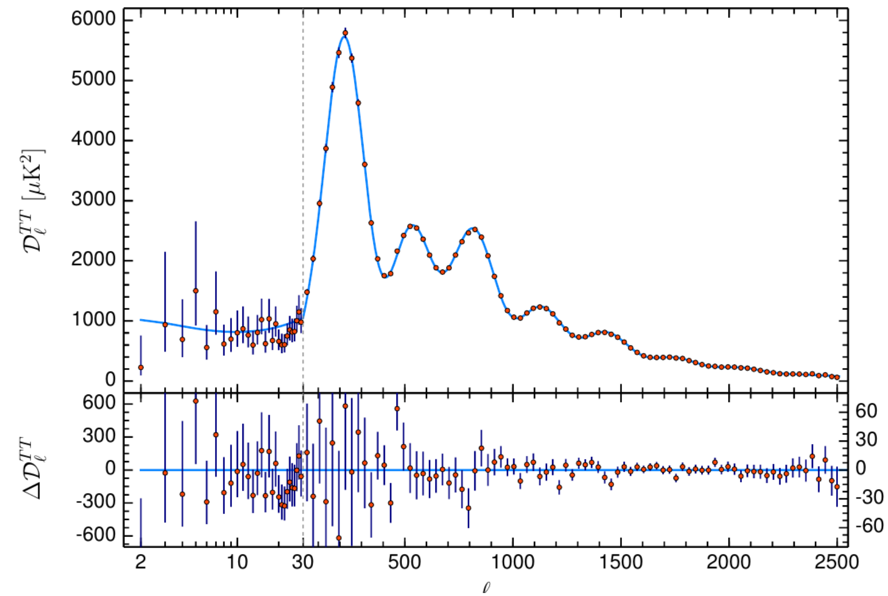
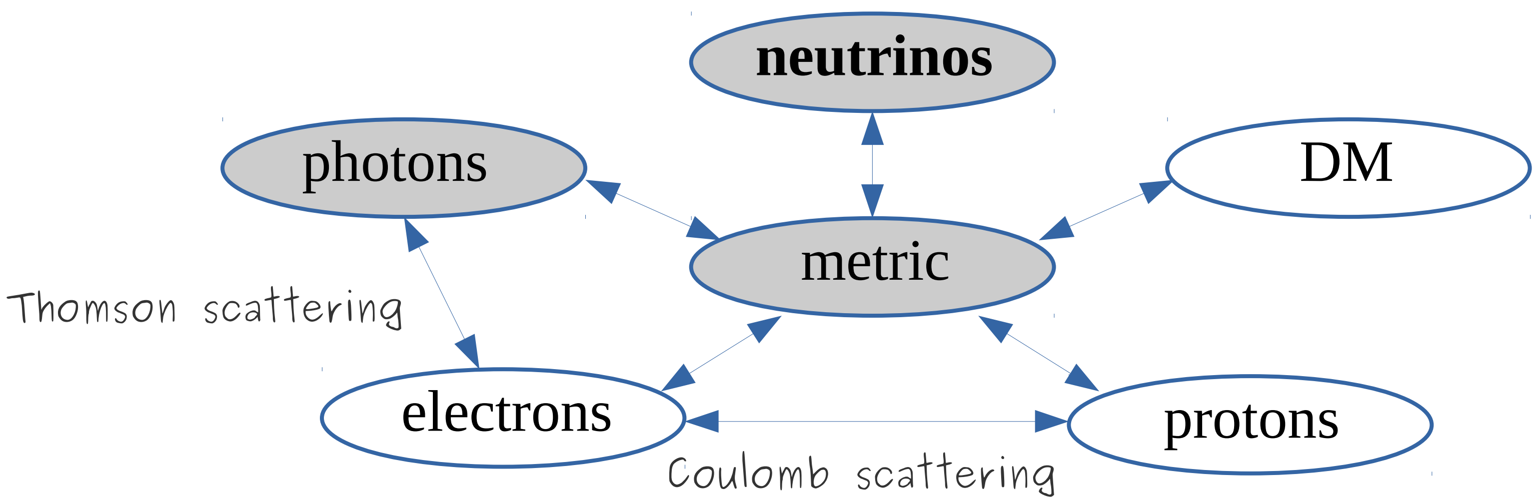


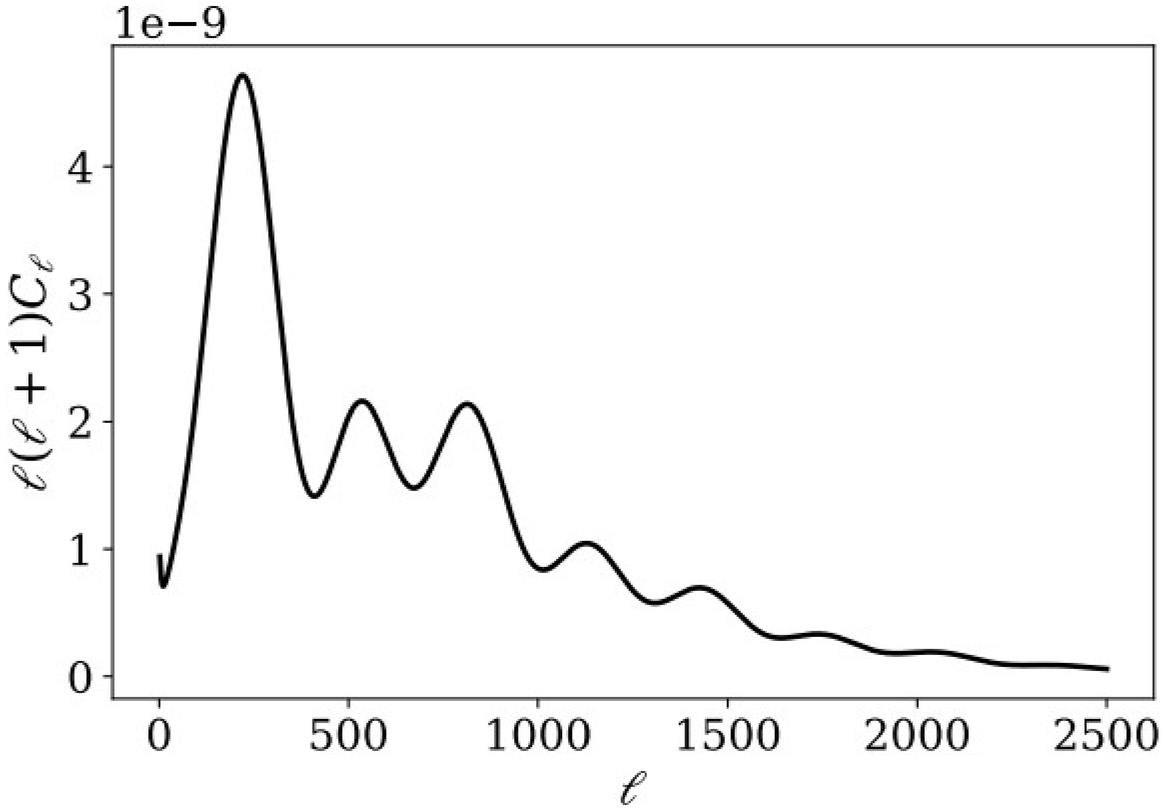


(Planck 2018)

