Gravitational Waves and Dark Matter

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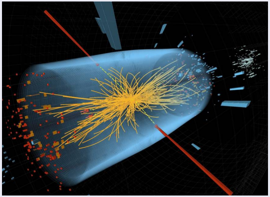
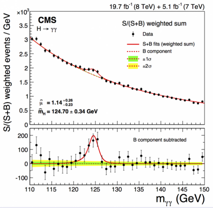
In collaboration with Camilo Garcia-Cely
arXiv:1809.01198

MPIK, Heidelberg
13 May 2019

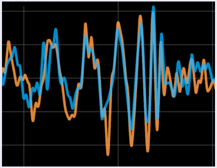
Two big discoveries in the past decade

2012. Discovery of the Brout Englert Higgs boson





2016. Direct Detection of Gravitational Waves



Let us merge the two ideas.

Gravitational Waves from an early Universe Phase Transition

Actually already done

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

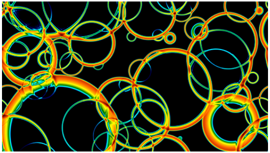
PHYSICAL REVIEW D VOLUME 30, NUMBER 2 15 JULY 1984

Cosmic separation of phases

Edward Witten*
Institute for Advanced Study, Princeton, New Jersey 08540
(Received 9 April 1984)

- Symmetry is typically restored at high T.
- Violent events (e.g. cosmological phase transitions) produce gravitational waves.

Gravitational Waves from an early Universe Phase Transition



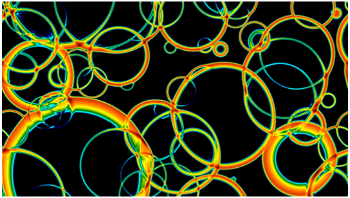
From a simulation by Weir et. al.

Since then

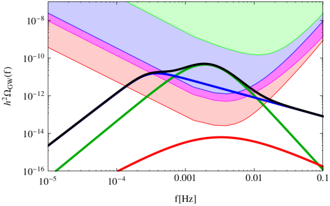
1. Detected Higgs and GWs.
2. Quantitative understanding of the predicted GW spectra has improved.
3. LISA pathfinder has successfully flown.
4. Concrete future proposals such as LISA have been developed.

Quick review of the predicted GW spectra from PTs

Predicted GW spectra



From a simulation by Weir et. al.



LISA working group 1512.06239

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

Three contributions

1. Scalar field contribution
2. Sound waves in the plasma
3. Magnetohydrodynamic Turbulence.

Predicted GW spectra

The spectra depend on the macroscopic properties

- Latent heat α
- Timescale of the transition β^{-1}
- The Hubble scale (or almost equivalently T_n)
- The wall velocity v_w

These are all calculable from microphysics (although v_w is technically challenging).
We can calculate these quantities and then match onto results from simulations/semi-analytic studies.

If enough of a plasma is present - Bodeker, Moore 1703.08215

- Runaway wall is prevented by $P_{\rm LO} \sim T^2 \Delta M^2$ or $P_{\rm NLO} \sim \gamma g^2 T^3 \Delta M$
- Scalar field contribution is suppressed.

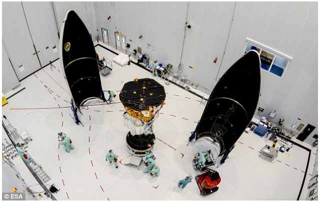
Quick review of future experimental prospects

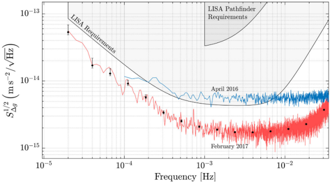
LISA Pathfinder. 3/12/15 - 30/6/17

PHYSICAL REVIEW LETTERS **120,** 061101 (2018)

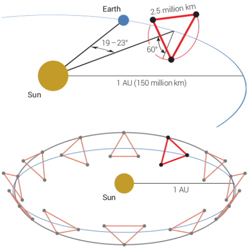
Editors' Suggestion | Featured in Physics

