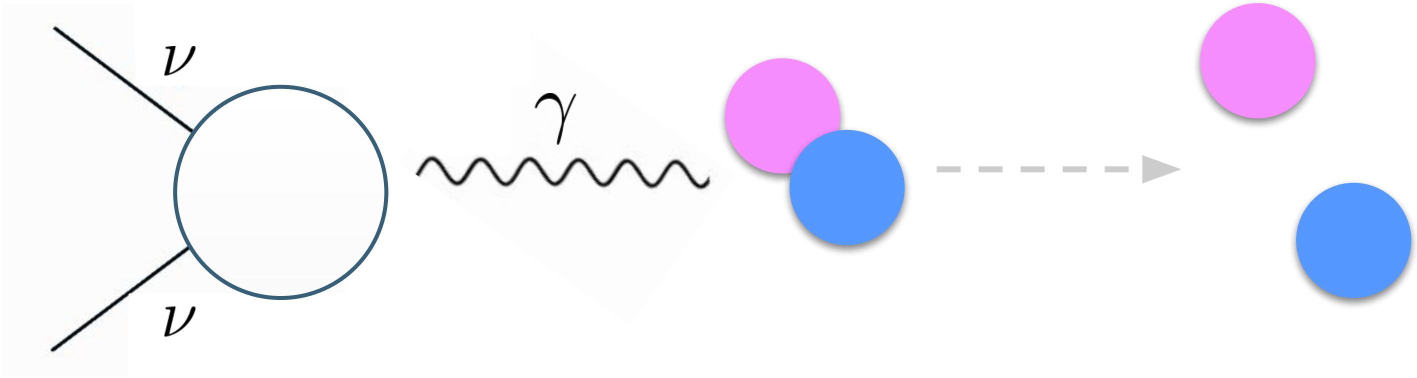
BBN photodisintegration limits from neutrino injections

Based on 2406/07.xxxxx

Sara Bianco
SUSY 2024, Madrid - 14th June 2024

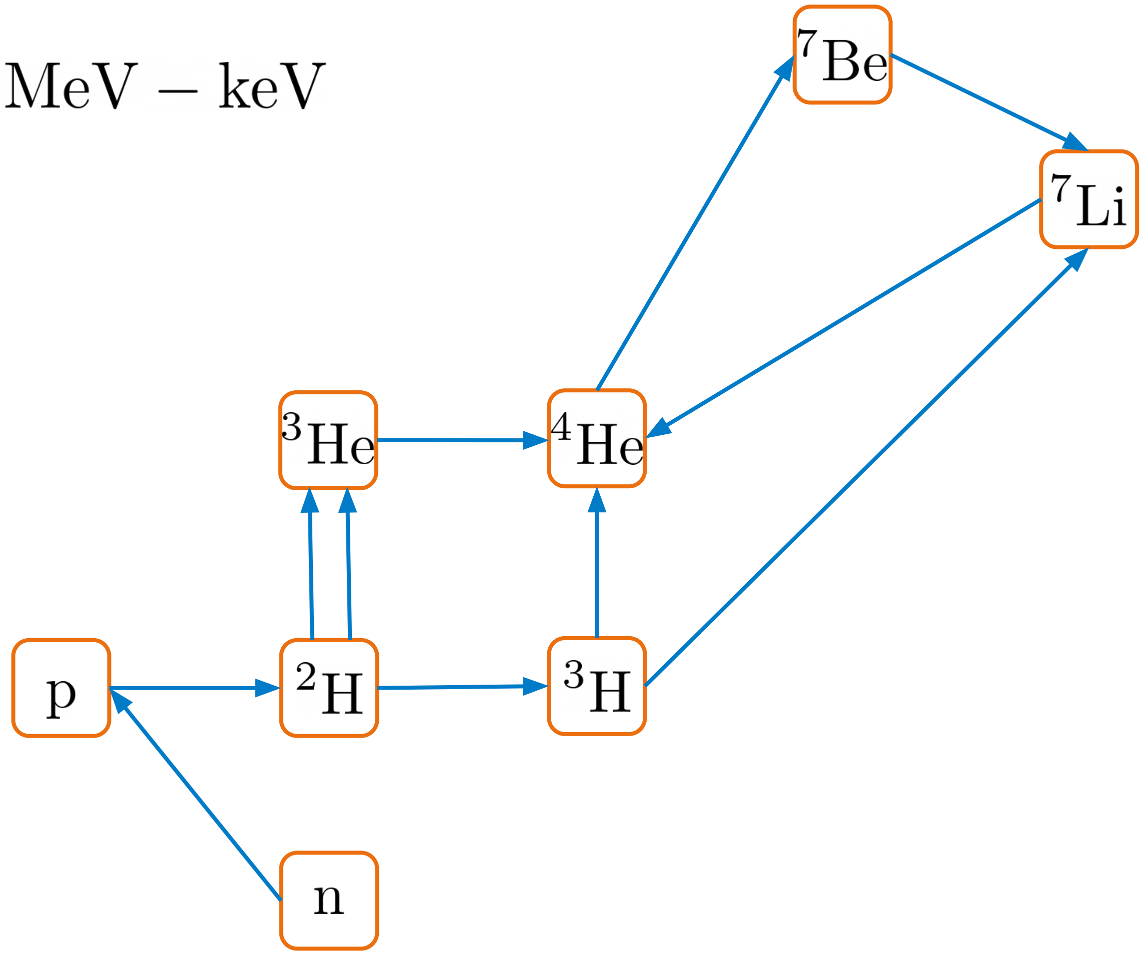


In collaboration with: P. F. Depta, J. Frerick, T. Hambye, M. Hufnagel, and K. Schmidt-Hoberg