→ Fluctuations in the photon temperature/density:



Neutrinos behave at early times as radiation, at late times matter



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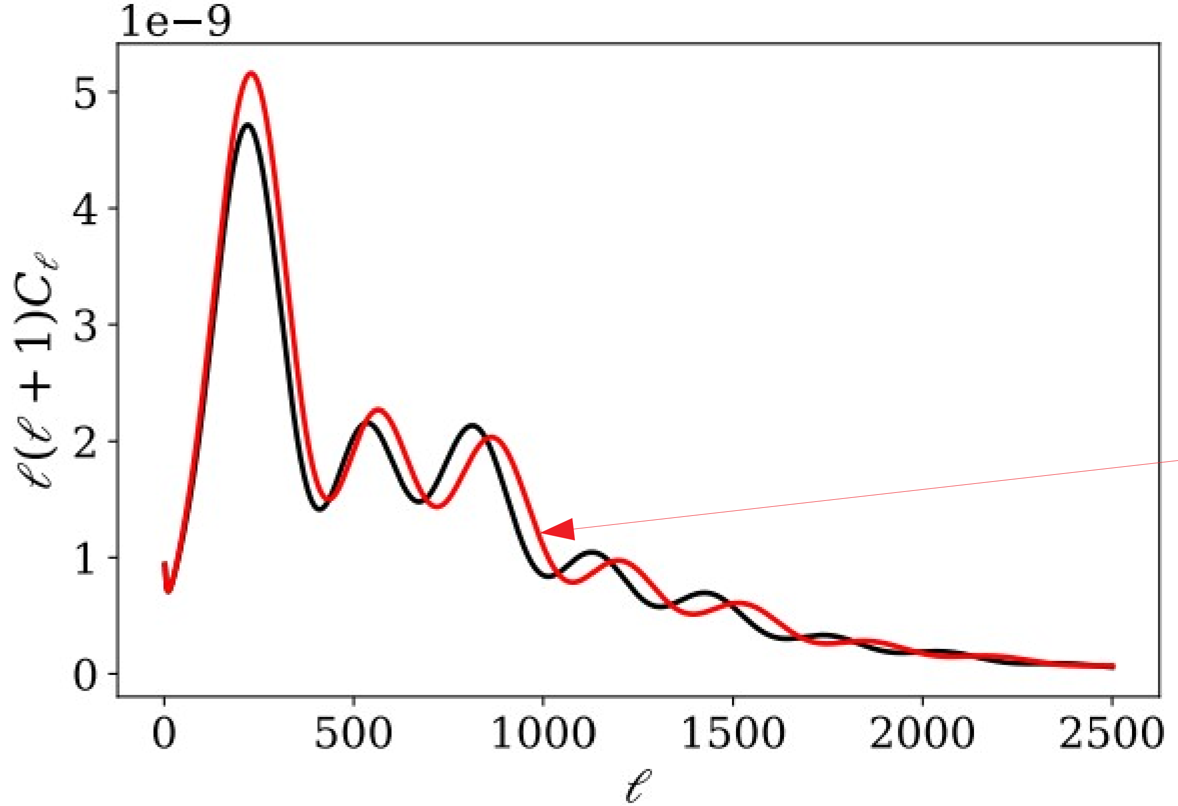


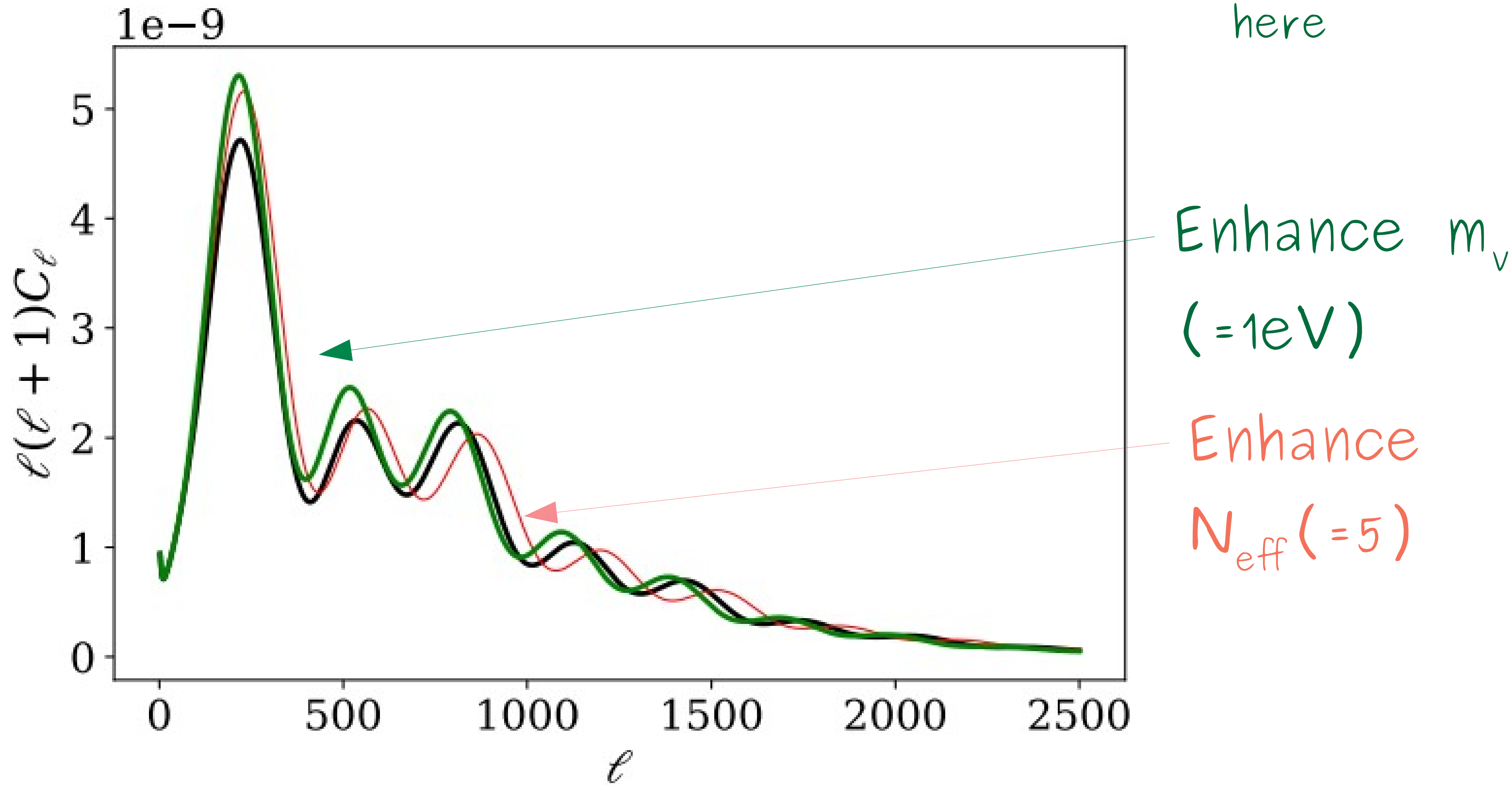
$N_{\rm eff} = 2.92^{+0.36}_{-0.37}$ (95% CL) (TT,TE,EE+lowE)

