CONSTRAINING LONG-LIVED PARTICLES WITH BIG BANG NUCLEOSYNTHESIS

based on

[1712.03972], [1808.09324], [2011.06519], [2112.09137]

by

Frederik Depta, Marco Hufnagel, Kai Schmidt-Hoberg,
Sebastian Wild, Thomas Hambye

Friday, November 17, 2023

fnrs
LA LIBERTÉ DE CHERCHER

ULB UNIVERSITÉ LIBRE DE BRUXELLES

Outline

- Big Bang Nucleosynthesis
- Influence of dark-sector states
- Electromagnetic decays
- Decays into Neutrinos
- Hadronic decays

Big Bang Nucleosynthesis

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

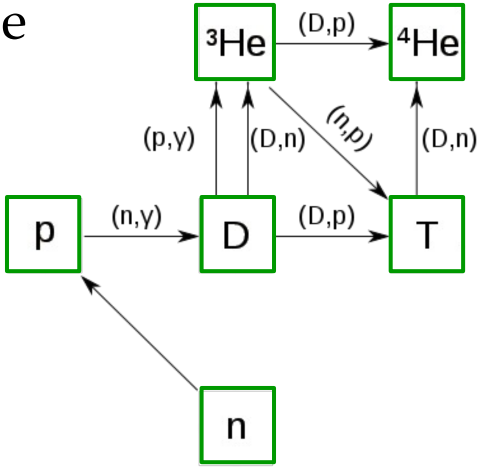
$$t \sim 1\,\mathrm{s} - 10^4\,\mathrm{s} \quad \leftrightarrow \quad T \sim 1\,\mathrm{MeV} - 10\,\mathrm{keV}$$

Big Bang Nucleosynthesis

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

$$t \sim 1\,\mathrm{s} - 10^4\,\mathrm{s} \quad \leftrightarrow \quad T \sim 1\,\mathrm{MeV} - 10\,\mathrm{keV}$$

- Production via nuclear fusion of protons & neutrons

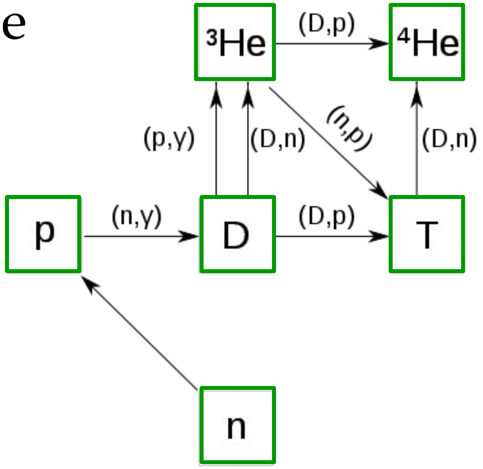


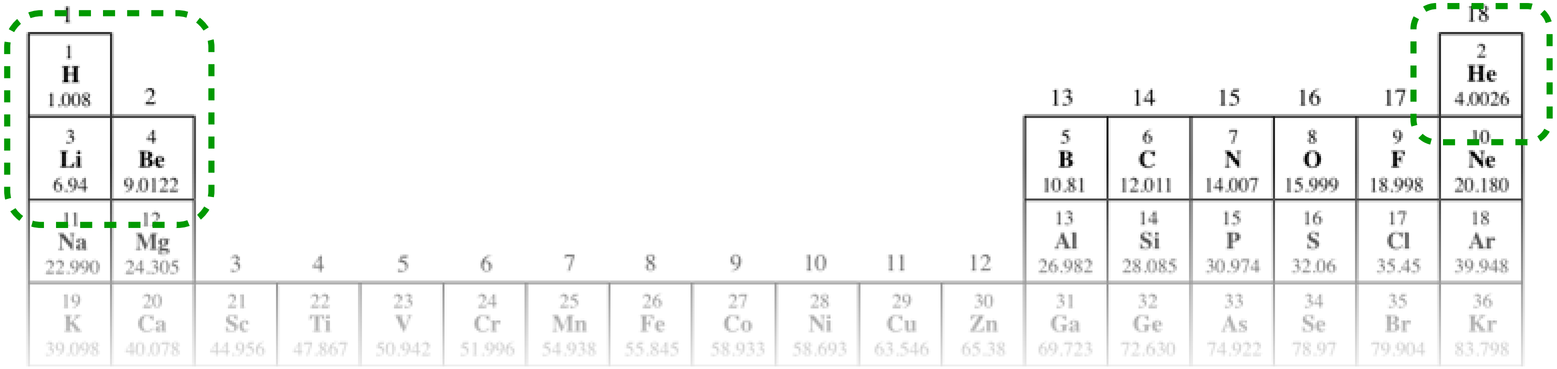
Big Bang Nucleosynthesis

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

$$t \sim 1\,\mathrm{s} - 10^4\,\mathrm{s} \quad \leftrightarrow \quad T \sim 1\,\mathrm{MeV} - 10\,\mathrm{keV}$$

- Production via nuclear fusion of protons & neutrons





1																	18
1 H 1.008	2											13	14	15	16	17	2 He 4.0026
3 Li 6.94	4 Be 9.0122											5 B 10.81	6 C 12.011	7 N 14.007	8 O 15.999	9 F 18.998	10 Ne 20.180
11 Na 22.990	12 Mg 24.305	3	4	5	6	7	8	9	10	11	12	13 Al 26.982	14 Si 28.085	15 P 30.974	16 S 32.06	17 Cl 35.45	18 Ar 39.948
19 K 39.098	20 Ca 40.078	21 Sc 44.956	22 Ti 47.867	23 V 50.942	24 Cr 51.996	25 Mn 54.938	26 Fe 55.845	27 Co 58.933	28 Ni 58.693	29 Cu 63.546	30 Zn 65.38	31 Ga 69.723	32 Ge 72.630	33 As 74.922	34 Se 78.97	35 Br 79.904	36 Kr 83.798

Big Bang Nucleosynthesis

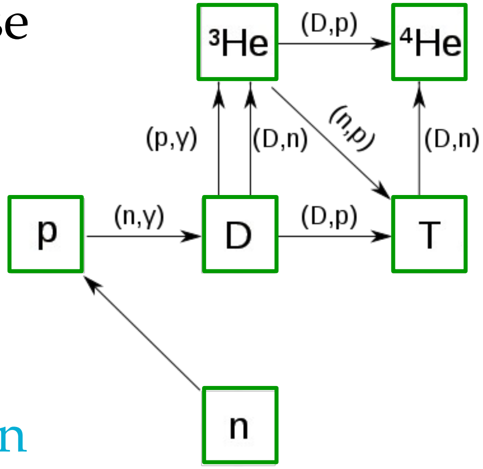
- Formation of light nuclei in the early phase of the universe

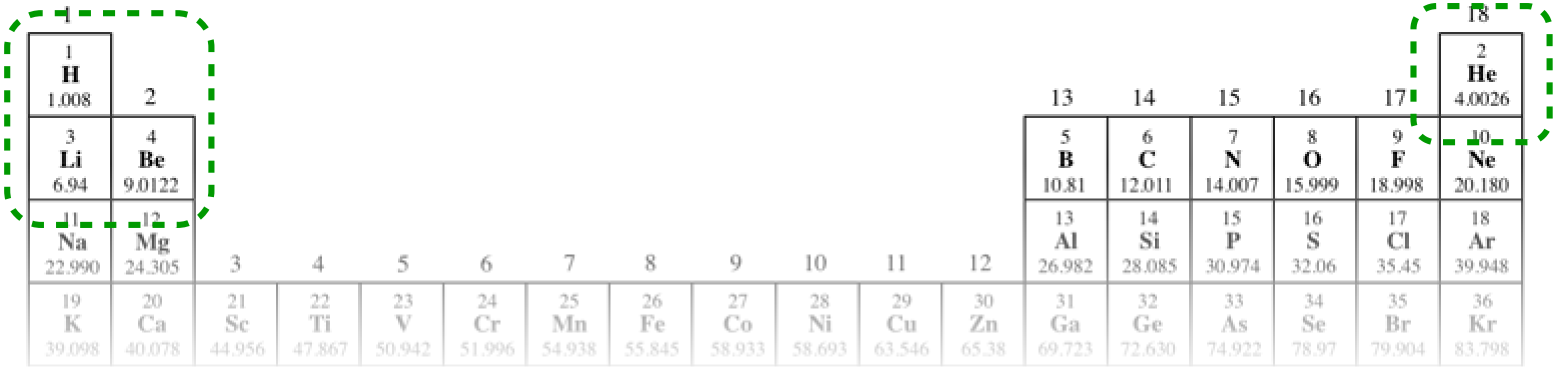
$$t \sim 1\,\mathrm{s} - 10^4\,\mathrm{s} \quad \leftrightarrow \quad T \sim 1\,\mathrm{MeV} - 10\,\mathrm{keV}$$

- Production via nuclear fusion of protons & neutrons

- Thermal evolution is governed by the Boltzmann equation

$$\frac{\mathrm{d}Y_X}{\mathrm{d}T} = \frac{\mathrm{d}t}{\mathrm{d}T} \times \sum_{r\in\mathcal{R}_X} \pm\Gamma_r \prod_{i\in\mathcal{I}_r} Y_i$$



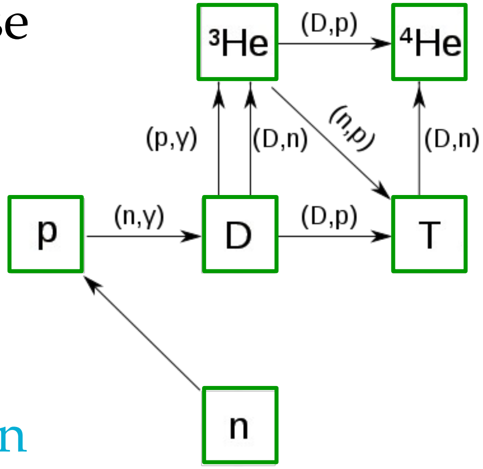


1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1 **H** 1.008																	2 **He** 4.0026
3 **Li** 6.94	4 **Be** 9.0122											5 **B** 10.81	6 **C** 12.011	7 **N** 14.007	8 **O** 15.999	9 **F** 18.998	10 **Ne** 20.180
11 **Na** 22.990	12 **Mg** 24.305											13 **Al** 26.982	14 **Si** 28.085	15 **P** 30.974	16 **S** 32.06	17 **Cl** 35.45	18 **Ar** 39.948
19 K 39.098	20 Ca 40.078	21 Sc 44.956	22 Ti 47.867	23 V 50.942	24 Cr 51.996	25 Mn 54.938	26 Fe 55.845	27 Co 58.933	28 Ni 58.693	29 Cu 63.546	30 Zn 65.38	31 Ga 69.723	32 Ge 72.630	33 As 74.922	34 Se 78.97	35 Br 79.904	36 Kr 83.798

Big Bang Nucleosynthesis

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

$$t \sim 1\,\mathrm{s} - 10^4\,\mathrm{s} \quad \leftrightarrow \quad T \sim 1\,\mathrm{MeV} - 10\,\mathrm{keV}$$

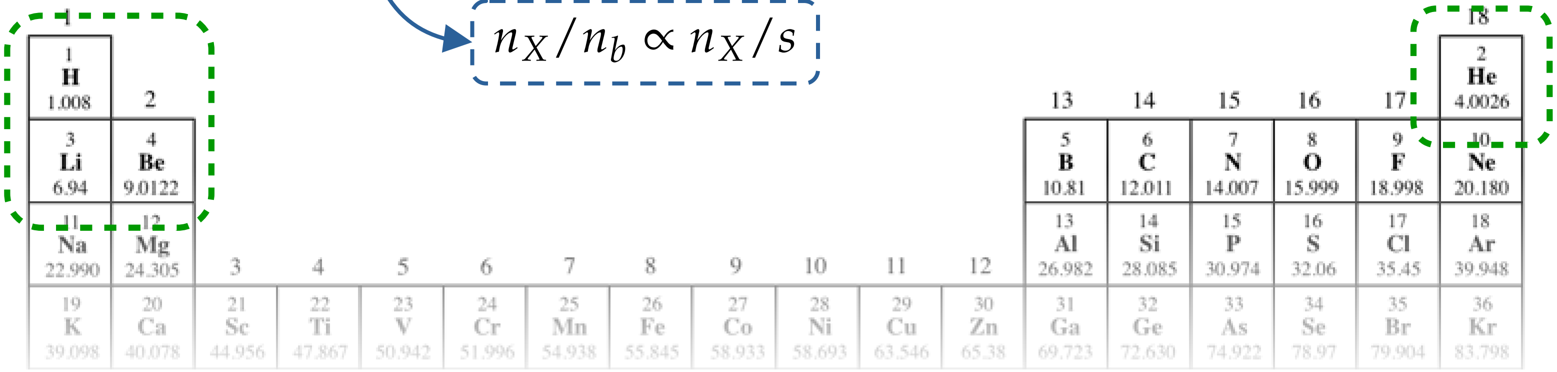


- Production via nuclear fusion of protons & neutrons

- Thermal evolution is governed by the Boltzmann equation

$$\frac{\mathrm{d}\boxed{Y_X}}{\mathrm{d}T} = \frac{\mathrm{d}t}{\mathrm{d}T} \times \sum_{r\in\mathcal{R}_X} \pm\Gamma_r \prod_{i\in\mathcal{I}_r} Y_i$$

$$\boxed{n_X/n_b \propto n_X/s}$$



1																	18
1 **H** 1.008	2											13	14	15	16	17	2 **He** 4.0026
3 **Li** 6.94	4 **Be** 9.0122											5 **B** 10.81	6 **C** 12.011	7 **N** 14.007	8 **O** 15.999	9 **F** 18.998	10 **Ne** 20.180
11 **Na** 22.990	12 **Mg** 24.305	3	4	5	6	7	8	9	10	11	12	13 **Al** 26.982	14 **Si** 28.085	15 **P** 30.974	16 **S** 32.06	17 **Cl** 35.45	18 **Ar** 39.948
19 K 39.098	20 Ca 40.078	21 Sc 44.956	22 Ti 47.867	23 V 50.942	24 Cr 51.996	25 Mn 54.938	26 Fe 55.845	27 Co 58.933	28 Ni 58.693	29 Cu 63.546	30 Zn 65.38	31 Ga 69.723	32 Ge 72.630	33 As 74.922	34 Se 78.97	35 Br 79.904	36 Kr 83.798

Big Bang Nucleosynthesis

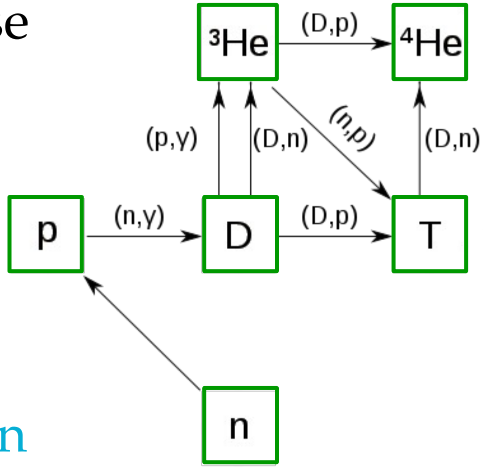
- Formation of light nuclei in the early phase of the universe

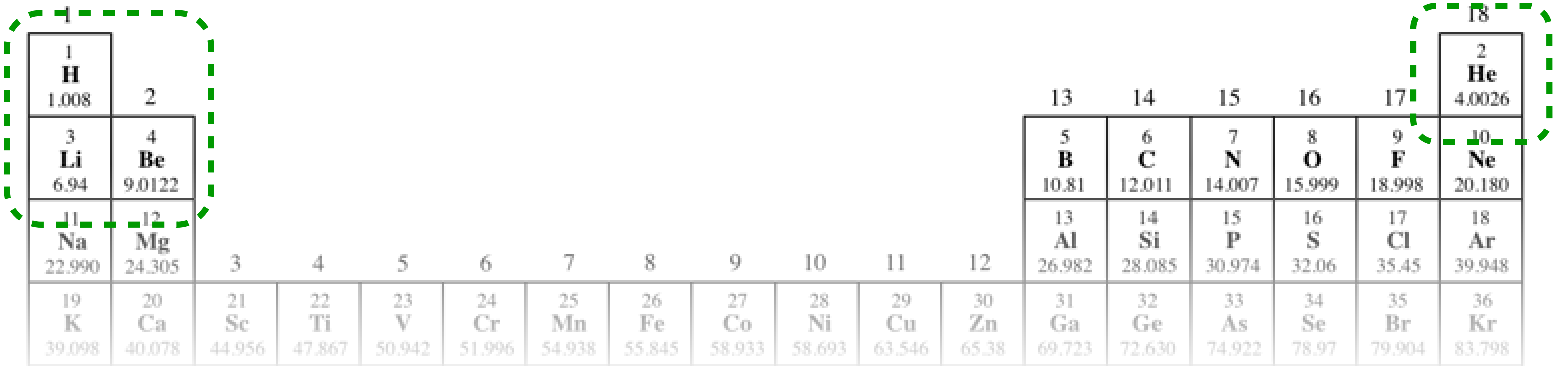
$$t \sim 1\,\mathrm{s} - 10^4\,\mathrm{s} \quad \leftrightarrow \quad T \sim 1\,\mathrm{MeV} - 10\,\mathrm{keV}$$

- Production via nuclear fusion of protons & neutrons

- Thermal evolution is governed by the Boltzmann equation

$$\frac{\mathrm{d}Y_X}{\mathrm{d}T} = \frac{\mathrm{d}t}{\mathrm{d}T} \times \sum_{r\in\mathcal{R}_X} \pm\Gamma_r \prod_{i\in\mathcal{I}_r} Y_i$$





1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1 **H** 1.008																	2 **He** 4.0026
3 **Li** 6.94	4 **Be** 9.0122											5 **B** 10.81	6 **C** 12.011	7 **N** 14.007	8 **O** 15.999	9 **F** 18.998	10 **Ne** 20.180
11 **Na** 22.990	12 **Mg** 24.305											13 **Al** 26.982	14 **Si** 28.085	15 **P** 30.974	16 **S** 32.06	17 **Cl** 35.45	18 **Ar** 39.948
19 K 39.098	20 Ca 40.078	21 Sc 44.956	22 Ti 47.867	23 V 50.942	24 Cr 51.996	25 Mn 54.938	26 Fe 55.845	27 Co 58.933	28 Ni 58.693	29 Cu 63.546	30 Zn 65.38	31 Ga 69.723	32 Ge 72.630	33 As 74.922	34 Se 78.97	35 Br 79.904	36 Kr 83.798

Big Bang Nucleosynthesis

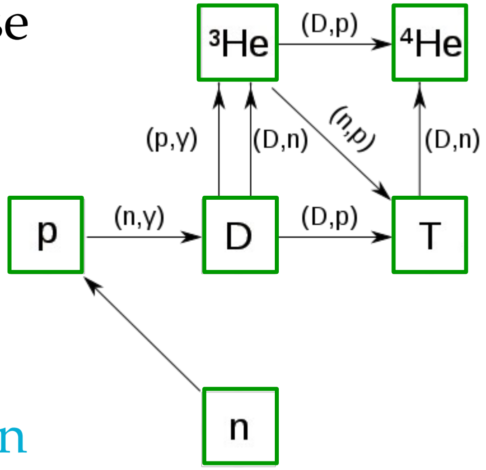
- Formation of light nuclei in the early phase of the universe

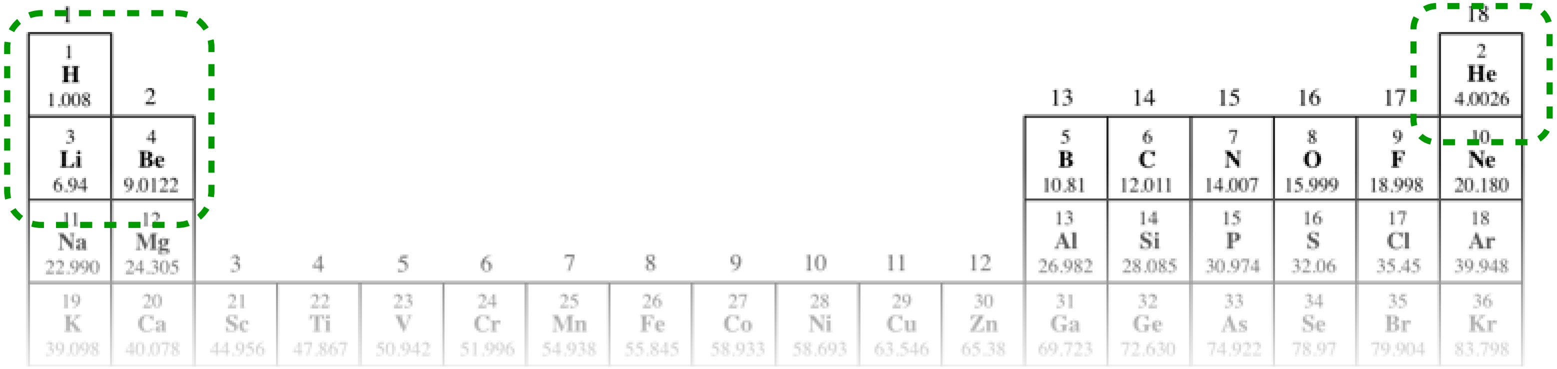
$$t \sim 1\,\mathrm{s} - 10^4\,\mathrm{s} \quad \leftrightarrow \quad T \sim 1\,\mathrm{MeV} - 10\,\mathrm{keV}$$

- Production via nuclear fusion of protons & neutrons

- Thermal evolution is governed by the Boltzmann equation

$$\frac{\mathrm{d}Y_X}{\mathrm{d}T} = \frac{\mathrm{d}t}{\mathrm{d}T} \times \sum_{r\in\mathcal{R}_X} \pm\Gamma_r \prod_{i\in\mathcal{I}_r} Y_i$$





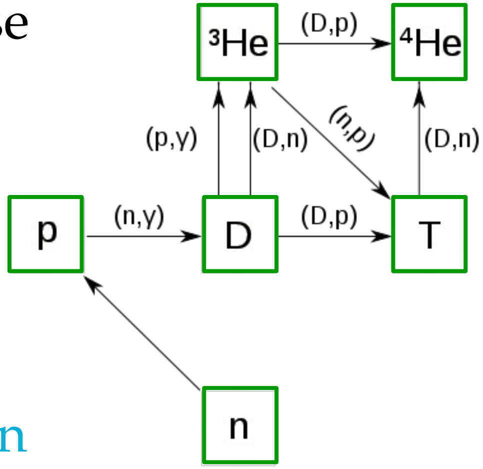
1																	18
1 **H** 1.008	2											13	14	15	16	17	2 **He** 4.0026
3 **Li** 6.94	4 **Be** 9.0122											5 **B** 10.81	6 **C** 12.011	7 **N** 14.007	8 **O** 15.999	9 **F** 18.998	10 **Ne** 20.180
11 **Na** 22.990	12 **Mg** 24.305	3	4	5	6	7	8	9	10	11	12	13 **Al** 26.982	14 **Si** 28.085	15 **P** 30.974	16 **S** 32.06	17 **Cl** 35.45	18 **Ar** 39.948
19 K 39.098	20 Ca 40.078	21 Sc 44.956	22 Ti 47.867	23 V 50.942	24 Cr 51.996	25 Mn 54.938	26 Fe 55.845	27 Co 58.933	28 Ni 58.693	29 Cu 63.546	30 Zn 65.38	31 Ga 69.723	32 Ge 72.630	33 As 74.922	34 Se 78.97	35 Br 79.904	36 Kr 83.798

Big Bang Nucleosynthesis

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

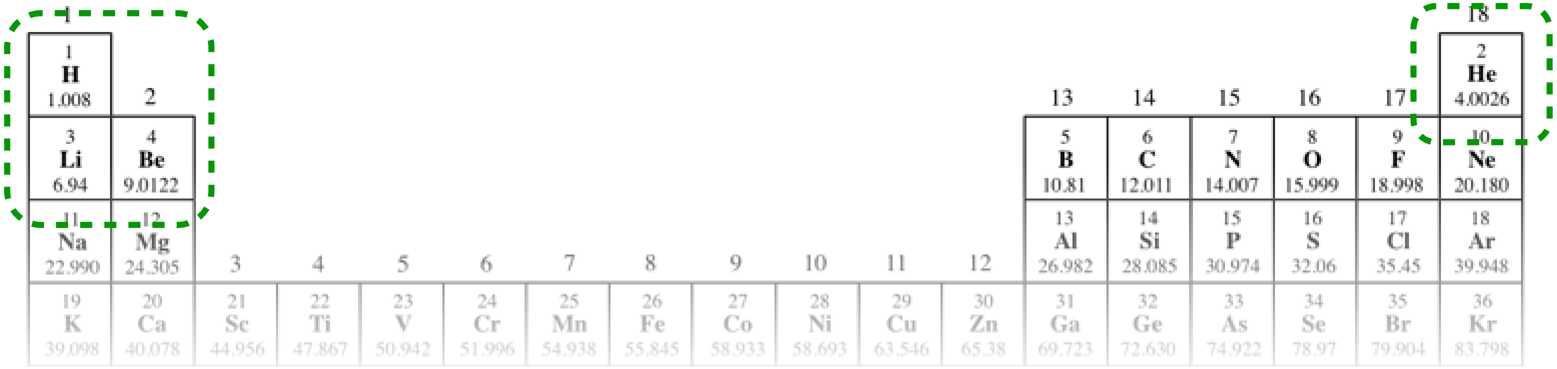
$$t \sim 1\,\mathrm{s} - 10^4\,\mathrm{s} \quad \leftrightarrow \quad T \sim 1\,\mathrm{MeV} - 10\,\mathrm{keV}$$

- Production via nuclear fusion of protons & neutrons



- Thermal evolution is governed by the Boltzmann equation

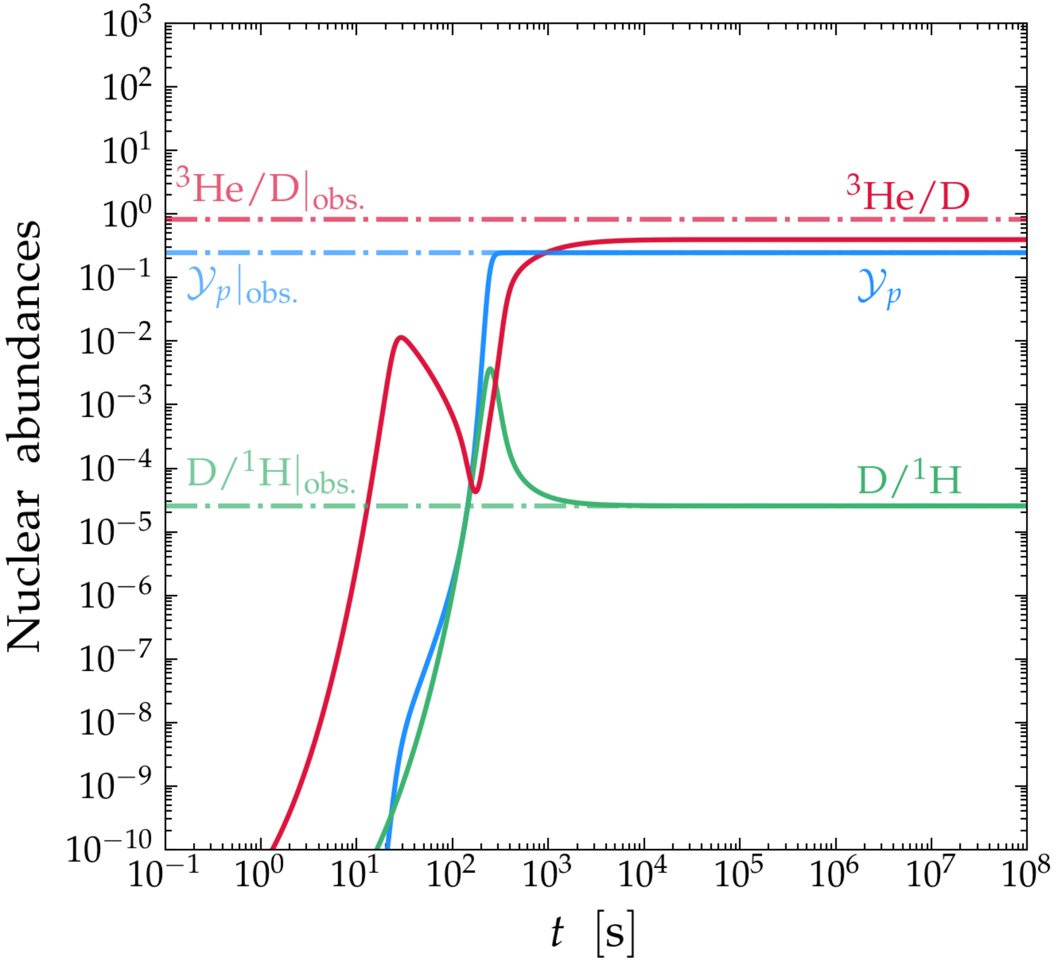
$$\frac{\mathrm{d}Y_X}{\mathrm{d}T} = \frac{\mathrm{d}t}{\mathrm{d}T} \times \sum_{r \in \mathcal{R}_X} \pm\Gamma_r \prod_{i \in \mathcal{I}_r} Y_i$$



1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1 H 1.008																	2 He 4.0026
3 Li 6.94	4 Be 9.0122											5 B 10.81	6 C 12.011	7 N 14.007	8 O 15.999	9 F 18.998	10 Ne 20.180
11 Na 22.990	12 Mg 24.305											13 Al 26.982	14 Si 28.085	15 P 30.974	16 S 32.06	17 Cl 35.45	18 Ar 39.948
19 K 39.098	20 Ca 40.078	21 Sc 44.956	22 Ti 47.867	23 V 50.942	24 Cr 51.996	25 Mn 54.938	26 Fe 55.845	27 Co 58.933	28 Ni 58.693	29 Cu 63.546	30 Zn 65.38	31 Ga 69.723	32 Ge 72.630	33 As 74.922	34 Se 78.97	35 Br 79.904	36 Kr 83.798

Evolution of the abundances during BBN

Predictions



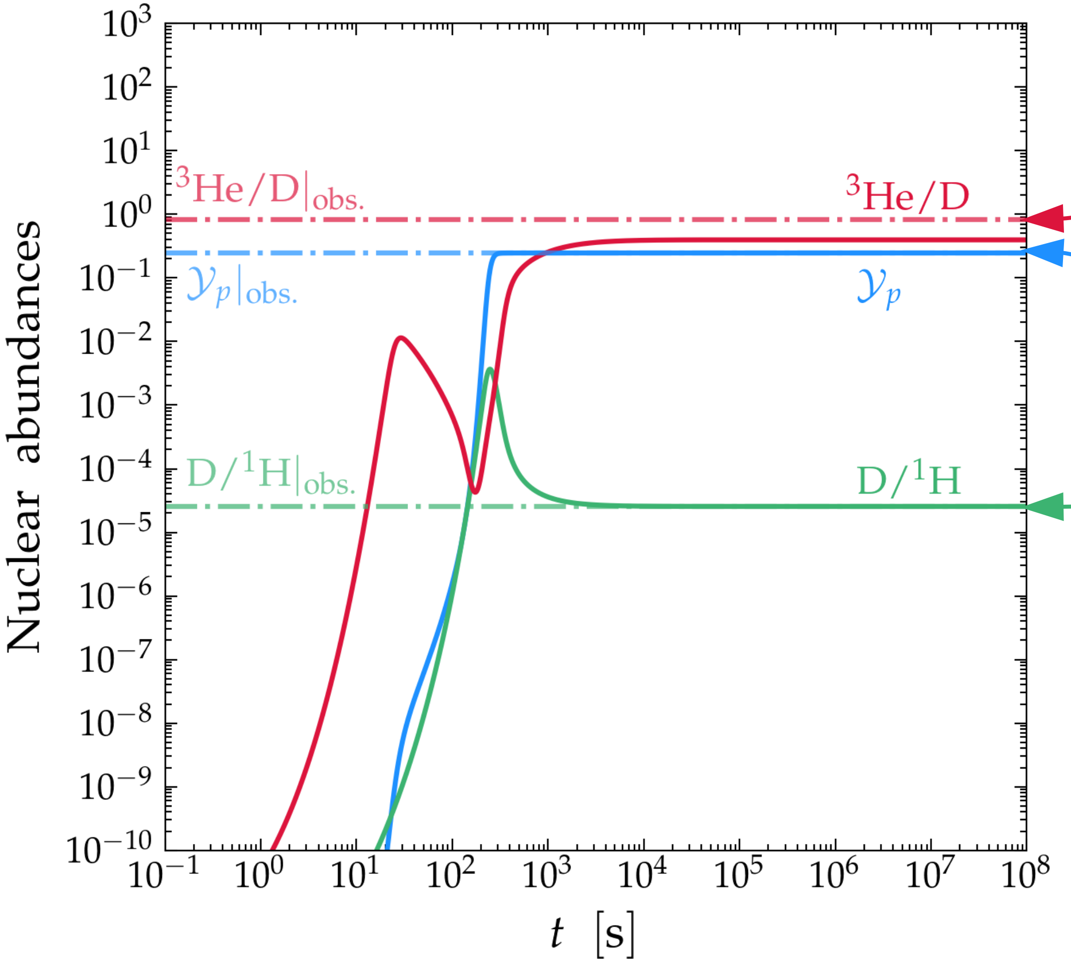
$Y_{^3\text{He}}/Y_\text{D}$

$4Y_{^4\text{He}}$

Y_D/Y_p

Evolution of the abundances during BBN

Predictions



Observations

[PDG18], [Geiss03]

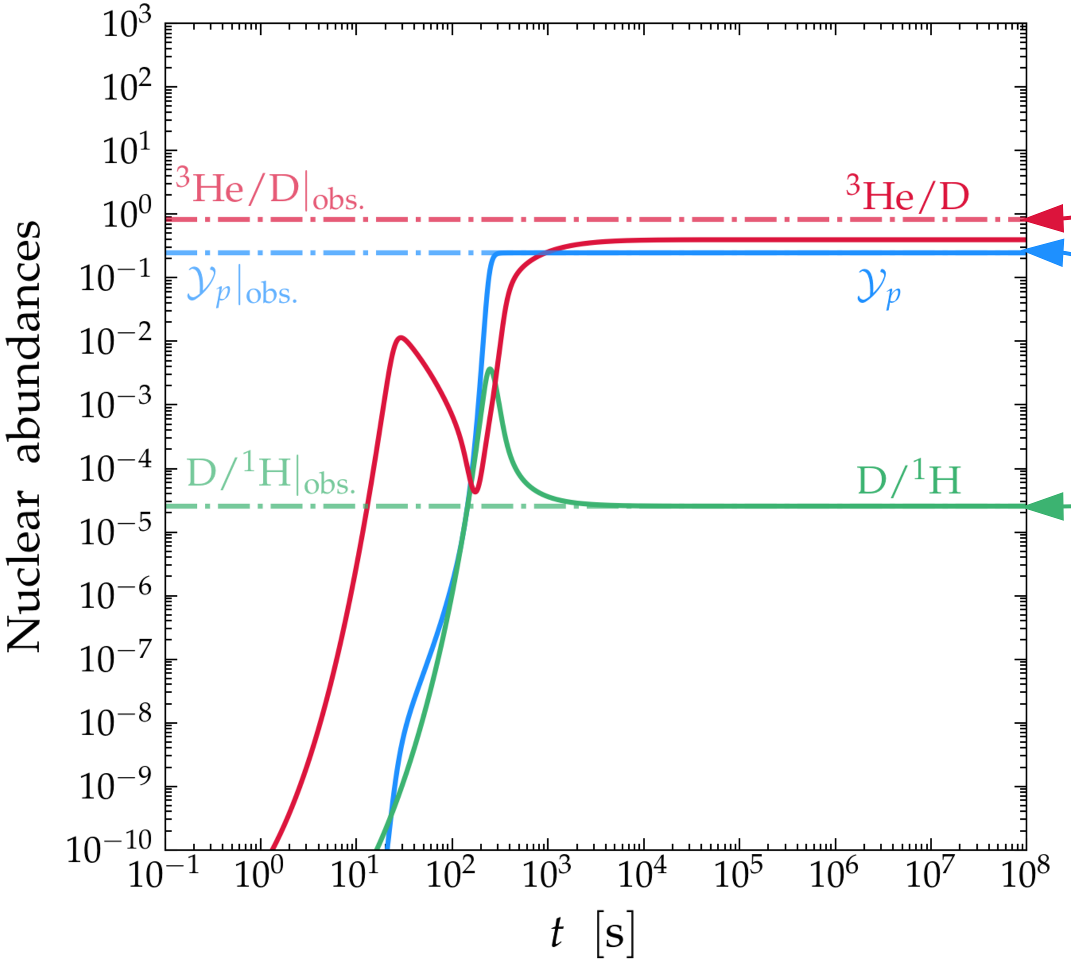
$^3\mathrm{He/D} = (8.3 \pm 1.5) \times 10^{-1}$

$\mathcal{Y}_p = (2.45 \pm 0.03) \times 10^{-1}$

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

Evolution of the abundances during BBN

Predictions



Observations

[PDG18], [Geiss03]

$^3\mathrm{He}/\mathrm{D} = (8.3 \pm 1.5) \times 10^{-1}$

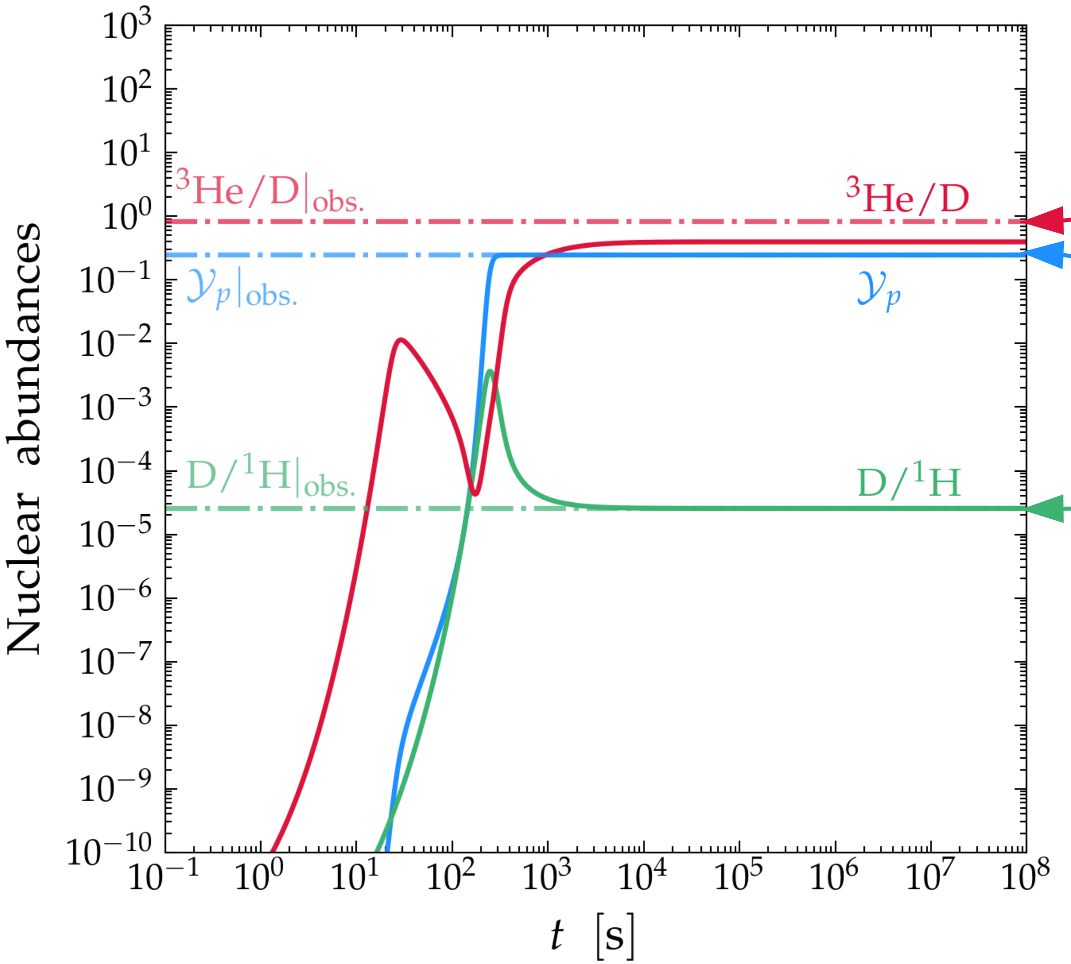
$\mathcal{Y}_p = (2.45 \pm 0.03) \times 10^{-1}$

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

Compatible within 1σ

Evolution of the abundances during BBN

Predictions



Observations

[PDG18], [Geiss03]

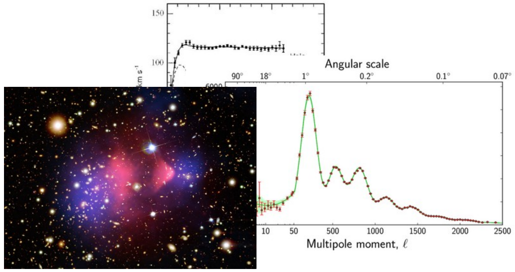
$^3\mathrm{He/D} = (8.3 \pm 1.5) \times 10^{-1}$

$\mathcal{Y}_p = (2.45 \pm 0.03) \times 10^{-1}$

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

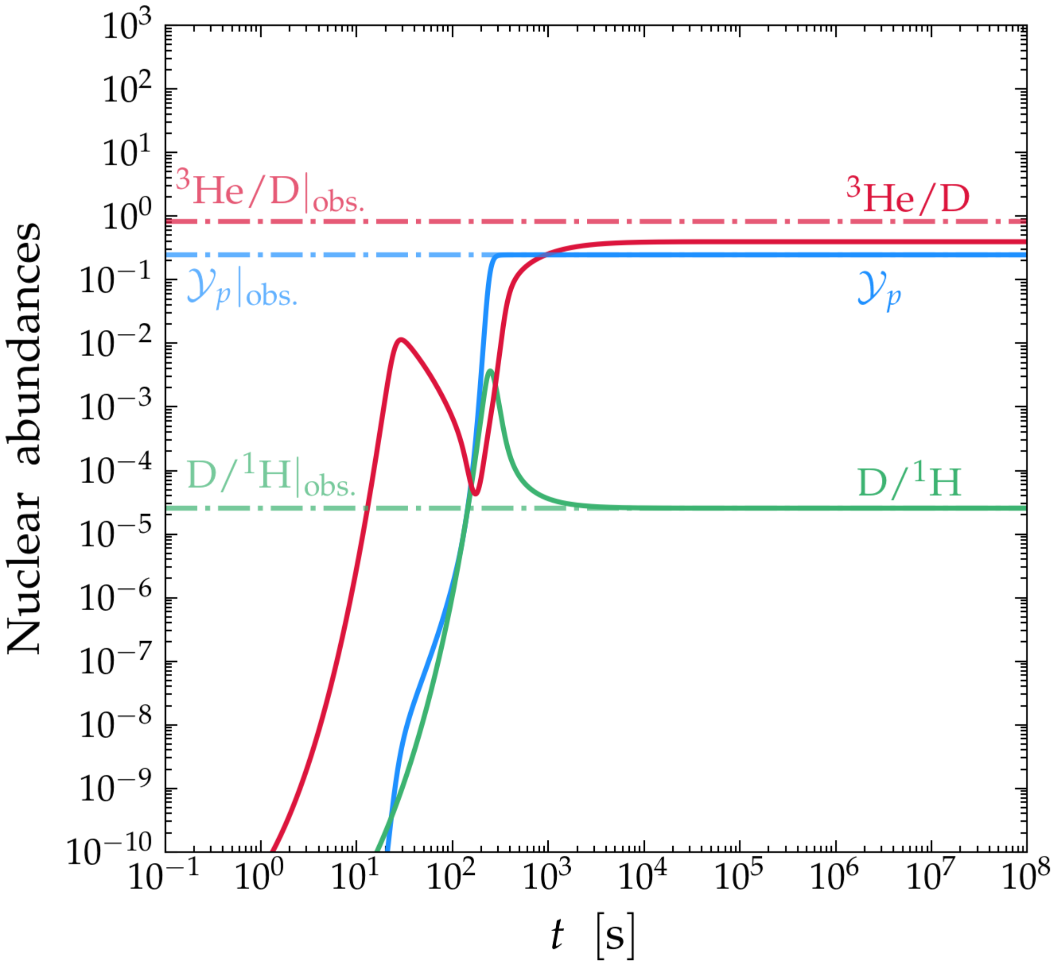
?

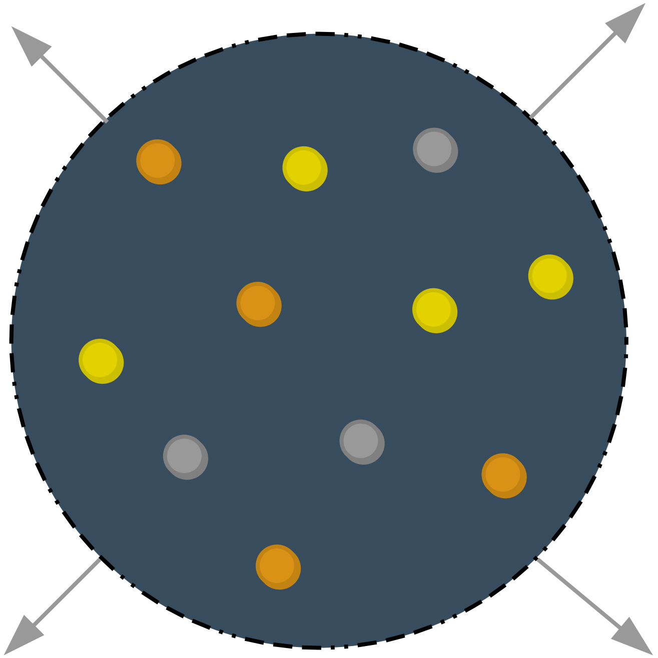
What happens in the presence of a dark sector?



