Dark Matter Freeze-in and LHC displaced signatures

Alberto Mariotti

Based on arXiv:1805.04423 with:
Lorenzo Calibbi, Laura Lopez Honorez, Steven Lowette

GGI workhop - Beyond Standard Model: Where do we go from here?
27 August 2018

Plan of the Talk

★*Introduction on DM simplified models*

★*Recap on Weakly interactive massive particle (WIMP)*

★*Feebly Interacting Massive Particle (FIMP)*

★*Displaced Signatures at the LHC*

Beyond the WIMP paradigm

★*Interplay of FIMP displaced signatures and cosmology*

★*FIMP and Displaced signatures in a minimal model*

Beyond Standard Model Physics

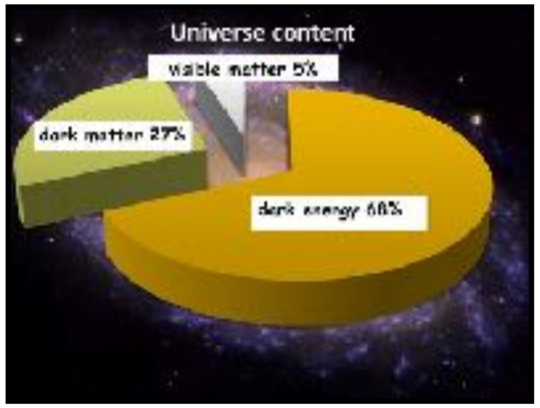
Many fundamental questions still open …

Hierarchy problem ?

Force Unification ?

Inflation ?

Dark matter nature?



Flavour hierarchies ?

Baryogenesis ?

? Where do we go ?

Beyond Standard Model Physics

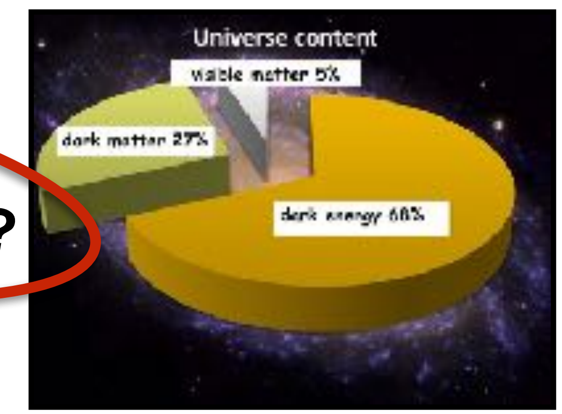
Many fundamental questions still open …

Hierarchy problem ?

Force Unification ?

Inflation ?

Dark matter nature?



Flavour hierarchies ?

Baryogenesis ?

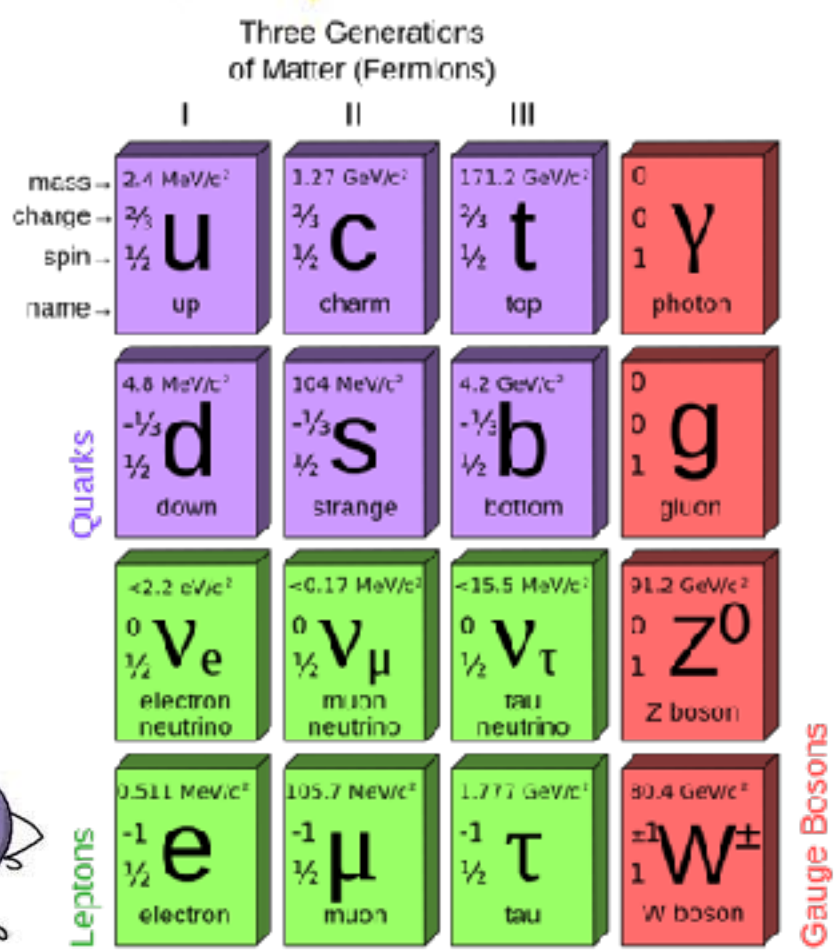
? Where do we go ?

Particle Dark Matter

Assume Dark Matter is a new elementary particle

Simplified models of Dark Matter

Useful framework for pheno studies



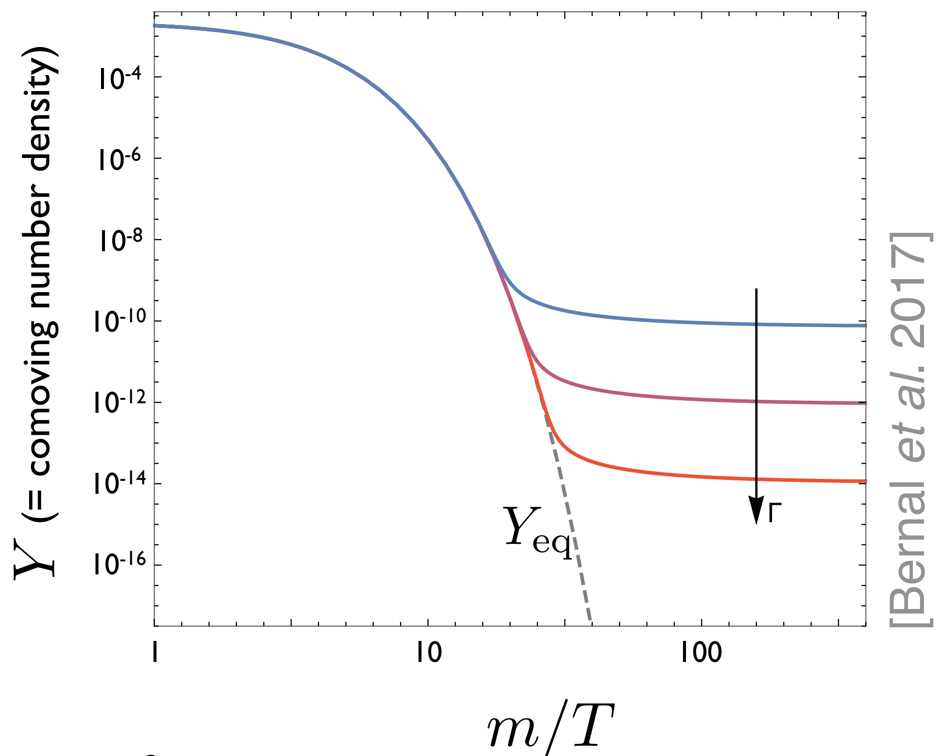
Portal

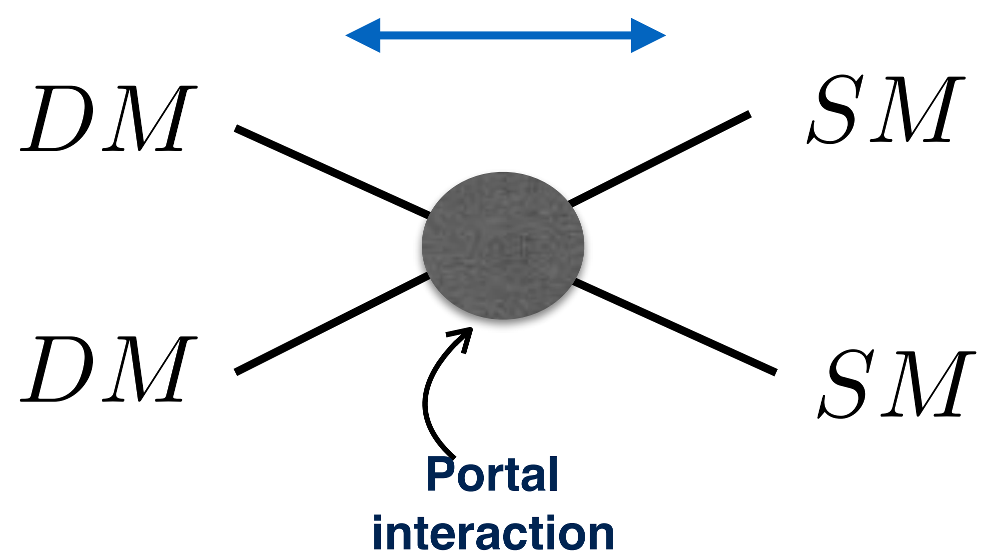
Typically inspired by the WIMP miracle

WIMP miracle

Dark Matter abundance through freeze-out mechanism

- ✦ *Dark Matter annihilates into Standard Model Particles*
- ✦ *Dark Matter abundance freeze-out during cooling of universe*





Independent on initial conditions

$$\Omega h^2 \sim 0.12 \times \frac{m_{DM}}{100\text{GeV}} \times \frac{0.2\text{pb}}{\langle \sigma v \rangle}$$

Typical weak coupling cross section

!!! Correct abundance for weakly interacting massive particle !!!

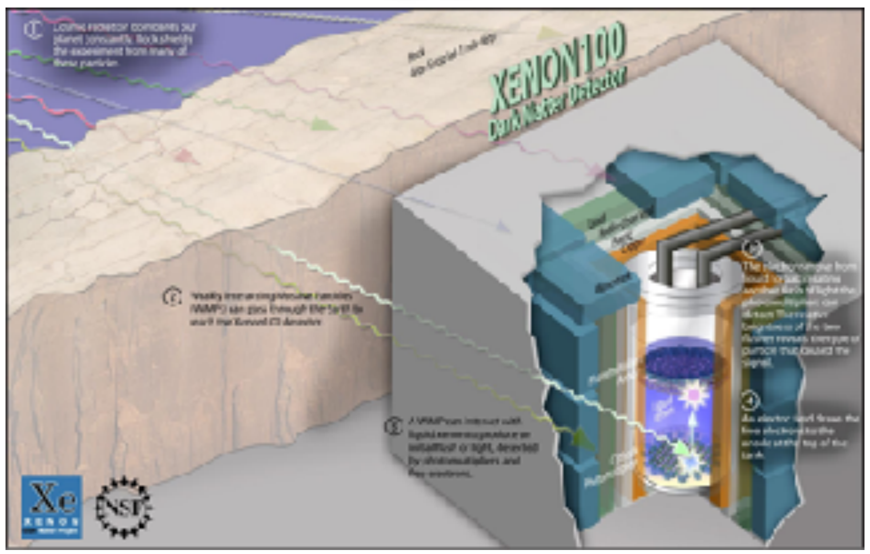
Probing DM at experiments

WIMP-like DM is prototype of DM simplified models

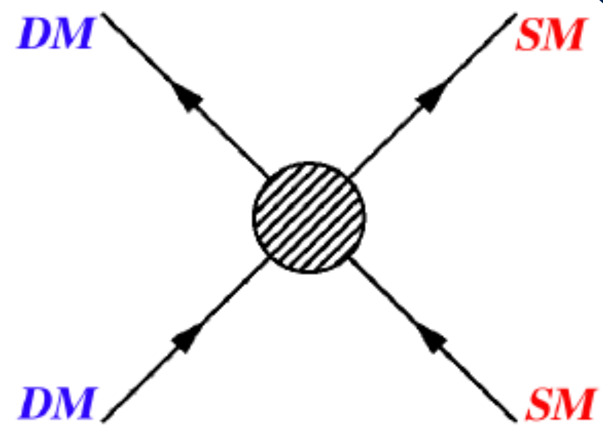
e.g. Neutralino dark matter in SUSY

thermal freeze-out (early Univ.)
indirect detection (now)

