Cosmological Constraints on Neutrinos

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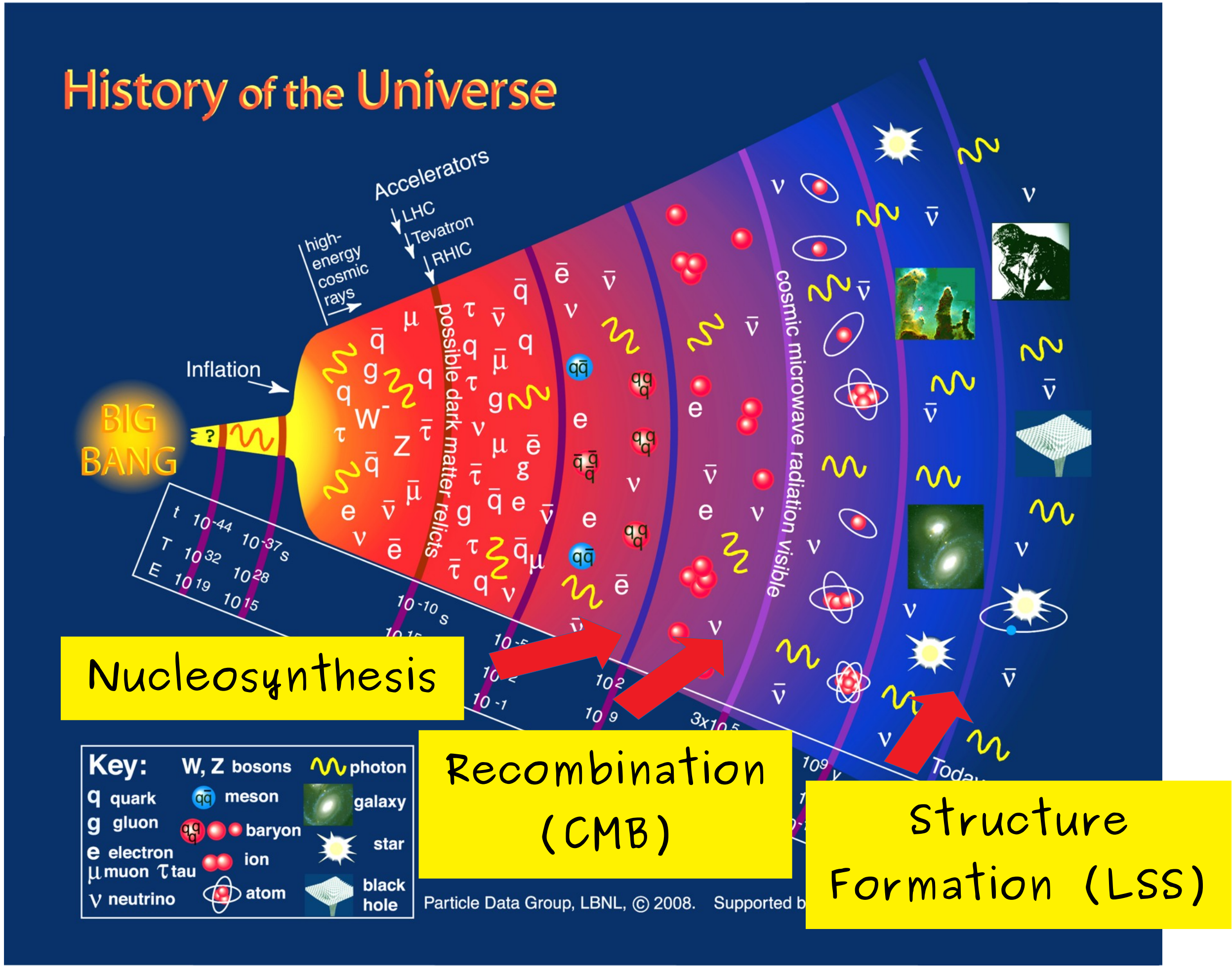
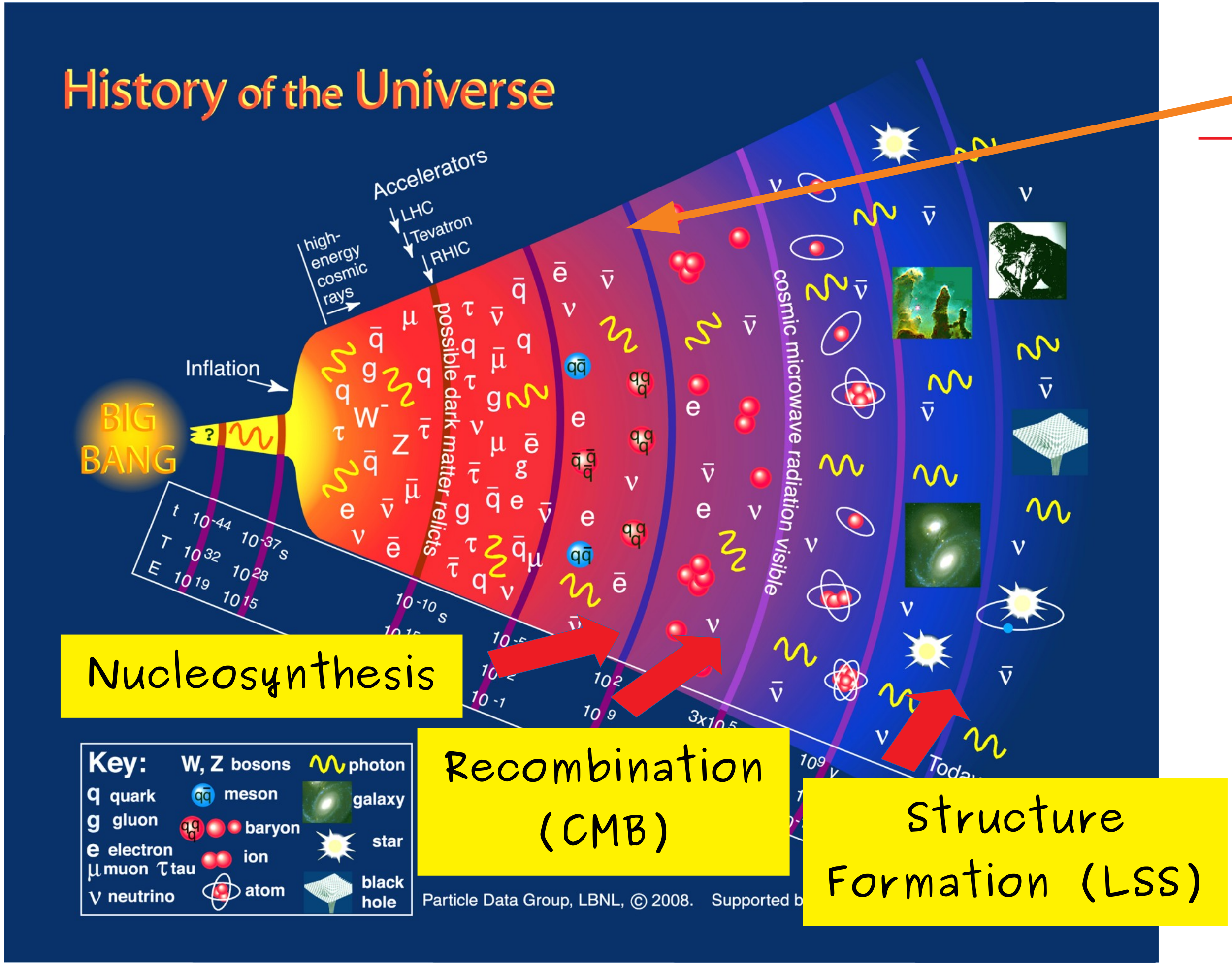
Rencontres de Blois



