MeV Scale Thermal Dark Matter and Relic Neutrino Decoupling

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based on ArXiv:1812.05605 JCAP 1902 (2019) 007

ArXiv:1904.XXXXX to appear with an improved treatment

DarkMatterUK

11th of April 2019

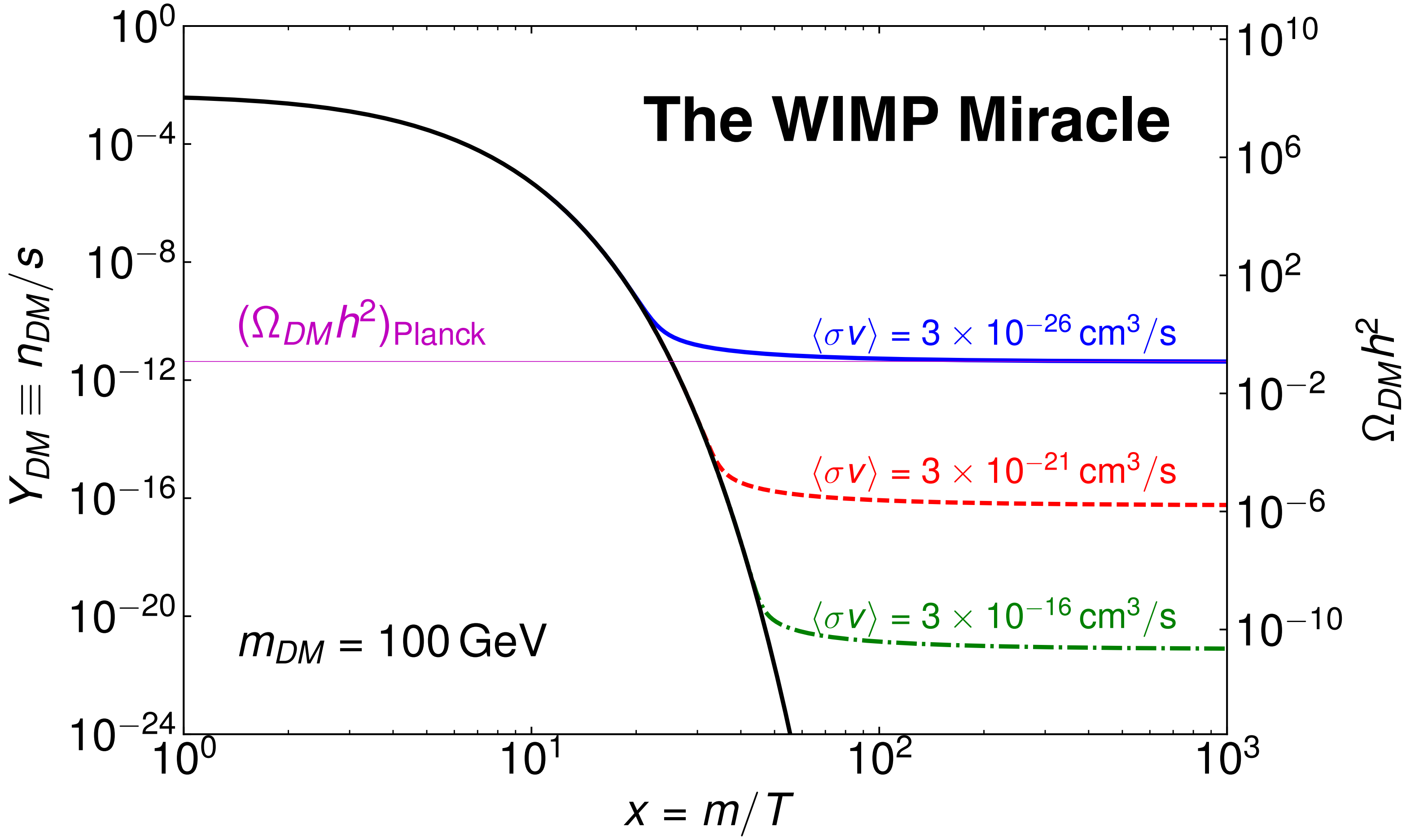
KING'S College LONDON

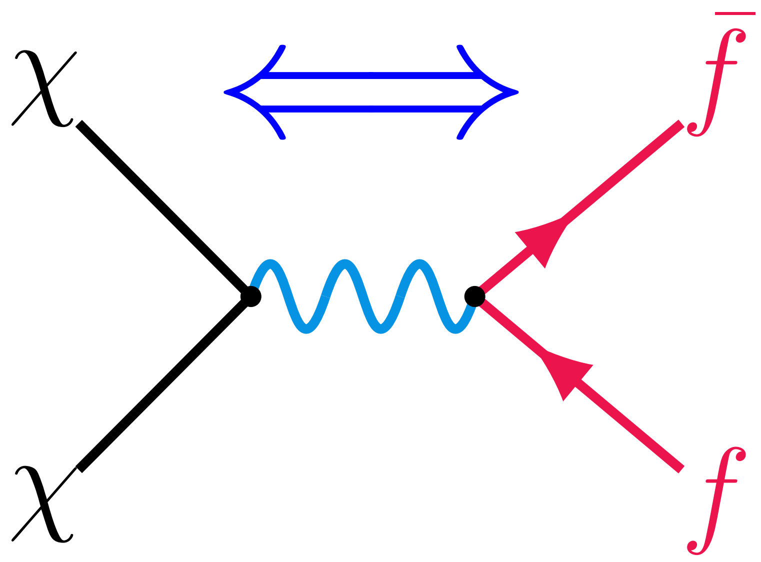
European Research Council

Established by the European Commission

Motivation I

Weakly Interacting Massive Particles





- **Stable particle with** $\langle\sigma v\rangle \simeq 3\times10^{-26}\,\mathrm{cm^3/s}$ **gives the correct abundance**
- **The annihilation process freezes out at T = m/20**
- **Light Thermal Dark Matter relics impact the process of neutrino decoupling**

MeV? —— **100 TeV**

Motivation II

Precision Cosmology:

$$N_{\rm eff}^{\rm BBN} = 2.88 \pm 0.27$$

Pitrou *et. al.* 1801.08023

$$N_{\rm eff}^{\rm Planck} = 2.92 \pm 0.18$$

Planck 2018: 1807.06209

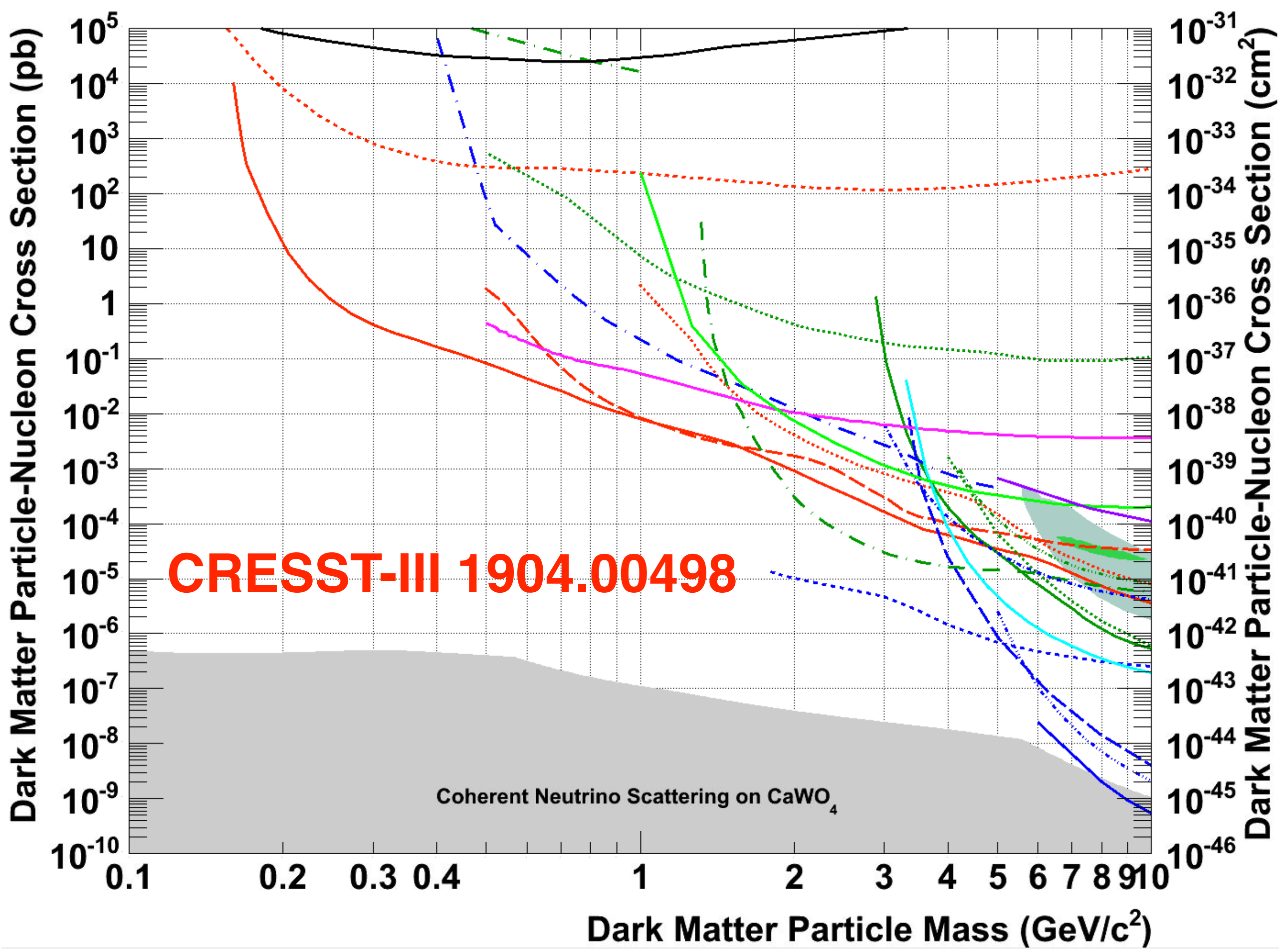
$$N_{\rm eff}^{\rm Stage-IV} = 3.04 \pm 0.03\,?$$

