Singlet Doublet Dark Matter Freeze-in

Alberto Mariotti

iihe BRUXELLES BRUSSEL

be

HEP@VUB VRIJE UNIVERSITEIT BRUSSEL

Based on arXiv:1805.04423 with:

Lorenzo Calibbi, Laura Lopez Honorez, Steven Lowette

LHC Long Lived Particle workshop -- CERN

16-18 May 2018

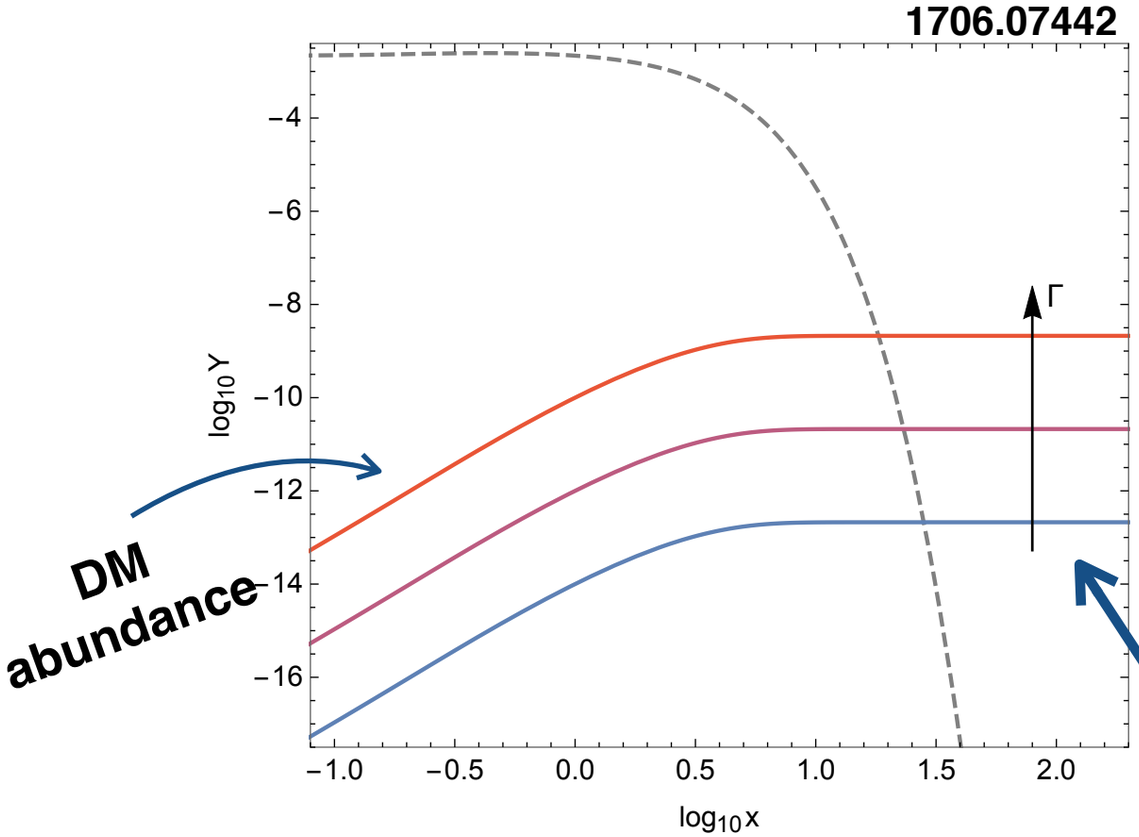
Freeze-In Dark Matter

- ✦ *Freeze in: alternative mechanism to obtain dark matter abundance*
- ✦ *It naturally involves small couplings (long-lived particles)*

See Bryan talk of yesterday

Hall, Jedamzik, March-Russell, West '09
Blennow, Fernandez-Martinez, Zaldivar '13
Bernal, Heikinheimo, Tenkanen, Tuominen, Vaskonen '17
G. Bélanger, H. Cai, N. Desai, A. Goudelis, J. Harz, A. Lessa, J. M. No, A. Pukhov, S. Sekmen, D. Sengupta, B. Zaldivar and J. Zurita

1706.07442



Freeze-in through decay

- ✦ *Mother (mediator) A in thermal equilibrium*
- ✦ *Decay to Dark Matter and produce it*

