Dark Radiation from Particle Decay

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Based on Jasper Hasenkamp, JK, JCAP **08** (2013), 024 [`arXiv:1212.4160`]

Outline

1. Introduction
2. Dark Radiation from Late Decays
3. Constraints for Model Building

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Dark Radiation

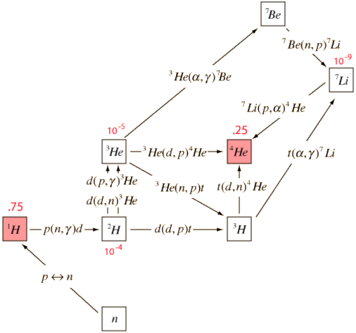
- Radiation $=$ relativistic particles
- Dark radiation: relativistic particles $\neq \gamma, \nu^{\mathrm{SM}}$
- Energy density (after e^+e^- annihilation at $T \sim 0.5\,\mathrm{MeV}$)

$$\rho_{\mathrm{rad}} \equiv \left[1 + N_{\mathrm{eff}}\,\frac{7}{8}\left(\frac{T_\nu}{T}\right)^4\right]\rho_\gamma$$

- $T \equiv T_\gamma$
- $\rho_\gamma = \frac{\pi^2}{15}T^4$
- N_{eff}: effective number of neutrino species
- Standard Model: $N_{\mathrm{eff}} = 3.046$
- Existence of dark radiation $\Leftrightarrow$ $\Delta N_{\mathrm{eff}} \equiv N_{\mathrm{eff}} - 3.046 > 0$

$$\rho_{\mathrm{DR}} = 0.13\,\Delta N_{\mathrm{eff}}\,\rho_{\mathrm{rad}}^{\mathrm{SM}}$$

Observable Effects



Big Bang Nucleosynthesis (BBN)

- $\rho_{\text{rad}} \uparrow \rightsquigarrow$ faster expansion
  $\rightsquigarrow$ more n available for D fusion
  $\rightsquigarrow$ more ^{4}He
- $N_{\text{eff}} = 3.8^{+0.8}_{-0.7}$ at 95% CL

  Izotov, Thuan, arXiv:1001.4440
- $\Delta N_{\text{eff}} \leq 1$ at 95% CL

  Mangano, Serpico, arXiv:1103.1261

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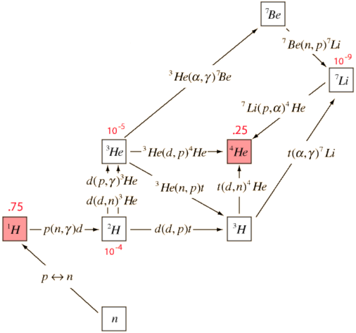
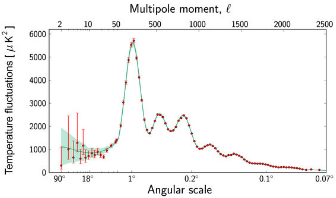
Cosmic Microwave Background (CMB)

- Increased Silk damping
  $\rightsquigarrow$ reduced power on small scales
  Hou et al., arXiv:1104.2333





Results from the CMB

$\Delta N_{\mathrm{eff}} = 1.51 \pm 0.75$ at 68% CL ACT, arXiv:1009.0866

$\Delta N_{\mathrm{eff}} = 0.81 \pm 0.42$ at 68% CL SPT, arXiv:1105.3182

$\Delta N_{\mathrm{eff}} = 0.31^{+0.68}_{-0.64}$ at 95% CL Planck, arXiv:1303.5076

$\Delta N_{\mathrm{eff}} = 0.47^{+0.48}_{-0.45}$ at 95% CL using H_0 from HST Planck, arXiv:1303.5076

$\Delta N_{\mathrm{eff}} < 0.71$ at 95% CL Hojjati et al., arXiv:1304.3724

$\Delta N_{\mathrm{eff}} = 0.61 \pm 0.30$ at 68% CL Hamann, Hasenkamp, arXiv:1308.3255

1. Introduction

2. **Dark Radiation from Late Decays**

3. Constraints for Model Building

New Physics in the Later Early Universe

- Late decays: after BBN, before recombination $\rightsquigarrow$ affect only CMB
- Mother $\rightarrow$ 2 light, weakly interacting daughters
- Masses m, $m_1 < m_2$

$$\delta \equiv \frac{m - m_2}{m_2}$$

- Daughters form dark radiation while relativistic
- Heavier daughter could form dark matter

