Non-thermal DM,
Not WIMPs

# Phenomenology of FIMPs

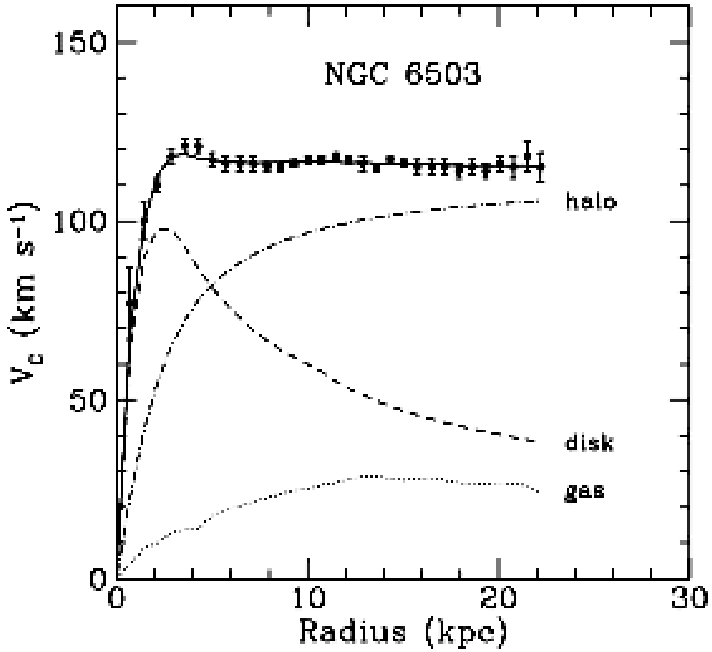
**Bryan Zaldívar**
(Annecy)

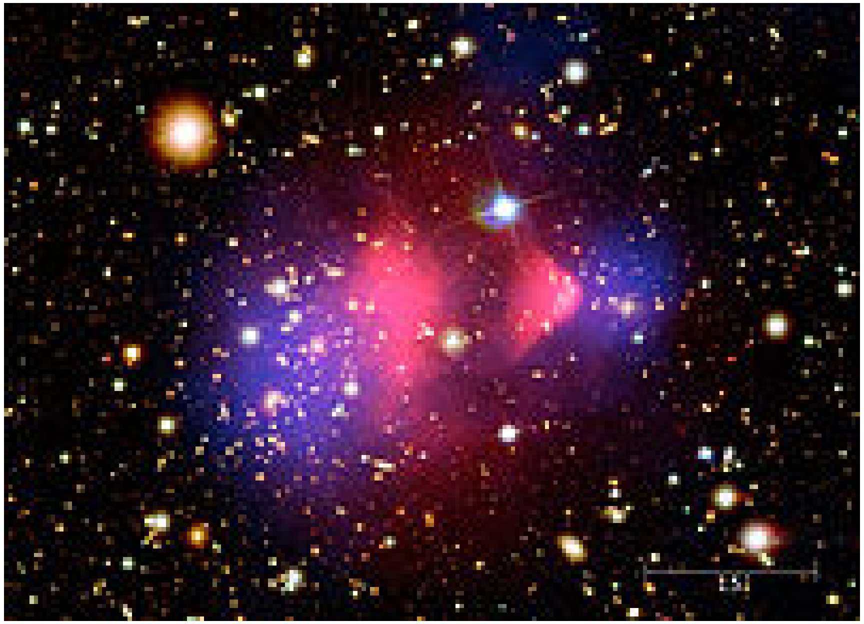
27/10/17, Bellaterra

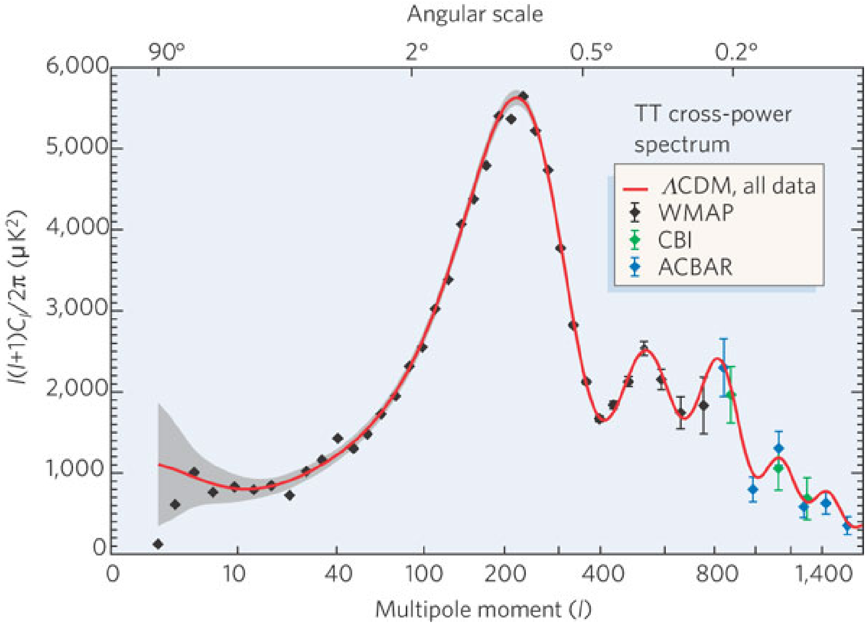
# Outline

- Motivation to go outside WIMPs
- Basics of FIMPs
- Phenomenology of FIMPs
  - LHC
  - Direct Detection
  - Astrophysics
- Conclusions

# Compelling evidence of DM





# What do we (don't) know about DM?

***We know...***

- Its abundance in the universe
- Non relativistic
- Its gravitational interactions
- Long-lived enough
- Electrically neutral enough

***We don't know...***

- if it is fundamental particle
- its properties (spin, mass)
- if it has non-gravitational interactions (with itself or with Standard Model)
- **thermal relic (chemical equilibrium with SM)**
- when it was produced

