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
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NB & X. Chu
arXiv:1510.08527

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

unesp
UNIVERSIDADE ESTADUAL PAULISTA "JÚLIO DE MESQUITA FILHO"

December 10th, 2015

The SIMPlest Dark Matter Model

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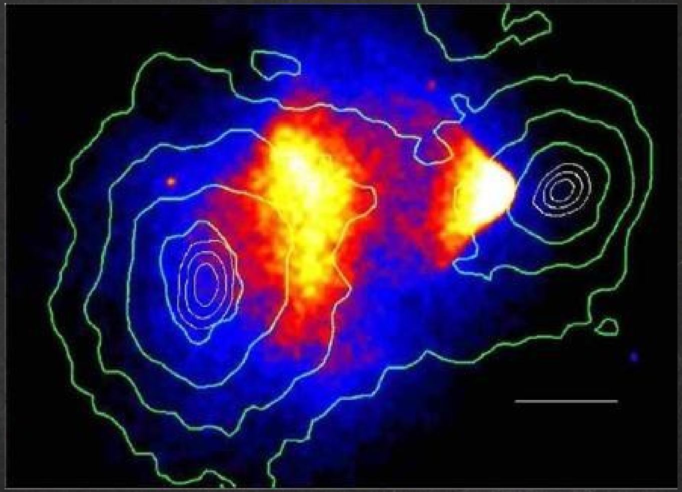
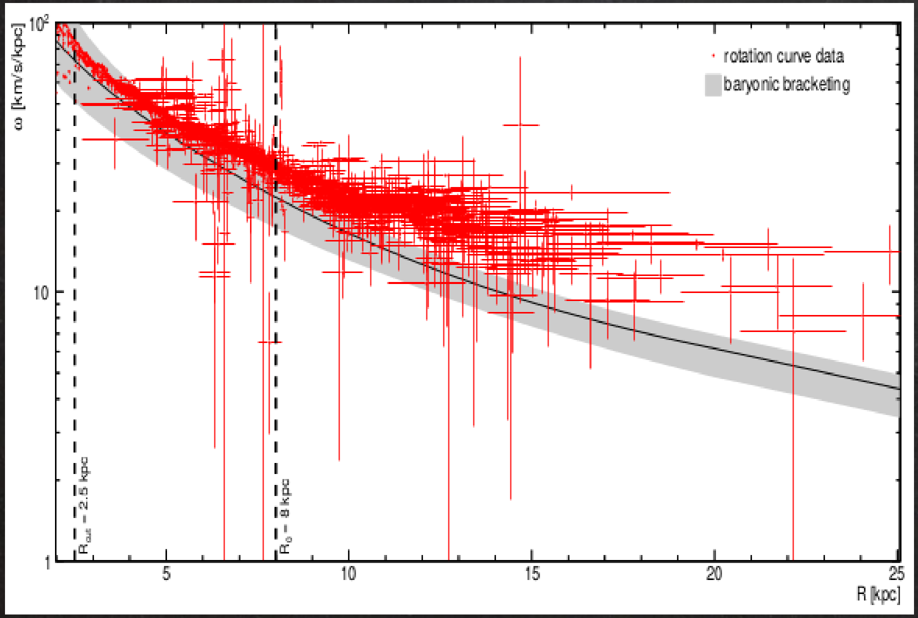
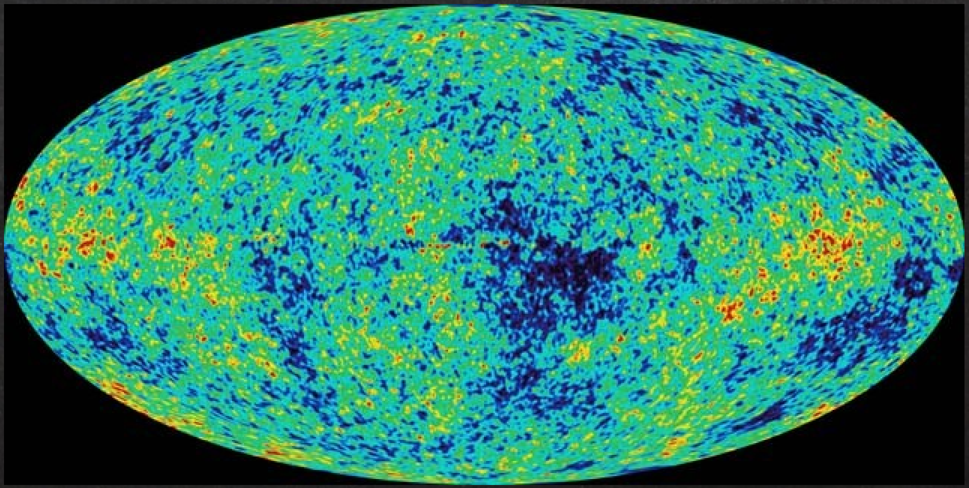
Evidences for Dark Matter

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

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



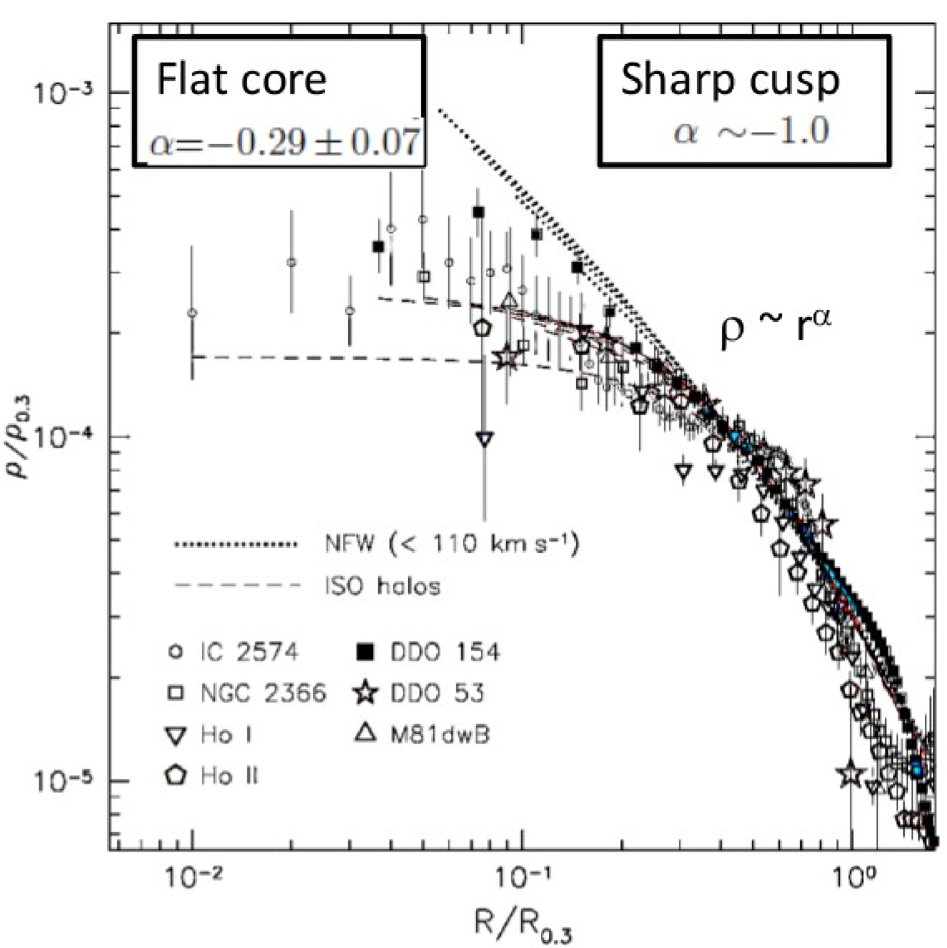




Cold Dark Matter in Trouble

* **Core-vs-cusp problem** Moore (1994), Flores & Primack (1994)
  - Central densities of halos exhibit cores
  - *N*-body simulations $\rho \sim r^{-1}$

THINGS (dwarf galaxy survey) - Oh et al. (2011)

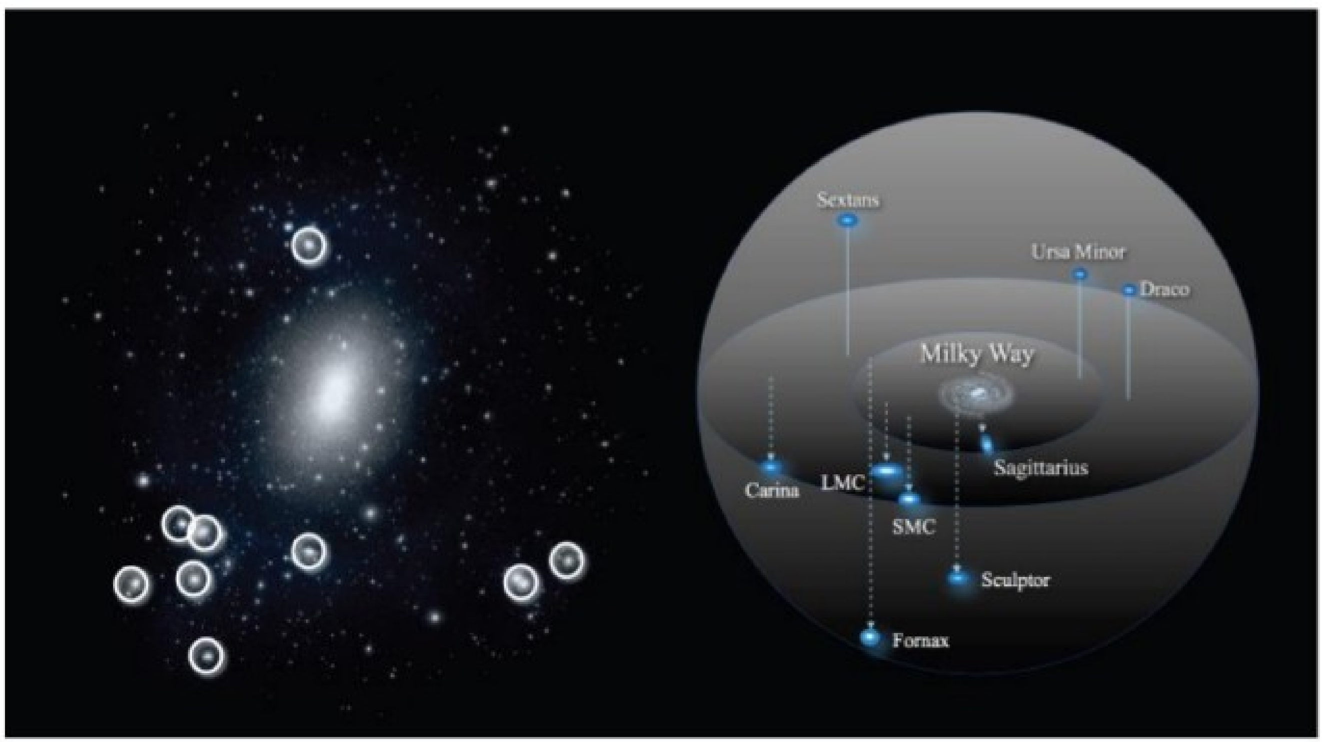


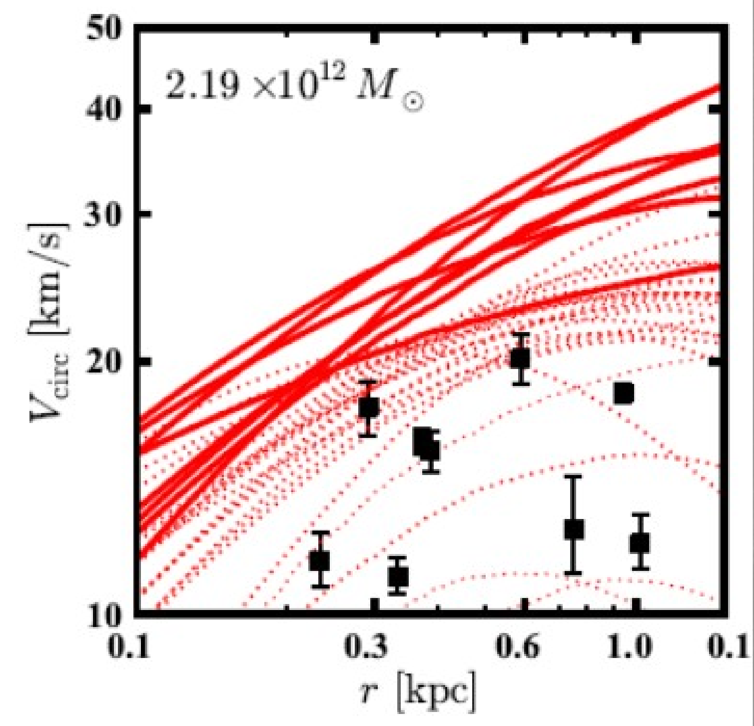
* Field dwarfs
* Satellite dwarfs galaxies
* Low surface brightness galaxies (LSBs)
* Clusters

Cold Dark Matter in Trouble

* **Too-big-to-fail problem** Boylan-Kolchin, Bullock, Kaplinghat (2011 + 2012)

MW galaxy should have ~10 satellite galaxies which are more massive than the most massive dwarf spheroidals





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...)