Stage-IV CMB: 1610.02743

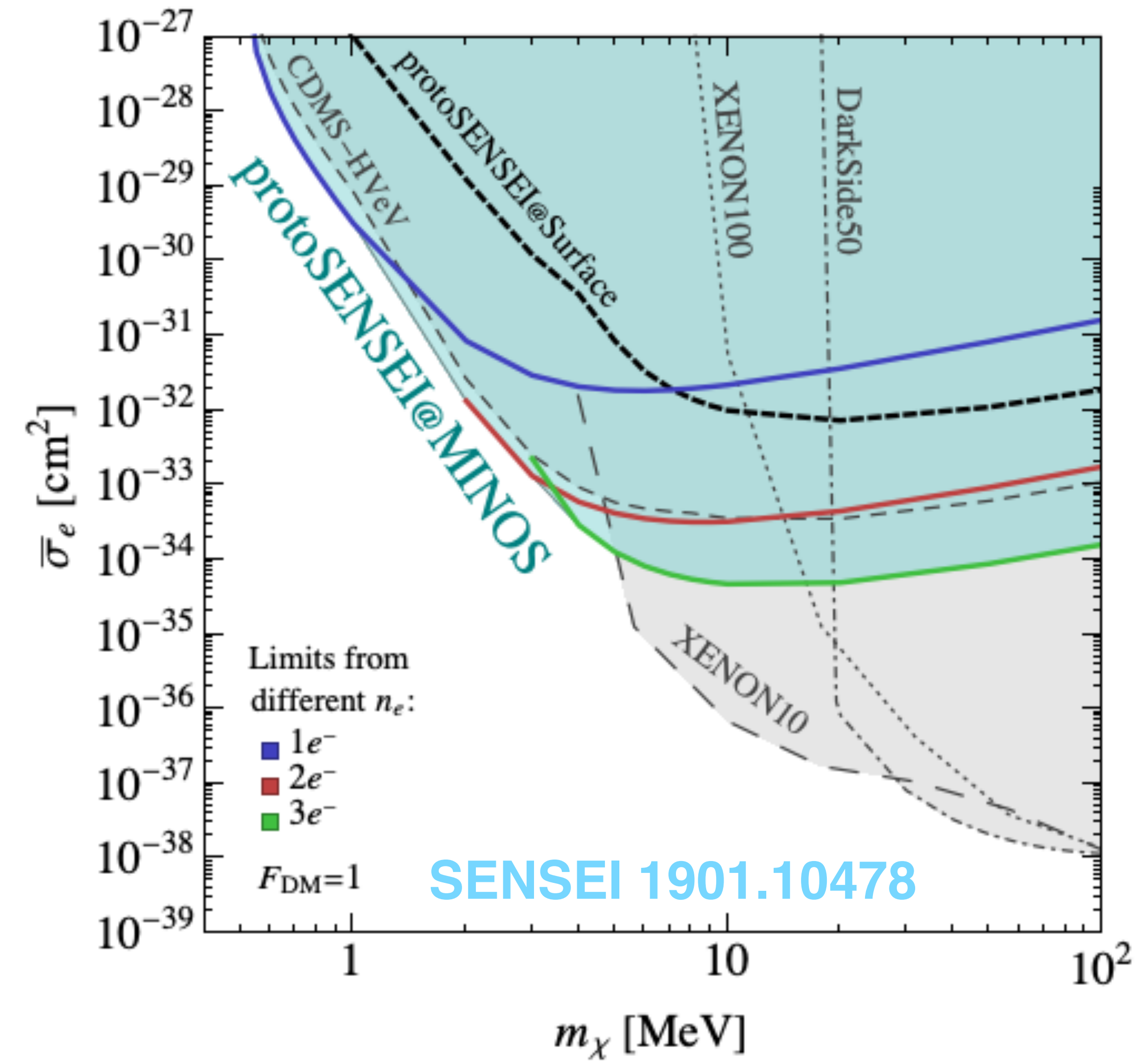
Motivation III

- **Hard to test MeV dark matter at Direct Detection experiments**

WIMP-Nucleus Scattering



WIMP-Electron Scattering



- **Experimental programme developed to search for them:**
  SENSEI, SuperCDMS, DAMIC, PTOLEMY, ... 1608.08632
  FASER, Belle-II, LDMX, SHIP, MATHUSLA, ... 1707.04591