Influence of additional dark-sector states

Predictions





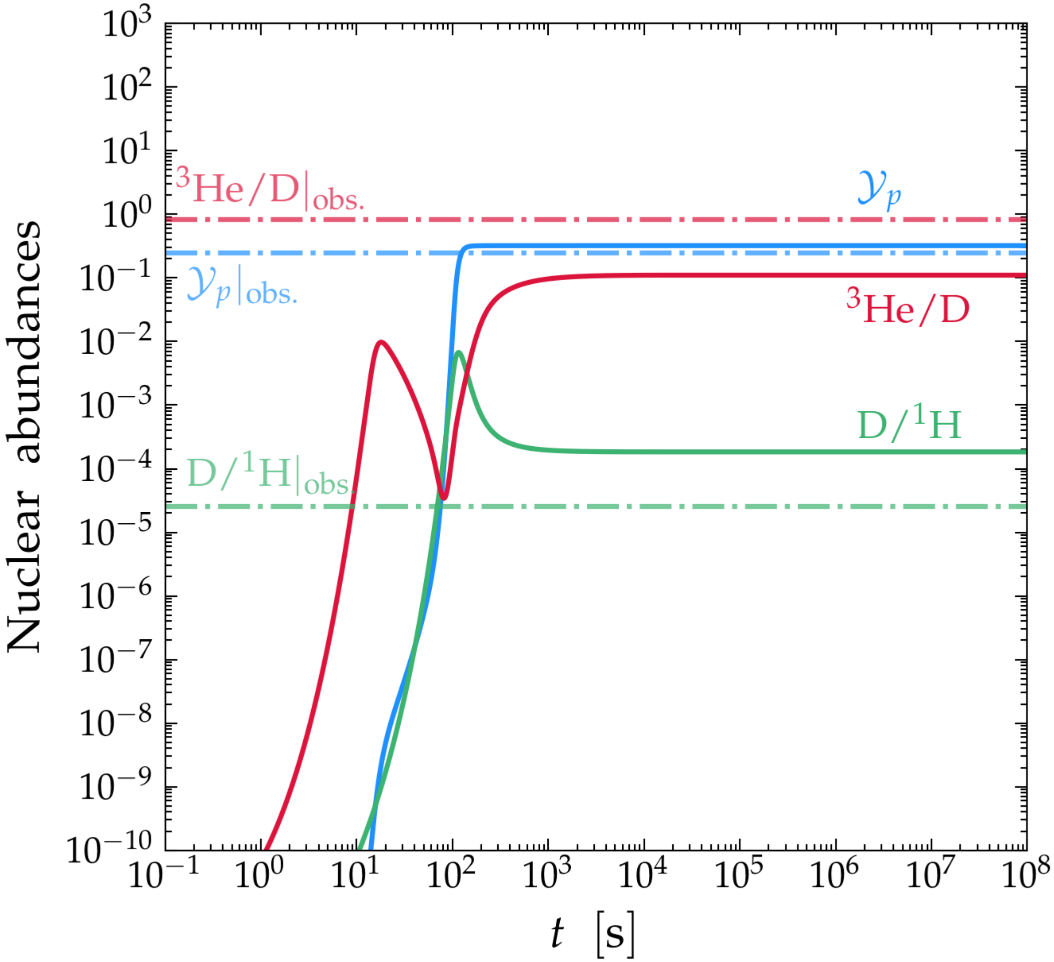
What happens in the presence of a dark sector?

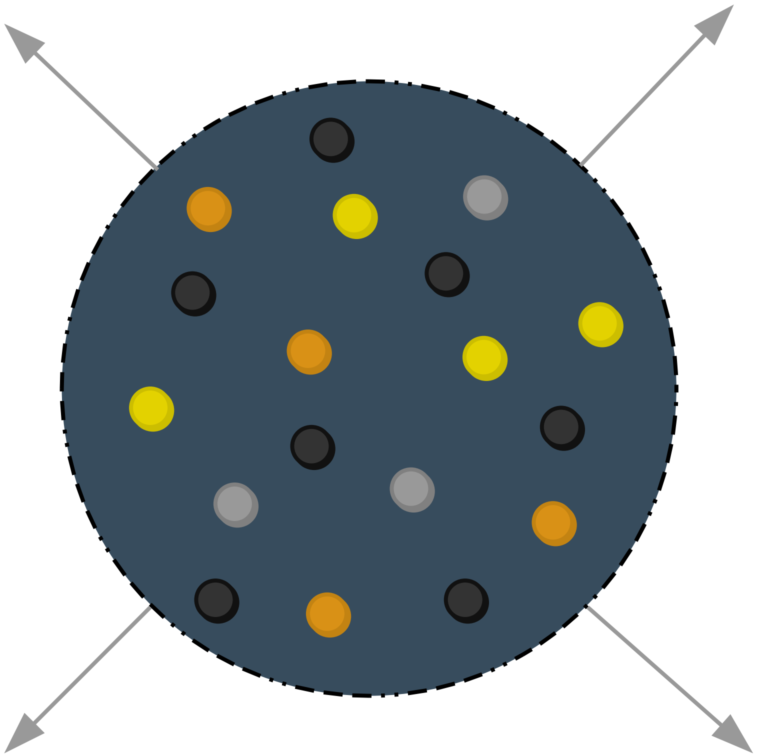
Hubble rate

$$\mathrm{d}T/\mathrm{d}t \sim H \qquad \text{with} \qquad H \propto [\rho_{\mathrm{sm}} + \rho_{\mathrm{dark}}]^{1/2}$$

Influence of additional dark-sector states

Predictions



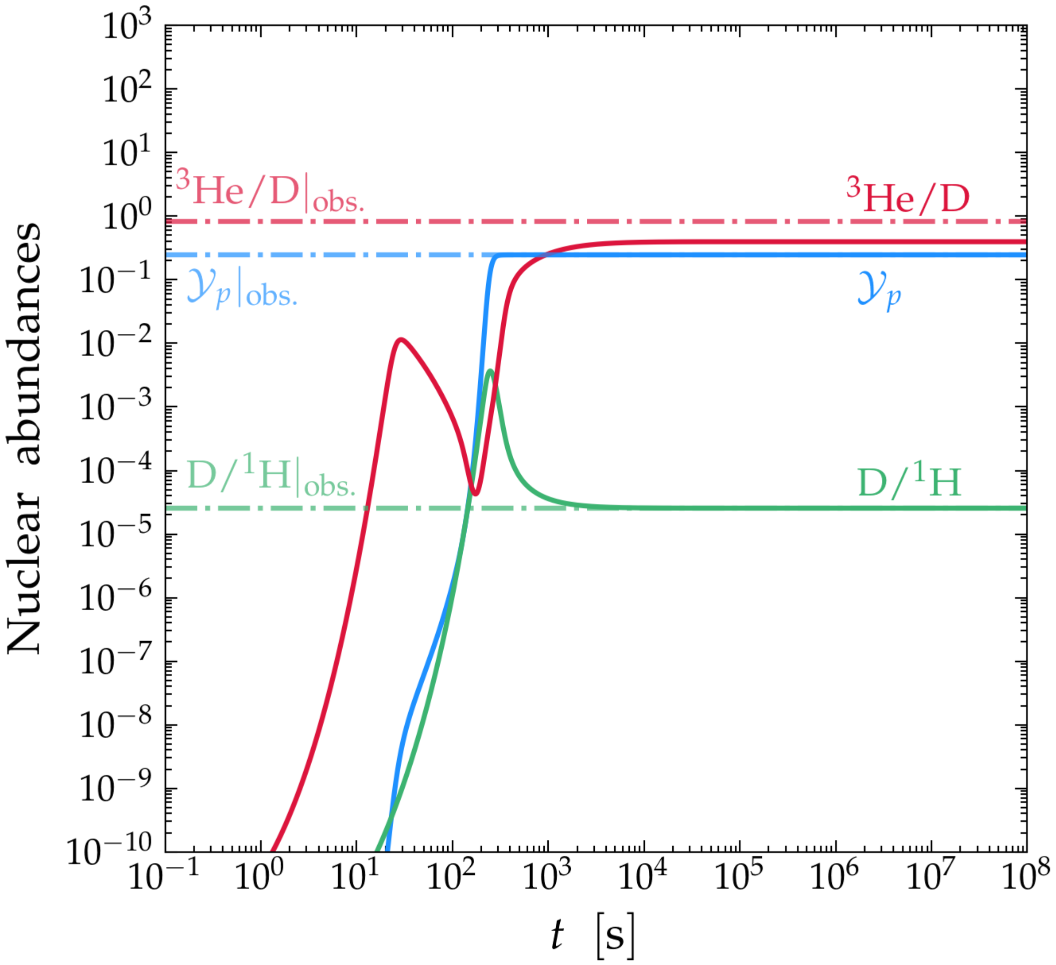


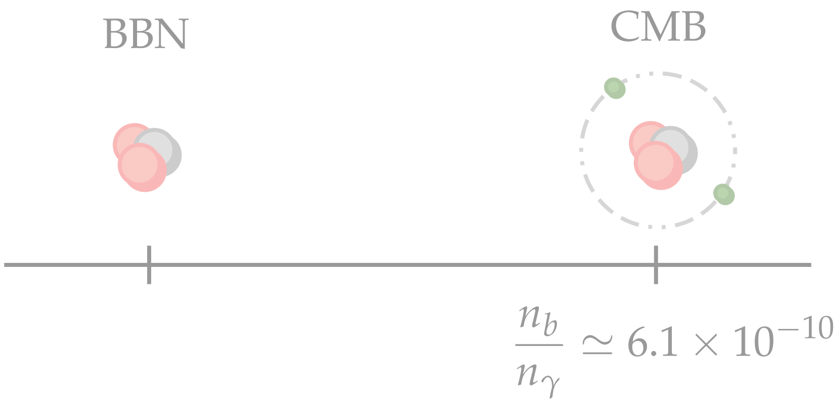
What happens in the presence of a dark sector?

Hubble rate $\mathrm{d}T/\mathrm{d}t \sim H$ with $H \propto [\rho_{\mathrm{sm}} + \rho_{\mathrm{dark}}]^{1/2}$

Influence of additional dark-sector states

Predictions





$$\frac{n_b}{n_\gamma} \simeq 6.1 \times 10^{-10}$$

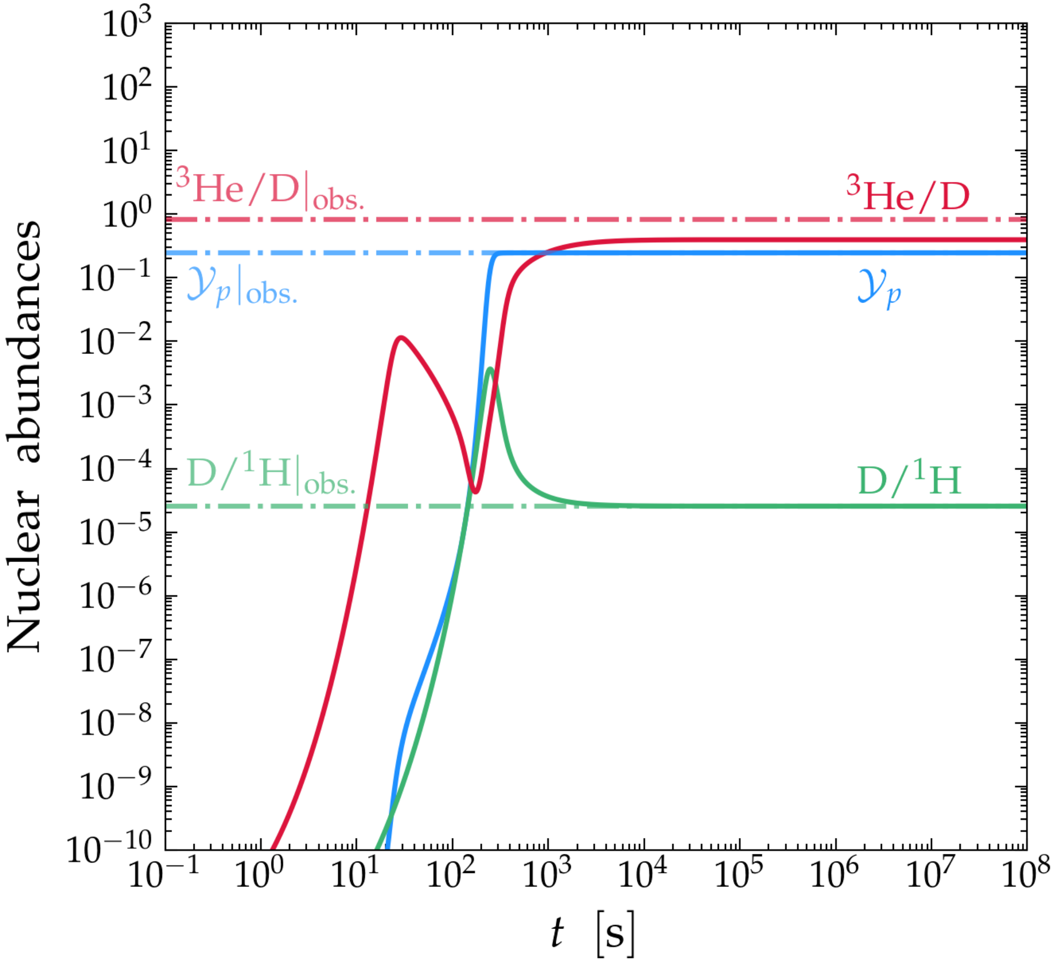
What happens in the presence of a dark sector?

Entropy

$$\dot{S}_{\mathrm{sm}} \neq 0 \quad : \quad \mathrm{d}T/\mathrm{d}t = -\left(\dot{q}_{\mathrm{dark}} + 3H\left[\rho_{\mathrm{sm}} + P_{\mathrm{sm}}\right]\right)/\rho'_{\mathrm{sm}}$$

Influence of additional dark-sector states

Predictions



$$\frac{n_b}{n_\gamma} \simeq 6.1 \times 10^{-10}$$

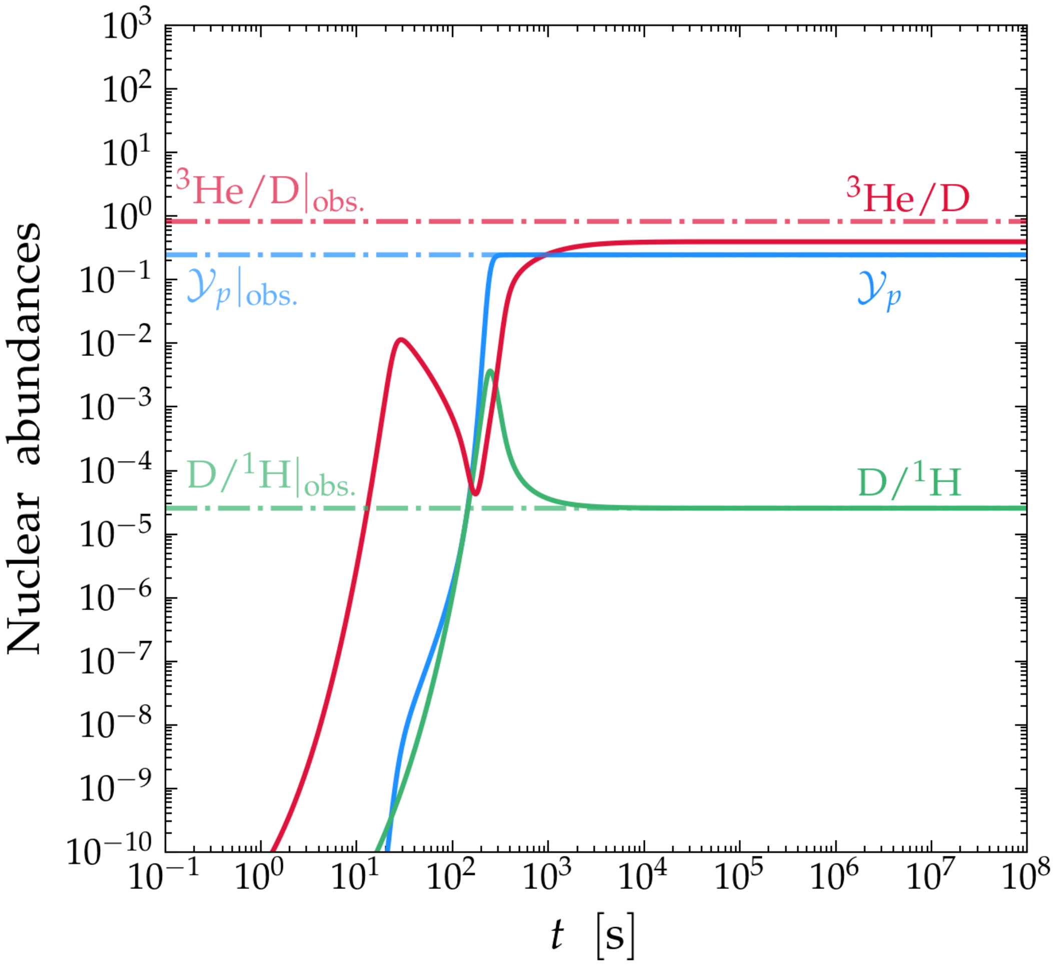
What happens in the presence of a dark sector?

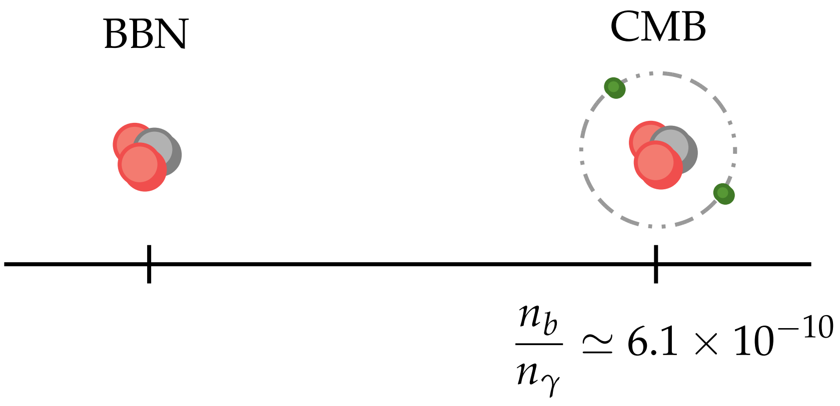
Entropy

$$\dot{S}_{\rm sm} \neq 0 \quad : \quad \mathrm{d}T/\mathrm{d}t = -\left(\dot{q}_{\rm dark} + 3H\left[\rho_{\rm sm} + P_{\rm sm}\right]\right)/\rho'_{\rm sm}$$

Influence of additional dark-sector states

Predictions





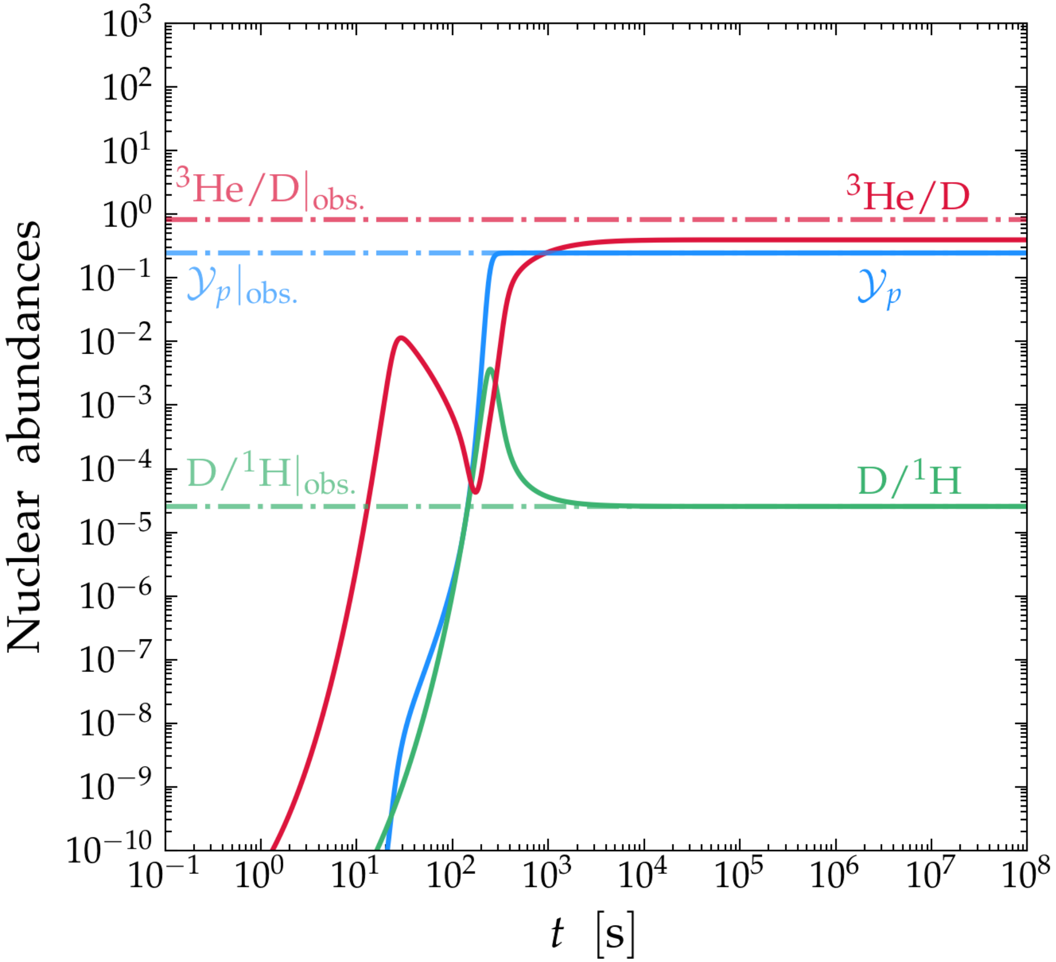
What happens in the presence of a dark sector?

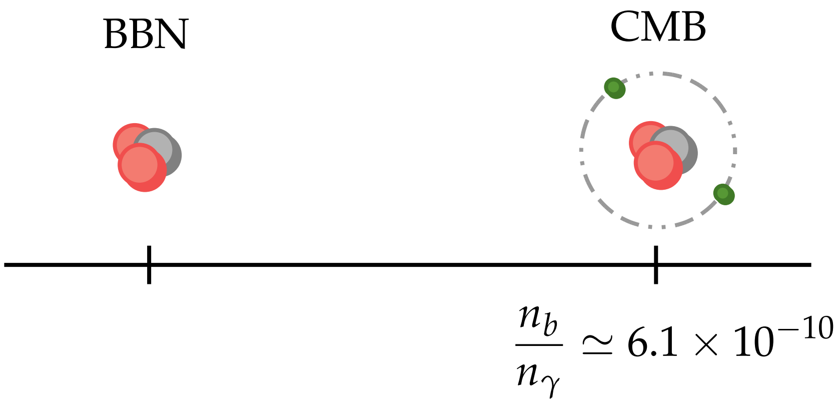
Entropy

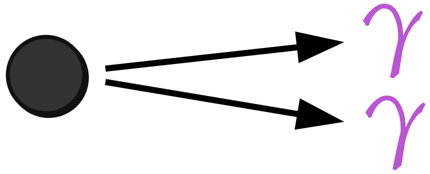
$$\dot{S}_{\mathrm{sm}} \neq 0 \quad : \quad \mathrm{d}T/\mathrm{d}t = -\left(\dot{q}_{\mathrm{dark}} + 3H\left[\rho_{\mathrm{sm}} + P_{\mathrm{sm}}\right]\right)/\rho'_{\mathrm{sm}}$$

Influence of additional dark-sector states

Predictions







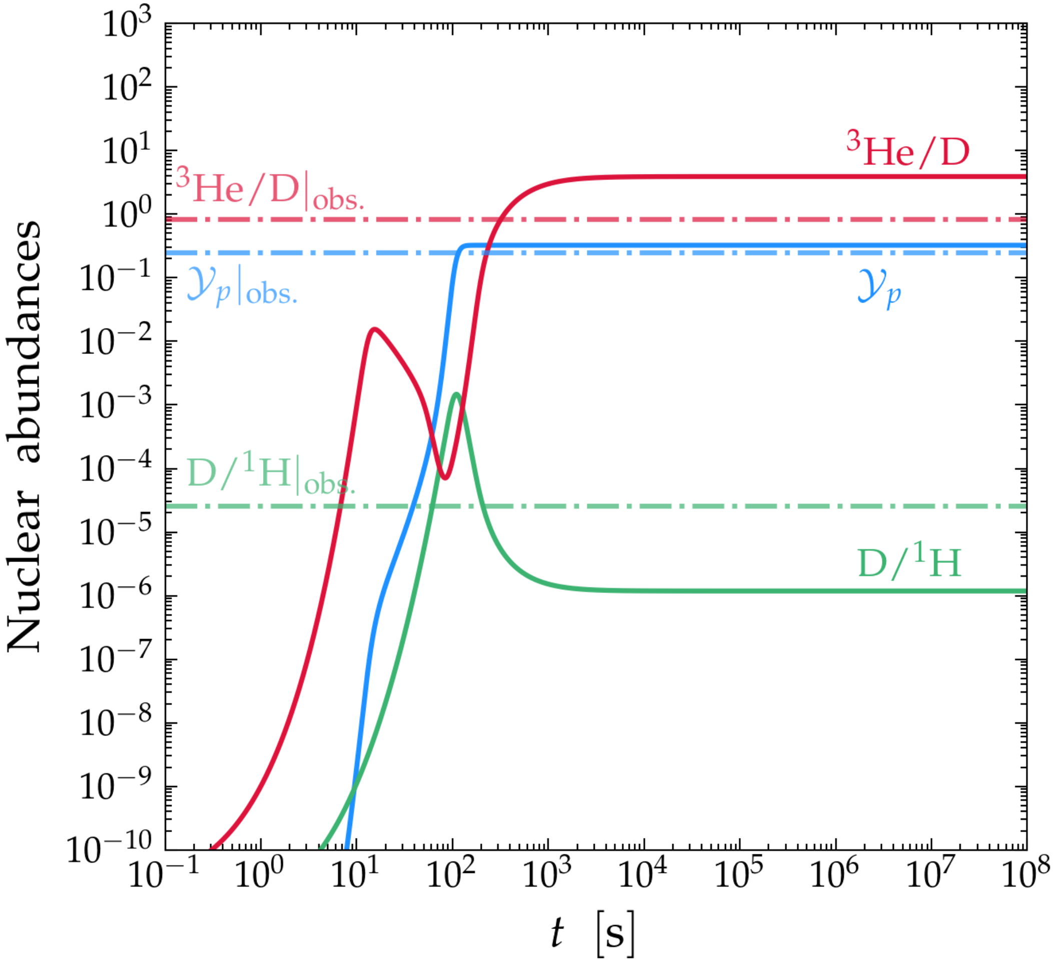
What happens in the presence of a dark sector?

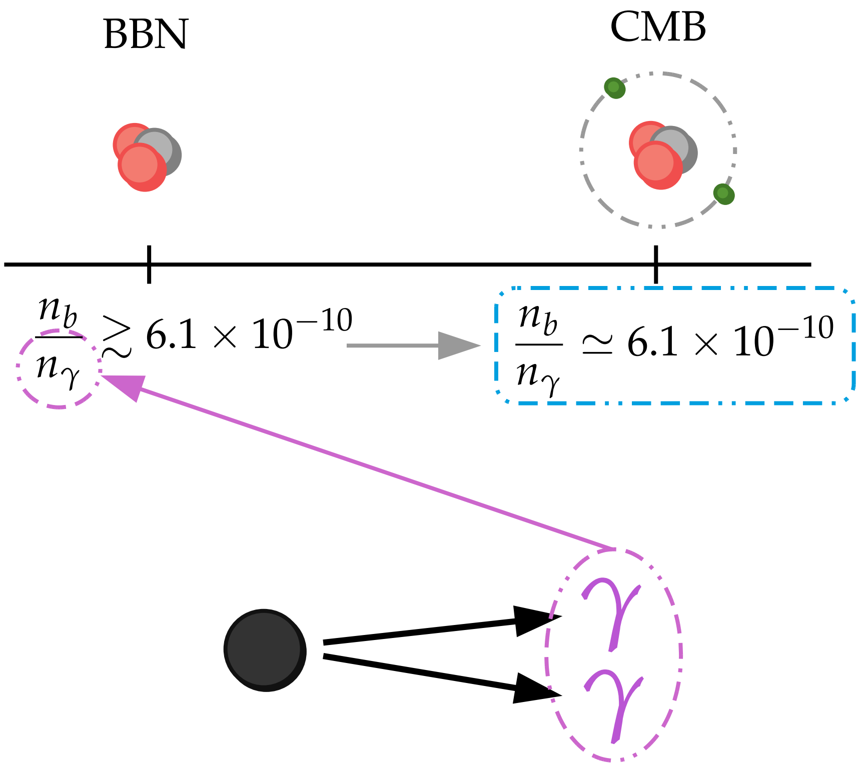
Entropy

$$\dot{S}_{\text{sm}} \neq 0 \quad : \quad \mathrm{d}T/\mathrm{d}t = -\left(\dot{q}_{\text{dark}} + 3H\left[\rho_{\text{sm}} + P_{\text{sm}}\right]\right)/\rho'_{\text{sm}}$$

Influence of additional dark-sector states

Predictions




BBN

CMB

$\frac{n_b}{n_\gamma} \gtrsim 6.1 \times 10^{-10}$

$\frac{n_b}{n_\gamma} \simeq 6.1 \times 10^{-10}$

$\mathrm{d}(\mathrm{D}/^{1}\mathrm{H})/\mathrm{d}\eta < 0$

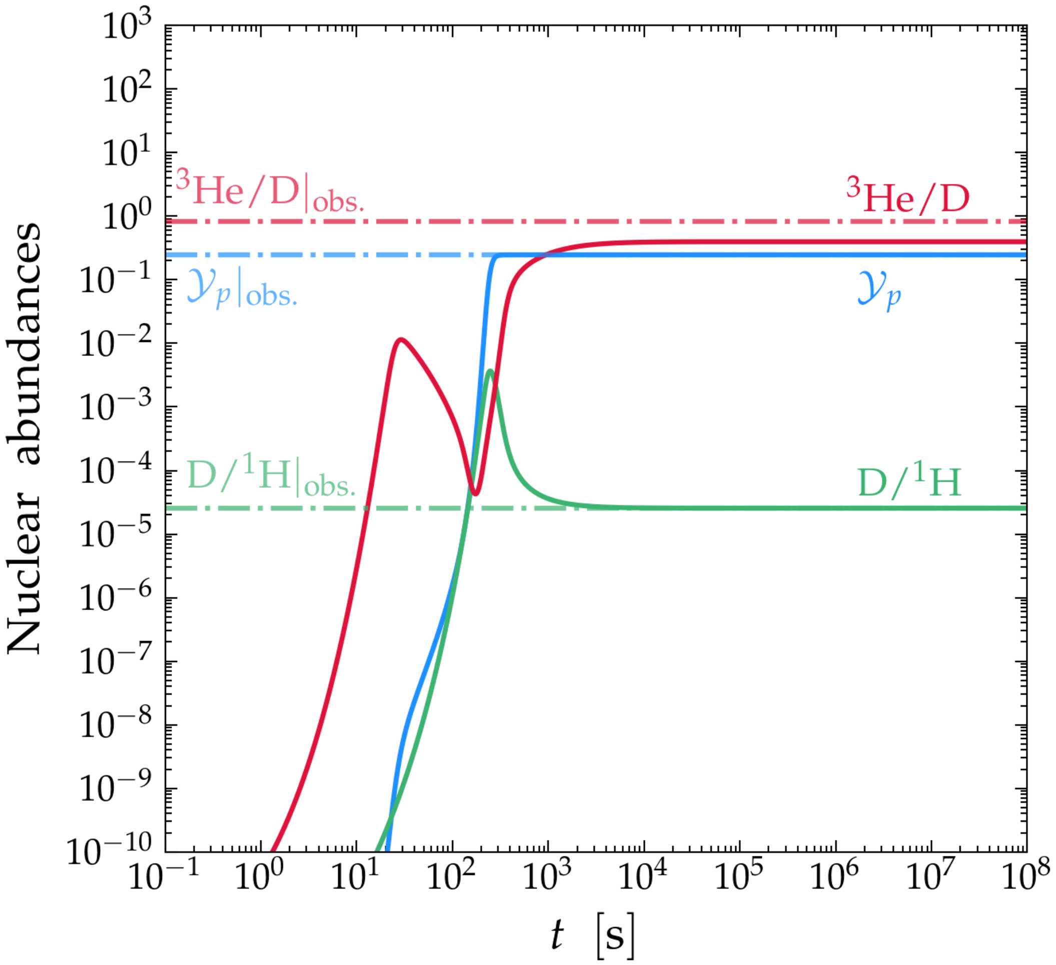
What happens in the presence of a dark sector?

Entropy

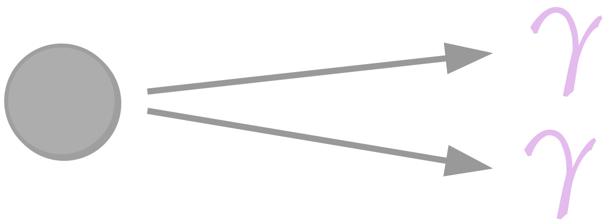
$\dot{S}_{\mathrm{sm}} \neq 0 \quad : \quad \mathrm{d}T/\mathrm{d}t = -\left(\dot{q}_{\mathrm{dark}} + 3H\left[\rho_{\mathrm{sm}} + P_{\mathrm{sm}}\right]\right)/\rho'_{\mathrm{sm}}$

Influence of additional dark-sector states

Predictions



$m_{\text{dark}} \sim E_\gamma \sim \mathcal{O}(\text{MeV})$



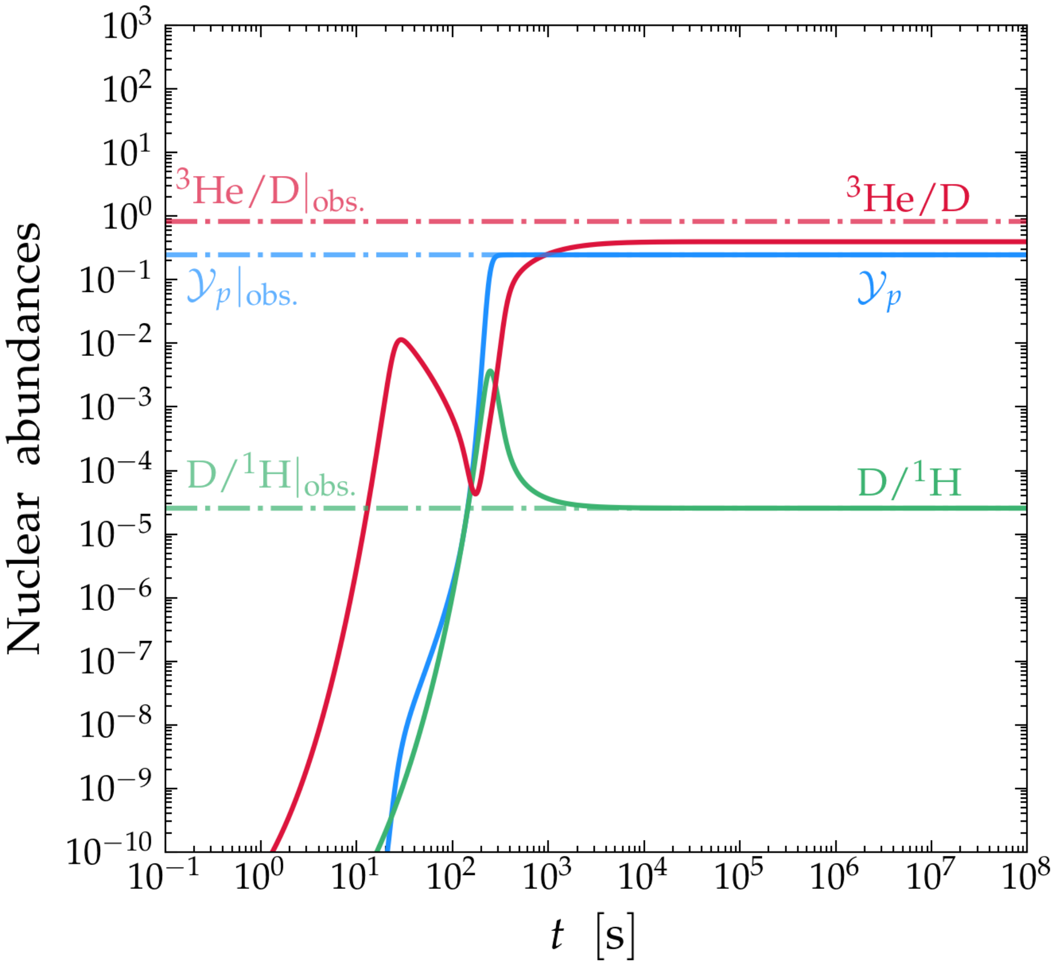
What happens in the presence of a dark sector?

Photodis.

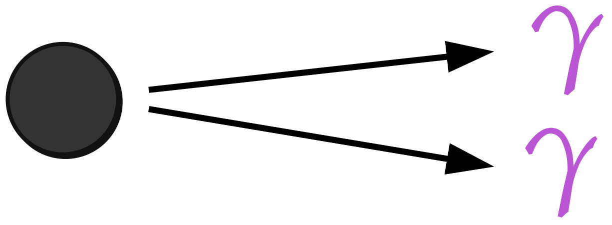
$$\text{DS} \to \gamma\gamma/e^+e^- \quad : \quad \text{D}\gamma \to pn\,, \ldots$$

Influence of additional dark-sector states

Predictions



$m_{\mathrm{dark}} \sim E_\gamma \sim \mathcal{O}(\mathrm{MeV})$



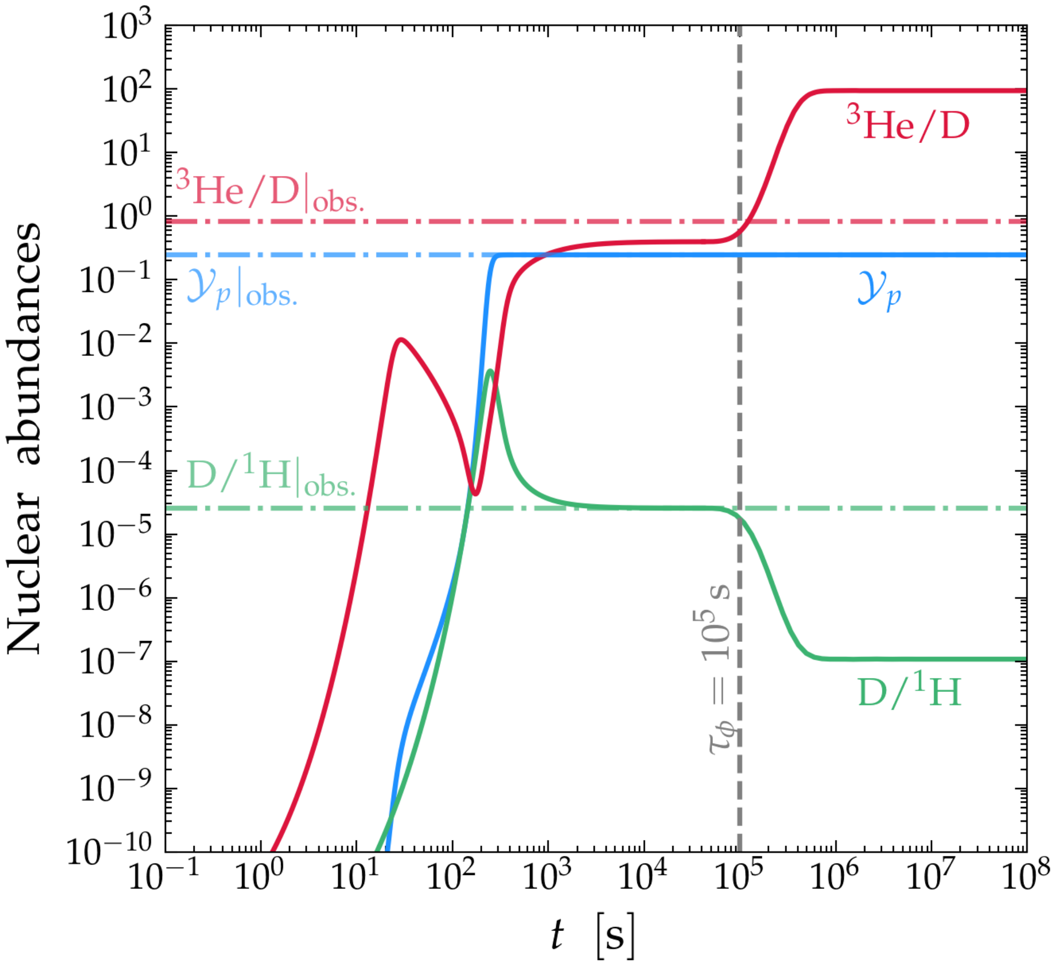
What happens in the presence of a dark sector?

Photodis.

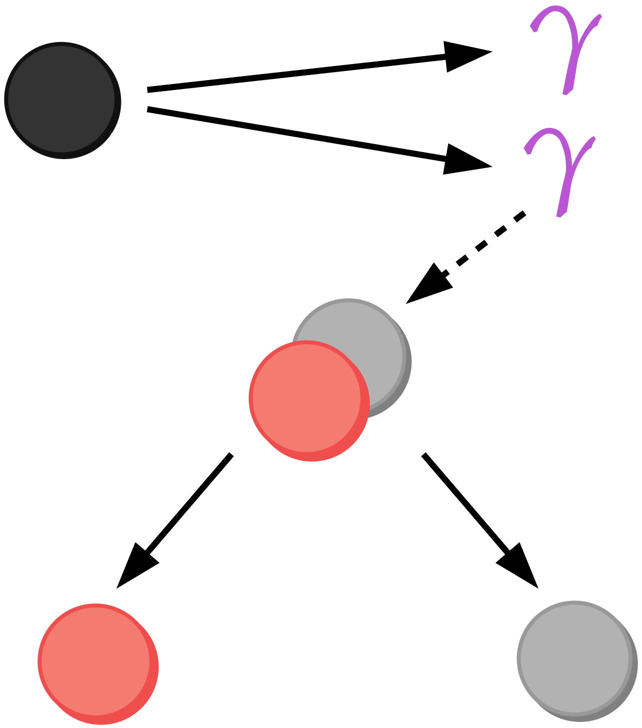
$\mathrm{DS} \to \gamma\gamma / e^+e^- \quad : \quad \mathrm{D}\gamma \to pn\,, \ldots$

Influence of additional dark-sector states

Predictions



$m_{\mathrm{dark}} \sim E_\gamma \sim \mathcal{O}(\mathrm{MeV})$

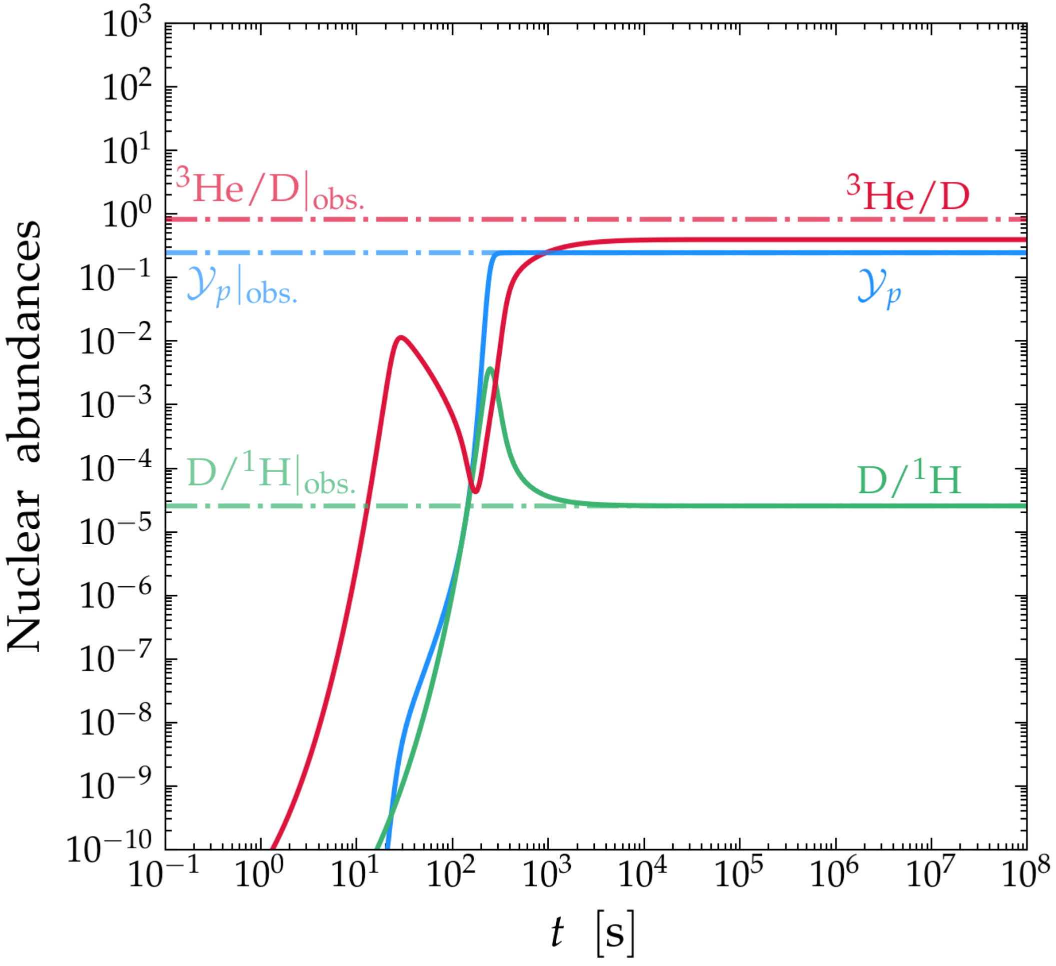


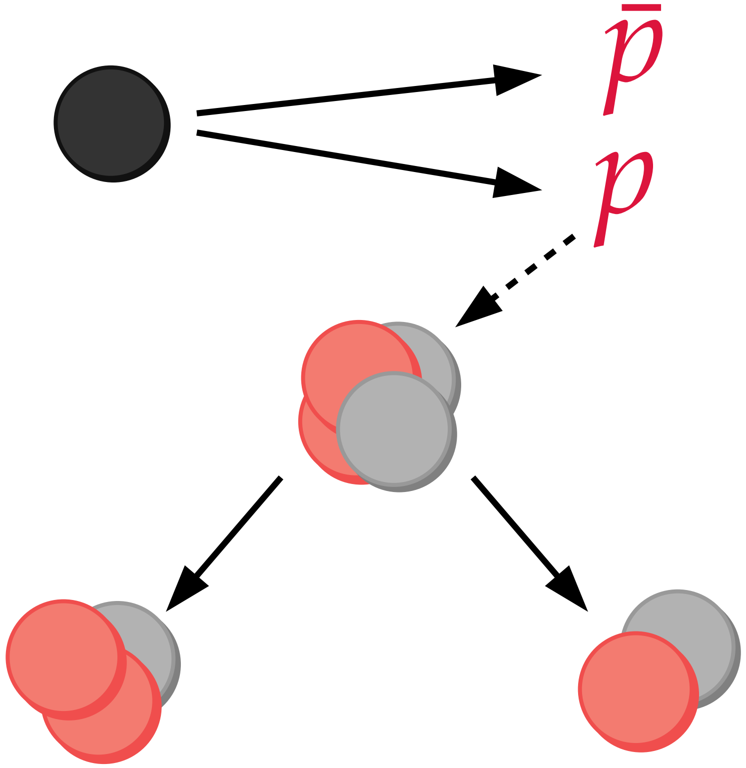
What happens in the presence of a dark sector?

