IAS Program on High Energy Physics 2020

HKUST, January 21st 2020

Freeze-in Dark Matter and displaced vertices at the LHC

Lorenzo Calibbi

南開大學
Nankai University

mainly based on arXiv:1805.04423 with L. Lopez-Honorez, S. Lowette, A. Mariotti
+ work in progress with F. D'Eramo, L. Lopez-Honorez, S. Junius, A. Mariotti

About 27% of the energy of the universe is due to some Dark Matter

A possibility is that DM is made of WIMPs that are thermal relics produced in the early universe through the freeze-out mechanism

Direct detection searches (the latest: XENON1T) and LHC searches are giving increasingly tight constraints on WIMP models

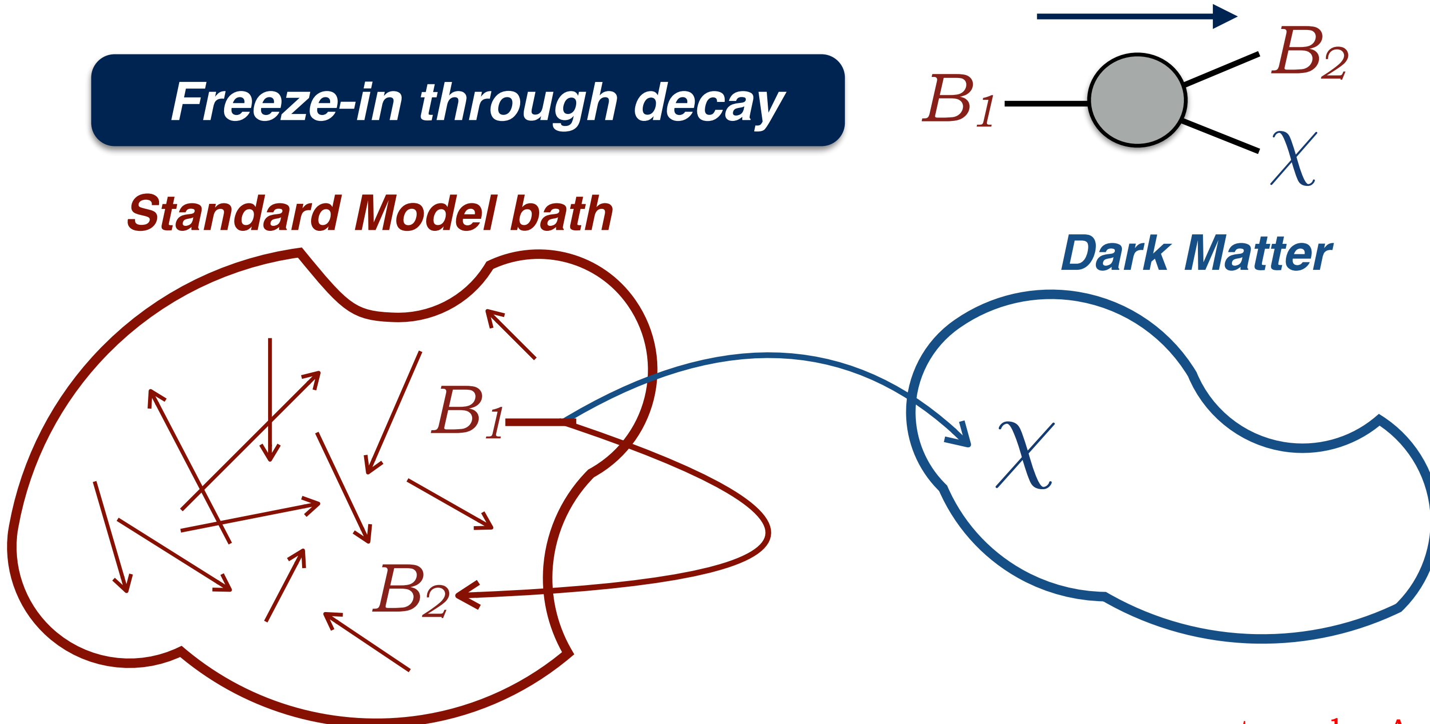
It is time to consider *also* alternative paradigms, *e.g.* axion DM or different DM production mechanisms

The freeze-in mechanism

Production mechanism for non-thermal (because *feebly-coupled*) Dark Matter

Hall, Jedamzik, March-Russell, West '09

DM never in thermal equilibrium with the SM bath, produced via scattering or decays of bath particles (the 'mediators')



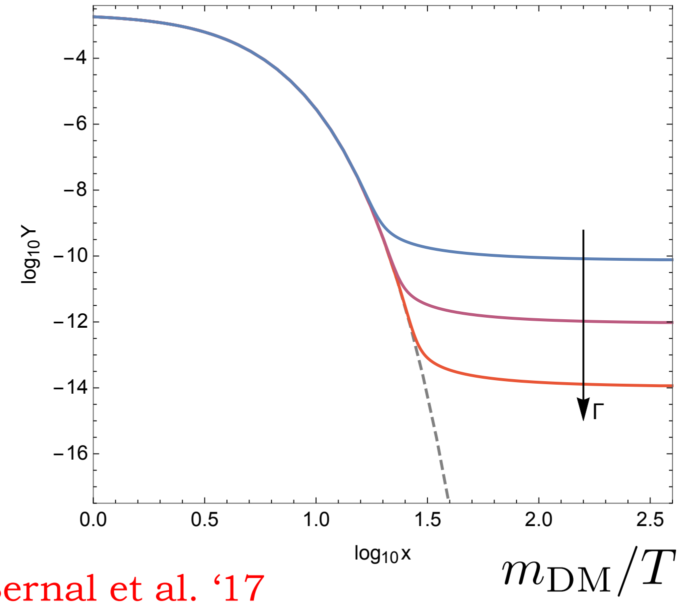
cartoon by A. Mariotti

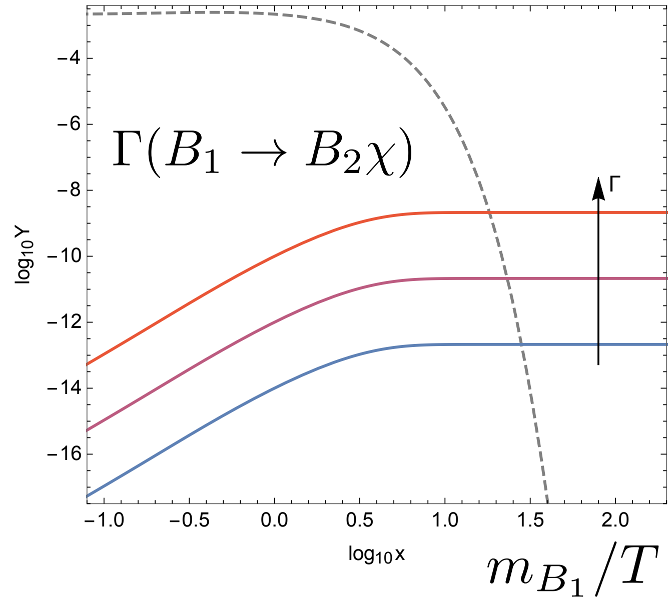
The freeze-in mechanism

Production mechanism for non-thermal (because *feebly-coupled*) Dark Matter

Hall, Jedamzik, March-Russell, West ‘09

DM abundance: Freeze-out versus Freeze-in (through decay)





Review: Bernal et al. ‘17

Resulting relic density from $B_1 \to B_2\,\chi_{\rm DM}$

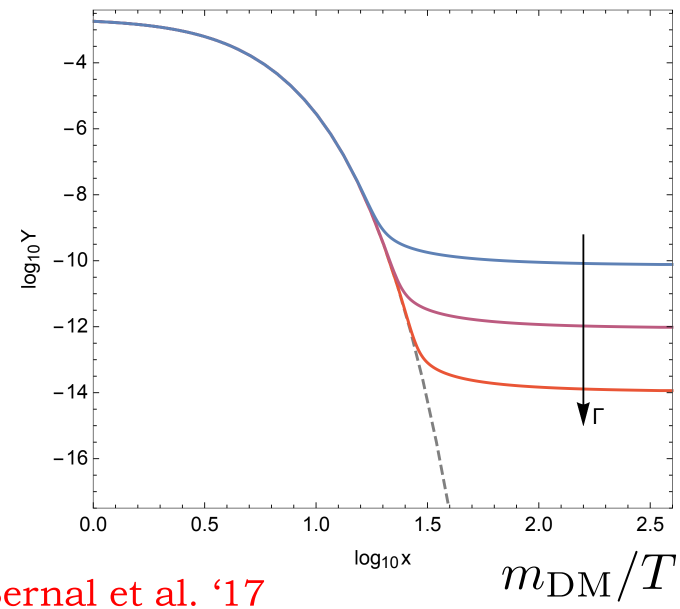
$$\Omega_{\rm DM}h^2 \simeq 0.1 \left(\frac{5\,{\rm cm}}{c\tau_{B_1}}\right)\left(\frac{600\,{\rm GeV}}{m_{B_1}}\right)^2\left(\frac{m_{\rm DM}}{10\,{\rm keV}}\right)$$

