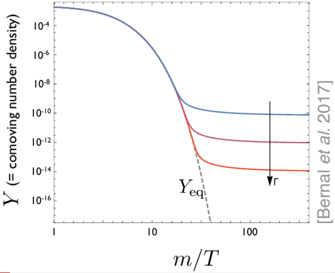
FIMPs: from freeze-in to conversion freeze-out

Laura Lopez Honorez

mainly based on **JHEP 1907 (2019) 136** & **JHEP 1809 (2018) 037**
in collaboration with L. Calibbi, S. Junius, S. Lowette & A. Mariotti

Scalars 2019 - Warsaw - 11-14/9/19

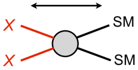
WIMP Freeze-out: The simple picture



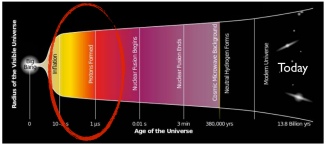
WIMP Freeze-out: The simple picture

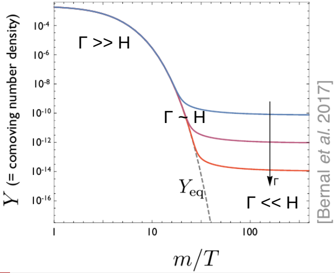
$$\Gamma \propto \langle \sigma v \rangle \sim H$$

Rate of thermalizing processes:



Expansion with Hubble rate *H*





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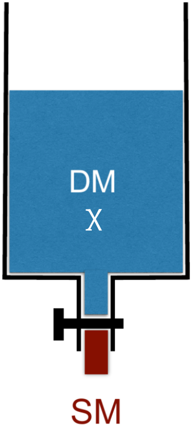
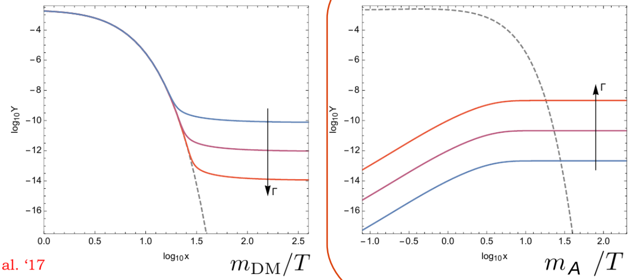


Freeze-out
DM annihilation driven

$$\Omega h^2 \propto 1/\langle \sigma v \rangle_{\chi\chi}$$

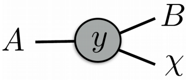
Freeze-out versus Freeze-in: going to $y \ll 1$

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



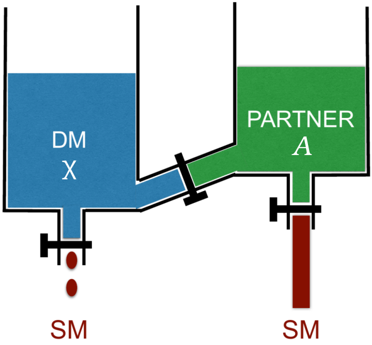
Bernal et al. '17

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



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

Annihilations vs coannihilations: going to $\Delta m \ll m$



Freeze-out

Partner annihilation driven

$$\Omega h^2 \propto 1/\langle \sigma v \rangle_{eff}$$

$$\langle \sigma v \rangle_{eff} \propto e^{-2x_f \frac{\Delta m}{m_\chi}} \langle \sigma v \rangle_{AA}$$

$$\Delta m = m_A - m_\chi$$

Simplified Model

Simplified Model

Simplified Model: 3 extra parameters m_χ, m_A, y

Dark matter χ ($\sim$ Majorana) fermion coupled to dark A and SM B through Yukawa-like interactions [see E. Ma, F. Kahlhoefer & O. Lebedev talks for FI with A from visible sector]

$$\mathcal{L} \subset y\,\chi AB$$

- Dark sector (Z_2 odd): $m_A > m_\chi$

Simplified Model: 3 extra parameters m_χ, m_A, y

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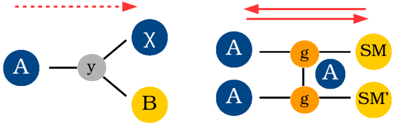
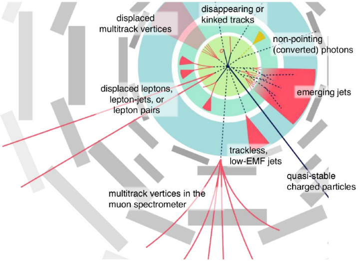


- Dark sector (Z_2 odd): $m_A > m_\chi$
- A is $SU(2) \times U(1)$ charged
    - fast $A^\dagger A \leftrightarrow$ SM SM through gauge interactions at early time
    - A is produced at colliders today
- χ-A-SM interactions:
    - $\chi \equiv$ FIMP $\leftrightarrow y \ll 10^{-4}$
    - long lived A at colliders through $A \to B\chi$



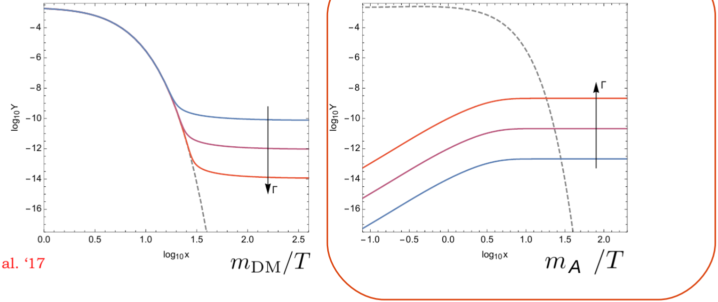
[Figure from Heather Russell]

[See also 1903.04497]

Frozen in FIMP:
Large mass splittings within the singlet doublet case

Freeze-in

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



Bernal et al. '17

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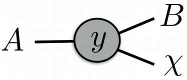


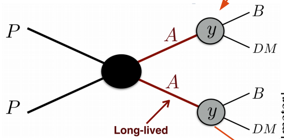
$y \sim 10^{-8}$ for $\Gamma_A \sim \frac{y^2}{8\pi} m_A$

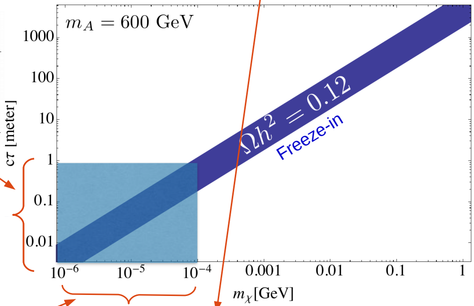
Freeze-in : displaced vertices and cosmology interplay

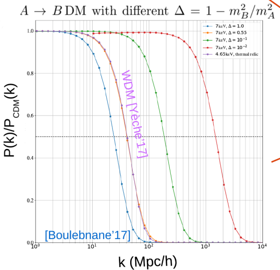
see also e.g. [Hall'09, Co'15, Hessler'16, d'Eramo'17, Buchmueller'17, Heeck'17, Boulebnane'17, Brooijmans'18, Garny'18]

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

Mediator mass range
reachable at colliders





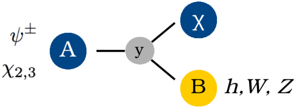


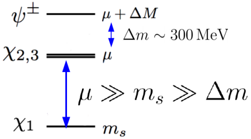
Warm DM like signatures
Suppressing small scale structures

[see also talk by Felix Kahlhoefer and Johannes Herms for other probes of

Framework: H-coupled fermionic Dark Matter

see also [Mahubani'05, D'Eramo'07, Enberg'07, Cohen'11,Clifford'14, Calibi'15, Freitas'15; etc]





$$-\mathcal{L} \supset \mu\, \psi_d \cdot \psi_u + y(\, \psi_d \cdot H\, \psi_s + \, H^\dagger \psi_u\, \psi_s) + m_s/2\, \psi_s \psi_s + h.c.\,,$$

- SM + 3 dark fermions$\rightsquigarrow$ Z_2 symmetry for DM stability

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

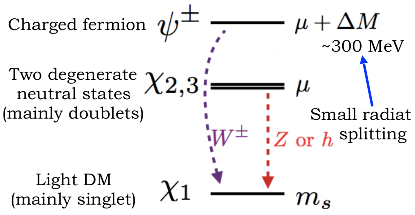
$$(\chi_1, \chi_2, \chi_3)^T = U\, \left(\psi_s, \psi_d^0, \chi_u^0\right)^T$$

- We work in the limit: $y \ll 1$ and $\mu \gg m_s$

Freeze-in from doublet decay

Freeze-in in the limit of $y \ll 1$ & $\mu \ll m_s$:

