Dark Radiation

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Outline

1. Effects of Dark Radiation
   - Definitions
   - Big Bang Nucleosynthesis
   - Cosmic Microwave Background
   - Impact on Hubble tension
2. Model Building Aspects
   - Dark Matter Interacting with Itself and Dark Radiation
   - Dark Radiation from Decays
3. Possible Future Directions

Lecture notes: https://ihepco.yonsei.ac.kr/event/192/

Dark Radiation

- Radiation in cosmological context $=$ relativistic particles ($p = \rho/3$)
- Expansion $\rightsquigarrow$ redshift $\rightsquigarrow$ radiation can become (non-relativistic) matter ($p = 0$) eventually $\rightsquigarrow$ equivalent to hot dark matter
- BBN, CMB: $T \sim$ 0.1 MeV..0.1 eV $\rightsquigarrow$ radiation in SM: γ, ν
- Dark: not in SM
  $\rightsquigarrow$ Dark Radiation (DR): relativistic particles $\neq \gamma$, SM ν
- Examples
  - (Light) sterile neutrino (fermion)
  - Dark photon (vector)

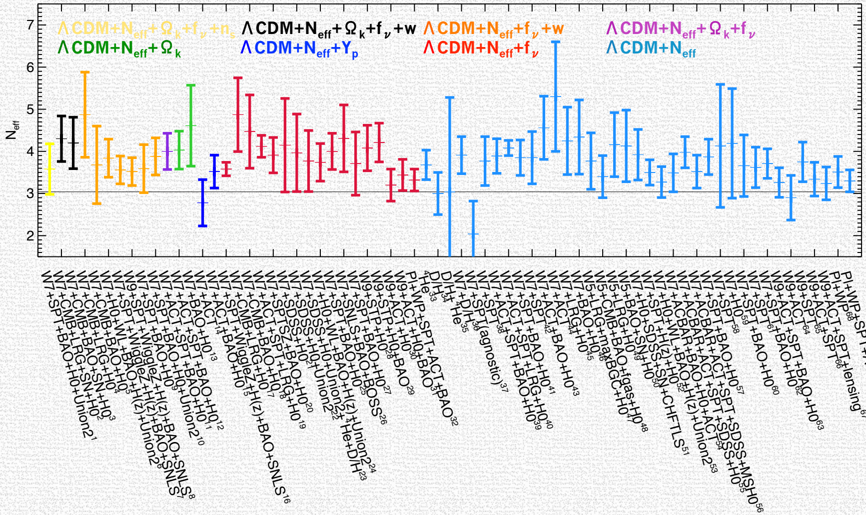
Dark Radiation Density

- Parameterized via radiation energy density

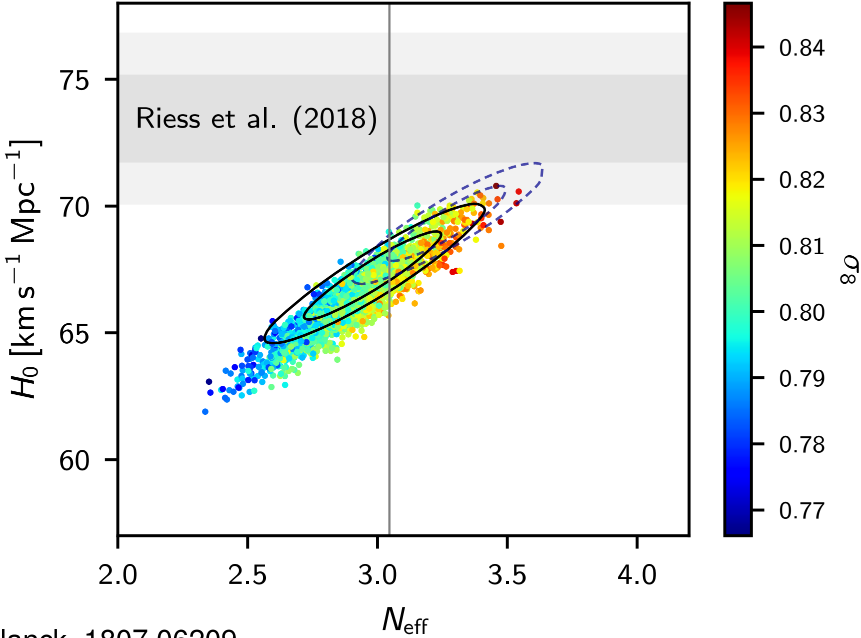
$$\rho_{\text{rad}} = \rho_\gamma + \rho_\nu + \rho_{\text{DR}} \equiv \left[1 + N_{\text{eff}} \frac{7}{8} \left(\frac{T_\nu}{T}\right)^4\right] \rho_\gamma$$