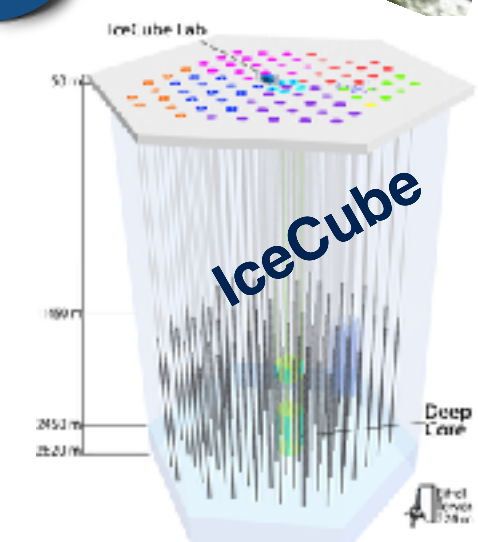
1



direct detection



2



production at colliders

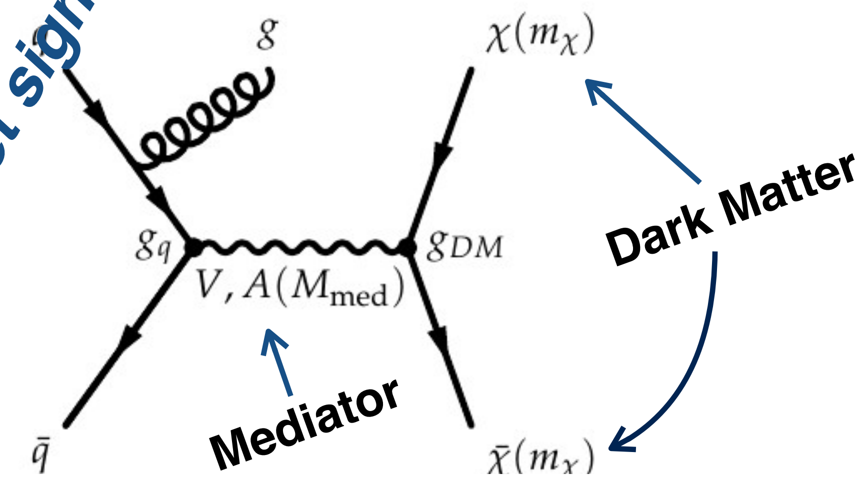
3

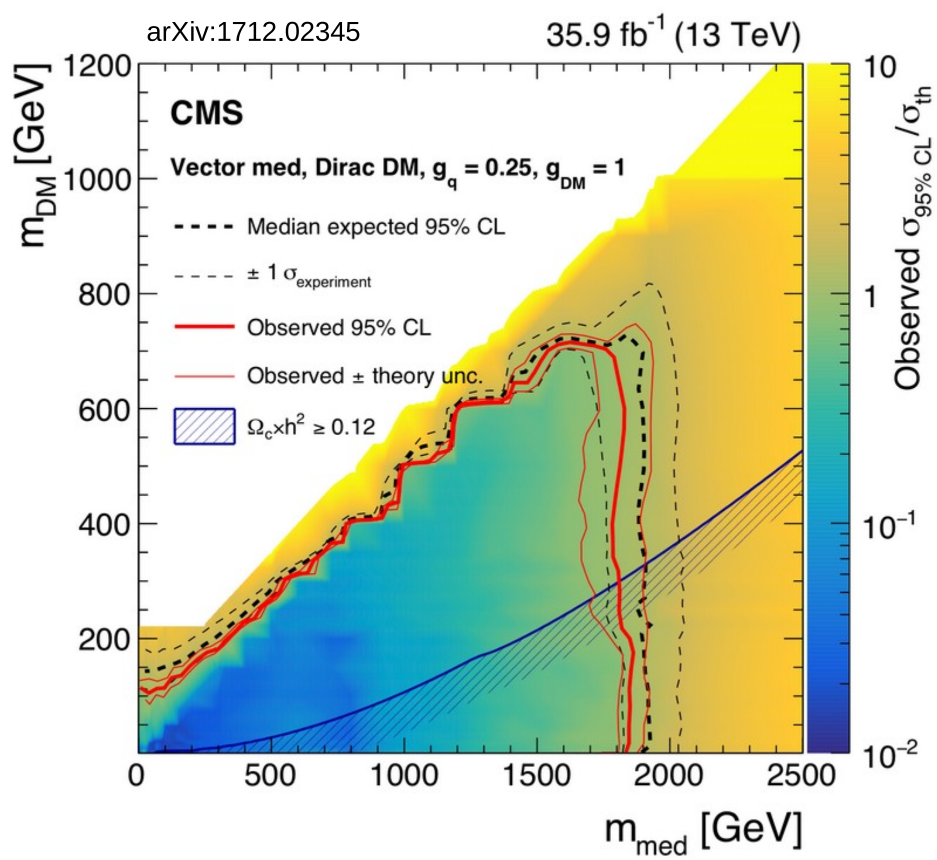
Three-fold way

WIMP under pressure

Limits on WIMP DM are improving continuosly

MonoJet signature

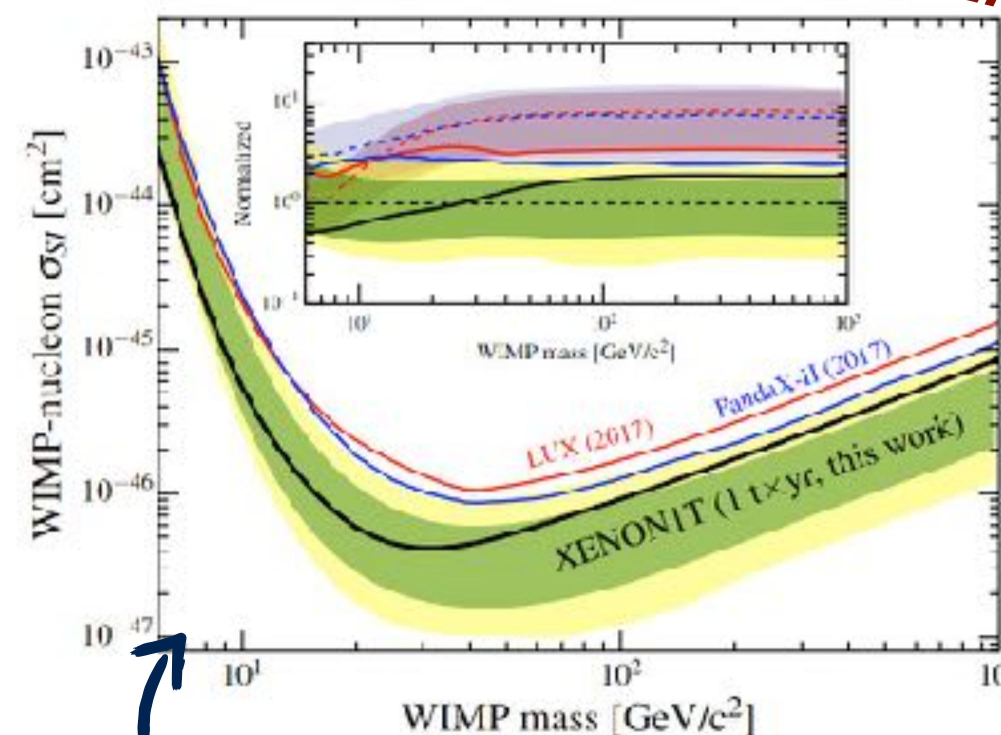




New LHC results

Mediator search

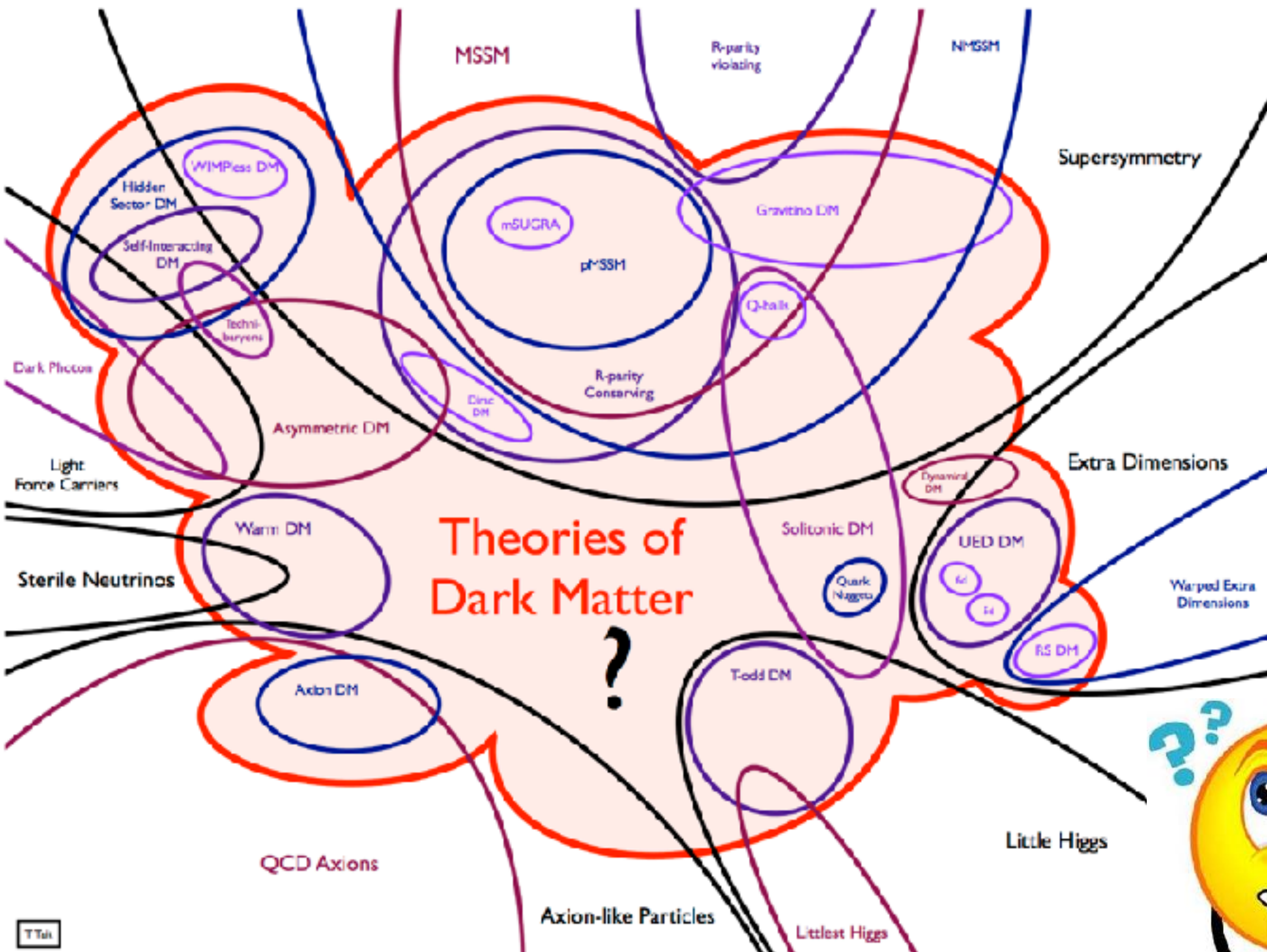
Recent limits from XENON1T



Very sensitive in 5-1000 GeV DM mass range

Dark Matter ZOO

But possibility for Dark Matter are much vaster



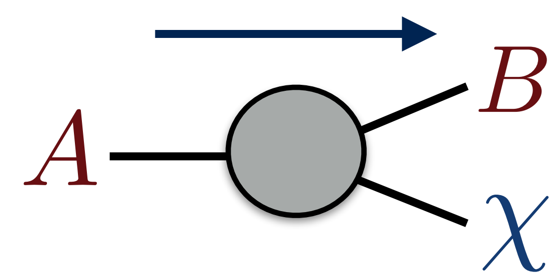
Feebly Interacting Massive Particle

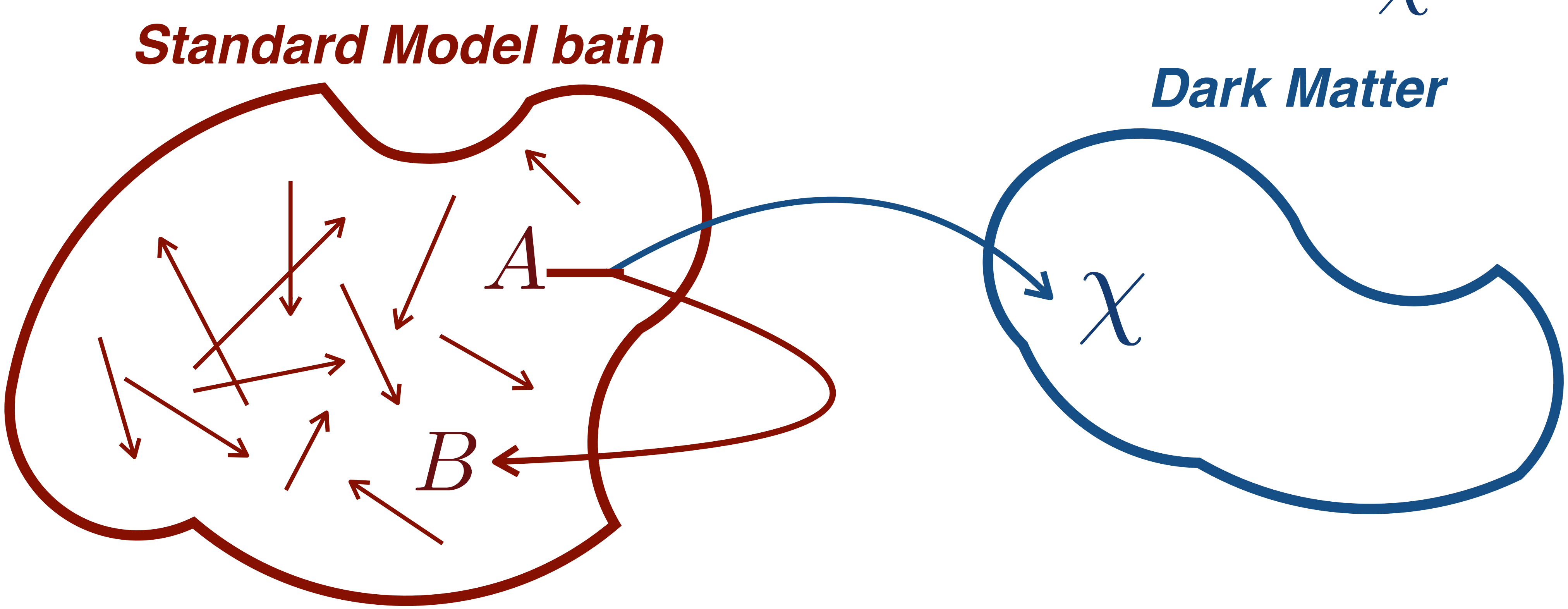
Dark Matter abundance through freeze-in mechanism