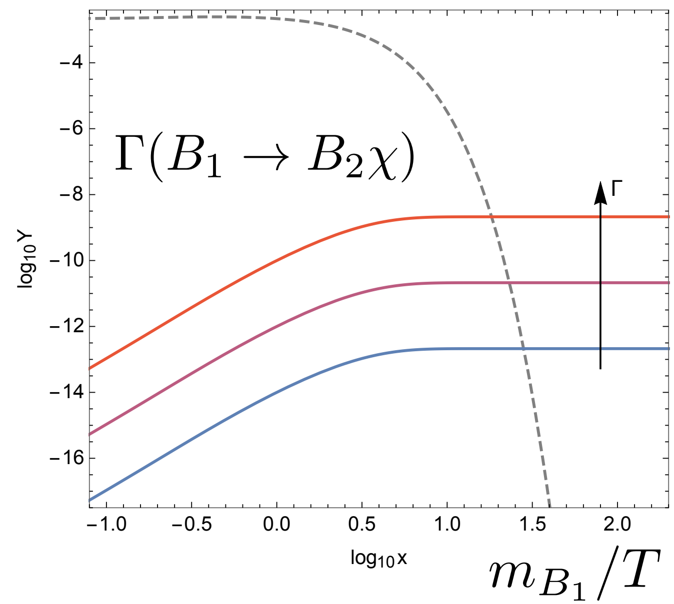
The freeze-in mechanism

Production mechanism for non-thermal (because *feebly-coupled*) Dark Matter

Hall, Jedamzik, March-Russell, West '09

DM abundance: Freeze-out versus Freeze-in (through decay)





Review: Bernal et al. '17

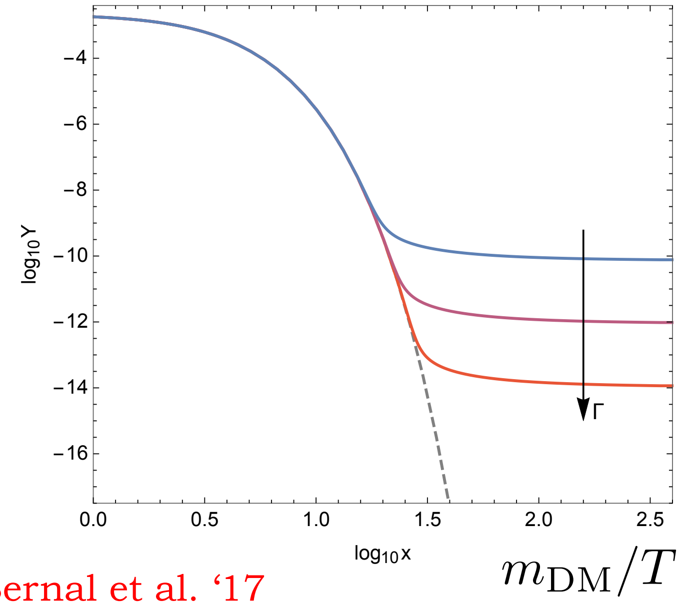
Light DM $\longleftrightarrow$ TeV-scale mediator $\longleftrightarrow$ Displaced decays at the LHC

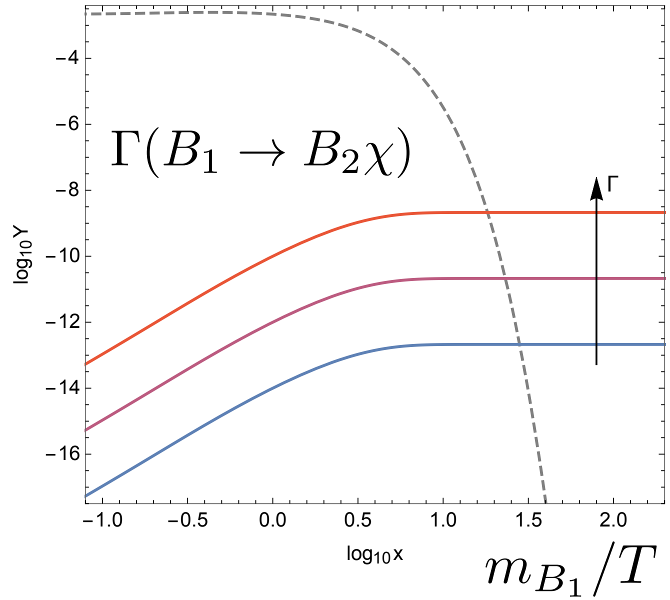
Co, D'Eramo, Hall, Pappadopulo '15

The freeze-in mechanism

Production mechanism for non-thermal (because *feebly-coupled*) Dark Matter
Hall, Jedamzik, March-Russell, West '09

DM abundance: Freeze-out versus Freeze-in (through decay)





Review: Bernal et al. '17

Other recent examples of this interplay
(in models with scalar DM and VL fermions 'mother particles'):
Belanger et al. arXiv:1811.05478

Freeze-in Singlet Double Dark Matter

Singlet-Doublet model: minimal extension of the Standard Model introducing Higgs- and Z-portal interactions between fermion DM and the SM

New (Z_2-odd) fields: a fermion singlet, a vectorlike pair of SU(2) doublets:

Mahbubani Senatore '05

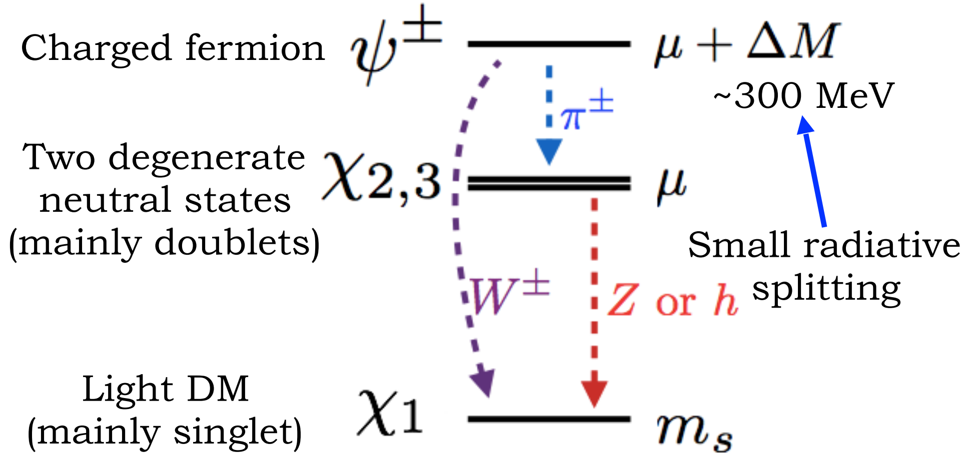
$$(\psi_u)_{2,\frac{1}{2}} = \begin{pmatrix} \psi^+ \\ \psi_u^0 \end{pmatrix}, \qquad (\psi_d)_{2,-\frac{1}{2}} = \begin{pmatrix} \psi_d^0 \\ \psi^- \end{pmatrix}, \qquad (\psi_s)_{1,0}$$

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

Generalisation of the Bino-Higgsino system of the MSSM:

$$\mathcal{M} = \begin{pmatrix} m_s & \frac{y_d v}{\sqrt{2}} & \frac{y_u v}{\sqrt{2}} \\ \frac{y_d v}{\sqrt{2}} & 0 & \mu \\ \frac{y_u v}{\sqrt{2}} & \mu & 0 \end{pmatrix}$$