Big Bang Nucleosynthesis

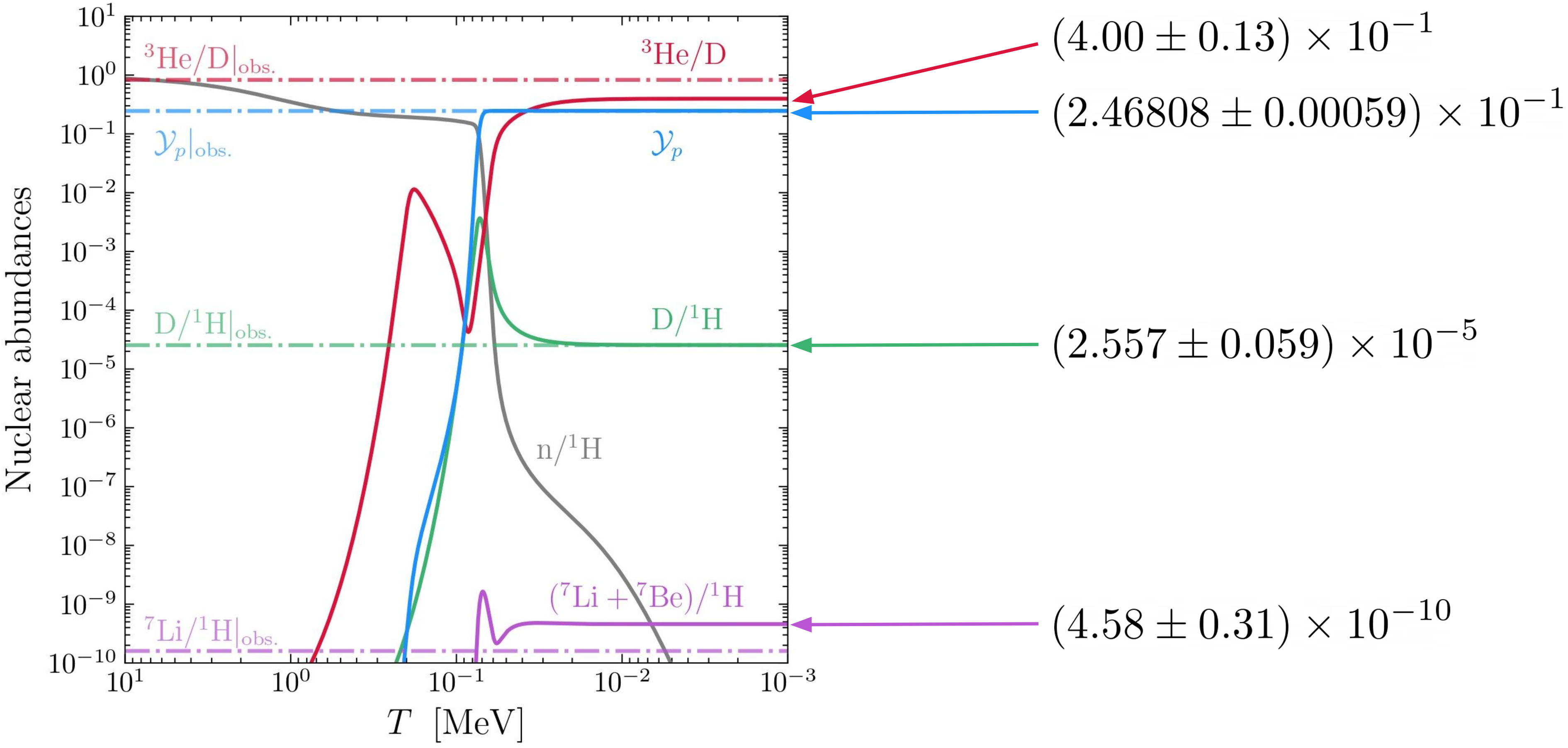
Describes the production of light elements in the early Universe:

$$t \sim 1\text{s} - 10^3\text{s} \Longleftrightarrow T \sim \text{MeV} - \text{keV}$$



Big Bang Nucleosynthesis

Good agreement between Standard Model predictions and observations:



Credits to P.F. Depta.

Big Bang Nucleosynthesis

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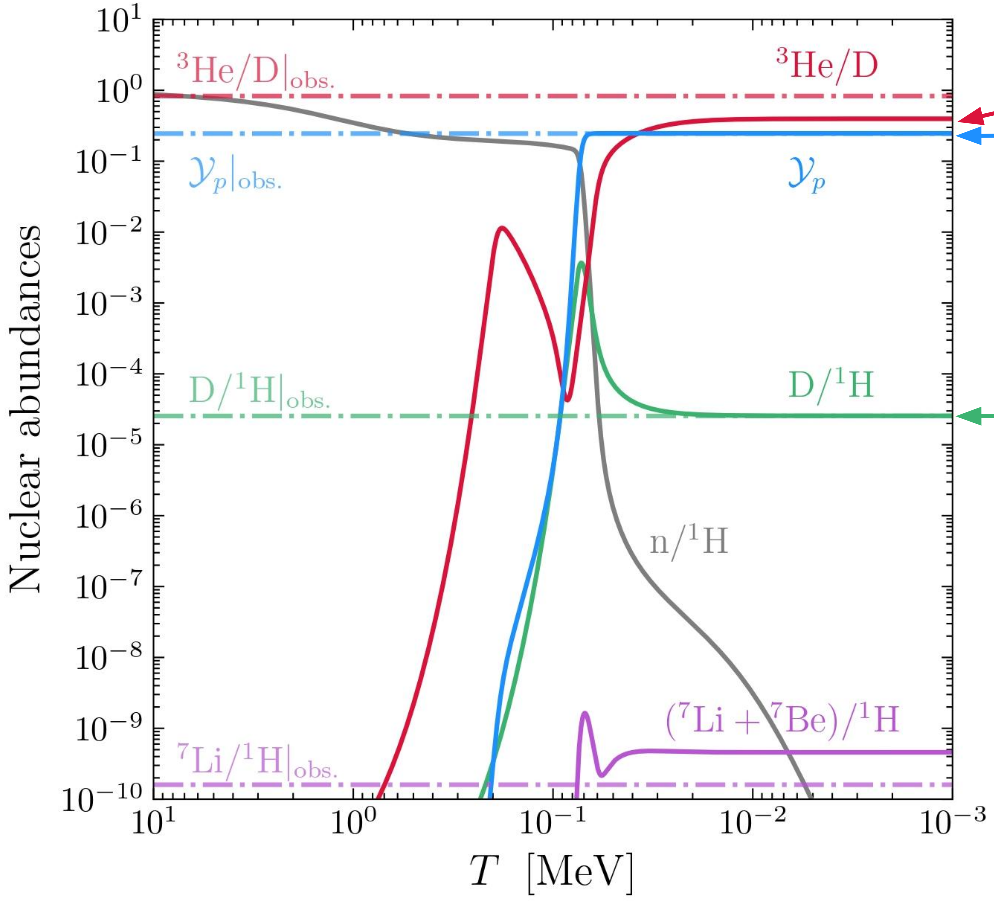

