Big Bang Nucleosynthesis
in photon to dark radiation models

Plan de Recuperación, Transformación y Resiliencia

GOBIERNO DE ESPAÑA — MINISTERIO DE UNIVERSIDADES

Financiado por la Unión Europea
NextGenerationEU

UNIVERSIDAD DE GRANADA

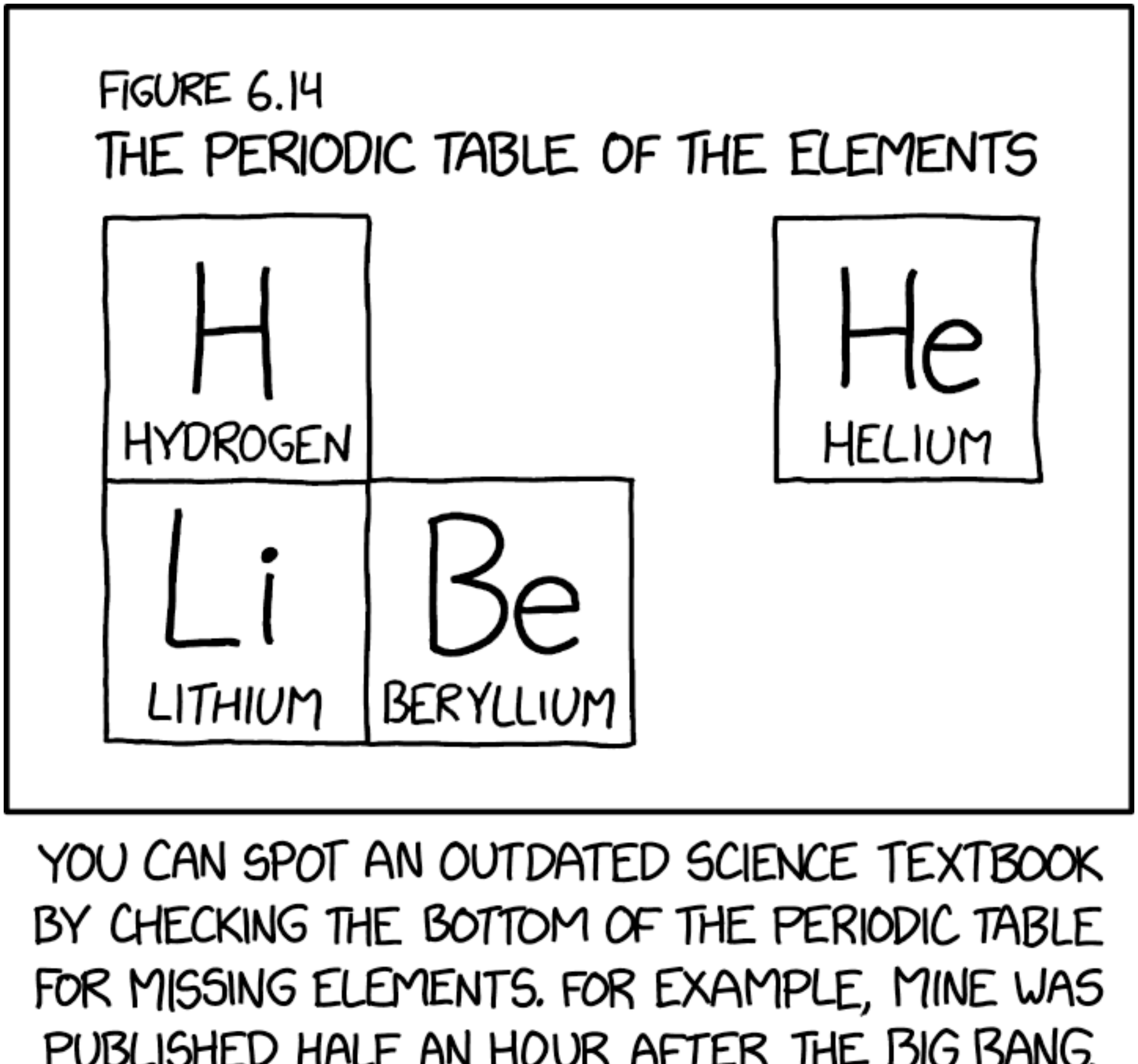
Antonio J. Cuesta — 3rd MeV2TeV Workshop 16-17 Feb 2023, Córdoba (Spain)

Credit: Megan Strand (University of Illinois Chicago)

Outline

- *Introduction to Standard BBN*
- *ALPs in the Early Universe and the H_0 tension*
- *Primordial abundances in the presence of light relics*
- *Conclusions*

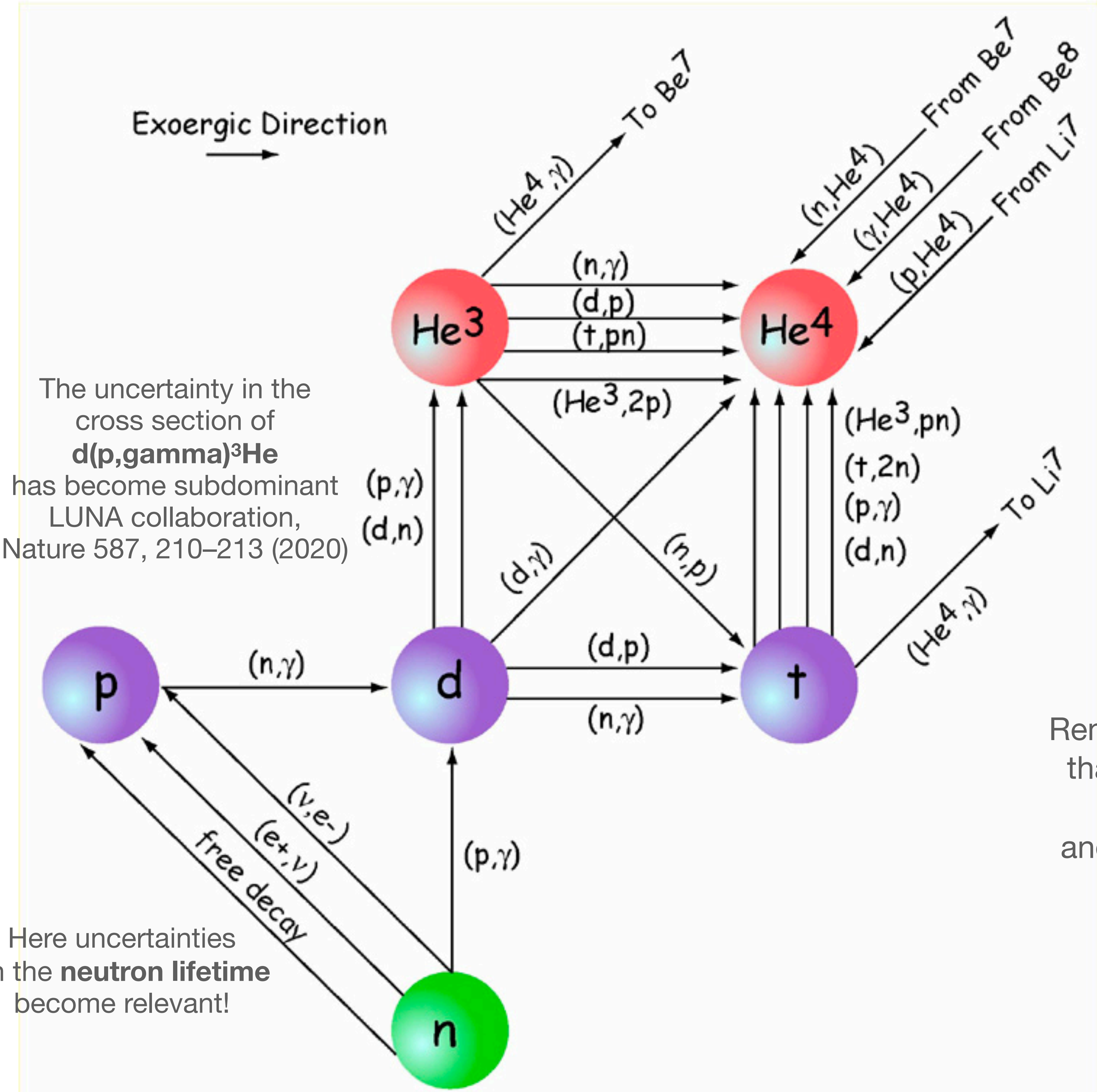
BBN: Big Bang Nucleosynthesis



Traditionally, BBN is considered one of the 3 pillars of the Hot Big Bang Model (together with the expansion of the universe, and the cosmic microwave background)

Source: XKCD
https://xkcd.com/2723/

BBN reaction network



The uncertainty in the cross section of **d(p,gamma)^{3}He** has become subdominant LUNA collaboration, Nature 587, 210–213 (2020)

Here uncertainties on the **neutron lifetime** become relevant!

+ traces (abundances < 10^{-13}) of ^{6}Li and A>8 elements (Observationally challenging)

Note: **Tritium and ^{7}Be are radioactive**, but on a **time scale >> BBN**
$T_{1/2}$=12.32 years for ^{3}H
$T_{1/2}$=53.22 days for ^{7}Be

Remember from basic nuclear physics courses that the binding energy of deuterium is small (“**deuterium bottleneck**”) and no stable elements of mass 5 and 8 exist (which suppresses A>8 abundances)

Standard BBN (SM+Standard cosmology)

Standard Big Bang Nucleosynthesis has ONLY ONE free parameter:

The baryon-to-photon ratio η

(the ratio of the number of baryons to the number of photons, fixed by baryogenesis)

$$\eta = \frac{n_b}{n_\gamma} = \frac{\rho_b/m_b}{n_\gamma} = \frac{\frac{\Omega_b h^2}{m_b}\frac{3\times(100\text{km s}^{-1}\,\text{Mpc}^{-1})^2}{8\pi G}}{\frac{2\zeta(3)}{\pi^2\hbar^3c^3}(k_B T_{CMB})^3} = 2.7374865\times 10^{-8}\Omega_b h^2$$

$m_b \simeq X(^1H)m_H + X(^4He)m_{He}/4$

Is the (mass-fraction weighted) mass of a baryon
taking into account the binding energies
(Note that 99.99% of baryons are in Hydrogen-1 or Helium-4 nuclides)

Since Tcmb=2.7255±0.0006 K (Fixsen 2009) is very precisely measured, the **conversion factor** between the **baryon-to-photon ratio** and the **physical baryon density** is **model-independent**

TECHNICALLY, all the **cross sections** of the nuclear reactions involved,
and the **neutron lifetime** are also parameters, but they are external to BBN
Besides, the **number of neutrinos** also plays a role, but that falls beyond the Standard Model

BBN codes

http://www2.iap.fr/users/pitrou/primat.htm

PRIMAT *(PRImordial MATter)*

PRIMAT is a *Mathematica* code which computes the abundances of elements at the end of the big-bang nucleosynthesis (BBN).
It can be downloaded by registering at http://www2.iap.fr/users/pitrou/primat.htm

