Photon to axion conversion during Big Bang Nucleosynthesis

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- An Axion-Like Majoron (ALM) model
- Cosmological evolution: H_0
- BBN: deuterium, helium, lithium

[1] A.J. Cuesta, M.E. Gómez, J.I. Illana, M. Masip, JCAP 04 (2022) 009
[2] A.J. Cuesta, J.I. Illana, M. Masip, 2305.16838

COSMIC WISPers, Bari, September 5-8, 2023

ALM model

• ΛCDM works extremely well, which underlines some *tensions...*

CMB observables favor

$$H_0 = 67.71 \pm 0.44 \ \frac{\text{km}}{\text{s Mpc}} \qquad\qquad \eta_{10} \equiv 10^{10} \frac{n_b}{n_\gamma} = 6.14 \pm 0.04 \,,$$

but type-Ia supernovae and the abundance of primordial deuterium indicate

$$H_0 = 73.01 \pm 0.99 \ \frac{\text{km}}{\text{s Mpc}} \qquad\qquad \eta_{10} = 5.98 \pm 0.07$$

while the observed lithium abundance suggests $\eta_{10} = 3.28 \pm 0.29\,.$

• Our understanding of the ν sector is still work in progress: Dirac particles with EW masses or is their mass revealing a new scale in particle physics?

SM $+\, y_\nu \ HL\nu^c$ Why is y_ν so small? What protects ν^c?

SM $+\, \frac{1}{\Lambda_\nu} \ HHLL$ Seesaw with $M_X \approx 10^{10}$ GeV or $M_X \approx$ TeV + approx. sym.?

• Extension of the SM with 3 fermion singlets N, N^c, n and several scalar singlets s_i, valid below a cutoff scale $\Lambda \approx 10$ TeV, invariant (up to grav. effects) under a global $U(1)_X$ symmetry broken by a VEV $\langle s \rangle \approx$ TeV

$$s = \frac{1}{\sqrt{2}} (v_X + \rho)\, e^{i \frac{\phi}{v_X}} = \frac{1}{\sqrt{2}} (v_X + \rho + i\, \phi + ...)$$

$$s = s_3 + \epsilon\, s_4 \quad \Longrightarrow \quad \langle s_4 \rangle = \epsilon\, \langle s_3 \rangle\ ; \quad \phi = \phi_3 + \epsilon\, \phi_4\ ; \qquad (\epsilon \ll 1)$$

	$(\nu\ e)$	e^c	N	N^c	n	$(h^+\ h^0)$	$s_1, s_2, s_3, s_4\ \ldots$
Q_X	$+1$	-1	-2	-1	0	0	$1, 2, 3, 4, \ldots$
Z_3	α	α^*	α	α^*	1	1	$\alpha, \alpha^*, 1, \alpha, \ldots$

Neutrino masses + ALM ϕ

$$-\mathcal{L} \supset i\, \lambda_{\nu_i}\, \phi\, \overline{\nu_i}\, \gamma_5\, \nu_i + \frac{1}{4}\, g_{\phi\gamma\gamma}\, \phi\, \widetilde{F}_{\mu\nu} F^{\mu\nu} + \frac{1}{2}\, m_\phi^2\, \phi^2$$

$$m_\phi = 0.5 \text{ eV}\ ; \quad v_X = 900 \text{ GeV}\ ; \quad g_{\phi\gamma\gamma} = 1.46 \times 10^{-11} \text{ GeV}^{-1}\ ; \quad \lambda_{\nu_3} = 6.8 \times 10^{-14}$$

$$\tau_\phi = 3.5 \times 10^{12} \text{ s}\ ; \quad \text{BR}(\phi \to \nu_3 \bar{\nu}_3) = 0.96\ ; \quad \text{BR}(\phi \to \gamma\gamma) = 10^{-15}$$

Cosmological evolution: H_0

- At (1 TeV $> T >$ 1 MeV) ϕ is decoupled, it's abundance negligible ($\Delta N_{\rm eff} \approx 0.026$)
- At $T \approx 26$ keV a fraction of CMB photons converts into majorons (!)