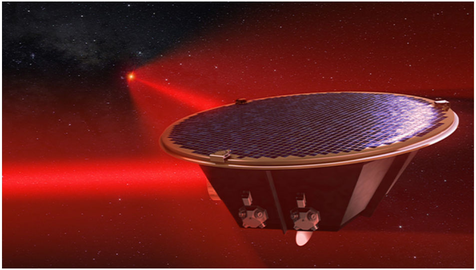
Beyond the Required LISA Free-Fall Performance: New LISA Pathfinder Results down to 20 μHz





LISA

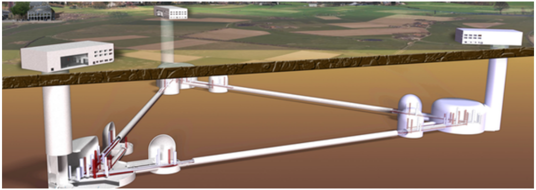


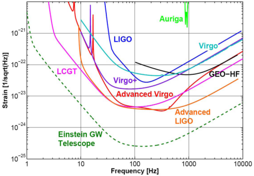


Proposal submitted to ESA - 1702.00786.
Planned launch: 2034.

Einstein Telescope

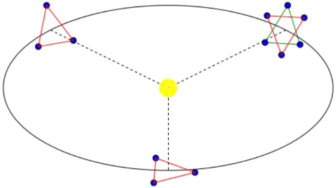
Underground LISA





Could be built in Sardinia or in Belgium.
The belgian site has particularly good rock.

BBO



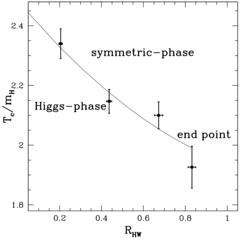
Big Bang Observer: a super LISA

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

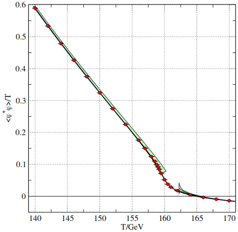
Having the predicted spectra and future experiments in mind...

We now need a strong PT!

EW phase transition



- Csikor, Fodor, Heitger, hep-ph/9809291,



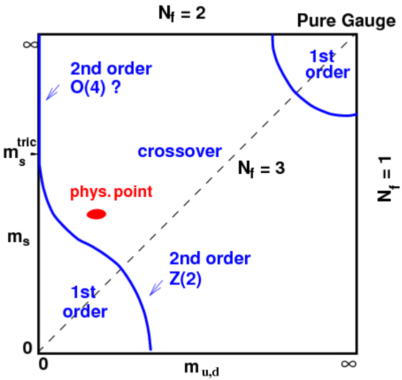
D'Onofrio, Rummukainen 1508.07161

SM with $m_h = 125$ GeV predicts a crossover. Nevertheless, only the minimum (VEV) of the potential, and the 2nd derivative there (m_h), is known.

Strong EW phase transition

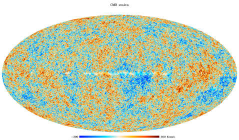
- BSM physics can give a strong EWPT.
- Attractive scenario: EWBG.
- However, EWBG requires a *sub-sonic* wall. This typically *disfavours* the very strong PTs which lead to GWs detectable at LISA.

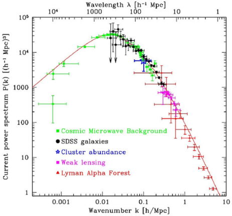
QCD confinement



Similarly the QCD phase transition in the SM is a crossover.

Phase Transitions in a Dark Sector



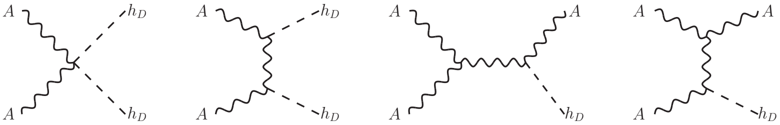


- We introduce some new fields as a solution to the DM puzzle.
- Additional scalar fields may result in a dark phase transition.
- The phase transition we study below can even set the DM density.

