Analyzing the Hubble tension through hidden sector dynamics in the early Universe

Michael Klasen

University of Münster and UNSW Sydney

The Dark Side of the Universe, December 5, 2022

Collaboration with A. Aboubrahim and P. Nath

UNSW Sydney Gordon Godfrey Bequest for Theoretical Physics

DFG

Graduiertenkolleg 2149 Research Training Group

Motivation

The 5σ Hubble tension:

- CMB (high z): $H_0 = (67.4 \pm 0.5)$ km/s/Mpc

[Planck Coll., AA 641 (2020) A6]

- Cepheids/SNe Ia: $H_0 = (73.04 \pm 1.04)$ km/s/Mpc

[A.G. Riess et al., AJL 934 (2022) 1 L7]

H is related to the total radiation density parameter ($\Omega_i := \rho_i/\rho_c$):

$$\frac{H^2}{H_0^2} = \frac{\Omega_m}{a^3} + \Omega_\Lambda + \frac{\Omega_r}{a^4}$$

Total radiation density below e^+e^- annihilation temperature:

$$\rho_r = \left[1 + \frac{7}{8}\left(\frac{4}{11}\right)^{\frac{4}{3}} N_{\mathrm{eff}}\right]\rho_\gamma \quad , \quad N_{\mathrm{eff}}^{\mathrm{SM}} \simeq 3.0440 + \Delta N_{\mathrm{eff}}$$

[Y.Y.Y. Wong et al., JCAP 04 (2021) 073]

Proposed solutions (e.g. BSM in equilibrium with neutrinos):

- Majoron [E. Fernandez-Martinez et al., EPJC 81 (2021) 954; Escudero, Witte, EPJC 81 (2021) 515]
- $Z' \to \nu\nu$ [J. Gehrlein, M. Pierre, JHEP 02 (2020) 068; M. Escudero et al., JHEP 03 (2019) 071]
- ... [E. Di Valentino et al., Class. Quant. Grav. 38 (2021) 153001; N. Schöneberg et al., PR 984 (2022) 1]

Cosmological constraints

Big Bang Nucleosynthesis (BBN):

$$N_{\rm eff} \;=\; 2.88 \pm 0.27 \text{ (68\% C.L.)} \;\simeq\; N_{\rm eff}^{\rm SM}$$

[R.H. Cyburt et al., Rev. Mod. Phys. 88 (2016) 015004]

CMB power spectrum:

$$N_{\rm eff} \;=\; 2.99^{+0.34}_{-0.33} \text{ (95\% C.L., TT,TE,EE+lowE+lensing+BAO)}$$

[Planck Coll., AA 641 (2020) A6]

Earlier local measurements (R18, R19) and sound horizon problem:

[A.G. Riess et al., AJ 855 (2018) 136; AJ 876 (2019) 85]

$$0.2 \;\lesssim\; \Delta N_{\rm eff} \;\lesssim\; 0.5 \quad \text{(CMB+BAO+R18)}$$
$$0.2 \;\lesssim\; \Delta N_{\rm eff} \;\lesssim\; 0.4 \quad \text{(CMB+BAO+Pantheon+R19+BBN)}$$

[O. Seto, Y. Toda, PRD 103 (2021) 123501; 104 (2021) 063019; S. Vagnozzi, PRD 102 (2020) 023518]

or somewhat larger (with new SH0ES data).

Millicharged DM with a Stueckelberg dark photon

K. Cheung, T.C. Yuan, JHEP 03 (2007) 120; D. Feldman, Z. Liu, P. Nath, Phys. Rev. D 75 (2007) 115001

Dark sector:

- Dirac fermion D, dark photon C_μ, scalar S, pseudoscalar ϕ

Lagrangian ($M_2, y_\phi \to 0$ for simplicity):

$$\begin{aligned}\mathcal{L} \supset & -\frac{1}{4}C_{\mu\nu}C^{\mu\nu} + i\bar{D}\gamma^\mu\partial_\mu D - m_D\bar{D}D - \frac{1}{2}(\partial_\mu\phi\partial^\mu\phi) - \frac{1}{2}(\partial_\mu S\partial^\mu S)\\ & + g_X Q_X \bar{D}\gamma^\mu D C_\mu + y_\phi \bar{D}\gamma_5 D\phi + y_S D\bar{D}S\\ & - \frac{\delta}{2}C_{\mu\nu}B^{\mu\nu} - \frac{1}{2}(\partial_\mu\sigma + M_1 C_\mu + M_2 B_\mu)^2\end{aligned}$$