$$\Gamma[A \to B\chi]$$

Particles in thermal equilibrium

Dark Matter

Width (lifetime) of the mediator A determines the DM abundance

FIMP (decay) phenomenology

Standard Cosmology history

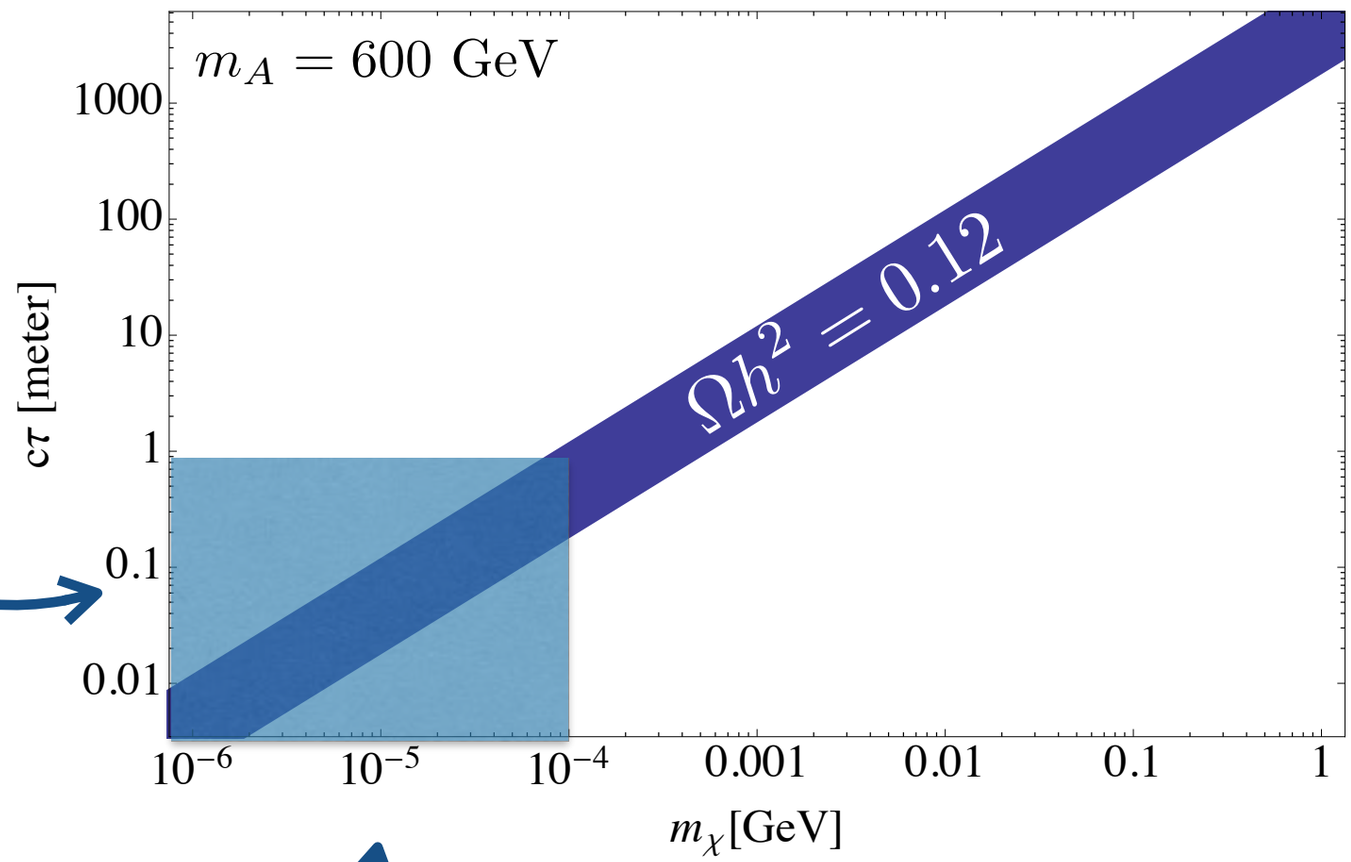
$$\Omega h^2 \sim 0.12 \left(\frac{5\ \mathrm{cm}}{c\tau_A}\right) \left(\frac{600\ \mathrm{GeV}}{m_A}\right)^2 \left(\frac{m_\chi}{10\ \mathrm{keV}}\right)$$

