Cosmology signals of new physics in the neutrino* sector

*** or weakly coupled light particle**

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Standard Model Cosmic Neutrino Background

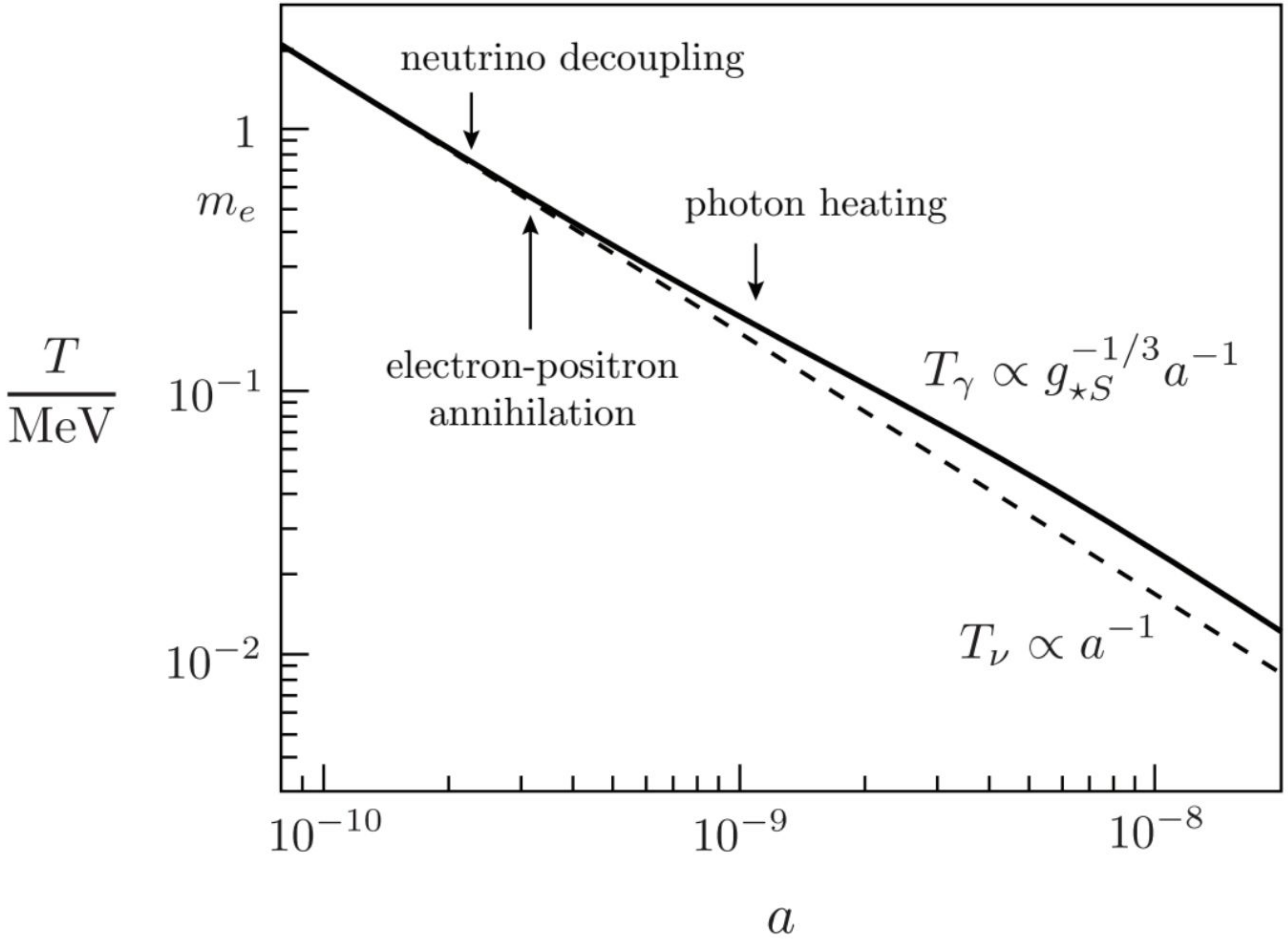


Image Credit: Baumann

$$N_{eff} = \left(\frac{11}{4}\right)^{4/3} \frac{8}{7} \frac{\rho_{radiation,\ total} - \rho_\gamma}{\rho_\gamma}$$

energy in relativistic fermions:

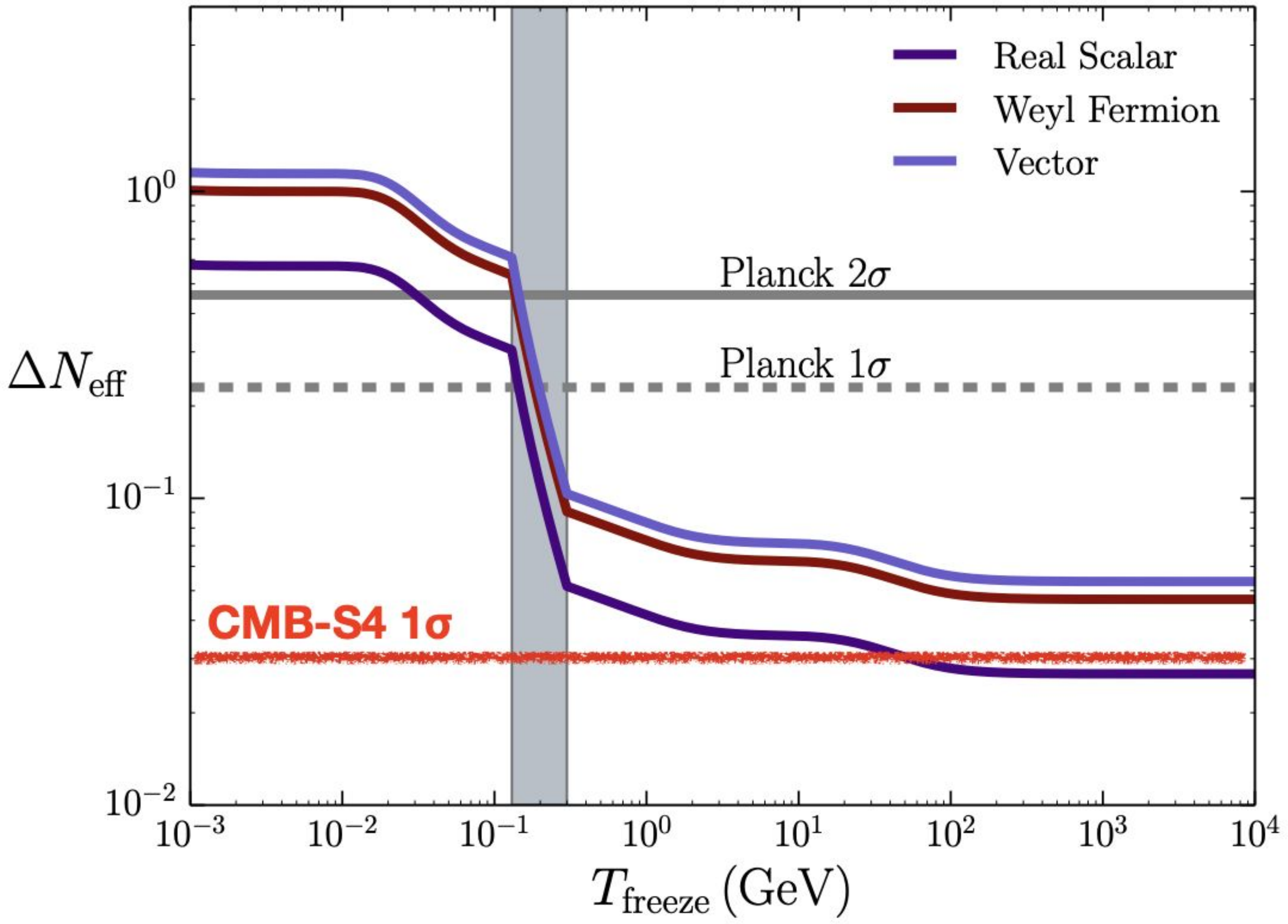
$$\rho_\nu = \frac{7}{8} \frac{\pi^2 g_* T_\nu^4}{30}$$

Standard Model CνB:
N_{eff}=3.044

N_{eff}

Total energy in relativistic particles

$$N_{eff} = \left(\frac{11}{4}\right)^{4/3} \frac{8}{7} \frac{\rho_{radiation,\ total} - \rho_{\gamma}}{\rho_{\gamma}}$$

