Indirect search for stable DM bound state formation

Results from the GPS on Indirect Detection

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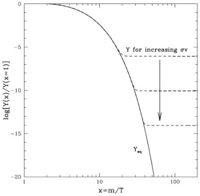
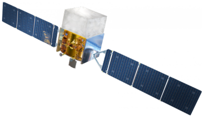
Xenon1T and friends IRN Terascale
8 July 2020

Long range interactions





- Consider thermal-relic DM, $\langle \sigma v_{\rm rel} \rangle \sim 10^{-9}$ GeV^2
- For $m_{\rm DM} \gtrsim$ TeV: Large couplings/light mediators; long range.
- Number of important phenomenological implications
- Sommerfeld enhancement well studied example
- Enhances indirect detection signal for heavy $m_{\rm DM}$.

$$\frac{d\Phi_\gamma}{dE} = \left[\frac{\langle (\sigma v_{\rm rel}) \rangle}{8\pi m_{\rm DM}^2} \right] \frac{dN}{dE_\gamma} J$$

- Similarly: unstable bound states. - e.g. Cirelli et al. 1612.07295

DM bound state formation

1. Symmetric or self-conjugate DM. (WIMP is the textbook example.)

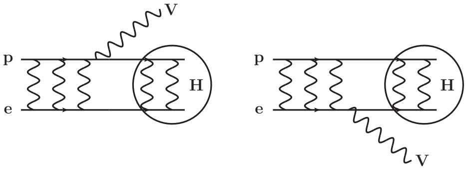
- Bound states are unstable.
  Analogue: $e^- + e^+ \to \mathrm{Ps} + \gamma\,,\, \mathrm{Ps} \to 3\gamma, 2\gamma$.
- Effectively contribute to enhance the DM annihilation rate.
- Signals from their decay considered in a number of studies.

2. Asymmetric DM

- No indirect detection from annihilation. (No antiparticles around.)
- Bound states are stable. Analogue: $p^+ + e^- \to H + \gamma$
- But produce low energy radiation in their formation.
  $E_{\rm LE} \approx \frac{\mu}{2}(\alpha_{\rm eff}^2 + v_{\rm rel}^2) \ll m_{\rm DM}$
- Dark radiation from secluded sector eventually produces SM γ's.

We will seek to constrain asymmetric DM through detection of the low energy radiation from BSF. - Pearce/Kusenko 1303.7294

The model



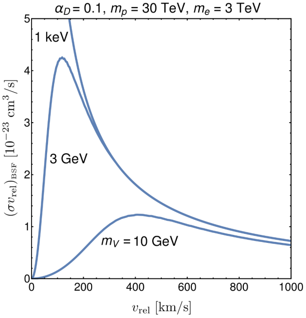
Dark QED DM

$$\mathcal{L} = \frac{1}{2} m_{\mathbf{V}}^2 \mathbf{V}_\mu \mathbf{V}^\mu - \frac{1}{4} F_{D\mu\nu} F_D^{\mu\nu} - \frac{\epsilon}{2c_W} F_{D\mu\nu} F_Y^{\mu\nu} + \bar{\mathbf{p}}(i\not{D} - m_{\mathbf{p}})\mathbf{p} + \bar{\mathbf{e}}(i\not{D} - m_{\mathbf{e}})\mathbf{e}.$$

- Model consists of dark protons, **p**, dark electrons **e**, dark photon **V**.
- Dark photon has Stuckelberg mass.
- Kinetic mixing ϵ allows it to decay to the SM.

Underlying parameters: α_D, $m_{\mathbf{V}}$, $m_{\mathbf{p}}$, $m_{\mathbf{e}}$, ϵ.

