Z_2 SIMP Dark Matter

based on
NB, C. Garcia-Cely & R. Rosenfeld
arXiv:1501.01973 - JCAP 1504 (2015) 04, 012

NB, X. Chu, C. Garcia-Cely, T. Hambye & B. Zaldivar
arXiv:1510.08063 - JCAP 1603 (2016) 03, 018

NB & X. Chu
arXiv:1510.08527 - JCAP 1601 (2016) 006

Nicolás BERNAL
ICTP - SAIFR

ICTP SAIFR International Centre for Theoretical Physics
South American Institute for Fundamental Research

unesp UNIVERSIDADE ESTADUAL PAULISTA "JÚLIO DE MESQUITA FILHO"

June 4th, 2016

The SIMPlest Dark Matter Model

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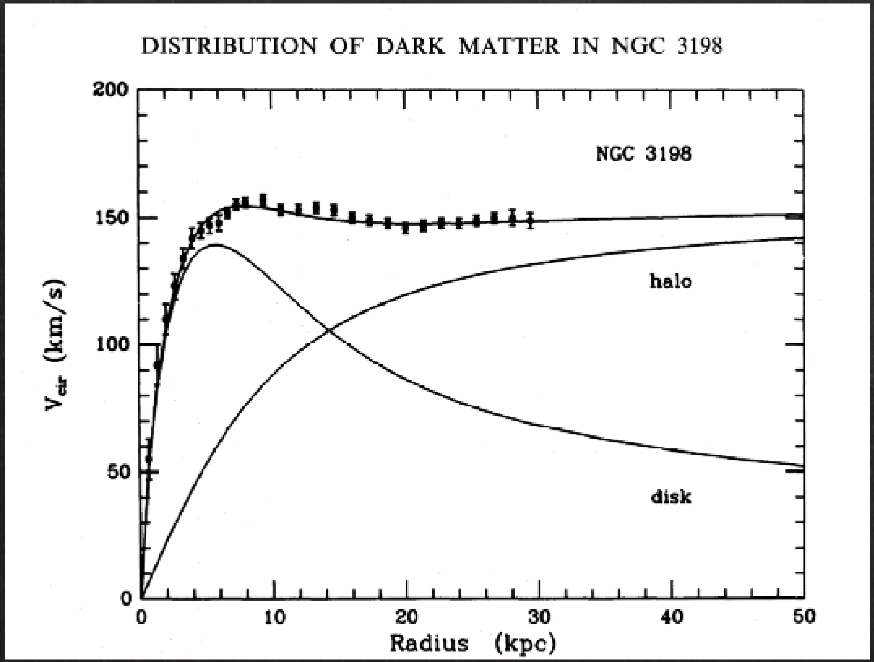
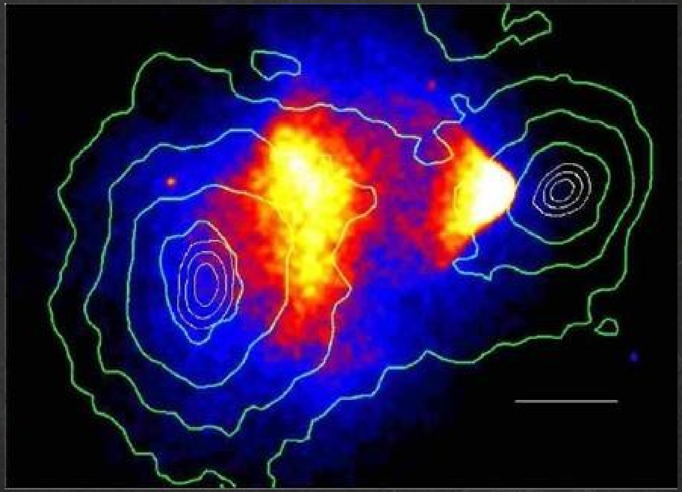
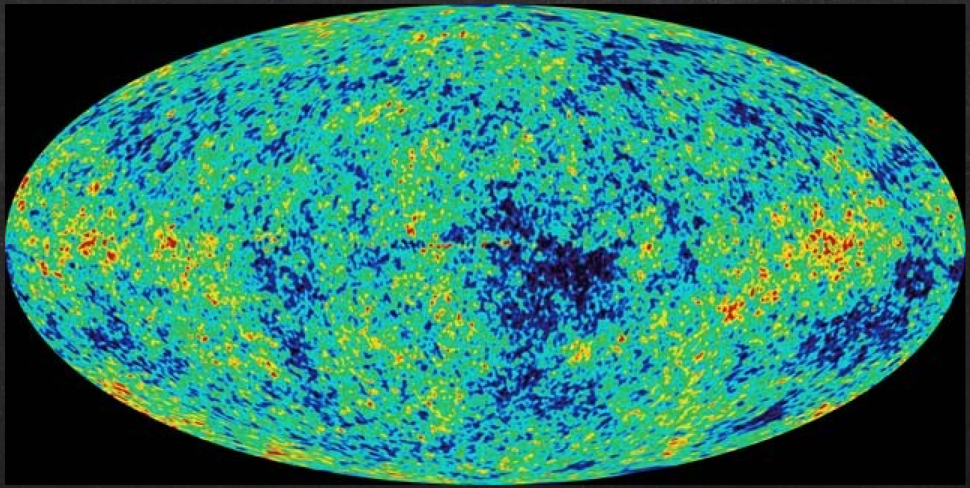
Evidences for Dark Matter

Several observations indicate existence of non-luminous Dark Matter (missing force) at very different scales!

* **Galactic rotation curves**
* **Clusters of galaxies**
* **CMB anisotropies**







Small-scale problems → Self-interacting DM

Small-scale problems:
* Core-vs-cusp
* Too-big-to-fail

Possible solutions:
* Baryonic physics
  - Can't use DM-only simulations to model real DM+baryon Universe
  - Astrophysical observations not being modeled correctly (Suppressed gas cooling efficiency, low star-formation efficiency, supernova feedback, large velocity anisotropy...)

* Dark matter
  DM may not be **collisionless**

$$\left(\frac{\sigma_{\rm scatter}}{m_X}\right)_{\rm obs} = (0.1 - 10)\ {\rm cm}^2/{\rm g} \quad \sim \ \text{few barns/GeV}$$

From the Bullet Cluster: $\frac{\sigma_{\rm scatter}}{m_X} \lesssim 1\ {\rm cm}^2/{\rm g}\,.$

H-B Yu's talk!

Small-scale problems → Self-interacting DM

Small-scale problems:
 * Core-vs-cusp
 * Too-big-to-fail

Possible sol...

Just an excuse for studying
Dark Matter with sizable self-Interactions!

→ Self-Interactions point towards
largely overlooked regions on the parameter space

... $10)\ \mathrm{cm}^2/\mathrm{g}$ $\sim$ few barns/GeV

... obs

From the Bullet Cluster: $\frac{\sigma_{\rm scatter}}{m_X} \lesssim 1\ \mathrm{cm}^2/\mathrm{g}\,.$

H-B Yu's talk!

The SIMPlest DM model ever:
Singlet Scalar Dark Matter

Singlet Scalar DM

McDonald '07

S is a singlet scalar, protected by a Z_2

$$V = \mu_S^2\, S^2 + \lambda_S\, S^4 + \lambda_{HS}\, |H|^2\, S^2$$

3 free parameters:

* $\mathbf{m_s}$ DM mass
* $\boldsymbol{\lambda_{HS}}$ Higgs portal
* $\boldsymbol{\lambda_s}$ DM quartic coupling

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} ←--- Up to now, concentrate on this

* $\boldsymbol{\lambda_s}$ DM quartic coupling ←--- Completely ignored!

The Minimal Model of Nonbaryonic Dark Matter: A Singlet Scalar

C.P. Burgess, M. Pospelov, T. ter Veldhuis

and the strength of its self-interactions. Of these, λ_s is largely unconstrained and can be chosen arbitrarily. We need only assume it to be small enough to permit the pertur-

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The Simplest Dark-Matter Model, CDMS II Results, and Higgs Detection at LHC

Xiao-Gang He, Tong Li, Xue-Qian Li, Jusak Tandean, Ho-Chin Tsai

and darkon masses m_h and m_D, respectively, the Higgs-darkon coupling λ, and the darkon self-interaction coupling λ_D. In our analysis, λ_D will not be involved.

$$V = \mu_S^2 S^2 + \lambda_S S^4 + \lambda_{HS} |H|^2 S^2$$

3 free parameters:

- * m_s DM mass
- * λ_{HS} Higgs portal
- * λ_s DM quartic coupling

} ←--- Up to now, concentrate on this (DM mass and Higgs portal)

←--- Completely ignored! (DM quartic coupling)

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Closing in on singlet scalar dark matter: LUX, invisible Higgs decays and gamma-ray lines

Lei Feng, Stefano Profumo, Lorenzo Ubaldi

The phenomenology of this model is completely determined by the parameters a_2 and b_2 (or m_S), since the self-interaction quartic coupling b_4 does not play any phenomenologically observable role (see e.g. [26, 39]).

3

- * m_s DM mass
- * λ_{HS} Higgs portal
- * λ_s DM quartic coupling

} ←--- Up to now, concentrate on this (for m_s and λ_{HS})

←--- Completely ignored! (for λ_s)

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Gamma rays from the annihilation of singlet scalar dark matter

Carlos E. Yaguna

$S \to -S$. The scalar singlet extension of the standard model, therefore, contains only 3 new parameters: m_0, λ, and λ_S. Because it only determines the strength of the singlet self-interactions, λ_S is unconstrained and largely irrelevant to the phenomenology of the model. In the following we will simply

n this

* λ_s DM quartic coupling ←--- Completely ignored!

