Non-minimally coupled Vector Dark Matter

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with

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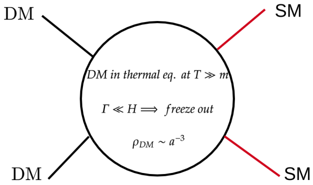
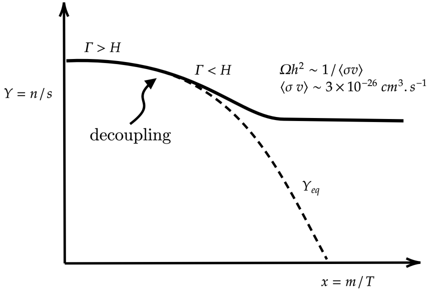
arXiv:2108.13447

DM GENESIS


DM
SM
DM in thermal eq. at $T \gg m$
$\Gamma \ll H \Longrightarrow$ freeze out
$\rho_{DM} \sim a^{-3}$
DM
SM


$\Gamma > H$
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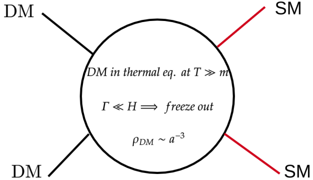
$\Omega h^2 \sim 1/\langle\sigma v\rangle$
$\langle\sigma\, v\rangle \sim 3\times10^{-26}\ cm^3.s^{-1}$
$Y = n/s$
decoupling
Y_{eq}
$x = m/T$

DM GENESIS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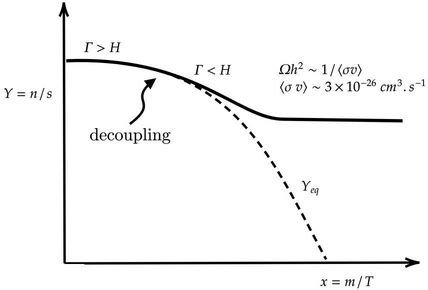
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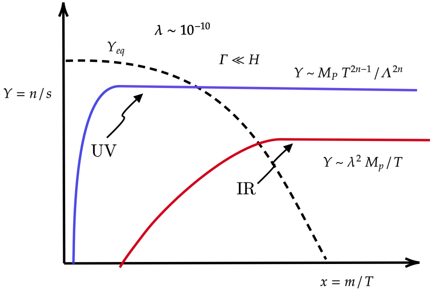
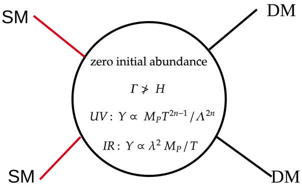
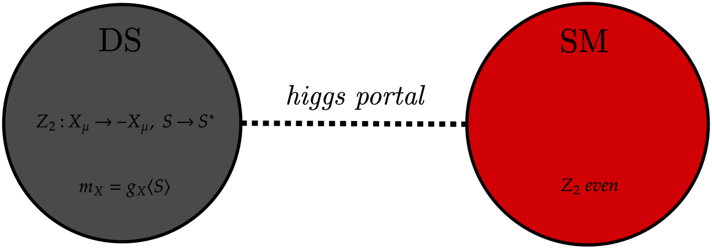

$\lambda \sim 10^{-10}$
Y_{eq}
$\Gamma \ll H$
$Y \sim M_P\, T^{2n-1}/\Lambda^{2n}$
$Y = n/s$
UV
IR
$Y \sim \lambda^2 M_p/T$
$x = m/T$


SM
DM
zero initial abundance
$\Gamma \not> H$
$UV: Y \propto M_P T^{2n-1}/\Lambda^{2n}$
$IR: Y \propto \lambda^2 M_P/T$
SM
DM

A 'standard' model for VDM (abelian)



$$\mathcal{L} = -\frac{1}{4} X_{\mu\nu} X^{\mu\nu} + \left|D^X_\mu S\right|^2 - V(H,S)\,;\ D^X_\mu = \partial^X_\mu - i\, g_X\, X_\mu$$

$$V(H,S) = -\mu_H^2 |H|^2 + \lambda_H |H|^4 - \mu_S^2 |S|^2 + \lambda_S |S|^4 + \lambda_{HS} |H|^2 |S|^2$$

For non-abelian one needs a $SU(2)$ fundamental scalar 0811.0172

A 'standard' model for VDM (abelian)

- For $\lambda_{HS} \sim \mathcal{O}(1) \to$ WIMP (e.g., 1207.4272, 1212.2131, 1506.08805...)
- For $\lambda_{HS} \sim \mathcal{O}(10^{-10}) \to$ FIMP (e.g., 1710.00320)

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What if we assume a Stueckleberg mass?

