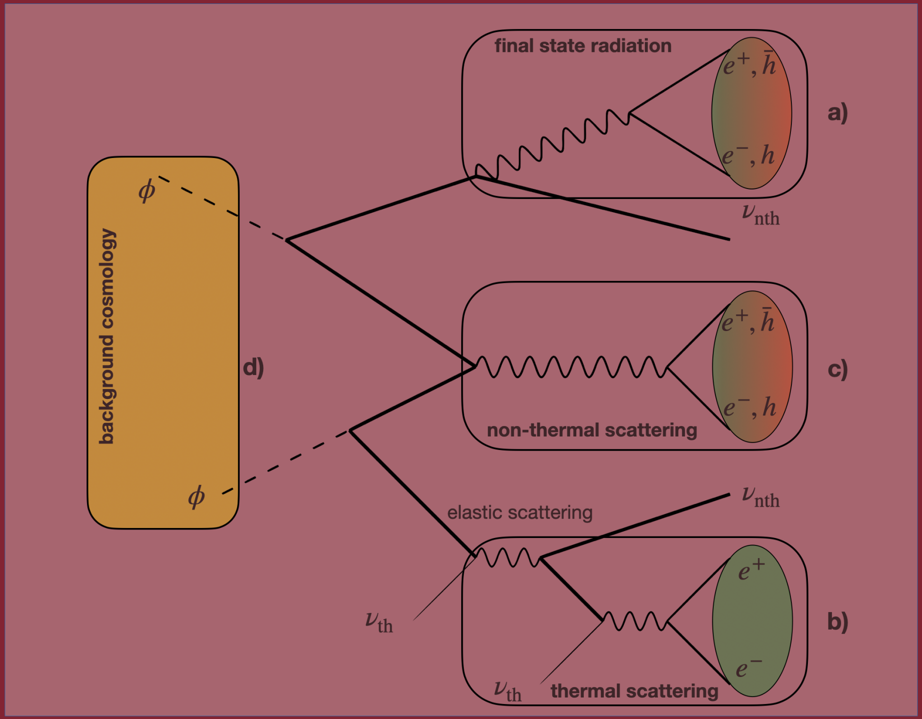
Photo- and Hadrodisintegration constraints on massive relics decaying into neutrinos

Jonas Frerick (jonas.frerick@uniroma1.it)



Based on 2505.01492

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

DESY Theory Workshop 2025

25.09.2025

DESY Hamburg

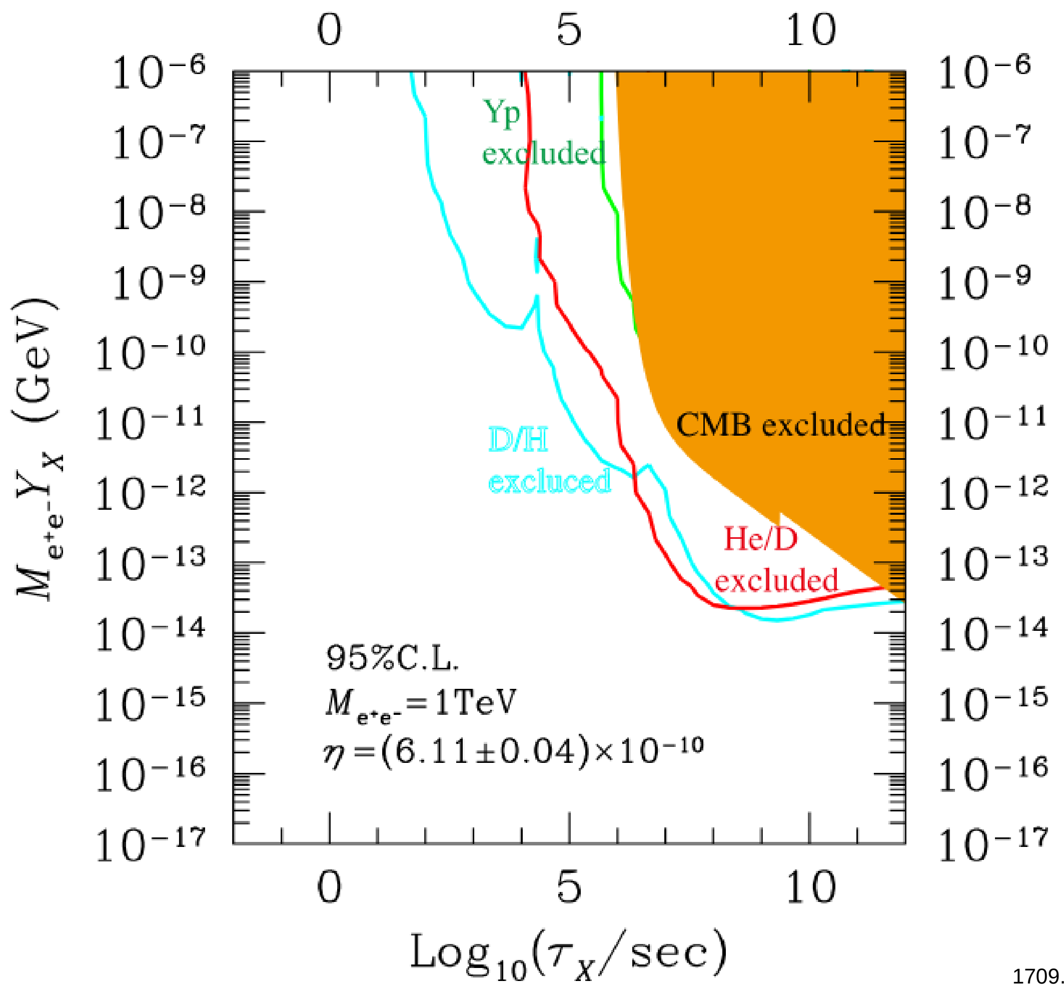
Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Research Council Executive Agency. Neither the European Union nor the granting authority can be held responsible for them. This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

Can you hide an unstable Dark Sector in neutrinos?

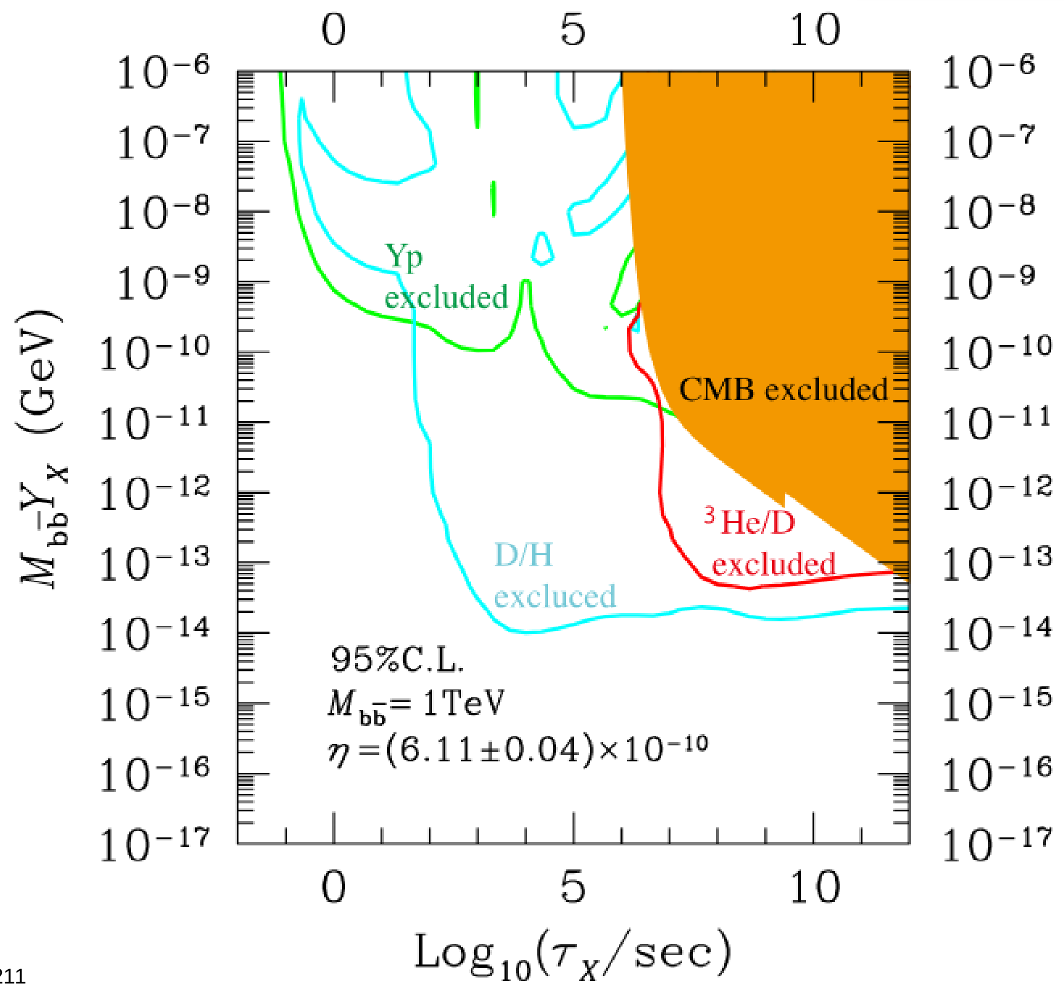
$$\phi \to \begin{cases} \text{EM Particles} \\ \text{Hadrons} \\ \text{Neutrinos} \\ \text{Dark Sector} \end{cases}$$

"trivial"

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

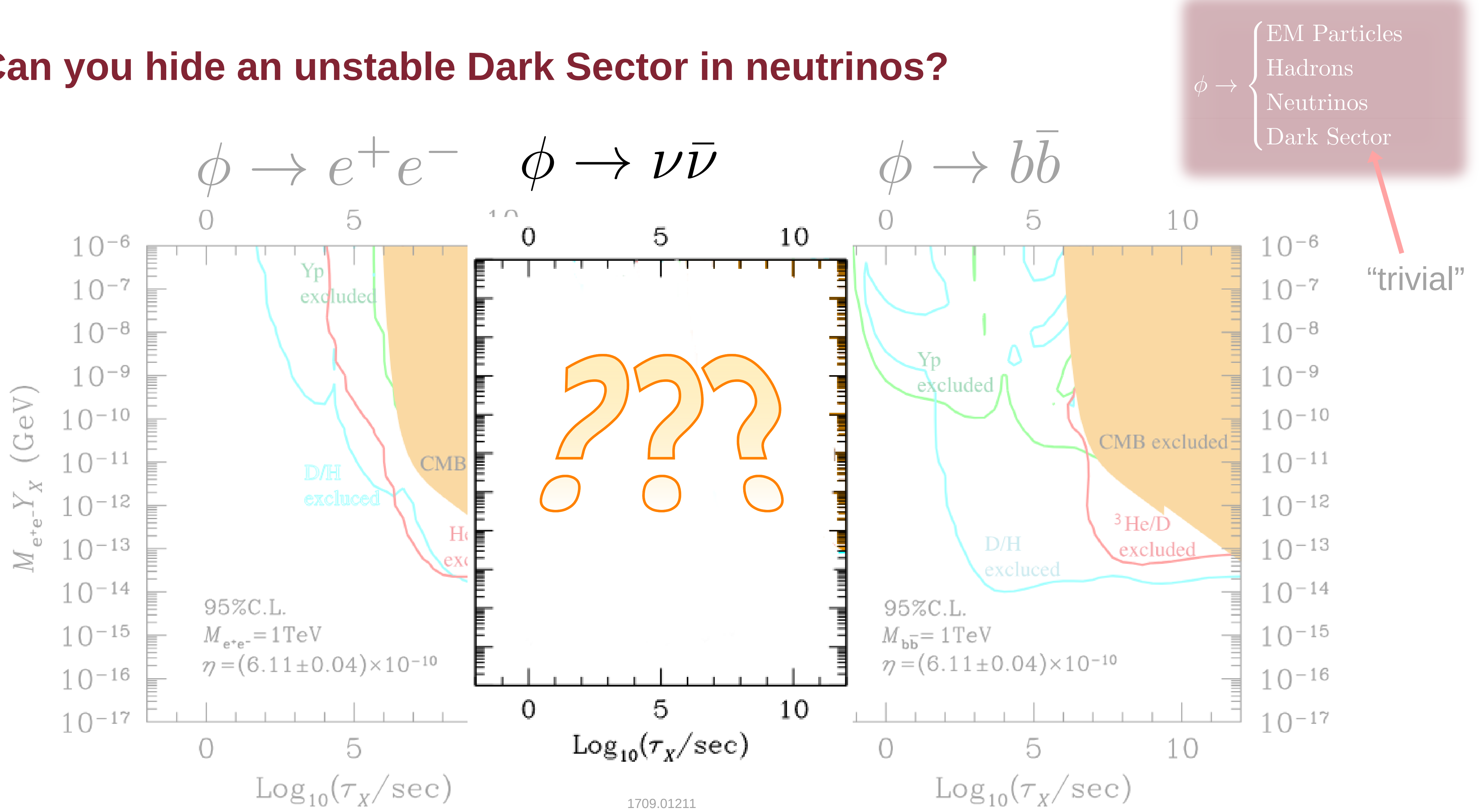


$\phi \to b\bar{b}$



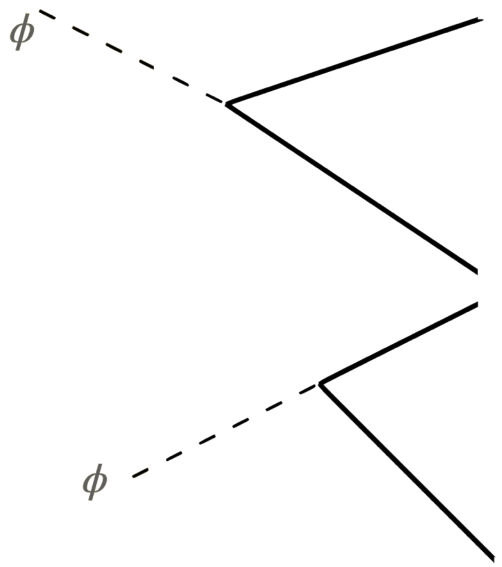
1709.01211

Can you hide an unstable Dark Sector in neutrinos?



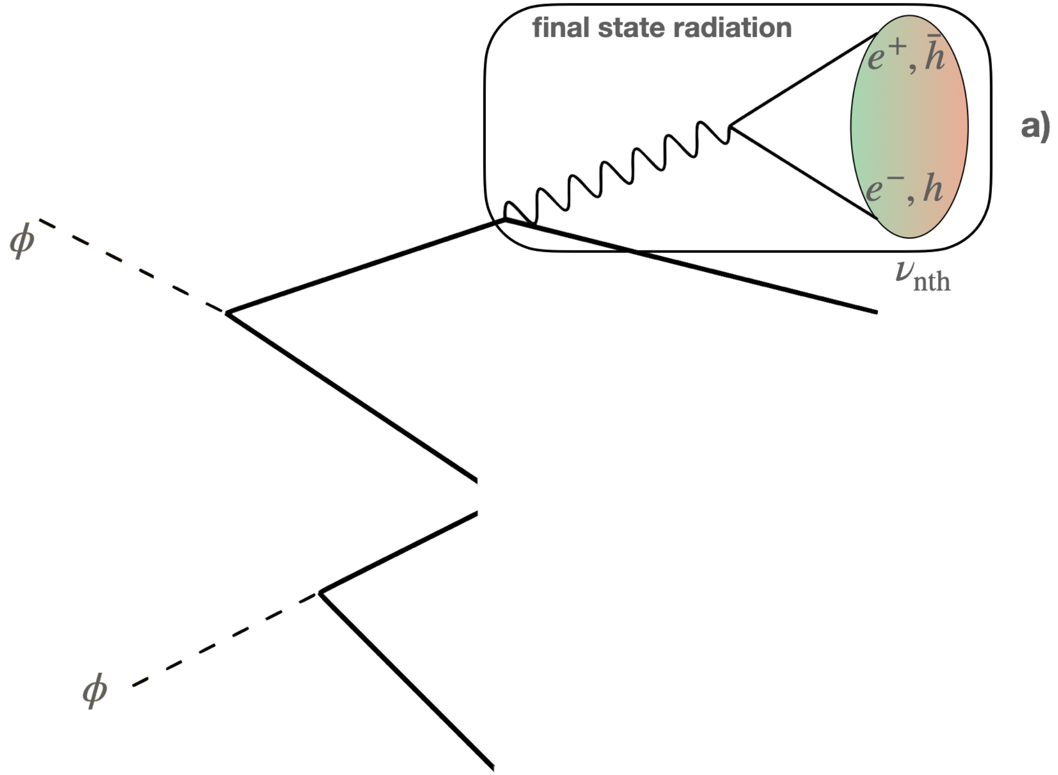
1709.01211

Neutrino injections ≠ Injection of only neutrinos



How much harm can a neutrino do?

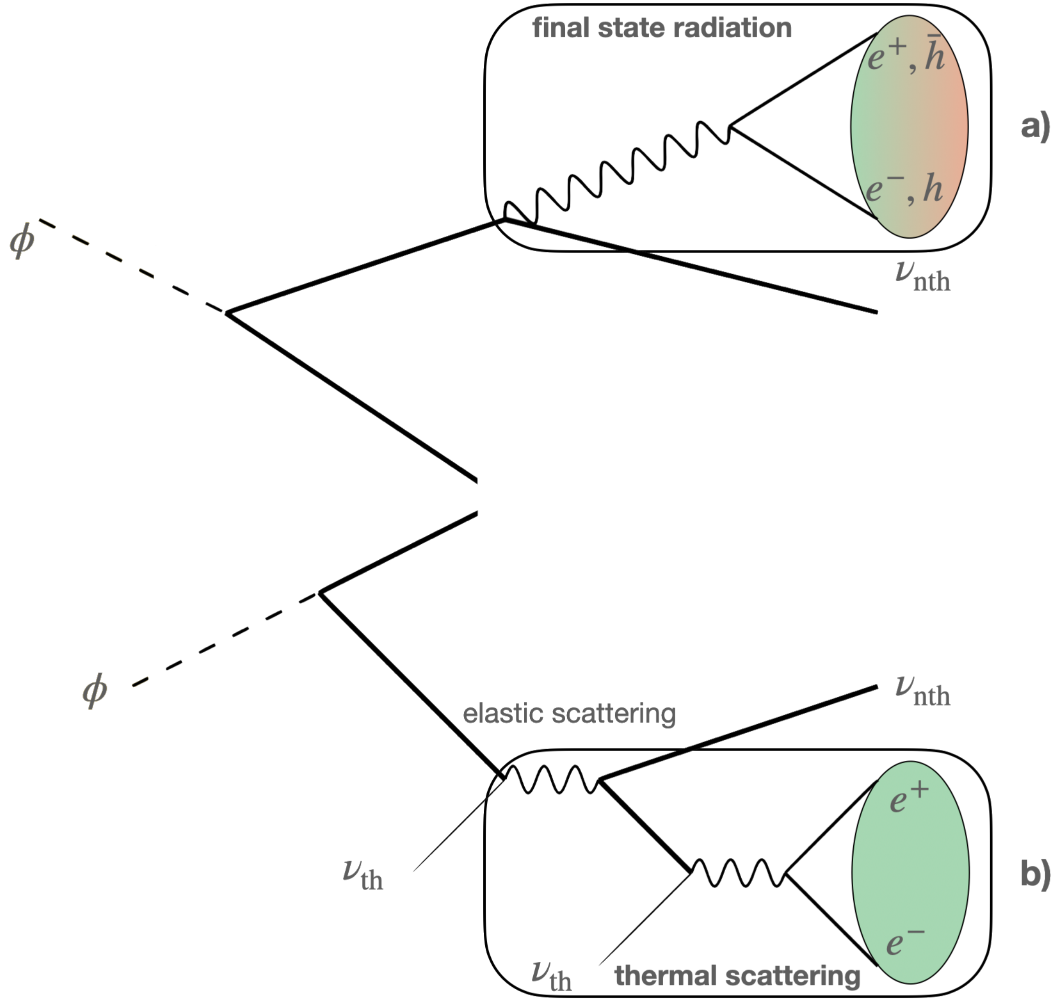
Neutrino injections ≠ Injection of only neutrinos



How much harm can a neutrino do?

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

Neutrino injections ≠ Injection of only neutrinos

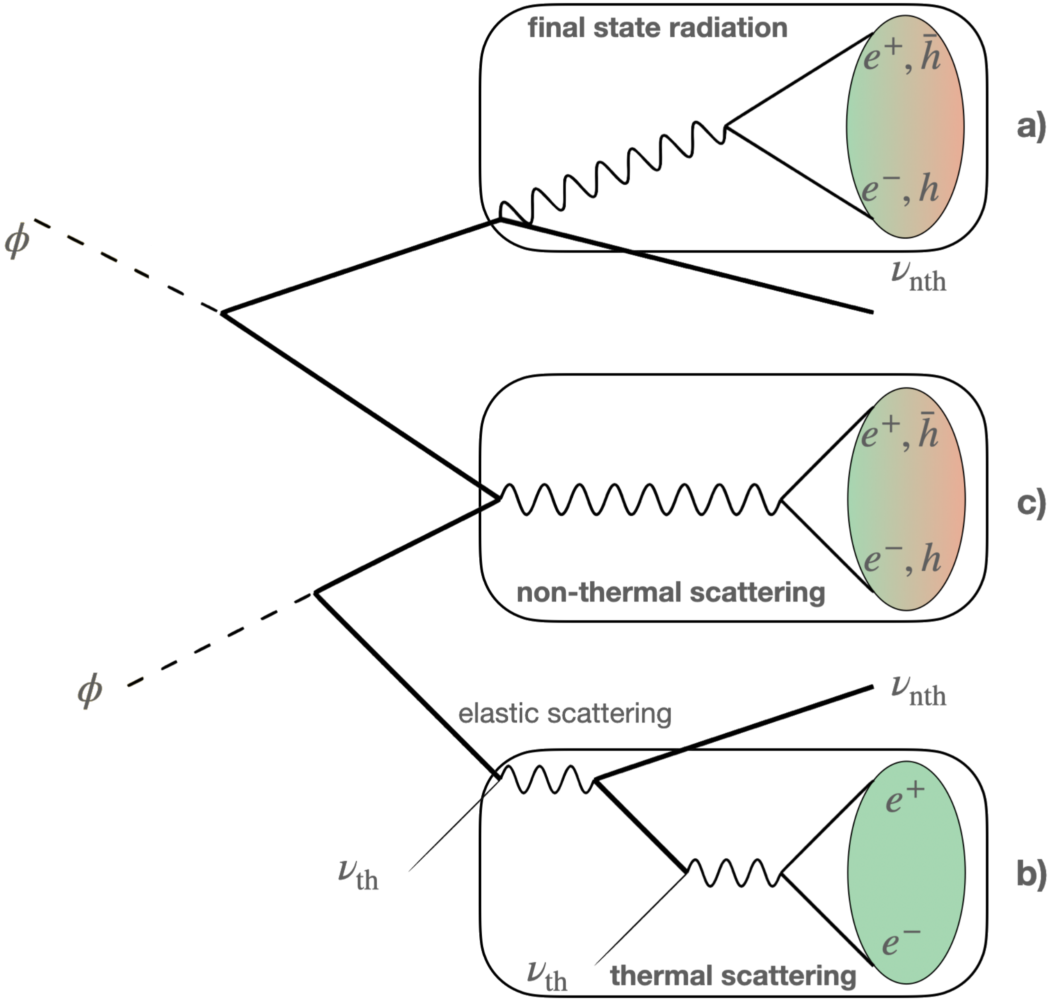


How much harm can a neutrino do?

