Gravitational waves from the asymmetric dark matter generating phase transition

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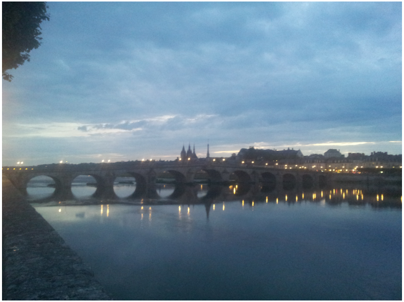

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Asymmetric Dark Matter

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

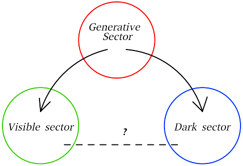
Observationally $Y_B \equiv n_B/s = (0.86 \pm 0.02) \times 10^{-10}$.

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

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

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...

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

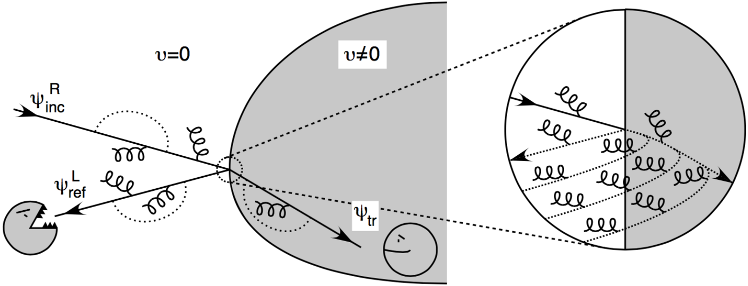


Image from - Gavela, Hernandez, Orloff, Pène, Quimbay [hep-ph/9406289]

- 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 model - Proposed by Petraki, Trodden, Volkas - 1111.4786

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

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

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

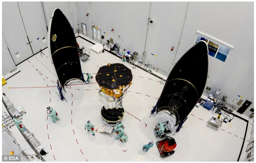
- Already discovered

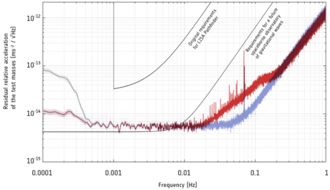
Dark sector

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

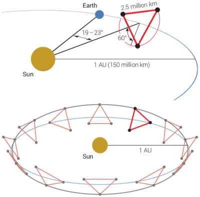
The LISA mission

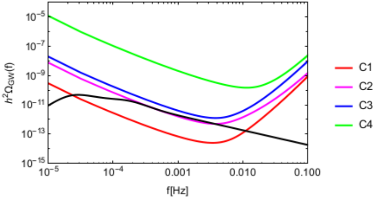
LISA pathfinder has provided promising results.





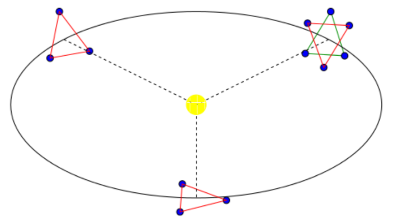
LISA will most likely fly around 2028.
LISA Mission L3 Proposal submitted to ESA Jan 13, 2017.

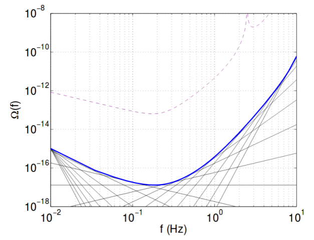




BBO

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

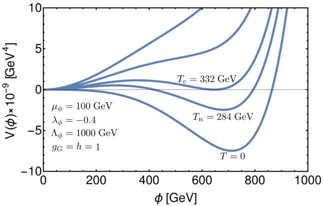
1. the tree level barrier μ_ϕ^2
2. cancellation between the thermal mass term $c_\phi \phi^2 T^2$ and $\lambda_\phi \phi^4$

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

Washout condition

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

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



Critical bubble

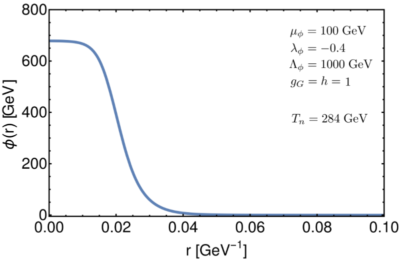
Bubbles will nucleate when $S_3/T \approx 140$ - Linde '80; Anderson, Hall '91; ...

