Photon to axion conversion during Big Bang Nucleosynthesis

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

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Motivation

- ΛCDM very successful, which underlines some tensions:

CMB observables

$$H_0 = 67.71 \pm 0.44 \text{ km/s/Mpc}$$

CMB ($\Omega_b h^2$)

$$\eta_{10} \equiv 10^{10}\frac{n_b}{n_\gamma} = 6.14 \pm 0.04$$

SNe-Ia

$$H_0 = 73.01 \pm 0.99 \text{ km/s/Mpc}$$

Primordial deuterium

$$\eta_{10} = 5.98 \pm 0.07$$

Primordial lithium

$$\eta_{10} = 3.28 \pm 0.29$$

- Neutrino sector not yet understood:

Dirac fermions with EW masses? or tiny masses revealing a new scale?

SM – $y_\nu \overline{L}\widetilde{H}\nu_R$ Why is y_ν so small? What protects ν_R?

SM – $\dfrac{1}{\Lambda_\nu}\overline{L}\widetilde{H}\widetilde{H}^T L^c$ Seesaw with $M_X \approx 10^{10}$ GeV or $M_X \approx$ TeV + symmetry ?

ALM model

- SM + 3 Majorana singlets (N_L, N_R^c, n_L) + scalar singlets (s_1, s_2, s_3, $\ldots$), valid below cutoff $\Lambda \approx 10$ TeV, invariant (up to grav effects) under global $U(1)_X$ spontaneously broken by a VEV $\langle s \rangle = v_X/\sqrt{2} \approx$ TeV:

	$L_i = (\nu_{iL}\ e_{iL})^T$	e^c_{iR}	N_L	N^c_R	n_L	$H = (h^+\ h^0)^T$	$s_1, s_2, s_3, s_4, \ldots$	
Q_X	$+1$	-1	-2	-1	0	0	$1,\ 2,\ 3,\ 4,\ \ldots$	$e^{-iQ_X\theta}$
Z_3	α	α^*	α	α^*	1	1	$\alpha,\ \alpha^*,\ 1,\ \alpha,\ \ldots$	$\alpha \equiv e^{i\frac{2\pi}{3}}$

pNGB ϕ : $\quad s = \dfrac{1}{\sqrt{2}}(v_X + \rho)\, e^{i\frac{\phi}{v_X}} = \dfrac{1}{\sqrt{2}}(v_X + \rho + i\phi + \ldots)$

In particular : $\quad \langle s_3 \rangle$ breaks $U(1)_X$ but preserves Z_3

$\Rightarrow \quad s = s_3$ would *not* generate neutrino masses *nor* couplings to ϕ

Take : $\quad s = s_3 + \epsilon\, s_4 \Rightarrow$ light $m_\nu \propto \epsilon v_X$ as in inverse seesaw models while the others are heavy with masses of order v_X, except for the Majoron (approximate symmetry)

ALM model

$$\left.\begin{array}{l} \boxed{s \equiv \quad s_3 + \epsilon\, s_4} \\ s' = -\epsilon\, s_3 + s_4, \quad \langle s' \rangle = 0 \end{array}\right\} \quad \Rightarrow \quad \langle s_4 \rangle = \epsilon \langle s_3 \rangle = \frac{\epsilon\, v_X}{\sqrt{2}} \qquad (\epsilon \ll 1)$$

$$-\mathcal{L} \supset y \overline{L}_3 \widetilde{H} N_R + y' s_3^\dagger \overline{N}_L N_R + \frac{1}{2}\Lambda_n \overline{n}_L n_L^c + y_{IS} s_4^\dagger \overline{N}_L N_L^c + \frac{\widetilde{y}}{\Lambda^2} s_3 s_4^\dagger \overline{L}_2 \widetilde{H} N_L^c + \frac{\widetilde{y}'}{\Lambda^2} s_3^\dagger s_4 \overline{L}_1 \widetilde{H} n_L^c + \text{h.c.}$$

$$\supset \frac{1}{2}\begin{pmatrix} \overline{\nu}_{1L} & \overline{\nu}_{2L} & \overline{\nu}_{3L} & \overline{N}_L & \overline{N}_R^c & \overline{n}_L \end{pmatrix} \begin{pmatrix} \cdot & \cdot & \cdot & 0 & 0 & \widetilde{\mu}' \\ \cdot & \cdot & \cdot & \widetilde{\mu} & 0 & \cdot \\ \cdot & \cdot & \cdot & \cdot & m & \cdot \\ 0 & \widetilde{\mu} & \cdot & \mu & M & \cdot \\ 0 & 0 & m & M & \cdot & \cdot \\ \widetilde{\mu}' & \cdot & \cdot & \cdot & \cdot & \Lambda_n \end{pmatrix} \begin{pmatrix} \nu_{1L}^c \\ \nu_{2L}^c \\ \nu_{3L}^c \\ N_L^c \\ N_R \\ n_L^c \end{pmatrix} + \text{h.c.} - \boxed{\mathrm{i}\lambda_{\nu_i'} \phi \overline{\nu}_i' \gamma_5 \nu_i'}$$

$$m = y\frac{v}{\sqrt{2}} \ll M = y' \frac{v_X}{\sqrt{2}} \qquad \frac{1}{2}\mu = y_{IS}\frac{\epsilon v_X}{\sqrt{2}} \qquad \frac{1}{2}\widetilde{\mu} = \frac{\widetilde{y}}{\Lambda^2}\frac{\epsilon v_X^2}{2}\frac{v}{\sqrt{2}} \qquad \frac{1}{2}\widetilde{\mu}' = \frac{\widetilde{y}'}{\Lambda^2}\frac{\epsilon v_X^2}{2}\frac{v}{\sqrt{2}}$$

$$\Rightarrow \boxed{m_{\nu_1'} \sim \frac{\widetilde{\mu}'^2}{\Lambda_n} \quad m_{\nu_2'} \sim \frac{\widetilde{\mu}^2}{\mu} \quad m_{\nu_3'} \sim \mu \frac{m^2}{M^2}} \ll m_{\nu_{4,5}'} \sim \sqrt{M^2 + m^2} \mp \tfrac{1}{2}\mu \quad m_{\nu_6'} \sim \Lambda_n \quad \boxed{\lambda_{\nu_{1,2,3}'} \sim \frac{m_{\nu_i'}}{v_X}}$$

light neutrinos heavy neutrinos ($\gtrsim$ TeV)

