Self-Interacting Dark Matter

(model building oriented)

Bryan Zaldívar
LAPTh, Annecy

GGI, Firenze, September 2017

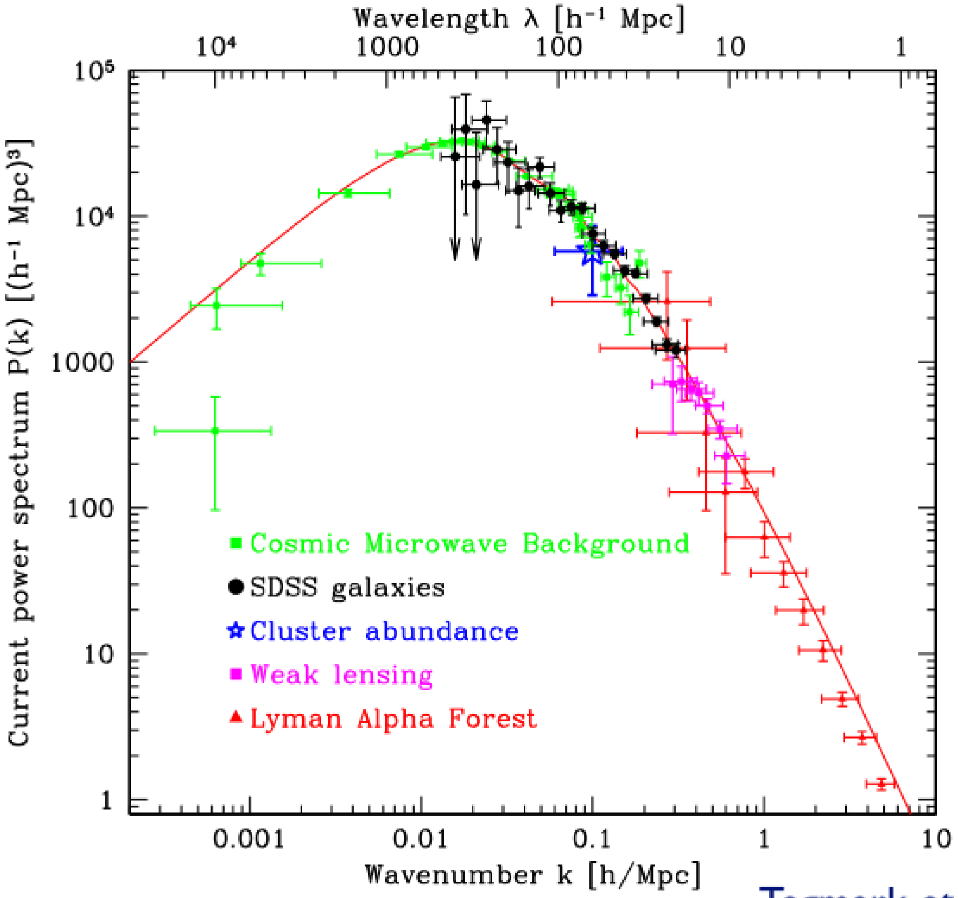
Outline

(brief introduction to the problem)

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

ΛCDM on Large Scales

- works very well, >O(100) kpc



Tegmark et al. (2004)

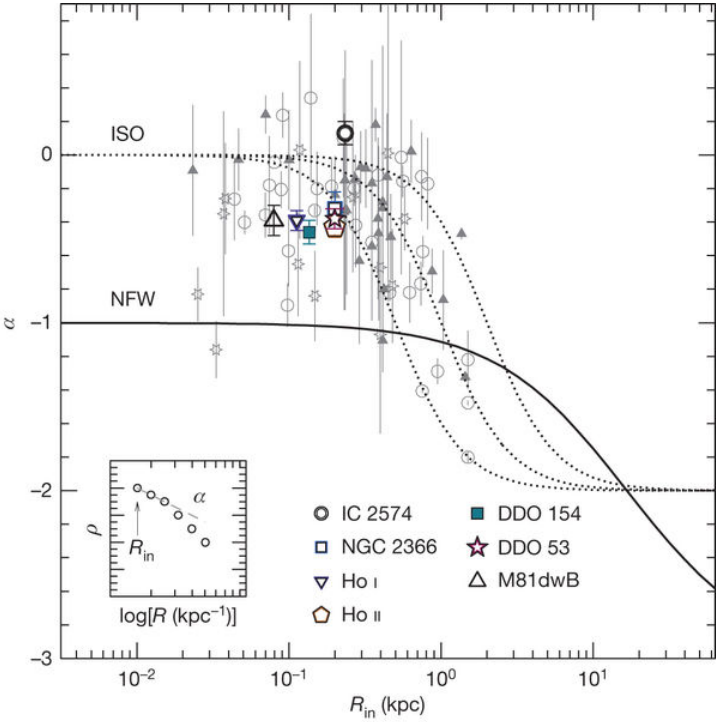
(taken from Haibo Yu, Copenhagen)

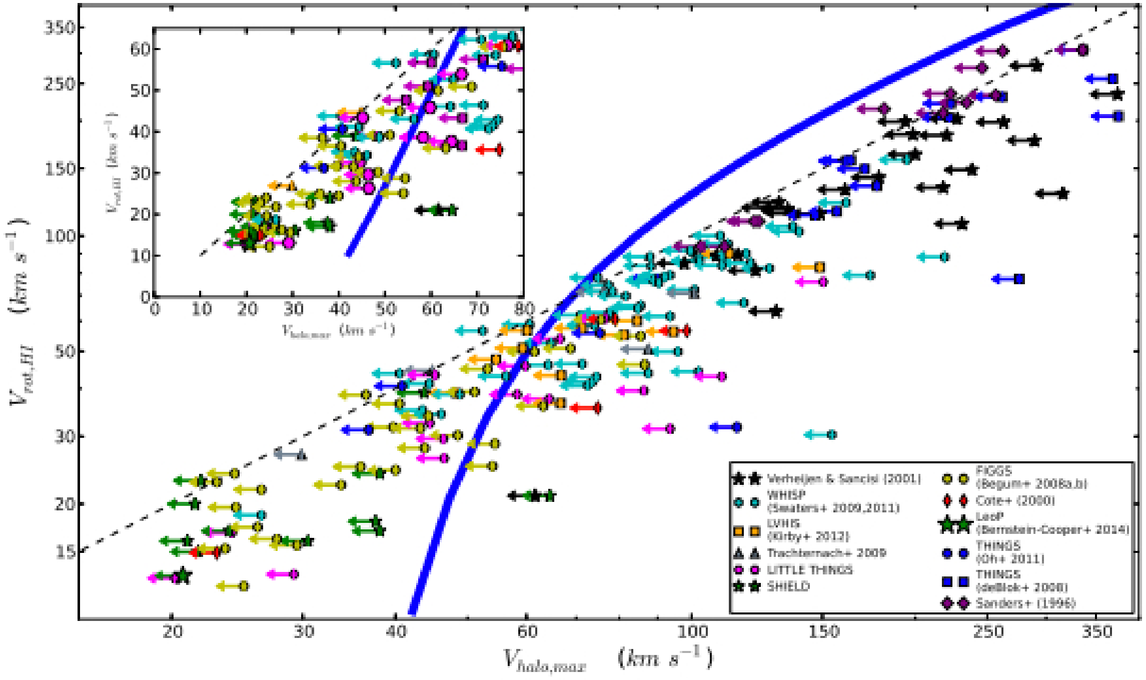
Small-scale problems of CDM

- Everything fine for ~ O(Mpc) or greater

- Below those scales, 4 main discrepancies with data:

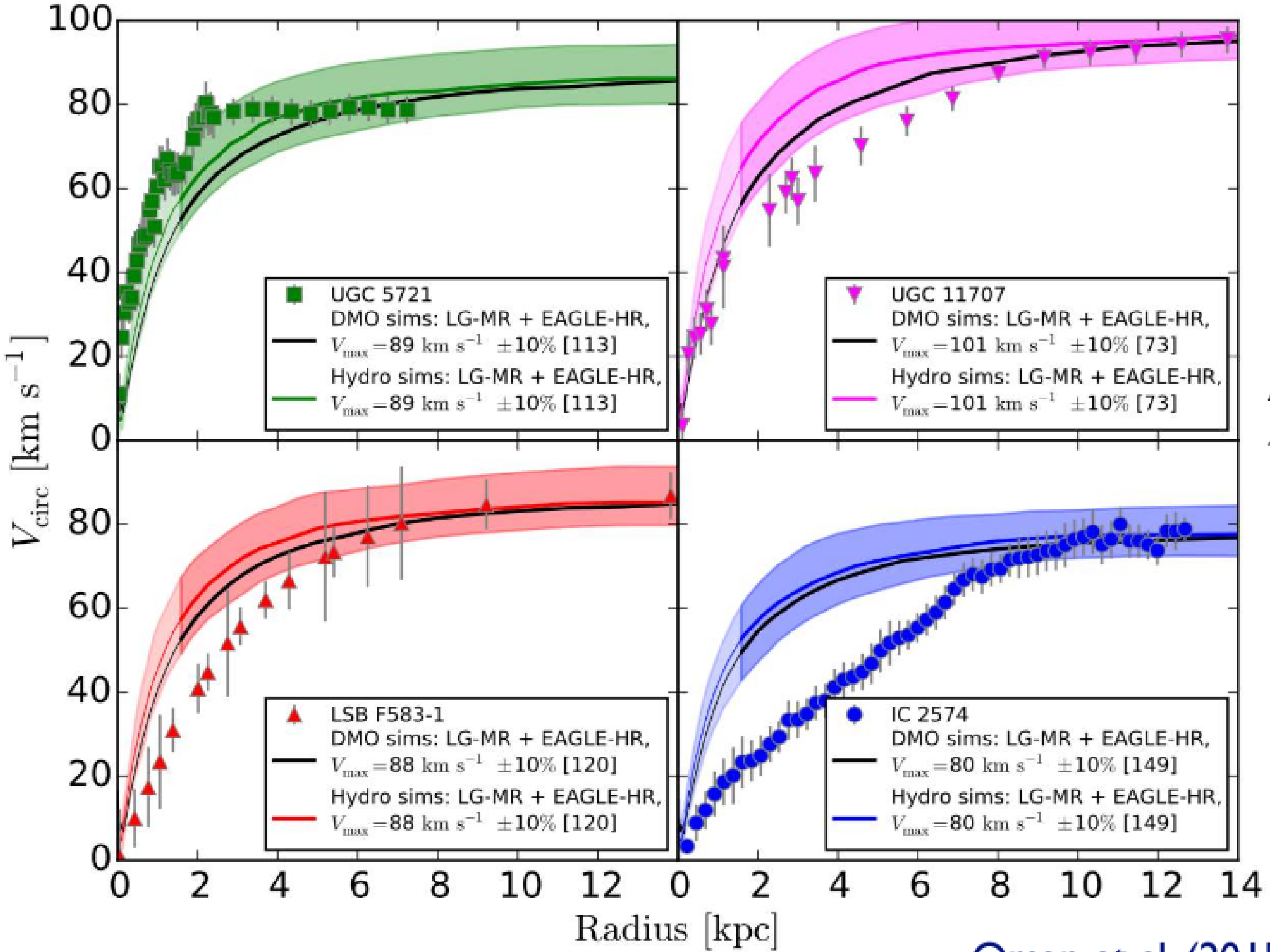
Cusp-vs-Core problem, Diversity problem, Missing satellite problem, Too-big-to-fail problem





