High-Precision Cosmology using Neutrinos and Nucleosynthesis

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Outline

I. Theory and Observational motivation

II. Radiation in the Cosmic Microwave Background

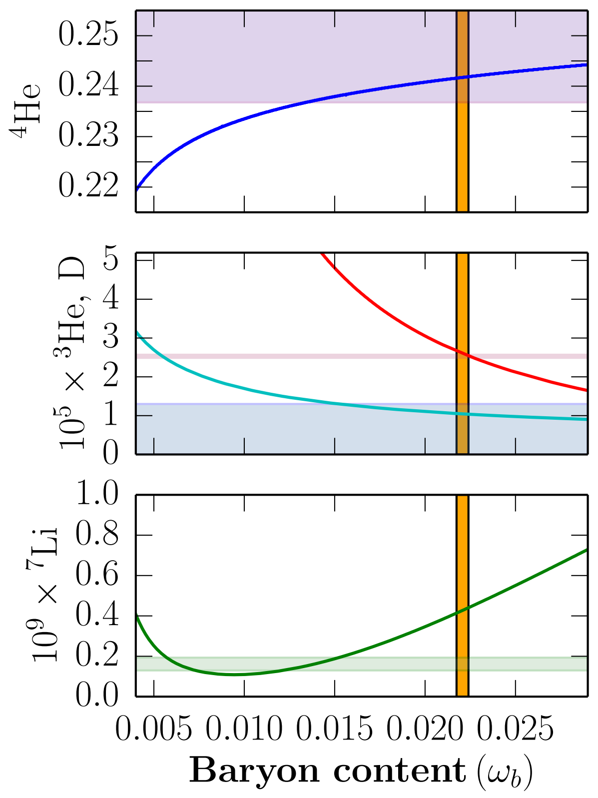
III. Matter Power Spectrum

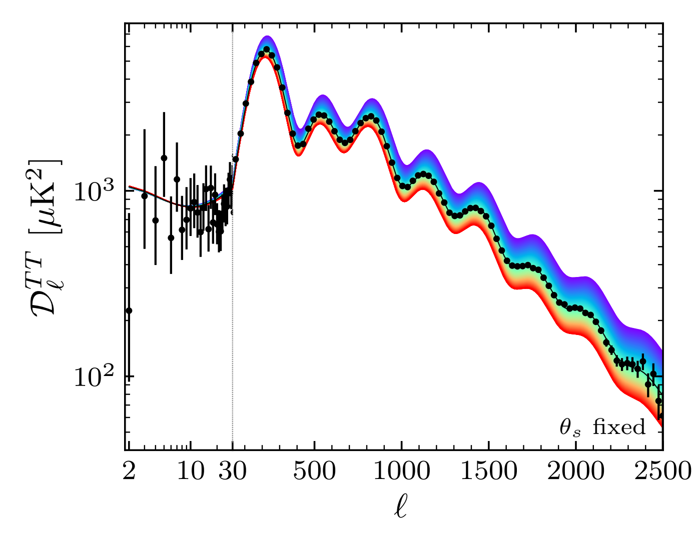
IV. Weak interactions in Big Bang Nucleosynthesis

V. Generalized Entropy Approach for neutrino distributions

VI. Preliminary Results on standard BBN

VII. Summary

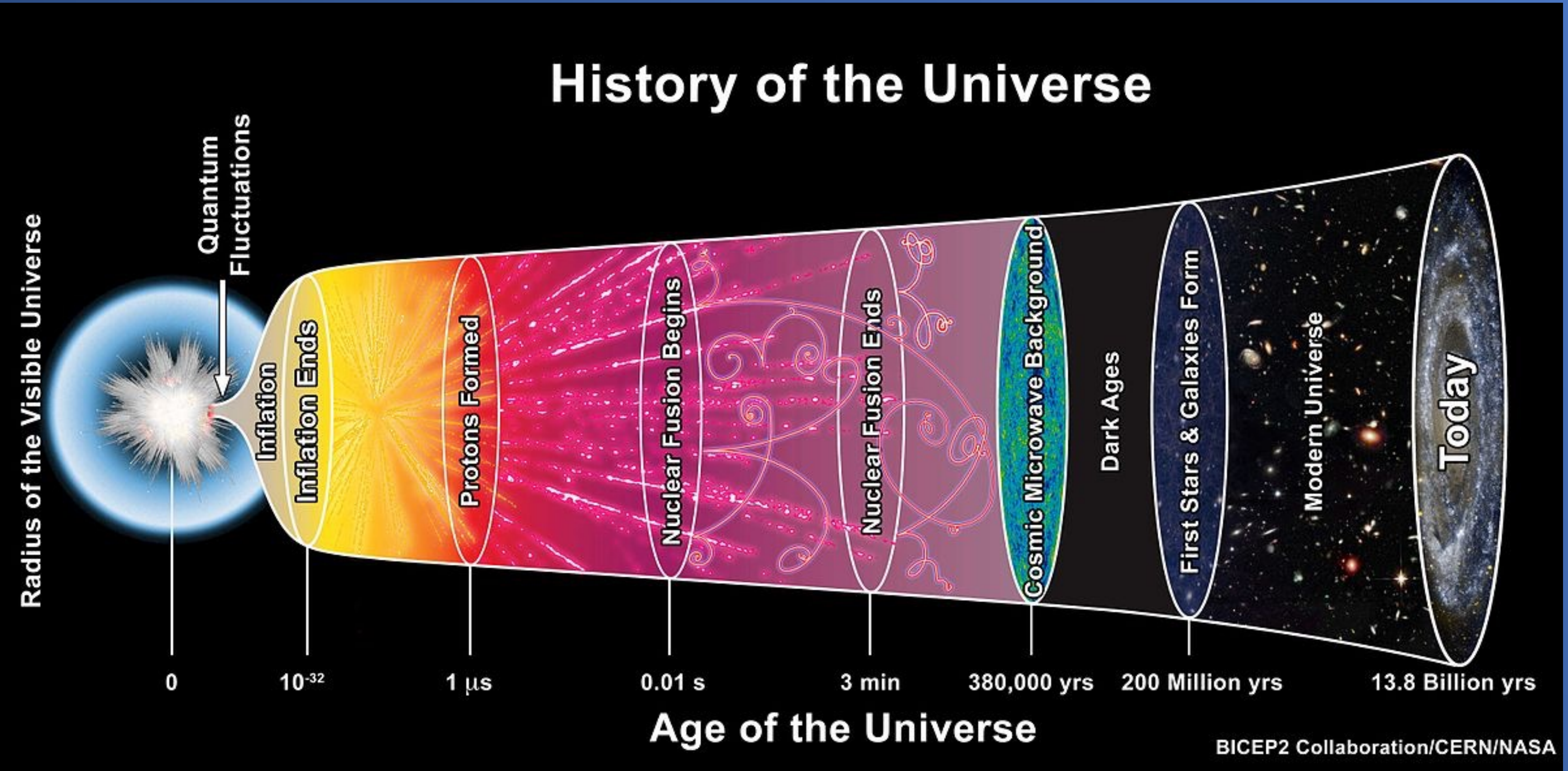




Cosmology: Overview of ΛCDM

Universe begins from a "singularity" – hot Big Bang
→Near Homogeneous, Isotropic spacetime geometry
→Close to Thermal and Chemical Equilibrium
→Subsequent Expansion and Cooling