ALM model

- Neutrino masses and couplings to **A**xion-**L**ike-**M**ajoron ϕ with (drop primes $'$)

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

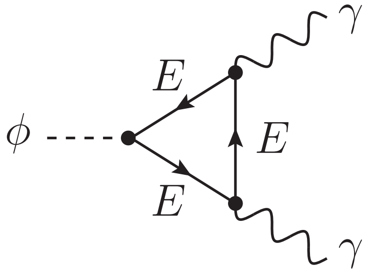
INPUTS: $m_\phi = 0.5$ eV , $g_{\phi\gamma\gamma} = 1.46\times 10^{-11}$ keV^{-1} , $\lambda_{\nu_3} = 6.8\times 10^{-14}$, $v_X = 900$ GeV

$$\tau_\phi = 3.5\times 10^{12}\ \mathrm{s}\ ,\ \mathcal{B}(\phi\to\nu_3\overline{\nu}_3) = 0.96 \Leftarrow\ \mathcal{B}(\phi\to\gamma\gamma) = \frac{g^2_{\phi\gamma\gamma}m^3_\phi}{16\lambda^2_{\nu_i}m_\phi} \sim 10^{-15}$$

$\Uparrow$ $\Gamma(\phi\to\nu\bar{\nu}) \propto \lambda_\nu^2 m_\phi$ (decays before recombination)

- Note: This small $g_{\phi\gamma\gamma}$ (astrophysical bounds) can be generated at one loop introducing 2 heavy vectorlike charged lepton singlets (E_{1L}, E^c_{-1L}) and (E^c_{-4R}, E_{4R}) with $Q_X = \pm 1, \pm 4$:

$$-\mathcal{L} \supset y_E\, s_3^\dagger \overline{E}_{1L}E_{4R} + M\,\overline{E}_{1L}E^c_{-1L} + M\,\overline{E}^c_{-4R}E_{4R} + \mathrm{h.c.} \supset -\boxed{\mathrm{i}\lambda_E\,\phi\overline{E}\gamma_5 E} \quad \lambda_E \sim y_E\frac{m'}{M} \sim y_E^2\frac{v_X}{M}$$



$$\Rightarrow \qquad g_{\phi\gamma\gamma} \sim \frac{\alpha\lambda_E}{\pi M} \sim \frac{\alpha y_E^2 v_X}{\pi M^2} \qquad (m_\phi^2 \ll 4M^2)$$

Cosmological evolution $T > 1$ MeV

- ϕ starts decoupling at $T \sim 10^6$ GeV [$\gamma A \leftrightarrow \phi A$, $\gamma \ell \leftrightarrow \phi \ell$ and $\phi \leftrightarrow \nu\bar{\nu}$ inefficient] until $T \approx 500$ GeV [heavy neutrinos become NR]

▷ Below $T \approx 500$ GeV, entropy transferred to lighter dof, not to ϕ. For $T \approx 1$ MeV:

$$\underbrace{g_{\star s}(T \gtrsim m_{\text{top}})}_{\text{all SM dof}} T_\phi^3 = \underbrace{g_{\star s}(1\ \text{MeV})}_{\gamma, e^\pm, \nu' s} T^3 \Rightarrow \frac{T_\phi}{T} = \left(\frac{10.75}{106.75}\right)^{1/3} \approx 0.463$$

▷ So far: $T_\nu = T$ and majorons represent a small contribution to energy density:

$$\rho_R = \rho_\gamma + \rho_\nu + \rho_\phi \equiv \rho_\gamma \left[1 + \frac{7}{8} N_{\text{eff}} \left(\frac{T_\nu}{T}\right)^4\right], \quad N_{\text{eff}} \equiv N_{\text{eff}}^\nu + \Delta N_{\text{eff}} \Rightarrow \Delta N_{\text{eff}} \approx 0.026$$

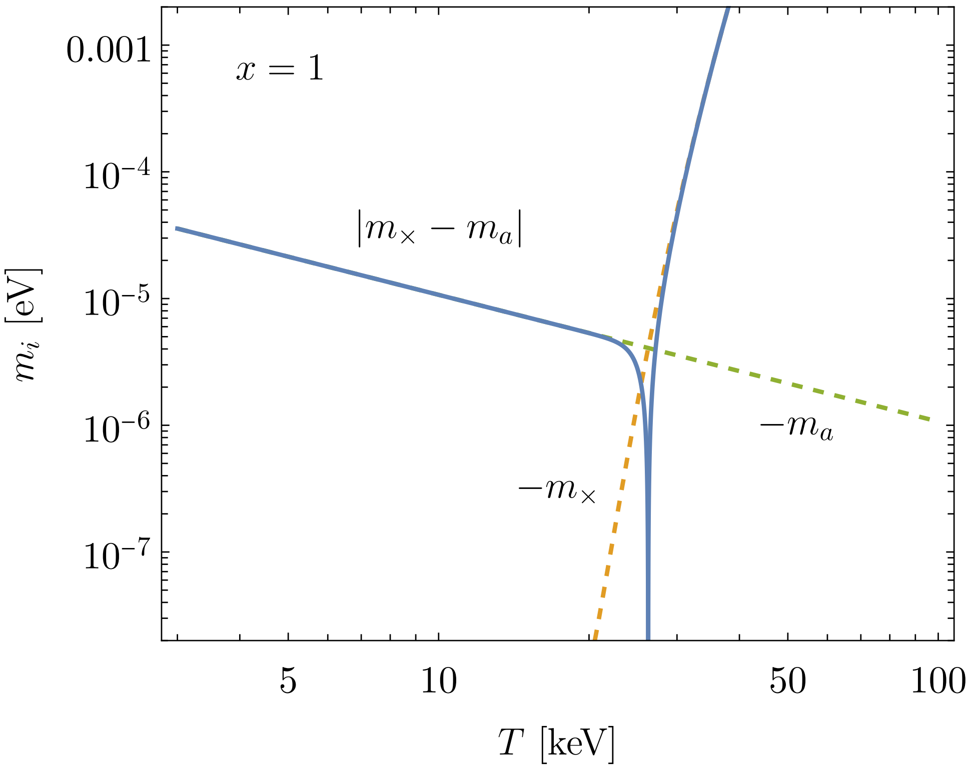
- Neutrinos decouple at $T \sim 1$ MeV and soon later e^+ annihilate e^-. For $T < m_{\mathrm{e}}$:

$$\underbrace{g_{\star s}(T > m_{\mathrm{e}})}_{\gamma, \mathrm{e}^\pm} T_\nu^3 = \underbrace{g_{\star s}(T < m_{\mathrm{e}})}_{\gamma} T^3 \Rightarrow \frac{T_\nu}{T} = \left(\frac{4}{11}\right)^{1/3}$$

