BBN disintegration constraints from neutrino injections

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Sara Bianco

In collaboration with: P. F. Depta, J. Frerick, T. Hambye, M. Hufnagel, and K. Schmidt-Hoberg

Introduction

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Their presence can, in general, have an impact on:

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What happens when we inject neutrinos?

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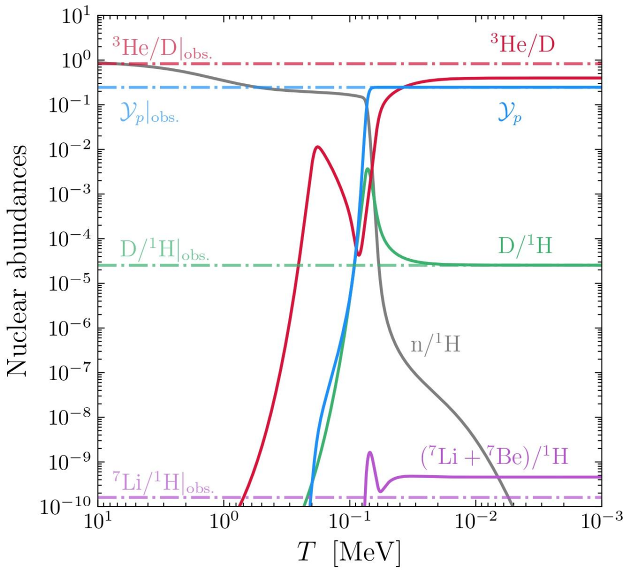
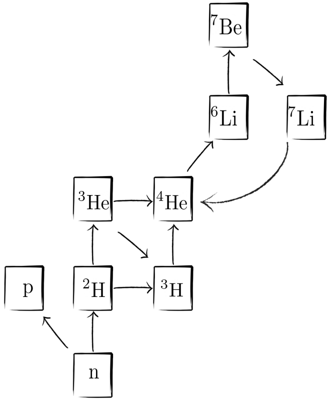


Credits to P. F. Depta

$$t \sim 1\text{s} - 10^4\text{s} \Longleftrightarrow T \sim \text{MeV} - 10\text{keV}$$



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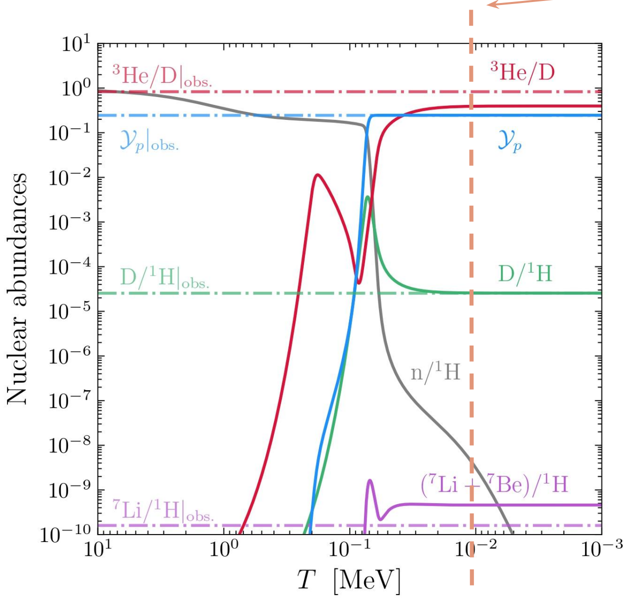

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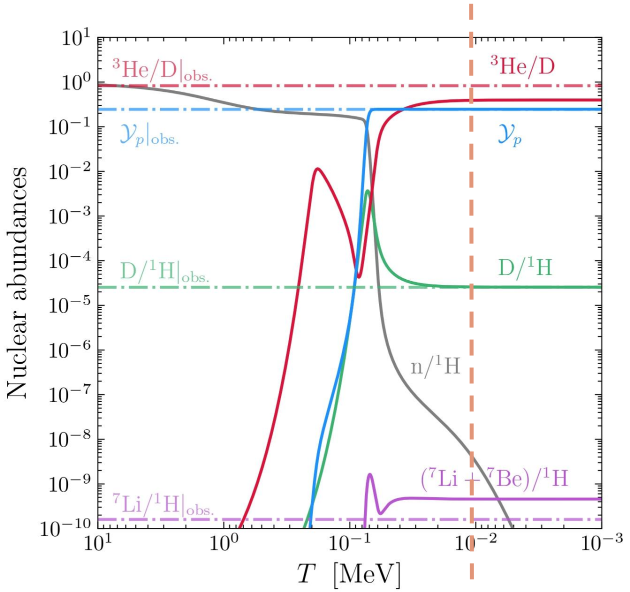

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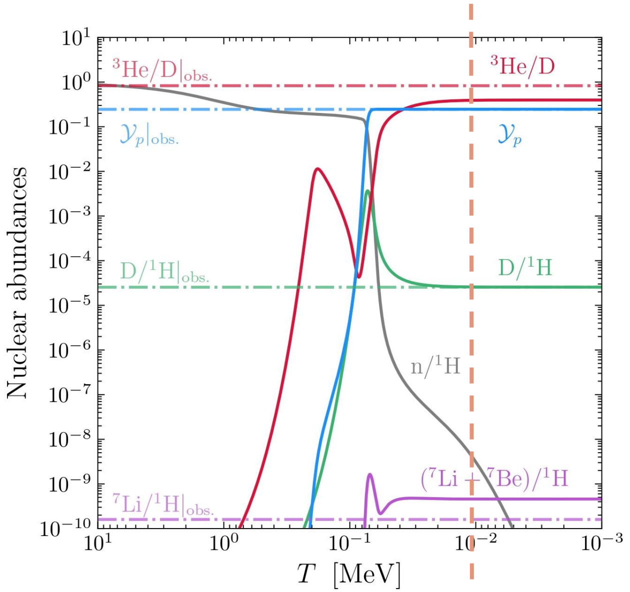

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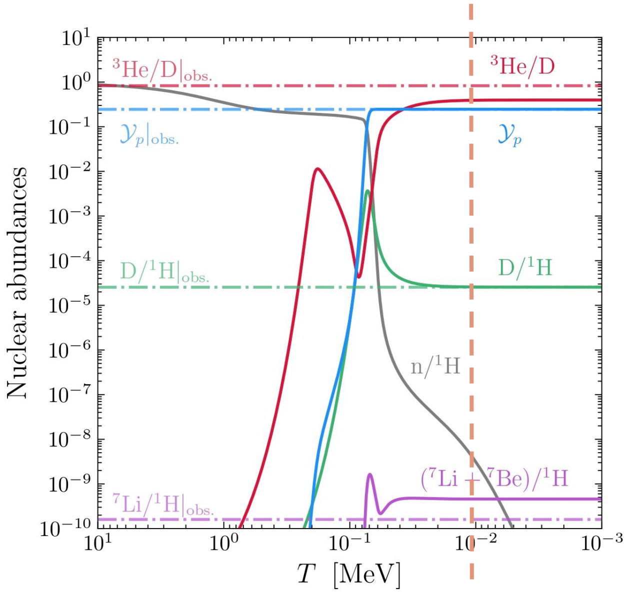

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How?

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$$N_{\rm eff} = \frac{\rho_\nu^{\rm th}(t_{\rm rec}) + \rho_\nu^{\text{n-th}}(t_{\rm rec})}{2\frac{7}{8}\frac{\pi^2}{30}\left(\frac{4}{11}\right)^{4/3} T(t_{\rm rec})^4} \equiv [3 + \Delta N_{\rm eff}(t_{\rm rec})]\left(\frac{11}{4}\right)^{4/3}\left(\frac{T_\nu(t_{\rm rec})}{T(t_{\rm rec})}\right)^4$$

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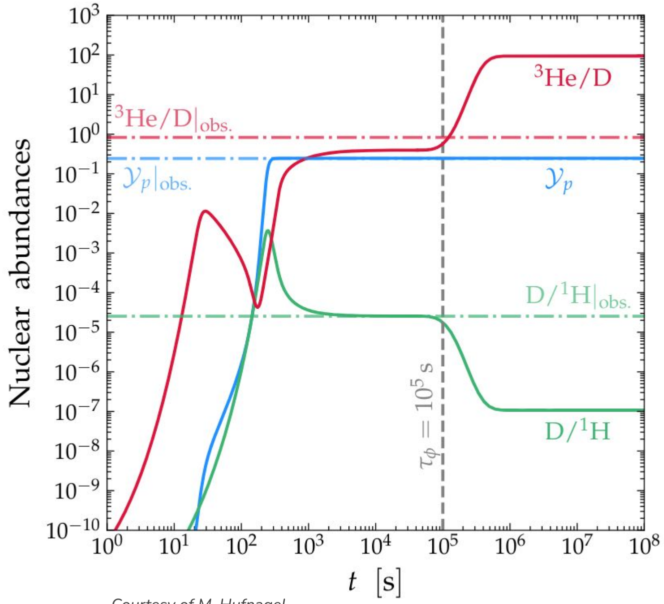
★ **Photo- and Hadrodisintegration!**

Introduction: Photodisintegration



Courtesy of M. Hufnagel

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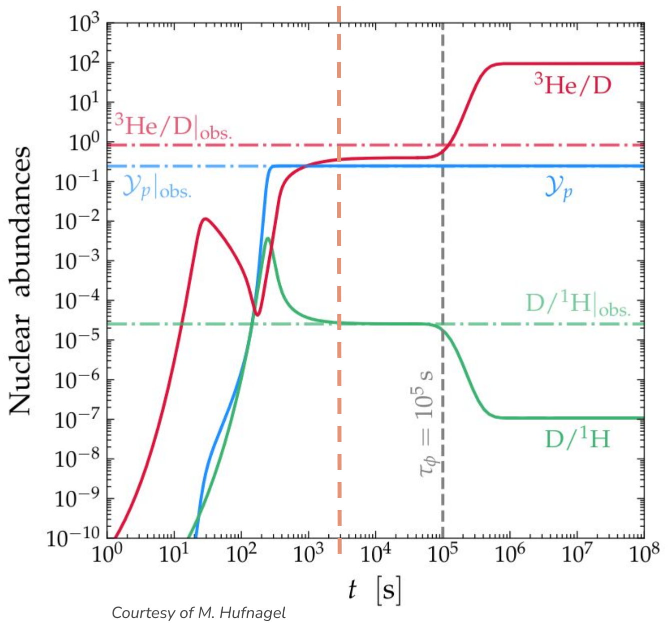

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Even after BBN abundances reach their asymptotic values, late EM injections can still alter the abundances!

