# The SIMPlest Dark Matter Model

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) 01, 006
NB, J. Pradler & X. Chu: arXiv:1612.soon

**Nicolás BERNAL**
Universidad Antonio Nariño

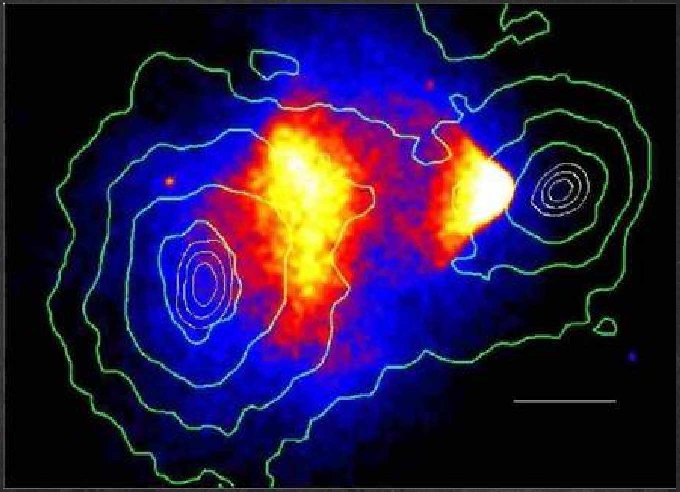
UNIVERSIDAD
ANTONIO NARIÑO

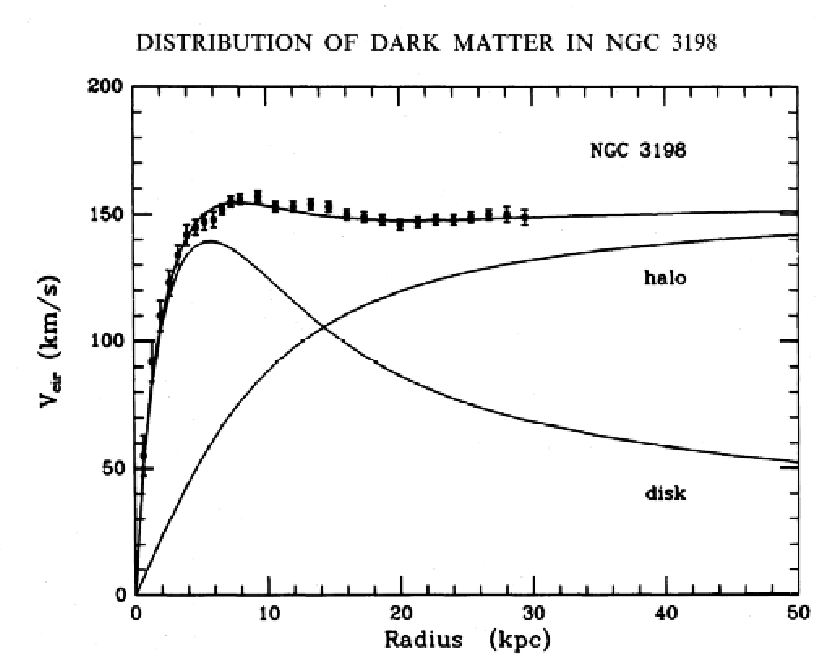
November 28th, 2016

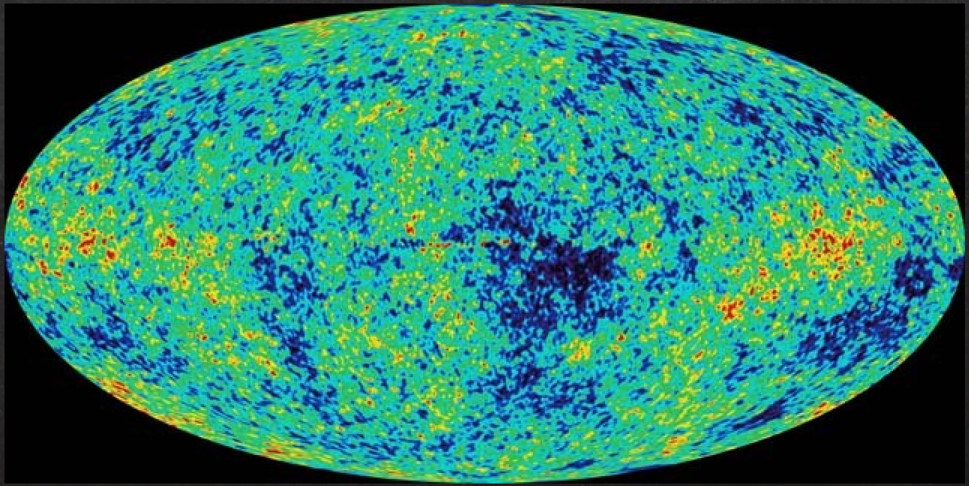
# Evidences for Dark Matter

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

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



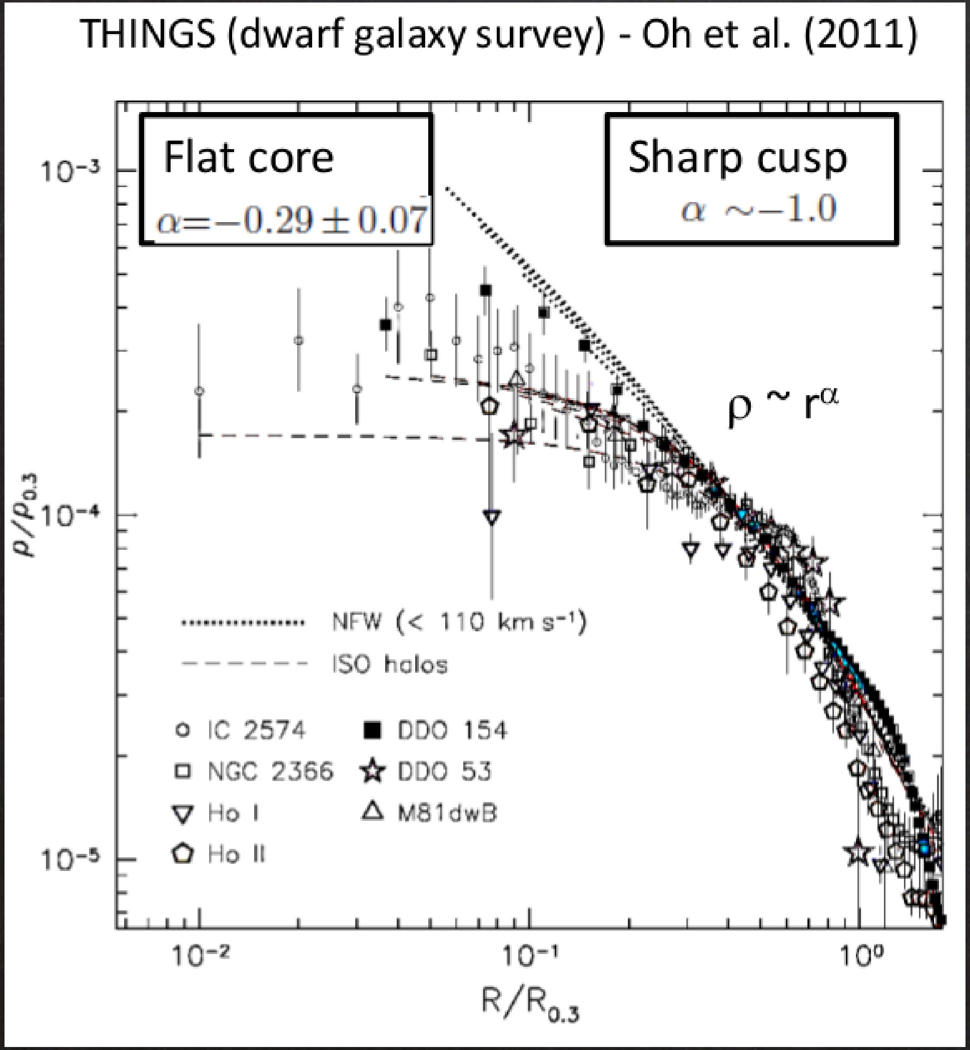




F. Iocco on Thursday! :-)

# Cold Dark Matter in Trouble

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

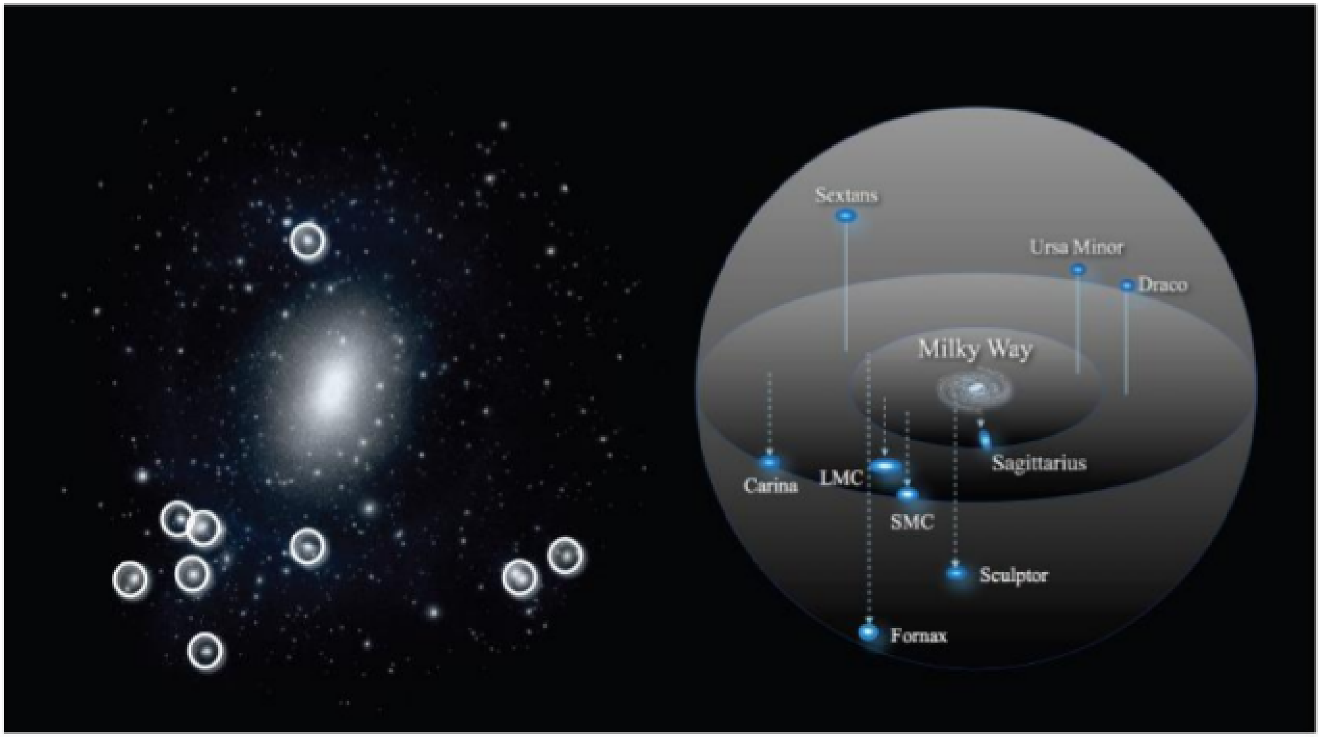

THINGS (dwarf galaxy survey) - Oh et al. (2011)

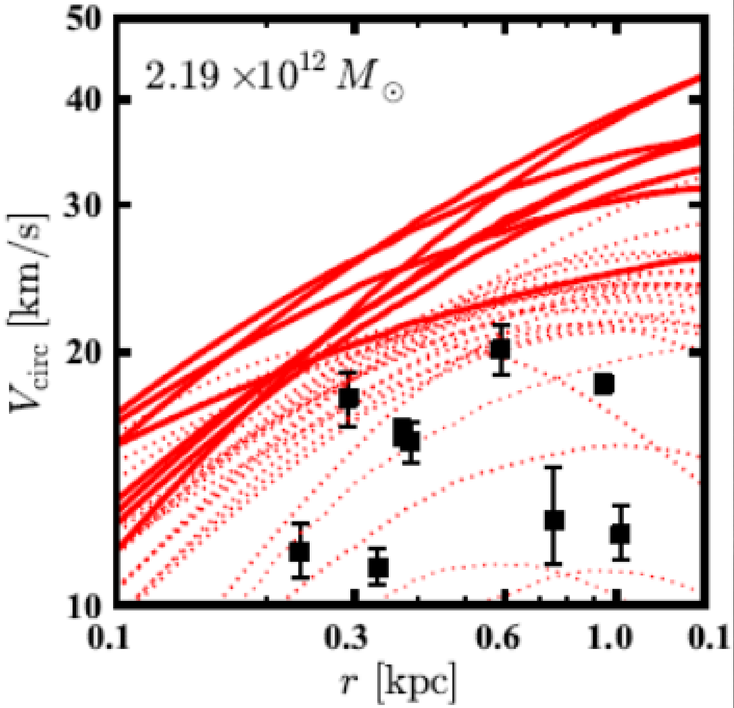
- Field dwarfs
- Satellite dwarfs galaxies
- Low surface brightness galaxies (LSBs)
- Clusters

# 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...)

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- Dark Matter

  DM may not be **collisionless**

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

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

# Small-scale problems → Self-interacting DM

Small-scale problems:
- Core-vs-cusp
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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: $\frac{\sigma_{\rm scatter}}{m_X} \lesssim 1\ \mathrm{cm}^2/\mathrm{g}\,.$

# 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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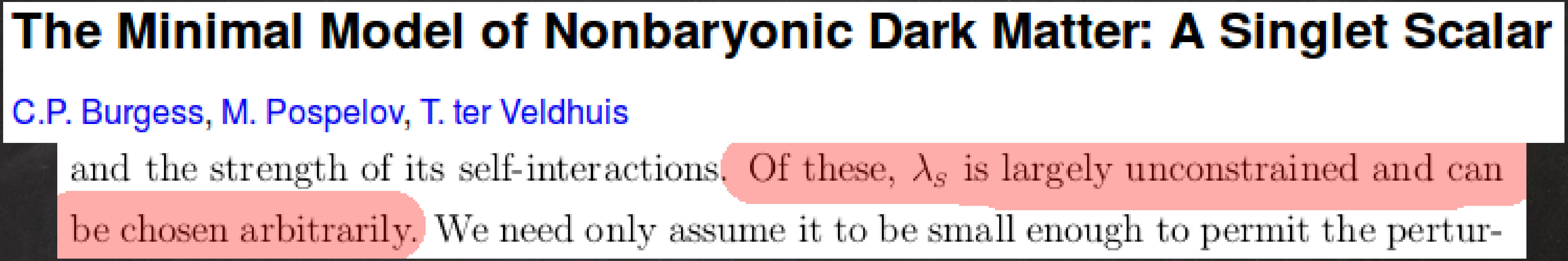

