Feebly-interacting dark matter and long-lived particles at the LHC

Alberto Mariotti

Based on works with different combinations of
Lorenzo Calibbi, Laura Lopez Honorez, Steven Lowette,
Sam Junius and Francesco D'eramo
JHEP 1809 037, JHEP 1907 136 and arXiv:20XX.XXXXX

Universita' Roma 3

21 November 2019

Beyond Standard Model Physics

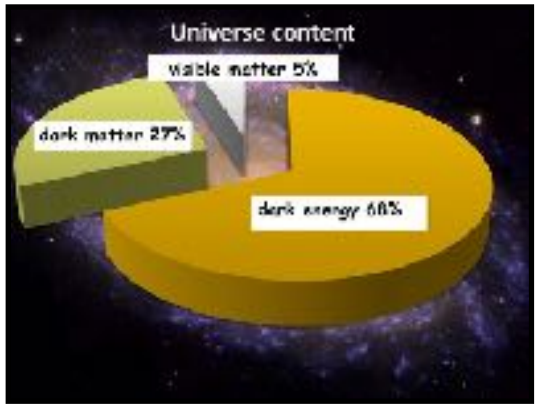
Many fundamental questions still open …

Hierarchy problem ?

Force Unification ?

Inflation ?

Dark matter nature?



Flavour hierarchies ?

Baryogenesis ?

? Where do we go ?

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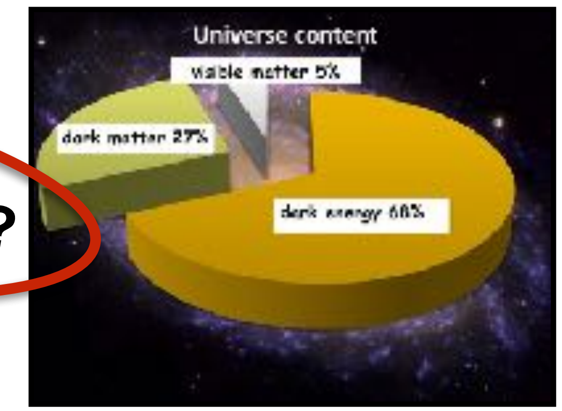


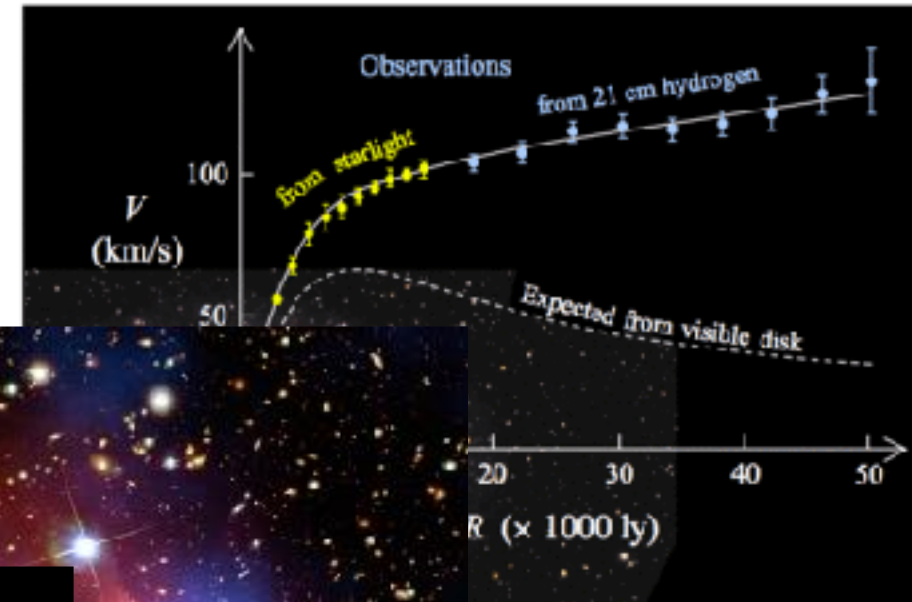
Flavour hierarchies ?

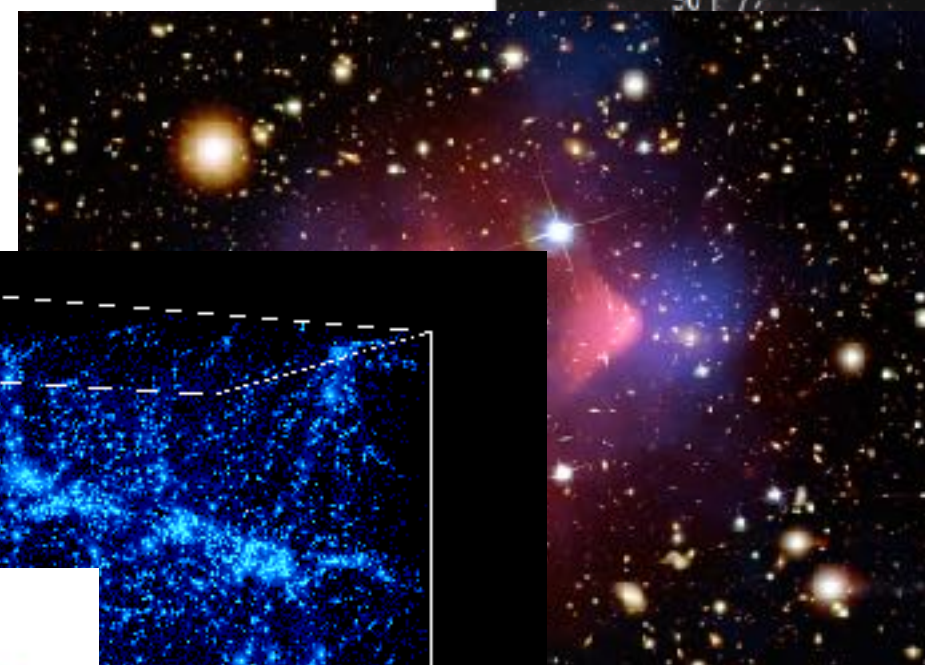
Baryogenesis ?

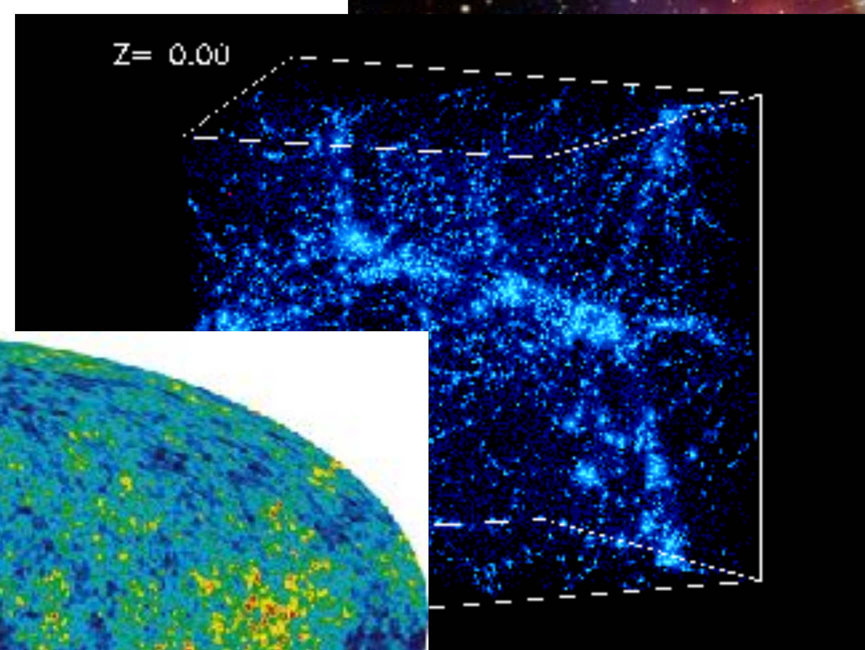
? Where do we go ?

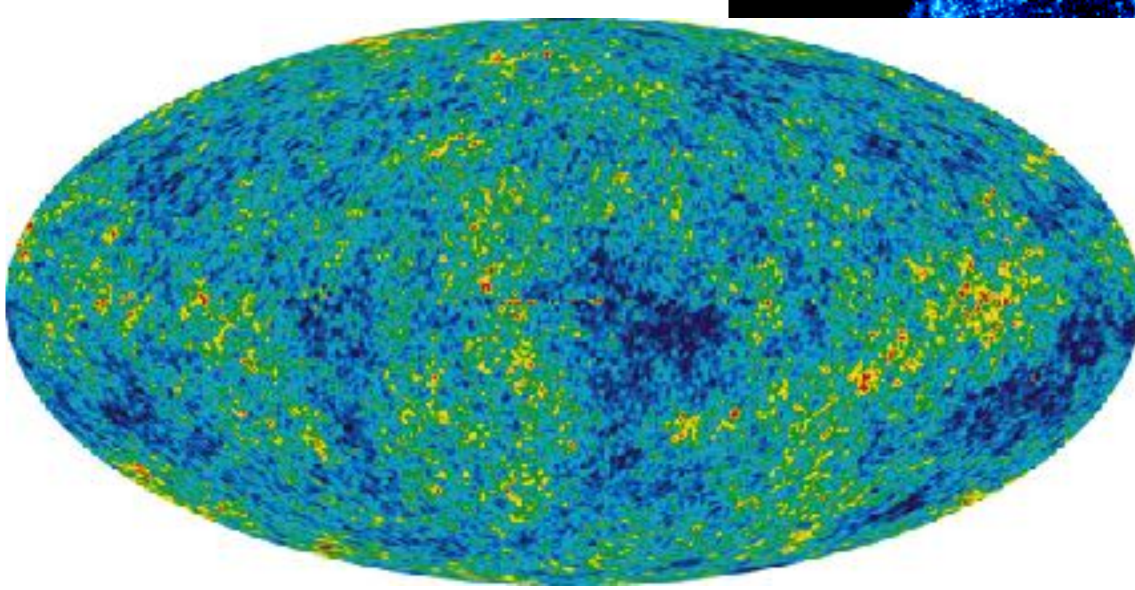
Evidence for Dark Matter

- ★ ***Galaxy rotation curves***
- ★ ***Gravitational lensing***
- ★ ***Bullet clusters***
- ★ ***Structure formations***
- ★ ***CMB***
- ★ ***...***









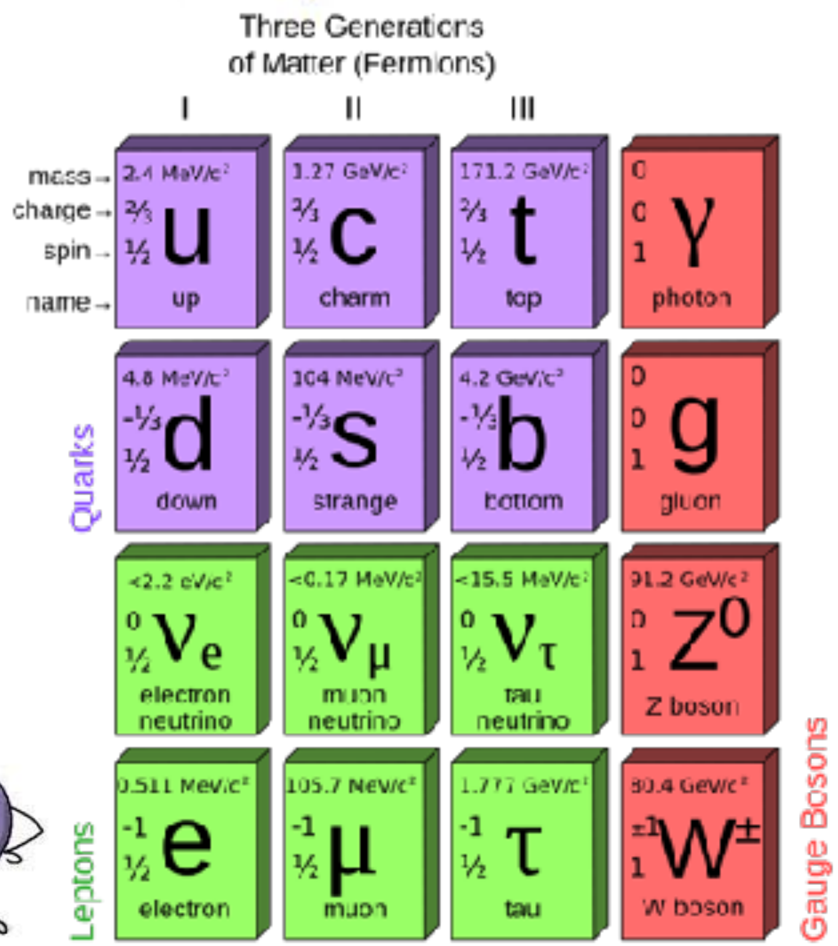
$$\Omega_{DM} h^2 \simeq 0.12$$

Particle Dark Matter

Assume Dark Matter is a new elementary particle

Simplified models of Dark Matter

Useful framework for pheno studies



Portal

Dark Matter basic questions

1.How does it couple with the Standard Model?

