Revisiting the minimal fermionic dark matter UV, IR, and inflaton driven freeze-in

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⟨Work in progress with F. D'Eramo and M. Becker.⟩

* No AI/ML/LLM tools were used to produce this presentation.
Everything shown here is the result of human effort; any mistakes are its natural by-products.

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Why?

- Simple.
- General.
- Generic low energy limit.
- Explore DM landscape.

N. Arkani-Hamed, A. Delgado and G. F. Giudice, Nucl. Phys. B **741** (2006), 108-130 [arXiv:hep-ph/0601041 [hep-ph]].

T. Cohen, J. Kearney, A. Pierce and D. Tucker-Smith, Phys. Rev. D **85** (2012), 075003 [arXiv:1109.2604 [hep-ph]].

A. Dedes, DK, and A. Pilaftsis, Phys. Rev. D **95** (2017) no.11, 115037 [arXiv:1704.01497 [hep-ph]].

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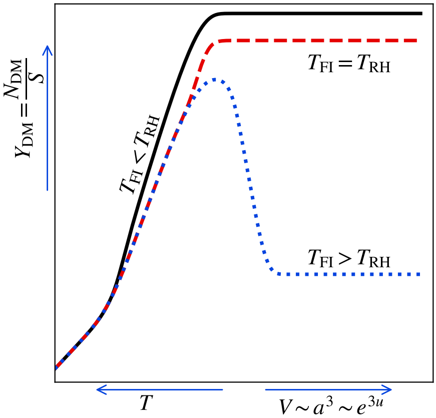

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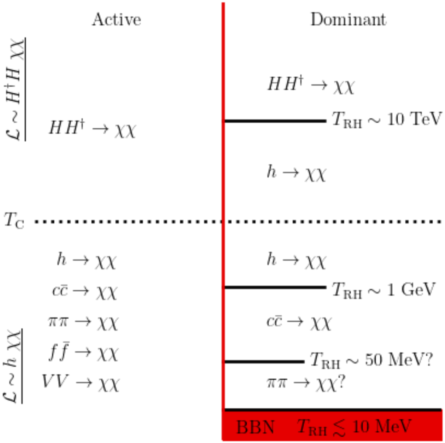

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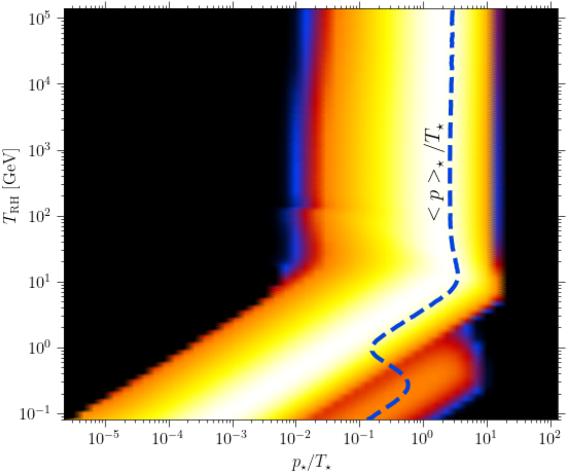

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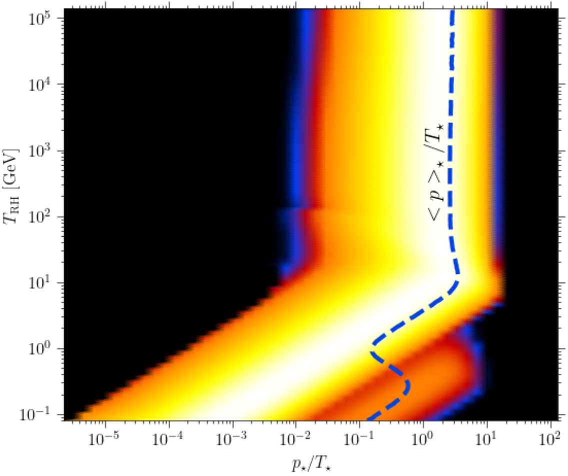

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What we do?

