Next Frontiers in the Search for Dark Matter

GGI, September 2nd 2019

Freeze-in Dark Matter and displaced vertices at the LHC

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Nankai University

mainly based on arXiv:1805.04423 with L. Lopez-Honorez, S. Lowette, A. Mariotti


Tianjin's Location in China Map
Russia
Mongolia
Beijing
Tianjin
Japan
The Pacific Ocean
India
Nepal
Myanmar
Vietnam
Laos
Thailand
Philippines
N
500 km
Tianjin Municipality

Motivation

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

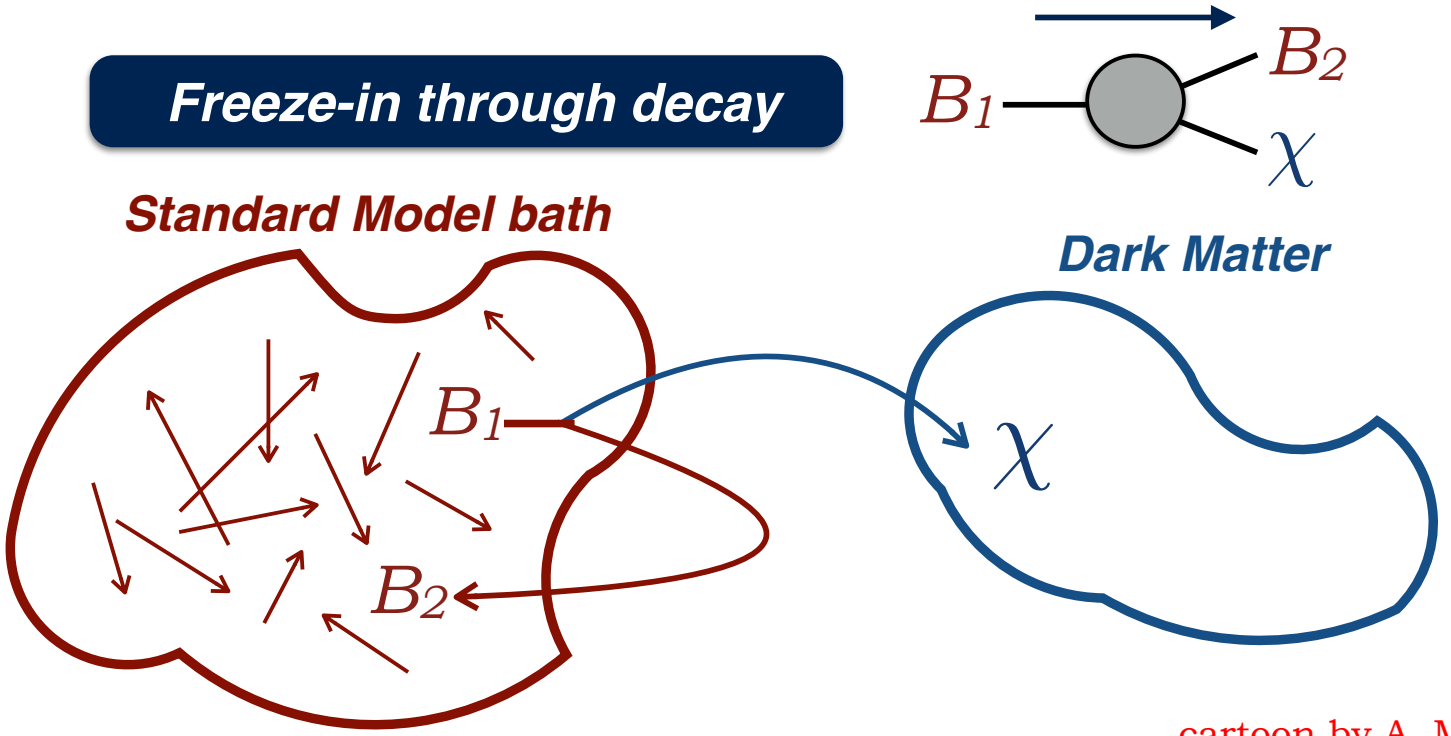
It is time to consider *also* alternative paradigms,
e.g. axion DM or different DM production mechanisms

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

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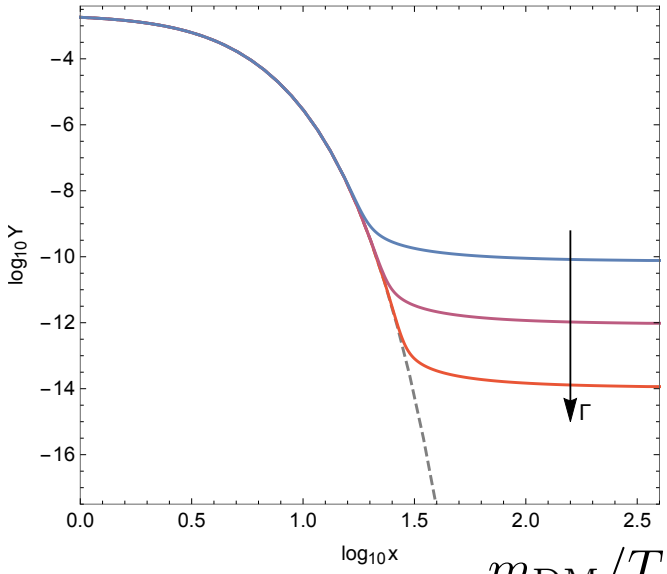
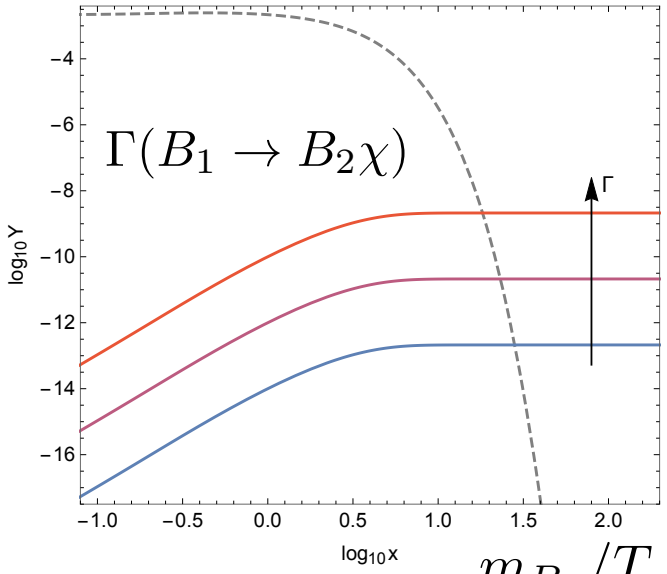
DM abundance: Freeze-out versus Freeze-in (through decay)



$m_{\rm DM}/T$



m_{B_1}/T

Review: Bernal et al. '17

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

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

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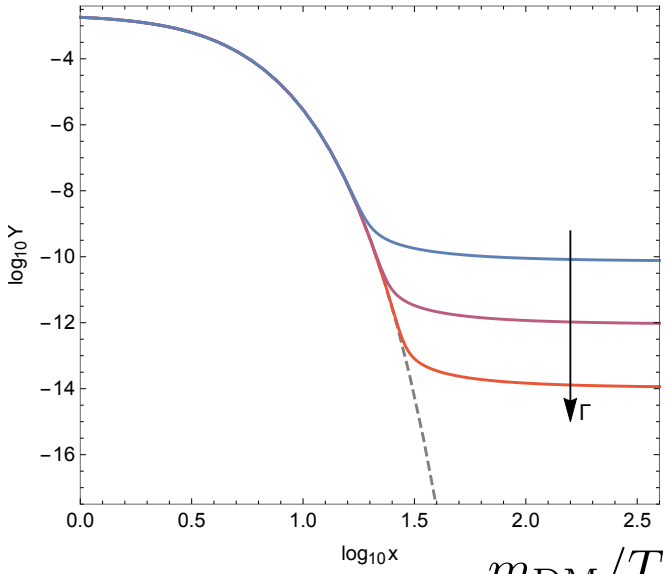

