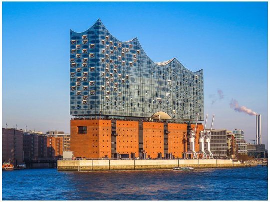
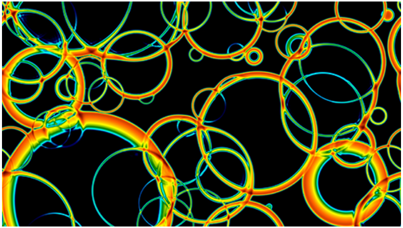
Asymmetric Dark Matter: Generation and Annihilation

Iason Baldes



Hamburg $\leftrightarrow$ Sydney,
August 1 2017

Overview



From a simulation by Weir et. al.

1. Asymmetric Dark Matter Generation - IB [1702.02117]
    - Example of a dark baryogenesis mechanism
      - using a strong first order phase transition
    - Signal of the phase transition: Gravitational waves
    - Dark sector phenomenology
2. Asymmetric Dark Matter Annihilation - IB, Petraki [1703.00478]
    - Annihilation of fermionic DM to vector or scalar mediators
    - Explore remnant DM antiparticle population
    - Indirect detection prospects
    - Unitarity constraints

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 $n_b = n_B \equiv n_b - n_{\overline{b}}$.

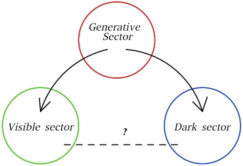
Observationally $Y_B \equiv n_B/s = (0.86 \pm 0.02) \times 10^{-10}$.

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...

ADM from a generative sector



Currently from particle physics we know the SM in detail.

$$SU(3) \times SU(2) \times U(1)$$

Non-minimal structure with chiral fermions and global $B + L$ anomaly.

Could similar BSM physics exist? Let us assume this is the case for now...
A first order phase transition in a generative sector could produce the baryon and a DM asymmetry. - Shelton, Zurek 1008.1997; Dutta, Kumar 1012.1341; Petraki, Trodden, Volkas 1111.4786; Walker 1202.2348; Davoudiasl, Giardino, Zhang 1612.05639
Such a phase transition will also result in gravitational waves.

Electroweak baryogenesis - basic picture

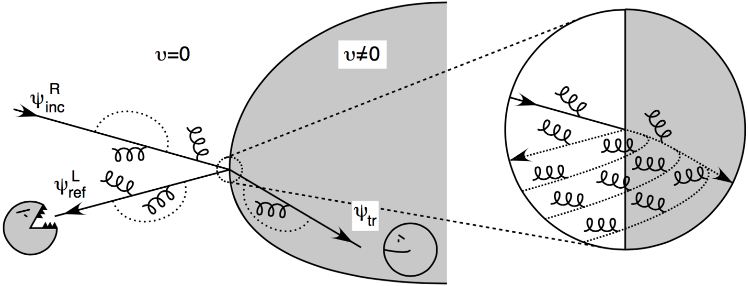


Image from - Gavela, Hernandez, Orloff, Pène, Quimbay [hep-ph/9406289]

- CP violating collisions with the bubble walls lead to a chiral asymmetry.
- Sphalerons convert this to a Baryon Asymmetry.
- This is swept into the expanding bubble where sphalerons are suppressed.

The EWBG picture can be mimicked in a BSM sector

$$\mathcal{L} \supset -\frac{1}{\sqrt{2}} \left(\sum_{j=1}^{2} h_j \overline{\Psi_L} \phi \Psi_{jR} + \tilde{h}_j \overline{\Psi_L} \tilde{\phi} \Psi_{jR} \right) + H.c.$$

Here $\phi \sim 2$, $\Psi_L \sim 2$, $\Psi_R \sim 1$ under $\mathrm{SU}(2)_G$. The asymmetry is transfered via

$$\mathcal{L} \supset -\frac{\kappa}{\sqrt{2}} \overline{\Psi_L} \chi f_R + H.c.$$

Asymmetry communicated to the visible sector via

$$\mathcal{L} \supset -\frac{y_1}{\sqrt{2}} \overline{l_L} H f_R + H.c.$$

Asymmetry communicated to the dark sector via

$$\mathcal{L} \supset -\frac{y_2}{\sqrt{2}} \overline{\xi} \chi \zeta + H.c.$$

DM consist of $m_\zeta + m_\xi \approx 1.5$ GeV. Symmetric component annihilated away with $U(1)_D$.

