BBN constraints on long-lived particles

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S. Ganguly, THJ, S. Yun, 2507.23354
THJ, T. Okui, K. Tobioka, J. Wang, 2510.23695

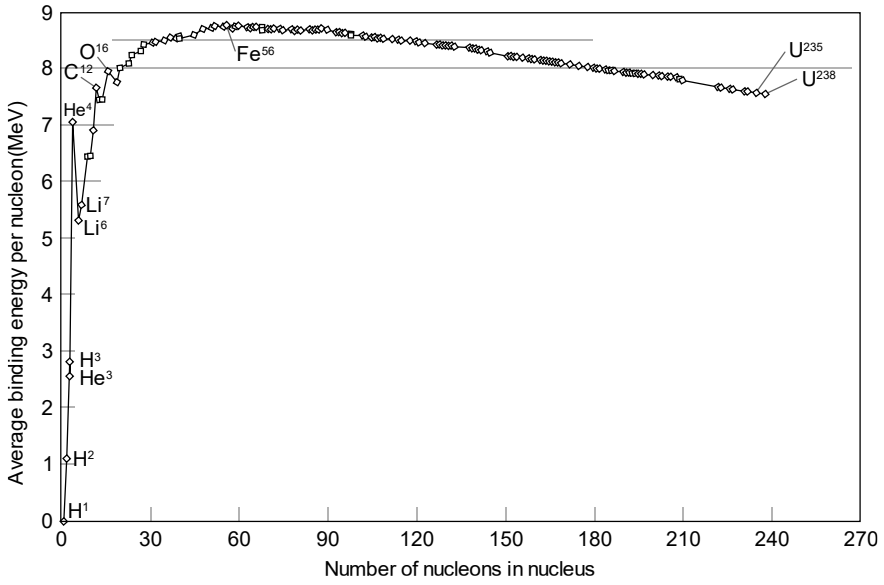
Outline

1. Introduction
2. N_{eff} bound from BBN
3. Bounds on hadronic injection (heavy QCD axion)
4. Conclusion

Big Bang nucleosynthesis

- Big Bang nucleosynthesis (BBN) is the process of forming light elements in the early Universe.

- Their primordial abundances are predicted by BBN, which **can be tested** in low metallicity stars.



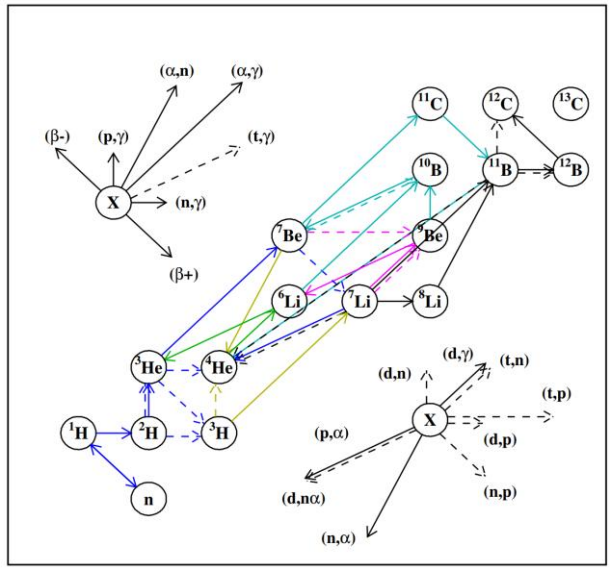
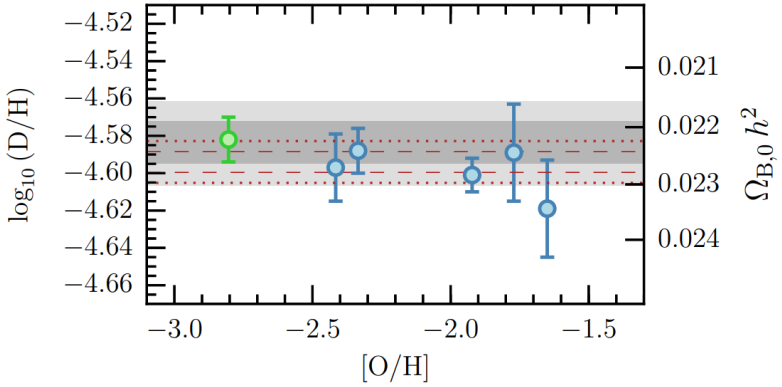
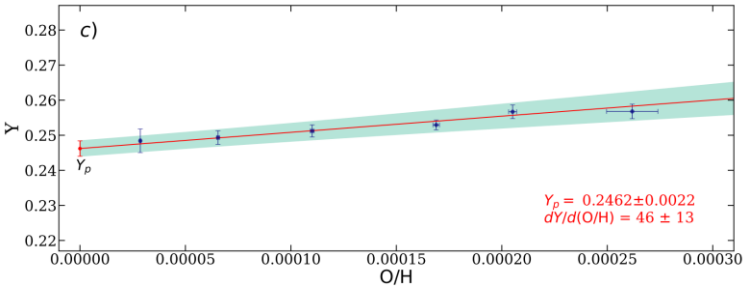


Fig. from Pitrou et al 1801.08023

Cooke et al, 1607.03900



Kurichin et al, 2101.09127



Standard BBN

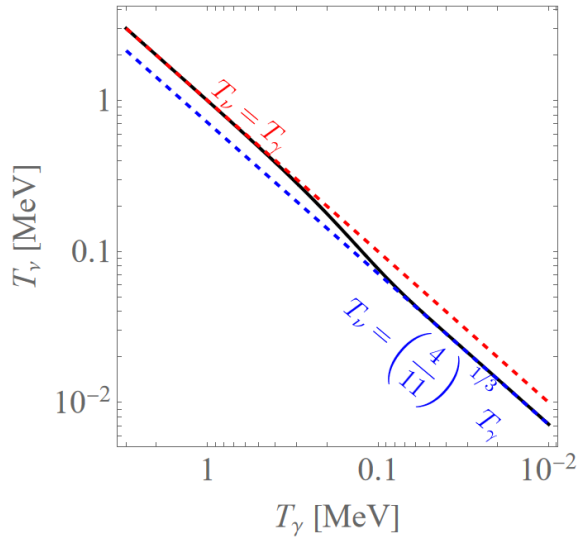
- In the standard BBN, there are two processes: decoupling of weak interactions and nuclear reaction chain.
- They are separated by the so-called deuterium bottleneck.

Decoupling of weak interactions ($T \sim$ MeV)

(1) Background neutrinos decouple
(1.5) $e^{\pm}$ annihilation $\rightarrow \gamma$

➡ $T_\nu \simeq \left(\frac{4}{11}\right)^{\frac{1}{3}} T_\gamma$

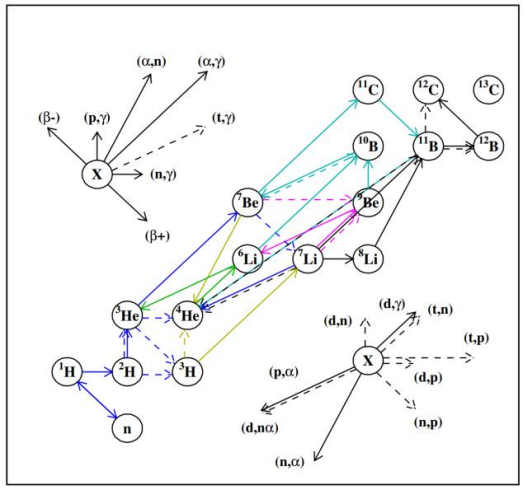
(2) n/p freezes out



$$p + n \leftrightarrow \mathrm{D} + \gamma$$

B. E. = 2.2 MeV

Nuclear reaction chain ($T \lesssim$ 80 keV)



