Freeze-in DM at the LHC

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DMWG meeting, CERN, 22·06·18

Outline

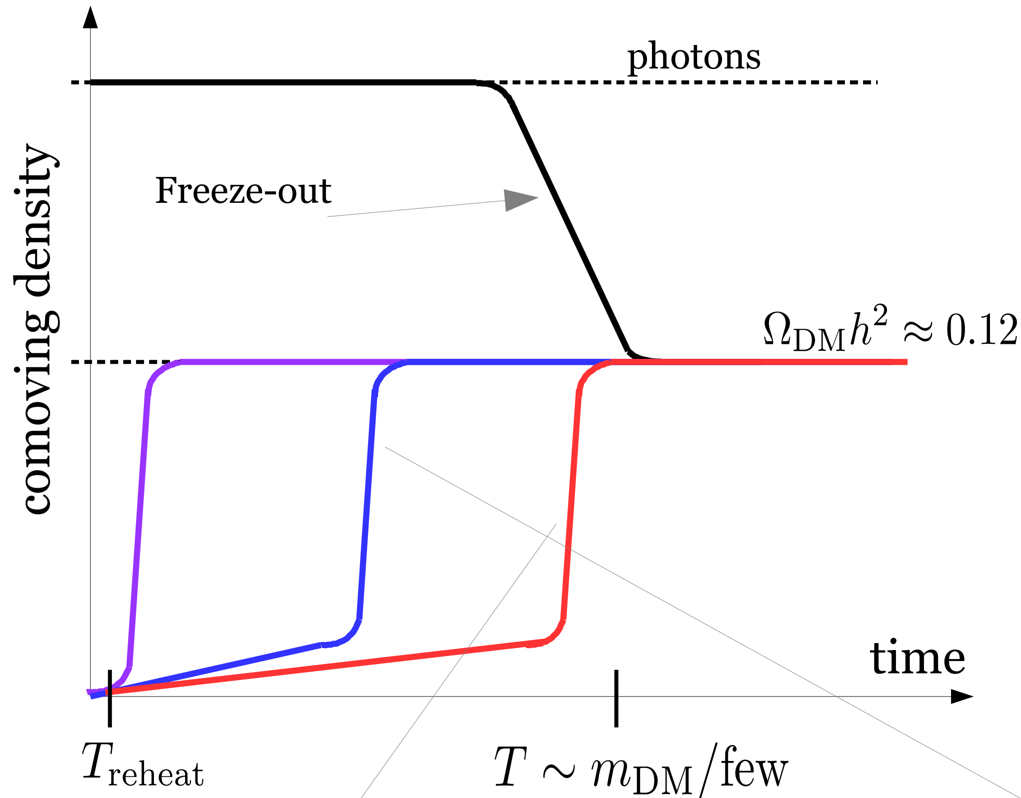
Trying to motivate the study of freeze-in DM at the DMWG

Freeze-in in a nutshell

$$\frac{dn_{\rm DM}}{dt} + 3Hn_{\rm DM} = \underbrace{n_{\rm bath}\Gamma_{\rm prod} - n_{\rm DM}\Gamma_{\rm ann}}_{\text{interaction rates}}$$

negligible

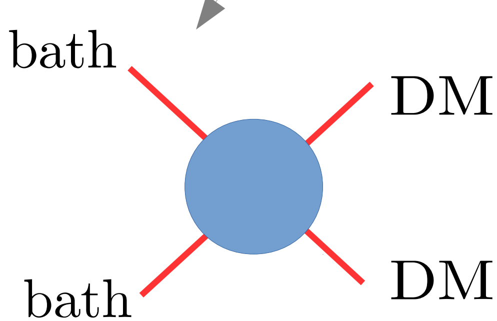
interaction rates



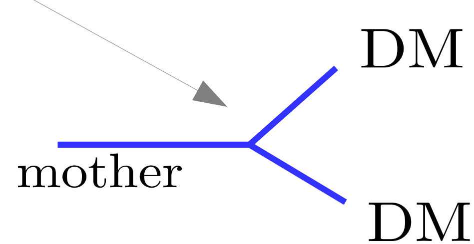
Characteristics:

- prod. period depends on benchmark: $m_{\rm DM}, m_{\rm mother}, T_{\rm reheat}$
- dark sector never thermalises with itself
- prod. via **scatterings** or **decays**

-Hall, Jedamzik, March-Russell, West, 0911.1120
-Blennow, Fernandez-Martinez, Zaldivar, 1309.7348
-Bernal, Heikinheimo, Tenkanen, Tuominen, Vaskonen, 1706.07442