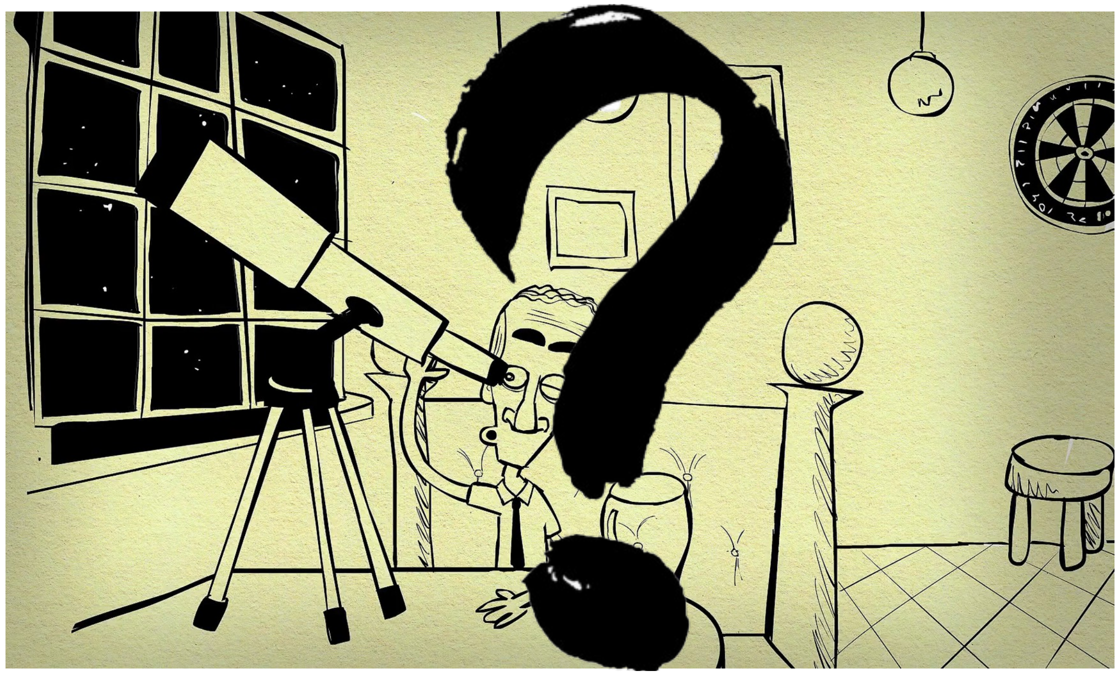
Dark Matter basic questions

1. *How does it couple with the Standard Model?*

2. *How it is produced at early times?*

Dark Matter basic questions

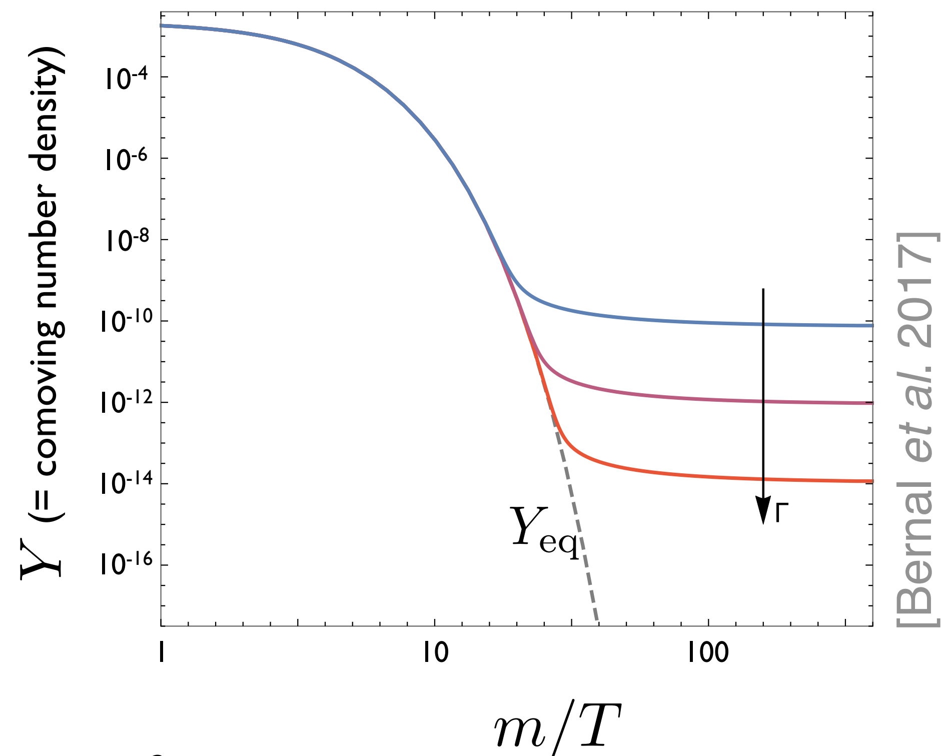
1. *How does it couple with the Standard Model?*
2. *How it is produced at early times?*
3. *How do we detect it?*

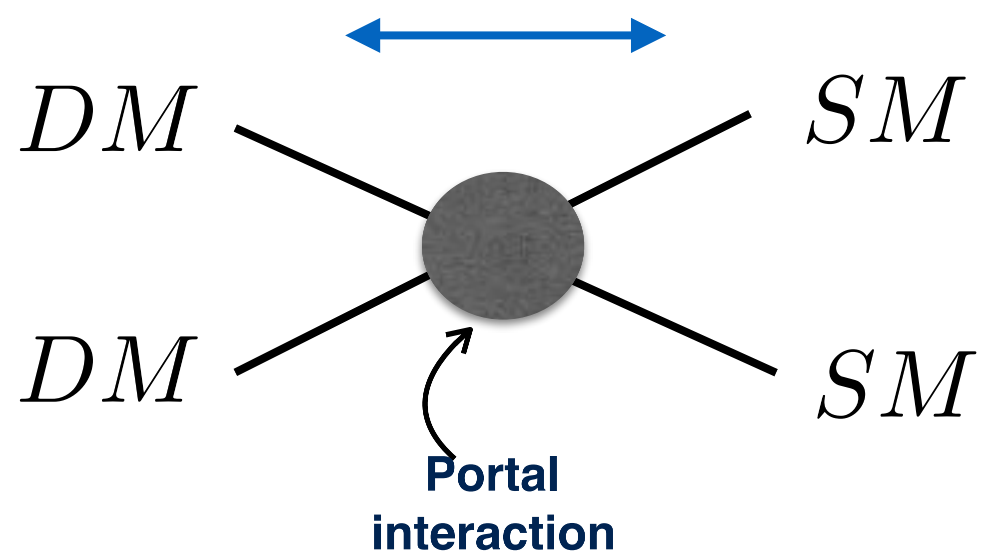


Weakly Interacting Massive Particle

Dark Matter abundance through freeze-out (FO) mechanism

- *Dark Matter annihilates into Standard Model Particles*
- *Dark matter in thermal equilibrium at high temperature*
- *Dark Matter abundance freeze-out during cooling of universe*





Independent on initial conditions

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

Typical weak coupling cross section

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

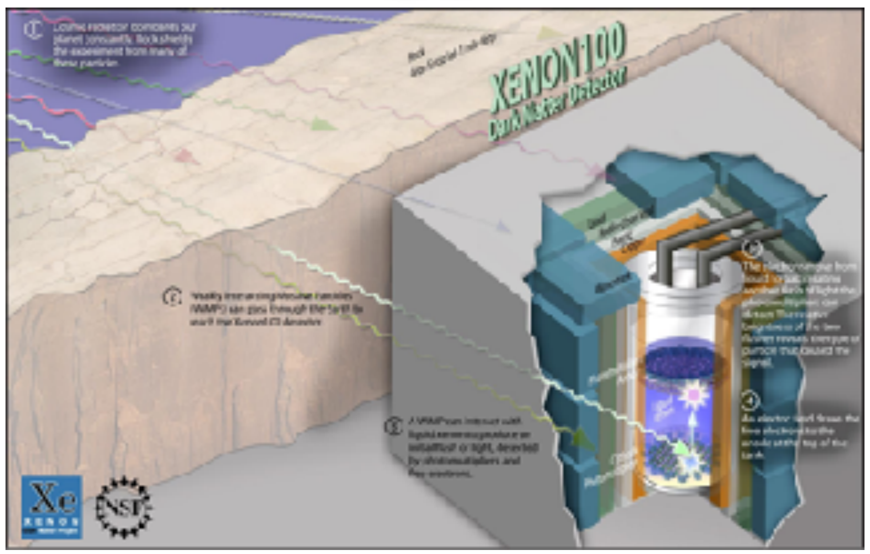
Probing DM at experiments

WIMP-like DM is prototype of DM simplified models

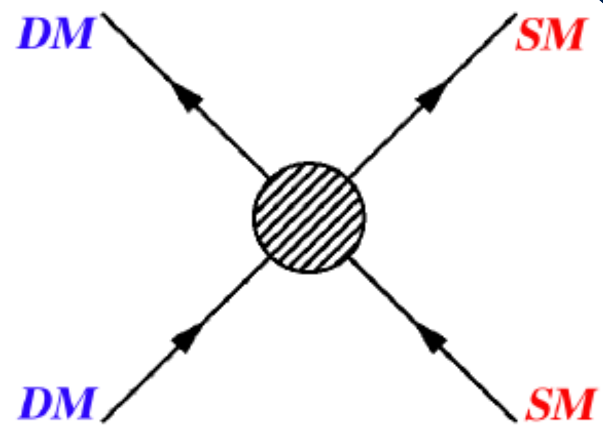
e.g. Neutralino dark matter in SUSY

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

1



direct detection



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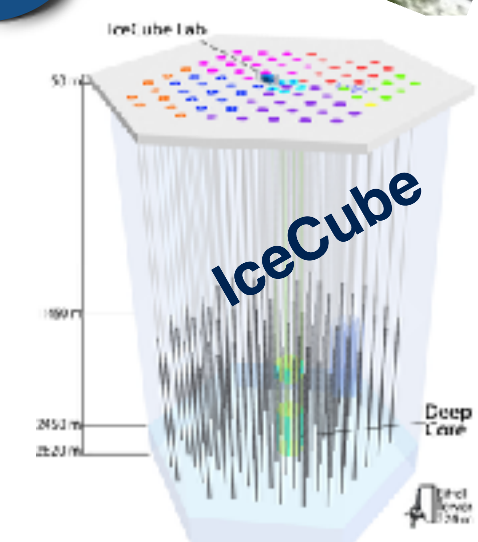


production at colliders

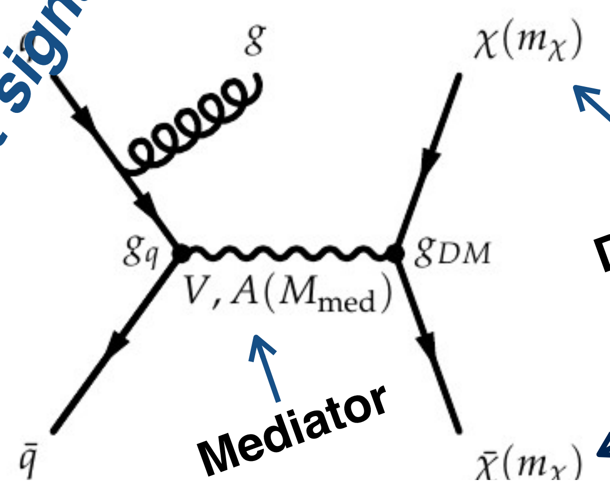
3

Three-fold way

WIMP under pressure

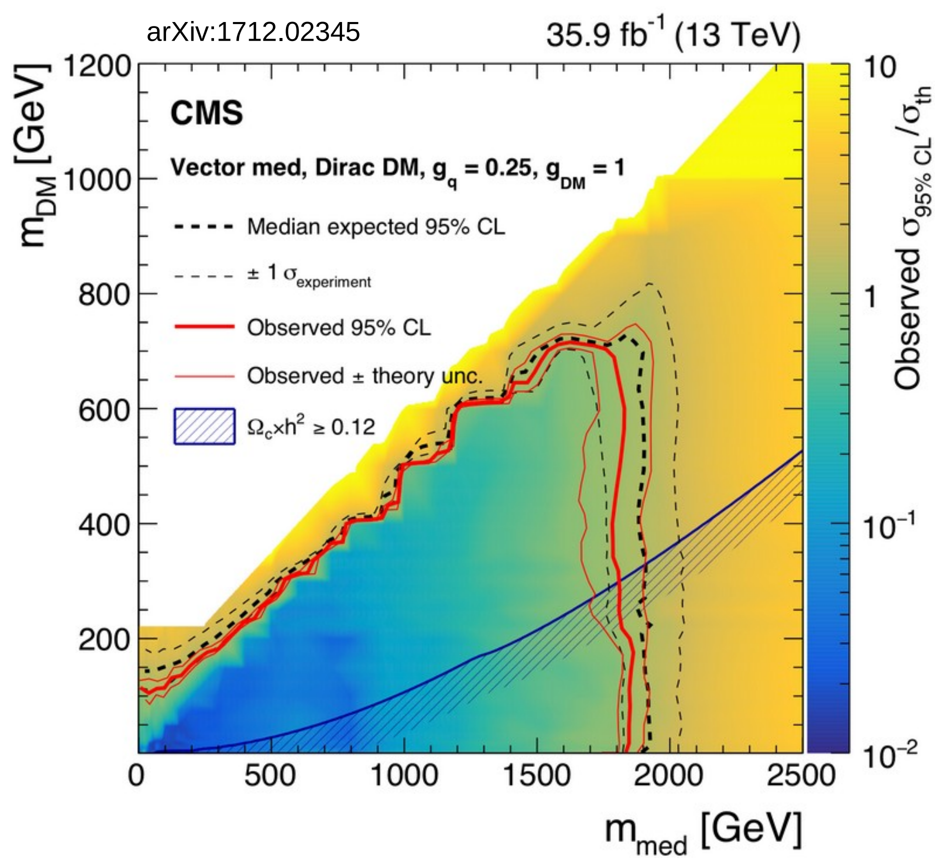
Limits on WIMP DM are improving continuosly