In ΛCDM: Non-instantaneous ν decoupling and QED effects $\Rightarrow$ $N_{\text{eff}}^\nu = 3.043$

Cosmological evolution | $1\ \text{MeV} > T > 10\ \text{eV}$ (includes BBN)

- Photon-axion oscillations in presence of a magnetic field
  - ▷ Photons in a medium get an effective mass from interactions with free electrons
  - ▷ If primodial magnetic field $B_T \approx B_0(T/T_0)^2$ $\quad (B_0 = 3$ nG, $\lambda_0 \gtrsim 1$ Mpc)
    - $\Rightarrow$ photon mass separated in $m_{+,\times}(T)$ $\quad$ (for $A_+, A_\times$ parallel, perp to $\vec{B}$)
    - $\Rightarrow$ photon-axion mixing $m_{\phi\gamma}(T) = g_{\phi\gamma\gamma} B_T/2$ $\qquad m_a = -m_\phi^2/\omega$



[Raffelt, Stodolsky (1988)]

$$\left((\omega + \mathrm{i}\nabla)\mathbb{1} + \begin{pmatrix} m_+ & 0 & 0 \\ 0 & m_\times & m_{\phi\gamma} \\ 0 & m_{\phi\gamma} & m_a \end{pmatrix} \right) \begin{pmatrix} A_+ \\ A_\times \\ \phi \end{pmatrix} = 0$$

$\Rightarrow$ Resonance at $\boxed{T \equiv \overline{T} \approx 26\ \text{keV}}$

(independent of $x = \omega/T$)

Cosmological evolution | $1\ \mathrm{MeV} > T > 10\ \mathrm{eV}$ (includes BBN)

- Resonant photon-axion oscillations in presence of a magnetic field

  ▷ If $\rho_\phi \ll \rho_\gamma \approx \rho_\gamma^{\mathrm{eq}}$ and $\Gamma_\phi \approx 0$ [Ejlli, Dolgov (2014)]

$$P_\phi(x,T) \approx -\left(\frac{2\pi}{3H}\right)\frac{m^2_{\phi\gamma}}{m_a}\Bigg|_{T=\overline{T}} \propto \omega = x\overline{T}$$

(photons of any energy convert to axions at the same T)

$\Rightarrow$ 4.4% of CMB γ carrying $r_\gamma \equiv 6.3\%$ of ρ_γ convert to ϕ at $T \approx 26$ keV

(by averaging with BE number (energy) density distributions $\dfrac{x^{2(3)}}{e^x - 1}$ respectively)

$\Rightarrow$ Sudden drop of γ temperature: $\Delta T/T_0 = 1 - (1-r_\gamma)^{1/4} = 1.6\%$

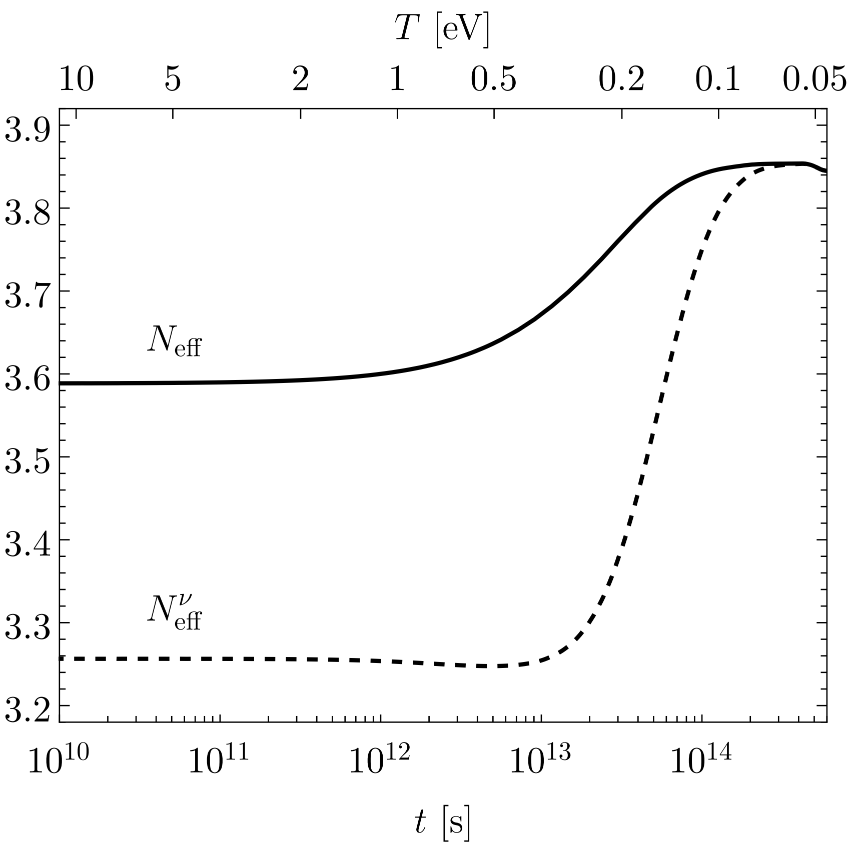
$\Rightarrow$ Sudden increase of N_{eff}:

$$\rho_\gamma^0\left[1+\frac{7}{8}N_{\mathrm{eff}}^0\left(\frac{4}{11}\right)^{4/3}\right] = \rho_\gamma\left[1+\frac{7}{8}N_{\mathrm{eff}}\left(\frac{4}{11}\right)^{4/3}\right] \qquad \rho_\gamma^{(0)} \equiv \frac{\pi^2}{15}T^4_{(0)}$$

