Pandemics and Cannibals

Some intriguing ways of producing dark matter in the early Universe

[2007.03696] [2206.10630] Torsten Bringmann, Paul Frederik Depta, Marco Hufnagel, Kai Schmidt-Hoberg, Jörn Kersten

[2212.09759] Marco Hufnagel, Michel Tytgat

Tuesday, June 6, 2023

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Overview

- Pandemic DM and its application to sterile neutrinos

Minimal sterile neutrino dark matter

Torsten Bringmann,[1,2,*] Paul Frederik Depta,[3,†] Marco Hufnagel,[4,‡]
Jörn Kersten,[5,6,§] Joshua T. Ruderman,[7,¶] and Kai Schmidt-Hoberg[8,**]

[1] *Department of Physics, University of Oslo,*
[2] *Theoretical Physics Department, CERN,*
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[4] *Service de Physique Théorique, Université Libre de Bruxelles, Bou*
[5] *Korea Institute for Advanced Study, Seo*
[6] *Department of Physics and Technology, Univers*
[7] *Center for Cosmology and Particle Physics, Department of Physi*
[8] *Deutsches Elektronen-Synchrotron DESY, Notk*
(Dated: April 26, 2

Dark Matter from Exponential Growth

Originally proposed as Pandemic Dark Matter

Torsten Bringmann,[1,*] Paul Frederik Depta,[2,†] Marco Hufnagel,[3,‡]
Joshua T. Ruderman,[4,2,5,6,§] and Kai Schmidt-Hoberg[2,¶]

[1] *Department of Physics, University of Oslo, Box 1048, N-0316 Oslo, Norway*
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[4] *Center for Cosmology and Particle Physics, Department of Physics, New York University, New York, NY 10003, USA*
[5] *Kavli Institute for Theoretical Physics, University of California, Santa Barbara, CA 93106, USA*
[6] *School of Physics and Astronomy, Tel-Aviv University, Tel-Aviv 69978, Israel*

- The domain of cannibal DM

The domain of a cannibal dark matter

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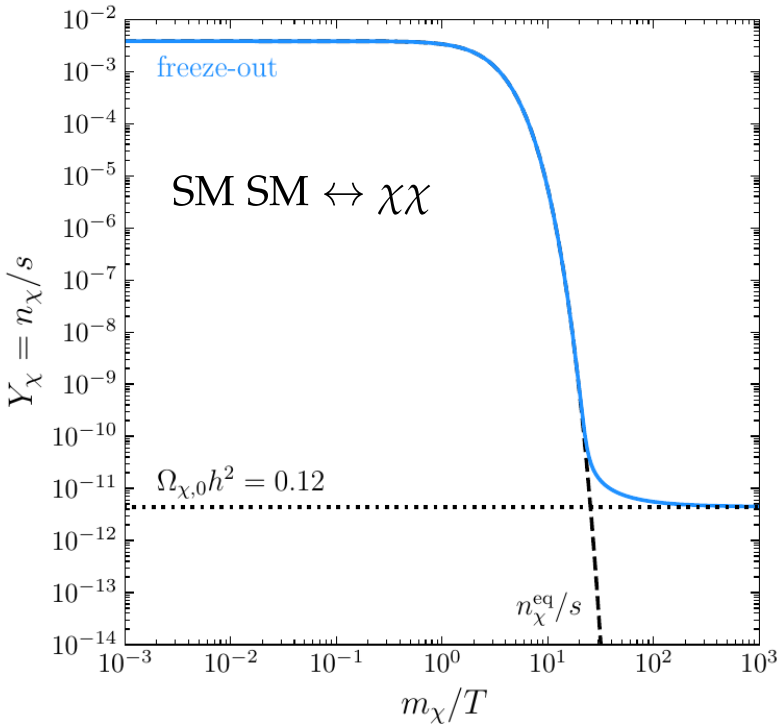
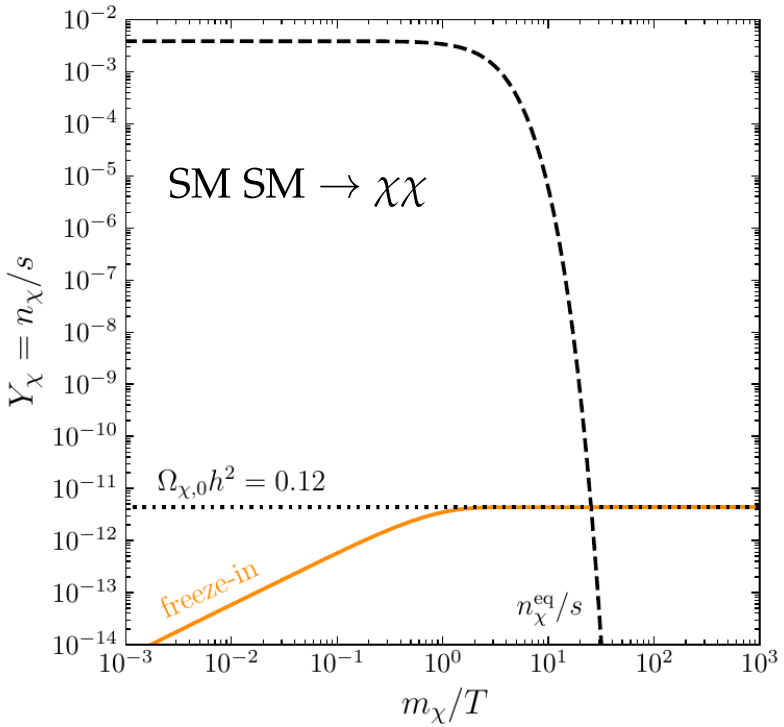
Dark Matter production

Thermal



Non-thermal



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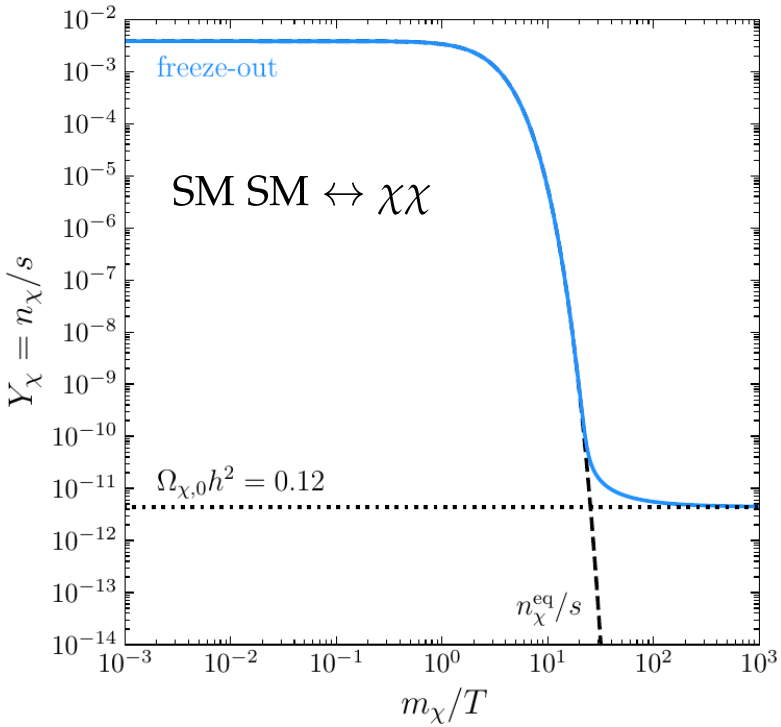

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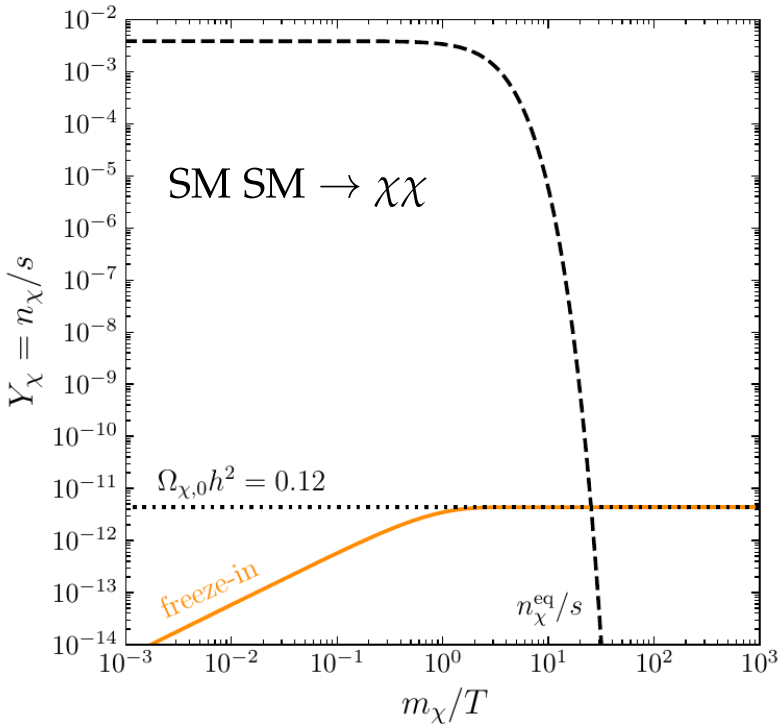

Many freeze-out variants:

- Hidden Sectors
- Cannibal DM [1607.03108]
- Zombie DM [2003.04900]

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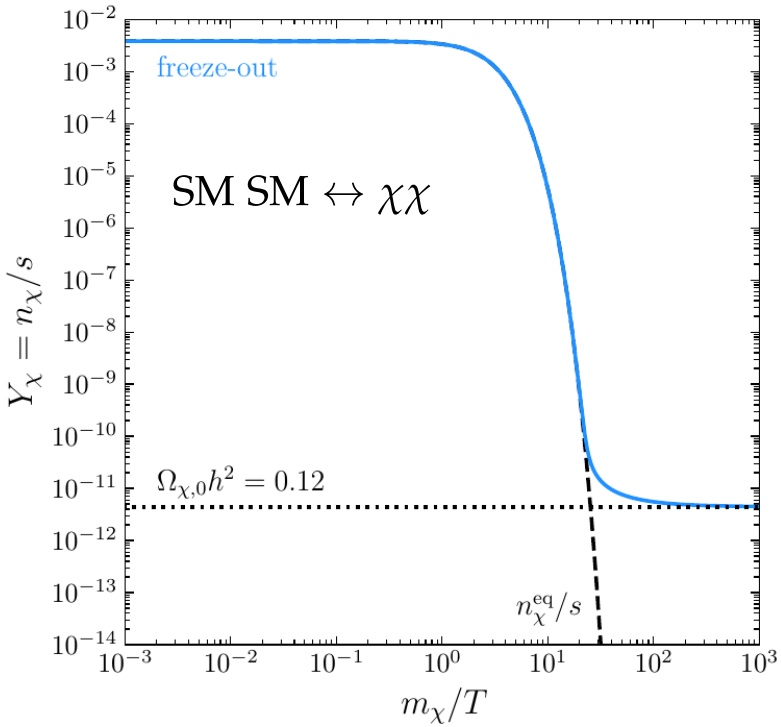

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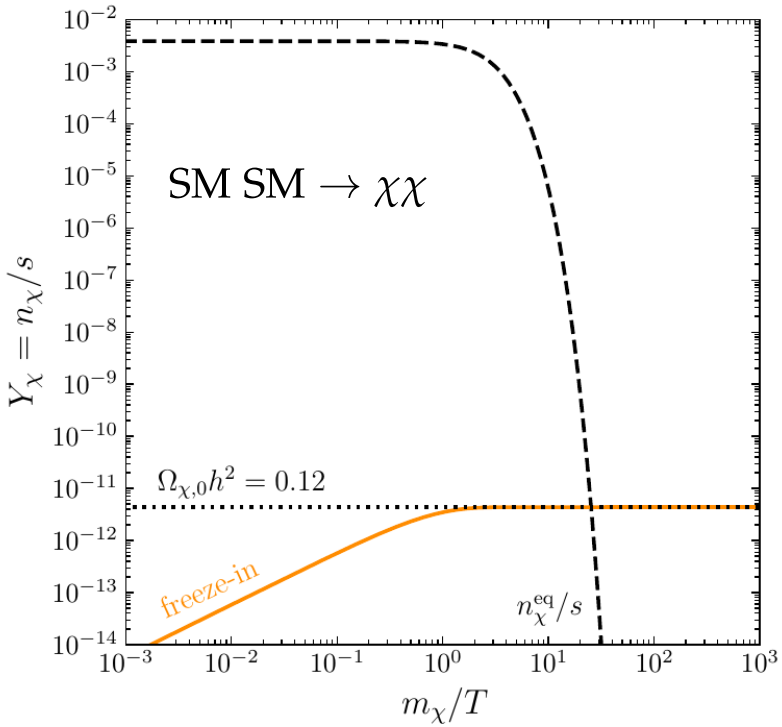
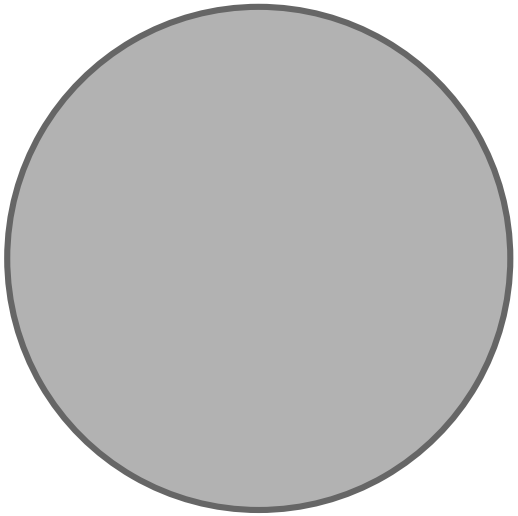


Less freeze-in variants:

Here: freeze-in with exponential instead of linear growth!

[2103.16572], [2104.05684]
Hryczuk, Laletin

Infection of the thermal bath



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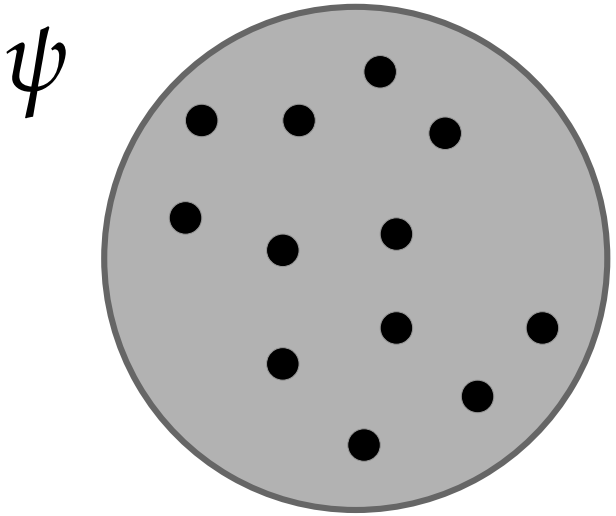

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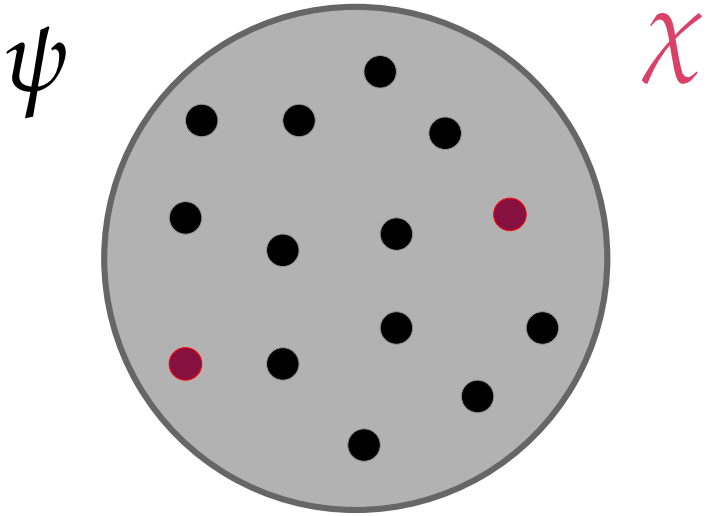

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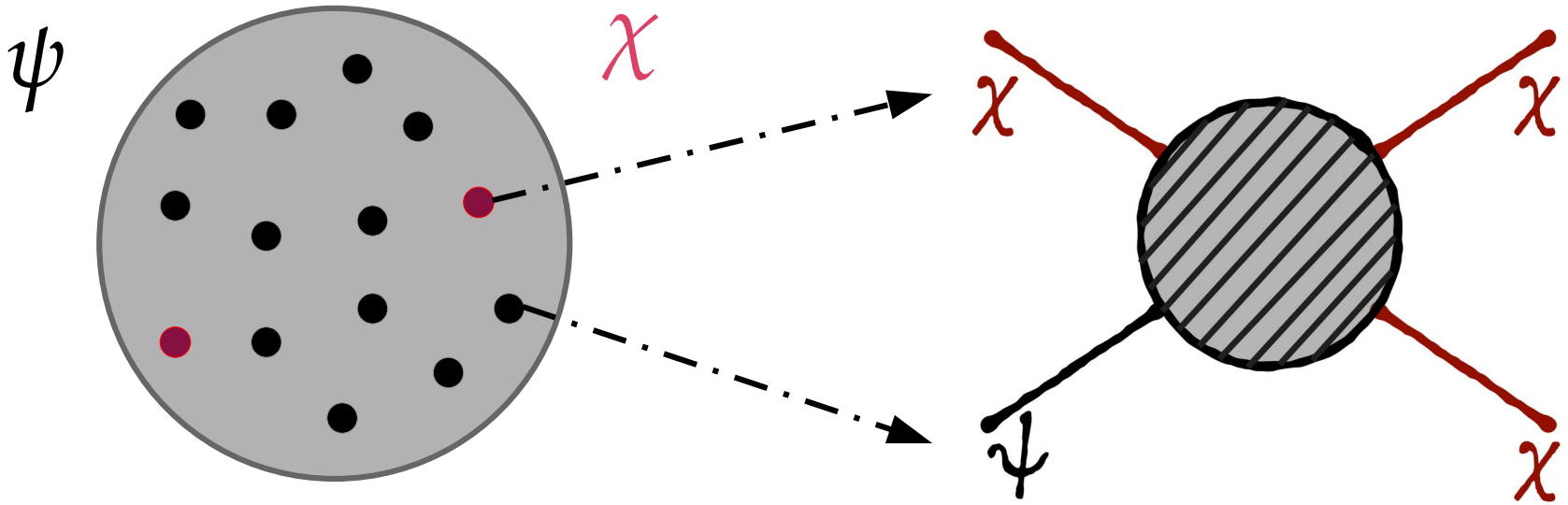

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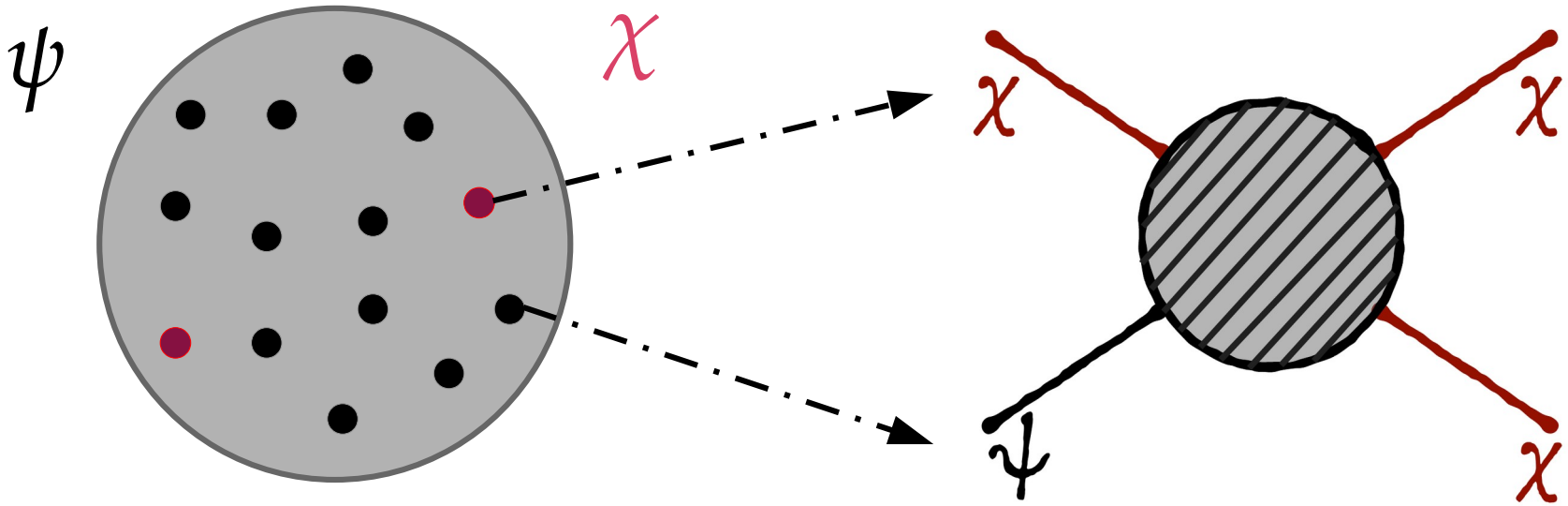

Boltzmann equation:

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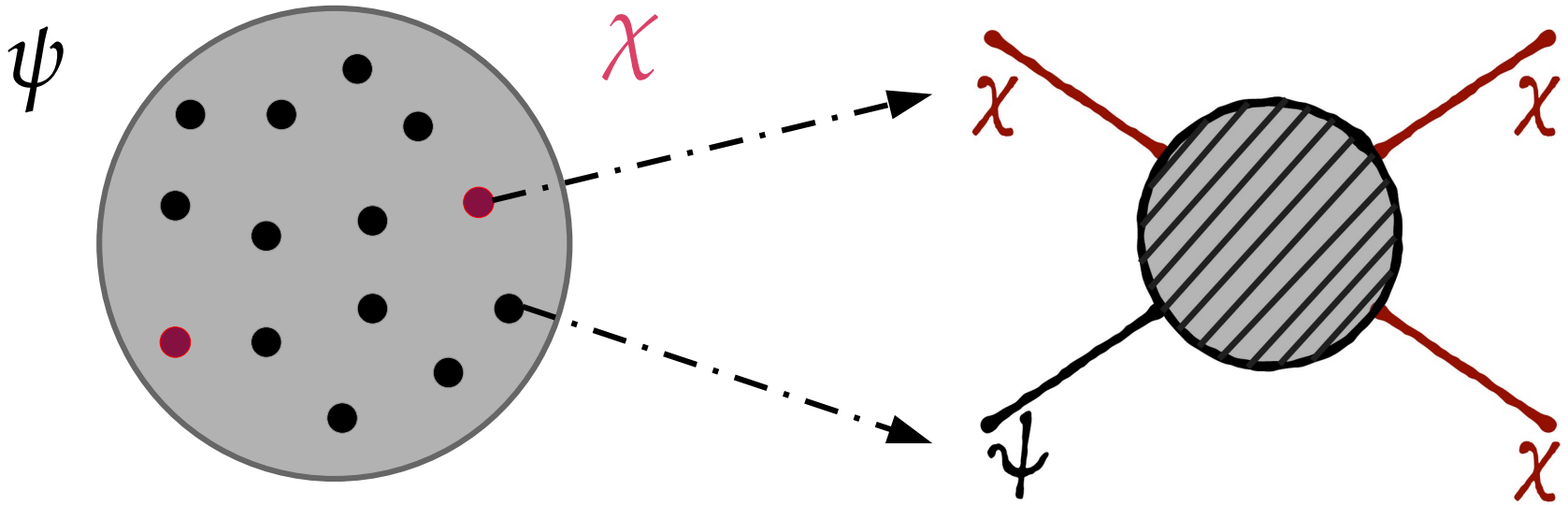

Assumptions:

- $f_\psi = \bar{f}_\psi = \exp(-E/T)$
- $f_\chi = \lambda(T)\exp(-E/T)$

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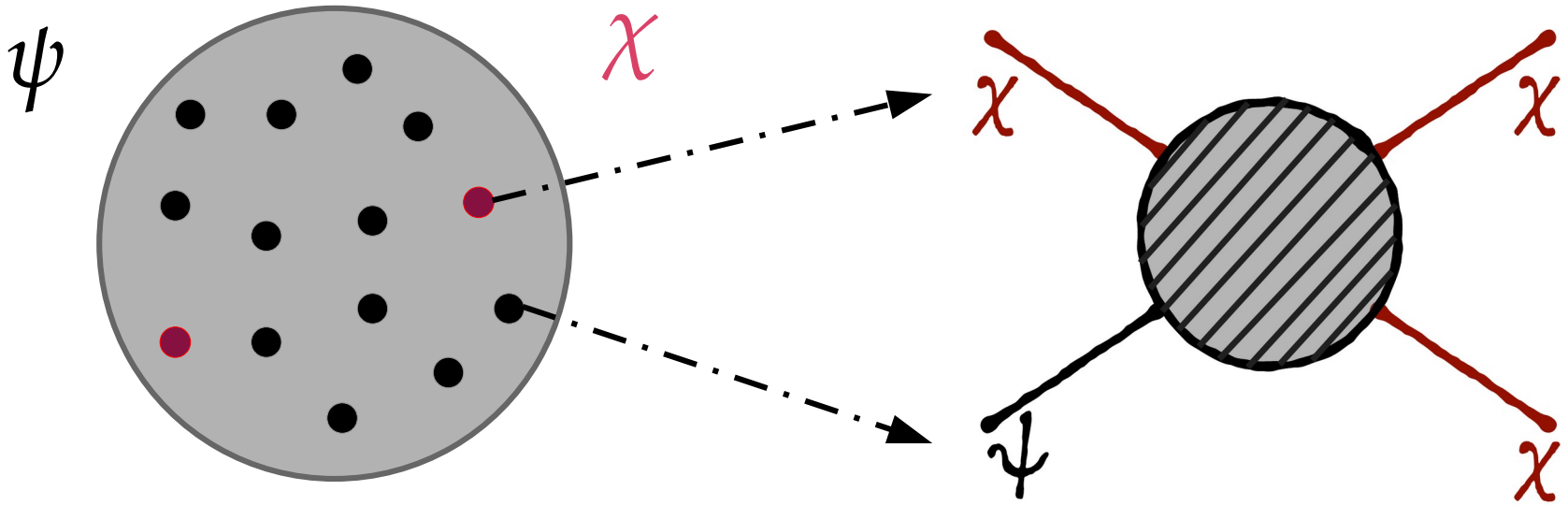

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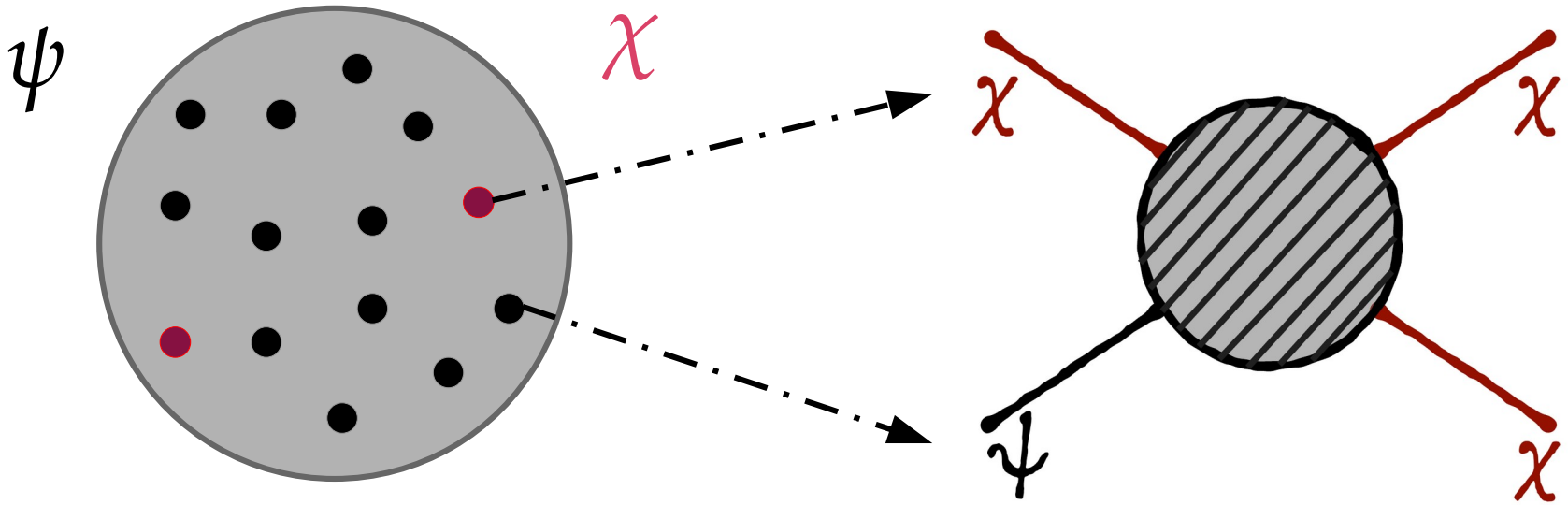