MonoJet signature



Dark Matter

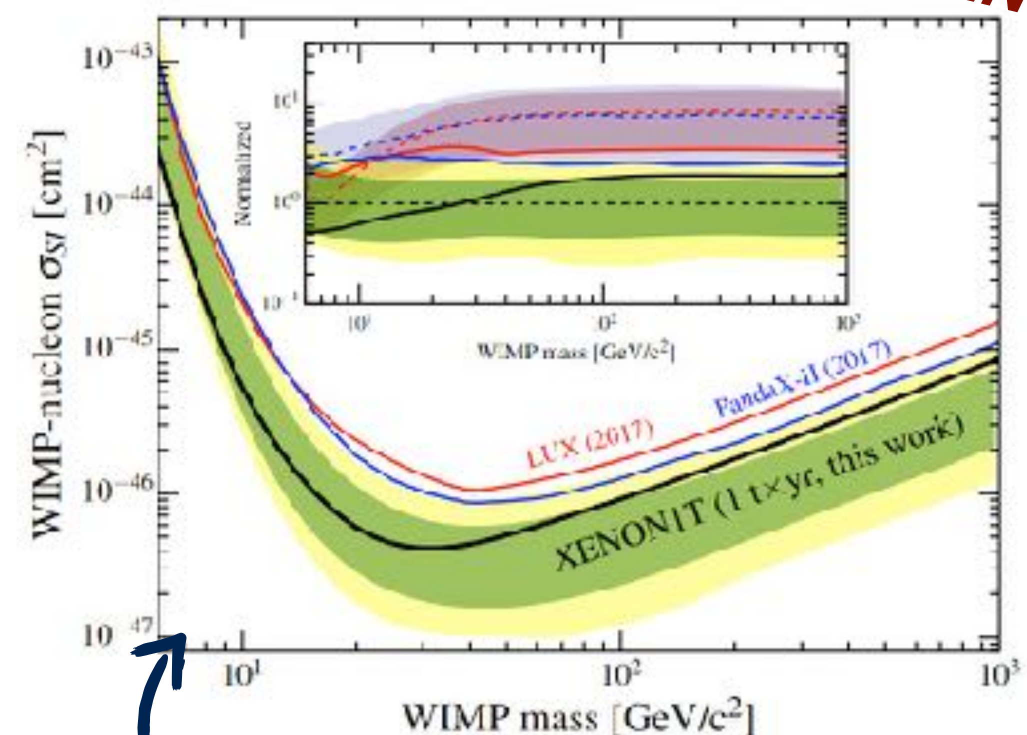
Mediator



LHC results

Mediator search

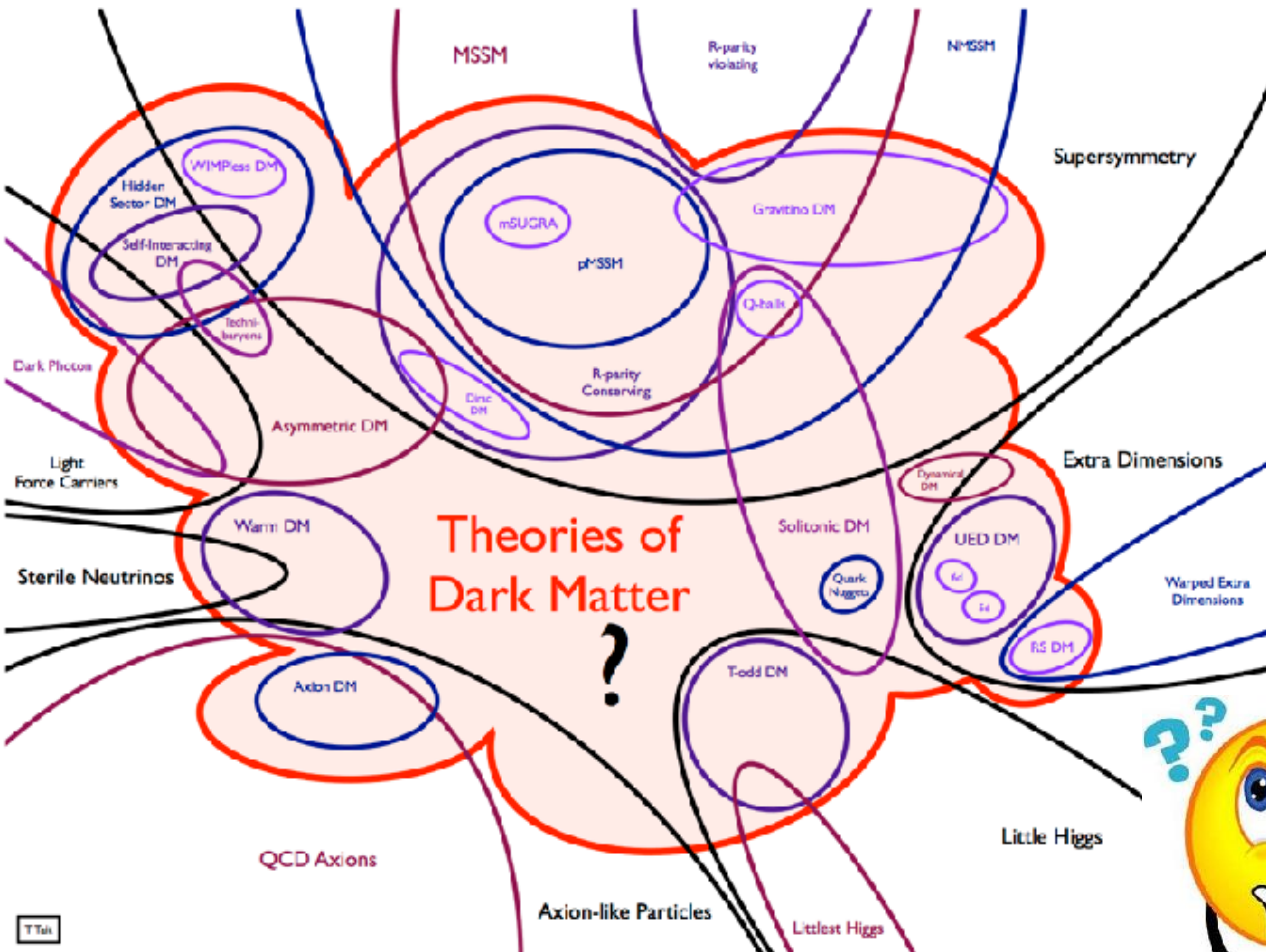
Strong limits from XENON1T



Very sensitive in 5-1000 GeV DM mass range

Dark Matter ZOO

But possibility for Dark Matter are much vaster



WIMP vs FIMP

WIMP

weakly interacting massive particle

- ✦ *Coupling of order 1 with the SM*
- ✦ *Thermal equilibrium with SM*
- ✦ *No dependence on initial cond.*
- ✦ *Freeze-out mechanism*
- ✦ *Testable in direct/indirect detection*
- ✦ *Testable @ LHC*

FIMP

feebly interacting massive particle

- ✦ *Coupling of order 10^(-10) with SM*
- ✦ *Not in thermal equilibrium with SM*
- ✦ *Dependence on initial cond.*
- ✦ *Freeze-in mechanism*
- ✦ *Elusive in direct/indirect detection*
- ✦ *Testable @ LHC (LLP signatures)*

WIMP vs FIMP

~~**WIMP**~~

~~*weakly interacting massive*~~

- ~~*Coupling of order 1 w… e SM*~~
- ~~*Thermal equilibri… n SM*~~
- ~~*No dependen… nitial cond.*~~
- ~~*Freeze-ou… anism*~~
- ~~*Testa… irect/indirect detection*~~
- ~~*Te… @ LHC*~~

In This Talk

FIMP

feebly interacting massive particle

- *Coupling of order 10^(-10) with SM*
- *Not in thermal equilibrium with SM*
- *Dependence on initial cond.*
- *Freeze-in mechanism*
- *Elusive in direct/indirect detection*
- *Testable @ LHC (LLP signatures)*

Features

- *What is freeze-in?*
- *Lead to longlived particles*
- *Cosmological history plays a role*

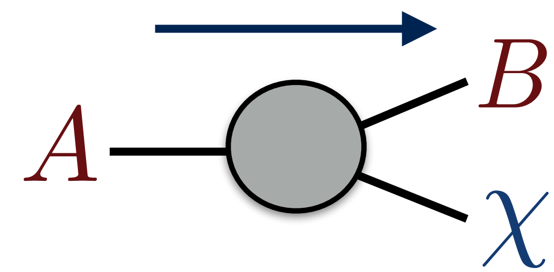
Freeze In Dark Matter

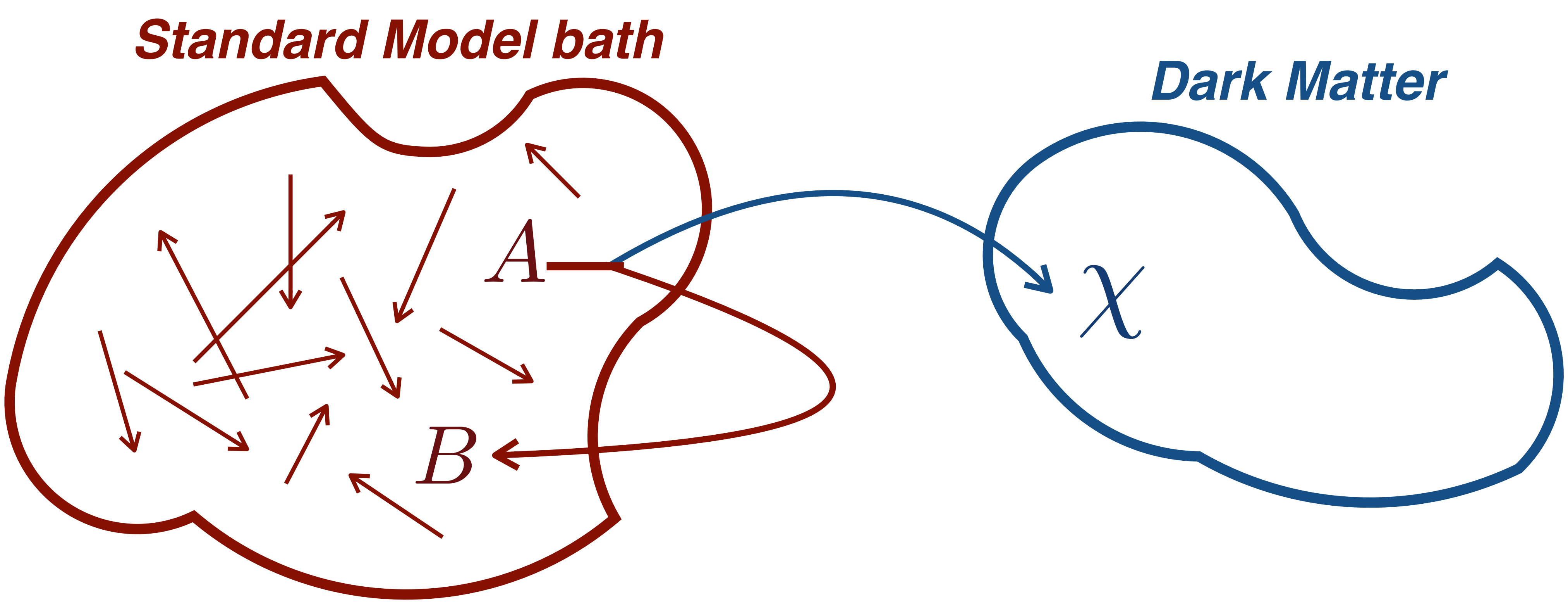
✦ ***Dark matter not in thermal equilibrium with SM bath***

✦ ***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

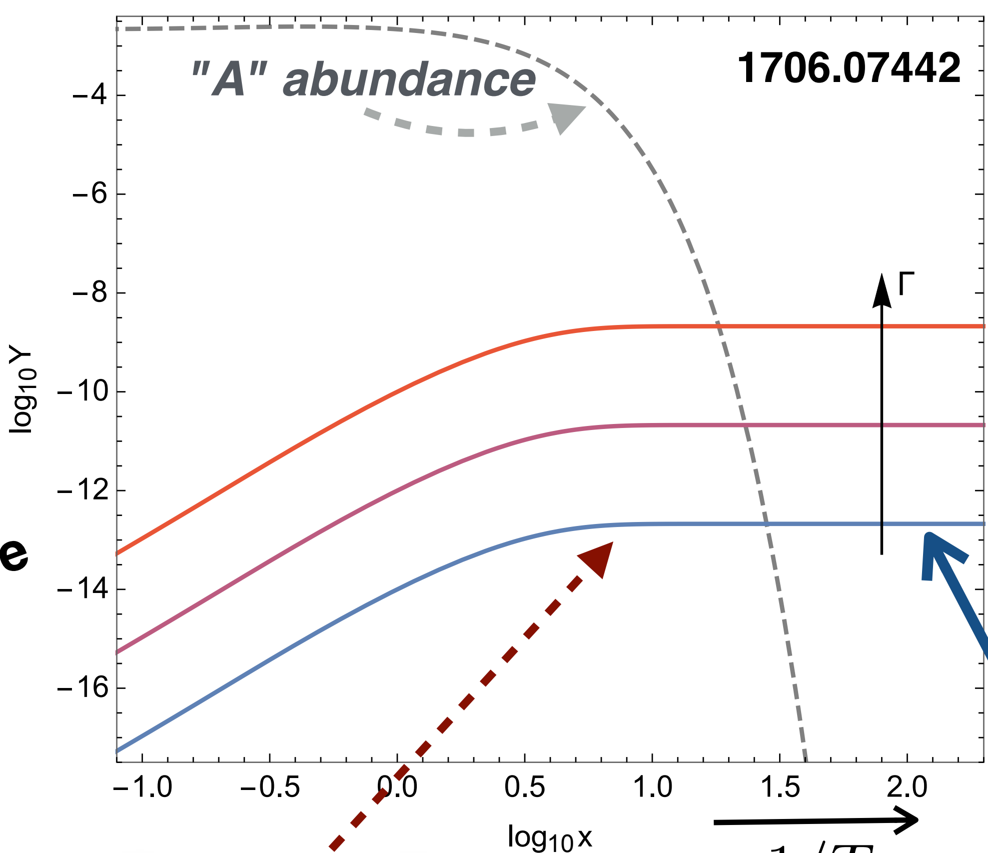
★*Mother (mediator) A in thermal equilibrium*

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

Boltzmann equation

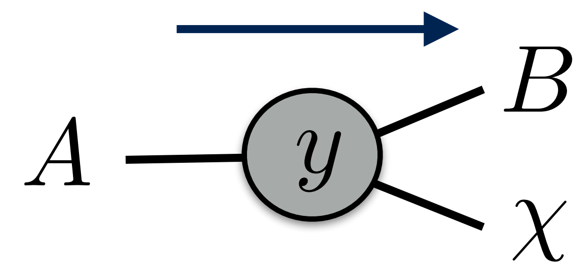
$$\frac{dn_\chi}{dt} = -3Hn_\chi + \Gamma_A n_A^{\text{eq}} \frac{K_1[m_A/T]}{K_2[m_A/T]}$$

DM abundance



$1/T$

IR dominated



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

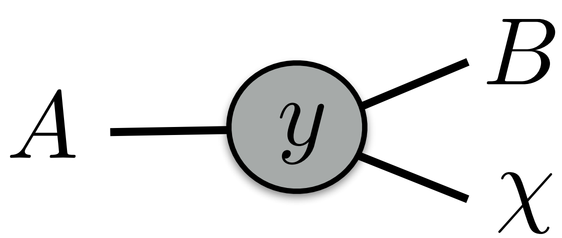
✦ ***What is typical value of portal coupling?***

✦ ***Can we probe FIMP DM experimentally?***

Standard Cosmology history

FIMP Dark Matter abundance

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



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

Very small coupling !!!

★ ***Suppressed signal in direct detection***

★ ***Suppressed signal in indirect detection***

Can LHC probe FIMP?

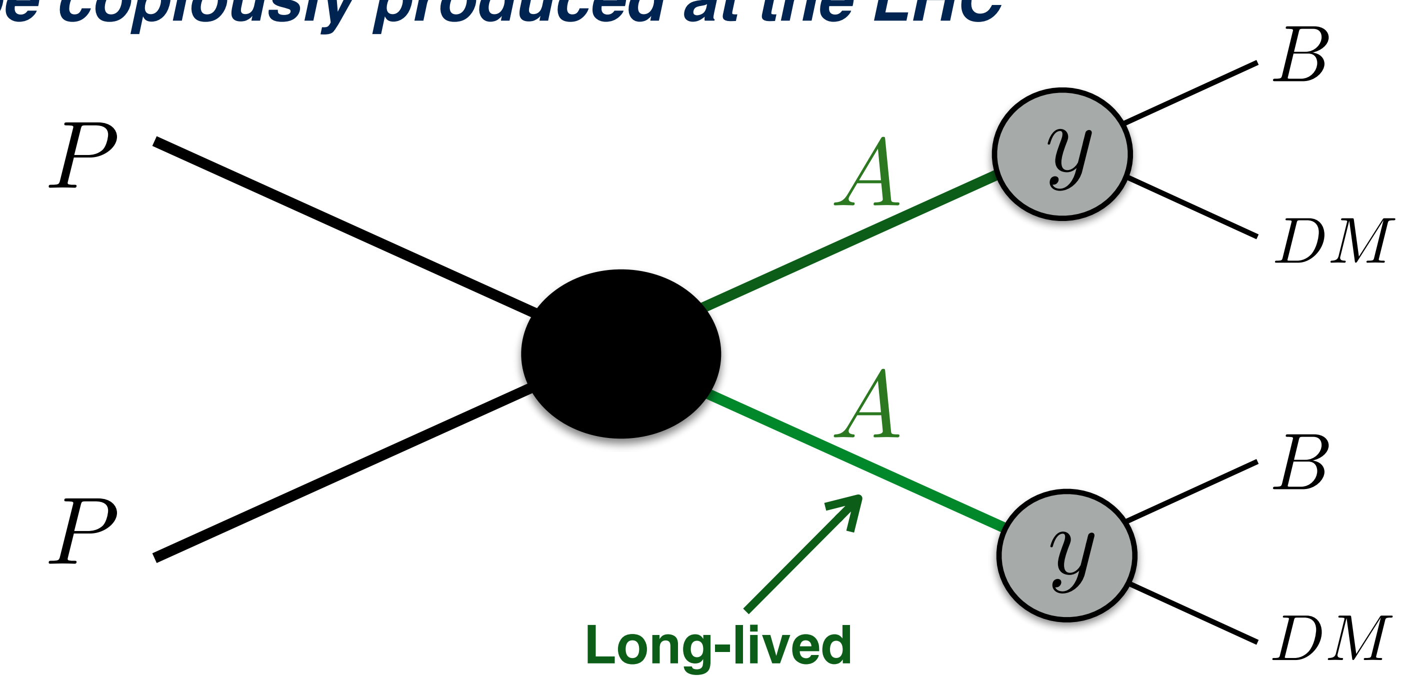
FIMP phenomenology

✦*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 !!!

