

Title: Thermal Relics Below an MeV

Date: Dec 05, 2017 01:00 PM

URL: <http://pirsa.org/17120018>

Abstract: <p>I will discuss a class of models in which thermal dark matter is lighter than an MeV. If dark matter thermalizes with the Standard Model below the temperature of neutrino-photon decoupling, constraints from measurements of the effective number of neutrino species are alleviated. This framework motivates new experiments in the direct search for sub-MeV thermal dark matter and light force carriers.</p>

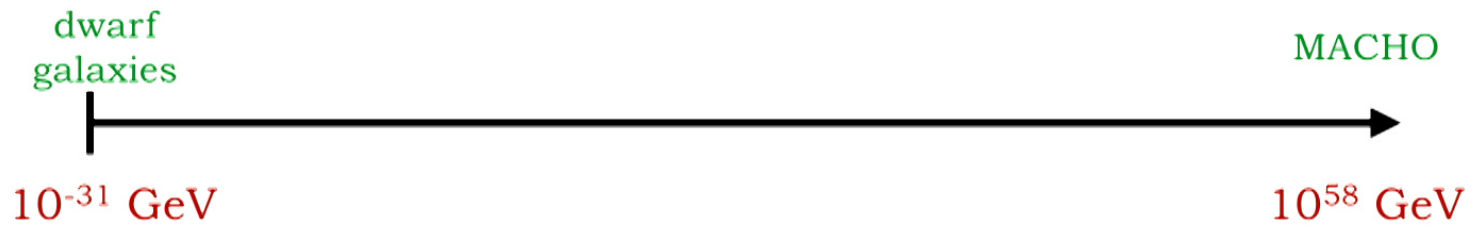
Thermal Relics Below an MeV

ASHER BERLIN

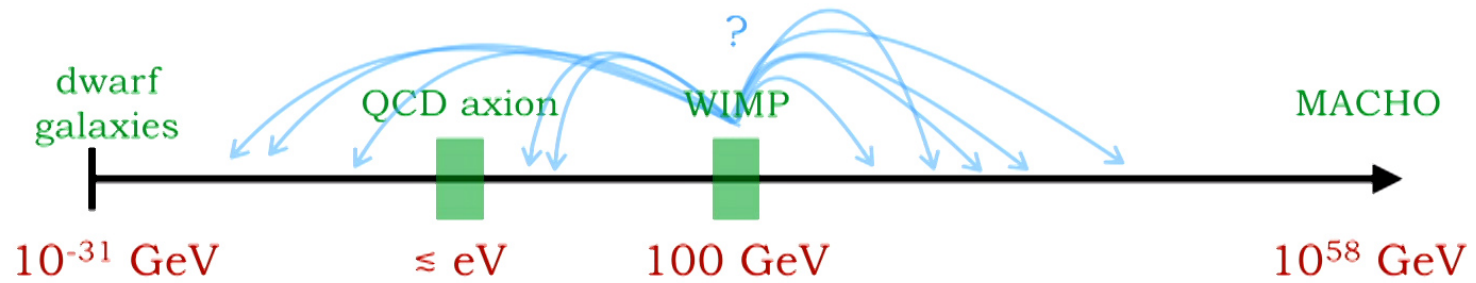
Perimeter Institute
December 5, 2017

Collaboration with Nikita Blinov, arXiv: 1706.07046

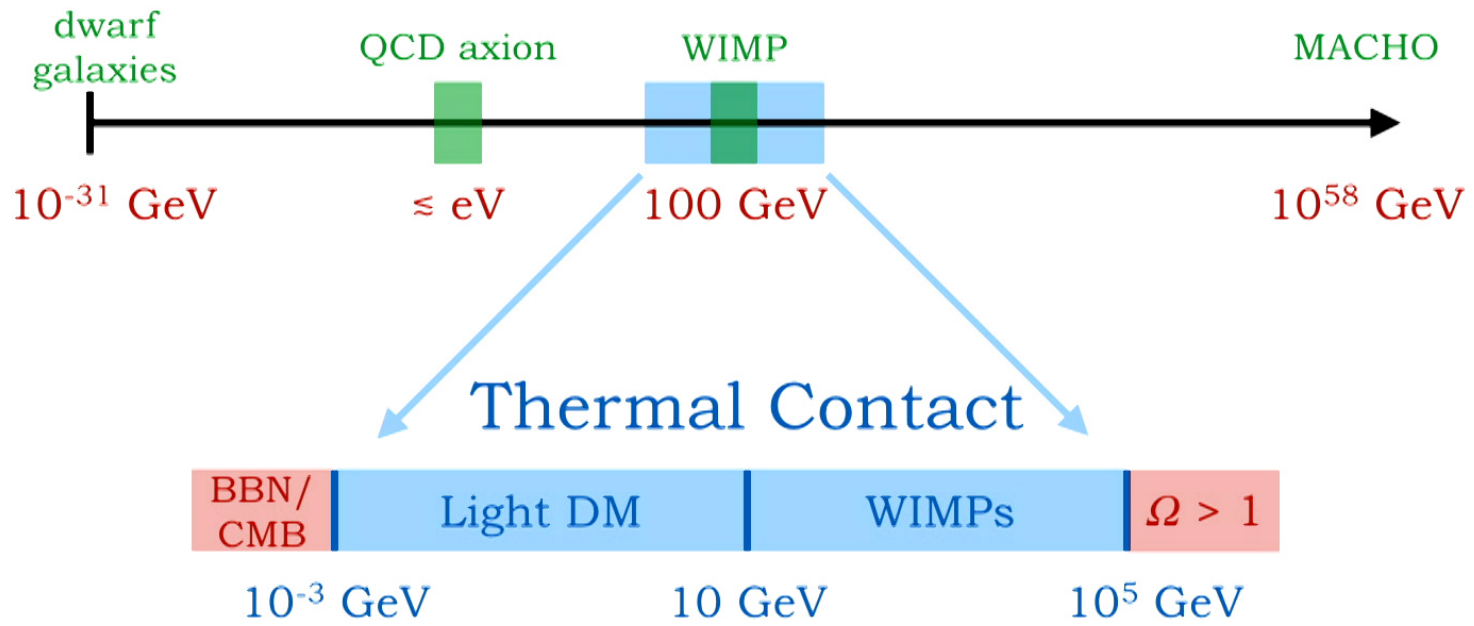
Dark Matter Mass



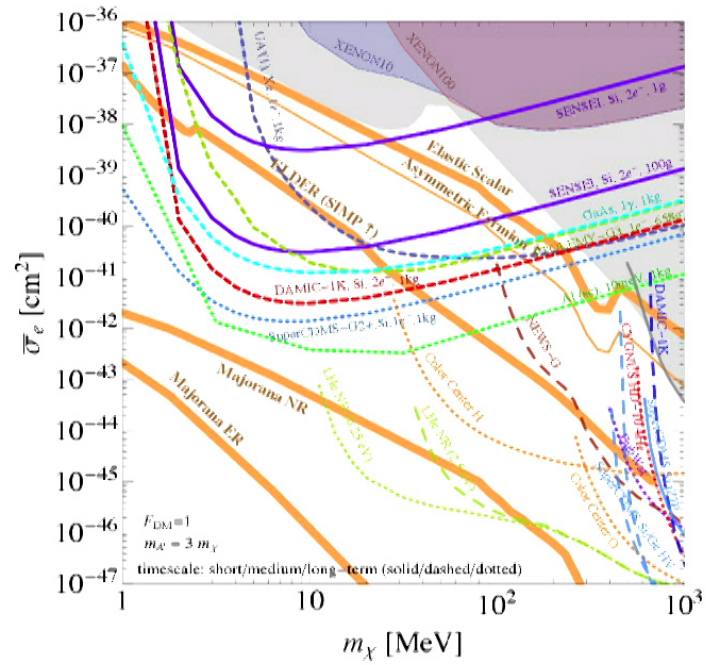
Dark Matter Mass



Dark Matter Mass



Cosmic Visions



US Cosmic Visions Community Report,
arXiv: 1707.04591

thermal dark matter

noun

Definition of THERMAL DARK MATTER

: dark matter that acquired its cosmological abundance through thermal contact with the Standard Model bath at large temperatures.

First Known Use: 1970s



TOP DEFINITION

Thermal Dark Matter

Dark matter that was in full relativistic thermal glory with the Standard Model before freezing out.

Q: Is this a model of [thermal dark matter](#)?

A: Yes, it is.



