Constraints on the Injection of Radiation in the Early Universe

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radiation in the early Universe

- a variety of BSM particle physics processes can deposit radiation (relativistic particles) in the early Universe
  - decay of new particles
  - latent heat produced by a cosmological first-order phase transition
- can be either SM radiation (photons, e^+/e^-) or dark radiation
- both dark and visible radiation deposition impact CMB observables
  - # of effective neutrinos → N_{eff}
- cosmology observables can constrain BSM particle physics

particle physics

- my perspective is as a particle physicist
- there's a lot of freedom in particle physics model
  - how much dark radiation and SM radiation is released
- we'd like to know how to use that freedom to build models which have interesting signals, address anomalies, and aren't ruled out

- example → cosmological FOPTs can produce GW waves
  - nanohertz range signals would arise from FOPTs around or after BBN
  - sound wave amplitude controlled by latent heat released in transition
  - constraints on injected latent heat limit sensitivity of GW observatories
  - particle physics determines how much of latent heat is dark vs. SM radiation
- how does playing with that ratio affect bounds on the GW amplitude?

goals/outline

- we'd like to know how much radiation we can inject if we remain agnostic about the particle physics?

- we'll first describe general considerations

- then outline the numerical calculations

- and then finally, our results

ΔN_{eff}

- in SM/ΛCDM, $N_{eff} \sim 3.046$
- radiation deposition contributes to ΔN_{eff}
- if dark radiation injected, $\Delta N_{eff} > 0$
- if EM radiation injected, $\Delta N_{eff} < 0$
- if both are injected, can tune contributions so that $\Delta N_{eff} = 0$

$$N_{eff}^{CMB} \equiv \frac{8}{7}\left(\frac{11}{4}\right)^{4/3} \frac{\rho_{rad} - \rho_{\gamma}}{\rho_{\gamma}}$$

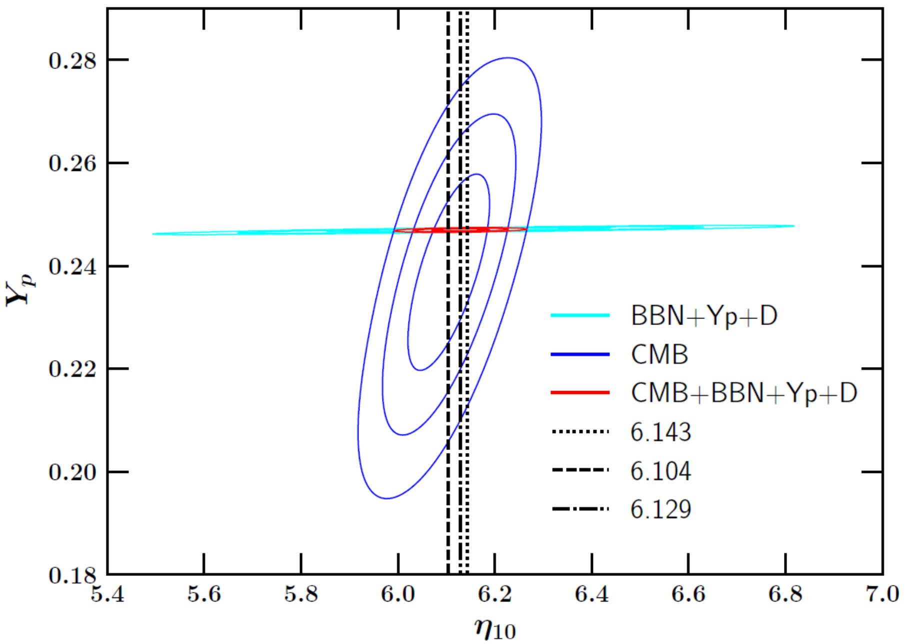
accounts for heating of photons by e^+e^- annihilation

$$N_{eff}^{CMB} = 2.92^{+0.36}_{-0.37}$$

Planck 2018 (1807.06209), 95%, TT,TE,EE+lowE

baryon dilution

- baryon-to-entropy density ratio is measured at BBN and at recomb.
- injecting EM radiation after BBN dilutes η_b / s
- even if we tune parameters to keep N_{eff} fixed …
- … expect a limit on entropy injection



Yeh, Olive, Fields 2011.13874

strategy

- define initial temperature/time at 8 MeV → pre-BBN
- define final temp./time at 10 keV → all radiation injection finished by then
  - EM radiation injection will not distort CMB
  - chosen for simplicity, or else there are more constraints