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

FIMP (decay) phenomenology

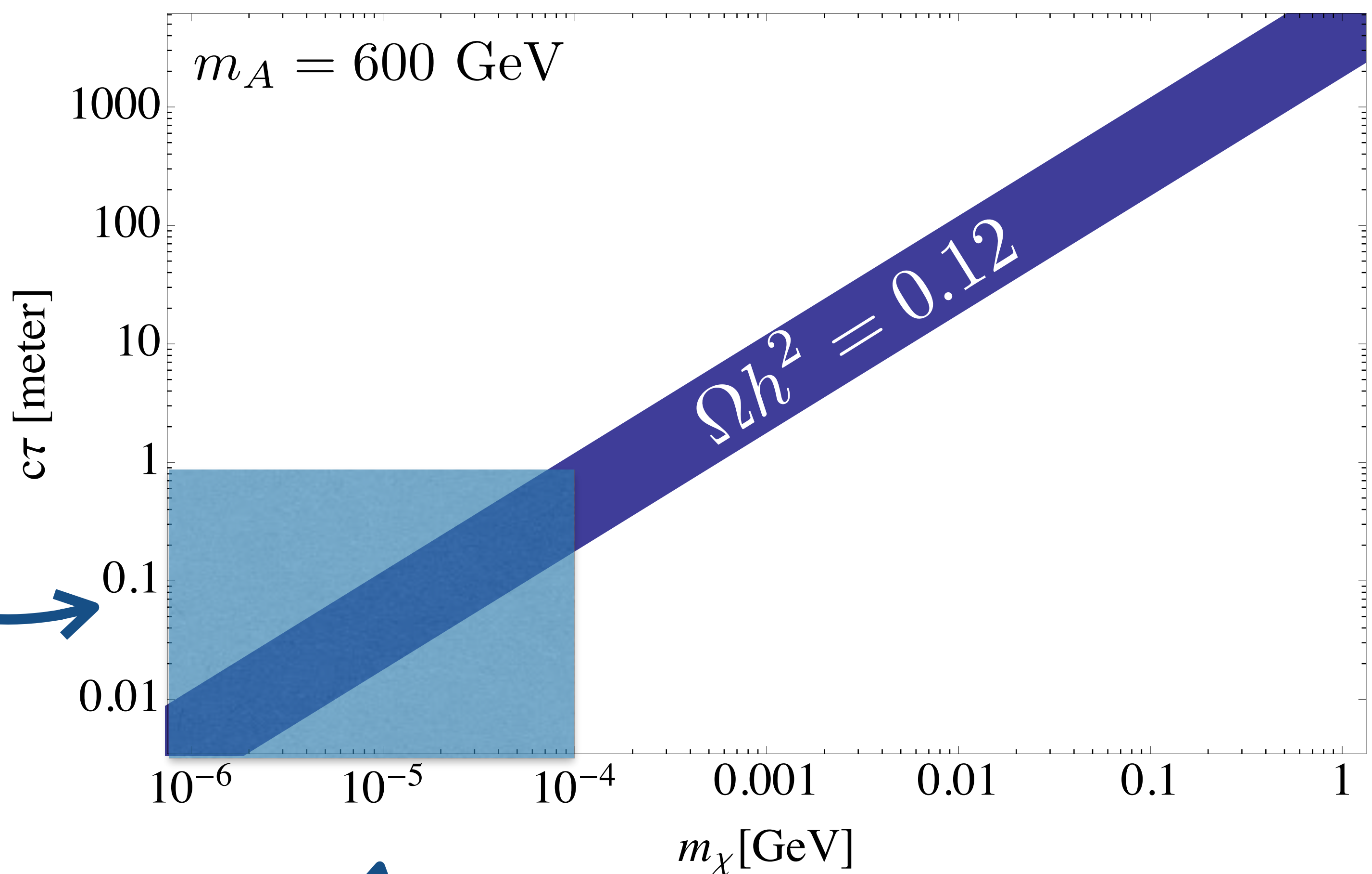
Standard Cosmology history

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

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

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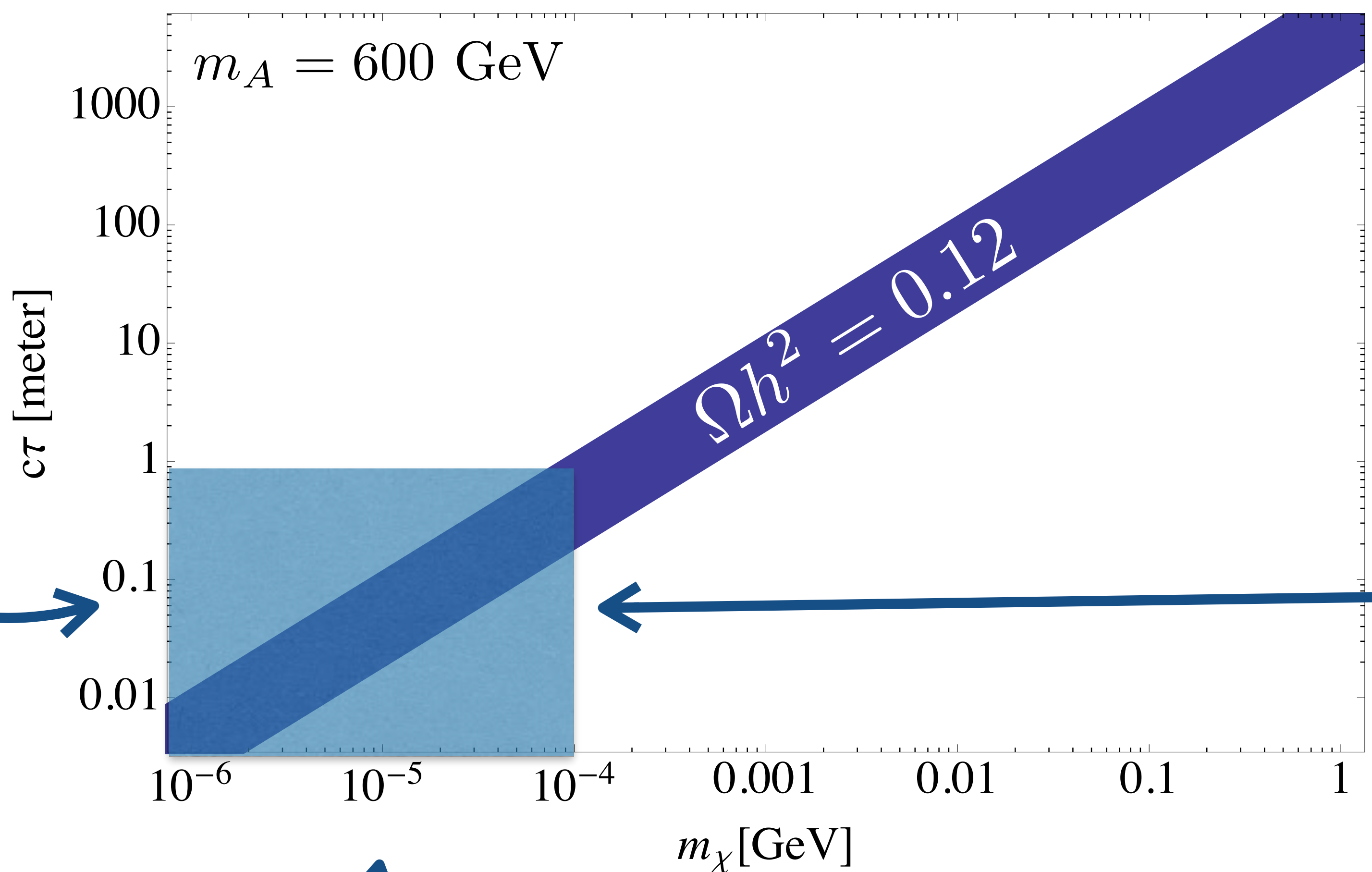


Displaced dark matter at LHC

?

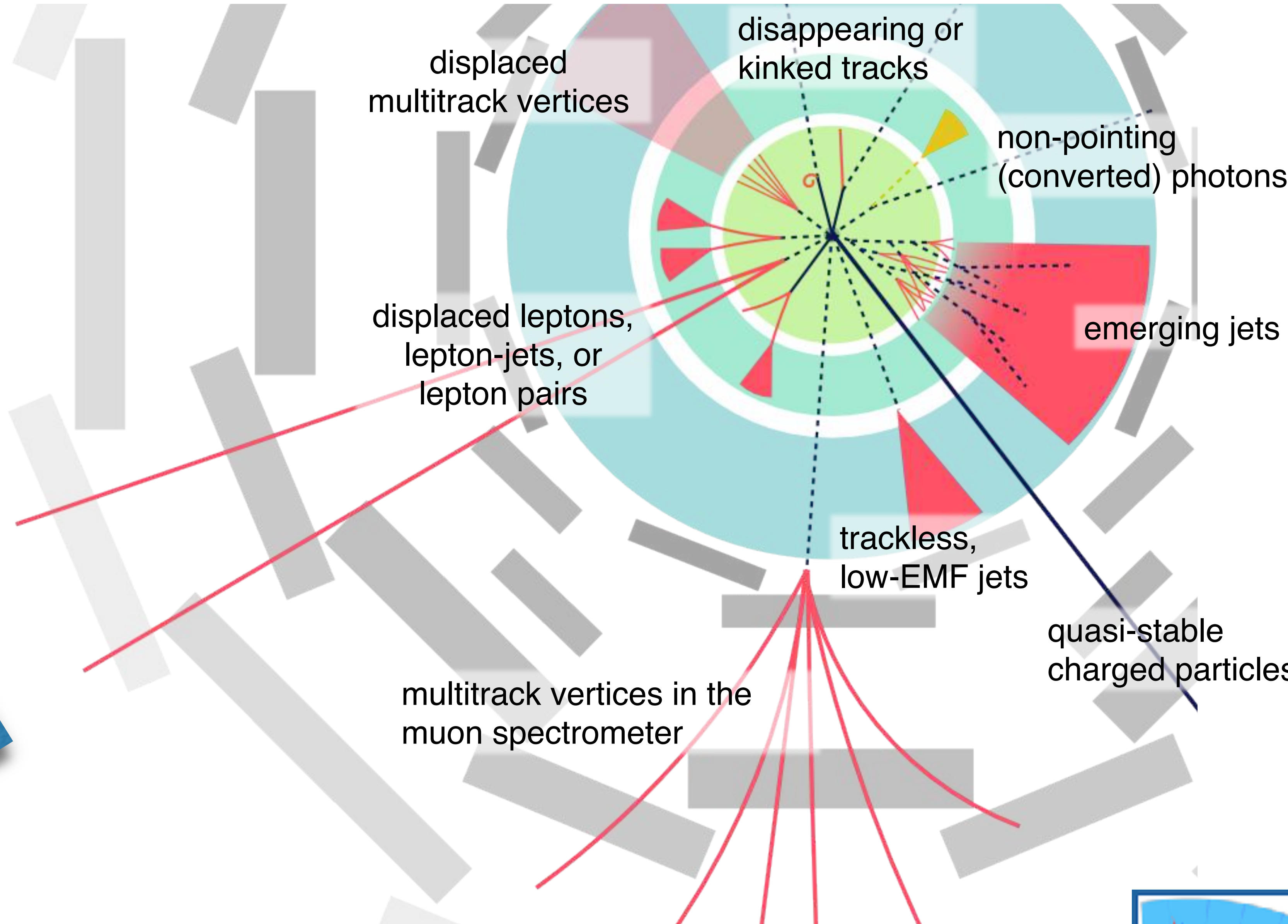
Warm DM signatures

Light Dark Matter regime

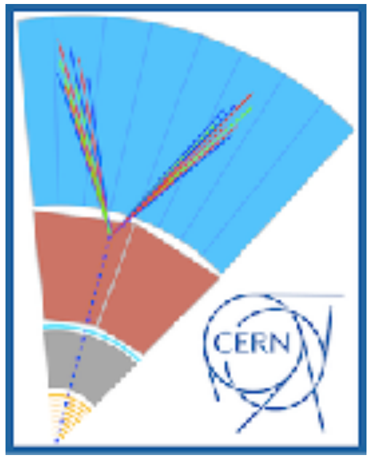
LongLived Signatures @ LHC

SM decays are typically prompt

New Physics signatures with low background

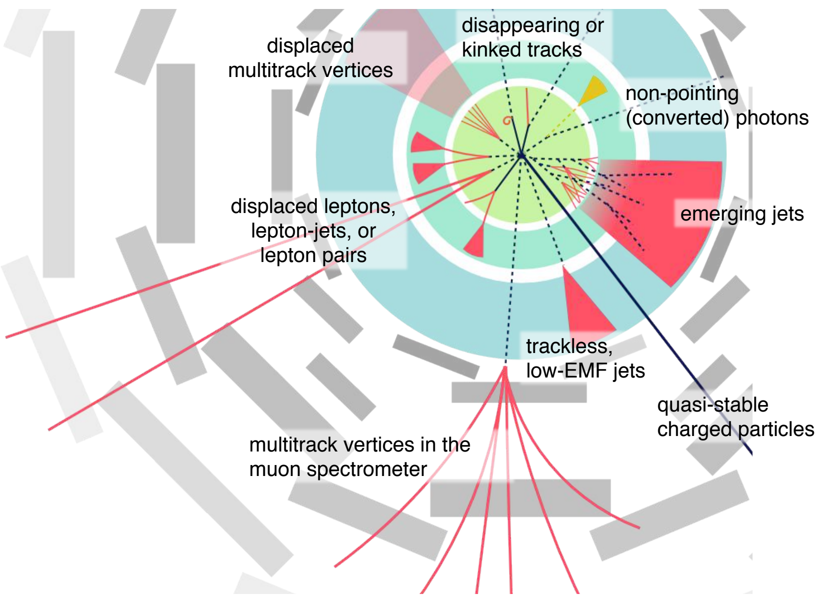


[Figure from Heather Russell]



Challenging but powerful

LongLived Signatures @ LHC



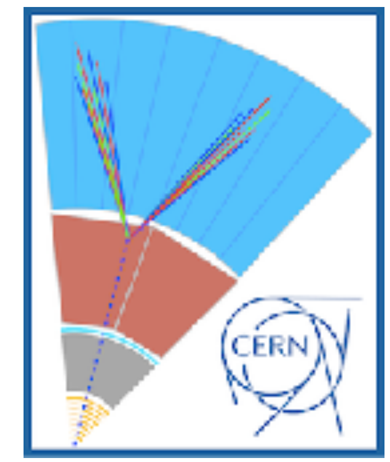
[Figure from Heather Russell]

- ✦ ***New CMS and ATLAS searches keep on coming***
- ✦ ***Many signatures not yet explored***
- ✦ ***HL-LHC will open new opportunities***
- ✦ ***Interesting for future detectors***
- ✦ ***Active Working Group***

Report: arXiv:1903.04497

Next meeting: 27-29 November in Ghent

BSM physic could hide there



DM connection

What are DM models with long-lived signatures?

