# BBN constraints on MeV-scale dark sectors: Electromagnetic decays.

based on

arXiv:1808.09324 (,arXiv:1712.03972)

Marco Hufnagel, Kai Schmidt-Hoberg, Sebastian Wild

Wednesday, September 26, 2018

HELMHOLTZ SPITZENFORSCHUNG FÜR GROSSE HERAUSFORDERUNGEN

# Big Bang Nucleosynthesis

- Formation of light nuclei in the early phase of the universe

  $t \sim 1\ \mathrm{s} - 10^3\ \mathrm{s} \quad \leftrightarrow \quad T \sim\ \mathrm{MeV} -\ \mathrm{keV}$

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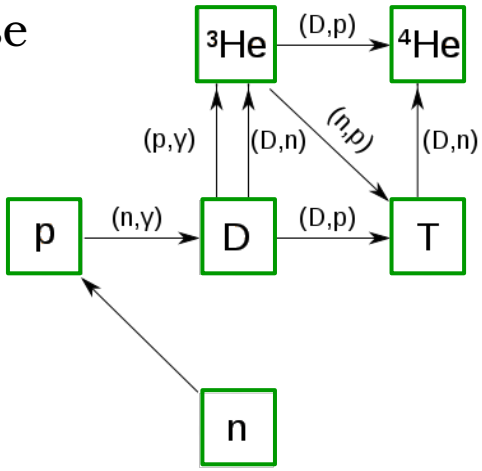

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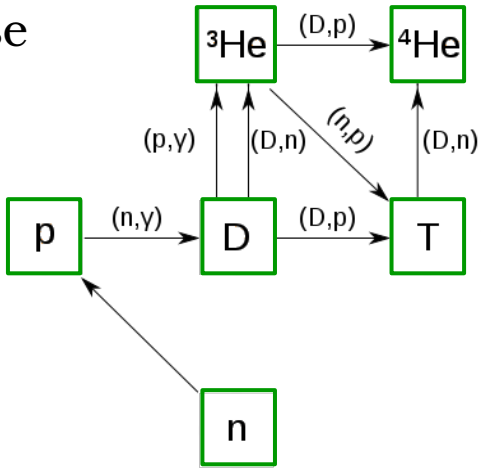


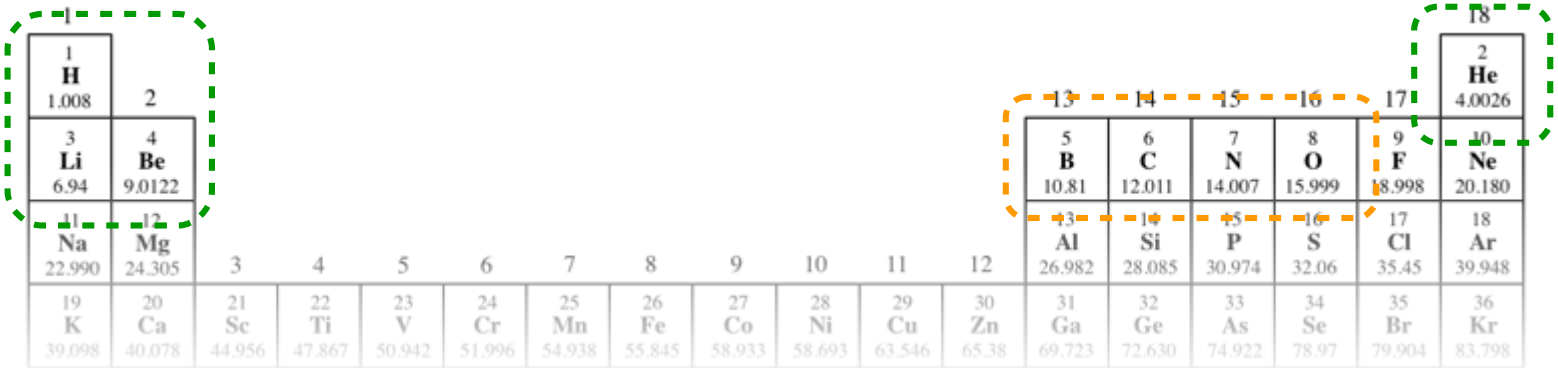

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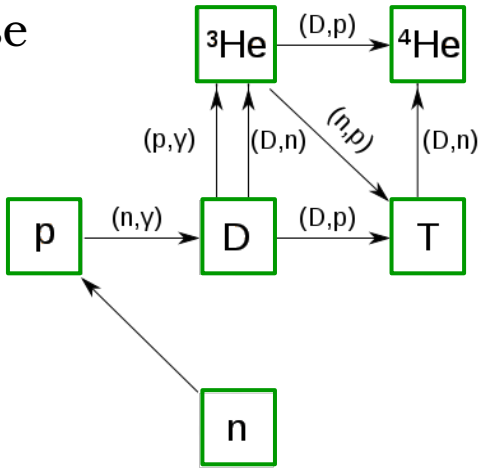


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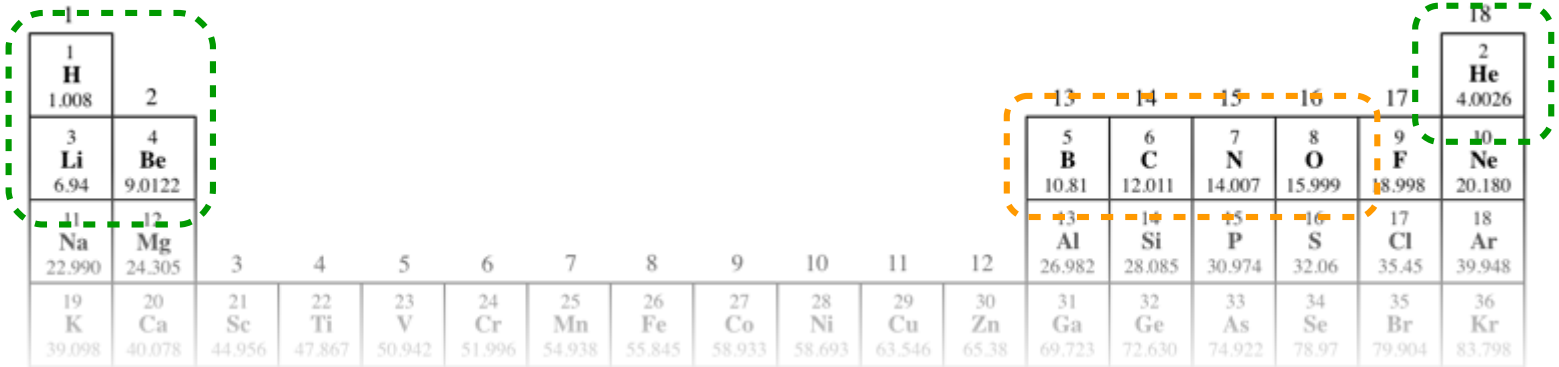

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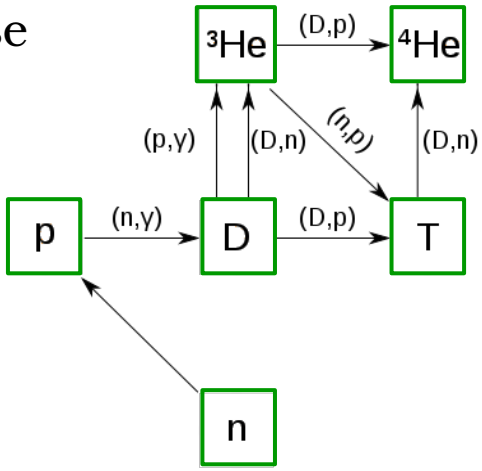


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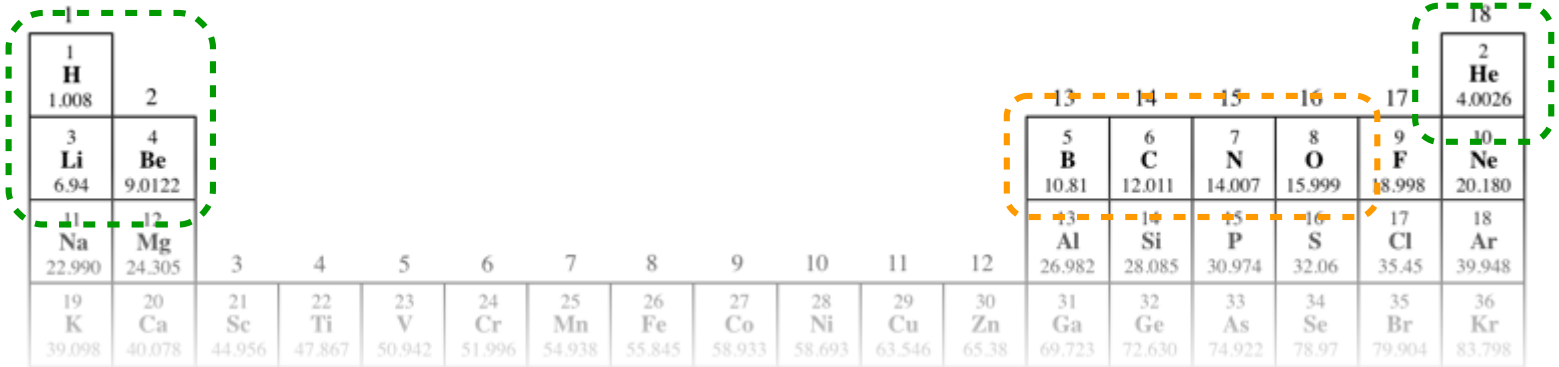

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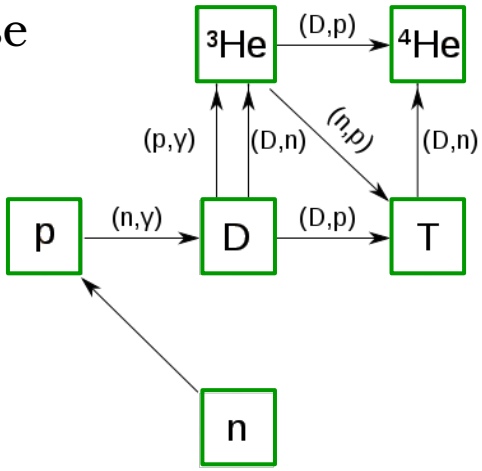


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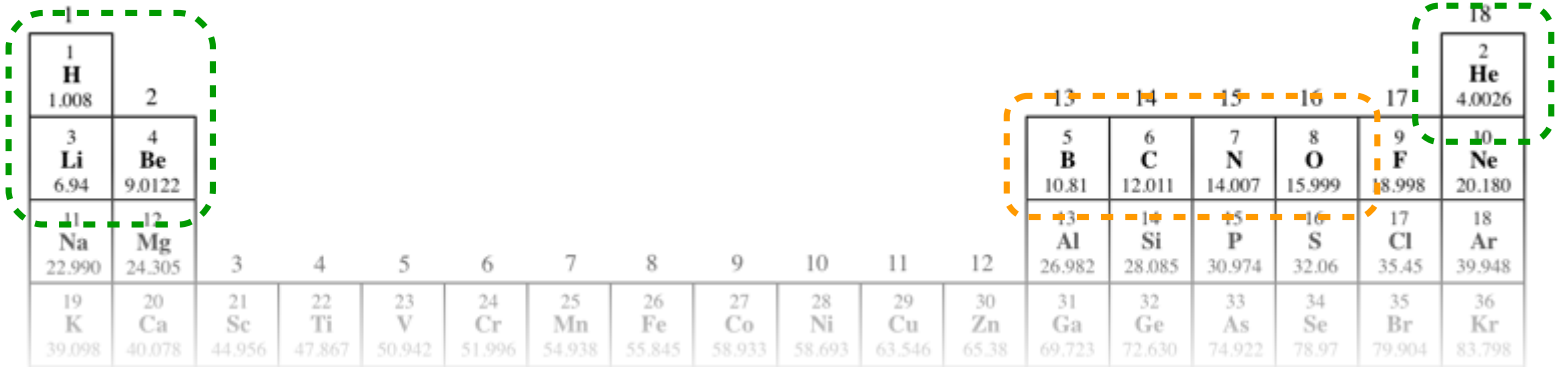

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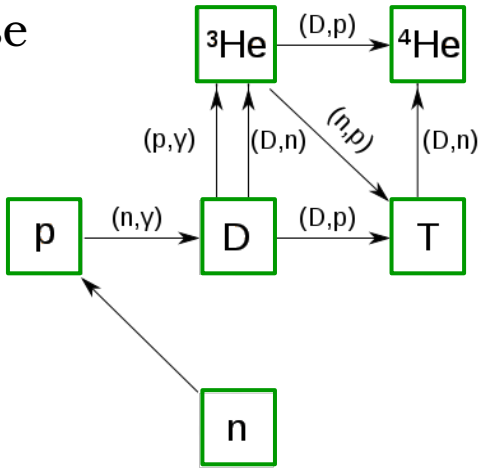


