Probing the early universe with displaced new physics at colliders

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Based on JHEP 05 (2021) 234
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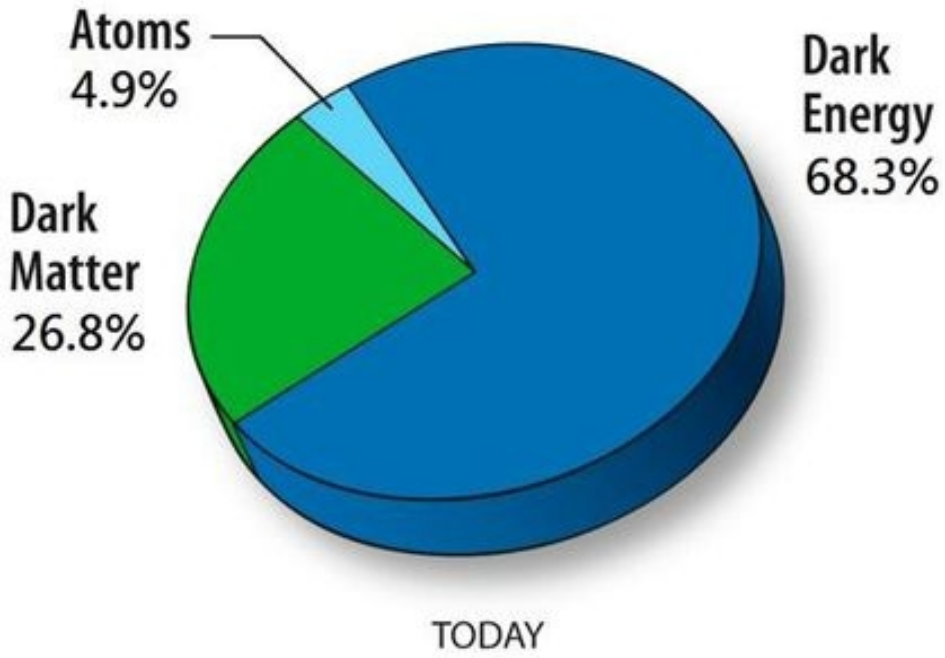
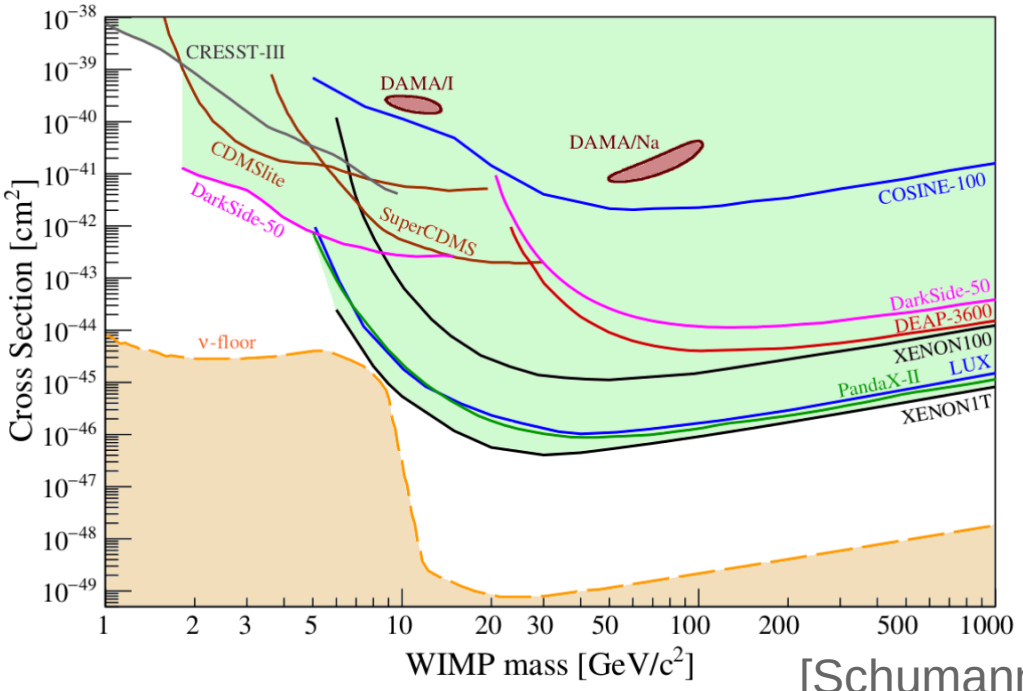
Despite dedicated experiments, nature of DM remains unknown



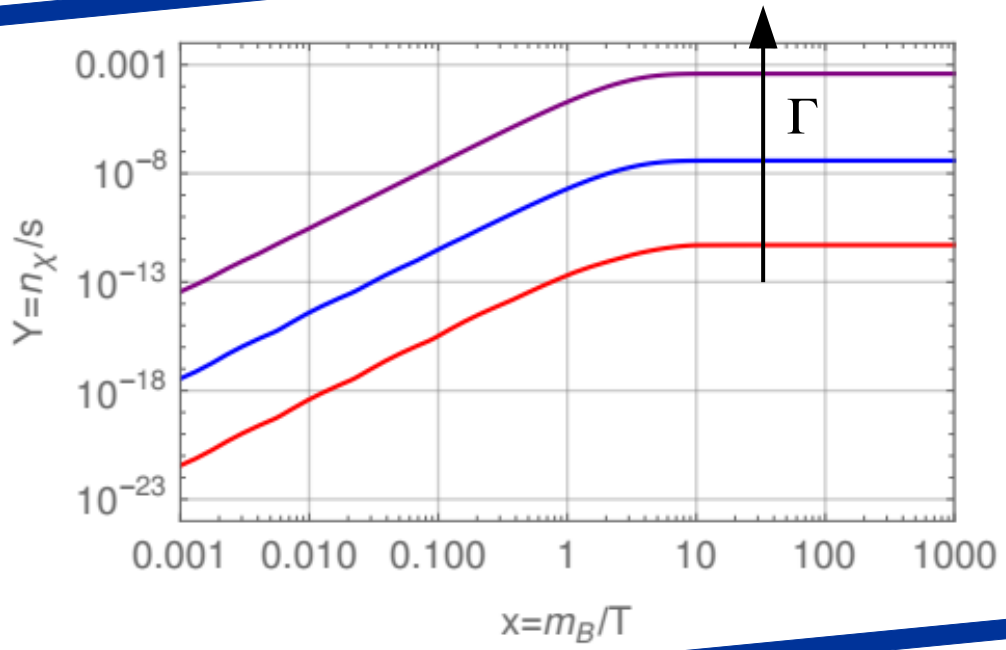
Direct detection puts strong bounds on DM-SM interactions