(i) Photons in a medium get a mass that can be expressed in terms of the index of refraction $n \equiv k/\omega$. In the cosmic plasma the main contribution to this mass comes from their interaction with free (not bounded in atoms) electrons

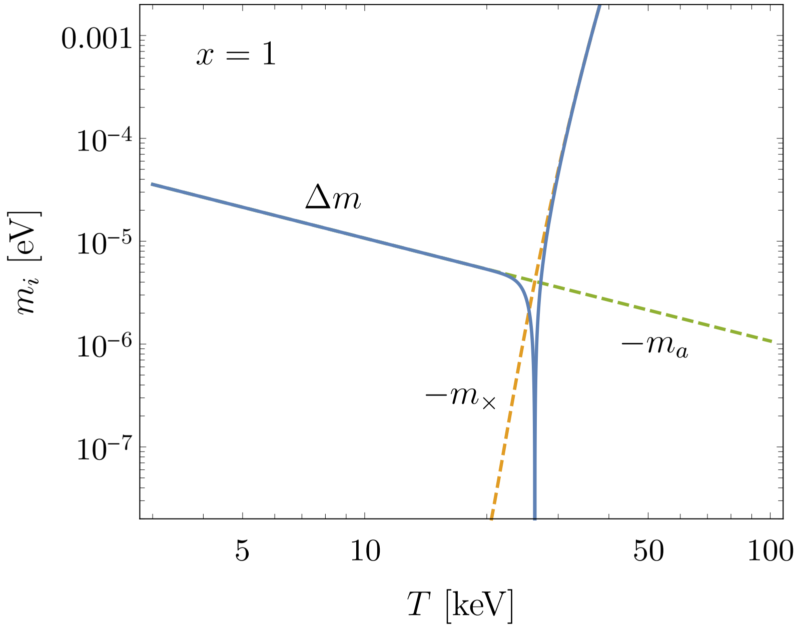
$$n_e(T) \approx 4\left(\frac{m_e T}{2\pi}\right)^{3/2} \exp\left(-\frac{m_e}{T}\right) + 0.88\,\eta_B\, n_\gamma(T)\,,$$

(ii) The presence of a background magnetic field mixes the photon with the axion-like particle ($m_{\phi\gamma} = g_{\phi\gamma\gamma} B_T/2$); this separates mass and interaction eigenstates and produces oscillations that become resonant when the two masses coincide

$$\text{Primordial } B_0 = 3\ \text{nG} \qquad \left[B \approx B_0\,(T/T_0)^2\,, \quad \lambda_0 \geq 1\ \text{Mpc}\right]$$

Raffelt, Stodolsky (1988): Stationary (quadratic) wave equation $\rightarrow \vec{B}$ changes on larger scales than the photon/axion wavelength & $\omega + k \approx 2\omega$ $\rightarrow$ linearized wave equation

$$\left((\omega + i\partial_{\mathbf{x}})\, I + \begin{pmatrix} m_+ & 0 & 0 \\ 0 & m_\times & m_{\phi\gamma} \\ 0 & m_{\phi\gamma} & m_a \end{pmatrix} \right) \begin{pmatrix} A_+ \\ A_\times \\ \phi \end{pmatrix} = 0\,,$$



$\omega = x\, T$

$\times$: photon polarization parallel to $\vec{B}$

$m_\times = \omega(n-1)_\times \qquad n_{\text{pla}} = 1 - \frac{2\pi n_e}{\omega^2 m_e}$

$m_a = -m_\phi^2/\omega$

$\overline{T} = 26$ keV (indep. from x)

Ejlli, Dolgov (2014): If $\rho_\phi \ll \rho_\gamma \approx \rho_\gamma^{\text{eq}}$ and the ALM interaction rate is $\Gamma_\phi \approx 0$