Bound state formation

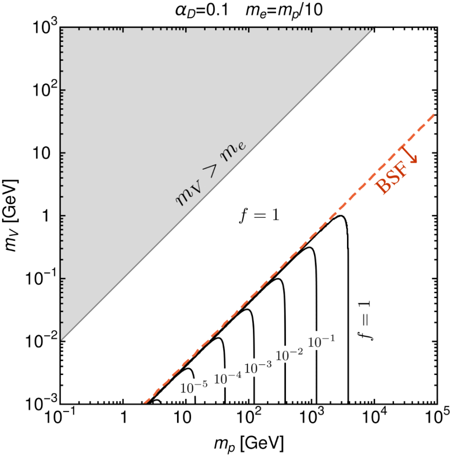


The cross section in the Coulomb limit is:

$$(\sigma v_{\rm rel})_{\rm BSF} \simeq \frac{2^9 \pi^2 \alpha_D^2}{3\,\mu_D^2} \frac{\zeta^5}{(1+\zeta^2)^2} \frac{e^{-4\zeta \operatorname{arccot}(\zeta)}}{1-e^{-2\pi\zeta}}\, s_{\rm ps} \qquad \text{where } \zeta = \alpha_D / v_{\rm rel}.$$

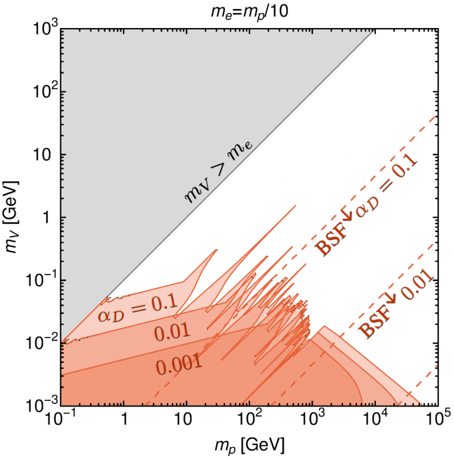
Energy of emitted dark photon $E_{\rm v} \simeq \alpha_D^2 \mu_D / 2$.
Scaling of $(\sigma v_{\rm rel})_{\rm BSF}$ changes at $v_{\rm rel} \sim m_{\rm v}/\mu_D$.

The Ionized Fraction



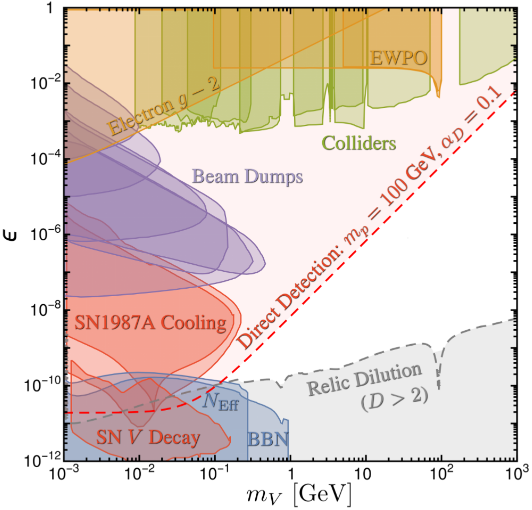
$$f \equiv \frac{n_{\mathbf{p}}}{n_{\mathbf{H}} + n_{\mathbf{p}}} \approx \min\left[1, 10^{-10}\frac{1}{\alpha_D^4}\left(\frac{m_{\mathbf{H}}\mu_D}{\mathrm{GeV}^2}\frac{1}{s_{\mathrm{ps}}}\right)\right]$$

Ejection of dark electrons?