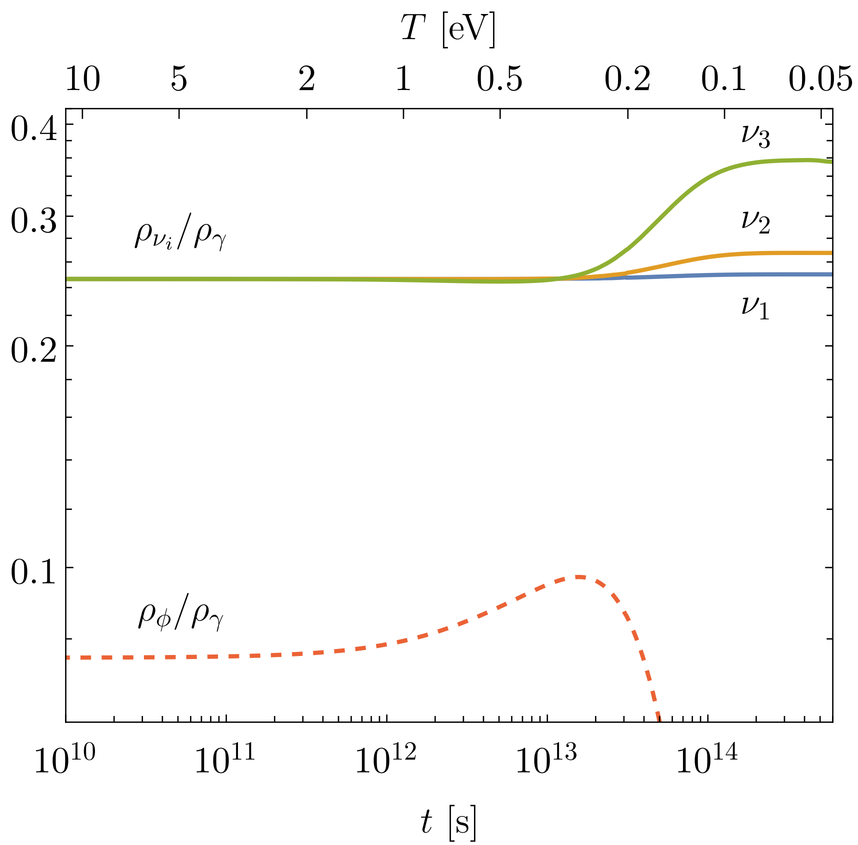
$$\Rightarrow \quad N_{\mathrm{eff}} = \underbrace{\frac{3.043}{1-r_\gamma}}_{N_{\mathrm{eff}}^\nu} + \underbrace{\frac{0.026}{1-r_\gamma} + \frac{r_\gamma}{(1-r_\gamma)\frac{7}{8}(\frac{4}{11})^{4/3}}}_{\Delta N_{\mathrm{eff}}} \quad \Rightarrow \quad \begin{cases} N_{\mathrm{eff}} \approx 3.58 \\ N_{\mathrm{eff}}^\nu \approx 3.25 \end{cases}$$

Cosmological evolution | $T < 10$ eV

- Neutrinos and ϕ enter in thermal contact at $T \approx m_\phi$ through $\phi \leftrightarrow \nu\bar{\nu}$
  - ▷ n_ϕ and ρ_ϕ of thermal (initial) plus non-thermal (after γ conversion) majorons at $T = 10$ eV replaced by those of equilibrium for given T_ϕ and μ_ϕ. Same for ν's.
  - ▷ Time evolution by solving numerically system of DE $\Rightarrow$ ρ_i, N_{eff}, Γ_{int} [Escudero (2020)]