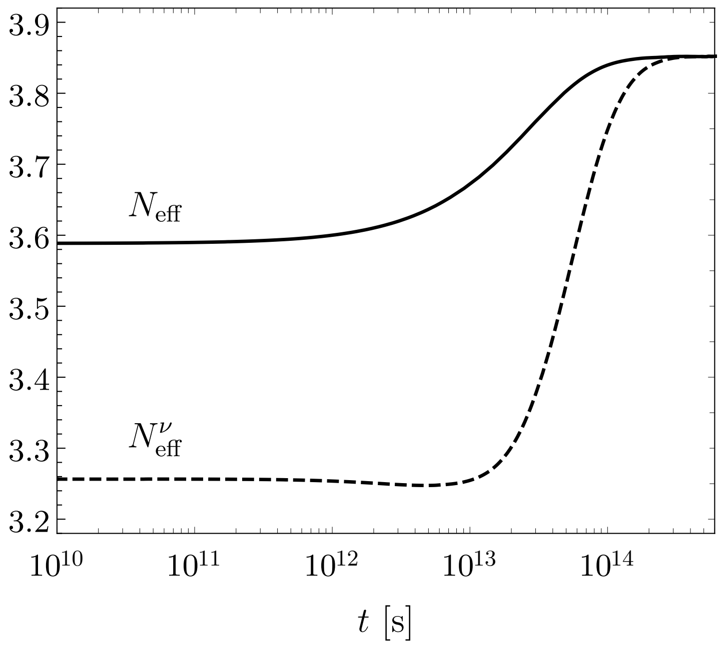
$$P_\phi(x,T) \equiv \frac{\Delta n_\phi}{n_\gamma^{\text{eq}}} \approx -\left(\frac{2\pi}{3H}\right) \frac{m_{\phi\gamma}^2}{m_a + m_{\text{QED}}}\bigg|_{T=\overline{T}}$$

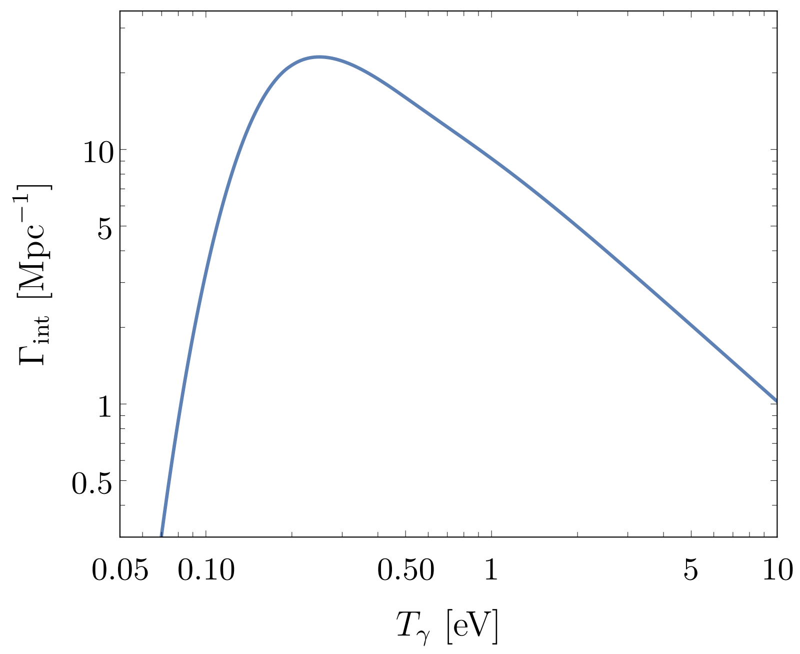
Photons of different energy ω convert at the same $\overline{T}$, but $P_\phi(x,T) \propto \omega = xT$.