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Antimatter signals of singlet scalar dark matter

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model field that directly couples to the singlet. This extension of the standard model contains, therefore, two new phenomenologically relevant parameters: m_0 and λ. Instead of m_0, it is useful to consider the physical mass of the singlet

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Singlet Scalar Dark Matter: monochromatic gamma rays and metastable vacua

Stefano Profumo, Lorenzo Ubaldi, Carroll Wainwright

[1] Note that the singlet self quartic coupling b_4 is completely irrelevant here.

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1

Update on scalar singlet dark matter

James M. Cline, Kimmo Kainulainen, Pat Scott, Christoph Weniger

forbidden by any symmetry. Apart from the S kinetic term and its quartic self-coupling (which plays no observable role in phenomenology), the two terms in eq.

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Constraining the Higgs portal with antiprotons

Alfredo Urbano, Wei Xue

$$\mathcal{L}_{\rm HP} = \mathcal{L}_{\rm SM} + \frac{1}{2}(\partial_\mu S)(\partial^\mu S) - \frac{m_0^2}{2}S^2 - \frac{\lambda_S}{2}|H|^2 S^2 \ ,$$

The Minimal Model of Nonbaryonic Dark Matter: A Singlet Scalar

C.P. Bu

Scalar Singlet Dark Matter and Gamma Lines

Michael Duerr, Pavel Fileviez Perez, Juri Smirnov

The Sin ... Detection at LHC

Xiao-Gang He, Tong Li,

physical dark matter mass M_S. The quartic coupling λ_S does not play any role in DM phenomenology. There-

Closing in on sin ... cays and gamma-ray lines

Lei Feng, Stefano Profumo, Lorenzo Ubaldi

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The singlet scalar as FIMP dark matter

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Lei Feng, Stefano

[1] λ_S is essentially irrelevant.

Gamma rays ... on of singlet scalar dark matter

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Signatures from Scalar Dark Matter with a Vector-like Quark Mediator

Federica Giacchino, Alejandro Ibarra, Laura Lopez Honorez, Michel H.G. Tytgat, Sebastian Wild

$$\mathcal{L} \supset -\frac{1}{2}m_S^2 S^2 - \frac{1}{2}\lambda S^2 H^\dagger H,$$

Antimatter signals o ... atter

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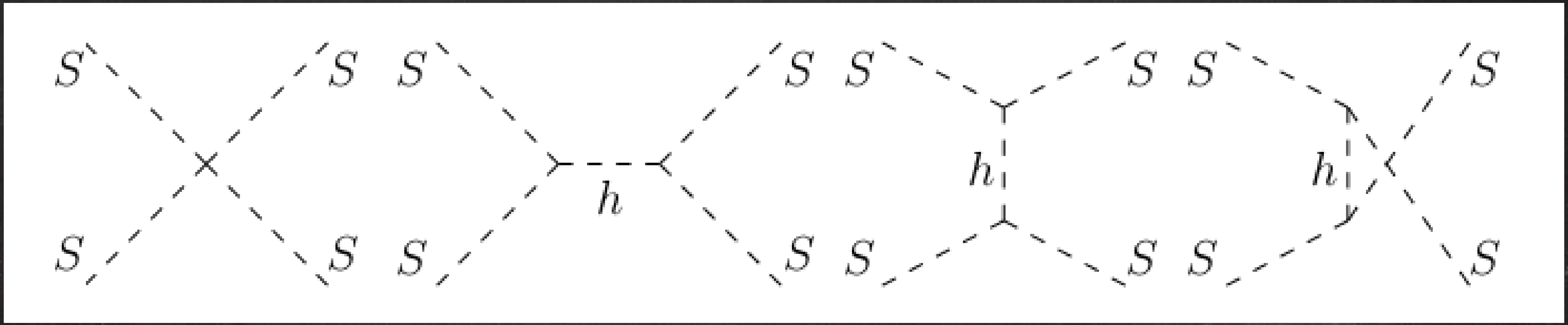
Dark Matter Self-Interactions

Dark Matter Self-Interactions

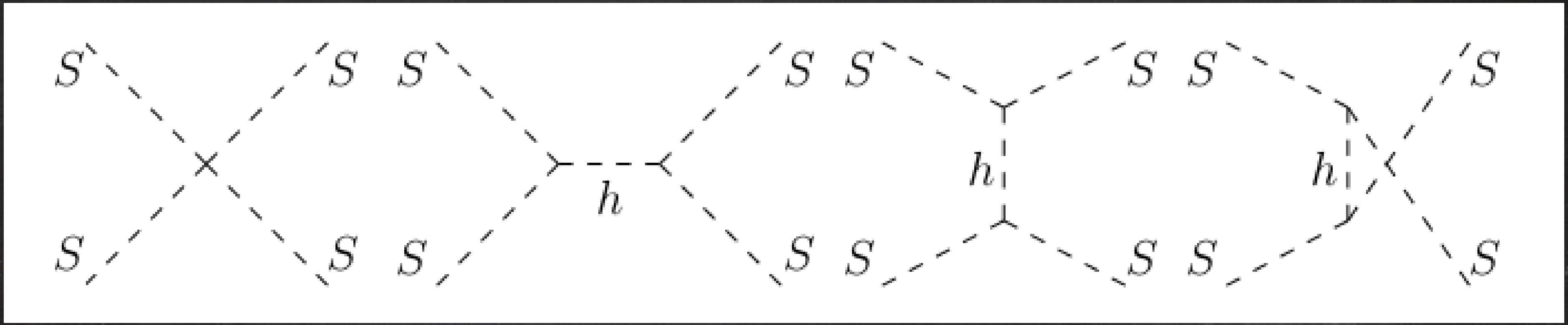


$$\frac{\sigma_{SS}}{m_S} \sim \frac{9}{8\pi}\,\frac{\lambda_S^2}{m_S^3}$$

$$0.1 \lesssim \frac{\sigma_{SS}}{m_S} \lesssim 10\ \mathrm{cm}^2/\mathrm{g}$$

Implies {
* $\lambda_s \sim 1$
* $m_s \sim 100$ MeV

Dark Matter Self-Interactions & Invisible Higgs decay



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$$0.1 \lesssim \frac{\sigma_{SS}}{m_S} \lesssim 10\ \text{cm}^2/\text{g}$$

Implies {
* $\lambda_S \sim 1$
* $m_S \sim 100$ MeV

The Higgs tends to annihilate into DM

BR(h→ inv.) < 20%

* $\lambda_{HS} < 7\cdot 10^{-3}$

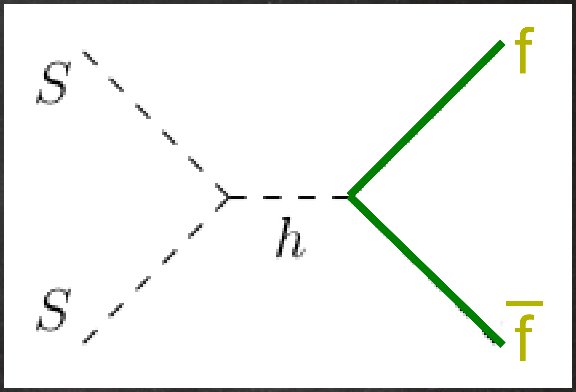
How to produce such a Self-Interacting Dark Matter?

WIMP DM

DM can (only) annihilate into light fermions

other annihilation channels kinematically closed!

$$\langle \sigma_{SS\to f\bar{f}}\, v\rangle \sim \frac{\lambda_{HS}^2}{\pi}\,\frac{m_f^2}{m_h^4}$$



$$\langle \sigma_{SS\to f\bar{f}}\, v\rangle \ll 10^{-26}\,\mathrm{cm}^3/\mathrm{s}$$ $\rightarrow$ Universe overclosed!

$\rightarrow$ **DM can not be a WIMP!!!**

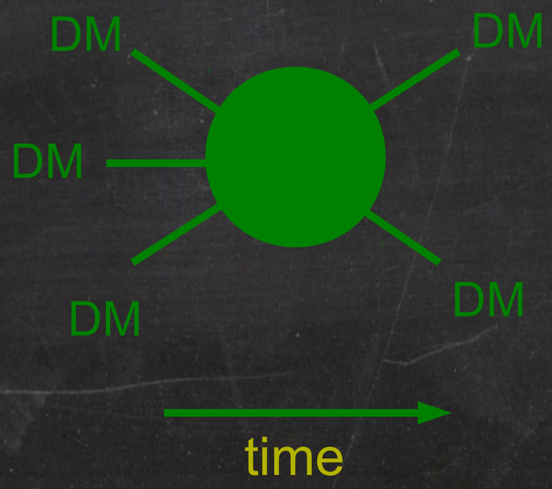
Again:
How to produce such a Self-Interacting Dark Matter?!