- $r_{SM} = a_f^4\, \rho_r^f \;/\; a_i^4\, \rho_{SM}^i$
  - = ratio of comoving final radiation density to initial SM radiation density
- in ΛCDM with no BSM physics, $r_{SM} \sim 1.205$, due to e^+/e^- annihilation

- we can measure how much extra radiation is injected by how much r_{SM} differs from 1.205

previous work

- idea was previously considered in Sobotka, Erickcek, Smith 2207.14308
- they considered particles which are non-relativistic at BBN, but decay to a mixture of EM radiation and dark radiation
- so energy density grows until particles decay
  - leads to tighter constraints
  - < 2.35% of total radiation density
- we'd like to weaken these assumptions, and see if it weakens the constraints

we consider two scenarios

- “decay” model
  - dark radiation present at BBN
- scalar Y relativistic at BBN
  - mass = m_Y
  - $\alpha = T_Y^i / T_\gamma^i$
- but decays when non-relativistic
  - lifetime = τ
- decays to photons and dark radiation
  - $BF_\gamma = f_\gamma$

- “PT” model
  - FOPT after BBN releases latent heat
- parameterize with r_γ, r_{ur}
  - ur = particles (except photons) which are relativistic even now
  - $r_\gamma = a_f^4 \rho_\gamma^f \; / \; a_i^4 \rho_\gamma^i$
  - $r_{ur} = a_f^4 \rho_{ur}^f \; / \; a_i^4 \rho_{ur}^i$
- T_{PT} = γ temperature of phase transition

cosmology parameters

- decay model
  - $\Delta N_{eff}^{BBN} = (4/7)\,\alpha^4$
  - T_γ^{decay} = photon temperature when age of universe = τ
  - $T_\gamma^{NR} = m_Y / \alpha$ = photon temperature when Y starts to redshift as matter
  - if $T_\gamma^{NR} / T_\gamma^{decay} \sim 1$, then Y spends little time redshifting as matter

- in PT model, $\Delta N_{eff,PT}^{BBN} = 0$

- we want to see how large r_{SM} can be
- we will compare to a ΛCDM + ΔN_{eff}, to see how much particle physics freedom buys us
  - ΔN_{eff} model is a subset of decay model, with $T_\gamma^{NR} / T_\gamma^{decay} \sim 1$, $f_\gamma = 0$

numerical analysis

- BBN code LINX
- CMB code CLASS takes Y_p from LINX as input
  - dilution of baryon-to-entropy density ratio accounted for
- take one massive neutrino with m_ν = 60 meV (other two are ultra-relativistic)
- base ΛCDM parameters: ω_b, ω_c, $100\ \theta_s$, A_s, η_s, τ_{reio}

CMB data

- use temperature and polarization anisotropy data from Planck 2018
- high multipole ($30 < \ell < 2508$) TT, TE, EE → Plik likelihood
- at low multipole ($2 < \ell < 30$) → SimAll (EE) and Commander (TT)
- use standard Planck collaboration priors on nuisance parameters

BBN data

- use two observables
  - ^{4}He fraction (Y_p)
  - deuterium-to-hydrogen ratio (D/H)

- calculated by `LINX`, using `PRIMAT` nuclear reaction network (Pitrou, Coc, Uzan, Vangioni 1801.08023)

- $Y_p^{obs} = 0.2449 \pm 0.0040$ (Aver, Olive, Skillman 1503.08146)

- $(D/H)^{obs} = (2.527 \pm 0.030) \times 10^{-5}$ (Cooke, Pettini, Steidel 1710.11129)

prior

- $T_\gamma^{NR} / T_\gamma^{decay} \geq 1$
  - Y decays while non-rel., but may redshift like matter only briefly
- $T_\gamma^{decay} \geq 10$ keV
  - CMB modes for $\ell < 2500$ enter horizon after decay
  - can use standard adiabatic initial conditions for CLASS
  - no CMB distortion
- for PT model, $\Delta N_{eff}^{BBN} = 0$
  - $T_{PT} \in [10,100]$ keV
  - $r_\gamma \in [(11/4)^{4/3}, 19]$
  - $r_{ur} \in [1,5]$

