

Photo- and Hadrodisintegration constraints on massive relics decaying into neutrinos



Jonas is not talking about Dark Photons????



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Jonas Frerick (jonas.frerick@uniroma1.it)

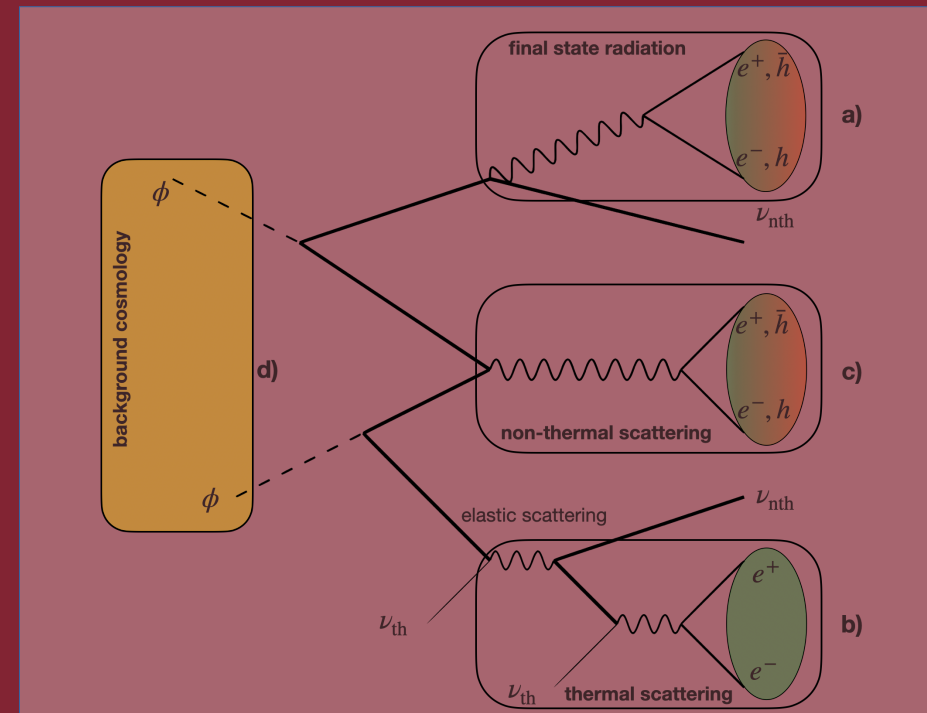
Based on 2505.01492

w/ Sara Bianco, Frederik Depta, Thomas Hambye,
Marco Hufnagel & Kai Schmidt-Hoberg

Theory Seminar

23.06.2025

DESY Hamburg



Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Research Council Executive Agency. Neither the European Union nor the granting authority can be held responsible for them. This work is supported by the ERC STG grant ("AstroDarkLS", grant No. 101117510).

What's on the menu today?

→ Motivation

Observable effects of unstable relics

Effects of decays into neutrinos

→ Interlude

BBN in the SM

Photodisintegration & Hadrodisintegration

→ Detailed treatment of neutrino injections

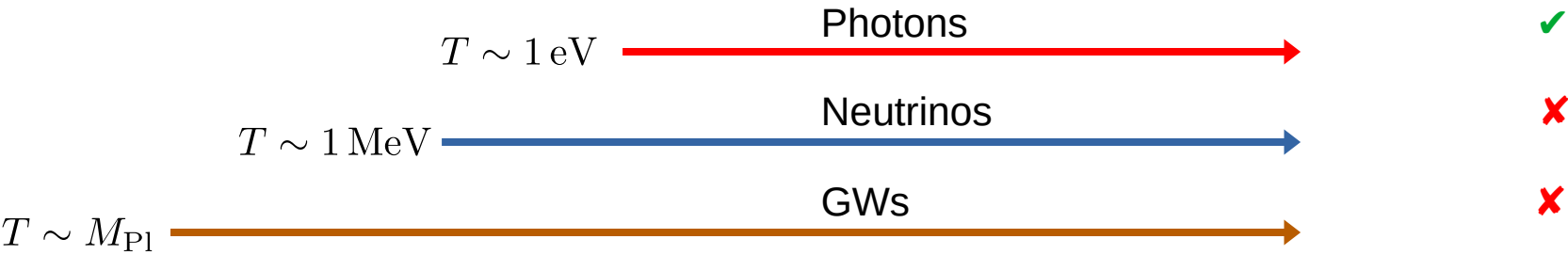
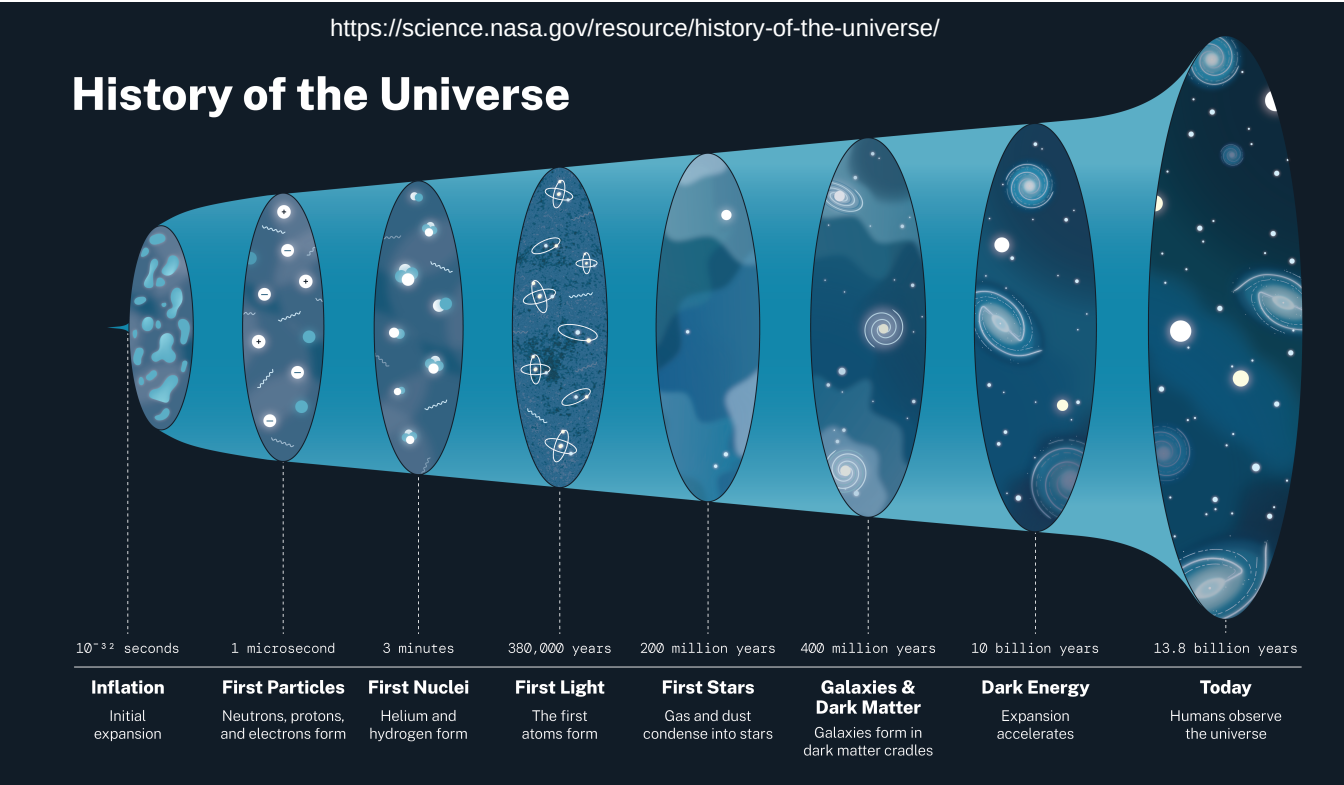
Ingredients for a full treatment

How to treat the injections in practice

→ Results, Conclusions & Outlook

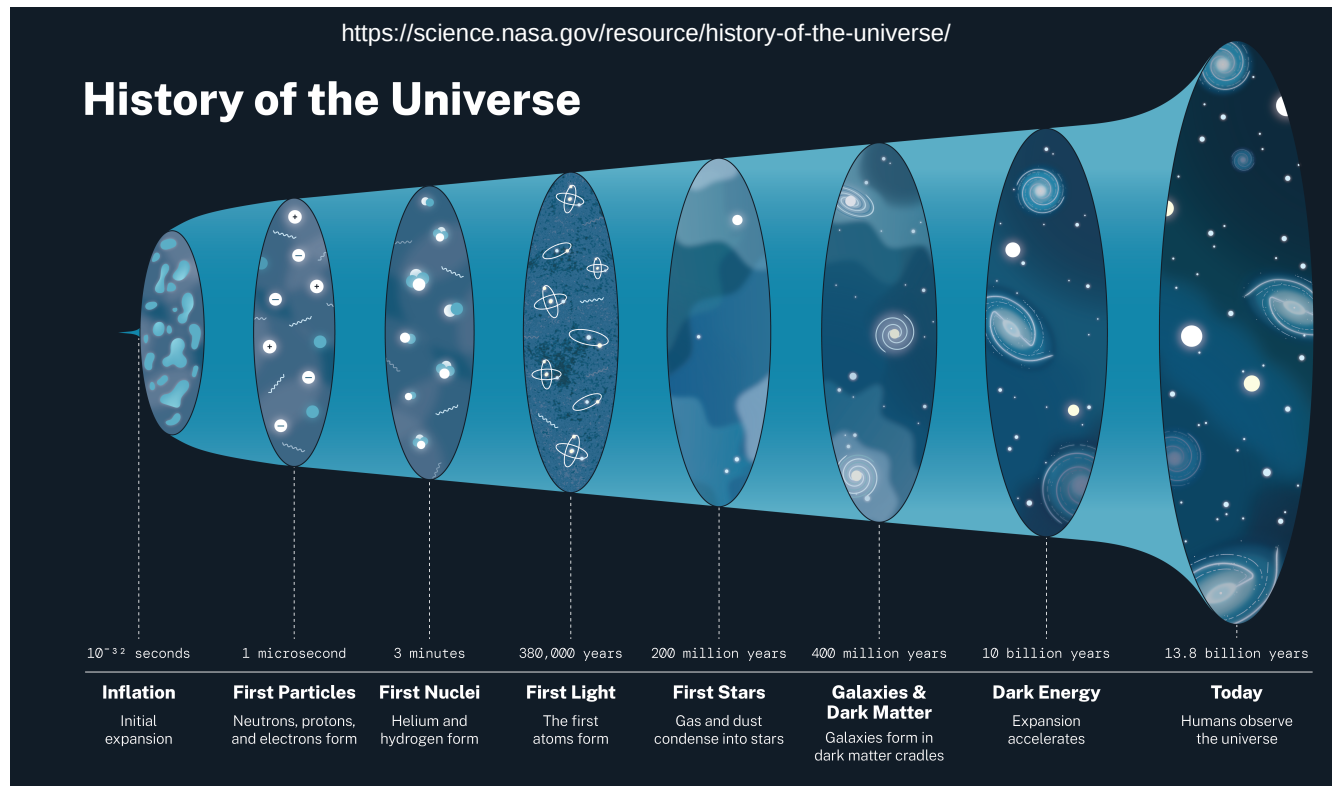


Investigating unstable relics in the early Universe

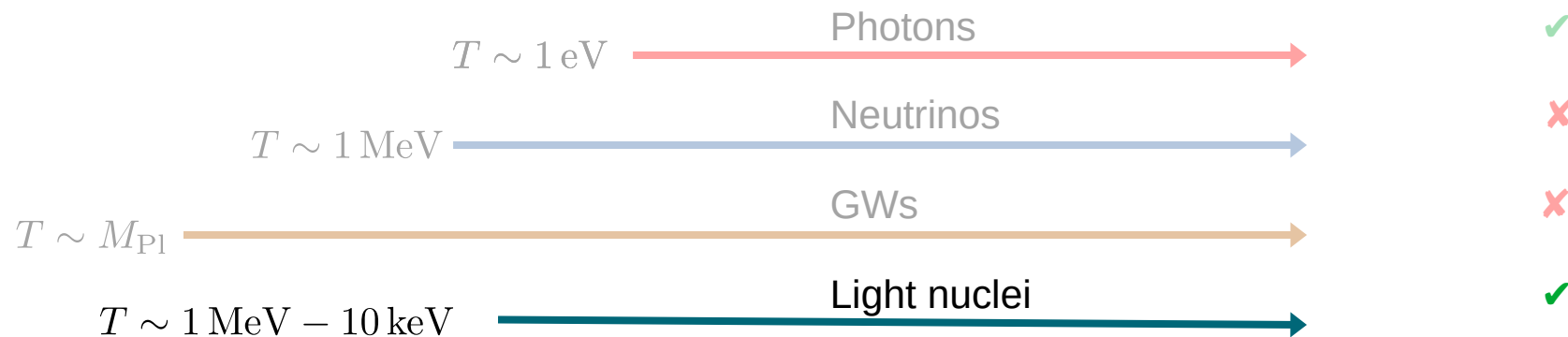


Detection:

Investigating unstable relics in the early Universe

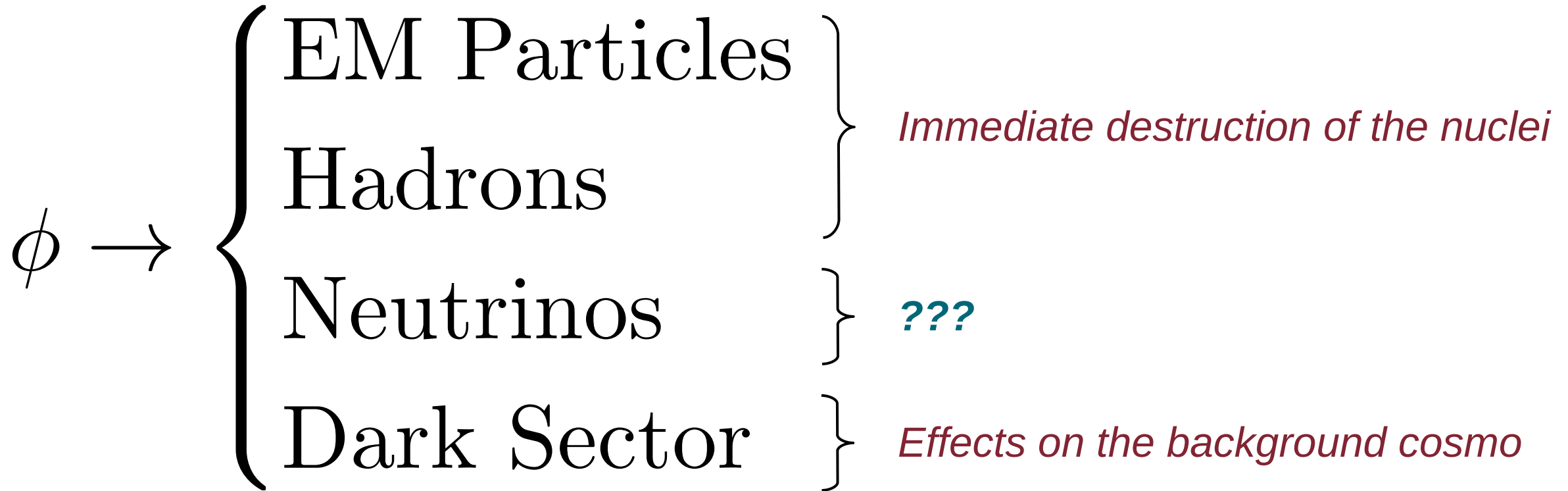


Light nuclei can be the strongest probe of new physics effects between MeV and eV temperatures

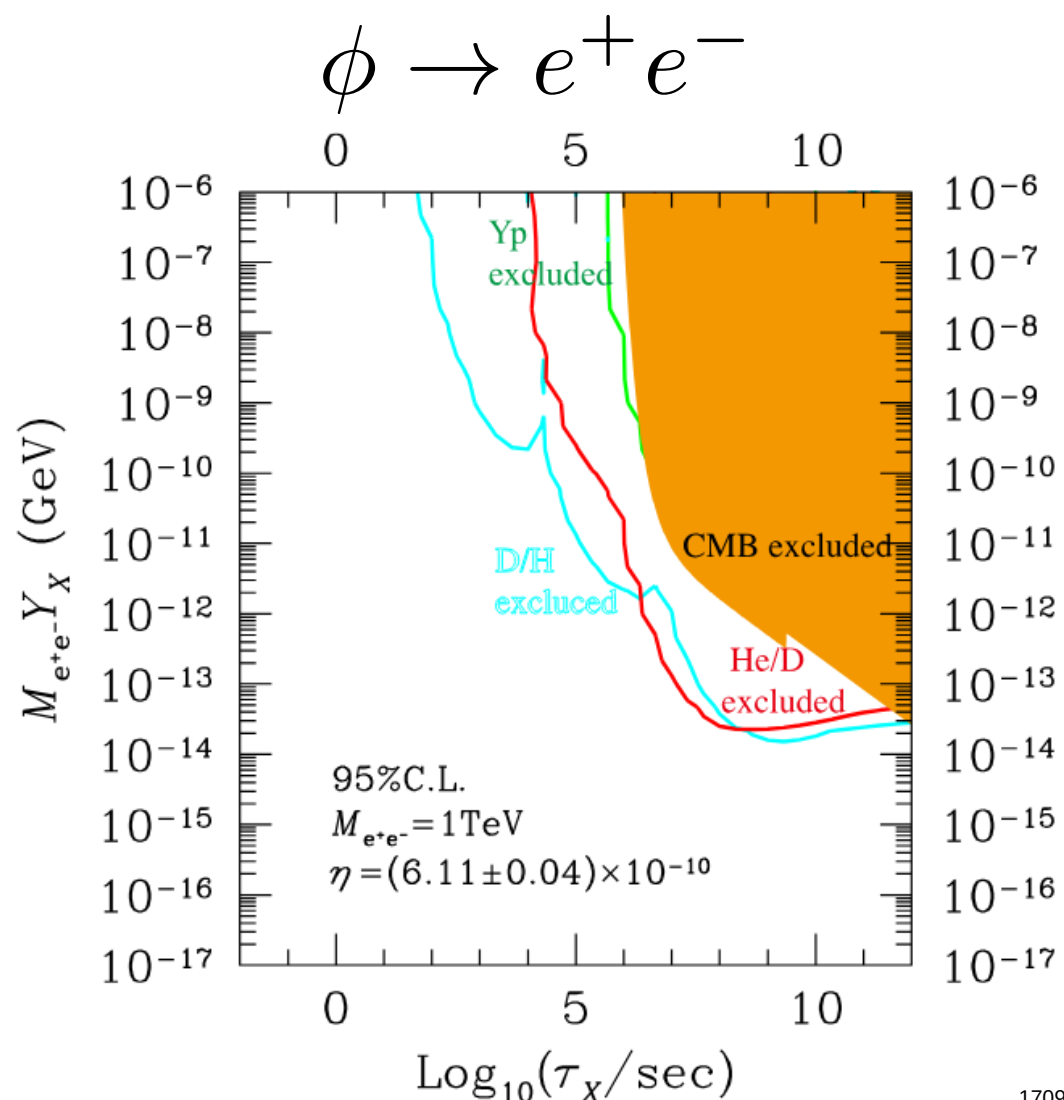


Detection:

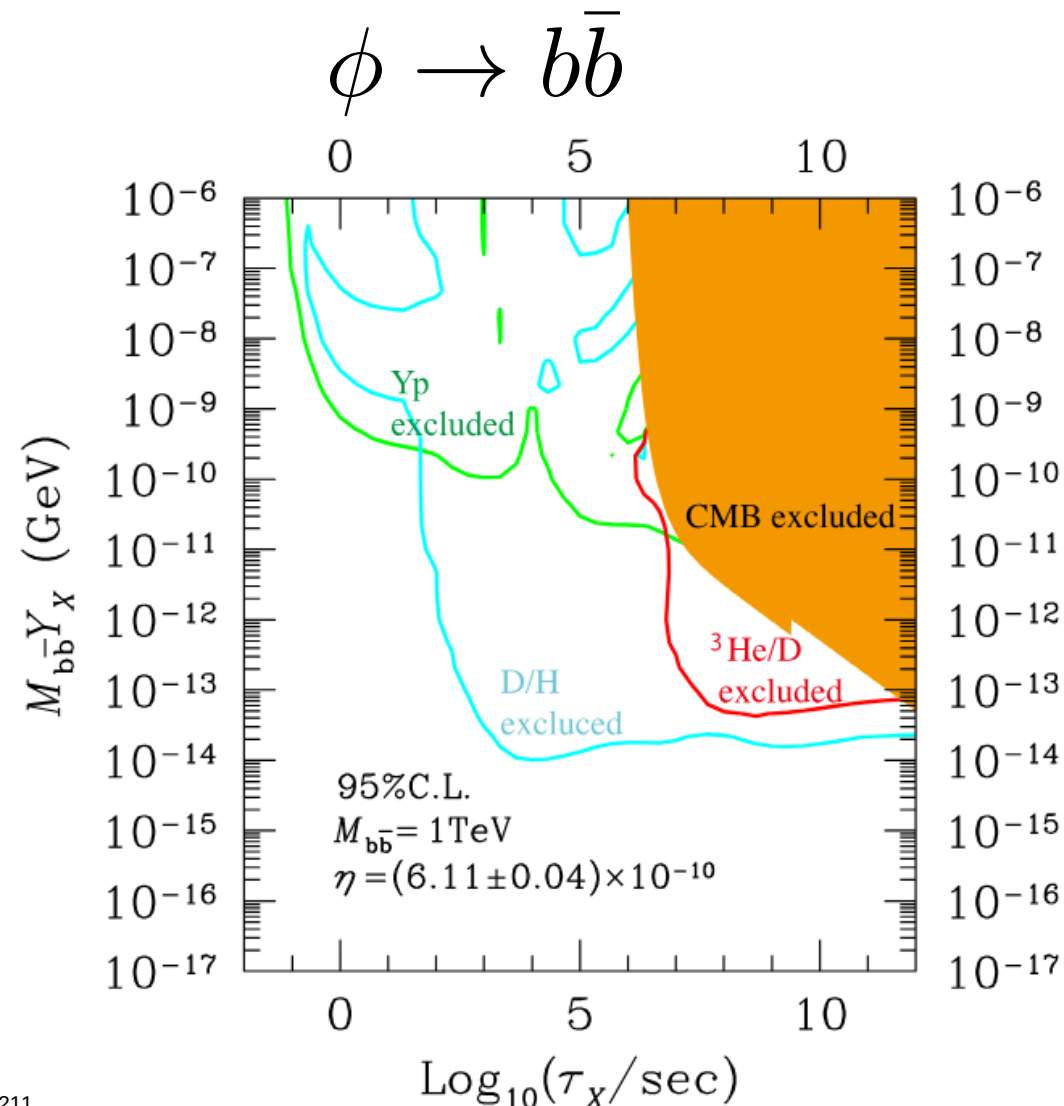
Introducing a new unstable (heavy) relic



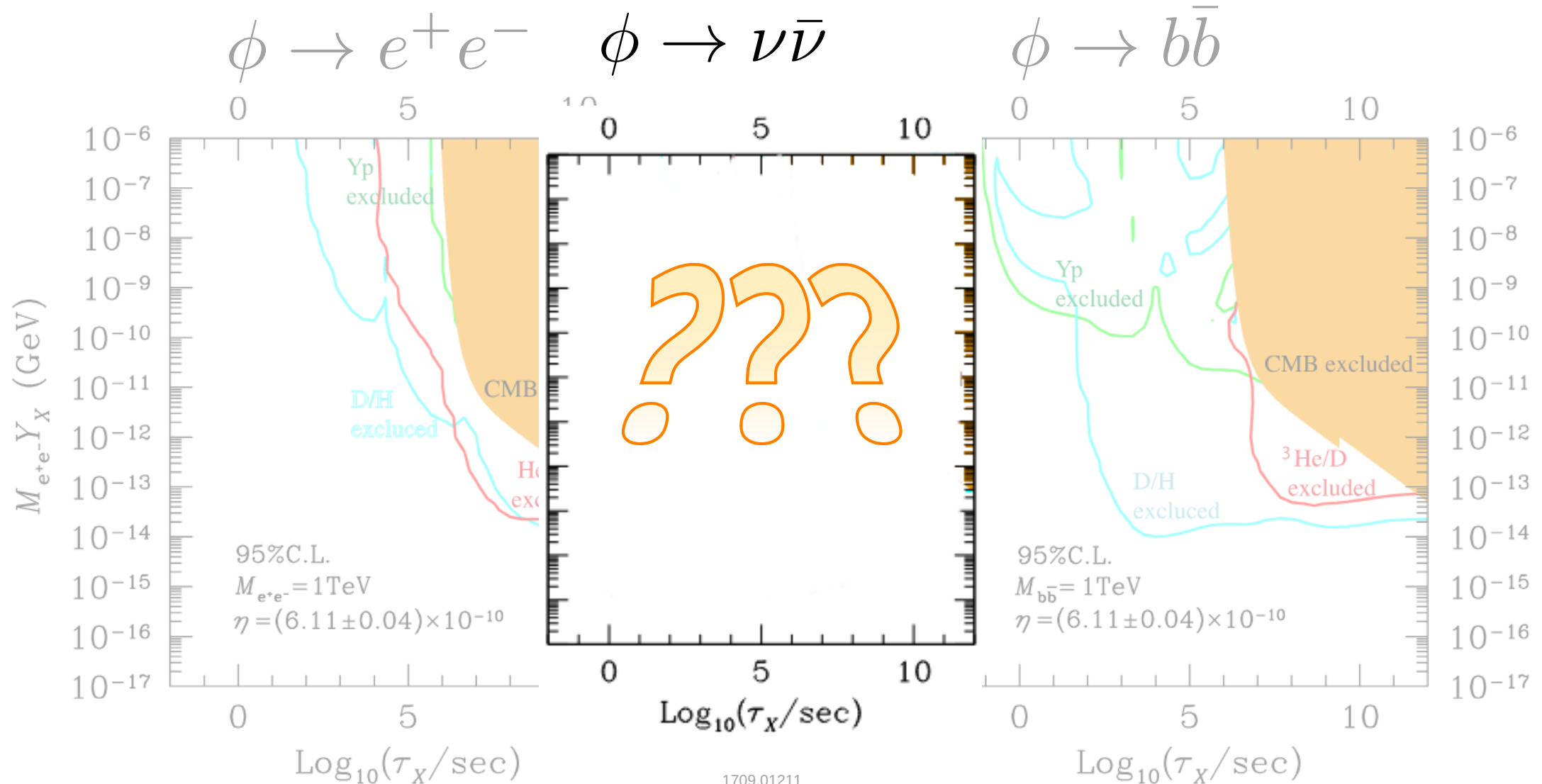
Can you hide an unstable Dark Sector in neutrinos?