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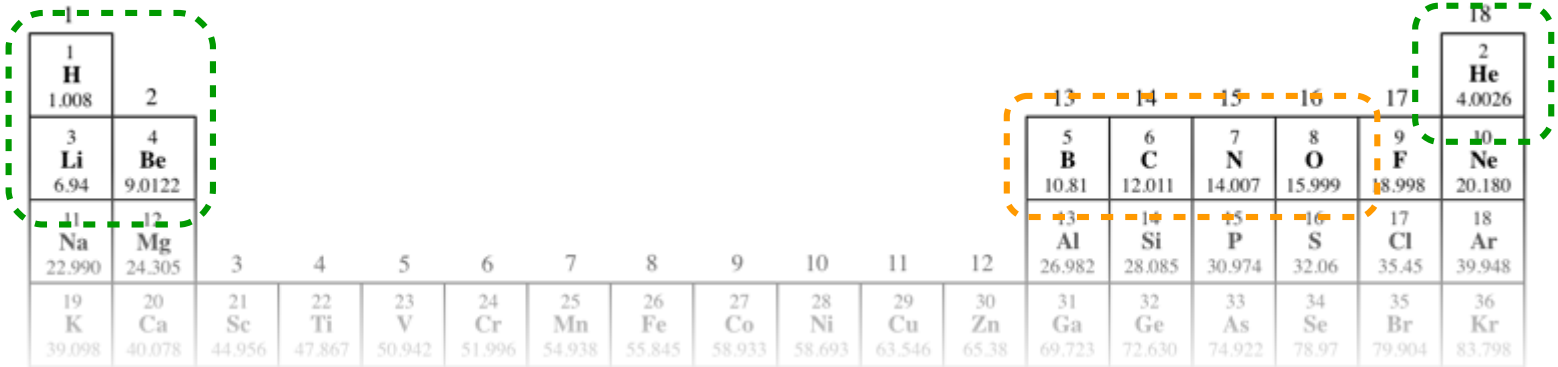
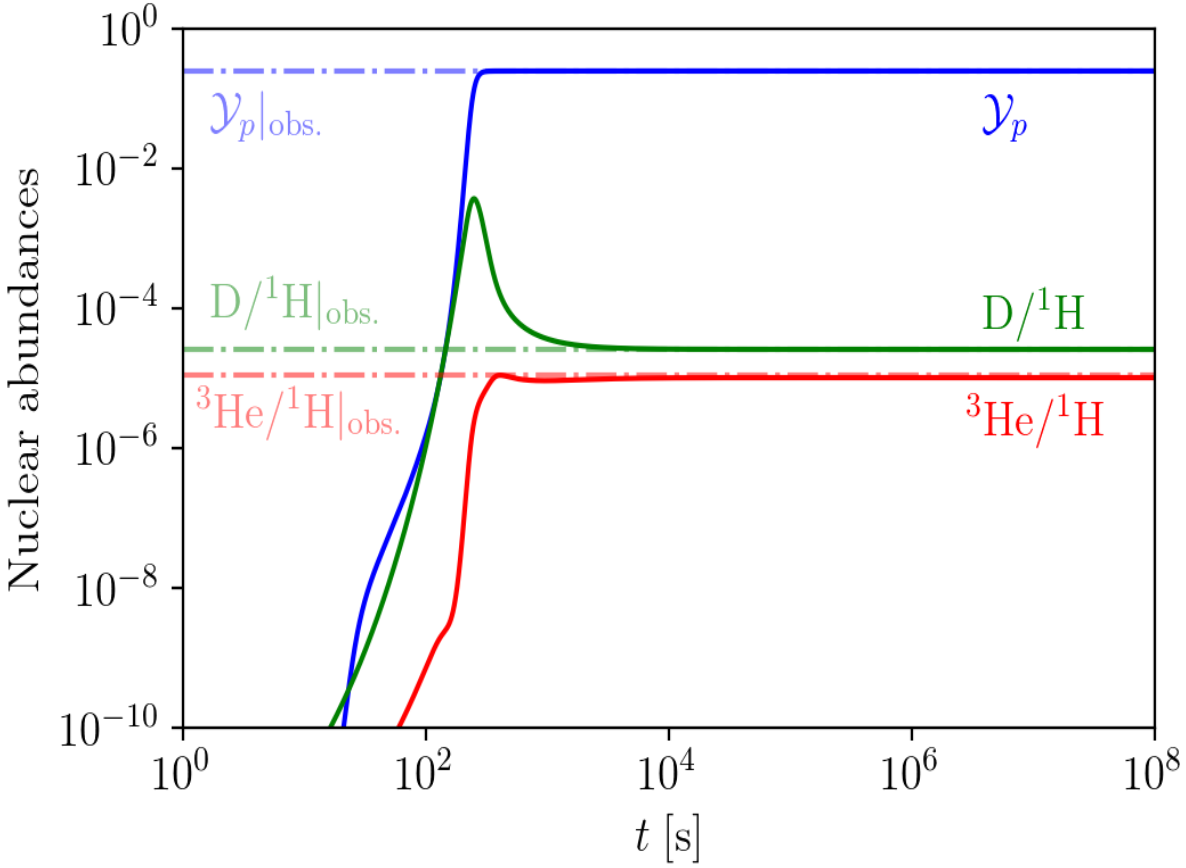
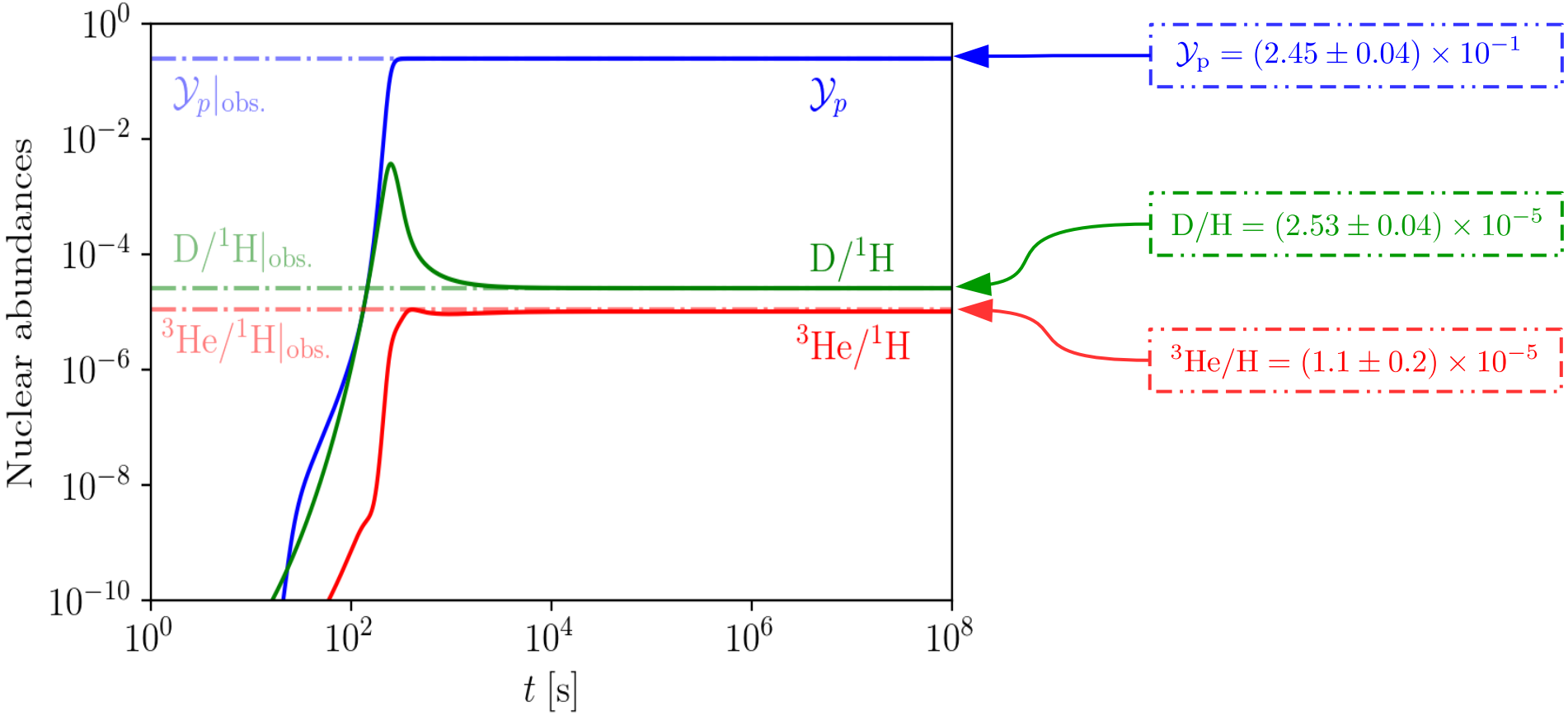


## SM prediction



SM prediction

Observation



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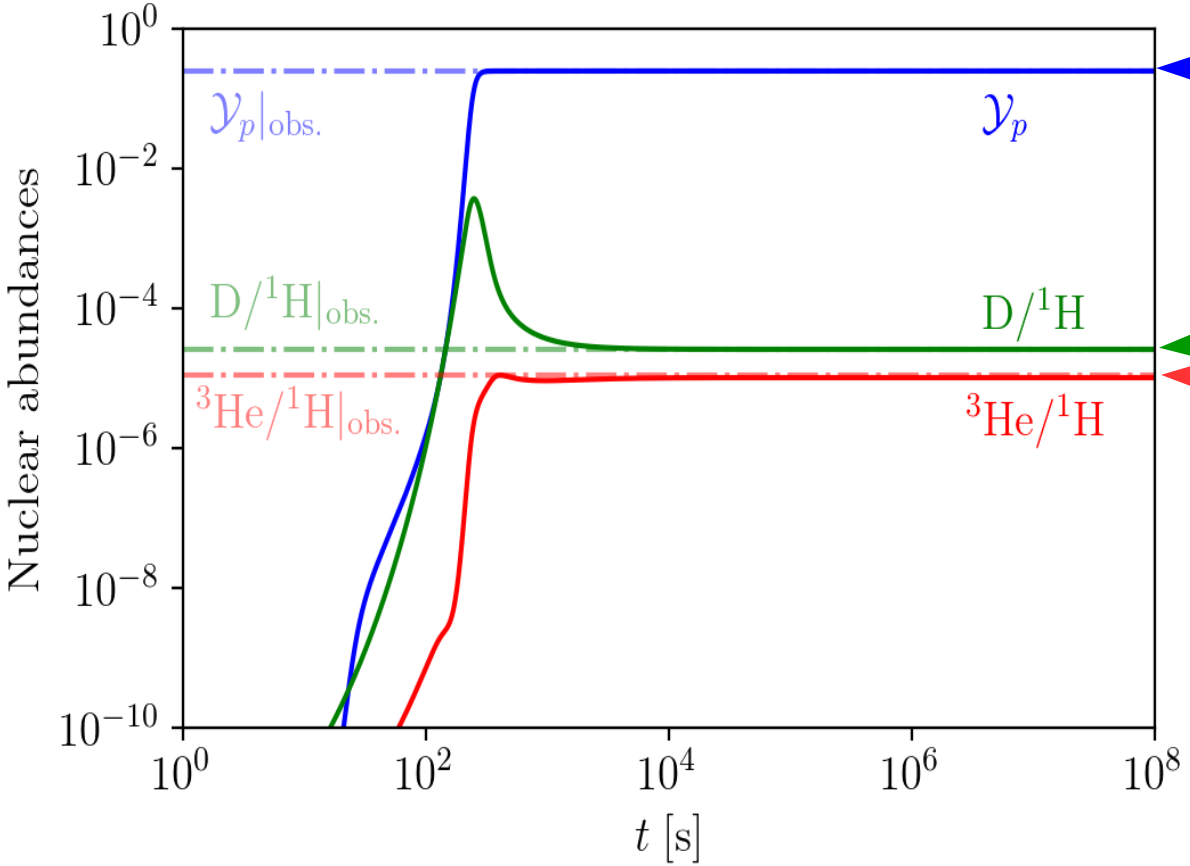



$\mathcal{Y}_\mathrm{p} = (2.45 \pm 0.04) \times 10^{-1}$

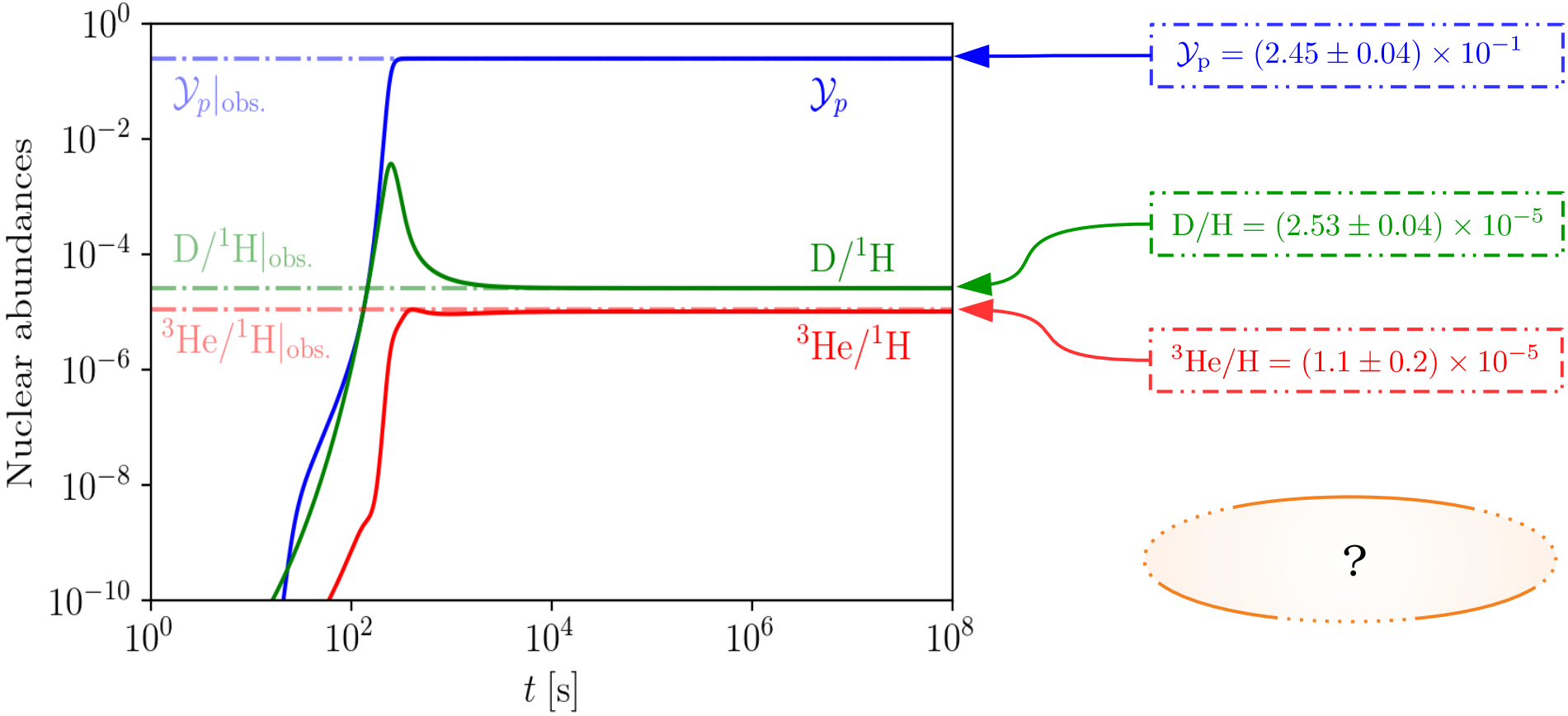
$\mathrm{D/H} = (2.53 \pm 0.04) \times 10^{-5}$

$^3\mathrm{He/H} = (1.1 \pm 0.2) \times 10^{-5}$

✔ Compatible within $1\sigma$

# Evolution of the abundances during BBN

SM prediction | Observation




However: In the presence of a dark sector:

Hubble rate | Entropy production | Spallation | Photodisintegration

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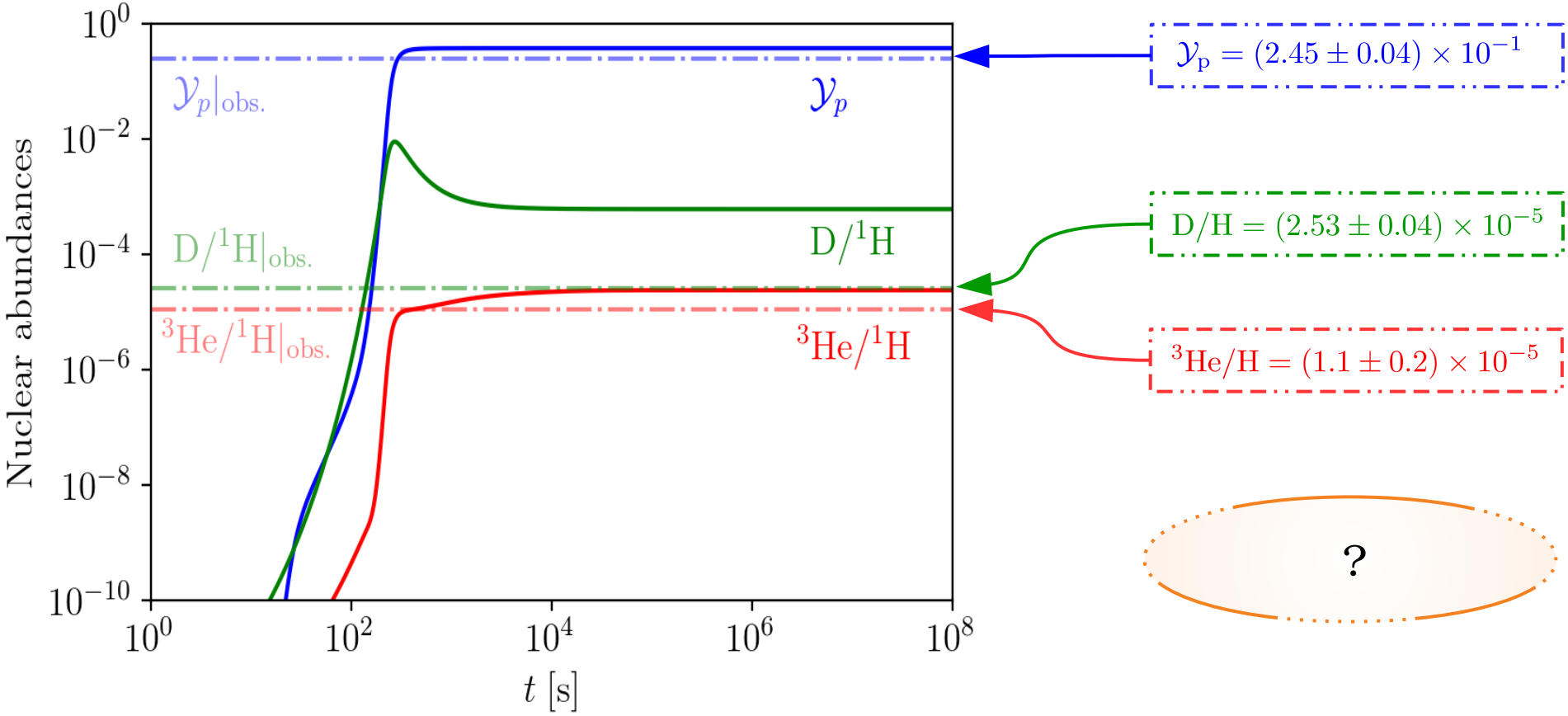
SM prediction | Observation