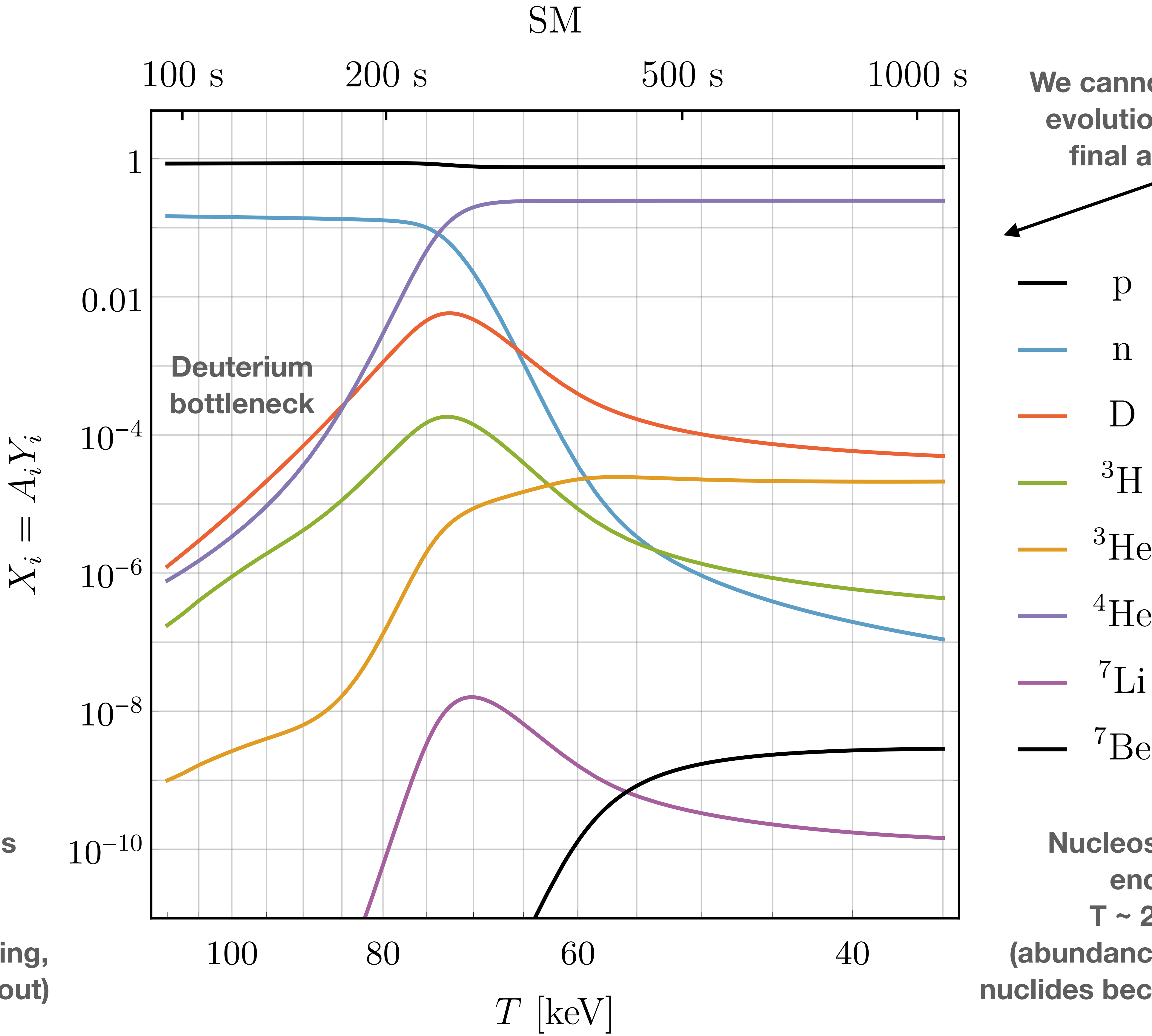
Version 0.2.0 (21/11/2020)

Short description

*The implementation follows the presentation of the companion paper Pitrou, Coc, Uzan, Vangioni, Physics Reports, 04, (2018) 005.
All equation numbers, when non specified, refer to this companion paper, in its arXiv version (arXiv:1801.08023).

Other BBN codes: PArthENoPE (https://parthenope.na.infn.it/), AlterBBN (https://alterbbn.hepforge.org/)

Time evolution of abundances



We cannot observe the evolution, only these final abundances

Nucleosynthesis starts at T ~ 1 MeV (neutrino decoupling, weak rate freeze-out)

Nucleosynthesis ends at T ~ 20 keV (abundances of stable nuclides become constant)

Observations of primordial abundances

The observed abundances are usually quoted as
number densities (not mass fractions) **normalized to the hydrogen number density.**
Except **Helium**, which is quoted as the **baryon fraction** (or “pseudo-mass fraction”)

$$Y_p = \frac{4n_{He}}{4n_{He} + n_H} = \frac{2n/p}{1 + n/p} = 0.25$$ (For $n/p \simeq 1/7$)

Values recommended by Particle Data Group (2022)
Review on Big Bang Nucleosynthesis

$$(\mathrm{D/H})_\mathrm{p} = (2.547 \pm 0.025) \times 10^{-5}$$ 1% precision

$$Y_p = 0.245 \pm 0.003$$ 1% precision

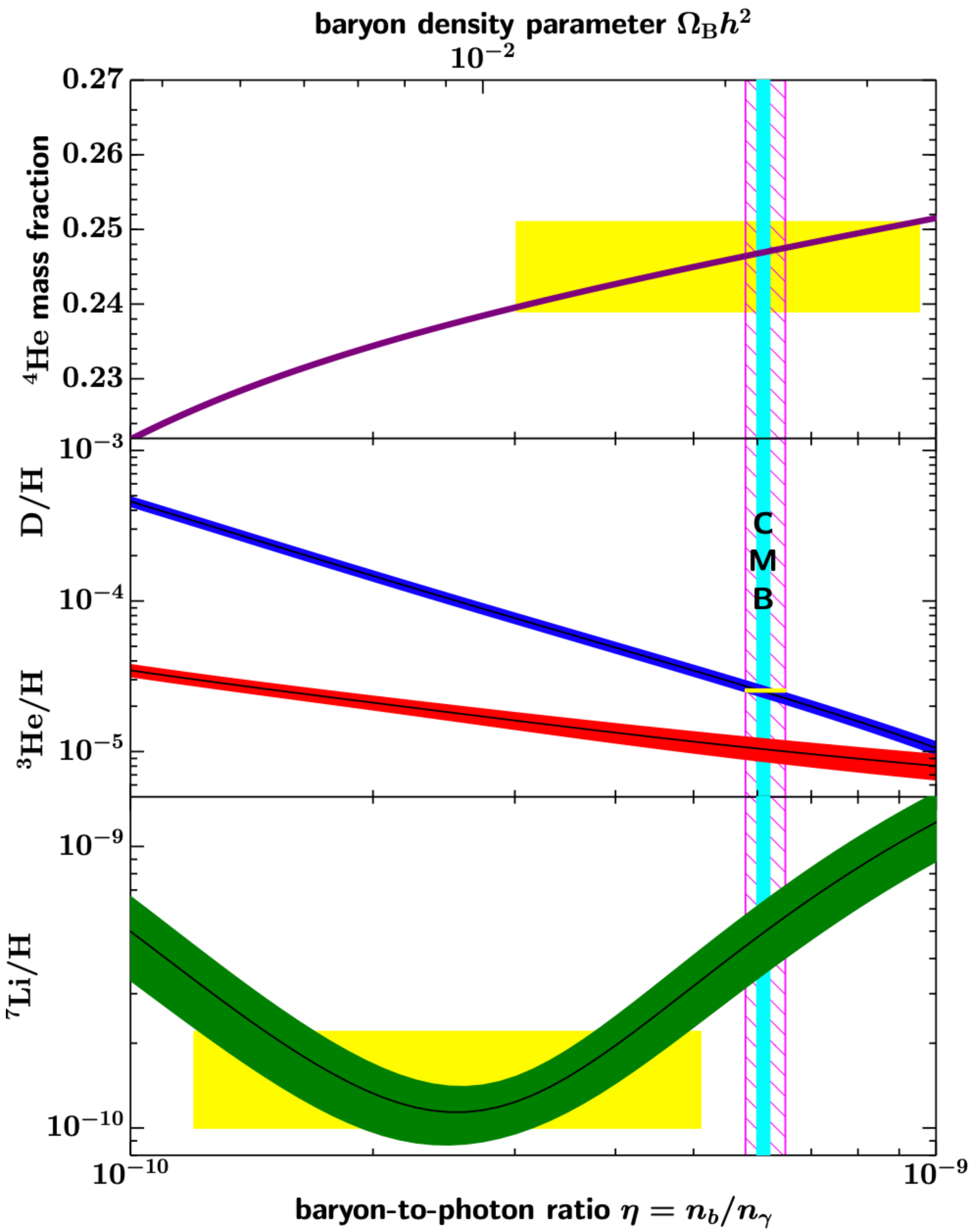
$$(\mathrm{Li/H})_\mathrm{p} = (1.6 \pm 0.3) \times 10^{-10}$$ 20% precision

This abundance receives primordial contributions from both 7Li and 7Be (7Be is dominant, but it is radioactive)

The Lithium abundance has been questioned: Fields, B.D. & Olive, K.A. (2022)
Implications of the non-observation of 6Li in halo stars for the primordial 7Li problem
JCAP 10, id.078, pp.1-25 [arXiv:arXiv:2204.03167]

Only upper limits on 3He, so usually ignored in this discussion

Schramm plot (theory + observations)



Note that when the theory lines have a larger slope (Not horizontal) they lead to better constraints in eta. Hence Deuterium is a good "baryometer", but Helium isn't.

Yellow regions indicate **observational** abundances (Only shown the region which intersects the theory curves, so we can clearly see the eta values allowed by observed abundances of that particular nuclide)

The yellow regions for Deuterium and Lithium do NOT overlap for ANY value of η ==> Cosmological lithium problem

Another way to state this problem is that, in **Standard BBN**, the baryon-to-photon ratio allowed by deuterium observations predicts a theoretical primordial abundance of Lithium which is **a factor of 3 above the obsevations**

CMB constraints on $\Omega_b h^2$ agree very well with η values from primordial deuterium observations + Standard BBN

"Schramm plot" Schramm & Wagoner (1977)
Element Production in the Early Universe.
Ann. Rev. Nucl. Sci. 27: 37-74

The BBN and CMB values for the baryon-to-photon ratio are very close: $\eta = 6.0 \times 10^{-10}$ vs. $\eta = 6.1 \times 10^{-10}$

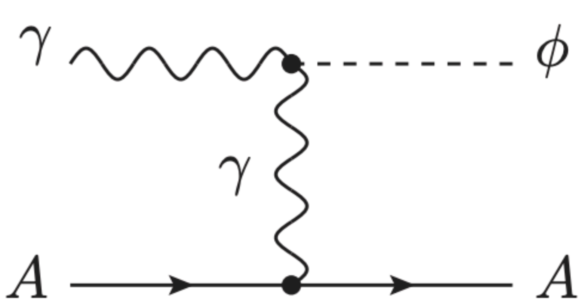
Axion-like particles in the Early Universe: the majoron

What if we have a mechanism that can transfer energy from **photons** to **dark radiation**, due to **resonant production** in the **primordial magnetic field** ($B \lesssim 1\mathrm{nG}$)

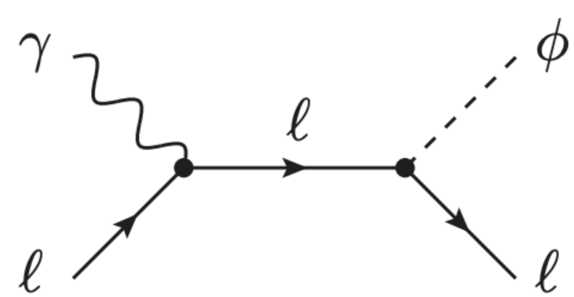
For example, we can have an axion-like particle like **the majoron** ϕ

Cosmology of an Axion-Like Majoron. A.J.Cuesta, J.I. Illana, M. Masip, M. Gómez
Journal of Cosmology and Astroparticle Physics* 04 (*2022*) 009 *[arXiv:2109.07336]