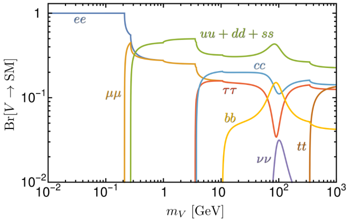


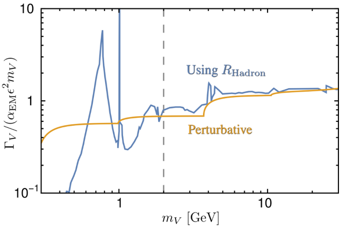
$$\Gamma_{\rm scat} = \sigma_{\rm elast} v_{\rm rel} n_{\mathbf{p}} = \sigma_{\rm elast} v_{\rm rel} \frac{\rho_{\rm DM}}{m_{\mathbf{p}} + m_{\mathbf{e}}}$$

Constraints on the dark photon

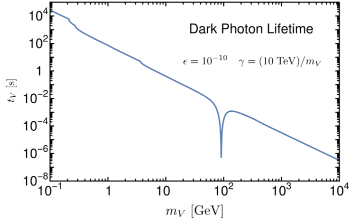


Dark photon decays

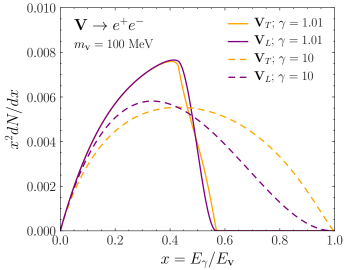


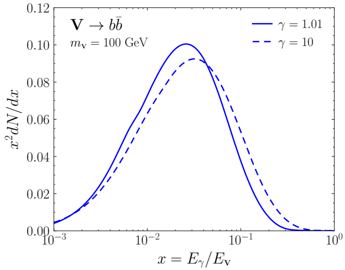


- We use a perturbative calculation (but see Plehn et al. 1911.11147)
- The error is acceptable for $m_V \gtrsim 2$ GeV
- The decay is prompt on astrophysical scales



Visible photon spectrum





- Pythia is used to find the spectrum
- Dark photon polarization taken into account for leptonic final states
- As E_V/m_v increases longitudinal state produced less often.

$$b_T = \frac{2}{3 - s_{\rm ps}}, \qquad b_L = \frac{1 - s_{\rm ps}}{3 - s_{\rm ps}} \qquad s_{\rm ps} \equiv 1 - \left(\frac{m_v}{E_v}\right)^2$$

The J-factor

The observed flux

$$\frac{d\Phi_\gamma}{dE} = \left[\frac{f^2(\sigma v_{\rm rel})_0}{4\pi\left(fm_{\mathbf{p}} + fm_{\mathbf{e}} + [1-f]m_{\mathbf{H}}\right)^2}\right]\frac{dN}{dE_\gamma}J$$

The J-factor

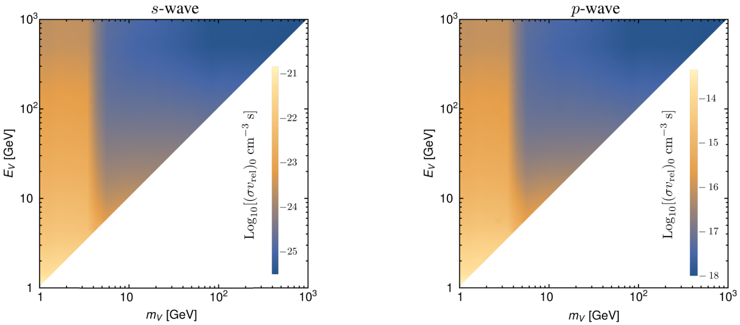
$$J = \int_0^\infty dr \int_\Sigma d\Omega \int d^3v_1 \int d^3v_2 f_{\rm ps}(r,\Omega,v_1) f_{\rm ps}(r,\Omega,v_2) S(v_{\rm rel})$$

The velocity dependence

$$(\sigma v_{\rm rel})_{\rm BSF} \equiv (\sigma v_{\rm rel})_0 S(v_{\rm rel})$$

$(\sigma v_{\rm rel})_0$ is velocity independent.
J-factors calculated for $S(v_{\rm rel}) = v_{\rm rel}^{-1},\ v_{\rm rel}^{0},\ v_{\rm rel}^{2},\ v_{\rm rel}^{4}$. Here we find results using s- and p-wave J-factors. Alvarez et al. 2002.01229, Boddy et al. 1909.13197