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



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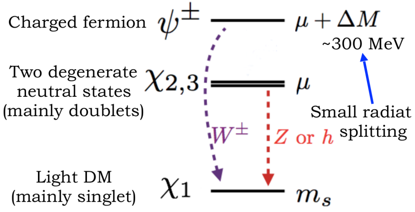
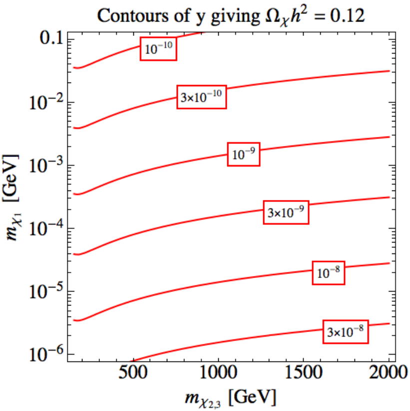




$\rightsquigarrow$ relevant H-coupling for freeze-in in 1M2D: $y < \mathcal{O}(10^{-8})$ for $m_{DM} >$ few keV

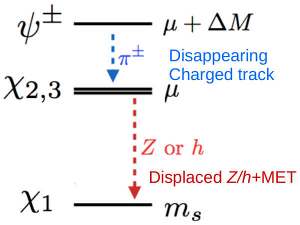
Results confirmed using micrOMEGAs5.0 [Belanger'18]

Disapearing track or displaced h/Z+ MET

Copious production of $\chi_{2,3}, \psi^{\pm}$ at colliders through EW processes

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

- $\chi_2\chi_3 \to ZZ/hh/Zh$+ MET



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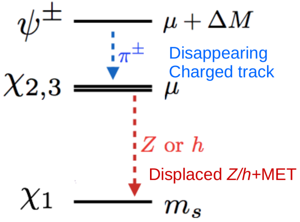
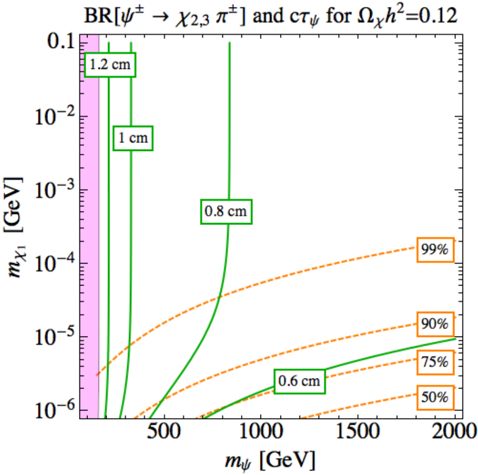
- $\psi^{\pm} \to \pi^{\pm}\chi_{2,3}$
  $\rightsquigarrow$ disapearing charged track
  with $c\tau \sim \mathcal{O}(\text{ cm})$
  $\rightsquigarrow$ $\mu > 150$ GeV from [ATLAS DT'17]
- $\chi_2\chi_3 \to ZZ/hh/Zh$+ MET





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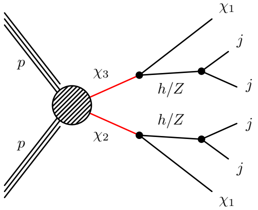
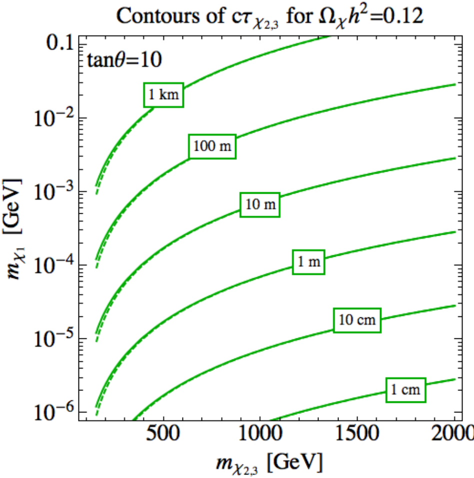
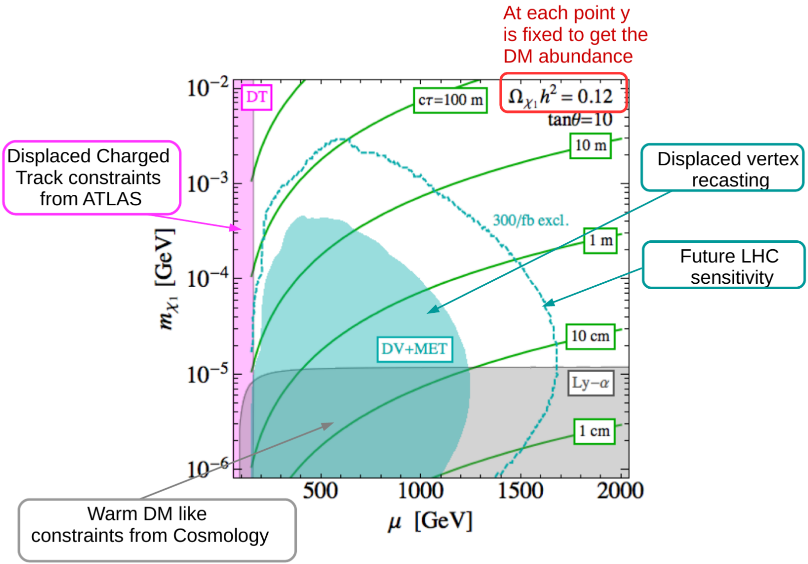
  $\rightsquigarrow$ disapearing charged track
  with $c\tau \sim \mathcal{O}(\text{ cm})$
  $\rightsquigarrow \mu > 150$ GeV from [ATLAS DT'17]
- $\chi_2\chi_3 \to ZZ/hh/Zh$+ MET
  $\rightsquigarrow$ displaced vertex with jet and MET with possibly $c\tau > \mathcal{O}(\text{ cm})$
  $\rightsquigarrow$ probe $\mu \leq 1.2$ TeV [ATLAS DV'17]





LHC & Cosmo complementarity



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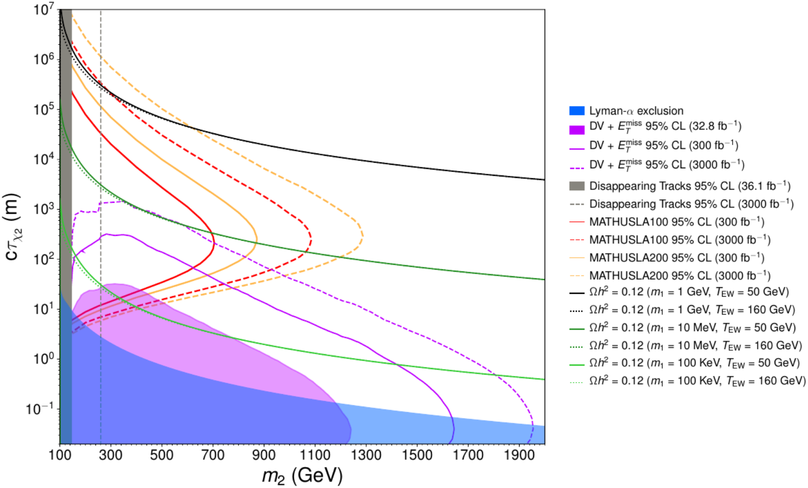
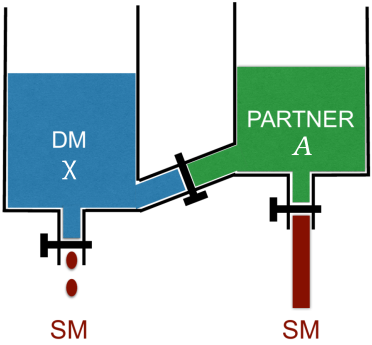


[No, Tunney & Zaldivar'0919]

Conversion driven freeze-out
Leptophilic DM

Annihilations vs coannihilations: going to $\Delta m \ll m$



Freeze-out
Partner annihilation driven

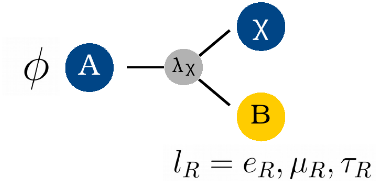
$$\Omega h^2 \propto 1/\langle \sigma v \rangle_{eff}$$

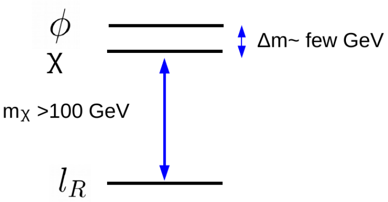
$$\langle \sigma v \rangle_{eff} \propto e^{-2x_f \frac{\Delta m}{m_\chi}} \langle \sigma v \rangle_{AA}$$

$$\Delta m = m_A - m_\chi$$

Framework: Leptophilic DM with compressed spectrum

see also [Bergstrom '89+, Bringmann '08+, Ciafaloni '11, Garny '11+,Toma '13, Giacchino'13++, Ibarra'14, Belanger'18, Calibbi'18...]



