Title: Thermal Relics Below an MeV

Speakers: Asher Berlin

Series: Particle Physics

Date: December 05, 2017 - 1:00 PM

URL: https://pirsa.org/17120018

Abstract: 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.

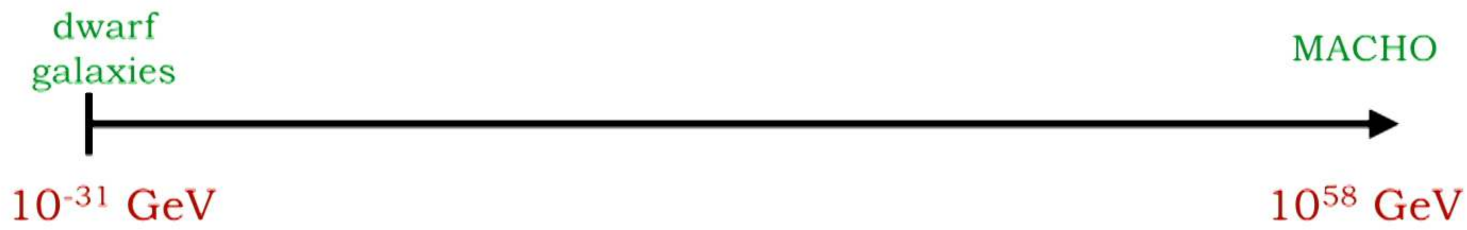
Thermal Relics Below an MeV

ASHER BERLIN

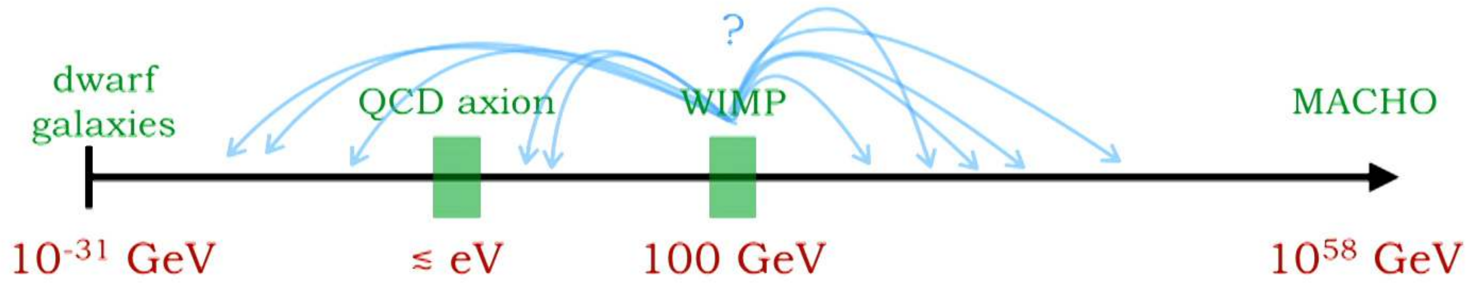
Perimeter Institute
December 5, 2017

Collaboration with Nikita Blinov, arXiv: 1706.07046

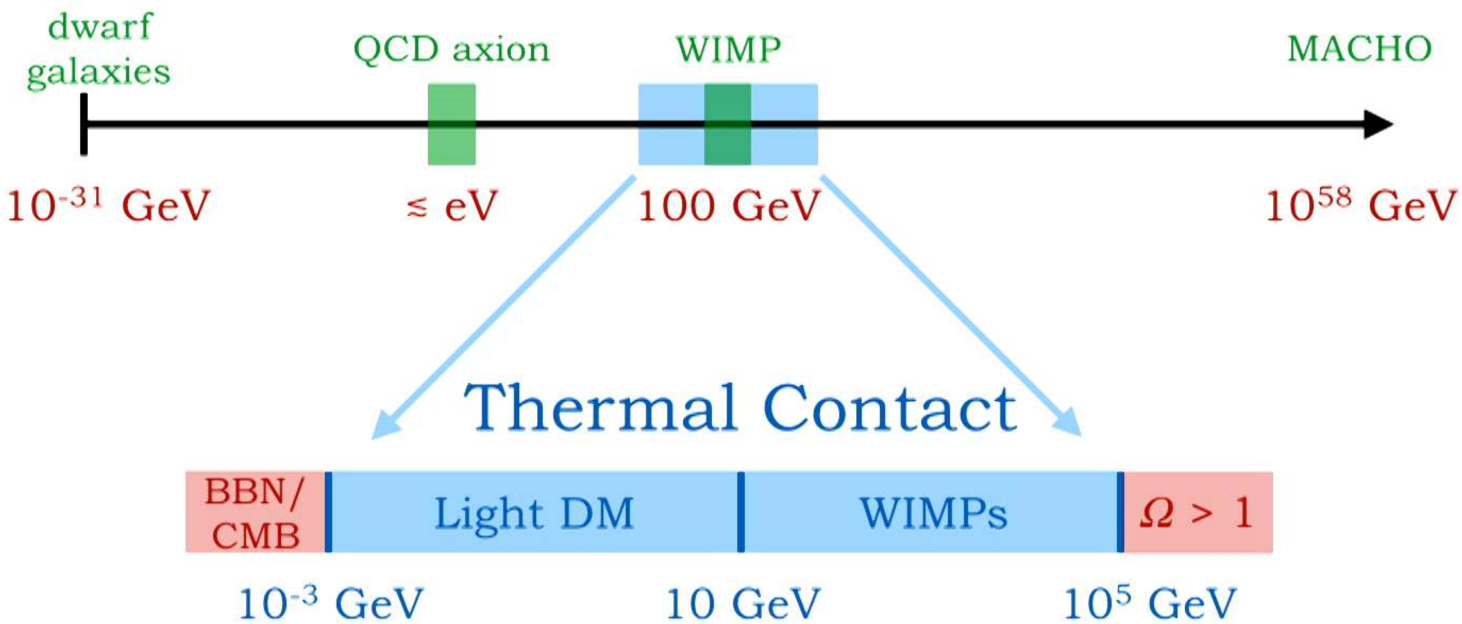
Dark Matter Mass



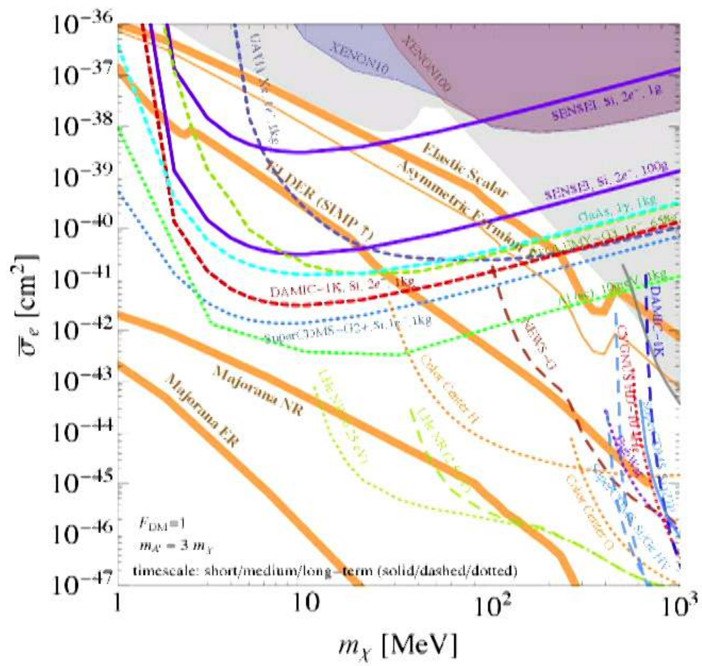
Dark Matter Mass



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

Merriam-Webster®

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.

urban DICTIONARY

Outline

I. Review of Sub-MeV Thermal Relics

II. A Way Out: Delayed Equilibration

III. Models

$\mathrm{N_{eff}}$

(effective number of neutrino species)

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

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

N_{eff}

DM-SM Equilibration ?

