

# Probing the early universe with displaced new physics at colliders

Based on arXiv:2102.06221 in collaboration with L. Calibbi, F. D'Eramo, L. Lopez-Honorez and A. Mariotti



ULB

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9<sup>th</sup> LLP workshop  
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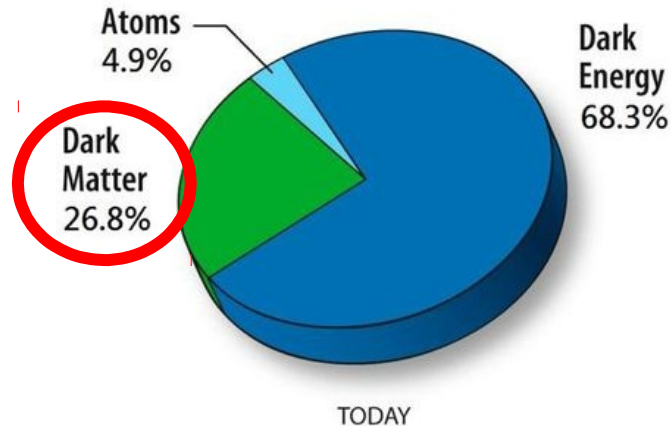


VUB

# Feebly interacting dark matter

- Nature of DM is still unknown despite many dedicated experiments
- Feebly interaction DM easily escapes (in)direct DM experiments
- DM can be produced through the freeze-in mechanism

[Hall et. al. 2009]



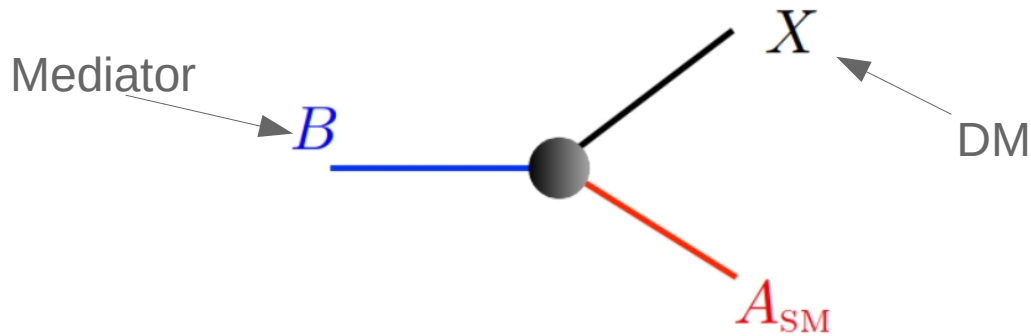
DM Relic Density:

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

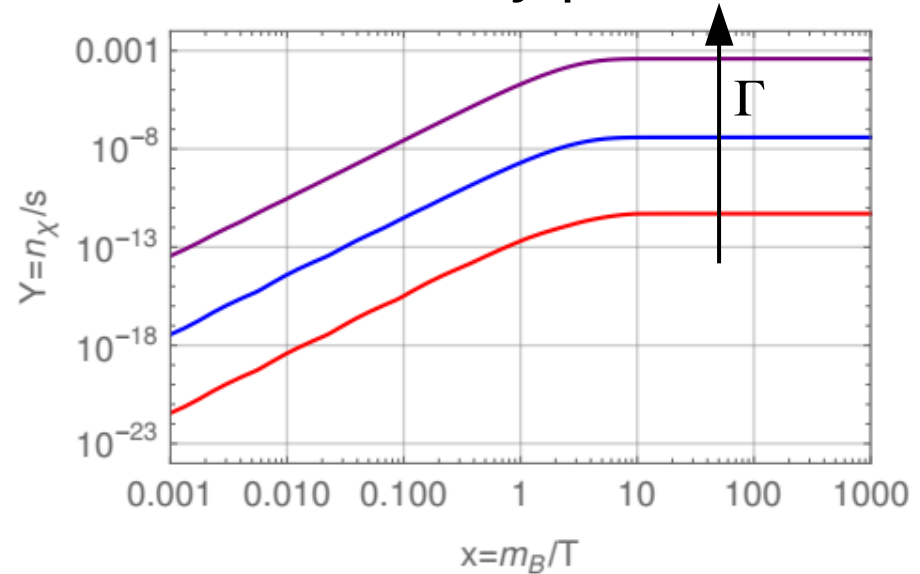
[Planck 2018]

# Freeze-in production of DM

- DM is never in equilibrium with any SM particle
- Abundance gradually builds up due to mediator decay processes