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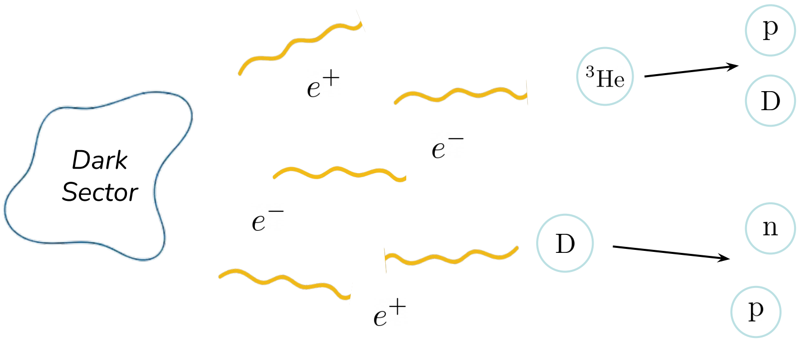
The ***late-time*** injection of ***high-energetic*** EM particles into the SM plasma induces an EM cascade that leads to non-thermal parts of the photon, electron, and positron spectra.



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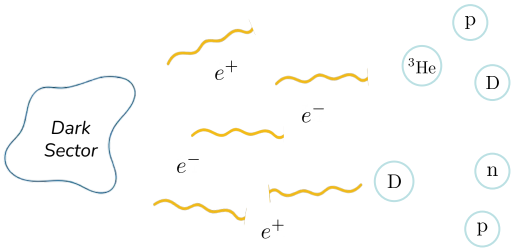
High-energy photons with energies above the pair-production threshold:

$$E_{e^\pm}^{\mathrm{th}} \simeq m_e^2/(22T)$$

are efficiently depleted via ***double-photon pair creation*** ($\gamma\gamma_{\mathrm{th}} \to e^+e^-$).



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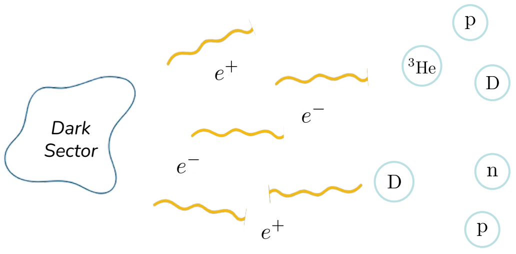

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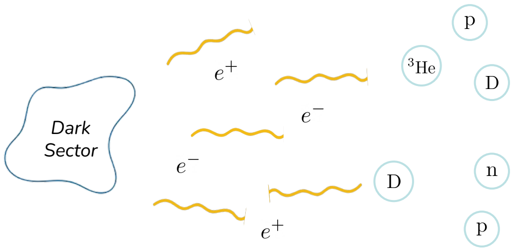

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At these T, BBN has already finished and we can simply factor out the two processes.

	T (keV)	$E^{\rm th}$ (MeV)
D	5.34	2.22
^{3}H	1.90	6.26
^{3}He	2.16	5.49
^{4}He	0.60	19.81
^{6}Li	3.21	3.70
^{7}Li	4.81	2.47
^{7}Be	7.48	1.59

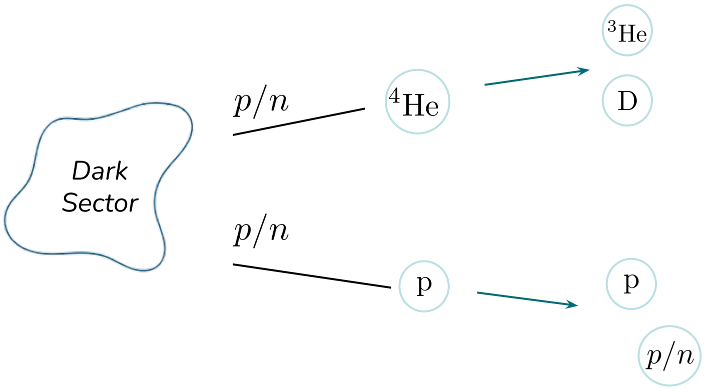
ACROPOLIS

Publicly available code 2011.06518, *P. F. Depta, M. Hufnagel, and K. Schmidt-Hoberg.*

https://github.com/hep-mh/acropolis/tree/main/acropolis

Introduction: Hadrodisintegration

Similarly to photodisintegration, hadrodisintegration describes the late-time destruction of the light elements, this time driven by hadrons.



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which can be then disintegrated by photons

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Even if few hadrons are injected compared to EM material:

1) He-4 destruction cross-section via p/n is **~2 orders of magnitude** bigger than D destruction via a photon.
2) He-4 is **>3 orders of magnitude** more abundant than D.

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★ **energy loss** due to EM interactions;

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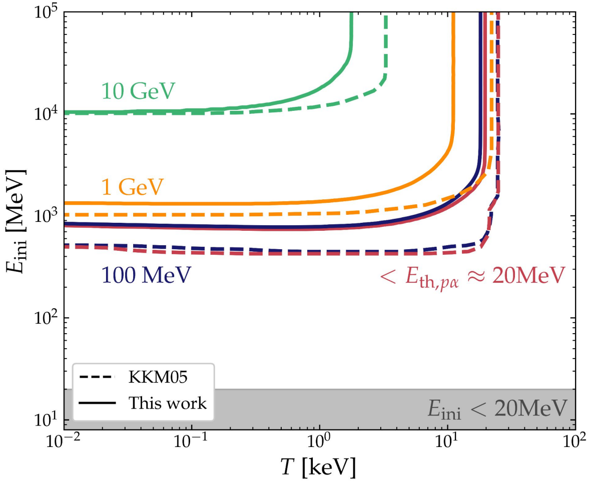

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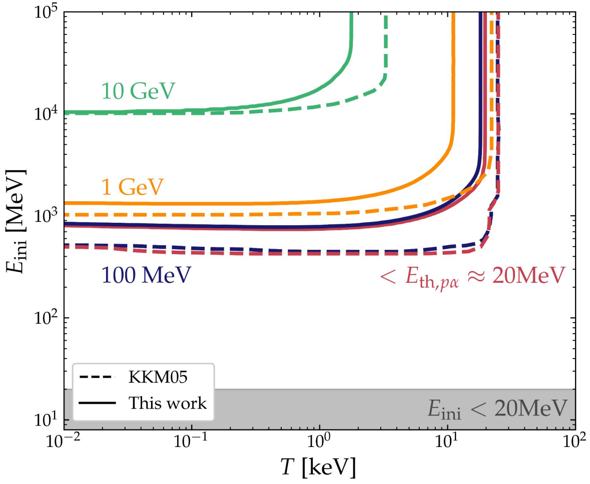

A quick overview of the neutrino cascade

We consider some relic ϕ with lifetime $\tau_\phi > 10^4\mathrm{s}$.
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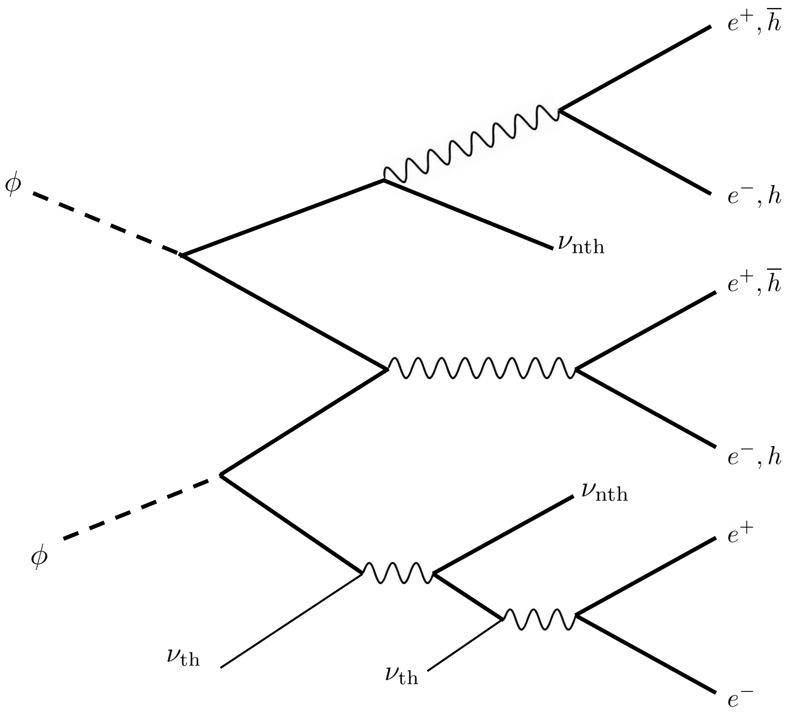

