Feebly coupled dark matter and displaced new physics at colliders

Based on JHEP 05 (2021) 234 (arXiv:2102.06221) in collaboration with L. Calibbi, F. D'Eramo, L. Lopez-Honorez and A. Mariotti

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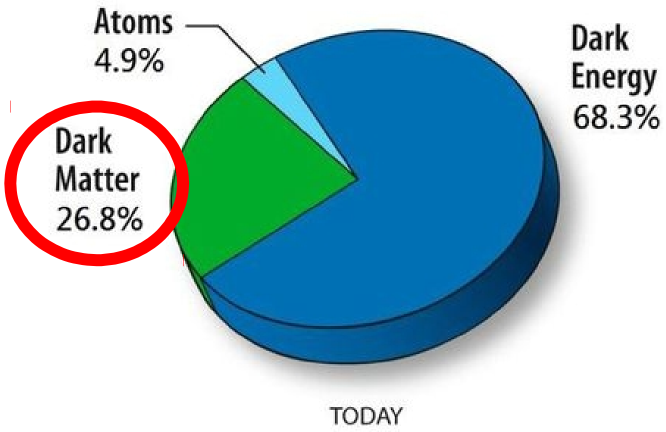
EOS be.h equinox meeting
09/09/2021

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]



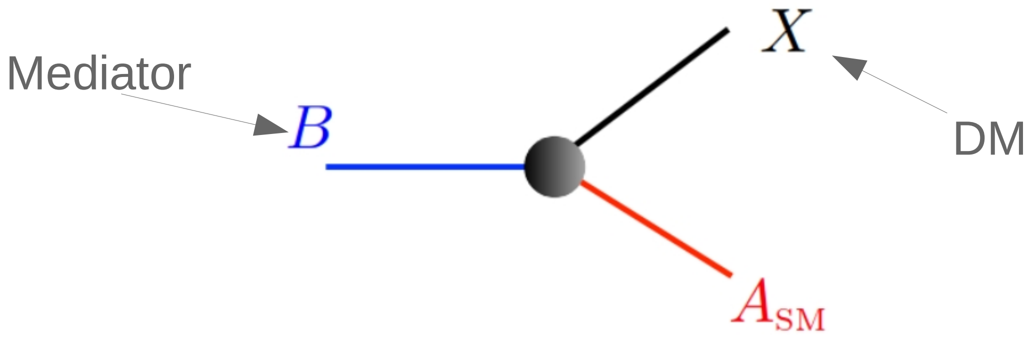
DM Relic Density:

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

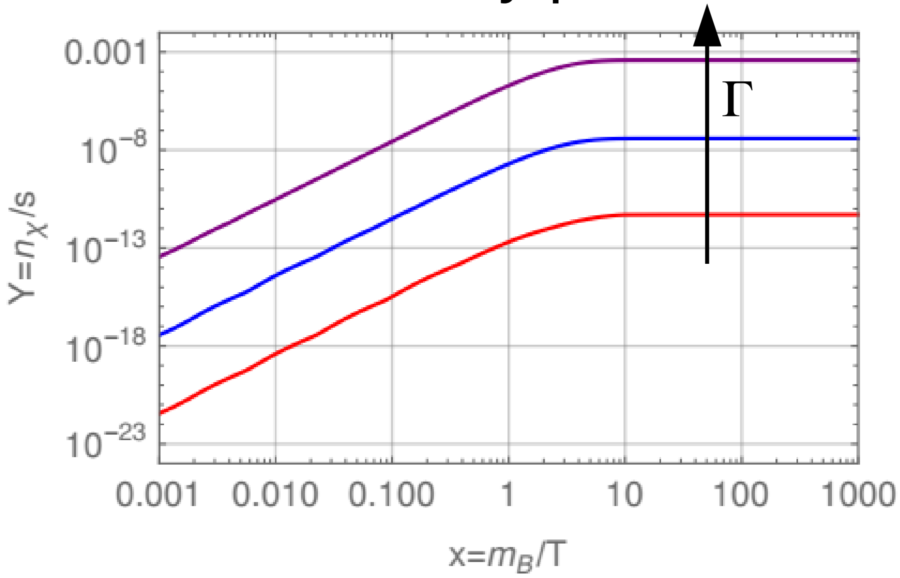
[Planck 2018]