Neutrino-Photon Decoupling ~ MeV

+t

End of BBN ~ 50 keV

+T

Recombination ~ eV

N_{eff} + Light Relic

(standard assumption)

+t

DM-ν Equilibration $\gg$ MeV

Neutrino-Photon Decoupling $\sim$ MeV

$\sim m_{DM}$

+T

DM-Neutrino Equilibration

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

N_{eff} + Light Relic

(standard assumption)

+t ↓			+T ↑
	DM-ν Equilibration	$\gg$ MeV	
	Neutrino-Photon Decoupling	~ MeV	
		~ m_{DM}	

DM-Neutrino Equilibration

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Big Bang Nucleosynthesis (BBN)

^4He

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

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

D

$$D\ p \to \gamma\ ^3{\rm He} \quad \to \quad ^3{\rm He}\ D \to p\ ^4{\rm He}$$

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

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

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<u>*D*</u>

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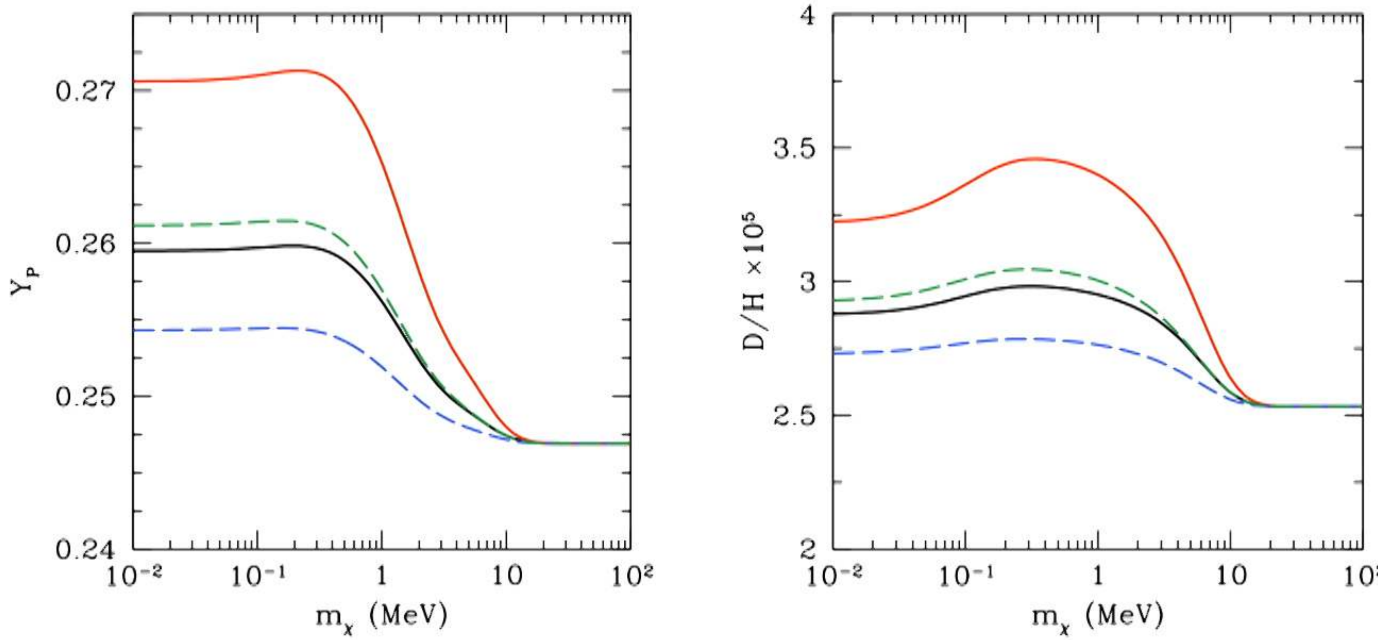
BBN + N_{eff}



N_{eff} increasing

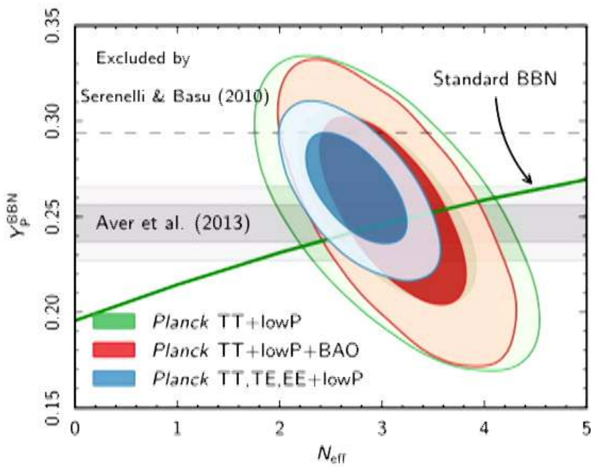
$\delta Y_p \simeq 0.013\ \delta N_{eff}$

