Theorie LHC France workshop
7-9 Novembre 2016
IPN Orsay

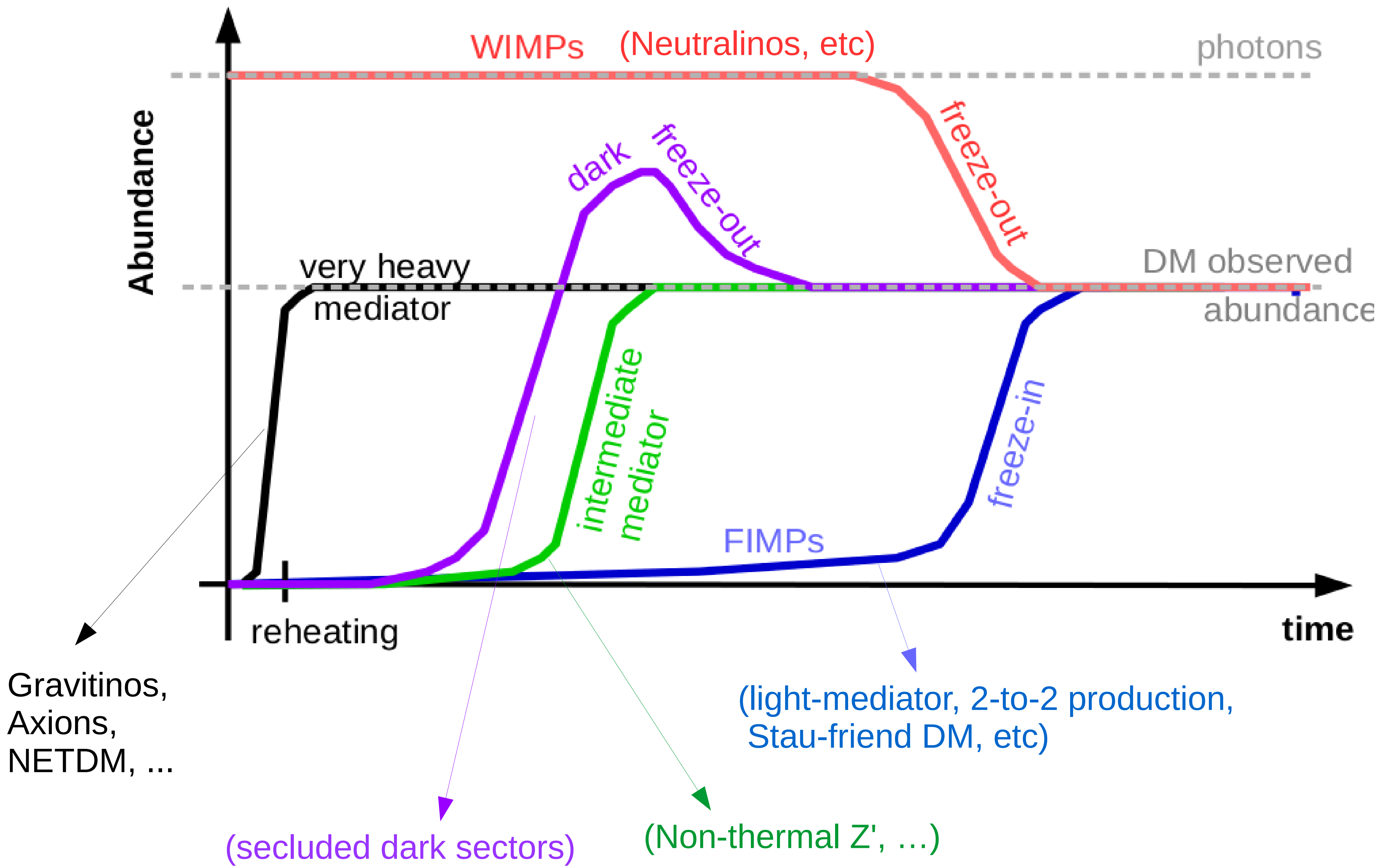
Self-interacting Dark Matter

Bryan Zaldívar @ Annecy

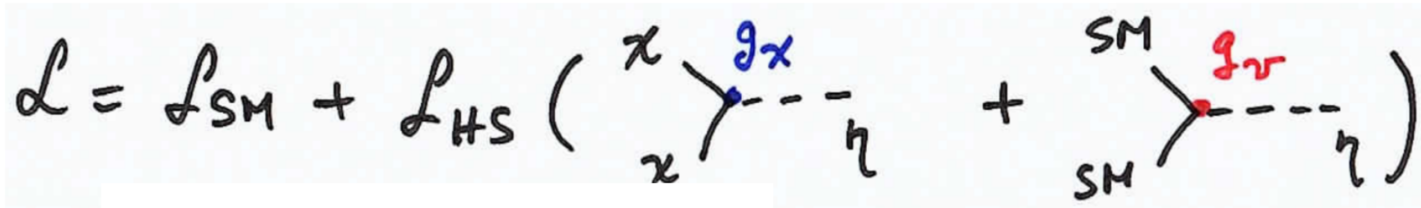
Outline

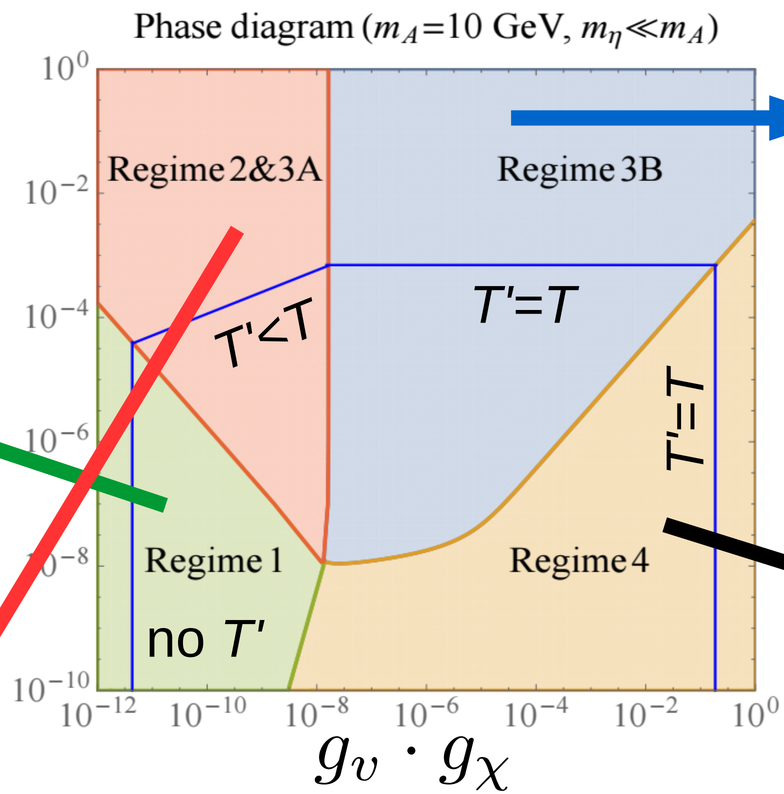
- Thermal histories of dark matter
- Small-scale problems of CDM
