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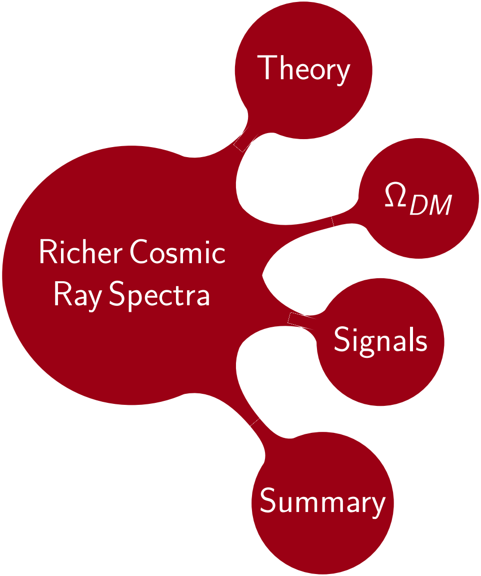
Richer Cosmic Ray Spectra from Expanding Dark Matter Theoretical Landscape

Tommaso Sassi Valencìa, November 5 2025

Based on - F.D'Eramo, TS: 2502.19491
F.D'Eramo, S.Manconi, TS: 2511.XXXXX

TeV Particle Astrophysics
TeVPA
Valencia 2025

Outline

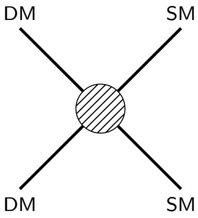


Expanding the DM landscape: starting point

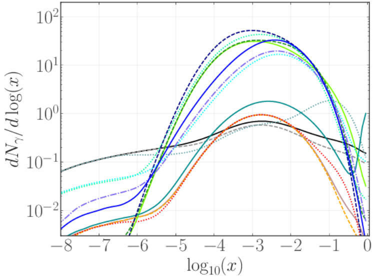
Cosmic ray injection spectra are one of the particle physics input needed to compute cosmic ray fluxes.

$$\frac{d\Phi_{\gamma\,\alpha}}{dE_\gamma} = \kappa_\alpha \frac{\langle \sigma v \rangle_\alpha}{8\pi m_{\rm DM}^2} \times \sum_{\rm SM} {\rm BR}_{\rm SM} \frac{dN^{\rm (SM)}_{\gamma\,\alpha}}{dE_\gamma} \times J(\Delta\Omega)$$

These are numerically computed for DM pair annihilations (or decay) [Cirelli et al: 1012.4515, Arina et al: 2312.01153]



$x = E_\gamma / m_{\rm DM}$



Expanding the DM landscape: one-step annihilation

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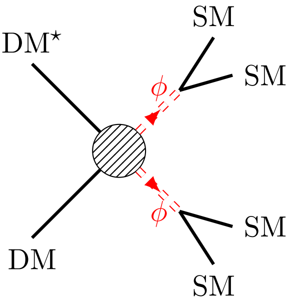
DM annihilation might proceed as a cascade process through light(er) mediators ϕ [Mardon et al: 0901.2926, Fortin et al: 0908.2258]



Predicted in DM models

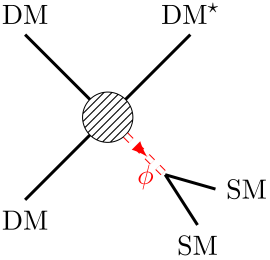
Pospelov et al: 0711.4866
Bohem et al: 1401.6458
Di Mauro, Wang: 2510.23771

Signal excess

Gamma [Elor et al: 1503.01773]
Positron [Cholis et al. 0802.2922]

Expanding the DM landscape: one-step semi-annihilation

DM semi-annihilation into light(er) mediators ϕ is also possible
[D'Eramo, Thaler: 1003.5912]