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- Examples:
  - Gravitino $\to$ axion $+$ axino ($\Gamma \sim m_{3/2}^3 / M_{\rm Pl}^2$)
  - Sneutrino $\to$ gravitino $+$ neutrino
  - Modulino $\to$ sneutrino $+$ neutrino, axion $+$ axino, …

Connecting ΔN_{eff} and Particle Physics

ΔN_{eff} measured $\rightsquigarrow$ know

$$\rho_{\text{DR}} = 0.13\,\Delta N_{\text{eff}}\,\rho_{\text{rad}}^{\text{SM}}$$

Goal: Constrain model parameters

- Ω: Energy density of the mother
- Lifetime τ (equivalently, temperature at decay T_{d})
- δ: Mass hierarchy between mother and heavier daughter

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Two-body decay kinematics for $m_1 \ll m_2$:

$$\rho_{\text{DR}}(T_{\text{d}}) = \frac{N_{\text{DR}}}{2}\,\frac{(\delta+1)^2-1}{(\delta+1)^2}\,\rho(T_{\text{d}}) \;\rightsquigarrow\; \Omega = \Omega(\Delta N_{\text{eff}}, \tau, \delta)$$

$N_{\text{DR}} = 1, 2$: number of relativistic dark particles during CMB times

$\rightsquigarrow$ Free parameters in the following: τ, δ

Constraints from Dark Matter Density

Today's density of heavier daughter $\Omega_2 \leq \Omega_{\mathrm{DM}} \rightsquigarrow$ lower limits

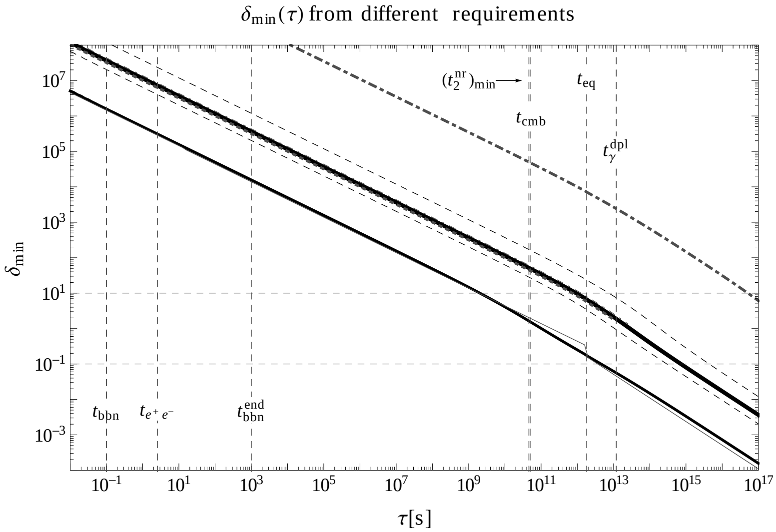
- Decay before matter-radiation equality at t_{eq}:

$$\delta \gtrsim 0.3\,\Delta N_{\mathrm{eff}} \left(\frac{t_{\mathrm{eq}}}{\tau}\right)^{\frac{1}{2}}$$

- Decay after matter-radiation equality (now also $\Omega < \Omega_{\mathrm{DM}}$):

$$\delta \gtrsim 0.15\,\Delta N_{\mathrm{eff}} \left(\frac{t_{\mathrm{eq}}}{\tau}\right)^{\frac{2}{3}}$$

Constraints from Dark Matter Density



Free Streaming of Heavier Daughter

Heavier daughter emitted with finite velocity
$\rightsquigarrow$ washes out structure on scales smaller than free-streaming scale

$$\lambda_2^{\mathrm{fs}} = \int_{\tau}^{t_0} \frac{v_2}{a} dt$$

Limit from Lyman-α forest:

$$\lambda_2^{\mathrm{fs}} \lesssim 1\ \mathrm{Mpc}$$

Abazajian, arXiv:astro-ph/0512631;
Viel et al., arXiv:0709.0131;
Boyarsky et al., arXiv:0812.0010