Freeze-in production of DM

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



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



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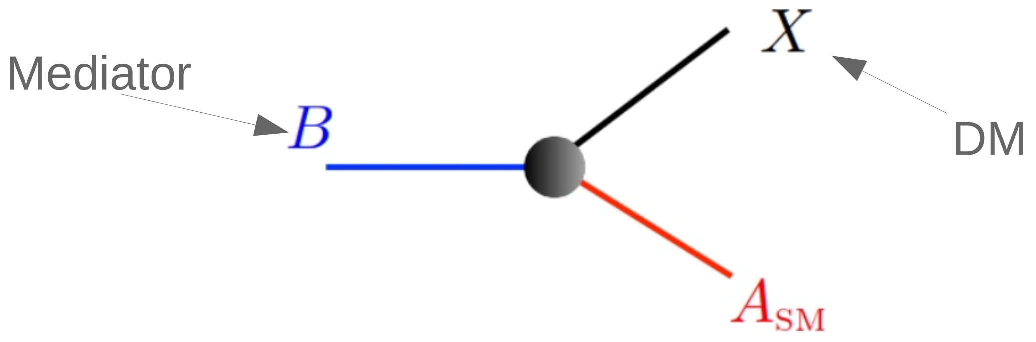
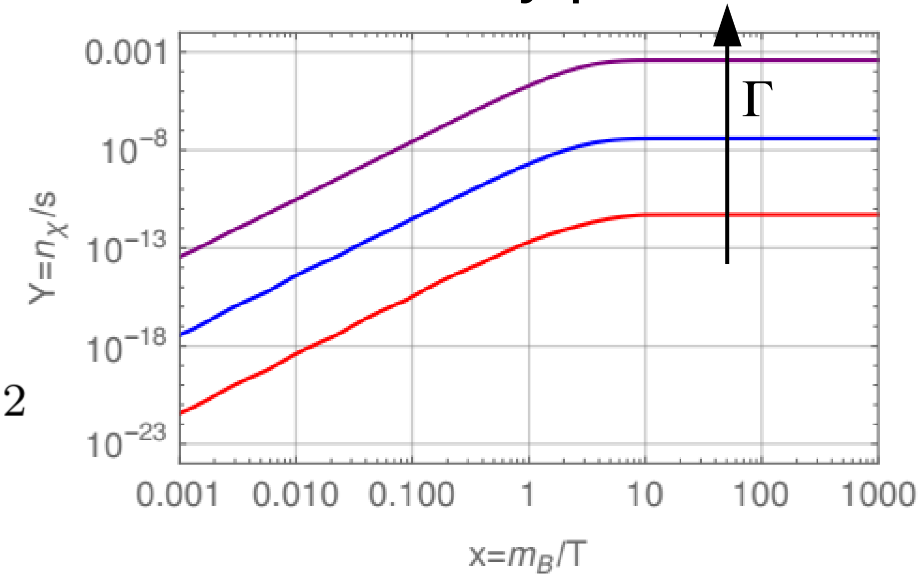
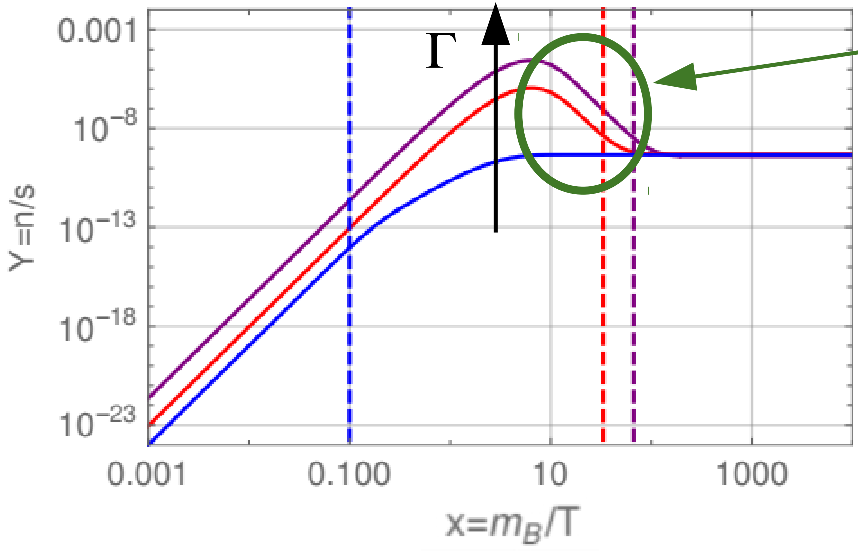


$$c\tau_B = 3.3 \times 10^6 \mathrm{cm} \left(\frac{m_X}{10\mathrm{GeV}}\right) \left(\frac{1\mathrm{TeV}}{m_B}\right)^2$$



Freeze-in during reheating era

- Standard freeze-in happens during radiation era ($T_R >> m_B$)
- 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

