The Dawn of FIMP Dark Matter

Based on:
NB, Matti Heikinheimo, Tommi Tenkanen, Kimmo Tuominen & Ville Vaskonen
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Nicolás BERNAL

UAN
UNIVERSIDAD
ANTONIO NARIÑO

Invisibles Workshop
September 6th, 2018

Thermal Collisionless Cold Dark Matter

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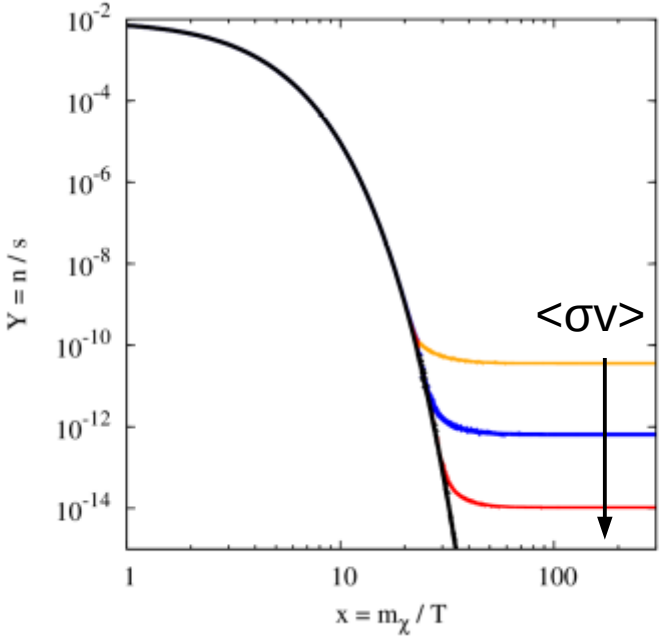
WIMP Dark Matter

talk by R. Catena



Early Universe:
DM in **thermal equilibrium** with the Standard Model.

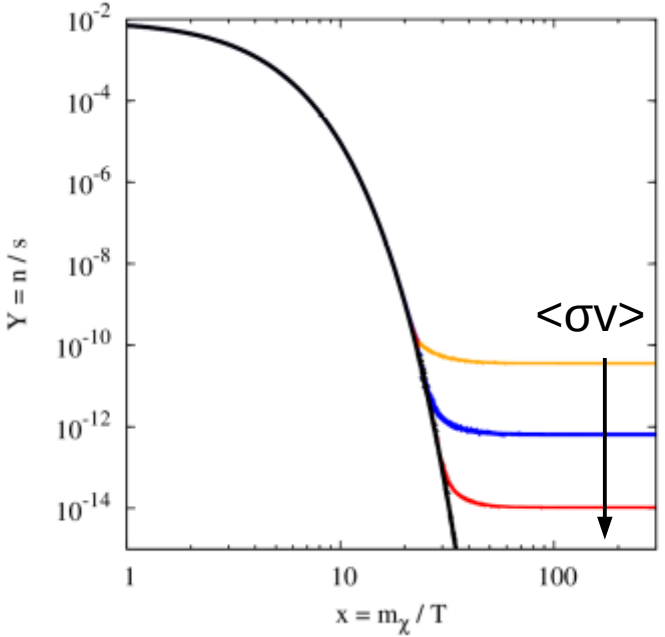
Due to the expansion of the Universe DM particles fall **out of chemical equilibrium** and cannot annihilate anymore.

A relic density of DM is obtained which remains constant.

→ ***Collisionless cold WIMP*** Dark Matter

WIMP Dark Matter

talk by R. Catena

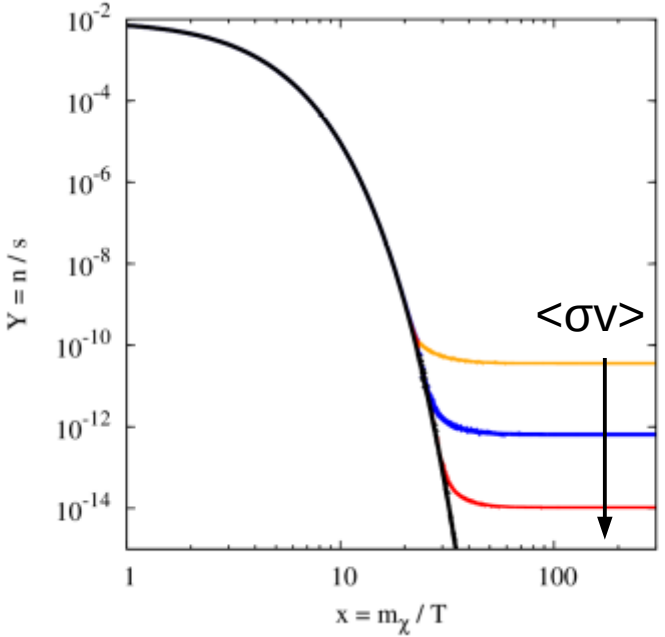


WIMP DM typically requires:
$\langle\sigma v\rangle \sim$ few 10^{-26} cm^3/s

* GeV to TeV masses
* $O(1)$ couplings DM-SM

→ Independent on initial conditions!

WIMP Dark Matter



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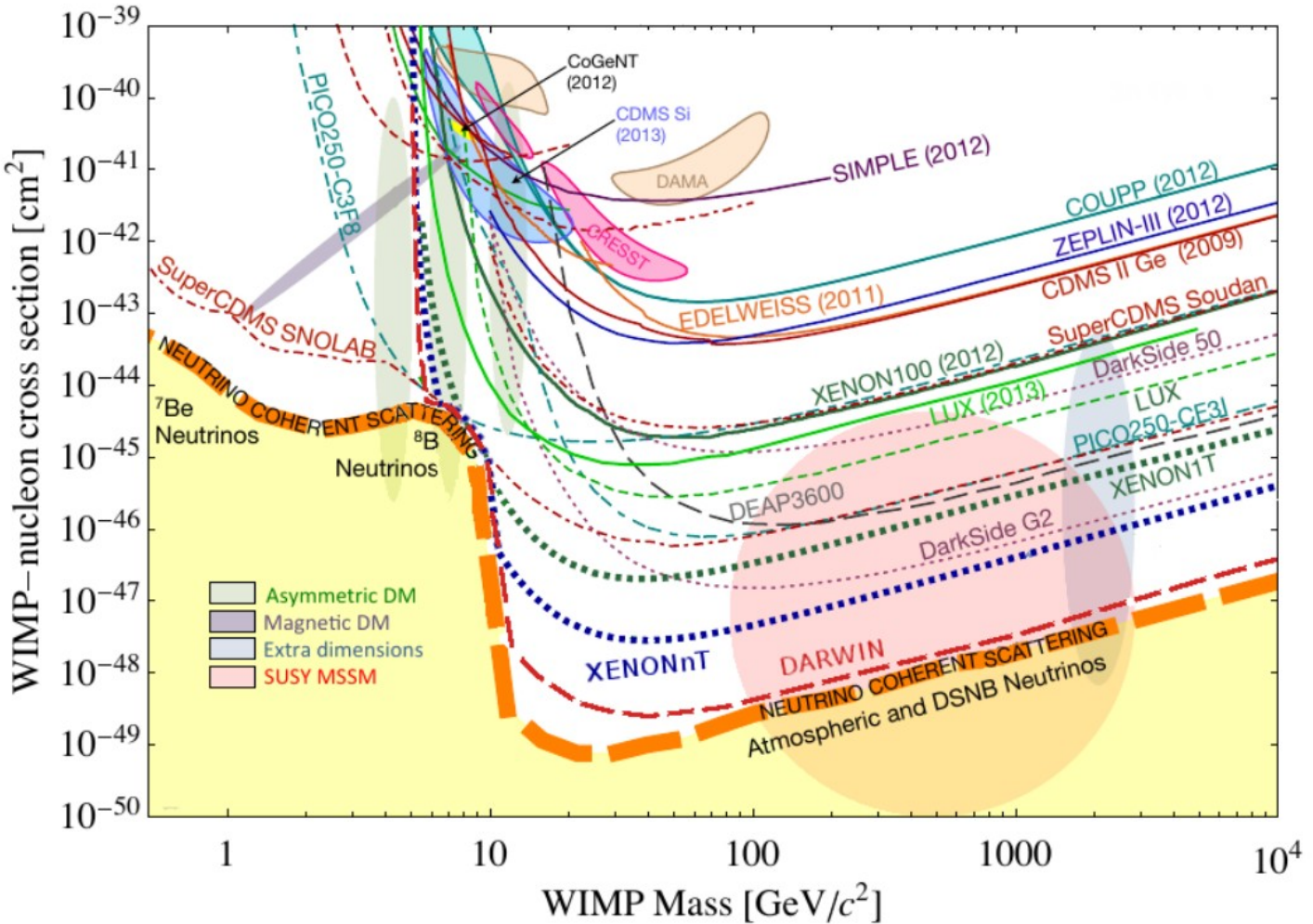
→ Independent on initial conditions!

Over the last decades a huge worldwide effort to detect WIMP DM using a multi-channel and multi-messenger approach...
but no compelling detection so far!

WIMP Dark Matter under Tension

talk by F. Gao



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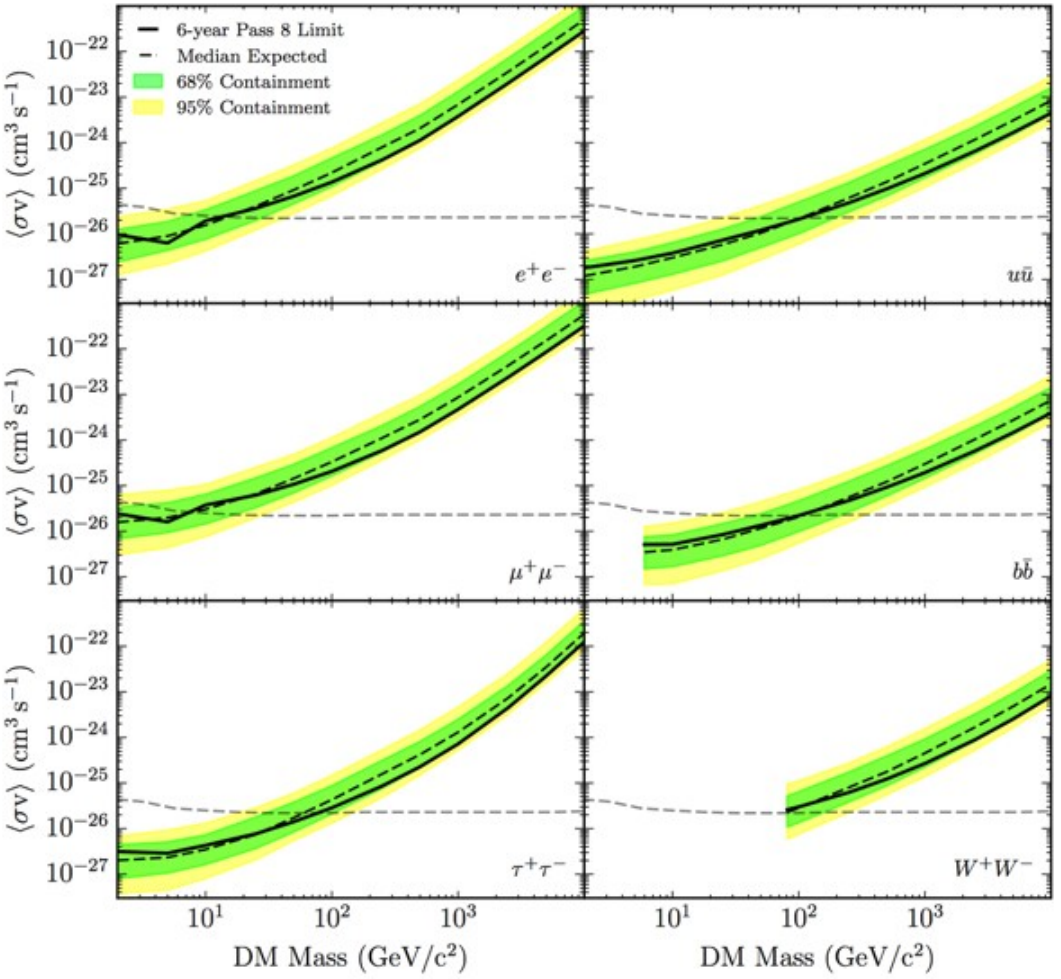
WIMP Dark Matter under Tension

talk by P. Sandick



But, what if DM is not a WIMP?