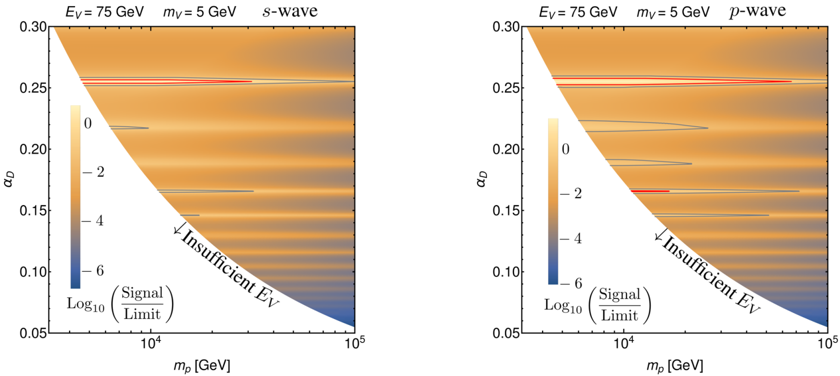
Setting the limit - using Fermi-LAT data



- We use a standard profile-likelihood method

  - Alvarez et al. 2002.01229
- Fully profiling over J-factor and background uncertainties
- We stack together the four most constraining dSphs: Draco, Sculptor, Ursa Minor, and Leo II
- Limits above with $f^2/(fm_{\mathbf{p}} + fm_{\mathbf{e}} + [1-f]m_{\mathbf{H}})^2 = 1/(100\ \mathrm{GeV})^2$

Results - DM Bound state formation



The limit on the model is a factor of ≈ 4 stronger when using the *p*-wave $J-$factor.

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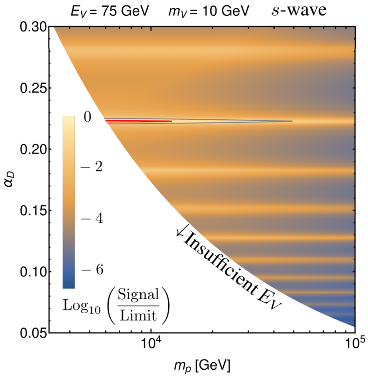

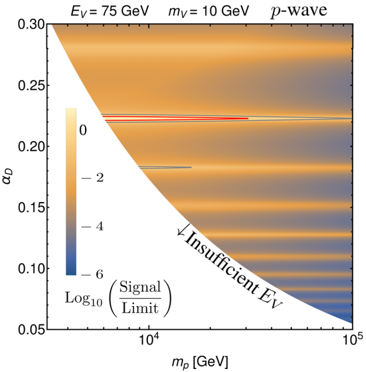

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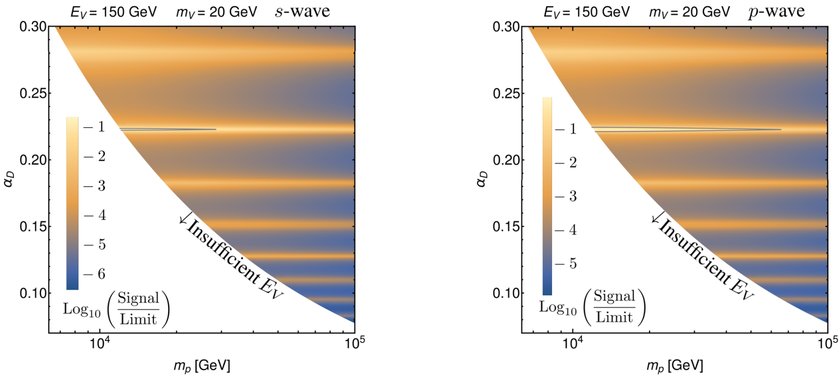
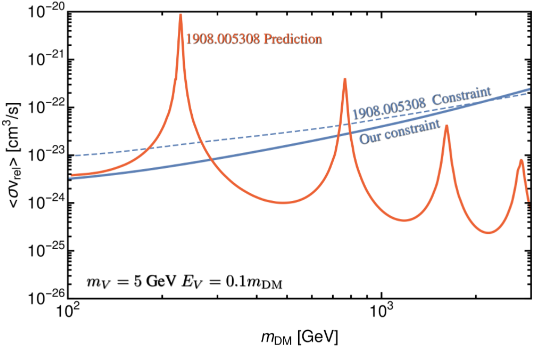