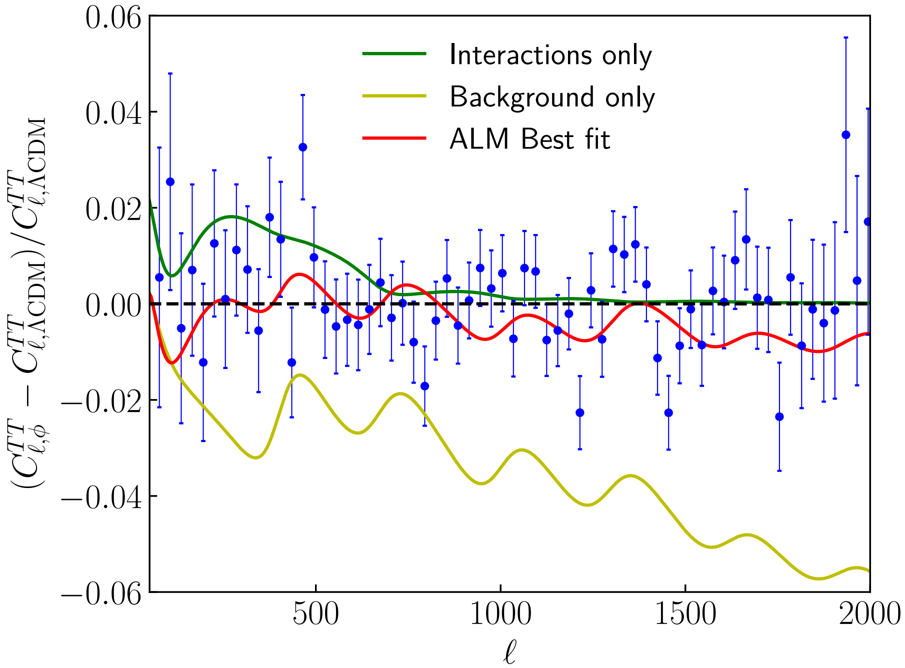
• 4.4% of the CMB photons carrying a 6.3% of ρ_γ convert into majorons at $T \approx \overline{T} = 26$ keV. Sudden 1.6% drop in $T_\gamma \implies N_{\rm eff} \approx 3.6$ (majorons + less photons but same ν's) and 4.7% increase in the baryon to photon ratio (less photons but same baryons)

After that all photons rethermalize and the spectral distortion is completely erased

• Escudero (2020): Final stage of the ALM evolution: from 10 eV to past recombination at $T_\gamma \approx 0.26$ eV (all majorons decayed). Neutrinos and majorons enter in thermal contact at $T \approx m_\phi$ through $\nu\bar{\nu} \leftrightarrow \phi$, which reduces their free streaming







Effect (relative to that of ΛCDM) on the TT power spectrum produced by *(i)* the increase in $N_{\rm eff}$; *(ii)* the damping of the ν free streaming; and *(iii)* the total effect after redefining the cosmological parameters in the ALM model (CLASS + MontePython)

Parameter	ΛCDM	ALM
$100\,\Omega_b h^2$	2.242 ± 0.015	2.295 ± 0.014
$\Omega_{\rm cdm} h^2$	0.119 ± 0.001	0.129 ± 0.001
$100\,\theta_s$	1.0420 ± 0.0003	1.0407 ± 0.0003
$\ln\left(10^{10} A_s\right)$	3.046 ± 0.015	3.062 ± 0.016
n_s	0.967 ± 0.004	0.991 ± 0.004
$\tau_{\rm reio}$	0.055 ± 0.008	0.056 ± 0.008
H_0 [km/s/Mpc]	67.71 ± 0.44	71.4 ± 0.5