[Papastergis, Giovanelli, Haynes and Shankhar, 1407.4665]

The Diversity Problem



All galaxies have the same Vmax!

Oman et al. (2015)

Colored bands: hydrodynamic simulations of ΛCDM

See also Kuzio de Naray, Martinez, Bullock, Kaplinghat (2009)

(taken from Haibo Yu, Copenhagen)

Possible solutions

1- Baryonic feedback (gas cooling, star formation, supernovae, …)

Dissipative (non-adiabatic) baryon physics can:

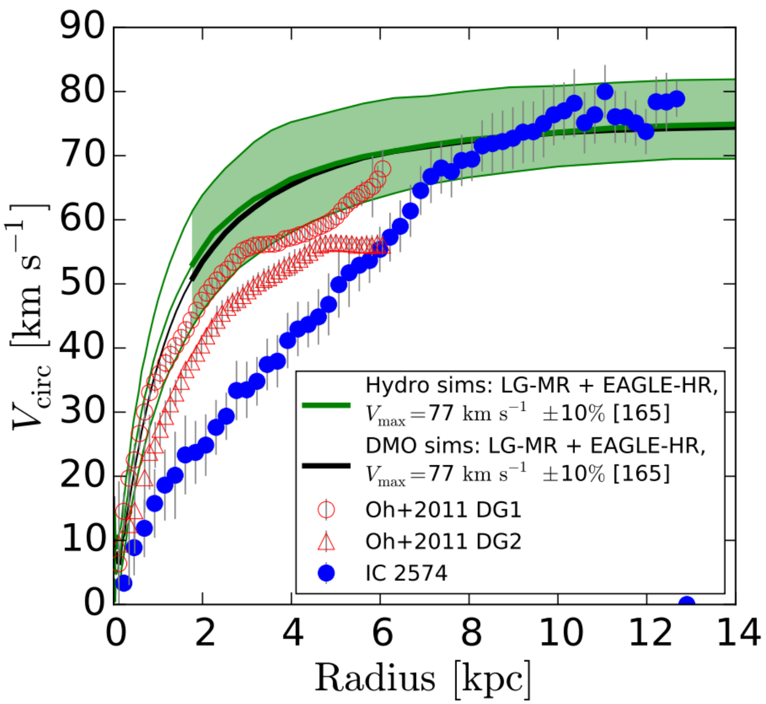
- erase DM cusps

However only the inner ~ 2kpc can be affected, so larger cores *remain unexplained*

- suppress structure formation

However for isolated ("field") dwarfs with halos having Vmax ~ 25 or greater, Baryonic feedback has shown to be insufficient

[Papastergis, Giovanelli, Haynes and Shankar, 1407.4665]



[Di Cintio, Brook, Macci, Stinson, Knebe, Dutton, Wadsley, 1306.0898]

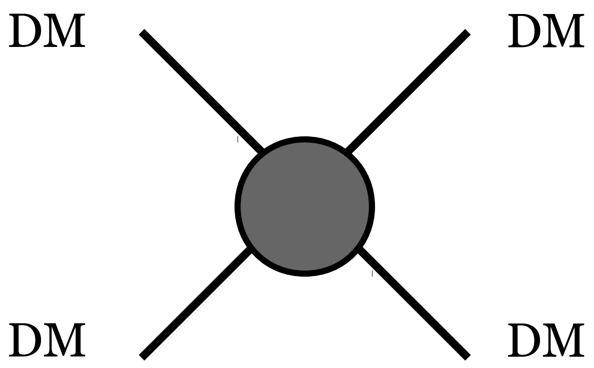
Possible solutions

2- Modification of the CDM paradigm

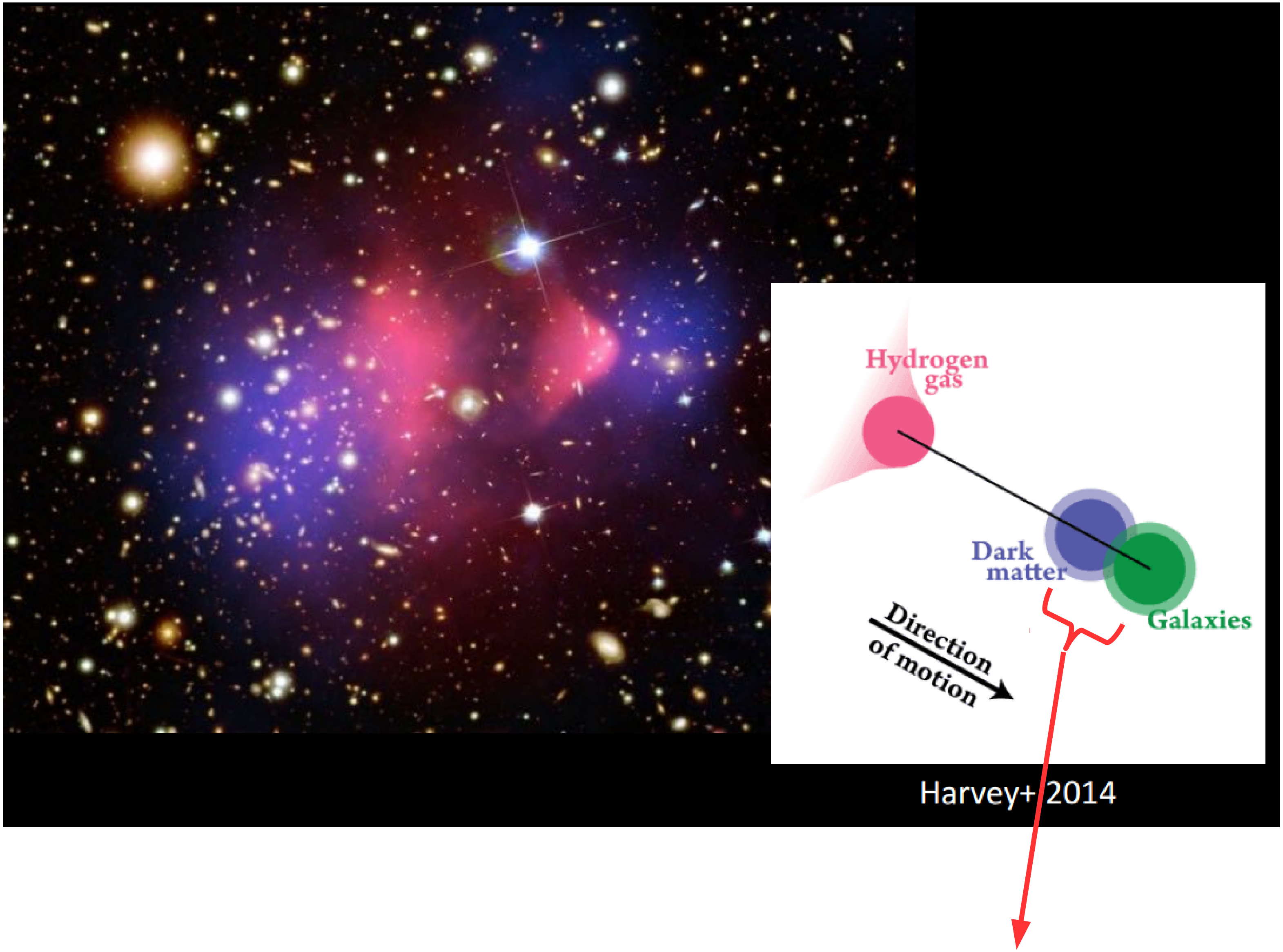
- Warm dark matter
  Yes but constraints from Ly-α put this in tension

[Yèche et al, 1702.03314,
Viel et al, 1306.2314,
Baur et al, 1512.01981, ...]