Experimental tests of such a scenario

Generative sector

Strong first order phase transition

- Search for stochastic background of gravitational waves
- Generative higgs could have some mixing with the SM higgs

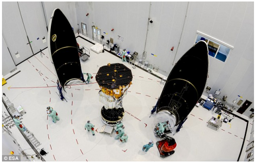
Visible sector

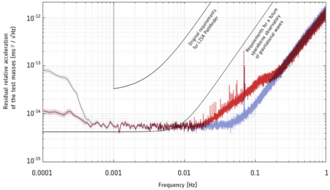
- Already discovered

Dark sector

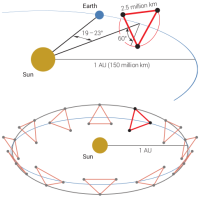
- Halo ellipticity
- $\Delta(N_{\mathrm{eff}})$
- Direct dection

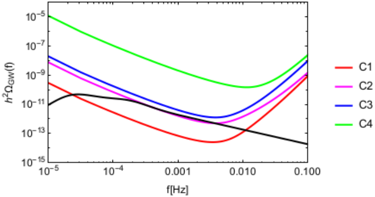
LISA pathfinder has provided promising results.





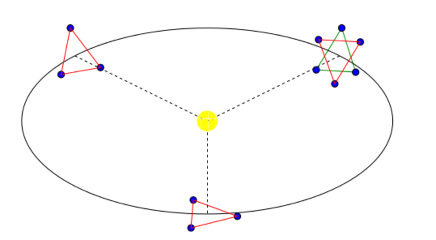
LISA will most likely fly in 2034. The LISA Mission L3 Proposal submitted to ESA Jan 13, 2017: Six arm configuration, 2Gm arm length, nominal four year mission duration.

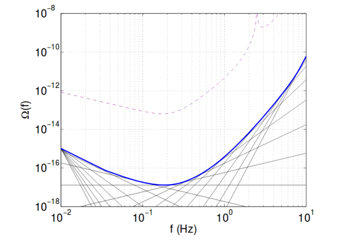




BBO

There has been some speculation as to possible follow up missions to LISA.





The sensitivity curve has been calculated using a six sattelite configuration. - Thrane, Romano 1310.5300

Currently this is a largely virtual experiment. However, it seems sensible to consider the possibility of post-LISA GW observatories with better sensitivity in the frequency range spanning the LISA and LIGO bands.

Characterising the phase transition

Assume a generative potential of the form: - Grojean, Servant, Wells '04; ...

$$V_G = \frac{\mu_\phi^2}{2}\phi^2 + \frac{\lambda_\phi}{4}\phi^4 + \frac{1}{8\Lambda_\phi^2}\phi^6$$

The strong phase transition is achieved here by either

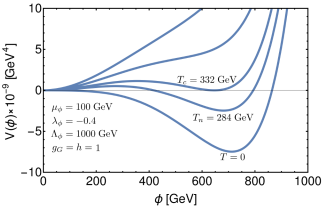
1. the tree level barrier μ_ϕ^2
2. cancellation between the thermal mass term $c_\phi \phi^2 T^2$ and $\lambda_\phi \phi^4$

$$\frac{\Gamma_{\rm sph}}{\mathcal{V}} \sim 10^{1\div 4}\left(\frac{\alpha_G T}{4\pi}\right)^4 \left(\frac{2M_G(\phi)}{\alpha_G T}\right)^7 {\rm Exp}\left[-\frac{4\pi B}{g_G}\frac{\phi}{T}\right]$$

Washout condition

$$\frac{\phi_n}{T_n} \gtrsim g_G\,(1.5 - 1.8)\left(\frac{2.0}{B}\right)$$

$$B \approx 1.58 + 0.91\sqrt{\lambda_\phi}/g_G - 0.4\lambda_\phi/g_G$$



Critical bubble

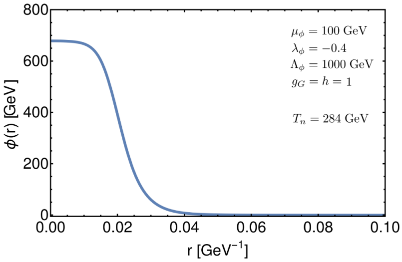
Bubbles will nucleate when $S_3/T \approx 140$ - Linde '80; Anderson, Hall '91; ...

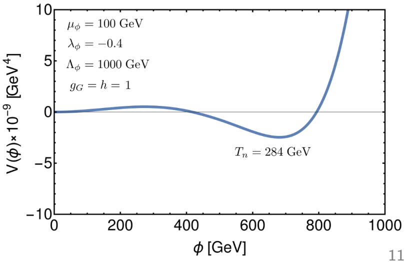
$$S_3 = 4\pi \int r^2 \left(\frac{1}{2} \left(\frac{d\phi}{dr} \right)^2 + V_{\rm eff} \right) dr$$