History of the Universe
Accelerators
LHC
Tevatron
RHIC
high-energy cosmic rays
Inflation
BIG BANG
possible dark matter relics
cosmic microwave radiation visible
Key:
W, Z bosons
photon
q quark
meson
galaxy
g gluon
baryon
e electron
star
µ muon τ tau
ion
ν neutrino
atom
black hole
Particle Data Group, LBNL, © 2008.
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:

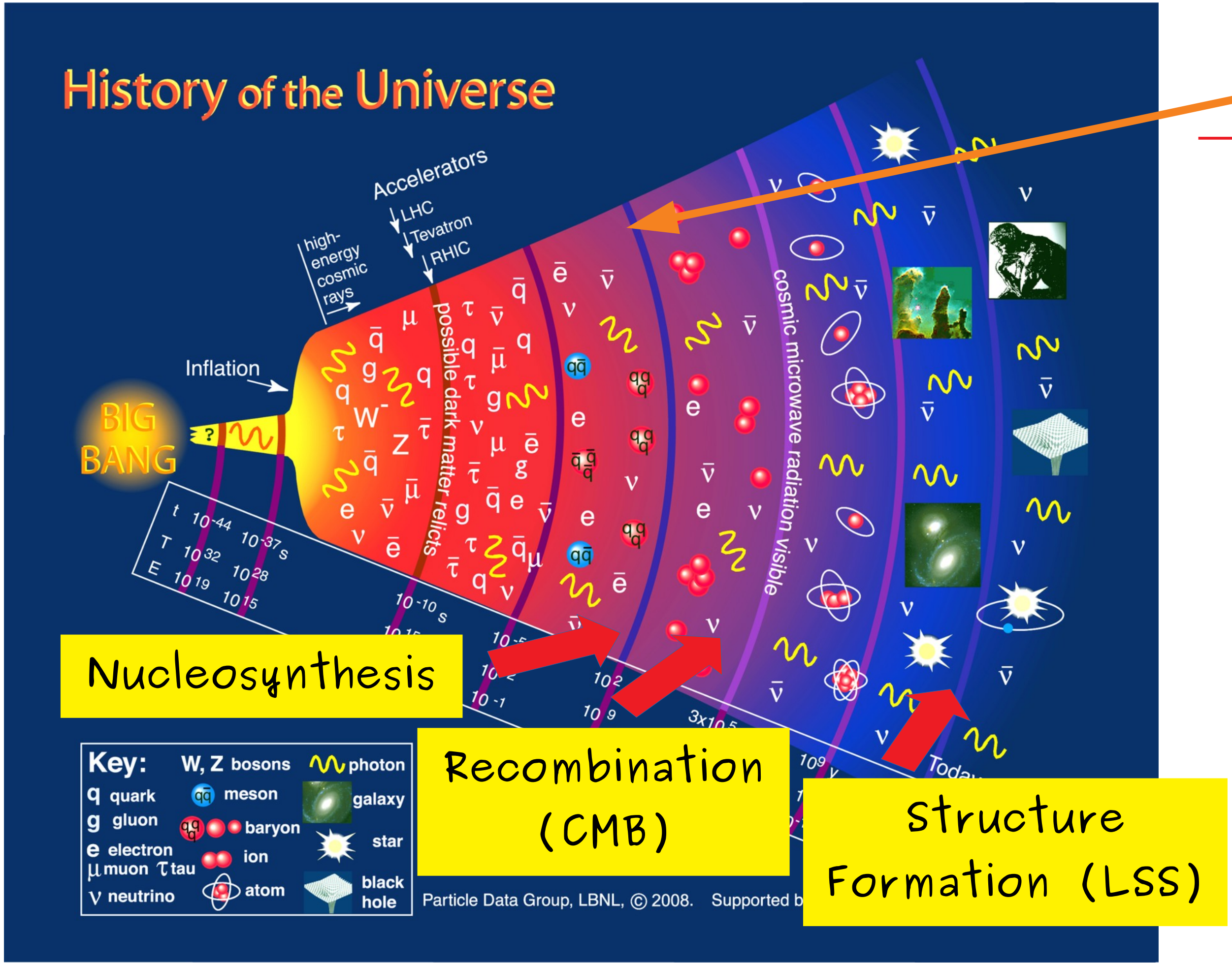
$$n_\nu^0 \approx 112\,\mathrm{cm}^{-3}$$

Energy density:

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

Standard: $\mathbf{N_{eff} = 3.044}$

(Drewes et al. 2024, Jackso & Laine 2023)



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Ways to enhance N_{eff}:

non-standard temperature, number of species, chemical potentials, distribution, etc.

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

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

freeze-out

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

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Onset of nuclear reactions

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→ ^{2}H, ^{3}H, ^{3}He, ^{4}He etc.

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

↑

Neutrinos

BBN codes:
PRIMAT (Pitrou et al.), ParthENoPE (Gariazzo et al.), PryMordial (Burns et al), AlterBBN (Arbey et al.)

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$$Y_\mathrm{p} = 0.245 \pm 0.003$$

$$y_{\mathrm{DP}} = 2.547 \pm 0.025$$

(PDG'22)

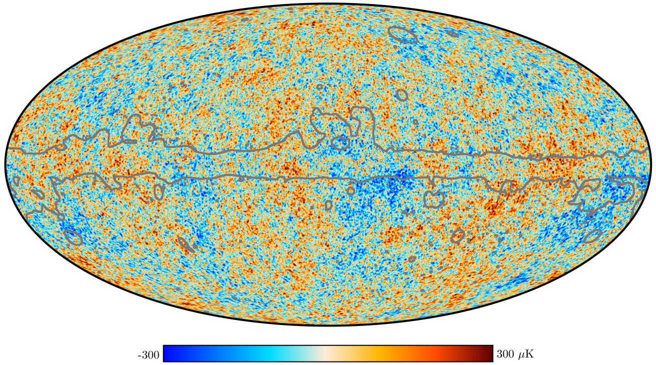
$$\Delta N_{\mathrm{eff}} = -0.10 \pm 0.21\ (68\%\ \mathrm{CL})$$

(Schöneberg 2024, arXiv: 2401.15054)

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

Recombination → Universe gets transparent to photons

(Redshifted) photo of the early Universe



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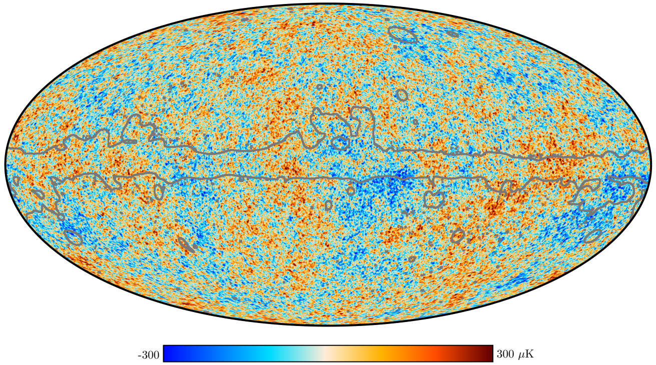