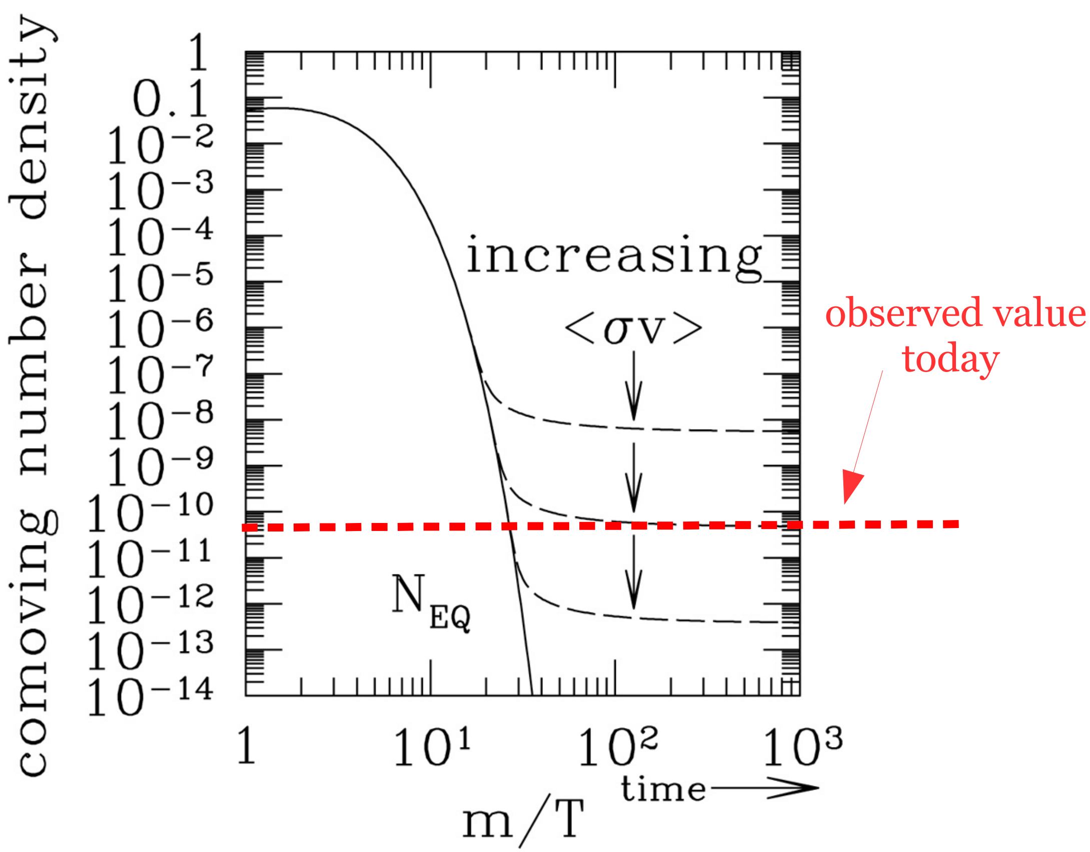
***Many questions to be answered!!***

# Motivation

**WIMP dark matter** and its situation to-date

- *Weakly* Interacting Massive Particle

(order electroweak couplings)

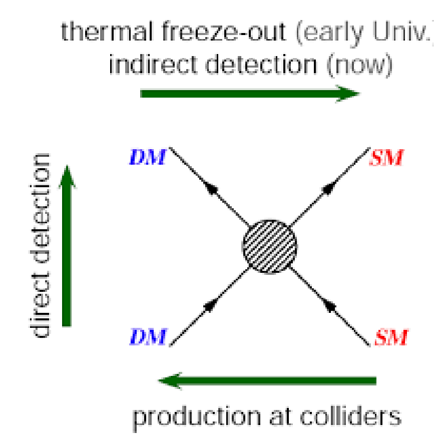



DM abundance:

$$\Omega \propto \frac{1}{\langle \sigma v \rangle}$$

“infrarred” dominated process

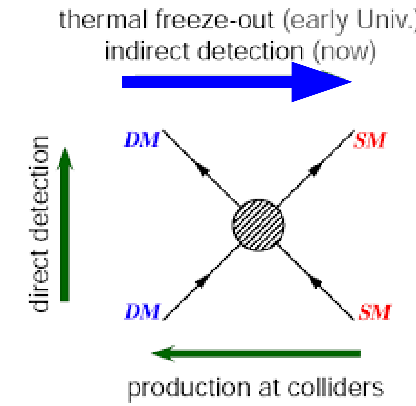
Rich phenomenology!



# Motivation

## WIMP dark matter and its situation to-date

## Indirect Detection




$$\Omega h^2 \simeq 0.1 \frac{3 \times 10^{-26} \mathrm{cm}^3/\mathrm{s}}{\langle \sigma v \rangle}$$

Ballpark of experimental sensitivities!

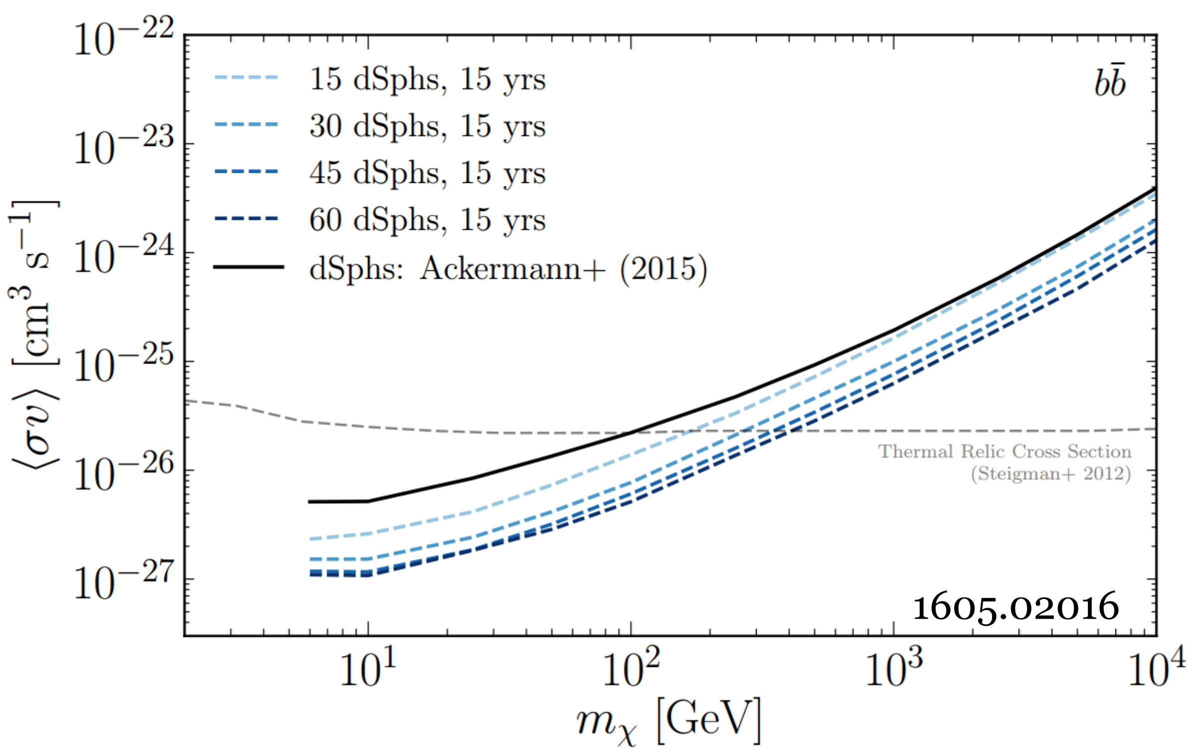

VLA, GBT, LOFAR,...

PLANCK,...

SDSS, DES,...

Chandra,...

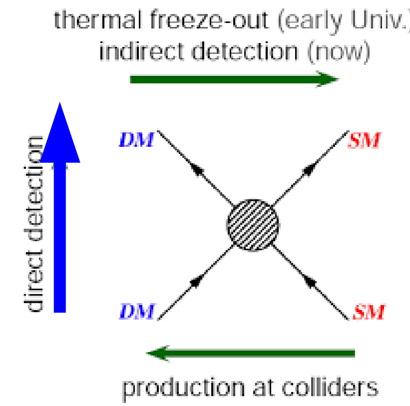
**Fermi-LAT,** HESS,...