Outline

1) Neutrino Decoupling beyond the Standard Model

a) Simplified approach to the neutrino decoupling

b) Comparison with traditional SM evaluations

2) An application: MeV scale Thermal Dark Matter

a) Purely Electrophilic and Neutrinophilic Relics

b) Generic Relic

3) Conclusions

The Process of Neutrino Decoupling

T > 3 MeV

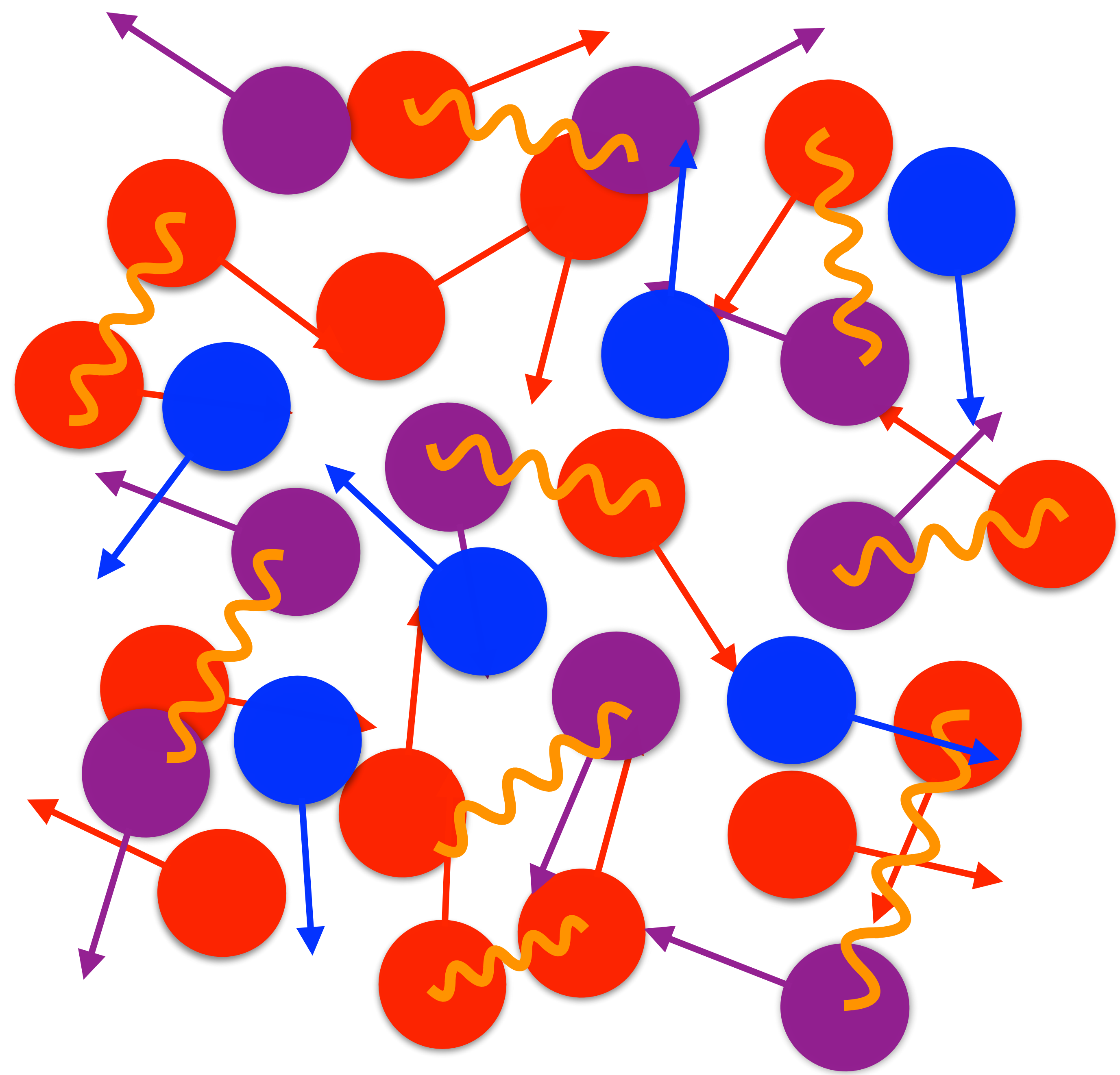
Highly Efficient Processes

$$e^+e^- \leftrightarrow \gamma\gamma$$

$$e^\pm\gamma \leftrightarrow e^\pm\gamma$$

$$e^+e^- \leftrightarrow \bar{\nu}_i\nu_i$$

$$e^\pm\nu_i \leftrightarrow e^\pm\nu_i$$



In comoving coordinates

Neutrinos **Electrons** **Photons** **Z-W (off-shell)**

The Process of Neutrino Decoupling

$m_e < T < 3$ MeV

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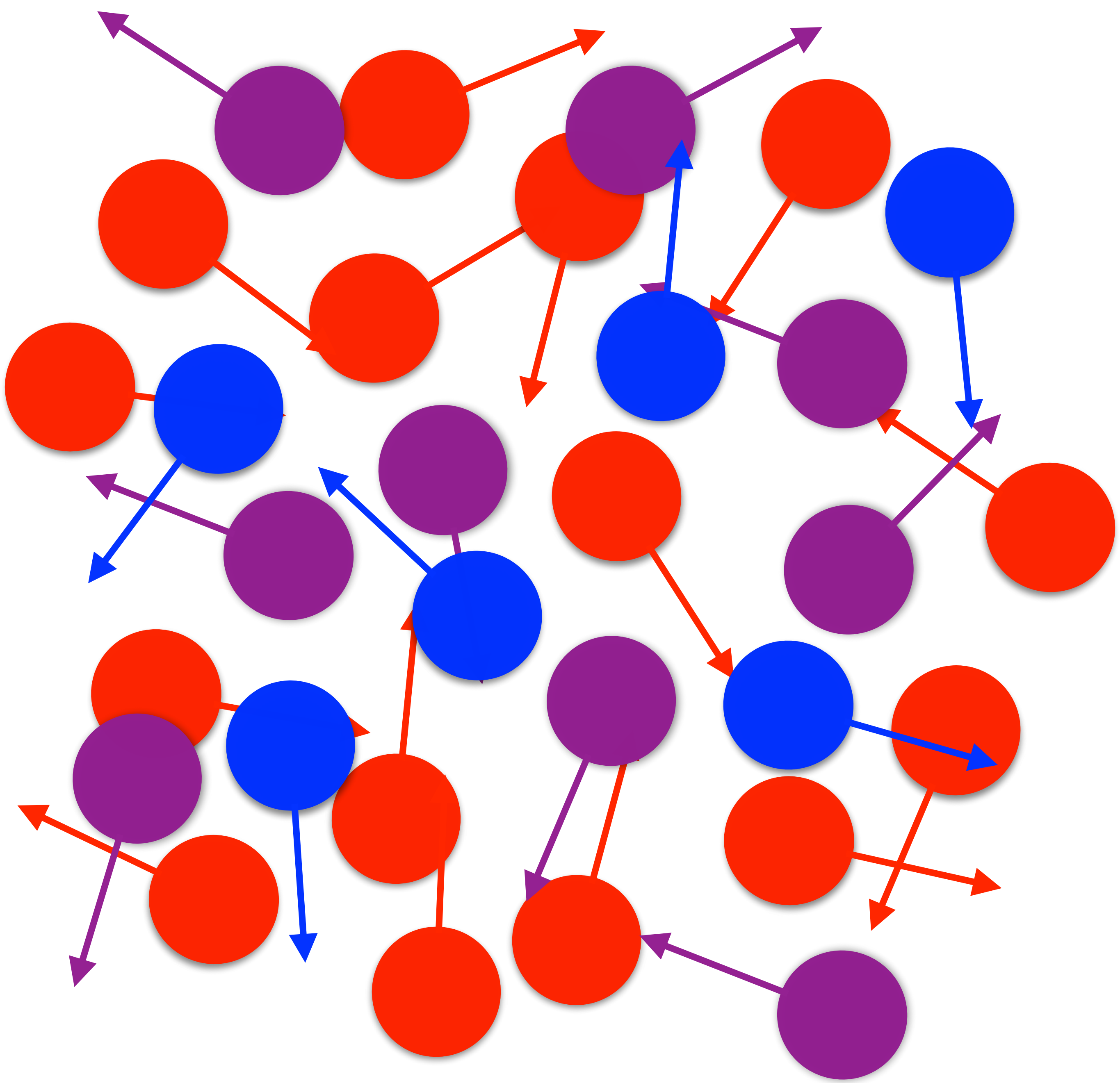
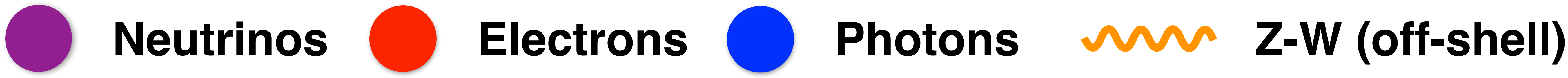


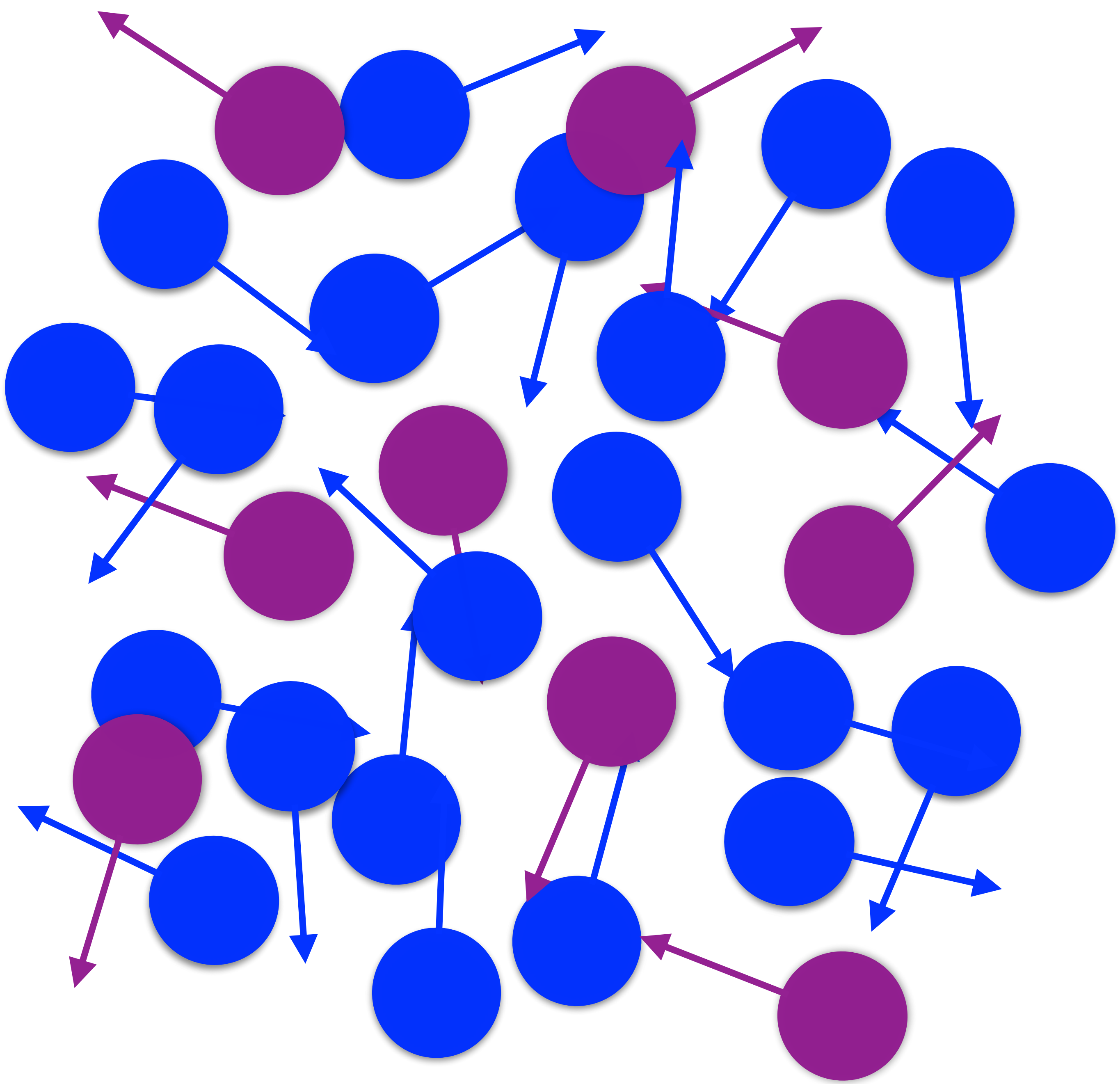
In comoving coordinates



The Process of Neutrino Decoupling

$T_\gamma < m_e/10$

- **Black Body Photon Radiation**
- **Only Neutrinos and Photons**
- $T_\gamma / T_\nu = 1.4$
- $\rho_\gamma / (\rho_\nu + \rho_\gamma) = 0.6$



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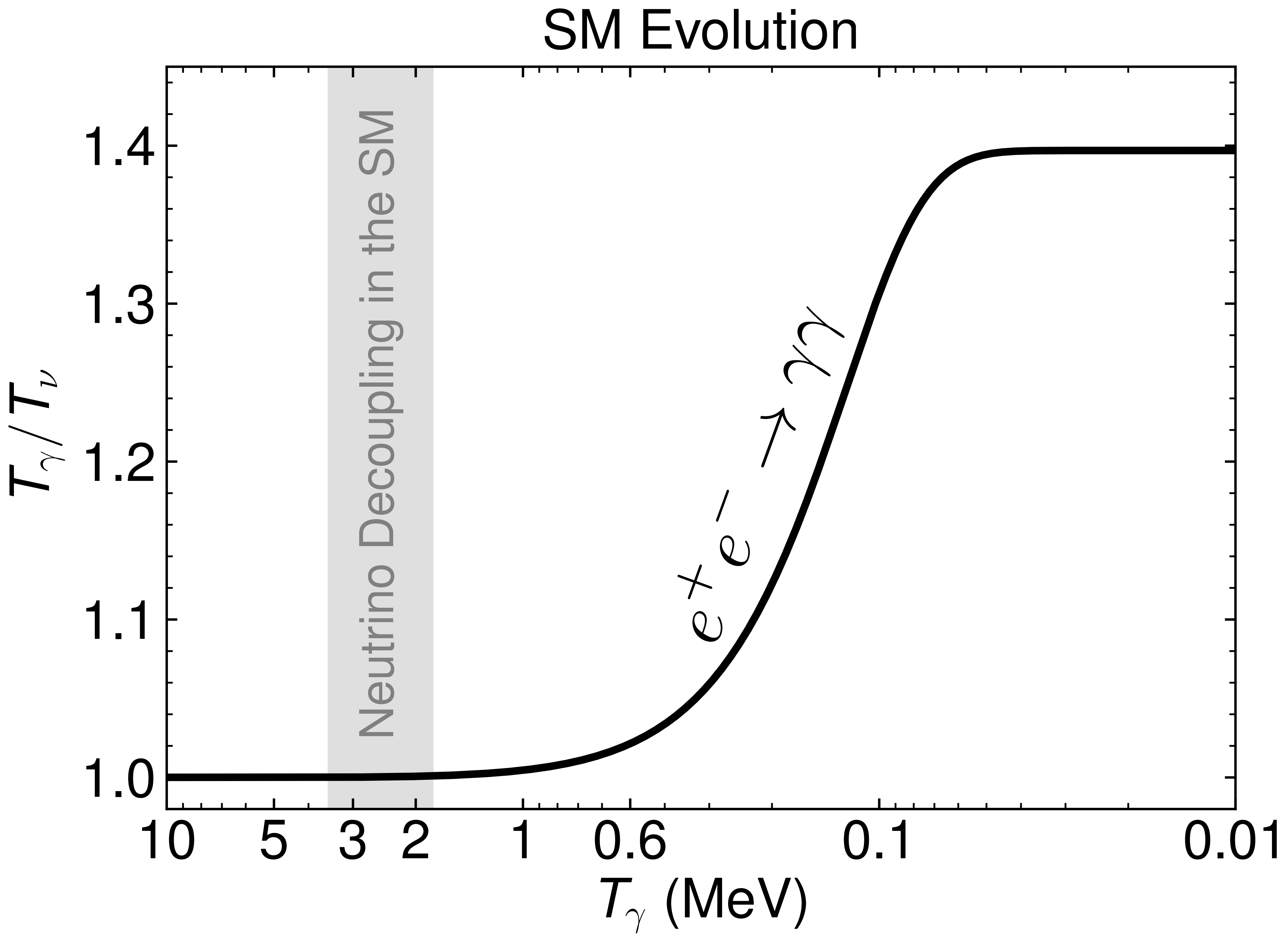
Temperature Evolution in the SM