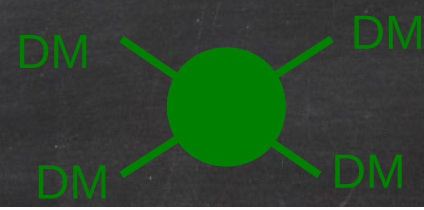
* Dark matter
  DM may not be **collisionless**

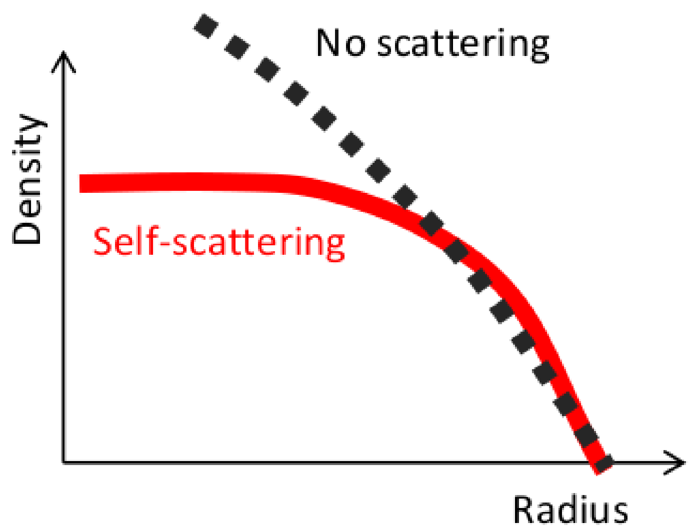
Self-interacting DM

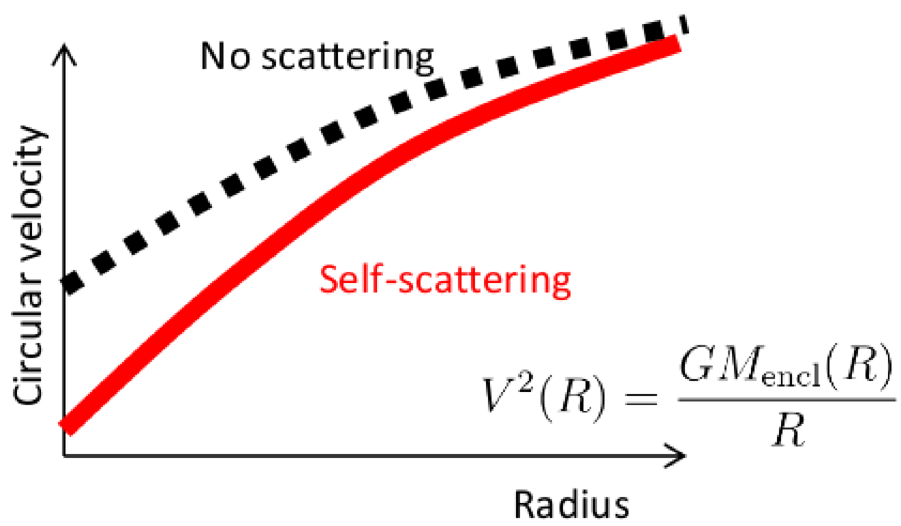
CDM structure problems are solved if dark matter is **self-interacting.**

Dark matter particles in halos elastically scatter with other dark matter particles.

Spergel & Steinhardt (2000)







Self-interactions solve core-vs-cusp

Particles get scattered out of dense halo centers

Self-interactions solve too-big-to-fail

Rotation curves reduced (less enclosed mass)

Simulated satellites matched to observations

S. Tulin

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

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

Fake Split SUSY Model ≡ FSSM

- FSSM-I: both the higgsinos and gauginos are swapped for fake gauginos and fake higgsinos. (K.B, Darmé, Goodsell and Slavich — Dudas, Goodsell, Heurtier, Tziveloglou, 2014)
  1. The fermions remain light because of a $U(1)$ flavour symmetry
  2. The f-gauginos are Dirac partners of the gauginos
  3. Yukawa couplings $\tilde{g}_{u,d}, \tilde{g}'_{u,d}$ are suppressed by $(\mathrm{TeV}/M_S)^2$
  4. Two pairs of vector-like electron superfields need to be added at M_S to insure unification at two-loop

- FSSM-II: Only the higgsinos are swapped for fake higgsinos. (K.B, Darmé, Goodsell 2015)
  1. The fermions remain light because of R-symmetry charges
  2. Yukawa couplings $\tilde{g}_{u,d}, \tilde{g}'_{u,d}$ are suppressed by (TeV/M_S)
  3. Two pairs of Higgs-like doublets needed for the f-higgsinos
  4. Two pairs of $(\mathbf{3},\mathbf{1})_{1/3} \oplus (\overline{\mathbf{3}},\mathbf{1})_{-1/3}$. In total we have added a vector-like pair of $\mathbf{5}+\overline{\mathbf{5}}$ of $SU(5)$

Small-scale problems → Self-interacting DM

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Small-scale problems → Self-interacting DM

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

Possible sol...

FAKE MOTIVATIONS! :-)

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

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

... 10) cm^2/g ... obs $\sim$ few barns/GeV

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

The Simplest DM model ever:
Singlet Scalar Dark Matter

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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3 free parameters:

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* **λ_{HS}** Higgs portal
* **λ_s** DM quartic coupling

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

←--- Completely ignored! (applies to λ_s)

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

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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:

- * $\mathbf{m_s}$ DM mass
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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

- * $\mathbf{m_s}$ DM mass
- * $\boldsymbol{\lambda_{HS}}$ Higgs portal

} ←--- Up to now, concentrate on this

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

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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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Update on scalar singlet dark matter

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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

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

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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

Closing in ... cays and gamma-ray lines

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Lei Feng, Stefano

[1] λ_S is essentially irrelevant.

Gamma rays ... n 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

Antimatter signals o ... **atter**

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

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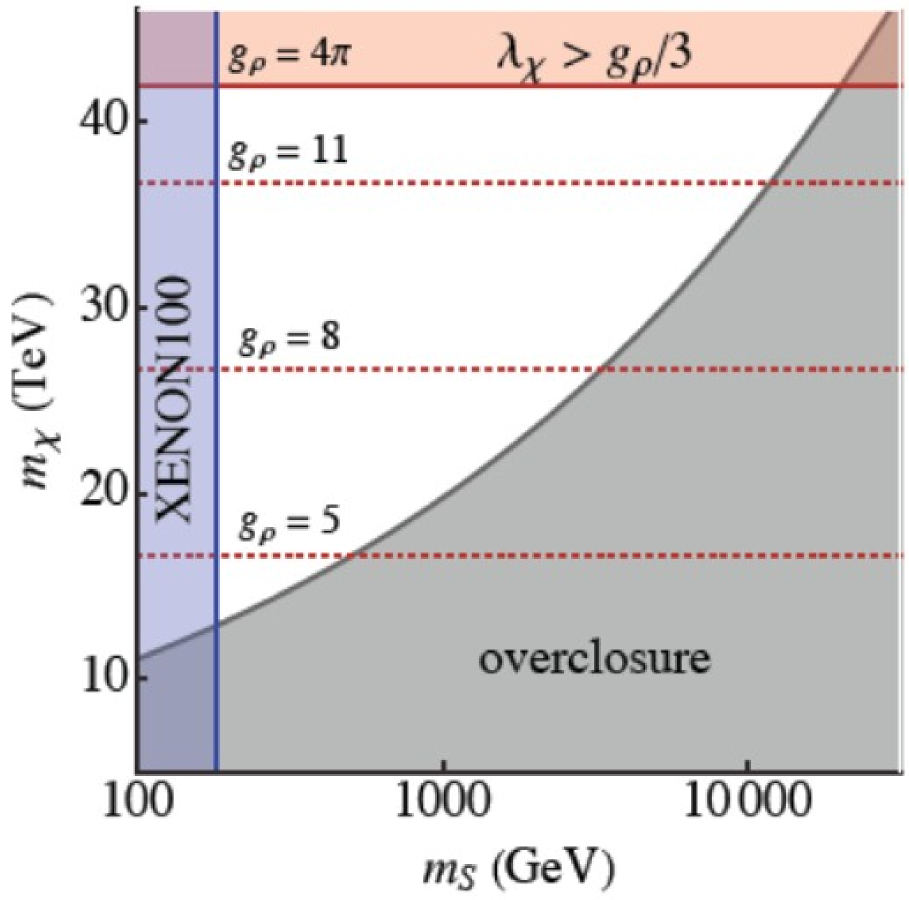
Dark matter constraints

singlet Higgs partner S -- Higgs portal coupling $V \supset \kappa |D|^2 |S|^2$



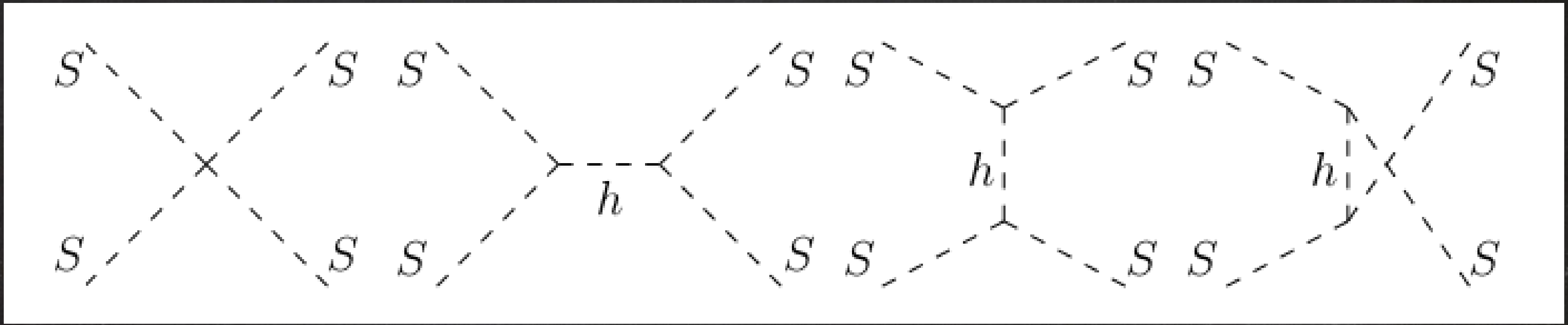
where $\kappa \sim 0.02 \left(\frac{m_\chi}{f}\right)^4$

$f = 10$ TeV

$180 \text{ GeV} \lesssim m_S \lesssim 10 \text{ TeV}$ $10 \text{ TeV} \lesssim m_\chi \lesssim 40 \text{ TeV}$

Dark Matter Self-Interactions

Dark Matter Self-Interactions

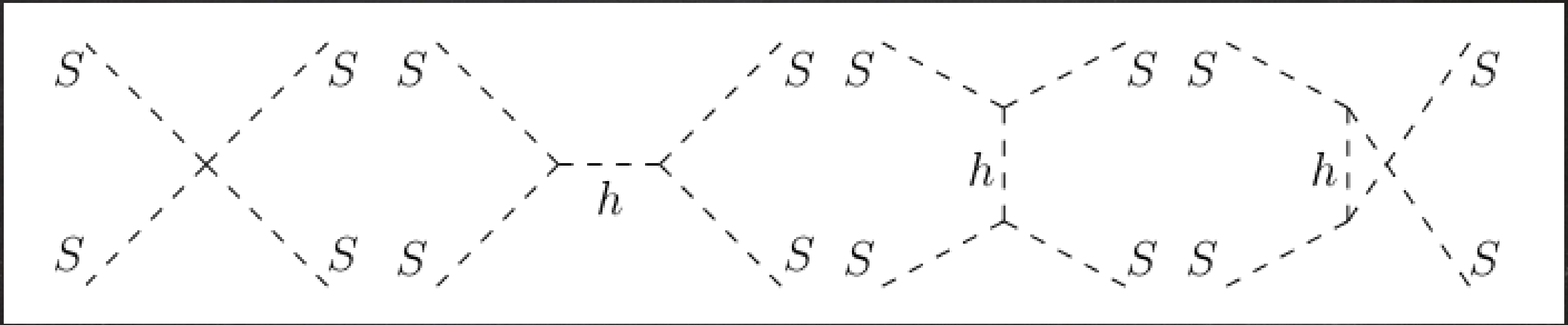


$$\frac{\sigma_{SS}}{m_S} \sim \frac{9}{8\pi}\frac{\lambda_S^2}{m_S^3}$$

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

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

Dark Matter Self-Interactions & Invisible Higgs decay



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Implies {
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* $m_S \sim 100$ MeV

The Higgs tends to annihilate into DM

BR(h→ inv.) < 20%

* $\lambda_{HS} < 7\cdot10^{-3}$

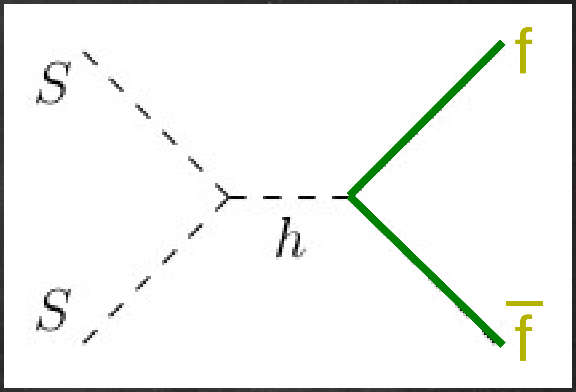
How to produce such a Self-Interacting Dark Matter?

WIMP DM

DM can (only) annihilate into light fermions

other annihilation channels kinematically closed!

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



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

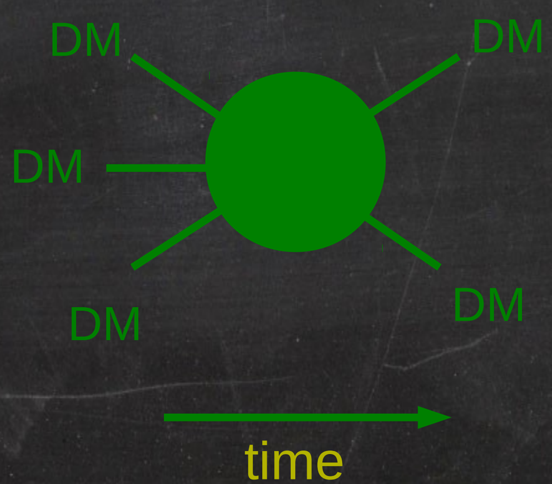
→ **DM can not be a WIMP!!!**

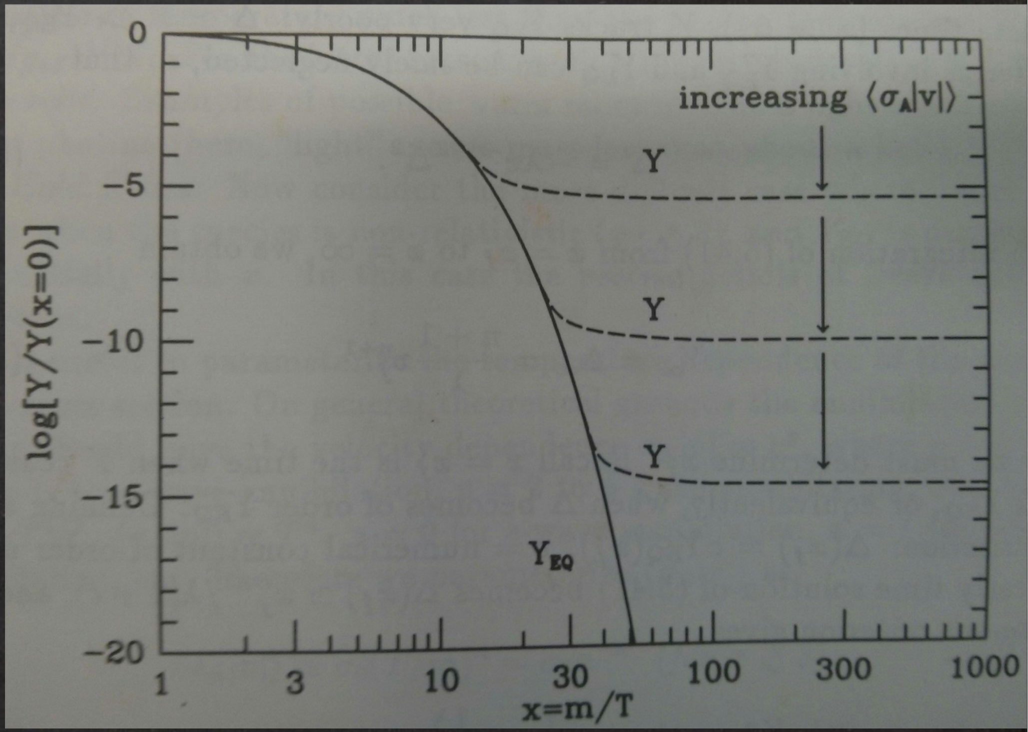
Again:
How to produce such a Self-Interacting Dark Matter?!