**The Minimal Model of Nonbaryonic Dark Matter: A Singlet Scalar**

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

and the strength of its self-interactions. Of these, $\lambda_s$ 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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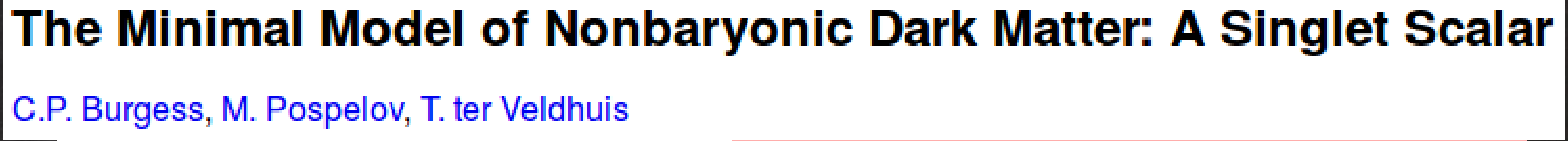
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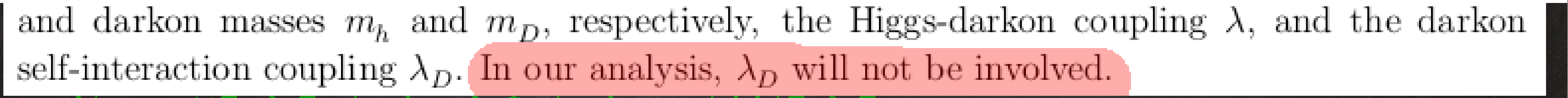
and darkon masses $m_h$ and $m_D$, respectively, the Higgs-darkon coupling $\lambda$, and the darkon self-interaction coupling $\lambda_D$. In our analysis, $\lambda_D$ will not be involved.

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

3 free parameters:

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

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

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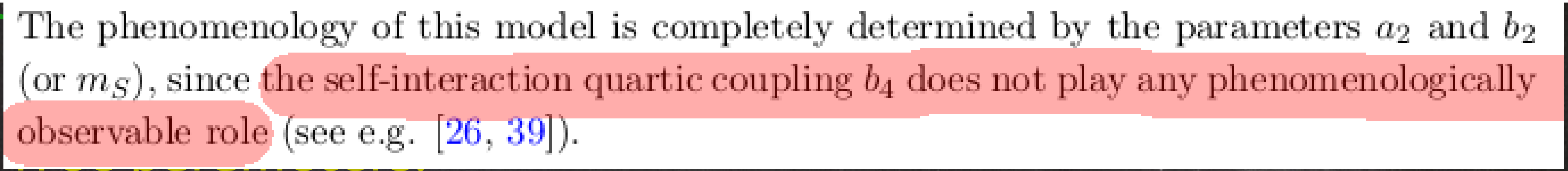

The phenomenology of this model is completely determined by the parameters $a_2$ and $b_2$ (or $m_S$), since the self-interaction quartic coupling $b_4$ does not play any phenomenologically observable role (see e.g. [26, 39]).

3

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

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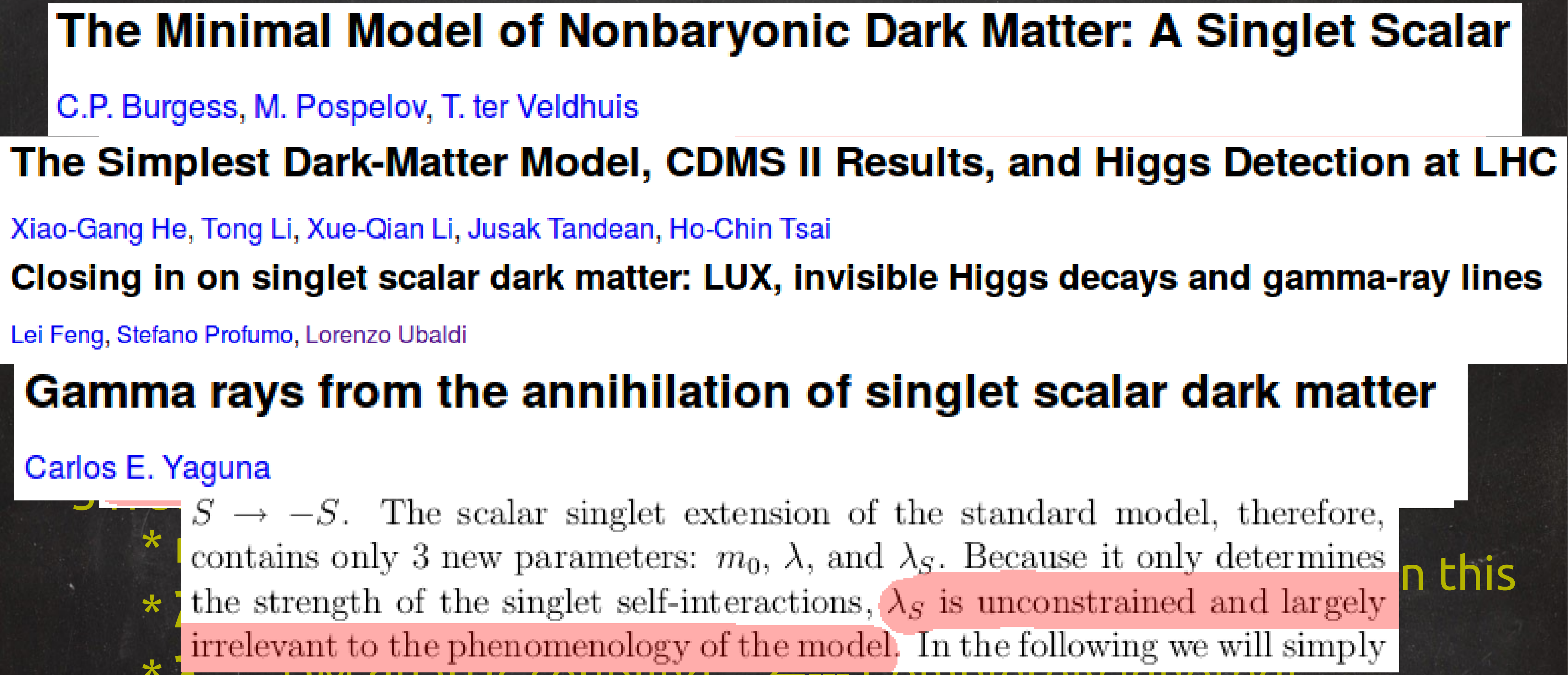

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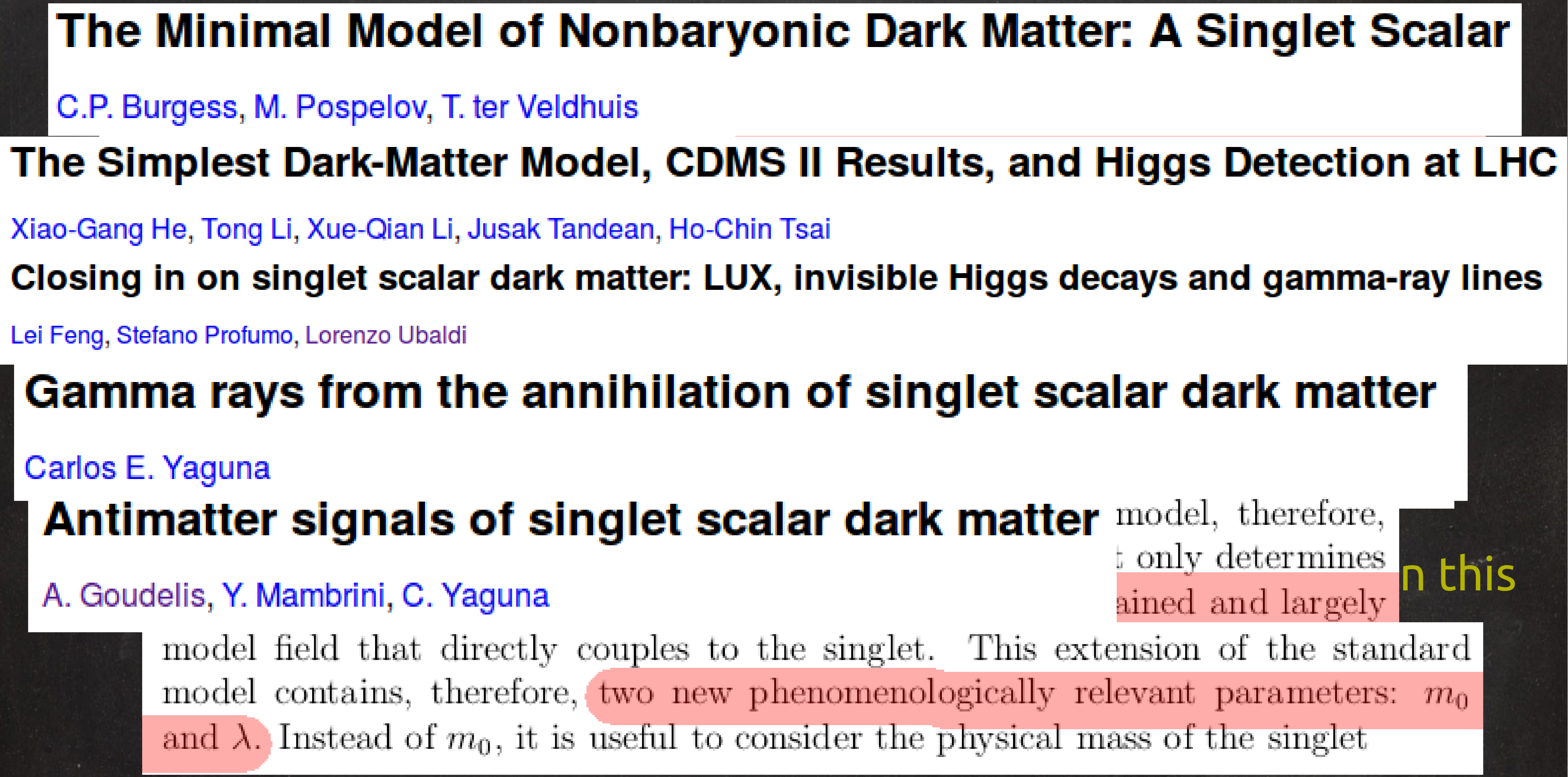
$S \to -S$. The scalar singlet extension of the standard model, therefore, contains only 3 new parameters: $m_0$, $\lambda$, and $\lambda_S$. Because it only determines the strength of the singlet self-interactions, $\lambda_S$ is unconstrained and largely irrelevant to the phenomenology of the model.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

n this

- $\lambda_s$ DM quartic coupling ←--- Completely ignored!



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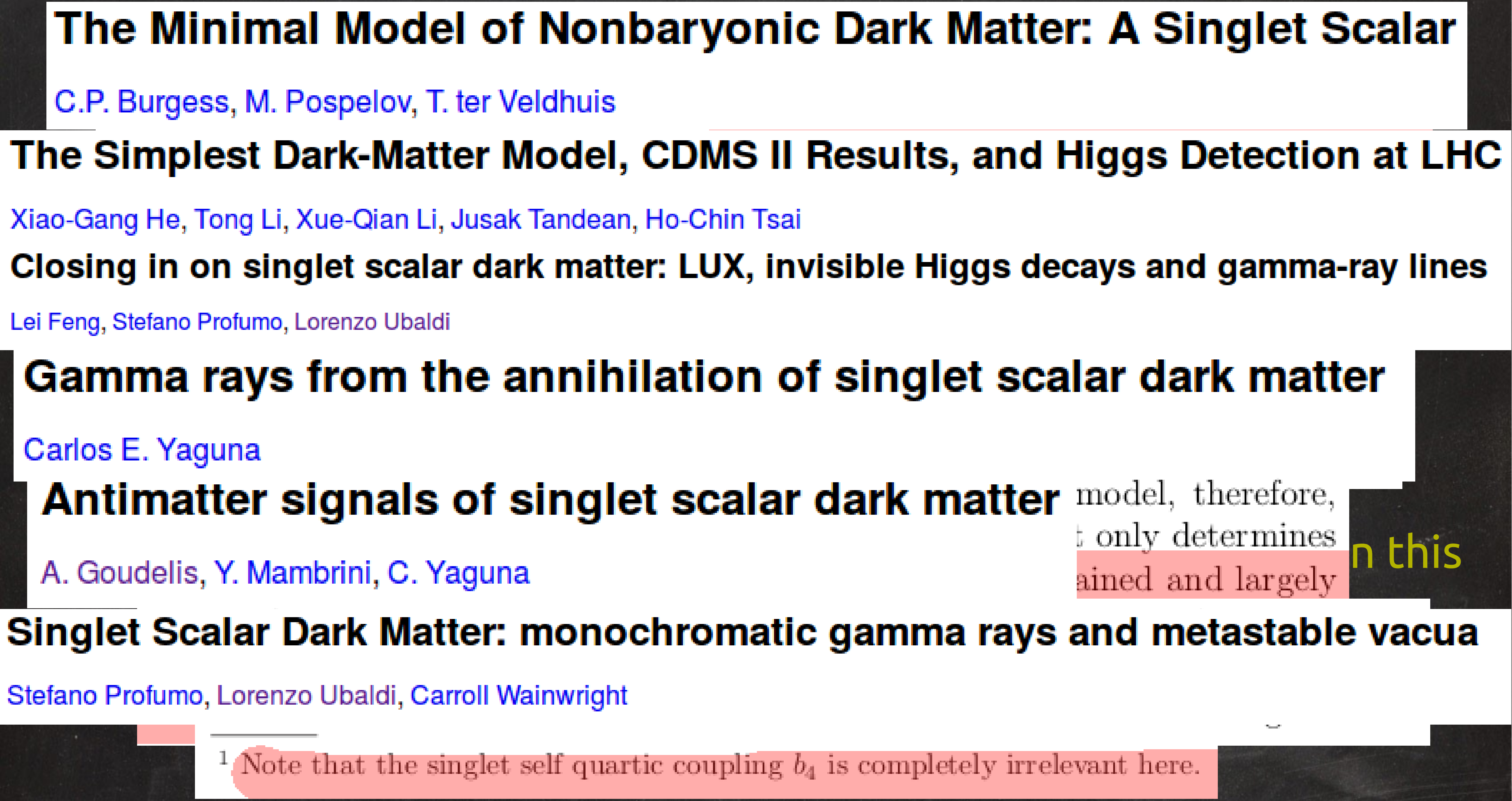
model field that directly couples to the singlet. This extension of the standard model contains, therefore, two new phenomenologically relevant parameters: $m_0$ and $\lambda$. Instead of $m_0$, it is useful to consider the physical mass of the singlet