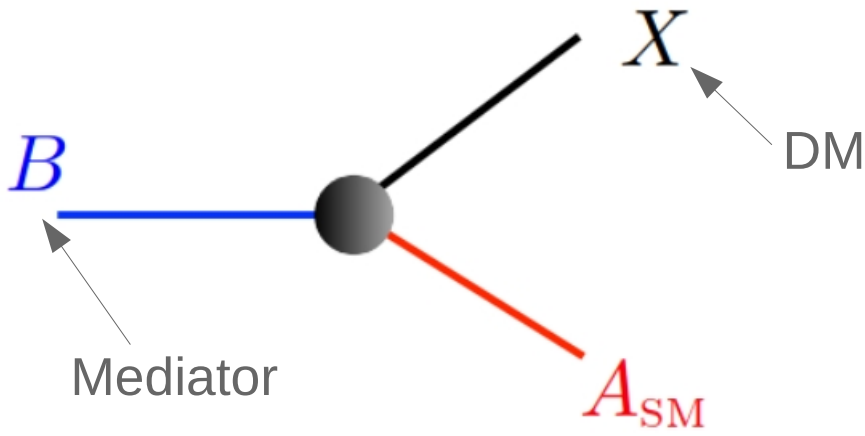


[Schumann '19]

Can we produce DM with feeble interactions?

Freeze-in





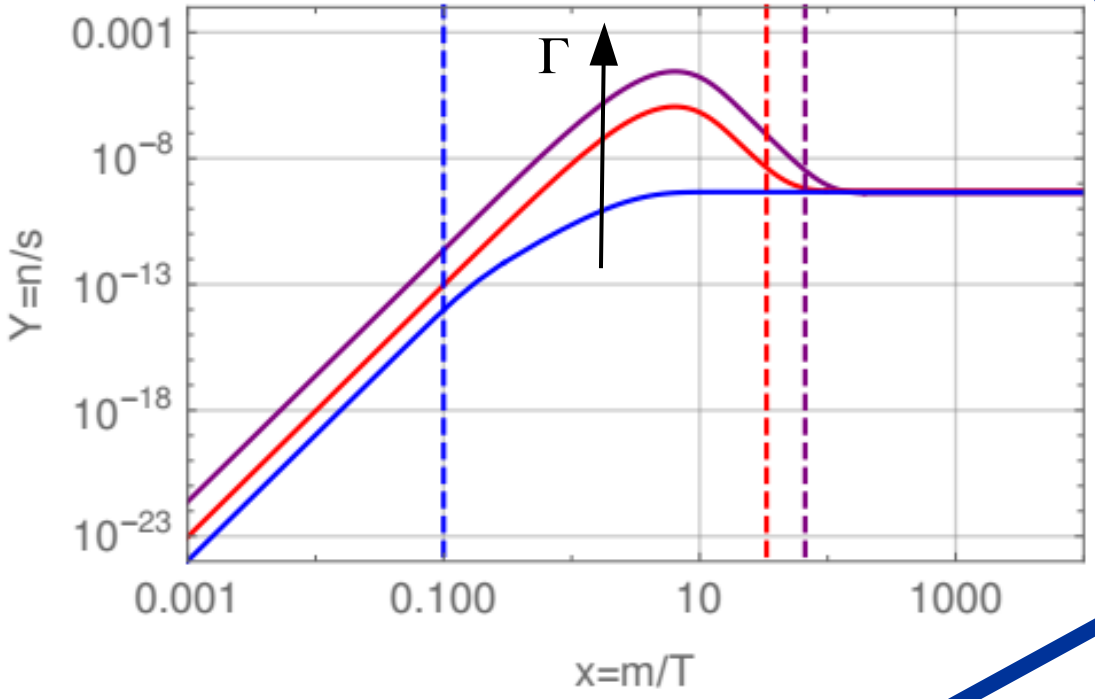
Decays gradually build up DM abundance

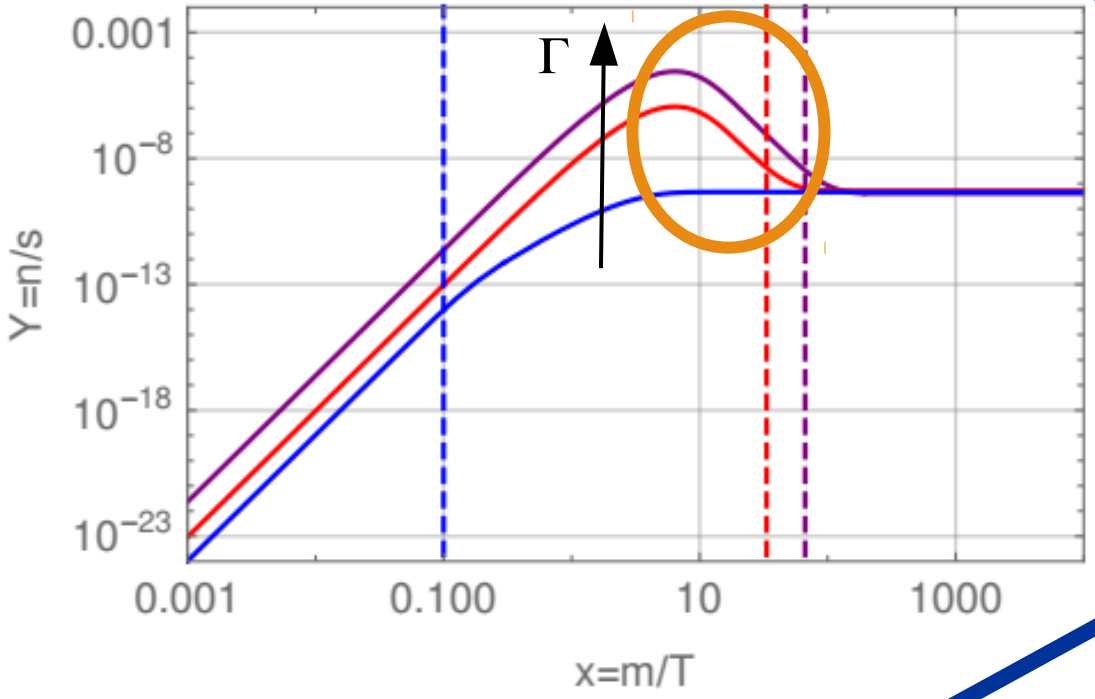
Freeze-in provides link between relic abundance and lifetime