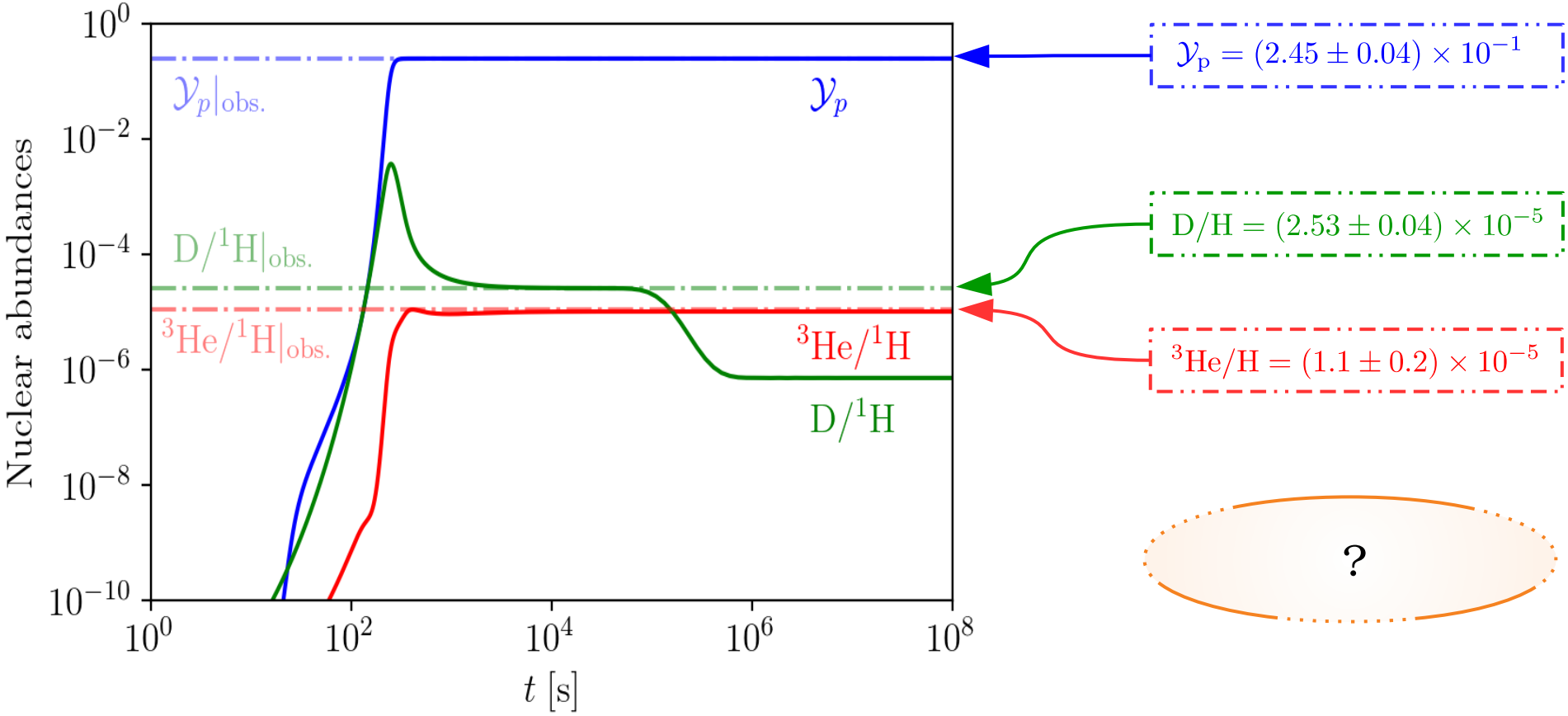



However: In the presence of a dark sector:

Hubble rate $\quad \dfrac{\mathrm{d}t}{\mathrm{d}T} \sim \dfrac{1}{H(T)} \quad$ with $\quad H(T) \sim \left[\rho_{\rm SM}(T) + \rho_{\rm D}(T)\right]^{1/2}$

# Evolution of the abundances during BBN

SM prediction | Observation




However: In the presence of a dark sector:

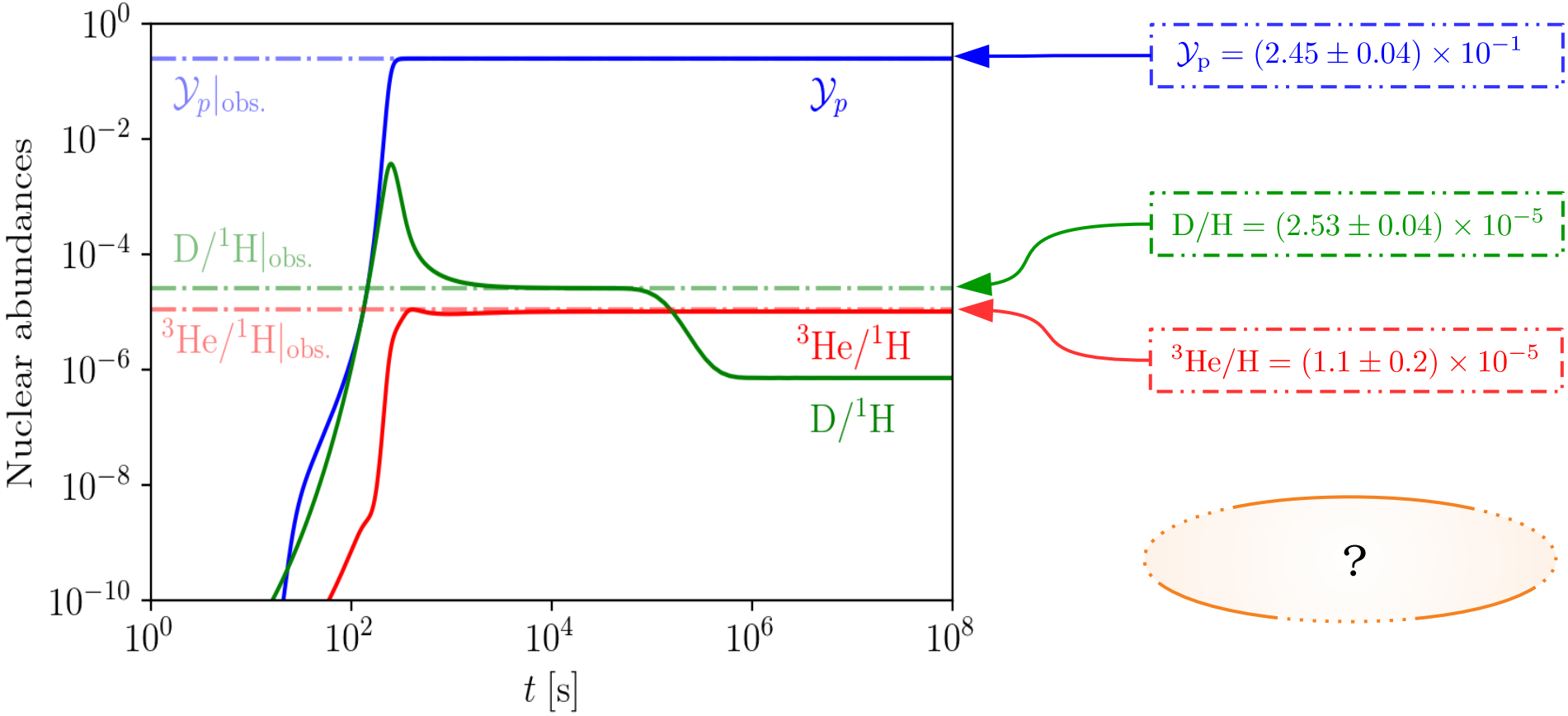
dark sector $\to \gamma\gamma$ : $d(\gamma, n)p$ , $^4\mathrm{He}(\gamma, np)d$ , ...

Photodisintegration

# Evolution of the abundances during BBN

SM prediction

Observation




Several studies already exist: [astro-ph/0211258] [hep-ph/0604251] [1503.04852]

However:

Decaying particle is always explicitly assumed to be non-relativistic

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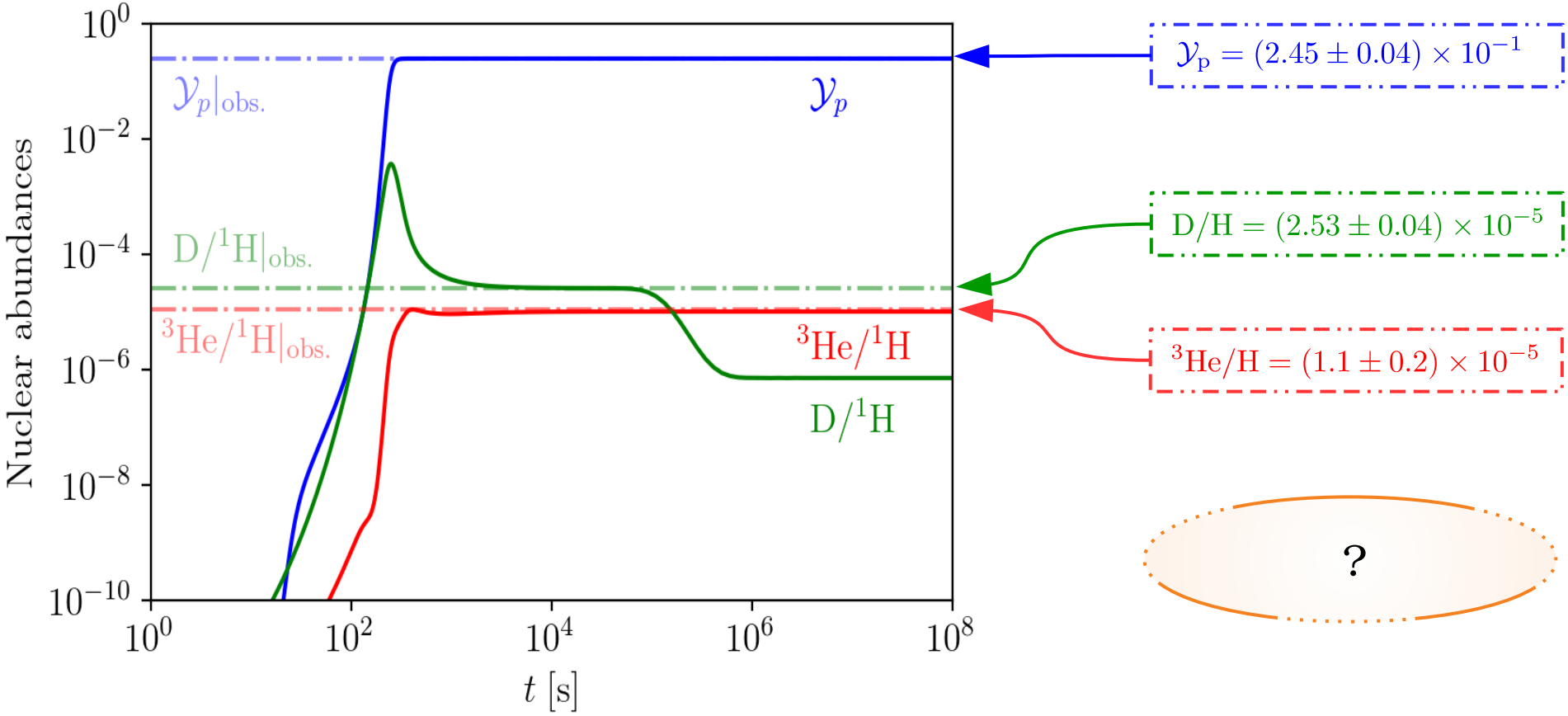
SM prediction | Observation

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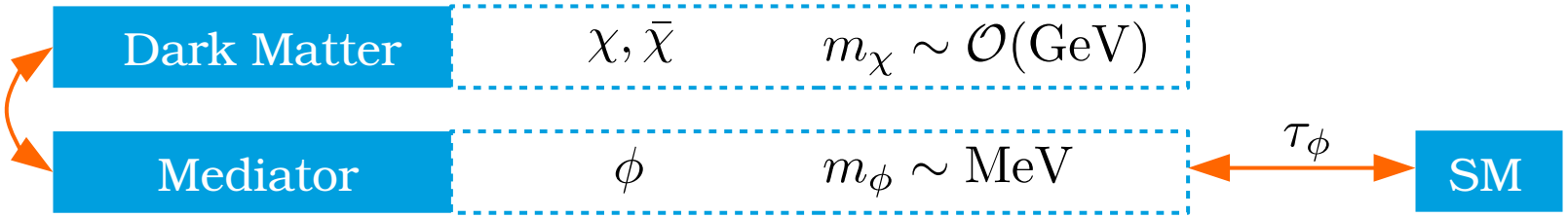
Here: $m_\phi \sim T_{\text{BBN}} \sim E_{\text{PDI}}$

→ Dedicated analysis needed due to the special scale

# Setup and Calculation

Particle content:



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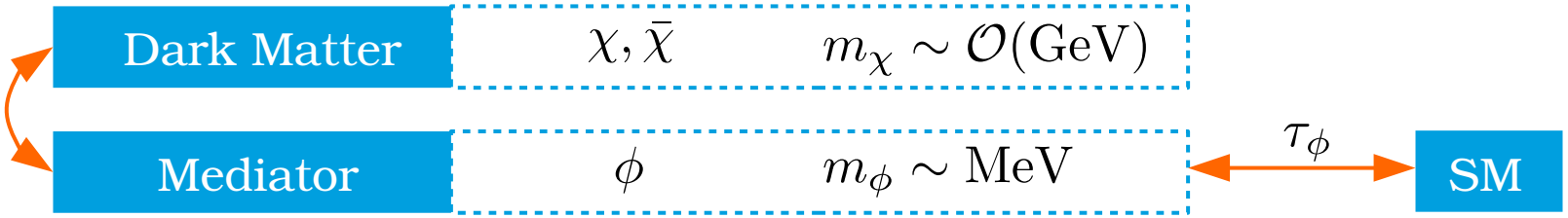


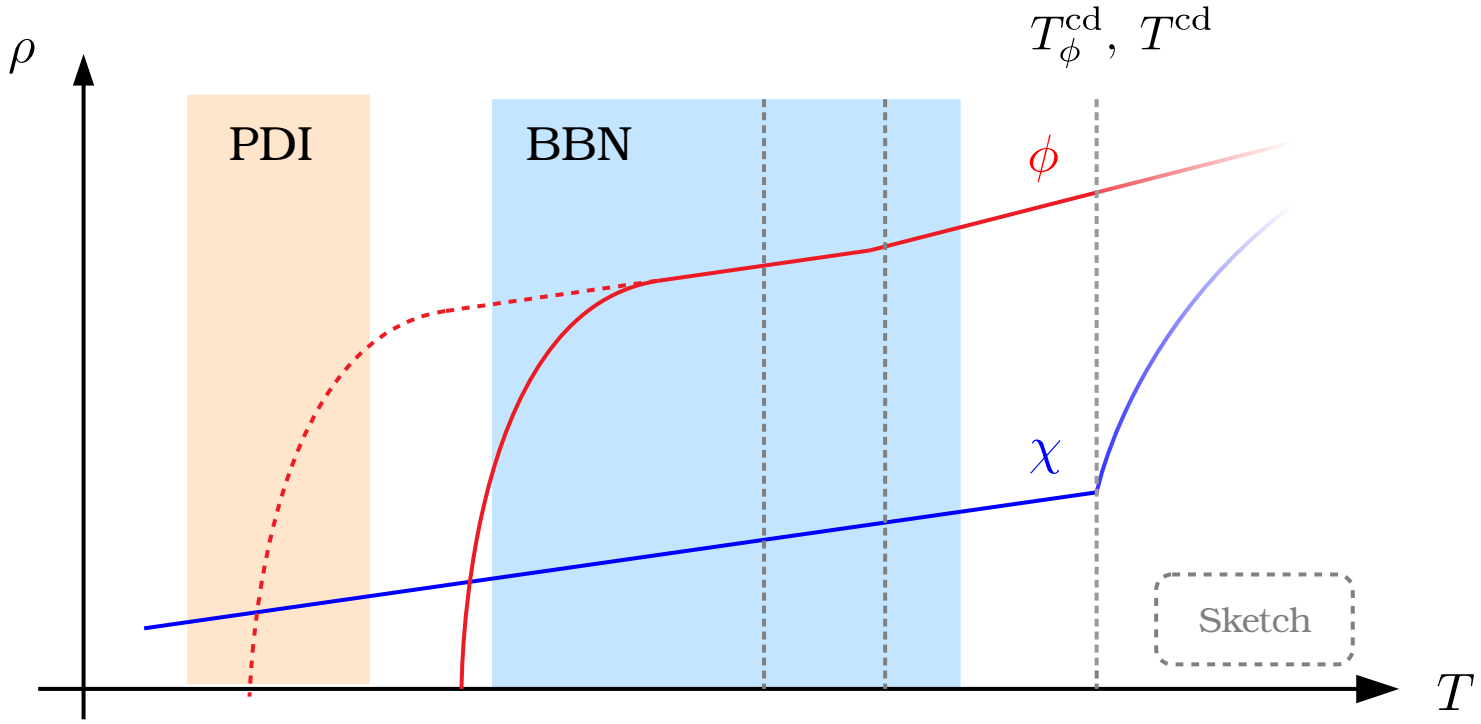

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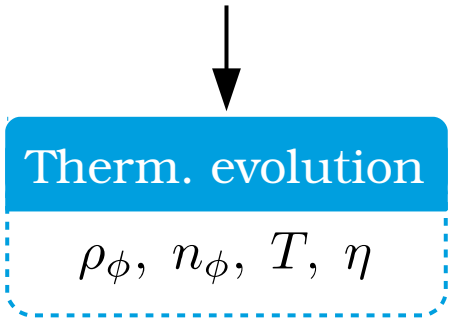