The limit on the model is a factor of ≈ 4 stronger when using the p-wave $J-$factor.

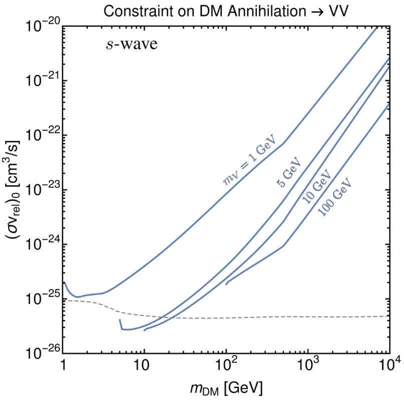
Variations



- Mahbubani et al 1908.00538

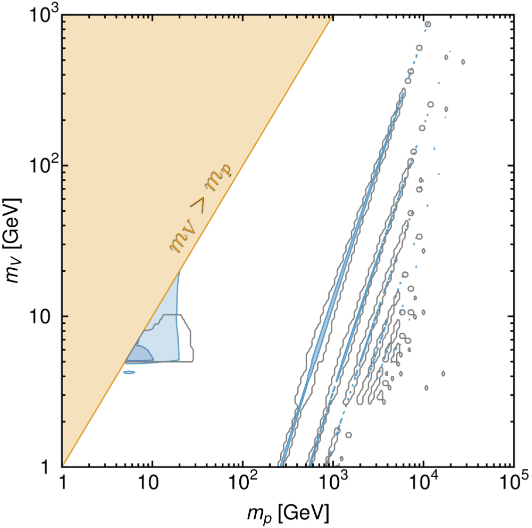
We can use our results to constrain other models which have appeared in the literature with fewer approximations.

Results - DM annihilation



Assuming a $\rho_{\rm DM}^2$ dependence. We now have generic constraints on the dark photon flux as a function of m_V and E_V.

We can use this to also set limits on the DM annihilation by setting $E_V = m_{\rm DM}$.



Applying this to the symmetric dark QED model.

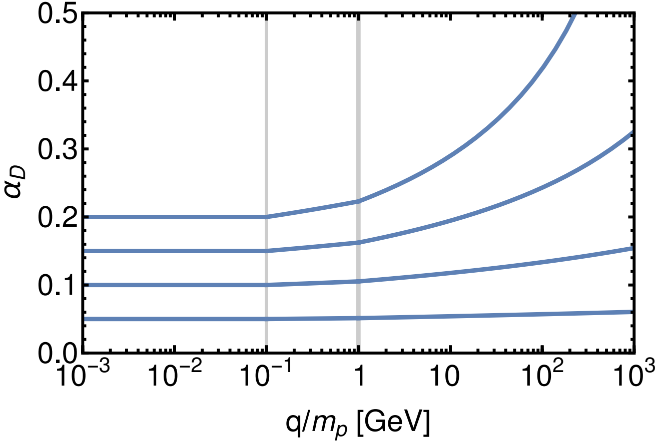
Summary

Conclusions

- Extended indirect detection formalism to consider formation of stable bound states.
- Of particular interest for asymmetric DM models which typically lack indirect detection signatures.
- These models are often also multi-component allowing for BSF.
- To achieve efficient annihilation we need large $\langle \sigma v_{\rm rel} \rangle$ for heavy $m_{\rm DM}$. Hence large α_D and the beginning of non-perturbative effects such as BSF. Thus BSF somehow natural for heavy ADM.
- Limits in terms of E_γ and m_γ are more general: we also cover standard DM annihilation. (Without additional work.)
- Although the simplest dark QED model is not overly constrained by this process - the limits are also useful for somewhat more complicated variations.