↓

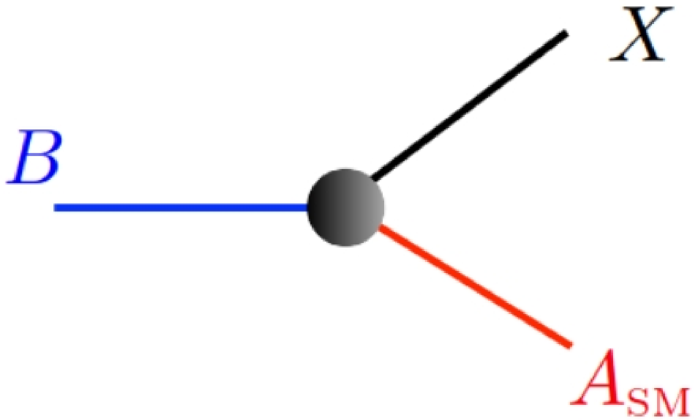
Requiring $\Omega h^2=0.12$ and $m_X > 10$keV (Ly-α bounds)

[D'Eramo et. al. 2020]

↓

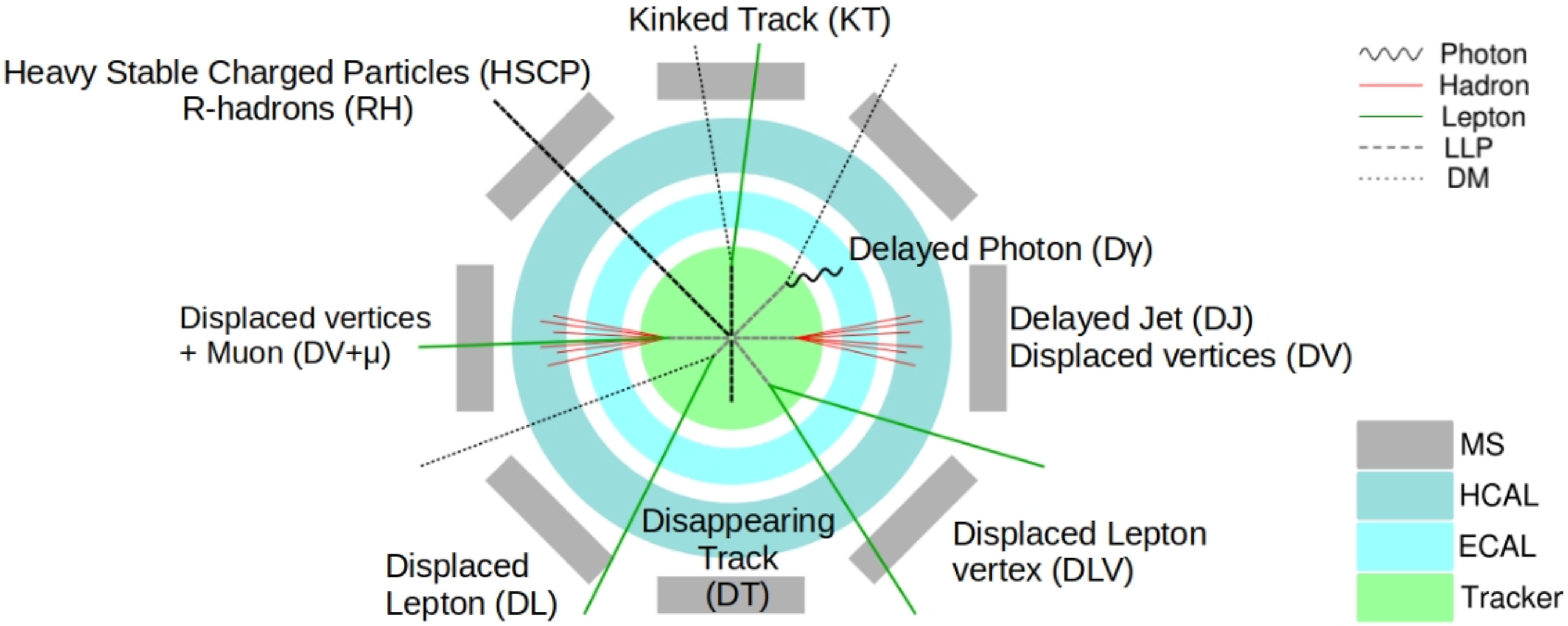
Upper Limit of T_R

Simplified model classification



A_{SM}	Spin DM	Spin B	Interaction	Label
ψ_{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	$\bar{\Psi}_B\chi H$	$\mathcal{F}_{H\chi}$