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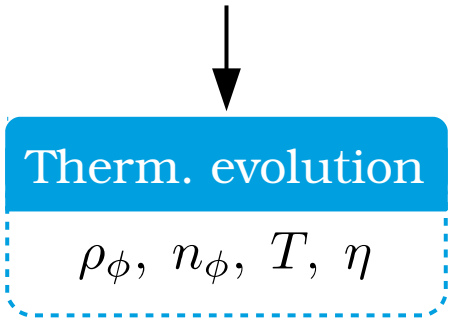
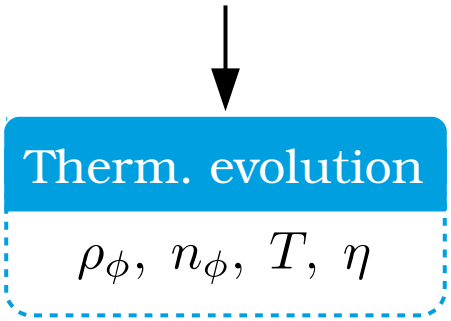



Mediator spectrum

$$\frac{\partial f_\phi}{\partial t} = Hp\frac{\partial f_\phi}{\partial p} - \frac{1}{\tau_\phi}\frac{m_\phi}{E} f_\phi$$

Dilution

Decay

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Time-temperature relation

$$\dot{T} - \dot{T}_{\mathrm{SM}} \sim \frac{m_\phi n_\phi}{\tau_\phi}$$

Neutrino decoupling

$$T(t_{\nu\mathrm{d}})^5/H(t_{\nu\mathrm{d}}) \sim \text{const.}$$

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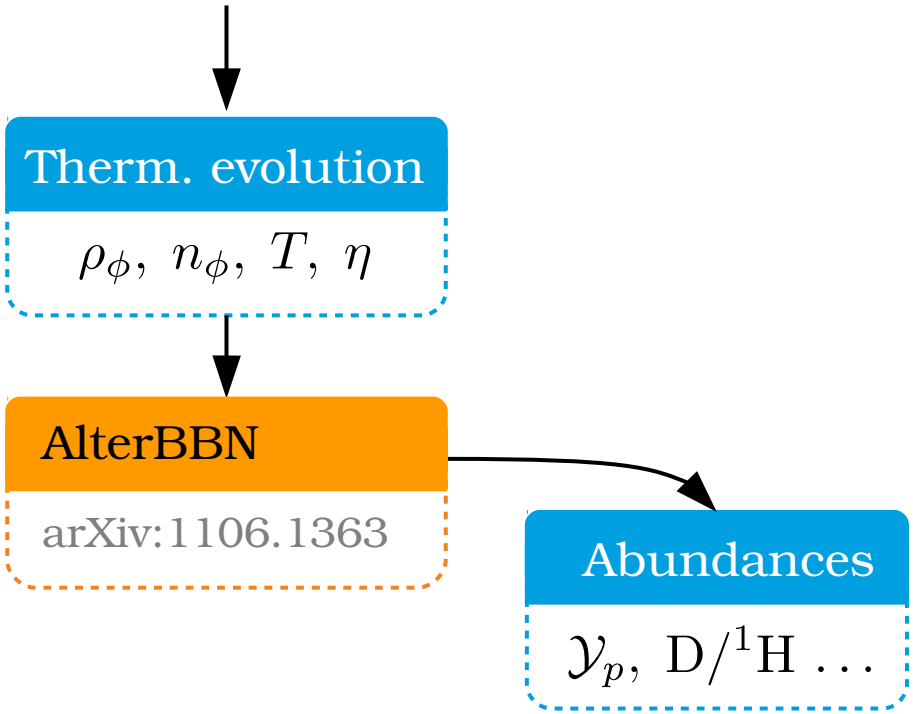


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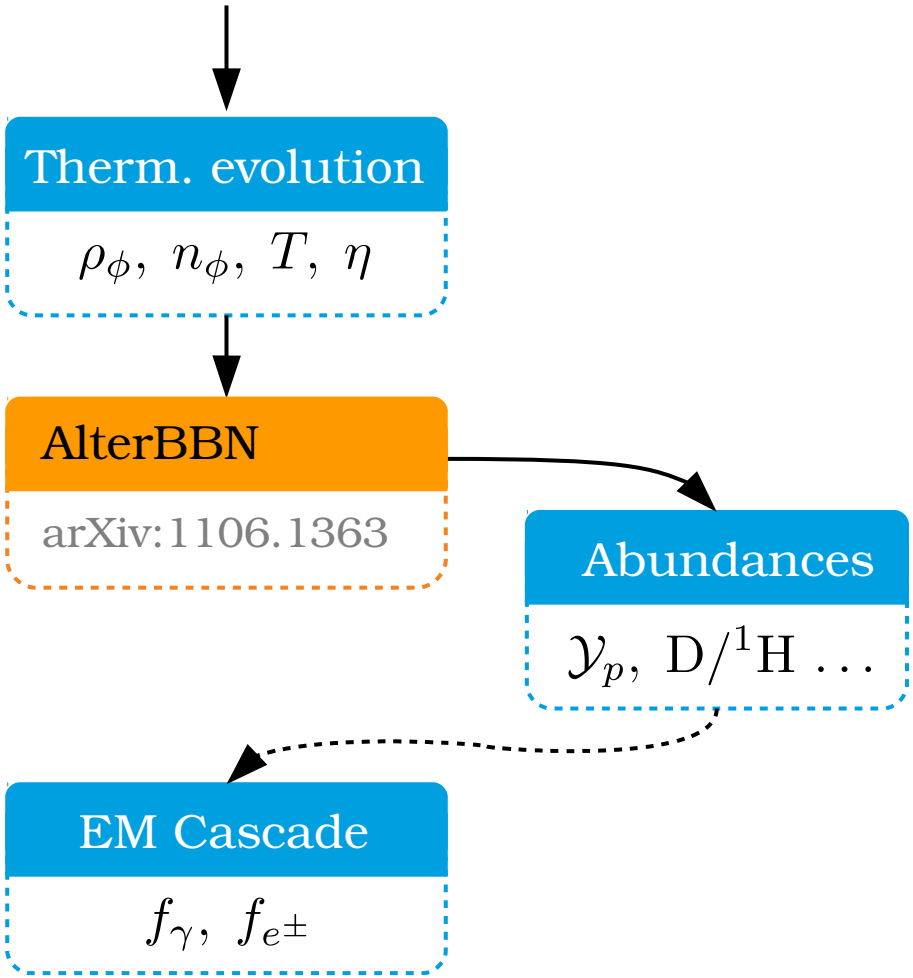


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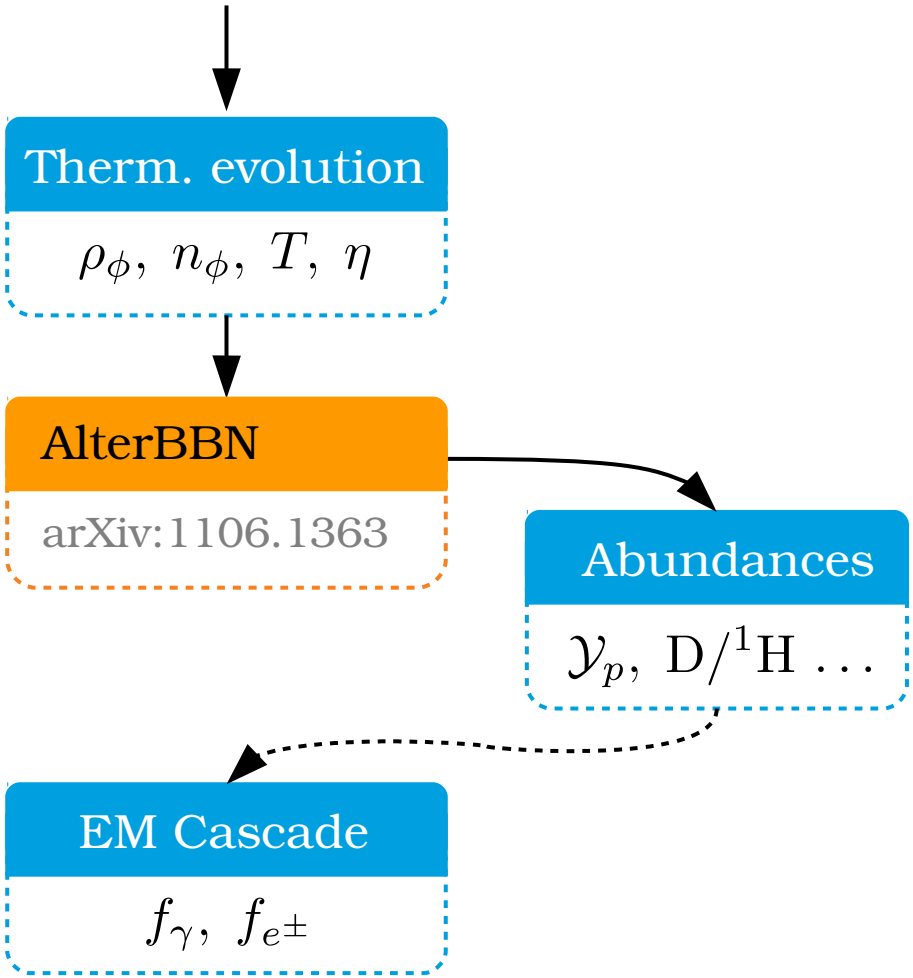


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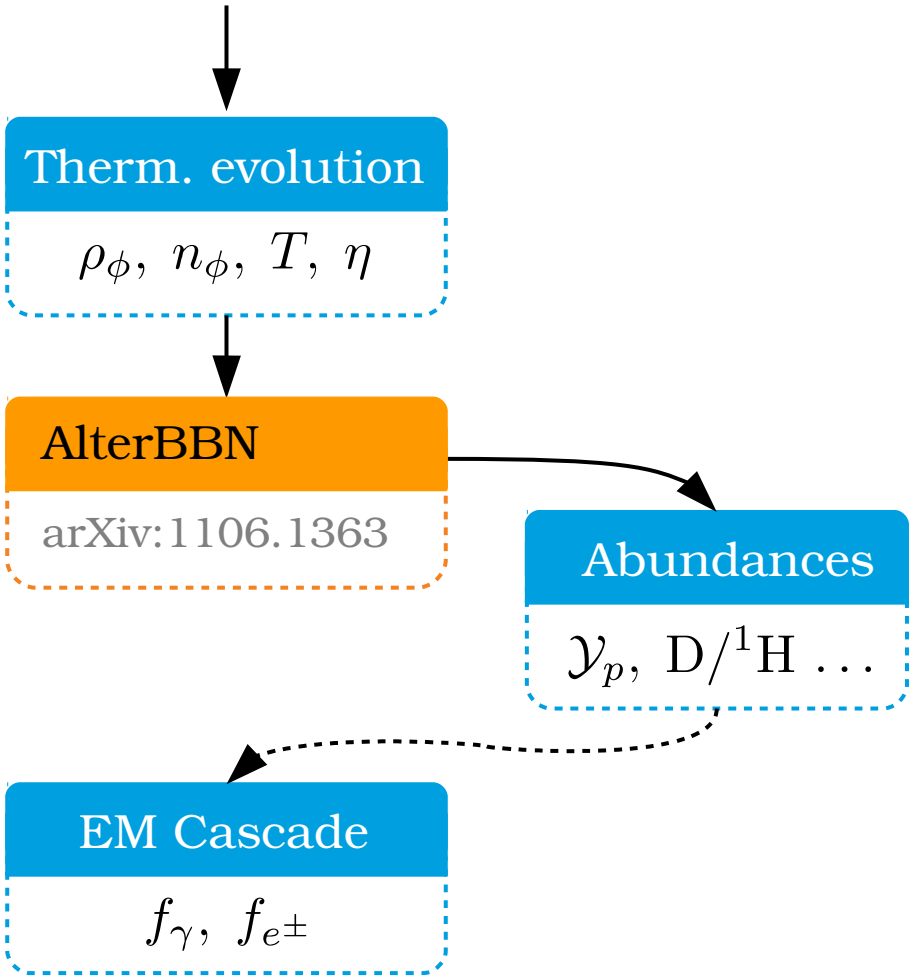


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$\gamma + \gamma_{\mathrm{th}} \to e^+ + e^-$

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$e^\pm + \gamma_{\mathrm{th}} \to e^\pm + \gamma$

$\gamma + e^-_{\mathrm{th}} \to \gamma + e^-$

$\gamma + N \to e^+ + e^- + N$

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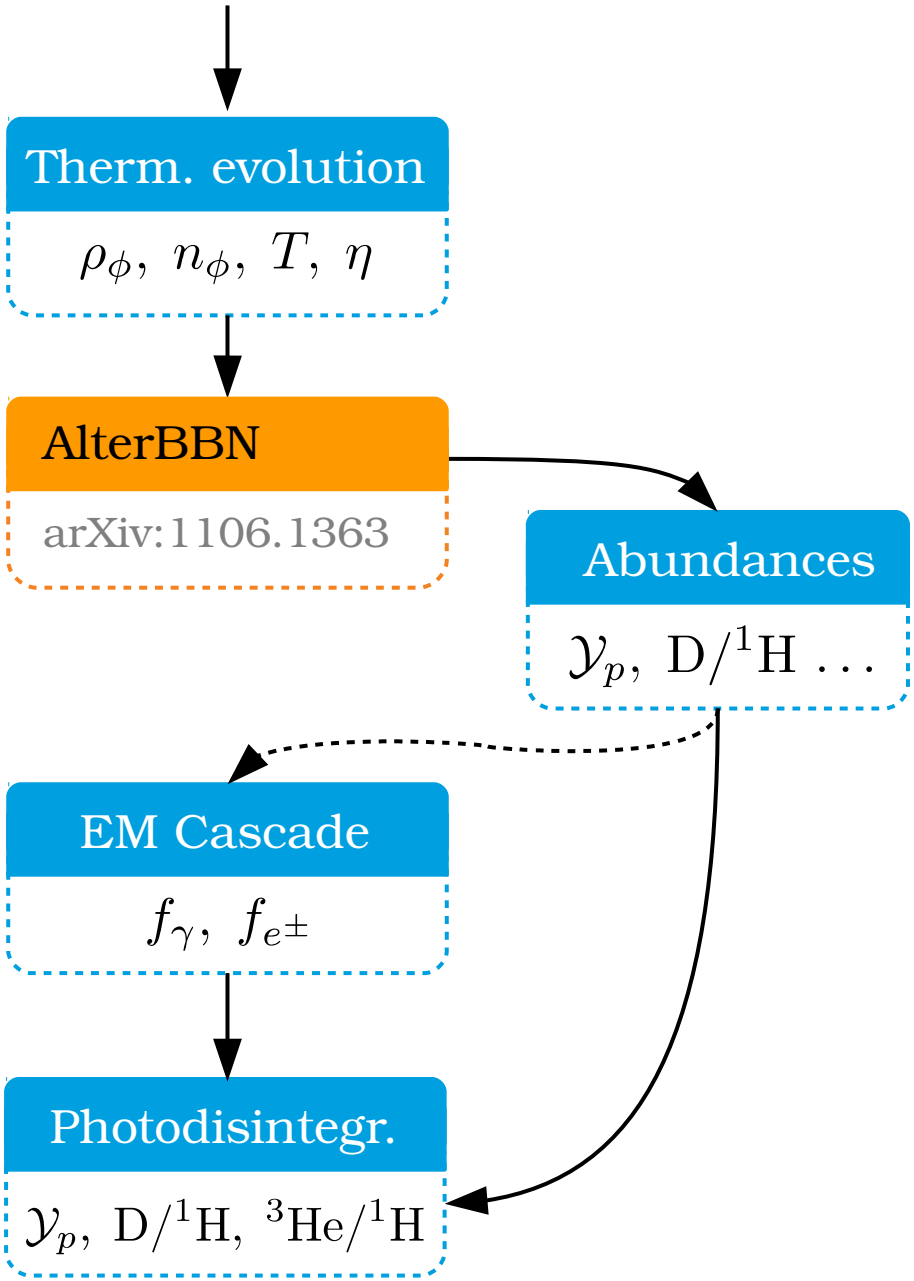