Predicted in DM models

Bandyopadhyay et al: 2206.05811
Beauchesn et al: 2403.01729

Phenomenology

Gamma [Queiroz, Siqueira: 1901.10494]
Antiproton [Arcadi et al: 1706.02336]

Pure one-step ID: a specific realisation [F.D'Eramo, TS: 2502.19491]

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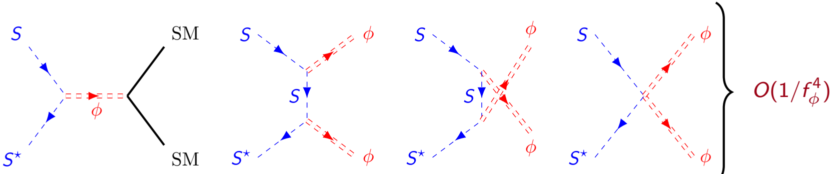
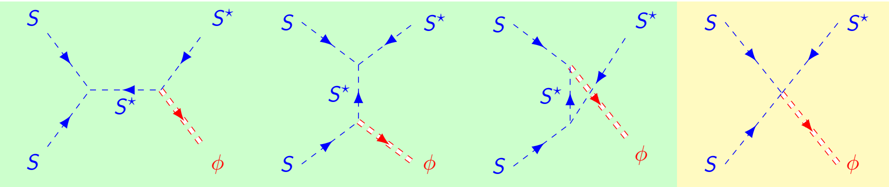
Consider a $\mathbb{Z}_3$ charged scalar with ALP portal interaction to SM

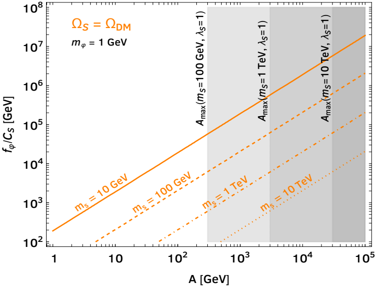
$$\mathcal{L}_{EFT} \supset \frac{\mathcal{C}_S}{2f_\phi}\partial_\mu\phi\, S^\dagger i\overleftrightarrow{\partial^\mu} S + \frac{\mathcal{C}'_S}{4f_\phi^2}(\partial_\mu\phi)^2|S|^2 + \mathcal{L}_{\phi-\mathrm{SM}} - \frac{A}{3!}(S^3 + S^{\dagger\,3})$$



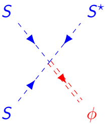
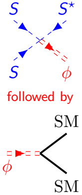
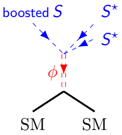
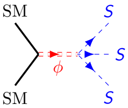
vanishing on-Shell

Only *semi-annihilations* are active at tree-level at $O(1/f_\phi^2)$





- Wide region of parameters space available
- $\Omega_{\rm DM}$ reproduced for $f_\phi/\mathcal{C}_S \sim$ few $\times$ $O(10^3)$GeV
- Direct detection naturally suppressed

Freeze-Out	Indirect	Direct	Collider
	 [Queiroz, Siqueira: 1901.10494]	 [Berger *et al.*: 1912.05558] [Kamenetskaia *et al.*: 2501.12117]	 [Toma: 2109.05911]

DM relic density

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DM scenarios with extended phenomenology allow for multiple collision types

$$a\,\mathrm{DM} + \mathrm{b}\,\mathrm{DM}^{(\star)} \leftrightarrow \mathrm{n}\,\mathrm{DM}^{(\star)} + \ell\,\phi + \mathrm{m}\,\mathrm{SM}$$

$$\text{with } (a, b, n, \ell, m) = \begin{cases} (1,1,0,0,2) & \text{annihilations} \\ (1,1,0,2,0) & \text{one-step annihilations} \\ (2,0,1,1,0) & \text{semi-annihilations} \end{cases}$$