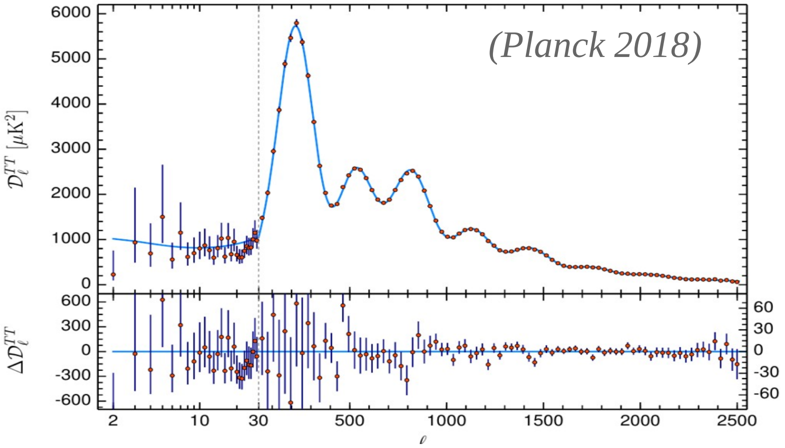

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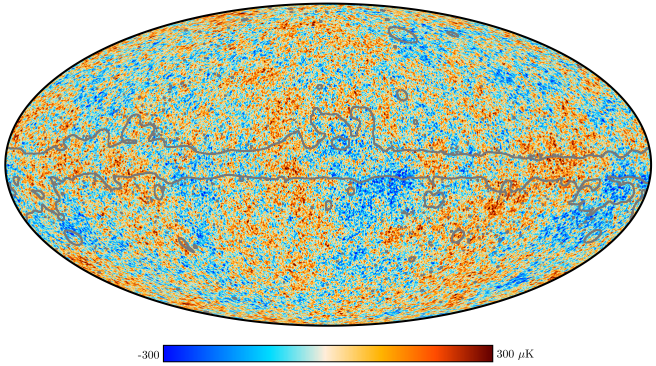
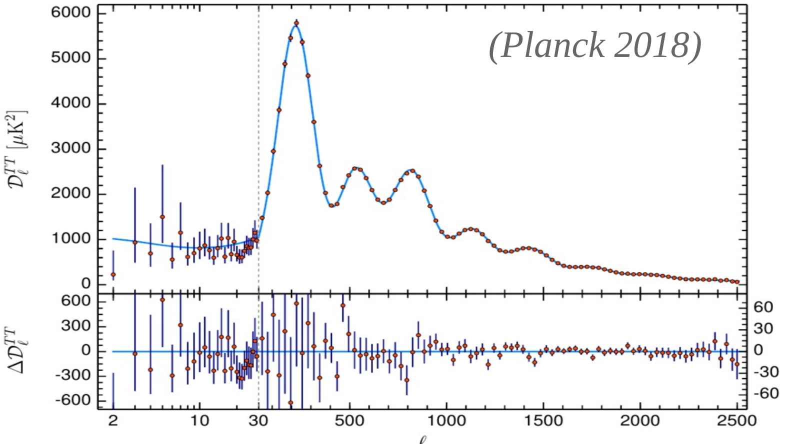
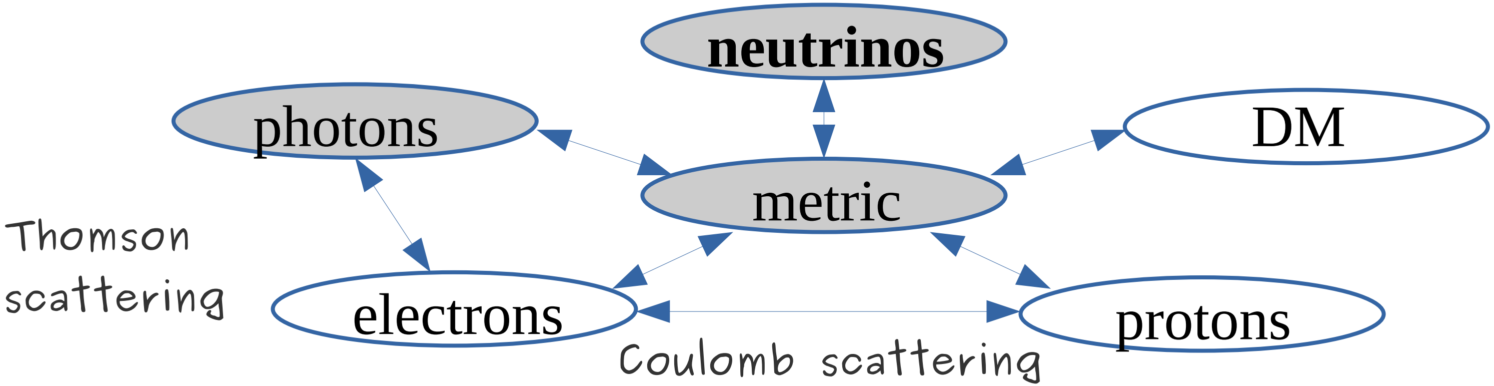




→ <u>Fluctuations in the photon temperature/density:</u>



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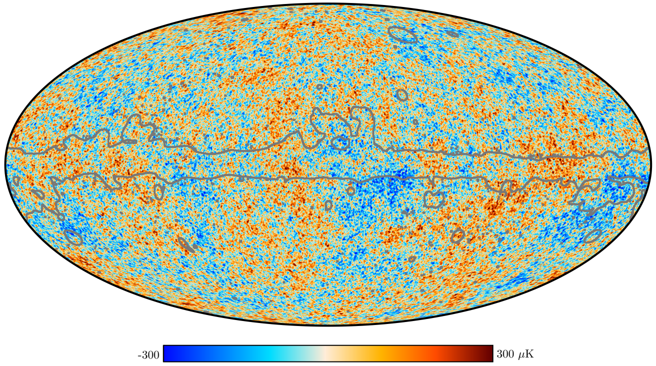