$(4.00 \pm 0.13) \times 10^{-1}$

$(2.46808 \pm 0.00059) \times 10^{-1}$

$(2.557 \pm 0.059) \times 10^{-5}$

Agree with observations:

$< 1\sigma$

Big Bang Nucleosynthesis

The presence of a dark sector can alter BBN predictions in different ways, for example:

Modified Hubble rate

$$H(T) \sim [\rho_{\rm SM} + \rho_{\rm D}(T)]^{1/2}$$

Time-temperature rel.

Photodisintegration

Big Bang Nucleosynthesis

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Time-temperature rel.

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

Photodisintegration

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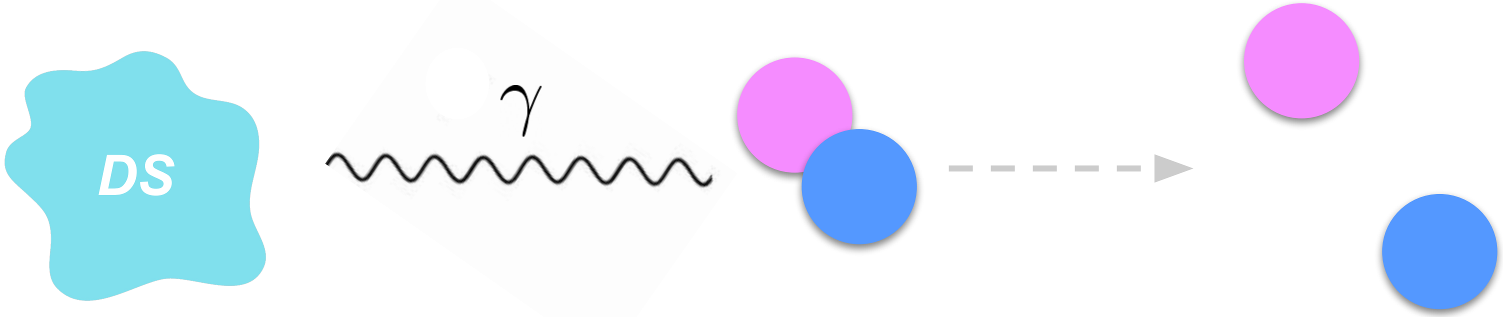
Photodisintegration

Late time decays or residual annihilations of dark sector particles.



Big Bang Nucleosynthesis

The presence of a dark sector can alter BBN predictions in different ways, for example:

Photodisintegration — Late time decays or residual annihilations of dark sector particles.

Big Bang Nucleosynthesis

The presence of a dark sector can alter BBN predictions in different ways, for example:

Photodisintegration

Late time decays or residual annihilations of dark sector particles.

Light elements abundances are fixed around ~keV.
High-energy, late-time EM injections can still alter BBN abundances.

Big Bang Nucleosynthesis

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$$E > 1.5\,\mathrm{MeV}$$
$$t > 10^4\,\mathrm{s}$$

⟹ Electromagnetic cascade that leads to non-thermal parts of the photon, electron, and positron spectra.

Big Bang Nucleosynthesis

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

If above pair-production threshold, high-energy photons are rapidly depleted.

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$T \lesssim 5.34\mathrm{keV}$ for D-disintegration at $E_D^{\rm th} \approx 2.22\mathrm{MeV}$

Big Bang Nucleosynthesis

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Photodisintegration — Late time decays or residual annihilations of dark sector particles.

	T (keV)	E^{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

BBN at these T has already finished.
Final abundances of BBN are initial abundances of photodisintegration.

ACROPOLIS

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

Big Bang Nucleosynthesis

The presence of a dark sector can alter BBN predictions in different ways, for example:

Photodisintegration — Late time decays or residual annihilations of dark sector particles.

Phase space distribution function $\mathrm{f}_x(E)$ where $x \in \{\gamma, e^{\pm}\}$

$$\mathrm{f}_x(E) = \frac{1}{\Gamma_x(E)} \left(S_x(E) + \sum_{x'} \int_E^{\infty} \mathrm{d}E' K_{x' \to x}(E, E') \mathrm{f}_{x'}(E') \right)$$

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$$S_x(E) = S_x^{(0)} \delta(E - E_0)$$

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Once we find the photon spectra, we can compute the effects on the primordial abundances:

$$\dot{Y}_N(t) = \sum_j Y_j(t) \int_0^{\infty} dE f_\gamma(t, E) \sigma_{j\gamma \to N}(E) - Y_N(t) \sum_{j'} \int_0^{\infty} dE f_\gamma(t, E) \sigma_{N\gamma \to j'}(E)$$

EM cascade from neutrinos

Heavy relic in the early Universe:

$$\phi \to N\overline{N}$$ → 1712.03972, *M. Hufnagel, K. Schmidt-Hoberg, and S. Wild*

EM cascade from neutrinos

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$\phi \rightarrow \gamma\gamma$

$\phi \rightarrow e^{+}e^{-}$ → 1808.09324, *M. Hufnagel, K. Schmidt-Hoberg, and S. Wild*; 2011.06519, *P. F. Depta, M. Hufnagel, and K. Schmidt-Hoberg*

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$\chi\chi \to e^+e^-$

$\chi\chi \to \gamma\gamma$ → 1901.06944, *P. F. Depta, M. Hufnagel, K. Schmidt-Hoberg, and S. Wild*

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$\phi \to \nu\nu$

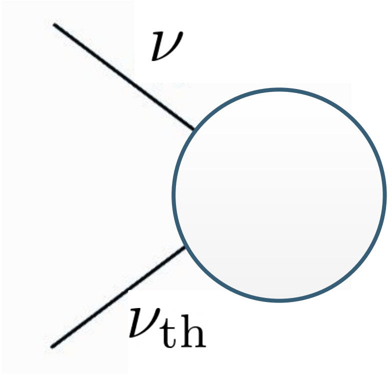
Can we get limits from BBN in this case?