The Boltzmann equation for the DM number density reads

$$\frac{dn_{\mathrm{DM}}}{dt} + 3Hn_{\mathrm{DM}} = \Sigma_{\mathrm{ann}}\left(n_{\mathrm{DM}}^2 - n_{\mathrm{DM}}^{\mathrm{eq}\,2}\right) + \Sigma_{\mathrm{semi}}\left(n_{\mathrm{DM}}^2 - n_{\mathrm{DM}}\,n_{\mathrm{DM}}^{\mathrm{eq}}\right)\,.$$

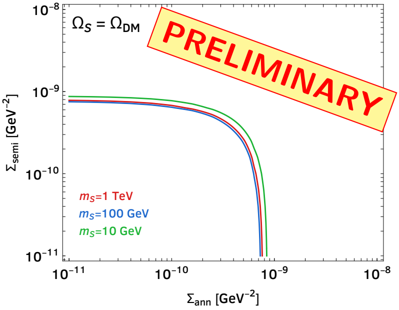
$$\Sigma_{\mathrm{ann}} = -\langle\sigma v\rangle_{\mathrm{DM\,DM^\star}\leftrightarrow\mathrm{SM\,SM}} - \langle\sigma v\rangle_{\mathrm{DM\,DM^\star}\leftrightarrow\phi\phi}$$

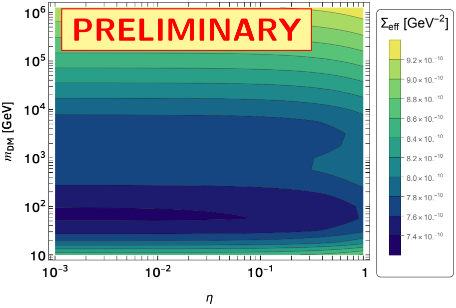
$$\Sigma_{\mathrm{semi}} = -\frac{1}{2}\langle\sigma v\rangle_{\mathrm{DM\,DM}\leftrightarrow\mathrm{DM}\,\phi}$$

DM relic density

We can define

$$\Sigma_{\rm eff}(x) = \Sigma_{\rm ann} + \Sigma_{\rm semi} \qquad \eta = \Sigma_{\rm semi}/\Sigma_{\rm eff}$$





One-step injection spectrum

One-step cascade processes kinematics affects the shape of injection spectra of a generic cosmic ray species X.
Boosting the spectrum at production (ϕ rest frame) gives (assuming isotropic emission) [Mardon et al: 0901.2926]

$$\frac{dN_X}{dE_X} = \frac{\ell}{2} \times \frac{1}{\gamma_L \beta_L} \int_{E'_X{}^{min}}^{E'_X{}^{max}} \left.\frac{dN_X}{dE'_X}\right|_{\phi\to \mathrm{SM\,SM}} \frac{dE'_X}{\sqrt{E'^2_X - m_X^2}}$$

Each process is characterised by Lorentz boost factors β_L, γ_L which modify also the integral range.

Results: Gamma ray spectra, pure scenarios

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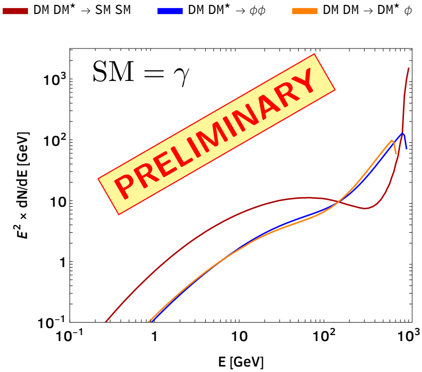
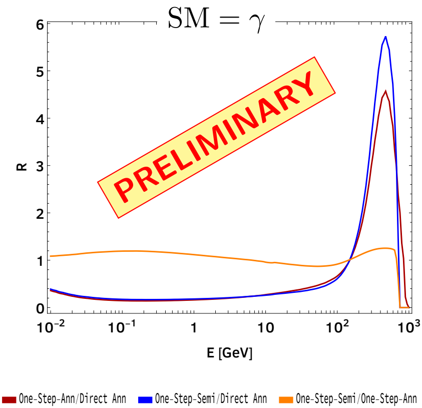