SIMP DM
3→2 annihilations

Hochberg, Kuflik, Volansky & Wacker '14

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





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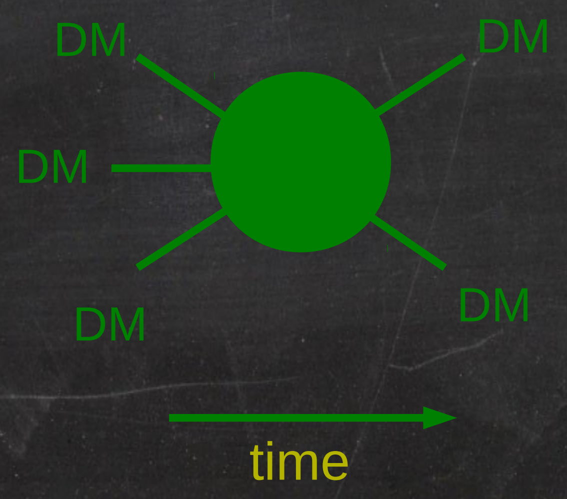

* DM in the MeV range

* Small DM-SM portal

* $\alpha \sim 1$
  'Strong' Self-interactions
  → SIMP

SIMP DM
3→2 annihilations

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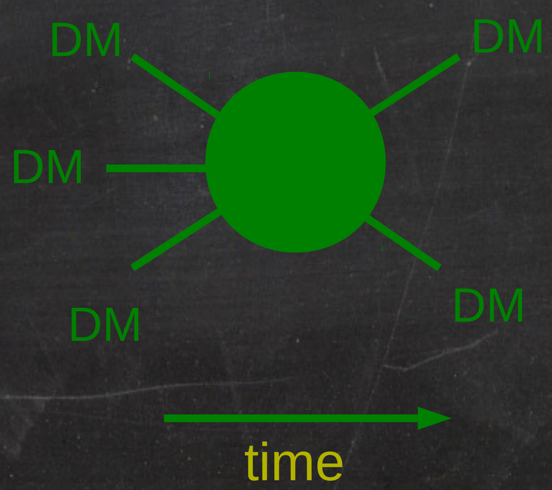


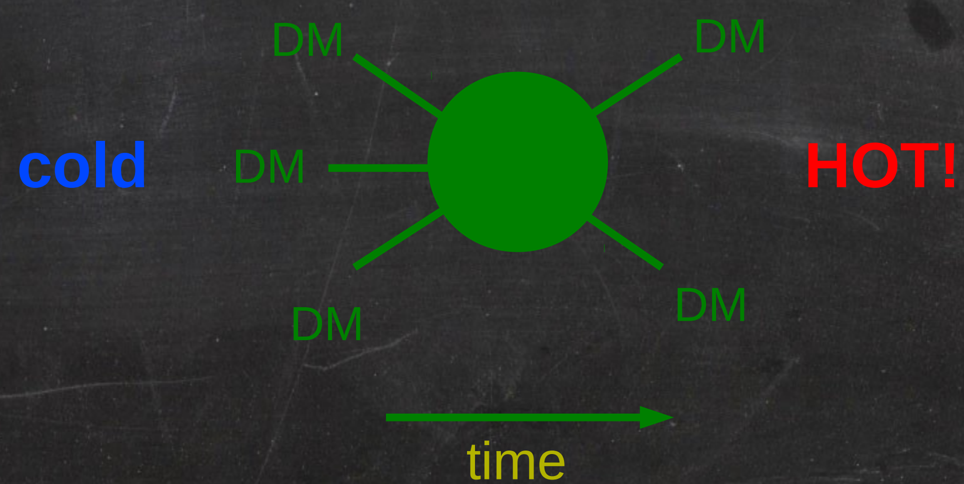
* DM in the MeV range

* Small DM-SM portal

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

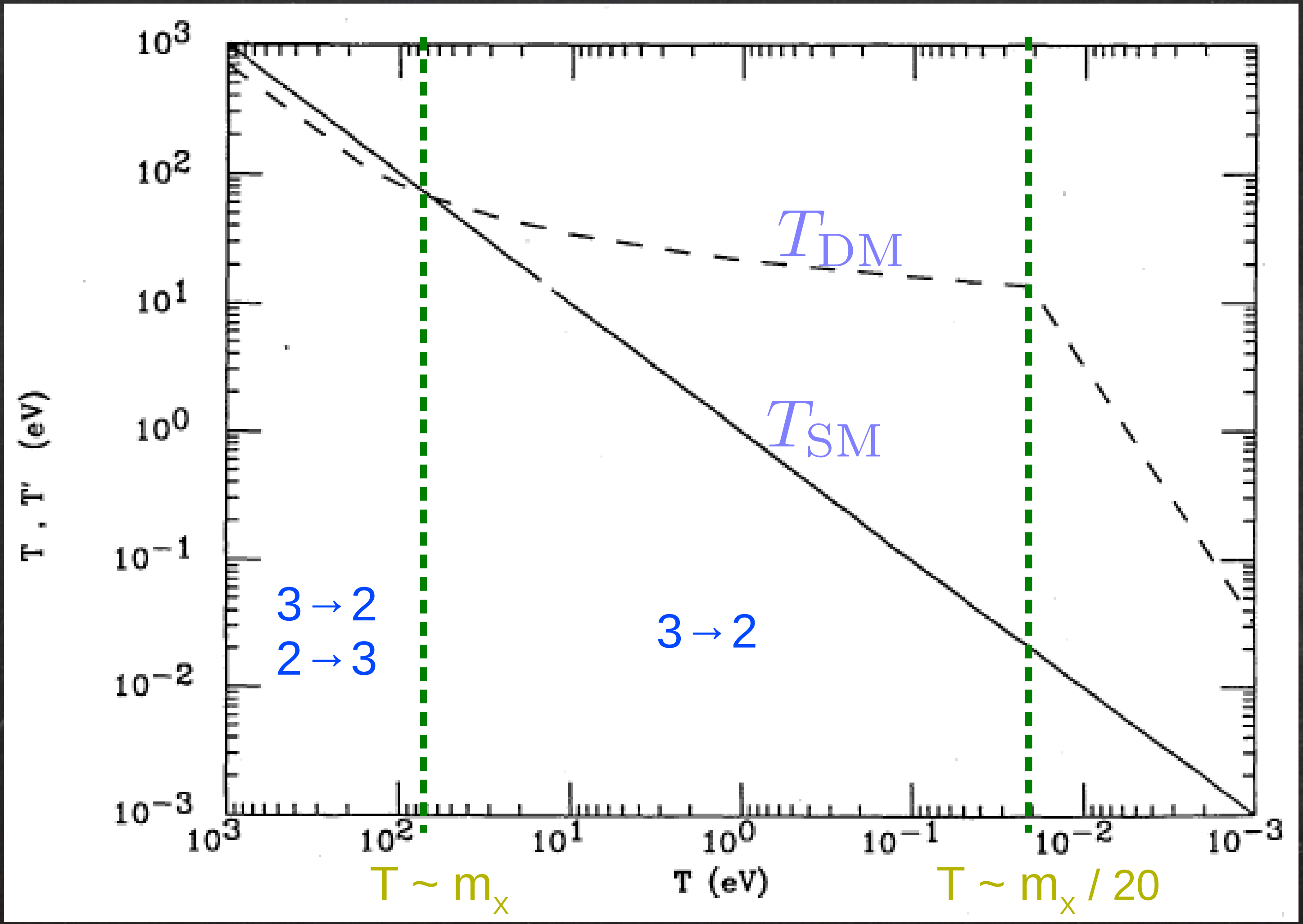
Caveat

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



3 → 2 annihilations
pump heat into the dark sector!

$3 \to 2$ DM annihilation



DM non-relativistic

DM Freeze-out

Carlson, Machacek & Hall
Astrophys.J. 398 (1992) 43–52.

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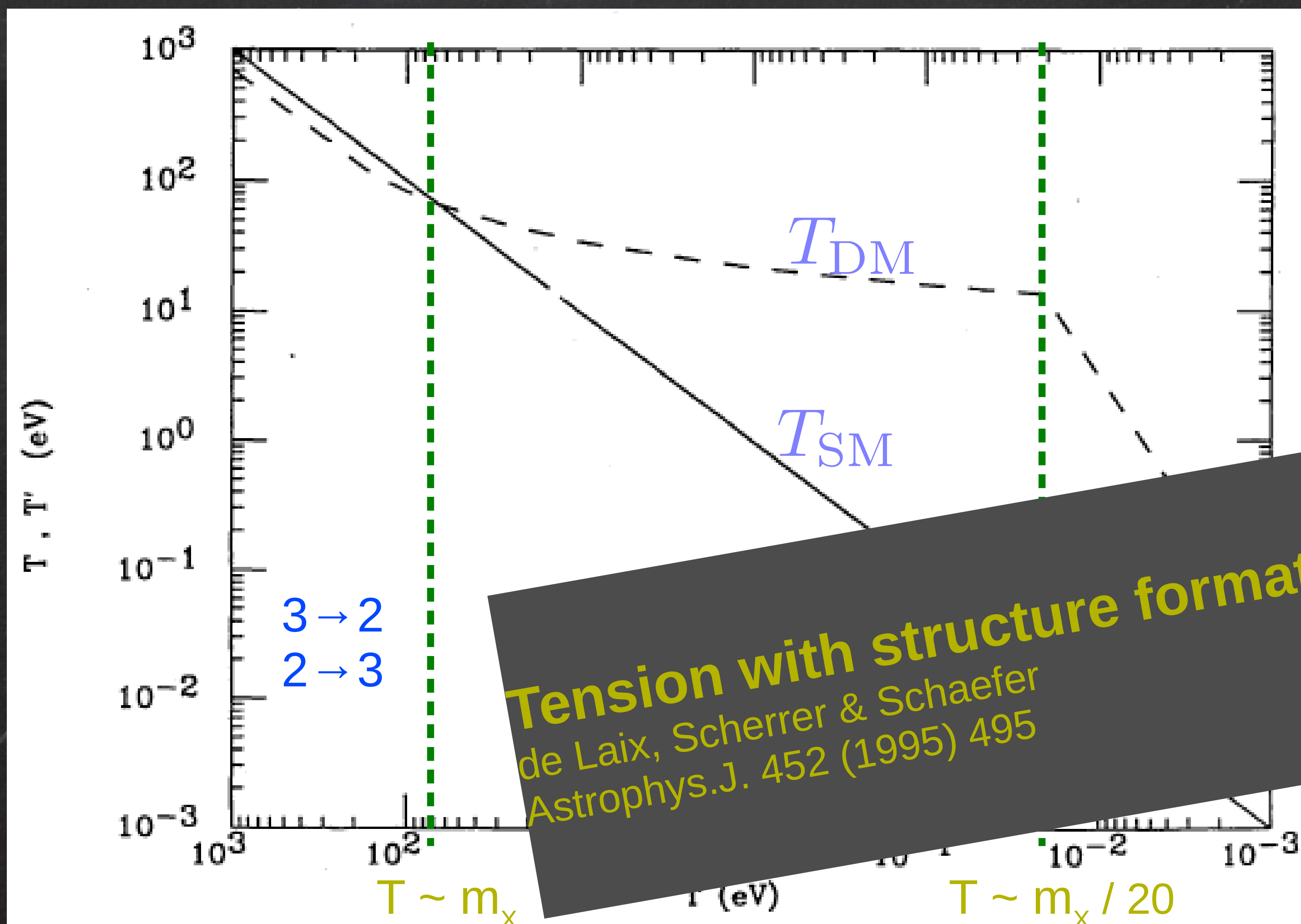

Tension with structure formation
de Laix, Scherrer & Schaefer
Astrophys.J. 452 (1995) 495

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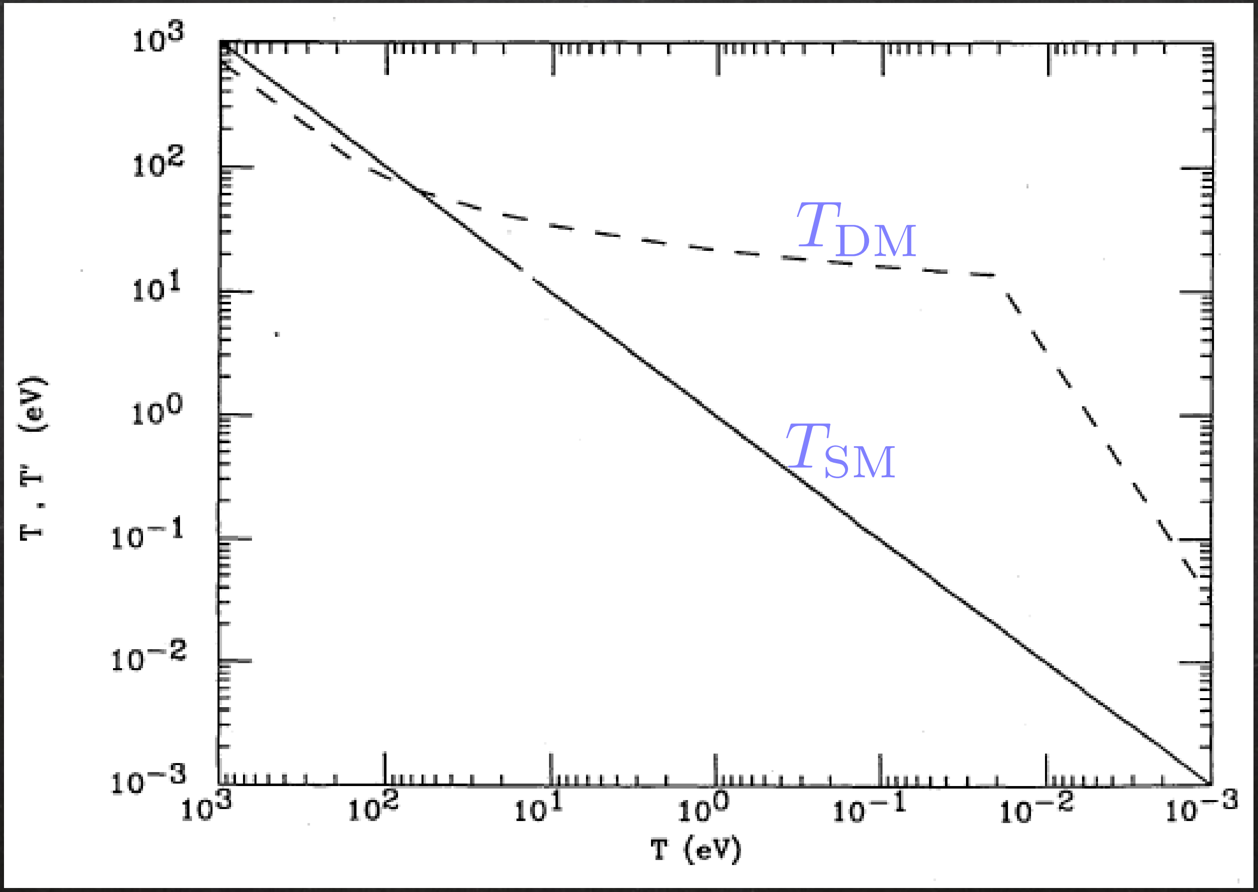
DM Freeze-out

Carlson, Machacek & Hall
Astrophys.J. 398 (1992) 43–52.