✦ ***Several DM scenarios with LLP signatures…***

- ✳ ***FIMP, SuperWIMP, Asymmetric DM, Pseudo-Dirac DM, Conversion Driven FO, …***
- ✳ ***And others to come?***

Calibbi, Lopez-Honorez, Lowette, AM

Singlet Doublet Freeze In

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

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

Z2 symmetry imposed

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

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

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

Calibbi, Lopez-Honorez, Lowette, AM

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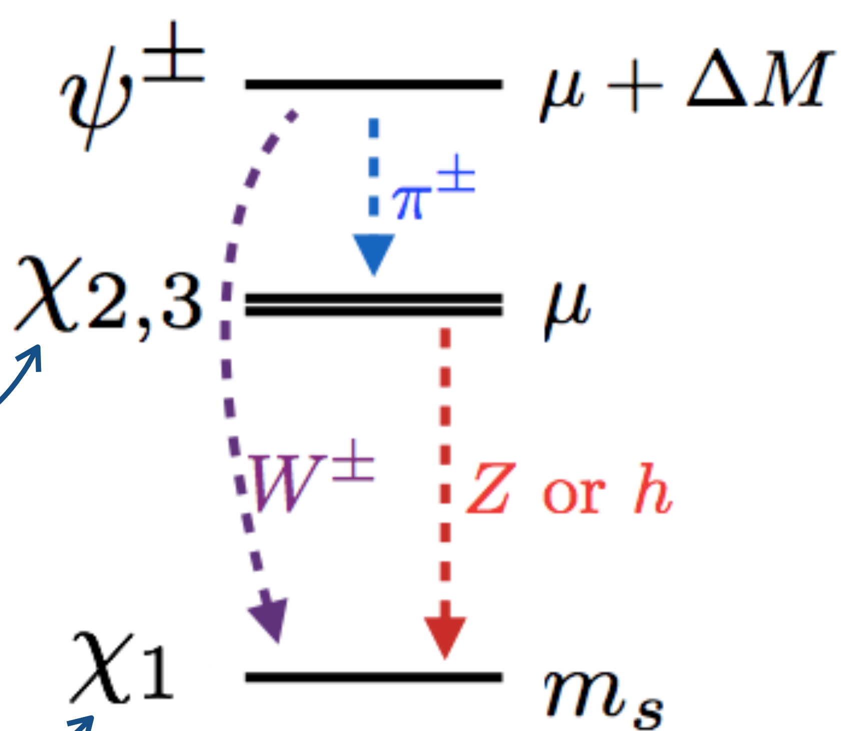
✦ *Regime for Freeze-in:* $y \ll 1, \quad |m_s| \ll |\mu|$

Similar to Higgsino-Bino with tiny mixing

Simple spectrum and decay modes

Radiative corrections



Long-lived states

Dark matter

Calibbi, Lopez-Honorez, Lowette, AM

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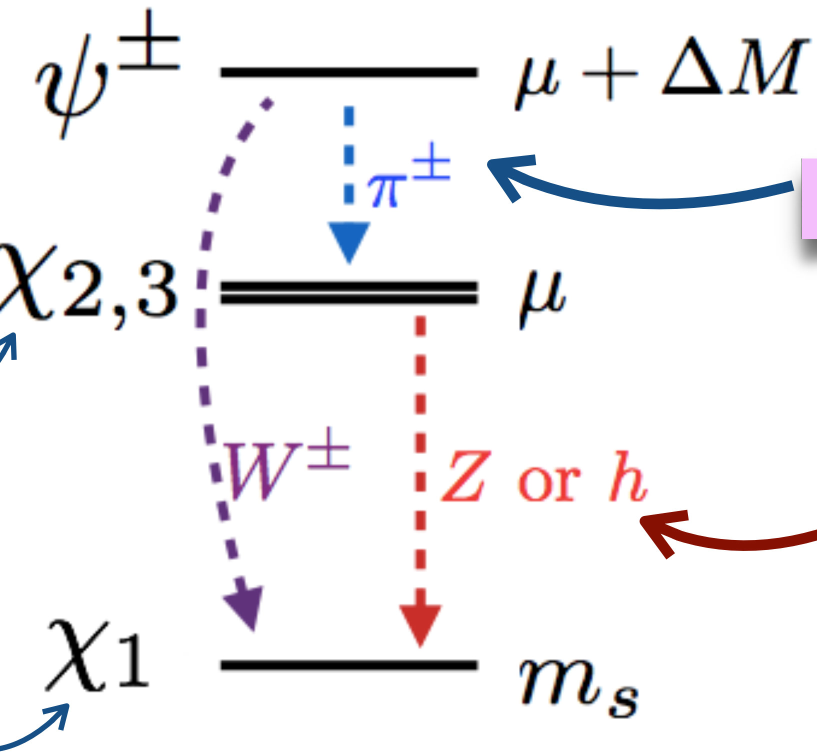