Photodis. $\mathrm{DS} \to \gamma\gamma / e^+e^-$: $\mathrm{D}\gamma \to pn\,, \ldots$

Influence of additional dark-sector states

Predictions





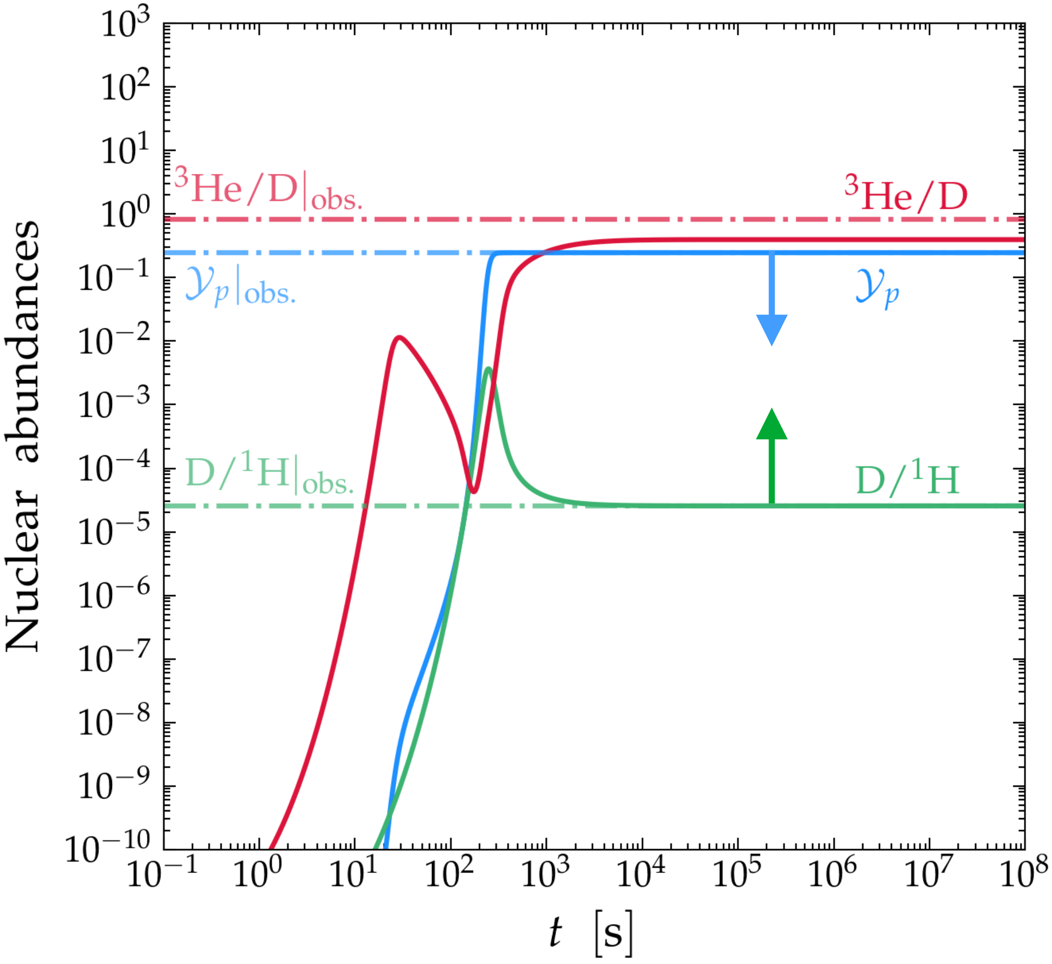
What happens in the presence of a dark sector?

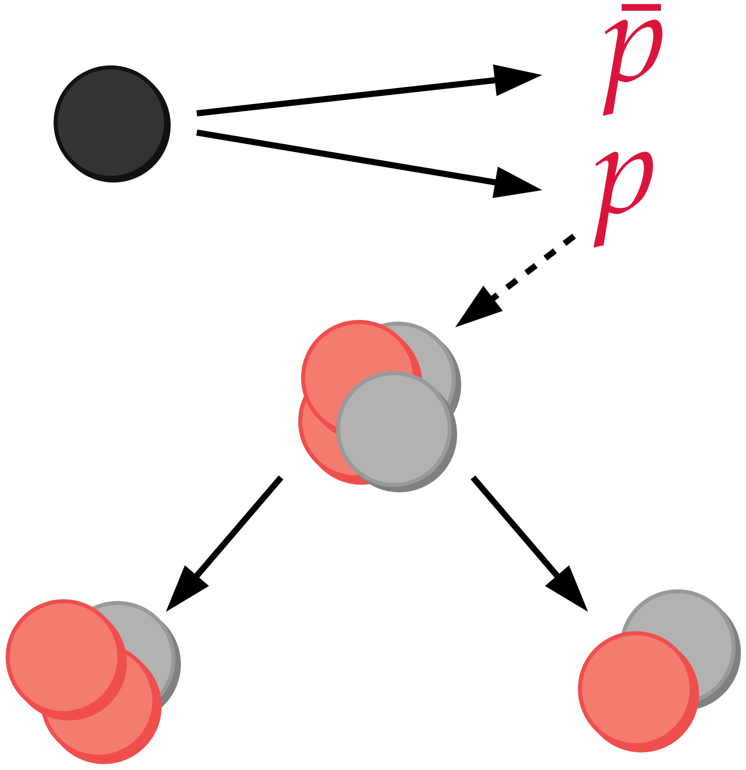
Hadrodis.

$$\mathrm{DS} \to h\bar{h} \quad : \quad {}^4\mathrm{He} + p \to {}^3\mathrm{He} + \mathrm{D}\,, \ldots$$

Influence of additional dark-sector states

Predictions





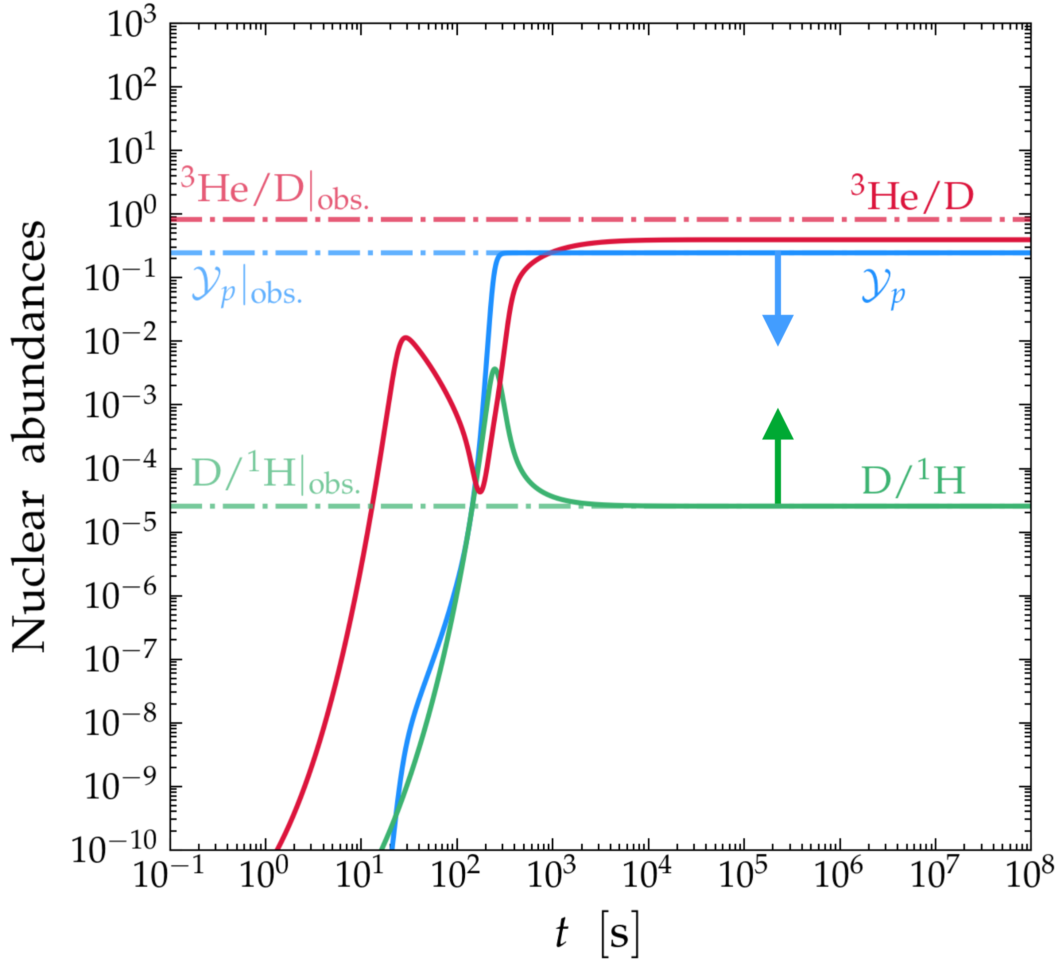
What happens in the presence of a dark sector?

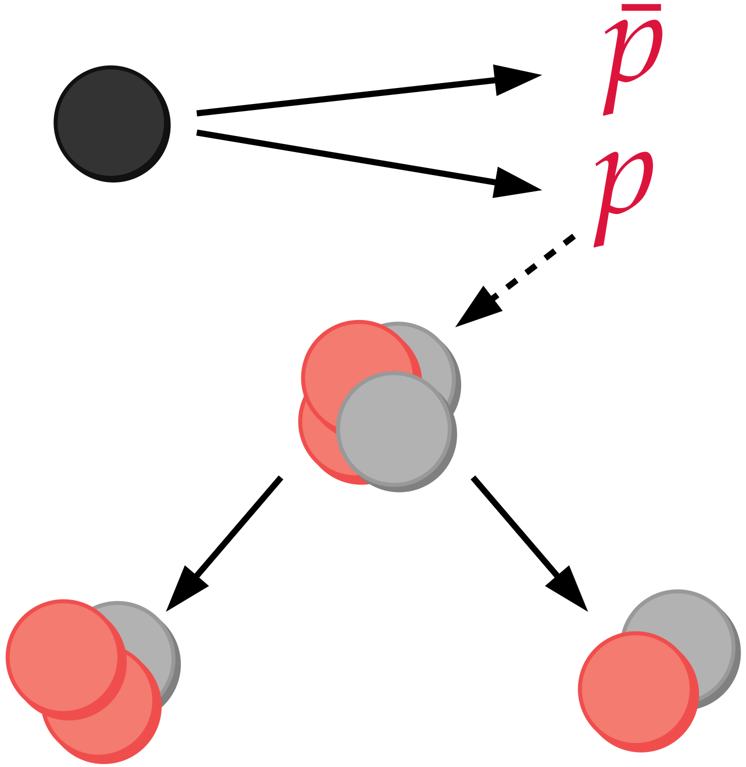
Hadrodis.

$$\text{DS} \to h\bar{h} \quad : \quad {}^4\text{He} + p \to {}^3\text{He} + \text{D}\,, \ldots$$

Influence of additional dark-sector states

Predictions



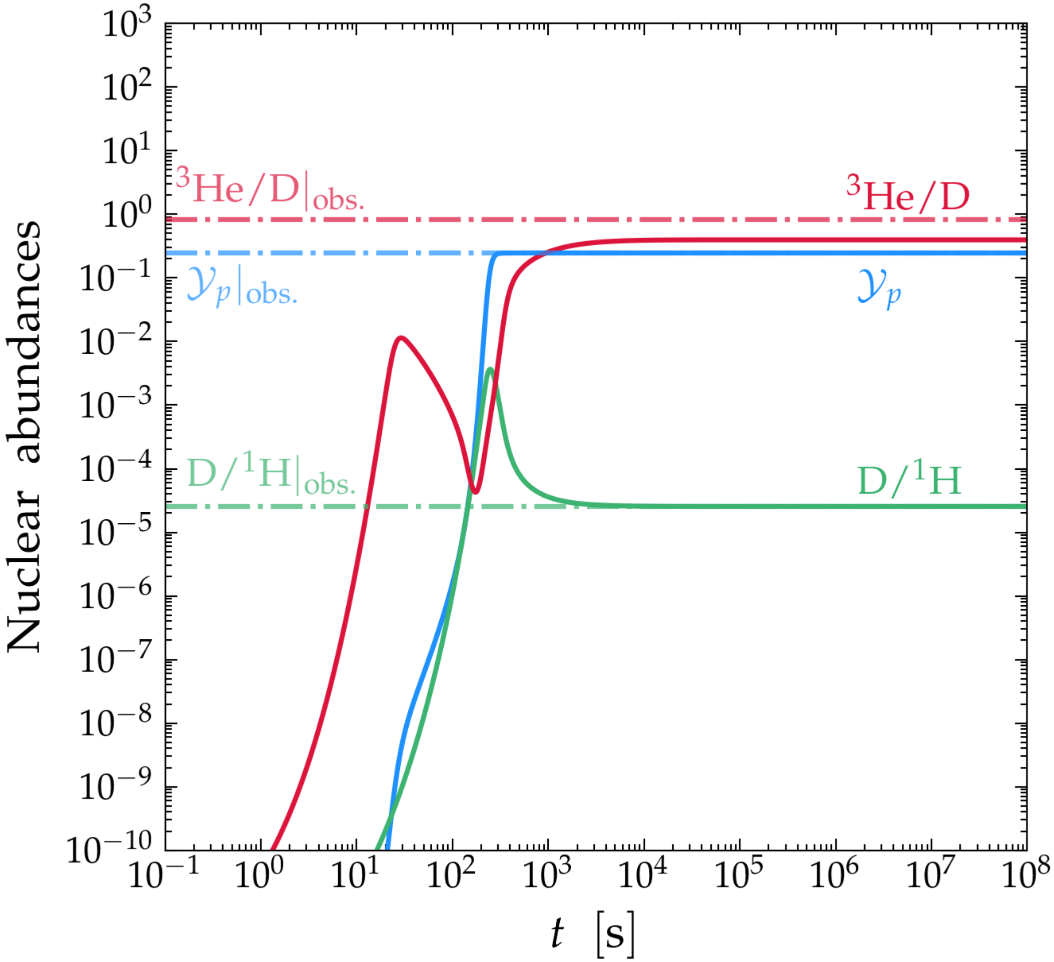


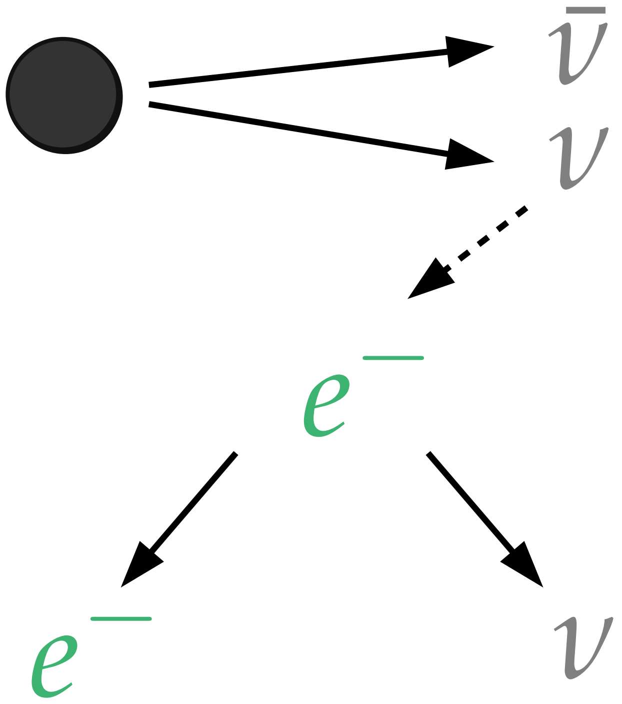
What happens in the presence of a dark sector?

Hadrodis. $\mathrm{DS} \to h\bar{h} \quad : \quad h \in \{p, n, \pi, K, \dots\}$

Influence of additional dark-sector states

Predictions



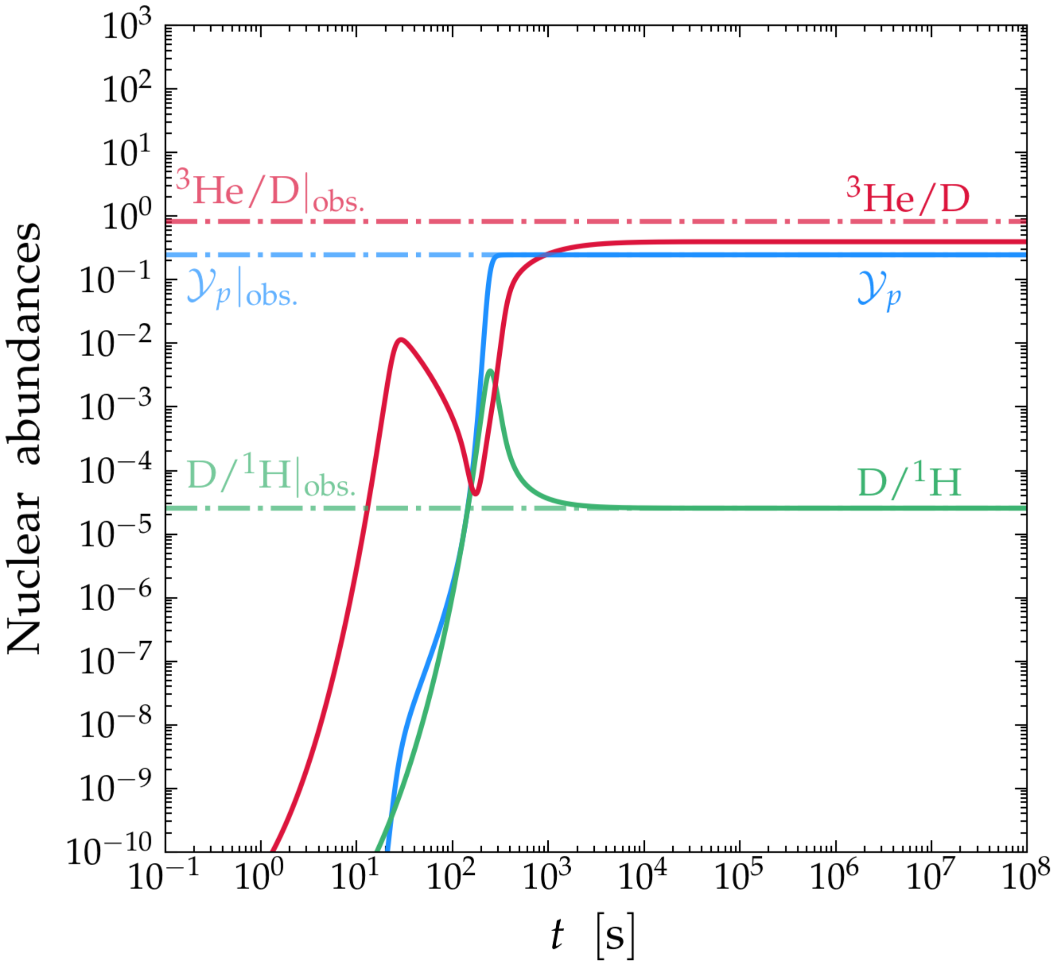


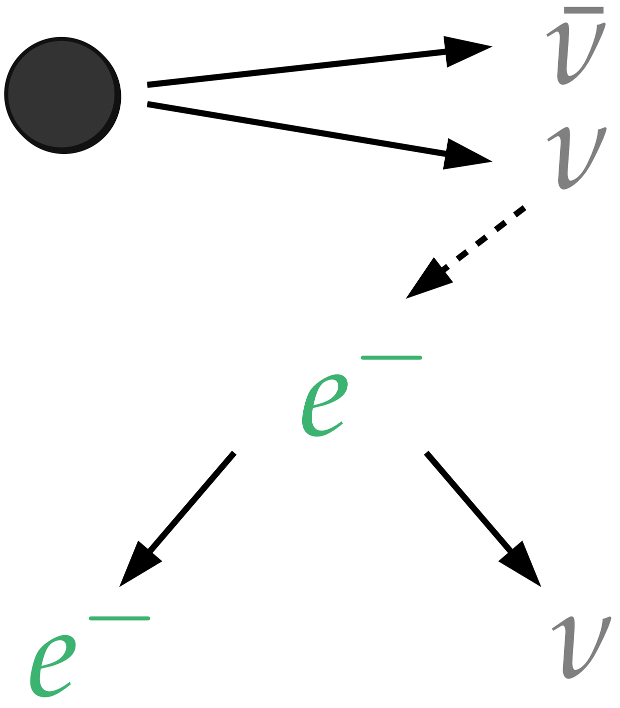
What happens in the presence of a dark sector?

ν dec.

Influence of additional dark-sector states

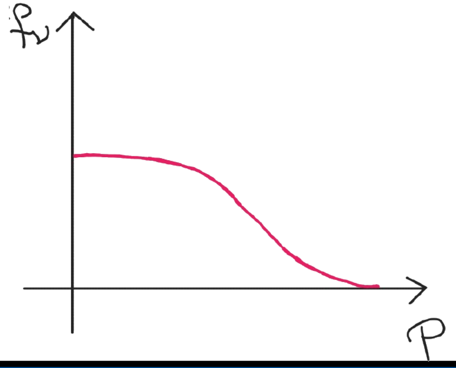
Predictions





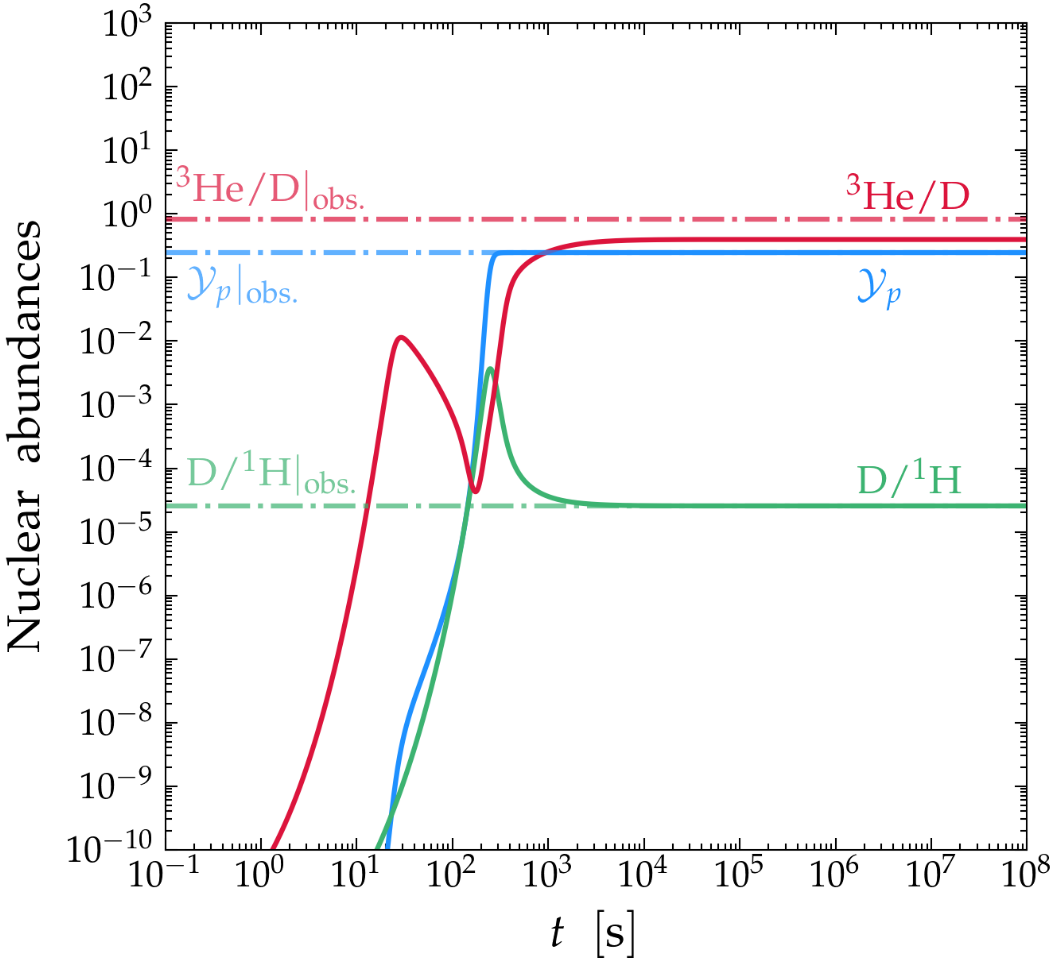
What happens in the presence of a dark sector?

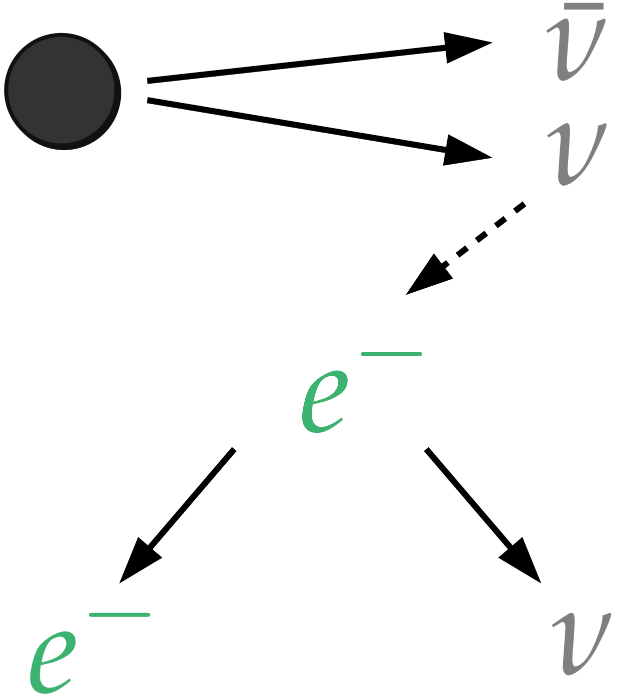
ν dec.

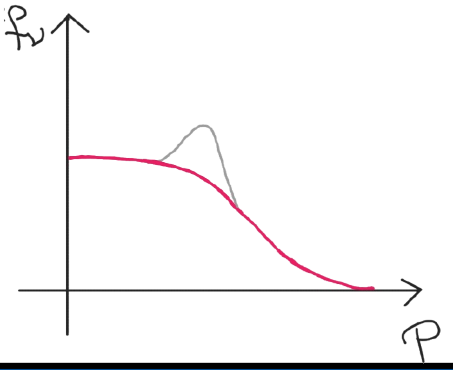


Influence of additional dark-sector states

Predictions





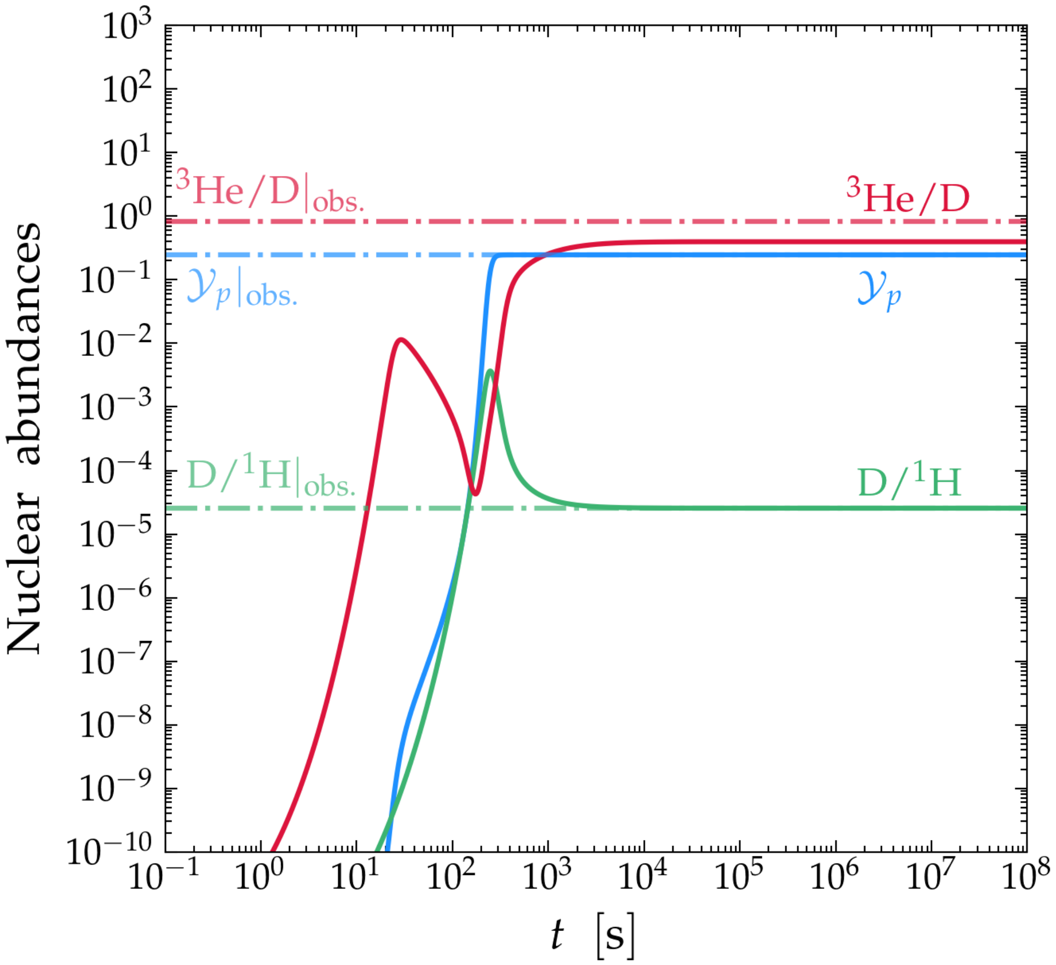


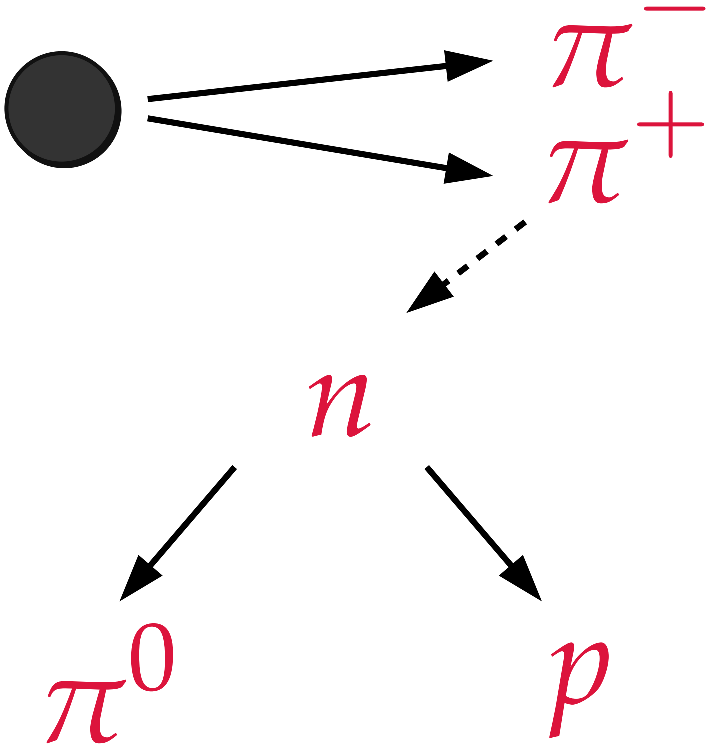
What happens in the presence of a dark sector?

ν dec.

Influence of additional dark-sector states

Predictions





$$\mathcal{Y}_p \simeq \frac{2(n/p)}{1+(n/p)}$$

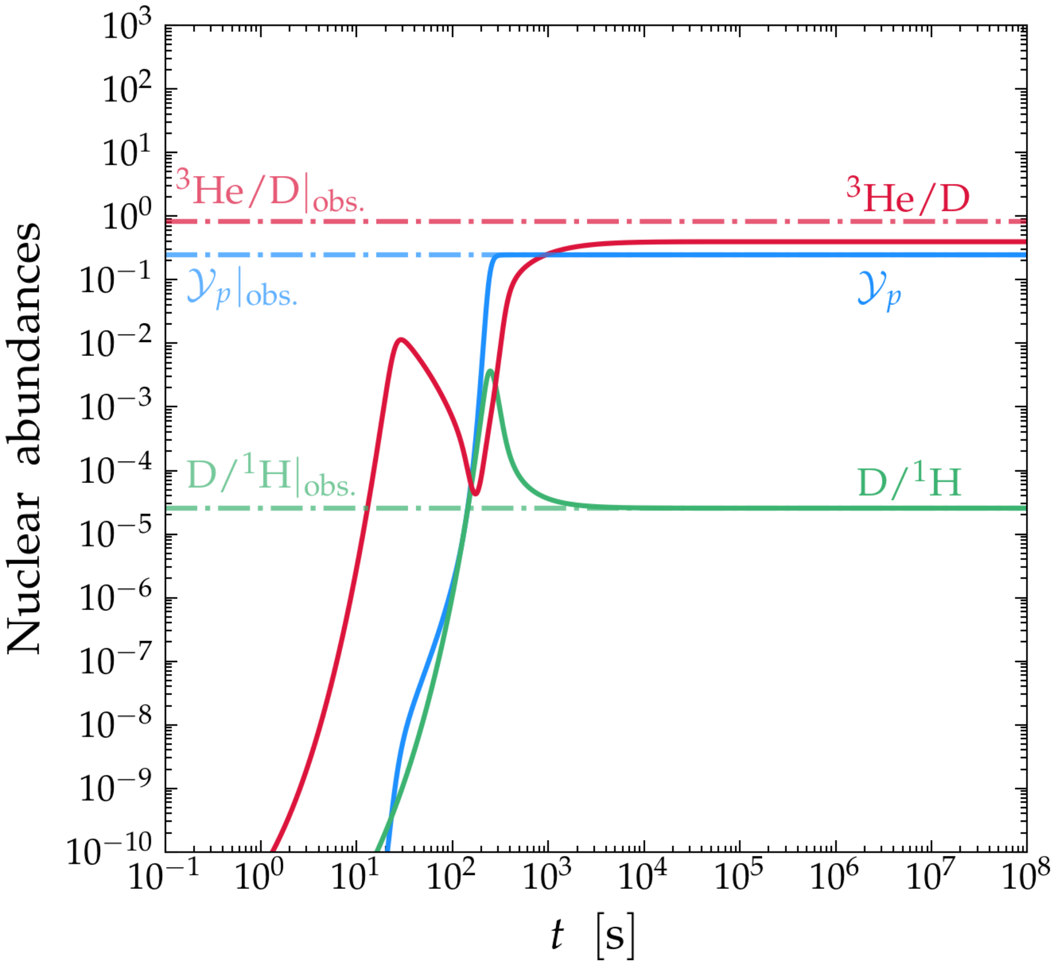
What happens in the presence of a dark sector?

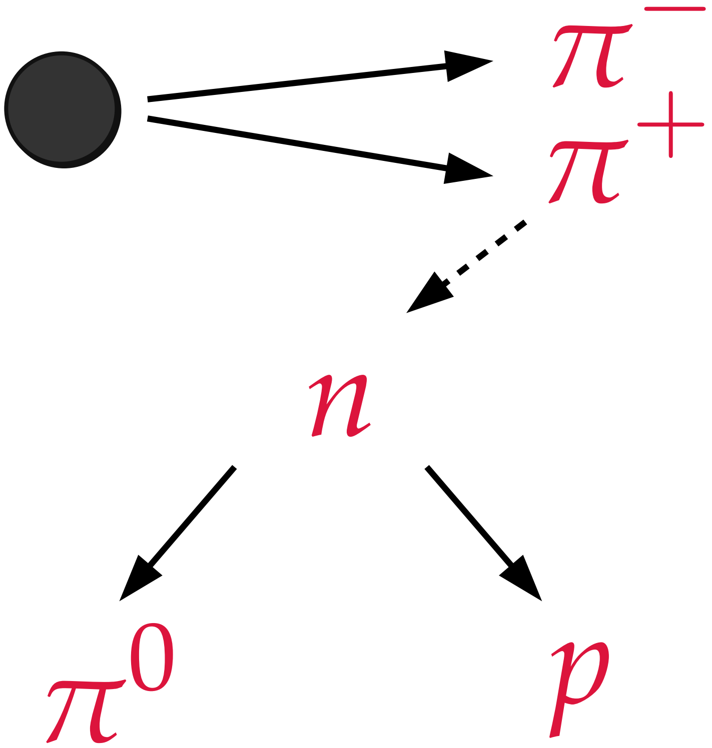
ν dec.

$n-p$ conv.

Influence of additional dark-sector states

Predictions





What happens in the presence of a dark sector?

ν dec.

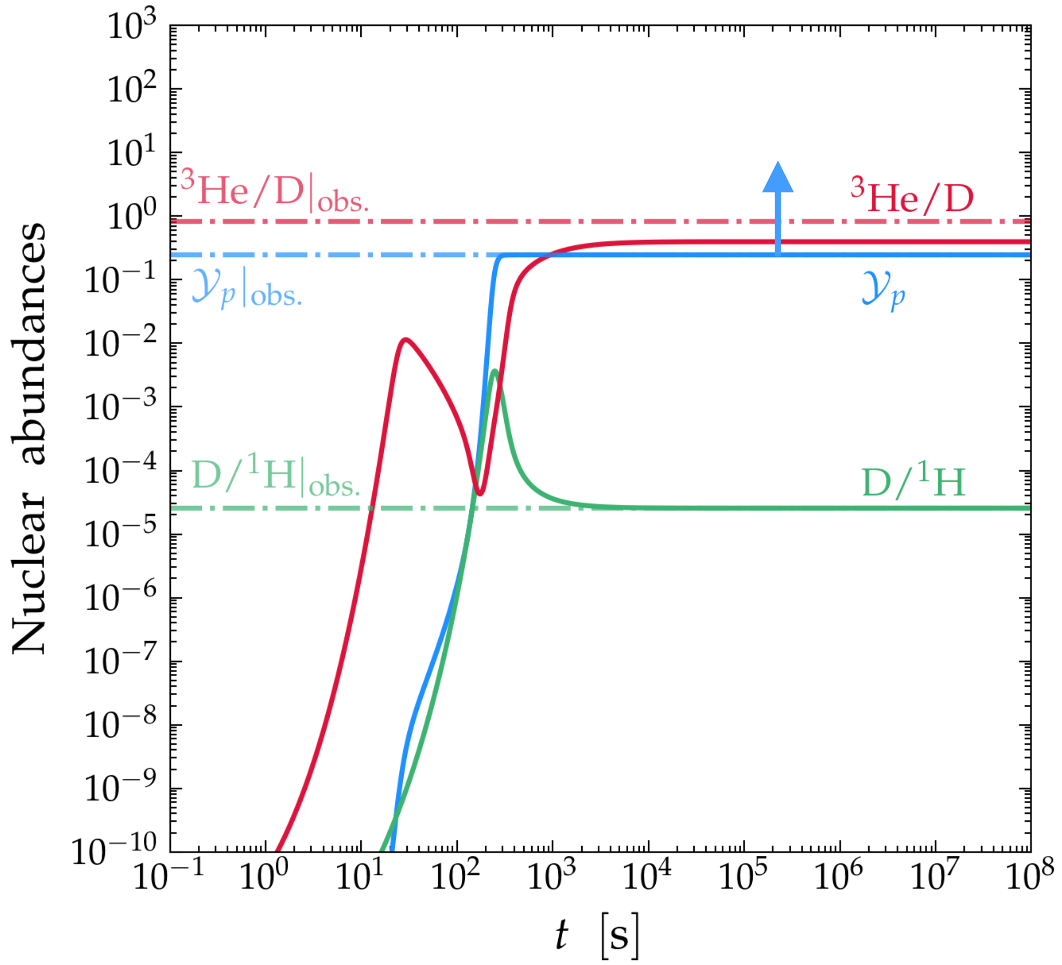
$n - p$ conv.

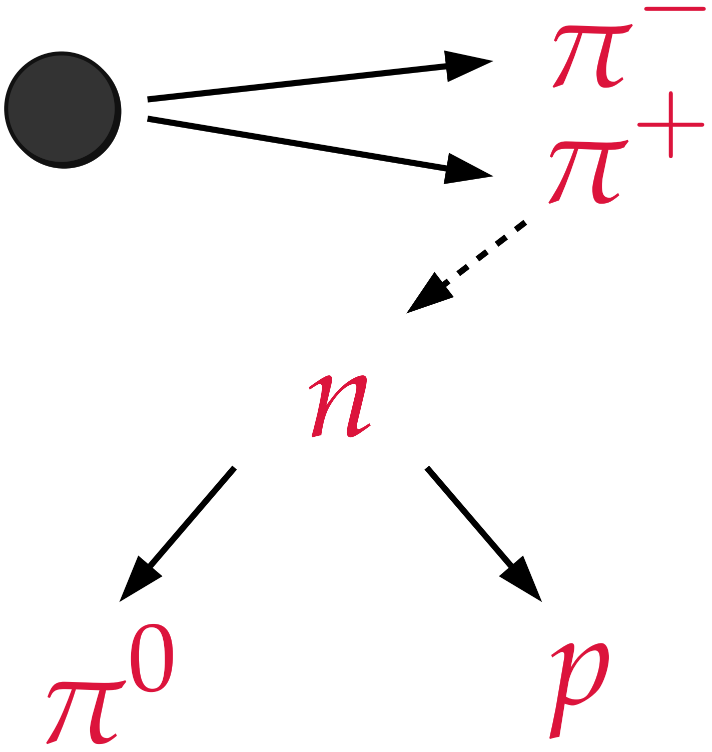
$$\mathcal{Y}_p \simeq \frac{2(n/p)}{1 + \boxed{(n/p)}}$$

$$(n/p) \sim 1/7 \to 1$$

Influence of additional dark-sector states

Predictions





What happens in the presence of a dark sector?

ν dec.

