Gravitational Waves from Dark Matter

Iason Baldes
In collaboration with Camilo Garcia-Cely
arXiv:1809.01198

EoS Solstice meeting, Brussels
20 December 2018

Two big discoveries in the past decade

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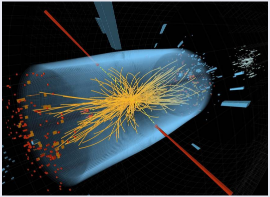

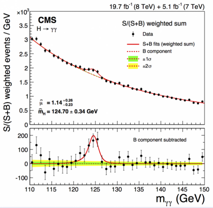

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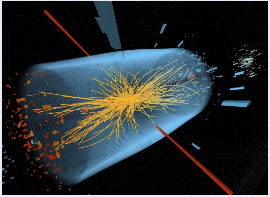
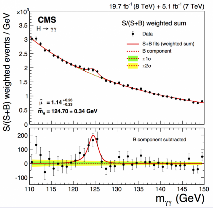
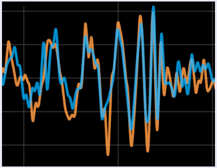




2016. Direct Detection of Gravitational Waves



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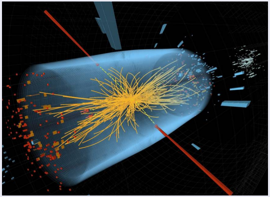

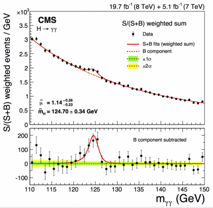

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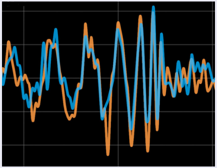

Let us merge the two ideas.

Gravitational Waves from an early Universe Phase Transition

Actually already done

by Witten '84, Hogan '86, ...

PHYSICAL REVIEW D VOLUME 30, NUMBER 2 15 JULY 1984

Cosmic separation of phases

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Institute for Advanced Study, Princeton, New Jersey 08540
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- Symmetry is typically restored at high T.
- Violent events (e.g. cosmological phase transitions) produce gravitational waves.

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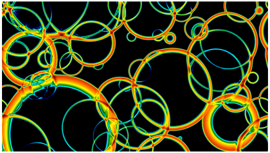

From a simulation by Weir et. al.

Since then

1. Detected Higgs and GWs.
2. Quantitative understanding of the predicted GW spectra has improved.
3. Concrete future proposals such as LISA have been developed.
4. LISA pathfinder has successfully flown.

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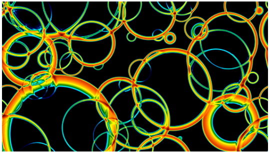

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The idea here is to explore a simple case study as to the feasibility of using GWs to detect SSB in a dark sector.

A simple DM model - Hambye 0811.0172

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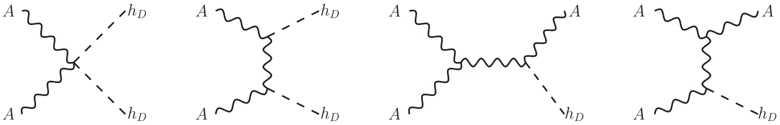

The Model: $SU(3)_C \times SU(2)_L \times U(1)_Y \times SU(2)_D$

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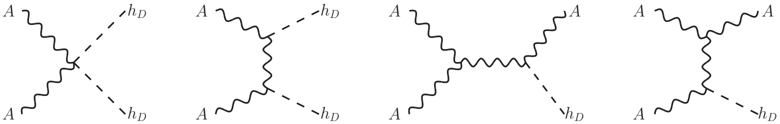

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Dark gauge bosons, A, are stable and form the DM!

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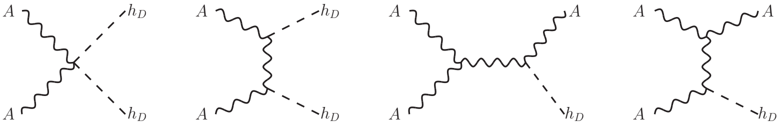

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Potential possibilities

1. Standard Potential with Mass terms - Hambye 0811.0172
2. Classically Scale Invariant
   - Hambye, Strumia 1306.2329, - Hambye, Strumia, Teresi 1805.01473

Standard Freezeout

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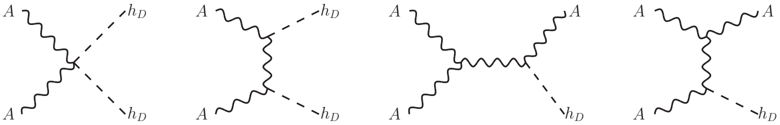