- ✦ *Dark matter not in thermal equilibrium with SM bath*
- ✦ *Produced via decay or scattering of particles in thermal equilibrium*

Hall, Jedamzik, March-Russell, West '09
Blennow, Fernandez-Martinez, Zaldivar '13
Bernal, Heikinheimo, Tenkanen, Tuominen, Vaskonen '17
Co, D'Eramo, Hall, Pappadopulo '15
Bélanger, Cai, Desai, Goudelis, Harz, Lessa, J.No, Pukhov, Sekmen, Sengupta, Zaldivar, Zurita '18

Freeze-in through decay

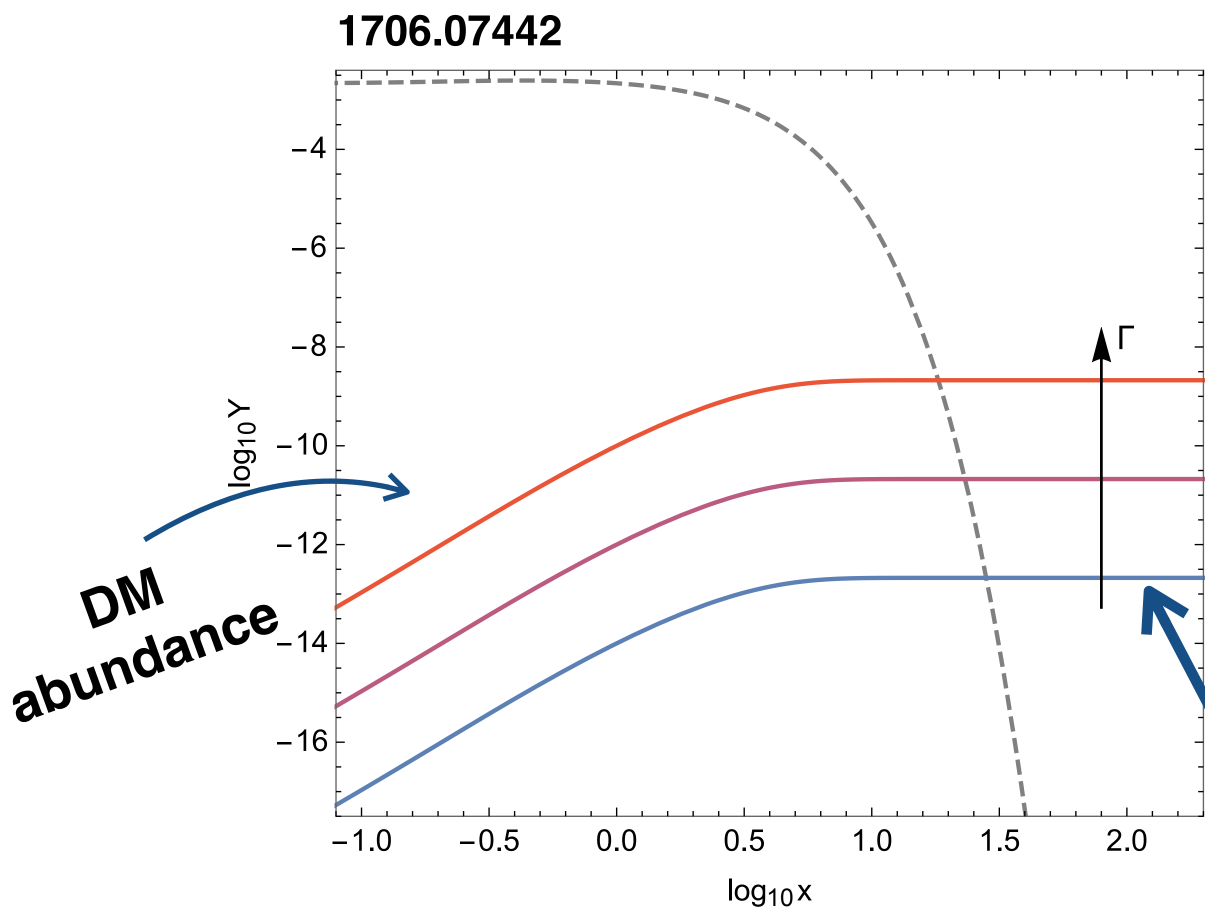


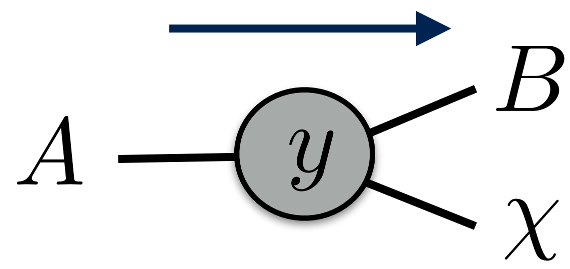


Freeze-in through decay

★*Mother (mediator) A in thermal equilibrium*

★*Mediator A decays to Dark Matter and produce it*





Tiny coupling

$y \ll 1$

$$\Gamma[A \to B\chi] \sim y^2$$

Particles in thermal equilibrium

Dark Matter

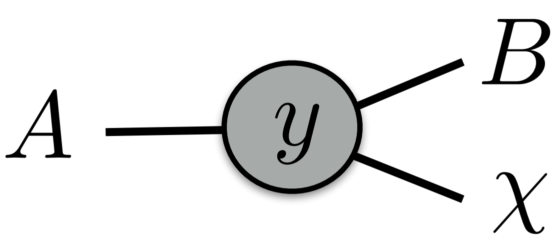
Width (lifetime) of the mediator A determines the DM abundance

FIMP phenomenology

- ✦ ***What is typical value of portal coupling?***
- ✦ ***Can we probe FIMP DM experimentally?***

FIMP Dark Matter abundance

$$\Omega h^2 \sim 0.12 \left(\frac{\Gamma_A}{4 \times 10^{-15}\ \text{GeV}} \right) \left(\frac{600\ \text{GeV}}{m_A} \right)^2 \left(\frac{m_{DM}}{10\ \text{keV}} \right)$$



$$\Gamma_A \sim \frac{y^2}{8\pi} m_A \quad \longrightarrow \quad y \sim 10^{-8}$$

Very small coupling !!!

- ★ ***Suppressed signal in direct detection***
- ★ ***Suppressed signal in indirect detection***

Can LHC probe FIMP?

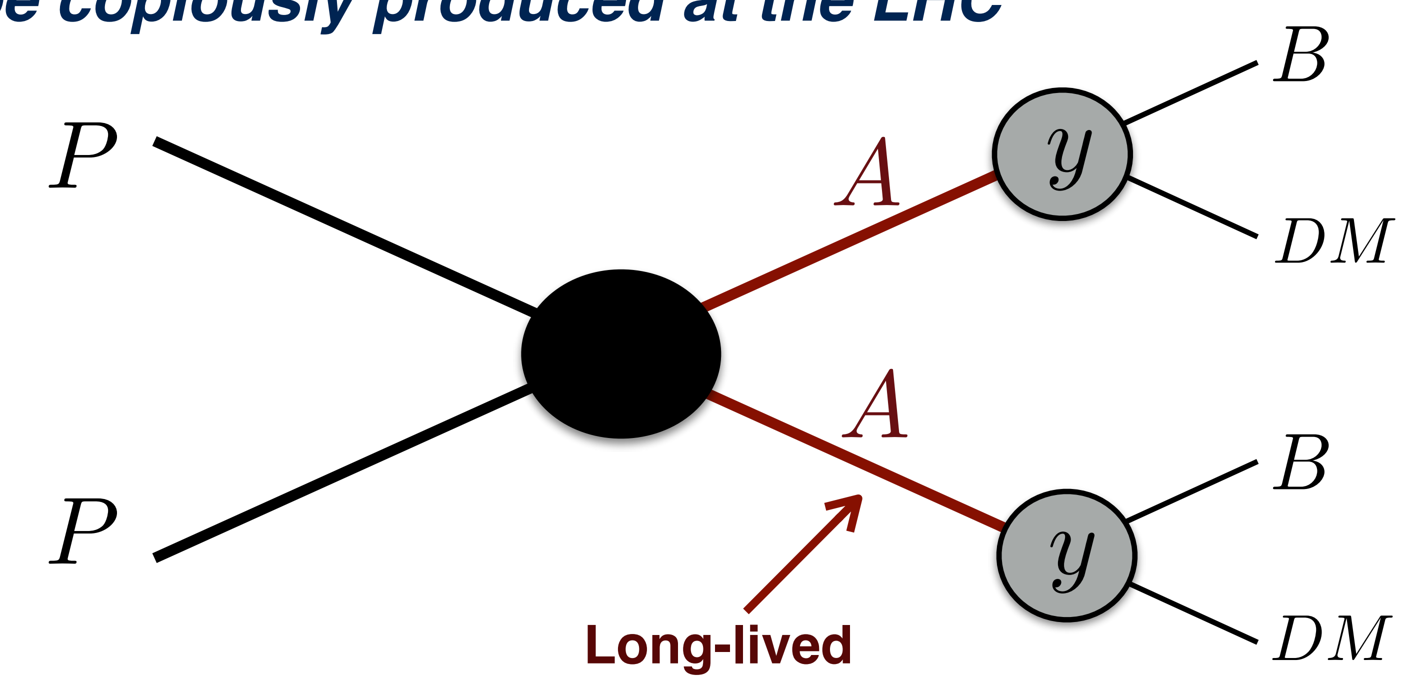
FIMP phenomenology

✦Can we probe FIMP DM at LHC? **YES !**

To be in thermal equilibrium

✦Mediator has sizeable coupling with SM particles

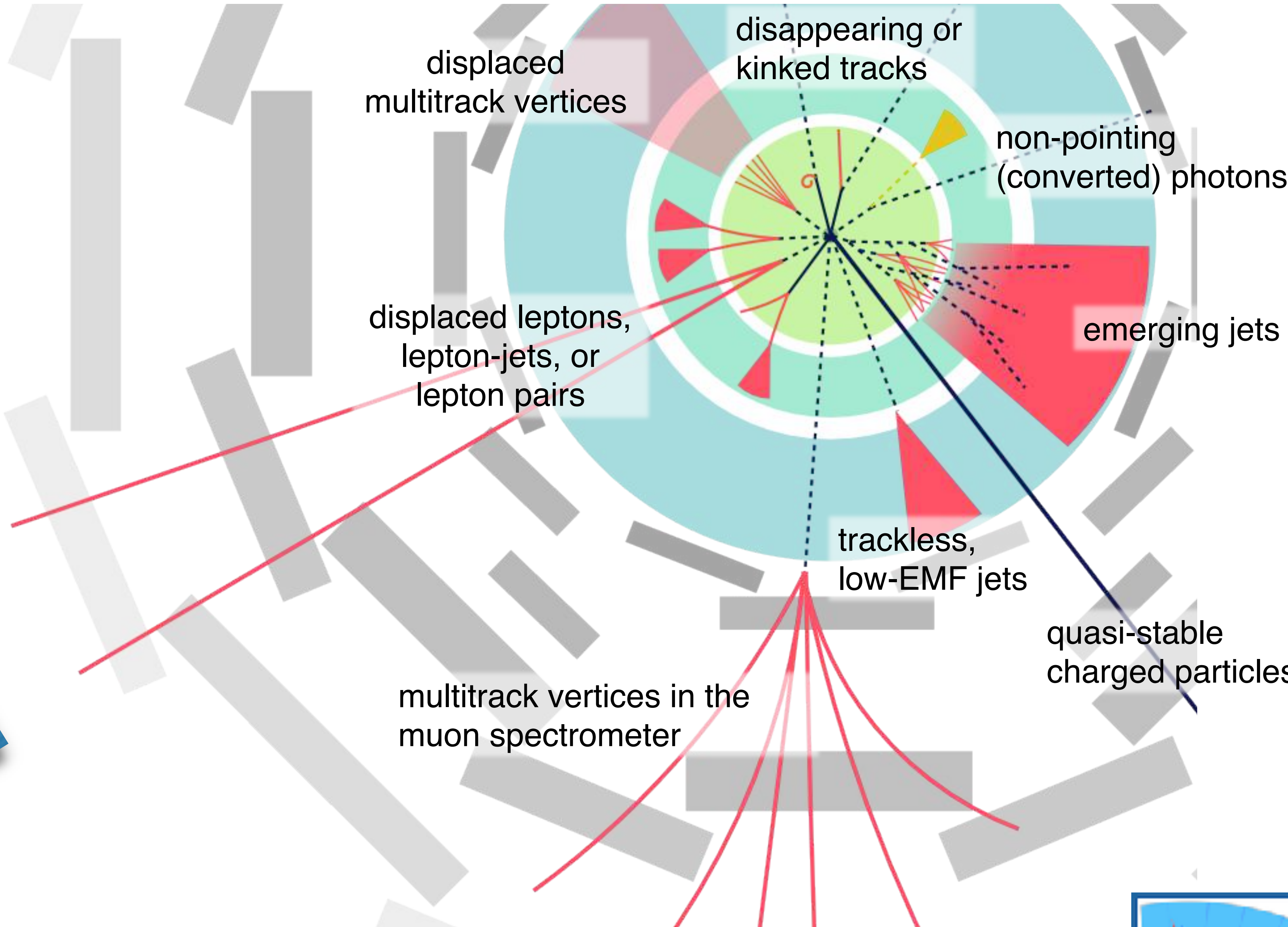
✦Can be copiously produced at the LHC



Typical mediator decay length is macroscopic: EXOTIC SIGNALS @ LHC !!!