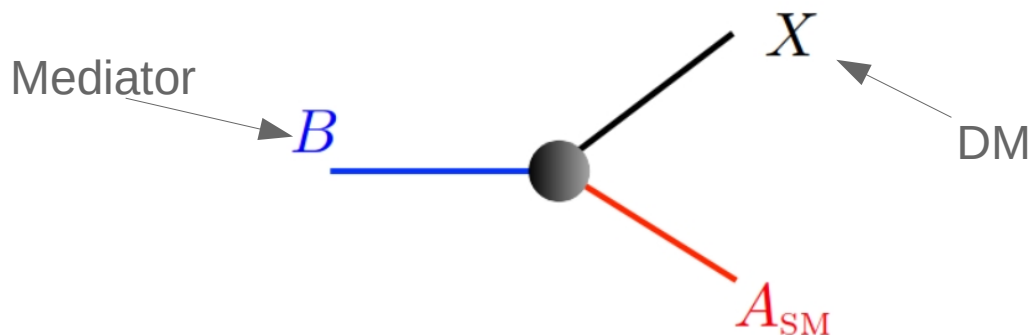


$$Y_{DM} = \frac{n_{DM}}{s} \approx \frac{\Gamma_B M_{pl}}{m_B^2} \approx \frac{M_{pl}}{cT_B m_B^2}$$

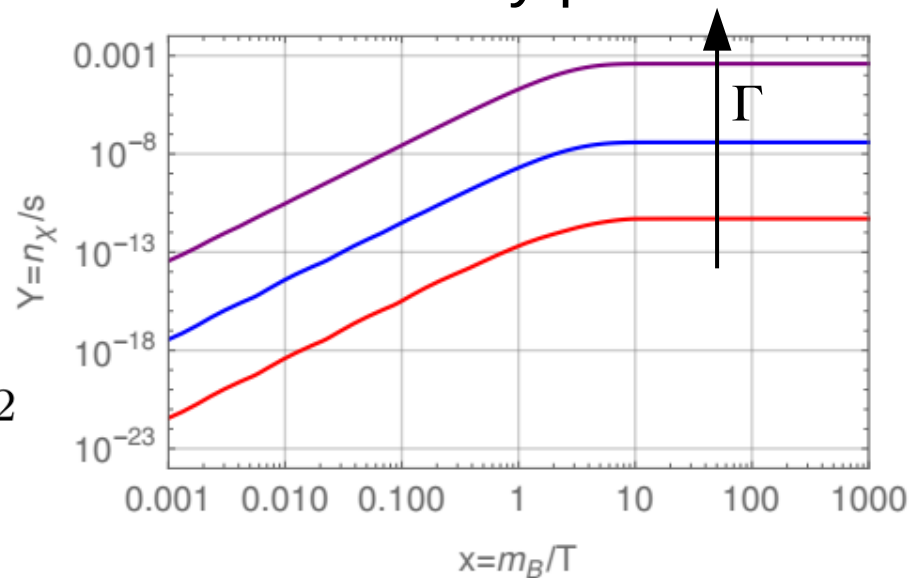


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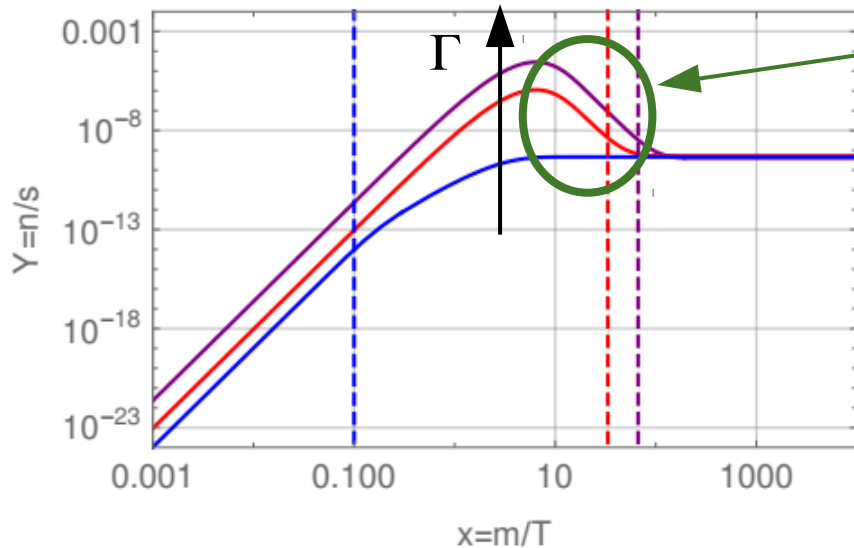


$$c\tau_B = 3.3 \times 10^6 \text{cm} \left( \frac{m_X}{10\text{GeV}} \right) \left( \frac{1\text{TeV}}{m_B} \right)^2$$



# Freeze-in during reheating era

- Standard freeze-in happens during radiation era ( $T_R \gg m_B$ )
- For  $T_R < m_B$ , freeze-in during early matter dominated era