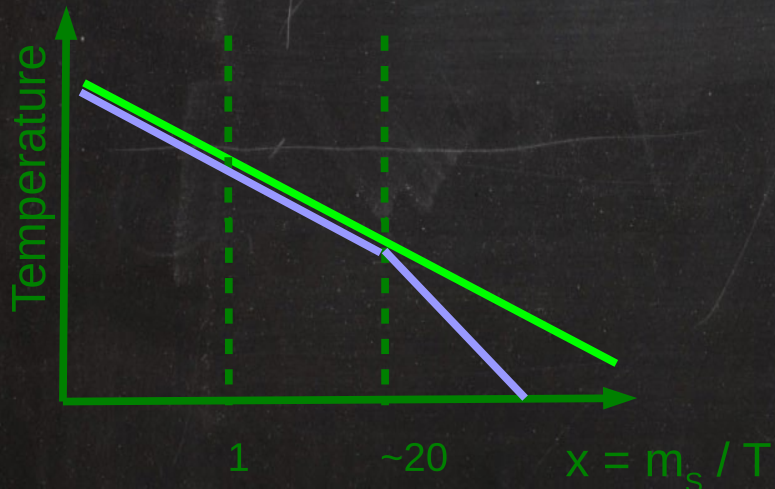
How to avoid the (relative) increase of temperature?



Avoiding the DM 'reheating'

* Keeping kinetic equilibrium between DM and SM

Hochberg, Kuflik, Volansky & Wacker '14 + Choi & Lee '15



Avoiding the DM 'reheating'

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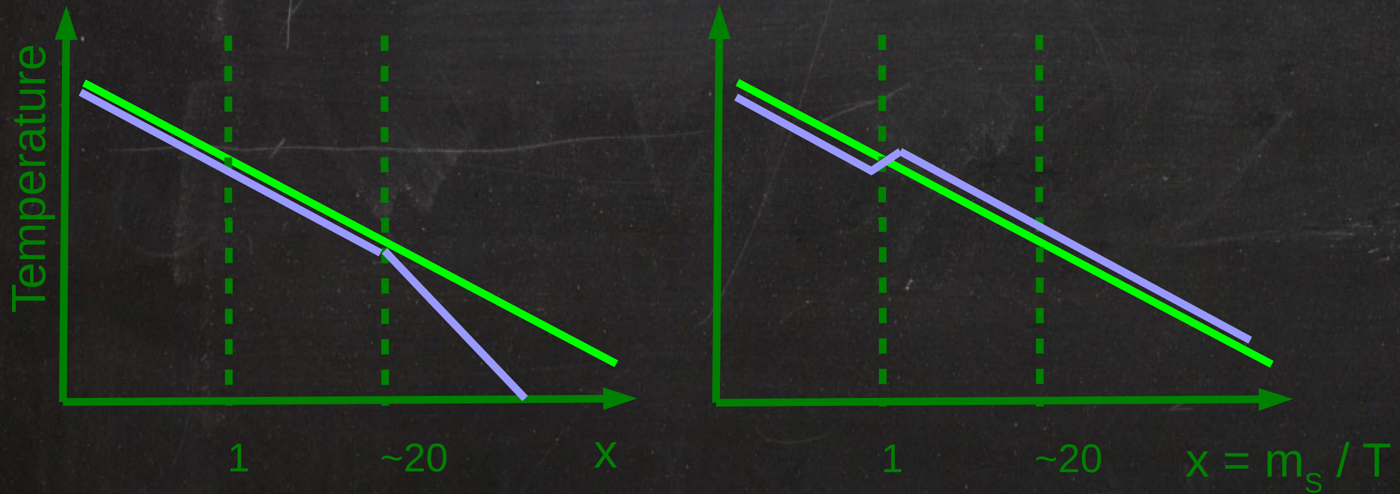
NB, Garcia-Cely & Rosenfeld '15



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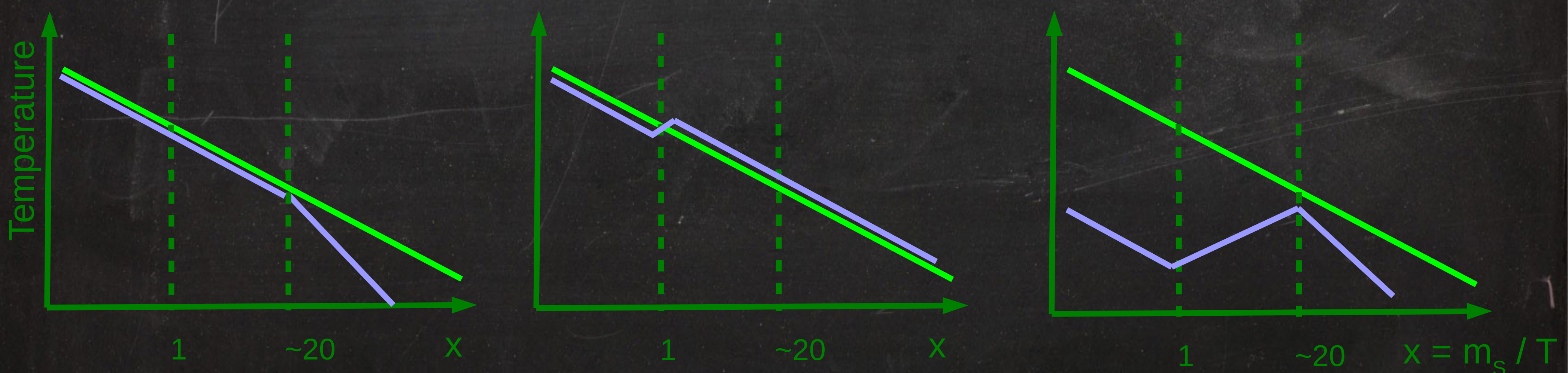
NB, Garcia-Cely & Rosenfeld '15

* DM and SM out of kinetic equilibrium: à la freeze-in

NB, Chu, Garcia-Cely, Hambye & Zaldivar '15

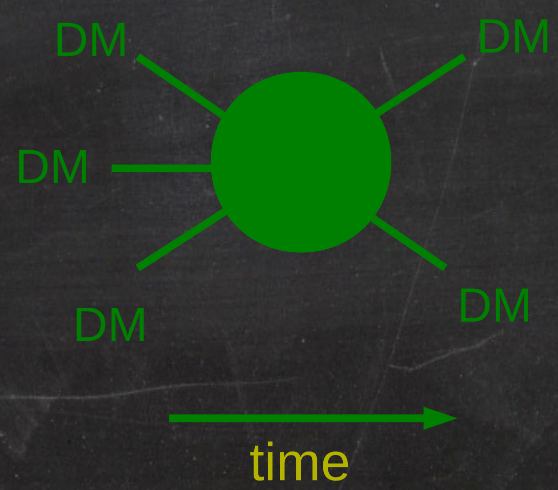


SIMP DM

3→2 annihilations

Hochberg, Kuflik, Volansky & Wacker '14

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



* DM in the MeV range

* Small DM-SM portal

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

SIMP DM

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Hochberg, Kuflik, Volansky & Wacker '14

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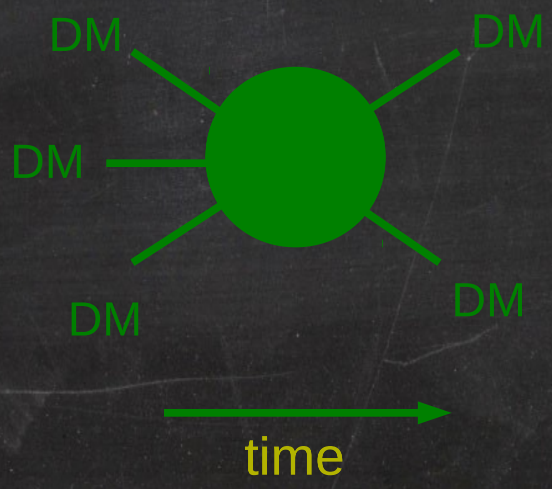


* DM in the MeV range

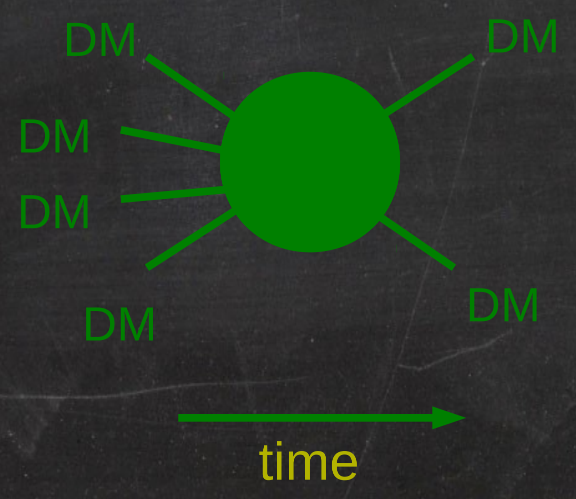
* Small DM-SM portal

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

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

SIMP DM
4→2 annihilations

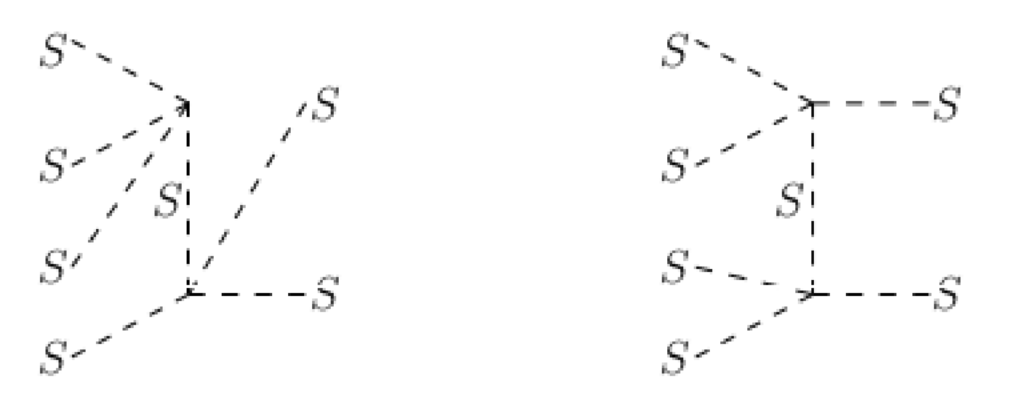
$$\frac{dn}{dt} + 3\,H\,n = -\langle\sigma v^3\rangle_{4\to2}\,\left(n^4 - n^2\,n_{\rm eq}^2\right)$$