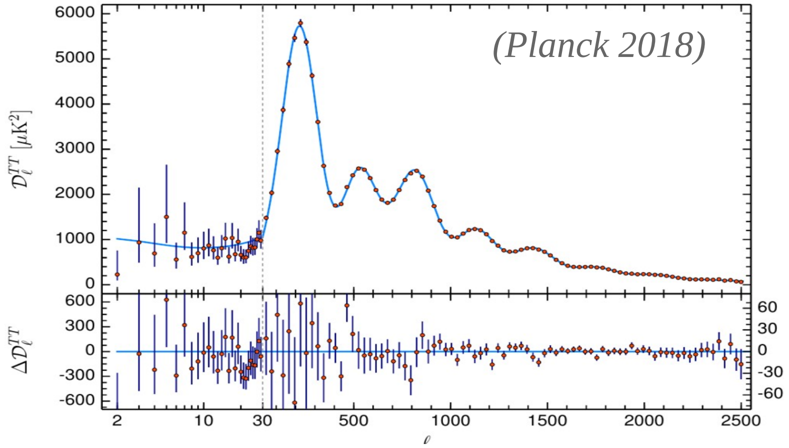

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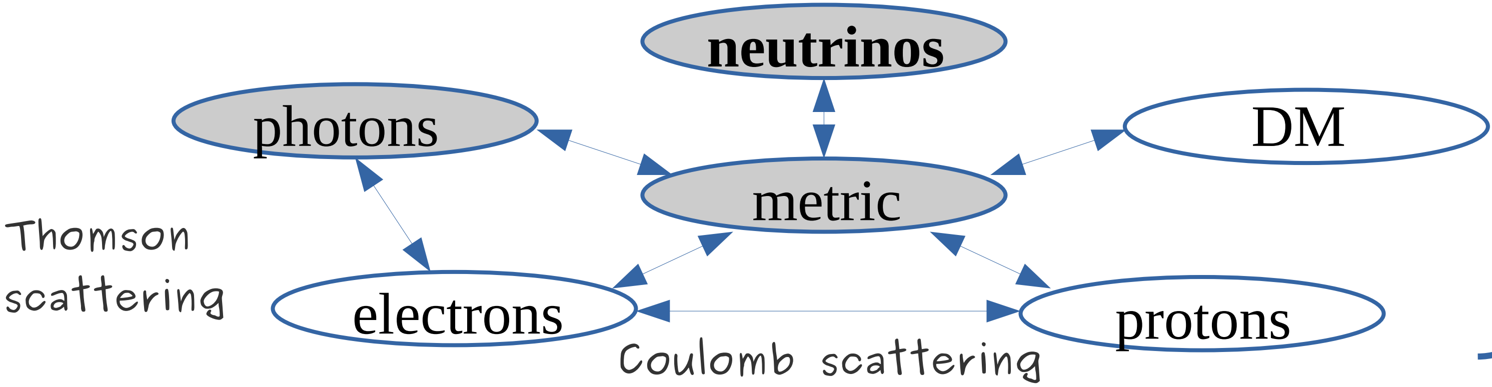
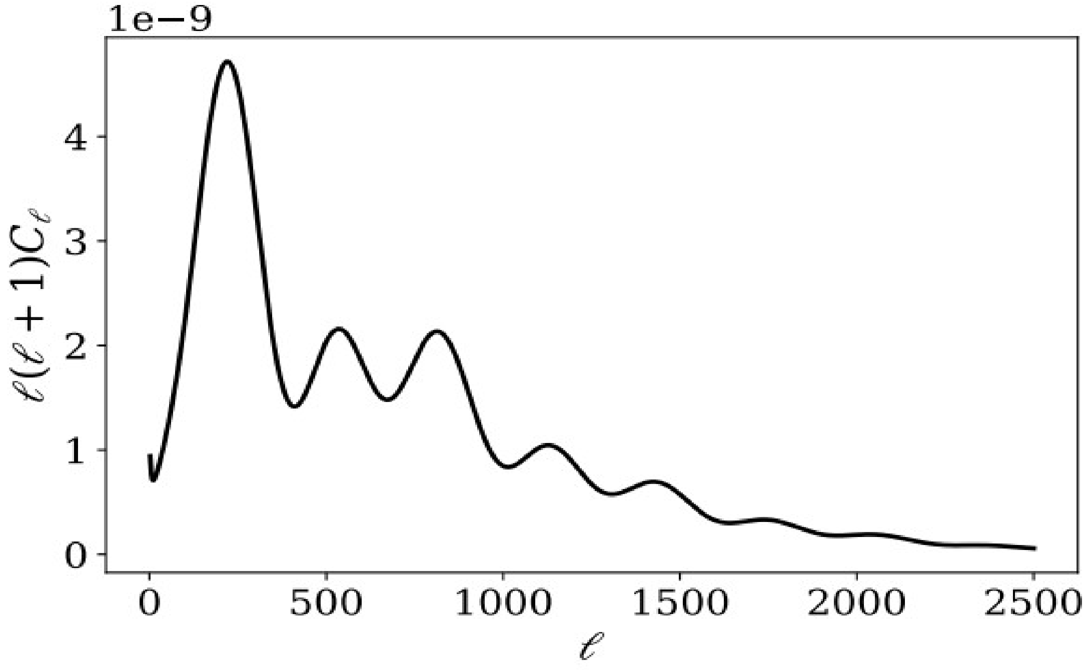
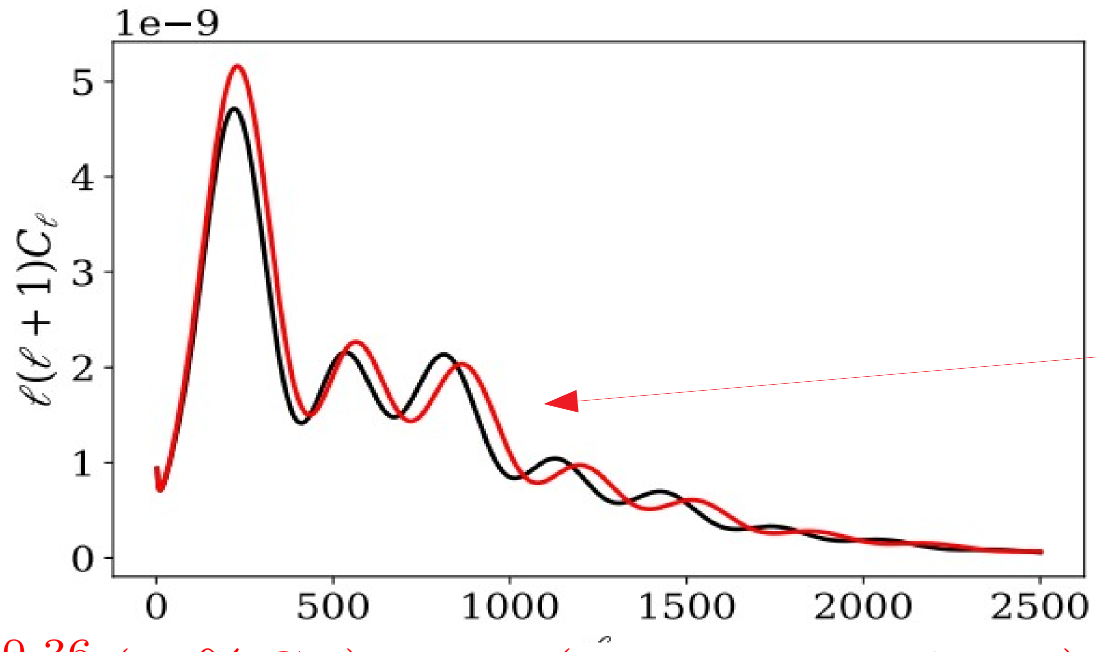