Freeze-in limit: $|y_{u,d}| \ll 1, \quad |m_s| \ll |\mu|$

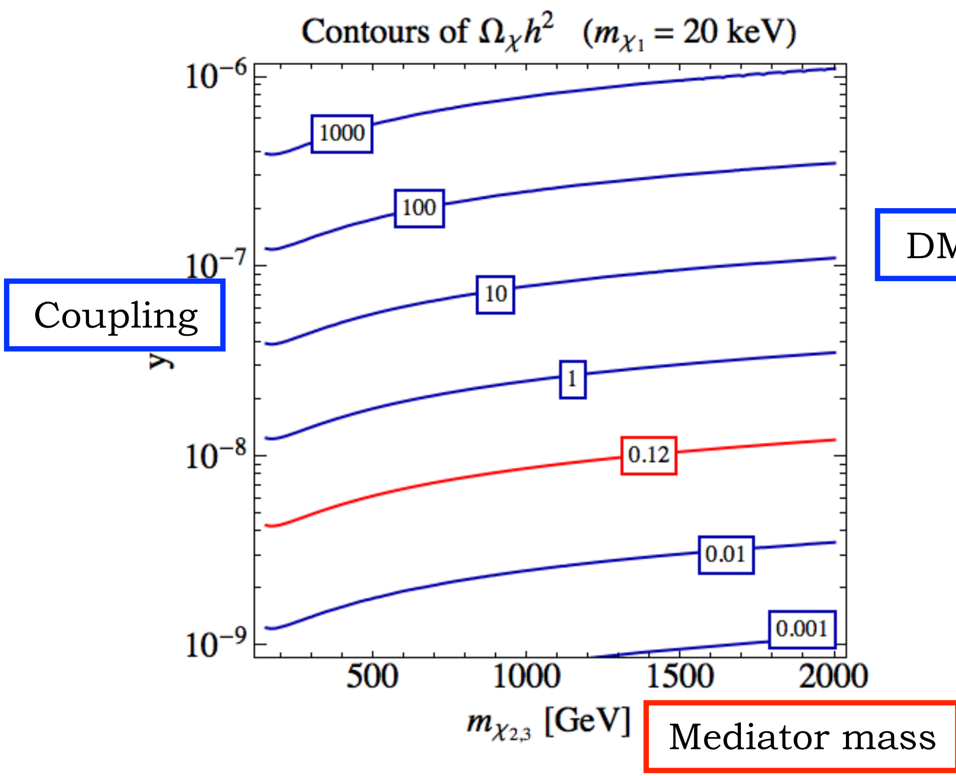


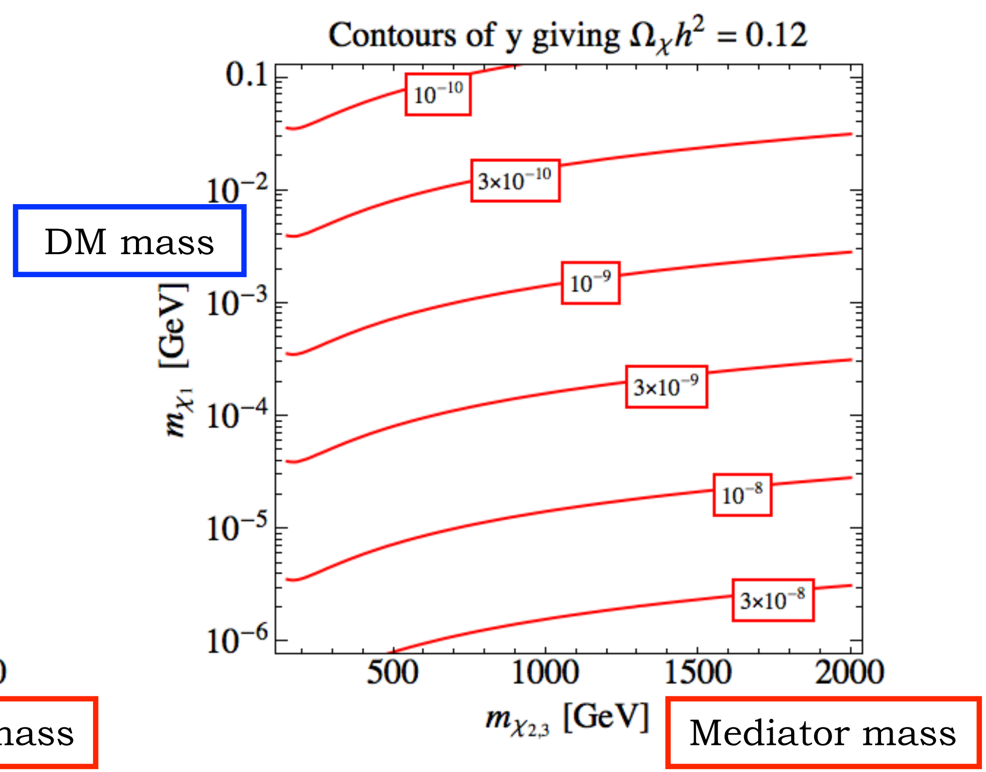
Dark Matter abundance

Dark Matter produced by decays of the doublet states (the freeze-in 'mediators'):

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

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





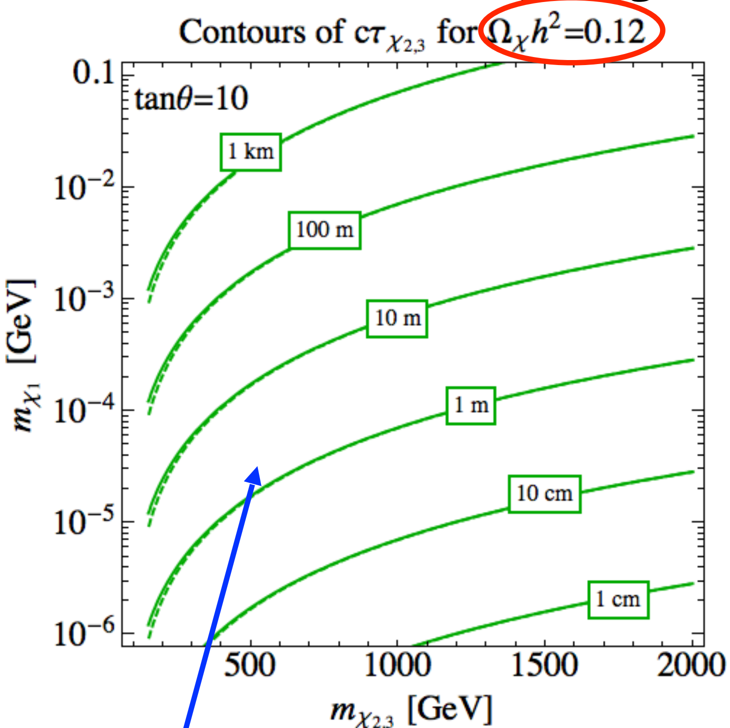
LHC phenomenology

Doublet states (with m~TeV) abundantly produced at the LHC:

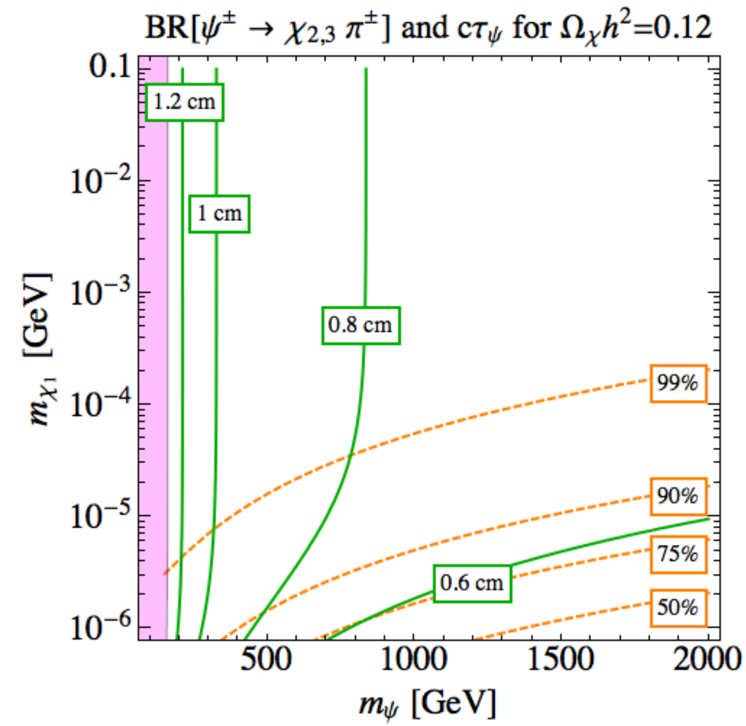
$$pp \to \chi_2\chi_3 + X, \quad pp \to \psi^+\psi^- + X, \quad pp \to \chi_{2,3}\psi^\pm + X.$$

Decays give Higgs/Z + MET: $\psi^\pm \to \pi^\pm + \chi_{2,3}, \quad \chi_{2,3} \to h/Z + \chi_1$

Neutral states decay length:



Charged states decay length:



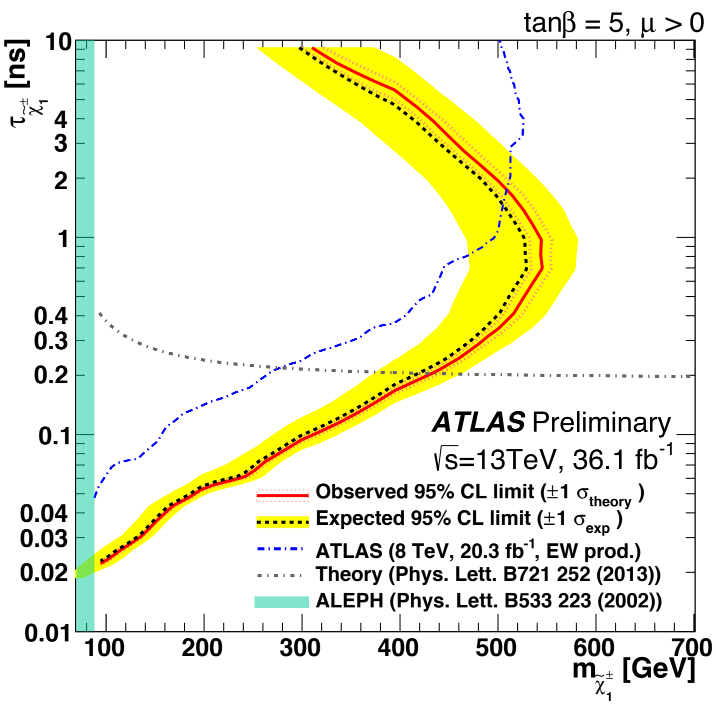
Displaced vertices!

Doublet states (with m~TeV) abundantly produced at the LHC:

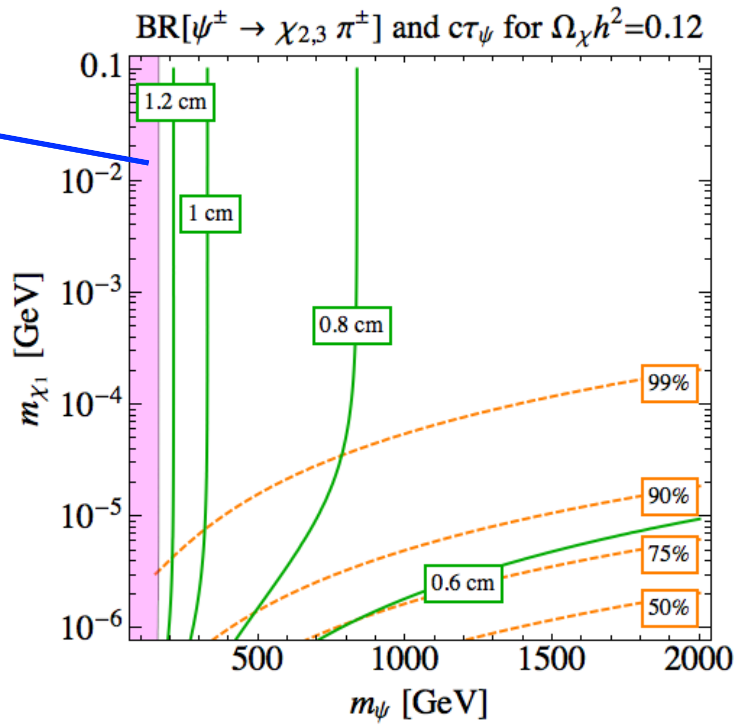
$$pp \to \chi_2\chi_3 + X, \quad pp \to \psi^+\psi^- + X, \quad pp \to \chi_{2,3}\psi^\pm + X.$$