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

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

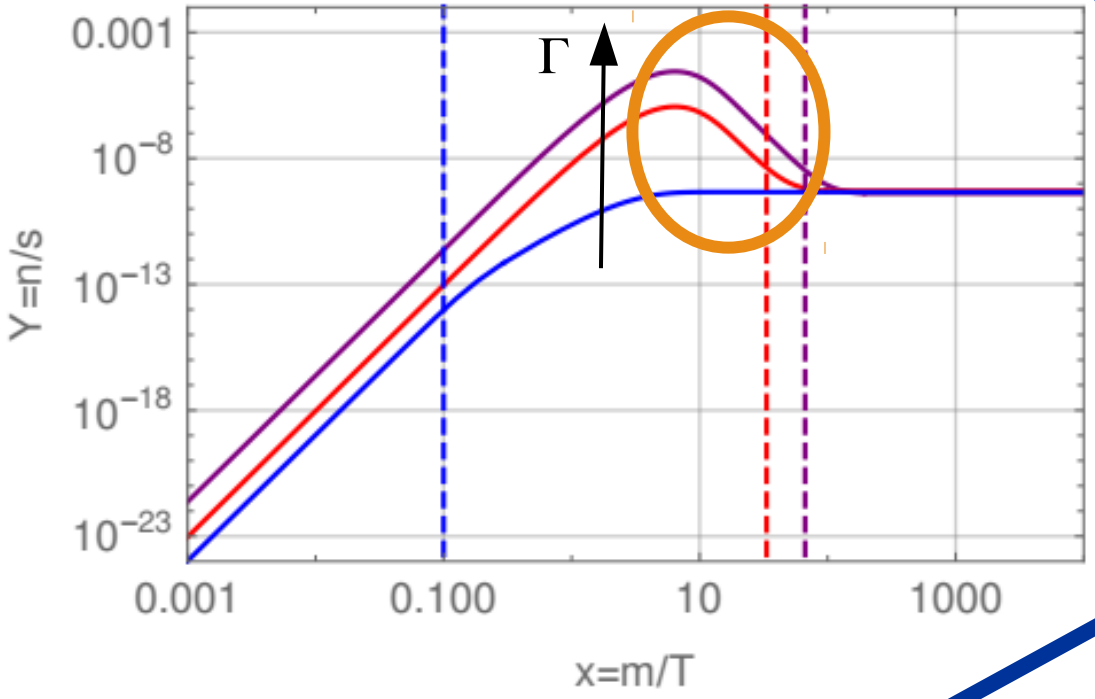
Freeze-in during early matter dominated era





Freeze-in during early matter dominated era

DM abundance gets diluted



Freeze-in during early matter dominated era

DM abundance gets diluted

$$c\tau_B \simeq 1.1 \times 10^8\,\mathrm{m} \left(\frac{T_R}{m_B}\right)^7 \left(\frac{m_X}{1\,\mathrm{GeV}}\right) \left(\frac{1\mathrm{TeV}}{m_B}\right)^2$$