$$H \equiv \frac{1}{a}\frac{da}{dt} = \sqrt{\frac{8\pi}{3m_{\rm pl}^2}\rho}$$



Various epochs:

1. Planck epoch ~ 10^{-44} s
2. Grand Unification ~ 10^{-38} s
3. Inflation ~ 10^{-32} s?
4. Electroweak breaking ~ 10^{-11} s
5. Quark-Hadron transition ~ 10^{-5} s
6. BBN ~ 1 s – 3 mins.
7. Atomic Recomb. ~ 10^5 yrs
8. Structure ~ 100 Myr
9. Reionization ~ 500 Myr
10. Galaxies, stars, planets ~ 1 Gyr

The coming era of precision cosmology

I. CMB Stage-IV (2203.07638) and others
   A. Simons Observatory - Atacama Desert, Chile
   B. South Pole Observatory - South Pole
   C. Other CMB experiments - CLASS and QUIET
   D. Satellites: LiteBIRD and PIXIE

II. Thirty-meter class telescopes
   A. EELT and GMT - Atacama
   B. TMT – Mauna Kea, Hawaii

III. Surveys
   A. DES - Cerro Tololo, Chile
   B. DESI - Kitt Peak, AZ
   C. Vera Rubin Observatory – Cerro Pachón, Chile
   D. Satellites: Euclid, Roman, SPHEREx

Snowmass 2021 White Paper

Synergy between cosmological and laboratory searches in neutrino physics: a white paper

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arXiv: 2203.07377

Radiation energy density during Recombination

Computing CMB observables requires energy density

$$\rho_{\rm rad} = \rho_\gamma + \rho_{\rm other} = \left[2 + 2\frac{7}{8}\left(\frac{4}{11}\right)^{4/3} N_{\rm eff} \right] \frac{\pi^2}{30} T^4$$

Photon Contribution

Non-Photon Contribution

Effective number of neutrinos: parameter for non-photon energy density

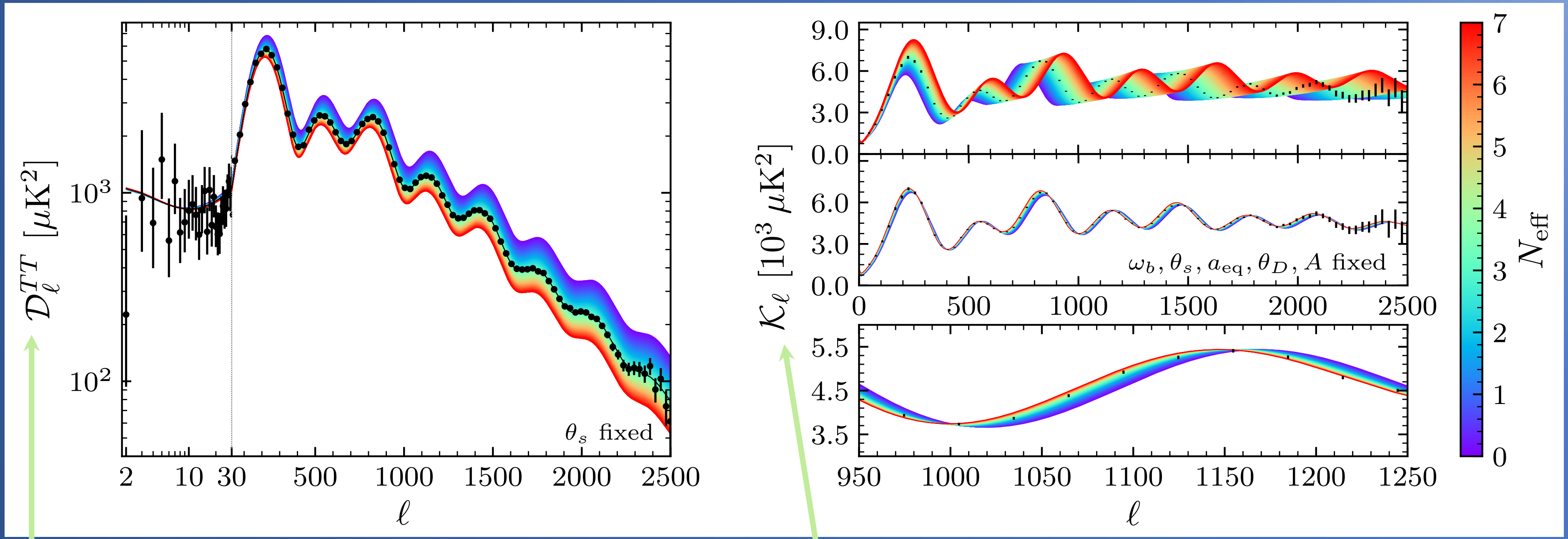
Need not be an integer!