0705.1200, *T. Kanzaki, K. Kawasaki, K. Kohri, T. Moroi*
2112.09137, *T. Hambye, M. Hufnagel, M. Lucca*

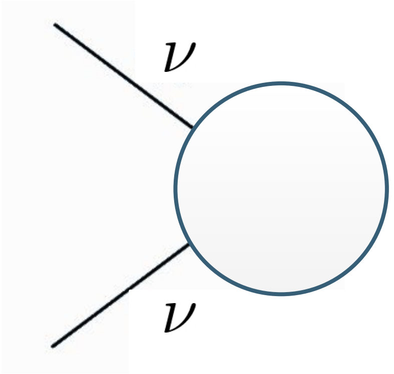
EM cascade from neutrinos

$$\phi \to \nu\nu$$

The injected high-energy neutrinos can scatter with other neutrinos:



(i) Scattering with thermal neutrinos



(ii) Scattering with non-thermal neutrinos

(iii) Redshift (no scattering)

EM cascade from neutrinos

$$\phi \to \nu\nu$$

The injected high-energy neutrinos can scatter with other neutrinos:

$$s_{\max} = 4EE'$$

$$\nu\nu_{\rm th} \to \nu\nu$$
$$\nu\bar{\nu}_{\rm th} \to \nu\bar{\nu}$$
$$\nu\bar{\nu}_{\rm th} \to e^+e^-$$
$$\nu\bar{\nu} \to \pi^-\pi^+$$
…

non-thermal scattering opens up new channels that must be considered.

EM cascade from neutrinos

$\phi \to \nu\nu$

The injected high-energy neutrinos can scatter with other neutrinos:

$$\nu\nu_{\rm th} \to \nu\nu$$
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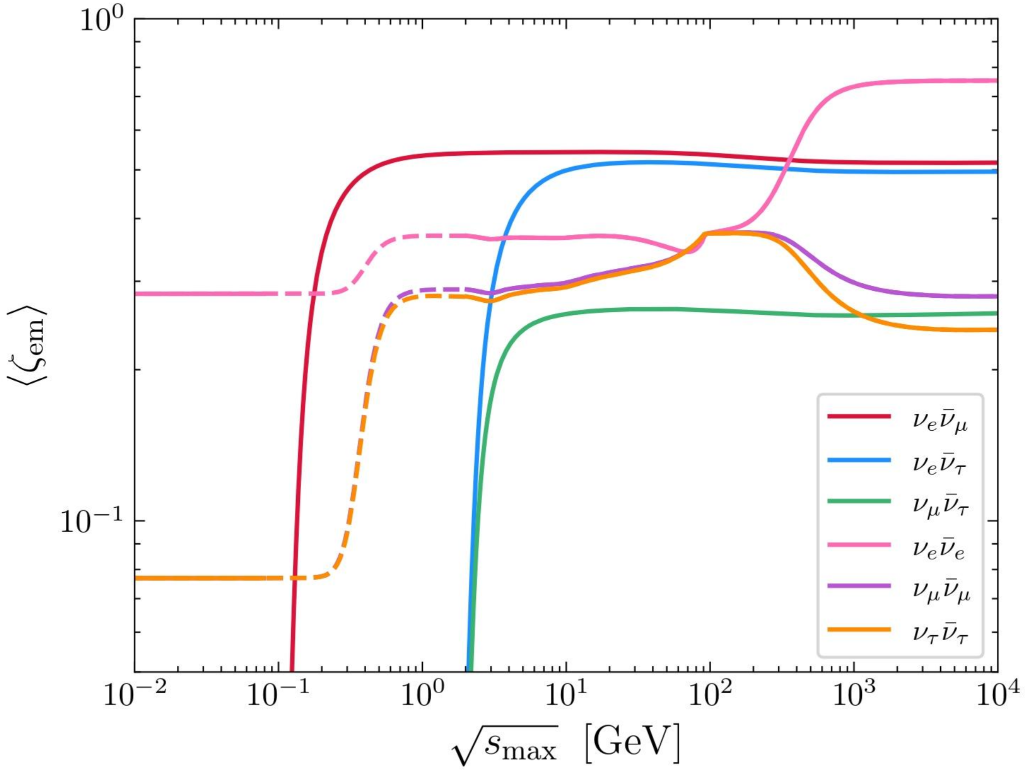
$$\ldots$$



EM cascade from neutrinos

$\phi \to \nu\nu$

"Boltzmann-free" realization of EM injection

Input values: $m_\phi,\ \tau_\phi,\ f_\phi \longrightarrow a_{\phi,0},\ T_0$

→ Primary loop: main loop in the code, goes on until reaching a *maxStep*. In each step, compute the injected energy $E_0 = m_\phi/2$ and define time-step as:

$$\Delta t = \frac{\varepsilon}{\max[H(T),\ \Gamma_{\rm tot}(T)]}$$

and compute the number of ϕ that decayed Δa_ϕ

EM cascade from neutrinos

$$\phi \to \nu\nu$$

<u>"Boltzmann-free" realization of EM injection</u>

Input values: $m_\phi,\ \tau_\phi,\ f_\phi \longrightarrow a_{\phi,0},\ T_0$

→ Primary loop: main loop in the code, goes on until reaching a maxStep.

→ Secondary loop: loop over available energy and compute the source term. Then adjust temperature and abundances.

$$T = T[1 - H(T)\Delta t] \text{ and } a_\phi = a_\phi - \Delta a_\phi$$

EM cascade from neutrinos

$$\phi \to \nu\nu$$

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→ Tertiary loop: compute the source term from non-thermal scatterings.