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### Singlet Scalar Dark Matter: monochromatic gamma rays and metastable vacua

Stefano Profumo, Lorenzo Ubaldi, Carroll Wainwright

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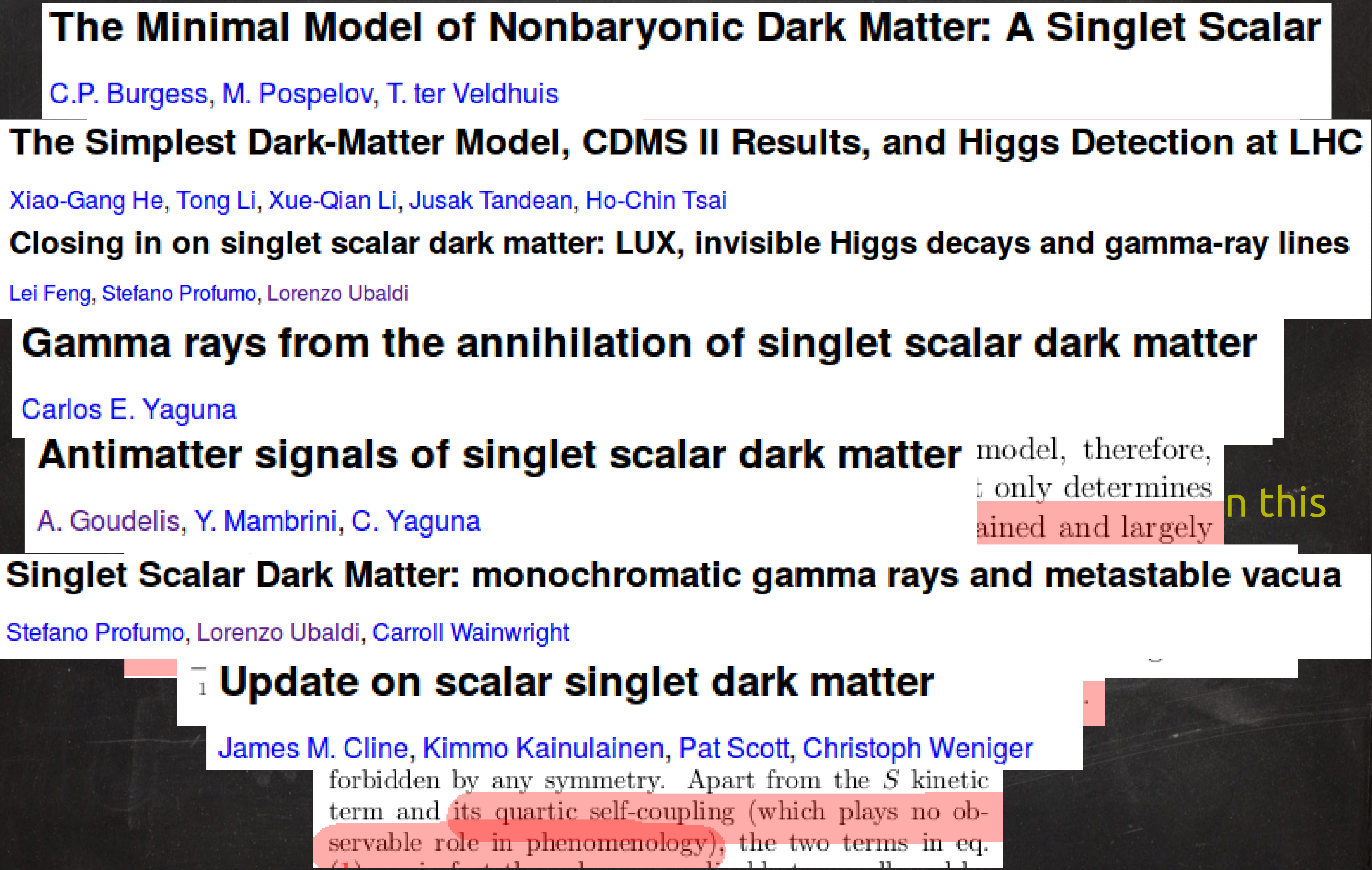
[1] Note that the singlet self quartic coupling $b_4$ is completely irrelevant here.



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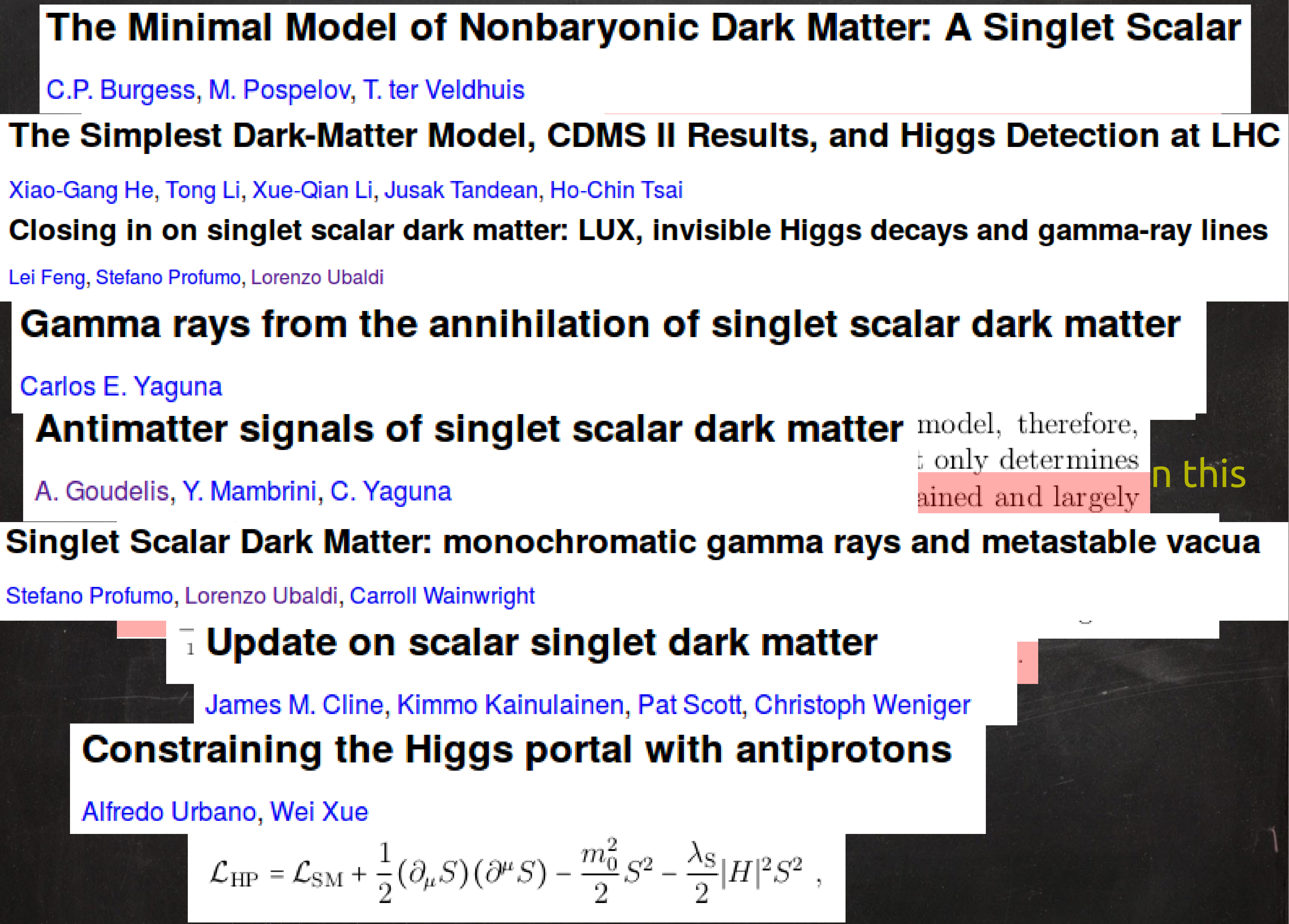
forbidden by any symmetry. Apart from the $S$ kinetic term and its quartic self-coupling (which plays no observable role in phenomenology), the two terms in eq.



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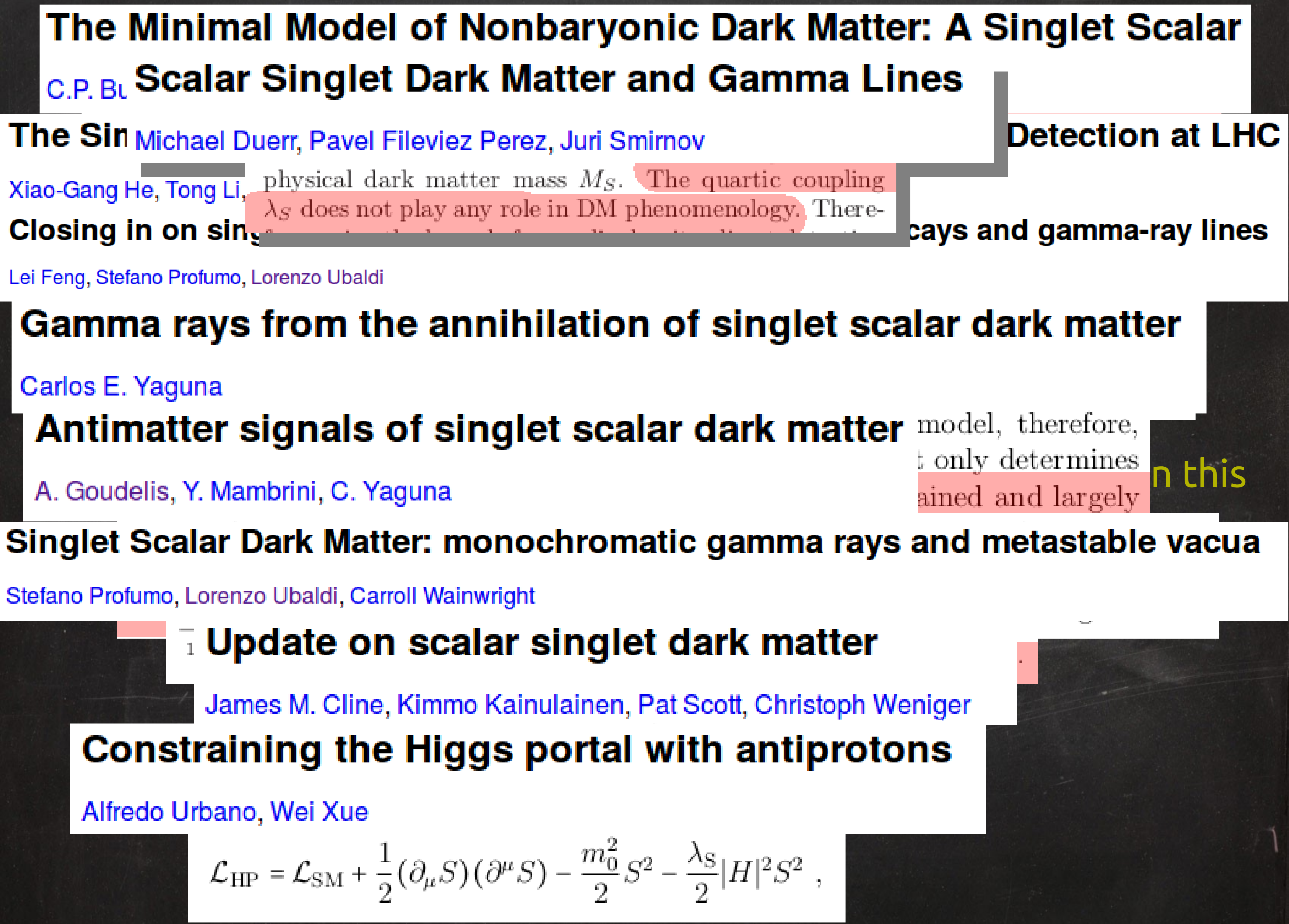
$$\mathcal{L}_{\rm HP} = \mathcal{L}_{\rm SM} + \frac{1}{2}(\partial_\mu S)(\partial^\mu S) - \frac{m_0^2}{2}S^2 - \frac{\lambda_S}{2}|H|^2 S^2 \ ,$$



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**The Sin Detection at LHC**

