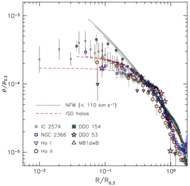
Residual annihilations of asymmetric DM

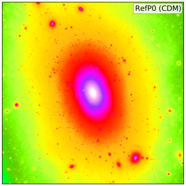
Iason Baldes

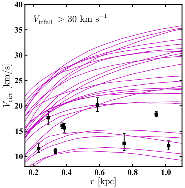
May 24, Planck 2018, Bonn

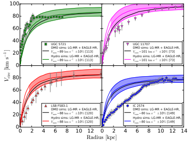
Talk based on
1703.00478 - IB, Petraki
1712.07489 - IB, Cirelli, Panci, Petraki, Sala, Taoso.

Small scale structure problems







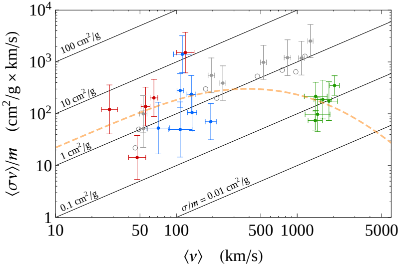


Small scale structure problems

- Core-Cusp problem: observations favour a cored profile.
- Missing Satellites: failed to observe many subhalos? (but see Kim et. al. [1711.06267]).
- Too-big-to-fail: CDM predicts more massive satellites.
- Diversity Problem. (see Kamada et. al. [1611.02716]).

These problems may well end up being solved by baryonic physics but they may also point towards a non-minimal DM sector.

Constraints on SIDM



- Kaplinghat, Tulin, Yu [1508.03339]

Remarkably the correct velocity dependence can be achieved with a $\sim 1 - 100$ MeV mediator.

SIDM - Spergel, Steinhardt '00. **Would severely constrain DM possibilities.**

$$R_{\rm scat} = \sigma v_{\rm rel}\rho_{\rm dm}/m \approx 0.1\ {\rm Gyr}^{-1} \times \left(\frac{\rho_{\rm dm}}{0.1\ M_{\rm sol}/{\rm pc}^3}\right)\left(\frac{v_{\rm rel}}{50\ {\rm km/s}}\right)\left(\frac{\sigma/m}{1\ {\rm cm}^2/{\rm g}}\right)$$

Asymmetric Dark Matter

The light mediator can be nicely accommodated in Asymmetric Dark Matter models.

Asymmetric Dark Matter Density

Baryonic Matter Density

$$\Omega_B = \frac{(n_b + n_{\bar{b}})m_p}{\rho_c} \simeq \frac{n_b m_p}{\rho_c} \simeq \frac{n_B m_p}{\rho_c}$$

The symmetric component is efficiently annihilated away resulting in $n_{\bar{b}} = 0$ and $n_b = n_B \equiv n_b - n_{\bar{b}}$.

Observationally $Y_B \equiv n_B/s = (0.86 \pm 0.02) \times 10^{-10}$.

Asymmetric Dark Matter Density

The DM density could be set in a similar way: Asymmetric Dark Matter

$$\Omega_{DM} = \frac{(n_{\rm dm} + n_{\overline{\rm dm}})m_{\rm dm}}{\rho_c} \simeq \frac{n_{\rm dm} m_{\rm dm}}{\rho_c} \simeq \frac{n_D m_{\rm dm}}{\rho_c}$$

The requires an asymmetry to be created in the DM sector, $n_D \equiv n_{\rm dm} - n_{\overline{\rm dm}}$, and the efficient annihilation of the symmetric component. - Nussinov '85; Gelmini, Hall, Lin '87; Barr '91; Kaplan '92...

DM mass relation

$$M_{p_D} = m_p \frac{Y_B}{Y_D} \frac{\Omega_{\rm DM}}{\Omega_{\rm B}} \left(\frac{1 - r_\infty}{1 + r_\infty} \right)$$

$r_\infty \equiv (Y_- / Y_+)_{t \to \infty}$ is the ratio of DM antiparticles to particles today.

Asymmetric Dark Matter - Annihilation

Assume we have asymmetric DM with $n_D \equiv n_d - \bar{n}_d$.

We want to annihilate away the symmetric component of the ADM to lighter states in a D preserving manner.