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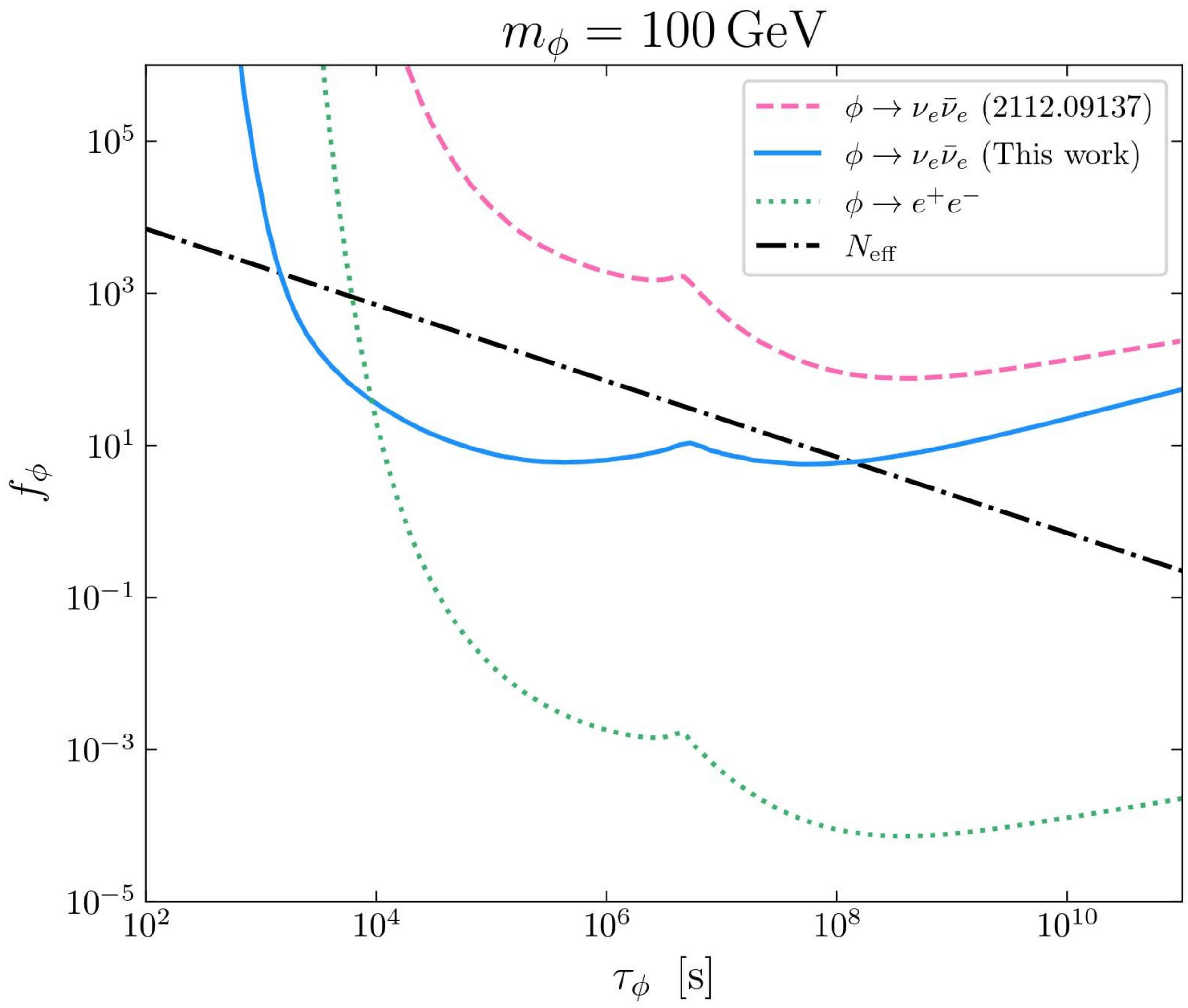
Output values: $S,\ T \longrightarrow$ ACROPOLIS

Preliminary results



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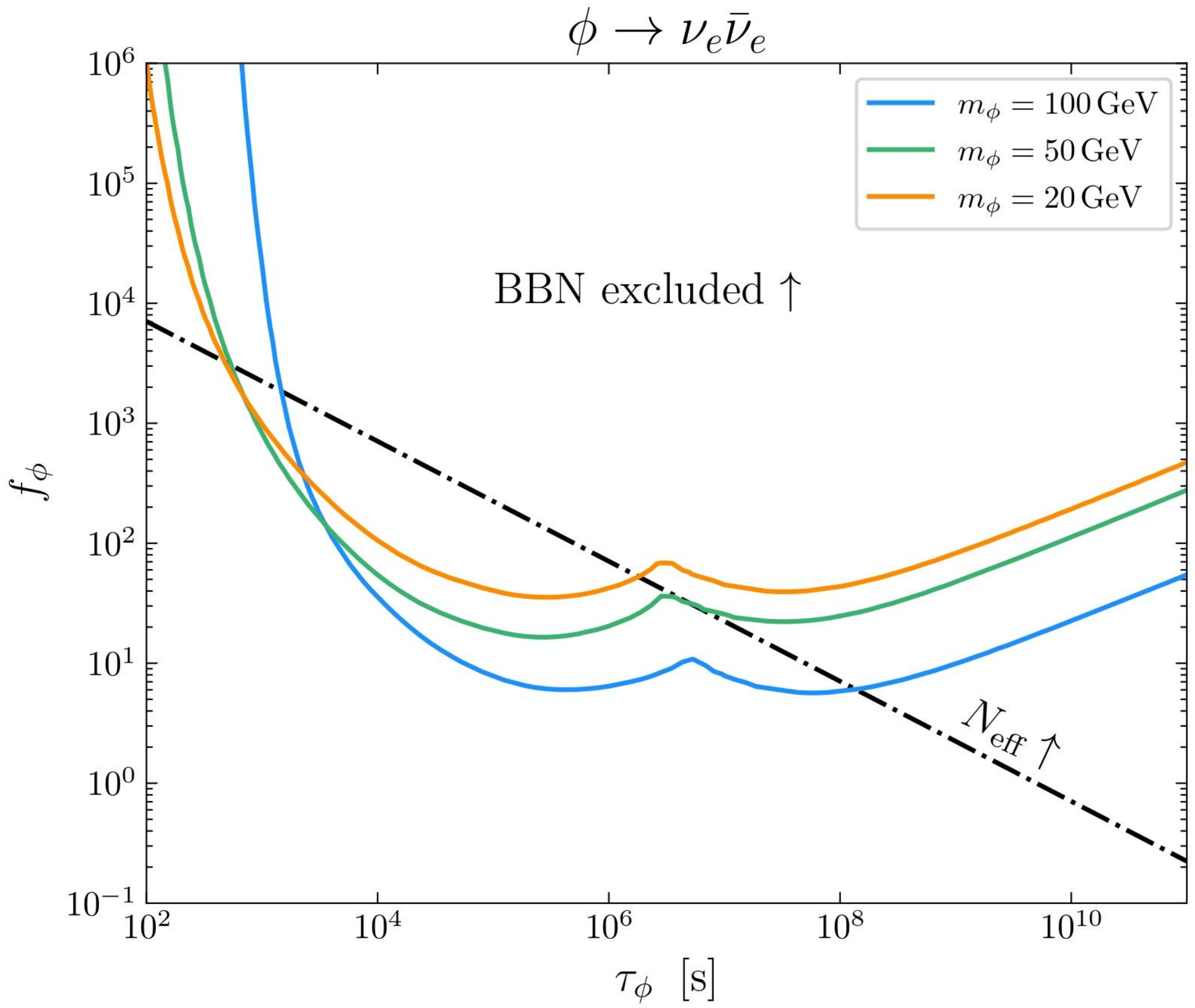