Theory: $N_{\rm eff}$ = 3.045

Cf. 2203.07943

Effects of Radiation on CMB

Black points are Planck 2018 data values



Temperature Power Spectrum

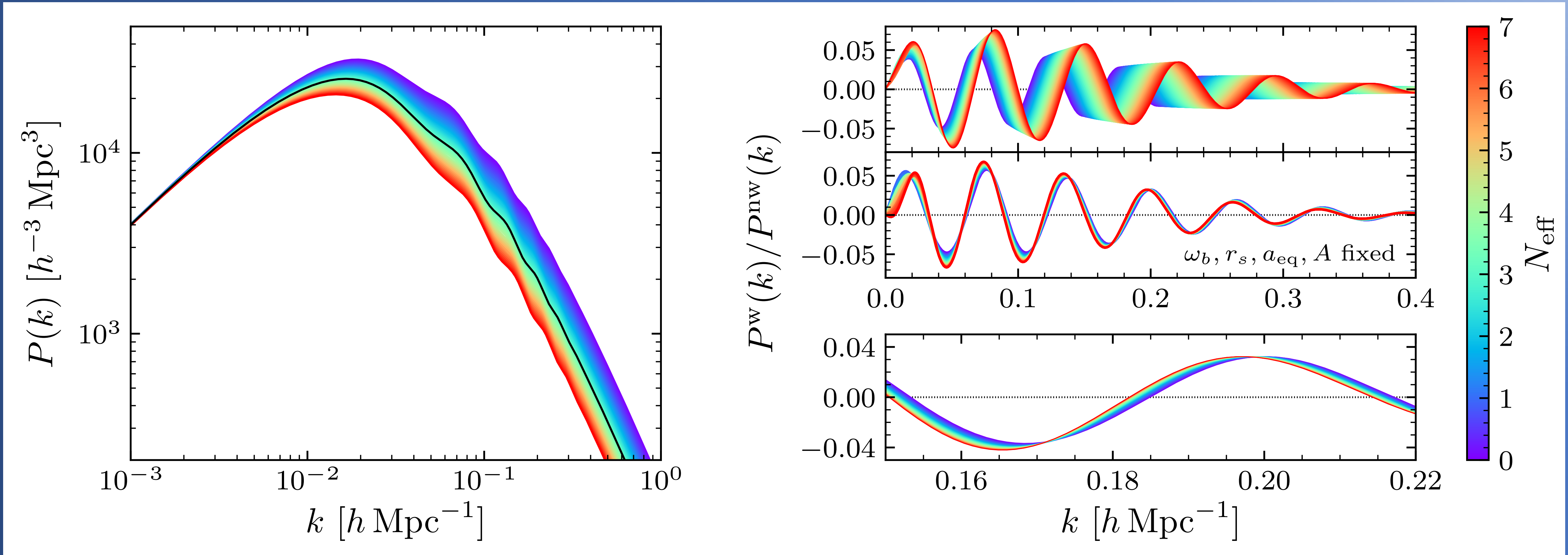
Non-damped Temperature Power Spectrum

Non-photon radiation

Free-streaming radiation

Planck 2018: $N_{\rm eff} = 2.92^{+0.18}_{-0.19}\,(1\sigma)$

Baryon-Acoustic Oscillation Phase Shift

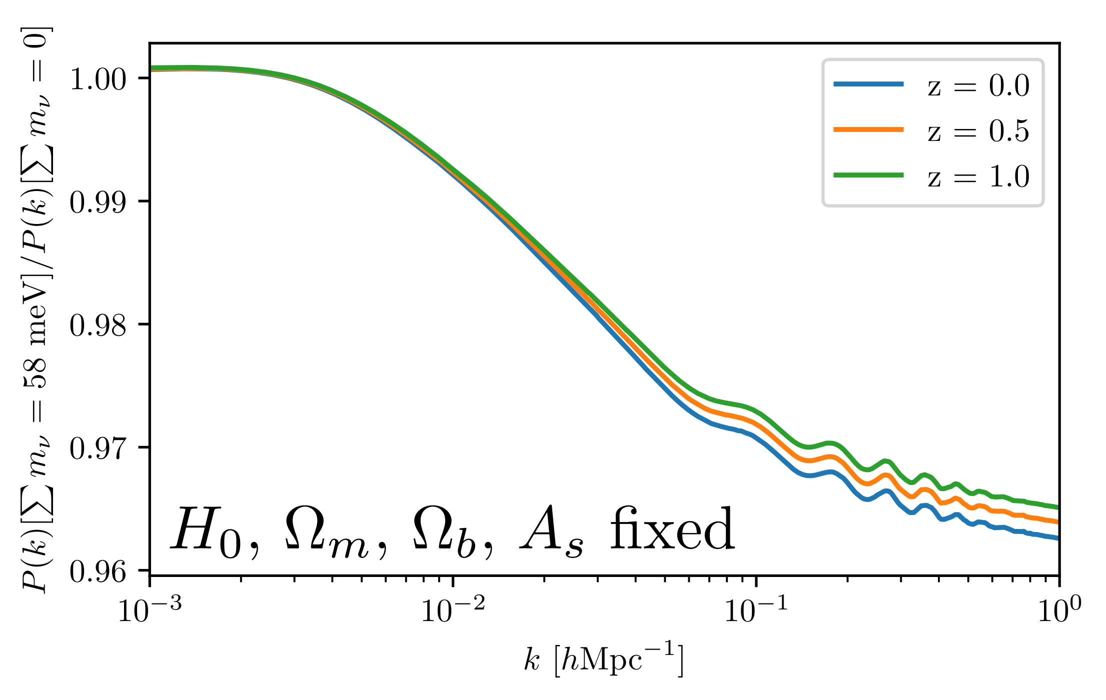


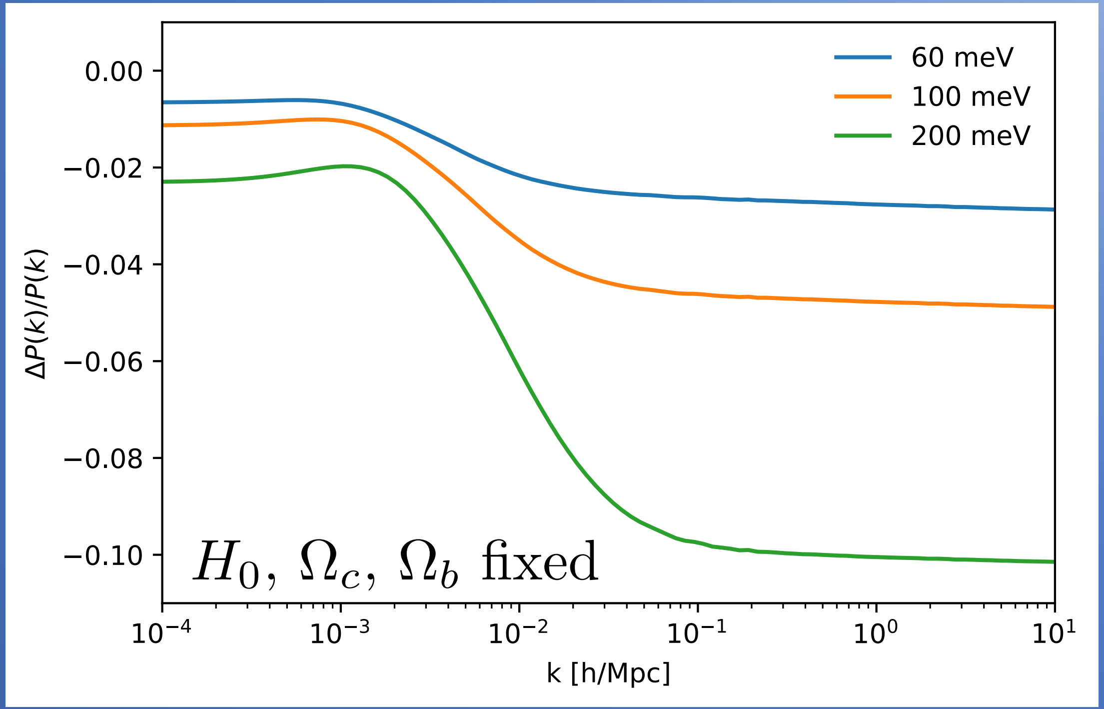
Similar physics of free-streaming radiation influencing CMB phase shifts