Macroscopic decay visible at LHC

Mediator accessible at the LHC

Very light Dark Matter

Typical size for detector



Light Dark Matter regime

FIMP (decay) phenomenology

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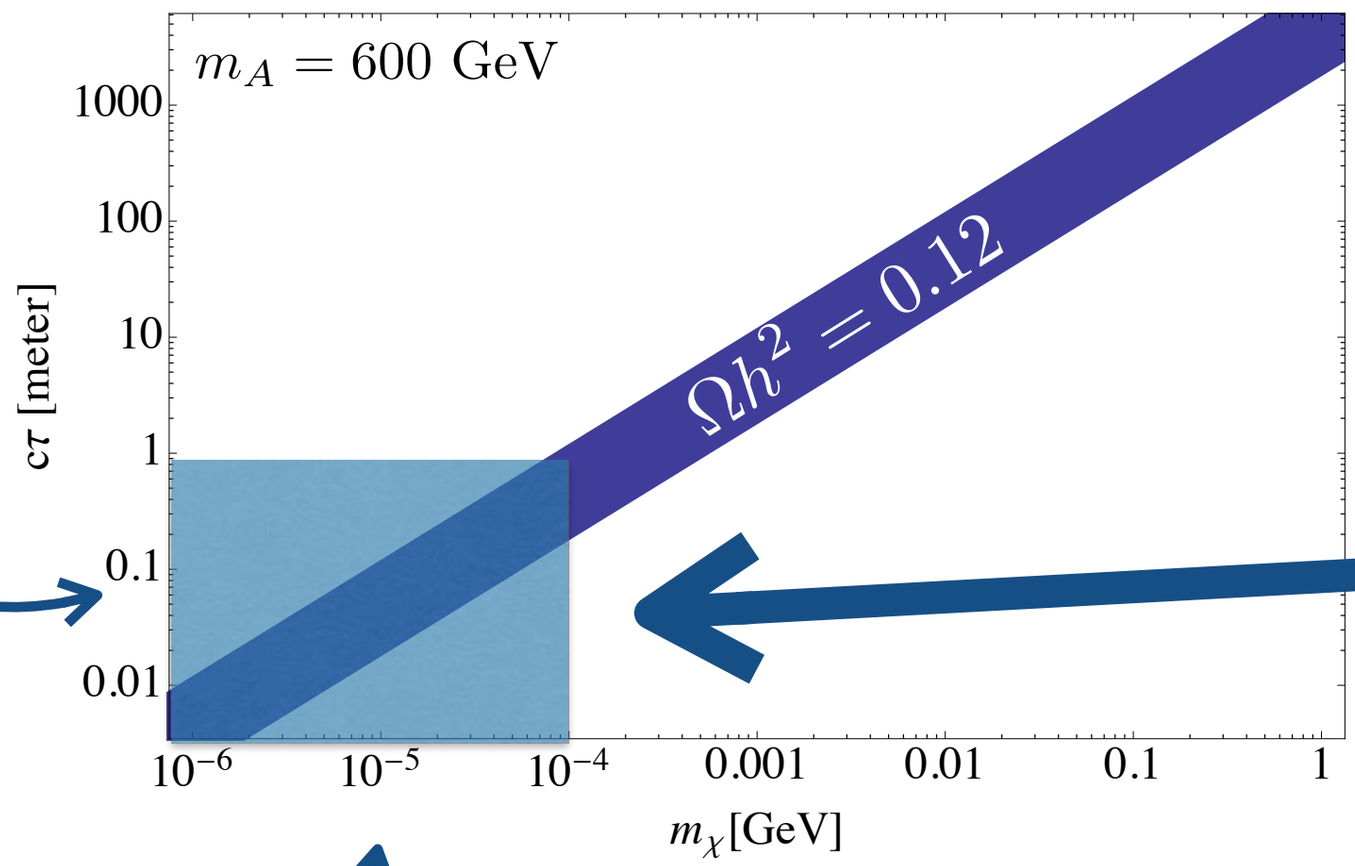


Typical size for detector

Light Dark Matter regime

Displaced dark matter at LHC

WDM signatures

Singlet Doublet Freeze In

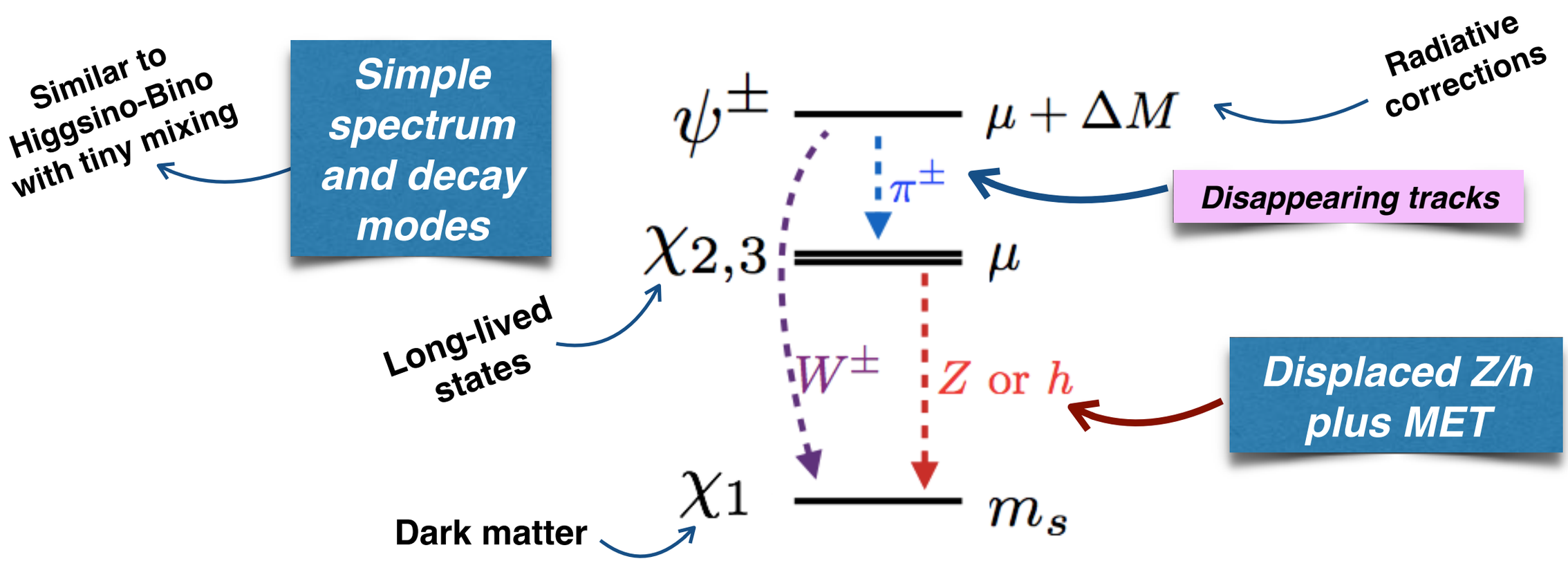
✦ ***Minimal model with few extra fermionic states*** **Mahbubani, Senatore '05**