Probing early universe using LHC

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

↓

Requiring $\Omega h^2 = 0.12$

↓

Exact prediction of T_R

Probing early universe using LHC

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

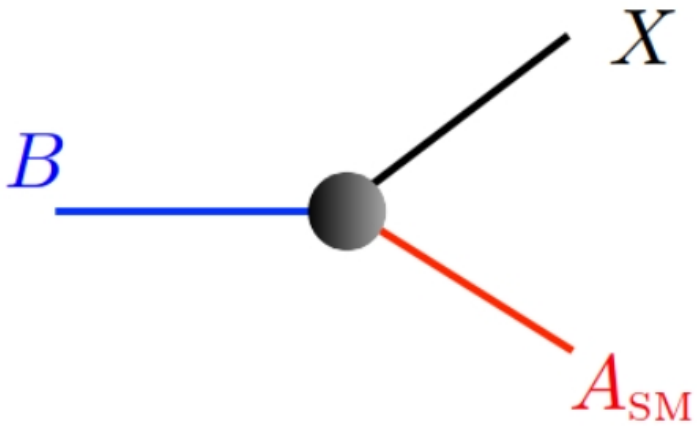
↓

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

↓

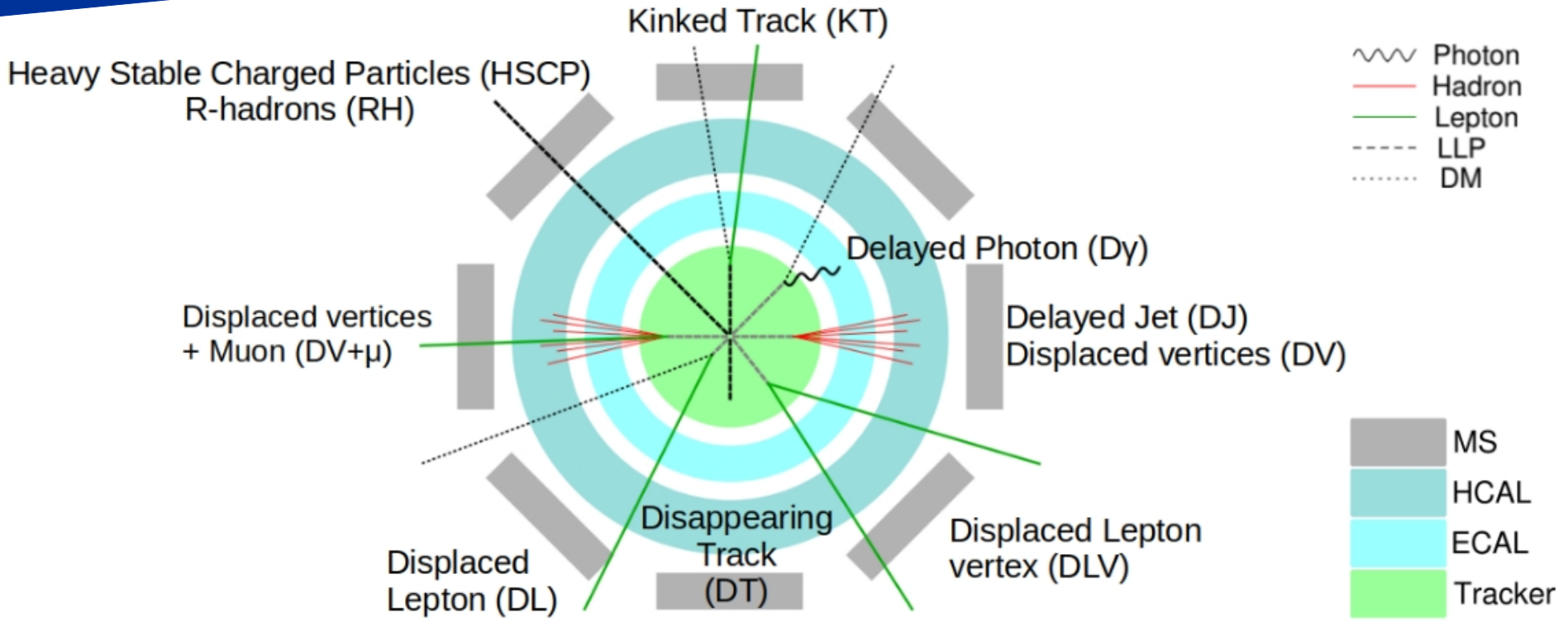
Upper Limit of T_R

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	$\bar{\Psi}_B\chi H$	$\mathcal{F}_{H\chi}$

Displaced signatures at LHC



Sensitivity to simplified models

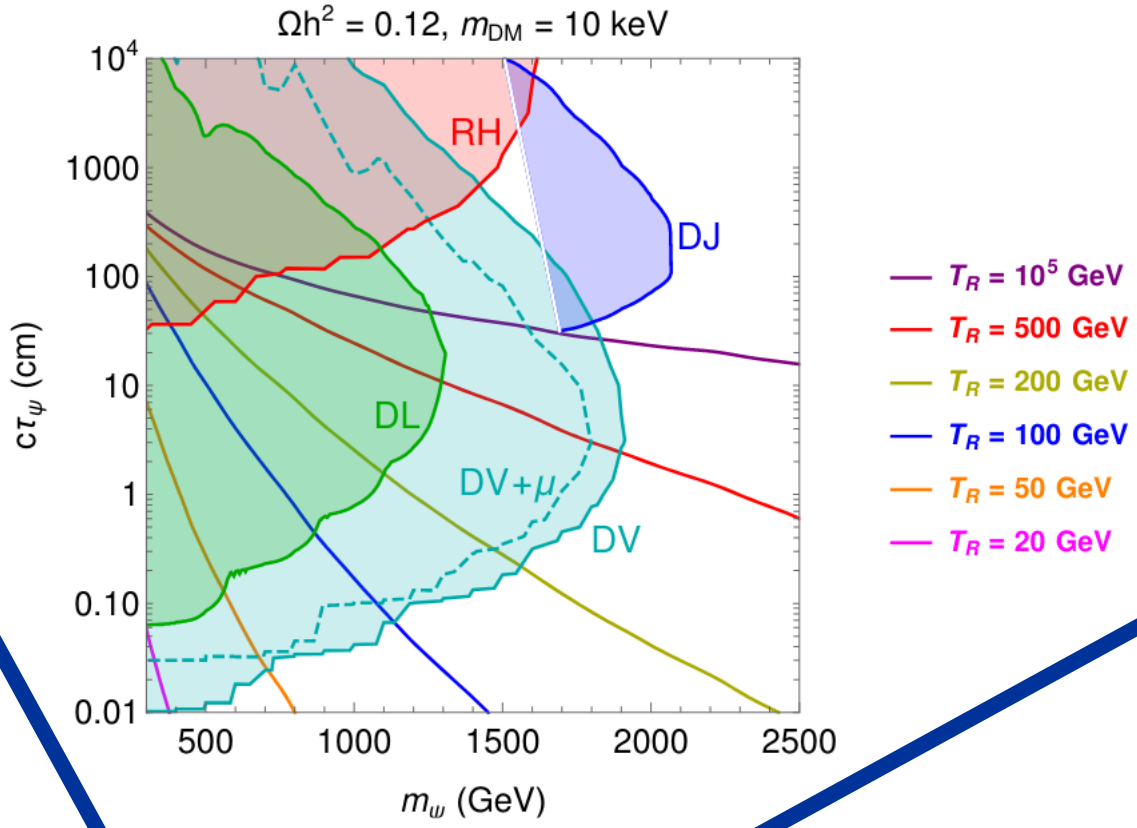
Label	DV + MET	DJ + MET	DV + μ	DL	DLV	Dγ	DT	RH	HSCP	KT
$\mathcal{F}_{\ell\phi}$ & $\mathcal{S}_{\ell\chi}$				✓					✓	✓
$\mathcal{F}_{\tau\phi}$ & $\mathcal{S}_{\tau\chi}$	✓	✓		✓					✓	✓
$\mathcal{F}_{q\phi}$ & $\mathcal{S}_{q\chi}$	✓	✓						✓		
$\mathcal{F}_{t\phi}$ & $\mathcal{S}_{t\chi}$	✓	✓	✓	✓	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