Scalar potential ($m_\phi = 0 \to$ thermal bath; $\kappa_S, \kappa_{\phi S} \sim m_{\rm EW}^2/M_{Pl.}$):

$$V \supset \frac{1}{2}m_S^2 S^2 + \frac{\kappa_S}{3}S^3 + \frac{\kappa_{\phi S}}{2}\phi^2 S + \frac{\lambda_S}{4}S^4 + \frac{\lambda_\phi}{4}\phi^4 + \frac{\lambda_{\phi S}}{2}\phi^2 S^2$$

Entropy/energy density and their time dependence

R. Foot, S. Vagnozzi, Phys. Rev. D 91 (2015) 023512; A. Aboubrahim et al., Phys. Rev. D 103 (2021) 075014

Entropy density and its conservation ($s := S/a^3$):

$$s = \frac{2\pi^2}{45}\left(h^h_{\rm eff} T_h^3 + h^v_{\rm eff} T^3\right), \quad ds/dt + 3Hs = 0$$

Energy density and its time evolution:

$$\rho = \frac{\pi^2}{30}\left(g^h_{\rm eff} T_h^4 + g^v_{\rm eff} T^4\right), \quad \frac{d\rho_h}{dt} + 3H(\rho_h + p_h) = j_h$$

Replace t as independent variable by T_h.

Friedman equation:

$$H^2 = \frac{8\pi G_N}{3}(\rho_v(T) + \rho_h(T_h))$$

Replace p by $\zeta := \frac{3}{4}(1 + p/\rho)$ (1 for radiation, $\frac{3}{4}$ for matter).

Visible-hidden sector heat exchange:

$$j_h = \sum_i \left[2Y_i^{\rm eq}(T)^2 J(i\,\bar{i} \to D\bar{D})(T) + Y_i^{\rm eq}(T)^2 J(i\,\bar{i} \to \gamma')(T)\right]s^2 - Y_{\gamma'} J(\gamma' \to f\bar{f})(T_h)s$$

Visible and hidden degrees of freedom

M. Hindmarsh, O. Philipsen, Phys. Rev. D 71 (2005) 087302; M. Drees, F. Hajkarim, E. Rossi Schmitz, JCAP 06 (2015) 025

Visible energy/entropy d.o.f.:

- Use parameterized (T-dependent) results from LQCD EoS

Hidden energy/entropy d.o.f.:

$$g^h_{\rm eff} = g^{\gamma'}_{\rm eff} + \frac{7}{8} g^D_{\rm eff} + g_\phi + g_S, \quad h^h_{\rm eff} = h^{\gamma'}_{\rm eff} + \frac{7}{8} h^D_{\rm eff} + h_\phi + h_S$$

with $g_\phi = g_S = h_\phi = h_S = 1$ (almost always out of equilibrium).

Dark photons/dark matter (T_h-dependent, reach equilibrium):

$$g^{\gamma'}_{\rm eff} = \frac{45}{\pi^4} \int_{x_{\gamma'}}^{\infty} \frac{\sqrt{x^2 - x^2_{\gamma'}}}{e^x - 1} x^2 dx, \;\; h^{\gamma'}_{\rm eff} = \frac{45}{4\pi^4} \int_{x_{\gamma'}}^{\infty} \frac{\sqrt{x^2 - x^2_{\gamma'}}}{e^x - 1} (4x^2 - x^2_{\gamma'}) dx,$$

$$g^D_{\rm eff} = \frac{60}{\pi^4} \int_{x_D}^{\infty} \frac{\sqrt{x^2 - x^2_D}}{e^x + 1} x^2 dx, \;\; h^D_{\rm eff} = \frac{15}{\pi^4} \int_{x_D}^{\infty} \frac{\sqrt{x^2 - x^2_D}}{e^x + 1} (4x^2 - x^2_D) dx.$$

with $x_i = m_i/T_h$. For $x_i \to 0$, $g^{\gamma'}_{\rm eff} = h^{\gamma'}_{\rm eff} \to 3$ and $g^D_{\rm eff} = h^D_{\rm eff} \to 4$.