- Self-interacting DM and issues
- Proposition and results

Different thermal histories of DM

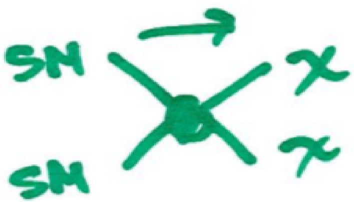


Different thermal histories of DM





Freeze-in



Dark Freeze-out (T' = T)

Freeze-out standard

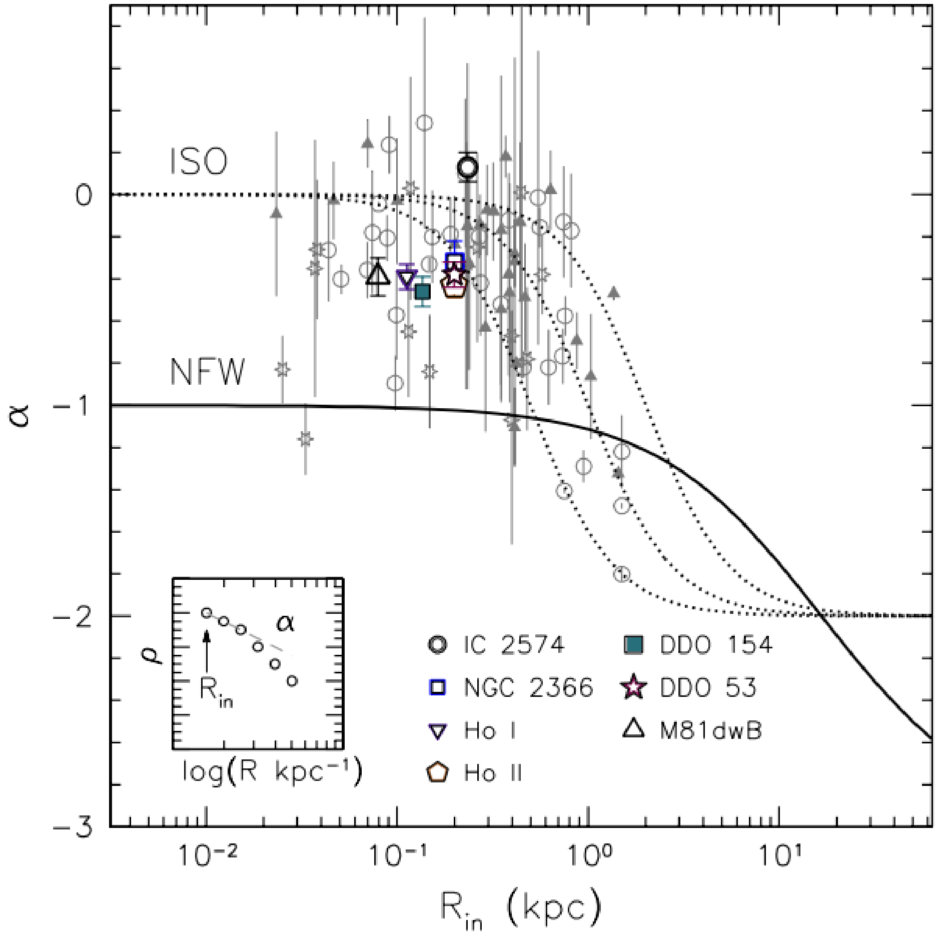
Dark Freeze-out (T' < T)