✗



✗



✔

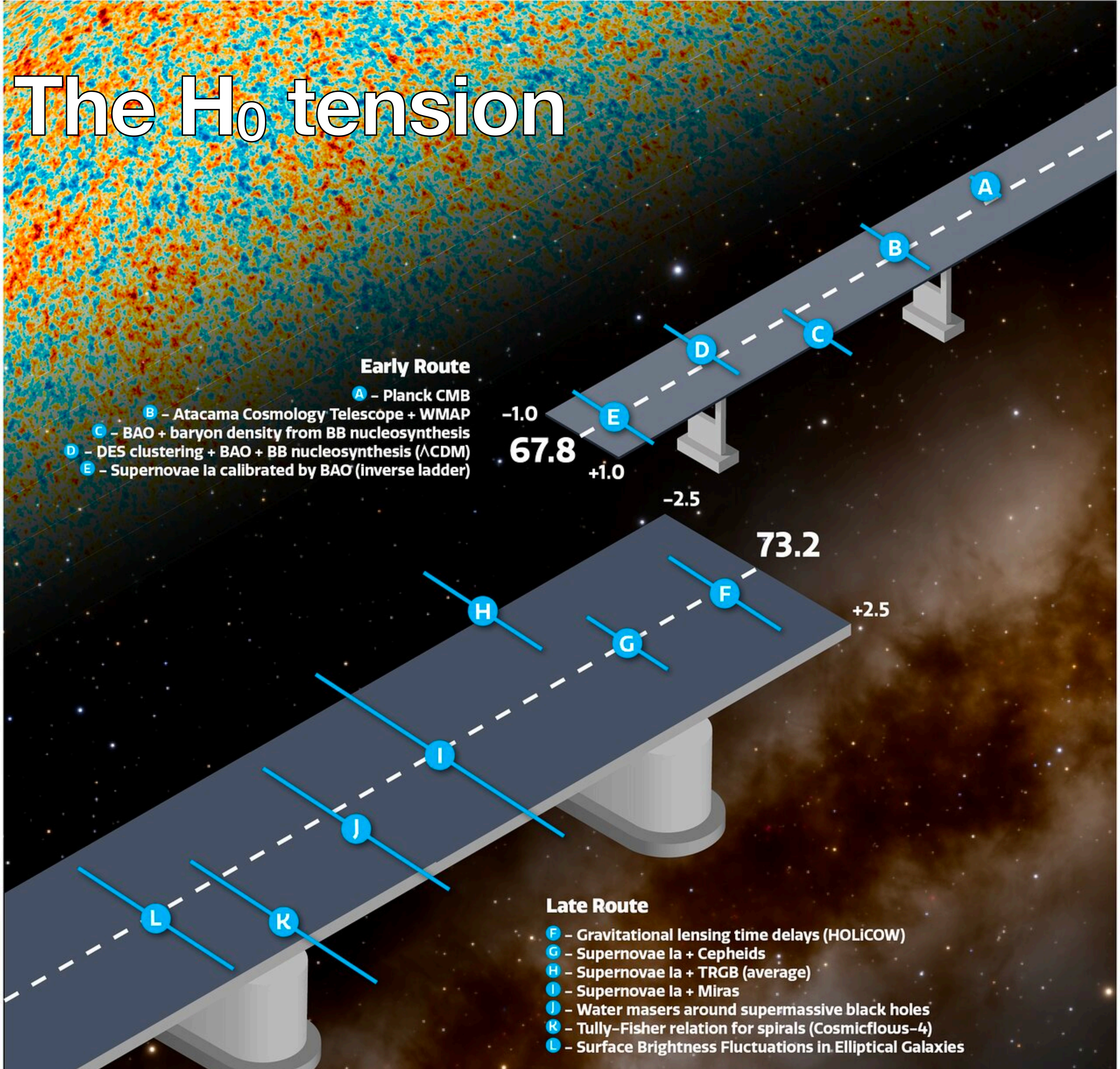
$$\gamma \overset{\vec{B}}{\longleftrightarrow} \phi$$

Our majoron has tiny couplings to charged leptons. Therefore, the **Primakoff and Compton production of majorons** is very inefficient

However, the presence of a primordial magnetic field can mediate **resonant production of majorons** in the primordial plasma **at a very specific temperature** (a very small range of temperatures)

Majoron parameters: mass (~eV) and interaction rate (only relevant before recombination)
Resonance parameters: fraction of photons oscillating into scalars, and temperature (time) at this transition

The H_0 tension



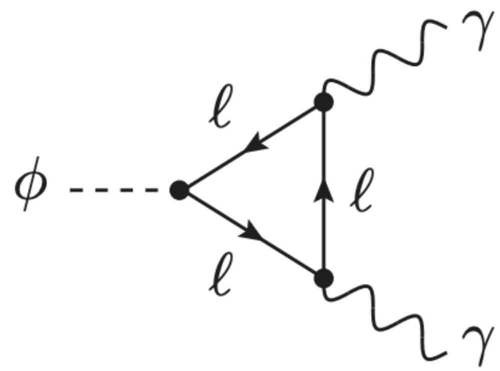
Credit: NOIRLab NSF

Solving the Hubble tension with the majoron

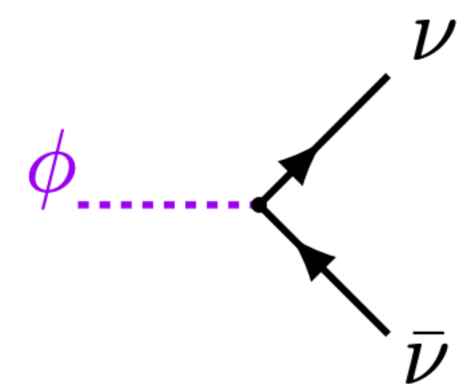
Cosmology of an Axion-Like Majoron. A.J.Cuesta, J.I. Illana, M. Masip, M. Gómez
Journal of Cosmology and Astroparticle Physics 04 (*2022*) 009 *[arXiv:2109.07336]*

Just before recombination, 3 major things happen:

1) the majorons (that evolved as a decoupled species) become in thermal contact with the neutrinos, **damping their free-streaming**
2) Since m_ϕ is similar to the temperature at recombination,
These particles will become **non-relativistic** when $T < m_\phi/3$
losing energy with the expansion **slower than radiation** (e.g. neutrinos)
3) When the temperature is lower than m_ϕ , the reaction $\phi \leftrightarrow \nu\bar{\nu}$
only happens in one direction, making them vanish into **neutrinos (not photons)**



✗



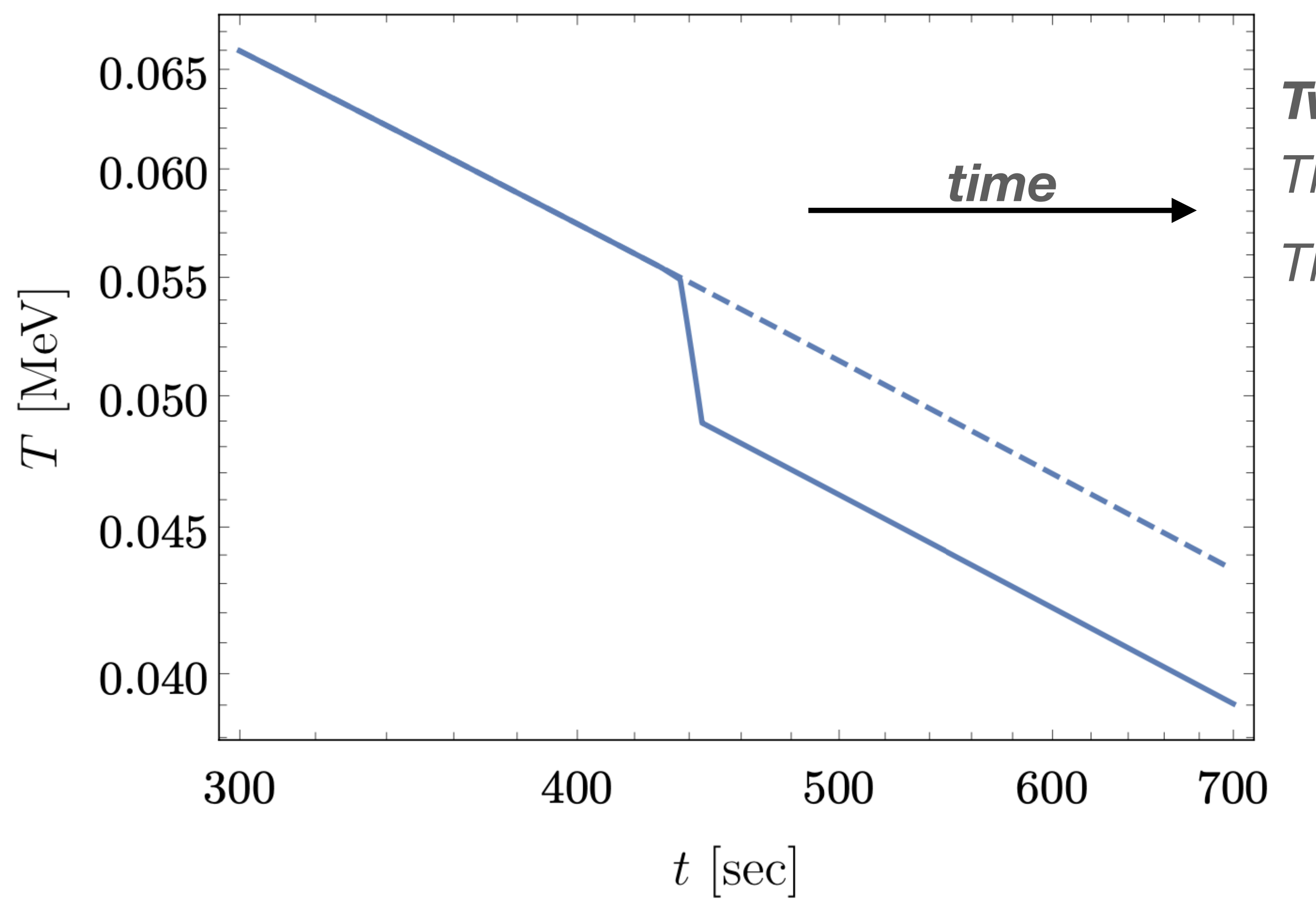
✔

$$\phi \leftrightarrow \nu\bar{\nu}$$

The result is a **net increase in the expansion rate** of the Universe
without spoiling the fit to CMB observations, thus reducing the Hubble tension.

Precision early universe thermodynamics made simple: Neff and neutrino decoupling in the Standard Model and beyond. Escudero, M. Journal of Cosmology and Astroparticle Physics, 05 (2020) 048. [arXiv:2001.04466]

Changing the thermal history of the Early Universe

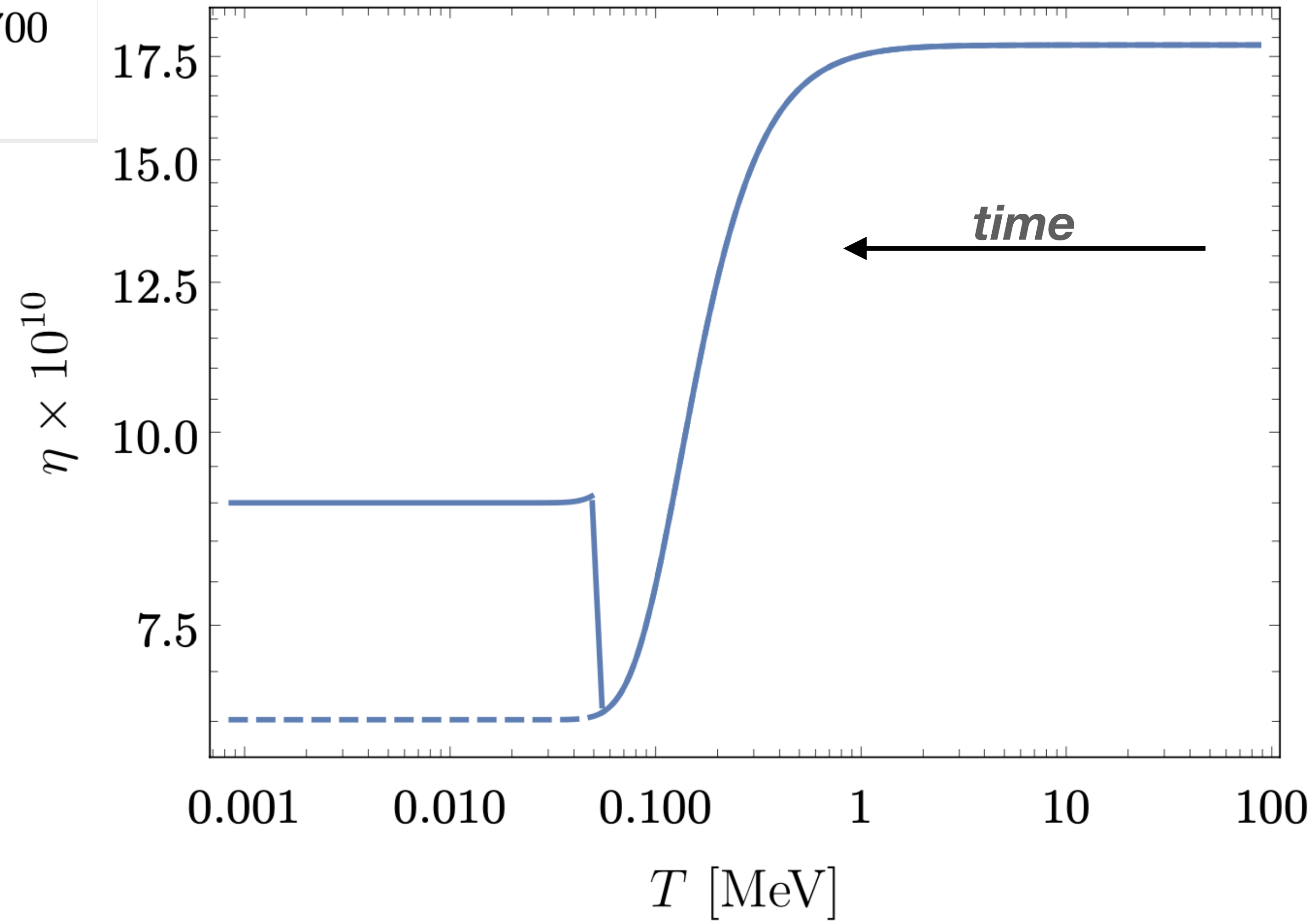


Two parameters (besides the baryon-to-photon ratio):
*The **fraction** of photon energy becoming dark radiation r_γ*
*The **temperature** at which the resonance happens $\overline{T}$*