Xiao-Gang He, Tong Li,

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

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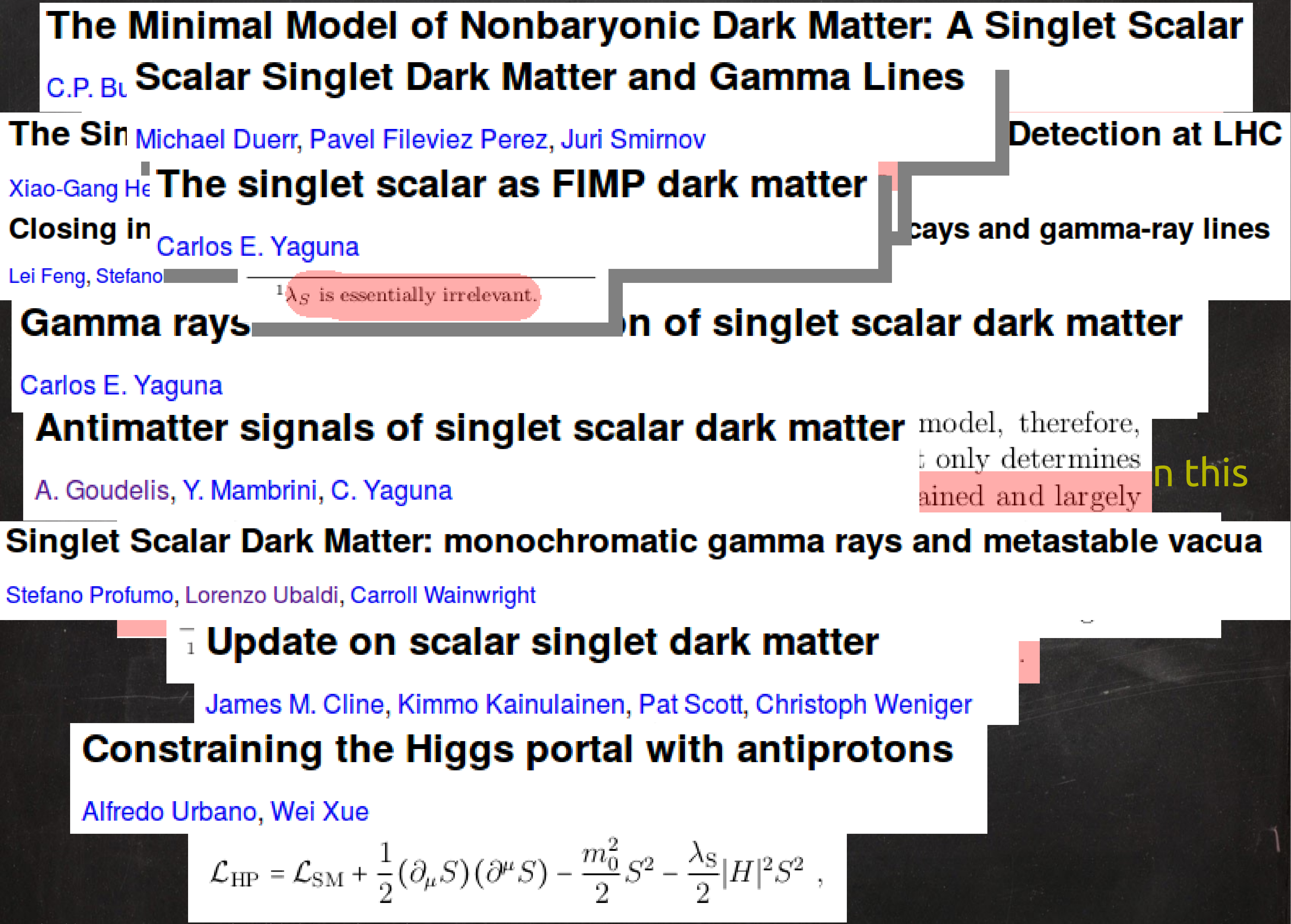

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**Closing in** ... **cays and gamma-ray lines**

Lei Feng, Stefano

[1] $\lambda_S$ is essentially irrelevant.

**Gamma rays** ... **n of singlet scalar dark matter**

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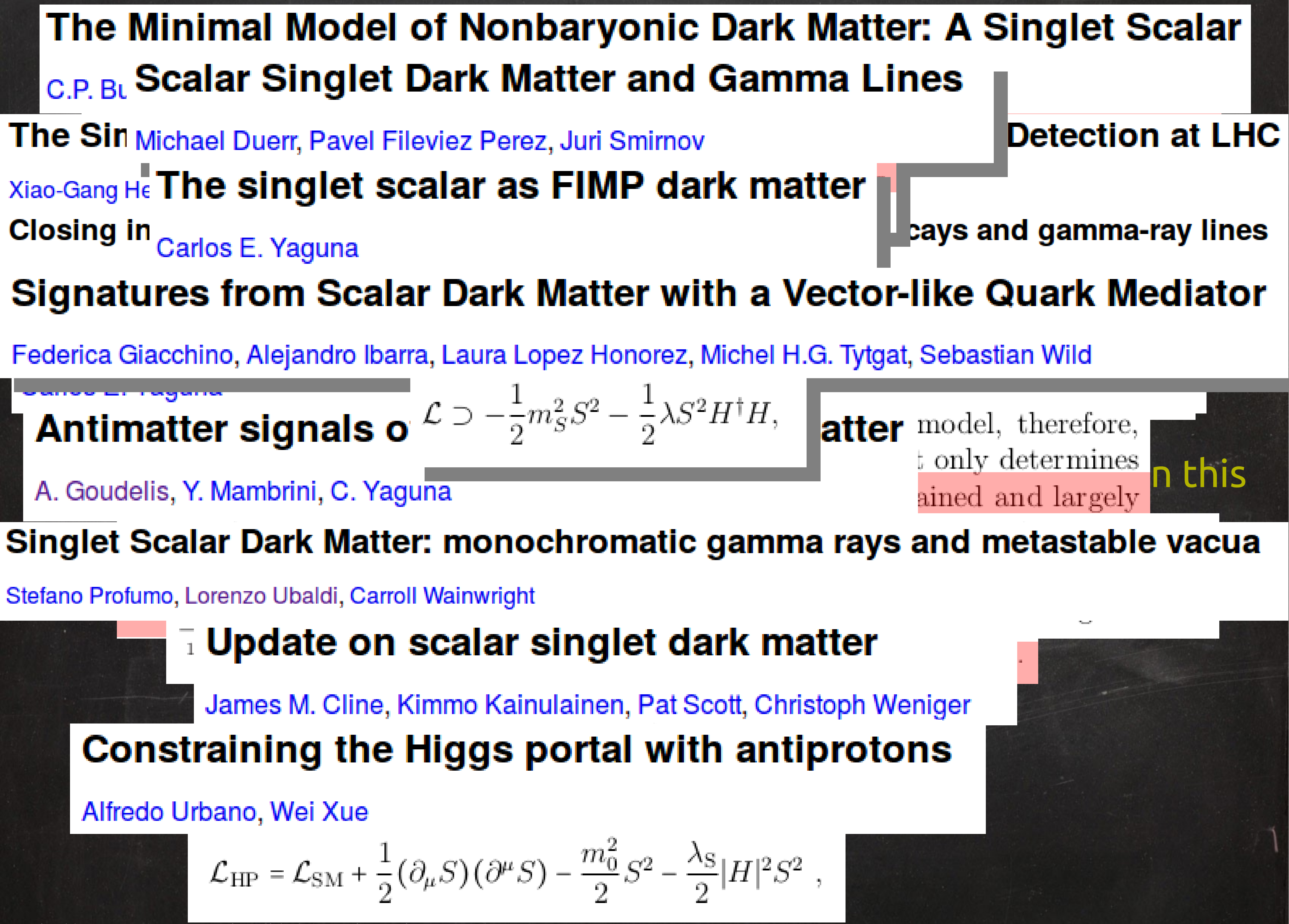

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**Signatures from Scalar Dark Matter with a Vector-like Quark Mediator**

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

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

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# Dark Matter Self-Interactions

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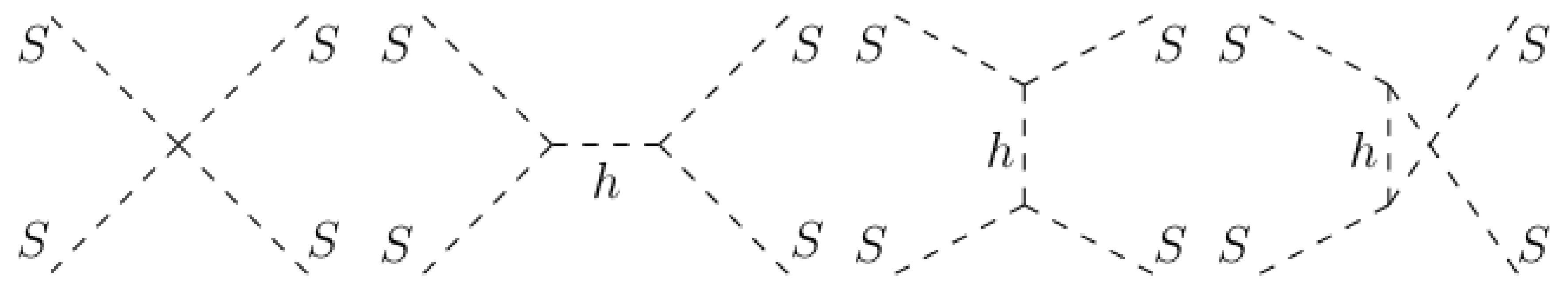
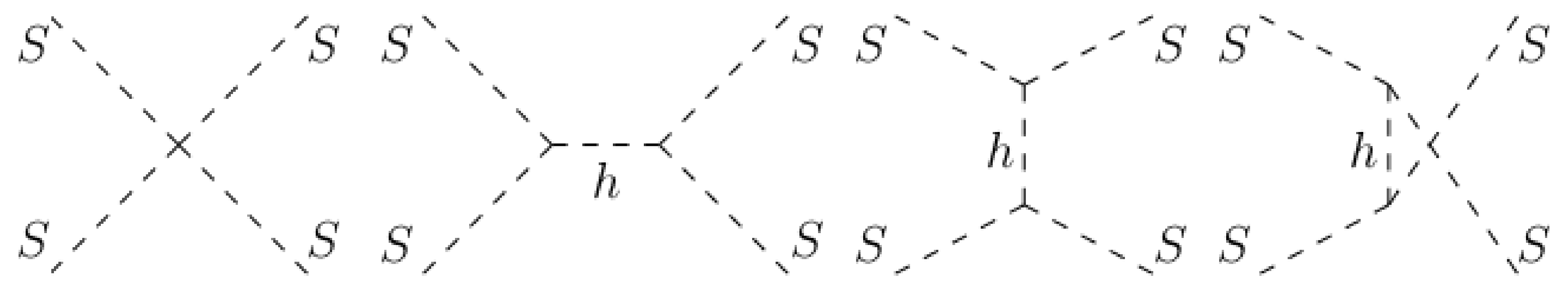


$$\frac{\sigma_{SS}}{m_S} \sim \frac{9}{8\pi}\frac{\lambda_S^2}{m_S^3}$$

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

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

# Dark Matter Self-Interactions & Invisible Higgs decay



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Implies {
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- * $m_S$ ~ 100 MeV

The Higgs tends to annihilate into DM

BR(h→ inv.) < 20%

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

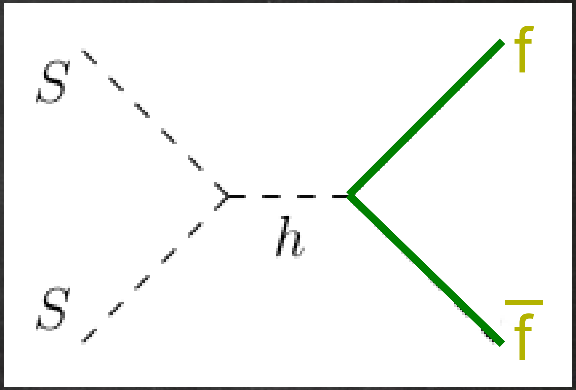
# How to produce such a Self-Interacting Dark Matter?

# WIMP DM

DM can (only) annihilate into light fermions

other annihilation channels kinematically closed!

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



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

→ **DM can not be a WIMP!!!**

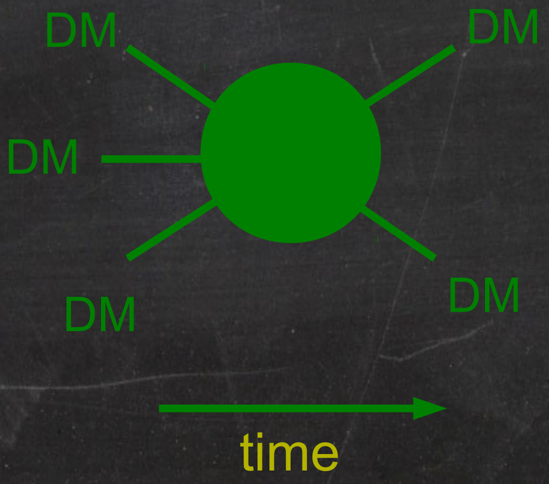
# Again:
# How to produce such a Self-Interacting Dark Matter?!