One-step cascade processes give ∼box-shaped spectra

[Ibarra et al: 1205.0007]

[Díaz Sáez et al: 2105.04255]

$$R = \frac{dN_\gamma}{dE_\gamma}\bigg|_i \bigg/ \frac{dN_\gamma}{dE_\gamma}\bigg|_j$$

Total injection spectrum

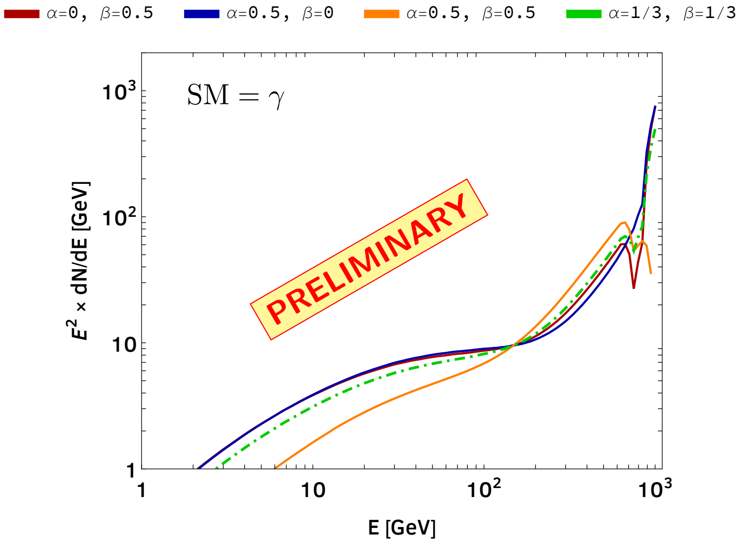
In general, these processes can coexist and the associated cosmic ray can be combined [F.D'Eramo, S.Manconi, TS: 2511.XXXXX]

$$\frac{dN_X}{dE_X} = (1-\alpha-\beta)\frac{dN_X}{dE_X}\bigg|_{\mathrm{DM\,DM^\star \to SM\,SM}} + \alpha\,\frac{dN_X}{dE_X}\bigg|_{\mathrm{DM\,DM^\star}\to\phi\phi} + \beta\,\frac{dN_X}{dE_X}\bigg|_{\mathrm{DM\,DM \to DM^\star}\phi}$$

where contribution weights are naturally defined as

$$\alpha = \frac{\langle\sigma v\rangle_{\mathrm{DM\,DM^\star}\to\phi\phi}}{\Sigma_{\mathrm{eff}}} \qquad \beta = 2\times\frac{\langle\sigma v\rangle_{\mathrm{DM\,DM\to DM^\star}\phi}}{\Sigma_{\mathrm{eff}}} = 2\eta$$

Gamma ray spectra: mixing



Prompt gamma ray flux

The very same combination enters the total prompt gamma-ray flux at the source ($\kappa = 1/2$ for all processes)

$$\frac{d\phi_\gamma}{dE_\gamma} = \frac{J(\Delta\Omega)}{16\pi\, m_{\rm DM}^2} \times \Sigma_{\rm eff} \sum_{\rm SM} \Bigg[{\rm BR}_{\rm SM}(1-\alpha-\beta) \frac{dN_\gamma^{\rm (SM)}}{dE_\gamma}\bigg|_{\rm DM\,DM^\star \to SM\,SM} + {\rm BR}_{\rm SM}\, \alpha \frac{dN_\gamma^{\rm (SM)}}{dE_\gamma}\bigg|_{\rm DM\,DM^\star \to \phi\phi} + {\rm BR}_{\rm SM}\, \beta \frac{dN_\gamma^{\rm (SM)}}{dE_\gamma}\bigg|_{\rm DM\,DM \to DM^\star\,\phi} \Bigg]$$

with $\Sigma_{\rm eff}$ the thermal cross section that reproduces the correct DM abundance

