Forbidden Freeze-In

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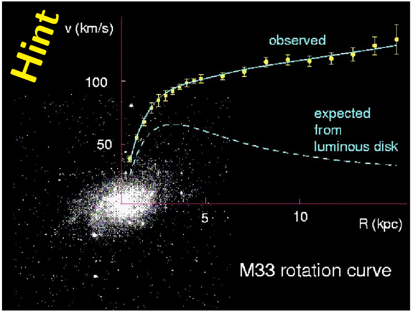
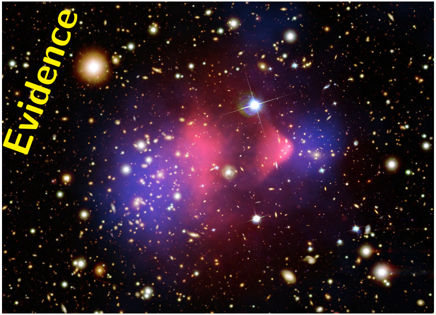
In collaboration with L. Darmé, A. Hryczuk, L. Roszkowski

arXiv:1907.XXXXX

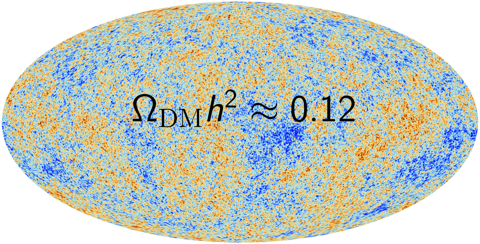
Outline



E. Corbelli and P. Salucci, *Mon. Not. Roy. Astron. Soc.* **311** *441* (2000), arXiv:astro-ph/9909252.



M. Markevitch, ESA Spec. Publ. **604** (2006) 723, astro-ph/0511345.
Clowe, Bradac, *et. al.* Astrophys. J. **648**, L109 (2006), astro-ph/0608407



N. Aghanim *et al.* [Planck Collaboration], arXiv:1807.06209 [astro-ph.CO].

The Dark Matter Particle

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- Cold/Warm and non-relativistic today.

Dark Matter production via Freeze-in: [1]

[1]

J. R. Ellis, J. E. Kim and D. V. Nanopoulos, Phys. Lett. **145B**, 181 (1984).

L. Covi, H. B. Kim, J. E. Kim and L. Roszkowski, JHEP **0105**, 033 (2001), hep-ph/0101009

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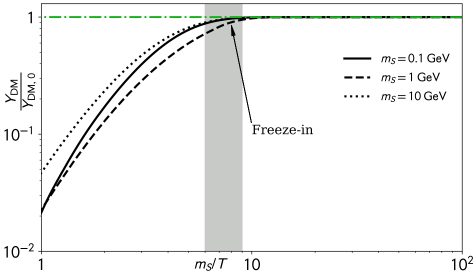
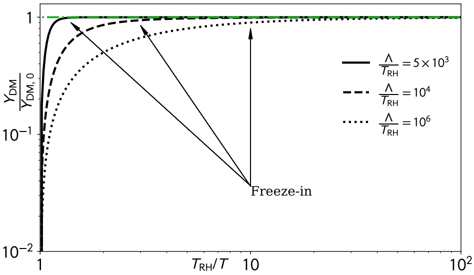
Consider χ the Dark Matter particle, and S in equilibrium with the plasma.

$$\mathcal{L}_{\rm int} = -yS\bar{\chi}\chi \qquad\qquad \mathcal{L}_{\rm int} = -\frac{1}{\Lambda}SS\bar{\chi}\chi$$



IR



UV

Forbidden Freeze-in

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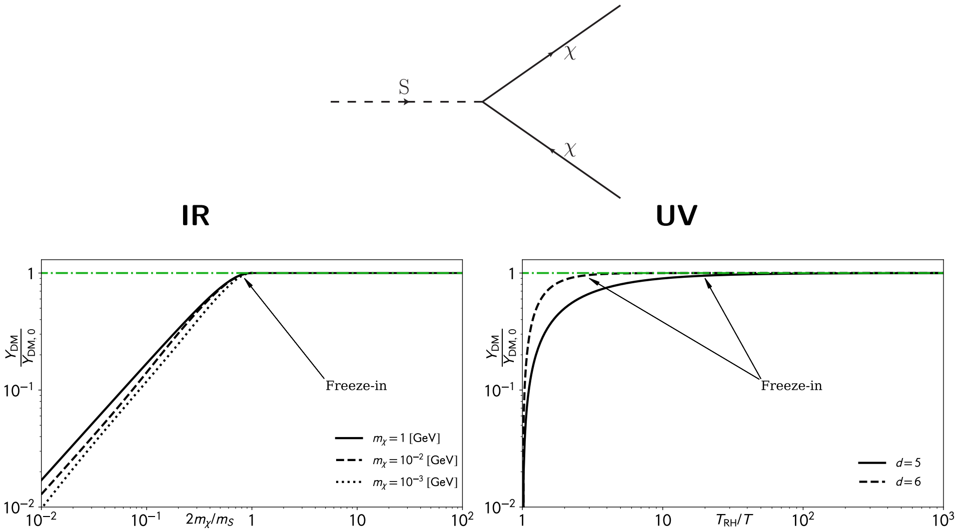
Behavior was noted in:

A. Strumia, JHEP **1006**, 036 (2010), arXiv:1003.5847 [hep-ph].

M. J. Baker, M. Breitbach, J. Kopp and L. Mittnacht, JHEP **1803**, 114 (2018), arXiv:1712.03962 [hep-ph].

L. Bian and Y. L. Tang, JHEP **1812**, 006 (2018), arXiv:1810.03172 [hep-ph].

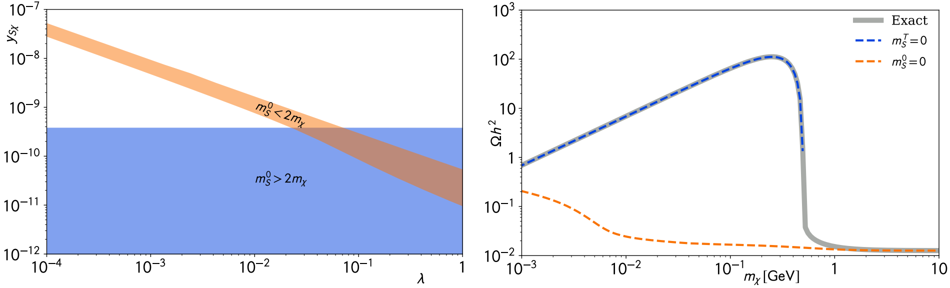
IR and UV Forbidden Freeze-in



Comparing the two types of Freeze-in.

$$\mathcal{L} \supset -y_{S\chi}\, S\,\bar{\chi}\chi \;-\; \frac{\lambda}{4!}S^4 - \frac{1}{2}m_S^{0\,2}S^2 - m_\chi\bar{\chi}\chi \;+ (\mathrm{SH-terms}),$$

$$m_S^2(T) \approx m_S^{0\,2} + \frac{\lambda}{24}T^2\ .$$



Higgs Portal

The Model

Assume Dark Matter (χ) a Dirac particle, and portal particle (S) that couples to the Higgs:

$$\mathcal{L}^{\rm DM} = \bar{\chi}\,(i\gamma_\mu D^\mu - \mu_\chi)\,\chi + \frac{1}{2}(D^\mu S)(D_\mu S) - y_{XS} S\bar{\chi}\chi - V_{HS}\ ,$$

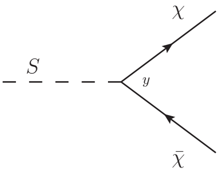
$$V_{HS} = \frac{\mu_S^2}{2}\,S^2 + \frac{\lambda_S}{4!}\,S^4 + A\,S\,H^\dagger H + \lambda_{HS}\,S^2\,H^\dagger H\,.$$

After Electroweak phase transition $S \to S - v_S$ ($v_S \ll \mu_S, v$), and S and h mix by $\theta \ll 1$. This induces interaction of the form

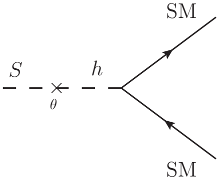
$$\mathcal{L}^{Y\rm SM} = \theta\frac{m_f}{v}\ S\ \bar{f}f\ .$$

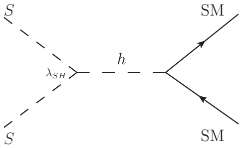
Relevant Processes

Dark Matter is produced by decays of S.

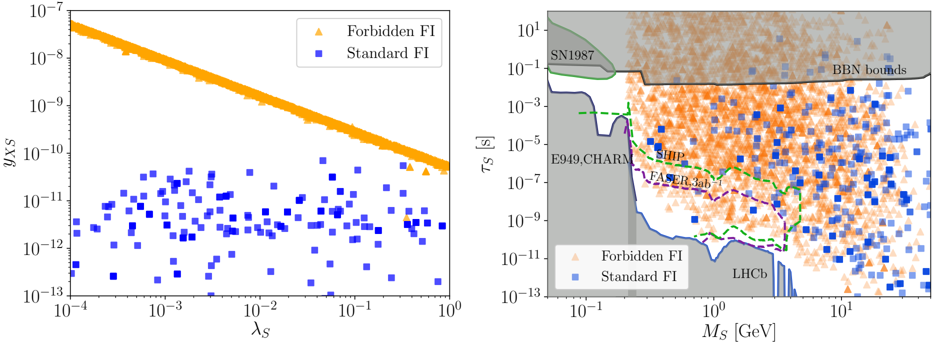


S is kept in equilibrium via its interactions with the SM.