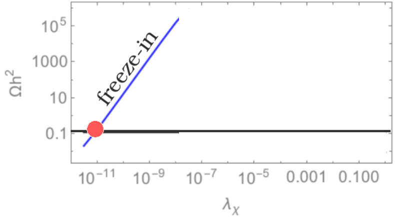


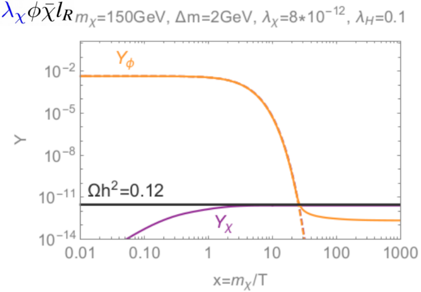
$$\mathcal{L} \subset \mathcal{L}_K - \frac{m_\chi}{2}\bar{\chi}\chi - m_\phi \phi^\dagger \phi \; - \; \lambda_\chi \phi \bar{\chi} l_R \; + \lambda_H |\phi|^2 |H|^2 + h.c.$$

- SM + 1 charged dark scalar ϕ + 1 Majorana dark fermions χ (Z_2 symmetry for DM stability)
- $m_\phi > m_\chi$ and we are mostly interested in $\lambda_\chi \ll 10^{-4}$
  $\rightsquigarrow$ ϕ LLP at colliders
- We work in the compressed limit: $\Delta m = m_\phi - m_\chi < m_\chi$

From freeze-in to Freeze-out through coannihilations

$\mathcal{L} \subset - \lambda_\chi \phi \bar{\chi} l_R$



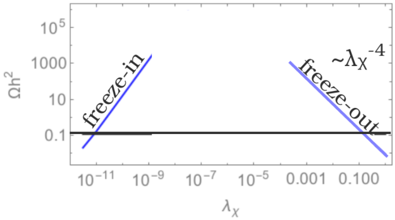


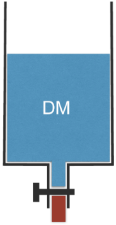
Freeze-in: feeble couplings $\lambda_\chi < 10^{-8}$
$Y_\chi \propto \Gamma_{\phi\to\chi\ell} \propto \lambda_\chi^2$

- Annihilations: $\phi\phi^\dagger \to$SM SM
  keep ϕ in eq. until ϕ fo (rate $\propto g^4$)
- Conversions: $\phi \to \ell\chi$ and ϕSM $\to \chi$SM
  DM production (rate $\propto \lambda_\chi^2, \lambda_\chi^2 g^2$)

From freeze-in to Freeze-out through coannihilations

$$\mathcal{L} \subset - \lambda_\chi \phi \bar{\chi} l_R$$





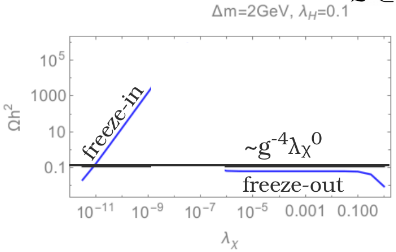
DM annihilations driven Freeze-out: weak couplings $\lambda_\chi \gtrsim 0.1$

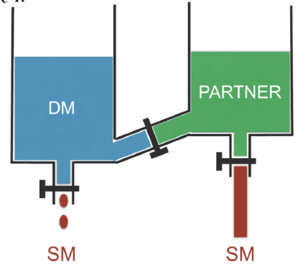
$$Y_\chi \propto 1/\sigma v_{\chi\chi} \propto \lambda_\chi^{-4}$$

- Annihilations: $\chi\chi \to \ell\ell$
  keep χ in eq. until χ fo (rate $\propto \lambda_\chi^4$)

From freeze-in to Freeze-out through coannihilations

$\mathcal{L} \subset - \lambda_\chi \phi \bar{\chi} l_R$





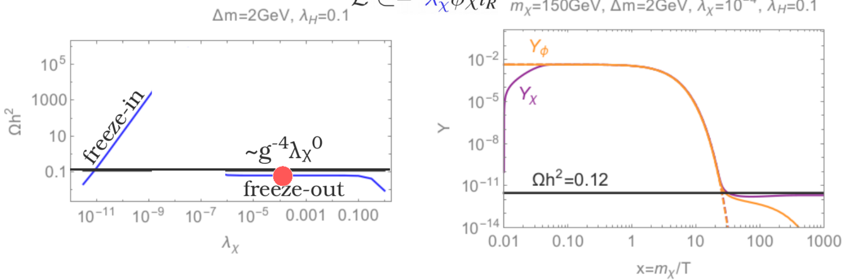
Mediator annihilation driven Freeze-out: weak couplings $\lambda_\chi \lesssim 0.1$

$$Y_\chi \propto 1/\sigma v_{\phi\phi^\dagger} \propto \lambda_\chi^0$$

- small mediator-DM splitting $\Delta m/m_\chi \lesssim 0.1$
- Annihilations: $\phi\phi^\dagger \to$SM SM
  keep ϕ in eq. until ϕ fo (rate $\propto g^4$)
- Conversions: $\phi \to \ell\chi$ and ϕSM $\to \chi$SM
  keep ϕ and χ in chemical equ. (rate $\propto \lambda_\chi^2, \lambda_\chi^2 g^2$)

From freeze-in to Freeze-out through coannihilations

$\mathcal{L} \subset -\ \lambda_\chi \phi \bar{\chi} l_R$



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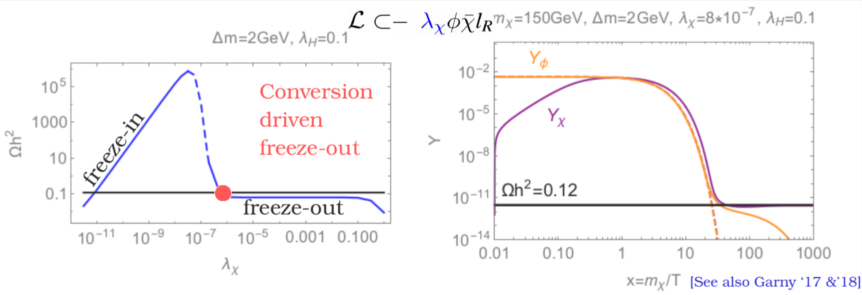
From freeze-in to Freeze-out through coannihilations

$\mathcal{L} \subset - \lambda_\chi \phi \bar{\chi} l_R$



[See also Garny '17 &'18]

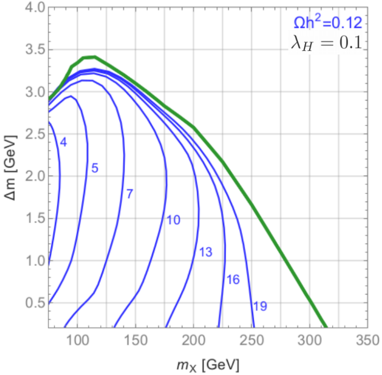
Conversion driven Freeze-out: feeble couplings $\lambda_\chi \lesssim 10^{-7}$

$Y_\chi \nearrow$ when $\Gamma_{\phi\leftrightarrow\chi} \searrow$

- small mediator-DM splitting $\Delta m/m_\chi \lesssim 0.1$
- Annihilations: $\phi\phi^\dagger \to$SM SM
  keep ϕ in eq. until χ fo (rate $\propto g^4$)
- Conversions: $\phi \to \ell\chi$ and ϕSM $\to \chi$SM
  barely keep ϕ and χ in chemical equ. (rate $\propto \lambda_\chi^2$) $\rightsquigarrow n_\chi(T) > n_\chi^{eq}(T)$

Conversion driven FO: Viable parameter space

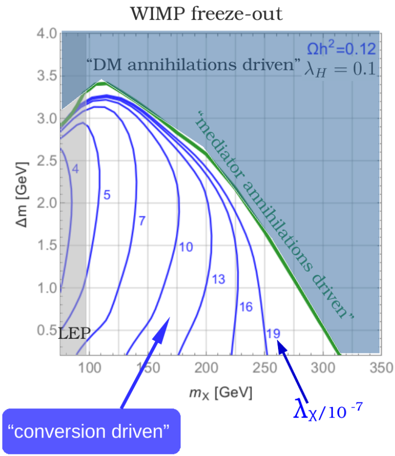
$\lambda_\chi \lesssim$ few $\times 10^{-6}$, $\Delta m <$ few GeV and $m_\chi \sim$ few $\times$ 100 GeV for $\lambda_H = 0.1$