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

Link to neutrino mass instead - Brdar, Helmboldt, Kubo 1810.12306

A simple DM model - Hambye 0811.0172



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

$$\mathcal{L} \supset -\frac{1}{4} F_D \cdot F_D + (\mathcal{D} H_D)^\dagger (\mathcal{D} H_D) - \mu_2^2 \, H_D^\dagger H_D - \lambda_\eta \, (H_D^\dagger H_D)^2 - \lambda_{h\eta} \, H_D^\dagger H_D \, H^\dagger H$$

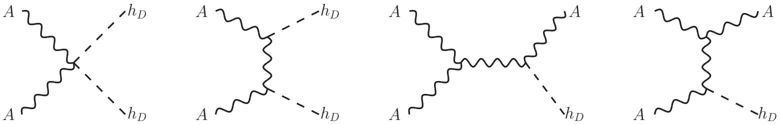
Custodial SO(3) symmetry

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

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



Relic abundance for $m_A \gg m_{h_D}$

$$g_D \approx 0.9 \times \sqrt{\frac{m_A}{1\ \mathrm{TeV}}}$$

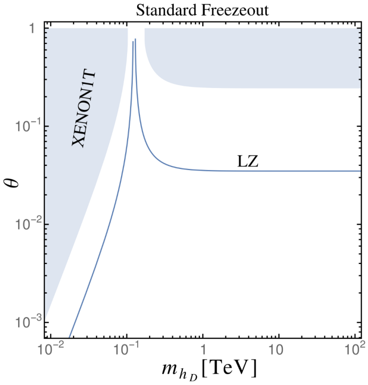
Gauge coupling g_D

- Determines relic abundance.
- Generates a thermal barrier $\rightarrow$ first order PT.

Close link between parameters determing Ω_{DM} and SSB
$\rightarrow$ Test using GWs!

But first let us check the experimental constraints on the model

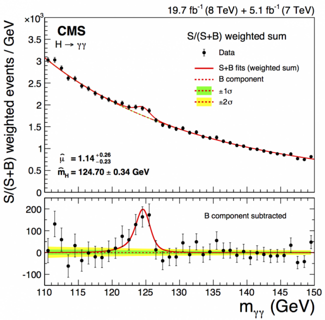
Direct Detection - Limit on Mixing

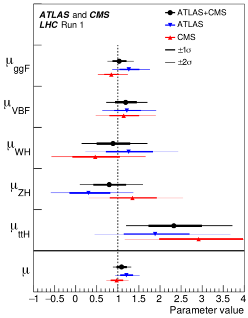


$$\sigma_{\rm SI} = \frac{g_D^4 \, f^2 \, m_N^4 \, v_\eta^2}{64\pi \, (m_N + m_A)^2 \, v_\phi^2} \left(\frac{1}{m_h^2} - \frac{1}{m_{h_D}^2} \right)^2 \sin^2 2\theta$$

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

LHC constraints - Limit on Mixing





$\mu = 1.09 \pm 0.11$	LHC Run 1	$7 + 8$ TeV	1606.02266
$\mu = 1.10 \pm 0.06$	LHC Run 2	13 TeV	1810.02521

$$\theta \lesssim \mathcal{O}(0.1)$$

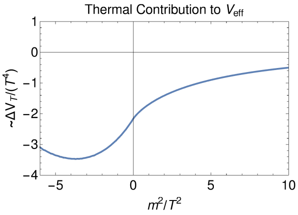
Let us now turn to the phase transition.

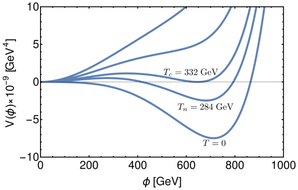
Reminder:

Gauge coupling g_D

- Determines relic abundance.
- Generates a thermal barrier $\rightarrow$ first order PT.