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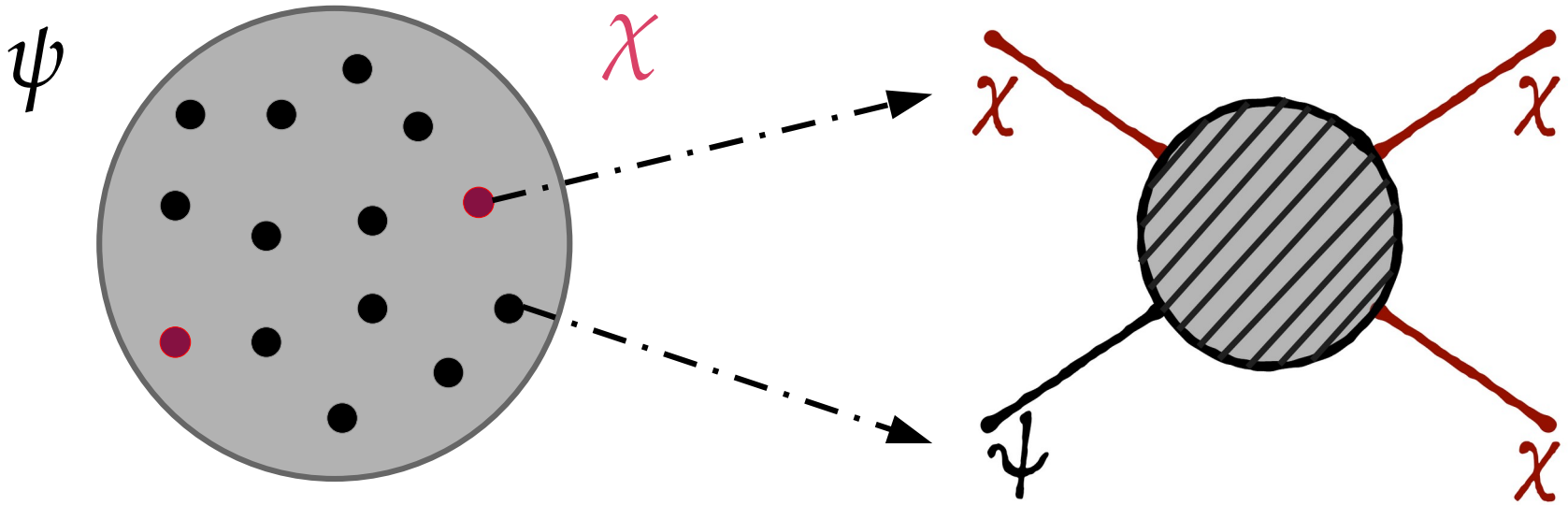

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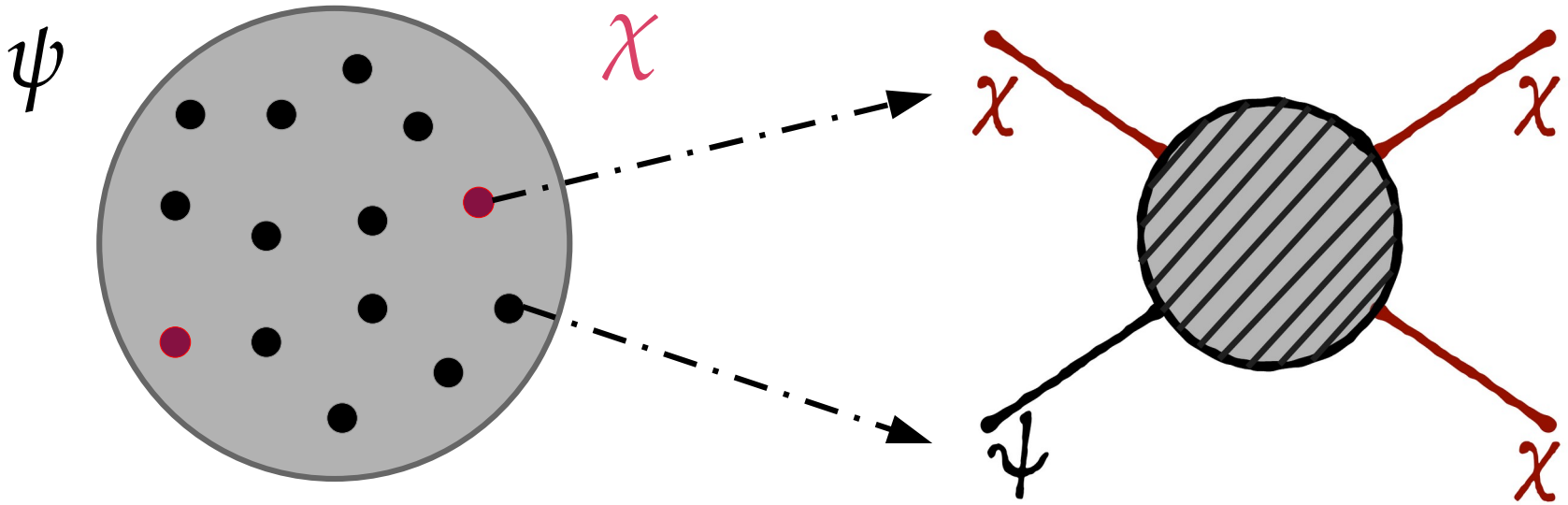

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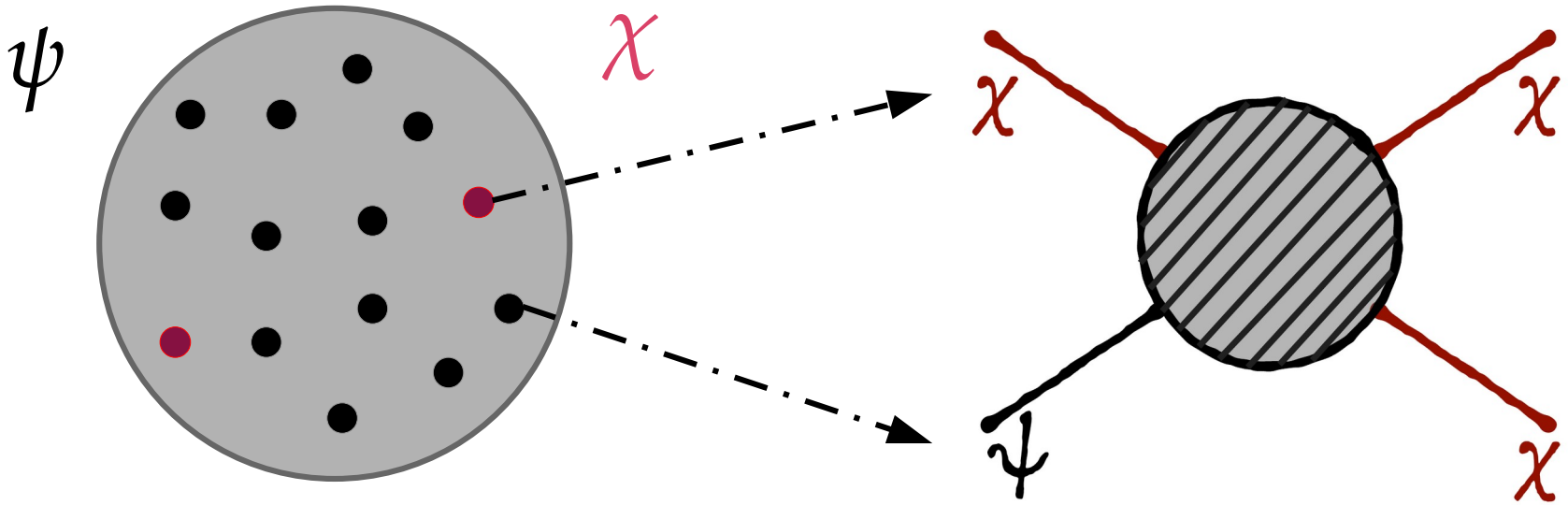

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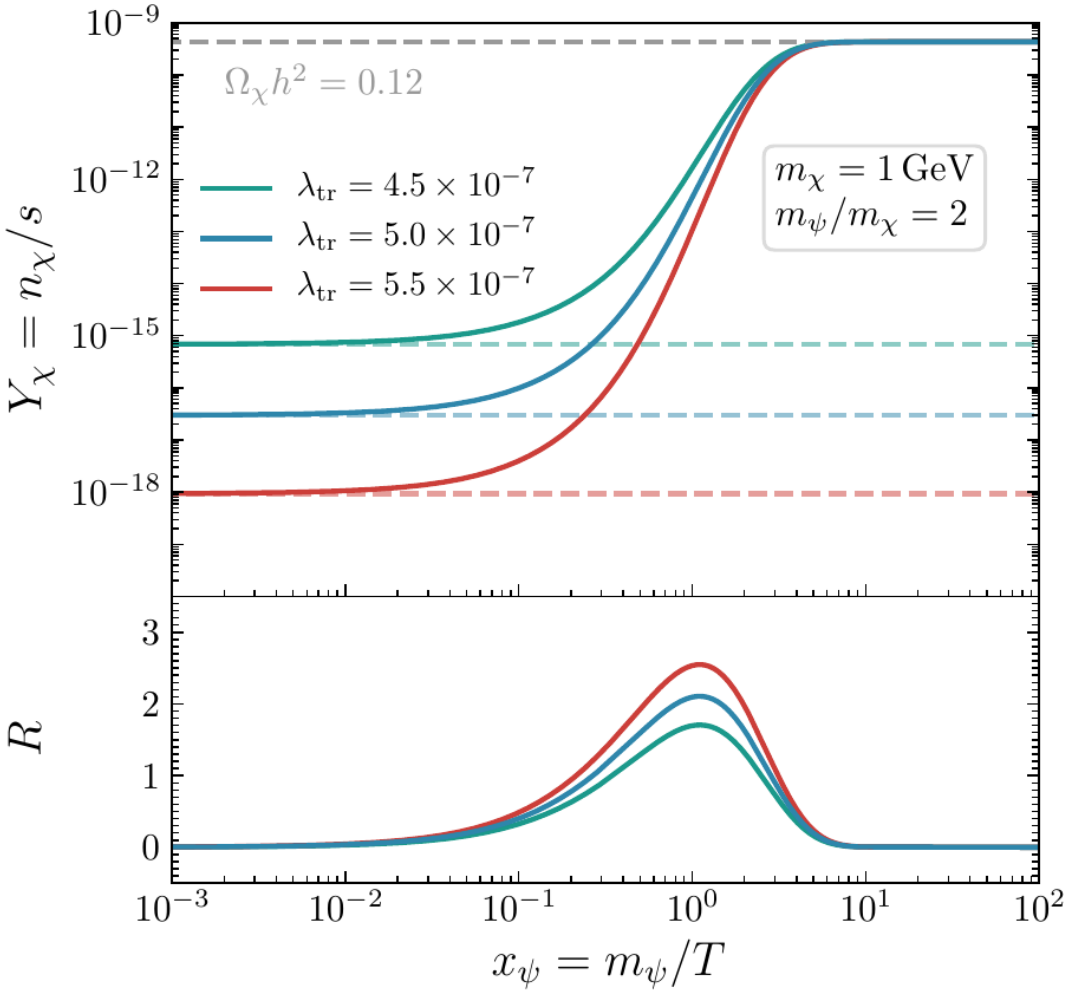
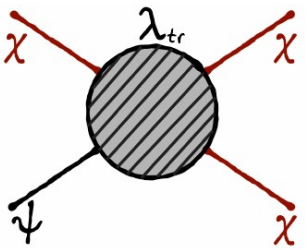
Evolution of the Dark Matter abundance

Exponential growth from an initial seed:

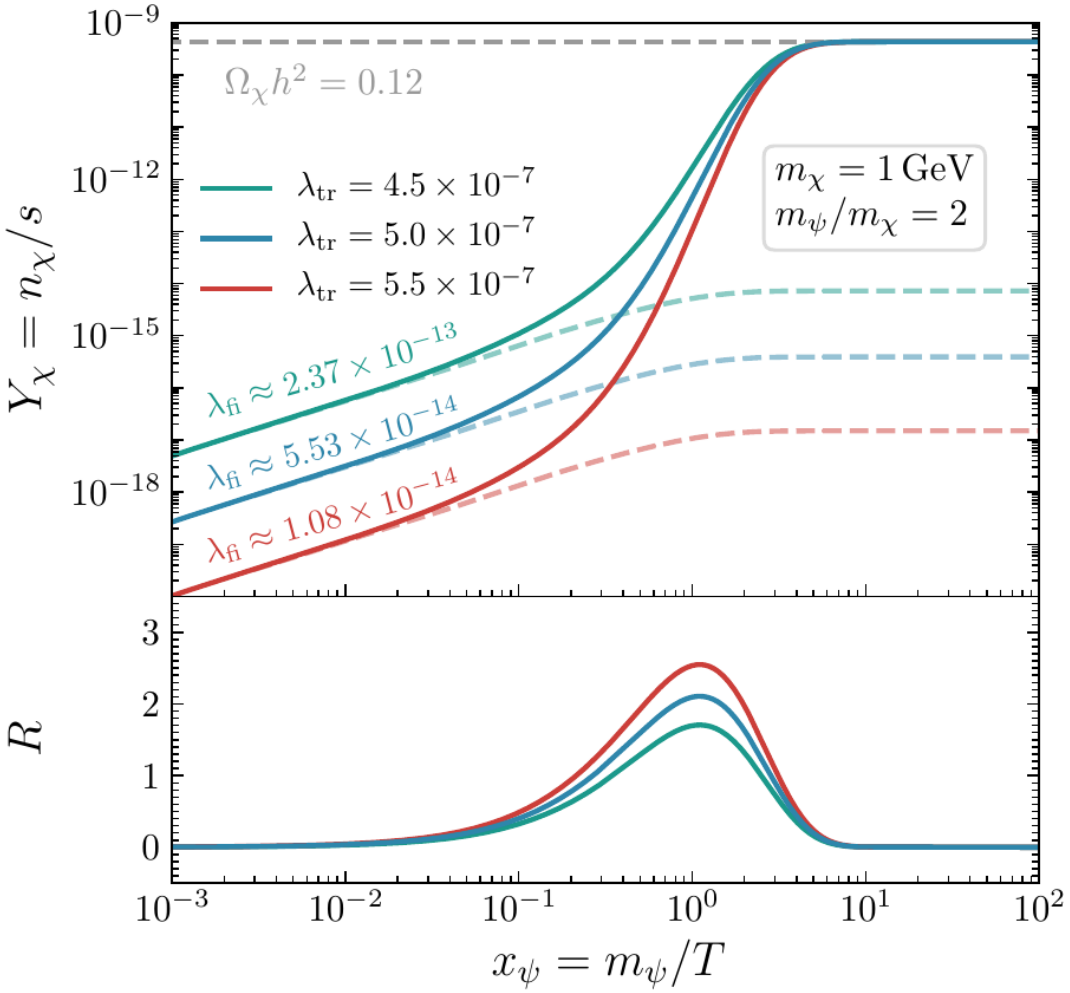


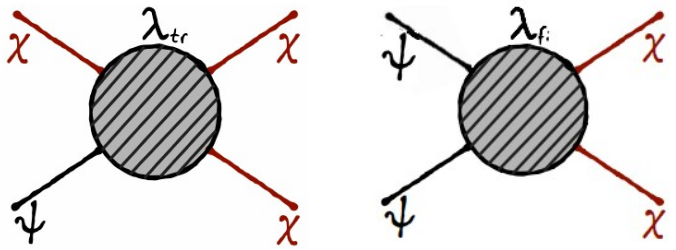


$$Y_\chi(x_\psi \ll 1) = \underbrace{Y_\chi^0 = \text{const.}}_{\text{Initial condition}}$$

Evolution of the Dark Matter abundance

Exponential growth after freeze-in phase:





Transmission

$$\dot{n}_\chi + 3Hn_\chi = \langle\sigma_{\chi\psi\to\chi\chi} v\rangle \bar{n}_\psi n_\chi$$

$$+\langle\sigma_{\psi\psi\to\chi\chi} v\rangle \bar{n}_\psi^2$$

Freeze-in

Evolution of the Dark Matter abundance

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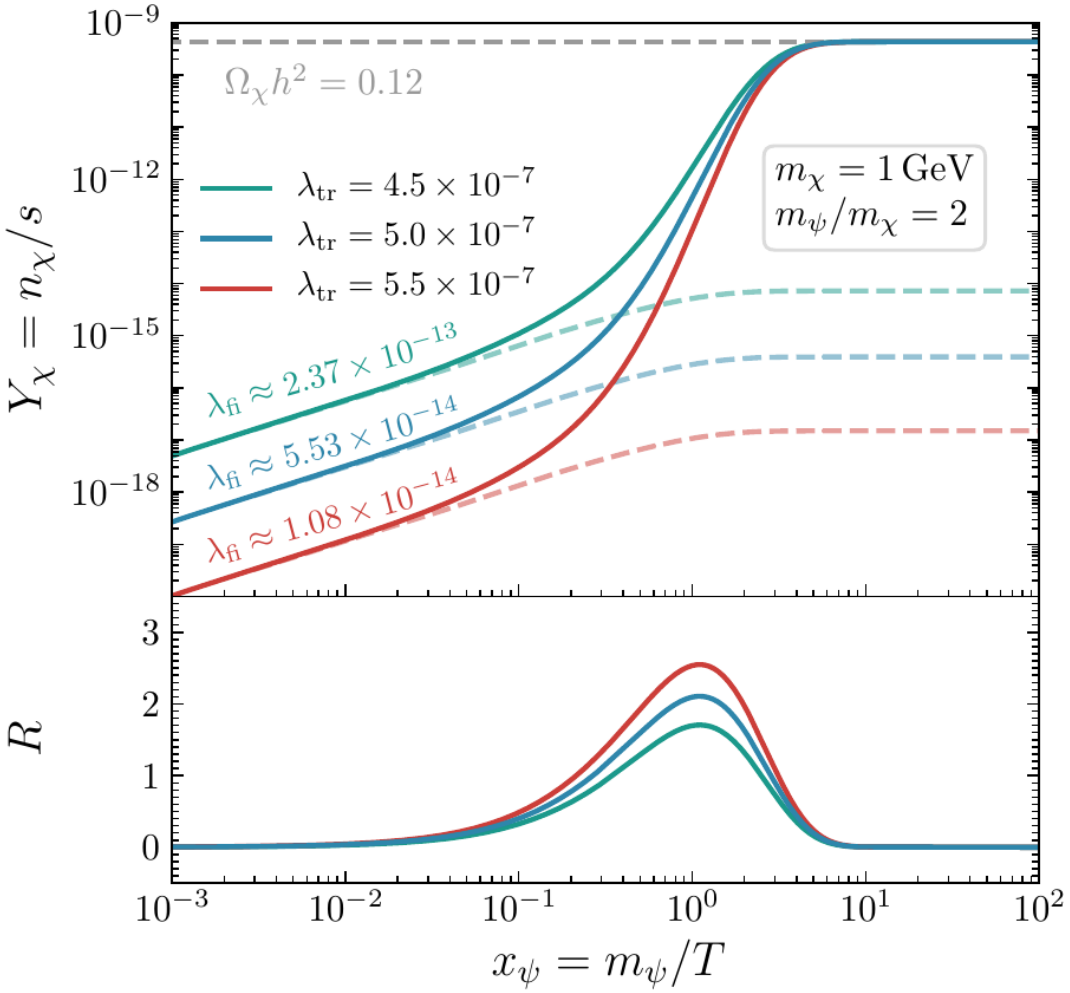

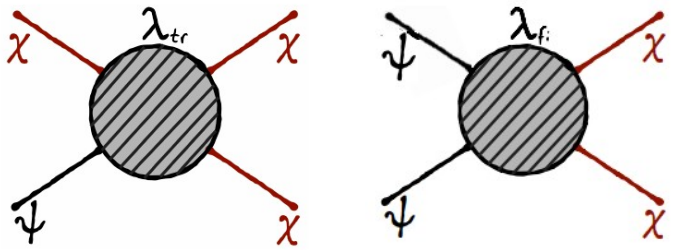

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Freeze-in

Prerequisite:

$$\langle\sigma_{\psi\psi\to\chi\chi}v\rangle \ll \langle\sigma_{\psi\chi\to\chi\chi}v\rangle$$

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- Yes! Add DS mediator and mass mixing

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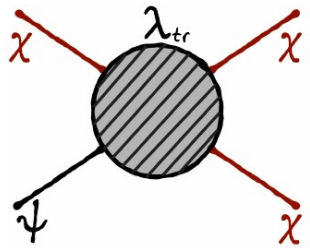
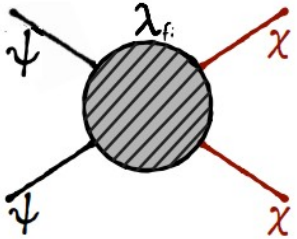


$\propto \theta$



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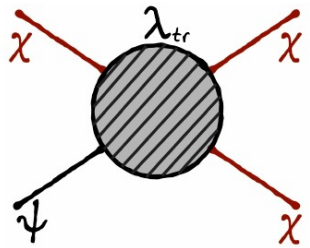

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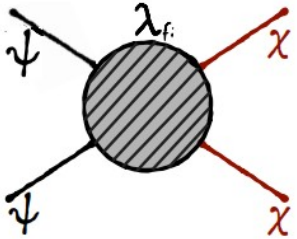

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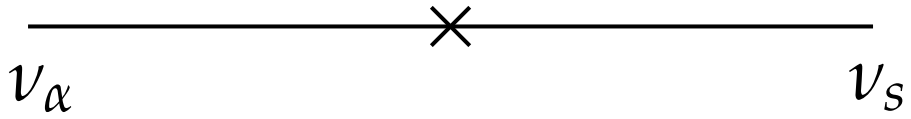

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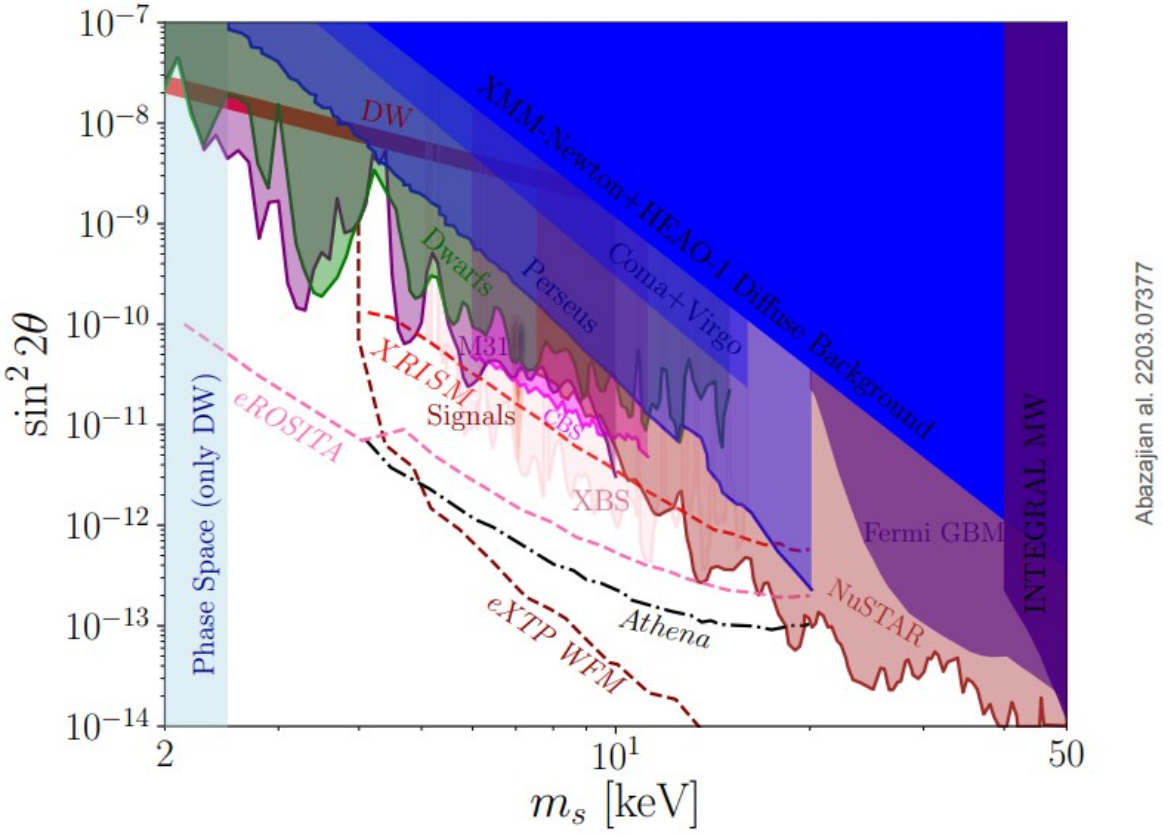

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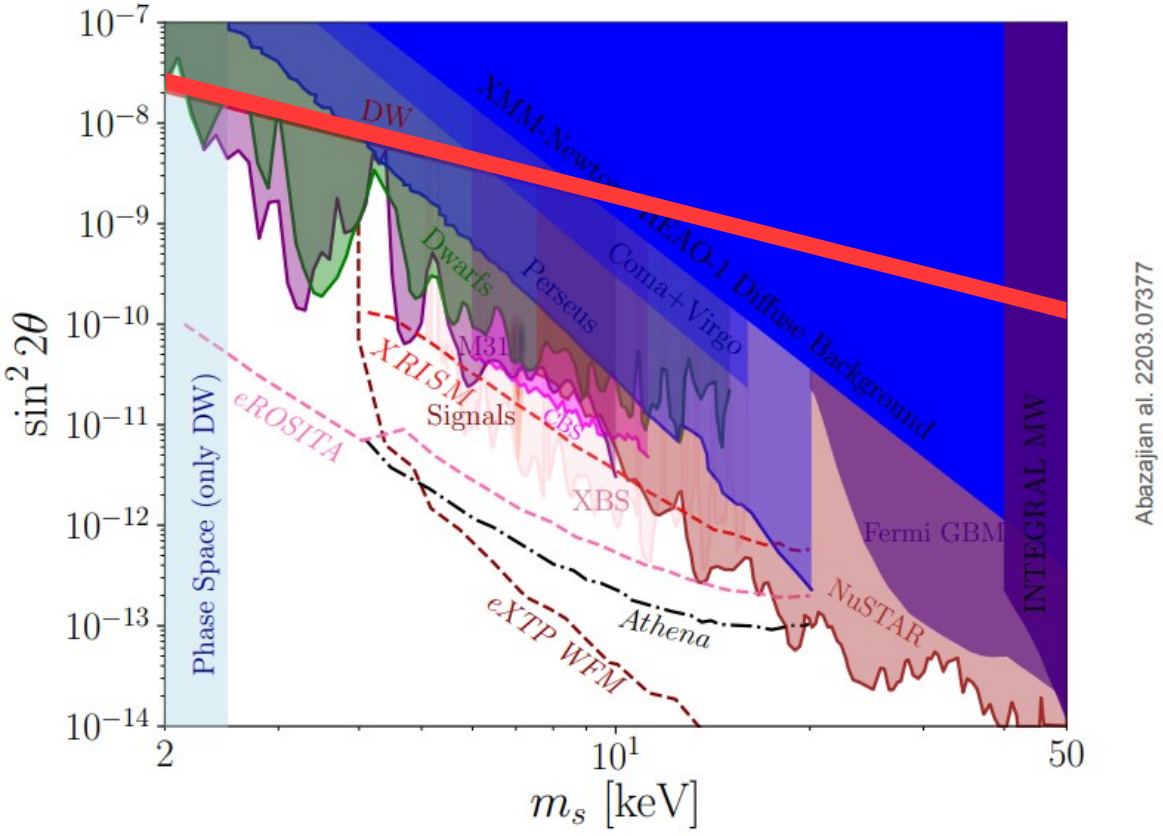