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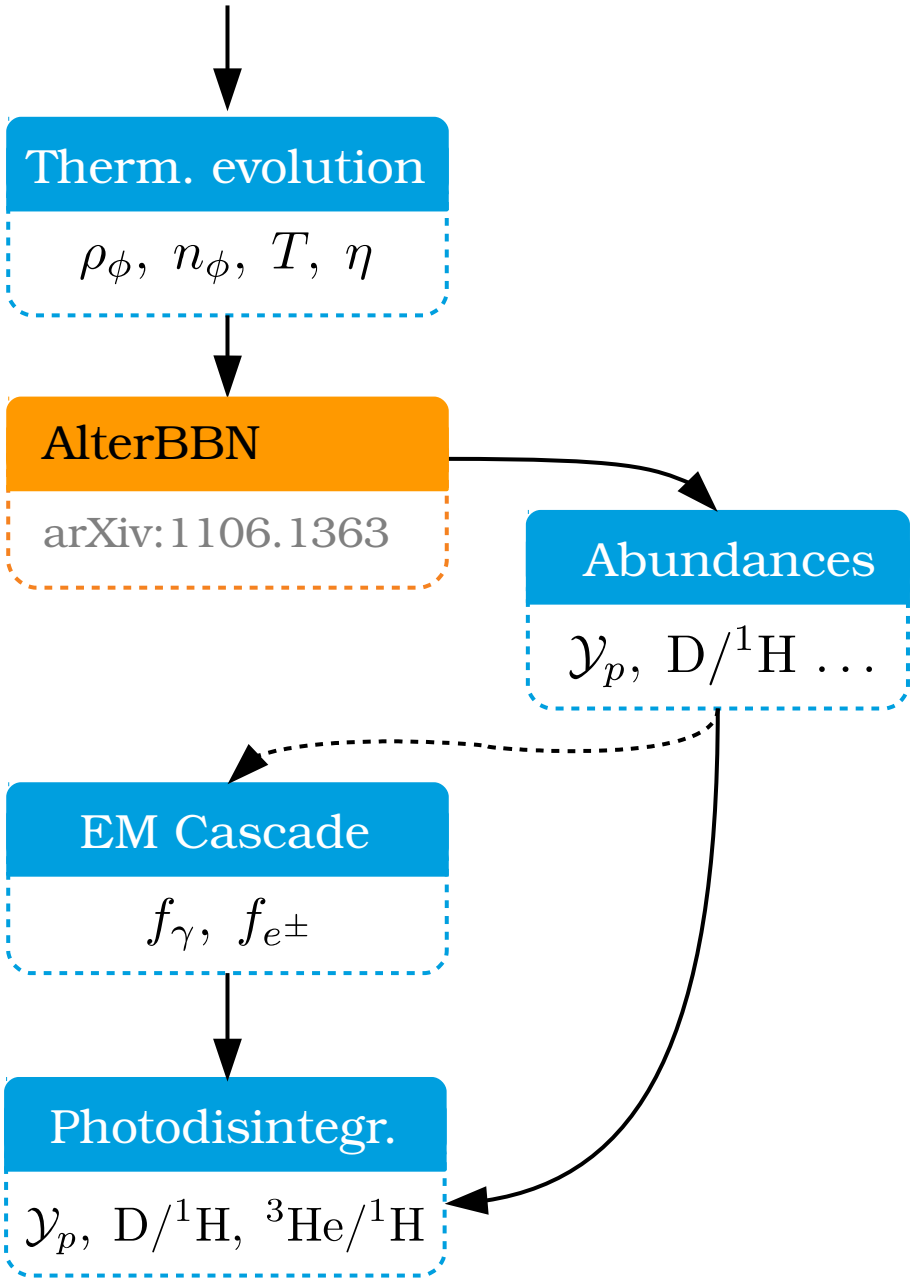


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Therm. evolution

$\rho_\phi,\ n_\phi,\ T,\ \eta$

AlterBBN

arXiv:1106.1363

Abundances

$\mathcal{Y}_p,\ \mathrm{D}/^1\mathrm{H}\ \ldots$

EM Cascade

$f_\gamma,\ f_{e^\pm}$

Photodisintegr.

$\mathcal{Y}_p,\ \mathrm{D}/^1\mathrm{H},\ ^3\mathrm{He}/^1\mathrm{H}$

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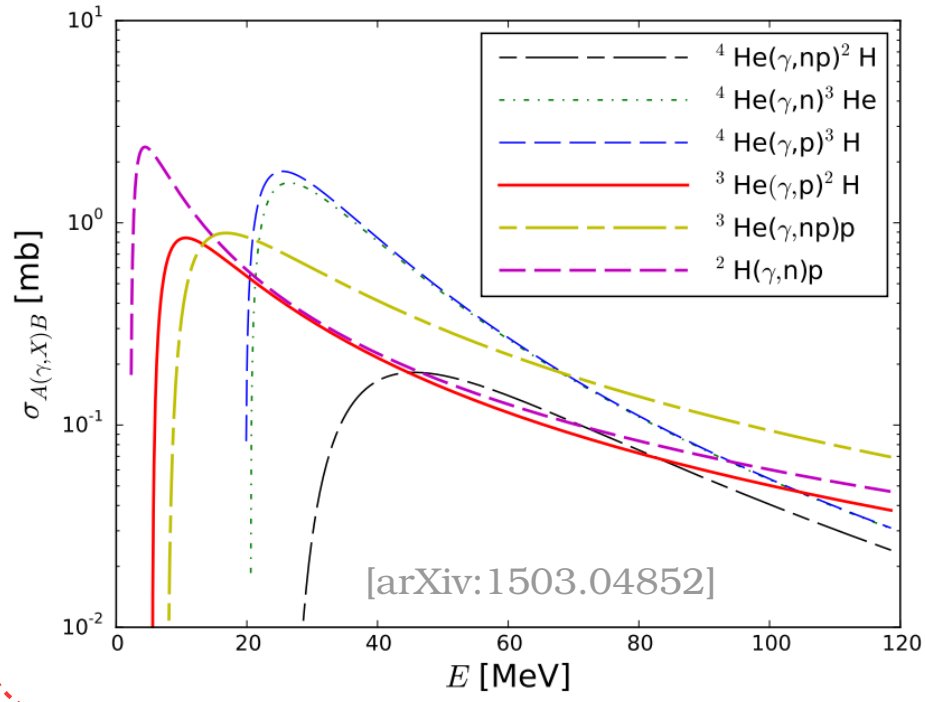
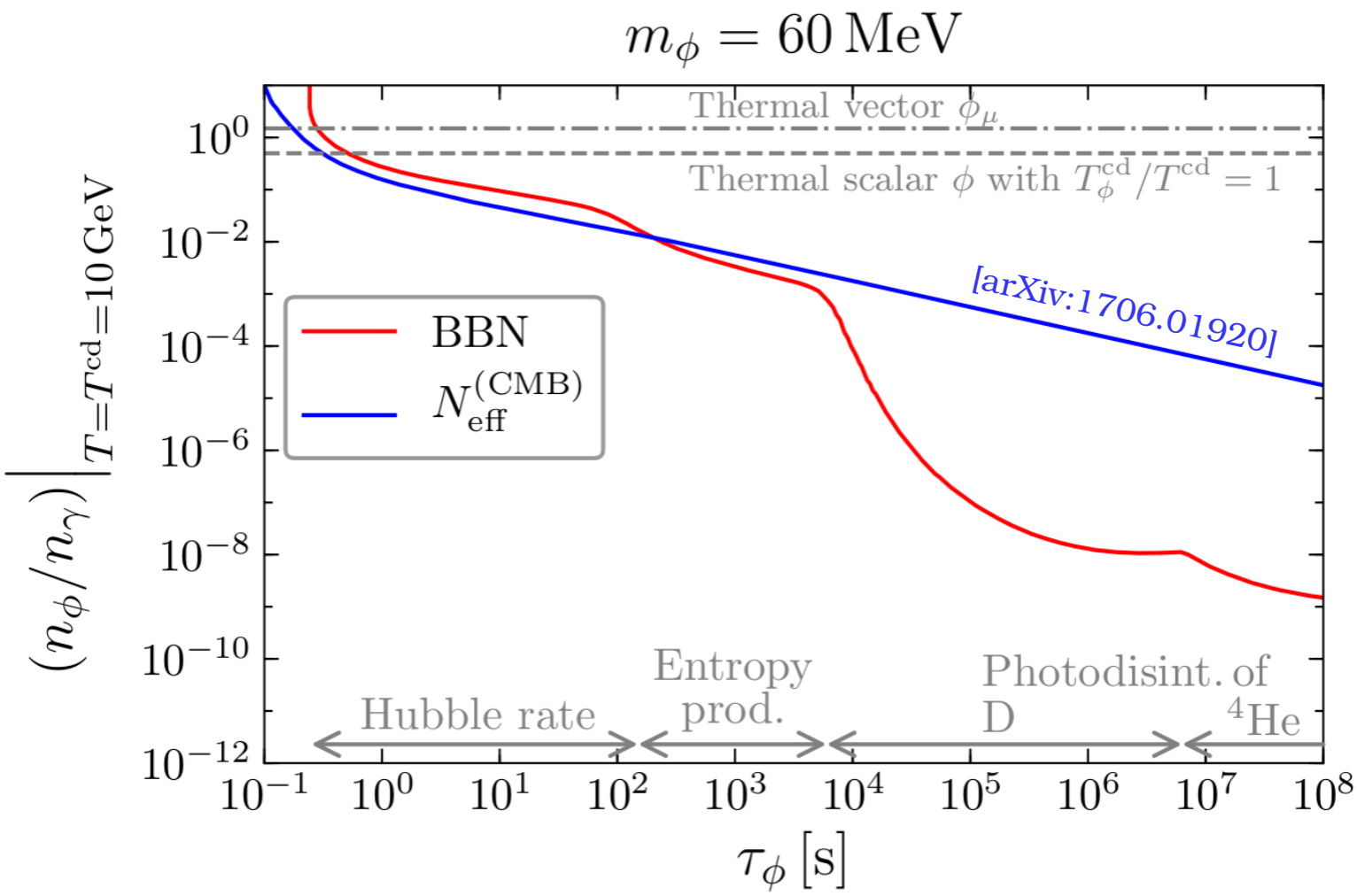


# Upper limits on the abundance ('large' masses)




- BBN bounds are sensitive to <u>three different effects</u>

  → A combined analysis is seemingly relevant

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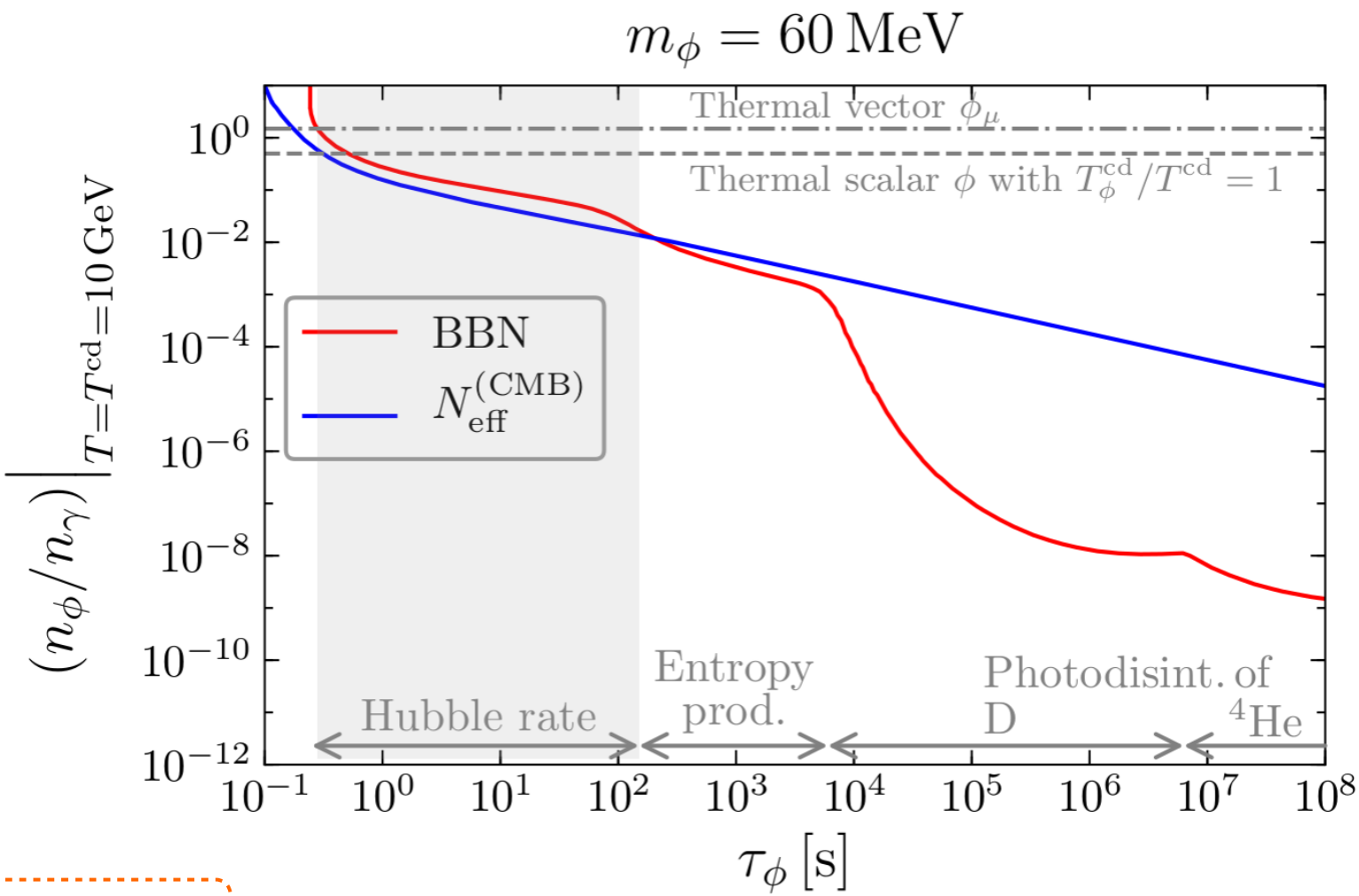


$\tau_\phi \lesssim 200\,\mathrm{s}$

- Modified Hubble rate causes modified time-temp. relation → base effect

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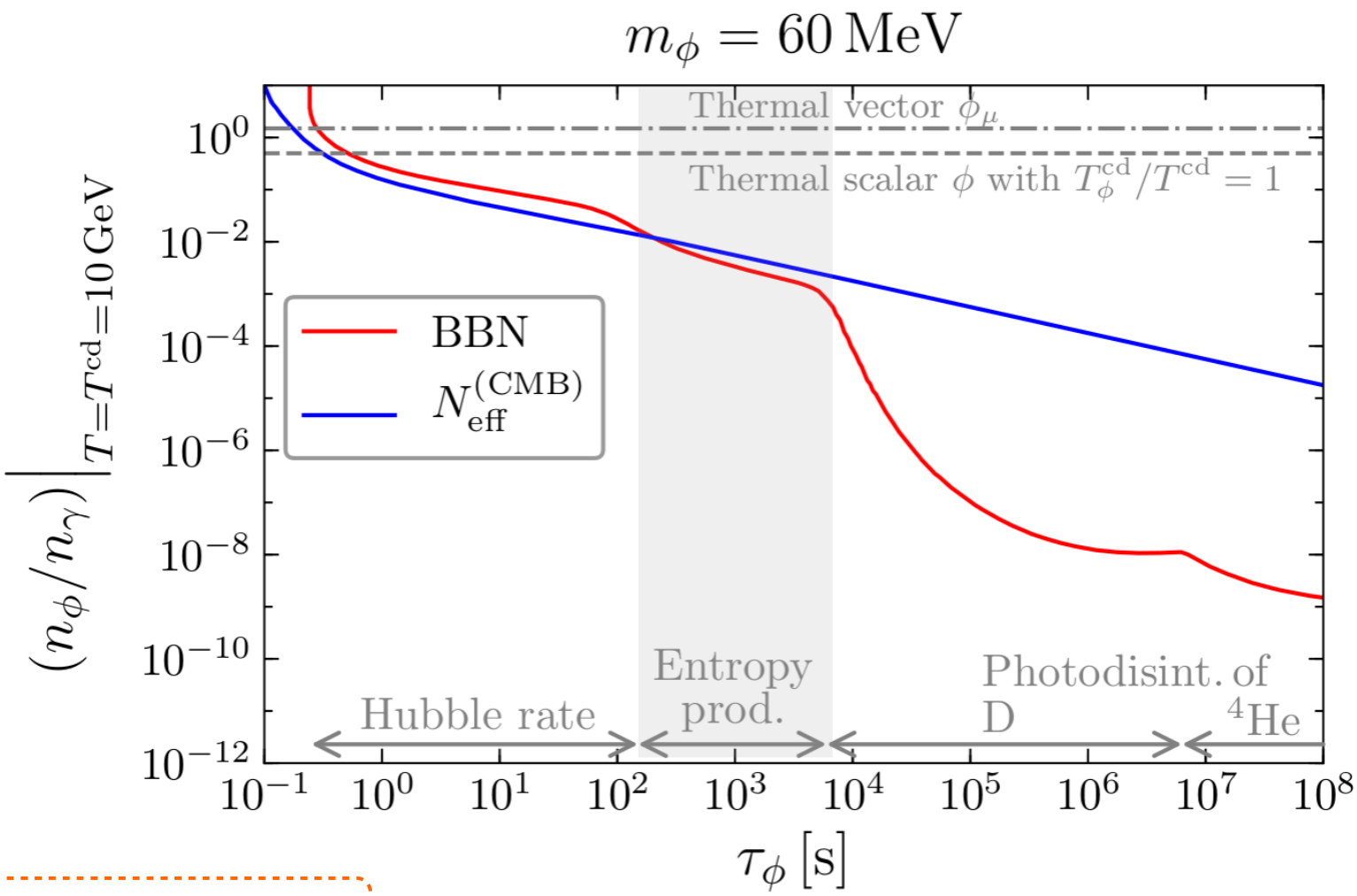


