# Asymmetric Dark Matter in Indirect Detection

Iason Baldes

Dark Matter at the Dawn of Discovery?
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Talk based on arXiv:1712.07489.
In collaboration with Marco Cirelli, Paolo Panci, Kalliopi Petraki, Filippo Sala, Marco Taoso.

# Asymmetric Dark Matter

## Baryonic Matter Density

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

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

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

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

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

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

# Asymmetric Dark Matter

**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.

**Possibilities**

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

# Annihilation to a light mediators

**A simple possibility: annihilation to a light mediators.**

- Interested in a generic DM sector.
- Here fermions $p_D \bar{p_D} \to VV$.
- Remnant asymmetry $\to$ possibility of indirect detection signals.
- Negligible remnant asymmetry $\to$ eventually constrain using direct detection.
- We also want to check the possibility of sizable self interactions. The symmetric case is severely constrained. - Bringmann et. al. '16, Cirelli et. al. '16, Kahlhoefer et. al. '17.

Similar to the symmetric case but with an the addition of $n_D \equiv n_d - \bar{n_d}$.

# Asymmetric Dark Matter

## Crucial ADM relation

$$\frac{\Omega_{\rm B}}{\Omega_{\rm DM}} = \frac{m_p}{M_{p_D}} \frac{Y_B}{Y_D} \left( \frac{1 - r_\infty}{1 + r_\infty} \right) \approx 5$$

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

- If $r_\infty = 0 \to$ no indirect detection signatures.
- But the DM needs to annihilate. The required cross section is higher for ADM (to get rid of the antiparticles).
- Annihilate into a light dark sector particle.
- This becomes a mediator for Sommerfeld enhancement $\to$ increases indirect detection signal again.

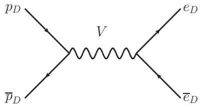
The point here is to QUANTITATIVELY study these competing effects .

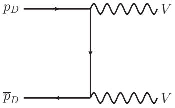
# The model

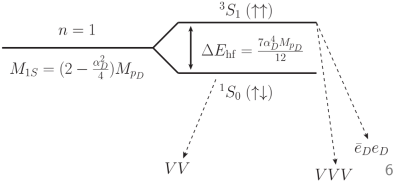
## Dark QED

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

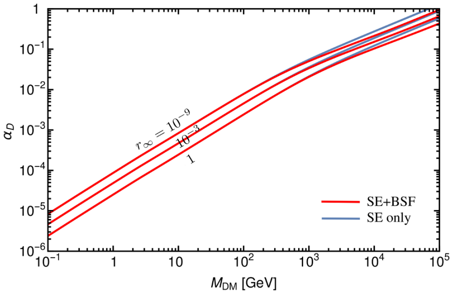
- Dark electrons are required for CHARGE CONSERVATION when there is a $p_D - \bar{p}_D$ asymmetry.
- Here $M_V$ is typically small compared to $M_{p_D}$ and $m_{e_D}$.
- The kinetic mixing allows the mediator to decay to SM particles (avoid DM overproduction) $\rightarrow$ experimental signatures.



# The relic abundance




- Smaller $r_\infty$ requires larger $\alpha_D$.
- SE+BSF important for large $M_{p_D}$ (large $\alpha_D$).
- Reannihilation is not taken into account here.
  - Binder et. al. [1712.01246]

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

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

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

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

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

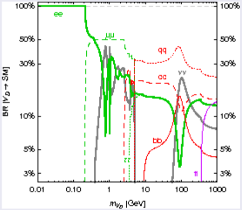
$$\Gamma(\uparrow\uparrow \to VVV) = \frac{2(\pi^2-9)\alpha_D^6 M_{p_D}}{9\pi}$$

# Indirect detection Constraints

## Effective cross section

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

## Constraints




- CMB: Planck constraint, taking $f_{\rm eff}$ from T. Slatyer.
- AMS: $\bar{p}$.
- FERMI Dwarfs: SE regime compensates the $\gamma$ poor $V \to$ leptons regime. (Galactic Halo: less severe constraints).
- ANTARES

# Further Constraints

## Direct Detection

CRESST-II, CDMS-lite, LUX

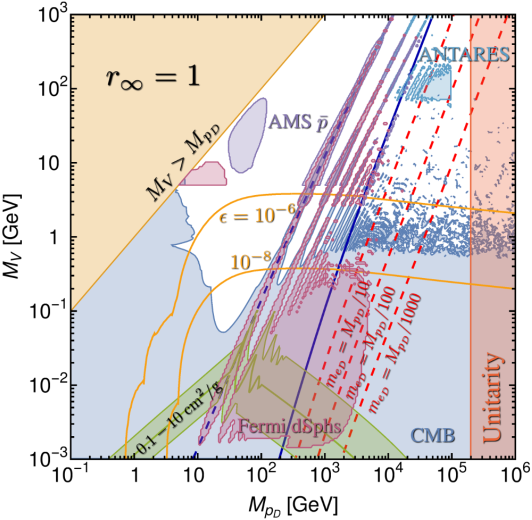
- Taking into account $q^2$ dependent propagator.
- Somewhat simplified analysis compared to the experimental papers.
- Shown as yellow $\epsilon$ (kinetic mixing) dependent contours.