Conversion driven FO: Viable parameter space

$\lambda_\chi \lesssim$ few $\times 10^{-6}$, $\Delta m <$ few GeV and $m_\chi \sim$ few $\times$ 100 GeV for $\lambda_H = 0.1$

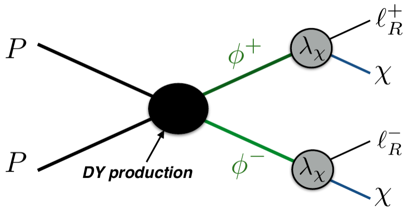
- right limit: freeze-out driven by mediator annihilations
- left limit: LEP constraints on charged mediators
- bottom limit: $\Delta m > m_l$ (or beyond $2 \to 2$)

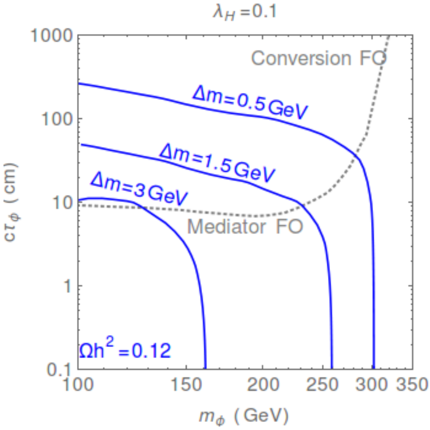


Collider constraints on charged (disapearing) track

Production of charged ϕ at colliders through EW processes (for small Δm):

$$\Gamma_{\phi\to\chi l} \approx \frac{1}{25\text{ cm}}\left(\frac{\lambda_\chi}{10^{-6}}\right)^2\left(\frac{\Delta m}{1\text{ GeV}}\right)^2\left(\frac{100\text{ GeV}}{m_\chi}\right)$$





$\ell_R = \mu_R$

Collider constraints on charged (disapearing) track

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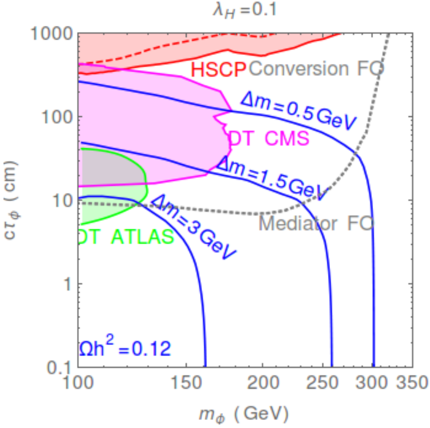
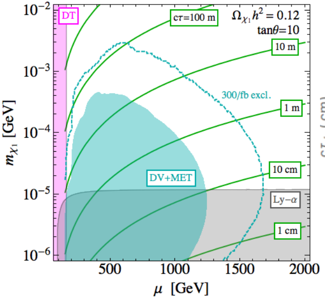
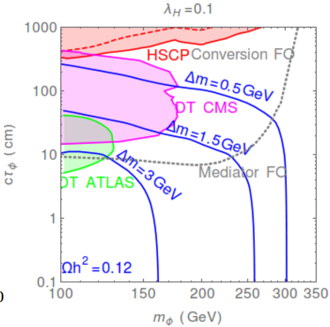


$\ell_R = \mu_R$

Conclusion





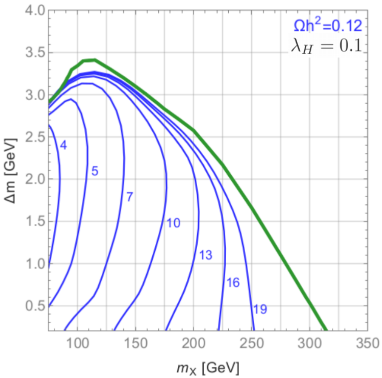
- H-coupled FIMP fermionic DM: freeze-in through decays
  - small couplings $y \sim 10^{-8} - 10^{-9}$ long lived mediator at colliders tested with displaced vertices and dispearing charged track
  - complementary constraints from cosmology with WDM-like behaviour of light FIMP.
- Leptophilic FIMP fermionic DM: Conversion driven freeze-out
  - small couplings $y \sim 10^{-6} - 10^{-8}$ but long lived mediator at colliders partially tested with charged tracks

Thank you for your attention!

Backup

Conversion driven FO: Viable parameter space

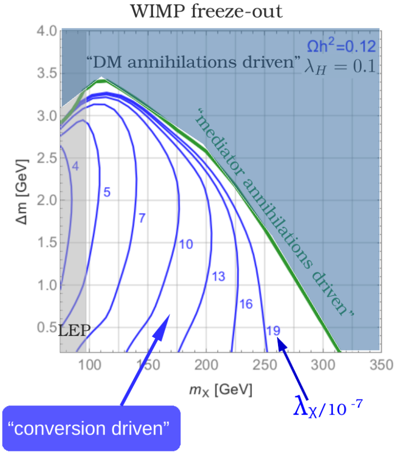
$\lambda_\chi \lesssim$ few $\times 10^{-6}$, $\Delta m <$ few GeV and $m_\chi \sim$ few $\times$ 100 GeV for $\lambda_H = 0.1$



Conversion driven FO: Viable parameter space

$\lambda_\chi \lesssim$ few $\times 10^{-6}$, $\Delta m <$ few GeV and $m_\chi \sim$ few $\times$ 100 GeV for $\lambda_H = 0.1$

- right limit: freeze-out driven by mediator annihilations
- left limit: LEP constraints on charged mediators
- bottom limit: $\Delta m > m_l$ (or beyond $2 \to 2$)



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- left limit: LEP constraints on charged mediators
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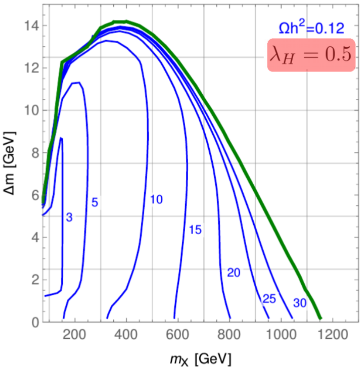
- Larger $\langle \sigma v \rangle_{\phi\phi}$ for larger λ_H increase the viable parameter space



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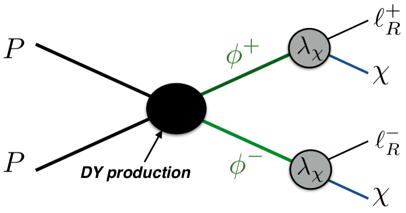

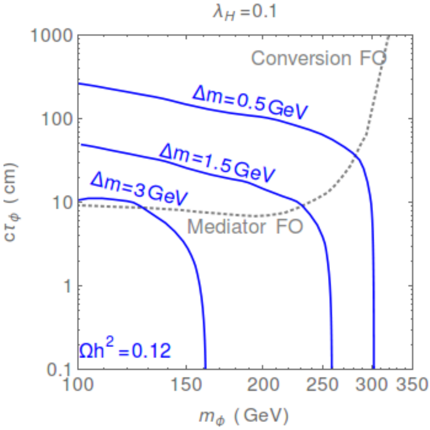

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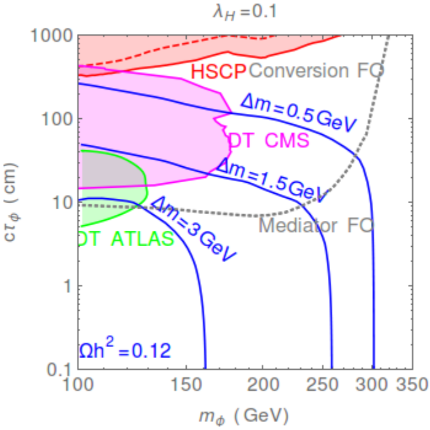

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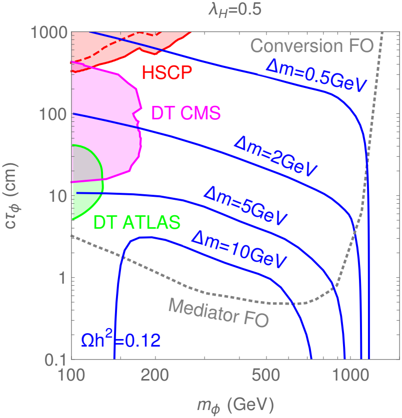
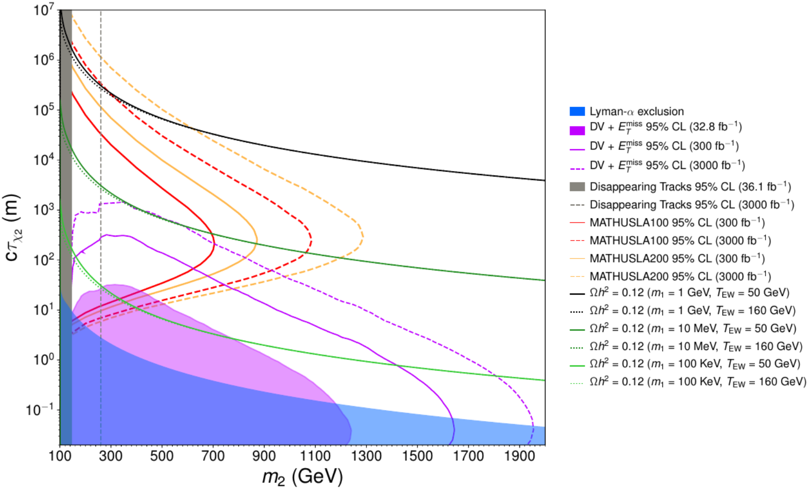