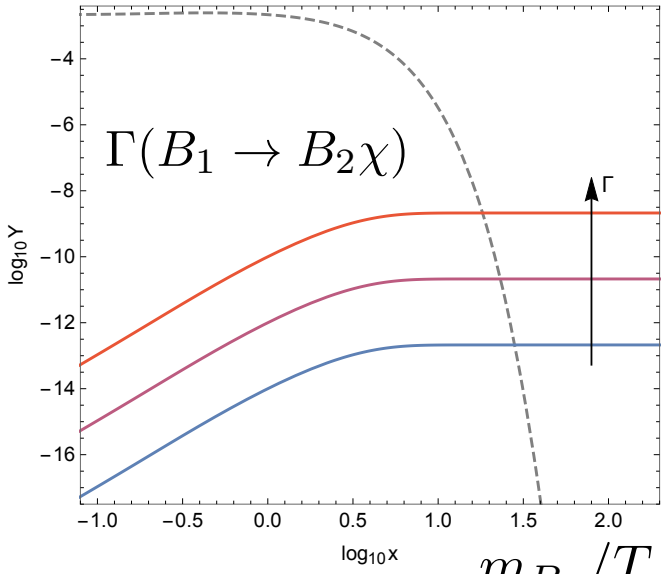

Review: Bernal et al. '17

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

Co, D'Eramo, Hall, Pappadopulo '15

The freeze-in mechanism

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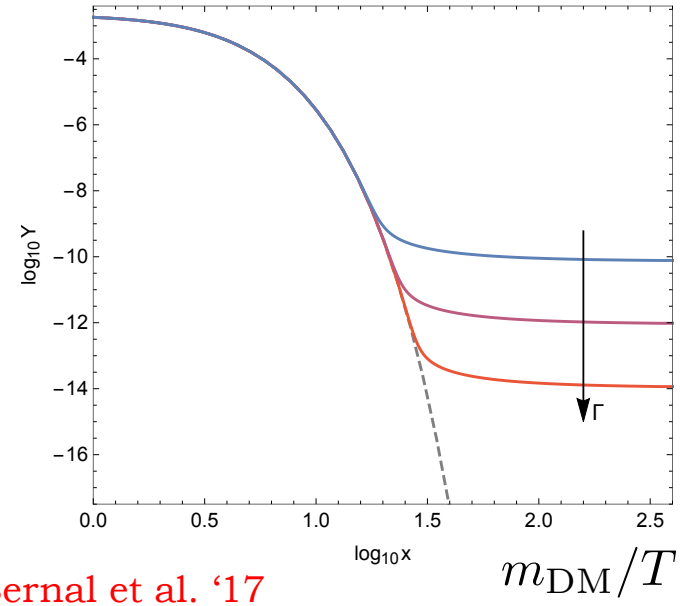
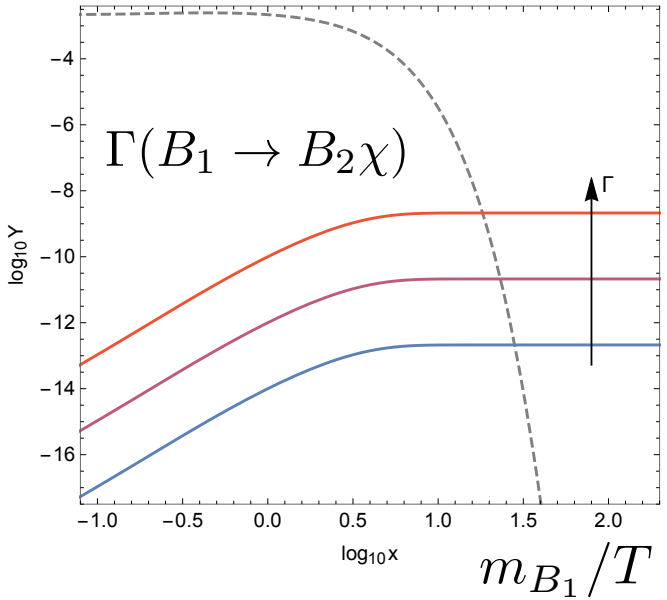




Review: Bernal et al. '17

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 DM-SM interactions

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

Mahbubani Senatore '05

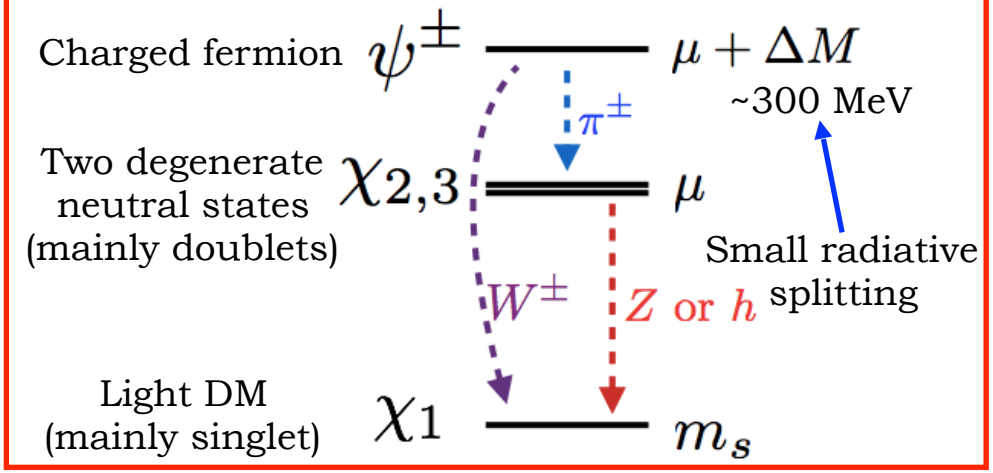
$$(\psi_u)_{2,\frac{1}{2}} = \begin{pmatrix} \psi^+ \\ \psi_u^0 \end{pmatrix}, \qquad (\psi_d)_{2,-\frac{1}{2}} = \begin{pmatrix} \psi_d^0 \\ \psi^- \end{pmatrix}, \qquad (\psi_s)_{1,0}$$

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

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: $|y_{u,d}| \ll 1, \quad |m_s| \ll |\mu|$

