Effective Theory of Dark Matter Freeze-in

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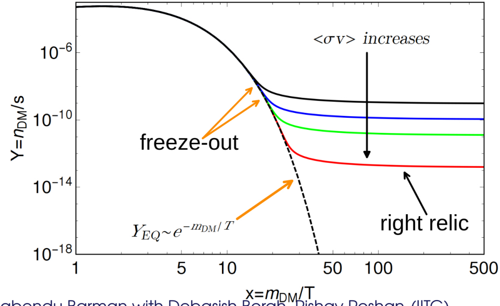
Plan of talk

- The WIMP paradigm & its drawback
- Freeze-in: a possible alternative
- DM freeze-in in Effective theory (based on **arxiv: 2007.08768**)
  - Relevant operators
  - DM yield via annihilation & decay
  - Comaprison with scale of neutrino mass generation
  - DM from radiative inflaton decay
- Concluding remarks

The Canonical story of Dark Matter

Standard lore:

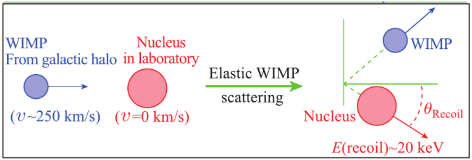
- DM in thermal equilibrium with SM at $T >> m_{\rm DM}$.
- Before $n_{\rm DM} \to 0$, DM is rescued by 'freeze-out' $\Gamma < H$.
- $\rho_{\rm DM} \sim a^{-3}$, eventually dominating over radiation.

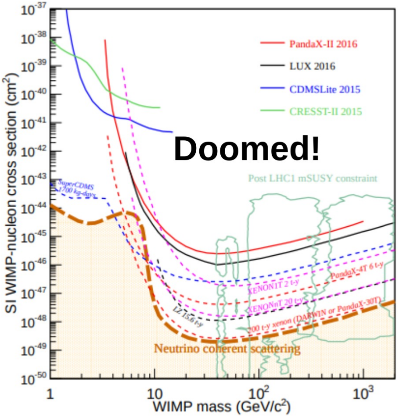


$$Y_{\rm DM} = n_{\rm DM}/s,\ x = m_{\rm DM}/T$$

WIMP miracle
a new particle with weak-scale interaction can account for DM density in the universe!

Direct Search: The Grim Reaper (Image:1709.00688,1611.06553,Zhao Yu talk)

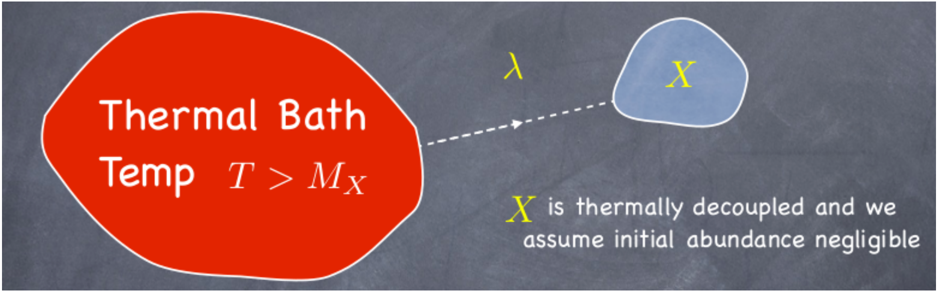




- Canonical WIMP scenario is getting cornered by DD.
- No significant excess @ colliders $\sim$ TeV scale.
- A possible alternative:
  - avoid thermal eq. with SM by extremely tiny DM-SM coupling $\rightarrow$ **Freeze-in**.
- Also: WIMPZillas (hep-ph/9810361), SIMP (1402.5143), ELDER (1706.05381)...