$\lambda_1\lambda_2 \sim 10^{-12}$

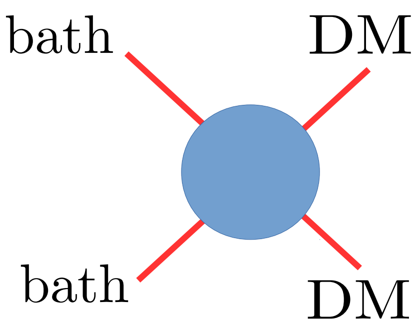


$\lambda \sim 10^{-13}\sqrt{\frac{m_{\rm mother}}{m_{\rm DM}}}$

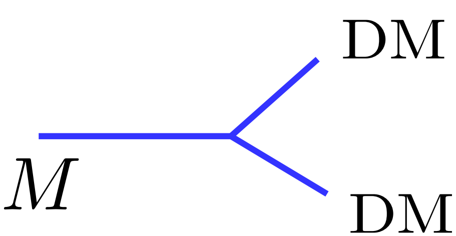
Freeze-in solutions

$$\frac{dn_{\rm DM}}{dt} + 3Hn_{\rm DM} = \underbrace{n_{\rm bath}\Gamma_{\rm prod} - n_{\rm DM}\Gamma_{\rm ann}}_{\text{interaction rates}}$$

negligible



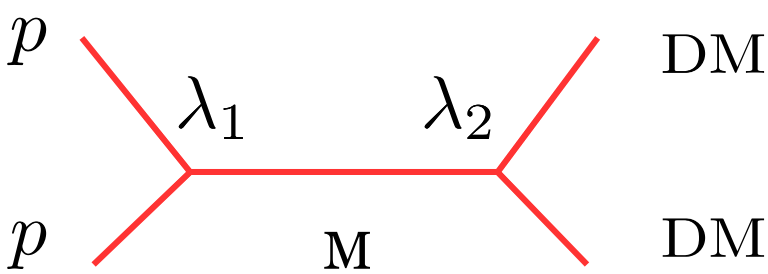
$$\begin{aligned}\Omega_\chi h^2|_0 &= 2\frac{m_\chi \mathbf{s}_0 Y_\chi|_0}{\rho_c} \\ &\approx 3\times 10^{24}\ m_\chi\ g_b^2 \int_{T_0}^{T_R} dT \int_{4m_\chi^2}^{\infty} ds \frac{1}{\sqrt{g_*}g_*^s}\frac{1}{T^5} s^{3/2} K_1(\sqrt{s}/T)\ \sigma(s)\end{aligned}$$



$$\Omega_\chi h^2|_0 = 2\frac{m_\chi}{3.6\times 10^{-9}{\rm GeV}}\frac{45\xi M_{\rm Pl} g_E}{4\pi^4\cdot 1.66 M^2}\Gamma \int_{M/T_R}^{M/T_0} dx x^3 \frac{K_1(x)}{\sqrt{g_*}g_*^s}$$

FIMPs *not* at the LHC

Typical DM ‘portal’ models



$$T_R \gg M$$

$$\lambda_1 \lambda_2 \sim 10^{-12}$$

Unless....

$$T_R \lesssim M \qquad \lambda_1 \lambda_2 \sim \mathcal{O}(1)$$

freeze-in suppression
coming from Boltzmann tail
instead of tiny couplings

(For masses accessible at the LHC, watch out low reheat temperature!)

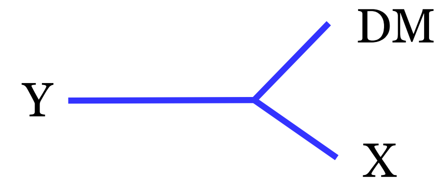
FIMPs at the LHC

Type of signals: **Displaced-vertices**

Degenerate spectrum

Khoze, Plascencia, Sakurai, 1702.00750
Mahbubani, Schwaller, Zurita, 1703.05327
Buchmueller, De Roeck, McCullough, Schwaller, Yu, 1704.06515
....
(and growing)

Very small couplings



$\lambda \sim 10^{-9}$ for $m_Y \sim 1\text{TeV}$

Far from WIMP regime!

So...can it be freeze-in DM ?

Remember the original estimation...

$$\lambda \sim 10^{-13}\sqrt{\frac{m_Y}{m_{\rm DM}}}$$

Yes, it can !

Co, D'Eramo, Hall, Pappadopulo, 1506.07532
Hessler, Ibarra, Molinaro, Vogl, 1611.09540
Gosh, Mondal, Mukhopadhyaya, 1706.06815
LesHouches WG , 1803.10379
Calibbi, Lopez-Honorez, Lowette, Mariotti, 1805.04423

FIMPs at the LHC

$$\Omega_{\rm DM} h^2 \approx 3 \times 10^8 \left(\frac{m_{\rm DM}}{\rm GeV}\right) Y_{\rm DM}$$

$\to s_0/\rho_{\rm crit}$

$$Y_{\rm DM} \propto \frac{M_{\rm Pl}\Gamma_{Y\to X,{\rm DM}}}{m_{\rm Y}^2} \int_{x_{\rm min}}^{x_{\rm max}} dx\ x^3 K_1(x)$$

$x \equiv \frac{m_{\rm Y}}{T}$

Boltzmann suppression

$$\lambda \sim 10^{-13} \sqrt{\frac{m_{\rm Y}}{m_{\rm DM}}} \left(\frac{3\pi/2}{\int_{x_{\rm min}}^{x_{\rm max}} dx\ x^3 K_1(x)}\right)^{1/2}$$

(*) Two choices to increase coupling to $\sim 10^{-9}$

- Increase mass-ratio as much as possible
- Change production time lapse / cosmological history

(*) Note that the "MATHUSLA" proposal could make it with much less 'cooking'

[Chou, Curtin, Lubatti, 1606.06298, **"MATHUSLA Physics case", 1806.07396**]

Option #1: Increasing mass-ratio

- Ex #1: "Singlet-Singlet Model"