Finite temperature effective potential





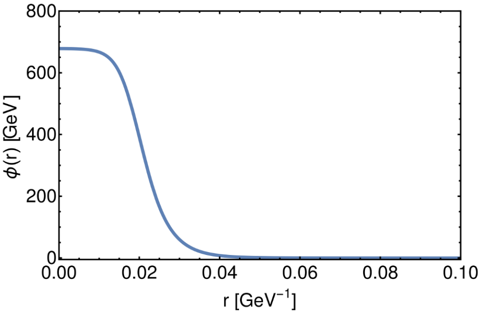
$$V_{\rm eff} = V_{\rm tree}(\phi) + V_1^0(\phi) + V_1^T(\phi, T) + V_{\rm Daisy}(\phi, T)$$

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

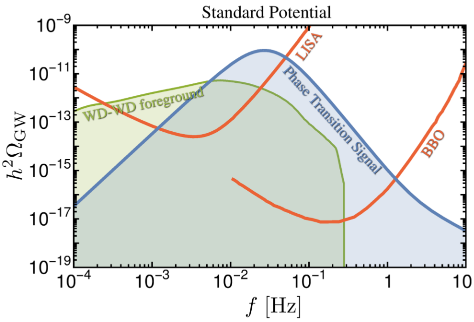


Euclidean Action

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

Nucleation when $\Gamma/V \sim T^4 e^{-S_3/T} \sim H^4$.

Calculation of the GW spectrum

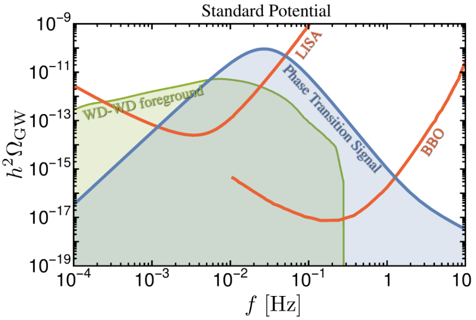


Find the latent heat and timescale of the PT

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

$$\beta = -\frac{d}{dt}\left(\frac{S_3}{T}\right) = H\, T_n \frac{d}{dT}\left(\frac{S_3}{T}\right)\Big|_{T_n}$$

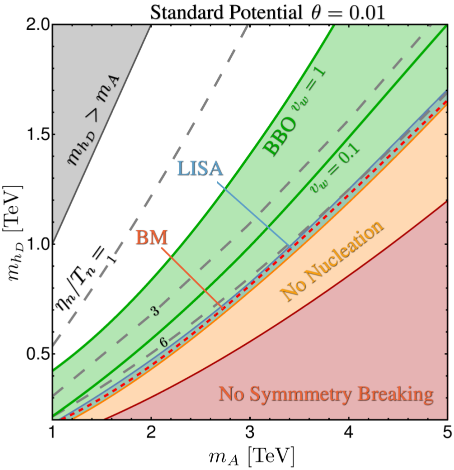
Detectability of the signal



$$\mathrm{SNR} = \sqrt{t_{\rm obs} \int \left[\frac{h^2\Omega_{\rm GW}(f)}{h^2\Omega_{\rm sens}(f)}\right]^2 df}$$

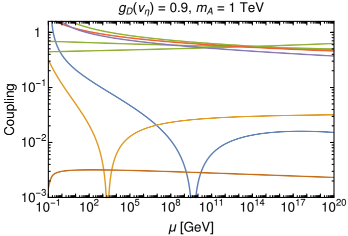
$$\mathrm{SNR}_{\rm FGL} = \sqrt{t_{\rm obs} \int \left[\frac{h^2\Omega_{\rm GW}(f)}{h^2\Omega_{\rm sens}(f) + h^2\Omega_{\rm FG}(f)}\right]^2 df}$$

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.