Decays give Higgs/Z + MET: $\psi^\pm \to \pi^\pm + \chi_{2,3}, \quad \chi_{2,3} \to h/Z + \chi_1$

Disappearing tracks
ATLAS 1712.02118



Charged states decay length:

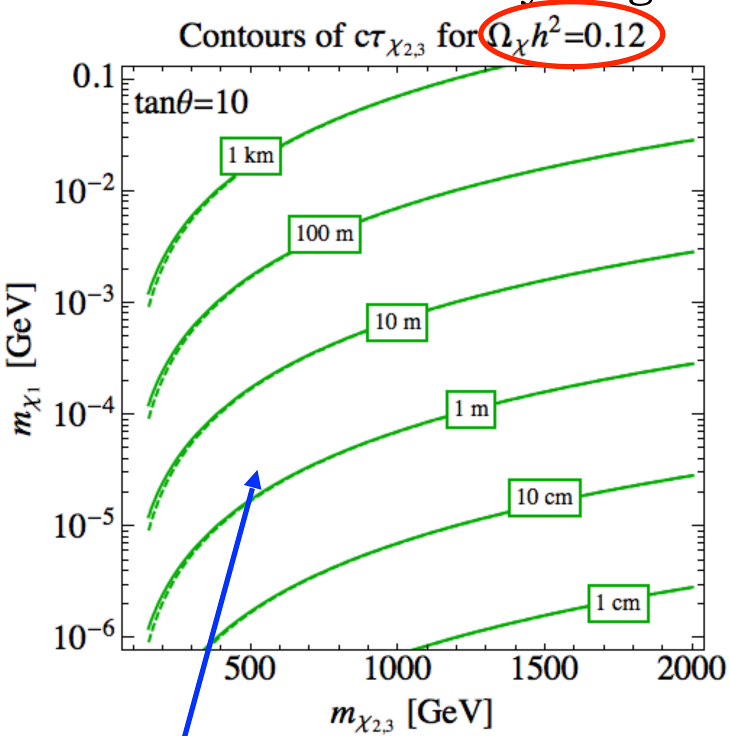


Doublet states (with m~TeV) abundantly produced at the LHC:

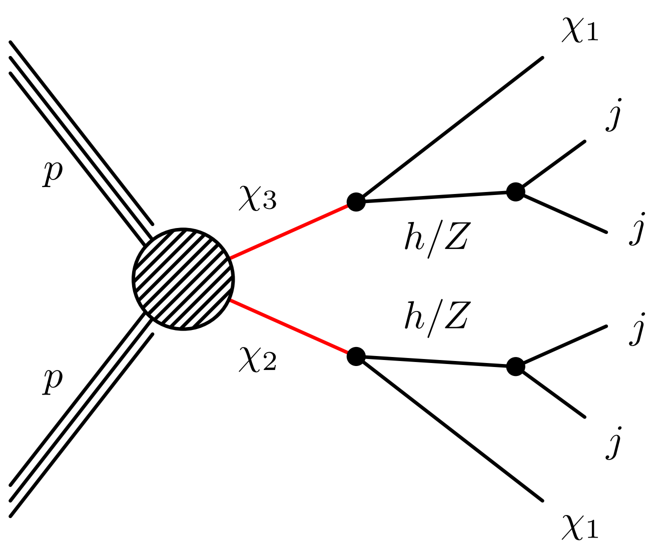
$$pp \to \chi_2\chi_3 + X, \quad pp \to \psi^+\psi^- + X, \quad pp \to \chi_{2,3}\psi^\pm + X.$$

Decays give Higgs/Z + MET: $\psi^\pm \to \pi^\pm + \chi_{2,3}, \quad \chi_{2,3} \to h/Z + \chi_1$

Neutral states decay length:



Displaced vertices!



LHC signature: displaced vertices with jets and MET (~0 SM background)

Recasting a DV+MET search by ATLAS

EUROPEAN ORGANISATION FOR NUCLEAR RESEARCH (CERN)

Submitted to: Phys. Rev. D.

CERN-EP-2017-202
October 16, 2017

Search for long-lived, massive particles in events with displaced vertices and missing transverse momentum in $\sqrt{s}$ = 13 TeV pp collisions with the ATLAS detector

The ATLAS Collaboration

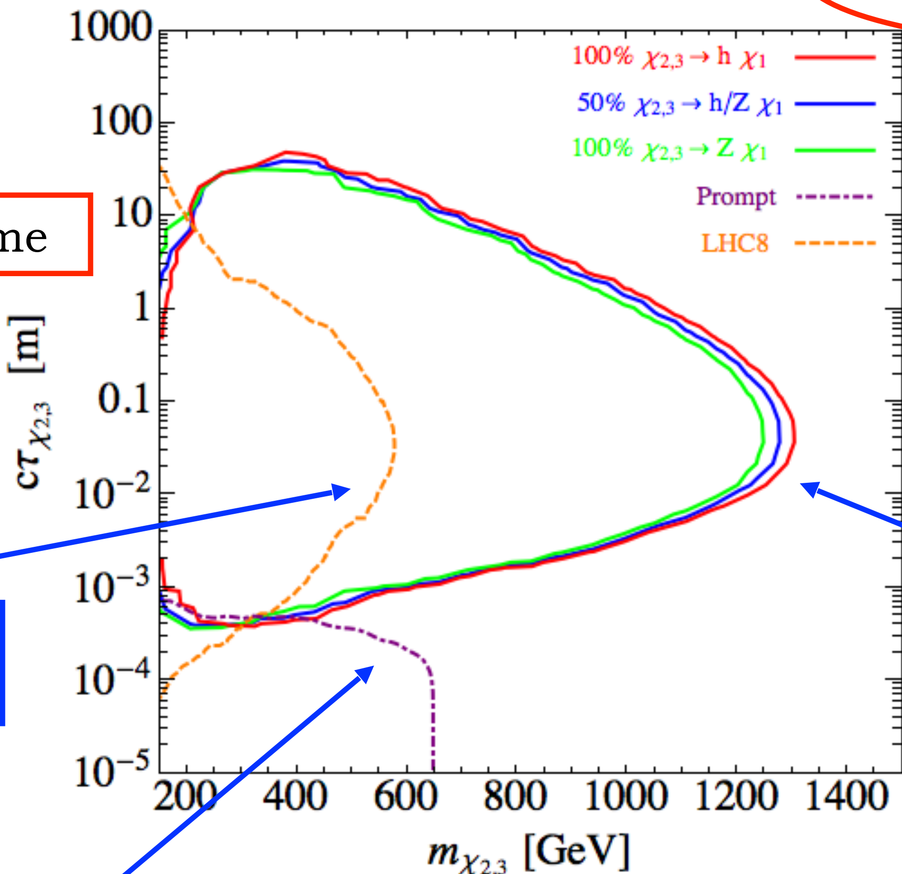
A search for long-lived, massive particles predicted by many theories beyond the Standard Model is presented. The search targets final states with large missing transverse momentum and at least one high-mass displaced vertex with five or more tracks, and uses 32.8 fb^{-1} of $\sqrt{s}$ = 13 TeV pp collision data collected by the ATLAS detector at the LHC. The observed yield is consistent with the expected background. The results are used to extract 95% CL exclusion limits on the production of long-lived gluinos with masses up to 2.37 TeV and lifetimes of $\mathcal{O}(10^{-2})$–$\mathcal{O}(10)$ ns in a simplified model inspired by Split Supersymmetry.

arXiv:1710.04901

Recasting a DV+MET search by ATLAS

Doublet mass excluded up to 1.2 TeV!

