BBN constraints on MeV-scale dark sectors: Sterile decays.

based on

arXiv:1712.03972

Marco Hufnagel, Kai Schmidt-Hoberg, Sebastian Wild

Wednesday, May 23, 2018

HELMHOLTZ SPITZENFORSCHUNG FÜR GROSSE HERAUSFORDERUNGEN

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DESY.

Big Bang Nucleosynthesis

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

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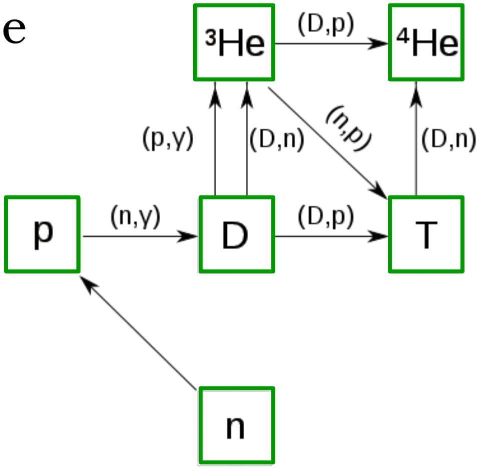

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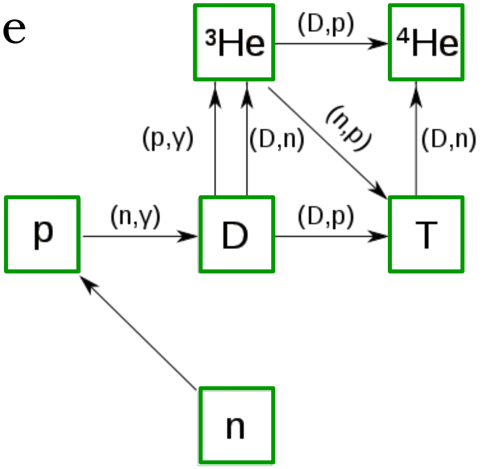

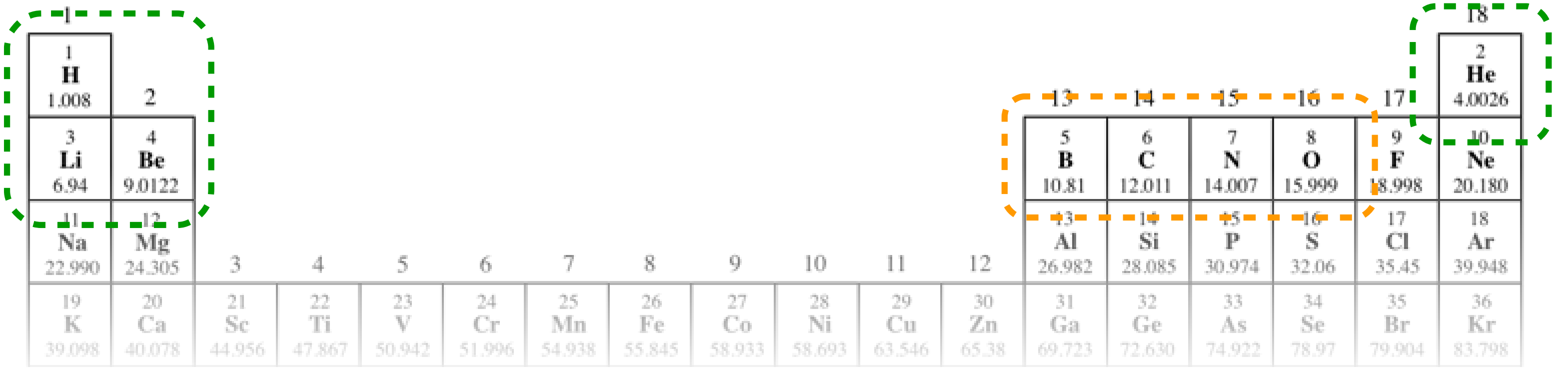

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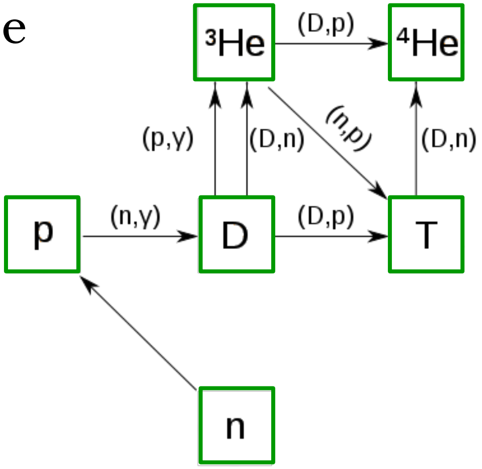

- Thermal evolution is governed by Boltzmann equation

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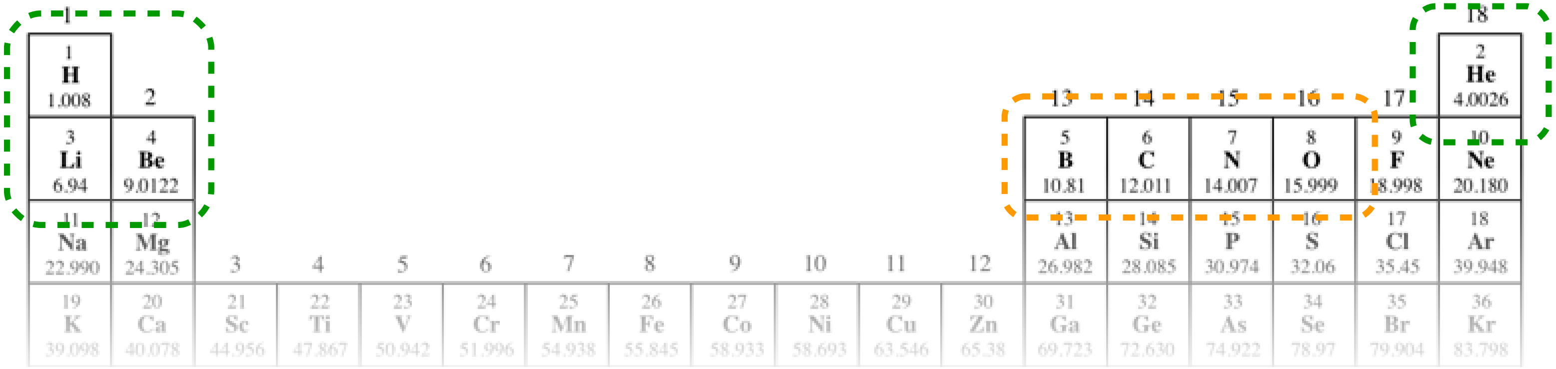

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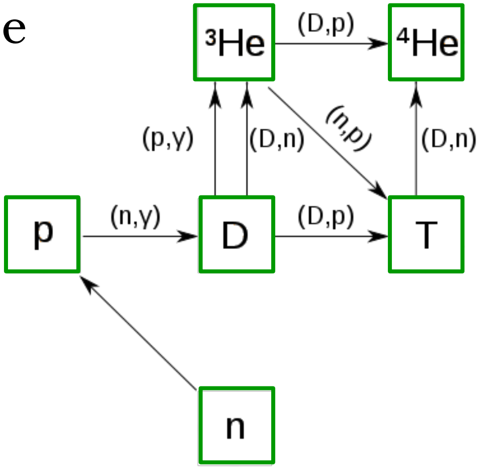

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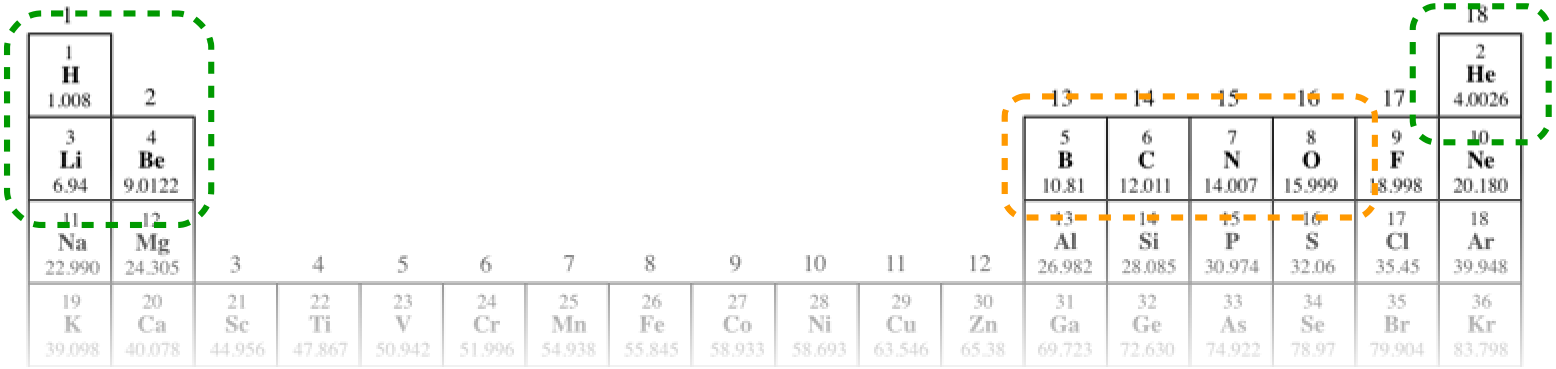

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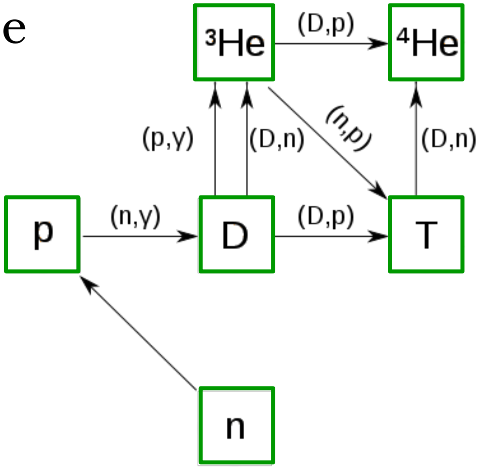

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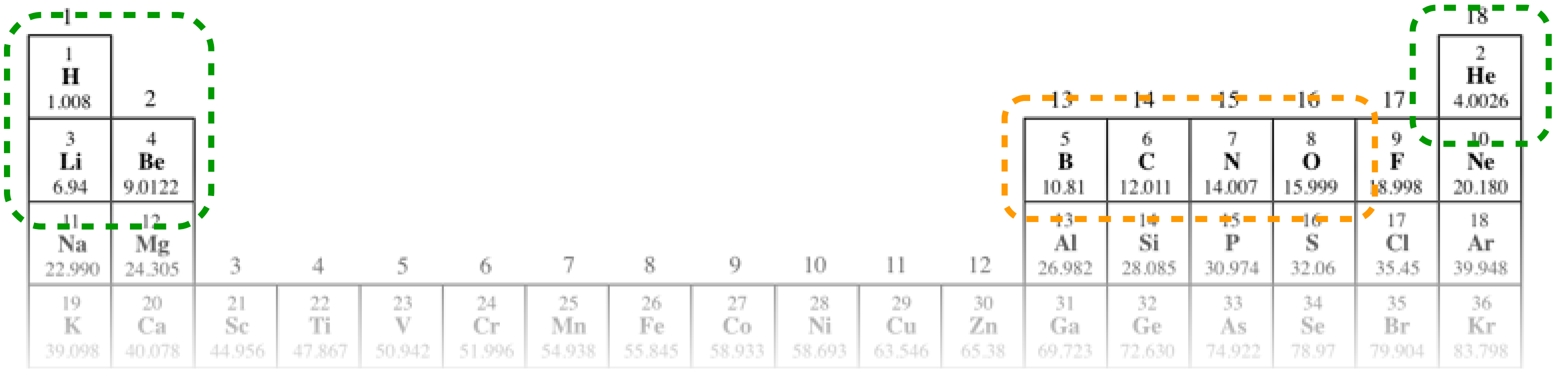

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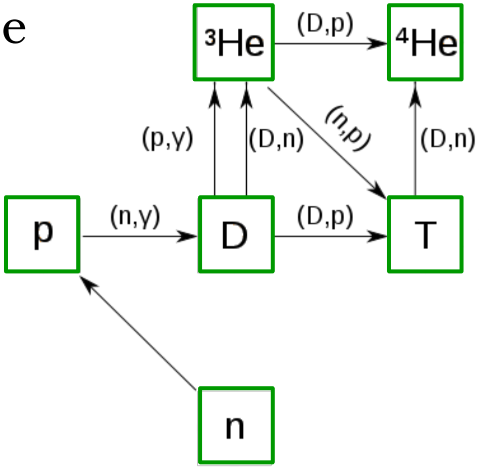

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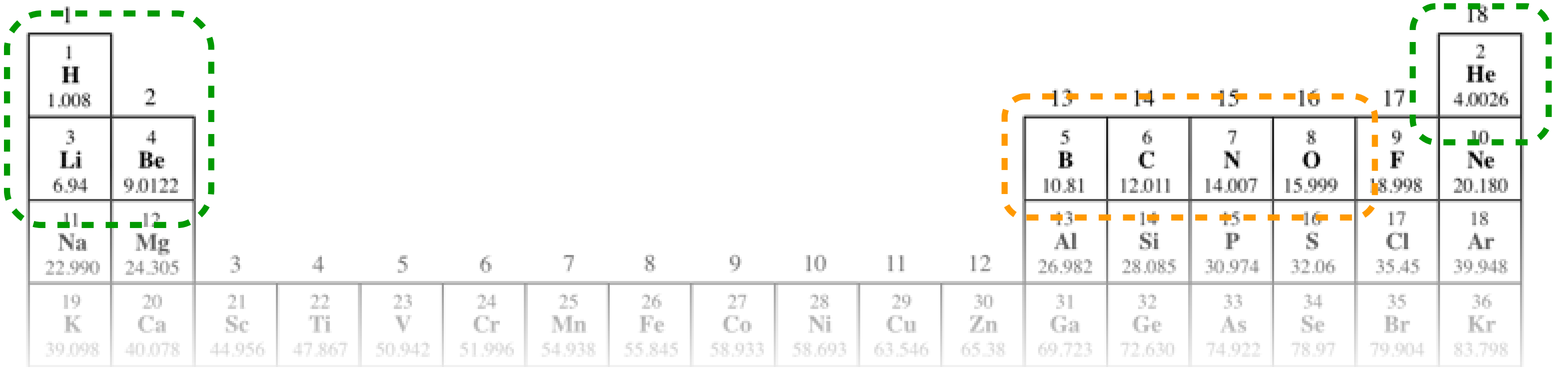