$n - p$ conv.

$$\mathcal{Y}_p \simeq \frac{2(n/p)}{1 + \boxed{(n/p)}}$$

$$(n/p) \sim 1/7 \to 1$$

Solution Strategy

Evolution of nuclei

$$\frac{\mathrm{d}Y_X}{\mathrm{d}T} = \frac{\mathrm{d}t}{\mathrm{d}T} \times \sum_{r \in \mathcal{R}_X} \pm \Gamma_r \prod_{i \in \mathcal{I}_r} Y_i$$

Solution Strategy

Evolution of nuclei

$$\frac{\mathrm{d}Y_X}{\mathrm{d}T} = \frac{\mathrm{d}t}{\mathrm{d}T} \times \sum_{r \in \mathcal{R}_X} \pm\Gamma_r \prod_{i \in \mathcal{I}_r} Y_i$$

Solution Strategy

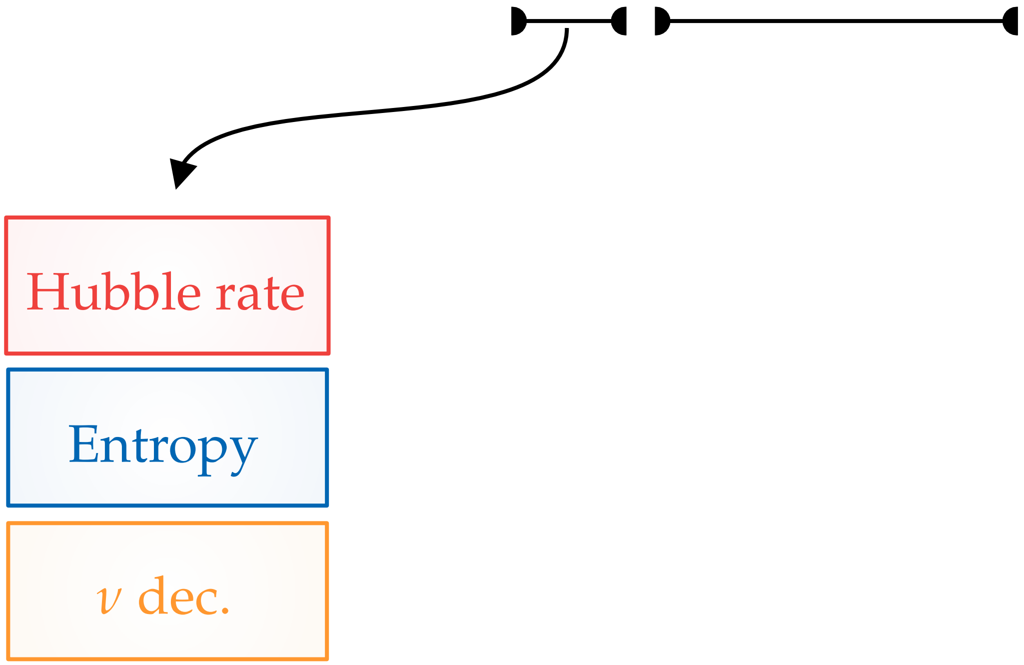
Evolution of nuclei

$$\frac{\mathrm{d}Y_X}{\mathrm{d}T} = \underbrace{\frac{\mathrm{d}t}{\mathrm{d}T}}_{} \times \underbrace{\sum_{r \in \mathcal{R}_X} \pm \Gamma_r \prod_{i \in \mathcal{I}_r} Y_i}_{}$$

Solution Strategy

Evolution of nuclei

$$\frac{\mathrm{d}Y_X}{\mathrm{d}T} = \frac{\mathrm{d}t}{\mathrm{d}T} \times \sum_{r\in\mathcal{R}_X} \pm\Gamma_r \prod_{i\in\mathcal{I}_r} Y_i$$



Hubble rate

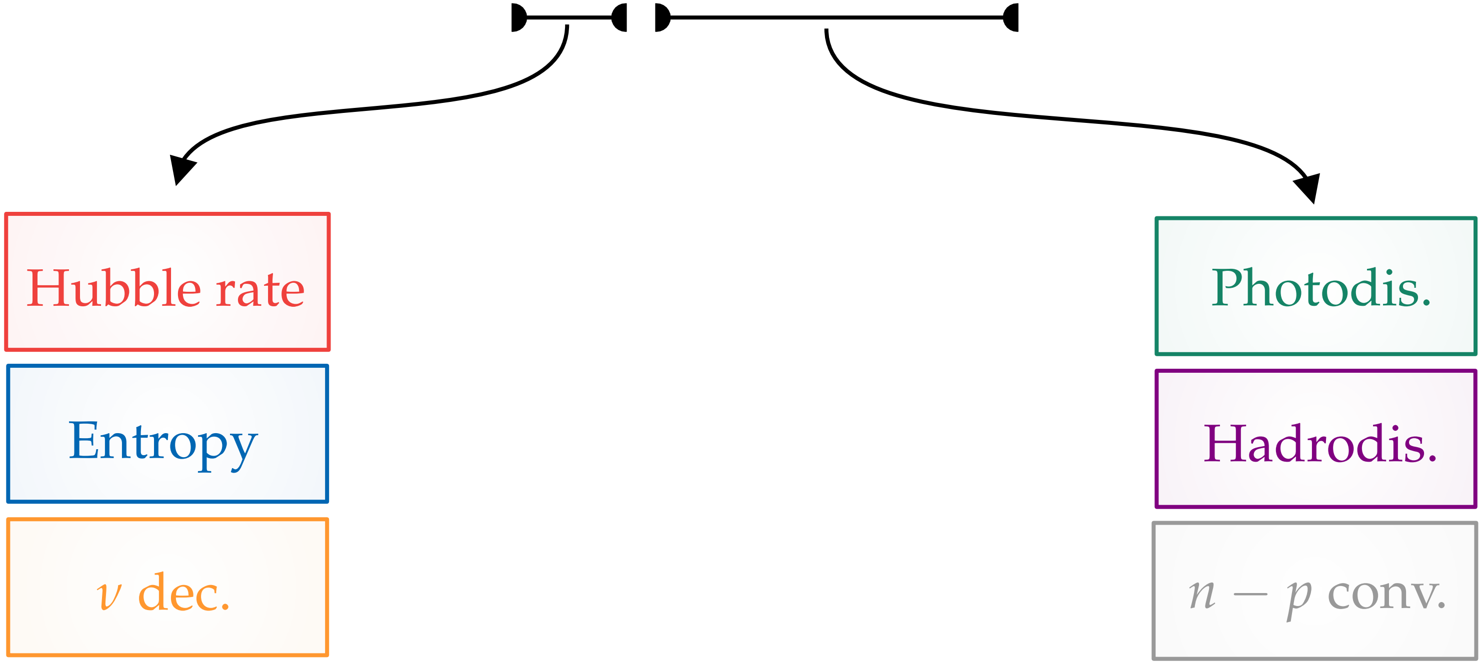
Entropy

ν dec.

Solution Strategy

Evolution of nuclei

$$\frac{\mathrm{d}Y_X}{\mathrm{d}T} = \frac{\mathrm{d}t}{\mathrm{d}T} \times \sum_{r\in\mathcal{R}_X} \pm\Gamma_r \prod_{i\in\mathcal{I}_r} Y_i$$



Hubble rate

Entropy

ν dec.

Photodis.

Hadrodis.

$n - p$ conv.

Solution Strategy

Evolution of nuclei

$$\frac{\mathrm{d}Y_X}{\mathrm{d}T} = \boxed{\frac{\mathrm{d}t}{\mathrm{d}T}} \times \sum_{r\in\mathcal{R}_X} \pm\Gamma_r \prod_{i\in\mathcal{I}_r} Y_i$$

Solution Strategy

Evolution of nuclei

$$\frac{\mathrm{d}Y_X}{\mathrm{d}T} = \boxed{\frac{\mathrm{d}t}{\mathrm{d}T}} \times \sum_{r\in\mathcal{R}_X} \pm\Gamma_r \prod_{i\in\mathcal{I}_r} Y_i$$

$$\frac{\mathrm{d}T}{\mathrm{d}t} = -\frac{\dot{q}_\mathrm{dark} + 3H\left[\rho_\mathrm{sm} + P_\mathrm{sm}\right]}{\mathrm{d}\rho_\mathrm{sm}/\mathrm{d}T}$$

Solution Strategy

Evolution of nuclei

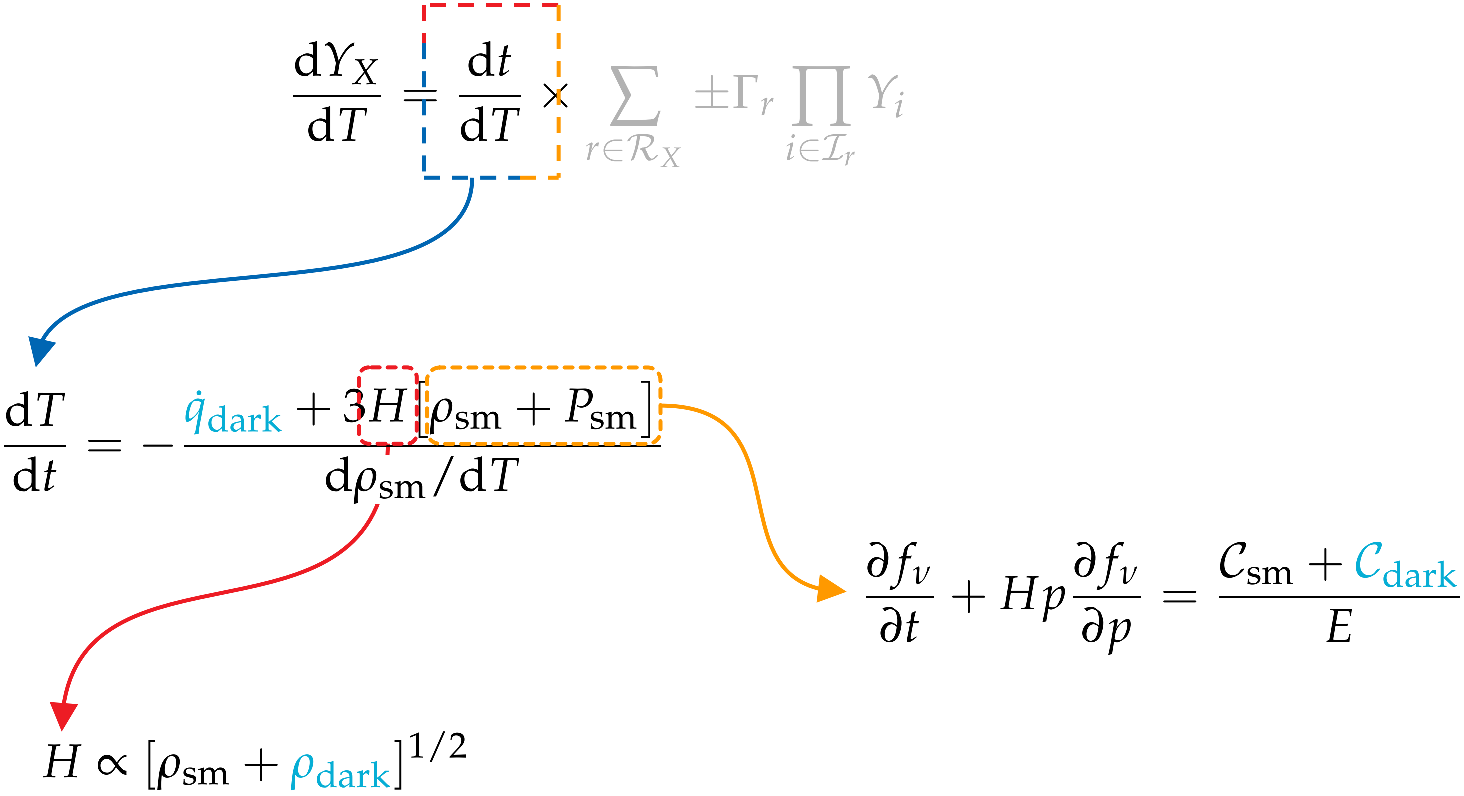
$$\frac{\mathrm{d}Y_X}{\mathrm{d}T} = \boxed{\frac{\mathrm{d}t}{\mathrm{d}T}} \times \sum_{r\in\mathcal{R}_X} \pm\Gamma_r \prod_{i\in\mathcal{I}_r} Y_i$$

$$\frac{\mathrm{d}T}{\mathrm{d}t} = -\frac{\dot{q}_{\mathrm{dark}} + 3\boxed{H}[\rho_{\mathrm{sm}} + P_{\mathrm{sm}}]}{\mathrm{d}\rho_{\mathrm{sm}}/\mathrm{d}T}$$

$$H \propto [\rho_{\mathrm{sm}} + \rho_{\mathrm{dark}}]^{1/2}$$

Solution Strategy

Evolution of nuclei



$$\frac{\mathrm{d}Y_X}{\mathrm{d}T} = \frac{\mathrm{d}t}{\mathrm{d}T} \times \sum_{r\in\mathcal{R}_X} \pm\Gamma_r \prod_{i\in\mathcal{I}_r} Y_i$$

$$\frac{\mathrm{d}T}{\mathrm{d}t} = -\frac{\dot{q}_{\mathrm{dark}} + 3H\left[\rho_{\mathrm{sm}} + P_{\mathrm{sm}}\right]}{\mathrm{d}\rho_{\mathrm{sm}}/\mathrm{d}T}$$

$$\frac{\partial f_\nu}{\partial t} + Hp\frac{\partial f_\nu}{\partial p} = \frac{\mathcal{C}_{\mathrm{sm}} + \mathcal{C}_{\mathrm{dark}}}{E}$$

$$H \propto \left[\rho_{\mathrm{sm}} + \rho_{\mathrm{dark}}\right]^{1/2}$$

Solution Strategy

Evolution of nuclei

$$\frac{\mathrm{d}Y_X}{\mathrm{d}T} = \frac{\mathrm{d}t}{\mathrm{d}T} \times \sum_{r \in \mathcal{R}_X} \pm \Gamma_r \prod_{i \in \mathcal{I}_r} Y_i$$

Solution Strategy

Evolution of nuclei

$$\frac{\mathrm{d}Y_X}{\mathrm{d}T} = \frac{\mathrm{d}t}{\mathrm{d}T} \times \left.\frac{\mathrm{d}Y_X}{\mathrm{d}t}\right|_{\mathrm{SBBN}}$$

Solution Strategy

Evolution of nuclei

$$\frac{\mathrm{d}Y_X}{\mathrm{d}T} = \frac{\mathrm{d}t}{\mathrm{d}T} \times \left(\left.\frac{\mathrm{d}Y_X}{\mathrm{d}t}\right|_{\mathrm{SBBN}} \qquad\qquad\qquad\qquad \right)$$

Solution Strategy

Evolution of nuclei

$$\frac{\mathrm{d}Y_\mathrm{X}}{\mathrm{d}T} = \frac{\mathrm{d}t}{\mathrm{d}T} \times \left(\left.\frac{\mathrm{d}Y_\mathrm{X}}{\mathrm{d}t}\right|_\mathrm{SBBN} + \left.\frac{\mathrm{d}Y_\mathrm{X}}{\mathrm{d}t}\right|_\mathrm{PDI} \right)$$

Solution Strategy

Evolution of nuclei

$$\frac{\mathrm{d}Y_X}{\mathrm{d}T} = \frac{\mathrm{d}t}{\mathrm{d}T} \times \left(\left.\frac{\mathrm{d}Y_X}{\mathrm{d}t}\right|_{\mathrm{SBBN}} + \left.\frac{\mathrm{d}Y_X}{\mathrm{d}t}\right|_{\mathrm{PDI}} + \left.\frac{\mathrm{d}Y_X}{\mathrm{d}t}\right|_{\mathrm{HDI}} \right)$$

Solution Strategy

Evolution of nuclei

$$\frac{\mathrm{d}Y_X}{\mathrm{d}T} = \frac{\mathrm{d}t}{\mathrm{d}T} \times \left(\left.\frac{\mathrm{d}Y_X}{\mathrm{d}t}\right|_{\mathrm{SBBN}} + \left.\frac{\mathrm{d}Y_X}{\mathrm{d}t}\right|_{\mathrm{PDI}} + \left.\frac{\mathrm{d}Y_X}{\mathrm{d}t}\right|_{\mathrm{HDI}} + \left.\frac{\mathrm{d}Y_X}{\mathrm{d}t}\right|_{\mathrm{IC}} \right)$$

Solution Strategy

Evolution of nuclei

$$\frac{\mathrm{d}Y_X}{\mathrm{d}T} = \frac{\mathrm{d}t}{\mathrm{d}T} \times \left(\frac{\mathrm{d}Y_X}{\mathrm{d}t}\bigg|_{\text{SBBN}} + \frac{\mathrm{d}Y_X}{\mathrm{d}t}\bigg|_{\text{PDI}} + \frac{\mathrm{d}Y_X}{\mathrm{d}t}\bigg|_{\text{HDI}} + \frac{\mathrm{d}Y_X}{\mathrm{d}t}\bigg|_{\text{IC}} \right)$$

$\propto n_{\text{dark}}$

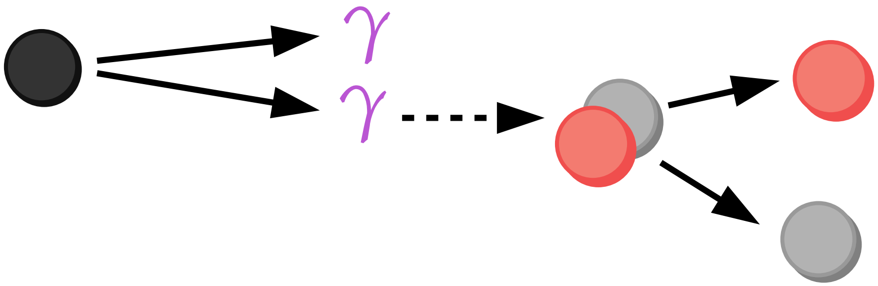
Solution Strategy

Evolution of nuclei

$$\frac{\mathrm{d}Y_X}{\mathrm{d}T} = \frac{\mathrm{d}t}{\mathrm{d}T} \times \left(\frac{\mathrm{d}Y_X}{\mathrm{d}t}\bigg|_{\text{SBBN}} + \frac{\mathrm{d}Y_X}{\mathrm{d}t}\bigg|_{\text{PDI}} + \frac{\mathrm{d}Y_X}{\mathrm{d}t}\bigg|_{\text{HDI}} + \frac{\mathrm{d}Y_X}{\mathrm{d}t}\bigg|_{\text{IC}} \right)$$

$\propto n_{\text{dark}}$

Example: Photodisintegration



$$\frac{\mathrm{d}Y_X}{\mathrm{d}t}\bigg|_{\text{PDI}} \supset \sum_j Y_j \int_0^\infty f_\gamma \sigma_{\gamma j \to X} \, \mathrm{d}E$$

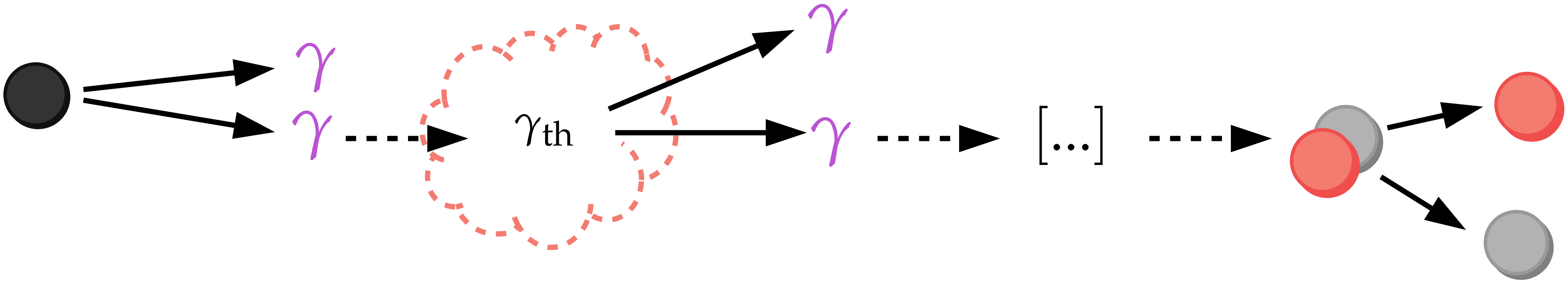
Solution Strategy

Evolution of nuclei

$$\frac{\mathrm{d}Y_X}{\mathrm{d}T} = \frac{\mathrm{d}t}{\mathrm{d}T} \times \left(\left.\frac{\mathrm{d}Y_X}{\mathrm{d}t}\right|_{\text{SBBN}} + \left.\frac{\mathrm{d}Y_X}{\mathrm{d}t}\right|_{\text{PDI}} + \left.\frac{\mathrm{d}Y_X}{\mathrm{d}t}\right|_{\text{HDI}} + \left.\frac{\mathrm{d}Y_X}{\mathrm{d}t}\right|_{\text{IC}} \right)$$

$\propto n_{\text{dark}}$

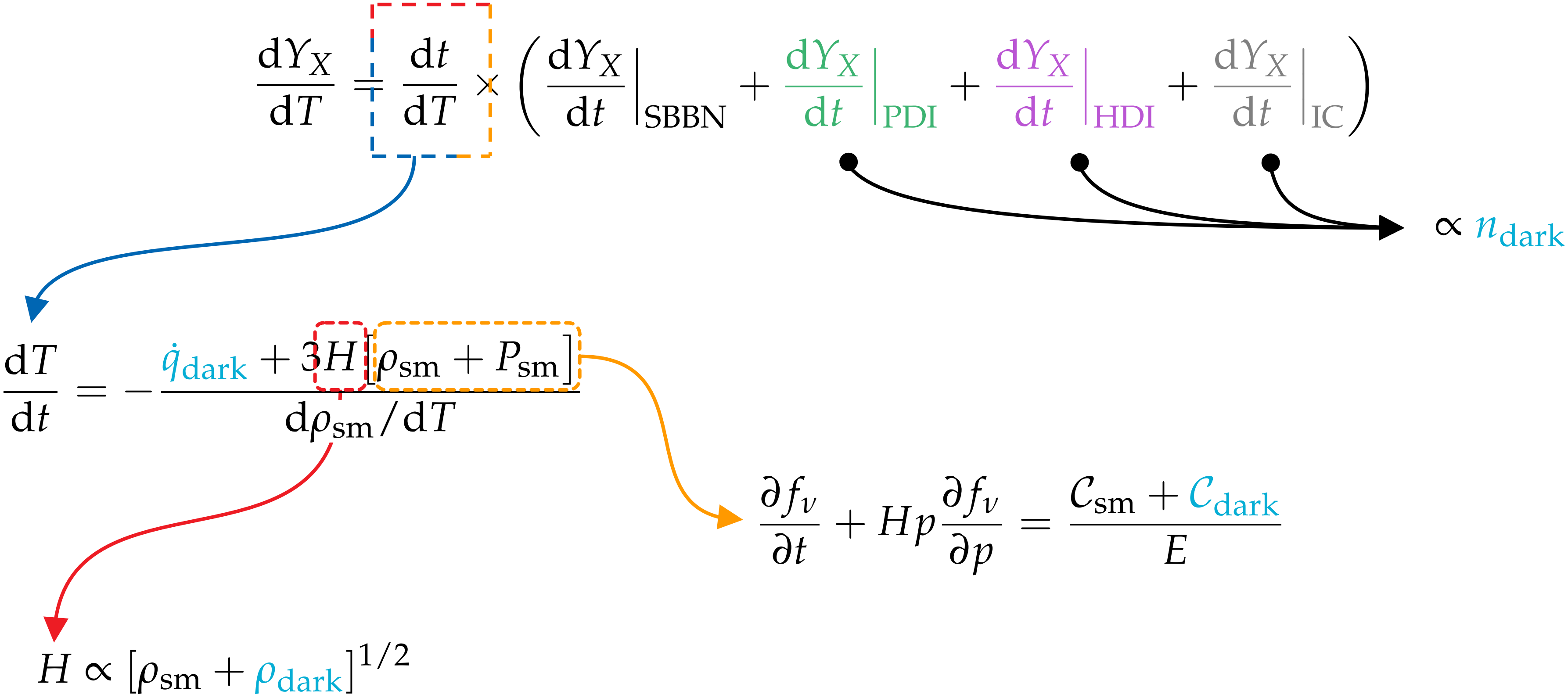
Example: Photodisintegration



$$\left.\frac{\mathrm{d}Y_X}{\mathrm{d}t}\right|_{\text{PDI}} \supset \sum_j Y_j \int_0^\infty f_\gamma \sigma_{\gamma j \to X} \, \mathrm{d}E$$

Solution Strategy

Evolution of nuclei



$$\frac{\mathrm{d}Y_X}{\mathrm{d}T} = \boxed{\frac{\mathrm{d}t}{\mathrm{d}T}} \times \left(\left.\frac{\mathrm{d}Y_X}{\mathrm{d}t}\right|_{\mathrm{SBBN}} + \left.\frac{\mathrm{d}Y_X}{\mathrm{d}t}\right|_{\mathrm{PDI}} + \left.\frac{\mathrm{d}Y_X}{\mathrm{d}t}\right|_{\mathrm{HDI}} + \left.\frac{\mathrm{d}Y_X}{\mathrm{d}t}\right|_{\mathrm{IC}} \right)$$

$$\propto n_{\mathrm{dark}}$$

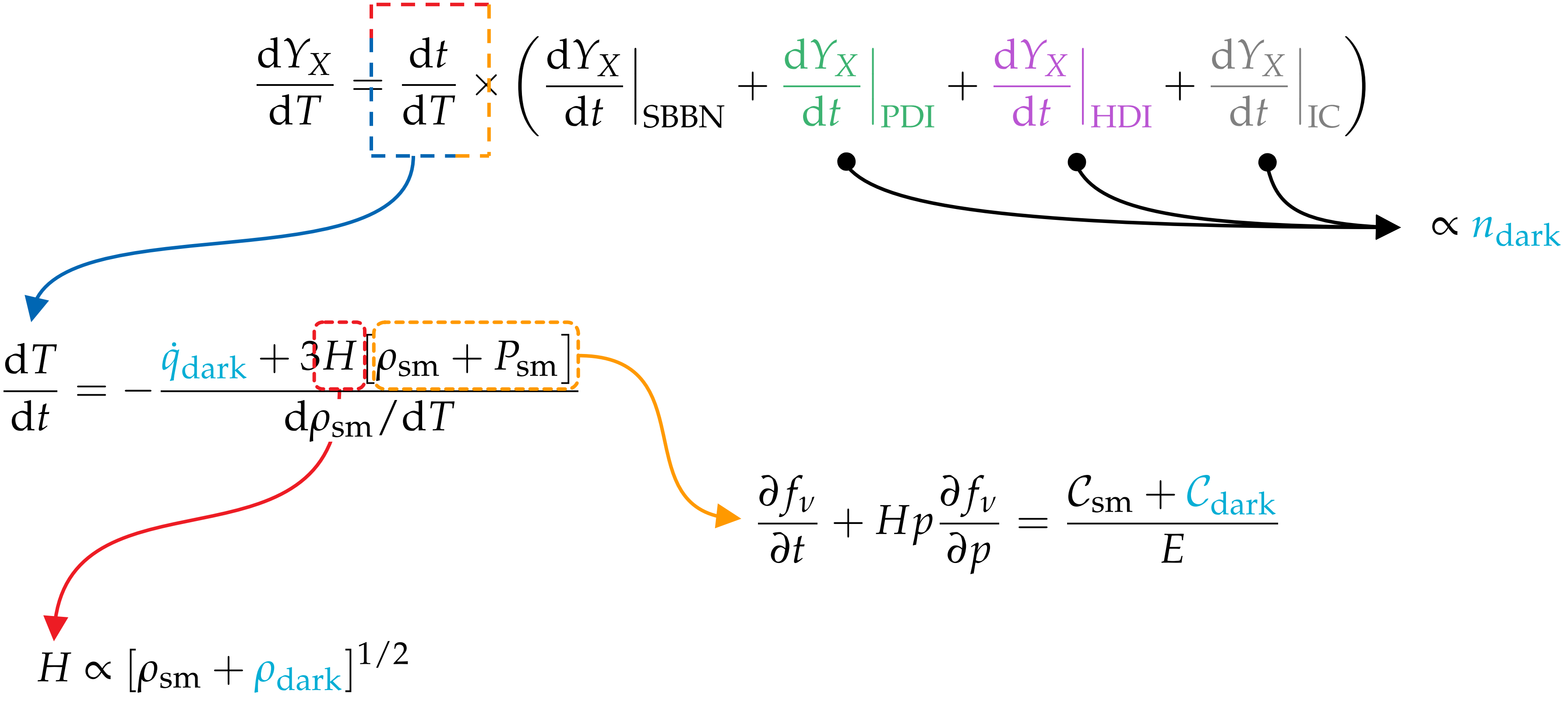
$$\frac{\mathrm{d}T}{\mathrm{d}t} = -\frac{\dot{q}_{\mathrm{dark}} + 3\boxed{H}\left[\boxed{\rho_{\mathrm{sm}} + P_{\mathrm{sm}}}\right]}{\mathrm{d}\rho_{\mathrm{sm}}/\mathrm{d}T}$$

$$\frac{\partial f_\nu}{\partial t} + Hp\frac{\partial f_\nu}{\partial p} = \frac{\mathcal{C}_{\mathrm{sm}} + \mathcal{C}_{\mathrm{dark}}}{E}$$

$$H \propto \left[\rho_{\mathrm{sm}} + \rho_{\mathrm{dark}}\right]^{1/2}$$

Solution Strategy

Evolution of nuclei



$$\frac{\mathrm{d}Y_X}{\mathrm{d}T} = \frac{\mathrm{d}t}{\mathrm{d}T} \times \left(\frac{\mathrm{d}Y_X}{\mathrm{d}t}\Big|_{\text{SBBN}} + \frac{\mathrm{d}Y_X}{\mathrm{d}t}\Big|_{\text{PDI}} + \frac{\mathrm{d}Y_X}{\mathrm{d}t}\Big|_{\text{HDI}} + \frac{\mathrm{d}Y_X}{\mathrm{d}t}\Big|_{\text{IC}} \right)$$

$\propto n_{\text{dark}}$

$$\frac{\mathrm{d}T}{\mathrm{d}t} = -\frac{\dot{q}_{\text{dark}} + 3H[\rho_{\text{sm}} + P_{\text{sm}}]}{\mathrm{d}\rho_{\text{sm}}/\mathrm{d}T}$$

$$H \propto [\rho_{\text{sm}} + \rho_{\text{dark}}]^{1/2}$$

$$\frac{\partial f_\nu}{\partial t} + Hp\frac{\partial f_\nu}{\partial p} = \frac{\mathcal{C}_{\text{sm}} + \mathcal{C}_{\text{dark}}}{E}$$

$$\boxed{\frac{\partial f_x}{\partial t} - 3Hp\frac{\partial f_x}{\partial p} = \frac{\mathcal{C}_x}{E_x}}$$

The setup

DS

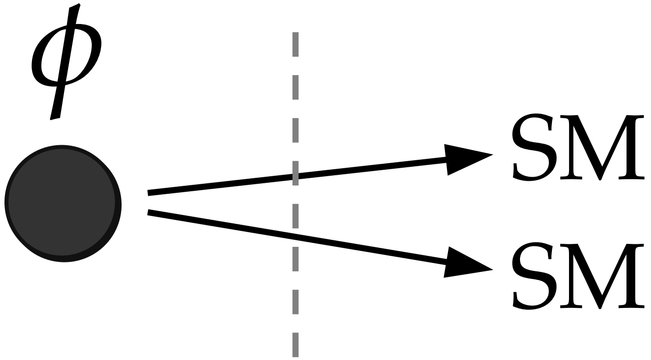
SM

The setup

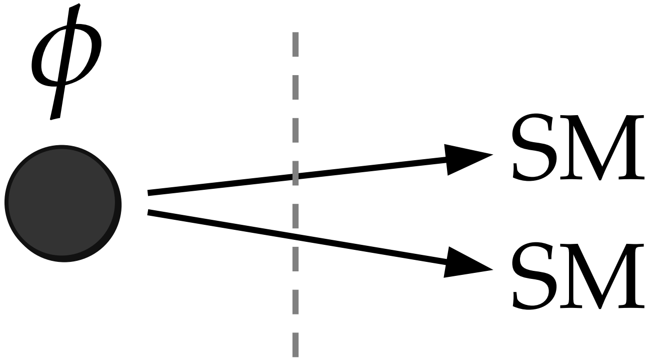
ϕ

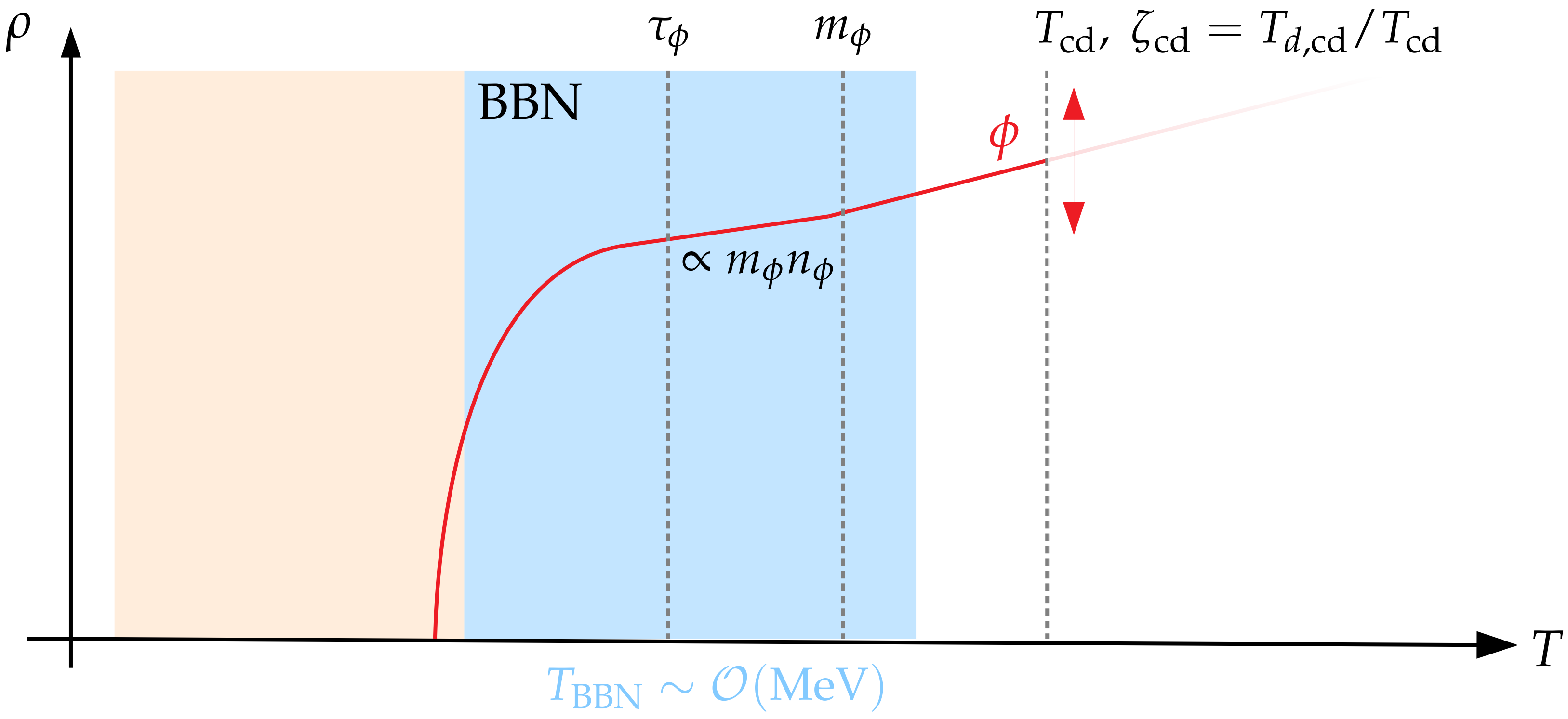
SM

The setup

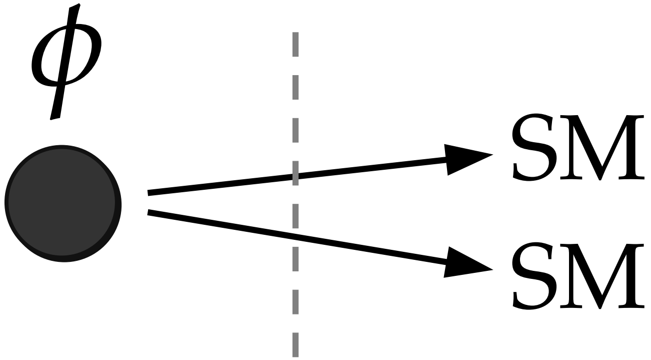


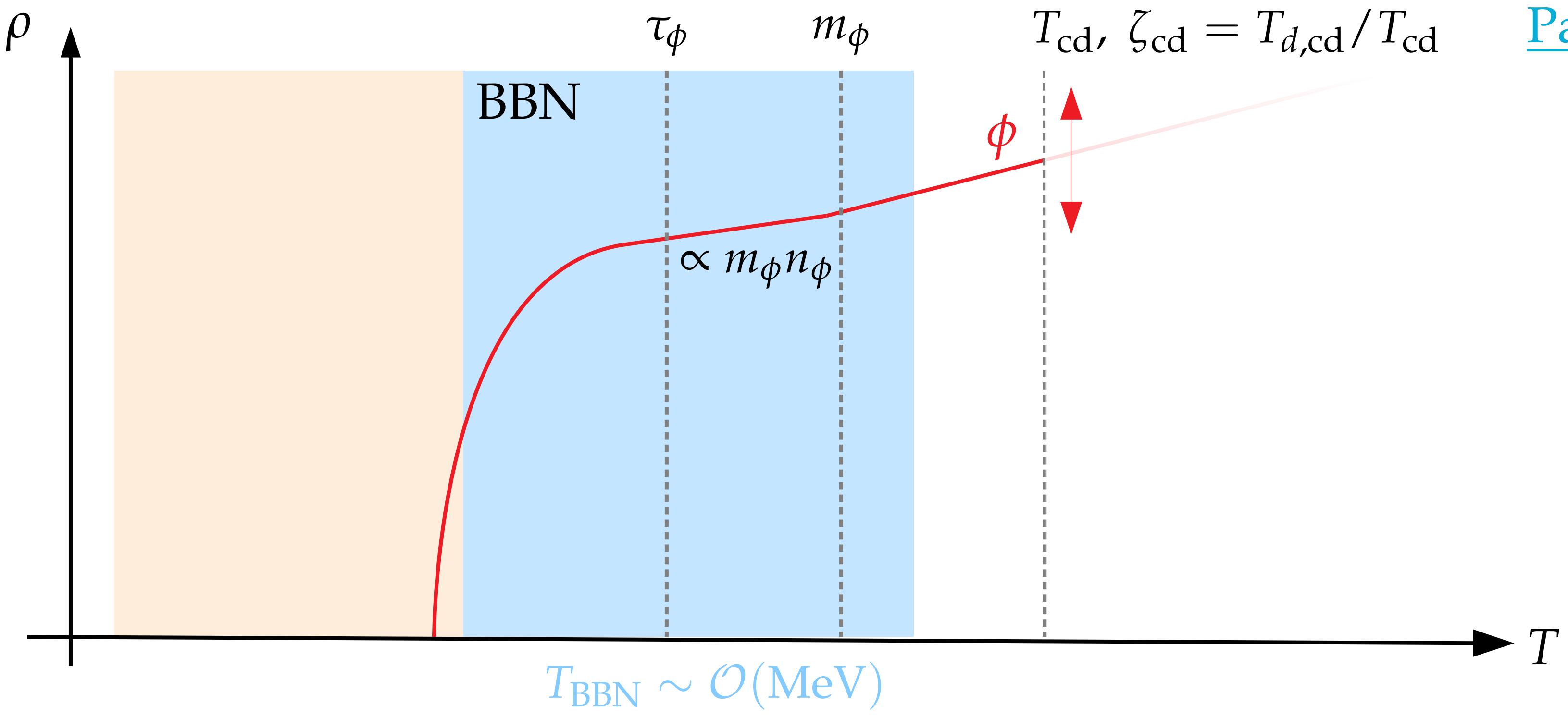
The setup


ϕ
SM
SM


ρ
τ_ϕ
m_ϕ
$T_{\rm cd}$, $\zeta_{\rm cd} = T_{d,\rm cd}/T_{\rm cd}$
BBN
ϕ
$\propto m_\phi n_\phi$
T
$T_{\rm BBN} \sim \mathcal{O}(\rm MeV)$

The setup

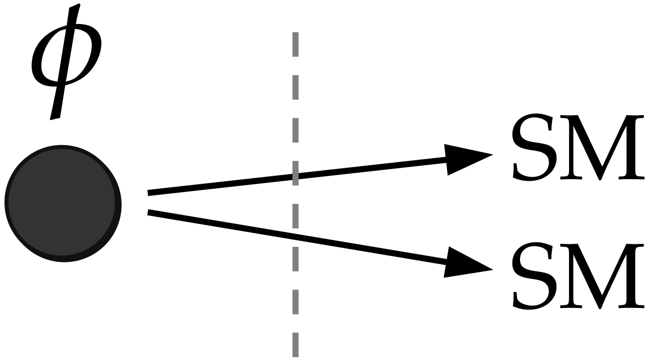


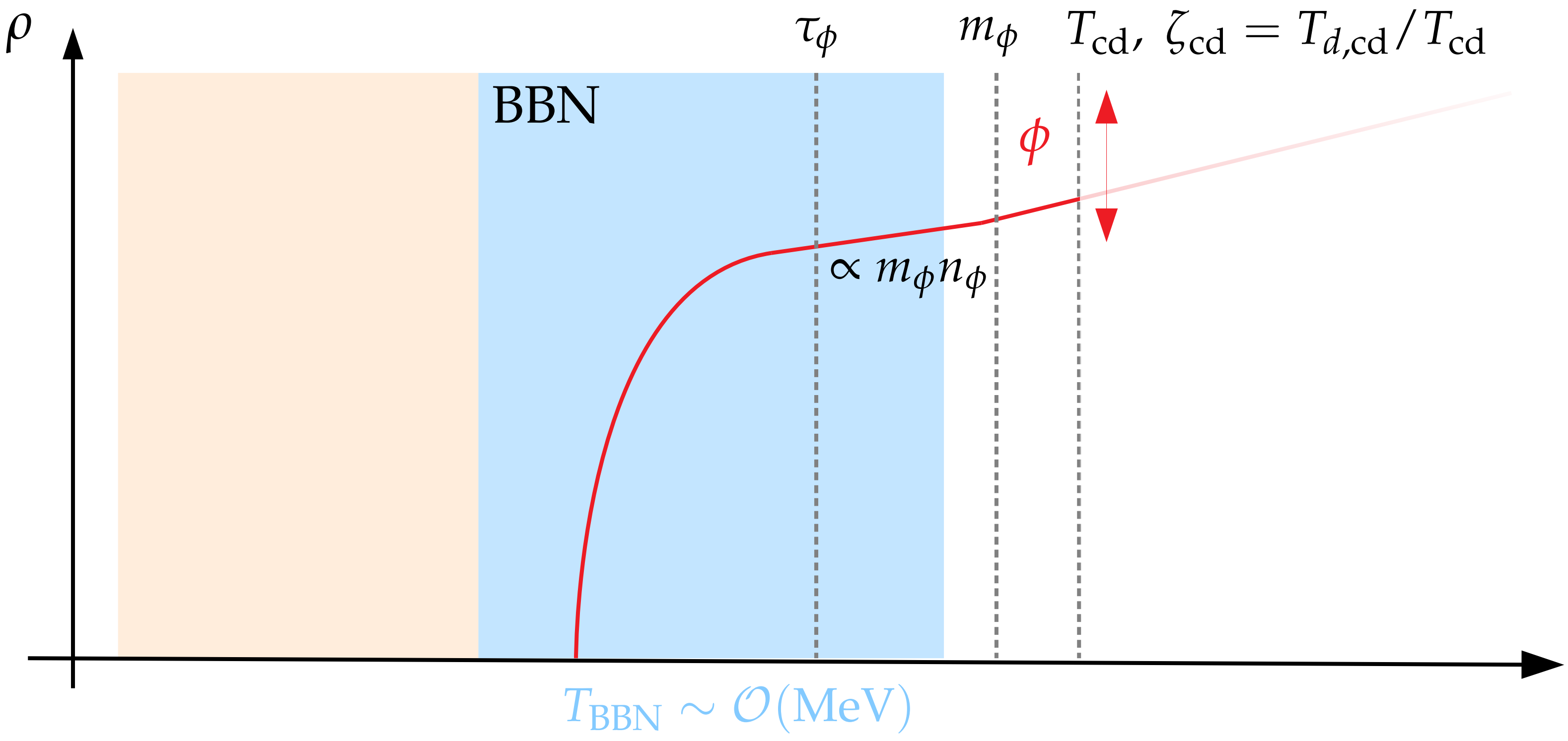


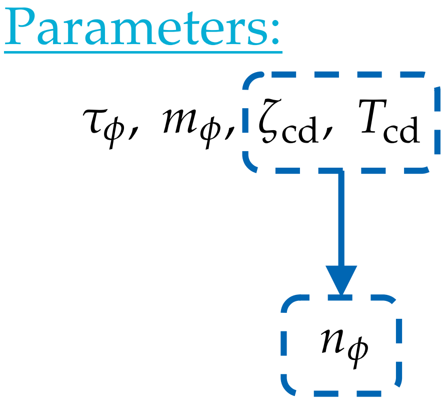
Parameters:

τ_ϕ, m_ϕ, $\zeta_{\rm cd}$, $T_{\rm cd}$

The setup







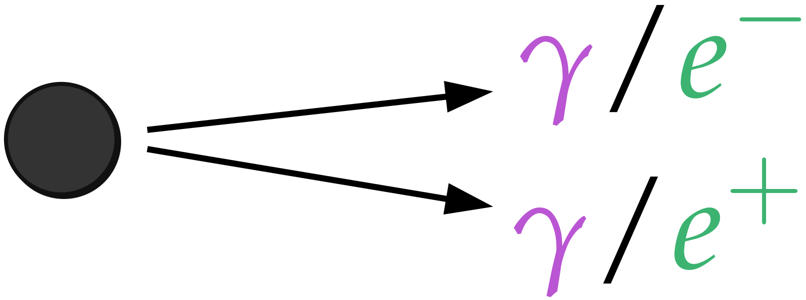
Parameters:

$\tau_\phi,\ m_\phi,\ \zeta_{\text{cd}},\ T_{\text{cd}}$

n_ϕ

Electromagnetic decays

Decay channel(s)



Relevant effects ?