## Unitarity

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

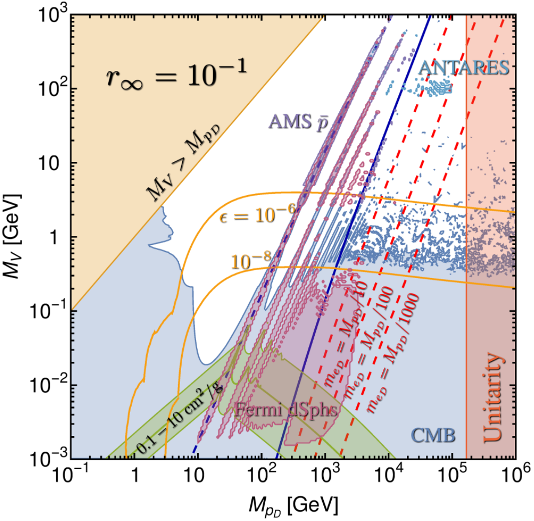
- LHS scales as $1/v_{\mathrm{rel}}$ with light mediator.
- Calculation becomes untrustworthy close to unitarity limit.
- Translates into a maximum possible DM mass.
- Depends on $r_\infty$. - IB, Petraki [1703.00478]

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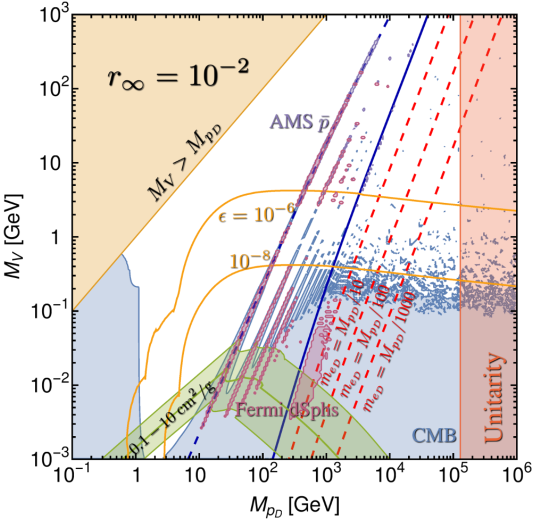
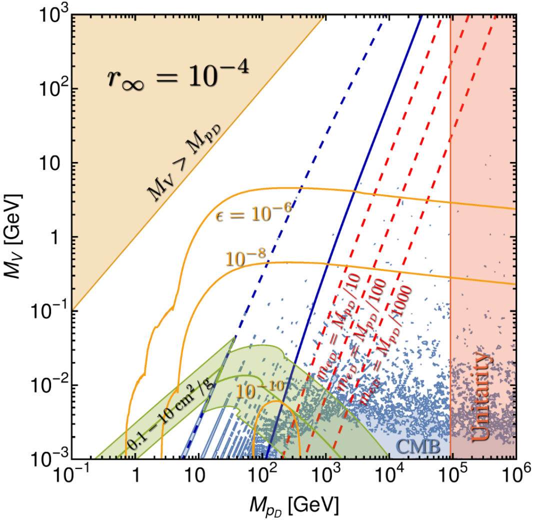
# Aymmetric DM - $r_\infty = 10^{-2}$



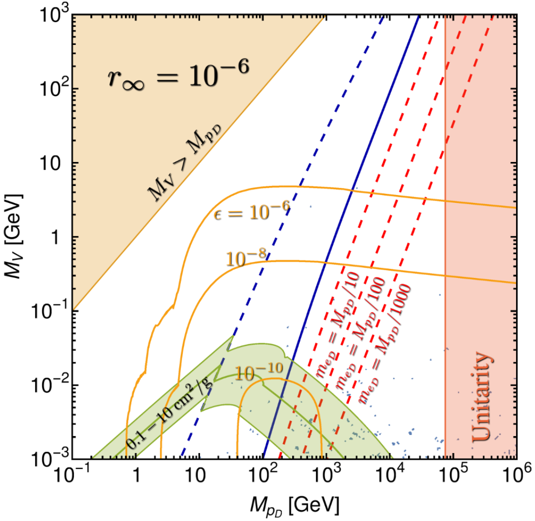

Stable atomic states form below red dashed lines - not treated here.

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



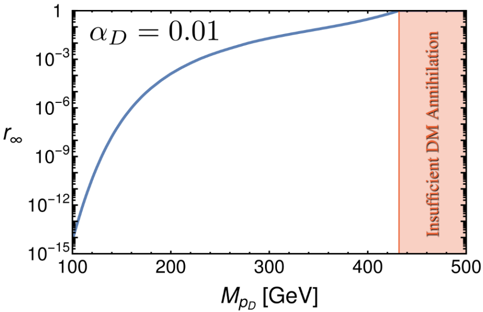

Stable atomic states form below red dashed lines - not treated here.