FIMPs:

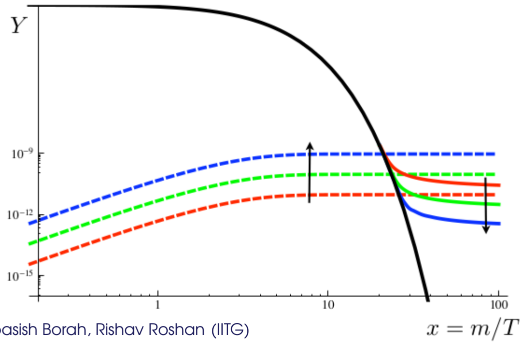
- DM-SM coupling $\mathcal{O}(10^{-10}) \implies$ DM can not freeze-'out'.
- Initial DM abundance $\to 0$ (by inflation or other mechanism).
- Produced via bath-particle annihilation/decay.
- Two classes: IR (Hall et.al.1402.5143,...) & UV (Elahi et.al.1410.6157,...).



(Image: Talk by Stephen West)

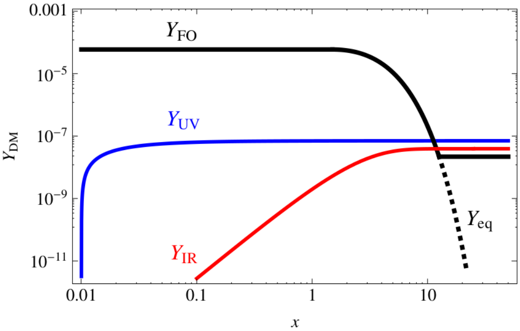
IR freeze-in (Image: 1706.07442)

- DM-SM renormalizable coupling: $\lambda X B_1 B_2$ $(B_1 \to B_2 X)$.
- $\lambda \sim \mathcal{O}(10^{-10})$ gives right abundance avoiding thermal eq.
- $Y_{\text{DM}} \sim \lambda^2 \frac{M_{\text{pl}}}{T} \implies$ IR dominated process favoring low T.
- Dominant production at $T \sim m$, $T < m \sim \exp(-m/T)$.
- Caveat: Unnaturally small coupling.



UV freeze-in (Image:1410.6157)

- Dark sector $\xrightarrow{\propto \frac{1}{\Lambda^n}}$ visible sector.
- Small coupling is natural when Λ is very large.
- $Y_{DM} \propto \frac{M_{pl} T^{2n-1}}{\Lambda^{2n}}$ if $T_{\text{RH}} >> m_i$.
- DM production dominated at highest T i.e., $T \sim T_{RH}$.
- DM freezes in immediately.



Freeze-in in EFT framework (with DB & RR, arxiv: 2007.08768)

- The DM χ is a singlet Majorana fermion (no tree-level coupling with SM):

$$\mathcal{L}_{\text{DM}} = i\overline{\chi^c}\partial\!\!\!/\chi - M_\chi\overline{\chi^c}\chi$$

- No other dark sector particle.
- ~~Vector current $\overline{\chi}\gamma^\mu\chi$ and dipole moments $\overline{\chi}\sigma^{\mu\nu}\chi, \overline{\chi}\sigma^{\mu\nu}\gamma^5\chi$~~.

✓ Scalar, pseudoscalar and axial vector DM bilinears.

- All our ignorances dumped into Λ.
- For simplicity we *only* consider scalar ops. for DM analysis.
- $\Lambda \gtrsim \frac{M_\chi}{2\pi}, T_{\text{RH}}$.