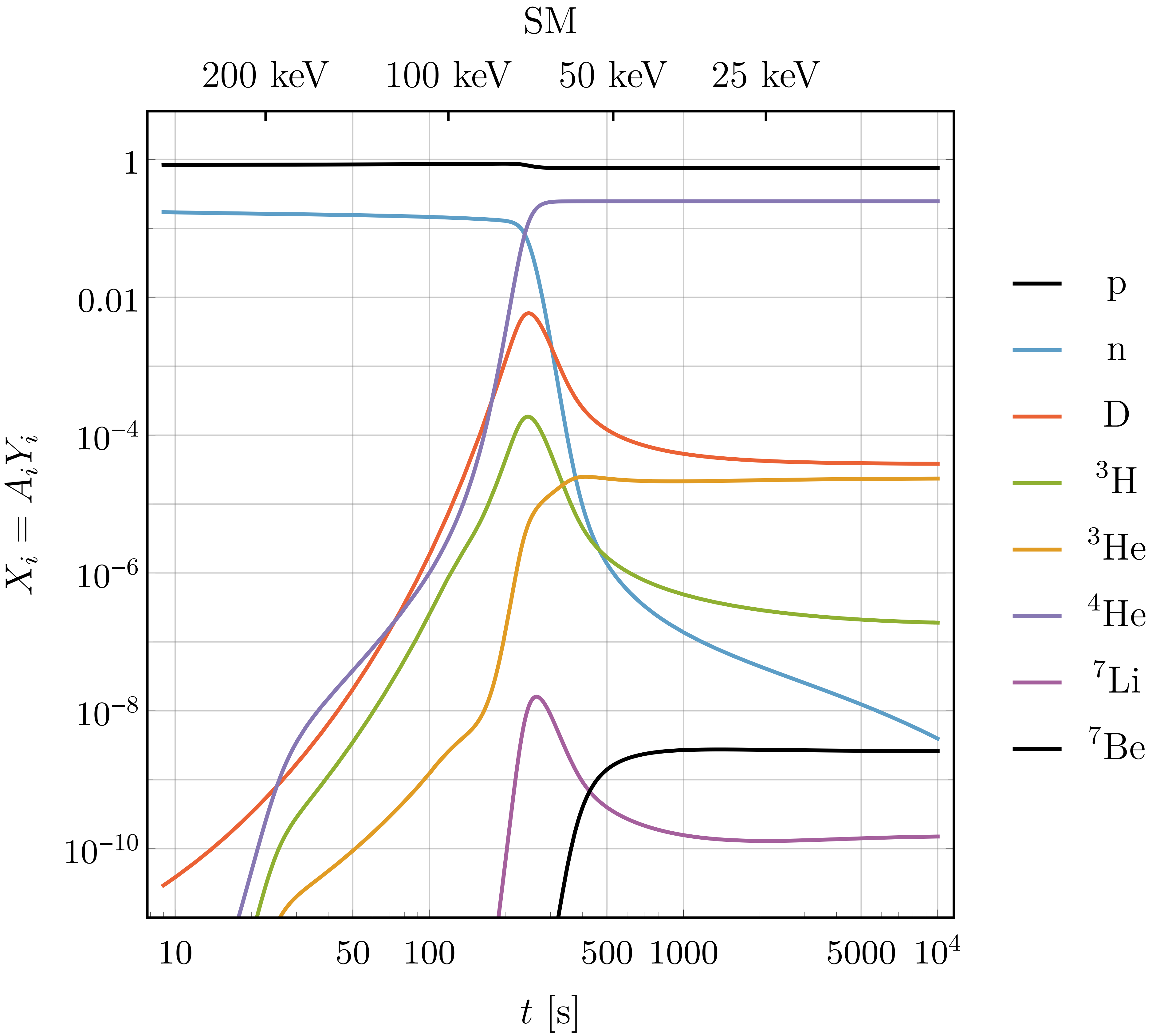
This resonance produces a sudden drop in the temperature of the Universe…

…while also enhancing the baryon-to-photon ratio (due to the loss of photons)

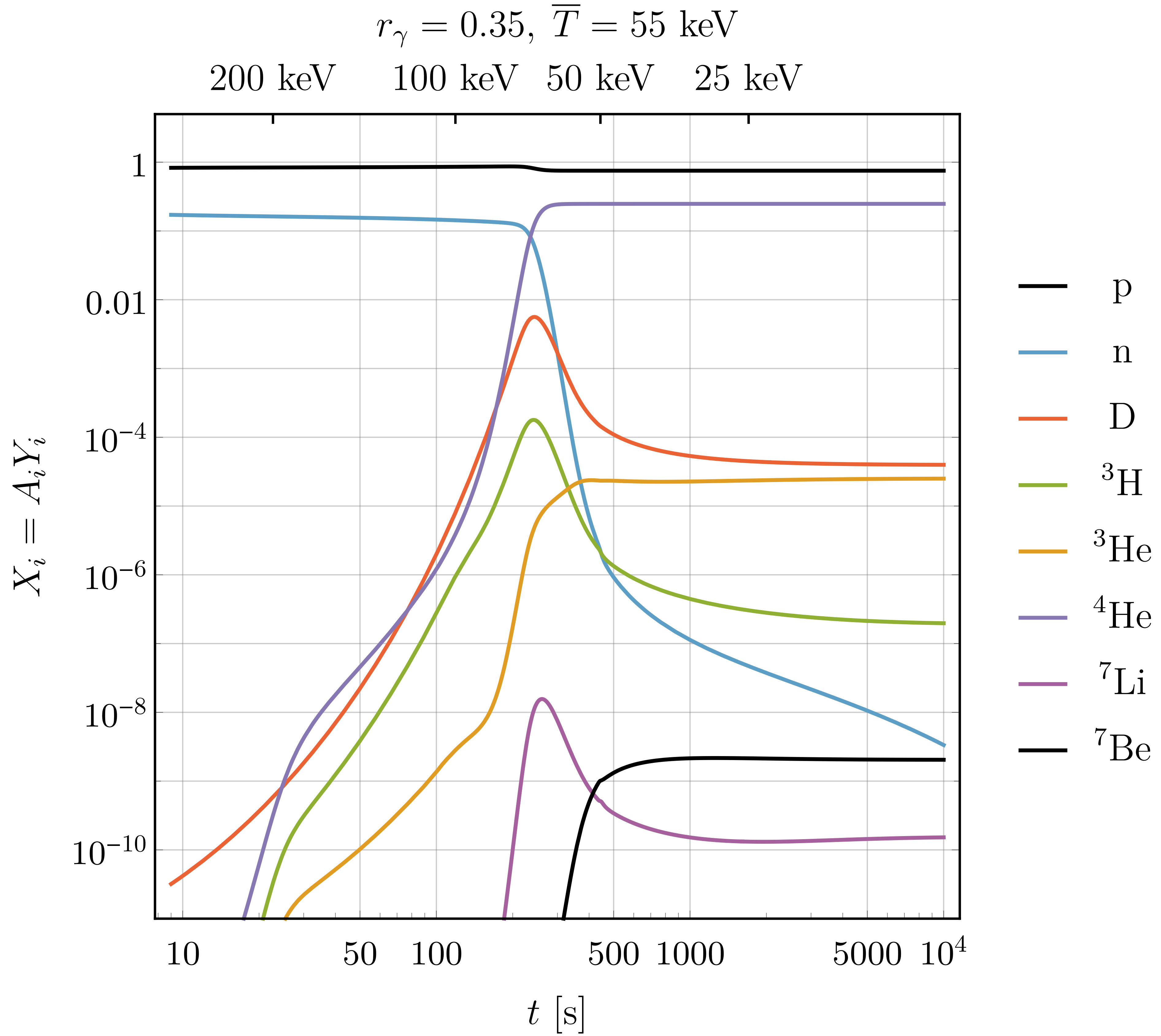
This is useful, since BBN prefers lower values than CMB (which happens at a later time)
—> this way we can accommodate BOTH