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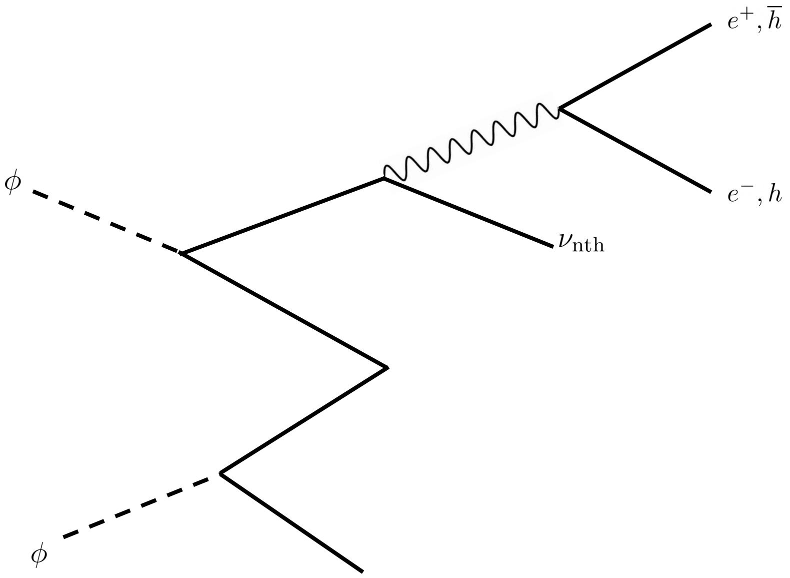

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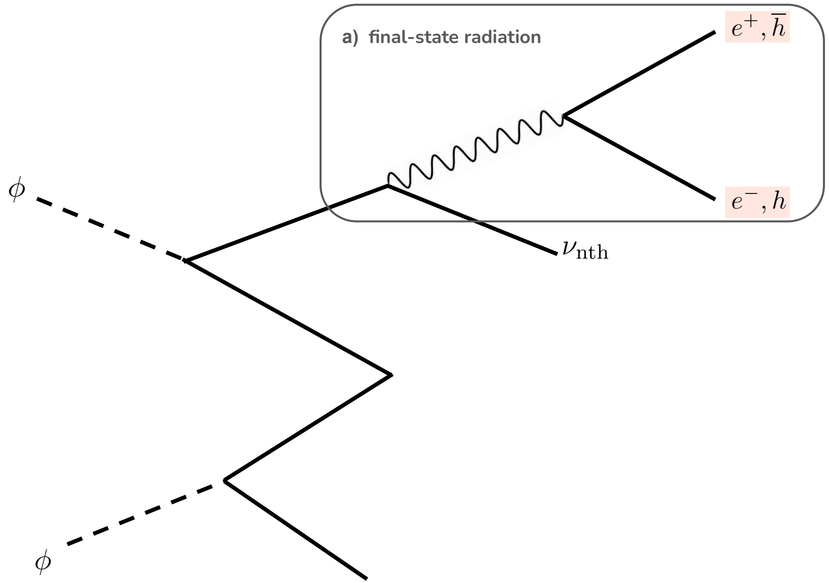

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Decay particle produce a neutrino emitting a W- or Z-boson
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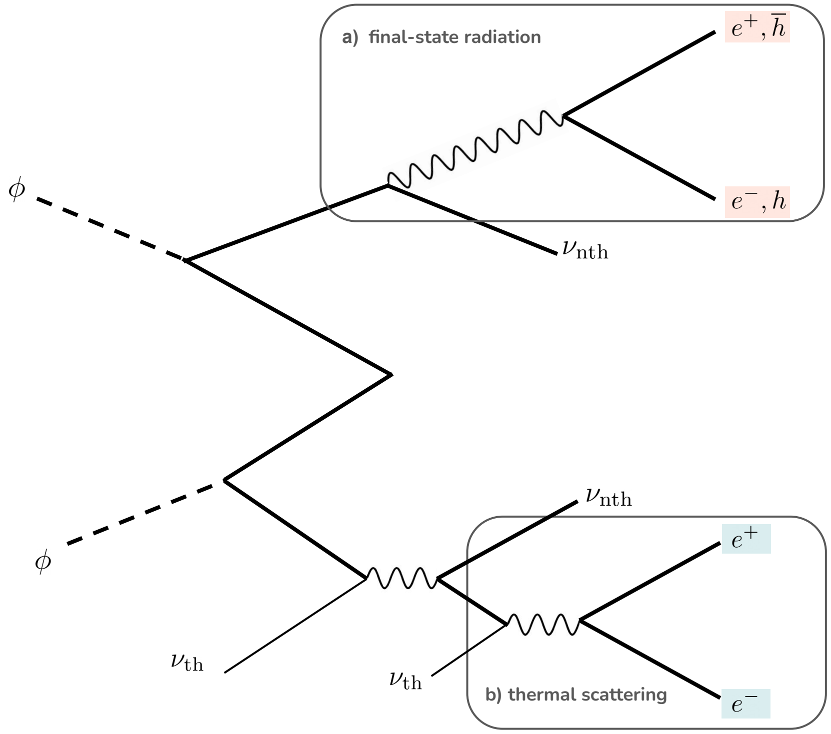

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Interactions with neutrino from the background
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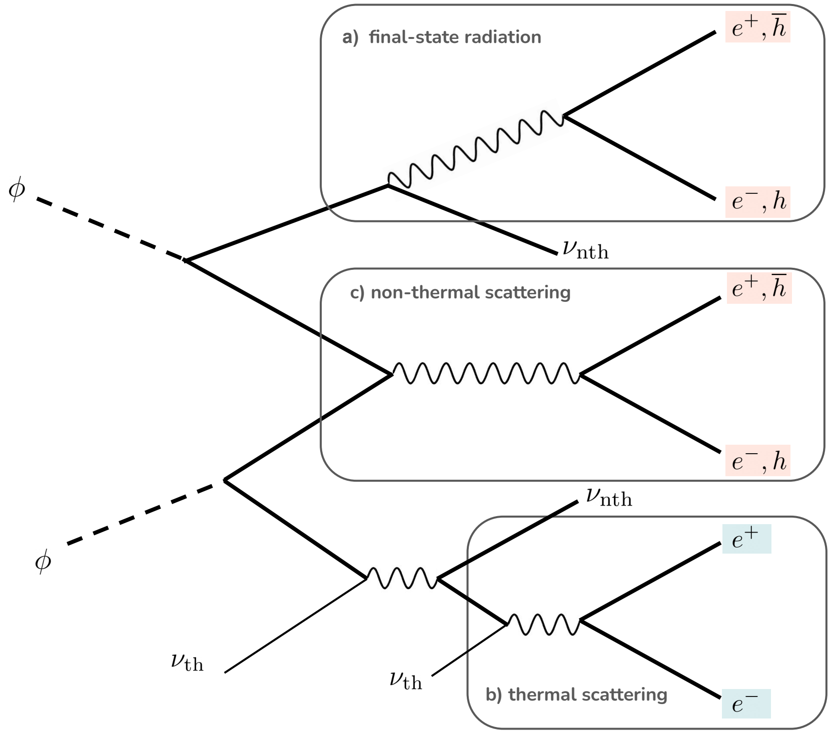

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Interactions with other non-thermal neutrinos
⟶ EM and **HD** injections

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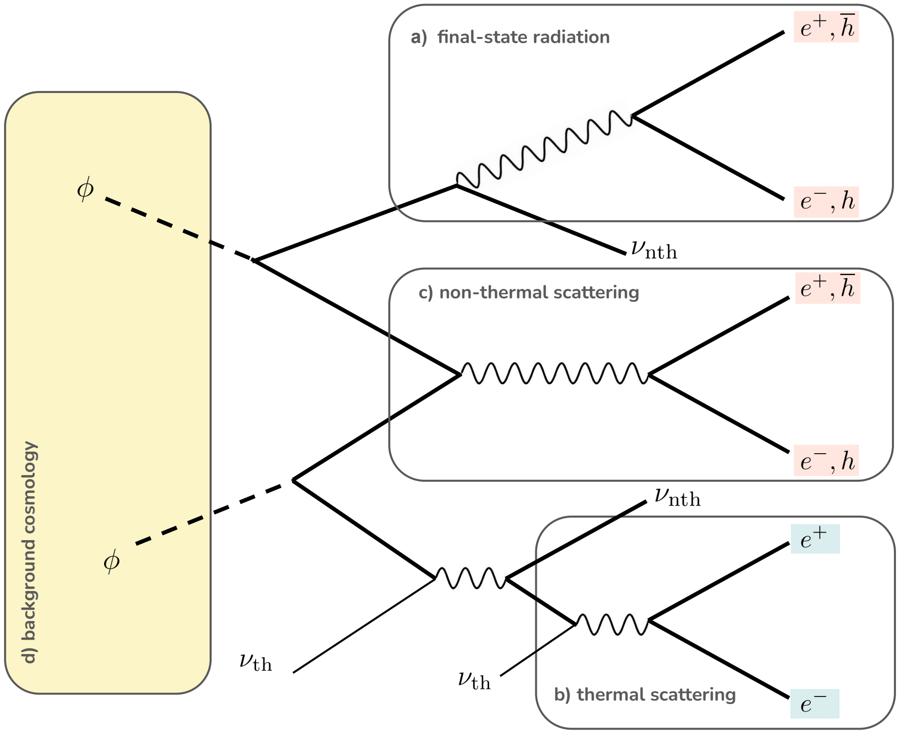