Radiative corrections

Disappearing tracks

Long-lived states

Displaced Z/h plus MET

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

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Dark matter abundance

Decay width of heavy doublet components into dark matter

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

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

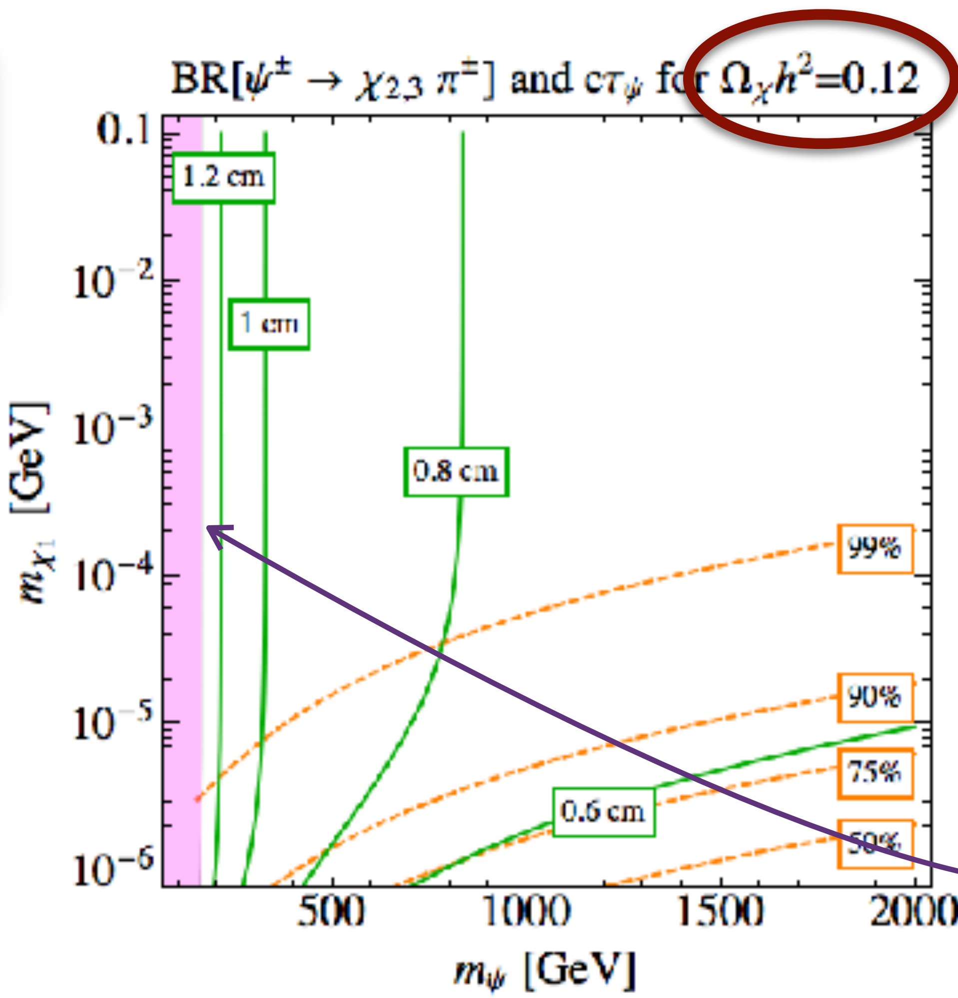
Calibbi, Lopez-Honorez, Lowette, AM

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

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

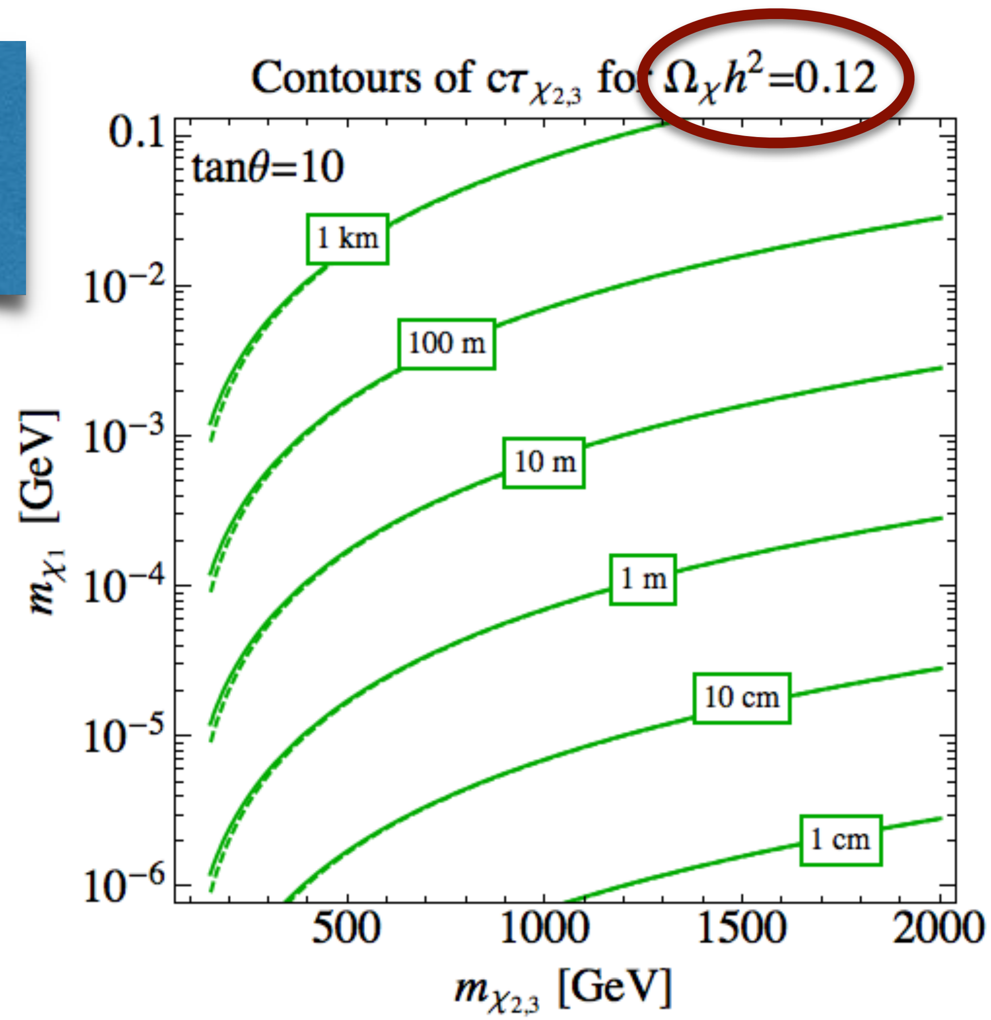
Calibbi, Lopez-Honorez, Lowette, AM

Freeze-in

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

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 0.01 to 1000 meter

Displaced Z/h plus MET

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

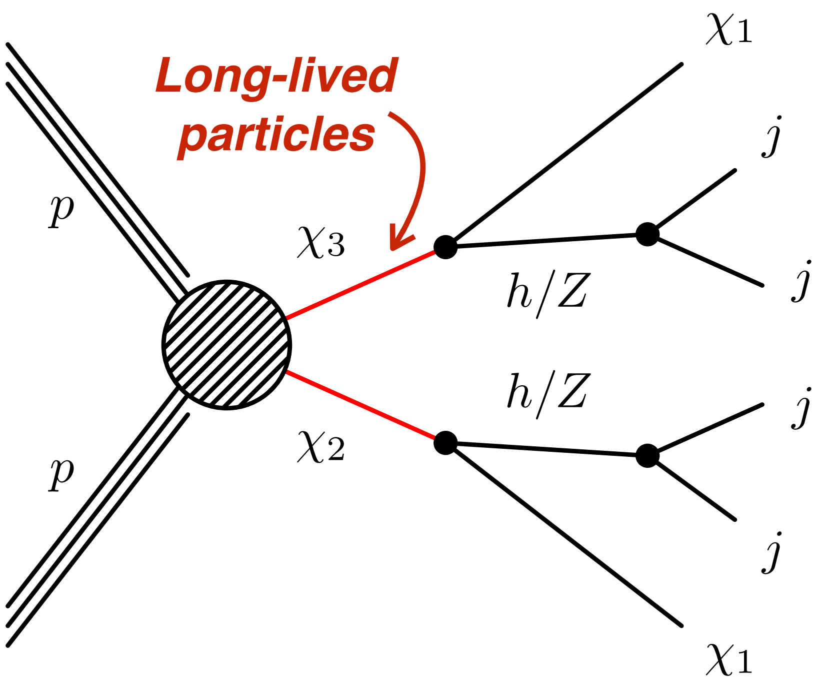
Calibbi, Lopez-Honorez, Lowette, AM

Collider signatures

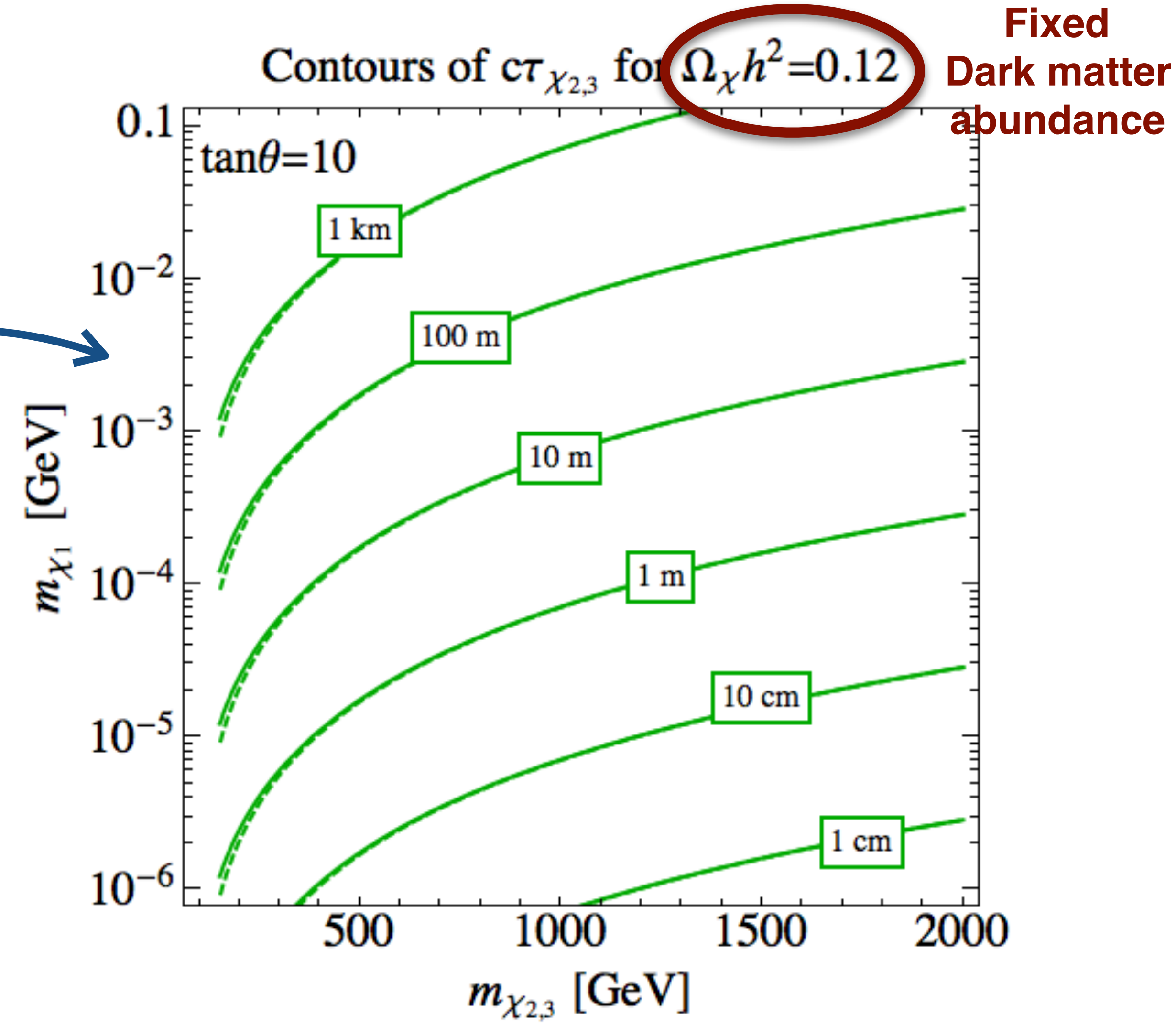
Production modes at the LHC

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

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 !

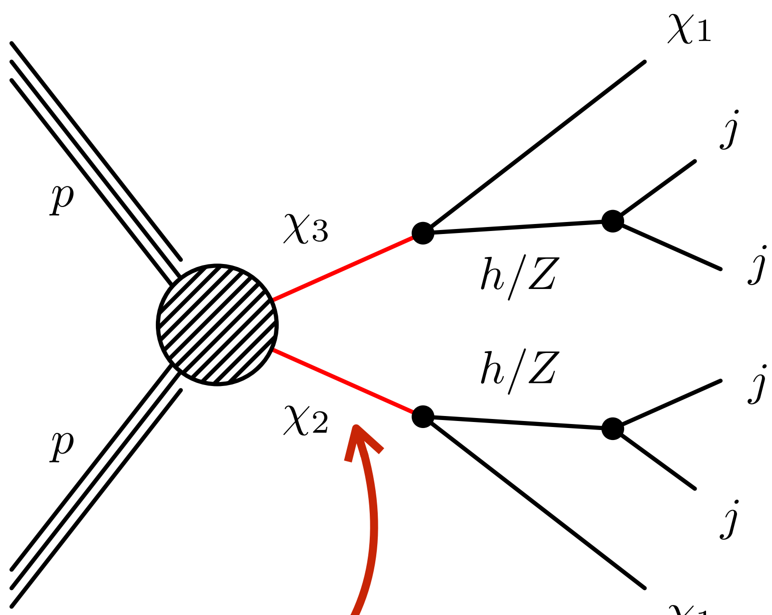
Calibbi, Lopez-Honorez, Lowette, AM

Recasting ATLAS DV+MET

ATLAS arXiv: 1710.04901
CERN-EP-2017-202

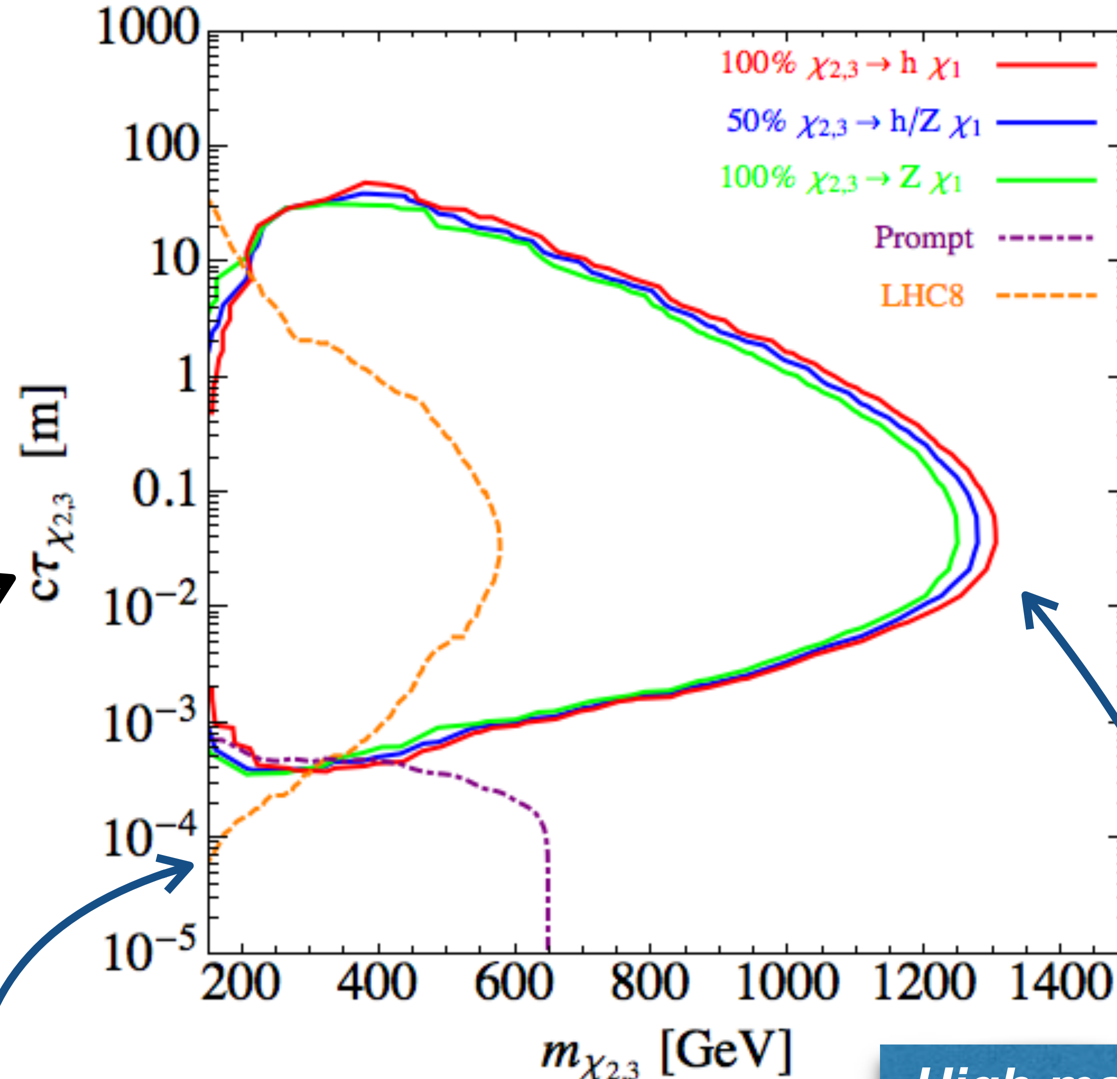
Search for Displaced Vertices + MET

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

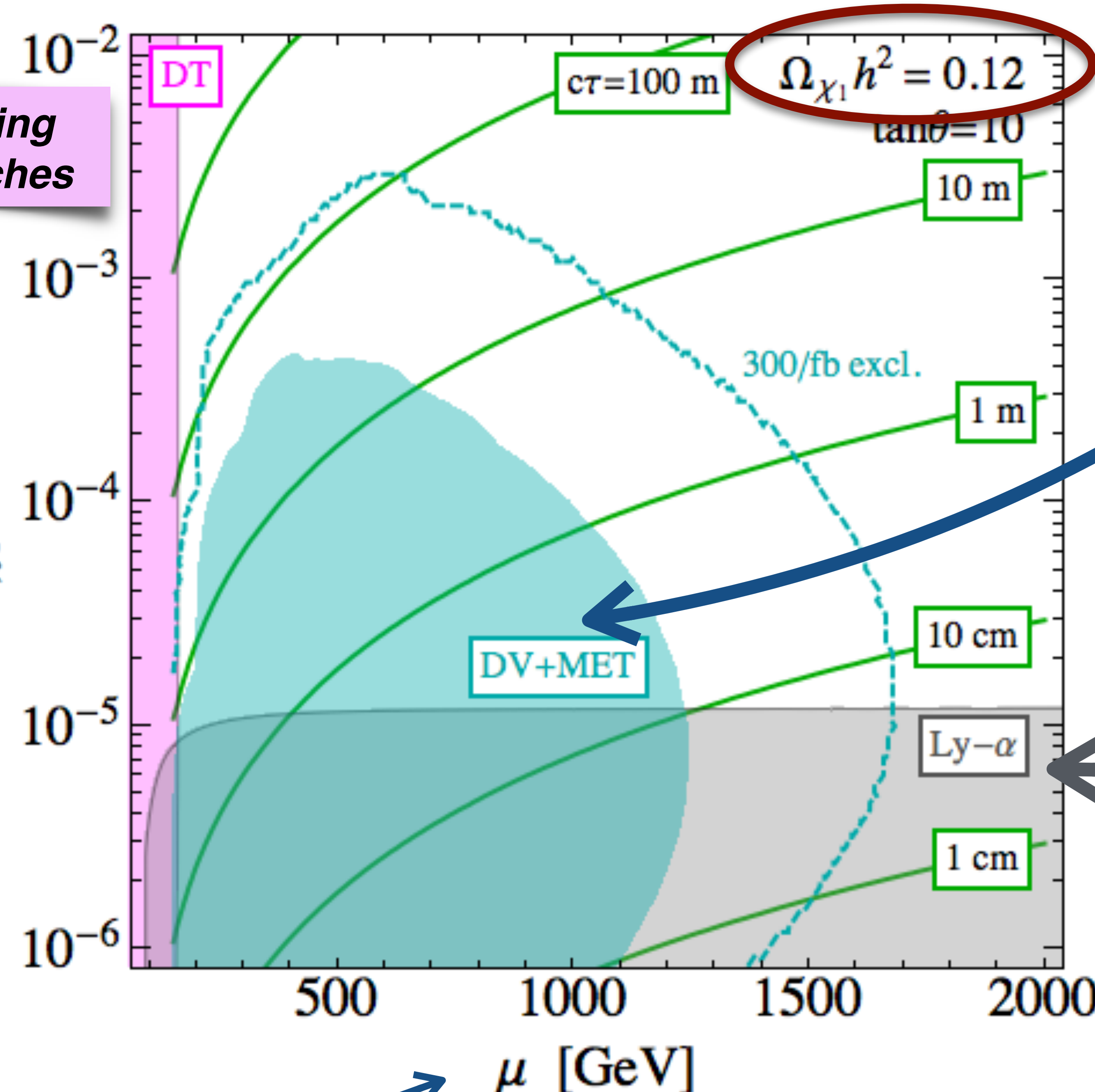
8TeV limits
Z.Liu, B.Tweedie, '15
CMS PAS EXO-12-038

Long lived particle mass

Calibbi, Lopez-Honorez, Lowette, AM

Combining LHC and Cosmo

Viable region on parameter space and pheno probes



Disappearing Track searches

Dark Matter Mass

Doublet mediator mass

Fixed Dark matter abundance

Our Recast of ATLAS DV+MET

"Warm" Dark Matter constraints (Lyman alpha)

J. Heeck and D. Teresi '17

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*

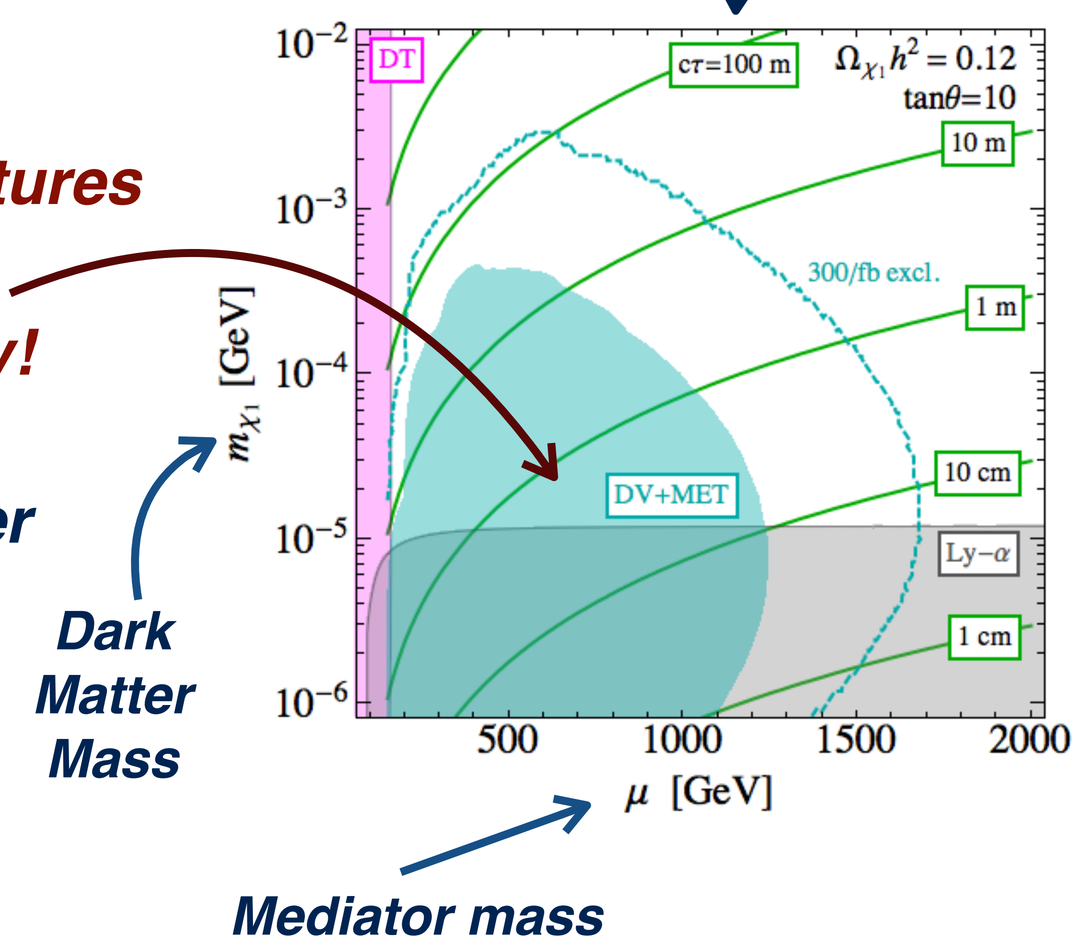
★*Naturally involves feeble coupling*

★*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*



In progress with Calibbi, D'Eramo, Junius, Lopez Honorez

What about reheating?