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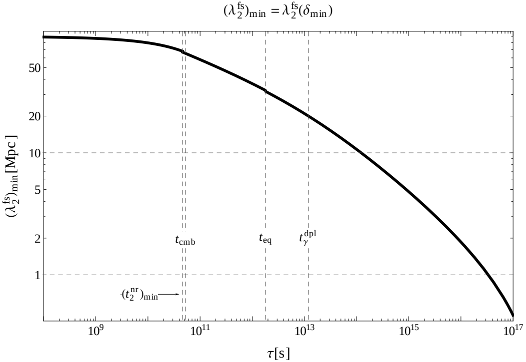


$\rightsquigarrow$ Heavier daughter too hot to form dark matter (or $\Delta N_{\text{eff}} \ll 1$)

Hot Dark Matter Constraint

Maximum amount of hot dark matter $\Omega_2 \lesssim 0.04\,\Omega_{\mathrm{DM}}$
(corresponding to $\sum m_\nu < 0.44$ eV Hamann et al., arXiv:1003.3999)
$\rightsquigarrow$ lower limits on δ rise by factor 25

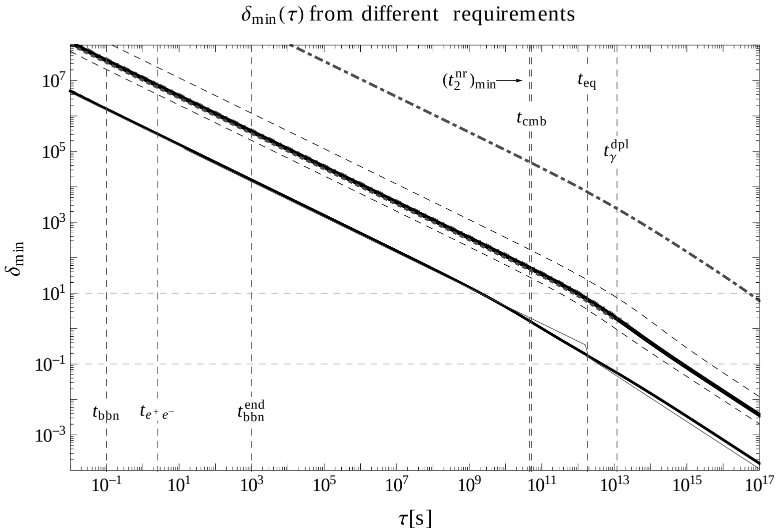
- Decay before matter-radiation equality at t_{eq}:

$$\delta \gtrsim 7\,\Delta N_{\mathrm{eff}} \left(\frac{t_{\mathrm{eq}}}{\tau}\right)^{\frac{1}{2}}$$

- Decay after matter-radiation equality:

$$\delta \gtrsim 3.5\,\Delta N_{\mathrm{eff}} \left(\frac{t_{\mathrm{eq}}}{\tau}\right)^{\frac{2}{3}}$$

Hot Dark Matter Constraint



Hot Dark Matter Opportunities

1. Imagine conflict between future measurements:
   - Cosmology $\rightsquigarrow$ $(\sum m_\nu)_{\text{cosmo}} > 0$ observed
   - Laboratory $\rightsquigarrow$ upper limit $< (\sum m_\nu)_{\text{cosmo}}$

   $\rightsquigarrow$ Indication for hot dark matter $\neq \nu$ from decay
2. Heavier daughter may become non-relativistic during CMB times
   $\rightsquigarrow$ observable consequences for CMB likely

Two Decay Modes

1. Mother $\to \phi + \phi$, branching ratio B_1
2. Mother $\to \psi + \psi$, branching ratio B_2

- Daughter masses $m_1 < m_2$
- $x_2 \equiv \dfrac{m_2}{m}$
- Lighter daughter forms dark radiation

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- Examples:
  - Saxion → axion + axion, axino + axino
  - Modulus → gravitino + gravitino, axion + axion

Adjustable Free Streaming

B_2 allows to adjust Ω_2 $\rightsquigarrow$ no dark matter density constraint on x_2