Dark Matter as a FIMP (Feebly Interacting Massive Particle)

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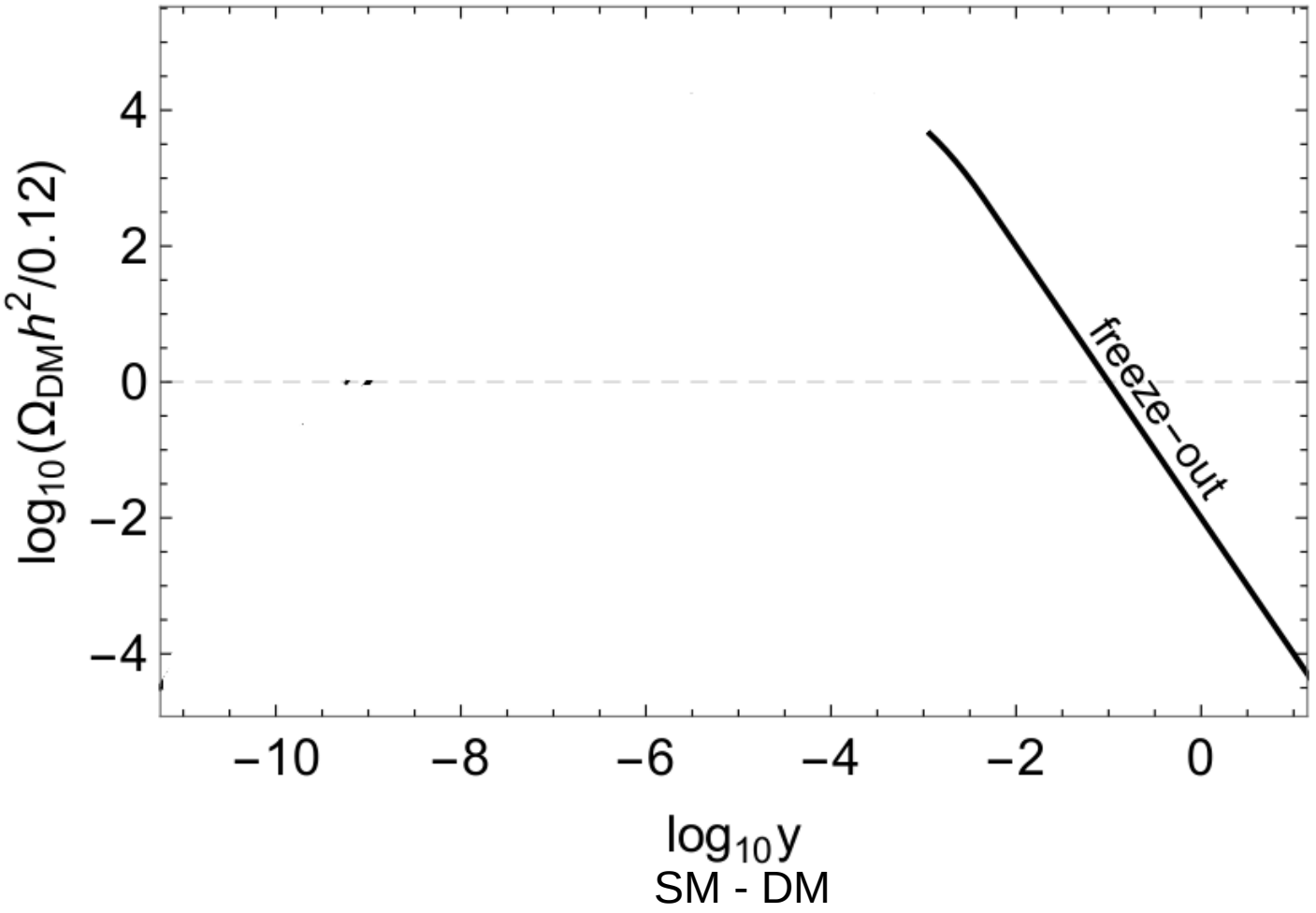
WIMP Dark Matter



SM - DM

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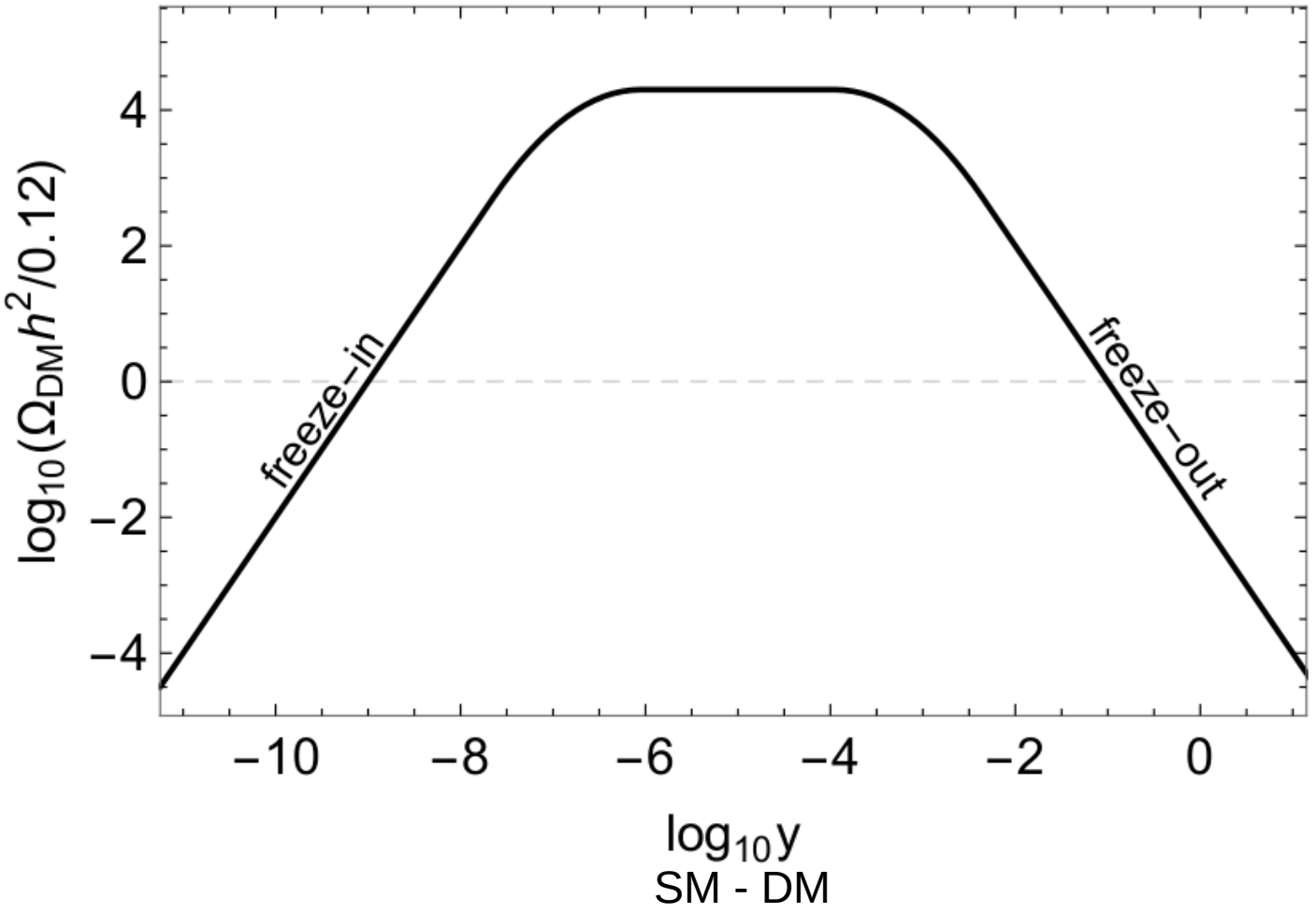
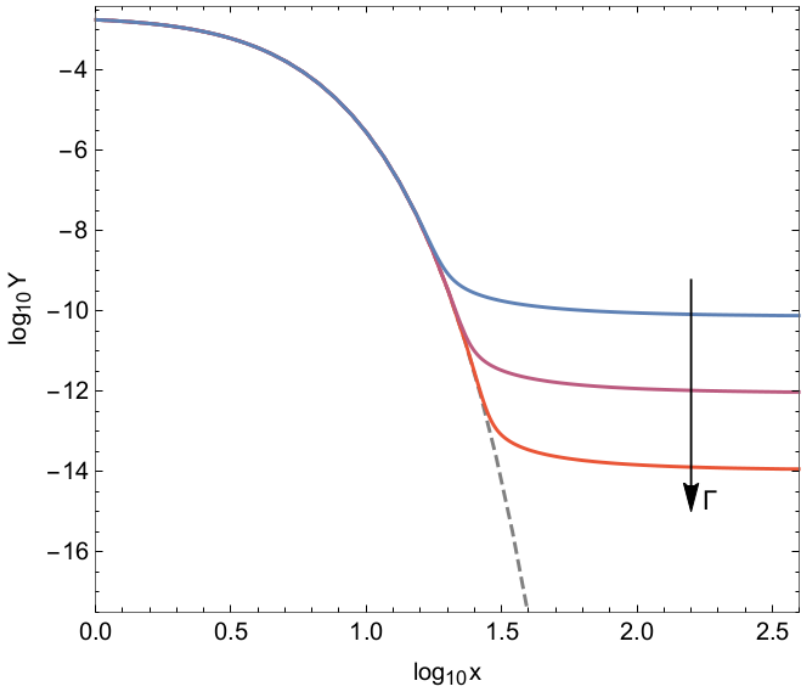
FIMP / WIMP Dark Matter

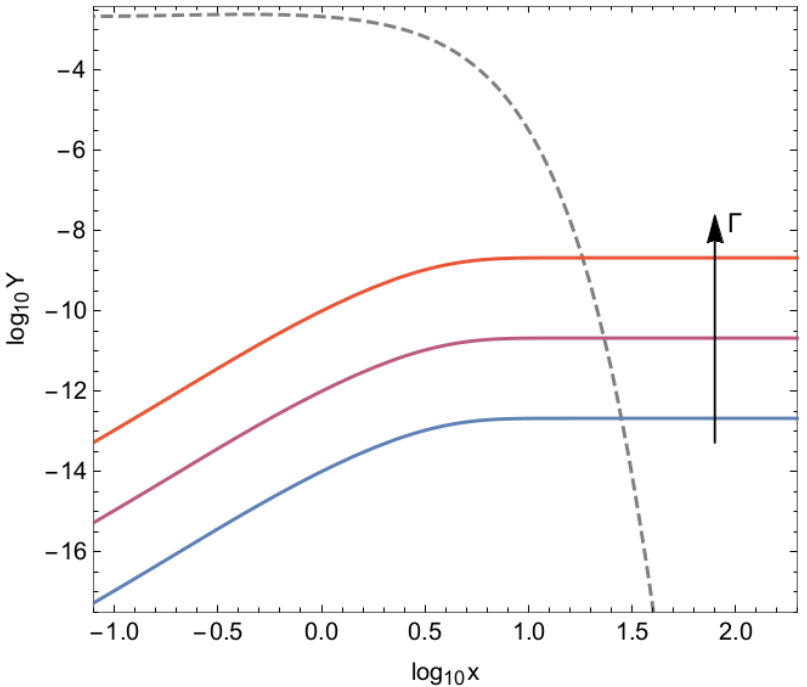


SM - DM

WIMP vs FIMP Dark Matter

$$\frac{dn_\chi}{dt} + 3\,H\,n_\chi = -\langle v\sigma_\chi\rangle\left[n_\chi^2 - (n_\chi^{\rm eq})^2\right]$$





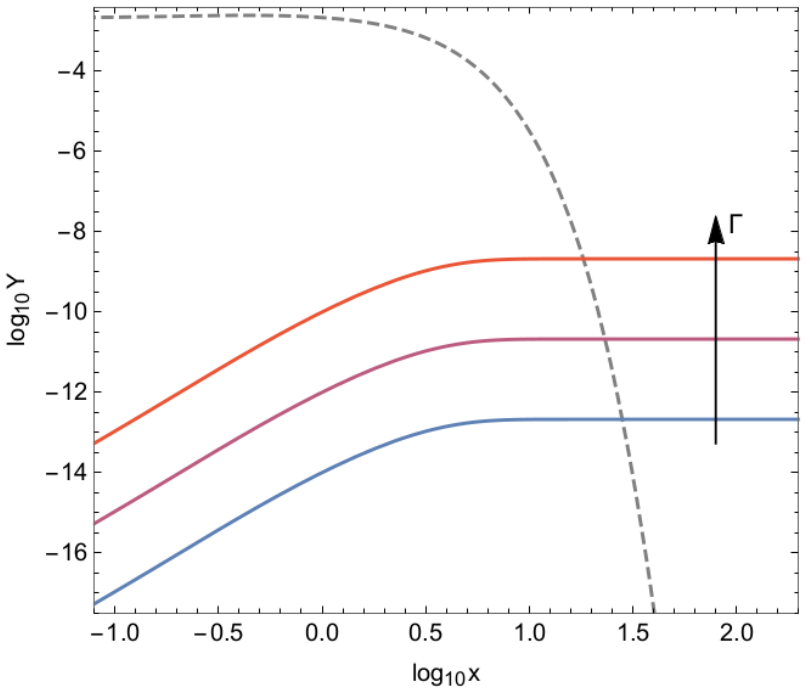
FIMP Dark Matter

$$\frac{dn_\chi}{dt} + 3\,H\,n_\chi = -\langle v\sigma_\chi\rangle\left[n_\chi^2 - (n_\chi^{\rm eq})^2\right]$$