Conclusions and Outlook

- We suggest a new scalar DM scenario with ALP portal interactions to the SM which phenomenology is mainly determined by semi-annihilations and one-step annihilations
- We investigate the features of cosmic ray injection spectra in a model independent approach, allowing for DM frameworks with rich phenomenology

Outlook

F.D'Eramo, S.Manconi, TS: 2511.XXXXX

- Systematic study of different channels
- Extend to different species $X = (\nu,\ e^+,\ \bar{p}, \bar{D})$

Thank you!

Backup material

A Possible UV Completion I

The UV theory contains extra fields and a global U_ϕ symmetry

Field	Φ	S	Ψ_L	Ψ_R
Type	Complex scalar	Complex scalar	Weyl	Weyl
U_ϕ charge	-3	1	ξ_Ψ	$\xi_\Psi - 3$

$$\mathcal{L}_{\rm UV} \supset -\left(y_\Psi \Phi^\dagger \bar{\Psi}_L \Psi_R + \text{h.c.}\right) + \overset{\ll 1}{\cancel{\lambda_{\Phi H}}} \Phi^\dagger \Phi\, H^\dagger H + \overset{\ll 1}{\cancel{\lambda_{\Phi S}}} \Phi^\dagger \Phi\, S^\dagger S + \left(\kappa_\star \Phi S^3 + \text{h.c.}\right)$$

A Possible UV Completion II

After Φ taking a VEV $\quad \Phi \to \left(\frac{v_\Phi + \rho}{\sqrt{2}}\right) \exp\left[i\frac{\phi}{v_\Phi}\right] \ldots$

$$\mathcal{L}_\phi = \frac{1}{2}(\partial_\mu\phi)^2 - \frac{v_\Phi}{\sqrt{2}}\left[\kappa_\star \exp\left[i\frac{\phi}{v_\Phi}\right] S^3 + y_\Psi \exp\left[-i\frac{\phi}{v_\Phi}\right]\bar{\Psi}_L\Psi_R + \text{h.c.}\right]$$

and integrating out heavy modes $\quad \ldots$

$$\mathcal{L}_\phi^{N\partial} \supset \frac{\phi}{8\pi v_\Phi}\left[\alpha_G G_{\mu\nu}\widetilde{G}^{\mu\nu} + 2Y_\Psi^2\alpha_B B_{\mu\nu}\widetilde{B}^{\mu\nu}\right] + \frac{v_\Phi}{\sqrt{2}}\left[\kappa_\star \exp\left[i\frac{\phi}{v_\Phi}\right] S^3 + \text{h.c.}\right]$$

$\mathbb{Z}_3$ *arises!*

Matching UV completion onto our EFT

The UV theory matches onto our EFT as ($\mathcal{C}_G = 1$):

$$f_\phi = v_\Phi \,, \qquad \mathcal{C}_B = 2Y_\Psi^2 \,, \qquad A = 3\sqrt{2}\,\kappa_\star v_\Phi$$

Higher order potential terms are naturally suppressed:

$$V_S(S) \supset \frac{\lambda_5}{4!}\frac{1}{v_\Phi} S^4 S^\dagger \,, \qquad \lambda_5 = \frac{6\sqrt{2}k_\star \lambda_{\Phi S}}{\lambda_\Phi} \ll 1$$

ϕ-dependent rotations $S \to e^{\left[i\phi/(3f_\phi)\right]} S$ recover ∂-basis Lagrangian up to dim-6 interaction terms

$$\delta\mathcal{L}^{(6)}_{\mathrm{INT}} = \frac{\mathcal{C}_S'^2}{4f_\phi^2} |\partial_\mu \phi|^2 S^\dagger S \qquad \mathcal{C}_S = \mathcal{C}_S' = \frac{2}{3}$$