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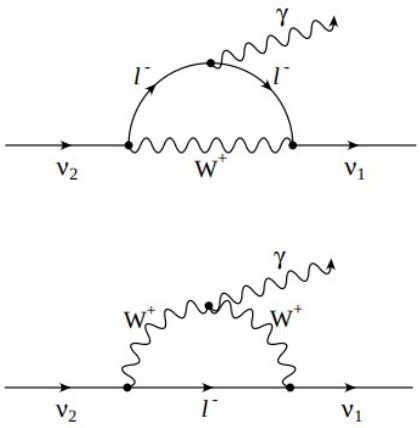
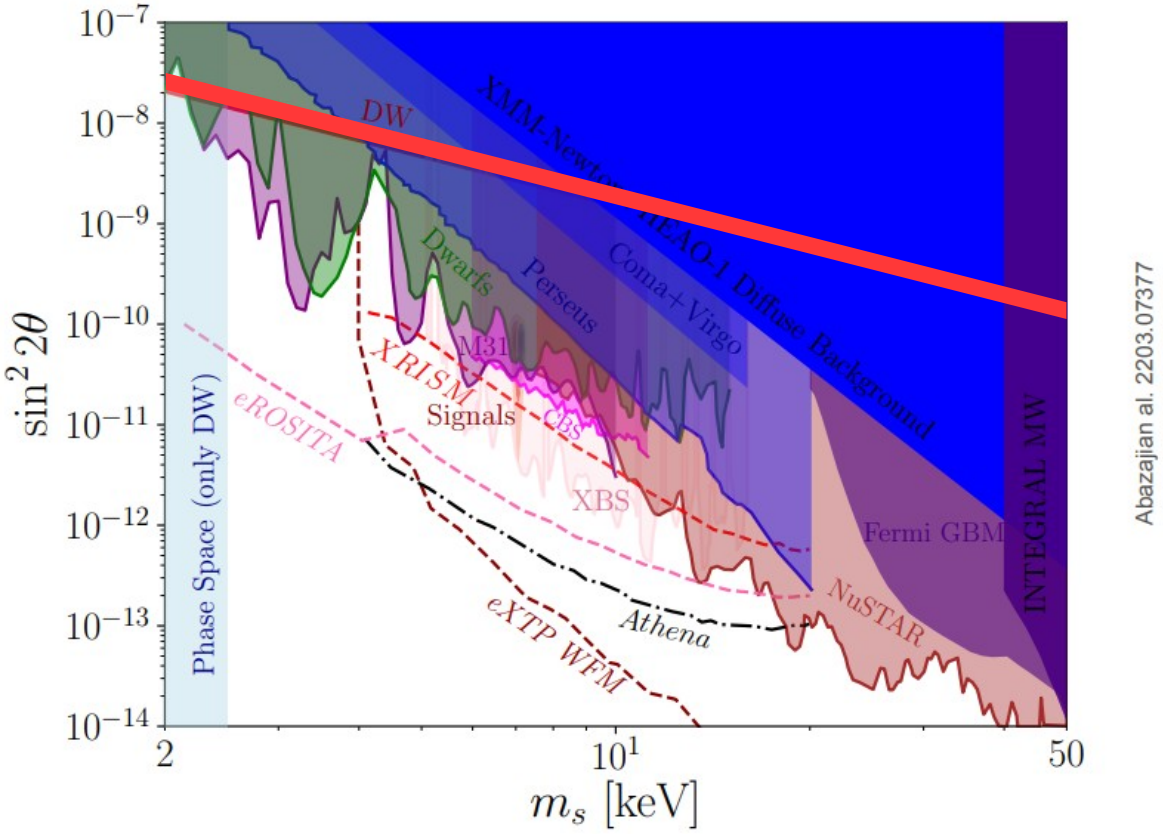


[astro-ph/0106002]



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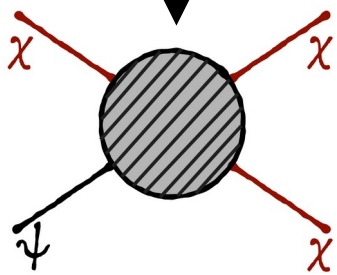
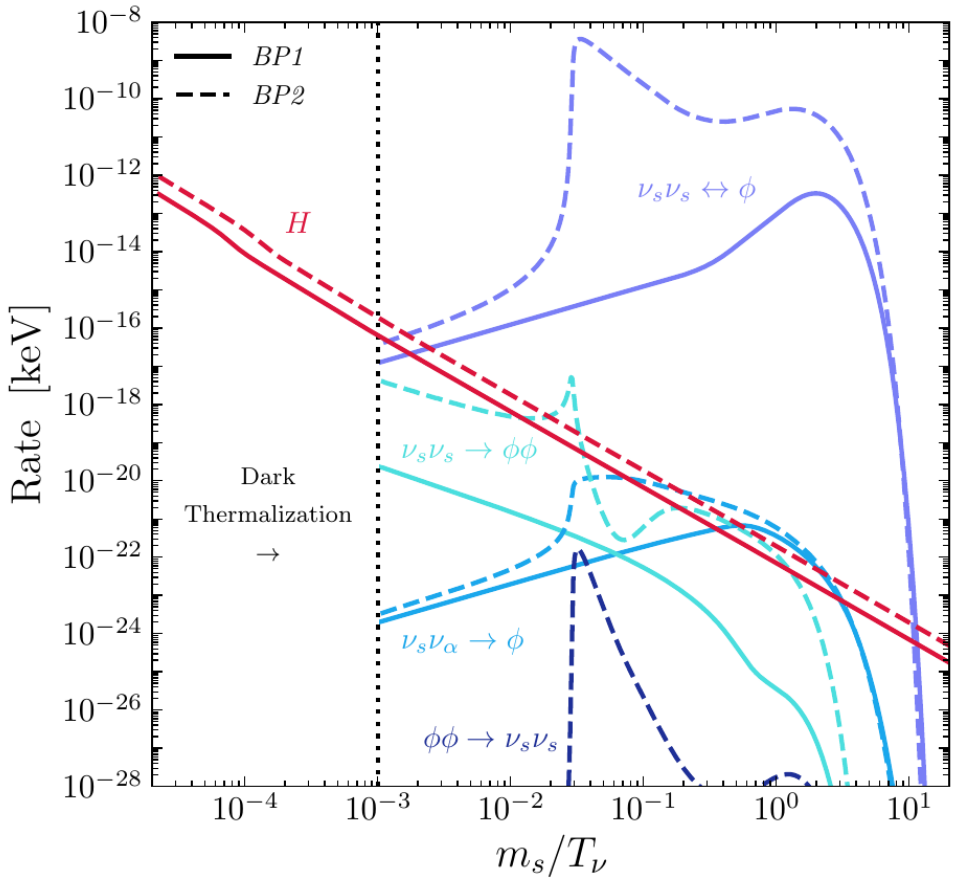


Cosmological evolution

Rapid DS thermalisation via
$\nu_s\nu_s \to \phi, \phi \to \nu_s\nu_s$

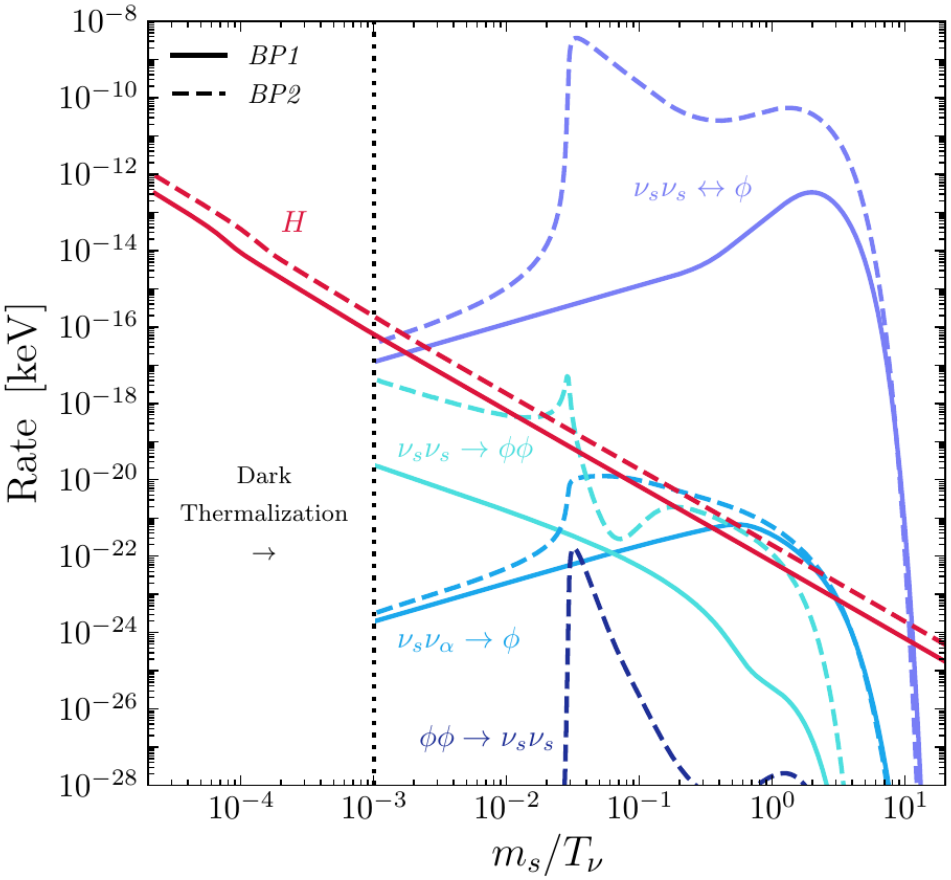


Cosmological evolution

Rapid DS thermalisation via

$\nu_s \nu_s \rightarrow \phi, \phi \rightarrow \nu_s \nu_s$

$$f_s = \frac{1}{e^{(E-\mu_s)/T_d} + 1} \qquad f_\phi = \frac{1}{e^{(E-\mu_\phi)/T_d} - 1}$$



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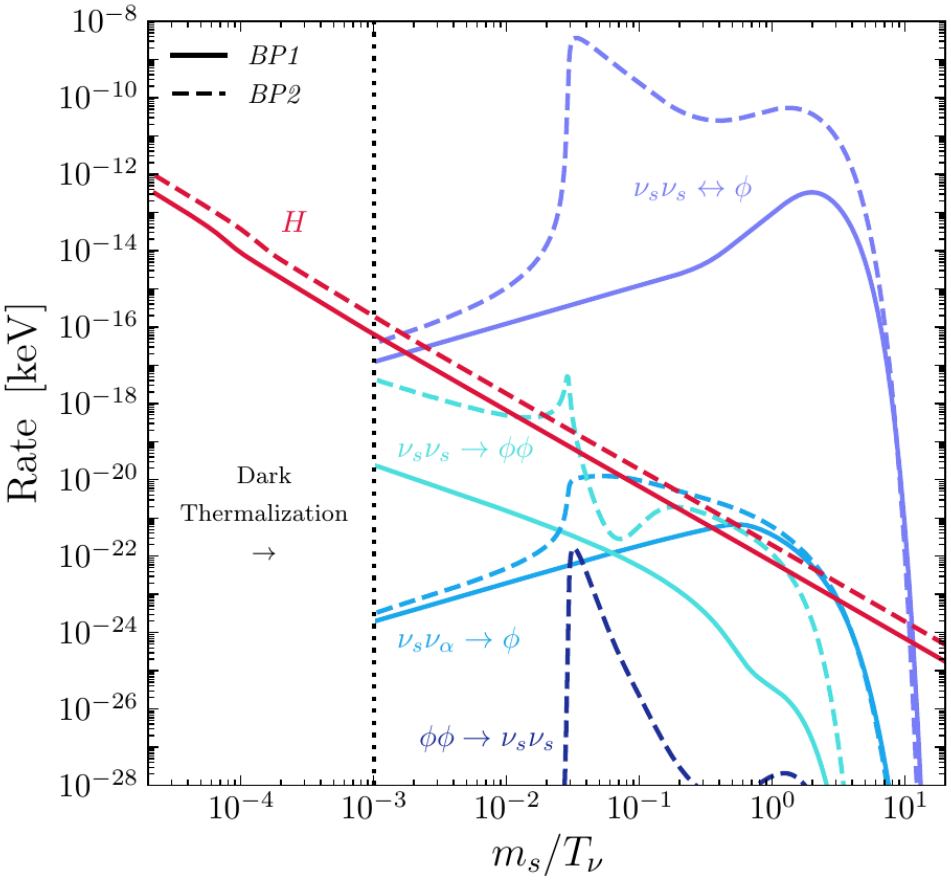

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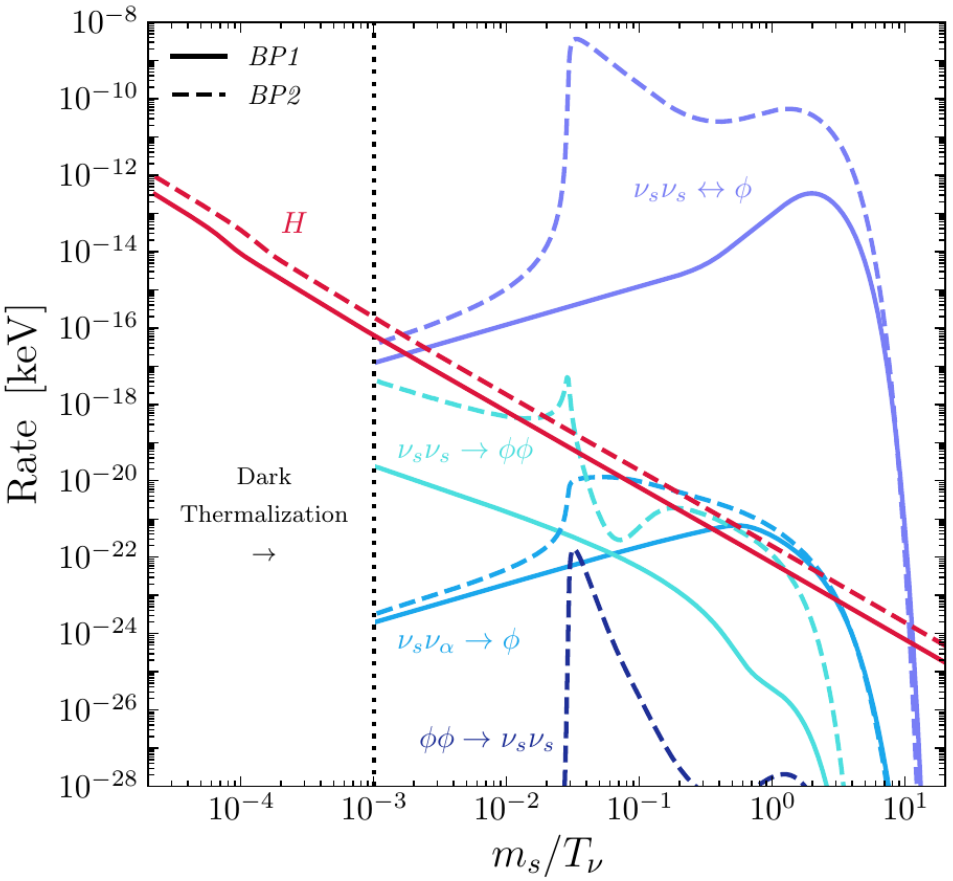
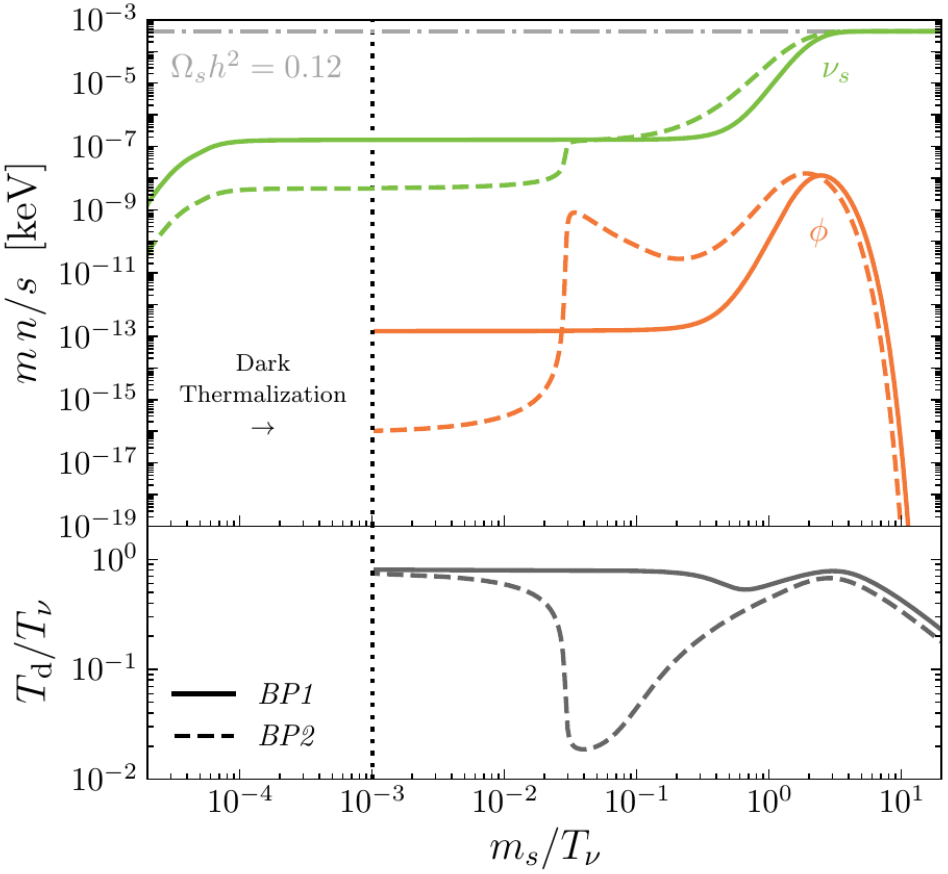
$$f_s = \frac{1}{e^{(E-\mu_s)/T_d}+1} \qquad f_\phi = \frac{1}{e^{(E-\mu_\phi)/T_d}-1}$$

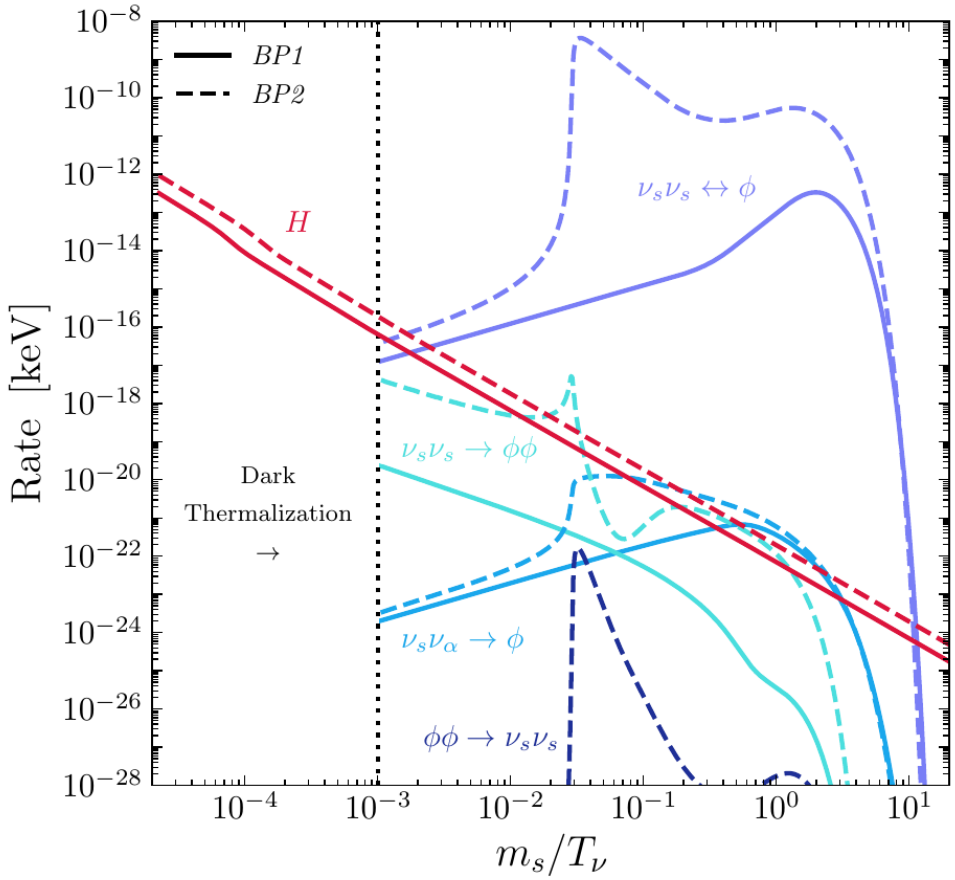
Boltzmann equations:

$$\dot{n}_s + 3Hn_s = C_s$$
$$\dot{n}_\phi + 3Hn_\phi = C_\phi$$
$$\dot{\rho} + 3H(\rho + P) = 0$$