Dilution of abundance if  $T_R < m_B$

$$Y_{DM} \approx 10^4 \left( \frac{T_R}{m_B} \right)^7 \frac{\Gamma_B M_{pl}}{m_B^2}$$

# Probing early universe using the LHC

- Exploit the link between DM abundance and decay length to probe the reheating temperature in case of a discovery

Case 1:  $m_X$ ,  $m_B$  and  $c\tau$  are reconstructed



Requiring  $\Omega h^2 = 0.12$



Exact prediction of  $T_R$



Case 2: Only  $m_B$  and  $c\tau$  are reconstructed



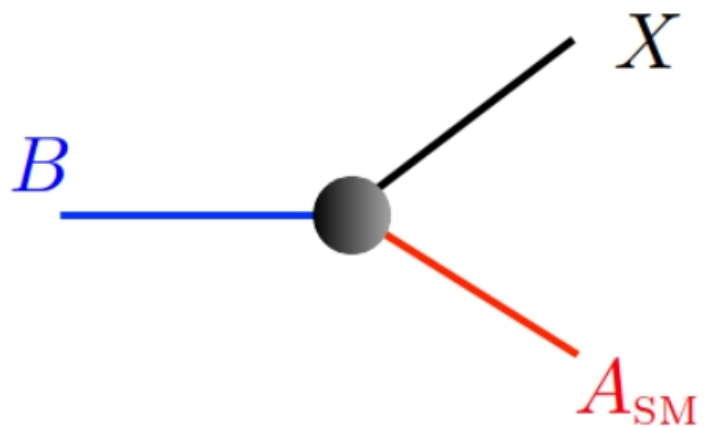
Requiring  $\Omega h^2 = 0.12$  and  $m_X > 10\text{keV}$   
(Ly $\alpha$  bounds)

[Boulebane et. al. 2017]