Sensitivity to simplified models

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

Topphilic scenario

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



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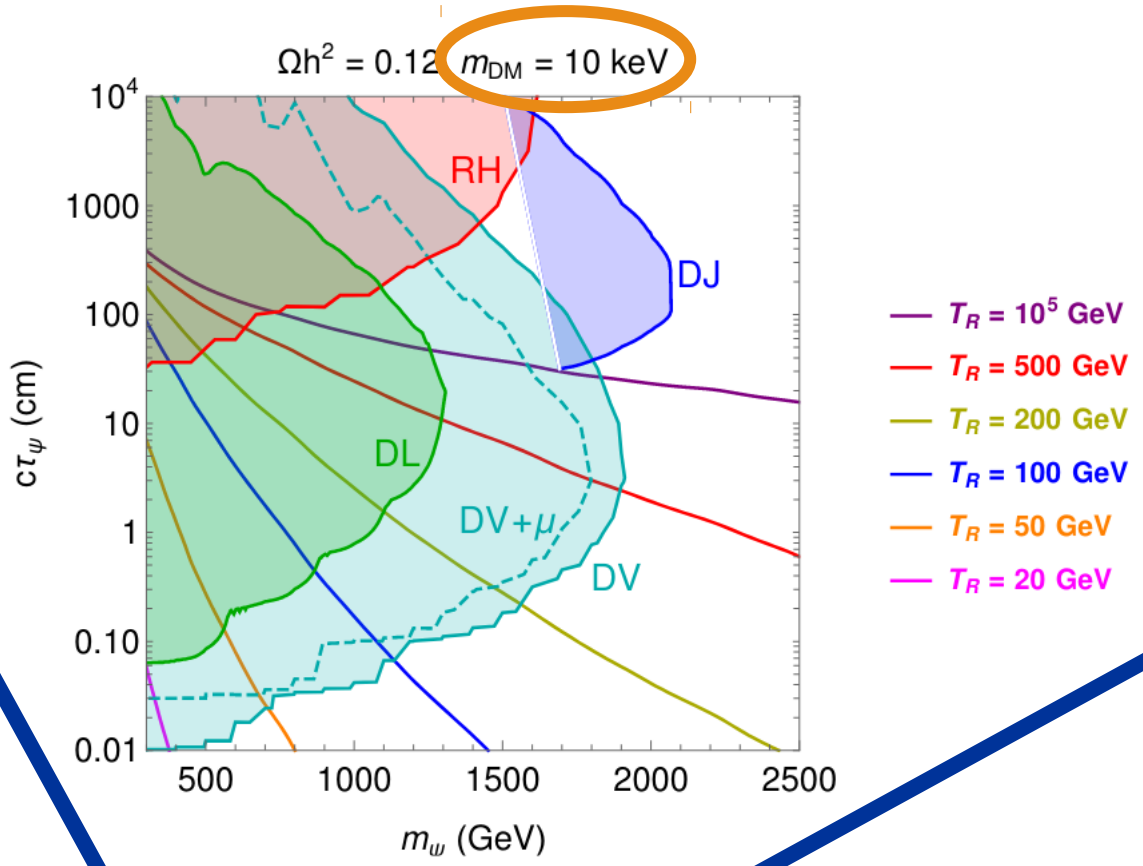
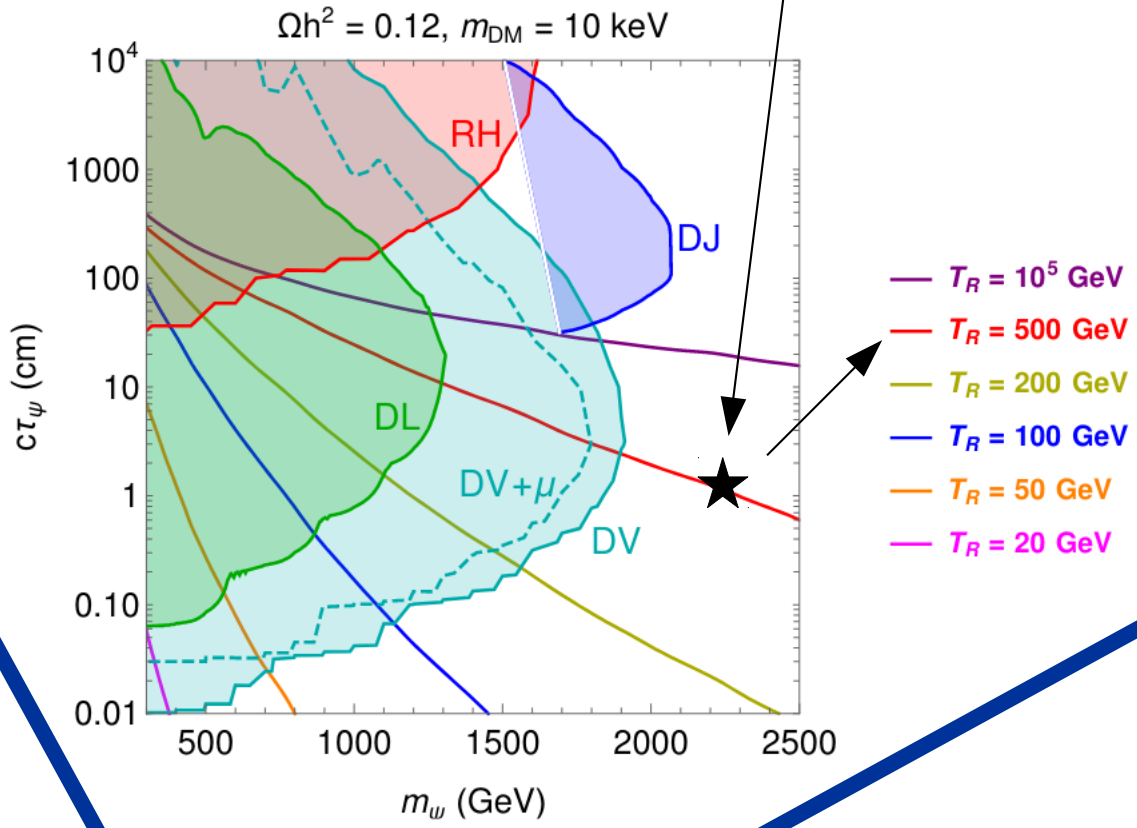