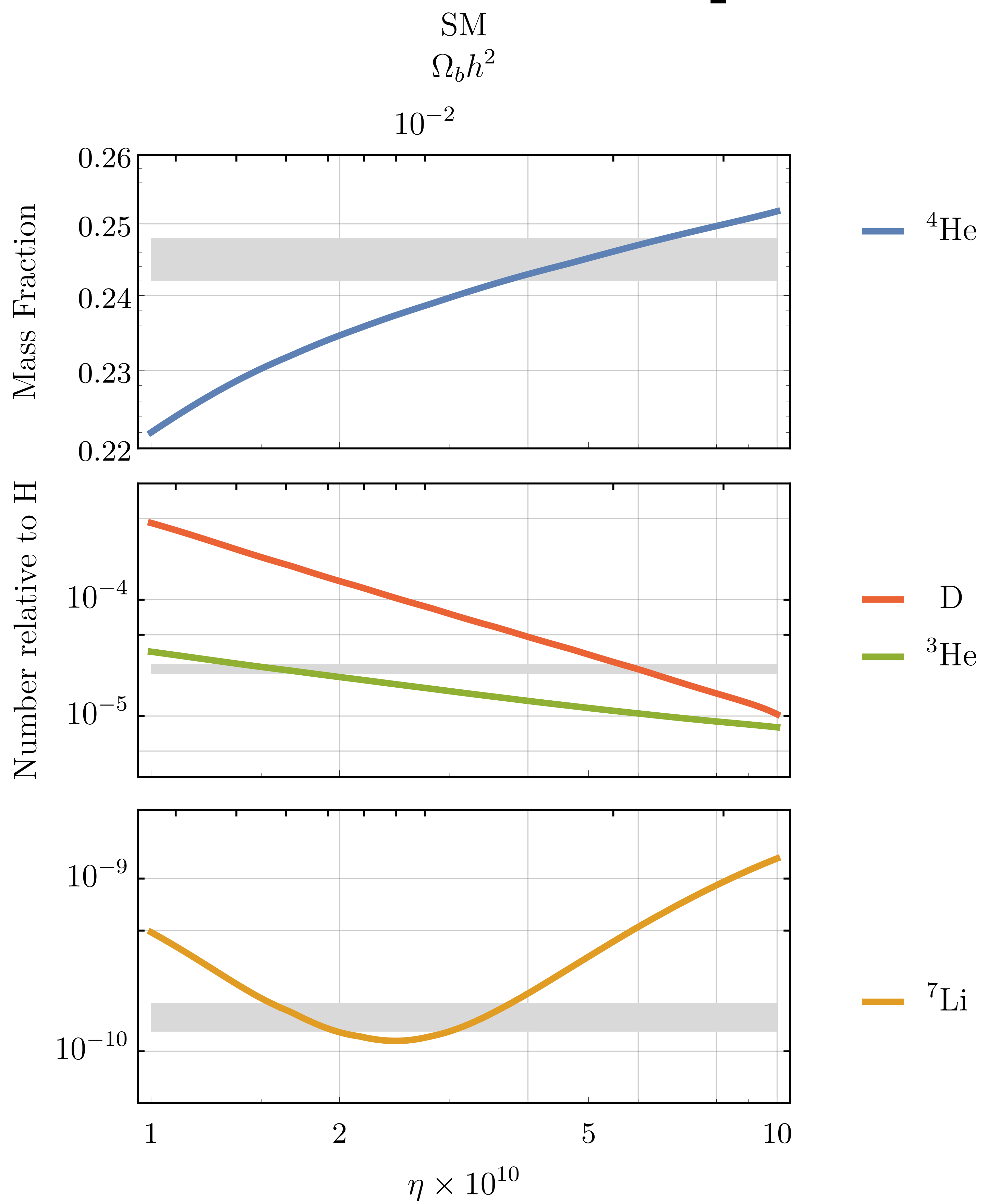
Impact on time evolution



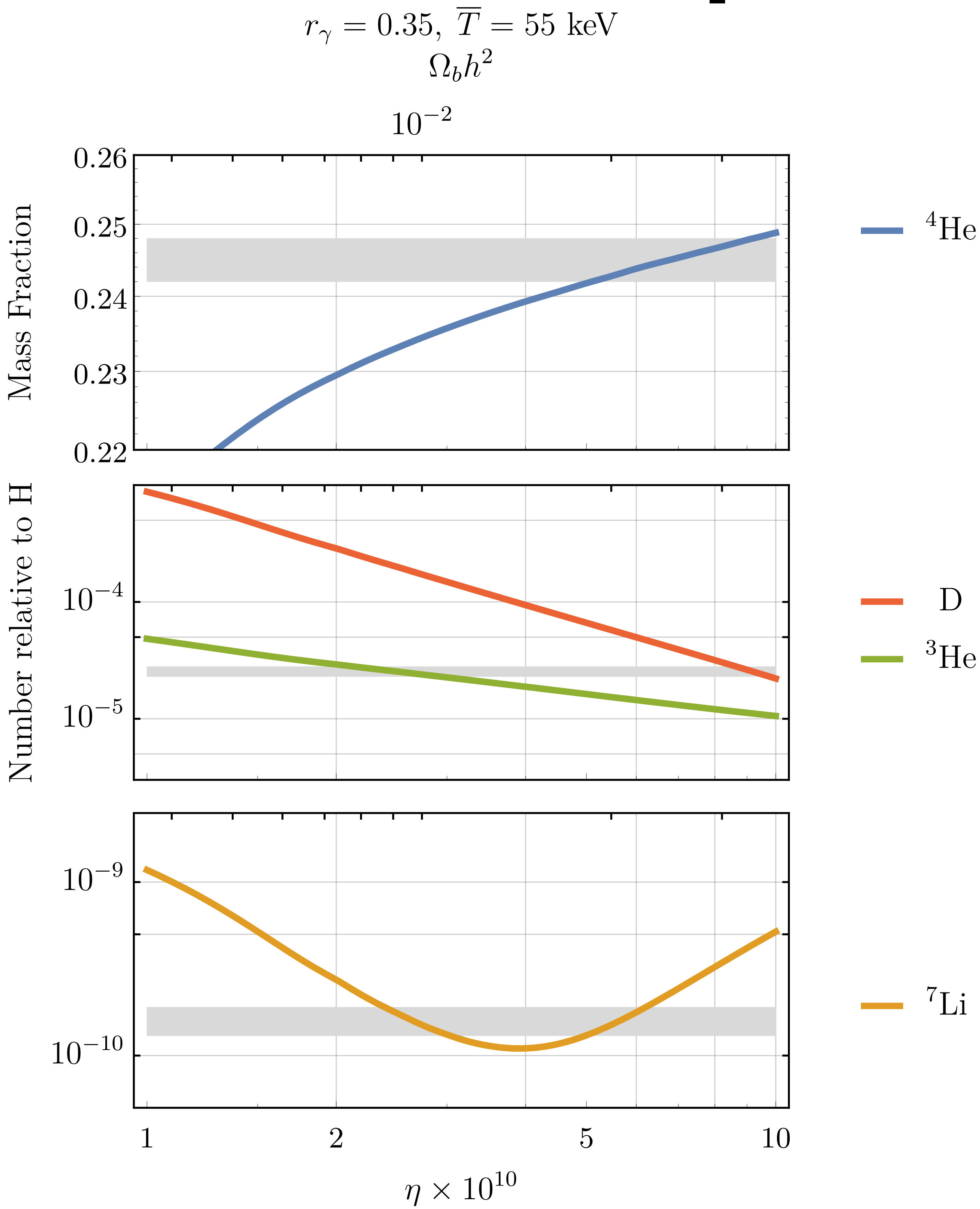
Impact on time evolution



Impact on Schramm plot

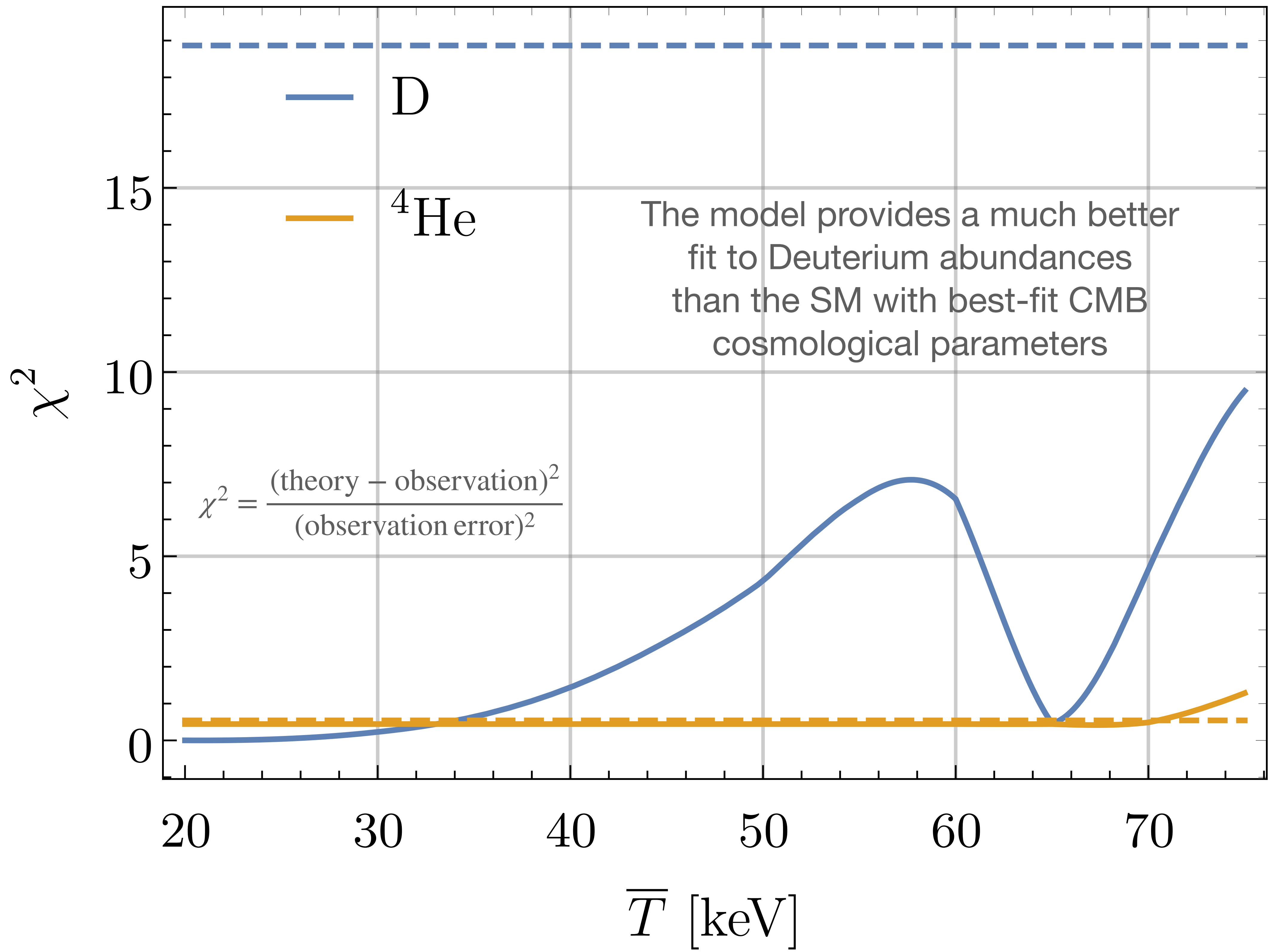


Impact on Schramm plot



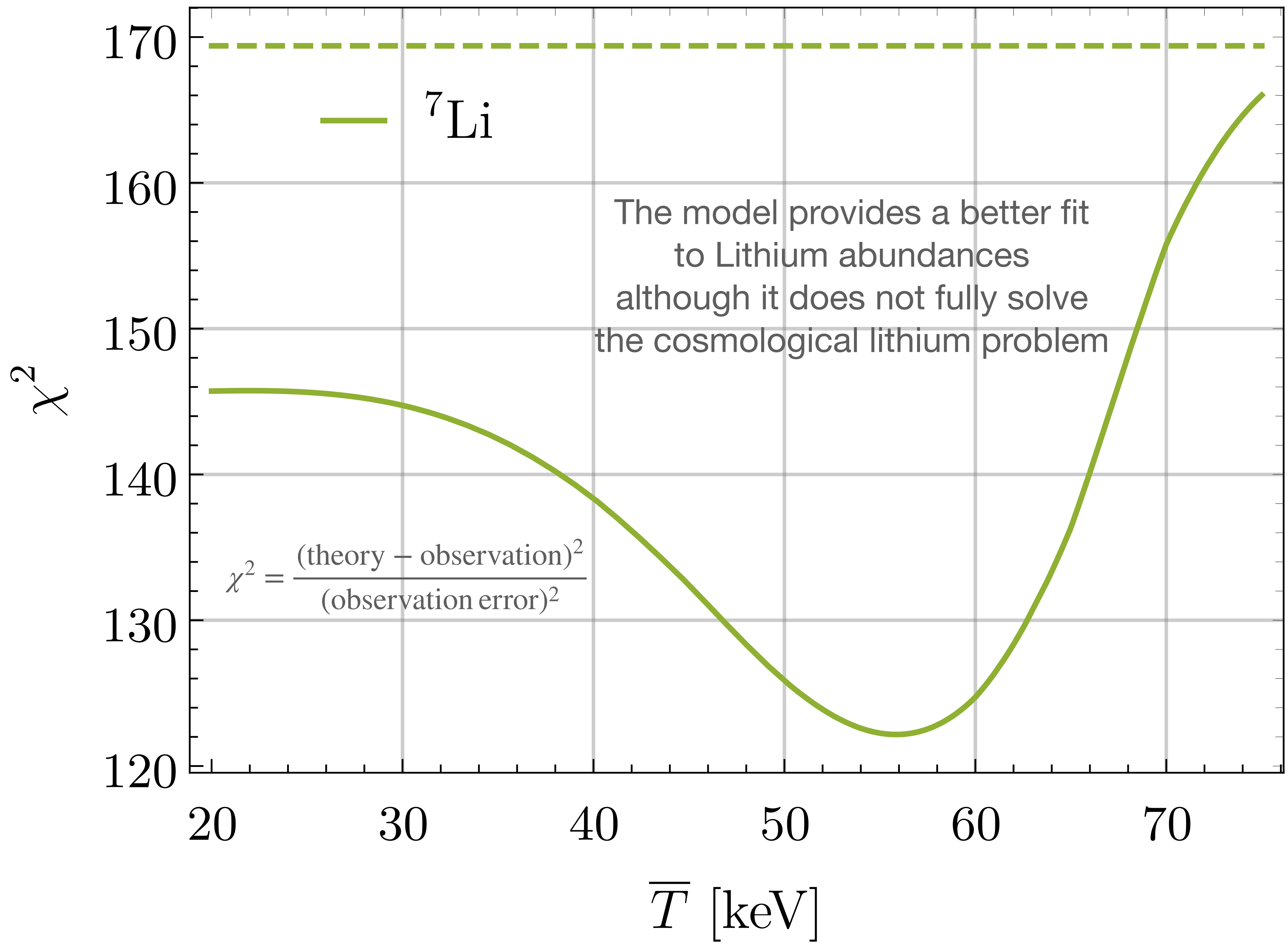
Impact on primordial abundance fitting

$r_\gamma = 0.063,\ \Omega_b h^2 = 0.02295,\ \Omega_c h^2 = 0.129$



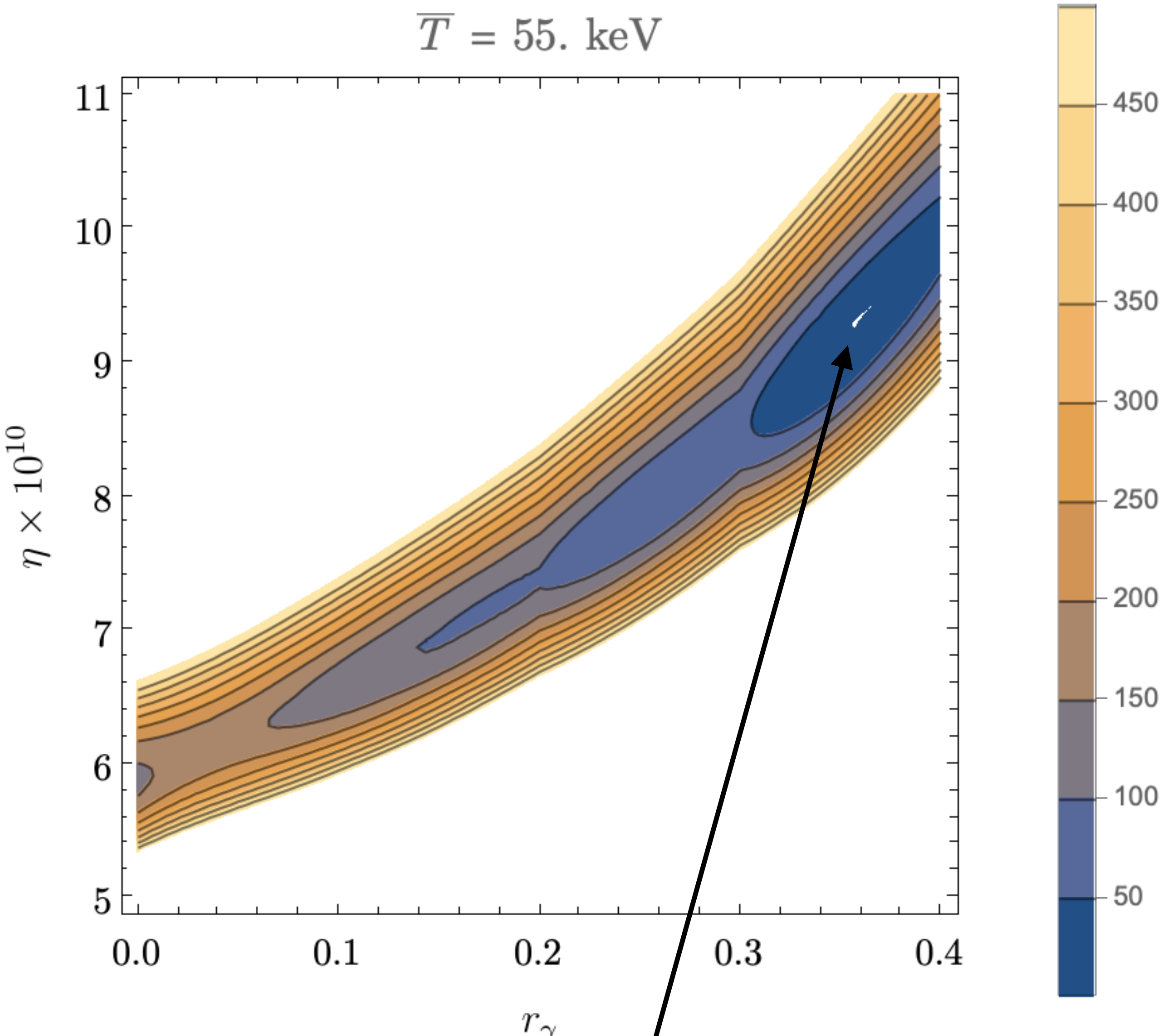
Impact on primordial abundance fitting

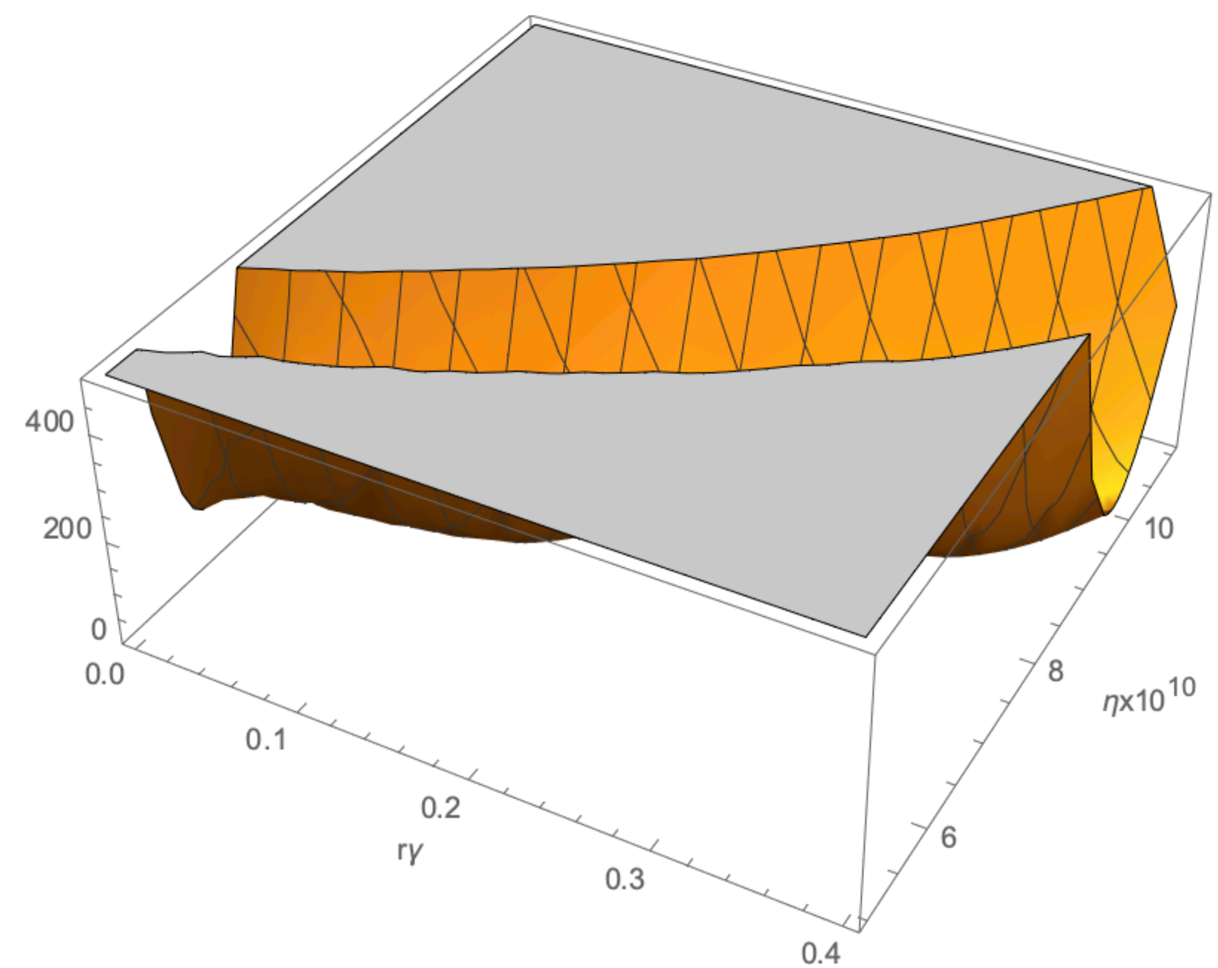