- Graesser, Shoemaker, Vecchi 1103.2771; Iminniyaz, Drees, Chen 1104.5548 ; IB, Petraki 1703.00478

Possibilities (see March-Russell, Planck 2017)

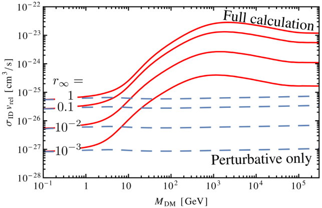
1. Direct annihilation to light SM dof. Severely constrained for $M_{\rm DM} \lesssim 10$ GeV. - March-Russell, Unwin, West 1203.4854
2. Annihilation to stable light Dark Sector particles (limits from $N_{\rm eff}$, structure)
3. Annihilation to light Dark Sector particles which then decay (limits from direct and indirect detection, colliders, structure)

Here we will be interested in option 3.

Asymmetric Dark Matter - Light Mediator

Light mediator can:

1. Provide an annihilation channel for the DM.
2. Give sizable self interactions. The symmetric case is severely constrained. - Bringmann et. al. '16, Cirelli et. al. '16
3. Give the velocity dependence required by the cluster constraint.
4. Will lead to experimental direct and indirect detection signatures once a decay channel to the SM opened
5. Leads to Sommerfeld enhancement of indirect detection
   - counteracts suppression of signal due to fewer antiparticles.



Aims of the work:

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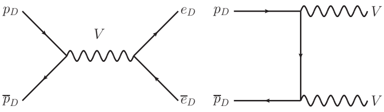
1. Identify areas of parameter space allowed by all constraints which give sizable self interactions.
2. Quantitatively explore indirect detection of ADM with Sommerfeld Enhancement.

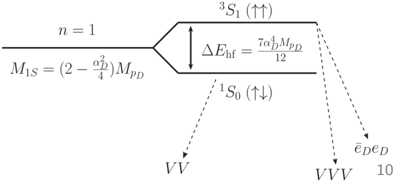
The model

Dark QED

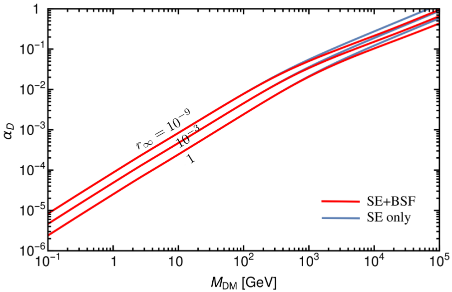
$$\mathcal{L} = \frac{1}{2} M_V V_\mu V^\mu - \frac{1}{4} F_{D\mu\nu} F_D^{\mu\nu} - \frac{\epsilon}{2c_w} F_{D\mu\nu} F_Y^{\mu\nu} + \bar{p}_D (i\not{D} - M_{p_D}) p_D + \bar{e}_D (i\not{D} - m_{e_D}) e_D$$

- Dark electrons are required for charge conservation when there is a $p_D - \bar{p}_D$ asymmetry.
- Here M_V is typically small compared to M_{p_D} and m_{e_D}.
- The kinetic mixing allows the mediator to decay to SM particles (avoid DM overproduction) $\rightarrow$ experimental signatures.





The relic abundance



- Smaller $r_\infty \equiv (Y_- / Y_+)_{t\to\infty}$ requires larger α_D.
- Sommmerfeld Enhacement + Bound State Formation important for large M_{p_D} (large α_D).

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

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

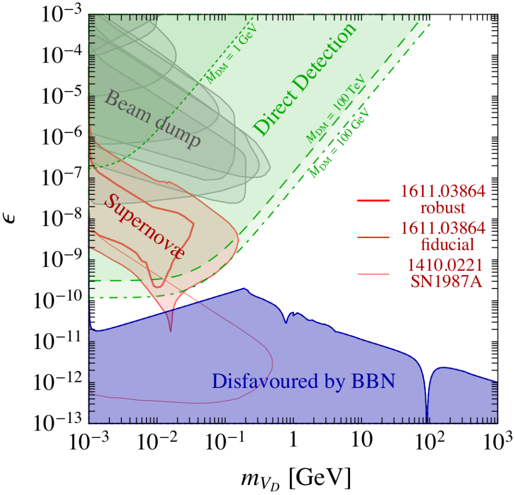
$$\sigma_{\rm BSF} v_{\rm rel} = \frac{\pi \alpha_D^2}{M_{p_D}^2} \times S_{\rm BSF}$$

$$\Gamma(\uparrow\downarrow \to VV) = \frac{\alpha_D^5 M_{p_D}}{2}$$

$$\Gamma(\uparrow\uparrow \to \bar{e}_D e_D) = \frac{\alpha_D^5 M_{p_D}}{6}$$

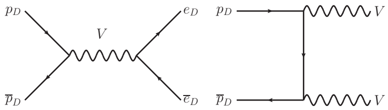
$$\Gamma(\uparrow\uparrow \to VVV) = \frac{2(\pi^2 - 9)\alpha_D^6 M_{p_D}}{9\pi}$$