1709.01211



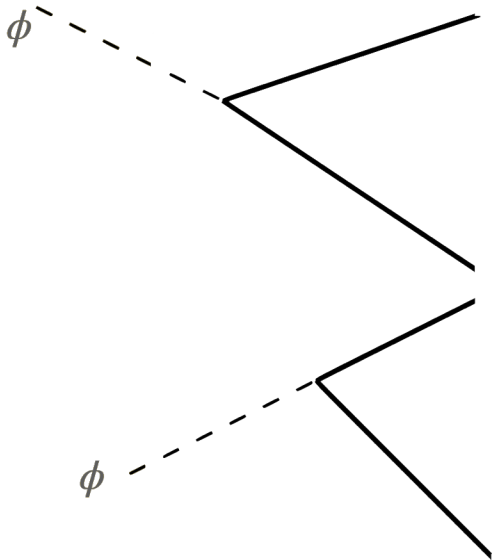
Can you hide an unstable Dark Sector in neutrinos?



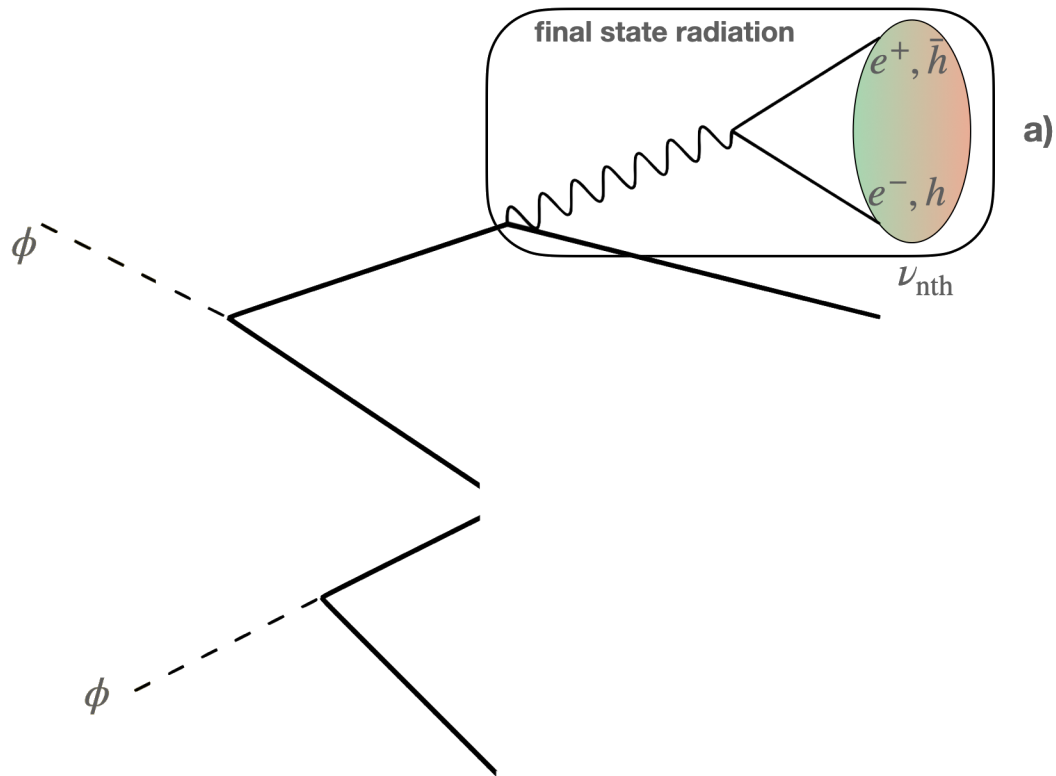
1709.01211

Neutrino injections $\neq$ Injection of only neutrinos

How much harm can a neutrino do?



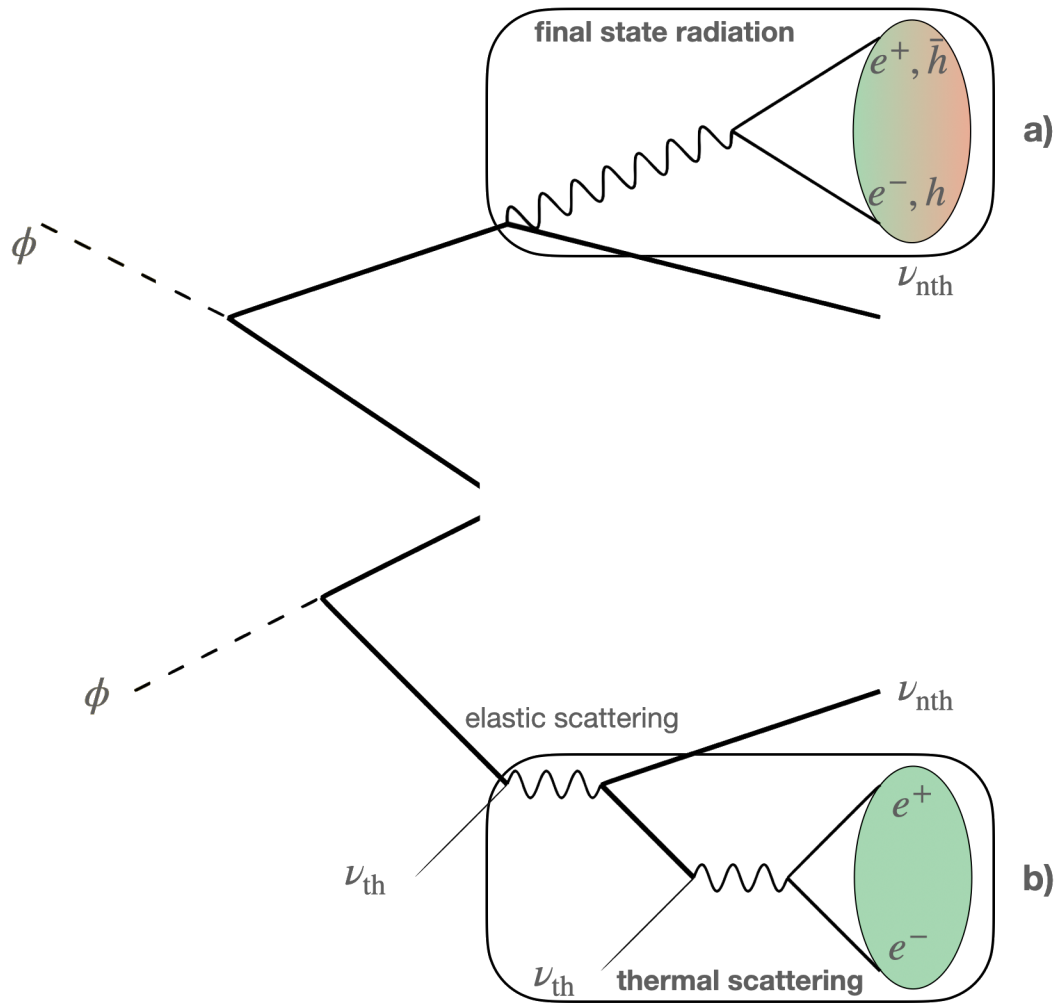
Neutrino injections $\neq$ Injection of only neutrinos



How much harm can a neutrino do?

a) **Final-state radiation**, injects **EM** and **hadrons**

Neutrino injections $\neq$ Injection of only neutrinos

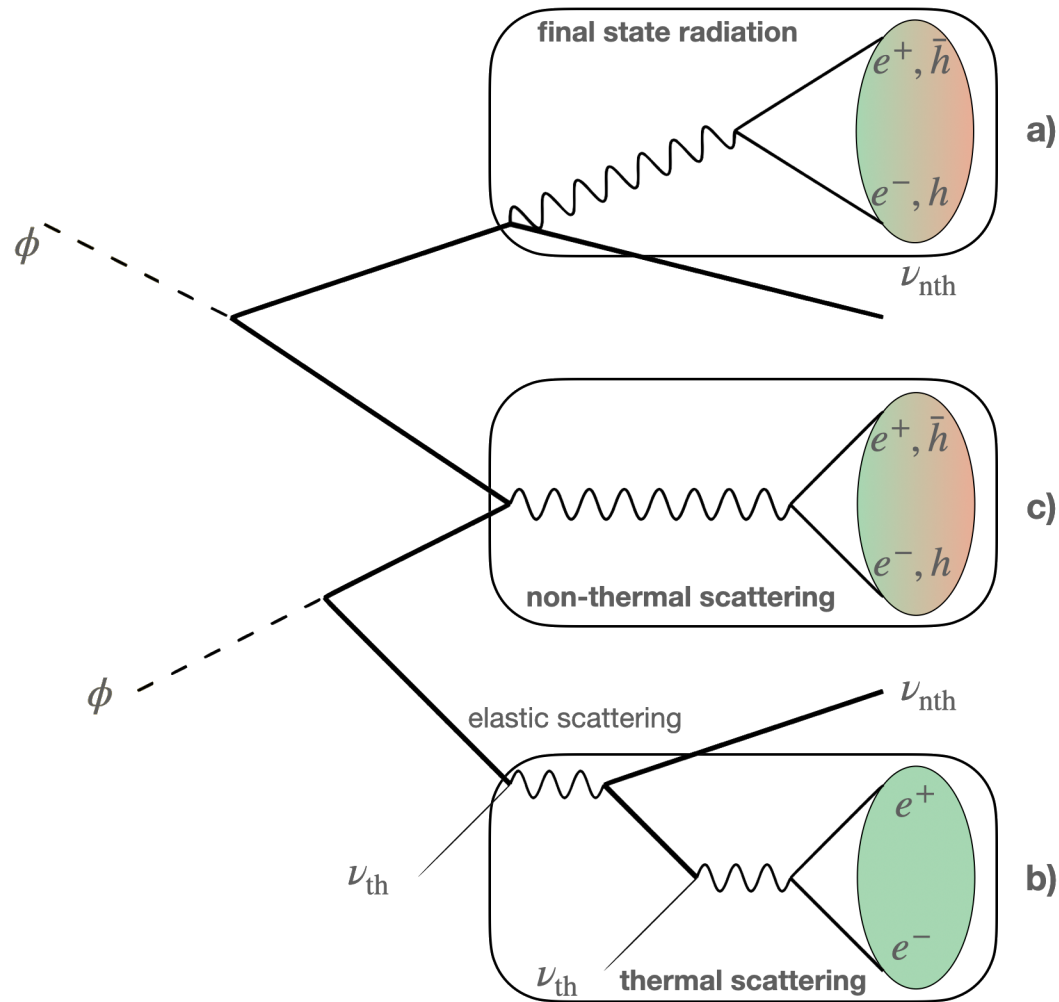


How much harm can a neutrino do?

a) **Final-state radiation**, injects **EM** and **hadrons**

b) **Thermal scattering**, injects **EM**

Neutrino injections $\neq$ Injection of only neutrinos



How much harm can a neutrino do?

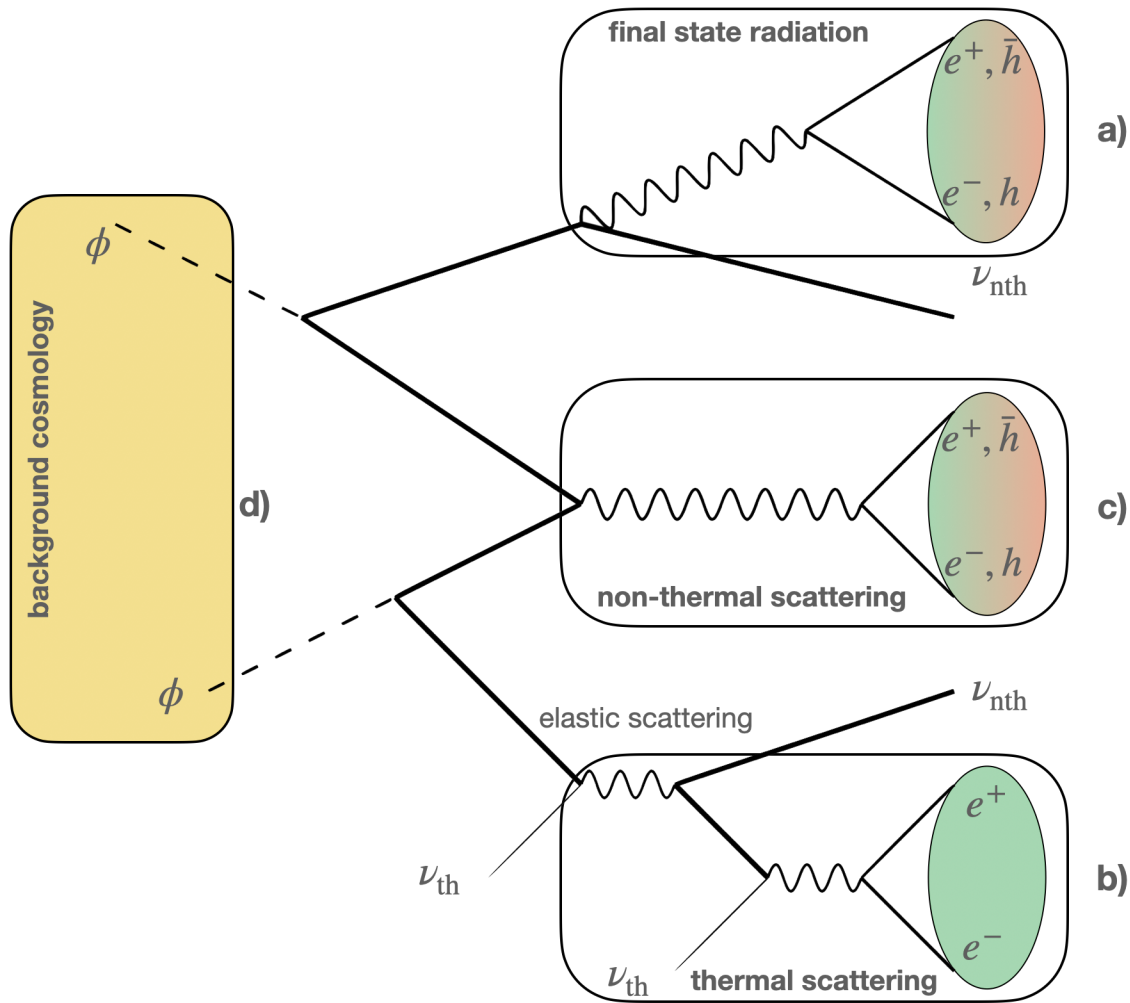
a) **Final-state radiation**, injects **EM** and **hadrons**

b) **Thermal scattering**, injects **EM**

c) **Non-thermal scattering**, injects **EM** and **hadrons**

Neutrino cascade

Neutrino injections $\neq$ Injection of only neutrinos



How much harm can a neutrino do?

a) **Final-state radiation**, injects **EM** and **hadrons**

b) **Thermal scattering**, injects **EM**

c) **Non-thermal scattering**, injects **EM** and **hadrons**

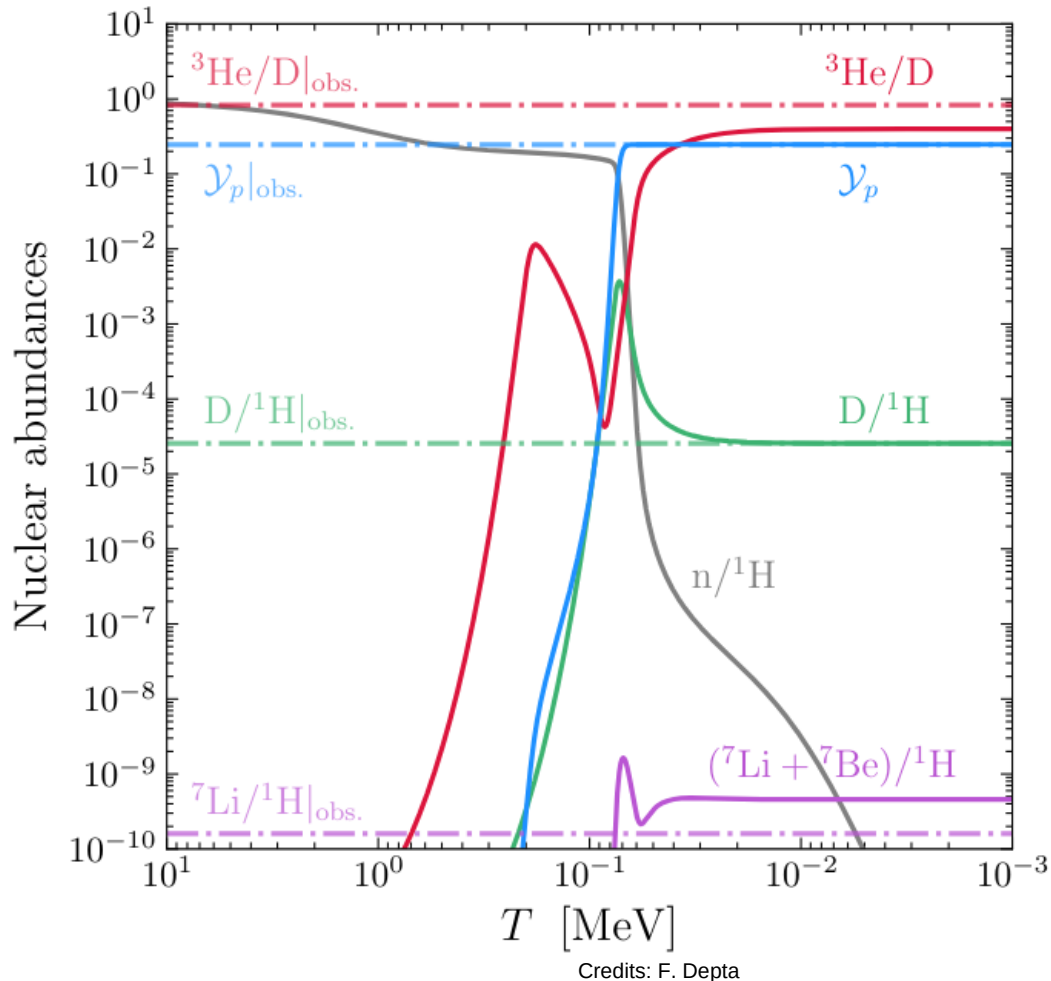
d) Changes in the **background cosmology**

Interlude:

A brief summary of BBN and disintegration

Interlude: BBN data, photodisintegration & hadrodisintegration

We use a modified version of AlterBBN [1806.11095].