In case of a discovery, we find upper limit on T_R



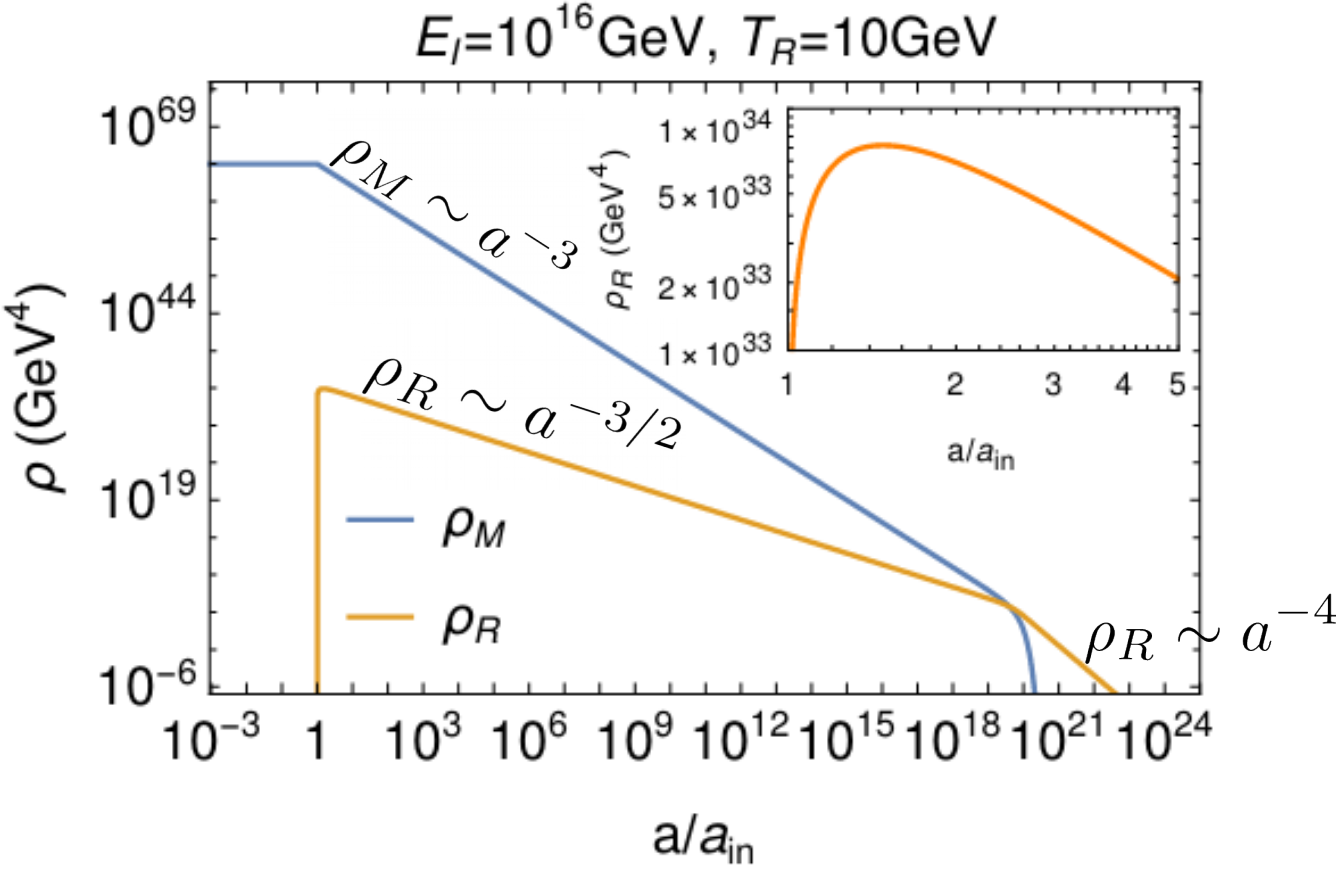
Topphilic scenario

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

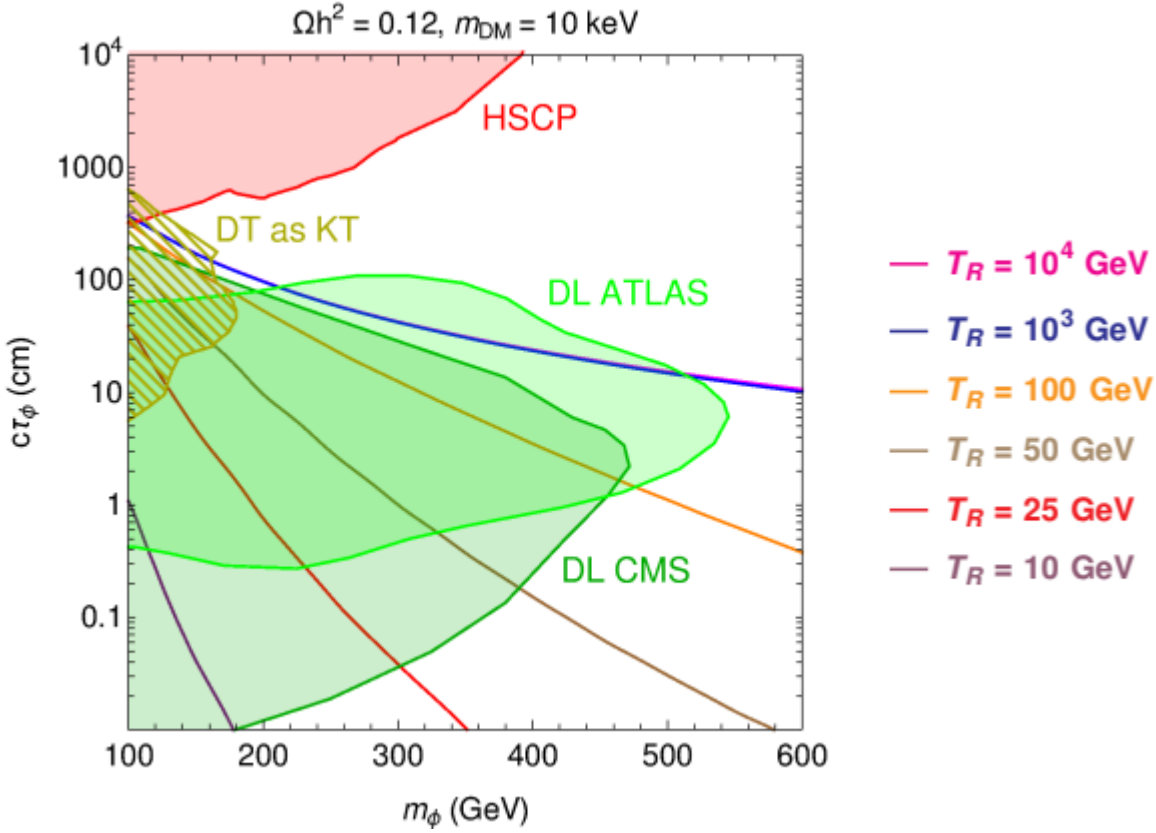
Conclusion

- Link between DM freeze-in production and mediator decay length
- If $T_R < m_B$, these models can be probed by LLP searches
- A discovery of displaced physics can provide information about the early universe
- Probing different signatures is of great importance to identify the exact model