Deuterium bottleneck

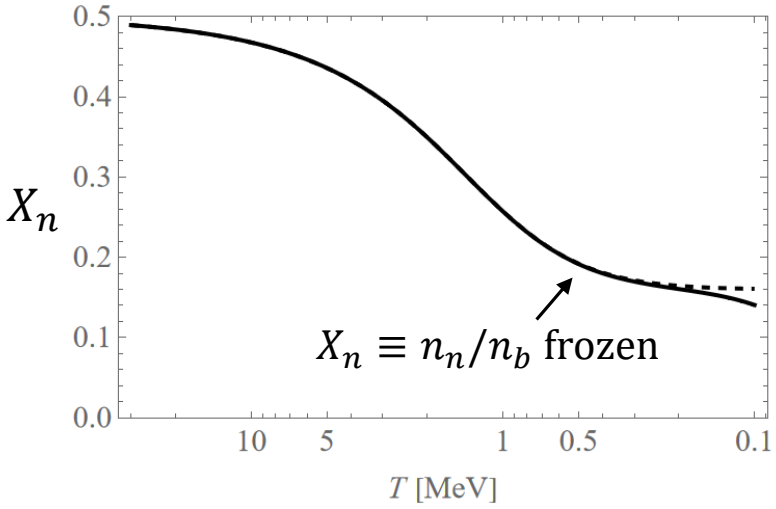
- D abundance is small because they can be easily destroyed by γ.
- Heavier elements require D $\rightarrow$ bottleneck
- It remains small until $n_\gamma(E > 2.2\ \mathrm{MeV}) \lesssim n_b$

($T_D \sim 2.2$ MeV/ln $\eta_b \sim$ 80 keV)

Standard BBN

- **How they evolve:**

$X_n = n_n/n_b$ freezes out



D bottleneck

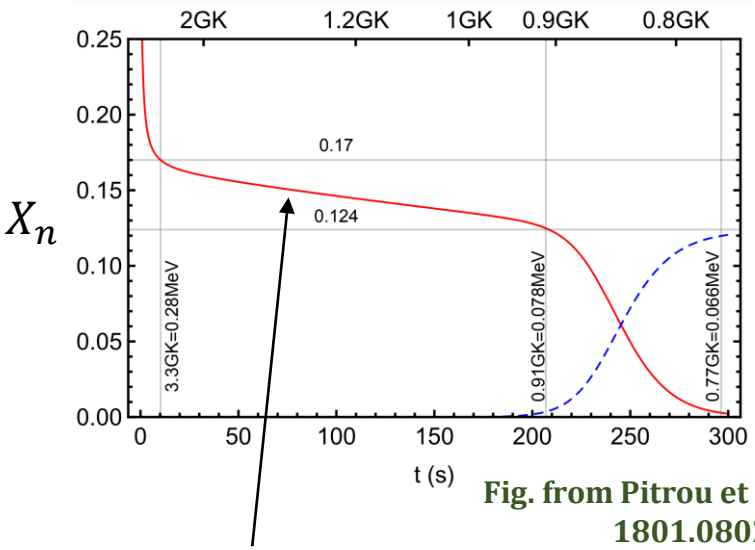


Fig. from Pitrou et al 1801.08023

- Neutrons decay with $\tau_n \simeq 878.4$ s (PDG)

Nuclear reaction chain

- Almost all neutrons become ^{4}He .

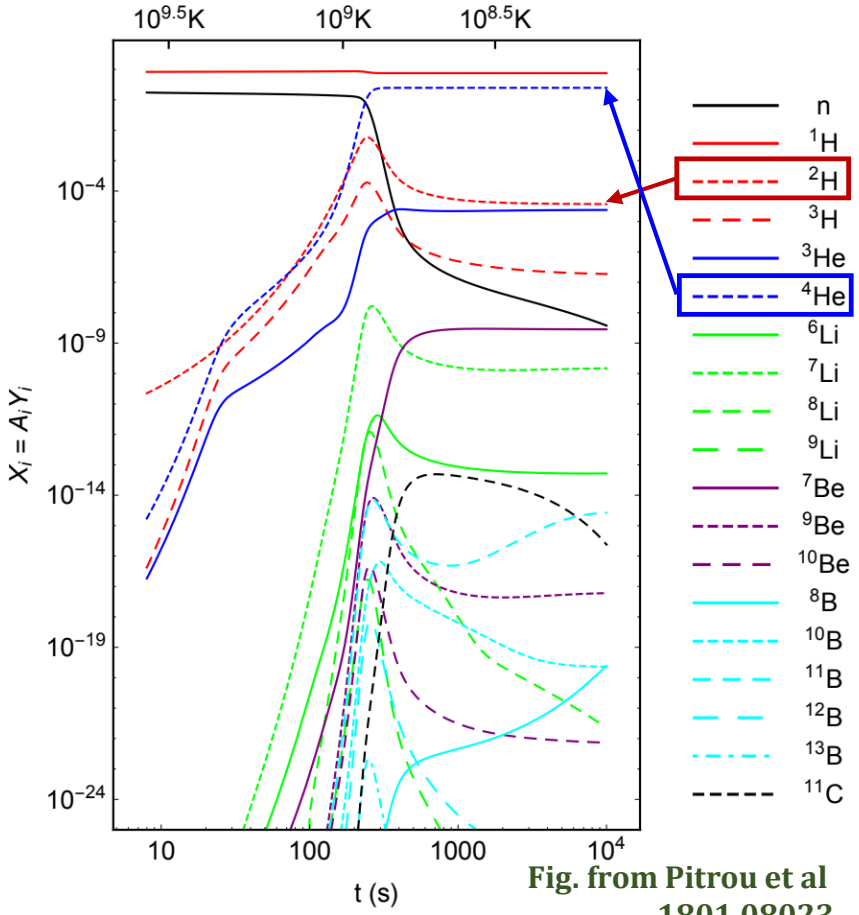
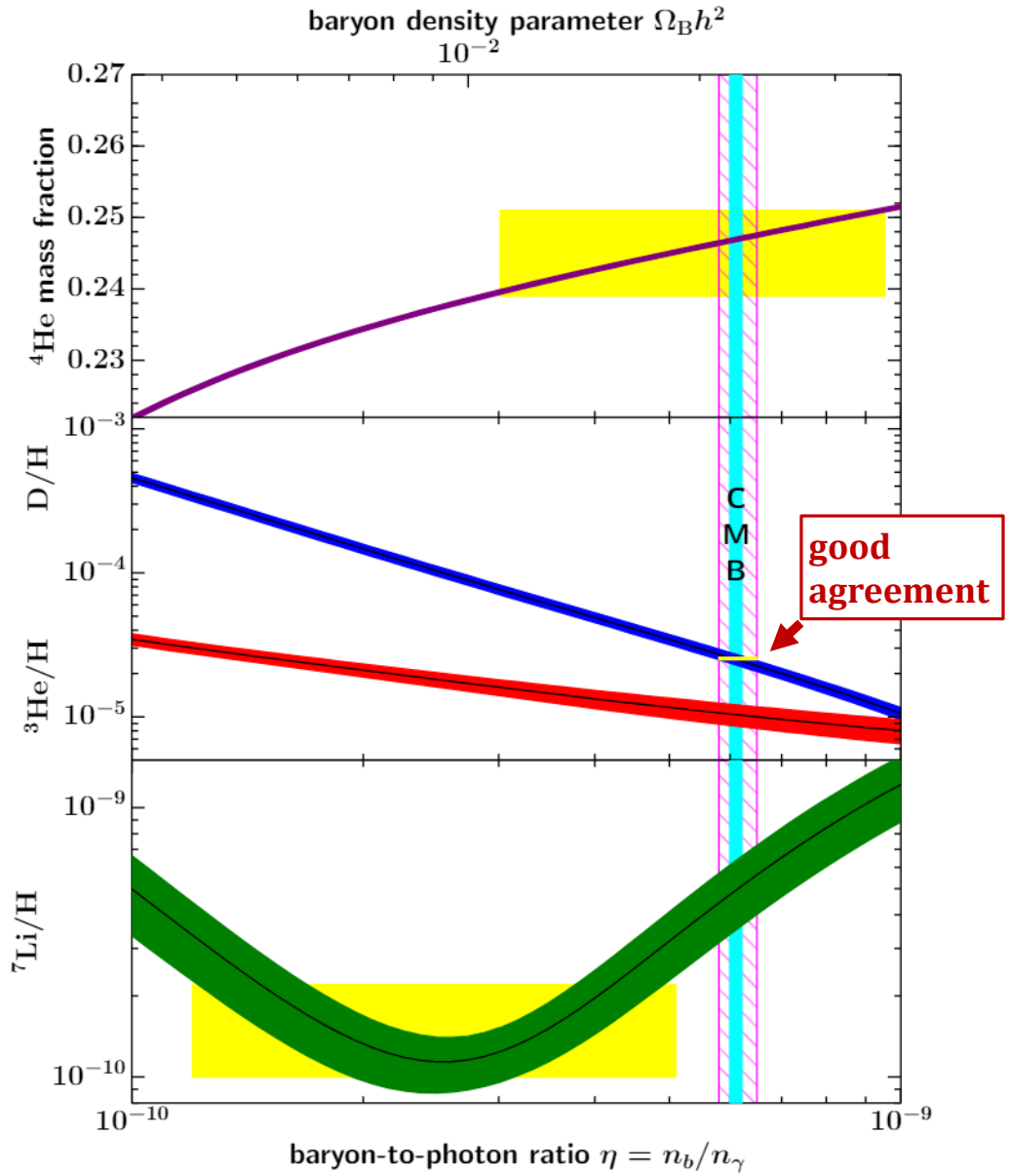