$$c\tau_A = \frac{10^{-15}\ \mathrm{GeV}}{\Gamma_A} \times 19\ \mathrm{cm}$$

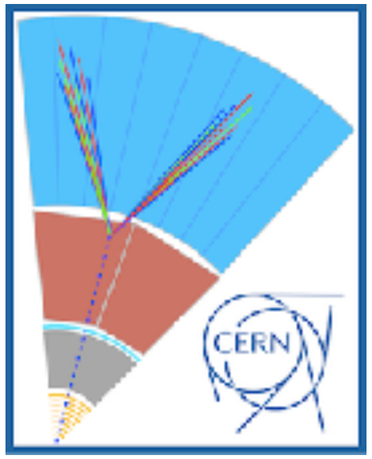
LongLived Signatures @ LHC



SM is mainly prompt

Signatures with low background

[Figure from Heather Russell]



Challenging but powerful

FIMP (decay) phenomenology

Standard Cosmology history

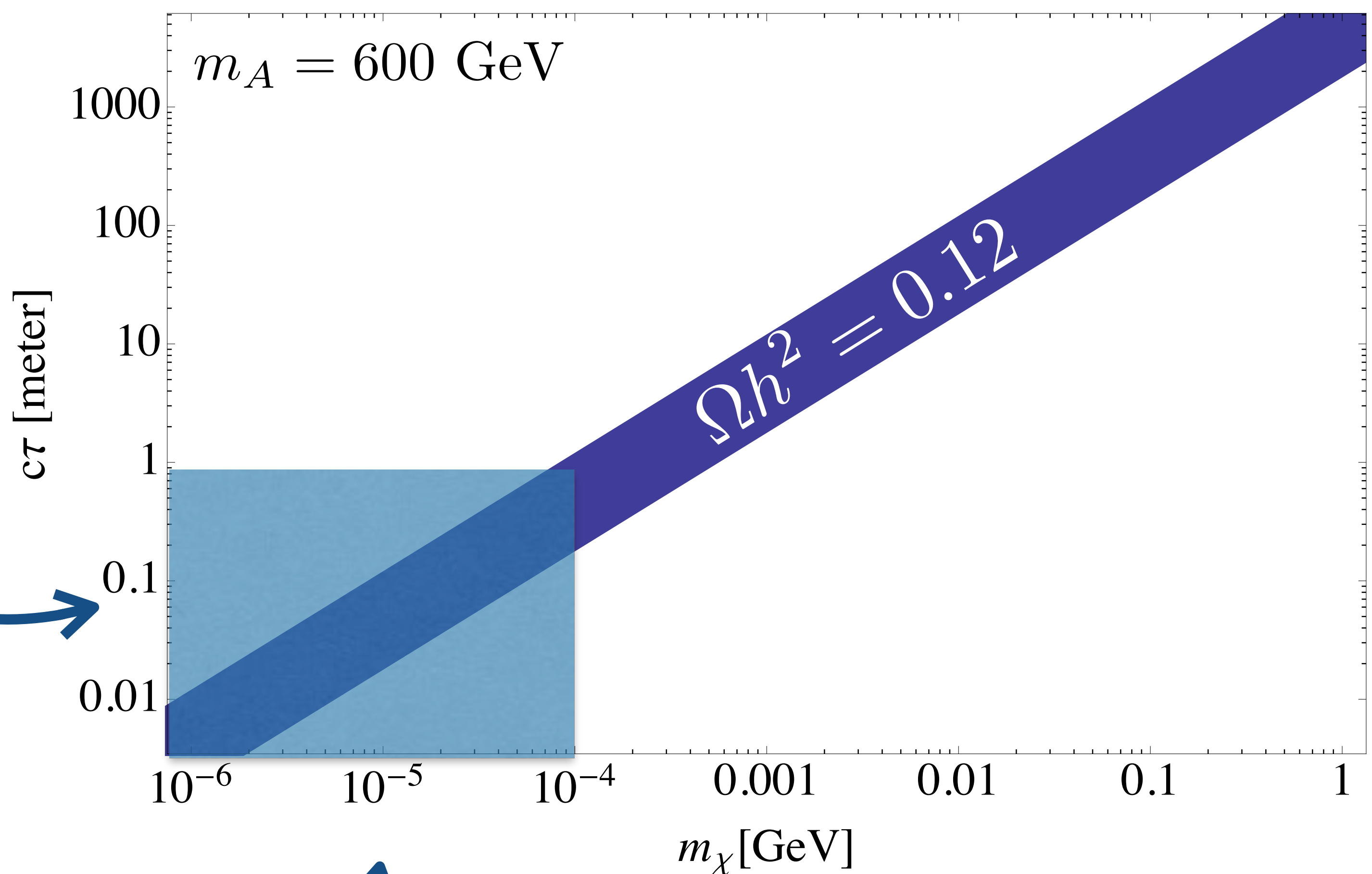
$$\Omega h^2 \sim 0.12 \left(\frac{5\ \text{cm}}{c\tau_A}\right)\left(\frac{600\ \text{GeV}}{m_A}\right)^2\left(\frac{m_\chi}{10\ \text{keV}}\right)$$

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

Standard Cosmology history

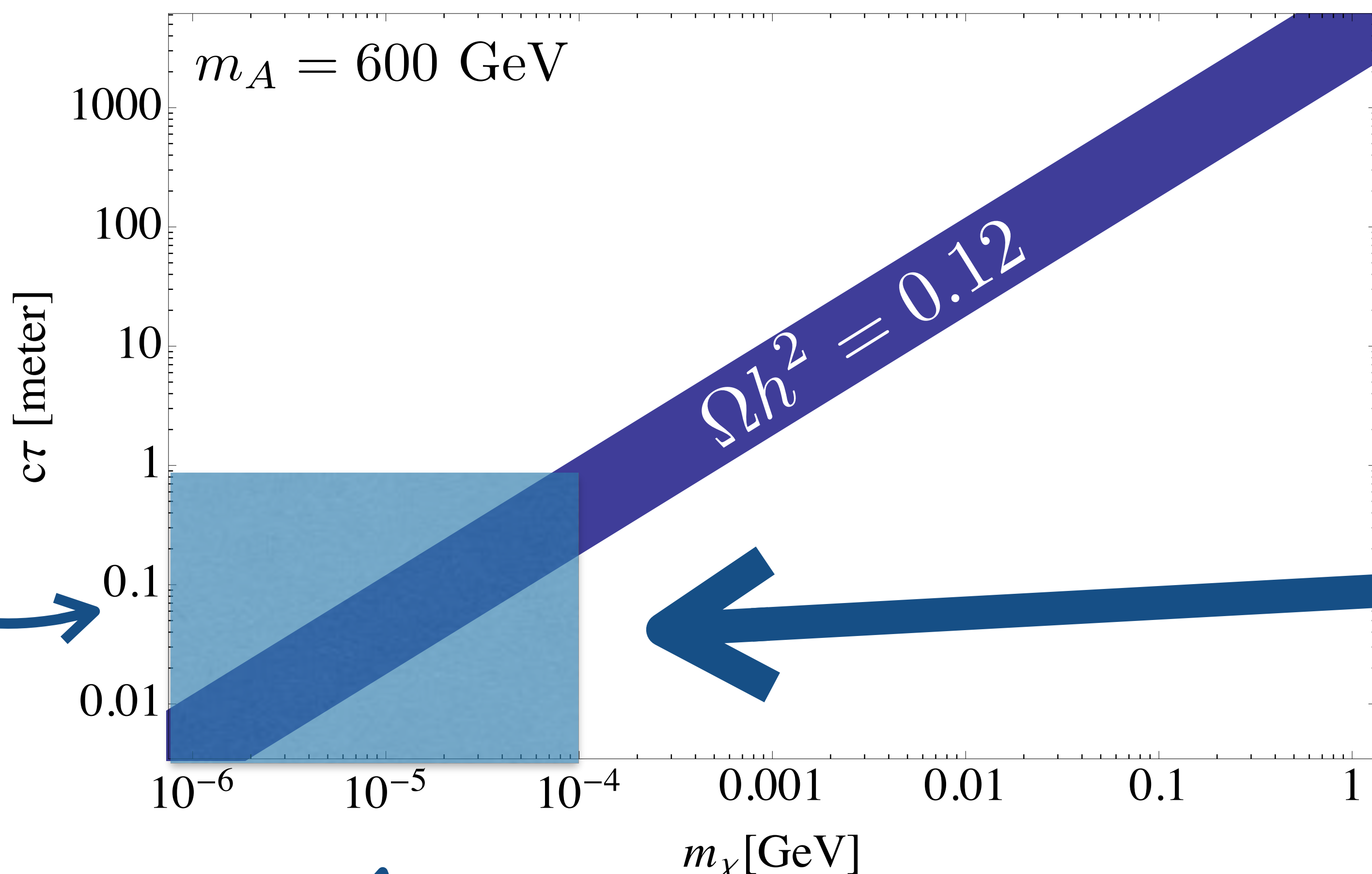
$$\Omega h^2 \sim 0.12 \left(\frac{5\ \text{cm}}{c\tau_A}\right)\left(\frac{600\ \text{GeV}}{m_A}\right)^2\left(\frac{m_\chi}{10\ \text{keV}}\right)$$

Macroscopic decay visible at LHC

Mediator accessible at the LHC

Very light Dark Matter

Typical size for detector



Displaced dark matter at LHC

WDM signatures

Light Dark Matter regime

Dark Matter and Long-lived signatures

Can we classify DM models with long-lived signatures?

Some explored cases ....