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

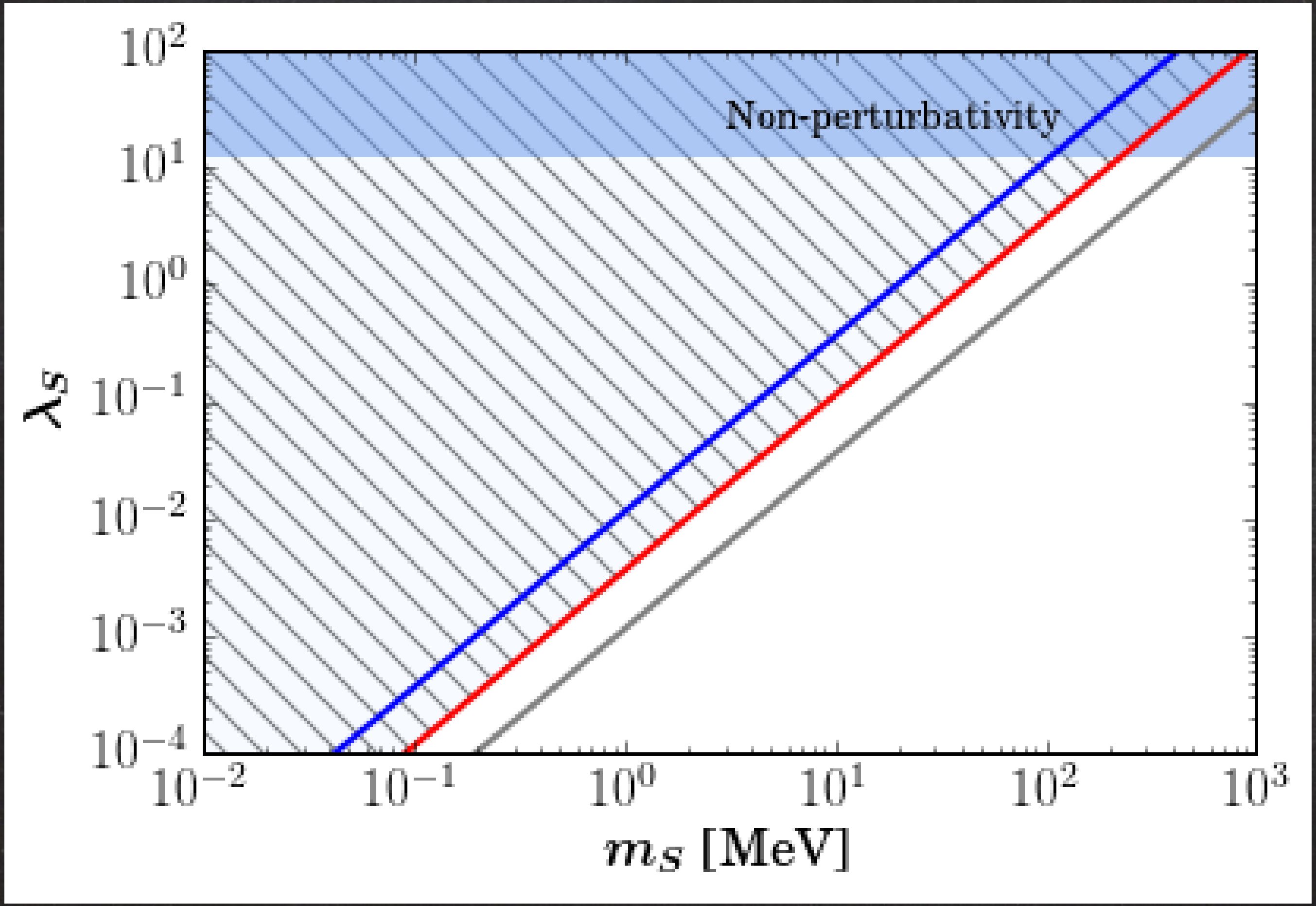
SIMP DM
4→2 annihilations

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



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

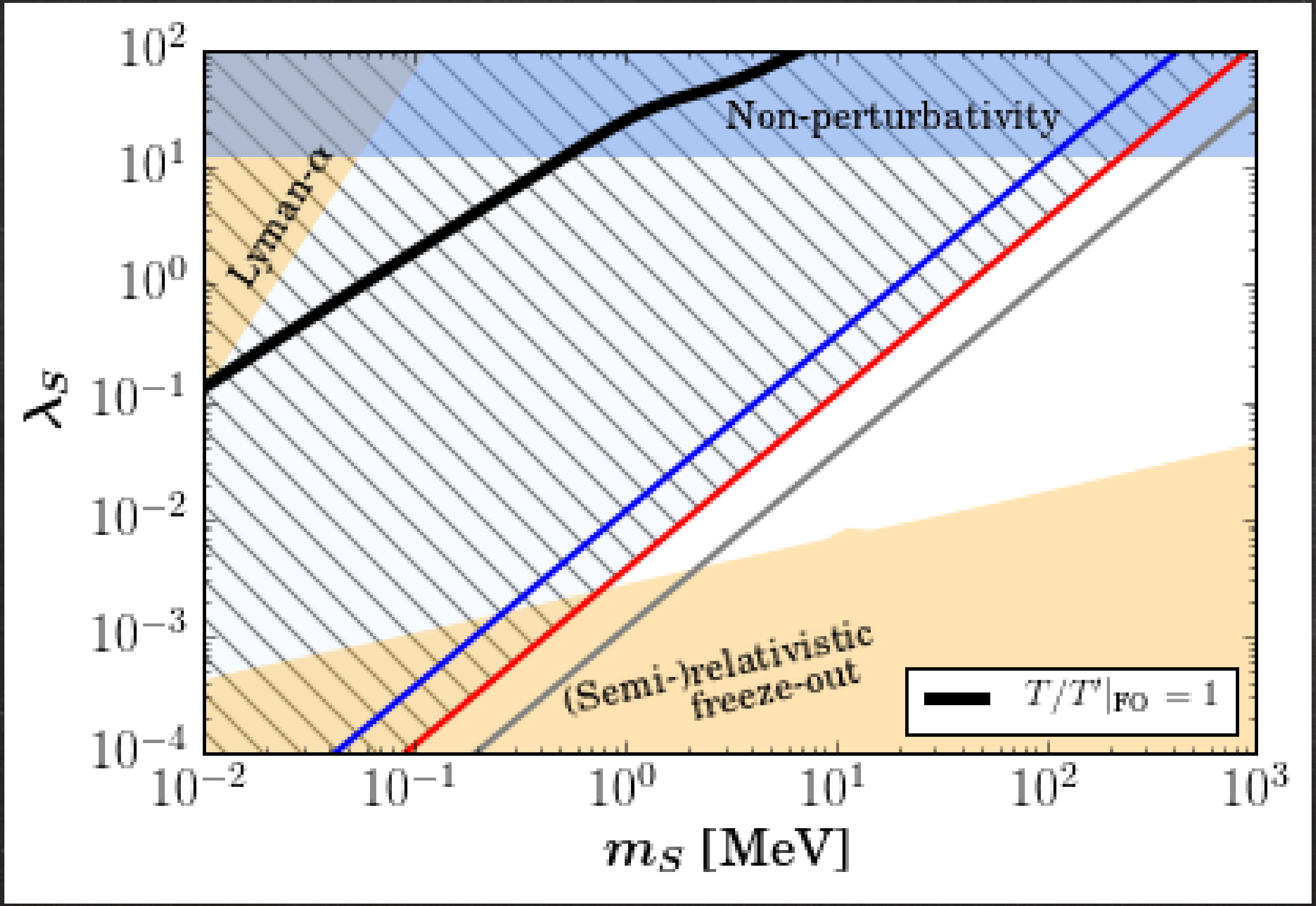
SIMP DM
4→2 annihilations



σ/m [cm²/g]
{ 10
1
0.1

SIMP DM
4→2 annihilations

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



SIMP DM
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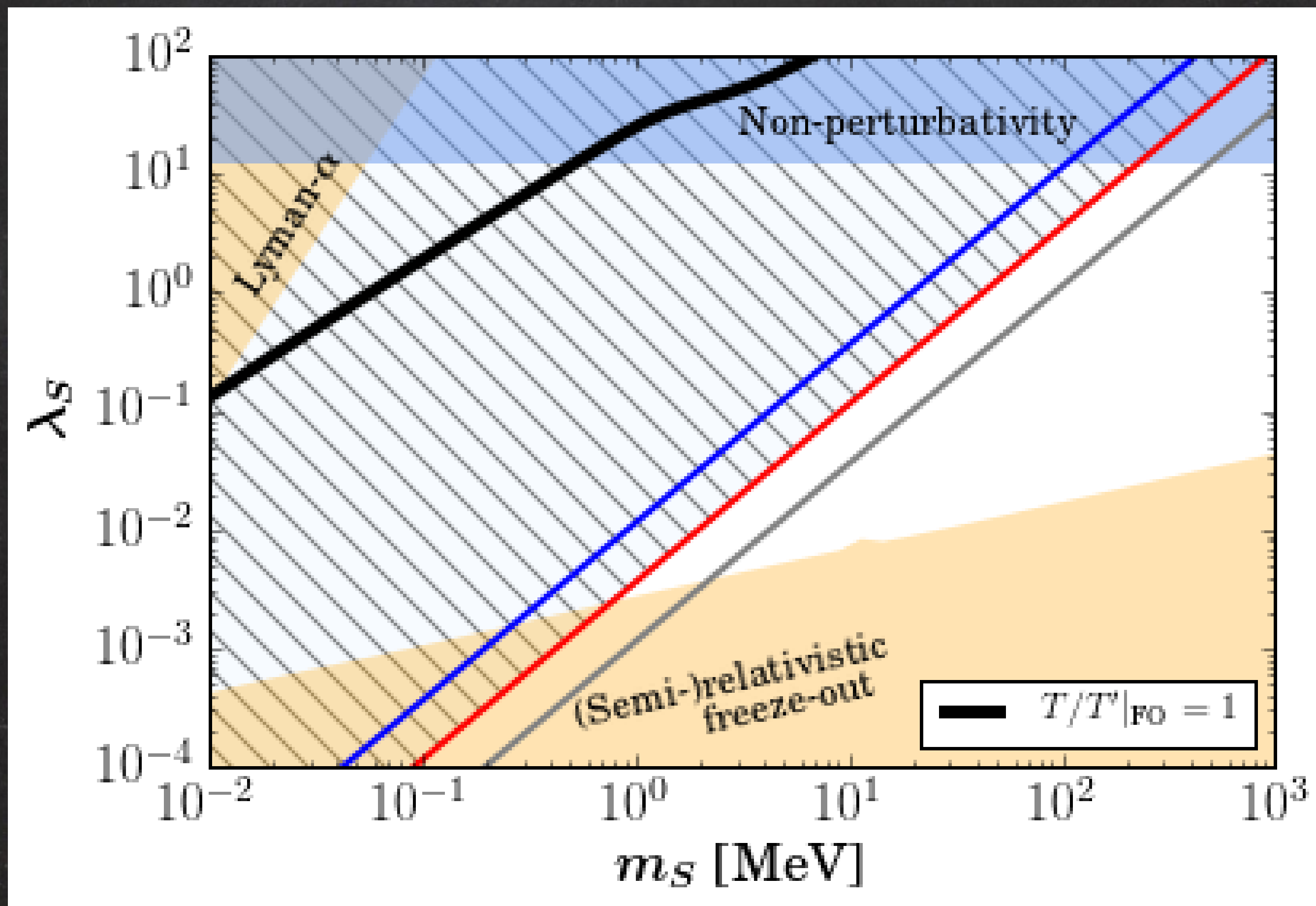

Such light DM in thermal equilibrium with electrons, photons or neutrinos is mostly excluded by BBN and CMB data, and is in tension with structure formation

Hochberg, Kuflik, Volansky & Wacker '14

SIMP DM
4→2 annihilations

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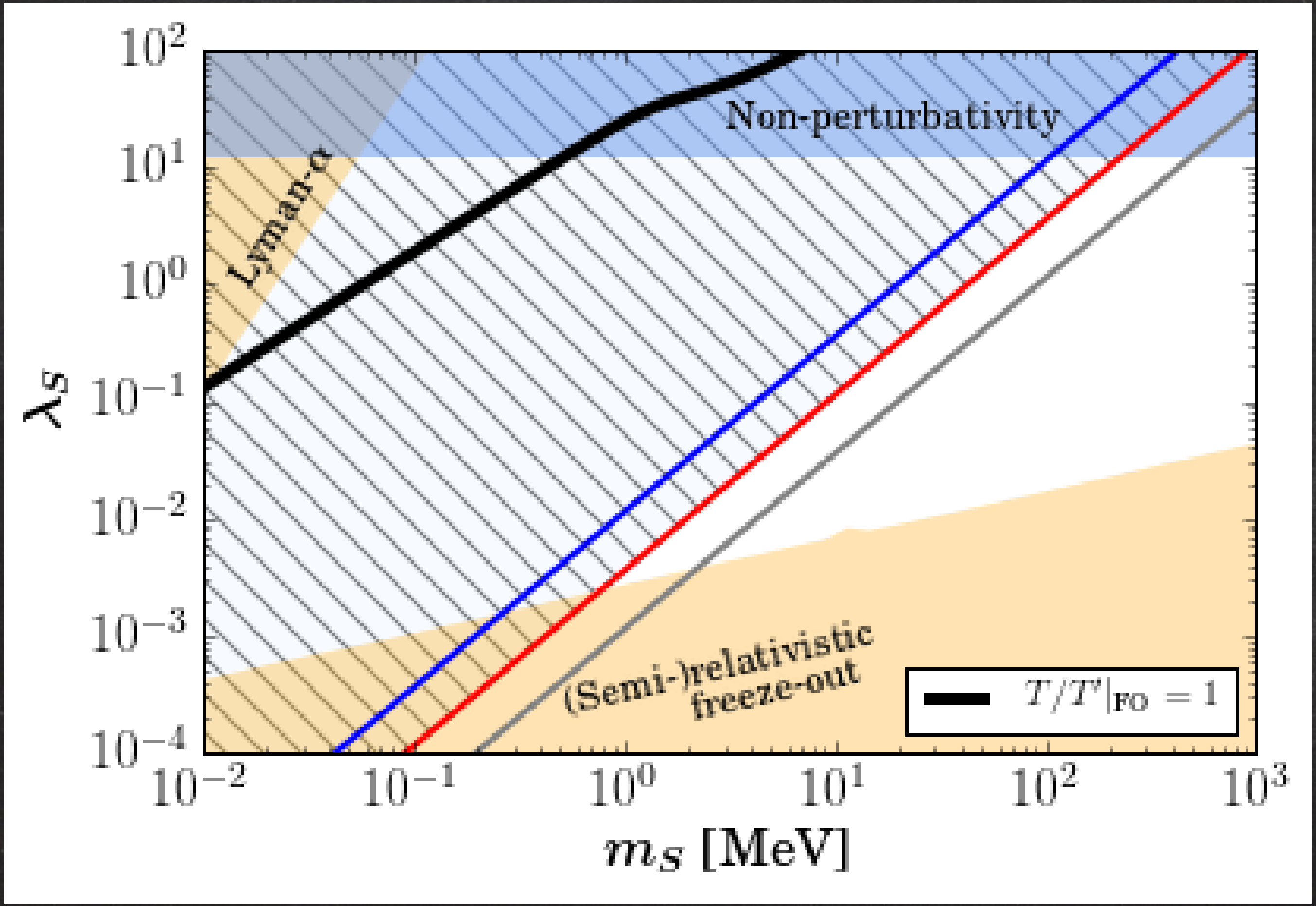