Outline

I. Review of Sub-MeV Thermal Relics

II. A Way Out: Delayed Equilibration

III. Models

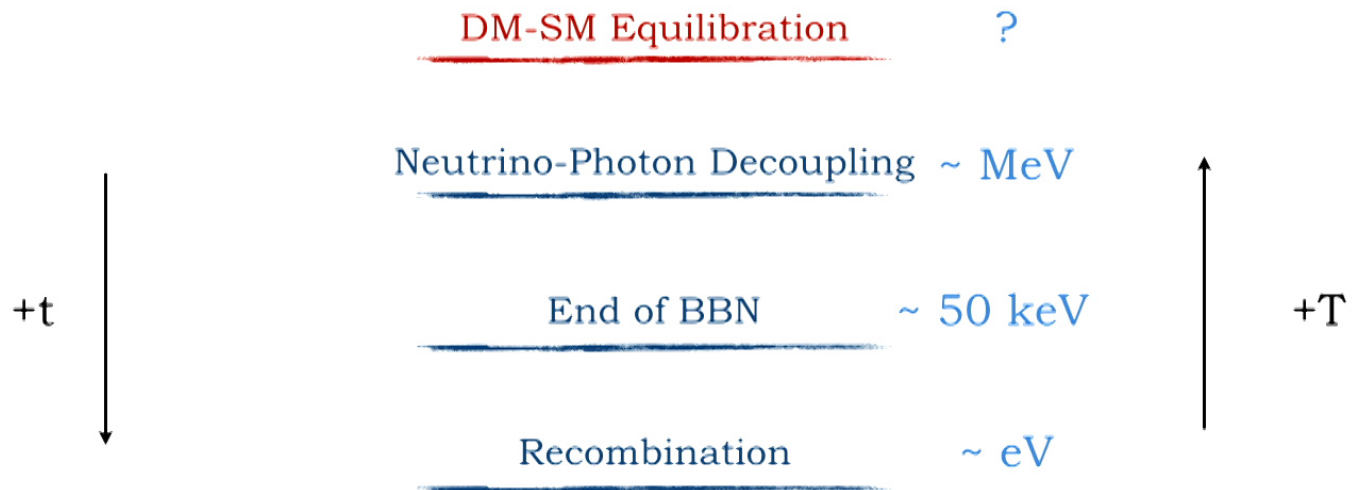
N_{eff}

(effective number of neutrino species)

$$H \sim \frac{\rho_{\text{rad}}^{1/2}}{m_{\text{Pl}}}$$

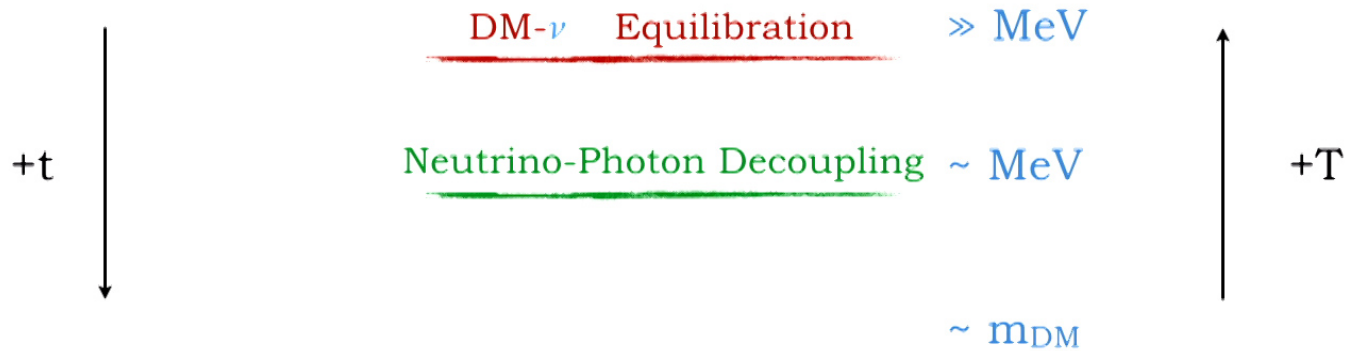
$$\rho_{\text{rad}} \equiv \rho_{\gamma} \left[1 + (7/8) (4/11)^{4/3} N_{\text{eff}} \right]$$

N_{eff}



$N_{\text{eff}} + \text{Light Relic}$

(standard assumption)

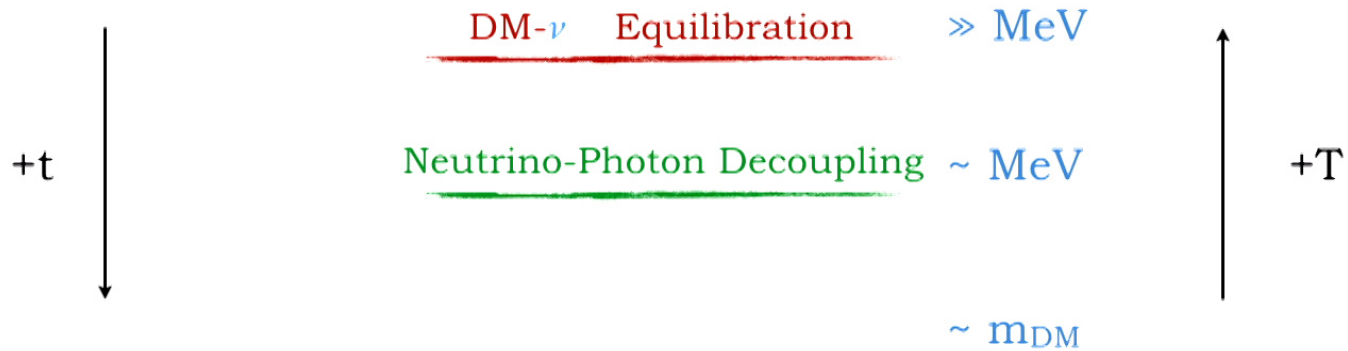


DM-Neutrino Equilibration

$$N_{\text{eff}} \simeq 3 \left(1 + \frac{4}{21} g_{\text{DM}} \right)^{4/3} \gtrsim 3.78$$

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Big Bang Nucleosynthesis (BBN)

${}^4\text{He}$

$$n e^+ \leftrightarrow p \bar{\nu}_e \implies T_{\text{FO}} \sim \text{MeV}$$

$$n/p \sim e^{-(m_n - m_p)/T_{\text{FO}}} \sim \frac{1}{7} \implies Y_p \sim 2(n/p)/(1 + n/p) \sim 1/4$$

D



$$B_D \sim 2 \text{ MeV} \quad , \quad \eta \sim 10^{-10} \implies \text{deuterium "bottleneck" until } T \sim 100 \text{ keV}$$

deuterium burning, $D \text{}^3\text{He} \rightarrow p \text{}^4\text{He}$ and $D p \rightarrow \gamma \text{}^3\text{He}$, until $T \sim 50 \text{ keV}$

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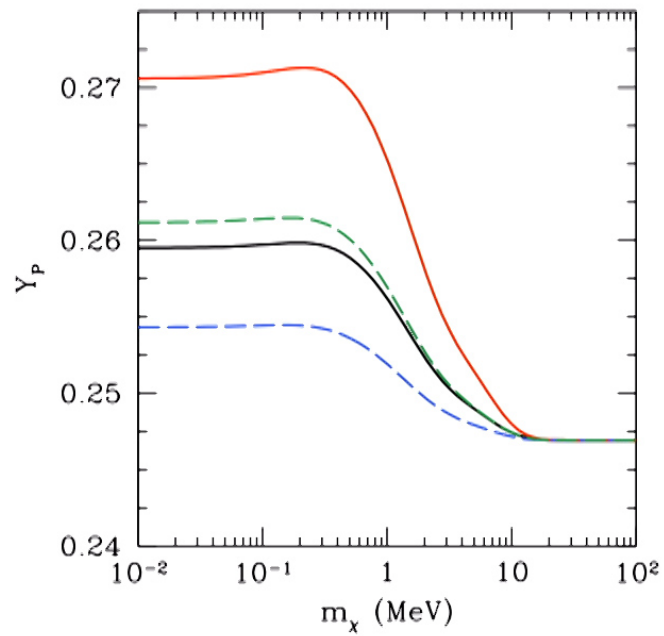
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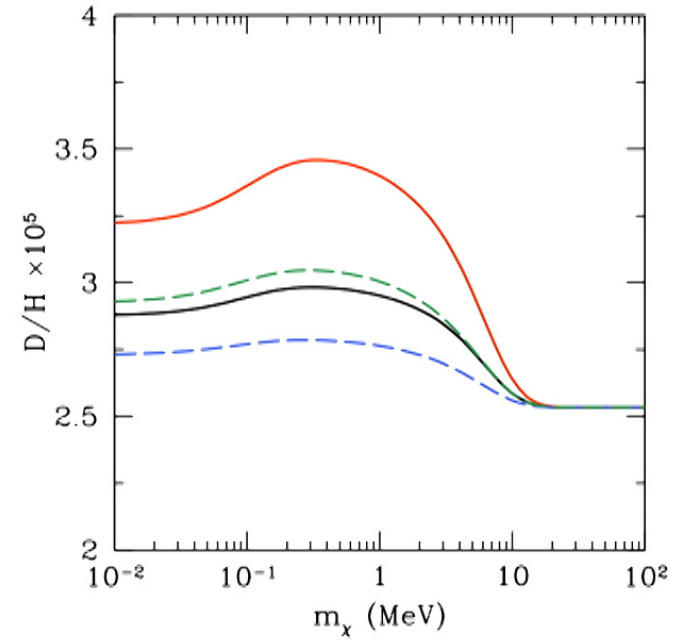
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BBN + N_{eff}