Planck 2018

Neutrinos behave at early times as radiation, at late times matter

Whenever we talk about the impact of neutrino masses → $\Omega_\Lambda + \Omega_b + \Omega_{cdm} + \Omega_\nu = 1$

here



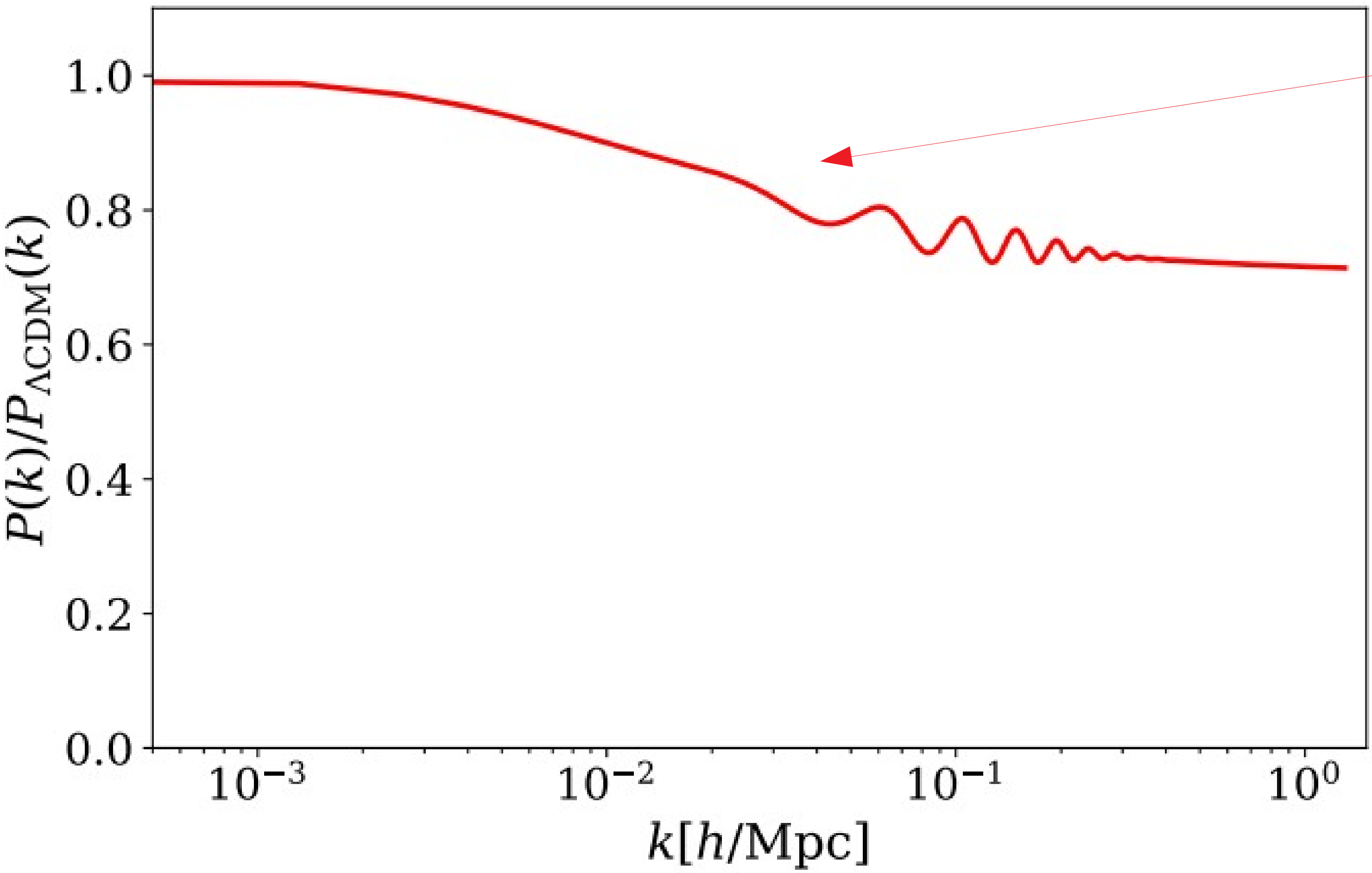
$N_{\rm eff} = 2.92^{+0.36}_{-0.37}$ (95% CL) (TT,TE,EE+lowE)

$\sum m_\nu < 0.257\,\mathrm{eV}$ (95% CL) (TT,TE,EE+lowE)

Planck 2018

Large Scale Structure

Free-streaming suppresses the growth of structure below the free-streaming length



Enhance N_{eff} (=5)

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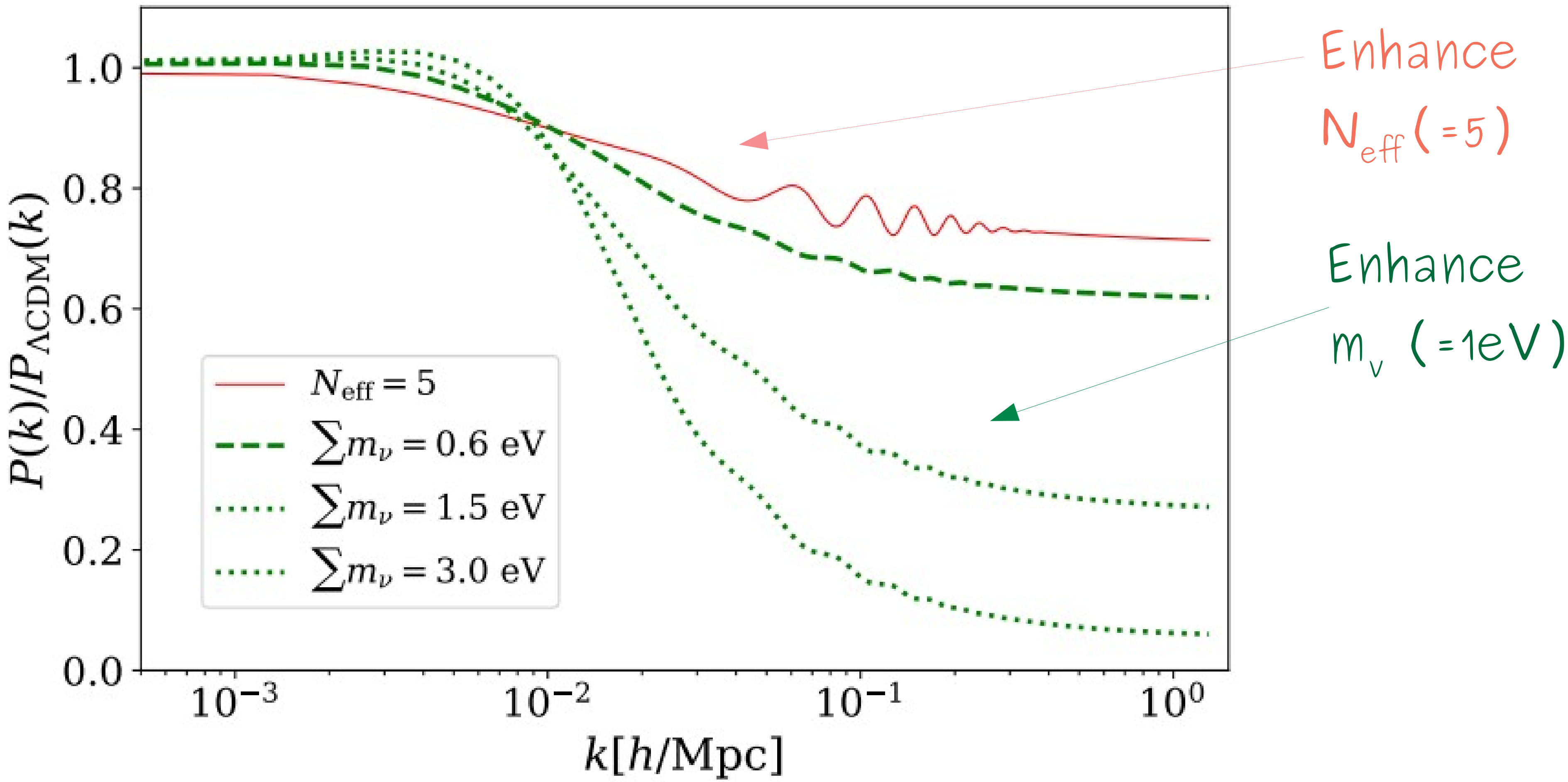