Set of five coupled (stiff) ODEs

A. Aboubrahim, MK, P. Nath, JCAP 04 (2022) 042

Visible/hidden temperature ratio ($\eta := T/T_h \gg 1$):

$$\frac{d\eta}{dT_h} = -\frac{\eta}{T_h} + \left[\frac{\zeta\rho_v + \rho_h(\zeta - \zeta_h) + j_h/(4H)}{\zeta_h\rho_h - j_h/(4H)}\right]\frac{d\rho_h/dT_h}{T_h(d\rho_v/dT)}$$

Boltzmann equations ($Y := n/s$, initially 0):

$$\frac{dY_\phi}{dT_h} = -\frac{s}{H}\left(\frac{d\rho_h/dT_h}{4\zeta\rho_h - j_h/H}\right)\left[\frac{1}{2}\langle\sigma v\rangle_{D\bar{D}\to\phi\gamma'}(T_h)\left(Y_D^2 - Y_D^{\rm eq}(T_h)^2\frac{Y_\phi Y_{\gamma'}}{Y_\phi^{\rm eq}(T_h)Y_{\gamma'}^{\rm eq}(T_h)}\right) + \ldots\right]$$

$$\frac{dY_S}{dT_h} = -\frac{s}{H}\left(\frac{d\rho_h/dT_h}{4\zeta\rho_h - j_h/H}\right)\left[\frac{1}{2}\langle\sigma v\rangle_{D\bar{D}\to S\gamma'}(T_h)\left(Y_D^2 - Y_D^{\rm eq}(T_h)^2\frac{Y_S Y_{\gamma'}}{Y_S^{\rm eq}(T_h)Y_{\gamma'}^{\rm eq}(T_h)}\right) + \ldots\right]$$

$$\frac{dY_{\gamma'}}{dT_h} = -\frac{s}{H}\left(\frac{d\rho_h/dT_h}{4\zeta\rho_h - j_h/H}\right)\left[-\langle\sigma v\rangle_{\gamma'\gamma'\to D\bar{D}}(T_h)\left(Y_{\gamma'}^2 - Y_{\gamma'}^{\rm eq}(T_h)^2\frac{Y_D^2}{Y_D^{\rm eq}(T_h)^2}\right) + \ldots\right]$$

$$\frac{dY_D}{dT_h} = -\frac{s}{H}\left(\frac{d\rho_h/dT_h}{4\zeta\rho_h - j_h/H}\right)\left[\langle\sigma v\rangle_{i\bar{i}\to D\bar{D}}(T)Y_D^{\rm eq}(T)^2 + \ldots\right]$$

D, S chemically decouple from γ', but remain in thermal bath (T_ϕ).
Later, D and S decouple also kinetically from ϕ.

Kinetic decoupling

P. Gondolo, J. Hisano, K. Kadota, Phys. Rev. D 86 (2012) 083523

Second moment of Boltzmann equation $[T_{D,S} \ll m_{D,S},\ \mathcal{O}(p^2/m_{D,S}^2)]$:

$$(\partial_t + 5H)T_{D,S} = 2m_{D,S}\gamma(T_\phi)(T_\phi - T_{D,S})$$

with

$$T_{D,S} = \frac{1}{3m_{D,S}n_{D,S}} \int \frac{d^3p}{(2\pi)^3} p^2 f(p).$$

Momentum transfer rate:

$$\gamma(T_\phi) = \frac{g_\phi}{384\pi^3 m_{D,S}^4 T_\phi} \int dE\, f^\pm(E)(1 \mp f(E)) \int_{-4k^2}^{0} (-t)|\mathcal{M}|^2\, dt$$