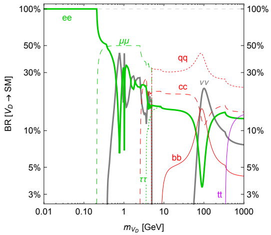
Dark Photon Constraints



- Cirelli, Panci, Petraki, Sala, Taoso [1612.07295]

Indirect detection Constraints



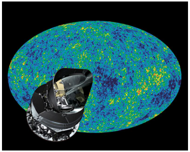


Effective cross section

$$\sigma_{\rm ID}\, v_{\rm rel} \equiv \frac{n_\infty^+ n_\infty^-}{(n_\infty^+ + n_\infty^-)^2}\sigma_{\rm inel}\, v_{\rm rel} = \frac{4 r_\infty}{(1+r_\infty)^2}\, \sigma_{\rm inel}\, v_{\rm rel}\,.$$

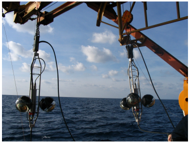
$$\tau_V \times (M_{p_D}/M_V) \simeq 0.26\ {\rm pc} \times \left(\frac{1}{\sum_f q_f^2}\right)\left(\frac{10^{-10}}{\epsilon}\right)^2 \left(\frac{M_{p_D}}{\rm TeV}\right)\left(\frac{\rm MeV}{M_V}\right)^2$$

Indirect detection Constraints

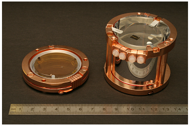


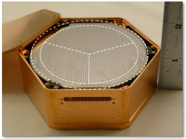
Constraints

- CMB: Planck constraint, taking f_{eff} from T. Slatyer.
- AMS: limits from antiproton spectrum.
- FERMI Dwarfs: SE regime compensates the γ poor $V \to$ leptons regime. (Galactic Halo: less severe constraints).
- ANTARES: limits from upward going muon tracks.



Direct Detection





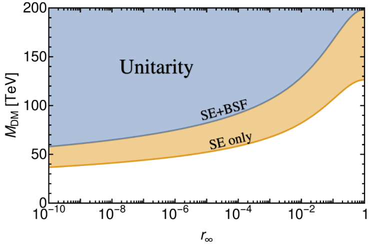
Direct Detection

CRESST-II, CDMS-lite, LUX

- Taking into account q^2 dependent propagator.
- Somewhat simplified analysis compared to the experimental papers.
- Limit depends on ϵ.

Recent updates from CRESST-III, DarkSide 50, XENON1T and PandaX-2 do not qualitatively change the picture.