- Self-Interacting Dark Matter



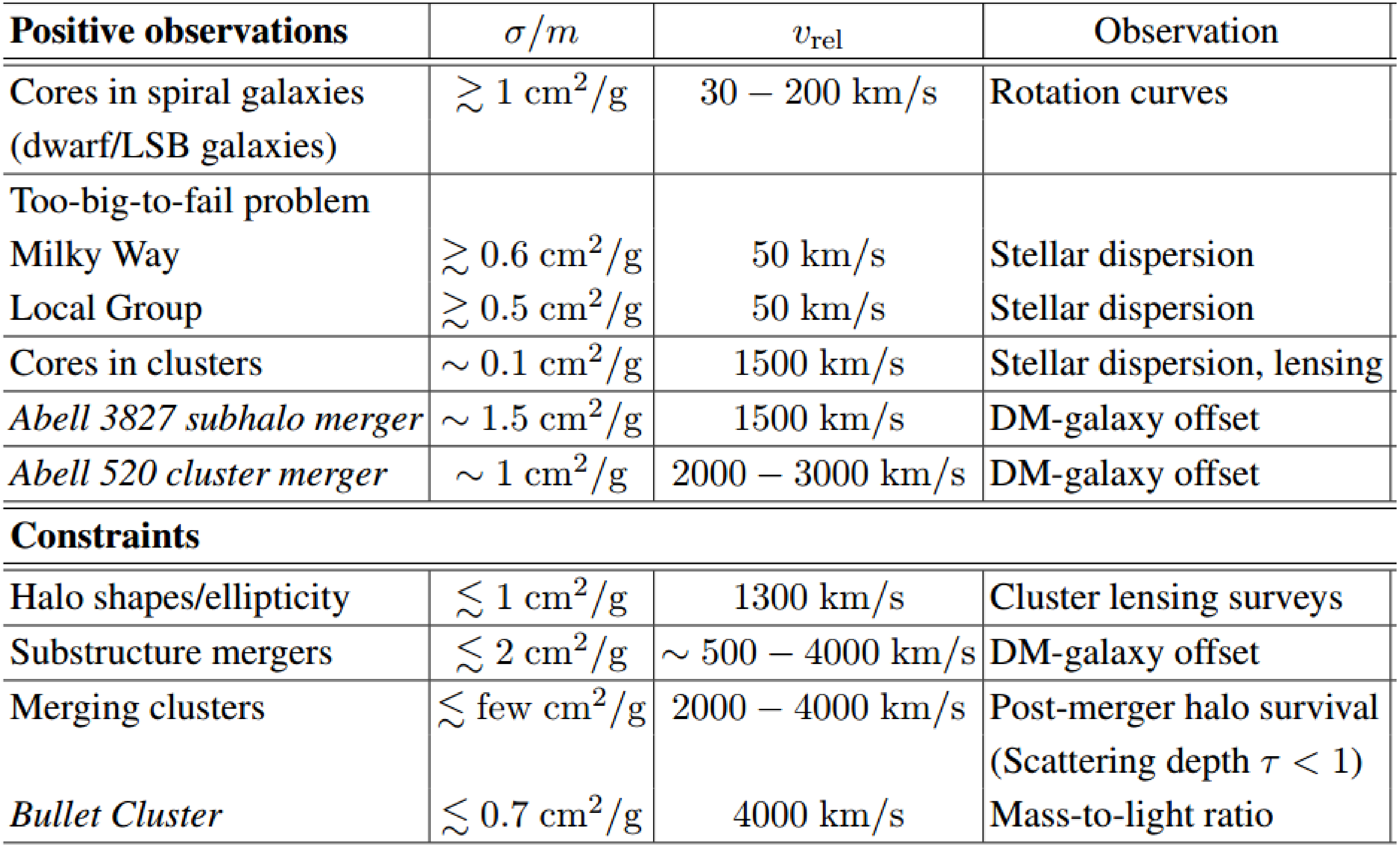
Gravitational lensing probes of SIDM



Harvey+ 2014

Looking for off-sets between DM and galaxies

Summary of constraints today



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

(Tulin and Yu, 1705.02358)

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

Original Idea

(Spergel and Steinhardt, astro-ph/9909386)

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

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

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

funnily, covering the ballpark of nucleon self-interactions ($np \rightarrow np$)
– 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

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

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

- 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

Roughly speaking:

Galaxy scales (~10km/s): $\sigma/m \sim 1 - 10\ \text{cm}^2/\text{g}$

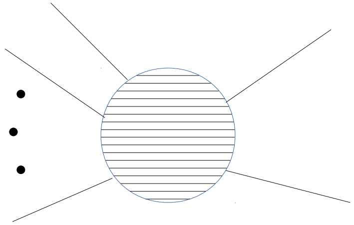
Cluster scales (~1000km/s): $\sigma/m \lesssim 1\text{cm}^2/\text{g}$

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)



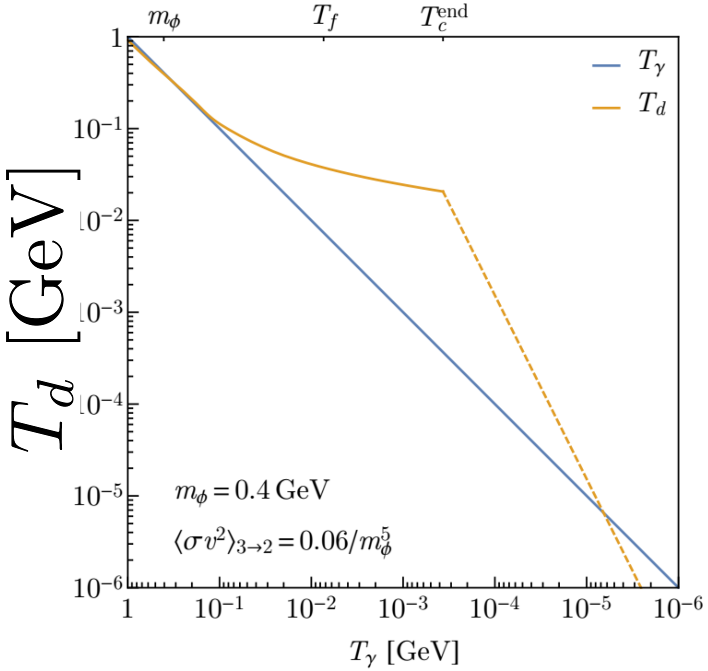
e.g. $\mathcal{L} \supset -\frac{g}{5!}\varphi_s^5$

Entropy density is conserved in each sector:

$$\frac{T_d}{m_{\mathrm{DM}}} \simeq \frac{1}{3\ln(a/\bar{a})}$$ (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)



Pappadopulo, Ruderman, Trevisan, 1602.04219

However...

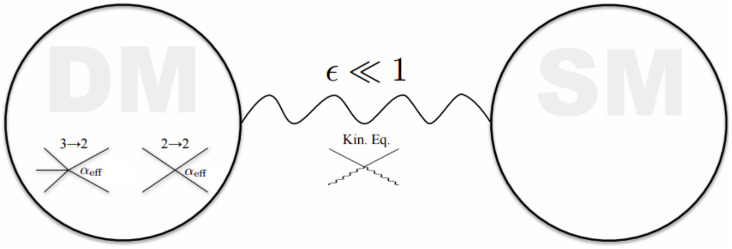
- Recent revival with the correct cosmology (Cannibal DM, SIMPs, non-thermal DM, ...)

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



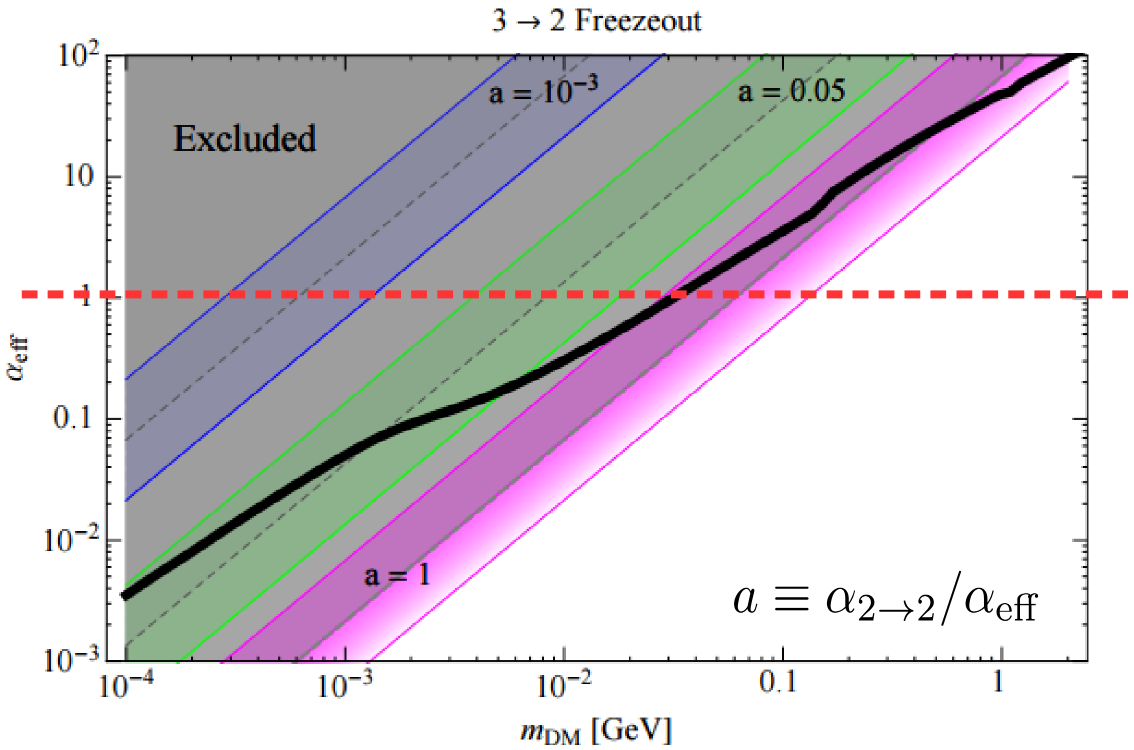
$$\langle \sigma v^2 \rangle_{3\to 2} = \frac{\alpha_{\rm eff}^3}{m_{\rm DM}^5}$$