$r_\gamma = 0.063,\ \Omega_b h^2 = 0.02295,\ \Omega_c h^2 = 0.129$



Fixing the resonance temperature to mid-BBN

Color code is $\chi^2_{BBN} = \chi^2_{Deuterium} + \chi^2_{Helium} + \chi^2_{Lithium}$



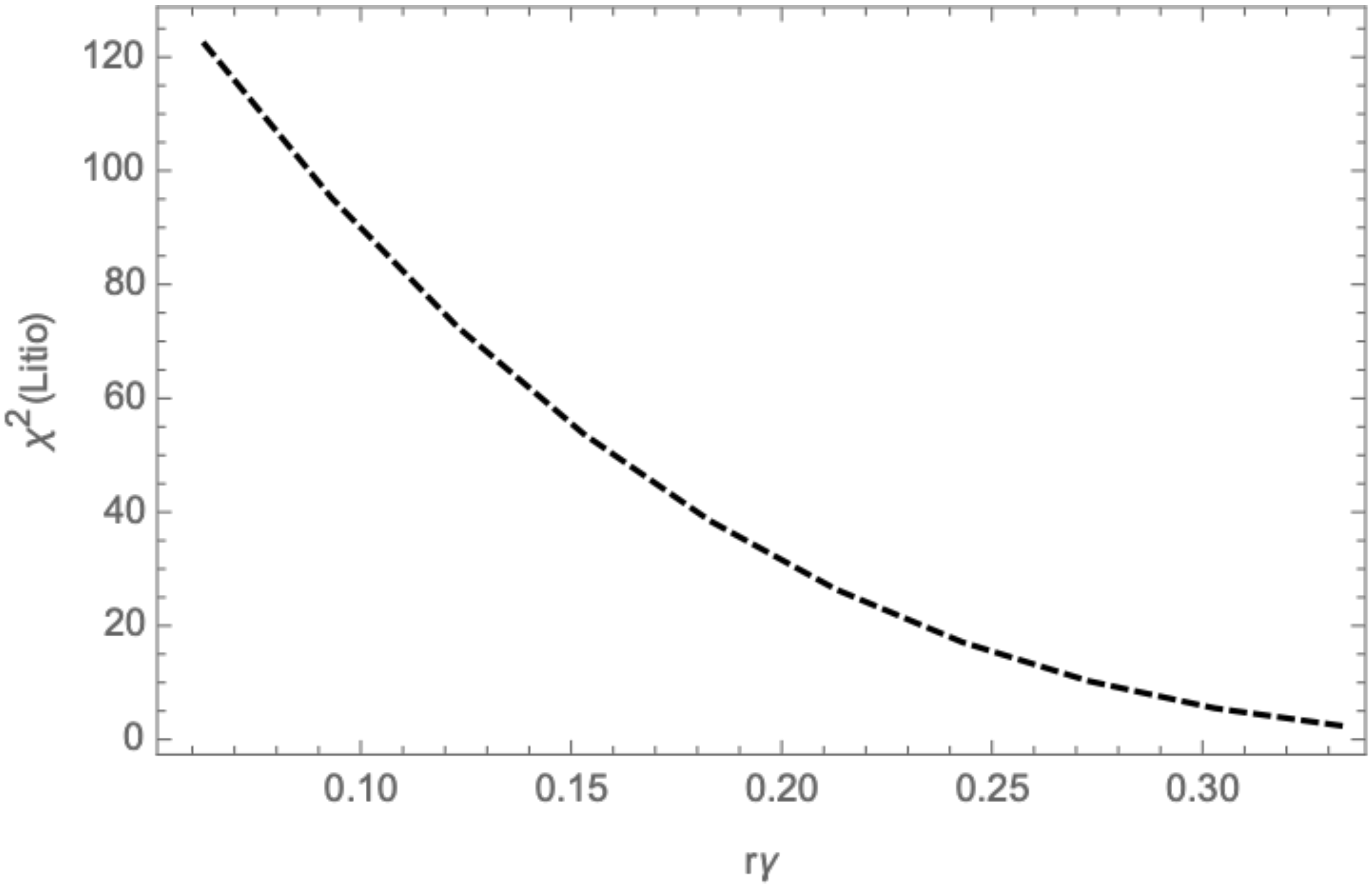


There is a **better global fit** if we choose a large value of the baryon-to-photon ratio, but probably it is **inconsistent with CMB** observations

Note that this also prefers a photon energy loss of ~1/3, corresponding to **equipartition** between the degrees of freedom of the scalar and the photon.