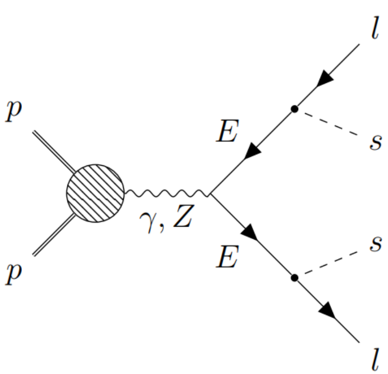
1803.10379 (sec.#4)
[Belanger, Cai, Desai, Goudelis, Harz, Lessa, No, Pukhov, Sekmen, Sengupta, Zaldivar, Zurita]

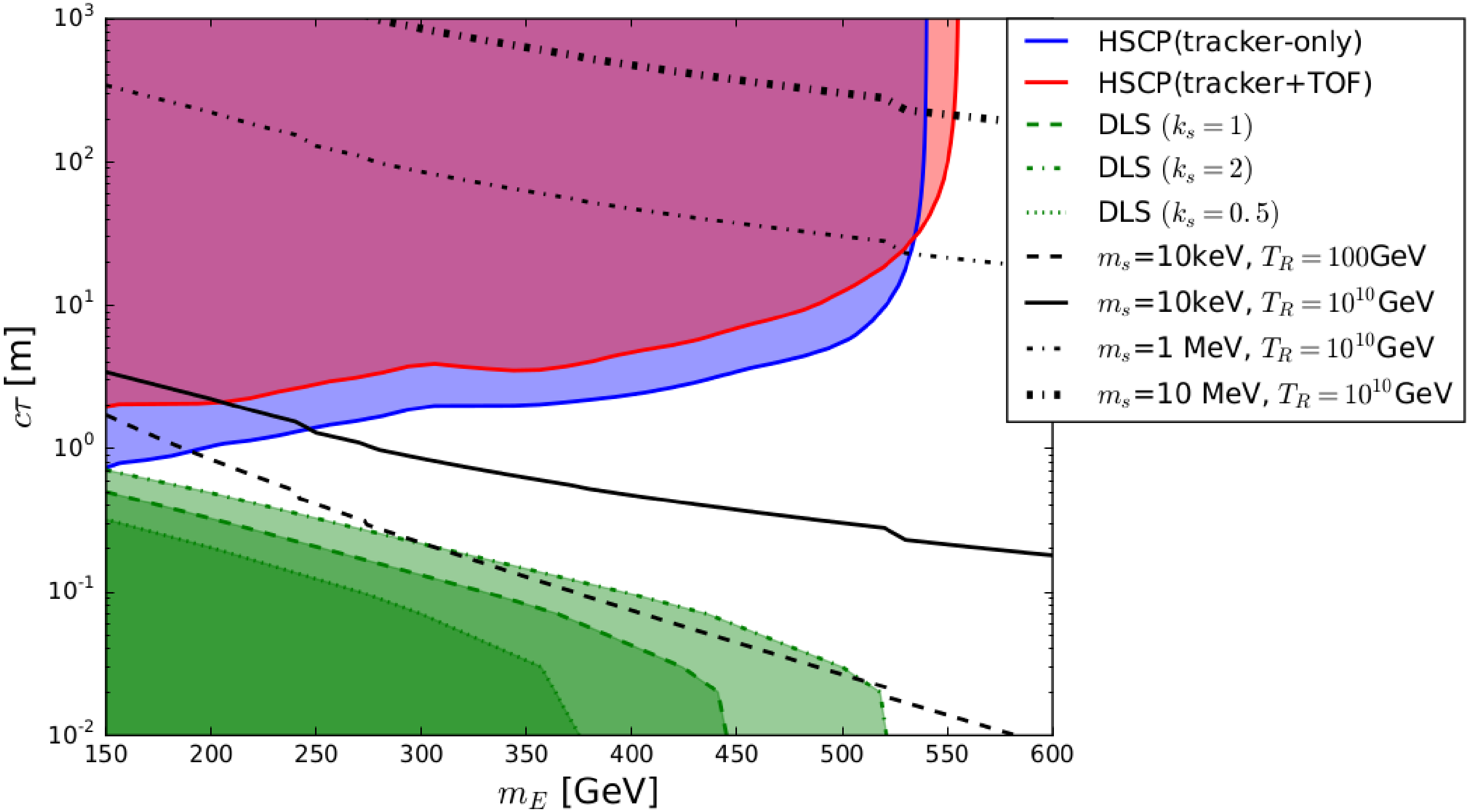
$$\mathcal{L} \supset y_e s \bar{E}_L e_R + y_\mu \bar{s} E_L \mu_R + \text{h.c.}$$