Fig. from Pitrou et al 1801.08023

Observation



Observation (summarized in PDG)

- $Y_p \equiv \frac{\rho\,{}^4\mathrm{He}}{\rho_b} = 0.245 \pm 0.003$
- $\mathrm{D/H} = (25.47 \pm 0.29) \times 10^{-6}$

} **% level !!**

- $^3\mathrm{He/H} = (1.10 \pm 0.28) \times 10^{-5}$
  (from $^3\mathrm{He}^+$ measurement, Balser & Bania 2018)
  $\leq (1.09 \pm 0.18) \times 10^{-5}$
  (from isotope ratio measurement, Cooke et al. 2022)

- $^7\mathrm{Li/H} = (1.6 \pm 0.3) \times 10^{-10}$ → 4σ deviation (lithium problem) maybe stellar depletion? e.g., Borisov et al, 2403.15534

BBN constraints on BSM scenarios

New physics scenarios are constrained not to mess up the successful BBN predictions.

1. A modification of the Hubble rate is constrained
   - the decoupling of weak interactions
   - the effectiveness of the beta decay
   - freeze-in/out of some light elements

} This provides constraints on ΔN_{eff} (combined with CMB)

(Part 1)

2. Injection of particles during BBN epoch is constrained
   - Energetic neutrinos
   - **Hadrons**
   - Photons/electrons

} They can change X_n or destroy nucleus.
e.g. long-lived particles
→ constraints on lifetime and abundance

(Part 2)

N_{eff} bound

- **Effective number of neutrino species**:

$$N_{\mathrm{eff}} = \frac{\rho_{\mathrm{rad}} - \rho_{\gamma}}{\rho_{\nu_i}^{(0)}},$$

where $\rho_{\nu_i}^{(0)} = 2 \cdot \frac{7}{8} T_{\nu}^4$ is the neutrino energy density for one species for instantaneous decoupling $T_{\nu} = \left(\frac{4}{11}\right)^{1/3} T_{\gamma}$

- Standard cosmology (neutrino decoupling is not instantaneous) $\rightarrow \boldsymbol{N_{\mathrm{eff}} \simeq 3.045}$

- In BSM, if ΔN_{eff} is nonzero, Hubble rate is modified and BBN predictions can be messed up.

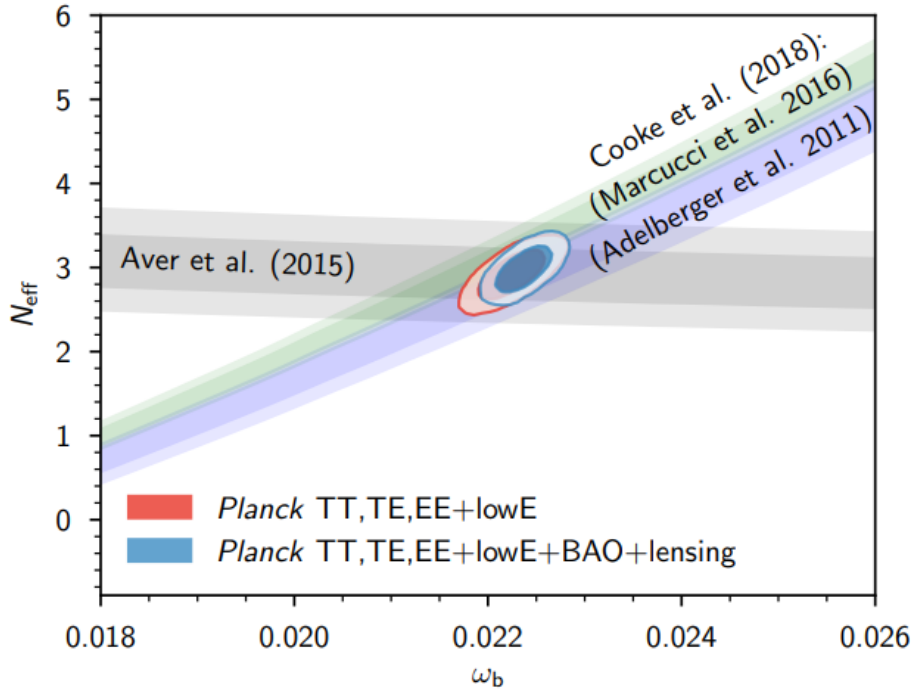
$$\Rightarrow \boldsymbol{N_{\mathrm{eff}} = 2.88 \pm 0.27\ (68\%)}$$ **Pitrou et al 1801.08023**

(for Y_p and D/H)

$N_{\rm eff}$ bound

- This bound is often combined with CMB fitting. ⇒ CMB error bars can be reduced by 15 – 30 %.

Planck 2018



$N_{\rm eff} = 2.99^{+0.34}_{-0.33}$ (95%) (without BBN) ➡ $N_{\rm eff} = 3.06^{+0.22}_{-0.22}$ (95%) (combined with BBN)

ACT DR6 (2025)

$N_{\rm eff} = 2.73 \pm 0.14$ (68%, P-ACT),
$= 2.86 \pm 0.13$ (68%, P-ACT-LB) (without BBN)

⬇

Given these results, we combine direct deuterium measurements, accounting for both observational and theoretical uncertainties, with the posterior distribution of $(\Omega_b h^2, N_{\rm eff})$ only under the assumption of `PRyMordial` BBN calculations. This approach yields joint CMB+BBN predictions. After marginalizing over $\Omega_b h^2$, we obtain

$N_{\rm eff} = 2.87 \pm 0.13$ (68%, P-ACT-LB-D)
$N_{\rm eff} = 2.89 \pm 0.11$ (68%, P-ACT-LB-D-He)

(combined with BBN)

BSM scenarios for $\Delta N_{\mathrm{eff}} \neq 0$

What do we imagine for a nonzero ΔN_{eff}?

1. $\Delta N_{\mathrm{eff}} > 0$
   - Dark radiation (no active interaction with the SM plasma)
   - Or, additional neutrinos injected after neutrino decoupling
     (e.g. a long-lived particle decaying into neutrinos)

2. $\Delta N_{\mathrm{eff}} < 0$
   - **There is no dark radiation with negative energy**
   - Photon plasma heated after neutrino decoupling (→ neutrinos get diluted)
     (e.g. a long-lived particle decaying into photons, electrons, hadrons, etc.)

BSM scenarios for $\Delta N_{\rm eff} \neq 0$

What do we imagine for a nonzero $\Delta N_{\rm eff}$?

1. $\Delta N_{\rm eff} > 0$
   - Dark radiation (no active interaction with the SM plasma) → **Consistent** with the conventional fitting (only Hubble change)
   - Or, additional neutrinos injected after neutrino decoupling (e.g. a long-lived particle decaying into neutrinos)

2. $\Delta N_{\rm eff} < 0$
   - **There is no dark radiation with negative energy**
   - Photon plasma heated after neutrino decoupling (→ neutrinos get diluted) (e.g. a long-lived particle decaying into photons, electrons, hadrons, etc.)

→ **Inconsistent** because neutrinos are important in BBN

$$n\,\nu_e \rightarrow p\,e^-$$
$$p\,\bar{\nu}_e \rightarrow n\,e^+$$

The conventional **BBN bound** in the **negative** $\Delta N_{\rm eff}$ region is useless.
(note: CMB bound is useful!)