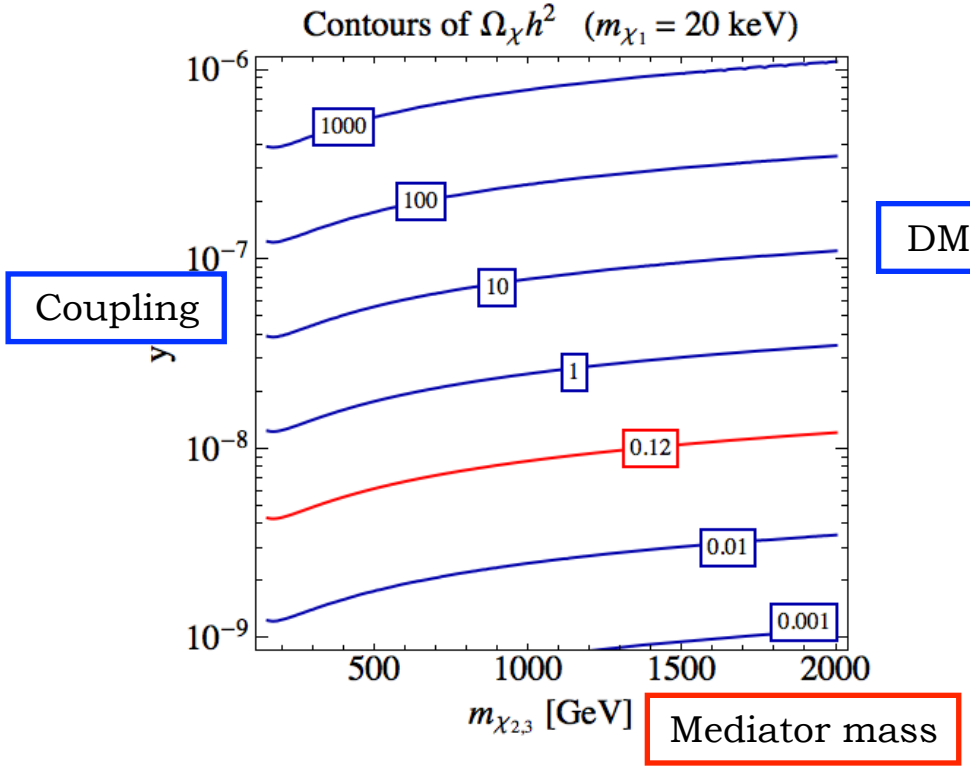


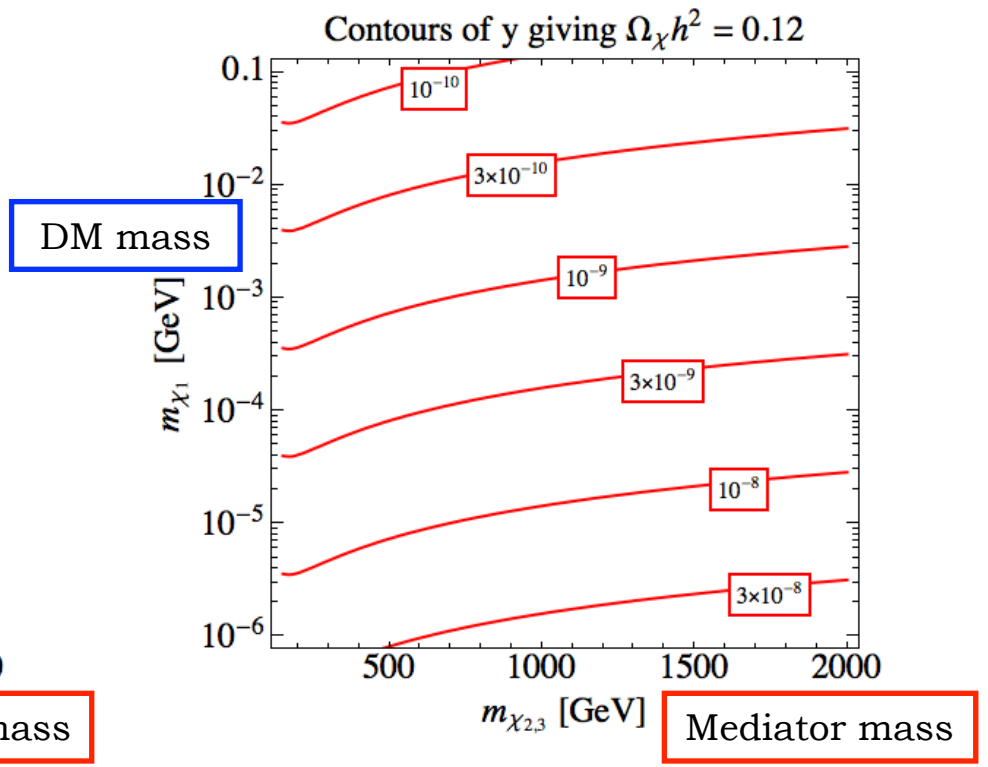
Dark Matter abundance

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

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

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



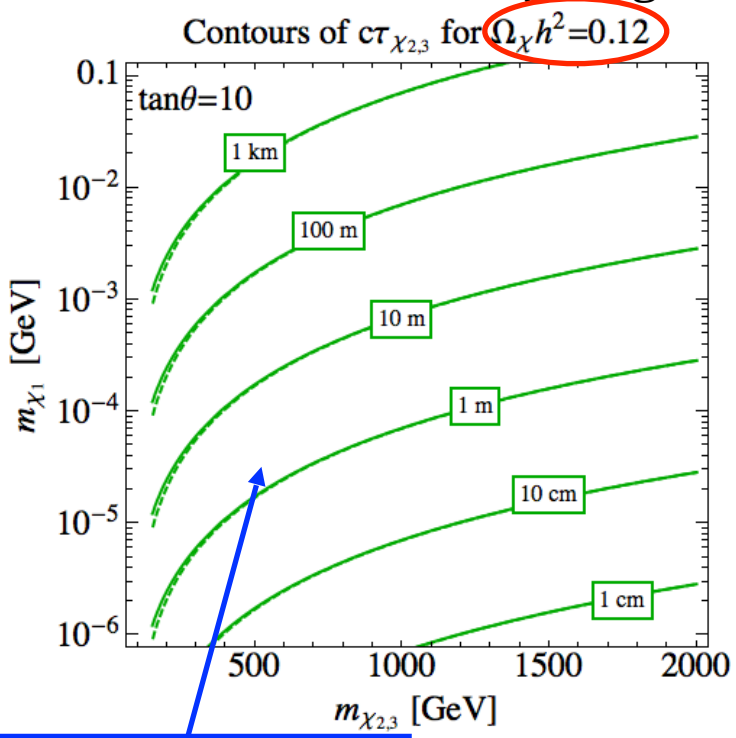


Doublet states (with m~TeV) abundantly produced at the LHC:

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

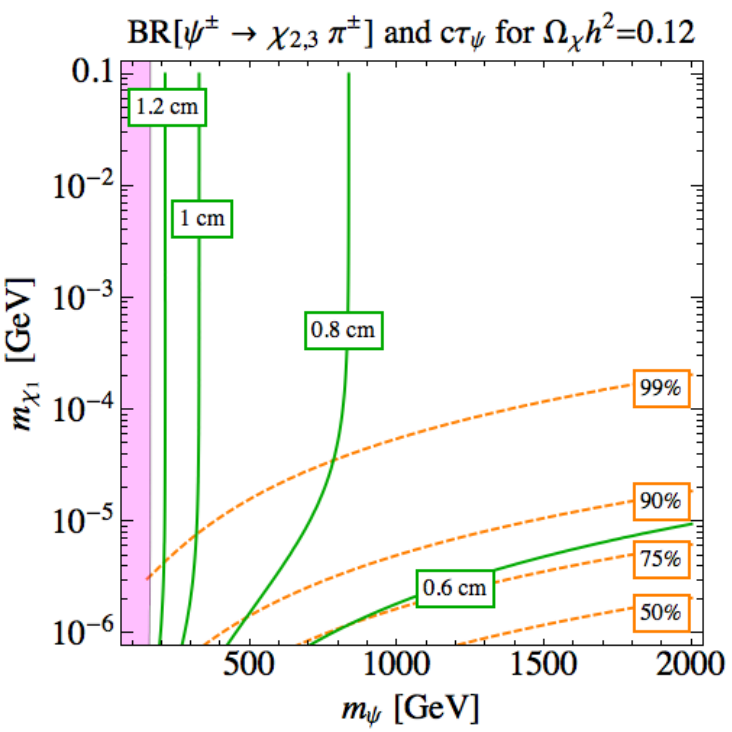
Decays give Higgs/Z + MET: $\psi^\pm \to \pi^\pm + \chi_{2,3}, \quad \chi_{2,3} \to h/Z + \chi_1$

Neutral states decay length:



Displaced vertices!

Charged states decay length:



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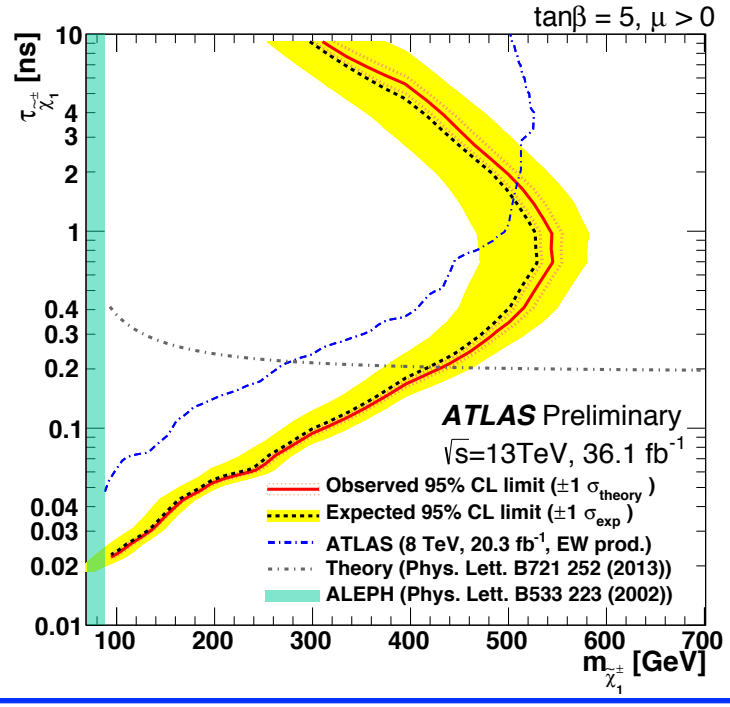
Disappearing tracks

ATLAS 1712.02118



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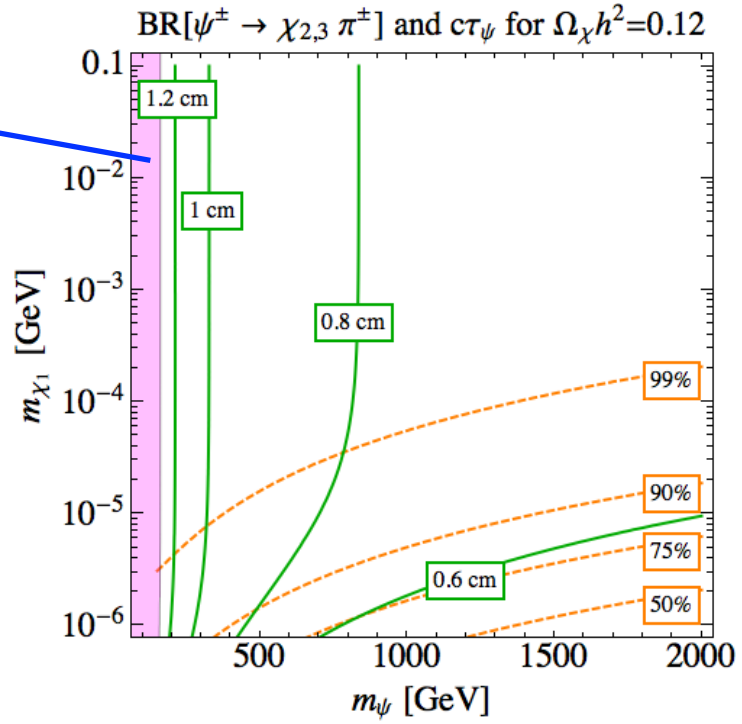