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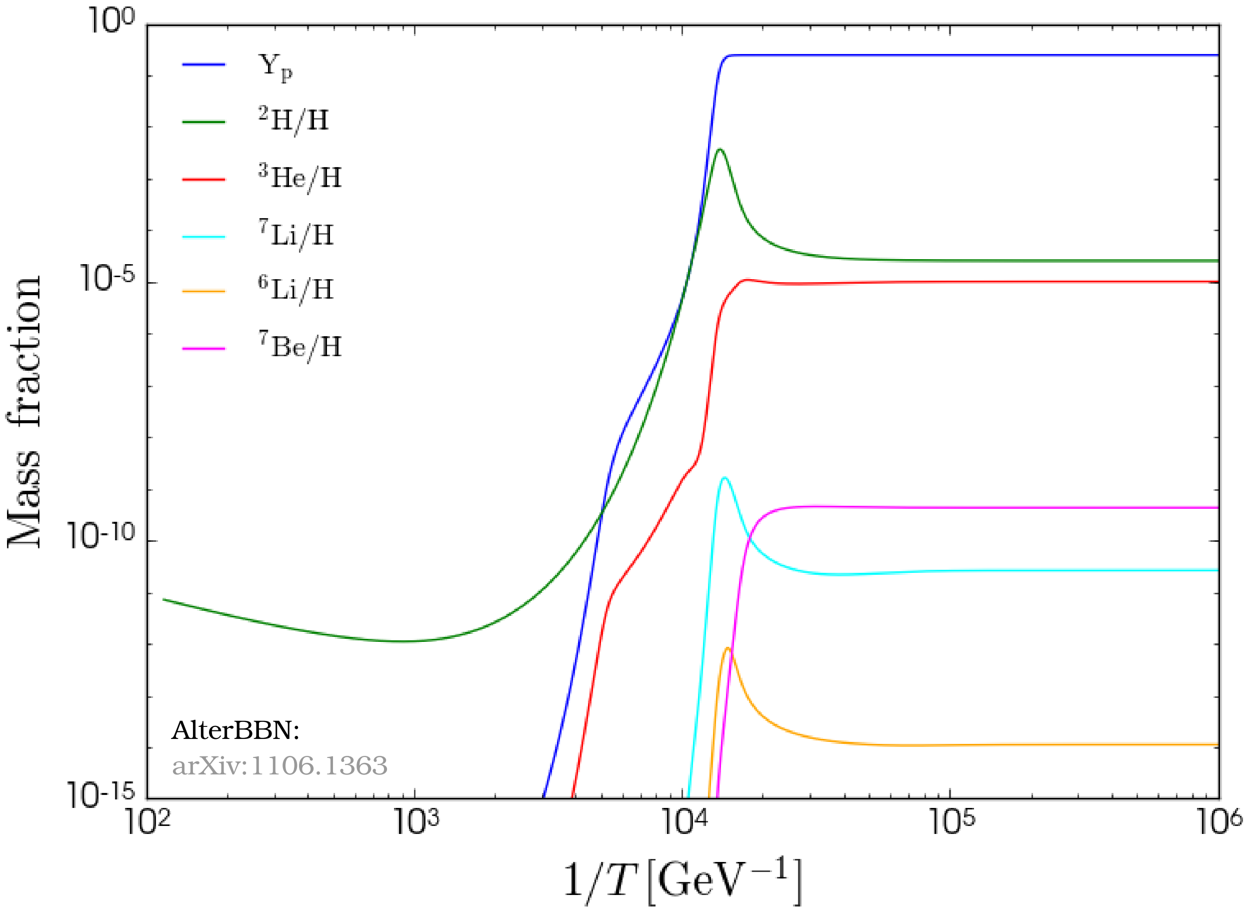
SM prediction



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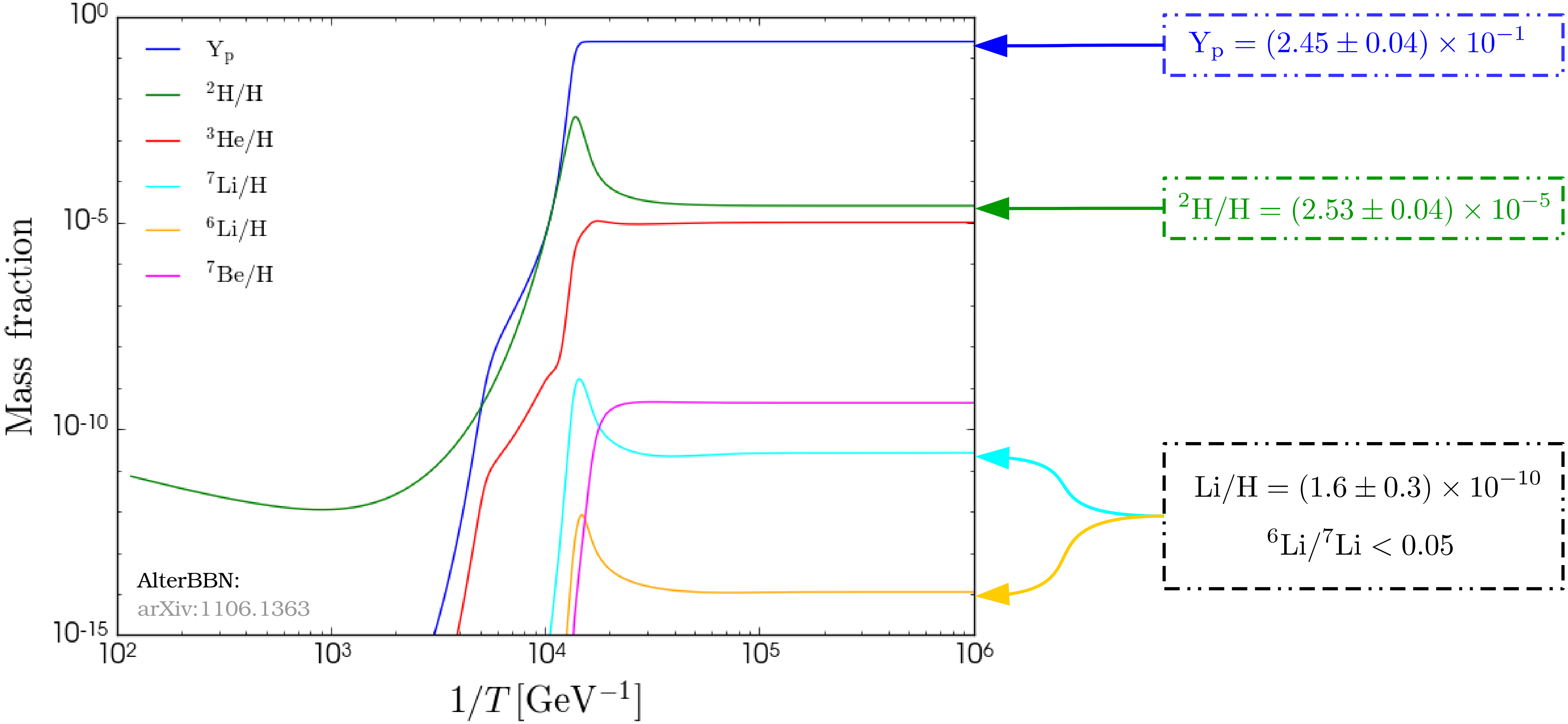

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arXiv:1106.1363

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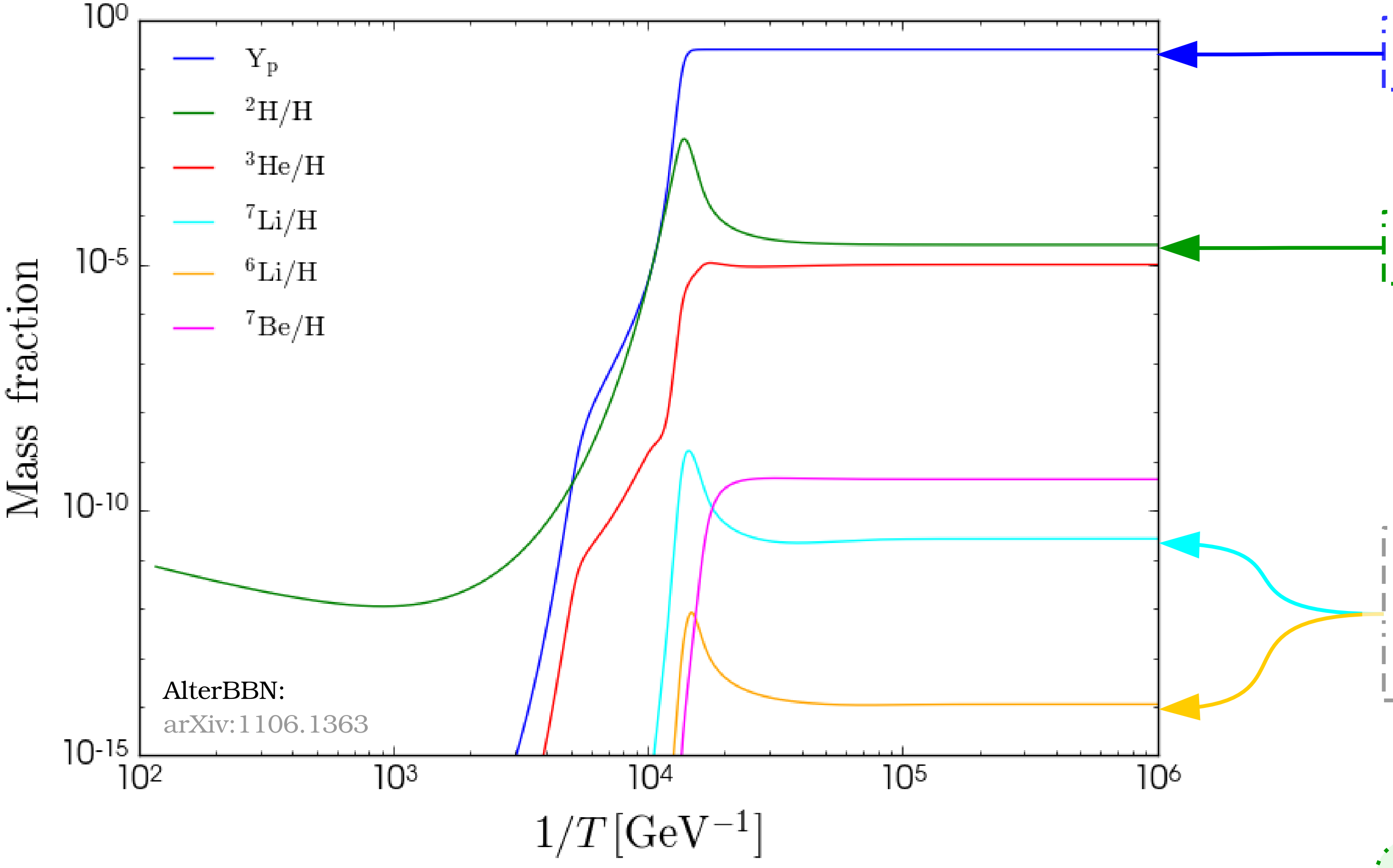

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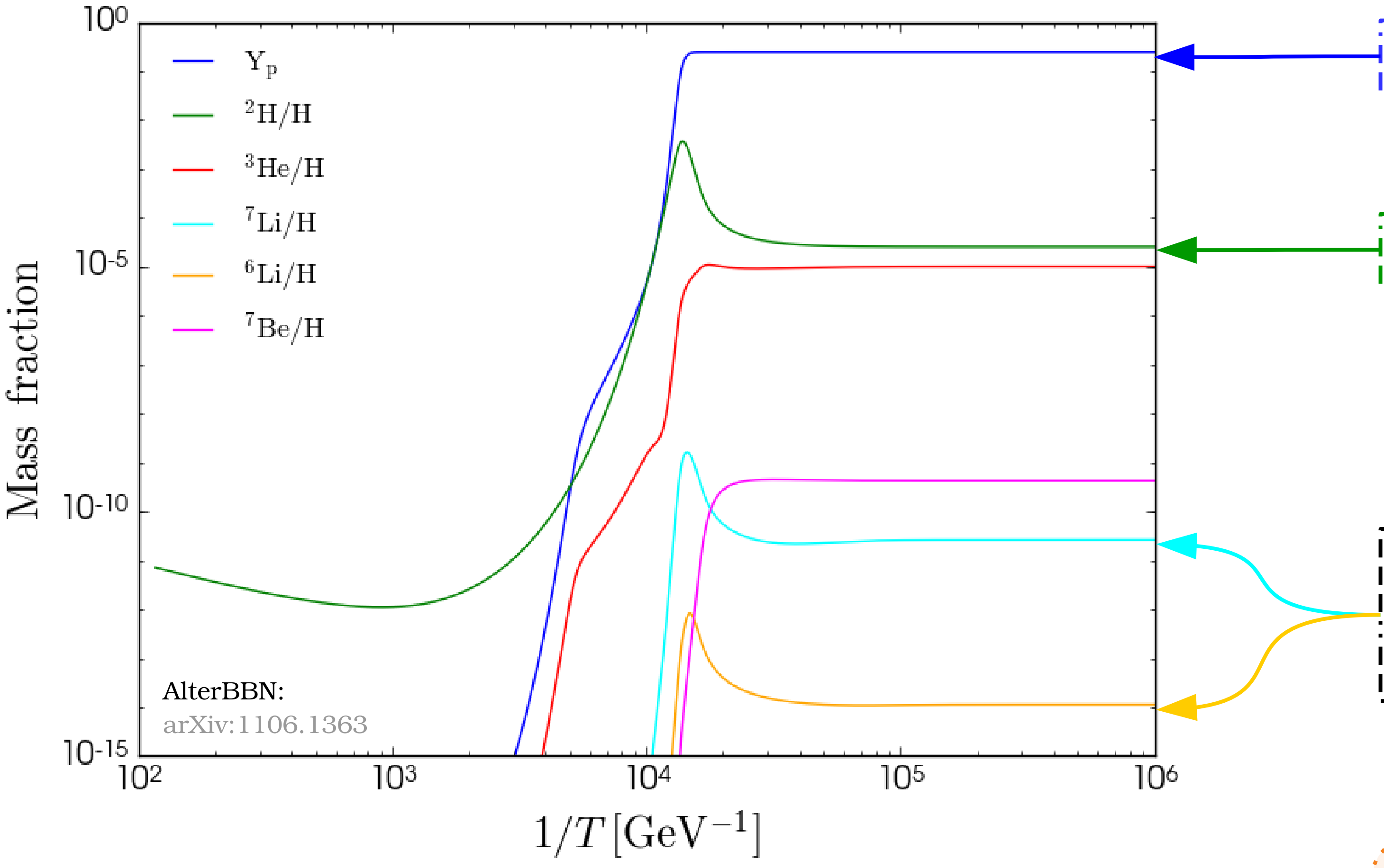

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Entropy production

Photodesintegration

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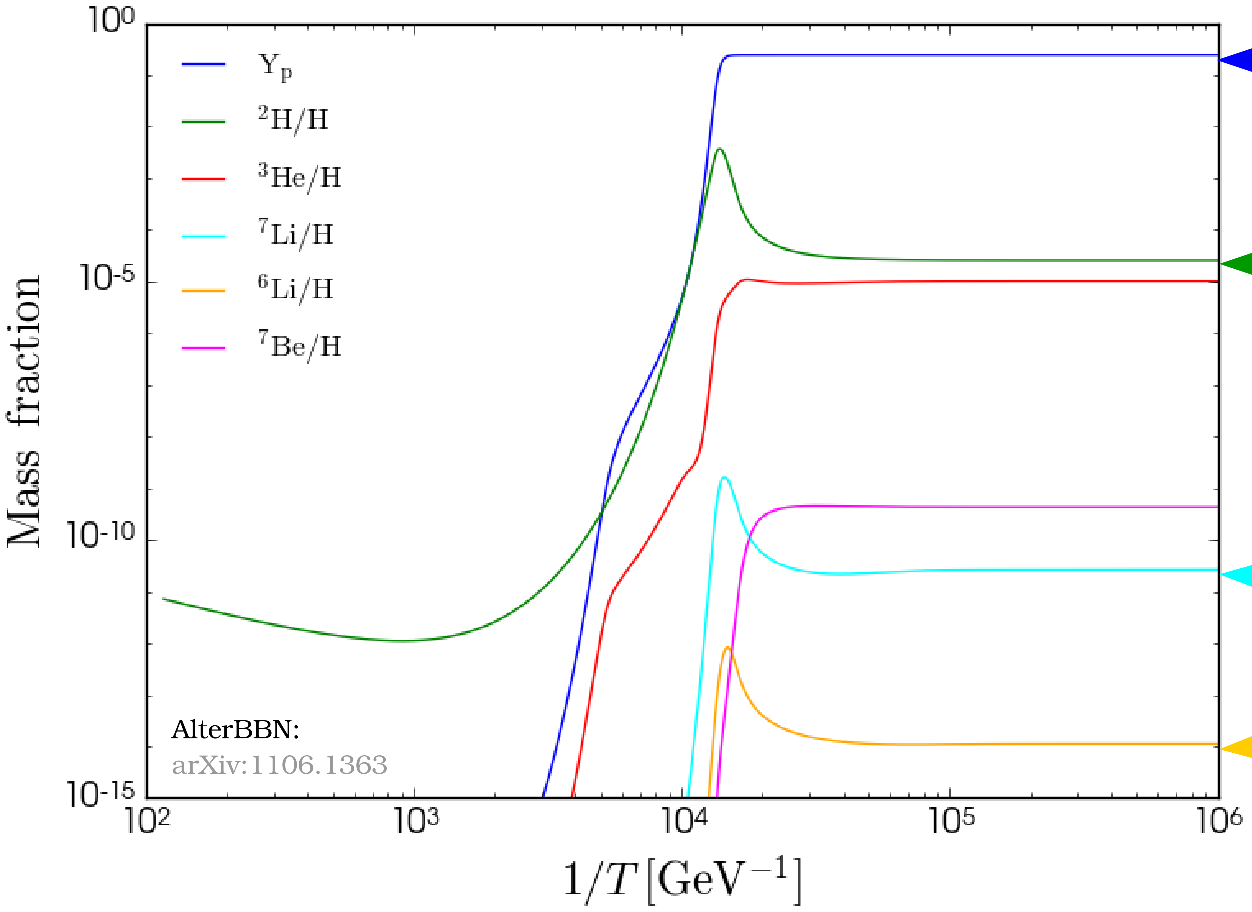