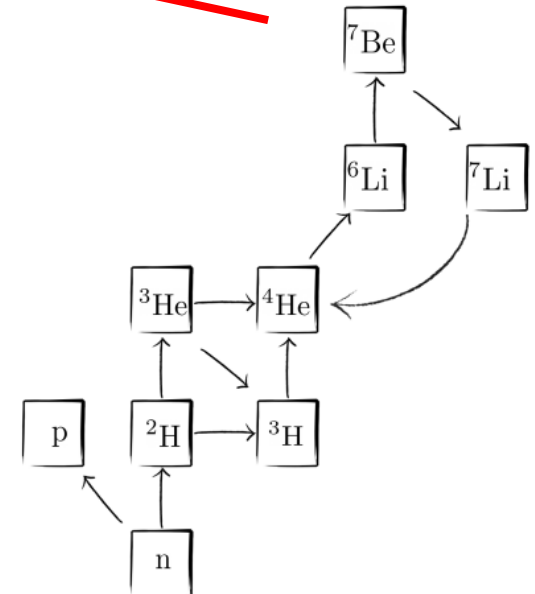
$$Y_p = (2.45 \pm 0.03) \times 10^{-1}$$

$$D/{}^1\text{H} = (2.547 \pm 0.029) \times 10^{-5}$$

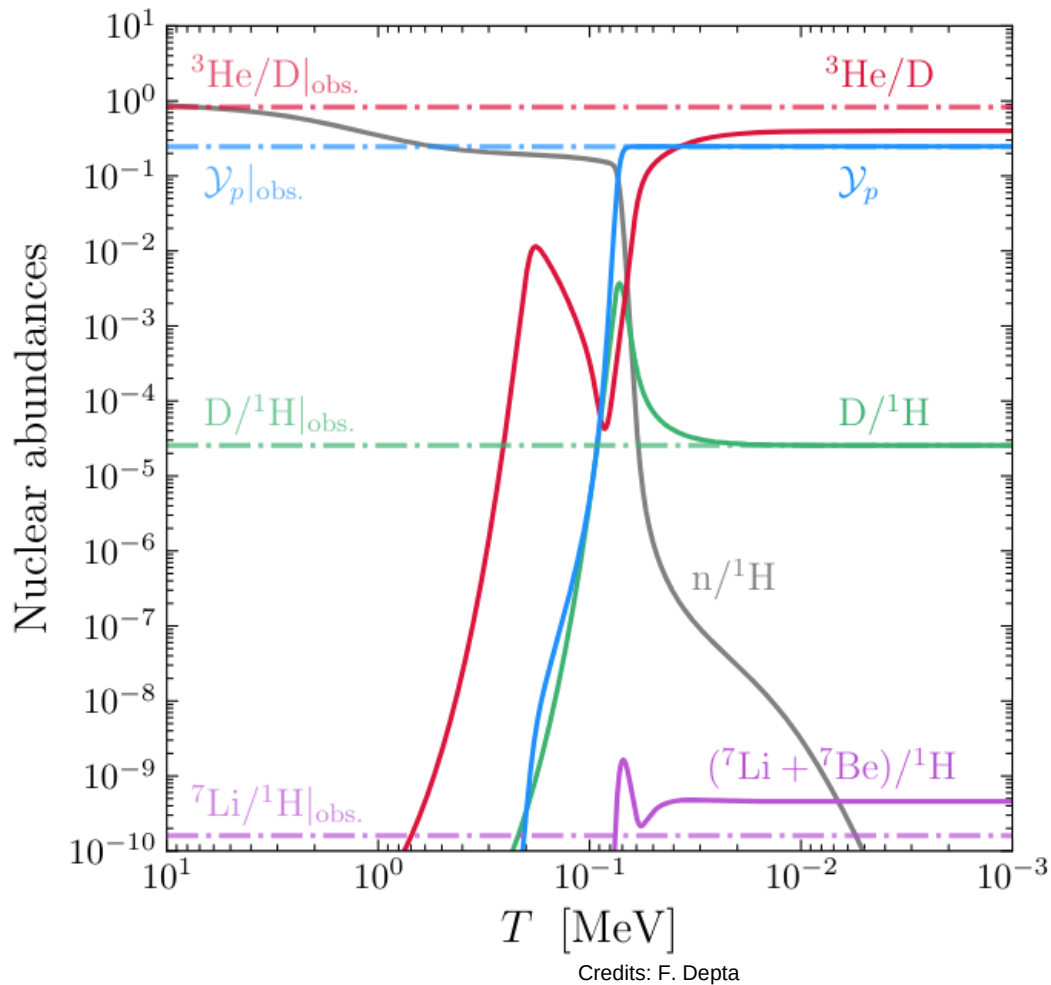
$${}^3\text{He}/D = (8.3 \pm 1.5) \times 10^{-1}$$

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

Reaction chain of
Standard BBN

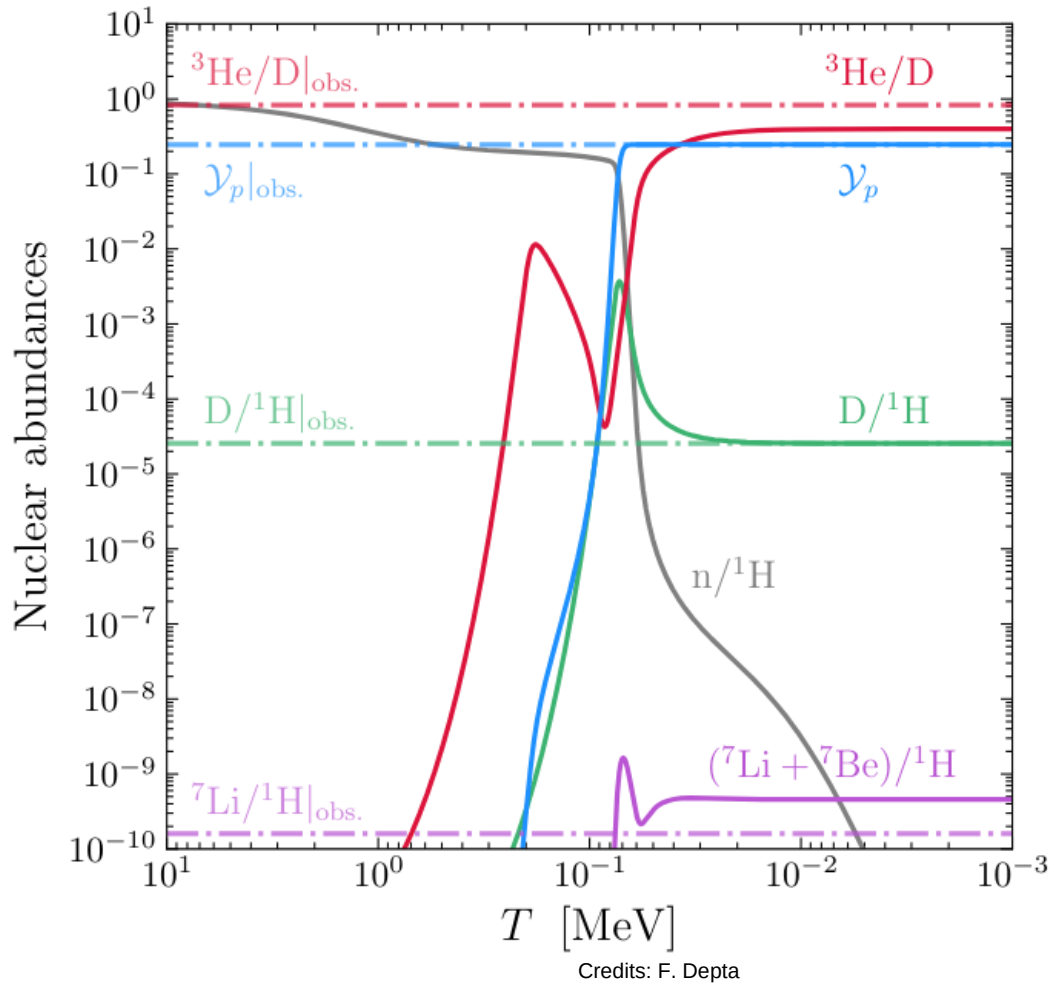


Interlude: BBN data, photodisintegration & hadrodisintegration



Effects of changes in the background cosmology

Interlude: BBN data, photodisintegration & hadrodisintegration

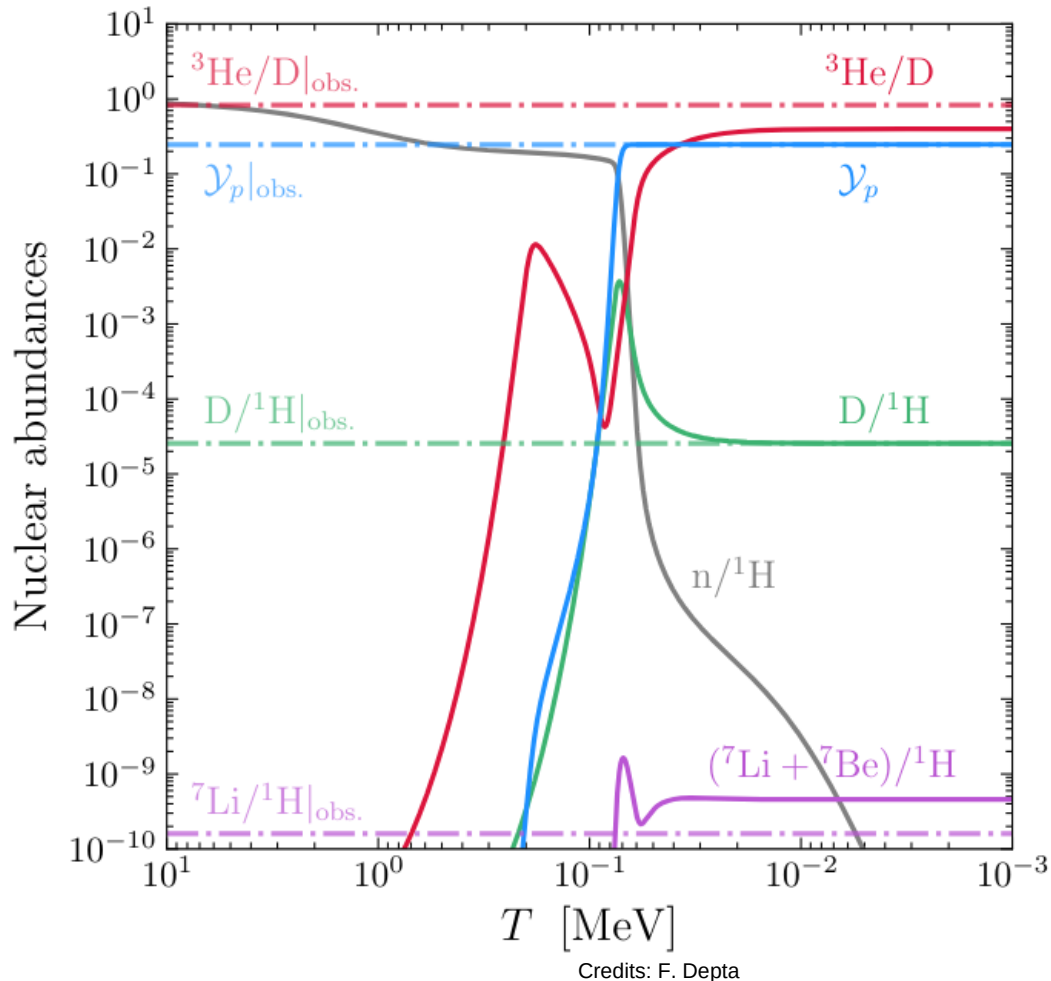


Effects of changes in the background cosmology

- Modification of the **Hubble rate**

$$H(t) \sim \sqrt{\rho_{\text{SM}} + \rho_{\text{DS}}}$$

Interlude: BBN data, photodisintegration & hadrodisintegration



Effects of changes in the background cosmology

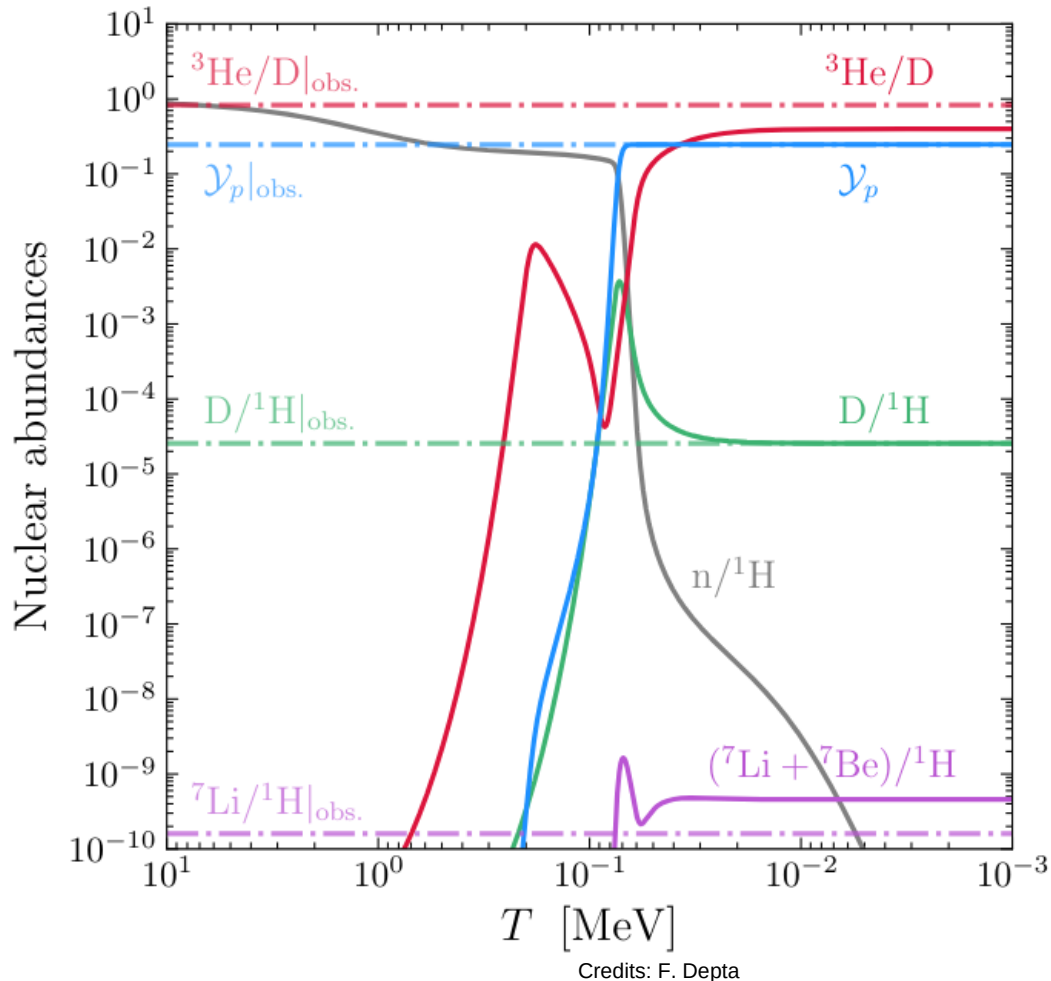
- Modification of the **Hubble rate**

$$H(t) \sim \sqrt{\rho_{\text{SM}} + \rho_{\text{DS}}}$$

- Modification of the **time-temperature relation**

$$\dot{T} = \frac{\dot{q}_{\text{SM}} - 3H(\rho_{\text{SM}} + P_{\text{SM}})}{d\rho_{\text{SM}}/dt}$$

Interlude: BBN data, photodisintegration & hadrodisintegration



Effects of changes in the background cosmology

- Modification of the **Hubble rate**

$$H(t) \sim \sqrt{\rho_{\text{SM}} + \rho_{\text{DS}}}$$

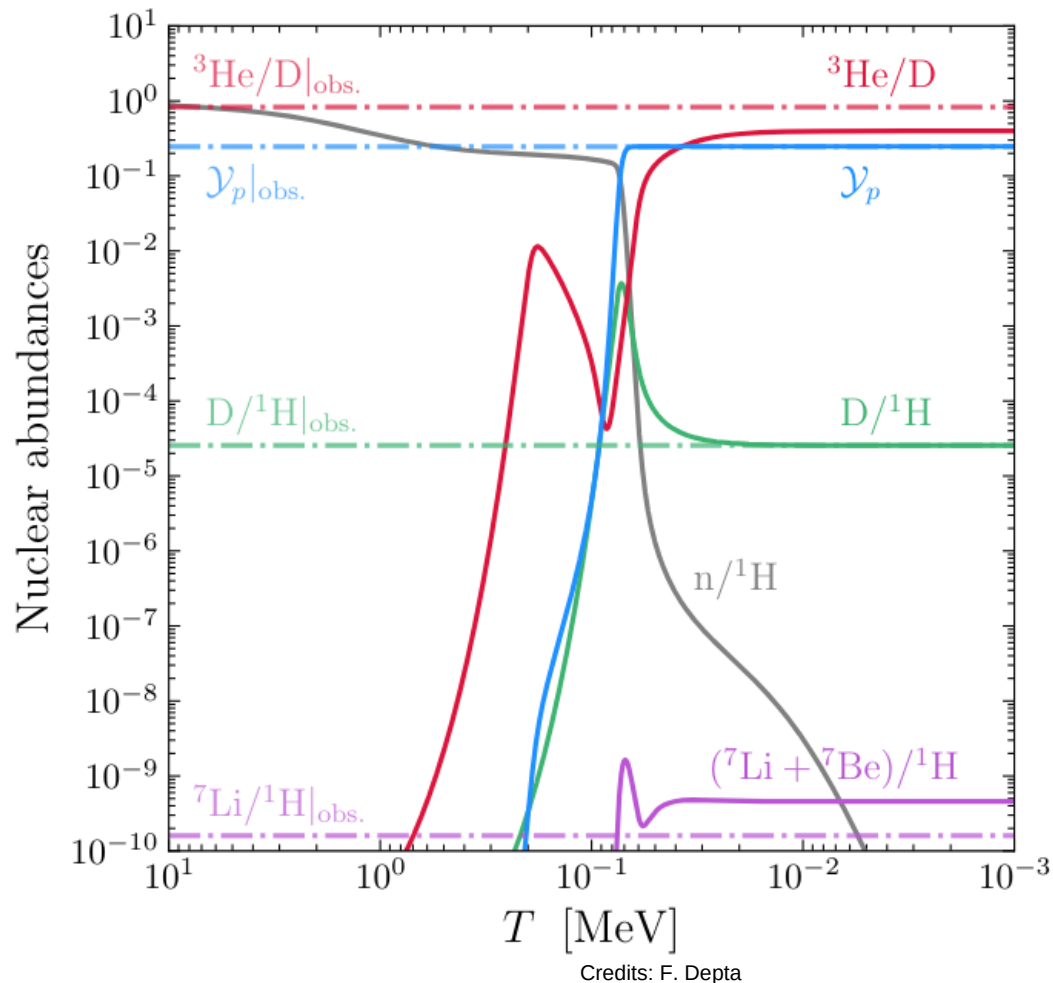
- Modification of the **time-temperature relation**

$$\dot{T} = \frac{\dot{q}_{\text{SM}} - 3H(\rho_{\text{SM}} + P_{\text{SM}})}{d\rho_{\text{SM}}/dt}$$

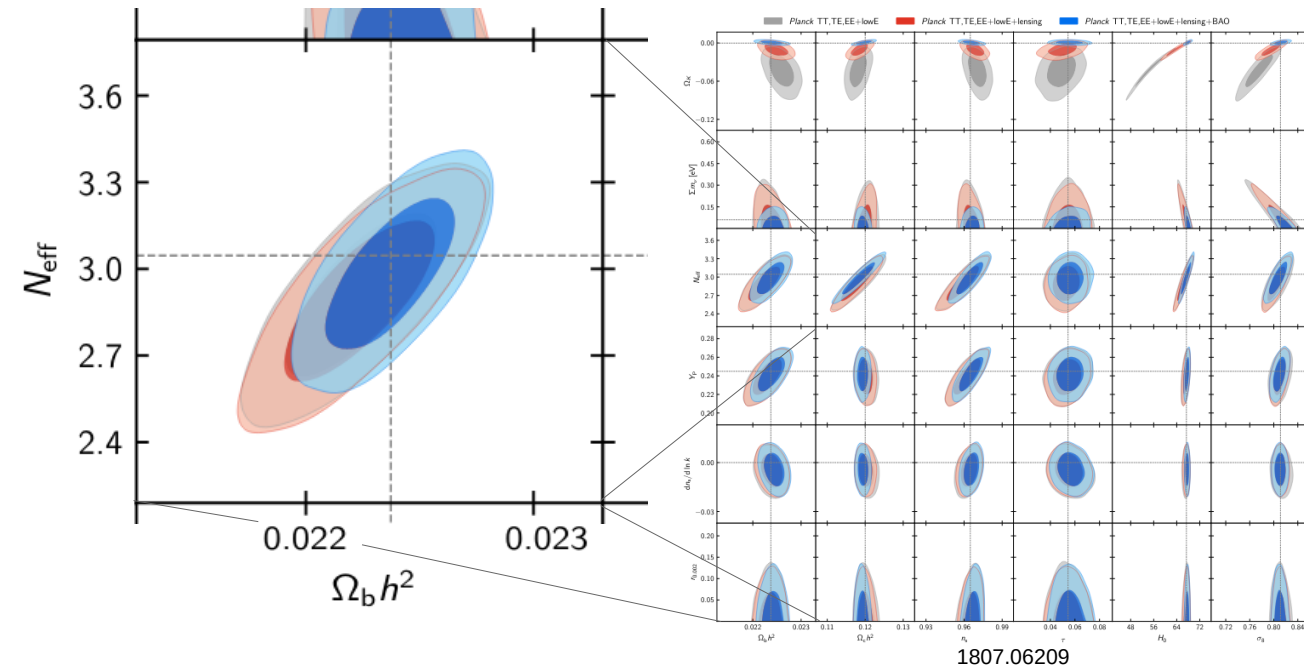
- Modification of the **baryon-to-photon ratio**

Interlude: BBN data, photodisintegration & hadrodisintegration

Modification is driven by correlation to the **effective number of relativistic neutrinos**:



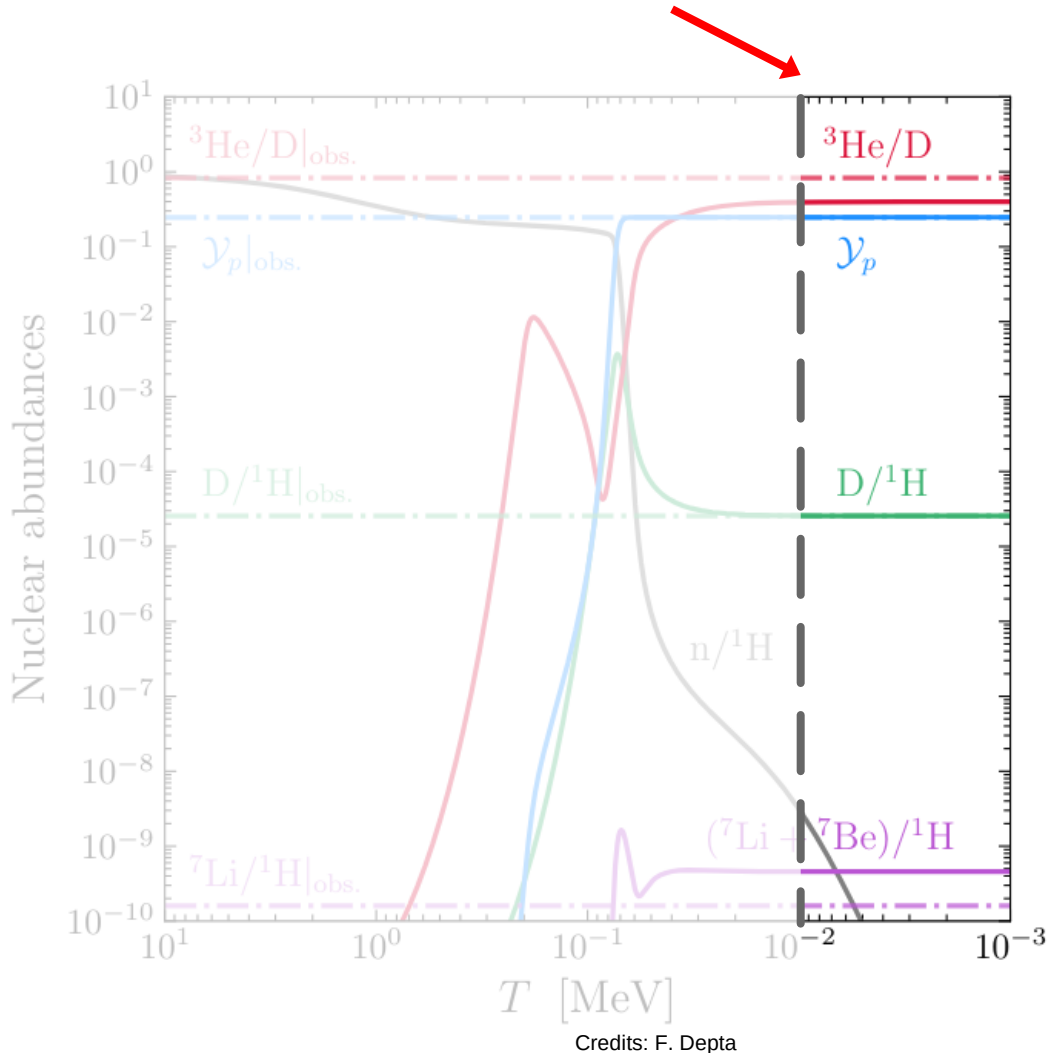
$$N_{\text{eff}} = \frac{\rho_{\nu}^{\text{th}}(t_{\text{rec}}) + \rho_{\nu}^{\text{n-th}}(t_{\text{rec}})}{2 \frac{7}{8} \frac{\pi^2}{30} \left(\frac{4}{11}\right)^{4/3} T(t_{\text{rec}})^4} \equiv [3 + \Delta(t_{\text{rec}})] \left(\frac{11}{4}\right)^{4/3} \left(\frac{T_{\nu}(t_{\text{rec}})}{T(t_{\text{rec}})}\right)^4.$$



$$\Rightarrow \eta = \bar{\eta} + r \sigma_{\eta} \frac{N_{\text{eff}} - \bar{N}_{\text{eff}}}{\sigma_{N_{\text{eff}}}}$$