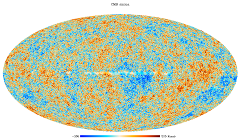
Thanks.

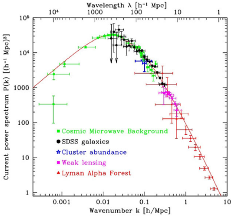
Running of the dark gauge coupling

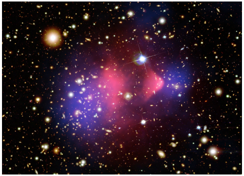


$$\frac{d\,\alpha_D}{d\ln q} = \beta_D(\alpha_D, n_F) = \frac{\alpha_D^2}{2\pi}\left(\frac{4}{3}n_F + \frac{\alpha_D}{\pi}n_F\right)$$

The DM density







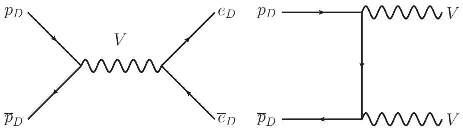
Crucial ADM relation

$$\frac{\Omega_B}{\Omega_{\rm DM}} \simeq \frac{m_p}{m_{pD}} \frac{Y_B}{Y_D} \left(\frac{1-r_\infty}{1+r_\infty}\right) \approx 5$$

- Y_B is the baryon asymmetry.
- $r_\infty \equiv (Y_- / Y_+)_{t\to\infty}$: ratio of DM antiparticles to particles today.
- $r_\infty \ll 1$ is somehow “natural” in ADM $\to$ no standard ID signal.

By charge conservation $n_{e_D} - n_{\bar{e}_D} = n_{p_D} - n_{\bar{p}_D}$

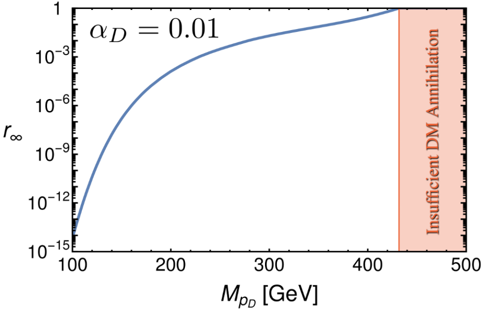
The symmetric population annihilates away



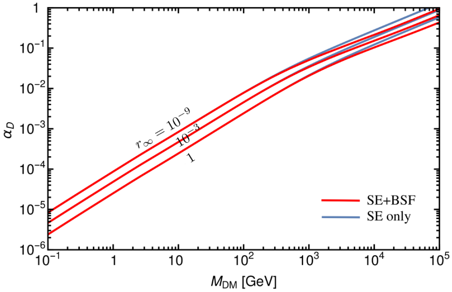
From previous projects we have a Boltzmann code for the relic density.

1703.00478 & 1712.07489

This includes Sommerfeld enhancement, unstable bound state formation, ...



Another view of the relic density



- Smaller r_∞ requires larger α_D.
- SE+BSF important for large $m_{\rm DM}$ (large α_D).
- Reannihilation is not taken into account here.