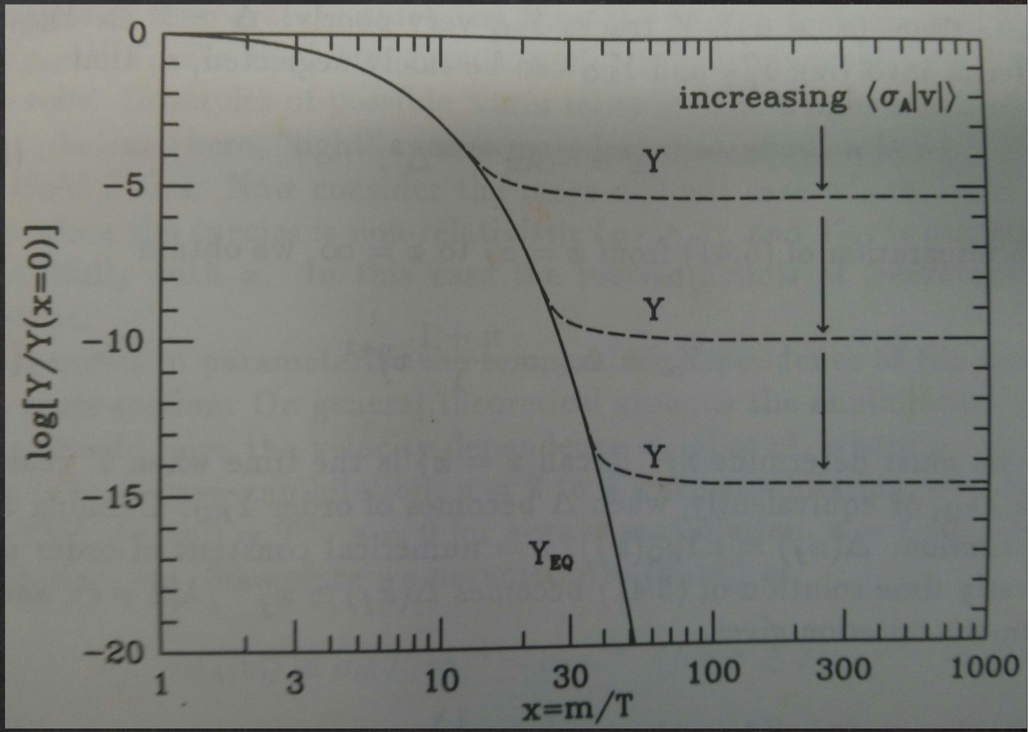
SIMP DM

3→2 annihilations

Hochberg, Kuflik, Volansky & Wacker '14

$$\frac{dn}{dt} + 3\,H\,n = -\langle\sigma v^2\rangle_{3\to2}\,\left(n^3 - n^2\,n_{\rm eq}\right)$$





SIMP DM
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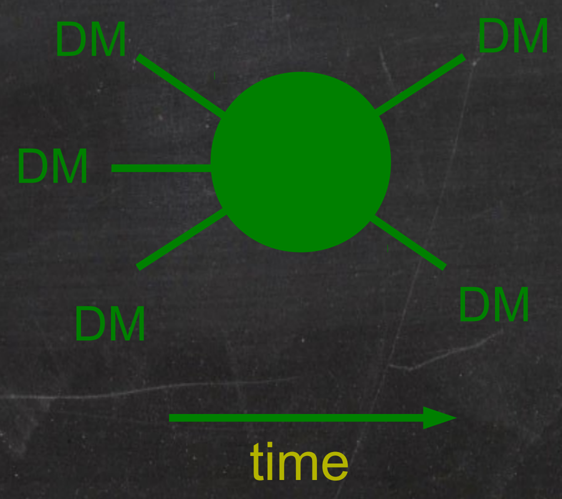


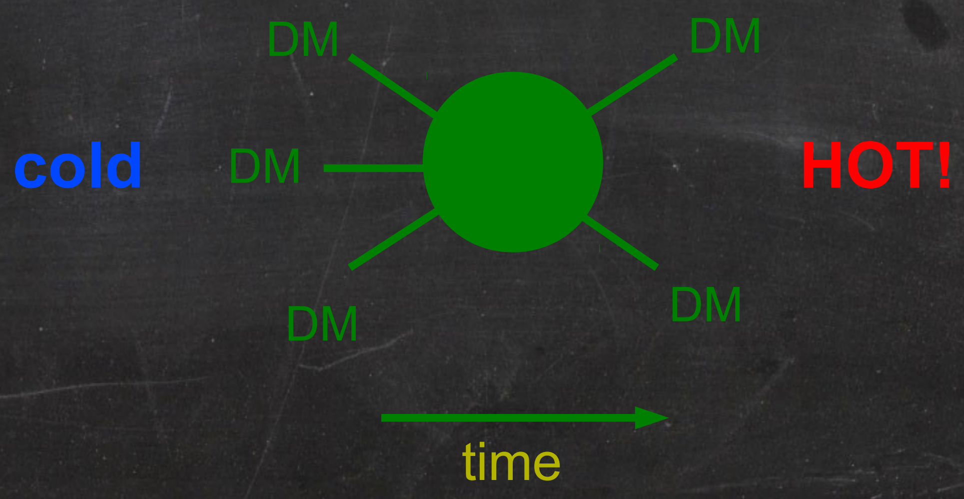
* DM in the MeV range

* Small DM-SM portal

* α ~ 1
'Strong' Self-interactions
→ SIMP

Caveat

$$\frac{dn}{dt} + 3\,H\,n = -\langle \sigma v^2 \rangle_{3\to 2}\,\left(n^3 - n^2\,n_{\rm eq}\right)$$



$3 \to 2$ annihilations
pump heat into the dark sector!

SIMP DM
3→2 annihilations

Hochberg, Kuflik, Volansky & Wacker '14

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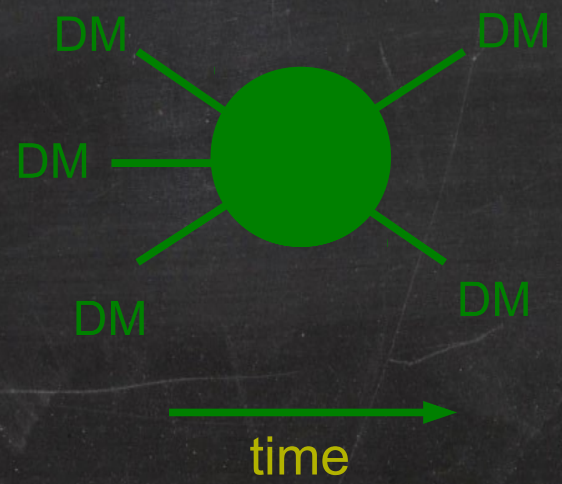


*** DM in the MeV range**

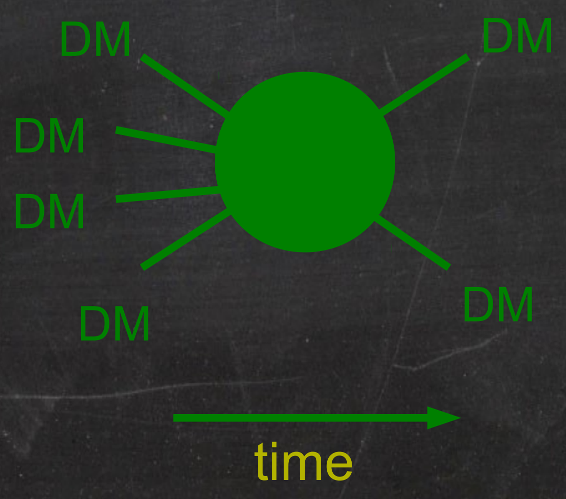
*** Small DM-SM portal**

*** α ~ 1**
'Strong' Self-interactions
→ SIMP

However 3→2 reactions are forbidden in most common scenarios where the DM stability is guaranteed by a **Z_2** symmetry
(R-parity in SUSY, K-parity in Kaluza-Klein...)

SIMP DM
4→2 annihilations

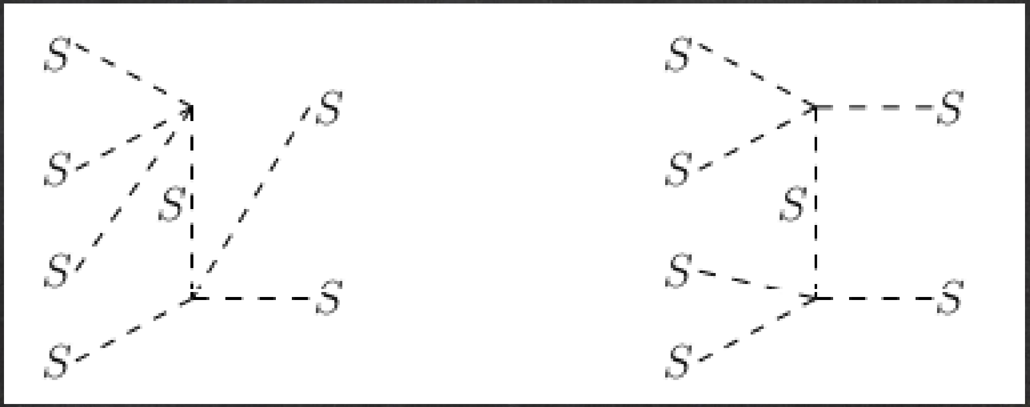
$$\frac{dn}{dt} + 3\,H\,n = -\langle\sigma v^3\rangle_{4\to 2}\,\left(n^4 - n^2\,n_{\rm eq}^2\right)$$



But $\mathbf{Z_2}$ symmetries allow 4→2 annihilations!