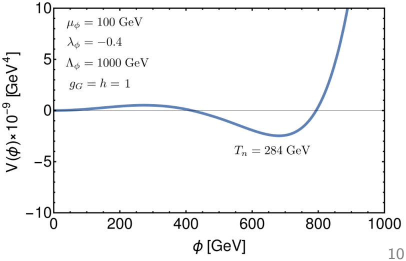
$$S_3 = 4\pi \int r^2 \left(\frac{1}{2} \left(\frac{d\phi}{dr} \right)^2 + V_{\rm eff} \right) dr$$

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

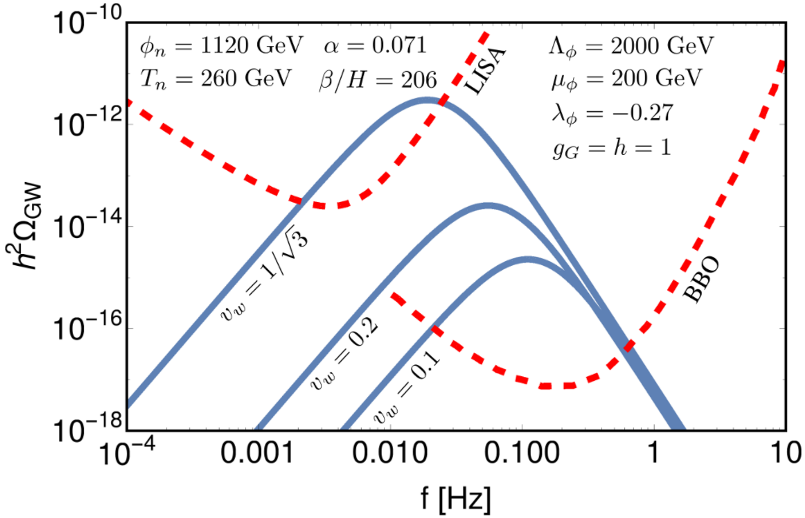
$$h^2\Omega_{\mathrm{GW}}(f) \equiv h^2 \frac{1}{\rho_c}\frac{d\rho_{\mathrm{GW}}}{d\,\mathrm{Ln} f}$$

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

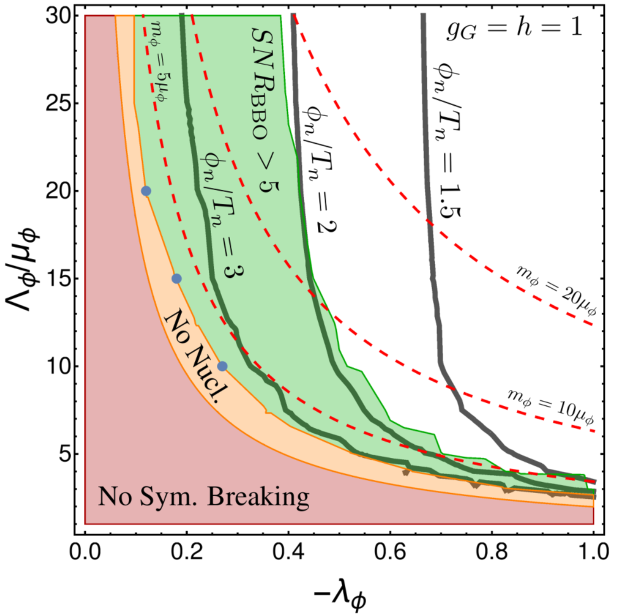
- The GW spectrum from sound waves in the plasma is expected to be the dominant contribution in this scenario.
- Standard parametrisations taken from simulations are used.
- We will use an optimistic value by setting $v_w = v_{\mathrm{sound}} = 1/\sqrt{3}$ in our scan.
- We check the Bodeker-Moore criterion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