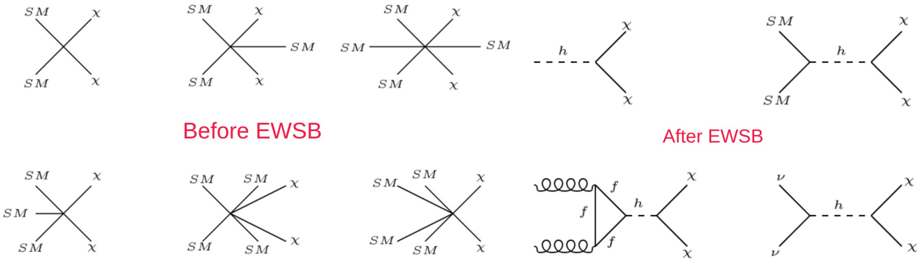
Relevant operators (with DB & RR, arxiv: 2007.08768)

- $\overline{\chi}\Gamma^{\mu}\left(1,\gamma^5,\gamma^{\mu}\gamma^5\right)\chi$ itself makes up dim.3.
- 13 dim.4, 1 dim.5, 63 dim.6 & 20 dim.7 SM invariant ops. (1008.4884, 1410.4193).
- DM-SM scalar ops. up to dim.8: $\mathcal{L}=\mathcal{L}_{\text{SM}}+\mathcal{L}_{\text{DM}}+\mathcal{L}_{d>4}$.

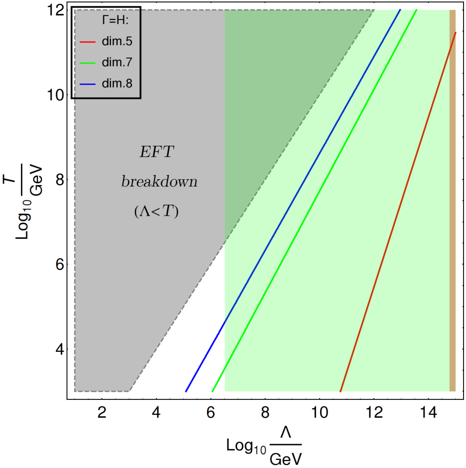
DM bilinear (dim.3)	Λ^{-1}	Λ^{-2}	Λ^{-3}	Λ^{-4}
$\overline{\chi^c}\chi$, $\overline{\chi^c}i\gamma^5\chi$	$H^\dagger H$		$X_{\mu\nu}X^{\mu\nu}, X_{\mu\nu}\widetilde{X^{\mu\nu}}$ $\lvert H^\dagger H\rvert^2$ $\lvert\mathcal{D}_\mu H\rvert^2$ $i\overline{L}\not{\mathcal{D}}L, i\overline{R}\not{\mathcal{D}}R$ $\overline{L}HR, \overline{L}\widetilde{H}R$	$\left(\overline{\ell_L}\widetilde{H}\right)\left(\overline{\ell_L}\widetilde{H}\right)$
$\overline{\chi^c}\gamma^\mu\gamma^5\chi$		$\overline{L(R)}\gamma_\mu L(R)$ $iH^\dagger\mathcal{D}_\mu H$		$\overline{L(R)}\gamma_\mu L(R)\left(H^\dagger H\right)$ $iH^\dagger\mathcal{D}_\mu H\left(H^\dagger H\right)$

Annihilation & decay channels (with DB & RR, arxiv: 2007.08768)

- $T > T_{\rm EW}$: $2 \to 2, 3 \to 2(2 \to 3), 4 \to 2(2 \to 4)$ channels (massless SM) $\implies$ UV.
- $T < T_{\rm EW}$: $1 \to 2$, $2 \to 2$ channels (massive SM) $\implies$ UV+IR.



Out of equilibrium (with DB & RR, arxiv: 2007.08768)



$$\mathcal{R} = \frac{\Gamma_{n\to m}}{H} \leq 1$$

Reaction rate:

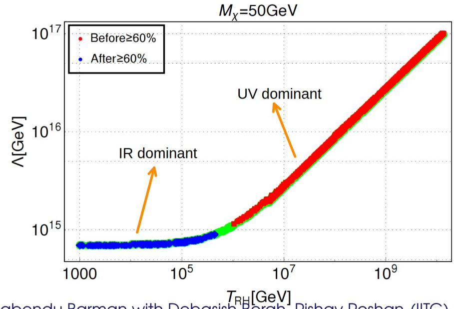
$$\Gamma_{n\to m} = \begin{cases} n_{\text{SM}}^{n-1}\langle\sigma v\rangle_{n\to m} \\ \Gamma_{\text{decay}} \end{cases}$$

