SIDM particle model building

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Outline

Start from the original idea, and then see where it takes you next…

Original Idea

(Spergel and Steinhardt, astro-ph/9909386)

Mean free path $\lambda \sim 1\mathrm{kpc} - 1\mathrm{Mpc}$

$$\lambda \approx \frac{1}{n\sigma} = \frac{m}{\rho\sigma}$$

$$\sigma/m \sim (0.4 - \underline{400})\frac{\mathrm{cm}^2}{\mathrm{g}}\left(\frac{0.4\mathrm{GeV/cm}^3}{\rho}\right)$$

:-/

funnily, covering the ballpark of nucleon self-interactions ($np \to np$)
– and ~10^{12} times larger than WIMP predictions –

"We propose [...] dark matter that is cold, non-dissipative, but self-interacting."

As a result:

- centres of halos are spherical
- DM will have cored profiles
- DM will remain collissionless at large scales

Summary of constraints today

Positive observations	σ/m	v_{rel}	Observation
Cores in spiral galaxies (dwarf/LSB galaxies)	$\gtrsim 1\ \text{cm}^2/\text{g}$	$30 - 200\ \text{km/s}$	Rotation curves
Too-big-to-fail problem			
Milky Way	$\gtrsim 0.6\ \text{cm}^2/\text{g}$	$50\ \text{km/s}$	Stellar dispersion
Local Group	$\gtrsim 0.5\ \text{cm}^2/\text{g}$	$50\ \text{km/s}$	Stellar dispersion
Cores in clusters	$\sim 0.1\ \text{cm}^2/\text{g}$	$1500\ \text{km/s}$	Stellar dispersion, lensing
Abell 3827 subhalo merger	$\sim 1.5\ \text{cm}^2/\text{g}$	$1500\ \text{km/s}$	DM-galaxy offset
Abell 520 cluster merger	$\sim 1\ \text{cm}^2/\text{g}$	$2000 - 3000\ \text{km/s}$	DM-galaxy offset
Constraints			
Halo shapes/ellipticity	$\lesssim 1\ \text{cm}^2/\text{g}$	$1300\ \text{km/s}$	Cluster lensing surveys
Substructure mergers	$\lesssim 2\ \text{cm}^2/\text{g}$	$\sim 500 - 4000\ \text{km/s}$	DM-galaxy offset
Merging clusters	$\lesssim \text{few cm}^2/\text{g}$	$2000 - 4000\ \text{km/s}$	Post-merger halo survival (Scattering depth $\tau < 1$)
Bullet Cluster	$\lesssim 0.7\ \text{cm}^2/\text{g}$	$4000\ \text{km/s}$	Mass-to-light ratio

(Tulin and Yu, 1705.02358)

Leads to the conclusion that SI xsection could have some velocity-dependence

Ways to obtain ballpark xsections

1) Light-ish dark matter with large couplings

e.g. $\mathcal{L} \supset -\frac{g}{4}\varphi^4$ [Bento, Bertolami, Rosenfeld & Teodoro, astro-ph/0003350]

(the simplest example)

$$m_\varphi = 13\ g^{2/3} \left(\frac{\text{Mpc}}{\lambda}\right) \text{ MeV}$$

using $\rho = 0.4\text{GeV}/\text{cm}^3$

$$\sigma(\varphi\varphi \to \varphi\varphi) = \frac{g^2}{64\pi m_\varphi^2}$$

- Higher order operators possibly present, $-\frac{g}{n! m^{n-4}}\varphi^n$ e.g. glueballs
- Relic abundance can be fixed via a Higgs portal, direct coupling to inflaton, etc

No velocity dependence here:

Some tension with bounds coming from clusters

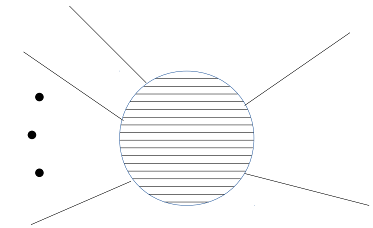
First example of SIDM

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

"...as the universe expands, the dark matter **cannibalizes** itself to keep warm."

New mechanism to generate the DM relic abundance,
(dark sector secluded from visible sector)

e.g. $\mathcal{L} \supset -\frac{g}{5!}\varphi_s^5$



Entropy density is conserved in each sector:

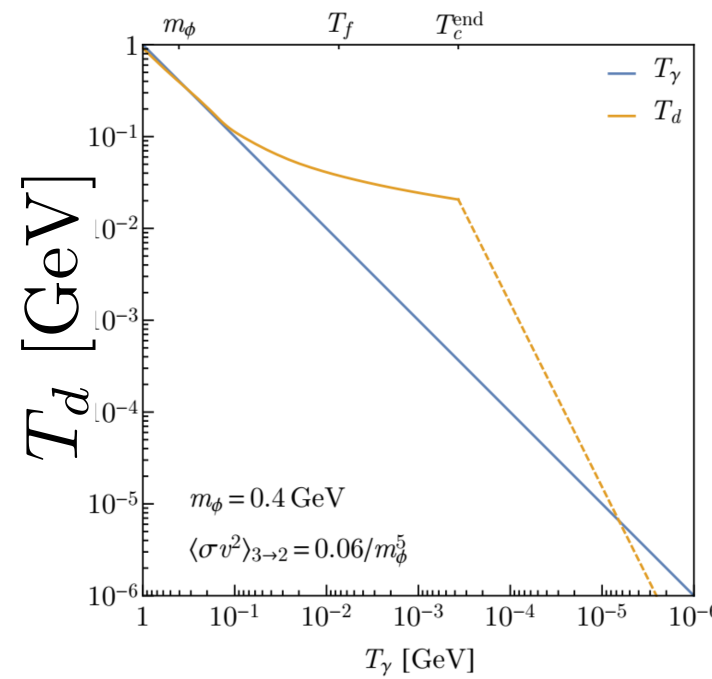
$$\frac{T_d}{m_{\rm DM}} \simeq \frac{1}{3\ln(a/\bar{a})}$$ (Temp. of dark sector)

- Original proposal designed for a universe with zero cosmological constant (possible back in '92 :-)

- Soon after excluded from Ly-α observations (small-scale power suppression at ~ 10Mpc)

However…

- Recent revival with the correct cosmology (Cannibal DM, SIMPs, non-thermal DM, …)

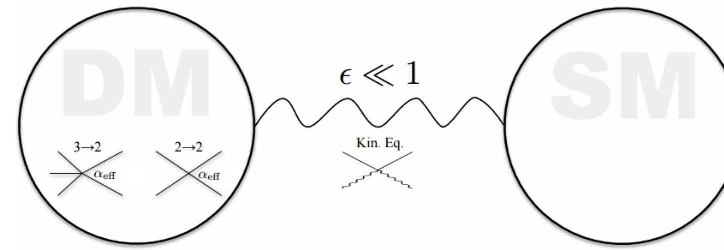


Pappadopulo, Ruderman, Trevisan, 1602.04219

The SIMP Miracle

(Hochberg, Kuflik, Volansky & Wacker, 1402.5143)

25% of the authors [...] are uncomfortable with with the term 'miracle' ...



- Relic abundance from cannibalization of 3→2

$$\langle \sigma v^2 \rangle_{3\to 2} = \frac{\alpha_{\rm eff}^3}{m_{\rm DM}^5}$$

(correct dimensions for scattering rate)