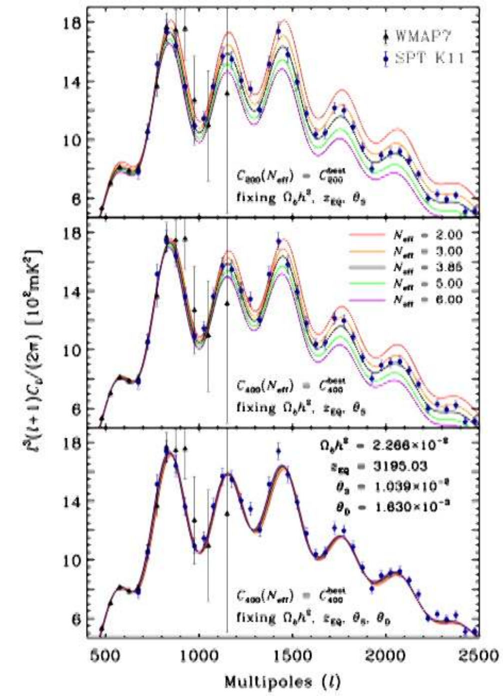
N_{eff} increasing

K. Nollett, G. Steigman, arXiv:1411.6005

Cyburt et al., arXiv:1505.01076

CMB + $\mathrm{N_{eff}}$





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

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

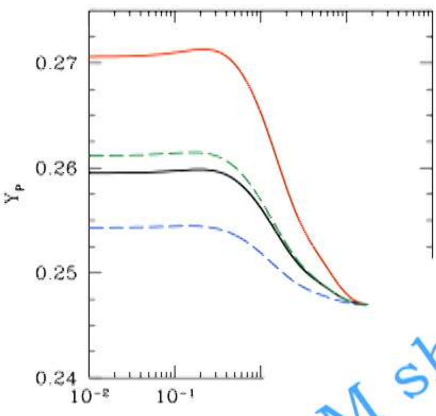
Planck, arXiv:1502.01589

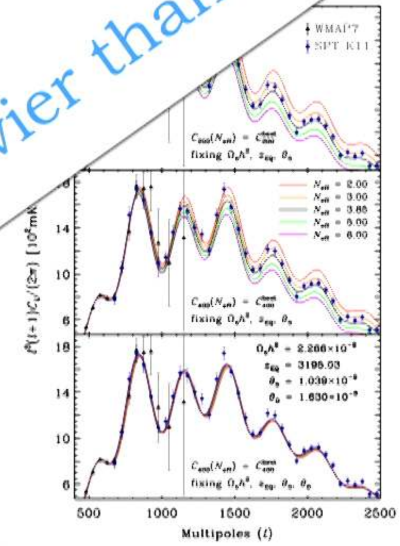
Z. Hou, et al. , arXiv:1104.2333

Sub-MeV: BBN + CM

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

$N_{\rm eff}$ (C .23





"Thermal DM should be heavier than an MeV"

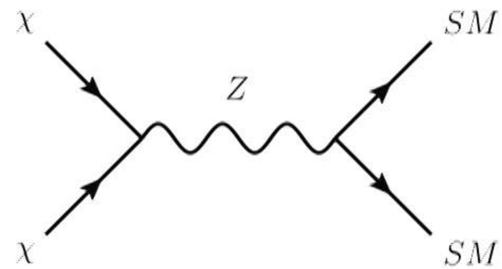
$$N_{\rm eff} \simeq 3 \left(1 + \frac{4}{21}\, g_{\rm DM}\right)^{4/3} \gtrsim 3.78$$

. 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



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

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

<u>Expansion</u>

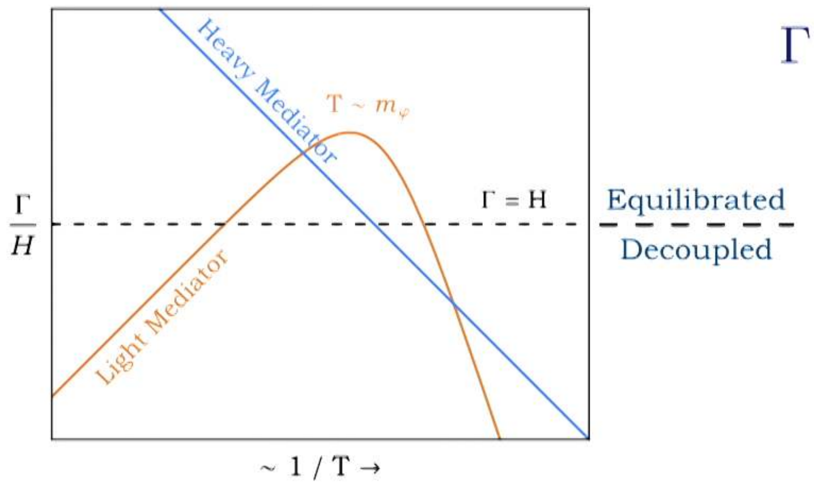
$H \sim T^2$

<u>Light Mediator</u>

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

<u>Heavy Mediator</u>

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



Equilibration

Expansion

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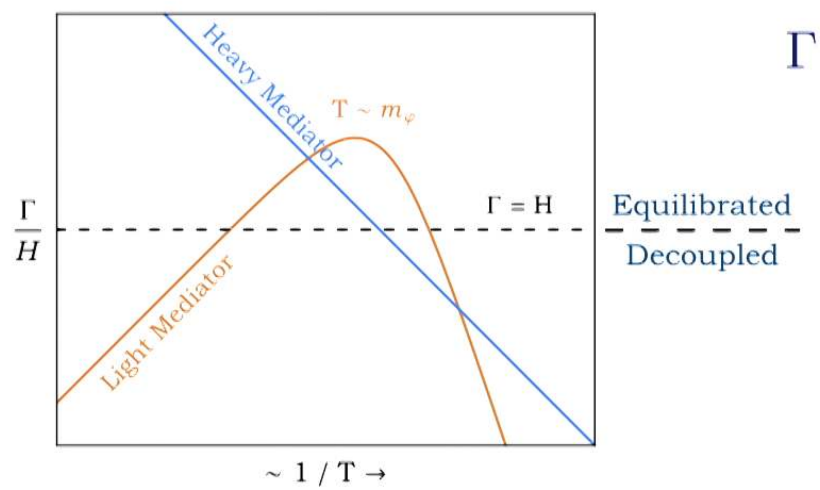
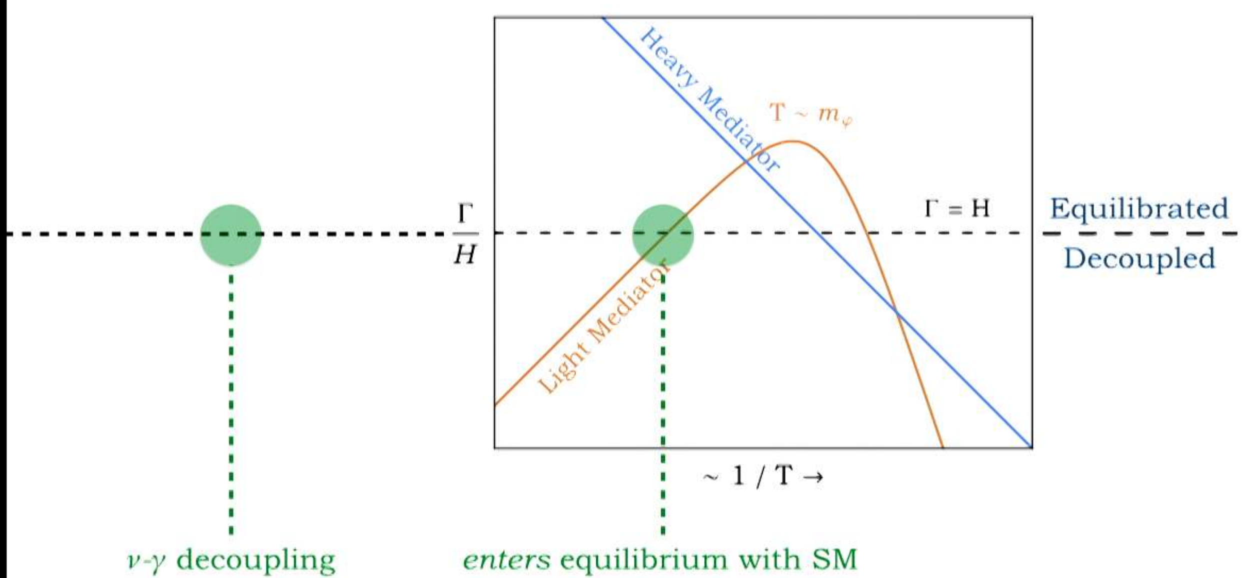