$\Delta N_{\rm eff}$ bound with minimal modification

S. Ganguly, THJ, S. Yun, 2507.23354

Two options

1. We may restrict the domain to be the positive $\Delta N_{\rm eff}$ region (→ only an upper bound of $N_{\rm eff}$).

2. Or, we can modify neutrino temperature properly in the negative $\Delta N_{\rm eff}$ region.

$$\frac{T_\nu(T_\gamma)}{T_\nu^{(0)}(T_\gamma)} = \left(\frac{N_{\rm eff}}{N_{\rm eff}^{(0)}}\right)^{1/4}$$

standard scenario

standard scenario

It changes neutrino-induced $n \leftrightarrow p$ conversions
($n\,\nu_e \to p\,e^-, p\,\bar{\nu}_e \to n\,e^+$)

<u>Assumptions and limitations</u>

- Valid only when entropy injection to the photon sector occurs **instantaneously around the neutrino decoupling** (→restricts the applicability, and maybe a crude approximation).
- It does not take into account distortion in neutrino distributions.
- It is only valid for photon/electron injection scenarios (no injection of hadrons or neutrinos).

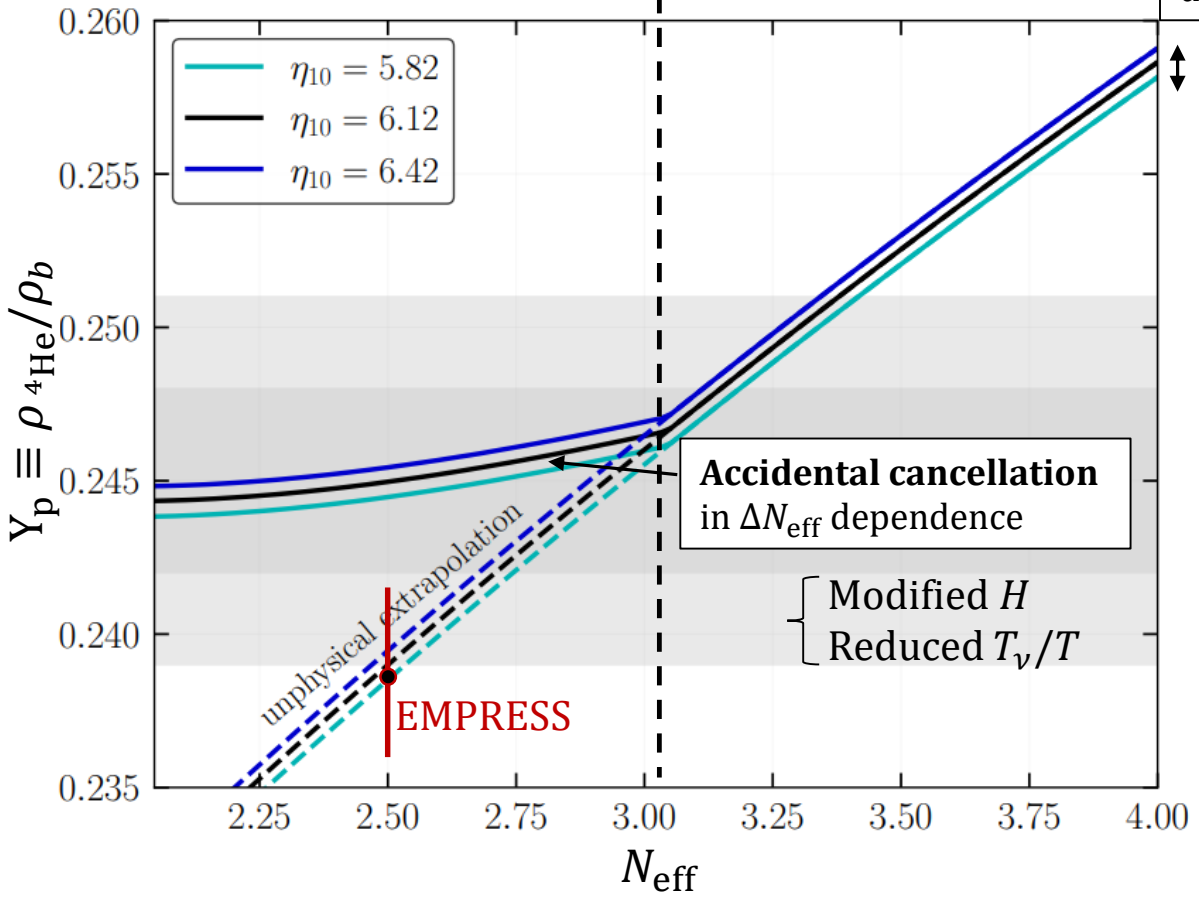
$\Delta N_{\rm eff}$ bound with minimal modification

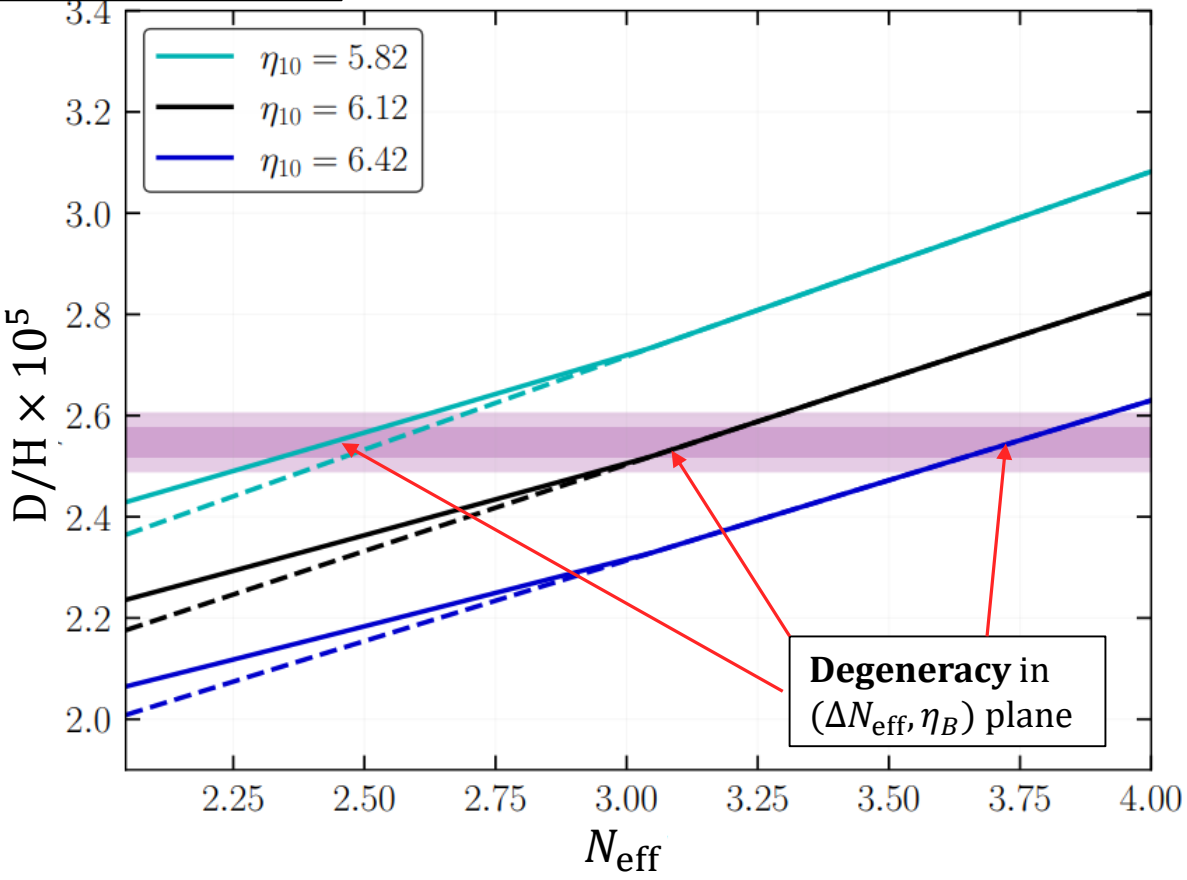
S. Ganguly, THJ, S. Yun, 2507.23354

$$\frac{T_\nu(T_\gamma)}{T_\nu^{(0)}(T_\gamma)} = \left(\frac{N_{\rm eff}}{N_{\rm eff}^{(0)}}\right)^{1/4}$$