Inflationary reheating

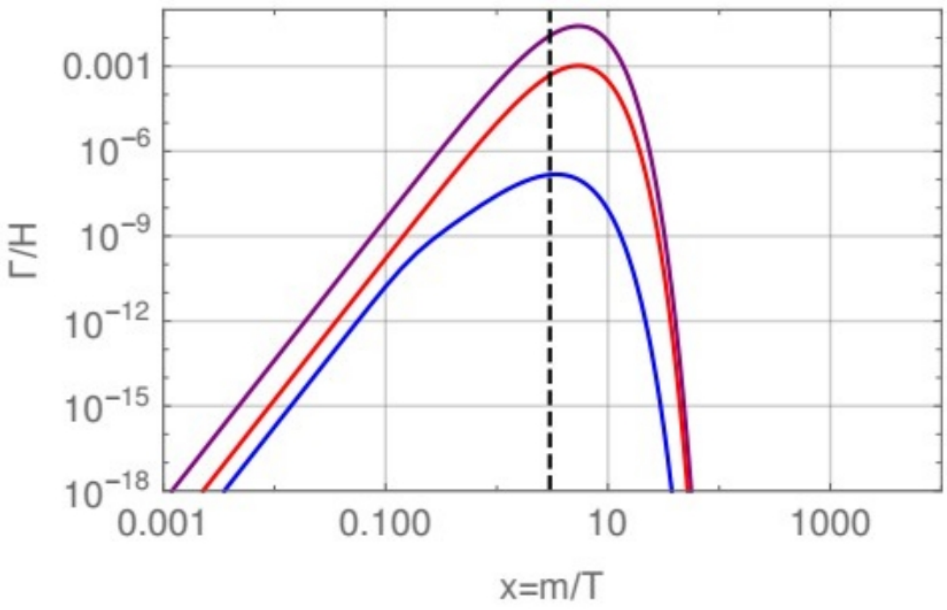


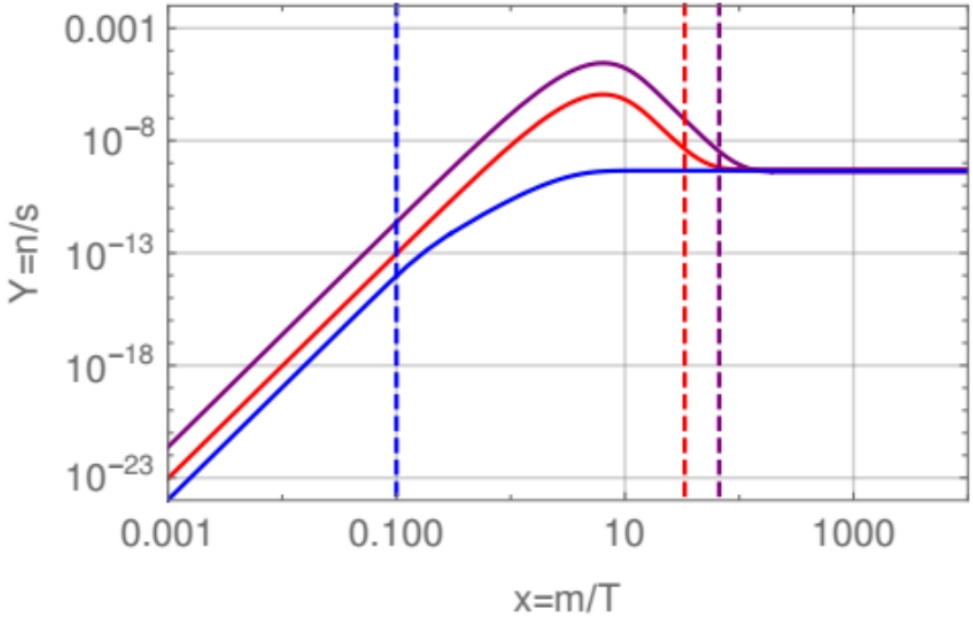
Leptophilic scenario



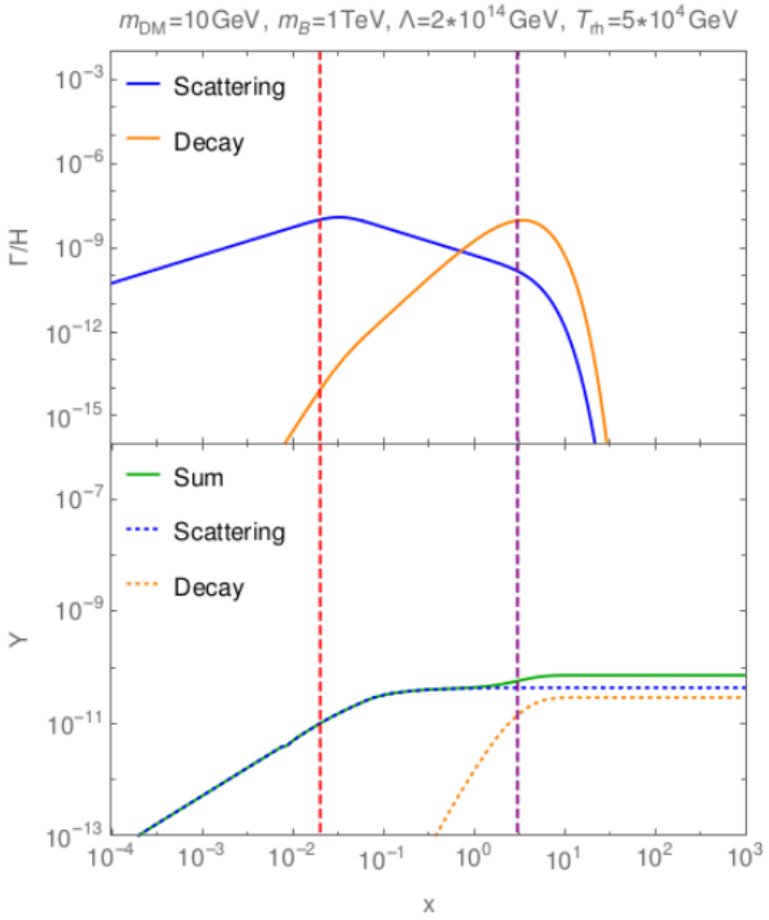
$$\mathcal{L}_{\mathcal{S}_{\ell_R \chi}} \supset - \lambda_\chi \Phi_B \bar{\chi} \mu_R$$