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




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

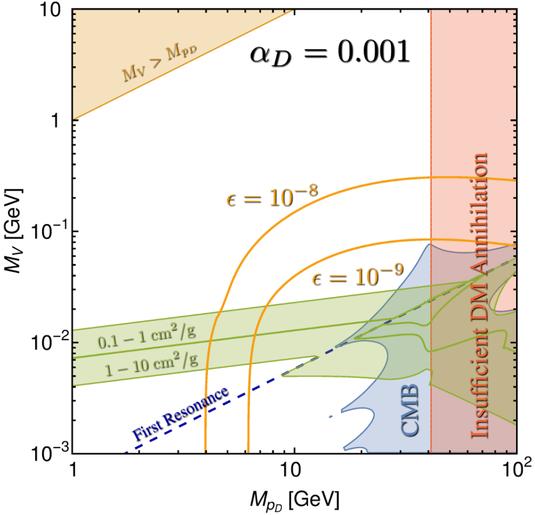
# Fixed $\alpha_D$




## Instead fix $\alpha_D$.

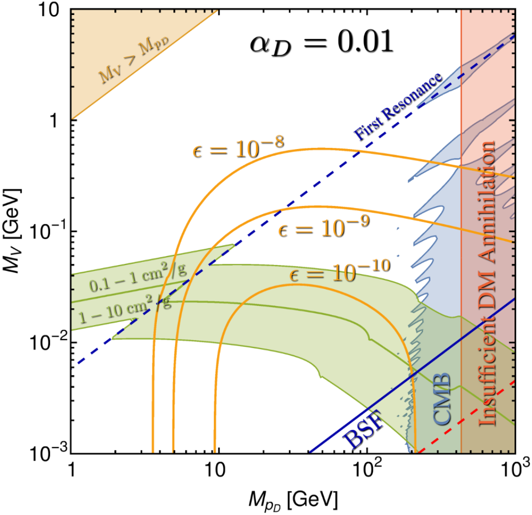
- DM antiparticle population now depends on $M_{p_D}$.
- Maximum possible $M_{p_D}$ corresponds to symmetric DM.
- Above this $M_{p_D}$: too much DM.
- Below this $M_{p_D}$: Asymmetry $Y_D$ to compensate underabundance and $r_\infty$ rapidly becomes suppressed.

# Fixed $\alpha_D = 0.001$



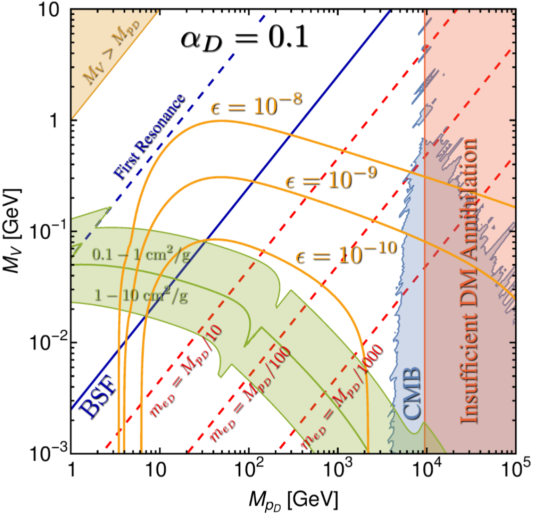

Here I include only LUX and CMB constraints.

# Fixed $\alpha_D = 0.01$




Here I include only LUX and CMB constraints.

# Fixed $\alpha_D = 0.1$




Here I include only LUX and CMB constraints.

# Future Prospects & Conclusions

## Future Prospects

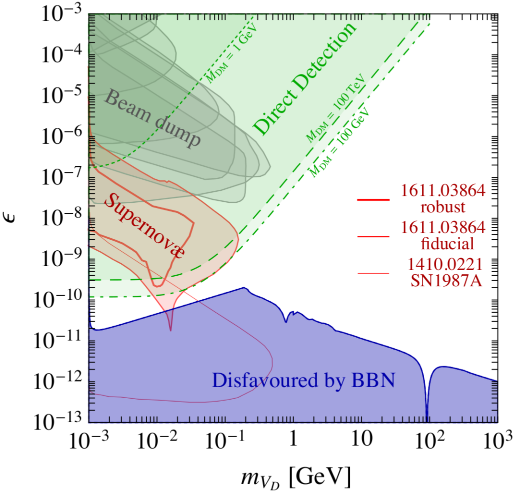
- 21 cm absorptions $\rightarrow$ possible strong constraint: $-\delta T_b \gtrsim 100$ mK is stronger than CMB - D'Amico, Panci, Strumia [1803.03629].
- High Energy Cosmic Ray Experiments: please provide flux as a function of $E$.
- Direct detection: will continue to probe highly asymmetric regime.
- Multi-component numerical simulations could be of interest.
- More careful treatment of reannihilation required.

## Conclusions

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

Thanks.

# Further bounds on the mediator




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

# Self Interactions

## Momentum transfer cross section

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

In case you think there are small scale structure problems which need to be addressed with SIDM.

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

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