(Not-yet-conclusive)

Conclusions

- Neutrino injections in the early Universe can alter BBN:
  - Electromagnetic injections due to neutrino scattering at later times can still lead to a change in the abundances of light elements due to photodisintegration.
  - Less efficient injections will allow us to constrain lower lifetimes.
- Implemented code to simulate the injection instead of solving the Boltzmann equations, making the computation easier.
- We consider scattering with other non-thermal neutrinos as these are relevant in our region of parameter space.
- New part of the parameter space ruled out by this work.
- *Work in progress:* Earlier injections may lead to changes in the BBN during the formation of light elements: this implies that the initial abundances used as input in ACROPOLIS may be different.

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Thank you for your attention!

Backup slides

Big Bang Nucleosynthesis

The presence of a dark sector can alter BBN predictions in different ways, for example:

Photodisintegration — Late time decays or residual annihilations of dark sector particles.

Light elements abundances are fixed around ~keV.
High-energy, late-time EM injections can still alter BBN abundances.

1. $\gamma\gamma_{\rm th} \to e^+e^-$
2. $\gamma\gamma_{\rm th} \to \gamma\gamma$
3. $\gamma N \to e^+e^-N$, with $N \in \{^1H, {}^4He\}$
4. $\gamma e^-_{\rm th} \to \gamma e^-$
5. $e^\pm\gamma_{\rm th} \to e^\pm\gamma$

Big Bang Nucleosynthesis

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Universal photon spectra:

$$\mathrm{f}_{\gamma,\mathrm{univ}}(E) \sim \begin{cases} K_0(E/E_X)^{-3/2} & \text{for } E < E_X \ , \\ K_0(E/E_X)^{-2} & \text{for } E_X < E < E^{\mathrm{th}}_{e^+e^-} \\ 0 & \text{for } E > E^{\mathrm{th}}_{e^+e^-} \ , \end{cases}$$

where we have $K_0 = E_0 E_X^{-2}[2+\ln(E^{\mathrm{th}}_{e^+e^-}/E_X)]^{-1}$ and $E^{\mathrm{th}}_{e^+e^-} = m_e^2/22T,\ E_X = m_e^2/80T$

Big Bang Nucleosynthesis

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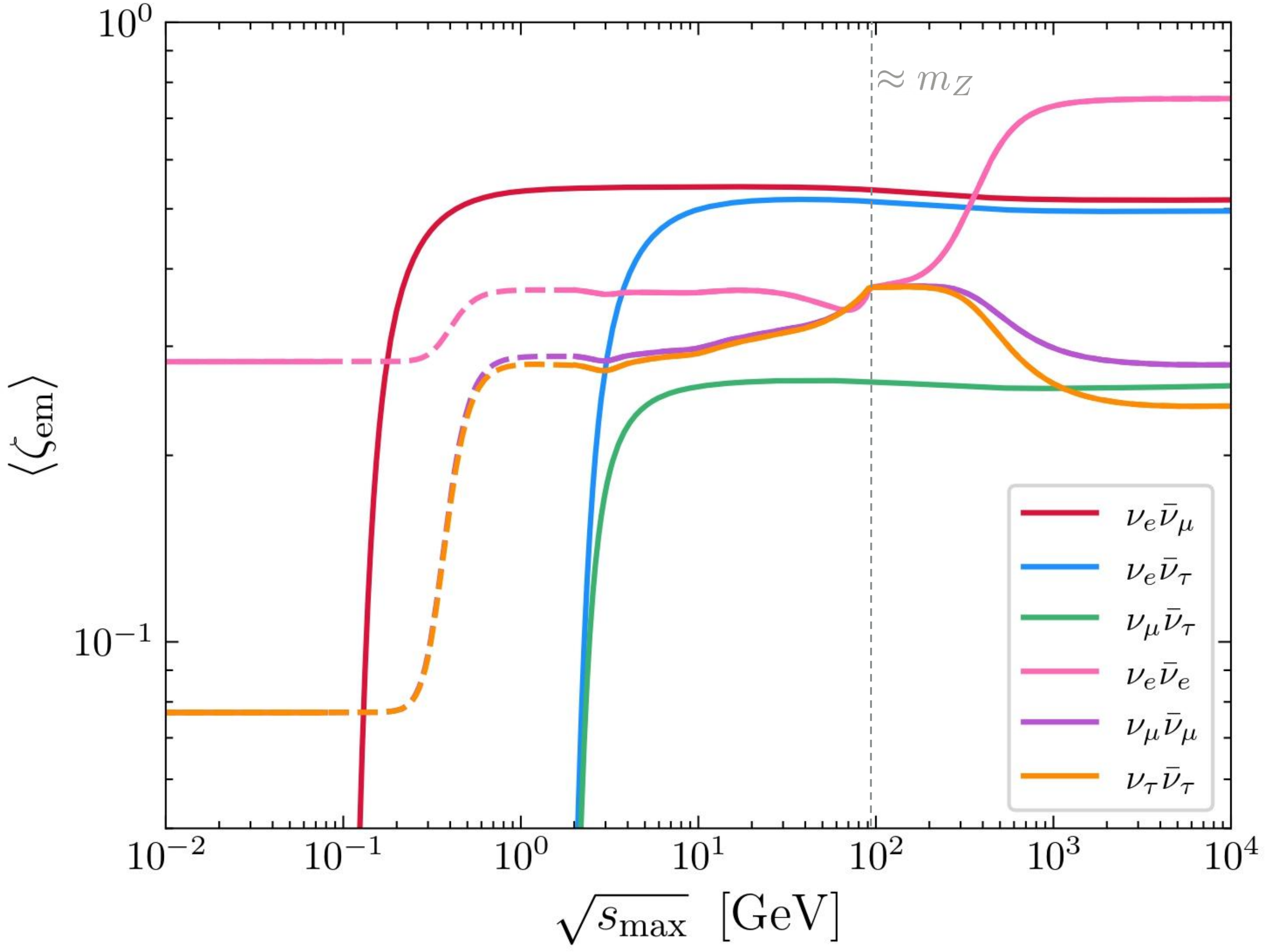
Reaction	$E^{\rm th}$ [MeV]
$D + \gamma \to p + n$	2.22
$^3H + \gamma \to D + n$	6.26
$^3H + \gamma \to p + n + n$	8.48
$^3He + \gamma \to D + p$	5.49
$^3He + \gamma \to n + p + p$	7.12
$^4He + \gamma \to {}^3H + p$	19.81
$^4He + \gamma \to {}^3He + n$	20.58
$^4He + \gamma \to D + D$	23.84
$^4He + \gamma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