←
 N_{eff} increasing

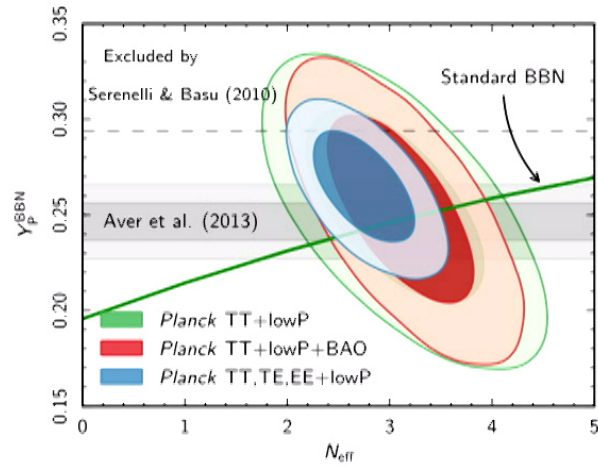
$$\delta Y_p \simeq 0.013 \delta N_{\text{eff}}$$



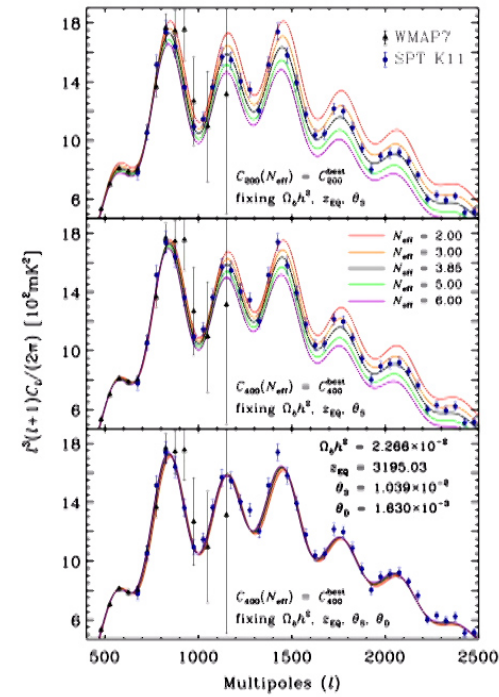
←
 N_{eff} increasing

K. Nollett, G. Steigman, arXiv:1411.6005
Cyburt et al., arXiv:1505.01076

CMB + N_{eff}



$$\frac{\theta_d}{\theta_s} \sim \frac{r_d}{r_s} \sim \sqrt{\frac{H}{n_e \sigma_T}}$$



$$N_{\text{eff}} (\text{CMB}) \simeq 3.15 \pm 0.23$$

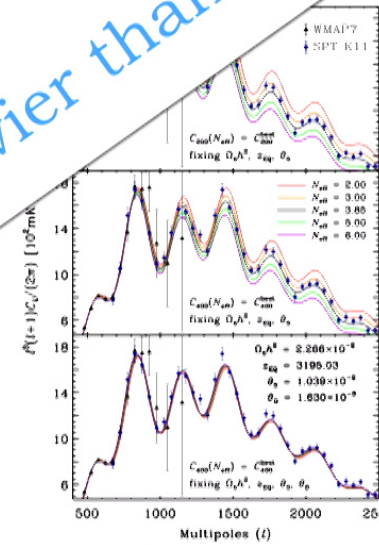
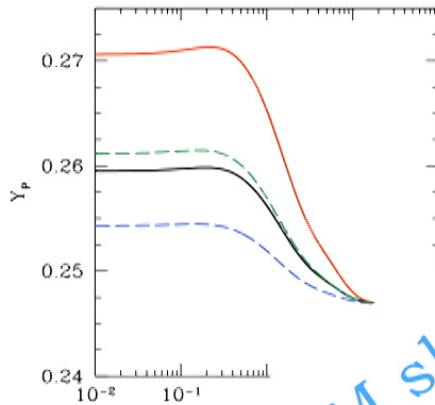
Planck, arXiv:1502.01589

Z. Hou, et al. , arXiv:1104.2333

Sub-MeV: BBN + CMB

$$N_{\text{eff}} (\text{BBN}) \simeq 2.85 \pm 0.28$$

$$N_{\text{eff}} (\text{CMB}) \simeq 3.23$$



“Thermal DM should be heavier than an MeV”

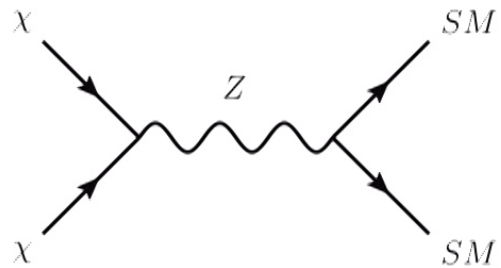
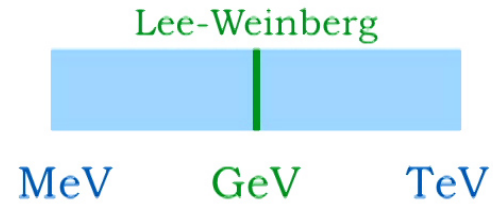
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C. Nollett, G. Steigman, arXiv:1411.6005

Z. Hou, et al. , arXiv:1104.2333

How ubiquitous is
DM-SM Equilibration Before
Neutrino-Photon Decoupling ?

Light Mediators



$$\sigma v \lesssim \frac{m_\chi^2}{m_Z^4} \implies m_\chi \gtrsim \frac{m_Z^2}{(T_{\text{eq}} m_{\text{pl}})^{1/2}} \sim \text{GeV}$$