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

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

Neutrino injections ≠ Injection of only neutrinos



How much harm can a neutrino do?

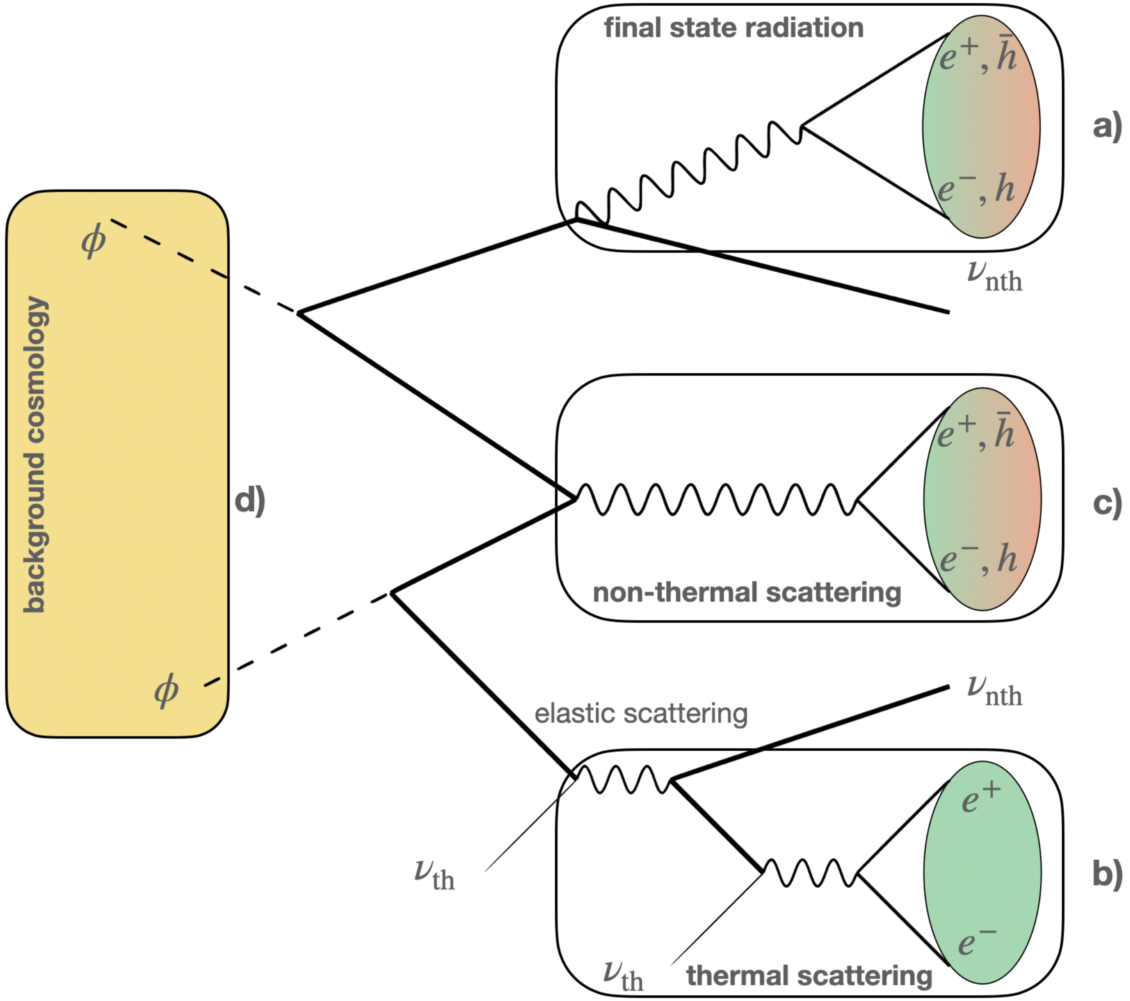
a) **Final-state radiation**, injects **EM** and **hadrons**

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

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

Neutrino cascade

Neutrino injections ≠ Injection of only neutrinos



How much harm can a neutrino do?

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

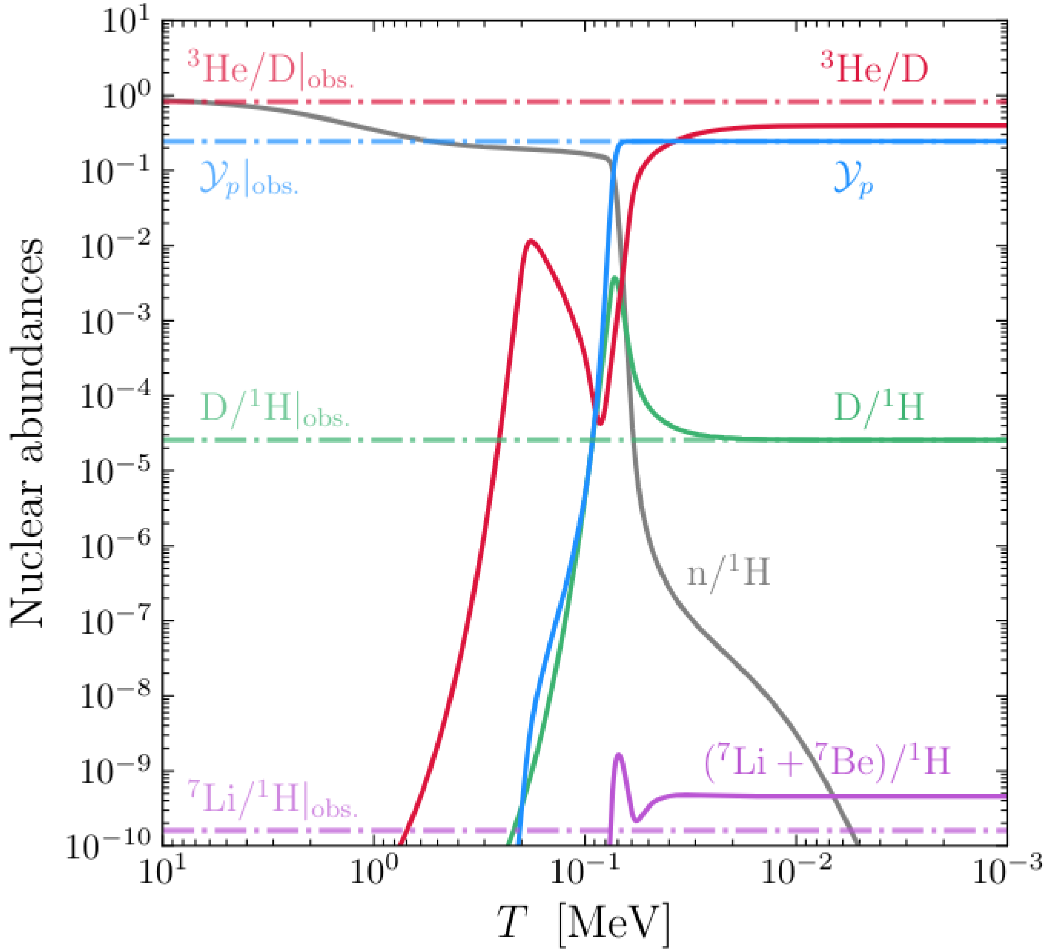
b) **Thermal scattering**, injects EM

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

d) Changes in the **background cosmology**

Interlude: BBN data, photodisintegration & hadrodisintegration

We use a modified version of AlterBBN [1806.11095].



Credits: F. Depta

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

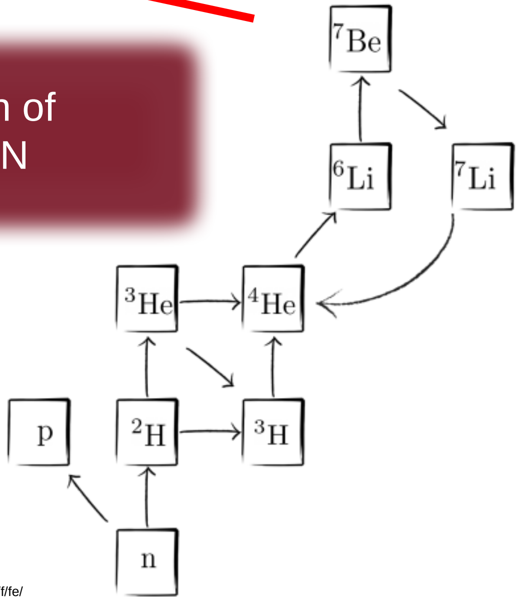
$$D/^1H = (2.547 \pm 0.029) \times 10^{-5}$$

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

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

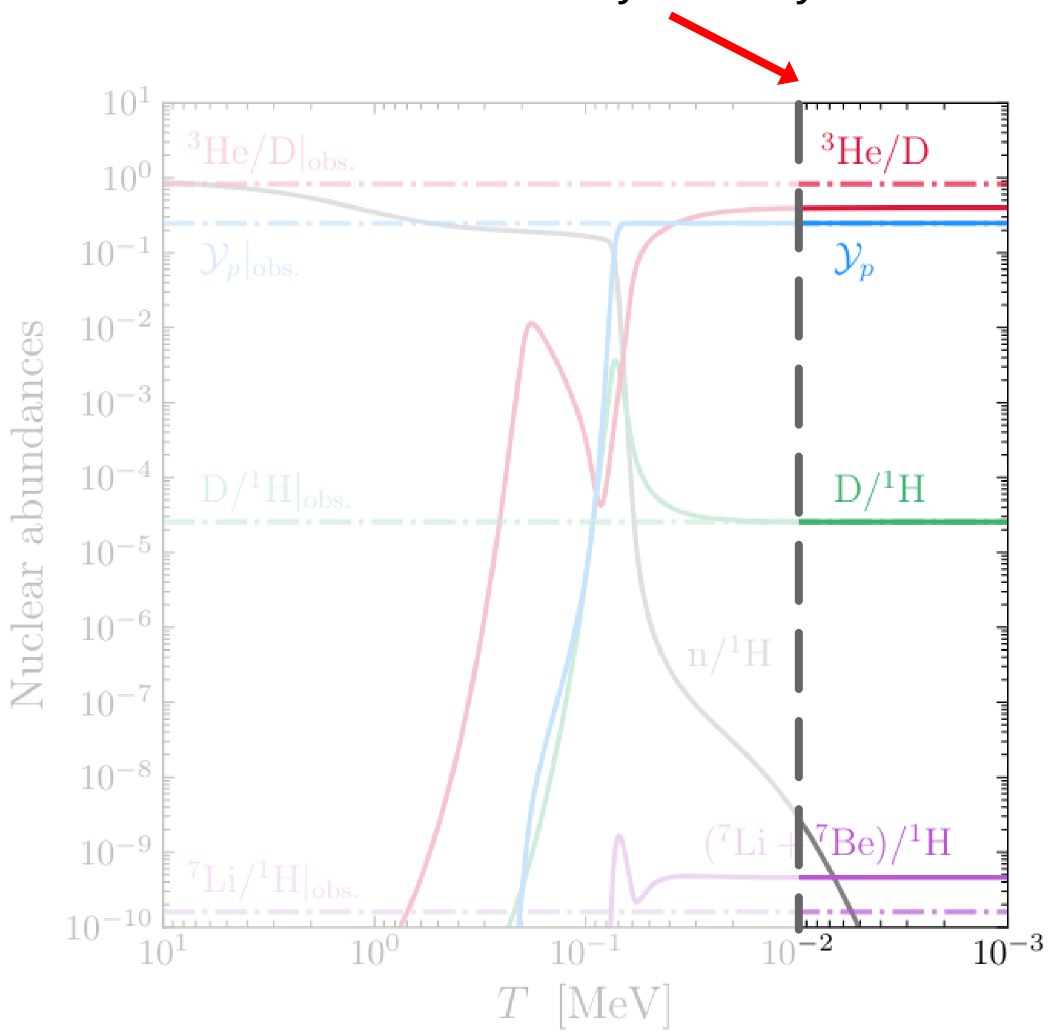
https://static.wikia.nocookie.net/asterix/images/f/fe/Getafix_brewing.png/revision/latest?cb=20150710202131

Reaction chain of Standard BBN



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

=

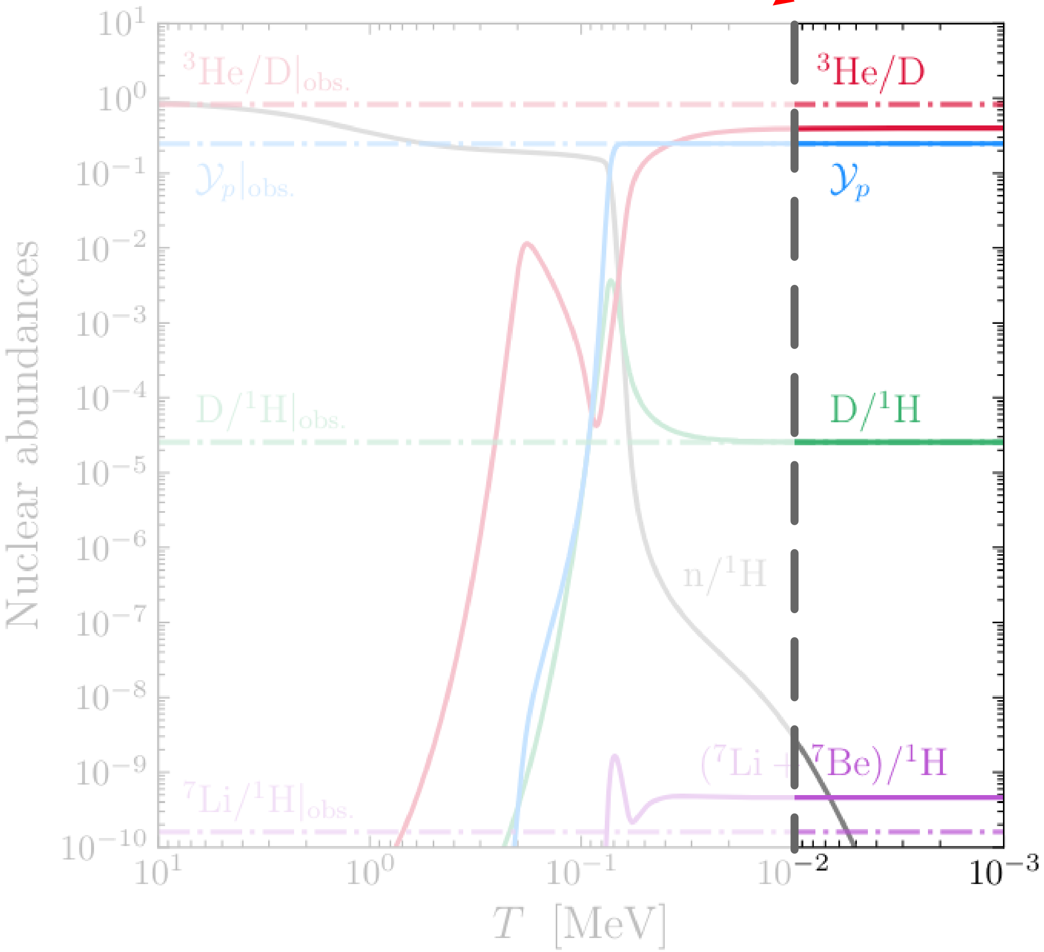
late-time destruction of the light elements by **EM** particles

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

allows factorisation of the processes

Interlude: BBN data, photodisintegration & hadrodisintegration

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



Credits: F. Depta

Photodisintegration

=

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

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

Numerical Framework **ACROPOLIS**
By Frederik, Marco and Kai
(2011.06518)

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

"universal spectrum"

$$\left[\frac{\mathrm{d}n_X}{\mathrm{d}t}\right]_{\mathrm{photo}} = \sum_j n_j N_{j\gamma\to X}\int_0^\infty \mathrm{d}E\,\mathrm{f}_\gamma(E)\sigma_{j\gamma\to X}(E) - n_X\sum_{j'}\int_0^\infty \mathrm{d}E\,\mathrm{f}_\gamma(E)\sigma_{X\gamma\to j'}(E)$$

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]:

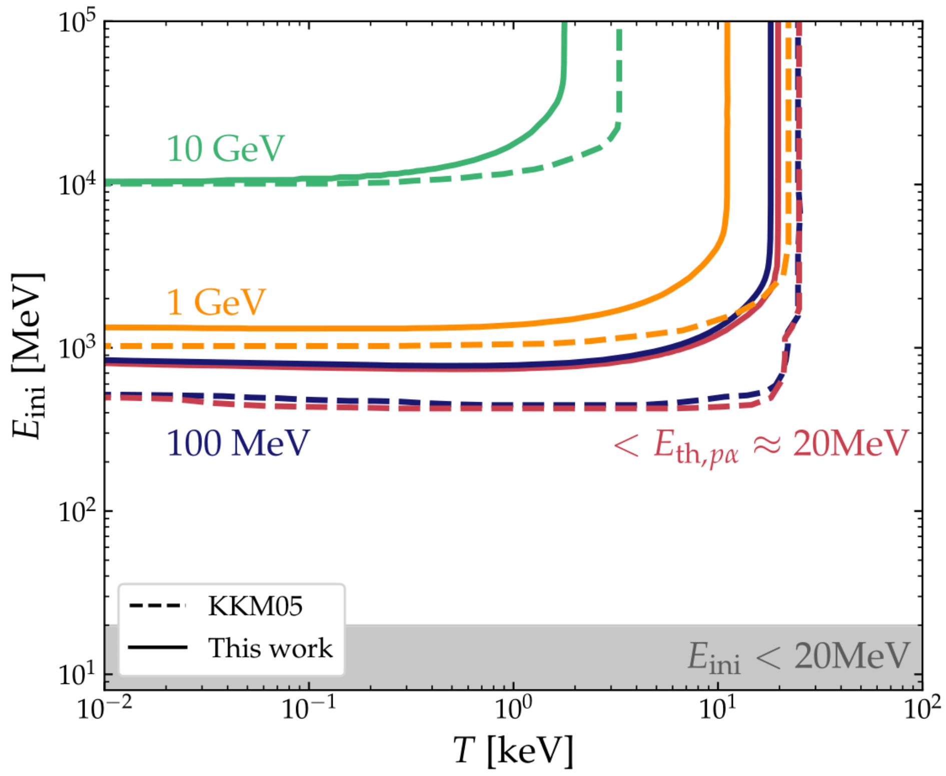
I. Inject hadrons (in our case: neutrons and protons)

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)	$n + p_{BG} \to n + p$	$p + p_{BG} \to p + p$	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

Redistribute the kinetic energy

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

Disintegrate ^{4}He

Interlude: BBN data, photodisintegration & hadrodisintegration

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

BrandNew

Hadrodisintegration in

ACROPOLIS

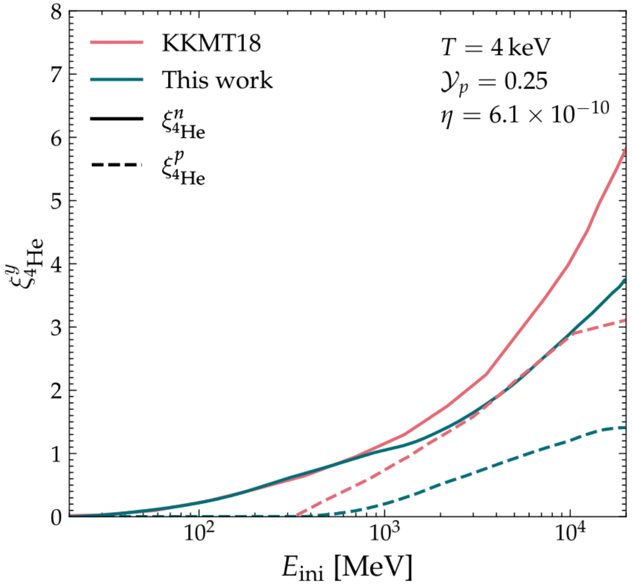
Also check out https://github.com/hep-mh/xena

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

II. Apply energy loss formalism

III. Calculate nuclear scattering and determine final products

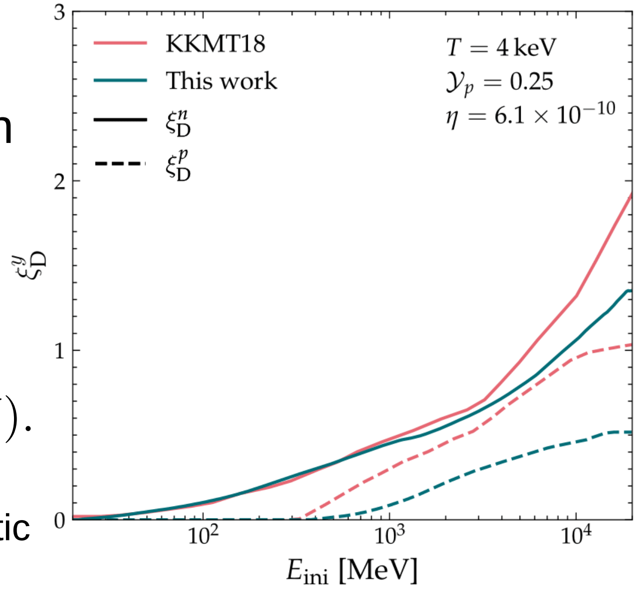
IV. Repeat until all particles in the cascade have negligible kinetic energy



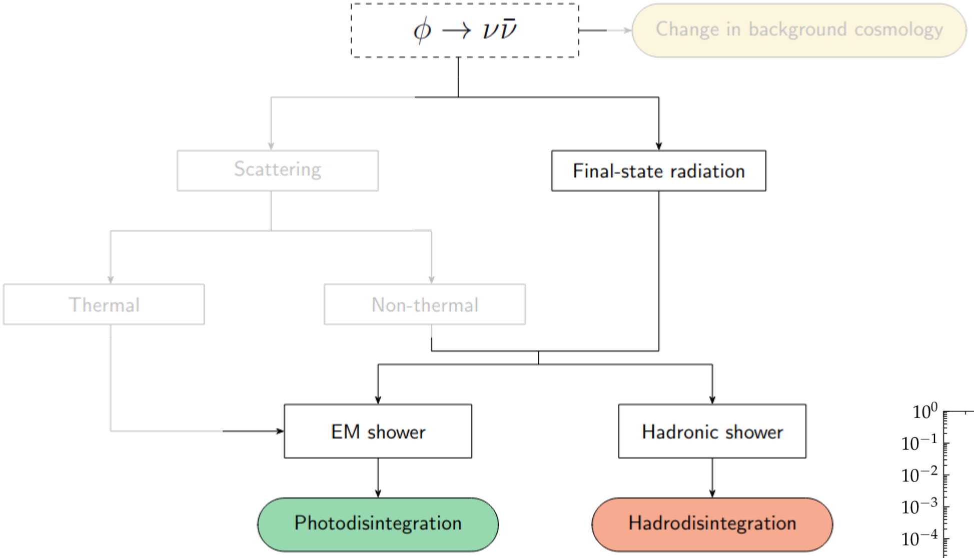
Number of nuclei produced per injected nucleon

$$\left[\frac{\mathrm{d}n_X}{\mathrm{d}t}\right]_\mathrm{hadro} = \sum_{y=n,p} \int_0^\infty \mathrm{d}K\, \xi^y_X[n_j](K) \frac{\mathrm{d}^2 n^\mathrm{inj}_y}{\mathrm{d}t\mathrm{d}K}(K).$$