- ***FIMP*** Hall, Jedamzik, March-Russell, West '09
  Co, D'Eramo, Hall, Pappadopulo '15
- ***SuperWIMP*** Feng, Rajaraman, Takayama '03
  Chang, Luty '09
- ***Asymmetric DM*** Kaplan, Luty, Zurek '09
  Schwaller, Stolarski, Weiler '15
- ***Pseudo-Dirac DM*** Davoli, De Simone, Jacques, Sanz '17
- ***Conversion driven FO (co-annihilation)***
  Garny, Heisig, Lülf, Vogl '17

  Hall, March-Russell , West '10
  Schwaller, Stolarski, Weiler '15
  Hessler, Ibarra, Molinaro, Vogl '16
  Buchmueller, De Roeck, McCullough, Hahn, Sung, Schwaller, Yu '17
  Stolarski '17
  Ghosh, Mondal, Mukhopadhyaya '18
  Davolia, De Simone, Jacquesa, Morandini '18
  D'Eramo, Fernandez, Profumo '18
  Garny, Heisig, Hufnagel, Lülf '18

Typically non thermal production

Calibbi, Lopez-Honorez, Lowette, AM

Singlet Doublet Freeze In

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

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

Improve gauge coupling unification

- ***Lagrangian coupling with the Higgs***

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

Similar to Higgsino-Bino, but with arbitrary couplings

Regime for Freeze-in

$$|y_u|,\ |y_d| \ll 1, \qquad |m_s| \ll |\mu|,$$

Feeble yukawa couplings

Singlet much lighter

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

Calibbi, Lopez-Honorez, Lowette, AM

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***

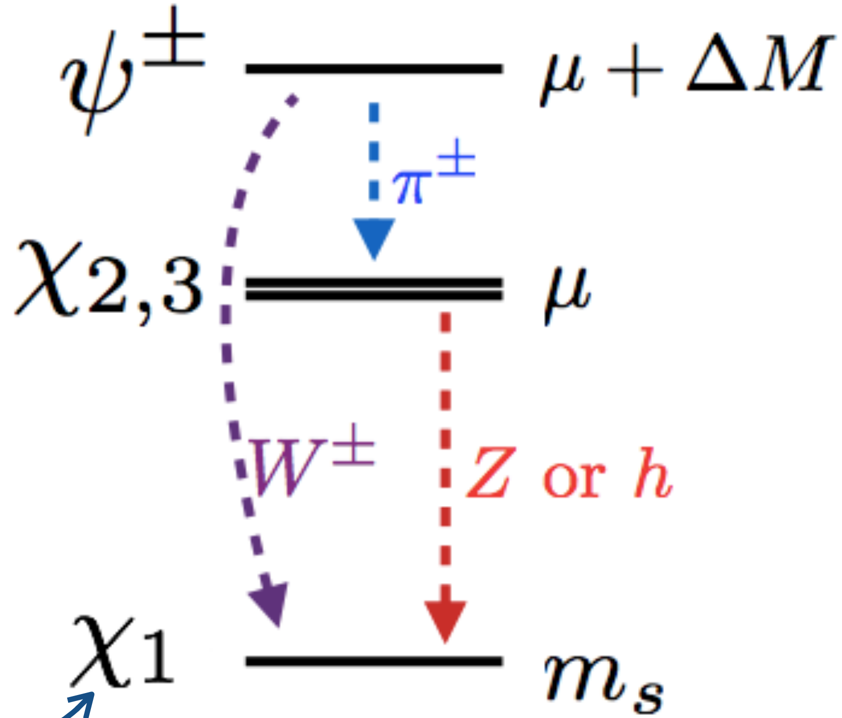
$$-\mathcal{L} \supset \mu\, \psi_d \cdot \psi_u + y_d\, \psi_d \cdot H\, \psi_s + y_u\, H^\dagger \psi_u\, \psi_s + \frac{1}{2} m_s\, \psi_s \psi_s + h.c.$$

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

- ***Regime for Freeze-in:*** $y \ll 1, \quad |m_s| \ll |\mu|$

Similar to Higgsino-Bino with tiny mixing

Simple spectrum and decay modes



Radiative corrections

Dark matter

Calibbi, Lopez-Honorez, Lowette, AM

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

Calibbi, Lopez-Honorez, Lowette, AM

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

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

Typical coupling size for displacement

Very light DM mass, cosmological constraints

Doublet mass scale accessible at the LHC

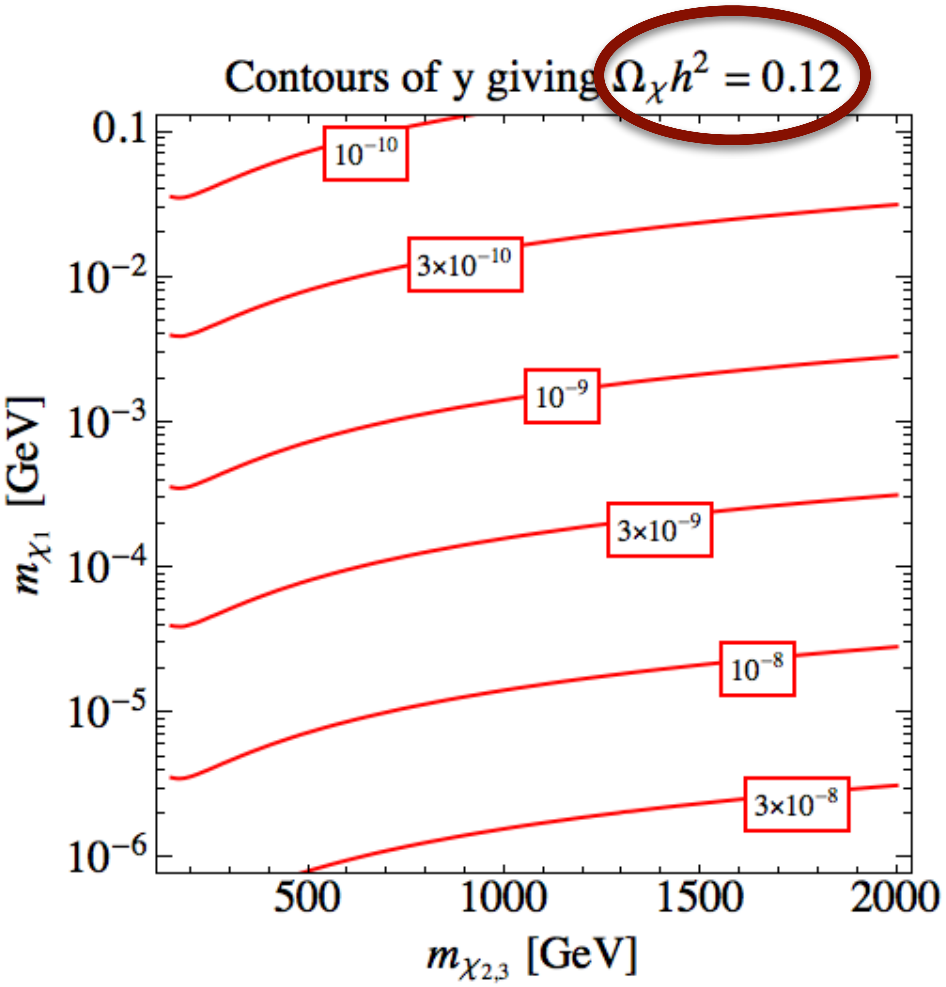
One can impose the correct relic abundance and reduce the parameter space

Calibbi, Lopez-Honorez, Lowette, AM

Freeze-in

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

Fix Dark Matter abundance to correct value



$$10^{-8} \lesssim y \lesssim 10^{-10}$$

Typical coupling size compatible with DM abundance

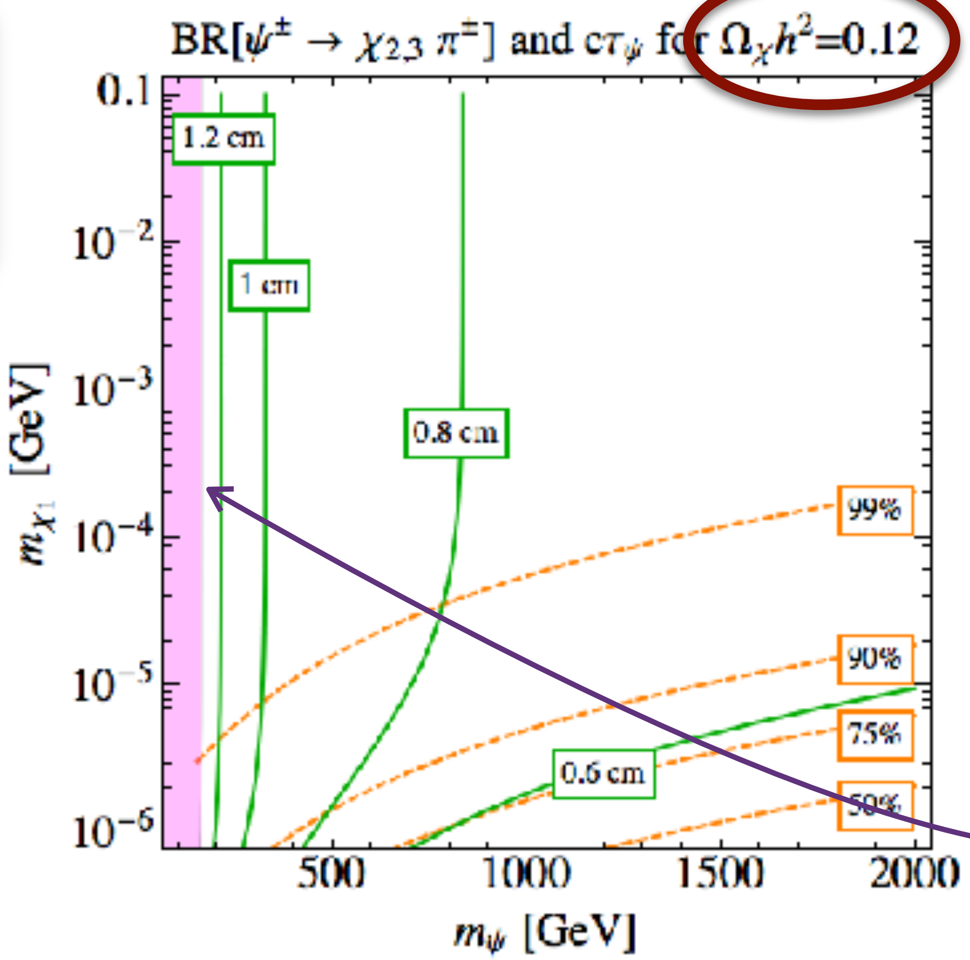
Calibbi, Lopez-Honorez, Lowette, AM

Freeze-in

$$\Omega_{\chi_1} h^2 \simeq 0.11 \left(\frac{y}{10^{-8}}\right)^2 \left(\frac{m_{\chi_1}}{10\ \mathrm{keV}}\right) \left(\frac{700\ \mathrm{GeV}}{\mu}\right)$$

Fix Dark Matter abundance to correct value

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

ATL-PHYS-PUB-2017-019
...
for pure Higgsino see e.g.
Mahbubani, Schwaller, Zurita '17
Fukuda, Nagata, Otono, Shirai '17