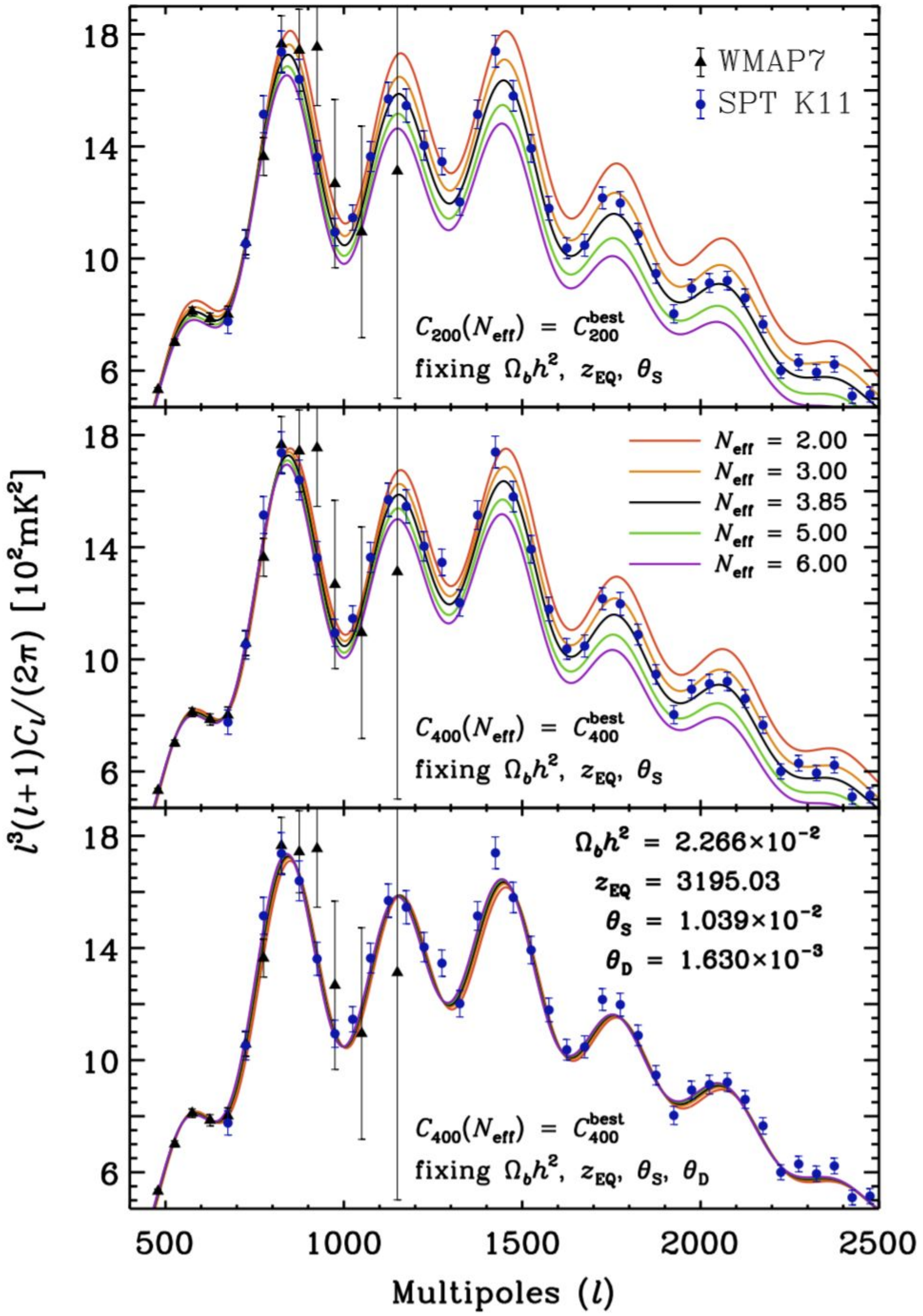


Planck: N_{eff} = 2.99 +/- 0.17

CMB-S4: $\sigma(N_{eff})$ = 0.03

N_{eff}

CMB probes of N_{eff}

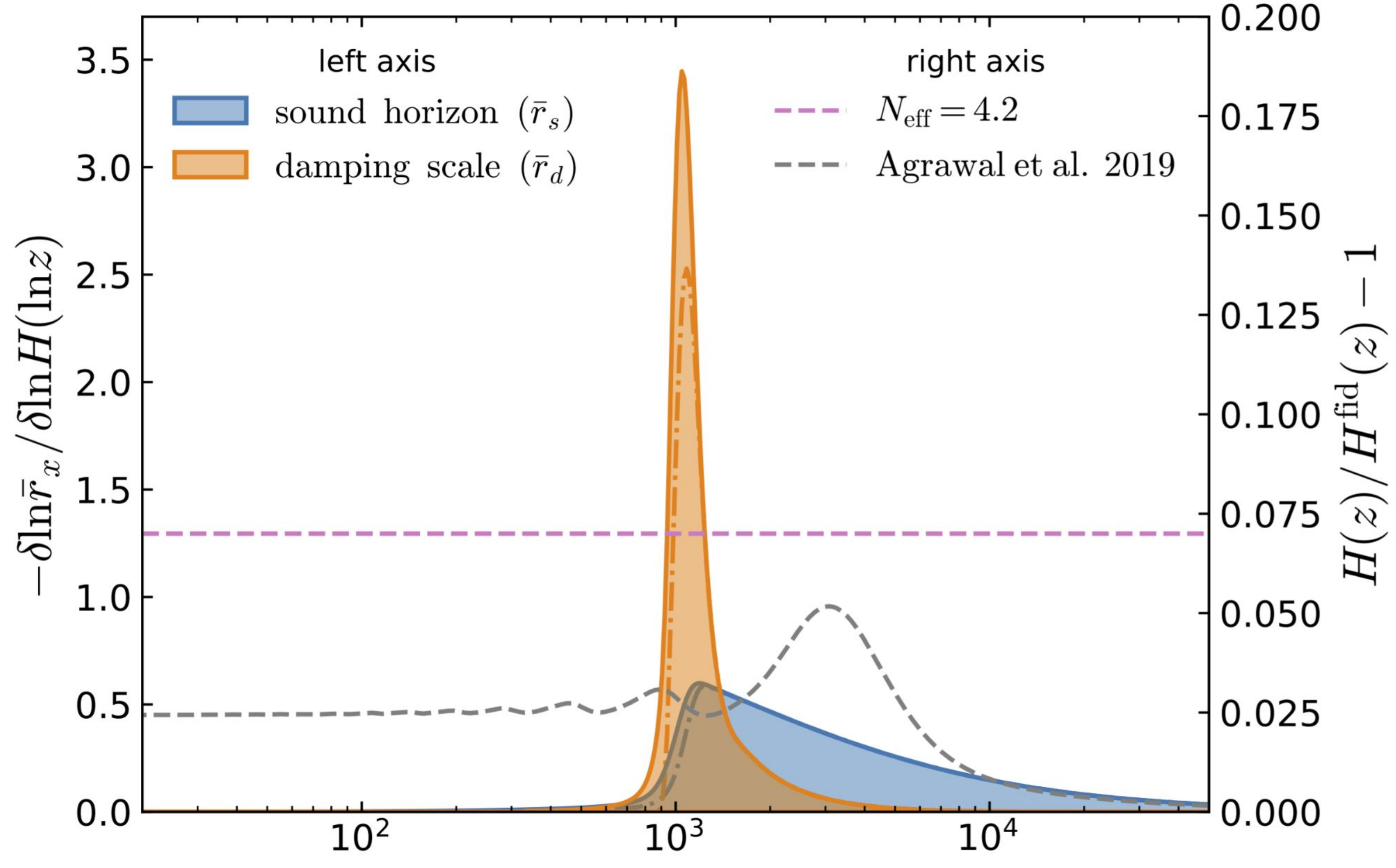


Hou, Keisler, Knox, Millea, Reichardt 2011

Damping Scale:

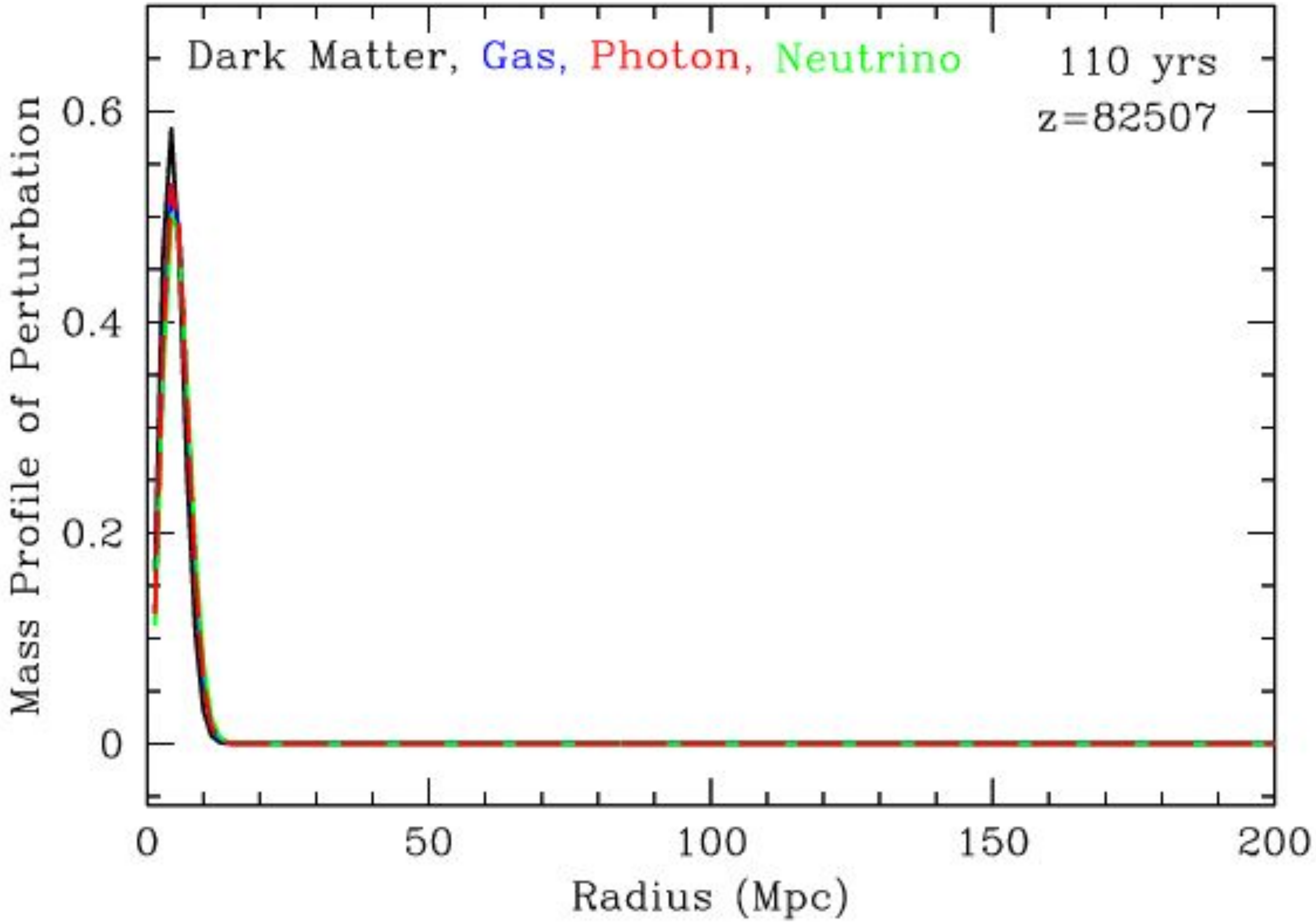
$$r_d^2 = \pi^2 \int_0^{a_*} \frac{da}{a^3 \sigma_T n_e H} \left[\frac{R^2 + \frac{16}{15}(1+R)}{6(1+R^2)} \right]$$