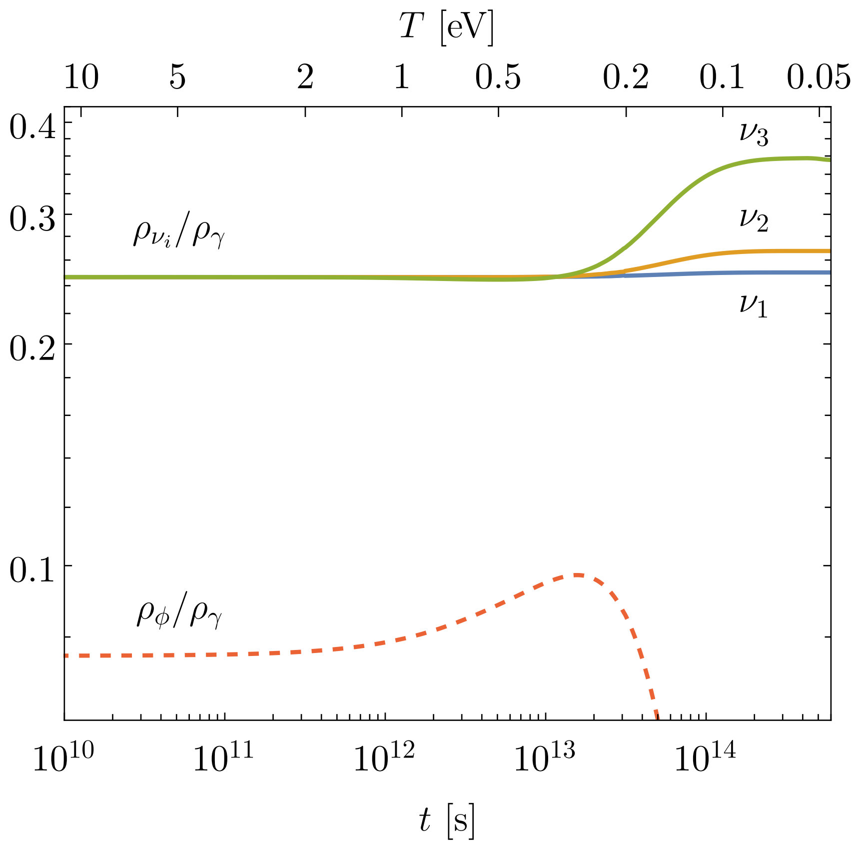


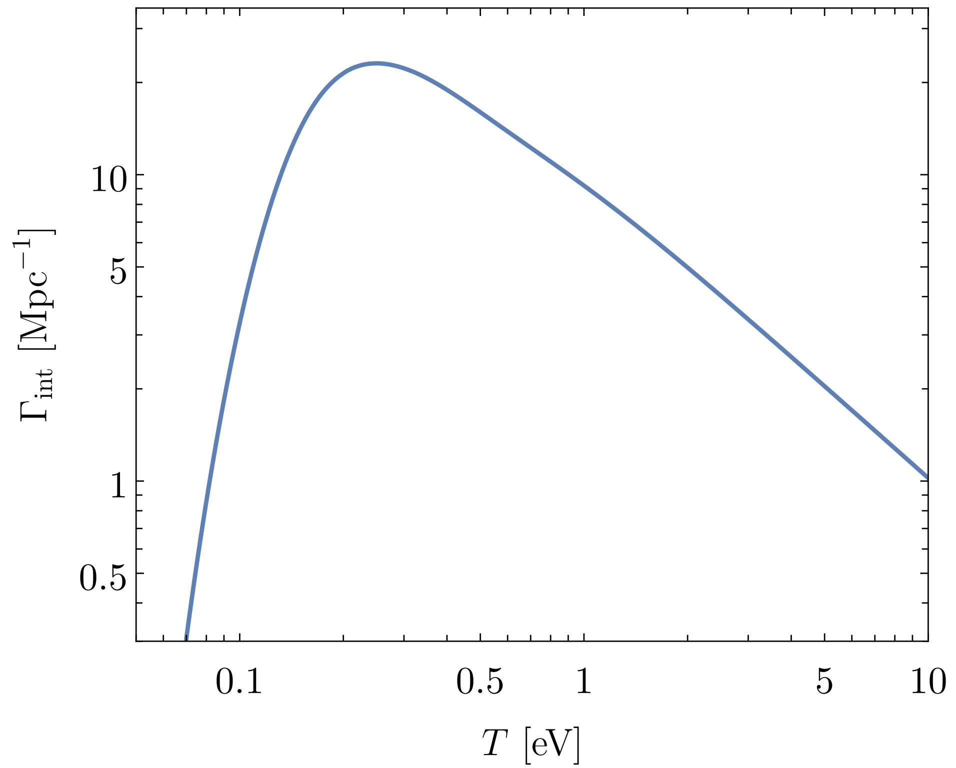
$\Leftrightarrow$



Cosmological evolution | $T < 10$ eV

- Neutrinos and ϕ enter in thermal contact at $T \approx m_\phi$ through $\phi \leftrightarrow \nu\bar{\nu}$
  - ▷ Increased $N_{\rm eff} \approx 3.85$ due to energy transfer from ϕ to ν's (mostly ν_3) when ϕ becomes NR ($T \lesssim 2m_\phi$) and later when it decays ($t \gtrsim 10\,\tau_\phi$)
  - ▷ $\Gamma_{\rm int}$ peaks at $T \sim m_\phi \Rightarrow$ reduction of neutrino free streaming at recombination ($t \approx 10^{13}$ s, $T \approx 0.26$ eV)

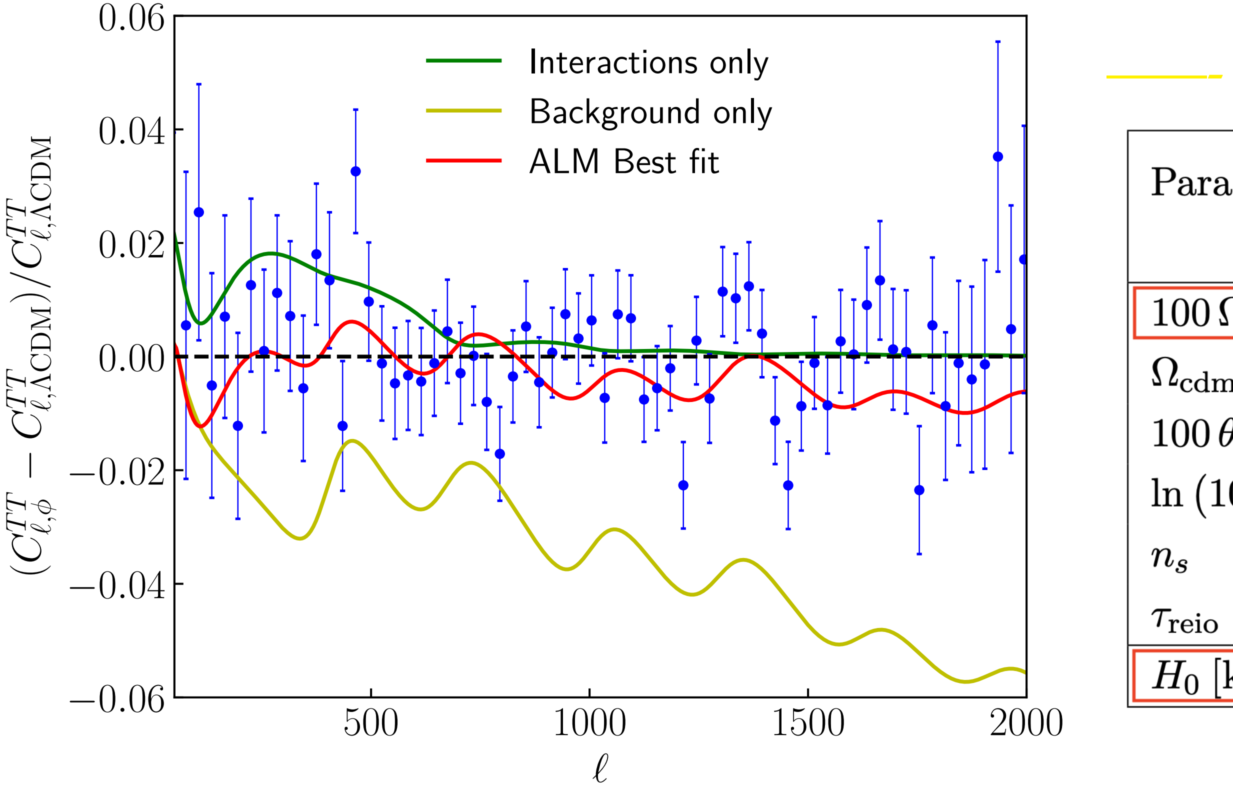




Cosmological evolution | $T < 10$ eV

- Effect on CMB and cosmological parameters [CLASS + MontePython]

TT power spectrum (relative to ΛCDM)