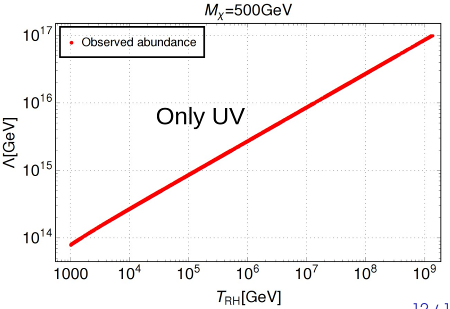
density of SM particles:

$$n_{\text{SM}} = \begin{cases} g_{\text{SM}}\,(T)\,\frac{3}{4}\,\frac{\zeta(3)}{\pi^2}\,T^3 \\ g_{\text{SM}}\,(T)\,\left(\frac{m_{\text{SM}}T}{2\pi}\right)^{3/2} e^{-m_{\text{SM}}/T} \end{cases}$$

Parameter space: $\{M_{\rm DM}, \Lambda, T_{\rm RH}\}$

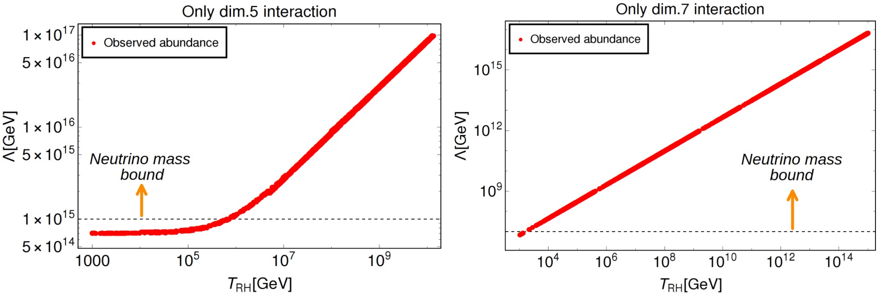
- $\underbrace{4.7\text{ MeV}}_{\text{BBN (1511.00672)}} \lesssim T_{\rm RH} \lesssim \underbrace{10^{16}\text{ GeV}}_{\text{model dependent}}$
- $Y_\chi \sim \underbrace{\int_{T_{\rm EW}}^{T_{\rm RH}} \overline{|\mathcal{M}_{n\to m}|^2}}_{\text{before EWSB}} + \underbrace{\int_{T_0}^{T_{\rm EW}} \overline{|\mathcal{M}_{1\to 2, 2\to 2}|^2}}_{\text{after EWSB}} \implies \Omega_X^{\rm PLANCK} \sim M_\chi Y_\chi(T_0)$
- $T_{\rm RH} > T_{\rm EW} \implies$ yield after EWSB is small.
- dim.5 interactions always dominate.



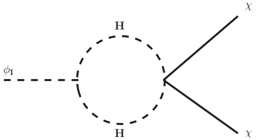


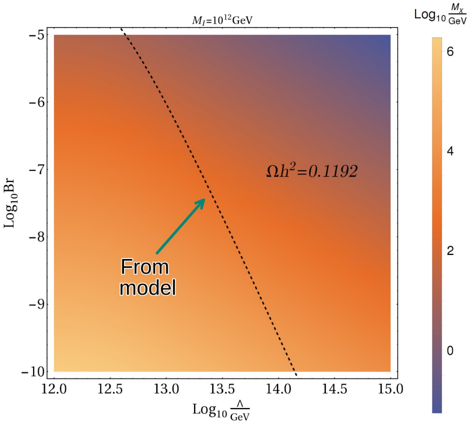
Connection with ν-mass scale (with DB & RR, arxiv: 2007.08768)

- $\frac{(LH)(LH)}{\Lambda_\nu}(\Delta L = 2) \to m_\nu \sim \frac{v_h^2}{\Lambda_\nu} \implies \Lambda_\nu \gtrsim 10^{14}$ GeV.
- $\frac{(LH)(LH)\left(H^\dagger H\right)}{\Lambda_\nu^3}(\Delta L = 2) \to m_\nu \sim \frac{v_h^4}{\Lambda_\nu^3} \implies \Lambda_\nu \gtrsim 10^{6}$ GeV.
- DM-SM ops. of same dim. can produce right relic.