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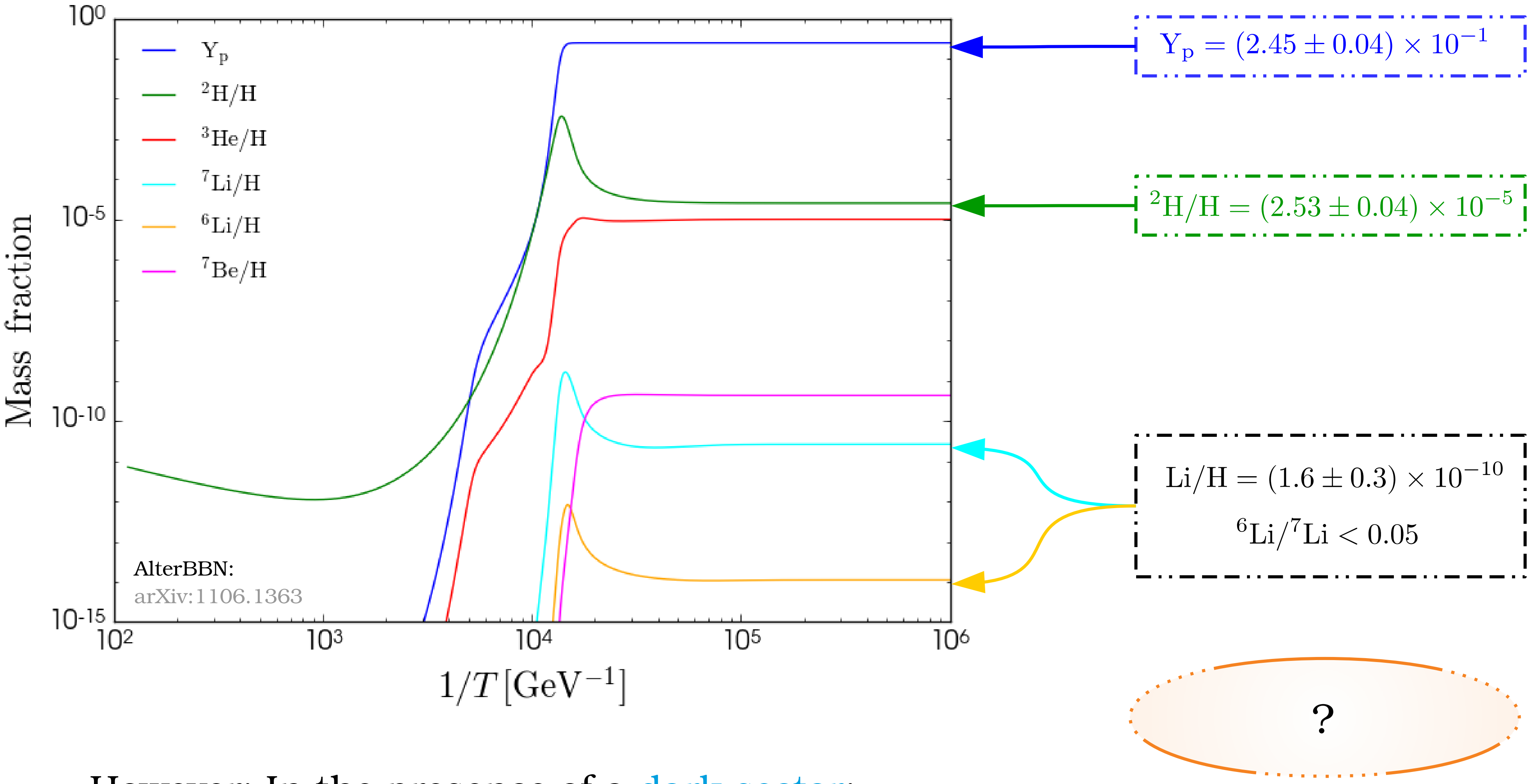

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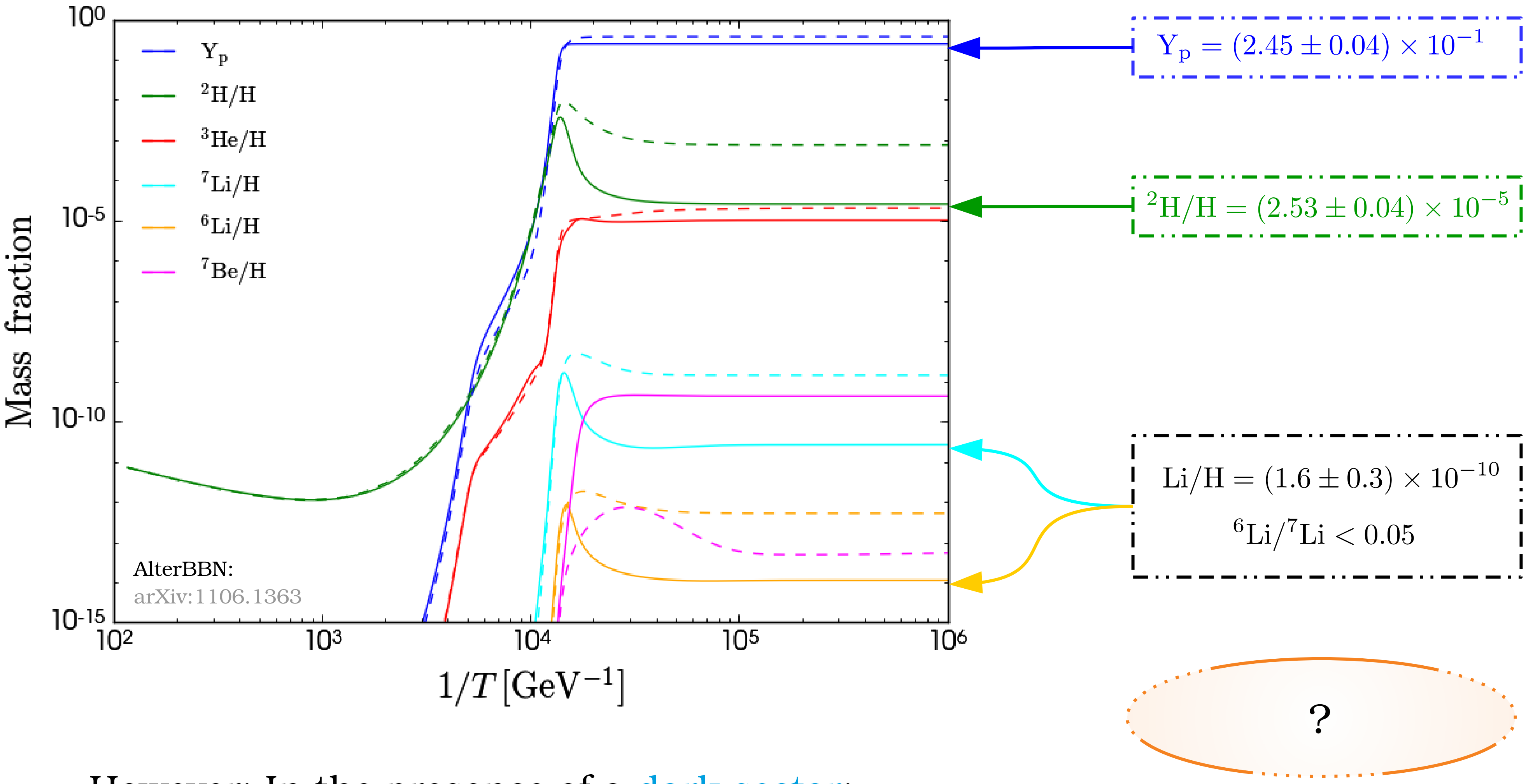

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Non-relativistic limit

Scherrer & Turner:
10.1086/166534 (1988)

Menestriner & Scherrer:
arXiv:1111.0605 (2011)

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Setup and Assumptions

Particle content:

Dark Matter	$\chi, \bar{\chi}$	$m_\chi \sim \mathcal{O}(\mathrm{GeV})$
Mediator	ϕ	$m_\phi \sim \mathrm{MeV}$
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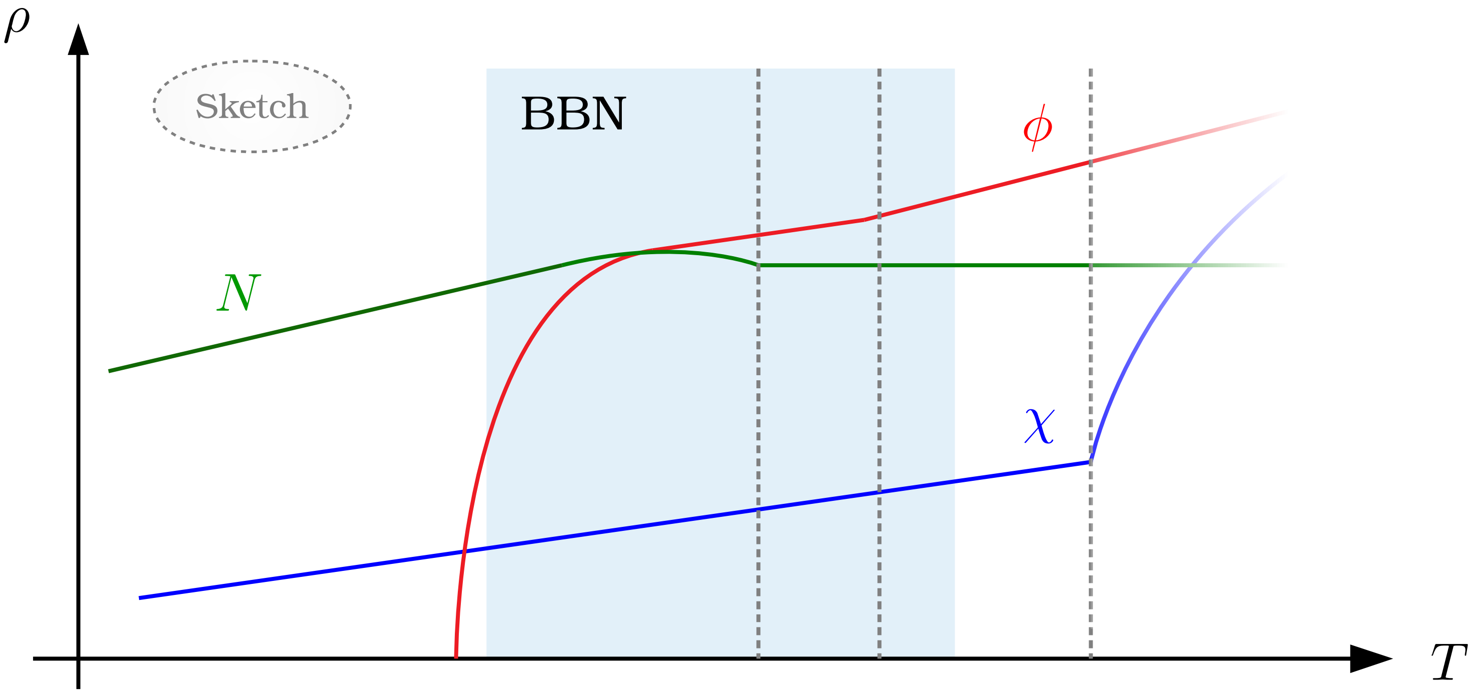

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Boltzmann equation for the mediator ϕ :

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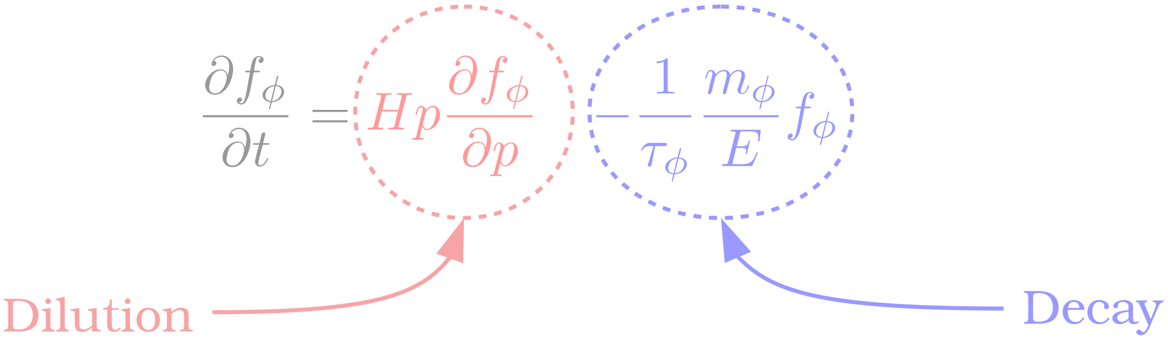
$$f_\phi(p,t) = \left[\exp\left(\frac{\sqrt{m_\phi^2 + p^2(R_{\text{cd}}/R)^2}}{T_D(t_{\text{cd}})}\right) + 1\right]^{-1} \exp\left(-\frac{t - t_{\text{cd}}}{\tau_\phi}\left\langle\frac{1}{\gamma}\right\rangle\right)$$

Thermal evolution of the dark sector

Boltzmann equation for the mediator ϕ :



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

Initial condition:

$$f_\phi(t = t_{\text{cd}}) = \bar{f}_\phi(t_{\text{cd}}) \qquad \rightarrow \text{ Bose-Einstein distribution}$$

Entropy conservation:

$$\frac{s_D(T_D)}{s_{\text{SM}}(T)} = \frac{s_D(T_D(T_{\text{cd}}))}{s_{\text{SM}}(T_{\text{cd}})} \qquad \Rightarrow \qquad T_D = T_D(T)$$

Thermal evolution of the dark sector

Boltzmann equation for the ‘dark neutrino’ N :

$$\frac{\mathrm{d}\rho_N}{\mathrm{d}t} = \underbrace{-4H\rho_N}_{\text{Dilution}} \underbrace{+\frac{1}{\tau_\phi}\frac{m_\phi}{E}n_\phi}_{\text{Decay}}$$

Thermal evolution of the dark sector

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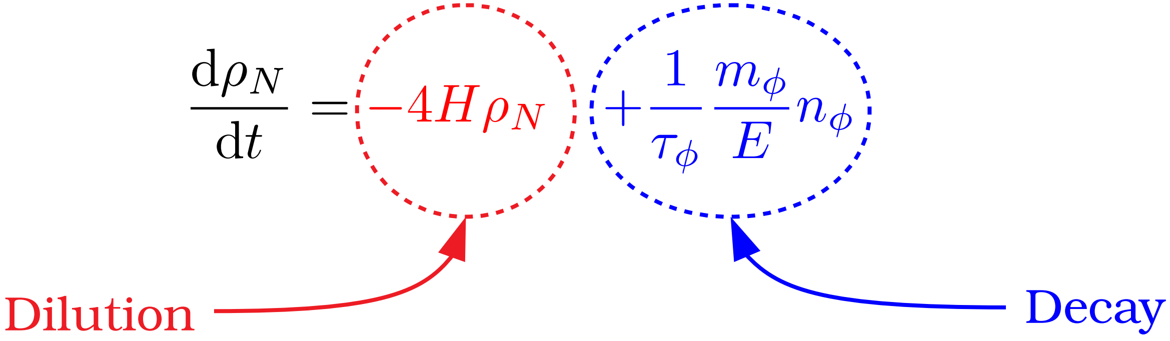

$$\frac{\mathrm{d}\rho_N}{\mathrm{d}t} = -4H\rho_N + \frac{1}{\tau_\phi}\frac{m_\phi}{E}n_\phi$$