Detectable [see Baumann et al (2019)]

Matter Power Spectrum

Neutrinos become non-relativistic: $z_{\mathrm{nr}} \sim 100$

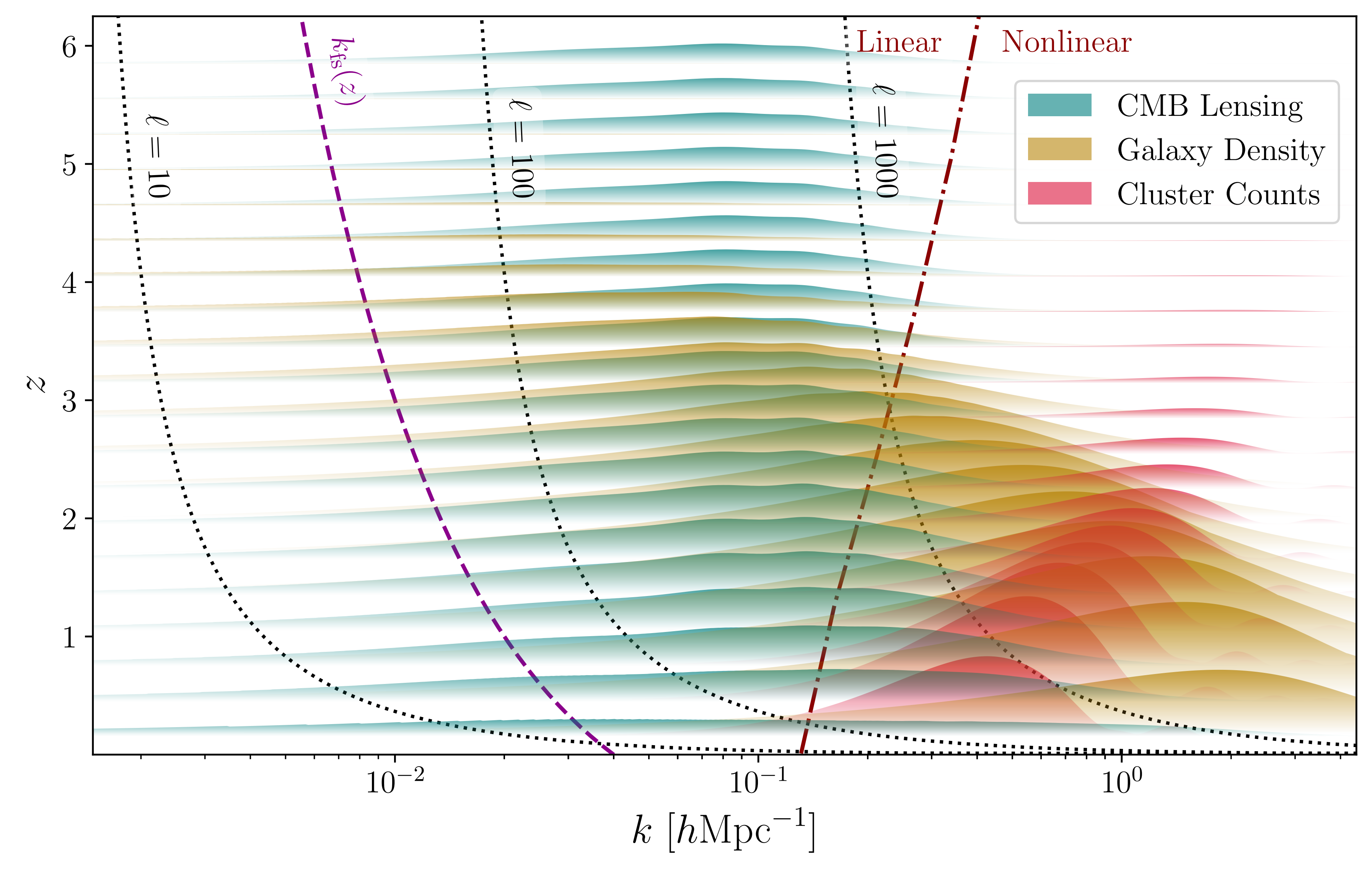




Power suppressed from neutrino free-streaming at small scales

Planck 2018: $\Sigma m_\nu < 0.120\,\mathrm{eV}\ (2\sigma)$

Contributions to Matter Power Spectrum (forecasts)



CMB Lensing
CMB-S4

Galaxy Density
VRO Gold sample

Cluster Counts
tSZ counts from CMB-S4

Contributions weighted by S/N (x3 for CMB Lensing)

Physics of Big Bang Nucleosynthesis

Setting the stage:

a. Homogeneous & Isotropic
b. Nearly CP symmetric (10^{-10}) [cf. 2204.08668]
c. No free quarks

Synthesis of light-elements:

- Hydrogen ~ 0.75
- Helium ~ 0.25
- Deuterium $\sim 10^{-5}$
- Lithium $\sim 10^{-10}$

Sub-epochs of BBN

Weak Decoupling: $\nu(\nu,\nu)\nu$ & $e(\nu,\nu)e$

Weak Freeze Out: $n(\nu,e)p$

EM equilibrium: $e(e,\gamma)\gamma$

Nuclear Freeze Out: $n(p,\gamma)d$

Baryogenesis $\sim$?