$$(\psi_u)_{2,\frac{1}{2}} = \begin{pmatrix} \psi^+ \\ \psi_u^0 \end{pmatrix}, \qquad (\psi_d)_{2,-\frac{1}{2}} = \begin{pmatrix} \psi_d^0 \\ \psi^- \end{pmatrix}, \qquad (\psi_s)_{1,0}$$

✦ ***Lagrangian coupling with the Higgs***

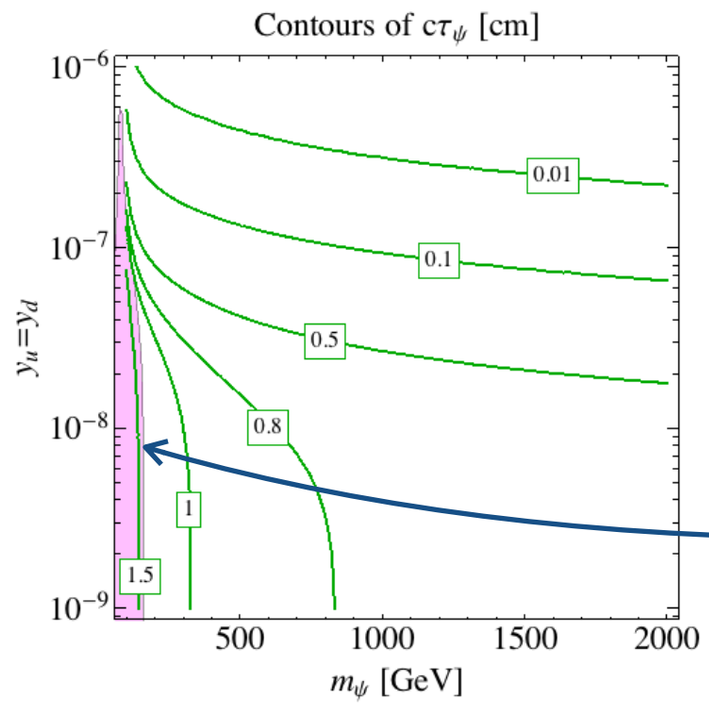
$$-\mathcal{L} \supset \mu\ \psi_d \cdot \psi_u + y_d\ \psi_d \cdot H\, \psi_s + y_u\ H^\dagger \psi_u\, \psi_s + \frac{1}{2} m_s\ \psi_s \psi_s + h.c.$$

✦ ***Regime for Freeze-in:*** $|y_u|,\ |y_d|\ \ll\ 1, \qquad |m_s|\ \ll\ |\mu|,$



Decay modes

Charged fermion decay



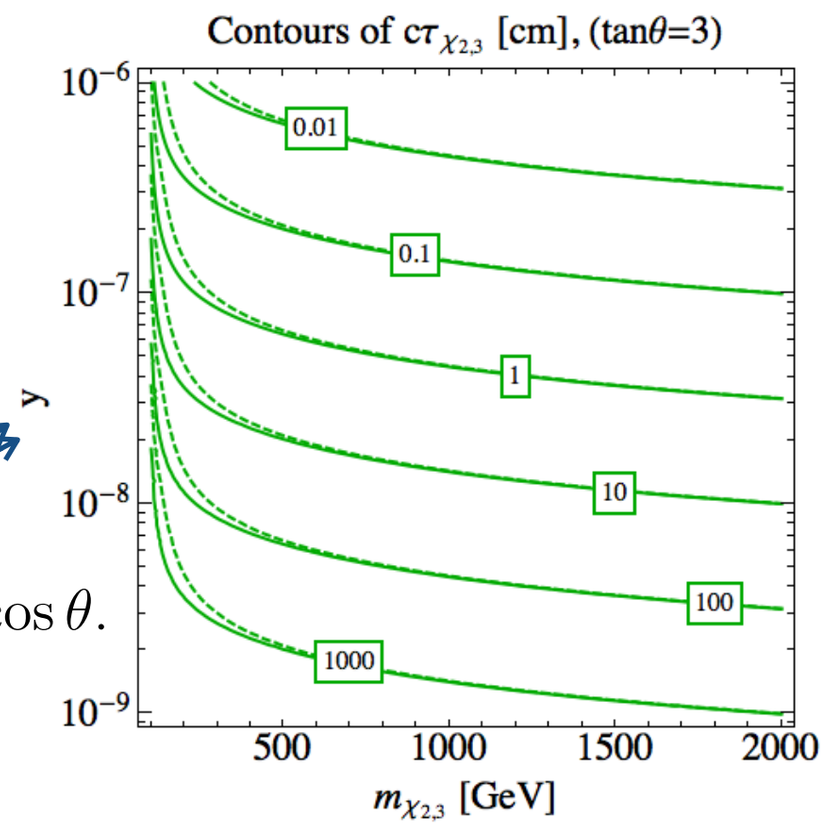
Decays mainly to pions and chi_2,3 on relevant parameter space