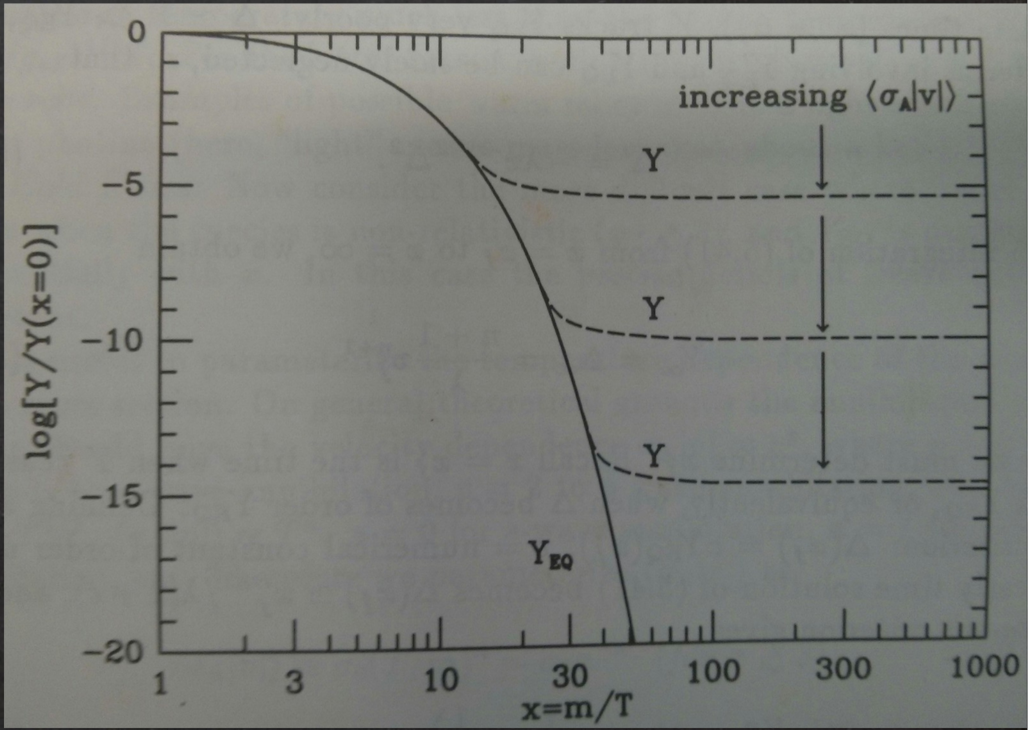
# SIMP DM

# 3→2 annihilations

Hochberg, Kuflik, Volansky & Wacker '14

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





# SIMP DM

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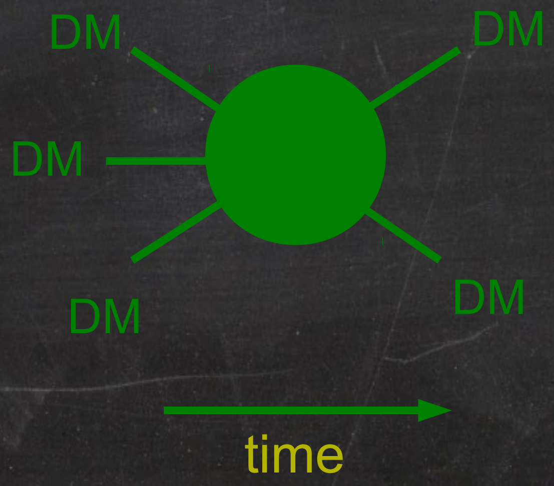
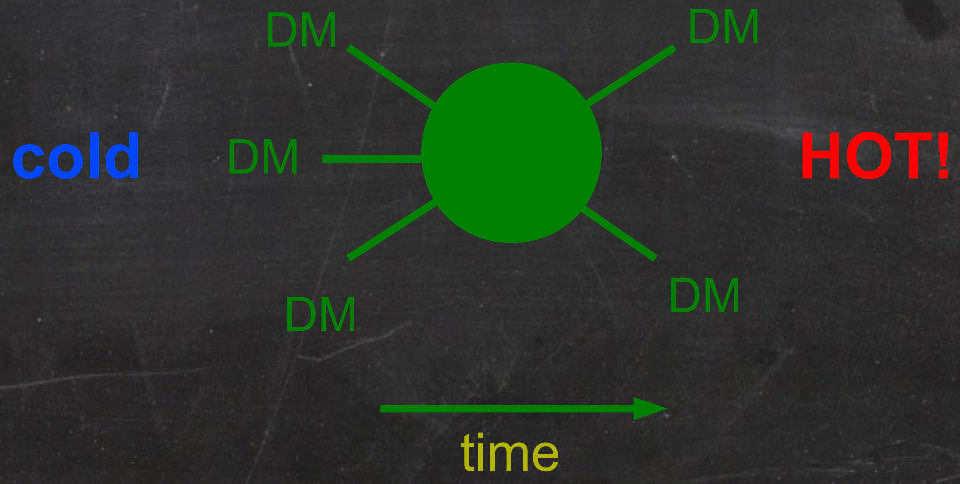


- **DM in the MeV range**
- **Small DM-SM portal**
- **α ~ 1**
  **'Strong' Self-interactions**
  **→ SIMP**

# Caveat

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



**cold**

DM

DM

DM

DM

DM

**HOT!**

time

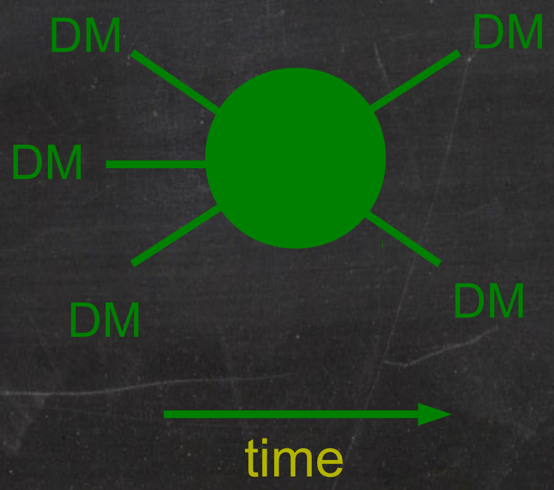
3 → 2 annihilations
pump heat into the dark sector!

# SIMP DM

# 3→2 annihilations

Hochberg, Kuflik, Volansky & Wacker '14

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

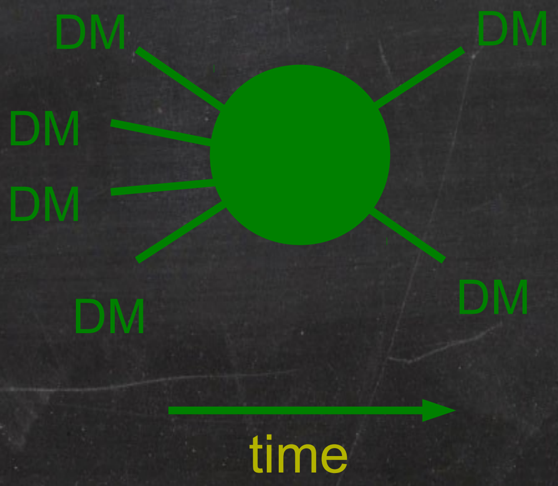


- * **DM in the MeV range**
- * **Small DM-SM portal**
- * **α ~ 1**
  **'Strong' Self-interactions**
  **→ SIMP**

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 **Z**$_2$ symmetries allow 4→2 annihilations!

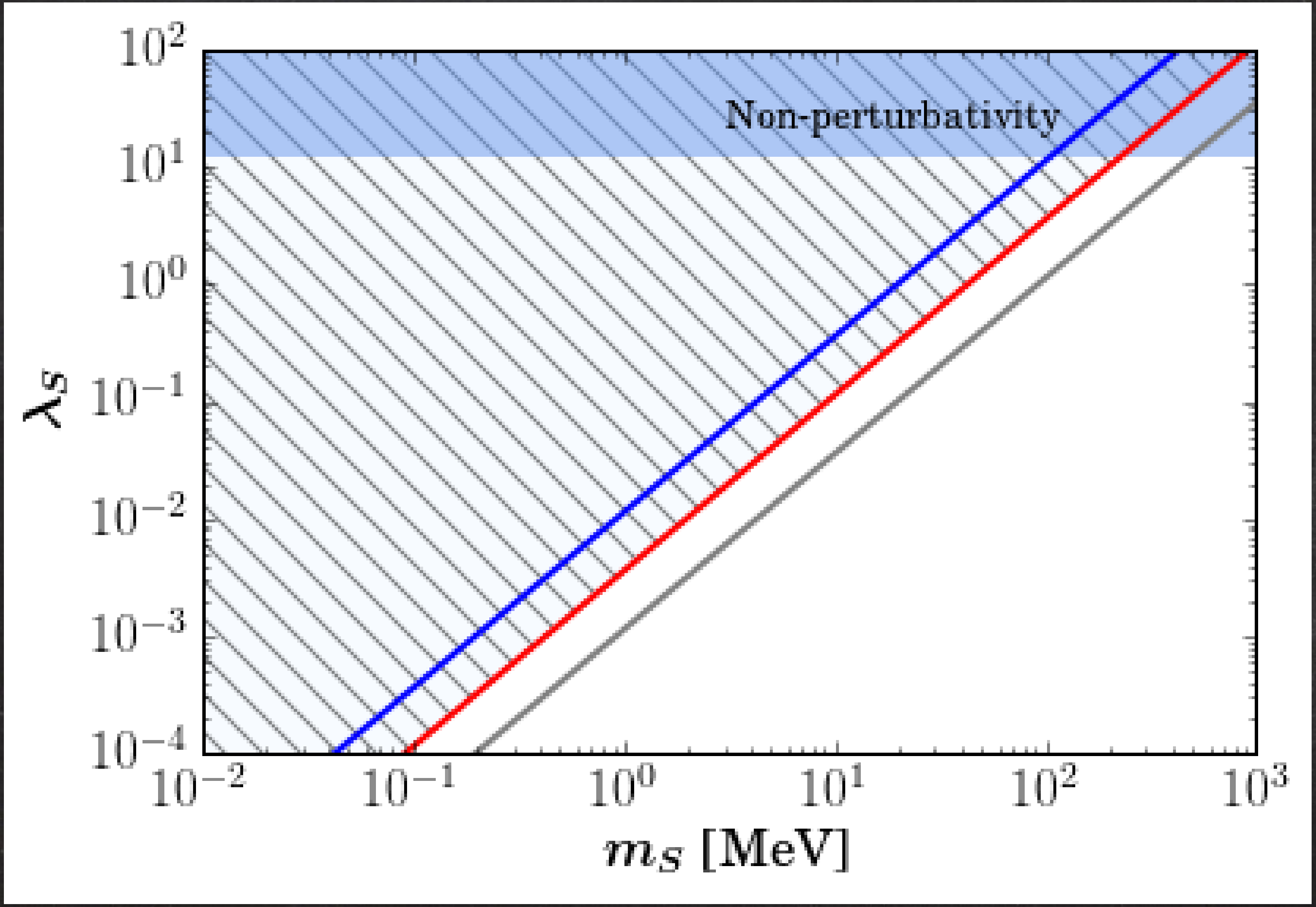
# SIMP DM
## 4→2 annihilations

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

$$\langle\sigma v^3\rangle_{4\to 2} \sim \frac{27\sqrt{3}}{8\pi}\,\frac{\lambda_S^4}{m_S^8}$$

# SIMP DM

# 4→2 annihilations

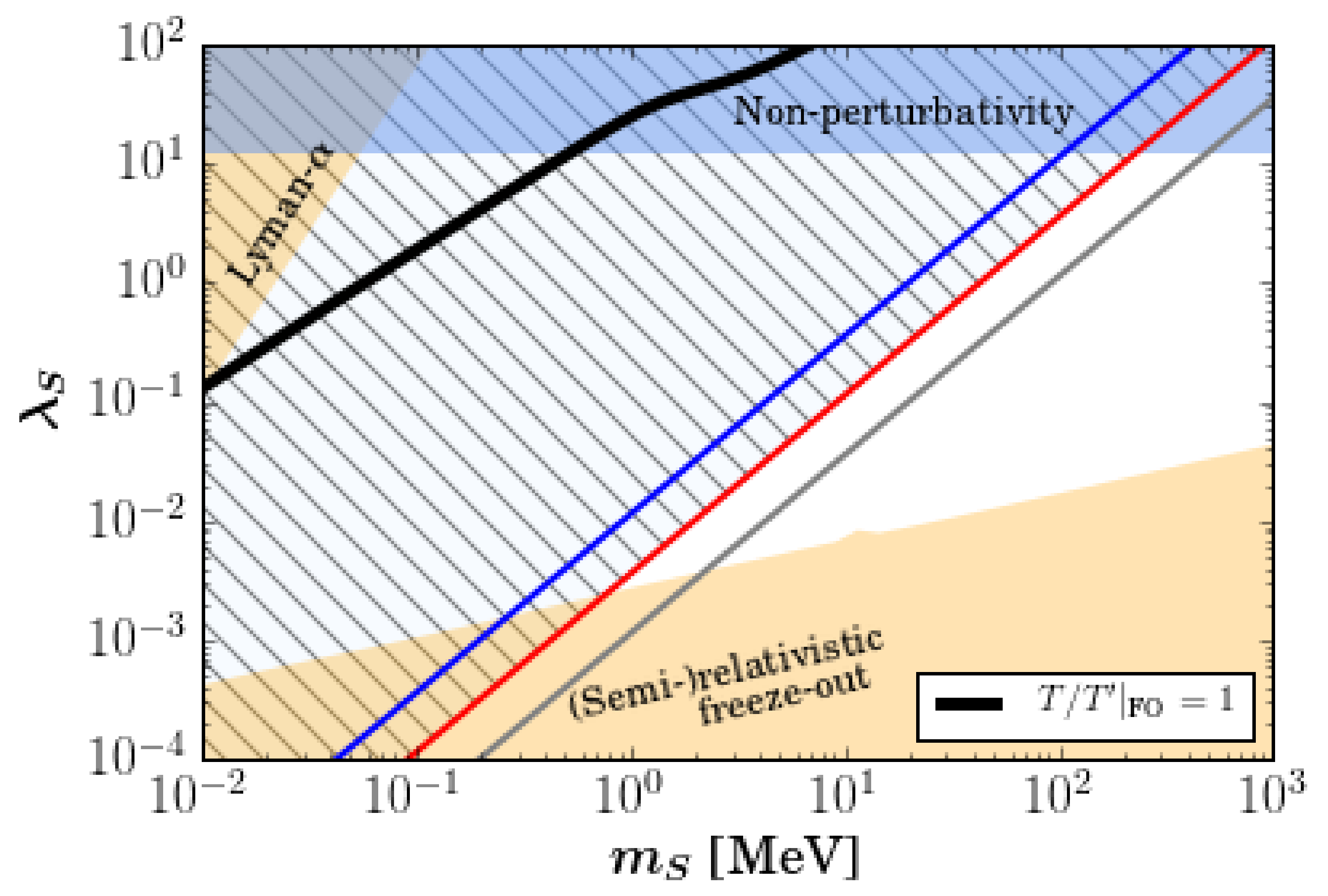


$\sigma/m$ [cm$^2$/g]