Sub-GeV thermal DM requires light mediators: $m_\varphi \sim m_\chi$

B. Lee and S. Weinberg,
Phys.Rev.Lett. 39 (1977) 165-168

C. Boehm and P. Fayet
arXiv: hep-ph/0305261

Equilibration

Expansion

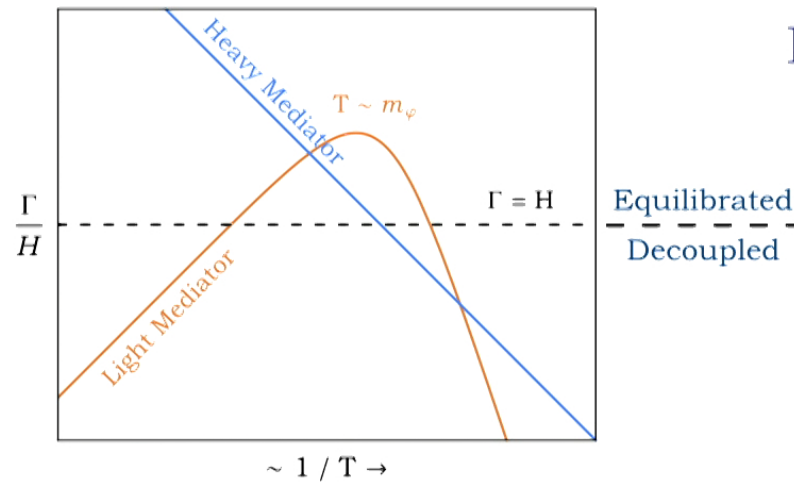
$$H \sim T^2$$

Light Mediator

$$\Gamma \sim T, \quad m_\varphi^2/T$$

Heavy Mediator

$$\Gamma \sim T^3/\Lambda^2$$



Equilibration

Expansion

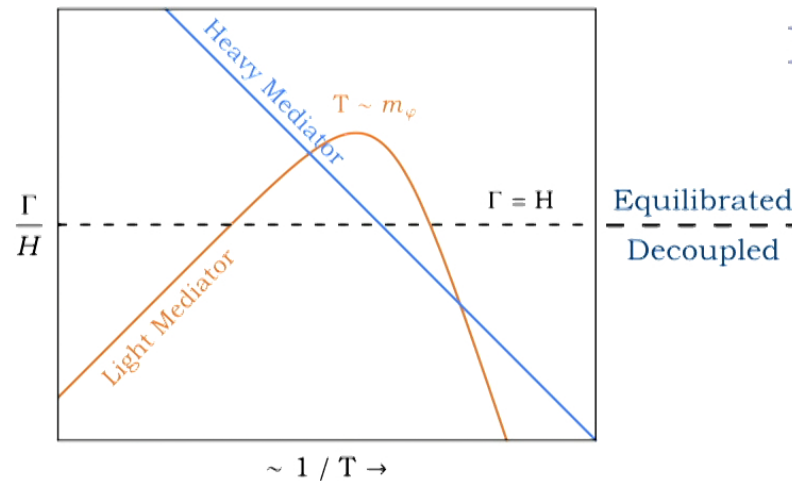
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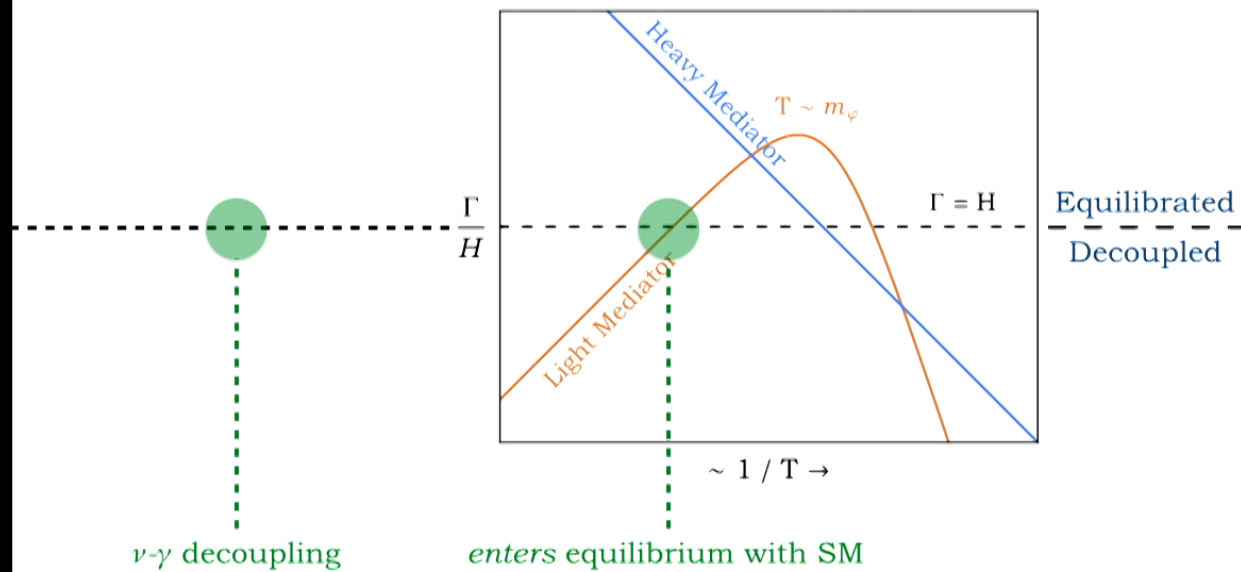
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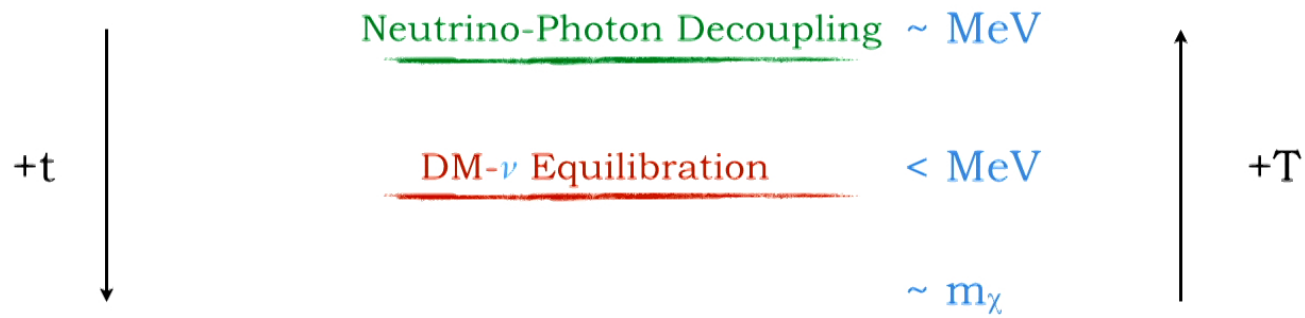
Light thermal DM naturally *enters* equilibrium
(for high enough T_{RH})

Equilibration



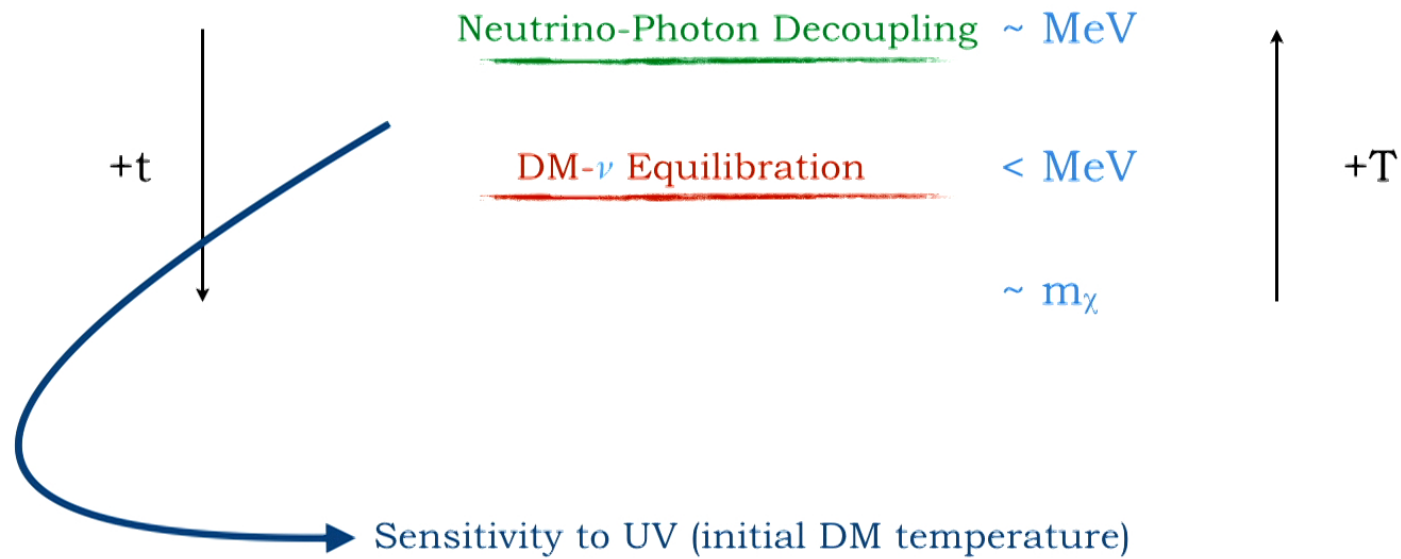
N_{eff}

(*non-standard assumption*)



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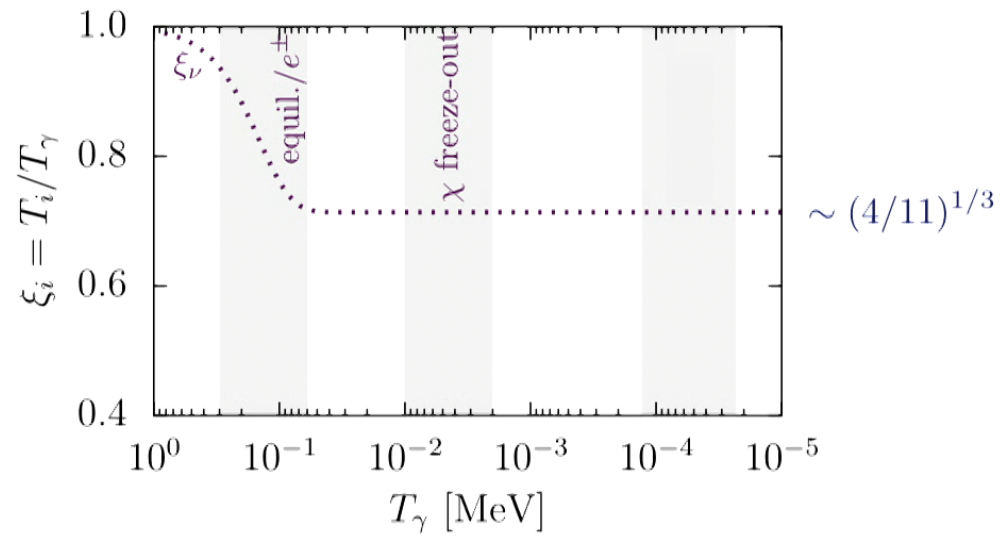