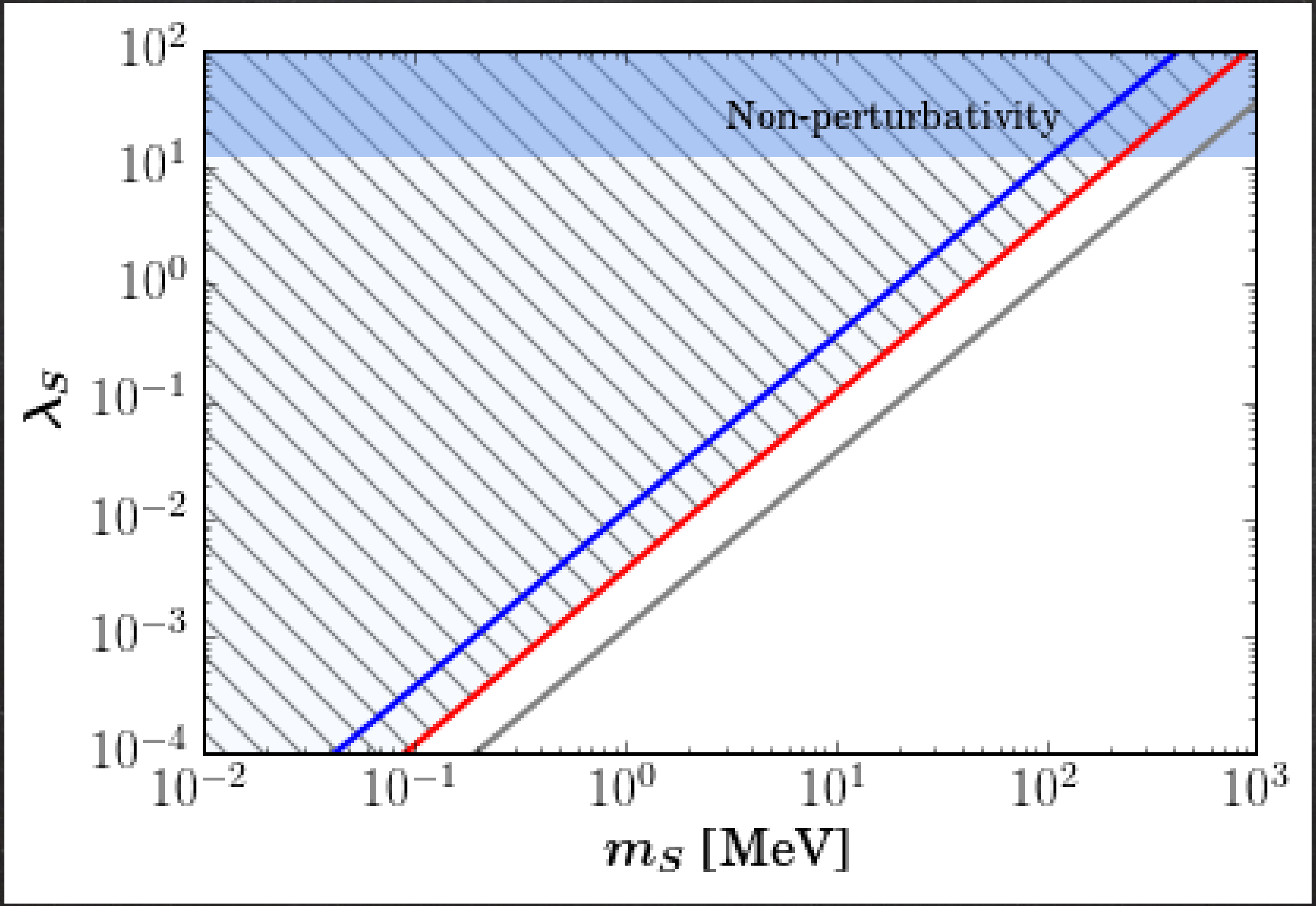
SIMP DM
4→2 annihilations

$$\frac{dn}{dt} + 3\,H\,n = -\langle\sigma v^3\rangle_{4\to2}\,\left(n^4 - n^2\,n_{\rm eq}^2\right)$$



$$\langle\sigma v^3\rangle_{4\to2} \sim \frac{27\sqrt{3}}{8\pi}\,\frac{\lambda_S^4}{m_S^8}$$