$$\psi^\pm \to \pi^\pm \chi_{2,3}$$

Typical decay length is cm

Disappearing track limit ~ 150 GeV

Neutral fermions decay



$$y_u \equiv y \sin\theta, \quad y_d \equiv y \cos\theta.$$

Decays to Z and h almost democratically

$$\chi_{2,3} \to h/Z + \chi_1$$

Decay length ranges from 0.1 to 1000 cm

Displaced Z/h plus MET

Freeze-in

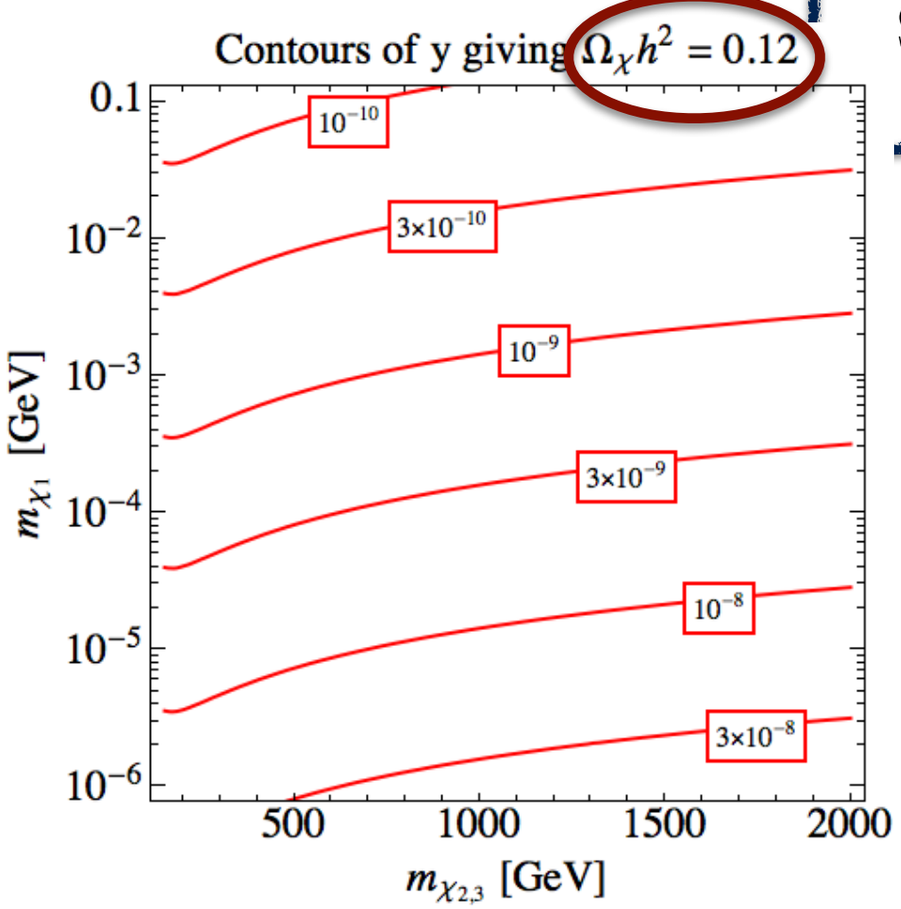
Where is region of parameter space suitable for freeze-in ?

$$Y_{\chi_1} = \frac{270 M_{Pl}}{(1.66) 8\pi^3 g_*^{3/2}} \left(\sum_{B=Z,h} \frac{\Gamma[\chi_3 \to B\chi_1]}{m_{\chi_3}^2} + \sum_{B=Z,h} \frac{\Gamma[\chi_2 \to B\chi_1]}{m_{\chi_2}^2} + g_\psi \frac{\Gamma[\psi^+ \to W^+\chi_1]}{m_\psi^2} \right)$$

Dark matter abundance

Decay width of heavy doublet components into dark matter

$$\Omega_{\chi_1} h^2 \simeq 0.11 \left(\frac{105}{g_*}\right)^{3/2} \left(\frac{y}{10^{-8}}\right)^2 \left(\frac{m_{\chi_1}}{10 \text{ keV}}\right) \left(\frac{700 \text{ GeV}}{\mu}\right)$$