Dilution

Decay

Initial condition:

$$\rho_N(t = t\mathrm{cd}) \simeq 0$$

Thermal evolution of the dark sector

Boltzmann equation for the ‘dark neutrino’ N :

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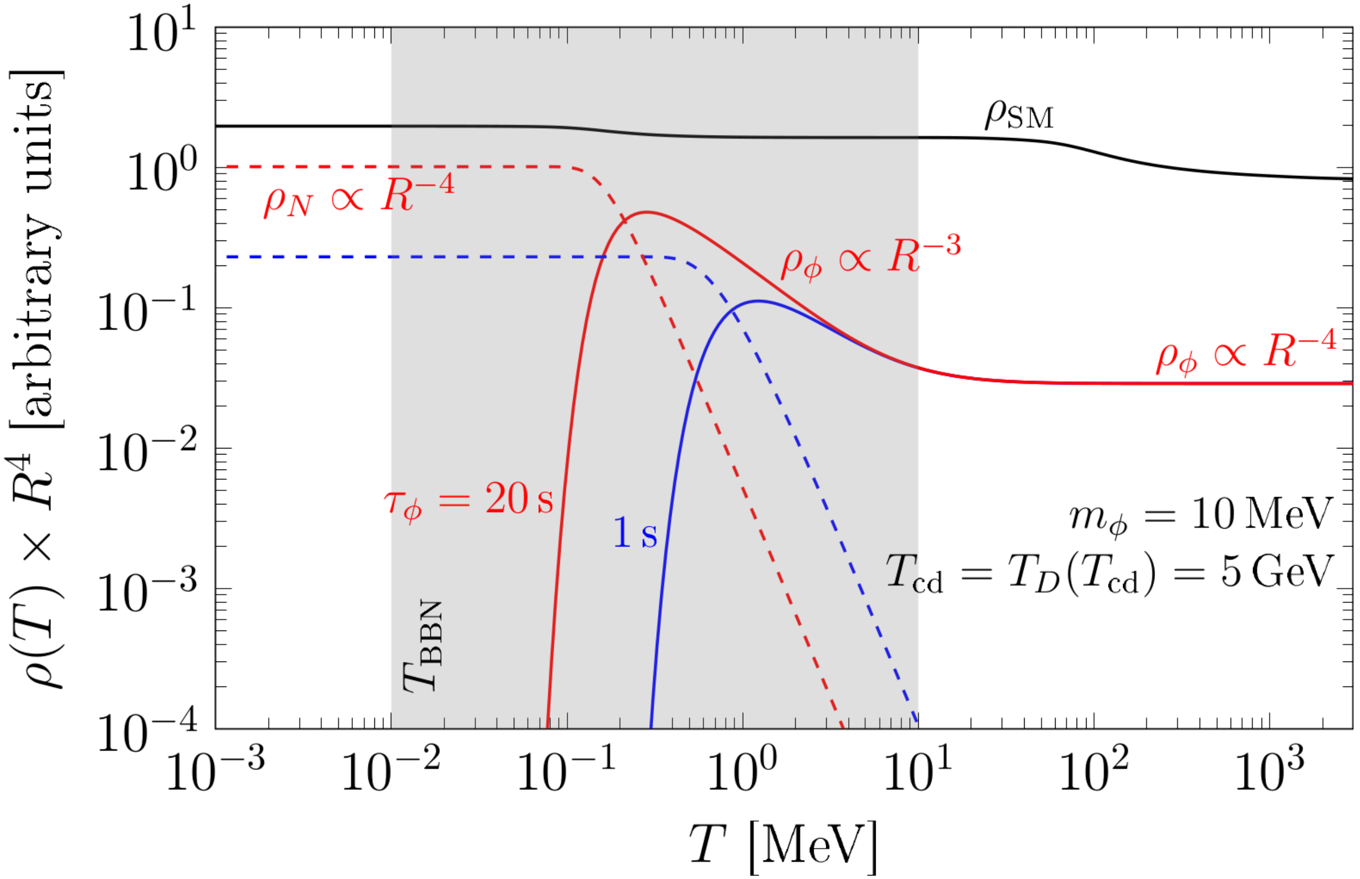
Initial condition:

$$\rho_N(t = t\mathrm{cd}) \simeq 0$$

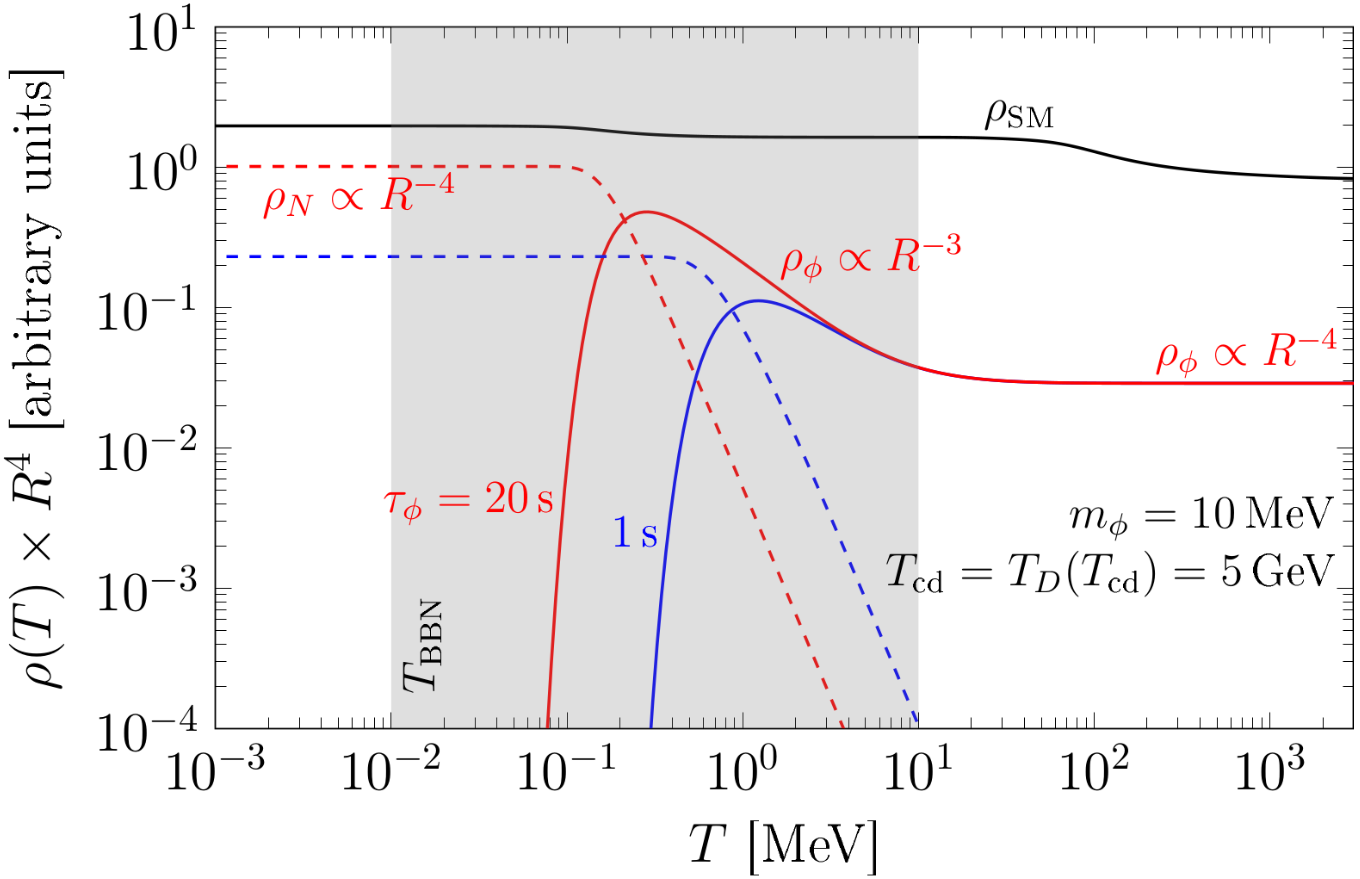
Solution:

$$\rho_N(t) = R(t)^4 \int_{t_{\mathrm{cd}}}^{t} \frac{1}{R(\lambda)^4} \frac{m_\phi n_\phi(\lambda)}{\tau_\phi} \mathrm{d}t$$

Thermal evolution of the dark sector

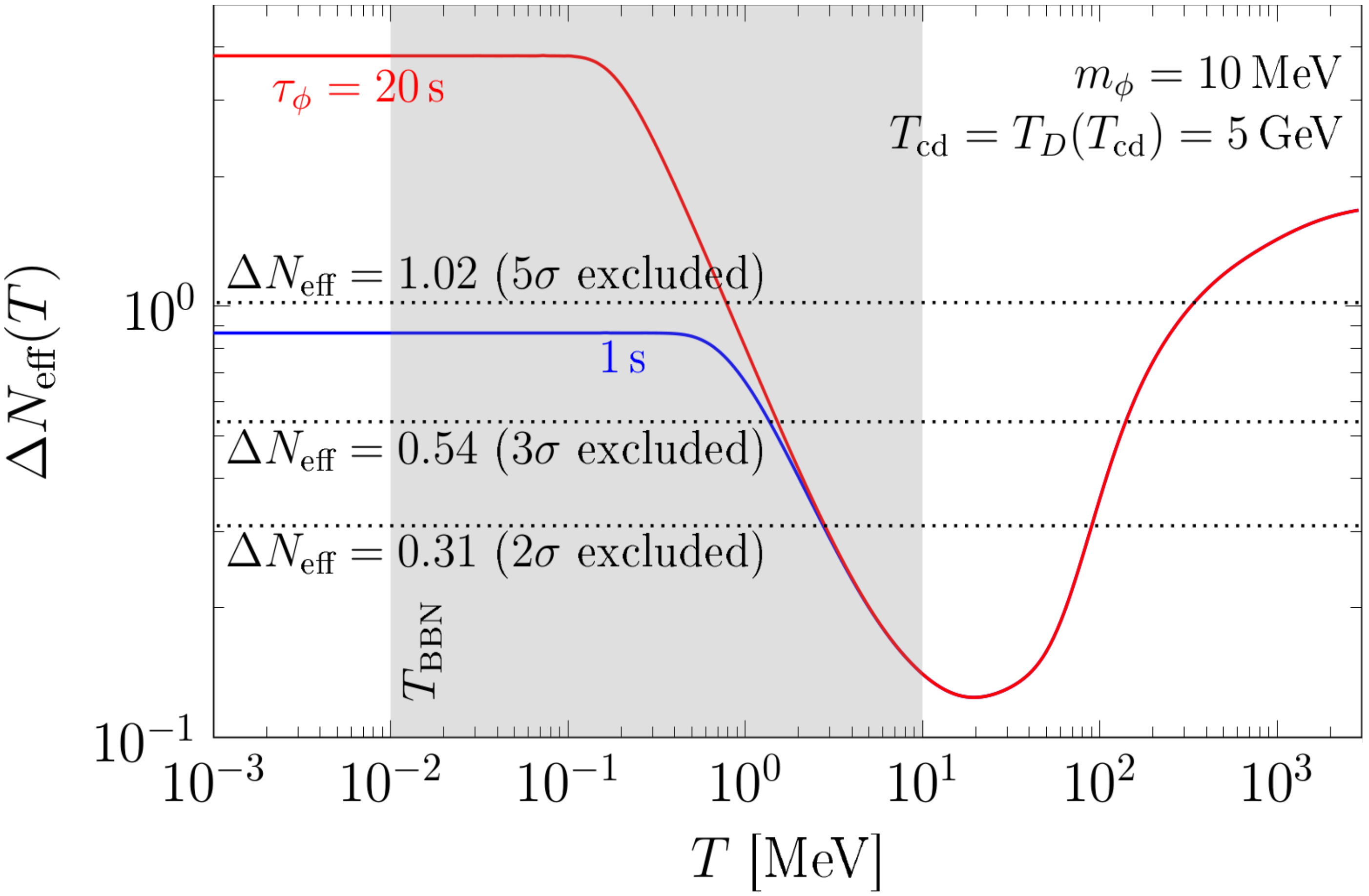


Thermal evolution of the dark sector

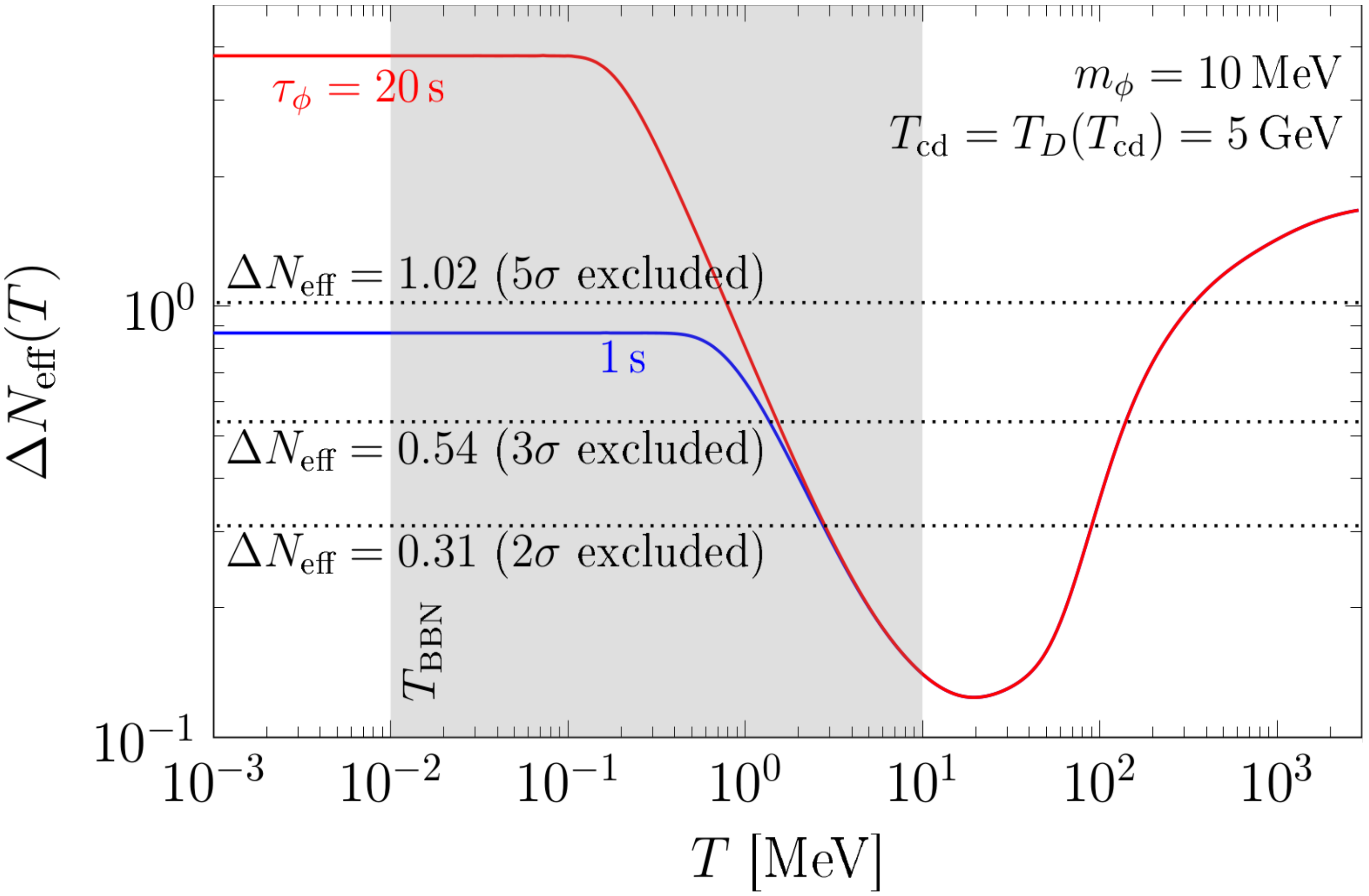


Question: Can the thermal evolution by quantified by

$$\Delta N_{\rm eff}(T) = \frac{\rho_D(T)}{\rho_\nu(T)} \quad ?$$


$\tau_\phi = 20\,\mathrm{s}$
$m_\phi = 10\,\mathrm{MeV}$
$T_\mathrm{cd} = T_D(T_\mathrm{cd}) = 5\,\mathrm{GeV}$
$\Delta N_\mathrm{eff} = 1.02$ (5σ excluded)
$1\,\mathrm{s}$
$\Delta N_\mathrm{eff} = 0.54$ (3σ excluded)
$\Delta N_\mathrm{eff} = 0.31$ (2σ excluded)
T_BBN
$\Delta N_\mathrm{eff}(T)$
10^0
10^{-1}
10^{-3}
10^{-2}
10^{-1}
10^0
10^1
10^2
10^3
T [MeV]