FIMP DM typically requires:

* Very suppressed DM-SM interaction rate
  to avoid thermalization between
  the dark and the visible sectors
* keV to > PeV masses!
* Usually assumed a dark sector
  with a negligible initial population

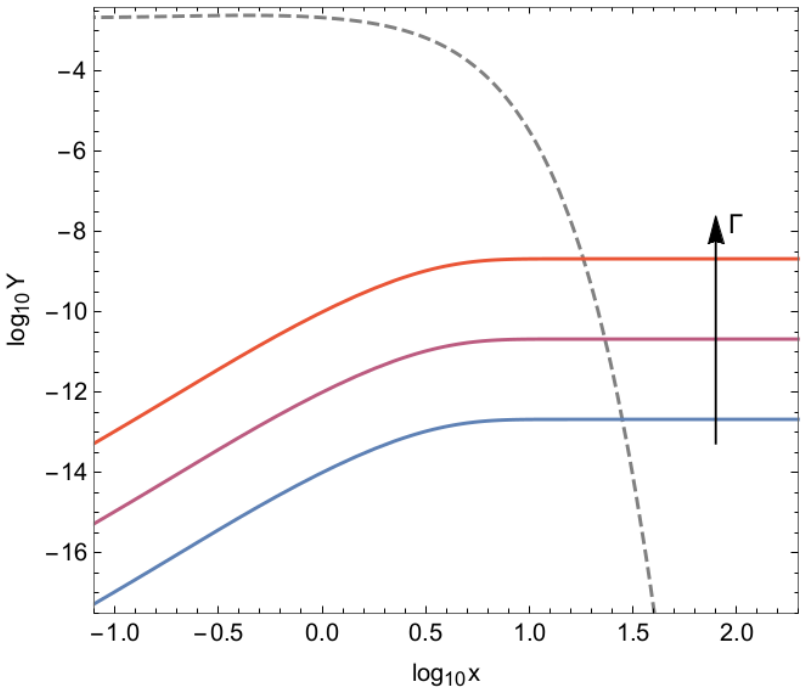
→ Dependent on initial conditions!



FIMP Dark Matter

A plethora of models for FIMP DM:

* different DM properties
* different mediators (spin, masses…)
* Higgs portal, vector portal, neutrino portal
* Decays or annihilations



The Simplest DM model ever: Singlet Scalar Dark Matter

just as an example :-)

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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:

* m_S DM mass
* λ_{HS} Higgs portal
* λ_S DM quartic coupling

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:

* m_S DM mass
* λ_{HS} Higgs portal
* λ_S DM quartic coupling

} ← Concentrated on this

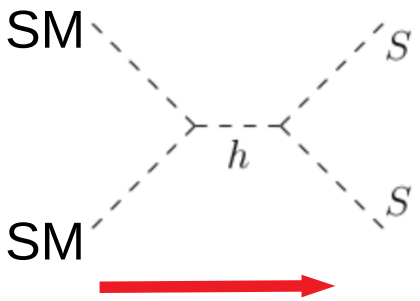
← ~ Ignored!

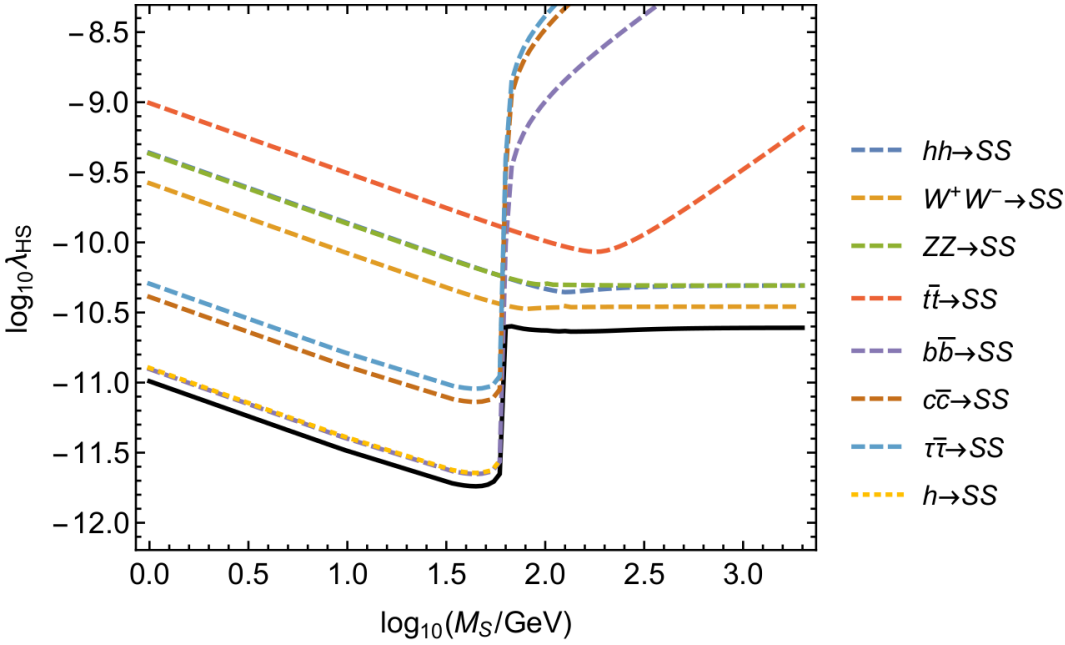
IR FIMP Dark Matter

IR FIMP:

* Small interaction rates due to renormalizable operators with $O(10^{-10})$ couplings SM-DM

* Production at T ~ Max($m_{DM,}$ $m_{mediator}$)





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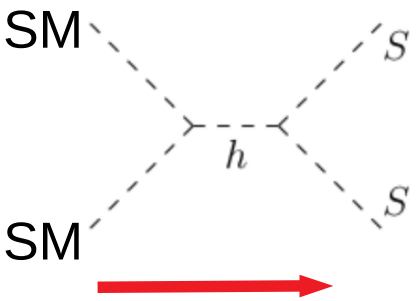
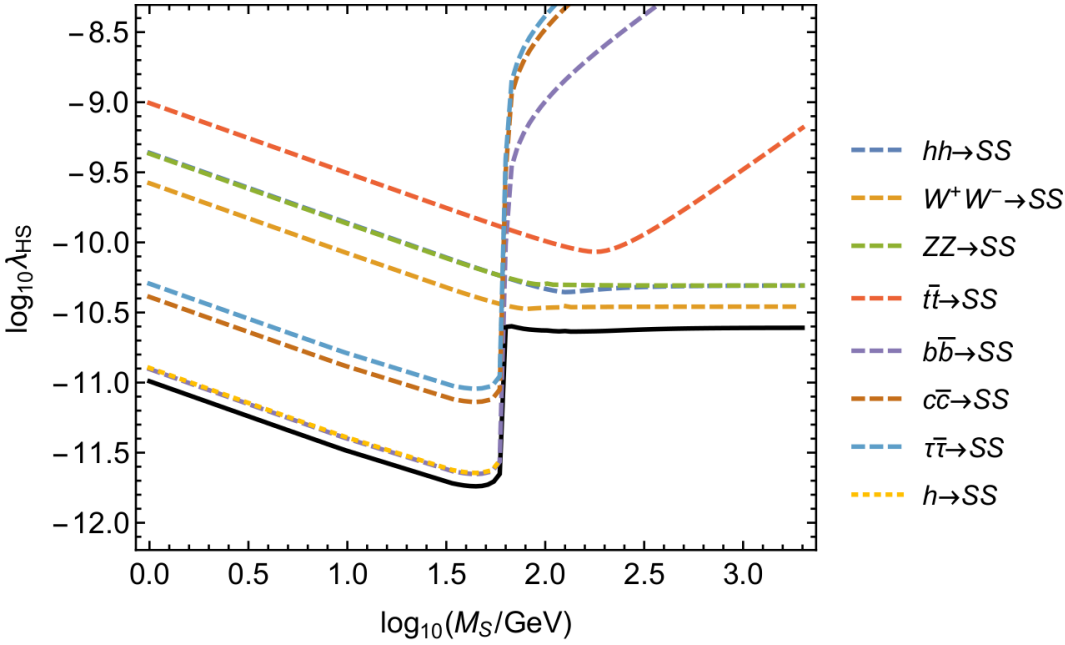




$O(10^{-10})$ is unnaturally small...
→ but could be *technically natural*!

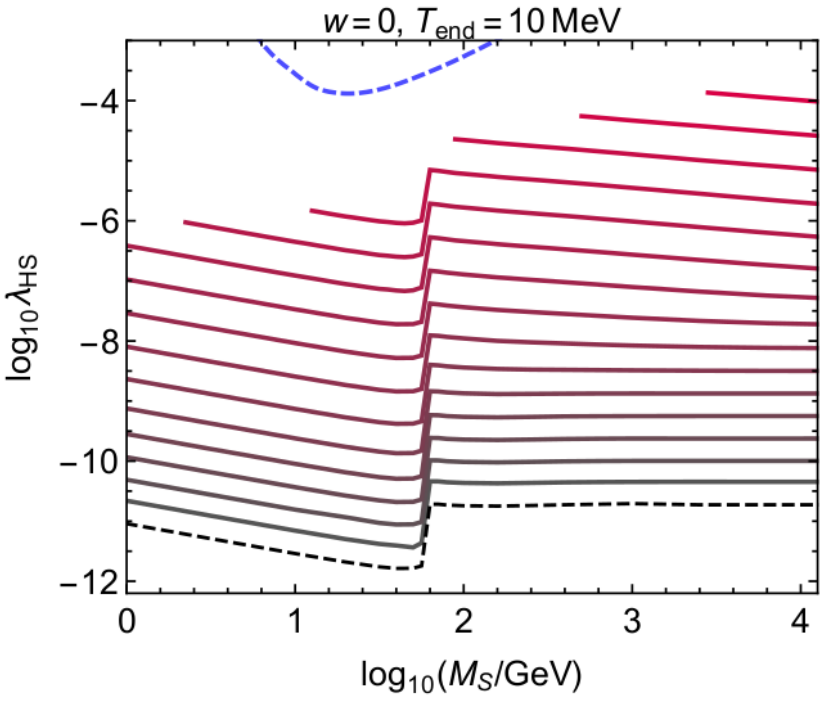
IR FIMP Dark Matter

IR FIMP:

* Small interaction rates due to renormalizable operators with $O(10^{-10})$ couplings SM-DM

* Production at T ~ Max($m_{DM,}$ $m_{mediator}$)

* But could be much larger $O(10^{-5})$ in non-standard cosmologies!!