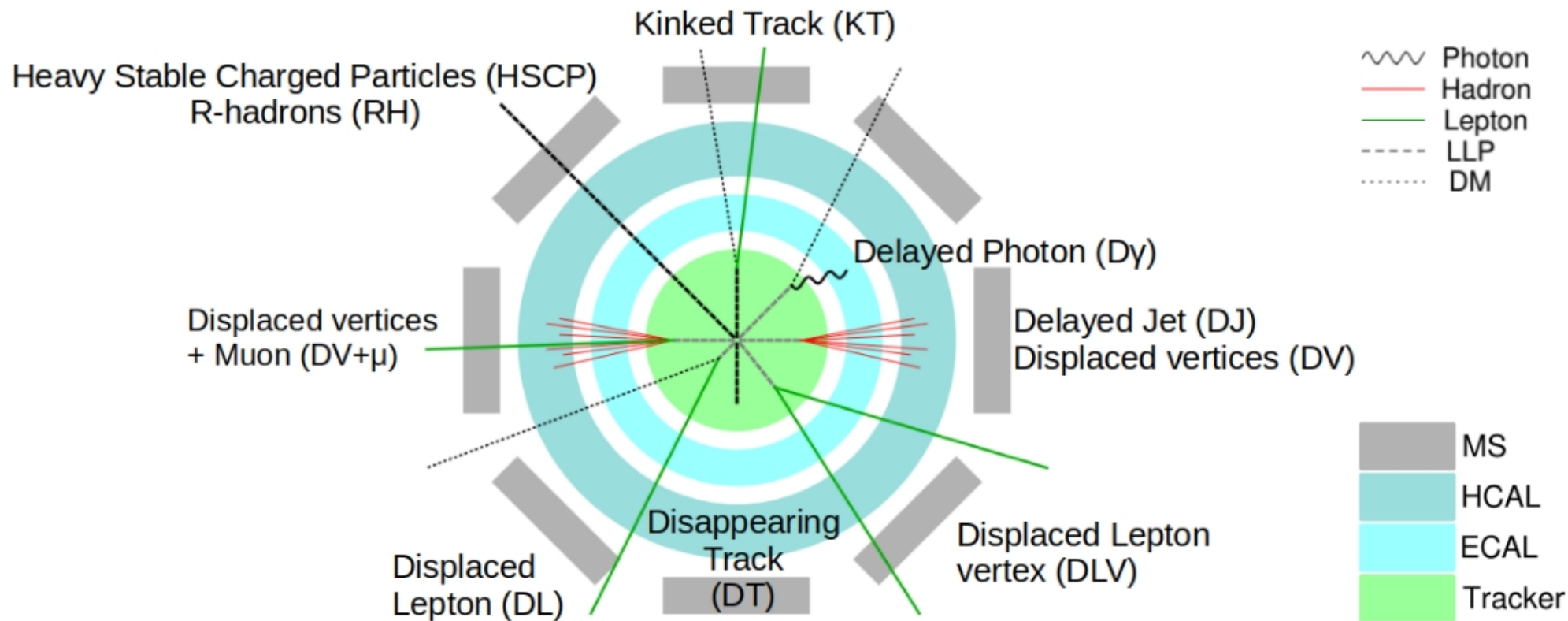
Upper Limit of  $T_R$

# Simplified model classification



$A_{SM}$	Spin DM	Spin B	Interaction	Label
$\psi_{SM}$	0	1/2	$\bar{\psi}_{SM}\Psi_B\phi$	$\mathcal{F}_{\psi_{SM}\phi}$
	1/2	0	$\bar{\psi}_{SM}\chi\Phi_B$	$\mathcal{S}_{\psi_{SM}\chi}$
$F^{\mu\nu}$	1/2	1/2	$\bar{\Psi}_B\sigma_{\mu\nu}\chi F^{\mu\nu}$	$\mathcal{F}_{F\chi}$
$H$	0	0	$H^\dagger\Phi_B\phi$	$\mathcal{S}_{H\phi}$
	1/2	1/2	$\bar{\Psi}_B\chi H$	$\mathcal{F}_{H\chi}$

# LLP signatures

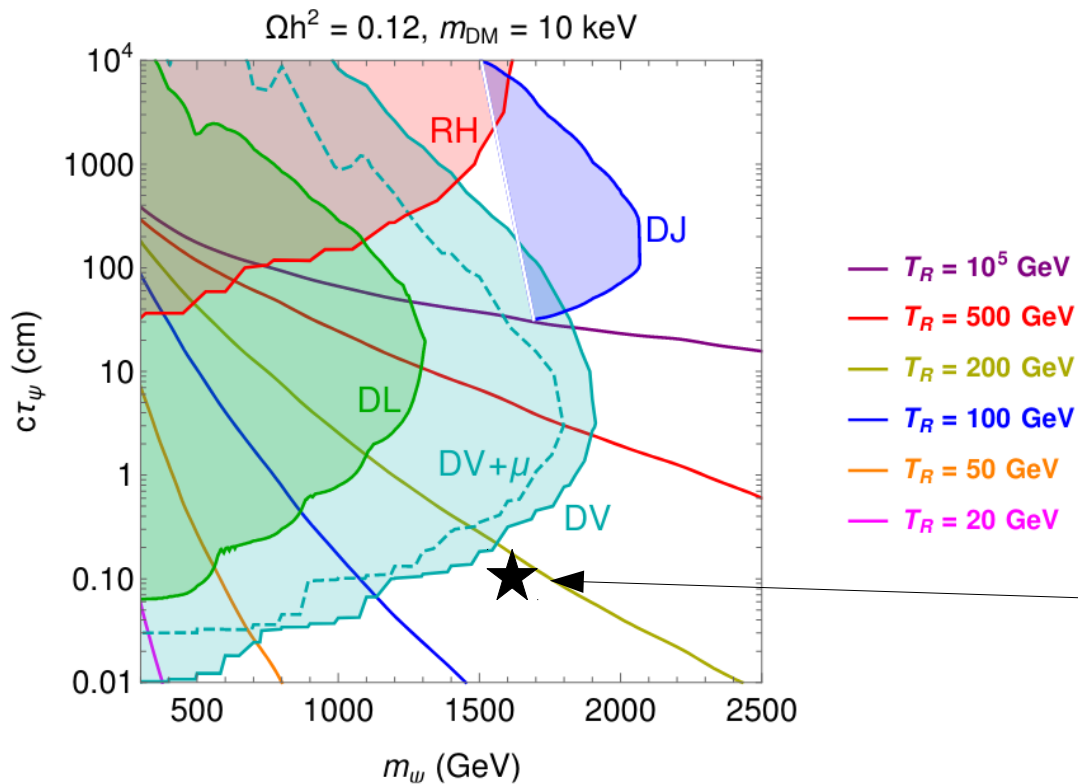




# Sensitivity to simplified models

Label	DV + MET	DJ + MET	DJ + $\mu$	DL	DLV	D $\gamma$	DT	RH	HSCP	KT
$\mathcal{F}_{l\phi} \& \mathcal{S}_{l\chi}$				✓					✓	✓
$\mathcal{F}_{\tau\phi} \& \mathcal{S}_{\tau\chi}$	✓	✓		✓					✓	✓
$\mathcal{F}_{q\phi} \& \mathcal{S}_{q\chi}$	✓	✓						✓		
$\mathcal{F}_{t\phi} \& \mathcal{S}_{t\chi}$	✓	✓	✓	✓				✓		
$\mathcal{F}_{G\chi}$	✓	✓						✓		
$\mathcal{F}_{W\chi}$	✓	✓	✓	✓	✓	✓	✓			✓
$\mathcal{S}_{H\phi} \& \mathcal{F}_{H\chi}$	✓	✓	✓	✓	✓		✓			✓