(correct dimensions for scattering rate)

- Portal to the visible sector:

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

- 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:

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

$$\hookrightarrow \mathcal{L}_{\mathrm{int}} \supset \frac{2N_c}{15\pi^2 f_\pi^5} \epsilon^{\mu\nu\rho\sigma} \underbrace{\mathrm{Tr}(\pi\partial_\mu\pi\partial_\nu\pi\partial_\rho\pi\partial_\sigma\pi)}_{\text{5-point interaction responsible for 3→2 processes}}$$

- 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

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

(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

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

To solve small-scale problems

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

Visible sector: MSSM

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

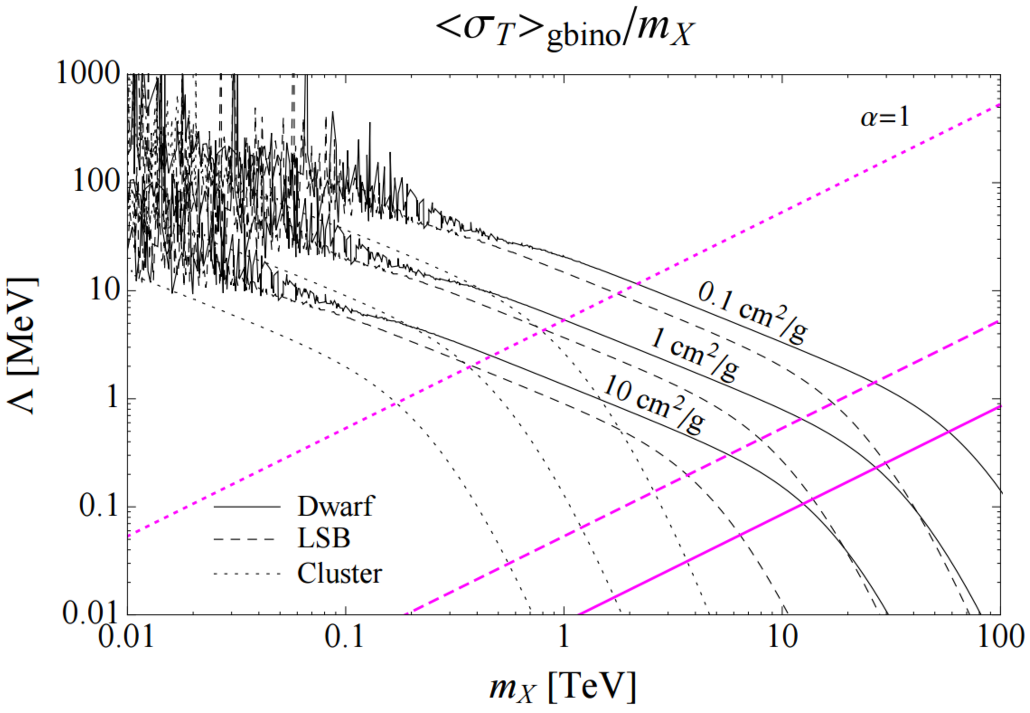
Hidden sector: glueballs+glueballinos

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

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

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

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



Velocity-dependent SI because of light-mediated

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

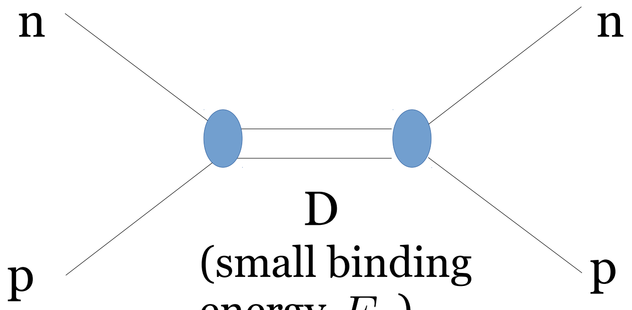
xsection expected to fall for:

(scattering length)

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

(Tulin and Yu, 1705.02358)

(subtlety about analogy with neutron-proton scattering)



(small binding energy E_b)

- 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

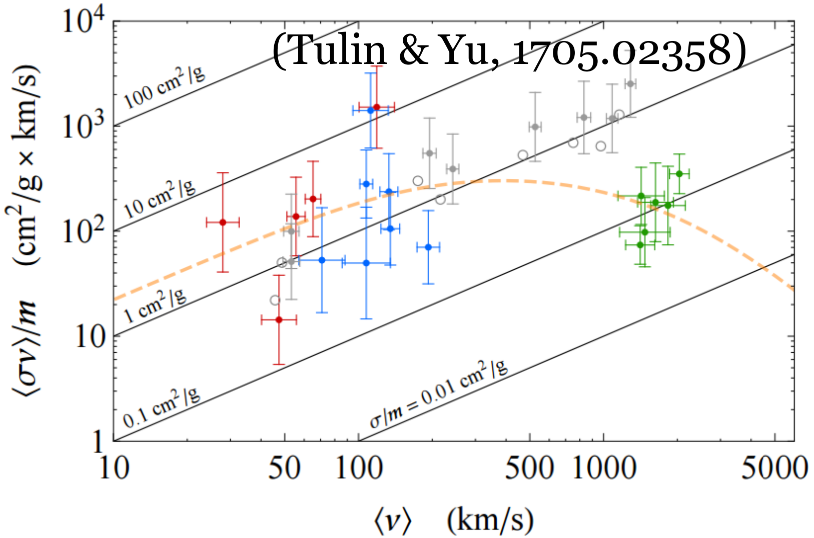
Ways to obtain ballpark xsections

(now with velocity-dependence!)

2) Long-range interactions

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

(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]

$$\sigma_T = \int d\Omega (1 - \cos\theta) \frac{d\sigma}{d\Omega} \qquad \sigma_V = \int d\Omega \sin^2 \frac{d\sigma}{d\Omega}$$

Regulates forward divergence

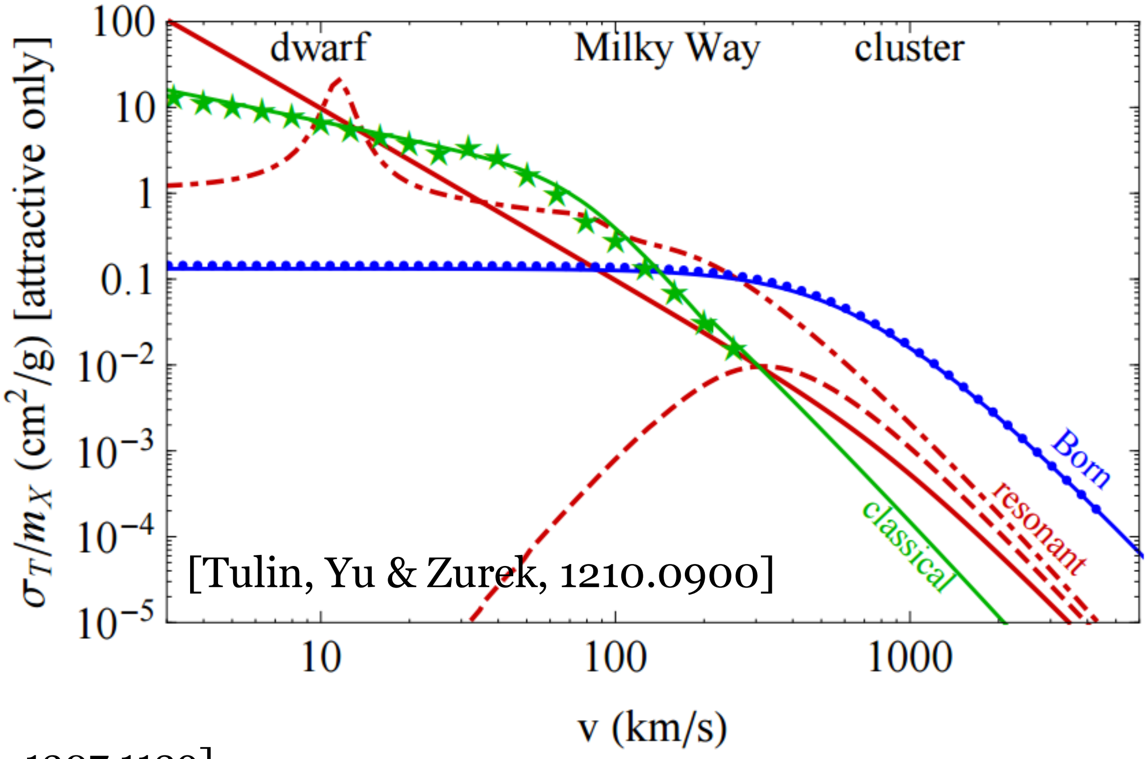
Regulates both forward & backward
(for identical DM particles)

Velocity dependence

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

- standard Yuwaka potential

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



[Tulin, Yu & Zurek, 1210.0900]

- other potentials are easily possible

[Bellazzini, Cliche & Tanedo, 1307.1129]

$$\boxed{\begin{aligned} V = \frac{1}{4\pi r}\Big[& g_1 + g_2(\mathbf{s_1}\cdot\mathbf{s_2}) \\ & + \frac{g_3}{\Lambda^2 r^2}(3\mathbf{s_1}\cdot\hat{r}\ \mathbf{s_2}\cdot\hat{r} - \mathbf{s_1}\cdot\mathbf{s_2}) \\ & + \frac{g_{7,8}}{\Lambda r}(\mathbf{s_1}\pm\mathbf{s_2})(\hat{r}\times\mathbf{v}) \end{aligned}}$$