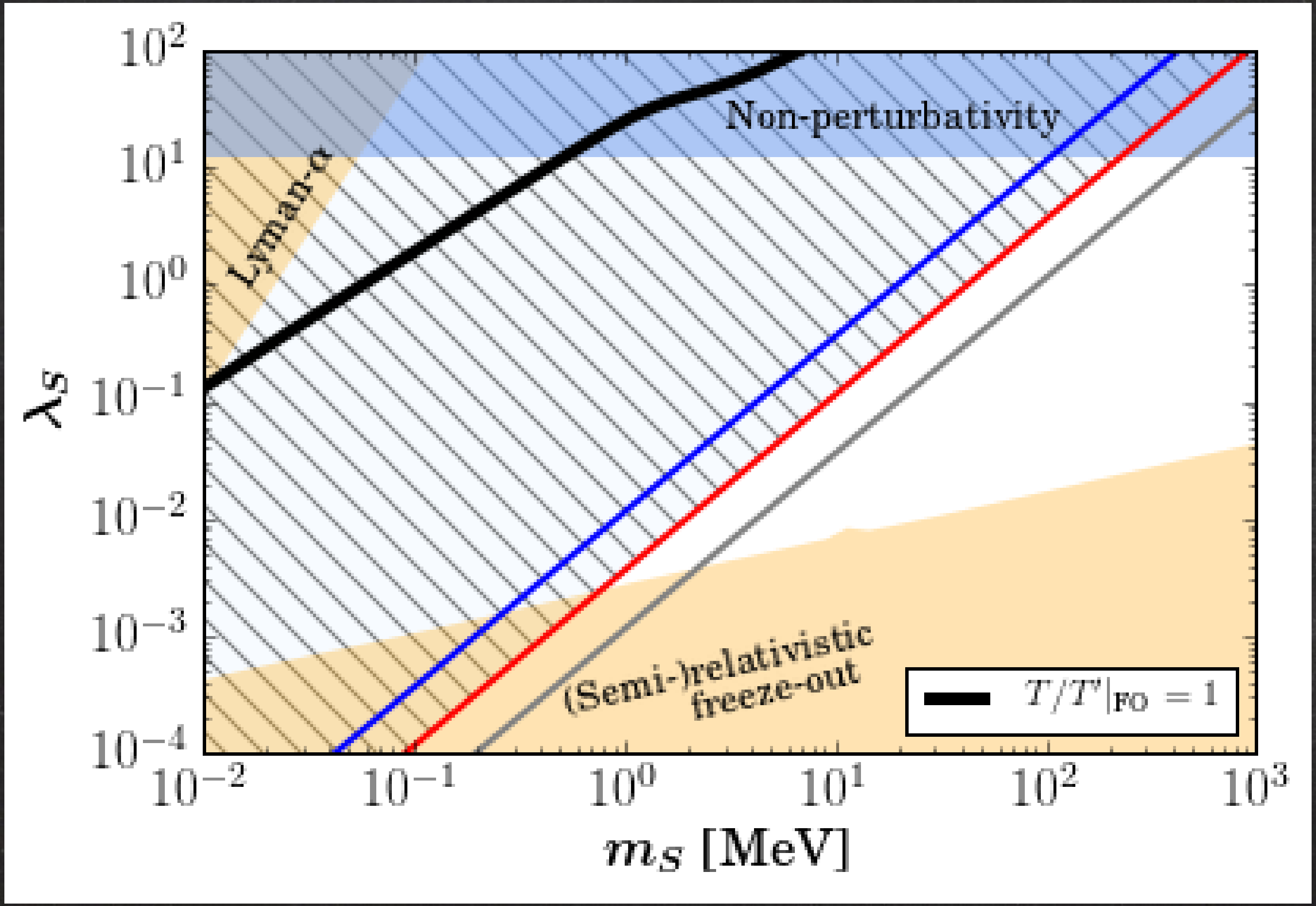
SIMP DM
4→2 annihilations



σ/m [cm²/g]
{ 10, 1, 0.1

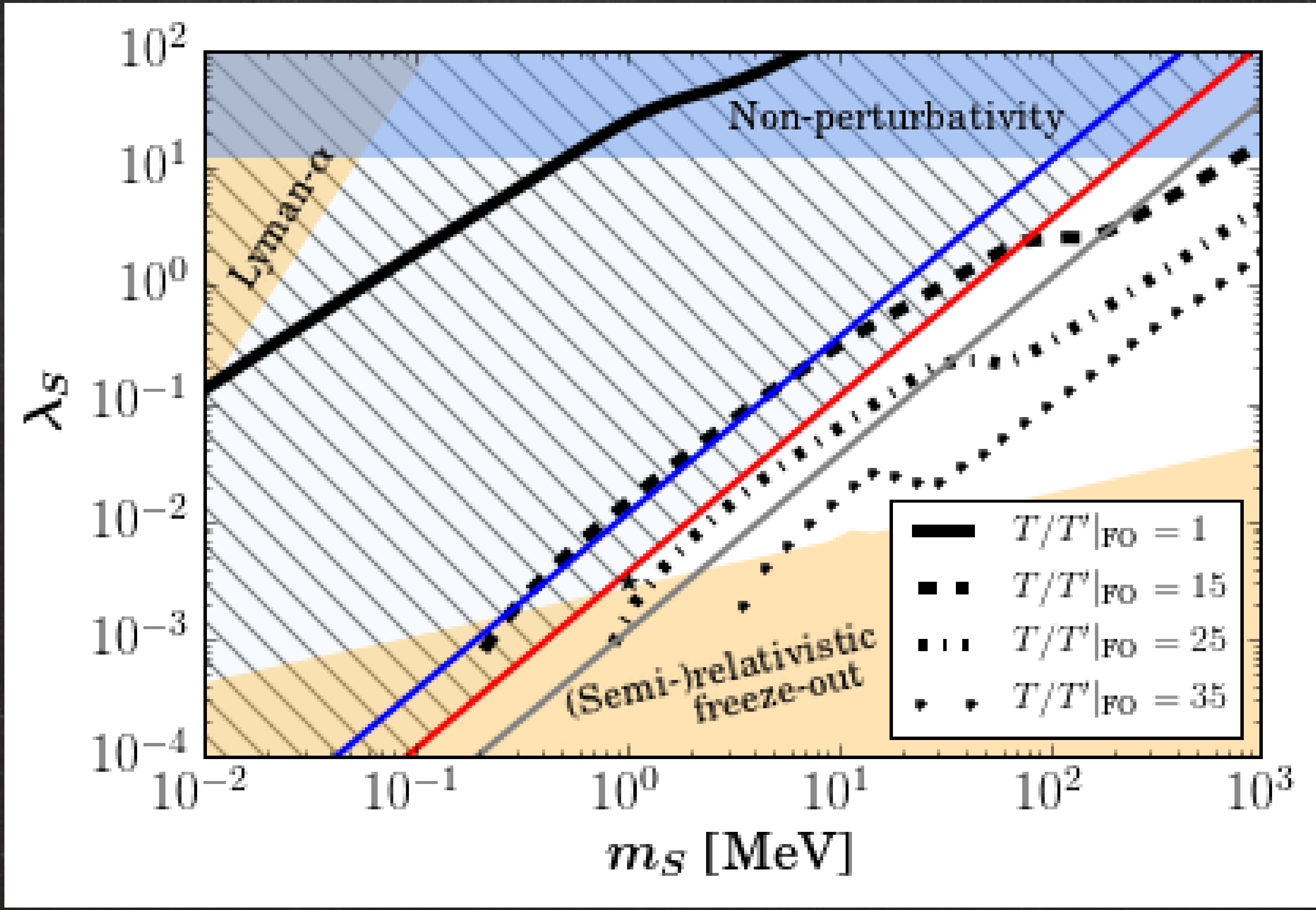
SIMP DM
4→2 annihilations

$T_{SM} = T_{DM}$ @ DM freeze-out



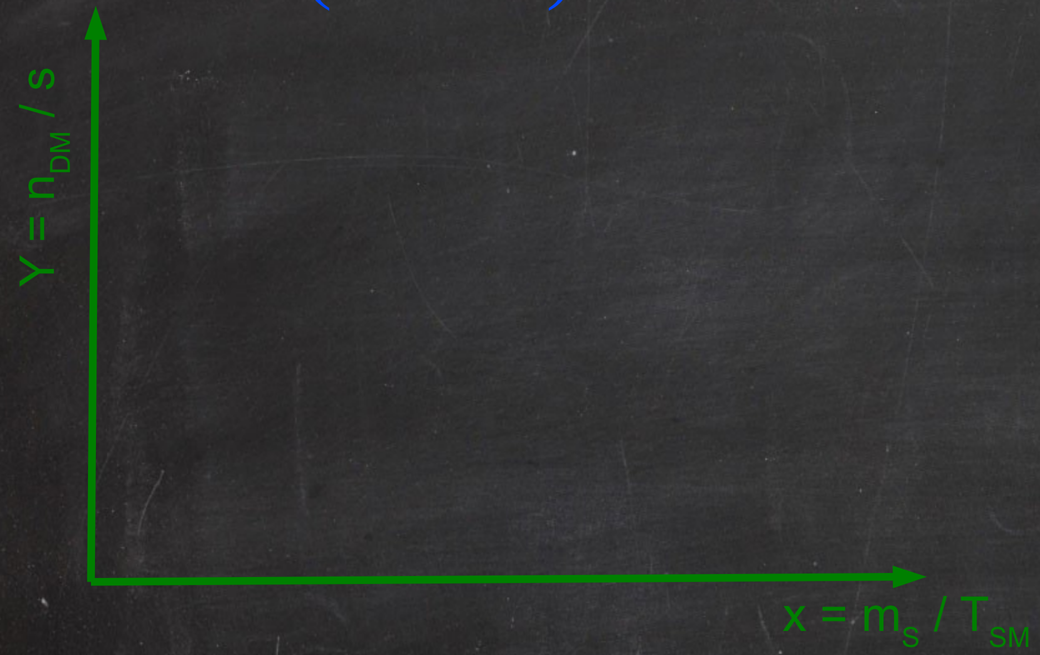
SIMP DM
4→2 annihilations

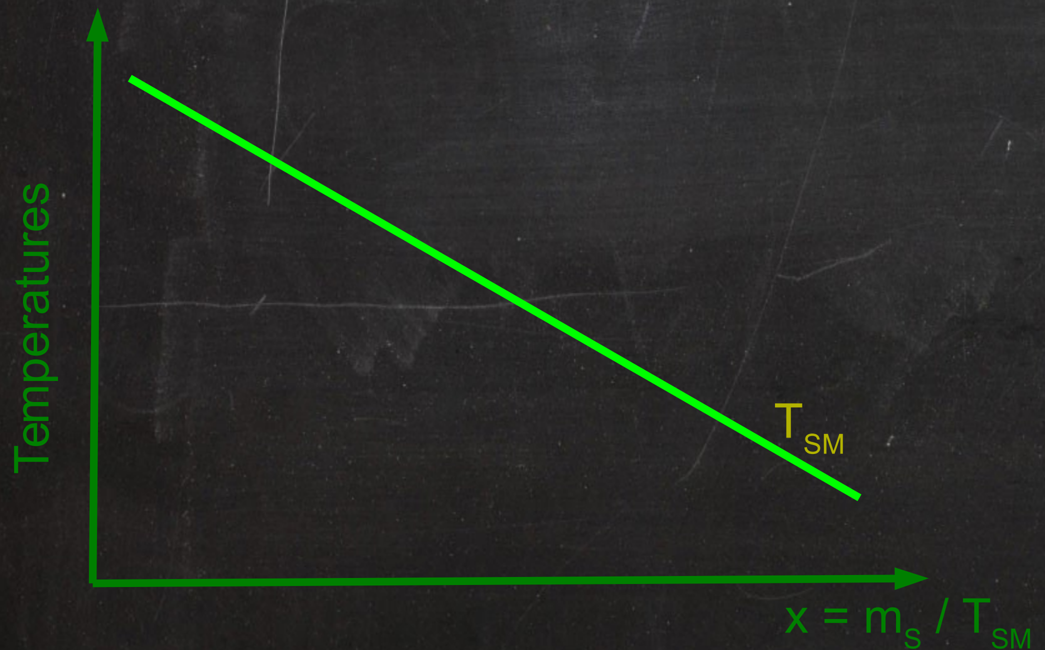
$T_{SM} \neq T_{DM}$ @ DM freeze-out



How to produce such a difference of temperatures?

(Non-) Thermal evolution of DM





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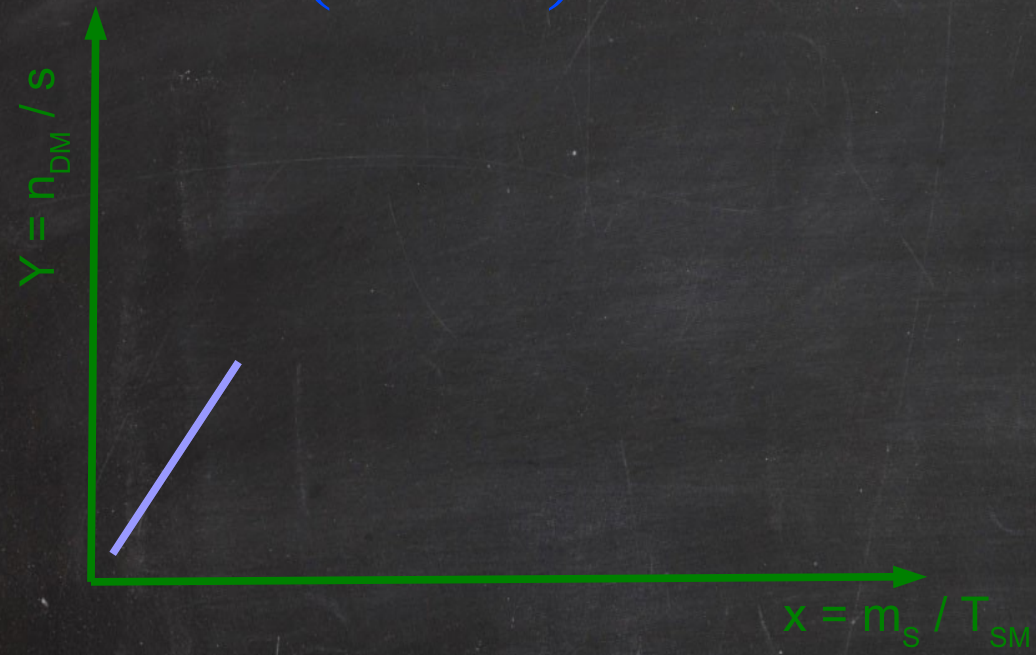
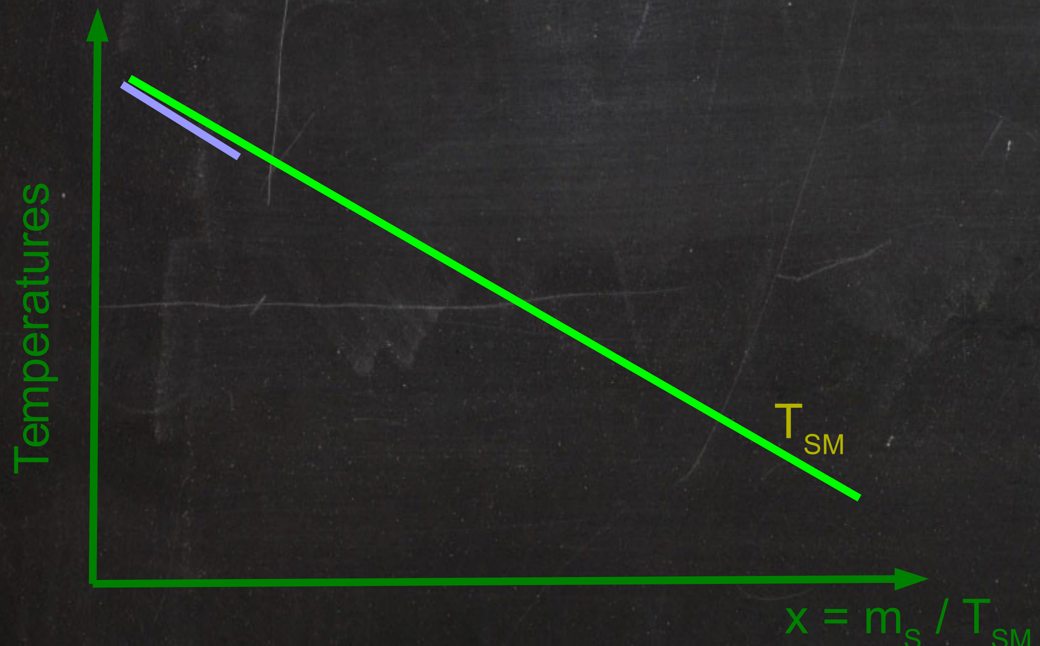
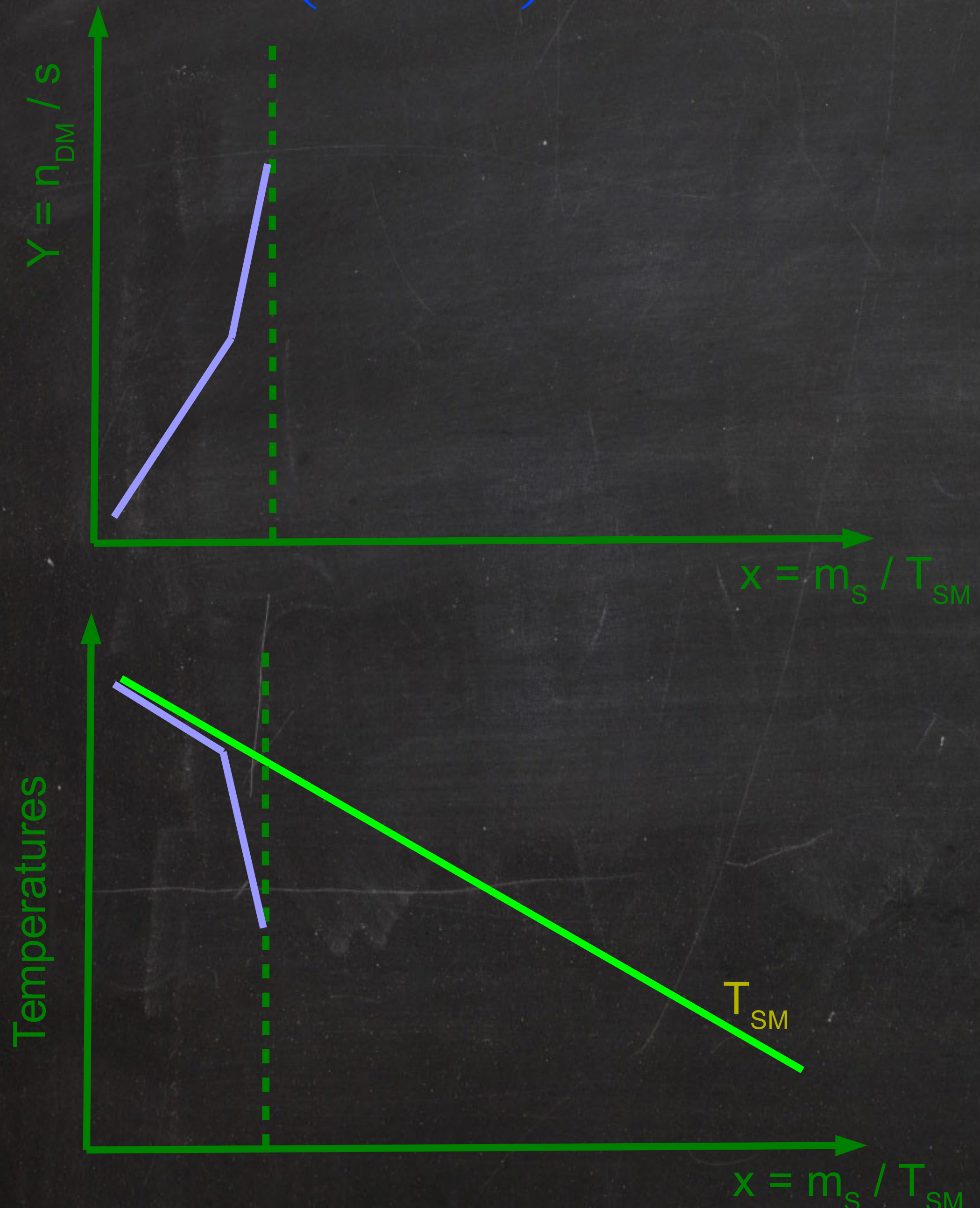