s, E : $\mathbb{Z}_2$-odd $SU(2)_L$ singlets

s → dark matter

Topology: displaced leptons or detector-stable charged particles



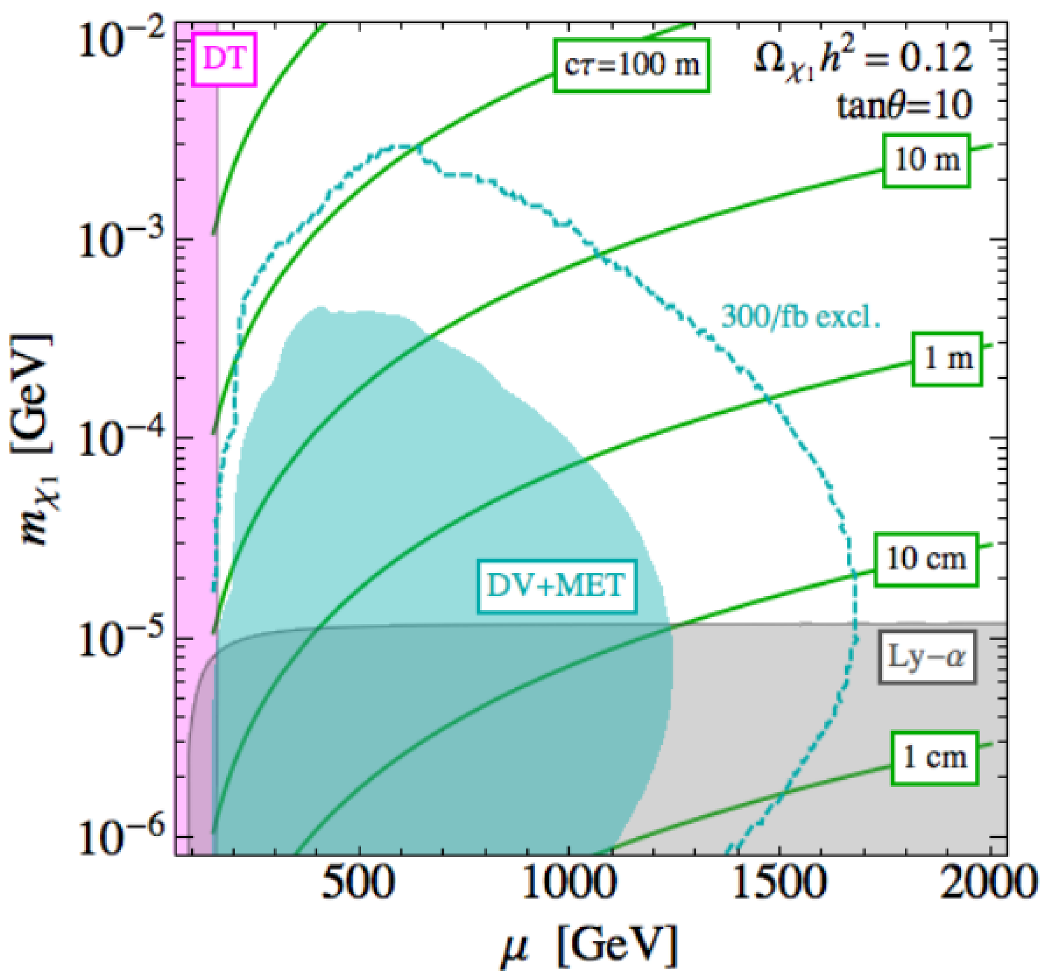


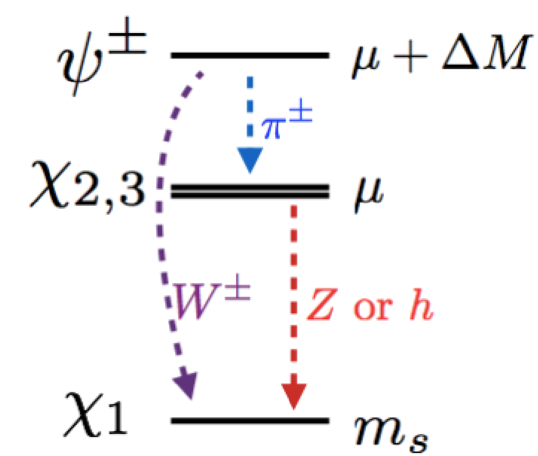
Option #1: Increasing mass-ratio

- Ex #2: "Singlet-Doublet Model"   1805.04423 [Calibbi, Lopez-Honorez, Lowette, Mariotti]

$$-\mathcal{L} \supset \mu\, \psi_d \cdot \psi_u + y_d\, \psi_d \cdot H\, \psi_s + y_u\, H^\dagger \psi_u\, \psi_s$$

<u>*Topology:*</u> displaced jets coming from *Z*- or *h*-decays





Option #1: Increasing mass-ratio

- Ex #3: "Scotogenic FIMP"