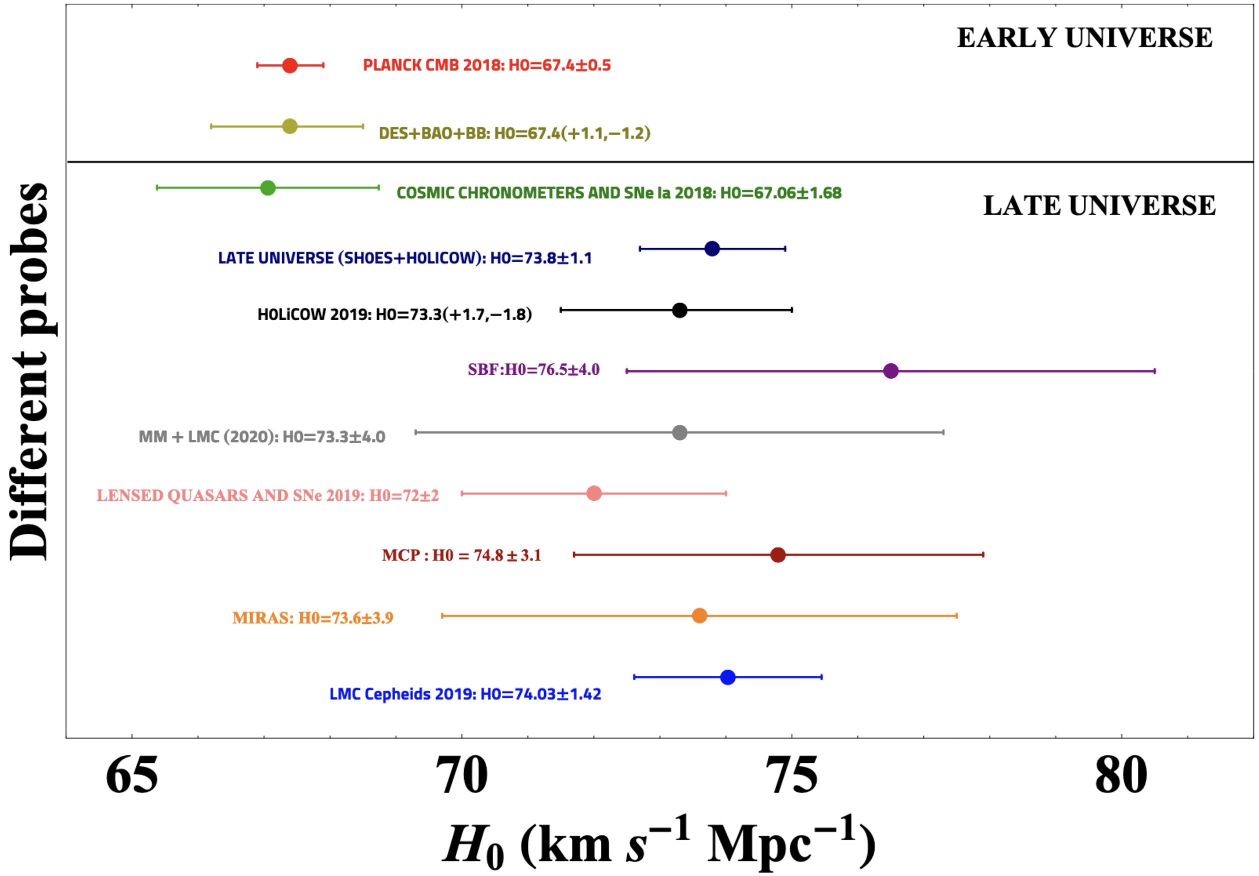
• Similar χ^2 for CMB observ., but

ALM:

$$H_0 = (71.4 \pm 0.5)\ \mathrm{km/s/Mpc}$$

ΛCDM:

$$H_0 = (67.7 \pm 0.44)\ \mathrm{km/s/Mpc}$$

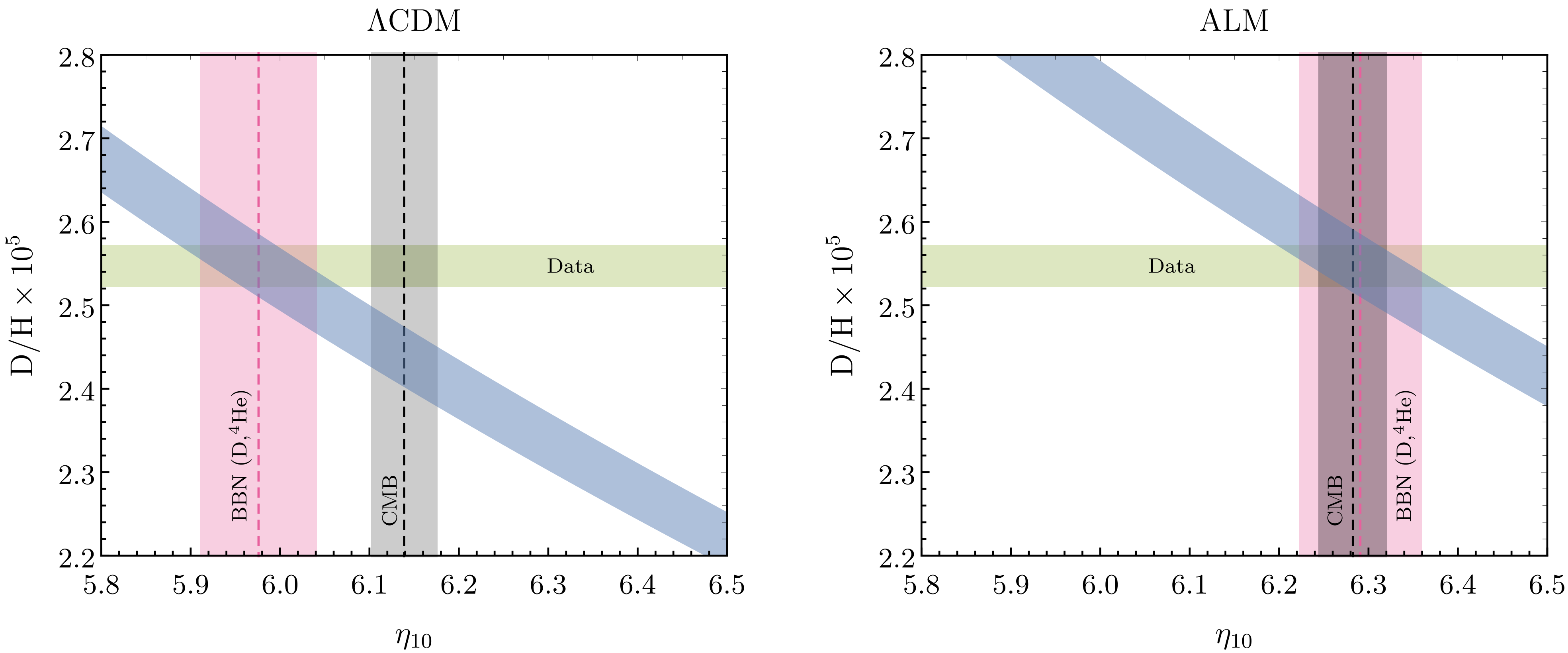


• We obtain $100\,\Omega_b h^2 = 2.295 \pm 0.014$ in the ALM model versus 2.242 ± 0.015 in ΛCDM (a 2.6σ difference).

What are the ALM predictions for the primordial abundance of deuterium, helium and lithium?