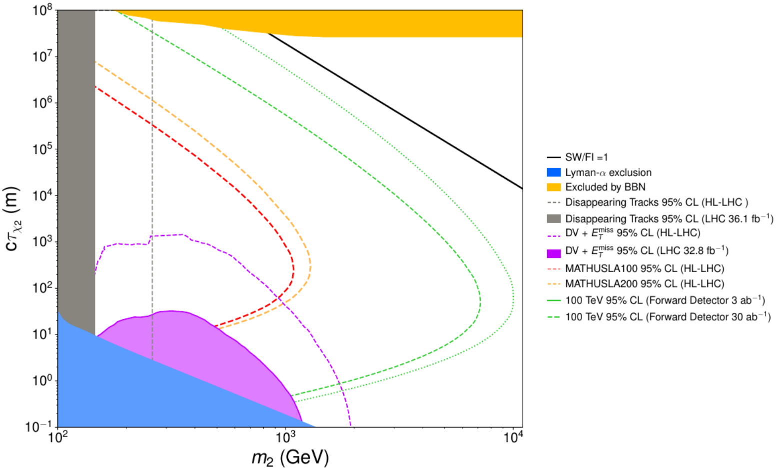
$\ell_R = \mu_R$

LHC & Cosmo complementarity



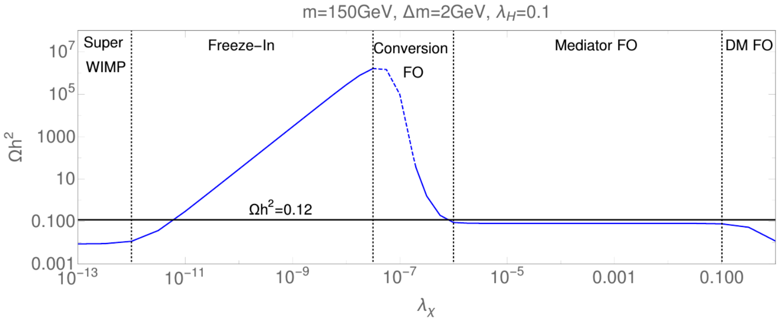
[No, Tunney & Zaldivar'0919]

LHC & Cosmo complementarity



[No'19]

From SuperWIMP to freeze-out



Relative scattering contribution to FI

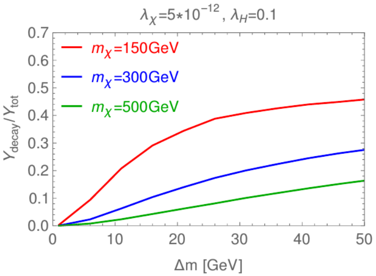


Figure 4: The ratio of the freeze-in yields $Y^{fi}_{\rm decay}/Y^{fi}_{\rm tot}$ as a function of Δm when taking only decay processes into account for $Y^{fi}_{\rm decay}$ and including all the relevant scattering and decay processes for $Y^{fi}_{\rm tot}$. We show the results for three different values of the DM mass $m_\chi \in \{150, 300, 500\}$ GeV while keeping $\lambda_\chi = 5 \cdot 10^{-12}$ and $\lambda_H = 0.1$ fixed.

Displaced lepton searches inappropriate

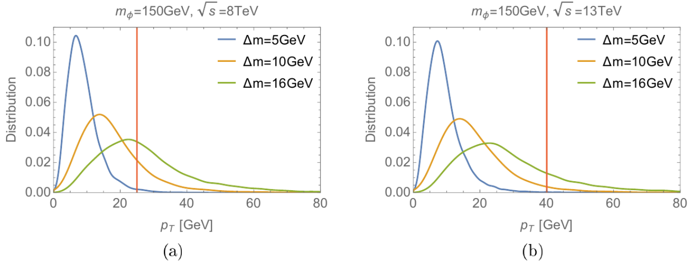


Figure 7: The p_T-distribution of the leading muons for the case when $m_\phi = 150$ GeV and different values of the mass splitting. The red vertical line denotes the cut on the p_T that is made in the search [67, 68] at 25GeV for $\sqrt{s} = 8$ TeV (left) and 40 GeV for $\sqrt{s} = 13$ TeV (right).

In the small mass splitting case, most events do not pass current p_T cuts

Conversion processes can affect the DM abundance

DM and mediator annihilation
and Co-annihilation processes

$$\frac{dY_{DM}}{dx} = \frac{s\langle\sigma v_{\rm eff}\rangle}{Hx}\left(Y_{DM}^2 - Y_{DM,eq}^2\right)$$

Conversion processes can affect the DM abundance

DM and mediator annihilation and Co-annihilation processes

$$\frac{dY_\chi}{dx} = \frac{-2}{Hxs}\left[\gamma_{\chi\chi}\left(\frac{Y_\chi^2}{Y_{\chi,eq}^2}-1\right)+\gamma_{\chi\phi}\left(\frac{Y_\chi Y_\phi}{Y_{\chi,eq}Y_{\phi,eq}}-1\right)\right.$$
$$\left.+\gamma_{\chi\to\phi}\left(\frac{Y_\chi}{Y_{\chi,eq}}-\frac{Y_\phi}{Y_{\phi,eq}}\right)+\gamma_{\chi\chi\to\phi\phi^\dagger}\left(\frac{Y_\chi^2}{Y_{\chi,eq}^2}-\frac{Y_\phi^2}{Y_{\phi,eq}^2}\right)\right],$$

$$\frac{dY_\phi}{dx} = \frac{-2}{Hxs}\left[\gamma_{\phi\phi^\dagger}\left(\frac{Y_\phi^2}{Y_{\phi,eq}^2}-1\right)+\gamma_{\chi\phi}\left(\frac{Y_\chi Y_\phi}{Y_{\chi,eq}Y_{\phi,eq}}-1\right)\right.$$
$$\left.-\gamma_{\chi\to\phi}\left(\frac{Y_\chi}{Y_{\chi,eq}}-\frac{Y_\phi}{Y_{\phi,eq}}\right)-\gamma_{\chi\chi\to\phi\phi^\dagger}\left(\frac{Y_\chi^2}{Y_{\chi,eq}^2}-\frac{Y_\phi^2}{Y_{\phi,eq}^2}\right)\right],$$

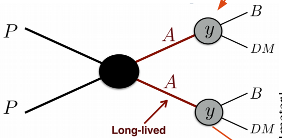
DM and mediator Conversion processes

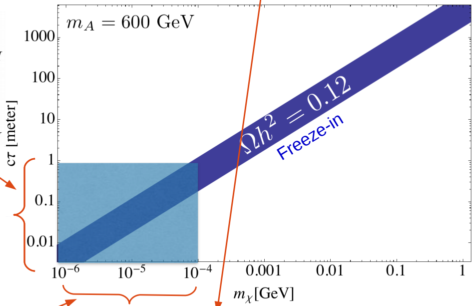
FIMP: displaced vertices and cosmology interplay

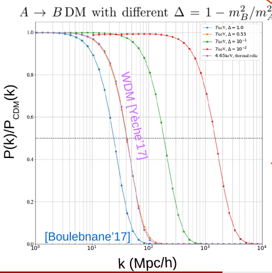
e.g. [Hall'09, Co'15, d'Eramo'17, Heeck'17, Boulebnane'17, Brooijmans'18, Garny'18, Calibbi'18, Belanger'18 ...]

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

Mediator mass range reachable at colliders



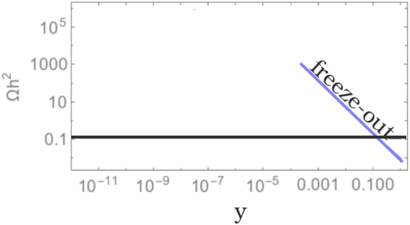


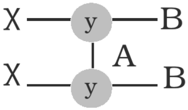


Warm DM like signatures
Suppressing small scale structures

Freeze-in versus Freeze-out: feeble vs weak

Assuming $\mathcal{L} \subset y\,\chi\,AB$ and $m_A \gg m_\chi$:





- Freeze-out ($y \gtrsim 0.01$):
  - $Y_{DM} \propto 1/\langle\sigma v\rangle_{\chi\chi\to BB} \sim 1/y^4$
  - A role is irrelevant
  - $Y_{DM}(t_i) = Y_{DM}^{eq}$ independent of init. cond.