- Freeze-in production **+** dark annihilation

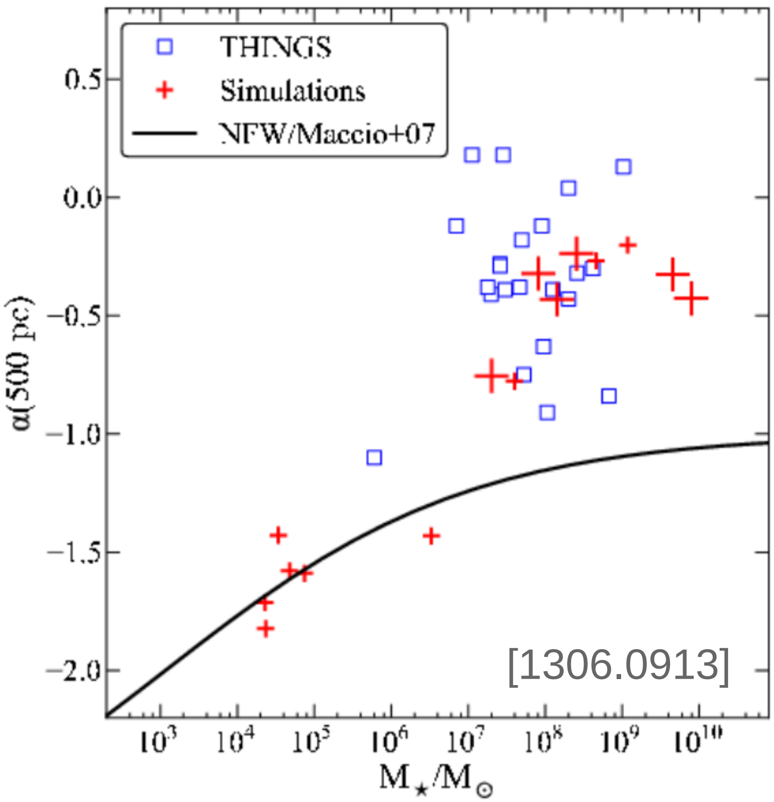
T’: temperature of dark sector
T’: temperature of visible sector

Small-scale problems of CDM

“Cusp vs. Core”



“Too big to fail”



“Missing satellite problem”: *it is going down with recent discoveries and prospects*

Alternatives so far...

1) Baryonic effects
Baryonic matter can evacuate DM from the central regions

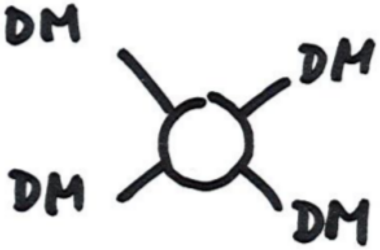
[Navarro et al, 1996, MNRAS, 283, L72]
[Pontzen and Governato, 2012, MNRAS, 421, 3464]

2) Warm dark matter
Free-streaming of ~keV DM predict less dense haloes today

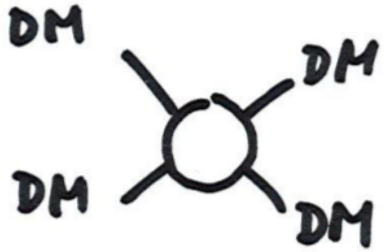
[Lovell et al, 2012, MNRAS, 420, 2318]
[Becker et al, 1306.2314]

3) Self-interacting dark matter
a) cored profiles, **b)** offset between centroids of galaxies and DM halos

[Carlson et al, Astrophys.J. 398 (1992) 43-52]
[Tulin et al, 1302.3898]
[Kahlhoefer et al, 1308.3419]
[Bernal et al, 1510.08063]



Self-interacting dark matter



★ **Galactic scales** ($v \sim 10\ \mathrm{km/s}$)

Simulations:

$$0.1 \lesssim \sigma/m \lesssim 10\ \mathrm{barn/GeV}$$

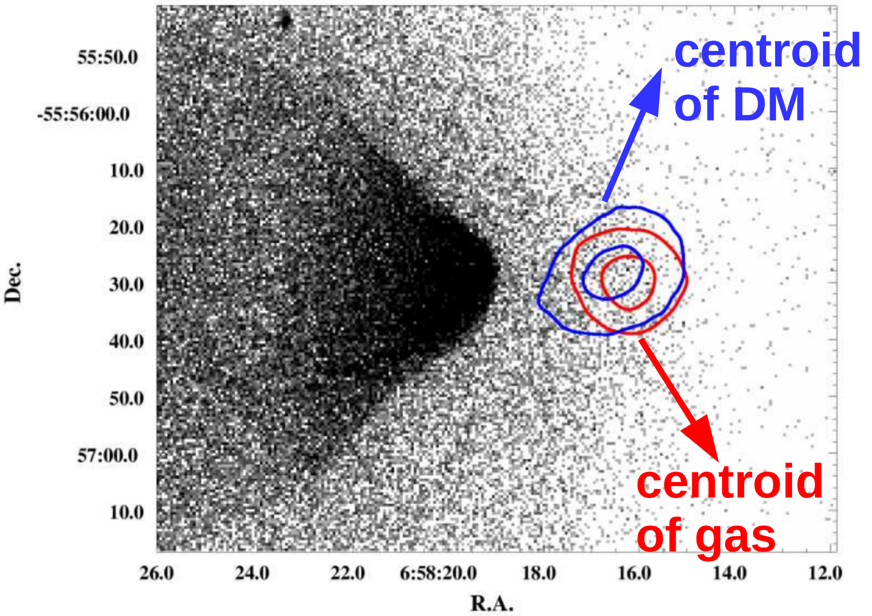
[Kaplinghat et al, 1508.03339]