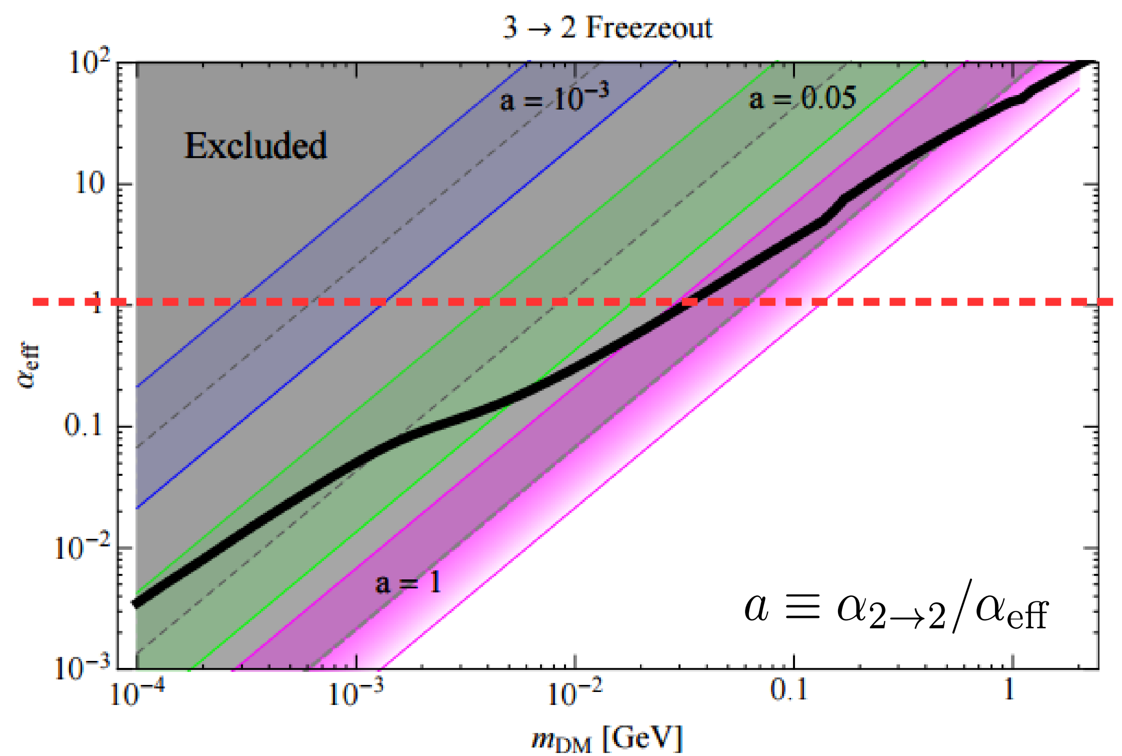
- Portal to the visible sector:

$$10^{-9}\sqrt{\alpha_{\rm eff}} \lesssim \epsilon \lesssim 3 \times 10^{-6}\alpha_{\rm eff}$$

- kinetic equilibrium with SM should be invoked (otherwise excluded by structure formation)

- Annihilation to SM should be suppressed wrt 3→2

- Tension between cluster bounds and **perturbativity**



Composite SIDM

(Hochberg, Kuflik, Murayama, Volansky & Wacker, 1411.3727)

- Pion-like dark matter from non-Abelian theory (e.g. $Sp(N_c)$ with $N_f \geq 2$)

  Chiral symmetry breaking from quark condensate, giving 5 pions.
  Non-vanishing Wess-Zumino-Witten term:

$$\mathcal{S}_{\text{WZW}} = \frac{-iN_c}{240\pi^2} \int_{\text{M}^5} \text{Tr}(d\Sigma\Sigma^{-1})^5 \qquad \Sigma = e^{2i\pi/f_\pi}(i\sigma_2 \otimes I_{N_f})$$

$$\to \mathcal{L}_{\text{int}} \supset \frac{2N_c}{15\pi^2 f_\pi^5} \epsilon^{\mu\nu\rho\sigma} \underbrace{\text{Tr}(\pi\partial_\mu\pi\partial_\nu\pi\partial_\rho\pi\partial_\sigma\pi)}$$

5-point interaction responsible for 3→2 processes

- Communication with the SM (for kinetic equilibrium) is not automatic,
  e.g. $U(1) \subset Sp(N_c)$ is gauged (and explicitly broken) leading to massive dark photon with assumed kinetic mixing with SM hypercharge.

Results:
Relevant scales of this model intriguingly similar to QCD

$$m_\pi \sim 300\text{MeV} \qquad f_\pi \sim \text{few} \times m_\pi$$

(Note that still no velocity-dependence)

Glueball SIDM

(Boddy, Feng, Kaplinghat and Tait, 1402.3629)

a) Pure non-Abelian gauge theory + confinement scale Λ

At temperatures smaller than Λ the d.o.f. are glueballs

$$\sigma_{SI} \simeq 4\pi/\Lambda^2 \Rightarrow \Lambda \sim 0.1 - 0.3\ \mathrm{GeV}$$

To solve small-scale problems

b) Supersymmetrize the above model (w/ Anomaly-mediated SB)

Visible sector: MSSM

$$m_v \simeq \frac{\alpha_v}{4\pi} m_{3/2}$$

Hidden sector: glueballs+glueballinos

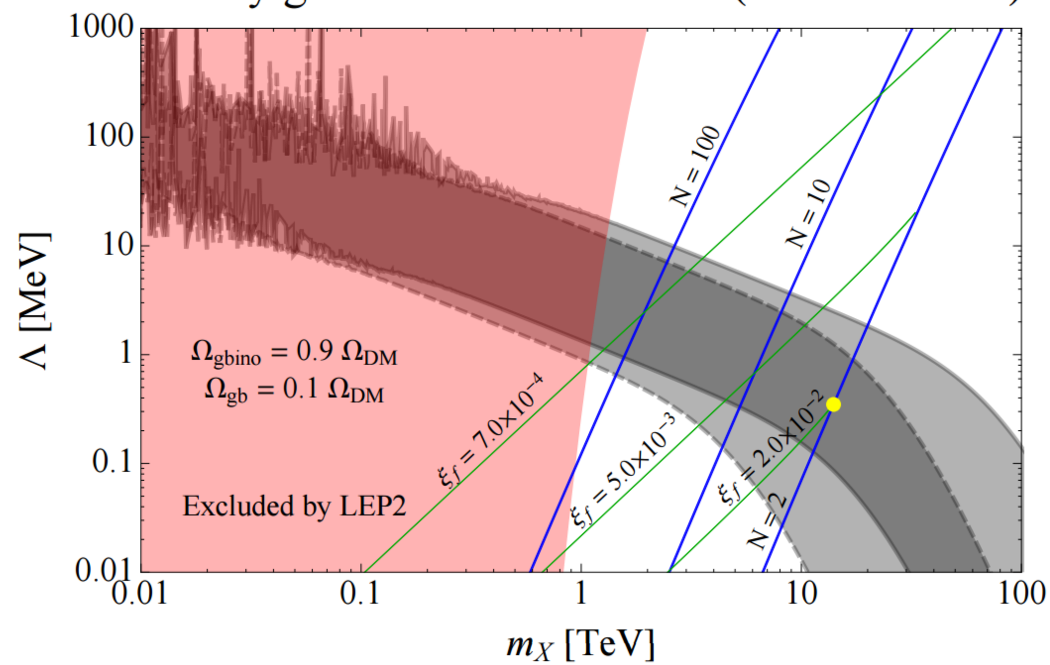
$$m_X \simeq \frac{\alpha_X}{4\pi} m_{3/2}$$

$$m_{\rm gb} \simeq \Lambda$$

For $m_v \sim \mathcal{O}(m_{\rm ew})$

$\Rightarrow m_X \simeq 10\mathrm{TeV}$

Mostly glueballino dark matter (no connectors)



Velocity-dependent SI because of light-mediated

So far, no velocity-dependence found in models without DM-mediator mass hierarchy

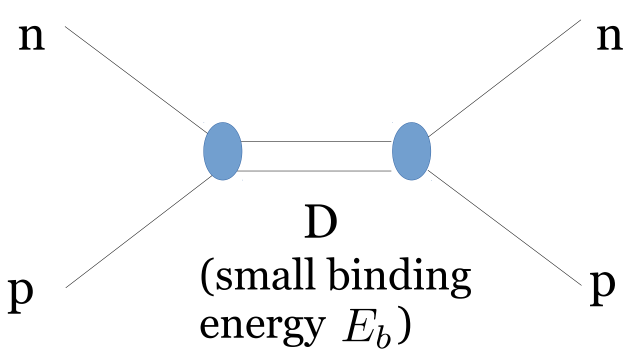
xsection expected to fall for:

$$a \gtrsim (m_{\rm DM} v)^{-1}$$

(scattering length)

(Tulin and Yu, 1705.02358)

(subtlety about analogy with neutron-proton scattering)



- large (~20b) xsection due to large scattering length

$$\lim_{k \to 0} \sigma = 4\pi a^2$$

- a diverges for $E_b \to 0$ bound state

[Atomic DM, Cline, Liu, Moore, 1311.6468, 1312.3325]

$$E_b \simeq \alpha^2 \mu_H / 2$$

...ultimately related to pion-exchange

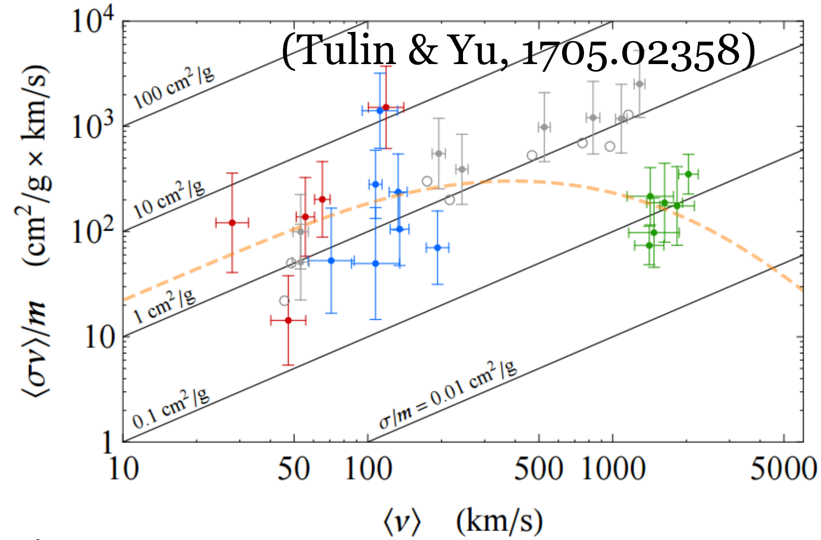
Ways to obtain ballpark xsections

(now with velocity-dependence!)