$\rightsquigarrow$ λ_2^{fs} arbitrary

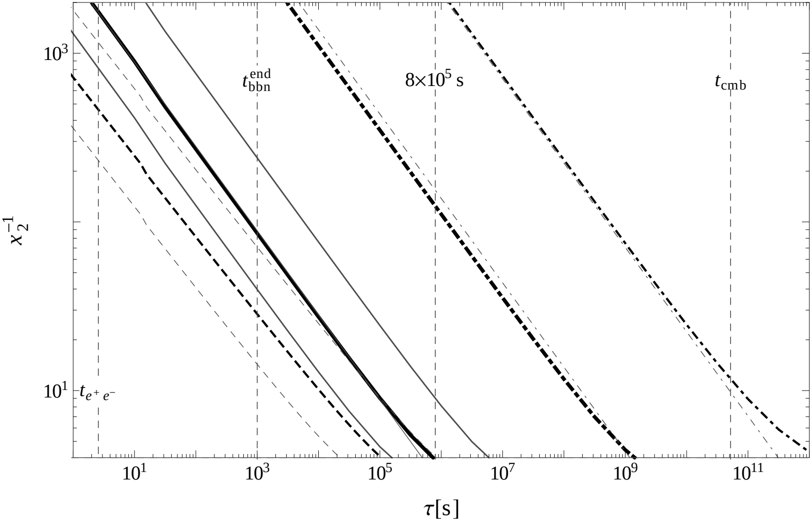
$$x_2 \simeq 0.1 \left(\frac{0.4\,\mathrm{Mpc}}{\lambda_2^{\mathrm{fs}}} \right)^{1.2} \left(\frac{\tau}{10^5\,\mathrm{s}} \right)^{0.5}$$

$$B_2 \simeq 5.6 \cdot 10^{-3} \left(\frac{\lambda_2^{\mathrm{fs}}}{0.4\,\mathrm{Mpc}} \right) \Delta N_{\mathrm{eff}}^{-1} \left(\frac{\Omega_{\mathrm{DM}} h^2}{0.1286} \right)$$

$\rightsquigarrow$ Heavier daughter may form dark matter

$\rightsquigarrow$ Can be cold or warm

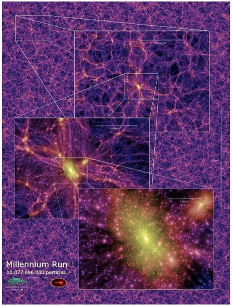
Adjustable Free Streaming



Solution of the Missing Satellites Problem

- Simulations of structure formation
  ⇝ more galactic satellites than observed
- Problem may well be solved by astrophysics
- … or by warm dark matter with
  $0.2\,\text{Mpc} \lesssim \lambda^{\text{fs}} \lesssim 1\,\text{Mpc}$
  Colín et al., arXiv:astro-ph/0004115;
  Lin et al., arXiv:astro-ph/0009003

  ⇝ possible in two-decay-mode scenario



Constraints on Decays into Standard Model Particles

$\text{Br}(\text{Mother} \to \text{SM} + \text{SM}) \neq 0$

- $\rightsquigarrow$ Change of primordial abundances from BBN

  Jedamzik, arXiv:hep-ph/0604251
- $\rightsquigarrow$ Spectral distortions of the CMB

  Hu, Silk, PRL 70 (1993); Chluba, Sunyaev, arXiv:1109.6552
- $\rightsquigarrow$ Change of ionization history

  Slatyer, arXiv:1211.0283

$\rightsquigarrow$ strict upper limits on branching ratio

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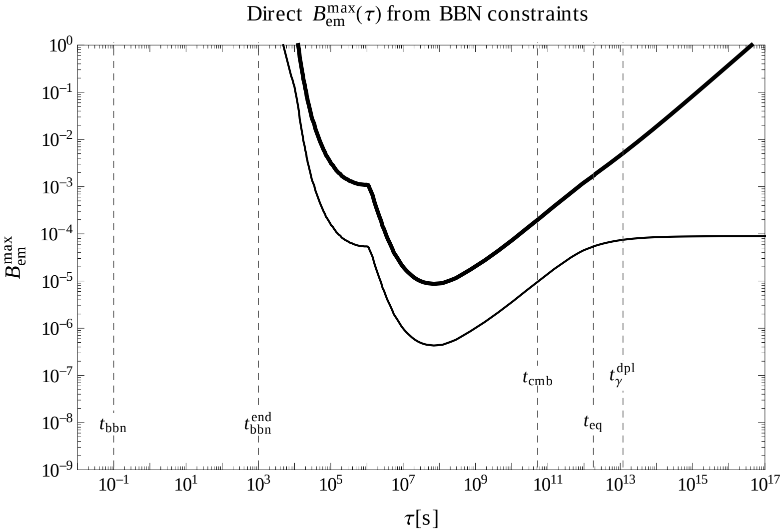