N_{eff}



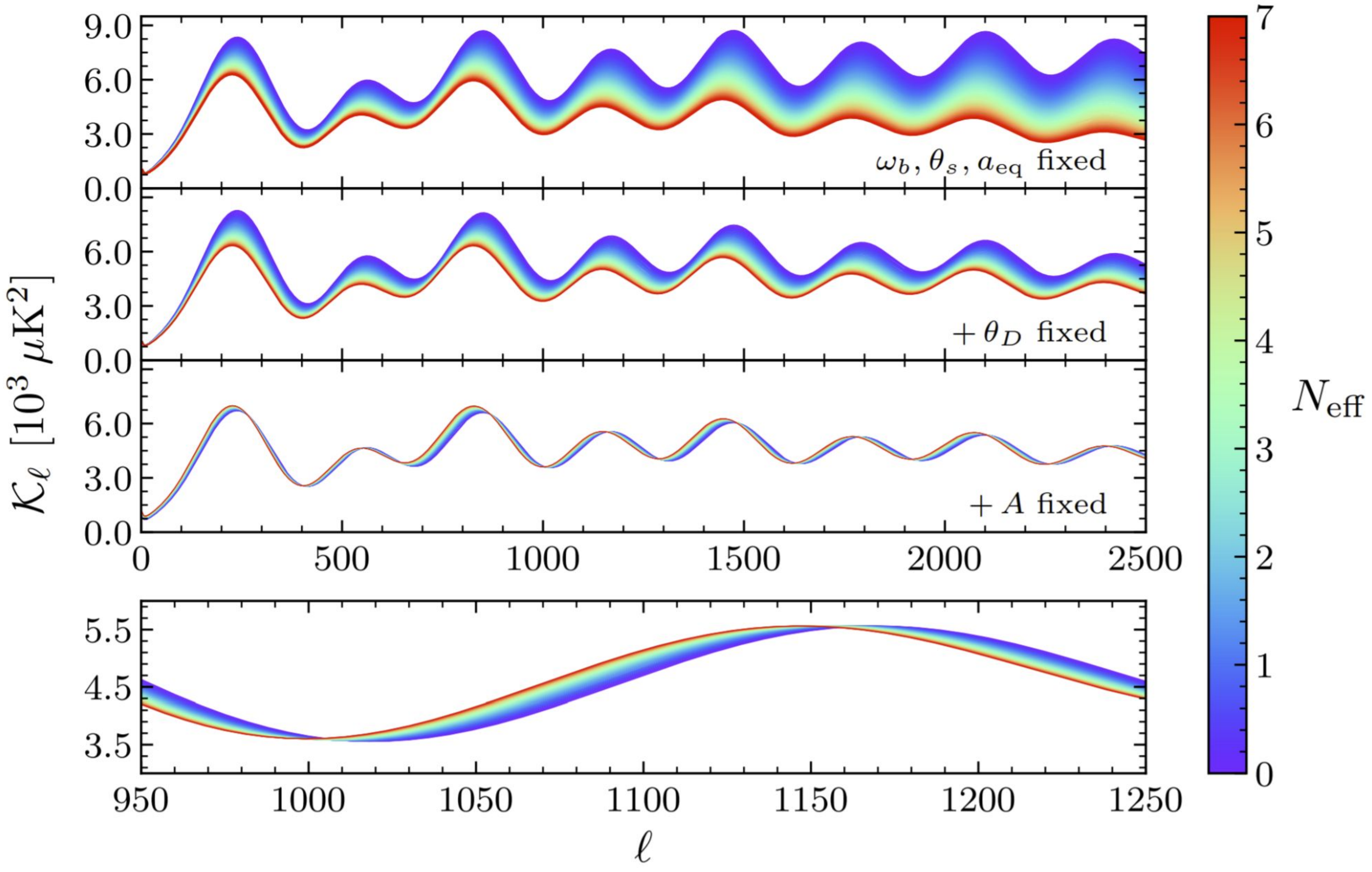
Knox & Millea 2019

Phase shift from $N_{free\text{-}streaming}$

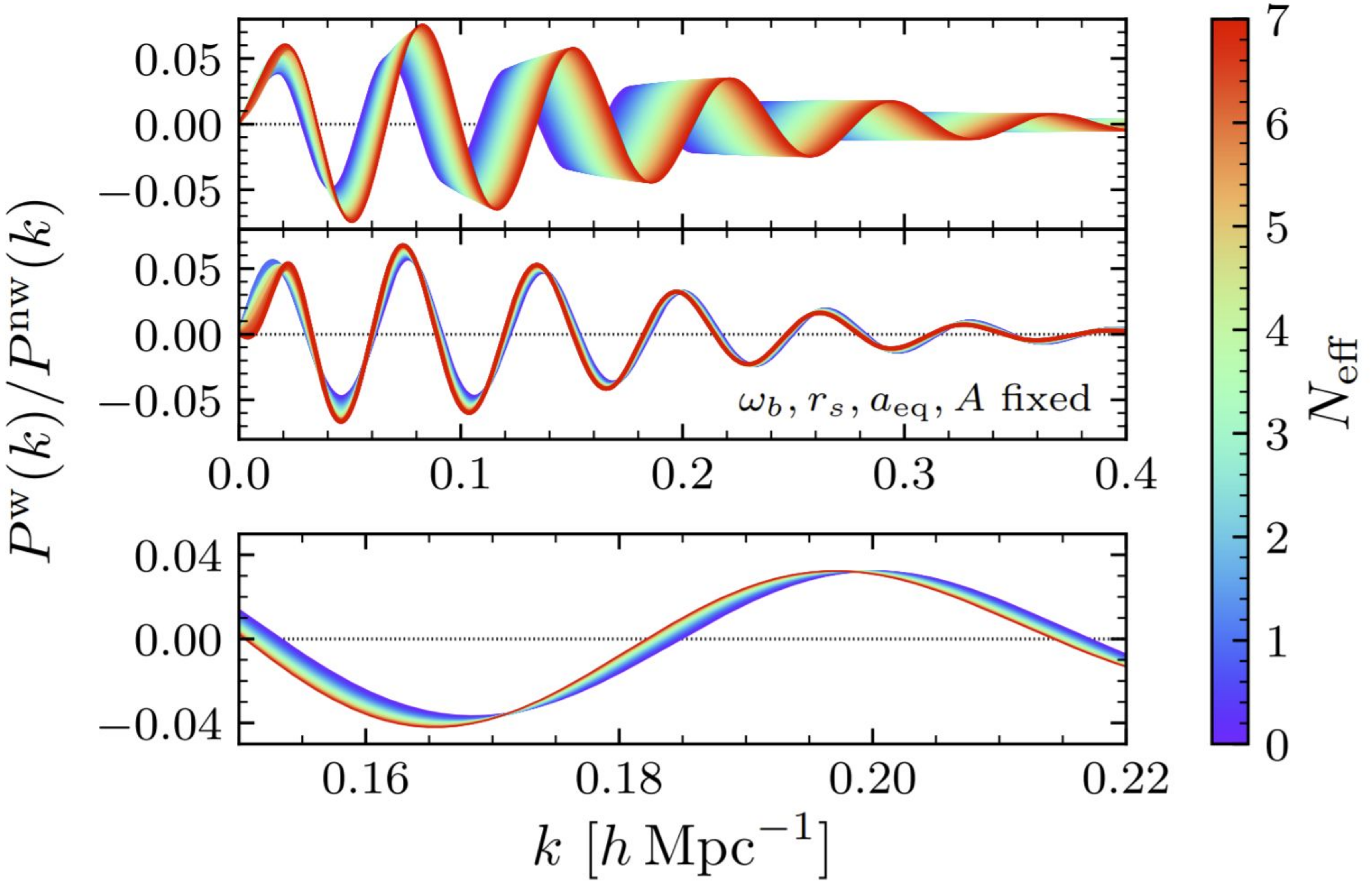


Eisenstein, Seo, White 2007

Phase shift from $N_{\text{free-streaming}}$



CMB Power Spectrum



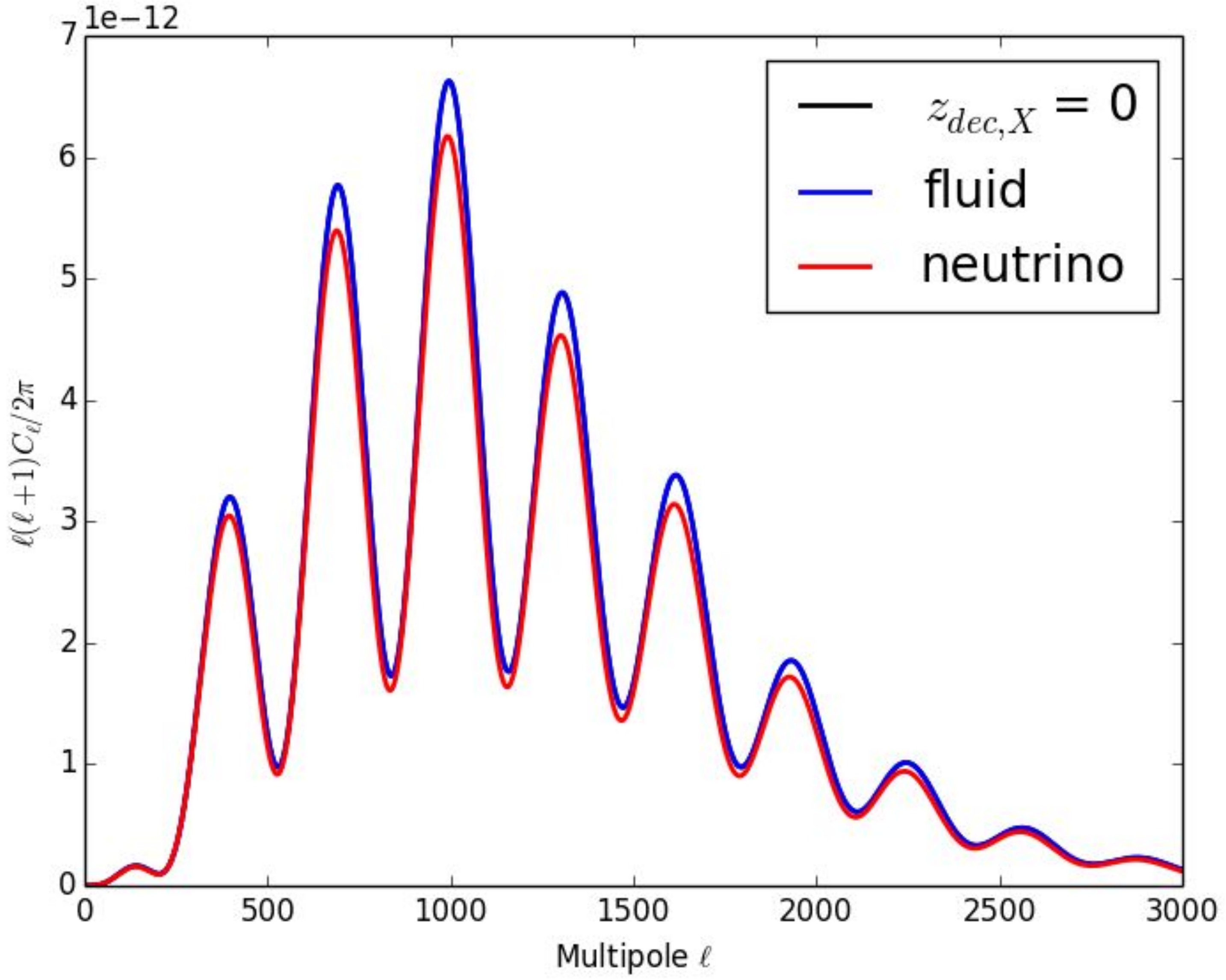
Baryon Acoustic Oscillations

Wallisch 2018

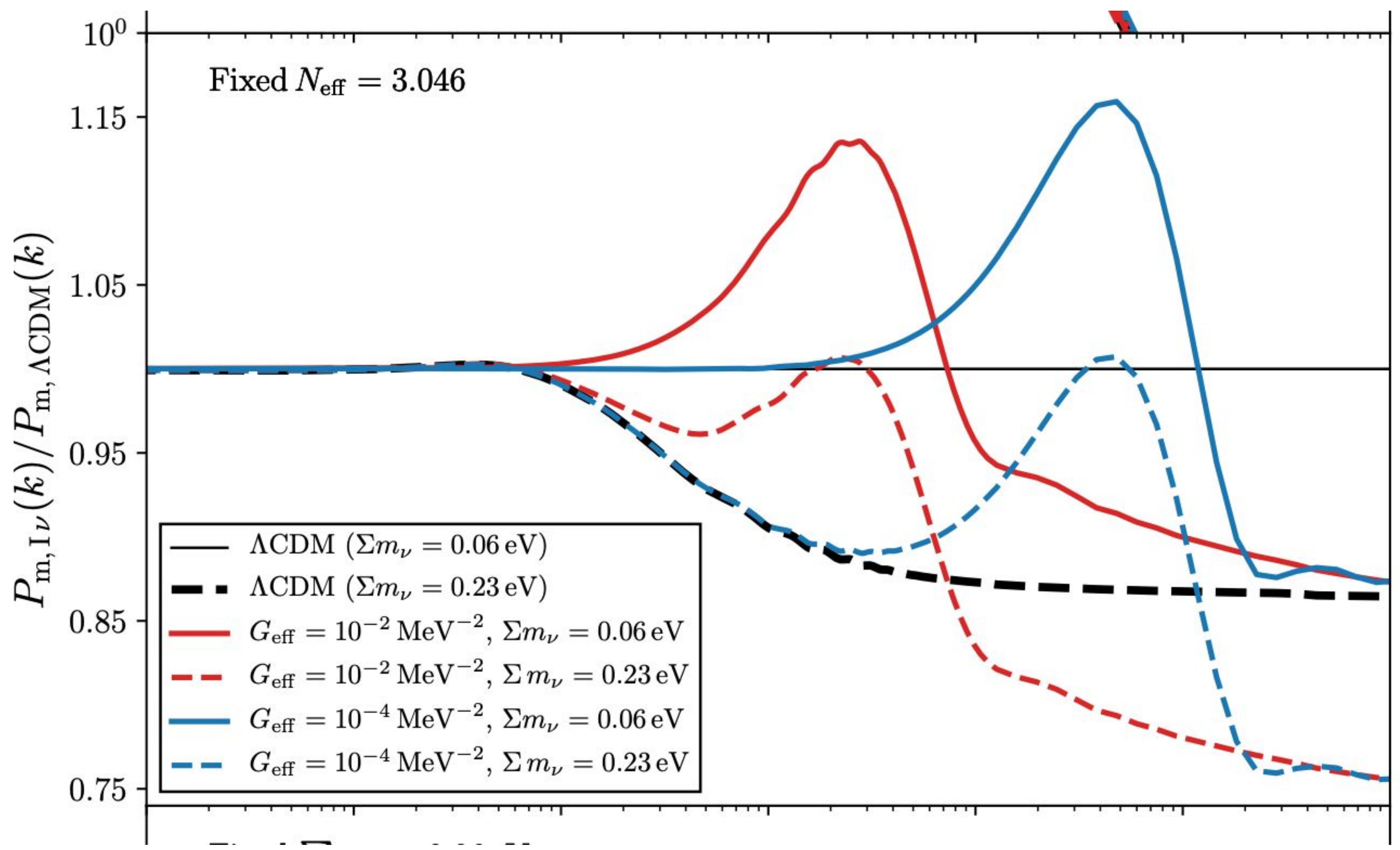
$N_{eff} = N_{free\text{-}streaming} + N_{fluid} + N_{interacting}$

Energy in perturbations of relativistic particles that are:

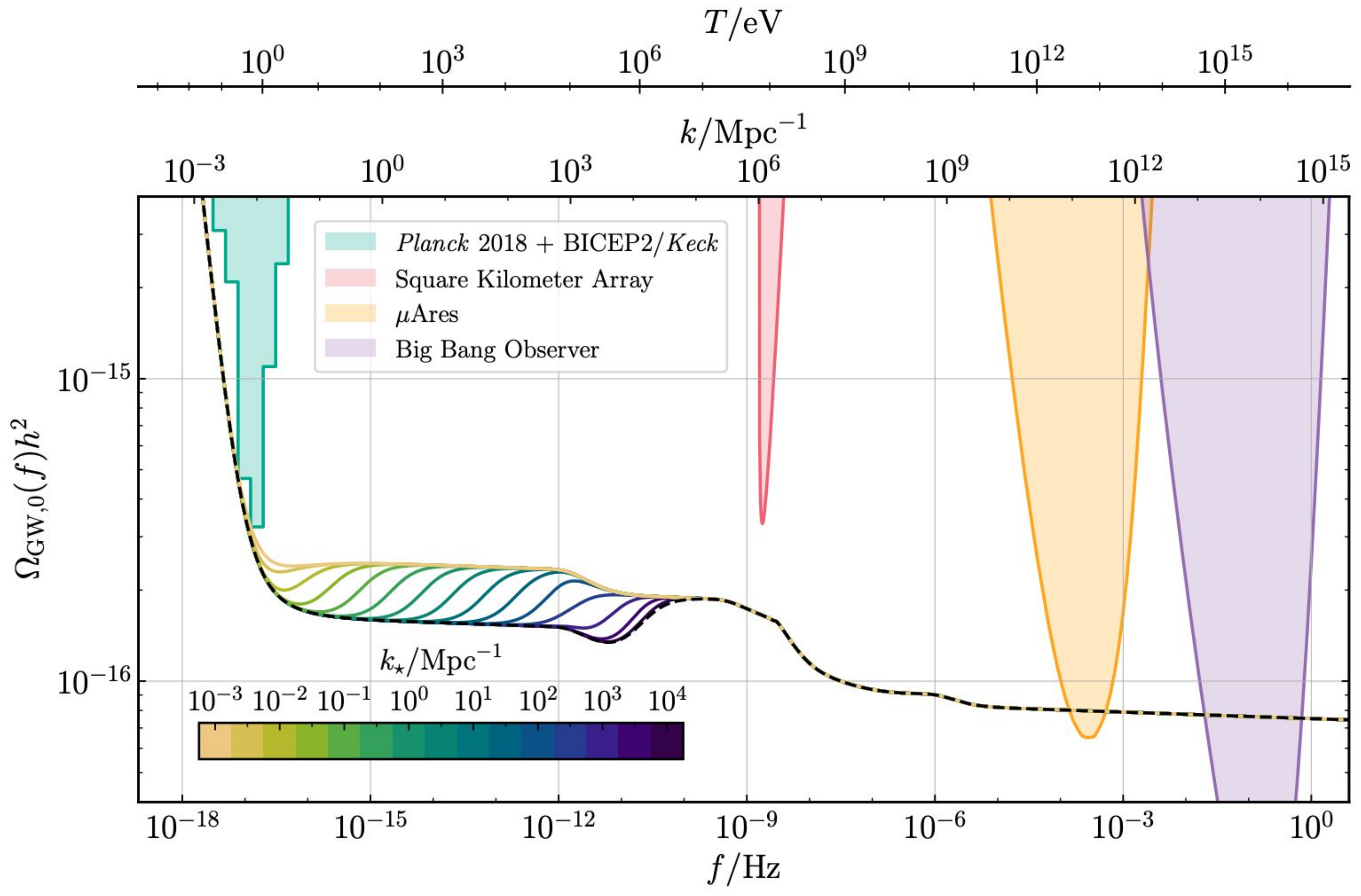
- Free-streaming at CMB times (Standard Model neutrinos) - ($N_{free\text{-}streaming}$)
- Tightly coupled throughout CMB times (N_{fluid})
- Transition between tightly coupled and free-streaming at CMB times ($N_{interacting}$)