DM Production

* Out-of-equilibrium production
à la freeze-in: **h→SS**
DM in kinetic equilibrium via **2↔2**
DM inherits SM temperature

(Non-) Thermal evolution of DM

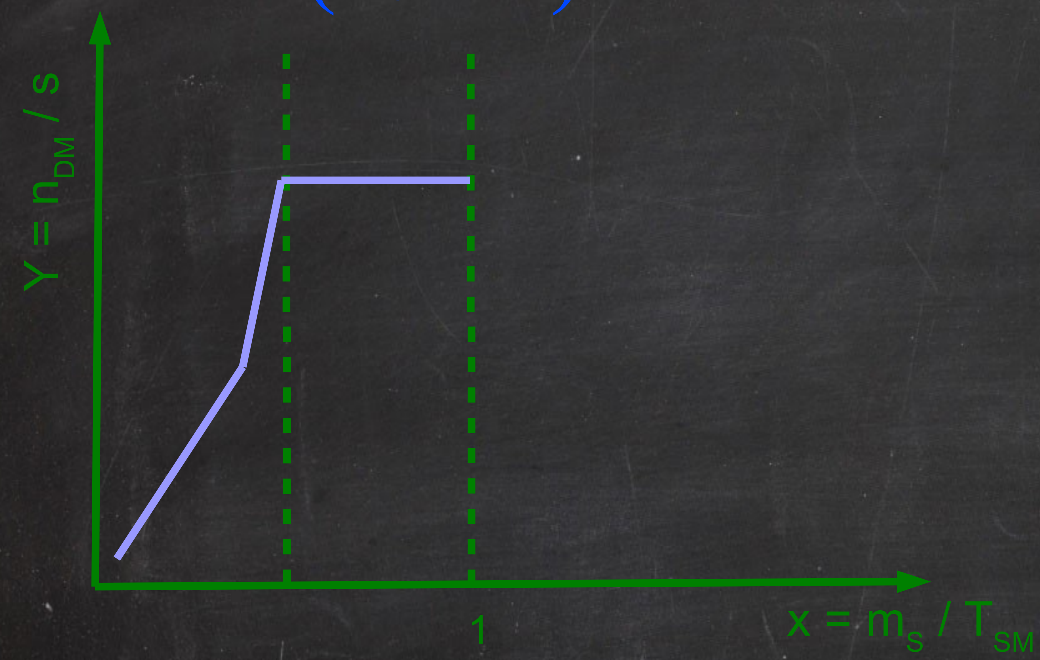


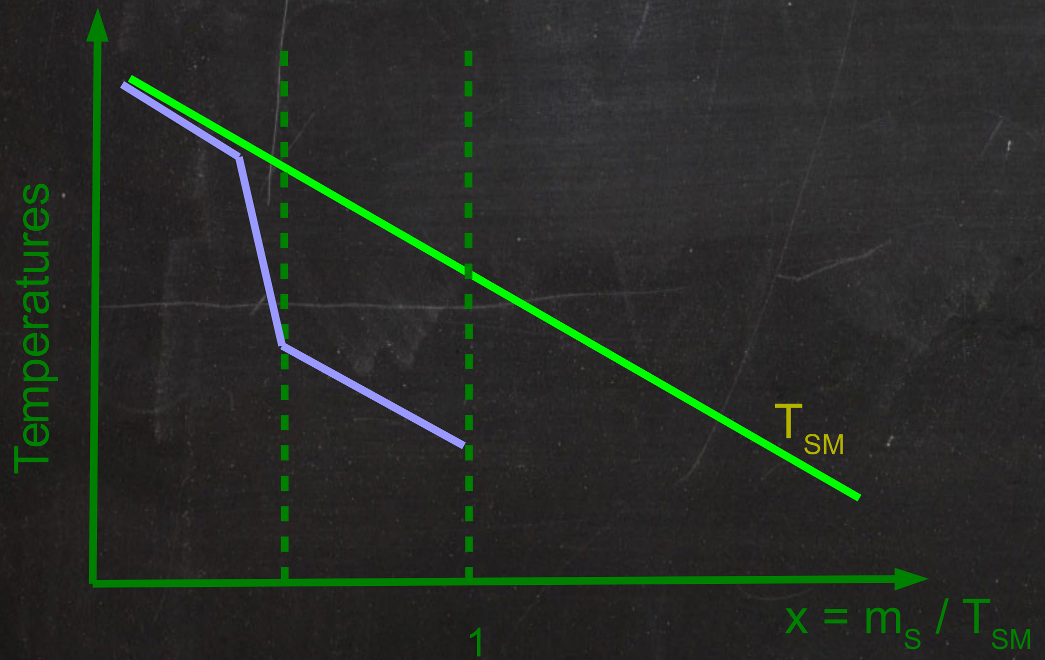
DM Production

* Out-of-equilibrium production à la freeze-in: **h→SS**
  DM in kinetic equilibrium via **2↔2**
  DM inherits SM temperature

* DM populates rapidly via out-of-equilibrium **2→4**.
  Price to pay: Dramatic decrease of T_{DM}

(Non-) Thermal evolution of DM





<u>DM Production</u>

* Out-of-equilibrium production
  à la freeze-in: **h→SS**
  DM in kinetic equilibrium via **2↔2**
  DM inherits SM temperature