Interlude: BBN data, photodisintegration & hadrodisintegration

Abundances are effectively fixed by $T \simeq 10 \text{ keV}$ ($t \sim 10^4 \text{ s}$)



Credits: F. Depta

Photodisintegration

=

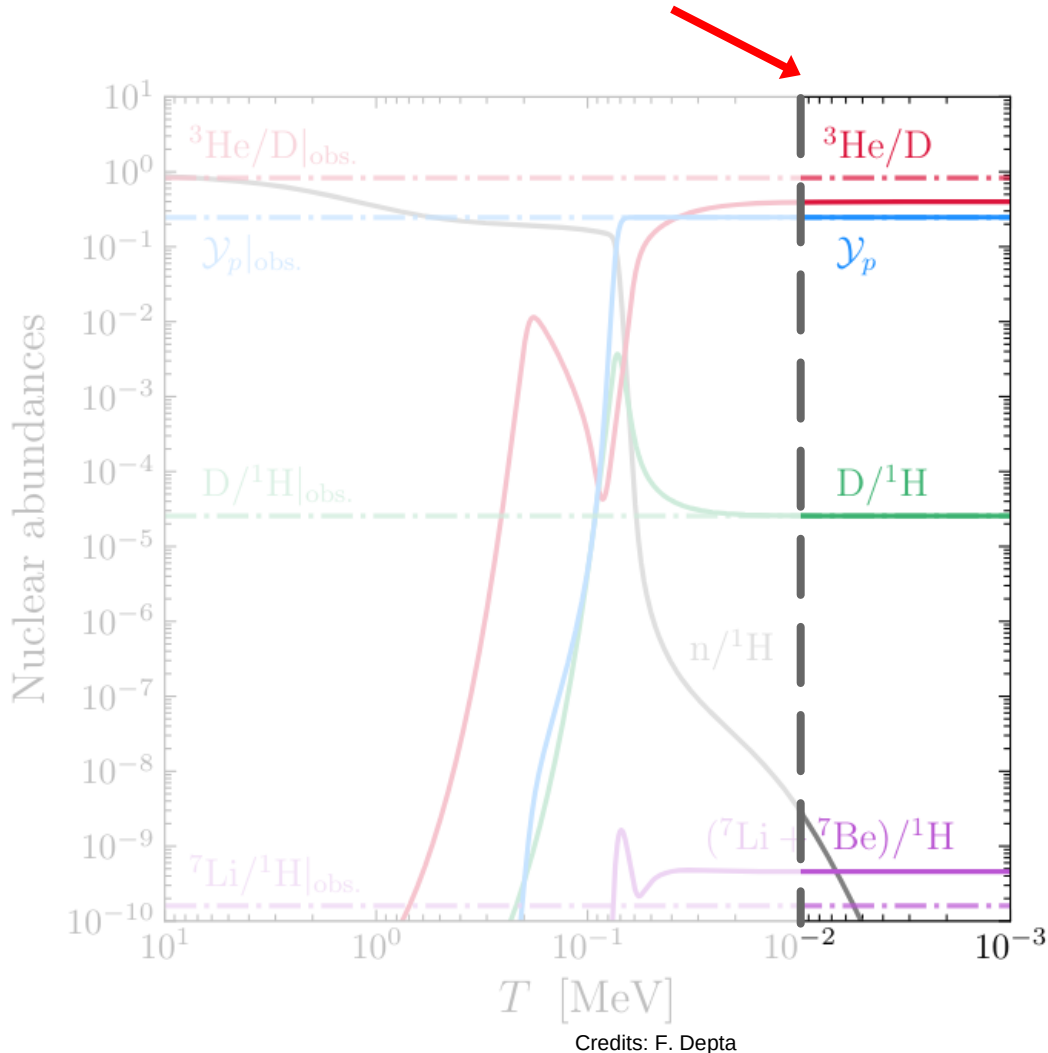
late-time destruction of the light elements by **EM** particles

$$\Rightarrow \tau_{\phi} \gtrsim 10^4 \text{ s}$$

allows factorisation of the processes

Interlude: BBN data, photodisintegration & hadrodisintegration

Abundances are effectively fixed by $T \simeq 10 \text{ keV}$ ($t \sim 10^4 \text{ s}$)



Photodisintegration

=

late-time destruction of the light elements by **EM** particles

$\Rightarrow \tau_\phi \gtrsim 10^4 \text{ s}$ allows factorisation of the processes

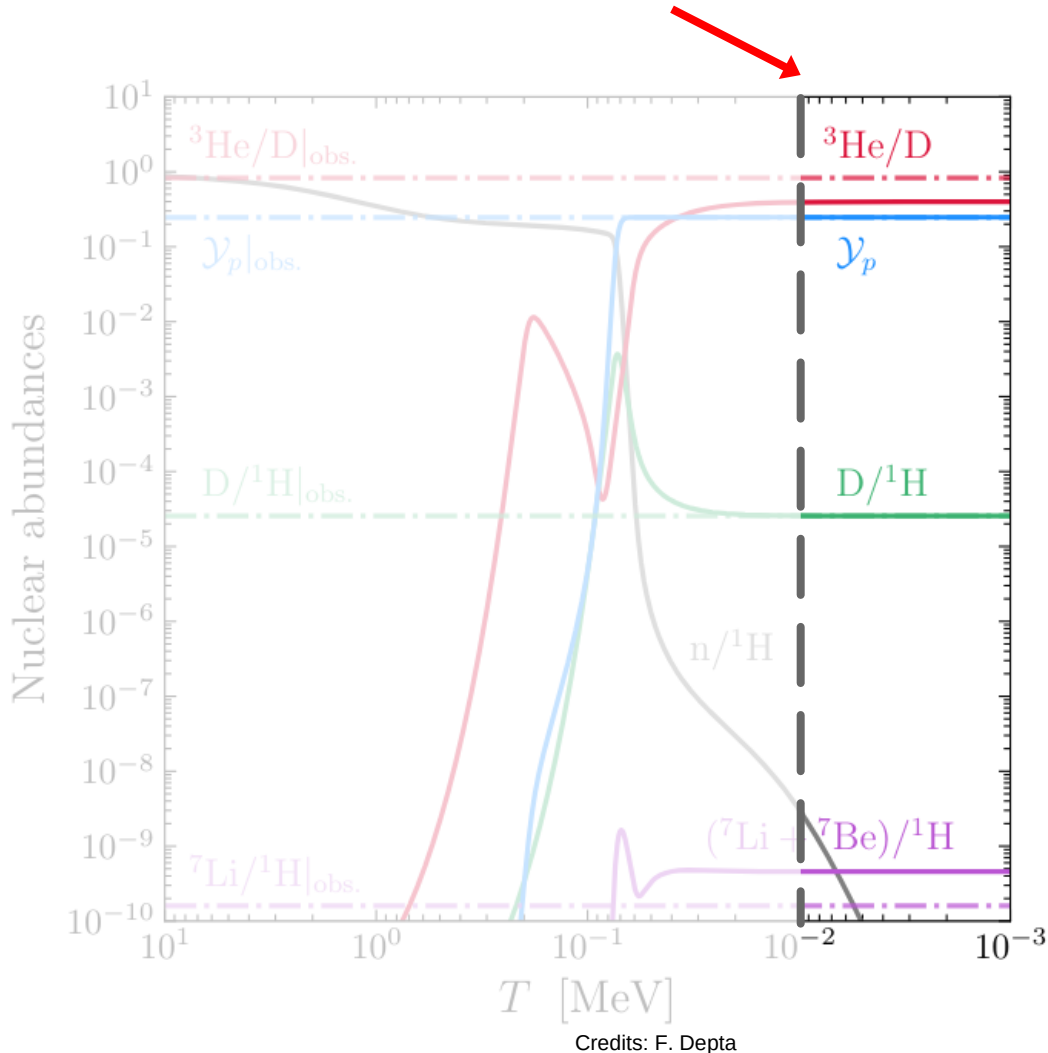
Rapid scattering on the CMB induces a **universal spectrum**

$$f_{\gamma, \text{univ}}(T, E) \sim \begin{cases} K_0 (E/E_X)^{-3/2} & , \quad E < E_X \\ K_0 (E/E_X)^{-2} & , \quad E_X < E < E_{ee}^{\text{th}} \\ 0 & , \quad E > E_{ee}^{\text{th}} \end{cases}$$

$$E_X = m_e^2 / (80T) , \quad E_{ee}^{\text{th}} = m_e^2 / (22T) , \quad K_0 \propto E_0$$

Interlude: BBN data, photodisintegration & hadrodisintegration

Abundances are effectively fixed by $T \simeq 10 \text{ keV}$ ($t \sim 10^4 \text{ s}$)



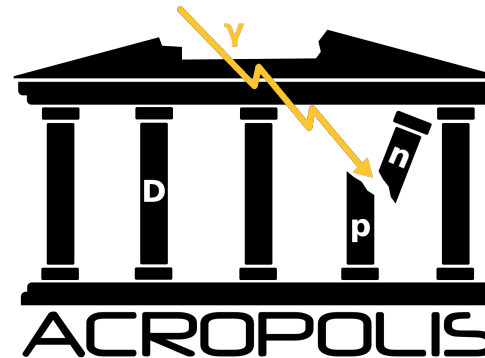
Photodisintegration

=

late-time destruction of the light elements by **EM** particles

$$\Rightarrow \tau_\phi \gtrsim 10^4 \text{ s}$$

allows factorisation of the processes



Numerical Framework **ACROPOLIS**

By Frederik, Marco and Kai
(2011.06518)

<https://github.com/hep-mh/acropolis/tree/v2>

$$\left[\frac{dn_X}{dt} \right]_{\text{photo}} = \sum_j n_j N_{j\gamma \rightarrow X} \int_0^\infty dE f_\gamma(E) \sigma_{j\gamma \rightarrow X}(E) - n_X \sum_{j'} \int_0^\infty dE f_\gamma(E) \sigma_{X\gamma \rightarrow j'}(E)$$

Interlude: BBN data, photodisintegration & hadrodisintegration

Hadrodisintegration treatment à la [astro-ph/0408426] and [1709.01211]:

Big-Bang Nucleosynthesis and Hadronic Decay of Long-Lived Massive Particles

Masahiro Kawasaki^(a), Kazunori Kohri^(b) and Takeo Moroi^(c)

Revisiting Big-Bang Nucleosynthesis Constraints on Long-Lived Decaying Particles

Masahiro Kawasaki^(a,b), Kazunori Kohri^(c,d), Takeo Moroi^(e,b),
and Yoshitaro Takaesu^(e,f)

Interlude: BBN data, photodisintegration & hadrodisintegration

Hadrodisintegration treatment à la [astro-ph/0408426] and [1709.01211]:

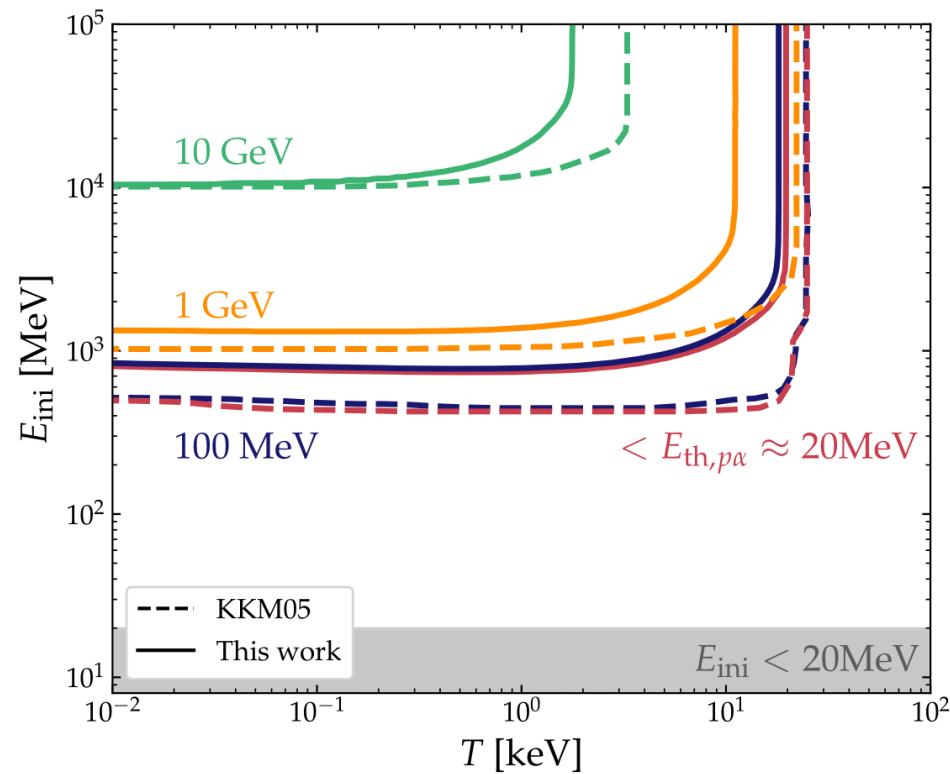
I. Inject hadrons (in our case: neutrons and protons)

Interlude: BBN data, photodisintegration & hadrodisintegration

Hadrodisintegration treatment à la [astro-ph/0408426] and [1709.01211]:

I. Inject hadrons (in our case: neutrons and protons)

II. Apply energy loss formalism*



* We actually found a small discrepancy with previous literature results.

Interlude: BBN data, photodisintegration & hadrodisintegration

Hadrodisintegration treatment à la [astro-ph/0408426] and [1709.01211]:

- I. Inject hadrons (in our case: neutrons and protons)
- II. Apply energy loss formalism
- III. Calculate nuclear scattering and determine final products

Observation:

While PDI tends to destroy deuterium, HDI produces it from destroying helium-4.

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

} Redistribute the kinetic energy

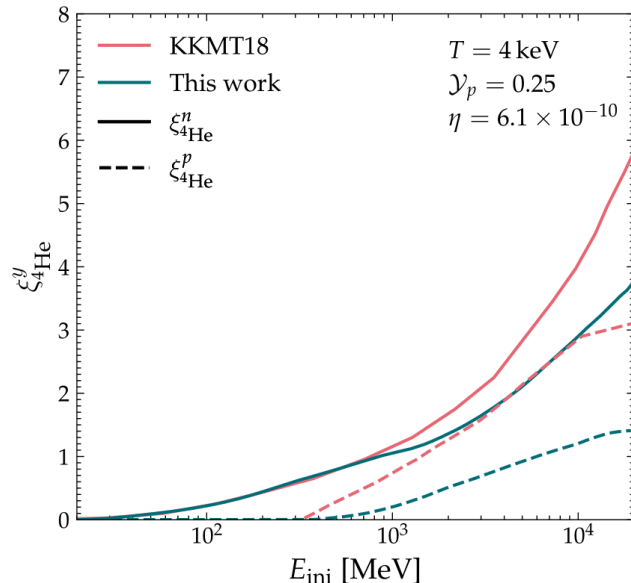
Process	$i = n$	$i = p$	Reaction Type
(i, α ; 1)	$n + \alpha_{BG} \rightarrow n + \alpha$	$p + \alpha_{BG} \rightarrow p + \alpha$	elastic
(i, α ; 2)	$n + \alpha_{BG} \rightarrow D + T$	$p + \alpha_{BG} \rightarrow D + {}^3\text{He}$	inelastic
(i, α ; 3)	$n + \alpha_{BG} \rightarrow 2n + {}^3\text{He}$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

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

Interlude: BBN data, photodisintegration & hadrodisintegration

Hadrodisintegration treatment à la [astro-ph/0408426] and [1709.01211]:

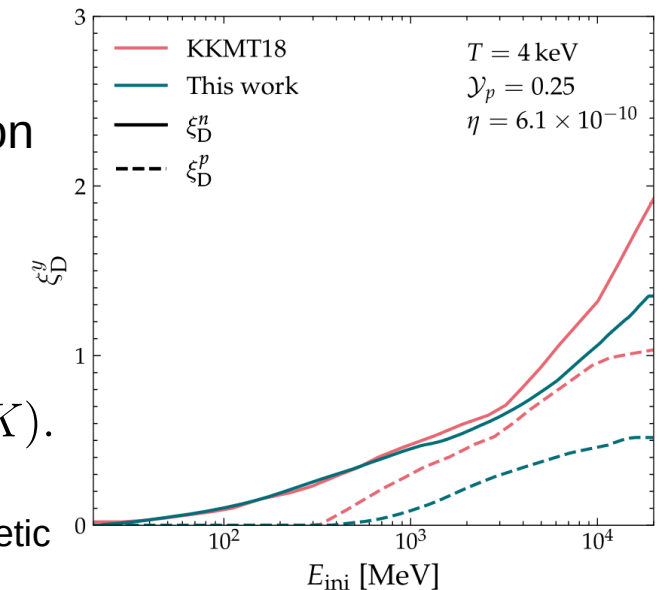
- I. Inject hadrons (in our case: neutrons and protons)
- II. Apply energy loss formalism
- III. Calculate nuclear scattering and determine final products
- IV. Repeat until all particles in the cascade have negligible kinetic energy**



Number of nuclei produced per injected nucleon

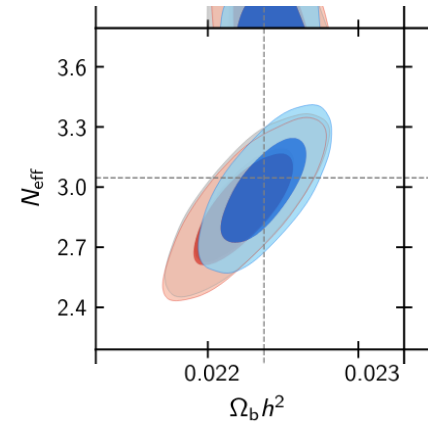
$$\left[\frac{dn_X}{dt} \right]_{\text{hadro}} = \sum_{y=n,p} \int_0^\infty dK \xi_X^y[n_j](K) \frac{d^2 n_y^{\text{inj}}}{dt dK}(K).$$

Note: We approximate the injection spectrum as monoenergetic



Back to neutrinos: Handling the different effects in detail

Handling the contributions step-by-step



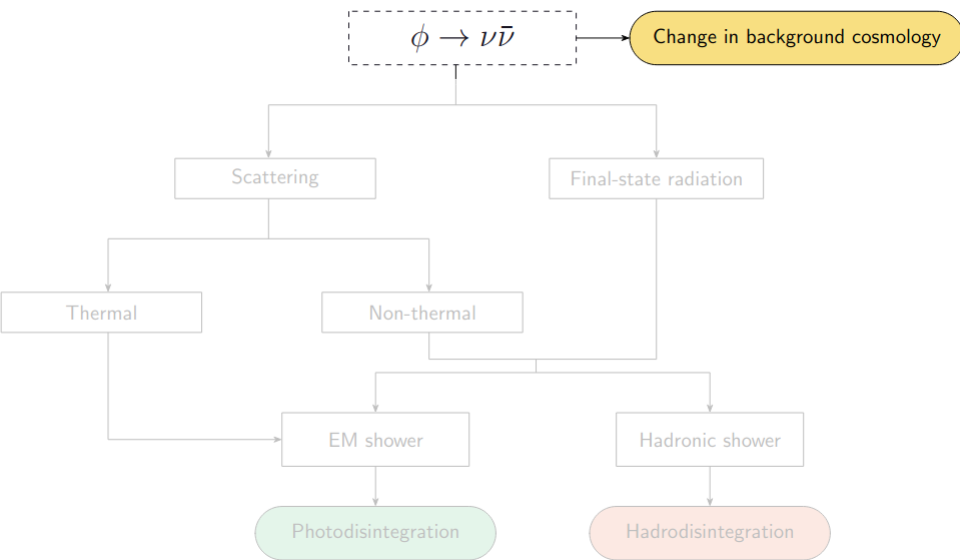
The dominant effect:

Additional energy density increases N_{eff}

Change in η due to correlation with N_{eff}

Initial conditions of BBN are varied due to η

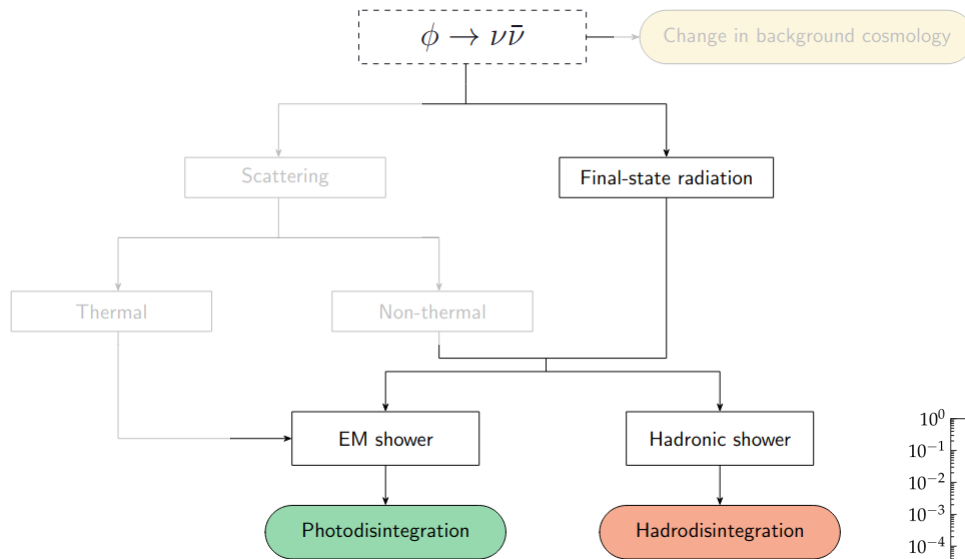
BBN is modified and we get different abundances