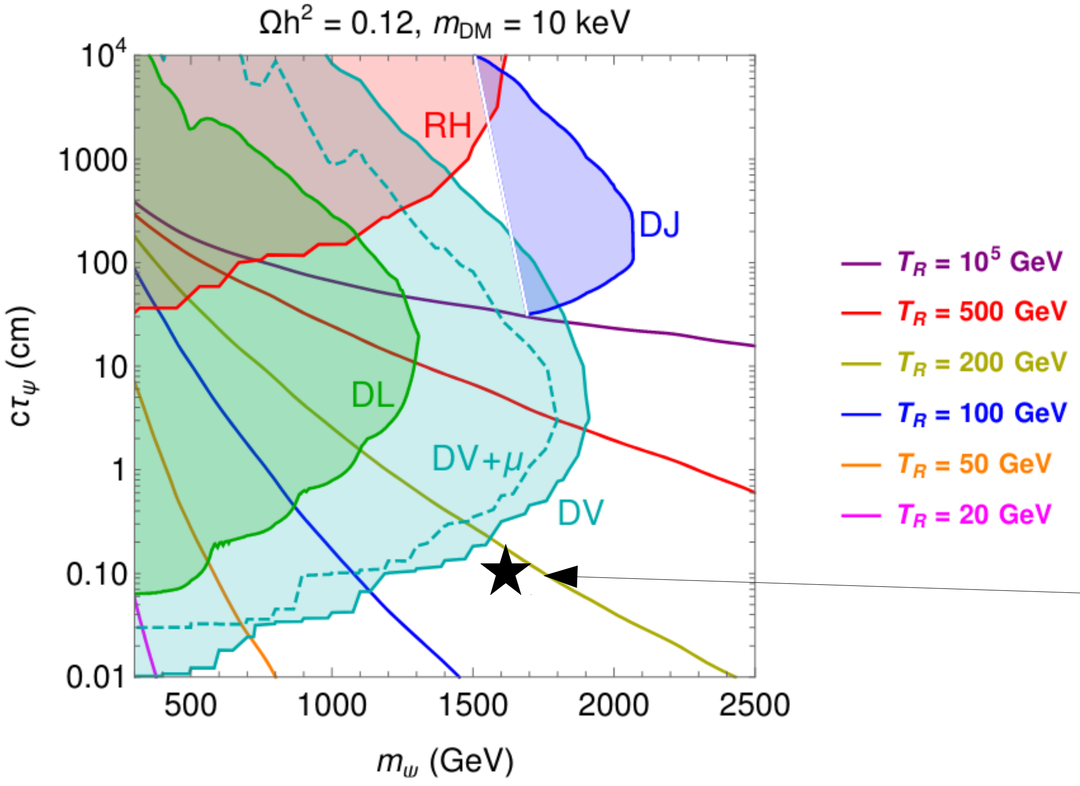
LLP signatures



Sensitivity to simplified models

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

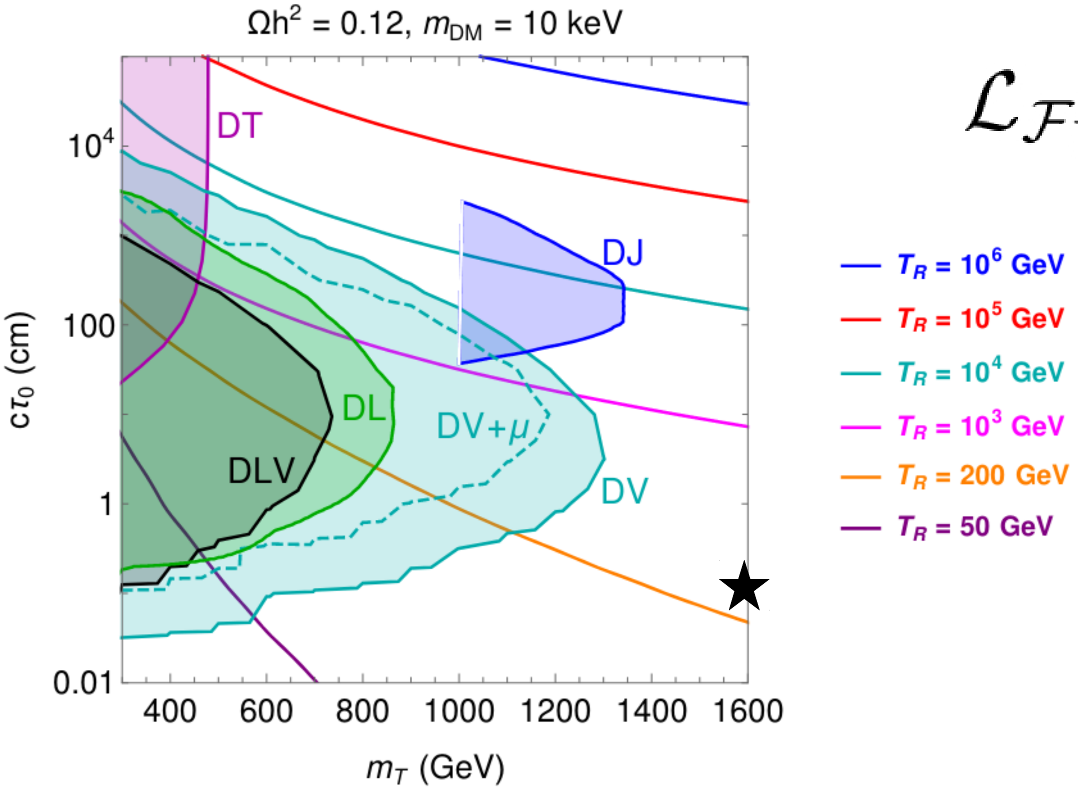
Topphilic scenario



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

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

Singlet-triplet model



$$\mathcal{L}_{\mathcal{F}_{W\chi}} \supset \frac{1}{\Lambda}\left(W^a_{\mu\nu}\bar{\chi_S}\sigma^{\mu\nu}\chi^a_T + \text{h.c.}\right)$$

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

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

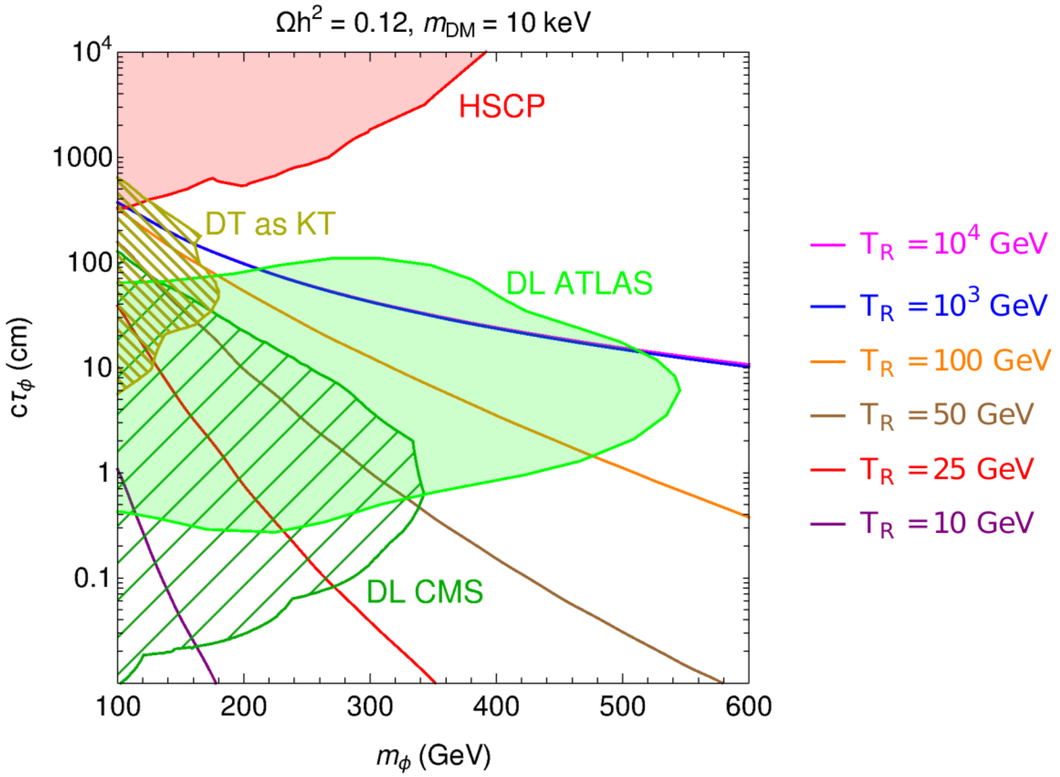
Back-up slides

Upper limit on reheating temperature

$$\Omega_{DM} h^2 \sim \rho_{DM} \sim m_{DM} \cdot Y_{DM} \qquad Y_{DM} \approx 10^4 \left(\frac{T_R}{m_B}\right)^7 \frac{\Gamma_B M_{pl}}{m_B^2}$$

- Decreasing m_{DM} allows for larger Y_{DM} and hence larger T_R
- m_{DM} cannot decrease indefinitely due to Ly-α bounds m_{DM}>10keV
- This leads to upper limit on T_R if m_B and $c\tau_B$ can be determined

Leptophilic scenario



$$\mathcal{L}_{S_{\ell_R\chi}} \supset - \lambda_\chi \Phi_B \bar{\chi} \mu_R$$

LLP searches used

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

LLP searches used

[59] **CMS** Collaboration, C. Collaboration, *Search for heavy stable charged particles with* 12.9 fb^{-1} *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^{-1} *of proton-proton collision data at* $\sqrt{s} = 13$ *TeV*, *Phys. Rev.* **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.* **D97** (2018), no. 5 052012, [arXiv:1710.04901].