Chioi, Chiang, Loverde 2018



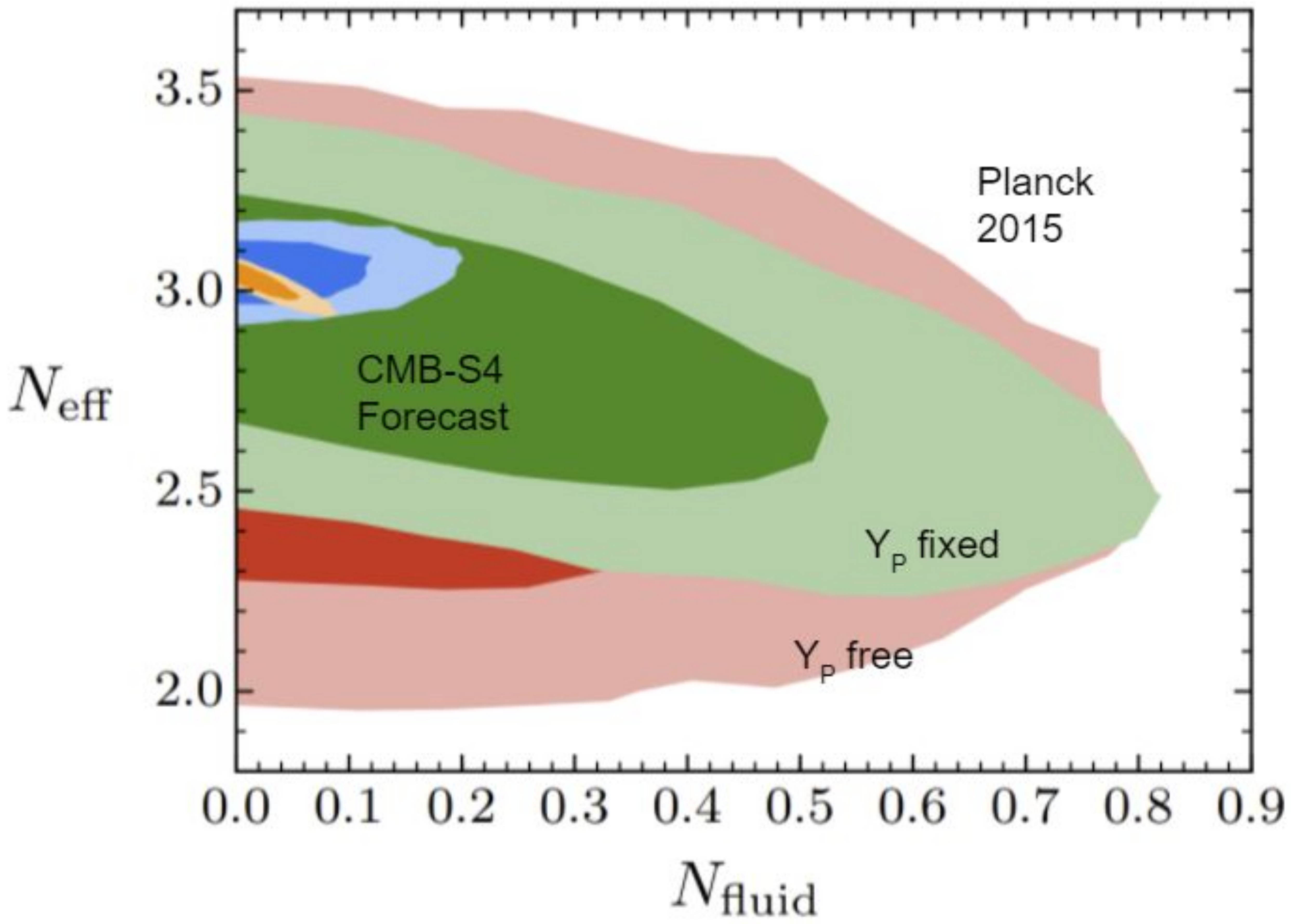
Kreisch, Cyr-Racine, Dore 2019



Loverde & Weiner 2022

$N_{eff} = N_{free\text{-}streaming} + N_{fluid} + N_{interacting}$

Energy in perturbations of relativistic particles that are:



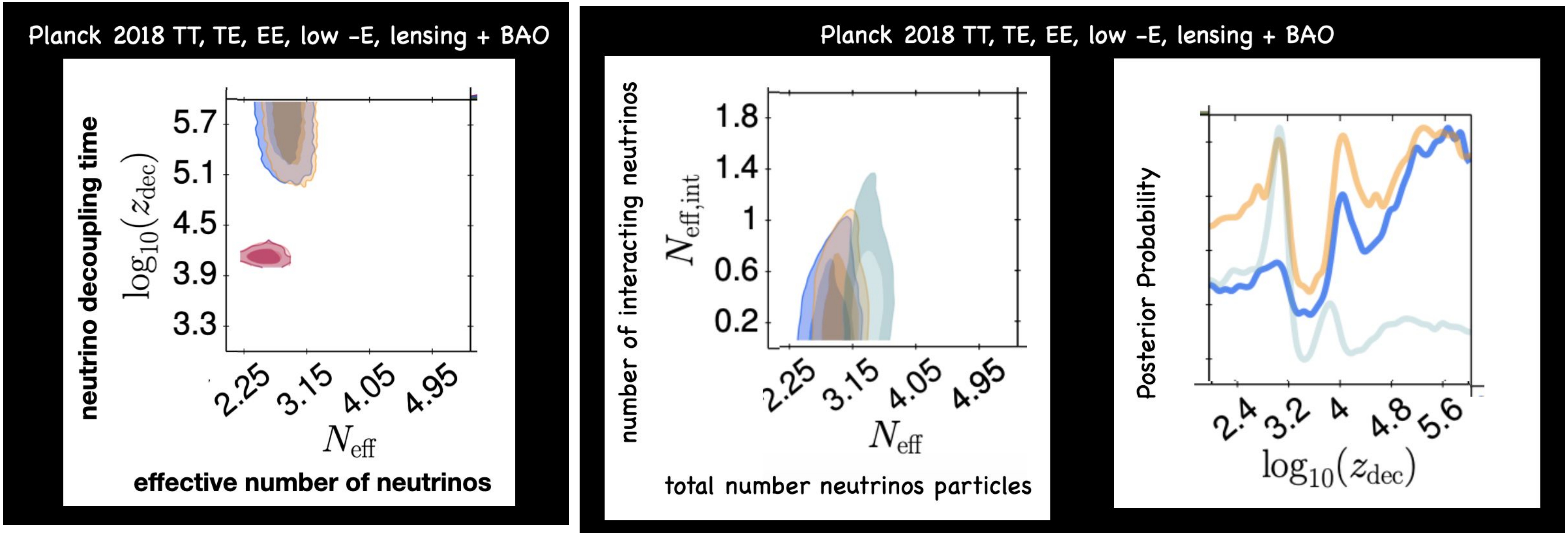
Baumann, Green, Meyers, Wallisch 2016

$N_{eff} = N_{free\text{-}streaming} + N_{fluid} + N_{interacting}$

Energy in perturbations of relativistic particles that are:

All species interacting

A free fraction interacting

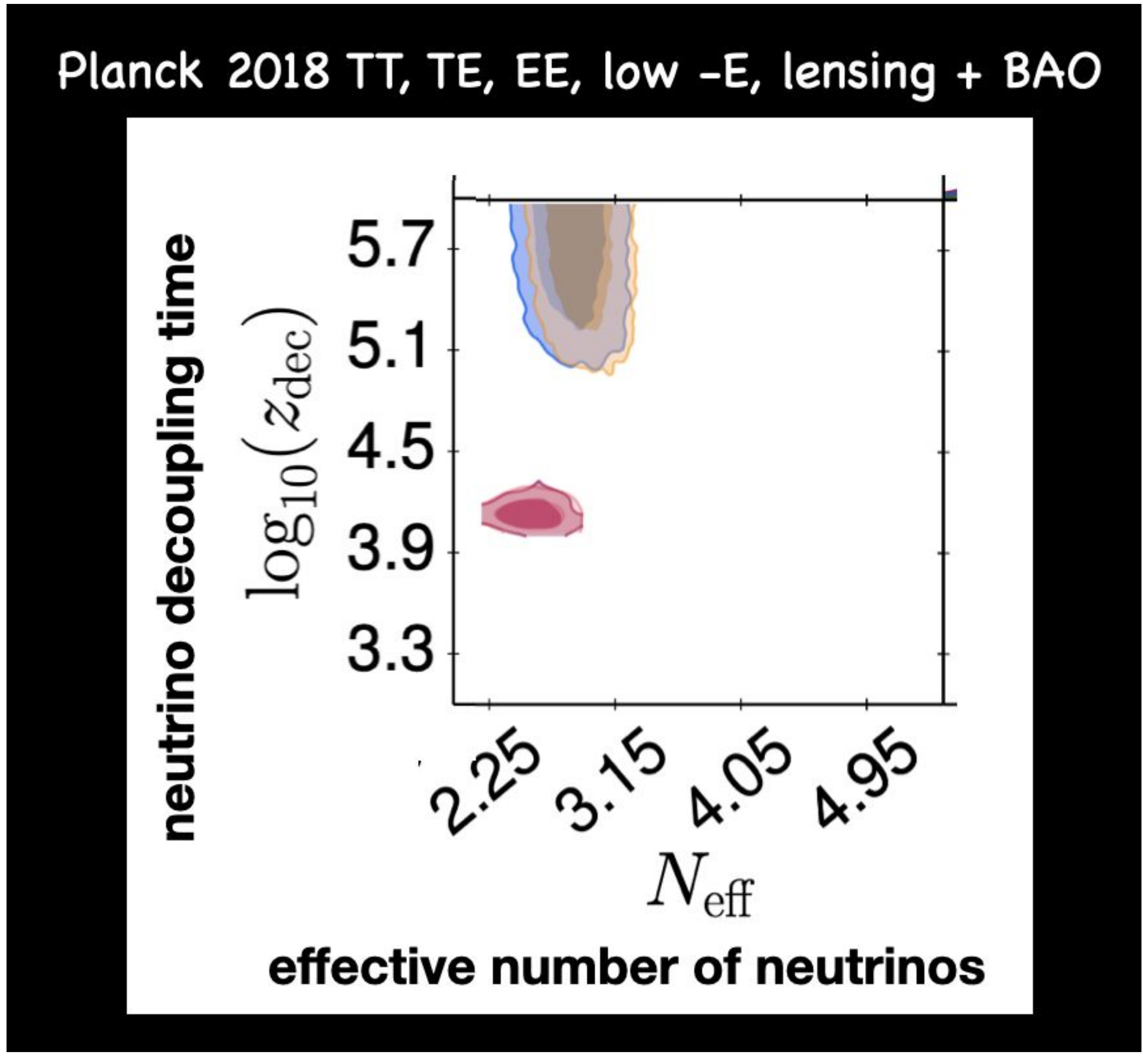


Brinckmann, Chang, Loverde 2020

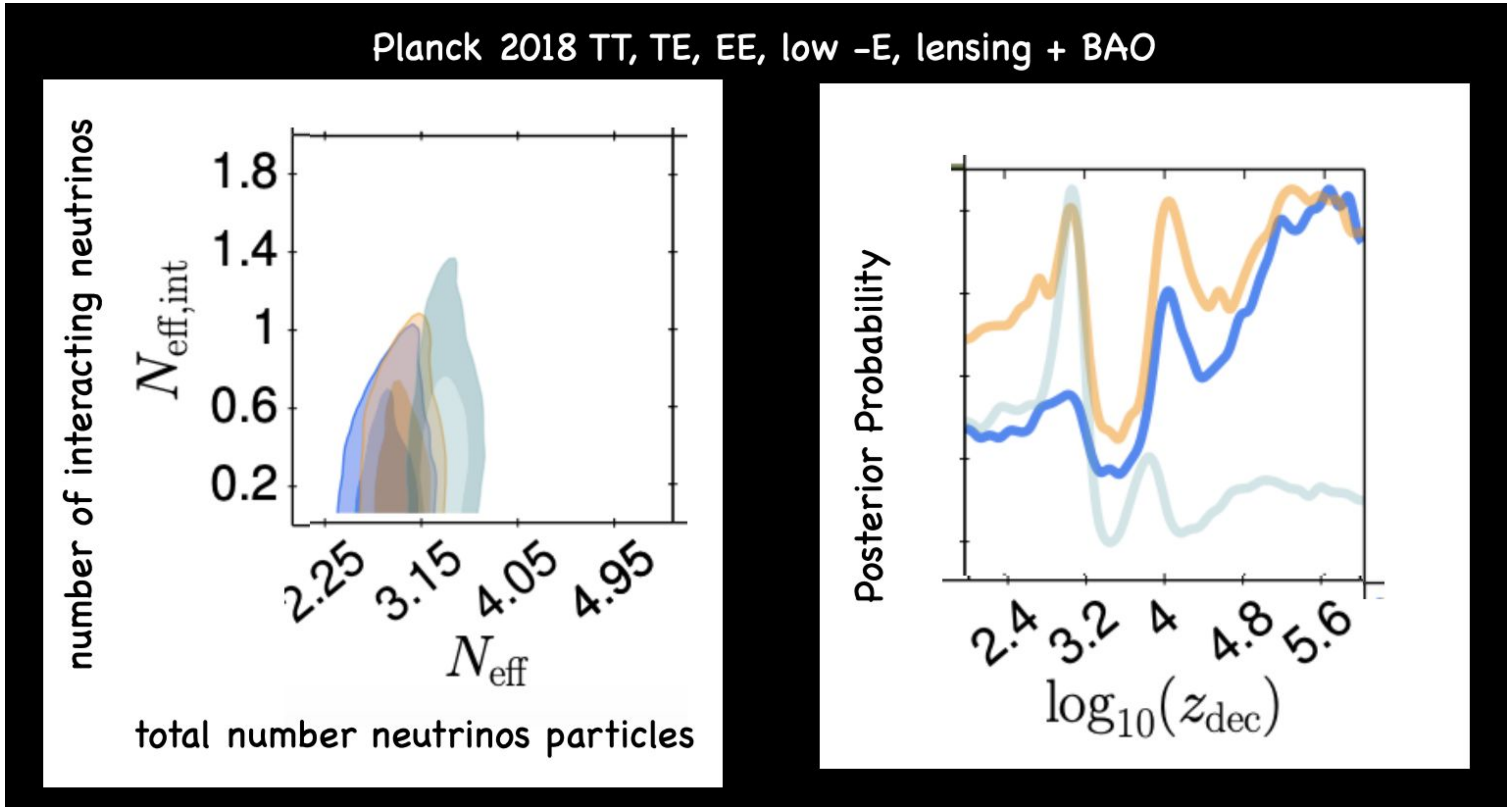
$$N_{eff} = N_{free\text{-}streaming} + N_{fluid} + N_{interacting}$$