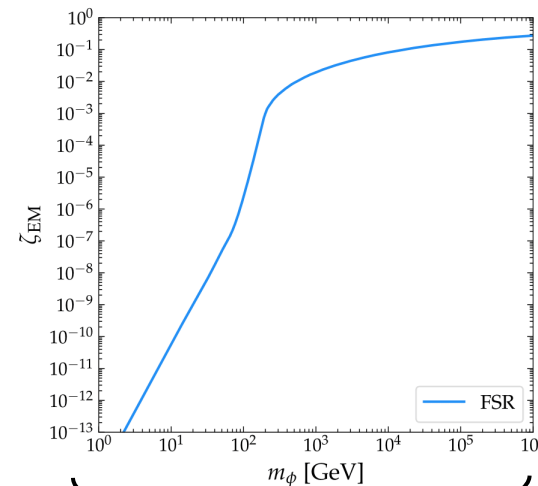
Handling the contributions step-by-step

Injection rate is determined by the decay rate

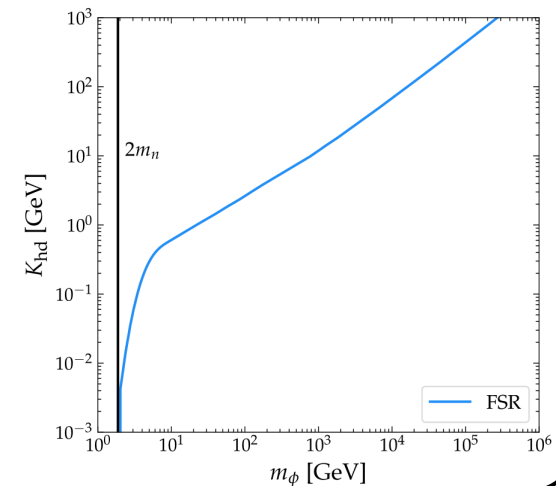
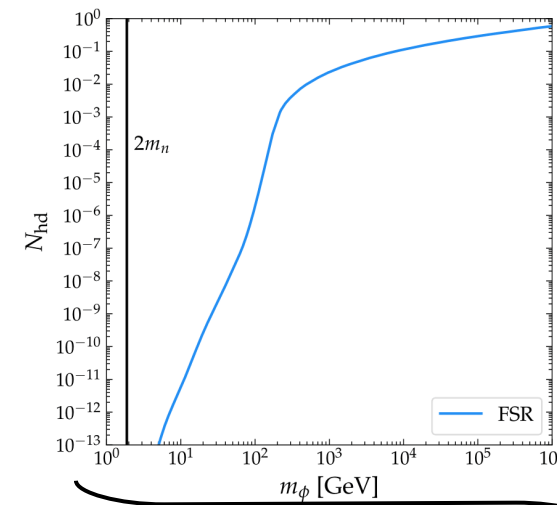
Effect of an individual injection determined by PYTHIA



PDI handled in [2112.09137]:



PDI requires 1 parameter (universal spectrum)



HDI requires 2 parameters

Handling the contributions step-by-step

Injection rate given by thermal scattering rate

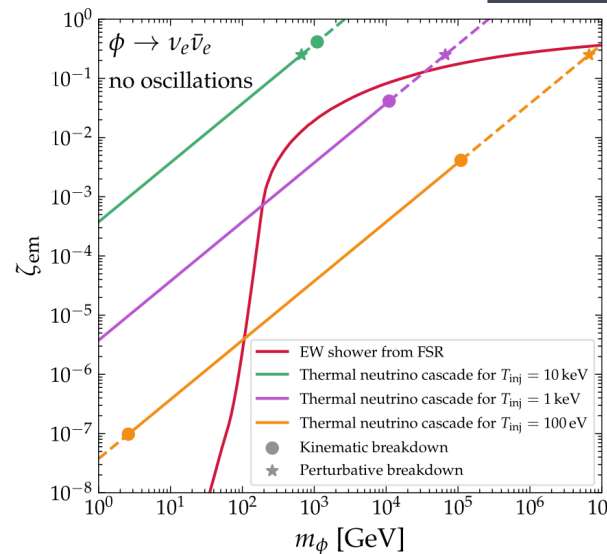
$$\Gamma_{ee}(T, E) \sim G_F^2 E T_\nu^4$$

Effect of an individual injection determined analytically

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

$$\Rightarrow \zeta_{\text{em}}(T_{\text{inj}}) = \frac{1}{4} \left(\frac{\Gamma_{ee}}{H} \right)_{\text{inj}}$$

$$s \sim 4ET \ll 4m_n^2$$



Handling the contributions step-by-step

Injection rate given by thermal scattering rate

$$\Gamma_{ee}(T, E) \sim G_F^2 E T_\nu^4$$

Effect of an individual injection determined analytically

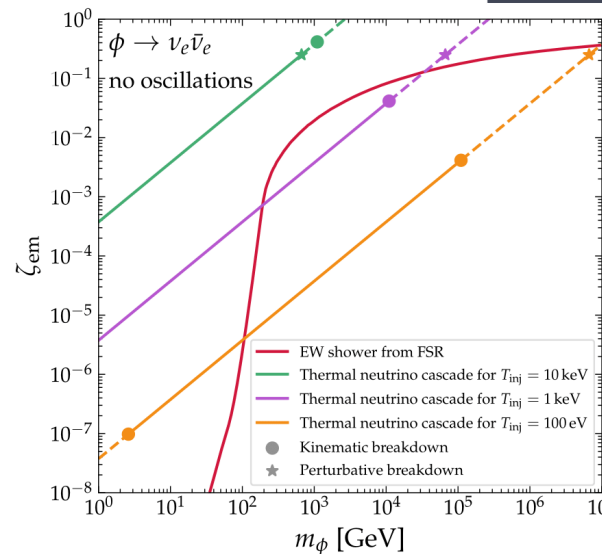
$$d\zeta_{\text{em}} \simeq \frac{E(t)}{E_{\text{inj}}} \Gamma_{ee}(t) dt$$

$$\Rightarrow \zeta_{\text{em}}(T_{\text{inj}}) = \frac{1}{4} \left(\frac{\Gamma_{ee}}{H} \right)_{\text{inj}}$$

“Elastic” scattering:

$$\begin{aligned} & \Gamma_{ee}(T, E_1) + \Gamma_{ee}(T, E_2) \\ &= \text{const.} \times G_F^2 T_\nu^4 (E_1 + E_2) \\ &= \Gamma_{ee}(T, E_1 + E_2) \end{aligned}$$

Redistribution of energy is irrelevant!



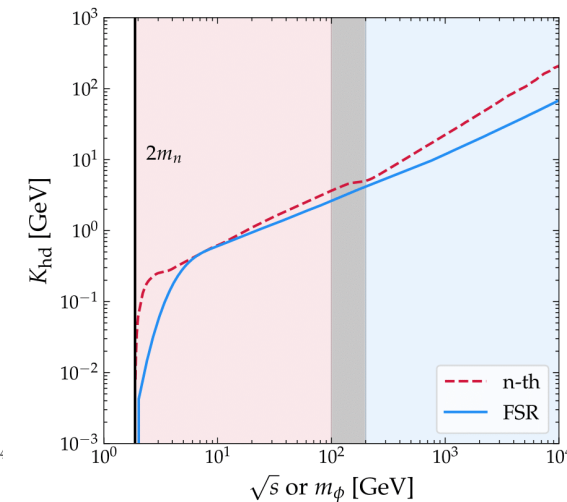
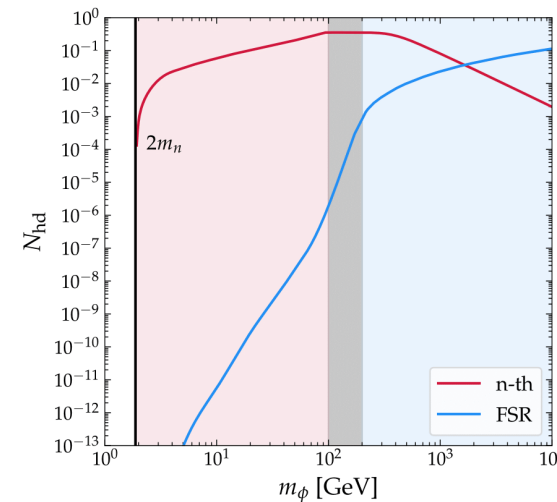
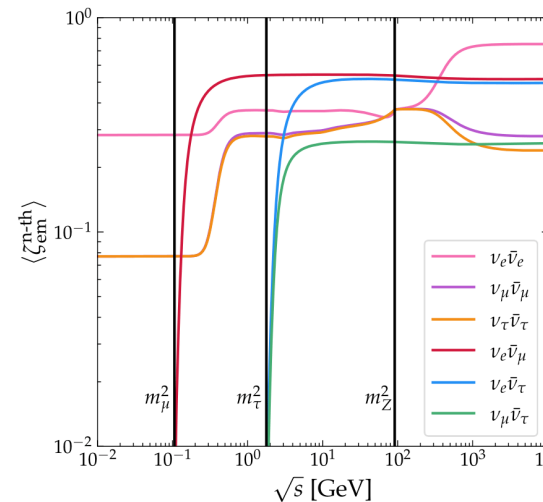
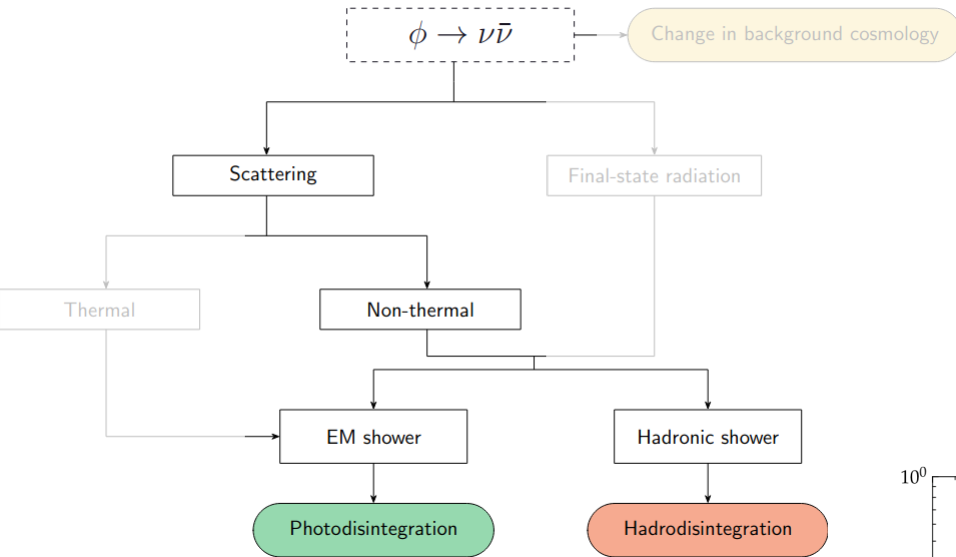
Handling the contributions step-by-step

Injection rate given in general by

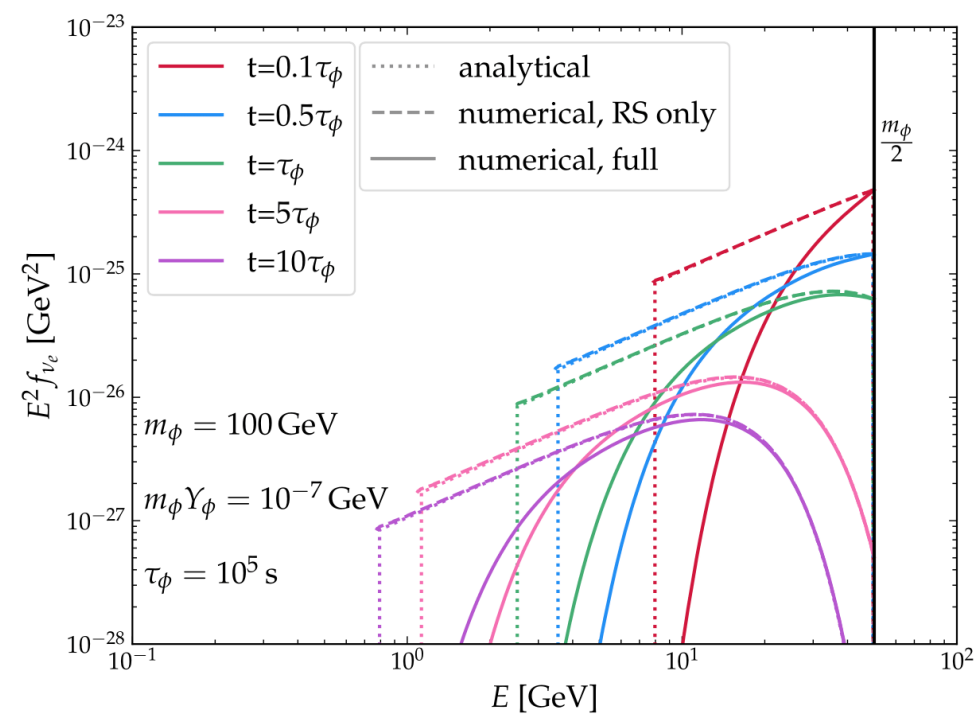
$$\Gamma_{\text{ann}}(T, E) = \frac{g_\nu}{16\pi^2 E^2} \int_0^\infty d\epsilon f_{\nu, \text{n-th}}(\epsilon) \int_0^{4E\epsilon} ds s \cdot \sigma_{\text{ann}}(s)$$

Requires knowledge of non-thermal spectrum!!!
See following slides for exact methodology

Effects of individual event determined by PYTHIA



How to track the neutrino cascade



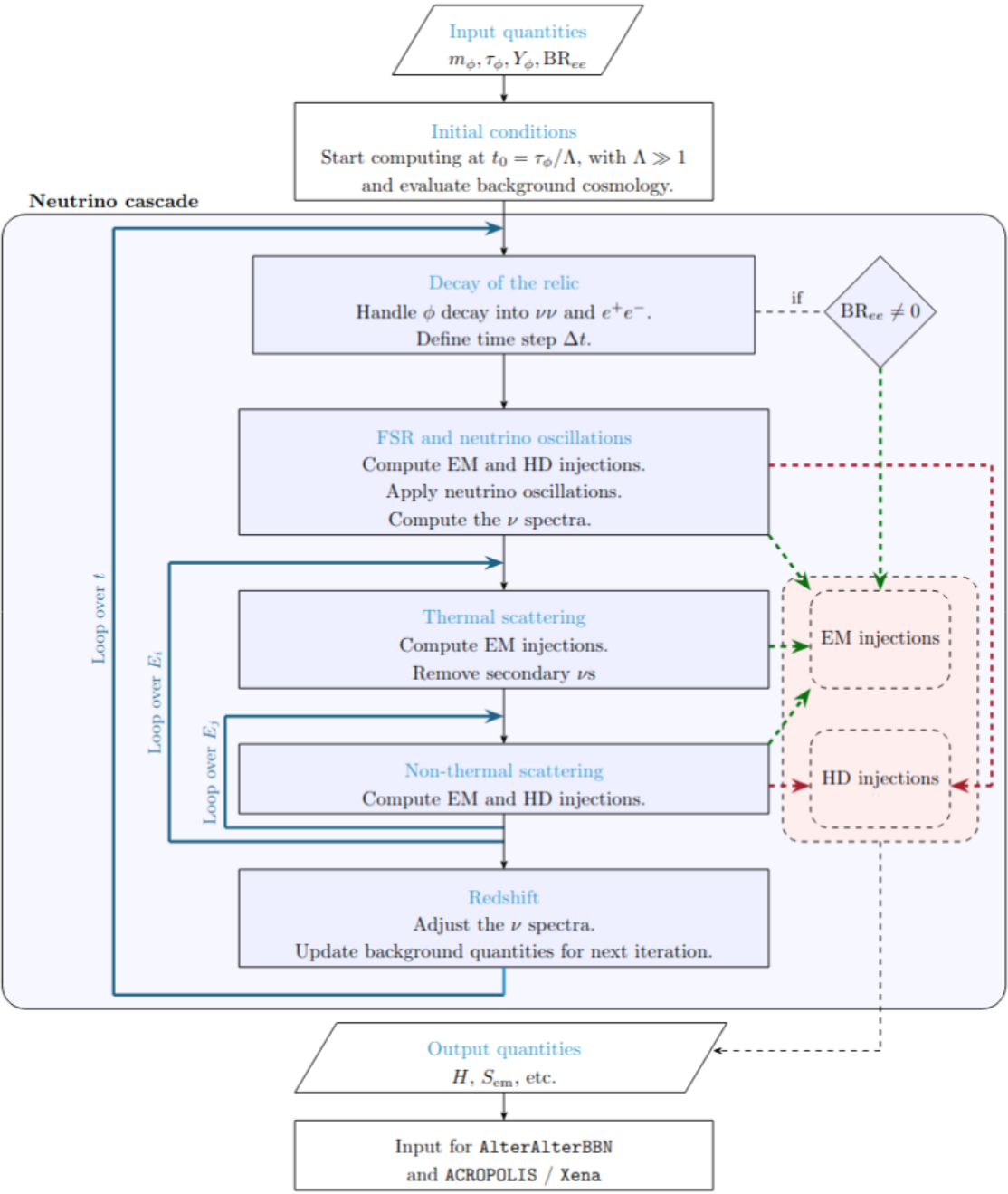
Is the Hubble rate dominant

Yes

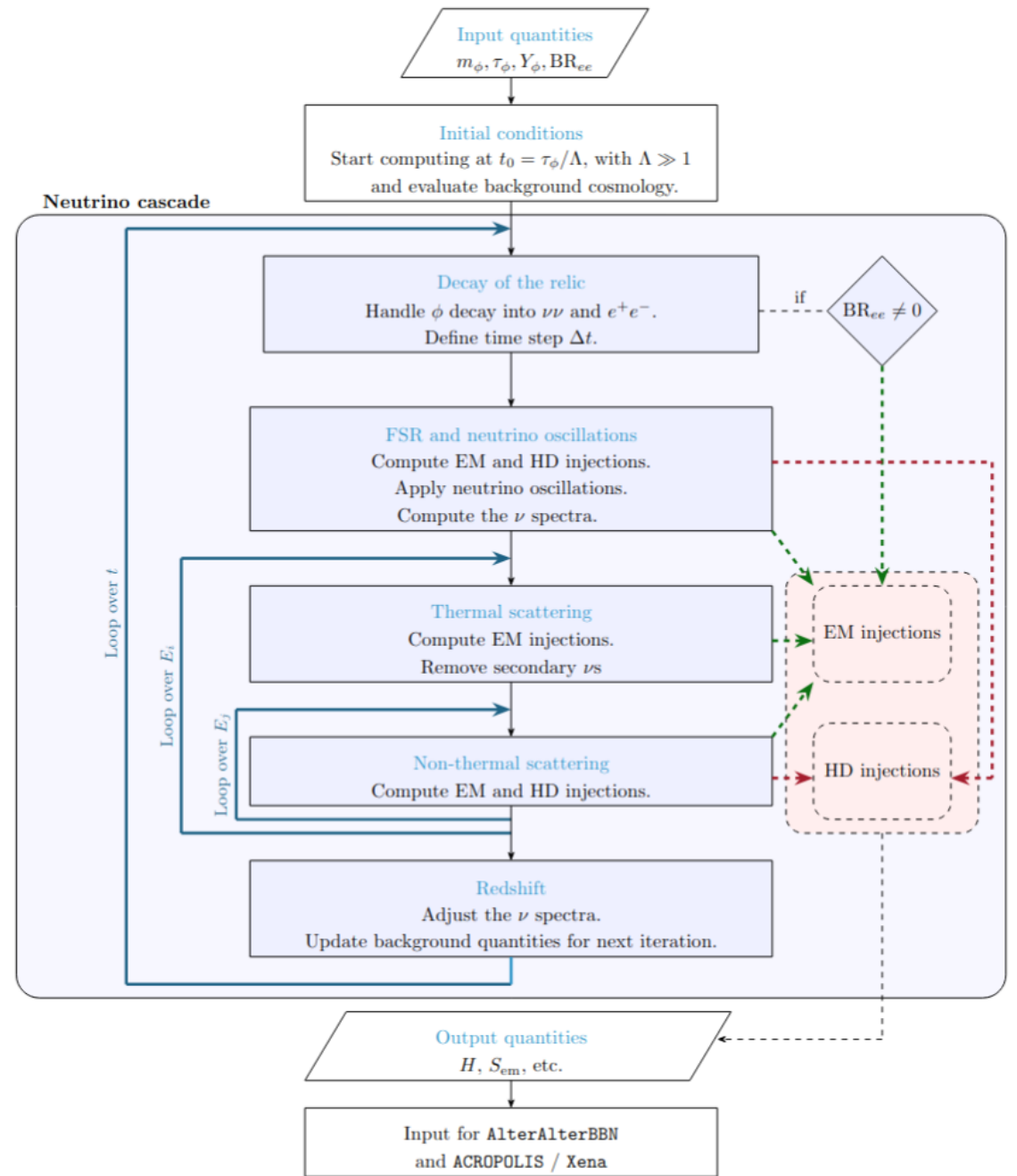
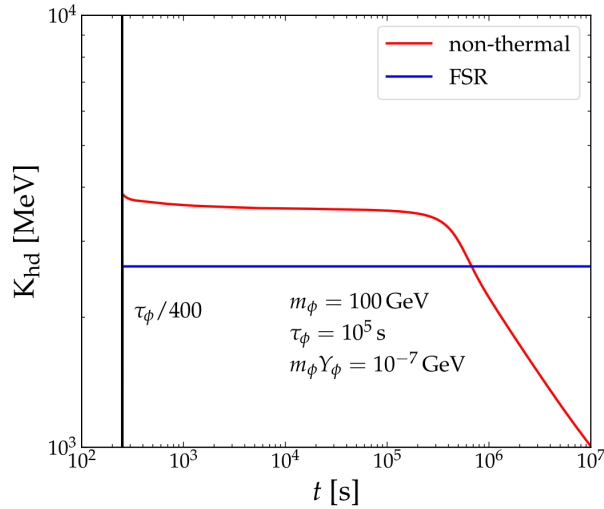
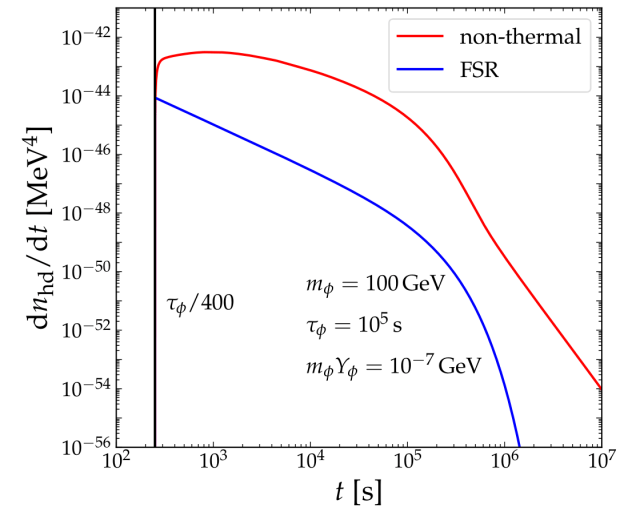
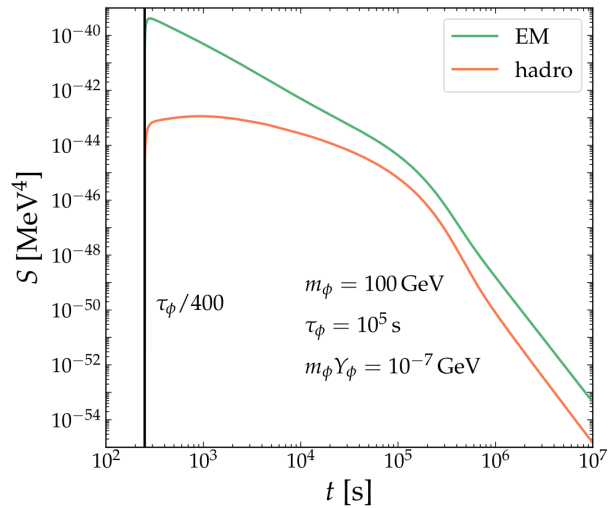
No

Spectrum mainly
redshifts

Elastic scattering
depletes the spectrum
Approximation: No redistribution of
energy

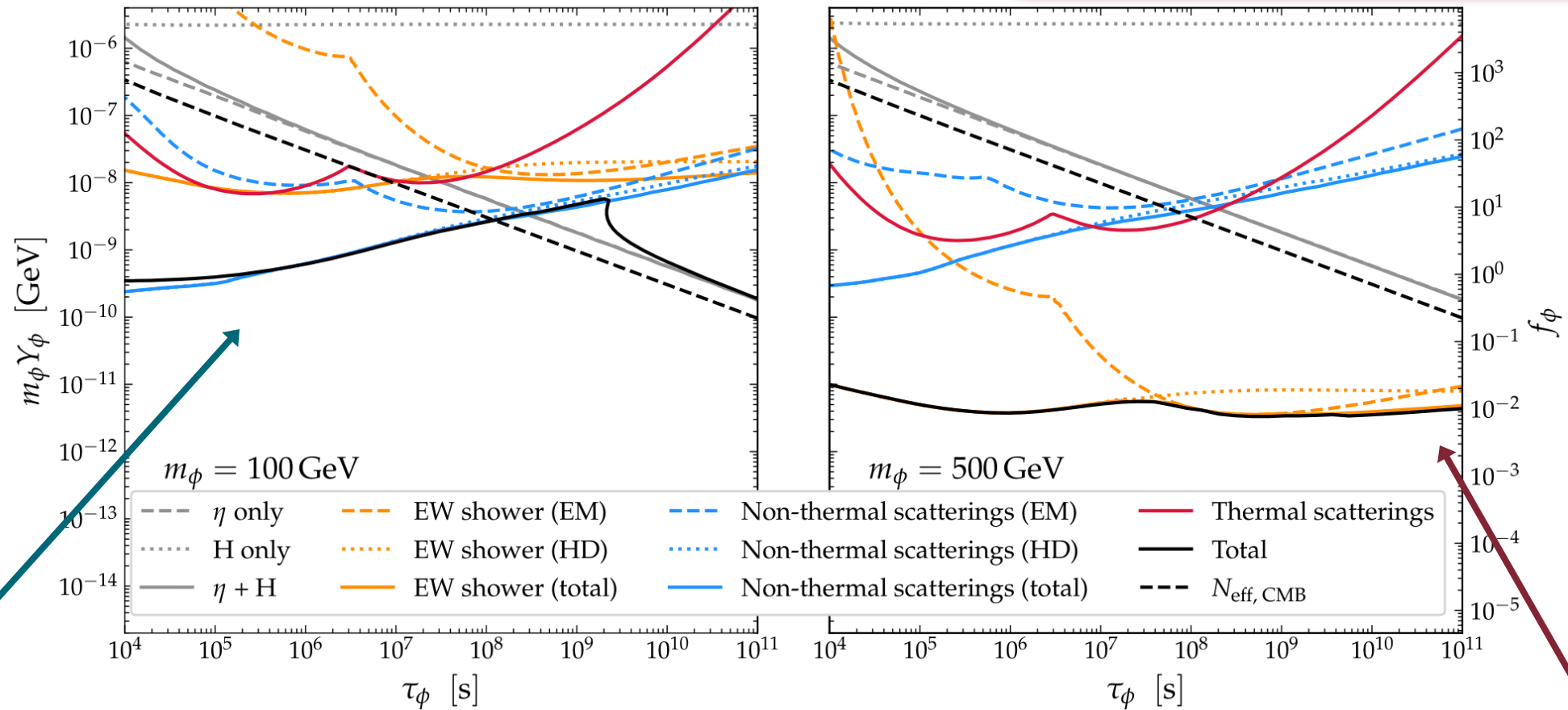


How to track the neutrino cascade



Detailed discussion of the resulting constraints

We observe both synergy effects and cancelations!