  - Binder et. al. [1712.01246]

$$\sigma v_{\rm rel}(\bar{p}_D p_D \to \mathbf{VV}) = \frac{\pi \alpha_D^2}{m_{\rm DM}^2} \times S_{\rm ann}$$

$$\sigma v_{\rm rel}(\bar{p}_D p_D \to \bar{e}_D e_D) = \frac{\pi \alpha_D^2}{m_{\rm DM}^2} \times S_{\rm ann}$$

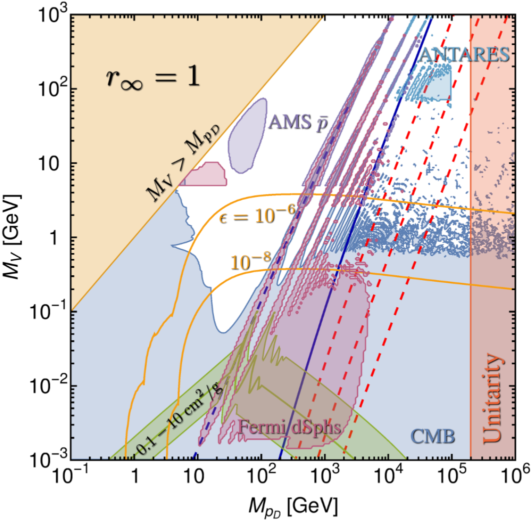
$$\sigma_{\rm BSF} v_{\rm rel} = \frac{\pi \alpha_D^2}{m_{\rm DM}^2} \times S_{\rm BSF}$$

$$\Gamma(\uparrow\downarrow \to \mathbf{VV}) = \frac{\alpha_D^5 m_{\rm DM}}{2}$$

$$\Gamma(\uparrow\uparrow \to \bar{e}_D e_D) = \frac{\alpha_D^5 m_{\rm DM}}{6}$$

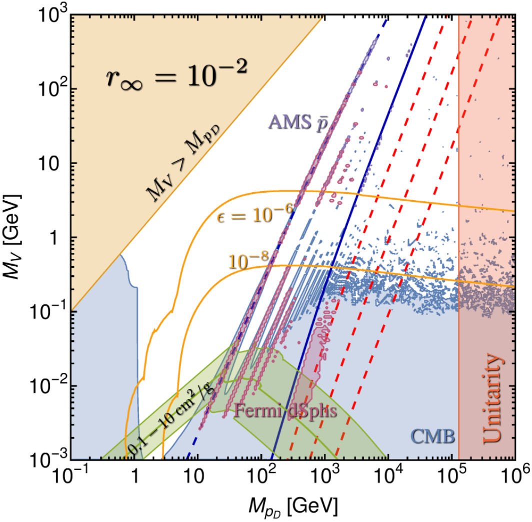
$$\Gamma(\uparrow\uparrow \to \mathbf{VVV}) = \frac{2(\pi^2 - 9)\alpha_D^6 m_{\rm DM}}{9\pi}$$