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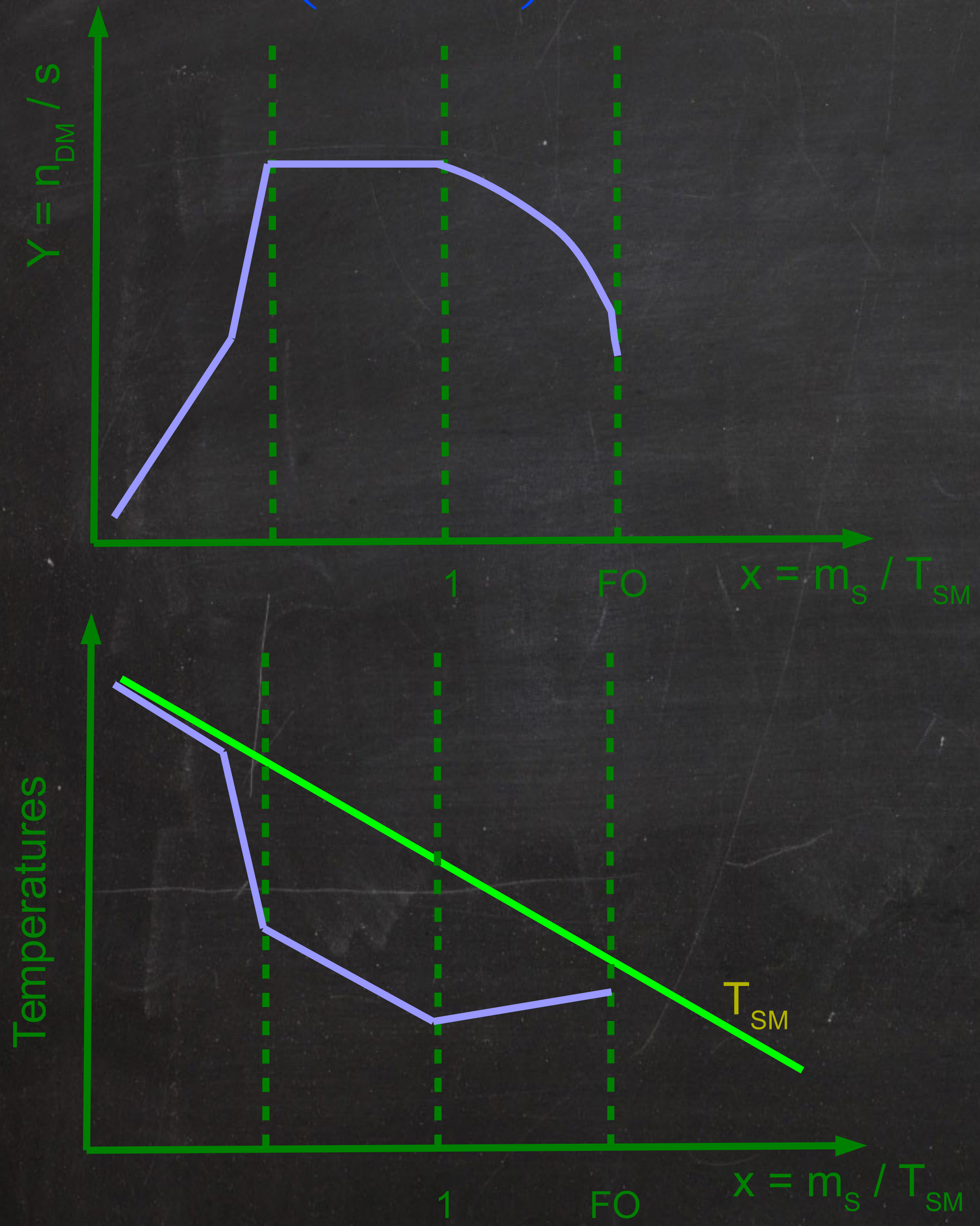
<u>Thermal Equilibrium</u>

* Chemical equilibrium **2↔4**

(Non-) Thermal evolution of DM



<u>DM Production</u>

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  à la freeze-in: **h→SS**
  DM in kinetic equilibrium via **2↔2**
  DM inherits SM temperature

* DM populates rapidly via
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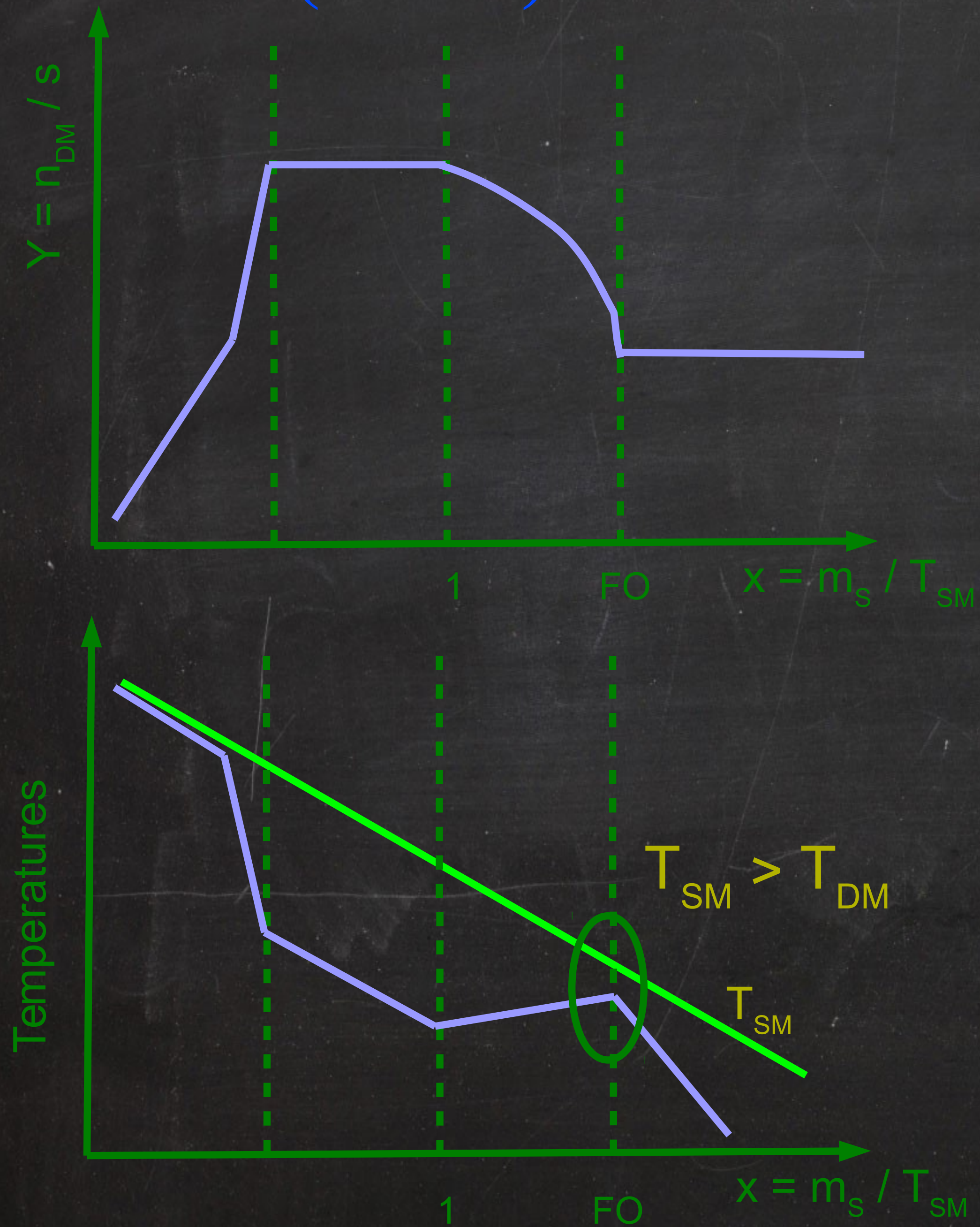