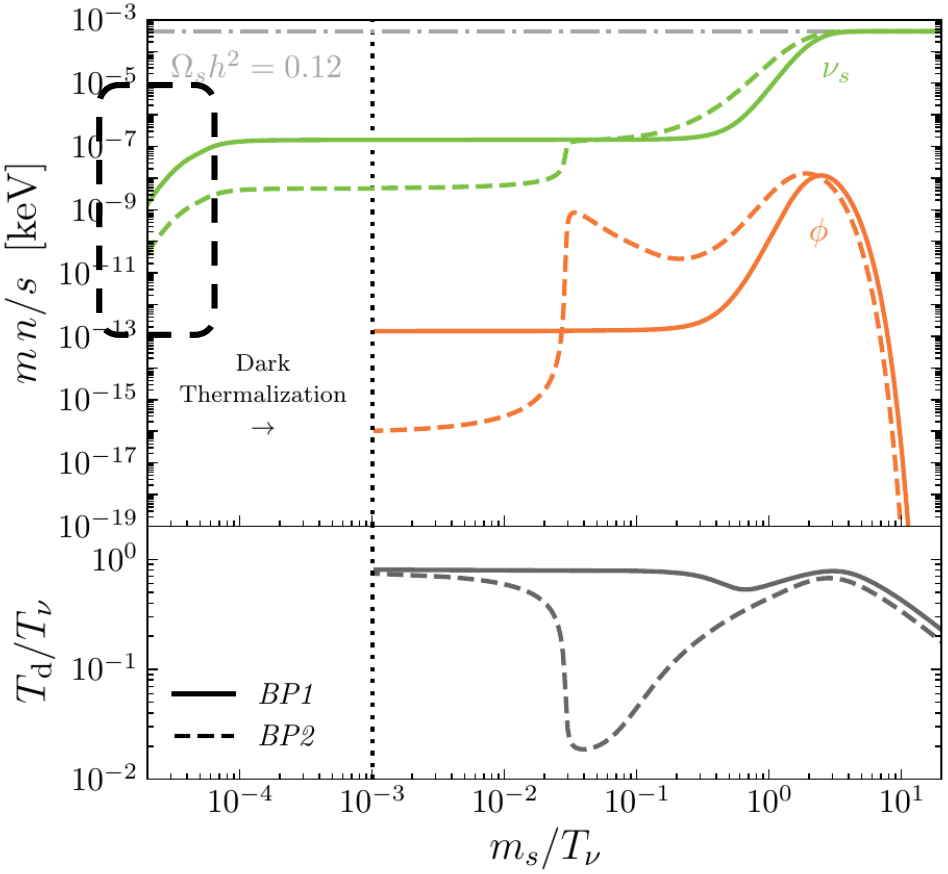
Cosmological evolution

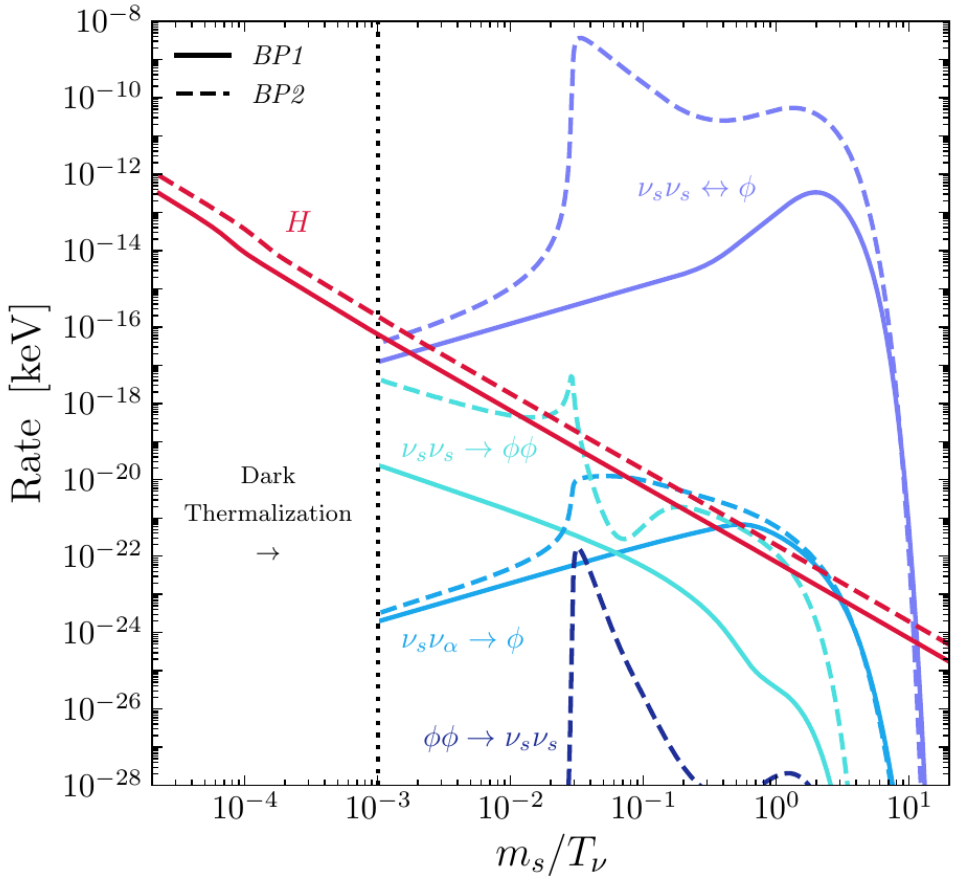




Cosmological evolution

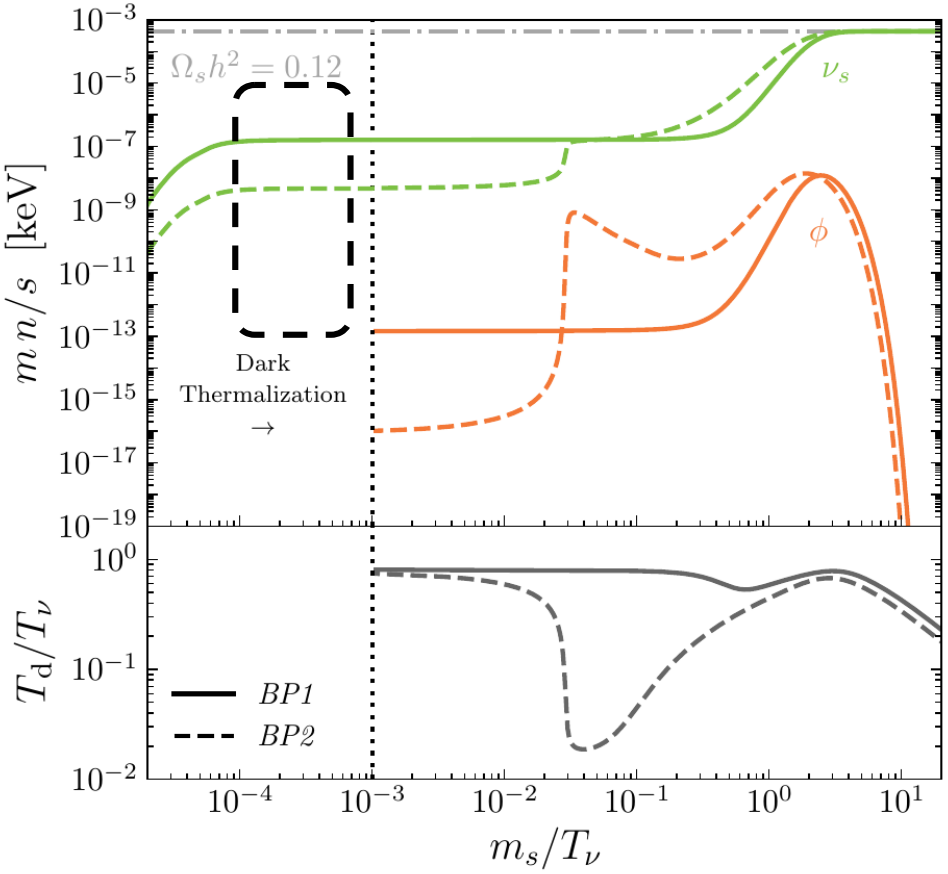
$$\nu_\alpha \longrightarrow \nu_s$$

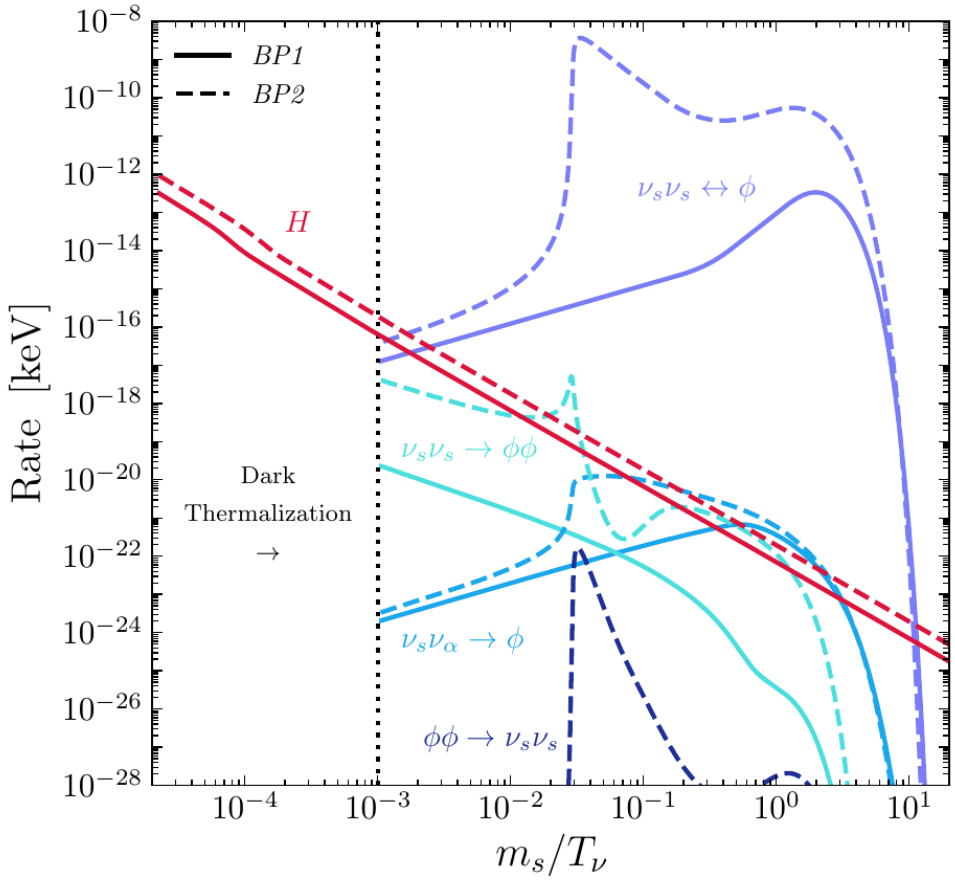




Cosmological evolution

$$\nu_s \nu_s \to \phi, \phi \to \nu_s \nu_s$$





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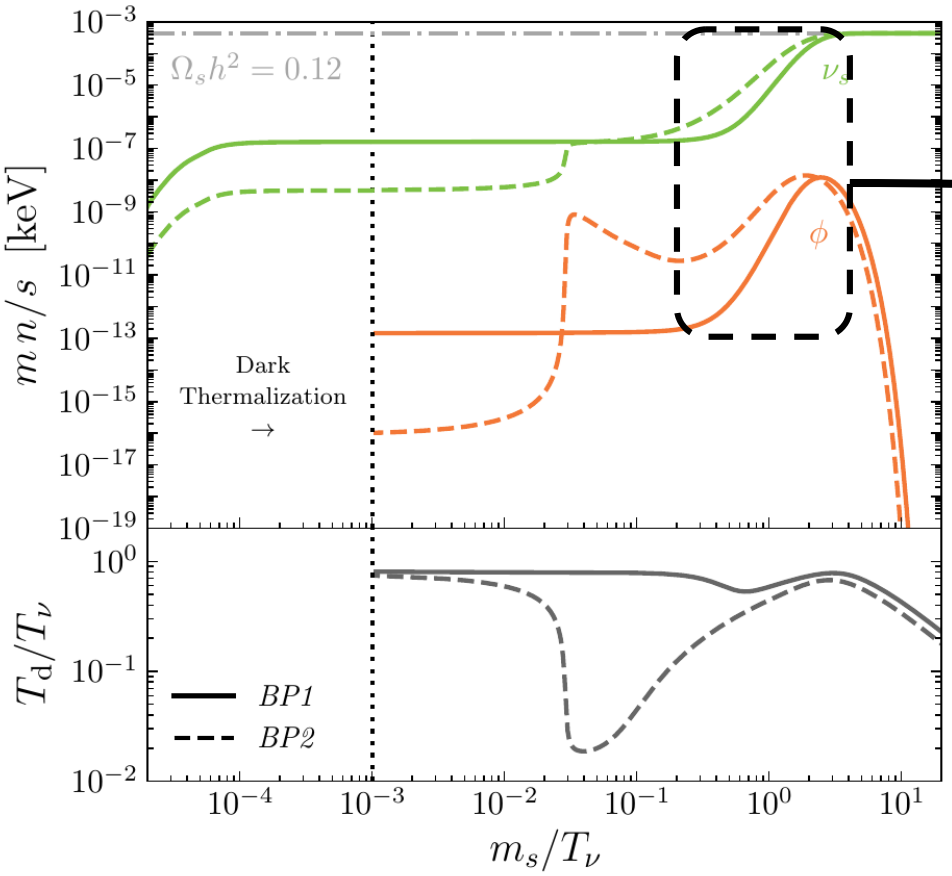
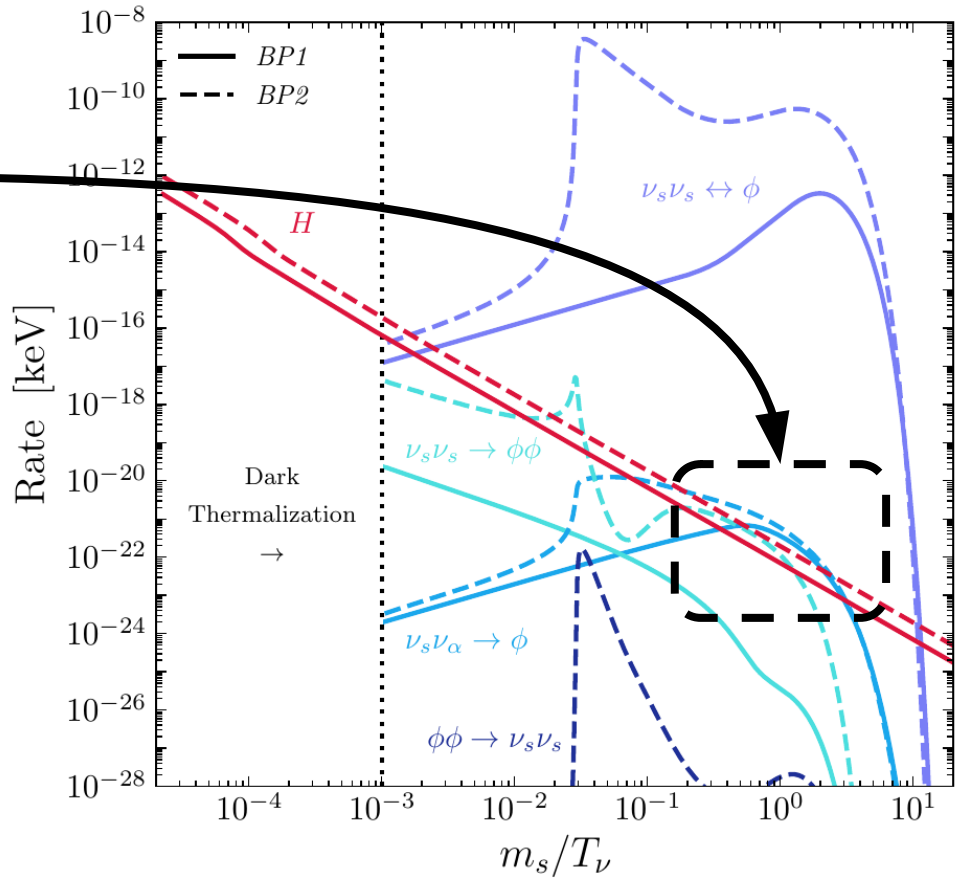
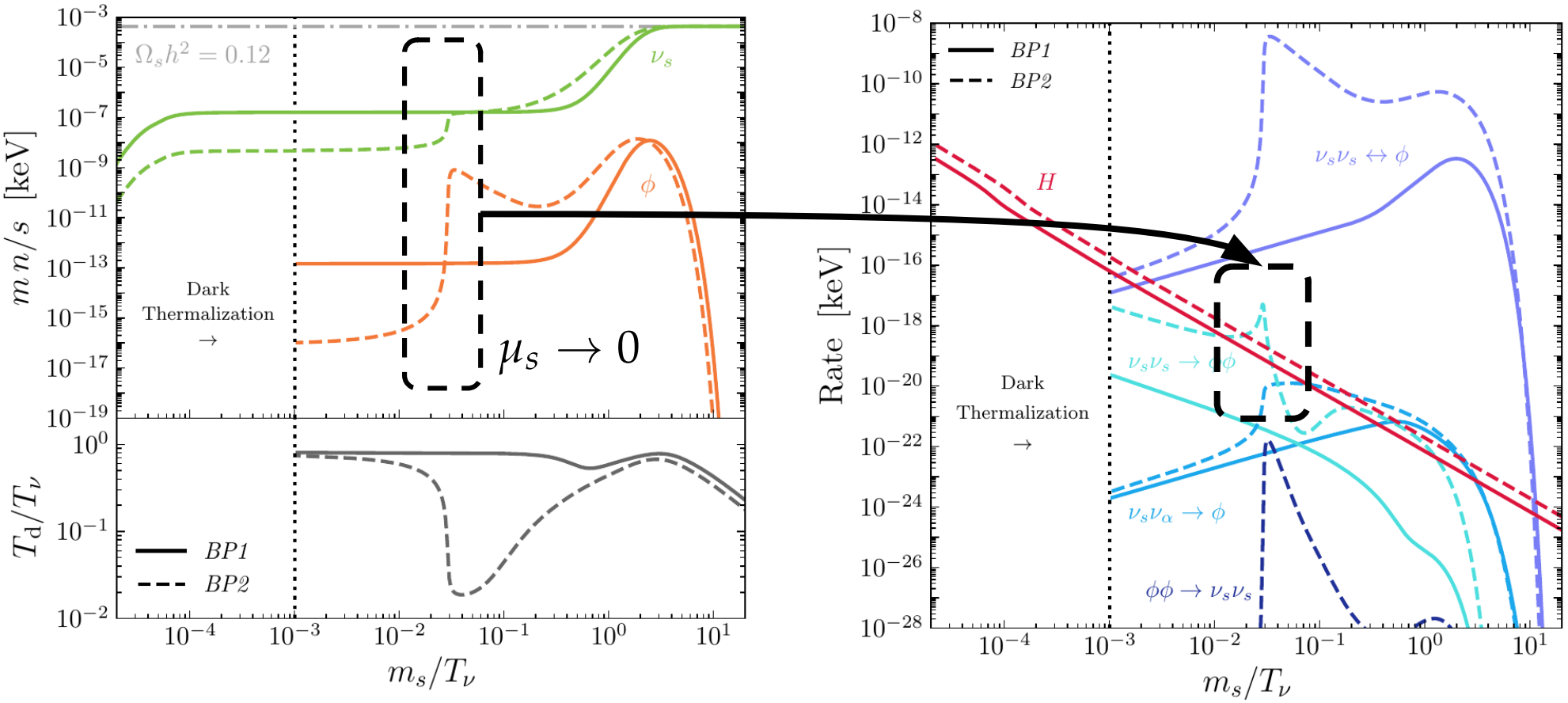