↓

QCD Epoch $\sim 10^{-5}$ s

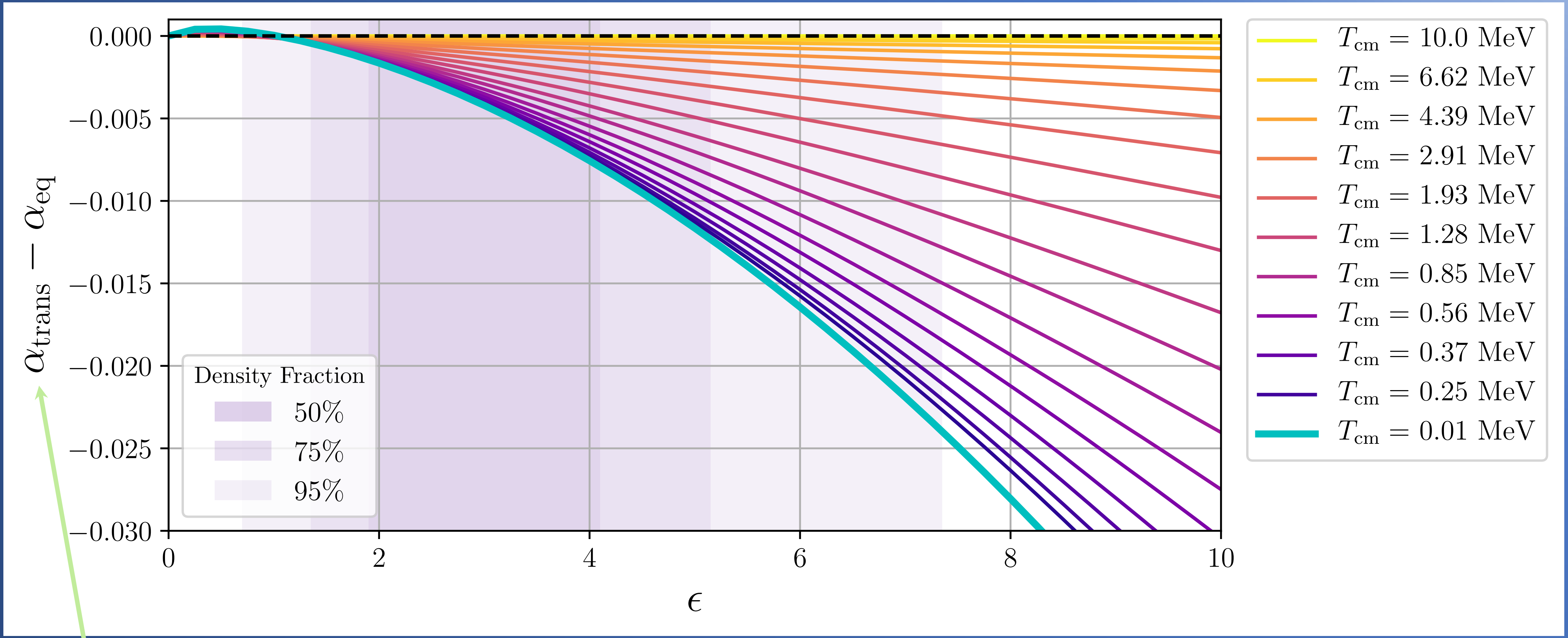
↓

Time $\lesssim 1$ sec.

↓

Time $\gtrsim 100$ sec.

Electron Neutrino Decoupling in BBN



Boltzmann neutrino energy transport calculation

Bond+
(In Prep.)

Generalized Entropy Formalism

Bond, Fuller, Grohs, Meyers, & Wilson (In Prep.)

Approach adopted from CMB studies; works well close to equilibrium

Parameterization of the neutrino distribution functions (ignoring oscillations)

$$n_{\nu_i}(\epsilon, T_{\rm cm}) = (\exp[\alpha^{(i)}(\epsilon, T_{\rm cm})] + 1)^{-1}$$

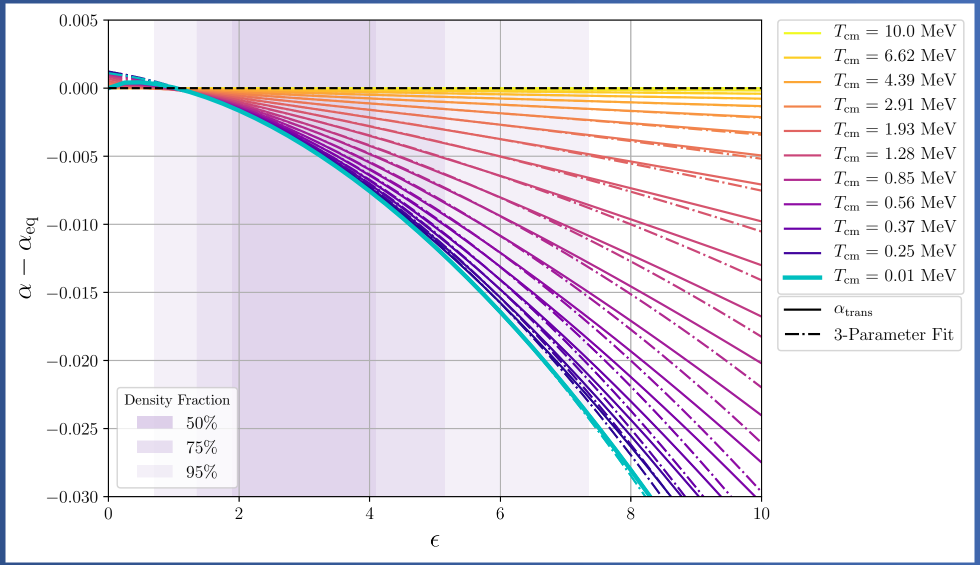
$$\alpha^{(i)}(\epsilon, T_{\rm cm}) = \sum_{j=0}^{2} \alpha_j^{(i)}(T_{\rm cm})\epsilon^j$$