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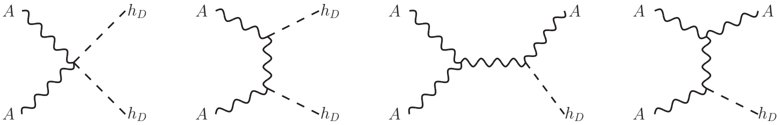

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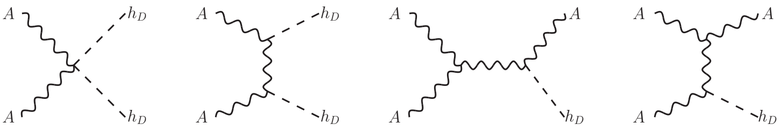

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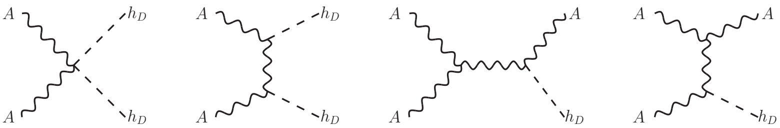

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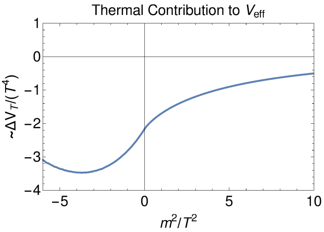
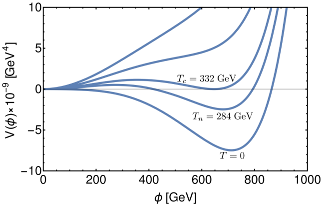
Close link between parameters determing Ω_{DM} and SSB

Finite temperature effective potential





$$V_{\mathrm{eff}} = V_{\mathrm{tree}}(\phi) + V_1^0(\phi) + V_1^T(\phi, T) + V_{\mathrm{Daisy}}(\phi, T)$$

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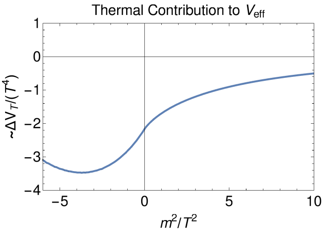

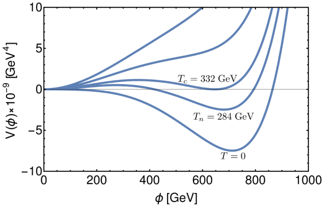

$$V_{\rm eff} = V_{\rm tree}(\phi) + V_1^0(\phi) + V_1^T(\phi, T) + V_{\rm Daisy}(\phi, T)$$

Thermal Contribution

$$\frac{2\pi^2}{T^4} V_1^T(\phi, T) = \int_0^\infty y^2 \mathrm{Log}\left(1 - e^{-\sqrt{y^2 + m_i^2(\phi)/T^2}}\right) \mathrm{d}y$$

$$\approx -\frac{\pi^4}{45} + \frac{\pi^2 m^2}{12\,T^2} - \frac{\pi\, m^3}{6\,T^3} - \frac{m^4}{32\,T^4}\mathrm{Ln}\left(\frac{m^2}{220\,T^2}\right)$$

Calculation of the GW spectrum

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Euclidean Action

$$S_3 = 4\pi \int r^2 \left(\frac{1}{2} \left(\frac{d\phi_i}{dr} \right)^2 + \Delta V(\phi, \eta, T) \right) dr$$

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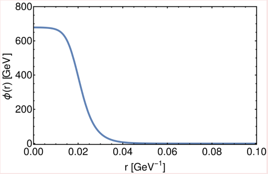

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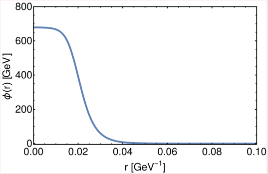

Find the latent heat and timescale of the PT

$$\alpha = \frac{1}{\rho_{\rm rad}} \left(1 - T\frac{\partial}{\partial T} \right) \left(V[\phi_0, \eta_0] - V[\phi_n, \eta_n] \right) \Big|_{T_n}$$

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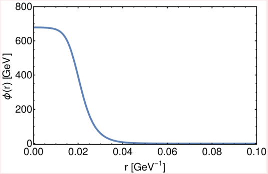