Doublet life-time



8 TeV searches
Liu Tweedie '15

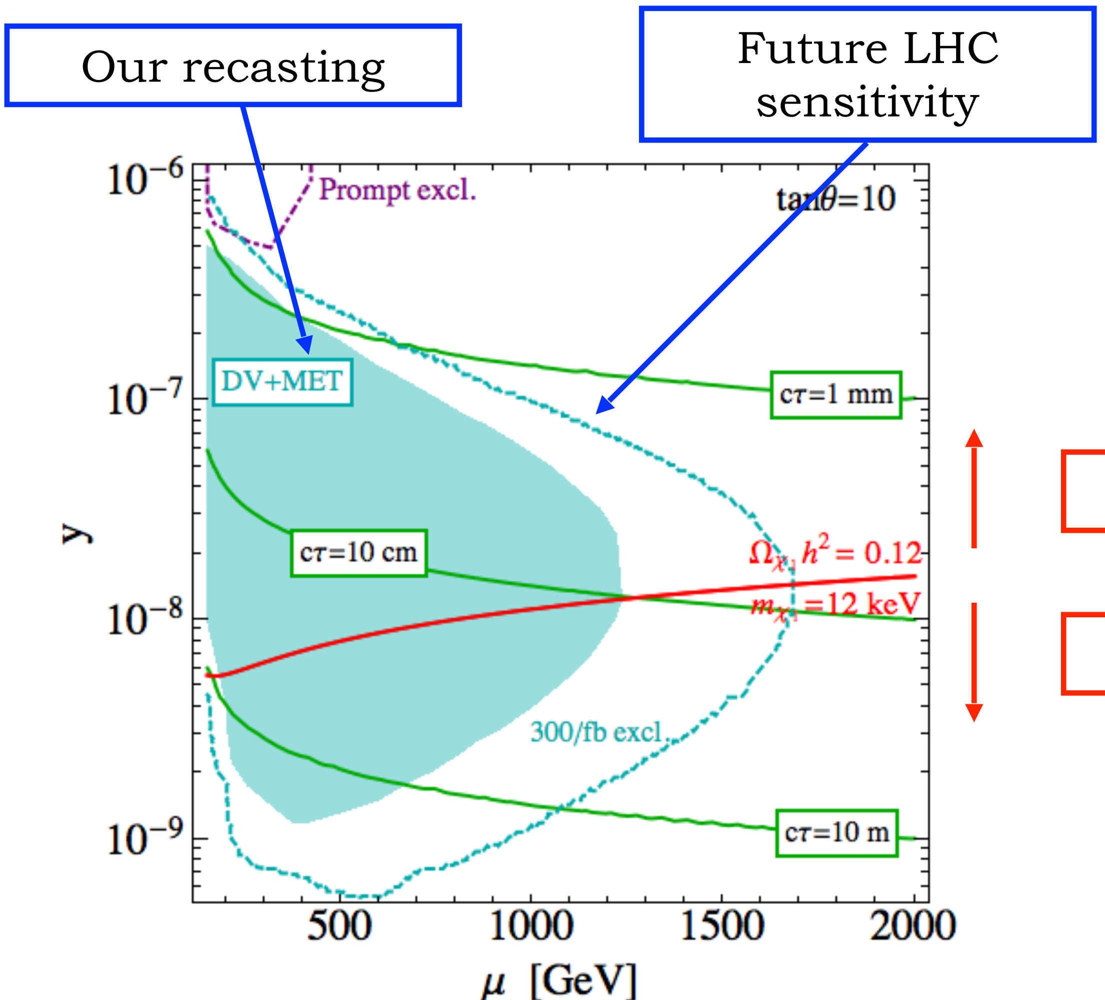
Our recasting
Madgraph/Pythia/Delphes

Prompt searches
CMS, 1801.03957

Doublet mass

Rather general result: it also applies e.g. to Higgsino decaying to gravitino

Impact on Singlet-Doublet Dark Matter

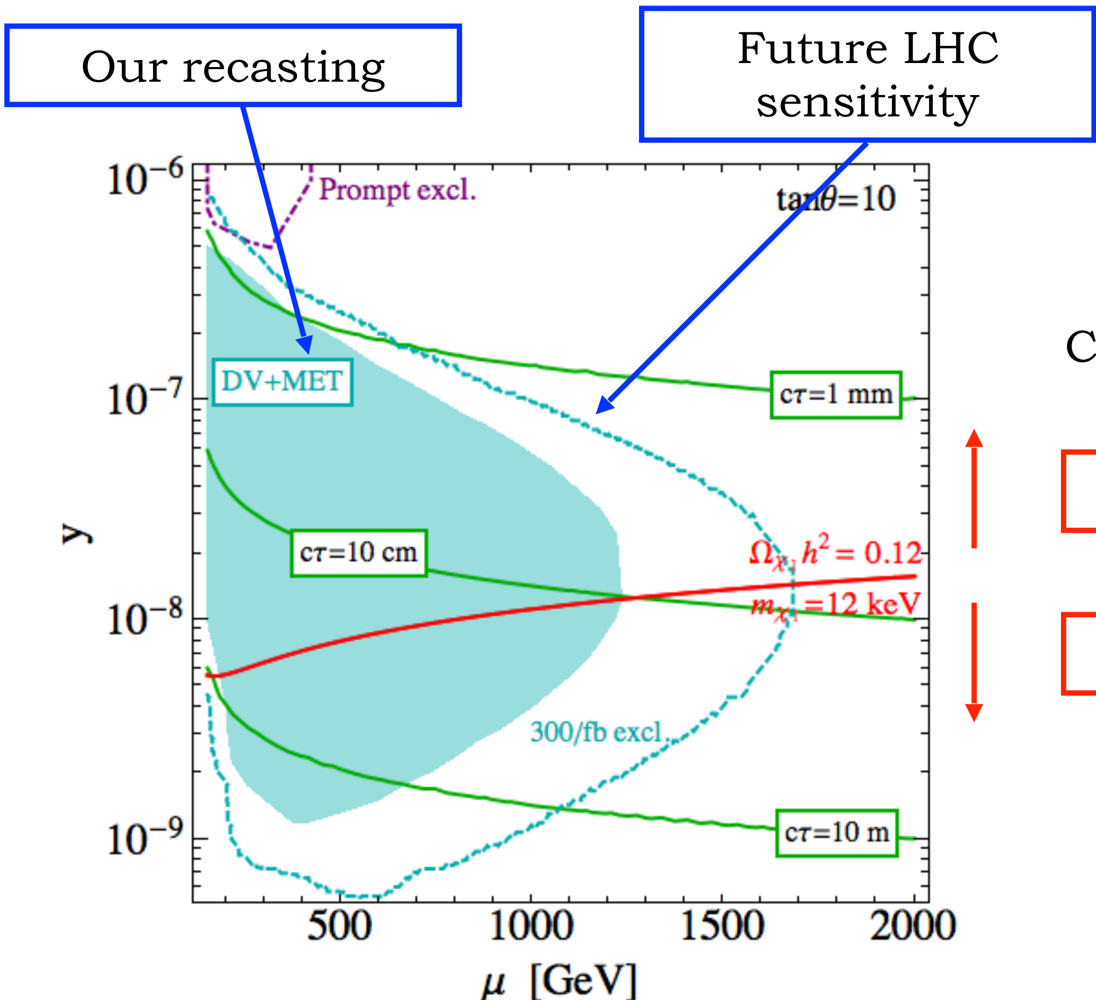


For a fixed DM mass:

DM overabundance

DM underabundance

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



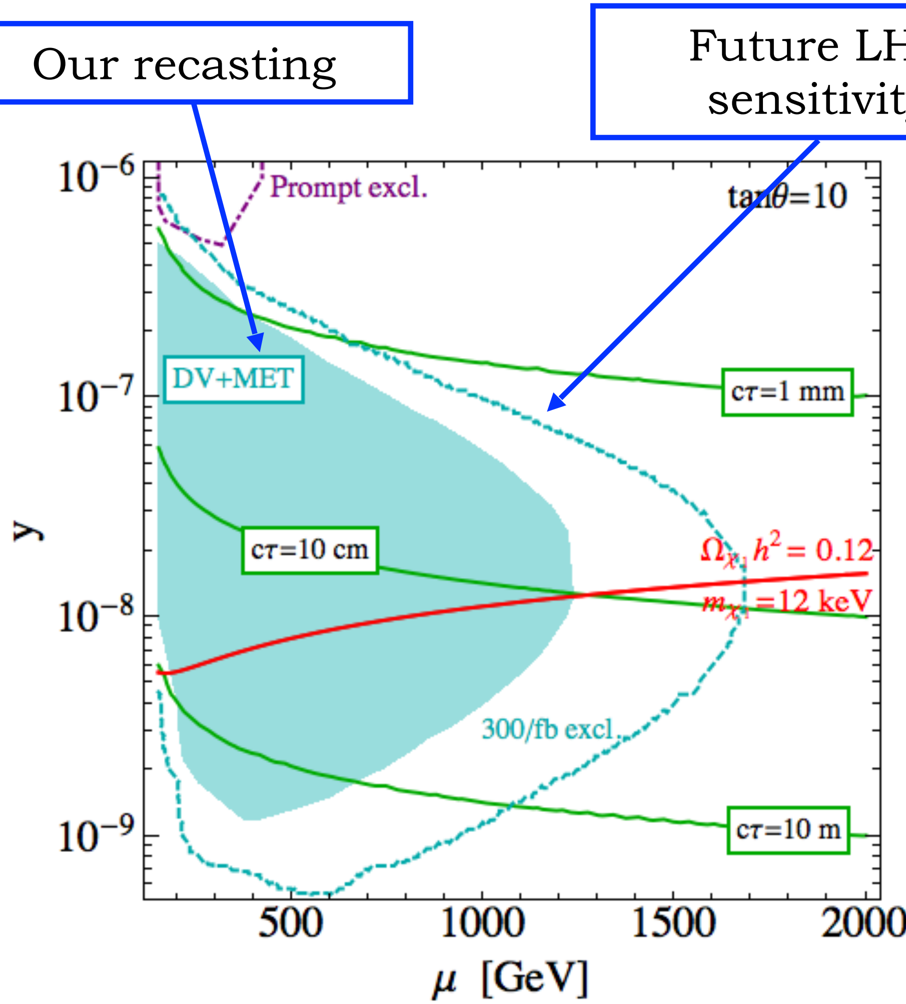
Correct relic density achieved by:

Lowering m_{DM}

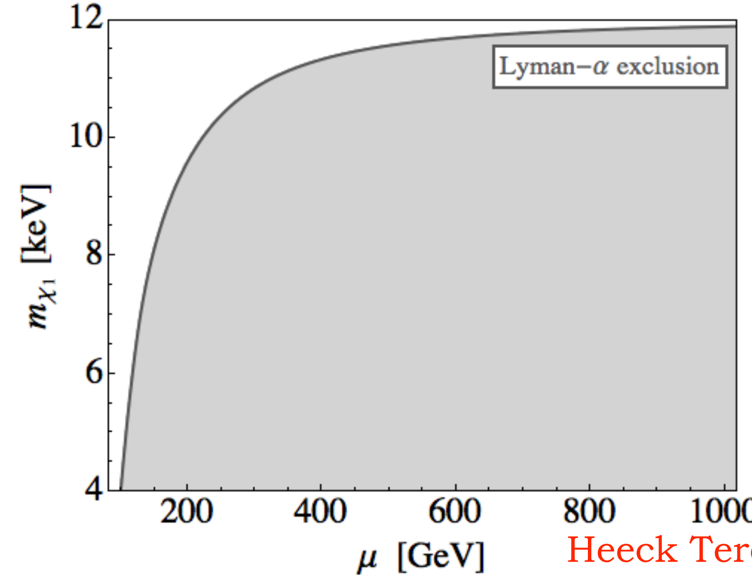
Raising m_{DM}

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

Impact on Singlet-Doublet Dark Matter



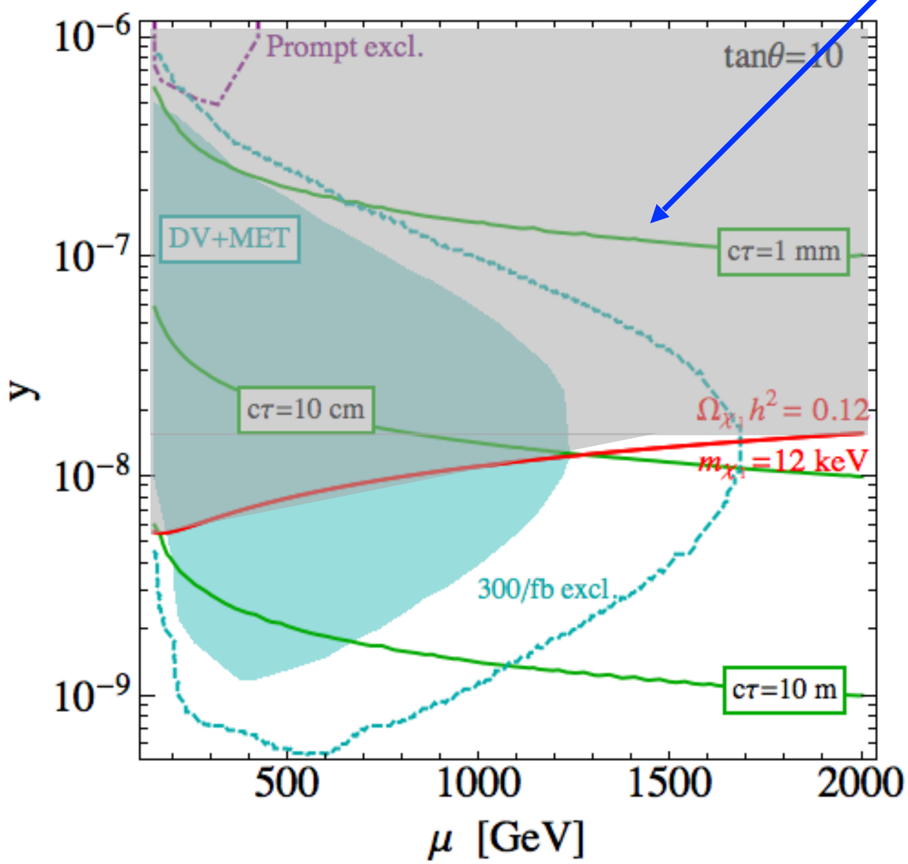
Bound from small structure formation
(based on Lyman-alpha data):



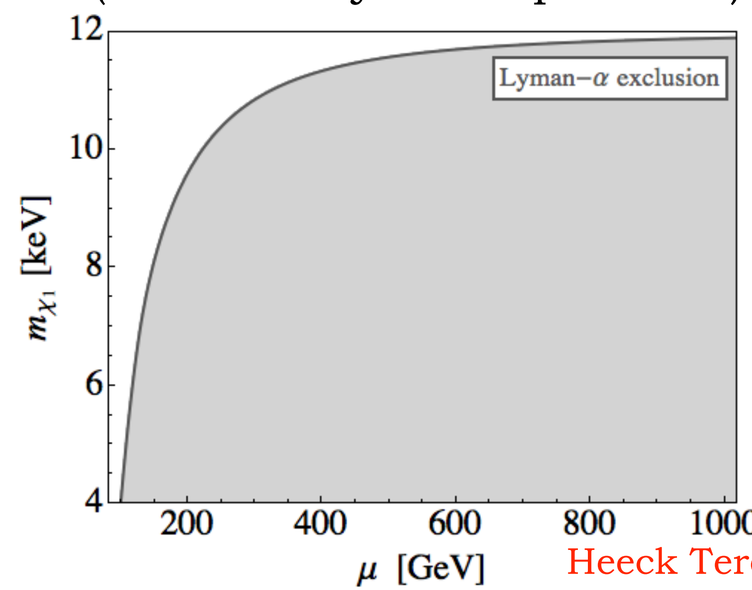
Heeck Teresi '17

Impact on Singlet-Doublet Dark Matter

Combined Lyman-alpha and relic density bound (assuming standard cosmology)



Bound from small structure formation (based on Lyman-alpha data):