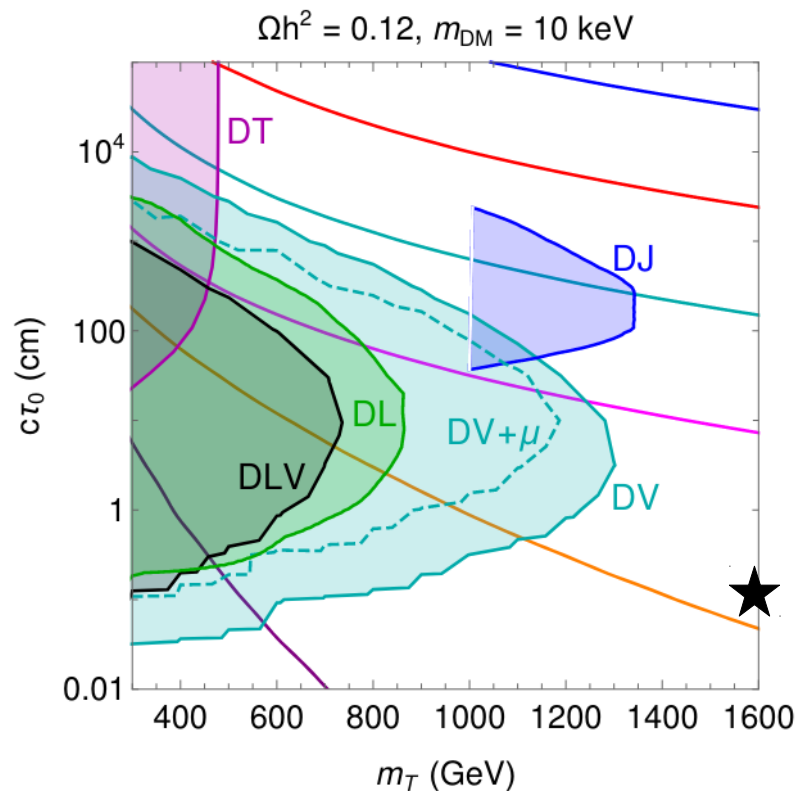
# Topphilic scenario



$$\mathcal{L}_{\mathcal{F}t_R\phi} \supset -\lambda_\phi \bar{\Psi}_B t_R \phi$$

In case of a discovery, this gives us an upper limit on  $T_R$

# Singlet-triplet model



$$\mathcal{L}_{\mathcal{F}W\chi} \supset \frac{1}{\Lambda} (W_{\mu\nu}^a \bar{\chi}_S \sigma^{\mu\nu} \chi_T^a + \text{h.c.})$$

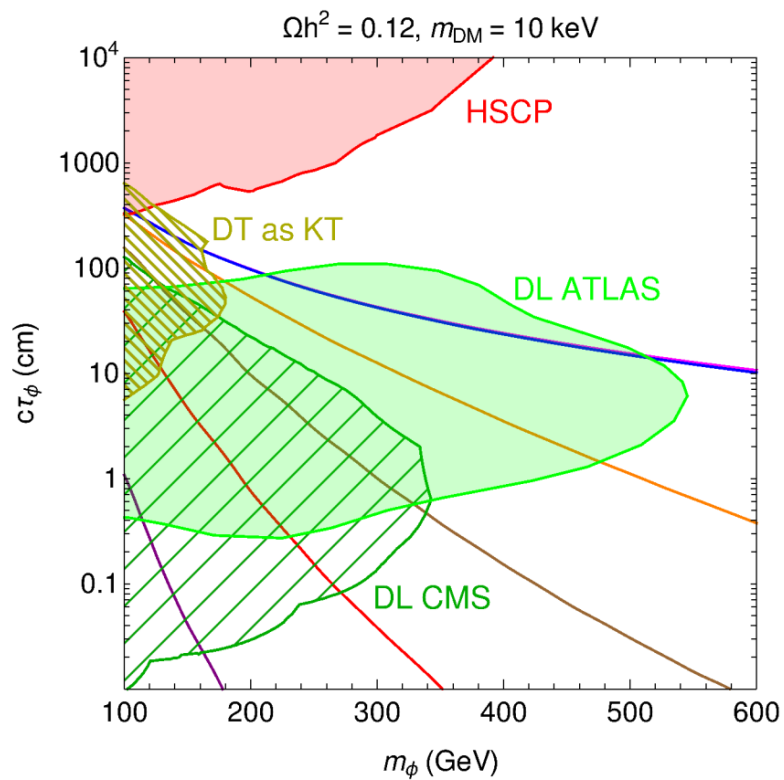
$$\chi_T = \begin{pmatrix} \chi_h^0 / \sqrt{2} & \chi^+ \\ \chi^- & -\chi_h^0 / \sqrt{2} \end{pmatrix}$$