★ **Cluster scales** ($v \sim 1000\ \mathrm{km/s}$)

Observations:

$$\sigma/m \lesssim \mathcal{O}(1)\ \mathrm{barn/GeV}$$

[Clowe et al, 0704.0261]

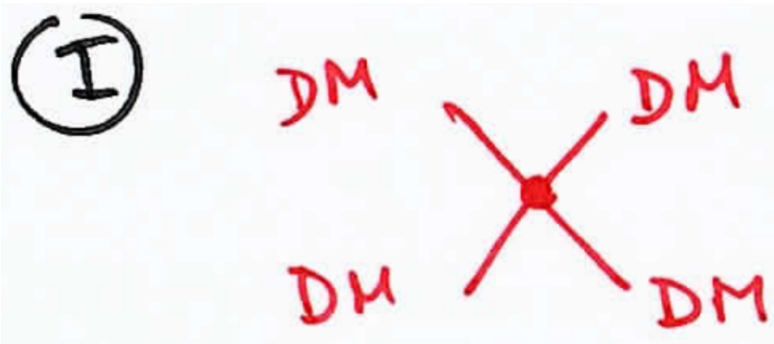


- Compatibility achieved by velocity dependence

- Typical WIMP cross sections are 10^{12} times smaller!

Self-interacting dark matter (SIDM)

Essentially two ways to obtain such large cross sections:



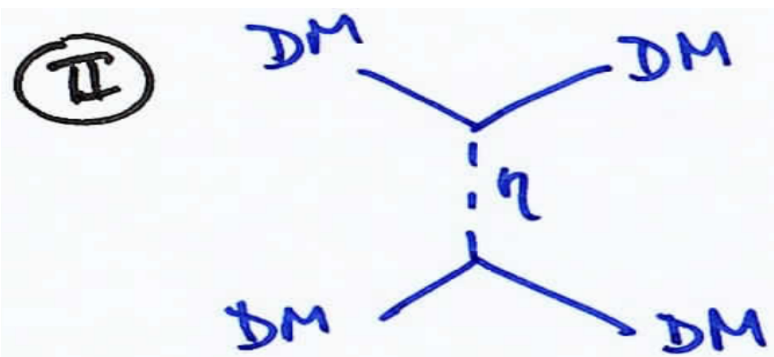
$$\sigma \sim \frac{\alpha^2_{\mathrm{DM}}}{m^2_{\mathrm{DM}}}$$

maximum possible

$\sim 100\ \mathrm{MeV}$

[Carlson et al, Astrophys.J. 398 (1992) 43-52]

[Volansky et al, 1402.5143]



e.g. $\mathcal{O}(\alpha_{\mathrm{EW}})$

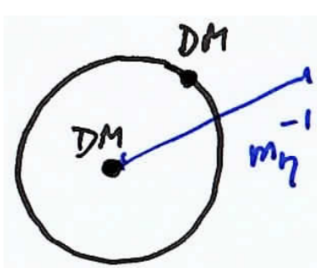
$$\sigma \sim \frac{\alpha^2_{\mathrm{DM}}}{m^2_{\mathrm{DM}}} \underbrace{f(m_{\mathrm{DM}}, m_\eta, \alpha_{\mathrm{DM}}, v)}_{f \gg 1}$$

wide range

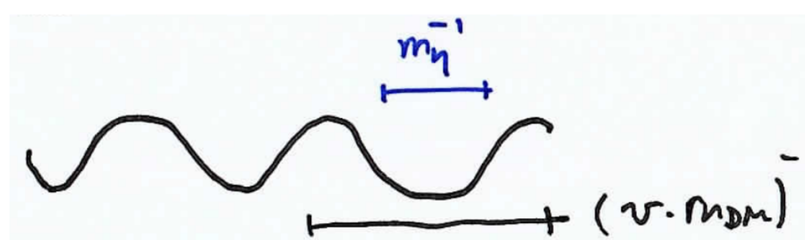
if long-range, non-relativistic interactions

"Landau-Lifshitz" physics (Schröndinger equation, non-perturbative enhancements,...)