N_{eff}

$$T_X^{\text{initial}} \ll T_\gamma$$

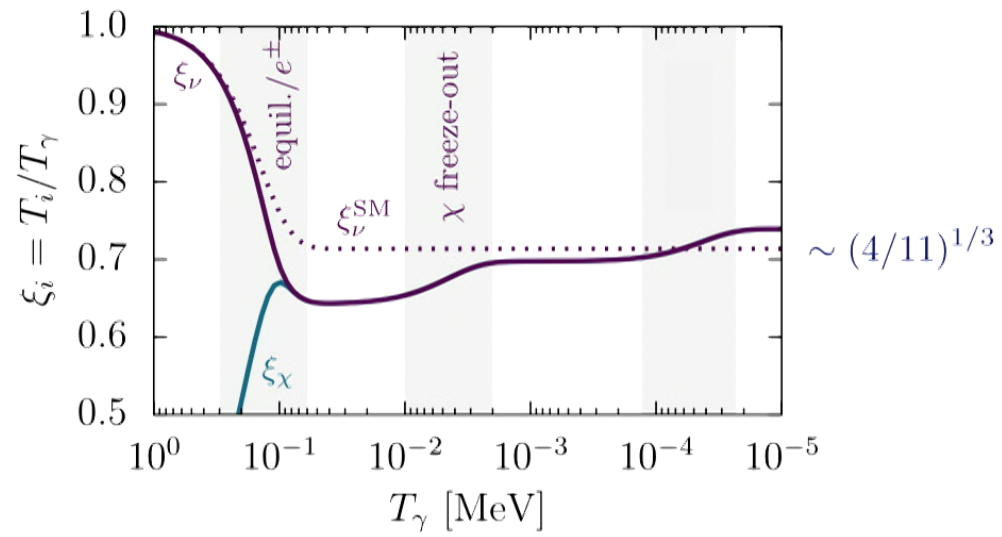
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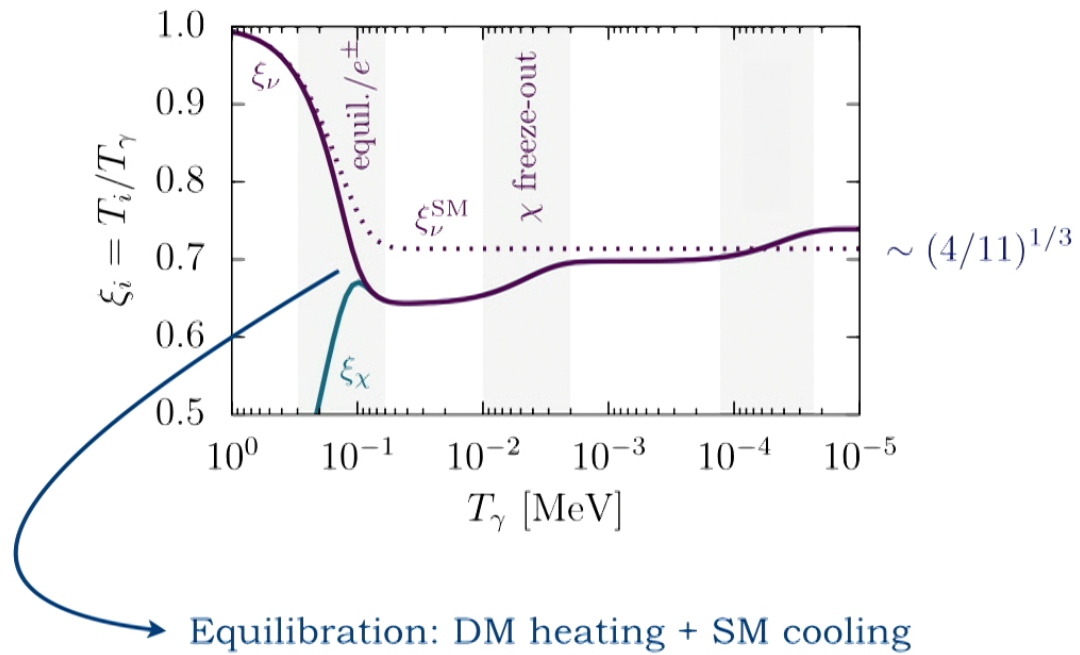
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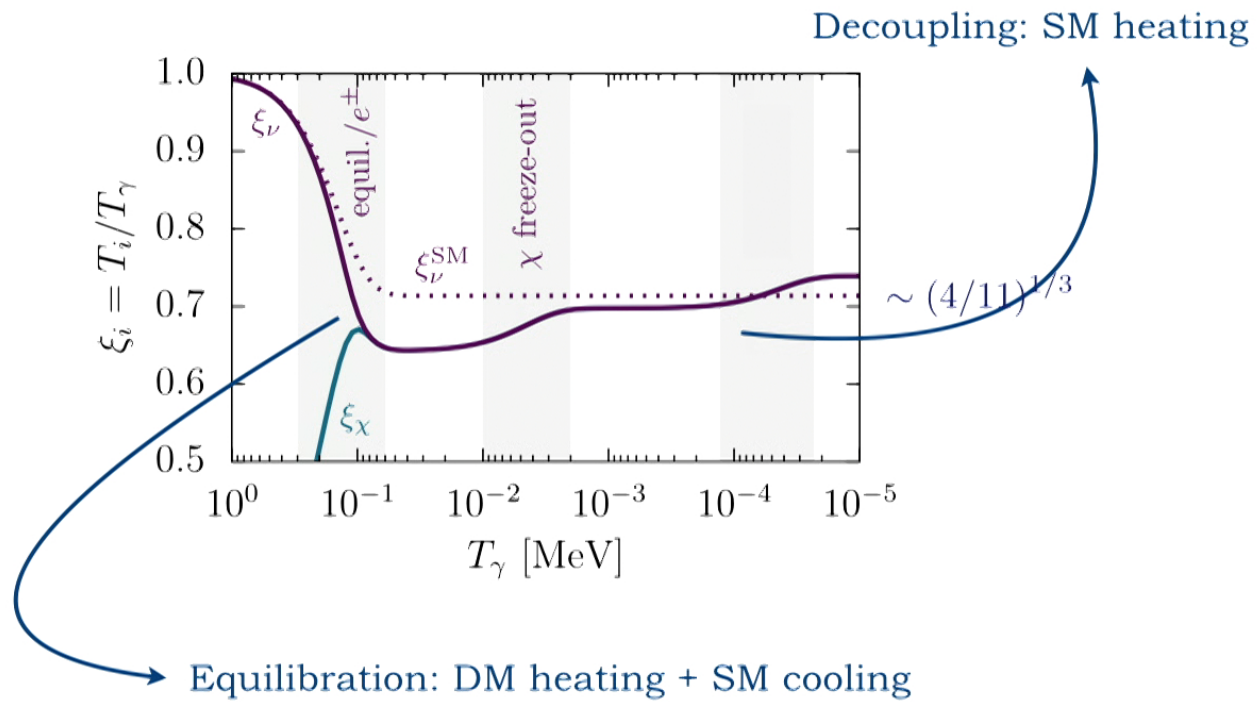
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N_{eff}

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$$\xi_x^0 \equiv T_x/T_\gamma \quad (\text{before equilibration})$$

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$$N_{\text{eff}} \simeq \left\{ \begin{array}{l} 3 \left(1 + \frac{g_*^X}{g_*^\nu} \xi_X^{0.4} \right), \quad T \gtrsim T^{X \text{ eq}} \quad (\text{uncoupled dark radiation}) \end{array} \right.$$

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(Conservation of comoving energy density)

$$N_{\text{eff}} \approx \begin{cases} 3 \left(1 + \frac{g_*^\chi}{g_*^\nu} \xi_\chi^{04} \right), & T \gtrsim T^{\chi \text{ eq}} & (\text{uncoupled dark radiation}) \\ 3 \left(1 + \frac{g_*^\chi}{g_*^\nu} \xi_\chi^{04} \right), & m_\chi \lesssim T \lesssim T^{\chi \text{ eq}} & (\text{coupled dark radiation}) \end{cases}$$

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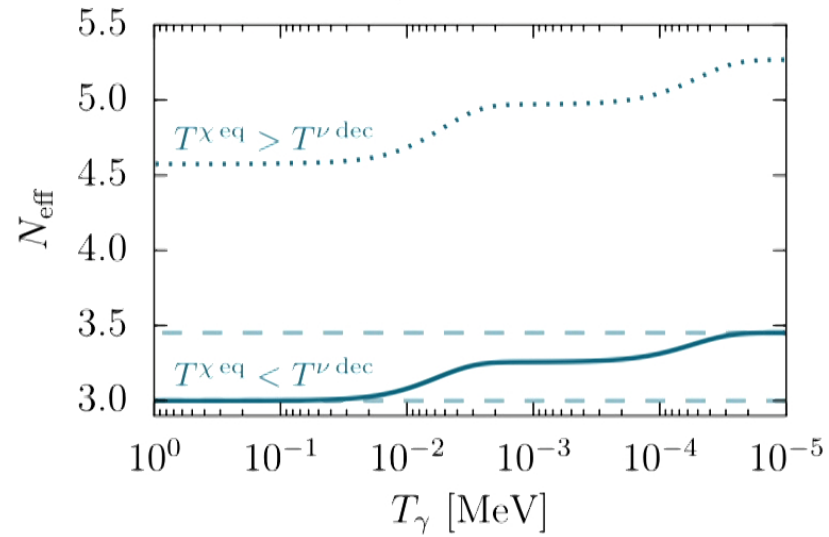
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N_{eff}

$$T_X^{\text{initial}} \ll T_\gamma$$

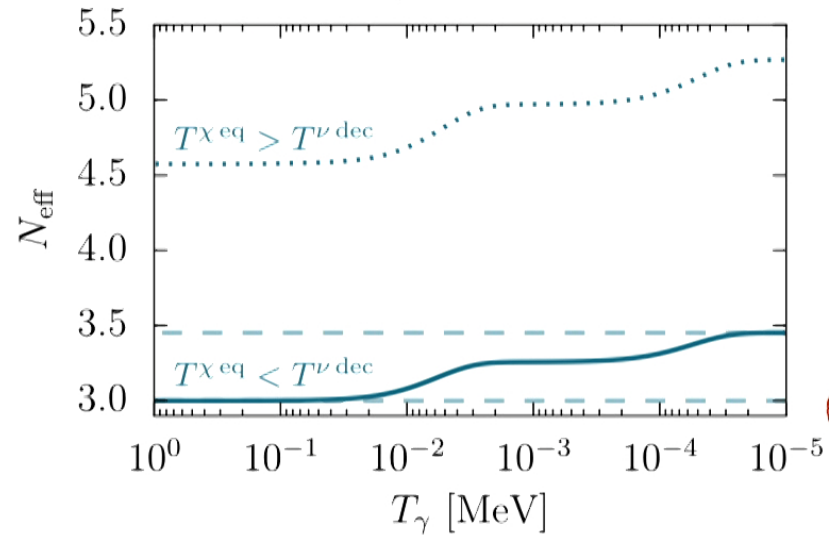


DM-Neutrino Equilibration

$$N_{\text{eff}} \simeq 3 \left(1 + \frac{4}{21} g_X \right)^{4/3} \gtrsim 3.18$$