Cosmic (linear) perturbation theory =

Boltzmann equations + Einstein equations

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

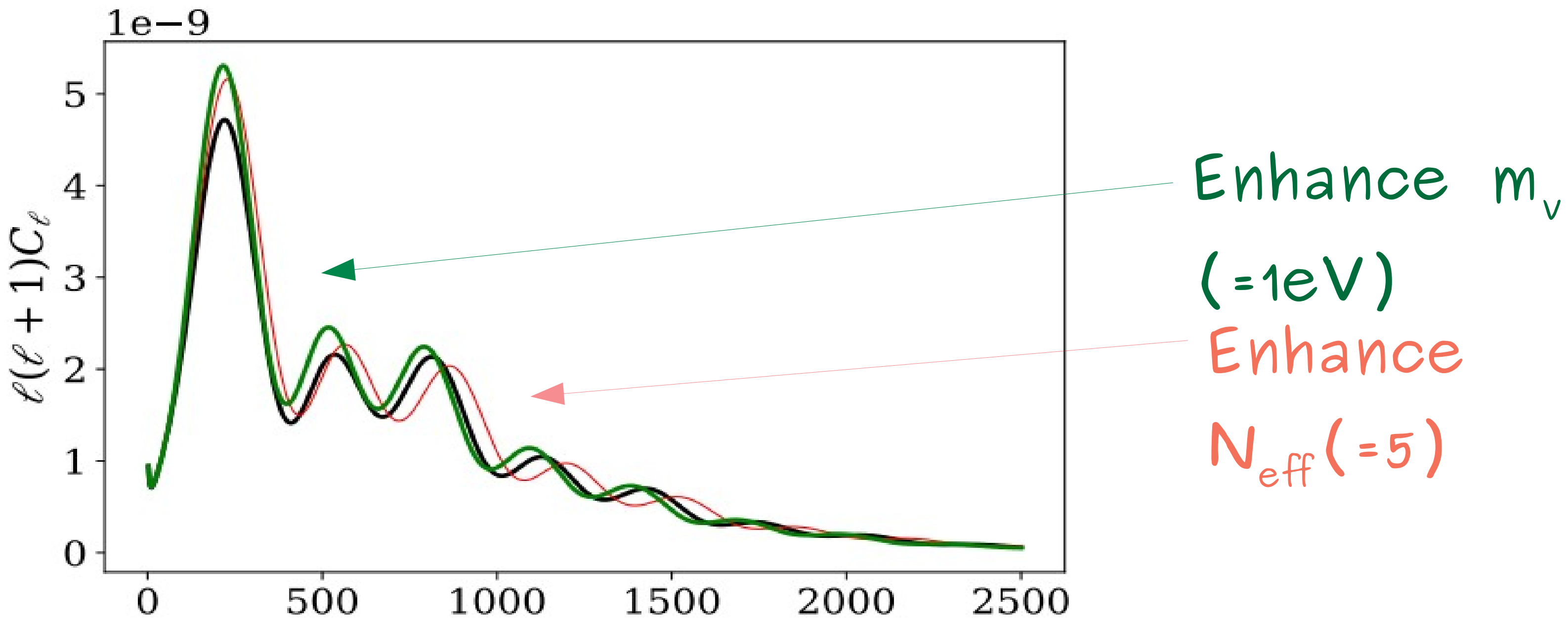

1e−9
$\ell(\ell+1)C_\ell$
0
1
2
3
4
0
500
1000
1500
2000
2500
ℓ



Enhance $N_{\rm eff}$ (=5)

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

(Planck 2018)



$N_{\rm eff} = 2.92^{+0.36}_{-0.37}$ (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

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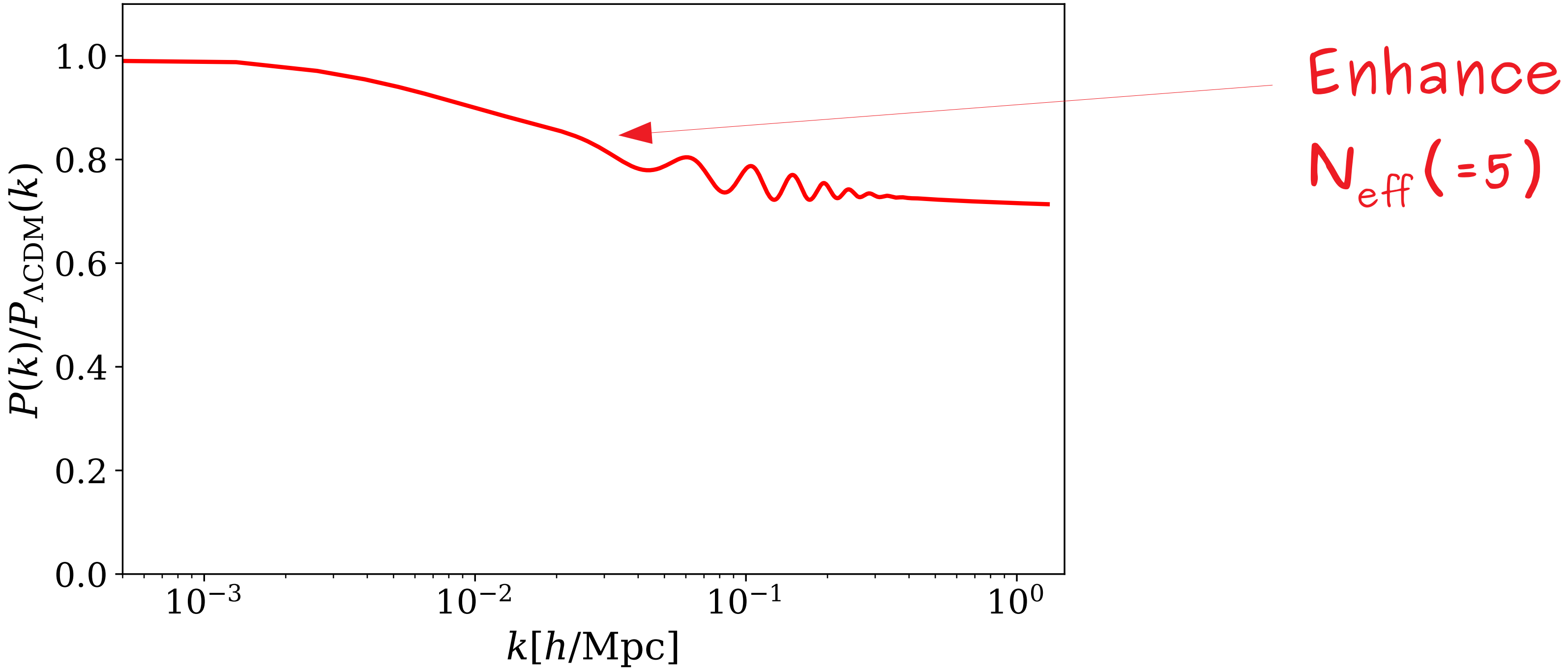