2) Long-range interactions

$$V = -\alpha'/r? \;\Rightarrow\; \sigma \sim 1/v_{\rm rel}^4$$

(steeper dependence than best fit)



(Tulin & Yu, 1705.02358)

Better:

$$V = -\frac{\alpha'}{r} e^{-m_\eta r}$$

mediator DM

SI fully determined by choice of: $m_\eta, m_\chi, \alpha', v_{\rm rel}$

Choices for cross sections [Tulin, Yu & Zurek, 1302.3898]

$$\sigma_T = \int d\Omega (1 - \cos\theta) \frac{d\sigma}{d\Omega}$$

Regulates forward divergence

$$\sigma_V = \int d\Omega \sin^2 \frac{d\sigma}{d\Omega}$$

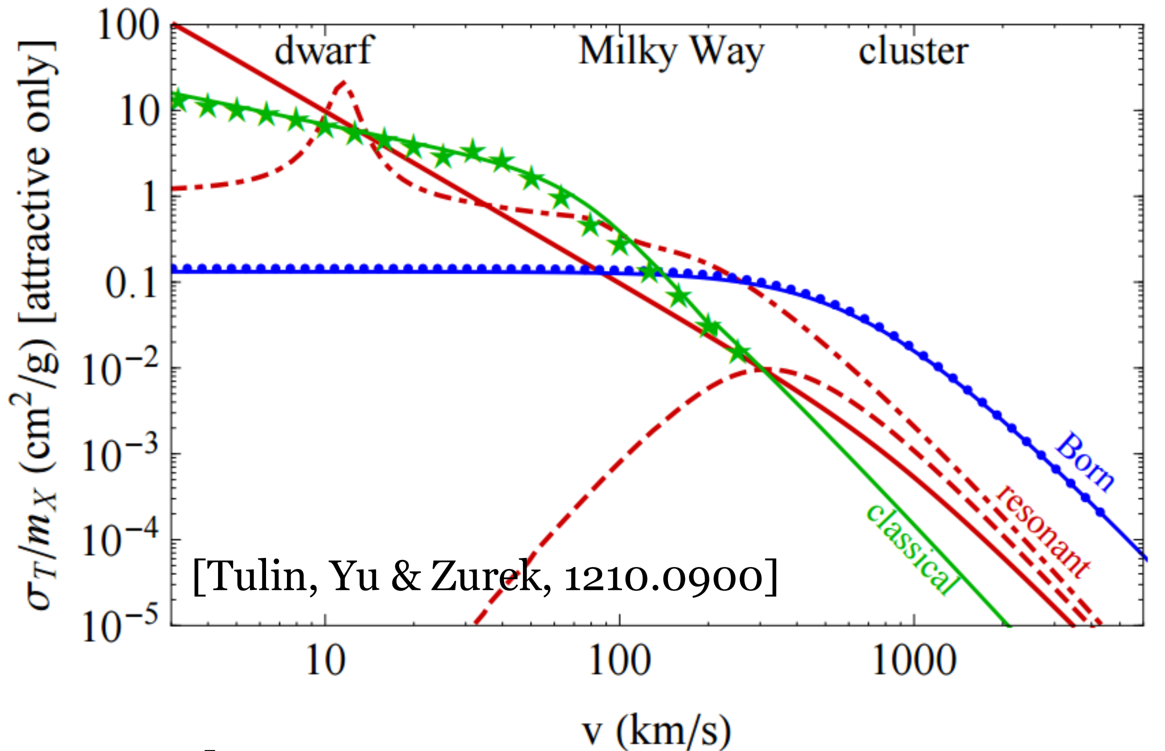
Regulates both forward & backward
(for identical DM particles)

Velocity dependence

$$\mathcal{L} \supset g' \bar{\chi}\gamma^\mu \chi A'_\mu$$

- standard Yuwaka potential

$$V = \pm \frac{\alpha'}{r} e^{-m_{A'} r}$$



- other potentials are easily possible

[Bellazzini, Cliche & Tanedo, 1307.1129]

$$V = \frac{1}{4\pi r}\left[g_1 + g_2(\mathbf{s_1}\cdot\mathbf{s_2}) + \frac{g_3}{\Lambda^2 r^2}(3\mathbf{s_1}\cdot\hat{r}\;\mathbf{s_2}\cdot\hat{r} - \mathbf{s_1}\cdot\mathbf{s_2}) + \frac{g_{7,8}}{\Lambda r}(\mathbf{s_1}\pm\mathbf{s_2})(\hat{r}\times\mathbf{v})\right.$$

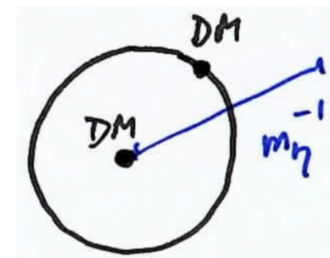
Interaction	g_1	g_2	g_3	g_7	g_8
$\bar{\chi}\chi\varphi$	✓	X	X	✓	X
$\bar{\chi}\gamma^5\chi\varphi$	X	X	✓	X	X
$i\bar{\chi}\gamma^\mu\gamma^5\chi\partial_\mu\varphi$	X	X	✓	X	X
$\bar{\chi}\gamma^\mu\chi A_\mu$	✓	X	X	✓	X
$i\bar{\chi}\gamma^5\gamma^\mu\chi A_\mu$	X	X	✓	X	X
$i\bar{\chi}\sigma^{\mu\nu}\chi F_{\mu\nu}$	X	X	✓	X	X

Interaction regimes

[Tulin, Yu & Zurek, 1302.3898]

$\alpha' m_\chi \ll m_\eta$ (perturbative)

$$\sigma_T^{\rm Born} = \frac{8\pi\alpha'^2}{m_\chi^2 v_{\rm rel}^4}\left(\log(1+m_\chi^2 v_{\rm rel}^2/m_\eta^2) - \frac{m_\chi^2 v_{\rm rel}^2}{m_\eta^2 + m_\chi^2 v_{\rm rel}^2}\right)$$

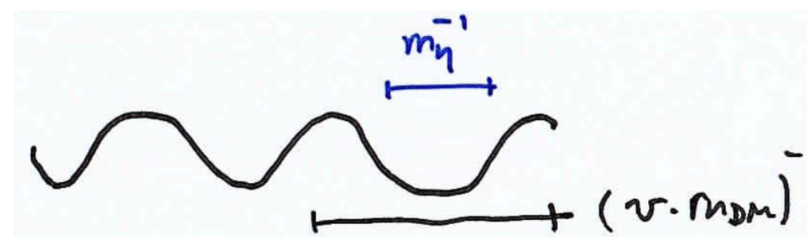


$\alpha' m_\chi \gg m_\eta$ $(m_\chi v_{\rm rel} \gg m_\eta)$ (classical)

$$\sigma_T^{\rm clas} = \begin{cases} \frac{4\pi}{m_\eta^2}\beta^2 \ln\left(1+\beta^{-1}\right) & \beta \lesssim 10^{-1} \\ \frac{8\pi}{m_\eta^2}\beta^2/\left(1+1.5\beta^{1.65}\right) & 10^{-1} \lesssim \beta \lesssim 10^3 \\ \frac{\pi}{m_\eta^2}\left(\ln\beta + 1 - \frac{1}{2}\ln^{-1}\beta\right)^2 & \beta \gtrsim 10^3 \end{cases}$$

$$\beta = 2\alpha' m_\eta/(m_\chi v_{\rm rel}^2)$$

$\alpha' m_\chi \gg m_\eta$ $(m_\chi v_{\rm rel} \ll m_\eta)$ (resonant)