Fixing the resonance temperature to mid-BBN

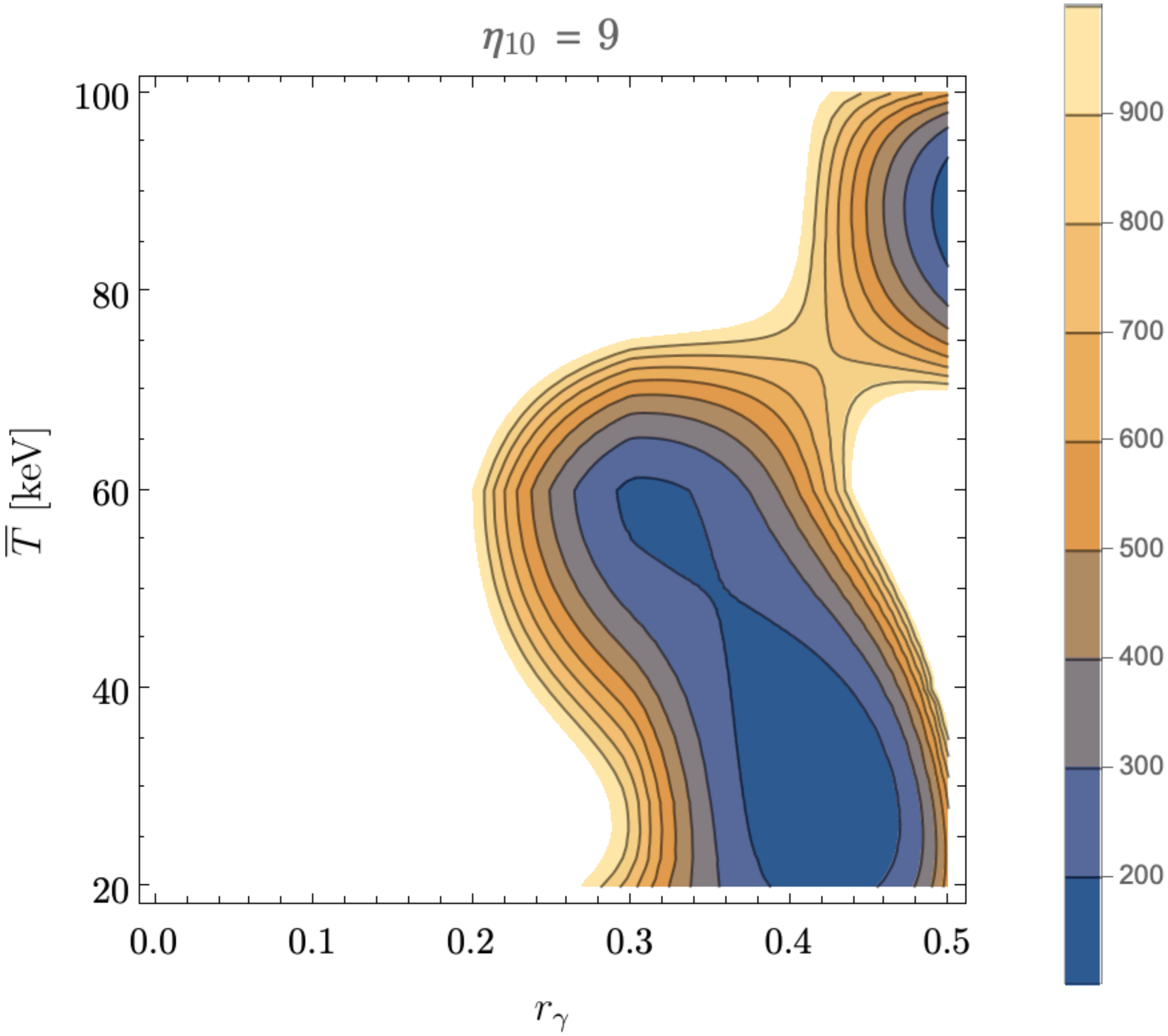
Color code is $\chi^2_{BBN} = \chi^2_{Deuterium} + \chi^2_{Helium} + \chi^2_{Lithium}$

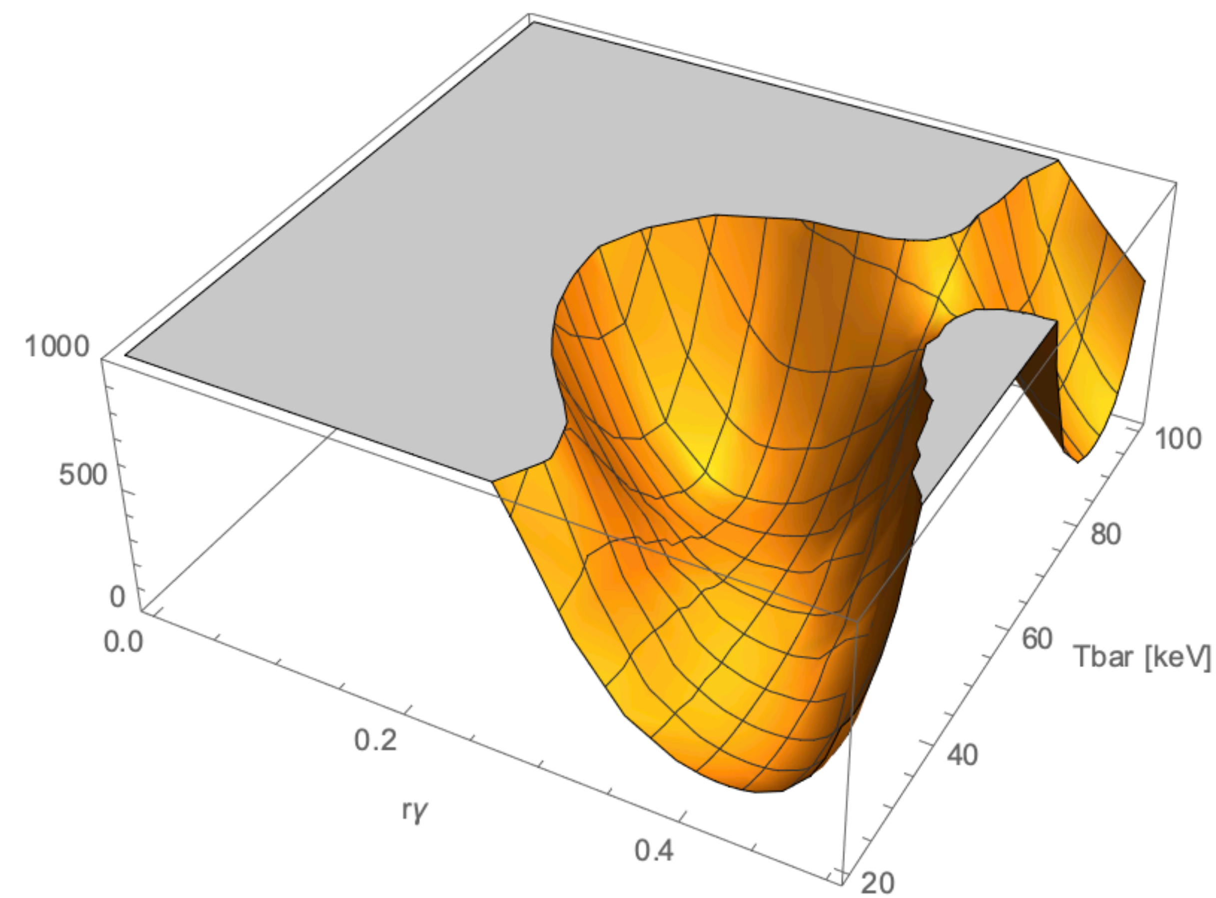


Interestingly, this case **may provide a solution to the Lithium problem**, but at the expense of becoming a much worse fit for the Deuterium.

Fixing a high value for the baryon-to-photon ratio

Color code is $\chi^2_{BBN} = \chi^2_{Deuterium} + \chi^2_{Helium} + \chi^2_{Lithium}$