$$\left\{ \begin{array}{l} 10 \\ 1 \\ 0.1 \end{array} \right.$$

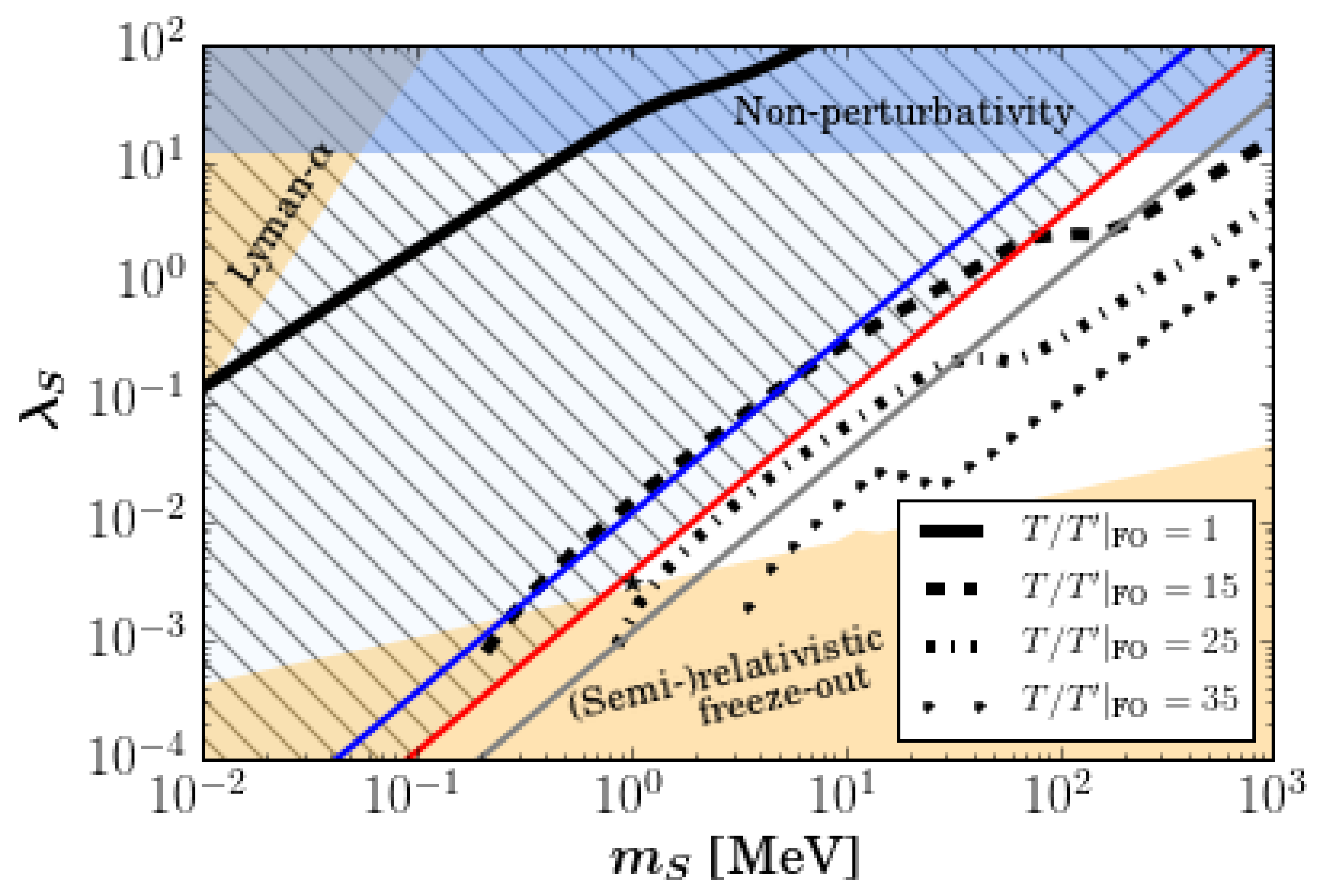
# SIMP DM
# 4→2 annihilations

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



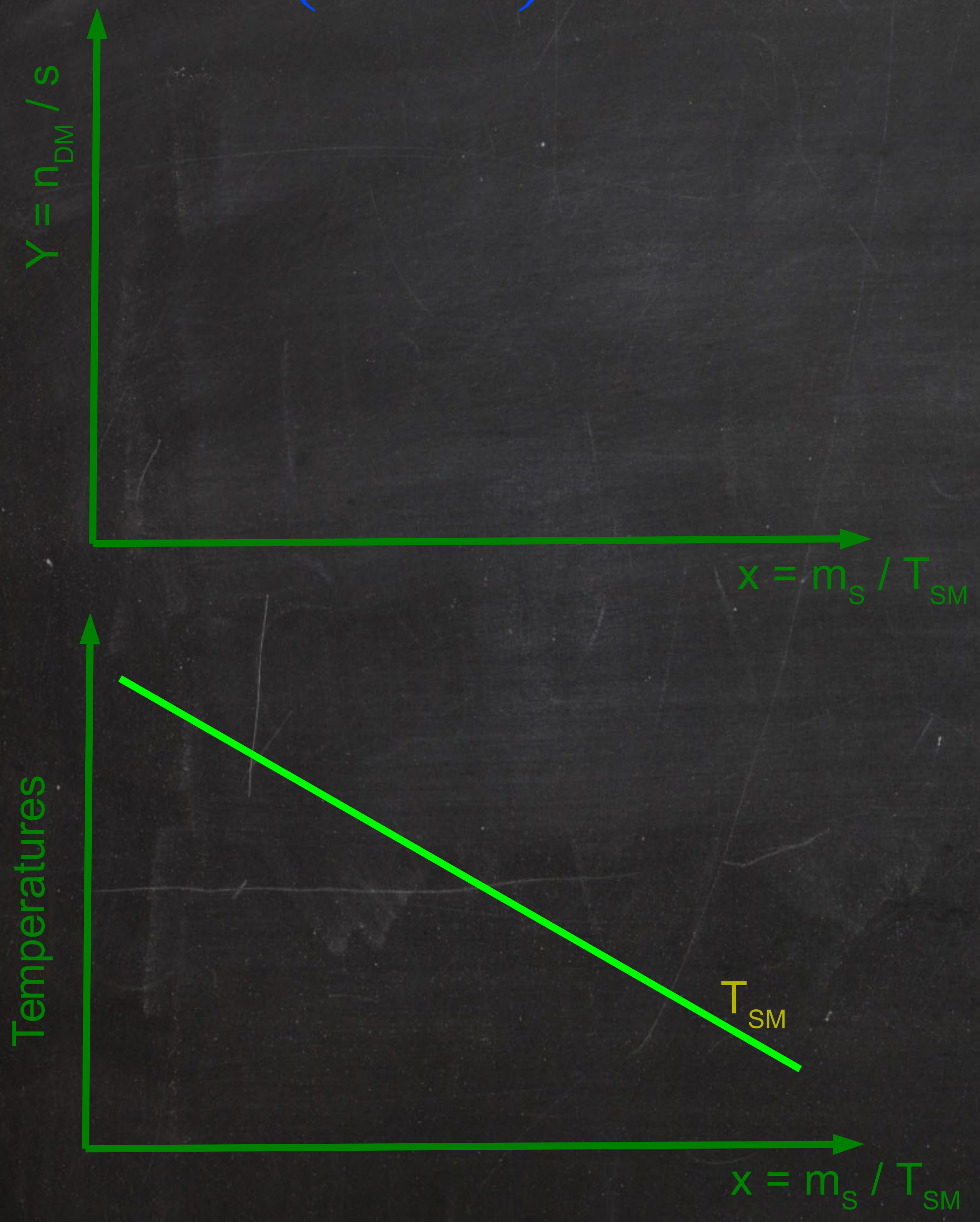
# SIMP DM
# 4→2 annihilations

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



# How to produce such a difference of temperatures?

# (Non-) Thermal evolution of DM



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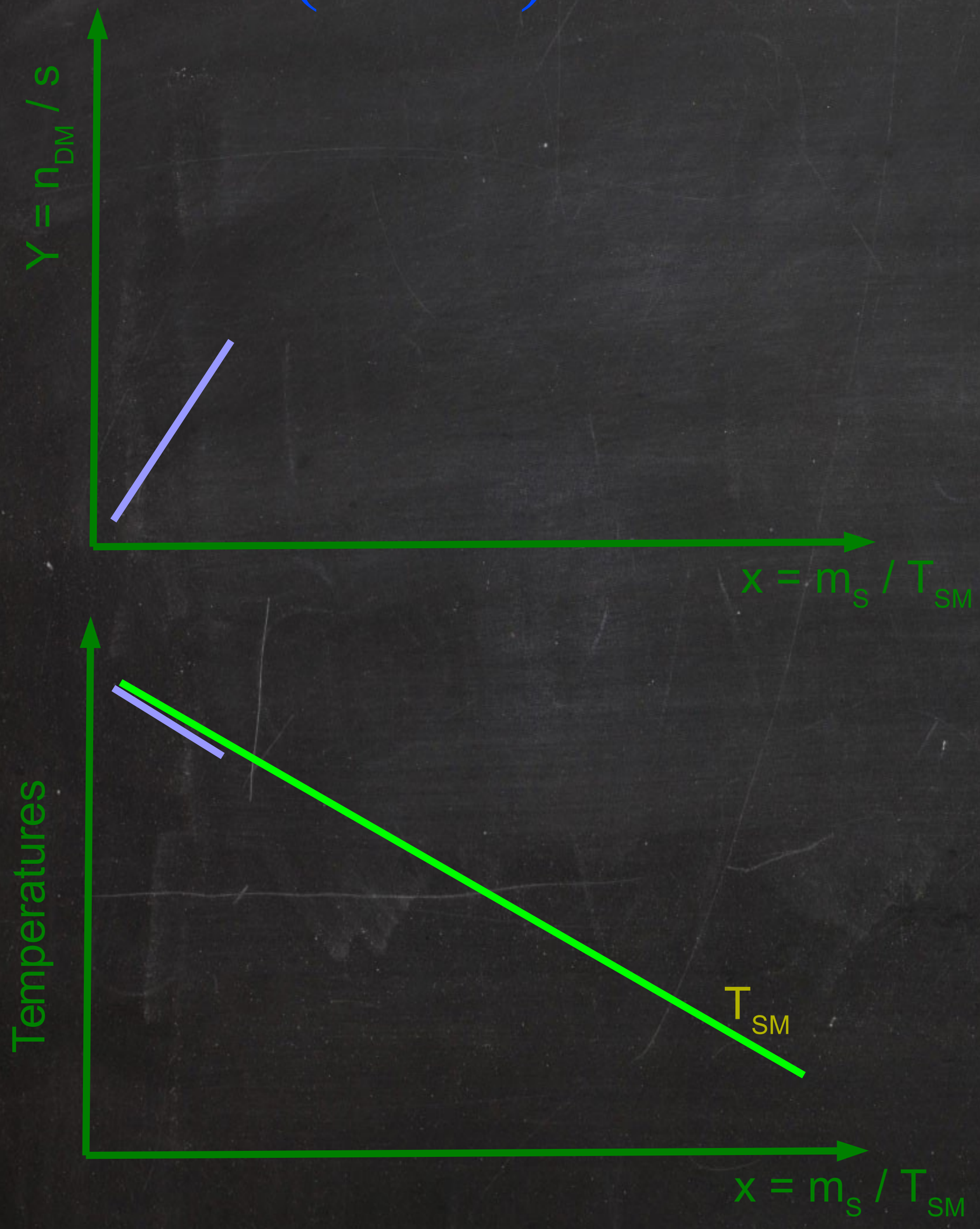

<u>DM Production</u>

* 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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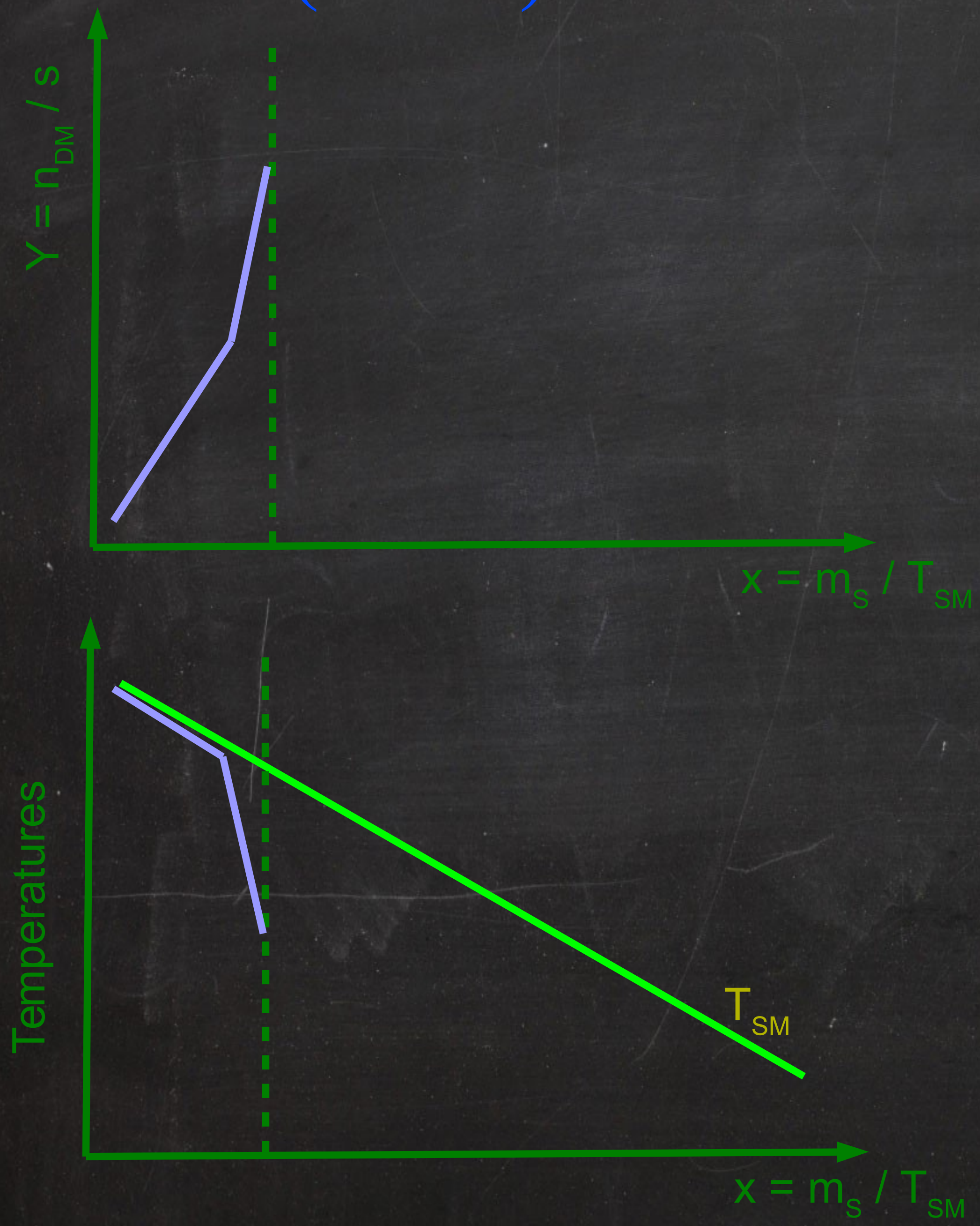