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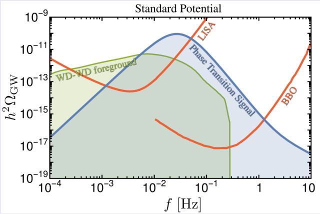
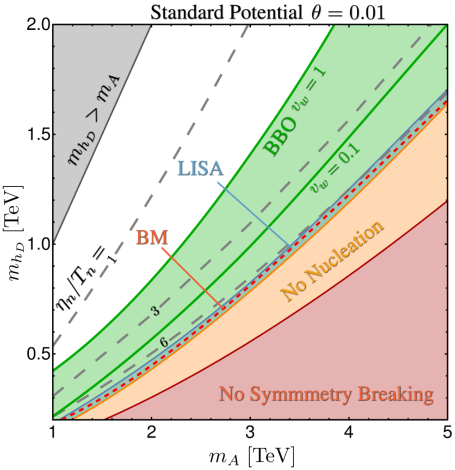
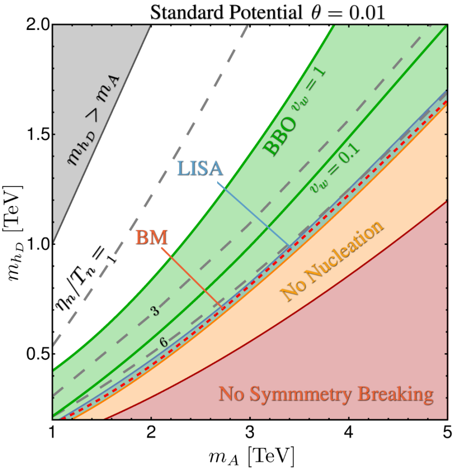


Results


Standard Potential $\theta = 0.01$
2.0
1.5
1.0
0.5
1
2
3
4
5
m_{h_D} [TeV]
m_A [TeV]
$m_{h_D} > m_A$
$\eta_n/T_n = 1$
3
6
LISA
BM
BBO
$v_w = 1$
$v_w = 0.1$
No Nucleation
No Symmmetry Breaking

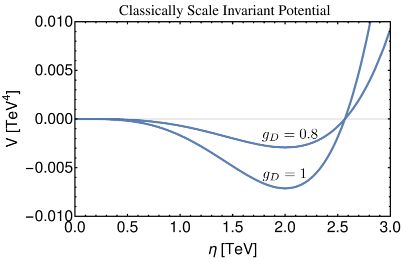
Results

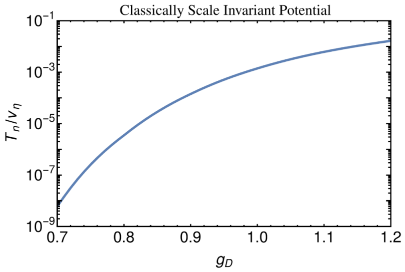


LISA can test only limited parameter space of standard, polynomial type, potentials. BBO can do somewhat better. But we are really after a scenario which generically returns a lot of supercooling.

Classically Scale Invariant Potential

- Hambye, Strumia 1306.2329





Potential at $T = 0$

$$V_1^0(\eta) \simeq \frac{9 g_D^4 \eta^4}{512\pi^2} \left(\mathrm{Ln}\left[\frac{\eta}{v_\eta}\right] - \frac{1}{4} \right)$$

The thermal contribution of the gauge bosons is added to this.

DM relic density

DM relic density

DM and PT possibilities

- **Regime (i): standard freeze-out.**
  (ia). $T_n > \Lambda_{\mathrm{QCD}}$.
  (ib). $T_n < \Lambda_{\mathrm{QCD}}$. (QCD effects must be added to V_{eff}.)

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Super-cool DM - Hambye, Strumia, Teresi 1805.01473

$$Y_{\rm DM}|_{\rm super-cool} = Y_{\rm DM}^{\rm eq} \frac{T_{\rm RH}}{T_{\rm infl}} \left(\frac{T_{\rm end}}{T_{\rm infl}} \right)^3$$

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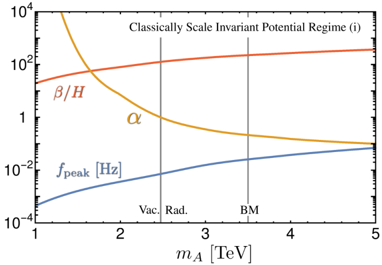
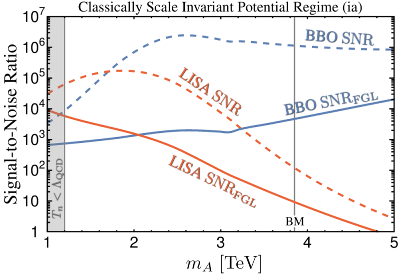
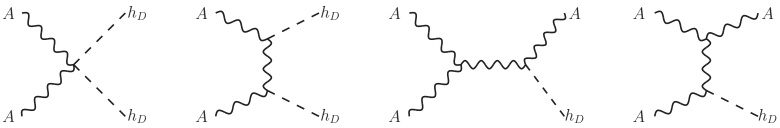
Regime (ia) and (iia) are ameable for testing using GWs!