Note: We approximate the injection spectrum as monoenergetic



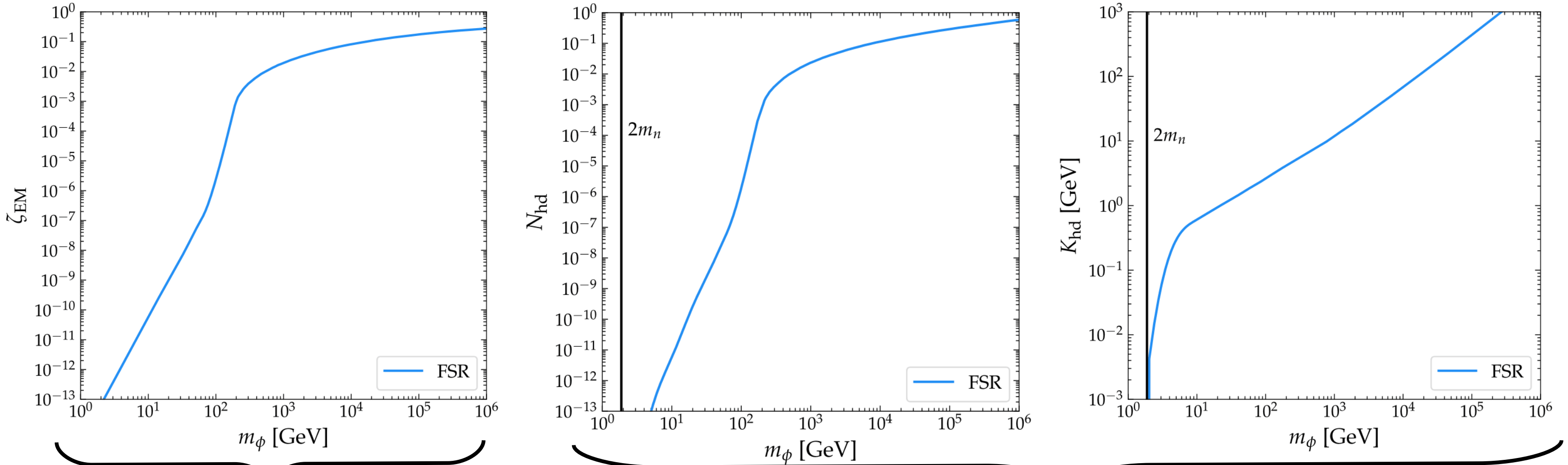
Handling the contributions step-by-step



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

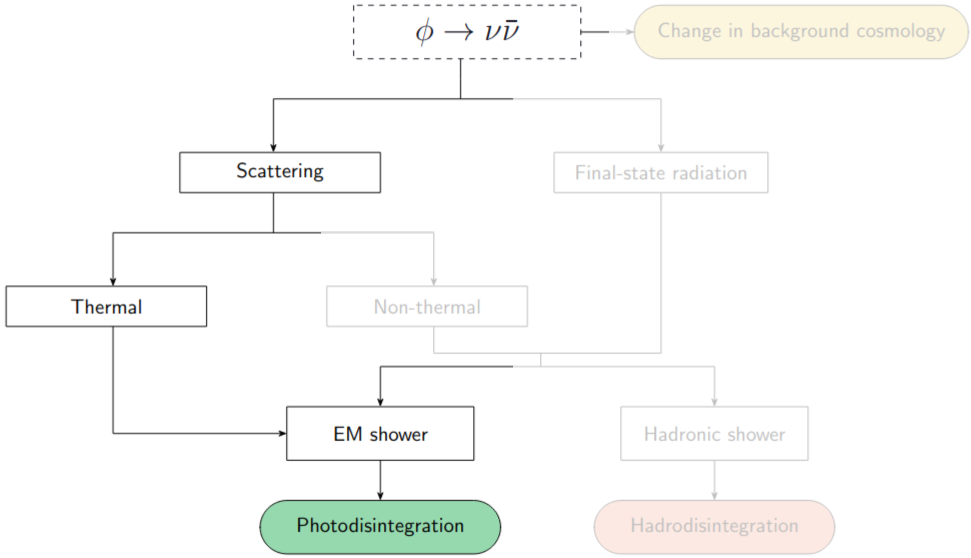
HDI requires 2 parameters

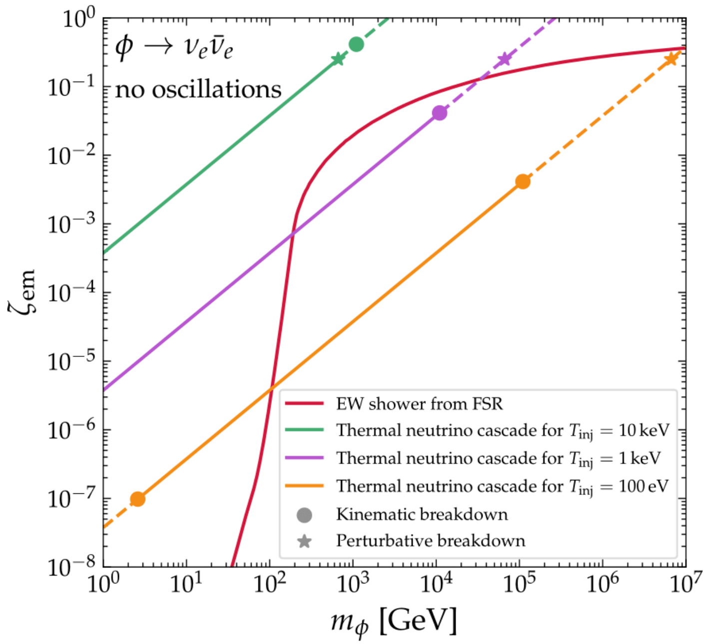
Handling the contributions step-by-step

Injection rate given by thermal scattering rate

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

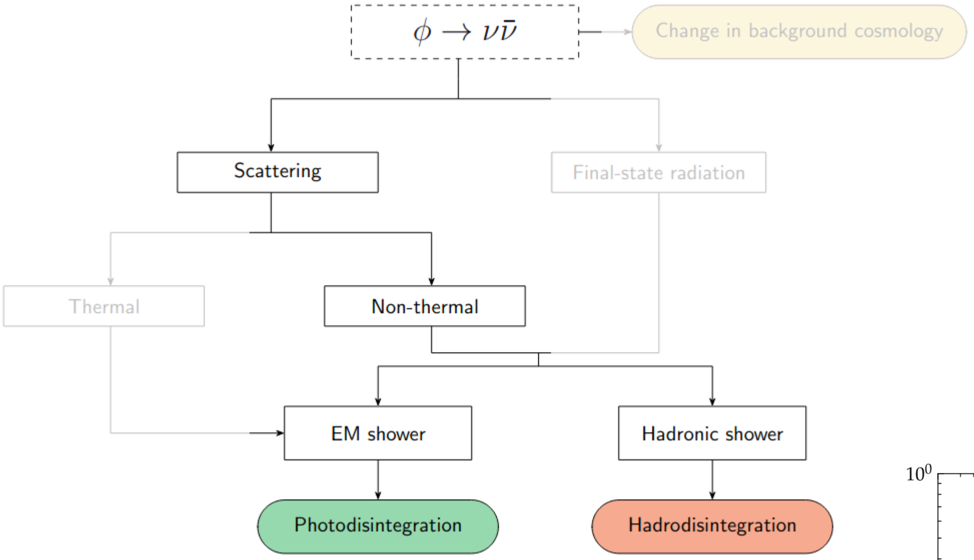
Effect of an individual injection determined analytically





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

Handling the contributions step-by-step

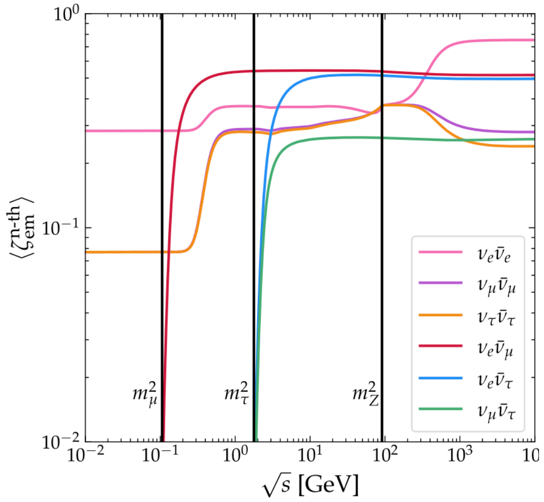


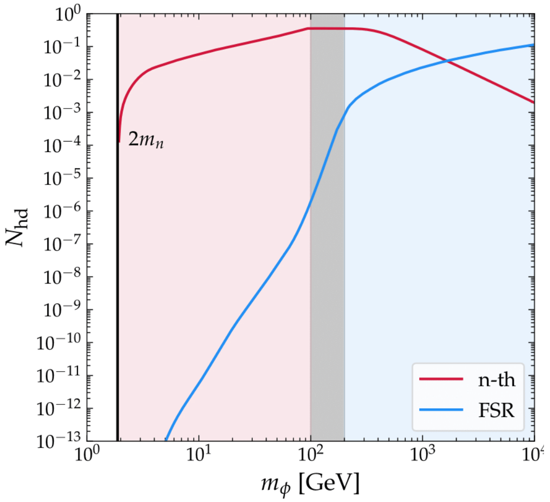
Injection rate given in general by

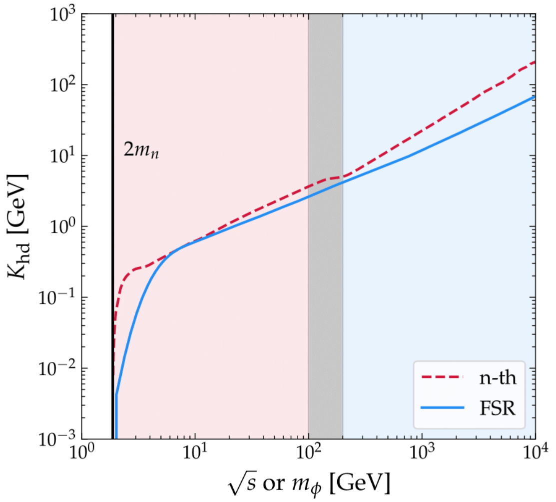
$$\Gamma_{\rm ann}(T,E) = \frac{g_\nu}{16\pi^2 E^2}\int_0^\infty {\rm d}\epsilon\ f_{\nu,\text{n-th}}(\epsilon)\int_0^{4E\epsilon} {\rm d}s\ s\cdot\sigma_{\rm ann}(s)$$

Requires knowledge of non-thermal spectrum!!! ☠️
Exact methodology very technical

Effects of individual event determined by PYTHIA

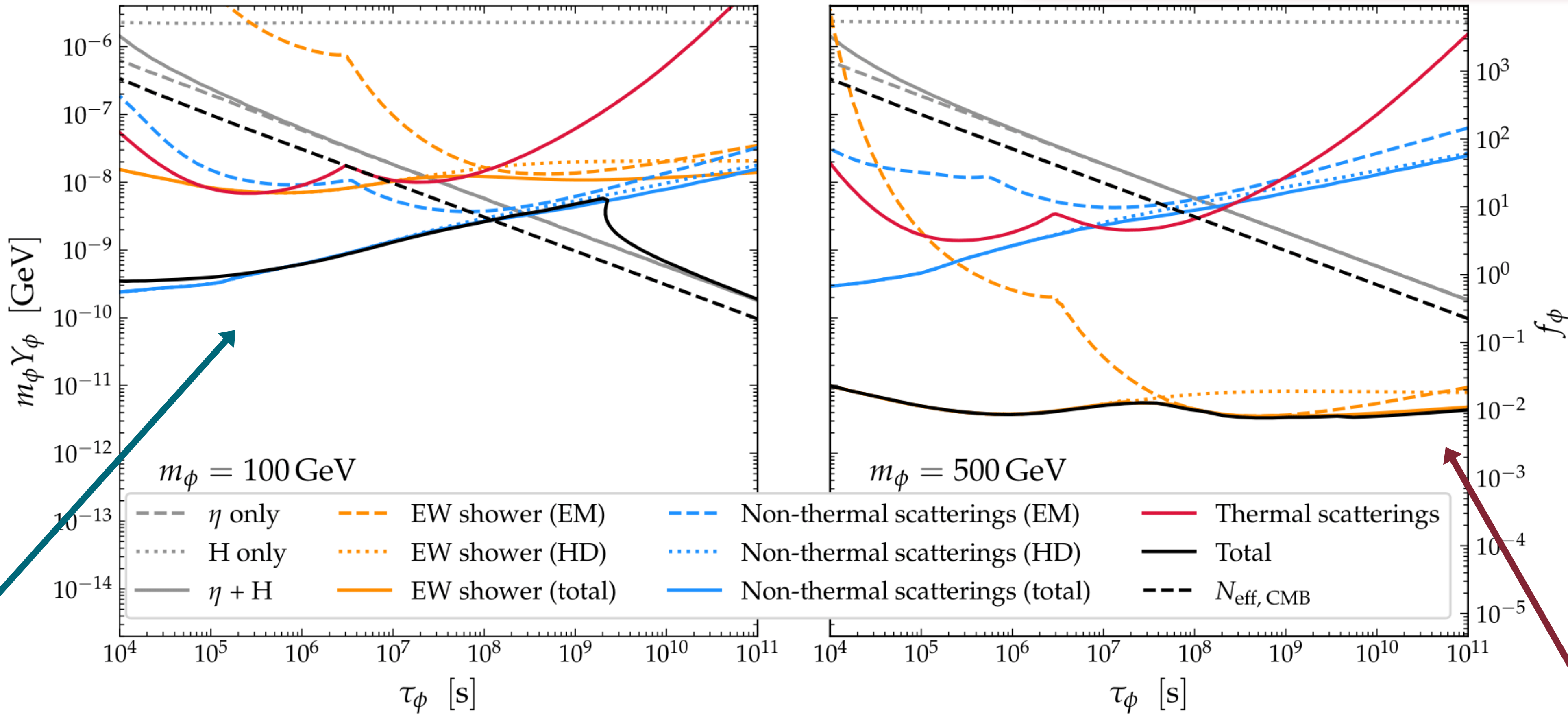






Detailed discussion of the resulting constraints

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

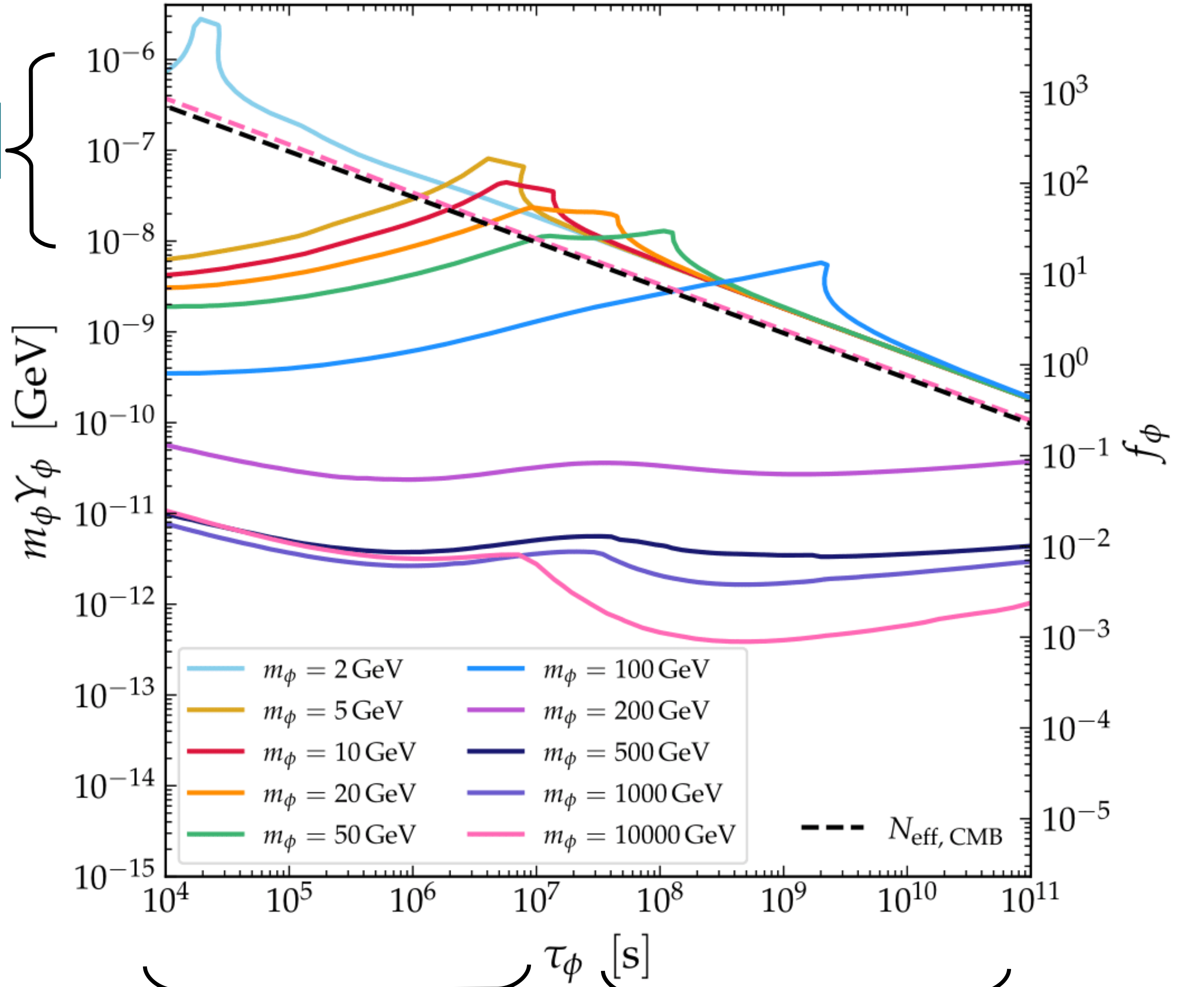
Non-thermal domination

Cosmo domination

Jump across nucleon mass threshold

Unlocking of Z resonance

Dominance of FSR begins

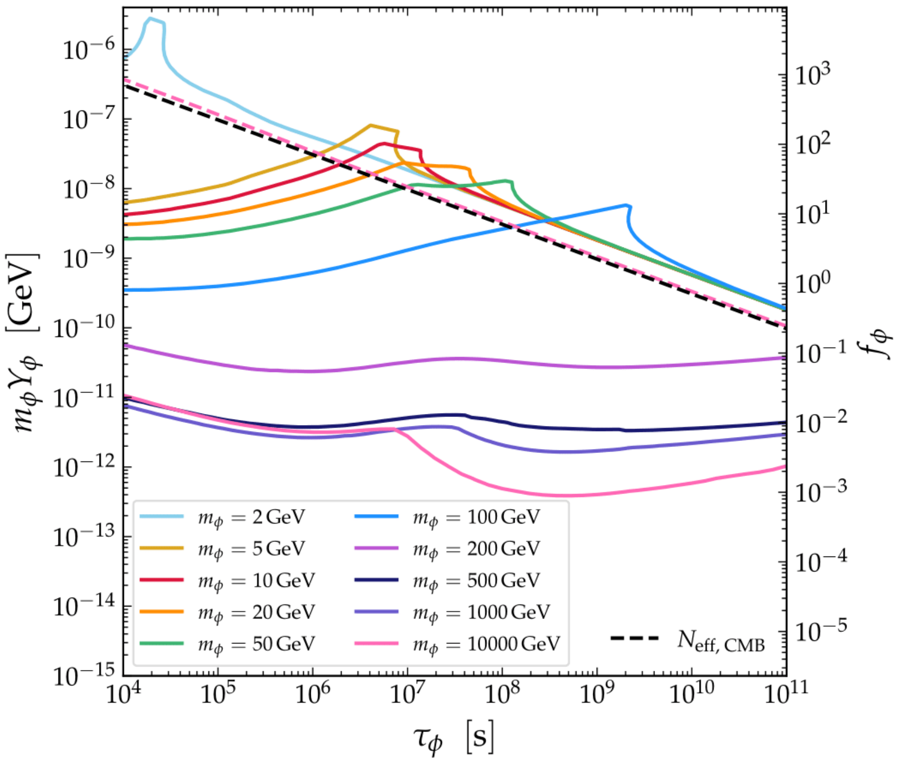


Hadronic domination

EM & mixed contribution

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.

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!)
- Combination of hadro- and photodisintegration is a powerful tool applicability to all other SM final states!
- This work is part of an upcoming review to summarise the contributions of Marco and Frederik to the field

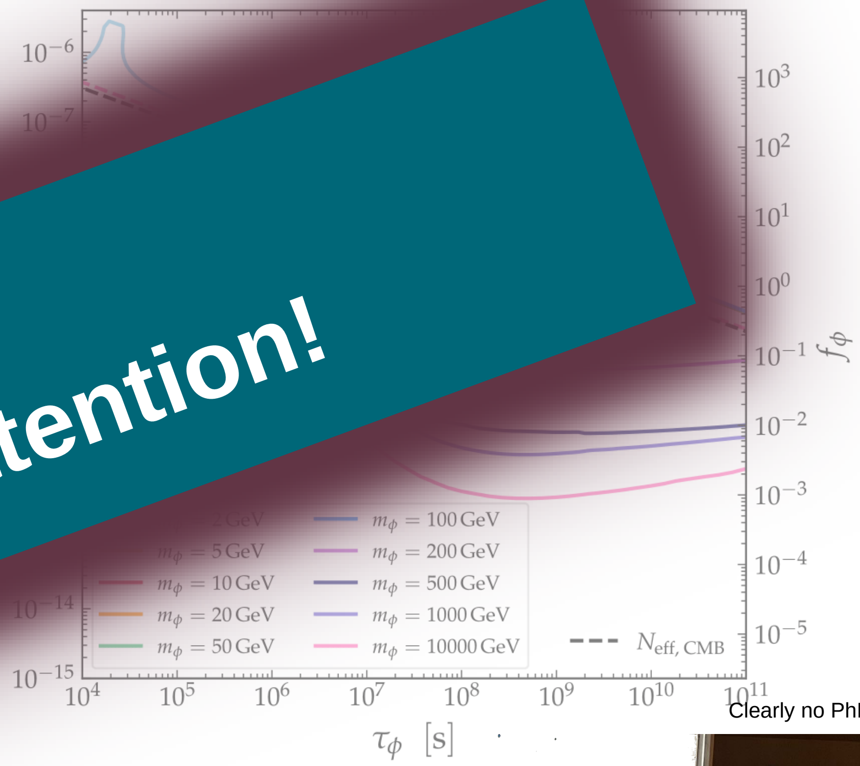
… and of course check the paper for (many) more details.