$N_{\rm eff}$ Review

Definition: $$N_{\rm eff} \equiv \frac{8}{7}\left(\frac{11}{4}\right)^{4/3}\left(\frac{\rho_{\rm rad}-\rho_\gamma}{\rho_\gamma}\right)$$

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SM prediction: $N_{\rm eff}^{\rm SM} = 3.045$

1606.06986 de Salas & Pastor
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Why is it not 3? **for an excellent review see hep-ph/0202122 by Dolgov**

1) Neutrino Decoupling not instantaneous $\quad \sigma \sim G_F^2 E_\nu^2$

2) Weak Interactions freeze out at T = 2-3 MeV
hence, some heating from e^+e^- annihilation $\quad n\langle\sigma v\rangle \simeq G_F^2 T^5 \simeq H$

3) Finite Temperature QED corrections $\quad \delta m_e^2(T),\ \delta m_\gamma^2(T)$

4) Neutrino oscillations are active at T < 3 MeV

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BSM traditional approach: Assume neutrinos decouple instantaneously

SM prediction machinery:

Density Matrix formalism and the binning of the neutrino distribution functions result in a system of 200 ***STIFF*** coupled integro-differential equations.

Neutrino Decoupling: 1812.05605

Simplified approach to the neutrino decoupling:

Well justified approximations:

1) **Assume neutrinos follow Fermi-Dirac distributions** $\delta\rho/\rho < 1\%$

2) **Neglect chemical potentials** $e^+e^- \leftrightarrow \bar{\nu}\nu \rightarrow \mu_\nu = 0$

3) **Neglect neutrino oscillations** $\Delta N_{\rm eff} \simeq 0.0007$

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Result in: 2-3 simple coupled differential equations for $T_\gamma,\, T_\nu$

$$\frac{dT_\gamma}{dt} = -\frac{4H\rho_\gamma + 3H\,(\rho_e + p_e) + \frac{\delta\rho_{\nu_e}}{\delta t} + 2\frac{\delta\rho_{\nu_\mu}}{\delta t}}{\frac{\partial\rho_\gamma}{\partial T_\gamma} + \frac{\partial\rho_e}{\partial T_\gamma}} \qquad \frac{dT_\nu}{dt} = -H\,T_\nu + \frac{\frac{\delta\rho_{\nu_e}}{\delta t} + 2\frac{\delta\rho_{\nu_\mu}}{\delta t}}{3\,\frac{\partial\rho_\nu}{\partial T_\nu}}$$

Analytical expressions for the SM energy transfer rates:

As a result of a 12 Dimensional integral!

$$\left.\frac{\delta\rho_{\nu_e}}{\delta t}\right|^{\rm MB}_{\rm SM} = \frac{G_F^2}{\pi^5}\left[1 + 4s_W^2 + 8s_W^4\right]\left[32\,(T_{\nu_\mu}^9 - T_{\nu_e}^9) + 56\,T_\gamma^4\,T_{\nu_e}^4\,(T_\gamma - T_{\nu_e})\right]$$

Neutrino Decoupling: 1812.05605

Neutrino Decoupling in the SM	$T_{\nu_e} = T_{\nu_\mu}$		$T_{\nu_e} \neq T_{\nu_\mu,\nu_\tau}$		
Scenario	T_γ/T_ν	$N_{\rm eff}$	T_γ/T_{ν_e}	T_γ/T_{ν_μ}	$N_{\rm eff}$
Instantaneous decoupling	1.4010	3	1.4010	1.4010	3
Instantaneous decoupling + QED	1.3998	3.011	1.3998	1.3998	3.011
MB collision term + QED	1.3949	3.053	1.3935	1.3958	3.052
FD collision term + QED	1.3954	3.049	1.3940	1.3962	3.048
FD+m_e collision term + QED	1.3957	**3.046**	1.3946	1.3965	**3.045**

Virtues of the simplified approach:

- 😃 **Simple** — Only 2-3 evolution equations
- 😃 **Physical** — Takes into account all relevant interactions and the time dependence of the process
- 😃 **Fast** — Takes O(10) seconds to evaluate $N_{\rm eff}$ on an average computer
- 😃 **Open** — Code can be found at https://github.com/MiguelEA/nudec_BSM
- 😃 **Precise** — Reproduces $N_{\rm eff}$ in the SM!
- 😃 **BSM** — Straightforward to include BSM species and interactions

MeV Thermal Dark Matter

- **Effect is to release entropy into the system, e. g.:**

Boehm, Dolan and McCabe 1207.0497, 1303.6270
Nollet and Steigman 1312.5725, 1411.6005

Serpico and Raffelt astro-ph/0403417
Kolb, Turner and Walker PRD 34 (1986) 2197

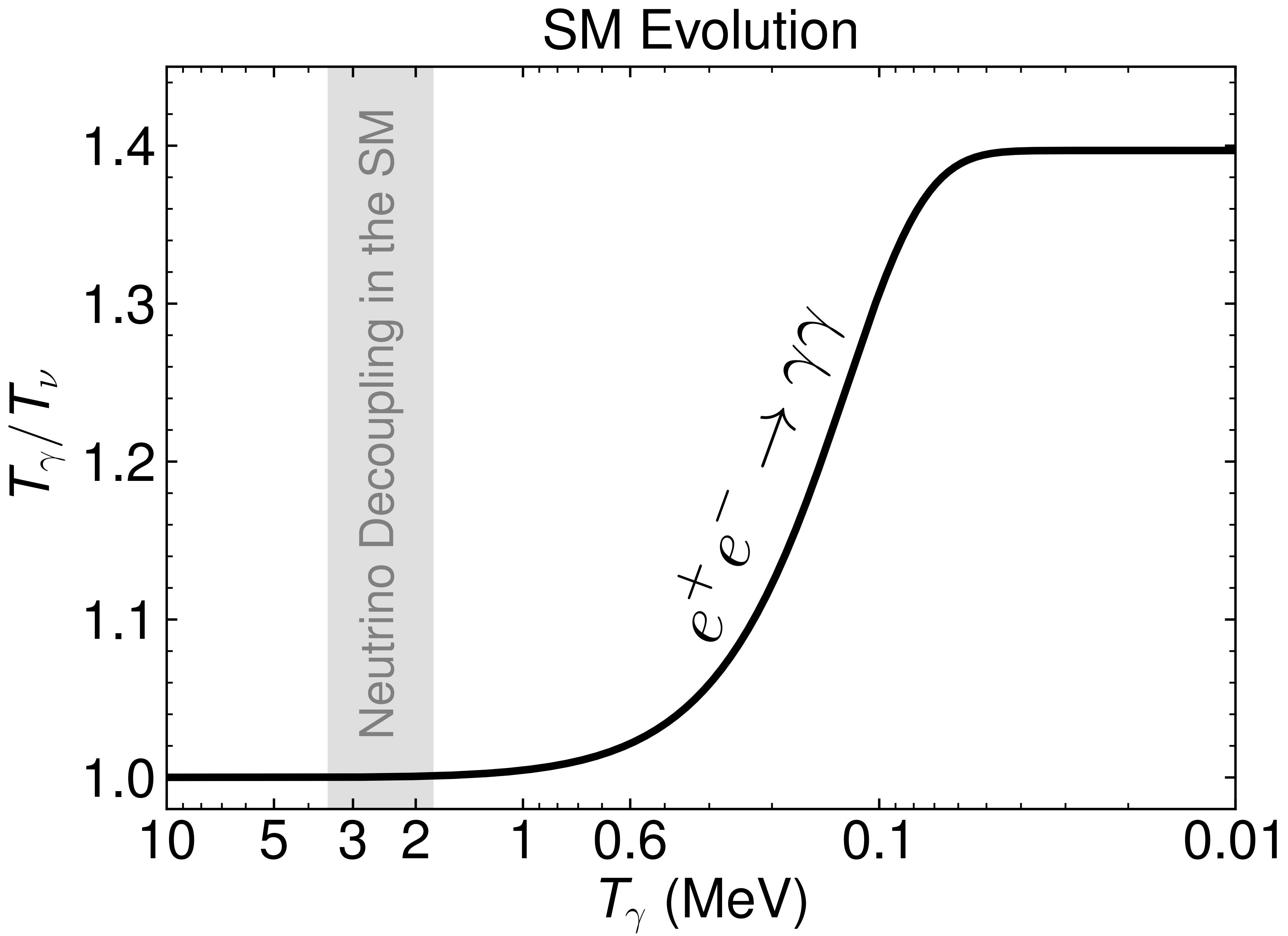
Thereby altering T_ν or T_γ and hence: $N_{\rm eff} = 3\left(\frac{11}{4}\right)^{4/3}\left(\frac{T_\nu}{T_\gamma}\right)^4$

This is independent of the angular momentum of the annihilation process!