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

GW spectrum


$\phi_n = 1120$ GeV
$T_n = 260$ GeV
$\alpha = 0.071$
$\beta/H = 206$
$\Lambda_\phi = 2000$ GeV
$\mu_\phi = 200$ GeV
$\lambda_\phi = -0.27$
$g_G = h = 1$
LISA
BBO
$v_w = 1/\sqrt{3}$
$v_w = 0.2$
$v_w = 0.1$
$h^2\Omega_{\rm GW}$
10^{-10}
10^{-12}
10^{-14}
10^{-16}
10^{-18}
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 $\mathrm{Min}[m_\zeta, m_\xi] \gtrsim 0.1$ 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 $\sigma^{\rm SI} \lesssim 2.7 \times 10^{-39}\ {\rm cm}^2$ (ν floor is $10^{-43}\ {\rm cm}^2$).

Z'_{B-L} exchange:

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

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

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

$U(1)_D$ symmetry broken:

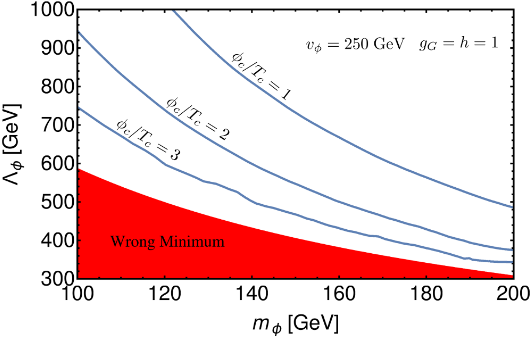
$$\sigma^{\rm SI}_{D} \sim 10^{-40}\ {\rm cm}^2 \left(\frac{\epsilon}{10^{-5}}\right)^2 \left(\frac{\alpha_D}{10^{-2}}\right) \left(\frac{300\ {\rm MeV}}{M_D}\right)^4 \left(\frac{\mu_N}{0.6\ {\rm GeV}}\right)^2$$

Conclusions

- 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.

Thanks.

Fixed VEV

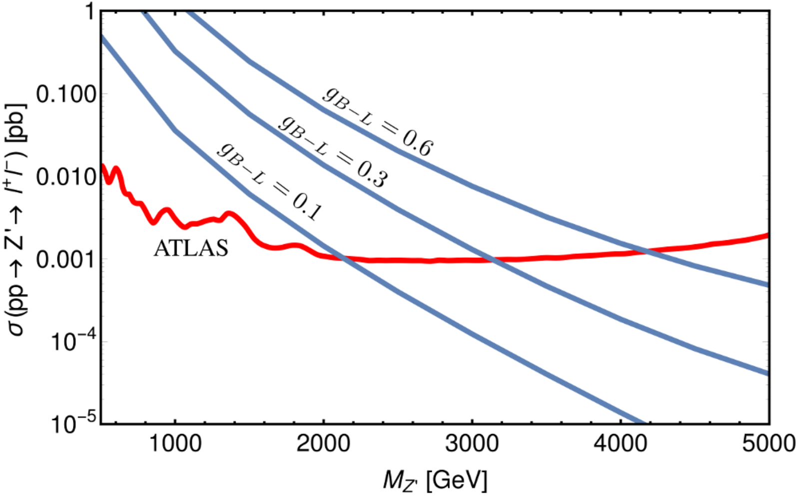


Here the phase transition strength is shown for a fixed vev, in analogy with similar plots for the EWPT. As one intuitively expects, as Λ_ϕ is increased, the strength of the phase transition decreases.

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.

Z'_{B-L} search


$\sigma\,(pp \to Z' \to l^+l^-)$ [pb]
1
0.100
0.010
0.001
10^{-4}
10^{-5}
1000
2000
3000
4000
5000
$M_{Z'}$ [GeV]
$g_{B-L} = 0.6$
$g_{B-L} = 0.3$
$g_{B-L} = 0.1$
ATLAS