Hubble rate

Entropy

Photodis.

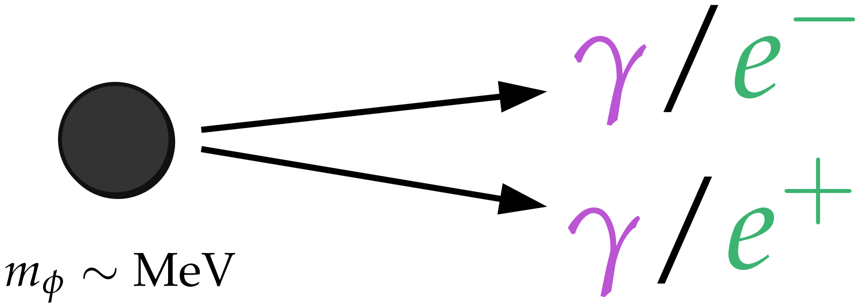
Hadrodis.

ν dec.

$n - p$ conv.

Electromagnetic decays

Decay channel(s)

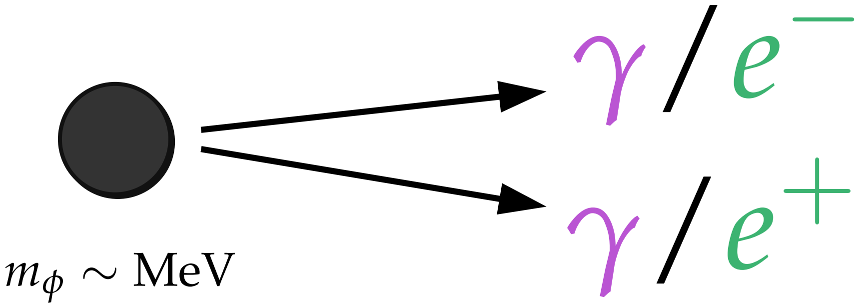


Relevant effects ?

Hubble rate | Entropy | Photodis. | Hadrodis. | ν dec. | $n-p$ conv.

Electromagnetic decays

Decay channel(s)



Relevant effects

Hubble rate

Entropy

Photodis.

Constraints for fixed $\zeta_{\mathrm{cd}} = 1$

Boltzmann equation

$$\dot{n}_\phi + 3Hn_\phi = -\frac{n_\phi - \bar{n}_\phi}{\tau_{\phi,\mathrm{eff}}}$$

Constraints for fixed $\zeta_{\mathrm{cd}} = 1$

Boltzmann equation

$$\dot{n}_\phi + \boxed{3Hn_\phi} = -\frac{n_\phi - \bar{n}_\phi}{\tau_{\phi,\mathrm{eff}}}$$

Dultion

Constraints for fixed $\zeta_{\text{cd}} = 1$

Boltzmann equation

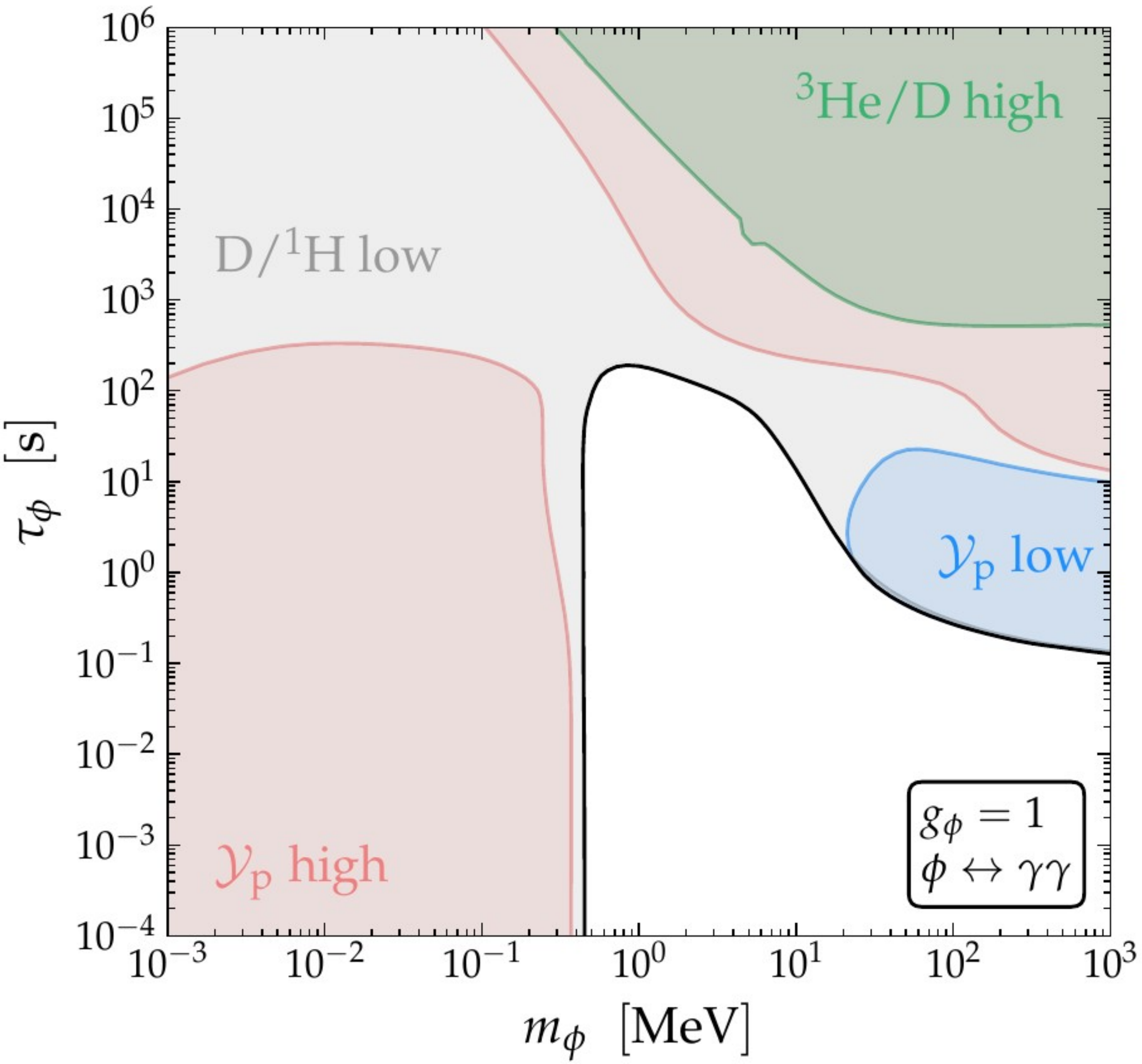
$$\dot{n}_\phi + \underbrace{\boxed{3Hn_\phi}}_{\text{Dultion}} = -\frac{\underbrace{\boxed{n_\phi}}_{\text{Decay}} - \bar{n}_\phi}{\tau_{\phi,\text{eff}}}$$

Constraints for fixed $\zeta_{\mathrm{cd}} = 1$

Boltzmann equation

$$\dot{n}_\phi + \underbrace{\boxed{3Hn_\phi}}_{\text{Dultion}} = -\frac{\underbrace{\boxed{n_\phi}}_{\text{Decay}} - \underbrace{\boxed{\bar{n}_\phi}}_{\text{Inverse Decay}}}{\tau_{\phi,\mathrm{eff}}}$$

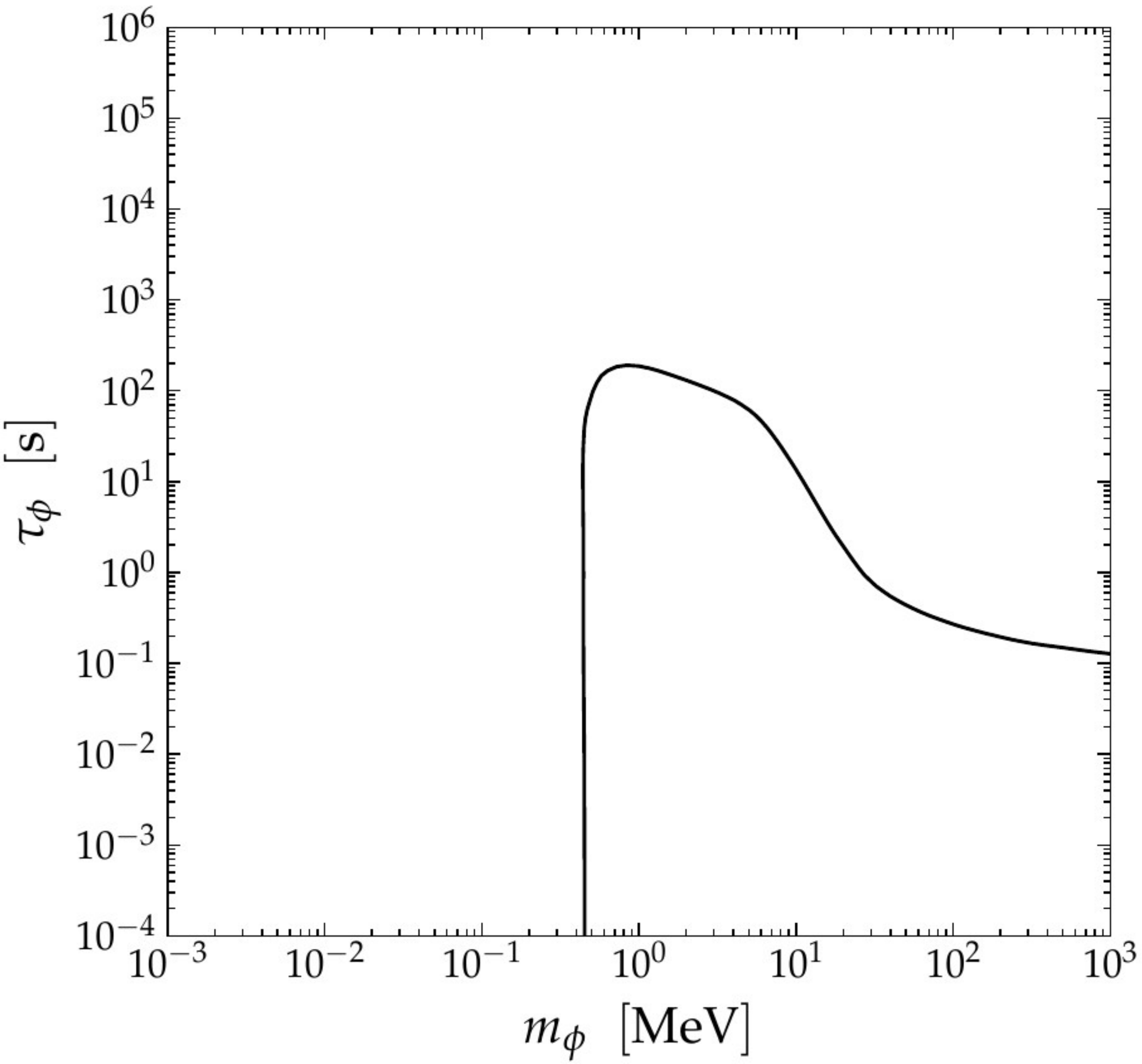
Constraints for fixed $\zeta_{\text{cd}} = 1$



Boltzmann equation

$$\dot{n}_\phi + 3Hn_\phi = -\frac{n_\phi - \bar{n}_\phi}{\tau_{\phi,\text{eff}}}$$

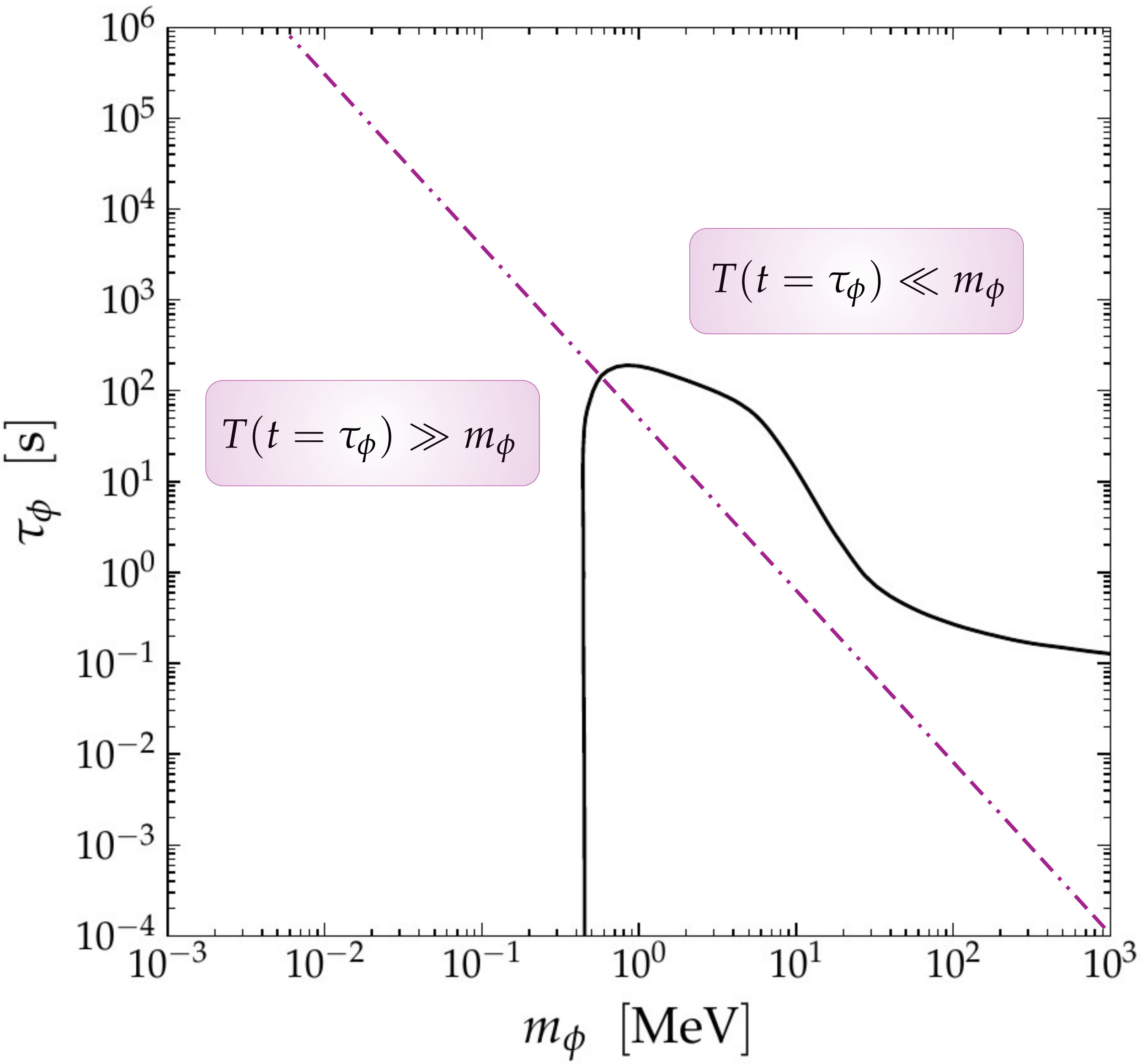
Constraints for fixed $\zeta_{\text{cd}} = 1$



Boltzmann equation

$$\dot{n}_\phi + 3Hn_\phi = -\frac{n_\phi - \bar{n}_\phi}{\tau_{\phi,\text{eff}}}$$

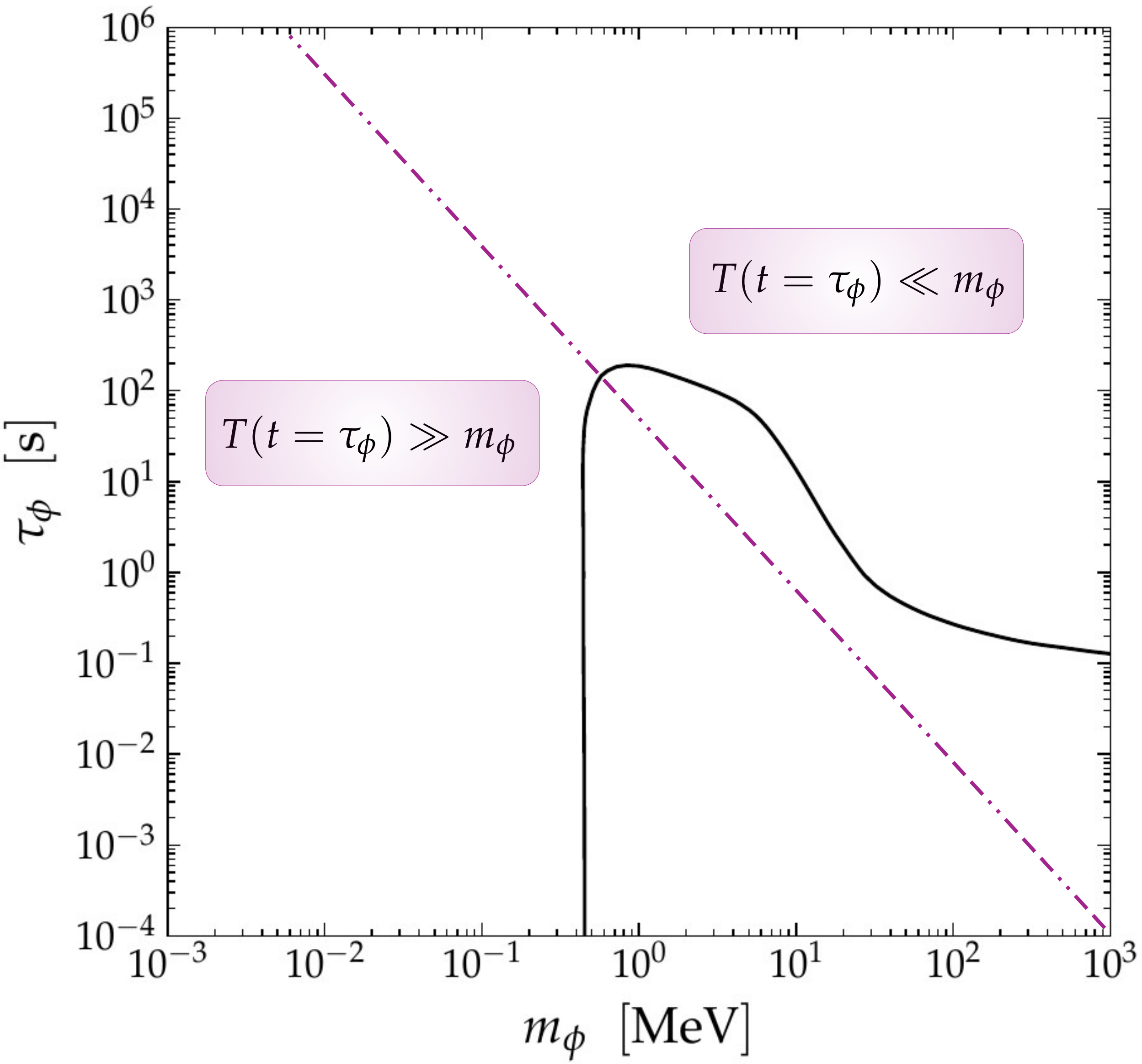
Constraints for fixed $\zeta_{\rm cd} = 1$



Boltzmann equation

$$\dot{n}_\phi + 3Hn_\phi = -\frac{n_\phi - \bar{n}_\phi}{\tau_{\phi,\rm eff}}$$

Constraints for fixed $\zeta_{\rm cd} = 1$

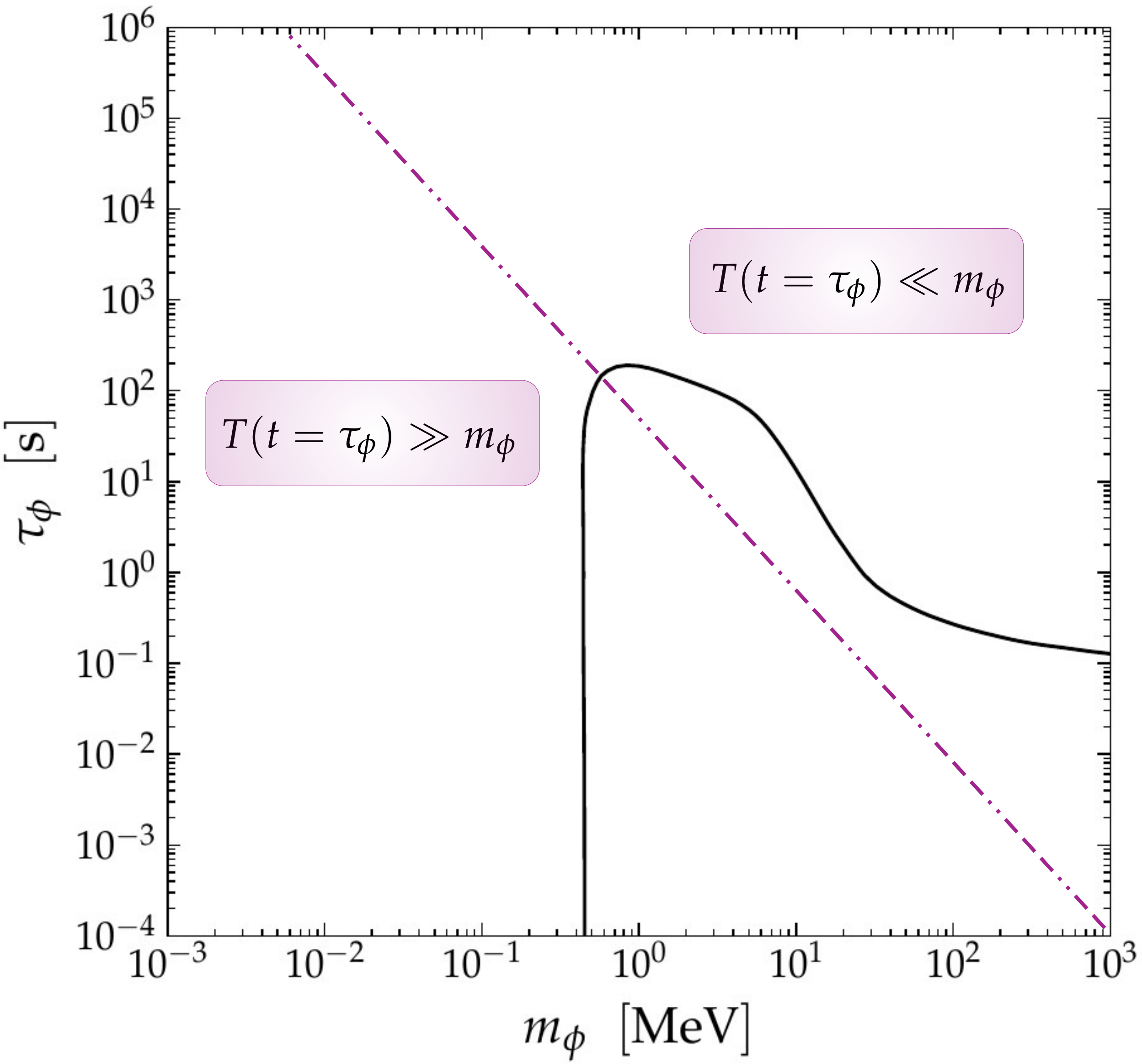


Boltzmann equation

$$\dot{n}_\phi + 3Hn_\phi = -\frac{n_\phi - \bar{n}_\phi}{\tau_{\phi,\text{eff}}}$$

$$\rightarrow \quad n_\phi \simeq \bar{n}_\phi \quad \text{for} \quad 1/\tau_{\phi,\text{eff}} \sim H$$

Constraints for fixed $\zeta_{\mathrm{cd}} = 1$

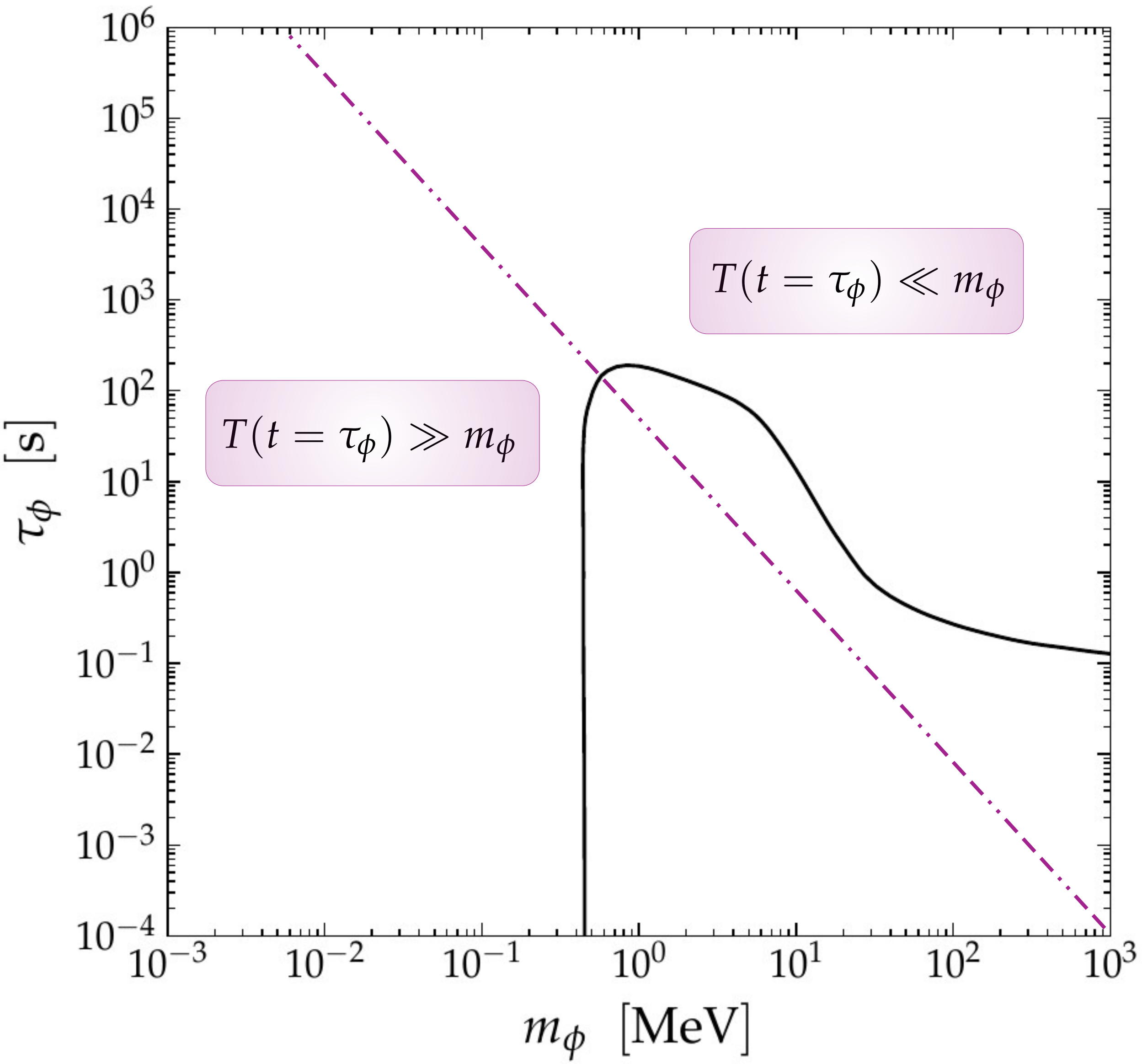


Boltzmann equation

$$\dot{n}_\phi + 3Hn_\phi = -\frac{n_\phi - \bar{n}_\phi}{\tau_{\phi,\mathrm{eff}}}$$

$$\rightarrow \quad n_\phi \simeq \bar{n}_\phi \quad \text{for} \quad t \sim \tau_\phi$$

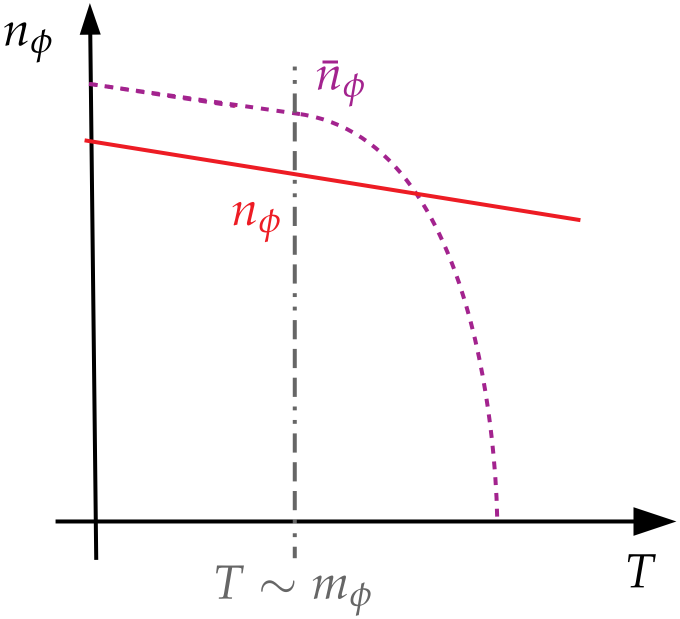
Constraints for fixed $\zeta_{\mathrm{cd}} = 1$



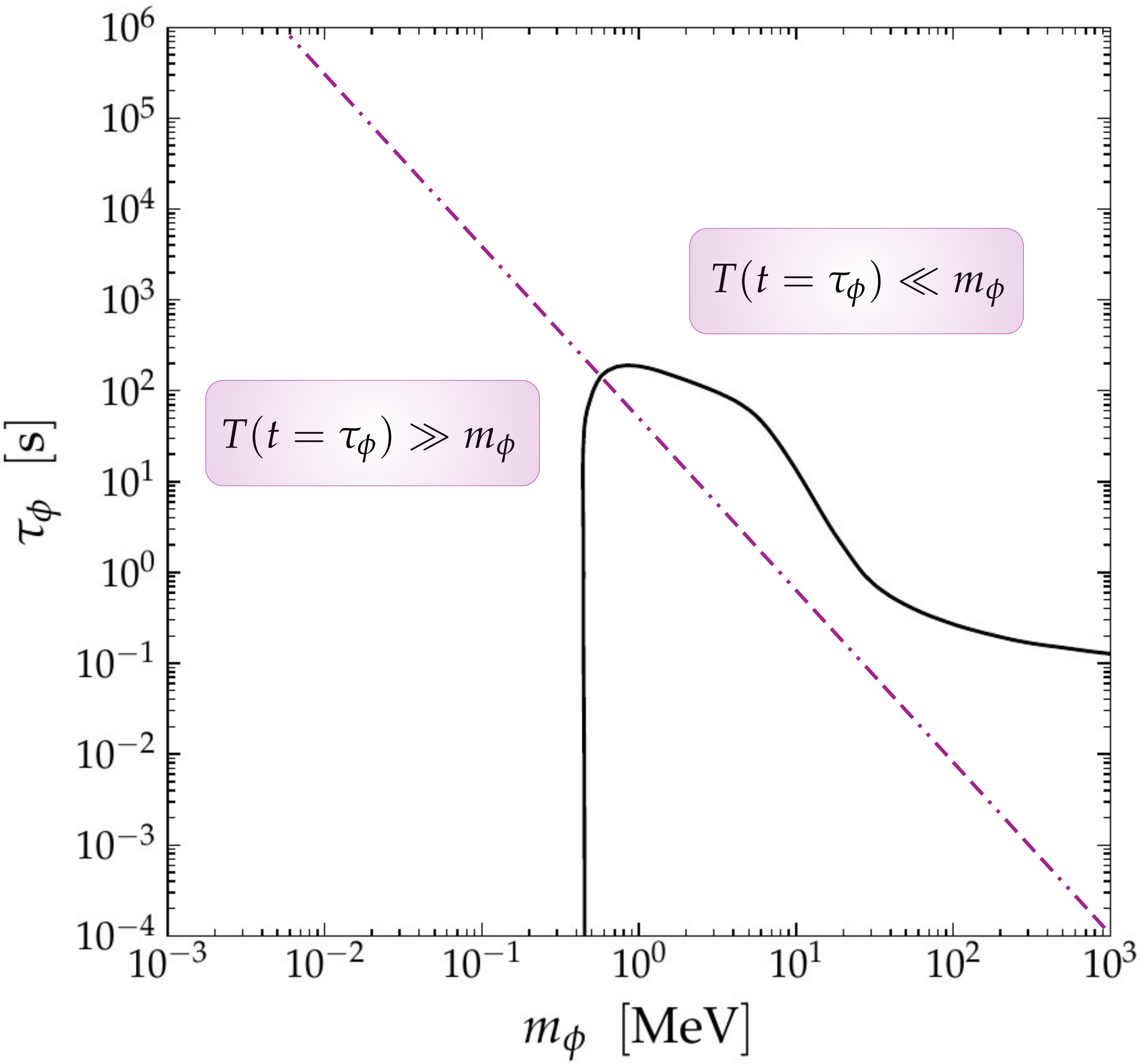
Boltzmann equation

$$\dot{n}_\phi + 3Hn_\phi = -\frac{n_\phi - \bar{n}_\phi}{\tau_{\phi,\mathrm{eff}}}$$

$$\rightarrow \quad n_\phi \simeq \bar{n}_\phi \quad \text{for} \quad t \sim \tau_\phi$$



Constraints for fixed $\zeta_{\rm cd} = 1$



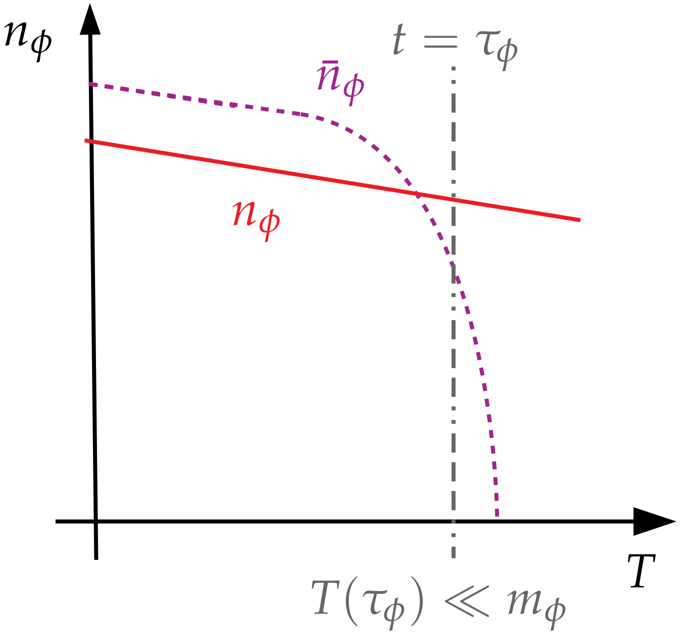
$T(t = \tau_\phi) \ll m_\phi$

$T(t = \tau_\phi) \gg m_\phi$

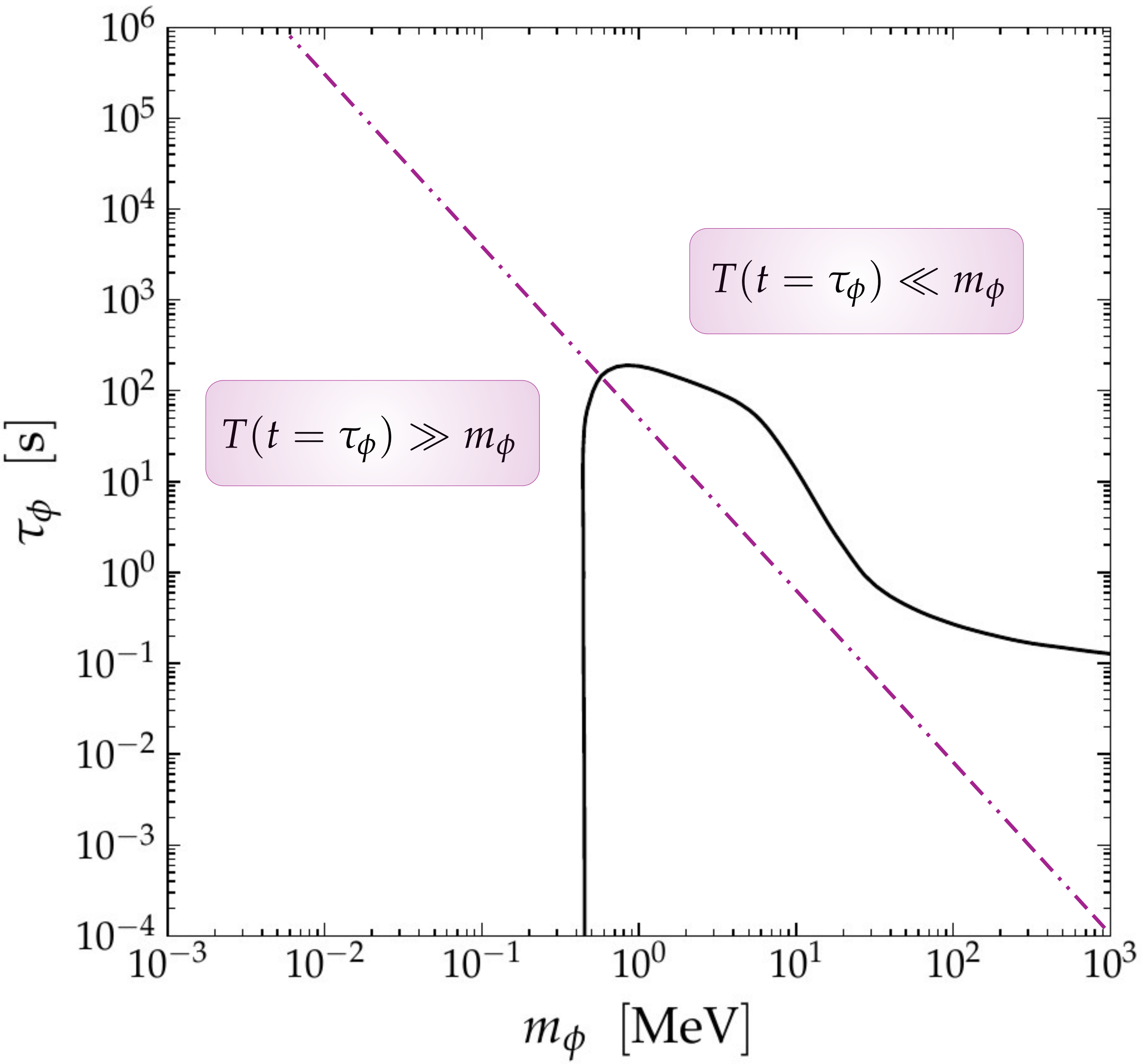
Boltzmann equation

$$\dot{n}_\phi + 3Hn_\phi = -\frac{n_\phi - \bar{n}_\phi}{\tau_{\phi,\rm eff}}$$

$$\rightarrow \quad n_\phi \simeq \bar{n}_\phi \quad \text{for} \quad t \sim \tau_\phi$$



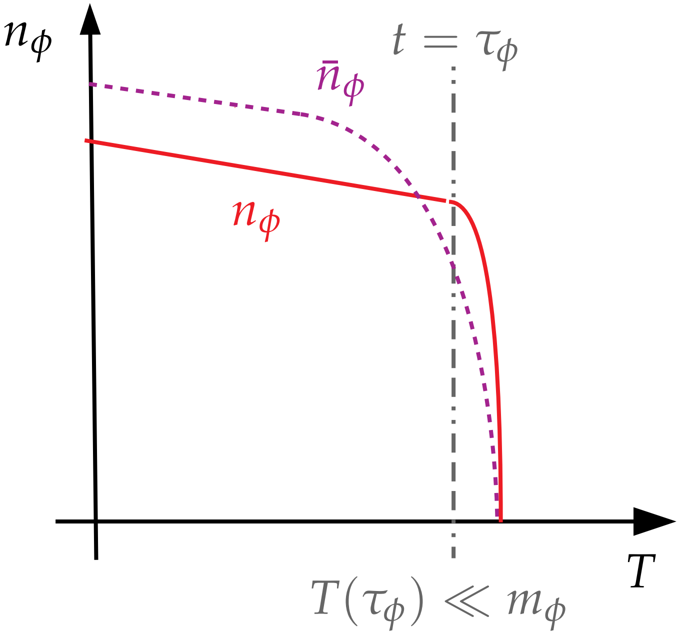
Constraints for fixed $\zeta_{\mathrm{cd}} = 1$



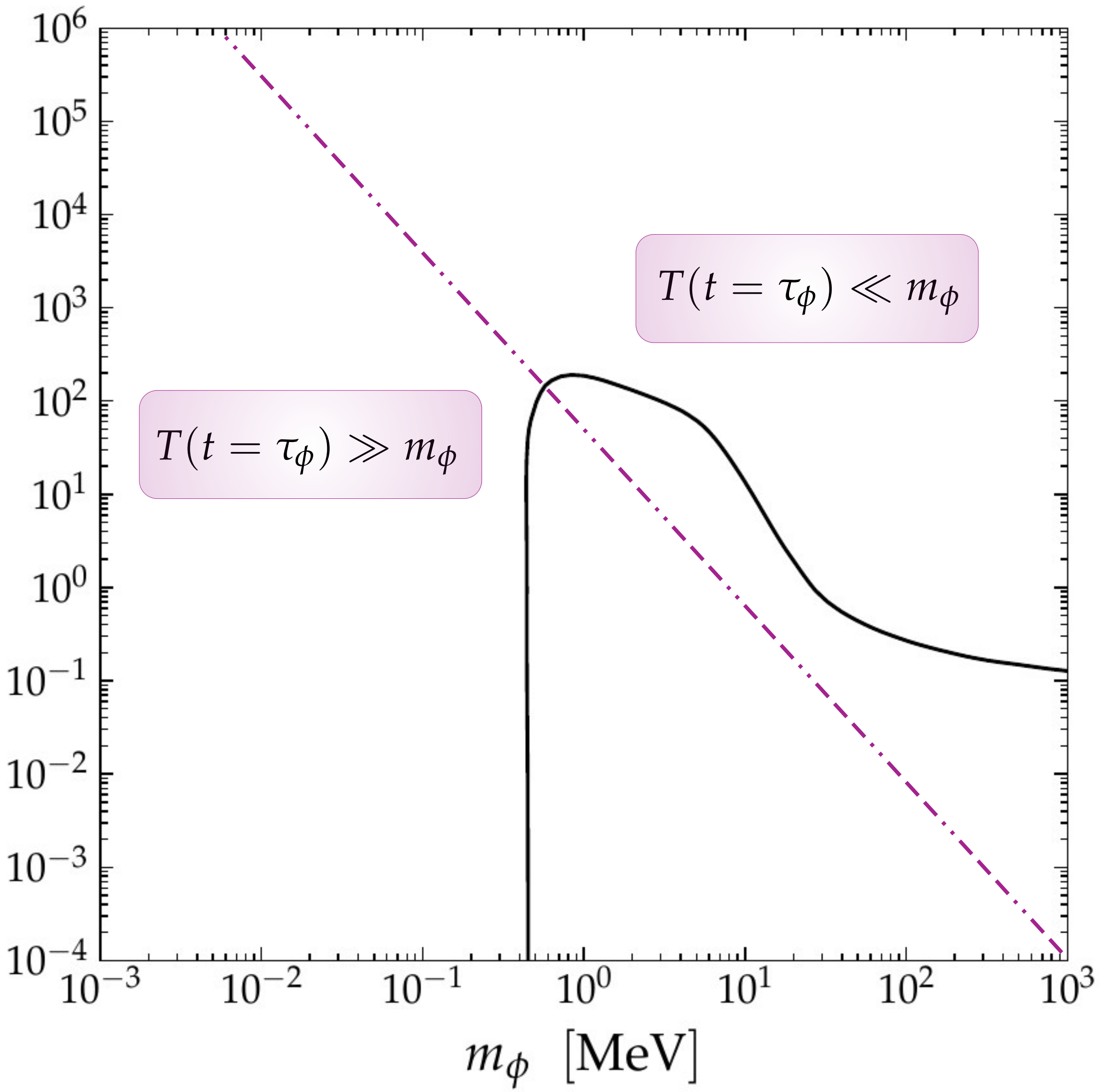
Boltzmann equation

$$\dot{n}_\phi + 3Hn_\phi = -\frac{n_\phi - \bar{n}_\phi}{\tau_{\phi,\mathrm{eff}}}$$

$$\rightarrow \quad n_\phi \simeq \bar{n}_\phi \quad \text{for} \quad t \sim \tau_\phi$$