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- All processes. ⟨Work in progress⟩
- *Phase-space distribution* (PSD).
- Focus on low m_χ.*
- Code for reproducibility. ⟨Work in progress⟩

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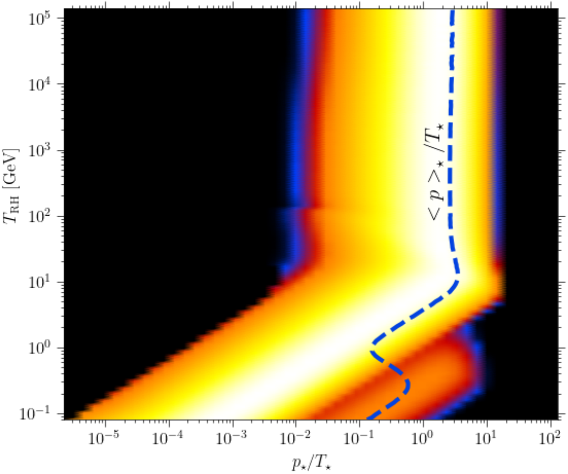

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Dark matter is likely:

- Mostly electrically neutral.
- Stable or very slow decay rate.
- Non-Baryonic.
- Cold/Warm.
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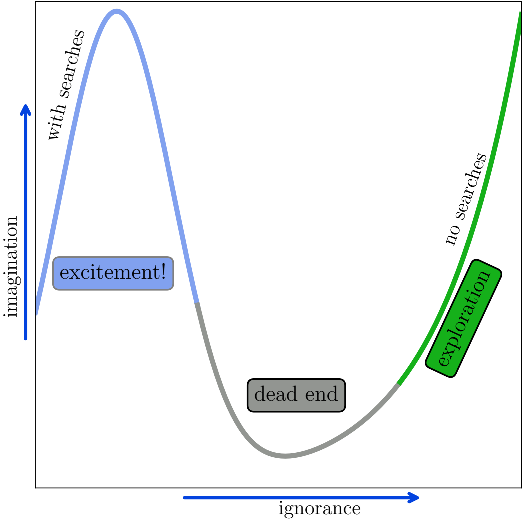

Dark matter – Candidates

There are many hypotheses for DM.

Dark matter – Candidates

Based on M. Cirelli, et al. arXiv:2406.01705

Candidate	When	Who
Primordial BH	1966, 1971	Zeldovich & Novikov, Hawking
MACHOs	1981, 1986	Petrou; Paczynski
WIMPs	1977, 1985	Lee & Weinberg; Steigman & Turner
Gravitinos	1981, 1982	Fayet; Witten; Pagel & Primack
Axions	1983	Preskill, Wise & Wilczek
Neutralinos	1984	Ellis et al.
Strangelets	1984	Witten; Fahri & Jaffe
Q-balls	1984	Witten
Extra-dimensional DM	1984	Kolb & Slansky; Servant & Tait
Sterile neutrinos	1993	Dodelson & Widrow
Fuzzy DM	2000	Hu, Barkana & Gruzinov
FIMPs	2001,2009	J. McDonald; Hall et al.
Sub-GeV DM	2003	Boehm, Fayet et al.

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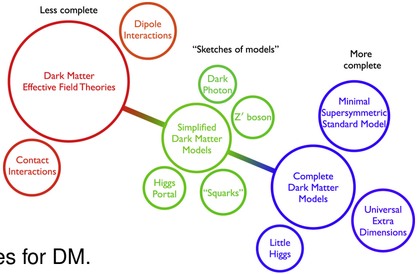

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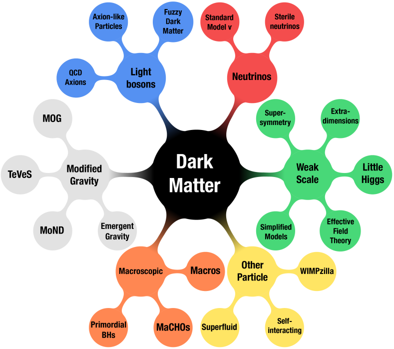