Partial-wave analysis

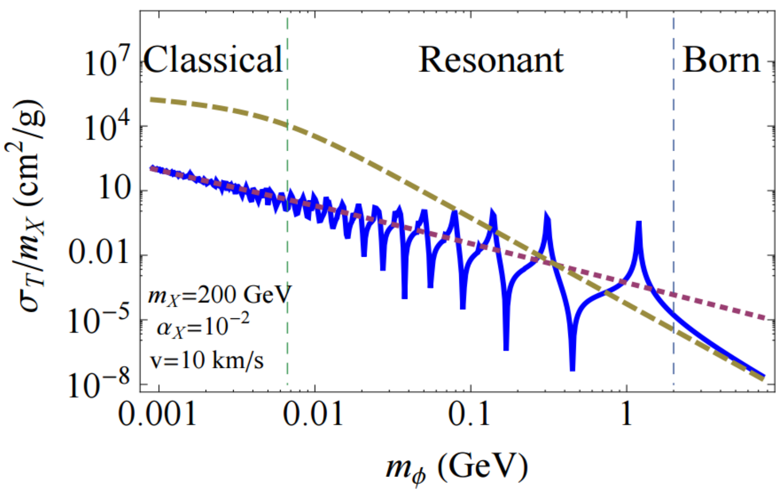
$$\sigma_T = \frac{4\pi}{k^2}\sum_{\ell=0}^{\infty}(\ell+1)\sin^2(\delta_{\ell+1}-\delta_\ell)$$

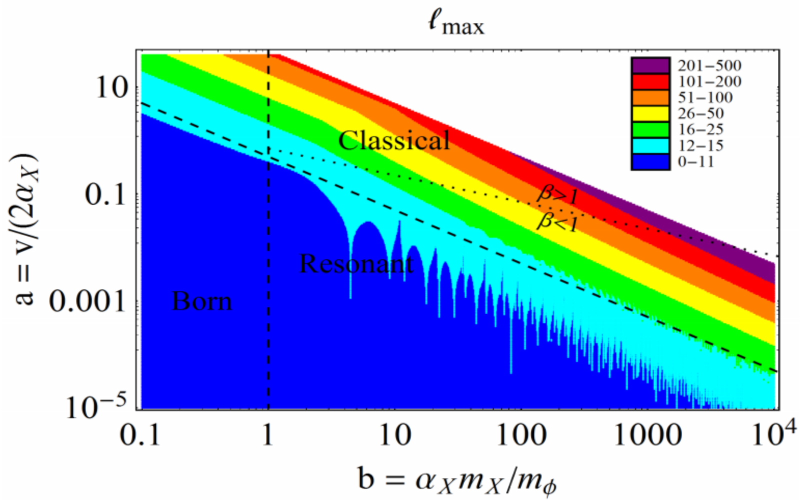
$$\frac{1}{r^2}\frac{d}{dr}\left(r^2\frac{dR_\ell}{dr}\right) + \left(k^2 - \frac{\ell(\ell+1)}{r^2} - 2\mu V(r)\right)R_\ell = 0 \qquad \lim_{r\to\infty} R_\ell(r) \propto \cos\delta_\ell\, j_\ell(kr) - \sin\delta_\ell\, n_\ell(kr)$$

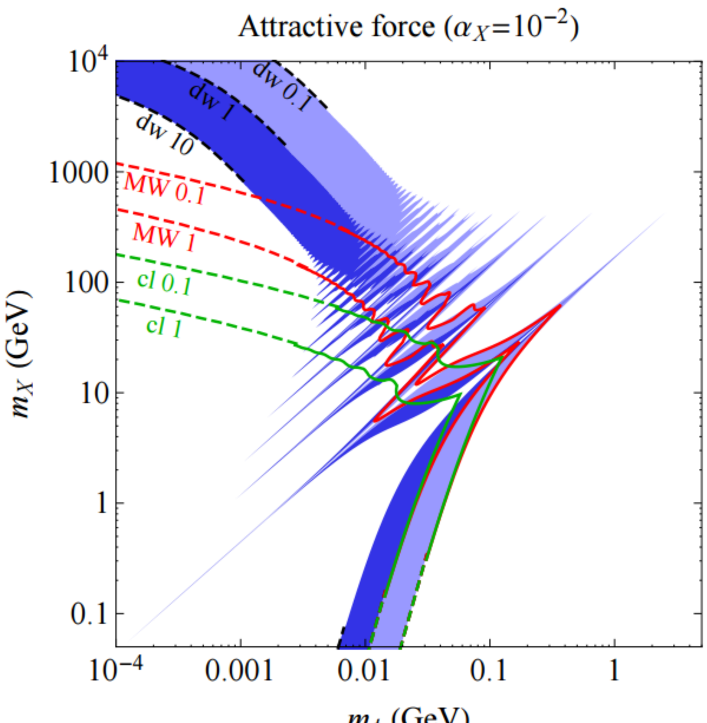
Features of long-range SI's

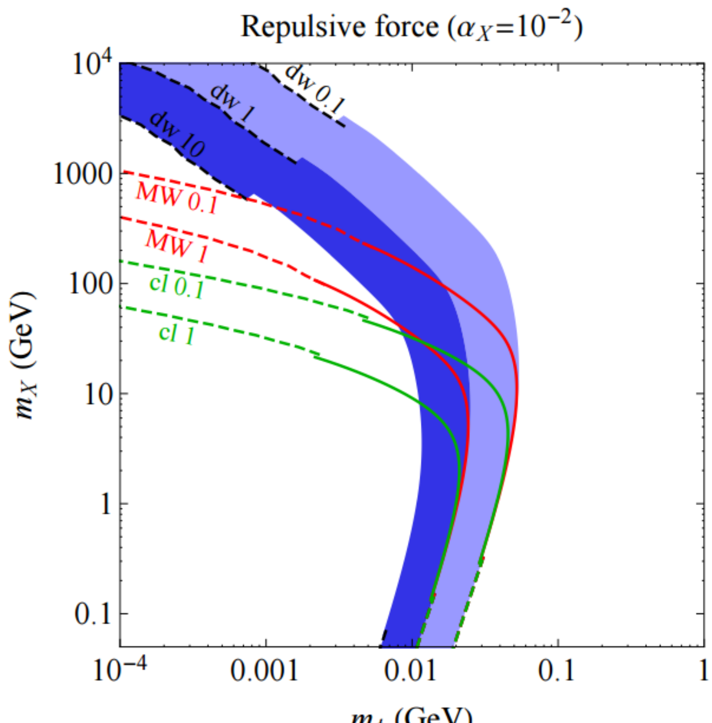
[Tulin, Yu & Zurek, 1302.3898]

Yukawa model









(a poor phenomenologist's next step)

What about complementary probes of SIDM ?

(**cosmology, colliders, indirect detection,** direct detection)

(See talk by Sean)