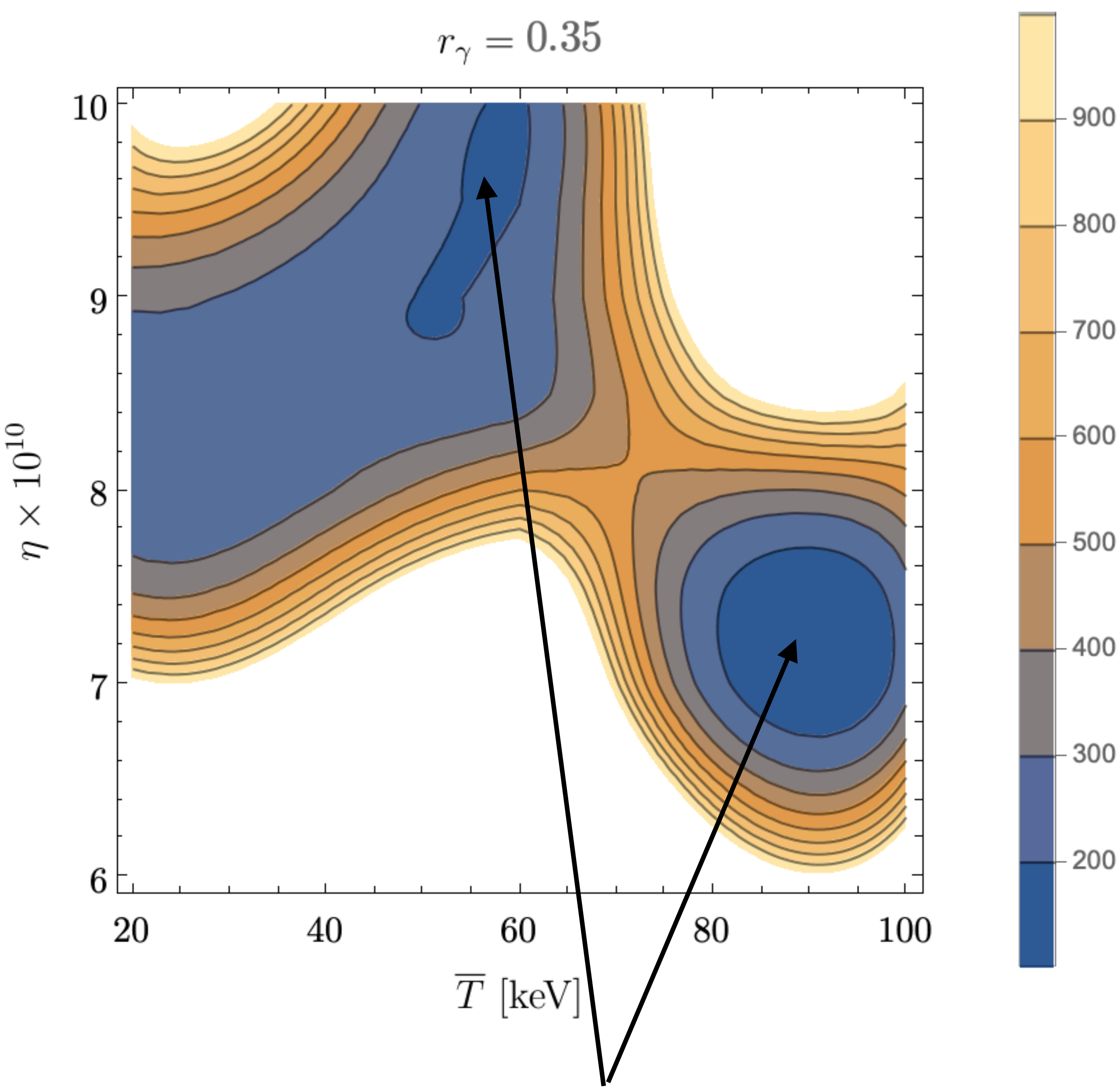


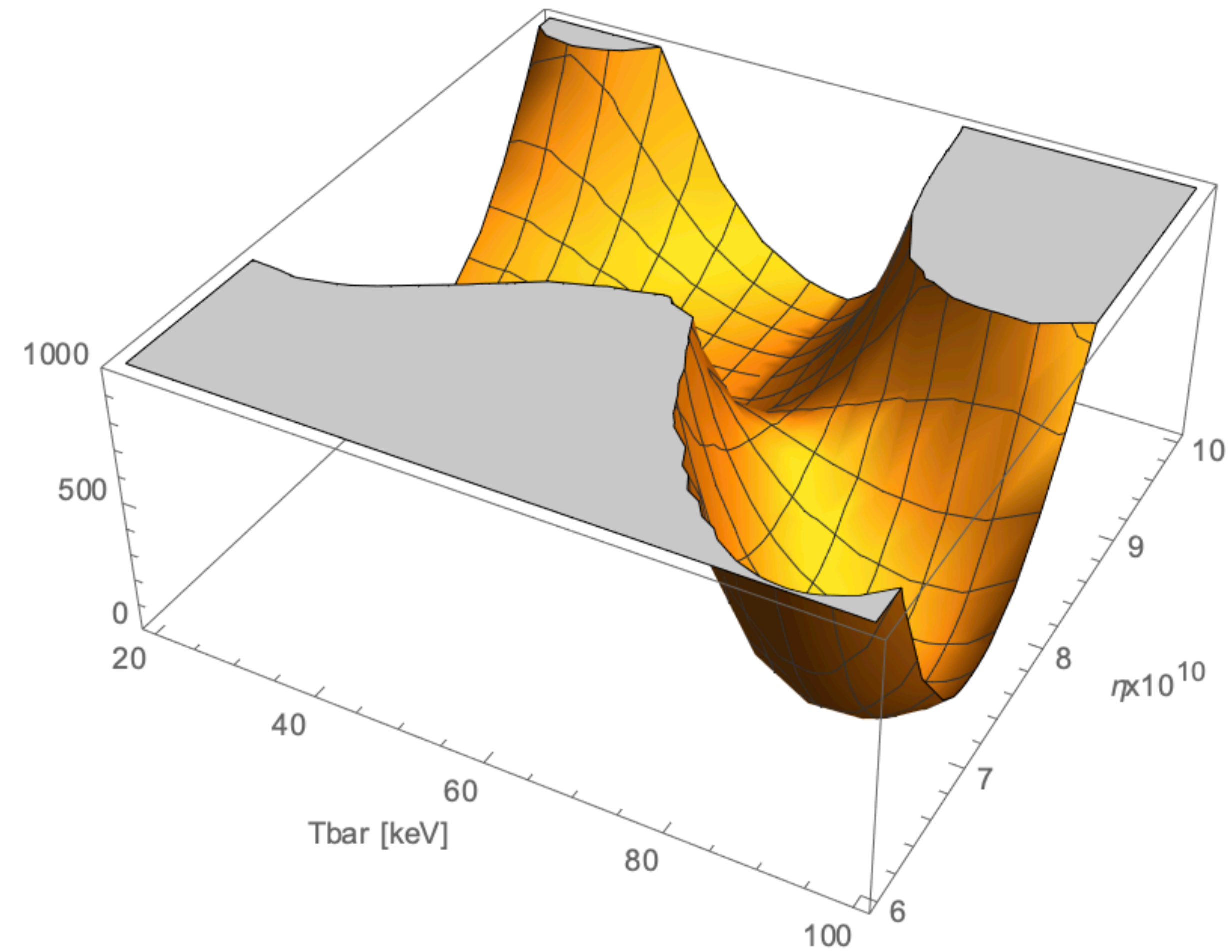
Fixing this large value of the baryon-to-photon ratio only photon energy loss values > 30% are allowed

Future work: pinpoint the particular nuclear reaction that drives the behavior (creation or destruction) of each nuclide as we vary these parameters in each case.

Varying both model parameters

Color code is $\chi^2_{BBN} = \chi^2_{Deuterium} + \chi^2_{Helium} + \chi^2_{Lithium}$





Assumming a photon energy loss of ~1/3 we find a **two-minimum structure**: the one at mid-BBN temperatures, and another one when BBN starts (for more reasonable values of the baryon-to-photon ratio)

Conclusions

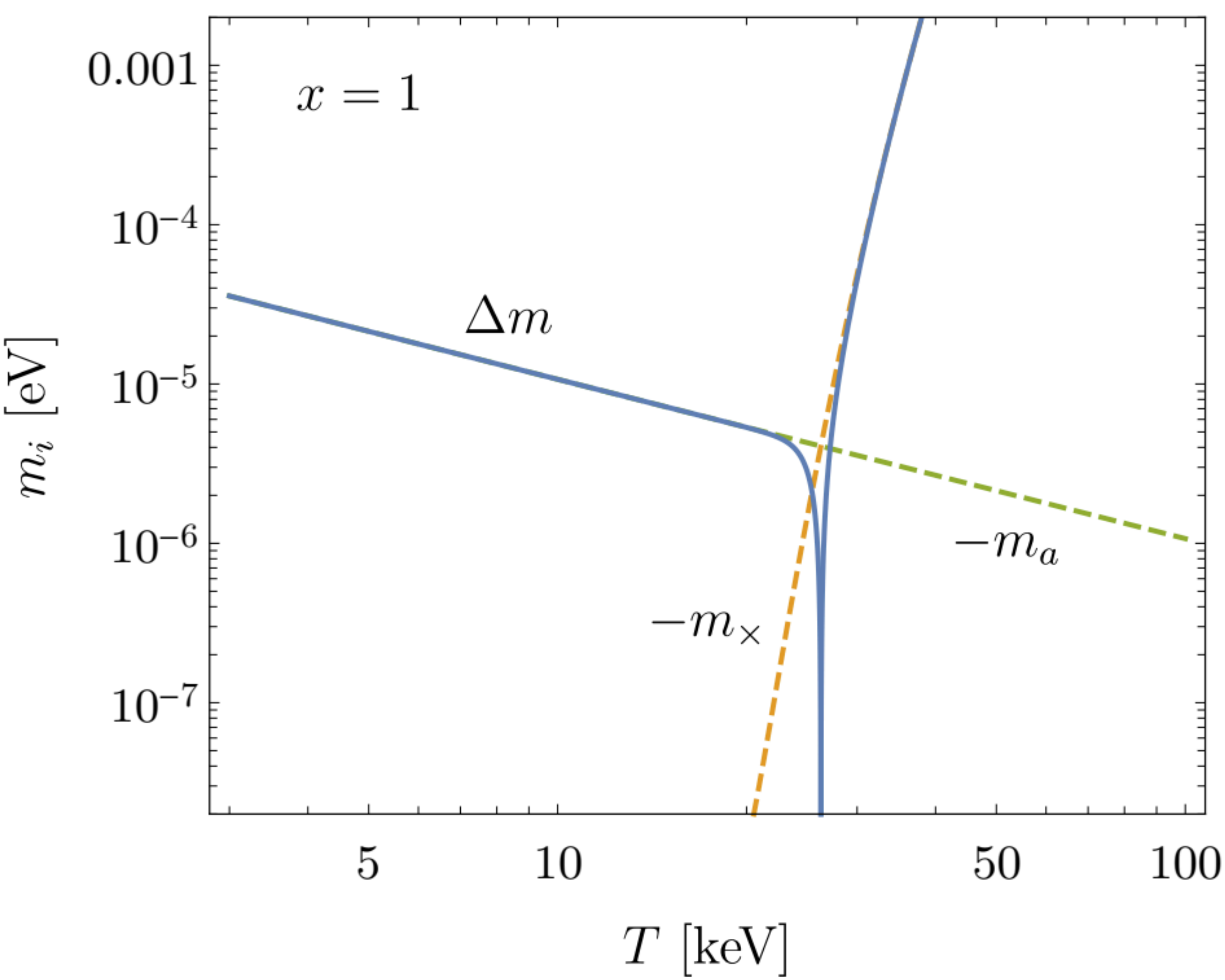
- ***Big Bang Nucleosynthesis*** *is now becoming* ***precision cosmology*** *from both the* ***theoretical*** *and* ***observational*** *sides.*

- *It probes an* ***energy regime*** *in the Early Universe which other probes (CMB, LSS) do not reach, providing a testbed for* ***BSM physics.***

- *A* ***general model*** *providing* ***transfer of energy*** *from photons to something else (such as the* ***majoron****) has relevant predictions for both the* ***Hubble tension*** *and the* ***cosmological Lithium problem.***

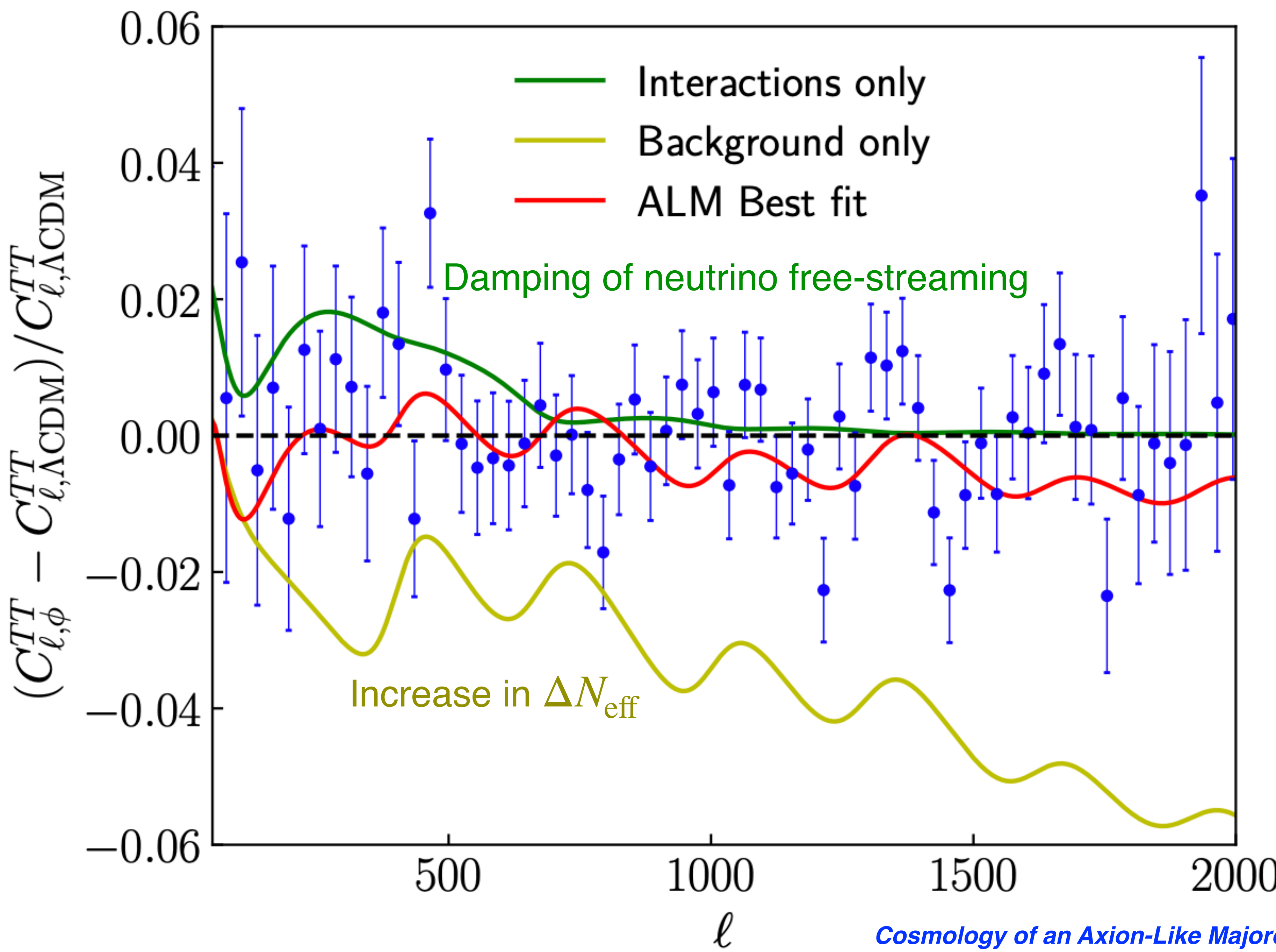
- ***Computational tools*** *for BBN are key to* ***test any model*** *affecting the energy window of BBN against* ***primordial abundance observations.***

The resonance: plasmon mass



Cosmology of an Axion-Like Majoron. A.J.Cuesta, J.I. Illana, M. Masip, M. Gómez
Journal of Cosmology and Astroparticle Physics 04 (*2022*) 009 *[arXiv:2109.07336]*

MCMC Fit to cosmological data



CLASS
the Cosmic Linear Anisotropy Solving System

https://lesgourg.github.io/class_public/class.html

Monte Python
The Monte Carlo code for CLASS in Python

https://github.com/brinckmann/montepython_public

Global fit to:
T+P CMB power spectrum (Planck),
CMB lensing (Planck),
BAO data (6dF, SDSS MGS, BOSS)

Cosmology of an Axion-Like Majoron. A.J.Cuesta, J.I. Illana, M. Masip, M. Gómez
Journal of Cosmology and Astroparticle Physics 04 (2022) 009 [arXiv:2109.07336]