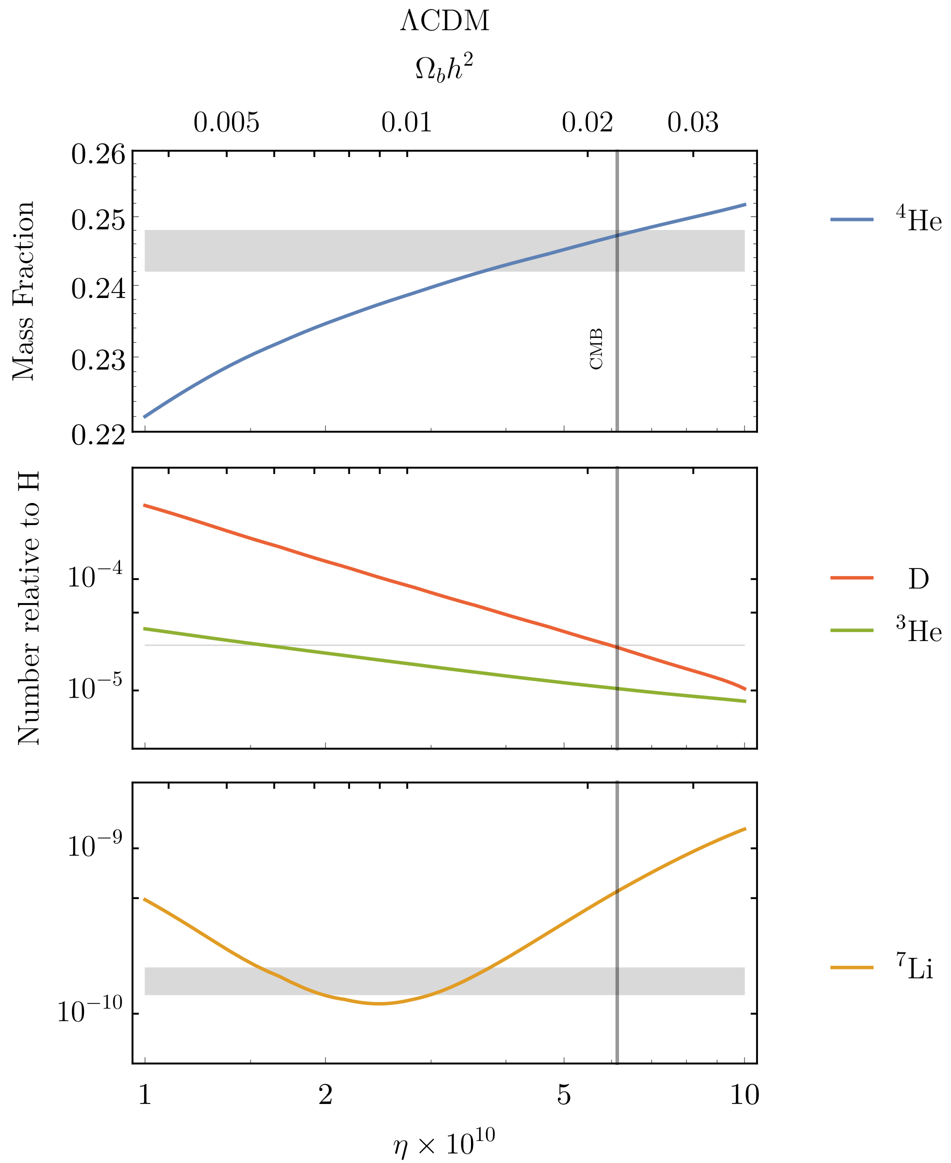


Parameter	ΛCDM	ALM $m_\phi = 0.5\,$eV $\tau_\phi = 3.5 \times 10^{12}\,$s
$100\,\Omega_b h^2$	2.242 ± 0.015	2.295 ± 0.014
$\Omega_{\rm cdm} h^2$	0.119 ± 0.001	0.129 ± 0.001
$100\,\theta_s$	1.0420 ± 0.0003	1.0407 ± 0.0003
$\ln(10^{10} A_s)$	3.046 ± 0.015	3.062 ± 0.016
n_s	0.967 ± 0.004	0.991 ± 0.004
$\tau_{\rm reio}$	0.055 ± 0.008	0.056 ± 0.008
H_0 [km/s/Mpc]	67.71 ± 0.44	71.4 ± 0.5

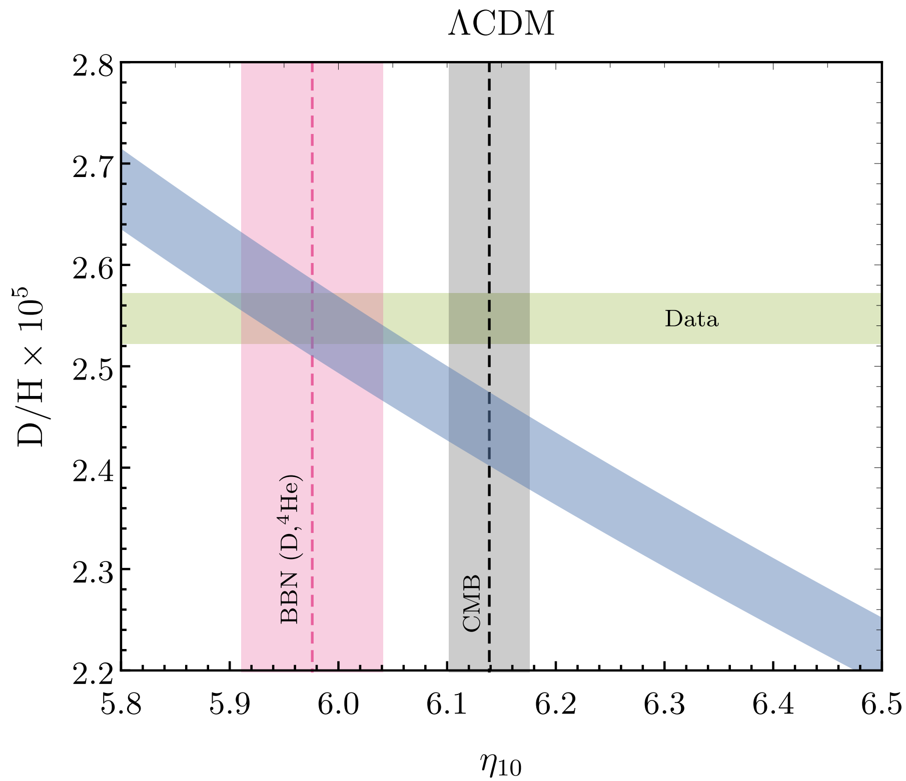
▷ H_0 in ALM model compatible with value from SNe-Ia !! (73.01 ± 0.99 km/s/Mpc)

▷ $\Omega_b h^2$ in ALM model larger than in ΛCDM $\Rightarrow$ how about BBN predictions !?