Conclusions & Outlook

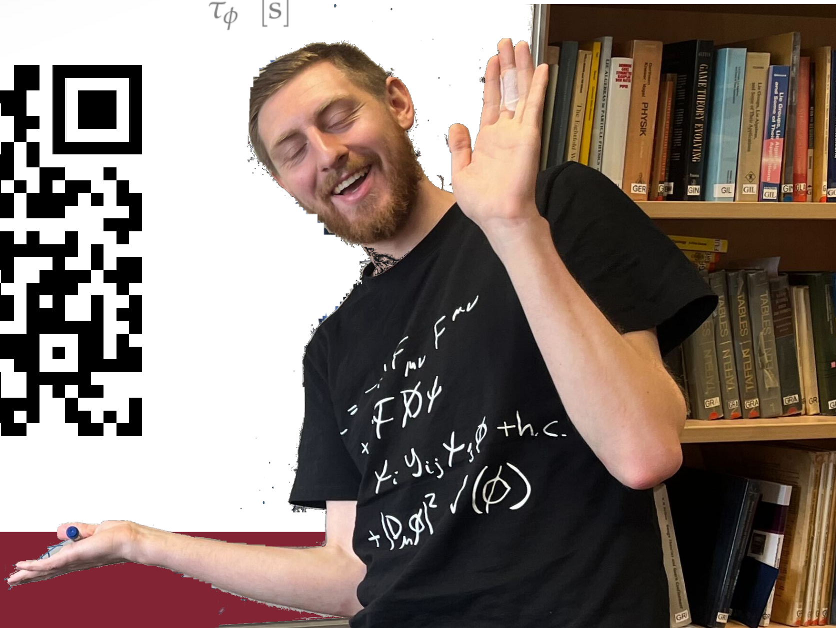
- Thorough study of neutrino injections after BBN
- Surprisingly strong limits, especially from h…
- Combination of improved lite…
- Breakdown of m…
  care (sta…
- C… a powerful tool
  ap…
- This … ing review to summarise the
  contri… o and Frederik to the field

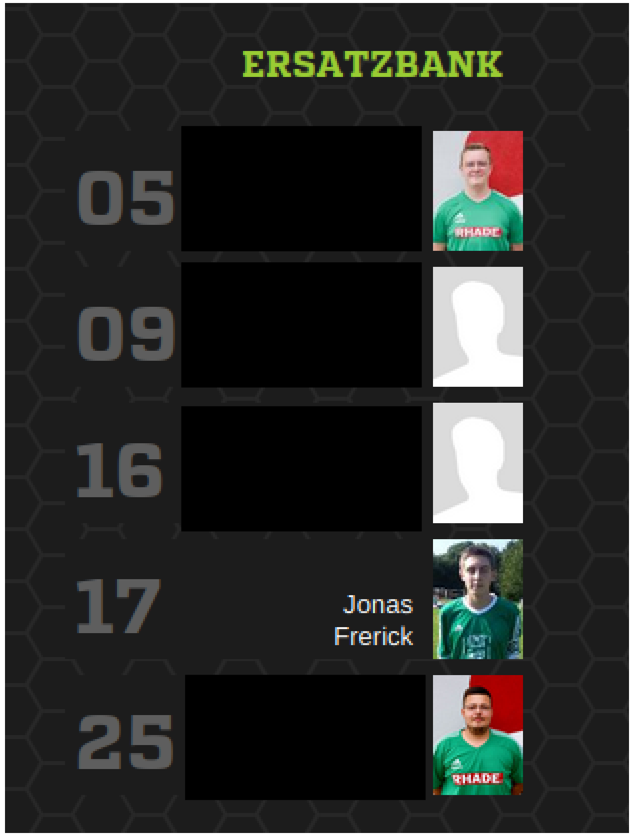
… and of course check the paper for (many) more details.

That's it!
Thank you for your attention!

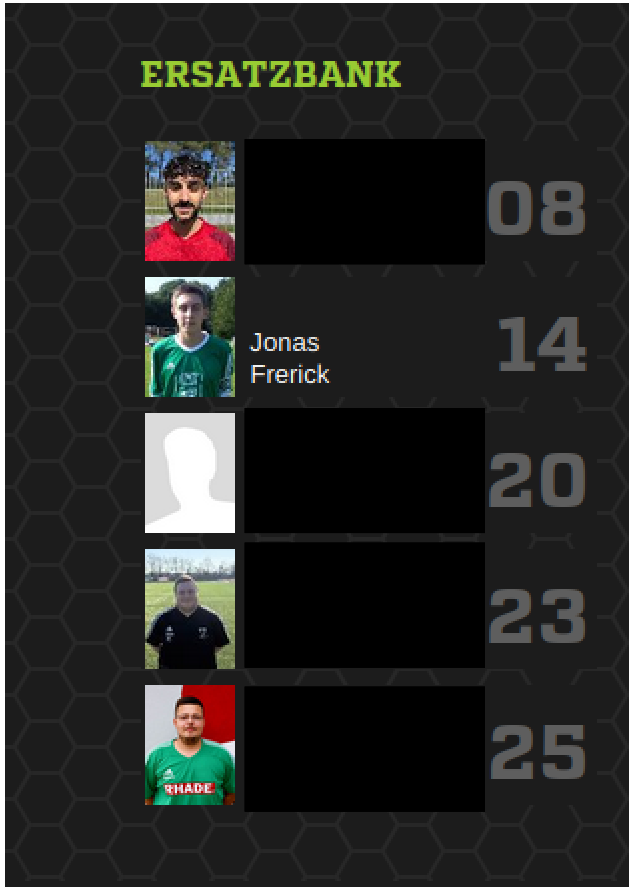


Clearly no PhD in GIMP

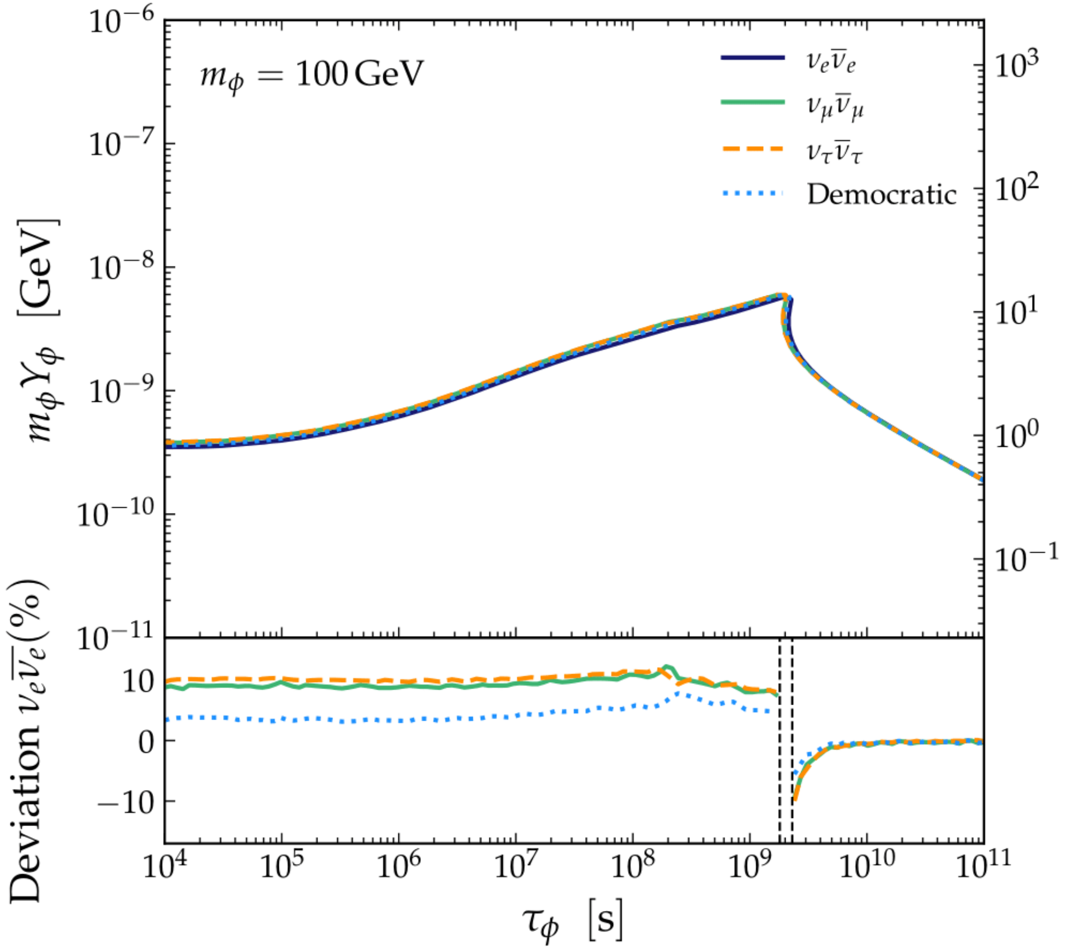


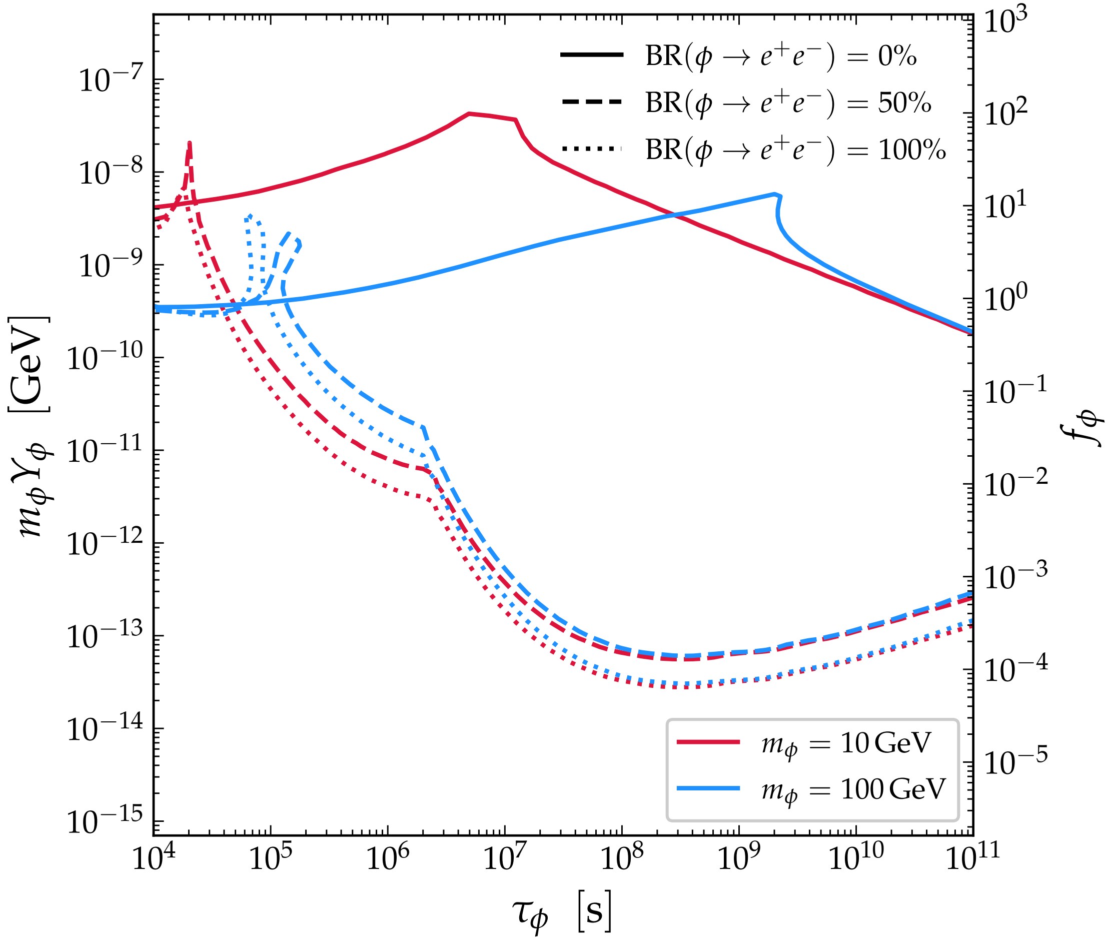

ERSATZBANK
05 [redacted]
09 [redacted]
16 [redacted]
17 Jonas Frerick
25 [redacted]

Back-up


ERSATZBANK
[redacted] 08
Jonas Frerick 14
[redacted] 20
[redacted] 23
[redacted] 25

How broadly applicable are these results?

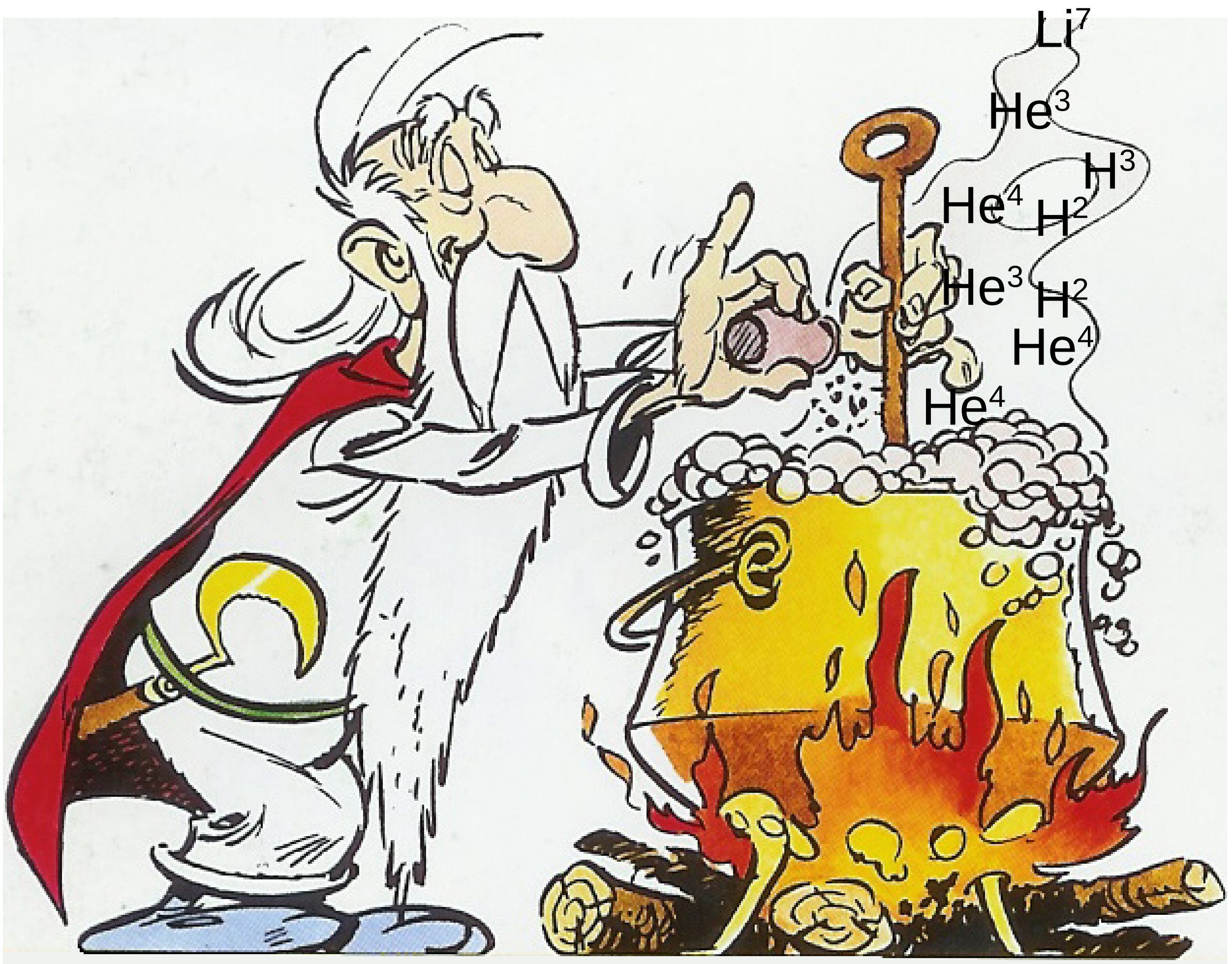




Results largely independent of initial neutrino composition ✔

Results likely still relevant for loop suppressed decay into electrons ✔

Prelude to the Interlude: ingredients for Big Bang Nucleosynthesis?



https://static.wikia.nocookie.net/asterix/images/f/fe/Getafix_brewing.png/revision/latest?cb=20150710202131

FLRW background

$$\mathrm{d}\tau^2 = \mathrm{d}t^2 - a(t)^2 \left(\mathrm{d}x^2 + \mathrm{d}y^2 + \mathrm{d}z^2\right)$$

$$\frac{\dot{a}}{a} \equiv H = \sqrt{\frac{8\pi G}{3}\rho} \quad , \quad \dot{\rho} + 3H(\rho + p) = 0$$

Baryon asymmetry

$$n_\mathrm{b} = \eta n_\gamma \quad , \quad \eta \approx 6 \cdot 10^{-10}$$

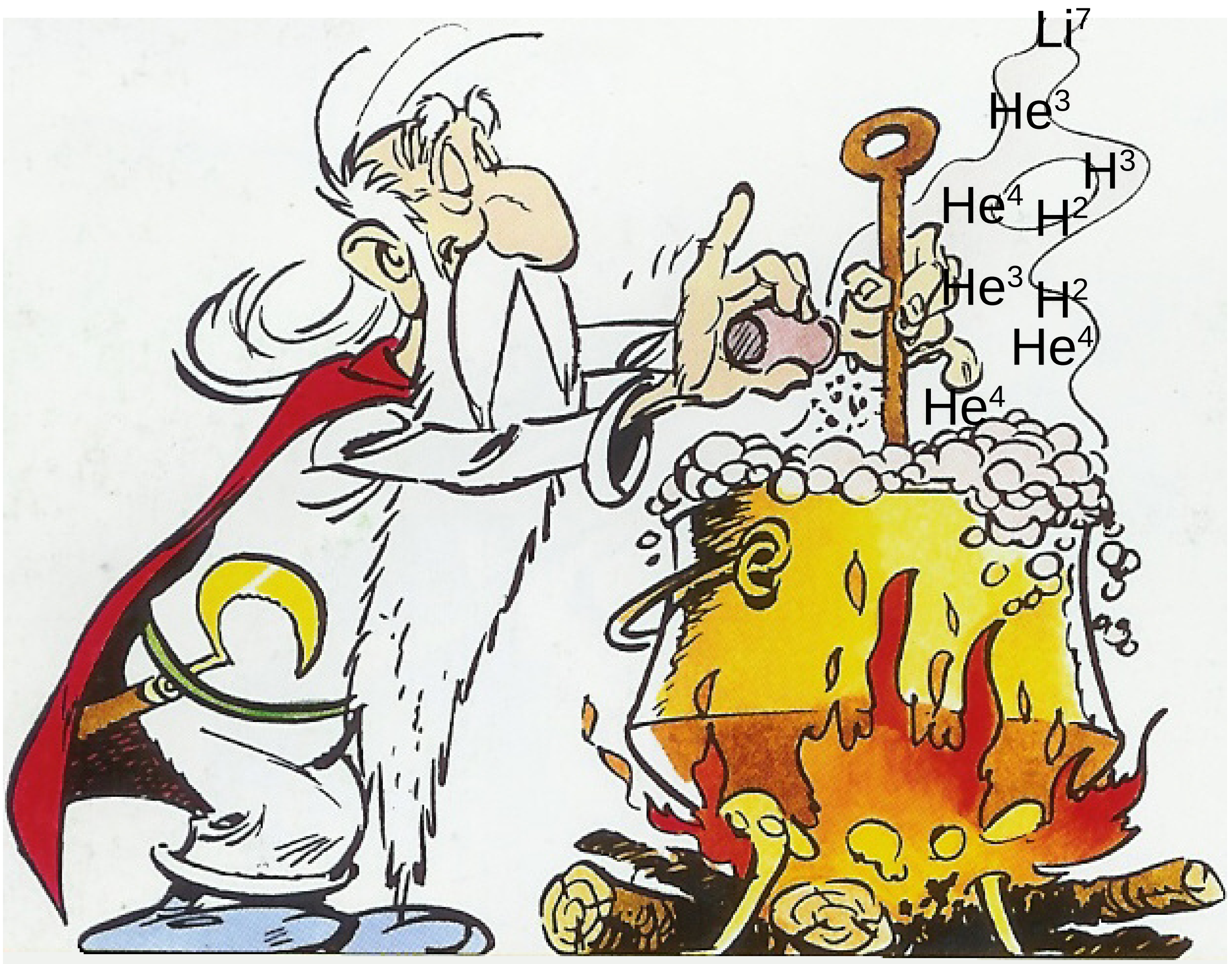
Equilibrium of the weak interactions

$$n \leftrightarrow p + e^- + \bar{\nu}_e \quad ne^+ \leftrightarrow p\bar{\nu}_e \quad n\nu_e \leftrightarrow pe^-$$

$$\frac{Y_n}{Y_p} \simeq \exp\left(-\frac{Q}{T}\right) \quad , \quad Y_N = \frac{n_N}{n_b}$$

Note: $\mathcal{Y}_p = 4Y_{^4He}$

Prelude to the Interlude: how to cook light elements



https://static.wikia.nocookie.net/asterix/images/f/fe/Getafix_brewing.png/revision/latest?cb=20150710202131

$T \sim 1\,\mathrm{MeV}$

Weak interactions drop out of equilibrium: neutron freeze-out

Now begins a race between the production of stable nuclei and the decay of neutrons!