# Summary

- Link between DM freeze-in production and mediator decay length
- If  $T_R < m_B$ , these models can be probed by LLP searches
- A displaced vertex discovery can probe the early universe
- Focusing on different signatures can help narrowing down the specific model

Back-up slides

# Leptophilic scenario



$$\mathcal{L}_{S_{\ell R X}} \supset - \lambda_\chi \Phi_B \bar{\chi} \mu_R$$

# LLP searches used

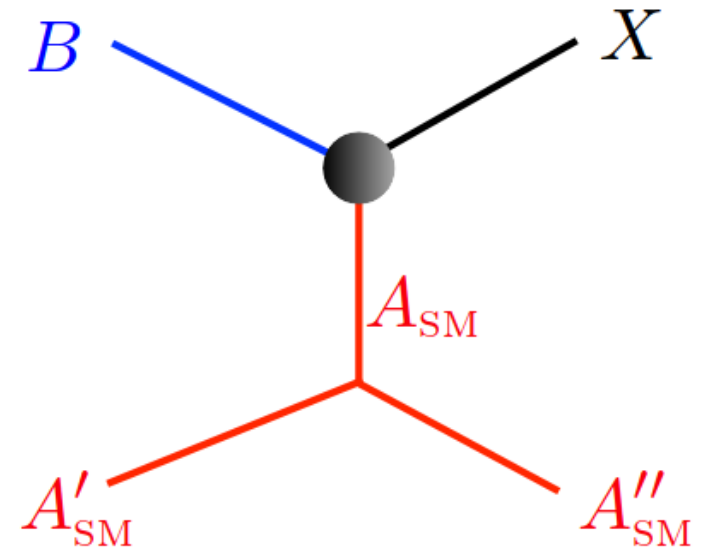
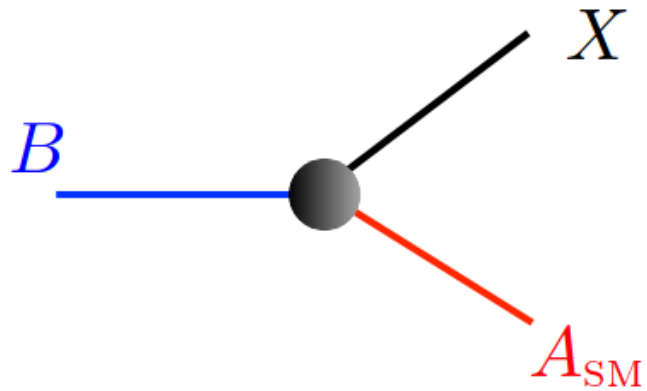
Signature	Exp. & Ref.	$\mathcal{L}$	Maximal sensitivity	Label
R-hadrons	CMS [59]	12.9 fb <sup>-1</sup>	$c\tau \gtrsim 10$ m	RH
Heavy stable charged particle	ATLAS [60]	36.1 fb <sup>-1</sup>		HSCP
Disappearing tracks	ATLAS [61]	36.1 fb <sup>-1</sup>	$c\tau \approx 30$ cm	DT
	CMS [62, 63]	140 fb <sup>-1</sup>	$c\tau \approx 60$ cm	
Displaced leptons	CMS [64] <sup>†</sup>	19.7 fb <sup>-1</sup>	$c\tau \approx 2$ cm	DL
	CMS [65]	2.6 fb <sup>-1</sup>	$c\tau \approx 5$ cm	
	ATLAS [66]	139 fb <sup>-1</sup>		
Displaced vertices + MET	ATLAS [67]	32.8 fb <sup>-1</sup>	$c\tau \approx 3$ cm	DV+MET
Delayed jets + MET	CMS [68]	137 fb <sup>-1</sup>	$c\tau \approx 1 - 3$ m	DJ+MET
Displaced vertices + $\mu$	ATLAS [69]	136 fb <sup>-1</sup>	$c\tau \approx 3$ cm	DV+ $\mu$
Displaced dilepton vertices	ATLAS [70]	32.8 fb <sup>-1</sup>	$c\tau \approx 1 - 3$ cm	DLV
Delayed photons	CMS [71]	77.4 fb <sup>-1</sup>	$c\tau \approx 1$ m	D $\gamma$