BBN $\Leftrightarrow$ primordial abundances as a function of $\eta_{10} \equiv 10^{10} \dfrac{n_b}{n_\gamma(T_0)} \approx 274\,\Omega_b h^2$



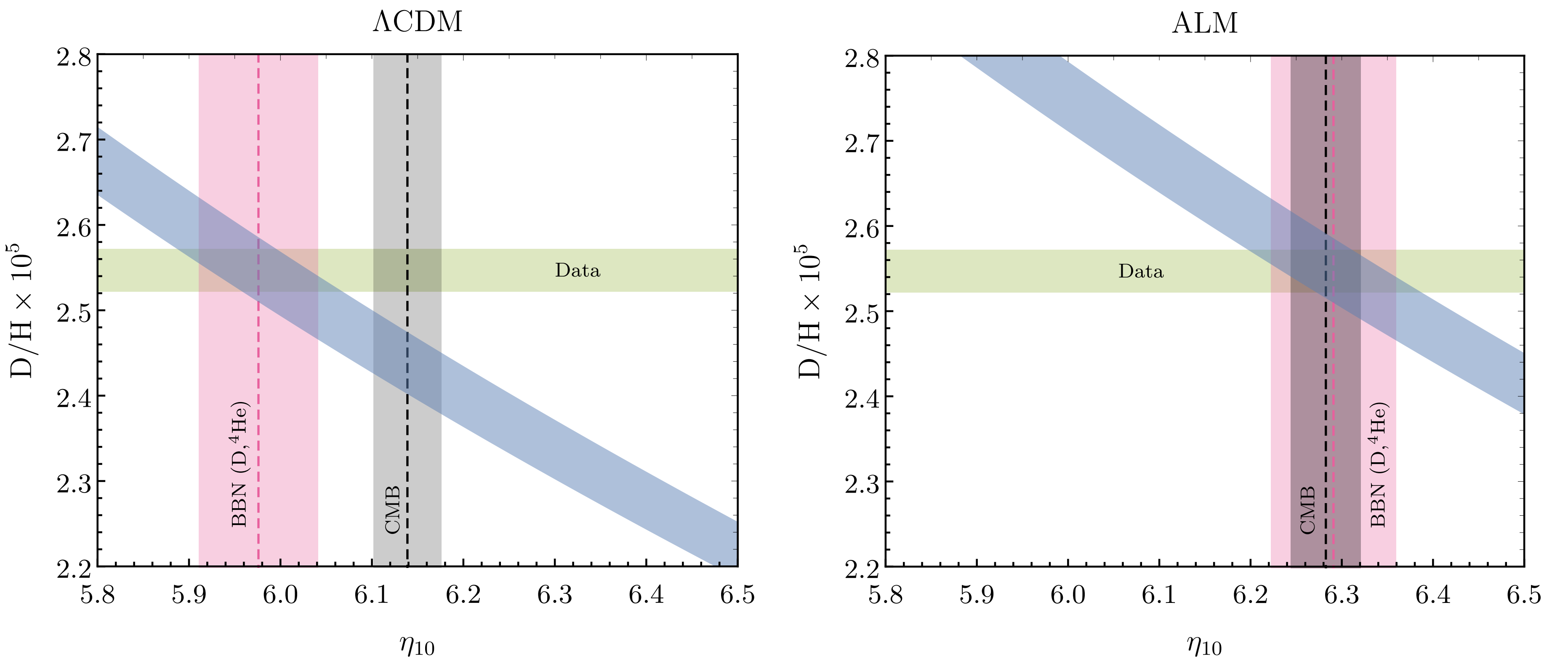
- From CMB obs [CLASS+MontePython]:
  $\eta_{10}^{\rm CMB}\big|_{\Lambda\rm CDM} = 6.14 \pm 0.04$
- From abundance of D and ^{4}He [PRIMAT]:
  $\eta_{10}^{\rm BBN}\big|_{\Lambda\rm CDM} = 5.98 \pm 0.07 \Rightarrow 2\sigma$!



- And lithium problem (10σ) !!

BBN | Deuterium (2σ) problem

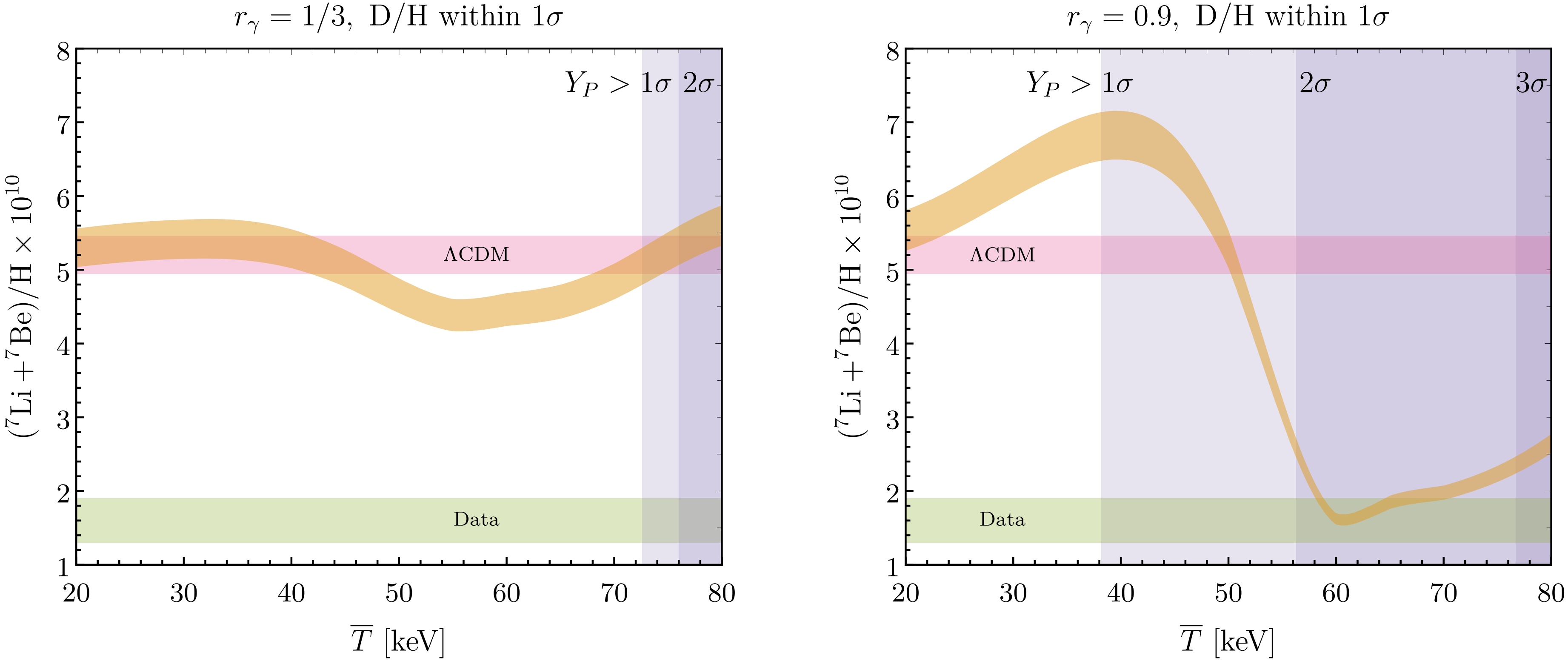
- $\boxed{\text{ALM model}}$ photon cooling ($r_\gamma = 0.063$) at $\overline{T} = 26$ keV ($t \approx 1900$ sec $\approx \frac{1}{2}$ hour)
  - ▷ From CMB observables [`CLASS` + `MontePython`]:
    $\eta_{10}^{\rm CMB}\big|_{\rm ALM} = 6.28 \pm 0.04$
  - ▷ From abundance of D and ^{4}He [modified `PRIMAT`] (nucl react $\sim$ untouched):
    $\eta_{10}^{\rm BBN}\big|_{\rm ALM} = 6.29 \pm 0.07 \Rightarrow$ perfect agreement ! $\approx (1 - r_\gamma)^{-3/4}\, \eta_{10}^{\rm BBN}\big|_{\Lambda\rm CDM}$



