# Connection to Dark Matter

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Gravitational Wave Workshop
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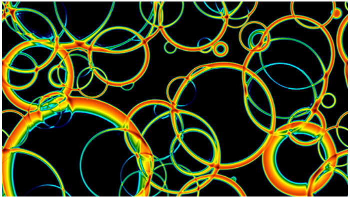
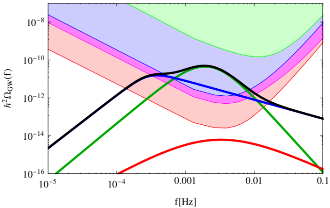
# Predicted GW spectra - Recap



From a simulation by Weir et. al.




LISA working group 1512.06239

Update: 1910.13125

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

## Three contributions

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

# Predicted GW spectra - Recap

## The spectra depend on the macroscopic properties

- Latent heat $\alpha$
- Timescale of the transition $\beta^{-1}$
- 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

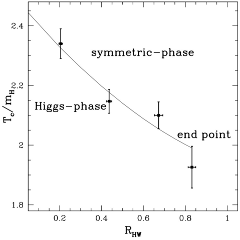
- Runaway wall is prevented by $P_{\mathrm{LO}} \sim T^2 \Delta M^2$ or $P_{\mathrm{NLO}} \sim \gamma g^2 T^3 \Delta M$
- Scalar field contribution is suppressed.

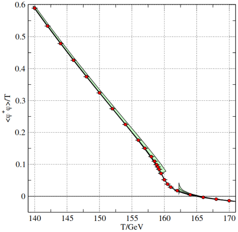
Having the predicted spectra and future experiments in mind...

**We now need a strong PT!**

We want to know which particle physics models will have been tested by LISA in 2040 say.

# EW phase transition



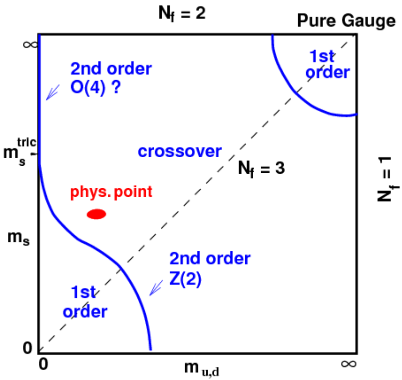

- Csikor, Fodor, Heitger, hep-ph/9809291, D'Onofrio, Rummukainen 1508.07161

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.

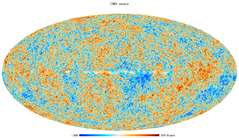
## Strong EW phase transition

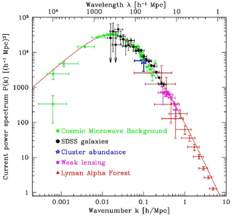
- BSM physics can give a strong EWPT.
- Attractive scenario: EWBG.
- However, EWBG requires a subsonic wall. This leads to some tension with the very strong PTs which lead to GWs detectable at LISA.

# QCD confinement




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






- 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 can actually be closely tied to the relic abundance.

The idea here is to explore the feasibility of using GWs to detect SSB in a dark matter sector.

# Three Examples

**I will discuss three examples:**

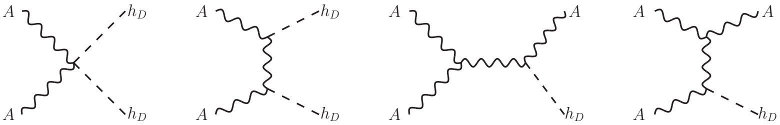
- I. $SU(2)_D$ Vector DM and associated Phase Transition.
- II. $SU(2)_D$ Vector DM with a classically scale invariant potential.
- III. Supercooled Composite DM from a Confining Phase Transition.

- The first two examples serve as a case study for GWs from DM.
- The last example, which has a natural realisation in the composite Higgs, shows some novel results (work in progress).

Part I.