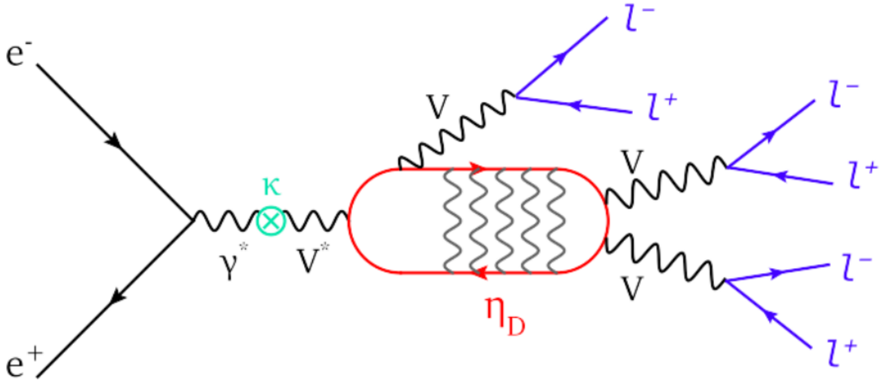
Collider searches

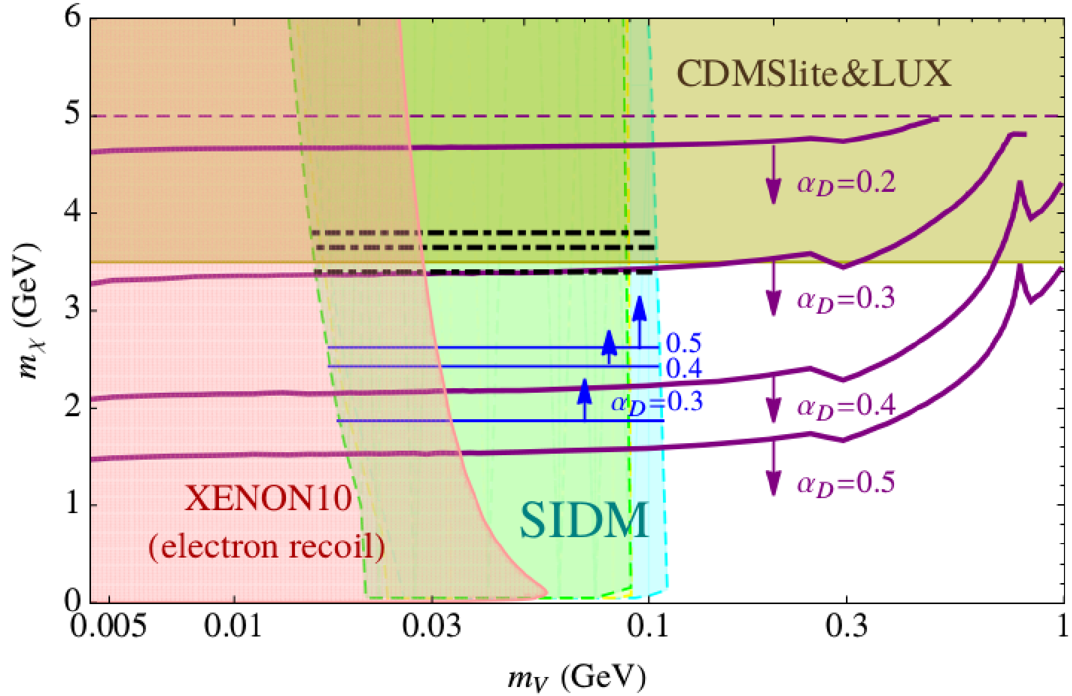
Assume **non-zero** coupling between mediator and SM

- bound-state production + decay
- complementarity with:

$$e^+e^- \to \bar{\chi}\chi + 2V$$

- Low SM backgrounds
- Also from fixed-target experiments





[An, Echenard, Pospelov & Zhang, 151005020]

See also:

- Higgs decaying to invisible [Kouvaris, Shoemaker, Tuominen, 1411.3730]

Cosmological probes

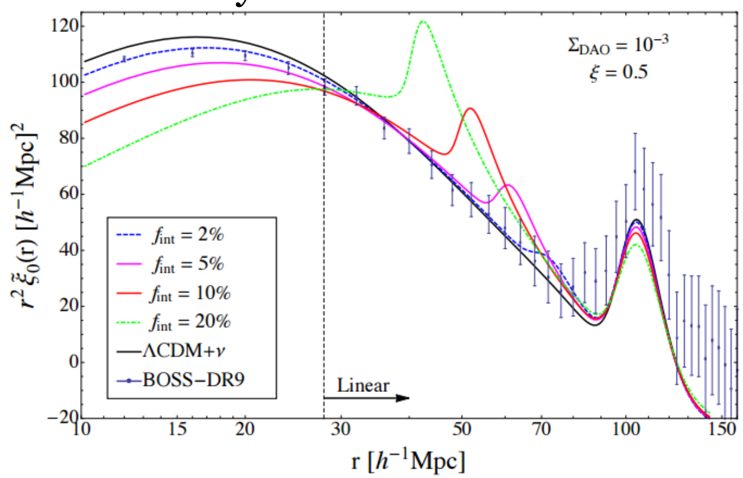
Assume **zero** coupling between (relativistic) mediator and SM

- DM coupling to bath of dark radiation give rise to DAO's until decoupling happens

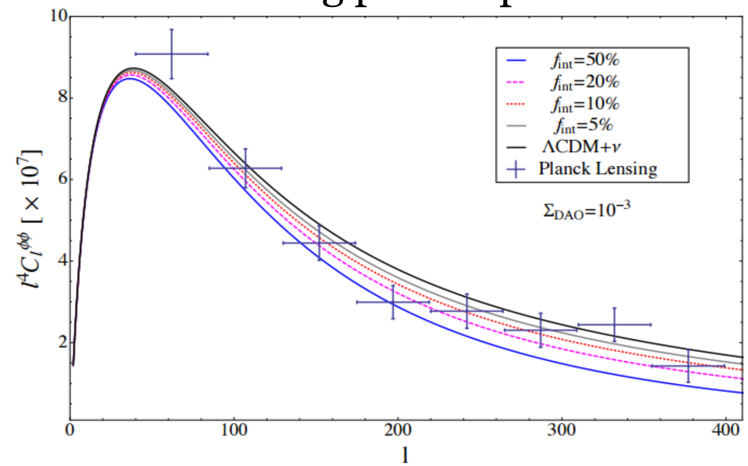
e.g. the PIDM model:

$$m_D, \alpha_D, B_D, \quad \xi = (T_D/T_{\rm cmb})_{z=0}, \quad f_{\rm int} = \rho_{\rm int}/\rho_{\rm DM}$$

Galaxy correlation function



CMB lensing power spectrum



[Cyr-Racine, Putter, Raccanelli, 1310.3278]

But also see:
deviations in matter power spectrum & structure of galactic halos

[Buckley, Zavala, Cyr-Racine, Sigurdson, Vogelsberger, 1405.2075]

Cosmological probes

Assume **non-zero** coupling between mediator and SM

- BBN:

Late decays of mediator η can spoil BBN predictions unless

$\tau_\eta \lesssim 10^4$ secs, or $\Omega_\eta h^2 \lesssim 10^{-5}$ [Jedamzik & Pospelov, 0906.2087]

(for $Br_h = 0$)

- CMB:

a) DM annihilating at redshifts $100 \lesssim z \lesssim 1400$ can be probed with CMB data, giving a limit of:

$m_{\rm DM} \lesssim 10\text{GeV}$

(depending on annihilation channel)

[Madhavacheril, Sehgal & Slatyer, 1310.3815; Slatyer, 1506.03811]

b) Late decays of mediator could distort the CMB spectrum unless

$\Omega_\eta h^2 \lesssim 10^{-8}$ for $10^{12}\text{s} \lesssim \tau_\eta \lesssim 10^{17}\text{s}$ [Slatyer, 1211.0283]

- X-ray emission: (EGRET, INTEGRAL, COMPTEL, ...)

For τ_η larger than age of the universe, $\eta \to \gamma\gamma$ could give too large X-ray excess unless

$\tau_\eta \gtrsim 10^{27} - 10^{28}\text{sec} \times (\Omega_\eta h^2/0.12)$

(depending on mediator mass)

[Essig, Kuflik, McDermott, Volansky & Zurek, 1309.4091]
[Boddy & Kumar, 1504.04024]

Cosmological probes

Assume **thermal equilibrium** between dark and visible sectors

Consider a model with light-mediator
(via Higgs-portal for definiteness)