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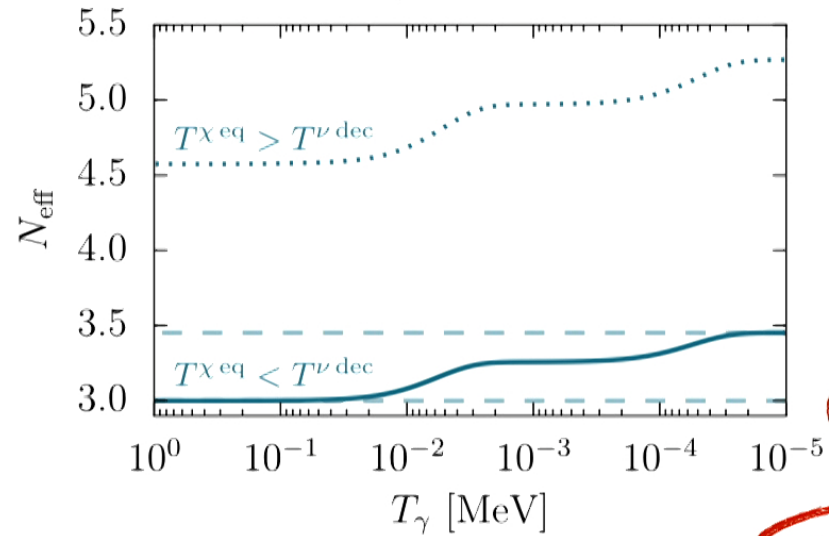
$g_x \lesssim \text{several}$

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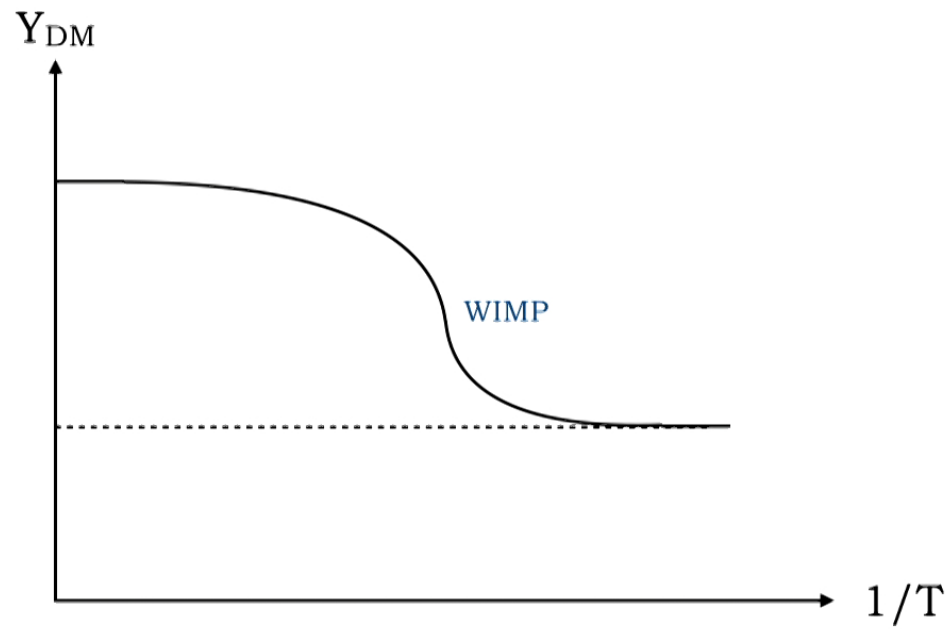
$g_x \lesssim \text{several}$

$\Delta N_{\text{eff}}(\text{CMB-S4}) \simeq \pm 0.027$

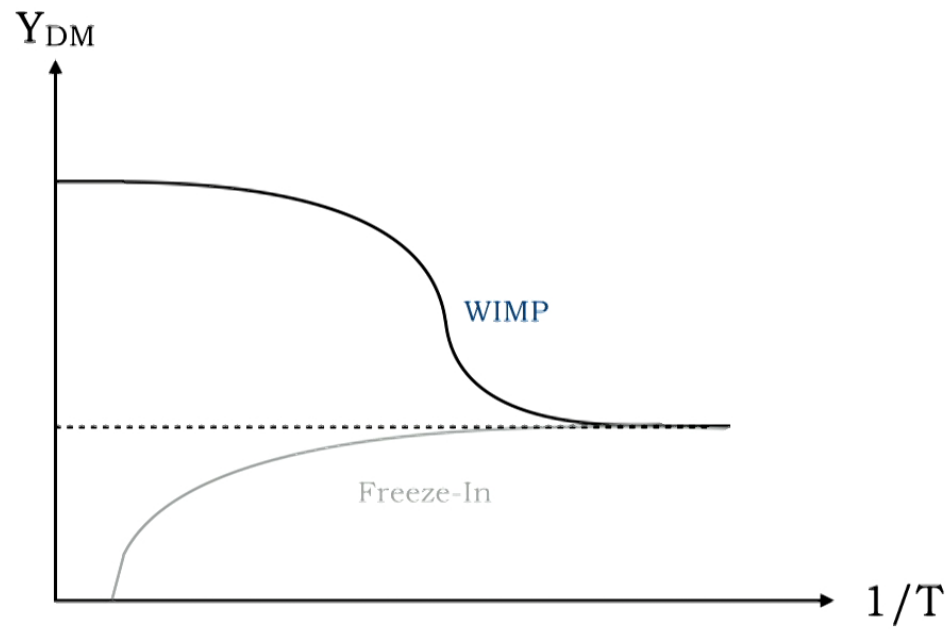
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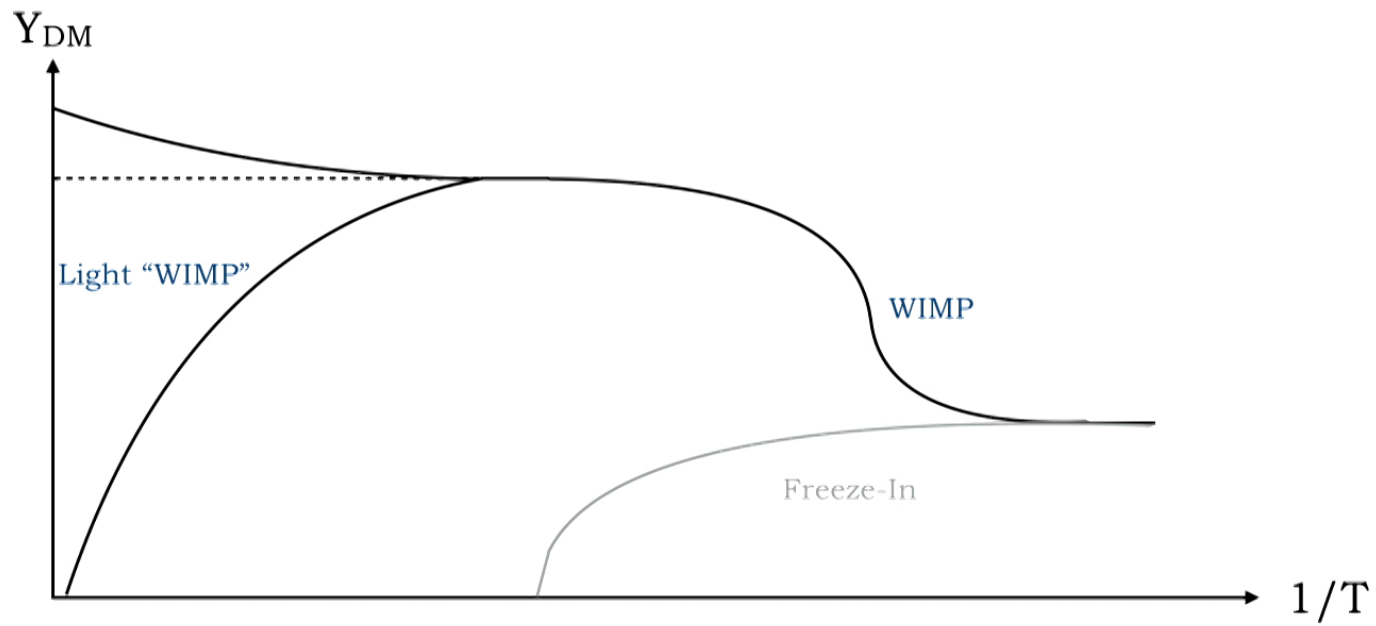
Thermal History