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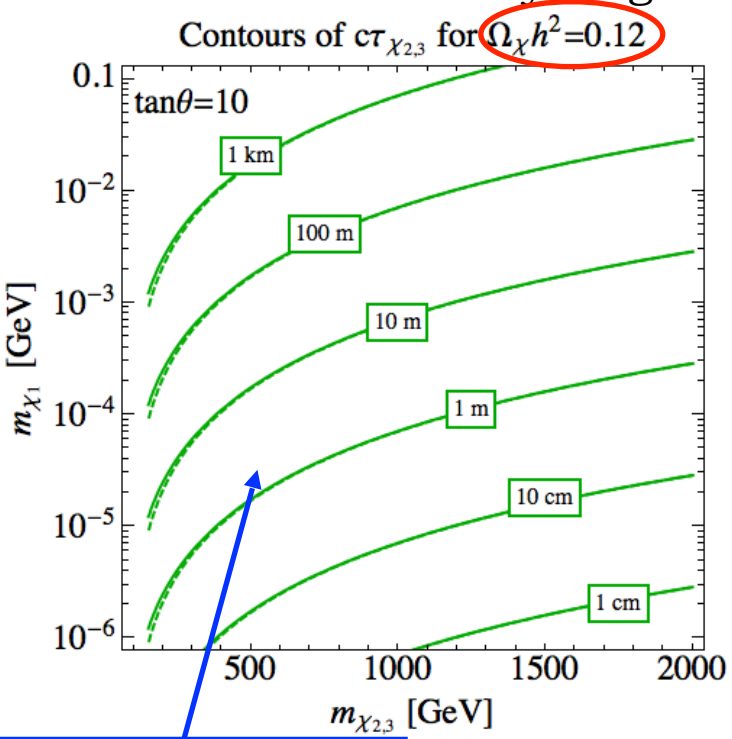

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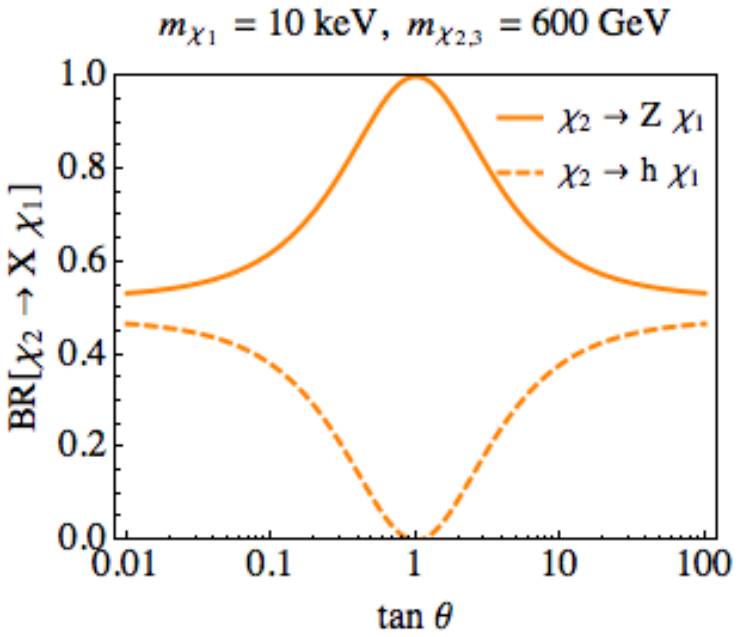

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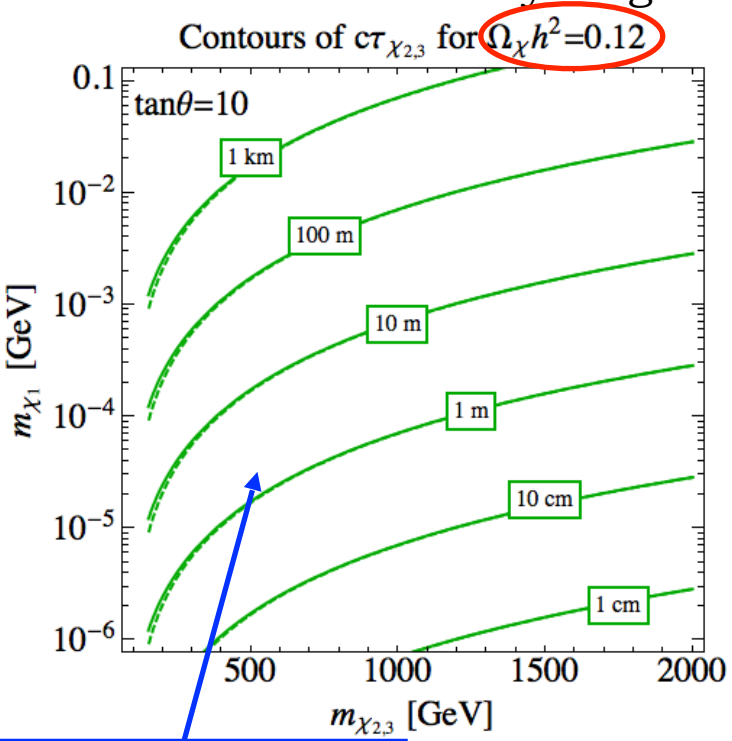

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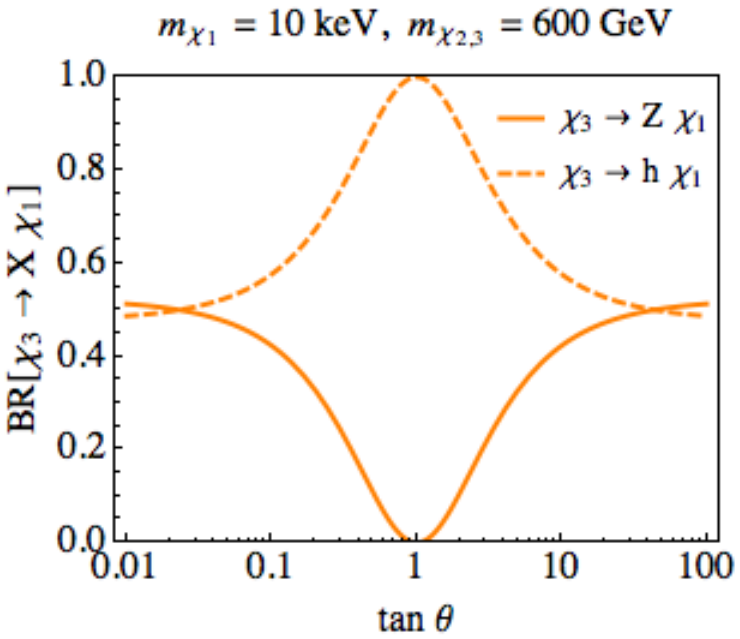

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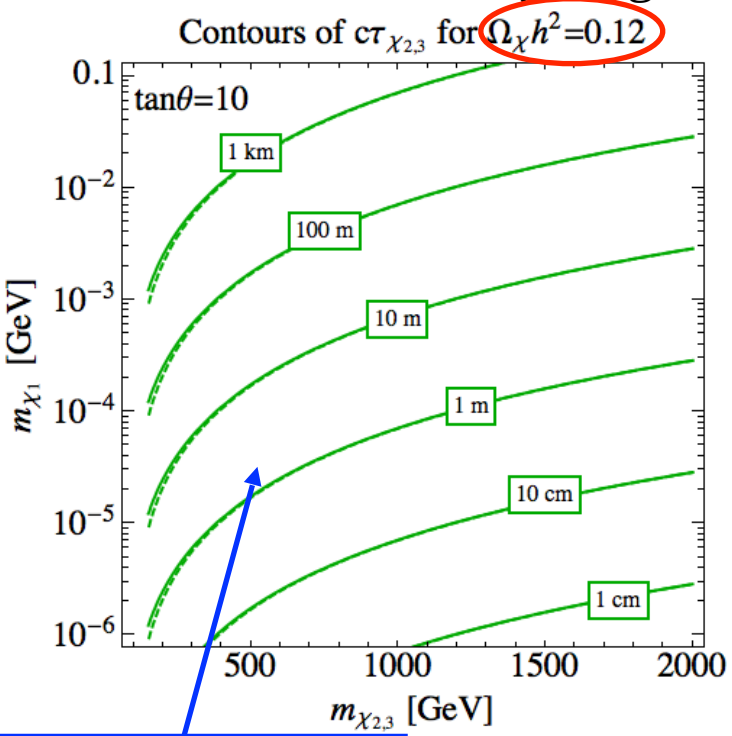