Heeck Teresi '17

Combined LHC and cosmology constraints

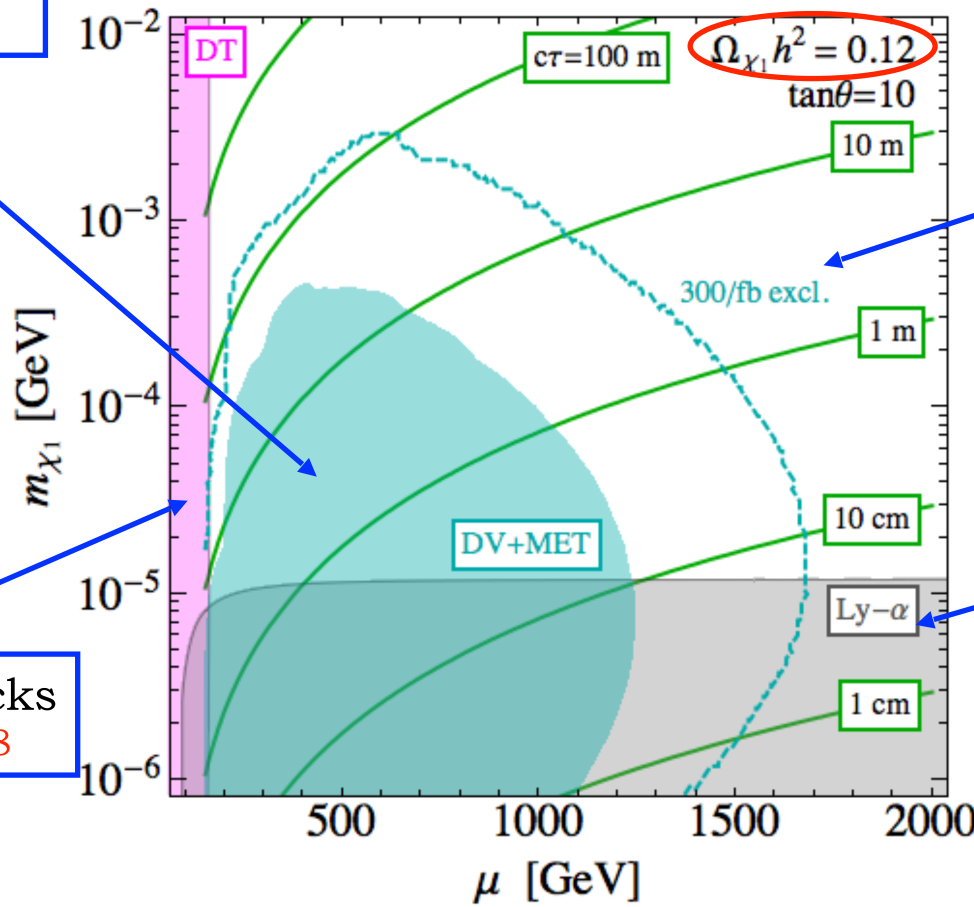
Our recasting

Future LHC sensitivity

DM mass

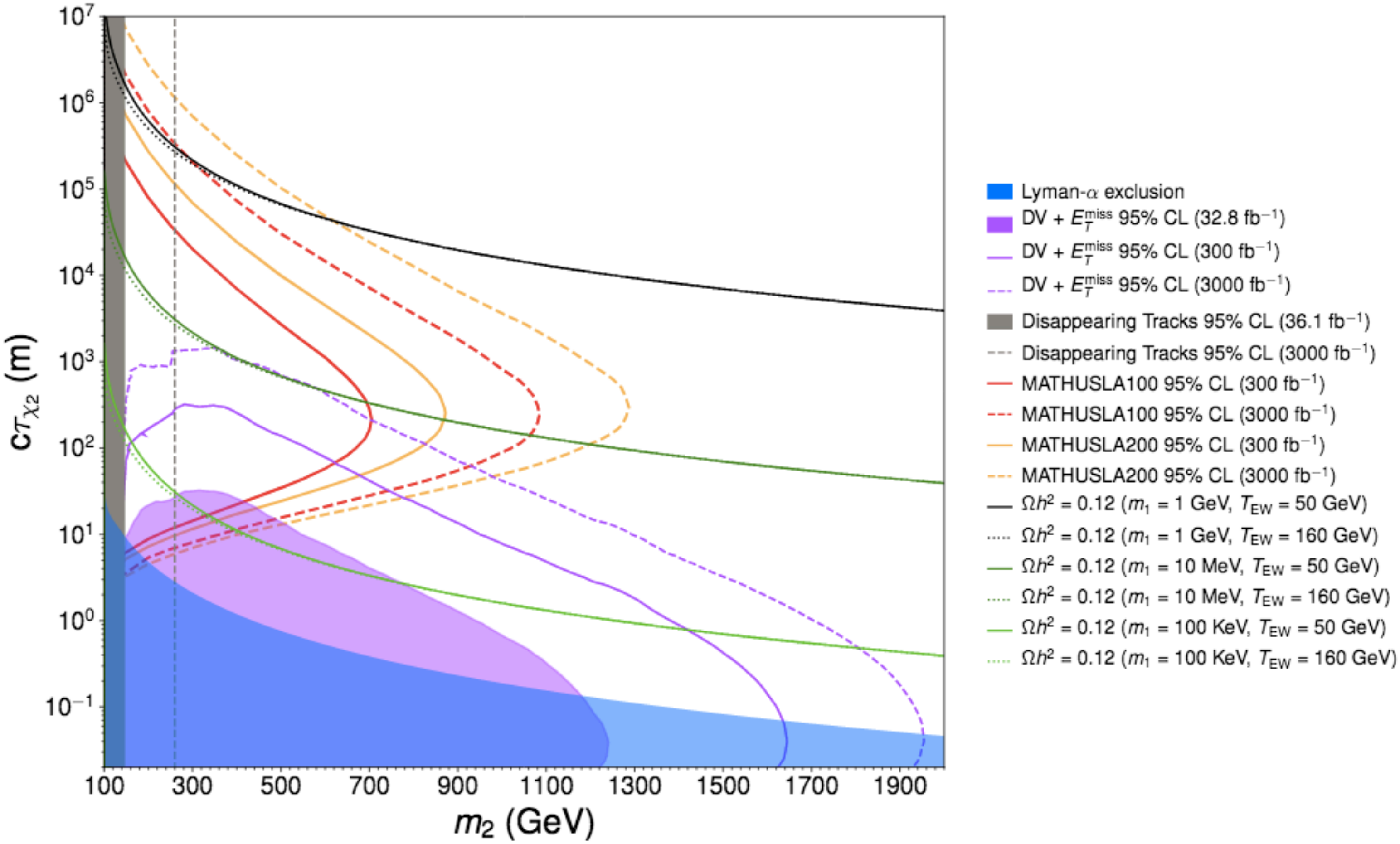
Lyman-alpha bound
Heeck Teresi ‘17

Disappearing tracks
ATLAS 1712.02118



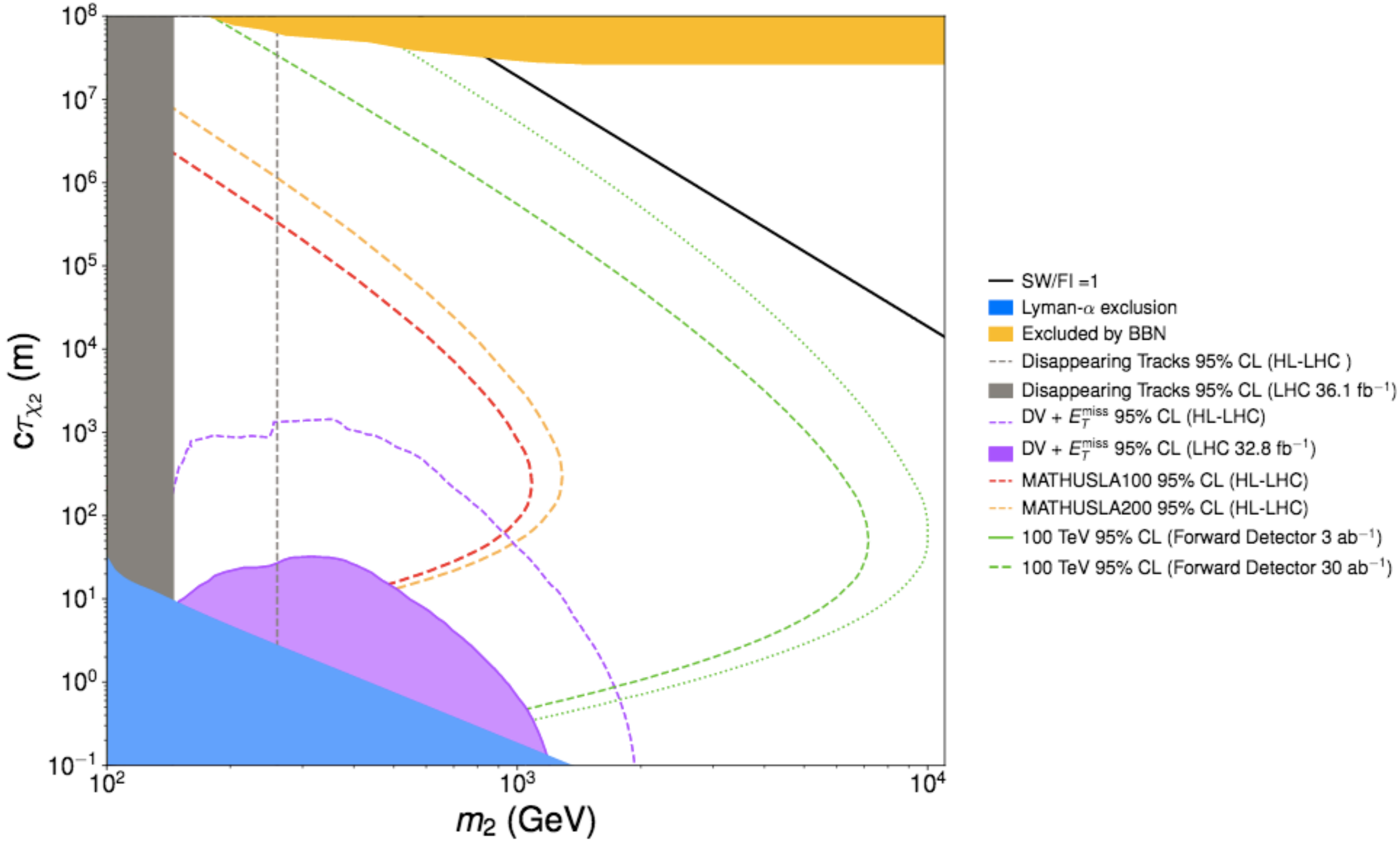
Doublet mass

Prospects at future experiments



No Tunney Zaldivar '19

Prospects at future experiments



No Tunney Zaldivar '19

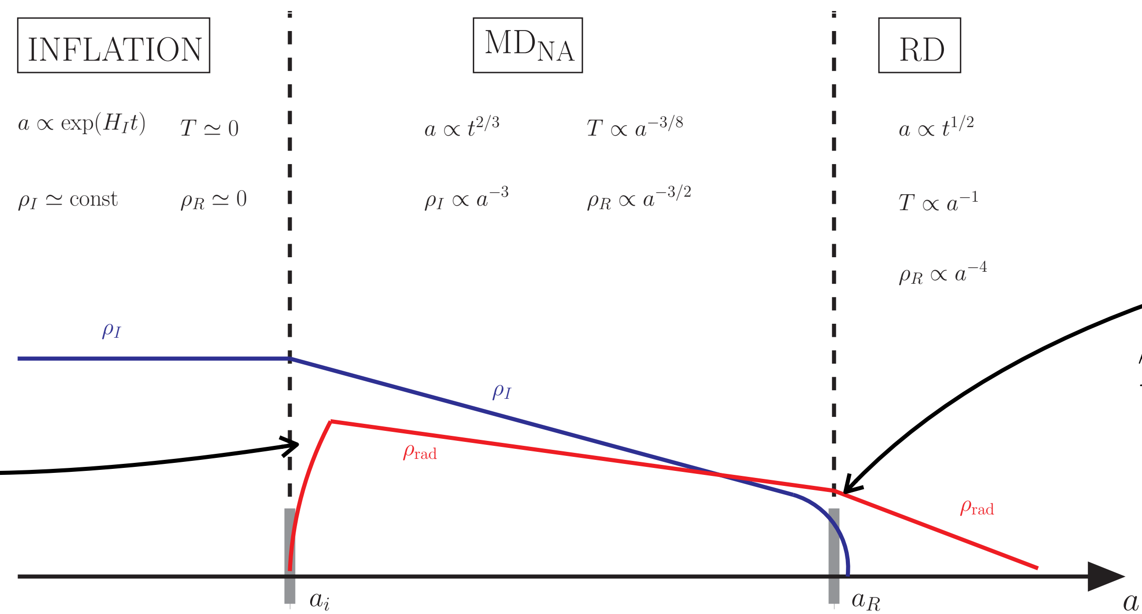
What if DM freeze-in during the inflaton decay (matter-dominated) epoch

Maximal radiation temperature

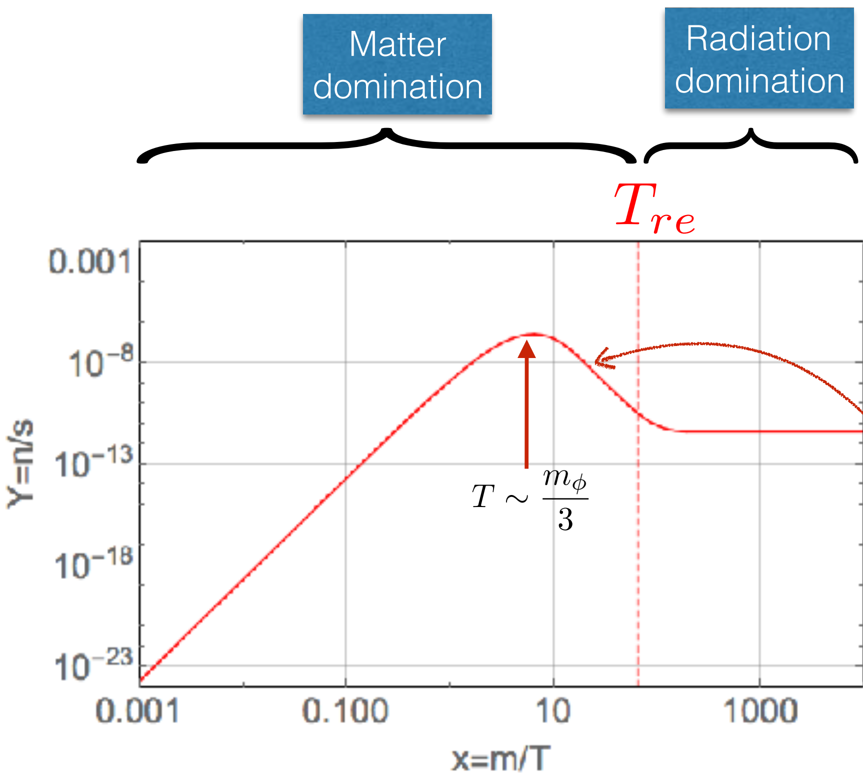
$$T_{\max} \sim \sqrt{\rho_i^{1/4} T_{re}}$$