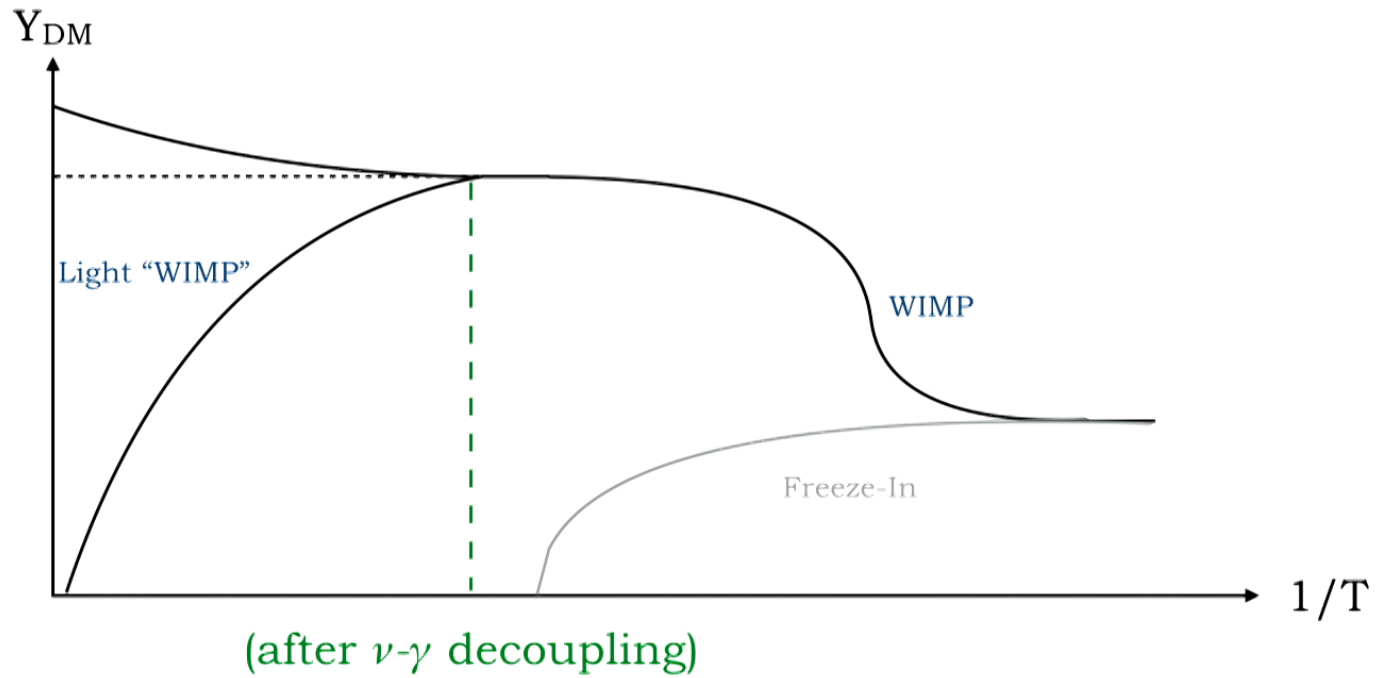
Thermal History



Thermal History



Thermal History



Delayed Equilibration

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$$\langle \sigma v \rangle_{\text{FO}} \sim \frac{\alpha_{\text{FO}}^2}{m_\chi^2} \implies m_\chi \sim \alpha_{\text{FO}} (T_{\text{eq}} m_{\text{Pl}})^{1/2}$$

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$$T_{\text{KE}} \lesssim T_{\nu-\gamma \text{ dec}} \sim 2 \text{ MeV} \implies m_\chi \lesssim \text{keV} \times (\alpha_{\text{FO}}/\alpha_{\text{KE}})$$

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$$\text{WDM bounds} \implies m_\chi \gtrsim \text{keV} \implies \alpha_{\text{FO}} \gg \alpha_{\text{KE}}$$

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Secluded DM

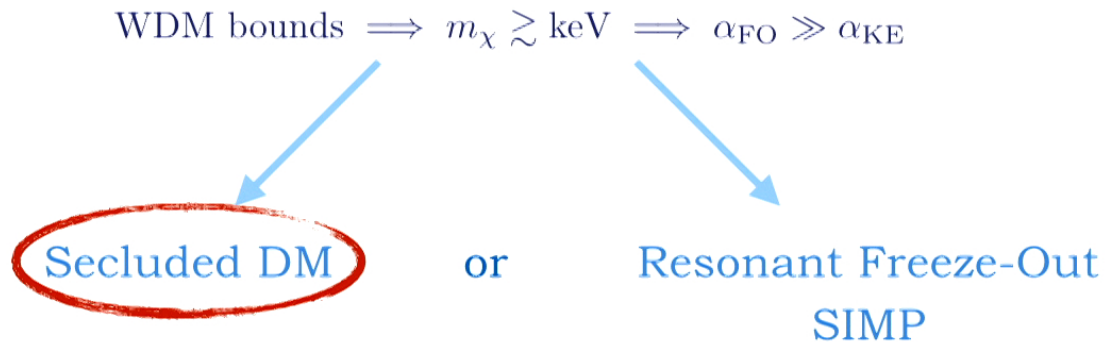
or

Resonant Freeze-Out
SIMP

Delayed Equilibration

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A Toy Model

A Toy Model

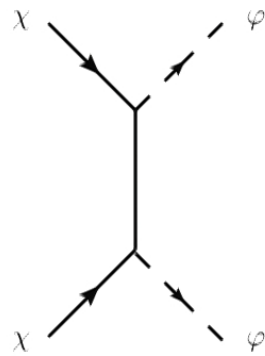
$$\mathcal{L} \sim \varphi (\lambda_X \chi^2 + \lambda_\nu \nu^2)$$

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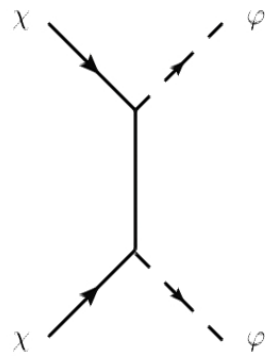
(Freeze-Out)

$$\lambda_X \sim 10^{-5} \times (m_X/\text{keV})^{1/2}$$

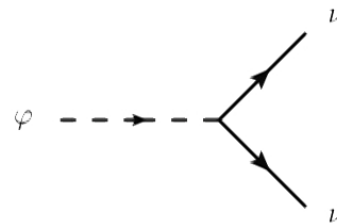
A Toy Model

$$\mathcal{L} \sim \varphi (\lambda_\chi \chi^2 + \lambda_\nu \nu^2)$$

$$m_\varphi \lesssim m_\chi$$



(Freeze-Out)



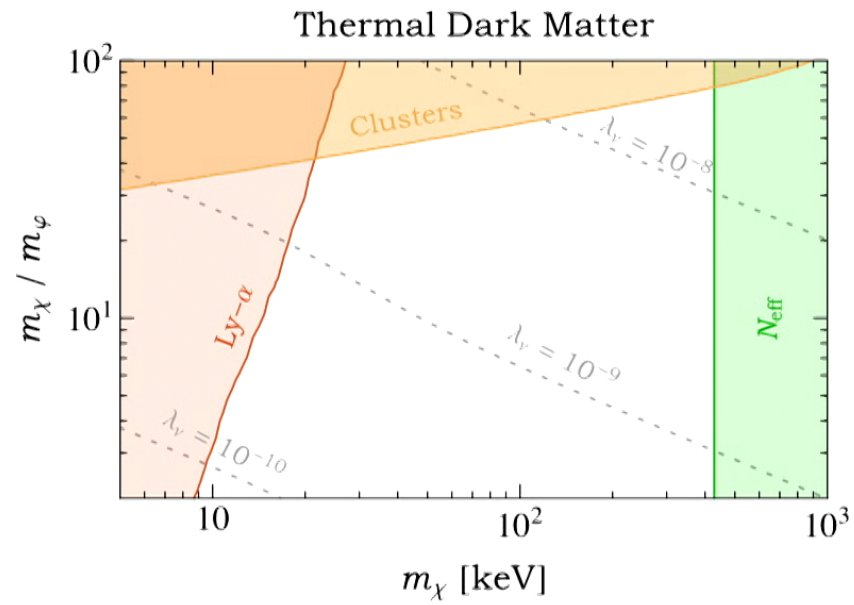
(Equilibration and Decay)

$$\lambda_\chi \sim 10^{-5} \times (m_\chi/\text{keV})^{1/2}$$

$$\lambda_\nu \sim 10^{-11} \times (m_\chi/m_\varphi) (m_\chi/\text{keV})^{1/2}$$

A Toy Model

$$\mathcal{L} \sim \varphi (\lambda_\chi \chi^2 + \lambda_\nu \nu^2)$$



A More Complete Model

(work in progress)