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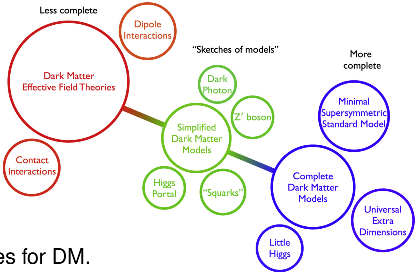

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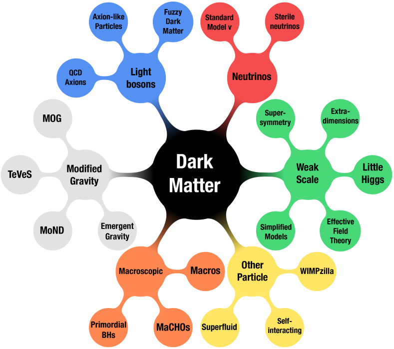
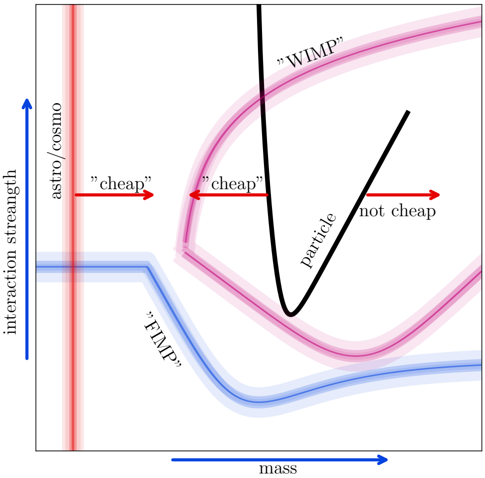


We could consider a more detailed view of simple cases.

Generalization of the basics:	Freeze-in + Reheating + PSD-level

Dark matter – Propaganda

* This is an simplified representation of an entire ecosystem of searches and models. It is meant for illustrative purposes during this talk.



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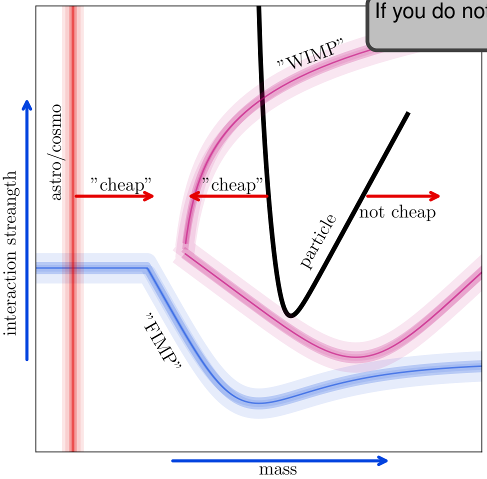

If you do not expect the unexpected, you will not find it.
– Attributed to Heraclitus

- Light DM
  - Relatively unexplored.
  - Accessibility.
  - Experimental complementarity.

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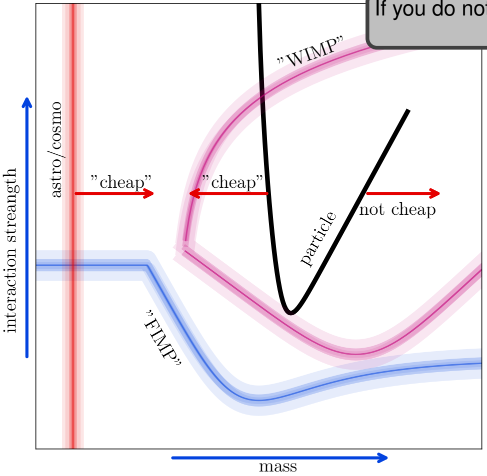