BBN — Lithium (10σ) problem

- Generalized ALM model
  - ▷ Take higher $\overline{T}$ that would require higher m_ϕ while keeping ϕ decay at recombination
  - ▷ Use constraints to yield D/H within 1σ and ^{4}He (Y_P) under control:

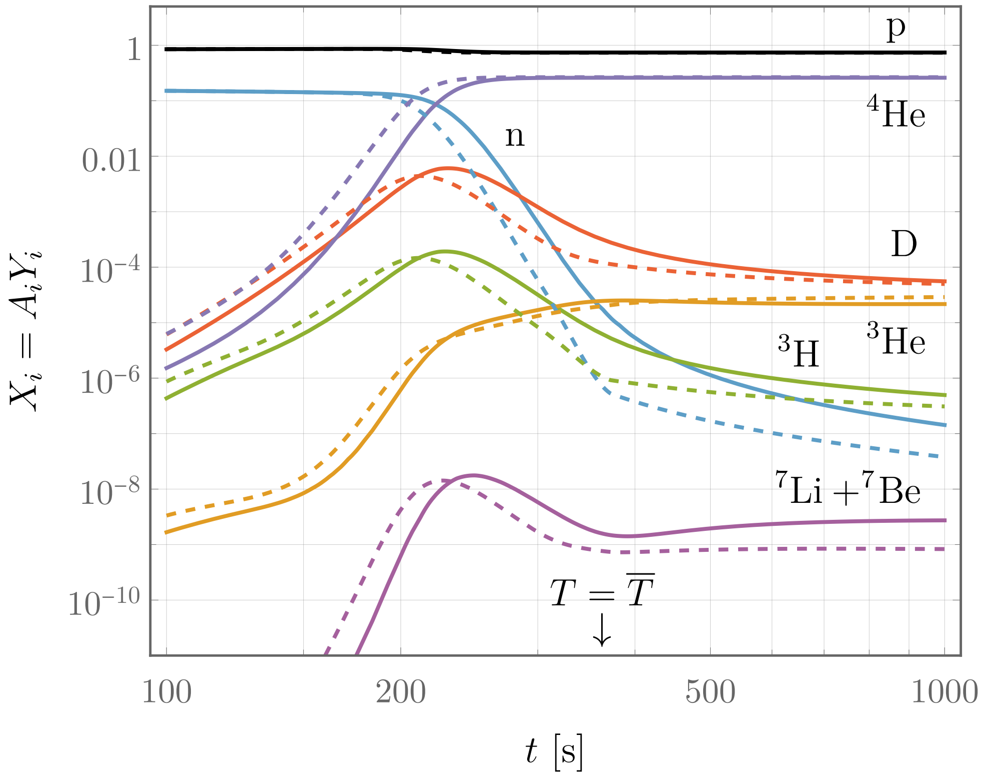
$r_\gamma = 1/3$ (multiple oscillations) $\qquad$ $r_\gamma = 0.9$ (several axions?)



▷ Extreme cooling ($r_\gamma = 0.9$) at $\overline{T} \approx 60$ keV does the job !! $\quad (\Leftrightarrow \overline{\eta}_{10}^{\text{BBN}} = (1 - r_\gamma)^{3/4} \eta_{10}^{\text{BBN}} \approx 11.4)$

BBN | Lithium (10σ) problem

- Generalized ALM model



——- ΛCDM

- - - - $r_\gamma = 0.9$, $\overline{T} = 60$ keV

($t \approx 340$ sec ≈ 6 min)

▷ Larger $\overline{\eta}_{10} \Rightarrow$ BBN starts earlier than in ΛCDM

$\Rightarrow$ Excess of heavier nuclei (^{3}He, ^{4}He) relative to more reactive n, D, ^{3}H

▷ Production of ^{7}Li and (particularly) ^{7}Be interrupted 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 $\Rightarrow$ one may expect a light ALM

- In the early universe a primordial magnetic field may induce the conversion of CMB photons into axions $\Rightarrow$ larger N_{eff} and a larger η after BBN, than in ΛCDM

- The ALM becomes NR and decays into neutrinos near recombination

- The $\boxed{\text{ALM model}}$ ($r_\gamma = 6.3\%$ and $\overline{T} = 26$ keV):

  – alleviates the H_0 tension

  – provides a *good* fit to CMB observables

  – yields the *right* deuterium abundance

- A $\boxed{\textit{generalized}\ \text{ALM model}}$ ($r_\gamma = 90\%$ and $\overline{T} \approx 60$ keV):

  – deuterium, helium and *also* lithium abundance *consistent* with observations