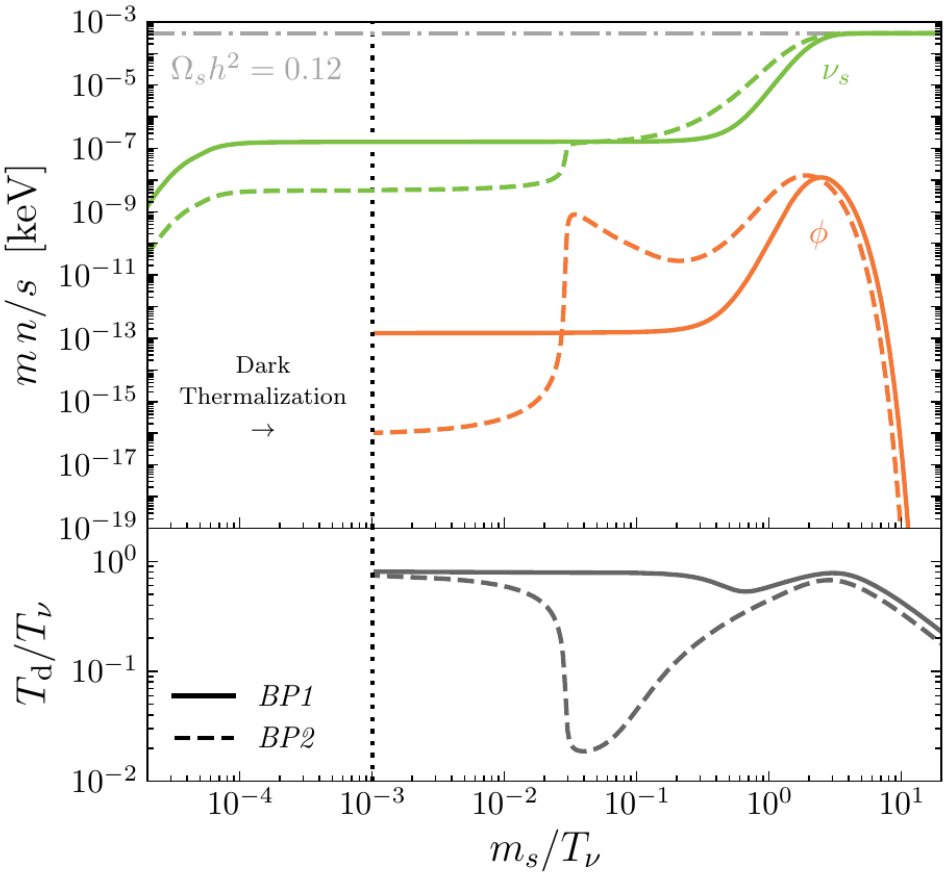


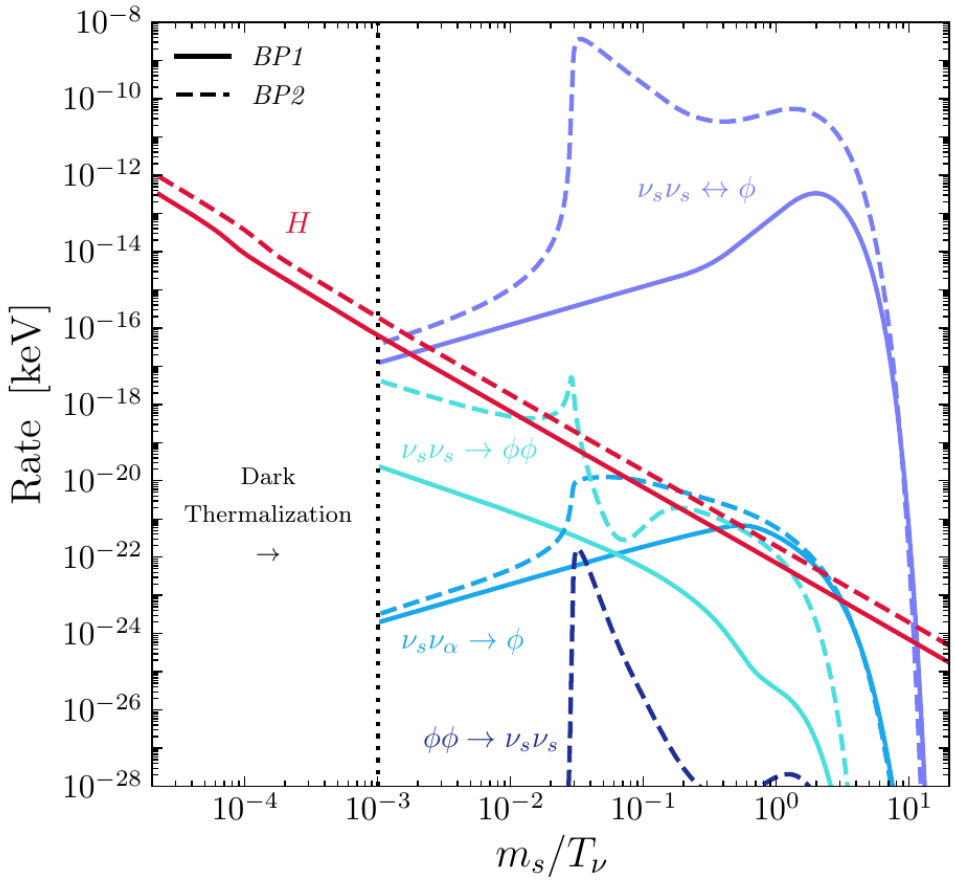
Cosmological evolution

$$\nu_s\nu_s \to \phi\phi, \phi\phi \to 4\nu_s$$



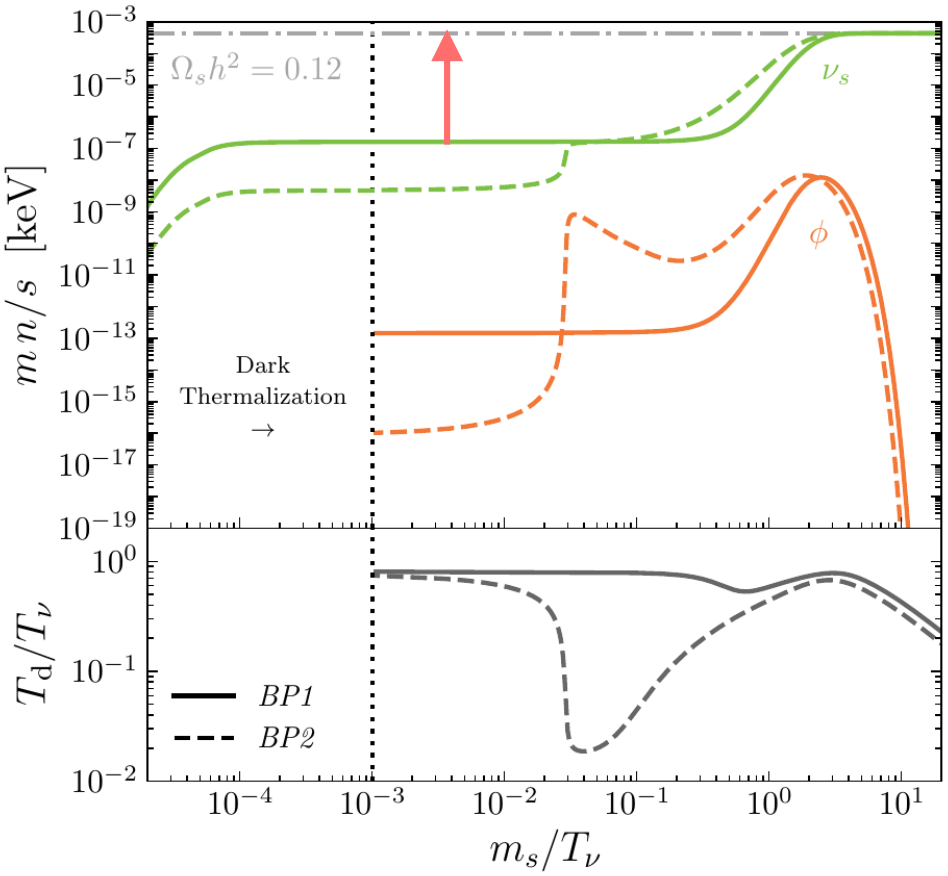
Cosmological evolution

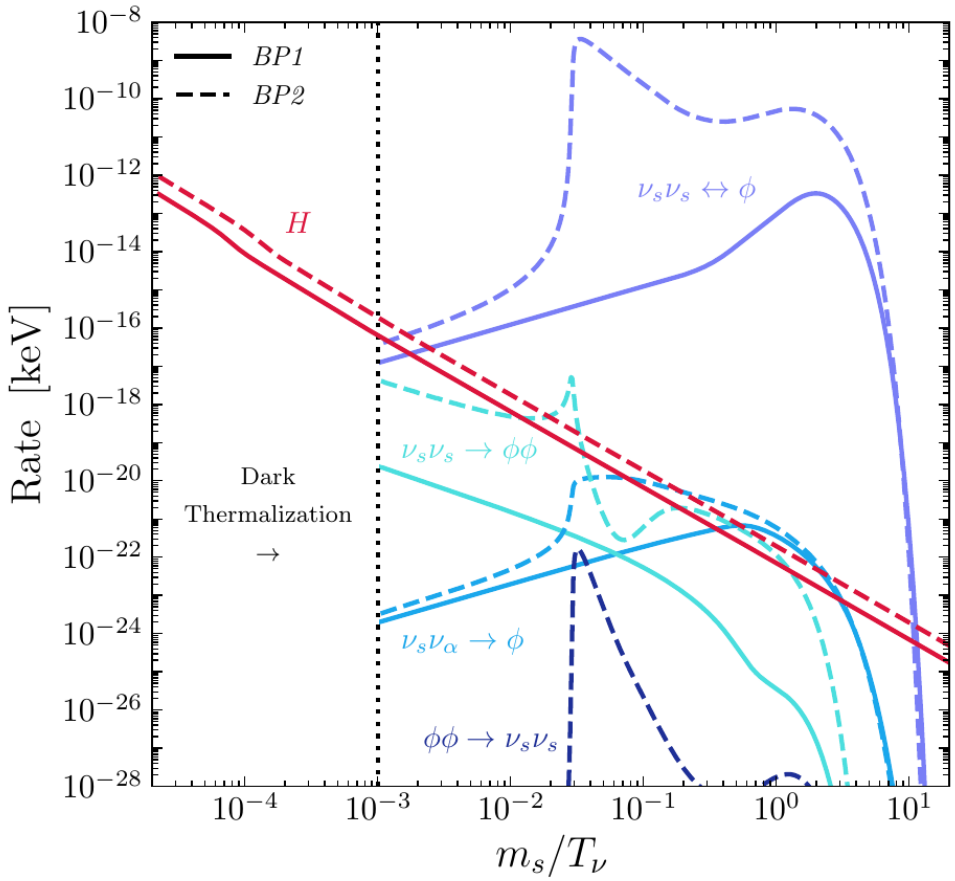




→ Correct relic abundance despite DW underproduction

Cosmological evolution





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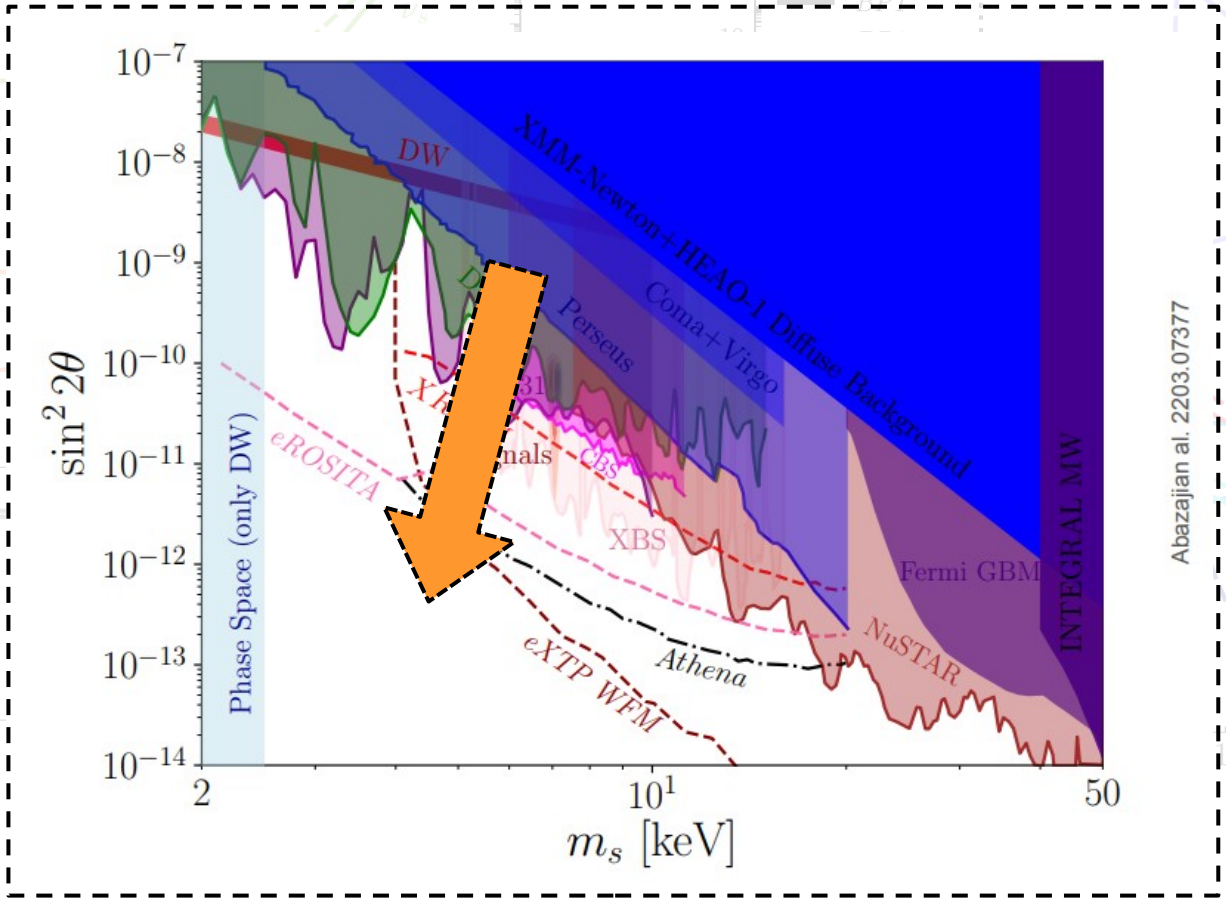
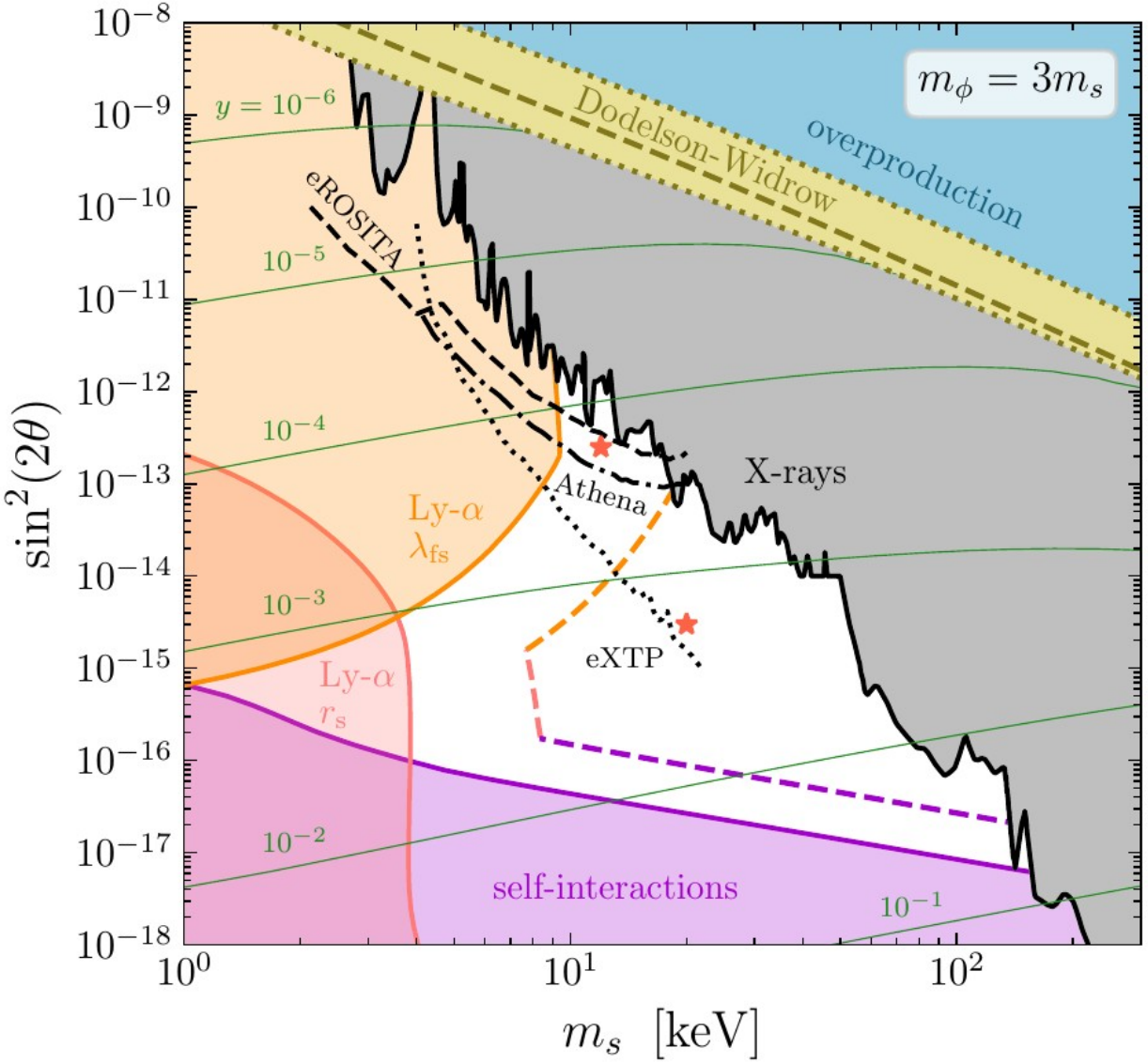


→ Correct relic abundance despite DW underproduction

Viable parameter space



Overview

- Pandemic DM and its application to sterile neutrinos

Minimal sterile neutrino dark matter

Torsten Bringmann,[1,2,*] Paul Frederik Depta,[3,†] Marco Hufnagel,[4,‡]
Jörn Kersten,[5,6,§] Joshua T. Ruderman,[7,¶] and Kai Schmidt-Hoberg[8,**]

[1] *Department of Physics, University of Oslo,*
[2] *Theoretical Physics Department, CERN,*
[3] *Max-Planck-Institut für Kernphysik, Saupfercheo*
[4] *Service de Physique Théorique, Université Libre de Bruxelles, Bou*
[5] *Korea Institute for Advanced Study, Seo*
[6] *Department of Physics and Technology, Univers*
[7] *Center for Cosmology and Particle Physics, Department of Physi*
[8] *Deutsches Elektronen-Synchrotron DESY, Notk*
(Dated: April 26,

Dark Matter from Exponential Growth

Originally proposed as Pandemic Dark Matter

Torsten Bringmann,[1,*] Paul Frederik Depta,[2,†] Marco Hufnagel,[3,‡]
Joshua T. Ruderman,[4,2,5,6,§] and Kai Schmidt-Hoberg[2,¶]

[1] *Department of Physics, University of Oslo, Box 1048, N-0316 Oslo, Norway*
[2] *Deutsches Elektronen-Synchrotron DESY, Notkestraße 85, D-22607 Hamburg, Germany*
[3] *Service de Physique Théorique, Université Libre de Bruxelles, Boulevard du Triomphe, CP225, B-1050 Brussels, Belgium*
[4] *Center for Cosmology and Particle Physics, Department of Physics, New York University, New York, NY 10003, USA*
[5] *Kavli Institute for Theoretical Physics, University of California, Santa Barbara, CA 93106, USA*
[6] *School of Physics and Astronomy, Tel-Aviv University, Tel-Aviv 69978, Israel*

- The domain of cannibal DM

The domain of a cannibal dark matter

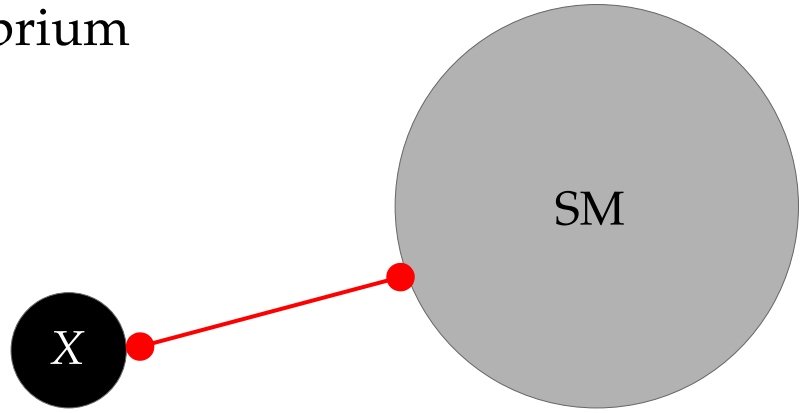
Marco Hufnagel[1,*] and Michel H.G. Tytgat[1,†]

[1] *Service de Physique Théorique, Université Libre de Bruxelles, Boulevard du Triomphe, CP225, 1050 Brussels, Belgium*

Cannibal Dark Matter

Premise: DM keeps itself in chemical equilibrium

$$XX \leftrightarrow \text{SM}\,\text{SM}$$



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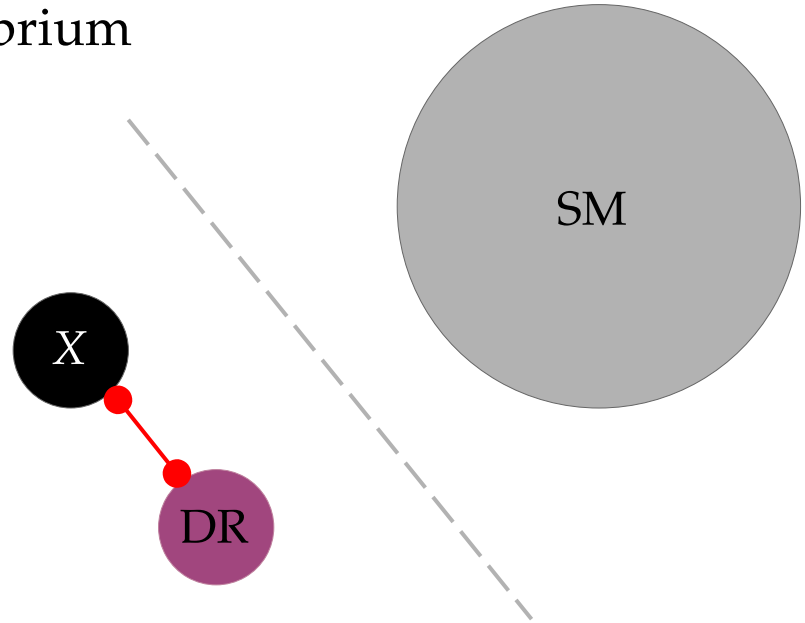
$$XX \leftrightarrow \mathrm{DR}\,\mathrm{DR}$$



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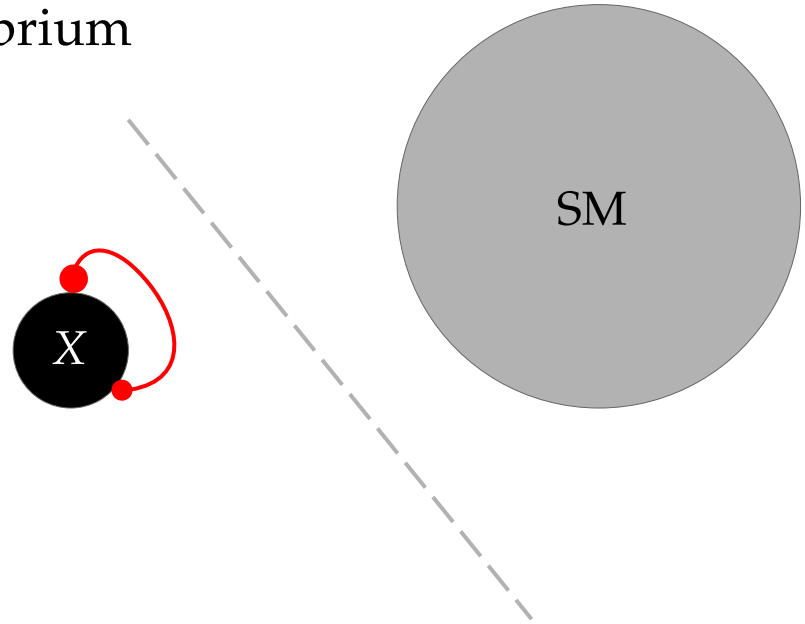

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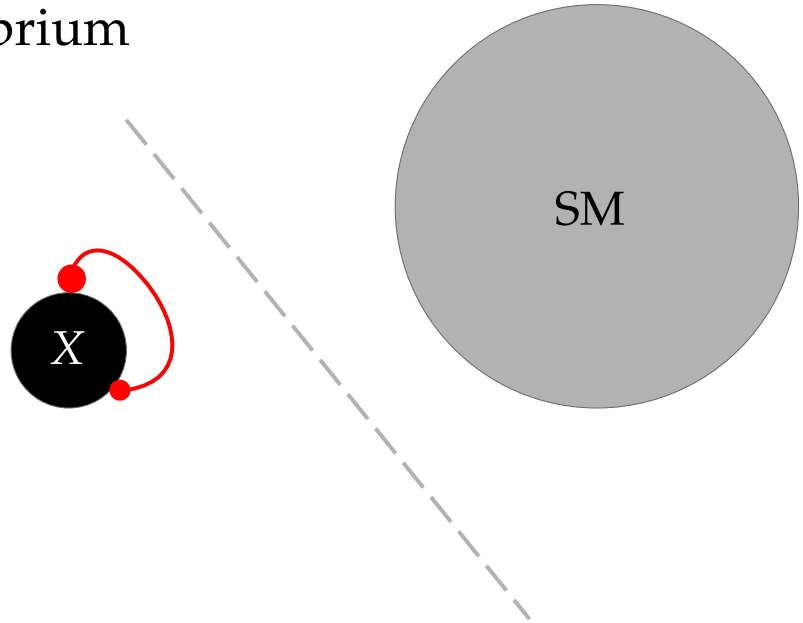
$\cancel{XX \leftrightarrow XX}$



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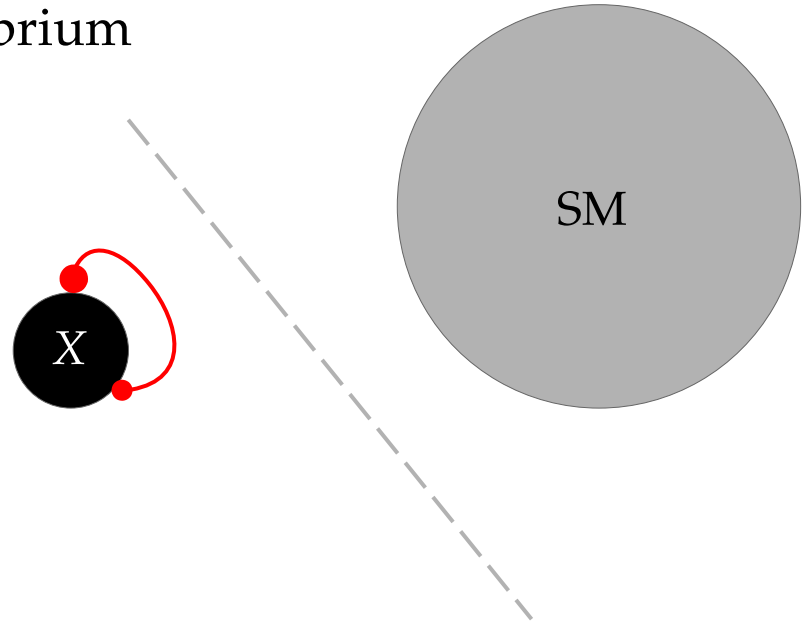
$$XX \leftrightarrow XXX$$



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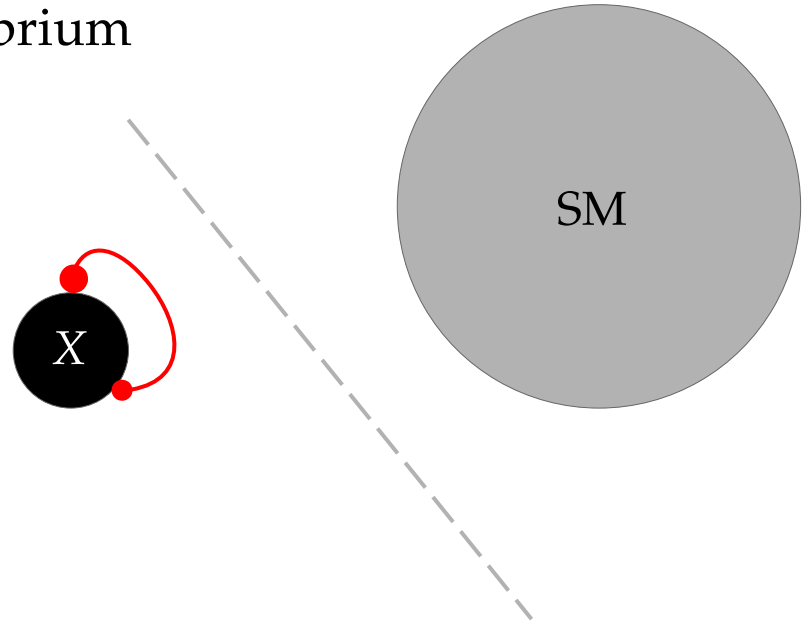
Premise: DM keeps itself in chemical equilibrium

$$XX \leftrightarrow XXX \quad XX \leftrightarrow XXXX$$



Cannibal Dark Matter

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$$\mathcal{L}_{\text{ds}} = \frac{1}{2}(\partial_\mu X)(\partial^\mu X) + \frac{1}{2}\mu^2 X^2 - \frac{\lambda}{4!}X^4$$

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$\mu^2 > 0, X = \phi$

$$\mathcal{L}^{\text{S}}_{\text{ds}} = \frac{1}{2}(\partial_\mu \phi)(\partial^\mu \phi) - \frac{1}{2}m_\phi^2 \phi^2 - \frac{\lambda}{4!}\phi^4$$

[1906.07659]

Cannibal Dark Matter

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$\mu^2 < 0, X = \phi + v$

$$\mathcal{L}^{\text{B}}_{\text{ds}} = \frac{1}{2}(\partial_\mu \phi)(\partial^\mu \phi) - \frac{1}{2}m_\phi^2 \phi^2 - \frac{\lambda v}{3!}\phi^3 - \frac{\lambda}{4!}\phi^4$$

[1906.07659]

Cannibal Dark Matter

Premise: DM keeps itself in chemical equilibrium

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$\mu^2 > 0, X = \phi$

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[1906.07659]

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$$\mathcal{L}^{\rm G}_{\rm ds} = \frac{1}{2}(\partial_\mu \phi)(\partial^\mu \phi) - \frac{1}{2}m_\phi^2\phi^2 - \frac{m_\phi g}{3!}\phi^3 - \frac{\lambda}{4!}\phi^4$$

[2206.11046]

Additional Considerations

Matrix element @threshold:

$$|\mathcal{M}_{3\phi\to\phi\phi}| \propto |3\lambda - g^2|$$
$$\to 0$$

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$$m_\phi \ll T_c' \simeq \frac{24|\mu^2|}{\lambda}$$

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$\lambda < 1$

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SSB before decoupling:

$$m_\phi \ll T_c' \simeq \frac{24|\mu^2|}{\lambda}$$

Domain wall formation:

$$\text{MeV} > \sigma_{\text{DW}} = \sqrt{\lambda} v^3$$

Thermal Evolution

$$f_\phi = \frac{1}{1 - e^{(E_\phi - \mu_\phi)/T'}}$$

$$\phi\phi \leftrightarrow \phi\phi\phi, \quad \phi\phi \leftrightarrow \phi\phi\phi\phi, \quad \dots$$

Thermal Evolution

$$f_\phi = \frac{1}{1 - e^{(E_\phi + \mu_\phi)/T'}}$$

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Boltzmann equation

$$(1) \qquad \dot{n}_\phi + 3Hn_\phi = \mathfrak{C}$$

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$$(1) \qquad \dot{n}_\phi + 3Hn_\phi = \sum_k (k-2) C_k \left[1 - e^{-(k-2)\mu_\phi/T'}\right]$$

$\phi\phi \leftrightarrow k\phi$ — reaction — inverse reaction

Thermal Evolution

$$f_\phi = \frac{1}{1 - e^{(E_\phi - \mu_\phi)/T'}}$$

$$\phi\phi \leftrightarrow \phi\phi\phi, \quad \phi\phi \leftrightarrow \phi\phi\phi\phi, \quad \dots$$

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(1) $\dot{n}_\phi + 3Hn_\phi = \sum_k (k-2) C_k \left[1 - e^{-(k-2)\mu_\phi/T'}\right]$

(2) $\dot{\rho}_\phi + 3H(\rho_\phi + P_\phi) = 0$

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Initial condition

(1) $\lim_{T\to\infty} \mu_\phi = 0$

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Thermal Evolution

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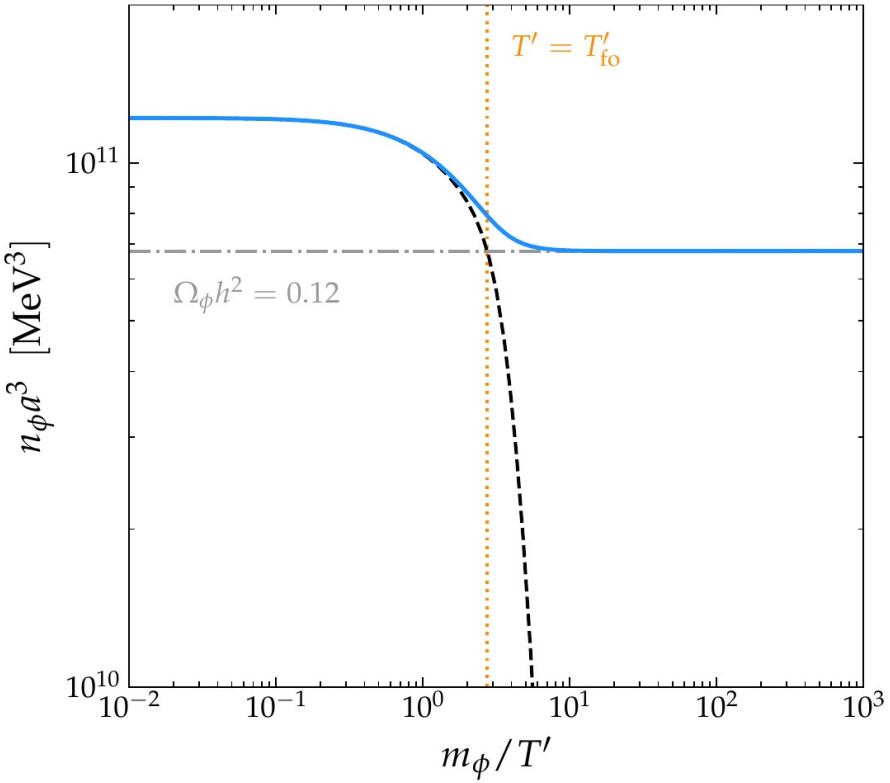
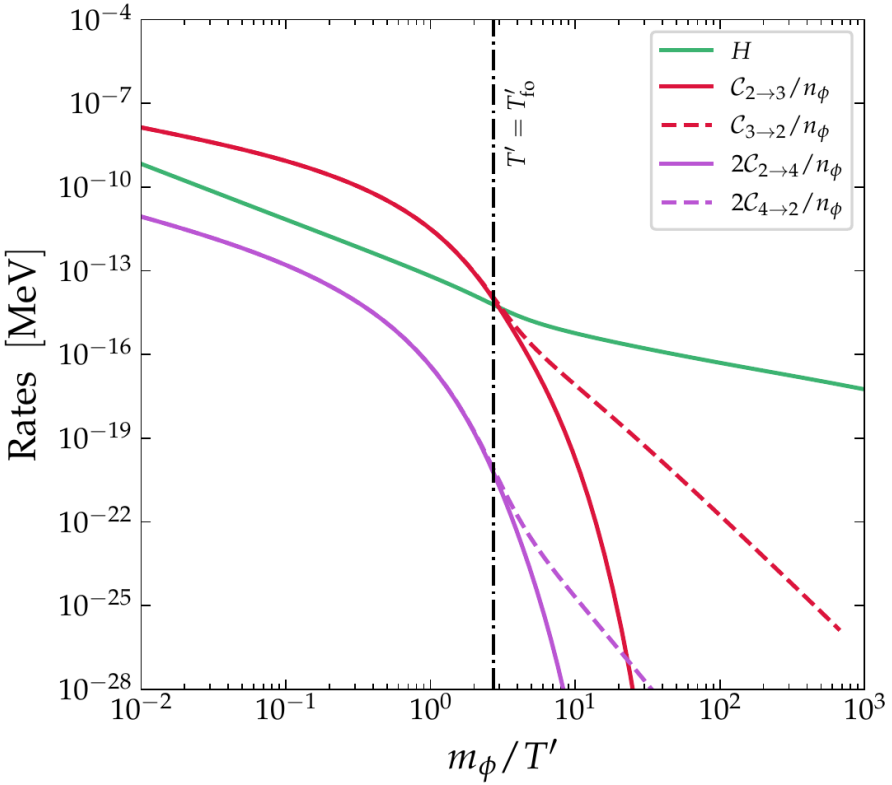
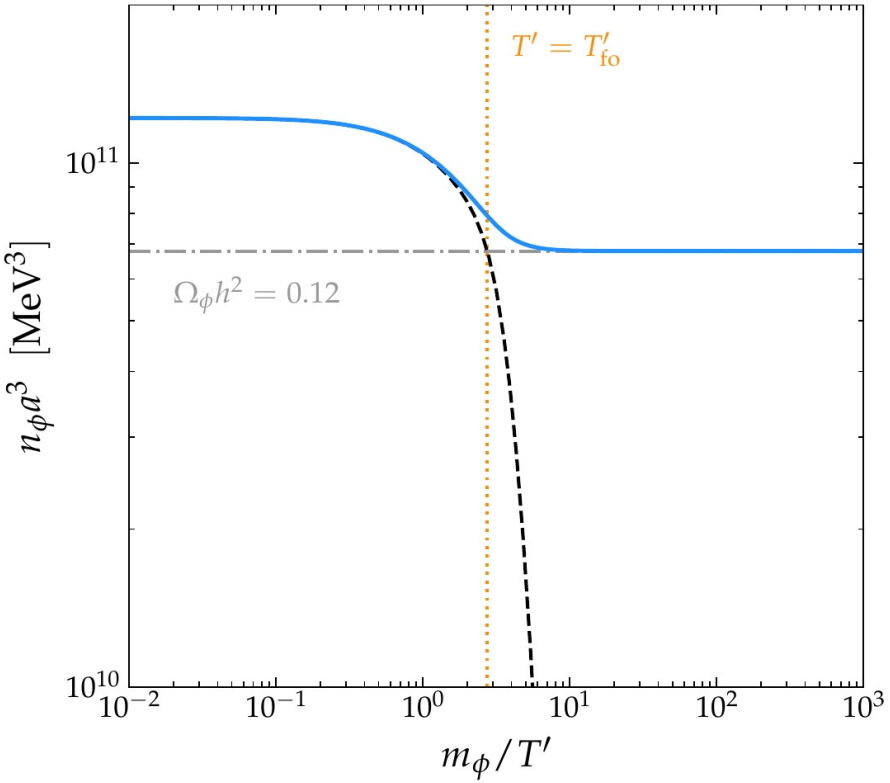
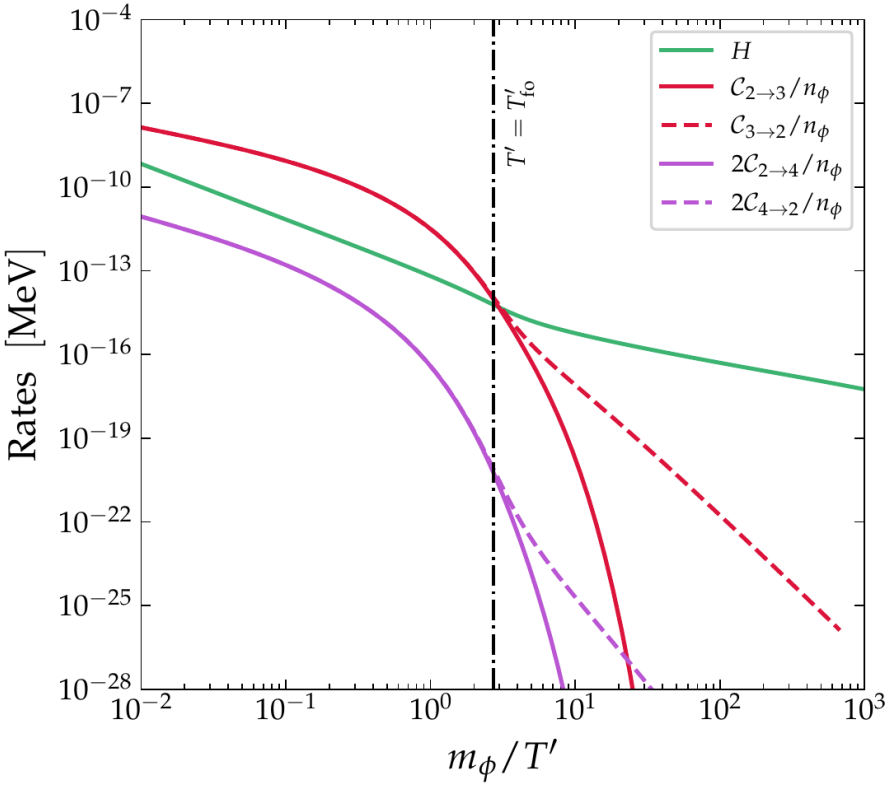
Thermal Evolution