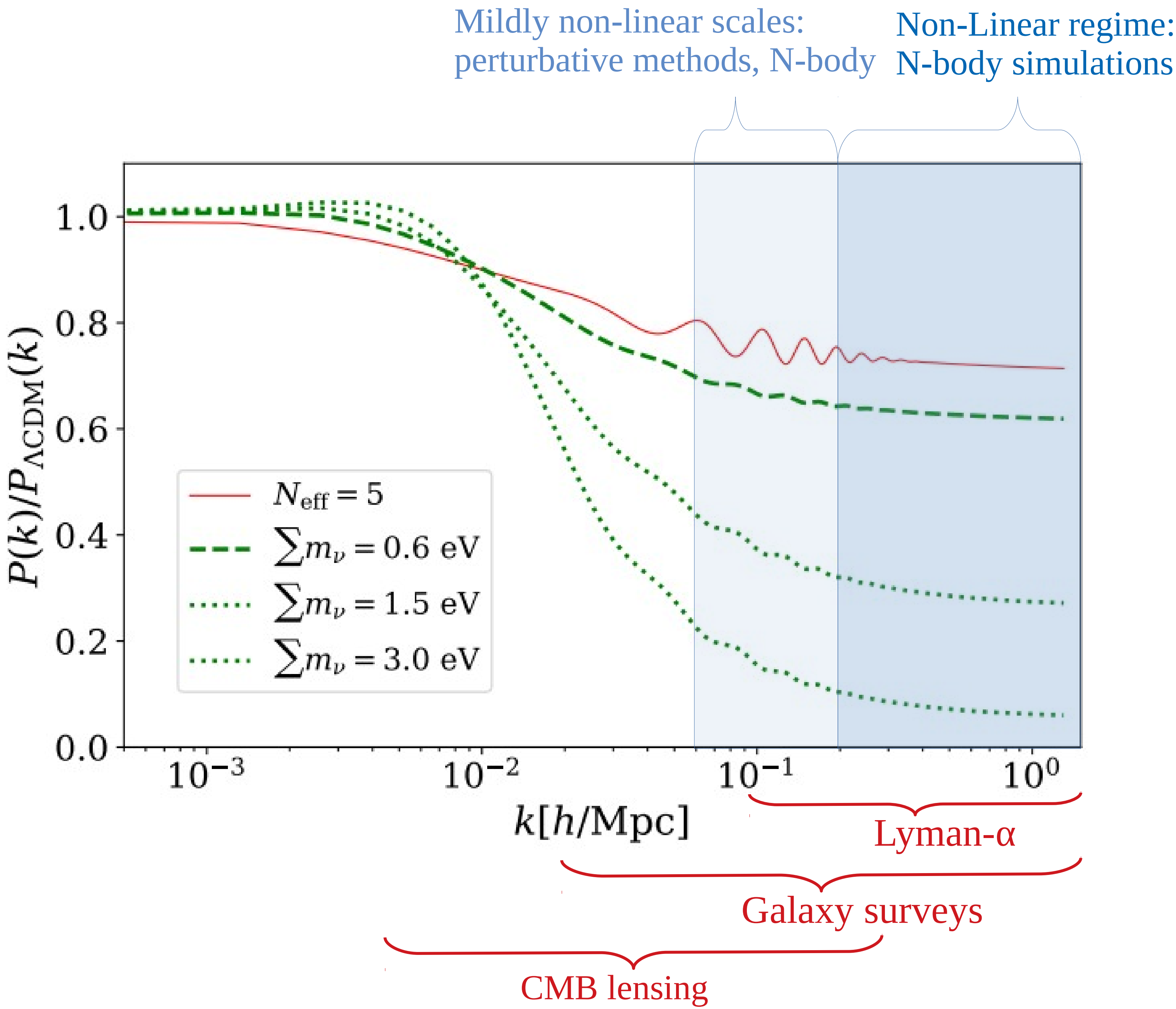
Mildly non-linear scales:
perturbative methods, N-body
Non-Linear regime:
N-body simulations
$P(k)/P_{\Lambda\mathrm{CDM}}(k)$
1.0
0.8
0.6
0.4
0.2
0.0
$N_{\mathrm{eff}} = 5$
$\sum m_\nu = 0.6$ eV
$\sum m_\nu = 1.5$ eV
$\sum m_\nu = 3.0$ eV
10^{-3}
10^{-2}
10^{-1}
10^{0}
$k[h/\mathrm{Mpc}]$
Lyman-α
Galaxy surveys
CMB lensing

Adding information from LSS

No big improvement on N_{eff}

$$\sum m_\nu < 0.241\,\mathrm{eV} \qquad \text{(TT,TE,EE+lowE +lensing)}$$

(Planck 2018)

$$\sum m_\nu < 0.120\,\mathrm{eV} \qquad \text{(TT,TE,EE+lowE +lensing +BaO)}$$

SDSS, BOSS, 6dFGS

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+ adding even more LSS data (but Planck 2015)…:

Lyman-α *(Palanque-Delabrouille et al. 2015)*

Full shape matter power spectrum *(Vagnozzi et al. 2017)*

Weak lensing *(KiDs, DES)*

Cluster counts *(SZ cluster count dataset, Planck)*

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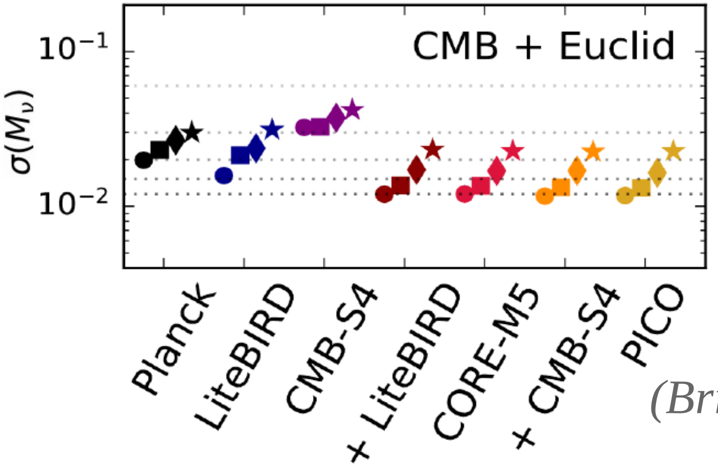