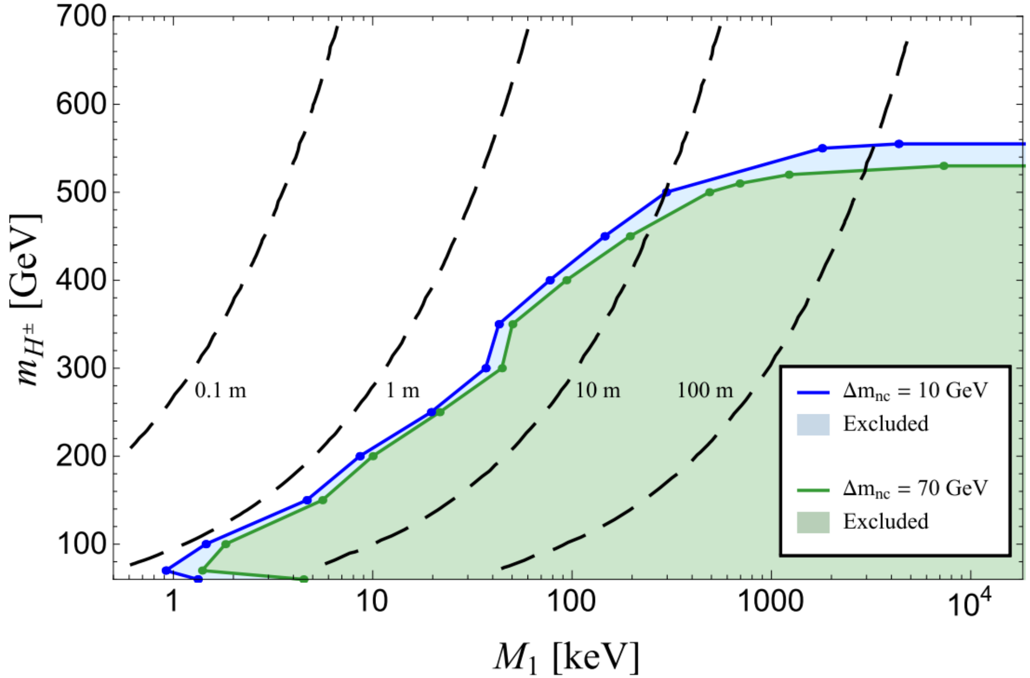
[Hessler, Ibarra, Molinaro, Vogl, 1611.09540
Molinaro, Yaguna, Zapata, 1405.1259
Ma, hep-ph/0601226]

$$\mathcal{L} \supset \mathcal{L}_{\rm SM} + \mathcal{L}_{H_2} + \mathcal{L}_{N_i} + Y(\bar{\nu}_L \cdot H_2^0 - \underline{\ell_L \cdot H^+) N_i} + \text{h.c.}$$

2nd Higgs doublet

3 fermionic singlets, lightest is DM } $\mathbb{Z}_2$-odd

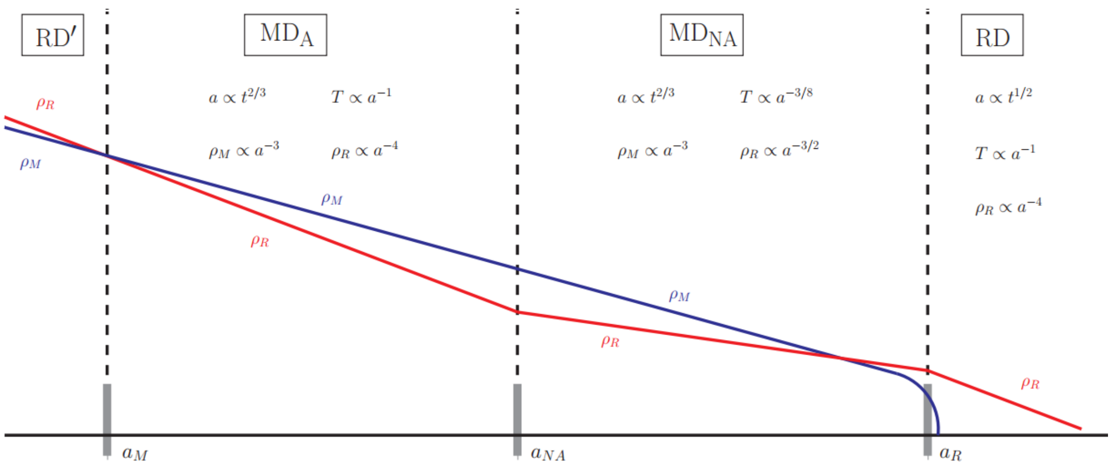
Topology: displaced leptons or detector-stable charged particles

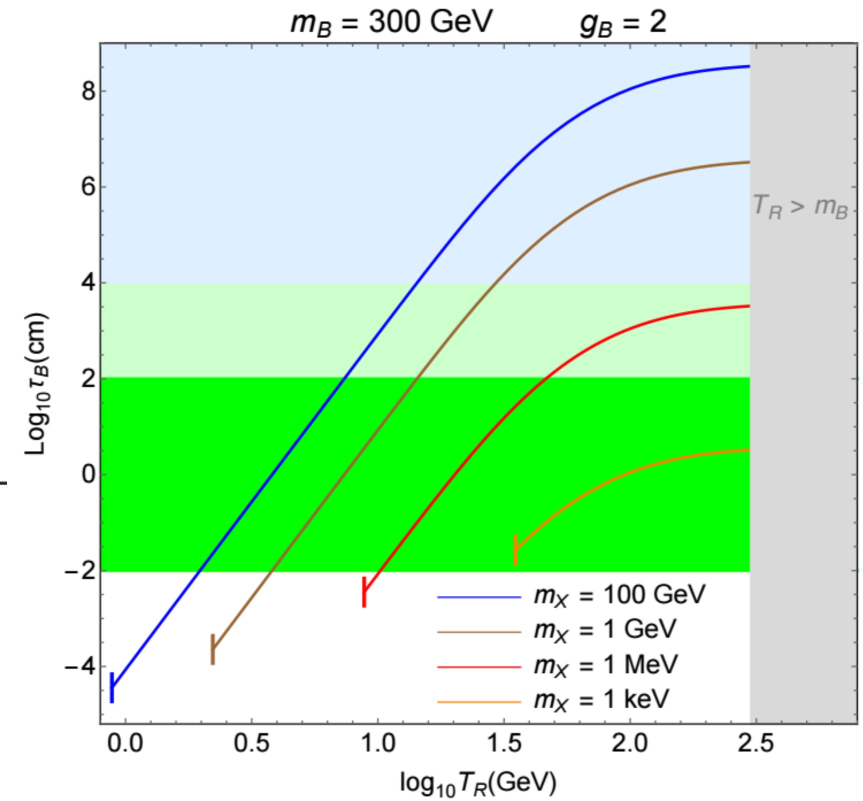


e.g. $M_{H^\pm} \gtrsim 400(200)$ GeV for $m_{\rm DM} = 100(10)$ keV

Option #2: Modifying cosmological history

- Ex #4: Freeze-in in matter-dominated era [Co, D'Eramo, Hall, Pappadopulo, 1506.07532]