* In general difficult to realize

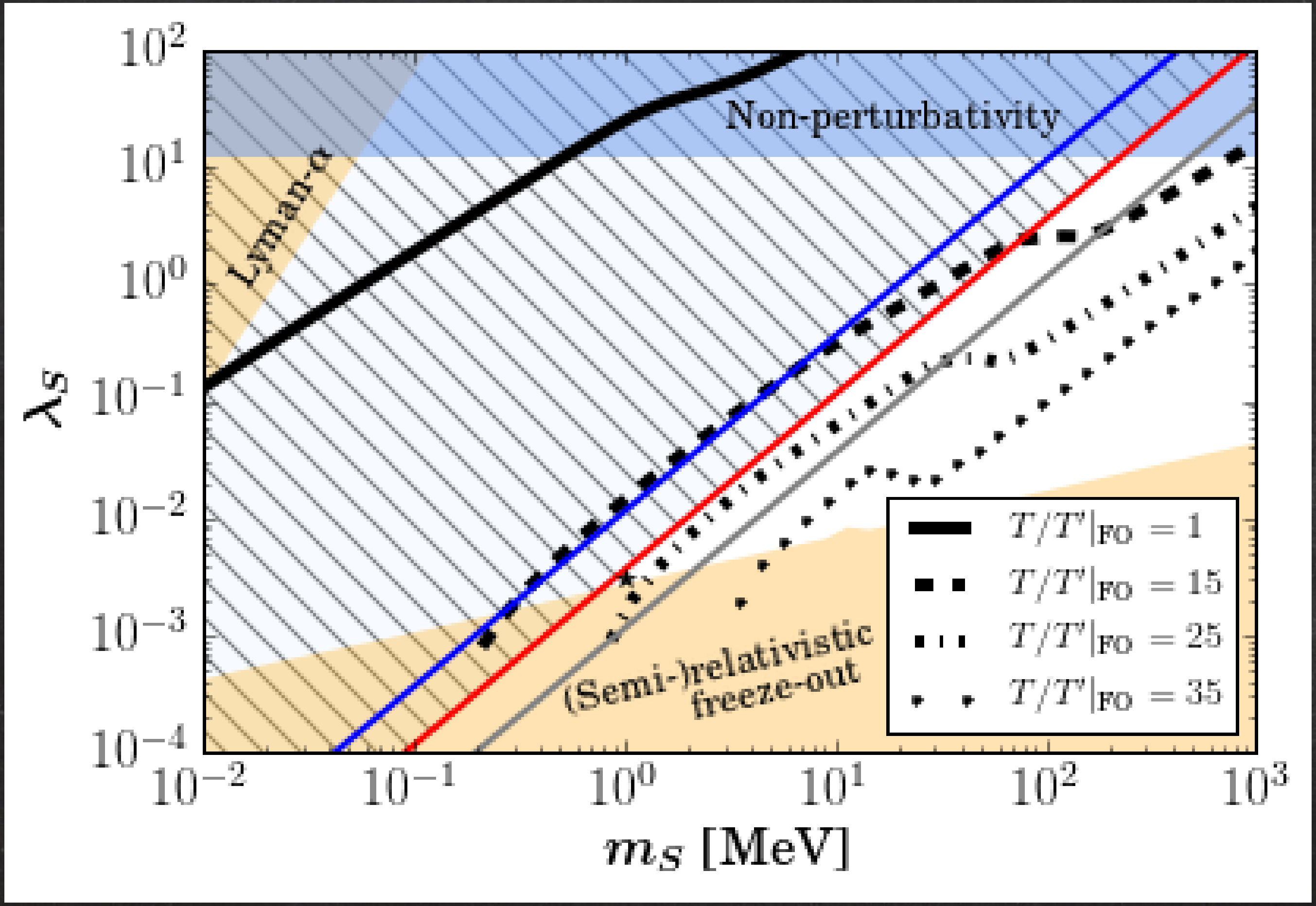
* Impossible in the SSDM

Such light DM in thermal equilibrium with electrons, photons or neutrinos is mostly excluded by BBN and CMB data, and is in tension with structure formation

Hochberg, Kuflik, Volansky & Wacker '14

SIMP DM
4→2 annihilations

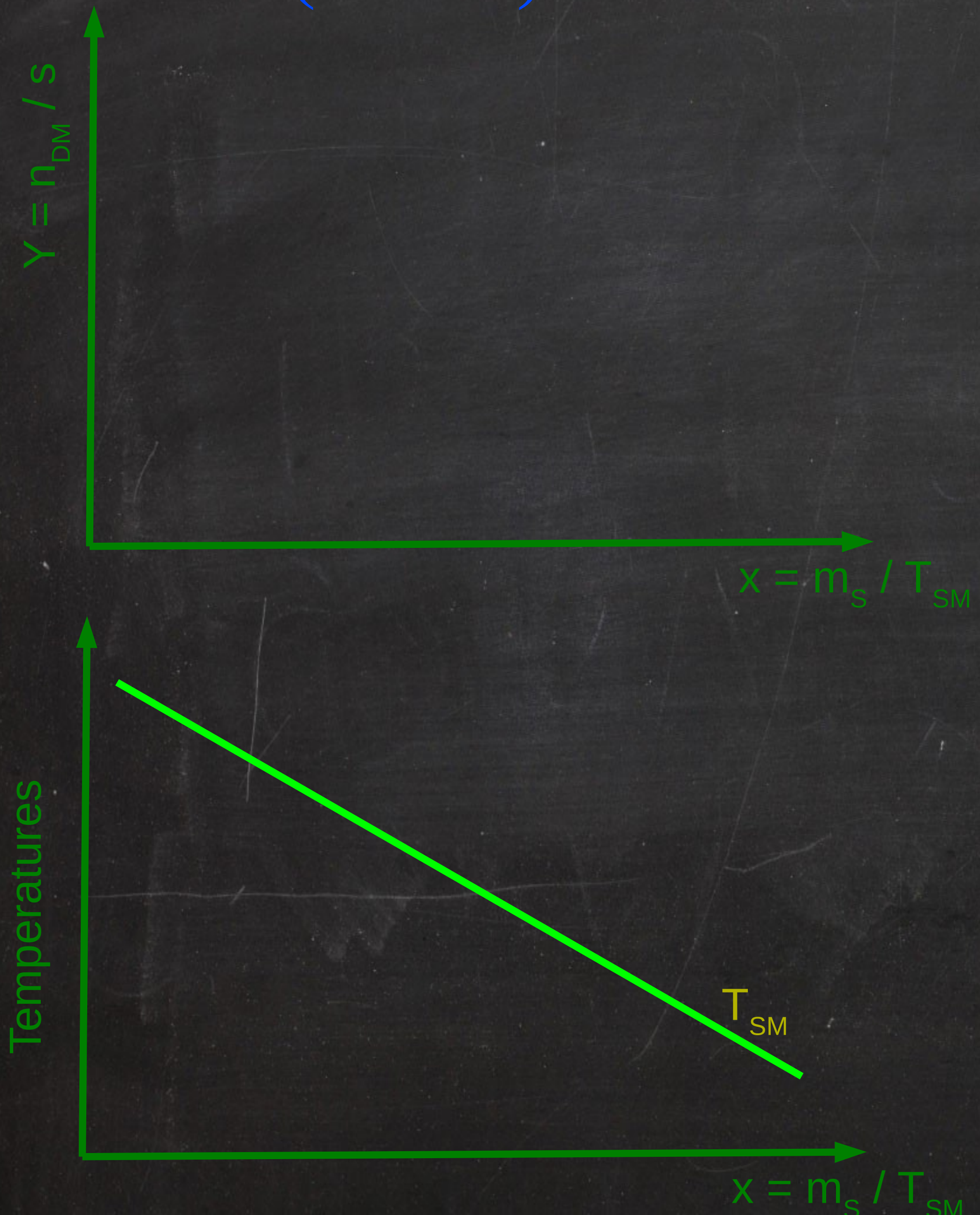
$T_{SM} \neq T_{DM}$ @ DM freeze-out



Possible (but boring) end.

How to produce such a difference of temperatures?

(Non-) Thermal evolution of DM



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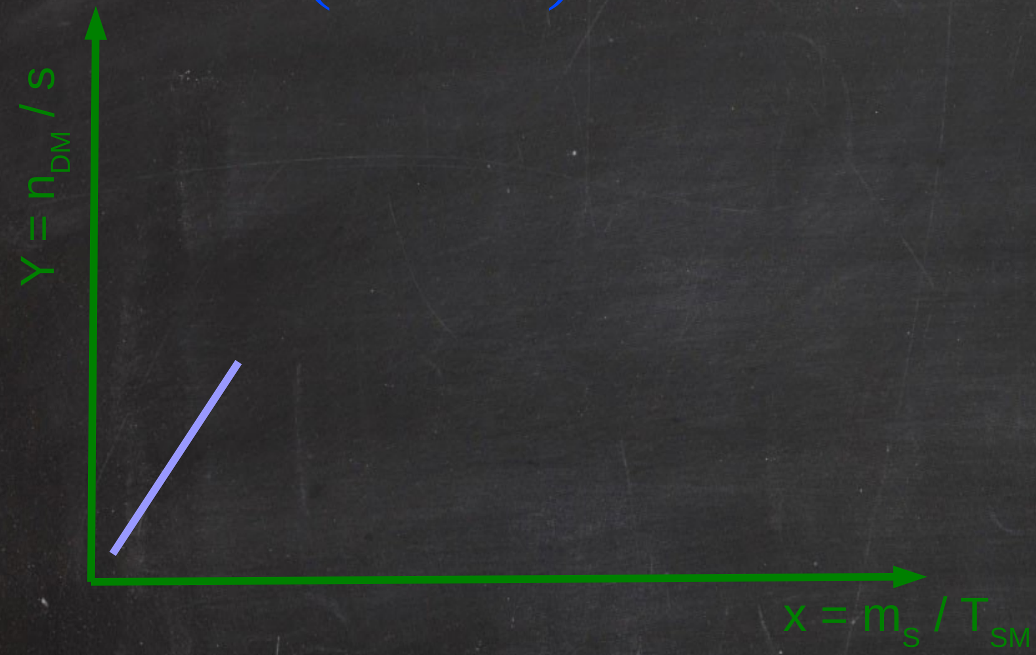
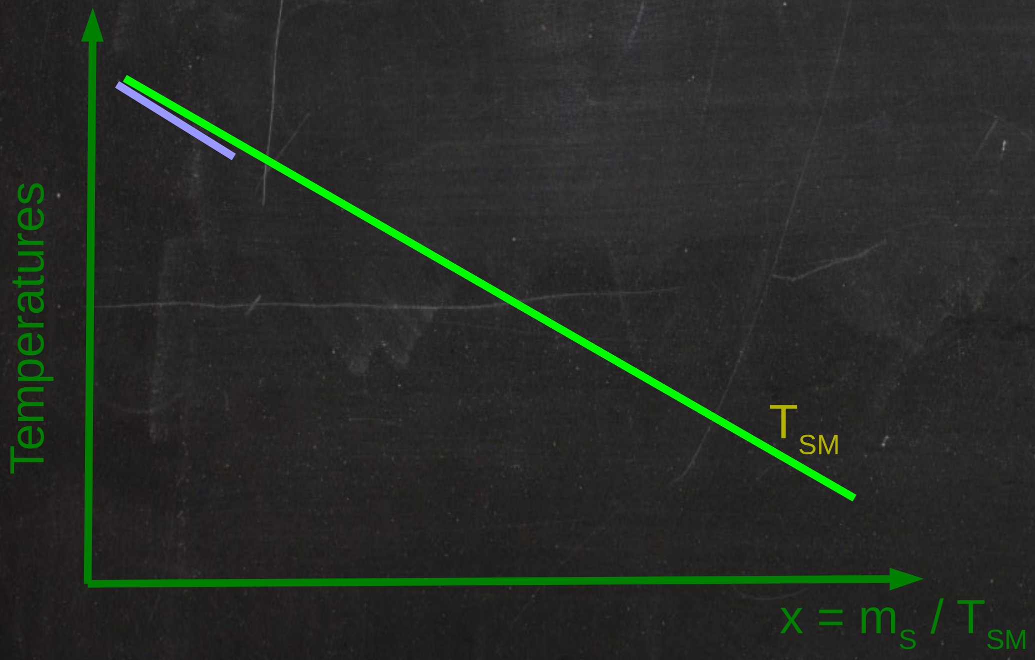
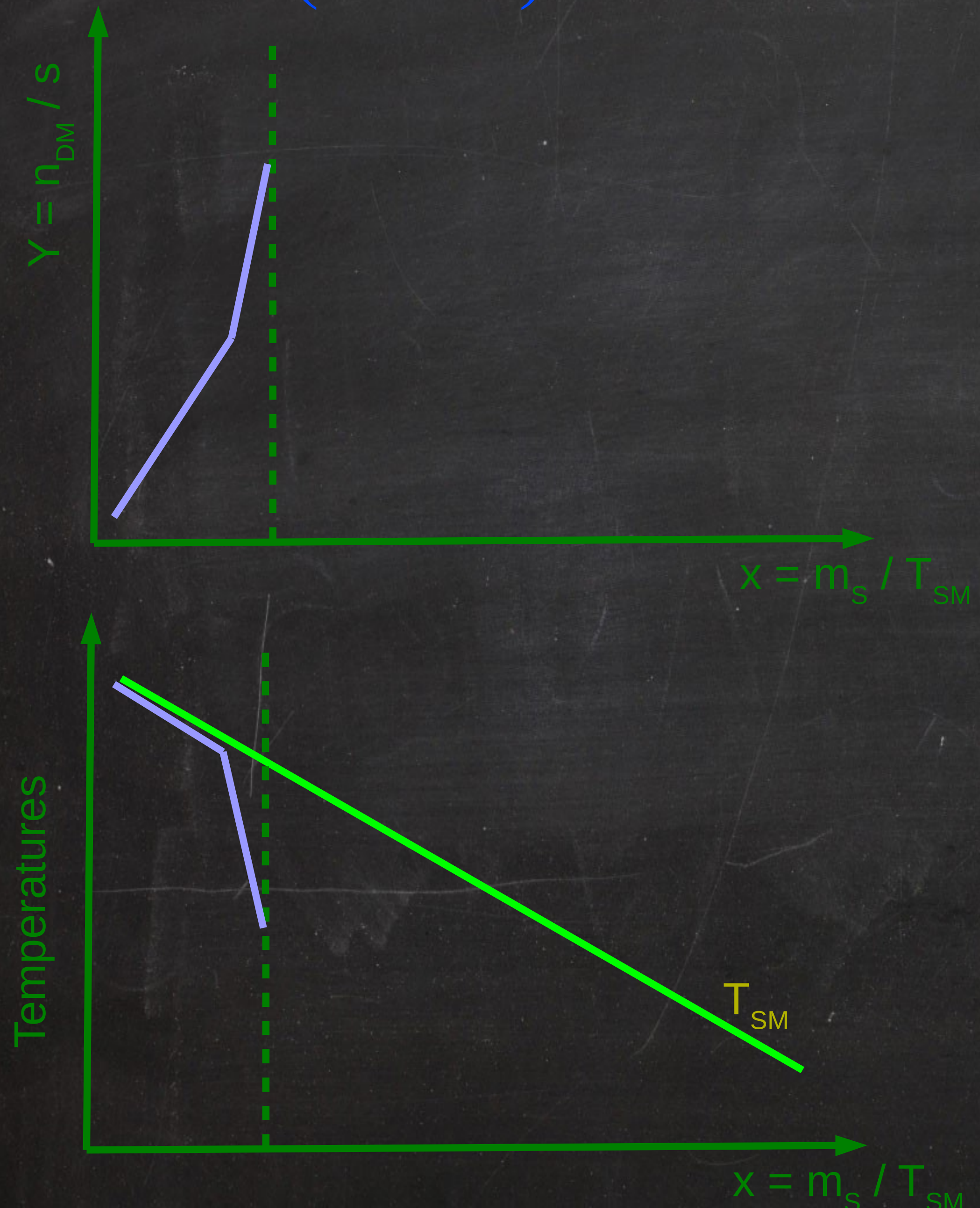