Below the EW scale:
Domination of non-thermal scattering (light) and indirect effects (heavy)

Above the EW scale:
Complete domination of EW shower from FSR

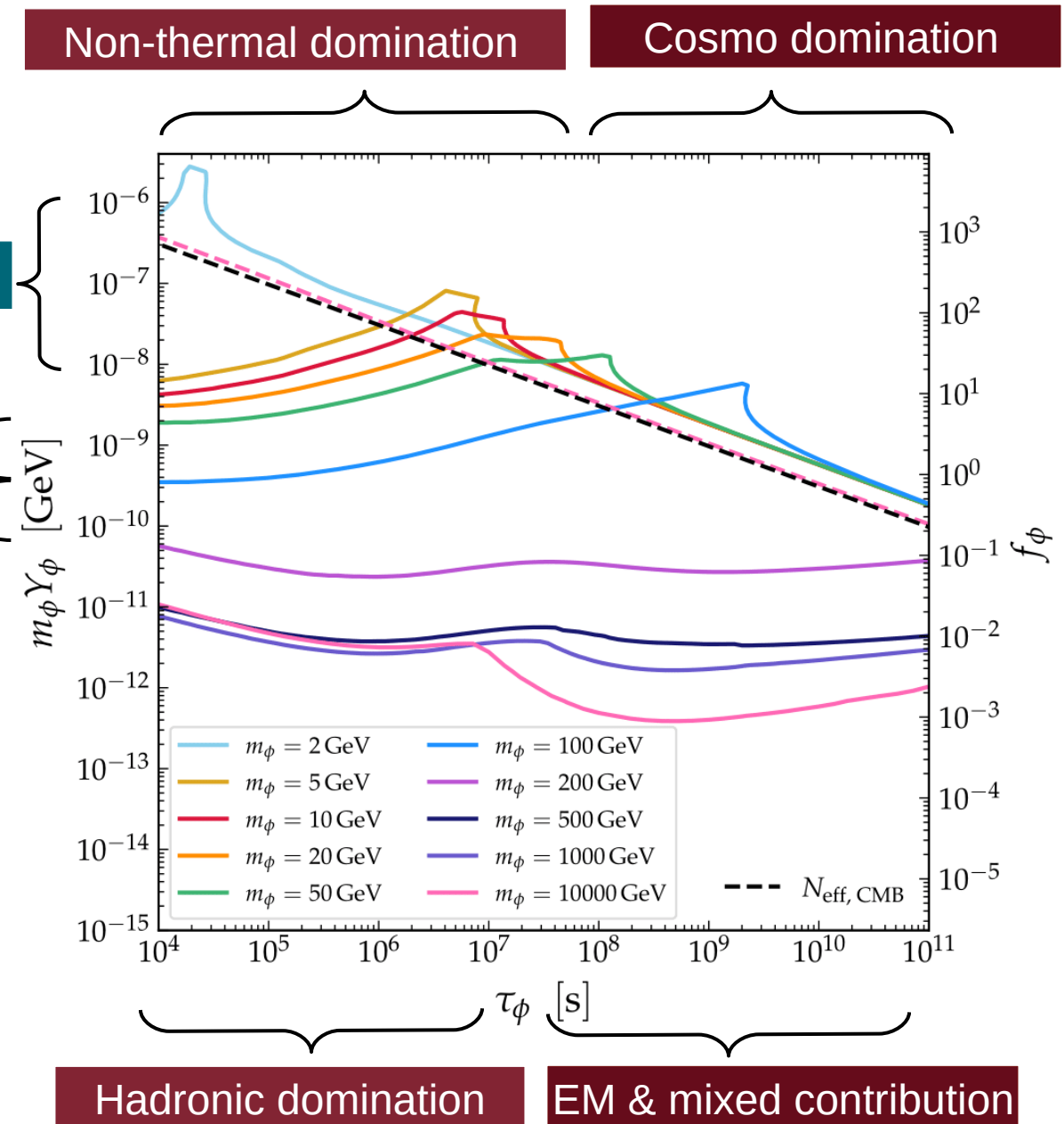
Scanning the full parameter space

Jump across nucleon mass threshold

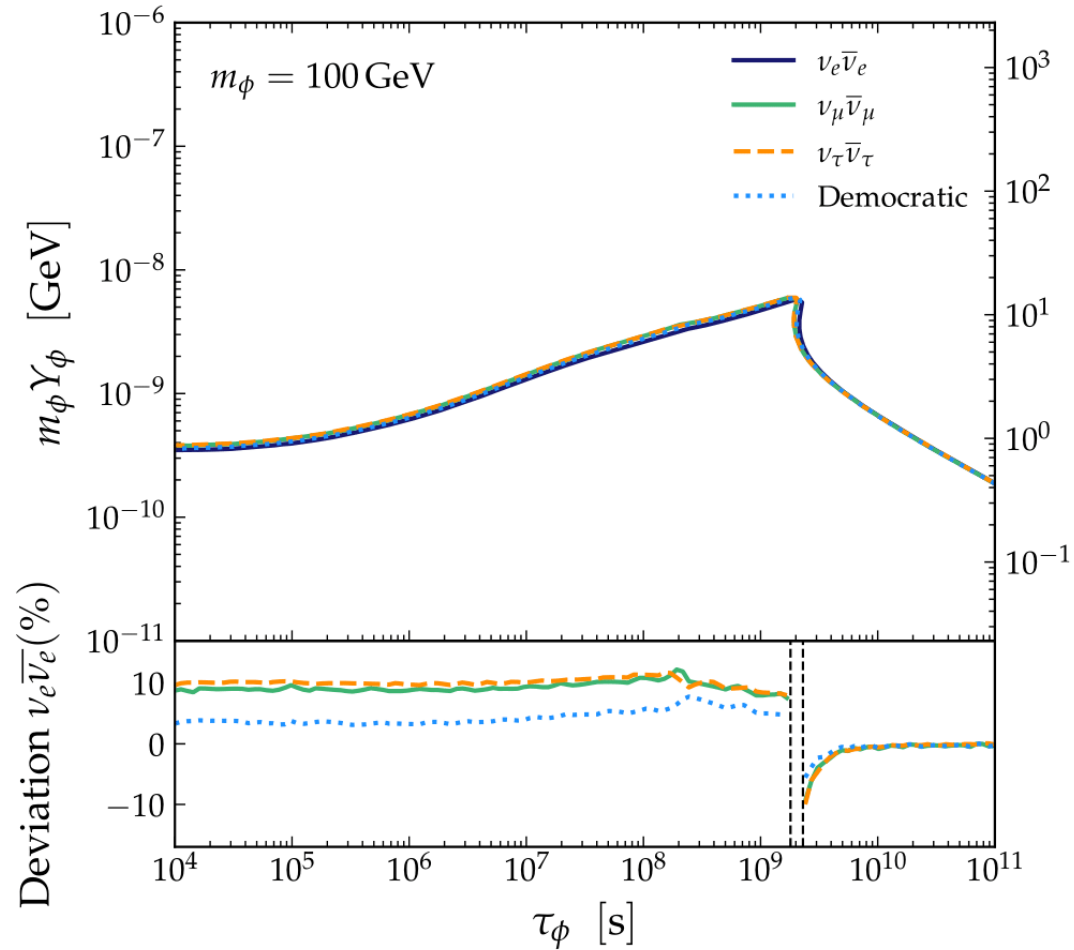
Unlocking of Z resonance

Dominance of FSR begins

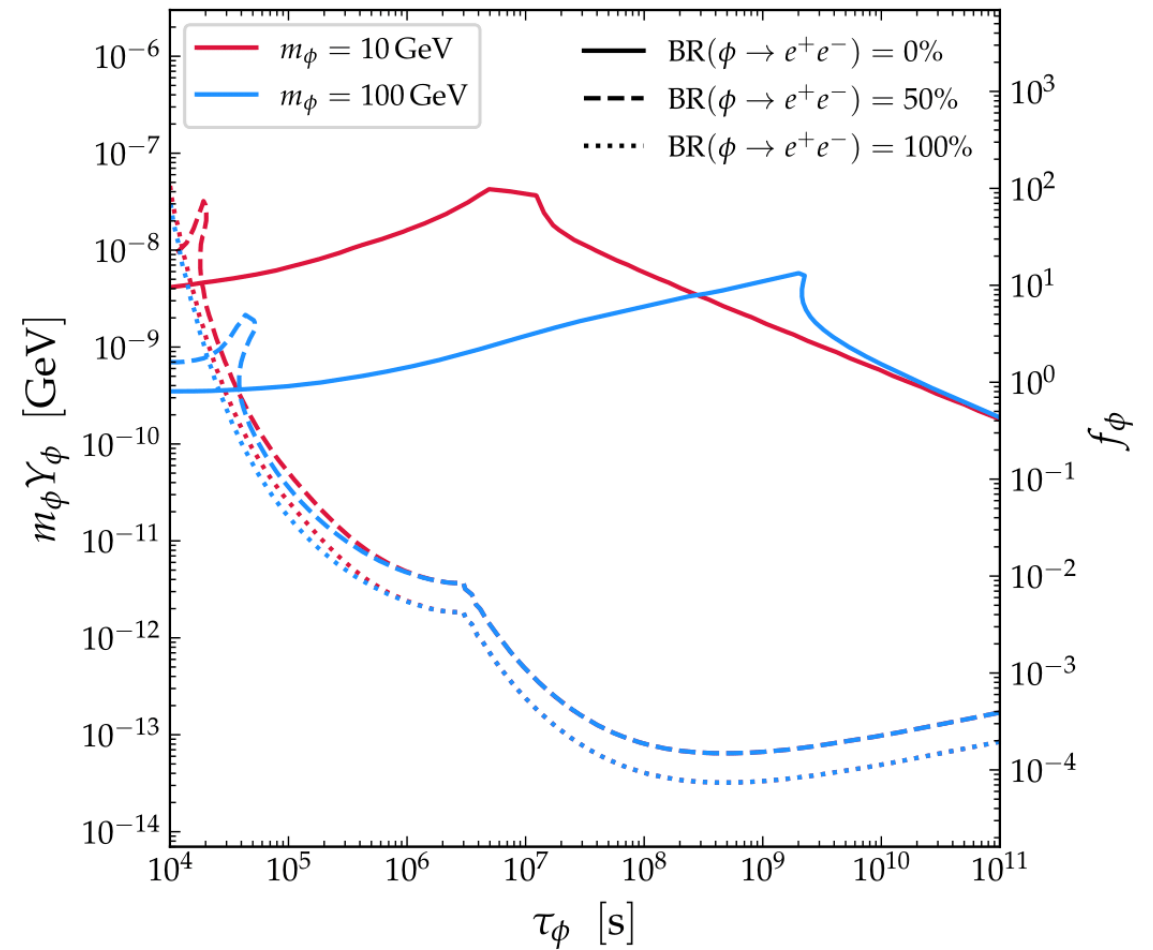
All 4 effects play an important role in some part of the parameter space, however the thermal scattering only due to the depletion of the spectrum.



How broadly applicable are these results?



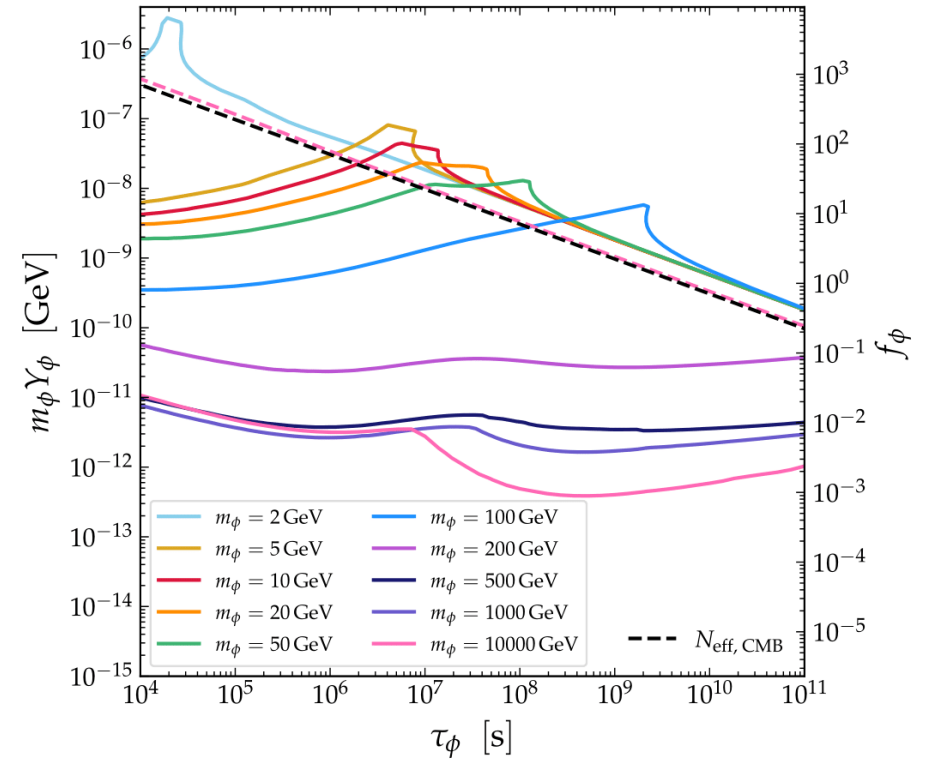
Results largely independent of initial neutron composition ✓



Results likely still relevant for loop suppressed decay into electron ✓

Conclusions & Outlook

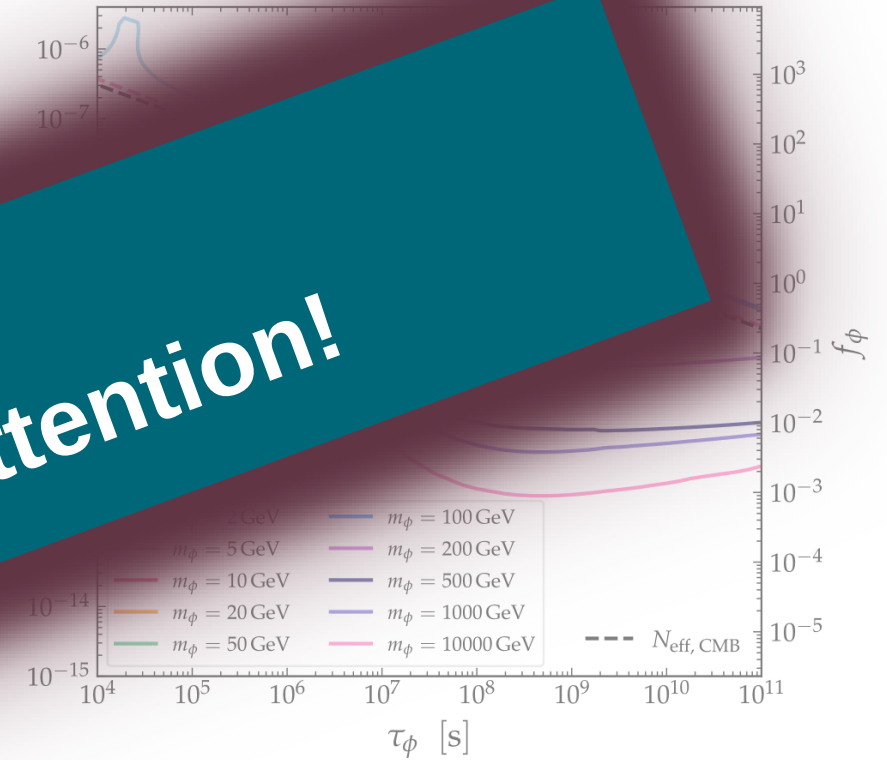
- Thorough study of neutrino injections after BBN
 - Surprisingly strong limits, especially from hadrons
 - Combination of improved literature results and new methods
 - Breakdown of many assumptions for low lifetimes requires more care (stay tuned!)
 - This work is part of an upcoming review to summarise the contributions of Marco and Frederik to the field
- ... and of course check the paper for (many) more details.

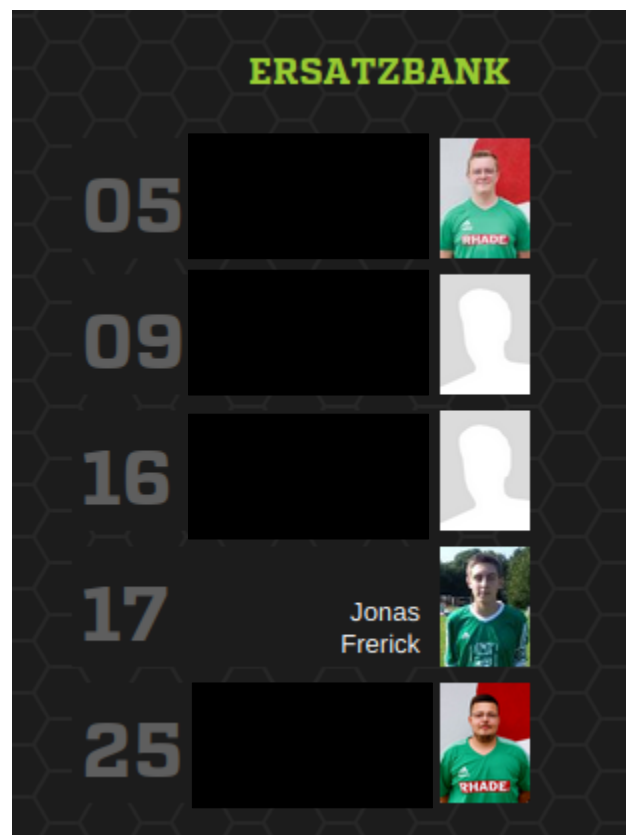


Conclusions & Outlook

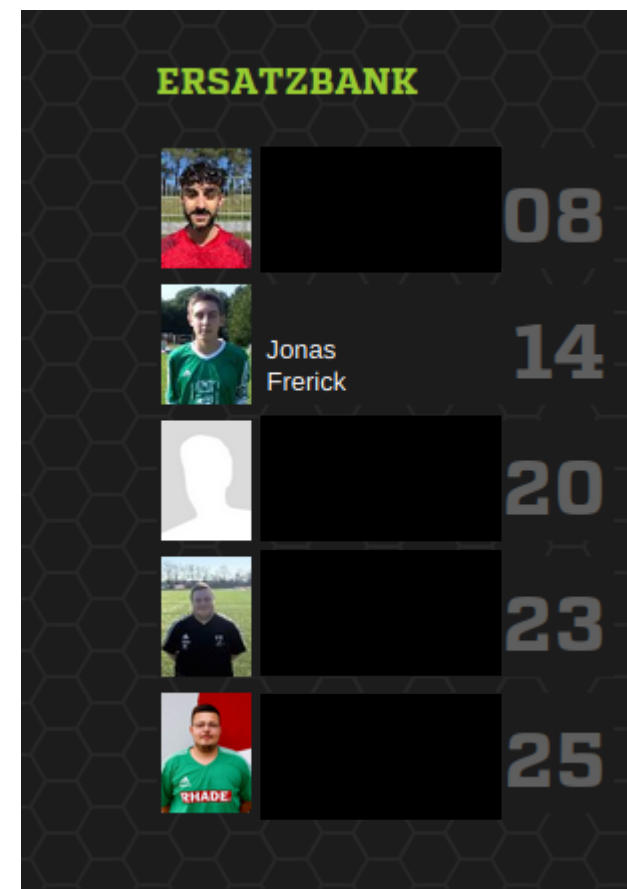
- Thorough study of neutrino injections after BBN
- Surprisingly strong limits, especially from ^4He
- Combination of improved literature and new calculations
- Breakdown of mass ranges, m_ϕ vs τ_ϕ (stay tuned for more)
- Theoretical constraints: τ_ϕ from the decay of the field
- ... and more to come for (many) more details.

That's it!
Thank you for your attention!