+ DESI + SKA

(Brinckmann et al. 2018)

Forecasts promise to reach a sensitivity of $\sigma(M_\nu) \approx 0.02$ eV & $\sigma(N_{eff}) \approx 0.06$

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Non-standard neutrino interactions

IMO et al. 2014, IMO et al. 2017, Barenboim et al. 2019*, Cyr-Racine et. al. 2013, Lancaster 2017, Kreisch et al. 2019*

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

Massive scalar → $G_{\rm eff} = \dfrac{g^2}{m_\phi^2}$

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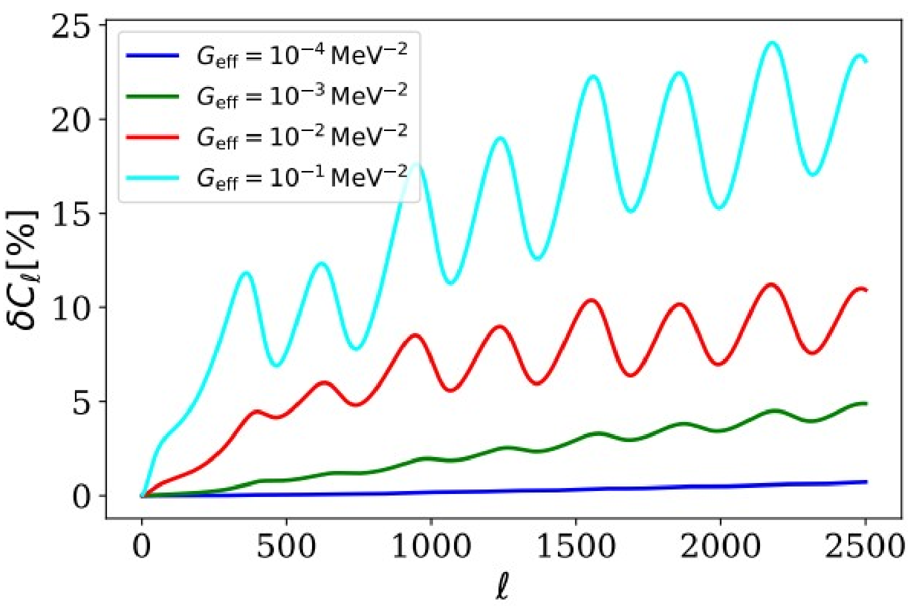
neutrino self-interactions → delayed decoupling → suppressed free-streaming:



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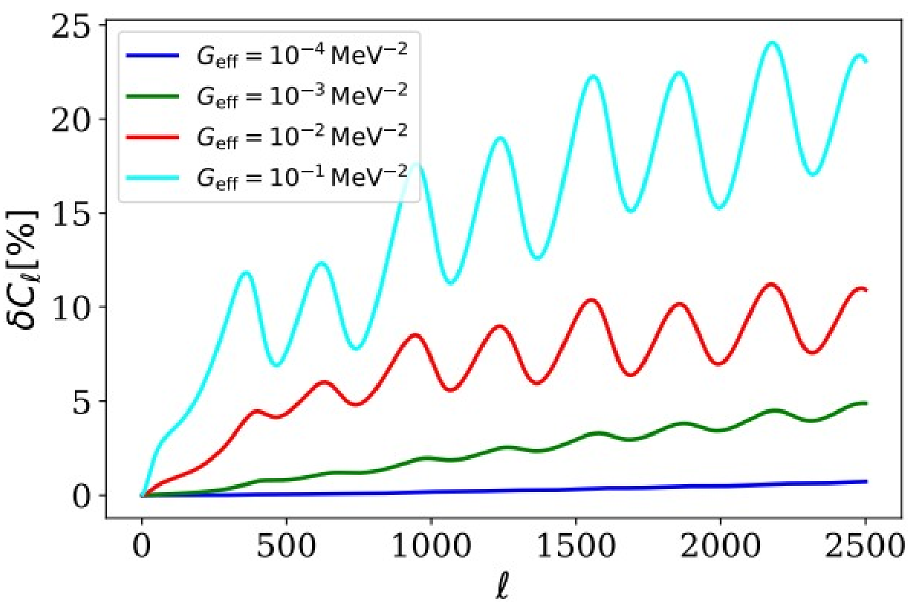
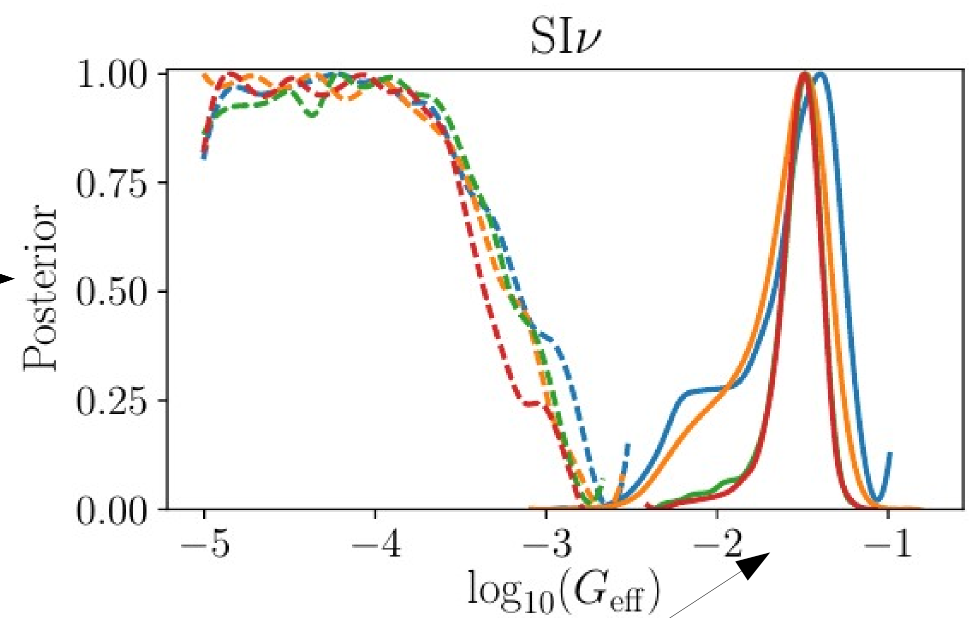