The resulting equation of motion is given by

$$\frac{d^2\phi}{dr^2} + \frac{2}{r}\frac{d\phi}{dr} = \frac{\partial V_{\rm eff}}{\partial \phi}$$

with the boundary conditions $\phi'(r=0) = 0, \qquad \phi(r \to \infty) = 0.$





Calculating the GW spectrum

Key parameters

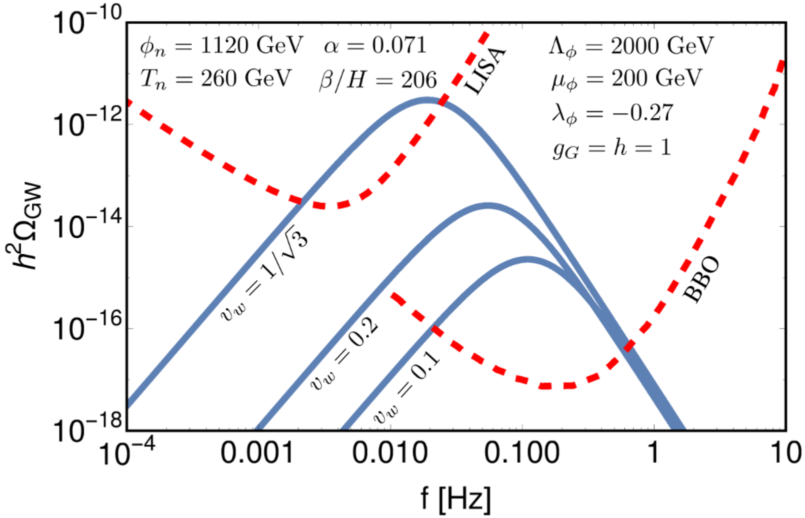
$$h^2\Omega_{\rm GW}(f) \equiv h^2 \frac{1}{\rho_c}\frac{d\rho_{\rm GW}}{d\,{\rm Ln}f}$$

$$\frac{\beta}{H} \equiv T_n \frac{d}{dT}\left(\frac{S_3}{T}\right)\Big|_{T_n} \qquad\qquad \alpha \equiv \frac{\rho_{\rm vac}}{\rho_{\rm rad}} = \frac{\rho_{\rm vac}}{g_*\pi^2 T_n^4/30}$$

- The GW spectrum from sound waves in the plasma is expected to be the dominant contribution in this scenario.
- Standard parametrisations taken from simulations are used.
- We will use an optimistic value by setting $v_w = v_{\rm sound} = 1/\sqrt{3}$ in our scan.
- We check the Bodeker-Moore criterion for a non-runaway wall, $\overline{V} > 0$, is fufilled.

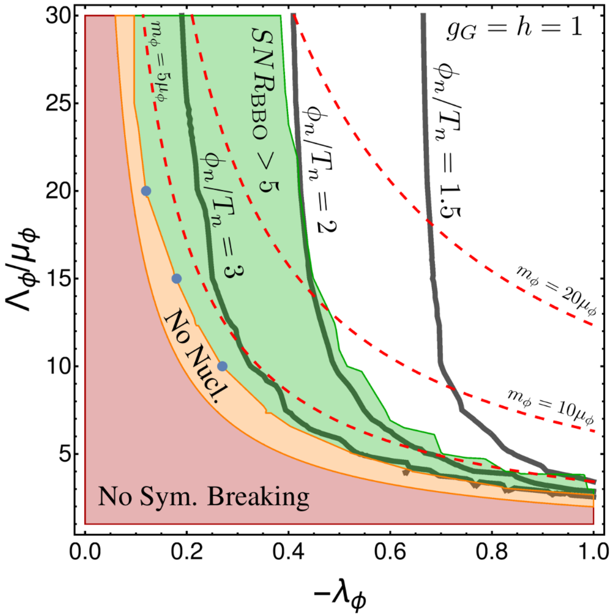
$$\overline{V} = V_{\rm tree}(\phi) + \frac{T^2}{24}\left(\sum_{\rm bosons} m_b^2(\phi) + \frac{1}{2}\sum_{\rm fermions} m_f^2(\phi)\right)$$

GW spectrum



$\phi_n = 1120$ GeV
$\alpha = 0.071$
$T_n = 260$ GeV
$\beta/H = 206$
LISA
$\Lambda_\phi = 2000$ GeV
$\mu_\phi = 200$ GeV
$\lambda_\phi = -0.27$
$g_G = h = 1$
$v_w = 1/\sqrt{3}$
$v_w = 0.2$
$v_w = 0.1$
BBO
10^{-10}
10^{-12}
10^{-14}
10^{-16}
10^{-18}
$h^2\Omega_{GW}$
10^{-4}
0.001
0.010
0.100
1
10
f [Hz]

Parameter scan



Halo ellipticity

- Consider relatively large dark fine structure constants, $\alpha_D \equiv g_D^2/4\pi \gtrsim 0.1$.
- DM constituent masses Min$[m_\zeta, m_\xi] \gtrsim 0.1$ GeV.
- The DM is sufficiently tightly bound to approach the collisionless limit.

The binding energy is given by

$$\Delta \approx \frac{\alpha_D^2}{2}\mu \equiv \frac{\alpha_D^2}{2}\frac{m_\zeta m_\xi}{m_\zeta + m_\xi}$$

The is tension with halo ellipticity observations even with relatively large binding energies, $\Delta > 10$ MeV. - Cyr-Racine, Sigurdson 1209.5752; Petraki, Pearce, Kusenko 1403.1077

The tension can be removed if $U(1)_D$ is broken.

$\Delta N_{\rm eff}$

PlanckTT+lowP+BAO

$$N_{\rm eff} = 3.15 \pm 0.23$$

If $U(1)_D$ is unbroken, the dark photons will contribute to $\Delta N_{\rm eff}$ at the CMB epoch.