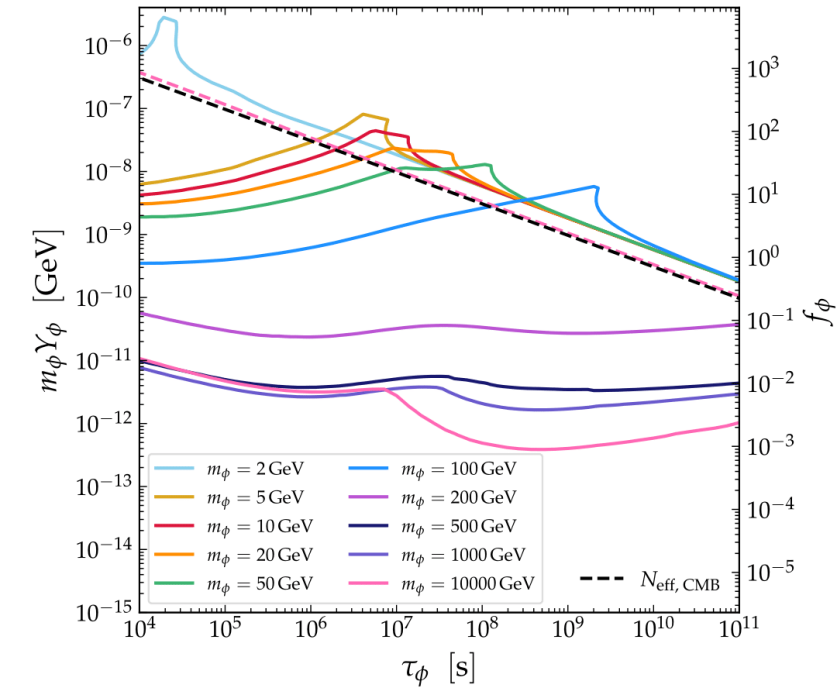


Back-up

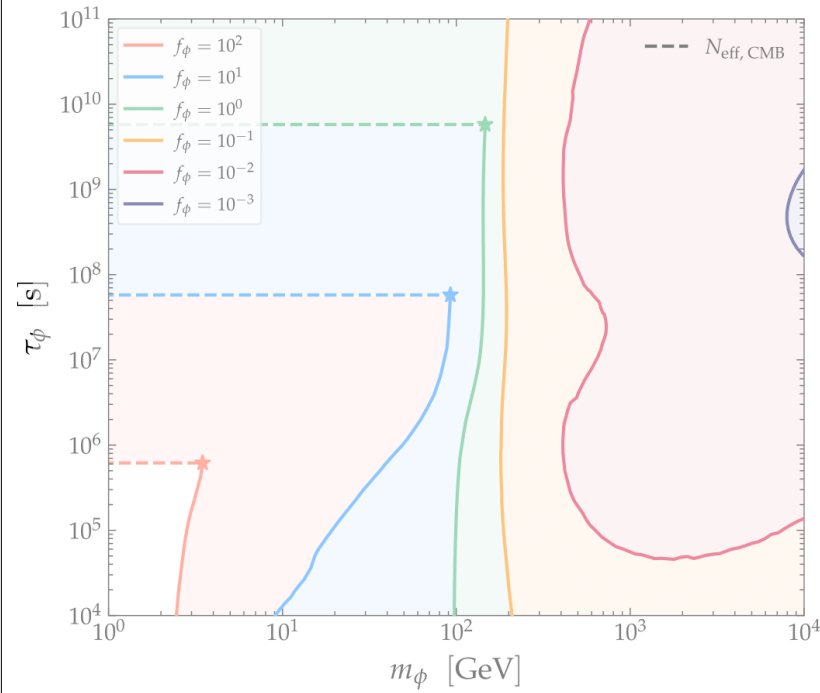


All three parameter planes

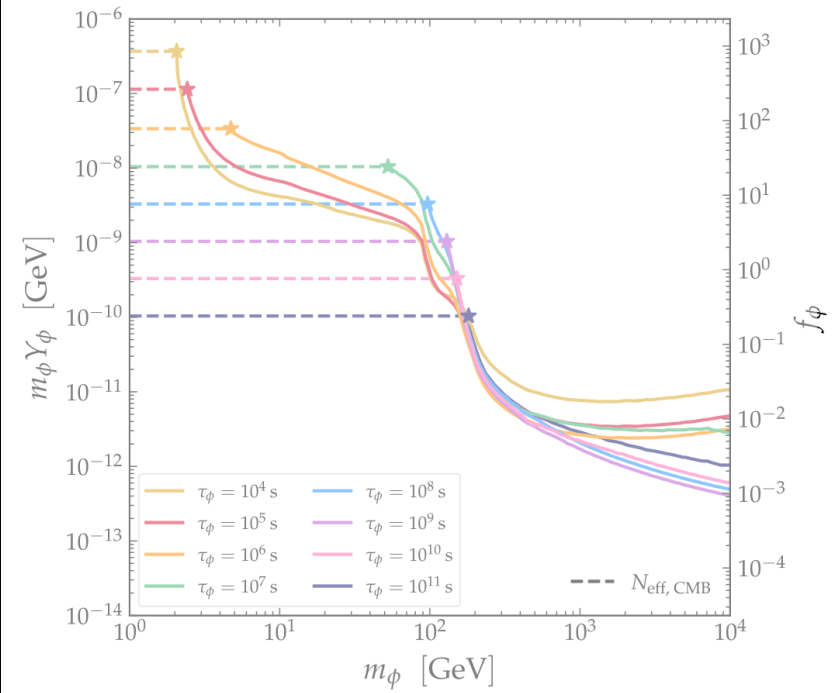
m_ϕ



f_ϕ

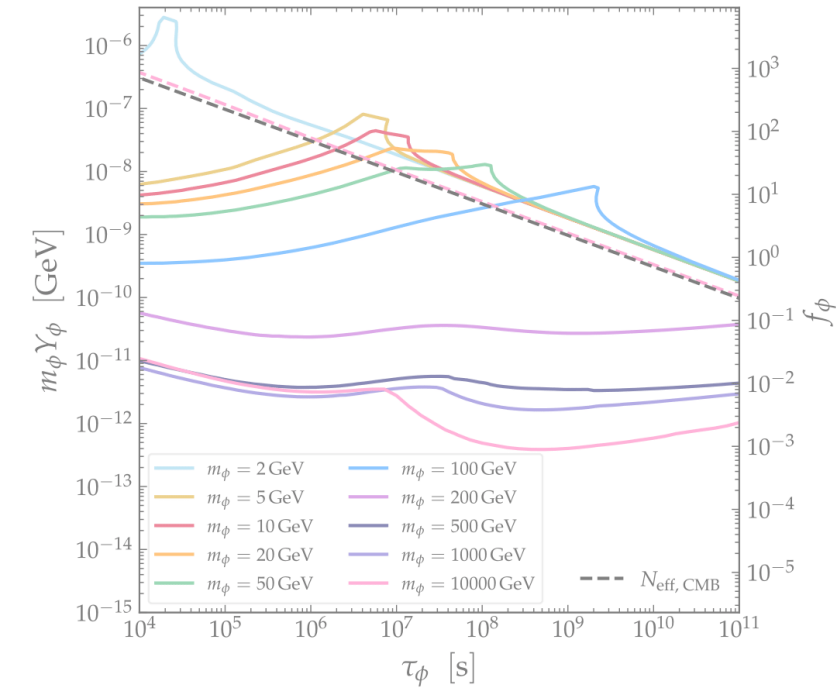


τ_ϕ

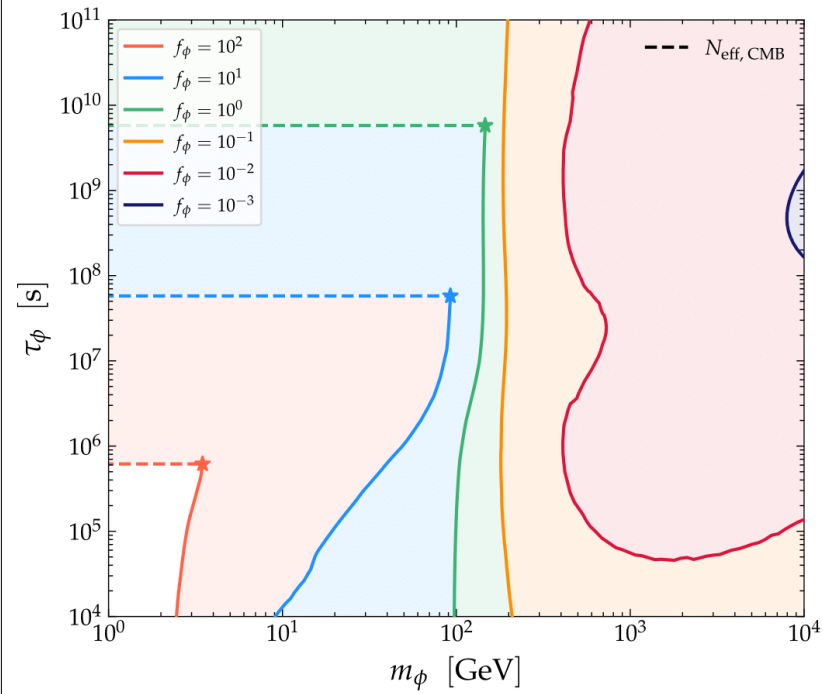


All three parameter planes

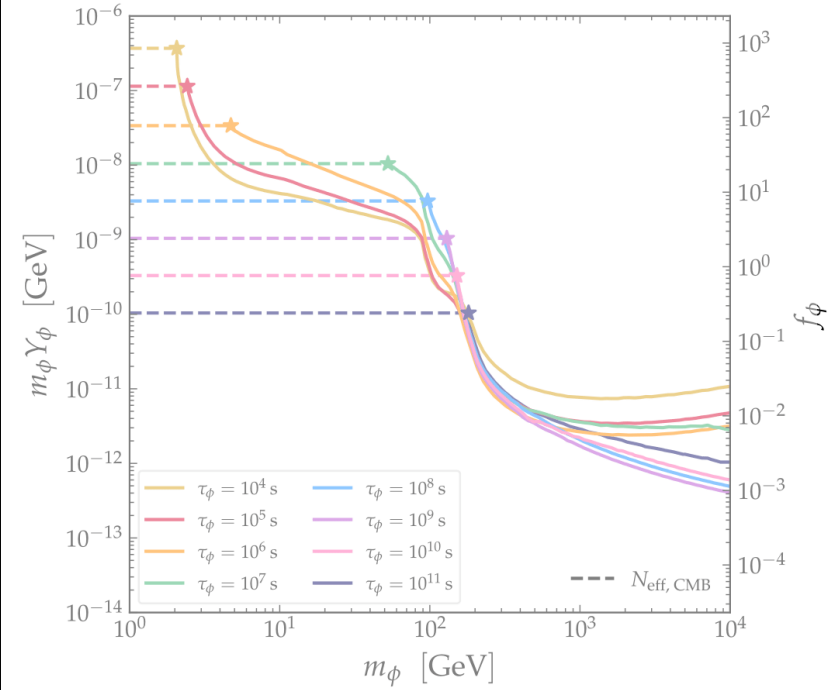
m_ϕ



f_ϕ

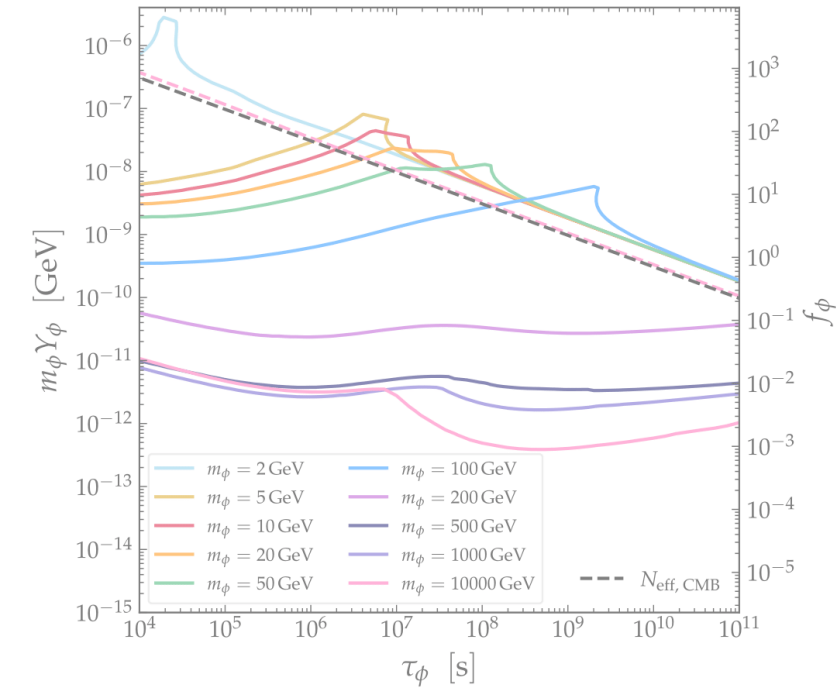


τ_ϕ

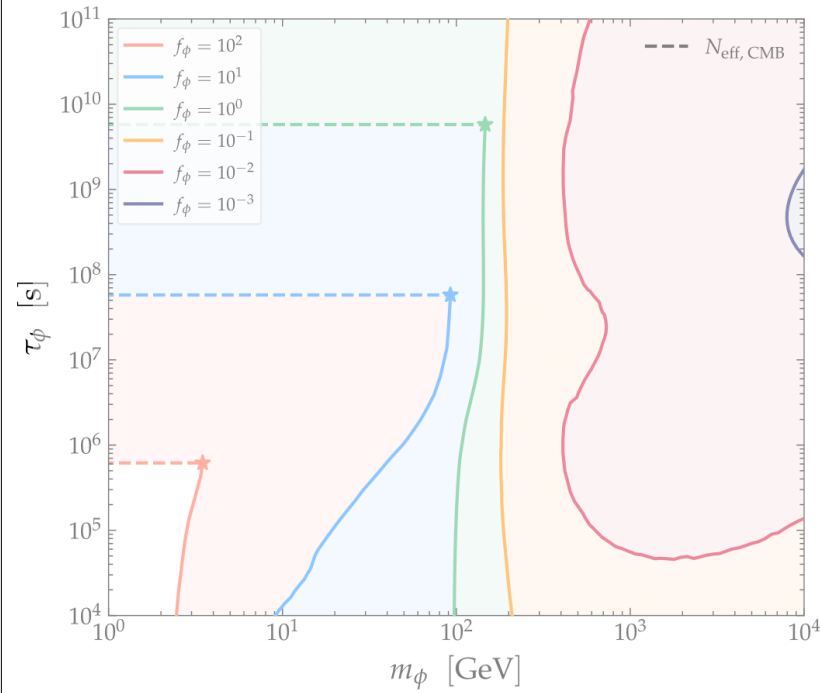


All three parameter planes

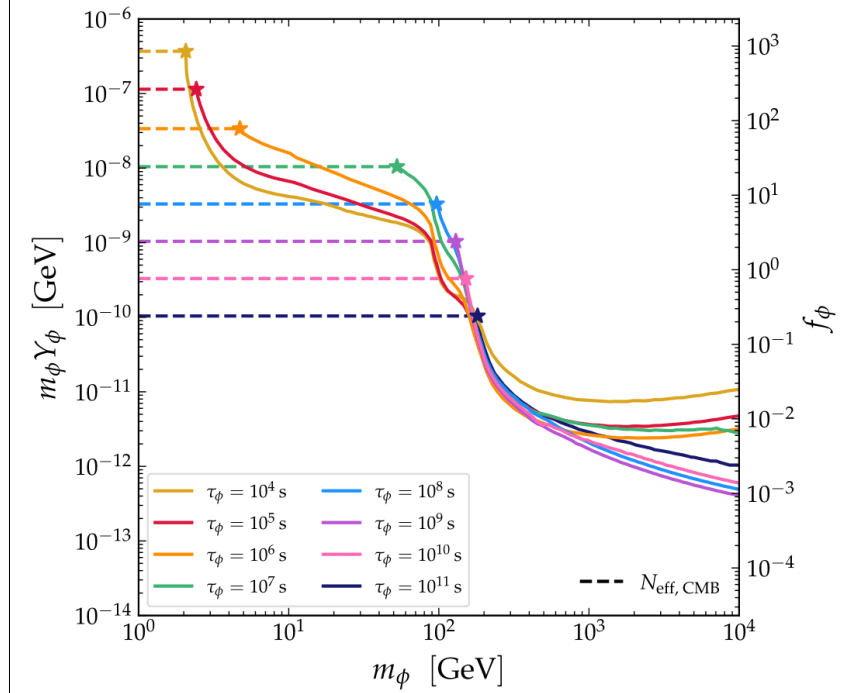
m_ϕ



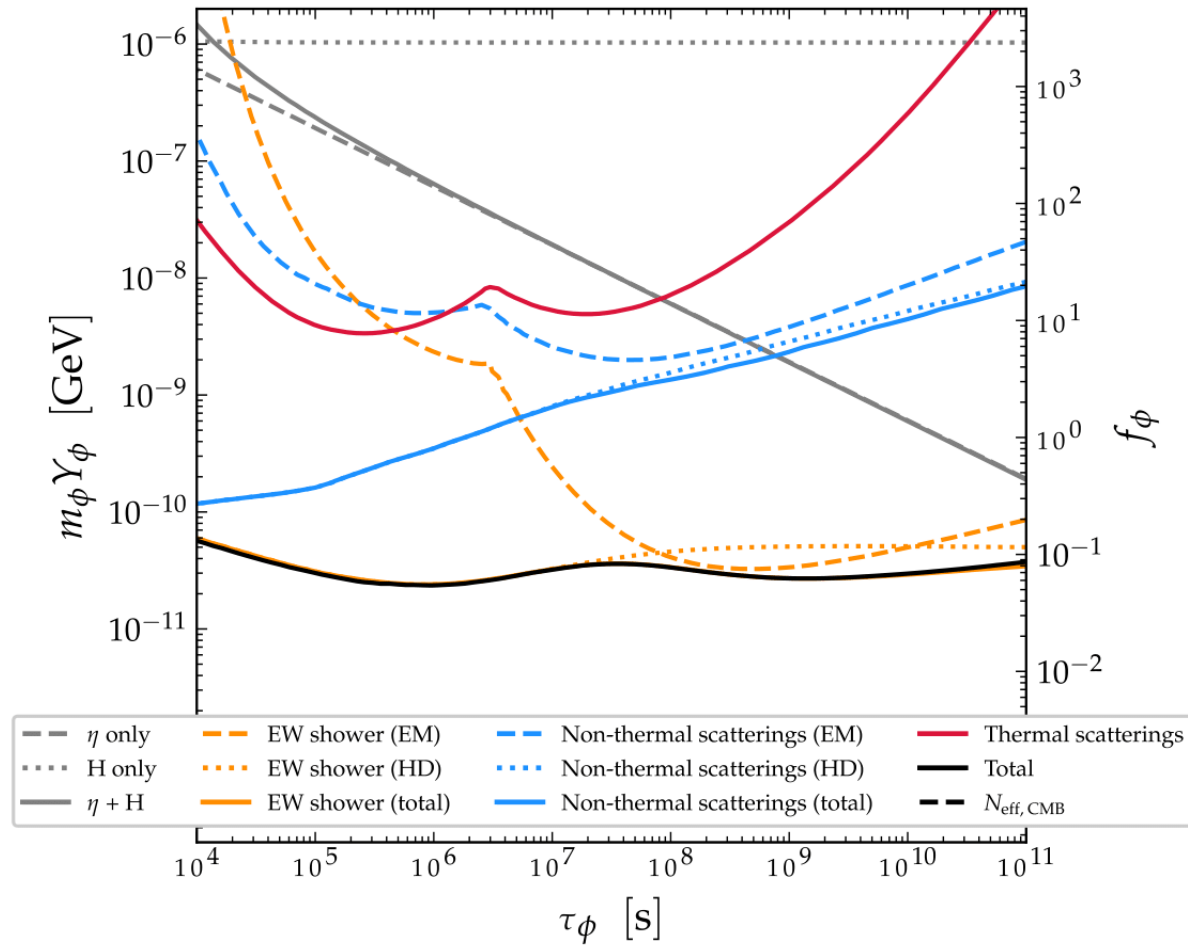
f_ϕ



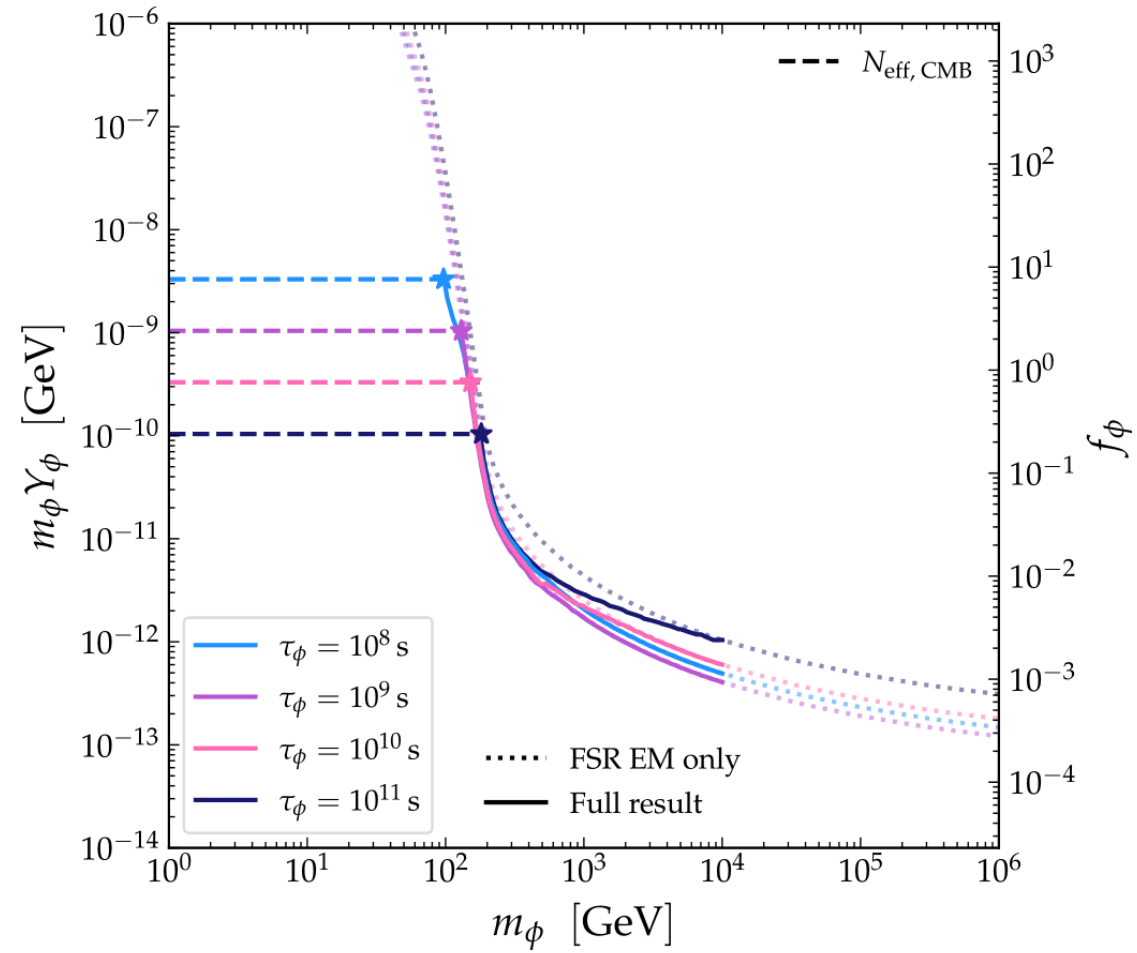
τ_ϕ



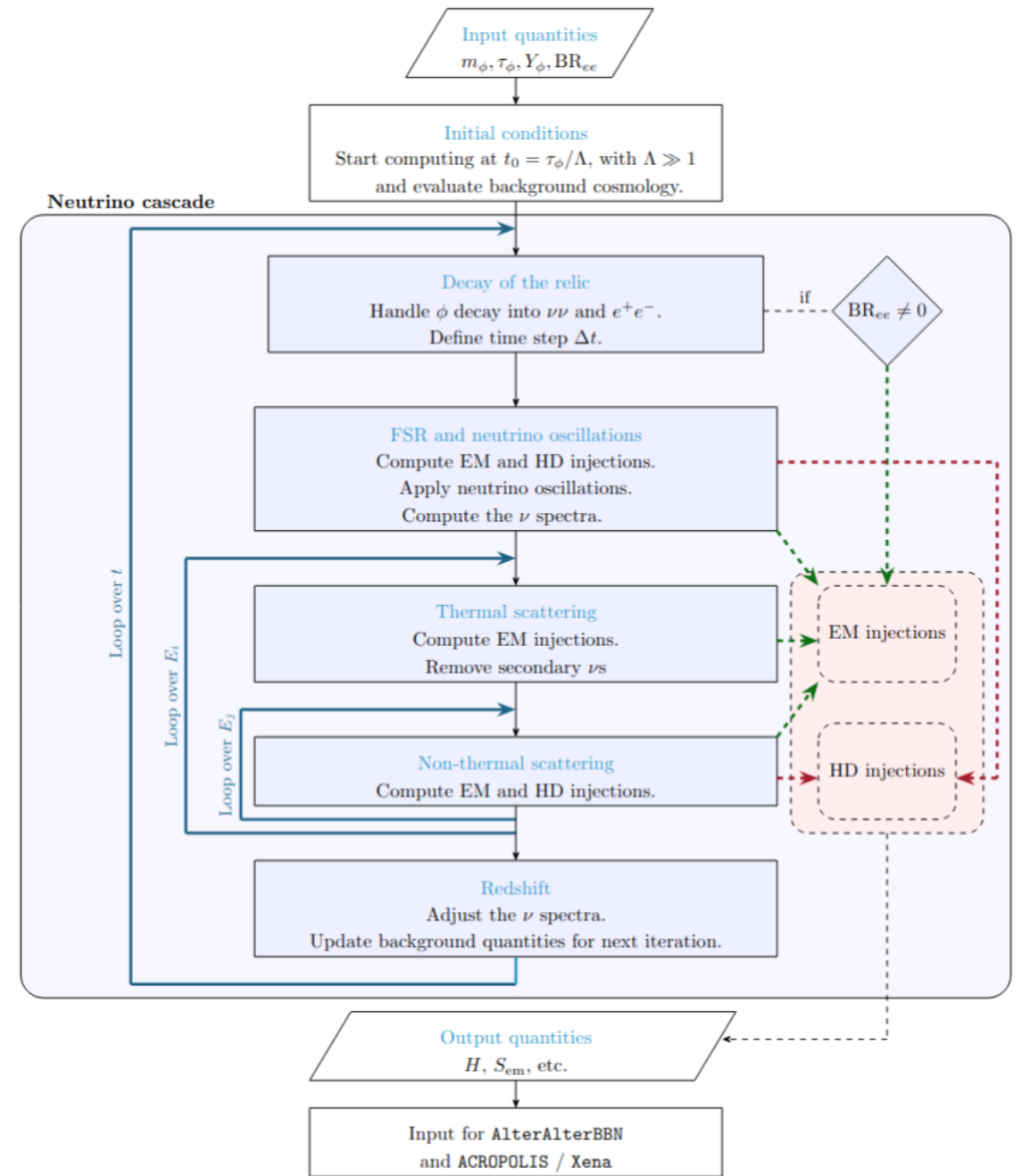
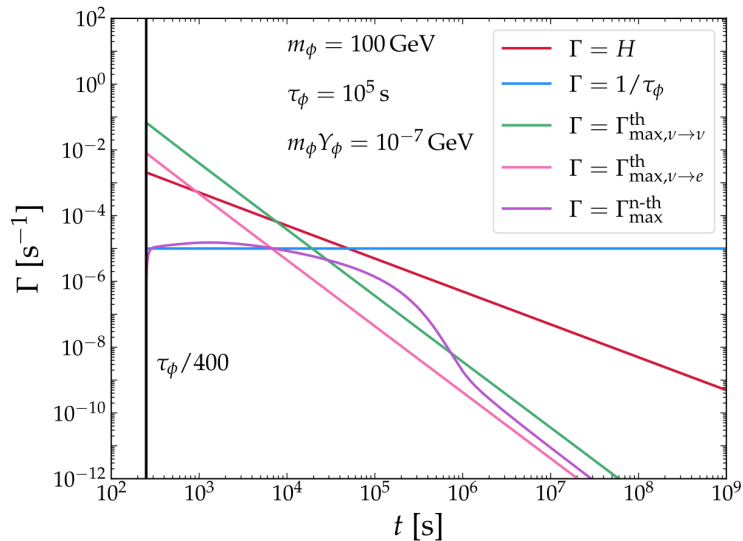
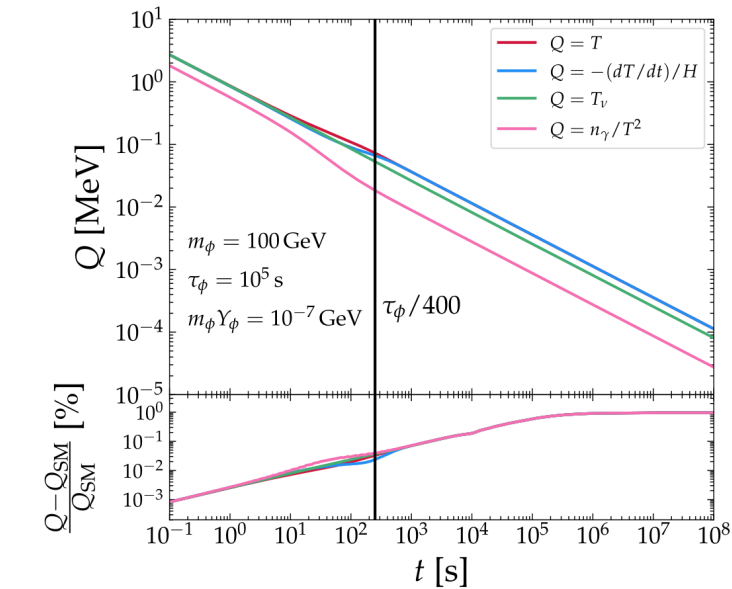
“Intermediate” mass result: 200GeV



Asymptotic behaviour

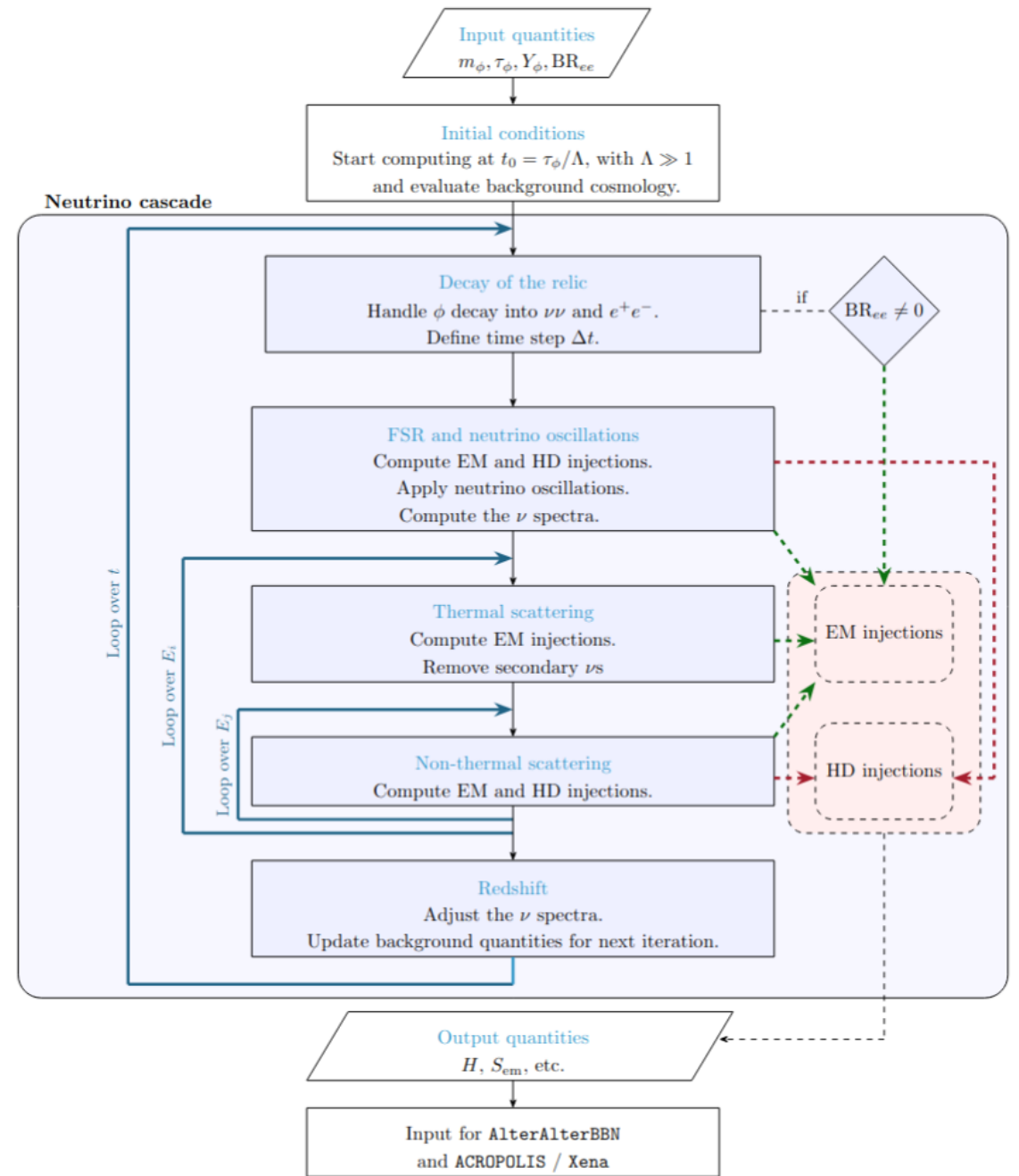


How to track the neutrino cascade

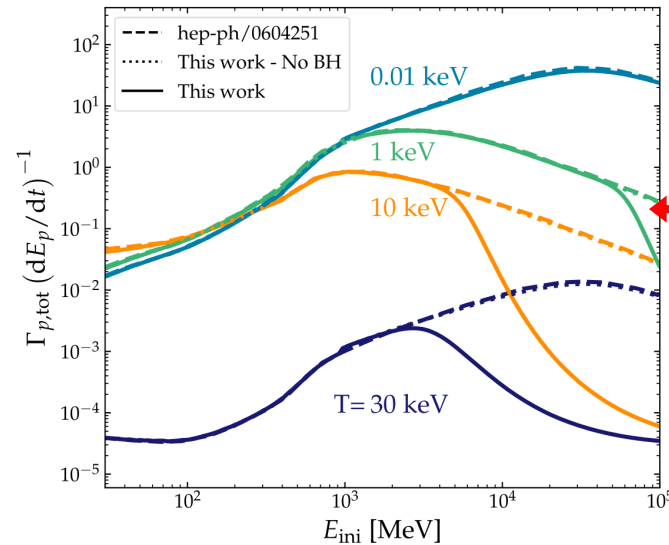


How to track the neutrino cascade

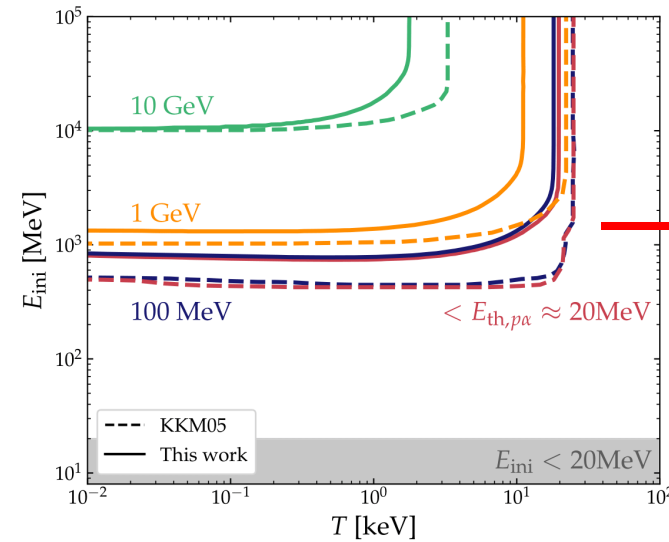
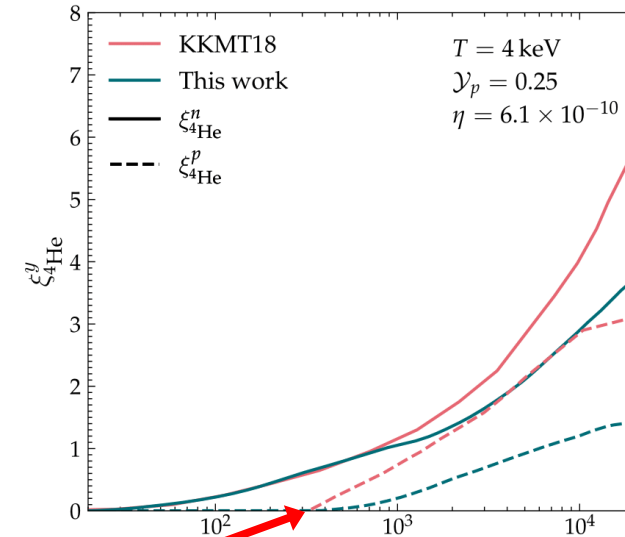
Variable	Description	Unit
Input parameters		
Y_ϕ	Abundance of ϕ	-
m_ϕ	Mass of ϕ	MeV
τ_ϕ	Lifetime of ϕ	s
BR_{ee}	Branching ratio into e^+e^-	-
One-dimensional output parameters		
f_ϕ	Fractional abundance of ϕ , $\frac{\Omega_\phi}{\Omega_{DM}}$	-
N_{eff}	Effective number of neutrinos	-
η	Baryon-to-photon ratio	-
Two-dimensional output parameters		
t	Time	s
T	Temperature	MeV
$\frac{dT}{dt}$	Time-temperature relation	MeV ²
T_ν	Neutrino temperature	MeV
H	Hubble rate	MeV
n_γ	Photon number density	MeV ³
S_{em}	Electromagnetic source term, eq. (4.11)	MeV ⁴
S_{hd}	Hadronic source term	MeV ⁴
$\frac{dn_{\text{hd}}^{\text{n-th}}}{dt}$	Injected hadrons per time from non-th. scattering, eq. (4.14)	MeV ⁴
$K_{\text{hd}}^{\text{n-th}}$	Avg. kinetic energy of hadrons from non-th. scattering, eq. (4.14)	MeV
$\frac{dn_{\text{hd}}^{\text{fsr}}}{dt}$	Injected hadrons per time interval from FSR, eq. (4.14)	MeV ⁴
$K_{\text{hd}}^{\text{fsr}}$	Avg. kinetic energy of hadrons from FSR, eq. (4.14)	MeV



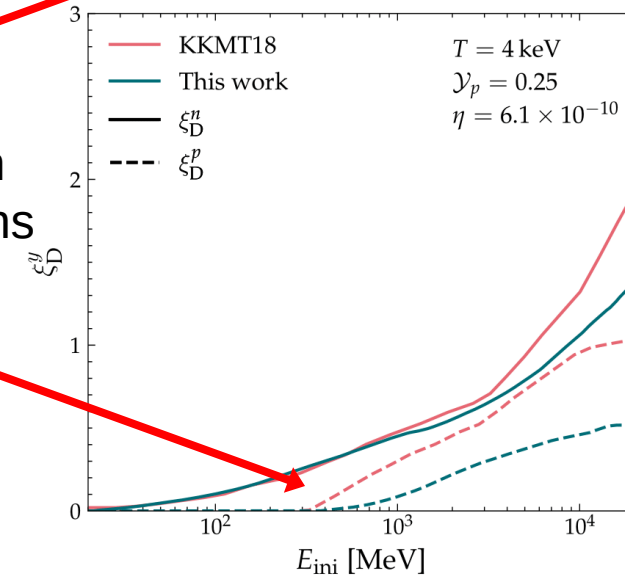
Details on hadrodisintegration & discrepancy with the literature



Cross check with the literature



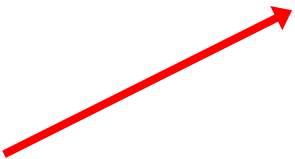
Related to difference in stopping power of protons



Note:
Discrepancy in