UV FIMP Dark Matter

UV FIMP:

* Small interaction rates due to non-renormalizable operators with *high dependence on T*

$$\langle \sigma v \rangle \simeq \frac{T^n}{M^{n+2}}$$

For n < 6: Production at $T \sim T_{RH}$

UV FIMP Dark Matter

poster by M. Dutra

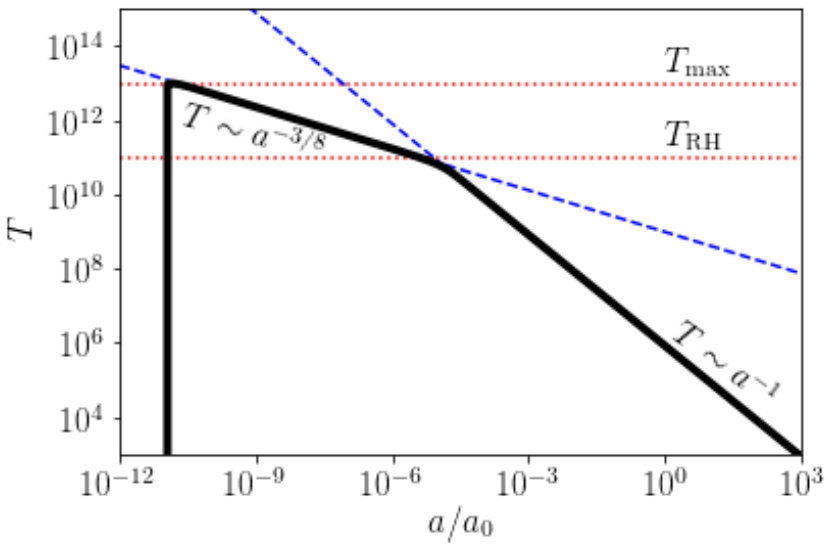
UV FIMP:

* Small interaction rates due to non-renormalizable operators with *high dependence on T*

$$\langle \sigma v \rangle \simeq \frac{T^n}{M^{n+2}}$$

For n < 6: Production at T ~ T_{RH}

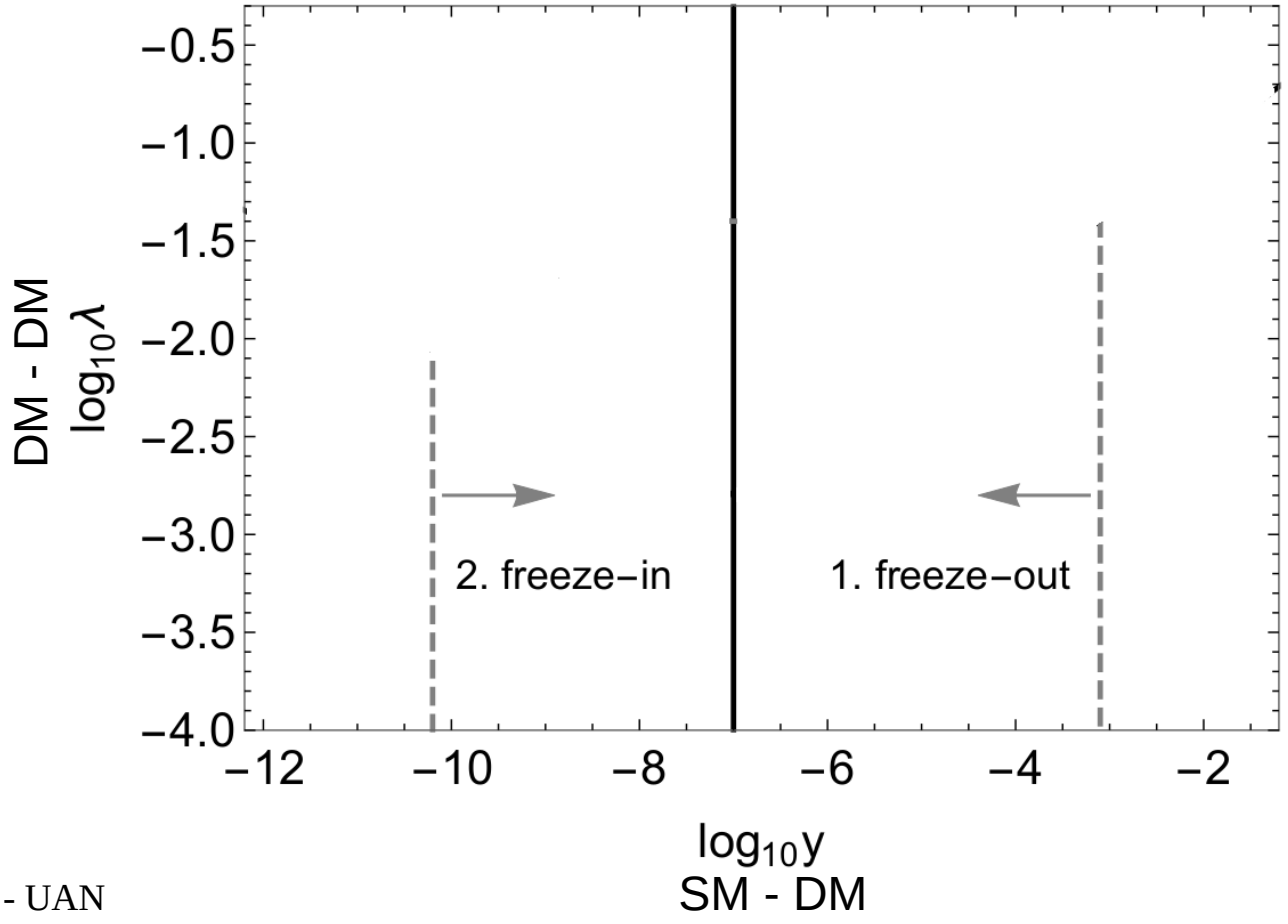
For n ≥ 6: Production at T ~ T_{max}



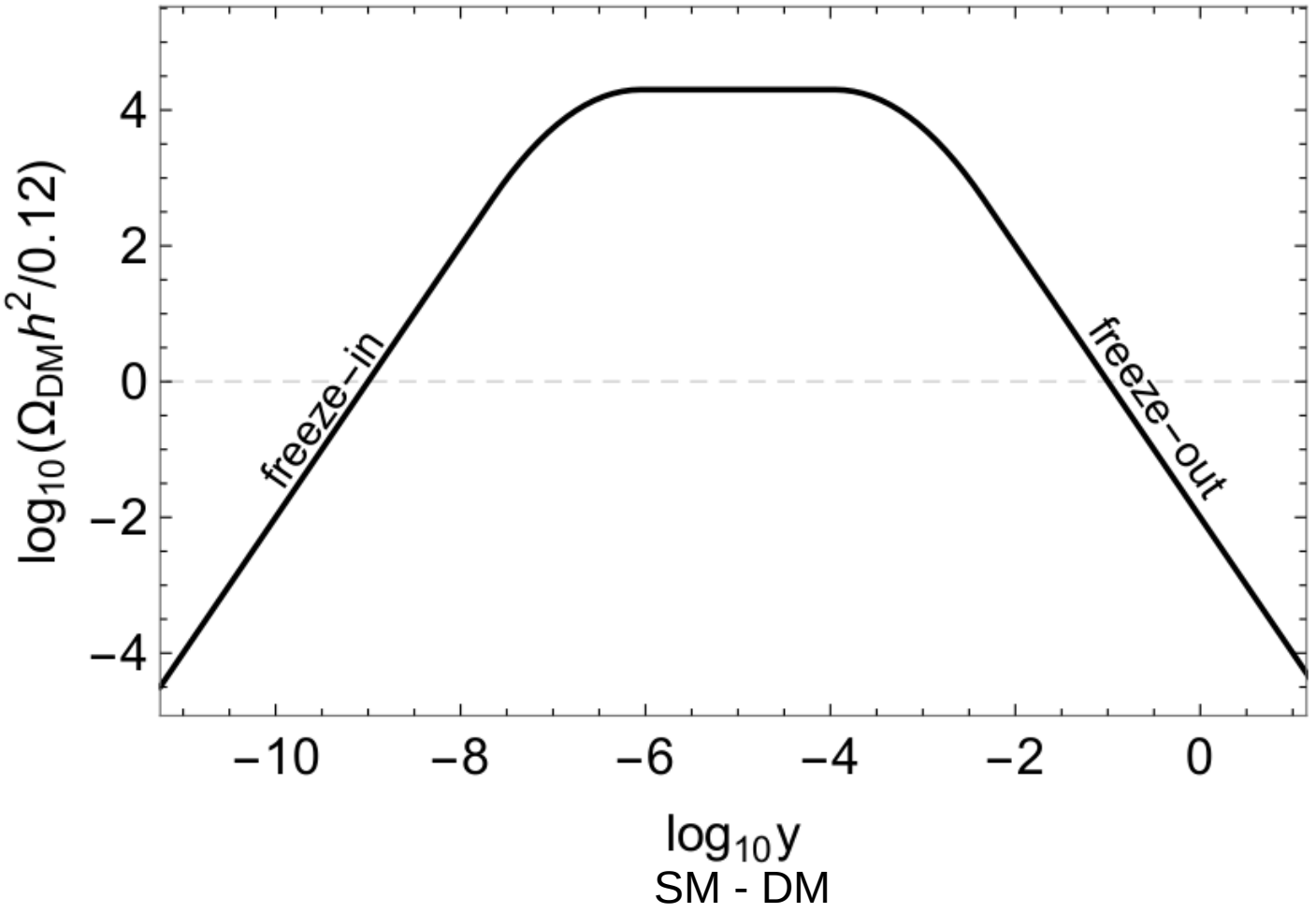
So far we have completely ignored possible interactions within the Dark Sector… :-/

Possible variations from the pure FIMP paradigm :-)

Dark Matter Phase Diagram



Dark Matter Phase Diagram



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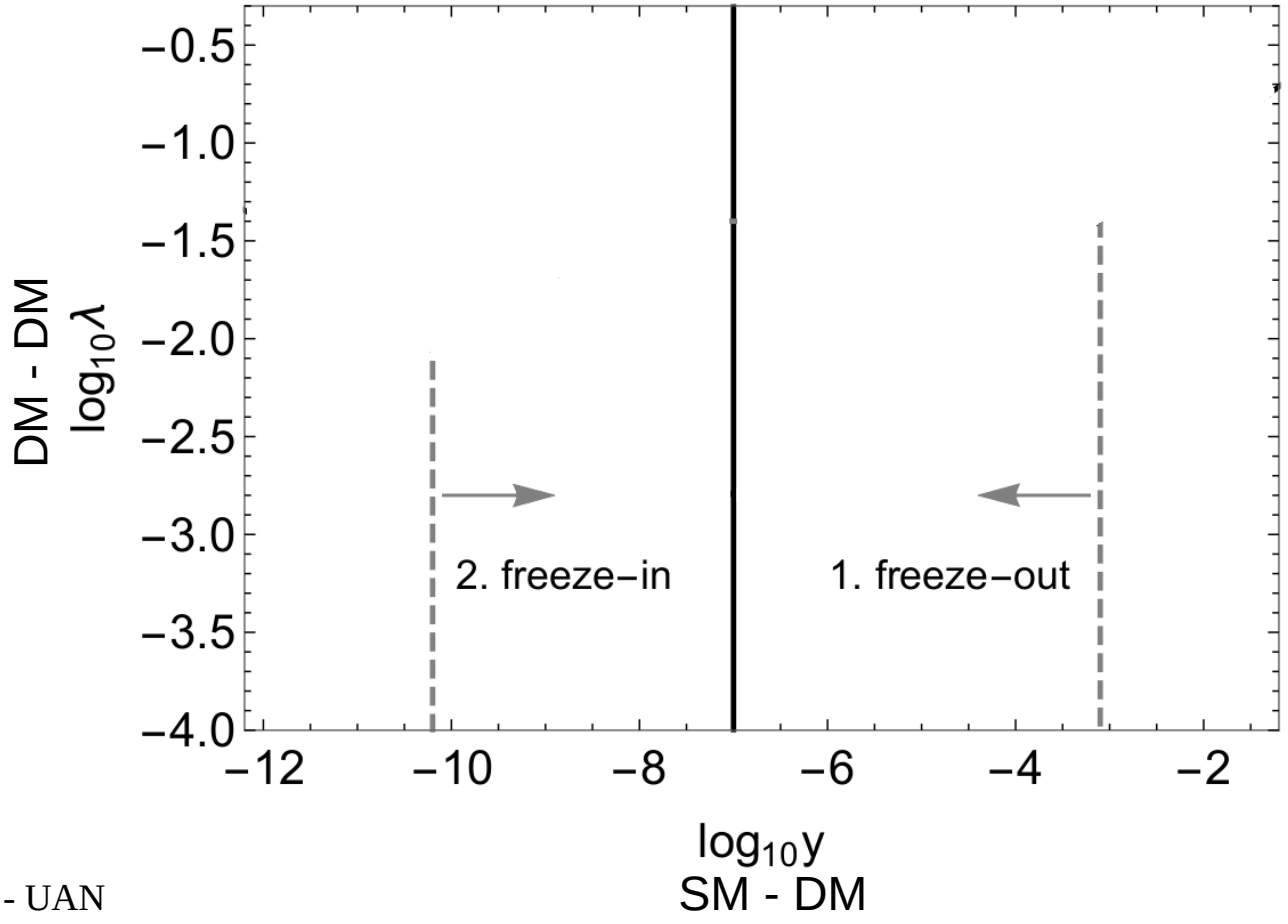
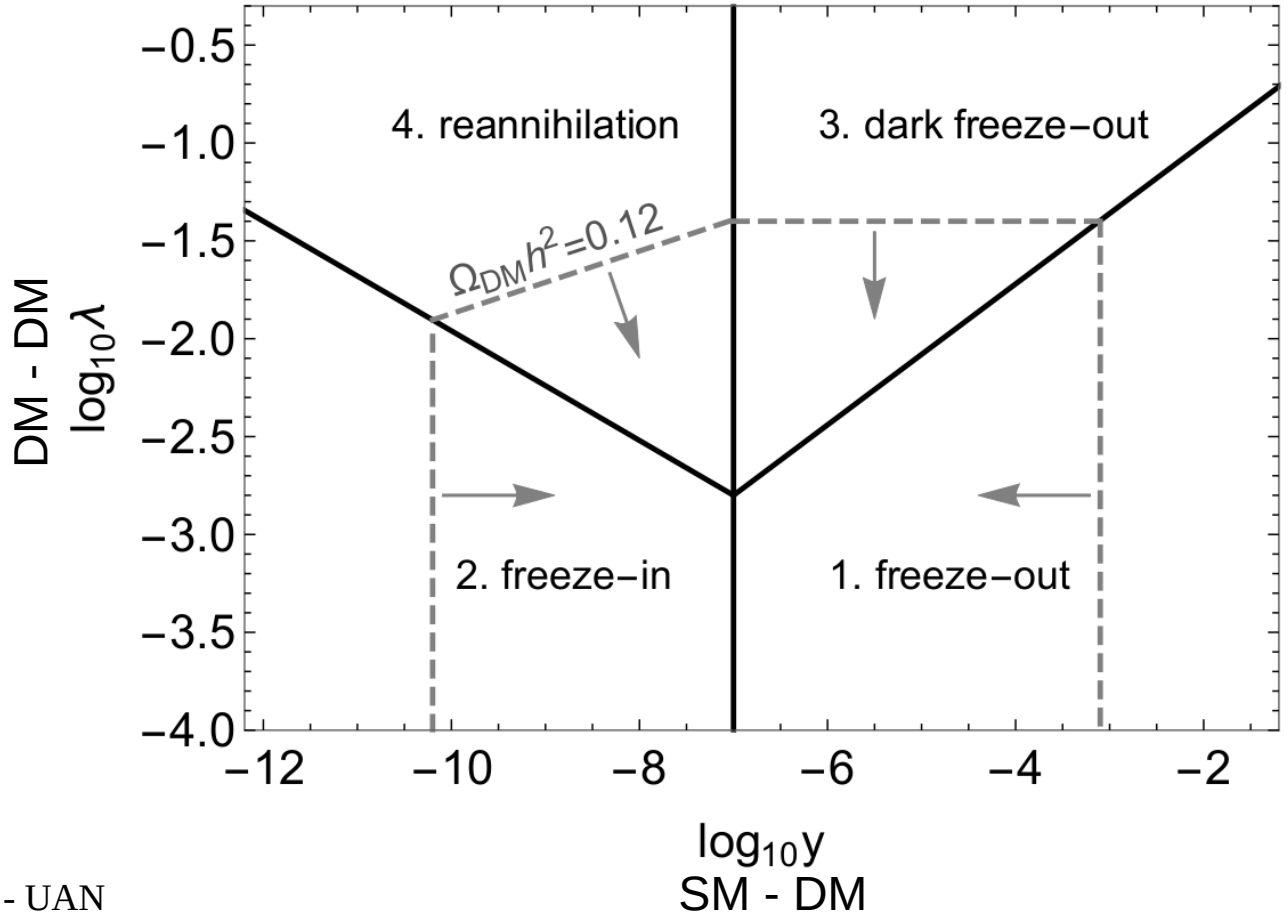