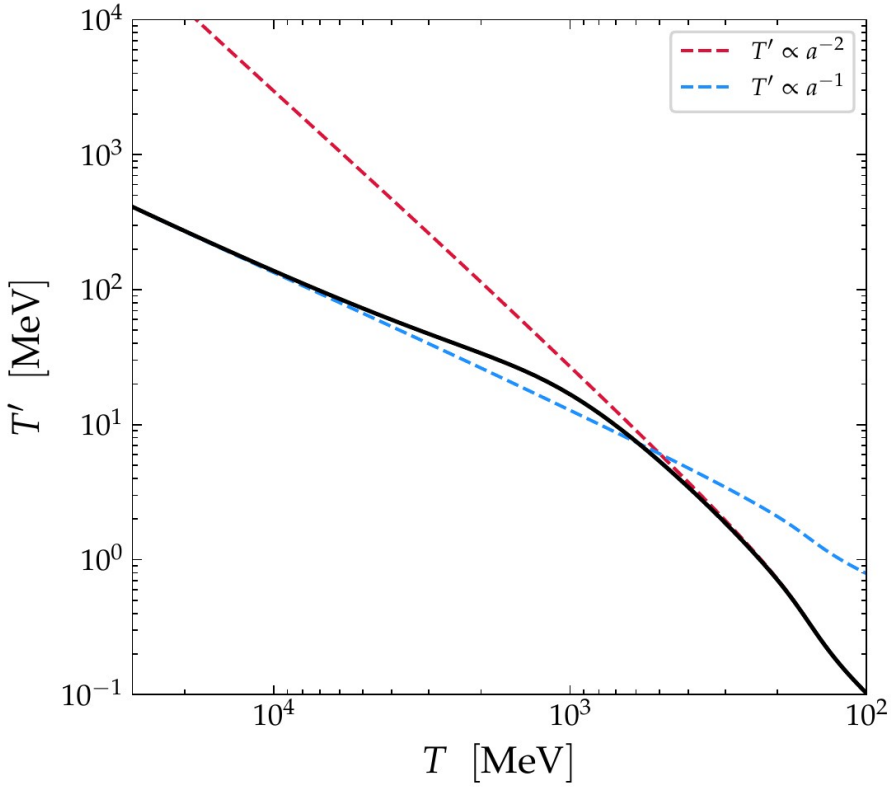
Thermal Evolution

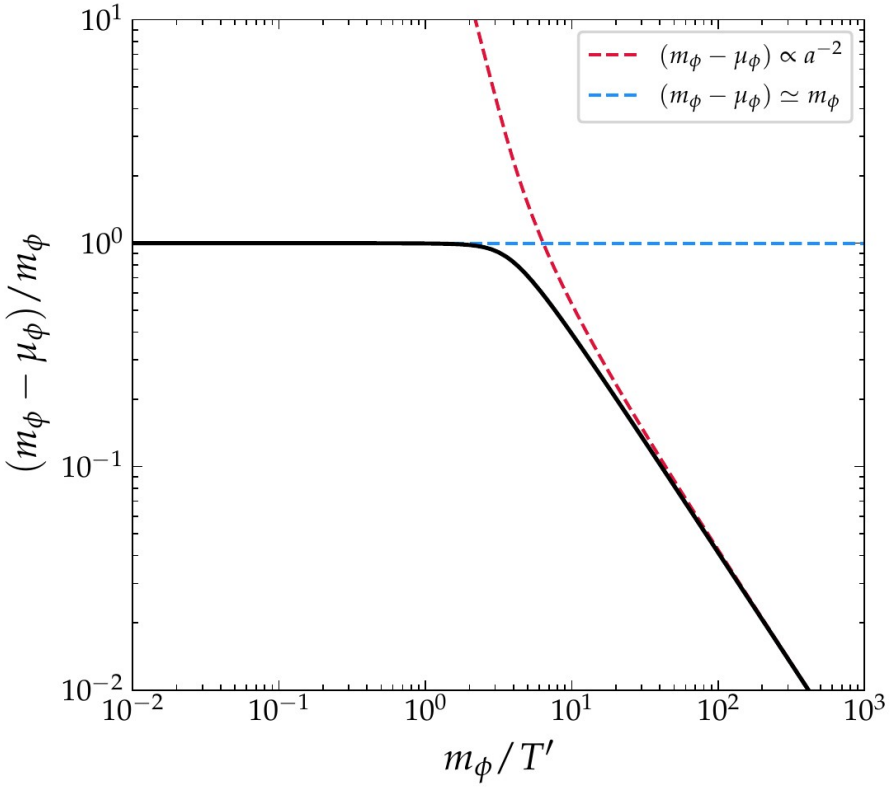




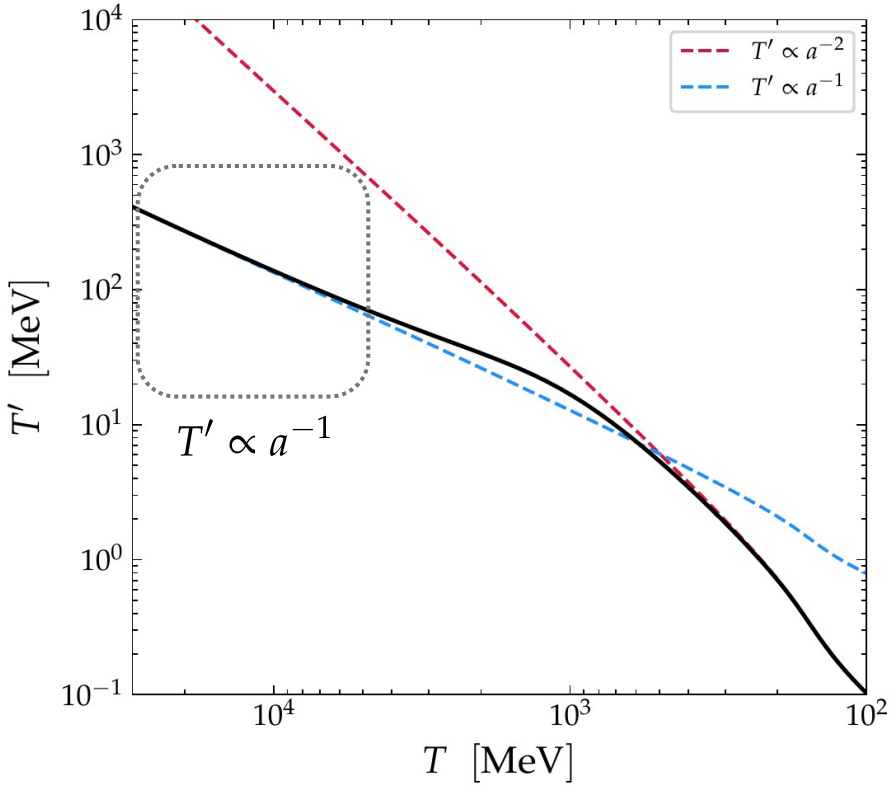
$m_\phi / T' \sim 1$

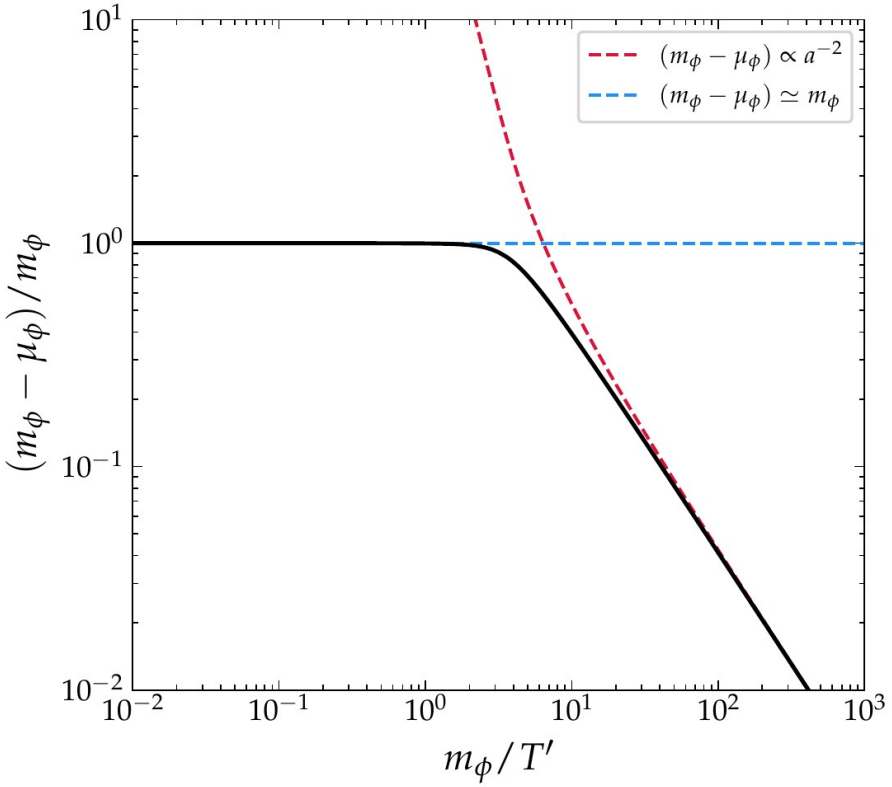
Thermal Evolution



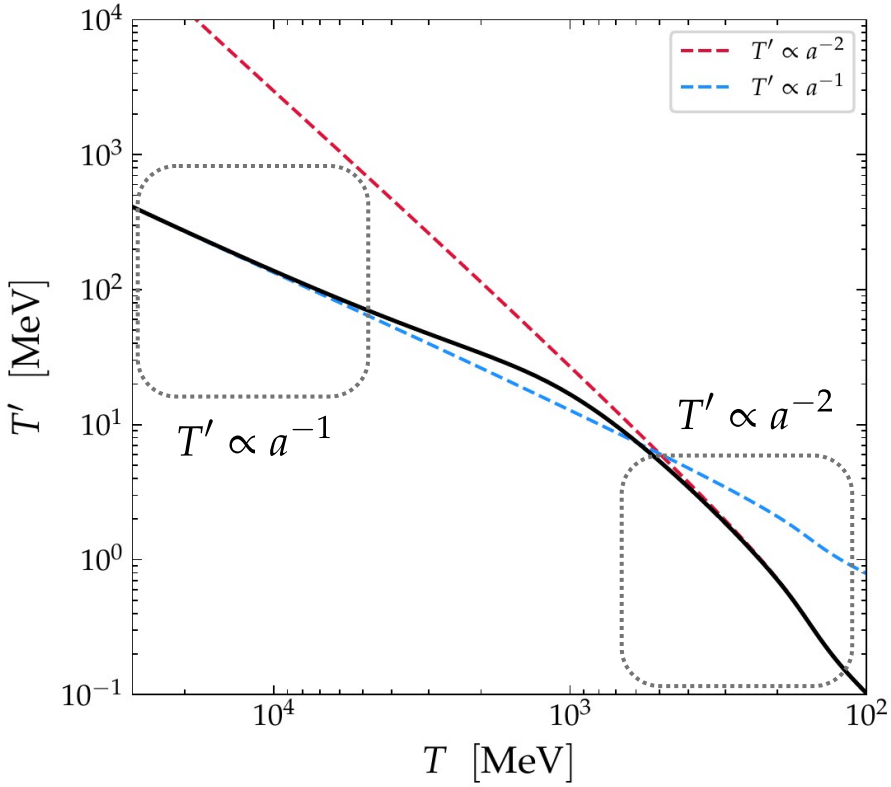


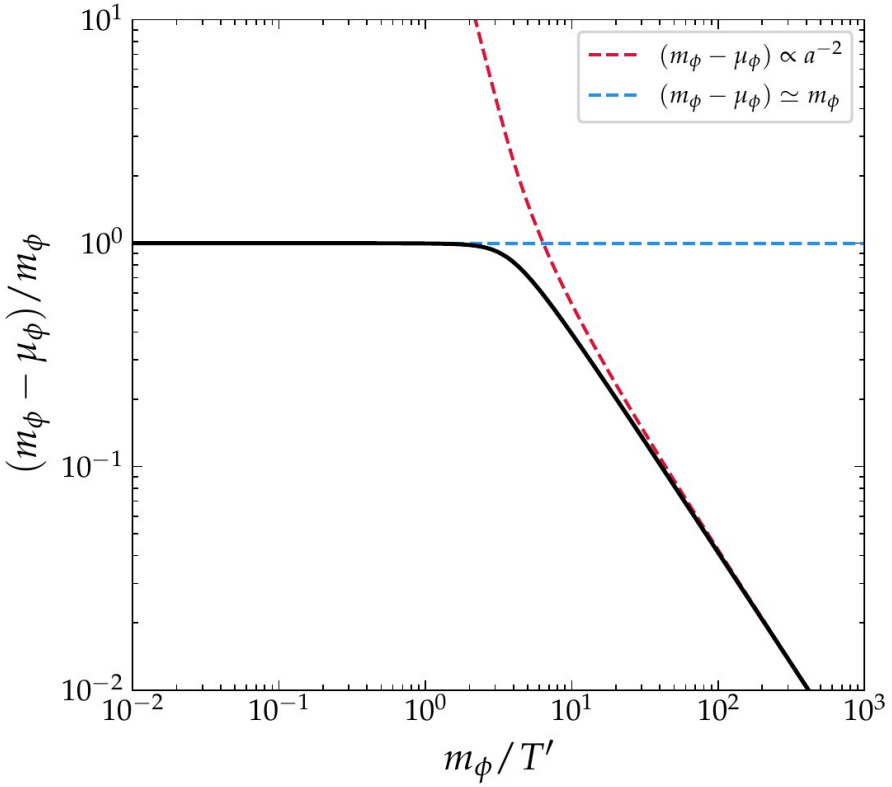
Thermal Evolution



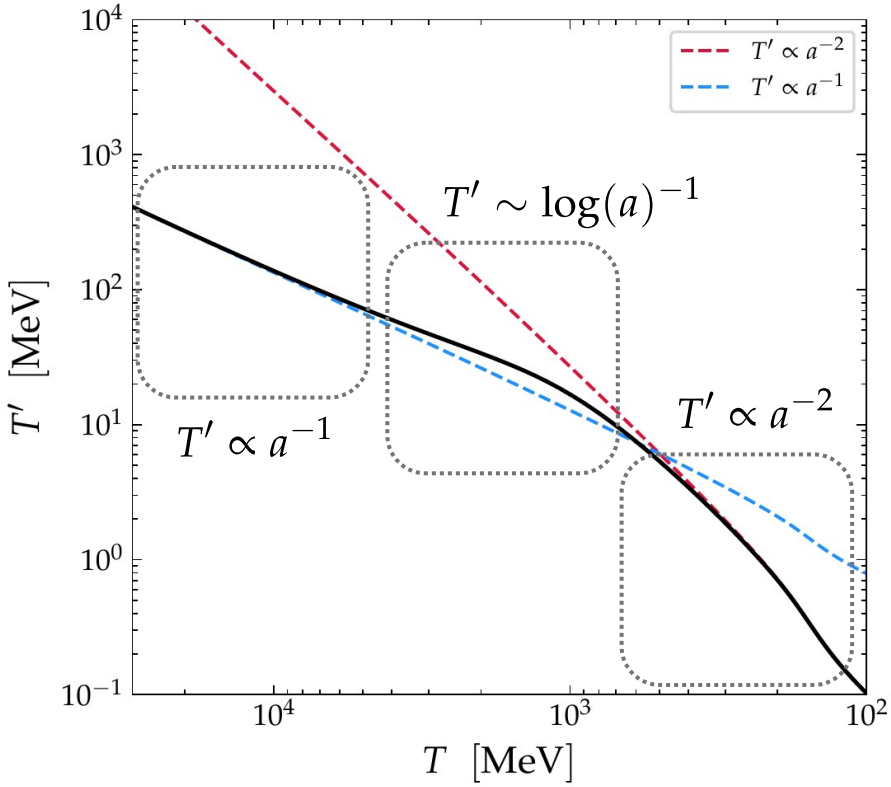


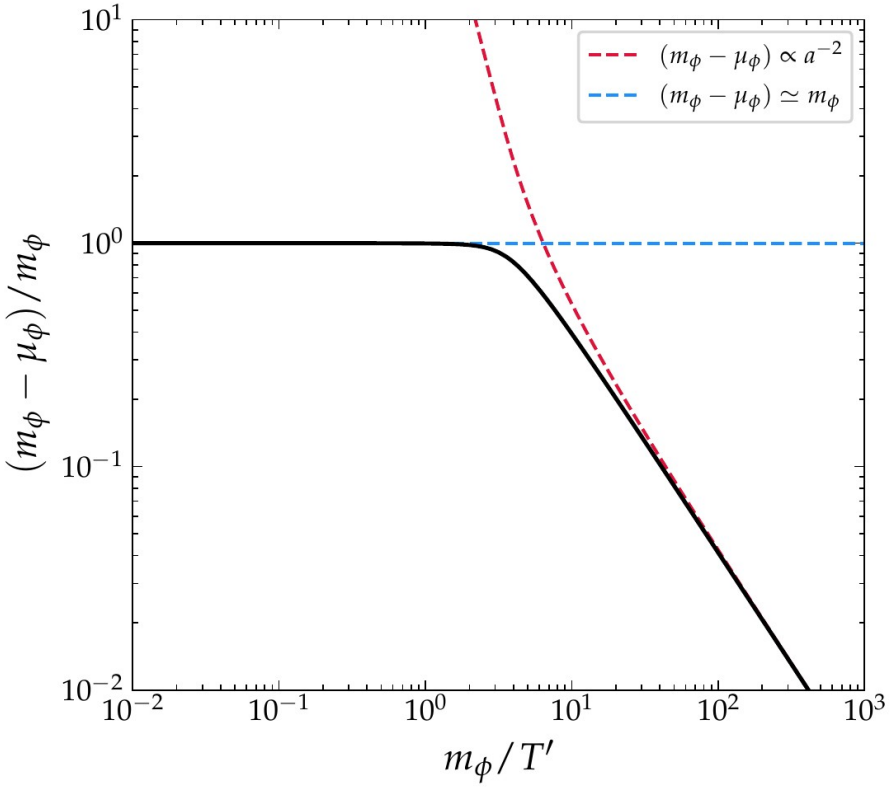
Thermal Evolution



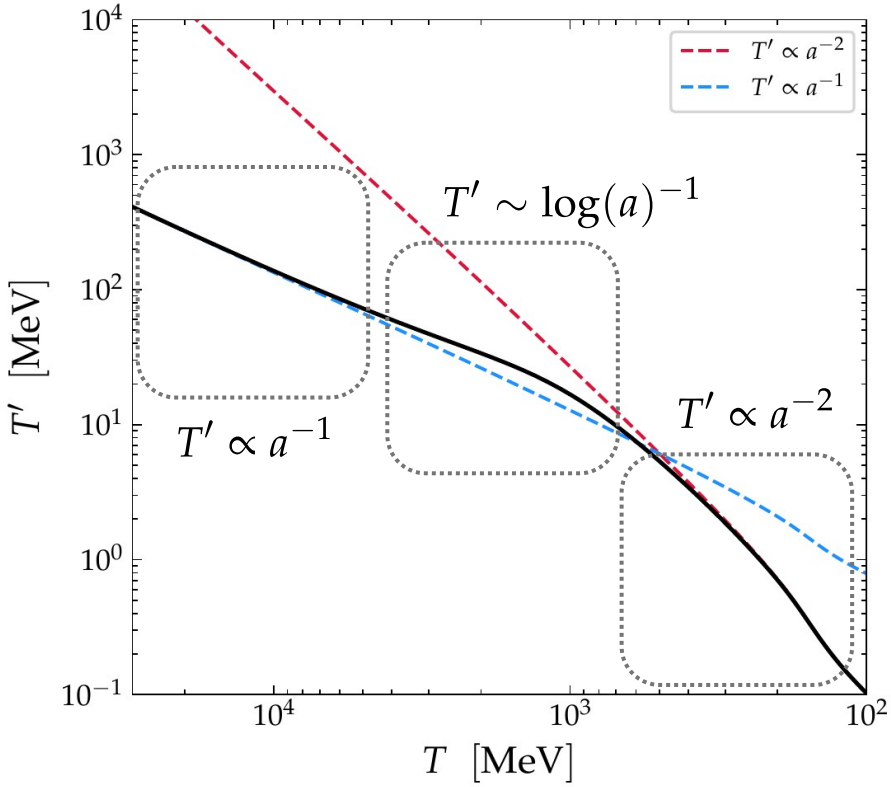


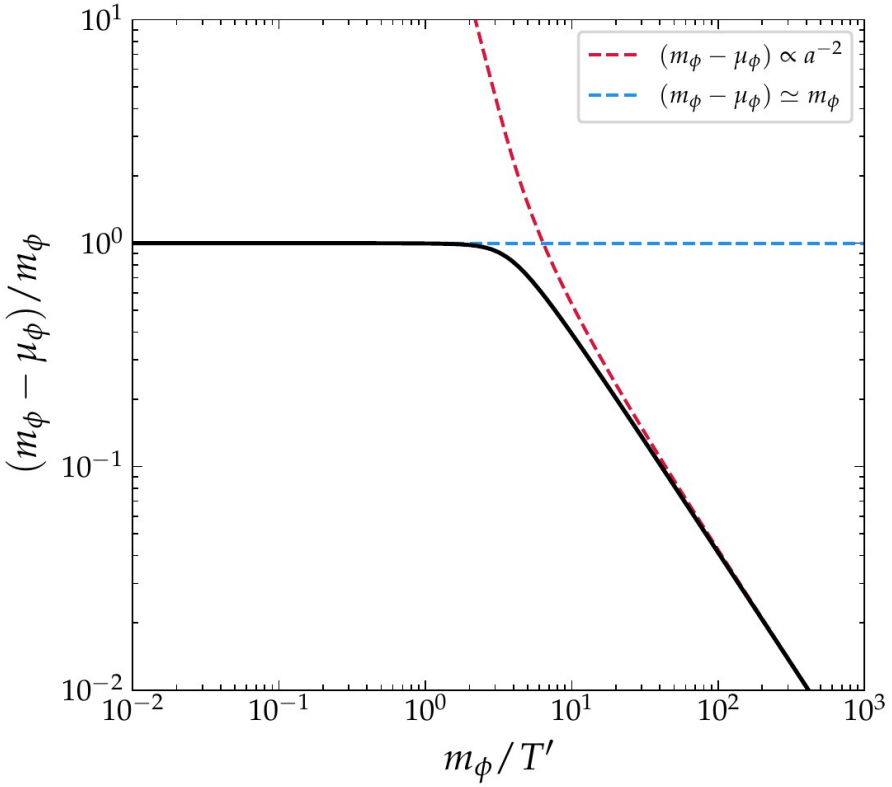
Thermal Evolution





Thermal Evolution

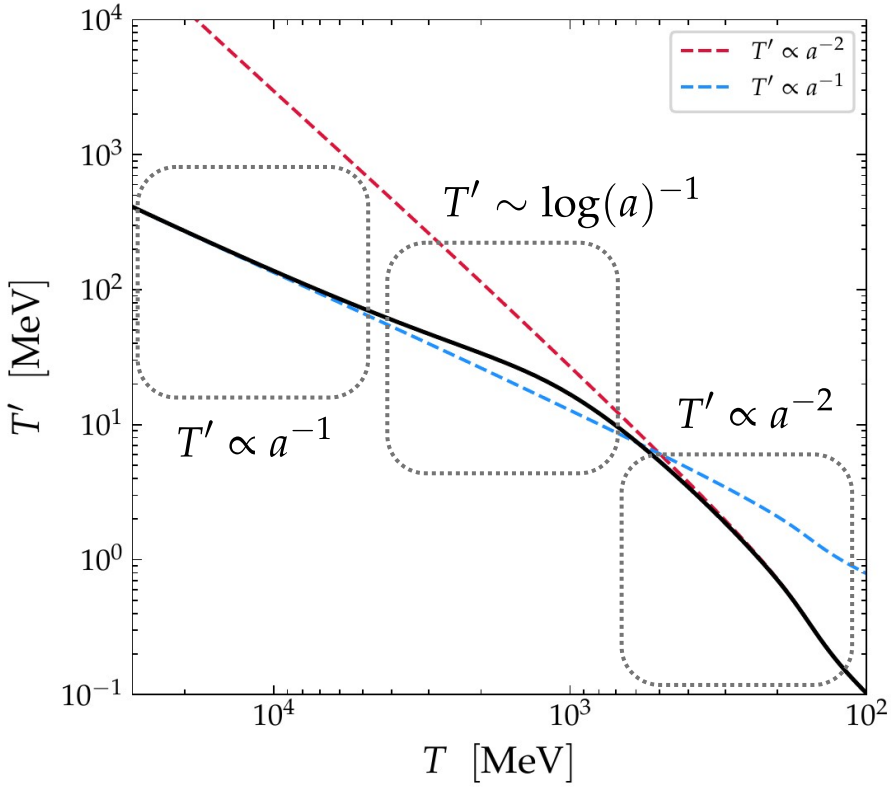


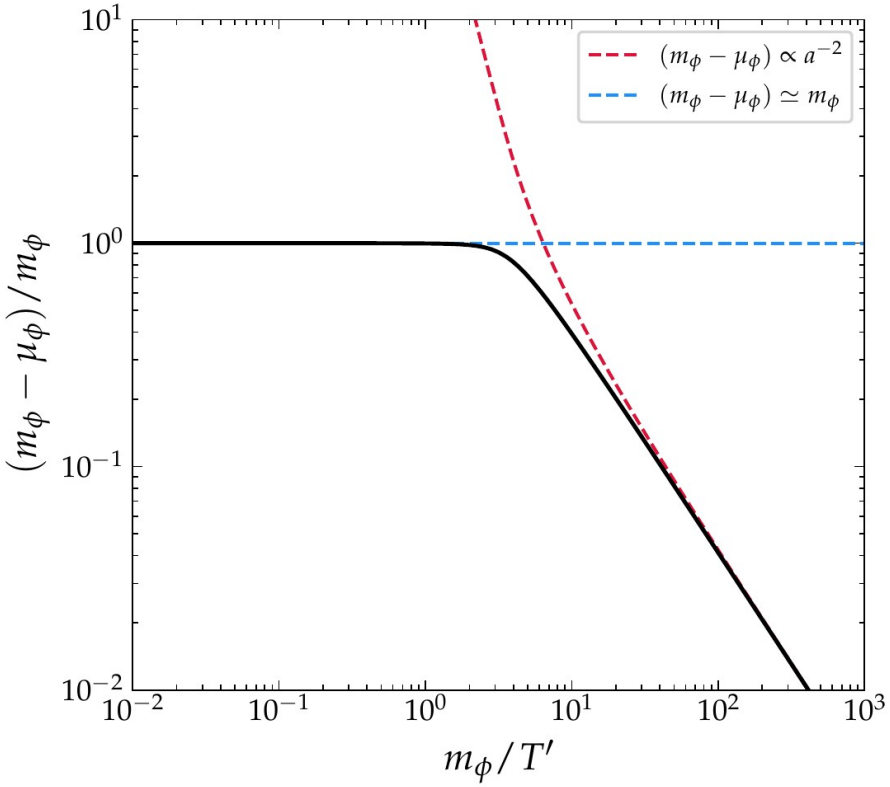


Non-relativistic limit

$$s_\phi = \frac{\rho_\phi + P_\phi - \mu_\phi n_\phi}{T'}$$

Thermal Evolution

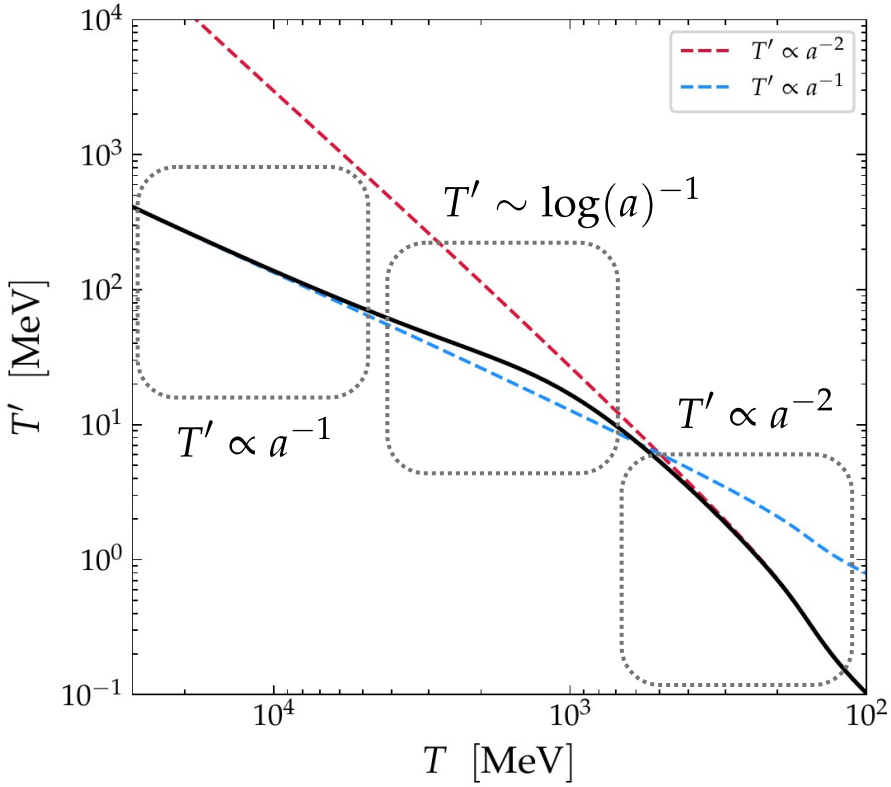


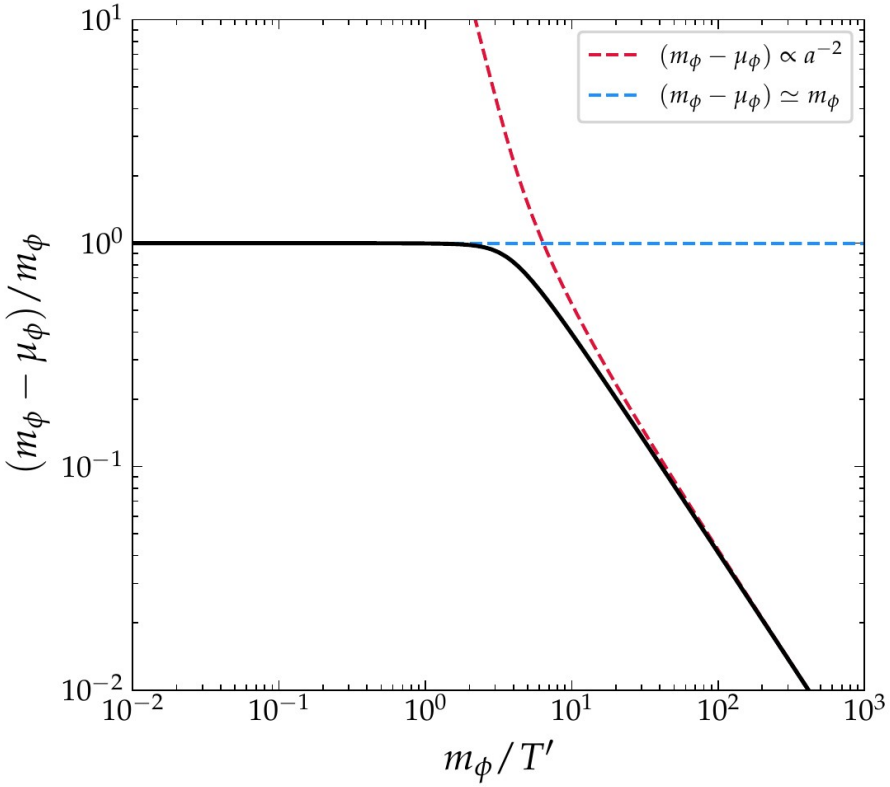


Non-relativistic limit

$$s_\phi = \frac{\rho_\phi + P_\phi - \mu_\phi n_\phi}{T'} \simeq m_\phi n_\phi$$

Thermal Evolution



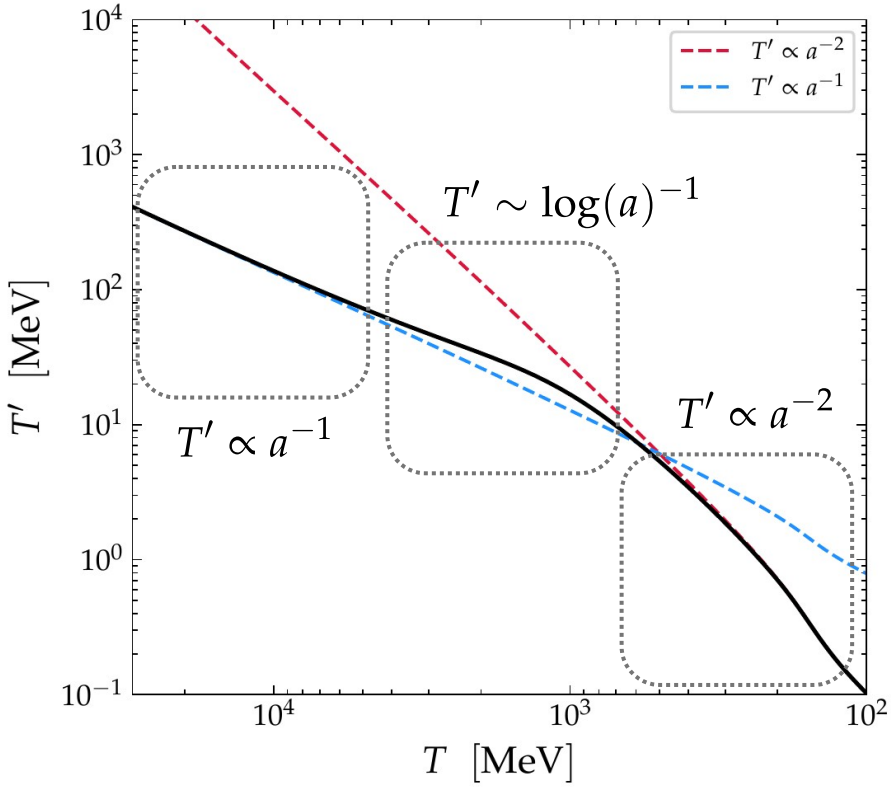