decay model priors

$$
\begin{aligned}
\omega_b &\in [0.005, 0.1], \\
\omega_c &\in [0.001, 0.99], \\
100\theta_s &\in [0.5, 10.0], \\
\ln(10^{10} A_s) &\in [1.61, 3.91], \\
n_s &\in [0.8, 1.2], \\
\tau_{\rm reio} &\in [0.01, 0.8], \\
\Delta N_{\rm eff}^{\rm BBN} &\in [0, 2.0], \\
T_\gamma^{\rm NR}\ [{\rm MeV}] &\in [0.1, 1], \\
T_\gamma^{\rm NR}/T_\gamma^{\rm decay} &\in [1.0, 10.0], \\
f_\gamma &\in [0.0, 1.0].
\end{aligned}
$$

results

- in ΔN_{eff} model, r_{SM} can differ from ΛCDM value (1.205) by 0.036
- for decay model, almost the same
  - almost no extra freedom to inject more energy
- for PT model, r_{SM} can exceed ΛCDM value by 0.047
- about 30% larger comoving energy density can be injected
  - post-BBN

Parameter	$\Delta N_{\rm eff}$	Decay model	PT model
$10^9 A_s$	$2.0971^{+0.0347}_{-0.0327}$	$2.0983^{+0.0289}_{-0.0293}$	$2.0958^{+0.03353}_{-0.03236}$
n_s	$0.9629^{+0.00631}_{-0.00694}$	$0.9630^{+0.00482}_{-0.00431}$	$0.9621^{+0.00480}_{-0.004599}$
h	$0.6711^{+0.01064}_{-0.01145}$	$0.6718^{+0.00699}_{-0.00590}$	$0.6706^{+0.00742}_{-0.00665}$
$100\omega_b$	$2.2230^{+0.01842}_{-0.01836}$	$2.2223^{+0.01288}_{-0.01281}$	$2.2176^{+0.01291}_{-0.01205}$
ω_c	$0.1214^{+0.00199}_{-0.00203}$	$0.12150^{+0.00165}_{-0.00138}$	$0.12211^{+0.00189}_{-0.00155}$
$100\tau_{\rm reio}$	$5.2229^{+0.72440}_{-0.66695}$	$5.2511^{+0.6546}_{-0.6405}$	$5.1249^{+0.74766}_{-0.68615}$
$\Delta N_{\rm eff}^{\rm BBN}$	$0.0305^{+0.120}_{-0.122}$, $< 0.234\,(95\%)$	$< 0.133\,(95\%)$	—
$N_{\rm ur}^{\rm CMB}$	$2.0632^{+0.1259}_{-0.1279}$	$2.0850^{+0.1949}_{-0.0539}$	$2.0921^{+0.0942}_{-0.0894}$
$N_{\rm eff}^{\rm CMB}$	$3.0764^{+0.1260}_{-0.1279}$	$3.0897^{+0.1801}_{-0.0488}$	$3.0975^{+0.0947}_{-0.1021}$
$T_\gamma^{\rm NR}$ [MeV]	—	$0.594^{+0.264}_{-0.289}$	—
$T_\gamma^{\rm NR}/T_\gamma^{\rm decay}$	—	$< 8.732\,(95\%)$	—
f_γ	—	$< 0.73\,(95\%)$	—
r_γ	—	$< 3.872\,(95\%)$	$< 3.934\,(95\%)$
$r_{\rm ur}$	—	$< 1.051\,(95\%)$	$< 1.123\,(95\%)$
r	$< 1.207\,(95\%)$	$< 1.219\,(95\%)$	$< 1.252\,(95\%)$
$r_{\rm SM}$	$< 1.241\,(95\%)$	$< 1.242\,(95\%)$	$< 1.252\,(95\%)$