Light thermal DM naturally *enters* equilibrium

(for high enough T_{RH})

Equilibration



N_{eff}

(*non*-standard assumption)

+t ↓

Neutrino-Photon Decoupling ~ MeV

DM-ν Equilibration < MeV

~ m_χ

↑ +T

N_{eff}

(*non*-standard assumption)

+t

Neutrino-Photon Decoupling ~ MeV

DM-ν Equilibration < MeV

~ m_χ

+T

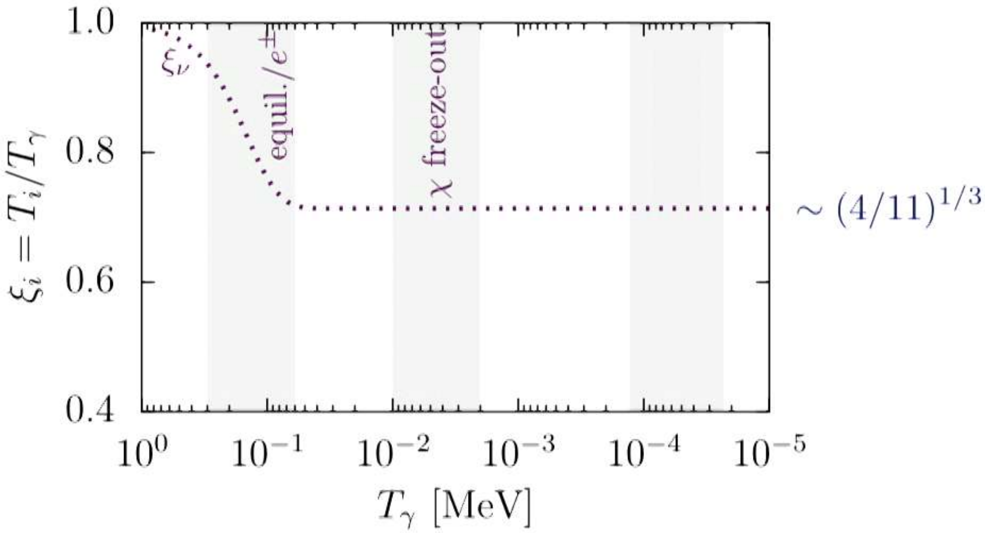
Sensitivity to UV (initial DM temperature)

N_{eff}

$$T_\chi^{\mathrm{initial}} \ll T_\gamma$$

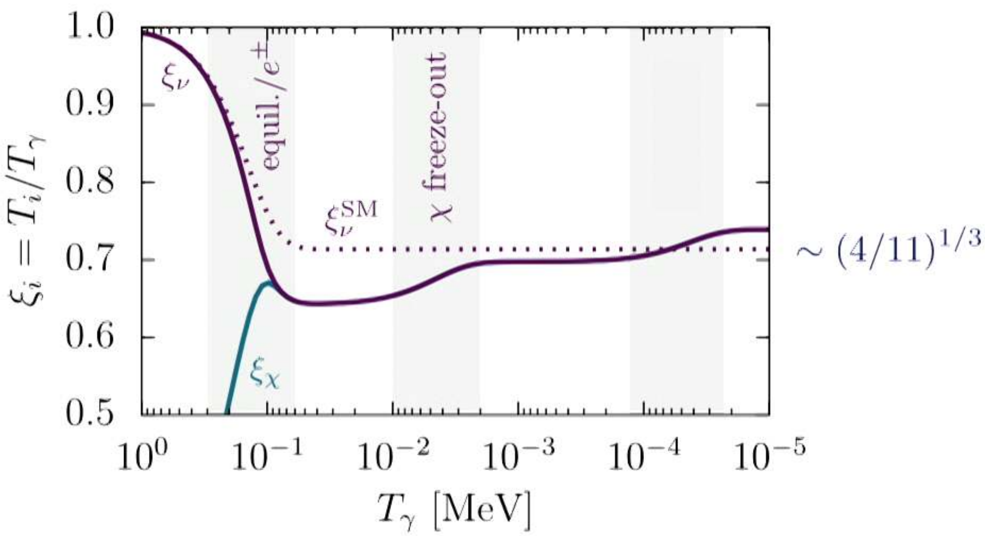
N_{eff}

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



$\mathrm{N_{eff}}$

$T_\chi^{\mathrm{initial}} \ll T_\gamma$



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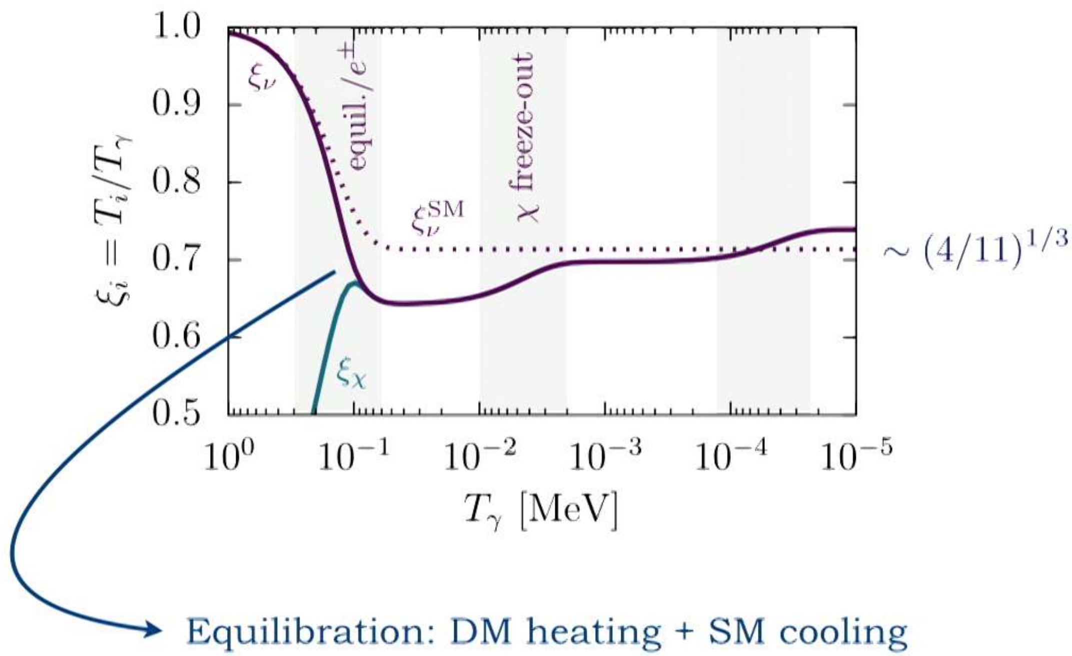
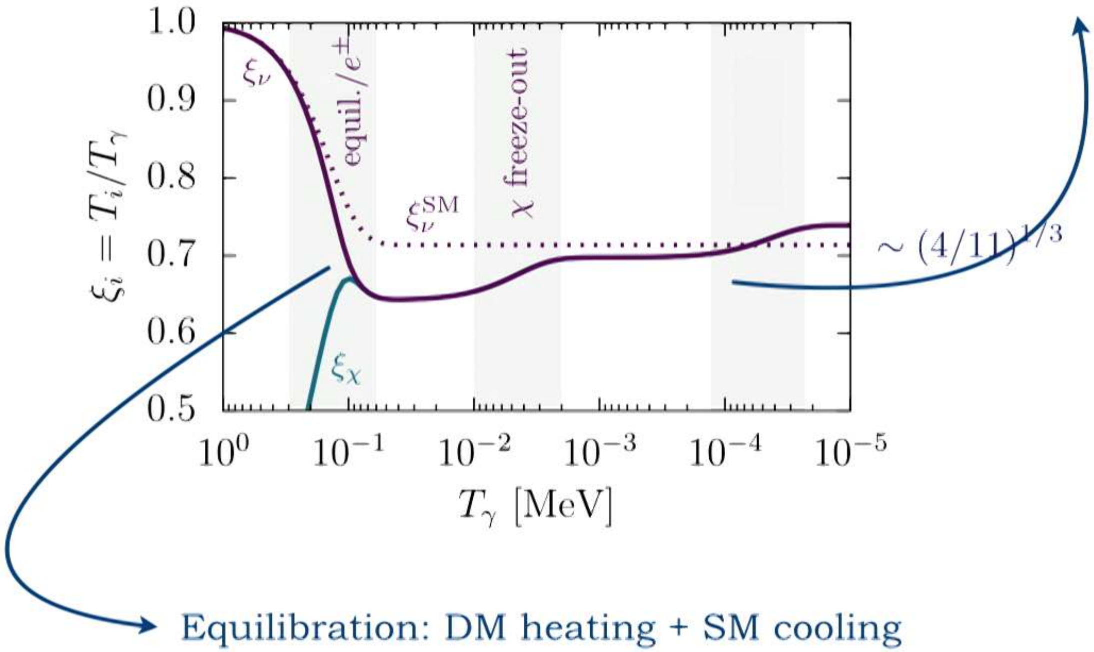