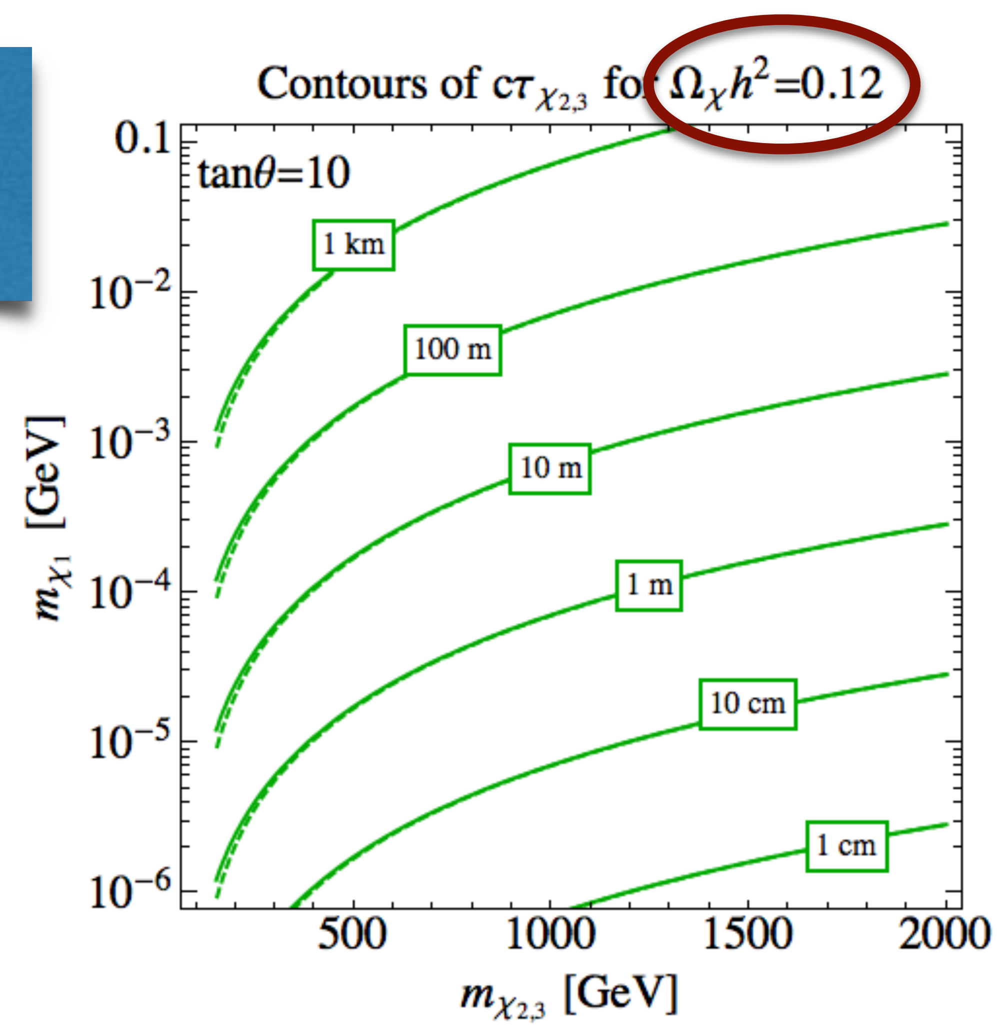
Calibbi, Lopez-Honorez, Lowette, AM

Freeze-in

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

Fix Dark Matter abundance to correct value

Neutral fermions decay



Decays to Z and h almost democratically

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

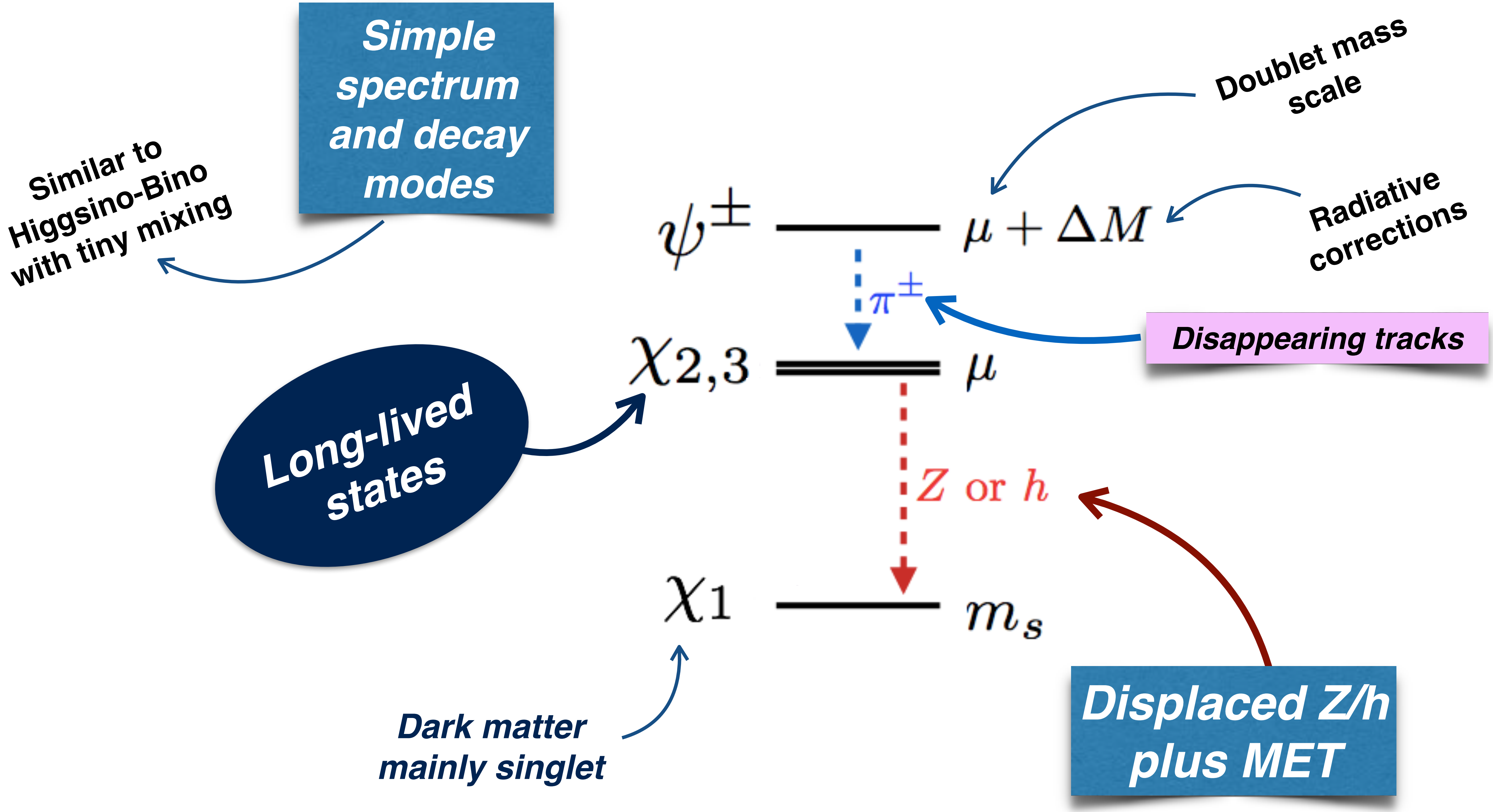
Decay length ranges from 0.1 to 1000 cm

Displaced Z/h plus MET

...
for Higgsino-gravitino see
Meade, Reece, Shih '10
Liu, Tweedie, '15

Calibbi, Lopez-Honorez, Lowette, AM

Recap on Singlet Doublet Freeze In



★***Phenomenological probes:***

LHC displaced signatures -- Light dark matter cosmology

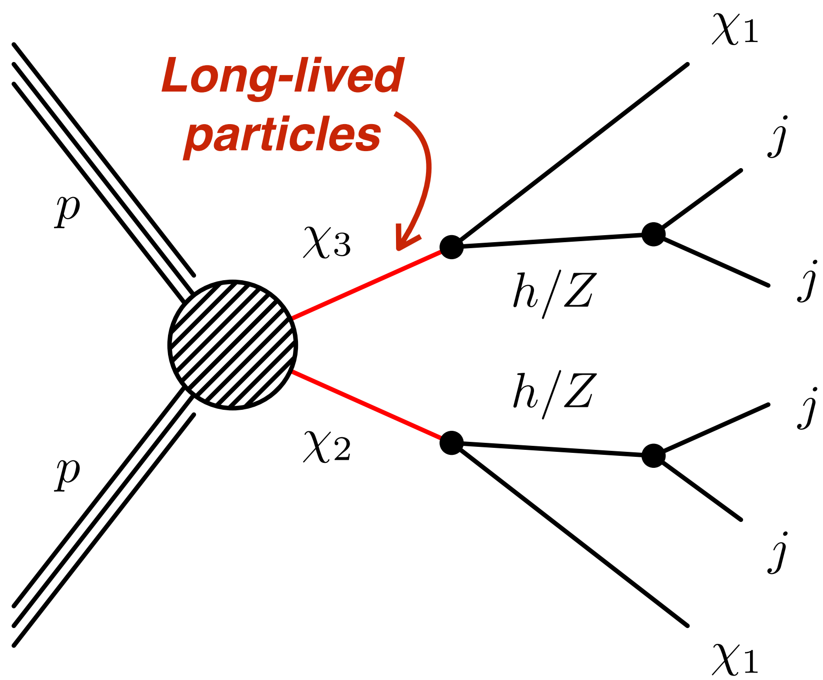
Calibbi, Lopez-Honorez, Lowette, AM

Collider signatures

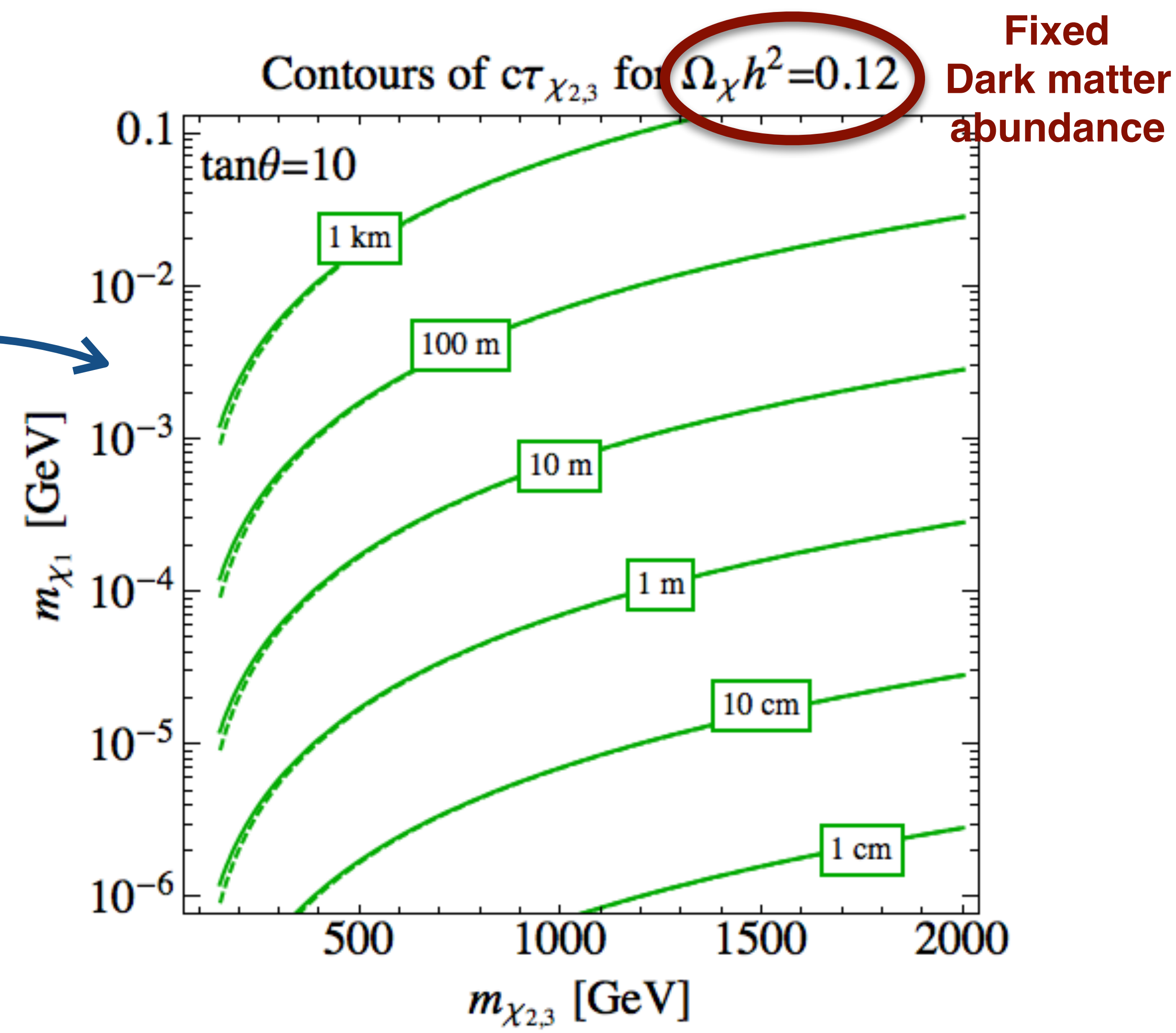
Production modes at the LHC

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

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 !

Calibbi, Lopez-Honorez, Lowette, AM

Recasting ATLAS DV+MET

ATLAS arXiv: 1710.04901
CERN-EP-2017-202

Search for Displaced Vertices + MET

- 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 also Allanach, Badziak, Cottin, Desai, Hugonie, Ziegler '16