T_ν unchanged

Y_p only logarithmically depends on η_B



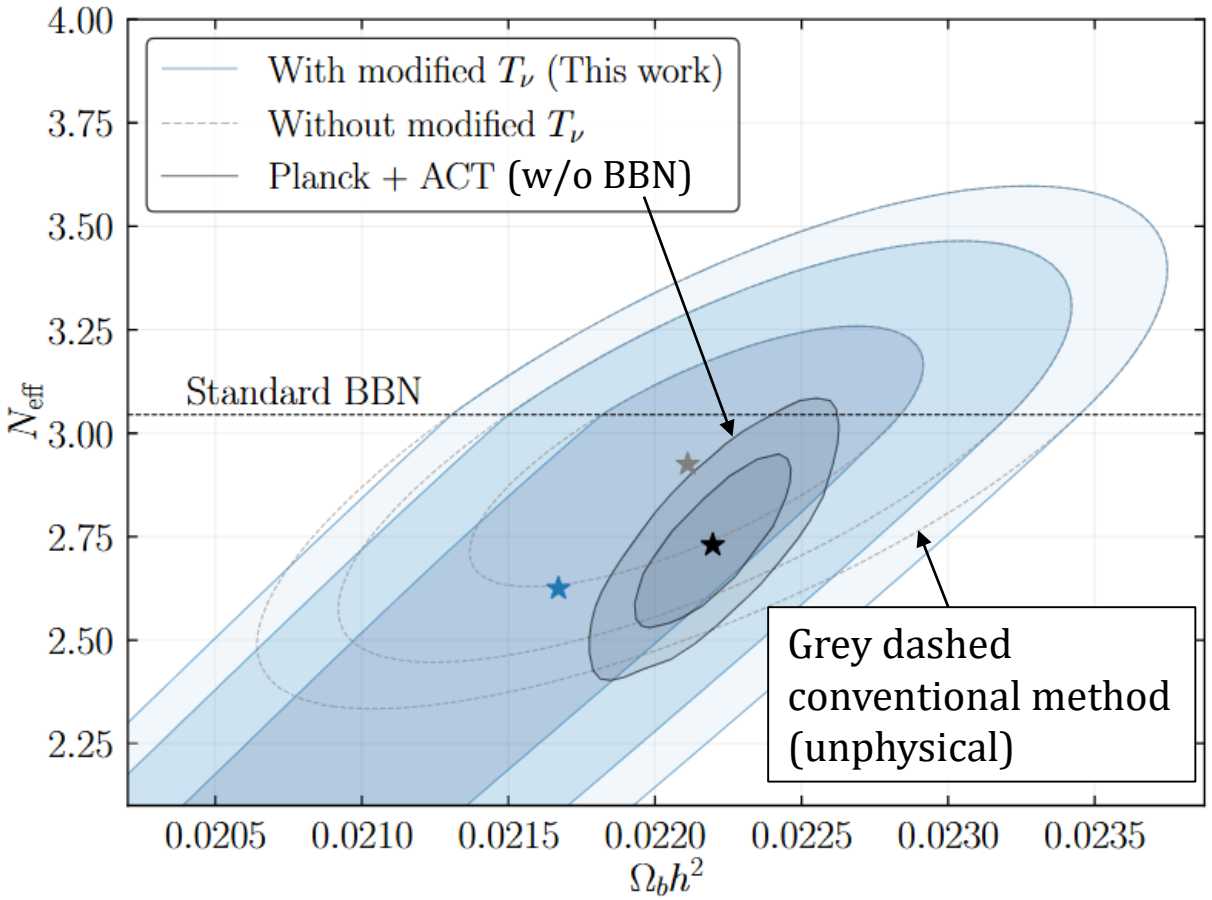


⇒ Y_p becomes insensitive to $\Delta N_{\rm eff} < 0$ (and EMPRESS He4 anomaly cannot be explained by a negative $\Delta N_{\rm eff}$)

$\Delta N_{\rm eff}$ bound with minimal modification

S. Ganguly, THJ, S. Yun, 2507.23354

Our fitting result



- We find that the constraint on the negative $\Delta N_{\rm eff}$ region becomes much weaker than the conventional fitting, because of the accidental cancellation in Y_p.

Hadronic injection in BBN (Part 2)

- **As mentioned, the previous bound cannot be applied to scenarios involving hadronic injection.**

- An injected hadron can affect $n \leftrightarrow p$ at $T \sim$ MeV, if its lifetime is longer than $O(10^{-8})$ sec. $(n_b\langle\sigma v\rangle \text{ vs } \Gamma_{\text{decay}})$

  Reno & Seckel, 1988

  ✓ Charged pions

  $$\tau_{\pi^\pm} = 2.603 \times 10^{-8}\,\text{s}$$

  e.g., $n\,\pi^+ \to p\,\pi^0(\text{or}\,\gamma), p\,\pi^- \to n\,\pi^0(\text{or}\,\gamma)$

  ✓ Kaons

  $$\tau_{K^\pm} = 1.238 \times 10^{-8}\,\text{s}$$
  $$\tau_{K_L} = 5.116 \times 10^{-8}\,\text{s}$$

  e.g., $N\,K^- \to Y\,\pi\ (Y: \Sigma^\pm, \Sigma^0, \Lambda)$,
  $p\,K^- \leftrightarrow n\,\bar{K}^0$,
  $n\,K^+ \leftrightarrow p\,K^0$

  ✓ Anti-nucleons

  (almost) stable

  e.g., $p\,\bar{n},\ n\,\bar{p} \to$ mesons,

- Typical cross sections are $O(1) - O(10)\ \text{GeV}^{-2} \gg \sigma_{\text{weak}} \sim G_F^2\,T^2 \sim 10^{-16}\text{GeV}^{-2}$ for $T \sim$ MeV.
  ⇒ 16 orders of magnitude difference → Tiny amount of hadronic injection can affect a lot.

Hadronic injection in BBN

- **Rough estimation of lifetime bound on a long-lived particle (X)**

THJ, T. Okui, K. Tobioka, J. Wang, 2510.23695

$$\Gamma^h_{n\leftrightarrow p} = \langle\sigma v\rangle_{n\leftrightarrow p} n_h \simeq \langle\sigma v\rangle_{n\leftrightarrow p} \frac{N_{a\to h}\Gamma_X n_X}{\langle\sigma v\rangle_{\rm dis} n_b + \Gamma_h}$$

$$\sim 10^{-15}\ {\rm GeV}\cdot N_{X\to h}\, e^{-t/\tau_X} \left(\frac{Y_X^{(0)}}{10^{-3}}\right)\left(\frac{10^{-2}\ {\rm sec}}{\tau_X}\right)$$

vs $\sim \mathbf{10^9}$

$$\Gamma^{\rm weak}_{n\leftrightarrow p} \sim G_F^2 T^5 \sim 10^{-24}\ {\rm GeV}\left(\frac{T}{\rm MeV}\right)^5$$

$\Rightarrow$

1. When $e^{-t/\tau_X} \sim 1$, hadrons govern the neutron fraction $X_n = \frac{n_n}{n_b}$.

2. Then, when $e^{-t/\tau_X} < 10^{-9}$, relaxation starts

$$t_{\rm relax} \sim \tau_X \left[20 + \log\left(N_{X\to h}\frac{Y_X^{(0)}}{10^{-3}}\right)\right]$$

- **Relaxation:** $\delta X_n(t) \propto \exp\left[-\int \Gamma^{\rm weak}_{n\leftrightarrow p}\, dt'\right] \sim \exp\left[-\left(\left(\frac{t}{t_{\rm relax}}\right)^{\frac{3}{2}} - 1\right)\right]$

Almost all neutrons become ^{4}He at T_D

$$\left(\frac{\delta X_n}{X_n}\right)_{T=T_D} \simeq \frac{\delta {\rm Y_p}}{\rm Y_p} < 2.45\ \%\ ({\rm PDG})$$

$$\Rightarrow\ t_{\rm relax} \lesssim t_n \left(1 - \log\frac{\delta {\rm Y_p}}{\rm Y_p}\right)^{-2/3} \sim 0.3\ {\rm sec}$$

$$\boxed{\tau_X \lesssim \frac{0.02\ {\rm sec}}{1 + \frac{1}{20}\log\left(N_{X\to h}\frac{Y_X^{(0)}}{10^{-3}}\right)}}$$