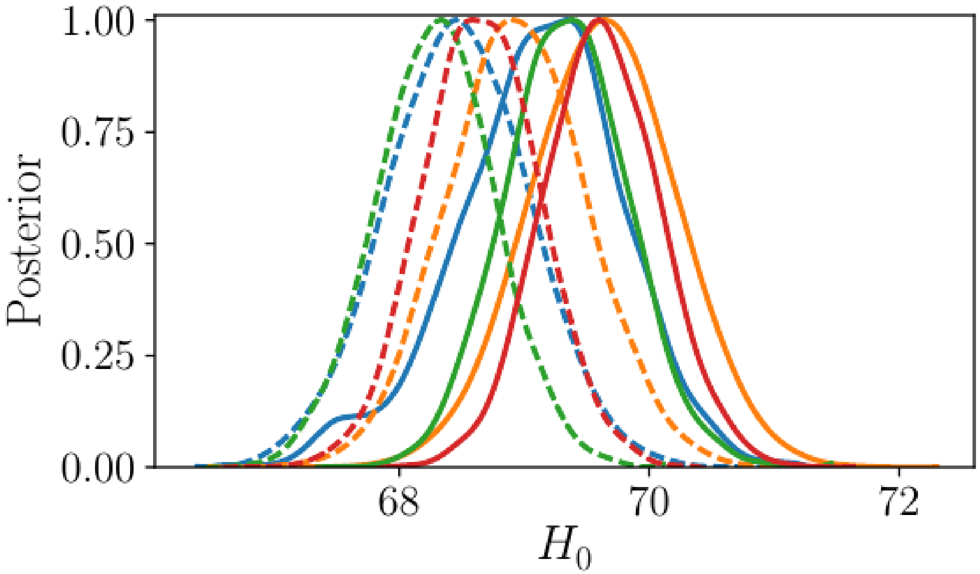
MCMC

Planck 2015



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

strongly interacting mode → consequences for constraints on n_s, H_0



→ Helps to weaken the Hubble tension

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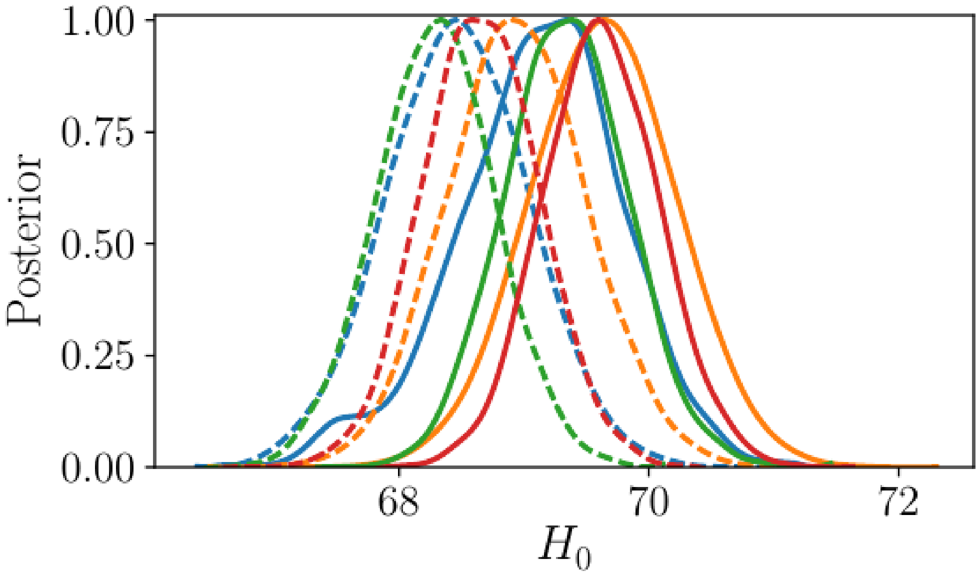

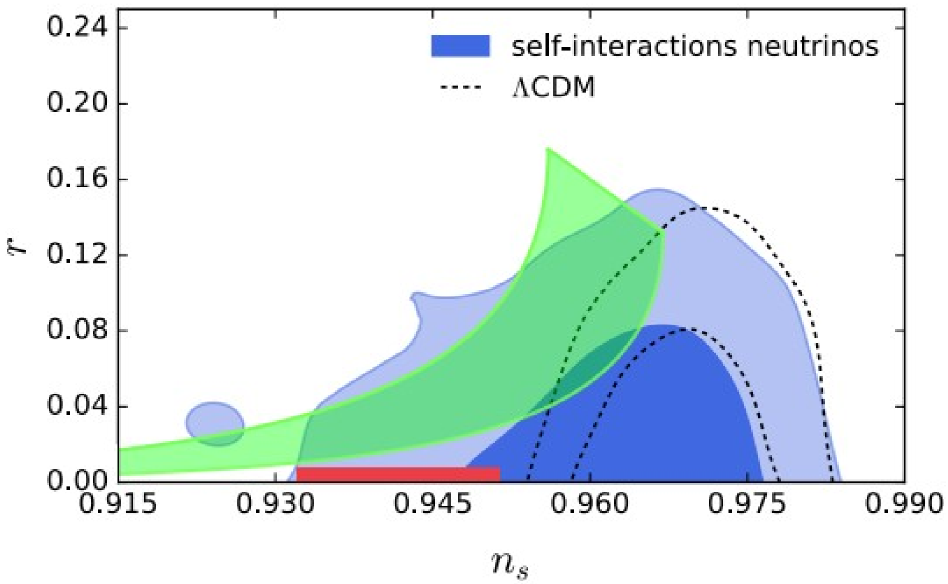

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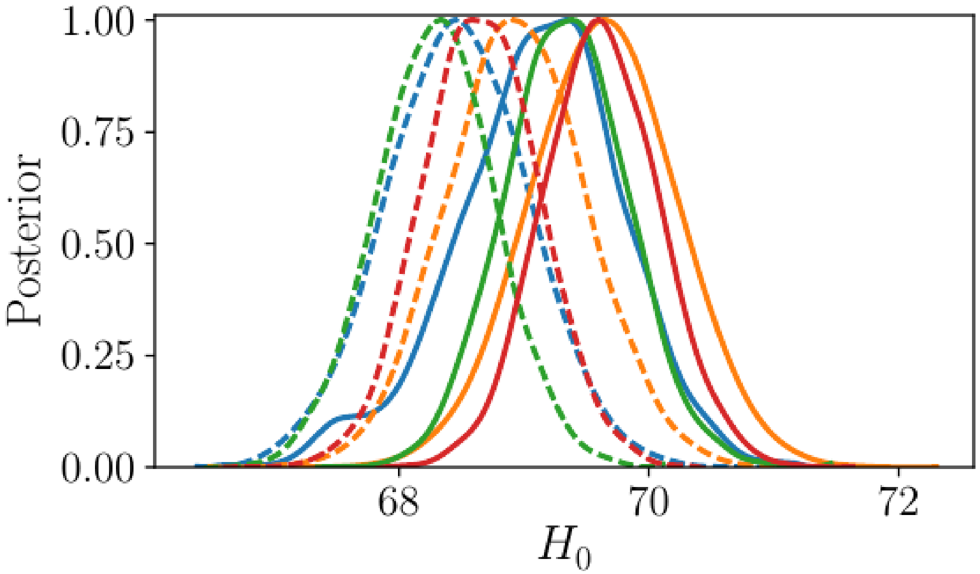
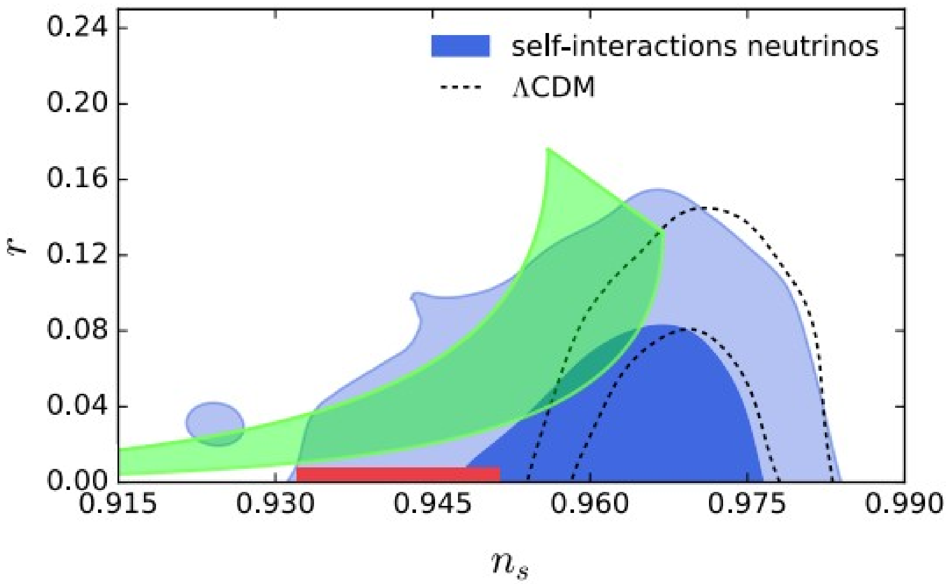
→ Interesting for inflationary model selection strongly interacting mode → consequences for constraints on n_s, H_0