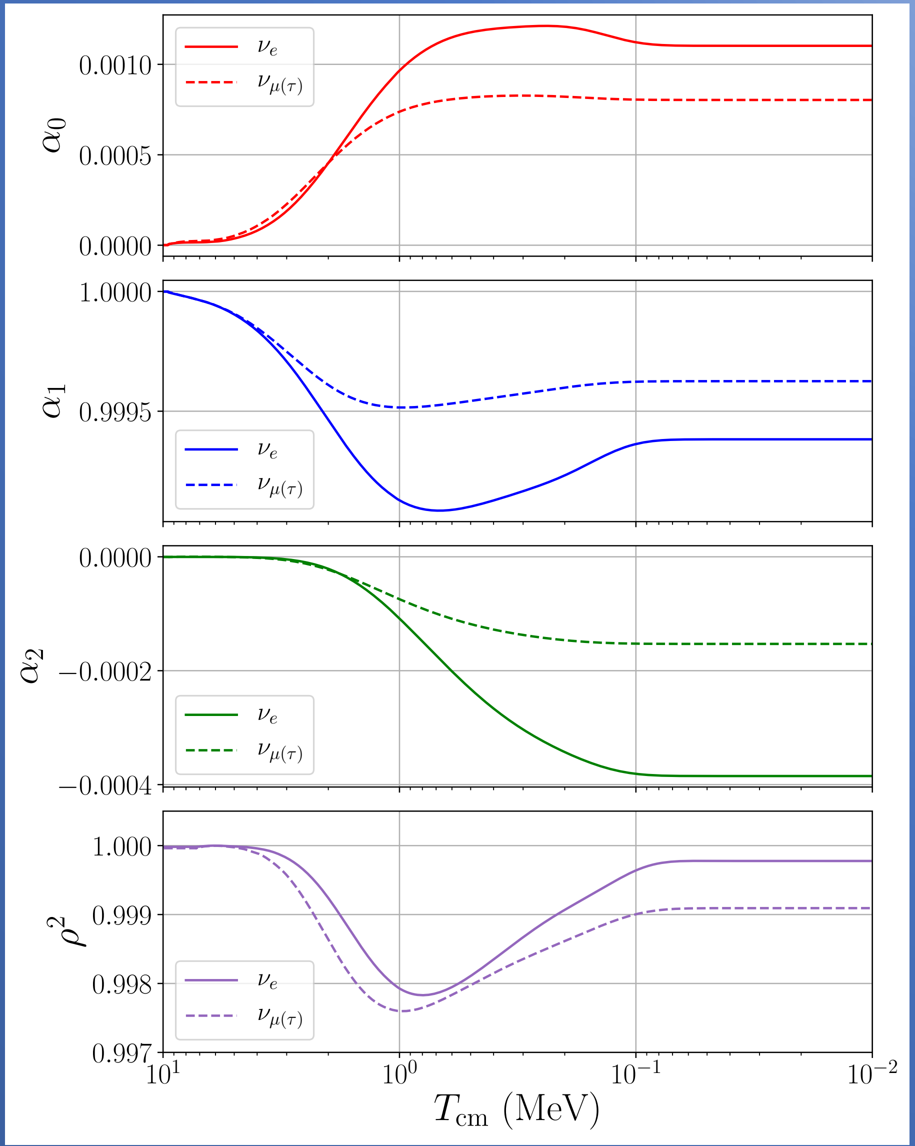
$$\alpha_{\rm eq}(\epsilon, T_{\rm cm}) \equiv \epsilon \qquad \epsilon \equiv E/T_{\rm cm}$$

In the mean field, use an entropy functional to find $\alpha_j^{(i)}$ at a given $T_{\rm cm}$

α_0: chemical potential
α_1: inverse temperature
α_2: fluctuation constraint

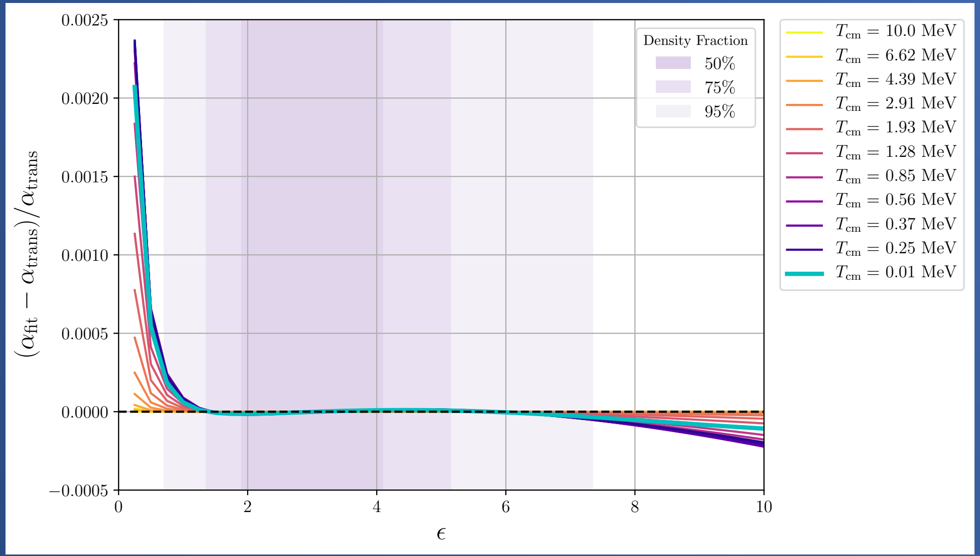
Fits to Out-of-Equilibrium Neutrino Spectra





Bond+
(In Prep.)