Unitarity

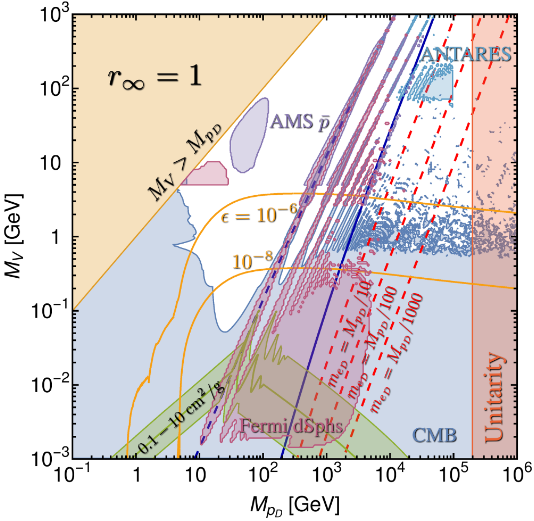


Unitarity

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

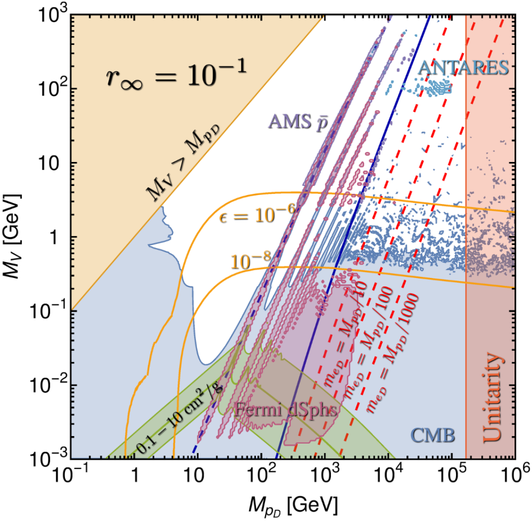
- LHS scales as $1/v_{\rm rel}$ with light mediator.
- Calculation becomes untrustworthy close to unitarity limit.
- Translates into a maximum possible DM mass.
- Depends on r_∞. - IB, Petraki [1703.00478]

Symmetric DM - $r_\infty = 1$



Stable atomic states form below red dashed lines - not treated here.

Aymmetric DM - $r_\infty = 10^{-1}$



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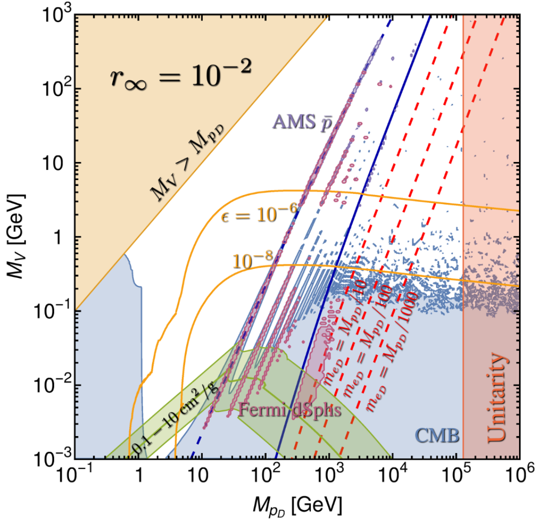
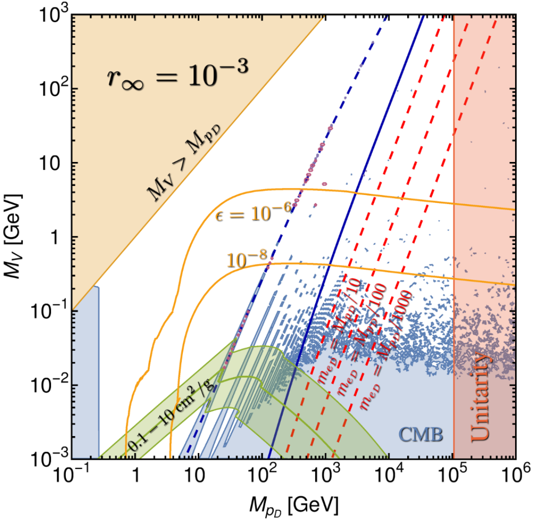
Aymmetric DM - $r_\infty = 10^{-2}$



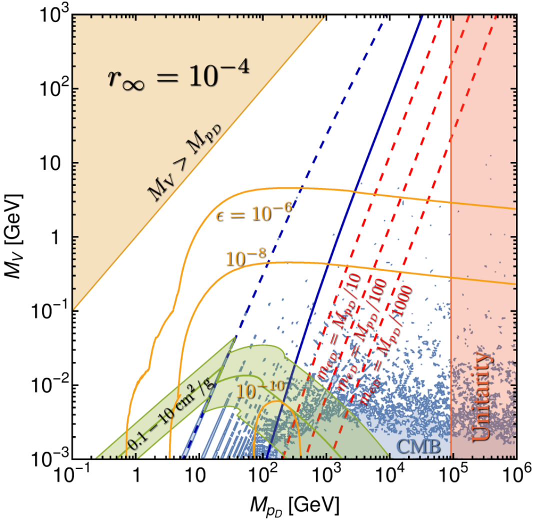
Stable atomic states form below red dashed lines - not treated here.