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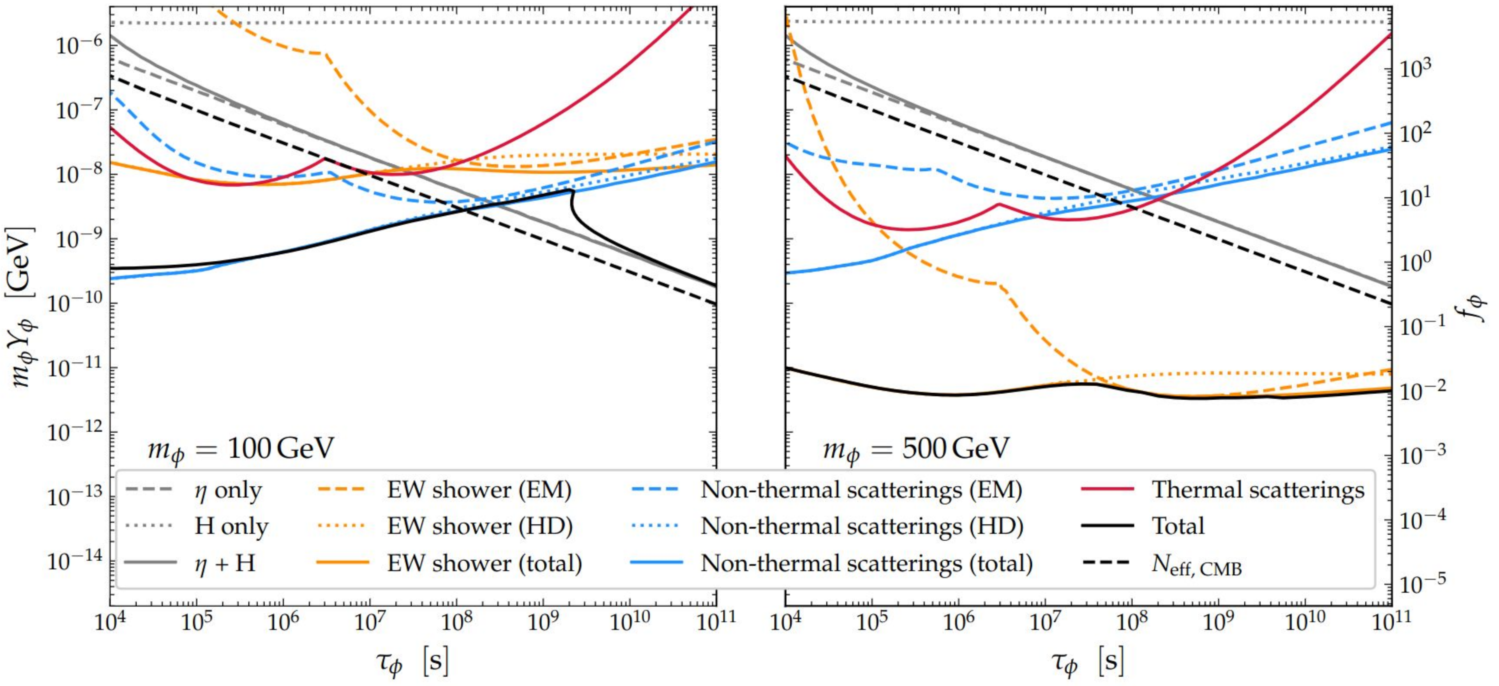
c) Non-thermal scattering
Interactions with other non-thermal neutrinos
⟶ **EM** and **HD** injections

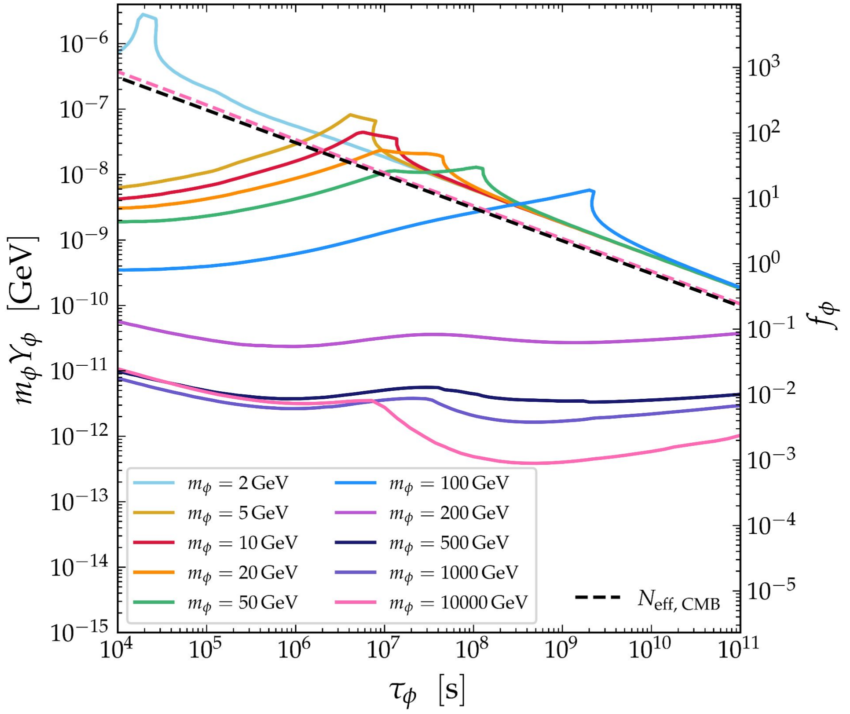
d) Background cosmology
The presence of an additional relic will modify the thermal history of the universe.

Results



$m_\phi = 100\,\mathrm{GeV}$
$m_\phi = 500\,\mathrm{GeV}$
$m_\phi Y_\phi$ [GeV]
f_ϕ
τ_ϕ [s]
η only
H only
η + H
EW shower (EM)
EW shower (HD)
EW shower (total)
Non-thermal scatterings (EM)
Non-thermal scatterings (HD)
Non-thermal scatterings (total)
Thermal scatterings
Total
$N_{\mathrm{eff,\,CMB}}$

Results



$m_\phi Y_\phi$ [GeV]
τ_ϕ [s]
f_ϕ
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{-14}
10^{-15}
10^{4}
10^{5}
10^{6}
10^{7}
10^{8}
10^{9}
10^{10}
10^{11}
10^{3}
10^{2}
10^{1}
10^{0}
10^{-1}
10^{-2}
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$m_\phi = 2\,\mathrm{GeV}$
$m_\phi = 5\,\mathrm{GeV}$
$m_\phi = 10\,\mathrm{GeV}$
$m_\phi = 20\,\mathrm{GeV}$
$m_\phi = 50\,\mathrm{GeV}$
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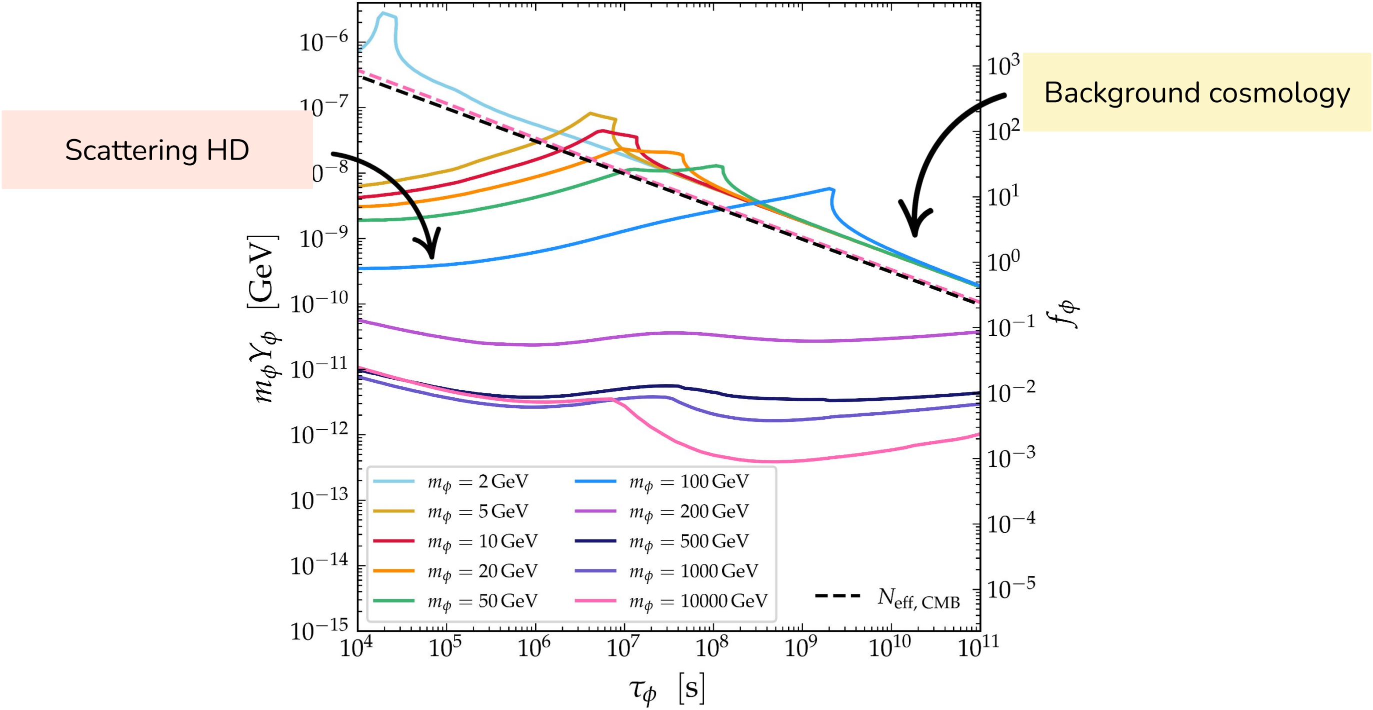