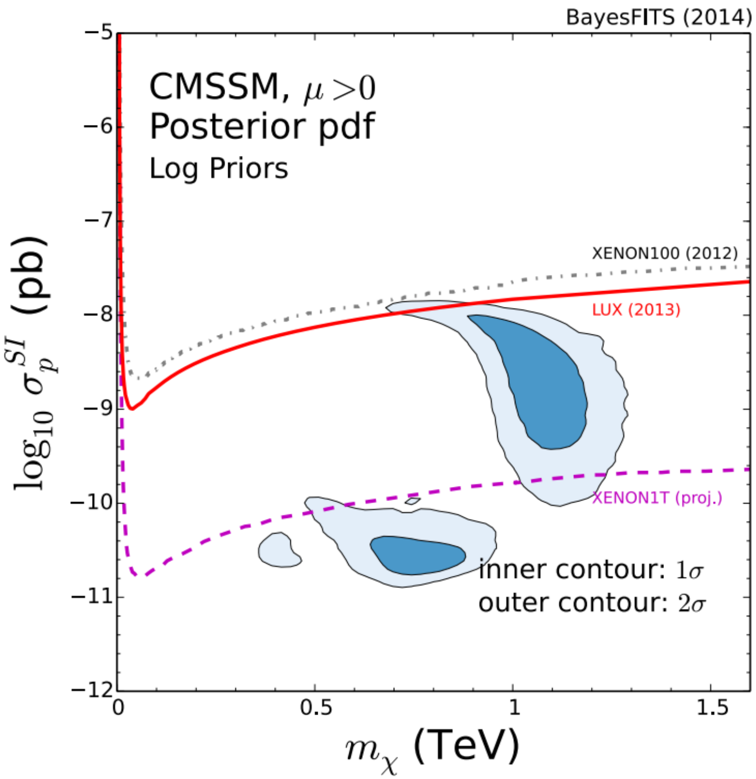


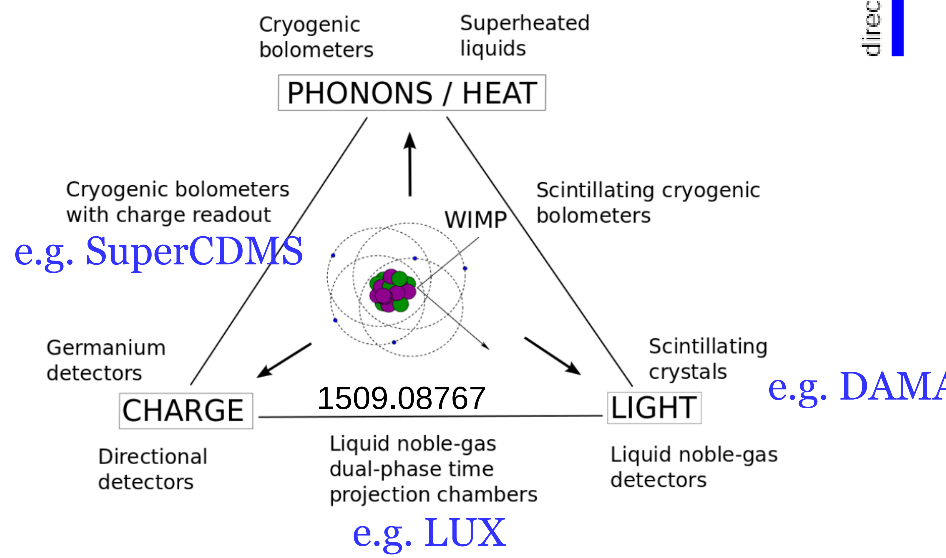
# Motivation

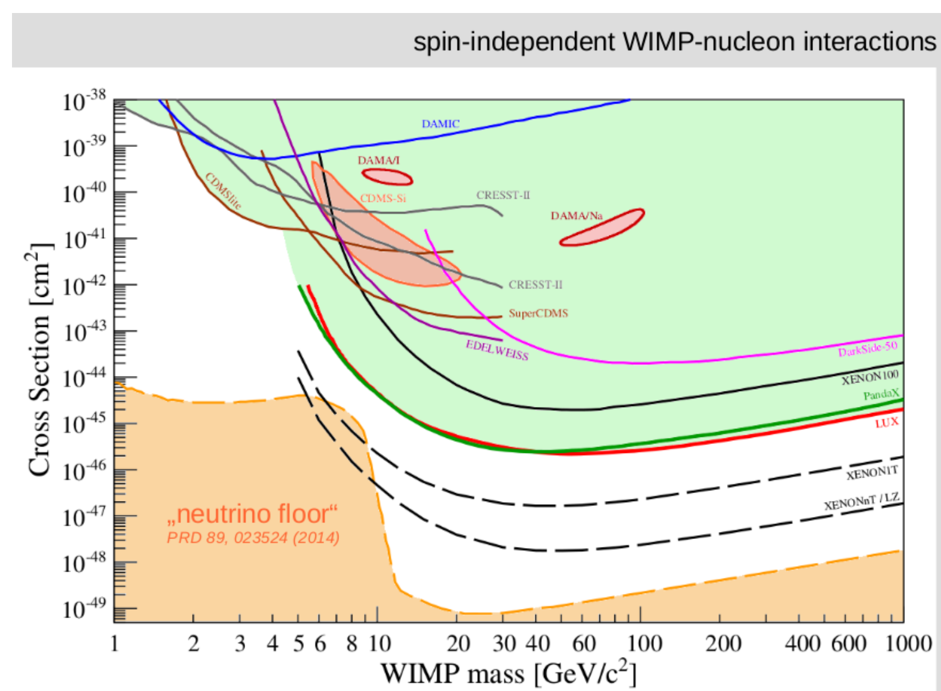
## WIMP dark matter and its situation to-date

### Direct Detection




Event rate:

$$R \propto N \frac{\rho_\chi}{m_\chi} \langle \sigma_{\chi-N} \rangle$$

detector

local DM density

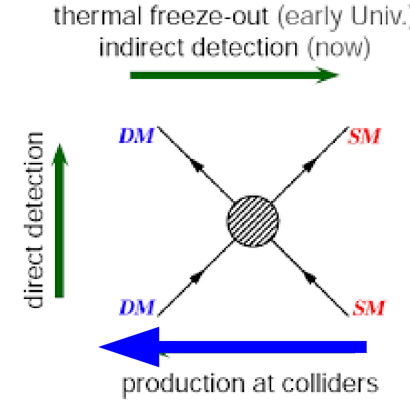
physics model

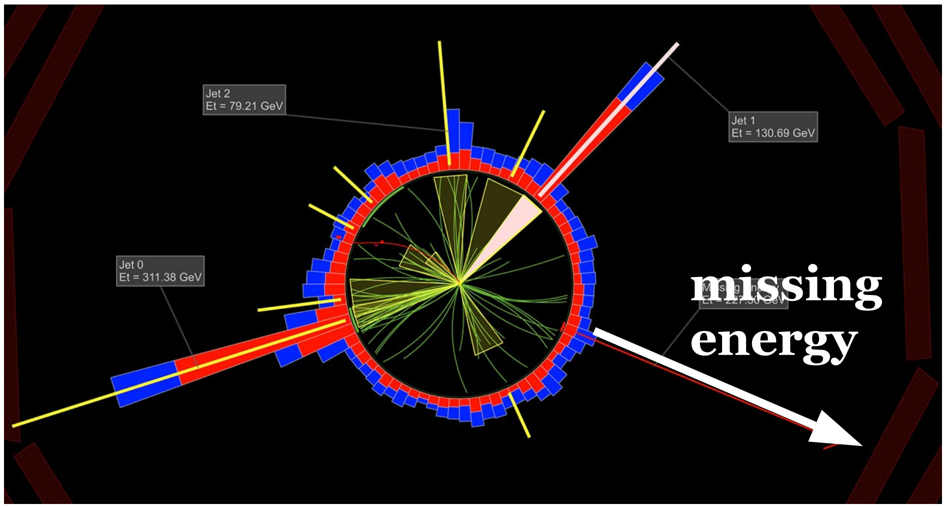
B.Zaldivar, IFAE, 10-2017

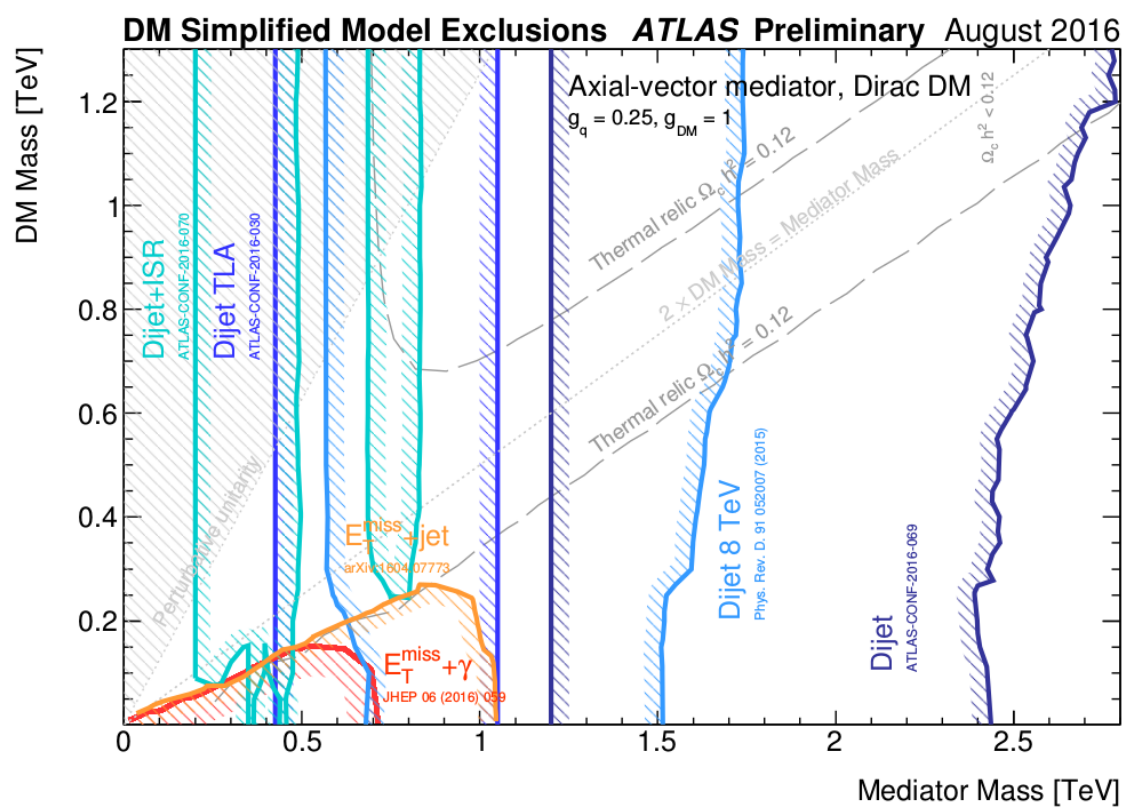
# Motivation

## WIMP dark matter and its situation to-date

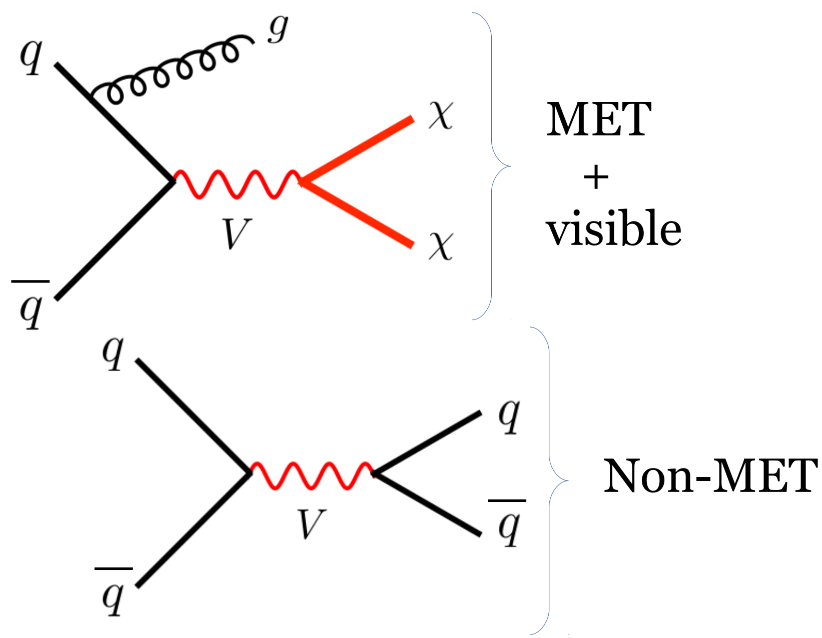
## Collider



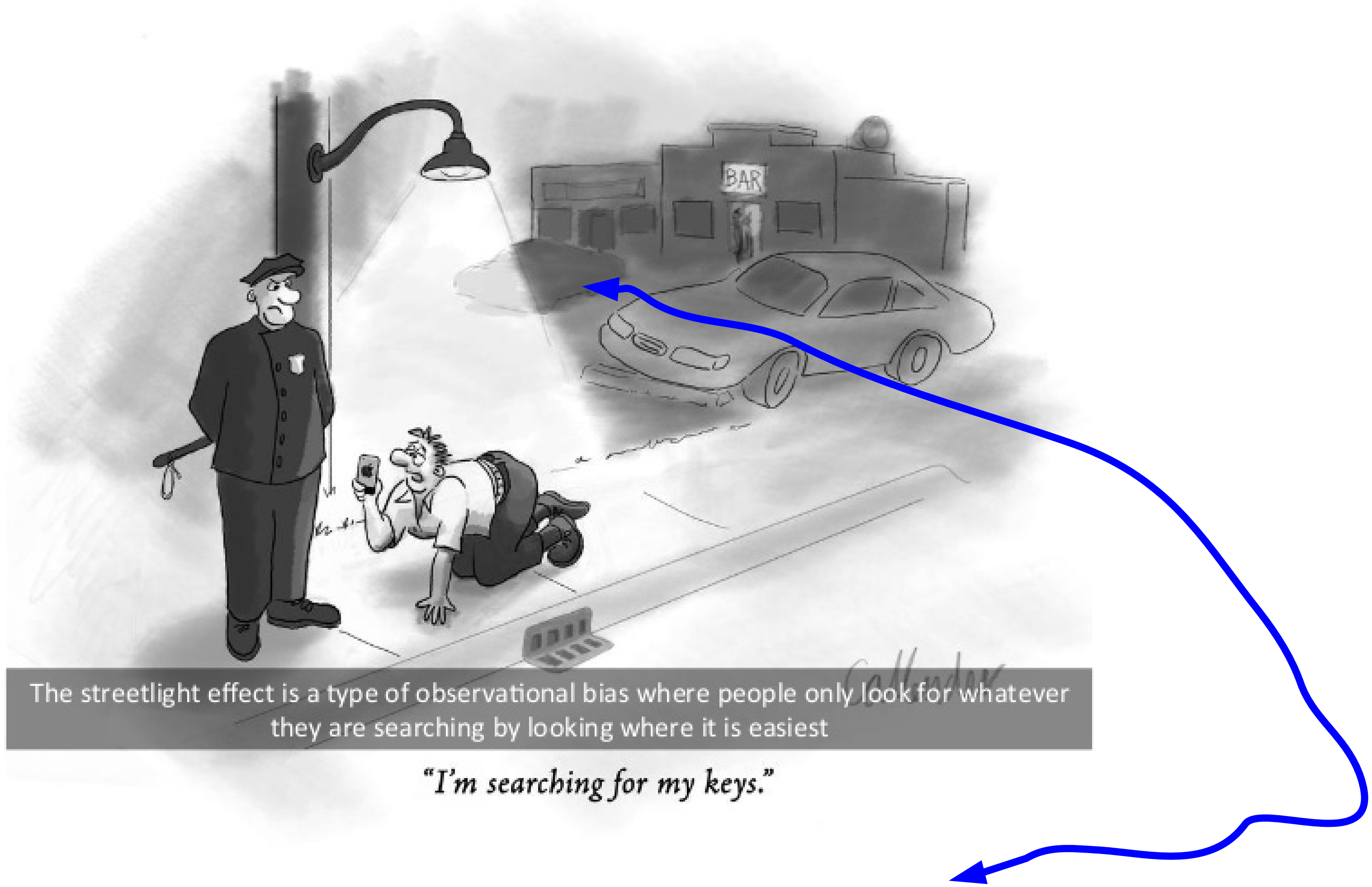

**Typical model**



# Motivation

**WIMP dark matter and its situation to-date:**

**No (conclusive) signals so far**




*"I'm searching for my keys."*