A More Complete Model

$$-\mathcal{L} \supset y_\nu L N H + \frac{y_N}{2} \sigma N^2 + \text{h.c.} \quad (\text{neutrino sector})$$

(work in progress)

A More Complete Model

$$-\mathcal{L} \supset y_\nu L N H + \frac{y_N}{2} \sigma N^2 + \text{h.c.} \quad (\text{neutrino sector})$$

$$\sigma = \frac{1}{\sqrt{2}} (f + S + iJ) \quad (\text{pseudo-Goldstone Majoron})$$

(U(1)_L scale) ←

(work in progress)

A More Complete Model

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(U(1)_L scale) ←

$$m_N \sim y_N f \quad , \quad m_\nu \sim y_\nu^2 v^2 / m_N \quad (\text{seesaw})$$

(work in progress)

A More Complete Model

$$-\mathcal{L} \supset y_\nu L N H + \frac{y_N}{2} \sigma N^2 + \text{h.c.} \quad (\text{neutrino sector})$$

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(U(1)_L scale) ←

$$m_N \sim y_N f \quad , \quad m_\nu \sim y_\nu^2 v^2 / m_N \quad (\text{seesaw})$$

$$-\mathcal{L} \supset \frac{1}{2} \lambda_X \chi^2 \sigma + \text{h.c.} \quad (\text{dark matter sector})$$

(work in progress)

A More Complete Model

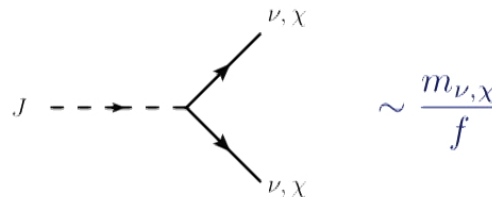
$$-\mathcal{L} \supset y_\nu L N H + \frac{y_N}{2} \sigma N^2 + \text{h.c.} \quad (\text{neutrino sector})$$

$$\sigma = \frac{1}{\sqrt{2}} (f + S + iJ) \quad (\text{pseudo-Goldstone Majoron})$$

(U(1)_L scale) ←

$$m_N \sim y_N f, \quad m_\nu \sim y_\nu^2 v^2 / m_N \quad (\text{seesaw})$$

$$-\mathcal{L} \supset \frac{1}{2} \lambda_X \chi^2 \sigma + \text{h.c.} \quad (\text{dark matter sector})$$

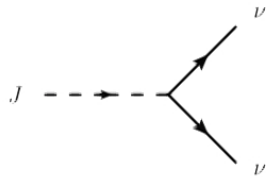


(work in progress)

MeV Motivation

Equilibration:

$$(m_\chi \sim m_J \sim T^{\text{KE}})$$

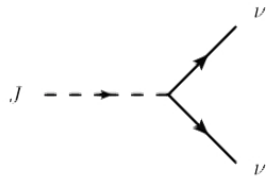


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MeV Motivation

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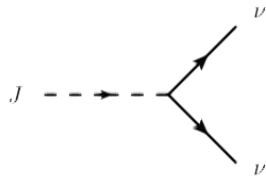
$$\Gamma(J \leftrightarrow \nu\nu) \sim \frac{m_\nu^2}{f^2} m_\chi \sim H \sim \frac{m_\chi^2}{m_{\text{Pl}}} \implies f^2 \sim \frac{m_\nu^2 m_{\text{Pl}}}{m_\chi} \quad (\text{A})$$

(work in progress)

MeV Motivation

Equilibration:

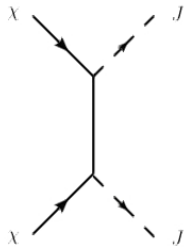
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Freeze-Out:

$$\sigma v \sim \frac{\alpha_{\text{FO}}^2}{m_\chi^2} \implies m_\chi \sim \alpha_{\text{FO}} (T_{\text{eq}} m_{\text{Pl}})^{1/2}$$

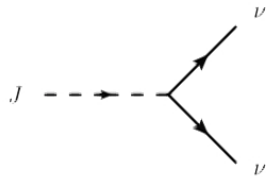


(work in progress)

MeV Motivation

Equilibration:

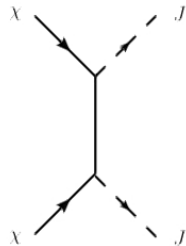
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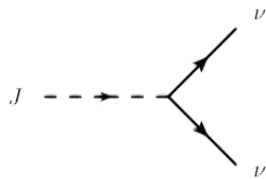
$$\sigma v \sim \frac{m_\chi^2}{f^4} \implies \alpha_{\text{FO}} \sim m_\chi^2 / f^2 \implies m_\chi \sim f^2 / (T_{\text{eq}} m_{\text{Pl}})^{1/2} \quad (\text{B})$$

(work in progress)

MeV Motivation

Equilibration:

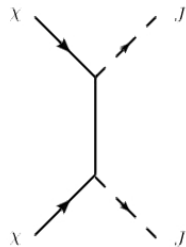
$$(m_\chi \sim m_J \sim T^{\text{KE}})$$



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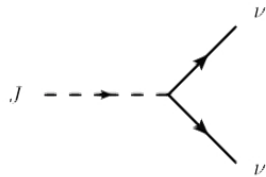
$$(\text{A} + \text{B}) \implies m_\chi \sim \left(\frac{m_{\text{Pl}}}{T_{\text{eq}}} \right)^{1/4} m_\nu$$

(work in progress)

MeV Motivation

Equilibration:

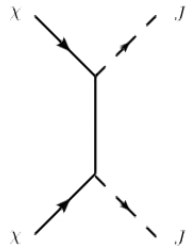
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$$(\text{A} + \text{B}) \implies m_\chi \sim \left(\frac{m_{\text{Pl}}}{T_{\text{eq}}} \right)^{1/4} m_\nu \lesssim \text{MeV}$$

(work in progress)

Other Constraints

supernova cooling ✓

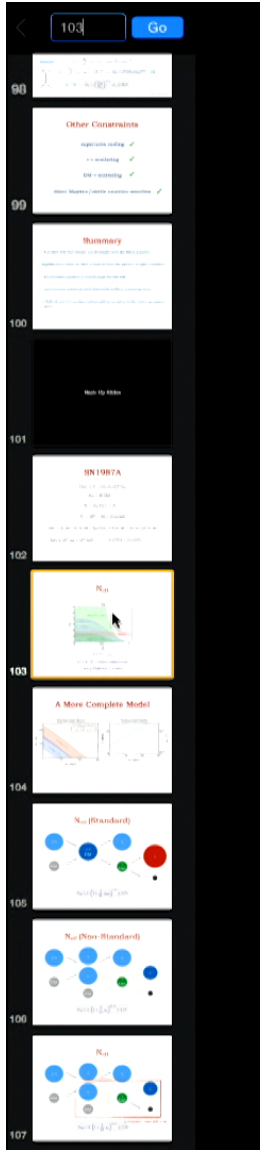
ν - ν scattering ✓

DM- ν scattering ✓

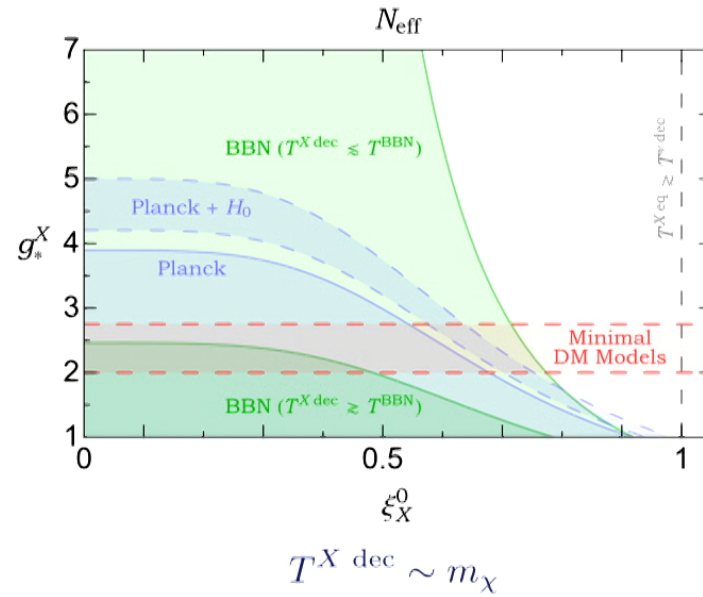
direct Majoron/sterile neutrino searches ✓

Summary

- Sub-MeV DM that freezes-out thermally with the SM is possible.
- Equilibration below an MeV is natural from the physics of light mediators.
- Equilibration predicts a limited range for DM-SM.
- Less minimal models predict detectable nucleon scattering rates.
- CMB-S4 and 21 cm observations will be sensitive to the entire parameter space.



N_{eff}



$$\xi_\chi^0 \equiv T_\chi / T_\gamma \quad (\text{before equilibration})$$

$$\Delta N_{\text{eff}}(\text{CMB-S4}) \simeq \pm 0.027$$

Abazajian, et al. , arXiv:1610.02743