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Including neutrino masses and N_{eff} makes the strongly interacting mode even more significant *(Kreisch et al. 2019)*

Other models

Light mediator *(Forastieri 2019, Forastieri 2015)*

0.1 eV – 1 MeV range *(Escudero & Witte 2019)*

Decaying neutrinos *(Esudero & Fairbairn 2019, Hannestad & Raffelt 2005)*

Sterile neutrino interactions *(Forastieri et al. 2017, Archidiacono 2014&2015&2016)*

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Non-standard relic neutrino distributions *(IMO et al. 2019)*

Impact on cosmological observables? → degenerate with N_{eff}

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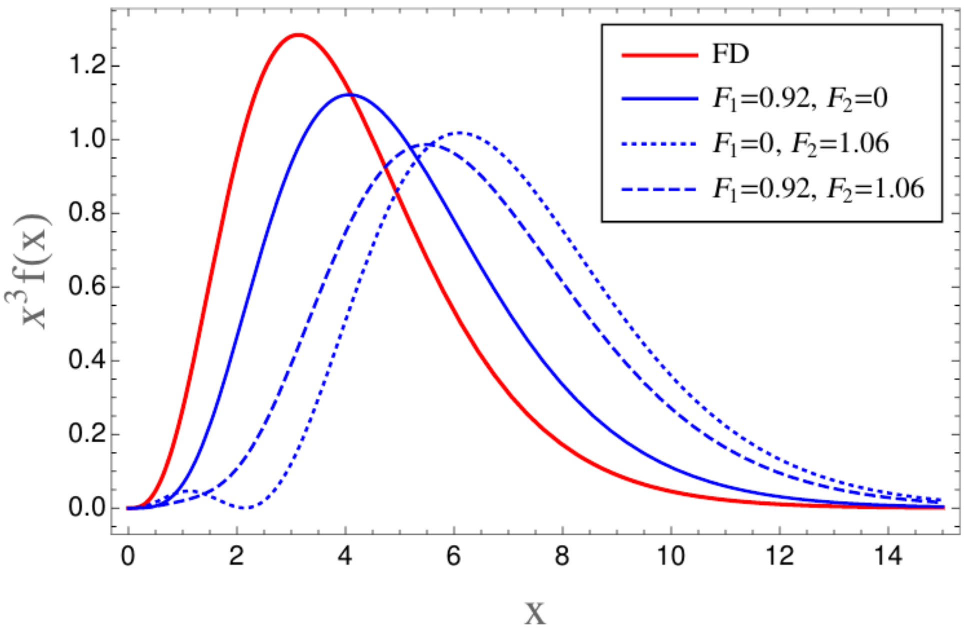

Model independent parametrization (expansion in orthonormal polynomials):

$$f_\nu(x) = N \cdot \frac{1}{e^x + 1}\Big(p_0(x) + F_1 p_1(x) + F_2 p_2(x)\Big)$$

Normalize such that N_{eff}=3.045

(Yes, there can be models for that.)

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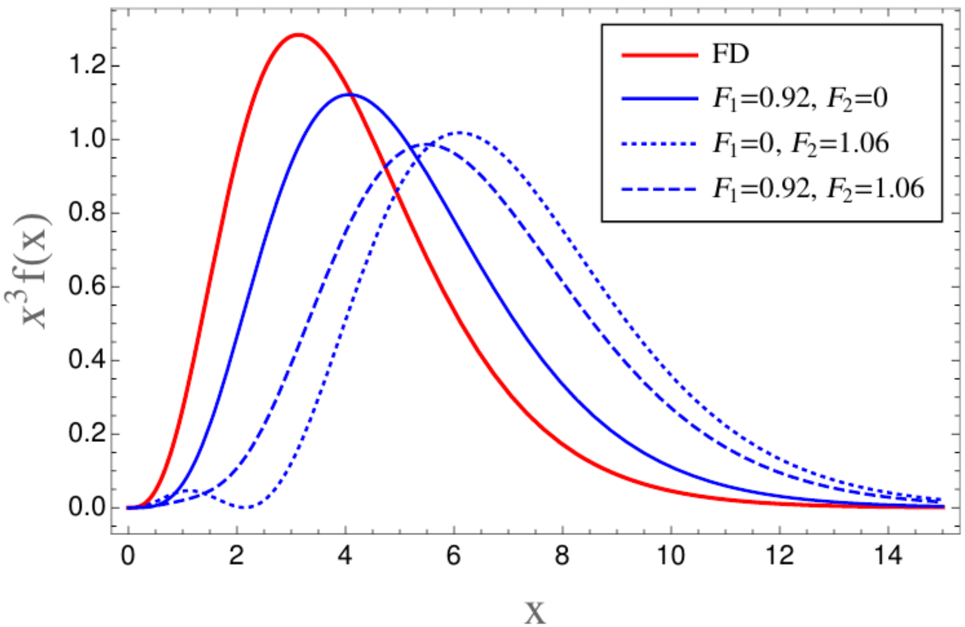