$200\,\mathrm{s} \lesssim \tau_\phi \lesssim 10^4\,\mathrm{s}$

- Decay of $\phi$ leads to <u>entropy injection</u> into the thermal bath

$$\eta \sim n_b/s, \qquad \eta_{\text{pre-decay}} \geq 6.1 \times 10^{-10} = \eta_{\mathrm{CMB}}$$

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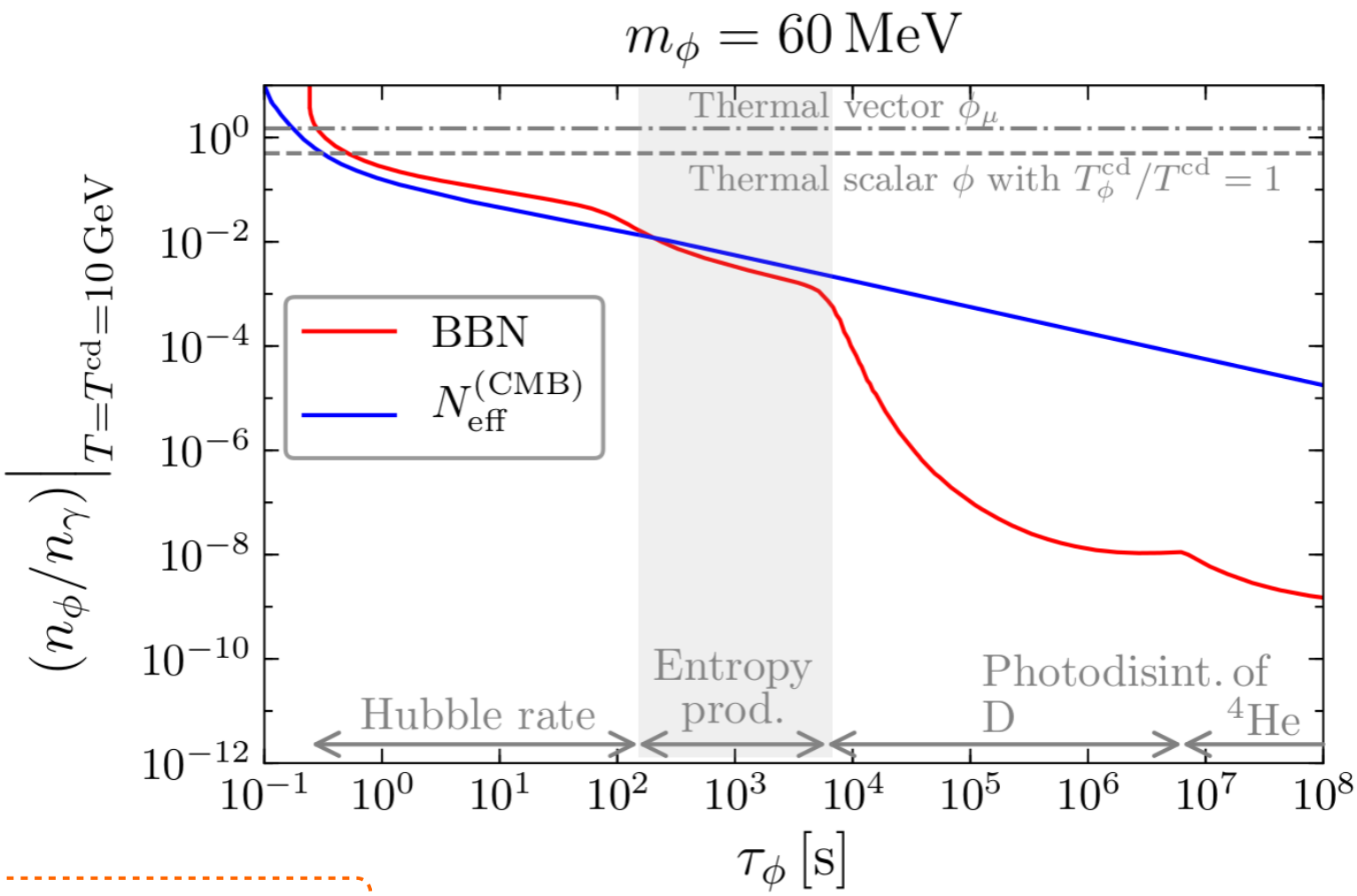


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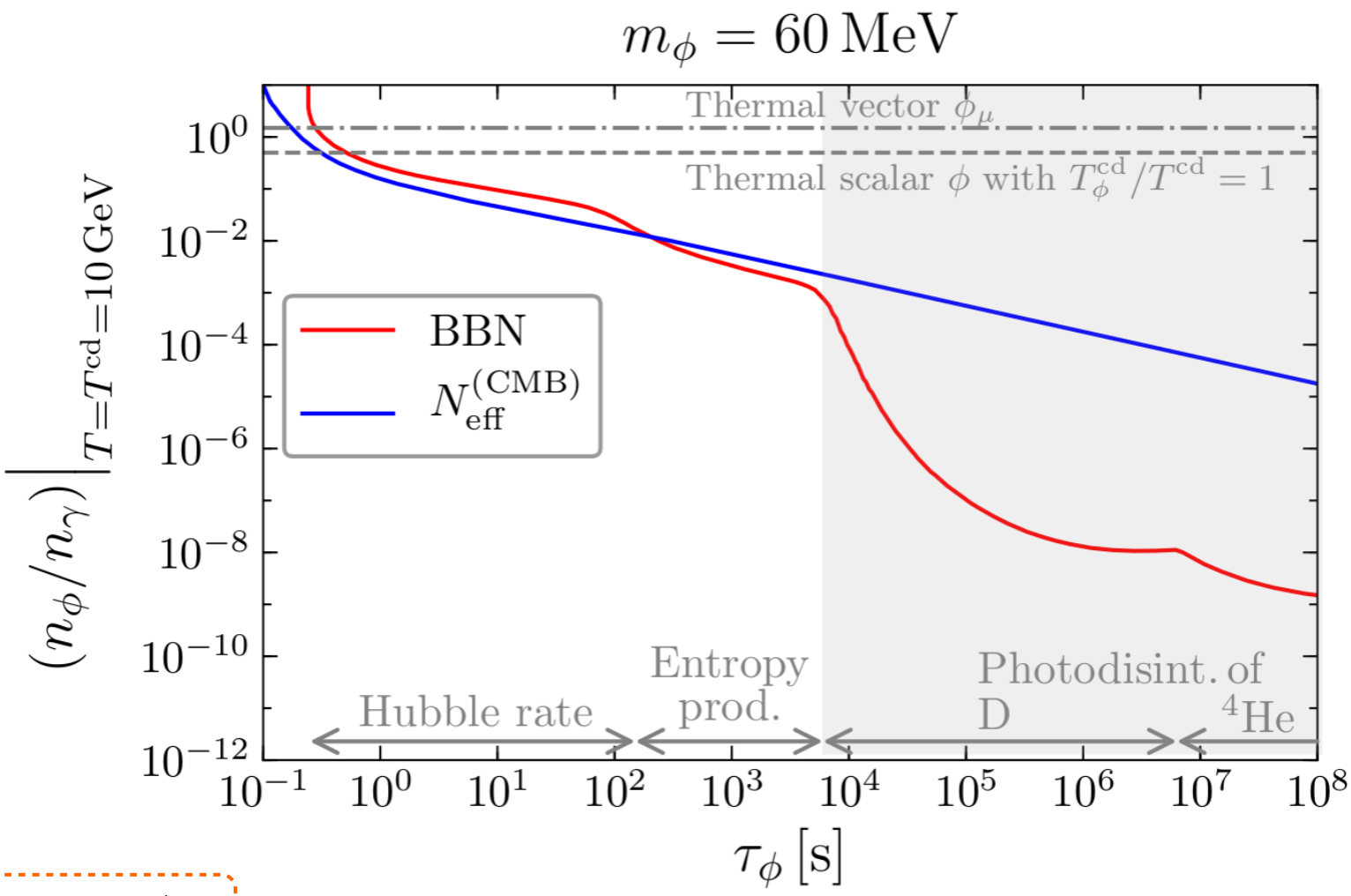
$$\eta \sim n_b/s, \qquad \eta_{\text{pre-decay}} \geq 6.1 \times 10^{-10} = \eta_{\mathrm{CMB}}$$

- Vanishes for smaller lifetimes: *deuterium bottleneck*

# Upper limits on the abundance ('large' masses)




$\tau_\phi \gtrsim 10^4\,\mathrm{s}$

- Photodis. causes underproduction of D and/or overproduction of $^3$He

$\mathrm{D}(\gamma, n)p$ ← D

$^4\mathrm{He}(\gamma, n)^3\mathrm{He}$ ← $^3$He

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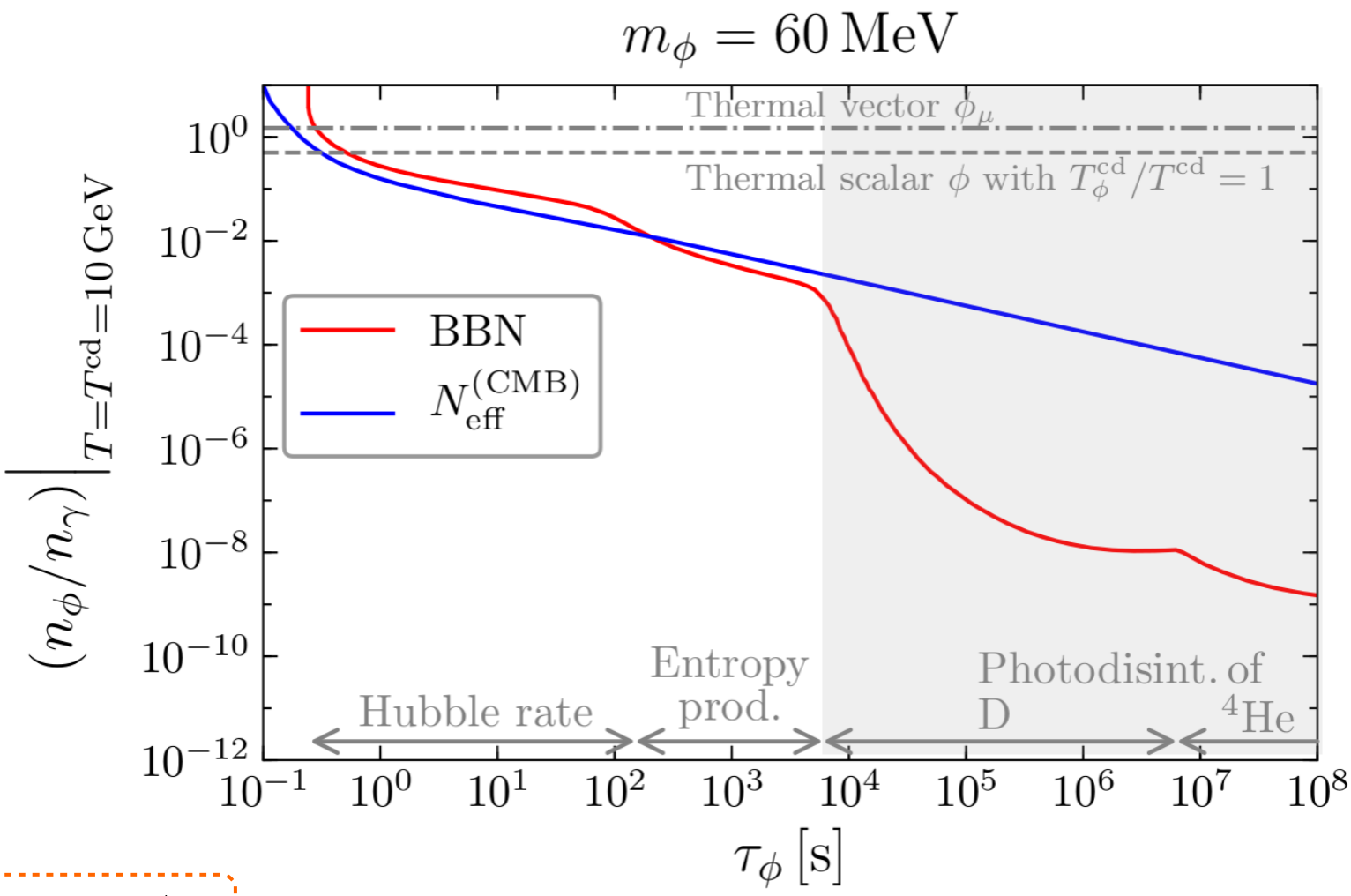