Thermal evolution of the dark sector



The limit cannot be expressed in terms of ΔN_{eff}

$\rightarrow$ A dedicated analysis is needed

Calculation of the bounds

Energy densities

$$\rho_D = \rho_\phi + \rho_N$$

Calculation of the bounds

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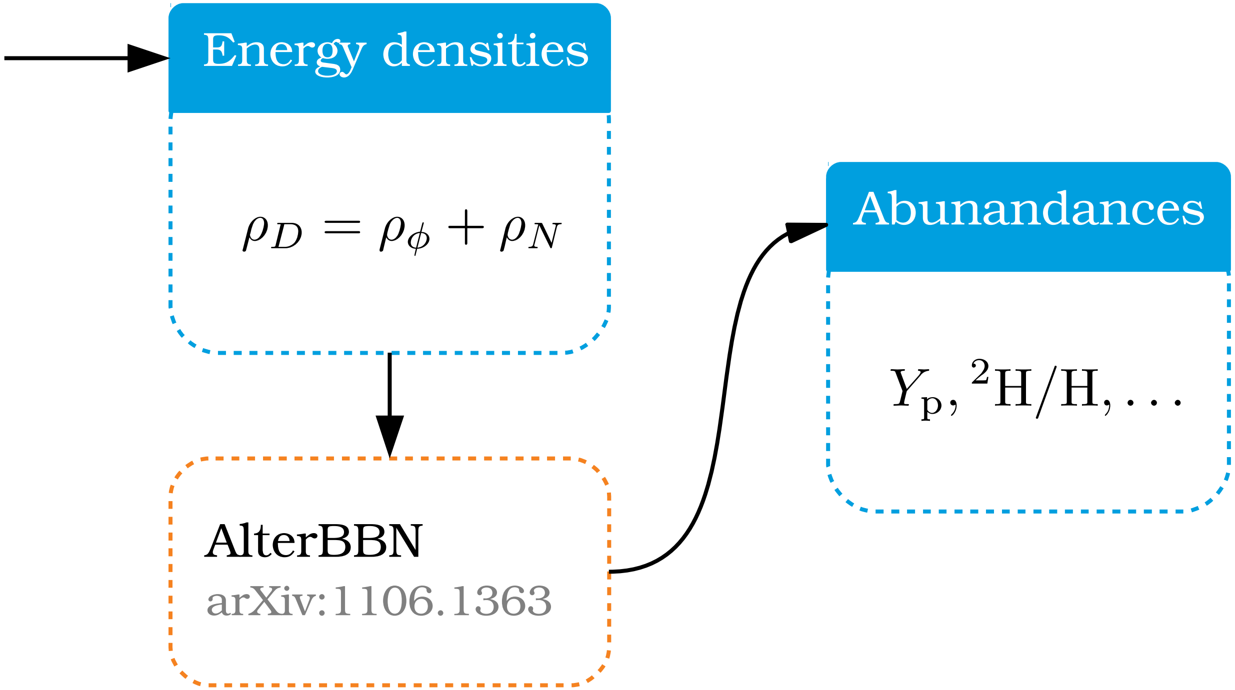
$$\rho_D = \rho_\phi + \rho_N$$

AlterBBN

arXiv:1106.1363

Calculation of the bounds



Energy densities

$$\rho_D = \rho_\phi + \rho_N$$

Abunandances

$$Y_\mathrm{p}, {}^2\mathrm{H}/\mathrm{H}, \ldots$$

AlterBBN
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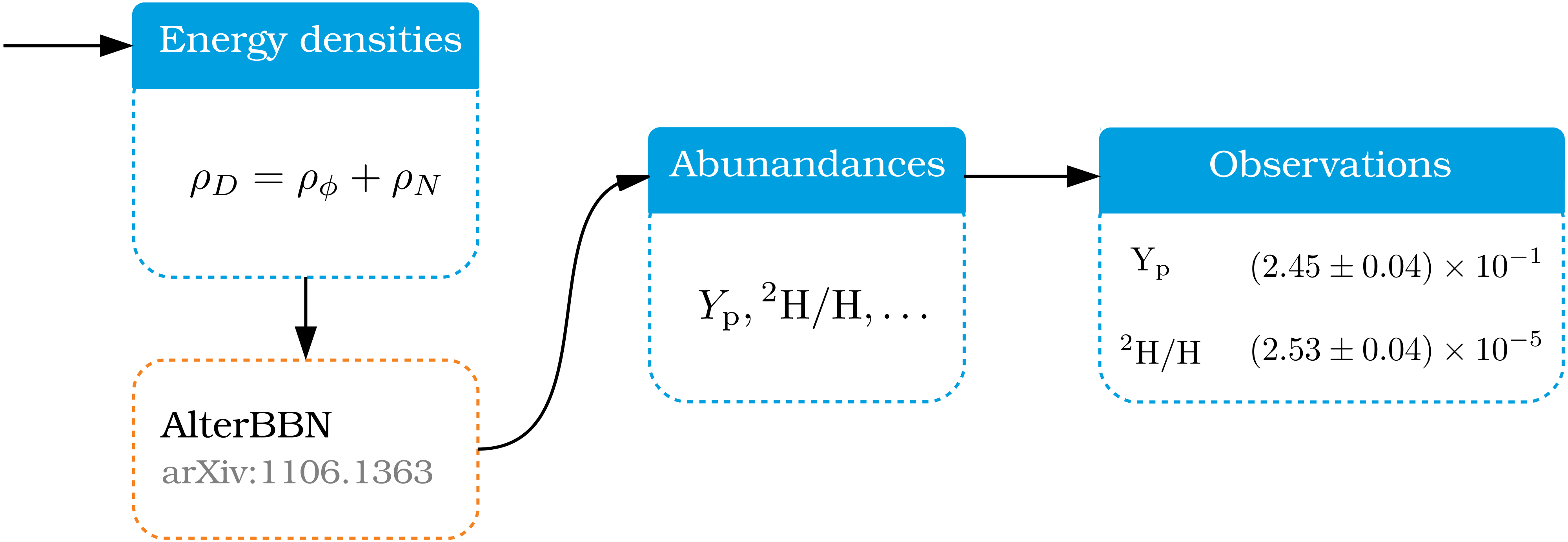
Calculation of the bounds



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AlterBBN

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Observations

$\mathrm{Y_p}$	$(2.45 \pm 0.04) \times 10^{-1}$
$^2\mathrm{H/H}$	$(2.53 \pm 0.04) \times 10^{-5}$

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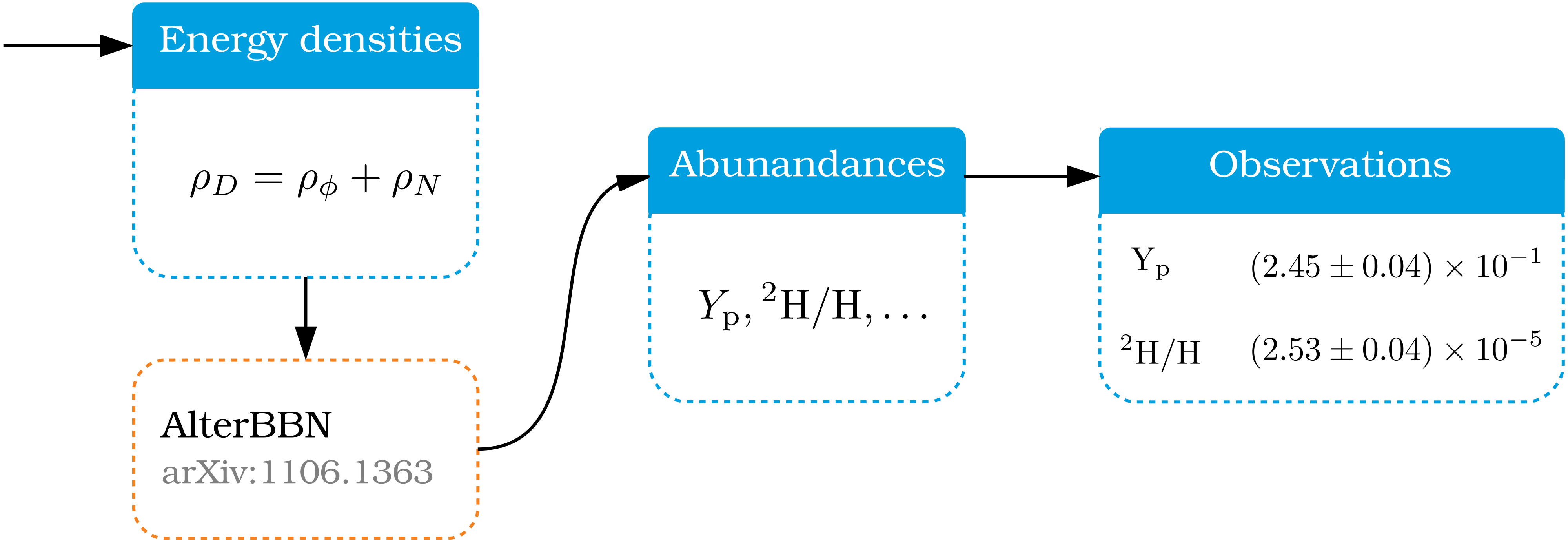

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Parameters of the calculation:

Neutron lifetime $\tau_n = 880\mathrm{s}$

Baryon-to-photon ratio $\eta = \dfrac{\rho_b}{\rho_\gamma}$

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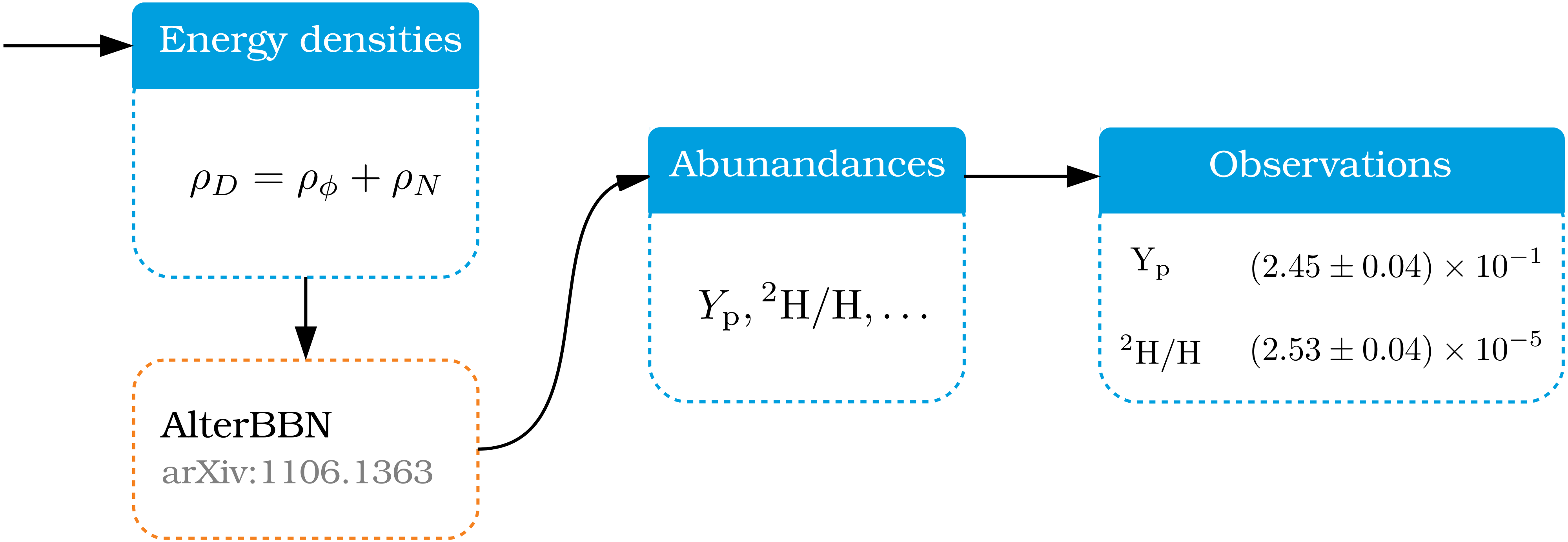

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Abunandances

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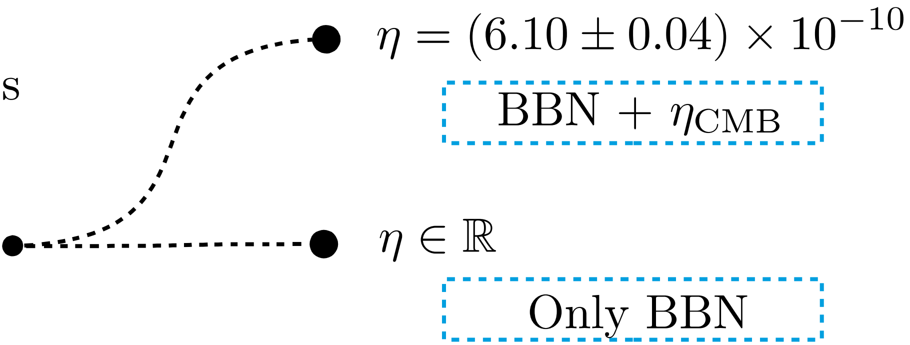