★*Assumption of radiation domination is very simplistic*

★*We know there is inflation!*

Reheating

★*At the end of inflation the SM bath is reheated at* T_{re}

Related to inflaton decay

★*Large allowed range for reheating temperature* $T_{re} > \mathrm{MeV}$

★*If* $T_{re} \sim m_A$ *the FIMP production mechanism is modified*

Q: How does the previous picture (freeze-in vs LLP) change with Tre?

R.Co, F. D'Eramo, L. Hall, D.Pappadopulo '15

Inputs from cosmology

★*After inflation: simple evolution of Universe energy density*

★*Governed by coupled Boltzmann equations*

Inflaton energy density

$$\frac{d\rho_M}{dt} + 3H\rho_M = -\Gamma_M \rho_M,$$

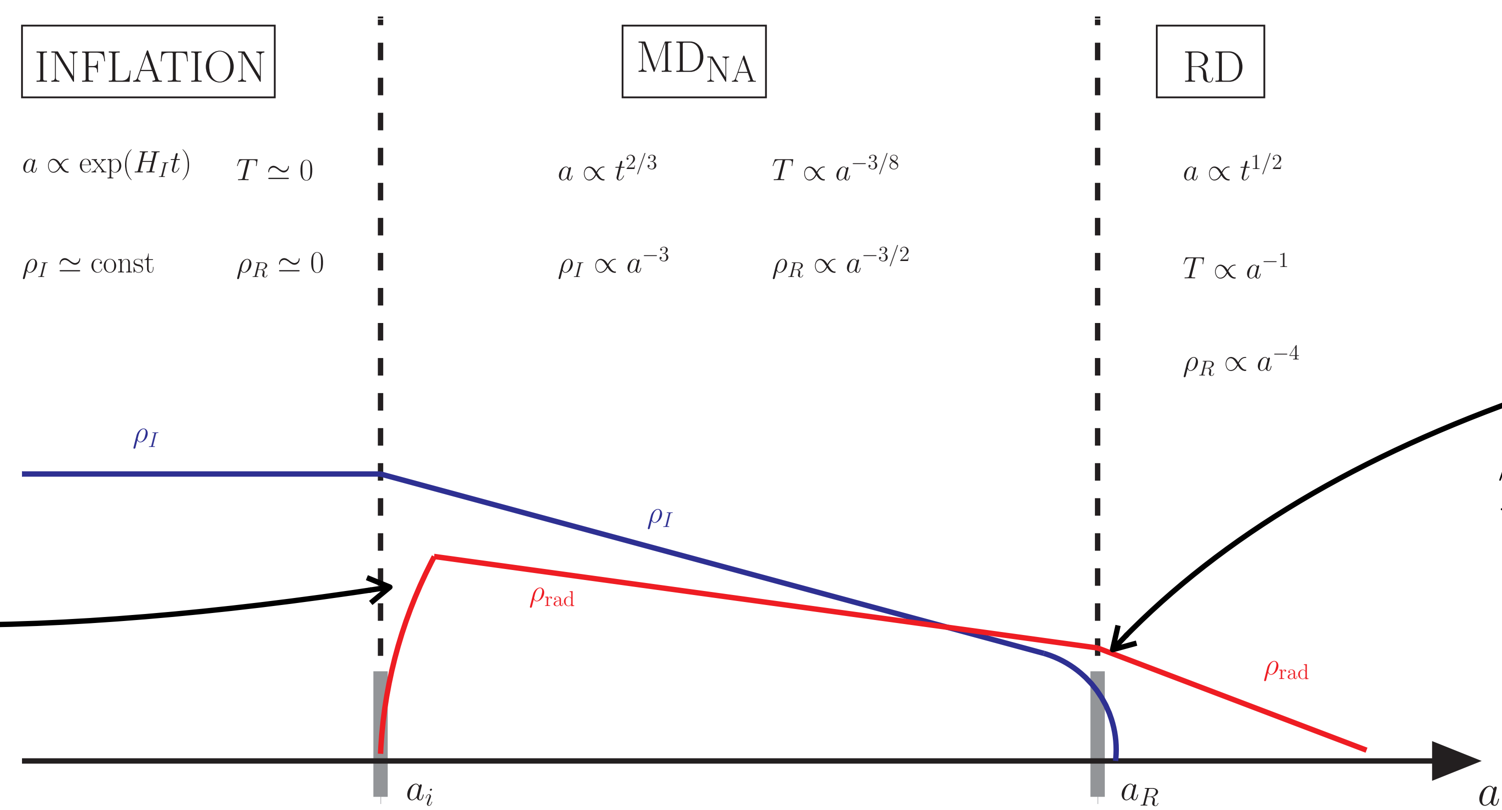
Radiation energy density

$$\frac{d\rho_R}{dt} + 4H\rho_R = \Gamma_M \rho_M.$$

Assume Inflaton decays into radiation

Maximal radiation temperature

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



Reheating temperature

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

Taken from R.Co, F. D'Eramo, L. Hall, D.Pappadopulo '15

T-reheating is new parameter in the model !!

See also Di Marco, De Gasperis, Pradisi, Cabella '19

In progress with Calibbi, D'Eramo, Junius, Lopez Honorez

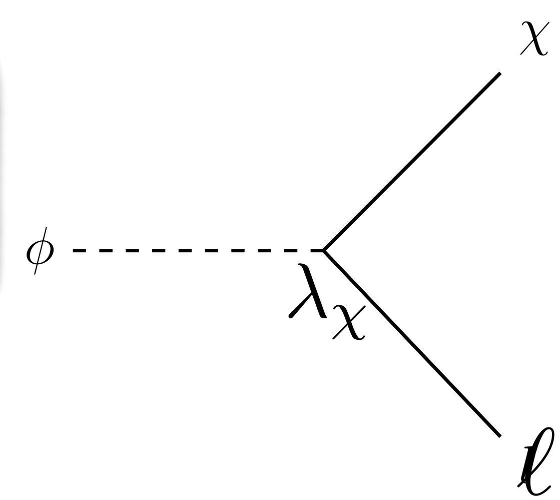
PRELIMINARY

A toy model

I consider a toy model to illustrate the impact of Tre on the DM pheno

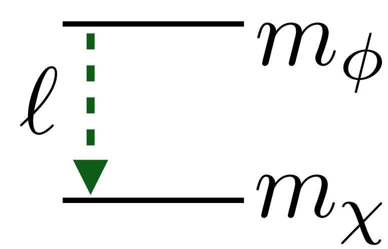
★SM plus leptophilic mediator ϕ plus DM χ

$$\mathcal{L} \supset \lambda_\chi \phi \bar{\chi} \ell_R + h.c.$$

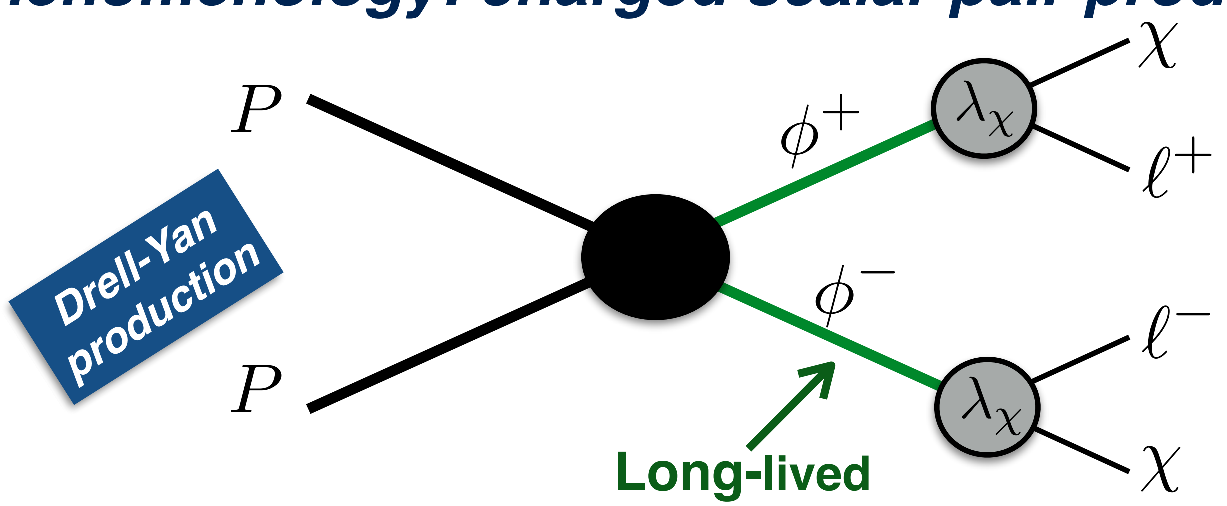


★Freeze-in through decay $\lambda_\chi \ll 1$

$$\frac{1}{c\tau_\phi} = \Gamma[\phi \to \ell\chi] \simeq \frac{\lambda_\chi^2}{16\pi} m_\phi$$



★LHC phenomenology: charged scalar pair production

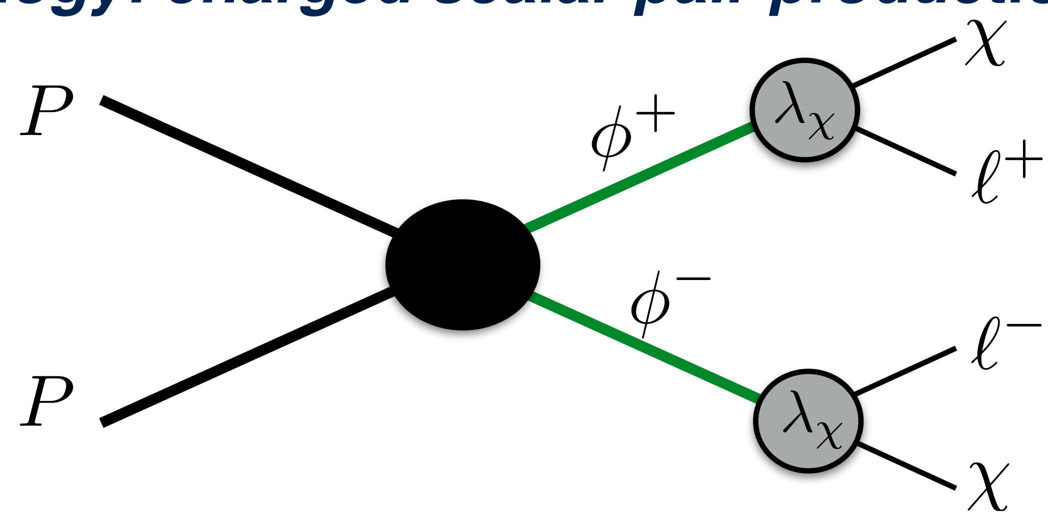


4 parameter model: $\{m_\phi, m_\chi, c\tau_\phi, T_{re}\}$

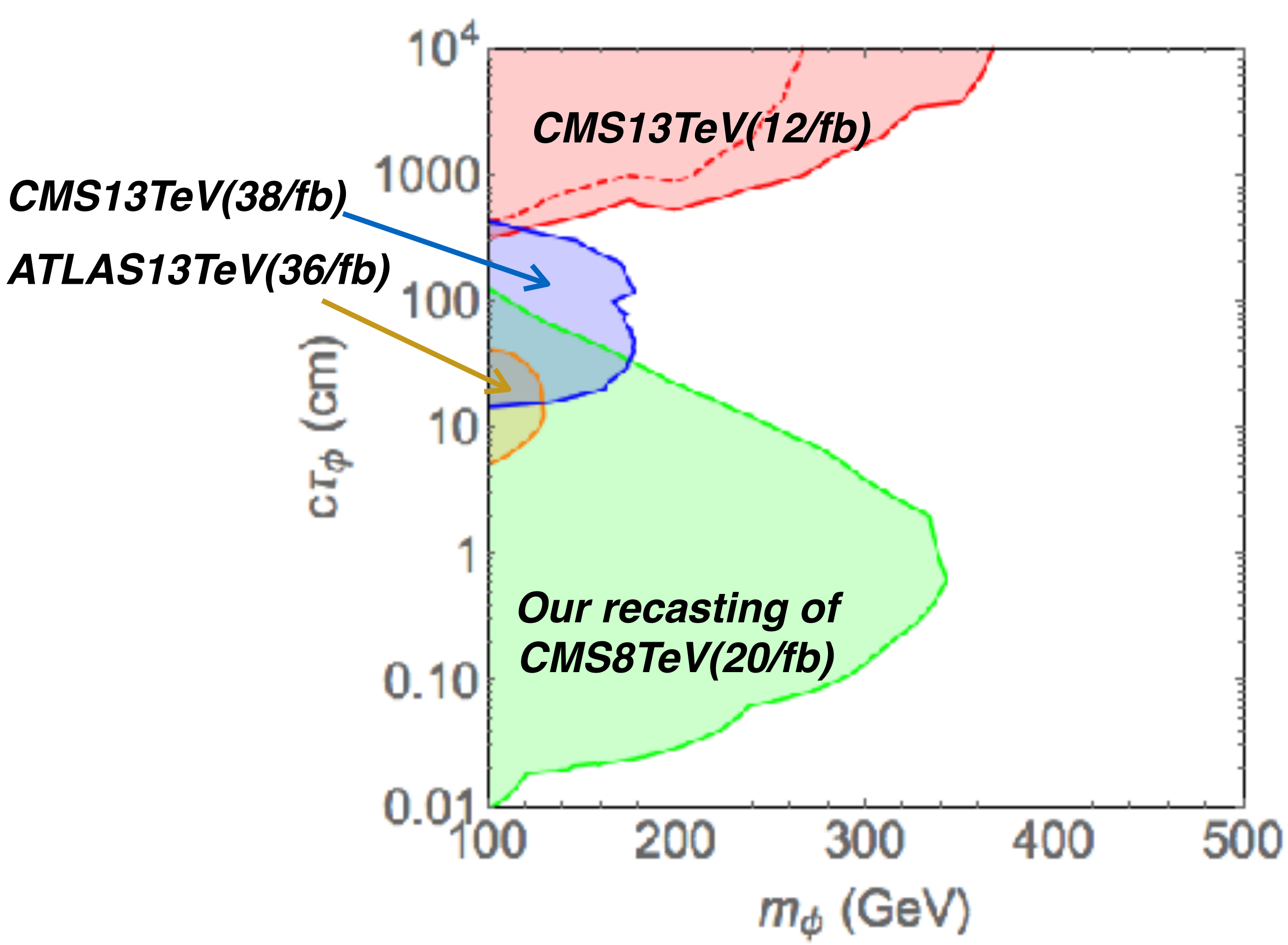
A toy model

PRELIMINARY

★ ***LHC phenomenology: charged scalar pair production***



★ ***Possible LHC signatures and constraints***



$c\tau_\phi \gtrsim$ meter — Charged tracks

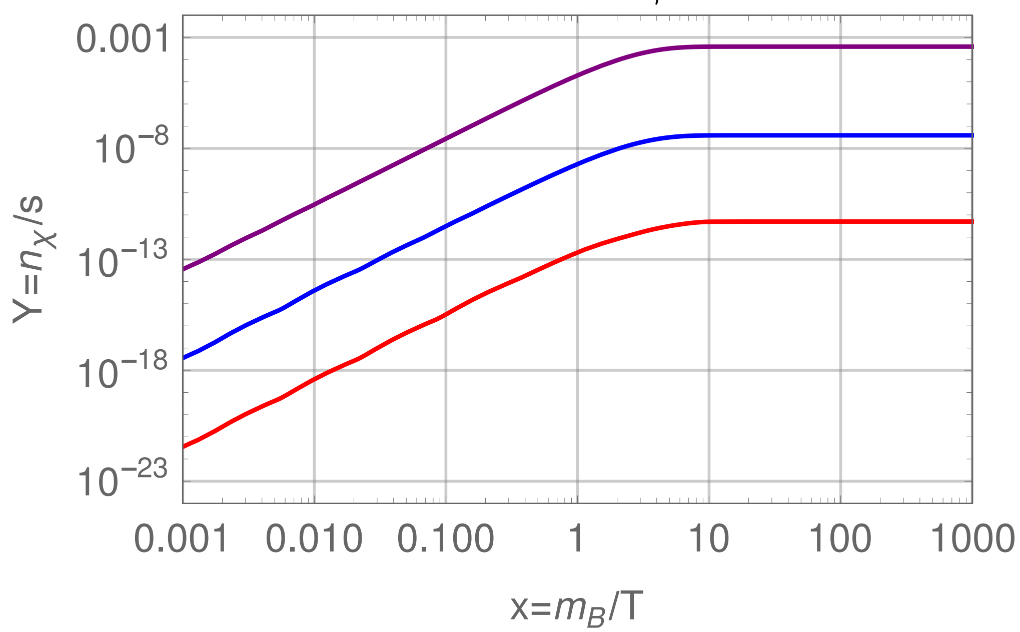
$c\tau_\phi \sim$ meter — Disappearing tracks*