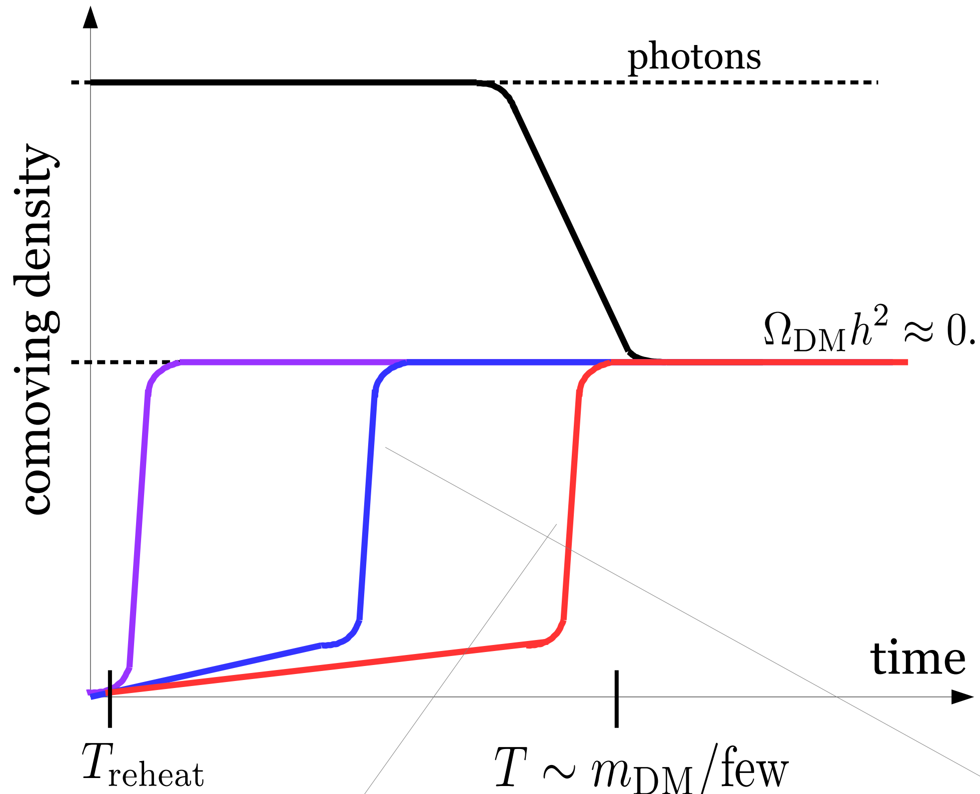
the rest of this talk

# Freeze-in in a nutshell

$$\frac{dn_{\rm DM}}{dt} + 3Hn_{\rm DM} = n_{\rm bath}\Gamma_{\rm prod} - n_{\rm DM}\Gamma_{\rm ann}$$

negligible

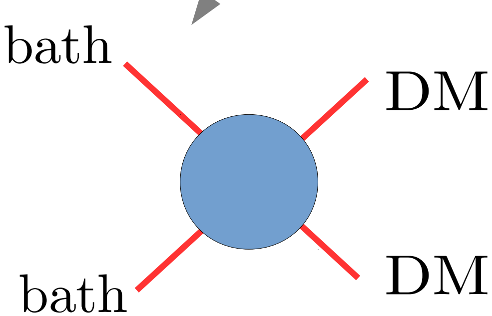
interaction rates



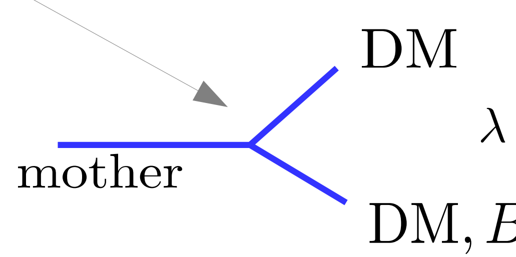

**Characteristics:**

- 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**

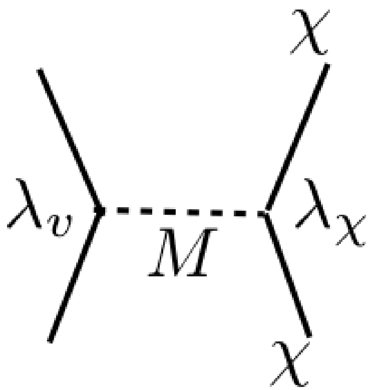
**-Hall, Jedamzik, March-Russell, West, 0911.1120**
-Blennow, Fernandez-Martinez, Zaldivar, 1309.7348
-Bernal, Heikinheimo, Tenkanen, Tuominen, Vaskonen, 1706.07442