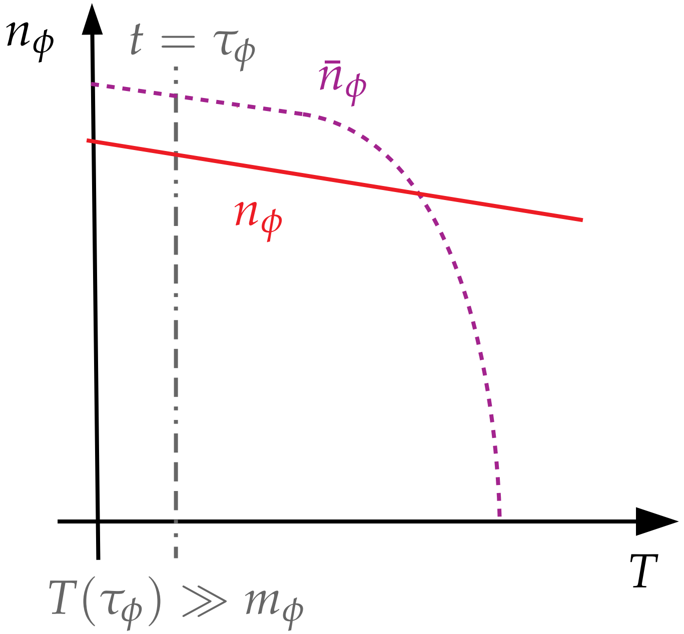
Constraints for fixed $\zeta_{\mathrm{cd}} = 1$



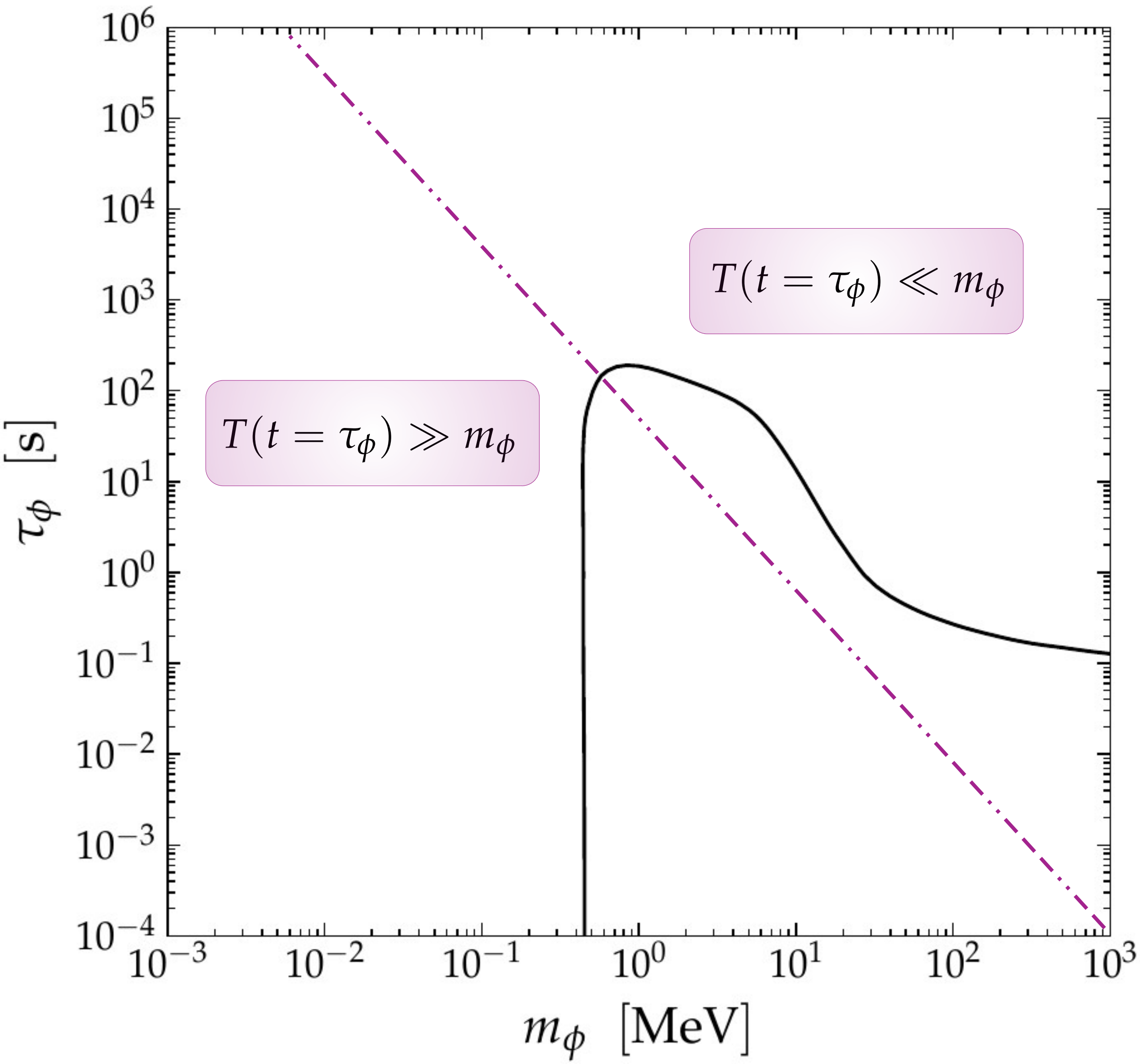
Boltzmann equation

$$\dot{n}_\phi + 3Hn_\phi = -\frac{n_\phi - \bar{n}_\phi}{\tau_{\phi,\mathrm{eff}}}$$

$$\rightarrow \quad n_\phi \simeq \bar{n}_\phi \quad \text{for} \quad t \sim \tau_\phi$$



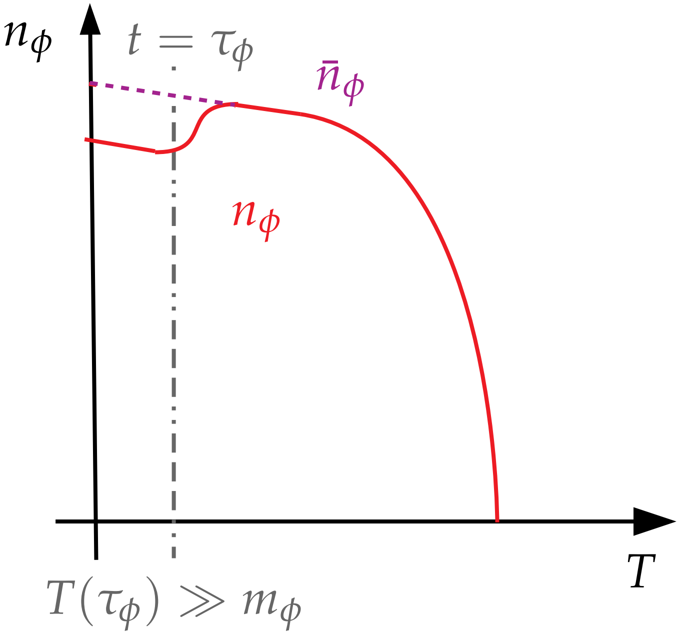
Constraints for fixed $\zeta_{\mathrm{cd}} = 1$



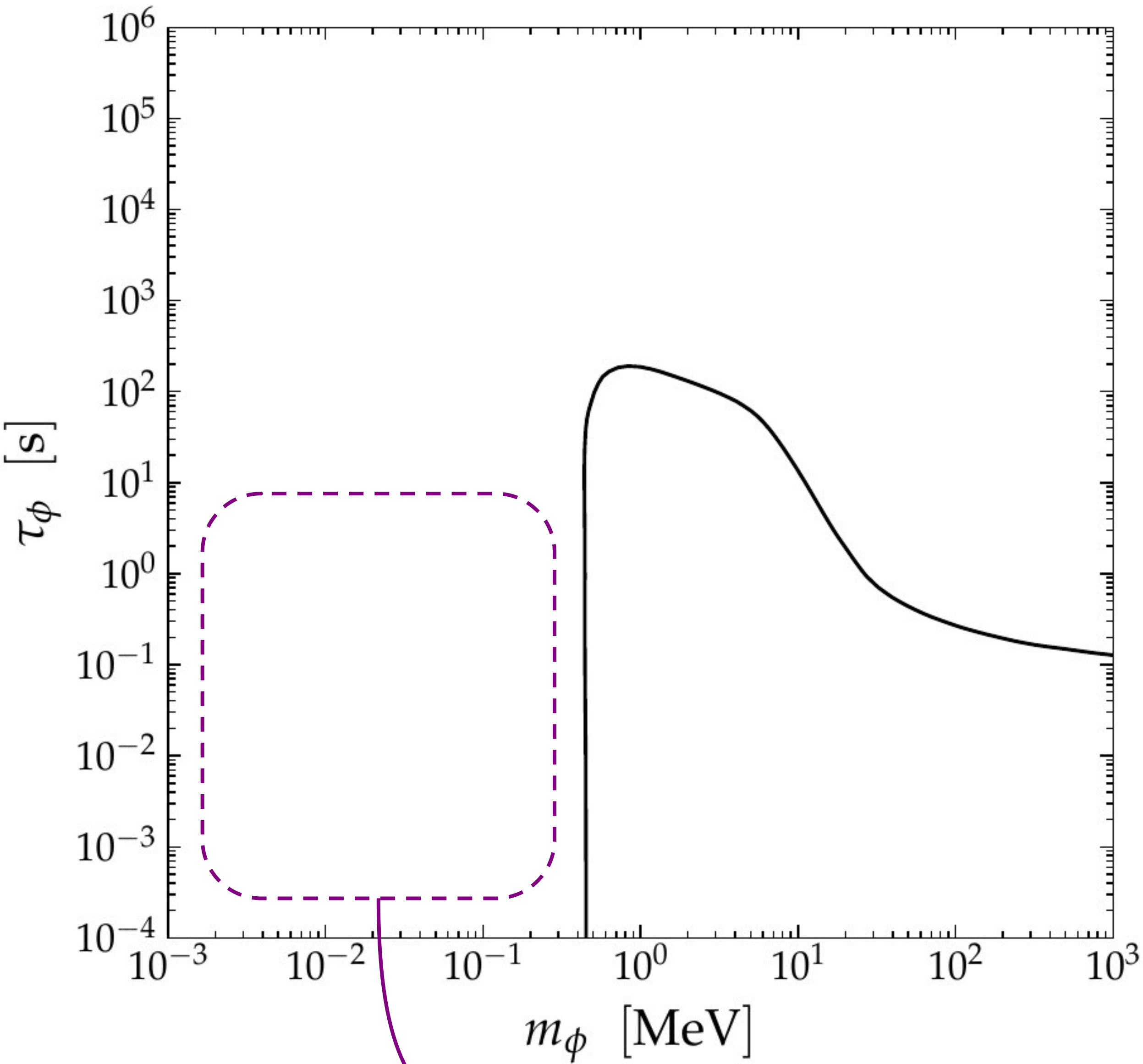
Boltzmann equation

$$\dot{n}_\phi + 3Hn_\phi = -\frac{n_\phi - \bar{n}_\phi}{\tau_{\phi,\mathrm{eff}}}$$

$$\rightarrow \quad n_\phi \simeq \bar{n}_\phi \quad \text{for} \quad t \sim \tau_\phi$$



Constraints for fixed $\zeta_{\text{cd}} = 1$

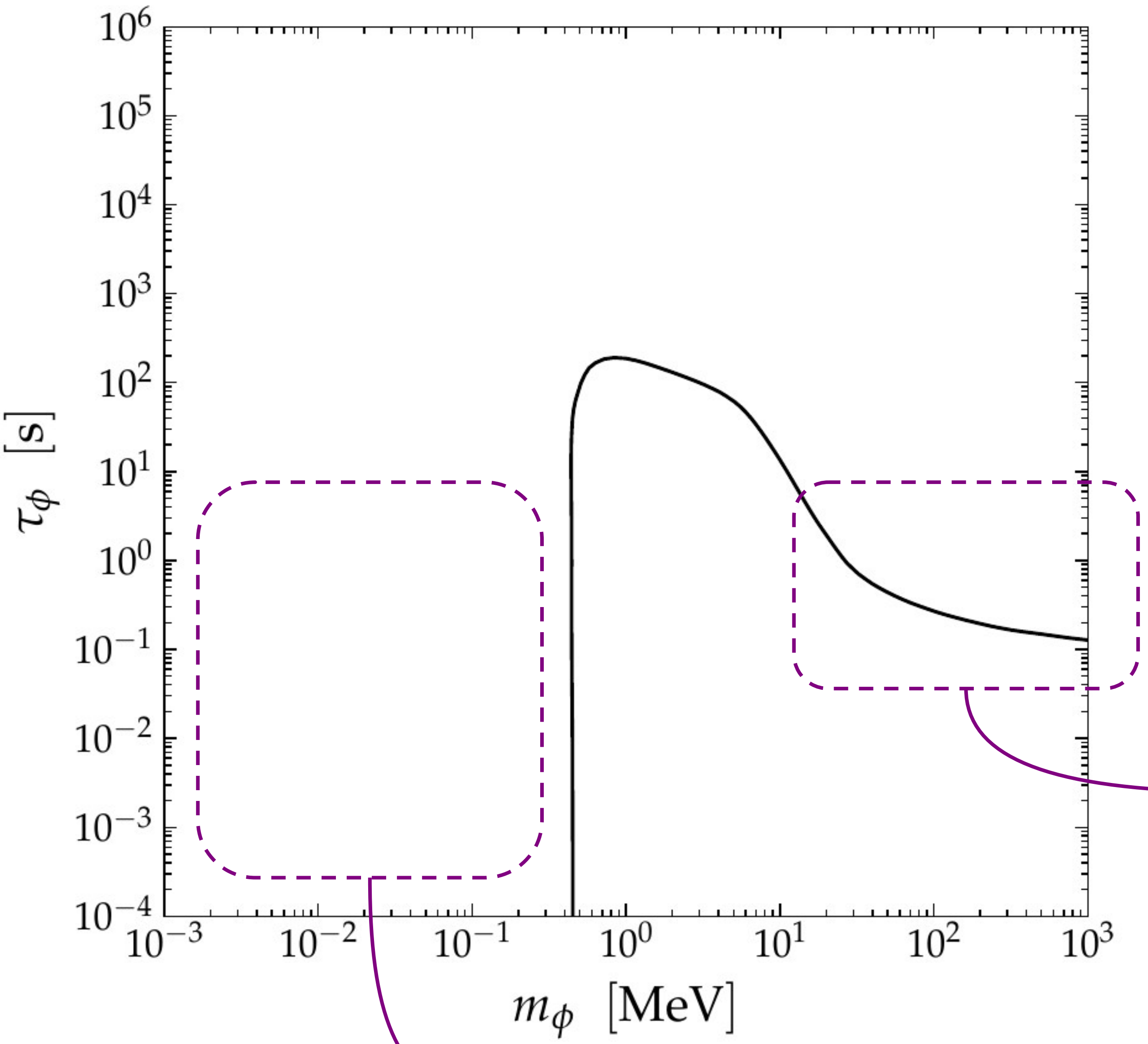


Boltzmann equation

$$\dot{n}_\phi + 3Hn_\phi = -\frac{n_\phi - \bar{n}_\phi}{\tau_{\phi,\text{eff}}}$$

Mediator is thermal during BBN: $m_\phi \lesssim 0.45\,\text{MeV}$

Constraints for fixed $\zeta_{\mathrm{cd}} = 1$



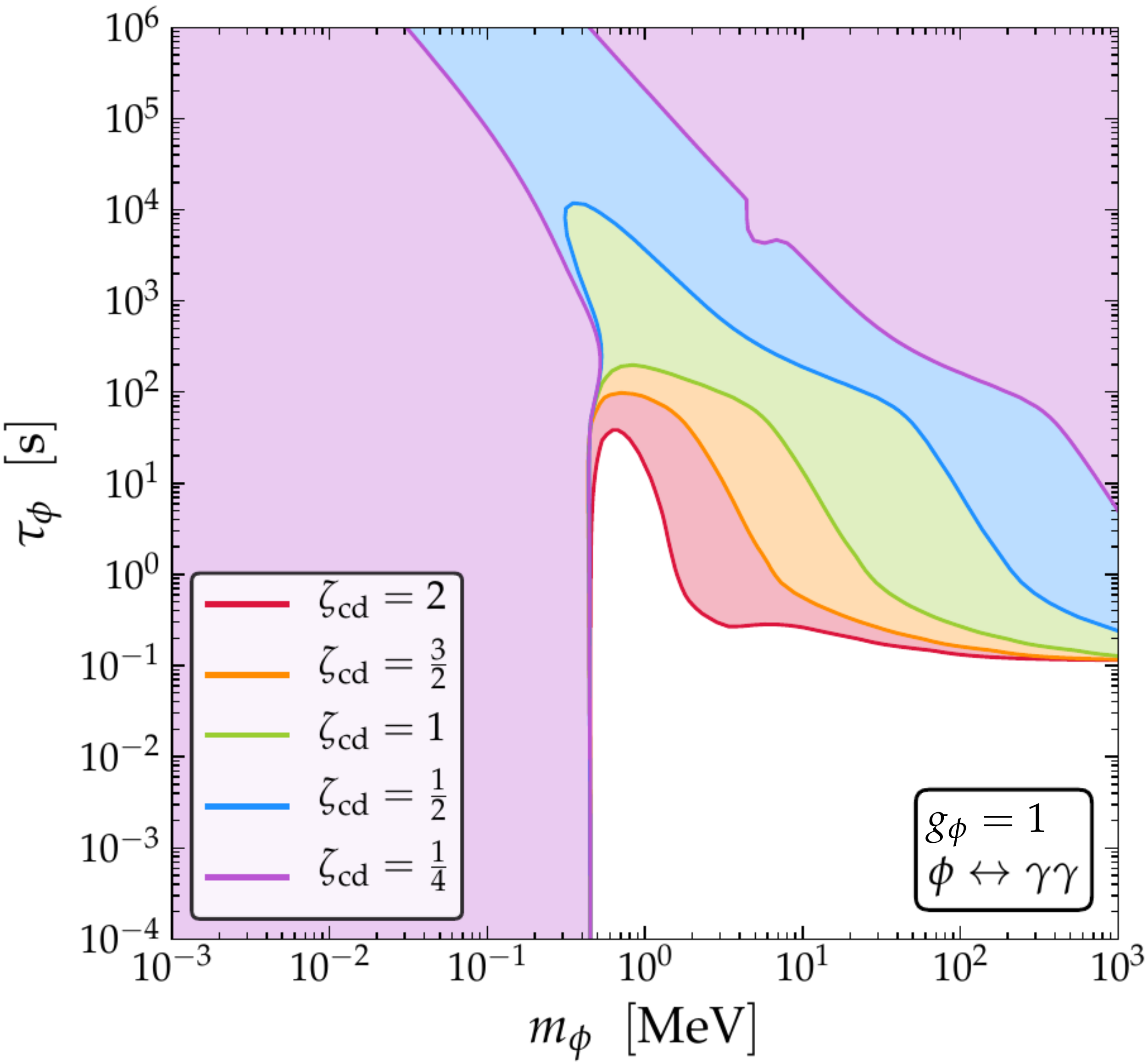
Boltzmann equation

$$\dot{n}_\phi + 3Hn_\phi = -\frac{n_\phi - \bar{n}_\phi}{\tau_{\phi,\mathrm{eff}}}$$

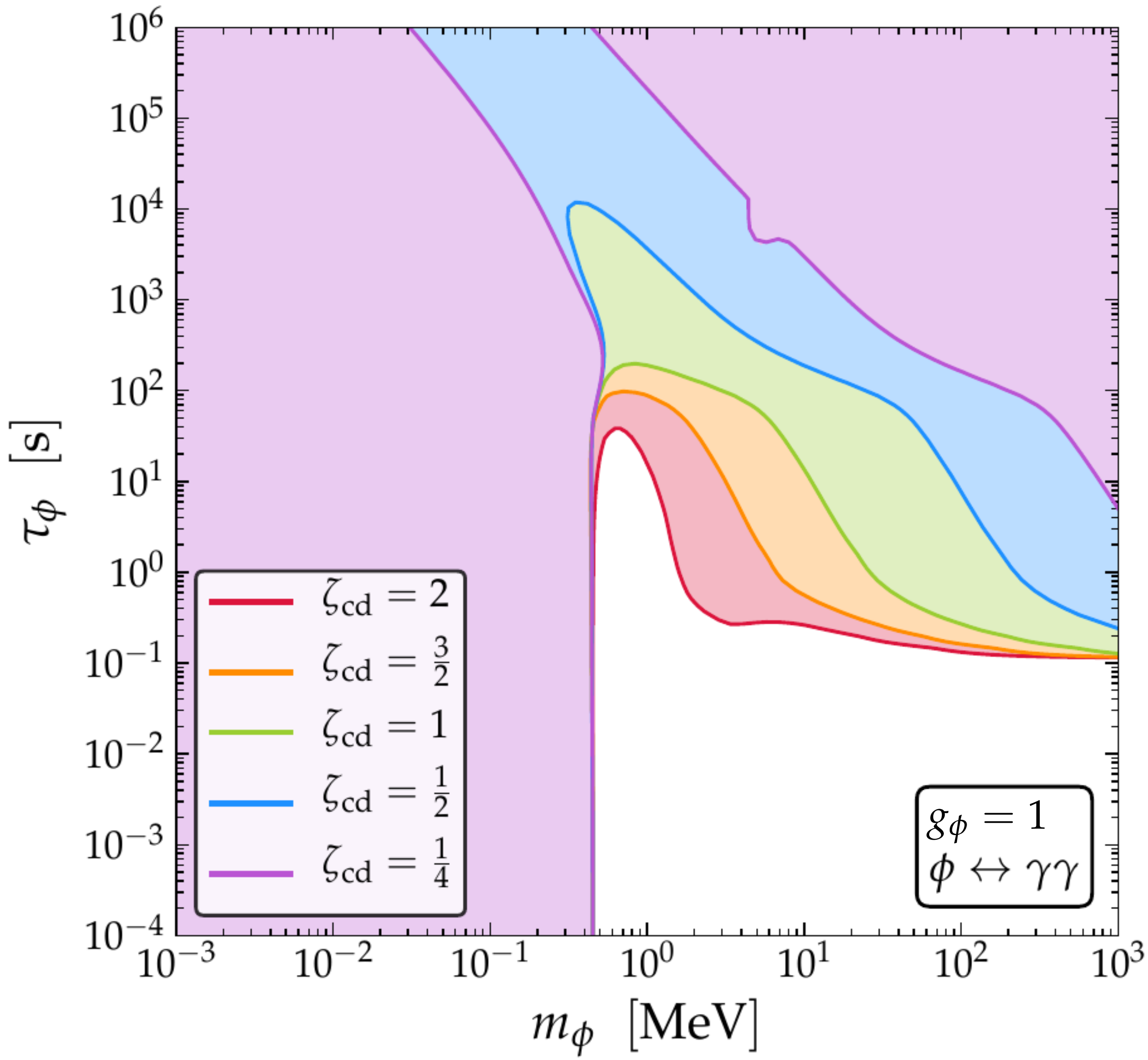
Mediator decays effectively before BBN: $\tau_\phi \gtrsim 0.1\,\mathrm{s}$

Mediator is thermal during BBN: $m_\phi \lesssim 0.45\,\mathrm{MeV}$

Constraints for fixed $\zeta_{\rm cd}$



Constraints for fixed ζ_{cd}

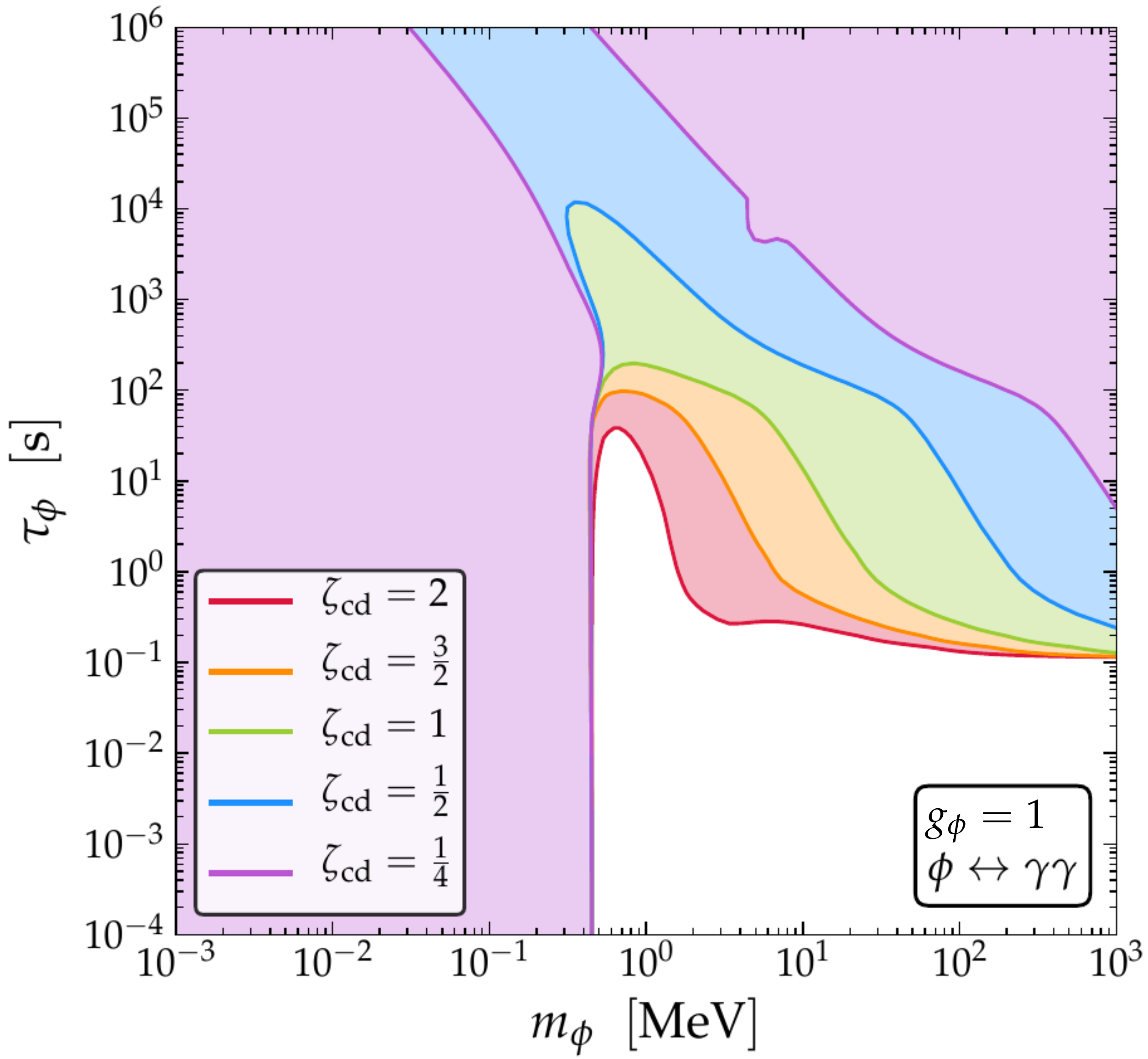


$T(t = \tau_\phi) \gg m_\phi$

Limits are **insensitive to** ζ_{cd}

→ full freeze-in
Thermalization renders initial condition meaningless

Constraints for fixed ζ_{cd}



$T(t = \tau_\phi) \gg m_\phi$

Limits are **insensitive to** ζ_{cd}

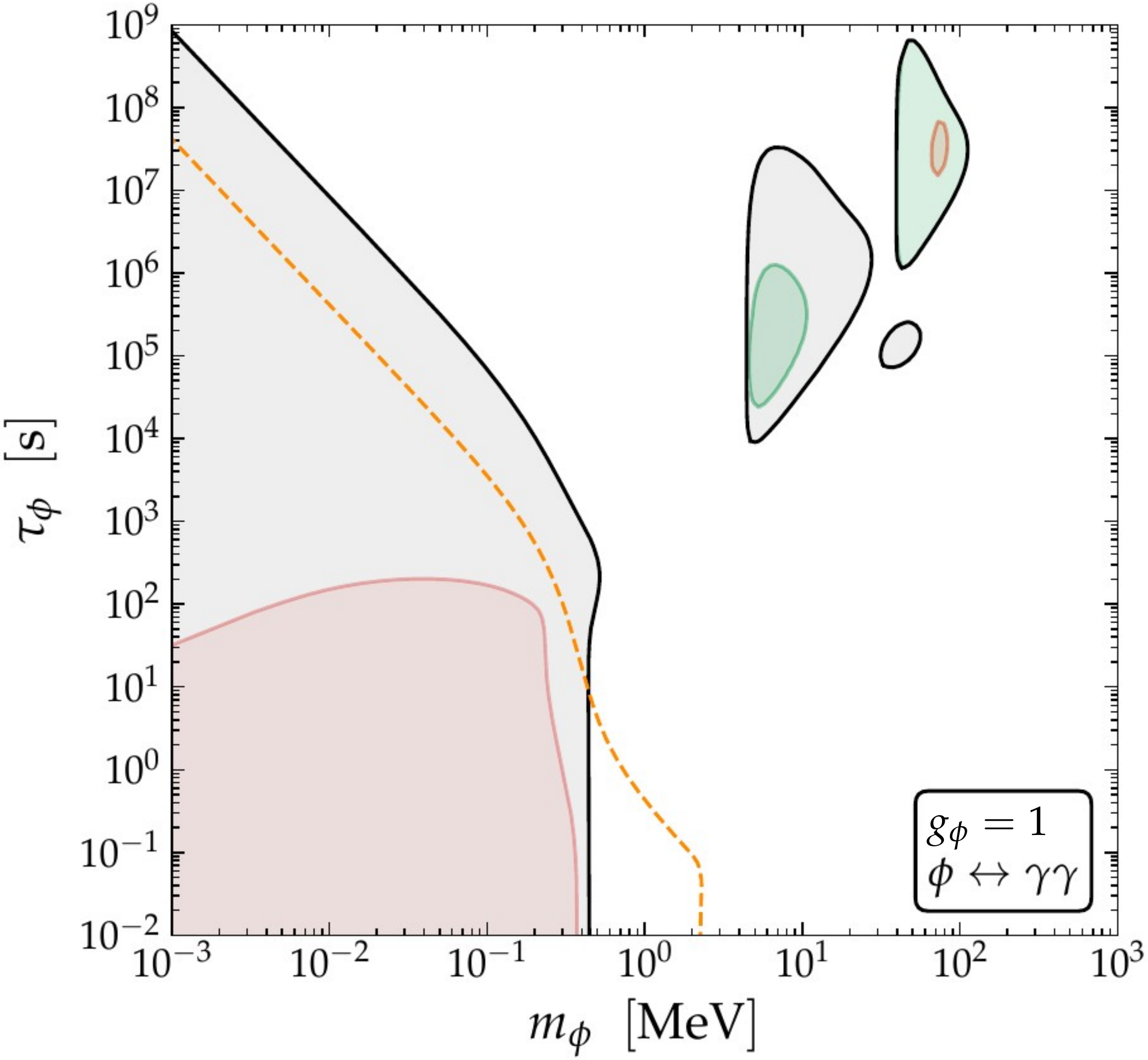
→ full freeze-in
Thermalization renders initial condition meaningless

$T(t = \tau_\phi) \ll m_\phi$

Limits mostly **scale with** ζ_{cd}

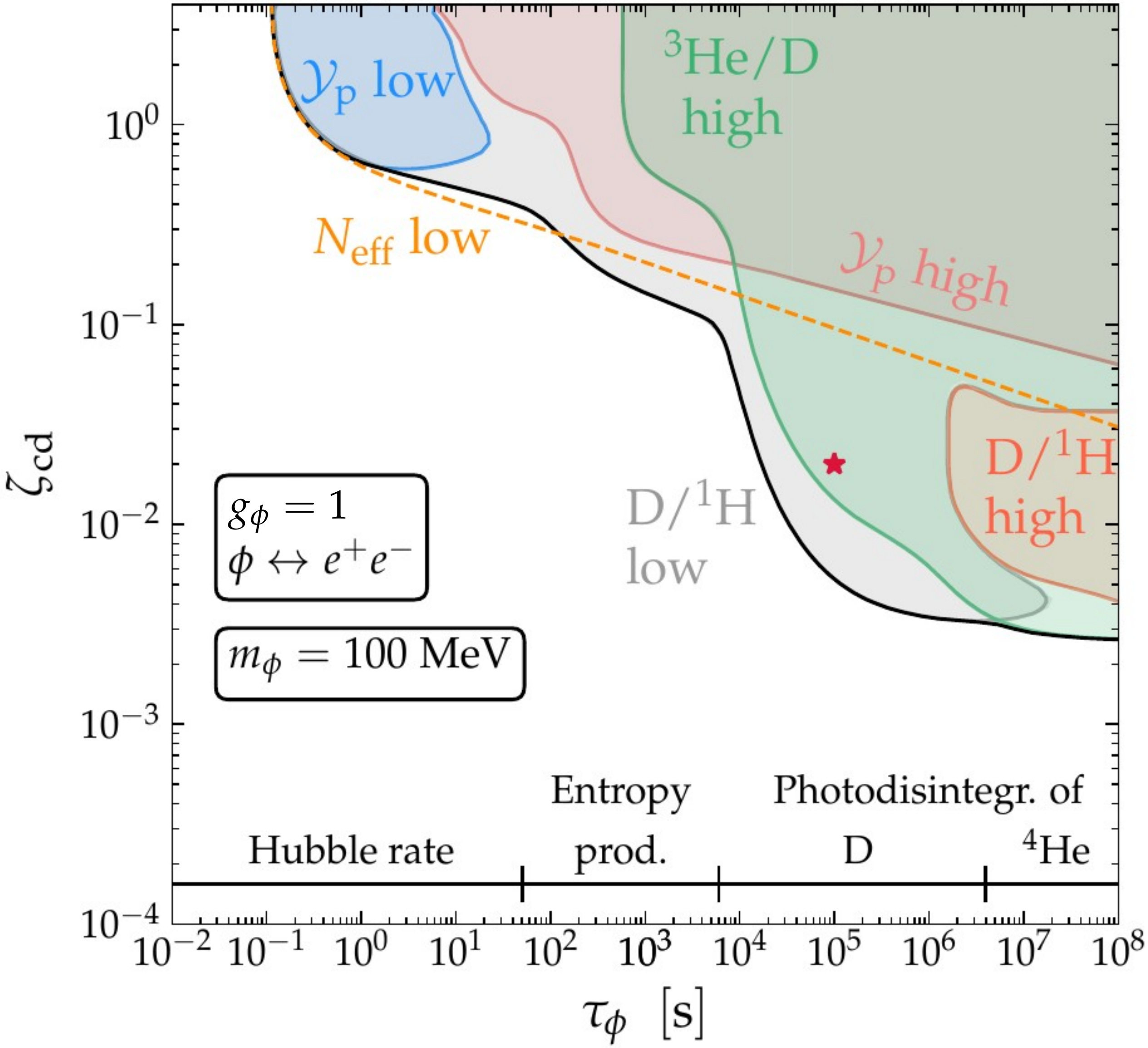
→ 'traditional' decay

Constraints for fixed $\zeta_{\mathrm{cd}} = 0$ (freeze-in)



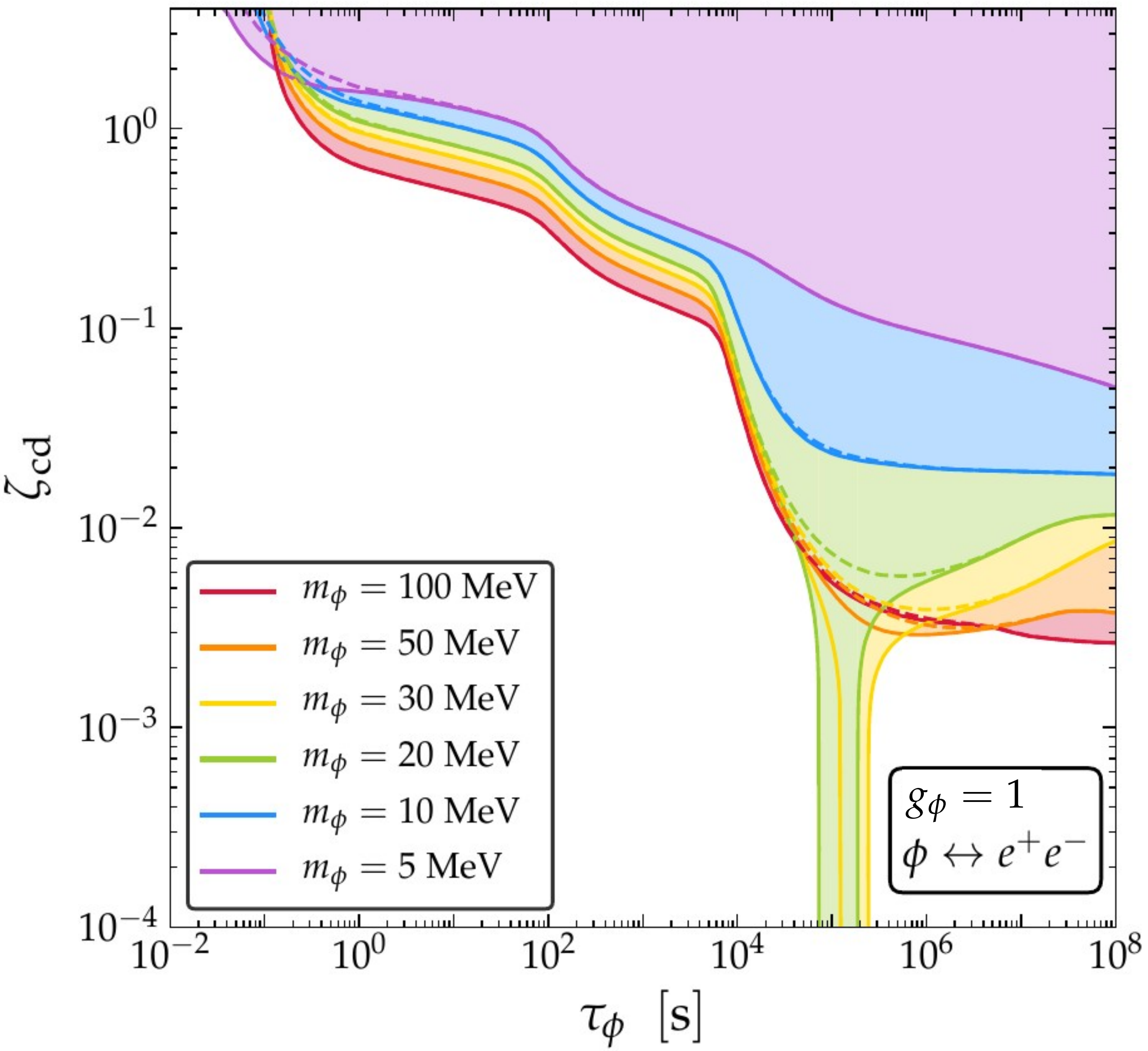
Constraints for fixed $m_\phi = 100\,\mathrm{MeV}$

$$n_\phi/n_\gamma|_{T_{\mathrm{cd}}} \propto \zeta_{\mathrm{cd}}^3$$



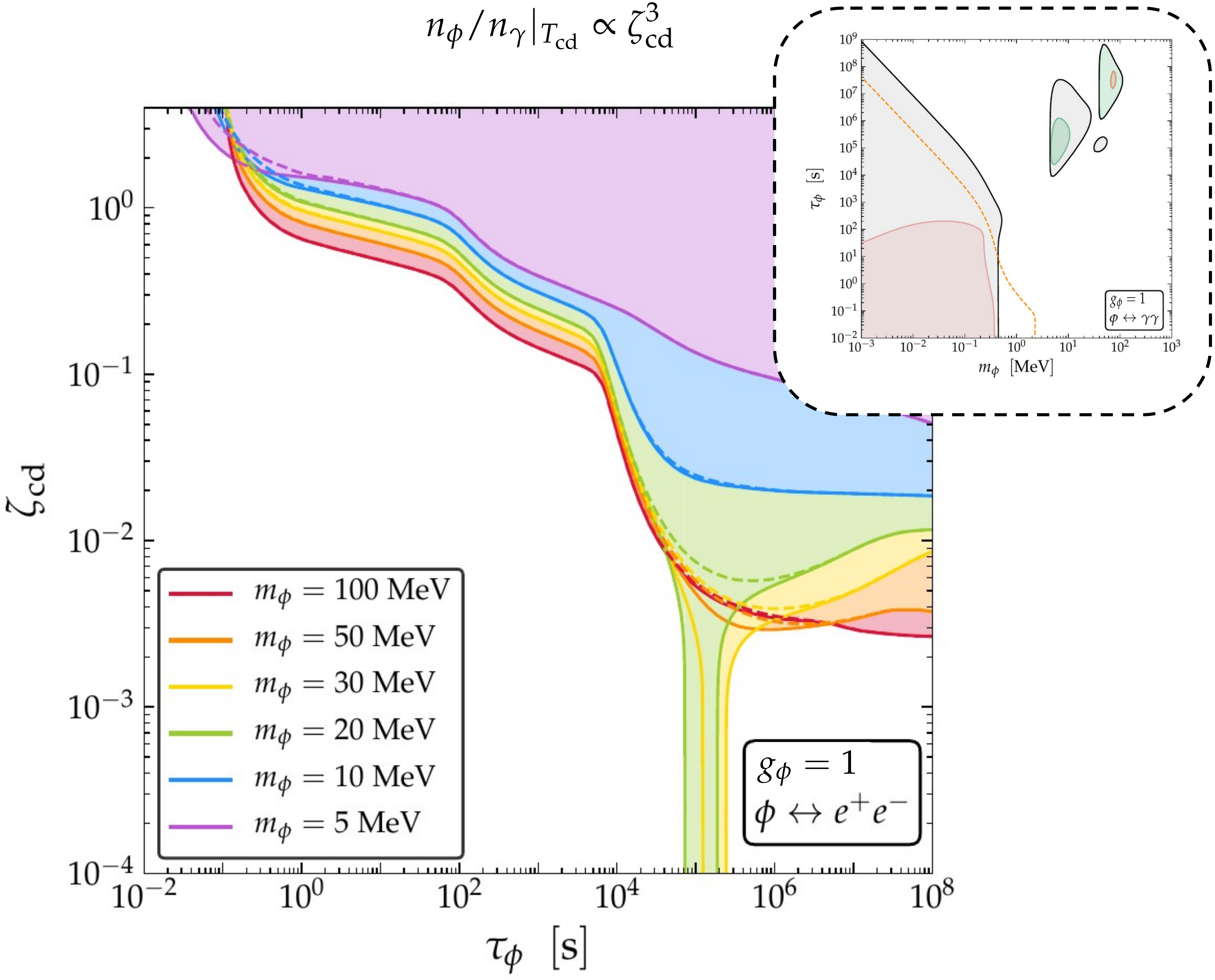
Constraints for fixed m_ϕ

$$n_\phi / n_\gamma |_{T_{\rm cd}} \propto \zeta_{\rm cd}^3$$



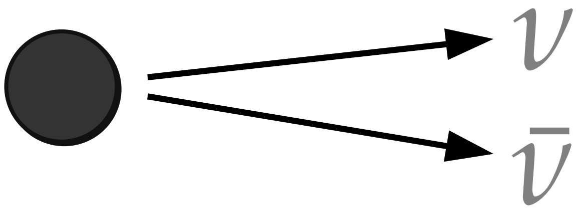
Constraints for fixed m_ϕ

$$n_\phi/n_\gamma|_{T_{\rm cd}} \propto \zeta_{\rm cd}^3$$



Decays into Neutrinos

Decay channel(s)



Relevant effects ?

Hubble rate

Entropy

Photodis.

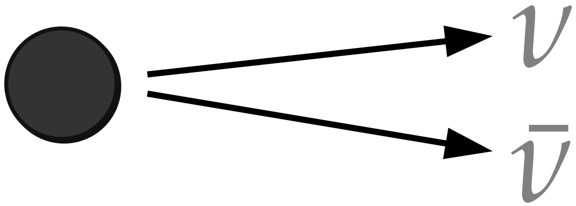
Hadrodis.

ν dec.

$n - p$ conv.

Decays into Neutrinos

Decay channel(s)



Relevant effects

Hubble rate

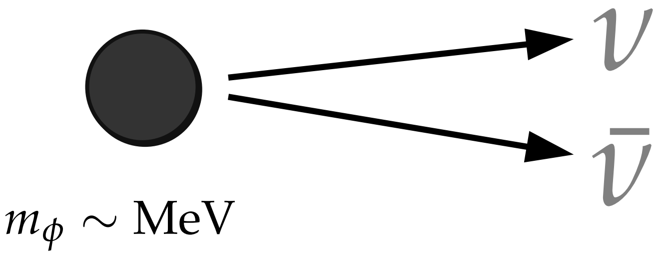
Entropy

ν dec.

$n - p$ conv.