Aymmetric DM - $r_\infty = 10^{-3}$



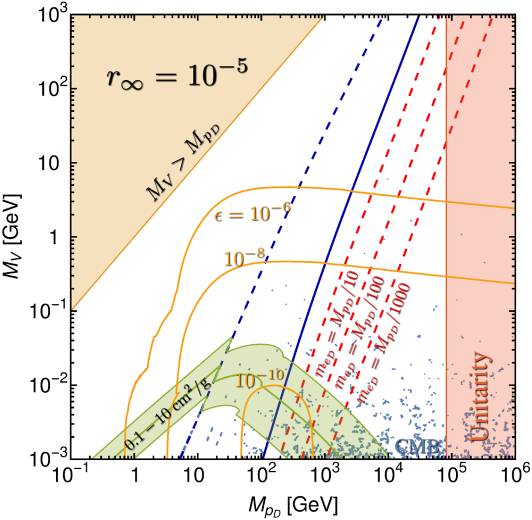
Stable atomic states form below red dashed lines - not treated here.

Aymmetric DM - $r_\infty = 10^{-4}$



Stable atomic states form below red dashed lines - not treated here.

Aymmetric DM - $r_\infty = 10^{-5}$



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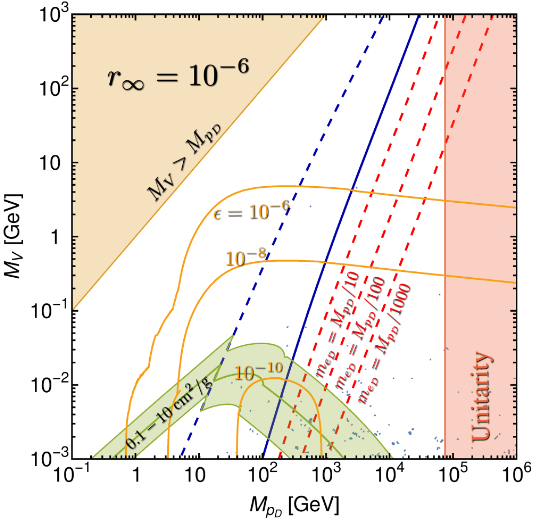
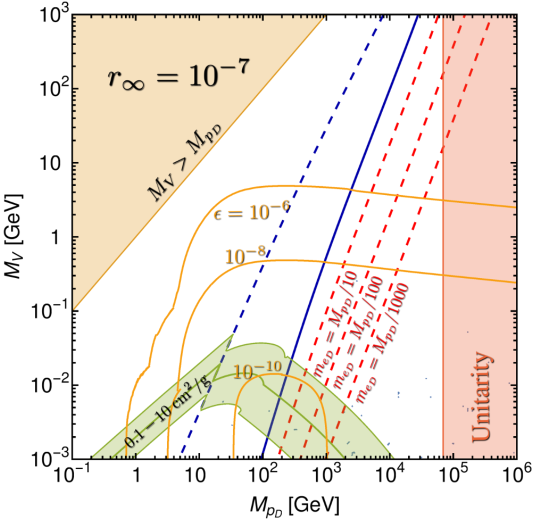
Aymmetric DM - $r_\infty = 10^{-6}$



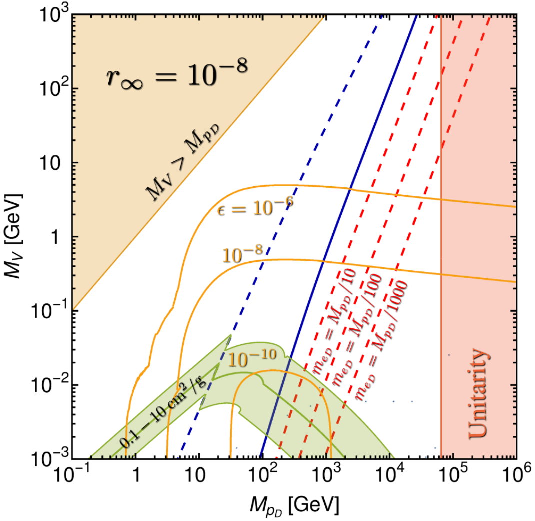
Stable atomic states form below red dashed lines - not treated here.

Aymmetric DM - $r_\infty = 10^{-7}$



Stable atomic states form below red dashed lines - not treated here.