- $T \equiv T_\gamma$
- N_{eff}: effective number of neutrino species
- Standard Model: $N_{\text{eff}}^{\text{SM}} = 3.0440 \pm 0.0002$
  Bennett et al., JCAP **04** (2021)
- Existence of dark radiation $\Leftrightarrow \Delta N_{\text{eff}} \equiv N_{\text{eff}} - N_{\text{eff}}^{\text{SM}} > 0$

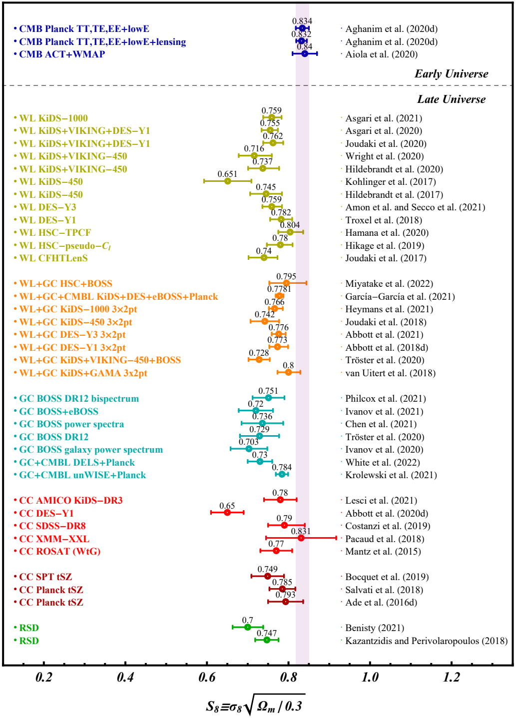
Measurements



Modified from Riemer-Sørensen et al. (2013 review) arXiv:1301.7102



Planck, 1807.06209


• CMB Planck TT,TE,EE+lowE 0.834 Aghanim et al. (2020d)
• CMB Planck TT,TE,EE+lowE+lensing 0.832 Aghanim et al. (2020d)
• CMB ACT+WMAP 0.84 Aiola et al. (2020)
Early Universe
Late Universe
• WL KiDS−1000 0.759 Asgari et al. (2021)
• WL KiDS+VIKING+DES−Y1 0.755 Asgari et al. (2020)
• WL KiDS+VIKING+DES−Y1 0.762 Joudaki et al. (2020)
• WL KiDS+VIKING−450 0.716 Wright et al. (2020)
• WL KiDS+VIKING−450 0.737 Hildebrandt et al. (2020)
• WL KiDS−450 0.651 Kohlinger et al. (2017)
• WL KiDS−450 0.745 Hildebrandt et al. (2017)
• WL DES−Y3 0.759 Amon et al. and Secco et al. (2021)
• WL DES−Y1 0.782 Troxel et al. (2018)
• WL HSC−TPCF 0.804 Hamana et al. (2020)
• WL HSC−pseudo−C_l 0.78 Hikage et al. (2019)
• WL CFHTLenS 0.74 Joudaki et al. (2017)
• WL+GC HSC+BOSS 0.795 Miyatake et al. (2022)
• WL+GC+CMBL KiDS+DES+eBOSS+Planck 0.7781 García−García et al. (2021)
• WL+GC KiDS−1000 3×2pt 0.766 Heymans et al. (2021)
• WL+GC KiDS−450 3×2pt 0.742 Joudaki et al. (2018)
• WL+GC DES−Y3 3×2pt 0.776 Abbott et al. (2021)
• WL+GC DES−Y1 3×2pt 0.773 Abbott et al. (2018d)
• WL+GC KiDS+VIKING−450+BOSS 0.728 Tröster et al. (2020)
• WL+GC KiDS+GAMA 3x2pt 0.8 van Uitert et al. (2018)
• GC BOSS DR12 bispectrum 0.751 Philcox et al. (2021)
• GC BOSS+eBOSS 0.72 Ivanov et al. (2021)
• GC BOSS power spectra 0.736 Chen et al. (2021)
• GC BOSS DR12 0.729 Tröster et al. (2020)
• GC BOSS galaxy power spectrum 0.703 Ivanov et al. (2020)
• GC+CMBL DELS+Planck 0.73 White et al. (2022)
• GC+CMBL unWISE+Planck 0.784 Krolewski et al. (2021)
• CC AMICO KiDS−DR3 0.78 Lesci et al. (2021)
• CC DES−Y1 0.65 Abbott et al. (2020d)
• CC SDSS−DR8 0.79 Costanzi et al. (2019)
• CC XMM−XXL 0.831 Pacaud et al. (2018)
• CC ROSAT (WtG) 0.77 Mantz et al. (2015)
• CC SPT tSZ 0.749 Bocquet et al. (2019)
• CC Planck tSZ 0.785 Salvati et al. (2018)
• CC Planck tSZ 0.793 Ade et al. (2016d)
• RSD 0.7 Benisty (2021)
• RSD 0.747 Kazantzidis and Perivolaropoulos (2018)
0.2 0.4 0.6 0.8 1.0 1.2
$S_8 \equiv \sigma_8 \sqrt{\Omega_m / 0.3}$

2203.06142

Motivations for Dark Radiation

- Tensions in ΛCDM (H_0, S_8, small scale structure, ...)
- Neutrino oscillation anomalies $\rightsquigarrow$ light sterile neutrinos?
- Dark sectors for physics BSM, lack of evidence for new EW-scale particles $\rightsquigarrow$ light new states?