Radiative Symmetry Breaking



We start with a classically scale invariant theory

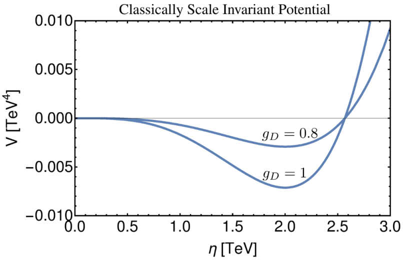
- The dark gauge coupling drives the exotic quartic negative in the IR

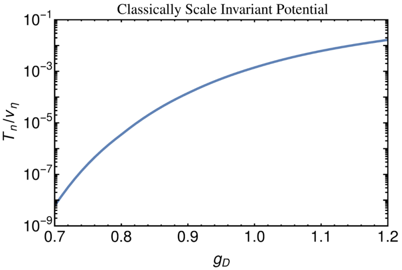
$$\beta_{\lambda_\eta} = \frac{1}{(4\pi)^2}\left(\frac{9}{8}g_D^4 - 9g_D^2\lambda_\eta + 2\lambda_{h\eta}^2 + 24\lambda_\eta^2\right)$$

- This signals radiative symmetry breaking - Coleman, E. Weinberg '73
- The potential is approximated in the flat direction in field space - Gildener, S. Weinberg '76

Classically Scale Invariant Potential

- Hambye, Strumia 1306.2329



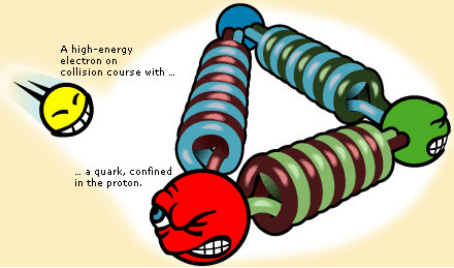


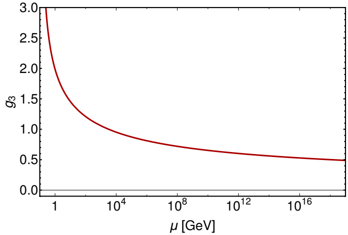
Potential at $T = 0$

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

The thermal contribution of the gauge bosons is added to this.
The EW Higgs mass is generated through the portal.
Universe generically becomes vacuum dominated before PT.

Taking into account QCD

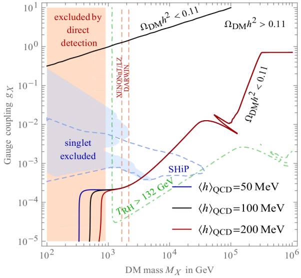




If $T_n \lesssim \Lambda_{\rm QCD}$, QCD confinement must be taken into account.

- When QCD confines a mass scale enters the potential.
- EW Symmetry is broken by the quark condensate.
- The Higgs gets a VEV $\langle h \rangle \sim \Lambda_{\rm QCD}$ induced by $y_t h \langle \overline{t_L} t_R \rangle$.
  - Witten '81
- This gives a mass term $V_{\rm eff} \supset -\lambda_{h\eta} \Lambda_{QCD}^2 \eta^2$.
- The thermal barrier disappears at $T \sim m_h \Lambda_{QCD} / m_A$.
  - Iso, Serpico, Shimada 1704.04955

DM relic density

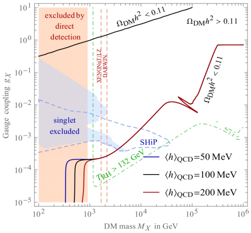


Super-cool DM - Hambye, Strumia, Teresi 1805.01473

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

$$Y_{\rm DM}\big|_{\rm sub-thermal} = M_{\rm Pl}M_{\rm DM}\langle\sigma_{\rm ann}v_{\rm rel}\rangle\sqrt{\frac{\pi g_*}{45}}\int_{z_{\rm RH}}^{\infty}\frac{dz}{z^2}Y_{\rm eq}^2$$

DM relic density



DM and PT possibilities

- **Regime (i): standard freeze-out.**
  (ia). $T_n > \Lambda_{\rm QCD}$.
  (ib). $T_n < \Lambda_{\rm QCD}$. (QCD effects must be added to $V_{\rm eff}$.)
- **Regime (ii): super-cool DM.**
  (iia). $T_n > \Lambda_{\rm QCD}$.
  (iib). $T_n < \Lambda_{\rm QCD}$. (QCD effects must be added to $V_{\rm eff}$.)