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* DM populates rapidly via
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Price to pay: Dramatic decrease of $T_{DM}$

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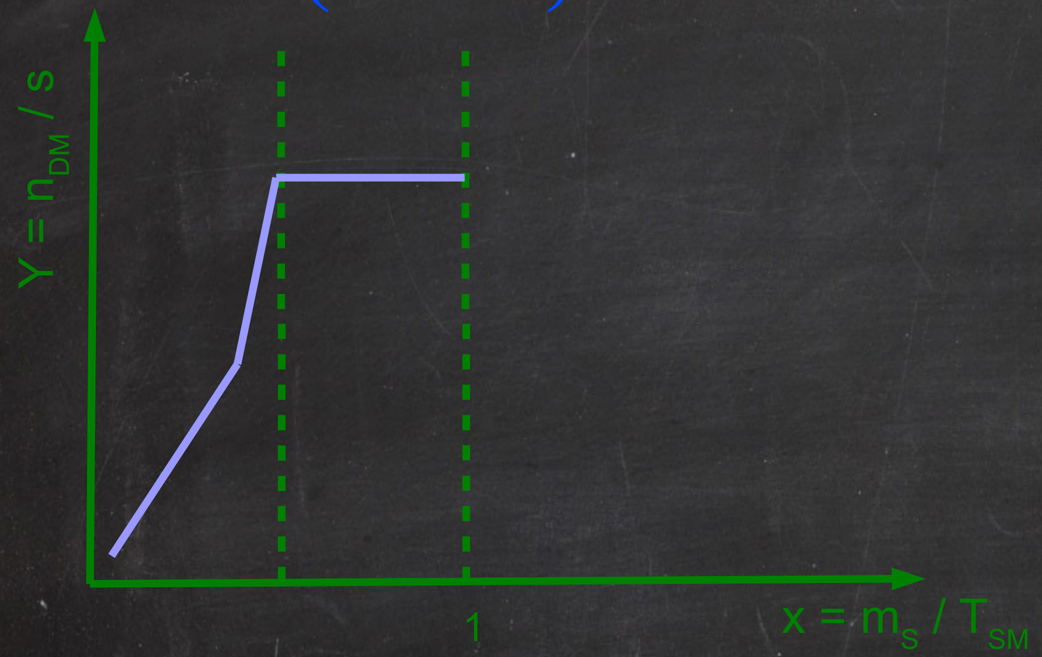

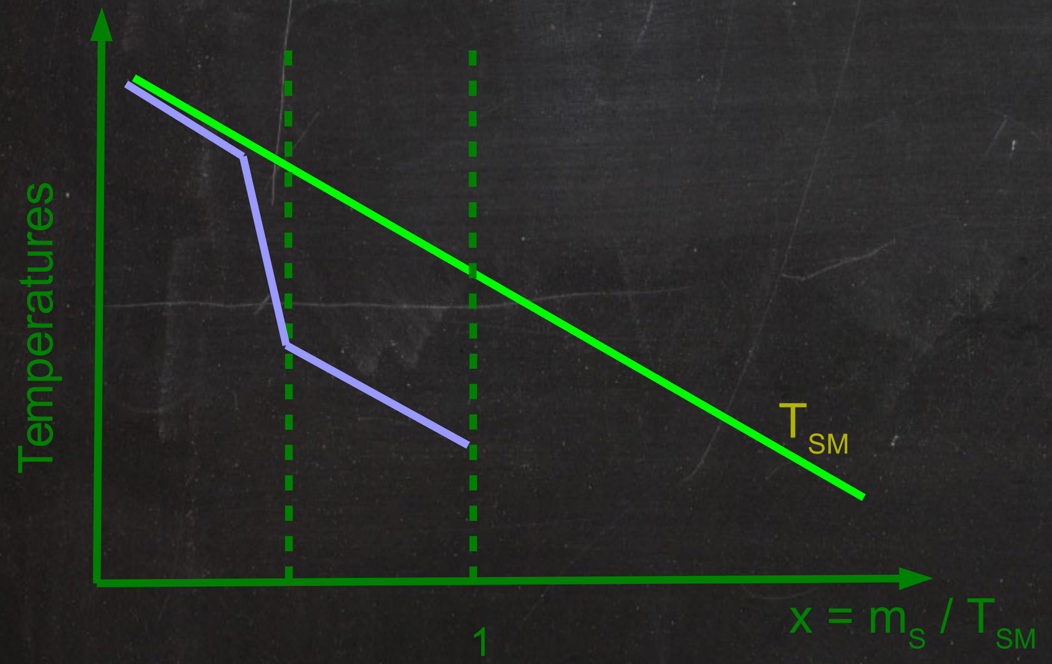

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## Thermal Equilibrium

* Chemical equilibrium **2↔4**

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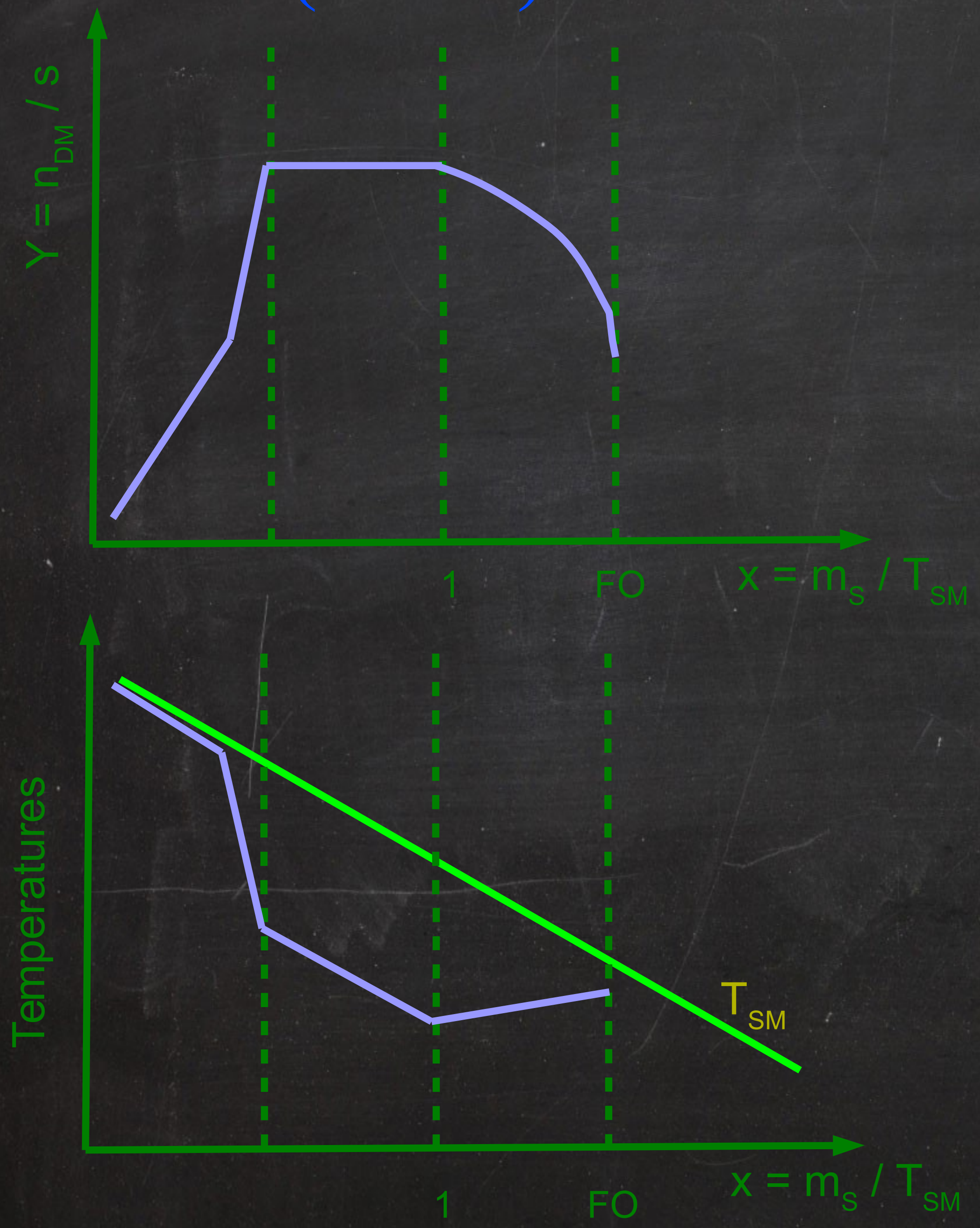

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Thermal Equilibrium

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DM Annihilation

* Freeze-out **4→2**

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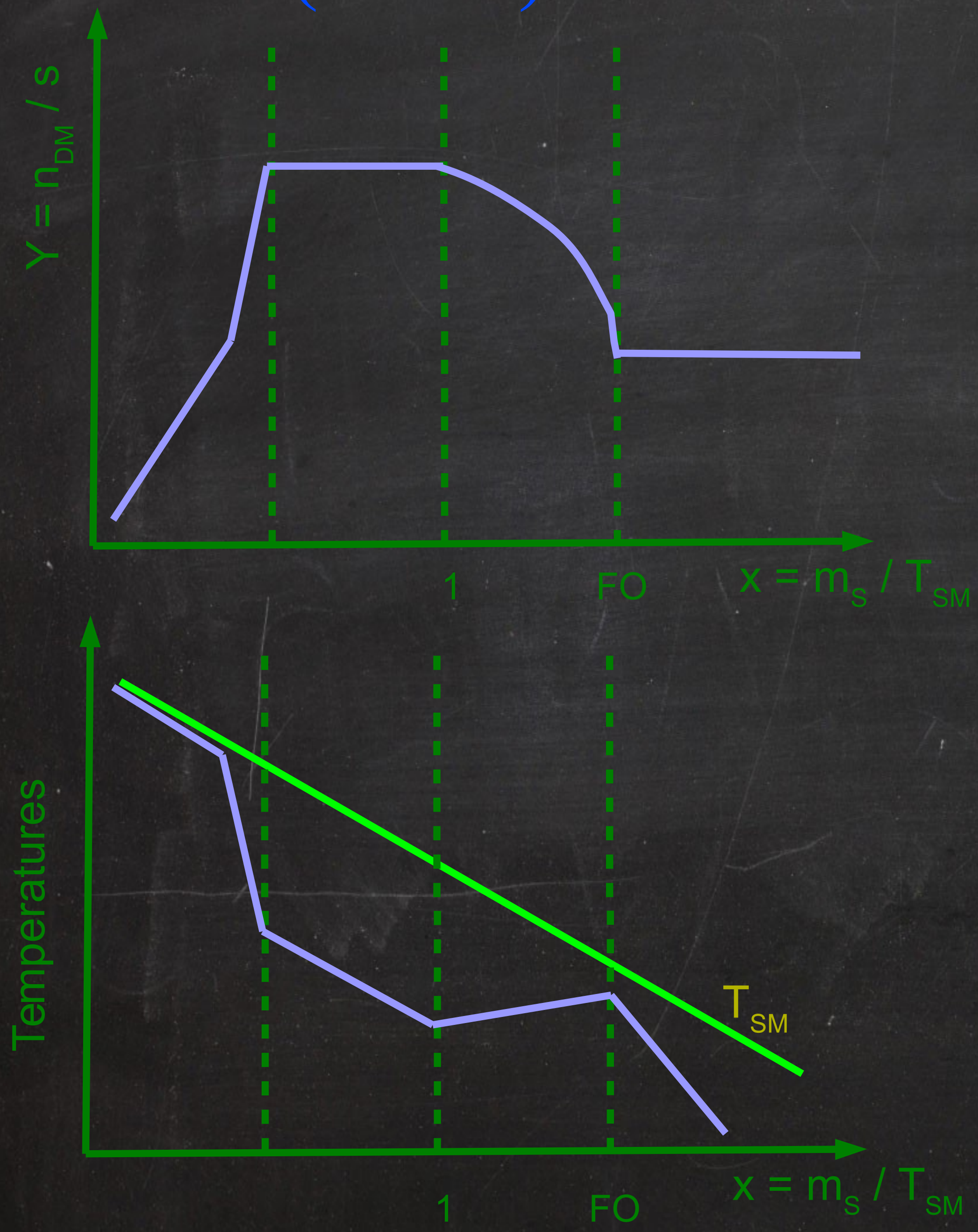