$T \sim 0.1\,\mathrm{MeV}$

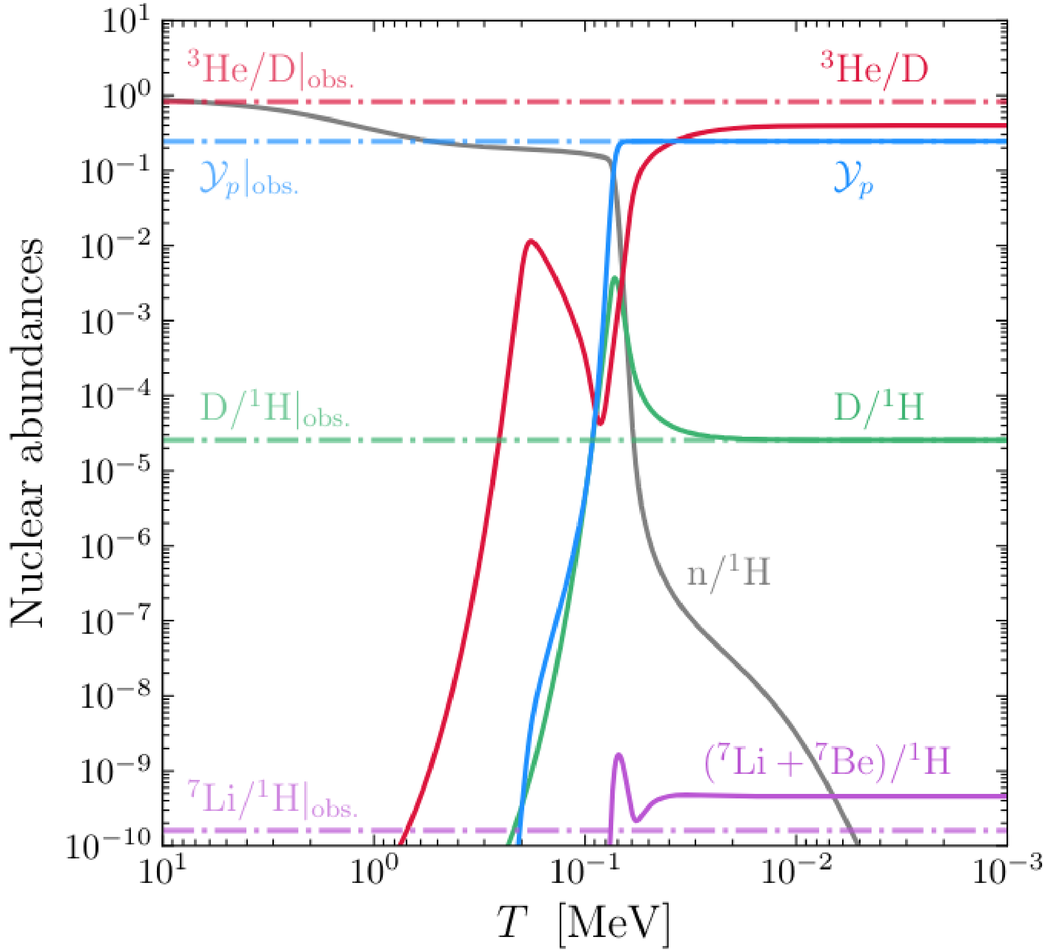
End of the deuterium bottleneck: Protons and neutrons can only produce deuterium initially: $n + p \to {}^2H + \gamma$

However, the tiny baryon-to-photon ratio means that the exponential high-energy tail of the photon distribution can still destroy deuterium!

$T \sim 10\,\mathrm{keV}$

End of fusion processes, final (SM) abundances are reached

Interlude: BBN data, photodisintegration & hadrodisintegration



Credits: F. Depta

Effects of changes in the background cosmology

- Modification of the **Hubble rate**

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

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

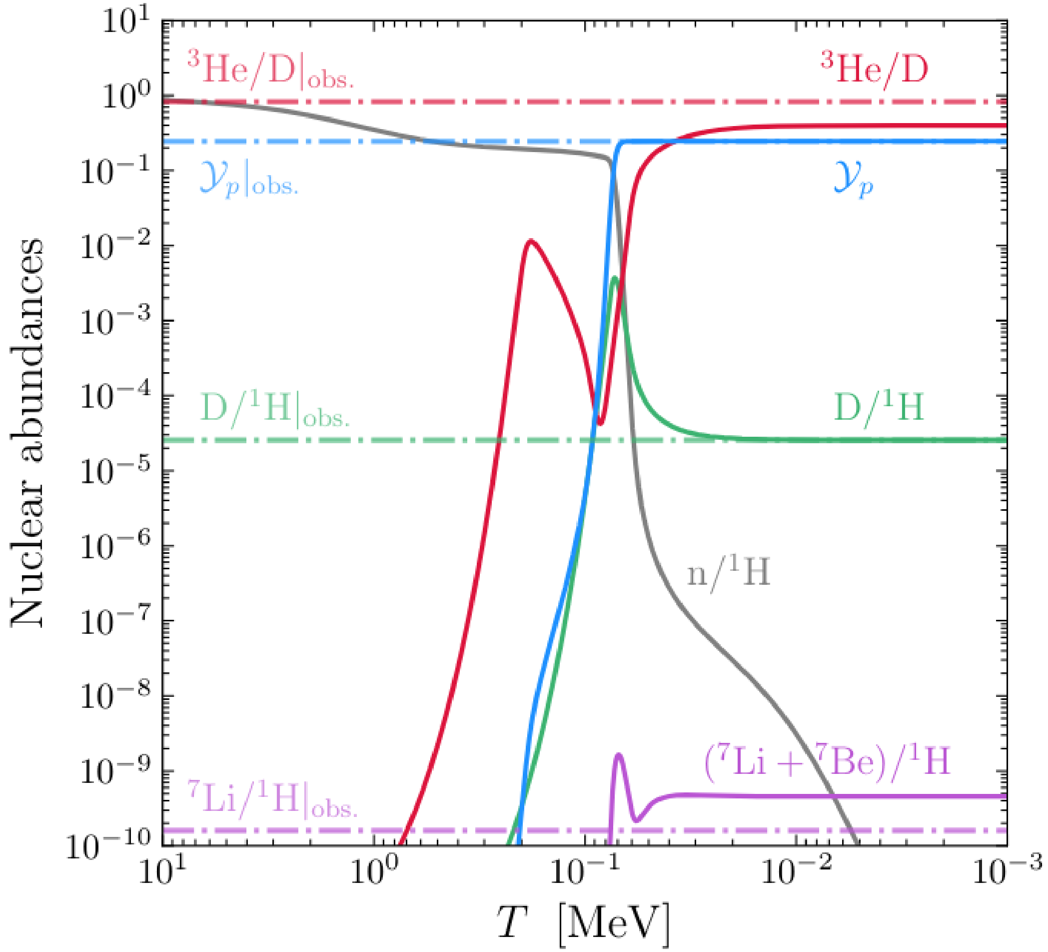
$$\dot{T} = \frac{\dot{q}_{SM} - 3H(\rho_{SM} + P_{SM})}{d\rho_{SM}/dt}$$

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

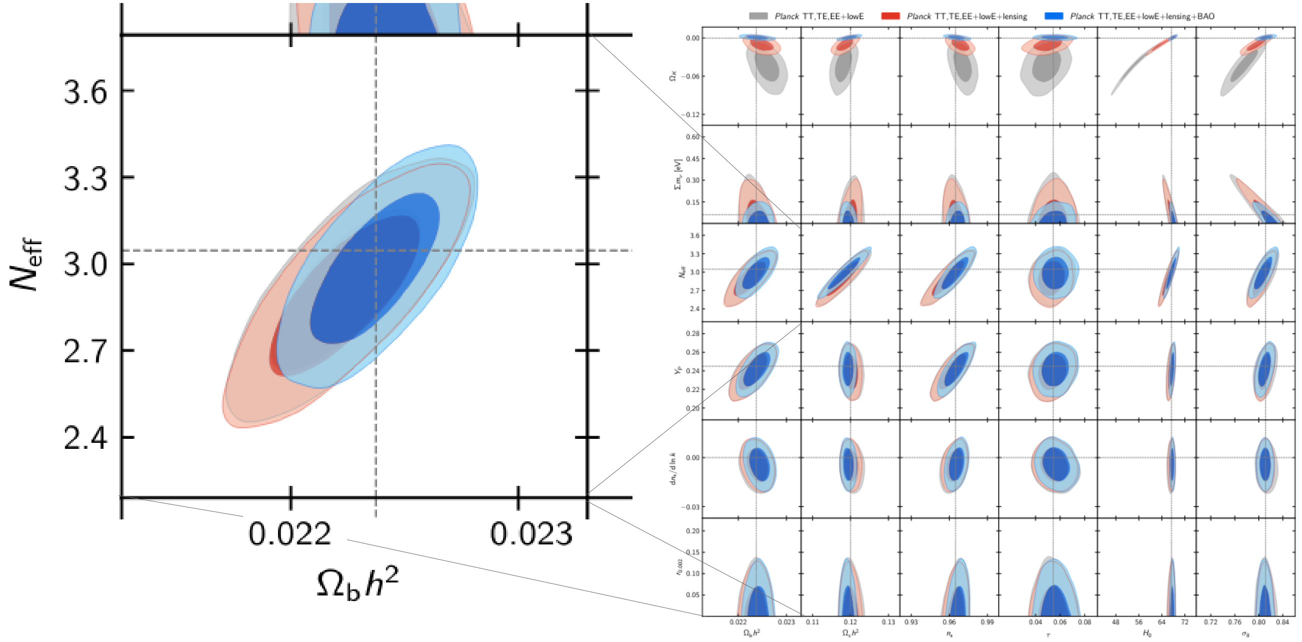
Interlude: BBN data, photodisintegration & hadrodisintegration

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

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



Credits: F. Depta

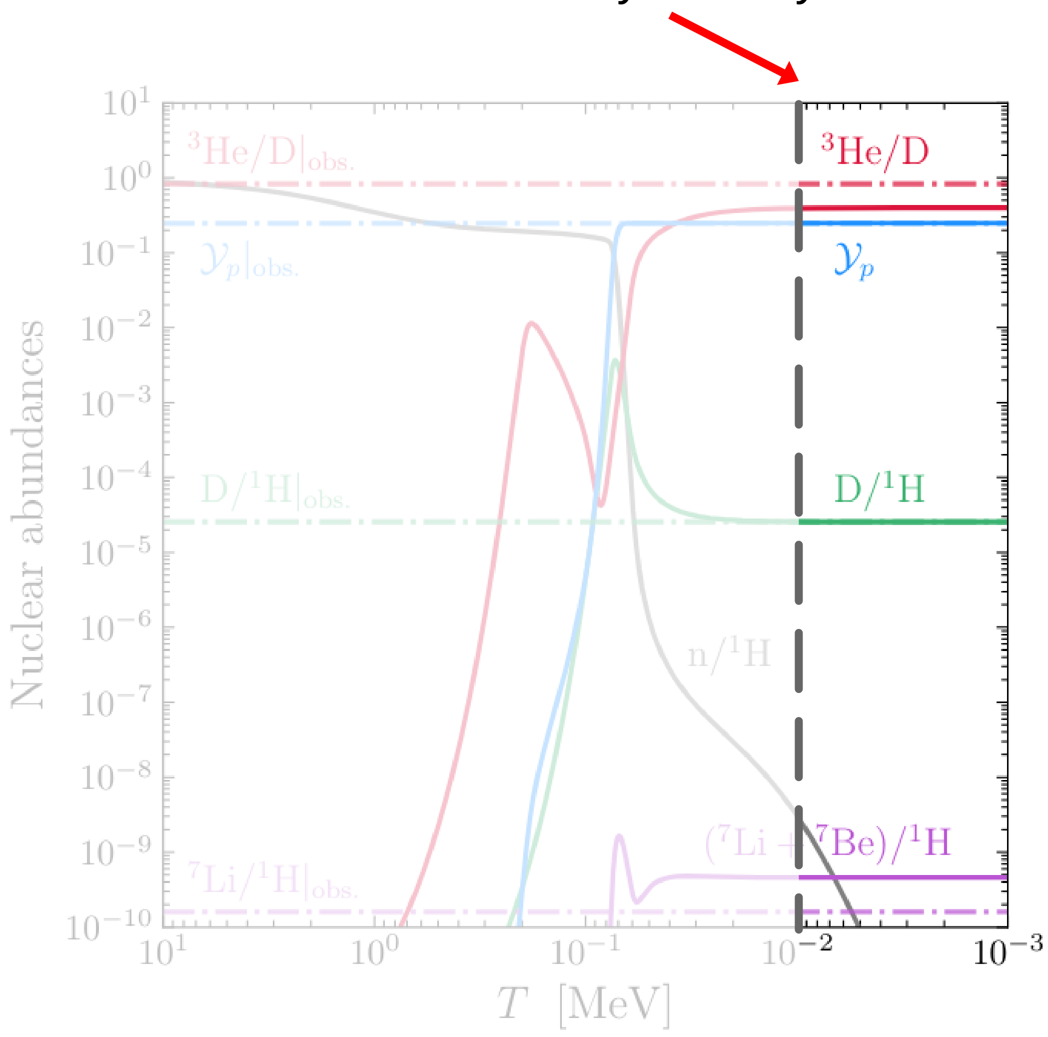


1807.06209

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

Interlude: BBN data, photodisintegration & hadrodisintegration

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



Credits: F. Depta

Photodisintegration

=

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

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

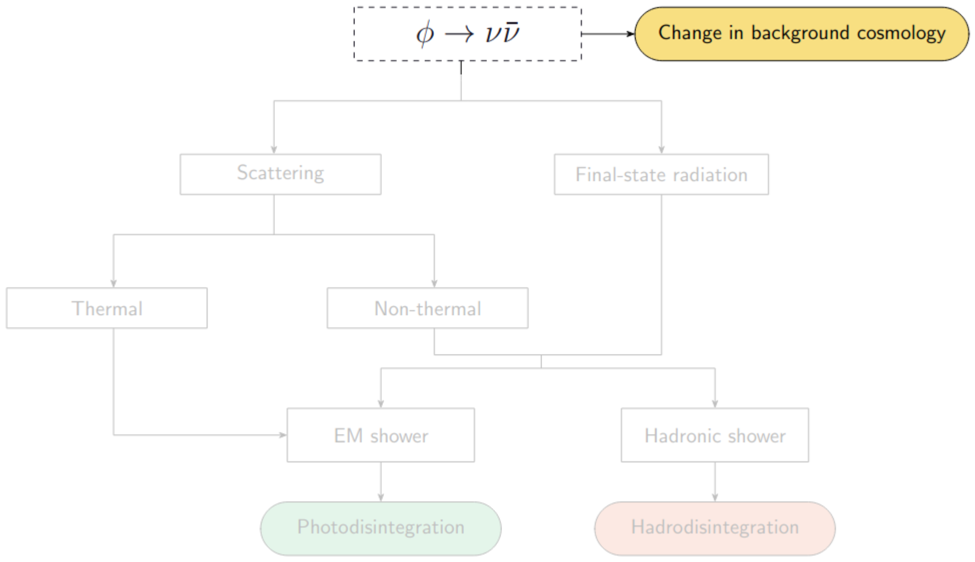
allows factorisation of the processes

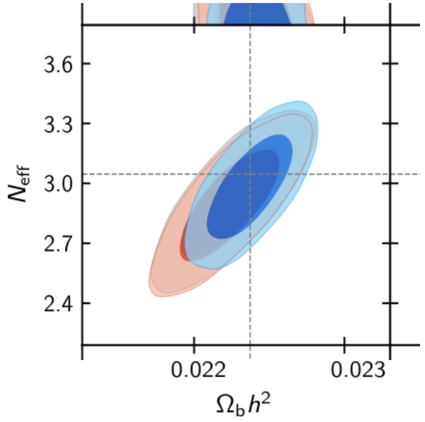
Rapid scattering on the CMB induces a **universal spectrum**

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

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

Handling the contributions step-by-step





The dominant effect:

Additional energy density increases $N_{\rm eff}$

↓

Change in η due to correlation with $N_{\rm eff}$

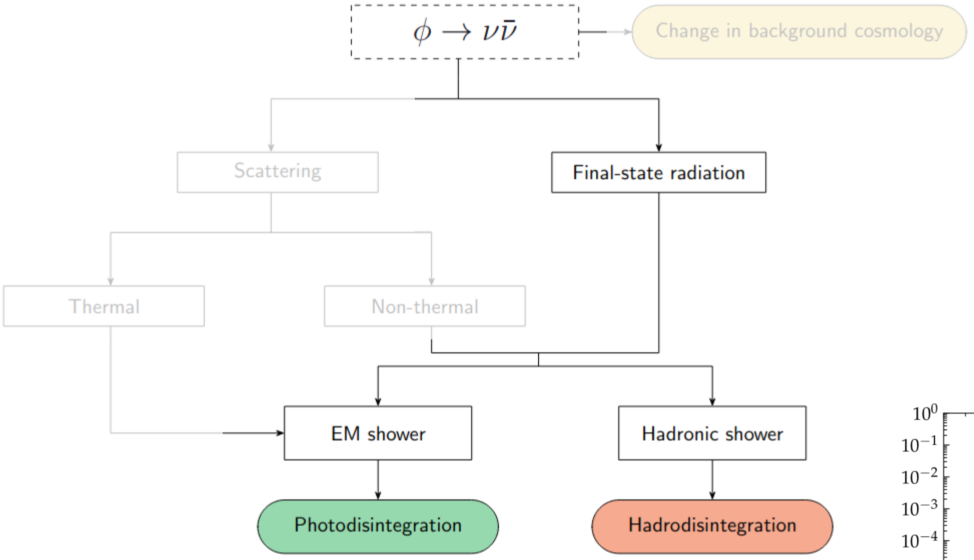
↓

Initial conditions of BBN are varied due to η

↓

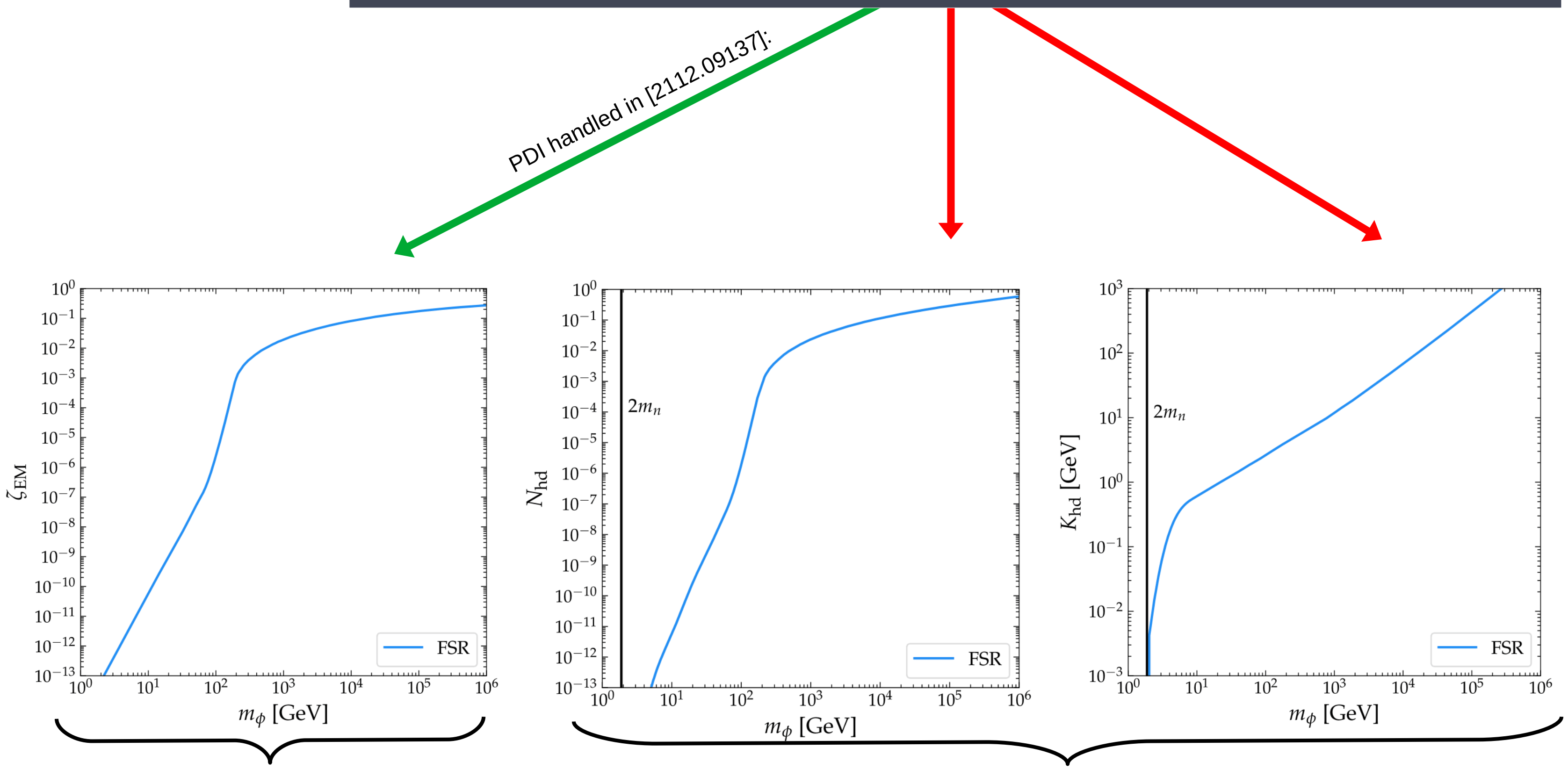
BBN is modified and we get different abundances

Handling the contributions step-by-step



Injection rate is determined by the decay rate

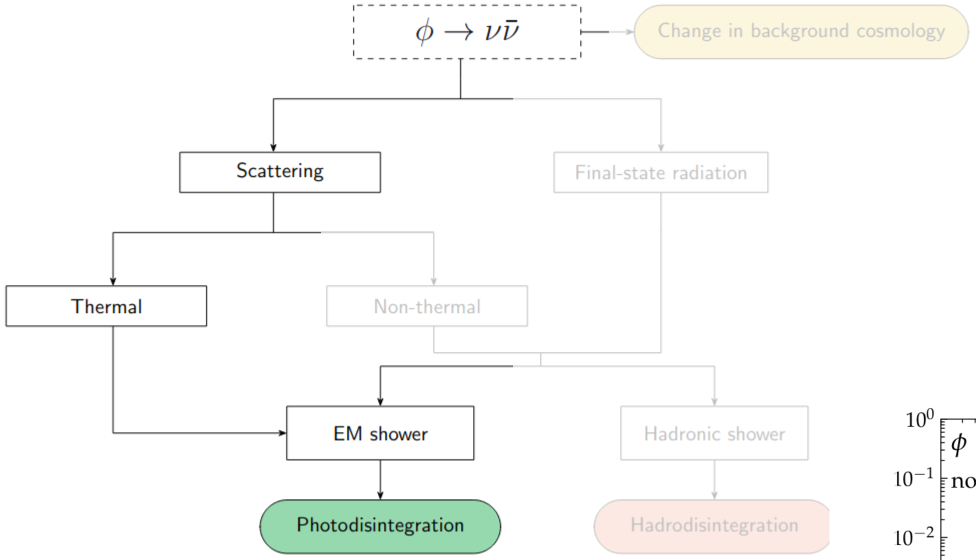
Effect of an individual injection determined by PYTHIA



PDI requires 1 parameter (universal spectrum)

HDI requires 2 parameters

Handling the contributions step-by-step



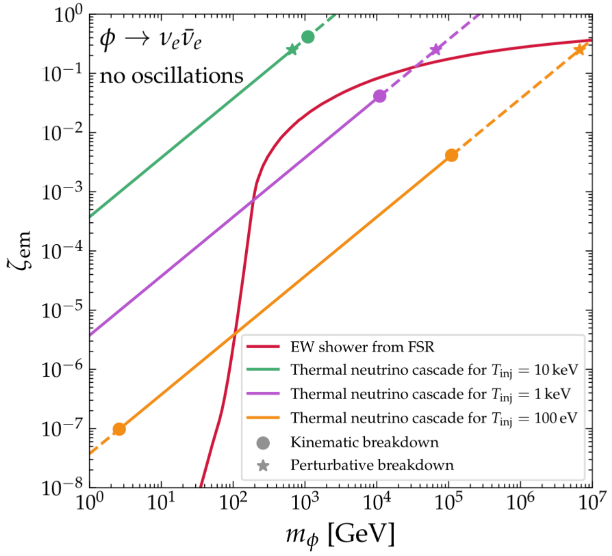
Injection rate given by thermal scattering rate