$$m_{\rm LLP} > T^*_{\rm reheat}$$

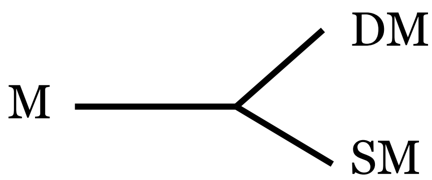
So coupling can be larger since a **second reheating** injects entropy which dilutes DM

Shaded region	Decay length	Signature from LOSP	Neutral	Charged
Dark green	10^{-2}cm $< \tau_B < 10^2$cm	Displaced vertices	✓	✓
Light green	10^2cm $< \tau_B < 10^4$cm	Displaced jets/leptons	✓	✓
Light blue	10^4cm $< \tau_B$	Stopped particle decays	X	✓

Table 1: Displaced Collider Signals

Résumé of FIMP DM pheno

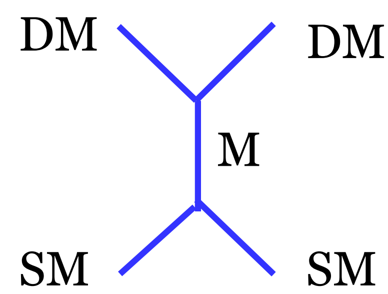
Production at the LHC



Can be few keV

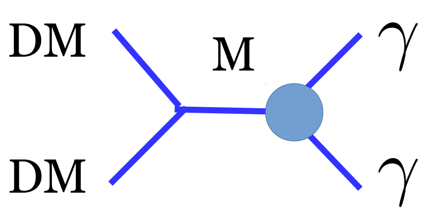
- DM lighter than mediator
- Naively escaping detectors
- Displaced-vertices if large mass-ratio or truncated production from cosmo

Direct Detection



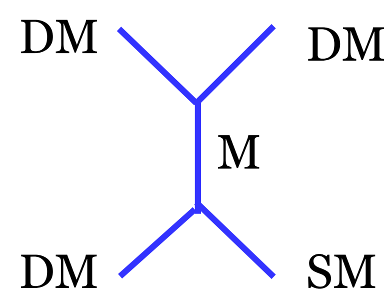
- DM (few keV – GeV) heavier than mediator
- mediator mass below experimental threshold
- DM-electron scattering. Rich variety of proposals for such light DM direct detection

Indirect Detection



- DM of ~ 10 keV could produce observable photon flux
- Mediator lighter than DM

Self-Interactions



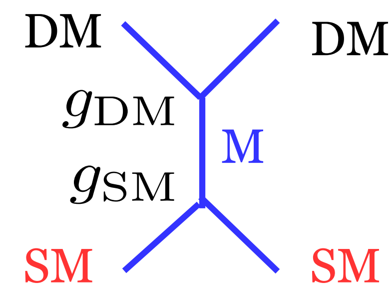
- DM can be ~ 1-10 GeV (model dependent)
- mediator should be much lighter (generic)

bckp

Direct Detection of FIMPs

Reminder:

$g_{\rm DM} g_{\rm SM} \sim 10^{-11}$



At first sight hopeless, but…

$$\sigma_{\chi e}(q) = \frac{1}{\pi} \frac{g_{\rm SM}^2 g_{\rm DM}^2 \mu_{\chi e}^2}{(M^2 + q^2)^2}$$