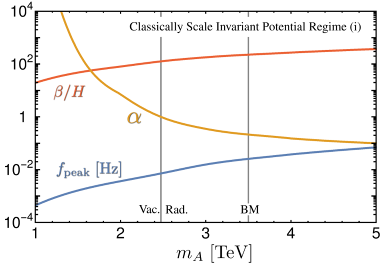
Regime (ia) and (iia) are amenable for testing using GWs!

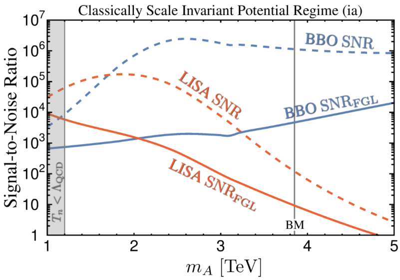
Why is the signal suppressed for $T_n < \Lambda_{\rm QCD}$?

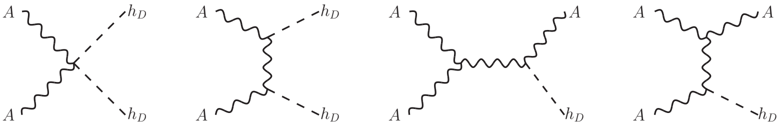
- With massless quarks QCD PT is first order at $T \sim \Lambda_{QCD}$: GW signal
  - Helmboldt, Kubo, van der Woude 1904.07891
- However inflation continues until $T \sim m_h \Lambda_{QCD} / m_A$
  $\rightarrow$ suppresses signal.
- $SU(2)_D$ PT is also first order.
- But due to mass term $V_{\rm eff} \supset -\lambda_{h\eta} \Lambda_{QCD}^2 \eta^2$ signal is weak.

So we focus on $T_n > \Lambda_{\rm QCD}$ instead.

GW signal Regime (ia) - Standard Freezeout



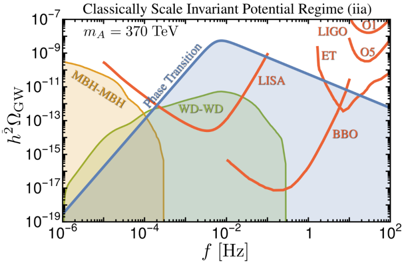


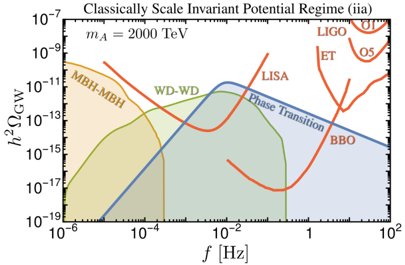


Standard Freezeout

$$g_D \approx 0.9 \times \sqrt{\frac{m_A}{1\ \mathrm{TeV}}}$$

GW signal Regime (iia) - Super-cool DM



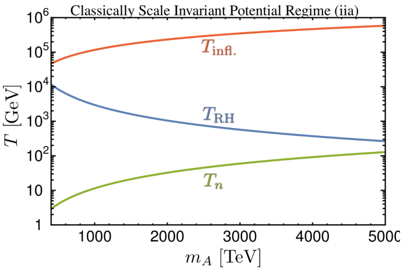


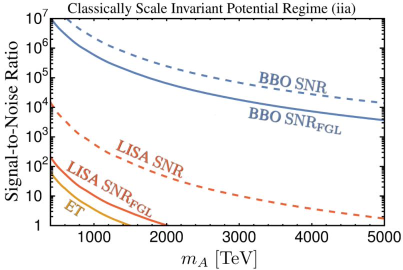
Super-cool DM

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

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

GW signal Regime (iia) - Super-cool DM

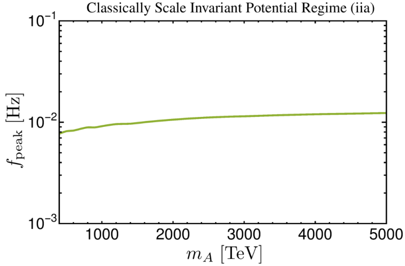




We correct for the period of matter domination after the PT.