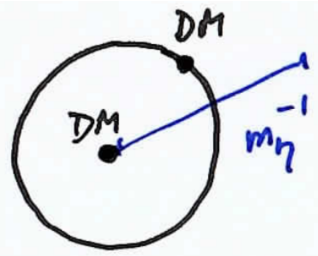
Interaction	g_1	g_2	g_3	g_7	g_8
$\bar{\chi}\chi\varphi$	✓	X	X	✓	X
$\bar{\chi}\gamma^5\chi\varphi$	X	X	✓	X	X
$i\bar{\chi}\gamma^\mu\gamma^5\chi\partial_\mu\varphi$	X	X	✓	X	X
$\bar{\chi}\gamma^\mu\chi A_\mu$	✓	X	X	✓	X
$i\bar{\chi}\gamma^5\gamma^\mu\chi A_\mu$	X	X	✓	X	X
$i\bar{\chi}\sigma^{\mu\nu}\chi F_{\mu\nu}$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

Interaction regimes

[Tulin, Yu & Zurek, 1302.3898]

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

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

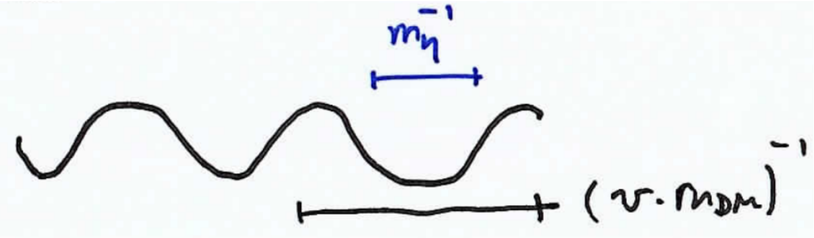


$\alpha' m_\chi \gg m_\eta \quad (m_\chi v_{\rm rel} \gg m_\eta)$ (classical)

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

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

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



Partial-wave analysis

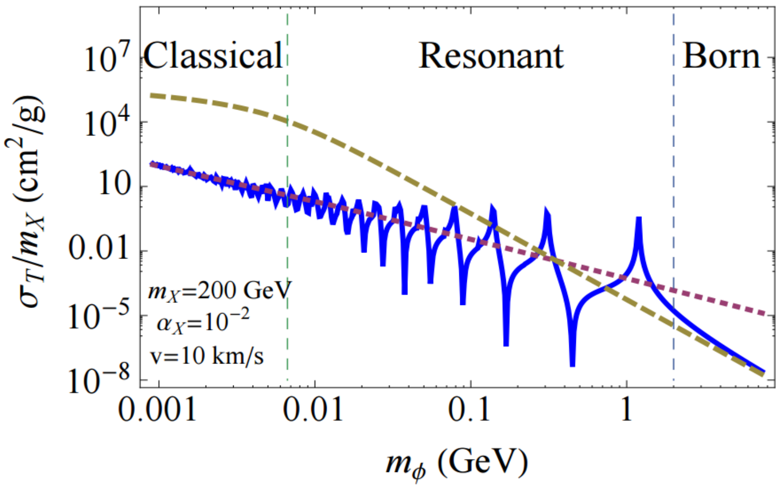
$$\sigma_T = \frac{4\pi}{k^2}\sum_{\ell=0}^{\infty}(\ell+1)\sin^2(\delta_{\ell+1}-\delta_\ell)$$

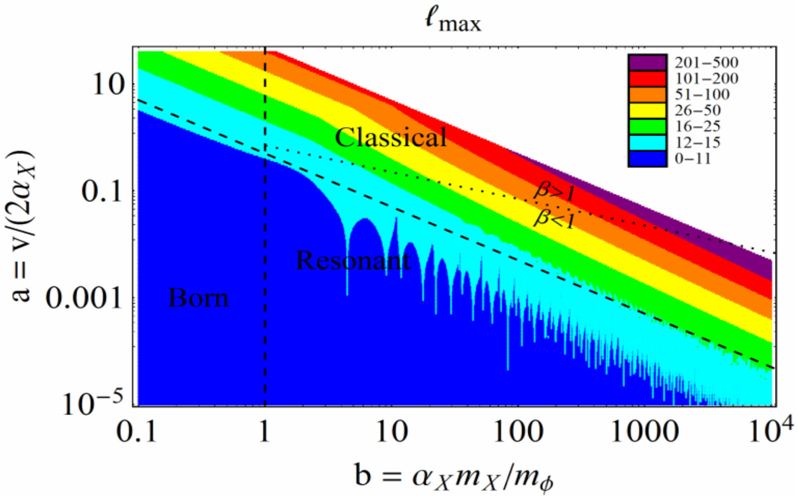
$$\frac{1}{r^2}\frac{d}{dr}\left(r^2\frac{dR_\ell}{dr}\right) + \left(k^2 - \frac{\ell(\ell+1)}{r^2} - 2\mu V(r)\right)R_\ell = 0 \qquad \lim_{r\to\infty} R_\ell(r) \propto \cos\delta_\ell\, j_\ell(kr) - \sin\delta_\ell\, n_\ell(kr)$$

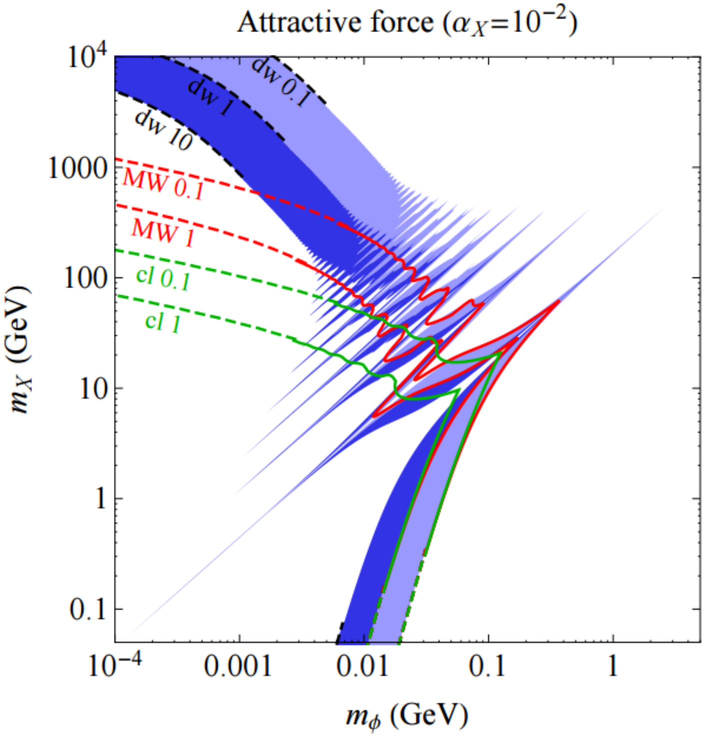
Features of long-range SI's

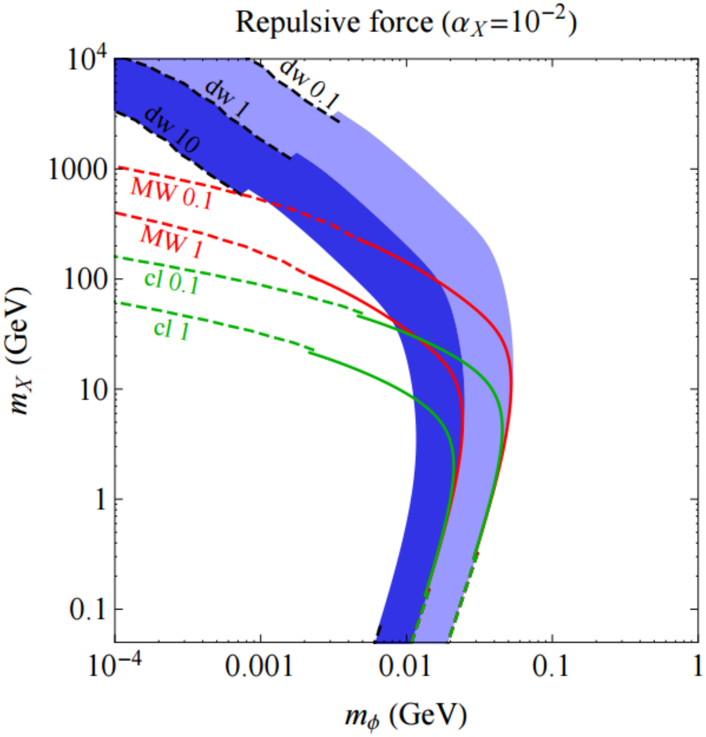
[Tulin, Yu & Zurek, 1302.3898]

Yukawa model









(a poor phenomenologist’s next step)

What about complementary probes of SIDM ?