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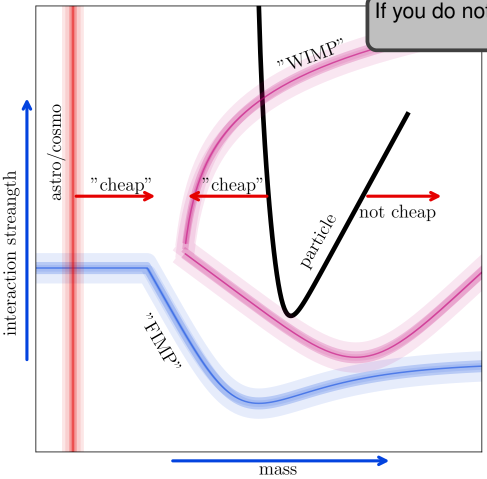

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– Phase-space distribution
  - Quantizaion of distortions.[1,*]
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  - PSD reconstruction? [2]

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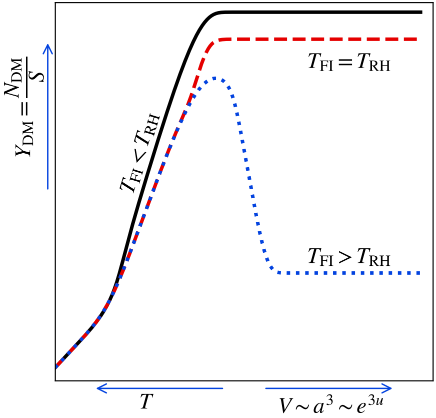
[2] K. R. Dienes, F. Huang, et.al. Phys. Rev. D **106** (2022) no.8, 083506 [arXiv:2101.10337].
[*] Also see talks from Stefan Lederer and Nicola Barbieri.

Dark matter – The role of reheating



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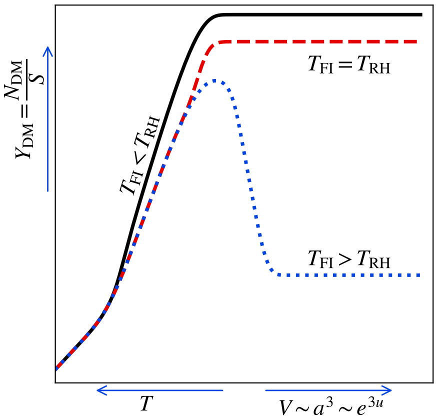
- Initially absent DM particles – $N_{\rm DM} \ll N_{\rm eq}$.



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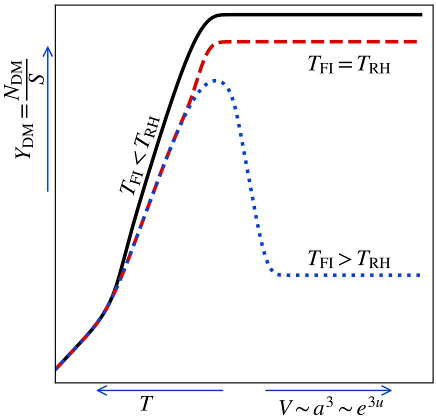

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Freeze-in:

- Initially absent DM particles – $N_{\mathrm{DM}} \ll N_{\mathrm{eq}}$.
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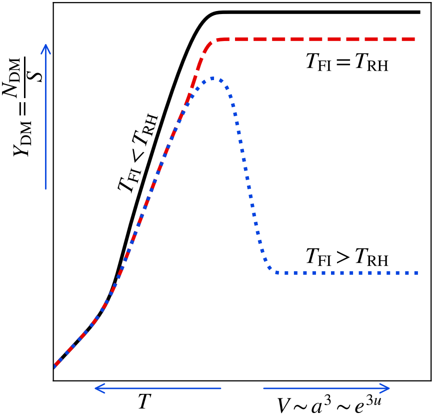

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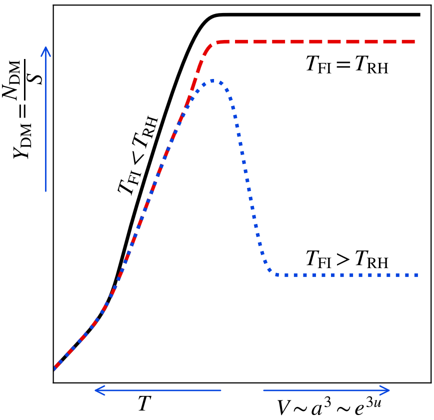
Freeze-in with reheating:



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Dark matter – The role of reheating

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Freeze-in with reheating:

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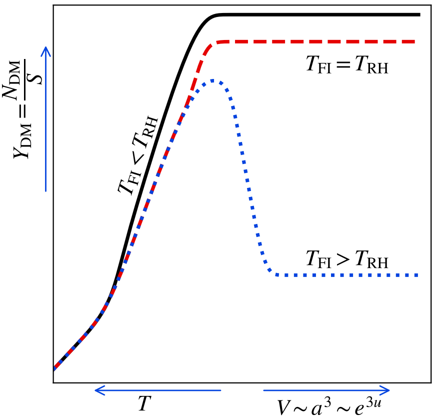

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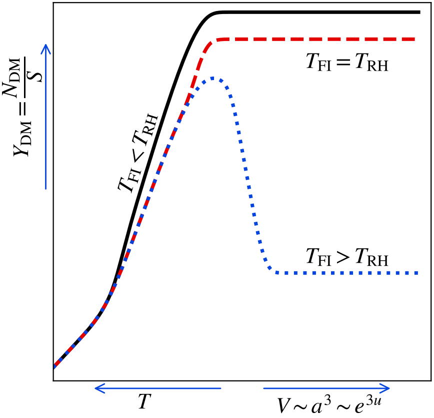
Freeze-in with reheating:

- Temperature evolution changes.
- Production becomes typically slower–compared to the expansion of the Universe.



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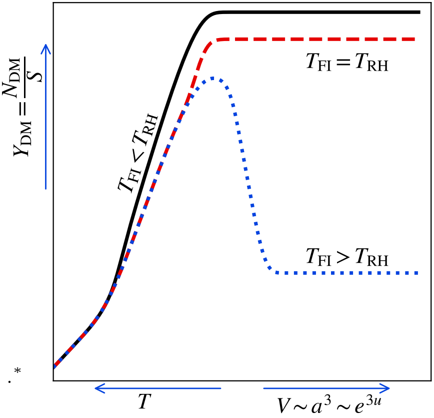
Freeze-in with reheating:

- Temperature evolution changes.
- Production becomes typically slower–compared to the expansion of the Universe.
- Reheating after freeze-in causes dilusion.

$$\frac{d \log Y_{\rm DM}}{du} = \frac{d \log N_{\rm DM}}{du} \left[1 - \frac{d \log S}{du} \left(\frac{d \log N_{\rm DM}}{du} \right)^{-1} \right] .^{*}$$



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Freeze-in with reheating:

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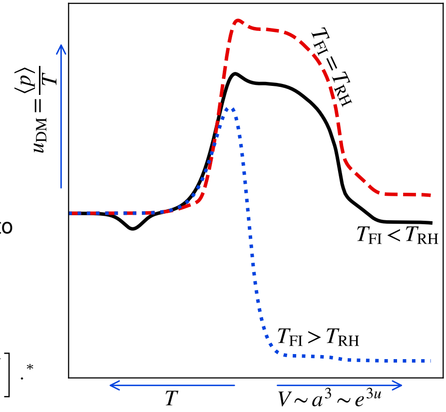
- Reheating changes the DM momentum.



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$$\frac{d\log u_{\rm DM}}{du} = \left[1 - \left(1 - \frac{\Gamma_\Phi}{H}\frac{\rho_\Phi}{\rho_{\rm R}}\right)^{-1}\right] + \left(\frac{1}{2u_{\rm DM}}\frac{\langle E_h\rangle}{T} - 1\right)\frac{d\log N_{\rm DM}}{du}.^*$$

* Details in:
P. Arias, DK, and L. Roszkowski, JCAP05 **041** (2021) [arXiv:2012.07202 [hep-ph]].

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F. Elahi, C. Kolda and J. Unwin, JHEP **03** (2015), 048 [arXiv:1410.6157 [hep-ph]].