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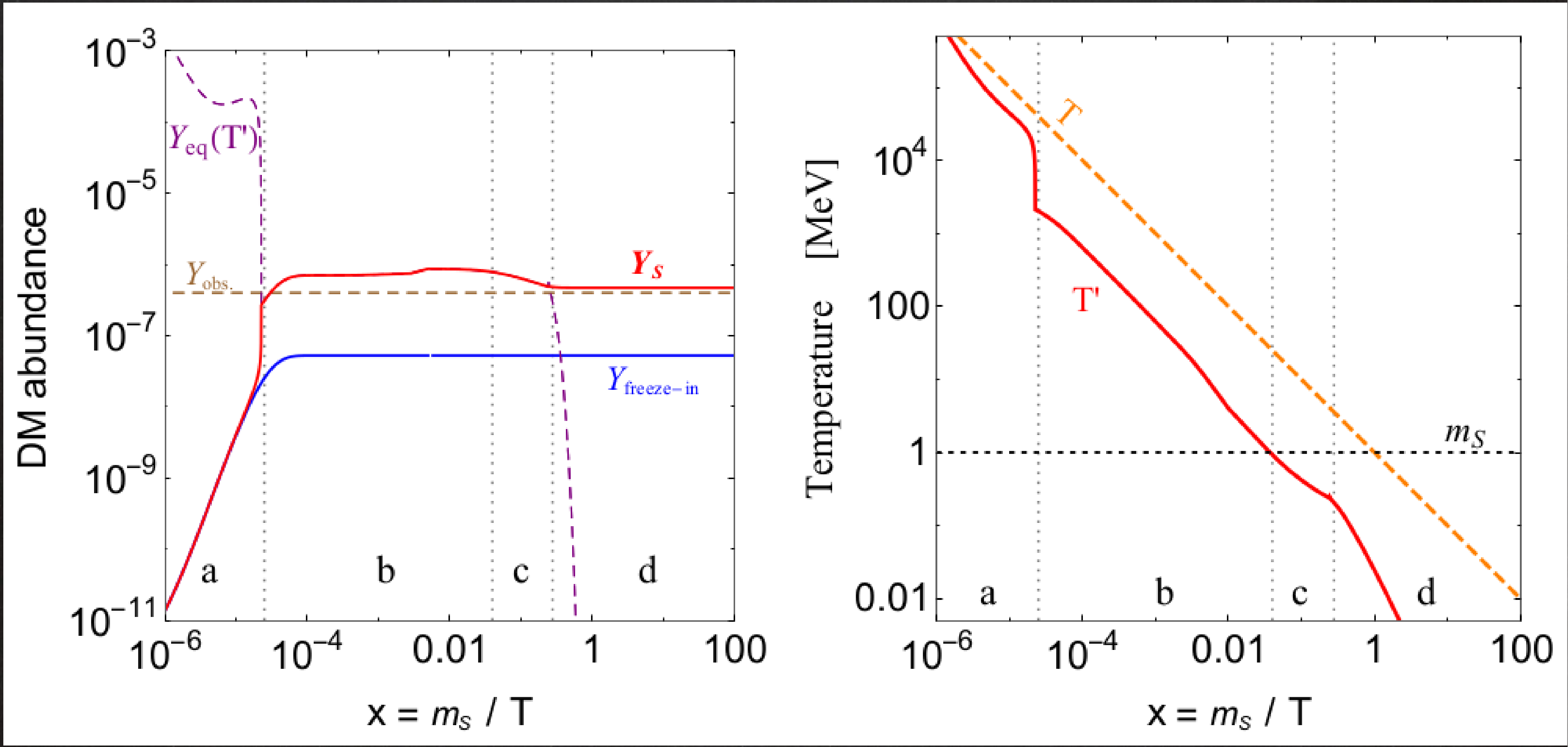
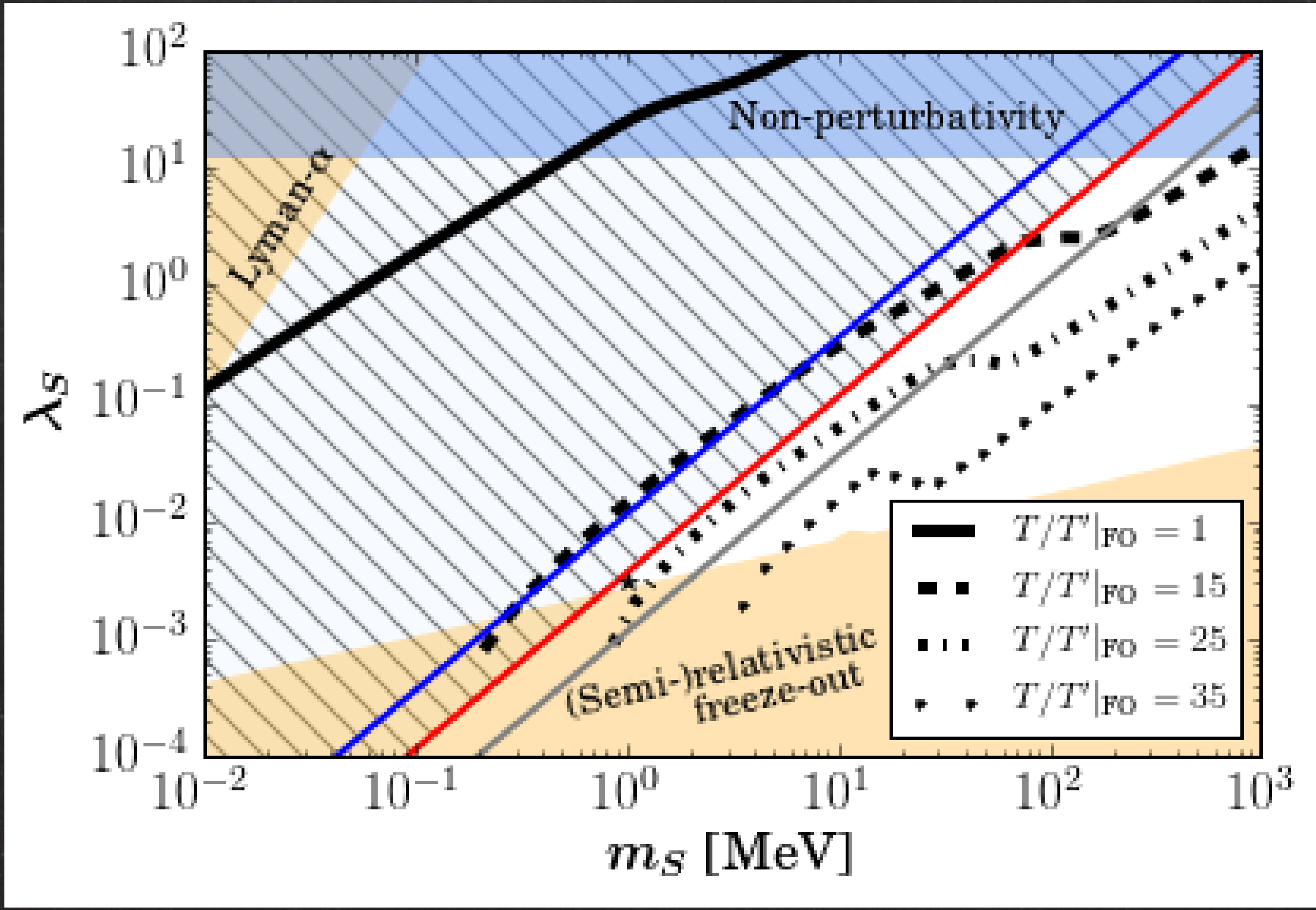
Generating $T_{DM} < T_{SM}$ via the Higgs Portal



SIMP DM
4→2 annihilations



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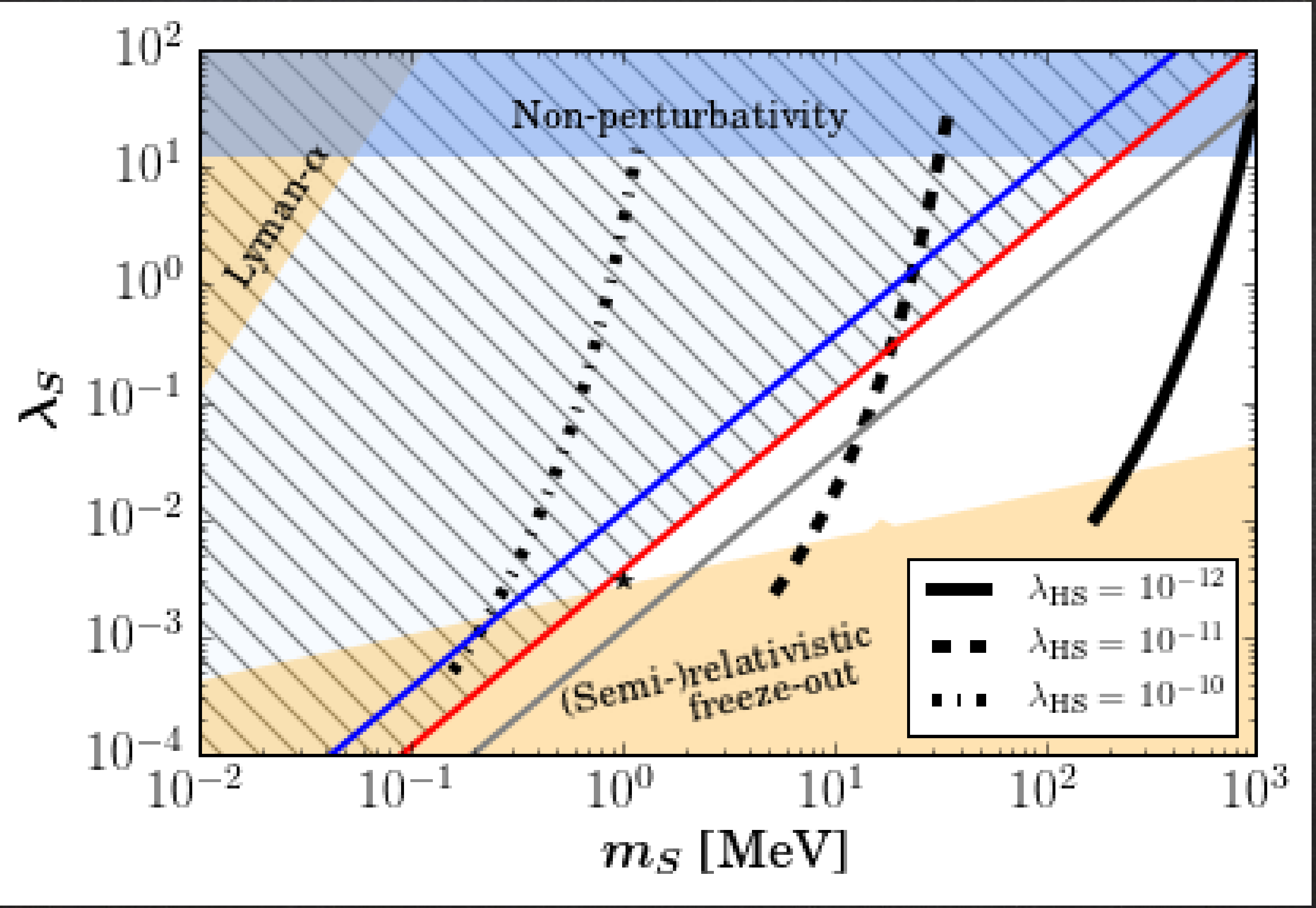

Conclusions

Small-scale anomalies

* Cusp-vs-core
* Too-big-to-fail

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→

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Dark Matter

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SIMP DM

* dominant **N→n**
* need to avoid the 'DM reheating'
  + kinetic equilibrium SM↔DM
  + dark sector with relativistic particles @ FO
  + SM and DM never in kinetic equilibrium

Conclusions

* SIMP DM *only* studied so far in the context of **3→2** annihilations, but they are forbidden in typical Z_2 invariant theories!

* If DM stability is guaranteed by a Z_2, **4→2** reactions can dominate!

* SIMPlest example: Singlet Scalar DM

  $m_S \sim 100$ MeV
  $\lambda_S \sim 1$ } DM self-interactions
  $\lambda_{HS} \sim 10^{-10}$ → Freeze-in

* Difference of temperatures can be dynamically generated via the small Higgs portal

* SIMPs offer a new window to DM: Points to different physical scales

* New model building challenges!