DM Production

* 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



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* DM populates rapidly via
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  Price to pay: Dramatic decrease of T_{DM}

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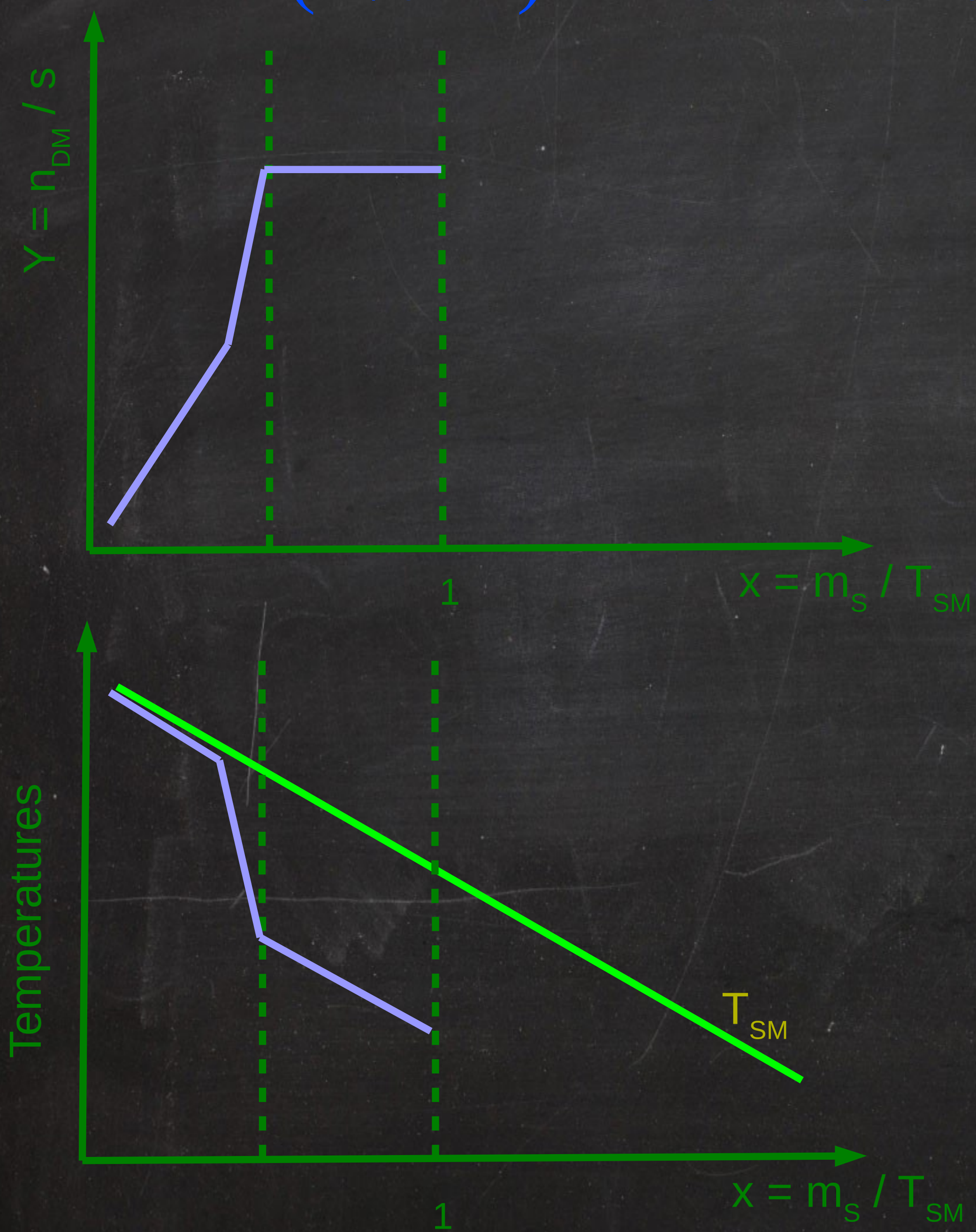

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Thermal Equilibrium

* Chemical equilibrium **2 ↔ 4**

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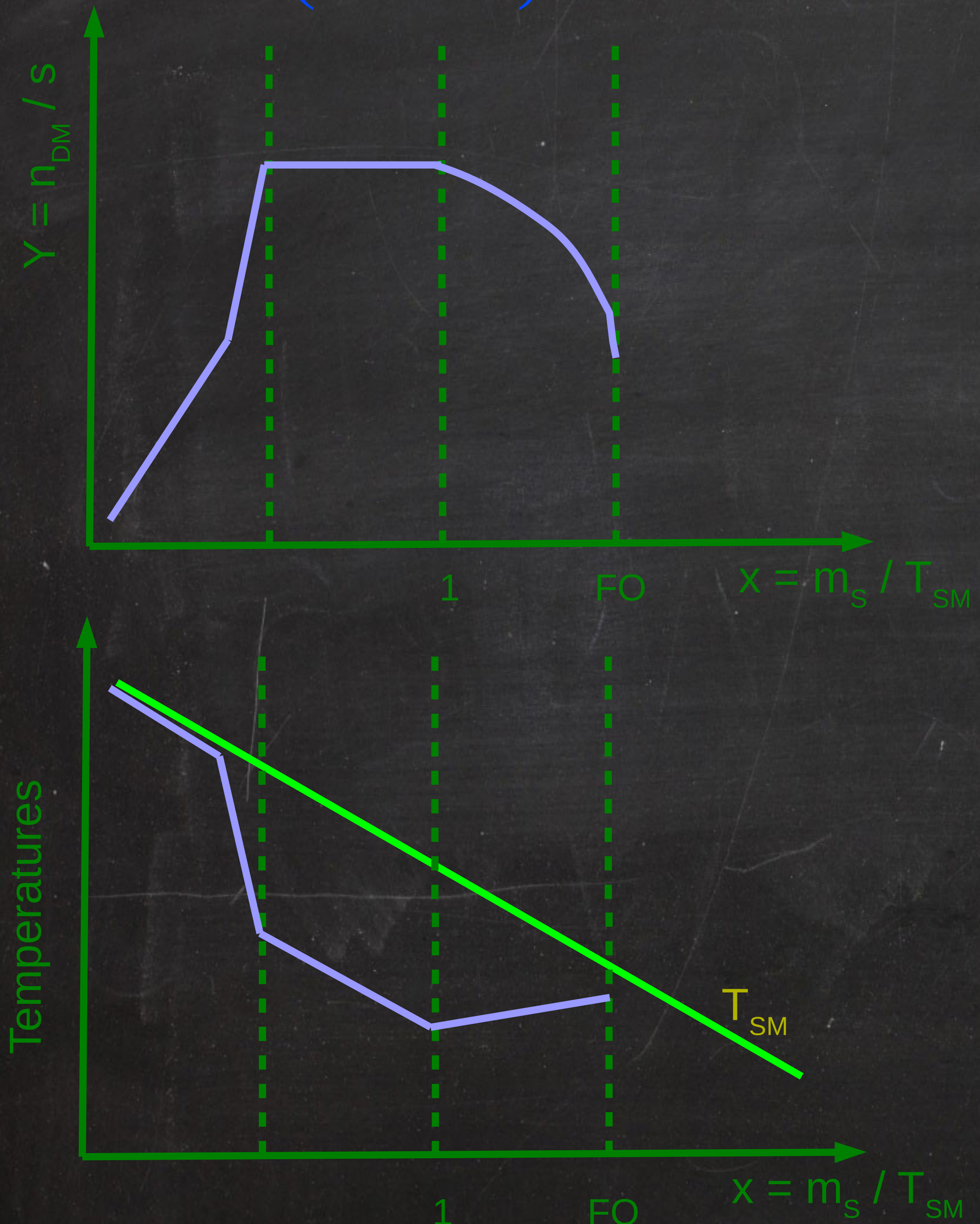

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<u>Thermal Equilibrium</u>

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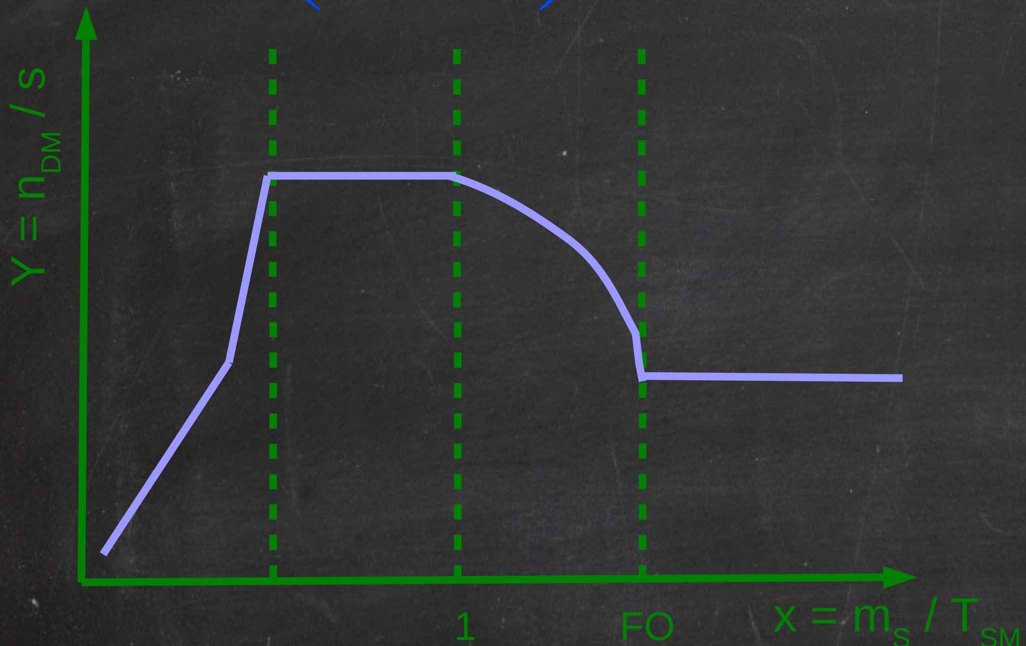
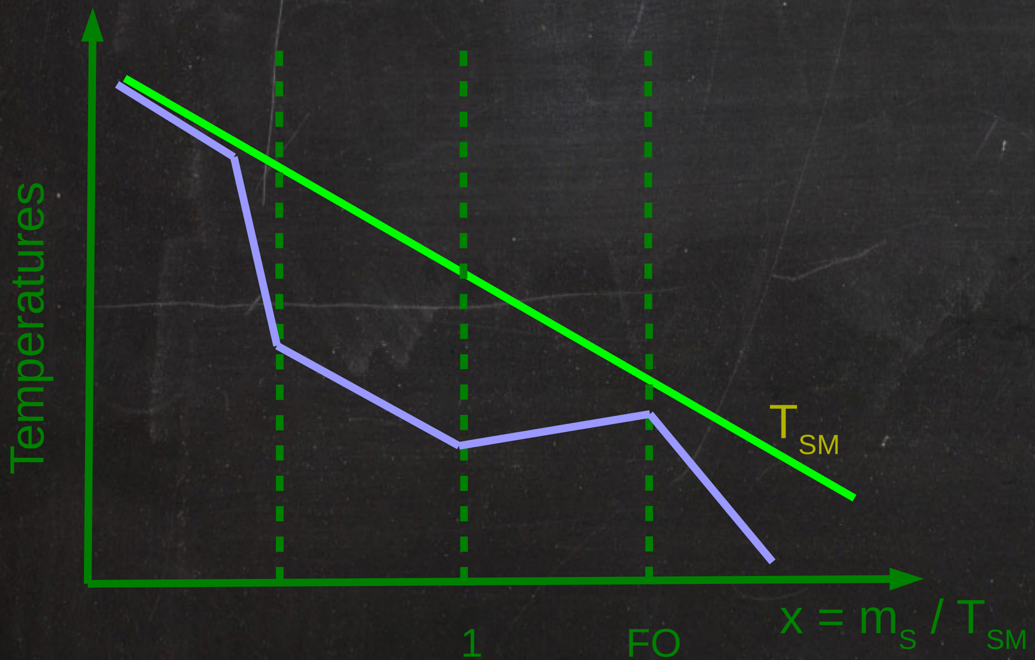
<u>DM Annihilation</u>

* Freeze-out **4 → 2**

(Non-) Thermal evolution of DM





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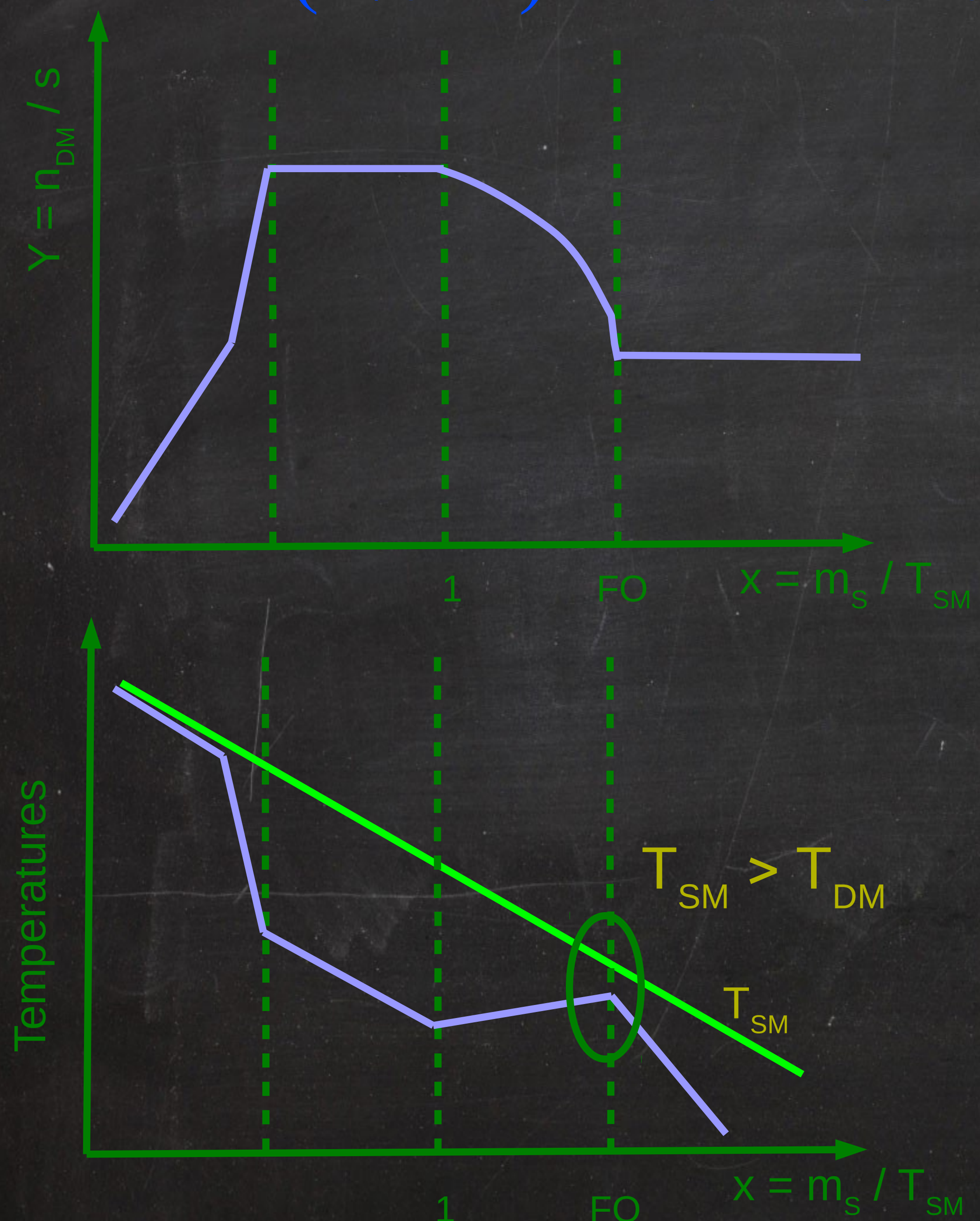
<u>DM Annihilation</u>