Typical coupling size for displacement

Doublet mass scale accessible at the LHC

Very light DM mass, complementary cosmological constraints

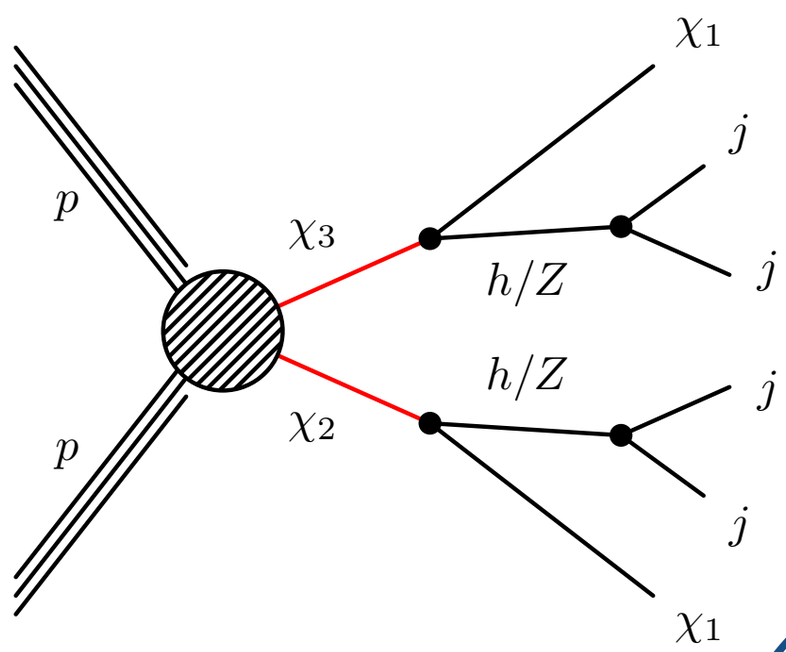
Calibbi, Lopez-Honorez, Lowette, AM

Collider signatures

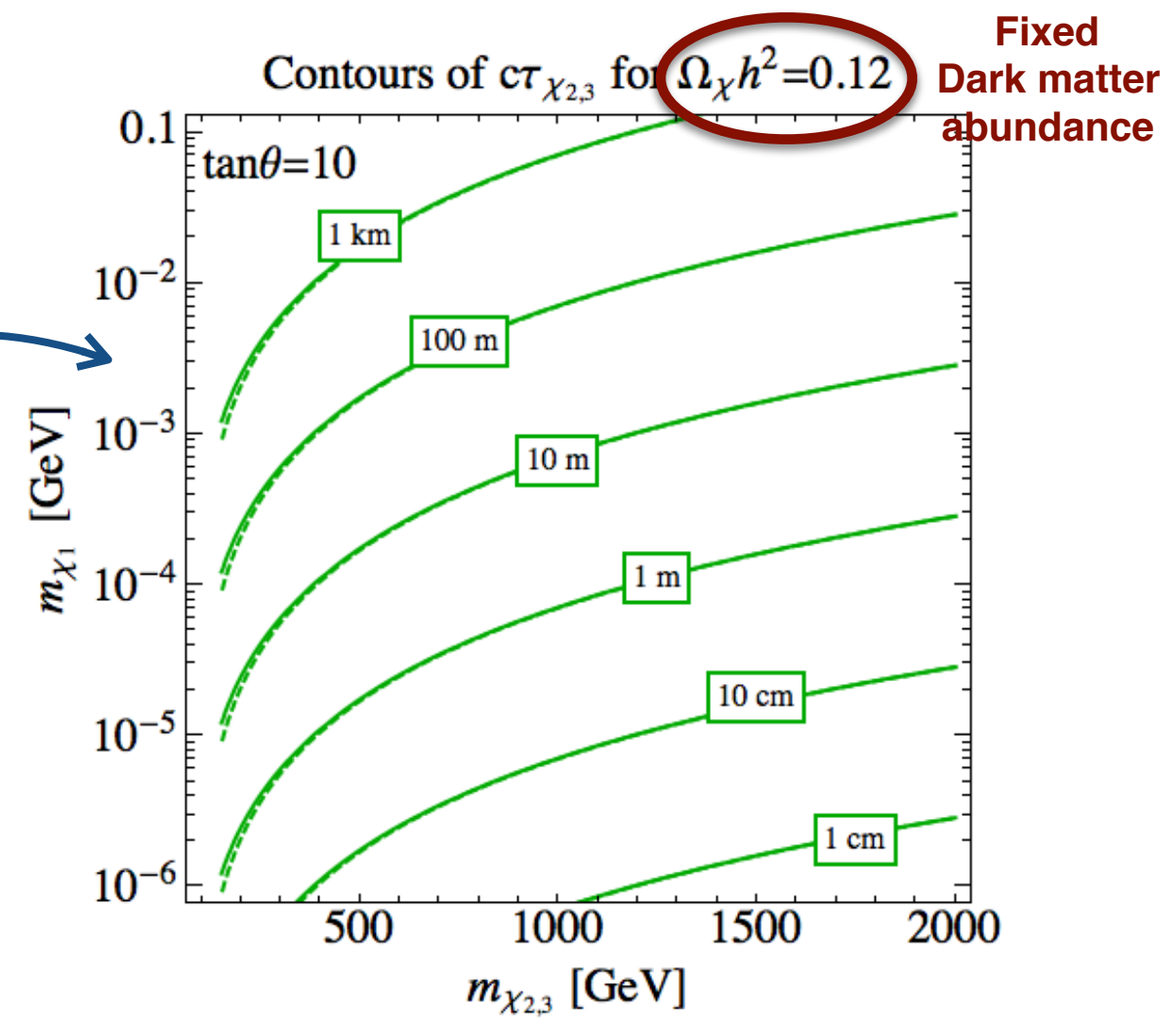
Production modes at the LHC

$$pp \to \chi_2\chi_3 + X, \quad pp \to \psi^+\psi^- + X, \quad pp \to \chi_{2,3}\psi^\pm + X.$$

Doublets production modes



Displacement in region of parameter space with correct relic abundance (from 1cm to 1Km)



Displaced Z/h+MET is main signature of the model !

Recasting ATLAS DV+MET