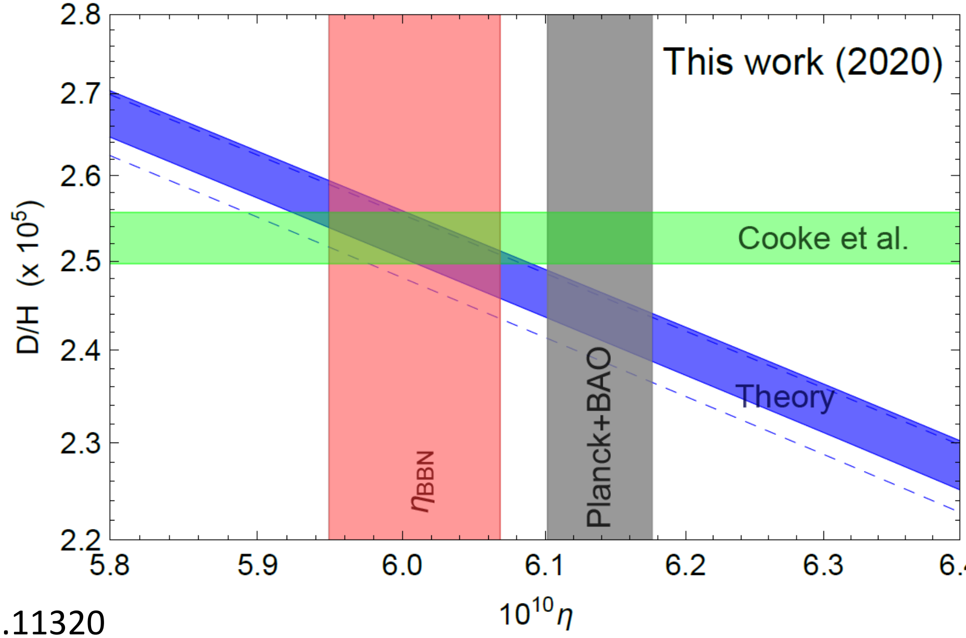
upshot

- for scalar decay model, particle physics freedom adds almost no extra room for radiation injection
- even if you tune particle physics to keep ΔN_{eff}^{CMB} fixed, dilution of baryon-to-entropy ratio yields tight constraints
- more freedom if energy is injected by a FOPT after BBN
  - $\sim$ 30% more radiation can be injected
- tight constraints arise because EM and dark radiation are tightly constrained at BBN and recombination
  - dark matter is less constrained at BBN
  - if injected dark radiation redshifts as matter at recombination (LiMRs), get more freedom (Kumar, Sandick, Xu 2512.14672; DePorzio, Imig, Shelton 2607.12021)

η_b/s at BBN vs. CMB

- there is mild tension between observed (D/H) and PRIMAT
  - at preferred ω_b, $(D/H)^{PRIMAT}$ is $\sim 1.8\sigma$ smaller than $(D/H)^{obs}$
- leads to a preference for $(\eta_b/s)^{BBN}$ which is smaller than $(\eta_b/s)^{recomb}$
- so diluting η_b/s after BBN worsens the tension
- how would these results be affected by a different reaction network?

- $(D/H)^{obs} = (2.527 \pm 0.030) \times 10^{-5}$ (Cooke, Pettini, Steidel 1710.11129)
- $(D/H)^{PRIMAT} = (2.439 \pm 0.037) \times 10^{-5}$
- $(D/H)^{YOF} = (2.51 \pm 0.11) \times 10^{-5}$ (Yeh, Olive, Fields 2011.13874)