Residuals



Goodness of fit

Neutron-to-Proton Rates

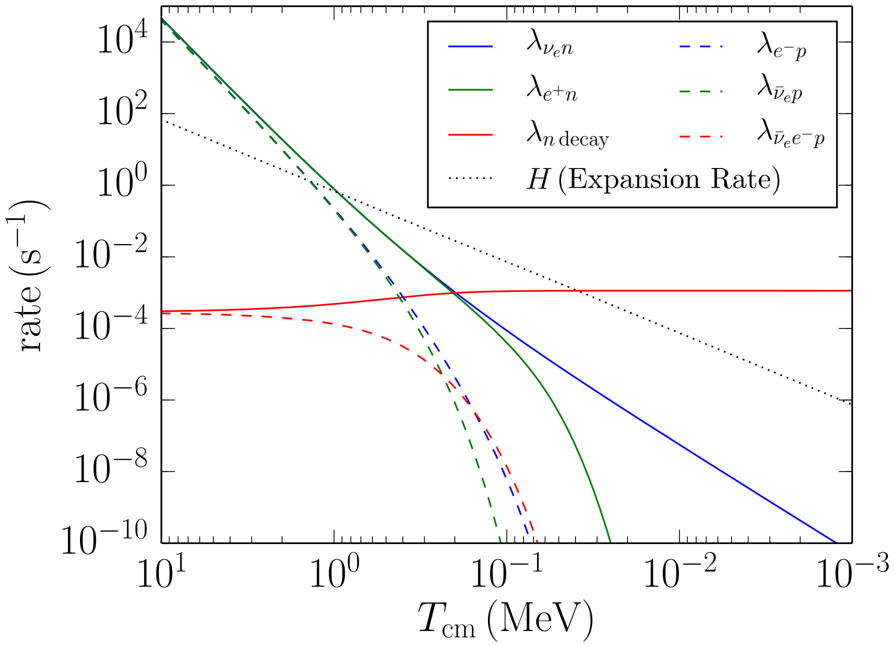
$$\nu_e + n \leftrightarrow p + e^-$$

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

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

6 rates normalized to neutron lifetime

$m_n - m_p \simeq 1.3$ MeV

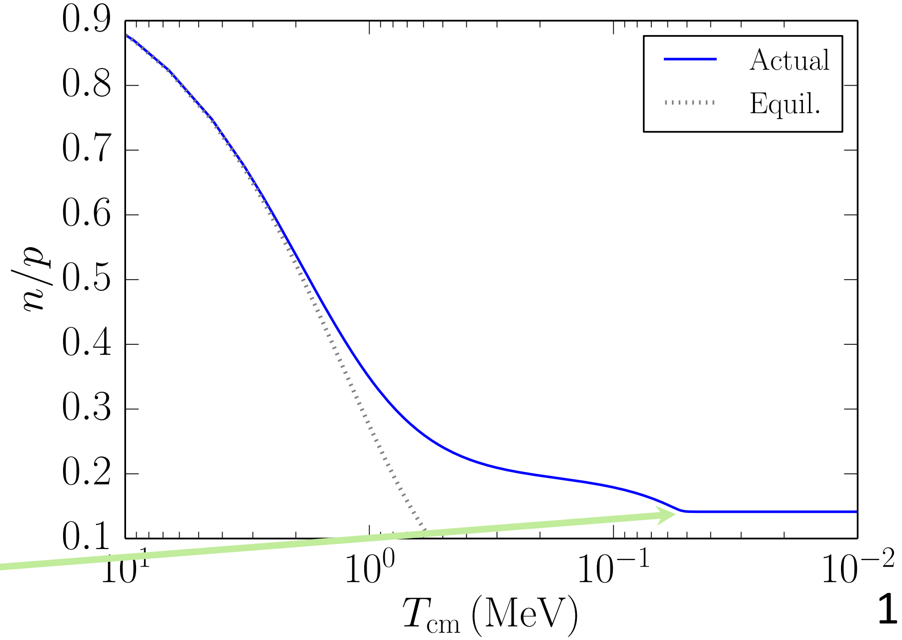


Grohs & Fuller (2016)