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

(See talk by Tulin, Copenhagen)

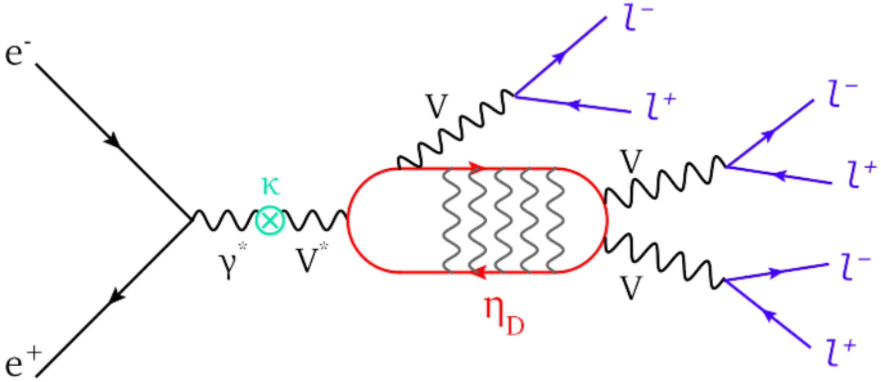
Collider searches

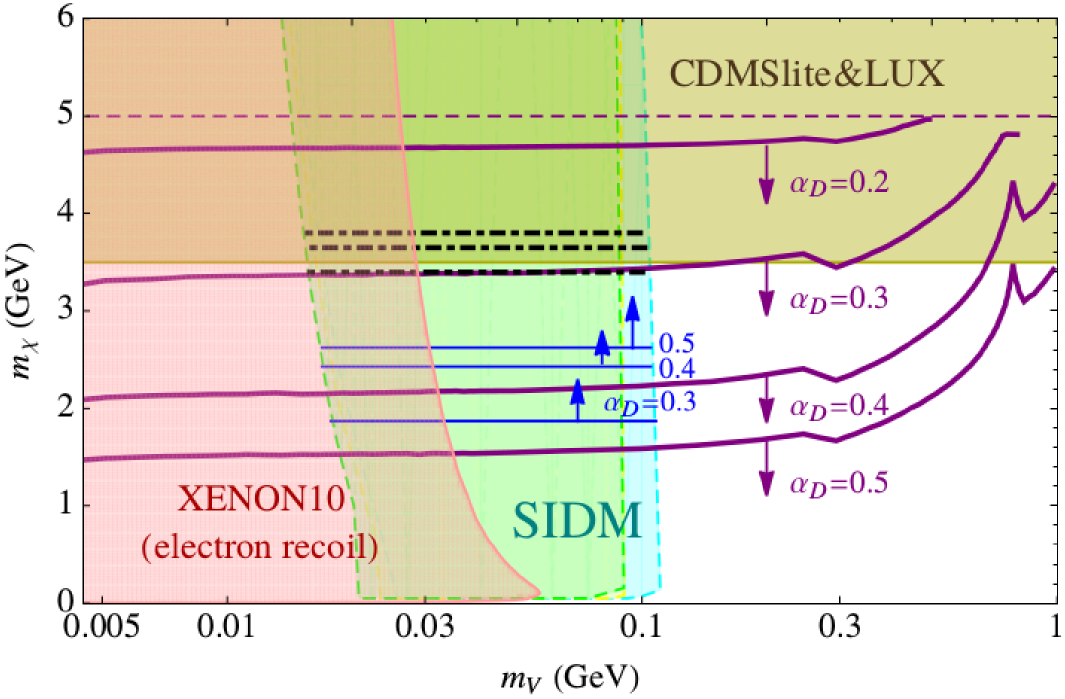
Assume **non-zero** coupling between mediator and SM

- 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

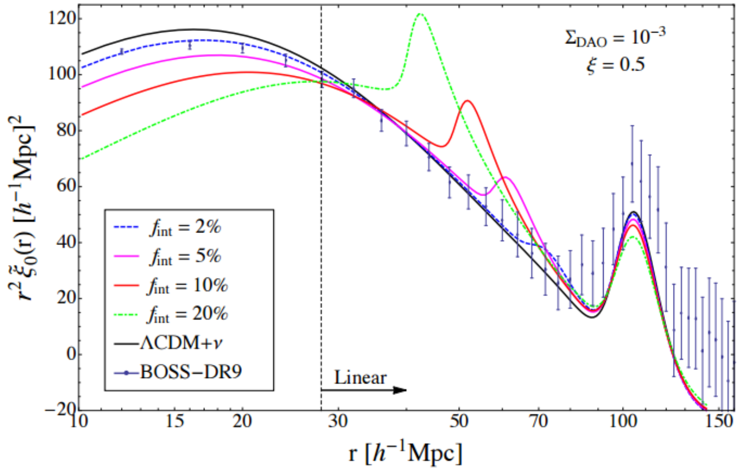
Assume **zero** coupling between (relativistic) mediator and SM

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

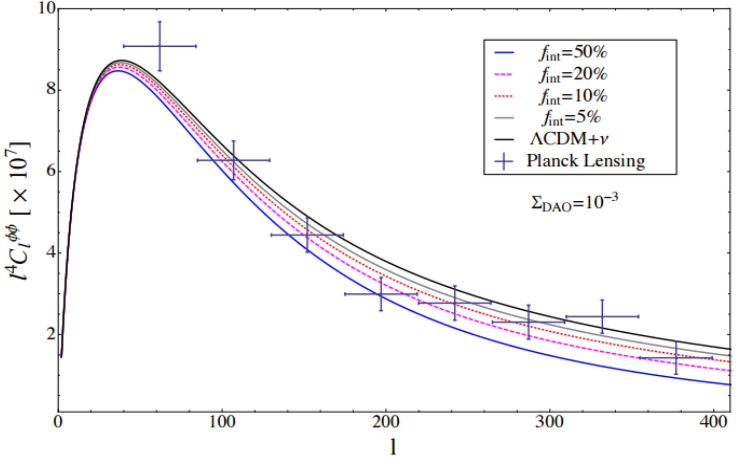
e.g. the PIDM model:

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

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:

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

(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 $10^{12}{\rm s} \lesssim \tau_\eta \lesssim 10^{17}{\rm s}$ [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

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

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

(depending on mediator mass)

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

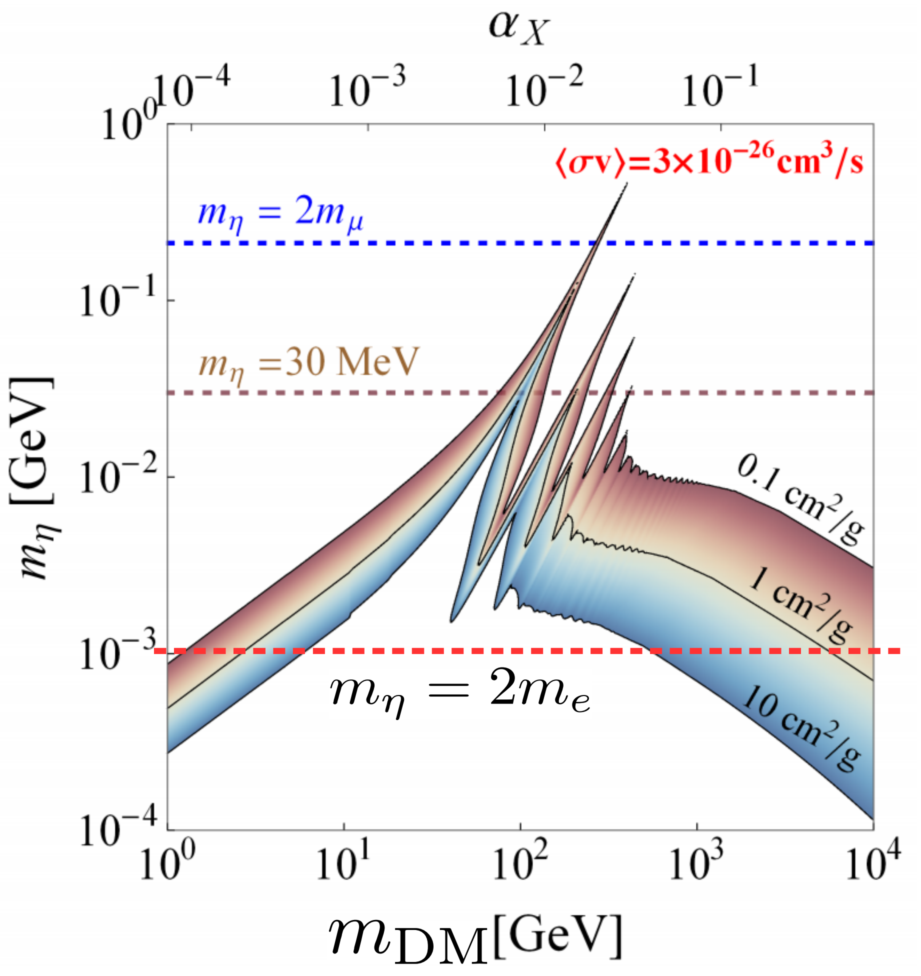
- However severely excluded:

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**

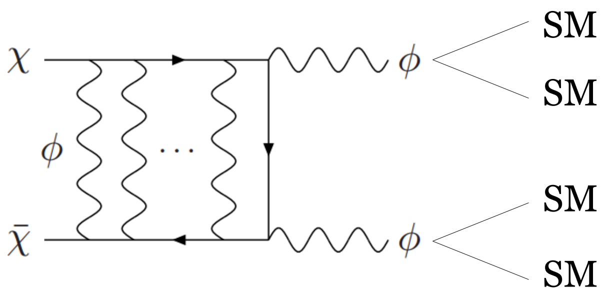
if $m_\eta < 2m_e$

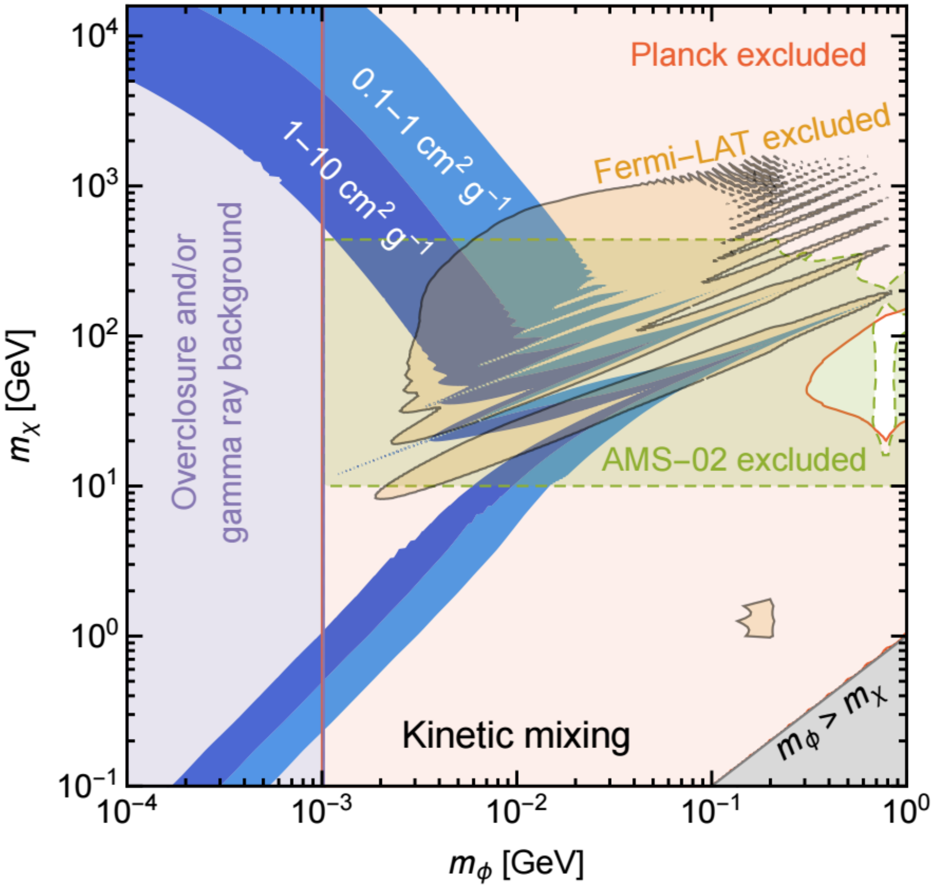
According to the value of τ_η, excluded by (DM) **annihilations from CMB**, (mediator) **late decays from CMB**, or **X-ray emission**