$m_\eta \ll \alpha_{\mathrm{DM}} m_{\mathrm{DM}}$

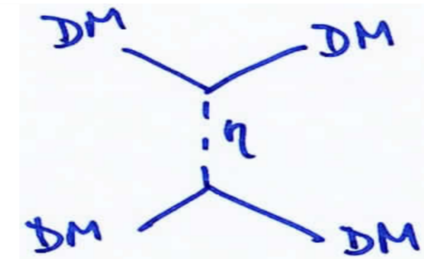


$m_\eta \gg v m_{\mathrm{DM}}$



Phenomenological issues of SIDM models

★ **If long-range interactions:**



a) if $m_{\rm DM} \gg 1~{\rm GeV}$

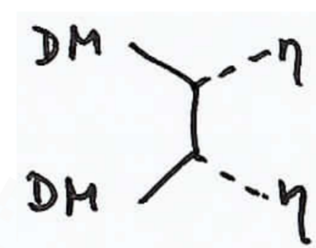
Direct detection cross sections are typically too large

light mediators

assuming $T_{\rm DM} = T_{\rm SM}$

(sizeable DM-SM couplings)

b) if $m_{\rm DM} < 1~{\rm GeV}$



"dark freeze-out"

Direct detection maybe OK, but…

- Challening to get correct abundance from freeze-out
- Typically face cosmological issues (BBN, CMB)

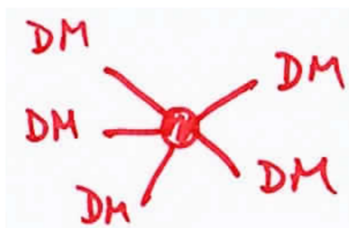
very light mediators decaying to SM d.o.f.

Phenomenological issues of SIDM models

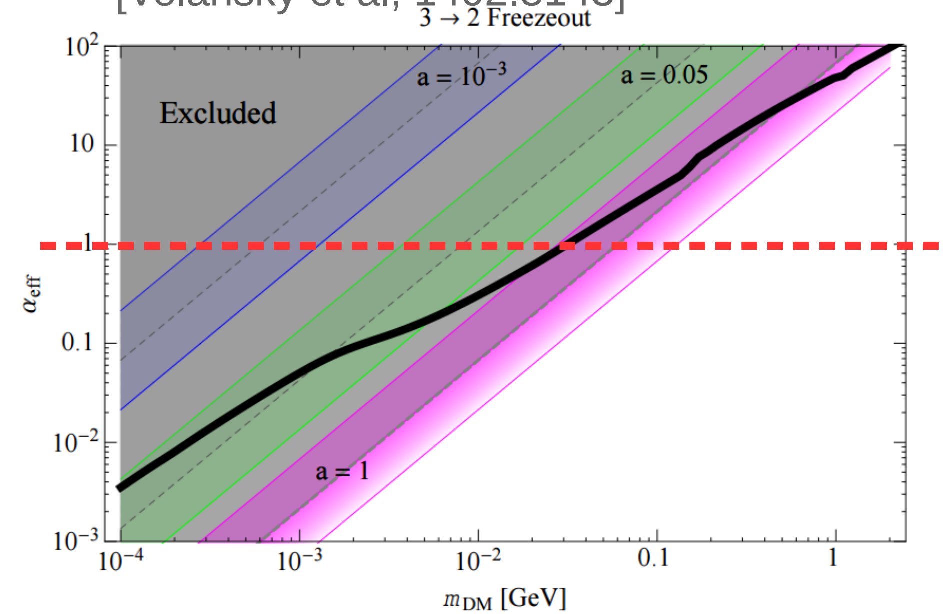
★ **If short-range interactions:**

a) Relic abundance

"on the verge" on non-perturbativity



[Volansky et al, 1402.5143]



b) DM bath reheats itself

problems with structure formation

Impose kinetic equilibrium with the SM bath

Constrained by many experiments
(e.g. fixed-target, etc.)

Proposal

Essentially all problems above came because of having sizeable couplings with the SM

Relax that, and find otherdark matter genesis comatible with self-interactions while having smaller couplings

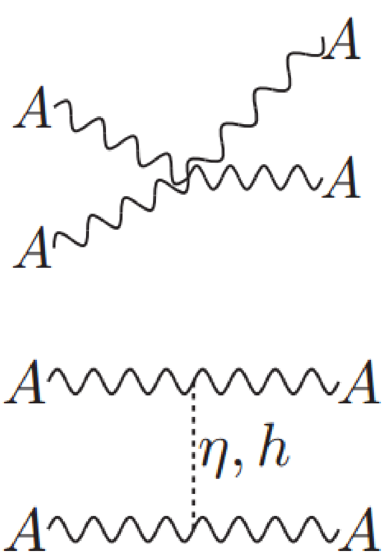
Illustrative model: HVDM

[Hambye, 0811.0172]

$$\mathcal{L} = \mathcal{L}_{SM} - \underbrace{\frac{1}{4} F'^{\mu\nu} \cdot F'_{\mu\nu}}_{SU(2)_X} + (D_\mu \phi)^\dagger (D^\mu \phi) - \mu_\phi^2 \, \phi^\dagger \phi - \lambda_\phi \, (\phi^\dagger \phi)^2 - \lambda_m \, \phi^\dagger \phi \, H^\dagger H$$