Dark Matter Phase Diagram



Dark Freeze-out:
FIMP + SIMP Dark Matter

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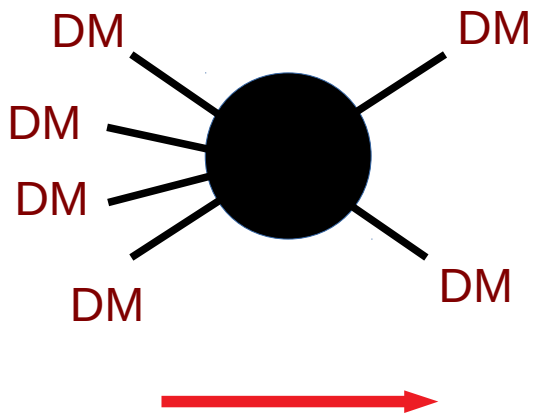
SIMP DM
$4 \to 2$ annihilations

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



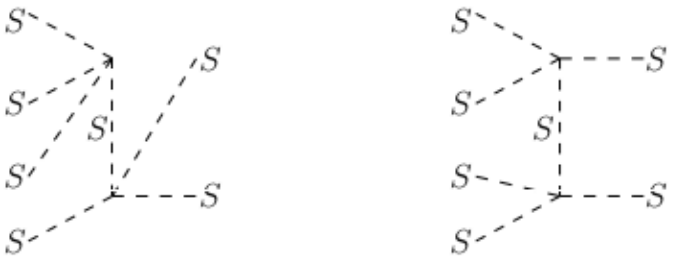
A Z_2 symmetry forbids $3 \to 2$ annihilations...
but allows $4 \to 2$ annihilations!

Could be the dominant channel if
the SM-DM portal is very suppressed…

… like in the FIMP scenario!

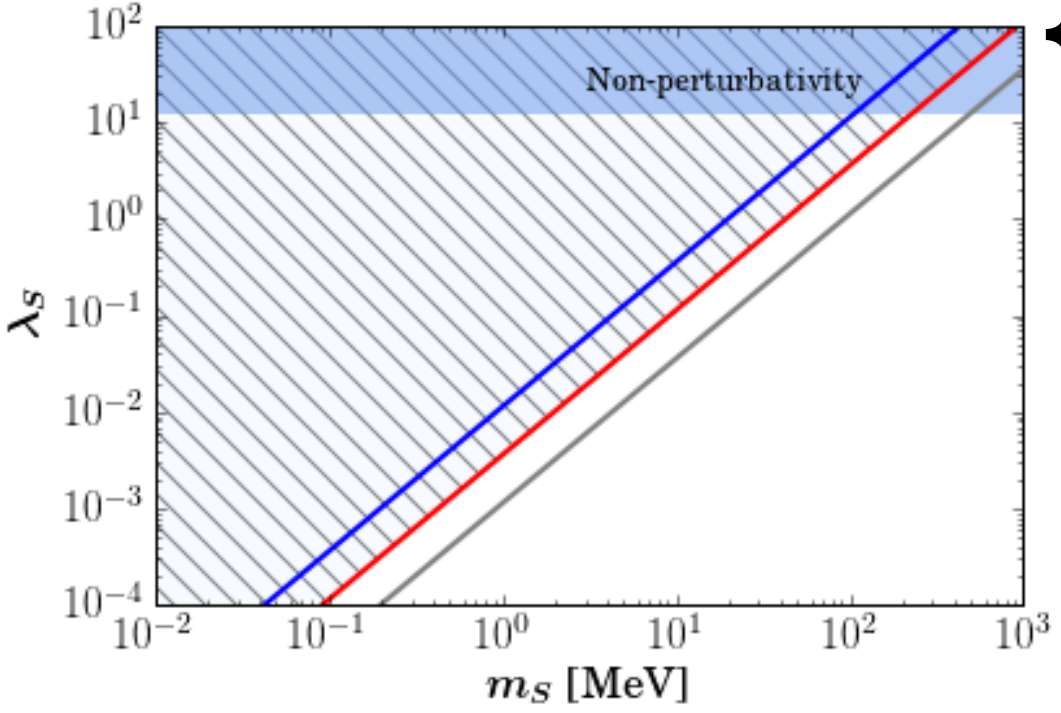
Singlet Scalar DM
$4 \to 2$ annihilations

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



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

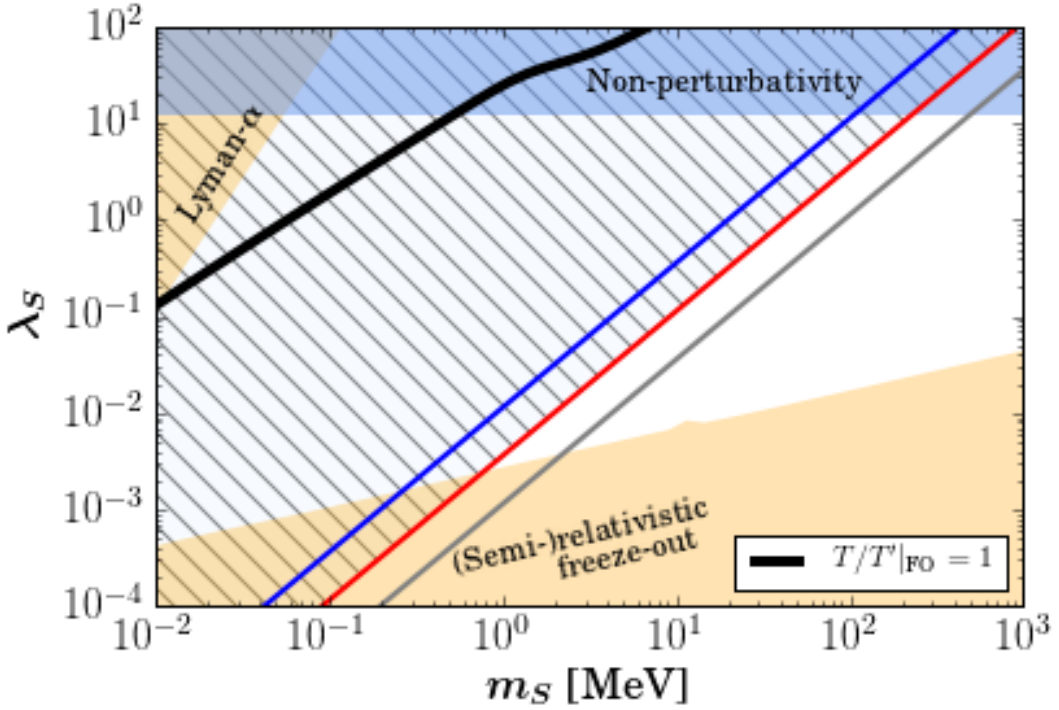
Singlet Scalar DM
$4 \to 2$ annihilations



10
1
0.1

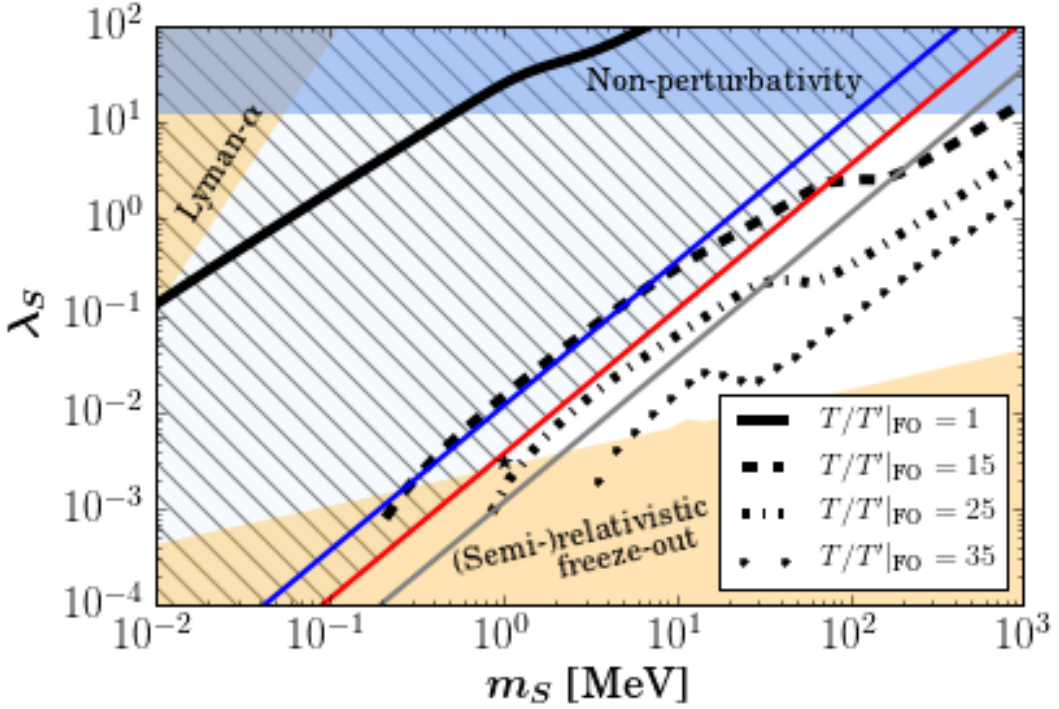
σ/m [cm²/g]