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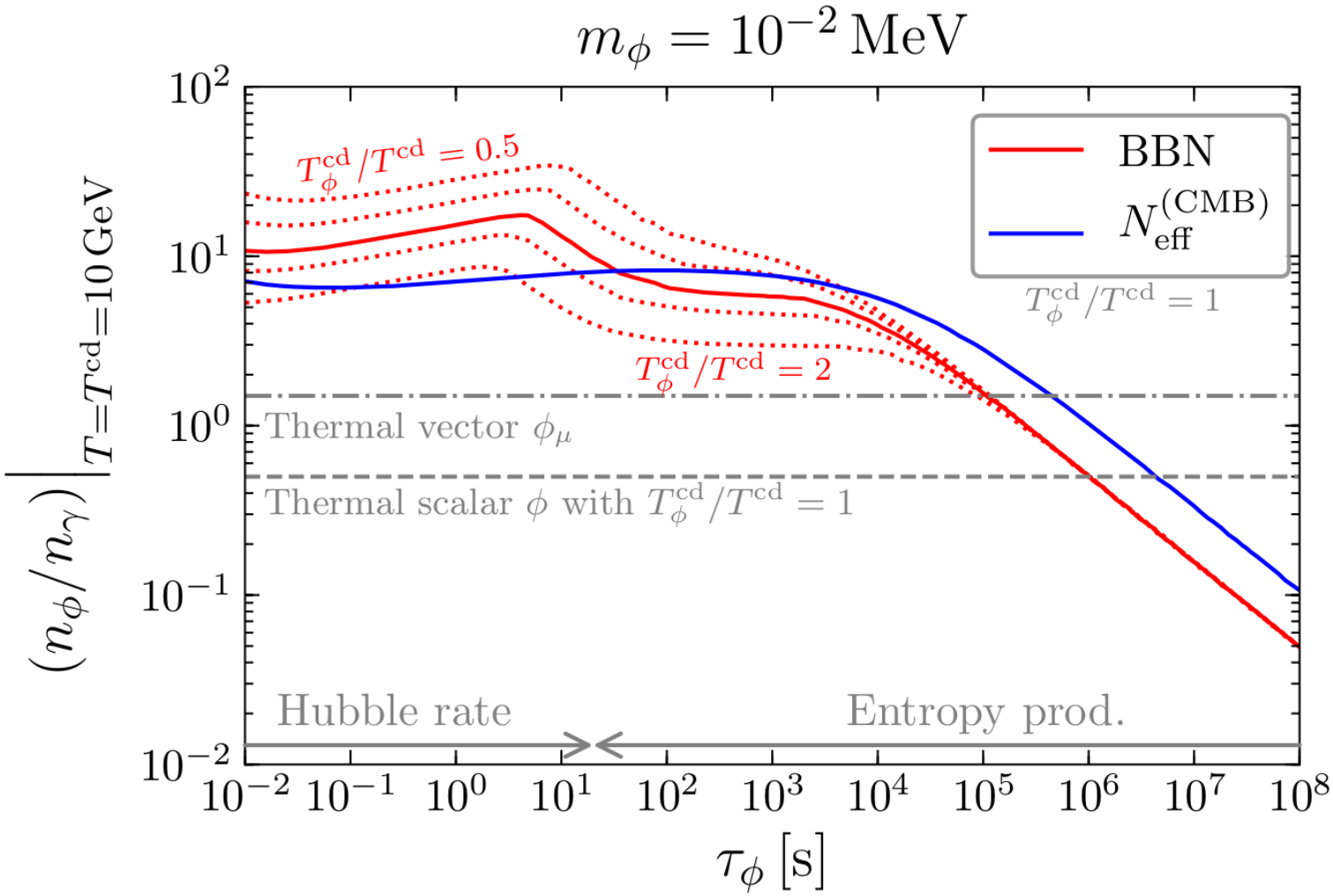
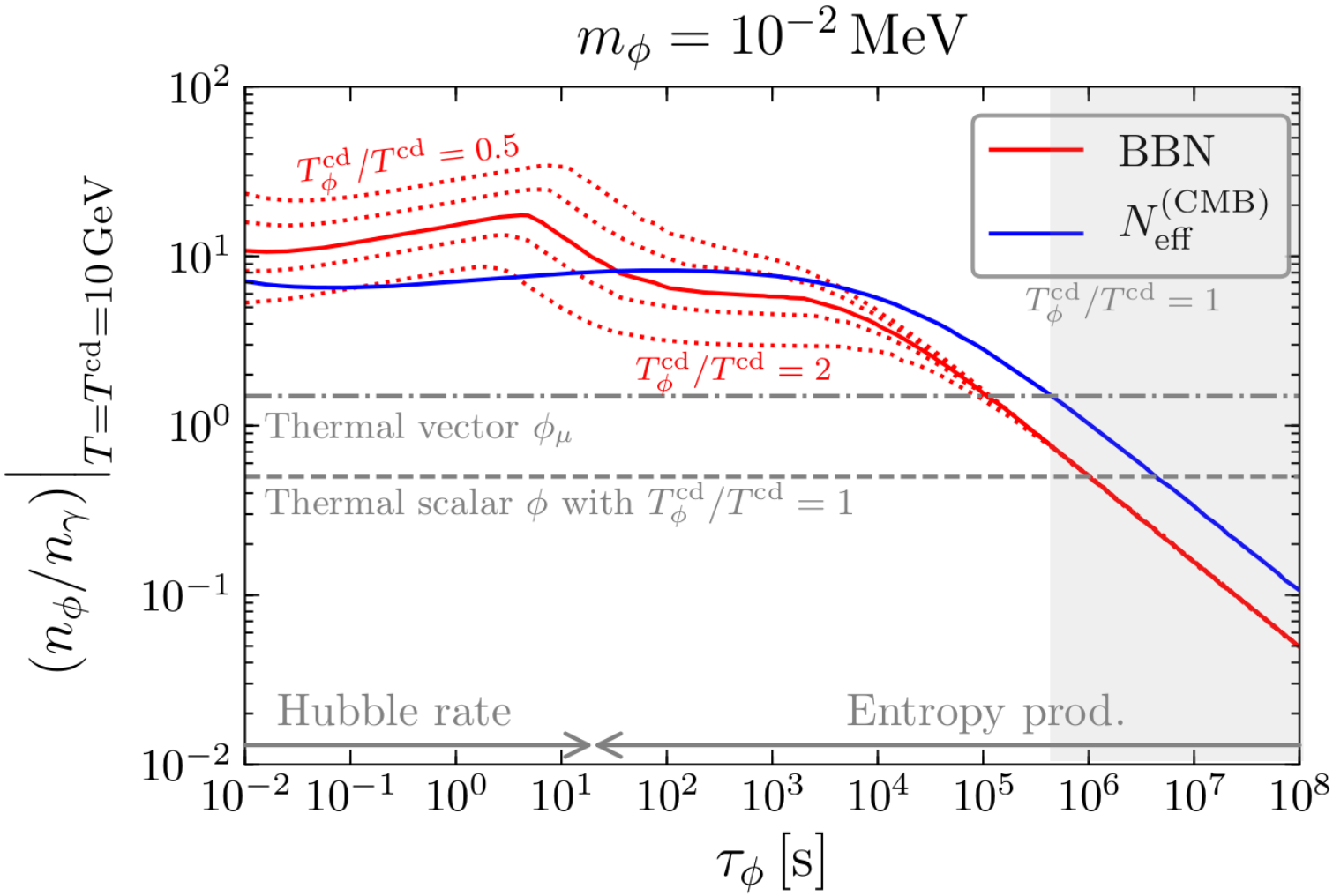
- Vanishes for smaller lifetimes: Injection energy below *deuterium threshold*

# Upper limits on the abundance (smaller masses)




- $m_\phi$ below *deuterium threshold* → photodisintegration irrelevant

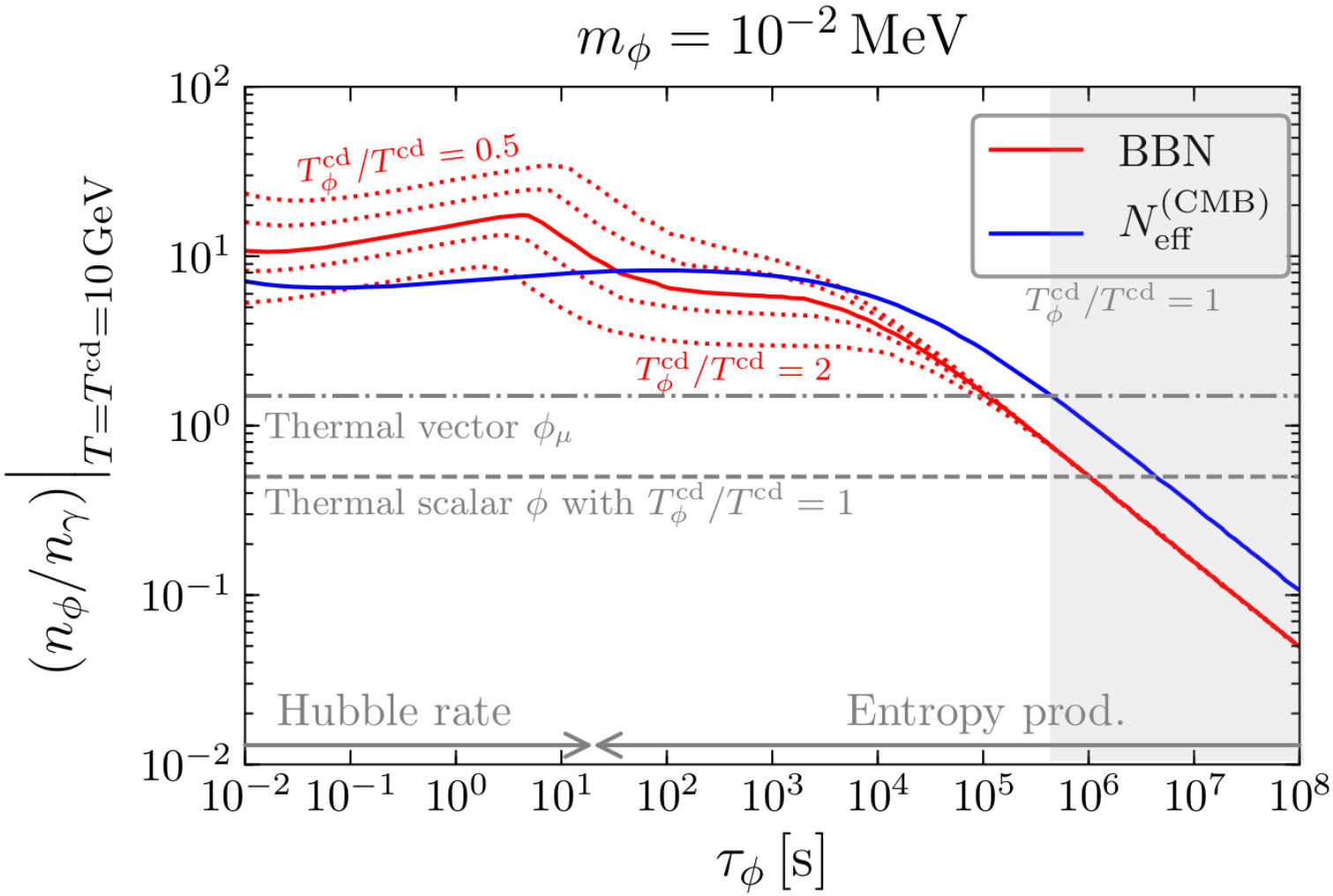
# Upper limits on the abundance (smaller masses)




- For relativistic particles $\rho_\phi \propto n_\phi$ : Dependence on $T_\phi^{\mathrm{cd}}/T^{\mathrm{cd}}$

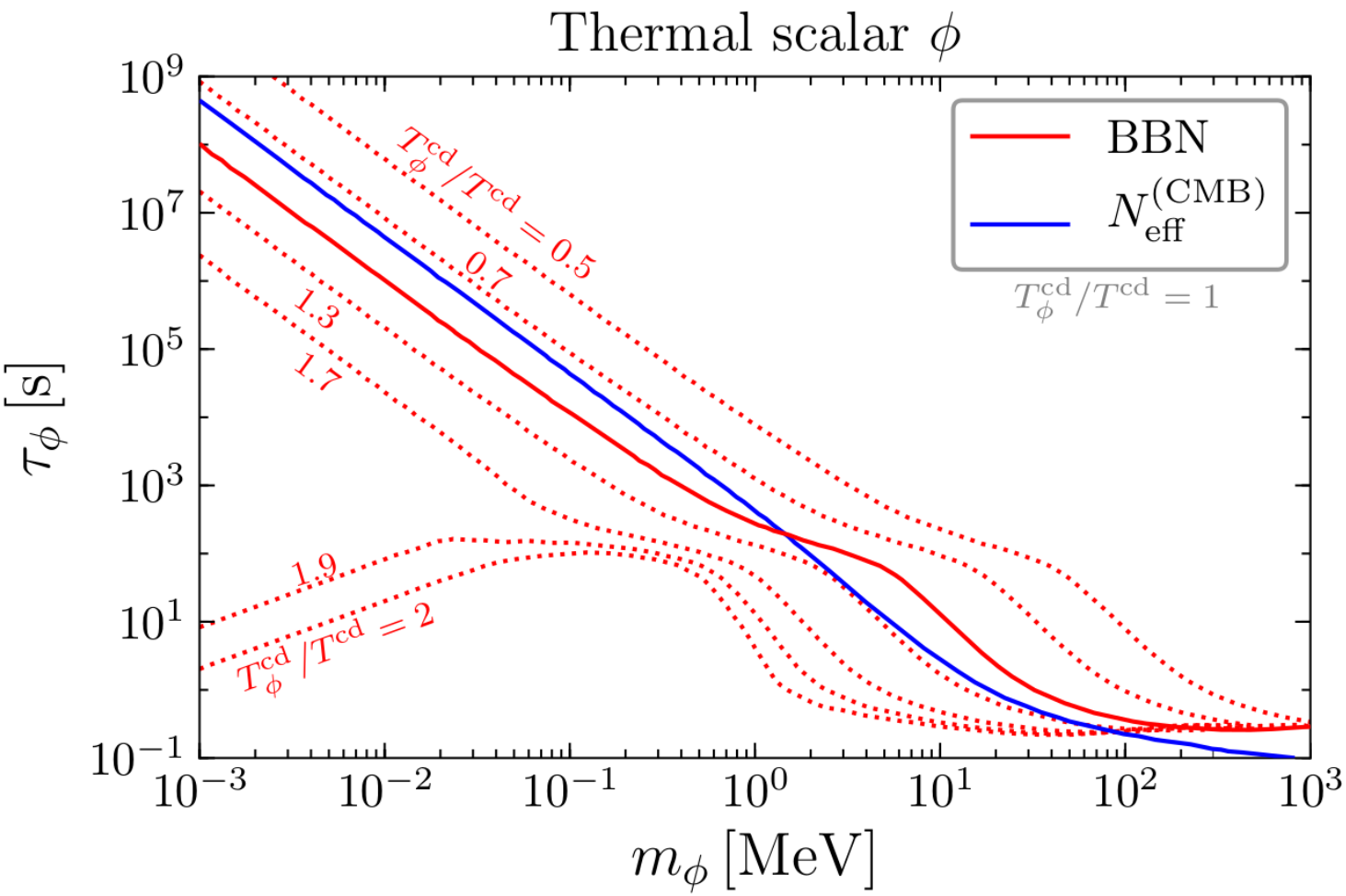
  → Stronger bounds for hotter dark sectors

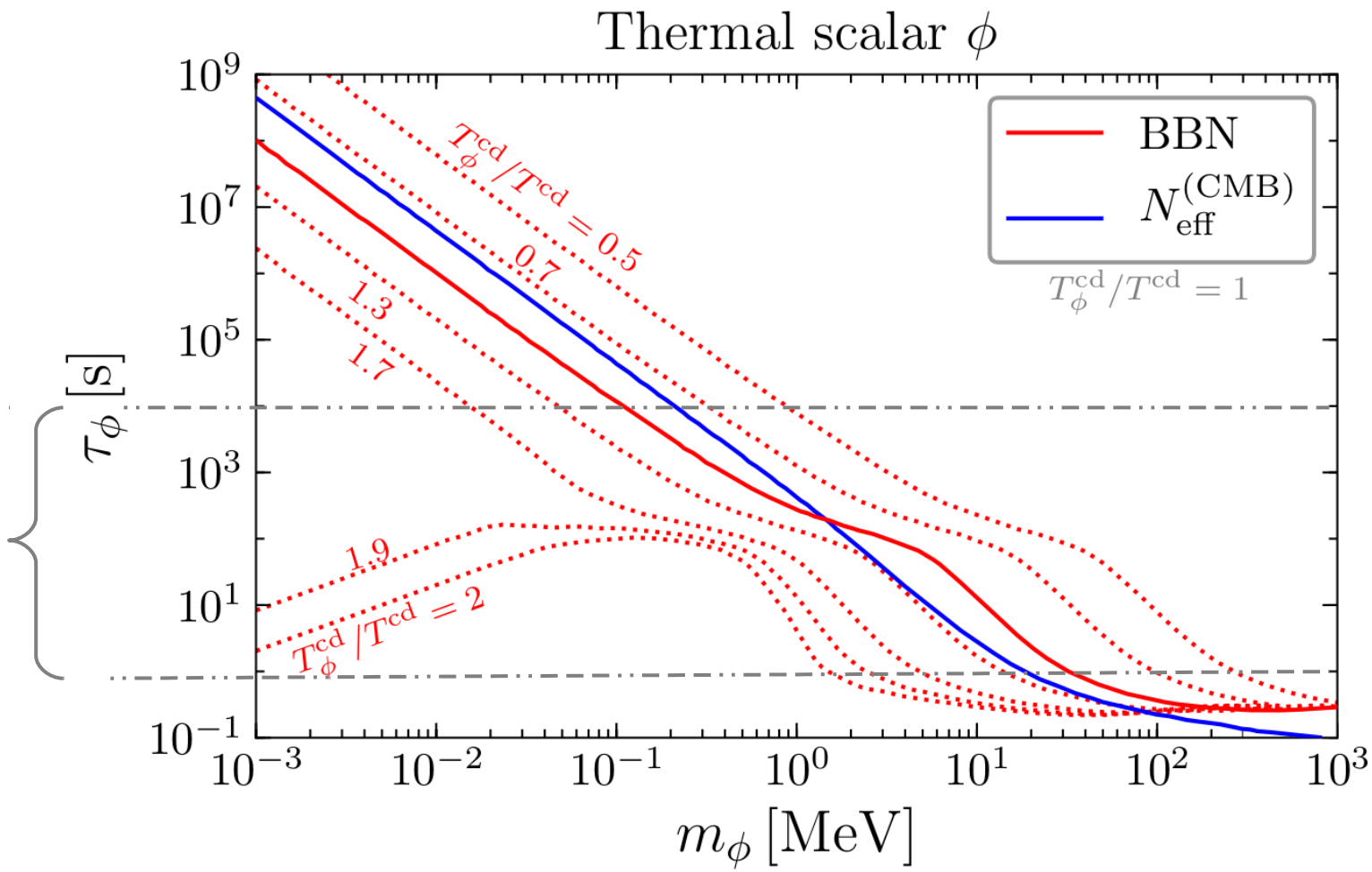
# Upper limits on the abundance (smaller masses)