GW signal Regime (ia) - Freezeout







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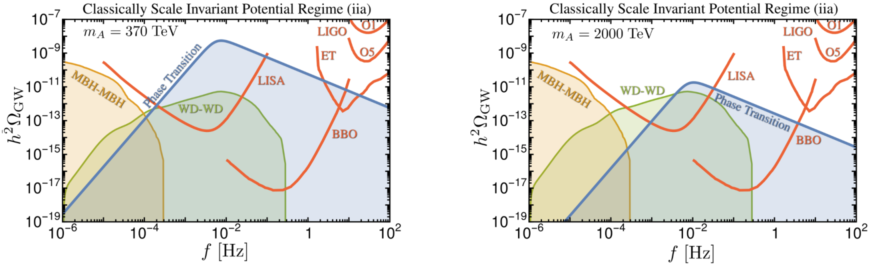

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Here $g_D \simeq 1$ and $m_A \gtrsim 370$ TeV.

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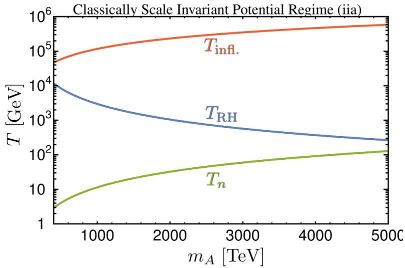

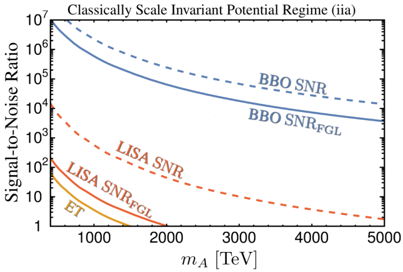

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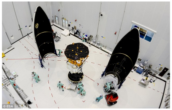
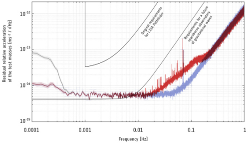
Summary





Summary

- Extensively studied the PTs for spin-one DM.
- Case study for sensitivity of future GW observatories to DM models.
- LISA, which will launch in 2034, will test scenarios with significant supercooling.
- ET also has some sensitivity.
- More advanced instruments needed for polynomial potentials.
- Phase transitions: another pheno avenue to explore in your favourite models.
- Much work still needed $\rightarrow$ exciting times ahead.

The terms of the one-loop effective potential

Effective Potential

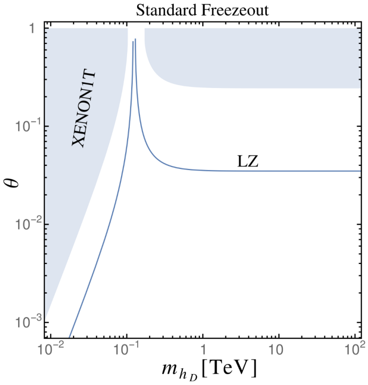
$$V_{\mathrm{eff}} = V_{\mathrm{tree}}(\phi) + V_1^0(\phi) + V_1^T(\phi, T) + V_{\mathrm{Daisy}}(\phi, T)$$

$$V_1^0(\phi) = \sum_i \frac{g_i(-1)^F}{64\pi^2}\left\{ m_i^4(\phi)\left(\mathrm{Log}\left[\frac{m_i^2(\phi)}{m_i^2(v)}\right] - \frac{3}{2}\right) + 2m_i^2(\phi)m_i^2(v)\right\}$$

$$V_1^T(\phi, T) = \sum_i \frac{g_i(-1)^F T^4}{2\pi^2} \times \int_0^\infty y^2 \mathrm{Log}\left(1 - (-1)^F e^{-\sqrt{y^2 + m_i^2(\phi)/T^2}}\right) \mathrm{d}y$$

$$V_{\mathrm{Daisy}}^{\phi}(\phi, T) = \frac{T}{12\pi}\left\{ m_\phi^3(\phi) - \left[m_\phi^2(\phi) + \Pi_\phi(\phi, T)\right]^{3/2}\right\}$$

Direct Detection - Limit on Mixing



$$\sigma_{\rm SI} = \frac{g_D^4\, f^2\, m_N^4\, v_\eta^2}{64\pi\,(m_N + m_A)^2\, v_\phi^2} \left(\frac{1}{m_h^2} - \frac{1}{m_{h_D}^2}\right)^2 \sin^2 2\theta$$

For $m_A \gtrsim \mathcal{O}(100)$ GeV, need $\theta \lesssim 0.2$.