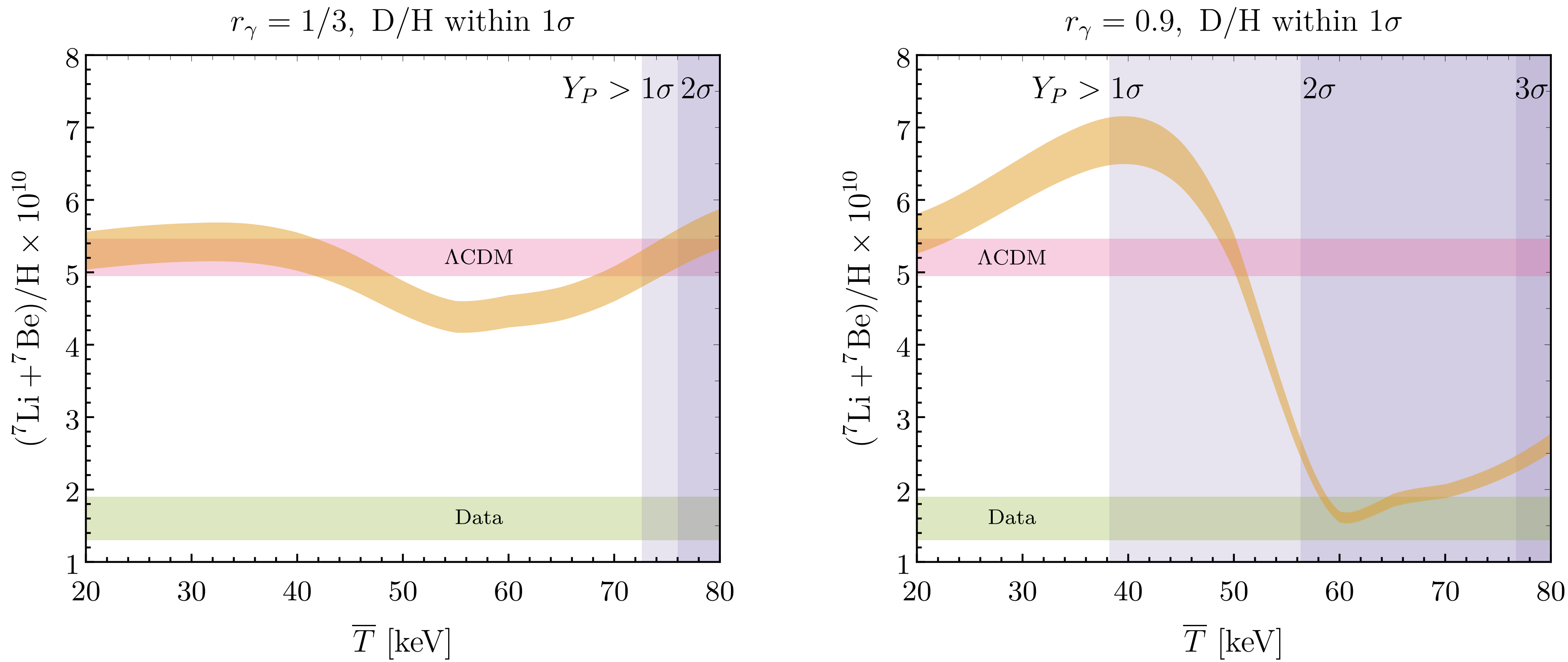
BBN: deuterium, helium, lithium

- ΛCDM: 2σ tension (`PRIMAT`) in ^{4}He & D versus CMB



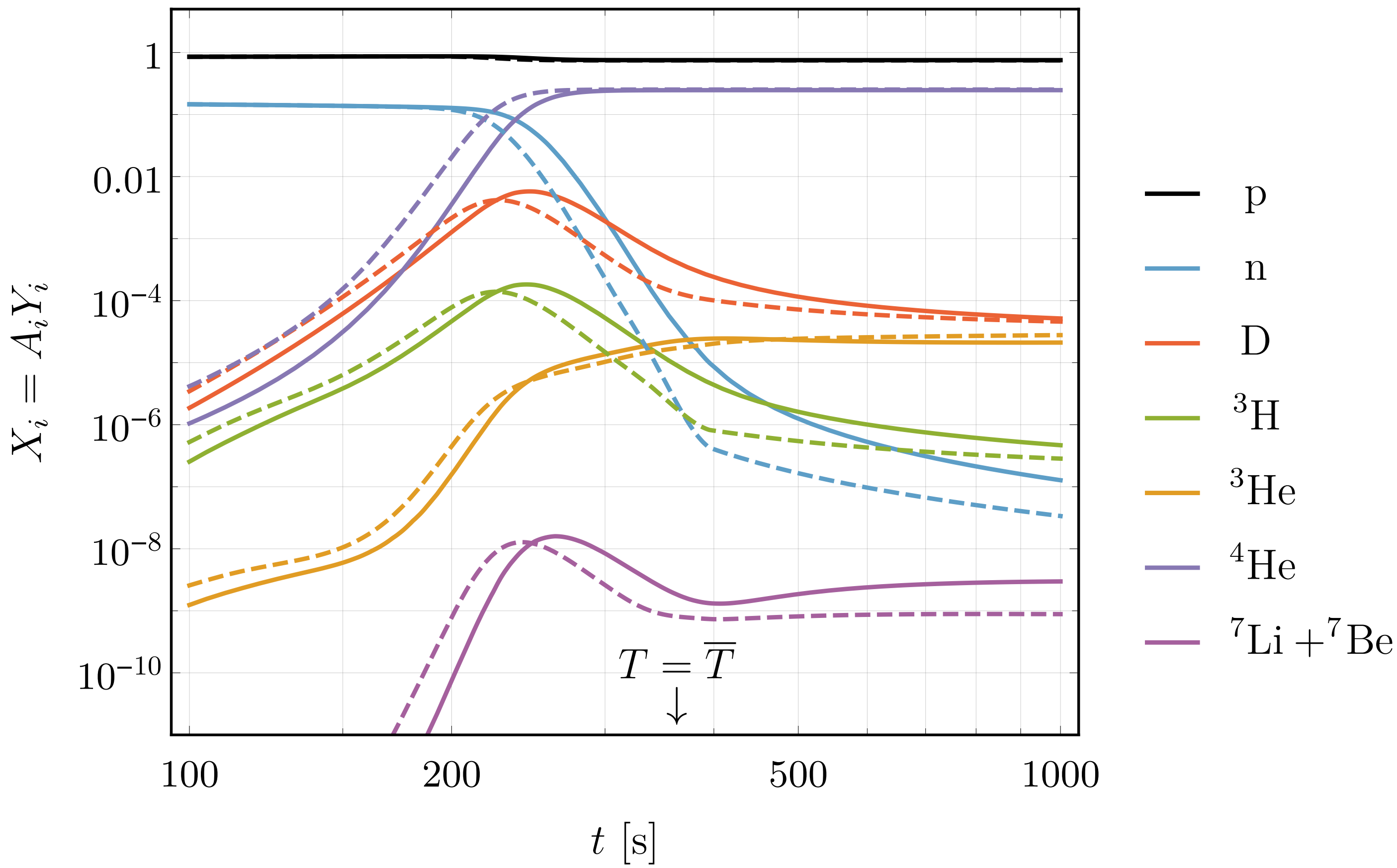
- ALM model (modified `PRIMAT`): at the resonant temperature $\overline{T} = 26$ keV, 6.3% of the CMB energy oscillates into axions, cooling the universe and increasing the baryon to photon ratio from $\eta_{10} = 5.89$ to $\eta_{10} = 6.28$ (the value during decoupling).

• We consider the Li abundance in generalized scenarios with a higher $\overline{T}$ and a larger fraction of energy r_γ transferred to axions (modified `PRIMAT`).



higher $\overline{T} \leftrightarrow$ higher m_ϕ (but similar lifetime to reduce the free streaming at $T \approx 1$ eV)

$r_\gamma = 1/3$ (multiple oscillations); $r_\gamma = 0.9$ (several axions?)



- Large value of η_{10}, BBN starts earlier than in ΛCDM
- Excess of heavier nuclei (^{3}He, ^{4}He) relative to the lighter ones (D, ^{3}H)
- No more ^{7}Li+^{7}Be is sinthesized after the sudden cooling at $\overline{T}$

Conclusions

• The smallness of neutrino masses may be explained by a large scale or by an approximate symmetry. In this second case one may expect a light ALM

• In the early universe a primordial magnetic field may induce the conversion of CMB photons into axions, implying a larger N_{eff} and a larger baryon to photon ratio after BBN than in ΛCDM. The ALM decays into neutrinos near recombination.

• This is a variation of the ΛCDM model that *solves* the H_0 tension, provides a similar fit to CMB observables and implies the *right* deuterium abundance.

• A sudden cooling of the universe at $T \approx 55$ keV in a generalized model could also imply a lithium abundance consistent with the observations.