$\eta = (6.10 \pm 0.04) \times 10^{-10}$

BBN + η_{CMB}

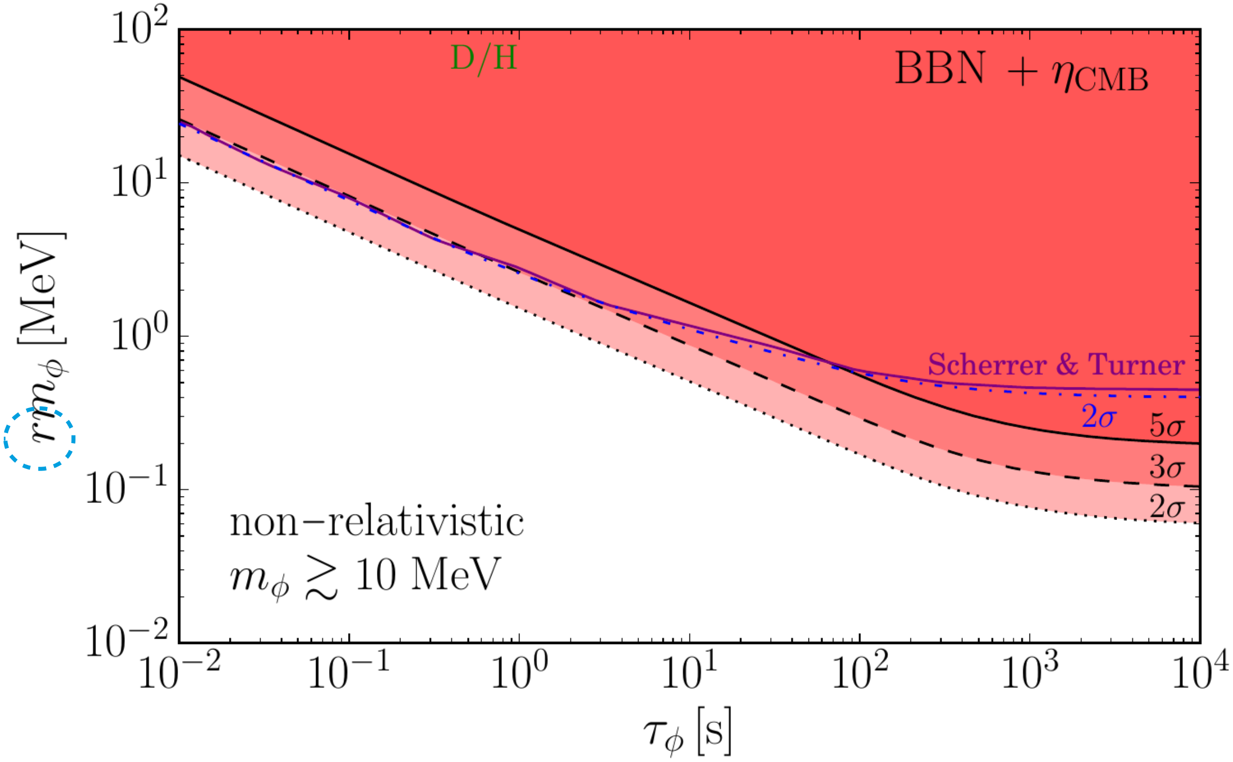
$\eta \in \mathbb{R}$

Only BBN

Resulting bounds from BBN

First check non-relativistic limit (Scherrer/Turner, 10.1086/166534):

$$r = \frac{n_\phi}{n_\gamma}\bigg|_{T=10^9\,\mathrm{K}}$$



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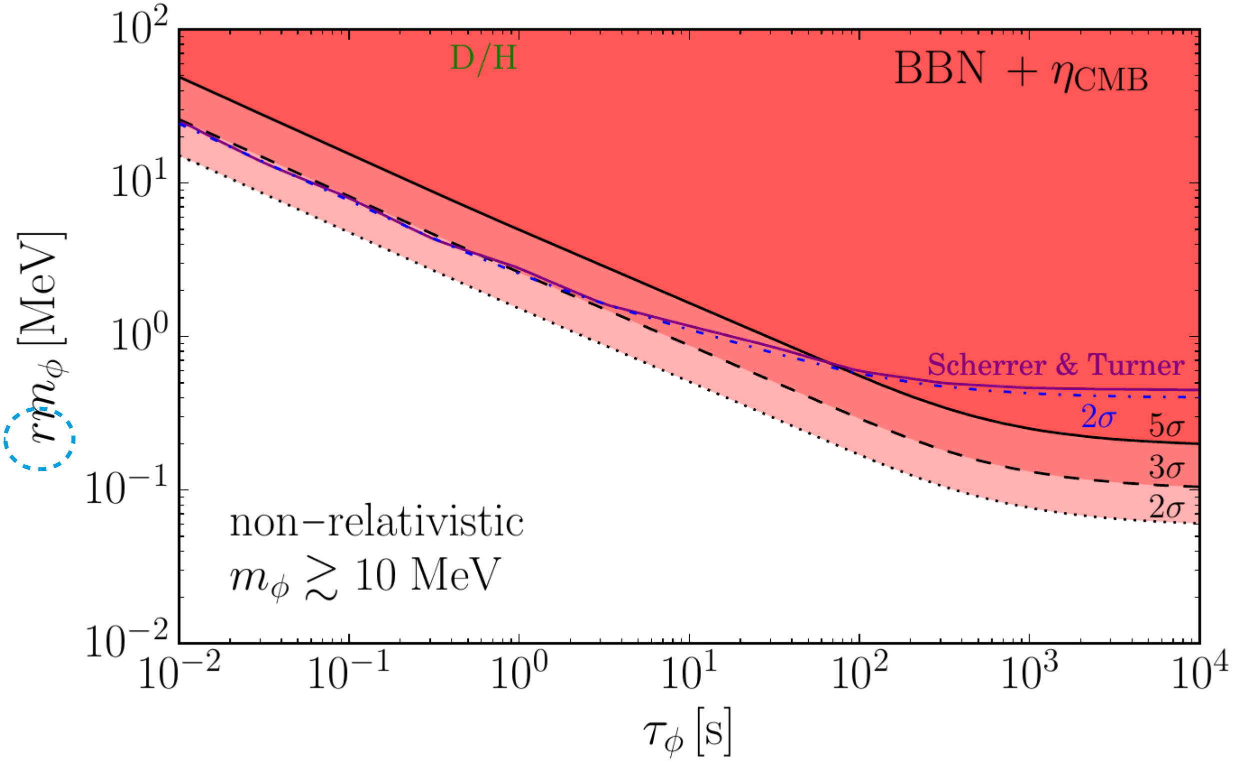
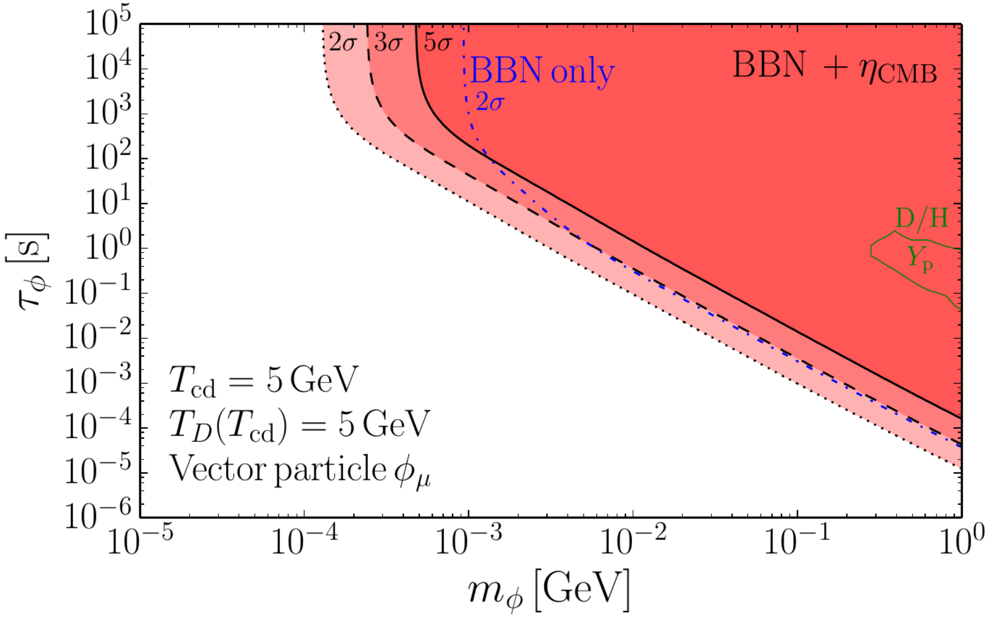
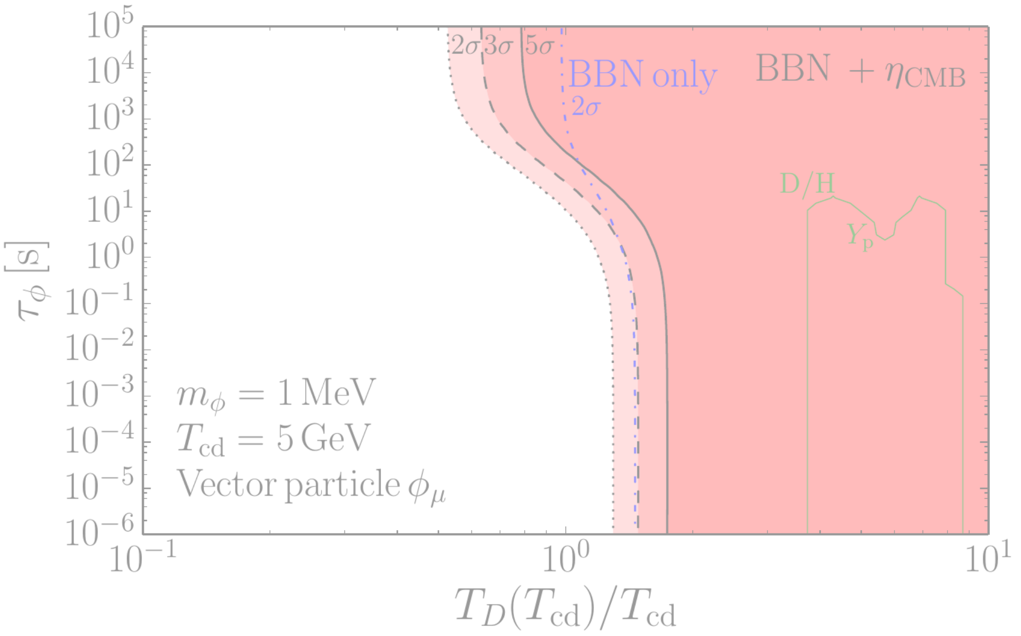


➡ Good agreement with the literature for $m_\phi \gtrsim 10\mathrm{MeV}$

Resulting bounds from BBN (Vector mediator)



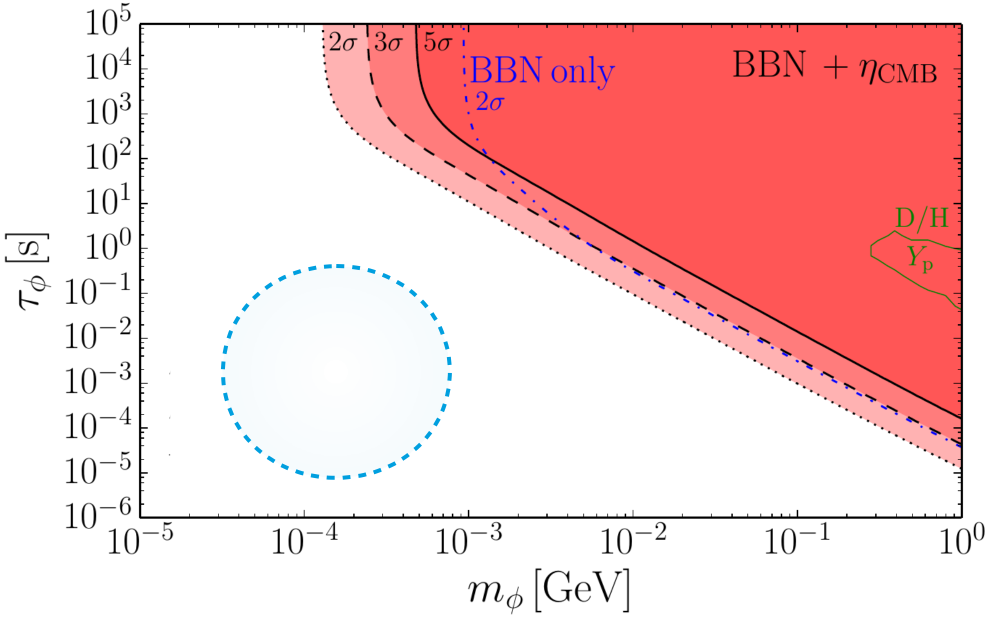


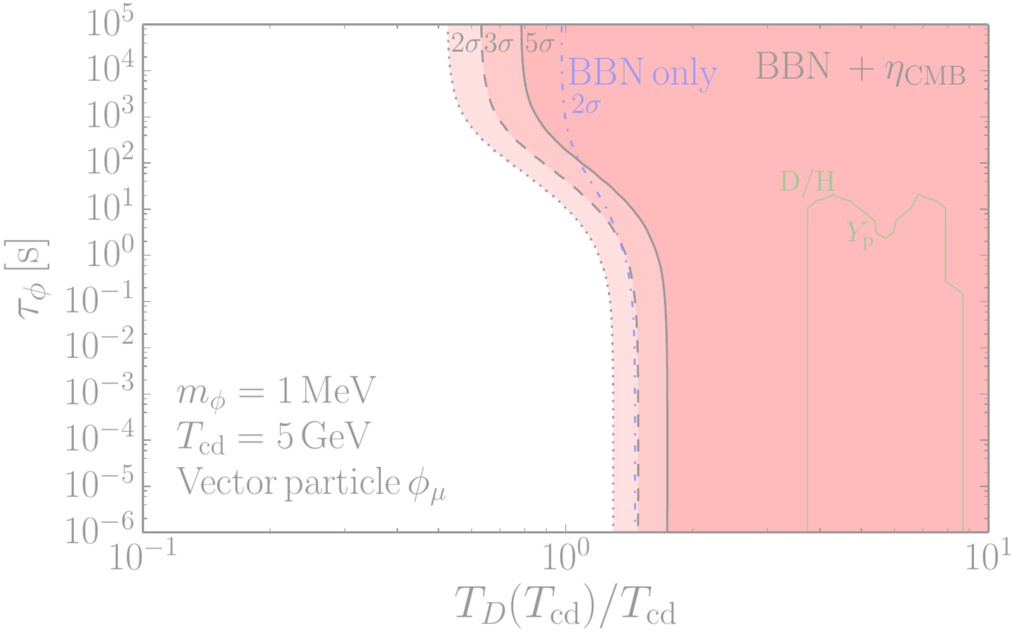
- For small m_ϕ, τ_ϕ , ϕ is relativistic during decay: $\Delta N_{\text{eff}} \sim 0.1 < 0.2$
- Diagonal exclusion line determined by $T(t = \tau_\phi) \sim m_\phi$

  → Above, ϕ is non-relativistic during decay: $\rho_\phi \propto R^{-3} > R^{-4}$
- For large τ_ϕ , ϕ is stable during BBN

  → Bounds become independent of τ_ϕ

Resulting bounds from BBN (Vector mediator)





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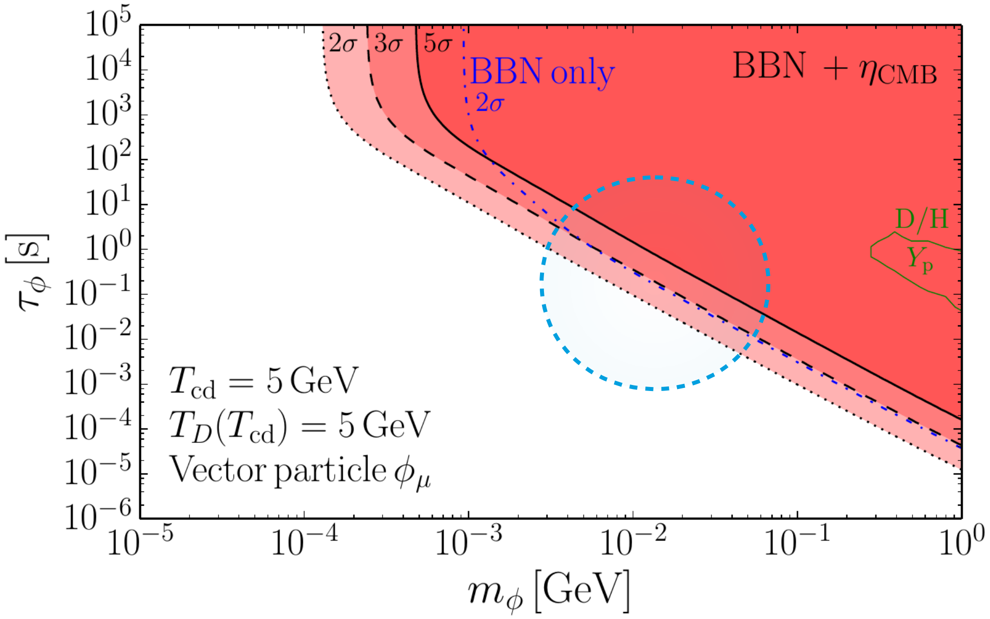