Large Scale Structure

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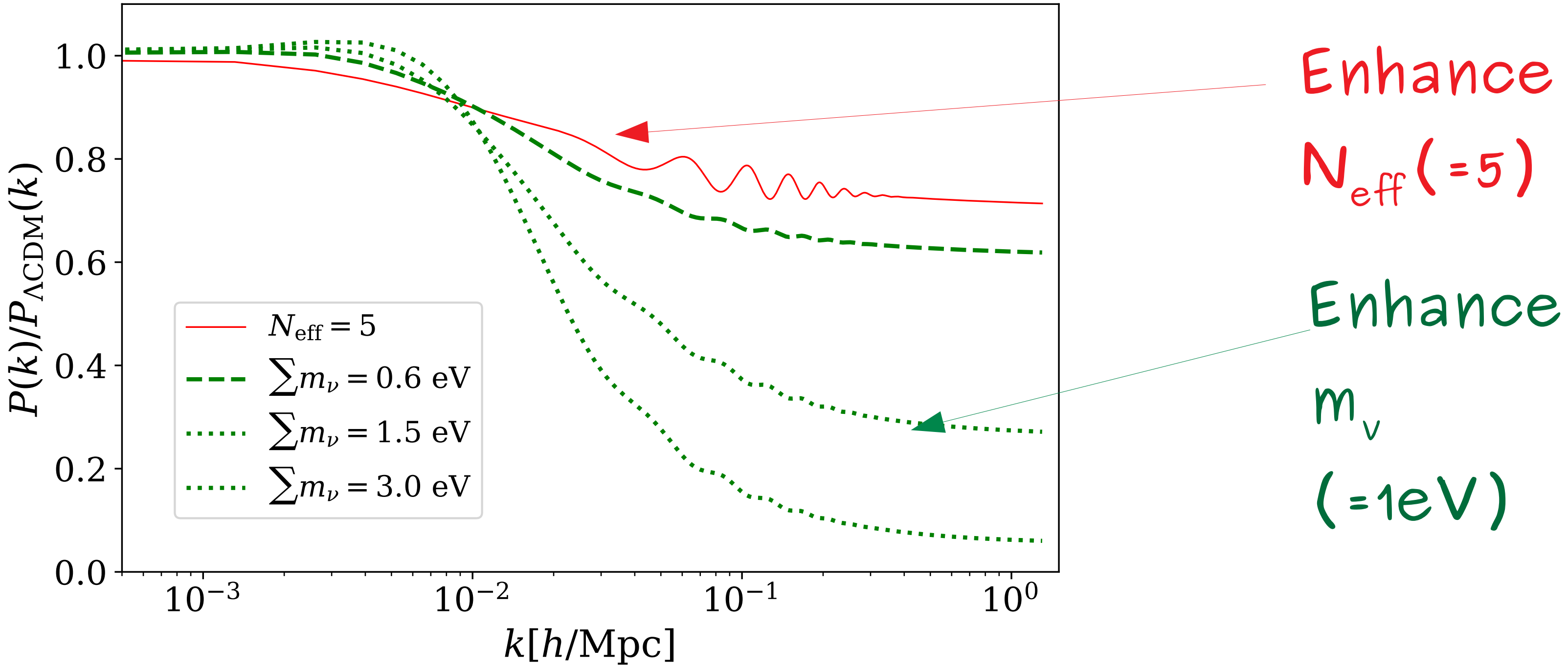
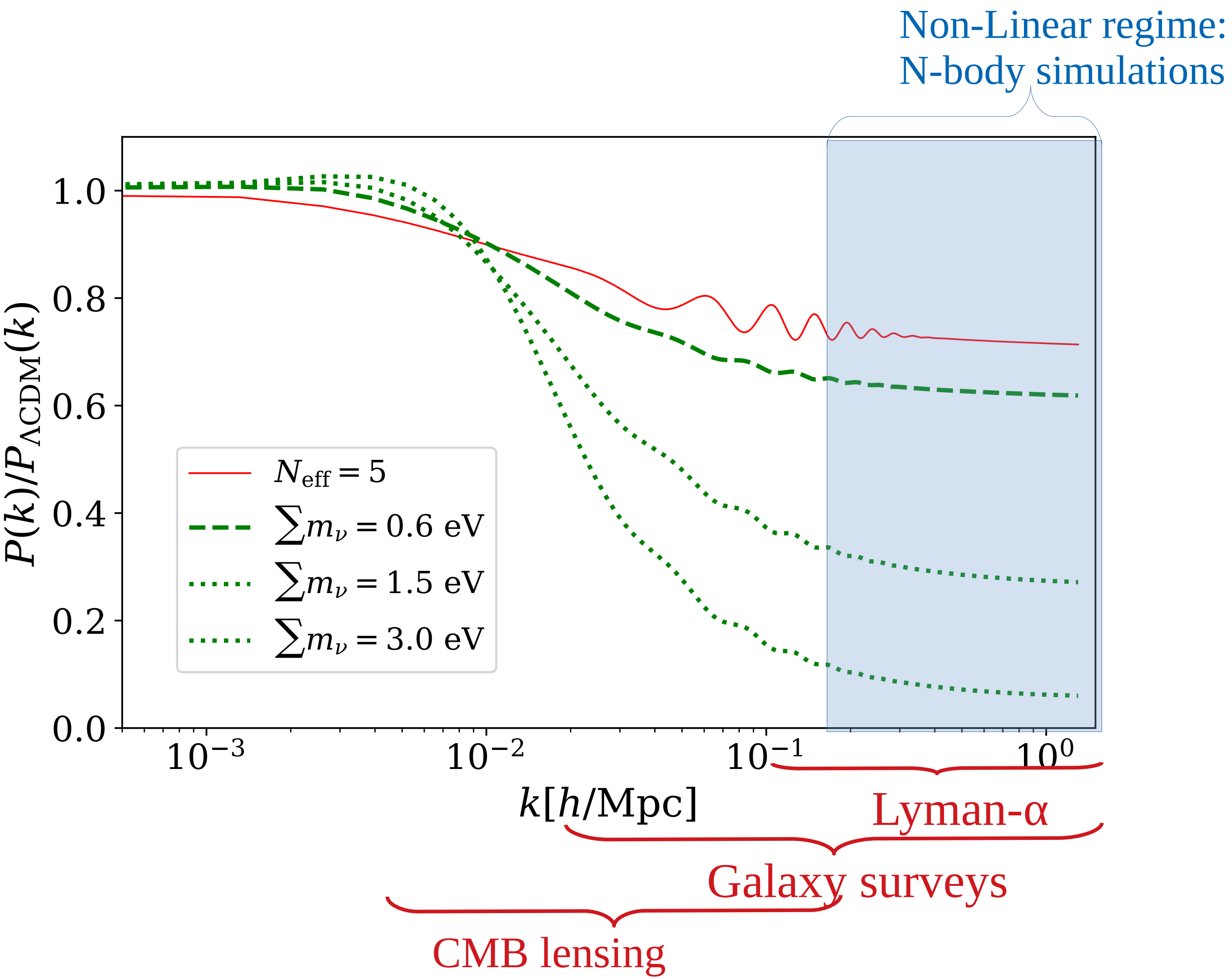


<u>Neutrinos behave at early times as **radiation**, at late times as **matter**</u>

here

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


Non-Linear regime:
N-body simulations
1.0
0.8
0.6
0.4
0.2
0.0
$P(k)/P_{\Lambda\mathrm{CDM}}(k)$
$N_{\mathrm{eff}} = 5$
$\sum m_\nu = 0.6$ 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}

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

(Planck 2018)