Decays into Neutrinos

Decay channel(s)



Relevant effects

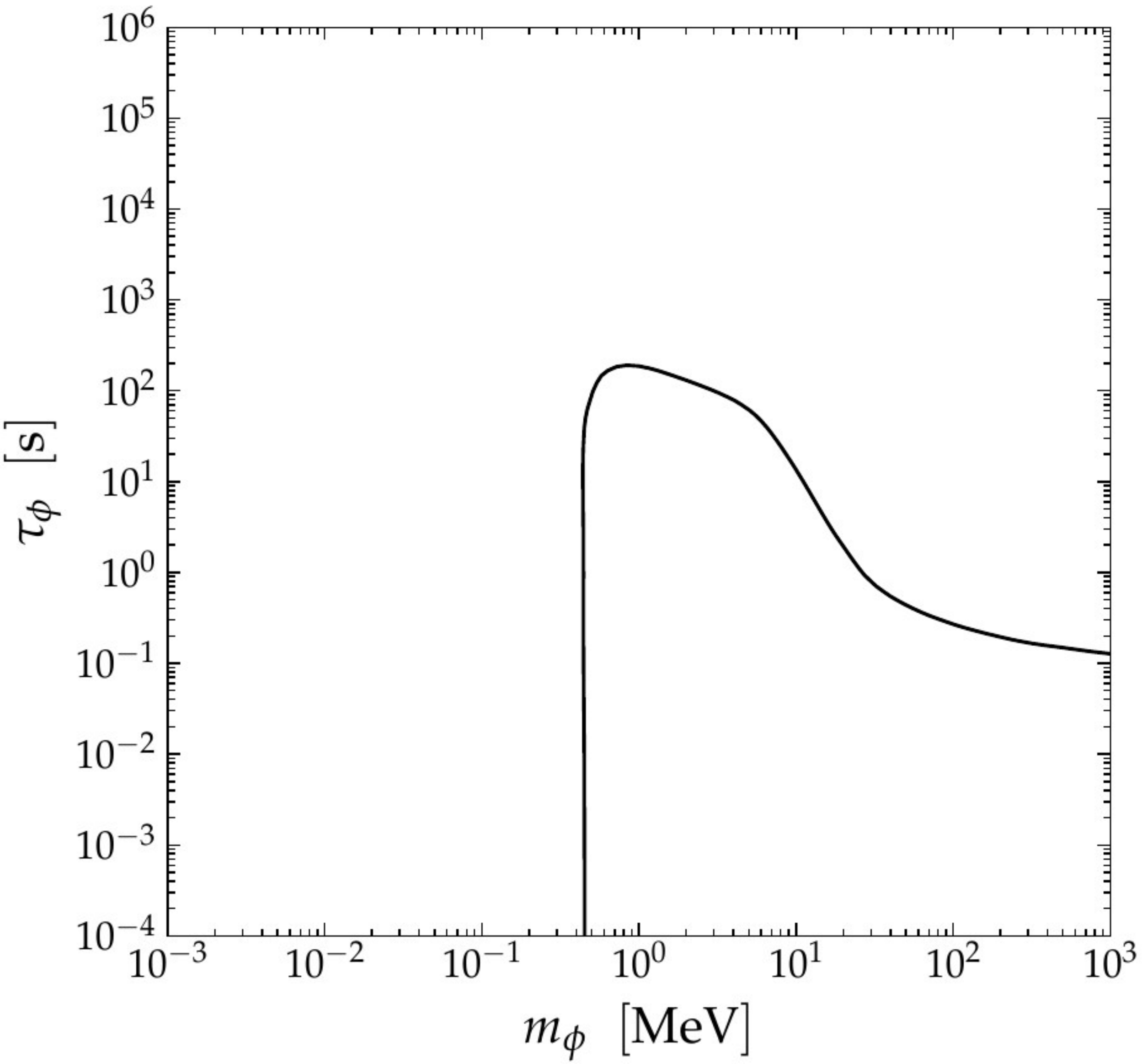
Hubble rate

Entropy

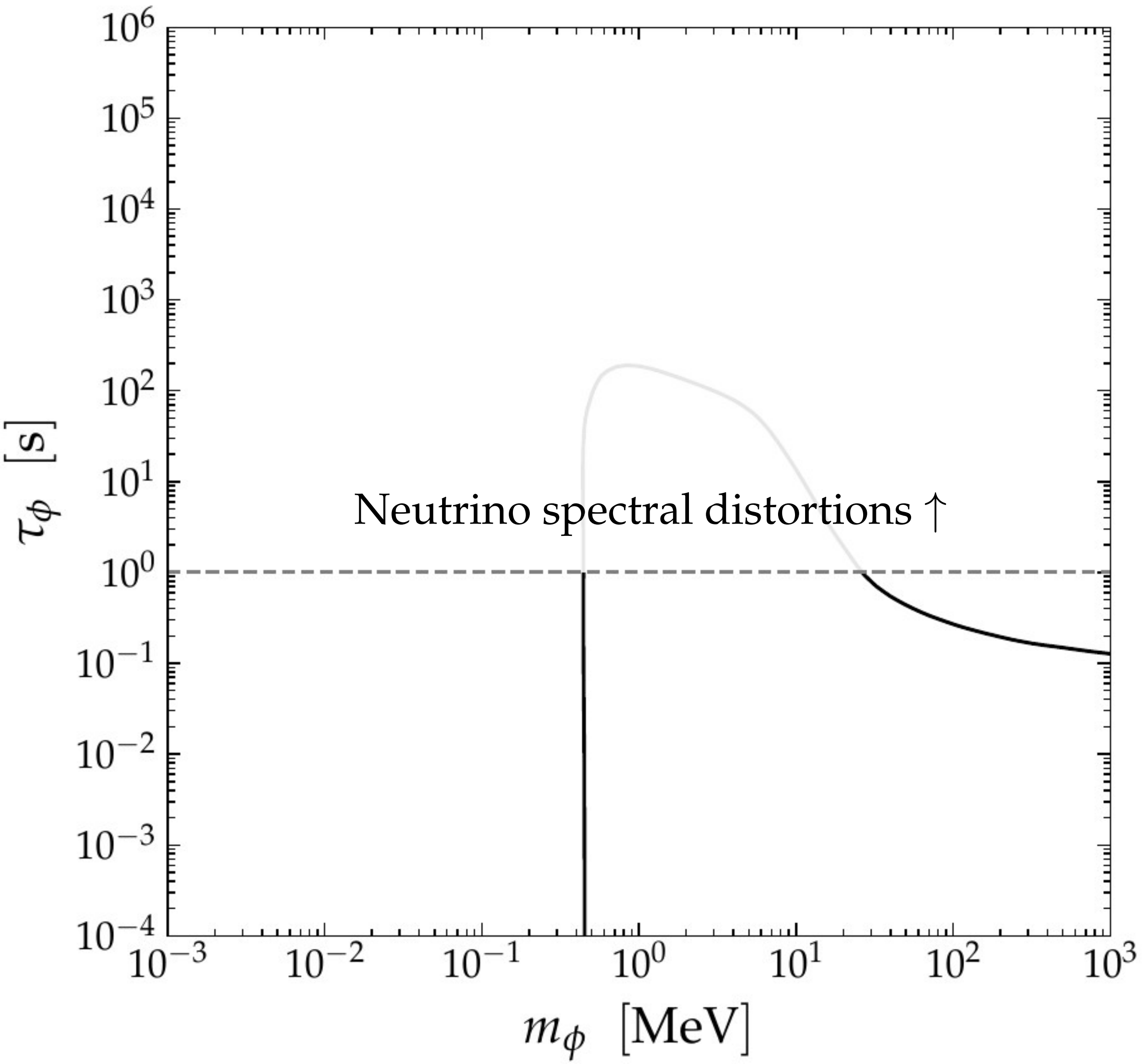
ν dec.

$n - p$ conv.

Constraints for fixed $\zeta_{\mathrm{cd}} = 1$ (again)

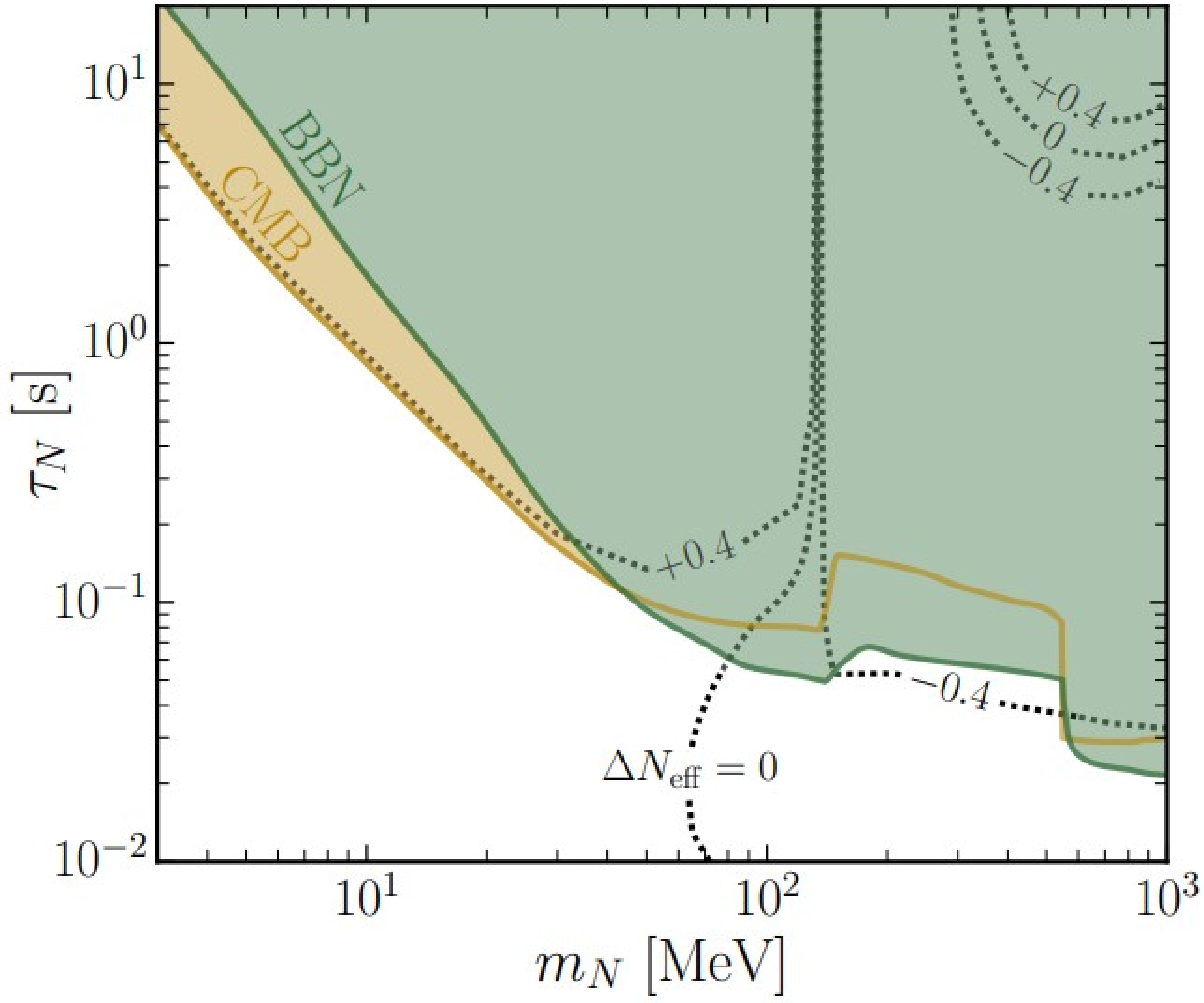


Constraints for fixed $\zeta_{\text{cd}} = 1$ (again)



Existing constraints for HNLs

[arXiv:2103.09831]

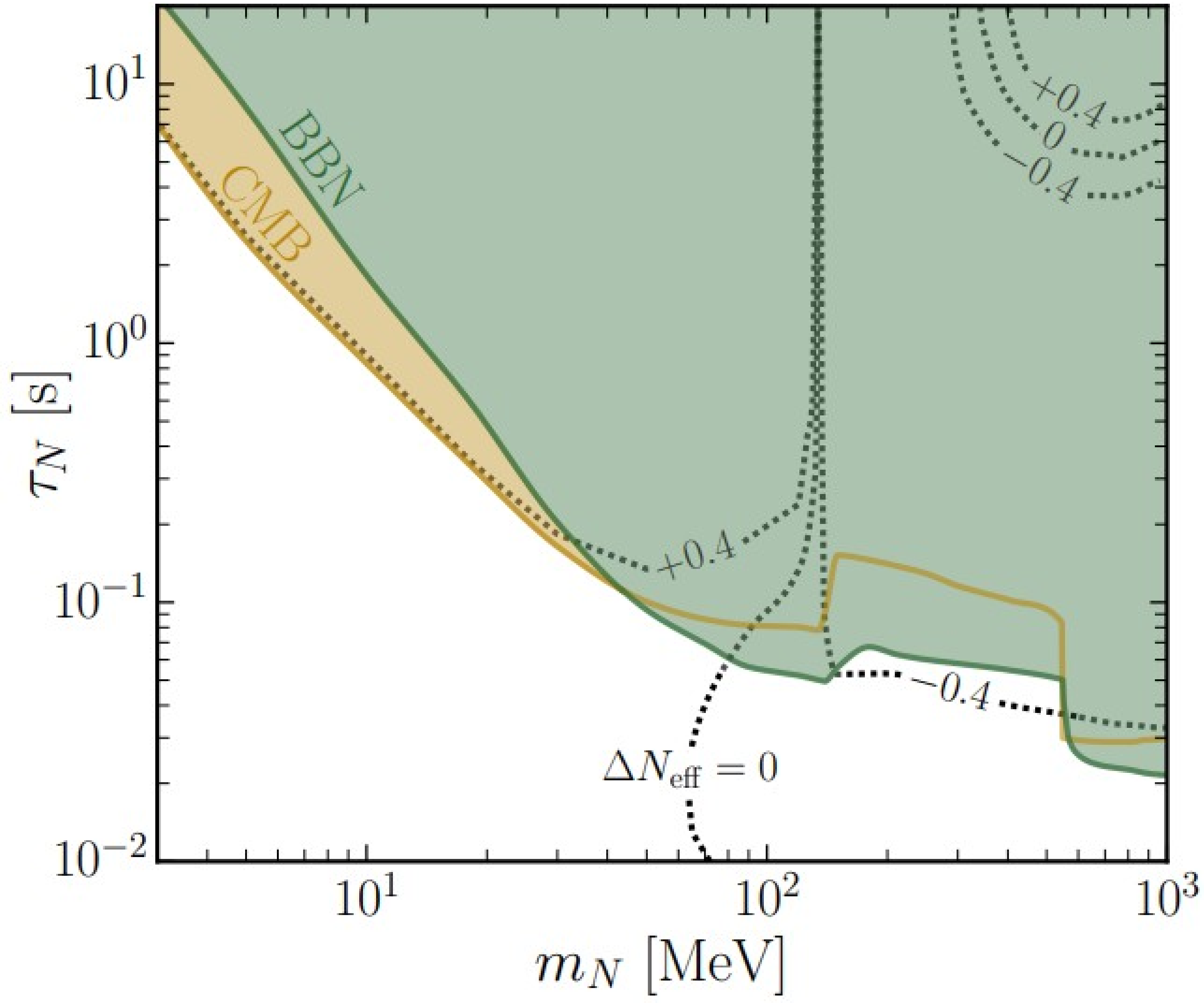


Lagrangian

$$\mathcal{L} = y_{ij}\bar{L}_i H^c N_j + \text{h.c.}$$

Existing constraints for HNLs

[arXiv:2103.09831]



Lagrangian

$$\mathcal{L} = y_{ij}\bar{L}_i H^c N_j + \text{h.c.}$$

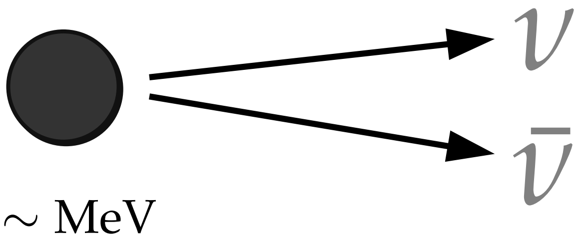
$$N \to \nu\nu\bar{\nu}$$

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

$$N \to \nu\pi\pi$$

Decays into Neutrinos

Decay channel(s)



Relevant effects ?

Hubble rate

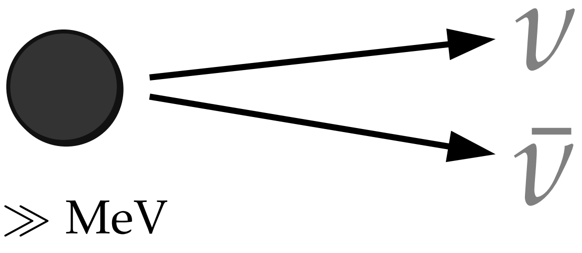
Entropy

ν dec.

$n - p$ conv.

Decays into Neutrinos

Decay channel(s)



Relevant effects ?

Hubble rate

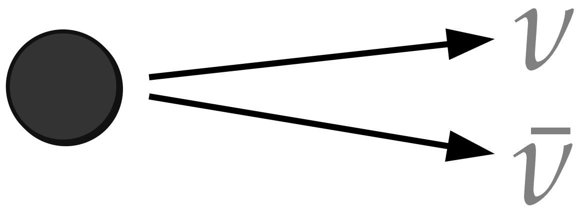
Entropy

ν dec.

$n - p$ conv.

Decays into Neutrinos

Decay channel(s)



Relevant effects ?

Hubble rate

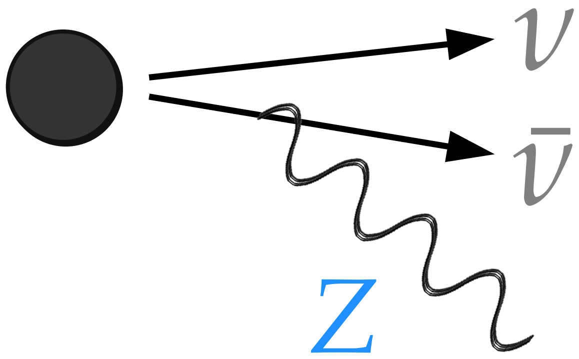
Entropy

ν dec.

$n - p$ conv.

Decays into Neutrinos

Decay channel(s)



Relevant effects ?

Hubble rate

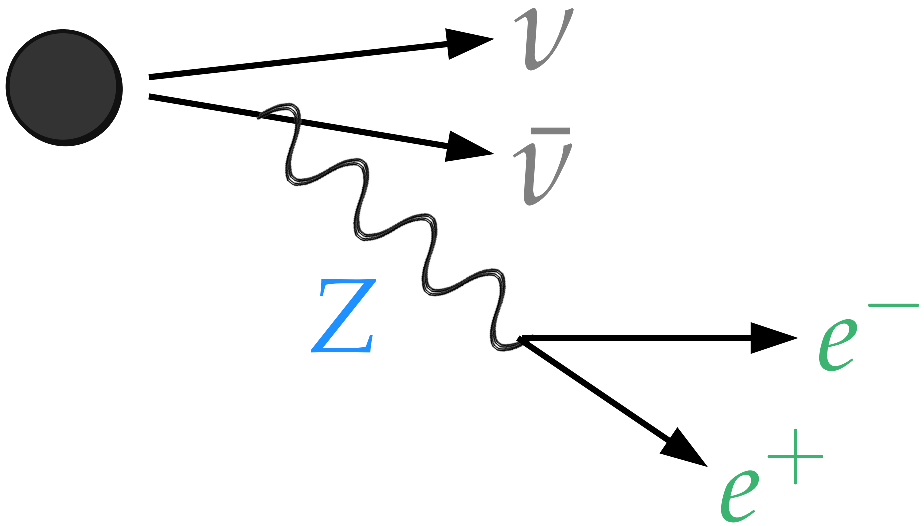
Entropy

ν dec.

$n - p$ conv.

Decays into Neutrinos

Decay channel(s)



Relevant effects ?

Hubble rate

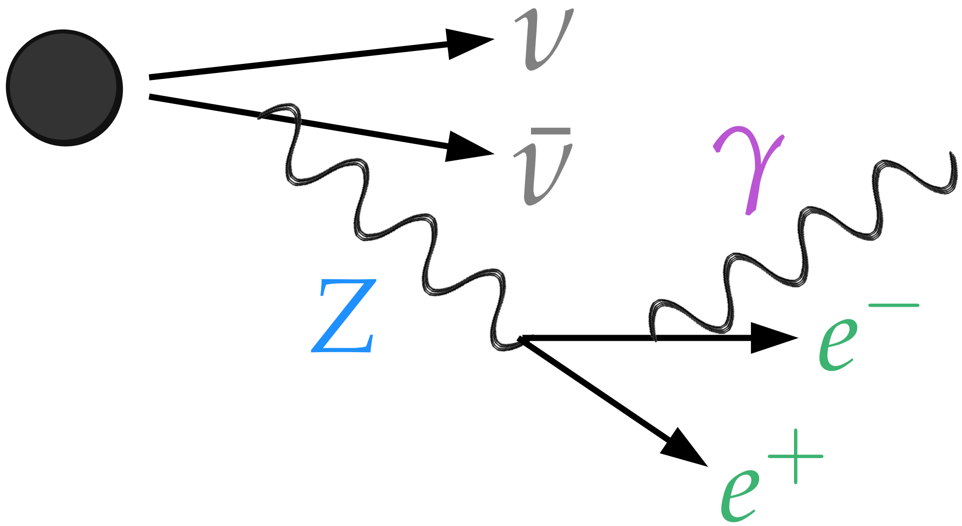
Entropy

ν dec.

$n - p$ conv.

Decays into Neutrinos

Decay channel(s)



Relevant effects ?

Hubble rate

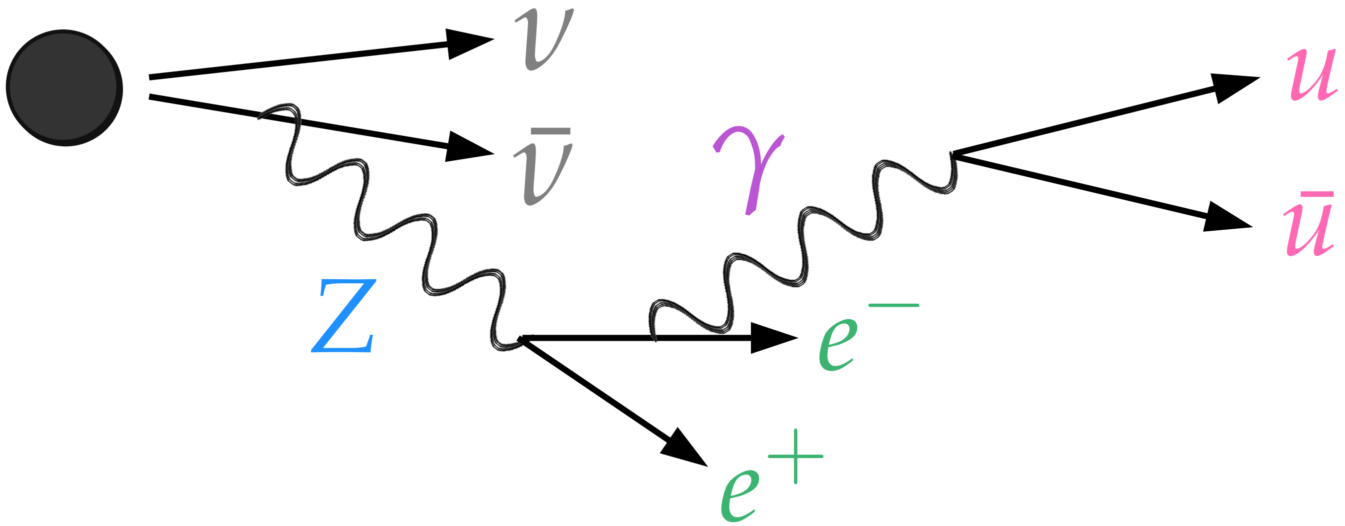
Entropy

ν dec.

$n - p$ conv.

Decays into Neutrinos

Decay channel(s)



Relevant effects ?

Hubble rate

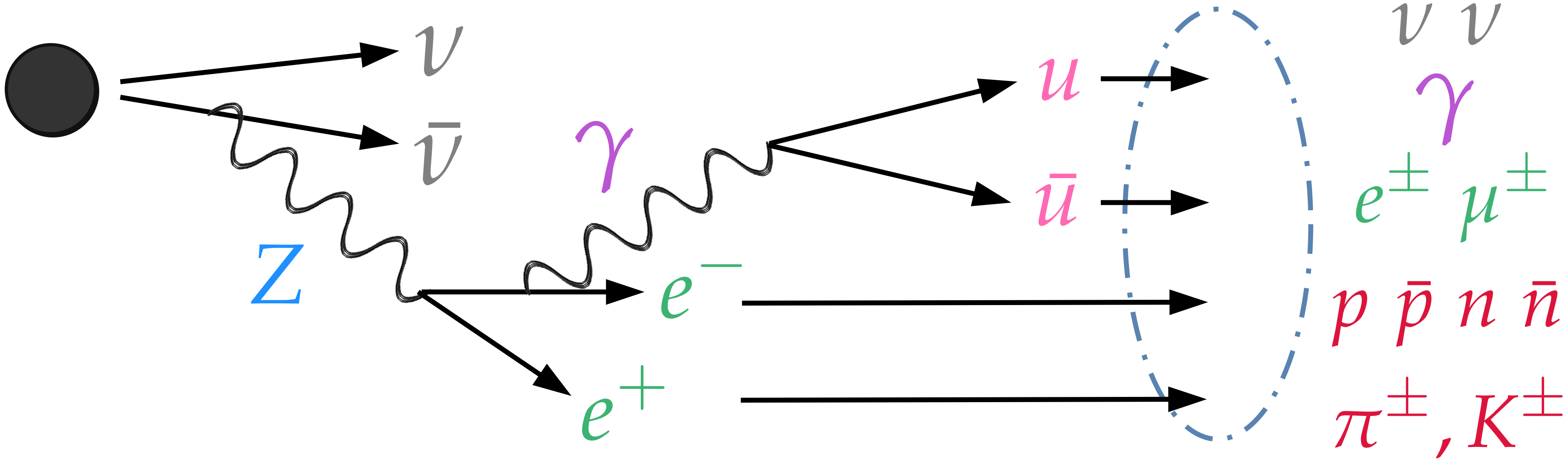
Entropy

ν dec.

$n - p$ conv.

Decays into Neutrinos

Decay channel(s)



Relevant effects ?

Hubble rate

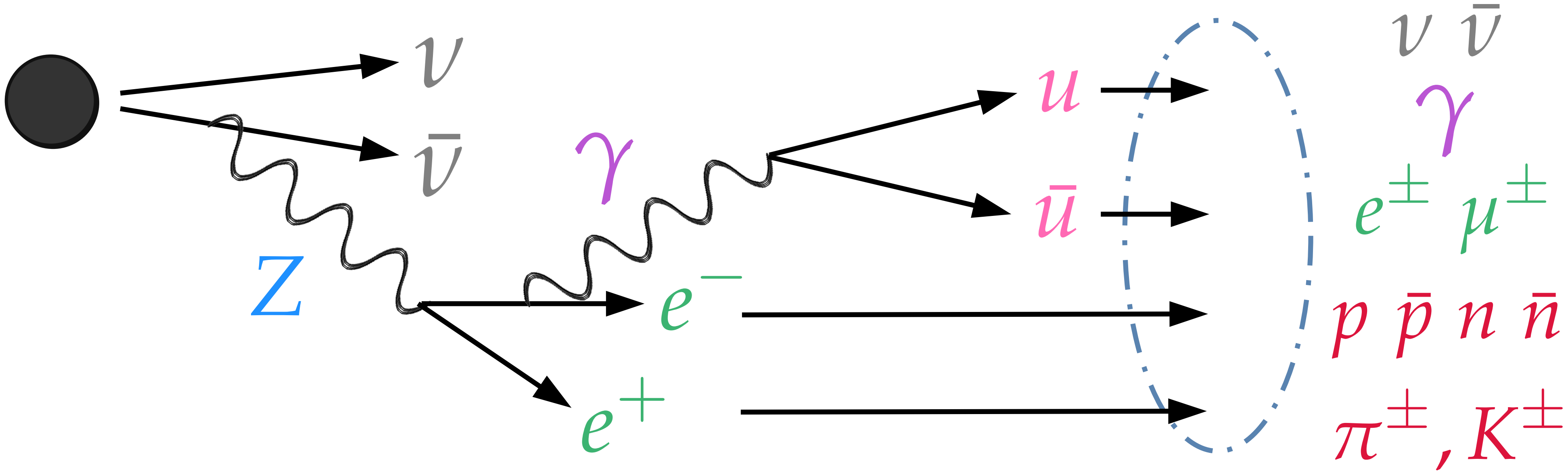
Entropy

ν dec.

$n - p$ conv.

Decays into Neutrinos

Decay channel(s)



Relevant effects

Hubble rate

Entropy

Photodis.

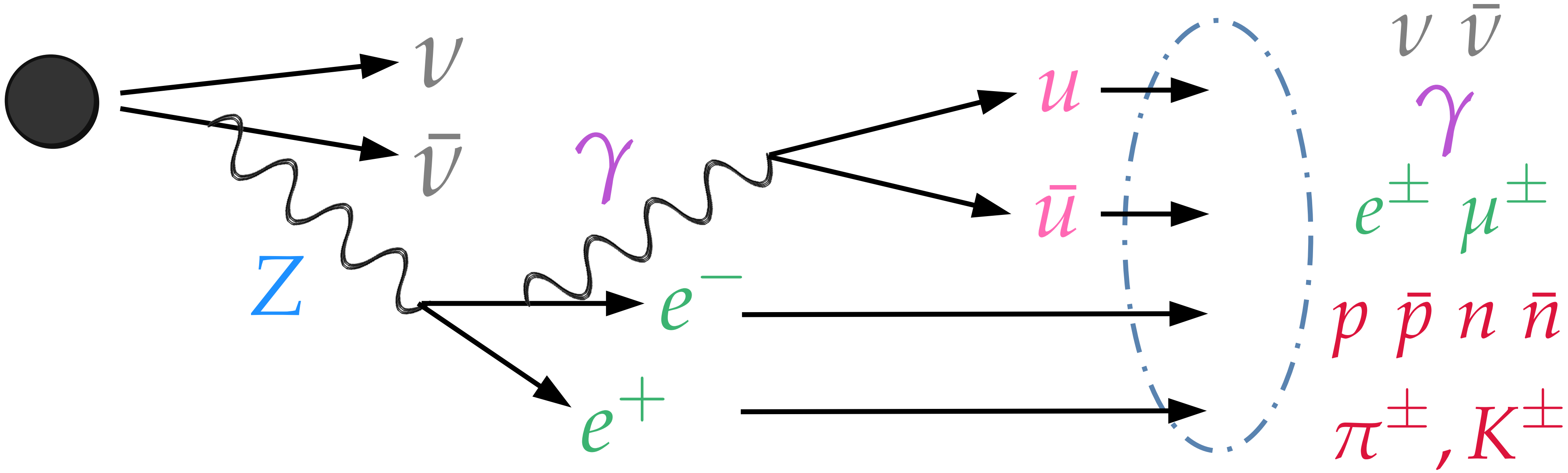
Hadrodis.

ν dec.

$n-p$ conv.

Decays into Neutrinos

Decay channel(s)



Relevant effects

Hubble rate

Entropy

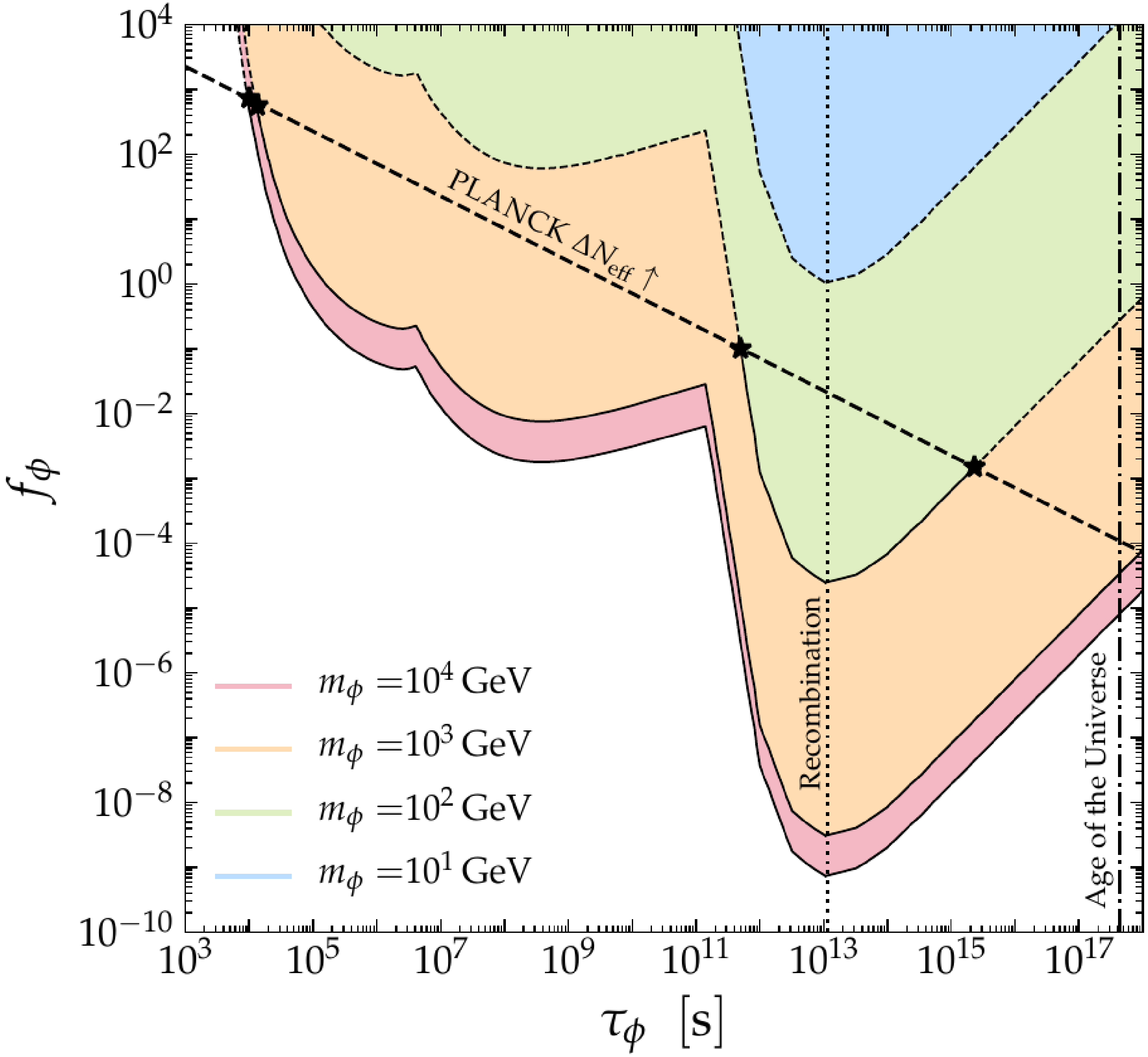
Photodis.

Hadrodis.

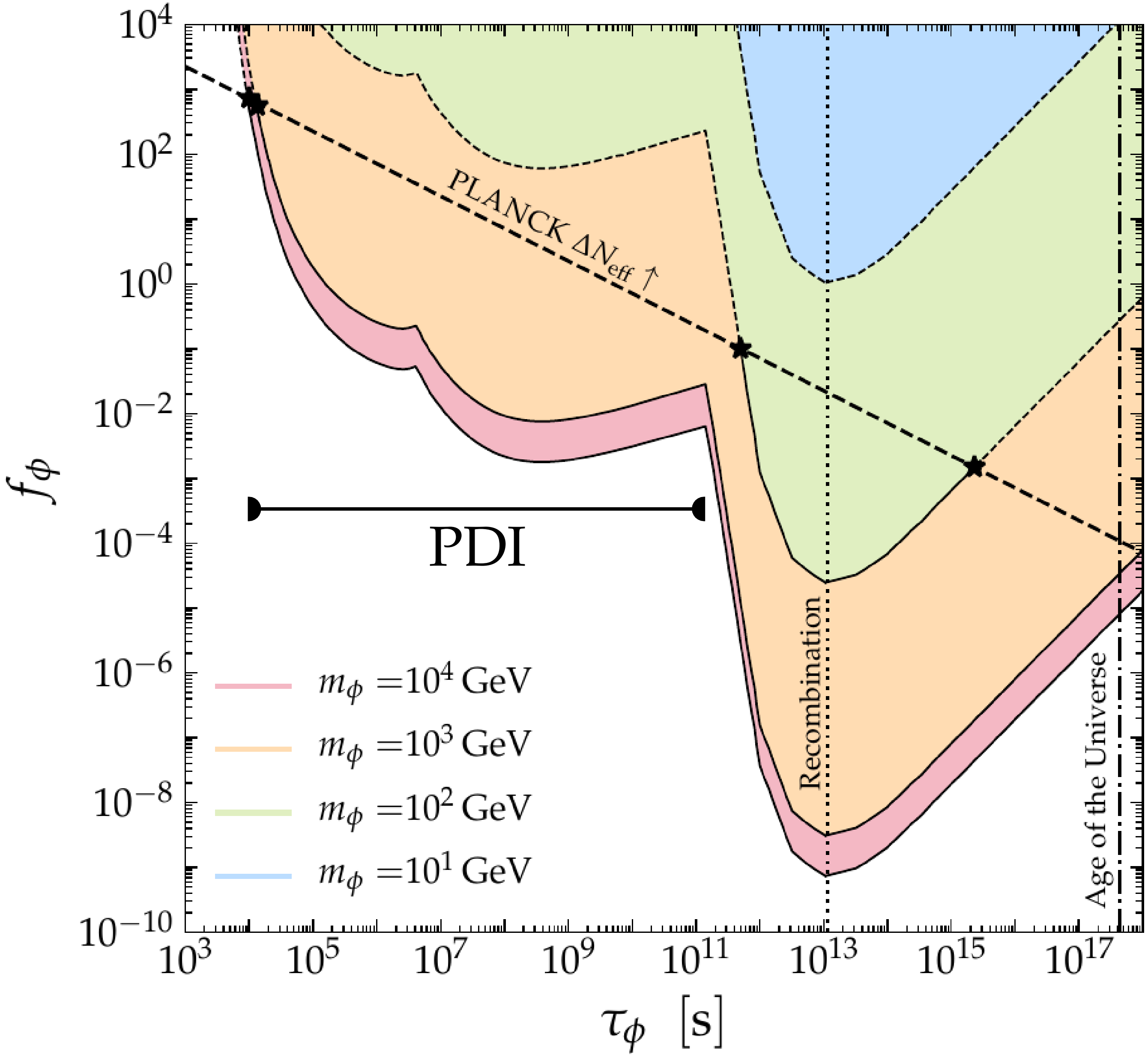
ν dec.

$n-p$ conv.

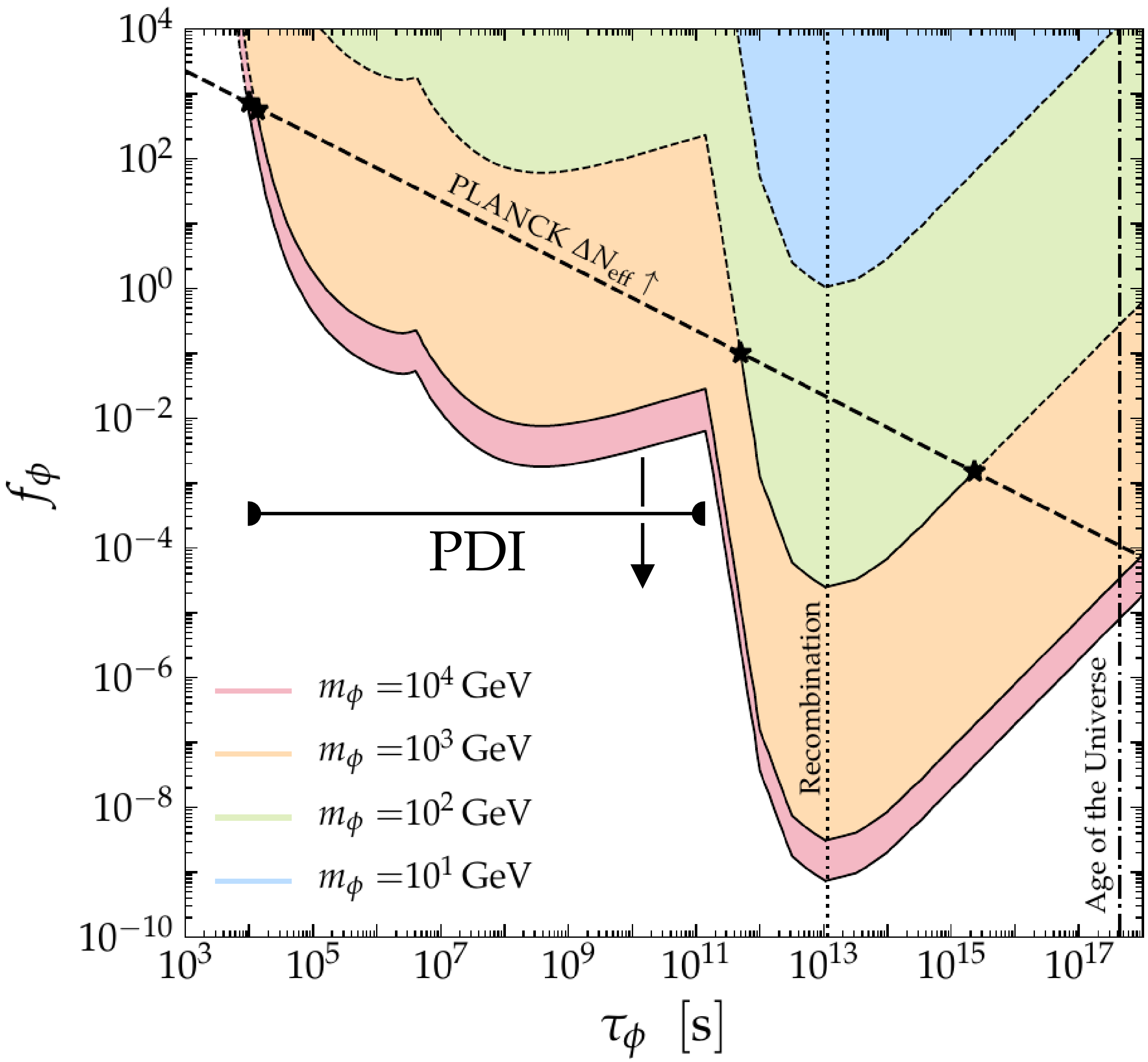
Constraints from PDI for fixed $m_\phi \gg$ MeV



Constraints from PDI for fixed $m_\phi \gg$ MeV

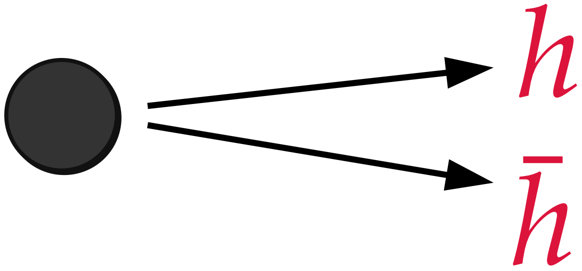


Constraints from PDI for fixed $m_\phi \gg \text{MeV}$



Hadronic decays

Decay channel(s)



Relevant effects ?

Hubble rate

Entropy

Photodis.

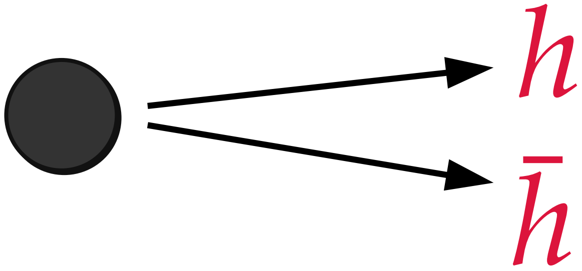
Hadrodis.

ν dec.

$n - p$ conv.

Hadronic decays

Decay channel(s)



Relevant effects

Hubble rate

Entropy

Photodis.

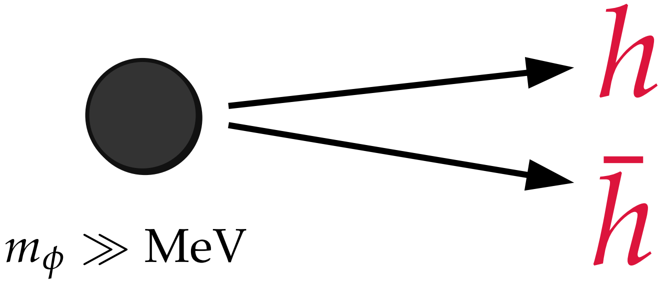
Hadrodis.

ν dec.

$n - p$ conv.

Hadronic decays

Decay channel(s)



Relevant effects

Hubble rate

Entropy

Photodis.