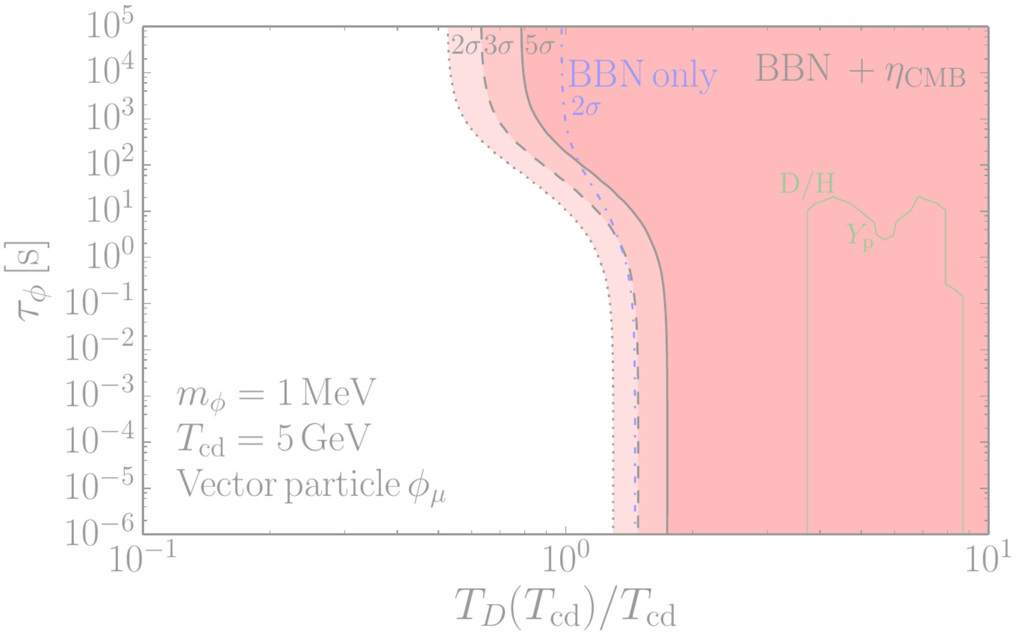

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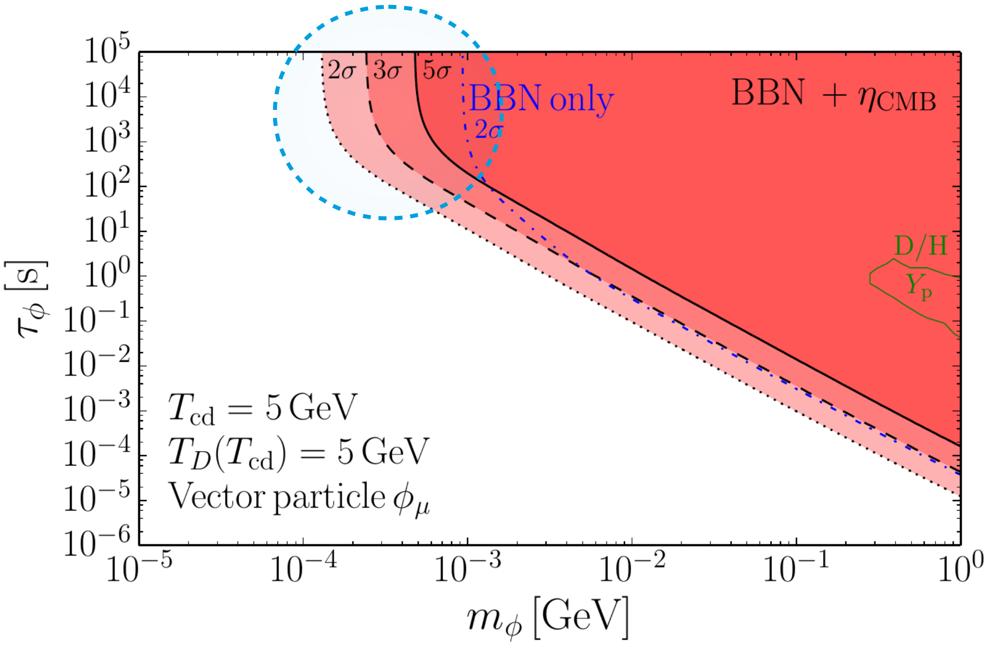
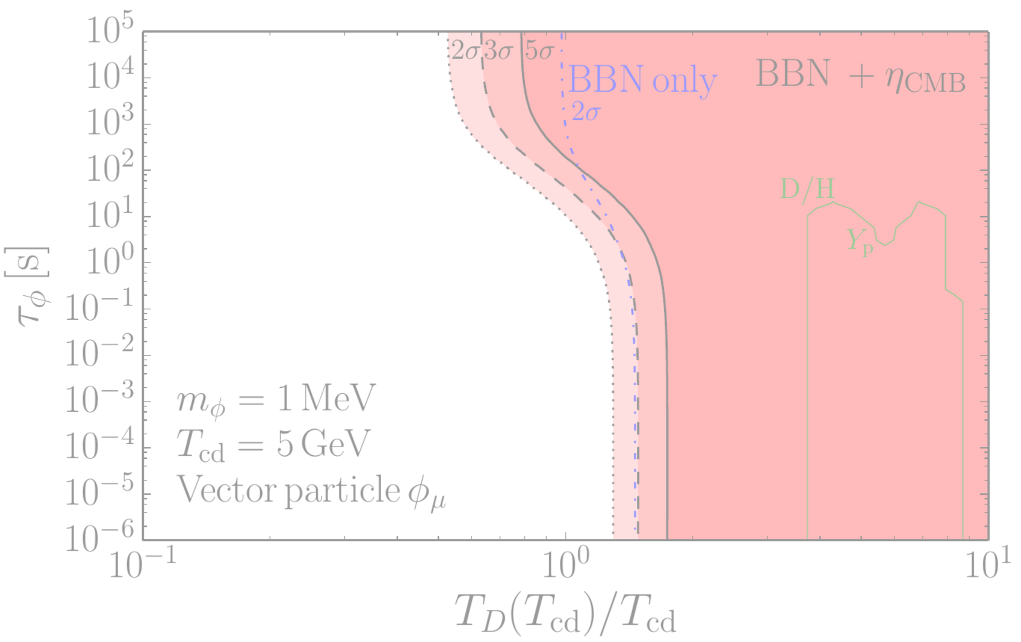
Resulting bounds from BBN (Vector mediator)





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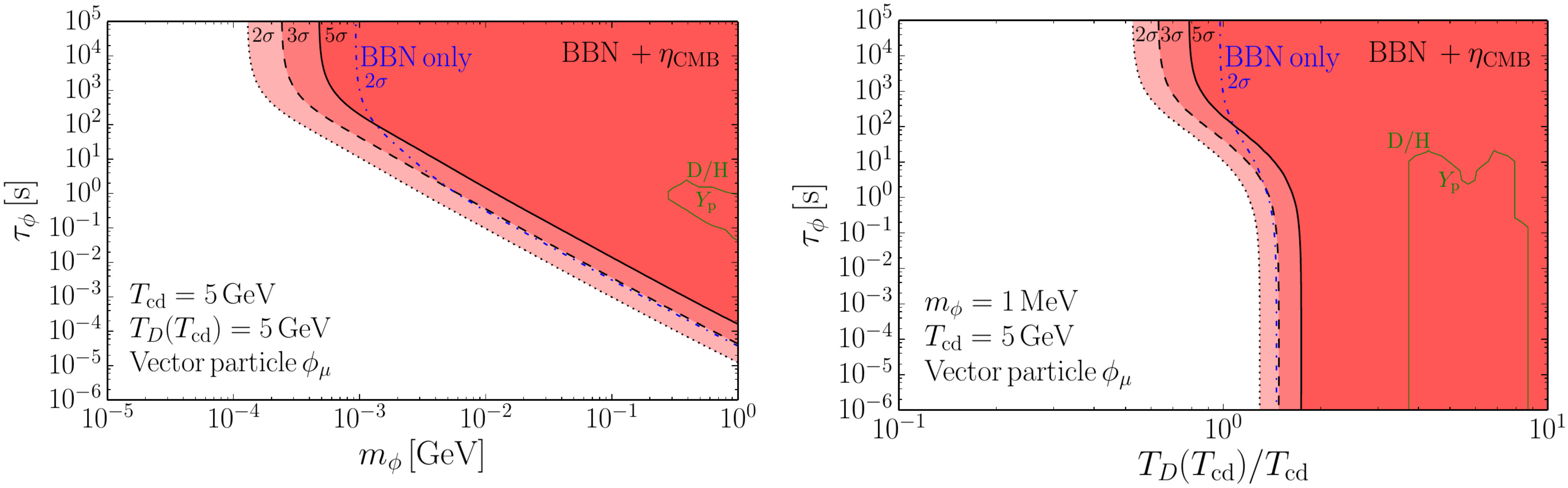
Resulting bounds from BBN (Vector mediator)



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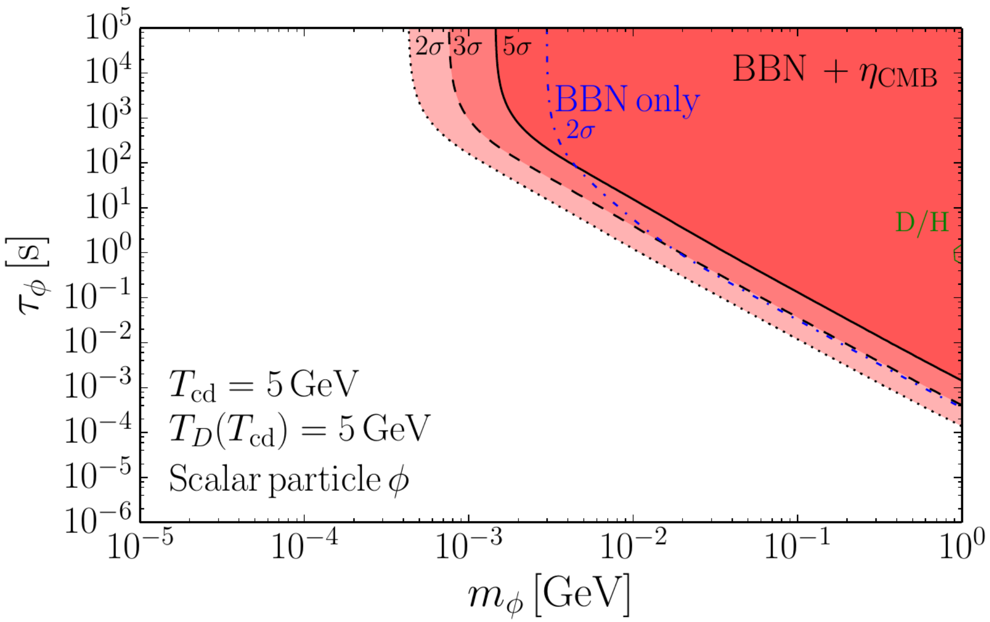
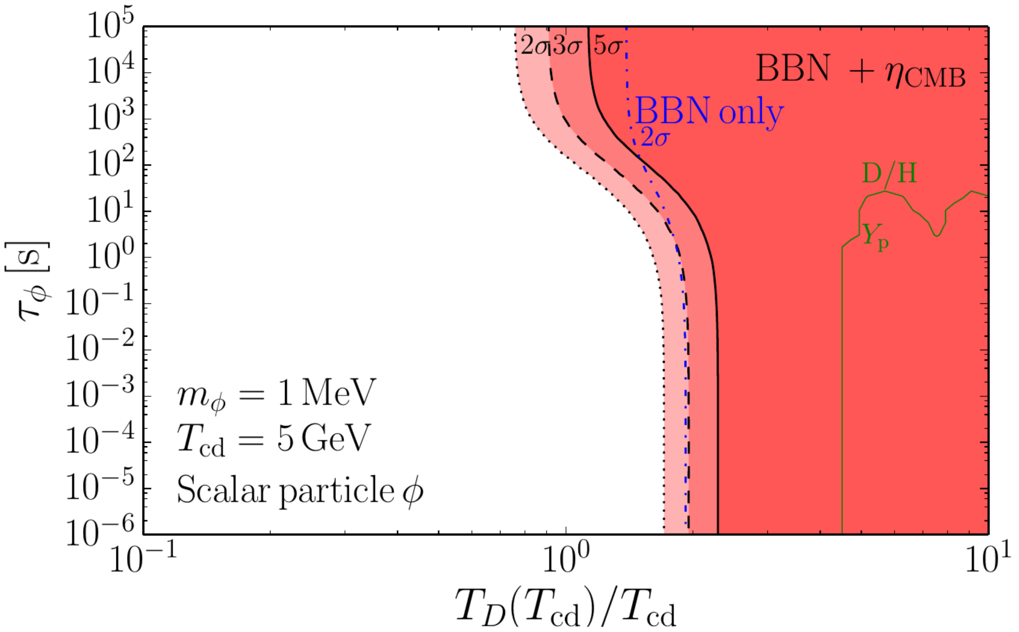
Resulting bounds from BBN (Scalar mediator)





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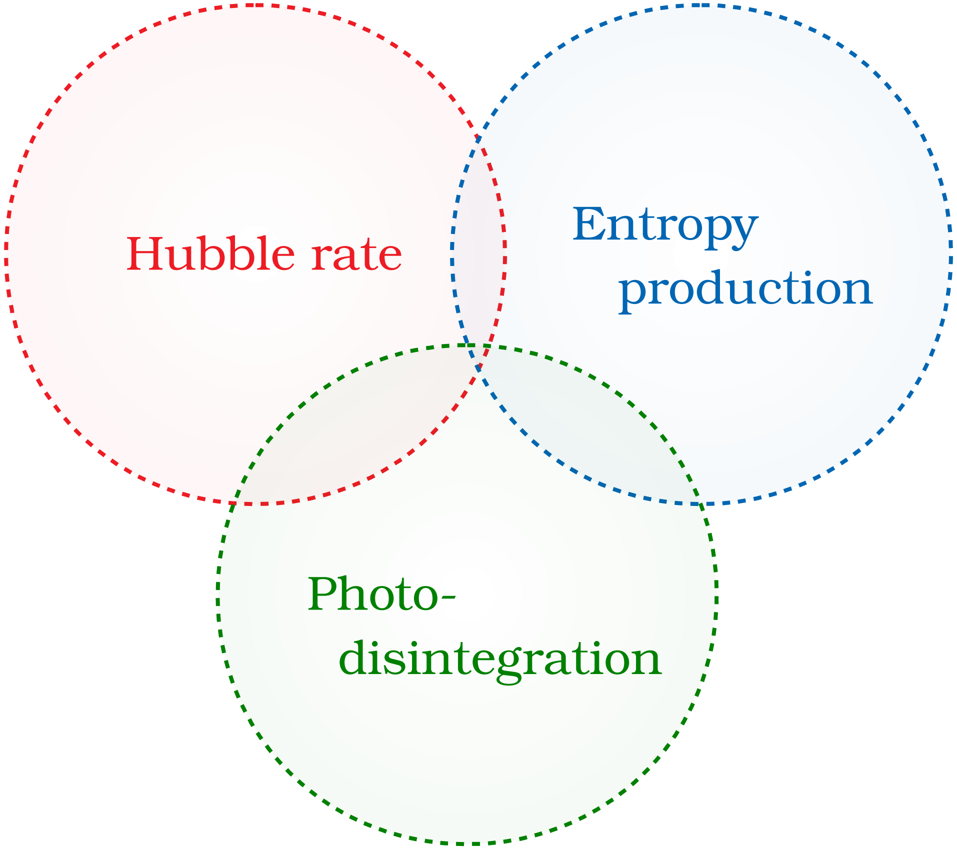
Work in progress

- Dark sectors with mediators decaying into electrons and/or photons

$$\phi \to e^+e^- \qquad \phi \to \gamma\gamma$$

- Need to consider three different effects:



Hubble rate

Entropy production

Photo-disintegration

Summary

- Possibility to constraint dark sectors without Standard Model interactions
- New (almost) model-independent study of BBN bounds for particles in the MeV range decaying into light states

Appetizer:

- Results can be applied to particular models, especially those with dark matter self-interactions

→ Strong bounds

Thank you for your attention!