meter $\gtrsim c\tau_\phi \gtrsim 0.1$ mm — Displaced leptons

High reheating T

PRELIMINARY

$$T_{re} \gg m_\phi$$



★ *Freeze-in during radiation domination*

★ *Freeze-in is IR dominated, stops at* $T \sim \frac{m_\phi}{3}$

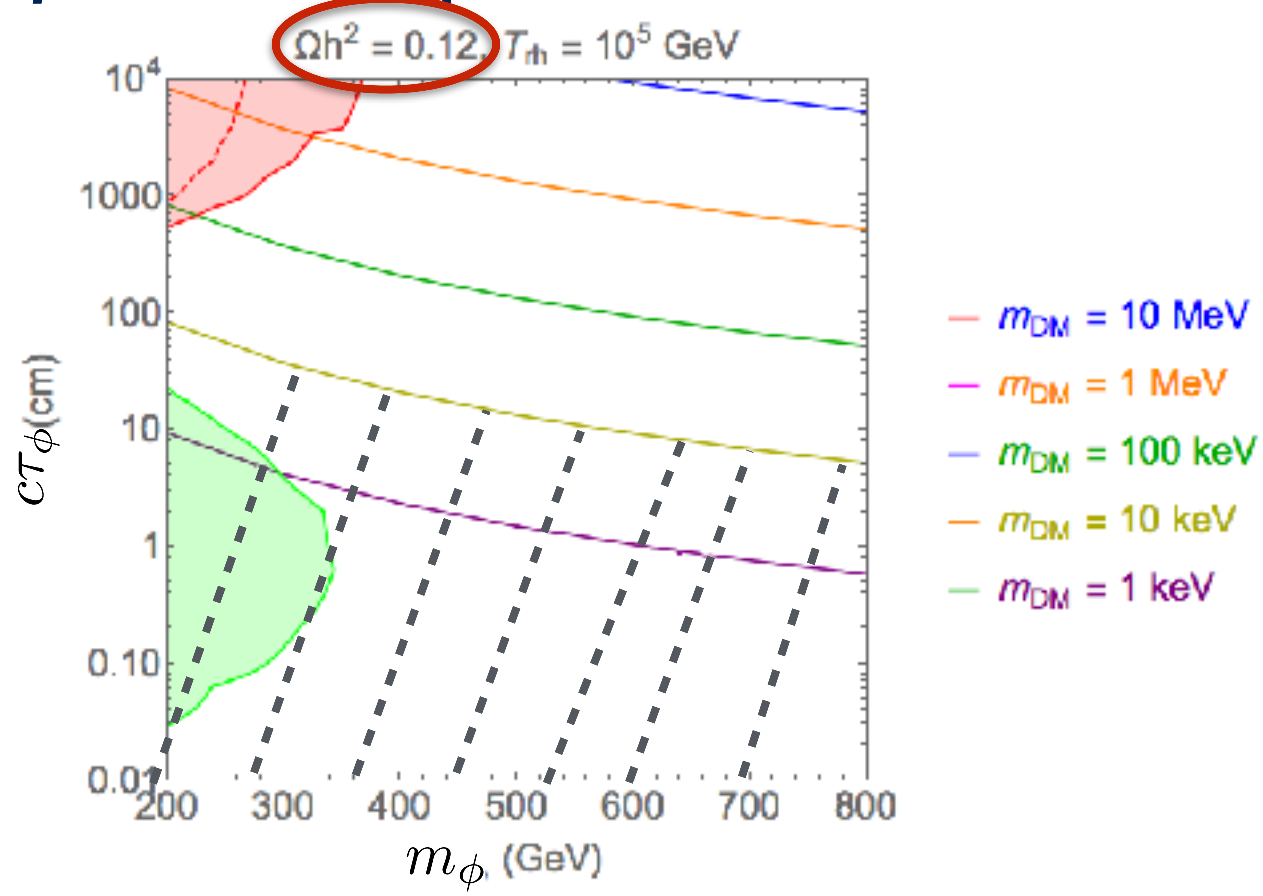
★ *DM abundance scales prop to mediator decay width*

★ ***Recover previous simplified assumptions results***

Cold DM
Very long lived mediator

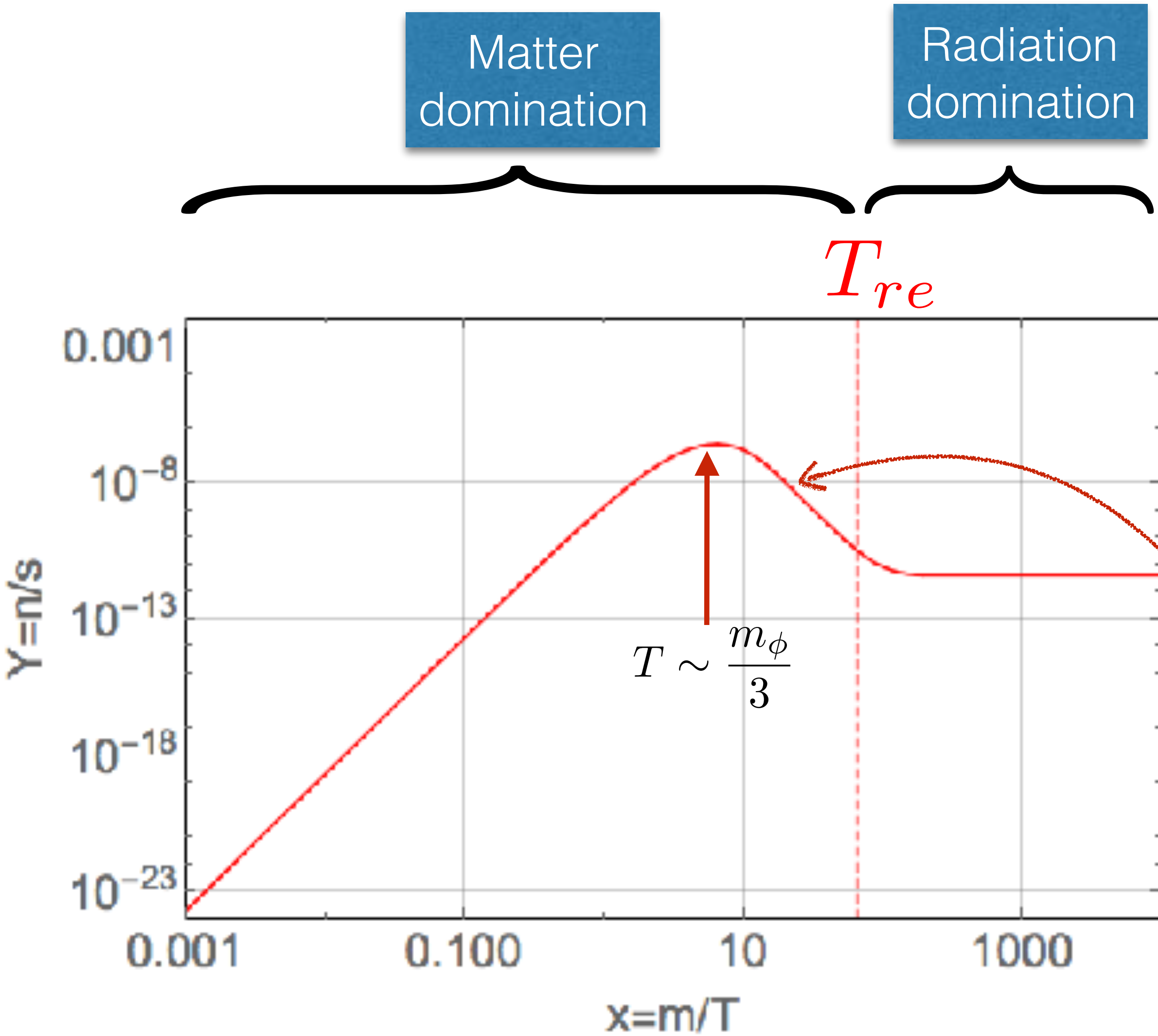
Very light DM
Displaced signatures

Tensions with Warm DM bounds



Small reheating Temp.

PRELIMINARY



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

★ ***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

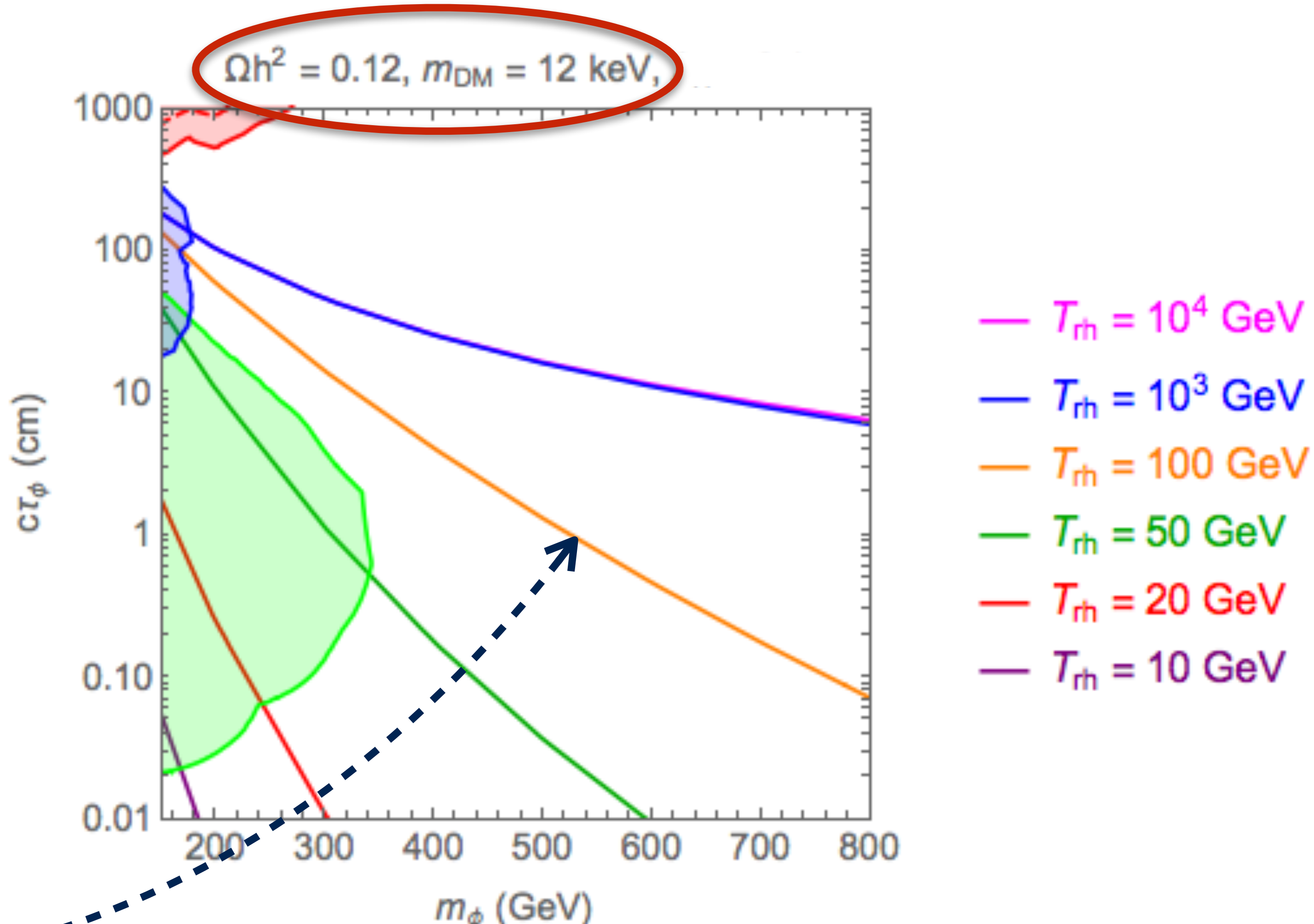
Max T reheating @ LHC

PRELIMINARY

We fix Dark Matter mass and impose correct DM relic abundance

Reheating temperature is predicted

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



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

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

Present and future plans

Calibbi, D'Eramo, Junius, Lopez Honorez, AM

★*Bottom-up approach for FIMP simplified models and LHC signatures*

★*Include higher dimensional operators study*

$$B \to \chi A_{SM}$$

Classify cases in base of spin and gauge quantum numbers

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

Provide connection between LLP signatures and DM cosmology

Some related works:

Calibbi, Lopez-Honorez, Lowette, AM '18 → *Singlet-Doublet model with light DM*

Bélanger, et al '18 → *Simplified models assuming instantaneous reheating*

No, Tunney, Zaldivar '19 → *Future detectors for Singlet-Doublet model*

Rychkov Strumia '07, ... Garcia, Mambrini, Olive, Peloso '17 .... → *Gravitino DM, High Dim.*

⋮

Conclusions

★*Explore alternative DM scenarios!*

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

★*Interplay with cosmology and reheating temperature*

...Take home messages ...

★*LHC can probe Feebly interacting DM!*

★*FIMP motivates further exotic LHC searches*

★*Rich phenomenology in DM production at early times*

★*Windows on DM cosmological history at the LHC*