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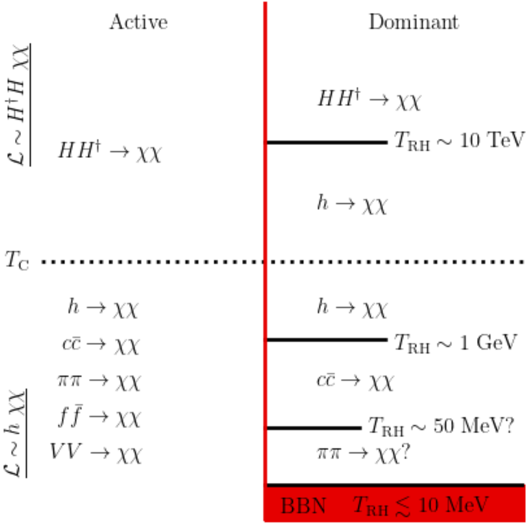


Production – Channels

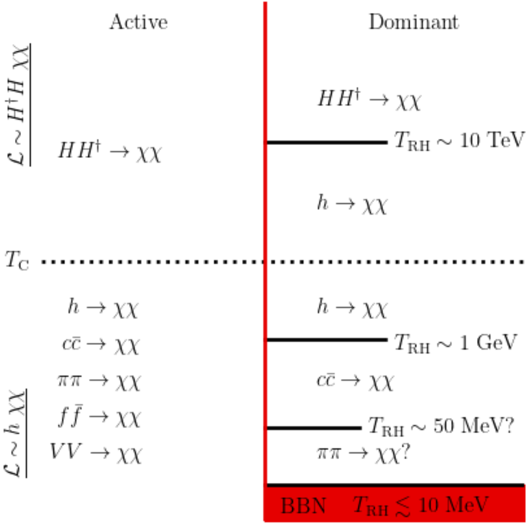
$$\mathcal{L}_{\rm int} = -\frac{1}{2\Lambda} H^\dagger H \ (\chi\chi + \chi^\dagger \chi^\dagger)$$

$$\frac{d\rho_\Phi}{du} + 3\rho_\Phi = -(1 + {\rm BR}_\chi)\ \frac{\Gamma_\Phi}{H}\rho_\Phi$$

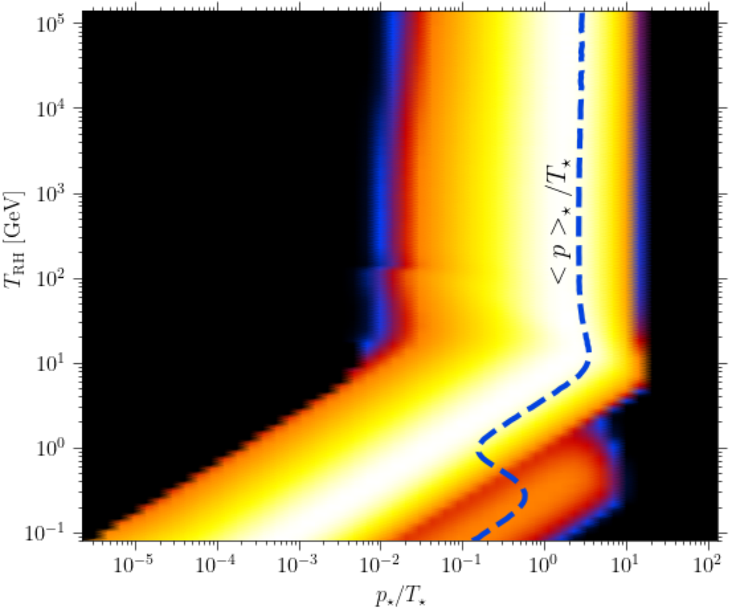
$$\frac{d\rho_{\rm R}}{du} + 3(\rho_{\rm R} + P_{\rm R}) = \frac{\Gamma_\Phi}{H}\rho_\Phi$$

$$\frac{df_{\tilde p}(u)}{du} = \sum_P \frac{\{P \to \chi\chi\}\,(u;\tilde p)}{H} +$$