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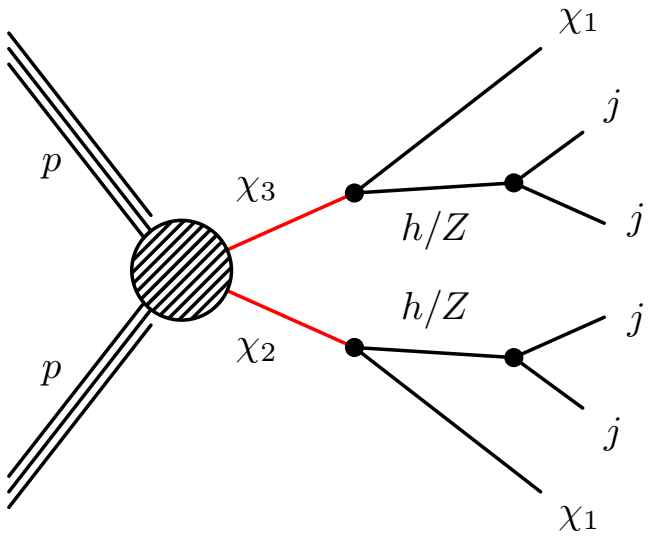


LHC signature: displaced vertices with jets and MET (~0 SM background)

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

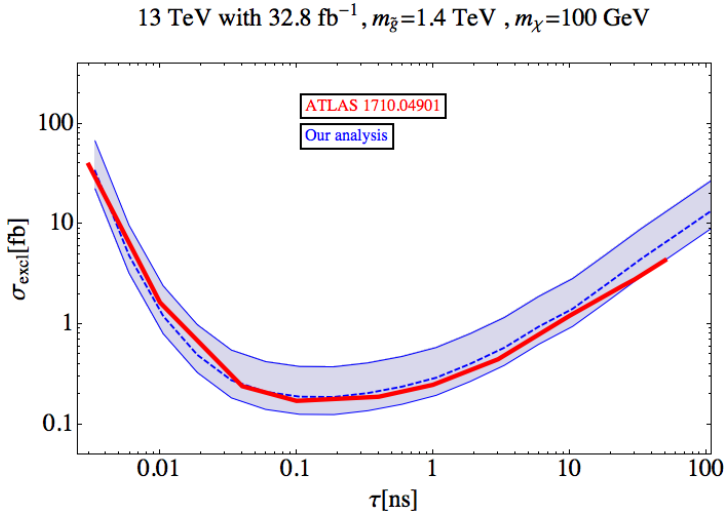
The ATLAS Collaboration

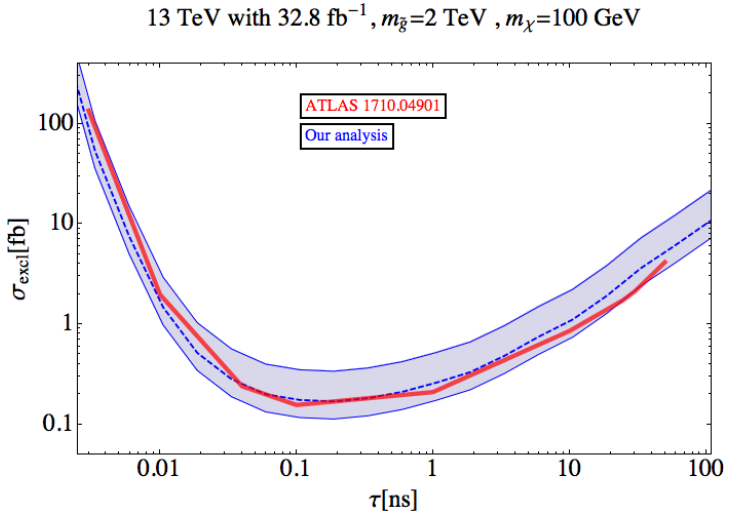
A search for long-lived, massive particles predicted by many theories beyond the Standard Model is presented. The search targets final states with large missing transverse momentum and at least one high-mass displaced vertex with five or more tracks, and uses 32.8 fb^{-1} of $\sqrt{s} = 13$ TeV pp collision 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 $O(10^{-2})$–$O(10)$ ns in a simplified model inspired by Split Supersymmetry.