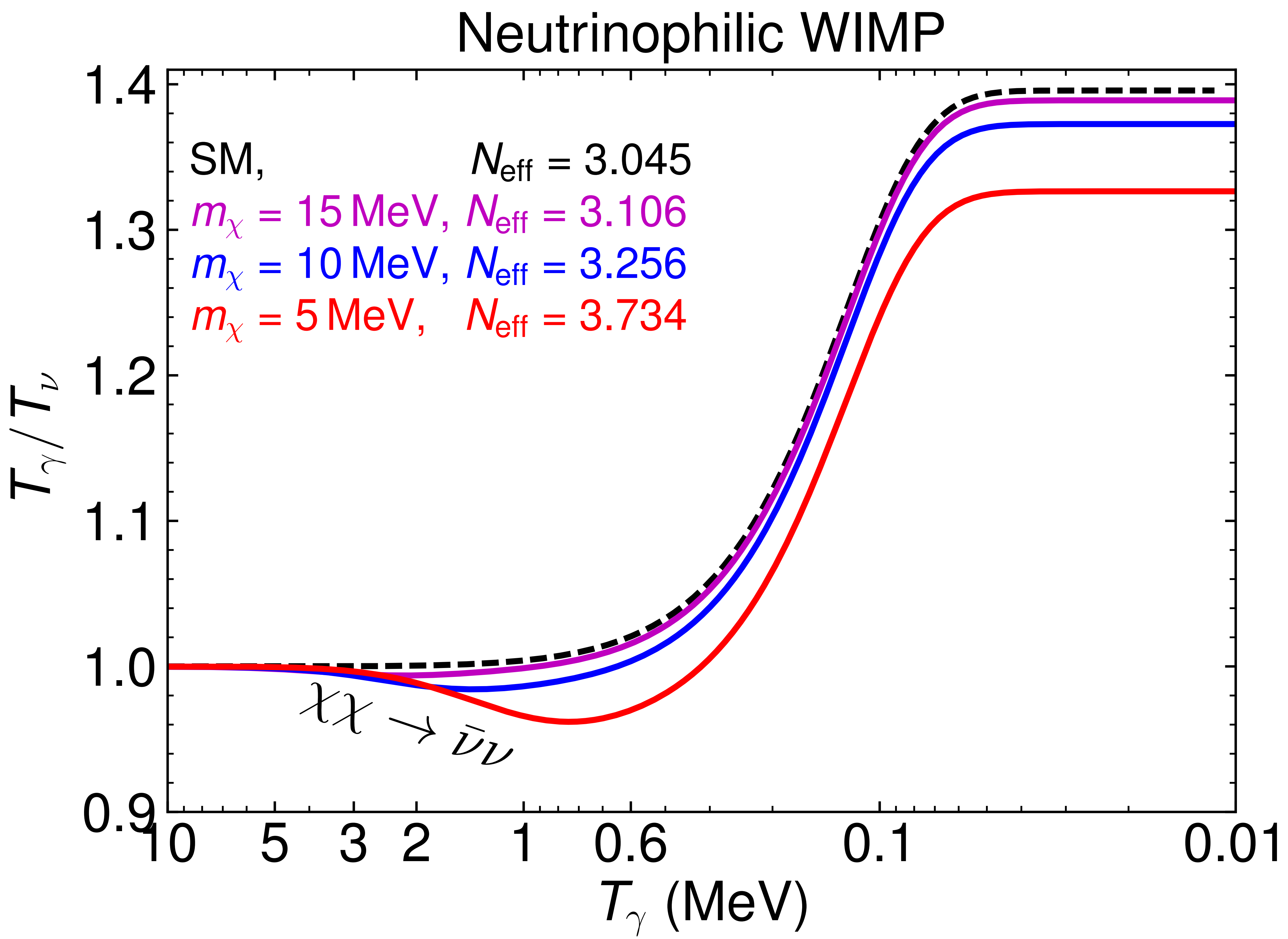
- **In general are also efficient delayers of the neutrino decoupling process via:**