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

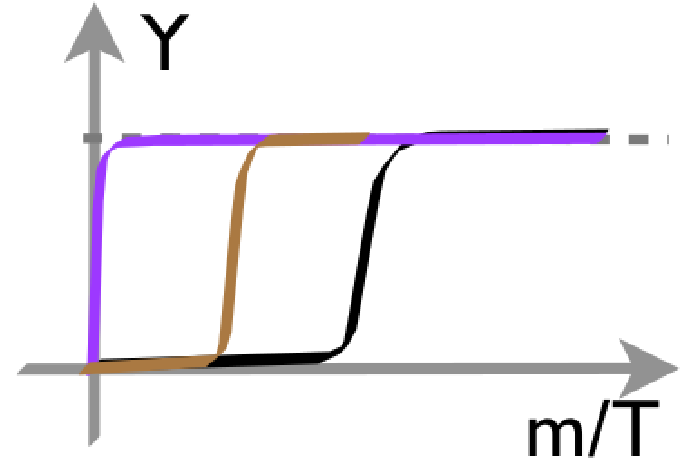



$$\lambda \sim 10^{-13}\sqrt{\frac{m_{\rm mother}}{m_{\rm DM}}}$$




# FIMPy Matters

$$\Omega h^2 = (\mathbf{s}_0/\rho_{\rm crit})\ m_\chi Y$$




| Light portal $M < 2m_\chi < T_{RH}$ | Intermediate portal $2m_\chi < M < T_{RH}$ | Heavy portal $2m_\chi < T_{RH} < M$ |
|---|---|---|
| $\sigma \sim \frac{\lambda_v^2\lambda_\chi^2}{s}$ | $\sigma \sim \lambda_v^2\lambda_\chi^2 \frac{M}{\Gamma}\delta(s - M^2)$ | $\sigma \sim \lambda_v^2\lambda_\chi^2 \frac{s}{M^4}$ |
| $Y \propto \lambda_v^2\lambda_\chi^2 \frac{M_{Pl}}{m_\chi}$ | $Y \propto \lambda_v^2\lambda_\chi^2 \frac{M_{Pl}}{\Gamma}$ | $Y \propto \lambda_v^2\lambda_\chi^2 M_{Pl} \frac{T_{RH}^3}{M^4}$ |

Blennow, Fernandez-Martinez, BZ, 2013

# Searching strategies

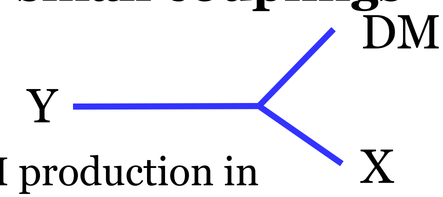
# FIMPs at the LHC

Type of signals: **Displaced-vertices** (seems like the topic of 2017!)

### 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




same process for DM production in early universe and at LHC

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

Far from WIMP regime!

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**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

+ several groups working on it right now (including myself)

# FIMPs at the LHC

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

$3\times 10^8 \rightarrow s_0/\rho_{\rm crit}$

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

$$x \equiv \frac{m_Y}{T}$$

$K_1(x)$: Boltzmann suppression

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

(*) 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]

# *Option #1: Increasing mass-ratio*

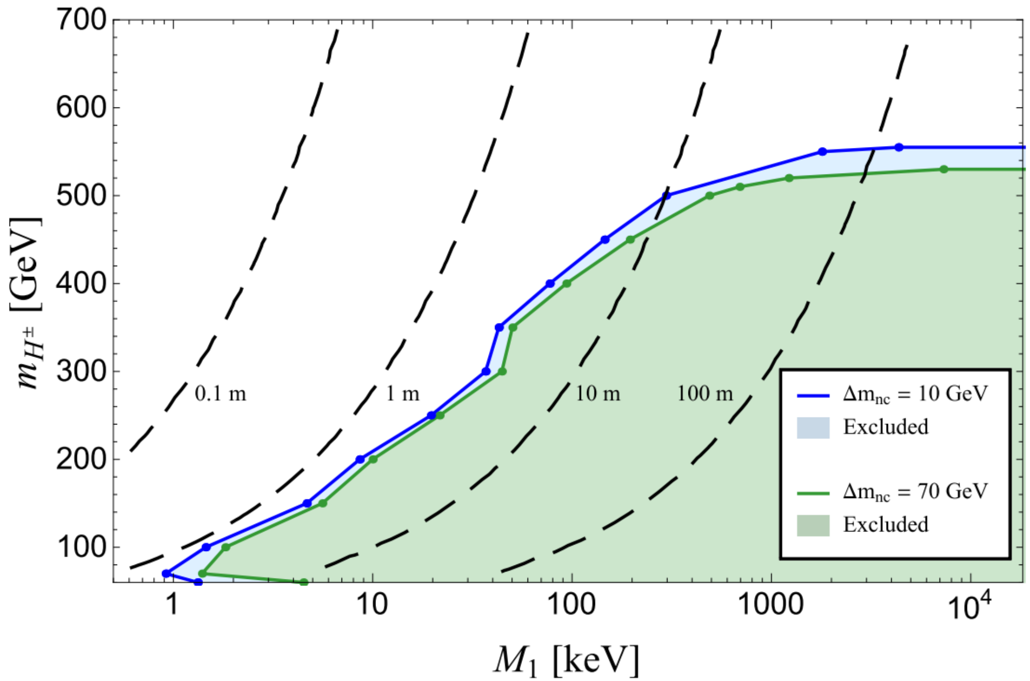
- Ex #1: Scotogenic FIMP [Hessler, Ibarra, Molinaro, Vogl, 1611.09540
  Molinaro, Yaguna, Zapata, 1405.1259
  Ma, hep-ph/0601226]

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

$\mathcal{L}_{H_2}$: 2nd Higgs doublet

$\mathcal{L}_{N_i}$: 3 fermionic singlets, lightest is DM } $\mathbb{Z}_2$-odd

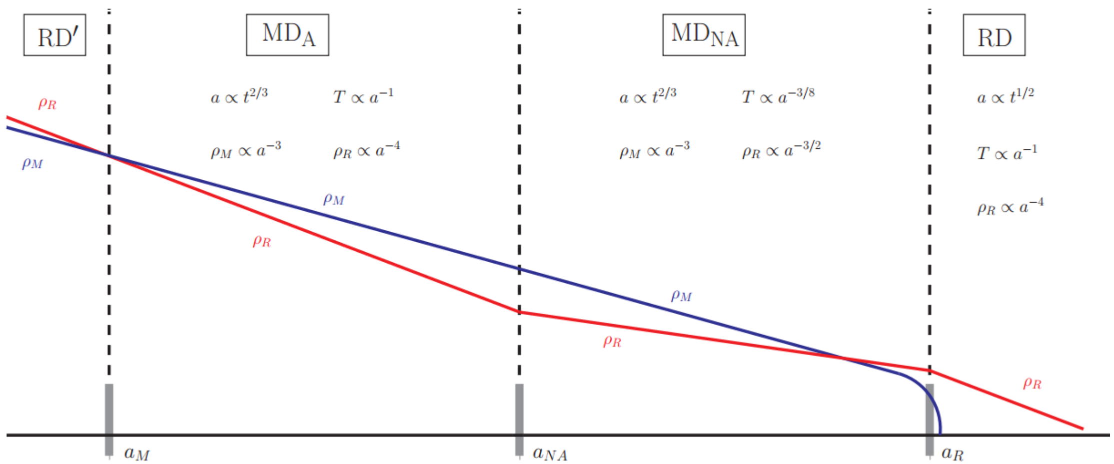
*Topology:* displaced leptons or detector-stable charged particles