Aymmetric DM - $r_\infty = 10^{-8}$



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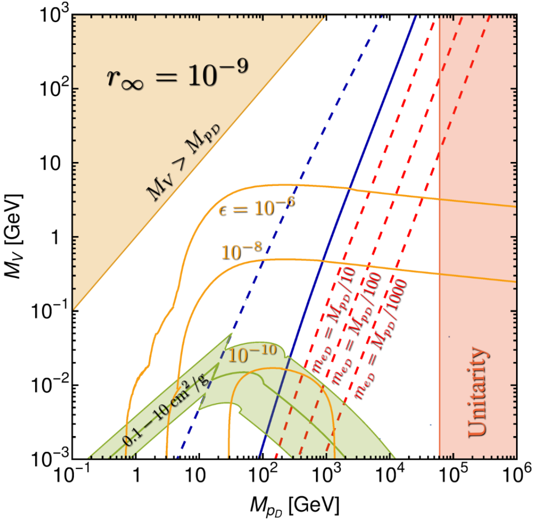
Aymmetric DM - $r_\infty = 10^{-9}$



Stable atomic states form below red dashed lines - not treated here.

Future Prospects

Future Prospects

- Direct detection: will continue to probe highly asymmetric regime.
- Careful BBN analysis could close light dark photon window.
- Multi-component numerical simulations could be of interest.
- More careful treatment of reannihilation required.
  - Binder et. al. [1712.01246]
- High Energy Cosmic Ray Experiments: please provide flux as a function of E.

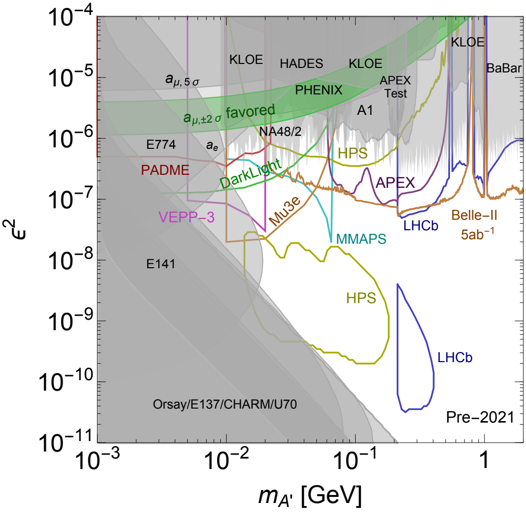
Conclusions

Conclusions

- SIDM regime still allowed in this model.
- Due to SE: residual annihilations imporant down to $r_\infty \sim 10^{-4}$.
- Complementarity with direct detection.
- Such models are multi-component: possible level transition signal (more careful consideration of atomic bound states required).

Thanks.

Dark Photon Constraints from Colliders



- J. Alexander et. al [1608.08632]

Dark Photon Constraints from Colliders

PHYSICAL REVIEW LETTERS **120**, 061801 (2018)

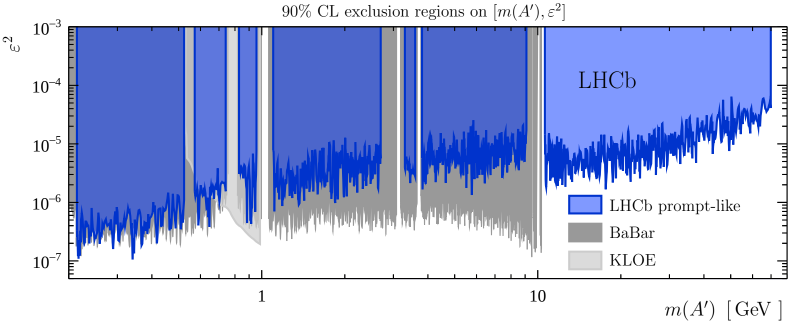
Editors' Suggestion | Featured in Physics

Search for Dark Photons Produced in 13 TeV *pp* Collisions

R. Aaij *et al.*[*]
(LHCb Collaboration)

(Received 15 December 2017; published 8 February 2018; corrected 26 March 2018)

Searches are performed for both promptlike and long-lived dark photons, A', produced in proton-proton collisions at a center-of-mass energy of 13 TeV, using $A' \to \mu^+\mu^-$ decays and a data sample corresponding



Self Interactions

Momentum transfer cross section

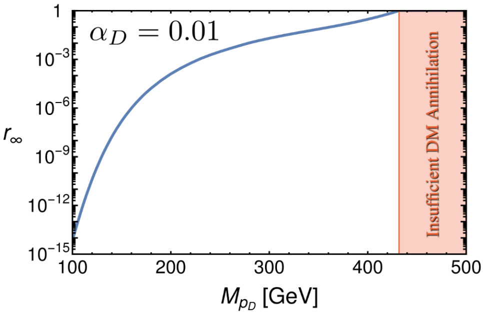
$$\sigma_T \equiv 2\pi \int_{-1}^{1} d\cos\theta \, (1-\cos\theta) \frac{d\sigma}{d\Omega}$$