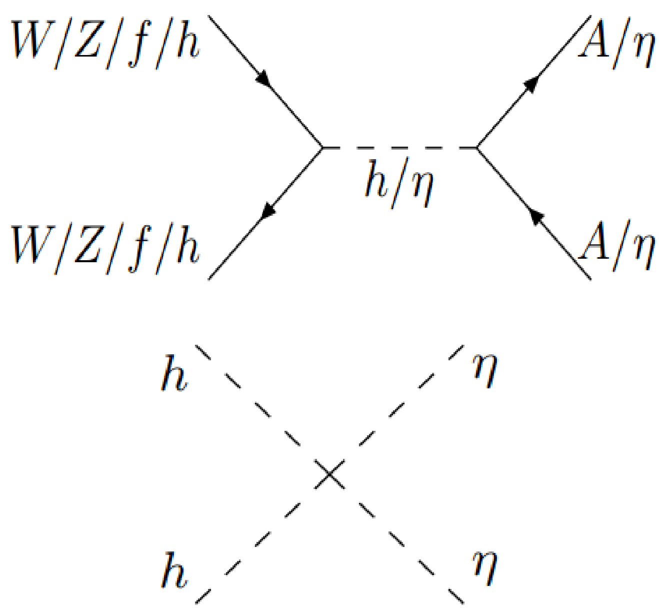
- **Gauge bosons: DM candidates** (degenerated, Custodial symmetry)
- **Real Scalar boson**, Higgs portal

Self-Interactions



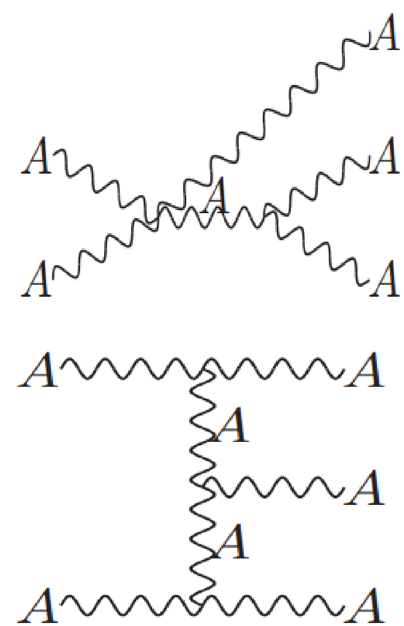
(plus some others...)

Production from SM



(plus some others...)