Singlet Scalar DM
$4 \to 2$ annihilations



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

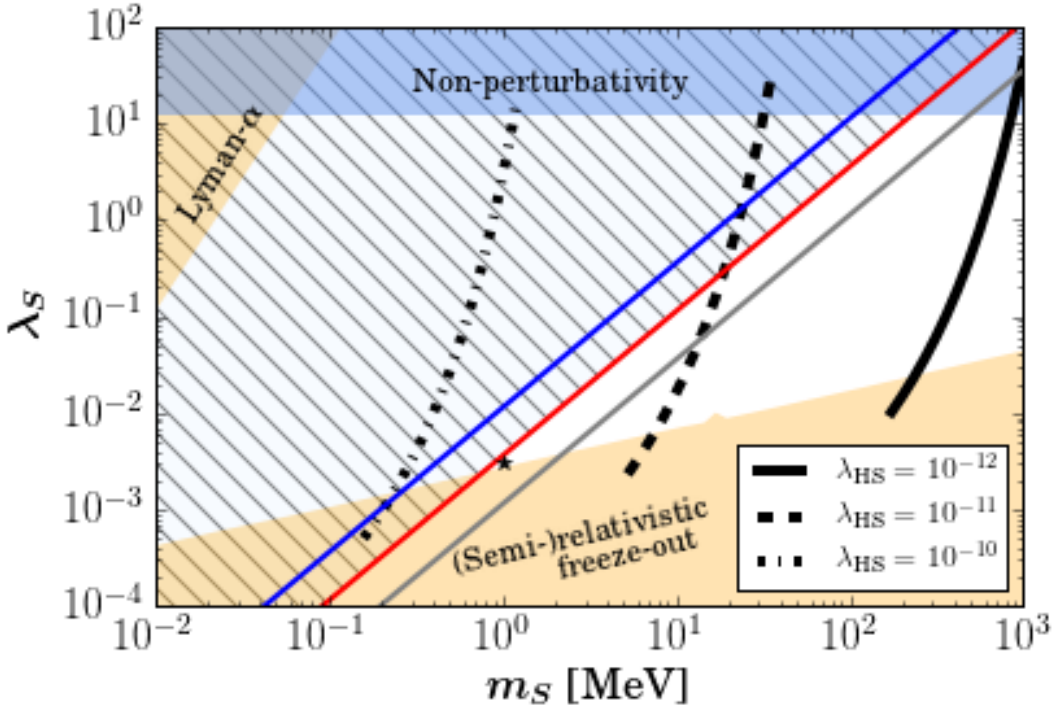
Singlet Scalar DM
$4 \to 2$ annihilations



$T_{SM} = T_{DM}$
&
$T_{SM} \neq T_{DM}$

@ DM freeze-out

Singlet Scalar DM
Dark Freeze-out via a FIMP mechanism



Reannihilation:
~ FIMP and Dark FO simultaneously

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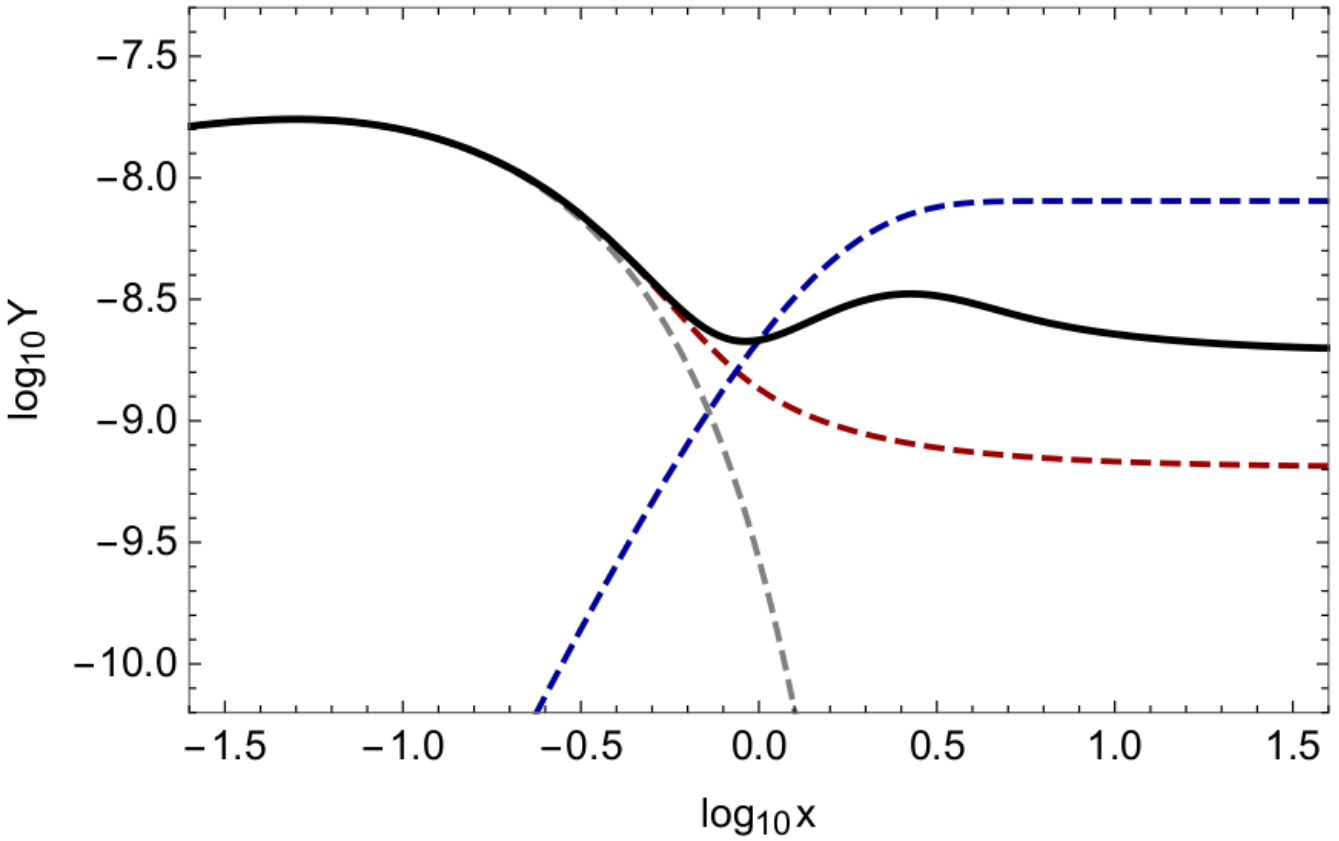
Reannihilation



The dark freeze-out occurs before the yield from the visible sector (à la FIMP) has ended

Detecting FIMPs

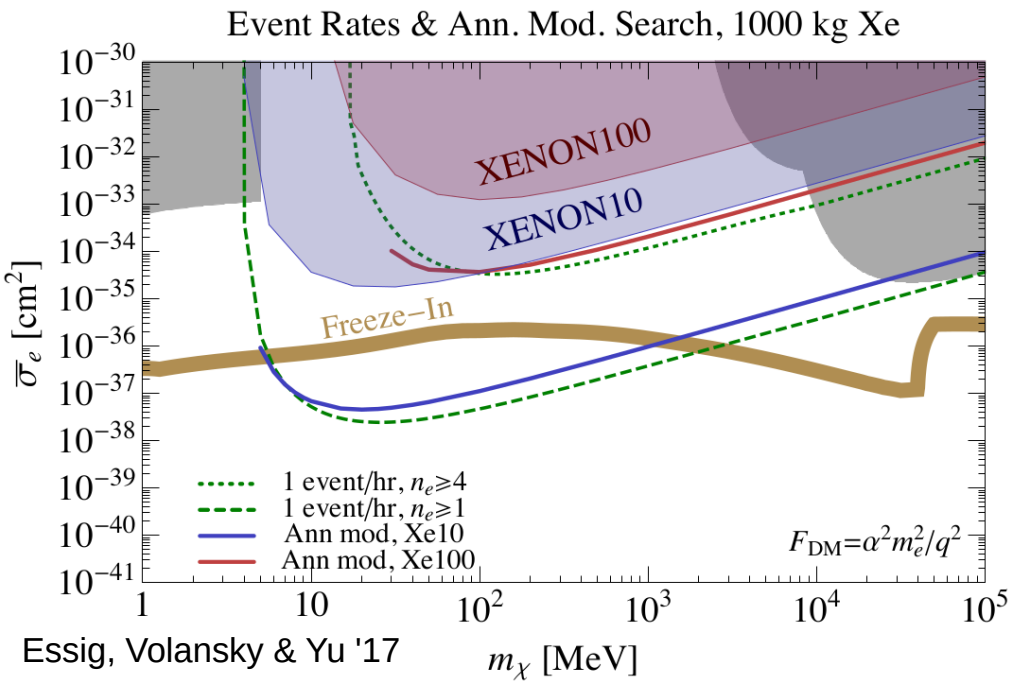
By construction, the coupling must be so feeble that the DM particle never reaches thermal equilibrium with the visible sector

$\Rightarrow$ FIMPs are inherently very difficult to test

Direct Detection

Light DM has to have a large number density
⇒ enhances the detection rates

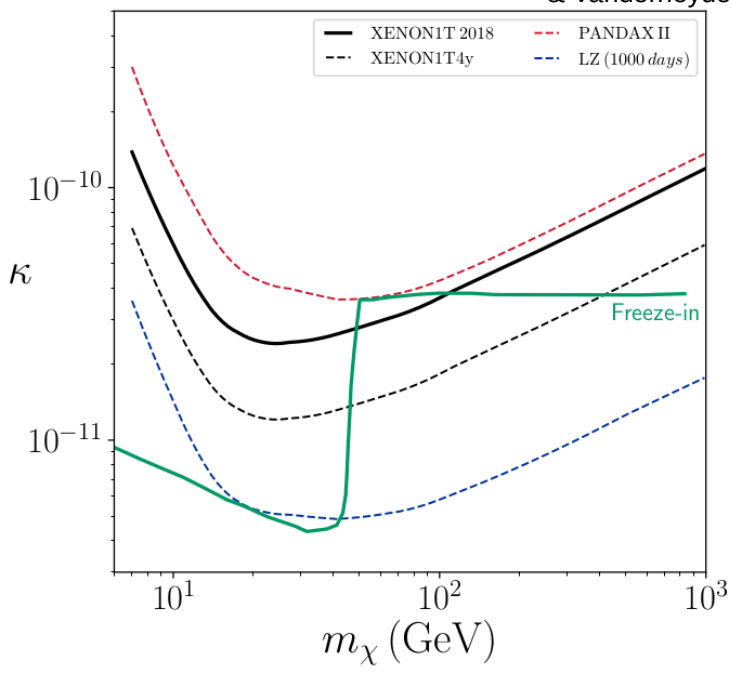
Multiple experimental setups have been suggested for the detection of sub-GeV DM



Essig, Volansky & Yu '17

DM with **Light mediators**
⇒ enhances the detection rates

Hambye, Tytgat, Vandecasteele & Vanderheyden '18



Indirect Detection

Very challenging...

- PeV IceCube events could come from decaying FIMP DM
- The 3.5 keV line from decaying FIMP DM
- X-rays bounds if light DM or light mediators

Collider Searches

Very challenging...

- Collider experiments are typically not sensitive to FIMP DM,
  due to the small production cross section
- However, appearance of *displaced vertices* is possible!
- Look for the mediators, which do not have to be feebly coupled to the SM

Astro & Cosmo Signatures

- Small-scale structures:
  FIMP DM with sizable self-interactions can have a strong impact in the structure formation
  → “too big to fail” and “missing satellites” problems

talk by F. Kahlhöfer

- Non-observation of DM isocurvature in CMB places constraints on FIMP properties
  → Lower bounds on the SM-DM coupling

- BBN bounds
- Lyman-α

Conclusions & Outlook

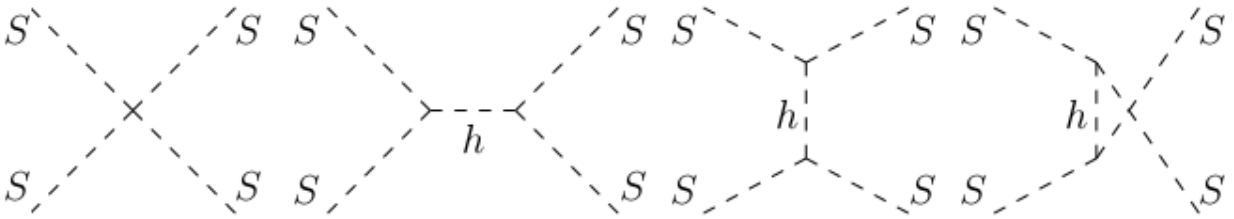
- The nature of Dark Matter is still unknown
- The FIMP framework provides for a compelling alternative to the standard WIMP paradigm
- The *unnatural* small couplings could be *technically natural* and enhanced by non-standard cosmologies
- DM could naturally have a different temperature
- FIMP DM: IR vs UV
- Multiple possibilities beyond the simplest FIMP scenario: Dark Freeze-out, Reannihilation...
- Cosmological and astrophysical observations provide a valuable resource on testing different DM models
- Continue searches for WIMPs, FIMPs, and other DM candidates

  (Colliders, direct and indirect detection...)