Scattering HD
Background cosmology
$m_\phi Y_\phi$ [GeV]
f_ϕ
τ_ϕ [s]
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{-14}
10^{-15}
10^{3}
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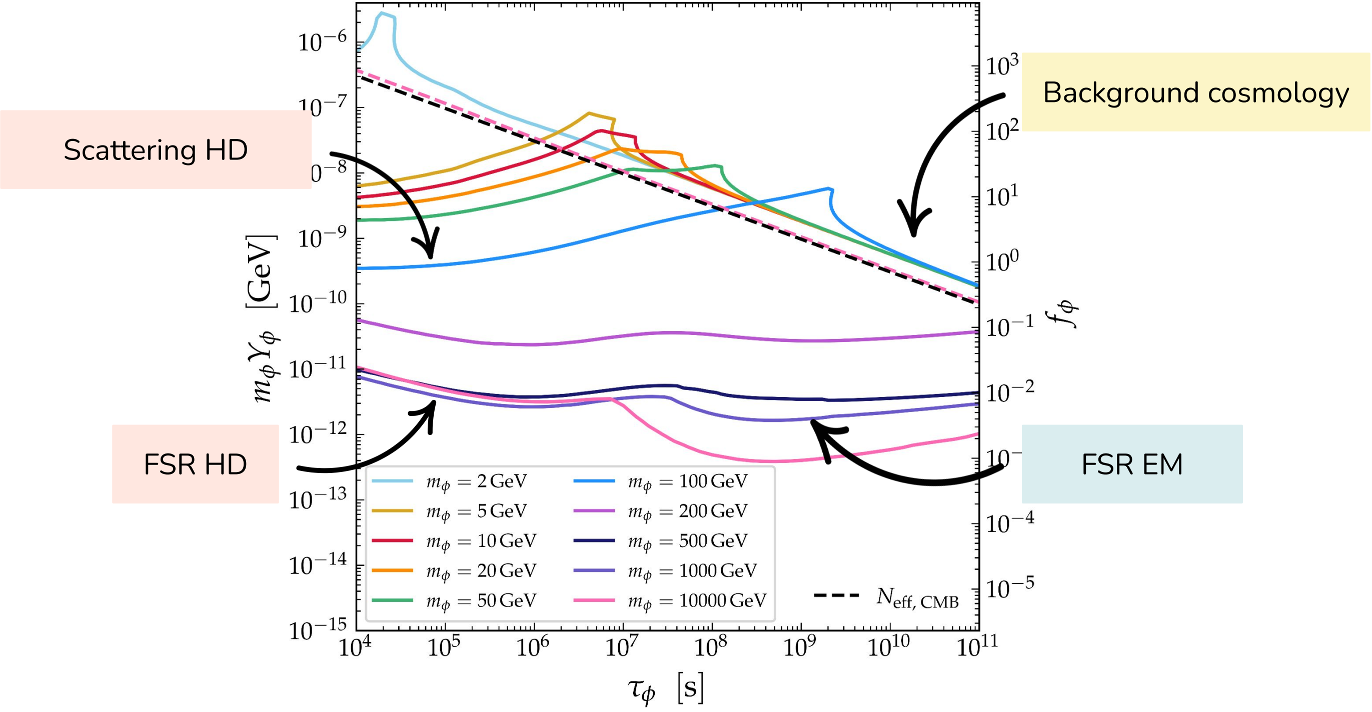

Scattering HD
Background cosmology
FSR HD
FSR EM
$m_\phi Y_\phi$ [GeV]
τ_ϕ [s]
f_ϕ
$m_\phi = 2\,\mathrm{GeV}$
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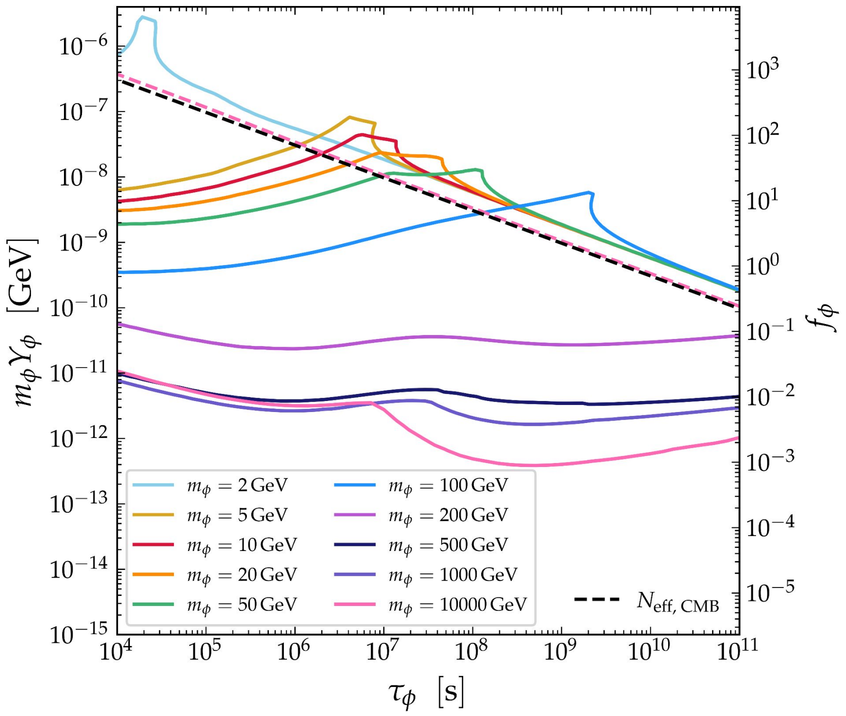
Conclusions



- ★ Thorough study of neutrino injections after BBN.
- ★ For most of the masses considered, the bounds are stronger than the ΔN_{eff} constraints.
- ★ At high masses, the EW shower dominates the limits.
- ★ Hadron injections boost the bounds by several order of magnitudes.
- ★ @ low lifetimes some assumptions break down → other effects have to be considered (e.g. pion induced p/n conversions): *stay tuned!*

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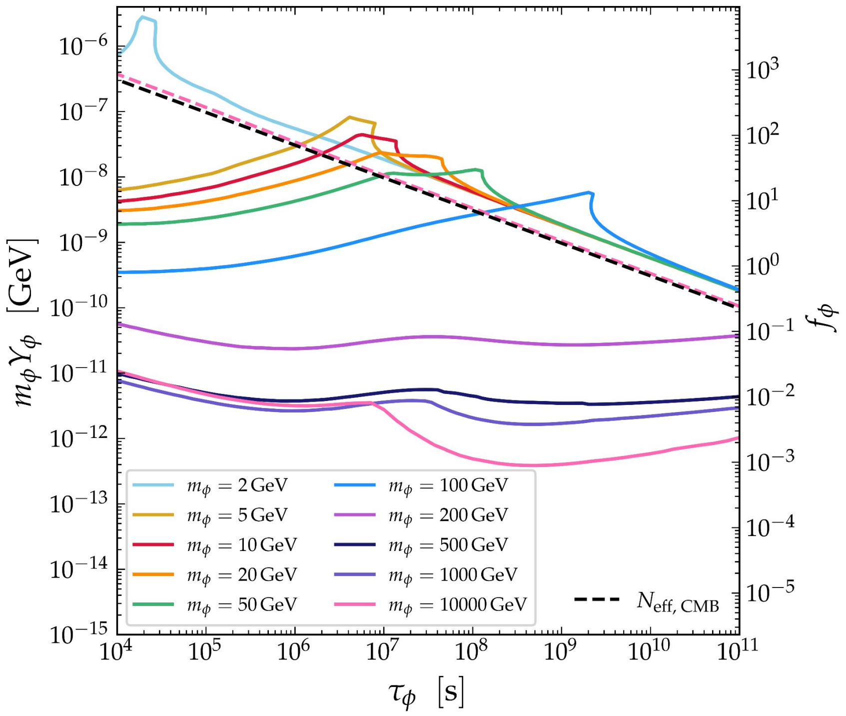

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Thank you for the attention!

...and check 2505.01492

Backup slides

Photodisintegration

The ***late-time*** injection of ***high-energetic*** EM particles into the SM plasma induces an EM cascade that leads to non-thermal parts of the photon, electron, and positron spectra.

- inverse Compton scattering $e^{\pm}\gamma_{\rm th} \to e^{\pm}\gamma$
- double photon pair creation $\gamma\gamma_{\rm th} \to e^{+}e^{-}$
- Bethe-Heitler pair creation $\gamma N \to e^{+}e^{-}N$, with $N \in \{^1H, {}^4He\}$
- Compton scattering $\gamma e^{-}_{\rm th} \to \gamma e^{-}$
- photon-photon scattering $\gamma\gamma_{\rm th} \to \gamma\gamma$

									$E^{\rm th}$ [MeV]
D	+	γ	$\to$	p	+	n			2.22
^{3}H	+	γ	$\to$	D	+	n			6.26
^{3}H	+	γ	$\to$	p	+	n	+	n	8.48
^{3}He	+	γ	$\to$	D	+	p			5.49
^{3}He	+	γ	$\to$	n	+	p	+	p	7.12
^{4}He	+	γ	$\to$	^{3}H	+	p			19.81
^{4}He	+	γ	$\to$	^{3}He	+	n			20.58
^{4}He	+	γ	$\to$	D	+	D			23.84
^{4}He	+	γ	$\to$	D	+	n	+	p	26.07
^{6}Li	+	γ	$\to$	^{4}He	+	n	+	p	3.70
^{6}Li	+	γ	$\to$	X	+	^3A			15.79
^{7}Li	+	γ	$\to$	^{3}H	+	^{4}He			2.47
^{7}Li	+	γ	$\to$	n	+	^{6}Li			7.25
^{7}Li	+	γ	$\to$	$2n$	+	p	+	^{4}He	10.95
^{7}Be	+	γ	$\to$	^{3}He	+	^{4}He			1.59
^{7}Be	+	γ	$\to$	p	+	^{6}Li			5.61
^{7}Be	+	γ	$\to$	$2p$	+	n	+	^{4}He	9.30

Hadrodisintegration

We consider the following hadrodisintegration processes:

Process	$i = n$	$i = p$	Reaction Type
(i, p_{BG}; 1)	$n + p_{BG} \to n + p$	$p + p_{BG} \to p + p$	elastic
(i, p_{BG}; 2)	$n + p_{BG} \to n + p + \pi$	$p + p_{BG} \to p + p + \pi$	inelastic
(i, p_{BG}; 3)	$n + p_{BG} \to n + n + \pi$	$p + p_{BG} \to p + n + \pi$	inelastic
(i, p_{BG}; 4)	$n + p_{BG} \to p + p + \pi$	$p + p_{BG} \to n + p + \pi$	inelastic
(i, p_{BG}; 5)	$n + p_{BG} \to p + p + \pi$	$p + p_{BG} \to n + n + \pi$	inelastic

Process	$i = n$	$i = p$	Reaction Type
(i, α; 1)	$n + \alpha_{BG} \to n + \alpha$	$p + \alpha_{BG} \to p + \alpha$	elastic
(i, α; 2)	$n + \alpha_{BG} \to \mathrm{D} + \mathrm{T}$	$p + \alpha_{BG} \to \mathrm{D} + {}^3\mathrm{He}$	inelastic
(i, α; 3)	$n + \alpha_{BG} \to 2n + {}^3\mathrm{He}$	$p + \alpha_{BG} \to p + n + {}^3\mathrm{He}$	inelastic
(i, α; 4)	$n + \alpha_{BG} \to p + n + \mathrm{T}$	$p + \alpha_{BG} \to 2p + \mathrm{T}$	inelastic
(i, α; 5)	$n + \alpha_{BG} \to n + 2\mathrm{D}$	$p + \alpha_{BG} \to p + 2\mathrm{D}$	inelastic
(i, α; 6)	$n + \alpha_{BG} \to p + 2n + \mathrm{D}$	$p + \alpha_{BG} \to 2p + n + \mathrm{D}$	inelastic
(i, α; 7)	$n + \alpha_{BG} \to 2p + 3n$	$p + \alpha_{BG} \to 3p + 2n$	inelastic
(i, α; 8)	$n + \alpha_{BG} \to n + \alpha + \pi$	$p + \alpha_{BG} \to p + \alpha + \pi$	inelastic

Hadrodisintegration

In order to account for the effect of the injected hadrons, we must consider energy loss processes.

$$H_i + e^\pm \to H_i + e^\pm$$
$$H_i + \gamma \to H_i' + \pi$$
$$H_i + \gamma \to H_i + \gamma$$
$$H_i + \gamma \to H_i + e^+ + e^-$$

$$\frac{\mathrm{d}E_{H_i}}{\mathrm{d}t} = \left(\frac{\mathrm{d}E_{H_i}}{\mathrm{d}t}\right)_{\text{Coulomb}} + \left(\frac{\mathrm{d}E_{H_i}}{\mathrm{d}t}\right)_{\text{Compton}} + \left(\frac{\mathrm{d}E_{H_i}}{\mathrm{d}t}\right)_{\text{BH}} + \left(\frac{\mathrm{d}E_{H_i}}{\mathrm{d}t}\right)_{\text{photo-pion}}$$

$$R_{H_i+A_j\to A_k}\left(E_{H_i}^{(\text{in})}, E'_{H_i}; T\right) \equiv \int_{E_{H_i}^{(\text{in})}}^{E'_{H_i}} \Gamma_{H_i+A_j\to A_k} \left(\frac{\mathrm{d}E_{H_i}}{\mathrm{d}t}\right)^{-1} \mathrm{d}E_{H_i}$$

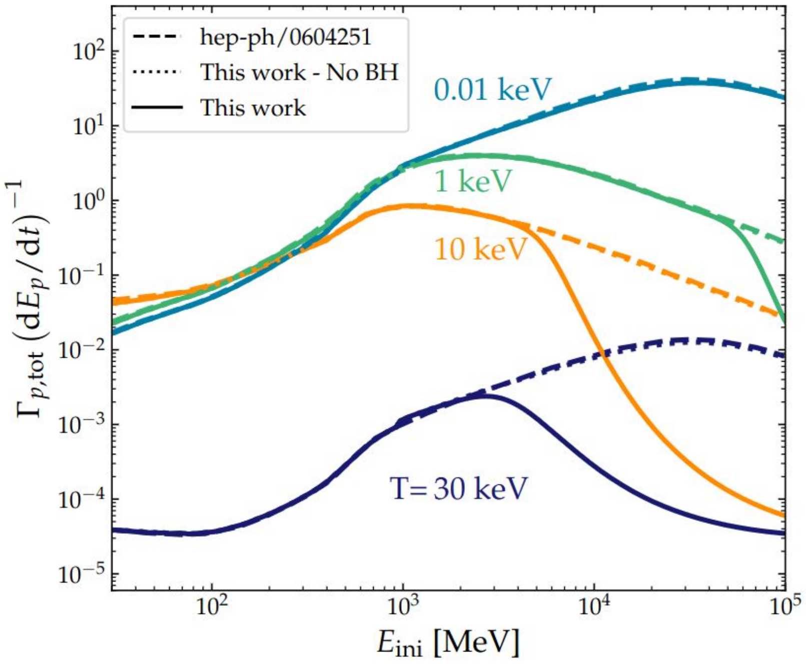
$$\Gamma_{H_i+A_j\to A_k} = n_{A_j}\sigma_{H_i+A_j\to A_k}\beta_{H_i}$$

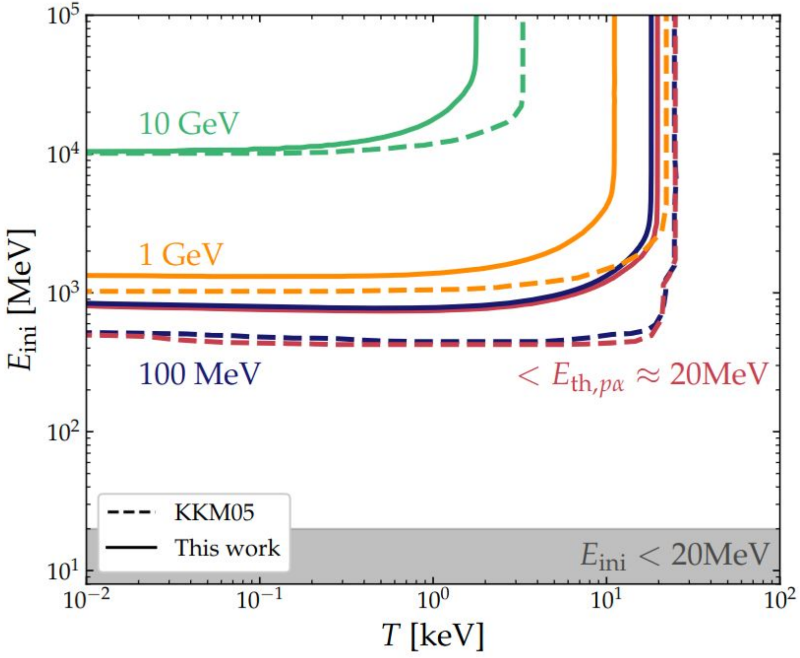
for unstable hadrons there is an additional contribution from the decay rate.

$$R^{H_i}\left(E_{H_i}^{(\text{in})}, E'_{H_i}; T\right) \equiv \sum_{j,k} R_{H_i+A_j\to A_k}\left(E_{H_i}^{(\text{in})}, E'_{H_i}; T\right) \longrightarrow R^{H_i}\left(E_{H_i}^{(\text{in})}, \tilde{E}_{H_i}^{(R=1)}; T\right) = 1$$

Hadrodisintegration

In order to account for the effect of the injected hadrons, we must consider energy loss processes.





Neutrino injections

★ Thermal scattering of the form $\nu\nu_{\rm th} \to e^+e^-$

Note on thresholds and timescales. In order to inject electron-positron pairs:

$$E_{ee} \sim \frac{m_e^2}{T} \gtrsim 26\,\mathrm{MeV}\left(\frac{10\,\mathrm{keV}}{T}\right)$$

For heavier particles we need:

$$E_{\mu\mu/\pi\pi} \sim \frac{m_{\mu/\pi}^2}{T} \gtrsim \boxed{(1.1/1.8)\ \mathrm{TeV}}\left(\frac{10\,\mathrm{keV}}{T}\right)$$

for such high E, limits are dominated by FSR!