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

SDSS, BOSS, 6dFGS

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DESI 2024 (BAO) + Planck 2018

$$\sum m_\nu < 0.072\,\text{eV} \qquad (\text{assuming a prior} \sum m_\nu > 0)$$

$$\sum m_\nu < 0.13\,\text{eV} \; (\text{assuming a prior} \sum m_\nu > 0.059\text{eV})$$

For a discussion see e.g. Naredo-Tuero et al., arXiv: 2407.13831

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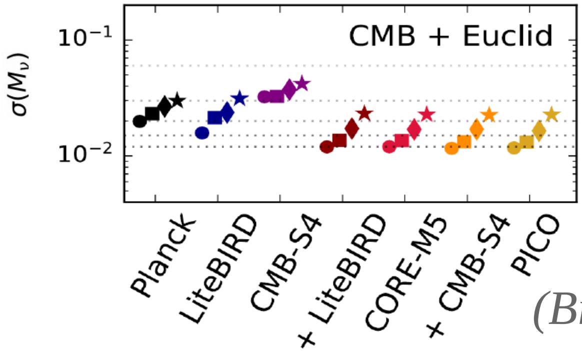


+ DESI, SKA

(Brinckmann et al. 2018)

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

What else can we learn?

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)

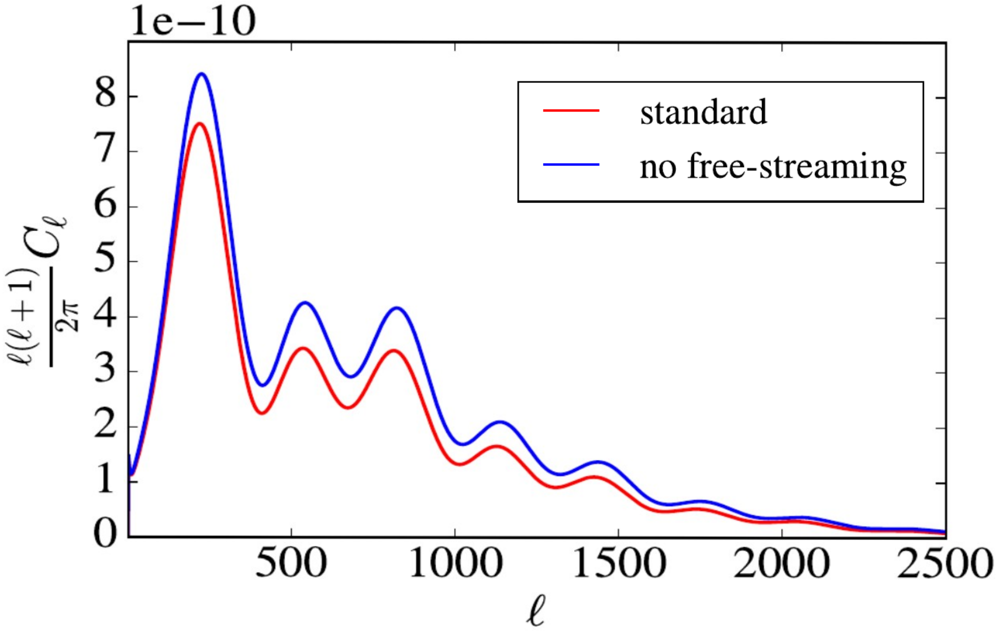
→ Non-standard neutrino interactions

General expected signal from (non-standard) neutrino interactions:

suppression of free-streaming → suppression of anisotropic stress

→ enhancement of neutrino (perturbed) energy density *(Hannestad 2005)*

→ enhancement of temperature anisotropies



+ free-streaming induces a small (but very characteristic) constant phase shift

(Bashinsky & Seljak 2004)

Different thermal histories depending on model parameters

Consider the effective Lagrangian: $\mathcal{L}_{\rm int} = g_{ij}\bar{\nu}_i\nu_j\phi$

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I)Massive scalar

Effective four-Fermi-like coupling $G_{\rm eff} = \frac{g^2}{m_\phi^2}$

→ **neutrino self-interactions**

Interaction rate: $\Gamma \sim G_{\rm eff}^2 T^5$

Comparison to Hubble expansion rate: $H \sim \frac{T^2}{m_{\rm Pl}}$

Delayed neutrino decoupling

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II) Massless scalar

(Active) neutrino decaying into (active) light neutrino plus invisible scalar

Lorentz-boosted decay rate: $\Gamma_{\rm dec} \sim g^2 \dfrac{m_\nu^2}{T_\nu}$

Comparison to Hubble expansion rate: $H \sim \dfrac{T^2}{m_{\rm Pl}}$

Recoupling scenario

(Barenboim, IMO et al. 2021; Chen, IMO et al. 2022)

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Other models / works

Light mediator: self-interactions *(Forastieri 2019, Forastieri 2015)*

0.1 eV – 1 MeV range *(Escudero & Witte 2019, Sandner et al 2023, Venzor et al. 2023)*

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

Recent summary of different type of interactions: *(Taule et al. 2022)*

The devil is in the details: Describing the impact of non-standard interactions can be a very challenging task (on both levels: analytically and numerically)…

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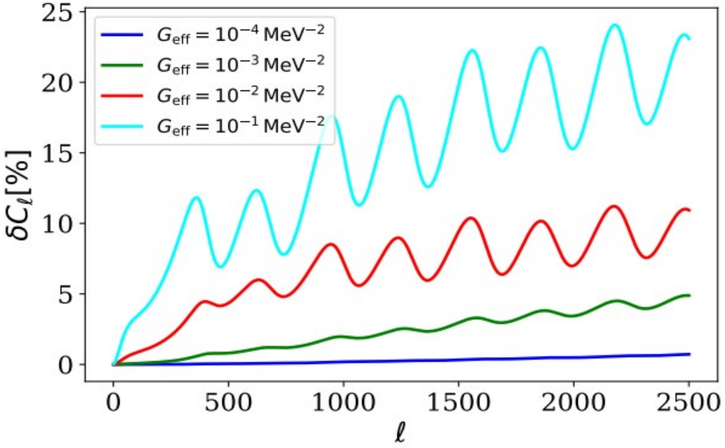
Neutrino self-interactions

*Cyr-Racine et. al. 2013, **IMO et al. 2014,** Lancaster 2017**, IMO et al. 2017, Barenboim, IMO et al. 2019**, Kreisch et al. 2019, A. Mazumdar et al. 2020, A. Das et al. 2020 , Kreisch et al. 2022, S. R. Choudhury et al. 2022 …*