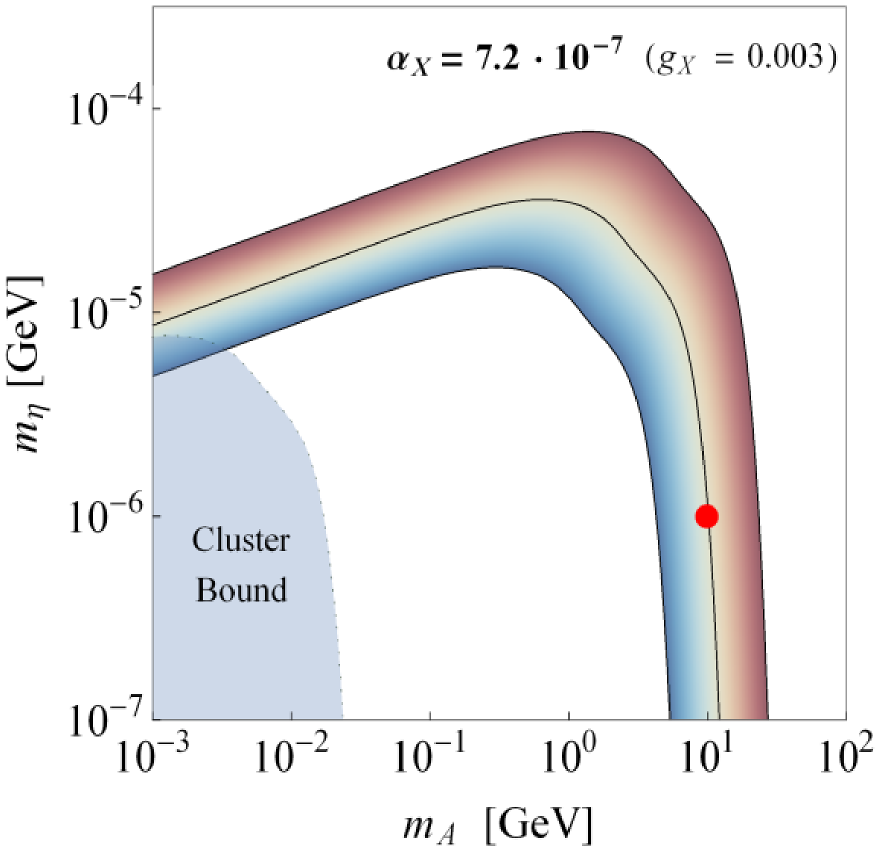
3-to-2 processes

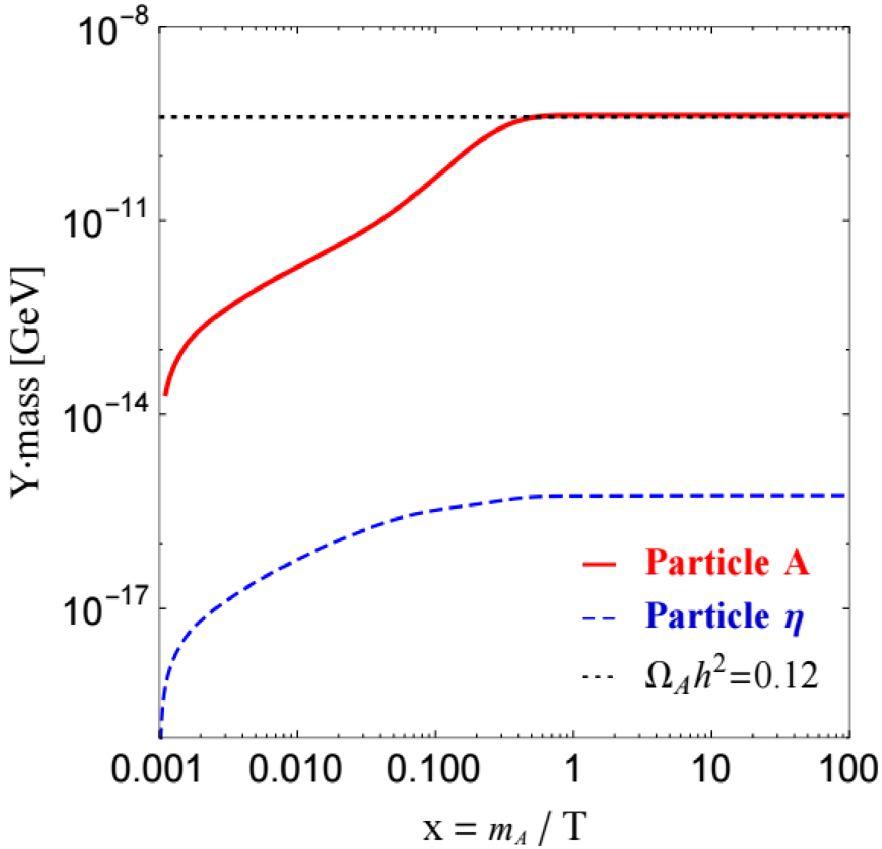


(plus some others...)

Light mediator, Freeze-In Regime

[Bernal et al, 1510.08063]