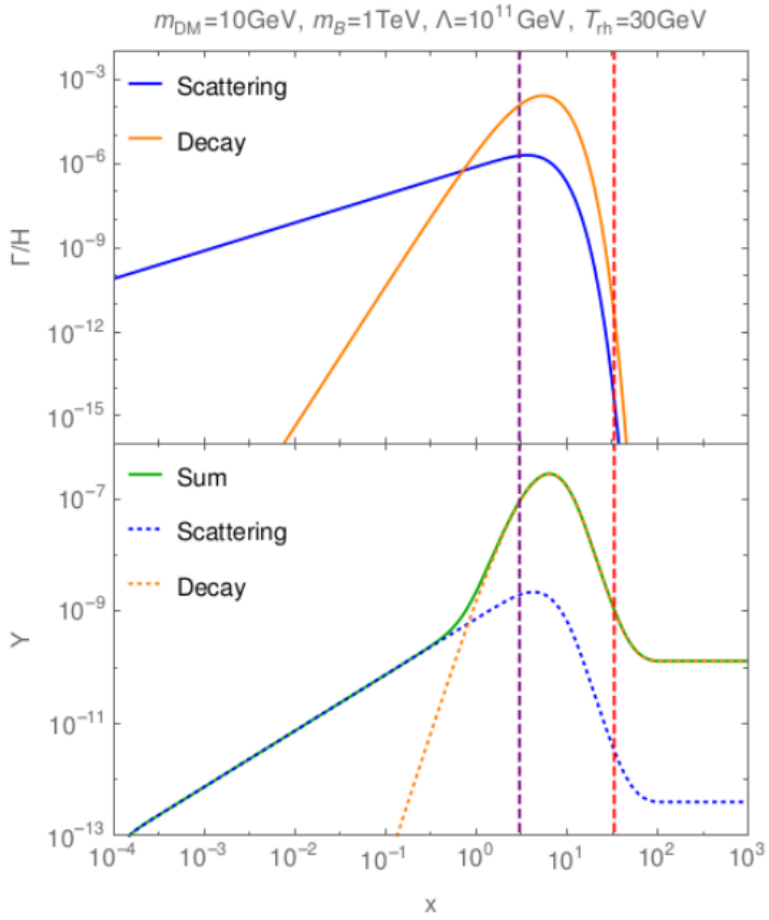
IR freeze-in


0.001
10^{-6}
10^{-9}
10^{-12}
10^{-15}
10^{-18}
Γ/H
0.001
0.100
10
1000
x=m/T

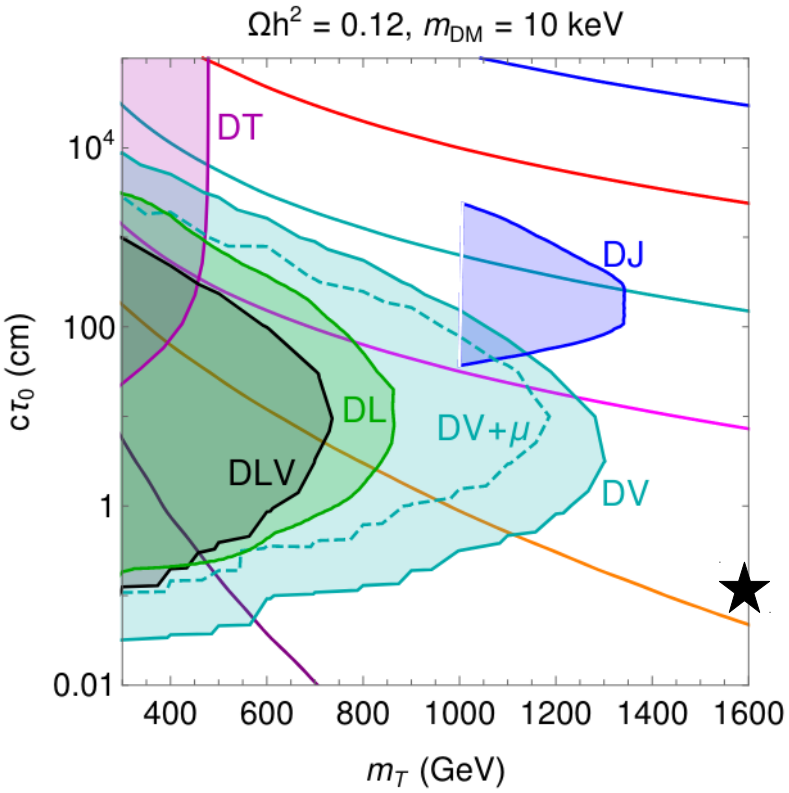

0.001
10^{-8}
10^{-13}
10^{-18}
10^{-23}
Y=n/s
0.001
0.100
10
1000
x=m/T

UV freeze-in


m_{DM}=10GeV, m_B=1TeV, Λ=2*10^14 GeV, T_{rh}=5*10^4 GeV
Scattering
Decay
Γ/H
Sum
Scattering
Decay
Y
x


m_{DM}=10GeV, m_B=1TeV, Λ=10^11 GeV, T_{rh}=30GeV
Scattering
Decay
Γ/H
Sum
Scattering
Decay
Y
x

Singlet-triplet



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

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

LHC LLP searches

Signature	Exp. & Ref.	$\mathcal{L}$	Maximal sensitivity	Label
R-hadrons Heavy stable charged particle	CMS [123] ATLAS [125]	12.9 fb^{-1} 36.1 fb^{-1}	$c\tau \gtrsim 10$ m	RH HSCP
Disappearing tracks	ATLAS [130] CMS [132, 133]	36.1 fb^{-1} 140 fb^{-1}	$c\tau \approx 30$ cm $c\tau \approx 60$ cm	DT
Displaced leptons	CMS [138] ATLAS [139]	118 fb^{-1} 139 fb^{-1}	$c\tau \approx 3$ cm	DL
Displaced vertices + MET	ATLAS [144]	32.8 fb^{-1}	$c\tau \approx 3$ cm	DV+MET
Delayed jets + MET	CMS [150]	137 fb^{-1}	$c\tau \approx 1 - 3$ m	DJ+MET
Displaced vertices + μ	ATLAS [156]	136 fb^{-1}	$c\tau \approx 3$ cm	DV+μ
Displaced dilepton vertices	ATLAS [141]	32.8 fb^{-1}	$c\tau \approx 1 - 3$ cm	DLV
Delayed photons	CMS [157]	77.4 fb^{-1}	$c\tau \approx 1$ m	Dγ