neutrons due to
interconversions

Model building

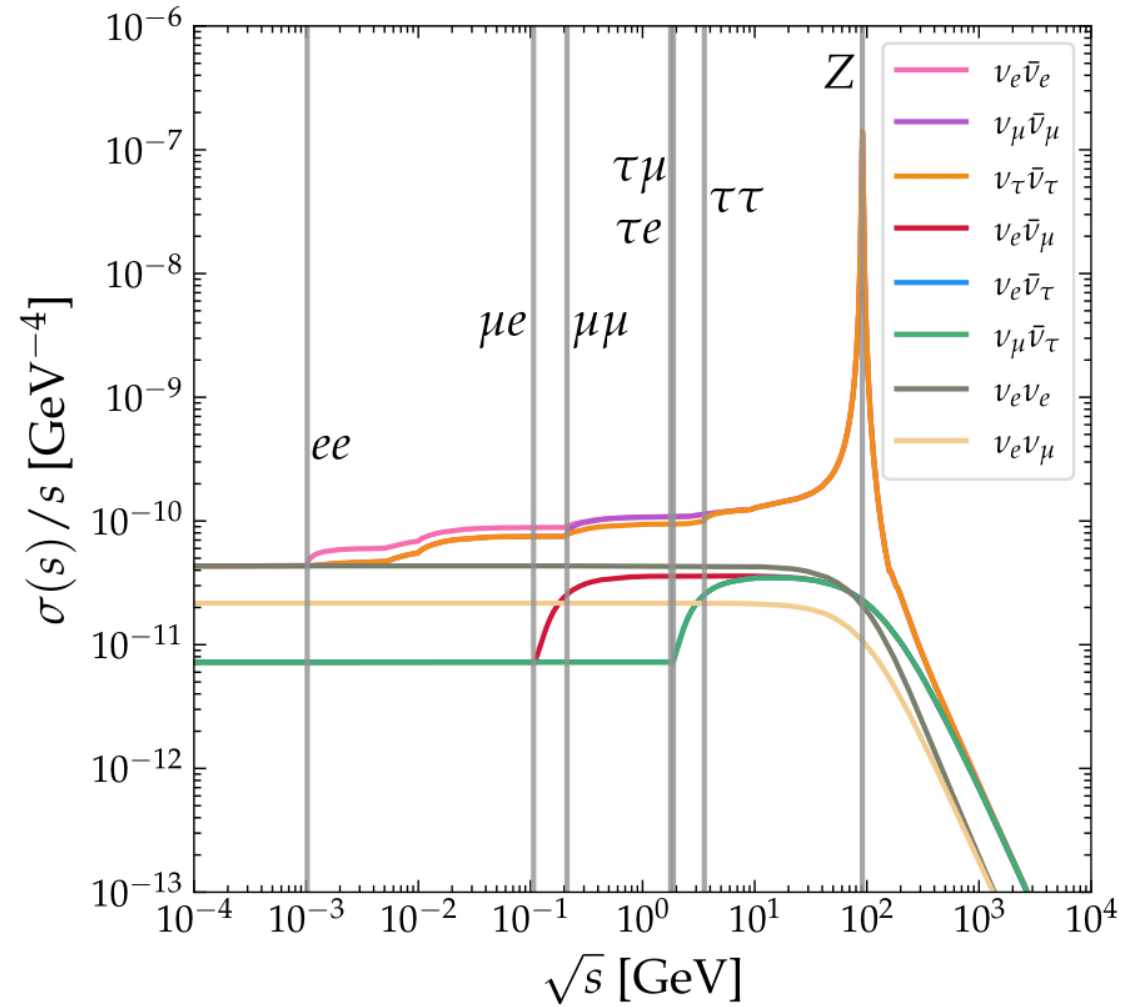
- Majoron: with loop suppressed decay into electrons
- Gauge boson coupled to two sterile neutrinos + seesaw mixing
- Neutral component of a scalar hypercharge 2 triplet
- Decay into one neutrino and one DS state is potentially also relevant


$$y_N \phi \overline{N^c} N$$


$$\Delta = (\delta^0, \delta^+, \delta^{++})$$

$$\Delta LL$$

The full EW cross sections



Details on photodisintegration processes

Important energy loss/redistribution processes

- Inverse Compton scattering
- Double-photon pair creation
- Photon-photon scattering
- Bethe-Heitler pair creation
- Compton scattering

$$e^{\pm} \gamma_{\text{th}} \rightarrow e^{\pm} \gamma$$

$$\gamma \gamma_{\text{th}} \rightarrow e^+ e^-$$

$$\gamma \gamma_{\text{th}} \rightarrow \gamma \gamma$$

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

$$\gamma e_{\text{th}}^{\pm} \rightarrow \gamma e^{\pm}$$

Disintegration processes

							E_r^{th} [MeV]
D	+	γ	$\rightarrow$	n	+	p	2.22
^3H	+	γ	$\rightarrow$	n	+	D	6.26
^3H	+	γ	$\rightarrow$	2n	+	p	8.48
^3He	+	γ	$\rightarrow$	p	+	D	5.49
^3He	+	γ	$\rightarrow$	n	+	2p	7.72
^4He	+	γ	$\rightarrow$	p	+	^3H	19.81
^4He	+	γ	$\rightarrow$	n	+	^3He	20.58
^4He	+	γ	$\rightarrow$	2D			23.85
^4He	+	γ	$\rightarrow$	n	+	p + D	26.07
^6Li	+	γ	$\rightarrow$	n	+	p + ^4He	3.70
^6Li	+	γ	$\rightarrow$	X	+	^3A	15.79
^7Li	+	γ	$\rightarrow$	^3H	+	^4He	2.47
^7Li	+	γ	$\rightarrow$	n	+	^6Li	7.25
^7Li	+	γ	$\rightarrow$	2n	+	p + ^4He	10.95
^7Be	+	γ	$\rightarrow$	^3He	+	^4He	1.59
^7Be	+	γ	$\rightarrow$	p	+	^6Li	5.61
^7Be	+	γ	$\rightarrow$	n	+	2p + ^4He	9.30
							τ_r [s]
n			$\rightarrow$	p	+	e^- + $\bar{\nu}_e$	8.802×10^2
^3H			$\rightarrow$	^3He	+	e^- + $\bar{\nu}_e$	5.61×10^8

Neutrino oscillations

$$t_{\text{osc}} \sim \frac{T}{\Delta m^2} \sim 10^{-5} \text{ s} \left(\frac{T}{\text{MeV}} \right)$$

1812.05605

Neutrino oscillation time scale much higher than other time scales in our setup!

Therefore, we can assume instantaneous oscillations using the following mixing matrix

$$(\mathbf{M}_{\text{osc}})_{\alpha\beta} = \sum_{i=1}^3 |U_{\alpha i}|^2 |U_{\beta i}|^2 \approx \begin{pmatrix} 0.55 & 0.17 & 0.28 \\ 0.17 & 0.45 & 0.37 \\ 0.28 & 0.37 & 0.35 \end{pmatrix}$$