DM from inflaton decay (with DB & RR, arxiv: 2007.08768)





- No direct inflaton-DM coupling.
- Inflaton decay via 1-loop can produce DM (1709.01549, 1901.04449, 2004.08404).
- $\Omega_\chi h^2 = f\left(\text{Br}, M_\chi, T_{\text{RH}}\right)$ with $\text{Br} = \frac{\Gamma_{\phi_I}^{\text{loop}}}{\Gamma_{\phi_I\to hh}+\Gamma_{\phi_I\to ff}+\Gamma_{\phi_I}^{\text{loop}}}$.
- Small branching to avoid over abundance.
- Can account for total DM abundance.

Conclusion

- We provide the simplest possible operators connecting DM and SM relevant for freeze-in scenario up to and including dim.8.
- $\{\Lambda, T_{\rm RH}\}$ can be simultaneously constrained from DM relic and neutrino mass generation from operators of the same dim.
- It is also possible to obtain right DM relic from inflaton decay even in the absence of DM-inflaton coupling.
- Connection to neutrino mass can be made more profound in a UV-complete set-up.

Conclusion

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Thank you!

Questions/comments/critique?

Backup Slides

Scalar kinetic term

Before EWSB:

$$|\mathcal{D}_\mu H|^2 \supset \left(\partial_\mu\phi^+\partial^\mu\phi^- + \partial_\mu\phi^0\partial^\mu\overline{\phi^0}\right) + \frac{g_1^2}{4}B_\mu B^\mu\left(\phi^+\phi^- + \phi^0\overline{\phi^0}\right)$$
$$+ \frac{g_2^2}{4}\sum_{i=1,2,3} W_{i\mu}W^{i\mu}\left(\phi^+\phi^- + \phi^0\overline{\phi^0}\right).$$

After EWSB:

$$|\mathcal{D}_\mu H|^2 \supset \frac{1}{2}\partial_\mu h\partial^\mu h + (h+v_h)^2\left\{\frac{g_2^2}{4}W_\mu^+W^{-\mu} + \frac{g_2^2}{8c_w^2}Z_\mu Z^\mu\right\}.$$

BEQ for $3 \to 2$ process

$$\dot{n_\chi} + 3Hn_\chi = \int d\Pi_1 d\Pi_2 d\Pi_3 d\Pi_4 d\Pi_5 \overline{|\mathcal{M}|}^2_{123\to 45} (2\pi)^4 \delta^4 (p_f - p_i) \prod_{i=1}^{3} f_i$$
$$= \int d\text{LIPS}_3 d\Pi_4 d\Pi_5 \overline{|\mathcal{M}|}^2_{123\to 45} f_1 f_2 f_3,$$

$$d\text{LIPS}_2 = d^3p_4 d^3p_5 = (4\pi |\vec{p_4}|)(4\pi |\vec{p_5}|) \frac{1}{2} d\cos\theta.$$

Change variables Nucl.Phys.B 360 (1991) 145-179:
$E_+ = E_4 + E_5, E_- = E_4 - E_5, s = 2M_\chi^2 + 2E_4E_5 - 2|\vec{p_4}||\vec{p_5}|\cos\theta$:

$$\int d\Pi_4 d\Pi_5 = \int \frac{1}{(2\pi)^4} \frac{\sqrt{E_+^2 - s}}{4} \sqrt{1 - \frac{4M_\chi^2}{s}} dE_+ ds,$$

Continued...

$$\dot{n_\chi} + 3Hn_\chi = \frac{T}{(2\pi)^4}\int_{4M_\chi^2}^{\infty} ds \frac{\sqrt{s}}{4}\sqrt{1-\frac{4M_\chi^2}{s}}\,\overline{|\mathcal{M}|}^2_{123\to 45} K_1\left(\frac{\sqrt{s}}{T}\right) d\text{LIPS}_3$$

as $E_1 + E_2 + E_3 = E_4 + E_5$.