Vielen Dank!

Nic

Dark Matter Self-Interactions

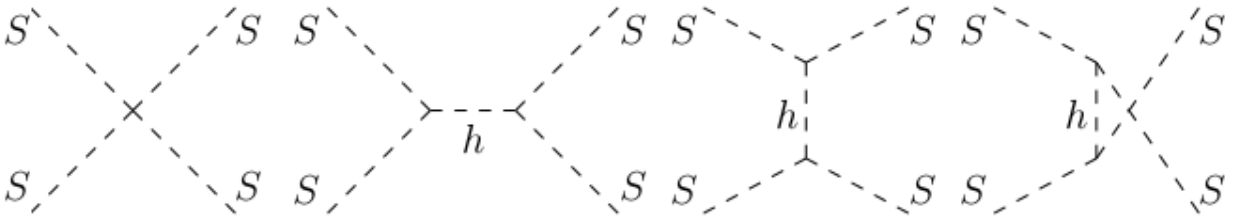


$$\frac{\sigma_{SS}}{m_S} \sim \frac{9}{8\pi}\,\frac{\lambda_S^2}{m_S^3}$$

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

Implies
- $\lambda_S \sim 1$
- $m_s \sim 100$ MeV

Dark Matter Self-Interactions & Invisible Higgs decay



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

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

The Higgs tends to annihilate into DM
BR(h → inv.) < 20%

* $\lambda_{HS} < 7\times10^{-3}$

How to produce such a Self-Interacting Dark Matter?

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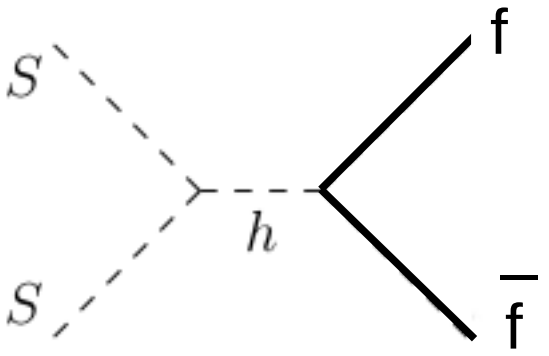
WIMP DM :-/

DM can (only) annihilate into light fermions

other annihilation channels kinematically closed!

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

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

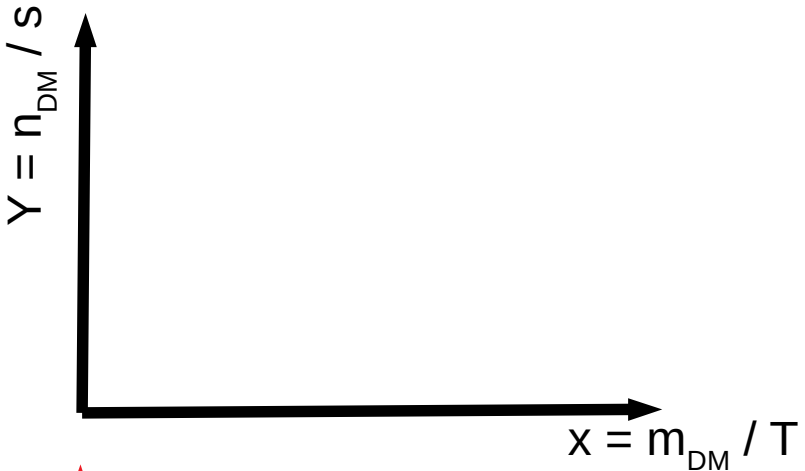


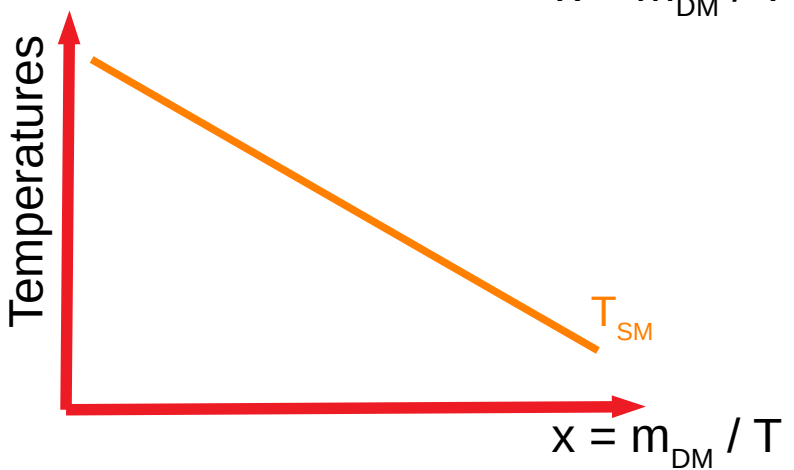
→ Universe overclosed

→ SSDM with sizable self-interactions can not be a WIMP

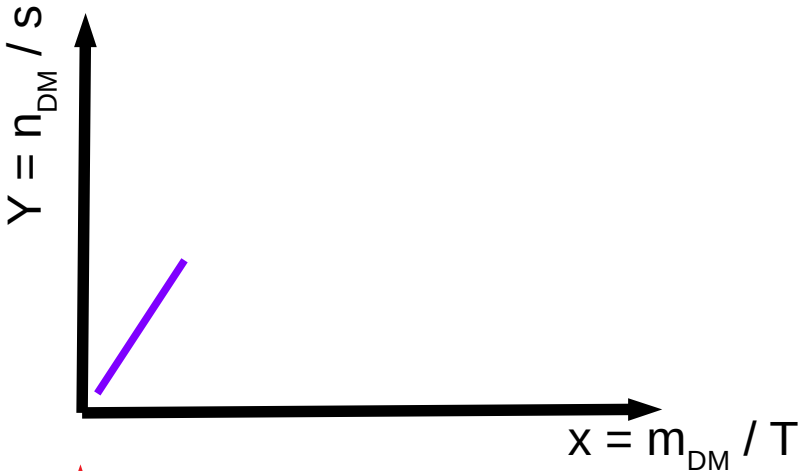
How to produce such a temperature difference?