Suppressing Dwarfs by Late Kinetic Decoupling

- Dark Matter χ, $m_\chi \sim$ TeV or GeV
- Dark Radiation N, $m_N \lesssim$ eV
- Dark photon V couples to both, $m_V \sim$ MeV

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- Dark Matter χ, $m_\chi \sim$ TeV or GeV
- Dark Radiation N, $m_N \lesssim$ eV
- Dark photon V couples to both, $m_V \sim$ MeV
- Dark Matter self-interactions $\rightsquigarrow$ most small-scale problems solved
- Dark Radiation free-streaming $\rightsquigarrow$ σ_8 lowered
- Efficient Dark Matter – Dark Radiation scattering

$\rightsquigarrow$ Late kinetic decoupling

$\rightsquigarrow$ Structure formation suppressed at small scales

$\rightsquigarrow$ Missing satellite problem solved for $T_{kd} \lesssim 1$ keV ($M_{cut} \simeq 10^{10}\, M_\odot$)

Bringmann, Hasenkamp, JK, JCAP **07** (2014)
Dasgupta, Kopp, PRL **112** (2014)

Big Bang Nucleosynthesis

- Dark sector thermalized for $T > T_X^{\text{dec}}$ via Higgs portal
- SM particles becoming non-relativistic afterwards heat SM bath, not $U(1)_X$ bath $\rightsquigarrow$ $T_X < T_\nu$ (depending on number of d.o.f. g_*)
- Entropy conservation

$$\Delta N_{\text{eff}}(T) = \left(\frac{T_X}{T_\nu}\right)^4 = \left[\frac{g_*^\nu(T)}{g_*^X(T)}\,\frac{g_*^X(T_X^{\text{dec}})}{g_*^\nu(T_X^{\text{dec}})}\right]^{\frac{4}{3}}$$

- Smallest value (obtained for $T_X^{\text{dec}} \gg m_t$): $\Delta N_{\text{eff}}(T_{\text{BBN}}) \simeq 0.33$

Variations

- Lighter dark photon or dark Higgs $\rightsquigarrow$ relativistic during BBN $\rightsquigarrow g_*^x(T_{\text{BBN}}) \uparrow \rightsquigarrow \Delta N_{\text{eff}} \downarrow$
- Additional light dark particles
  $\rightsquigarrow g_*^x(T_{\text{BBN}}) \uparrow$ and $g_*^x(T_x^{\text{dec}}) \uparrow$ but $\frac{g_*^x(T_x^{\text{dec}})}{g_*^x(T_{\text{BBN}})} \downarrow \rightsquigarrow \Delta N_{\text{eff}} \downarrow$
  Ko, Tang, PLB **739** (2014)
- Non-trivial interplay between decrease of T_x and increase of number of DR species
- Related models (different particle spins, more sterile neutrinos, . . .)
  Archidiacono et al., PRD **91** (2015)
  Chu, Dasgupta, PRL **113** (2014)
  Cherry, Friedland, Shoemaker, `arXiv:1411.1071`
  Kouvaris, Shoemaker, Tuominen, PRD **91** (2015)
  Binder et al., JCAP **11** (2016)
  Tang, PLB **757** (2016)
- Classification of minimal possibilities
  Bringmann, Ihle, JK, Walia, PRD **94** (2016)

Sterile Neutrino Production by Oscillations

- Standard scenario: mixing between active and sterile neutrinos $\rightsquigarrow$ oscillations $\rightsquigarrow$ $\Delta N_{\text{eff}} \simeq 1$ $\rightsquigarrow$ ruled out by Planck and BBN
- $U(1)_X$ interactions $\rightsquigarrow$ effective matter potential suppresses mixing $\rightsquigarrow$ no production by oscillations for $T \gtrsim$ MeV

  Hannestad, Hansen, Tram, PRL **112** (2014)
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  Dasgupta, Kopp, PRL **112** (2014)
- $T <$ MeV: mixing unsuppressed
  - $\rightsquigarrow$ sterile neutrinos from oscillations $+$ $U(1)_X$-mediated scatterings
    Bringmann, Hasenkamp, JK, JCAP **07** (2014)
    Mirizzi et al., PRD **91** (2015)
    Tang, PLB **750** (2015)
    Chu, Dasgupta, Kopp, JCAP **10** (2015)
    Cherry, Friedland, Shoemaker, `arXiv:1605.06506`
    Forastieri et al., JCAP **07** (2017)
    Chu et al., JCAP **11** (2018)