Freeze-in versus Freeze-out: feeble vs weak

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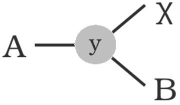
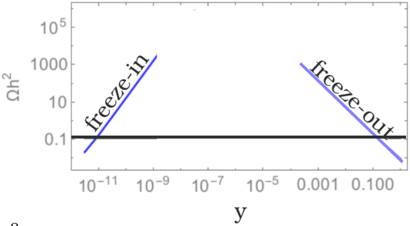
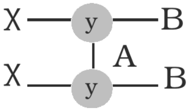
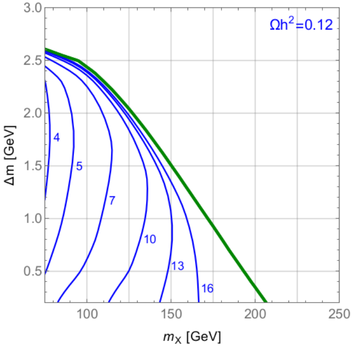


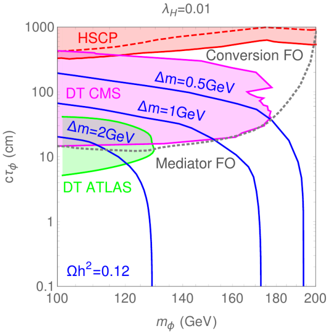




- Freeze-in ($y \lesssim 10^{-8}$):
  - $Y_{DM} \propto \Gamma_{A\to\chi B} \sim y^2$
  - A plays the leading role
  - We assume $Y_{DM}(t_i) = 0$ (dependence in init. cond.)
- Freeze-out ($y \gtrsim 0.01$):
  - $Y_{DM} \propto 1/\langle\sigma v\rangle_{\chi\chi\to BB} \sim 1/y^4$
  - A role is irrelevant
  - $Y_{DM}(t_i) = Y_{DM}^{eq}$ independent of init. cond.

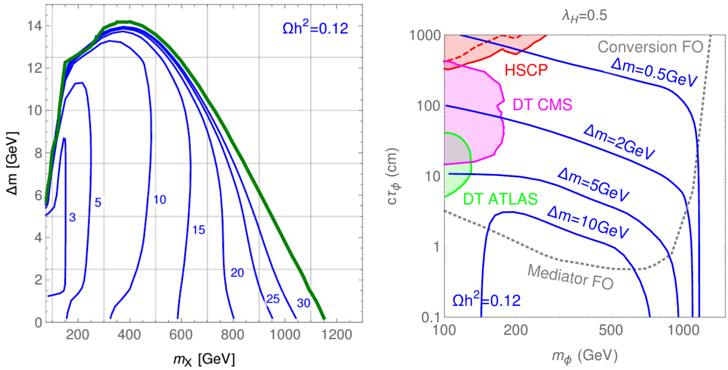
Conversion driven freeze-out



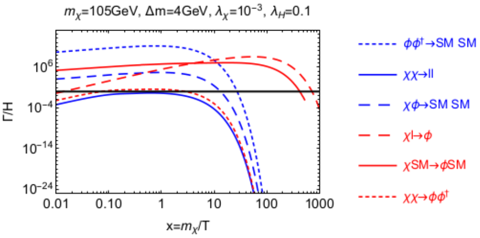


$$\lambda_H = 0.01$$

Conversion driven freeze-out



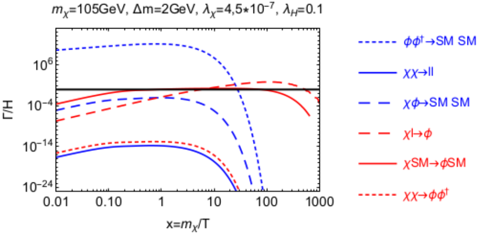
$$\lambda_H = 0.5$$



$$\frac{dY_{DM}}{dx} = \frac{s\langle\sigma v_{\rm eff}\rangle}{Hx}\left(Y_{DM}^2 - Y_{DM,eq}^2\right)$$

$$\langle\sigma v_{\rm eff}\rangle \quad \simeq \quad \frac{1}{g_{\rm eff}^2}\sum_{ij} r_i r_j \langle\sigma v_{ij}\rangle \qquad g_{\rm eff} = \sum_i g_i$$

$$\text{and} \quad r_i = g_i(1+\Delta_i)^{3/2}\exp(-x_f\Delta_i)$$



$$\frac{dY_\chi}{dx} = \frac{-2}{Hxs}\left[\gamma_{\chi\chi}\left(\frac{Y_\chi^2}{Y_{\chi,eq}^2}-1\right)+\gamma_{\chi\phi}\left(\frac{Y_\chi Y_\phi}{Y_{\chi,eq}Y_{\phi,eq}}-1\right)\right.$$
$$\left.+\gamma_{\chi\to\phi}\left(\frac{Y_\chi}{Y_{\chi,eq}}-\frac{Y_\phi}{Y_{\phi,eq}}\right)+\gamma_{\chi\chi\to\phi\phi^\dagger}\left(\frac{Y_\chi^2}{Y_{\chi,eq}^2}-\frac{Y_\phi^2}{Y_{\phi,eq}^2}\right)\right],$$

$$\frac{dY_\phi}{dx} = \frac{-2}{Hxs}\left[\gamma_{\phi\phi^\dagger}\left(\frac{Y_\phi^2}{Y_{\phi,eq}^2}-1\right)+\gamma_{\chi\phi}\left(\frac{Y_\chi Y_\phi}{Y_{\chi,eq}Y_{\phi,eq}}-1\right)\right.$$
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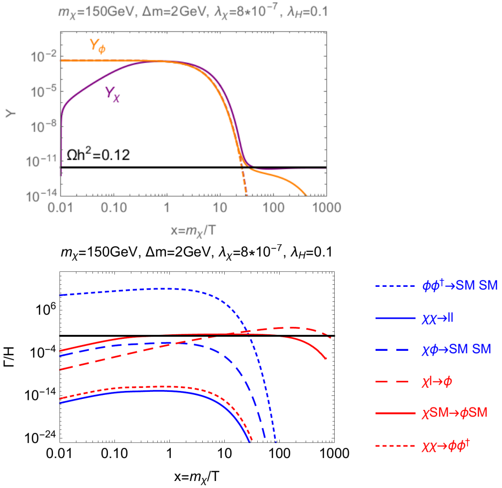
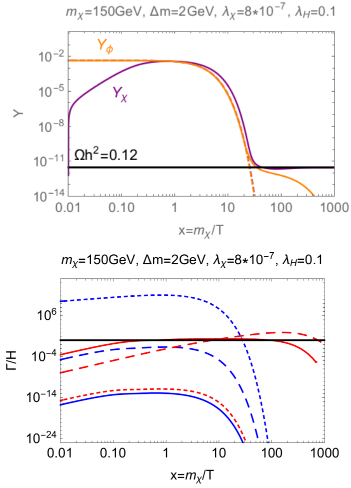
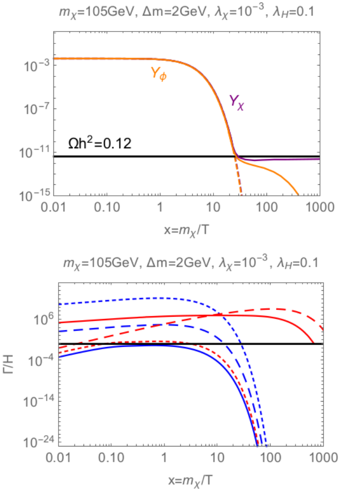
Conversion driven