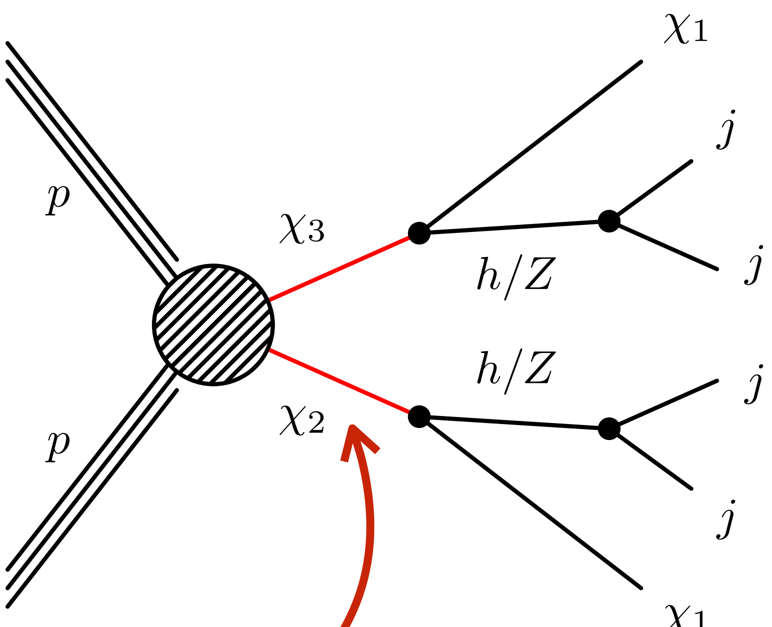
Calibbi, Lopez-Honorez, Lowette, AM

Recasting ATLAS DV+MET

ATLAS arXiv: 1710.04901
CERN-EP-2017-202

Search for
Displaced Vertices + MET

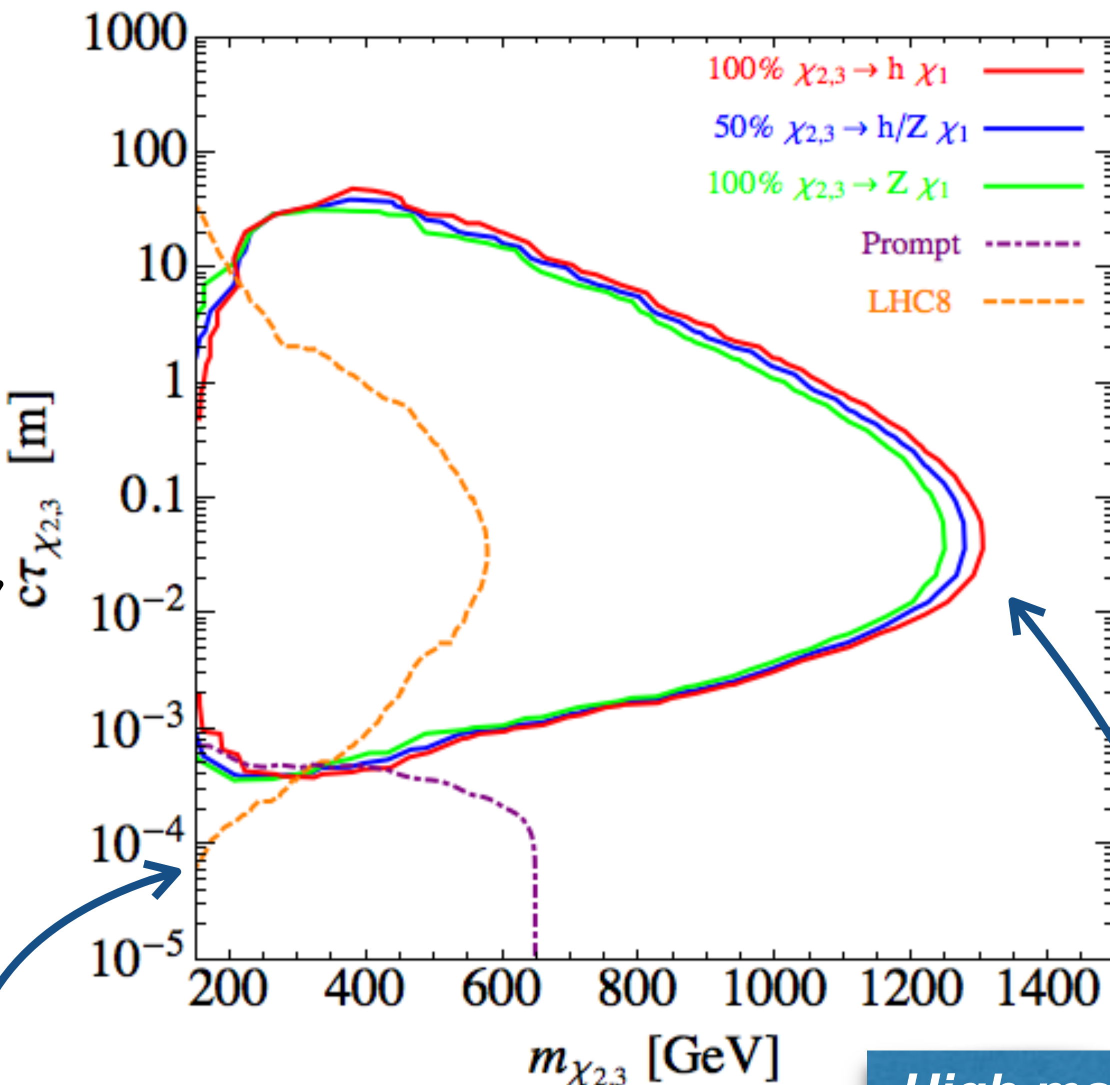
We reinterpreted it for our final state



Long-lived particles

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

Decay distance



High mass reach

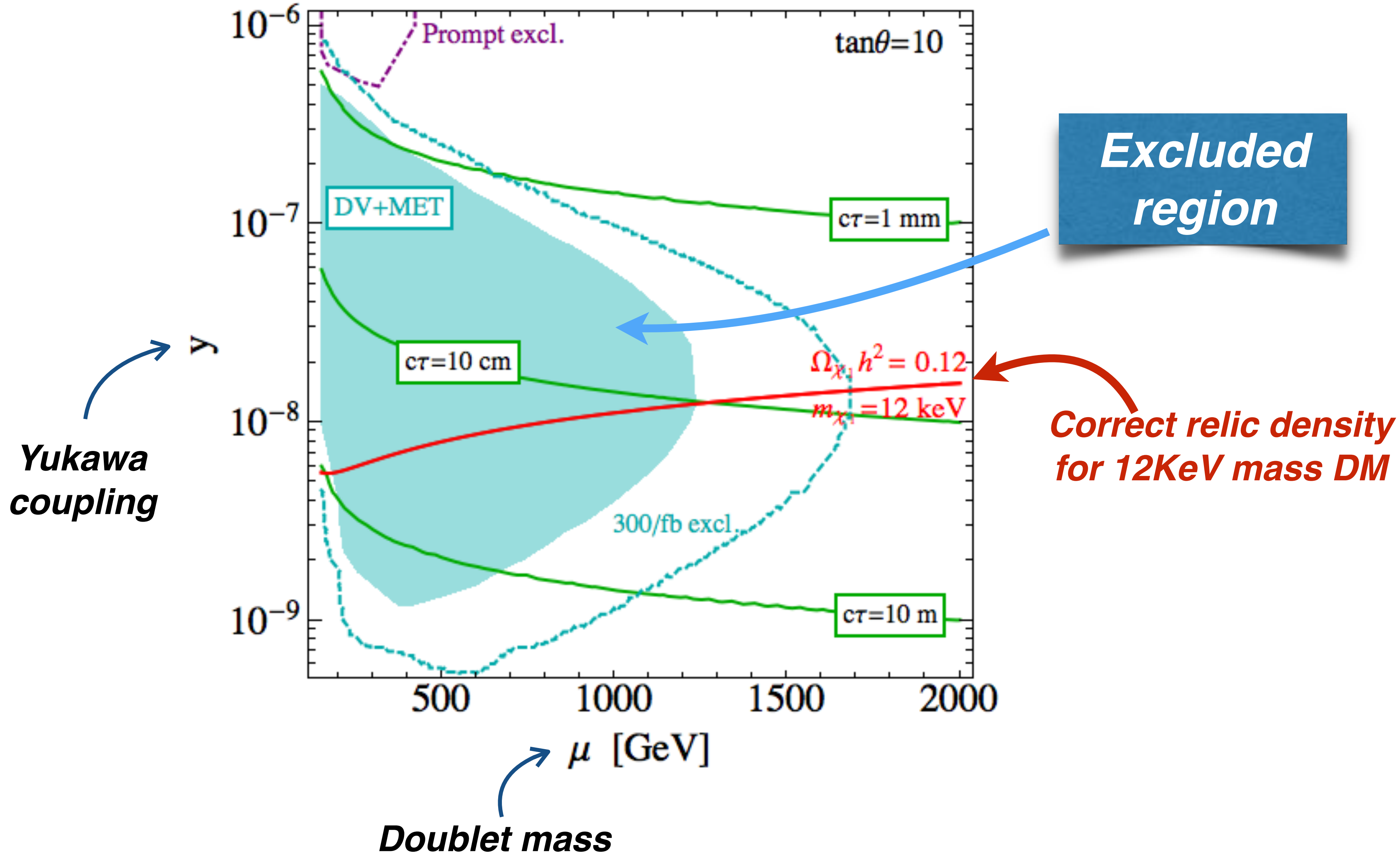
8TeV limits
Z.Liu, B.Tweedie, '15
CMS PAS EXO-12-038

Long lived particle mass

Calibbi, Lopez-Honorez, Lowette, AM

Impact on Singlet Doublet DM

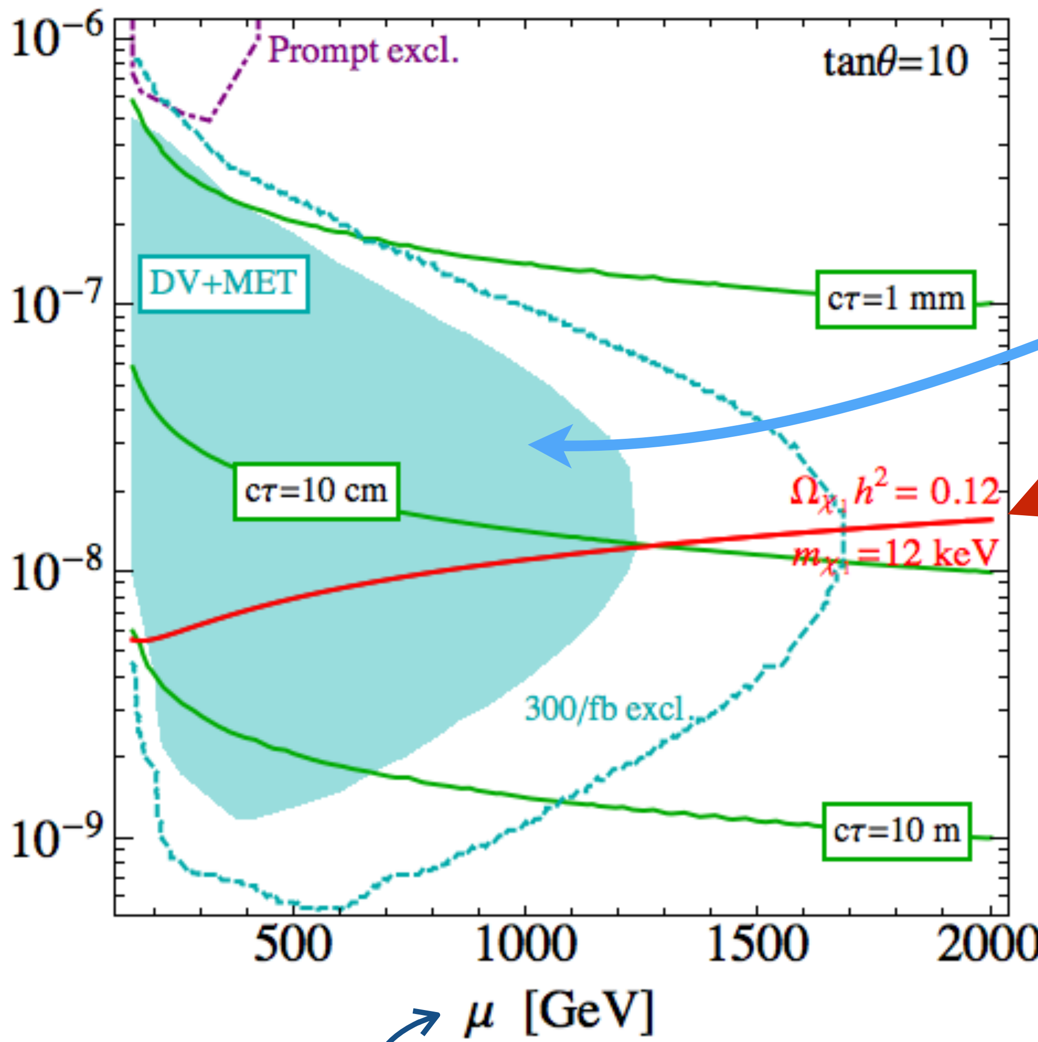
Translate model independent bound on Singlet Doublet DM model



Calibbi, Lopez-Honorez, Lowette, AM

Impact on Singlet Doublet DM

Translate model independent bound on Singlet Doublet DM model



Yukawa coupling

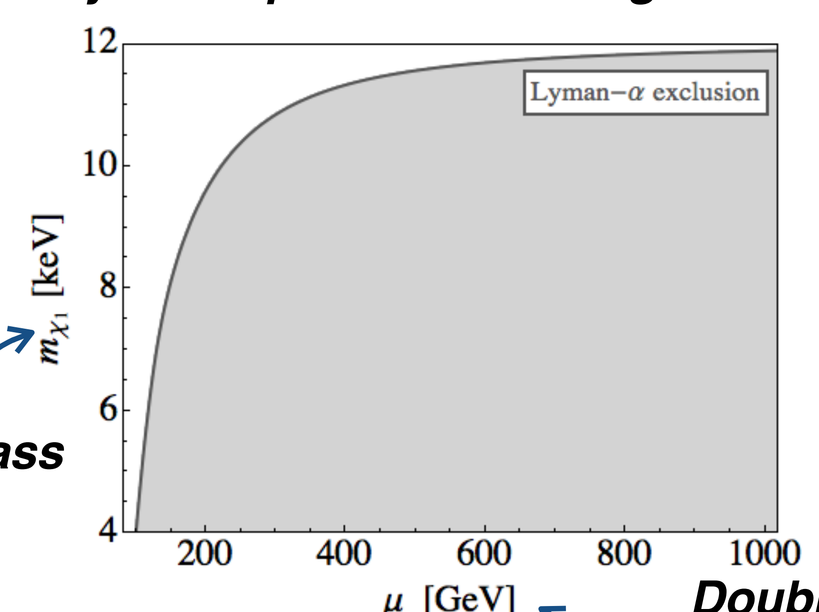
Doublet mass

Excluded region

Correct relic density for 12KeV mass DM

Cosmological constraint!