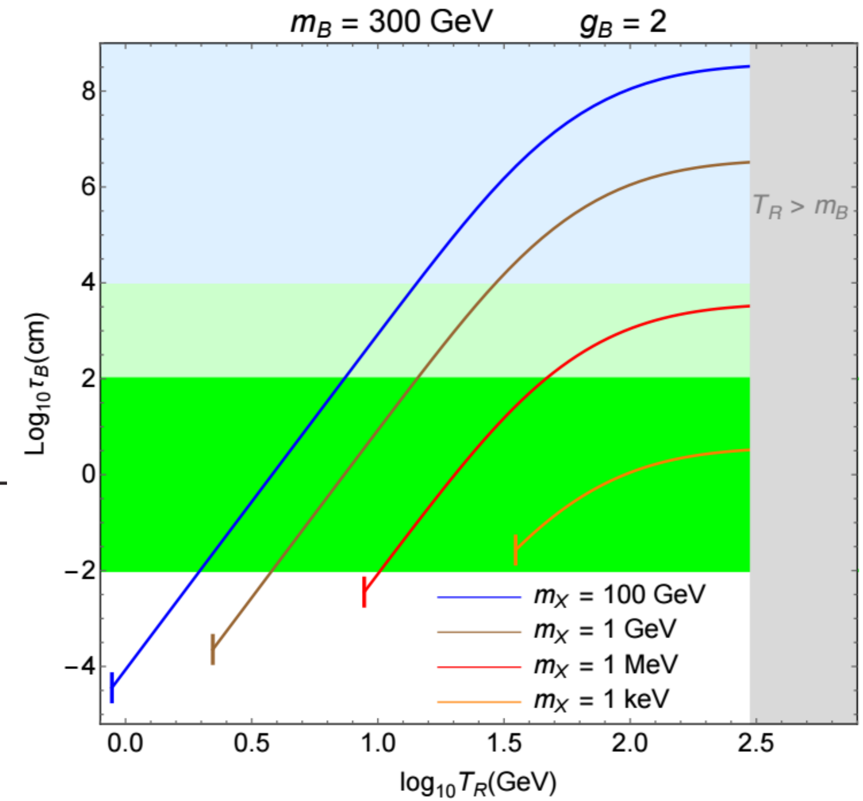



e.g. $M_{H^\pm} \gtrsim 400(200)$ GeV for $m_{\rm DM} = 100(10)$ keV

# *Option #2: Modifying cosmological history*

- Ex #2: 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 (non-minimal cosmological history)

→ not necessary…**(work in progress)**

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

Table 1: Displaced Collider Signals

# Classification(i)

$$\mathcal{L} \supset g(Y \cdot b)\chi$$

$g \ll 1$

$Y$ : decaying particle $b$ : SM particle $\chi$ : DM candidate

Criteria: i) $SU(2)_L$ representation of $b$ ii) spins of, say, $\chi$ and $Y$

---

1) $b$ is a lepton singlet (thus $Y$ is singlet)

e.g. $\mathcal{L} \supset gEe_R\chi$ (probably the simplest implementation of LLP + freeze-in)

$$pp \to E^+E^-$$

$$E^\pm \to e^\pm\chi$$

**Signal**: charged LLPs (e.g. displaced electron + MET)

---

2) $b$ is a quark (singlet or doublet)

The lightest $Y$ state (LLP) should hadronise (R-hadron)

**Signal**: $R \to \text{jet} + \text{MET}$

# Classification(ii)

$\mathcal{L} \supset g(Y \cdot b)\chi$

3) $b$ is a lepton doublet, $\chi$ is a scalar

$Y^0, Y^\pm \quad \Delta M_Y \sim 340\text{MeV}$

$Y^\pm \to Y^0\ \pi^\pm$ (dominant)

$Y^0 e^\pm \nu_e$

$\ell^\pm \chi$ (suppressed by $g$)

$Y^0 \to \chi\nu_\ell$ long-lived, yes, but invisible

$\tau_\pm \sim 25$ cm

**Signal**: charged tracks (but decay products very soft!)

Unrelated to freeze-in DM :(

---

4) $b$ is a lepton doublet, $\chi$ is a fermion

$Y = (H^+, H^0 + iA^0)$

- can mix with the SM Higgs in the scalar potential,
- $\Delta M_Y$ can have either sign

| | |
|---|---|
| $\Delta M_Y > 0$ | same pheno as before |
| $\Delta M_Y < 0$ | $Y^\pm \to \ell^\pm \chi$ |

only possible decay mode,
LLP decaying to high pT lepton + MET

Freeze-in DM produced by slow decays of $Y^\pm$ and $Y^0$

# Classification(iii)

$$\mathcal{L} \supset g(Y \cdot b)\chi$$

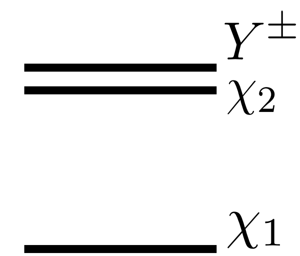
5) $b$ is the SM Higgs, $\chi$ is a fermion (~ higgsino-bino)

$\chi$ and $Y^0$ mix (very little) after EW symmetry breaking

$$\sin\theta = \frac{gv}{m_{Y^0}}$$

| | |
|---|---|
| $pp \to Y^+ Y^-$ | $Y^\pm \to W^\pm \chi_2$ |
| $\to Y^\pm \chi_2$ | $\chi_2 \to h\chi_1$ |
| $\to \chi_2 \chi_2$ | $\to Z\chi_1$ |

Spectrum:




Neutral LLP decaying to MET + $b\bar{b}, jj, \ell^+\ell^-$

6) $b$ is the SM Higgs, $\chi$ is a scalar ( $Y$ also scalar)

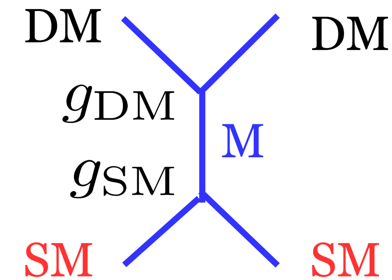
| | | |
|---|---|---|
| $\Delta M_Y > 0$ | $Y^0 \to (h, Z)\chi$ | Neutral LLP |
| $\Delta M_Y < 0$ | $Y^\pm \to W^\pm \chi$ | Charged LLP |