# LLP searches used

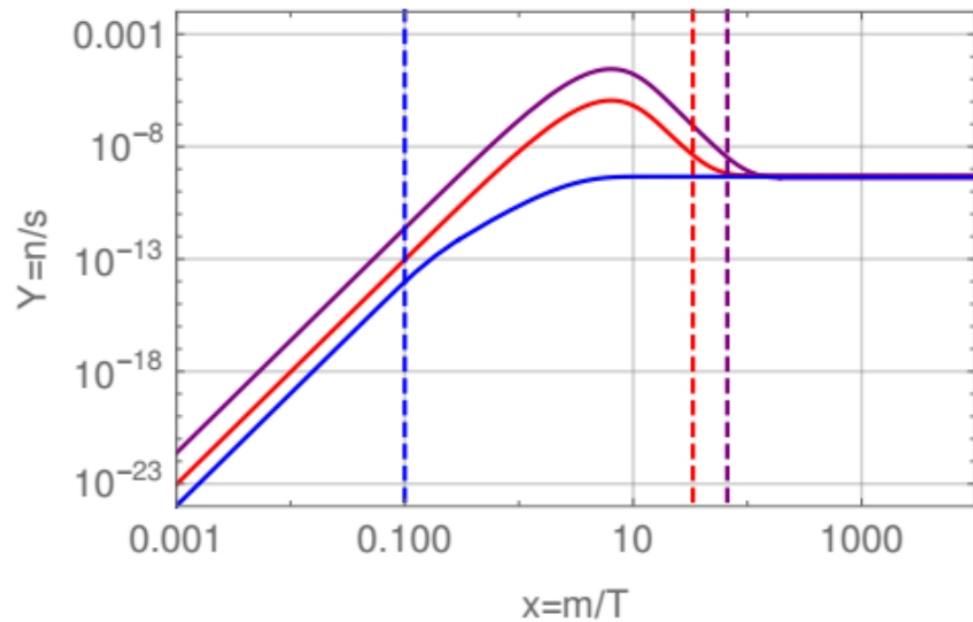
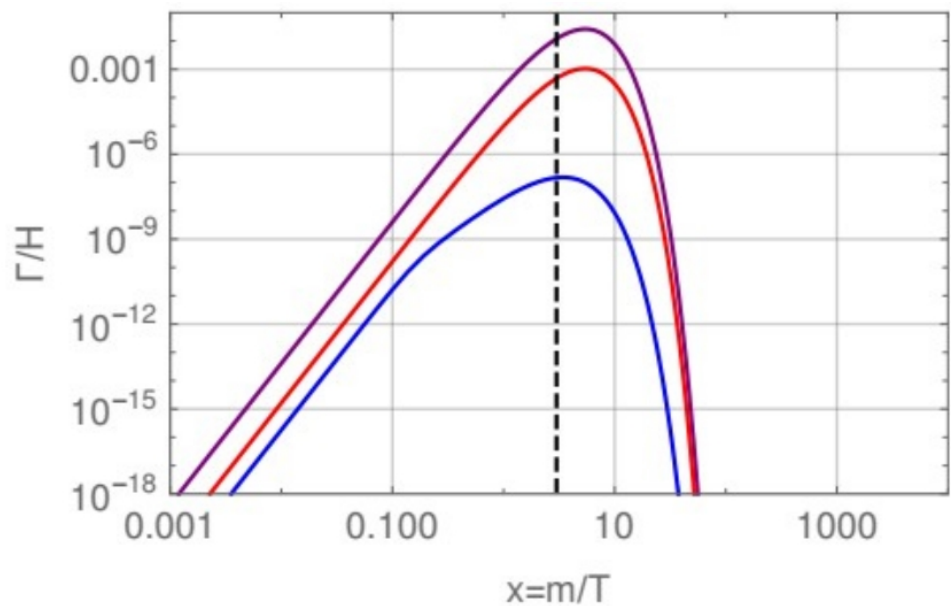
- [59] **CMS** Collaboration, C. Collaboration, *Search for heavy stable charged particles with 12.9 fb<sup>-1</sup> of 2016 data*, .
- [60] **ATLAS** Collaboration, M. Aaboud et al., *Search for heavy charged long-lived particles in the ATLAS detector in 36.1 fb<sup>-1</sup> of proton-proton collision data at  $\sqrt{s} = 13$  TeV*, *Phys. Rev. D* **D99** (2019), no. 9 092007, [[arXiv:1902.01636](#)].
- [61] **ATLAS** Collaboration, M. Aaboud et al., *Search for long-lived charginos based on a disappearing-track signature in pp collisions at  $\sqrt{s} = 13$  TeV with the ATLAS detector*, *JHEP* **06** (2018) 022, [[arXiv:1712.02118](#)].
- [62] **CMS** Collaboration, A. M. Sirunyan et al., *Search for disappearing tracks as a signature of new long-lived particles in proton-proton collisions at  $\sqrt{s} = 13$  TeV*, [arXiv:1804.07321](#).
- [63] **CMS** Collaboration, A. M. Sirunyan et al., *Search for disappearing tracks in proton-proton collisions at  $\sqrt{s} = 13$  TeV*, [arXiv:2004.05153](#).
- [64] **CMS** Collaboration, V. Khachatryan et al., *Search for Displaced Supersymmetry in events with an electron and a muon with large impact parameters*, *Phys. Rev. Lett.* **114** (2015), no. 6 061801, [[arXiv:1409.4789](#)].
- [65] **CMS** Collaboration, *Search for displaced leptons in the e-mu channel*, CMS-PAS-EXO-16-022.
- [66] **ATLAS** Collaboration, G. Aad et al., *Search for displaced leptons in  $\sqrt{s} = 13$  TeV pp collisions with the ATLAS detector*, [arXiv:2011.07812](#).
- [67] **ATLAS** Collaboration, M. Aaboud et al., *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*, *Phys. Rev. D* **D97** (2018), no. 5 052012, [[arXiv:1710.04901](#)].
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- [70] **ATLAS** Collaboration, G. Aad et al., *Search for displaced vertices of oppositely charged leptons from decays of long-lived particles in pp collisions at  $\sqrt{s} = 13$  TeV with the ATLAS detector*, *Phys. Lett. B* **B801** (2020) 135114, [[arXiv:1907.10037](#)].
- [71] **CMS** Collaboration, A. M. Sirunyan et al., *Search for long-lived particles using delayed photons in proton-proton collisions at  $\sqrt{s} = 13$  TeV*, *Phys. Rev. D* **100** (2019), no. 11 112003, [[arXiv:1909.06166](#)].