Hadronic injection in BBN

THJ, T. Okui, K. Tobioka, J. Wang, 2510.23695

- ***n/p* converting processes**

isospin symmetric
$\Rightarrow X_n \simeq \frac{1}{2}$

isospin asymmetric
(due to the absence of K_S)

isospin symmetric
$\Rightarrow X_n \simeq \frac{1}{2}$

	$n \to p$	$p \to n$	Q/MeV	Secondary
π^-		$p\pi^- \to n\pi^0$	3.30	
		$p\pi^- \to n\gamma$	138	
π^+	$n\pi^+ \to p\pi^0$		5.89	
	$n\pi^+ \to p\gamma$		141	
K^-		$pK^- \to \pi Y\ (Y \to n)$	$\gtrsim 100$	$\pi^\pm$
		$pK^- \to n\bar{K}^0$	-5.23	$K_S{}^\ddagger$, $K_L{}^\ddagger$
	$nK^- \to \pi Y\ (Y \to p)$		$\gtrsim 100$	π^-
K^+	$nK^+ \to pK^0$		-2.64	$K_S{}^\ddagger$, $K_L{}^\ddagger$
K_L		$pK_L \to \pi Y\ (Y \to n)$	$\gtrsim 100$	$\pi^\pm$
		$pK_L \to nK^+$	2.64	K^+
	$nK_L \to \pi Y\ (Y \to p)$		$\gtrsim 100$	$\pi^\pm$
	$nK_L \to pK^-$		5.23	K^-
	$pK_L \to pK_S$		0	$K_S(\to \pi^\pm)$
	$nK_L \to nK_S$		0	$K_S(\to \pi^\pm)$
$\bar{n}$		$p\bar{n} \to$ mesons	1600	mesons‡
$\bar{p}$	$n\bar{p} \to$ mesons		1600	mesons‡

+

- *n/p* **non**-converting processes
(e.g. $p\,\bar{p}$, $n\,\bar{n} \to$ mesons, $N\,K_L \to N\,K_S$, ...)

What's new in our work

***Cross sections are updated/added**

***Secondary hadrons**
e.g., $n\,K^- \to \pi^-\Lambda\ (\to p\,\pi^-:\ 64\ \%\ )$
- without secondary: $n \to p$
- with secondary: $p \to n$

***We take momentum-dependent treatment of K_L**
K_L does not get kinetically thermalized.

BBN constraint on heavy QCD axion

- **We applied this to heavy QCD axion**

THJ, T. Okui, K. Tobioka, J. Wang, 2510.23695

$$\mathcal{L} = \frac{\alpha_s}{8\pi}\frac{a}{f_a} G\tilde{G} + \frac{1}{2} m_a^2 \, a^2$$

→ abundance, lifetime, branching ratio are important input in BBN

- **Abundance** is obtained by assuming $T_{\rm RH} > T_{\rm FO} \;\rightarrow Y_a \sim 1/g_*(T_{FO})$
  $ag \leftrightarrow gg$ ($T > 2$ GeV), $a\pi \leftrightarrow \pi\pi$ ($T < T_{QCD} = 100$ MeV), max/min in between

  Dunsky, Harigaya, Hall, 2205.11540 Salvio, Strumia, Xue, 1310.6932
  D'Eramo, Hajkarim, Yun, 2108.04259

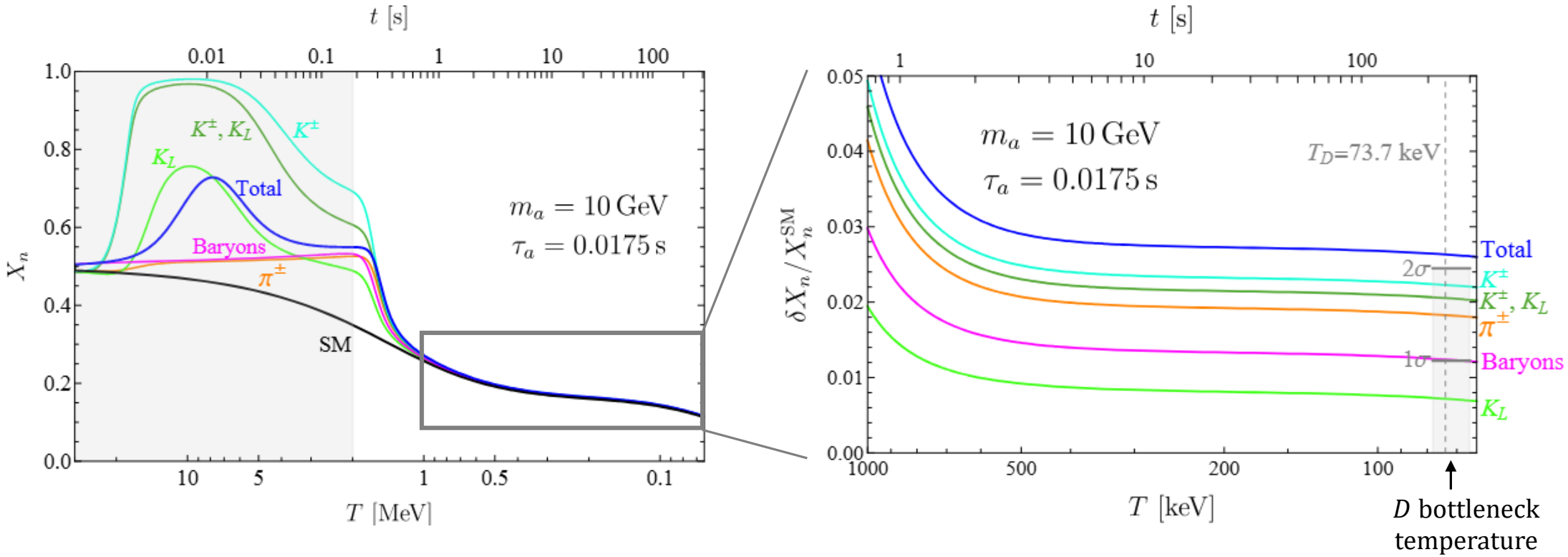
- **Lifetime**: pQCD NNLO ($m_a > 2$ GeV) and data-driven method ($m_a < 2$ GeV)
  ($\tau_a \leftrightarrow f_a$) Chetyrkin et. al. 9807241

  Aloni, Soreq, Williams, 1811.03474
  Cheng, Li, Salvioni, 2110.10691
  Bisht, Chakraborty, Samanta, 2412.09678

- **Branching ratios:** PYTHIA/Herwig ($m_a > 2$ GeV) and data-driven method ($m_a < 2$ GeV)
  ($N_{a\to h}$: averaged hadron number per axion decay)

BBN constraint on heavy QCD axion

- With those inputs, we solve Boltzmann equations and obtain the evolution of X_n.

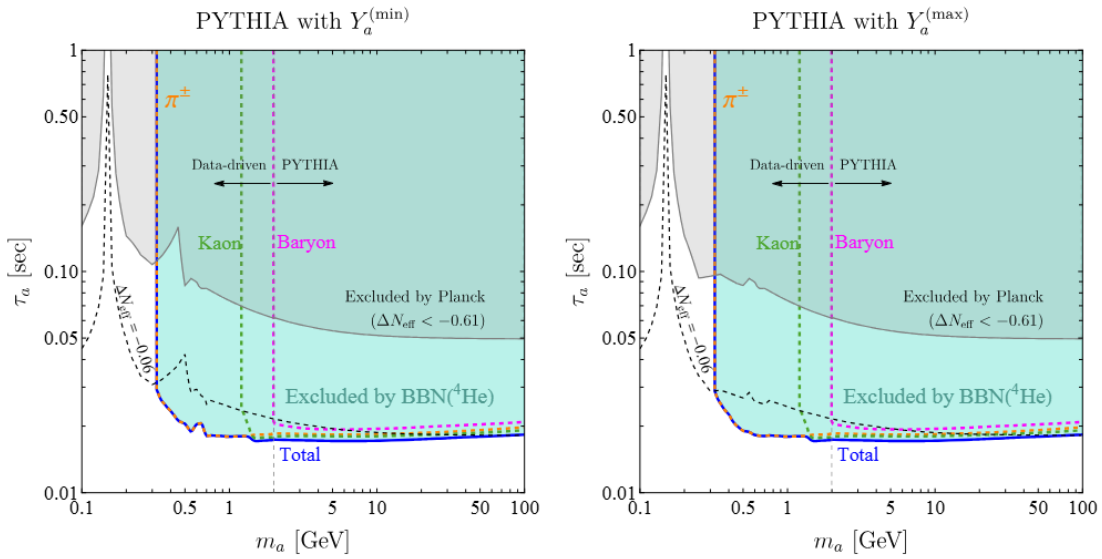


- At high T ($e^{-t/\tau_a} > 10^{-9}$), X_n is governed by hadrons.
- At low T ($e^{-t/\tau_a} < 10^{-9}$), relaxation happens.