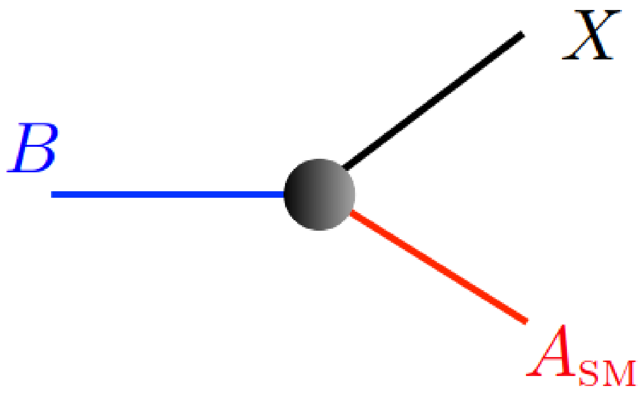
[68] **CMS** Collaboration, A. M. Sirunyan et al., *Search for long-lived particles using nonprompt jets and missing transverse momentum with proton-proton collisions at* $\sqrt{s} =$ *13 TeV*, *Phys. Lett.* **B797** (2019) 134876, [arXiv:1906.06441].

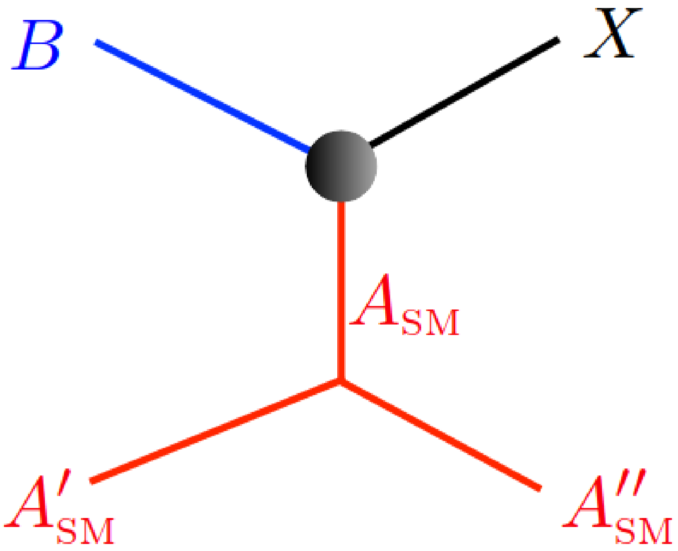
[69] **ATLAS** Collaboration, G. Aad et al., *Search for long-lived, massive particles in events with a displaced vertex and a muon with large impact parameter in pp collisions at* $\sqrt{s} = 13$ *TeV with the ATLAS detector*, arXiv:2003.11956.

[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.* **B801** (2020) 135114, [arXiv:1907.10037].

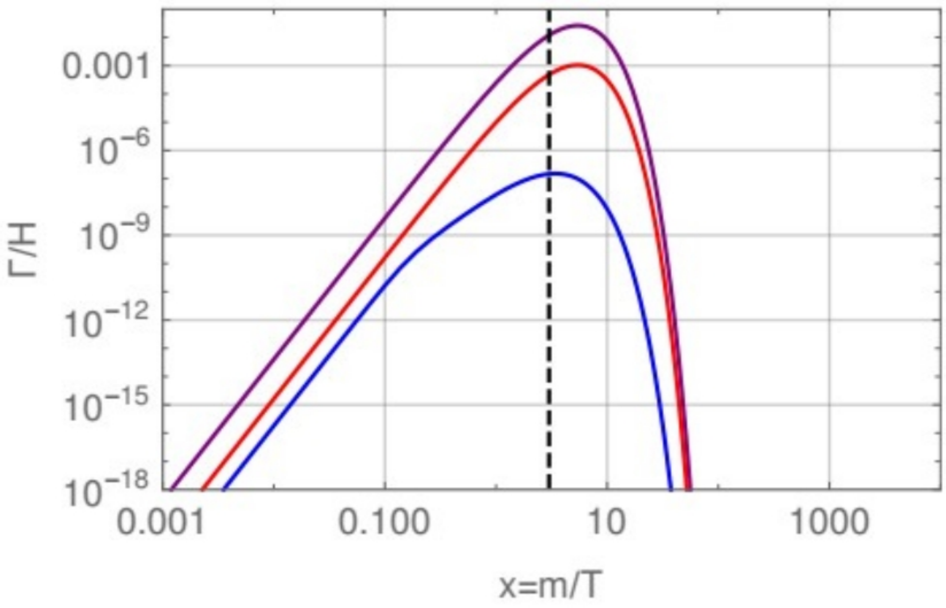
[71] **CMS** Collaboration, A. M. Sirunyan et al., *Search for long-lived particles using delayed photons in proton-proton collisions at* $\sqrt{s} =$ *13 TeV*, *Phys. Rev. D* **100** (2019), no. 11 112003, [arXiv:1909.06166].