Limit on dark sector dof and decoupling

$$g_{\rm ds}(T_{\rm dec}) \lesssim 12.6 \left(\frac{\Delta N_{\rm eff}}{0.6}\right)^{3/4} \left(\frac{g_{\rm vs}(T_{\rm dec})}{110.25}\right)$$

The dark sector has $g_{\rm ds} = 16.5$ (12.5) including (excluding) the contribution of χ.

Direct detection

For $m_{DM} = 1.5$ GeV:
CRESST-II requires $\sigma^{\mathrm{SI}} \lesssim 2.7 \times 10^{-39}\ \mathrm{cm}^2$ (ν floor is $10^{-43}\ \mathrm{cm}^2$).

Z'_{B-L} exchange:

$$\sigma^{\mathrm{SI}}_{B-L} \sim 10^{-45}\ \mathrm{cm}^2 \left(\frac{g_{B-L}}{0.1}\right)^4 \left(\frac{2\ \mathrm{TeV}}{M_{Z'}}\right)^4 \left(\frac{\mu_N}{0.6\ \mathrm{GeV}}\right)^2$$

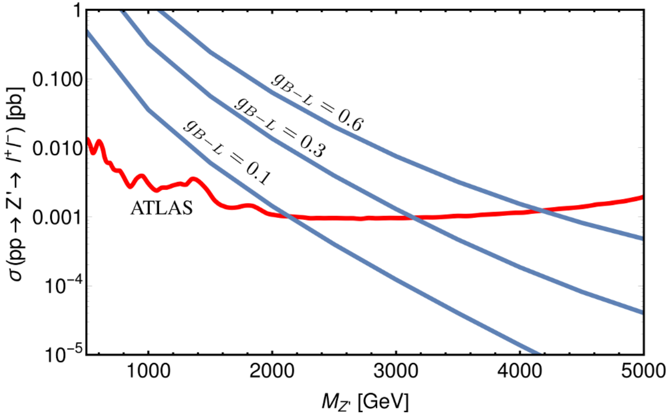
$U(1)_{\mathrm{EM}} - U(1)_{\mathrm{D}}$ kinetic mixing:

$$\sigma^{\mathrm{SI}}_{\gamma} \sim 10^{-39}\ \mathrm{cm}^2 \left(\frac{\epsilon}{10^{-6}}\right)^2 \left(\frac{0.3}{\alpha_D}\right)^3 \left(\frac{0.5\ \mathrm{GeV}}{m_\zeta}\right)^4 \left(\frac{\mu_N}{0.6\ \mathrm{GeV}}\right)^2$$

$U(1)_D$ symmetry broken:

$$\sigma^{\mathrm{SI}}_{D} \sim 10^{-40}\ \mathrm{cm}^2 \left(\frac{\epsilon}{10^{-5}}\right)^2 \left(\frac{\alpha_D}{10^{-2}}\right) \left(\frac{300\ \mathrm{MeV}}{M_D}\right)^4 \left(\frac{\mu_N}{0.6\ \mathrm{GeV}}\right)^2$$

Z'_{B-L} search

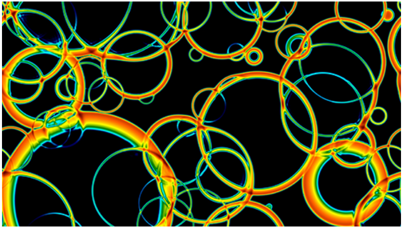


Using 13.3 fb^{-1} of data at $\sqrt{s} = 13$ TeV [ATLAS-CONF-2016-045]

Conclusions - Part 1

- The visible and DM densities may be a consequence of EW-style genesis in an exotic phase transition.
- Future gravitational wave observatories provide a unique probe of phase transitions.
- The scenario is also constrained by the LHC, Halo ellipticity, CMB, direct detection.
- More work is required to determine the bubble wall velocity in such a scenario.

Intermission



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Part 2

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 $M_{\rm DM} \lesssim 10$ GeV. - March-Russell, Unwin, West 1203.4854
2. Annihilation to stable light Dark Sector particles (limits from $N_{\rm eff}$, self interactions)
3. Annihilation to light Dark Sector particles which then decay (limits from indirect detection, self interactions)

(See also talk by March-Russell, Planck '17).

Annihilation to a light mediators

A simple possibility: annihilation to a light mediators.