$$f_{\text{peak}} \to \left(\frac{T_{\text{RH}}}{T_{\text{infl}}}\right)^{1/3} f_{\text{peak}} \qquad \Omega_{\text{GW}} \to \left(\frac{T_{\text{RH}}}{T_{\text{infl}}}\right)^{4/3} \Omega_{\text{GW}}$$

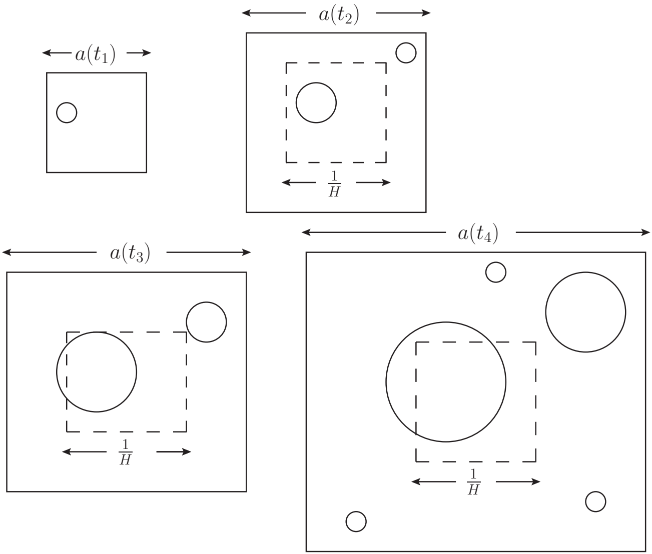
Peak Frequency Regime (iia) - Super-cool DM



Key prediction of the model

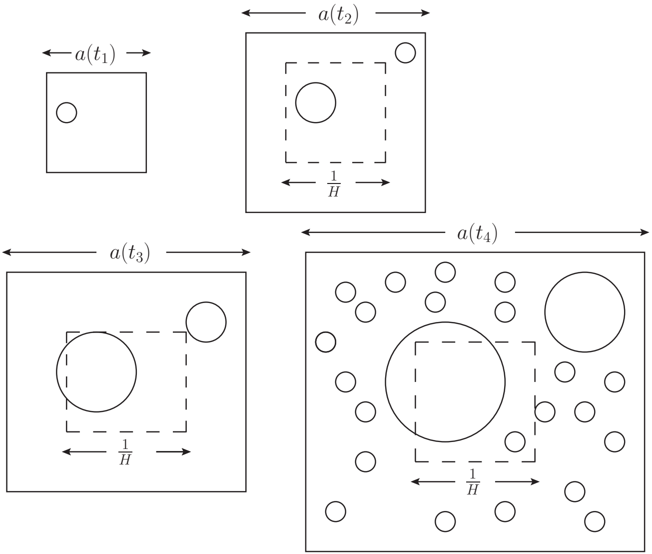
We find the peak frequency here is $\sim 10^{-2}$ Hz almost independent of m_A.

Completion of the Phase Transtion



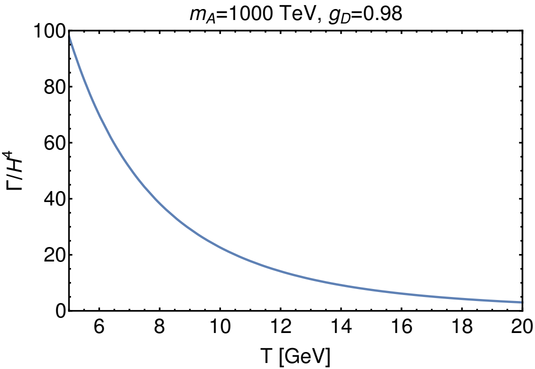
If nucleation rate is low, we can form bubbles which never meet.

Completion of the Phase Transtion



If nucleation grows enough, sufficient bubbles to meet will nucleate.