$\mathrm{N_{eff}}$

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

Decoupling: SM heating



Equilibration: DM heating + SM cooling

N_{eff}

$$\left(g_*^\nu \equiv \frac{7}{8} \times 3 \times 2 = \frac{21}{4}\right)$$

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

$\mathrm{N_{eff}}$

$$\left(g_*^\nu \equiv \frac{7}{8} \times 3 \times 2 = \frac{21}{4} \right)$$

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$$N_{\text{eff}} \simeq \begin{cases} 3 \left(1 + \frac{g_*^\chi}{g_*^\nu} \, \xi_\chi^{0\,4} \right) \;, \; T \gtrsim T^{\chi \text{ eq}} & \text{(uncoupled dark radiation)} \\ & \\ & \end{cases}$$

$\mathrm{N}_{\mathrm{eff}}$

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(Conservation of comoving energy density)

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(uncoupled dark radiation)

(coupled dark radiation)

$\mathrm{N_{eff}}$

$$\left(g_*^\nu \equiv \frac{7}{8} \times 3 \times 2 = \frac{21}{4} \right)$$

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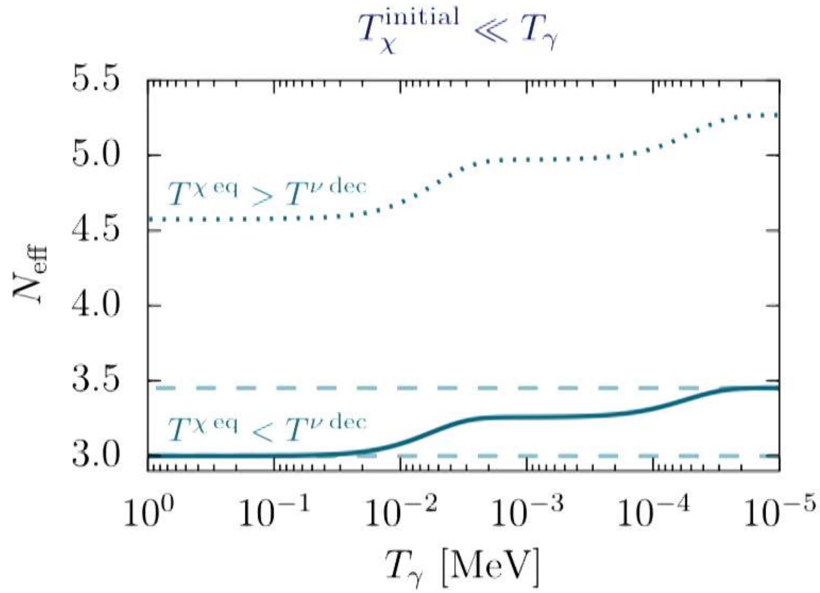
N_{eff}

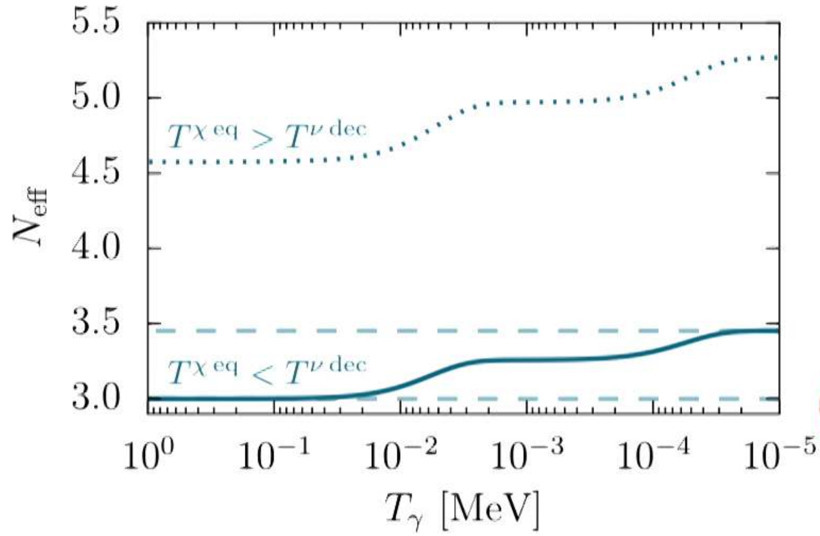


DM-Neutrino Equilibration

$$N_{\text{eff}} \simeq 3 \left(1 + \frac{4}{21}\, g_\chi\right)^{\not{4}1/3} \gtrsim 3.18$$