$\rightarrow$ two sectors are decoupled (effective operator? JHEP12(2020)162 Bohdan Grzadkowski,Subhaditya Bhattacharya& BB)

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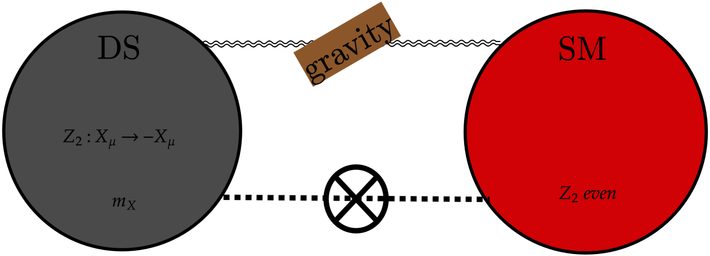
$\to$ two sectors are decoupled (effective operator? JHEP12(2020)162 Bohdan Grzadkowski,Subhaditya Bhattacharya& BB)

$\to$ gravity can still connect them!



Non-minimal VDM (0802.2068,0809.1055,0809.2779,0810.4304,1007.1426...)

Action in Jordan frame:

$$\widetilde{\mathcal{S}} = \int d^4x\,\sqrt{-\widetilde{g}}\left[\frac{1}{2}\left(M_P^2 - \xi\,\widetilde{X}_\mu\widetilde{X}^\mu\right)\widetilde{R} + \widetilde{\mathcal{L}}_{\text{DM}} + \widetilde{\mathcal{L}}_{\text{SM}}\right]$$

$$\widetilde{\mathcal{L}}_{\text{DM}} = -\frac{1}{4}\widetilde{X}_{\mu\nu}\widetilde{X}^{\mu\nu} + \underbrace{\frac{1}{2}m_X^2\widetilde{X}_\mu\widetilde{X}^\mu}_{\text{Stueckleberg}}$$

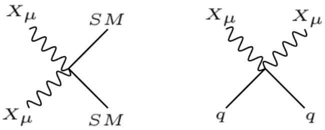
Conformal transformation:

$$g_{\mu\nu} = \omega^2\,\widetilde{g}_{\mu\nu}\,,\;\omega = \sqrt{1 - \frac{\xi}{M_P^2}\widetilde{X_\mu}\,\widetilde{X^\mu}} \to 1 - \frac{\xi}{2\,M_P^2}\,X_\mu\,X^\mu + \mathcal{O}\left(M_P^{-4}\right)$$

non-minimally coupled scalar DM: 1410.6436,1604.04701,1611.00725,1709.09688...

Non-minimal VDM (0802.2068,0809.1055,0809.2779,0810.4304,1007.1426...)

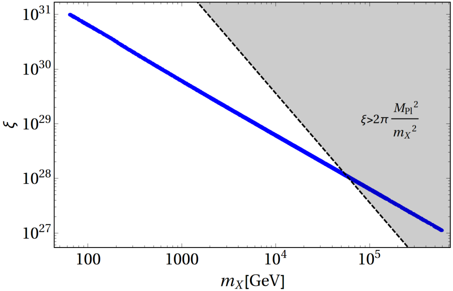
Action in Einstein frame (DM-SM interaction)