ATLAS arXiv: 1710.04901
CERN-EP-2017-202

- ***Follow object selection of auxiliary materials***

$$E_T^{\text{truth}}, d_0, n_{\text{tracks}}^{DV}, m_{DV}, R_{\text{decay}}, z_{\text{decay}}$$

- ***Apply the efficiency grids***

- ***Validate recasting with model in ATLAS paper as advocated in Les Houches 2017***

G. Cottin, N. Desai, J. Heisig, A. Lessa

See Nishita Desai talk of yesterday

See Hideyuki Oide talk of yesterday

Calibbi, Lopez-Honorez, Lowette, AM

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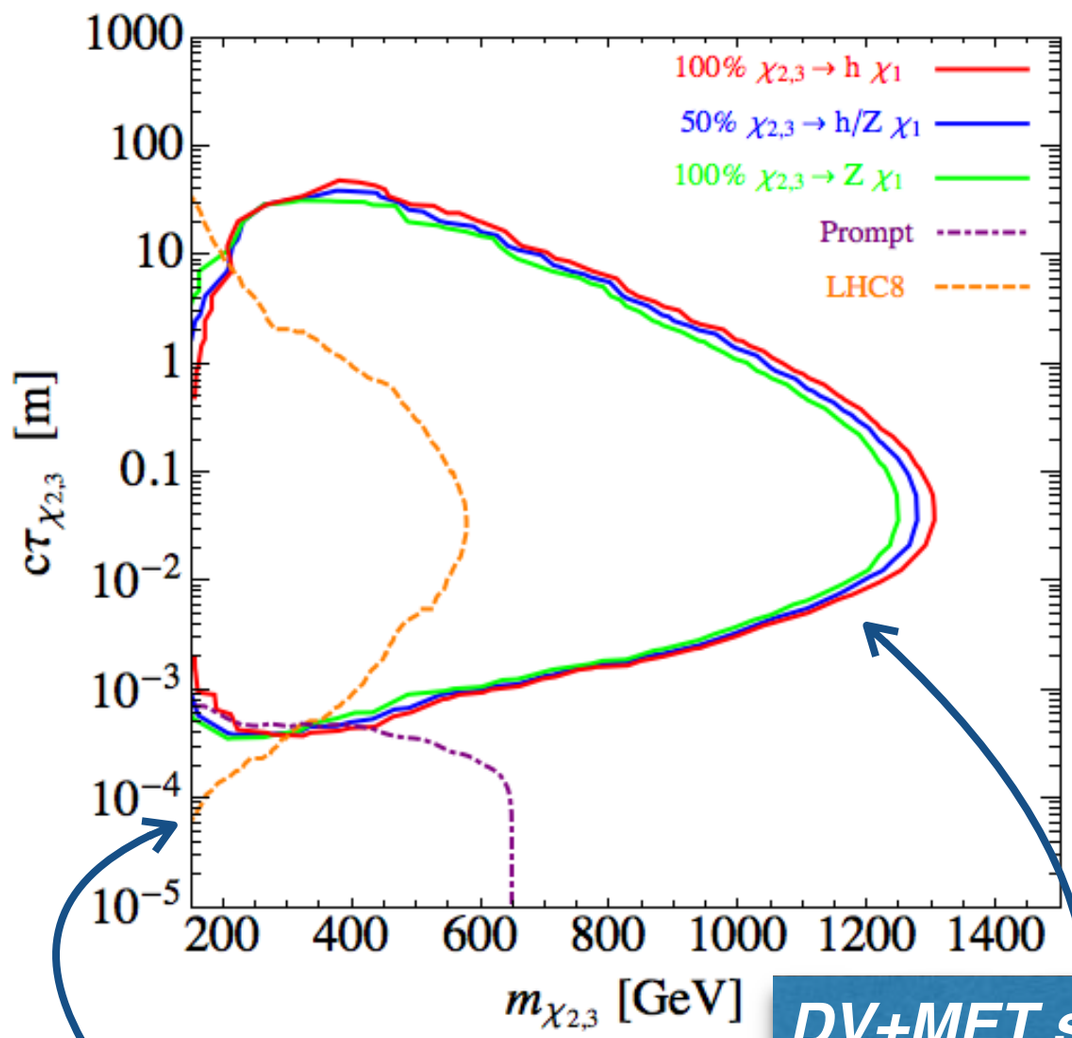
Simplified models with fixed BR into h(+MET) or Z(+MET)