Reheating temperature

$$T_{re} \sim \sqrt{M_{Pl}\Gamma_M}$$



Co, D'Eramo, Hall, Pappadopulo '15



$$T_{re} \lesssim \frac{m_\phi}{3}$$

★ ***Abundance grows up to*** $T \sim \frac{m_\phi}{3}$

★ ***Then diluted by inflaton up to*** T_{re}

★ ***Dilution scales approximately as***

$$Y_\chi \sim T^5 \quad \textbf{for} \quad \frac{m_\phi}{3} > T > T_{re}$$

Low reheating temperature reduces DM abundance

slide by A. Mariotti

Classification of all possible operators mediating the decay

$$B \to \mathrm{SM} + X$$

For each choice of the SM particle, we know the quantum numbers of B (X must be a gauge singlet)

$A_{\rm SM}$	Spin X	Spin B	Interaction	Label
$\psi_{\rm SM}$	0	1/2	$\overline{\psi_{\rm SM}}\Psi_B\,\phi$	$\mathcal{F}_{\psi_{\rm SM}\phi}$
	1/2	0	$\overline{\psi_{\rm SM}}\chi\,\Phi_B$	$\mathcal{S}_{\psi_{\rm SM}\chi}$
		1	$\overline{\psi_{\rm SM}}\Gamma^\mu\chi\,V_B^\mu$	$\mathcal{V}_{\psi_{\rm SM}\chi}$
$F_{\mu\nu}$	0	1	$V_B^{\mu\nu}F_{\mu\nu}\phi$	$\mathcal{V}_{F\phi}$
	1/2	1/2	$\overline{\psi_{\rm SM}}\sigma_{\mu\nu}\chi\,F^{\mu\nu}$	$\mathcal{F}_{F\chi}$
H	0	0	$\Phi_B^\dagger H\,\phi$	$\mathcal{S}_{H\phi}$
		1	$V_B^\mu(c_\phi H\partial_\mu\phi + c_H\phi D_\mu H)$	$\mathcal{V}_{H\phi}$
	1/2	1/2	$\overline{\Psi_B}\chi\,H$	$\mathcal{F}_{H\chi}$

We consider:
spin 0 and 1/2 DM
spin 0, 1/2 and 1 for B

Example: Fermion dark matter with a scalar partner coupled to leptons $\bar{l}\,\chi\,\Phi_B$

slide by F. D'Eramo

We fix Dark Matter mass and impose correct DM relic abundance

→ ***Reheating temperature is predicted***

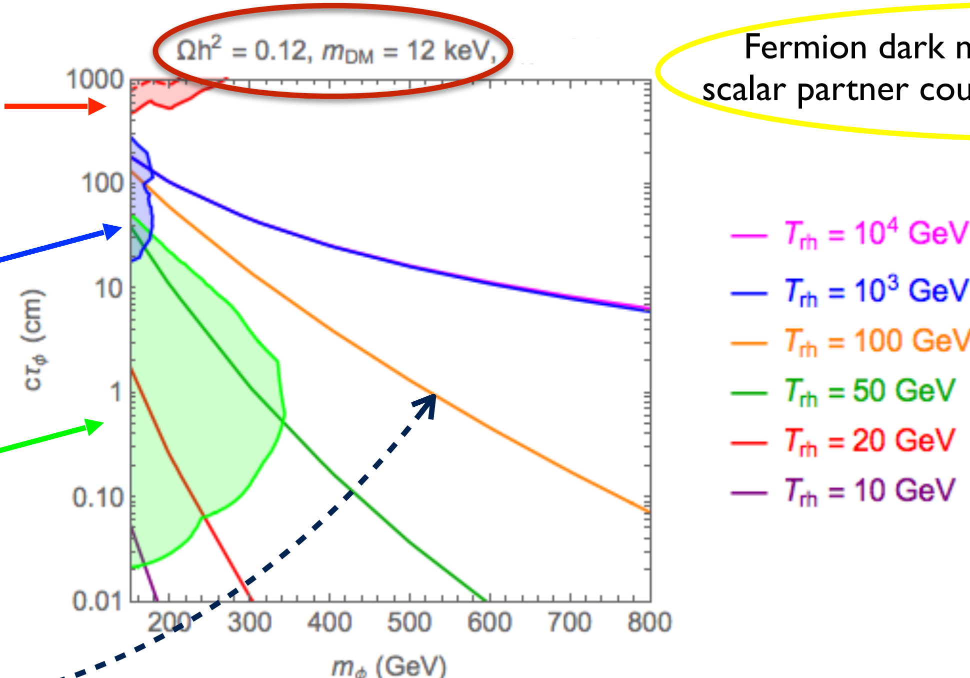
★ ***Fix Dark Matter mass at the lowest allowed value***

Fermion dark matter with a scalar partner coupled to leptons $\bar{l}\,\chi\,\Phi_B$

Charged tracks →

Disappearing tracks →

Displaced leptons →



★ ***Contours of Maximal T reheating compatible with DM hypothesis***

!!! Indirect LHC probe of T reheating !!!

slide by A. Mariotti

Summary

Freeze-in Dark Matter is naturally feebly coupled.
This implies long-lived mediators so that LHC can test FI scenarios
via exotic (and virtually background-free) signatures

LHC searches for displaced vertices set non-trivial constrains
on the FI regime of our model. Nice interplay with cosmology/astrophysics!

Long-lived particles are a general consequence of the freeze-in mechanism
Similar results are found within other FI models (with LHC/future exps)

Searches for long-lived particles (decaying into missing energy) can give us
information on the thermal history of the universe

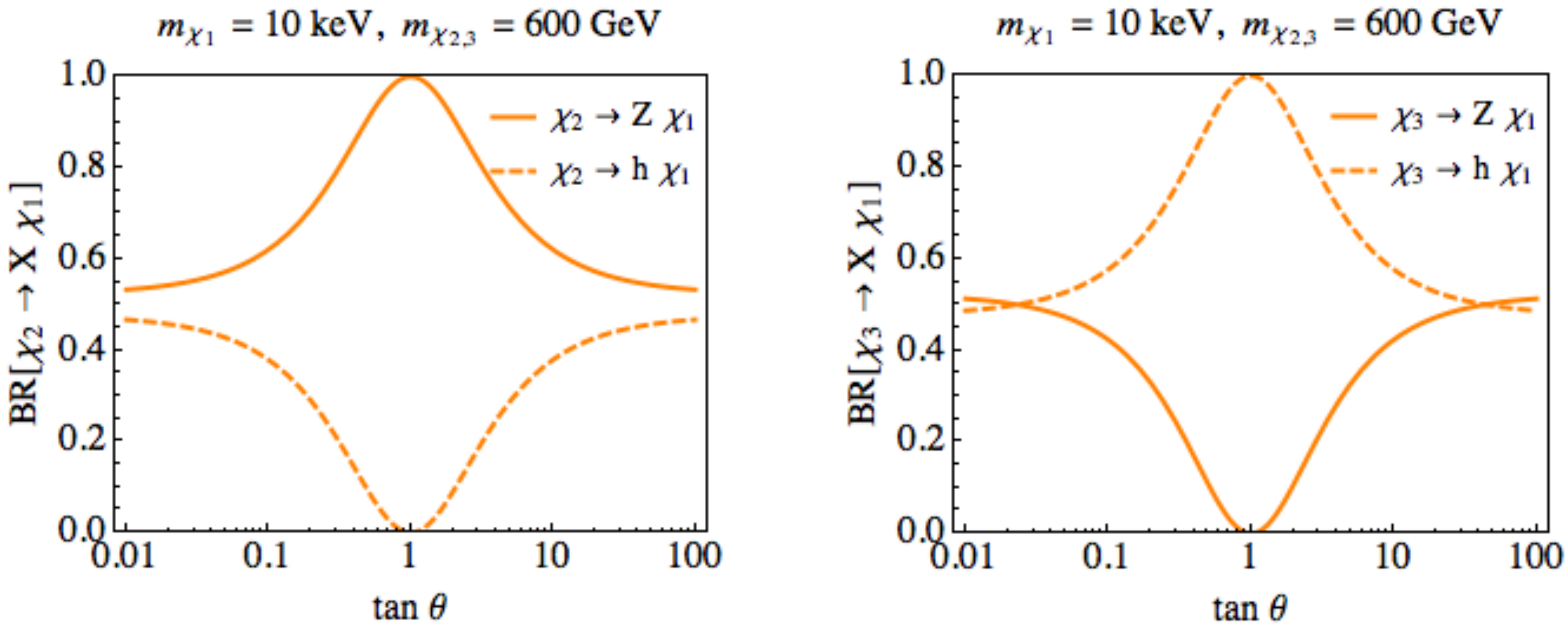

鼠
新年快乐
Happy Chinese new year

Doublet states (with m~TeV) abundantly produced at the LHC:

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

Decays give Higgs/Z + MET: $\psi^\pm \to \pi^\pm + \chi_{2,3}, \quad \chi_{2,3} \to h/Z + \chi_1$

Neutral states BRs:



Recasting a DV+MET search by ATLAS

Our recasting
Madgraph/Pythia/Delphes