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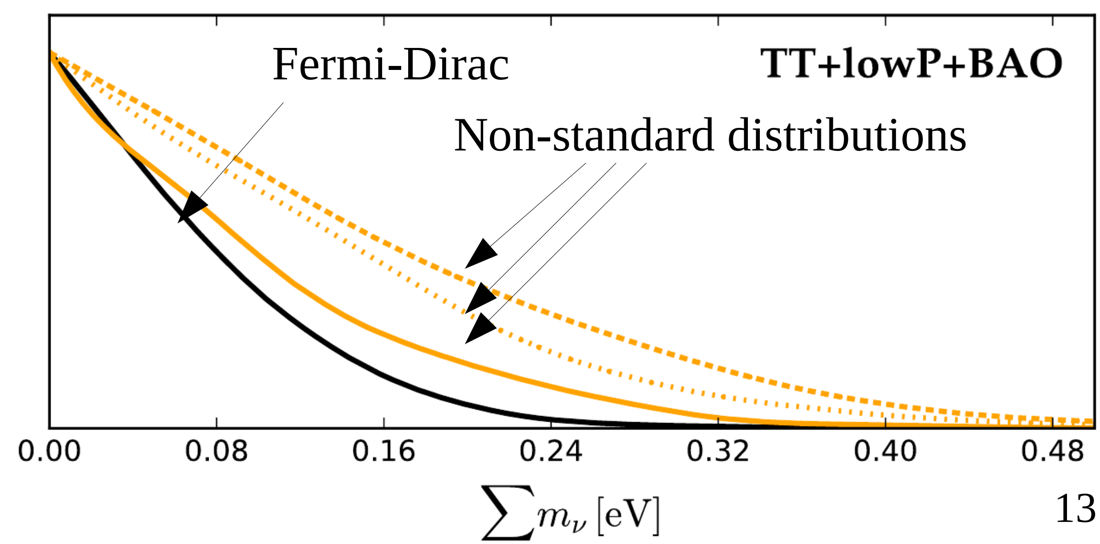
→ no unique imprint: **intrinsically degenerate with Σm_ν** and N_{eff}

Cosmological neutrino mass bound strongly depends on our assumption about the relic neutrino distribution

(here: relaxation about ≈ 100%)



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Non-negligible Lepton Asymmetry

Baryon asymmetry $$\eta_b = \frac{n_b - n_{\bar{b}}}{n_\gamma} = (6.099 \pm 0.044) \times 10^{-10}$$ → Tiny and very well measured

Standard assumption: lepton asymmetry ≈ baryon asymmetry

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Agnostic point of view: lepton asymmetry = free parameter for cosmology

Large lepton asymmetry: $$\eta_{\rm l} \approx \sum_{\alpha=e,\mu,\tau} \eta_{\nu,\alpha} = \frac{1}{12\zeta(3)} \left(\frac{4}{11}\right) \sum_{\alpha=e,\mu,\tau} (\pi^2 \xi_\alpha + \xi_\alpha^3)$$

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I) Change energy density $$\Delta N_{eff} = \frac{15}{7} \sum_\alpha \left(\frac{\xi_\alpha}{\pi}\right)^2 \left[2 + \left(\frac{\xi_\alpha}{\pi}\right)^2\right] \geq 0$$

II) Change weak interactions (only ν_e)

} Change expansion rate and Y_p

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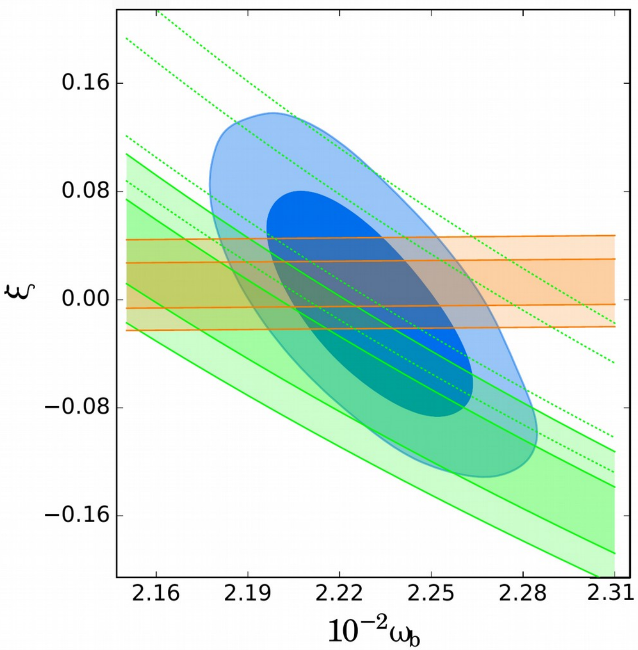

CMB analysis *(IMO & Schwarz 2017)*

$$\xi = -0.002^{+0.053}_{-0.060}\ (68\%\ \mathrm{CL}) \Rightarrow -0.046 \leq \eta_l \leq 0.038$$

→ Could still be orders of magtnitude larger than baryon asymmetry

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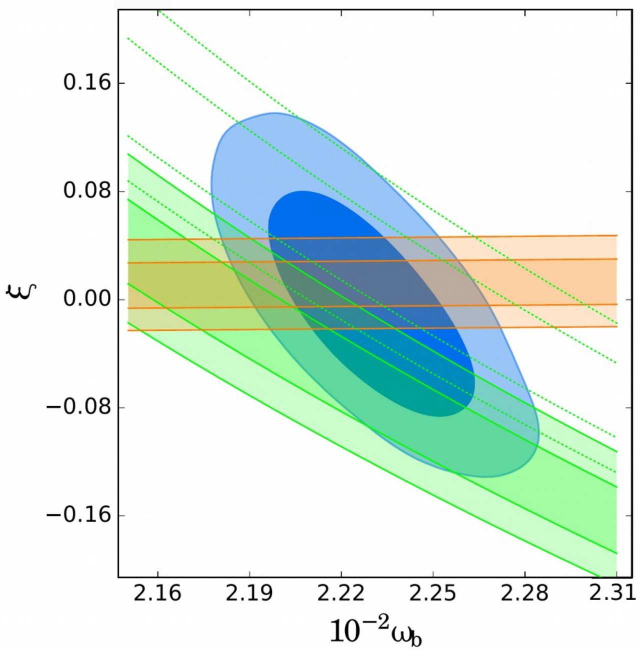
Agnostic point of view: lepton asymmetry = free parameter for cosmology

Large lepton asymmetry: $$\eta_l \approx \sum_{\alpha=e,\mu,\tau} \eta_{\nu,\alpha} = \frac{1}{12\zeta(3)} \left(\frac{4}{11}\right) \sum_{\alpha=e,\mu,\tau} (\pi^2 \xi_\alpha + \xi_\alpha^3)$$

I) Change energy density $$\Delta N_{eff} = \frac{15}{7} \sum_\alpha \left(\frac{\xi_\alpha}{\pi}\right)^2 \left[2 + \left(\frac{\xi_\alpha}{\pi}\right)^2\right] \geq 0$$

II) Change weak interactions (only ν_e)

} Change expansion rate and Y_p



CMB analysis *(IMO & Schwarz 2017)*

$$\xi = -0.002^{+0.053}_{-0.060} \; (68\% \text{ CL}) \Rightarrow -0.046 \leq \eta_l \leq 0.038$$

→ Could still be orders of magnitude larger than baryon asymmetry

BBN analysis *(Pitrou et al 2018)*

PRIMAT (Pitrou et al. 2018) $\xi = 0.001^{+0.016}_{-0.016} \; (68\% \text{ CL})$

ParthENoPE (Consiglio et al. 2017) $\xi = 0.021^{+0.016}_{-0.016} \; (68\% \text{ CL})$

→ theoretical uncertainties in deuterium prediction…

Cosmological data provide insights into neutrino properties at energies of $\approx 10^{-5}$ eV – 0.1 MeV.

They are a powerful tool in order to constrain N_{eff} and m_v. But this is not the end of the story, they can also be used to learn about non-standard scenarios.

New data are coming in the next years, so stay tuned.

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Thank you!