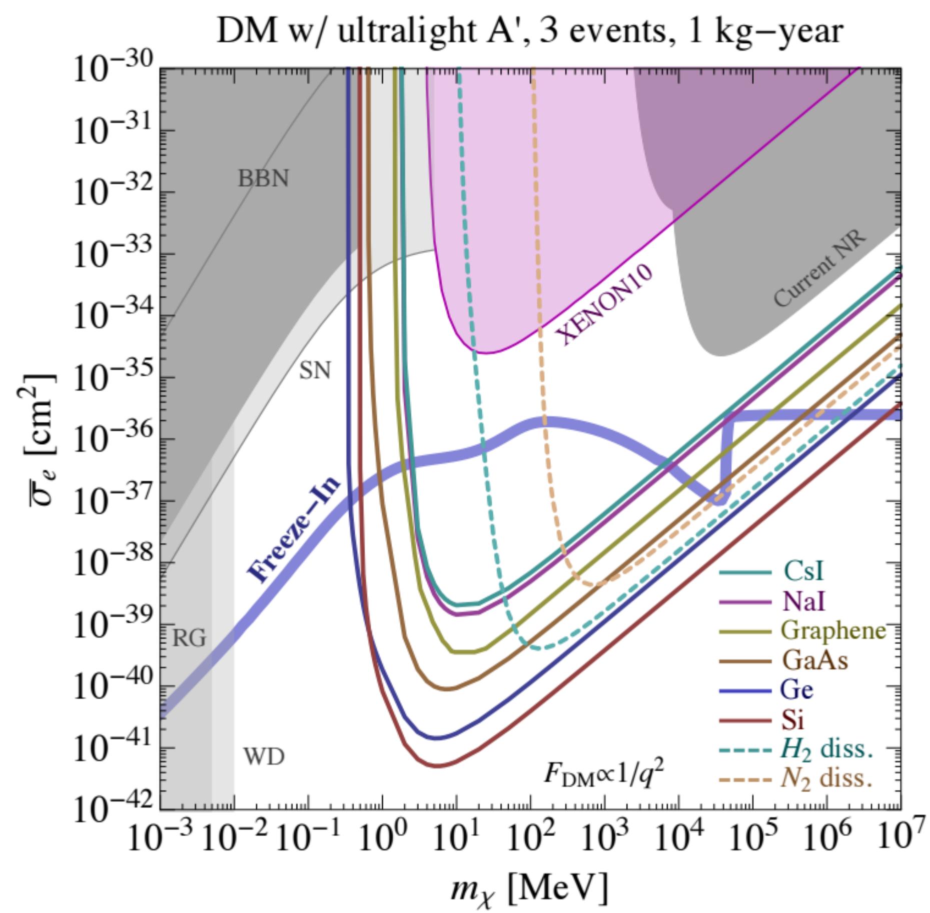
(scattering off electrons bounded in atoms)

If $M^2 \ll q^2$:

$$\sigma_{\chi e}(q) \approx \frac{1}{\pi} \frac{g_{\rm SM}^2 g_{\rm DM}^2 \mu_{\chi e}^2}{q^4}$$

q can be sufficiently small to compensate the smallness of the couplings

Essig, Mardon, Volansky, 1108.5383



Dark Sectors 2016, 1608.08632

Self-Interactions of FIMPs

Bernal, Chu, Garcia-Cely, Hambye, Zaldivar, 1510.08063

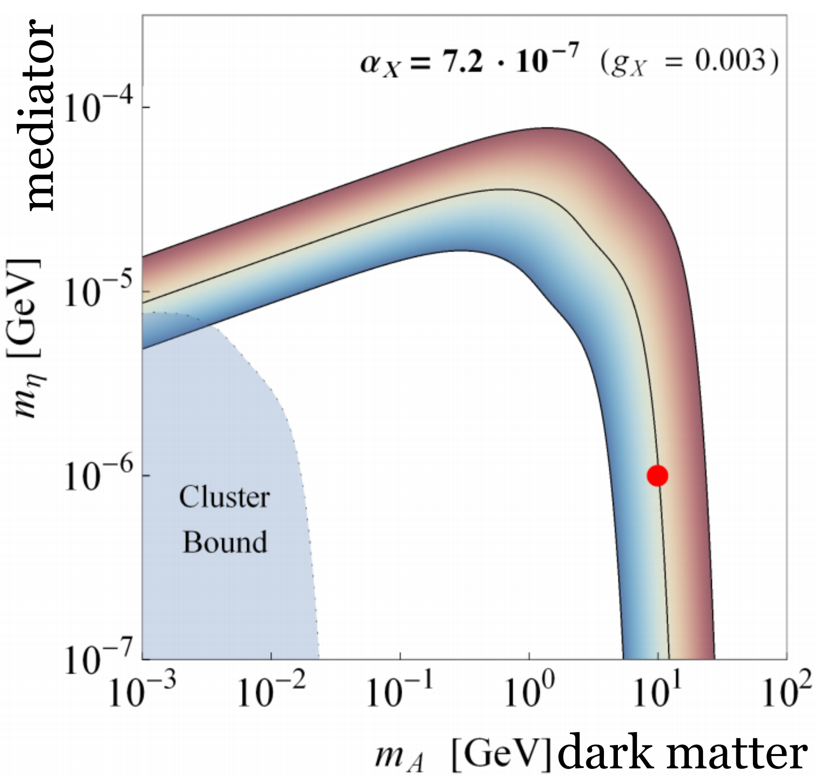
*Self.Int.DM as mechanism to solve small-scale problems of CDM

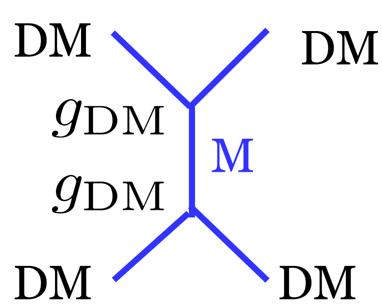
a) $0.2\ \mathrm{b/GeV} \lesssim \sigma/m \lesssim 20\ \mathrm{b/GeV}$