It can happen that, depending on the energy of the injected neutrino, the scattering time is faster than the Hubble time:

$$t_H \sim \frac{1}{H(T)} \sim \frac{m_P}{T^2} \sim 1\,s\left(\frac{T}{\mathrm{MeV}}\right)^{-2}$$

$$t_{\rm th} \sim \frac{1}{G_F^2 T^4 E} \sim 10^{-3}\,\mathrm{s}\left(\frac{T}{\mathrm{MeV}}\right)^{-4}\left(\frac{E}{10\,\mathrm{GeV}}\right)^{-1}$$

$t_{\rm th} < t_H$ →

$$E \gtrsim 100\,\mathrm{GeV}\left(\frac{10\,\mathrm{keV}}{T}\right)^2$$

Neutrino injections

★ Thermal scattering of the form $\nu\nu_{\rm th} \to e^+e^-$
We can compute the interaction rate:

$$\Gamma_{ee}(T,E) = \frac{g_\nu}{16\pi^2 E^2}\int_0^\infty \mathrm{d}\epsilon\, f_{\nu,\rm th}(\epsilon)\int_0^{4E\epsilon} \mathrm{d}s\, s\cdot \sigma_{ee}(s) \xrightarrow{s \ll m_Z^2} \sigma(s) = \Sigma(s)\frac{G_F^2 s}{6\pi}$$

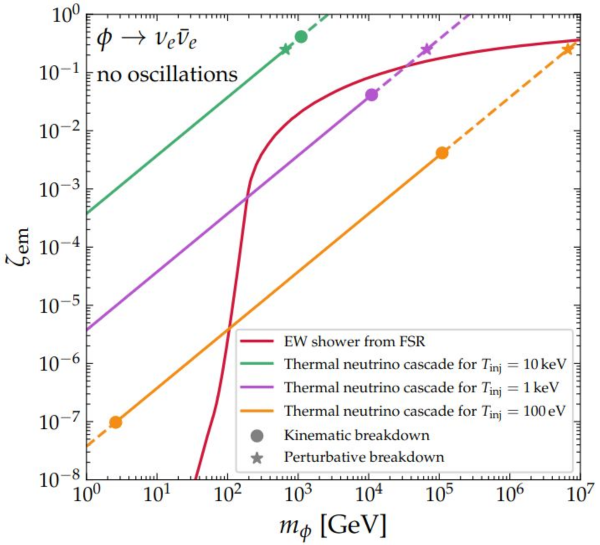
Assuming for simplicity $m_e = 0,\ \Sigma(s) = \text{const.} \equiv \Sigma_\infty$

$$\Gamma_{ee}(T,E) \overset{m_e=0}{\simeq} \frac{7\pi}{90}\Sigma_\infty G_F^2 E T_\nu^4$$

Let us now introduce the quantity:

$$\mathrm{d}\zeta_{\rm em} \simeq \frac{E(t)}{E_{\rm inj}}\Gamma_{ee}(t)\mathrm{d}t$$

as **fraction of EM energy** that is transferred into the plasma in a certain time dt.

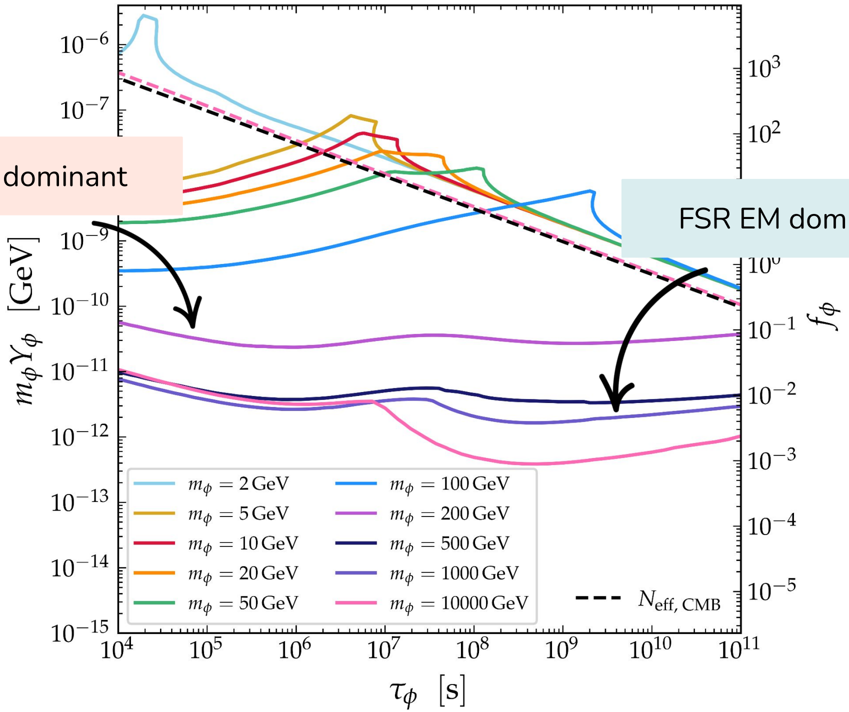


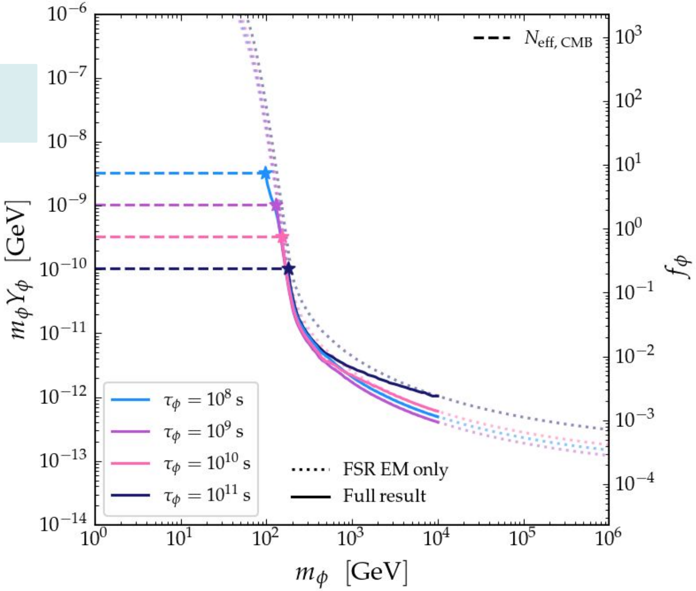
A note on model-building

Possible realization of this scenario include:

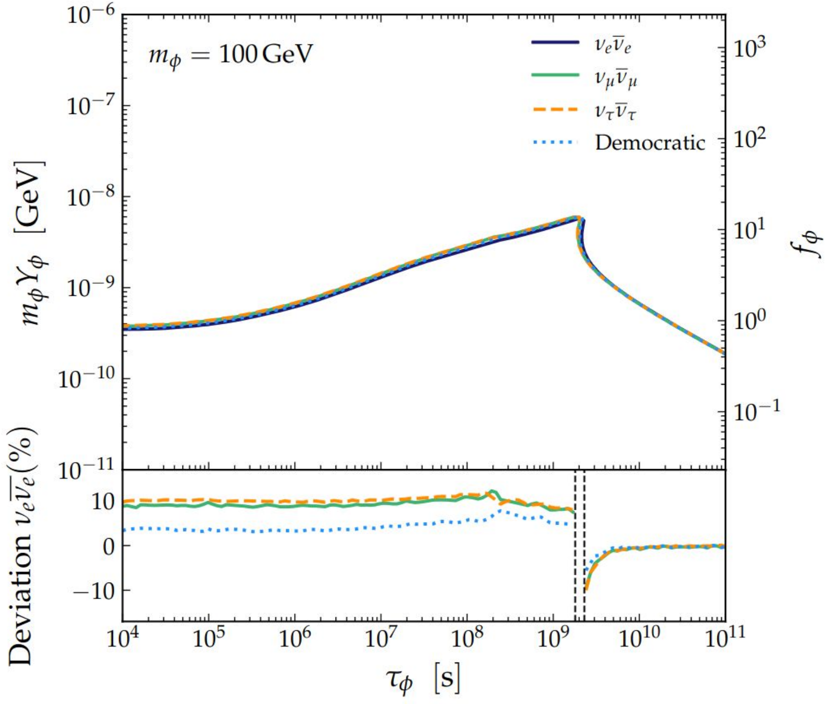
- ★ **Majoron**, with loop-suppressed decay into electrons.
- ★ **Gauge boson coupled to two sterile neutrinos** + seesaw mixing
- ★ Neutral component of a **scalar triplet** of hypercharge 2
- ★ Decay into one neutrino and one DS state is potentially also relevant.

Results

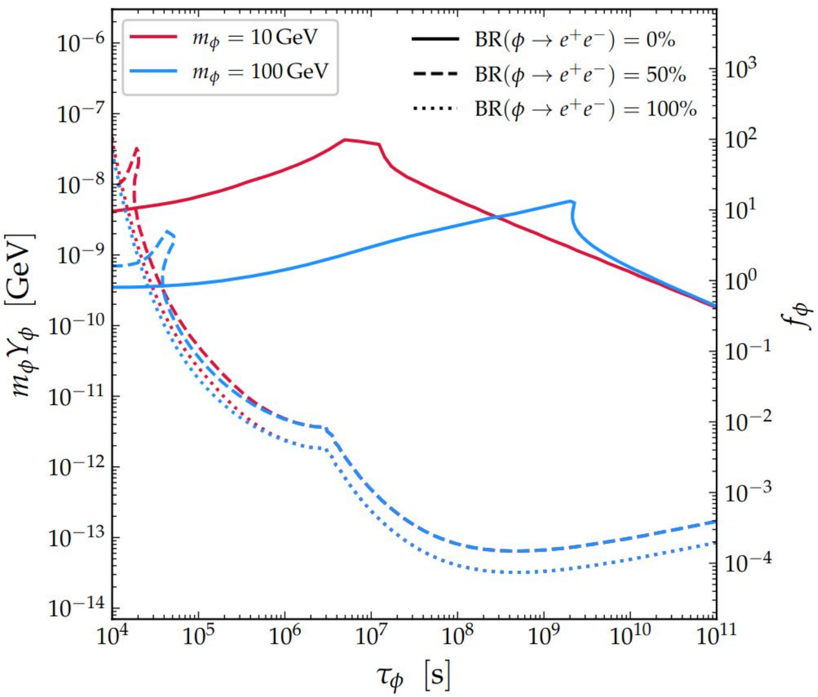

FSR HD dominant
FSR EM dominant
$m_\phi Y_\phi$ [GeV]
f_ϕ
τ_ϕ [s]
$m_\phi = 2\,\mathrm{GeV}$
$m_\phi = 5\,\mathrm{GeV}$
$m_\phi = 10\,\mathrm{GeV}$
$m_\phi = 20\,\mathrm{GeV}$
$m_\phi = 50\,\mathrm{GeV}$
$m_\phi = 100\,\mathrm{GeV}$
$m_\phi = 200\,\mathrm{GeV}$
$m_\phi = 500\,\mathrm{GeV}$
$m_\phi = 1000\,\mathrm{GeV}$
$m_\phi = 10000\,\mathrm{GeV}$
$N_{\mathrm{eff,\,CMB}}$