Performing all the integrals for overall rotations:

$$\int d\text{LIPS}_3 = \int \frac{ds_{23}}{2\pi}\frac{1}{8\pi}\left(1-\frac{s_{23}}{s}\right)\frac{d\cos\theta_{23}}{2}\frac{1}{8\pi},$$

where

$$x_1 = 1 - \frac{s_{23}}{s}$$

$$x_2 = \frac{1}{2}\left(2 - x_1 + x_1\cos\theta_{23}\right),$$

$$E_1 = x_1\frac{\sqrt{s}}{2},\; E_2 = x_2\frac{\sqrt{s}}{2},$$

$$E_3 = \frac{\sqrt{s}}{2}\left(2 - x_1 - x_2\right).$$

BEQ for $4 \to 2$ process

$$\dot{n_\chi} + 3Hn_\chi = \int \prod_{i=1}^{6} d\Pi_i \overline{|\mathcal{M}|}^2_{1234\to 56} (2\pi)^4 \delta^4 (p_f - p_i) \prod_{i=1}^{4} f_i$$
$$= \int d\text{LIPS}_4 d\Pi_5 d\Pi_6 \overline{|\mathcal{M}|}^2_{1234\to 56} f_1 f_2 f_3 f_4,$$

Use energy conservation:

$$\dot{n_\chi} + 3Hn_\chi = \frac{T}{(2\pi)^4} \int_{4M_\chi^2}^{\infty} ds \frac{\sqrt{s}}{4} \sqrt{1 - \frac{4M_\chi^2}{s}} \overline{|\mathcal{M}|}^2_{1234\to 56} K_1 \left(\frac{\sqrt{s}}{T}\right) d\text{LIPS}_4,$$

Continued...

For massless initial states:

$$\int d\text{LIPS}_4 = \frac{1}{4\pi^2(8\pi)^3}\int_0^{\sqrt{s}} ds_{12}$$
$$\int_0^{(\sqrt{s}-\sqrt{s_{12}})^2} ds_{34}\sqrt{1+\frac{s_{12}^2}{s^2}-\frac{2s_{12}s_{34}}{s^2}+\frac{s_{34}^2}{s^2}-\frac{2s_{12}}{s}-\frac{2s_{34}}{s}}$$
$$\int\frac{d\cos\theta_{12}}{2}\int\frac{d\cos\theta_{34}}{2}.$$

BEQ in terms of yield:

$$\frac{dY_\chi^{4\to 2}}{dT} \simeq -\frac{1}{s(T).H(T)}\frac{1}{64\,(2\pi)^9}\int_{4M_\chi^2}^{\infty} ds\sqrt{s}\sqrt{1-\frac{4M_\chi^2}{s}}\overline{|\mathcal{M}|}^2_{1234\to 56}K_1\left(\frac{\sqrt{s}}{T}\right)$$
$$\int_0^{\sqrt{s}} ds_{12}\int_0^{(\sqrt{s}-\sqrt{s_{12}})^2} ds_{34}\sqrt{1+\frac{s_{12}^2}{s^2}-\frac{2s_{12}s_{34}}{s^2}+\frac{s_{34}^2}{s^2}-\frac{2s_{12}}{s}-\frac{2s_{34}}{s}}$$
$$\int\frac{d\cos\theta_{12}}{2}\int\frac{d\cos\theta_{34}}{2},$$