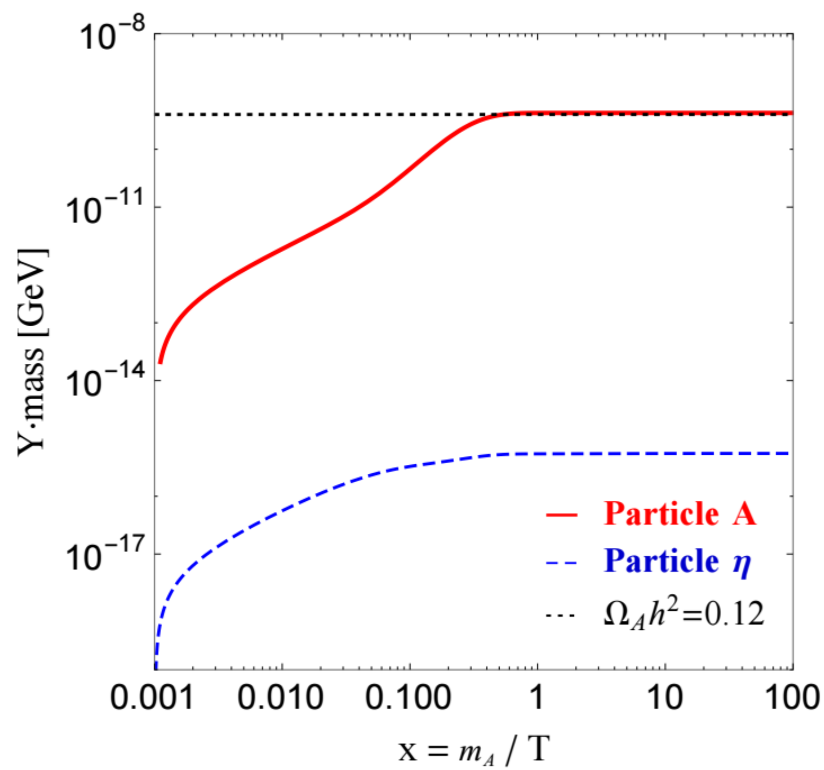
(simulations)
Galactic scales, $v \sim 10\ \mathrm{km/s}$

b) $\sigma/m \lesssim \mathcal{O}(2\ \mathrm{b/GeV})$

(observations, Gravit. Lensing)
Cluster scales, $v \sim 1000\ \mathrm{km/s}$



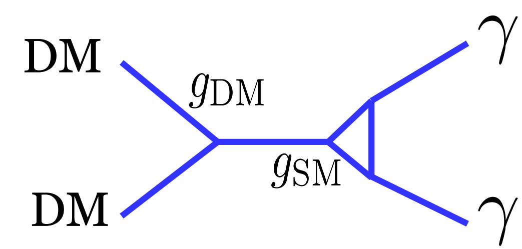




Indirect Detection of FIMPs

Reminder:

$$g_{\rm DM} g_{\rm SM} \sim 10^{-11}$$



Idea: go to very light DM masses
to compensate for the small couplings

Take photon emission:

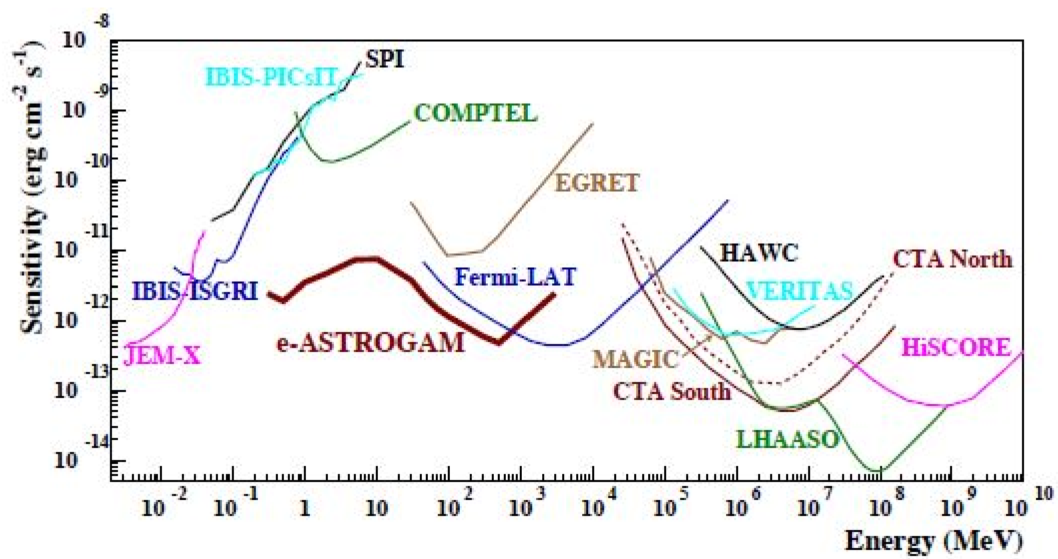
$$\langle \sigma v \rangle_{\gamma\gamma} \sim k_{\rm loop} \frac{g_{\rm DM}^2 g_{\rm SM}^2}{m_{\rm DM}^2} \sim 10^{-31} {\rm cm}^3/{\rm s} \left(\frac{10{\rm keV}}{m_{\rm DM}} \right)^2$$

Constraints: (work in progress)

CMB: [1106.1528]

$$\langle \sigma v \rangle_{\gamma\gamma} \lesssim 2.4 \times 10^{-27} {\rm cm}^3/{\rm s} \left(\frac{m_{\rm DM}}{\rm GeV} \right)$$

but also
CHANDRA,NuSTAR, INTEGRAL,
e-ASTROGRAM, ...



See also: Kopp et al, [1710.02146] on
freeze-in in the context of 3.5keV line