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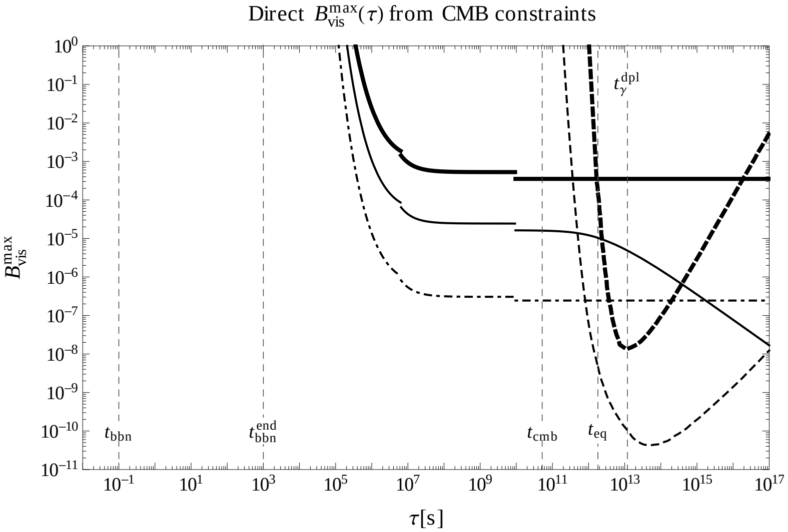

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. . . even if only suppressed decay possible (loop, 3- or 4-body decay)

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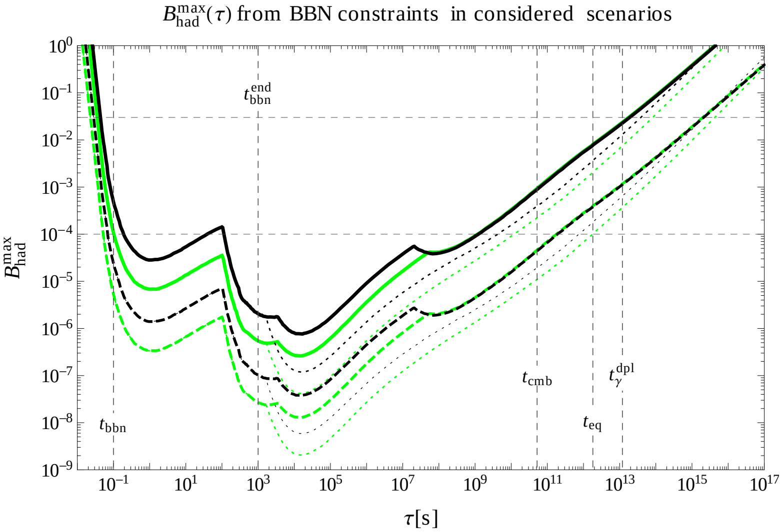

Conclusions

- Dark universe may contain dark radiation
- Production in late decays $\rightsquigarrow$ different impact on BBN and CMB
- Energy density of mother determined by $\Delta N_{\mathrm{eff}}, \tau, \delta$
- Single dark decay mode: heavier daughter too hot for dark matter
- Two dark decay modes: heavier daughter may form dark matter and solve missing satellites problem
- Severe constraints on branching ratio into Standard Model particles $\rightsquigarrow$ input for construction of concrete models

Effects on the Cosmic Microwave Background (CMB)

- $\rho_\mathrm{rad} \uparrow \rightsquigarrow$ later matter-radiation equality
- $1^\mathrm{st}/3^\mathrm{rd}$ peak ratio $\rightsquigarrow$ no change $\rightsquigarrow \rho_\mathrm{m} \uparrow \rightsquigarrow t_\mathrm{eq}$ unchanged
- $\rho_\mathrm{rad} \uparrow \rightsquigarrow$ sound horizon $r_s \propto 1/H \downarrow$
- Peak positions $\rightsquigarrow$ no change of angular size $\theta_s = \frac{r_s}{D_A} \rightsquigarrow D_A \propto 1/H \downarrow$ (by $\rho_\Lambda \uparrow$)
- Remaining effect: increased Silk damping $\rightsquigarrow$ reduced power on small scales

Hou et al., arXiv:1104.2333