$\mathrm{N_{eff}}$

$T_\chi^{\mathrm{initial}} \ll T_\gamma$



$g_\chi \lesssim$ several

DM-Neutrino Equilibration

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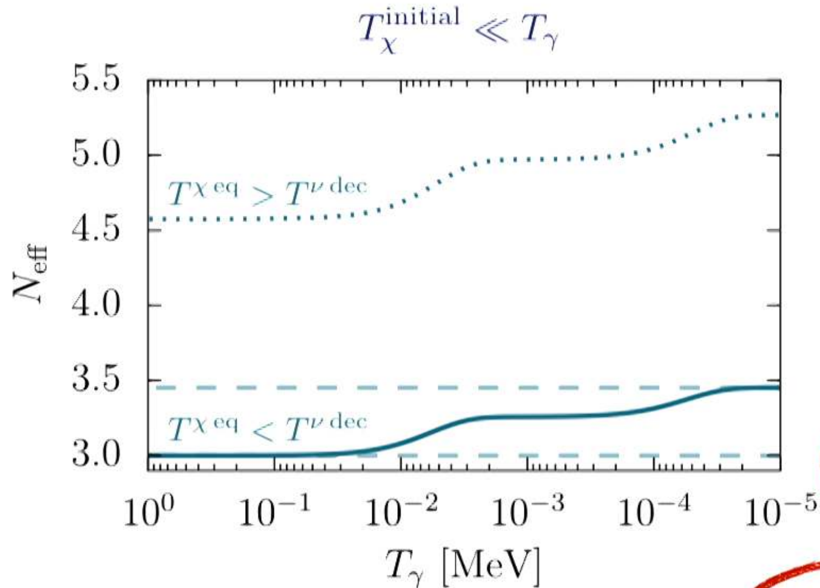
N_{eff}



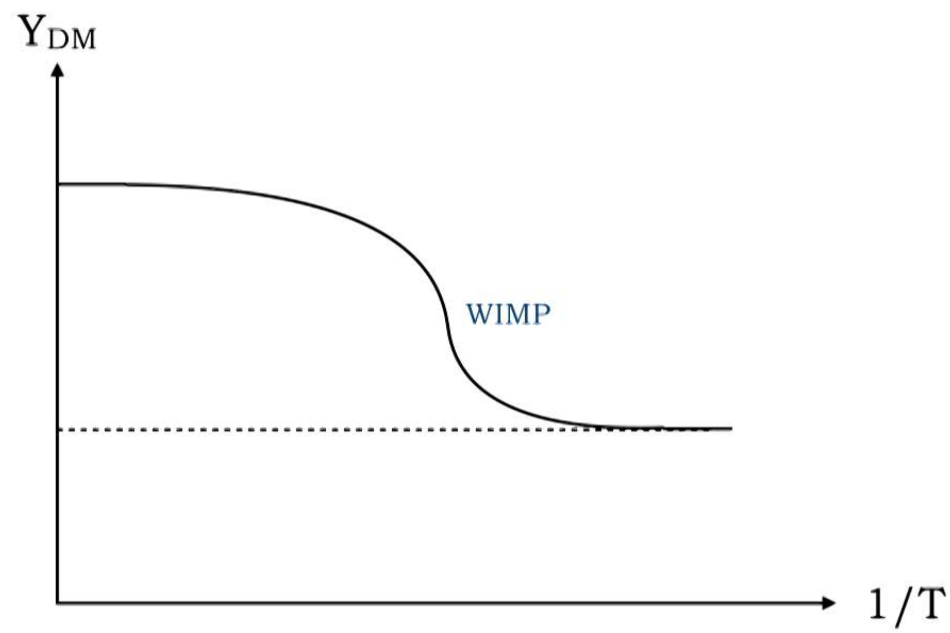
$g_\chi \lesssim$ several

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

DM-Neutrino Equilibration

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

Thermal History



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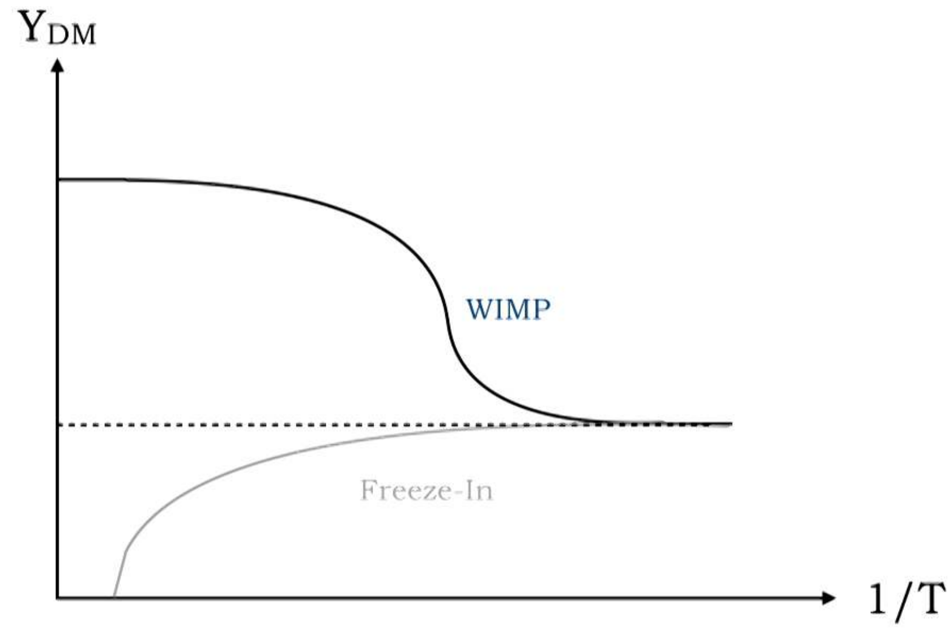

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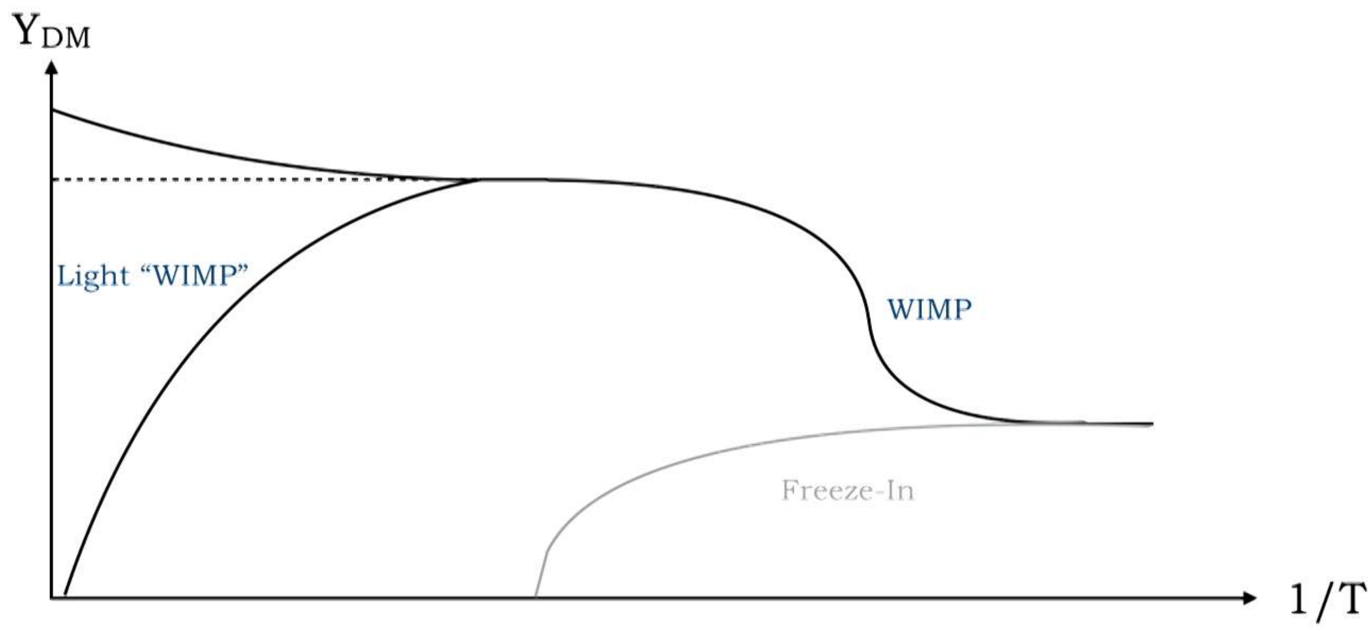