$$\dot{Y}_N(t) = \sum_j Y_j(t) \int_0^\infty \mathrm{d}E\, \mathrm{f}_\gamma(t,E)\sigma_{j\gamma\to N}(E) - Y_N(t) \sum_{j'} \int_0^\infty \mathrm{d}E\, \mathrm{f}_\gamma(t,E)\sigma_{N\gamma\to j'}(E)$$

$$N \in \{n, p, D, {}^3H, {}^3He, {}^4He, {}^6Li, {}^7Li, {}^7Be\}$$

EM cascade from neutrinos



EM cascade from neutrinos

For the non-thermal scattering, we define:

$$\gamma_{\nu\nu' \to X}(s_{\max}) \equiv \int_0^{s_{\max}} \mathrm{d}s \; s \cdot \sigma_{\nu\nu' \to X}(s)$$

Using:

$$f_{\nu'}(E, T_\nu) = \frac{2\pi^2}{E^2} \sum_i \tilde{n}_{\nu'}(E_i, T_\nu) \delta(E - E_i)$$

The scattering rate will be given by:

$$\Gamma_{\nu\nu' \to X}(E, T_\nu) = \sum_i \frac{\tilde{n}_{\nu'}(\epsilon_i, T_\nu)}{2E^2 \epsilon_i^2} \times \gamma_{\nu\nu' \to X}(4E\epsilon_i)$$

As a average over all possible reactions, the fraction of injected electromagnetic material is given by:

$$\langle \zeta_{\mathrm{em}} \rangle_{\nu\nu' \to X}(s_{\max}) = \frac{1}{\gamma_{\nu\nu' \to X}(s_{\max})} \int_0^{s_{\max}} \mathrm{d}s \; \zeta_{\mathrm{em}}^{\nu\nu' \to X}(s) \cdot s \cdot \sigma_{\nu\nu' \to X}(s)$$

EM cascade from neutrinos

The source term we use as an input in ACROPOLIS takes the form:

$$S = S_{\rm th} + S_{\rm non\text{-}th}$$

$$S_{\rm th} = \frac{E/m}{\Delta t} \underbrace{\left(\Gamma_{\rm th,\ EM} \Delta t\right) n_{\rm beam}}$$

$$S_{\rm non\text{-}th} = \frac{E/m}{\Delta t} \underbrace{\langle \zeta_{\rm EM} \rangle \left(\Gamma_{\rm non\text{-}th} \Delta t\right) n_{\rm beam}}$$