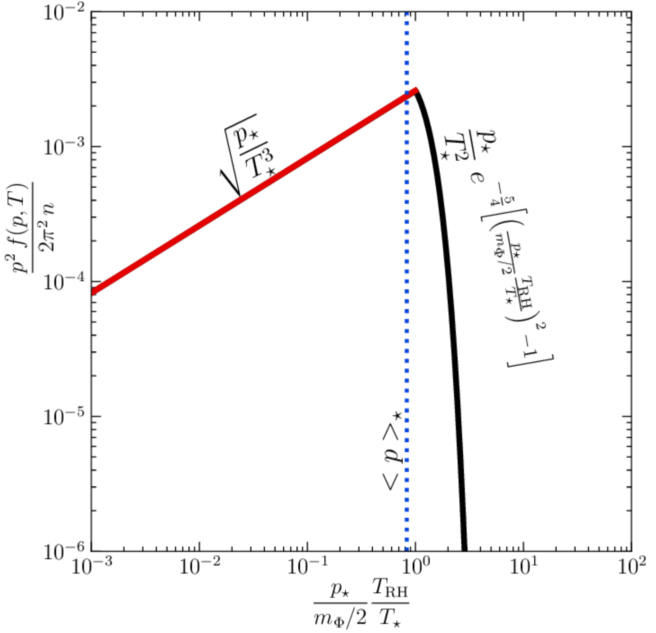
$$+16\pi^2 {\rm BR}_\chi \frac{\Gamma_\Phi}{H}\frac{\rho_\Phi}{m_\Phi^4}\delta\left(u - \log\frac{2\tilde p}{m_\Phi}\right)$$