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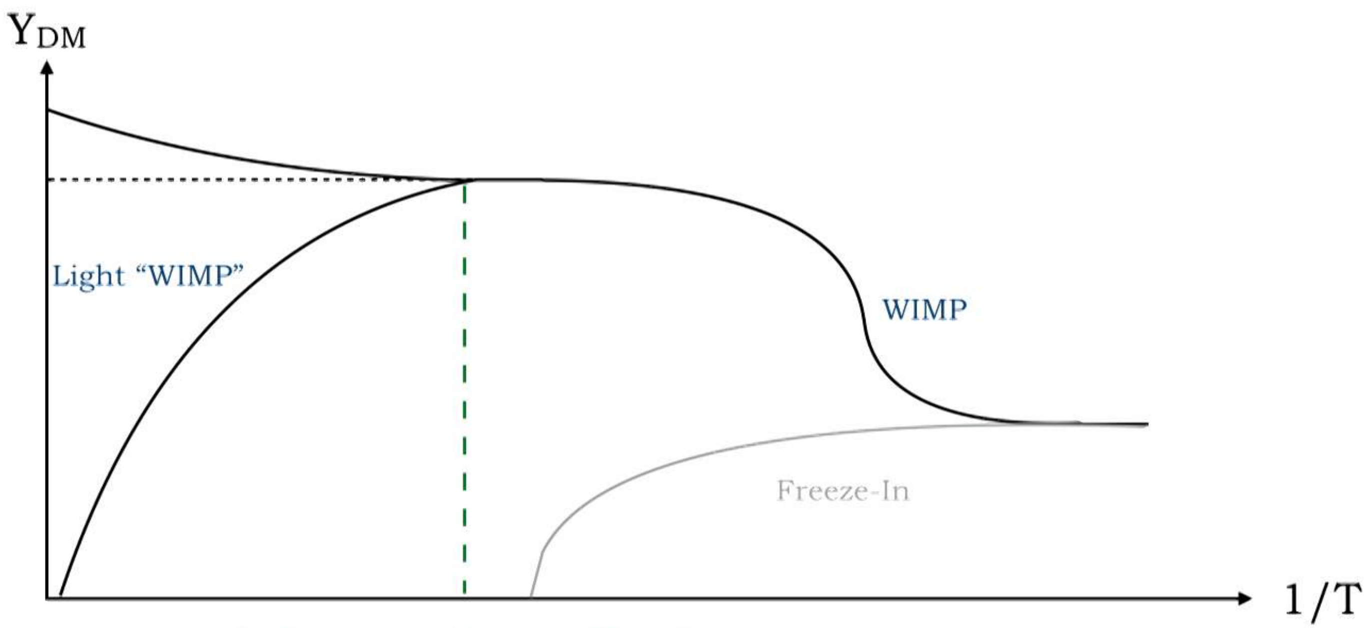

(after ν-γ decoupling)

Delayed Equilibration

Delayed Equilibration

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

Delayed Equilibration

$$\begin{cases} \langle \sigma v \rangle_{\rm FO} \sim \frac{\alpha_{\rm FO}^2}{m_\chi^2} \implies m_\chi \sim \alpha_{\rm FO}\ \left(T_{\rm eq}\, m_{\rm Pl}\right)^{1/2} \\ \Gamma_{\rm scatt}^{\rm KE} \sim \alpha_{\rm KE}^2\, T_{\rm KE} \sim H(T_{\rm KE}) \end{cases}$$

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

Delayed Equilibration

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

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Secluded DM or Resonant Freeze-Out SIMP

Delayed Equilibration

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Secluded DM or Resonant Freeze-Out SIMP

Outline

I. Review of Sub-MeV Thermal Relics

II. A Way Out: Delayed Equilibration

<u>III. Models</u>

A Toy Model

A Toy Model

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

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

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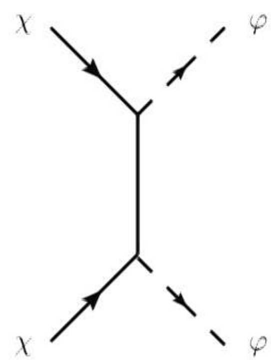


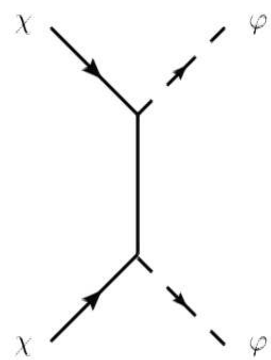
(Freeze-Out)

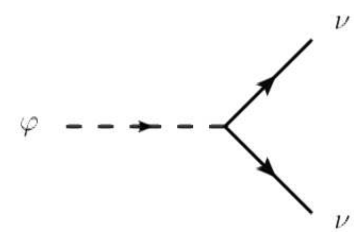
$$\lambda_\chi \sim 10^{-5} \times (m_\chi/\text{keV})^{1/2}$$

A Toy Model

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

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





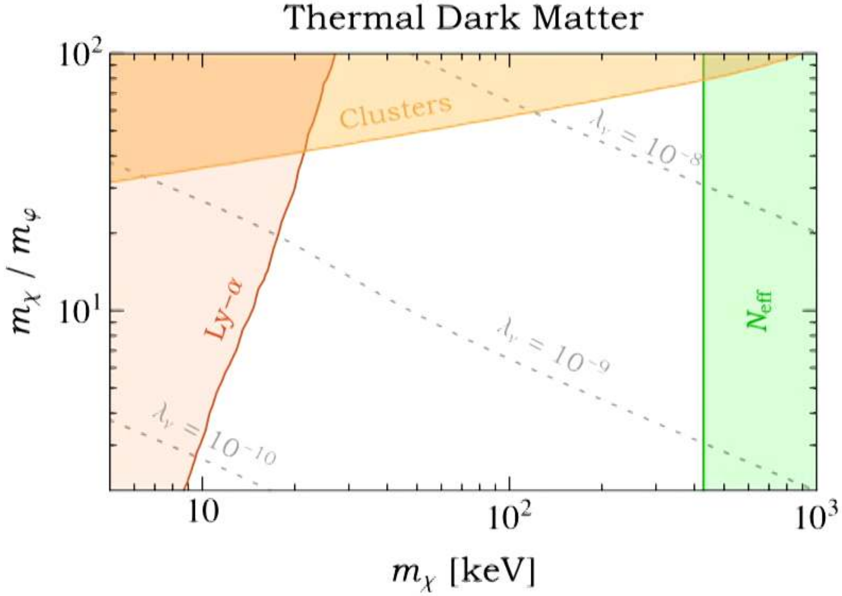
(Freeze-Out) (Equilibration and Decay)