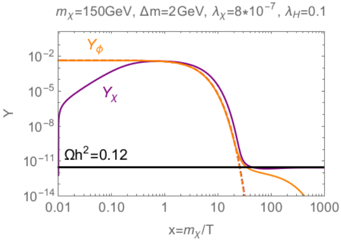
Conversion driven



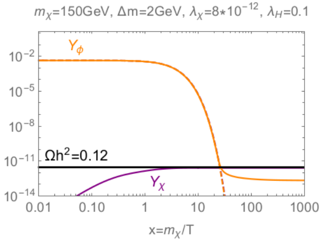
Co-annihilation driven

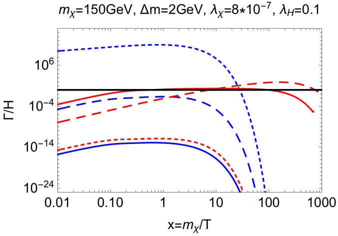


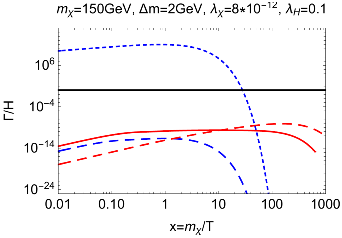
Conversion driven



Freeze-in







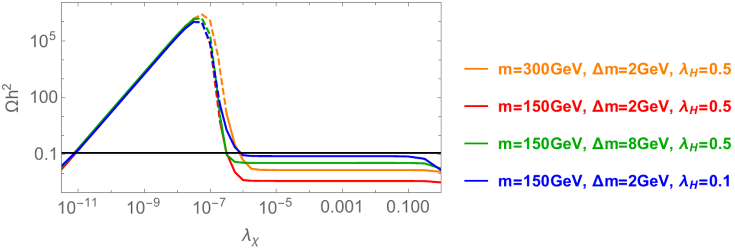


Figure 8: DM abundance as a function of the Yukawa coupling (as in Fig. 2) for different values of the parameters m_χ, Δm and λ_H

Relevant processes in Leptophilic DM

(co-)annilations

initial state		final state		scaling
χ	χ	l^-	l^+	λ_χ^4
χ	ϕ	l^-	γ, Z, H	λ_χ^2
		W^-	ν_l	
ϕ	$\phi^\dagger$	γ, Z, W^+	γ, Z, W^-	λ_χ^0
		q	$\bar{q}$	
		H	Z	
		l^-	l^+	
ϕ	ϕ	l^-	l^-	λ_χ^4

conversions

initial state		final state		scaling
χ	l^-	ϕ	γ, Z, H	λ_χ^2
	γ, Z, H		l^+	
	W^-		$\bar{\nu}_l$	
	ν_l		W^+	
ϕ		χ	l^-	λ_χ^2
χ	χ	ϕ	$\phi^\dagger$	λ_χ^4

Conversion driven freeze-out coupling to q

$$\mathcal{L}_{\rm int} = |D_\mu \tilde{q}|^2 - \lambda_\chi \tilde{q} \bar{q} \frac{1-\gamma_5}{2} \chi + \text{h.c.}$$

[Heisig garny et al '17 & '18]

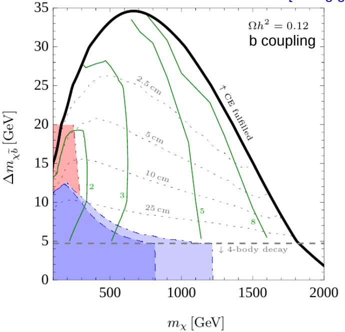


FIG. 4. Viable parameter space in the plane spanned by m_χ and $\Delta m_{\chi\tilde{b}} = m_{\tilde{b}} - m_\chi$. We adjust λ_χ such that $\Omega h^2 = 0.12$. Above the thick black curve CE holds, while below this curve CE breaks down and the freeze-out is conversion-driven. The corresponding coupling $\lambda_\chi/10^{-7}$ (decay length $c\tau$) of the mediator is denoted by the thin green (gray) dotted lines. The blue dashed (dot-dashed) curve shows our estimates for the limits from R-hadron searches at 8 (13) TeV. The constraint from monojet searches is shown as the red dot-dot-dashed curve.

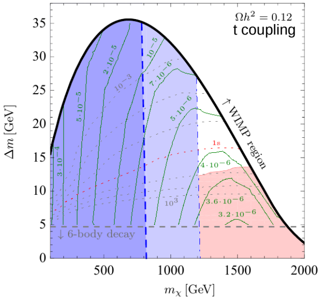
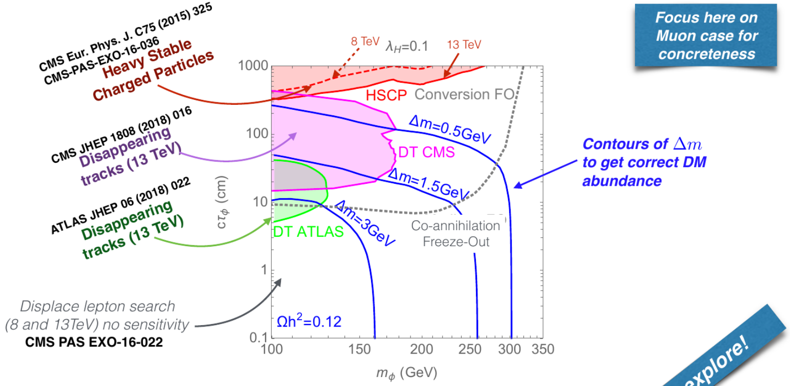


FIG. 9. Cosmologically viable parameter space ($\Omega h^2 = 0.12$) in the conversion-driven freeze-out region (below black thick curve). Contours of constant λ_χ are show in green while contours of constant $\tilde{t}$ lifetimes are show as gray dotted curves spanning from 10^{-3} s to 10^3 s in steps of an order of magnitude (the curve for 1 s is highlighted in red for better readability). 95% C.L. exclusion regions from R-hadron searches at the 8 and 13 TeV LHC are shown in dark and light blue, respectively. The red shaded region denotes the constraint from BBN. Below the horizontal gray dashed line (~ 5 GeV) the 4-body decay of the mediator is kinematically forbidden rendering the 6-body decay to be dominant.

Conversion driven freeze-out: Collider probes



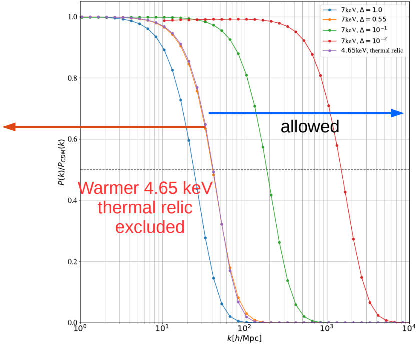
- ✦ ***Weak constraints from LHC***
- ✦ ***Large regions unconstrained***
- ✦ ***No signal expected in direct/indirect detection***

Still much to explore!

WDM constraints on FIMPs

See Heeck et al ’1706 and ’1709

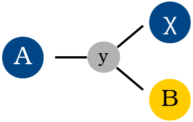
- WDM: free-streeming (collision-less damping): collisionless particles can stream out of overdense to underdense regions



smooth out inhomogeneities for $\lambda < \lambda_{FS} = \int_0^{t_0} \frac{v}{a} dt$
$\rightsquigarrow$ particles relativistic at the time of decoupling can give substancial λ_{FS}

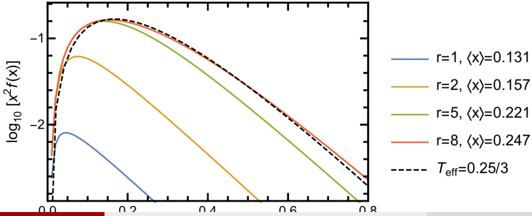
WDM constraints on FIMPs

See Heeck et al '1706 and '1709

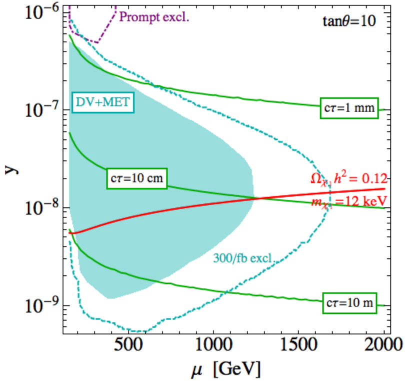


$$\frac{\partial f_{\rm DM}}{\partial t} - Hp\frac{\partial f_{\rm DM}}{\partial p} = \mathcal{C}(p)$$

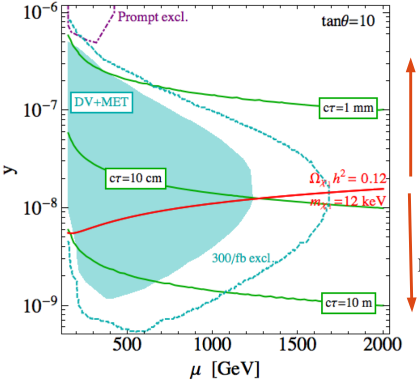
$$\frac{\partial f_{\rm DM}}{\partial r} = \frac{g_A\, S\, \Gamma\, M_0\, r^2}{2\, p_{\rm DM}\, x\, \sqrt{m_A^2 x^2 + m_{\rm DM}^2 r^2}} \int_{\xi^-}^{\xi^+} {\rm d}\xi\, f_A(\xi)$$