# Other search strategies

# Direct Detection of FIMPs

Reminder:

$$g_{\rm DM}\,g_{\rm SM} \sim 10^{-12}$$




**At first sight hopeless, but...**

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

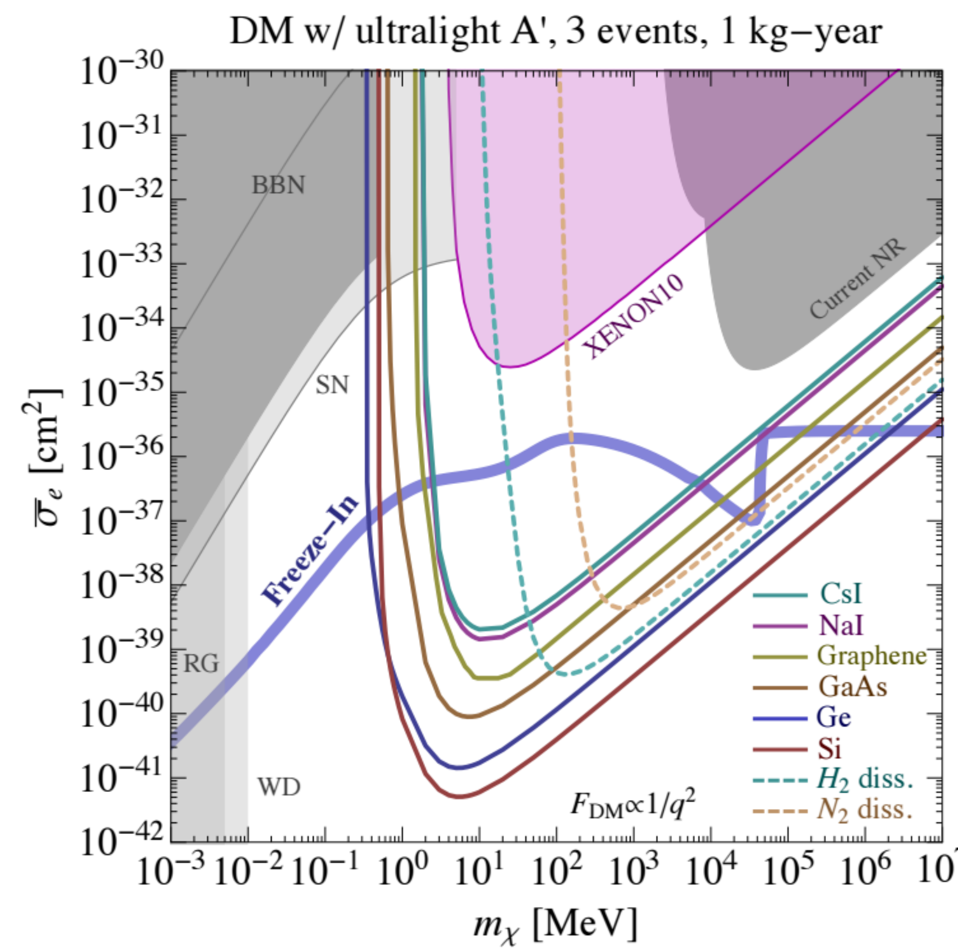
(scattering off electrons bounded in atoms)

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

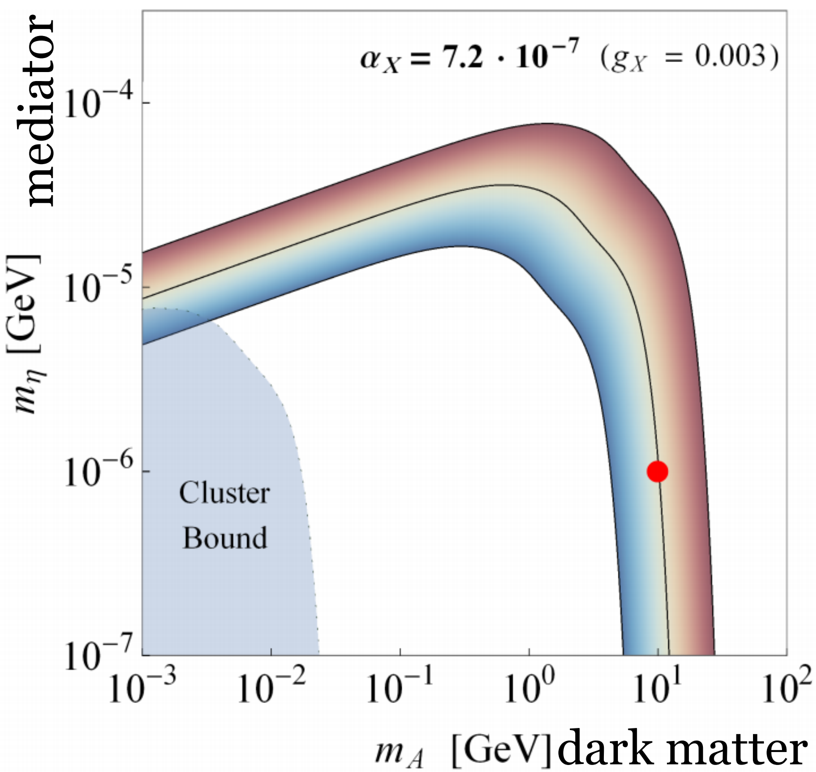
*Self.Int.DM as mechanism to solve small-scale problems of CDM

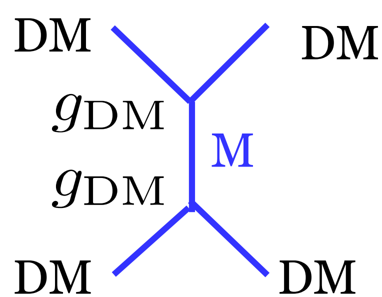
a) $0.2\ \mathrm{b/GeV} \lesssim \sigma/m \lesssim 20\ \mathrm{b/GeV}$

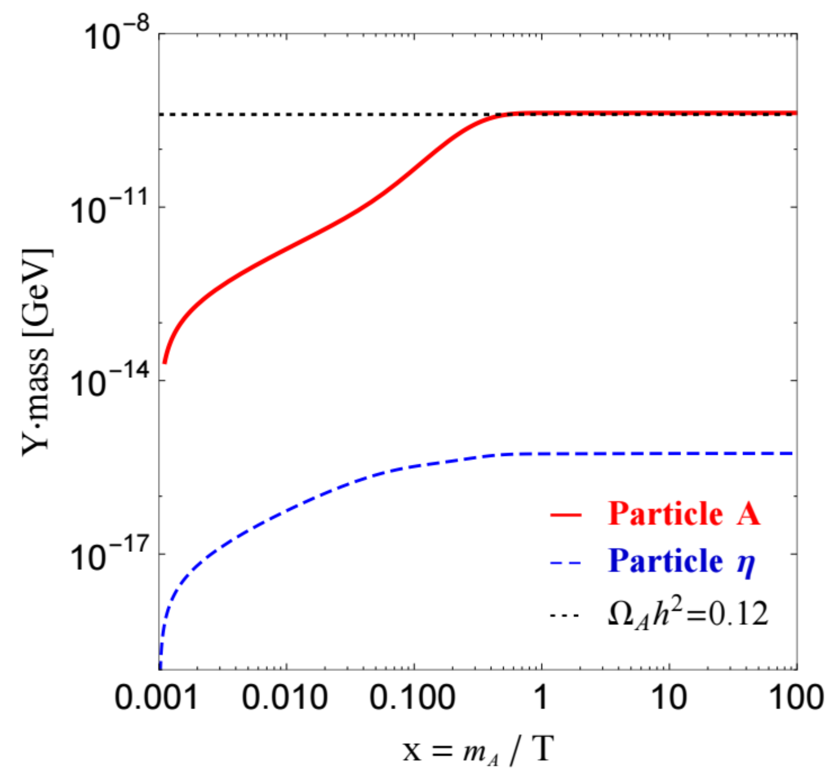
(simulations)
Galactic scales, $v \sim 10\ \mathrm{km/s}$

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

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



# Conclusions

- FIMP dark matter has **much richer** phenomenology than naïve expectations

- FIMPs are a natural (and feasible) interpretation of LLP searches at the LHC

Thanks!