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

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

A Toy Model

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



A More Complete Model

(work in progress)

A More Complete Model

$$-\mathcal{L} \supset y_\nu \, L \, N \, H + \frac{y_N}{2} \, \sigma \, N^2 + \text{h.c.}$$

(neutrino sector)

(work in progress)

A More Complete Model

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

$$\sigma = \frac{1}{\sqrt{2}} \, (f + S + i \, J)$$

(U(1)$_L$ scale) ← f

J → (pseudo-Goldstone Majoron)

(work in progress)

A More Complete Model

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

$$\sigma = \frac{1}{\sqrt{2}} \, (f + S + i \, J)$$

($U(1)_L$ scale) ← f ; J → (pseudo-Goldstone Majoron)

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

(work in progress)

A More Complete Model

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

$$\sigma = \frac{1}{\sqrt{2}}\, (f + S + i\, J)$$

(U(1)$_\text{L}$ scale) (pseudo-Goldstone Majoron)

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

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

(work in progress)

A More Complete Model

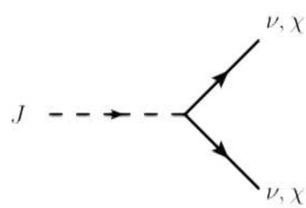
$$-\mathcal{L} \supset y_\nu \, L\, N\, H + \frac{y_N}{2}\, \sigma\, N^2 + \text{h.c.}$$ (neutrino sector)

$$\sigma = \frac{1}{\sqrt{2}}\,(f + S + i\,J)$$

(U(1)$_{\mathrm{L}}$ scale) ← f; J → (pseudo-Goldstone Majoron)

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

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

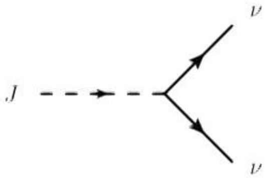


$$\sim \frac{m_{\nu,\chi}}{f}$$

(work in progress)

MeV Motivation

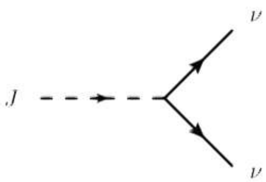
Equilibration: $(m_\chi \sim m_J \sim T^{\mathrm{KE}})$



(work in progress)

MeV Motivation

Equilibration: $(m_\chi \sim m_J \sim T^{\rm KE})$



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

(work in progress)

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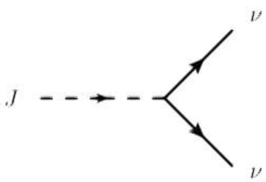

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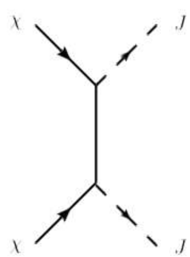
Freeze-Out:

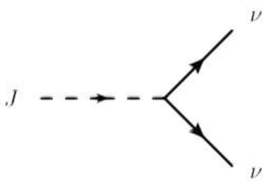
$$\sigma v \sim \frac{\alpha_{\mathrm{FO}}^2}{m_\chi^2} \implies m_\chi \sim \alpha_{\mathrm{FO}}\, (T_{\mathrm{eq}}\, m_{\mathrm{Pl}})^{1/2}$$



(work in progress)

MeV Motivation

Equilibration: $(m_\chi \sim m_J \sim T^{\rm KE})$



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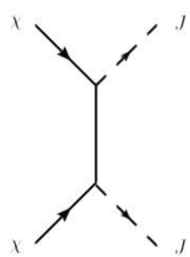


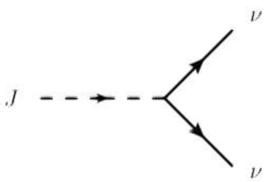
$$\sigma v \sim \frac{m_\chi^2}{f^4} \implies \alpha_{\rm FO} \sim m_\chi^2/f^2 \implies m_\chi \sim f^2/(T_{\rm eq}\, m_{\rm Pl})^{1/2} \qquad \text{(B)}$$

(work in progress)

MeV Motivation

Equilibration:

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



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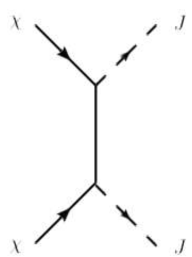

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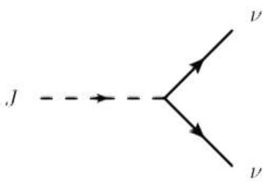
$$\text{(A + B)} \implies m_\chi \sim \left(\frac{m_{\rm Pl}}{T_{\rm eq}}\right)^{1/4} m_\nu$$

(work in progress)

MeV Motivation

Equilibration:

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



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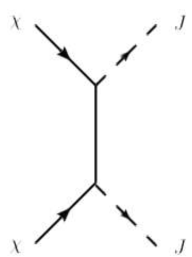

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$$\text{(A + B)} \implies m_\chi \sim \left(\frac{m_{\rm Pl}}{T_{\rm eq}}\right)^{1/4} m_\nu \lesssim \text{MeV}$$

(work in progress)

Other Constraints

supernova cooling ✓

ν-ν scattering ✓

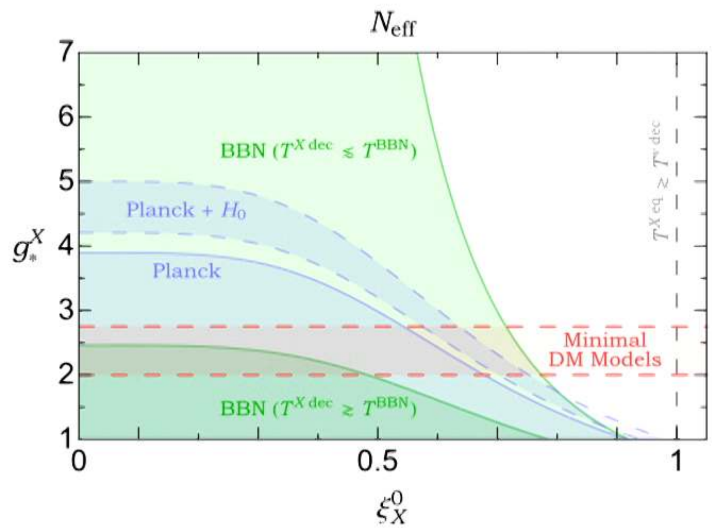
DM-ν scattering ✓

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.

$N_{\rm eff}$



$$T^{X\ \rm dec} \sim m_\chi$$

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

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

Abazajian, et al. , arXiv:1610.02743