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

Effect of an individual injection determined analytically

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

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



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

Handling the contributions step-by-step

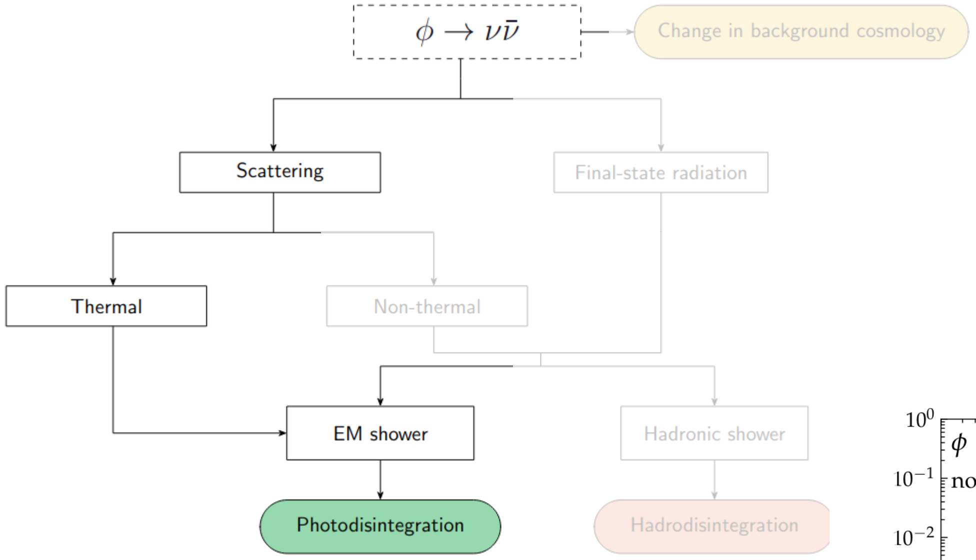
Injection rate given by thermal scattering rate

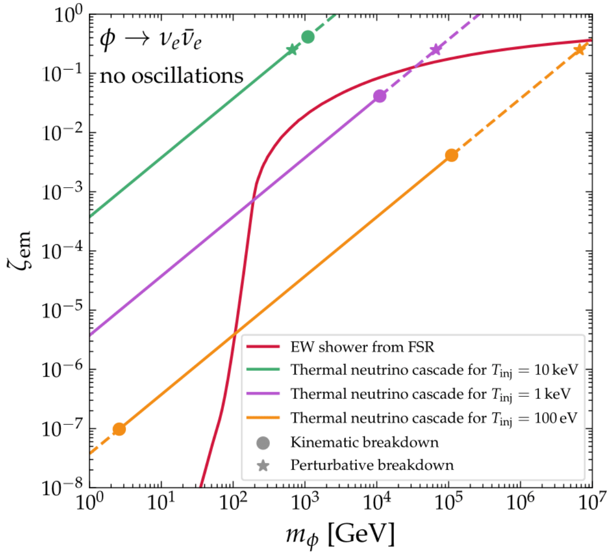
$$\Gamma_{ee}(T,E) \sim G_F^2 E T_\nu^4$$

Effect of an individual injection determined analytically

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

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





"Elastic" scattering:

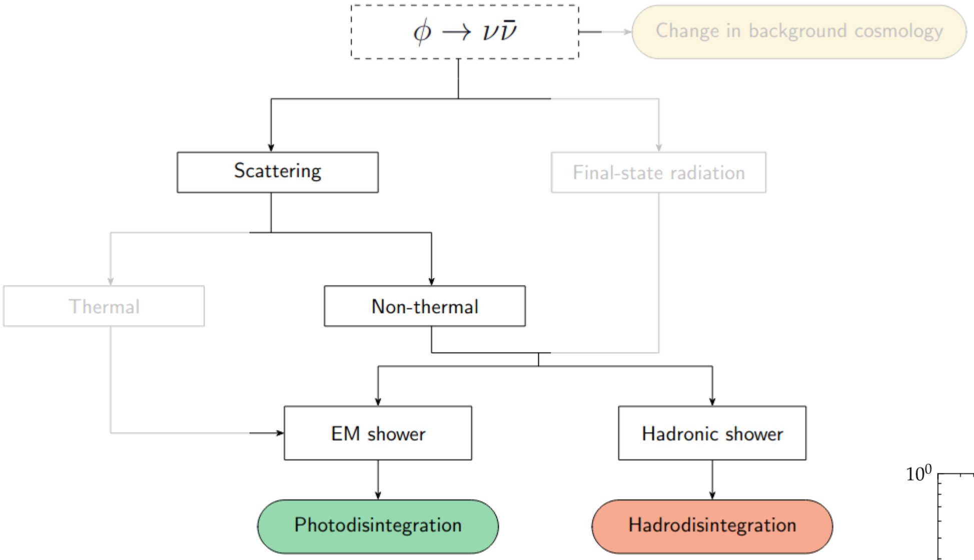
$$\Gamma_{ee}(T,E_1) + \Gamma_{ee}(T,E_2)$$

$$= \text{const.} \times G_F^2 T_\nu^4 \left(E_1 + E_2\right)$$

$$= \Gamma_{ee}(T, E_1 + E_2)$$

Redistribution of energy is irrelevant!

Handling the contributions step-by-step

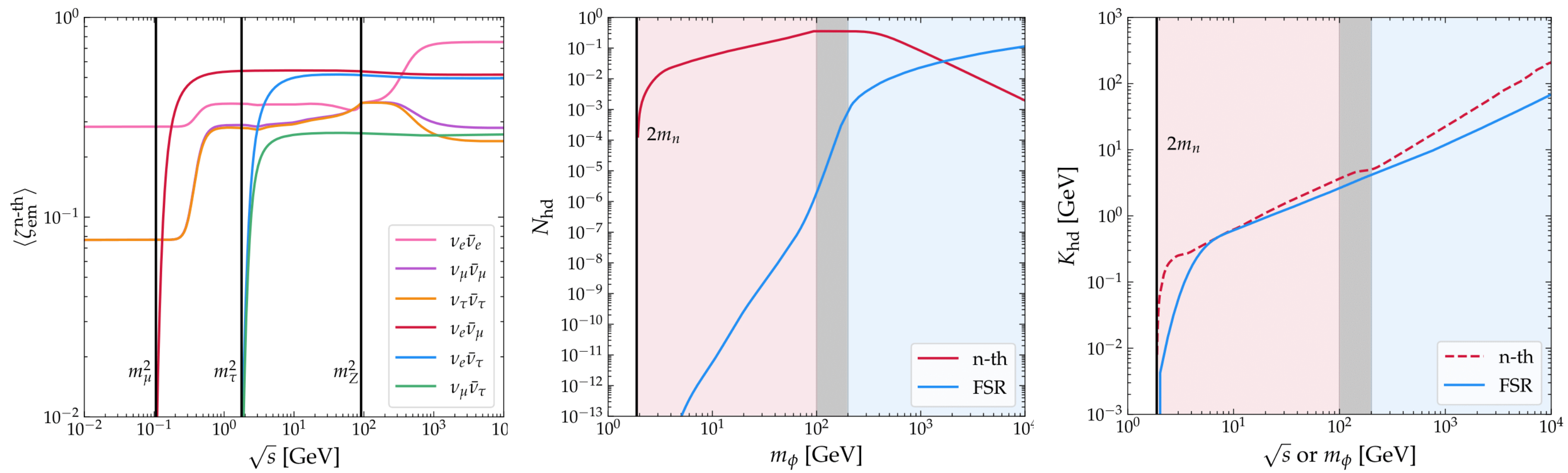


Injection rate given in general by

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

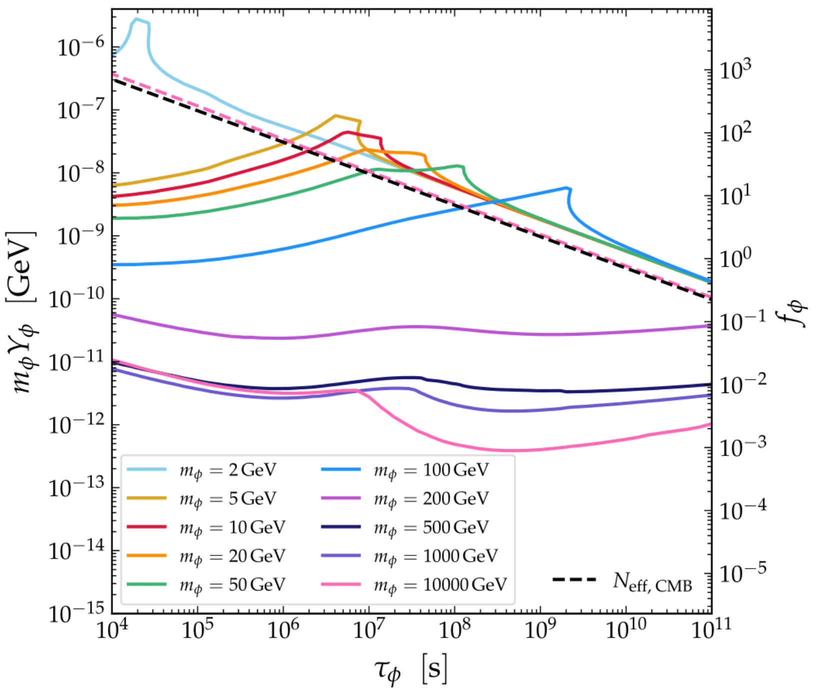
Requires knowledge of non-thermal spectrum!!! ☠️
See following slides for exact methodology