(Instantaneous) decoupling temperature:

$$\gamma(T_\phi) = H(T_\phi)\Big|_{T_\phi = T_{\rm kd}}$$

Reheating of the dark sector prior to recombination

A. Aboubrahim, MK, P. Nath, JCAP 04 (2022) 042

Dark scalar decay ($S \to \phi\phi$):

$$\Gamma_S = \frac{\kappa_{\phi S}^2}{32\pi m_S}$$

Boltzmann equations:

$$\begin{aligned} \frac{d\rho_S}{dt} + 3H\rho_S &= -\Gamma_S\,\rho_S \quad , \quad \frac{d\rho_D}{dt} + 3H\rho_D = 0, \\ \frac{d\rho_\phi}{dt} + 4H\rho_\phi &= \Gamma_S\,\rho_S \quad , \quad \frac{d\rho_\gamma}{dt} + 4H\rho_\gamma = 0 \end{aligned}$$

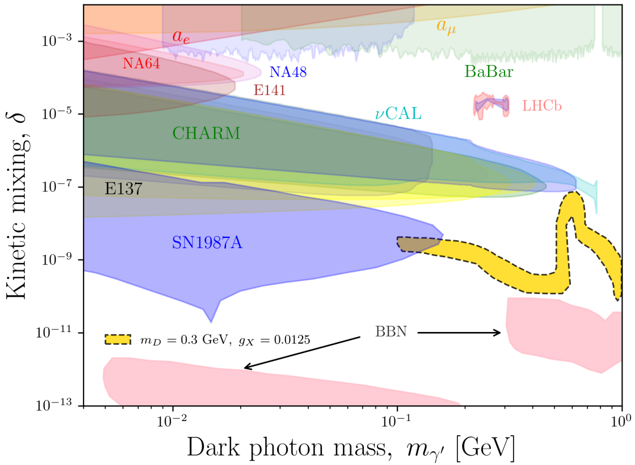
ϕ is the only remaining relativistic d.o.f.:

$$\Delta N_{\text{eff}} = \frac{8}{7}\left(\frac{11}{4}\right)^{4/3}\frac{\rho_\phi(T_\phi)}{\rho_\gamma(T_\gamma)}$$

Dark photon mass and kinetic mixing angle

A. Aboubrahim, MK, P. Nath, JCAP 04 (2022) 042

Fixed target/collider experiments + SN1987A + BBN:



Resonance at $m_{\gamma'} = 2m_D$ requires larger mixing angle for correct Ωh^2.

Further constraints and benchmark points

A. Aboubrahim, MK, P. Nath, JCAP 04 (2022) 042

Cosmology:

- $\Delta N_{\rm eff}^{\rm BBN} < 10^{-2}$
- $T_{\rm kd} < T_{\rm cd}$
- No free-streaming ($\not\to$ phase shift in CMB and BAO peaks):

$$H(T_\phi) \leq n_\phi(T_\phi)\langle\sigma v\rangle_{\phi\phi\to\phi\phi} = \frac{9x\lambda_\phi^2}{64\pi^2}T_\phi \quad \text{with} \quad x = n_\phi/n_\phi^{\rm eq}$$

$$\to \lambda_\phi \geq 10^{-12}$$

- $\Omega h^2 = \frac{m_D Y_D^\infty s_0 h^2}{\rho_c} \sim 0.1 - 0.125$

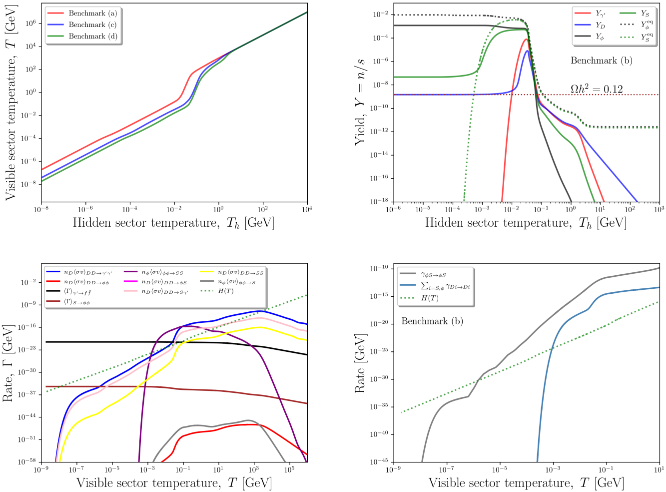
Benchmark points:

Model	m_D	$m_{\gamma'}$	m_S	δ	y_S	$\kappa_{\phi S}$ [GeV]	$\lambda_{\phi S}$	$\Delta N_{\rm eff}^{\rm CMB}$
(a)	0.1	0.9	10^{-2}	4.6×10^{-11}	3.0×10^{-3}	1.9×10^{-18}	1.0×10^{-7}	0.43
(b)	0.3	0.2	10^{-2}	1.6×10^{-9}	1.0×10^{-3}	6.0×10^{-18}	5.0×10^{-6}	0.55
(c)	0.6	0.5	10^{-3}	6.0×10^{-10}	3.0×10^{-3}	3.3×10^{-19}	5.0×10^{-7}	0.36
(d)	1.0	0.3	10^{-2}	1.7×10^{-9}	5.0×10^{-3}	8.5×10^{-19}	1.0×10^{-8}	0.54

All masses are in GeV. Fixed parameters: $g_X = 0.0125$, $\kappa_S = 10^{-18}$ GeV.

Evolution of T vs. T_h, DS build-up, chem./kin. decoupling

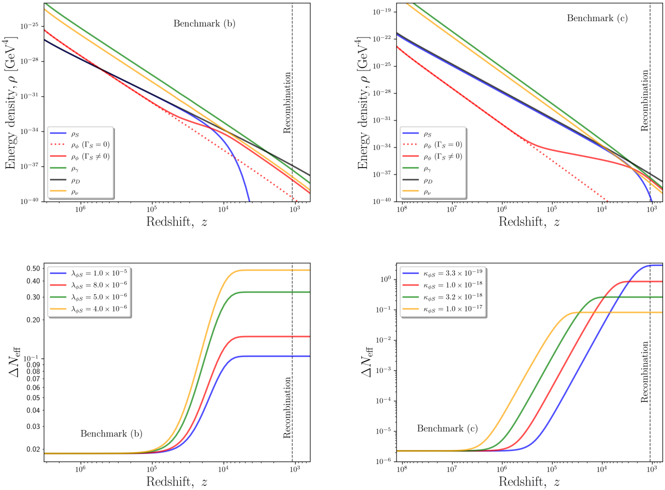
A. Aboubrahim, MK, P. Nath, JCAP 04 (2022) 042



Lyman-α limit for late kinetic decoupling: $T_{\rm kd} > 100$ eV.

ρ and $\Delta N_{\rm eff}$ from BBN to recombination

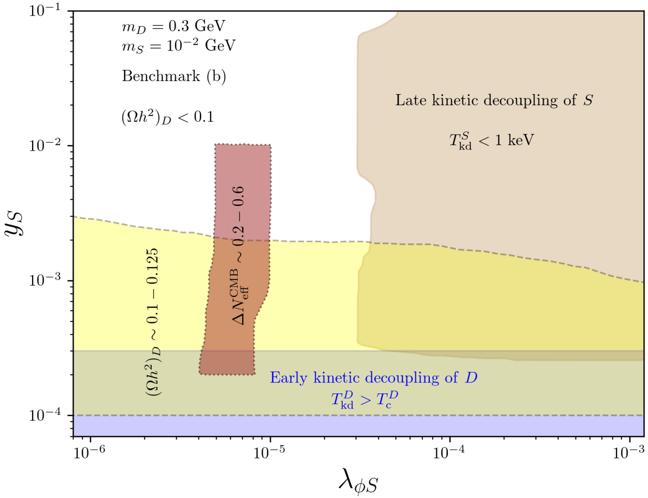
A. Aboubrahim, MK, P. Nath, JCAP 04 (2022) 042



Note: ρ_ϕ increases towards ρ_γ, as S decays away.

Viable parameter space for $\Delta N_{\rm eff}$

A. Aboubrahim, MK, P. Nath, JCAP 04 (2022) 042



Conclusion

- Hubble tension between CMB and SNe Ia now 5σ
- Proposed solutions: Dark radiation, dark energy, inflation, ...

- Our model: Visible sector + dark sector (initially empty)
- Build-up of fermionic dark matter via dark photons
- DM generates light scalars and pseudoscalars (heat bath)
- DM freeze-out generates Ωh^2
- Late decay of scalars generates ΔN_{eff} at CMB
- No contribution at BBN time

- Requires solution of five coupled stiff ODEs
- Respects cosmological and dark photon constraints