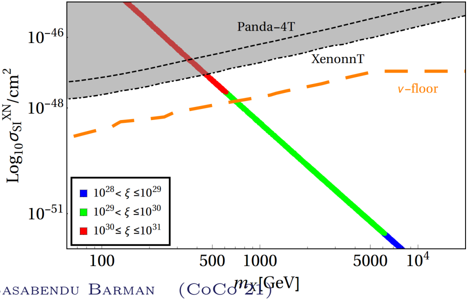


$$\mathcal{S} = \int d^4x\sqrt{-g}\Bigg[\underbrace{\frac{M_P^2\,R}{2}}_{\text{Pure gravity}} + \underbrace{(D_\mu H)^\dagger(D^\mu H) + (\mathcal{L}_Y - V(H)) + i\,\bar{f}\,\gamma^\alpha\,\partial_\alpha\,f - \frac{1}{4}\,F_{\mu\nu}\,F^{\mu\nu}}_{\text{SM}} + \frac{2\xi}{M_P^2}\,X_\alpha X^\alpha\,(\mathcal{L}_Y - V(H)) + \frac{\xi}{M_P^2} X_\alpha X^\alpha\,(D_\mu H)^\dagger(D^\mu H) + \frac{3i\,\xi}{2\,M_P^2}\,X_\alpha X^\alpha\,\bar{f}\,\gamma^\mu\,\partial_\mu\,f + ...\Bigg]$$

- Only pair-annihilation/production of DM
- 4-point interactions

DM freeze-out



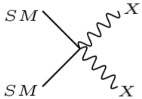


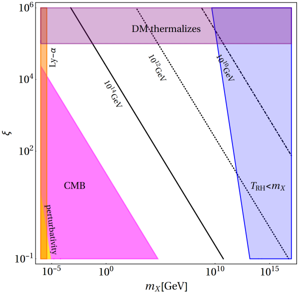
- BEQ:

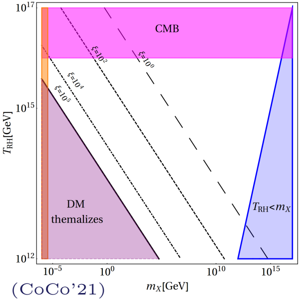
$$\dot{n}_X + 3\,H\,n_X = \gamma$$
$$= -\langle\sigma v\rangle\left(n_X^2 - n_{X\,\mathrm{eq}}^2\right)$$

- Spin-independent scattering: $\sigma_{\rm SI}^{X\,N} = \frac{\mu_{X\,N}^2}{\pi\, m_X^2}\left[Z f_p + (A-Z)\, f_n\right]^2 ; f_q \simeq \xi\, m_q/M_P^2$
- Tree-level unitarity: $\sqrt{s} < \sqrt{\frac{8\pi}{\xi}}\, M_P$
- $\xi \sim \mathcal{O}(10^{30})$ satisfies relic+DD

Non-minimal freeze-in







- DM reaction density:

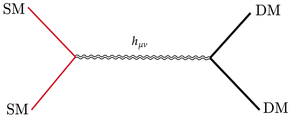
$$\gamma \propto \frac{\xi^2\, T^8}{M_P^4}$$

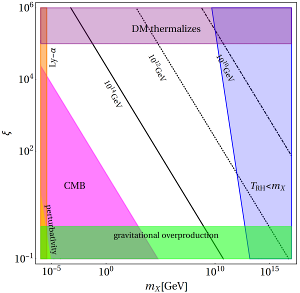
- Assuming *instantaneous* decay

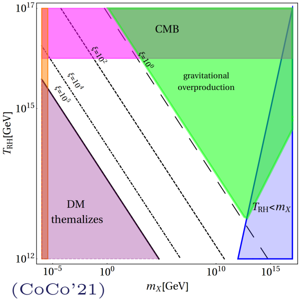
$$Y_X\ (\equiv n_X/s) \propto \xi^2\, \frac{(T_{\text{rh}}^3 - T^3)}{\pi^7\, M_P^3}$$

- $\xi \gtrsim 10^5 \rightarrow$ thermalization.
- CMB: $H_I^{\text{CMB}} \leq 2.5\times 10^{-5}\ M_P$
- Perturbativity: $\sqrt{s} < \sqrt{\frac{8\pi}{\xi}}\ M_P$
- WDM limit $m_X \gtrsim 3.5$ keV

What if $\xi = 0$?