Production – The phase-space distribuiton: dim-5

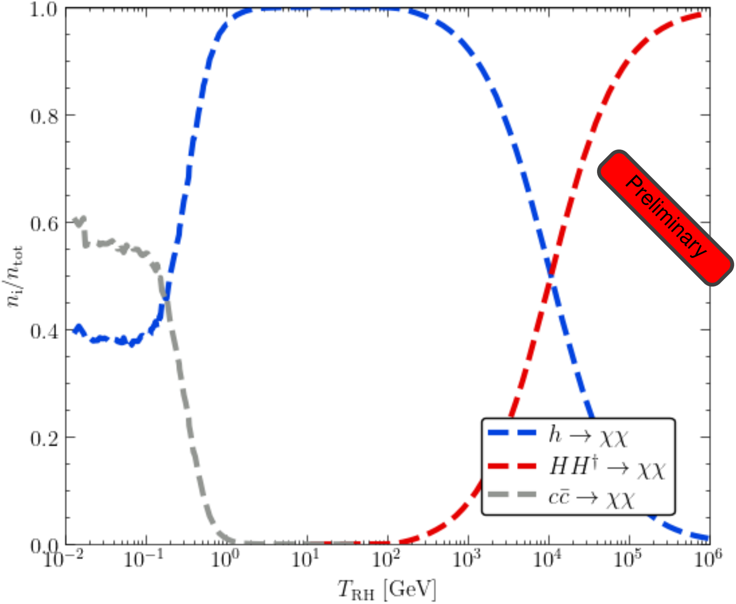


Production – The phase-space distribuiton: $\Phi \to \chi\chi$

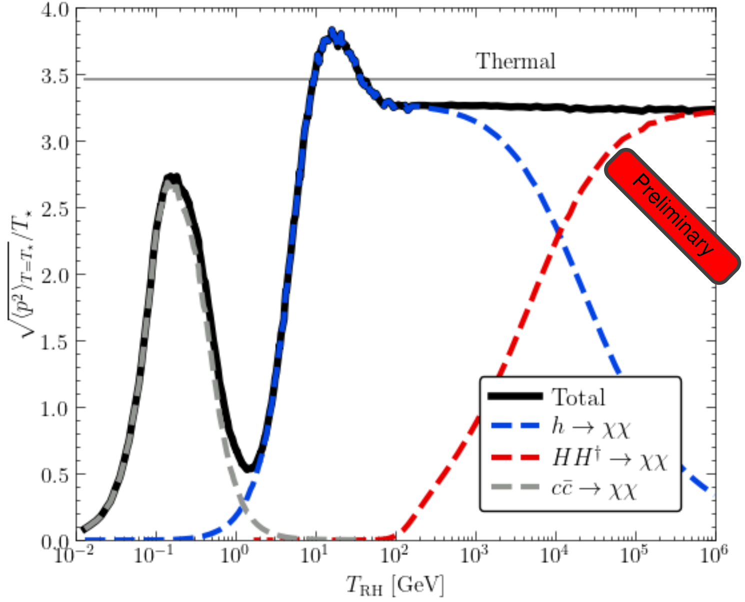


Results

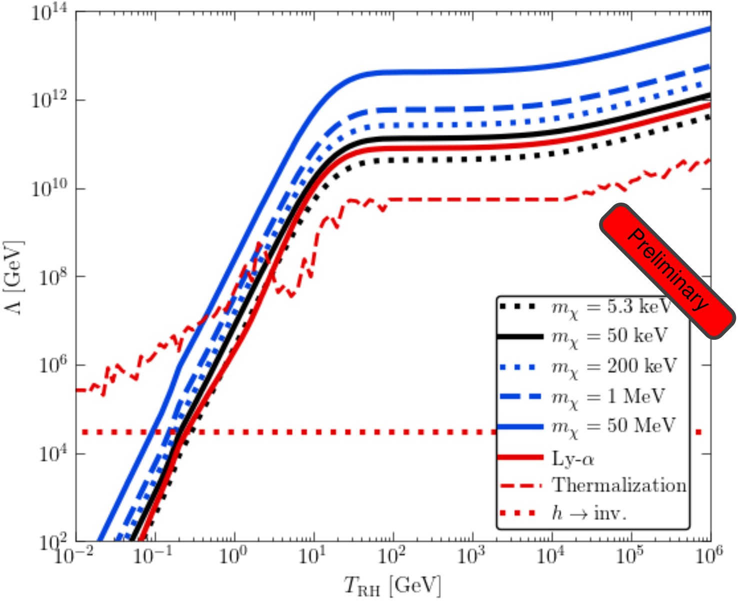
Results – Populations: dim-5



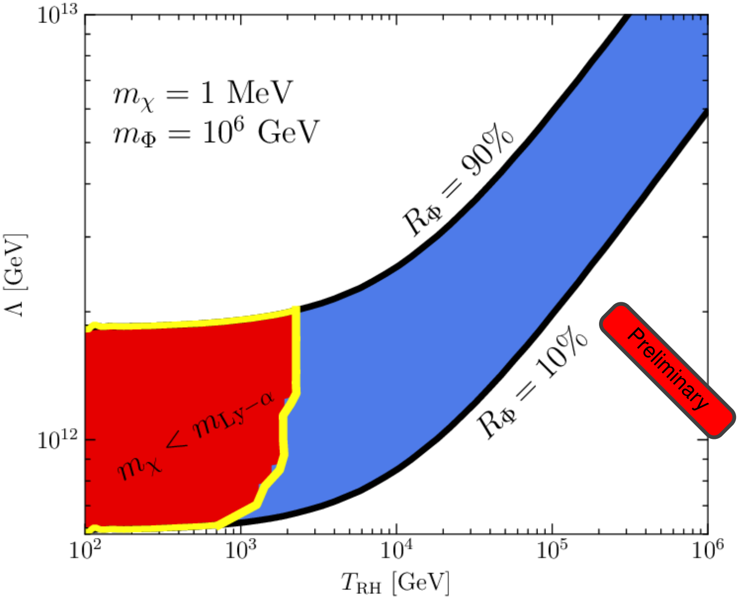
Results – Momentum dispersion: dim-5



Results – Parameter space: dim-5



Results – Parameter space: dim-$5 + \Phi \to \chi\chi$



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It remains an interesting possibility.

- It has a rich production history.
- It is a window to many other models (*e.g.* singlet-doublet DM, 2HDM + sub-GeV DM, and many more).
- The PSD shows the potential impact of reheating on multiple production channels.

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- Thermalization at the PSD-level.
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- UV complete "simple DM" models at the PSD-level.

Thank you!