$$e^+e^- \leftrightarrow \chi\chi \leftrightarrow \bar{\nu}\nu$$

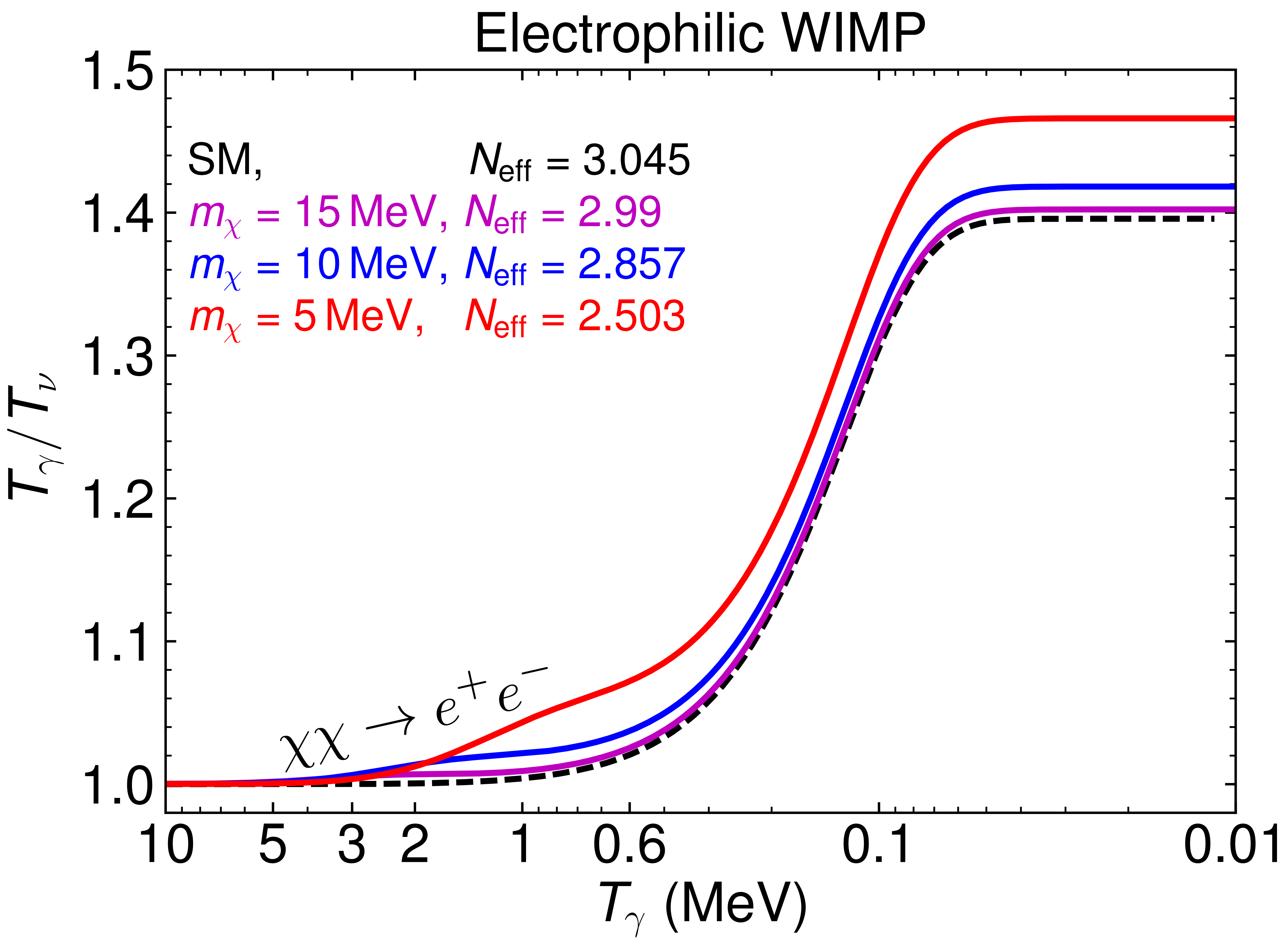
Impact of Thermal Dark Matter



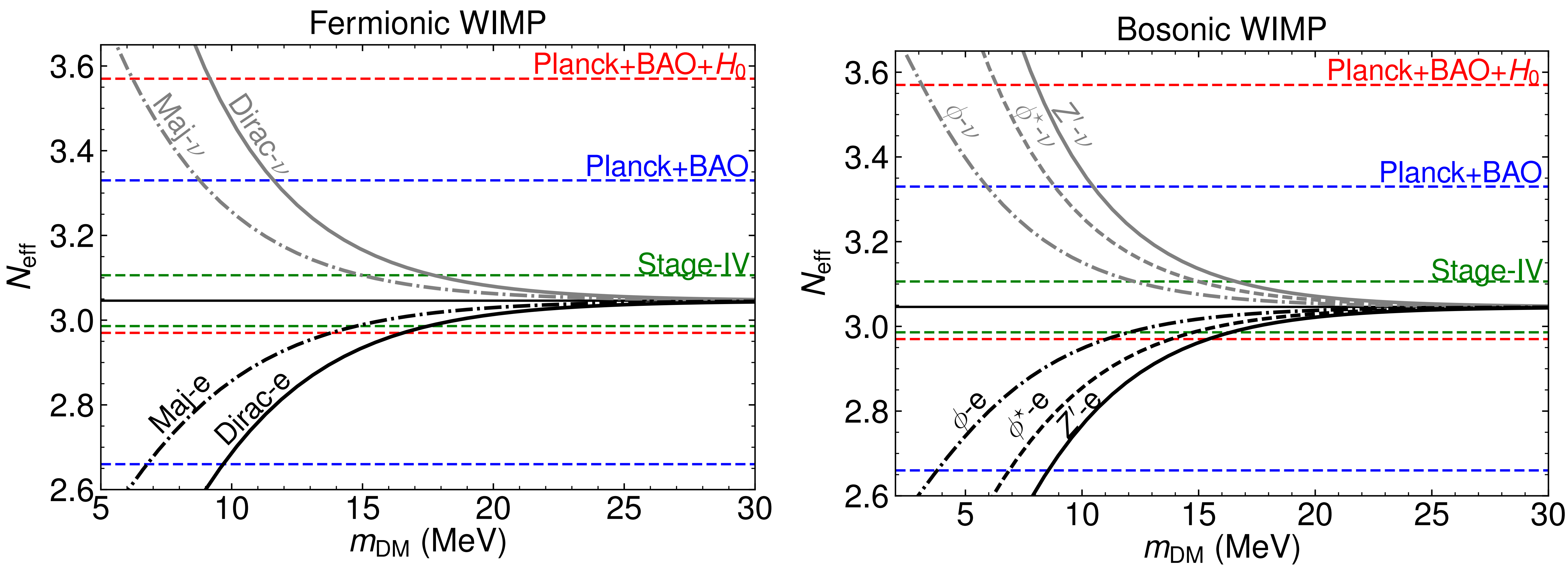
Neutrinophilic Relic: N_{eff} > 3.045



Electrophilic Relic: $N_{eff} < 3.045$



Bounds on MeV scale Dark Matter



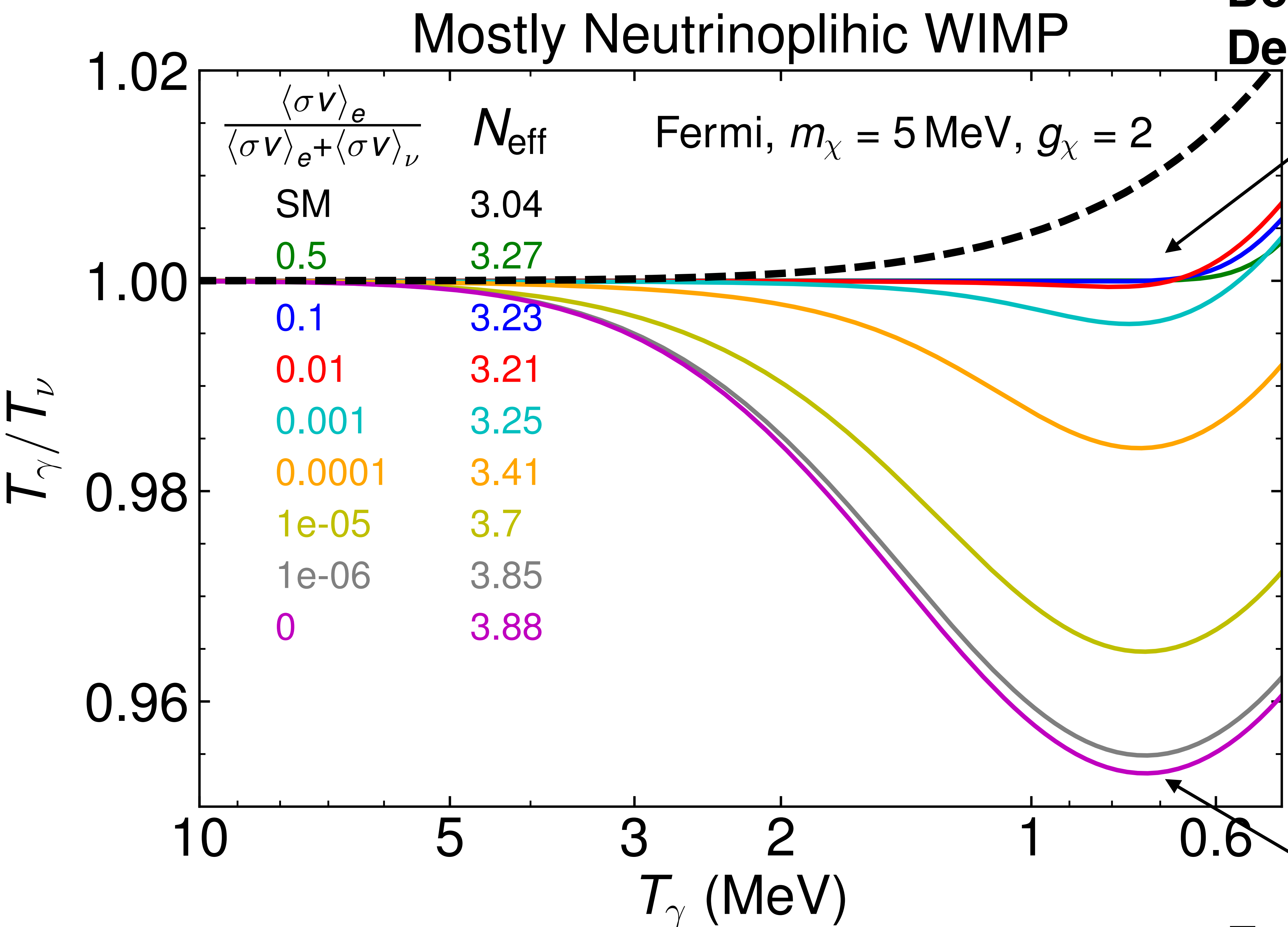
Lower bound on electrophilic and neutrinophilic thermal dark matter particles independent of their spin and annihilation being s-wave or p-wave

$$m_{\rm DM} > 3\,\rm MeV$$ at 95%CL

Particularly relevant bound for p-wave annihilating relics to electrons and for both s-wave and p-wave annihilating relics to neutrinos.

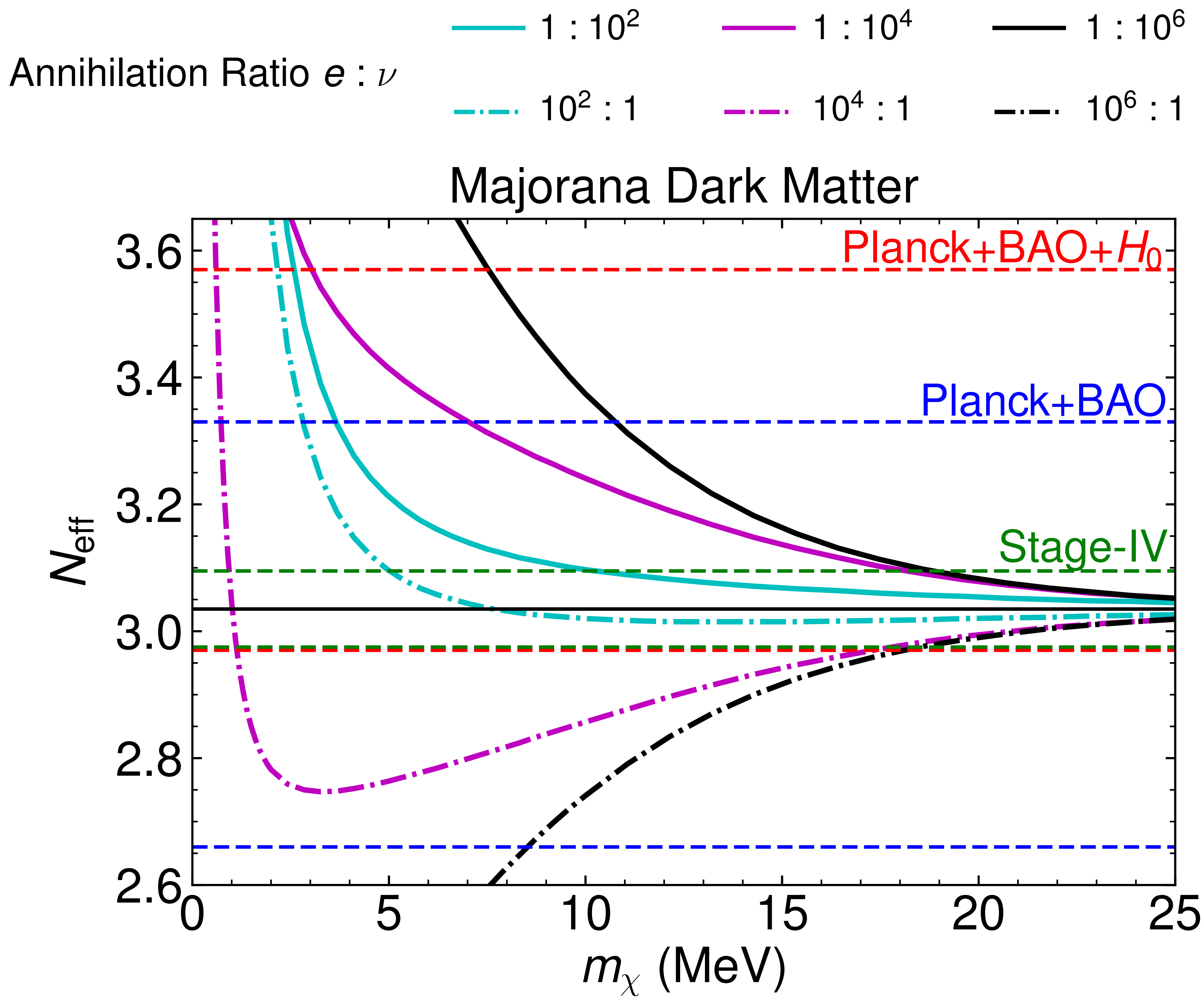
Generic Thermal Dark Matter

Delayed neutrino Decoupling



Entropy Release

Generic Thermal Dark Matter



WIMPs that interact with electrons and neutrinos are more elusive to CMB observations