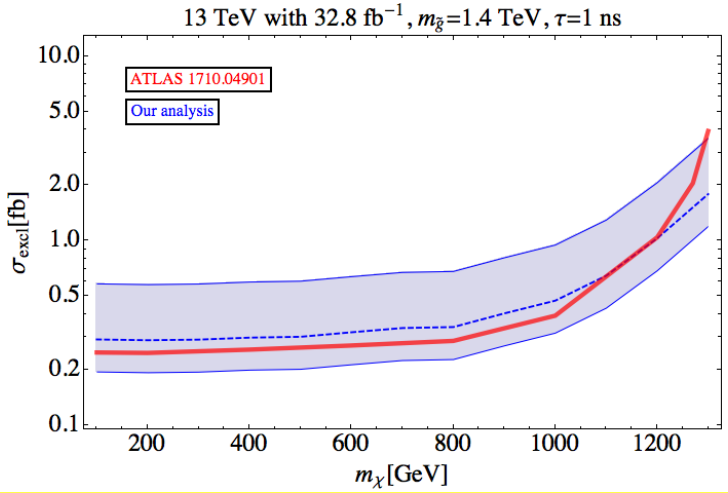
arXiv:1710.04901

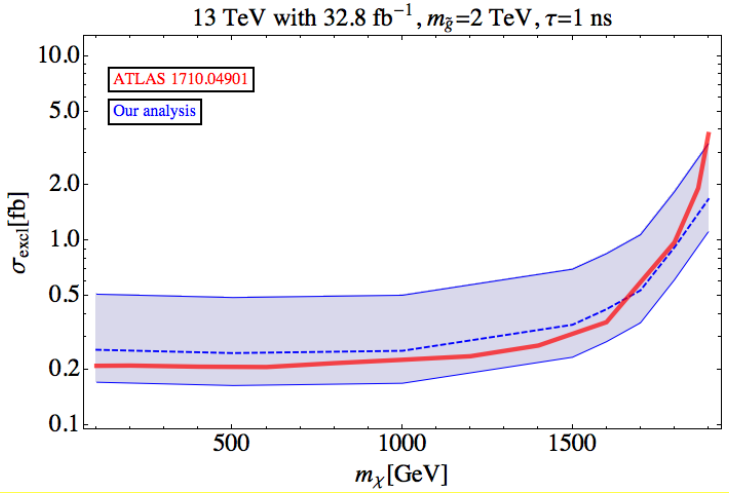
Recasting a DV+MET search by ATLAS

Our recasting
Madgraph/Pythia/Delphes



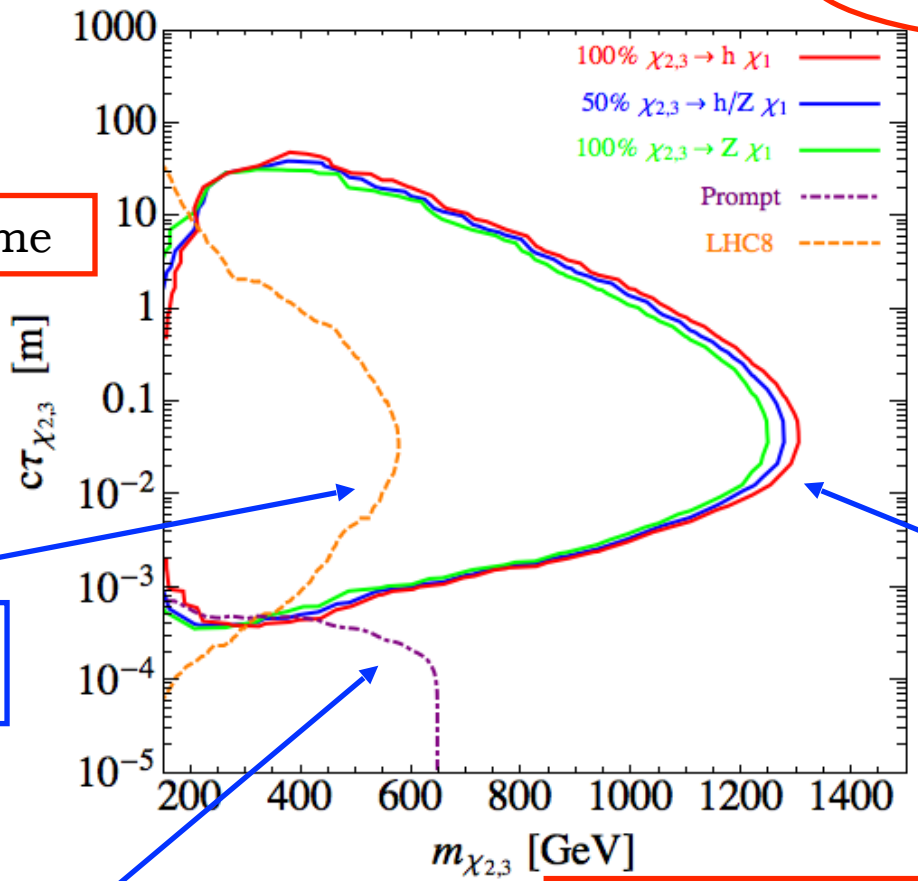






Recasting a DV+MET search by ATLAS

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

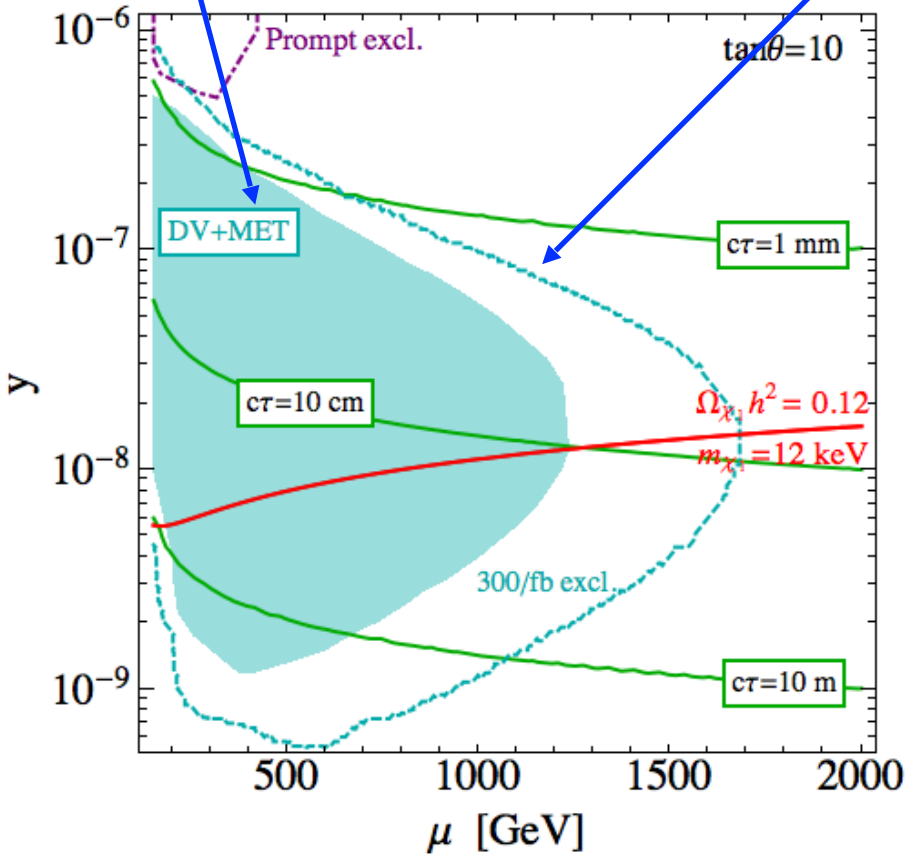
Doublet mass

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

Impact on Singlet-Doublet Dark Matter

Our recasting

Future LHC sensitivity



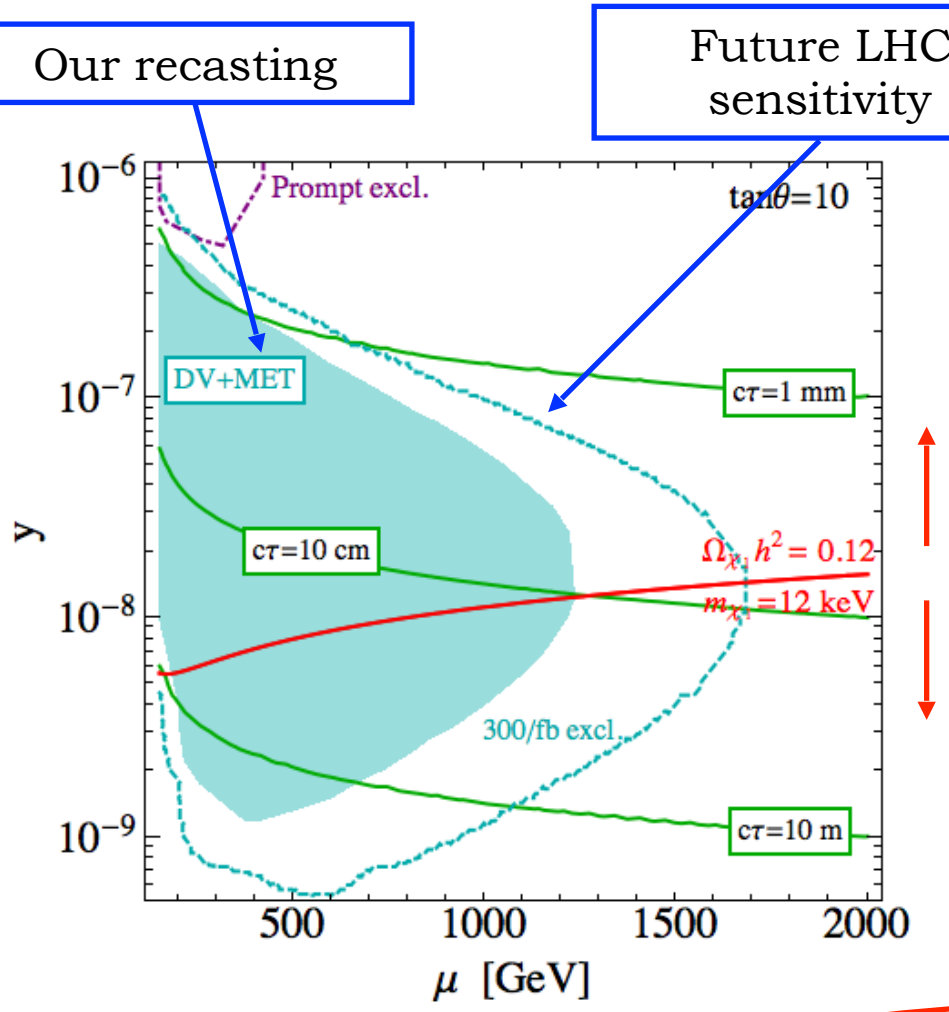
For a fixed DM mass:

DM overabundance

DM underabundance

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

Impact on Singlet-Doublet Dark Matter



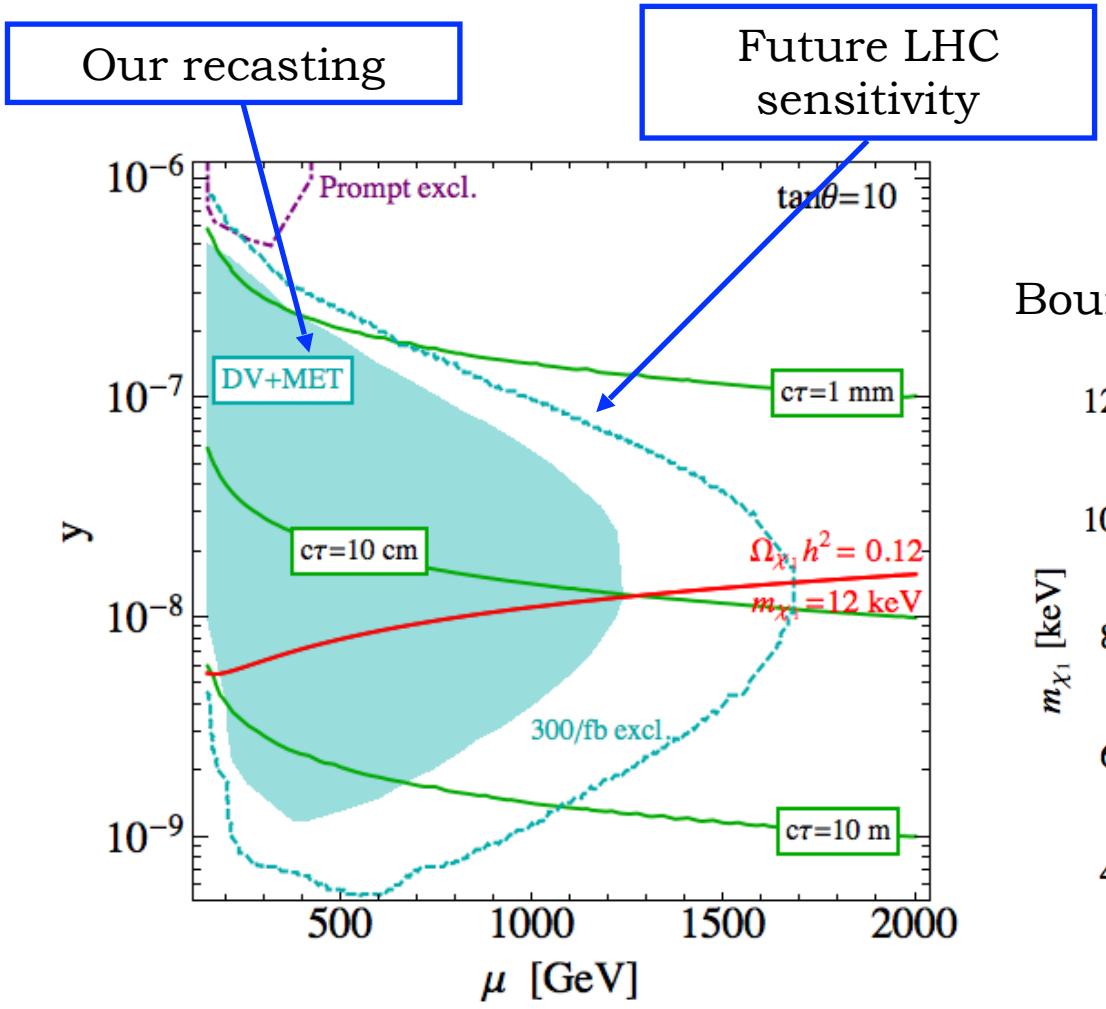
Correct relic density achieved by:

Lowering m_{DM}

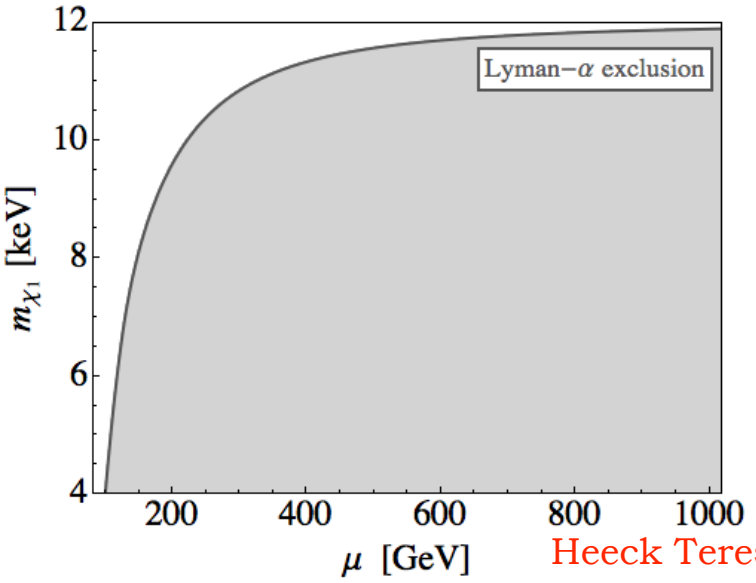
Raising m_{DM}

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

Impact on Singlet-Doublet Dark Matter



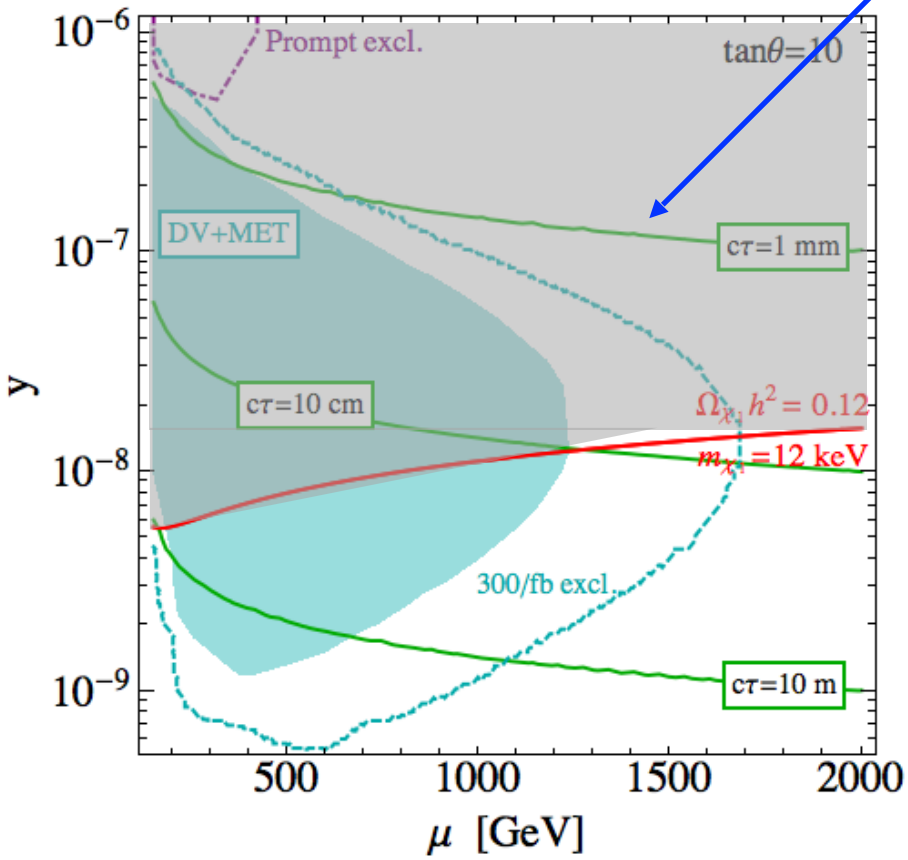
Bound from small structure formation (based on Lyman-alpha data):



Heeck Teresi '17

Impact on Singlet-Doublet Dark Matter

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



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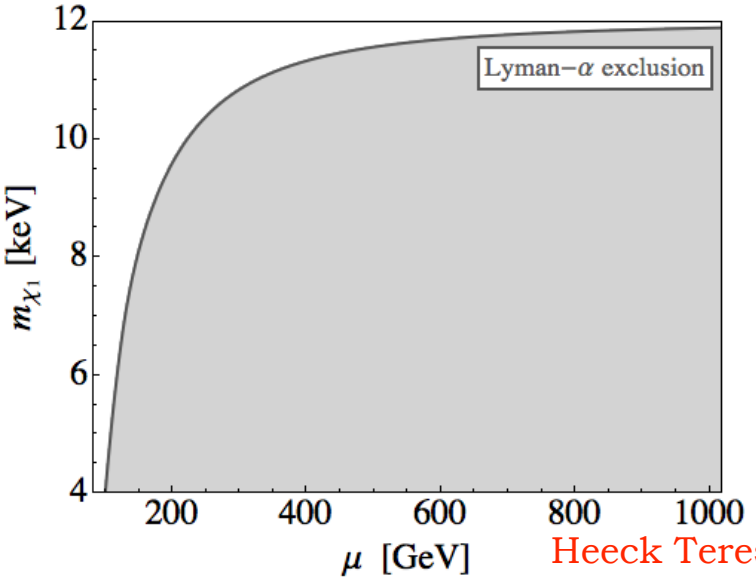