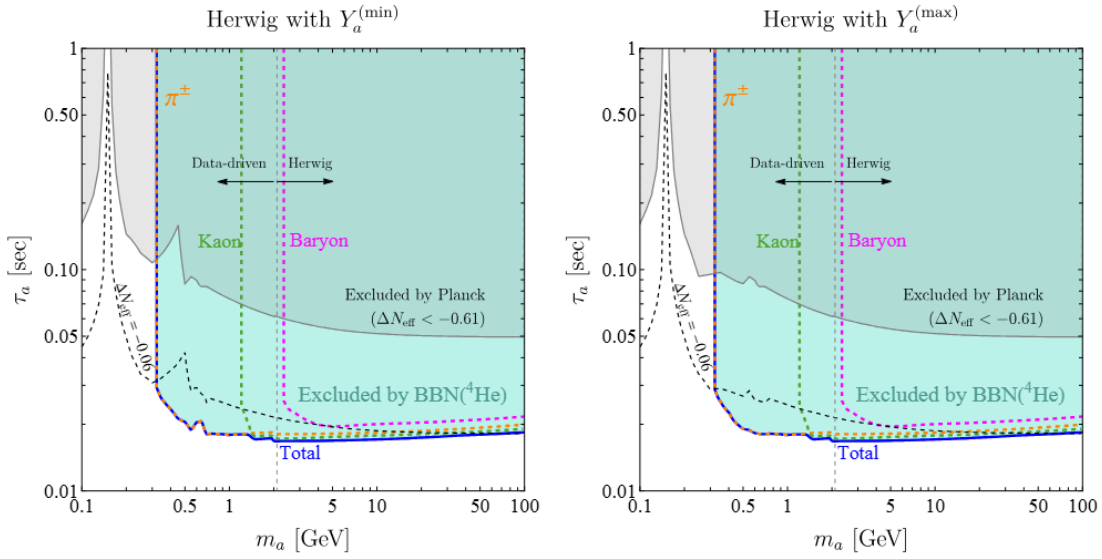
$$\left(\frac{\delta X_n}{X_n}\right)_{T=T_D} \simeq \frac{\delta \mathrm{Y_p}}{\mathrm{Y_p}} < 2.45\ \%\ \text{(PDG)}$$

- Both kaons and pions are important.
  $(\sigma_K \sim O(10)\sigma_{\pi^\pm},\ \ N_{a\to K} \sim O(0.1)N_{a\to\pi^\pm})$

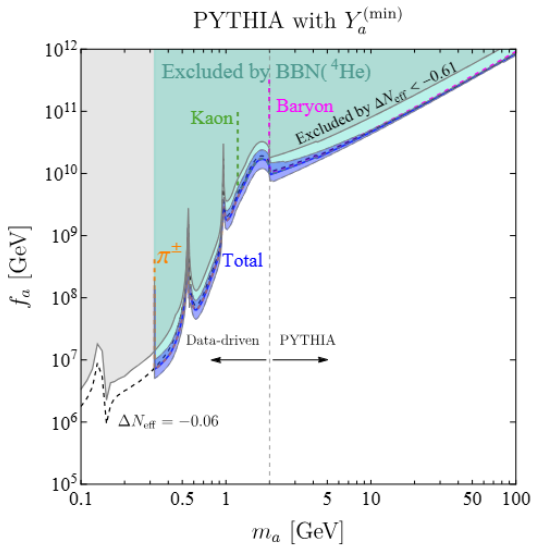
Results

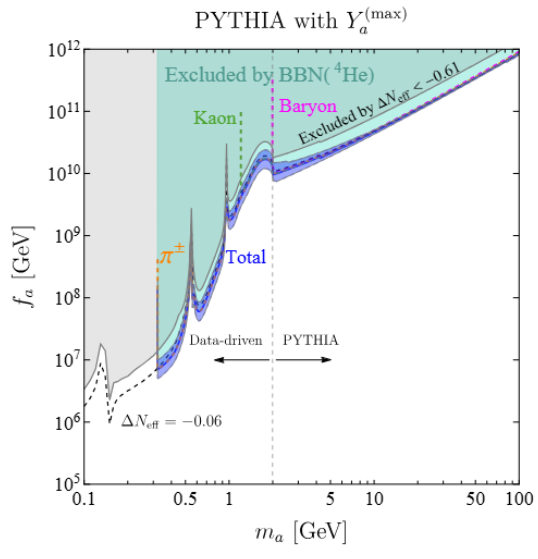

PYTHIA with $Y_a^{(\min)}$
τ_a [sec]
m_a [GeV]
$\pi^\pm$
Data-driven
PYTHIA
Kaon
Baryon
Excluded by Planck
($\Delta N_{\rm eff} < -0.61$)
Excluded by BBN(^{4}He)
Total
$\Delta N_{\rm eff} = -0.06$

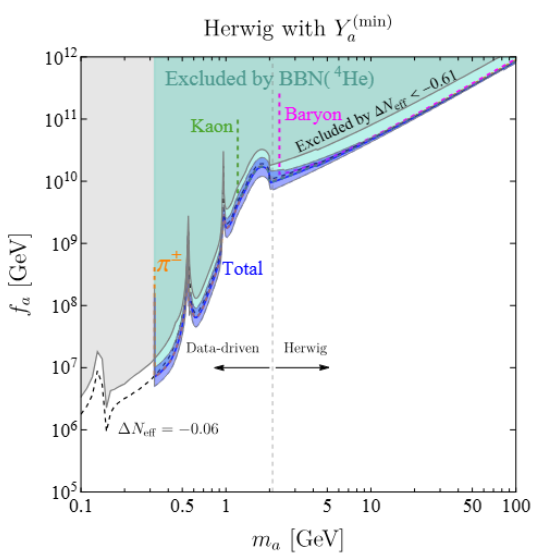
PYTHIA with $Y_a^{(\max)}$
τ_a [sec]
m_a [GeV]
$\pi^\pm$
Data-driven
PYTHIA
Kaon
Baryon
Excluded by Planck
($\Delta N_{\rm eff} < -0.61$)
Excluded by BBN(^{4}He)
Total
$\Delta N_{\rm eff} = -0.06$

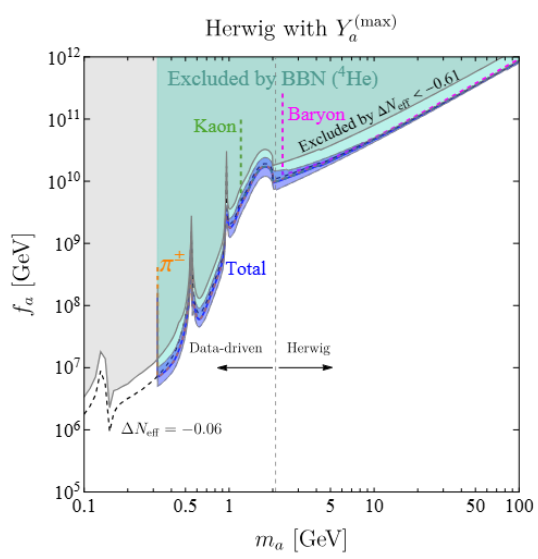

Herwig with $Y_a^{(\min)}$
τ_a [sec]
m_a [GeV]
$\pi^\pm$
Data-driven
Herwig
Kaon
Baryon
Excluded by Planck
($\Delta N_{\rm eff} < -0.61$)
Excluded by BBN(^{4}He)
Total
$\Delta N_{\rm eff} = -0.06$

Herwig with $Y_a^{(\max)}$
τ_a [sec]
m_a [GeV]
$\pi^\pm$
Data-driven
Herwig
Kaon
Baryon
Excluded by Planck
($\Delta N_{\rm eff} < -0.61$)
Excluded by BBN(^{4}He)
Total
$\Delta N_{\rm eff} = -0.06$