Summary and Conclusions

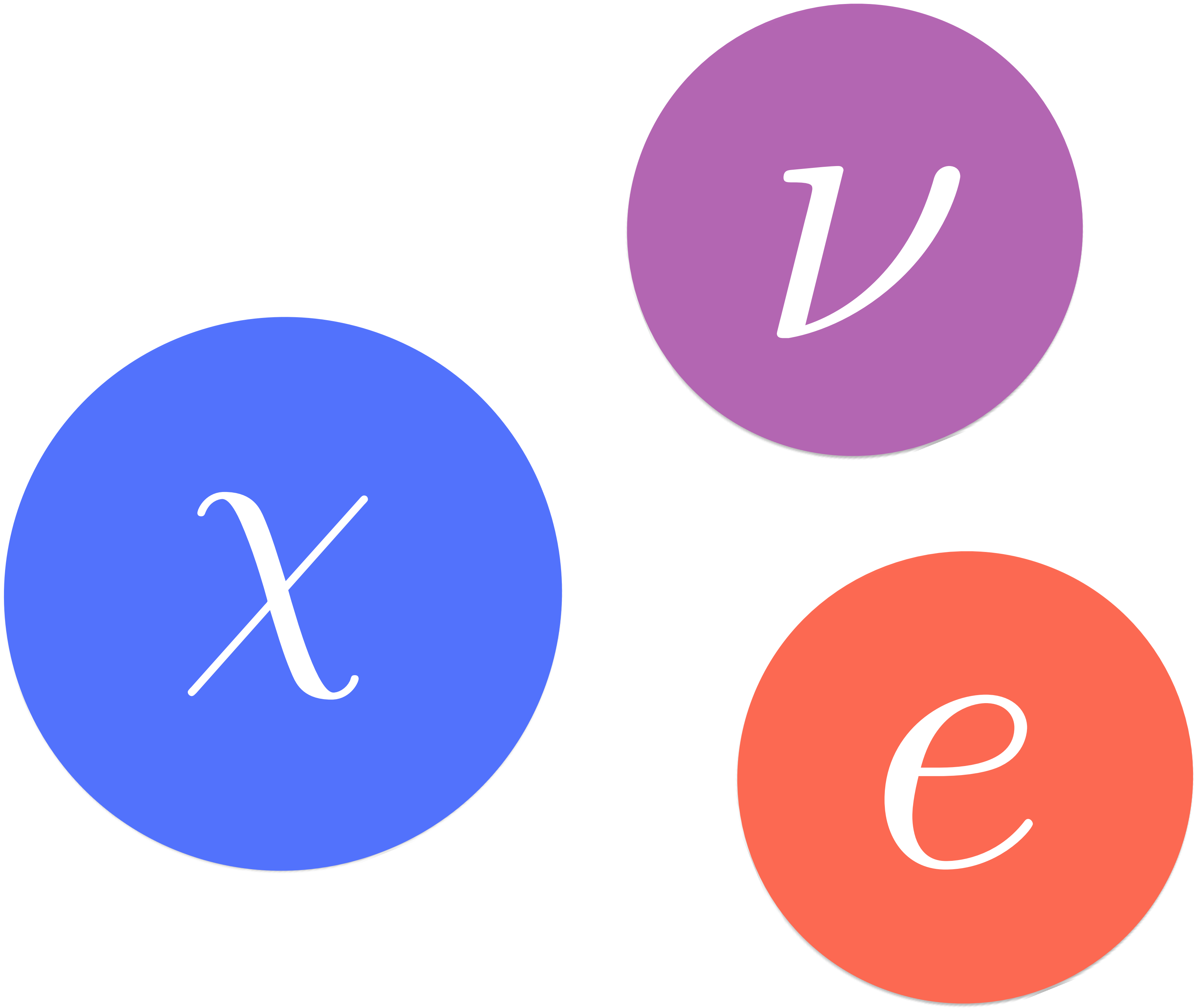
- **N_{eff} represents a powerful probe of the thermal history of the early Universe. 1% precision expected in the upcoming future. This will represent a strong constraint on BSM physics.**

- **Developed a simplified, fast and precise approach to the neutrino decoupling, *i.e.* to N_{eff} and BBN. Could be useful to test many BSM models.**

- **Thermal Dark Matter:**
  - **Lower bound on the Dark Matter mass of** $m_{\rm DM} > 3\,{\rm MeV}$
  - **Generic light WIMPs tend to delay the process of neutrino decoupling and are mode elusive to CMB observations**

Thank you for your attention!