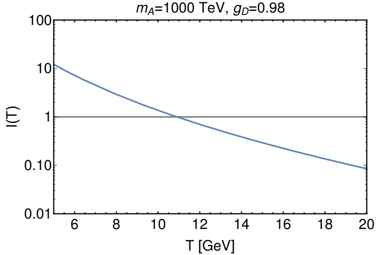
Completion of the Phase Transtion

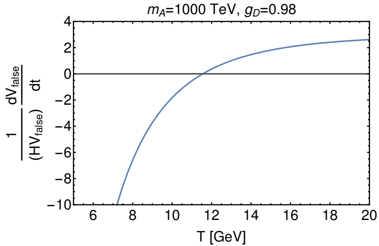


In the classically scale invariant potential we have a slow transition but an exponentially growing nucleation rate.

Completion of the Phase Transtion

We can explicitly check the volume of false vacuum decreases and the bubbles will percolate.





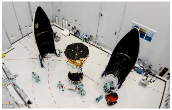
$$P(T) \equiv e^{-I(T)} \lesssim 1/e \implies I(T) = \frac{4\pi}{3} \int_{t_c}^{t} dt' \Gamma(t') a(t')^3 r(t, t')^3 \gtrsim 1$$

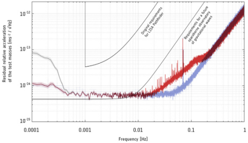
$$\frac{1}{H\mathcal{V}_{\rm false}} \frac{d\mathcal{V}_{\rm false}}{dt} = 3 + T \frac{dI}{dT} \lesssim -1.$$

Future Work

- Calculation can be improved: running of g_D potentially important.
- Super cool DM in composite Higgs scenario - Baratella, Pomarol, Rompineve 1812.06996
- Detailed pheno study - IB, Gouttenoire, Sala, Servant (In progress)
- GW signal from QCD PT in other models? - Helmboldt, Kubo, van der Woude 1904.07891

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 → exciting times ahead.

The terms of the one-loop effective potential

Effective Potential

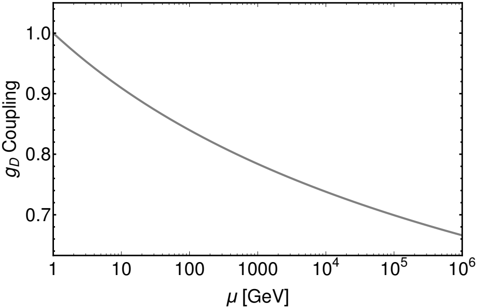
$$V_{\rm eff} = V_{\rm tree}(\phi) + V_1^0(\phi) + V_1^T(\phi, T) + V_{\rm Daisy}(\phi, T)$$

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

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

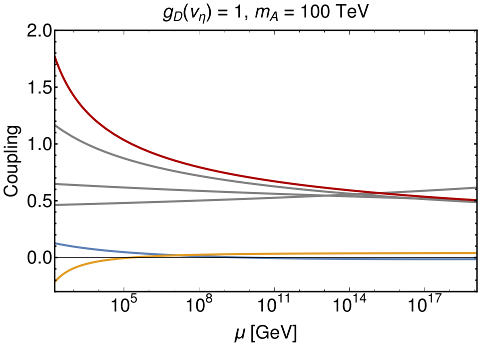
$$V_{\rm Daisy}^{\phi}(\phi, T) = \frac{T}{12\pi}\left\{m_\phi^3(\phi) - \left[m_\phi^2(\phi) + \Pi_\phi(\phi, T)\right]^{3/2}\right\}$$

Dark Running



$$\frac{dg_D}{d\,ln(\mu)} = \frac{g_D^3}{(4\pi)^2}\left(-\frac{22}{3}+\frac{1}{6}\right)$$

Dark Running - Including All Couplings



$$\frac{dg_D}{d\,ln(\mu)} = \frac{g_D^3}{(4\pi)^2}\left(-\frac{22}{3}+\frac{1}{6}\right)$$

$g_D(v_\eta) = 0.9,\ m_A = 1$ TeV