- Lorentz boost extends entropy constraint down to

$$\tau_\phi \sim 20\,\mathrm{s} \quad \leftrightarrow \quad t_{\mathrm{decay}} \sim 200\,\mathrm{s}$$


Thermal scalar $\phi$
BBN
$N_{\rm eff}^{\rm (CMB)}$
$T_\phi^{\rm cd}/T^{\rm cd} = 1$
$T_\phi^{\rm cd}/T^{\rm cd} = 0.5$
0.7
1.3
1.7
1.9
$T_\phi^{\rm cd}/T^{\rm cd} = 2$
$\tau_\phi$ [s]
$m_\phi$ [MeV]
$10^9$
$10^7$
$10^5$
$10^3$
$10^1$
$10^{-1}$
$10^{-3}$
$10^{-2}$
$10^{-1}$
$10^0$
$10^1$
$10^2$
$10^3$




Usual estimates

- The bounds significantly differ from the naive estimates in large parts of the parameter space

$$0.3\,\mathrm{s} \lesssim \tau_\phi \lesssim 10^8\,\mathrm{s}$$

# Conclusions

- For the first time, we present a comprehensive study on *electromagnetically decaying MeV-scale* particles

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$$\tau_\phi \lesssim 1\,\mathrm{s} \qquad\qquad \tau_\phi \lesssim 10^4\,\mathrm{s}$$

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~~$\tau_\phi \lesssim 1\,\mathrm{s}$~~ ~~$\tau_\phi \lesssim 10^4\,\mathrm{s}$~~

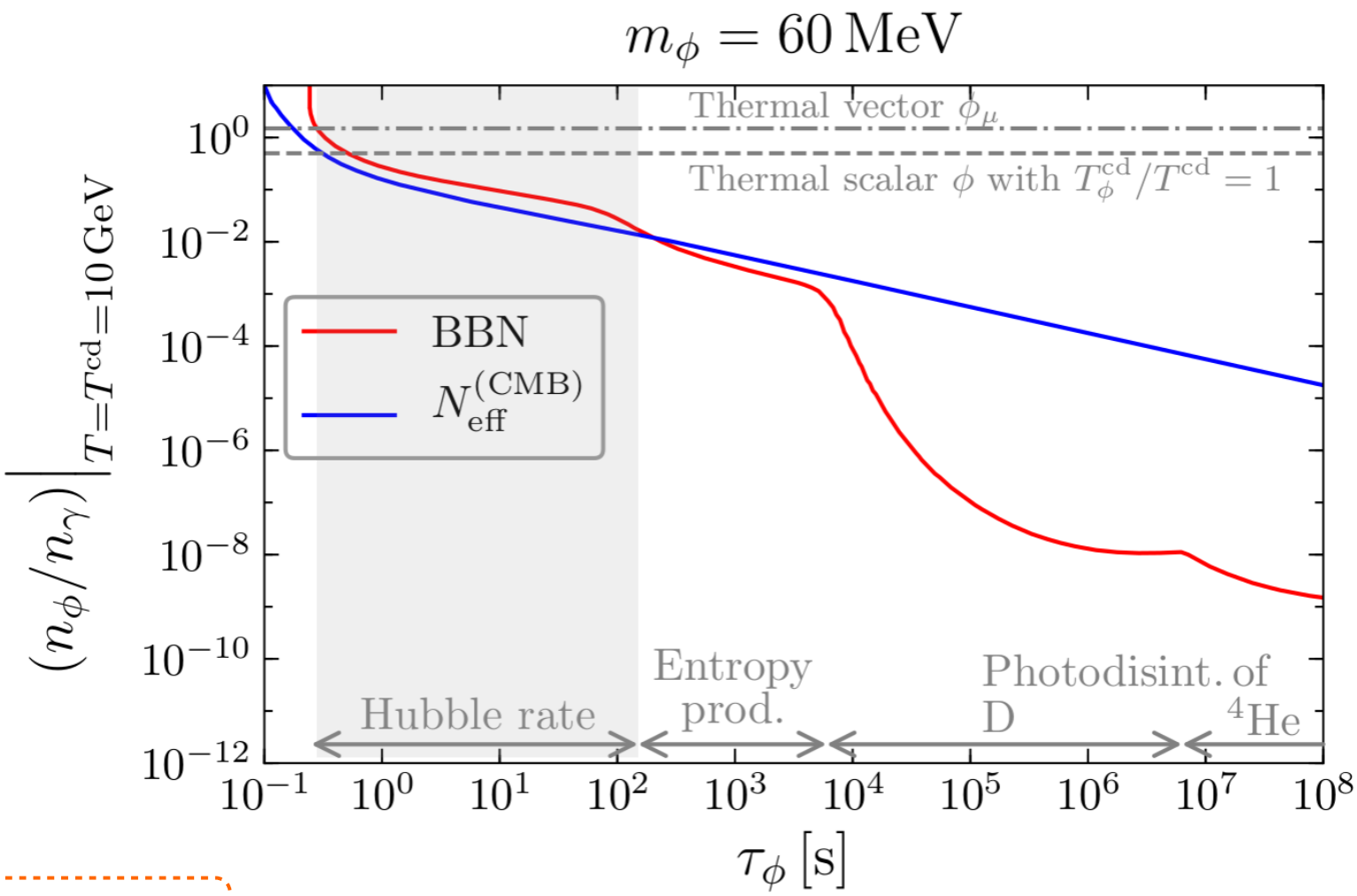
$$0.3\,\mathrm{s} \lesssim \tau_\phi \lesssim 10^8\,\mathrm{s}$$

→ Strongly depends on the region of parameter space

Thank you for
your attention!

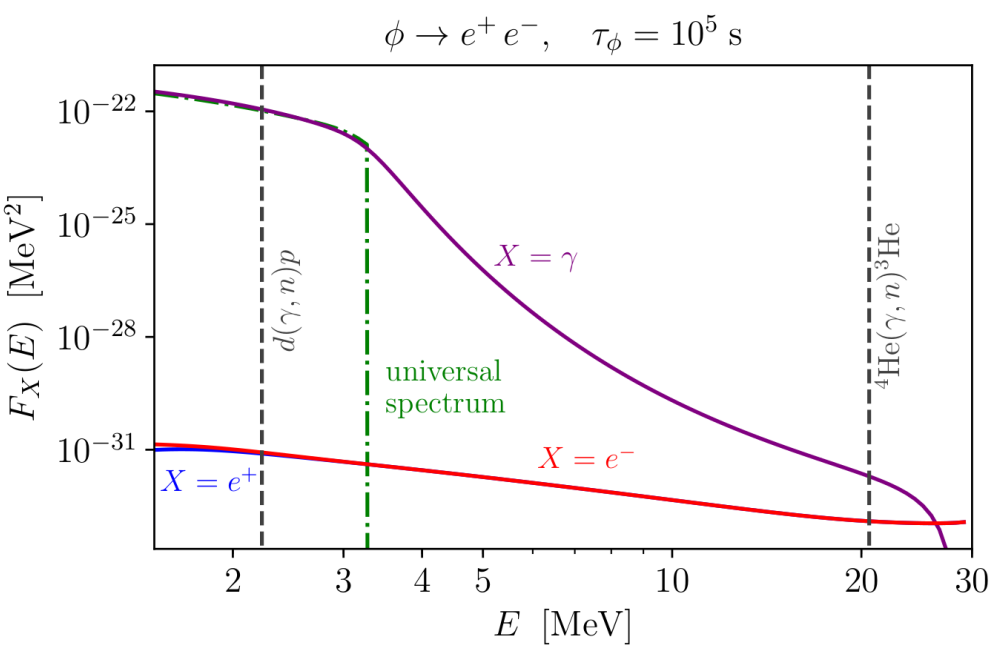
# Backup Slides

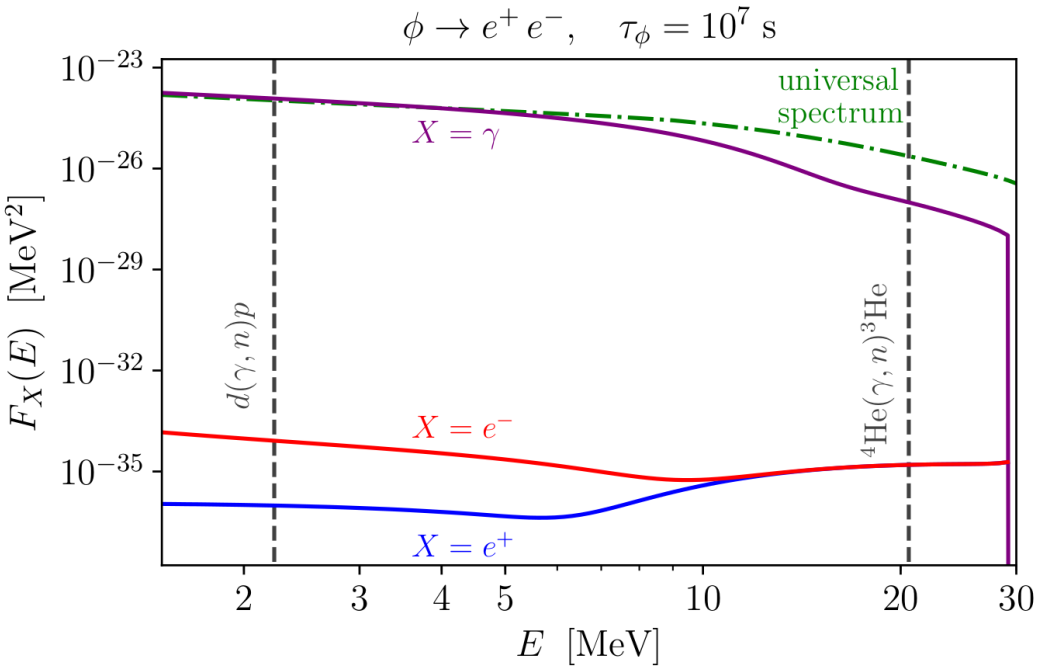
# Upper limits on the abundance ('large' masses)

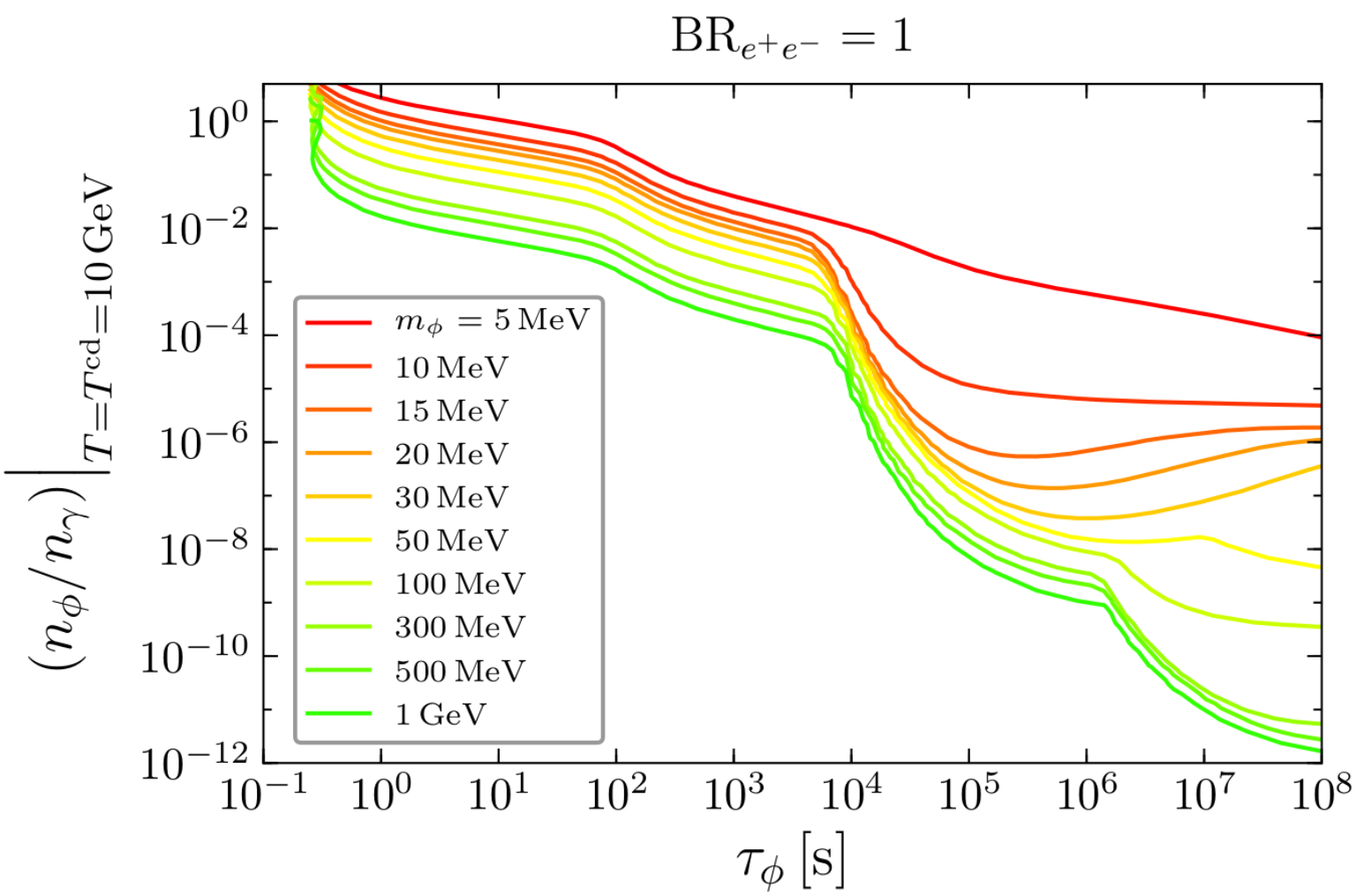



$\tau_\phi \lesssim 200\,\mathrm{s}$

- Modified Hubble rate causes modified time-temp. relation → base effect
- Limit increases with increasing lifetime: Non-rel. scaling


$\phi \to e^+ e^-, \quad \tau_\phi = 10^5$ s
$10^{-22}$
$10^{-25}$
$10^{-28}$
$10^{-31}$
$F_X(E)$ [MeV$^2$]
$d(\gamma, n)p$
$^4$He$(\gamma, n)^3$He
universal spectrum
$X = \gamma$
$X = e^-$
$X = e^+$
2
3
4
5
10
20
30
$E$ [MeV]


$\phi \to e^+ e^-, \quad \tau_\phi = 10^7$ s
$10^{-23}$
$10^{-26}$
$10^{-29}$
$10^{-32}$
$10^{-35}$
$F_X(E)$ [MeV$^2$]
$d(\gamma, n)p$
$^4$He$(\gamma, n)^3$He
universal spectrum
$X = \gamma$
$X = e^-$
$X = e^+$
2
3
4
5
10
20
30
$E$ [MeV]


$\mathrm{BR}_{e^+e^-} = 1$
$\left(n_\phi/n_\gamma\right)\Big|_{T=T^{\mathrm{cd}}=10\,\mathrm{GeV}}$
$10^{0}$
$10^{-2}$
$10^{-4}$
$10^{-6}$
$10^{-8}$
$10^{-10}$
$10^{-12}$
$m_\phi = 5\,\mathrm{MeV}$
$10\,\mathrm{MeV}$
$15\,\mathrm{MeV}$
$20\,\mathrm{MeV}$
$30\,\mathrm{MeV}$
$50\,\mathrm{MeV}$
$100\,\mathrm{MeV}$
$300\,\mathrm{MeV}$
$500\,\mathrm{MeV}$
$1\,\mathrm{GeV}$
$10^{-1}$ $10^{0}$ $10^{1}$ $10^{2}$ $10^{3}$ $10^{4}$ $10^{5}$ $10^{6}$ $10^{7}$ $10^{8}$
$\tau_\phi\,[\mathrm{s}]$