- Interested in a generic DM sector.
- Here fermions $X\bar{X} \to \gamma_D \gamma_D$ or $X\bar{X} \to \phi\phi$.
- Remnant asymmetry $\to$ possibility of indirect detection signals.
- Negligible remnant asymmetry $\to$ eventually constrain using direct detection (future work).
- We also want to check the possibility of sizable self interactions (future work).
  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 Freezeout

Assume we have a DM asymmetry

Asymmetry $\eta_D \equiv Y^+ - Y^-$ frozen during freeze-out.
Also define $\epsilon \equiv \eta_D/\eta_B$

Fractional asymmetry

This ratio changes during freezout.

$$r \equiv \frac{Y^-}{Y^+}$$

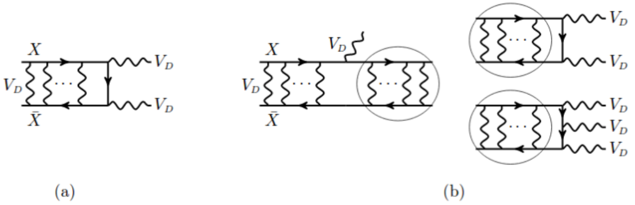
DM mass relation

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

- Graesser, Shoemaker, Vecchi 1103.2771; Iminniyaz, Drees, Chen 1104.5548

New here: Sommerfeld enhancement, bound state formation and unitarity

Vector mediator



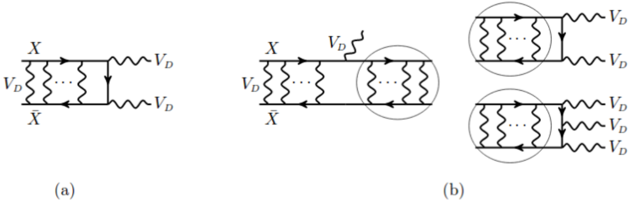
$$\mathcal{L} = \bar{X}(i\not{D} - M_{\rm DM})X - \frac{1}{4}F_{D\mu\nu}F_D^{\mu\nu}$$

- X denotes the DM particle
- Covariant derivative $D^\mu = \partial^\mu + ig_d V_D^\mu$
- $F_D^{\mu\nu} = \partial^\mu V_D^\nu - \partial^\nu V_D^\mu$, with V_D^μ being the dark photon field
- $\alpha_D \equiv g_d^2/(4\pi)$ being the dark fine-structure constant.

If X carries a particle-antiparticle asymmetry, another field is required to balance the implied $U(1)_D$ charge asymmetry in X.

Vector mediator - Sommerfeld enhancement and bound state formation

Symmetric case: - von Harling, Petraki 1407.7874

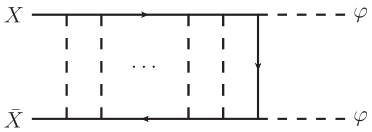


Here $\sigma v_{\rm rel} = \sigma_0 (S^{(0)}_{\rm ann} + S_{\rm BSF})$. In the Coulomb limit, $S^{(0)}_{\rm ann}$ and $S_{\rm BSF}$ depend only on the ratio $\zeta \equiv \alpha_D / v_{\rm rel}$

$$S^{(0)}_{\rm ann}(\zeta) = \frac{2\pi\zeta}{1 - e^{-2\pi\zeta}} \qquad \sigma_0 \equiv \pi \alpha_D^2 / M_{\rm DM}^2$$

$$S_{\rm BSF}(\zeta) = \frac{2\pi\zeta}{1 - e^{-2\pi\zeta}} \, \frac{\zeta^4}{(1+\zeta^2)^2} \, \frac{2^9}{3} \, e^{-4\zeta \, {\rm arccot}(\zeta)}$$

Scalar mediator

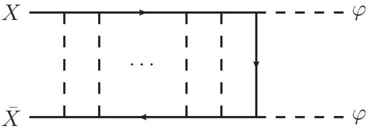


$$\mathcal{L} = \bar{X}(i\partial\!\!\!/ - M_{\rm DM})X + \frac{1}{2}\partial_\mu\varphi\,\partial^\mu\varphi - \frac{1}{2}m_\varphi^2\varphi^2 - g_d\;\varphi\bar{X}X$$

- φ is the dark scalar force mediator with mass m_φ
- $\alpha_D \equiv g_d^2/(4\pi)$.

This is a p-wave process. However, as long as $m_\varphi \lesssim \alpha_D M_{\rm DM}/2$, the $X - \bar{X}$ interaction manifests as long range. The velocity suppression is lifted due to the Sommerfeld enhancement!

Scalar mediator - Sommerfeld enhancement



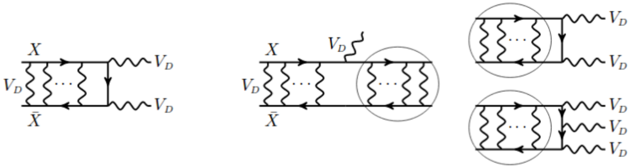
This is a *p*-wave annihilation process

$$\sigma_{\rm ann} v_{\rm rel} = \sigma_1 \, v_{\rm rel}^2 \, S_{\rm ann}^{(1)}$$

$$\sigma_1 = \frac{3\pi\alpha_D^2}{8M_{\rm DM}^2} \qquad\qquad S_{\rm ann}^{(1)}(\zeta) = \frac{2\pi\zeta}{1-e^{-2\pi\zeta}}\,(1+\zeta^2)$$

- As before, $\zeta \equiv \alpha_D / v_{\rm rel}$.
- At $v_{\rm rel} \lesssim \alpha_D$, $\sigma_{\rm ann} v_{\rm rel} \propto 1/v_{\rm rel}$.
- The $v_{\rm rel}^2$ suppression of the perturbative cross-section morphs into an α_D^2 suppression, with $\sigma_{\rm ann} v_{\rm rel} \propto \alpha_D^5$.