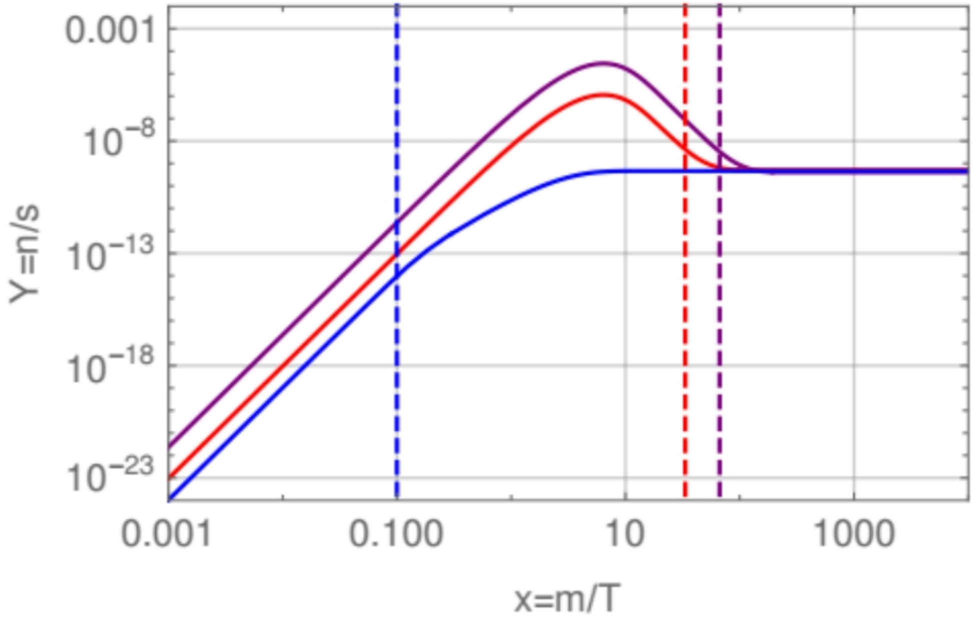
Freeze-in contribution diagrams



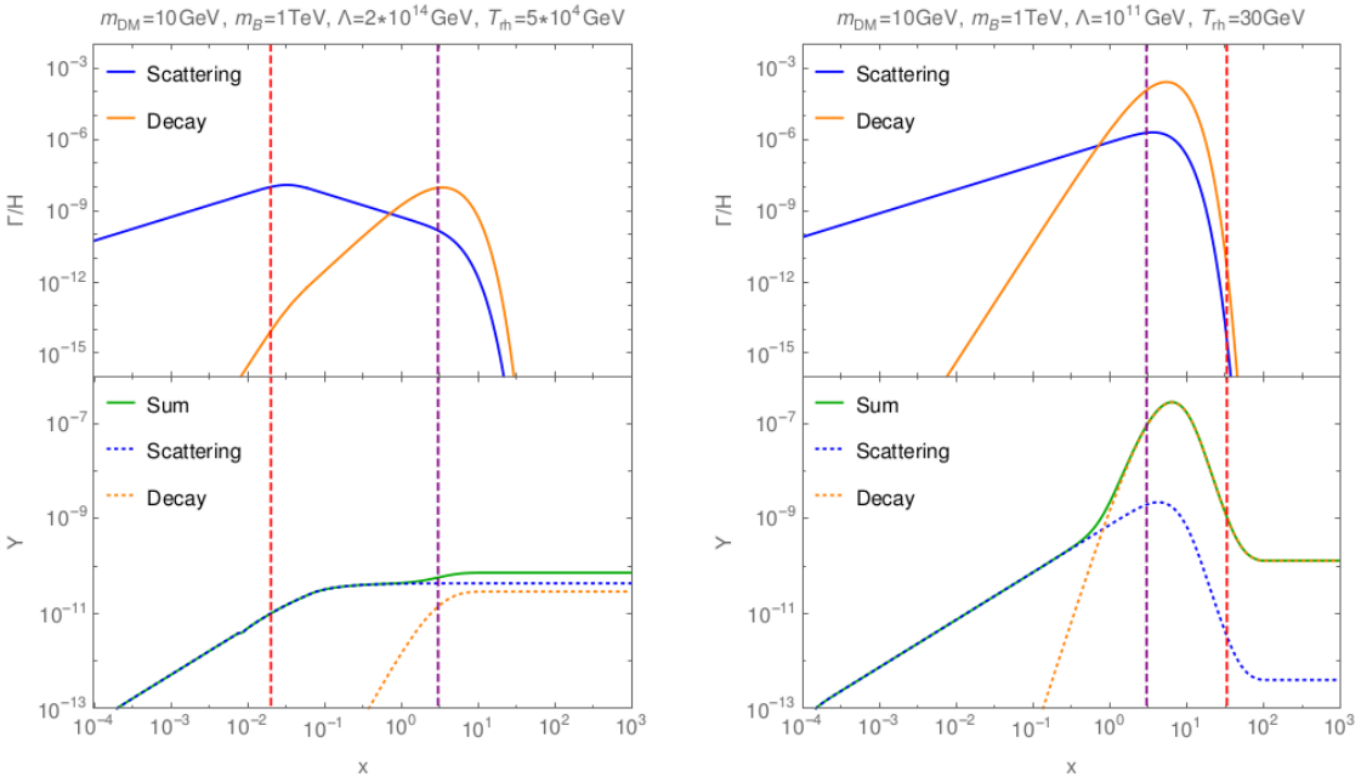


IR freeze-in (renormalizable operator)

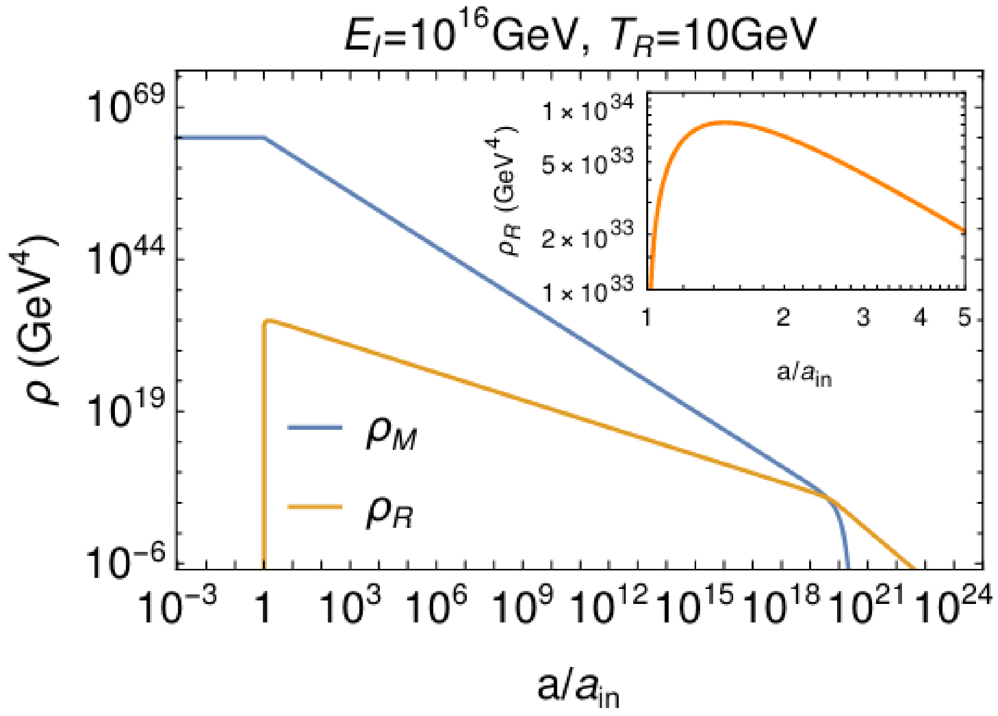




UV freeze-in (non-renormalizable operator)



Inflationary reheating



- After inflation, inflaton starts oscillating and produces thermal bath

  $$\rho_M \sim a^{-3} \quad \rho_R \sim a^{-3/2}$$

- At T=T_R, the inflaton decays away and universe is radiation dominated

  $$\rho_R \sim a^{-4}$$