LHC & Cosmology complementarity



LHC & Cosmology complementarity

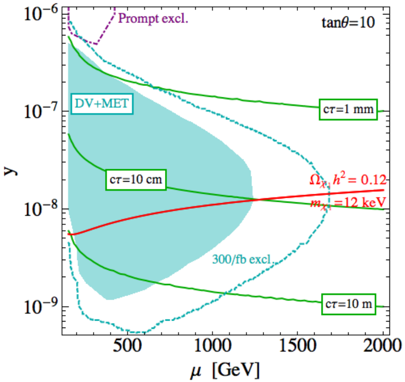


Fixed DM mass: overabundant
Fixed DM abundance: need lower mass

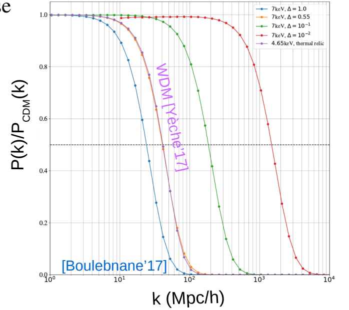
Fixed DM mass: underabundant
Fixed DM abundance: need higher mass

LHC & Cosmology complementarity

Light FIMP can behave as WDM:
Freestreams from overdense to underdense regions in the early universe

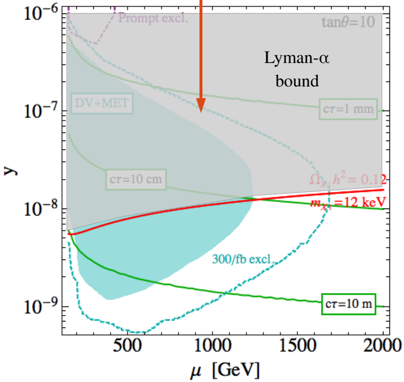


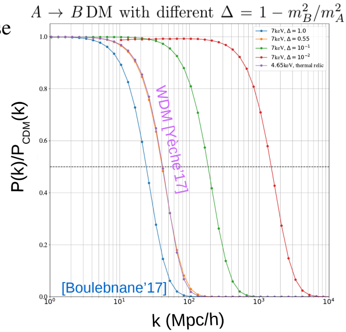
$A \to B$ DM with different $\Delta = 1 - m_B^2/m_A^2$

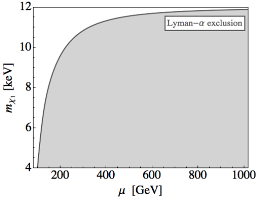


LHC & Cosmology complementarity

Light FIMP can behave as WDM:
Freestreams from overdense to underdense regions in the early universe







Displaced vertices recasting

Calibbi, Lopez-Honorez, Lowette, AM

Recasting ATLAS DV+MET

ATLAS arXiv: 1710.04901
CERN-EP-2017-202

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

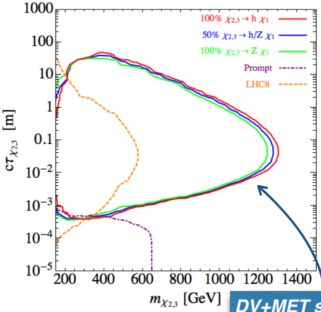
- Follow object selection of auxiliary materials

$$E_T^{\rm truth}, d_0, n^{DV}_{\rm tracks}, m_{DV}, R_{\rm decay}, z_{\rm decay}$$

- 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



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

See Nishita Desai talk of yesterday

See Hideyuki Oide talk of yesterday

Displaced vertices recasting

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

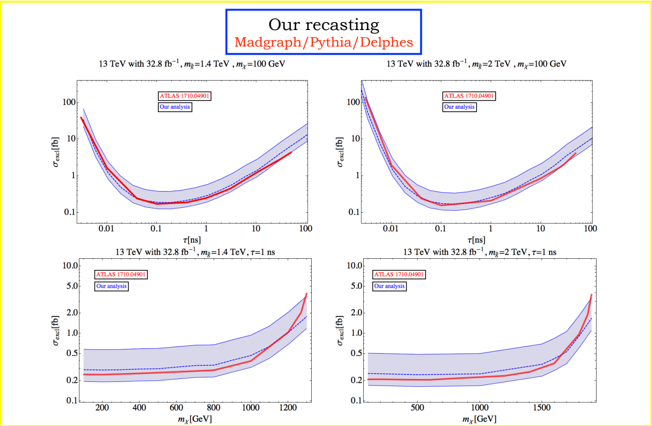
A search for long-lived, massive particles predicted by many theories beyond the Standard Model is presented. The search targets final states with large missing transverse momentum and at least one high-mass displaced vertex with five or more tracks, and uses 32.8 fb^{-1} of $\sqrt{s}$ = 13 TeV pp collision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

arXiv:1710.04901

Freeze-in DM at the LHC Lorenzo Calibbi (ITP)

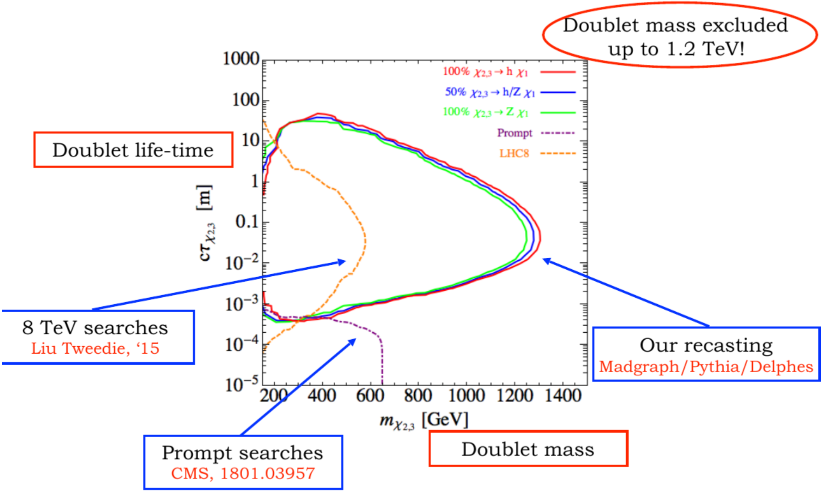
Displaced vertices recasting

Recasting a DV+MET search by ATLAS



Displaced vertices recasting

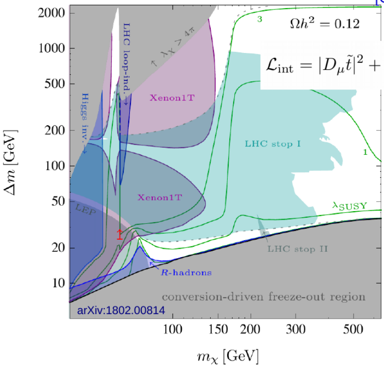
Recasting a DV+MET search by ATLAS

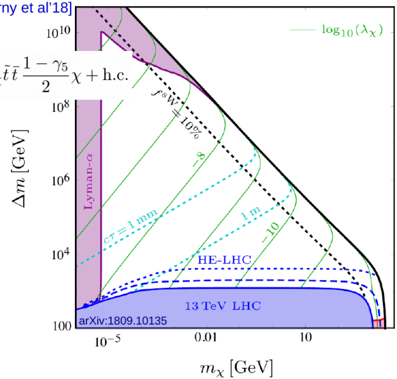


Rather general result: it also applies e.g. to Higgsino decaying to gravitino

[Garny et al'18]

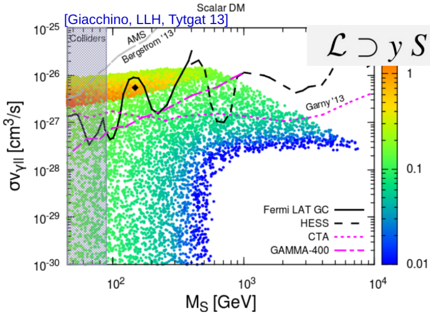
$$\mathcal{L}_{\rm int} = |D_\mu \tilde{t}|^2 + \lambda_\chi \tilde{t}\,\bar{t}\,\frac{1-\gamma_5}{2}\chi + \text{h.c.}$$



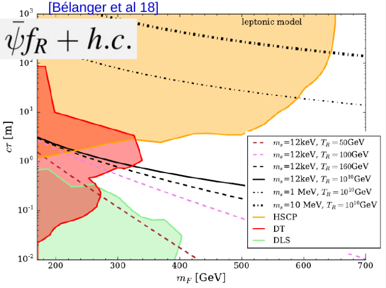


$$\mathcal{L} \supset y\, S\, \bar{\psi} f_R + h.c.$$

[Giacchino, LLH, Tytgat 13]



[Bélanger et al 18]



bla

This is really the end