Boltzmann Equations - Vector Mediator

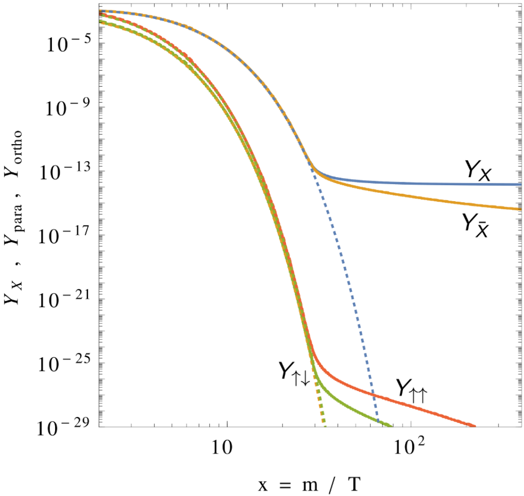


(a) (b)

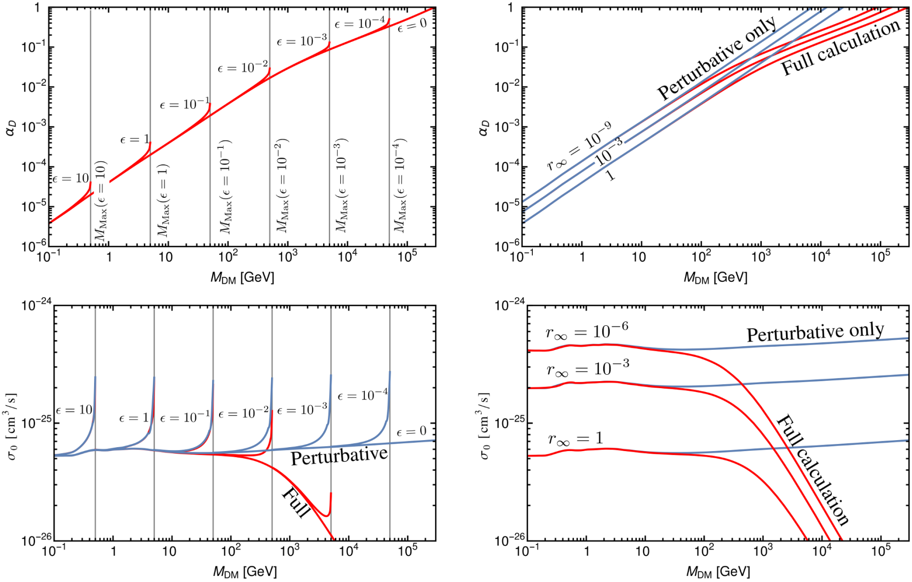
- Three coupled equations, taking into account Y^+ ($Y^- = Y^+ - \eta_D$), and the two bound states $Y_{\uparrow\downarrow}$ and $Y_{\uparrow\uparrow}$.
- At some stage T drops enough so bound state decay becomes quicker than ionization.
- Annihilation through the bound state then becomes significant.
- We take into account the T difference between the visible and dark sectors.

Similarly for the scalar mediator but without the bound states.

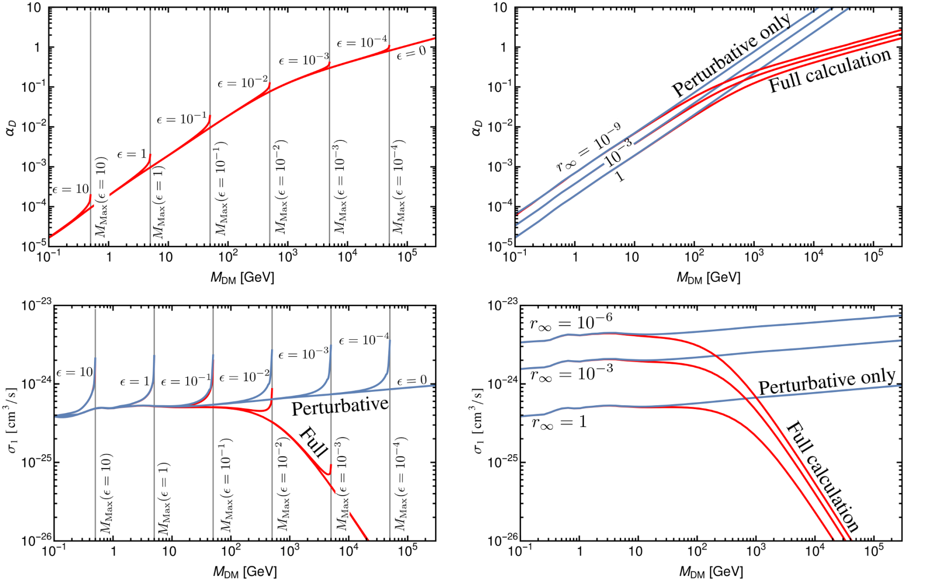
Relic abundance - Example



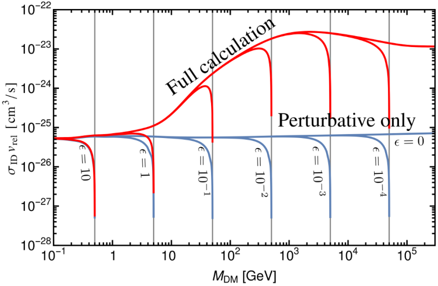
Required couplings/cross-section - vector mediator