Lyman-alpha bound for light DM



J. Heeck and D. Teresi '17

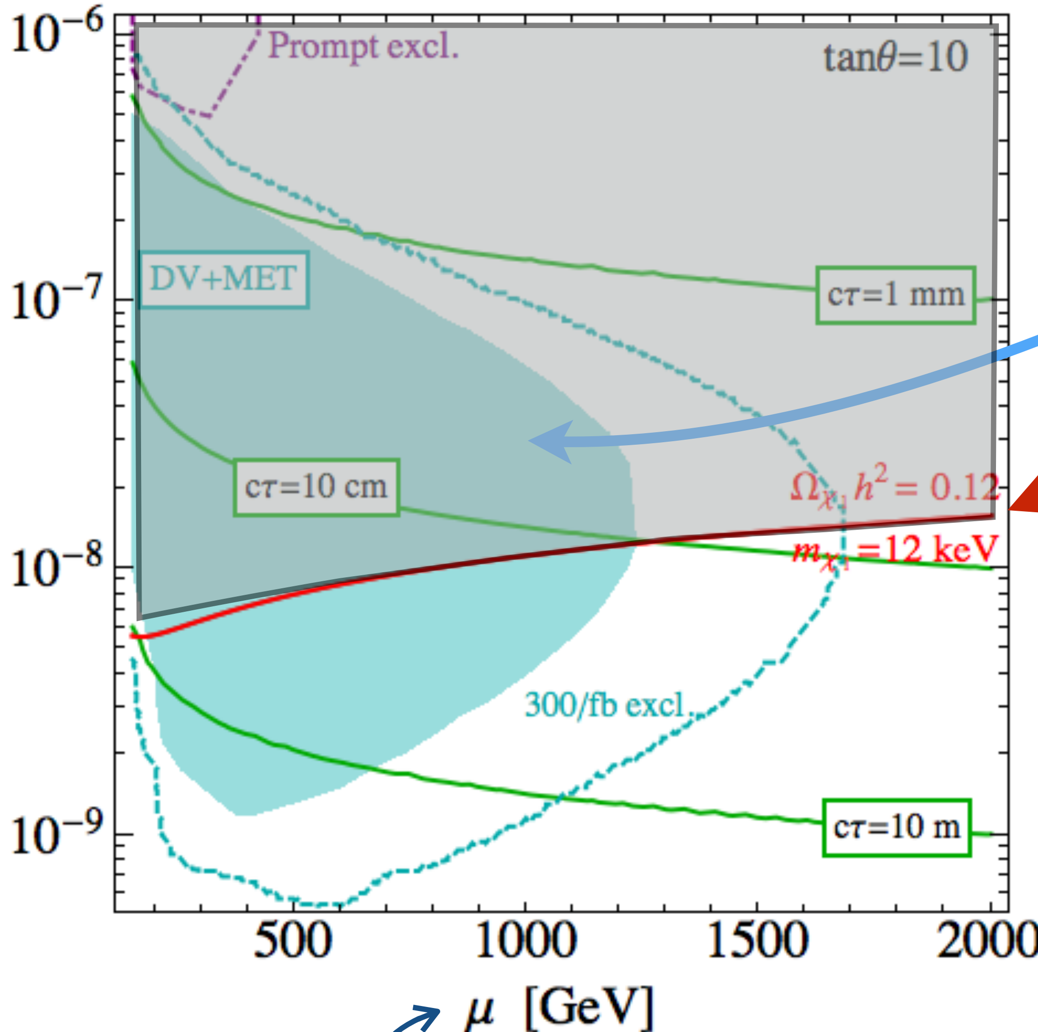
DM mass

Doublet mass

Calibbi, Lopez-Honorez, Lowette, AM

Impact on Singlet Doublet DM

Translate model independent bound on Singlet Doublet DM model



Excluded region

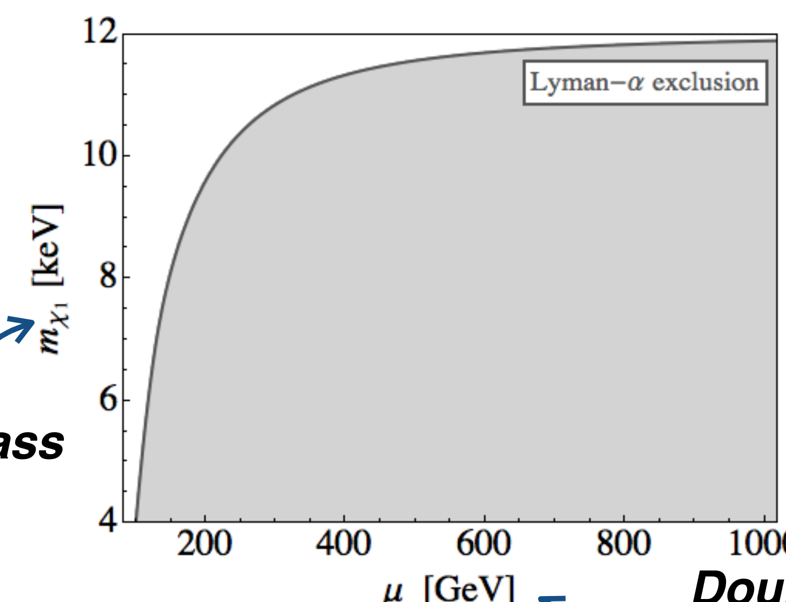
Yukawa coupling

Doublet mass

Correct relic density for 12KeV mass DM

Cosmological constraint!

Lyman-alpha bound for light DM



J. Heeck and D. Teresi '17

DM mass

Doublet mass

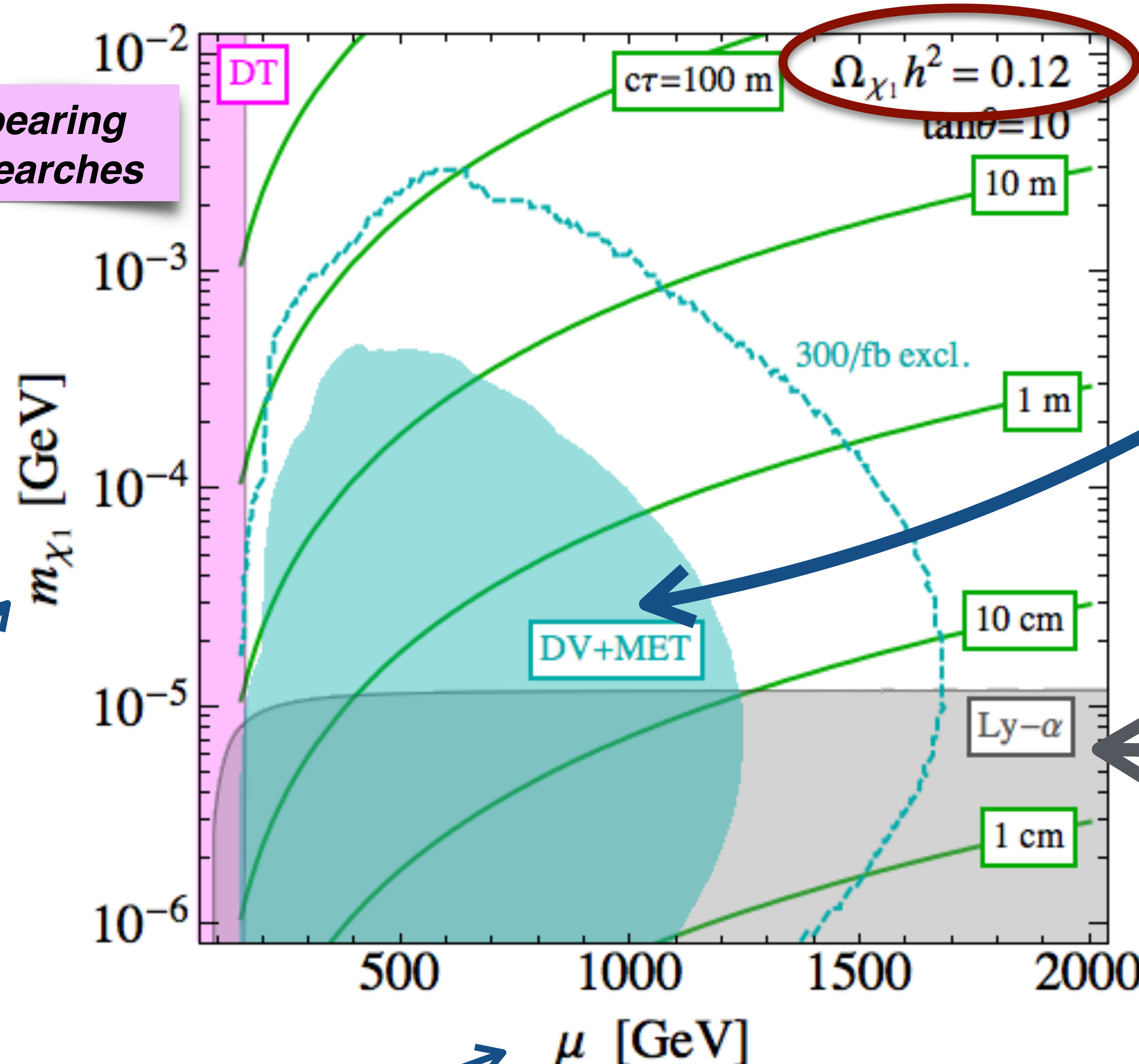
Calibbi, Lopez-Honorez, Lowette, AM

Combining LHC and Cosmo

Viable region on parameter space and pheno probes

Disappearing Track searches

Fixed Dark matter abundance



ATLAS DV+MET

"Warm" Dark Matter constraints (Lyman alpha)

Dark Matter Mass

Doublet mediator mass

LHC can be competitive in large displacement region!

Calibbi, Lopez-Honorez, Lowette, AM

FIMP at the LHC

Feebly Interacting Singlet Doublet Model

★*FIMP is alternative paradigm to set dark matter abundance*

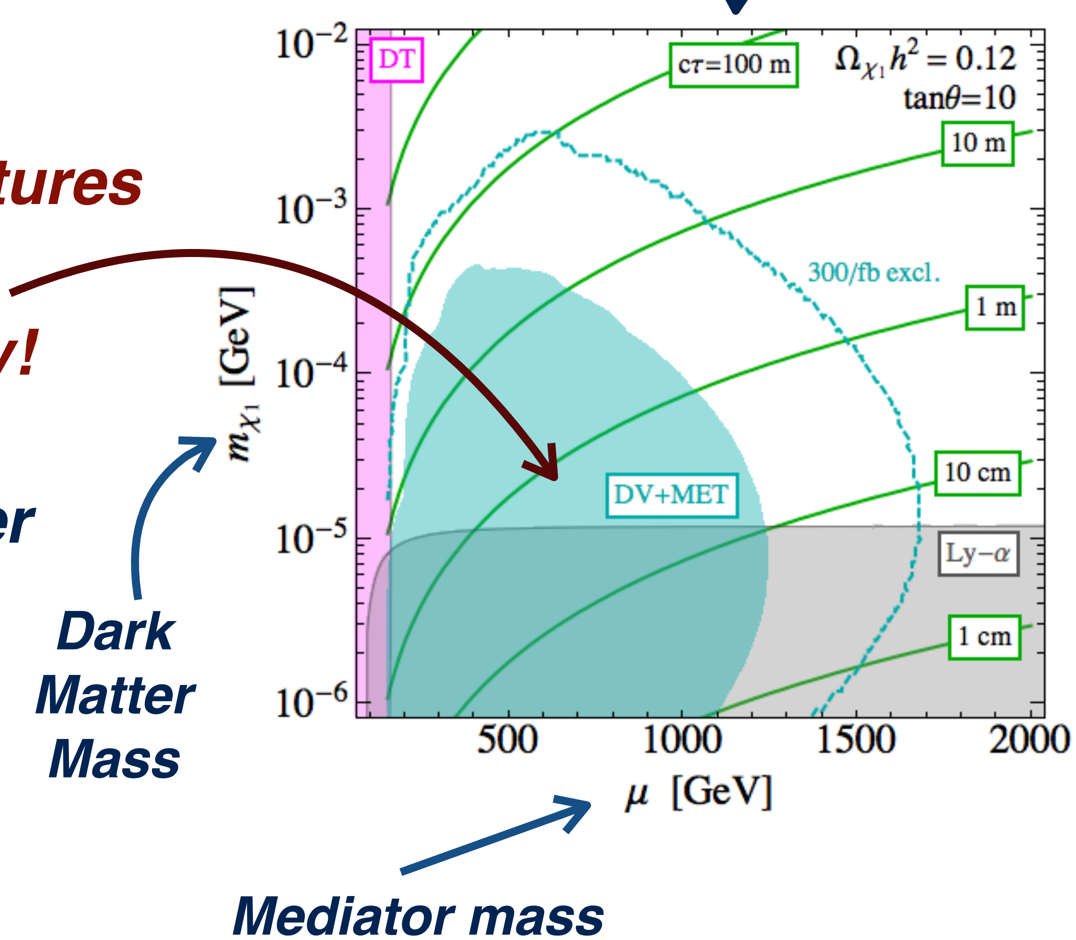
★*Naturally involves feeble coupling*

★*Extremely hard to detect in experiments*

★*LHC can probe these models via exotic signatures*

★*Interplay of displaced vertices and cosmology!*

★*LHC reach can extend to not-warm dark matter*



Conclusions

★*LHC negative results challenge BSM proposals*

★*Dark matter remains as important BSM motivation*

★*Alternative scenarios should be explored!*

★*FIMP links DM to long-lived/displaced signatures @ LHC*

★*Interplay with cosmology and WDM constraints*

★*Singlet-Doublet DM as illustrative minimal prototype*

★*Several directions to explore in FIMP phenomenology*

★*Other FIMP-like models: non-reno operators, co-ann. ...*

★*Reheating temperature dependence, inflation ...*

★*Neutrino physics connection ...*