Time for questions and comments

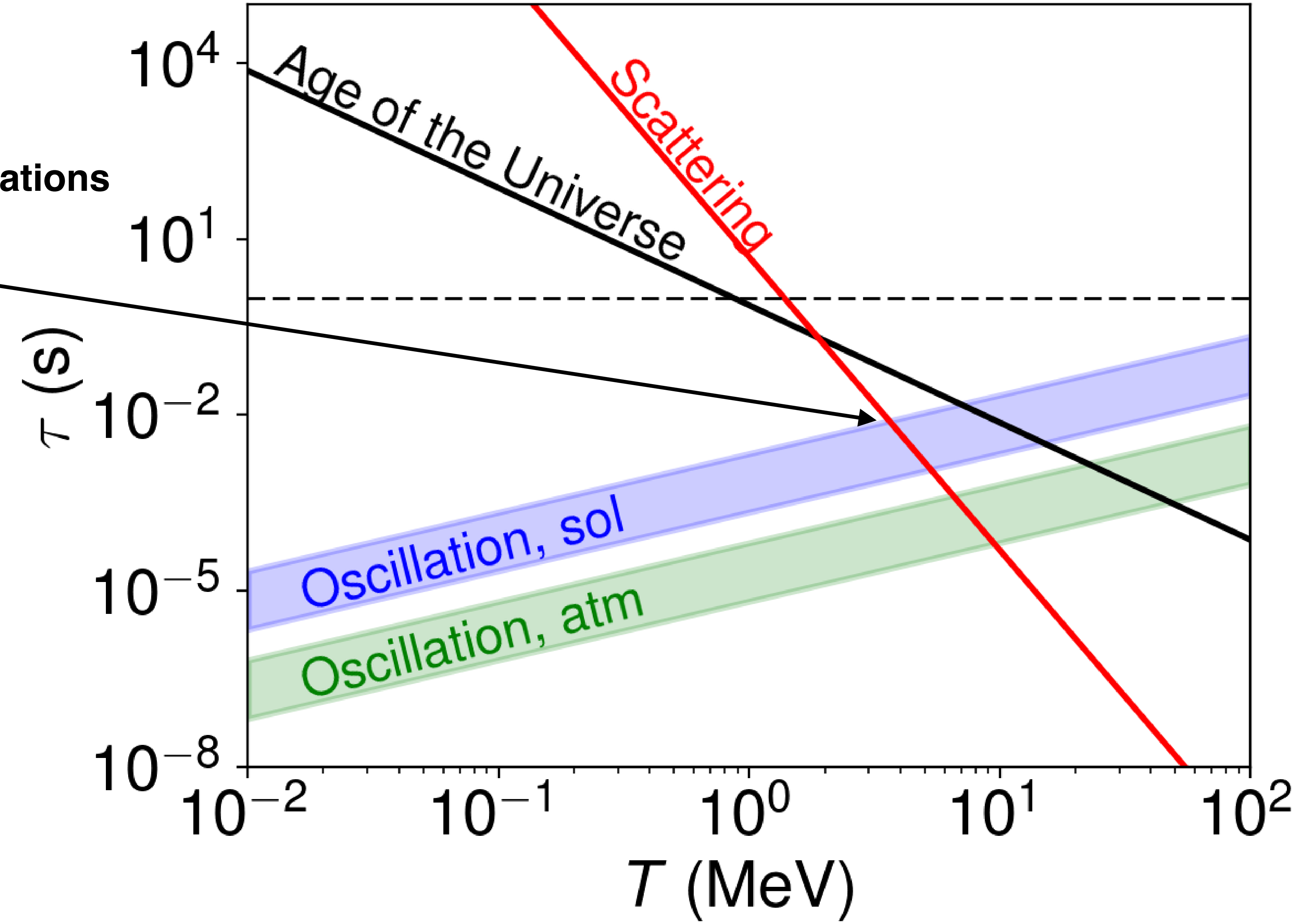


Check the code at: https://github.com/MiguelEA/nudec_BSM

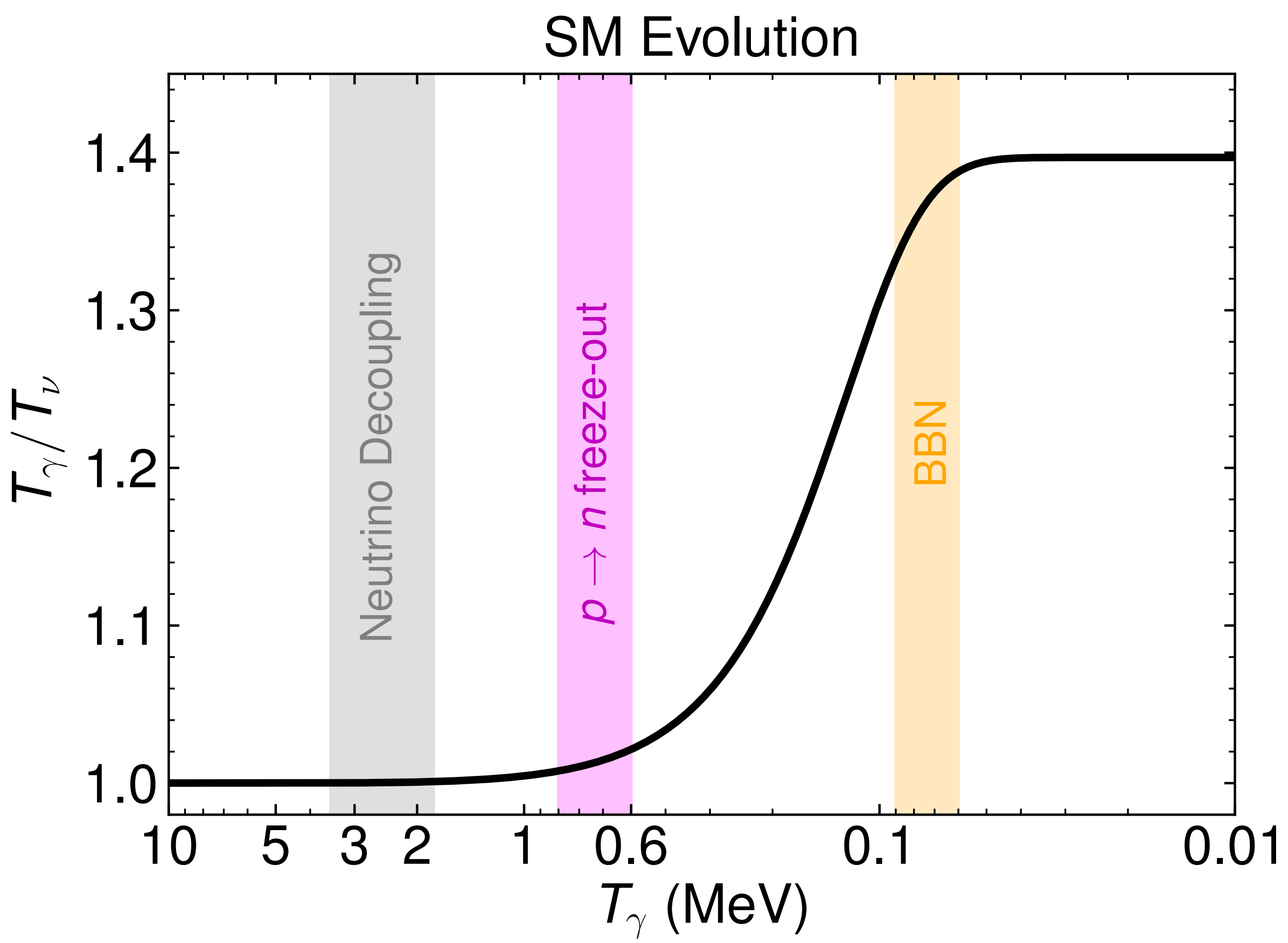
Back UP

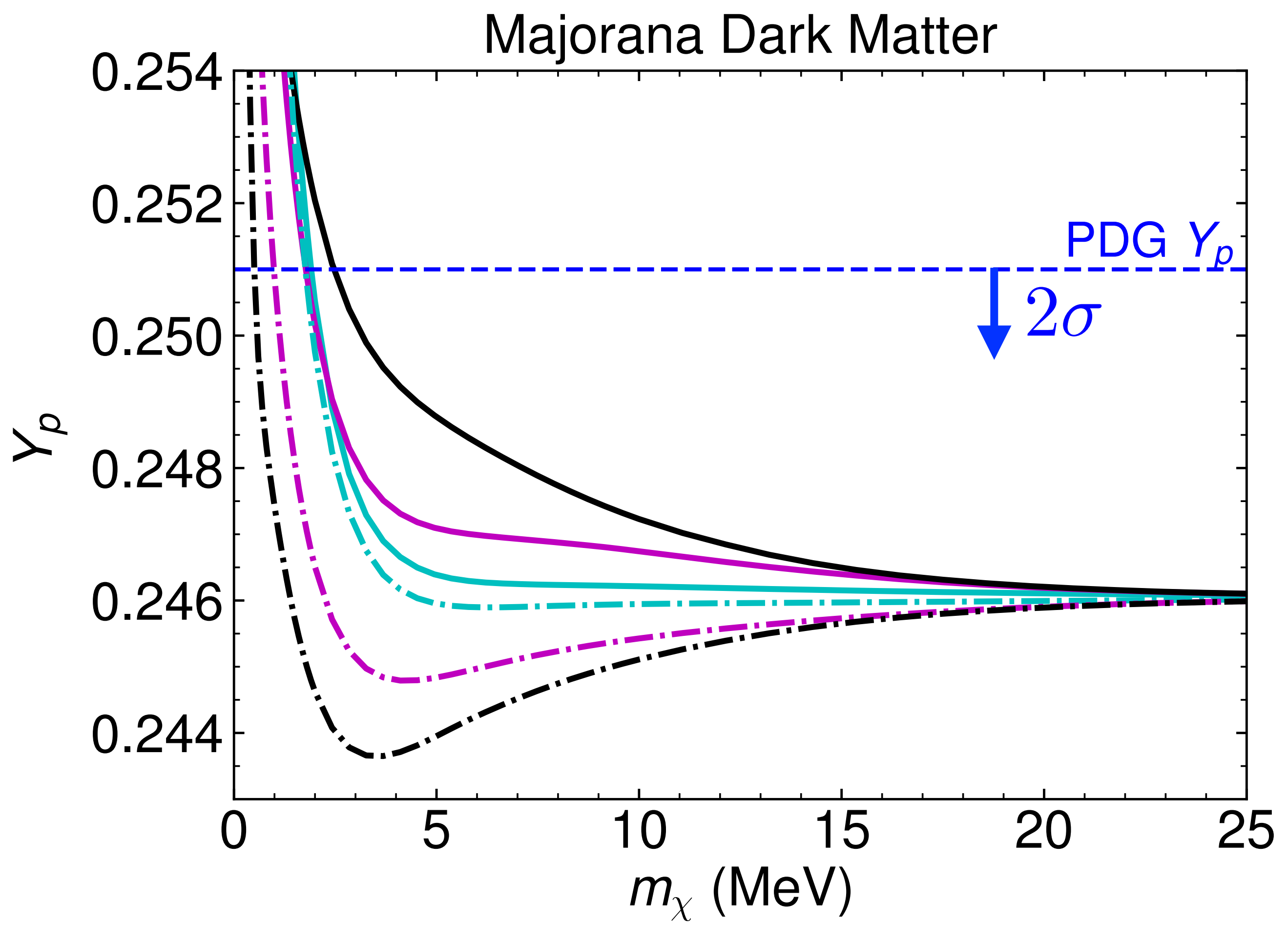
Neutrino Oscillations

Neutrino Oscillations become active



What about BBN?





$$D/H|_p = (2.569 \pm 0.027) \times 10^{-5} \qquad Y_p = 0.245 \pm 0.003$$

Percent precision on the primordial element abundances!

Would be very interesting to code the evolution in:

PArthENoPE 1712.04378
AlterBBN 1806.11095
PRIMAT 1801.08023

Neutrino Decoupling with Dark Matter

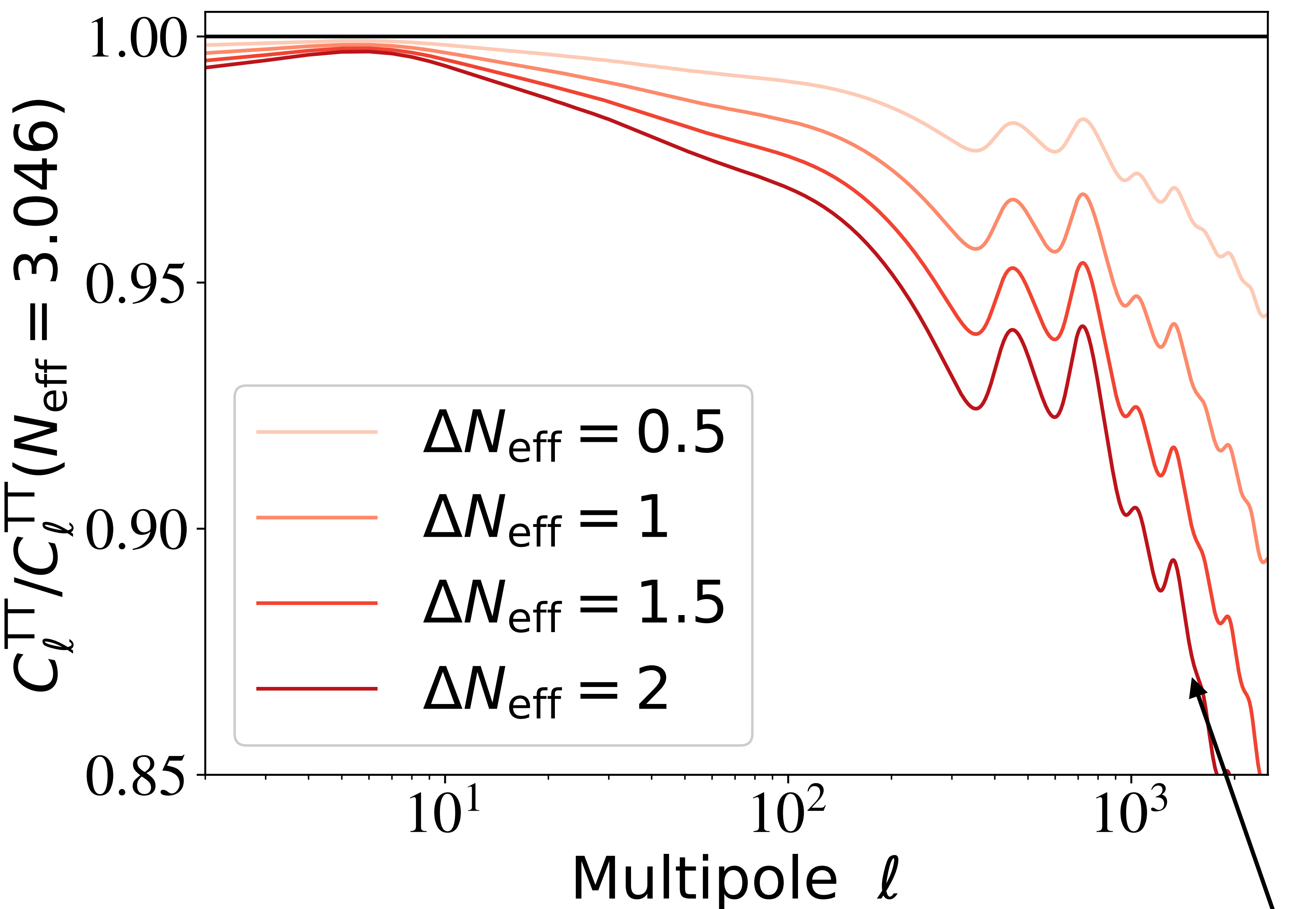
$$\frac{\delta \rho_\chi}{\delta t} \simeq m_\chi \frac{\delta n_\chi}{\delta t} \simeq -m_\chi \left<\sigma v\right> \left(n_\chi^2 - n_\chi^{2\,\mathrm{eq}}\right) \,.$$

$$\left.\frac{\delta \rho_\chi}{\delta t}\right|_\nu = \frac{g_\chi^2 m_\chi^5}{4\pi^4} \left<\sigma v\right>_{\chi\chi\to\bar{\nu}\nu} \left[T_\nu^2 \, K_2^2\left[\frac{m_\chi}{T_\nu}\right] - T_\gamma^2 \, K_2^2\left[\frac{m_\chi}{T_\gamma}\right]\right]$$

$$\frac{m_\chi}{T} \simeq 6.6 + \frac{1}{2}\log\left[\frac{\left<\sigma v\right>_{\chi\chi\to\bar{\nu}\nu}}{10^{-3}\times\left<\sigma v\right>_{\mathrm{WIMP}}} \frac{10\,\mathrm{MeV}}{m_\chi} \frac{g_\chi^2}{4}\sqrt{\frac{10.75}{g_\star}}\right] + 2\log\left[\frac{m_\chi/T}{6.6}\right]$$

N_{eff} at the CMB

PDG review, Lesgourgues & Verde



CMB Stage IV

$\ell_{max}^{TT} \sim 3000$

$\ell_{max}^{pol} \sim 5000$

Genuine effect of a change in Neff