$N_{\mathrm{eff,\,CMB}}$
$m_\phi Y_\phi$ [GeV]
f_ϕ
m_ϕ [GeV]
$\tau_\phi = 10^8$ s
$\tau_\phi = 10^9$ s
$\tau_\phi = 10^{10}$ s
$\tau_\phi = 10^{11}$ s
FSR EM only
Full result

Results

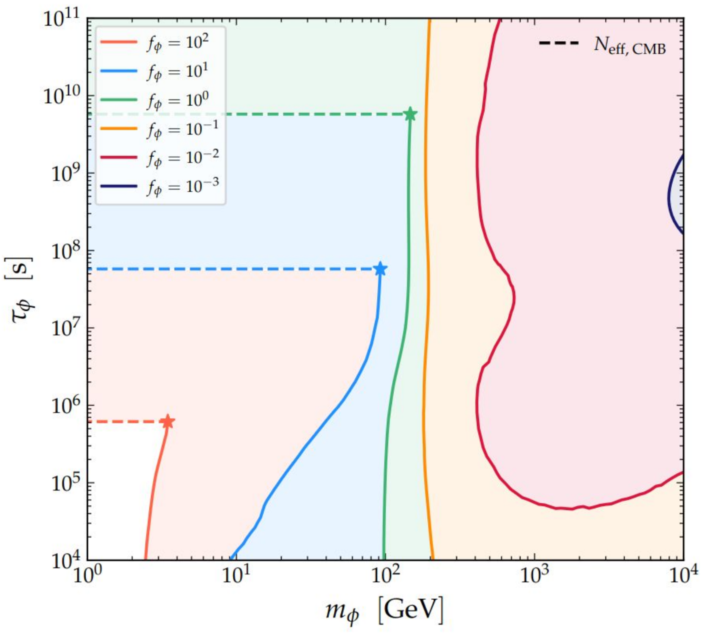


$m_\phi = 100\,\mathrm{GeV}$
$\nu_e\overline{\nu}_e$
$\nu_\mu\overline{\nu}_\mu$
$\nu_\tau\overline{\nu}_\tau$
Democratic
$m_\phi Y_\phi$ [GeV]
f_ϕ
Deviation $\nu_e\overline{\nu}_e(\%)$
τ_ϕ [s]

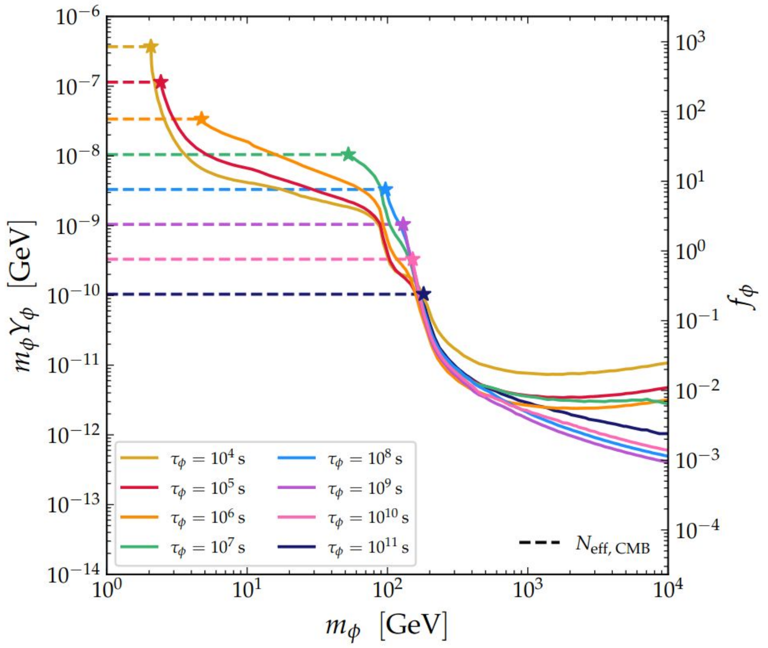


$m_\phi = 10\,\mathrm{GeV}$
$m_\phi = 100\,\mathrm{GeV}$
$\mathrm{BR}(\phi \to e^+e^-) = 0\%$
$\mathrm{BR}(\phi \to e^+e^-) = 50\%$
$\mathrm{BR}(\phi \to e^+e^-) = 100\%$
$m_\phi Y_\phi$ [GeV]
f_ϕ
τ_ϕ [s]

Results

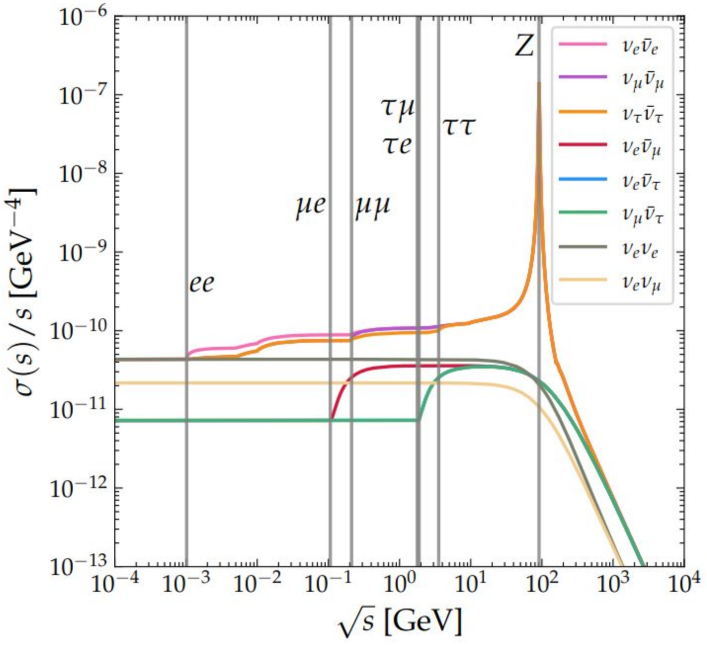


$f_\phi = 10^2$
$f_\phi = 10^1$
$f_\phi = 10^0$
$f_\phi = 10^{-1}$
$f_\phi = 10^{-2}$
$f_\phi = 10^{-3}$
$N_{\rm eff,\,CMB}$
τ_ϕ [s]
m_ϕ [GeV]

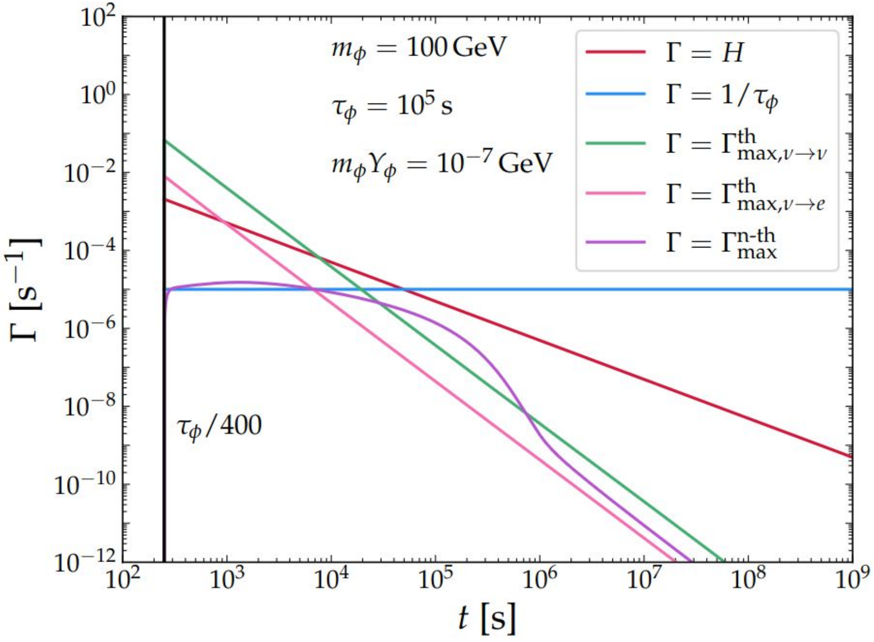


$\tau_\phi = 10^4$ s
$\tau_\phi = 10^5$ s
$\tau_\phi = 10^6$ s
$\tau_\phi = 10^7$ s
$\tau_\phi = 10^8$ s
$\tau_\phi = 10^9$ s
$\tau_\phi = 10^{10}$ s
$\tau_\phi = 10^{11}$ s
$N_{\rm eff,\,CMB}$
$m_\phi Y_\phi$ [GeV]
f_ϕ
m_ϕ [GeV]

Results



$\sigma(s)/s$ [GeV^{-4}]
$\sqrt{s}$ [GeV]
ee
μe
$\mu\mu$
$\tau\mu$
τe
$\tau\tau$
Z
$\nu_e\bar{\nu}_e$
$\nu_\mu\bar{\nu}_\mu$
$\nu_\tau\bar{\nu}_\tau$
$\nu_e\bar{\nu}_\mu$
$\nu_e\bar{\nu}_\tau$
$\nu_\mu\bar{\nu}_\tau$
$\nu_e\nu_e$
$\nu_e\nu_\mu$



Γ [s^{-1}]
t [s]
$m_\phi = 100\,$GeV
$\tau_\phi = 10^5\,$s
$m_\phi Y_\phi = 10^{-7}\,$GeV
$\tau_\phi/400$
$\Gamma = H$
$\Gamma = 1/\tau_\phi$
$\Gamma = \Gamma^{\rm th}_{{\rm max},\nu\to\nu}$
$\Gamma = \Gamma^{\rm th}_{{\rm max},\nu\to e}$
$\Gamma = \Gamma^{\rm n\text{-}th}_{\rm max}$