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

Indirect detection

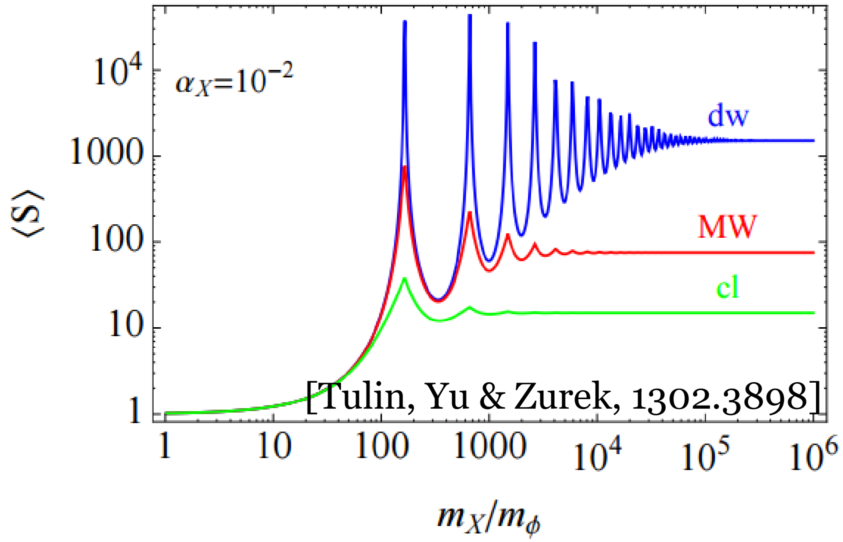




[Bringmann, Kahlhoefer, Schmidt-Hoberg & Walia, 1612.00845]

Sommerfeld enhancement:

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



[Tulin, Yu & Zurek, 1302.3898]

Assumptions:

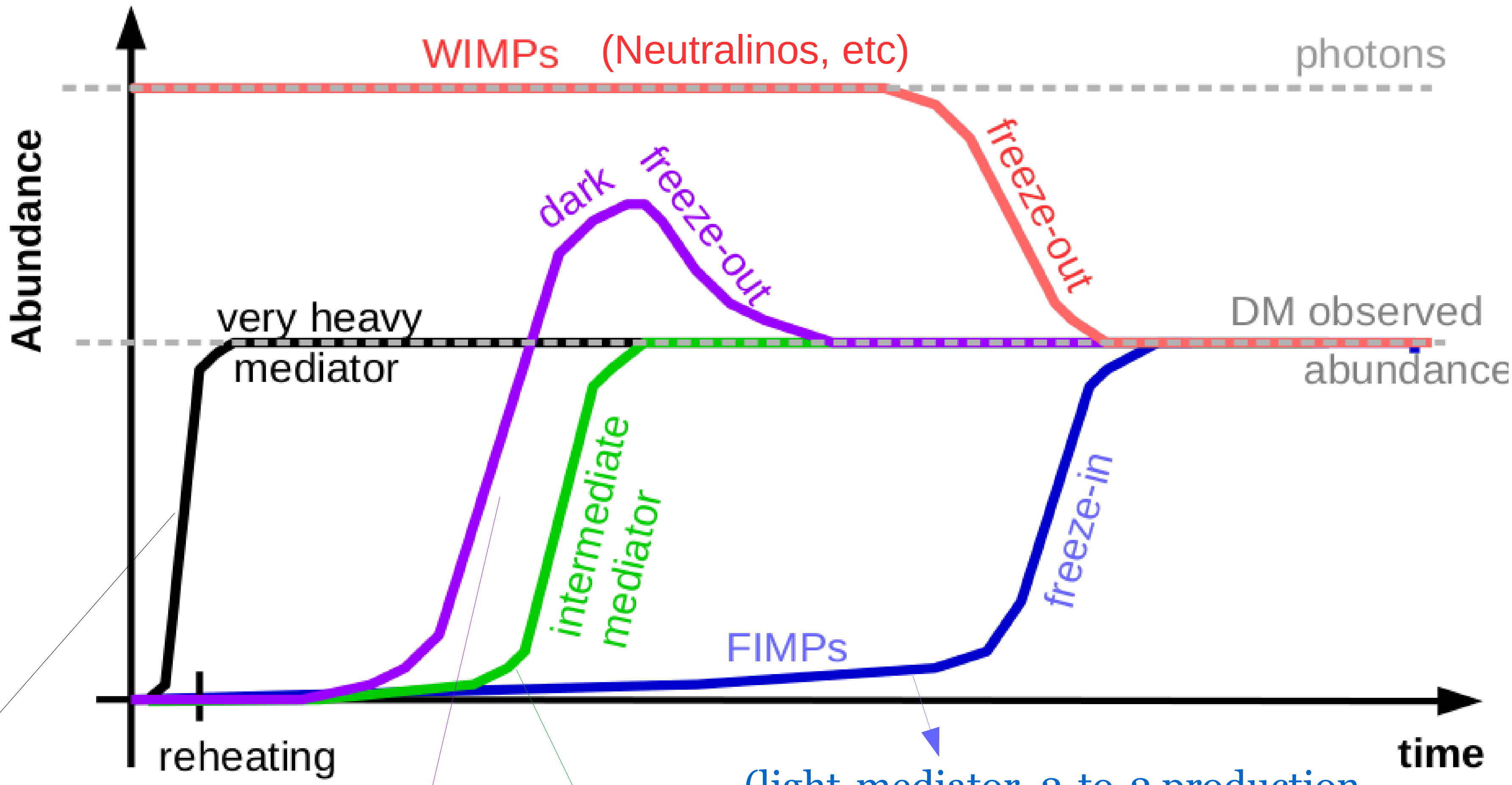
1) s-wave DM annihilation

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, ...

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

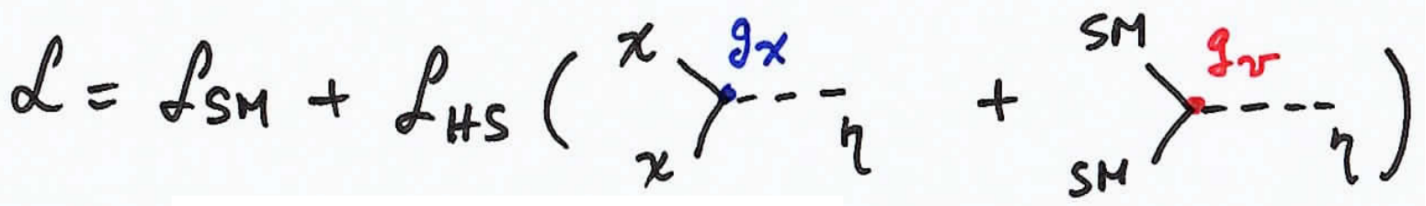
(Non-thermal Z', ...)

(secluded dark sectors)

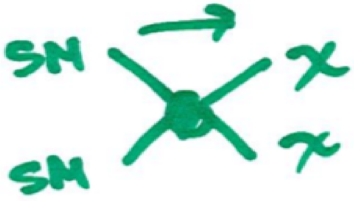
Generic:
[Chu, Hambye & Tytgat, 1112.0493]

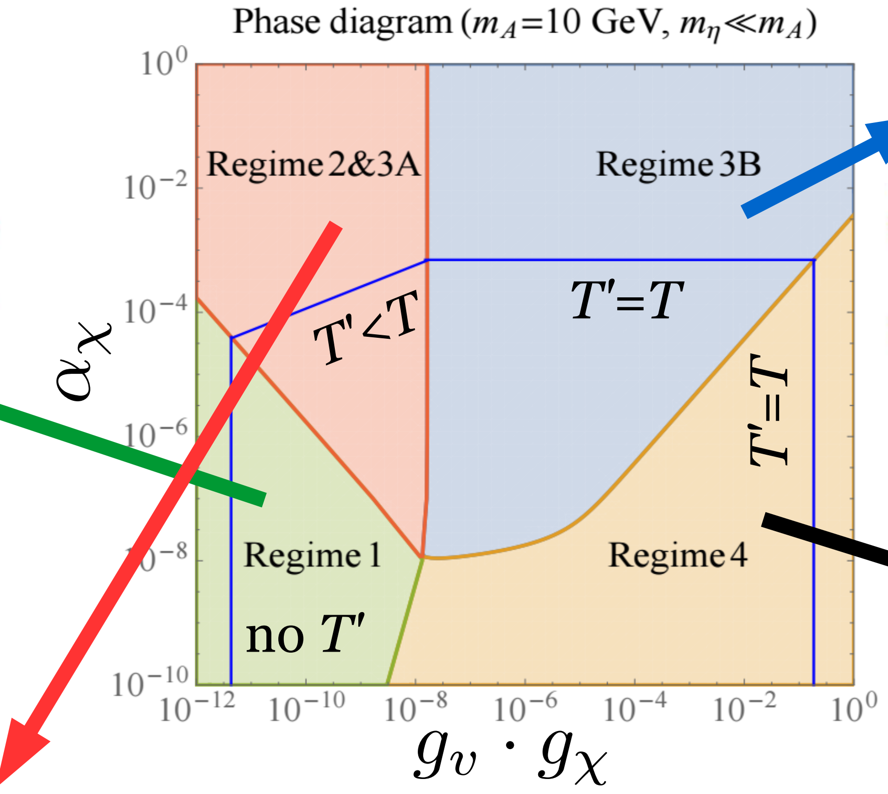
Pure freeze-in:
[Blennow, Fernandez & Zaldivar, 1309.7348]