- Easily produce the right amount of self-interactions

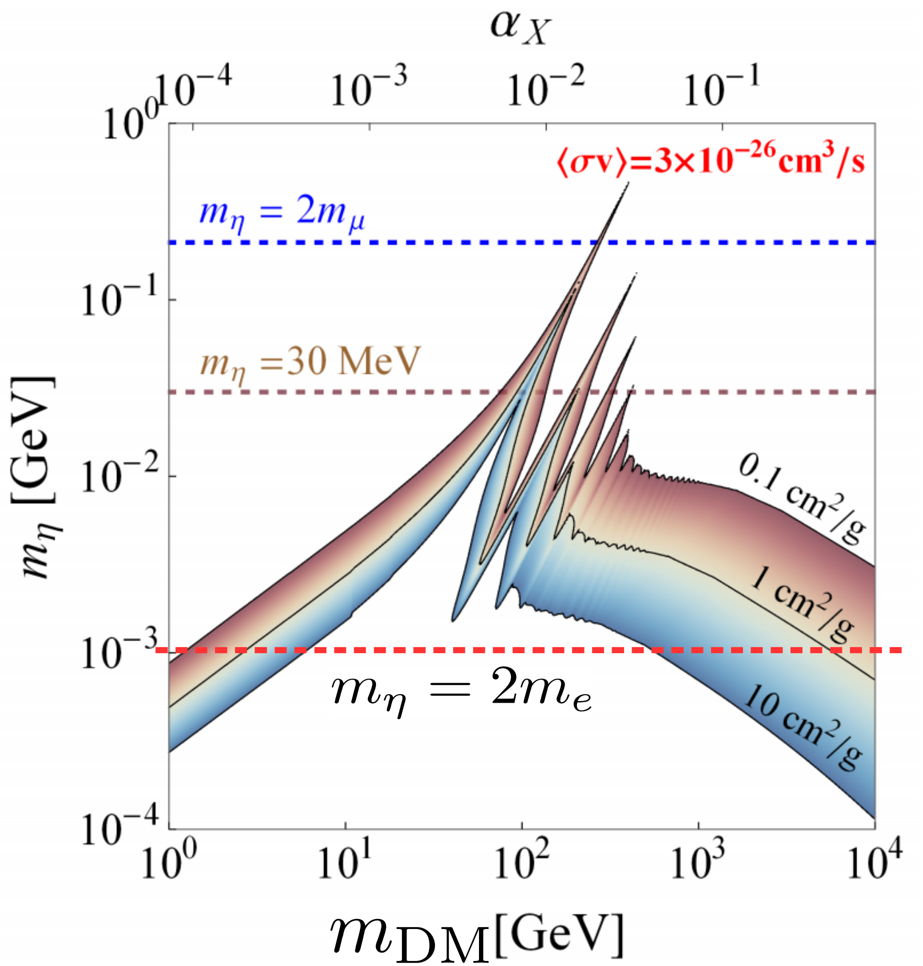
- However severely excluded:

if $2m_e < m_\eta < 2m_\mu$

Large abundance of mediator, thus **BBN** lower bound on mixing incompatible with upper bound from **LUX** plus (DM) **annihilations from CMB**

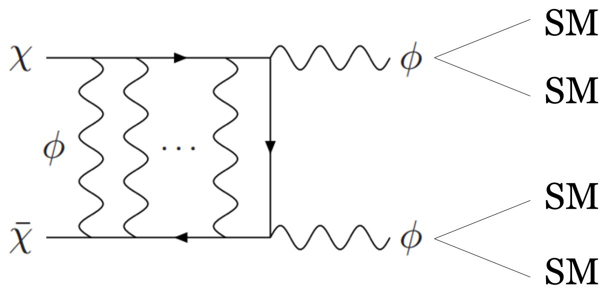
if $m_\eta < 2m_e$

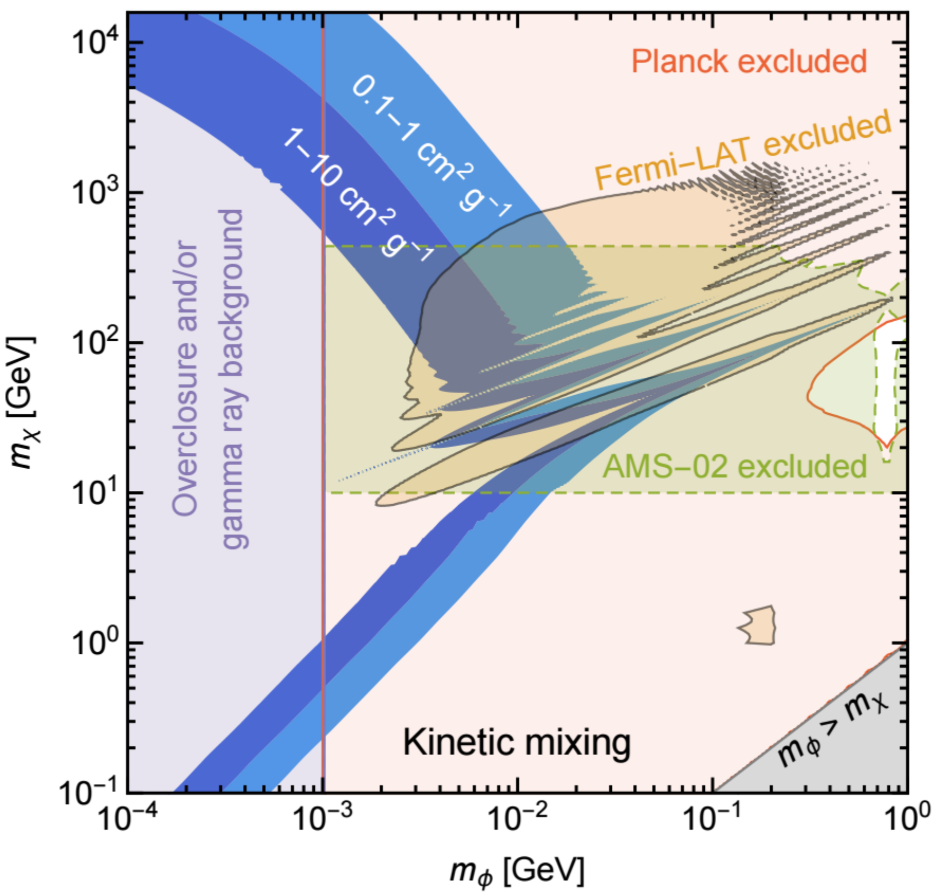
According to the value of τ_η, excluded by (DM) **annihilations from CMB**, (mediator) **late decays from CMB**, or **X-ray emission**



[Bernal, Chu, Garcia-Cely, Hambye & Zaldivar, 1510.08063]

Indirect detection

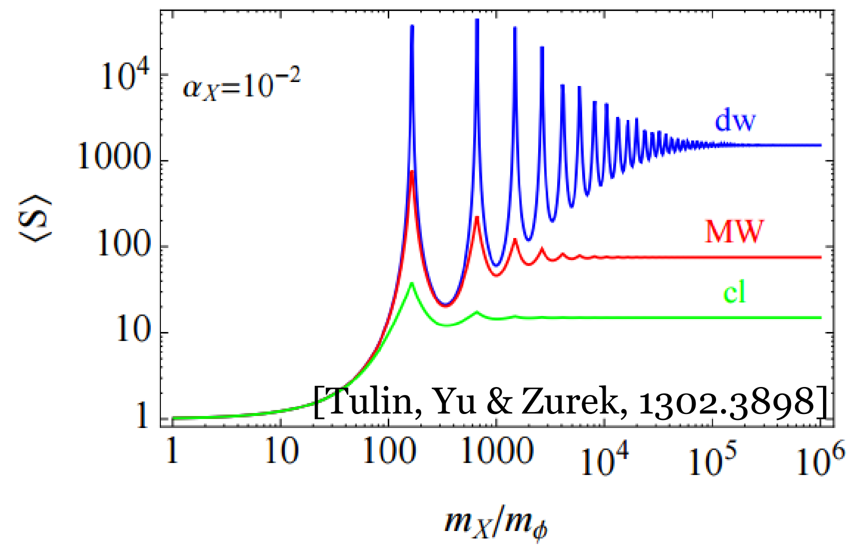




[Bringmann, Kahlhoefer, Schmidt-Hoberg & Walia, 1612.00845]

Sommerfeld enhancement:

$$\sigma v_{\mathrm{rel}} = (\sigma v_{\mathrm{rel}})_{\mathrm{pert}} \times S(v_{\mathrm{rel}})$$



Assumptions:

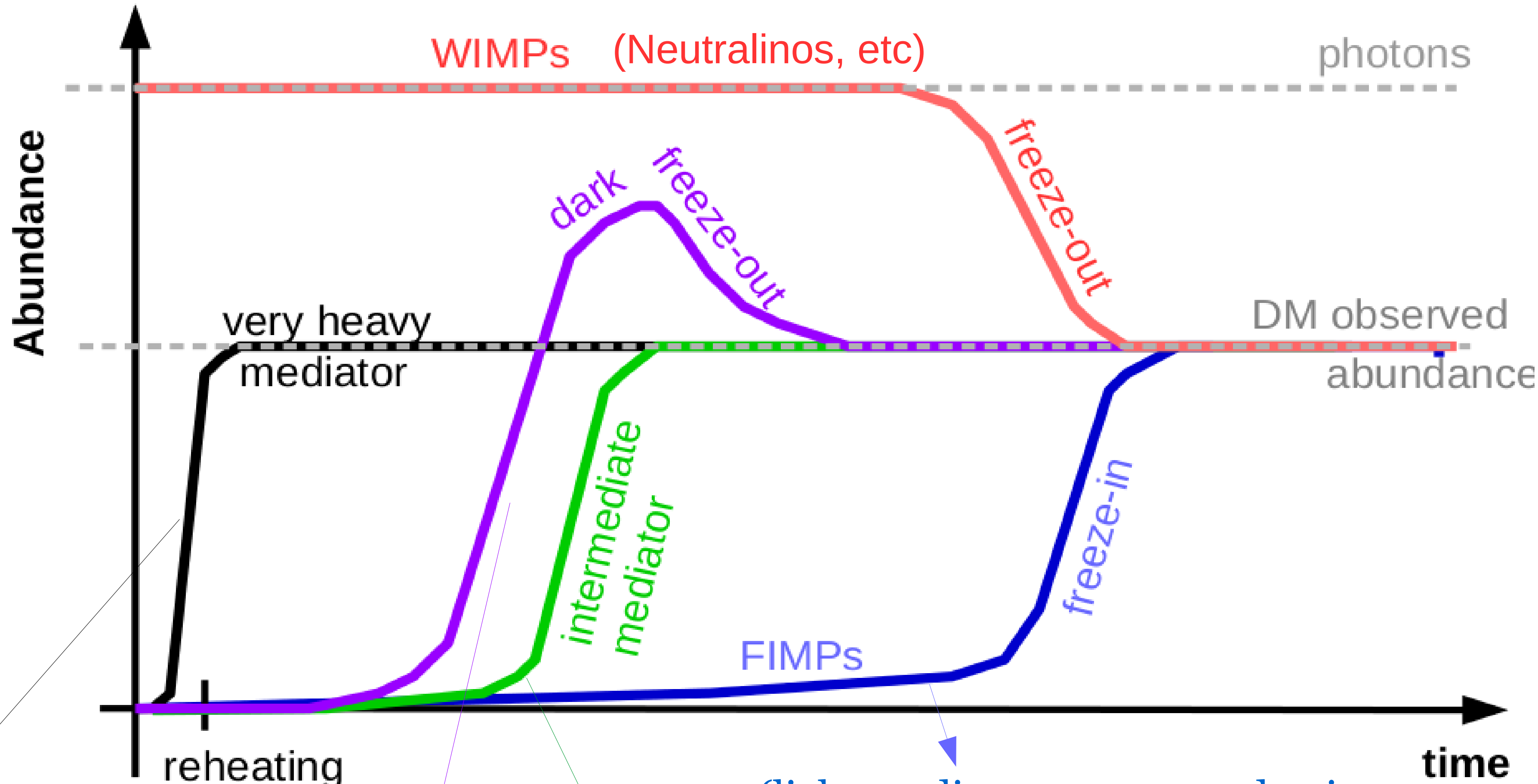
1) s-wave DM annihilation

2) kinetic-mixing w/ photons

3) dark sector thermalised with SM at some point before freeze-out

What if SIDM was never in thermal equilibrium with the visible sector?

Different thermal histories of DM



Gravitinos,
Axions,
NETDM, ...

(secluded dark sectors)

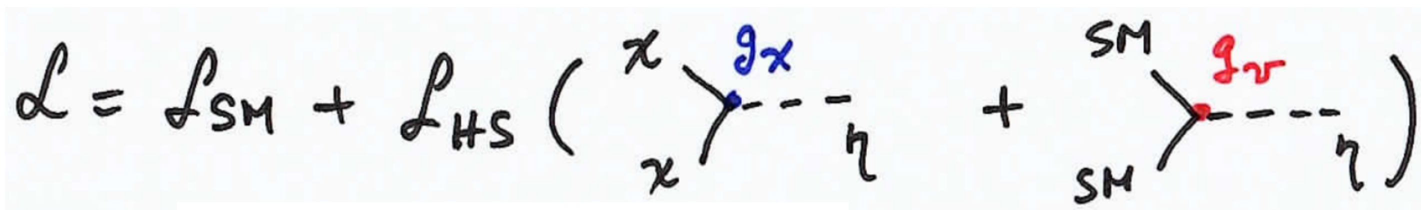
(Non-thermal Z', ...)

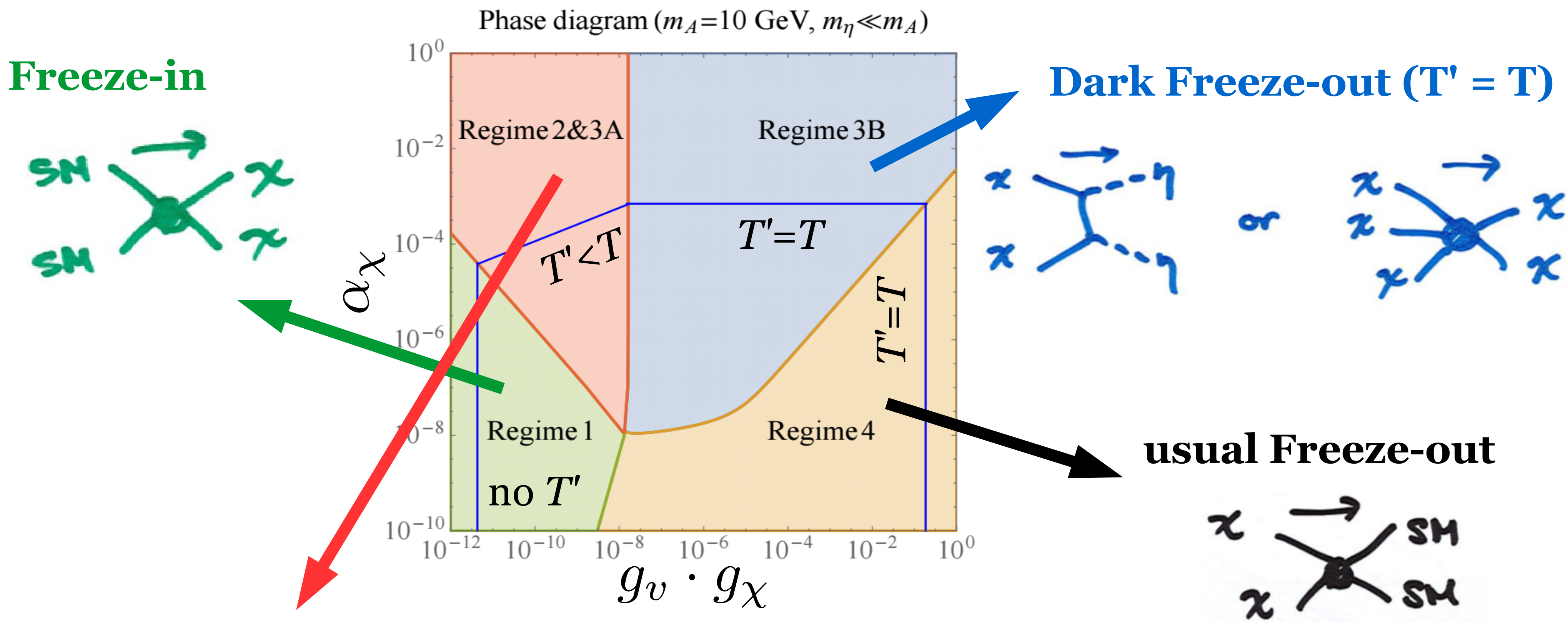
(light-mediator, 2-to-2 production,
Stau-friend DM, etc)

Generic:
[Chu, Hambye & Tytgat, 1112.0493]

Pure freeze-in:
[Blennow, Fernandez & Zaldivar, 1309.7348]

Different thermal histories of DM



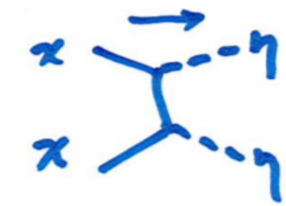


Dark Freeze-out (T' < T)