Energy in perturbations of relativistic particles that are:

All species interacting



A free fraction interacting



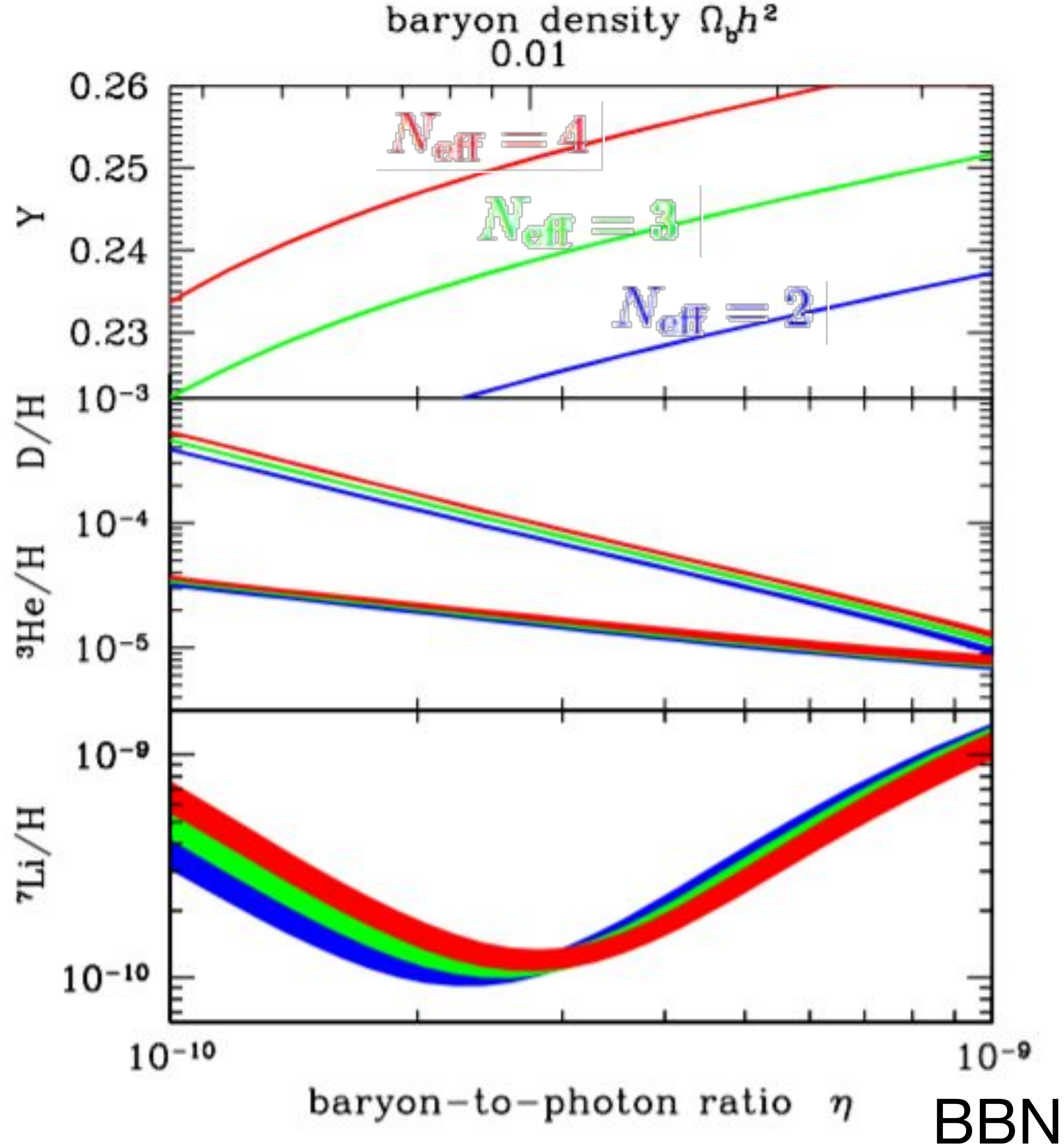
Brinckmann, Chang, Loverde 2020

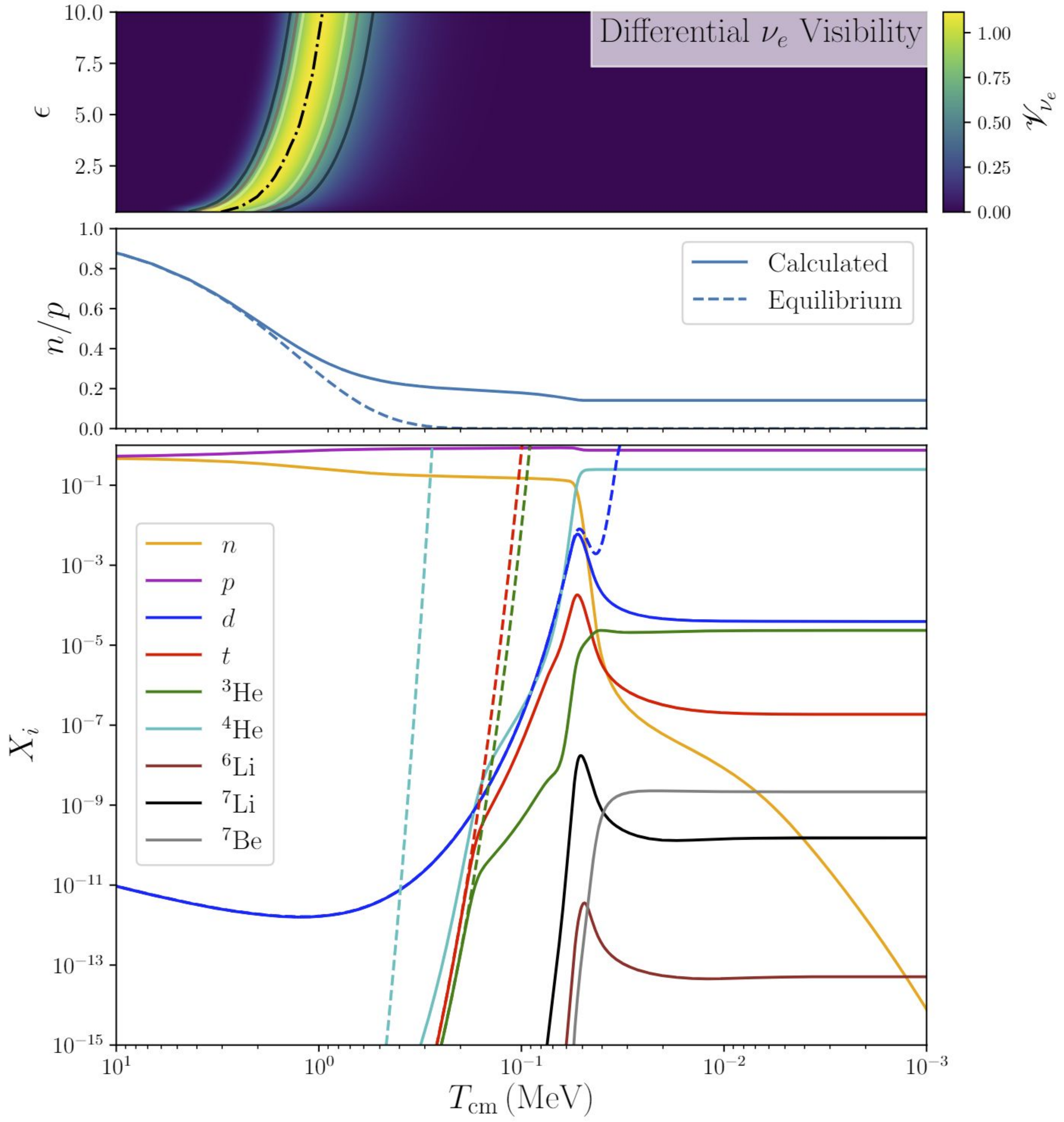
(Also isocurvature!)

If N_{eff} were limited to 3.044 +/- 0.03, how would that affect thinking about dark matter and dark sectors?

BBN

Relativistic energy density at T~1 MeV
+ effects on n/p ratio from weak interactions





BBN: N_{eff} = 2.88 +/- 0.27

Cyburt, Fields, Olive, Yeh 2015

Pitrou 2018

Bond, Fuller, Grohs, Meyers, Wilson (In prep)