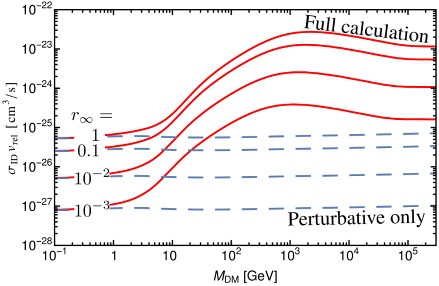


Required couplings - scalar mediator



Indirect detection - vector mediator



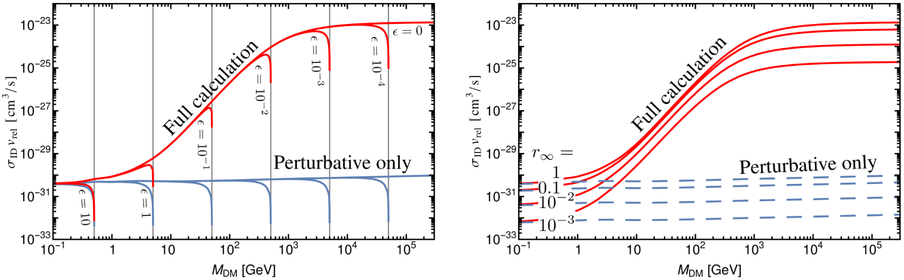


The effective cross-section for indirect detection signals,

$$\sigma_{\rm ID}\, v_{\rm rel} = \left[\frac{4 r_\infty}{(1 + r_\infty)^2}\right] \sigma_{\rm inel}\, v_{\rm rel}.$$

We have used $v_{\rm rel} = 10^{-3}$, which is relevant for indirect searches in the Milky Way.

Indirect detection - scalar mediator



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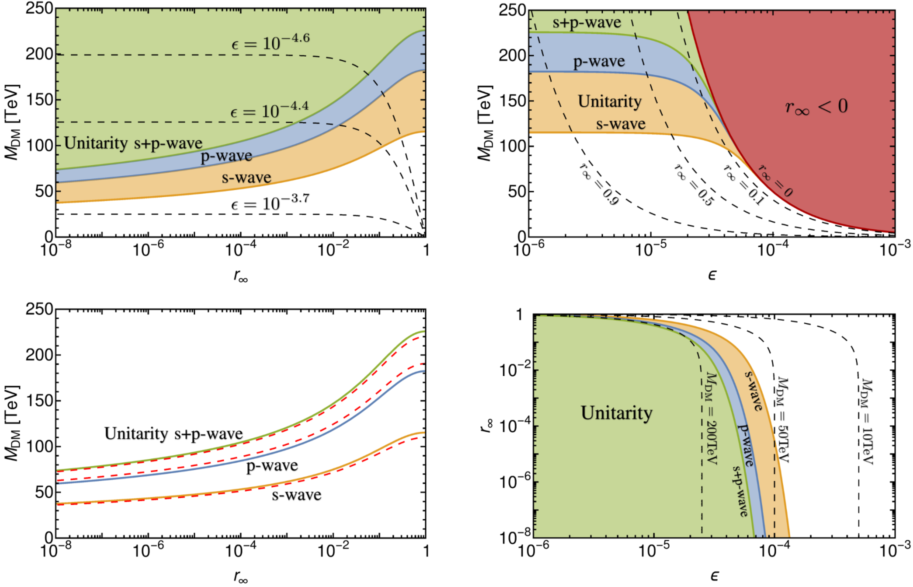
Unitarity constraint

In the non-relativistic regime

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

- Note that with SE $\sigma v_{\rm rel} \propto 1/v_{\rm rel}$, meaning there is no need to insert an arbitrary $v_{\rm rel}$ on the RHS of the inequality, as would be the case if naively using $\sigma v_{\rm rel} \sim \alpha_D^2/M_{\rm DM}^2$ or $\sigma v_{\rm rel} \sim \alpha_D^2 M_{\rm DM}^2/m_{\rm med}^4$.
- We obtain some $\alpha_{\rm uni}$ above which the unitarity constraint is violated. However, $\sigma v_{\rm rel}$ is based on a perturbative calculation - the relevant approximations will break down before this.
- The $\sigma_{\rm uni}^{(J)}\, v_{\rm rel} \propto 1/v_{\rm rel}$ behaviour indicates that to approach the unitarity limit, the cross section will necessarily display some long range $1/v_{\rm rel}$ behaviour, at least in the types of scenarios explored here.