Different thermal histories of DM



Freeze-in





Dark Freeze-out (T' = T)

usual Freeze-out

Dark Freeze-out (T' < T)

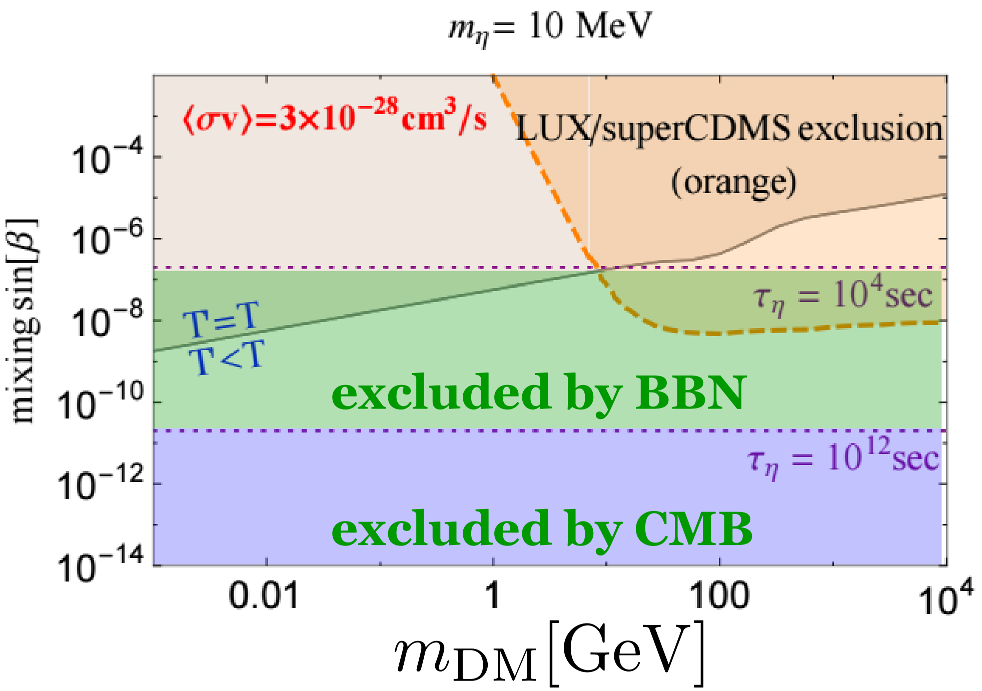
- Freeze-in production + dark annihilation

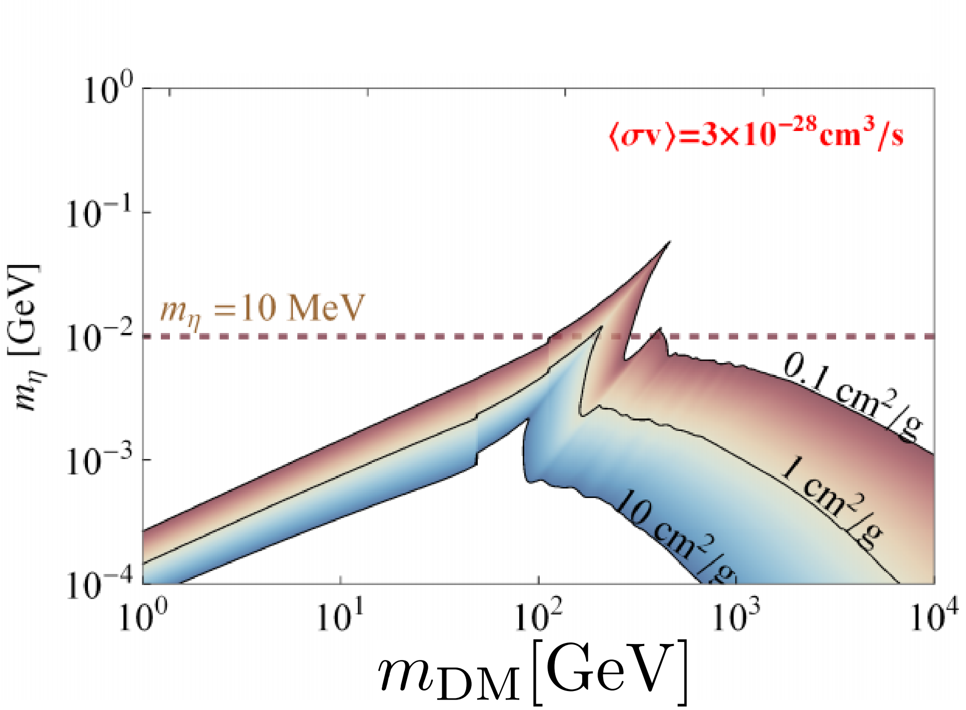
T': temperature of dark sector
T': temperature of visible sector

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**





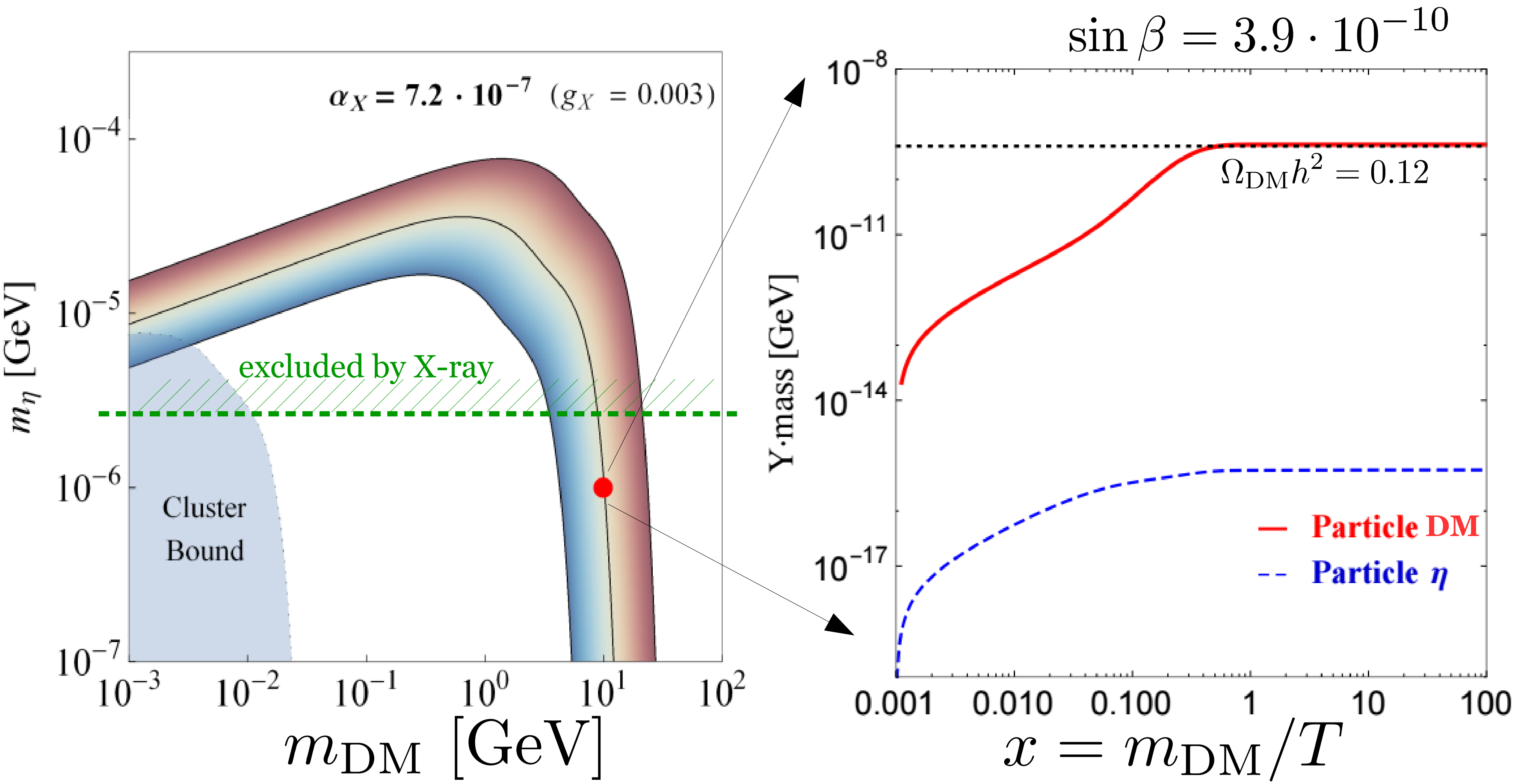
Thus, **excluded.**
(Similar conclusions for mediators lighter than electrons)

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!