BBN

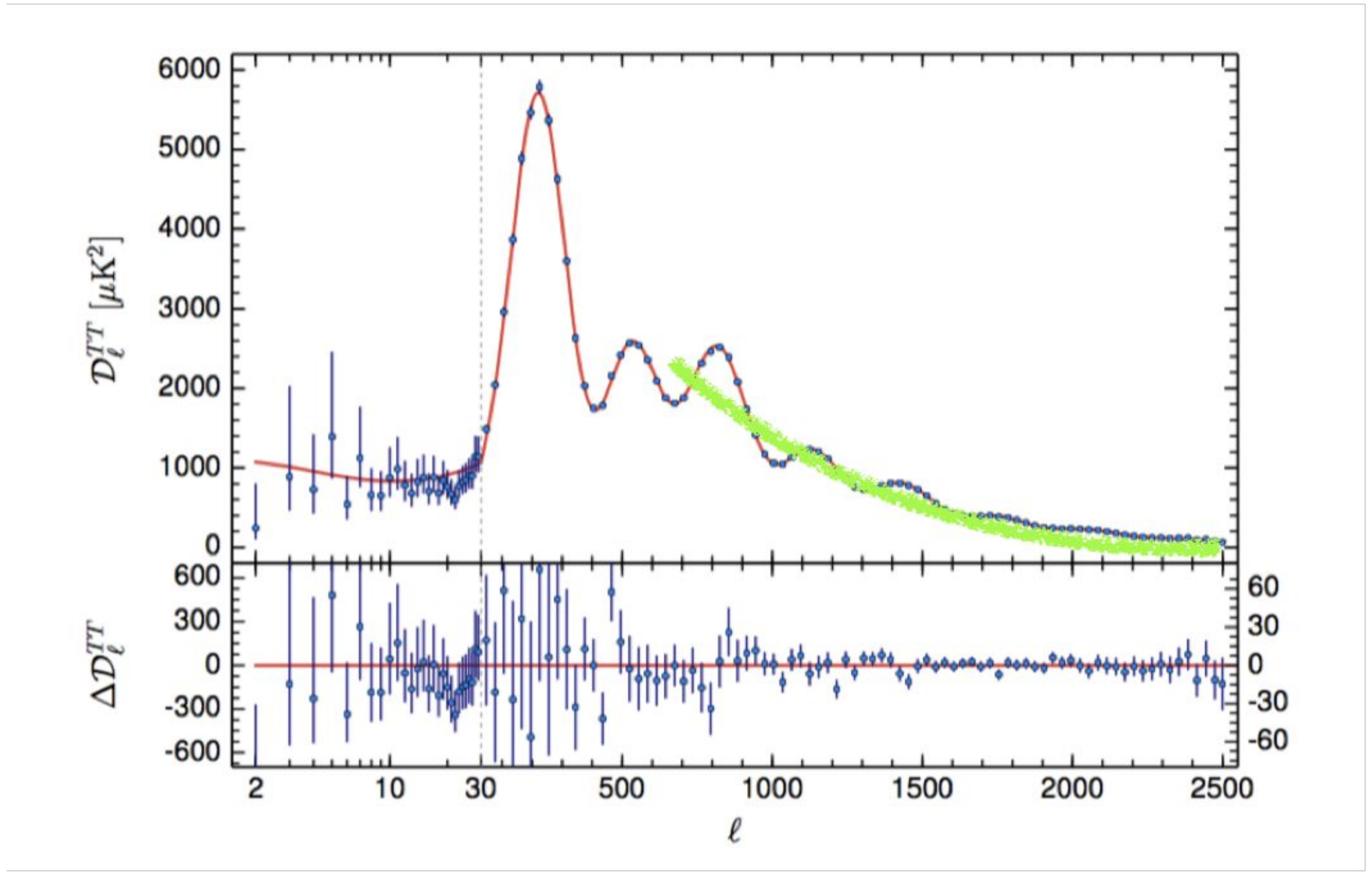
Y_p = Helium abundance by mass

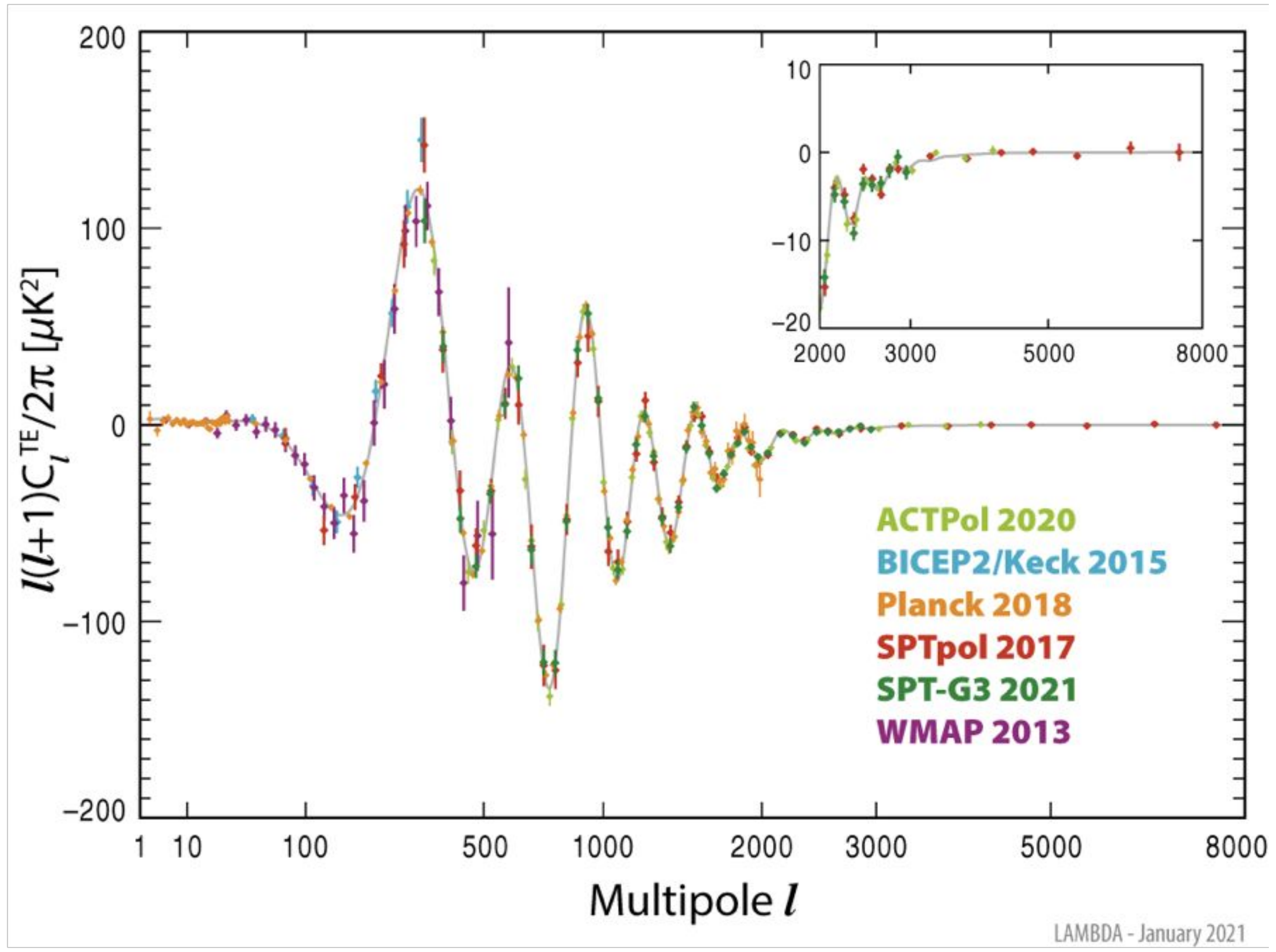
Abundance of helium affects number of free electrons —> affects damping of CMB and amplitude of polarization

Damping Scale:

$$r_d^2 = \pi^2 \int_0^{a_*} \frac{da}{a^3 \sigma_T n_e H} \left[\frac{R^2 + \frac{16}{15}(1+R)}{6(1+R^2)} \right]$$

Y_p (→ n_e)





Standard Model: $Y_p \approx 0.2311 + 0.9502\ \Omega_b h^2$

BBN

Examples of Yp ≠ standard value

- Neff, BBN ≠ Neff, CMB implies decay of particles or photon heating between BBN & CMB decoupling
- Existence of large (≫ 10-9) lepton asymmetry
- . . .

$$Y_{\mathrm{P}}^{\mathrm{BBN}} = 0.243^{+0.023}_{-0.024} \quad \text{(95 \%, \textit{Planck} TT,TE,EE+lowE +lensing+BAO).}$$

CMB-S4:

$\sigma_{Yp} \approx 0.005$

$L_\nu \approx 10^{-2}$ changes Y_p by 1σ

e.g. Grohs et al 1612.01986, 1903.09187, Oldengott 1706.01705, Planck 1807.06209

What parameter after N_{eff} would you most want to see part of standard analyses?

e.g.

- N_{CMB} & N_{BBN}
- N_{CMB} at different times? (e.g. multiple N_{eff} at CMB and a transition for the step models)
- $N_{free\text{-}streaming}$, N_{fluid}, $N_{interacting}$

Neutrino mass

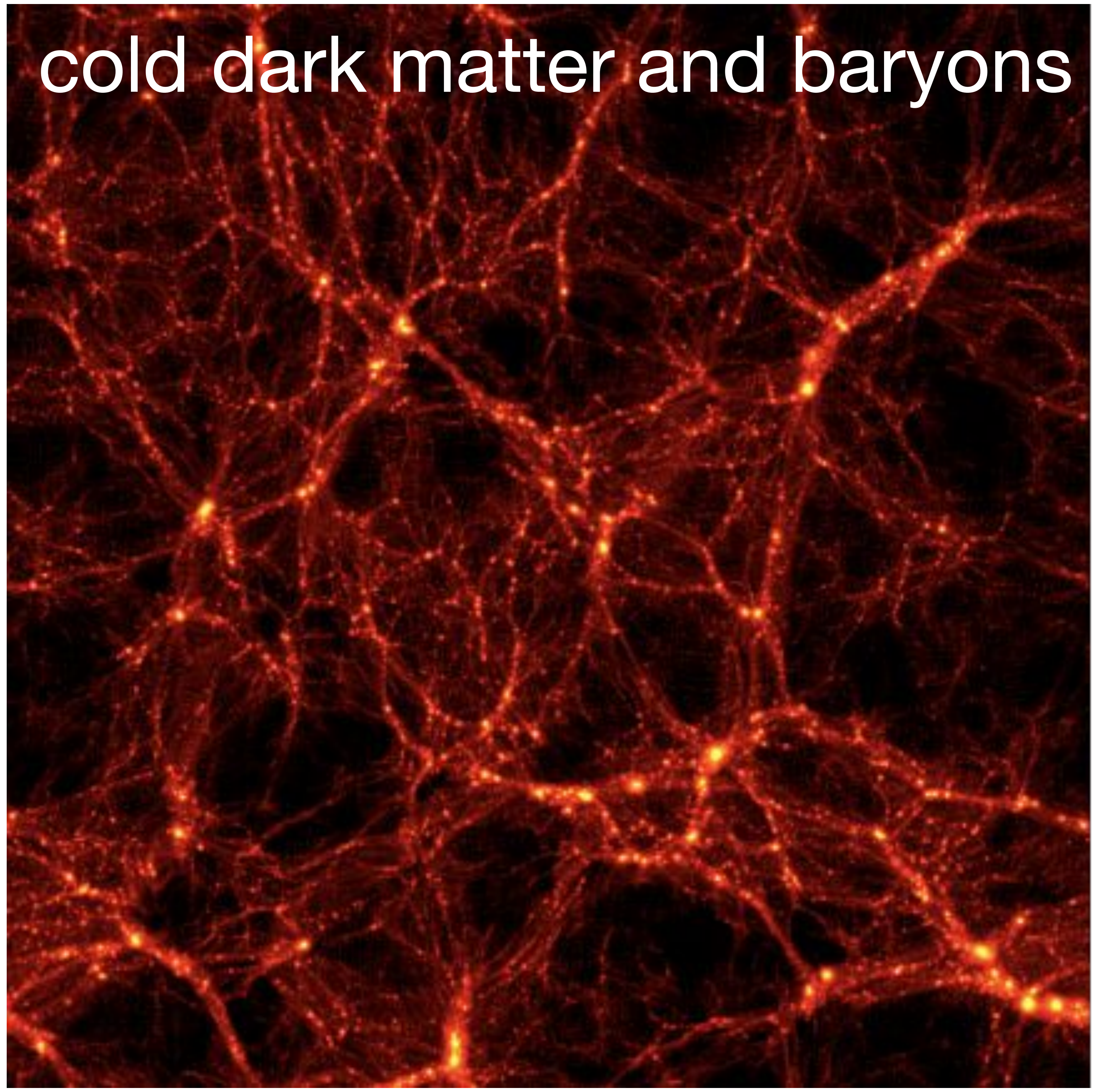
At times when $m_{\nu i} > T_{\nu i}$, neutrinos contribute to non-relativistic energy budget Ω_m but are distributed much more smoothly

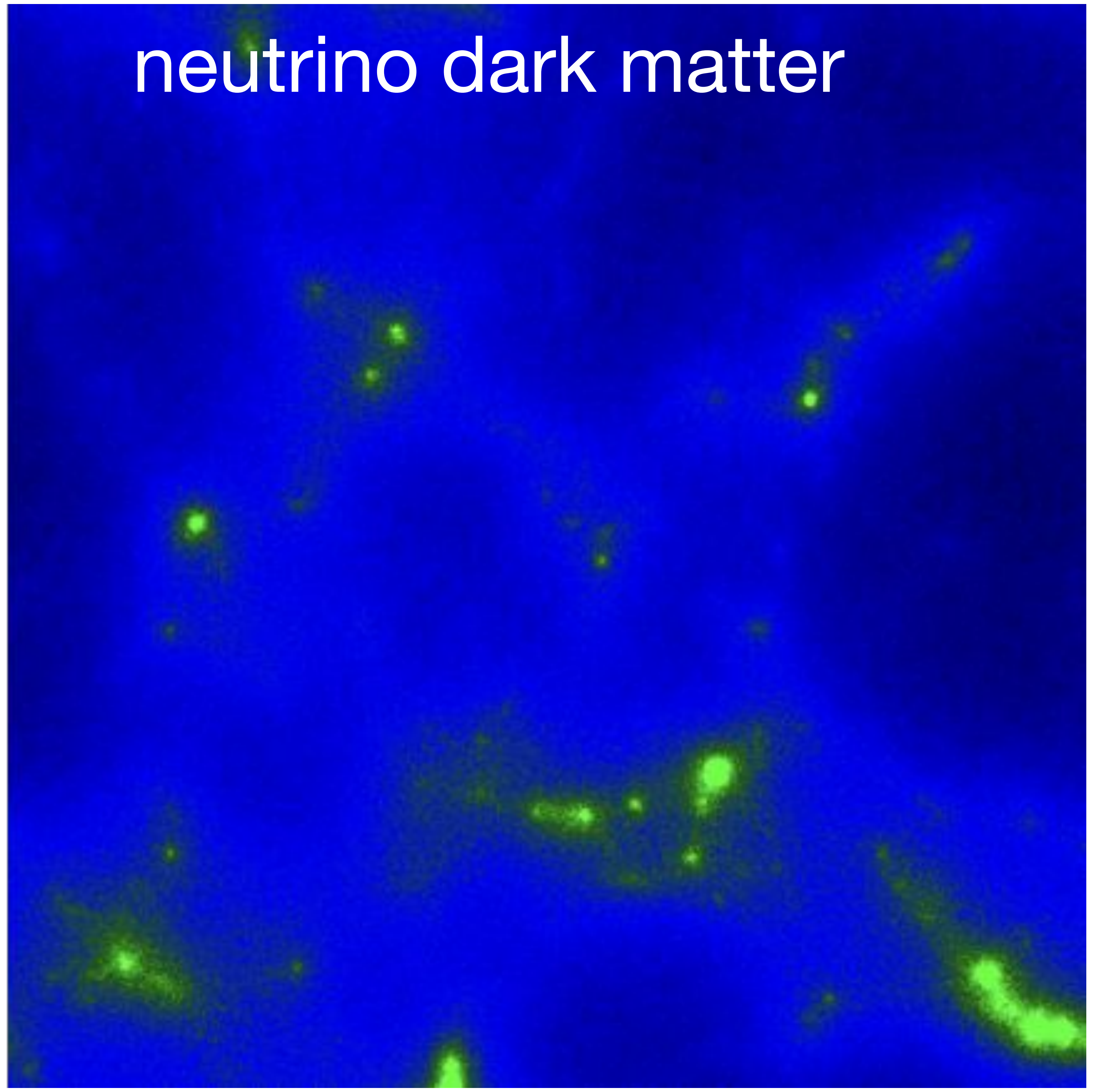
$$\rho_\nu \approx \sum m_{\nu i}\, n_{\nu i} \approx \left(\sum m_{\nu i}\right) n_\nu$$