PYTHIA with $Y_a^{(\min)}$
f_a [GeV]
m_a [GeV]
Excluded by BBN(^{4}He)
Excluded by $\Delta N_{\rm eff} < -0.61$
Kaon
Baryon
$\pi^\pm$
Total
Data-driven
PYTHIA
$\Delta N_{\rm eff} = -0.06$


PYTHIA with $Y_a^{(\max)}$
f_a [GeV]
m_a [GeV]
Excluded by BBN(^{4}He)
Excluded by $\Delta N_{\rm eff} < -0.61$
Kaon
Baryon
$\pi^\pm$
Total
Data-driven
PYTHIA
$\Delta N_{\rm eff} = -0.06$


Herwig with $Y_a^{(\min)}$
f_a [GeV]
m_a [GeV]
Excluded by BBN(^{4}He)
Excluded by $\Delta N_{\rm eff} < -0.61$
Kaon
Baryon
$\pi^\pm$
Total
Data-driven
Herwig
$\Delta N_{\rm eff} = -0.06$


Herwig with $Y_a^{(\max)}$
f_a [GeV]
m_a [GeV]
Excluded by BBN (^{4}He)
Excluded by $\Delta N_{\rm eff} < -0.61$
Kaon
Baryon
$\pi^\pm$
Total
Data-driven
Herwig
$\Delta N_{\rm eff} = -0.06$

Uncertainties and model dependence

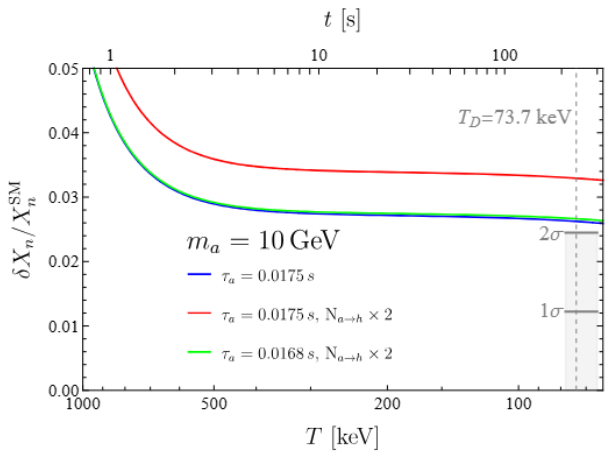
$$\tau_a \lesssim \frac{0.0175\ \text{sec}}{1 + \frac{1}{20}\log\left(N_{a\to h}\frac{Y_a^{(0)}}{10^{-3}} \times (\text{ftn of cross sections})\right)}$$

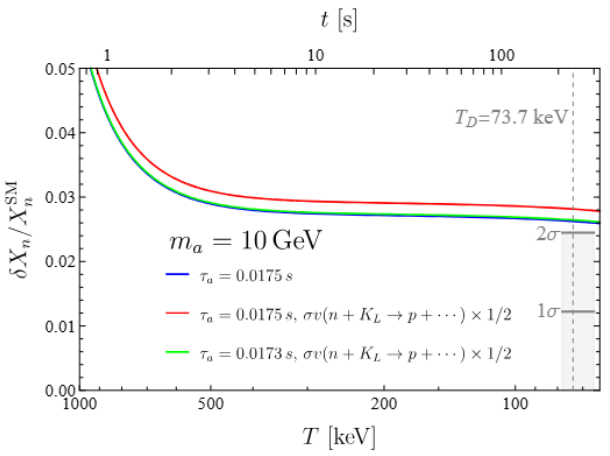
- This shows the lifetime upper bound is very insensitive to the uncertainties.
- 100% uncertainty in $N_{a\to h}$ (e.g. Pythia vs Herwig)
  $\Rightarrow$ 25 % in $\delta X_n|_{T=T_D}$ $\Rightarrow$ 4 % in τ_a bound
- 100% uncertainty in $\sigma\ (K_L)$
  $\Rightarrow$ 7 % in $\delta X_n|_{T=T_D}$ $\Rightarrow$ 1 % in τ_a bound
- This also means a mild model dependence
  (different model $\rightarrow$ different $N_{X\to h}$ and $Y_X^{(0)}$)

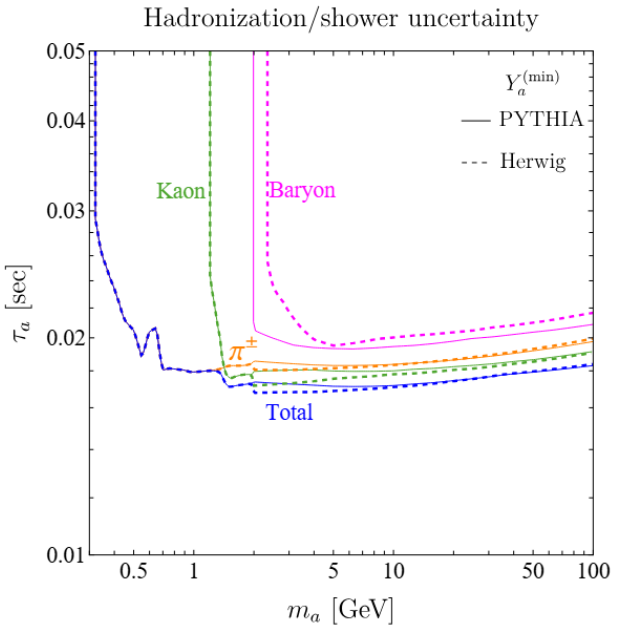
$\Rightarrow$ **Bounds on τ_a is robust.**

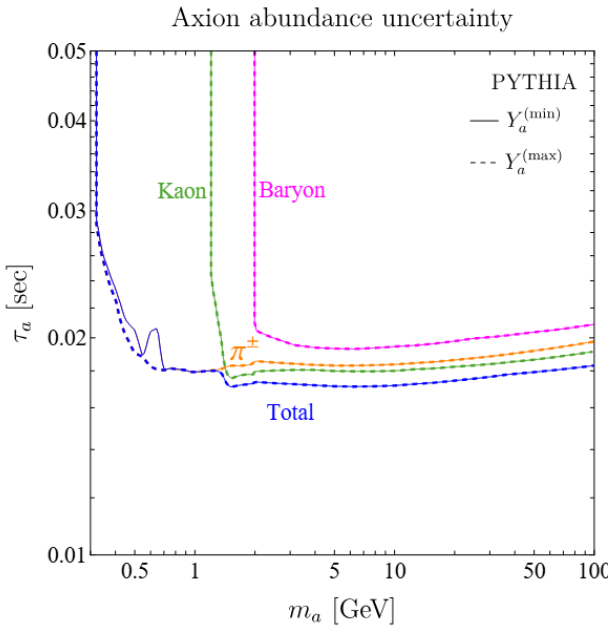
More precise version:

$$\tau_a \lesssim \frac{t_n}{\left(1+\ln\left[\frac{1}{R_{Y_p}}\frac{\delta X_n(t_{wf})}{X_n^{SM}(t_n)}\right]\right)^{\frac{2}{3}} \ln\left[\frac{Y_a\Gamma_a s}{\Gamma_{n\to p}^{weak}+\Gamma_{p\to n}^{weak}}\frac{N_{a\to h}(\langle\langle n\,h\rangle\rangle_c+\langle\langle p\,h\rangle\rangle_c)}{(\tilde{\Gamma}_h+\langle\langle n\,h\rangle\rangle n_n+\langle\langle p\,h\rangle\rangle n_p)}\right]}$$









Summary

- BBN provides strong constraints on BSM scenarios.

- Regarding $N_{\rm eff}$ bounds,
  - Conventional treatment is inconsistent with any BSM scenarios for the negative $\Delta N_{\rm eff}$ region.
  - We introduced minimal modification in T_ν/T for $\Delta N_{\rm eff} < 0$ and found an accidental cancellation in $\mathrm{Y_p}$.
  - It leads to a much weaker constraint in the lower bound.
  - It implies that EMPRESS He4 anomaly cannot be explained by a negative $\Delta N_{\rm eff}$.

- Hadronic injection scenarios are more strongly constrained. $$\tau_a \lesssim \frac{0.0175\ \mathrm{sec}}{1+\frac{1}{20}\log\left(N_{a\to h}\frac{Y_a^{(0)}}{10^{-3}}\times(\text{ftn of cross sections})\right)}$$

- We improved the BBN analysis of hadronic injection scenarios, and applied it to the heavy QCD axion.

Thank you!