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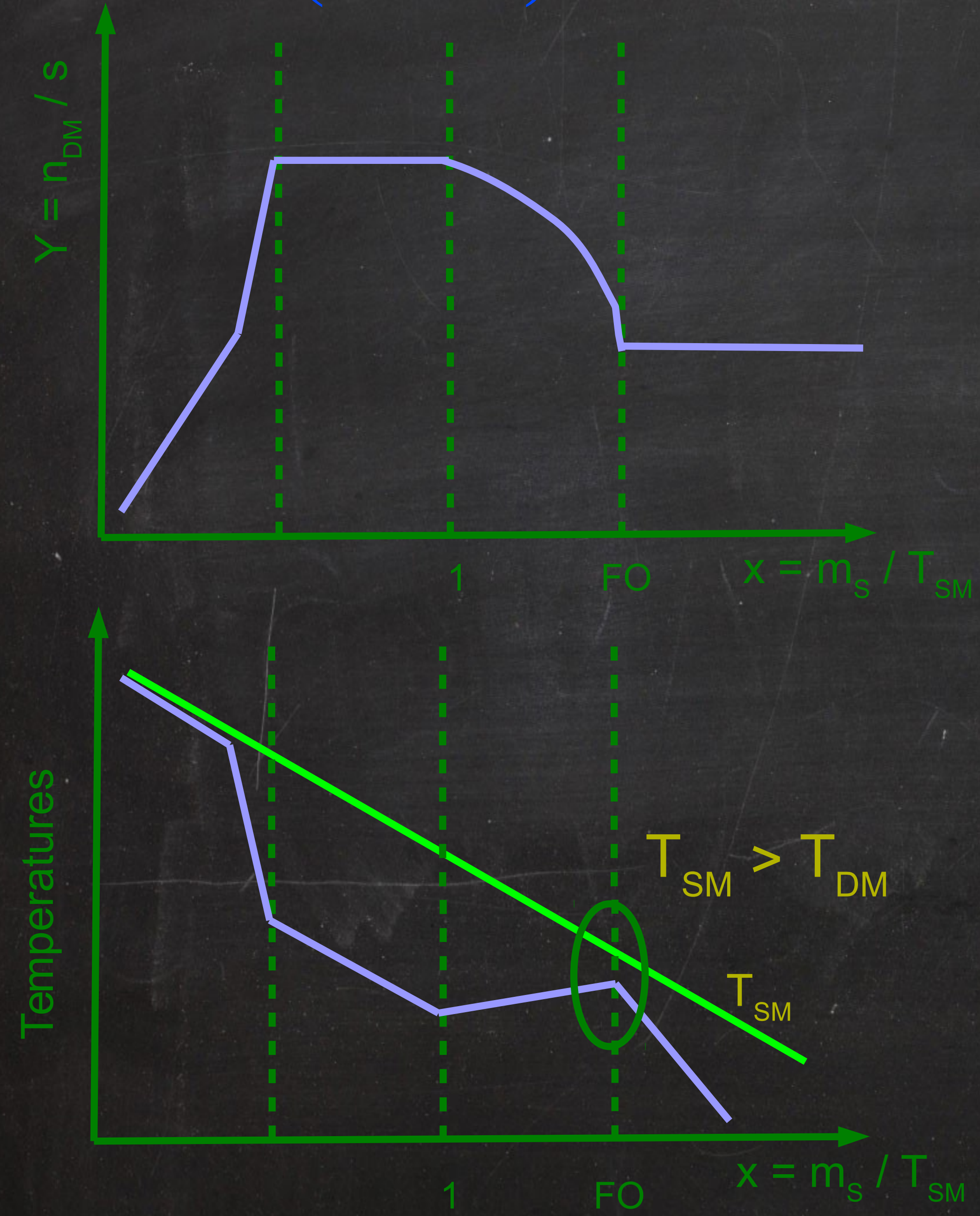
<u>DM Annihilation</u>

* 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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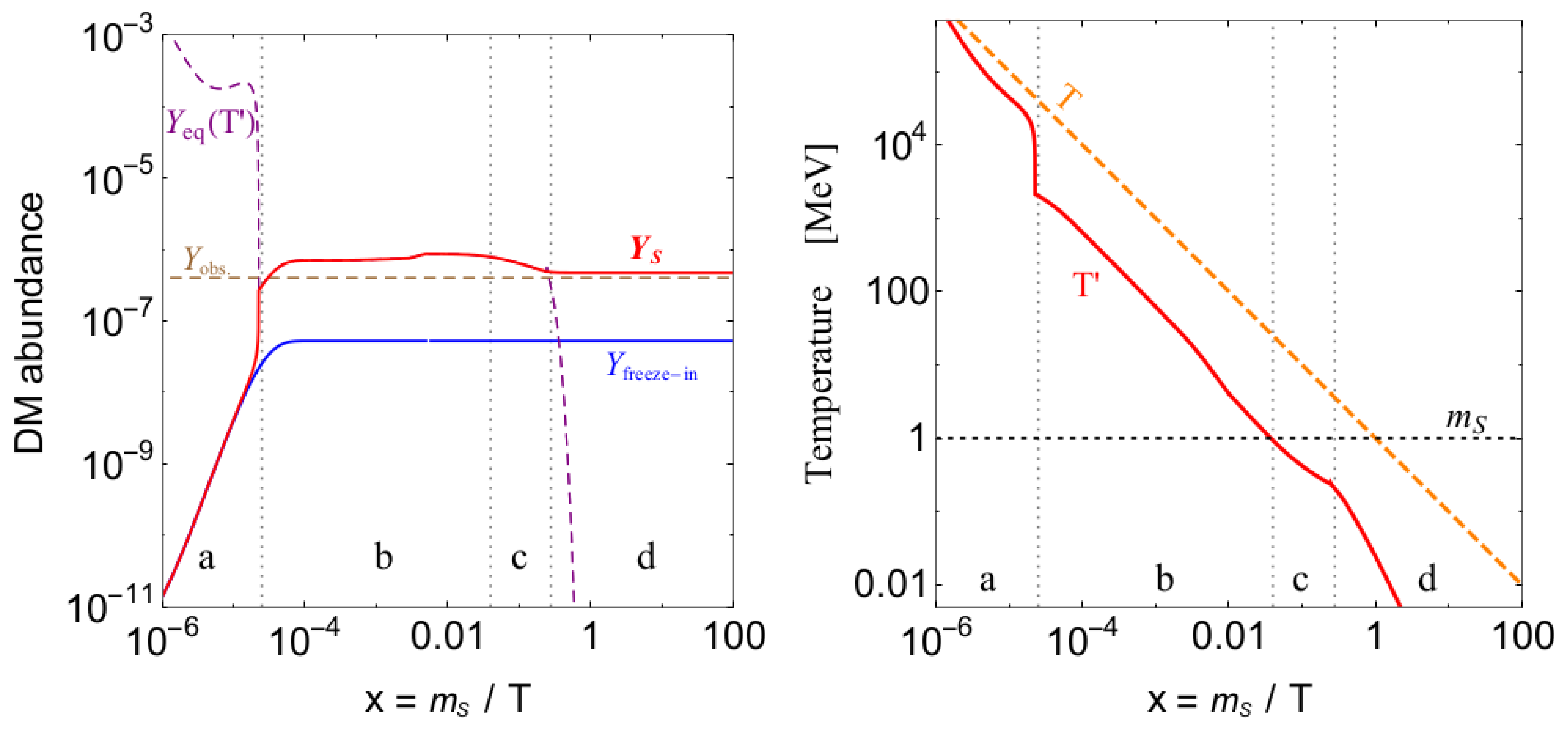
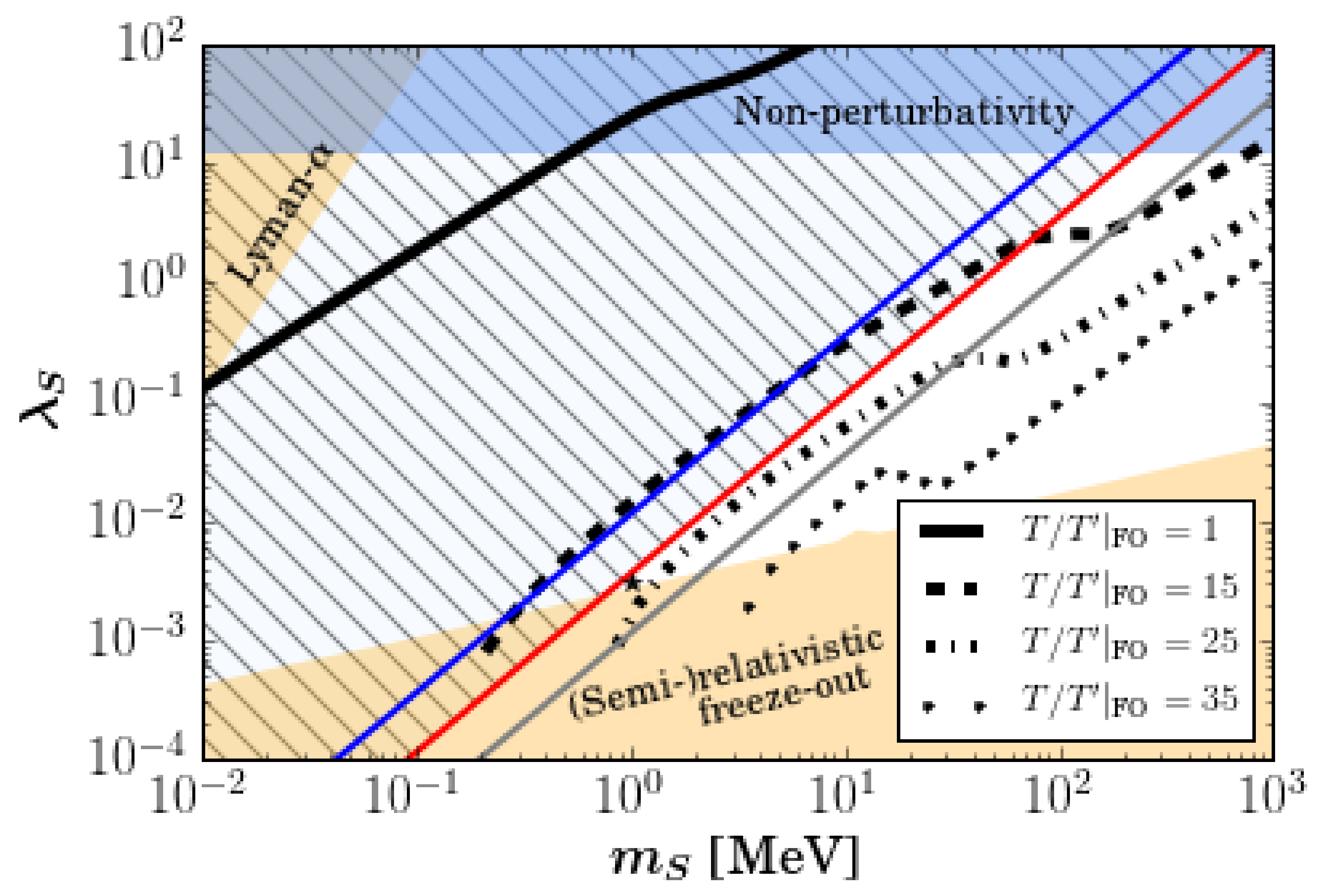
Non-relativistic DM cools down faster

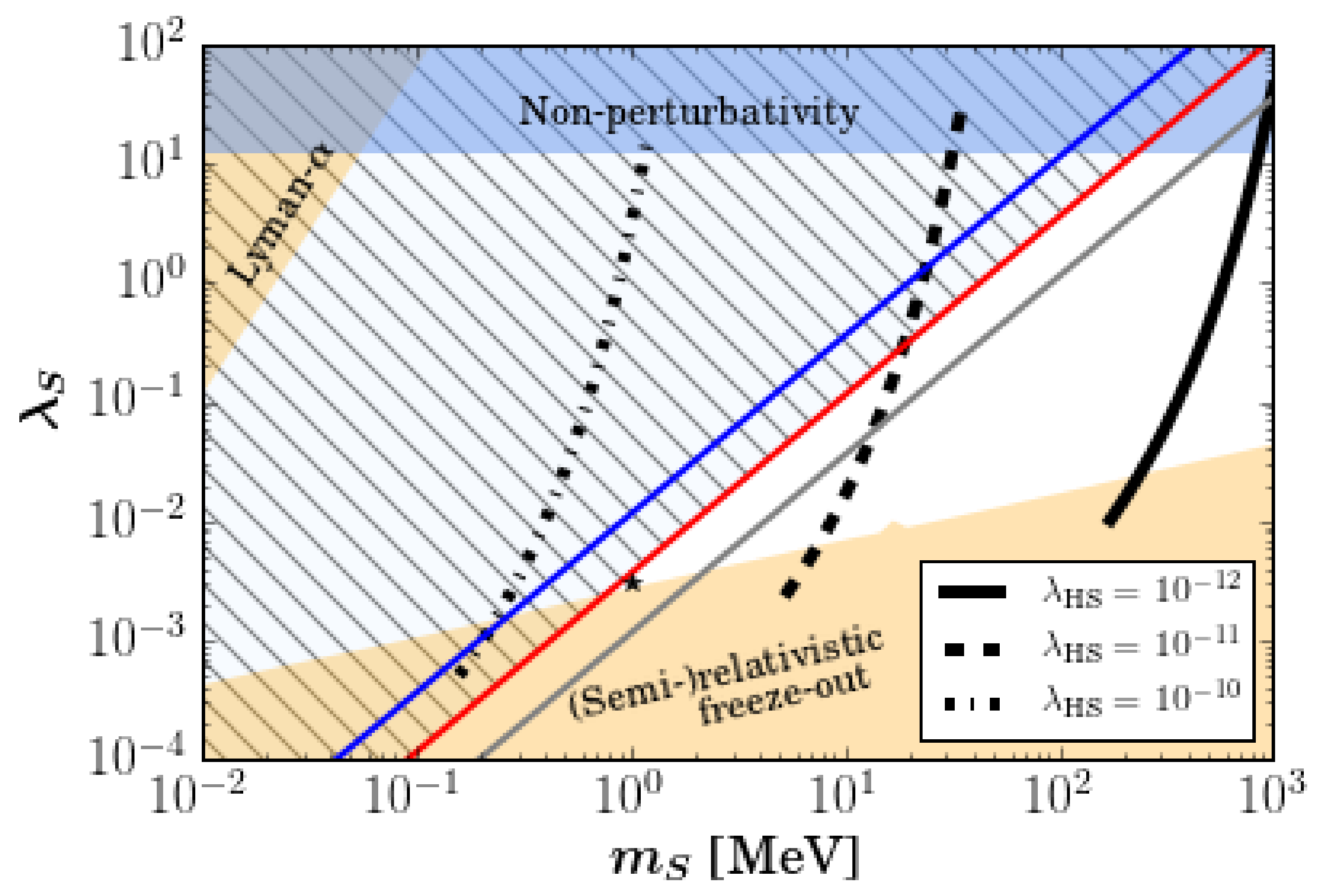
# Generating $T_{DM} < T_{SM}$ via the Higgs Portal



# SIMP DM
# 4→2 annihilations



# SIMP DM
# 4→2 annihilations



# Conclusions

**Small-scale anomalies**

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

# Conclusions

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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

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

$$\left.\begin{array}{l} m_S \sim 100\ \mathrm{MeV} \\ \lambda_S \sim 1 \\ \lambda_{HS} < 10^{-3} \end{array}\right\}$$

# Conclusions

**Small-scale anomalies**

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

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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

$\left.\begin{array}{l} m_S \sim 100 \text{ MeV} \\ \lambda_S \sim 1 \end{array}\right\}$ DM self-interactions

$\lambda_{HS} \sim 10^{-10}$ → Freeze-in → Natural to have different temperatures!

* 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!