Oscillation data + standard cosmology:

$$\frac{\rho_\nu}{\rho_{cdm} + \rho_{baryon} + \rho_\nu} \gtrsim 0.005$$

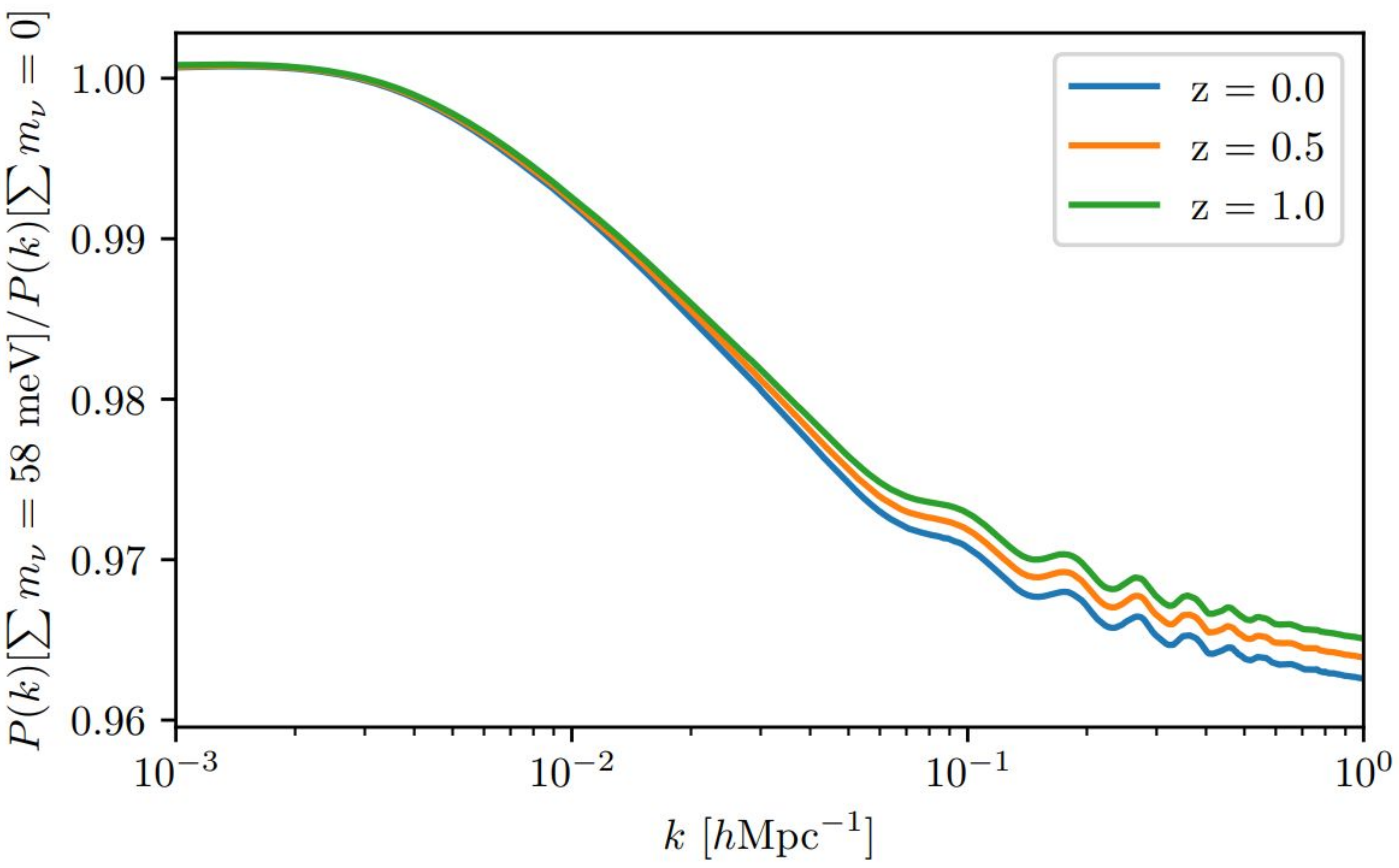
$$n_\nu \sim 10^{10} n_{baryon}$$



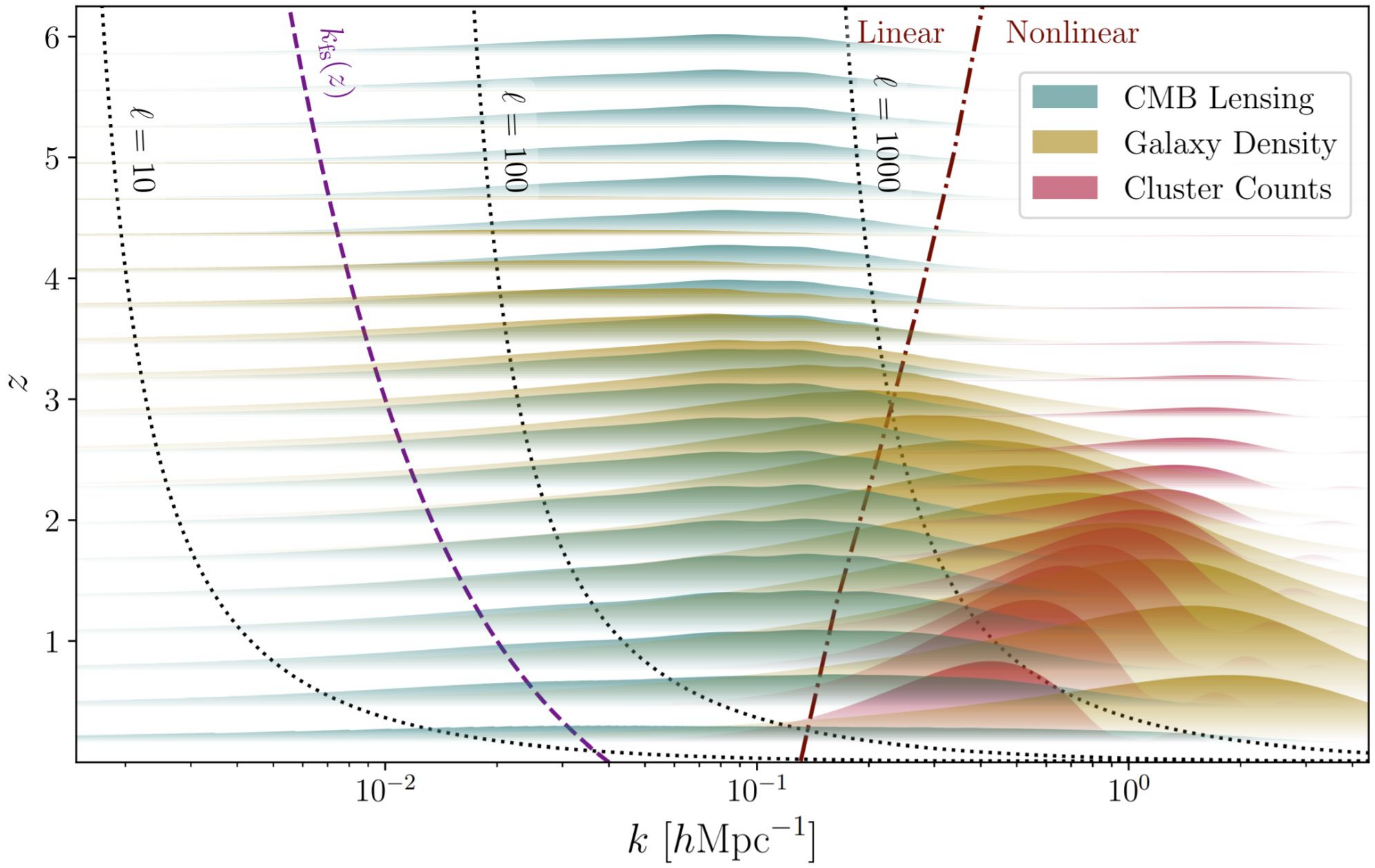


(Villaescusa-Navarro, Bird, Pena-Garay, Viel 2013)

$\sum m_\nu$ Suppression of Matter Clustering



Gerbino, Grohs, Lattanzi, et al 2022



Green, Meyers 2021

$\sum m_\nu$ Suppression of Matter Clustering

Current CMB constraints:

$$\sum m_\nu < 0.24 \text{ eV} \quad (95\,\%,\ \text{TT,TE,EE+lowE+lensing}).$$

$$\sum m_\nu < 0.12 \text{ eV} \quad (95\,\%,\ \textit{Planck}\ \text{TT,TE,EE+lowE+lensing+BAO}).$$

In combination with oscillation data roughly implies:

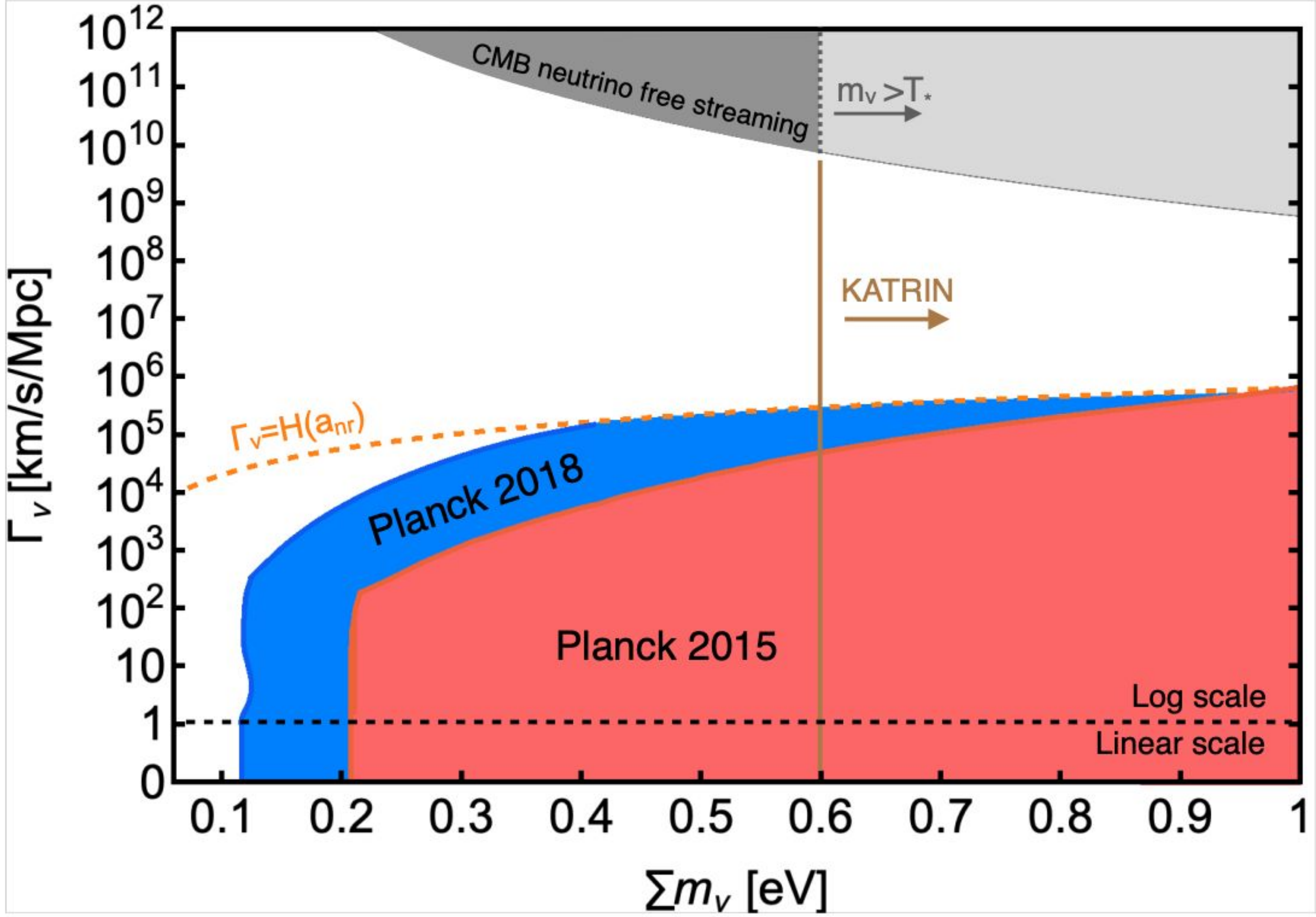
Normal: $m_1 \lesssim 0.03$eV, 0.009 eV $\lesssim m_2 < 0.032$ eV, 0.049 eV $\lesssim m_3 < 0.058$ eV

Inverted: $m_3 \lesssim 0.017$eV, 0.048 eV $\lesssim m_1 < 0.051$ eV, 0.049 eV $\lesssim m_2 < 0.052$ eV

CMB-S4+DESI: $\sigma(\sum m_\nu) \sim 0.01$- 0.02 eV

Beyond Σ mv:

Neutrino lifetime



Abellan, Chacko, Dev, Du, Poulin 2021

In principle, some sensitivity to individual masses, energy spectrum

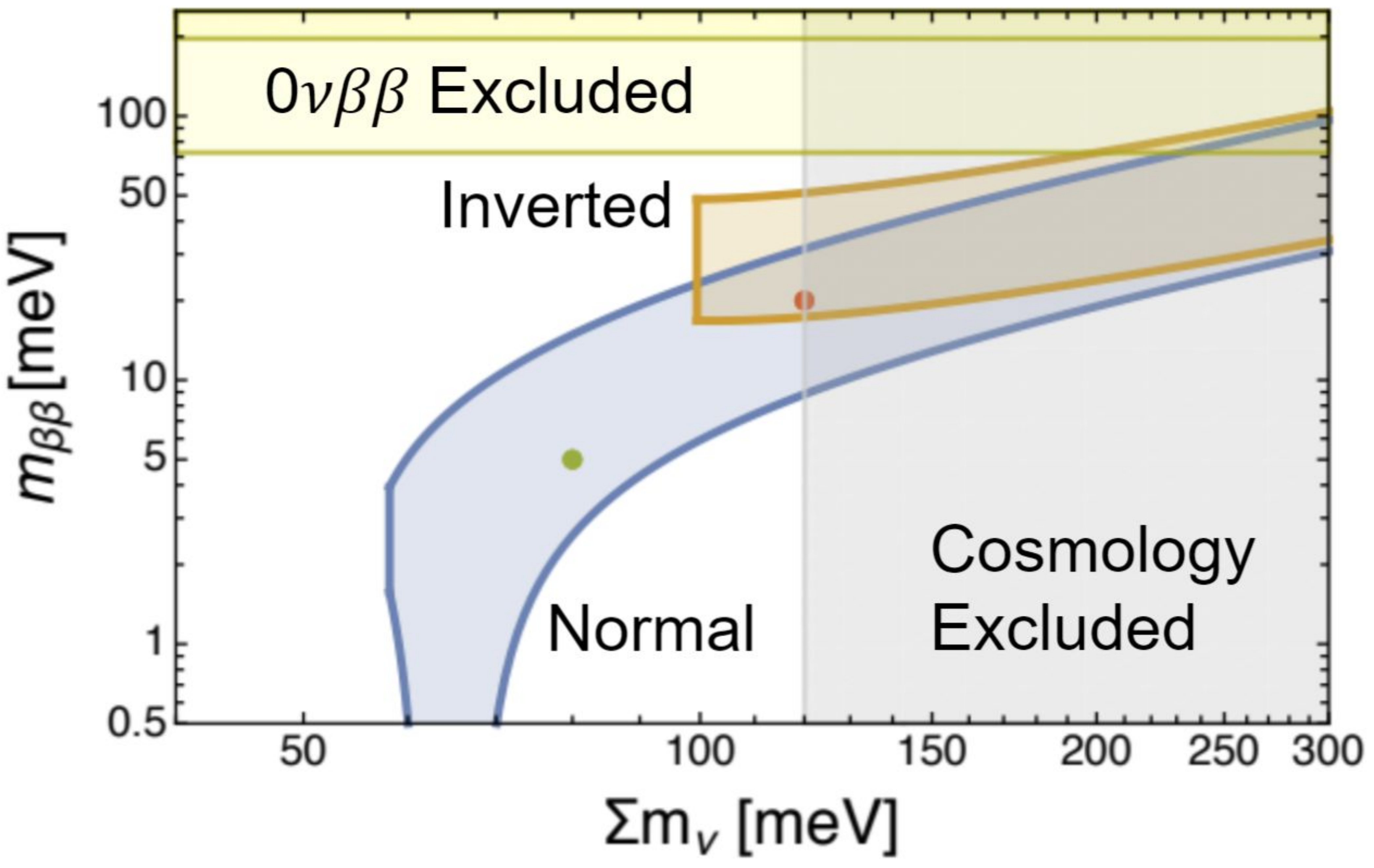
Neutrino mass

- What will it take for cosmologists to accept a detection? For particle physicists? For neutrino physicists (Will hell freeze over!)?
- What does $\sum m_\nu$ teach us, given that we probably can't detect $m_{lightest}$, that $M_{see\text{-}saw}$ not going to be constrained much further
- What are some straw man scenarios where KATRIN sees something? Where cosmology limits $\sum m_\nu$ below oscillation mass splittings?

What would be the most compelling explanation for a cosmological observation of $\sum m_\nu < 60$ meV at high significance?

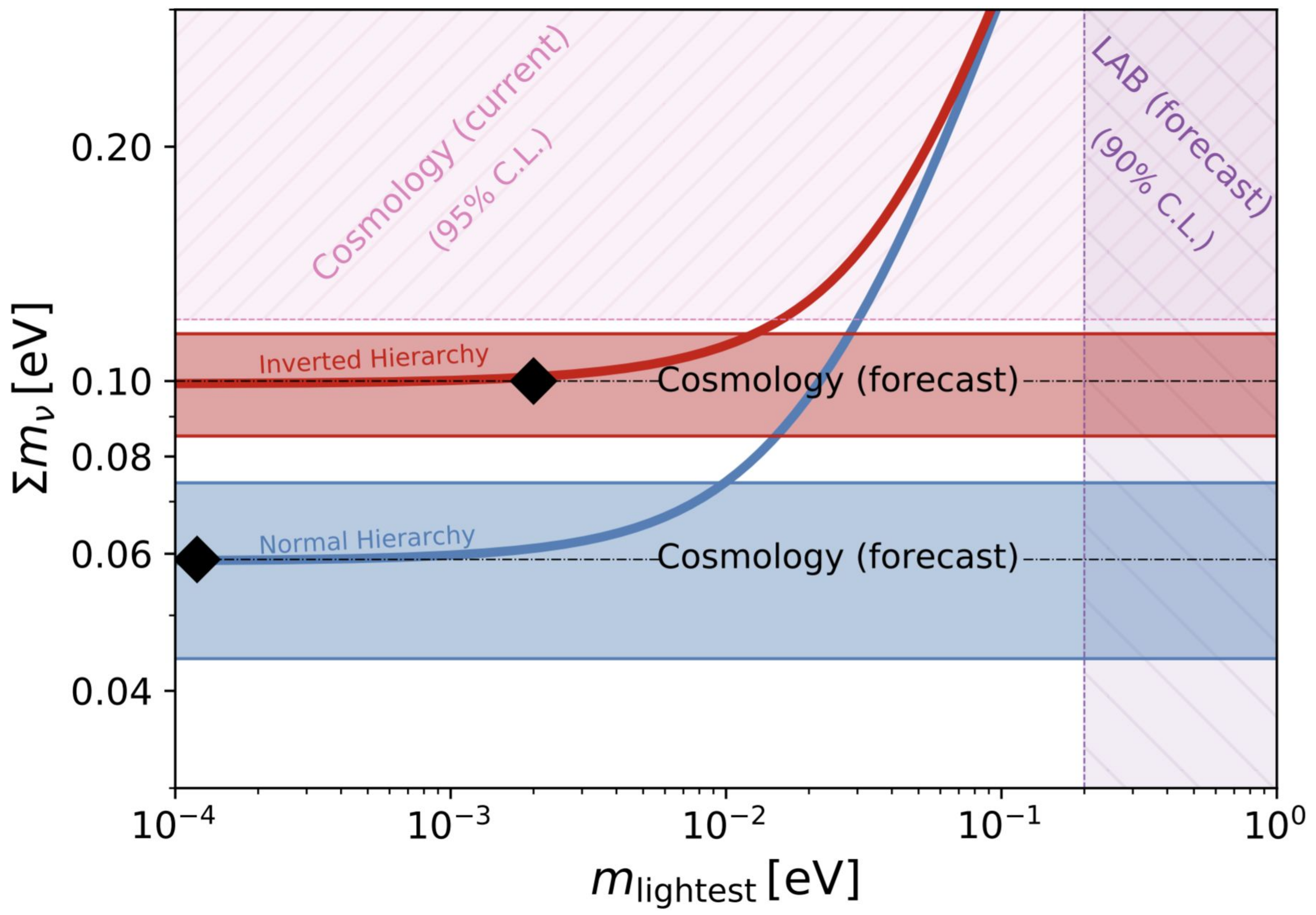
Neutrino mass in cosmology and the lab

Neutrinoless Double Beta Decay



Gerbino, Grohs, Lattanzi, et al 2022

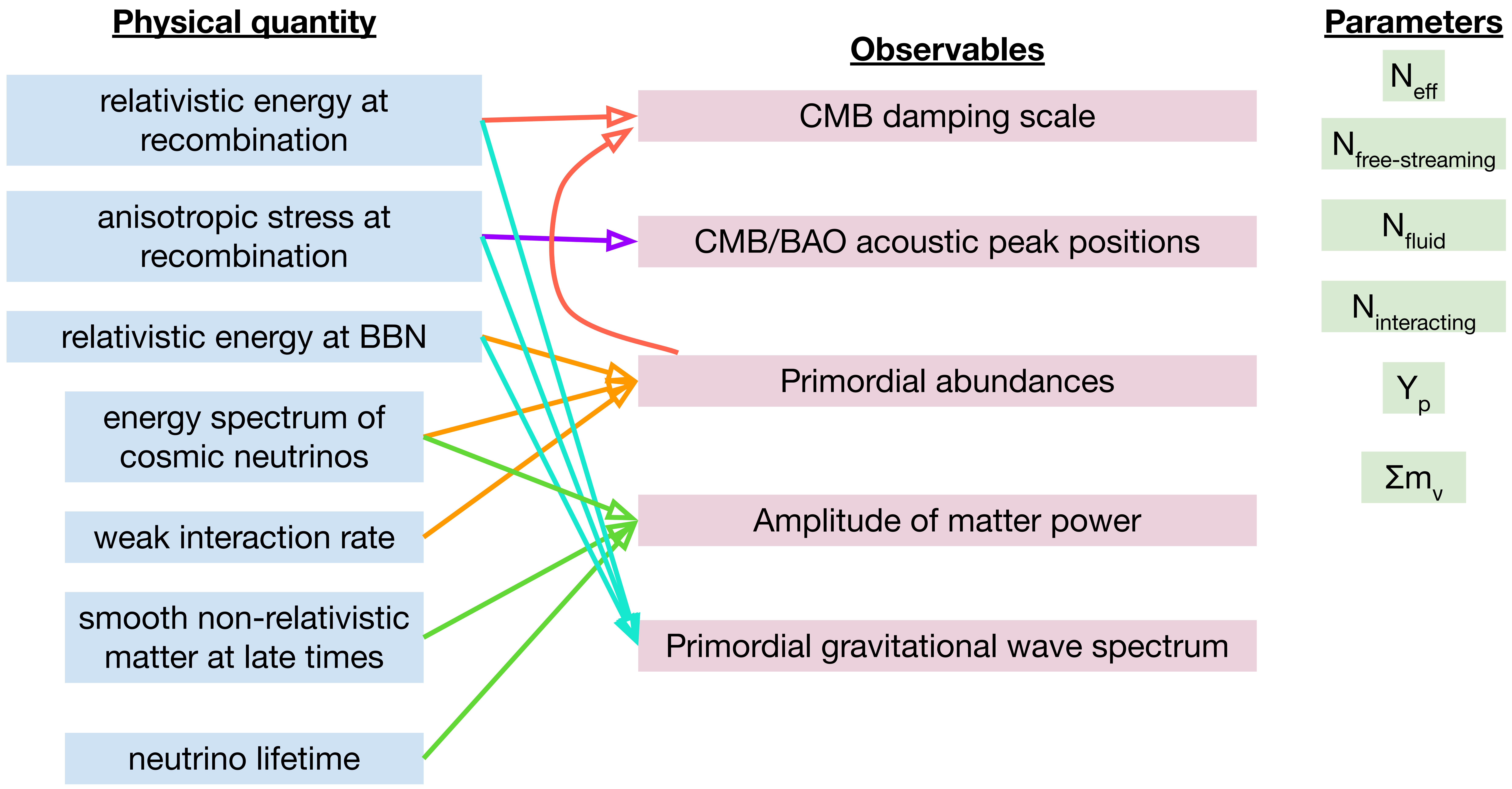
Beta Decay Endpoint Measurements



Dvorkin, et al 2018

What else? Do current parameterizations observables to capture range of models?

- Basics: N_{eff}, $\sum m_\nu$
- Beyond in early universe: N_{eff} at different epochs, $N_{dec/rec}$, $z_{dec/rec}$
- Beyond in late universe: neutrino lifetime, generalizations of $\sum m_\nu$ to allow for heavier steriles?
- Some fraction that interacts with dark matter?


Physical quantity
Observables
Parameters
relativistic energy at recombination
anisotropic stress at recombination
relativistic energy at BBN
energy spectrum of cosmic neutrinos
weak interaction rate
smooth non-relativistic matter at late times
neutrino lifetime
CMB damping scale
CMB/BAO acoustic peak positions
Primordial abundances
Amplitude of matter power
Primordial gravitational wave spectrum
N_{eff}
$N_{free\text{-}streaming}$
N_{fluid}
$N_{interacting}$
Y_p
Σm_ν

Which measurement over the next decade do you expect to have the biggest impact on your theoretical priors?

- N_{eff} / $N_{free\text{-}streaming}$ / N_{fluid} / $N_{interacting}$
- Y_p
- Deuterium abundance
- $\sum m_\nu$
- m_β
- $m_{\beta\beta}$

Which measurement do you anticipate is most likely to deviate from the standard expectation?

- N_{eff} / $N_{free\text{-}streaming}$ / N_{fluid} / $N_{interacting}$
- Y_p
- Deuterium abundance
- $\sum m_\nu$
- m_β
- $m_{\beta\beta}$