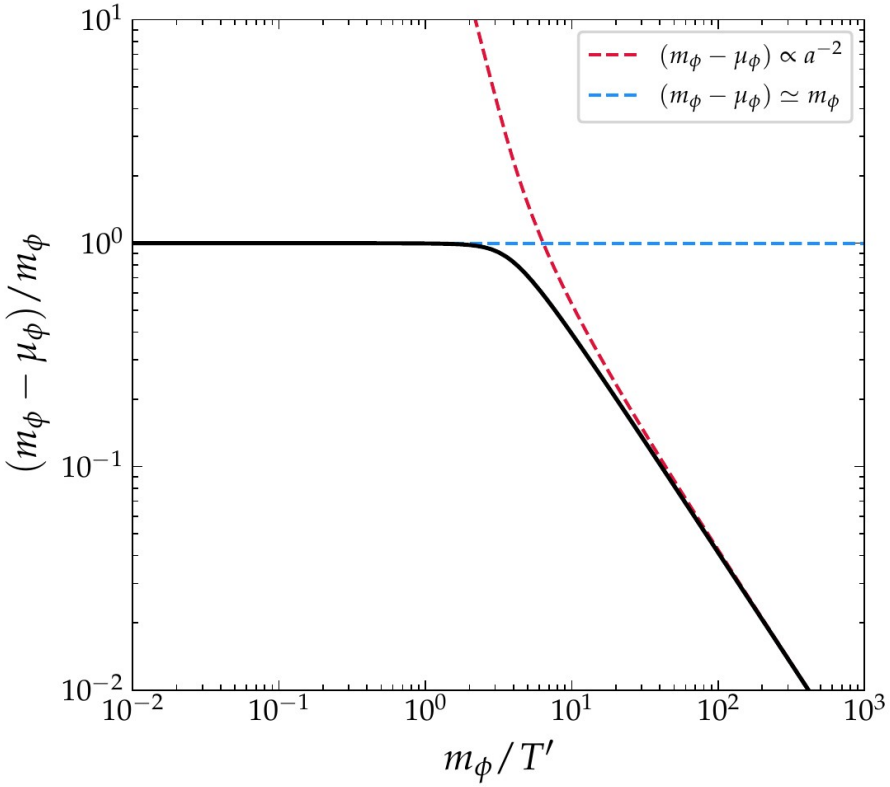
Non-relativistic limit

$$s_\phi = \frac{\rho_\phi + P_\phi - \mu_\phi n_\phi}{T'} \simeq (m_\phi/T')n_\phi$$

$$\rho_\phi \simeq m_\phi n_\phi$$

Thermal Evolution





Non-relativistic limit

$$s_\phi = \frac{\rho_\phi + P_\phi - \mu_\phi n_\phi}{T'} \simeq (m_\phi/T')n_\phi \propto e^{-m_\phi/T'}$$

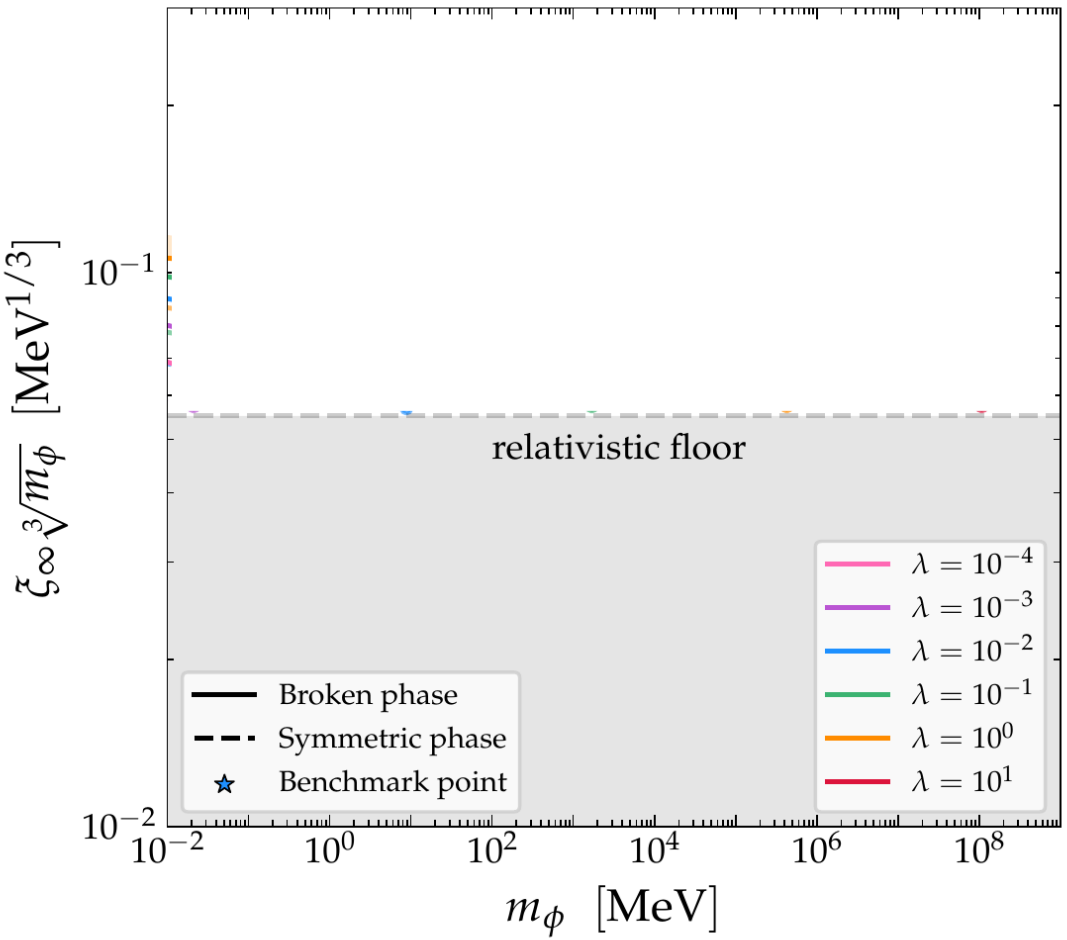
$$\rho_\phi \simeq m_\phi n_\phi$$

Results

$$\xi_\infty,\ \lambda,\ m_\phi$$

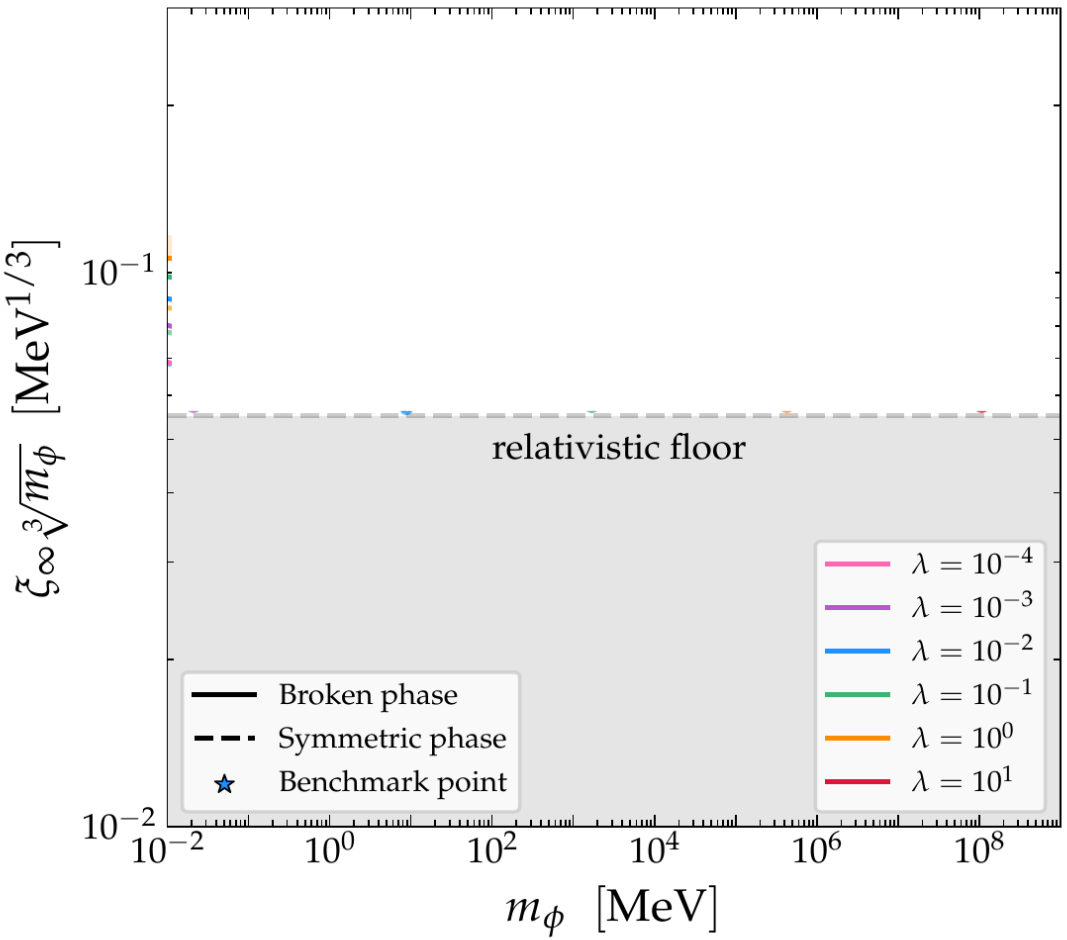
Results

$\xi_\infty,\ \lambda,\ m_\phi$



Results

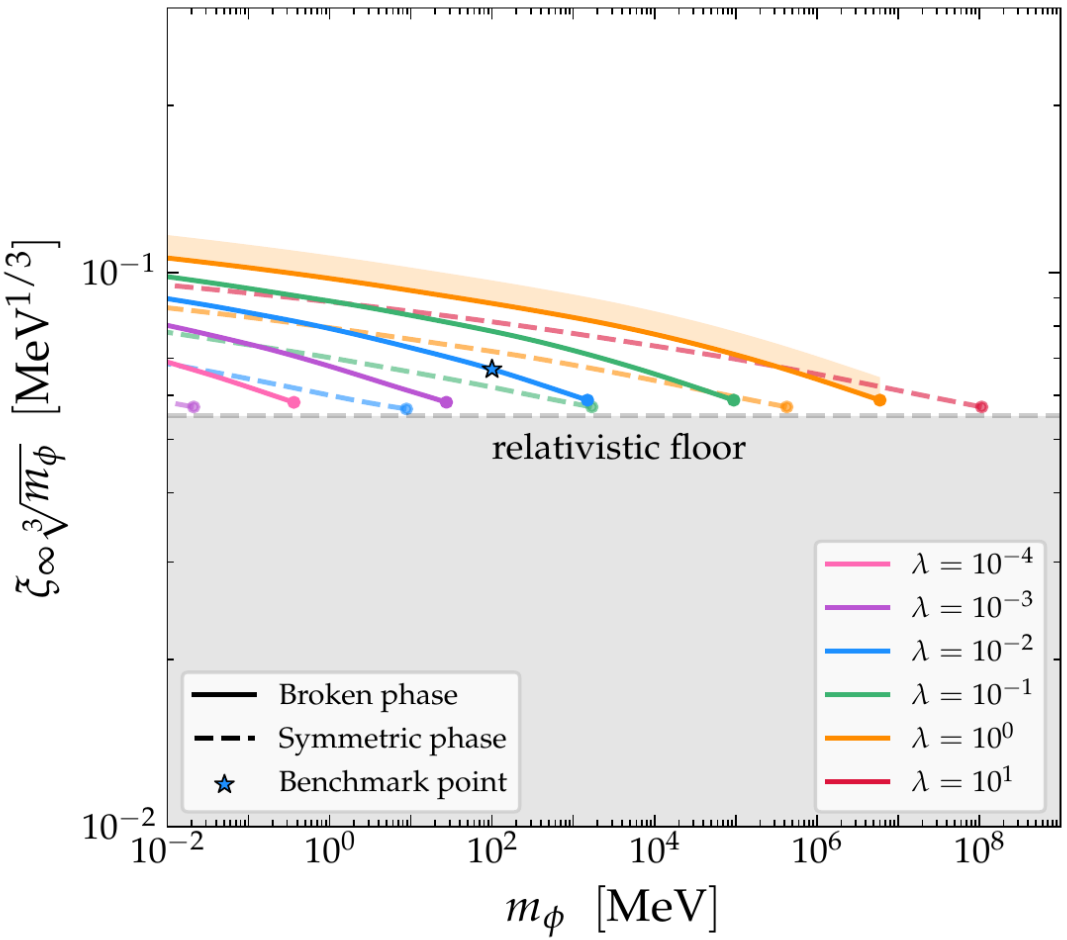
$\xi_\infty,\ \lambda,\ m_\phi$



$\xi_\infty \sim m_\phi^{-1/3}$

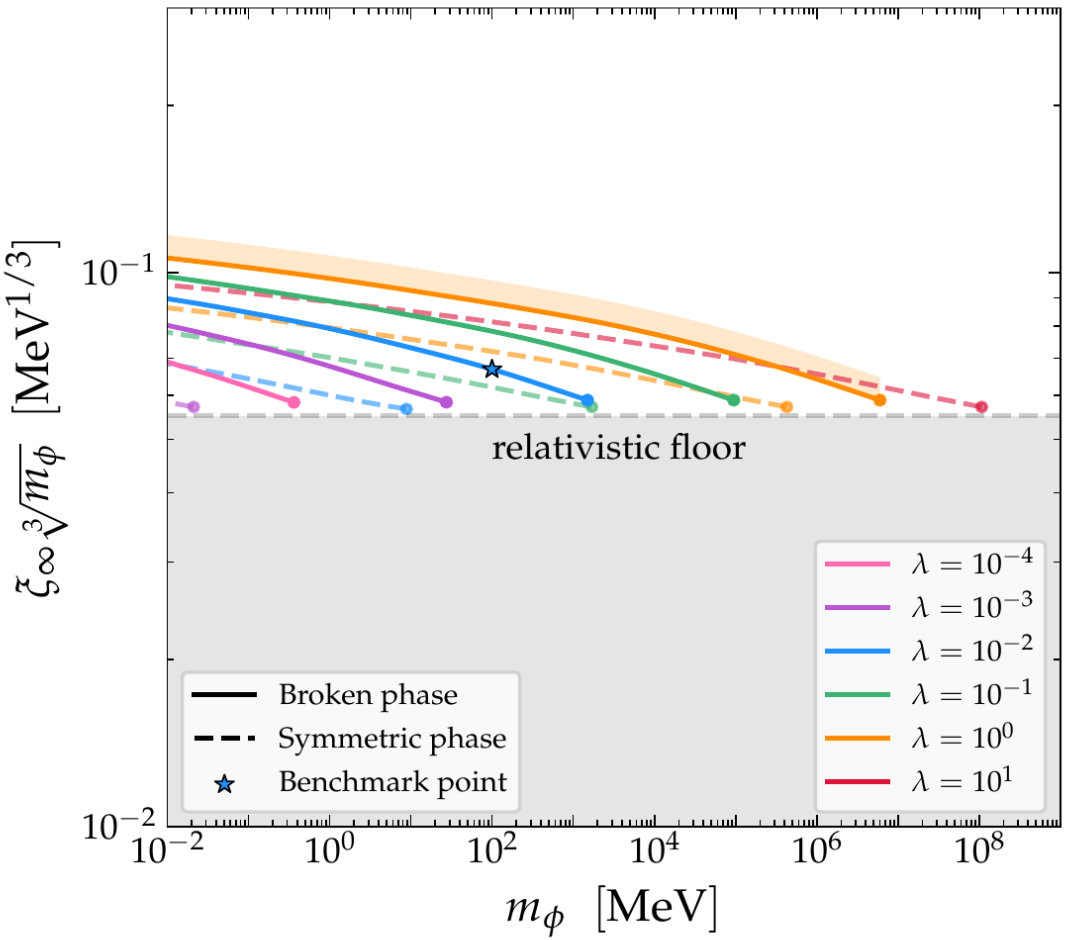
Results

$\xi_\infty,\ \lambda,\ m_\phi$



Results

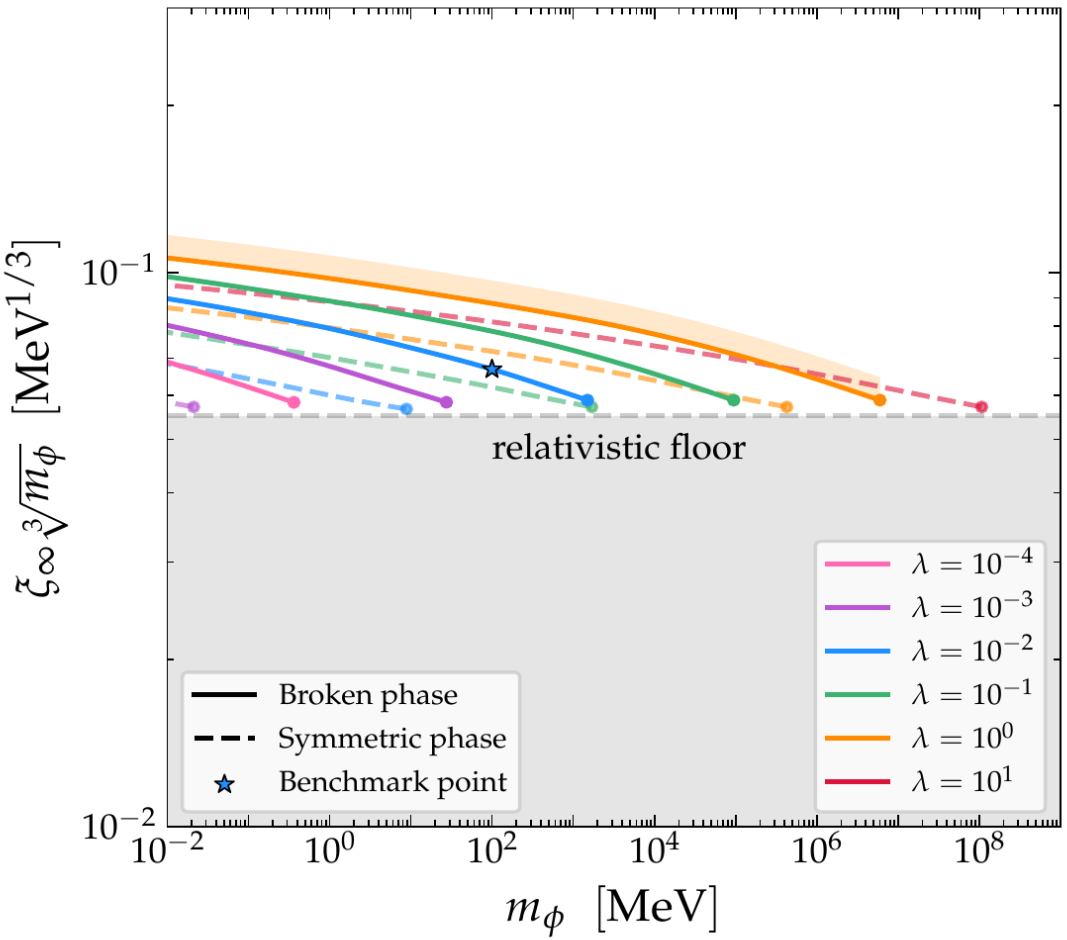
$\xi_\infty,\ \lambda,\ m_\phi$



$$\mathrm{d}\left(m_\phi Y_\phi|_{T=T_{\mathrm{fo}}}\right) = \mathrm{d}\left(m_\phi \frac{n_\phi}{s_{\mathrm{sm}}}\Big|_{T=T_{\mathrm{fo}}}\right) = 0$$