Searching for observed relic using MultiNest [2]:



[2] F. Feroz, M. P. Hobson and M. Bridges Mon. Not. Roy. Astron. Soc. **398**, 1601 (2009) [arXiv:0809.3437 [astro-ph]].

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- Easily manifested in a simple portal model, which may be probed by SHIP and FASER.

Future direction:

- Study *a lot* of models under Forbidden Freeze-in.

Thank you

Backup

Cosmology

$$s = \frac{2\pi^2}{45} h(T)\, T^3$$

$$\delta_h = 1 + \frac{1}{3} \frac{d\ \log(h)}{d\ \log(T)}$$

$$H = \sqrt{\frac{4\pi^3}{45\, m_P^2} g(T)}\, T^2\,,$$

Standard Freeze-in

$$x = \frac{m_S}{T} \,,$$

$$\frac{dY_{\rm DM}}{dx} = \left(\frac{\Gamma_\chi(m_S, m_\chi)}{5.93 \times 10^{-19}\,{\rm GeV}}\right) \left(\frac{1~{\rm GeV}}{m_S}\right)^2 \frac{K_1(x)x^3}{\sqrt{g}h}\,\delta_h \,,$$

$${Y_{\rm DM,0}}^{\rm UV} \approx \frac{4^n n!(n+1)!}{2.3 \times 10^{-15}\, g_\star^{3/2}(T_{RH})} \left(\frac{\rm GeV}{m_S}\right) \left(\frac{m_S}{\Lambda}\right)^{2n} \frac{x_{RH}^{1-2n}}{2n-1} \,,$$

$${Y_{\rm DM,0}}^{\rm IR} \approx \left(\frac{\Gamma_\chi(m_S, m_\chi)}{1.6 \times 10^{-36}\,{\rm GeV}}\right) \left(\frac{1~{\rm GeV}}{m_S}\right)^2 m_\chi \left(\frac{1}{\sqrt{g}~h}\right)\Big|_{x=\langle x\rangle} \,,$$

$$\langle x \rangle \equiv \frac{\int_0^\infty dx\, x^3 K_1(x) \times x}{\int_0^\infty dx\, x^3 K_1(x)} \approx 3.4 \,.$$

Forbidden Freeze-in

$$z \equiv \frac{2m_\chi}{\alpha T} \; ,$$

$$\Gamma_\chi \sim \frac{\gamma s_\chi}{16\pi} \, m_S \, \left(\frac{m_S}{\Lambda}\right)^{2n} = \frac{\gamma s_\chi}{16\pi} \, \alpha^{2n+1} \, \left(\frac{T}{\Lambda}\right)^{2n} T \; ,$$

$$\frac{dY_{\rm DM}}{dz} = \left(\frac{\Gamma_\chi}{5.93 \times 10^{-19}\,{\rm GeV}}\right)\left(\frac{1\ {\rm GeV}}{2m_\chi}\right)^2 \frac{\alpha^4 \, K_1(\alpha)}{\sqrt{g}\ h}\delta_h \, z^3 \; .$$

$$Y_{\rm DM,0}{}^{\rm UV} = \frac{z_{\rm RH}^{1-2n} - 1}{2n-1}\left(\frac{\alpha^4 \, K_1(\alpha)\,\gamma s_\chi}{2.96 \times 10^{-17}}\right)\left(\frac{2m_\chi}{\Lambda}\right)^{2n} \left(\frac{1\ {\rm GeV}}{2m_\chi \, g_\star^{3/2}(T_{\rm RH})}\right) \; ,$$

$$Y_{\rm DM,0} = \left(\frac{\alpha^2 \, y s_\chi}{7.1 \times 10^{-9}}\right)^2 \left(\frac{\rm GeV}{m_\chi}\right) \, K_1(\alpha) \, \left(\frac{1}{\sqrt{g}\ h}\right)_{z=\langle z\rangle} \; ,$$

$$\langle z\rangle \equiv \frac{\int_0^1 dz \, \left(1-z^2\right)^{3/2} \times z}{\int_0^1 dz \, (1-z^2)^{3/2}} \approx 0.34 \; .$$