Effects of individual event determined by PYTHIA

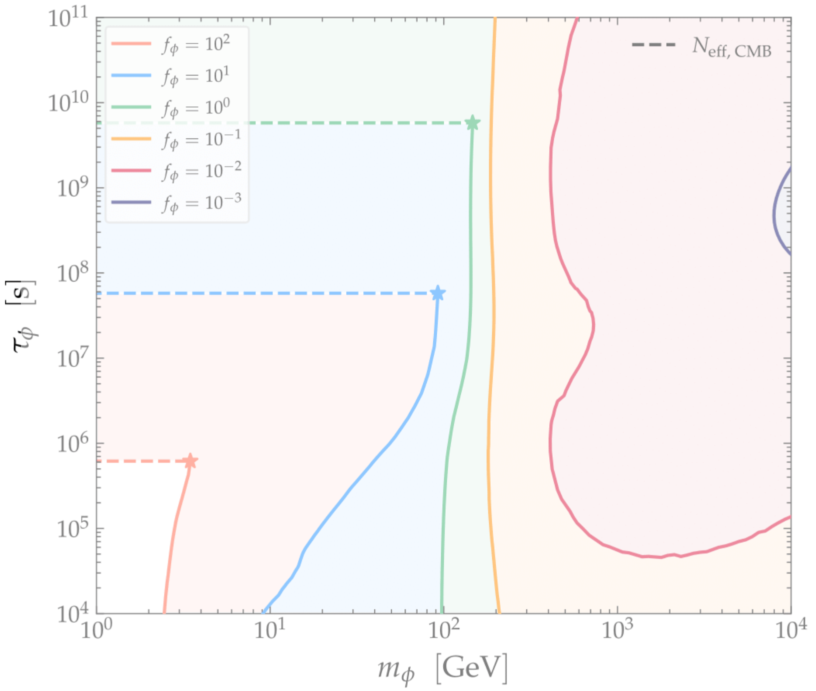


All three parameter planes

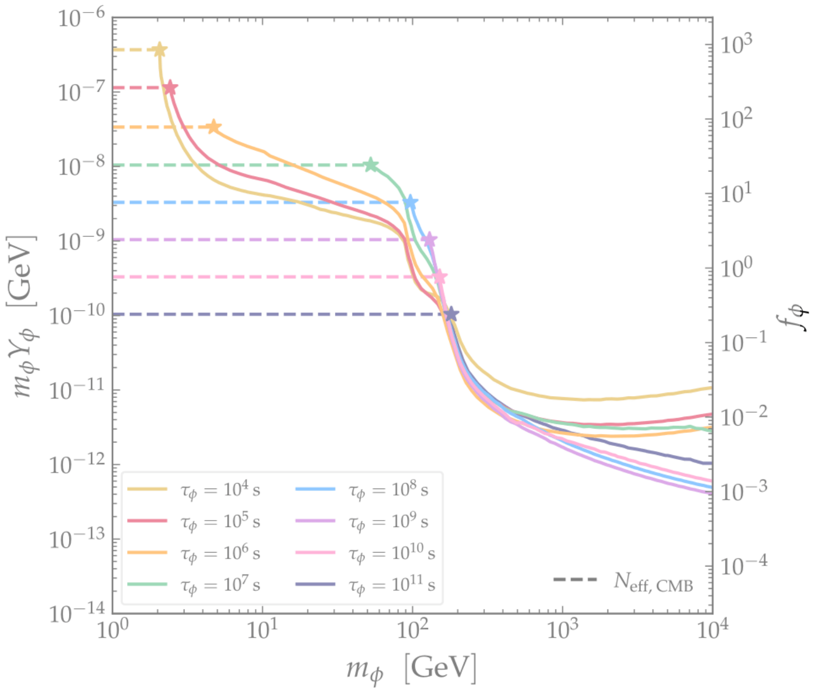
m_ϕ



f_ϕ

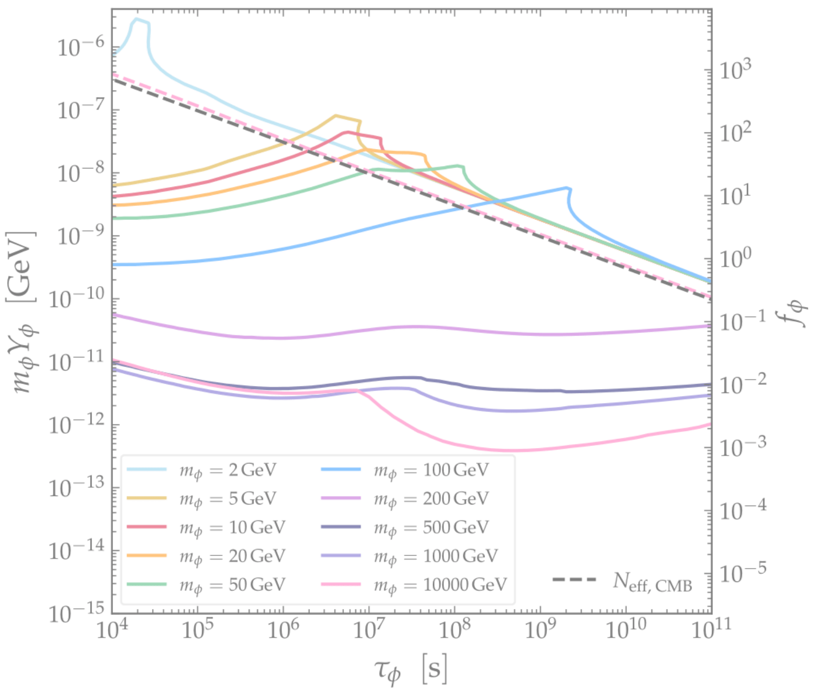


τ_ϕ

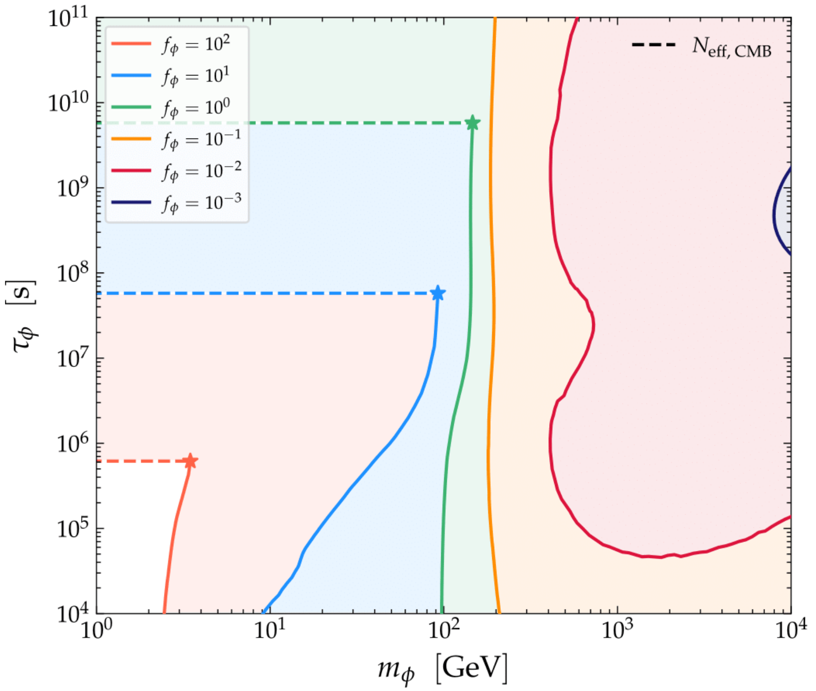


All three parameter planes

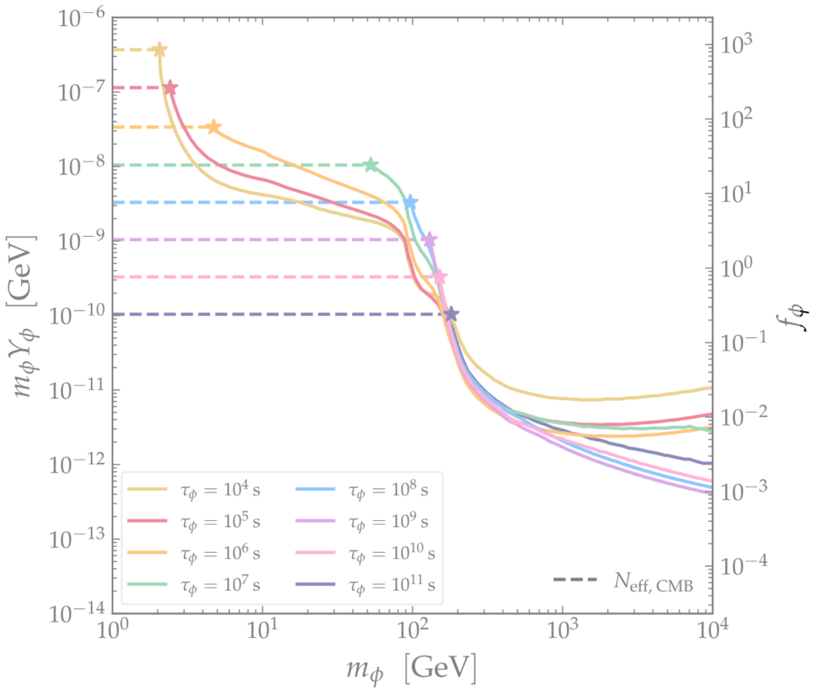
m_ϕ



f_ϕ

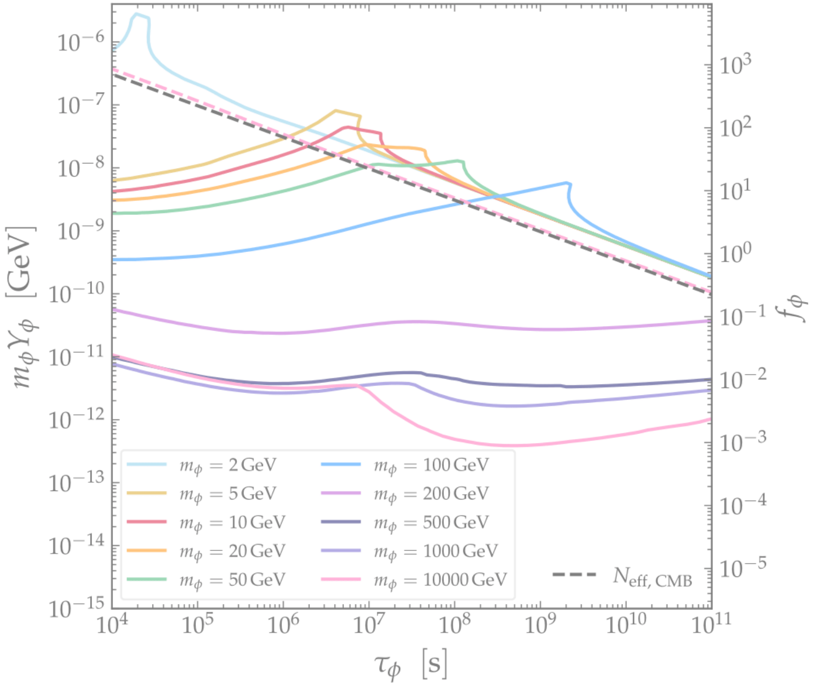


τ_ϕ

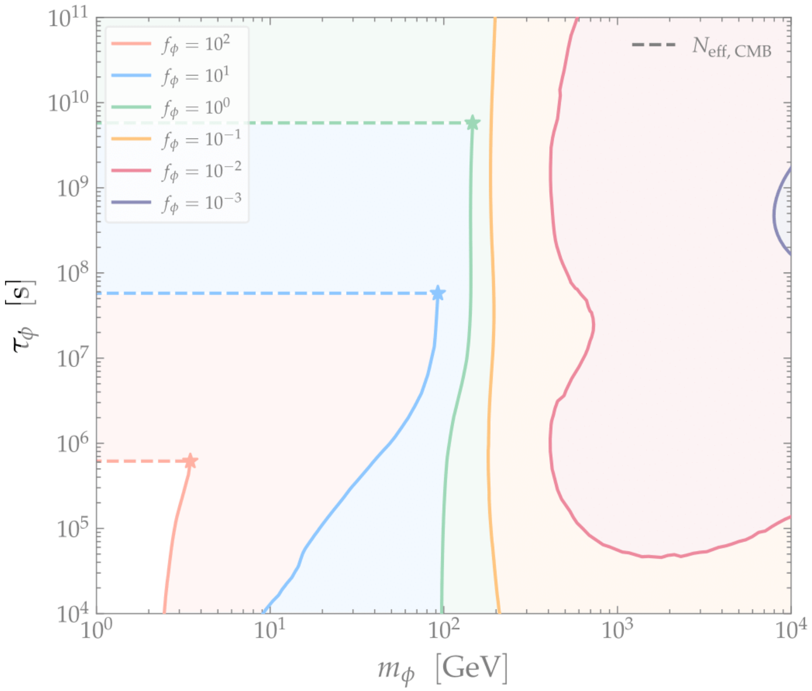


All three parameter planes

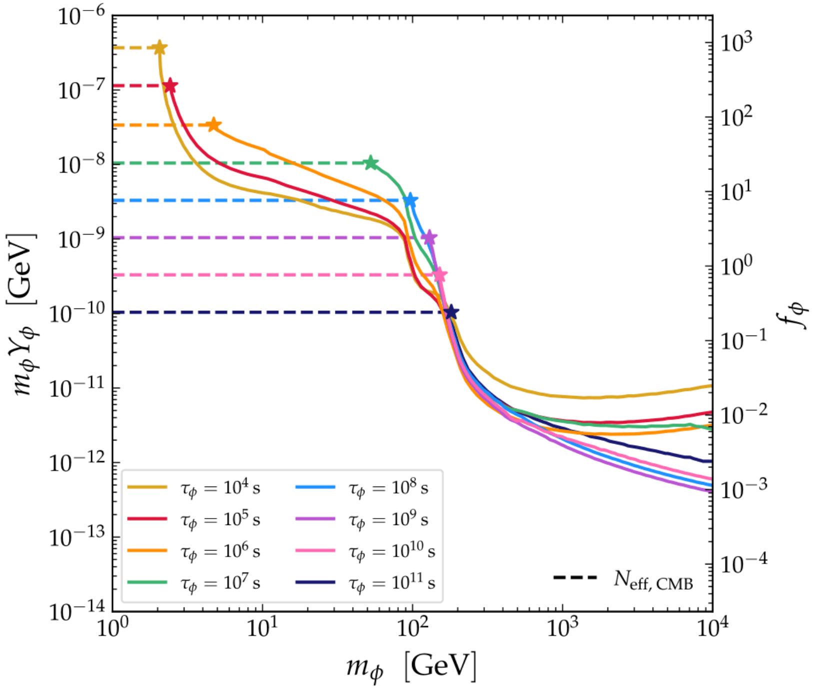
m_ϕ



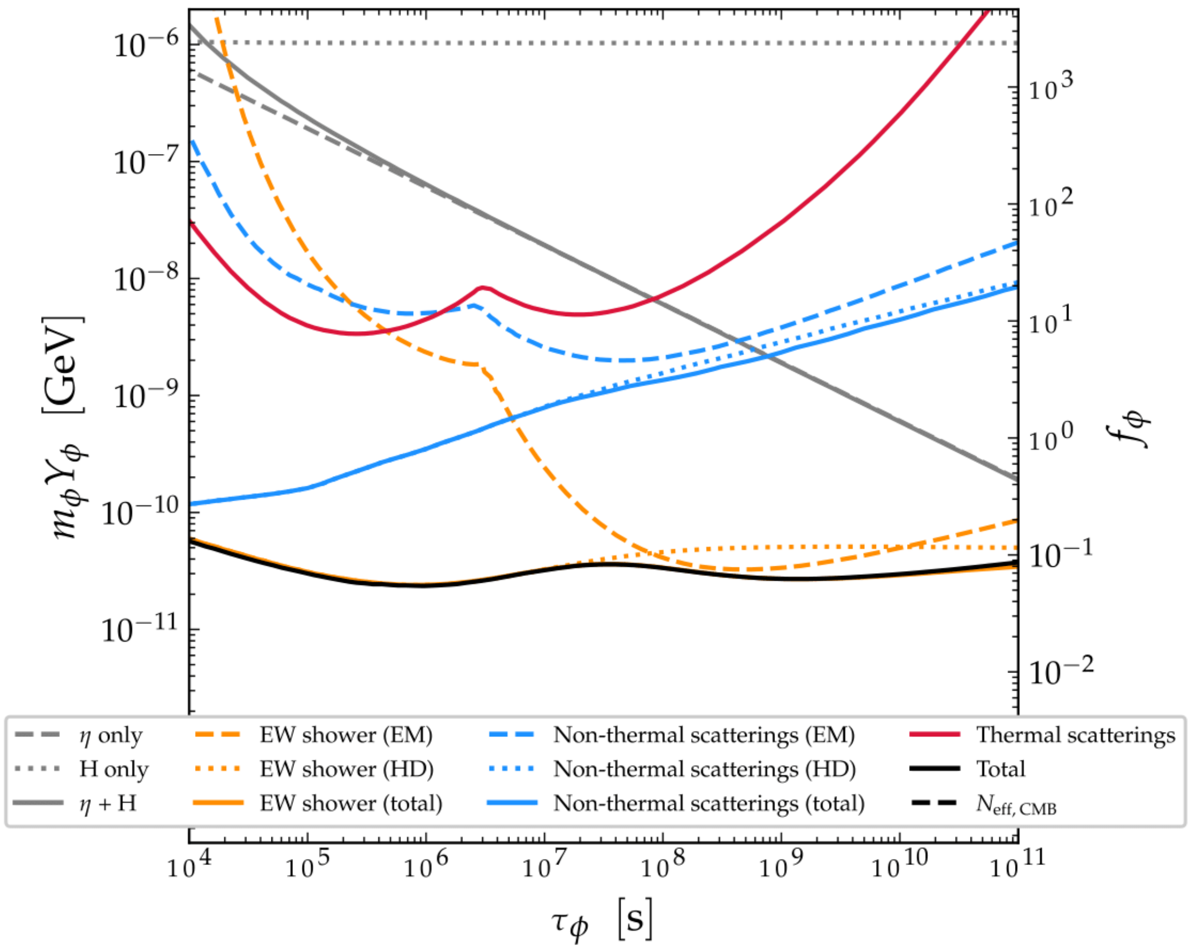
f_ϕ



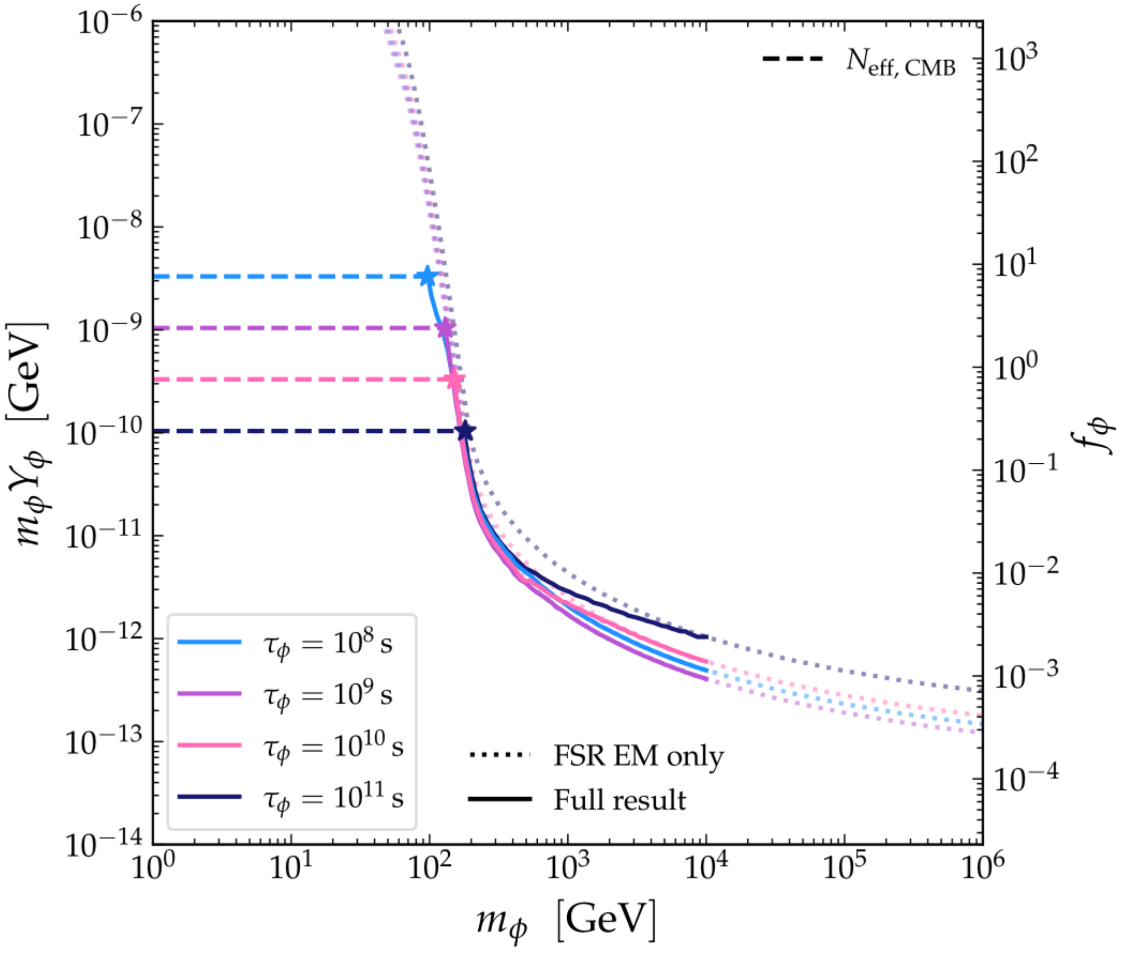
τ_ϕ



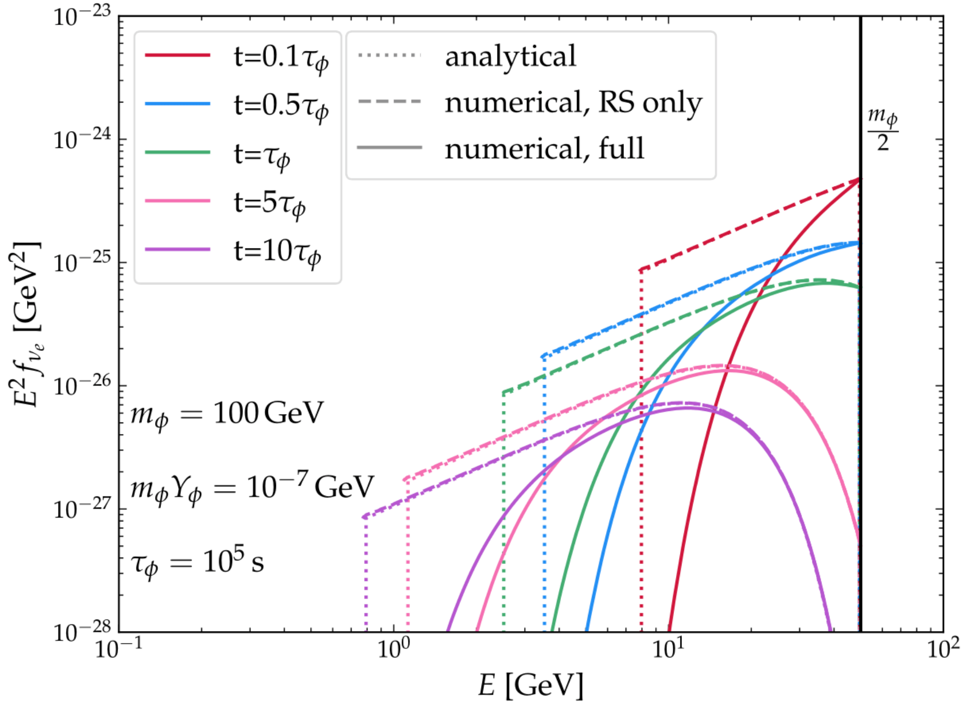
“Intermediate” mass result: 200GeV



Asymptotic behaviour



How to track the neutrino cascade



Is the Hubble rate dominant

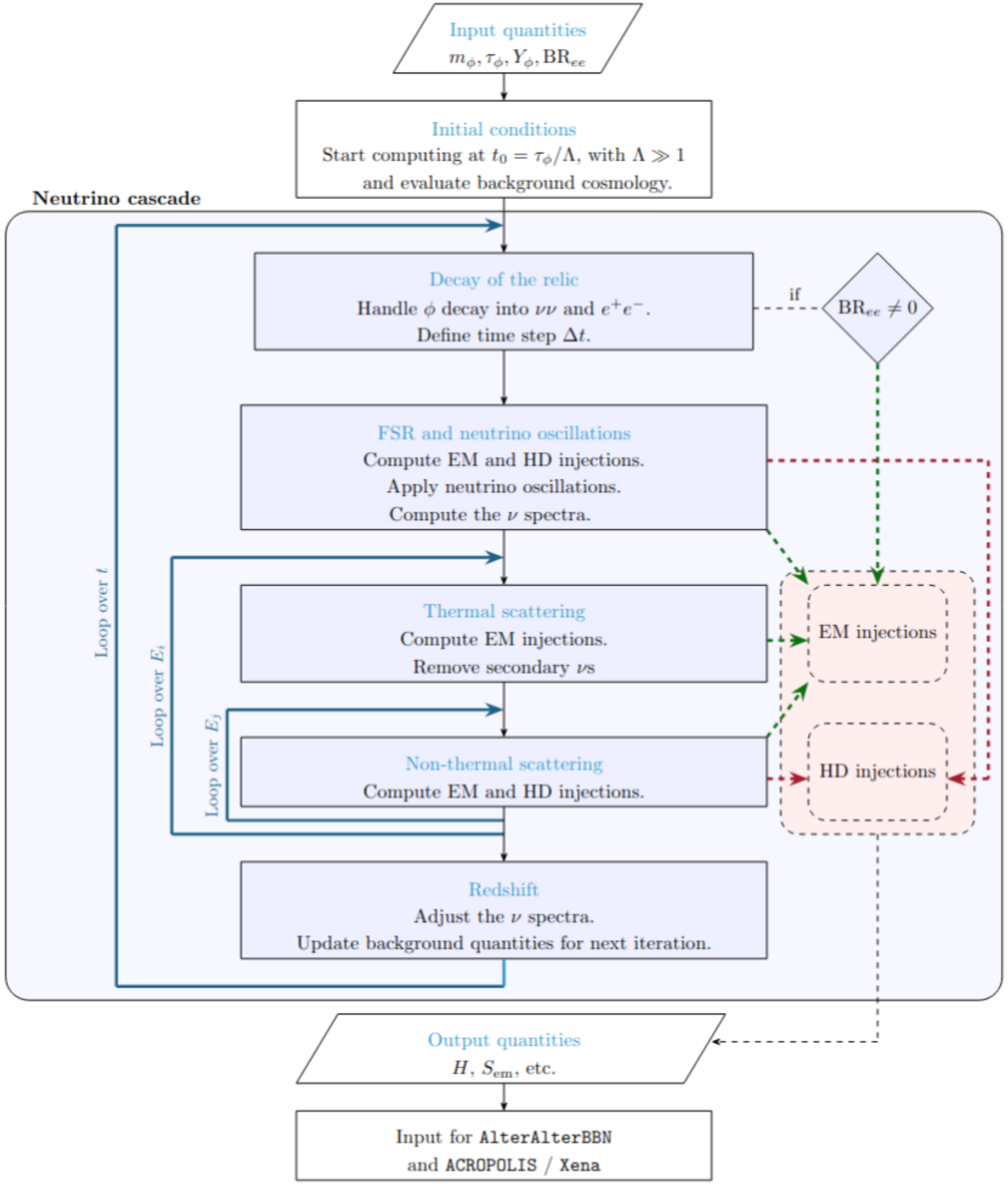
Yes

Spectrum mainly redshifts

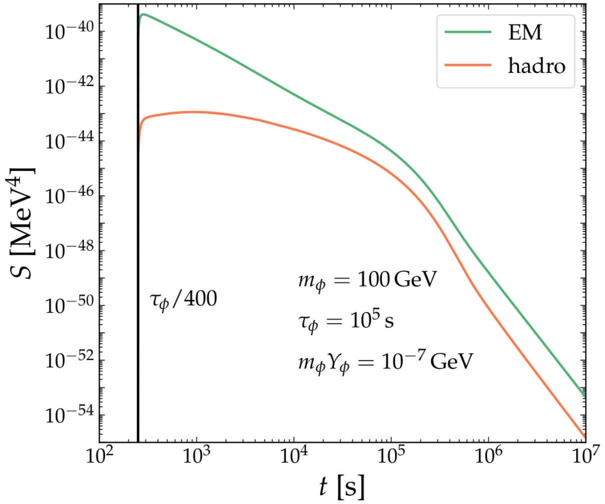
No

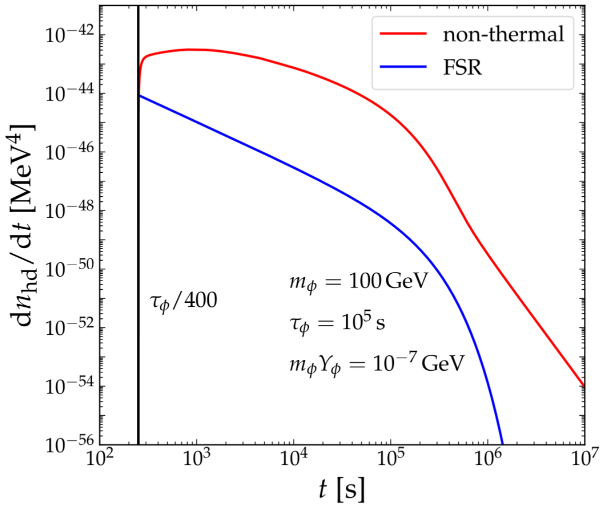
Elastic scattering depletes the spectrum

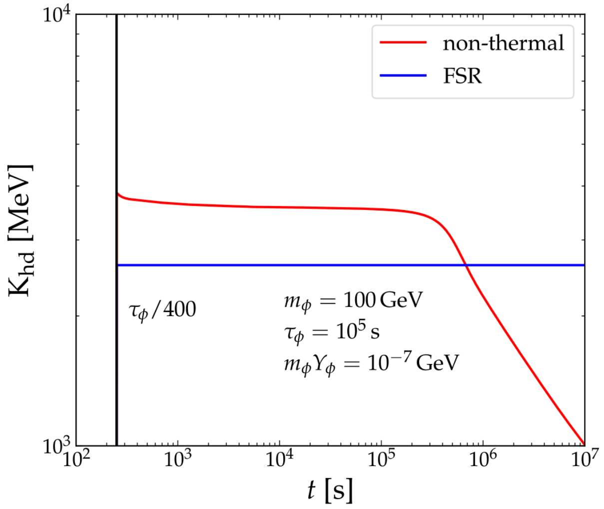
Approximation: No redistribution of energy