Some previously derived constraints - no stable BSF



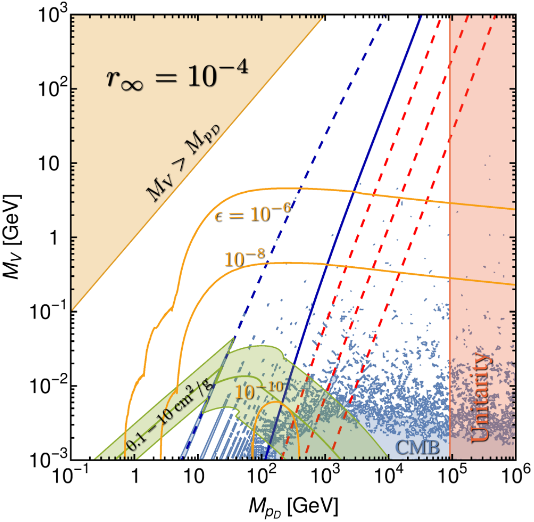
IB et. al. 1712.07489

Some previously derived constraints - no stable BSF



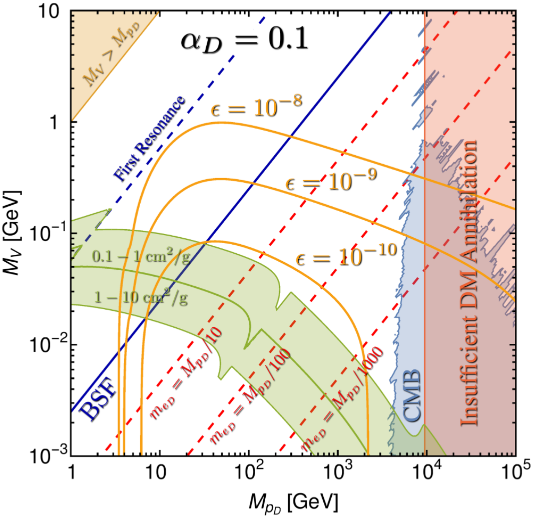
IB et. al. 1712.07489

Some previously derived constraints - no stable BSF



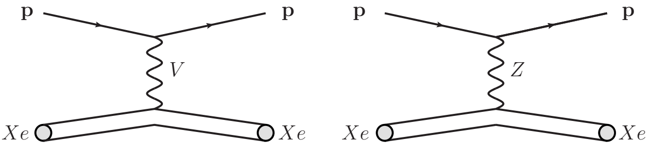
IB et. al. 1712.07489

Some previously derived constraints II - no stable BSF



IB et. al. 1712.07489

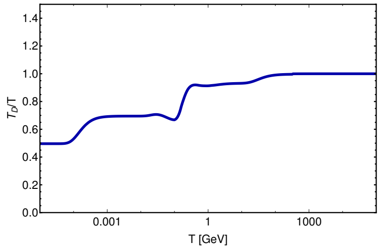
Direct Detection

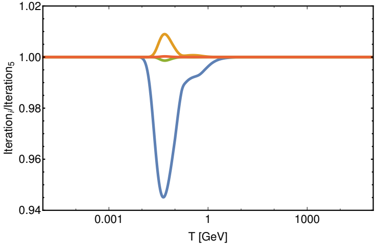


$$\frac{d\sigma}{dE_R} \to \frac{M_T F_{\text{Helm}}^2}{2\pi v_{\text{rel}}^2} \left(\frac{\epsilon g_{\text{EM}} g_D Z_T}{2 M_T E_R + m_V^2} \right)^2$$

- XENON1T reported 14 events in their nuclear recoil signal reference region in 278.8 days of exposure time of their 1.3 tonnes of fiducial mass.
- The estimated background is 7.36 ± 0.61 events.
- We take the 90% C.L. limit which corresponds to DM contributing 12.8 events..
- We find an exclusion by demanding the expected number of events at a given parameter point in our model not exceed this.

The Temperature Ratio

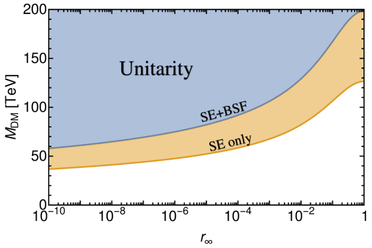




Temperature ratio determined through entropy accounting

$$\xi \equiv \frac{T_{\rm D}}{T} = \left(\frac{h_{\rm SM}(T)}{h_{\rm SM}(T_i)} \frac{h_{\rm D}(T_i)}{h_{\rm D}(T)} \right)^{1/3} \xi_i$$

Unitarity



Unitarity

$$\sigma^{(J)}_{\rm inel}\, v_{\rm rel} \leqslant \sigma^{(J)}_{\rm uni}\, v_{\rm rel} = \frac{4\pi(2J+1)}{m^2_{\rm DM}\, v_{\rm rel}}$$

- LHS scales as $1/v_{\rm rel}$ with light mediator.
- Calculation becomes untrustworthy close to unitarity limit.
- Translates into a maximum possible DM mass.
- Depends on r_∞. - IB, Petraki [1703.00478]