- Freeze-in production + dark annihilation

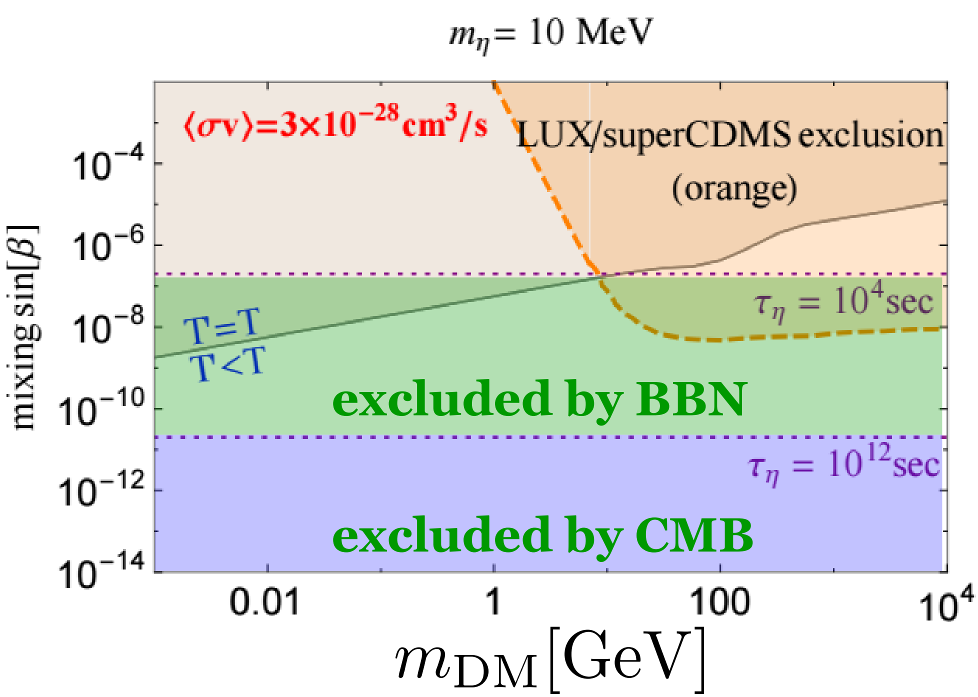
T': temperature of dark sector
T': temperature of visible sector

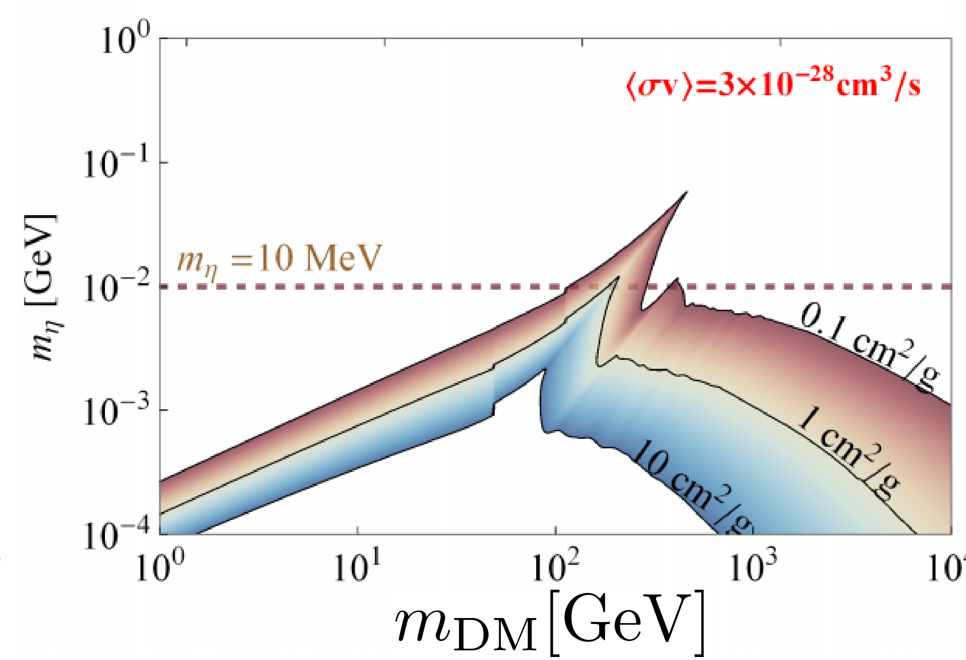
Dark freeze-out (T' < T)



Consider the same model with light-mediator as before
(via Higgs-portal) [Bernal, Chu, Garcia-Cely, Hambye & Zaldivar, 1510.08063]

Dark thermalisation **still** produces **large population of mediators**





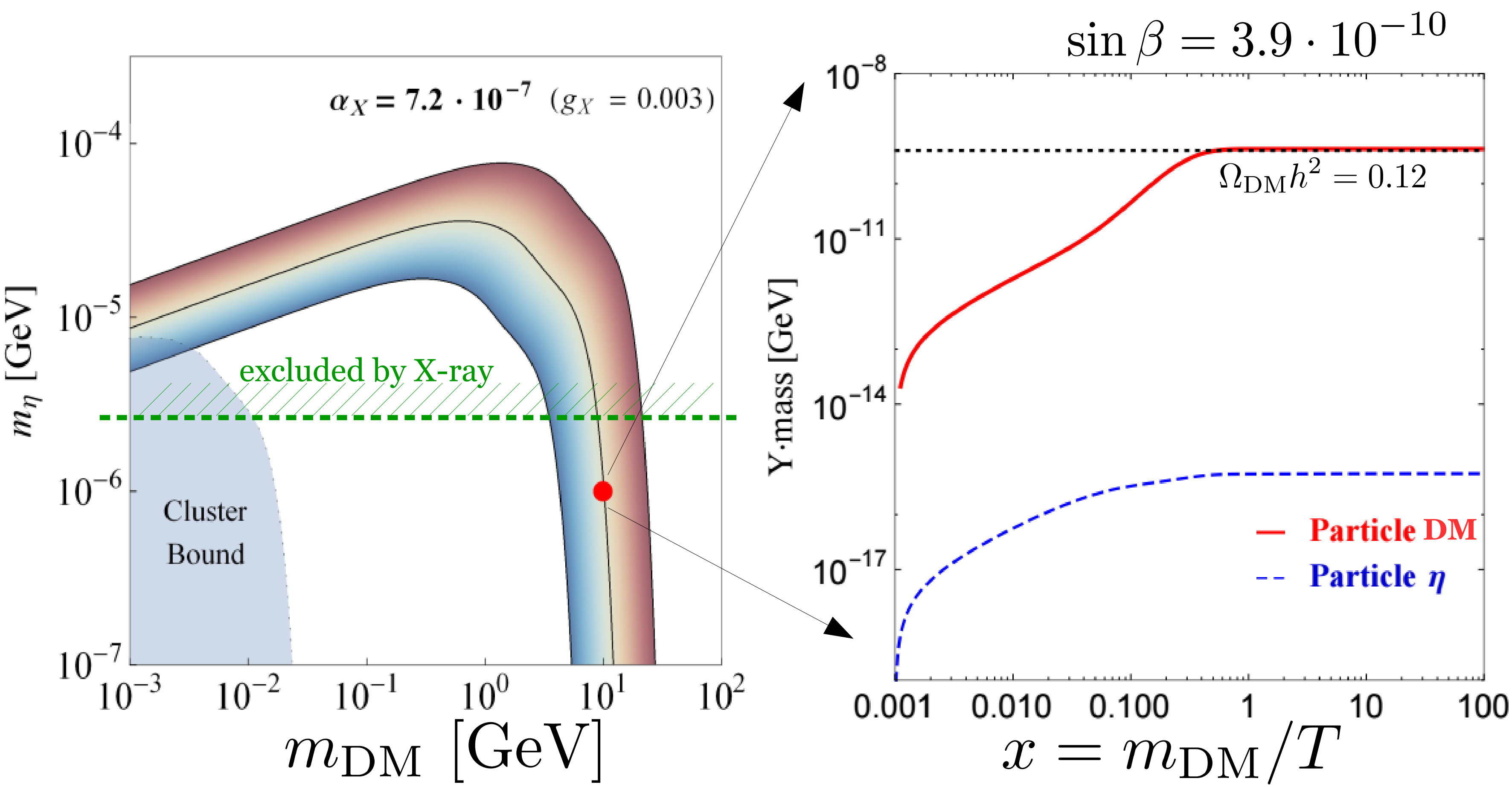
Thus, **excluded.**
(Similar conclusions for mediators lighter than electrons)

All of these naturally leads (me) to **freeze-in** ...

Freeze-in

Sticking to same model with light-mediator
(via Higgs-portal) [Bernal, Chu, Garcia-Cely, Hambye & Zaldivar, 1510.08063]

No dark thermalisation, thus **low abundance of light mediators** w.r.t. DM



FIMPs could have sufficient amount of self-interactions while avoiding the rest of complementary constraints

Conclusions

Assuming SIDM is the solution to small-scale problems,
data seems to prefer the freeze-in DM production mechanism.

Thanks!