Backup Slides

Models with self-interacting dark matter

Model Lagrangian:

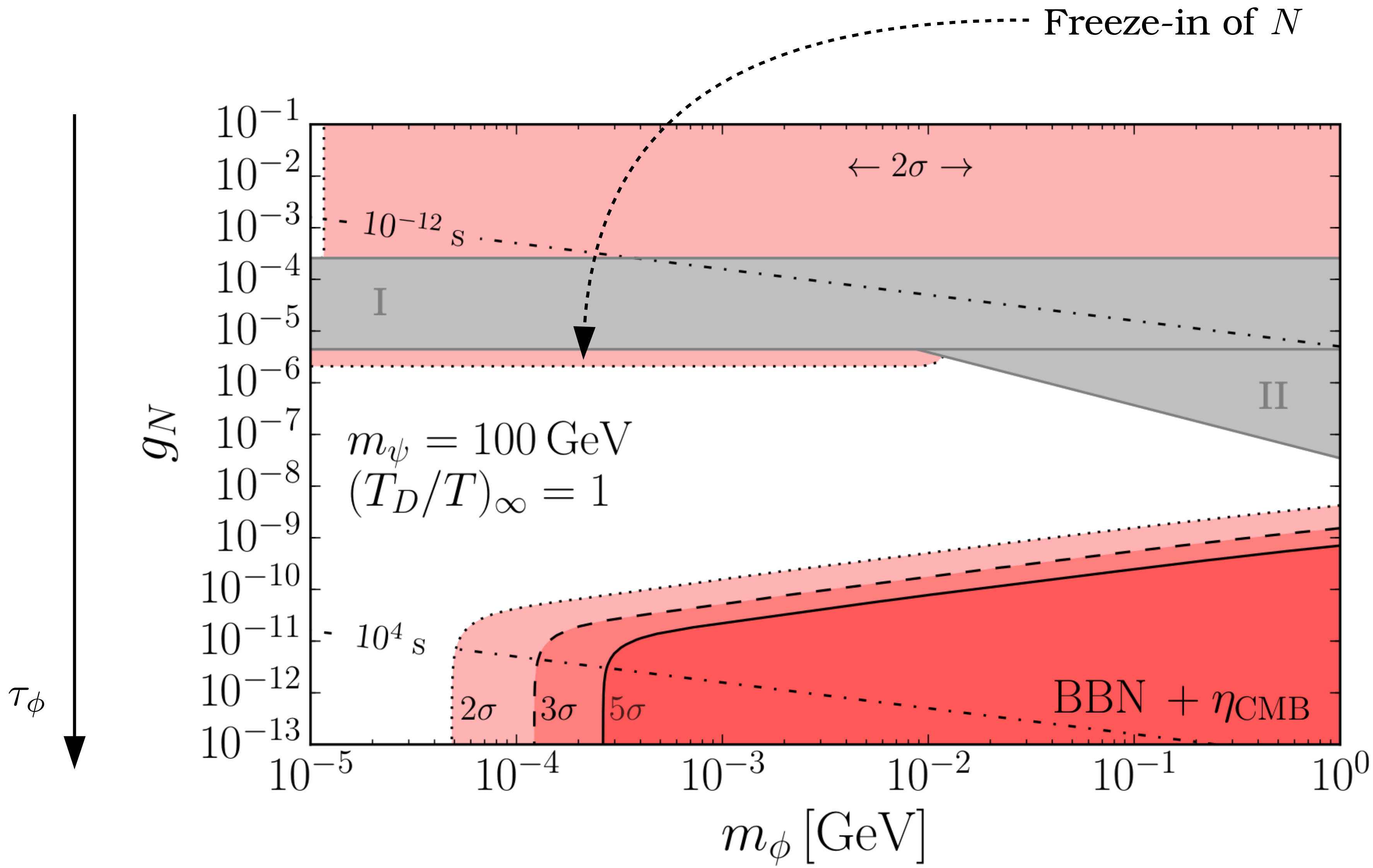
$$\mathcal{L} = g_\psi \bar{\psi}\psi\phi + g_N \bar{N} N \phi$$

Discriminate between two regimes:

1. *Large coupling regime*
2. *Small coupling regime*

However: Two *intermediate regions* remain

Model-dependent constraints



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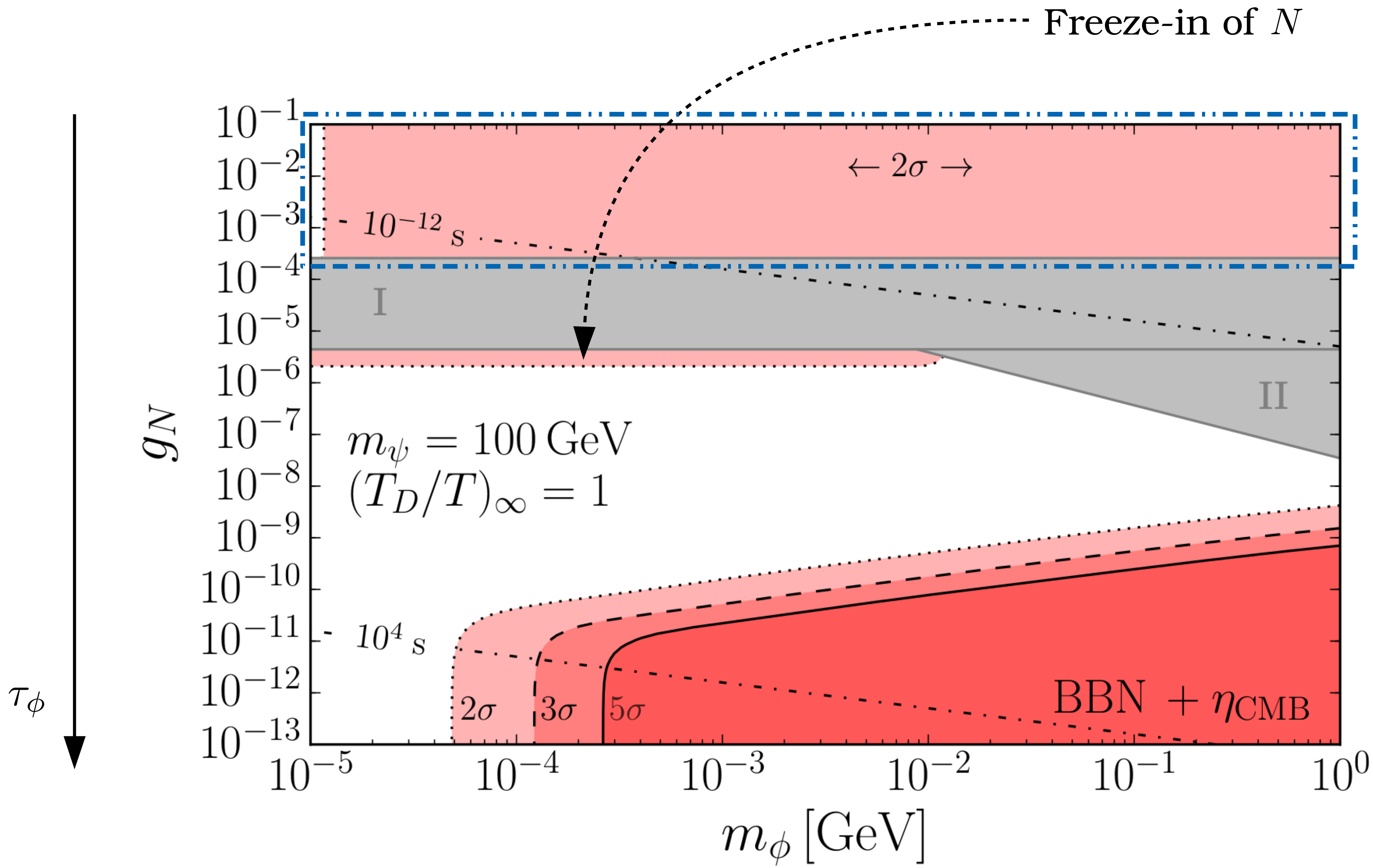

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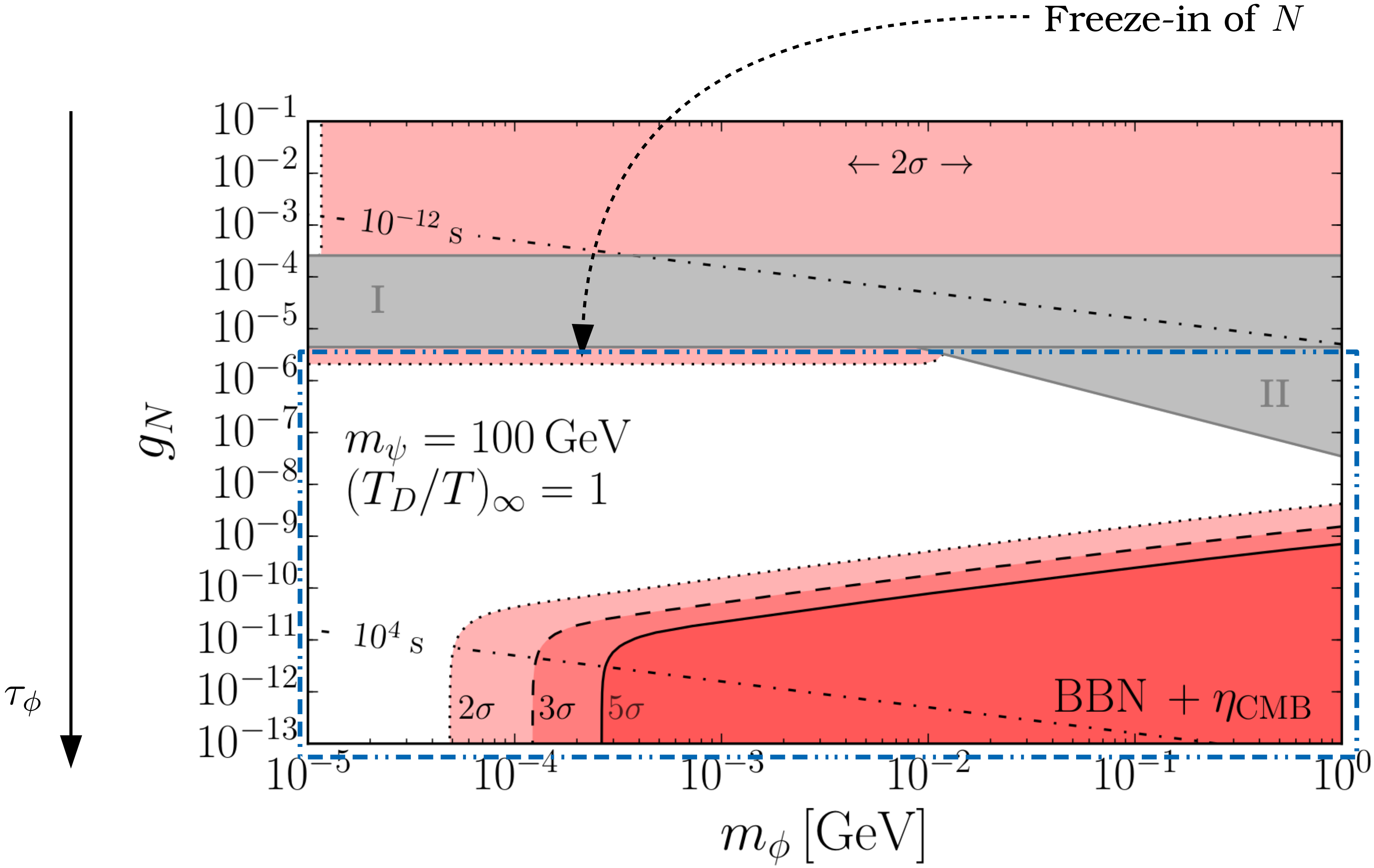

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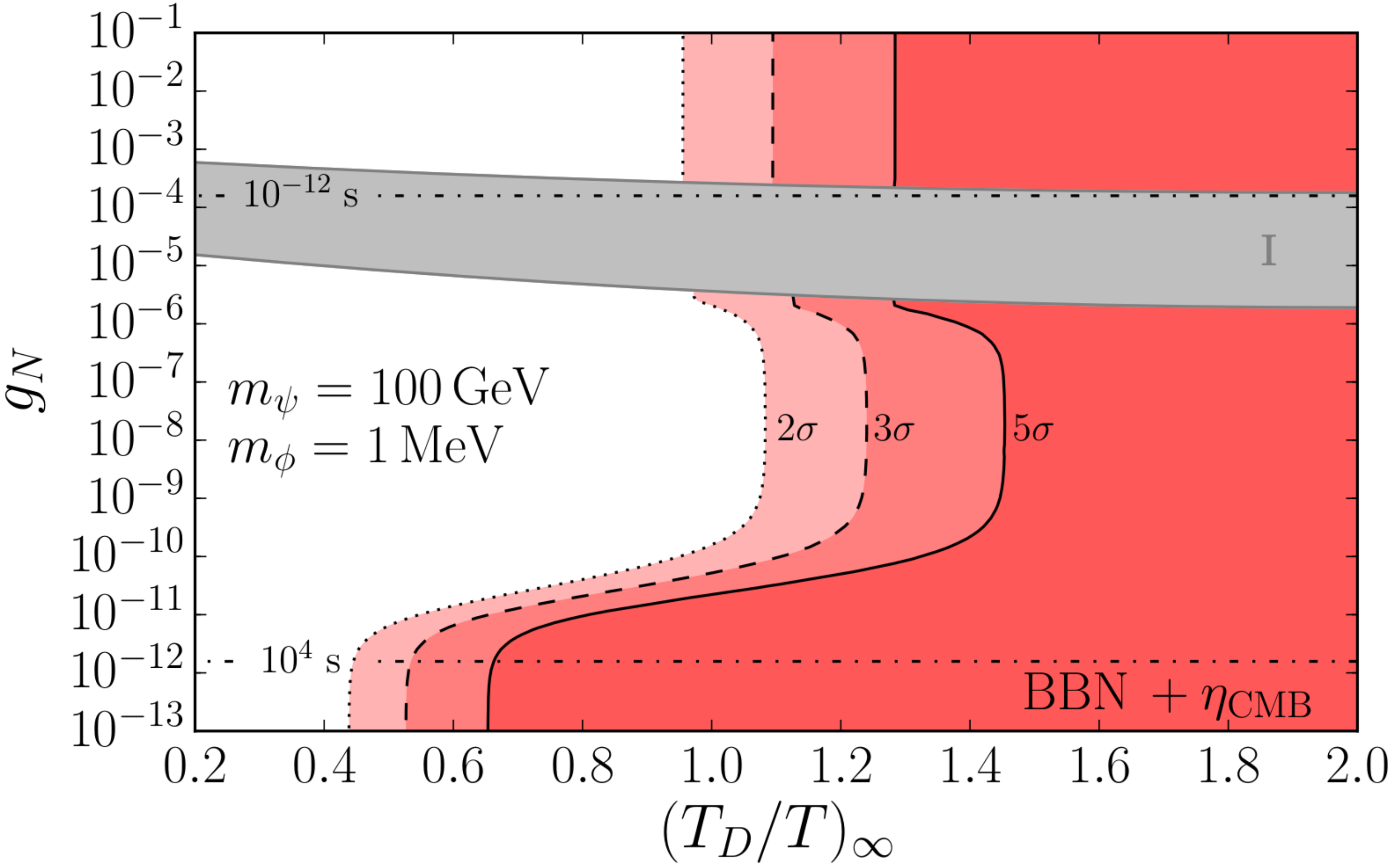

BBN and dark matter models with self-interactions