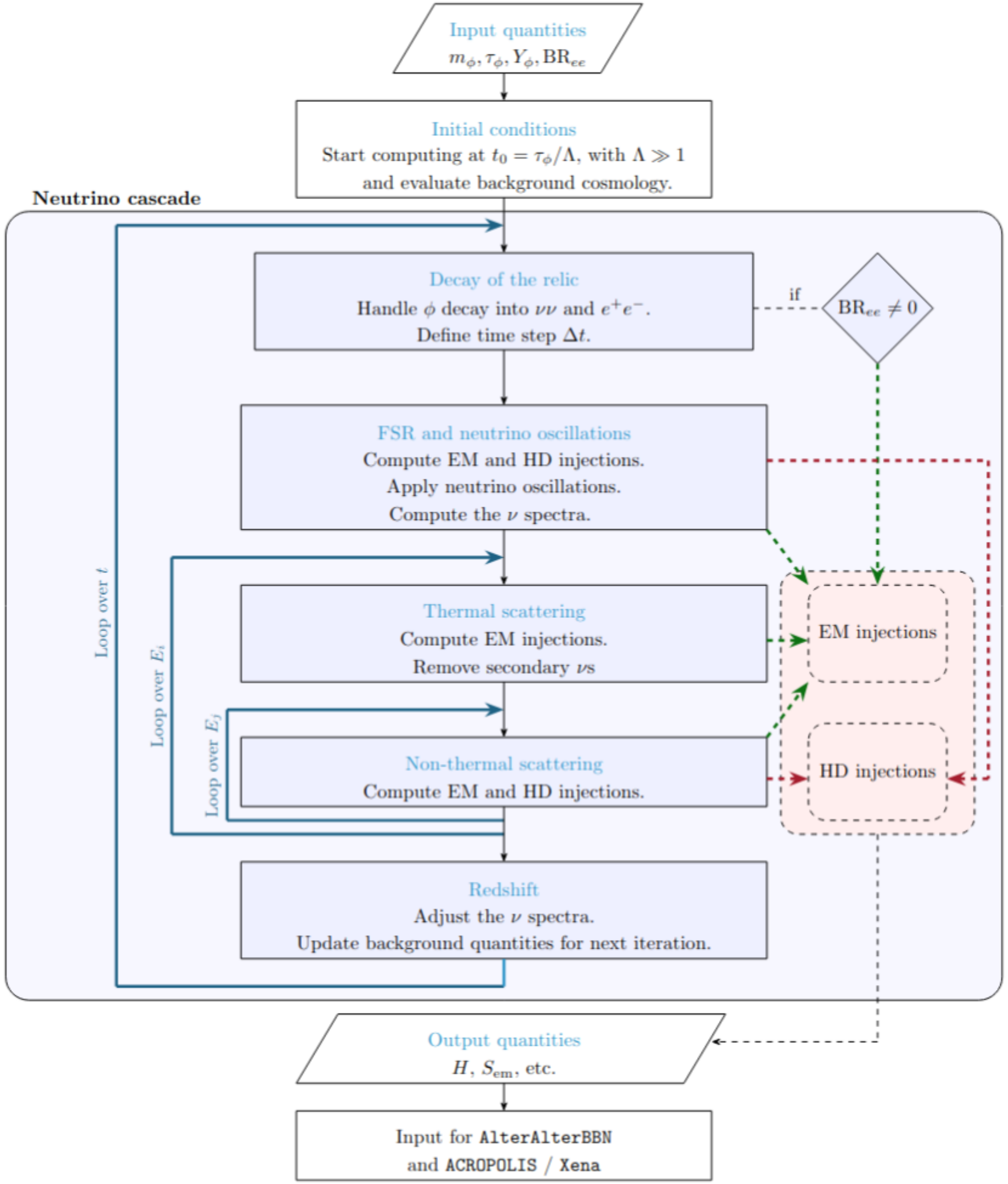


How to track the neutrino cascade

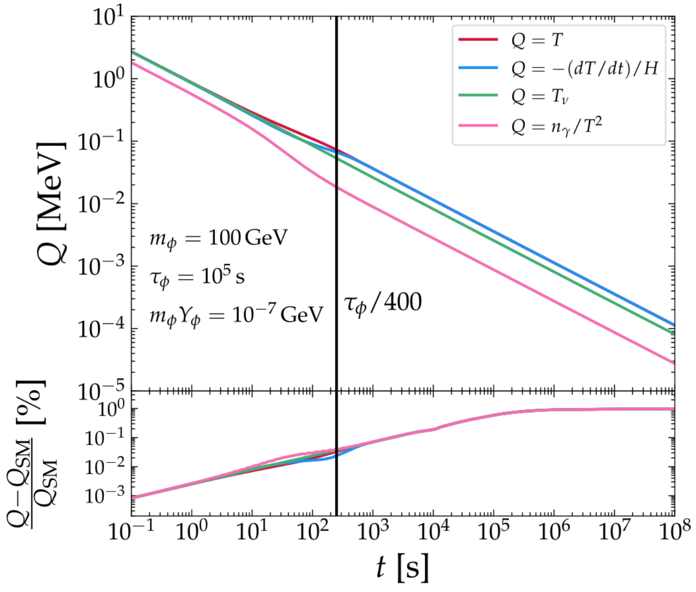


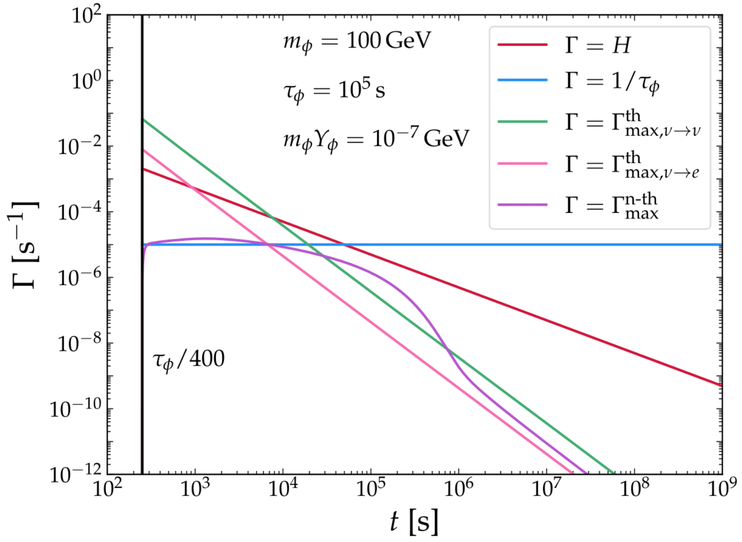


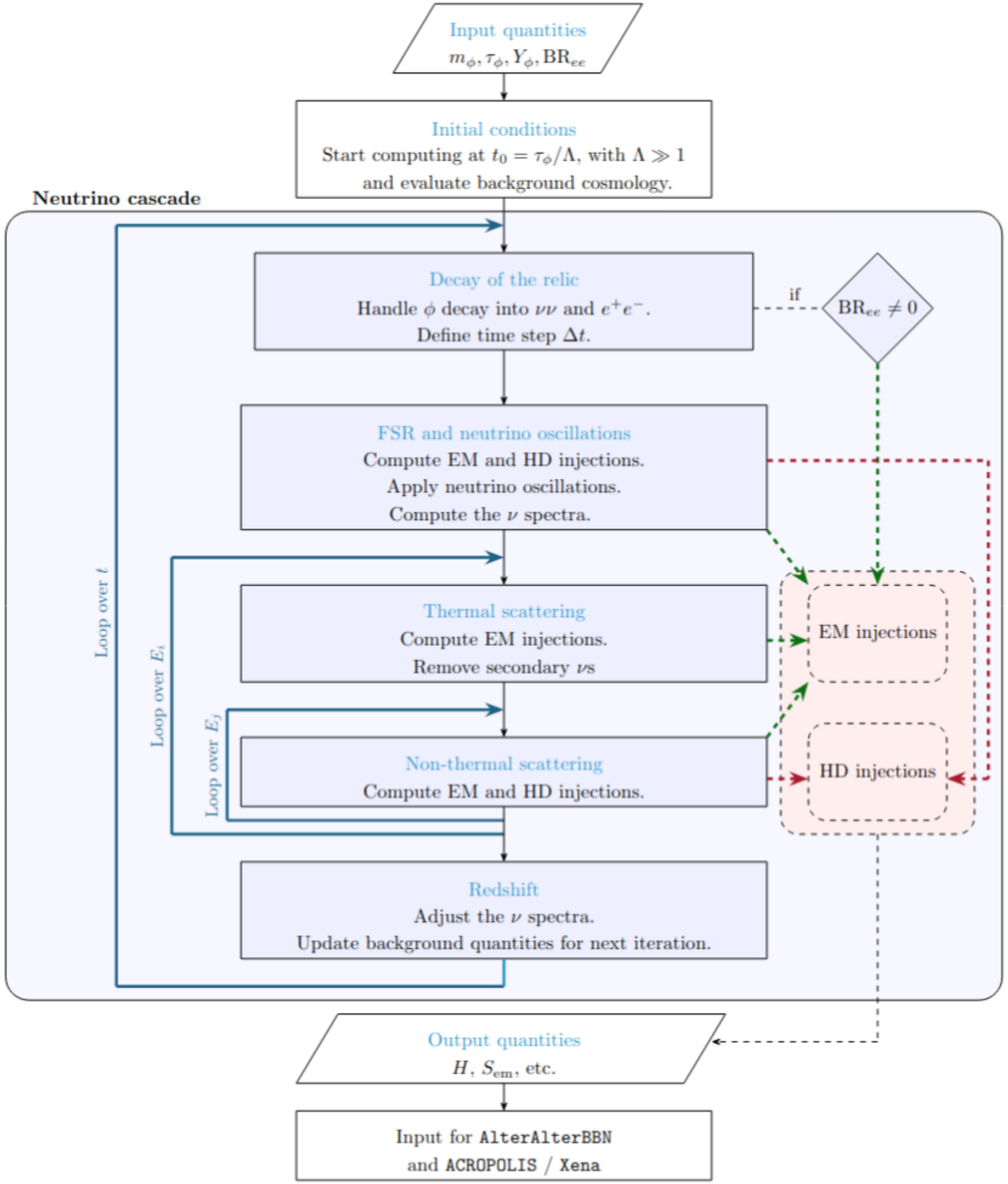




How to track the neutrino cascade

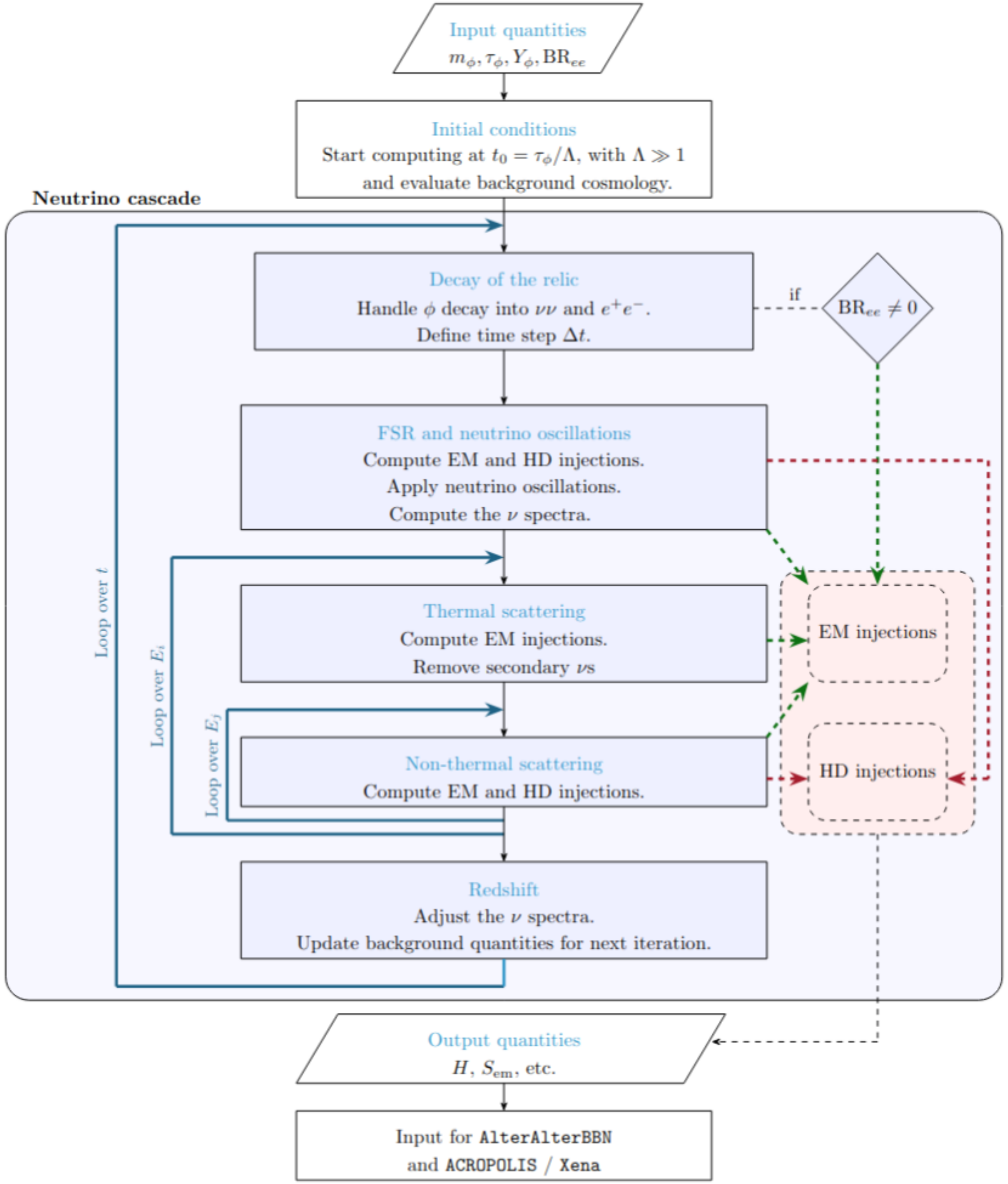




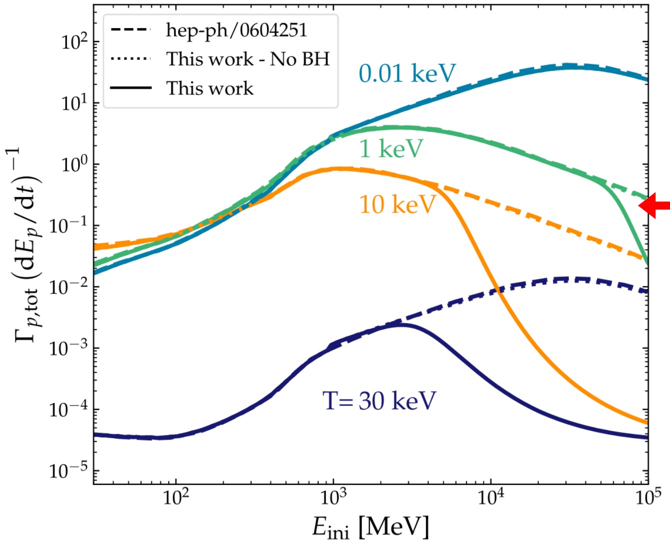


How to track the neutrino cascade

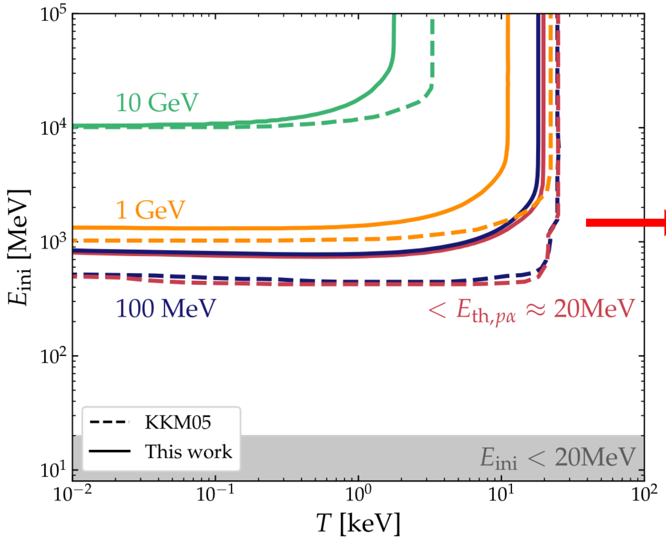
Variable	Description	Unit
Input parameters		
Y_ϕ	Abundance of ϕ	-
m_ϕ	Mass of ϕ	MeV
τ_ϕ	Lifetime of ϕ	s
BR_{ee}	Branching ratio into e^+e^-	-
One-dimensional output parameters		
f_ϕ	Fractional abundance of ϕ, $\frac{\Omega_\phi}{\Omega_{\mathrm{DM}}}$	-
N_{eff}	Effective number of neutrinos	-
η	Baryon-to-photon ratio	-
Two-dimensional output parameters		
t	Time	s
T	Temperature	MeV
$\frac{\mathrm{d}T}{\mathrm{d}t}$	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
$\frac{\mathrm{d}n_{\mathrm{hd}}^{\mathrm{n\text{-}th}}}{\mathrm{d}t}$	Injected hadrons per time from non-th. scattering, eq. (4.14)	MeV^4
$K_{\mathrm{hd}}^{\mathrm{n\text{-}th}}$	Avg. kinetic energy of hadrons from non-th. scattering, eq. (4.14)	MeV
$\frac{\mathrm{d}n_{\mathrm{hd}}^{\mathrm{fsr}}}{\mathrm{d}t}$	Injected hadrons per time interval from FSR, eq. (4.14)	MeV^4
$K_{\mathrm{hd}}^{\mathrm{fsr}}$	Avg. kinetic energy of hadrons from FSR, eq. (4.14)	MeV



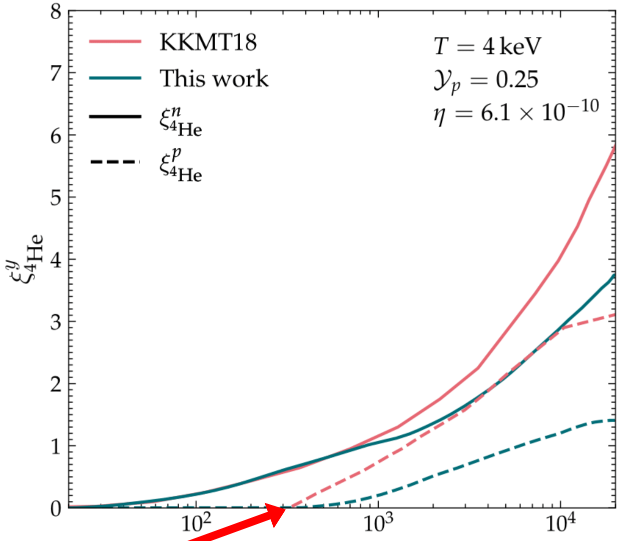
Details on hadrodisintegration & discrepancy with the literature

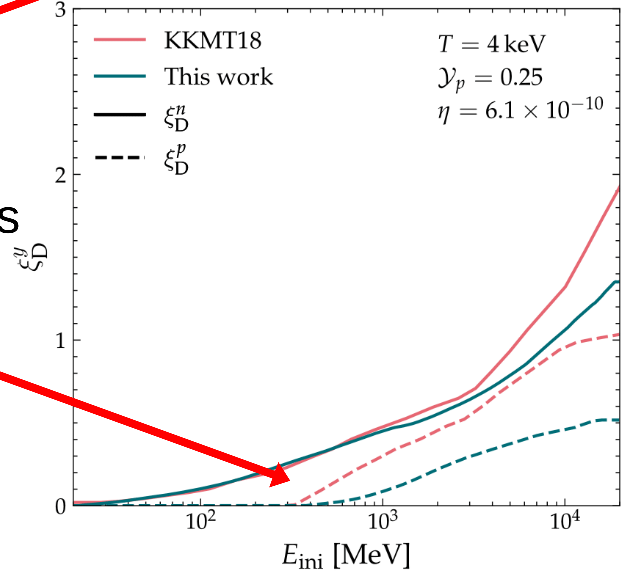


Cross check with the literature



Related to difference in stopping power of protons





Note: Discrepancy in neutrons due to interconversions

Model building

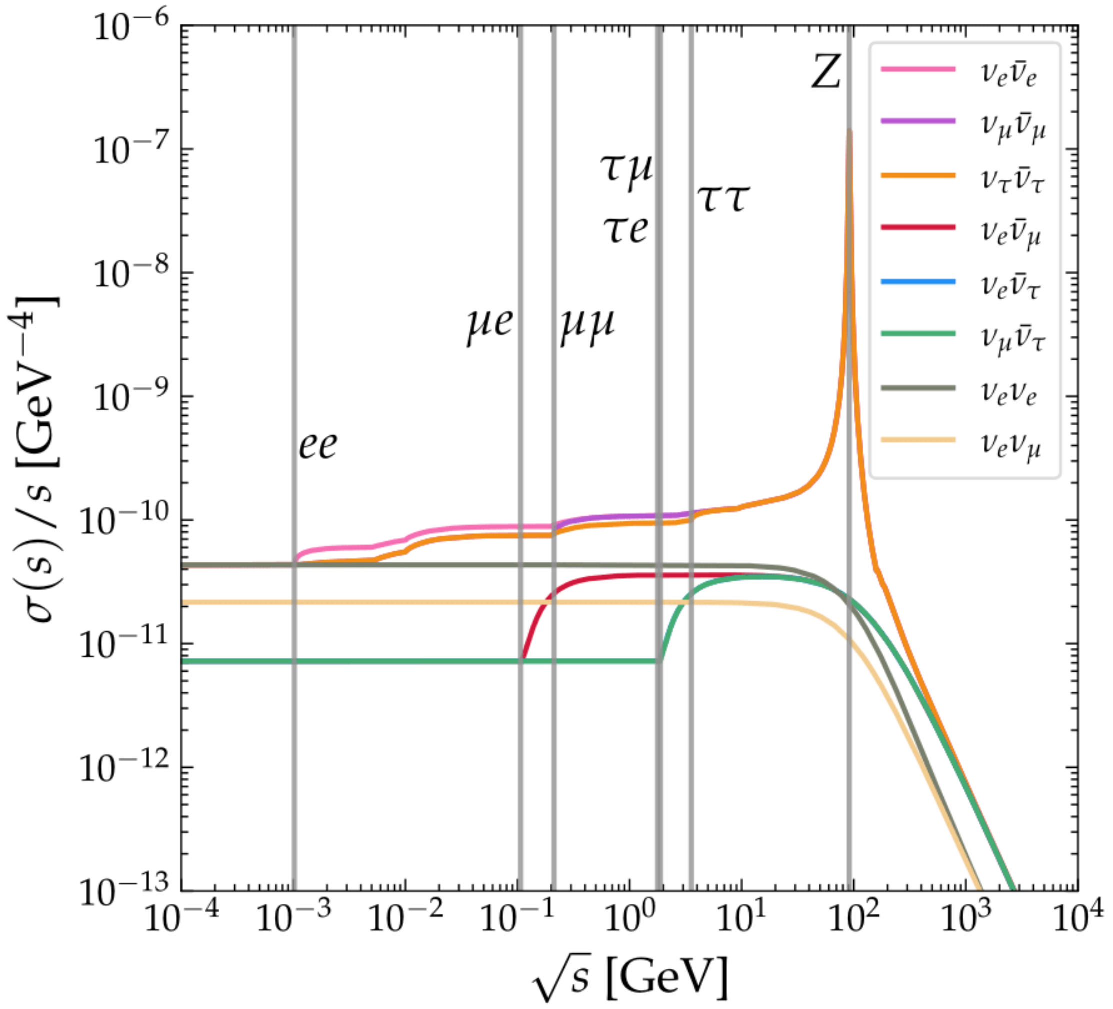
$$y_N \phi \overline{N^c} N$$

- 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

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

$$\Delta L L$$

The full EW cross sections



Details on photodisintegration processes

Important energy loss/redistribution processes

- Inverse Compton scattering $$e^{\pm}\gamma_{\mathrm{th}} \rightarrow e^{\pm}\gamma$$
- Double-photon pair creation $$\gamma\gamma_{\mathrm{th}} \rightarrow e^{+}e^{-}$$
- Photon-photon scattering $$\gamma\gamma_{\mathrm{th}} \rightarrow \gamma\gamma$$
- Bethe-Heitler pair creation $$\gamma N \rightarrow N e^{+}e^{-}$$
- Compton scattering $$\gamma e^{\pm}_{\mathrm{th}} \rightarrow \gamma e^{\pm}$$

Disintegration processes

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

Details on photodisintegration processes

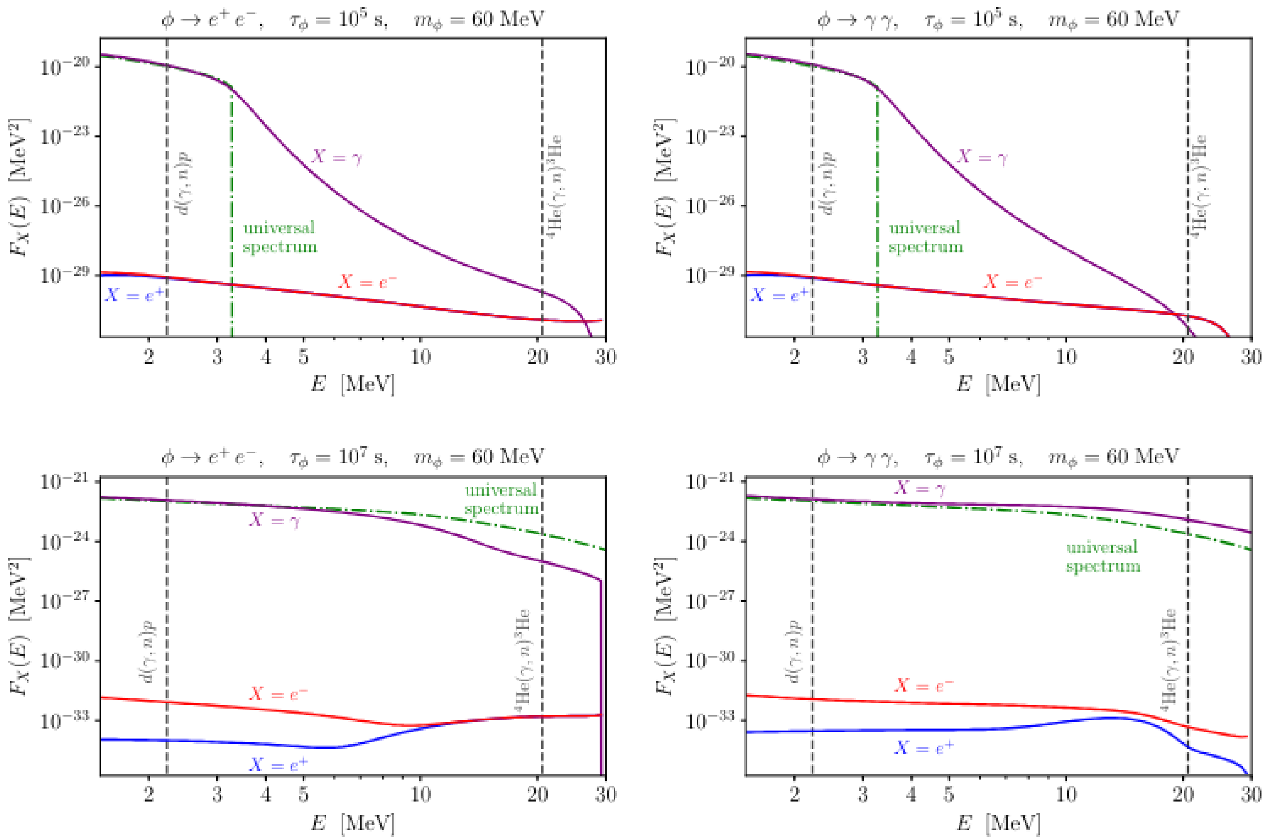


Figure 1. Comparison of the differential spectra for $\phi \to e^+e^-$ (left) and $\phi \to \gamma\gamma$ (right) for two different lifetimes, $\tau_\phi = 10^5$s (top) and $\tau_\phi = 10^7$s (bottom) with $m_\phi = 60\,\mathrm{MeV}$ and $n_\phi/n_\gamma|_{T=T^{\mathrm{cd}}=10\,\mathrm{GeV}} = 10^{-5}$, evaluated at a temperature T corresponding to $t \simeq \tau_\phi$. For reference also the universal spectrum as well as the photodisintegration thresholds of deuterium and ^{4}He are shown.

1808.09324

Neutrino oscillations

$$\mathrm{t}_{\mathrm{osc}} \sim \frac{T}{\Delta m^2} \sim 10^{-5}\,\mathrm{s}\left(\frac{T}{\mathrm{MeV}}\right)$$

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

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