Unitarity constraint - Results



Approaching Unitarity constraint implies a long range interaction

In the non-relativistic regime

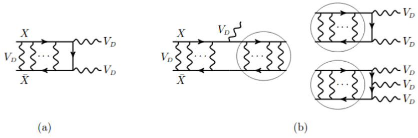
$$\sigma^{(J)}_{\mathrm{inel}}\, v_{\mathrm{rel}} \leqslant \sigma^{(J)}_{\mathrm{uni}}\, v_{\mathrm{rel}} = \frac{4\pi(2J+1)}{M^2_{\mathrm{DM}}\, v_{\mathrm{rel}}}$$

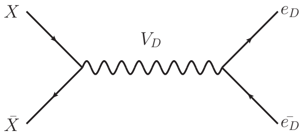
- Interaction mediated by a heavy force carrier of mass $m_{\mathrm{med}} \gtrsim M_{\mathrm{DM}}$.
- $\sigma v_{\mathrm{rel}} \sim \alpha_D^2 M^2_{\mathrm{DM}}/m^4_{\mathrm{med}}$.
- Realising unitarity limit $\alpha_D^{\mathrm{uni}} \sim (m_{\mathrm{med}}/M_{\mathrm{DM}})^2/\sqrt{v_{\mathrm{rel}}} \gtrsim m_{\mathrm{med}}/M_{\mathrm{DM}} \gtrsim 1$.
- This implies $m_{\mathrm{med}} \lesssim \alpha_D^{\mathrm{uni}} M_{\mathrm{DM}}$.
- That is range of the interaction between two DM particles, m^{-1}_{med}, is comparable or larger than their Bohr radius, $(\alpha_D^{\mathrm{uni}} M_{\mathrm{DM}}/2)^{-1}$.
- Interaction manifests as long-range, thereby contradicting the original premise of a contact-type interaction.

Including dark electrons

If we have an excess X over $\bar{X}$ we will most likely* need to balance the charge with another field.

Let us introduce e_D and $\overline{e_D}$.





Additional FO processes:

$$\sigma_0 \to 2\sigma_0 = 2\frac{\pi\alpha_D^2}{M_{\mathrm{DM}}^2}$$

$$\Gamma_{\uparrow\uparrow} = 0.123\alpha_D^6 M_{\mathrm{DM}}/2 \to (0.123\alpha_D + 1/3)\alpha_D^5 M_{\mathrm{DM}}/2 \qquad (\Gamma_{\uparrow\downarrow} = \alpha_D^5 M_{\mathrm{DM}}/2)$$

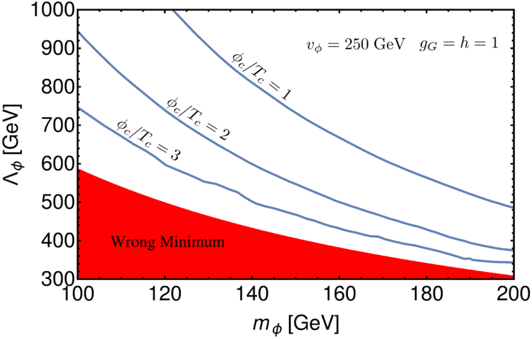
Also: possibility of bound states today.

Conclusions - part 2

- Asymmetric DM scenarios require a slightly larger annihilation cross section.
- We have calculated the required α_D in some simple example scenarios including Sommerfeld enhancement and bound state formation.
- We have explored the unitarity constraint.
- This is a first step needed in order to constrain these models experimentally. - IB, Cirelli, Panci, Petraki , Sala, Taoso, In preperation

Thanks.

Fixed VEV



Here the phase transition strength is shown for a fixed vev, in analogy with similar plots for the EWPT. As one intuitively expects, as Λ_ϕ is increased, the strength of the phase transition decreases.

Sector	Particles	SU(2)$_G$ (gauged)	U(1)$_{B-L}$ (gauged)	U(1)$_D$ (gauged)	U(1)$_X$ (anomalous)
Generative	Ψ_L	2	0	0	-2
	Ψ_{1R}, Ψ_{2R}	1	0	0	-2
	ϕ	2	0	0	0
Visible	$f_{L,R}$	1	-1	0	-1
	ν_R	1	-1	0	-1
Dark	χ	2	1	0	-1
	$\xi_{L,R}$	2	0	1	0
	$\zeta_{L,R}$	1	-1	1	1
$B-L$ Higgs	σ	0	q^{σ}_{B-L}	0	0

The field content and charges of the model. The three right-handed neutrinos are introduced to cancel the cubic $B-L$ anomaly. The $SU(2)_G$ and $U(1)_{B-L}$ symmetries are broken spontaneously at a high, $\mathcal{O}$(TeV), scale. The $U(1)_D$ symmetry can either remain exact or be broken spontaneously at a suitably low scale, to allow the $\mathcal{O}$(GeV) scale DM to annihilate into dark photons.