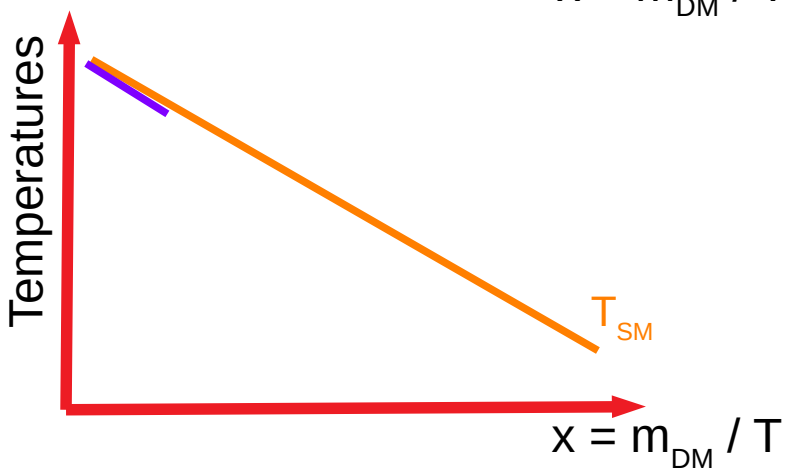
(Non-) Thermal evolution of DM





(Non-) Thermal evolution of DM

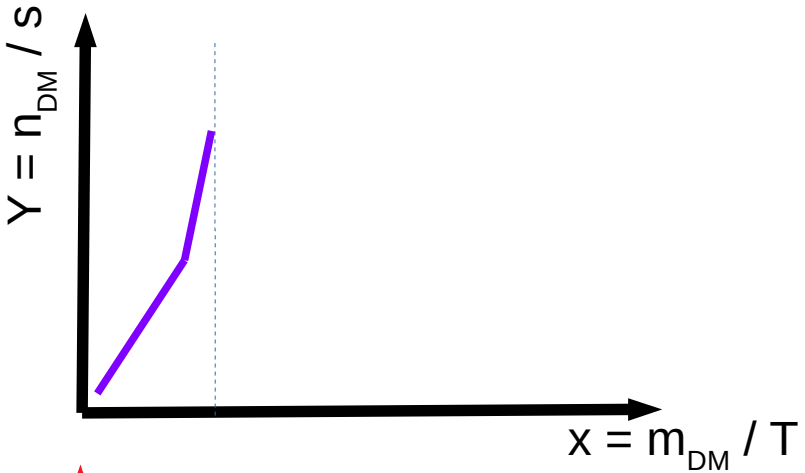


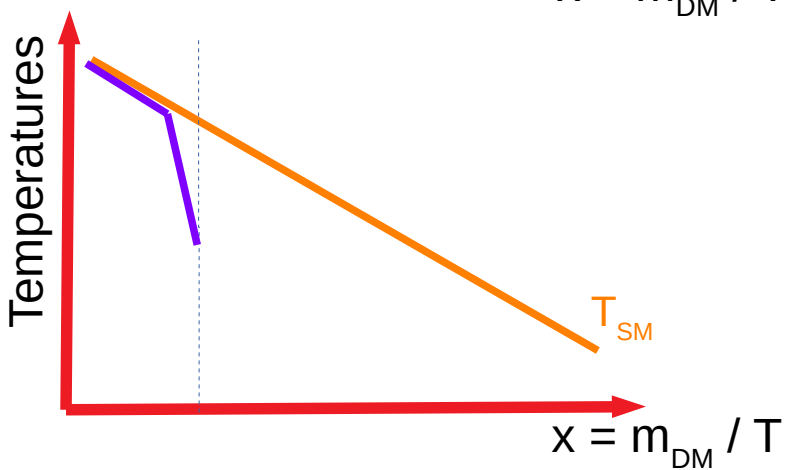


DM Production

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

(Non-) Thermal evolution of DM



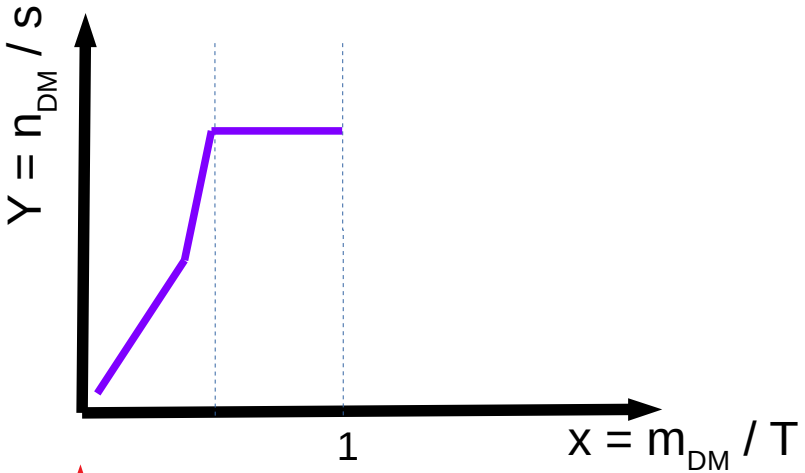


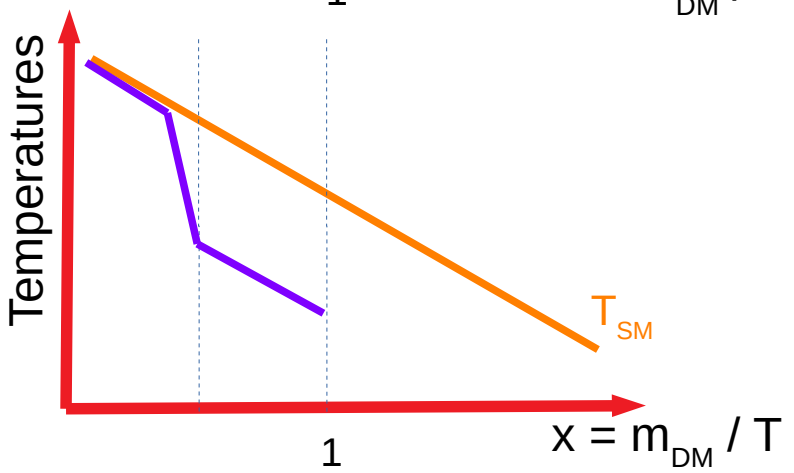
DM Production

* *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





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**.
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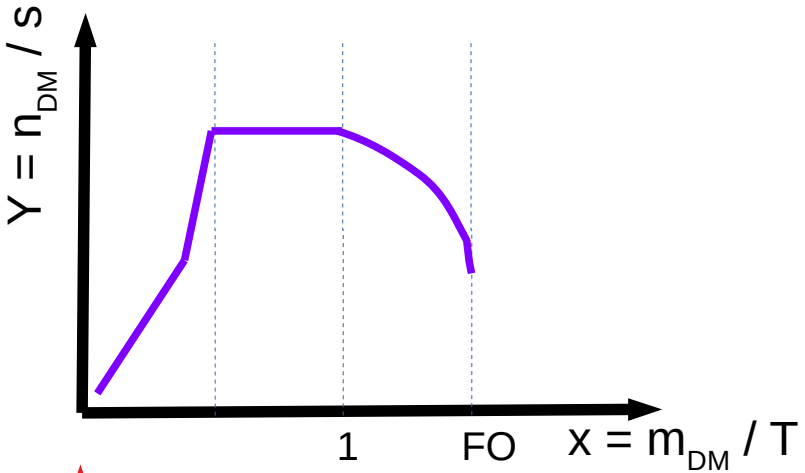
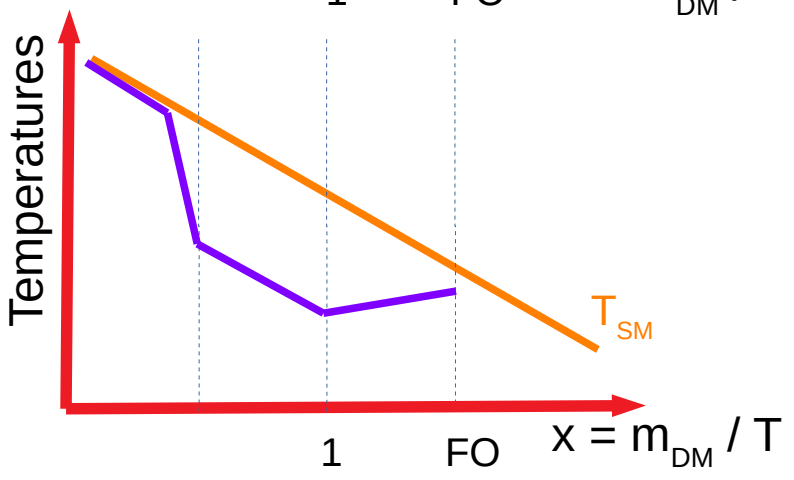
Thermal Equilibrium

* Chemical equilibrium **2 ↔ 4**

(Non-) Thermal evolution of DM





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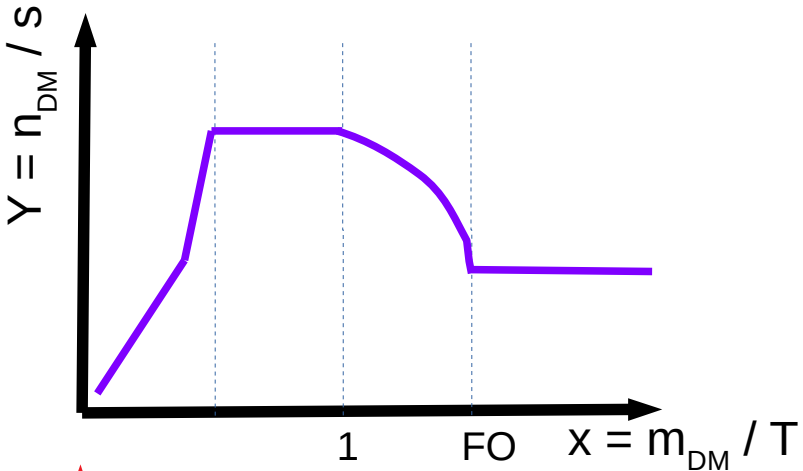
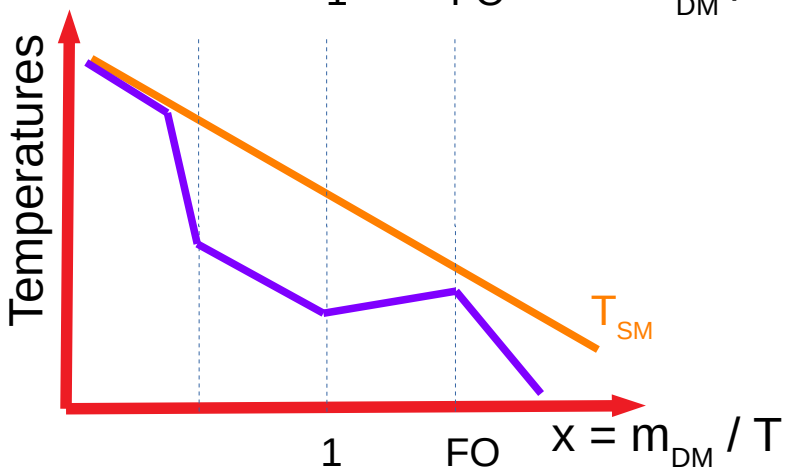
DM Annihilation

* Dark freeze-out **4 → 2**

(Non-) Thermal evolution of DM





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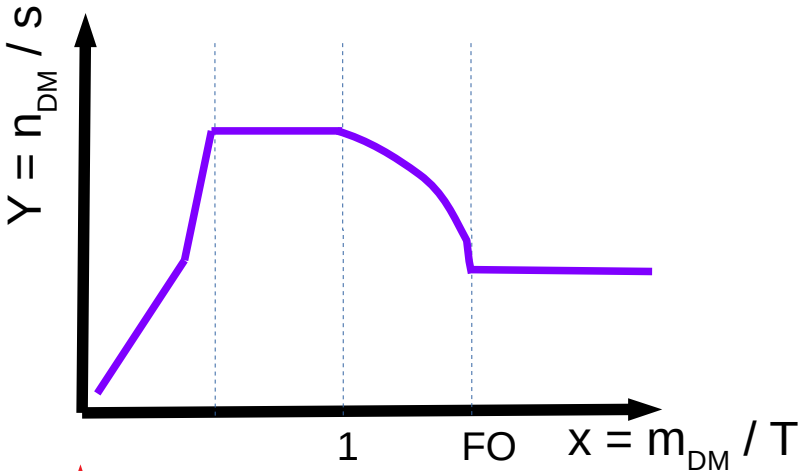
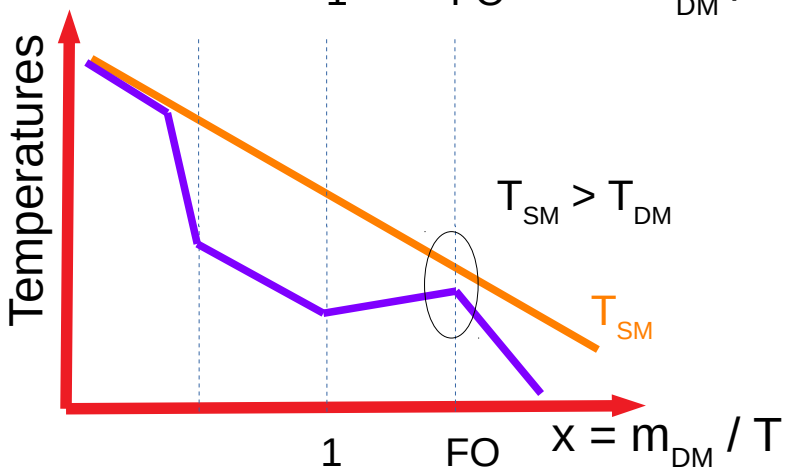
After the Freeze-out

* Relic abundance
  Non-relativistic DM cools down faster

(Non-) Thermal evolution of DM





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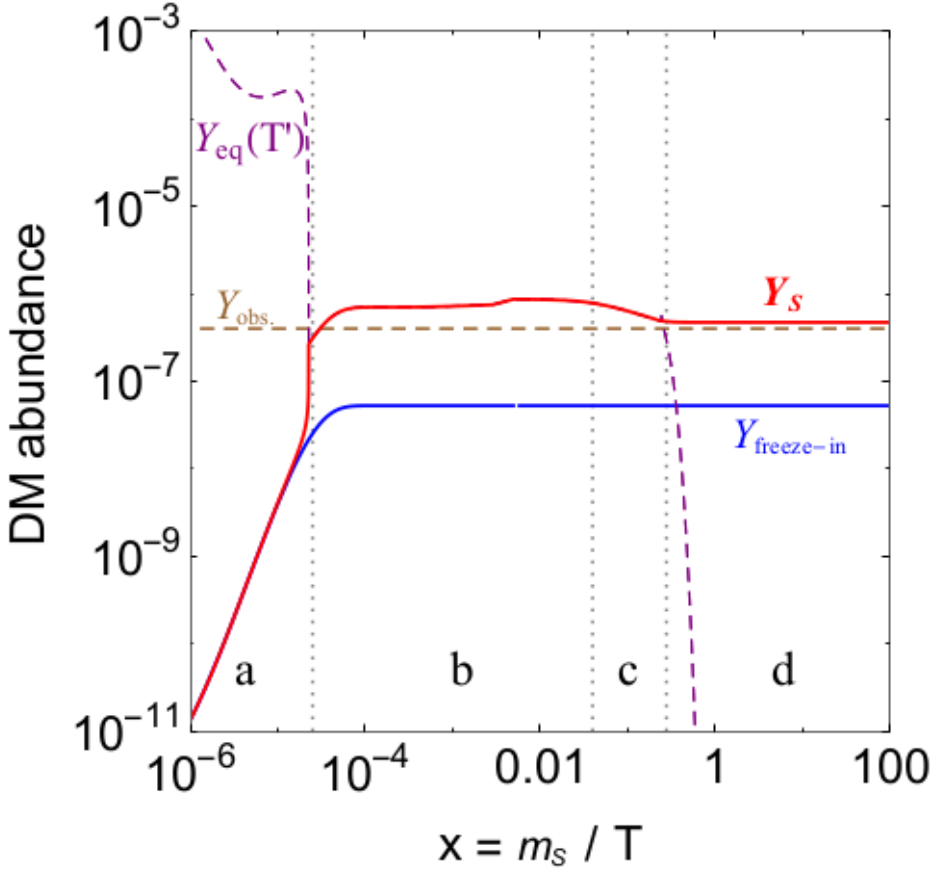
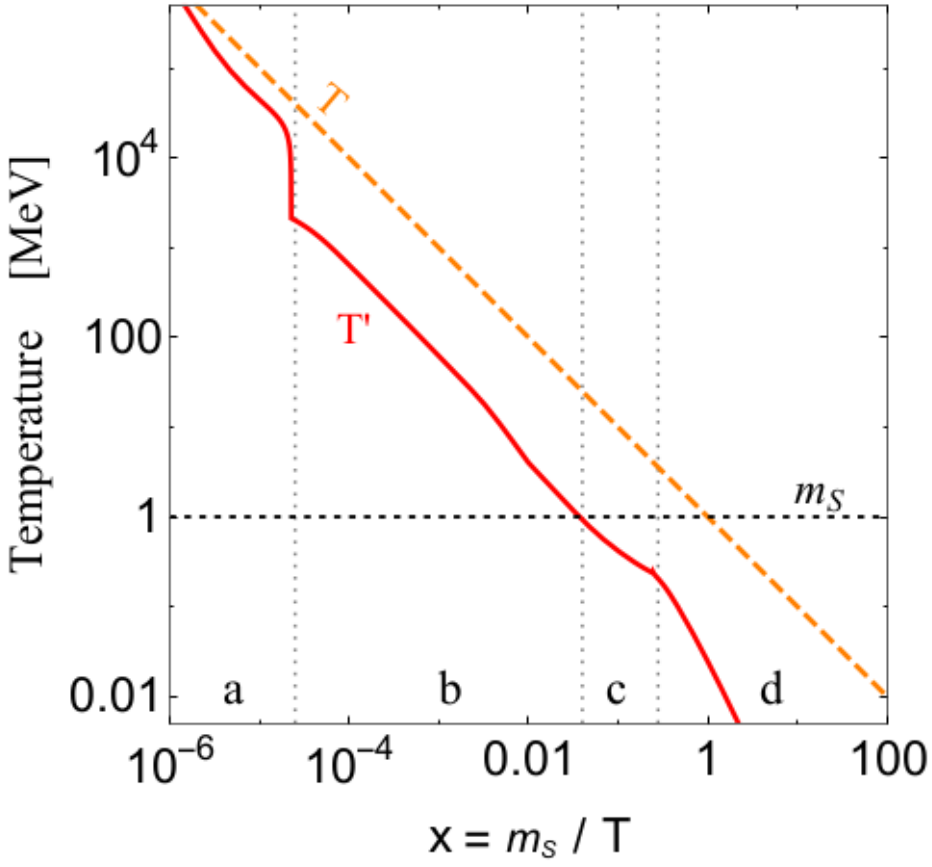
Generating $T_{DM} < T_{SM}$ via the Higgs Portal





Singlet Scalar DM
Dark Freeze-out via a FIMP mechanism