* Freeze-out **4** → **2**

<u>After the Freeze-out</u>

* Relic abundance
  Non-relativistic DM cools down faster

(Non-) Thermal evolution of DM



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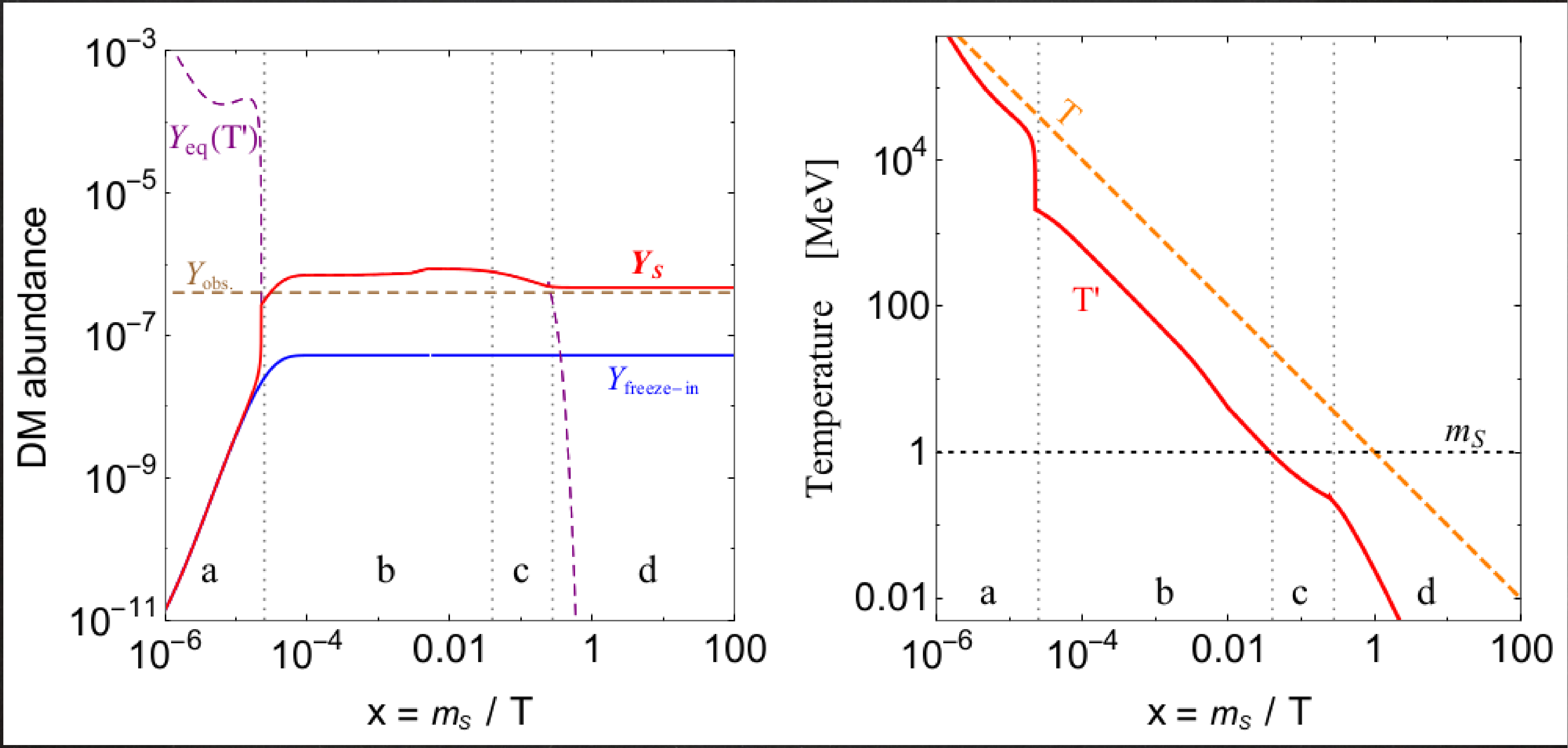
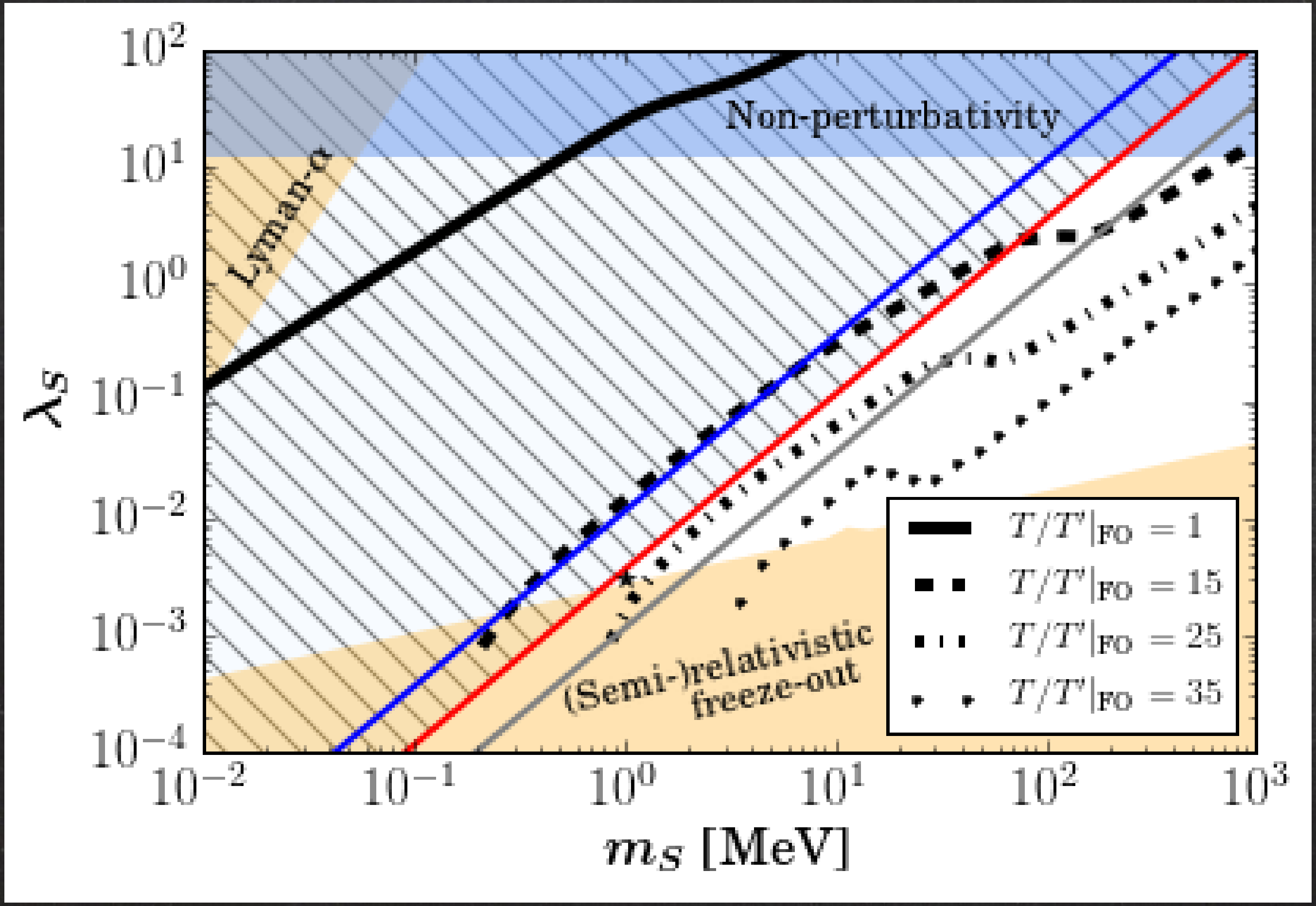
After the Freeze-out

* Relic abundance
  Non-relativistic DM cools down faster

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



SIMP DM
4→2 annihilations



SIMP DM
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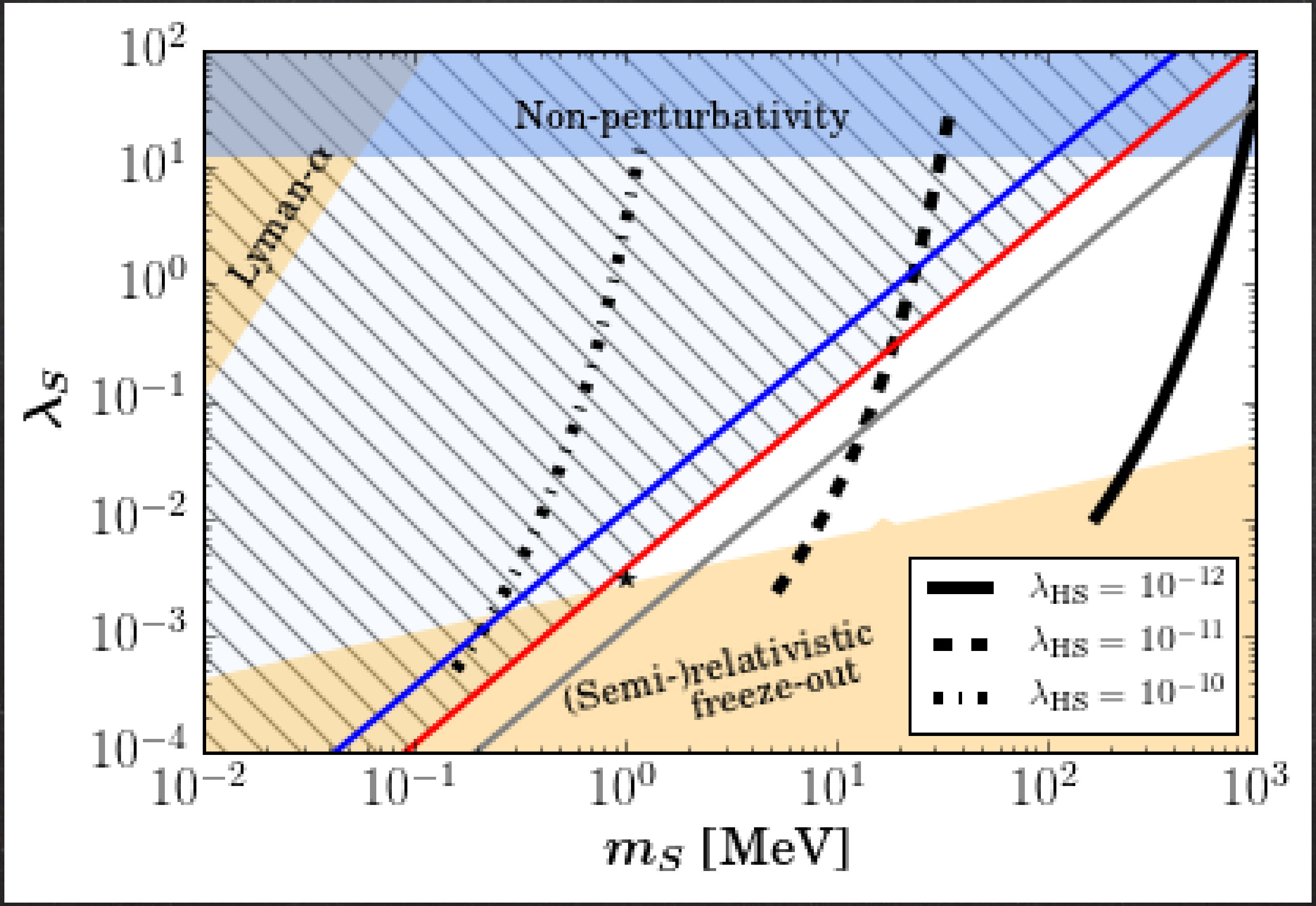

Conclusions

Small-scale anomalies

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

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Small-scale anomalies

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Self-Interacting

Dark Matter

$$\frac{\sigma_{SS\to SS}}{m_S} \sim 1\,\mathrm{cm}^2/\mathrm{g}$$

Conclusions

Small-scale anomalies
* Cusp-vs-core
* Too-big-to-fail

→

Self-Interacting
Dark Matter
$$\frac{\sigma_{SS\to SS}}{m_S} \sim 1\,\mathrm{cm}^2/\mathrm{g}$$

←

$m_S \sim 100$ MeV
$\lambda_S \sim 1$
$\lambda_{HS} < 10^{-3}$

Conclusions

Small-scale anomalies
* Cusp-vs-core
* Too-big-to-fail

Self-Interacting
Dark Matter

$$\frac{\sigma_{SS\to SS}}{m_S} \sim 1\,\mathrm{cm}^2/\mathrm{g}$$

$m_S \sim 100$ MeV
$\lambda_S \sim 1$
$\lambda_{HS} < 10^{-3}$

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 } DM self-interactions
  $\lambda_S \sim 1$
  $\lambda_{HS} < 10^{-3}$ → Invisible Higgs decay

* 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!