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  - $\rightsquigarrow$ $\sum m_\nu$ bound violated or too little free-streaming
  - $\rightsquigarrow$ Ruled out for $m_N \sim$ eV and $\mathcal{O}(0.1)$ mixing

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  - $\rightsquigarrow$ $\Delta N_{\text{eff}}(T_{\text{CMB}}) < 0$ possible for non-relativistic sterile neutrino

    Mirizzi et al., PRD **91** (2015)
    Tang, PLB **750** (2015)
    Chu, Dasgupta, Kopp, JCAP **10** (2015)

Suppressing σ_8 by Late Kinetic Decoupling

- DM – Dark Radiation scattering via massless exchange particle
  $\rightsquigarrow$ Cross section $\propto T_x^{-2}$
  $\rightsquigarrow$ Increases as Universe expands
  $\rightsquigarrow$ suppression in the matter power spectrum: $\sigma_8 \downarrow$
- ΔN_{eff} alleviates Hubble tension

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- Dark Radiation could be same as exchange particle (dark gluon)
  Buen-Abad et al., PRD **92** (2015)
  Lesgourgues et al., JCAP **02** (2016)
  Ko & Tang, PLB **768** (2017)
- …or different (massless dark fermion)
  Ko & Tang, PLB **762** (2016)
  Ko et al., PLB **773** (2017)
- Vector DM and Dark Radiation could stem from same multiplet of dark $SU(N) \xrightarrow{\langle\Phi\rangle} SU(N-1)$ Ko & Tang, PLB **768** (2017)
- Potential problems: too large DM self-interactions? ΔN_{eff} too large for BBN?

Dark Radiation from Decays

- Long-lived particle X, lifetime τ
- Decay after BBN, before recombination $\rightsquigarrow$ only CMB affected, strong BBN bound avoided
- Decay products (daughters) form DR while relativistic
- $\Delta N_{\mathrm{eff}} = \Delta N_{\mathrm{eff}}(\Omega_X, m_2/m_X, \tau)$ (m_2: mass of heavier daughter)
- Single decay mode: heavier daughter is hot DM (or $\Delta N_{\mathrm{eff}} \ll 1$) $\rightsquigarrow$ can only be small fraction of DM
- Two decay modes: produce DR and DM with adjustable free-streaming length $\rightsquigarrow$ address missing satellites, H_0, S_8
- Examples
  - Saxion $\rightarrow$ axion $+$ axion, axino $+$ axino
  - Modulus $\rightarrow$ gravitino $+$ gravitino, axion $+$ axion

Hasenkamp & JK, JCAP **08** (2013)

Decaying Dark Matter

- DM $\rightarrow$ WDM $+$ DR $\rightsquigarrow$ velocity-kick for massive daughter $\rightsquigarrow$ $\sigma_8 \downarrow$
  Abellán et al., 2008.09615
- CMB, LSS $\rightsquigarrow$ strong constraints $\rightsquigarrow$ H_0 tension cannot be resolved
  Anchordoqui et al., 2203.04818
- S_8 tension can be alleviated
  Simon et al., 2203.07440
- H_0 and S_8 tensions cannot be resolved
  Davari & Khosravi, 2203.09439

Conclusions

- Dark Radiation (= BSM relativistic species) influences expansion history of the Universe
- Energy density parametrized by ΔN_{eff}
- Big Bang Nucleosynthesis $\rightsquigarrow$ $\Delta N_{\mathrm{eff}} < 0.124$ @ 95% C.L.
- Cosmic Microwave Background $\rightsquigarrow$ $\Delta N_{\mathrm{eff}} < 0.29$ @ 95% C.L.
- Constraints on specific scenarios
  - BBN constraints on MeV-scale particles decaying into DR
    Hufnagel et al., 1712.03972
  - BBN, CMB $\rightsquigarrow$ lower bound on DM mass in thermal dark sector
    Sabti et al., 1910.01649, 2107.11232
- Short review on sterile neutrinos and Dark Radiation
  Archidiacono & Gariazzo, 2201.10319

Outlook

- Biggest issues: Hubble and S_8 tensions
- Dark sectors have become quite popular
- Connections to neutrino physics (steriles, seesaw, secret interactions)
- HDM hints still valid?
- BBN precision has improved a lot
  $\rightsquigarrow$ still room for interesting effects of Dark Radiation?
- CMB precision will improve further
- Non-trivial impact of models on CMB and structure formation
  $\rightsquigarrow$ room for discoveries?
- Can any DR models lead to gravitational wave production?