"abundance" going into EM

EM cascade from neutrinos

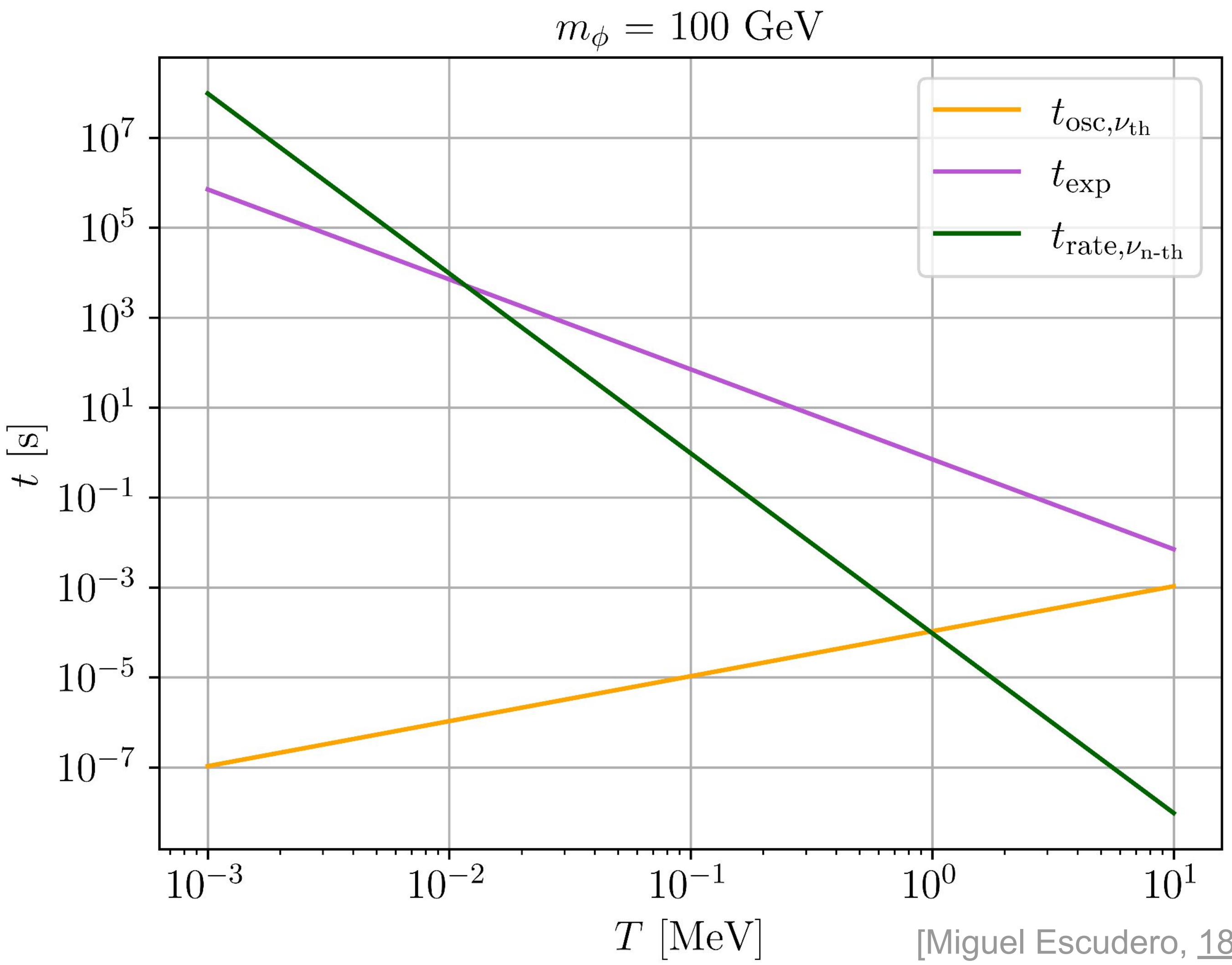
$$\phi \to \nu\nu$$

"Boltzmann-free" realization of EM injection

Conservative approximations:

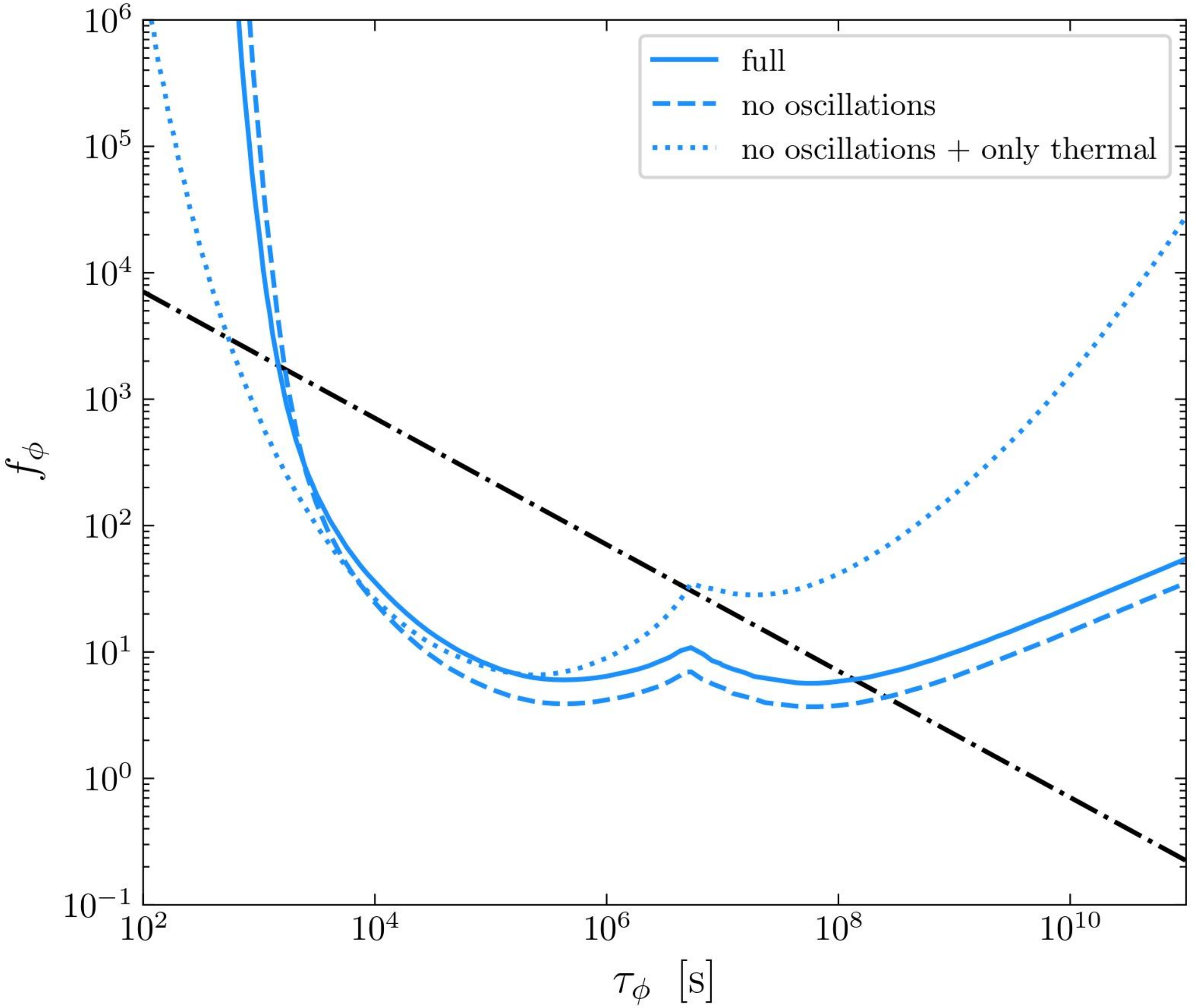
- We neglect secondary reactions: the number of scattered particles is suppressed compared to the number of particles that redshift. In the next step, the number of particles that scatter will be even more suppressed, and including secondary particles would anyway just increase the injection.
- When running PYTHIA, we do not consider continuous energy loss. This would again just contribute positively to the EM injection.

Neutrino oscillation



[Miguel Escudero, 1812.05605]

Preliminary results



Preliminary results