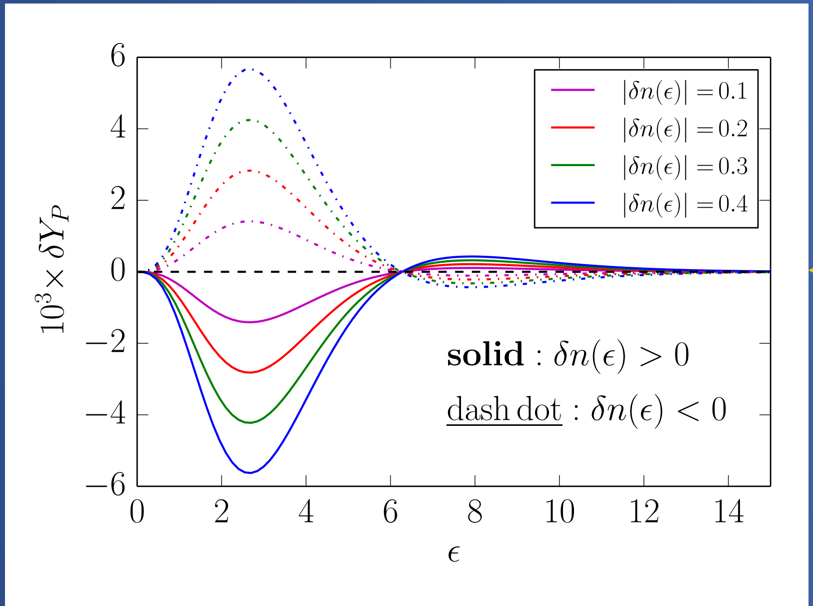
Rule of thumb: ^{4}He 25% by mass

$$p\ p\ p\ p\ p\ p\ p\ n$$
$$p\ p\ p\ p\ p\ p\ p\ n$$

$$n/p \sim 1/7$$



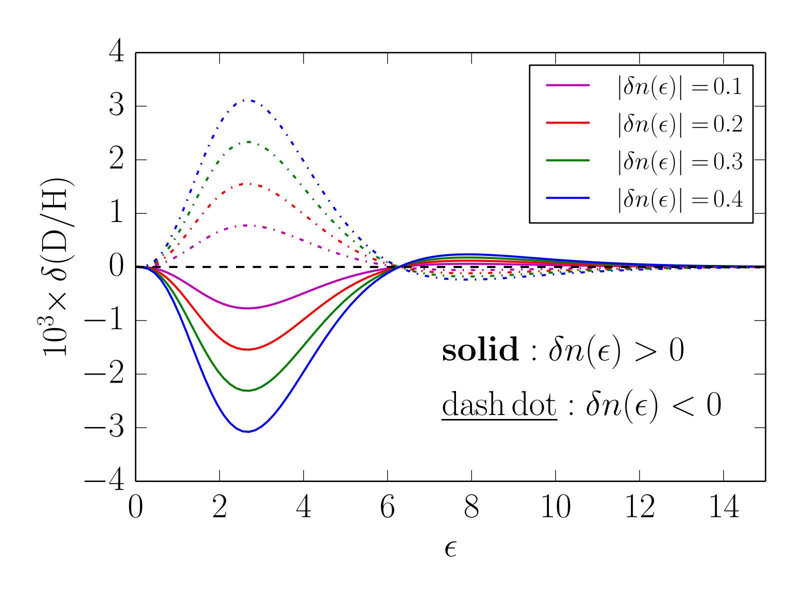
Linear Response to Spectral Distortions



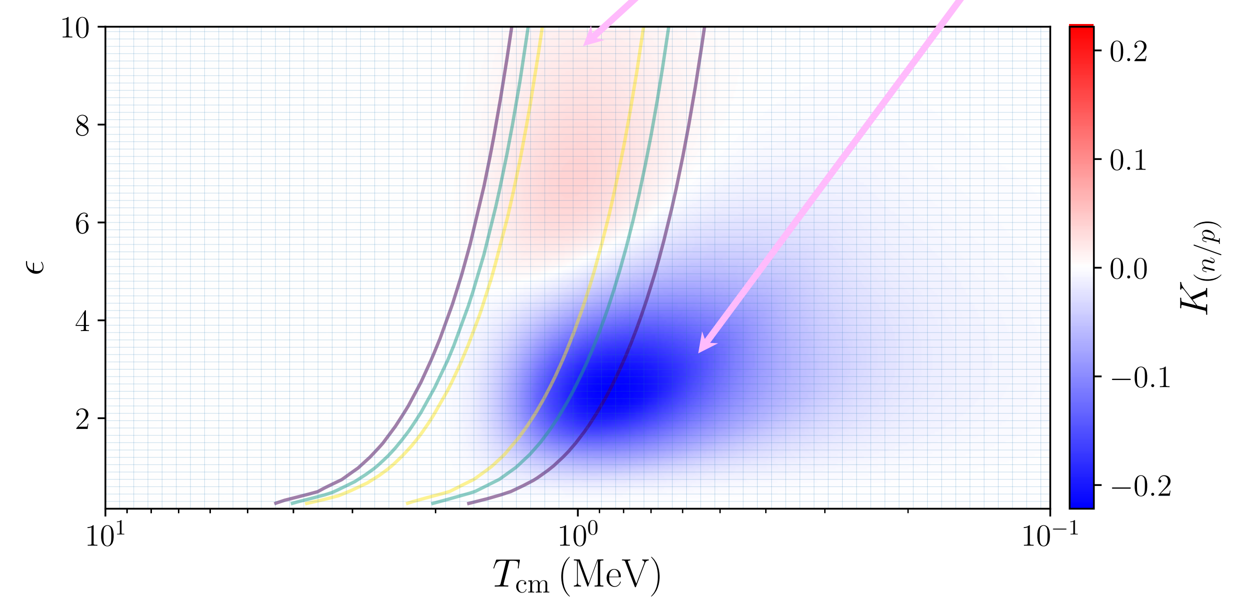
Time-*independent* perturbations

Time-dependent perturbations

Increase/Decrease in n/p



Bond+ (In Prep.)



Neutrino physics occurring during BBN

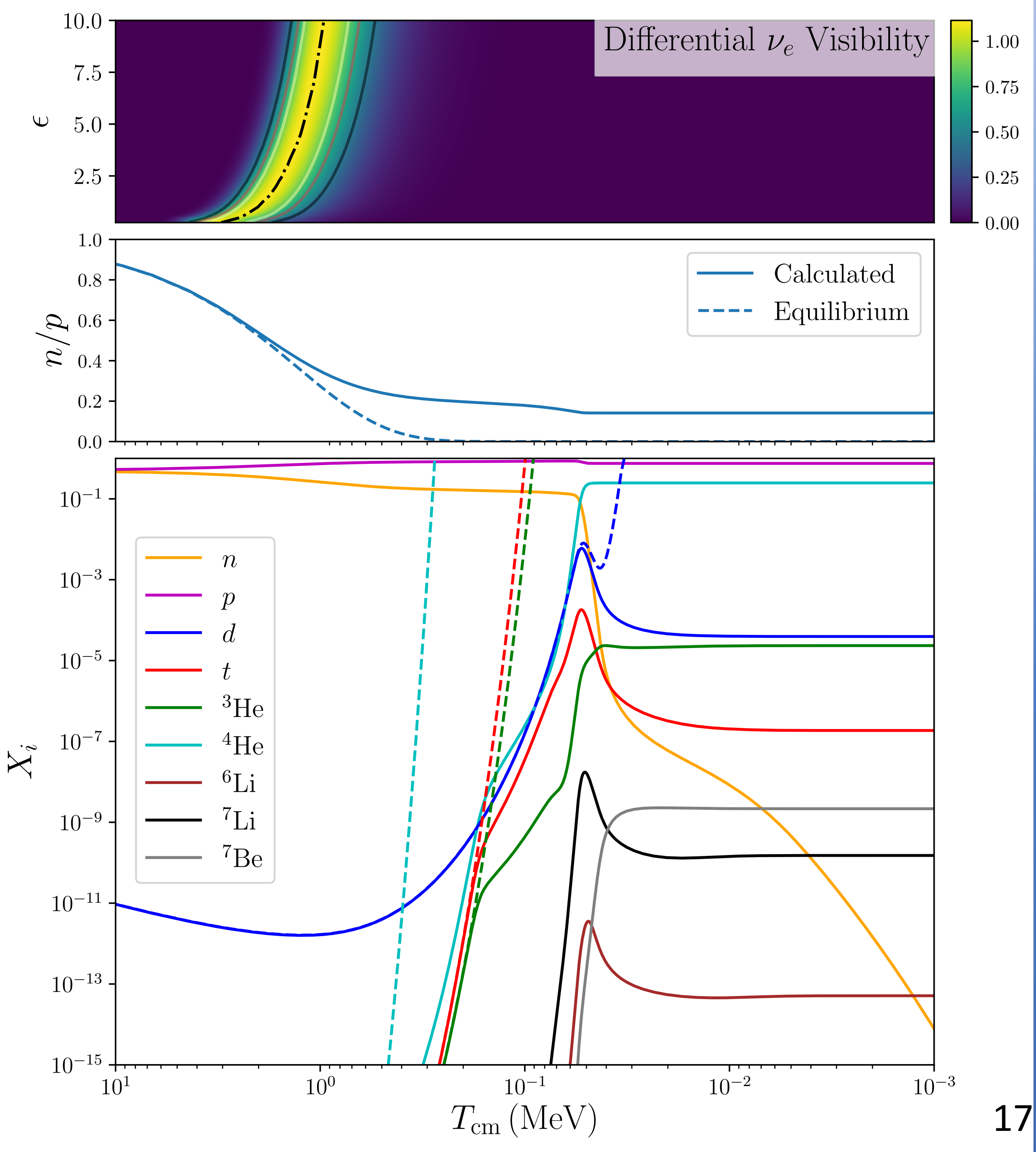
Coincident epochs during BBN:

Weak Decoupling (Diff. Vis.)

Weak Freeze-Out (n/p)

Nuclear Freeze-Out (X_i)

Dashed lines: weak equilibrium or NSE



Bond+ (In Prep.)

Summary

1. Solid evidence for the existence of neutrinos in hot big bang cosmology
   a. CMB and BAO show N_{eff} not equal to zero
   b. BBN shows neutrinos have ~thermal spectra

2. Future probes will show even more sensitivity to neutrino energy spectra

3. Generalized entropy formalism can capture out-of-equilibrium neutrino distributions

4. Abundance predictions require:
   a. Neutrino spectra
   b. Radiation energy density of the universe
   c. Phasing between time and photon temperature

Backup Slides

Helium vs. Neutron lifetime

UCNτ
Bottle expt.
(1707.01817)
$\tau_n = 877.7 \pm 1.1\,\mathrm{s}$

Tension ~4σ

NCNR
Beam expt.
(1309.2623)
$\tau_n = 887.7 \pm 3.1\,\mathrm{s}$