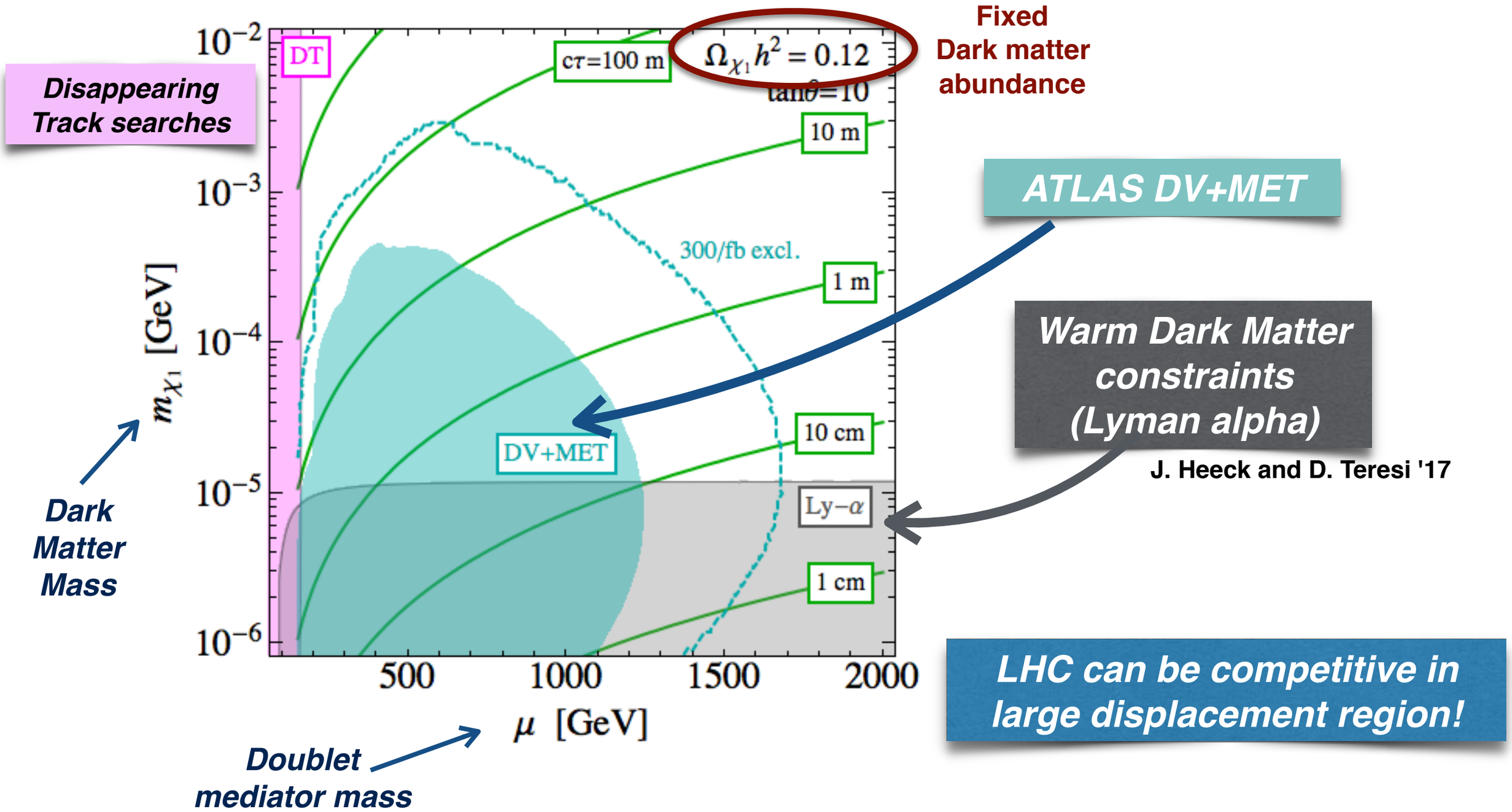
8TeV limits
Z.Liu, B.Tweedie, '15
CMS PAS EXO-12-038

DV+MET search has strong reach on EW states in SD-FI

Calibbi, Lopez-Honorez, Lowette, AM

Combining LHC and Cosmo

Viable region on parameter space and pheno probes



Conclusions

★*FIMP links to long-lived/displaced signatures*

★*Interplay with cosmology and WDM constraints*

★*We explored Singlet-Doublet DM model*

★*Motivate dedicated h/Z+MET displaced search*

★*Several classes of models can be considered*

★*Different long-lived/displaced type of signatures*