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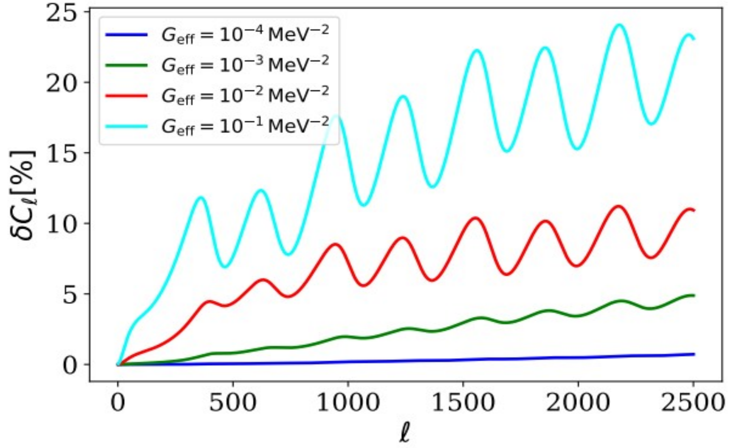
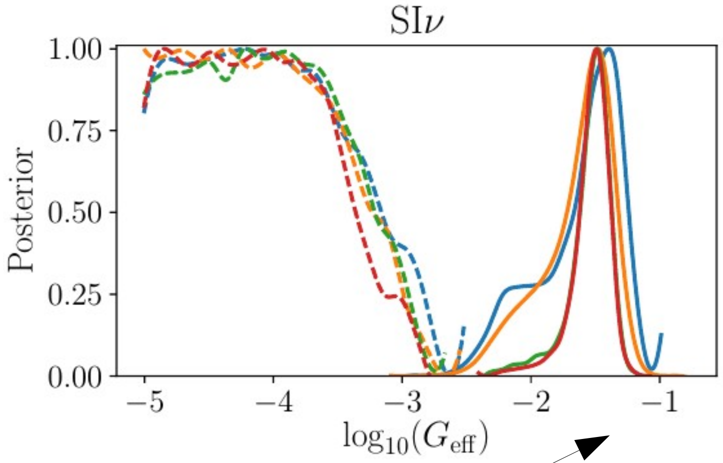


MCMC

Planck 2015



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

→ accompanied by bimodality in some other parameter degeneracies…

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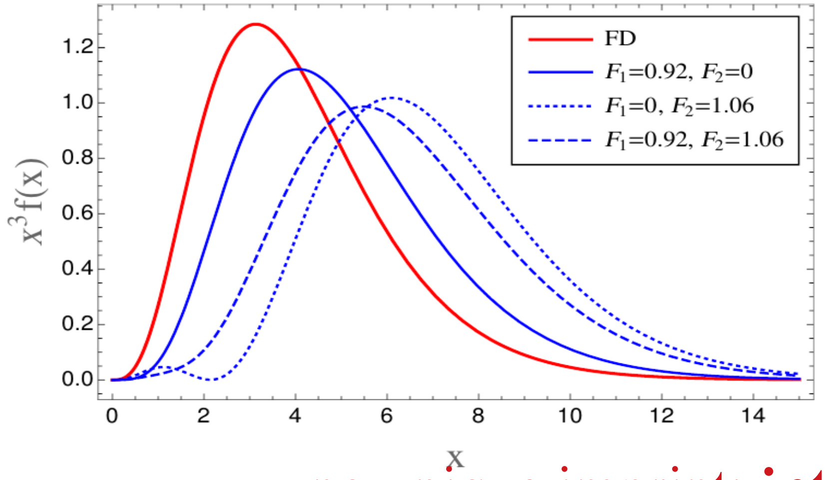
Non-standard relic neutrino distributions *(IMO et al. 2019)*

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

well known… and well measured



Model independent parametrization (expansion in orthonormal polynomials):

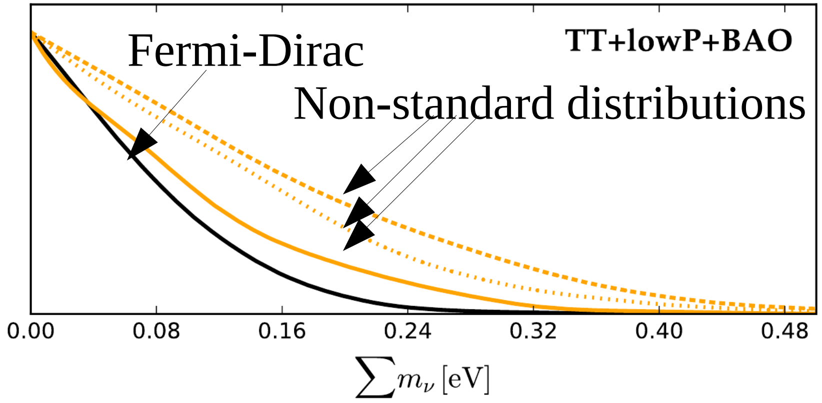
$$f_\nu(x) = N \cdot \frac{1}{e^x + 1}\left(p_0(x) + F_1 p_1(x) + F_2 p_2(x)\right)$$

Normalize such that N_{eff}=3.044

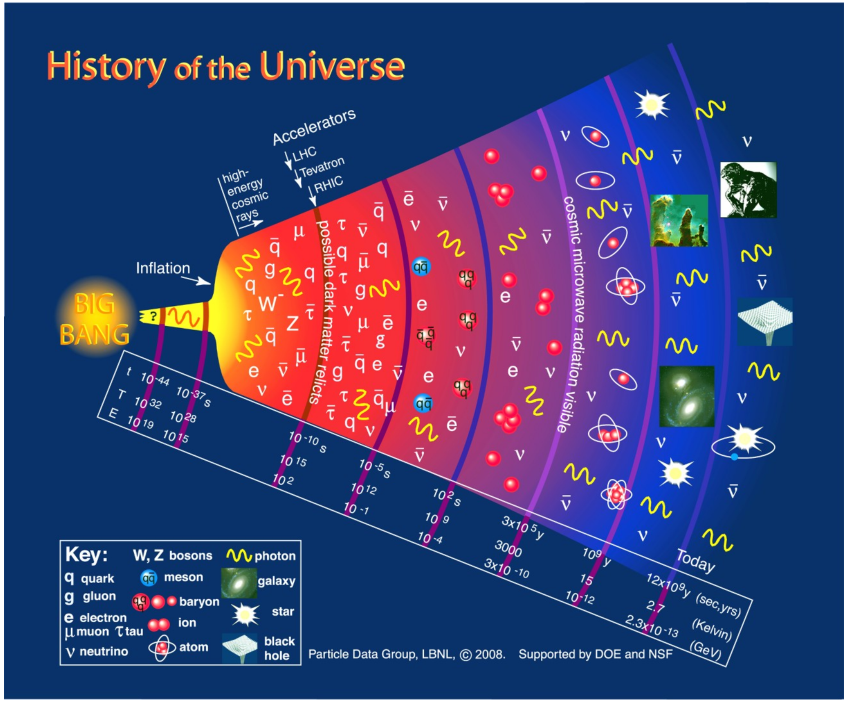
→ no unique imprint: **intrinsically degenerate with Σm_ν** and N_{eff}

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

(here: relaxation about ≈ 100%)



→ *See also **J. Alvey** at al., arXiv: 2111.12726*



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Omitting assumptions

- Constraining non-standard neutrino interactions
- Found that cosmological neutrino mass bound can be relaxed by enhancing average momentum

Bounds on N_{eff} and $\sum m_\nu$:

$$\sum m_\nu < 0.072\,\mathrm{eV} \quad \textit{(Planck 2018 + DESI 2024)}$$

$$\Delta N_{\mathrm{eff}} = -0.10 \pm 0.21\,(68\%\,\mathrm{CL}) \quad \textit{(BBN)}$$

$$N_{\mathrm{eff}} = 2.92^{+0.36}_{-0.37}\,(95\%\,\mathrm{CL}) \quad \textit{(Planck 2018)}$$