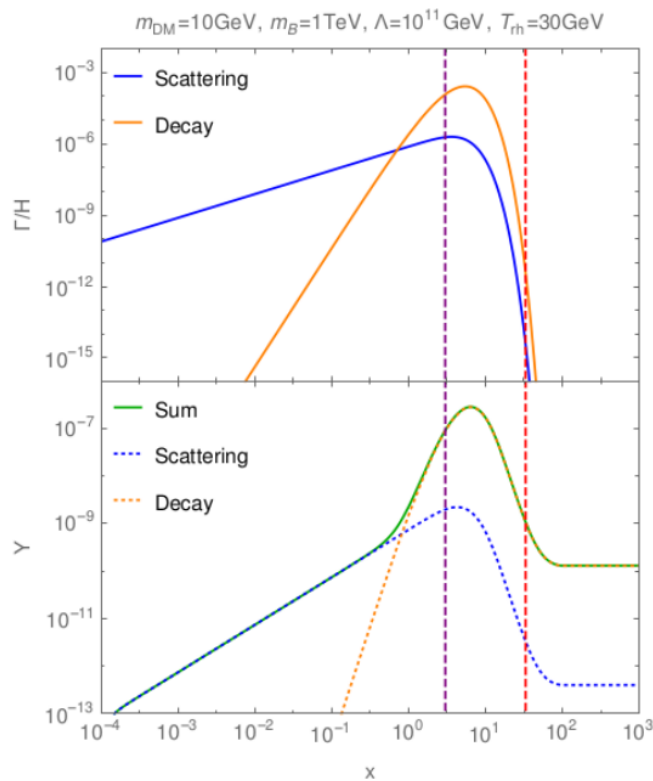
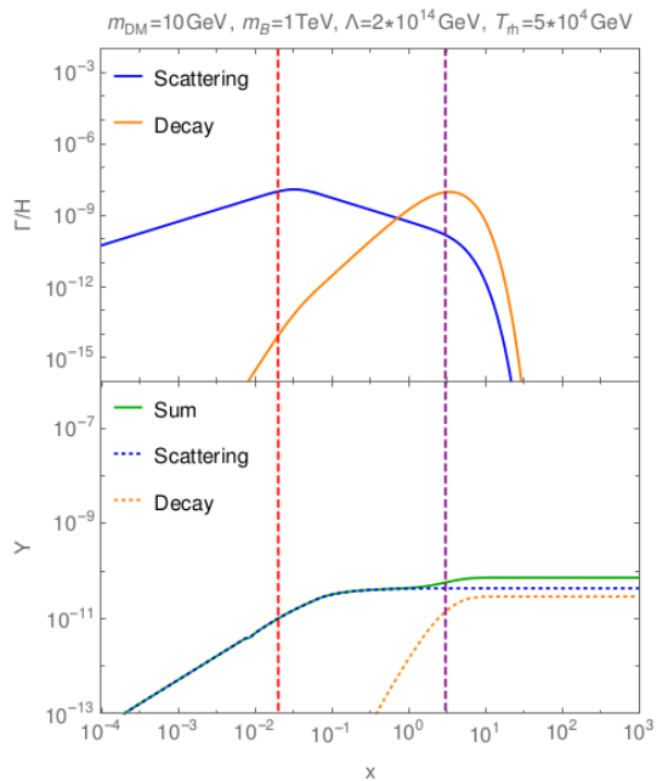
# Freeze-in contribution diagrams



# IR freeze-in (renormalizable operator)



# UV freeze-in (non-renormalizable operator)



# Inflationary reheating