Pitrou, Coc, Uzan, Vangioni 2011.11320

conclusion

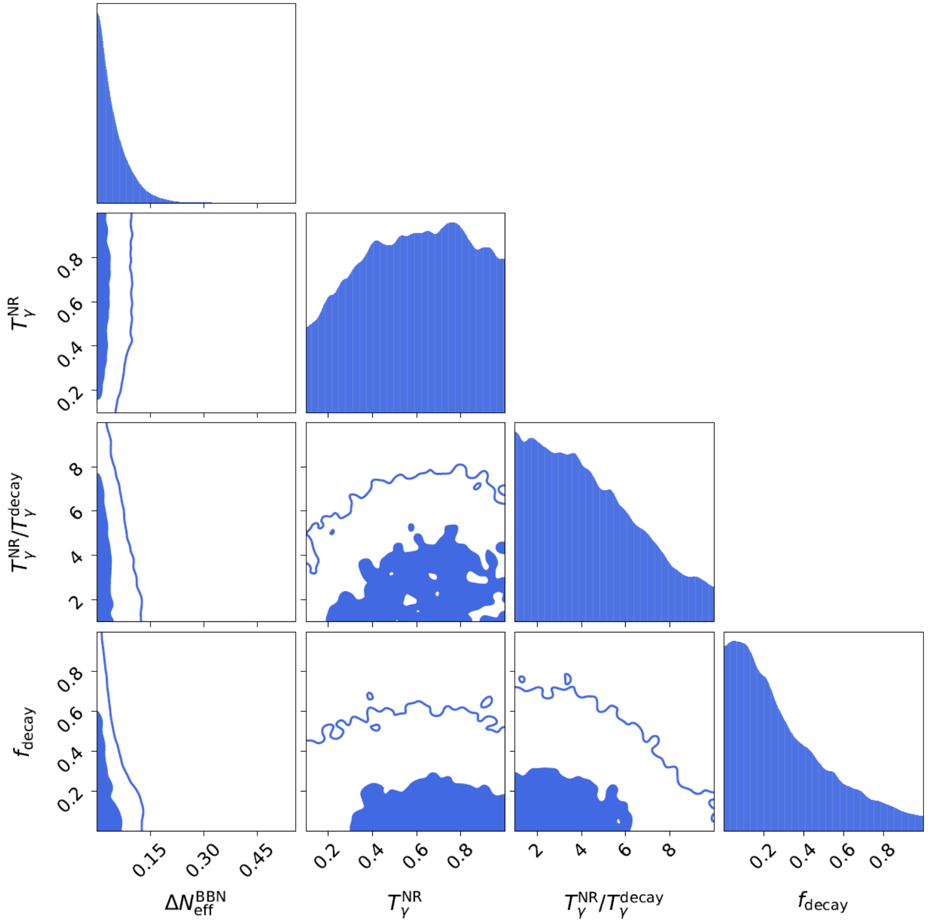
- we consider constraints on the deposition of radiation in the early Universe if we are agnostic about its composition
  - consider scalar decay, and FOPTs
- tight constraints, but for an FOPT, about 30% extra freedom to inject energy

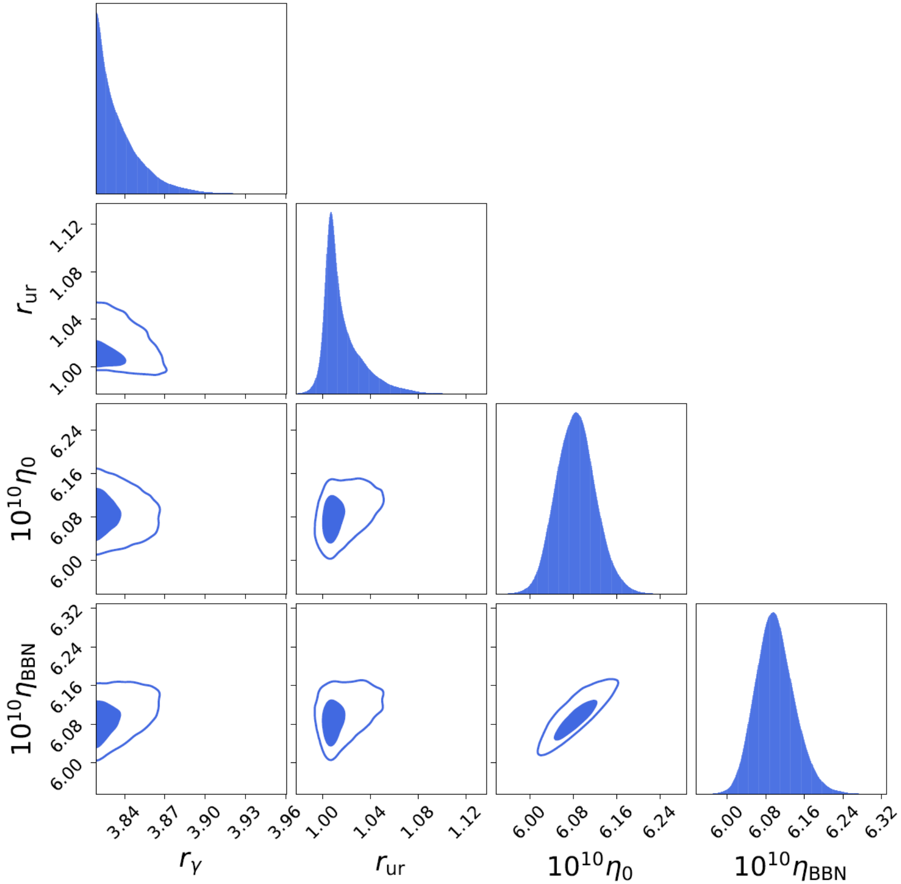
- better understanding of nuclear reaction rates underlying BBN may have impact on these constraints

Mahalo!

Backup Slides

posteriors – decay model





posteriors – PT model