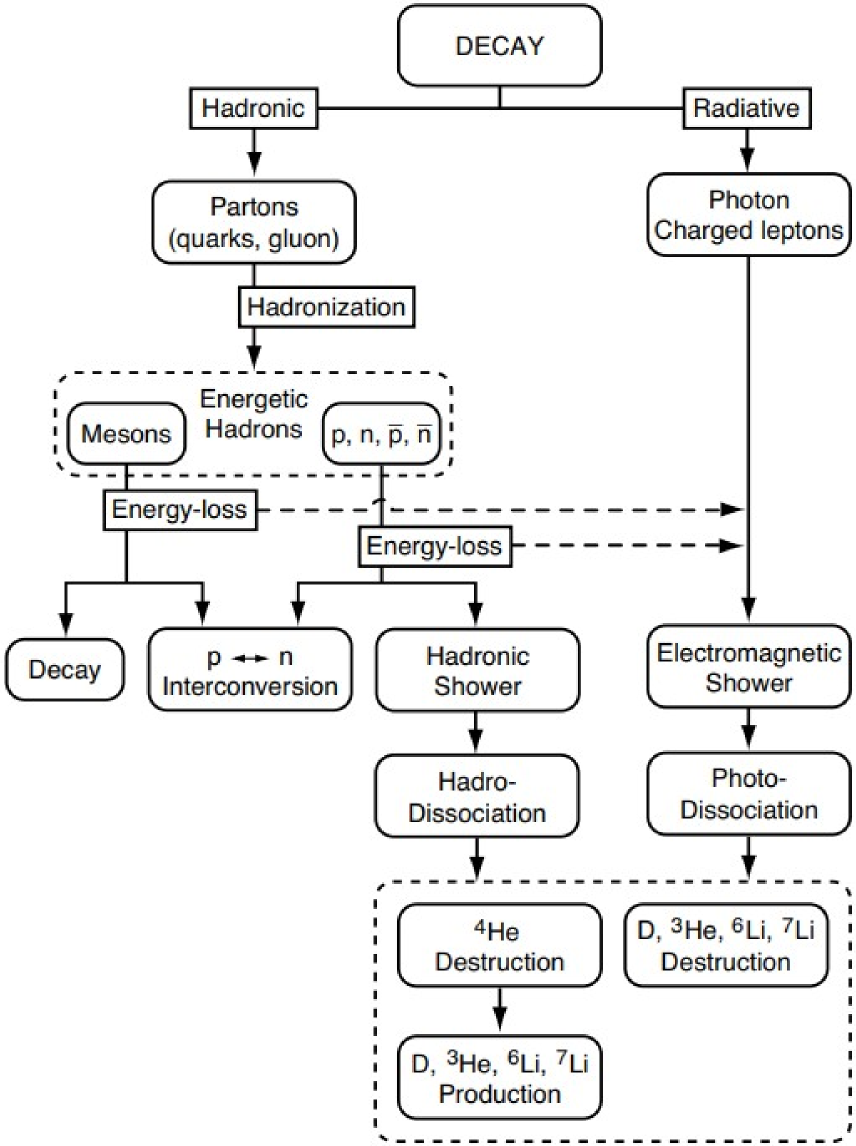
Hadrodis.

ν dec.

$n - p$ conv.

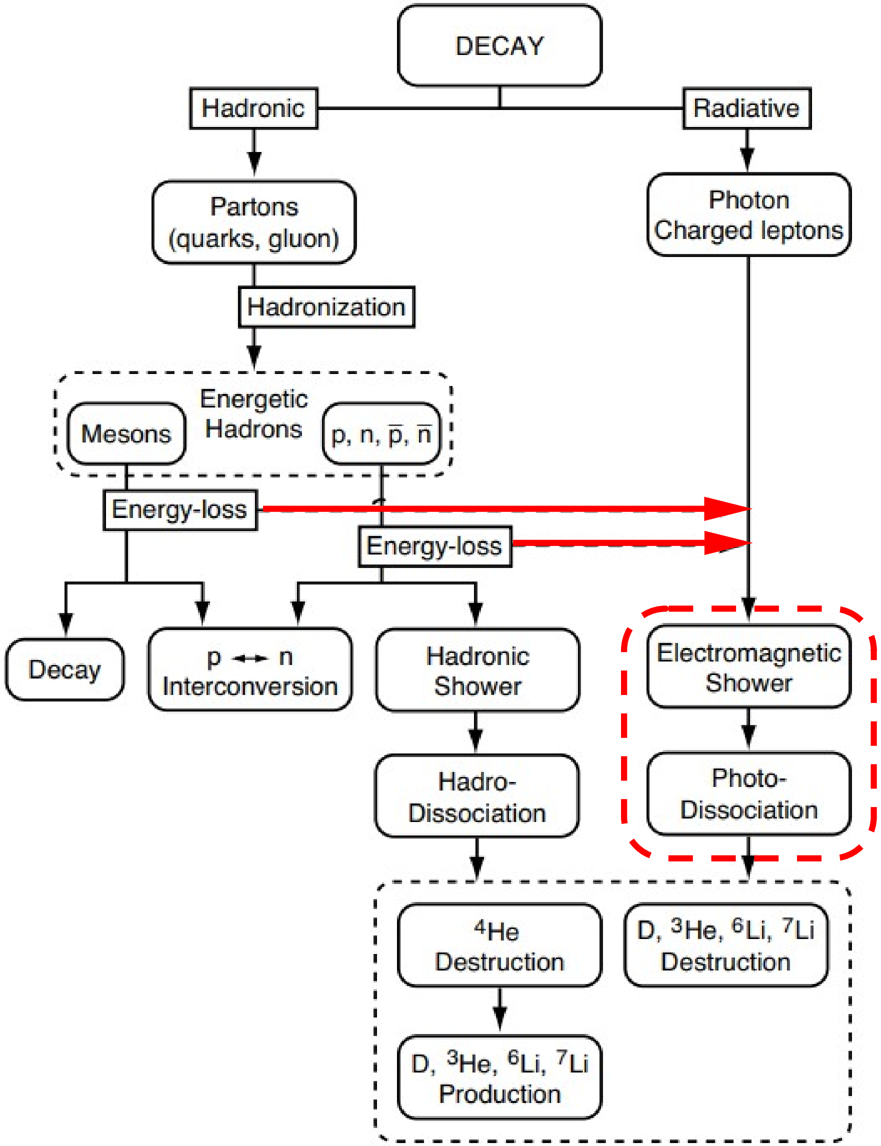
Flowchart for hadronic decays

[arXiv:2103.09831]



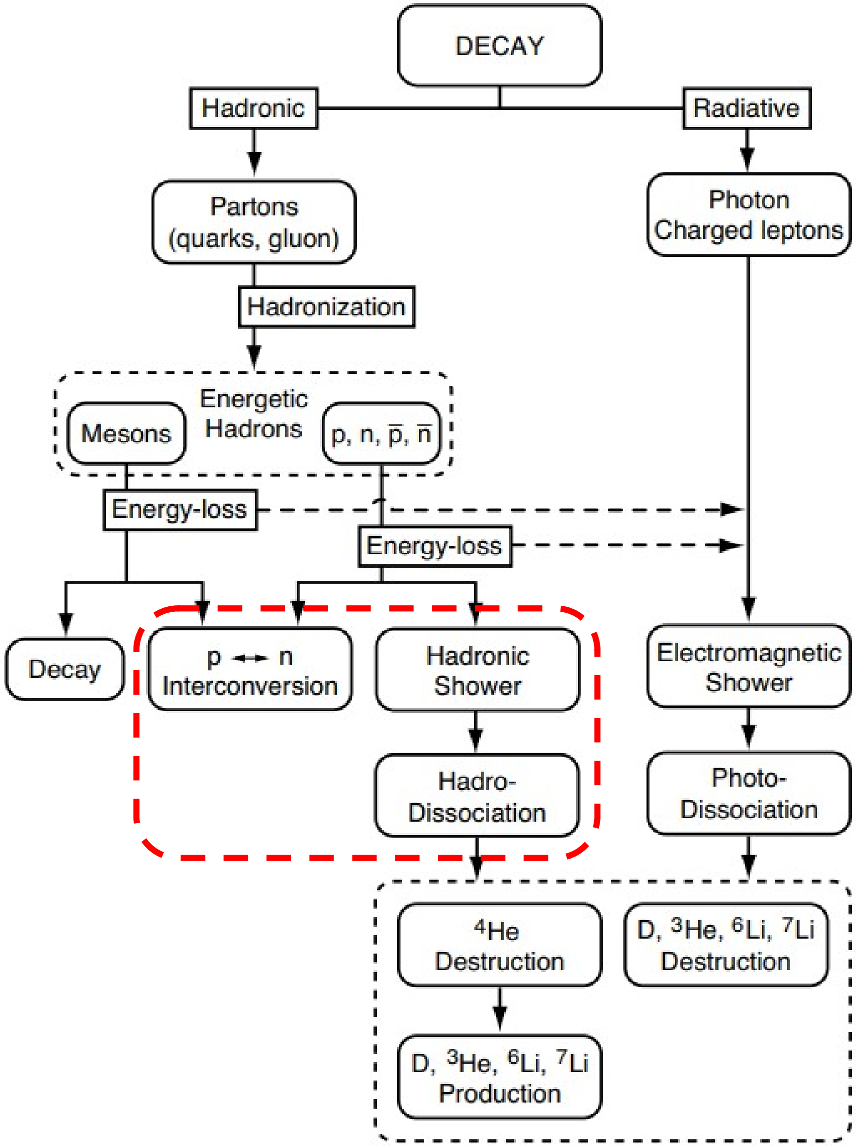
Flowchart for hadronic decays

[arXiv:2103.09831]



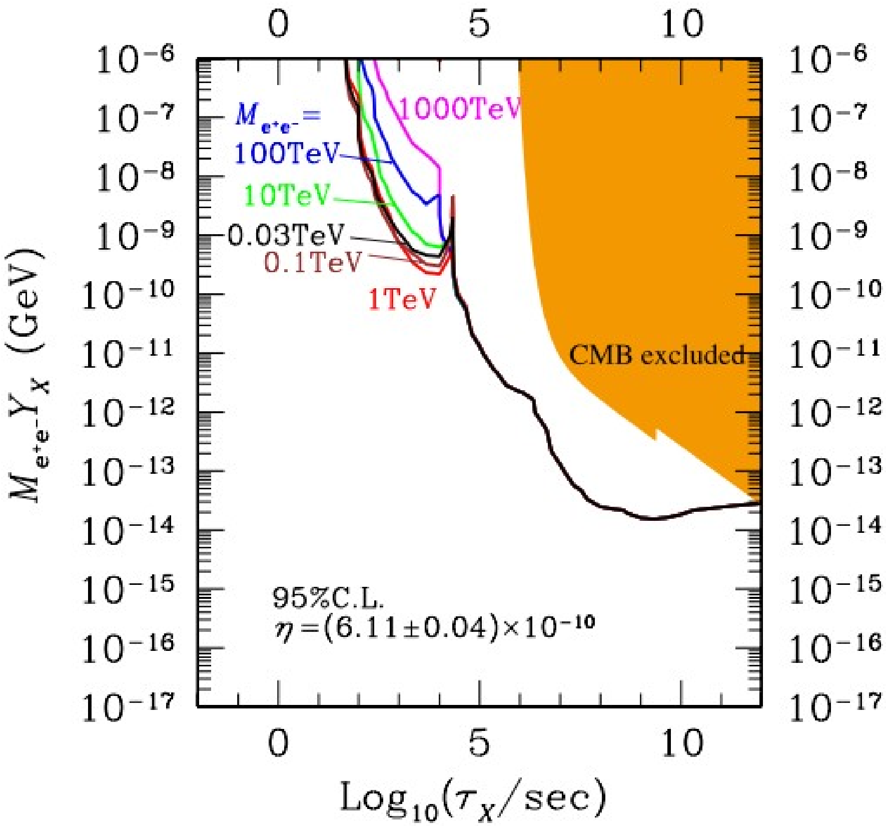
Flowchart for hadronic decays

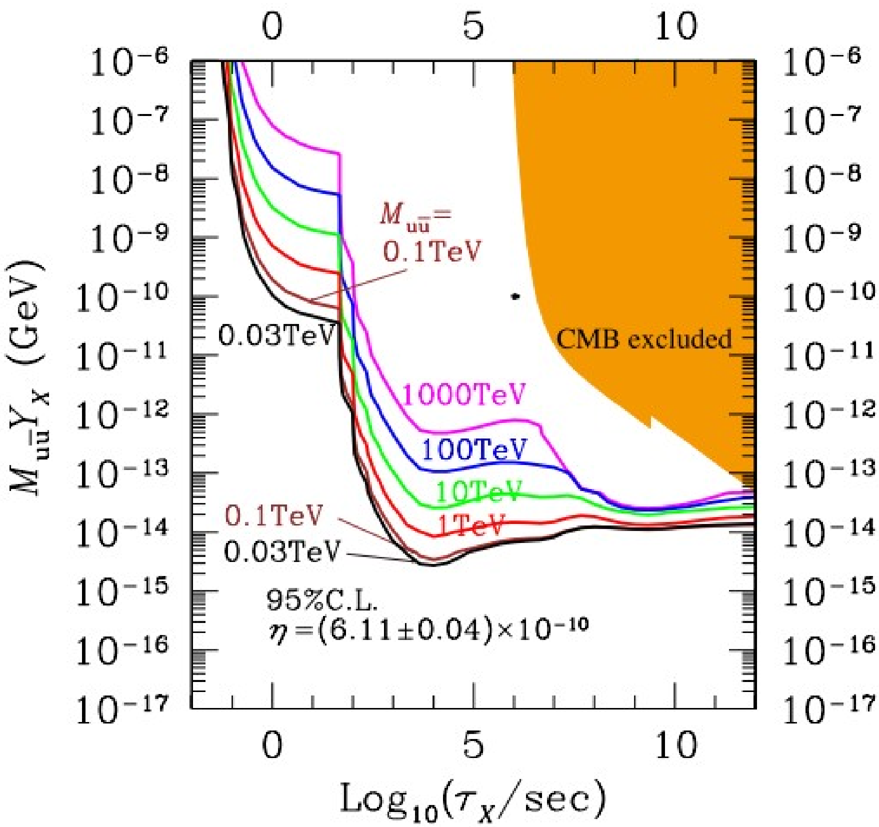
[arXiv:2103.09831]



Existing constraints for different final states

[arXiv:1709.01211]





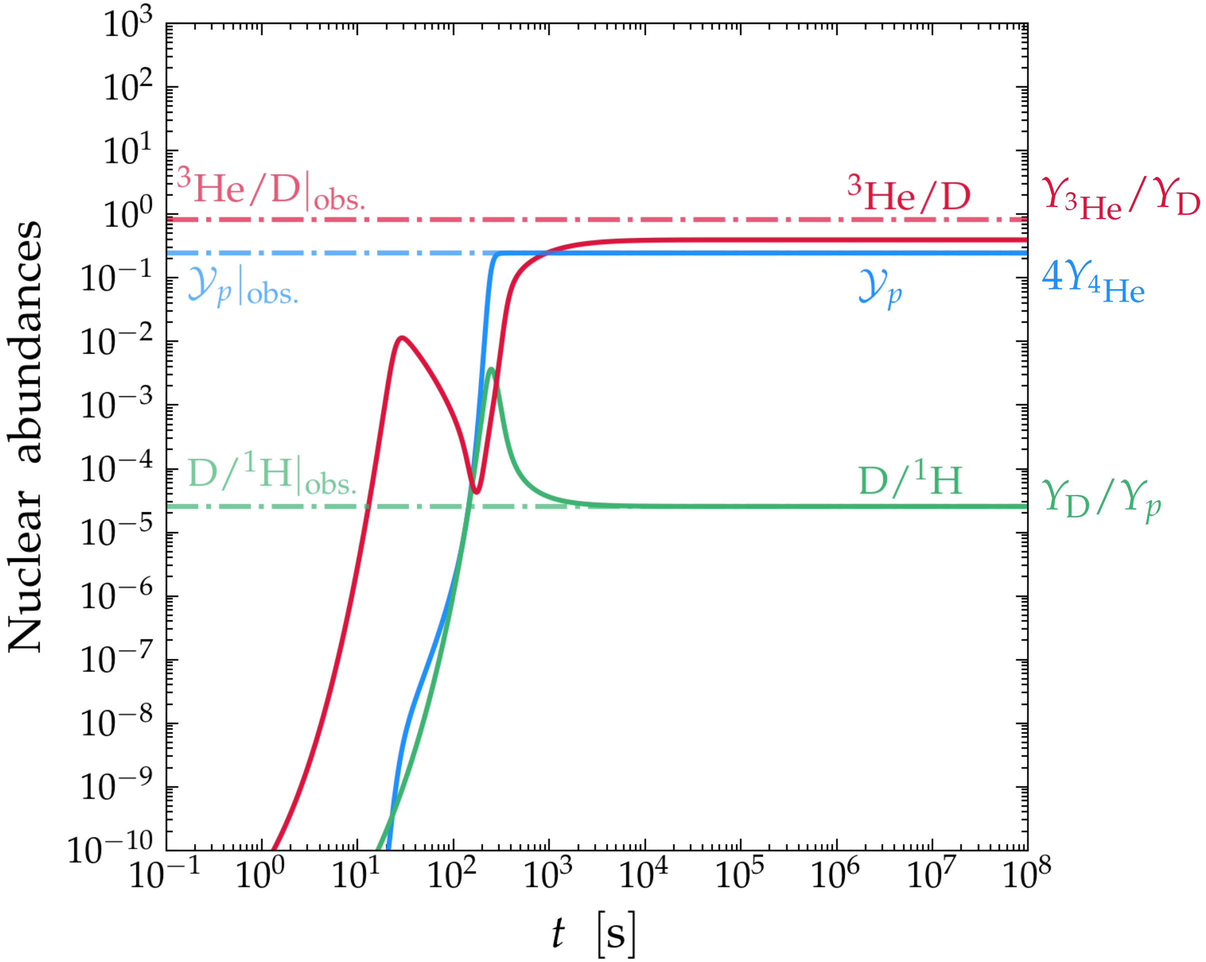
Conclusions

- BBN is a powerful tool to constrain physics beyond the SM
- Depening in the injected particles, different effects can influence the light element abundances
- The limits can be very different from the naive estimate $\tau_\phi < 1\,\mathrm{s}$
- Radiative corrections can lead to stringent limits, even for neutrinos

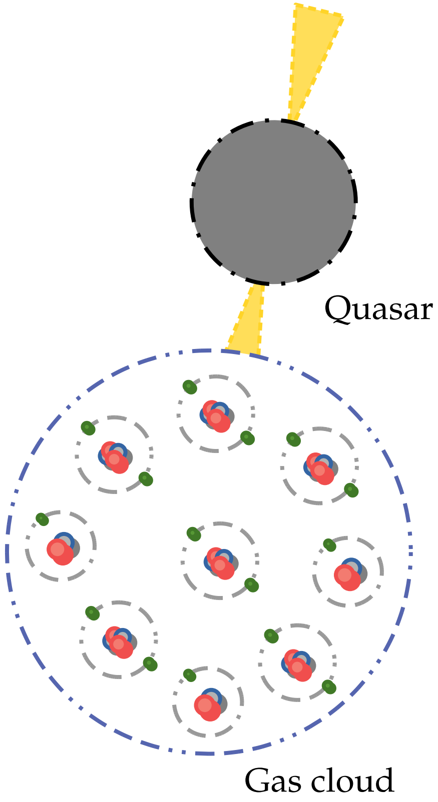

рахмат
danke
謝謝
ngiyabonga
teşekkür ederim
Баярлалаа
mersi
kia ora
barka
welalin
tack
spas
спасибо
faafetai lava
vinaka
спасибі
blagodaram
dank je
misaotra
matondo
paldies
grazzi
mahalo
tapadh leat
thank you
gracias
kiitos
dankie
nanni
nandri
dhanyavad
hvala
mauruuru
köszönöm
хвала
asante
manana
obrigada
murakoze
tenki
bedankt
bayarlalaa
gràçie
akun dankon
acìu
djiere dieuf
tau
mochchakkeram
enkosi
dziękuję
chnorakaloutioun
gratias ago
gràcies
sulpáy
дякую
mamnun
chokrane
taiku
go raibh maith agat
sobodi
děkuji
sagolun
sukriya
kop khun krap
obrigado
mèsi
ありがとう
arigatô
takk
dakujem
trugarez
didi madloba
najis tuke
terima kasih
tanemirt
grazie
rahmet
kam sah hamnida
rahmat
diolch
dhanyavadagalu
shukriya
mercé
мерси
তোমাকে ধন্যবাদ
감사합니다
xièxie
ευχαριστώ
merci

Evolution of the abundances during BBN

Predictions

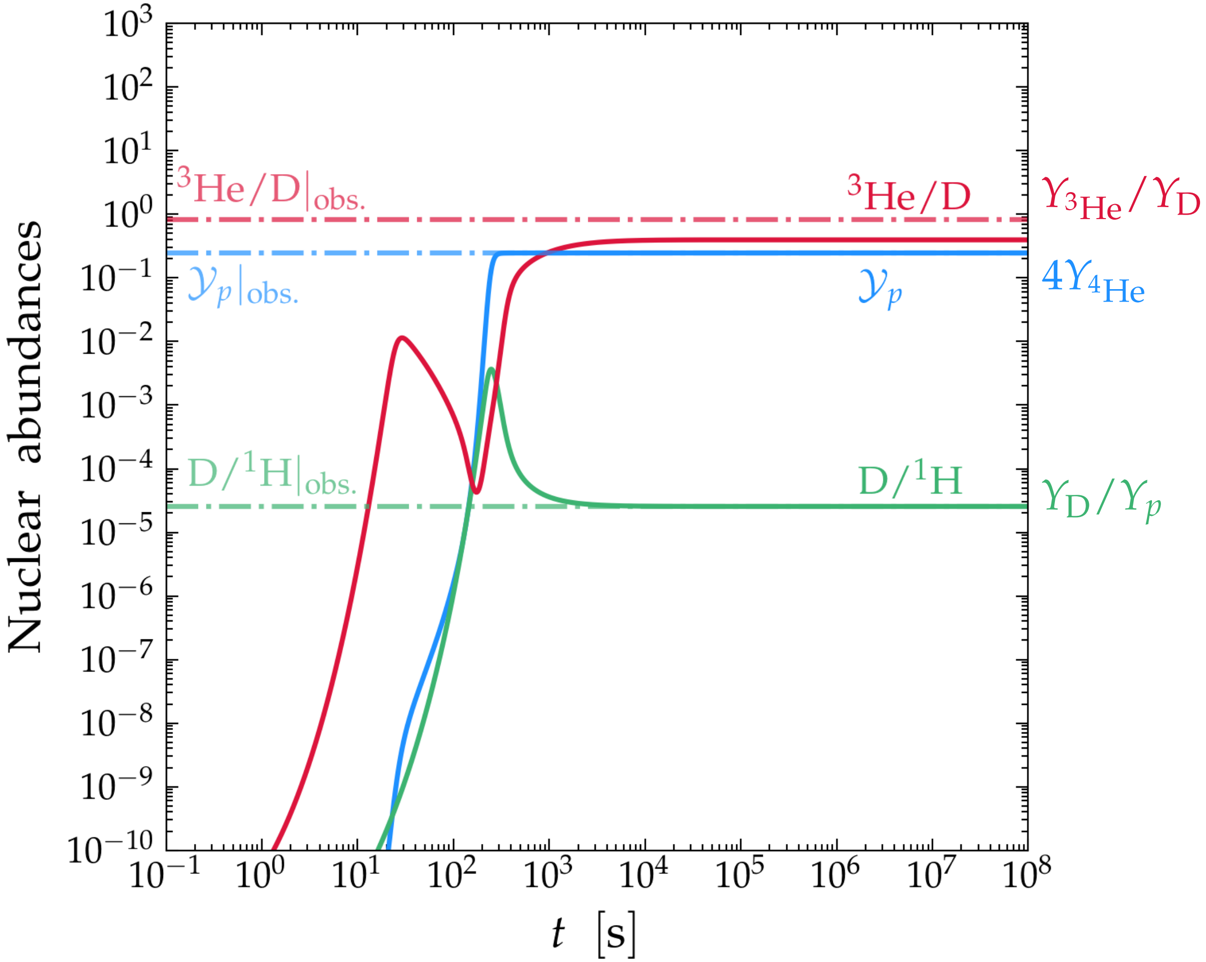


Observations

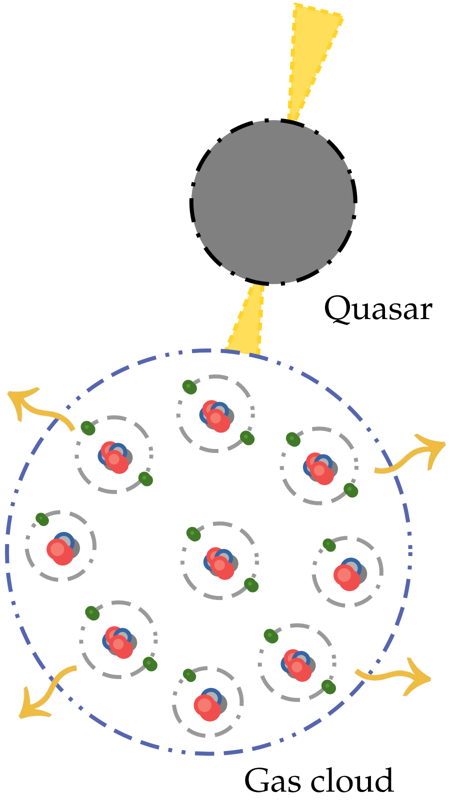


Evolution of the abundances during BBN

Predictions

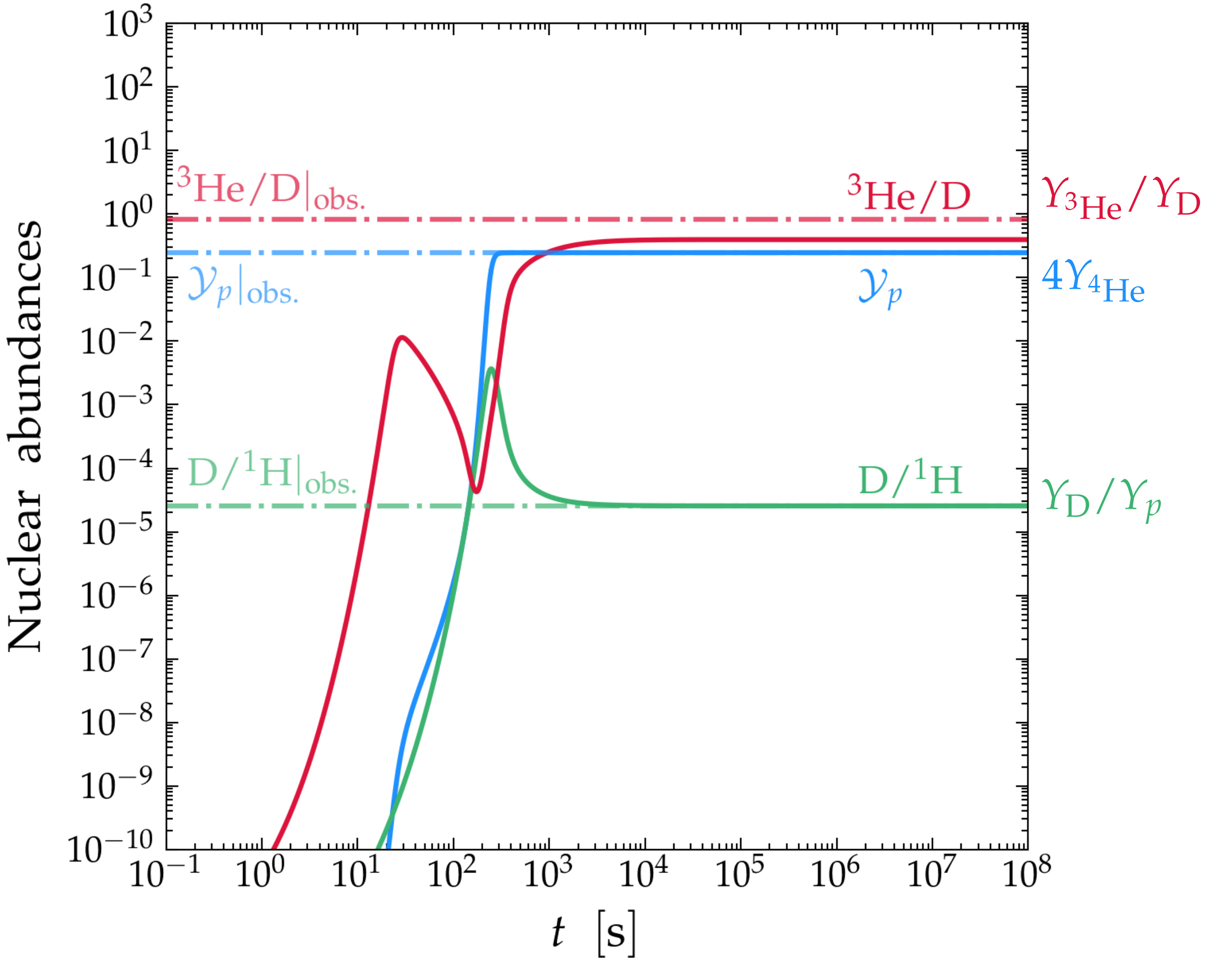


Observations

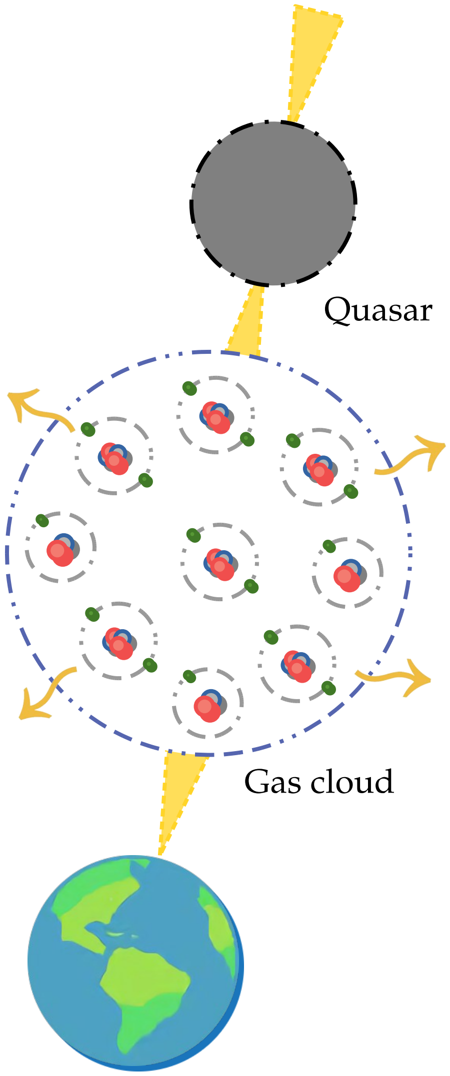


Evolution of the abundances during BBN

Predictions

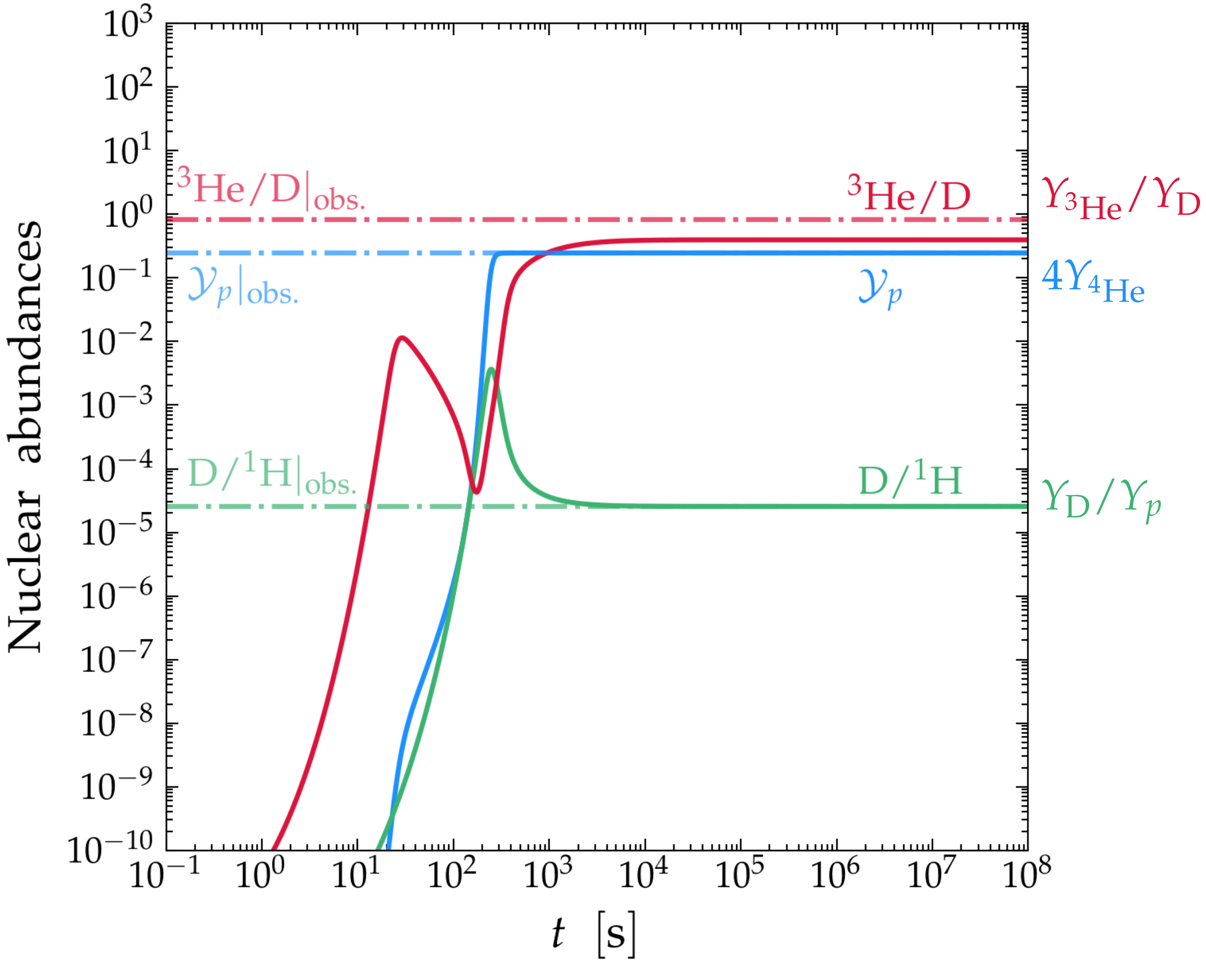


Observations

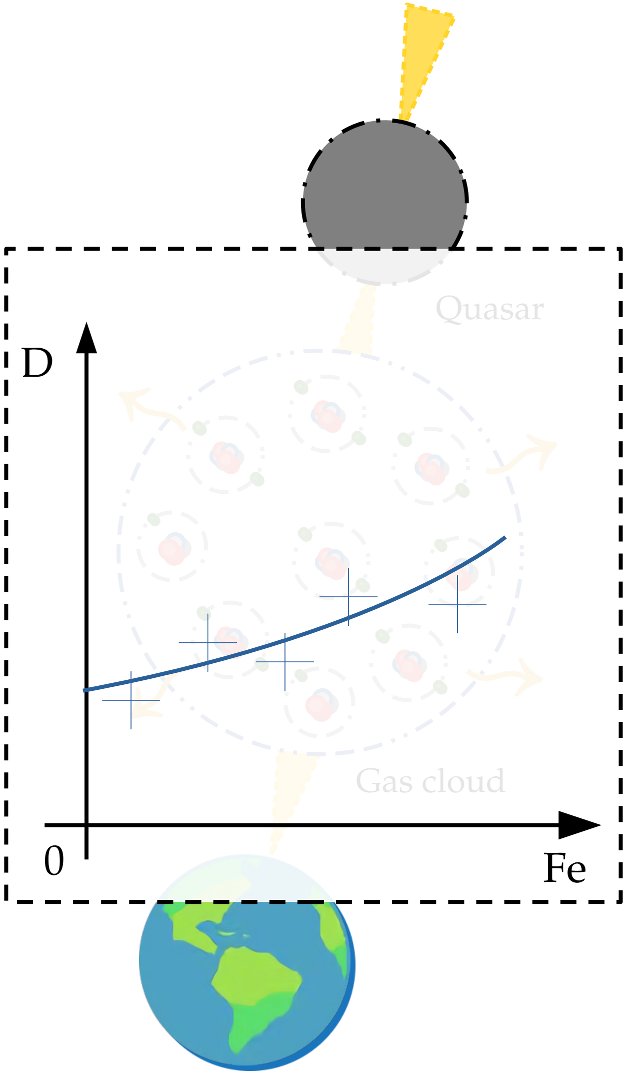


Evolution of the abundances during BBN

Predictions

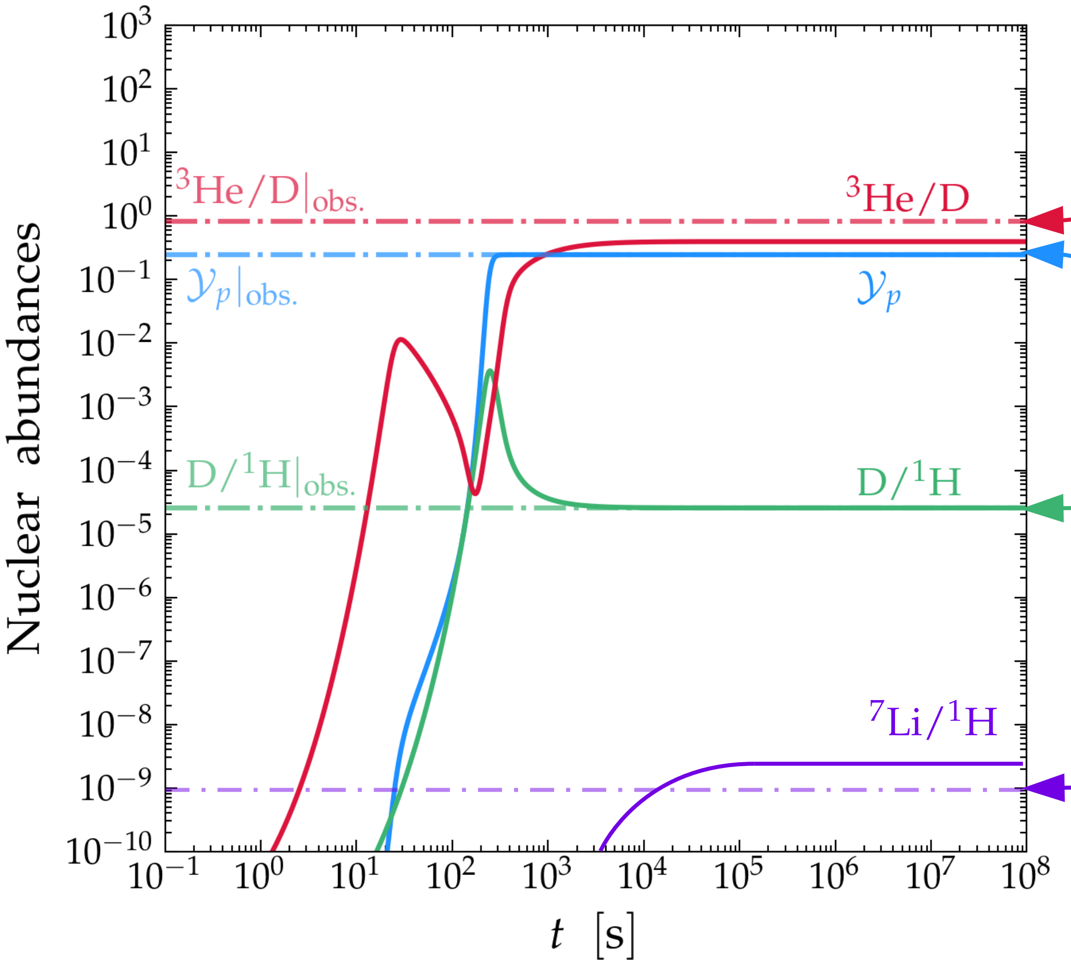


Observations



Evolution of the abundances during BBN

Predictions



Observations

[PDG18], [Geiss03]

$^3\mathrm{He/D} = (8.3 \pm 1.5) \times 10^{-1}$

$\mathcal{Y}_p = (2.45 \pm 0.03) \times 10^{-1}$

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

$^7\mathrm{Li}/^1\mathrm{H} = (1.6 \pm 0.3) \times 10^{-10}$

Li-Problem

Evolution of the dark sector

Boltzmann equation

$$\frac{\partial f_\phi}{\partial t} - 3Hp\frac{\partial f_\phi}{\partial p} = -\left[\mathrm{BR}_{\gamma\gamma} D_\gamma^+ + \mathrm{BR}_{ee} D_e^-\right] \times \left[f_\phi - \bar{f}_\phi\right]$$

Evolution of the dark sector

Boltzmann equation

$$\frac{\partial f_\phi}{\partial t} - \boxed{3Hp\frac{\partial f_\phi}{\partial p}} = -\left[\mathrm{BR}_{\gamma\gamma} D_\gamma^+ + \mathrm{BR}_{ee} D_e^-\right] \times \left[f_\phi - \bar{f}_\phi\right]$$

Dilution

Evolution of the dark sector

Boltzmann equation

$$\frac{\partial f_\phi}{\partial t} - \underbrace{3Hp\frac{\partial f_\phi}{\partial p}}_{\text{Dilution}} = \underbrace{-\left[\mathrm{BR}_{\gamma\gamma} D_\gamma^+ + \mathrm{BR}_{ee} D_e^-\right] \times \left[f_\phi - \bar{f}_\phi\right]}_{\text{(Inverse) Decay}}$$

Dilution

(Inverse) Decay

$\phi \leftrightarrow z\bar{z}$

Evolution of the dark sector

Boltzmann equation

$$\frac{\partial f_\phi}{\partial t} - \boxed{3Hp\frac{\partial f_\phi}{\partial p}} = \boxed{-\boxed{\left[\mathrm{BR}_{\gamma\gamma}D_\gamma^+ \; + \mathrm{BR}_{ee}D_e^-\right]} \times \left[f_\phi - \bar{f}_\phi\right]}$$

Dilution

(Inverse) Decay

$\phi \leftrightarrow z\bar{z}$

$$D_z^\pm = \frac{1}{\tau_\phi} \times \frac{m_\phi}{E_\phi} \times \left[1 + \frac{2T}{\beta_z p} \ln\left(\frac{1 \mp \exp[-(E_\phi + \beta_z p)/2T]}{1 \mp \exp[-(E_\phi - \beta_z p)/2T]}\right)\right]$$

Evolution of the dark sector

Boltzmann equation

$$\frac{\partial f_\phi}{\partial t} \boxed{- 3Hp\frac{\partial f_\phi}{\partial p}} = \boxed{- \boxed{\left[\mathrm{BR}_{\gamma\gamma}D_\gamma^+ + \mathrm{BR}_{ee}D_e^-\right]} \times \left[f_\phi - \bar{f}_\phi\right]}$$

Dilution

(Inverse) Decay

$\phi \leftrightarrow z\bar{z}$

$$D_z^\pm = \boxed{\frac{1}{\tau_\phi}} \times \frac{m_\phi}{E_\phi} \times \left[1 + \frac{2T}{\beta_z p}\ln\left(\frac{1 \mp \exp[-(E_\phi + \beta_z p)/2T]}{1 \mp \exp[-(E_\phi - \beta_z p)/2T]}\right)\right]$$

Lifetime

$$\frac{\partial f_\phi}{\partial t} \sim -\frac{1}{\tau_\phi}f_\phi$$

Evolution of the dark sector

Boltzmann equation

$$\frac{\partial f_\phi}{\partial t} - 3Hp\frac{\partial f_\phi}{\partial p} = -\left[\mathrm{BR}_{\gamma\gamma}D_\gamma^+ + \mathrm{BR}_{ee}D_e^-\right]\times\left[f_\phi - \bar{f}_\phi\right]$$

Dilution

(Inverse) Decay

$\phi \leftrightarrow z\bar{z}$

$$D_z^\pm = \frac{1}{\tau_\phi}\times\frac{m_\phi}{E_\phi}\times\left[1+\frac{2T}{\beta_z p}\ln\left(\frac{1\mp\exp[-(E_\phi+\beta_z p)/2T]}{1\mp\exp[-(E_\phi-\beta_z p)/2T]}\right)\right]$$

Lifetime γ-factor

$$\frac{\partial f_\phi}{\partial t} \sim -\frac{1}{\tau_\phi}f_\phi$$

Evolution of the dark sector

Boltzmann equation

$$\frac{\partial f_\phi}{\partial t} - \boxed{3Hp\frac{\partial f_\phi}{\partial p}} = \boxed{- \boxed{\left[\mathrm{BR}_{\gamma\gamma} D_\gamma^{+} + \mathrm{BR}_{ee} D_e^{-}\right]} \times \left[f_\phi - \bar{f}_\phi\right]}$$

Dilution

(Inverse) Decay
$\phi \leftrightarrow z\bar{z}$

$$D_z^{\pm} = \boxed{\frac{1}{\tau_\phi}} \times \boxed{\frac{m_\phi}{E_\phi}} \times \boxed{\left[1 + \frac{2T}{\beta_z p} \ln\left(\frac{1 \mp \exp[-(E_\phi + \beta_z p)/2T]}{1 \mp \exp[-(E_\phi - \beta_z p)/2T]}\right)\right]}$$

Lifetime γ-factor   Pauli blocking / Bose enhancement

$$\frac{\partial f_\phi}{\partial t} \sim -\frac{1}{\tau_\phi} f_\phi$$

≥ 1 for photons

≤ 1 for electrons/positrons