If we want to address small scale structure problems with SIDM.

$$\begin{aligned}\sigma_T &= \frac{1}{2(n_\infty^{\rm sym})^2}\left[n_\infty^+ n_\infty^- \sigma_{\rm att} + \frac{1}{2}(n_\infty^+ n_\infty^+ + n_\infty^- n_\infty^-)\sigma_{\rm rep}\right] \\ &= \frac{2}{(1+r_\infty)^2}\left[r_\infty \sigma_{\rm att} + \frac{1}{2}(1+r_\infty^2)\sigma_{\rm rep}\right]\end{aligned}$$

The self interactions become purely repulsive as the DM becomes more asymmetric.

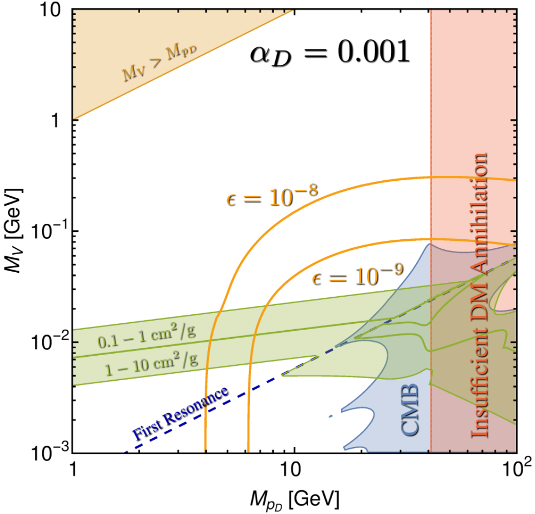
Fixed α_D



Instead fix α_D.

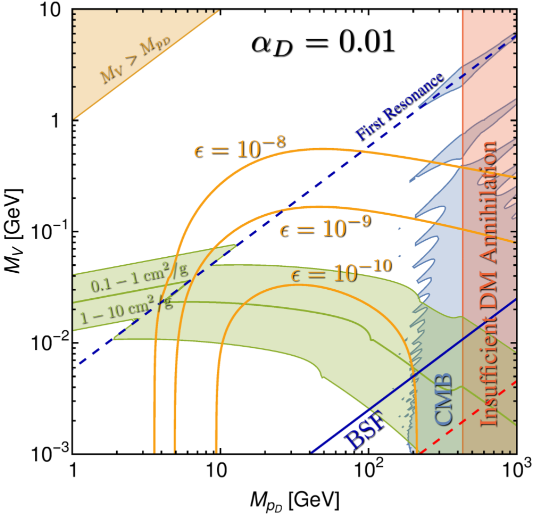
- DM antiparticle population now depends on M_{p_D}.
- Maximum possible M_{p_D} corresponds to symmetric DM.
- Above this M_{p_D}: too much DM.
- Below this M_{p_D}: Asymmetry Y_D to compensate underabundance and r_∞ rapidly becomes suppressed.

Fixed $\alpha_D = 0.001$



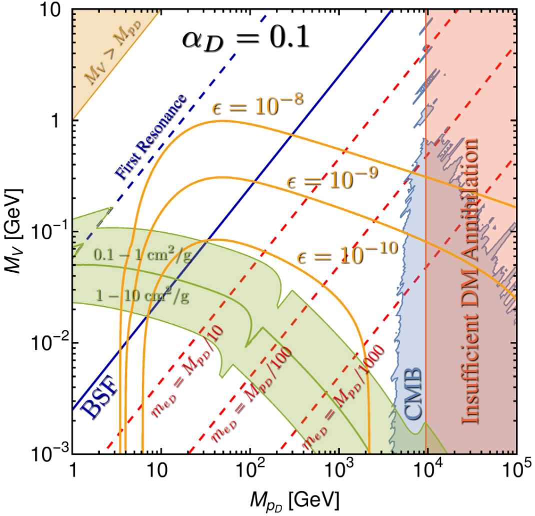
Here I include only LUX and CMB constraints.
Due to the SE the CMB constraint is still relevant for large M_{p_D}.

Fixed $\alpha_D = 0.01$



Here I include only LUX and CMB constraints.
Due to the SE the CMB constraint is still relevant for large M_{p_D}.

Fixed $\alpha_D = 0.1$



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