Results

$\xi_\infty,\ \lambda,\ m_\phi$



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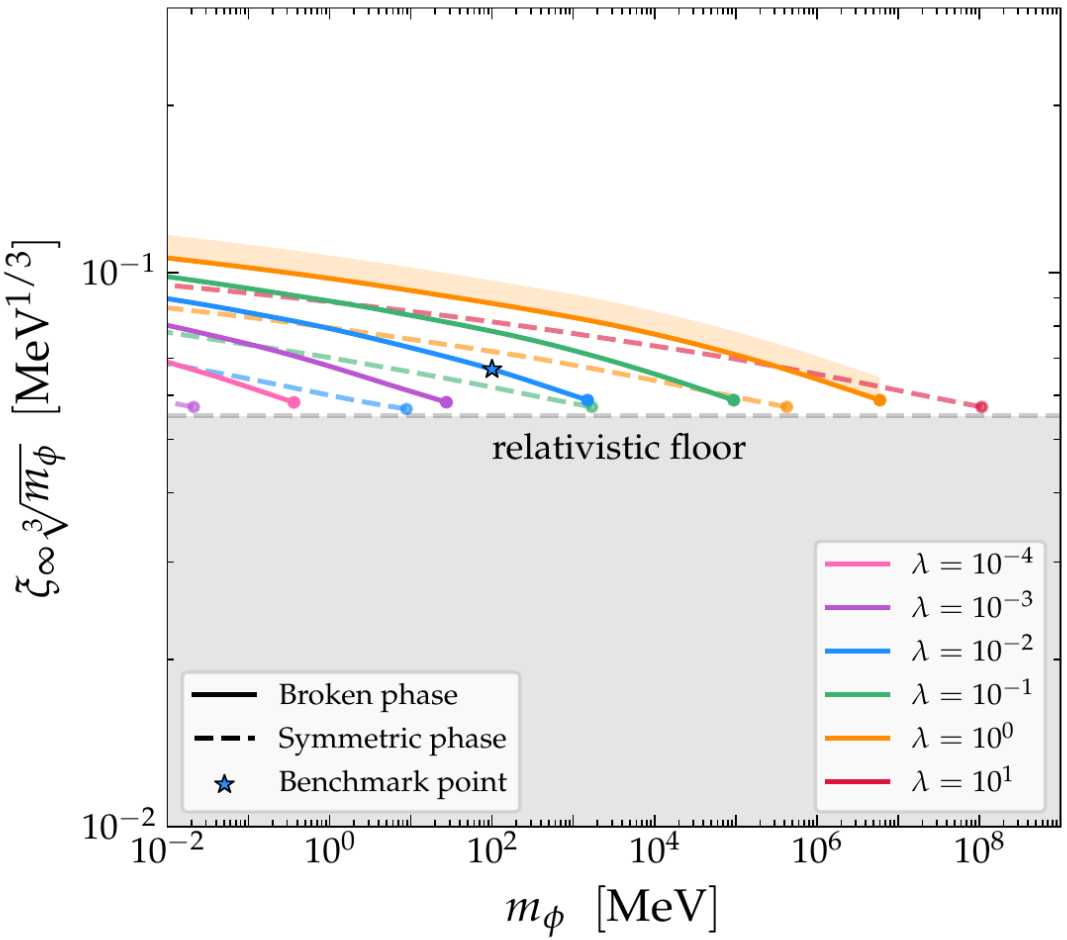
Results

$\xi_\infty,\ \lambda,\ m_\phi$



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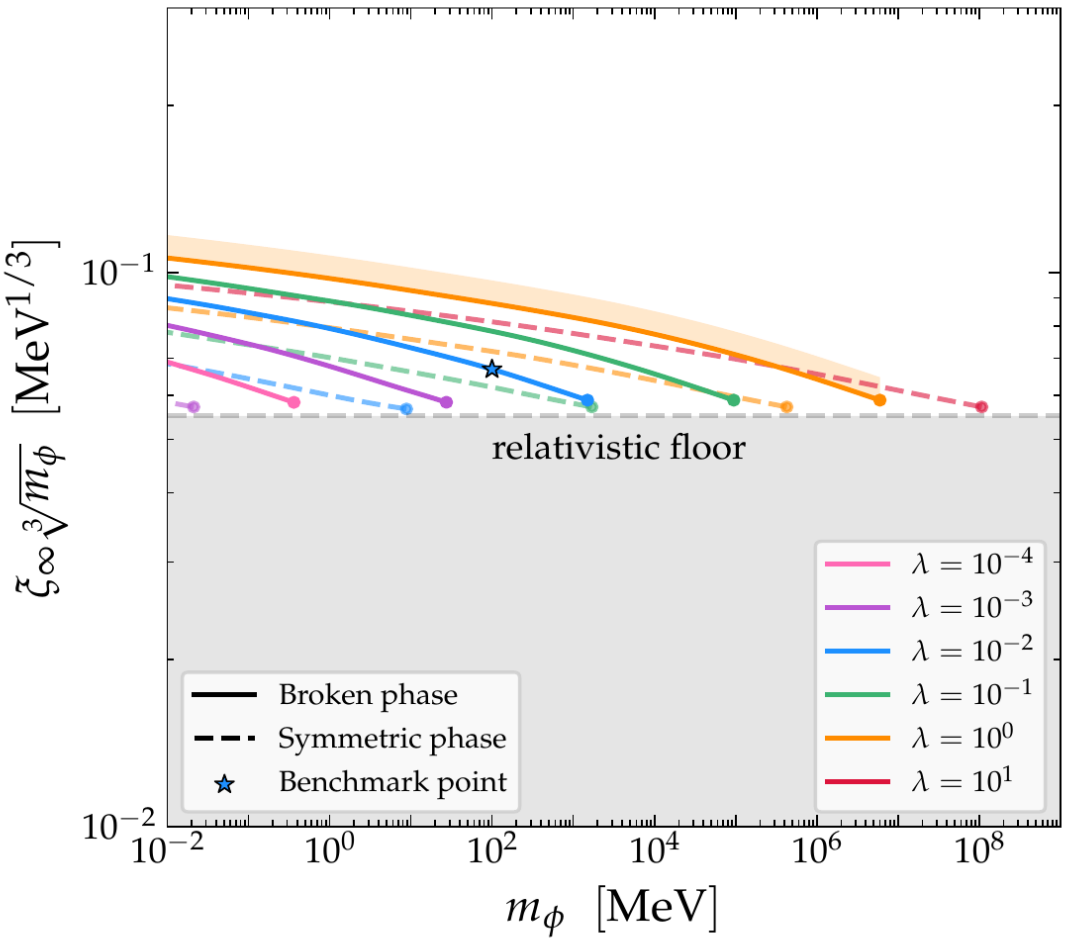
$$s_\phi \sim x'_{\rm fo} n_\phi$$

$$\rightarrow \quad \mathrm{d}\left[m_\phi x'^{-1}_{\rm fo} \xi^3_\infty\right] \simeq 0$$

Results

$\xi_\infty,\ \lambda,\ m_\phi$



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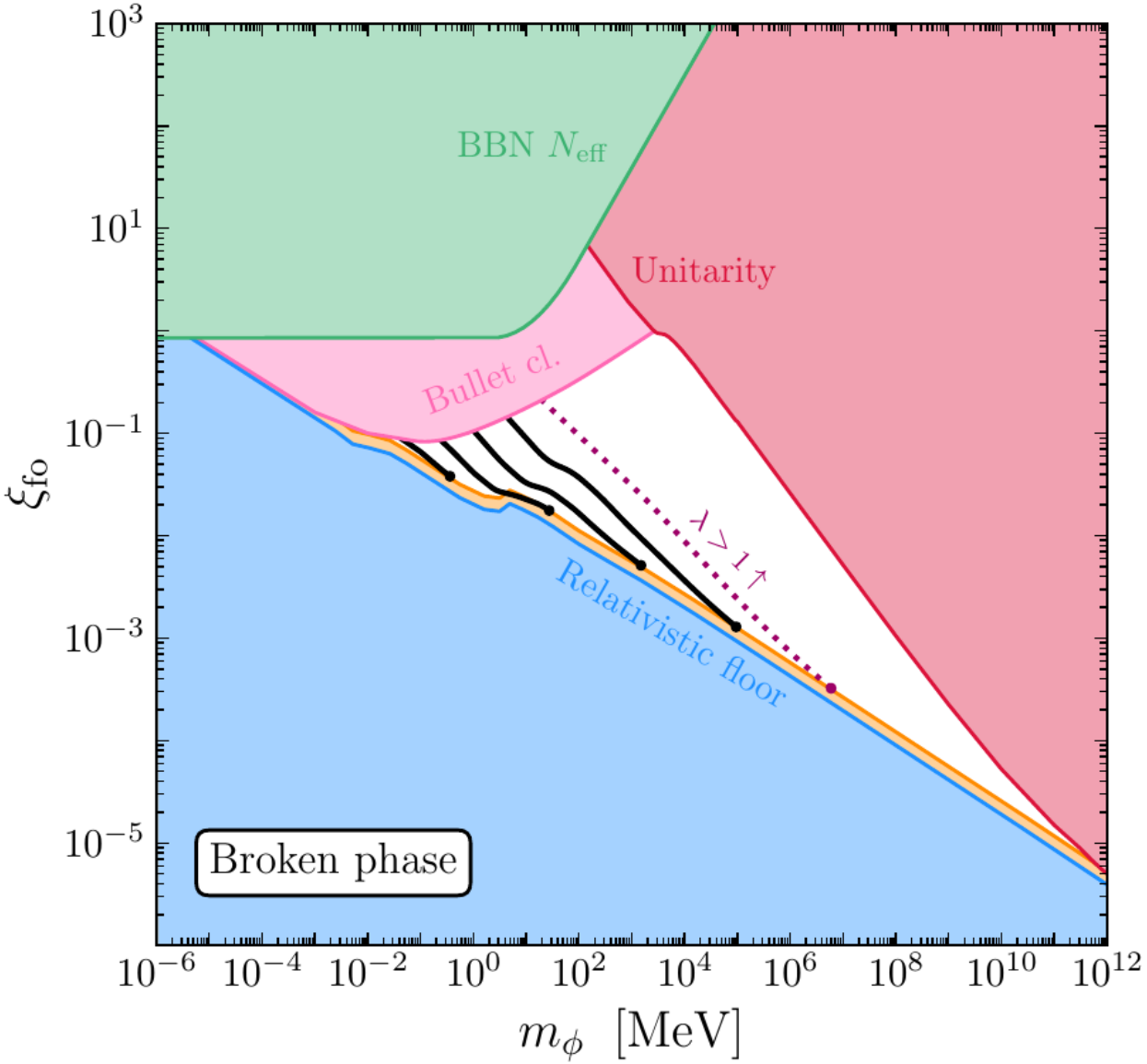
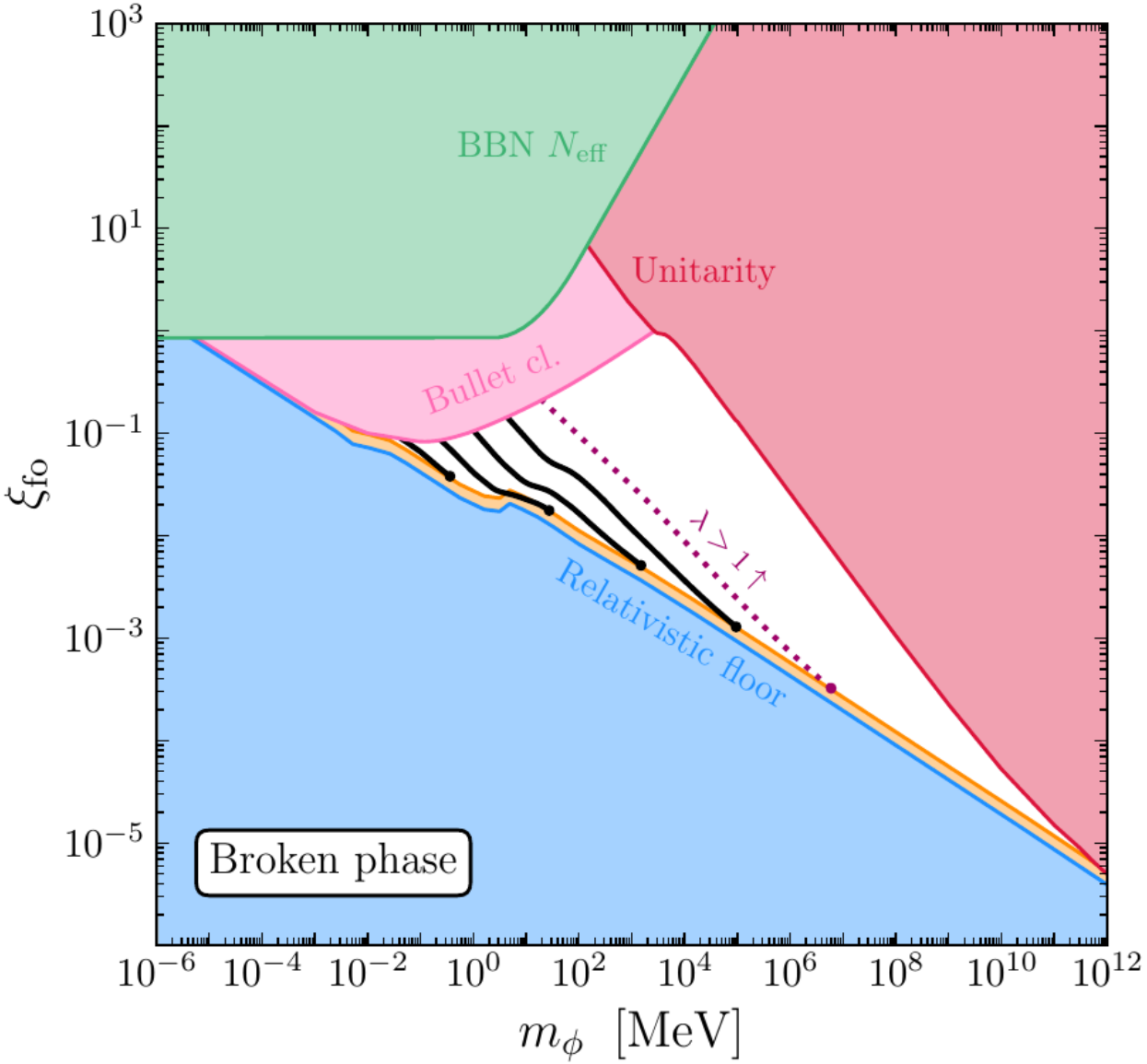
Precise scaling

$$\frac{\mathrm{d}\xi_\infty}{\mathrm{d}m_\phi} \simeq -\frac{1}{3}\frac{\xi_\infty}{m_\phi}\left[1 + \frac{5}{3k-5} \times \frac{1}{x'_{\rm fo}} + \mathcal{O}\left(\frac{1}{x'^2_{\rm fo}}\right)\right]$$

The domain of cannibal DM

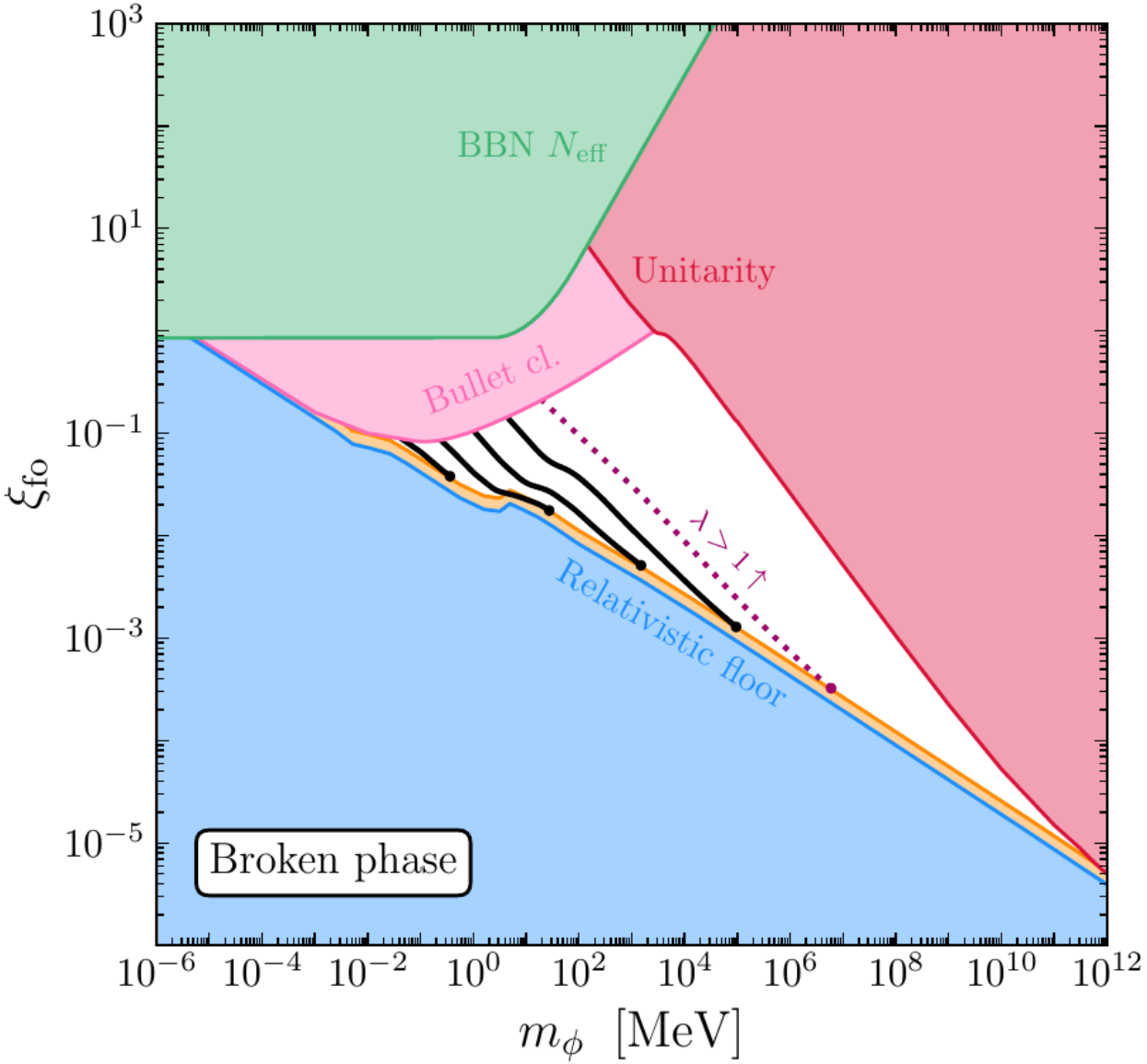


The domain of cannibal DM



$$\langle \sigma_{\phi\phi\to 3\phi} v^2 \rangle < \langle \sigma_{\phi\phi\to 3\phi} v^2 \rangle_{\rm max}$$

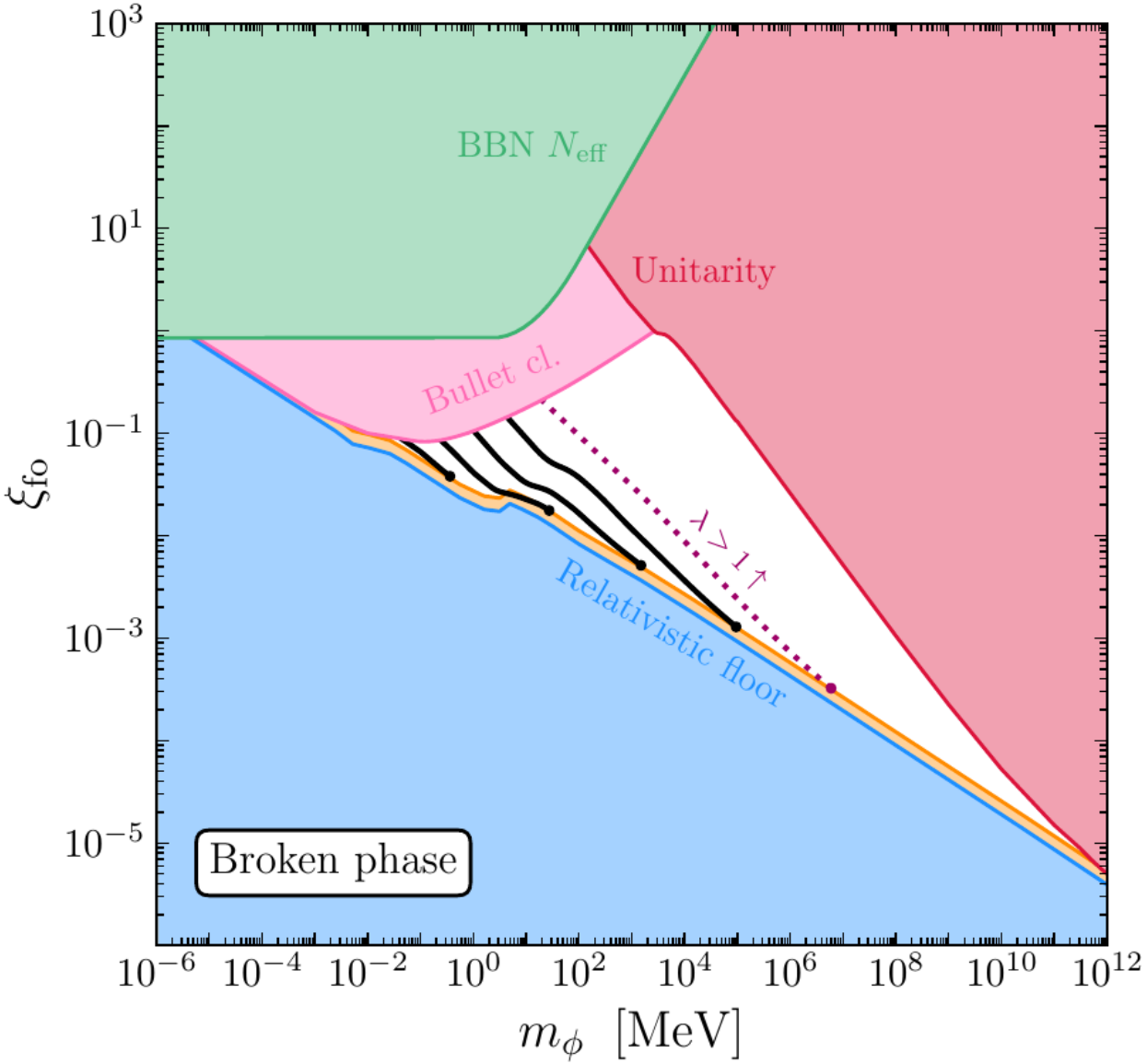
The domain of cannibal DM



$$\langle \sigma_{\phi\phi\to 3\phi} v^2 \rangle < \langle \sigma_{\phi\phi\to 3\phi} v^2 \rangle_{\rm max}$$

$$\sigma_{\phi\phi\leftrightarrow\phi\phi}/m_\phi < 1 {\rm cm}^2/{\rm g}$$

The domain of cannibal DM



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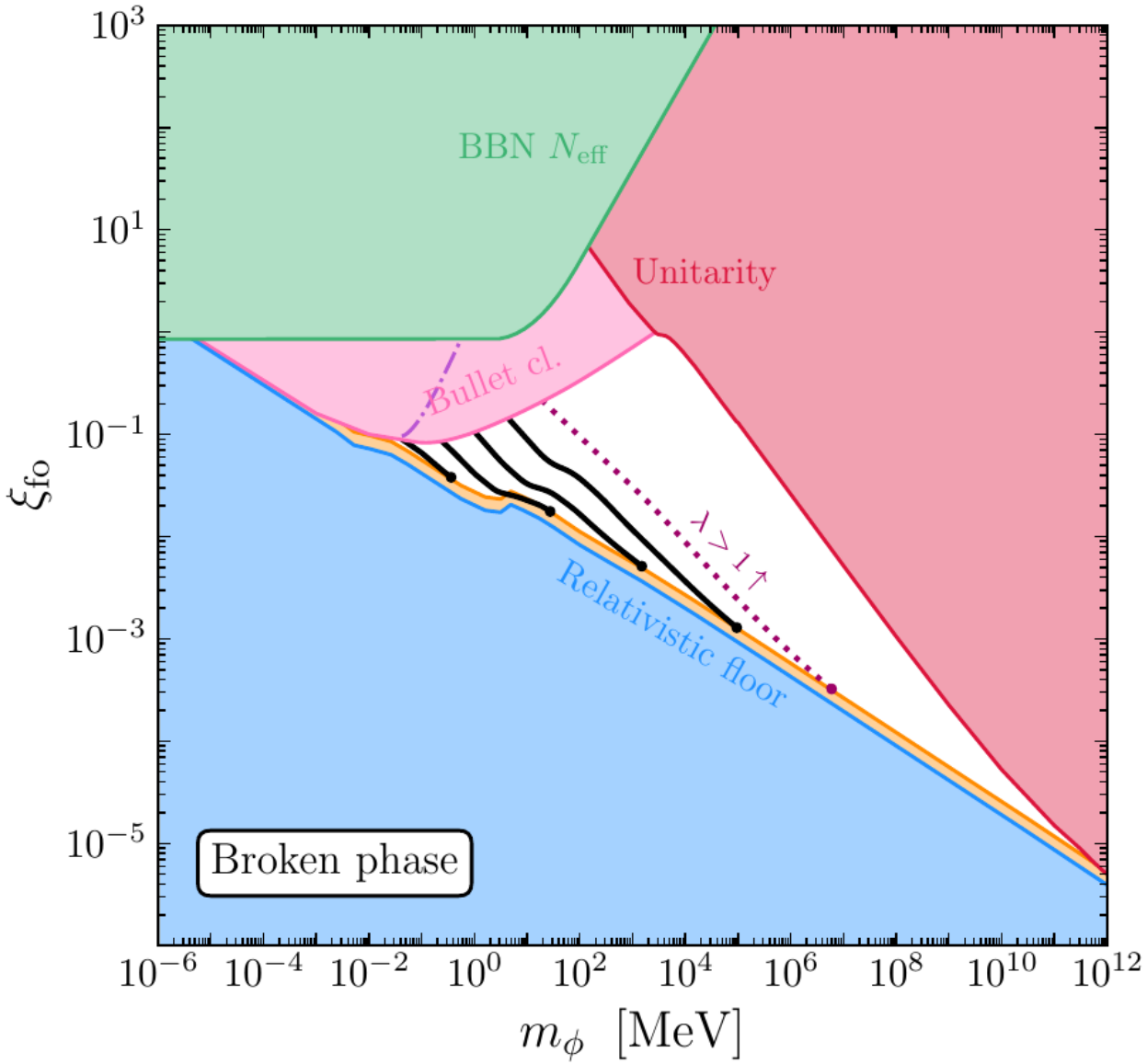
$$T_{\rm cd} < 1\,{\rm MeV}$$

The domain of cannibal DM



$\langle \sigma_{\phi\phi\to 3\phi} v^2 \rangle < \langle \sigma_{\phi\phi\to 3\phi} v^2 \rangle_{\rm max}$

$\sigma_{\phi\phi\leftrightarrow\phi\phi}/m_\phi < 1 {\rm cm}^2/{\rm g}$

$T_{\rm cd} < 1\,{\rm MeV}$

$\sigma_{\rm DW} < {\rm MeV}$

Conclusions

- New non-thermal production mechanism for DM involving exponential growth
- Pandemic production can realize a *minimal model for sterile neutrino DM*
  $\rightarrow$ Potentially testable in the future

- Cannibal DM in the SSB phase needs special care due to vanishing *tree-level* cross-section
- Potential candidates lie close to the relativistic floor and *follow well defined scaling relations*
  $\rightarrow$ Potentially in conflict with constraints on domain walls

рахмат
danke
謝謝
ngiyabonga
teşekkür ederim
Баярлалаа
mersi
kia ora
barka
welalin
tack
spas
mahalo
tapadh leat
спасибо
faafetai lava
vinaka
blagodaram
спасибі
dank je
misaotra
matondo
paldies
grazzi
thank you
gracias
хвала
nanni
nandri
kiitos
dankie
dhanyavad
mauruuru
asante
manana
obrigada
tenki
bedankt
bayarlalaa
gràcie
hvala
köszönöm
akun
dankon
aćiū
djiere dieuf
tau
mochchakkeram
murakoze
enkosi
dziękuję
chnorakaloutioun
gratias ago
gràcies
sulpáy
дякую
mamnun
chokrane
go raibh maith agat
sobodi
děkuji
sukriya
kop khun krap
taiku
obrigado
sagolun
ありがとう
arigatô
takk
dakujem
trugarez
mèsi
didi madloba
najis tuke
tanemirt
grazie
terima kasih
rahmet
kam sah hamnida
rahmat
diolch
dhanyavadagalu
shukriya
mercé
мерси
তোমাকে ধন্যবাদ
감사합니다
xièxie
ευχαριστώ
merci