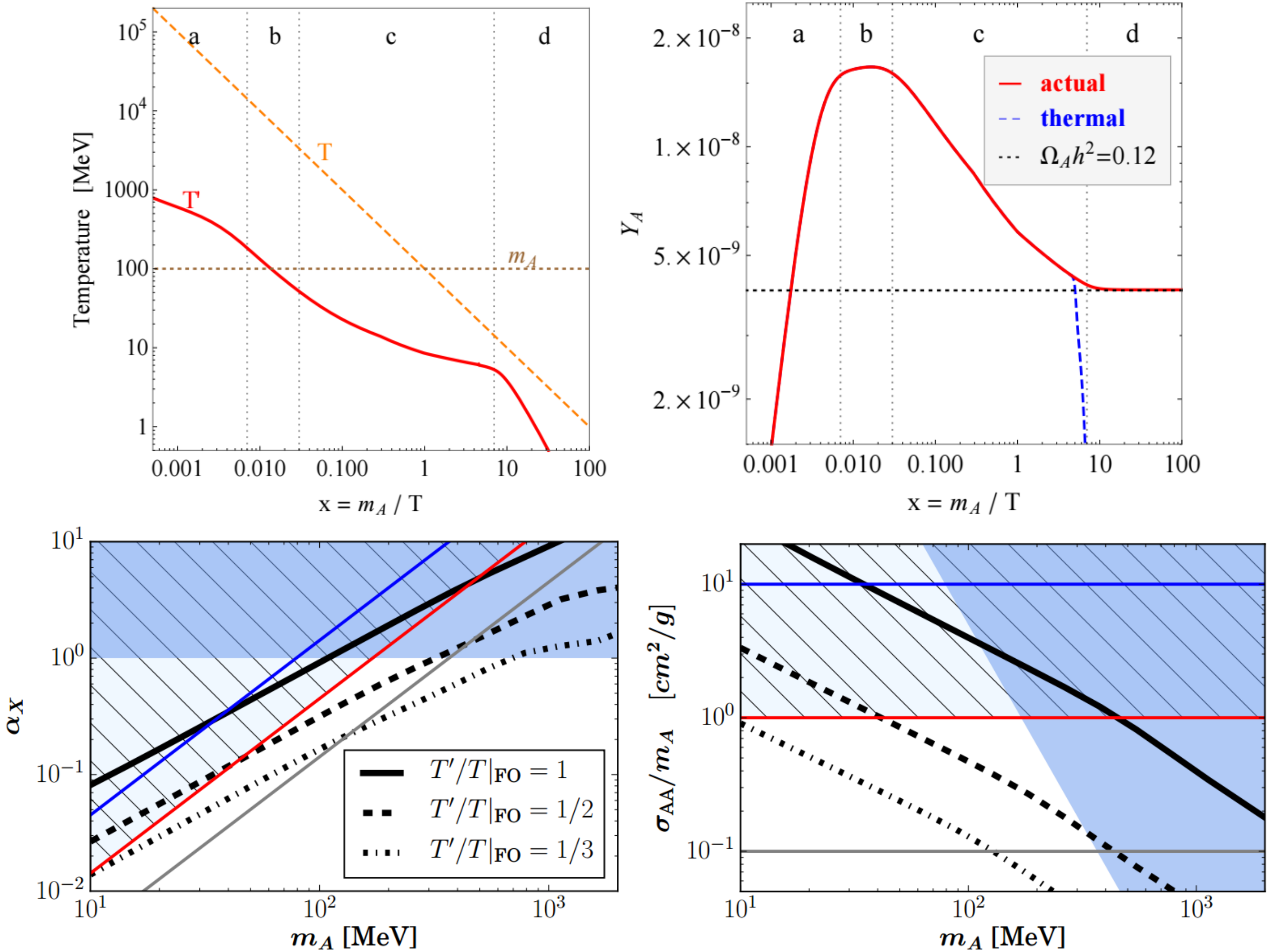


From Self-Interactions *From relic abundance*

OK with all the rest of constraints

Heavy mediator, colder dark freeze-out

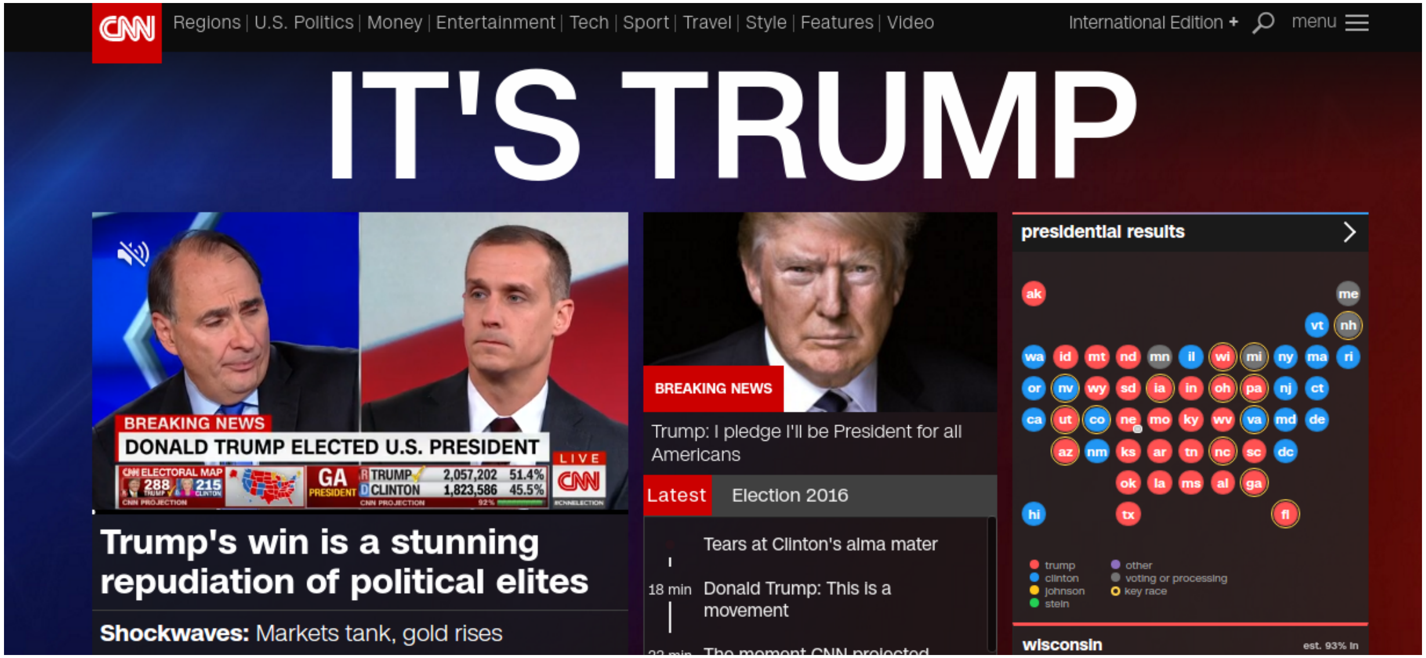
[Bernal et al, 1510.08063]



Conclusions

Out-of-equilibrium DM can accommodate enough self-interactions, while successfully avoiding several phenomenological issues

Thank you!



Are you kidding me??

Bckp slides

Proposal:

Relax the equilibrium condition with the visible sector

	Lighter mediator $(m_\eta \ll m_\chi)$	Heavier mediator $(m_\eta \gtrsim m_\chi)$
Freeze-In *(no T')*	$Y_\eta \sim Y_A$ (same creation from SM) $\Omega_\eta \ll \Omega_\chi$ (ok with BBN) $g_\chi \sim 10^{-3}$ (ok with Self-Int)	$g_\chi \ll 1$ (No Self-Int) or $m_\eta \sim \mathcal{O}(\mathrm{keV})$ (watch-out Hot DM)
Dark Freeze-out *(T' < T)*	$Y_\eta \gg Y_A$ (from eq.) Life-time < 10^4 s : Direct Det. Life-time < 10^{12} s : BBN/Self-Int Life-time > 10^{12} s : CMB/Self-Int	3-to-2 dominates over 2-to-2 (requiring self-int and Small connector couplings) Ok with Structure Form. Smaller g_χ (ok with perturb.)