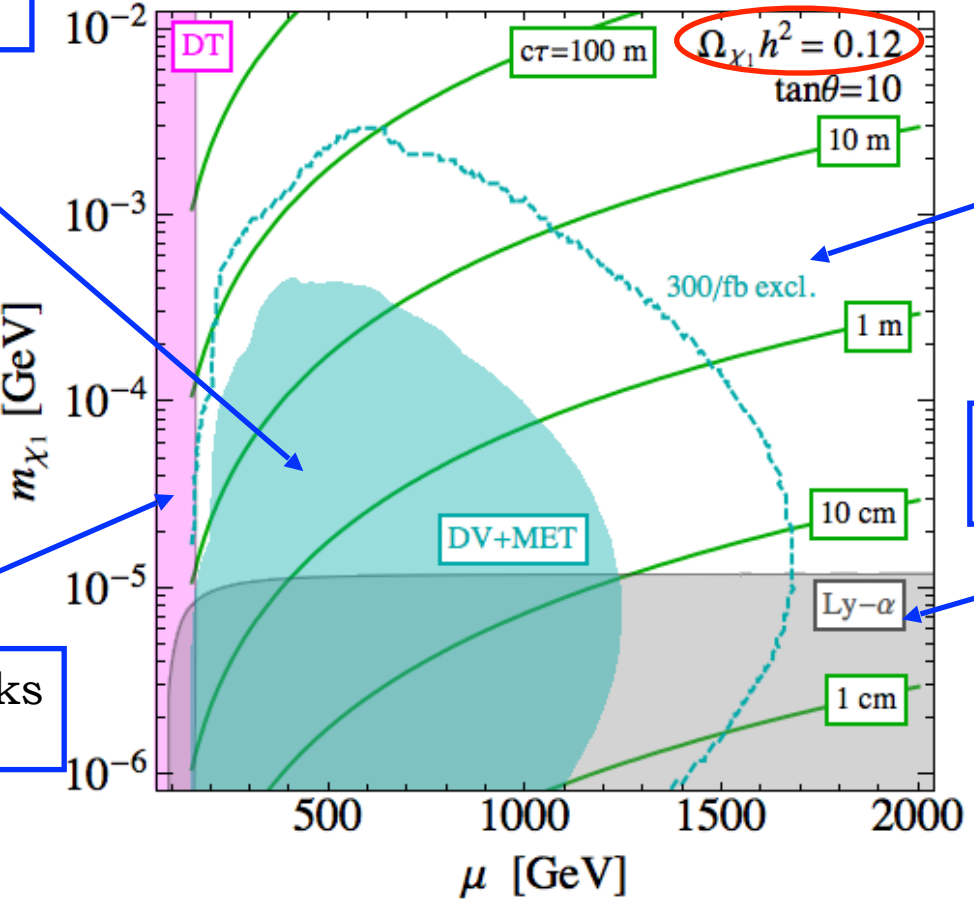
Heeck Teresi '17

Combined LHC and cosmology constraints

Our recasting

DM mass

Disappearing tracks
ATLAS 1712.02118

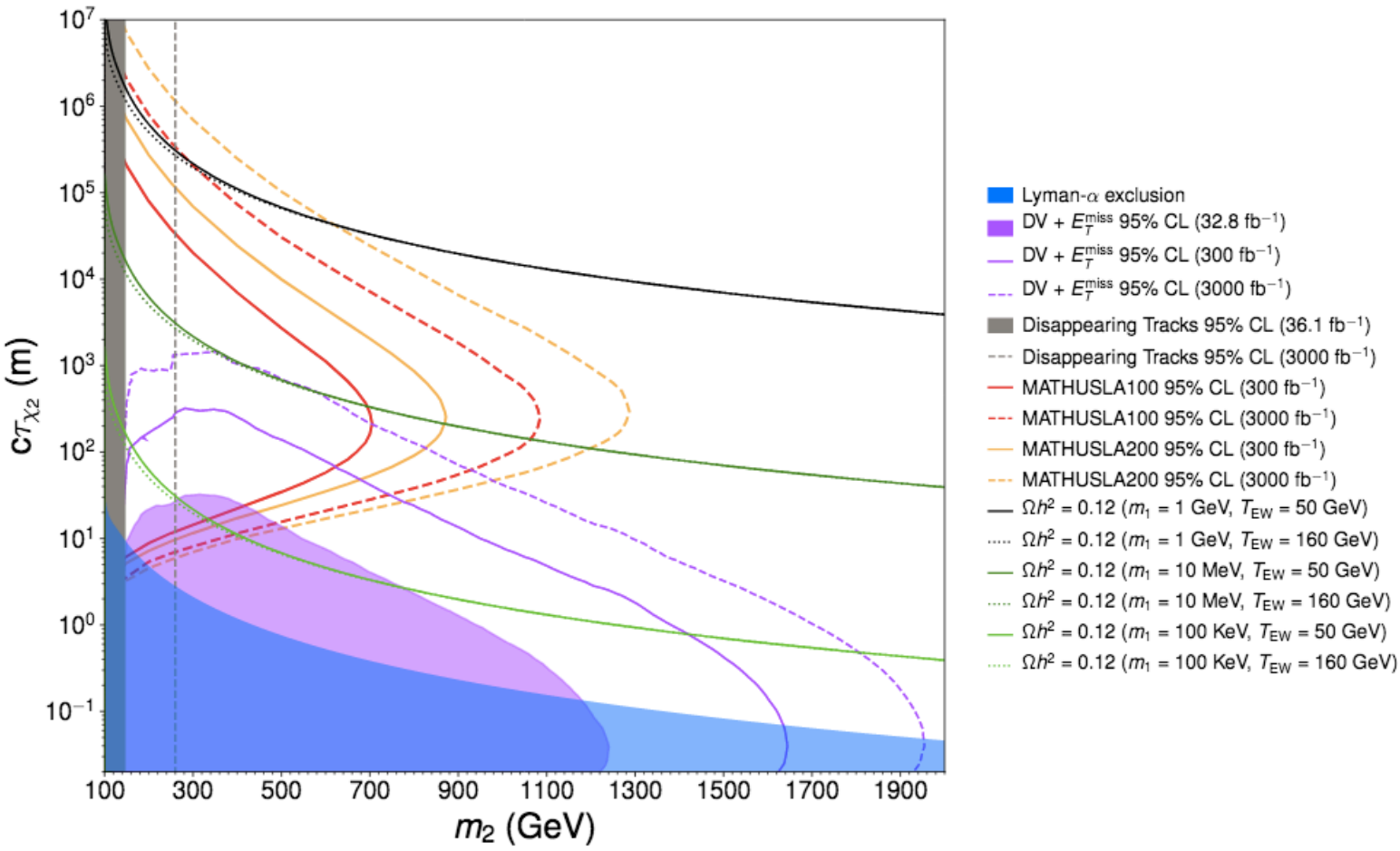


Future LHC sensitivity

Lyman-alpha bound
Heeck Teresi '17

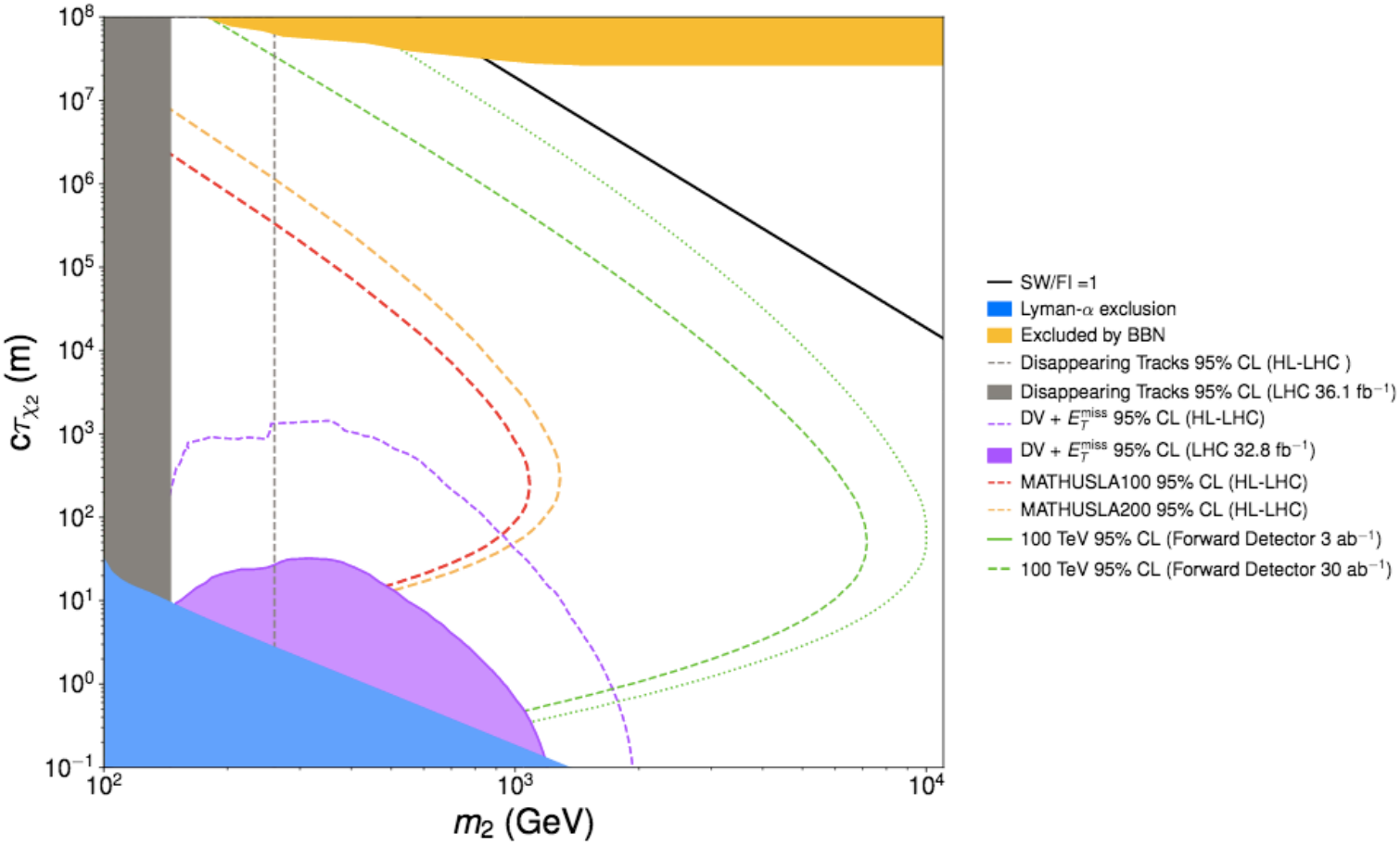
Doublet mass

Prospects at future experiments



No Tunney Zaldivar, today

Prospects at future experiments



No Tunney Zaldivar, today

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!

Dedicated searches for heavy particles with displaced decays to Z and h and missing energy would increase the LHC sensitivity

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

Grazie!

谢 谢 !