- *Minimal* DM production.
- Gravitational interaction:

$$\mathcal{L} \supset \frac{1}{2M_P} h_{\mu\nu} T^{\mu\nu}_{\text{DM}}$$

deviation from flat space:

$$g_{\mu\nu} \simeq \eta_{\mu\nu} + \frac{1}{M_P} h_{\mu\nu}$$

- Reaction rate density (2103.06896,2104.10699)

$$\gamma(T) = \alpha \frac{T^8}{M_P}$$

- Minimal DM yield

$$Y_X \propto (T_{\text{rh}}/M_P)^3$$

Conclusions

- Non-minimal coupling can provide viable VDM even in the absence of Higgs portal.
- Simplest set-up with only TWO free parameters.
- $\xi_{\text{freeze-out}} \ll \xi_{\text{freeze-in}}$.
- For $\xi = 0$ the two sectors can still communicate via graviton exchange.
- Minimal gravitational DM production is unavoidable.

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¡Muchas gracias!

Backup Slides

Freeze-out annihilation cross-section

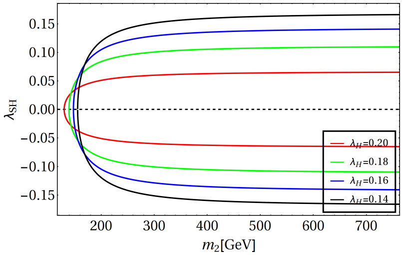
$$(\sigma v)_{XX\to \mathsf{SMSM}} \simeq \begin{cases} \frac{4N_c m_X^2 \xi^2}{M_P^4\,\pi}\sqrt{1-x^2}\left(4-x^2-3x^4\right) + \mathcal{O}[v^2] \\ \frac{\delta_V\,\xi^2}{144\,\pi m_X^2}\left(\frac{g_2 v_d}{c_w M_P}\right)^4\sqrt{1-x^2}\left(1+2x^2+3x^4\right) + \mathcal{O}[v^2] \\ \frac{\xi^2 m_X^2}{9\,\pi\,M_P^4}\sqrt{1-x^2}\left(1+2x^4\right) + \mathcal{O}[v^2] \end{cases}$$

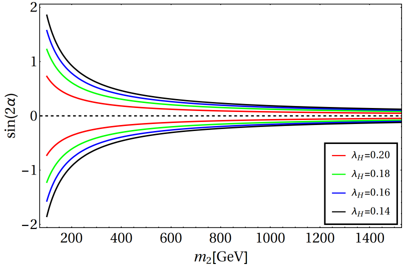
$$(\sigma v)_{\mathsf{total}} \sim \mathcal{A}\,\frac{\xi^2\,m_X^2}{M_P^4}\left(1+\mathcal{C}\,\frac{M_P^4}{m_X^4}\right)$$

$$\implies \Omega_X h^2 \sim \frac{1}{(\sigma v)_{\mathsf{total}}} \sim m_X^2\,M_P^4/\left(\mathcal{A}\,\xi^2\left[m_X^4+\mathcal{B}\,M_P^4\right]\right)$$

$\mathcal{A} = \left(\frac{16N_c}{\pi}+\frac{1}{9\pi}\right)$, $\mathcal{C}=\mathcal{B}/\mathcal{A}$ with $\mathcal{B}=\frac{\delta_v}{144\pi}\left(\frac{g_2\,v_d}{c_w\,M_P}\right)^4$

DECOUPLING LIMIT (follwoing JHEP12(2020)162)





$$v_s^2 = m_2^2/2\,\lambda_S + \frac{\lambda_{SM} - \lambda_H}{\lambda_S}\, v_h^2$$

$$\lambda_{SH}^2 = 4\lambda_S \left[\lambda_H - \frac{\lambda_{SM} m_2^2}{m_2^2 + 2(\lambda_{SM} - \lambda_H) v_h^2}\right] = 4\lambda_S(\lambda_H - \lambda_{SM}) + \mathcal{O}\left(\frac{1}{m_2^2}\right)$$

$$\sin 2\alpha = -2\sqrt{2(\lambda_H - \lambda_{SM})}\,\frac{v_h}{m_2} + \mathcal{O}\left(\frac{1}{m_2^3}\right)$$