## $SU(2)_D$ Vector Dark Matter

# A simple DM model - Hambye 0811.0172



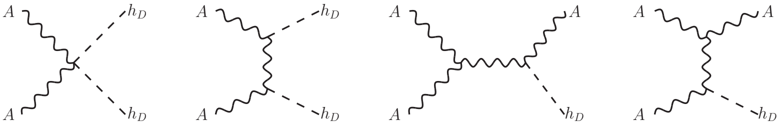

## The Model: $SU(3)_C \times SU(2)_L \times U(1)_Y \times SU(2)_D$

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

## Custodial SO(3) symmetry

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

# Standard Freezeout




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

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

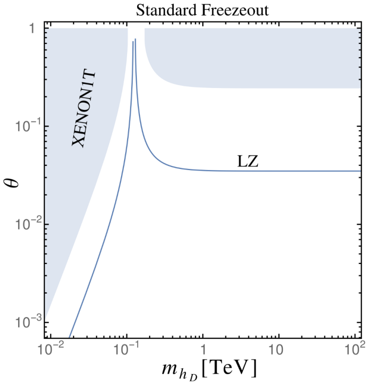
## Gauge coupling $g_D$

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

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

But first let us check the experimental constraints on the model

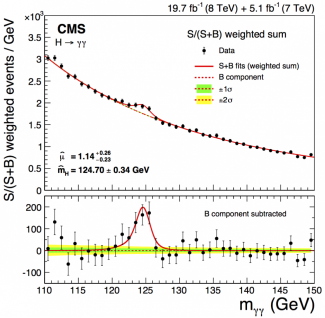
# Direct Detection - Limit on Mixing

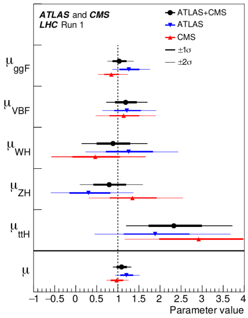



$$\sigma_{\rm SI} = \frac{g_D^4\, f^2\, m_N^4\, v_\eta^2}{64\pi\,(m_N + m_A)^2\, v_\phi^2}\left(\frac{1}{m_h^2} - \frac{1}{m_{h_D}^2}\right)^2 \sin^2 2\theta$$

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 |

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

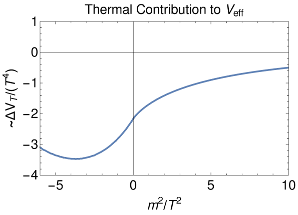
Let us now turn to the phase transition.

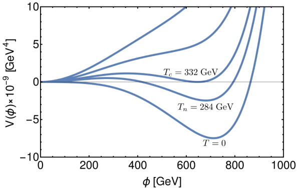
Reminder:

**Gauge coupling $g_D$**

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

# Finite temperature effective potential



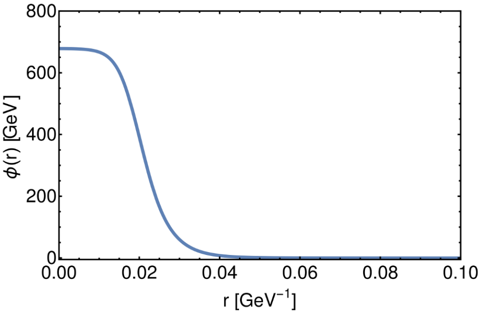

$$V_{\rm eff} = V_{\rm tree}(\phi) + V_1^0(\phi) + V_1^T(\phi, T) + V_{\rm Daisy}(\phi, T)$$

## 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

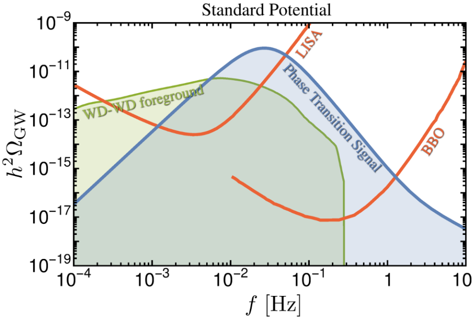



## Euclidean Action

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

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

# Calculation of the GW spectrum

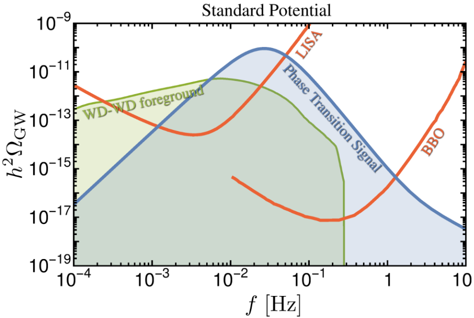



## Find the latent heat and timescale of the PT

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

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

# Detectability of the signal



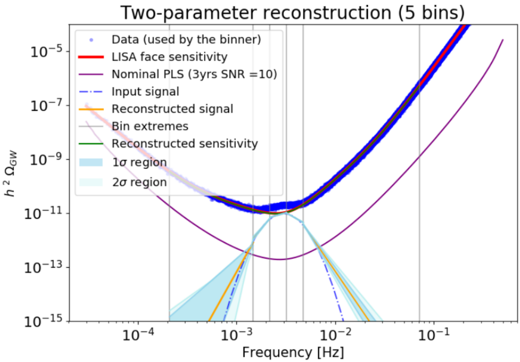

$$\mathrm{SNR} = \sqrt{t_{\rm obs} \int \left[\frac{h^2\Omega_{\rm GW}(f)}{h^2\Omega_{\rm sens}(f)}\right]^2 df}$$

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

Astro Foregrounds: Farmer, Phinney '03, Regimbau '11, Rosado '11

# Aside: Shape Reconstruction

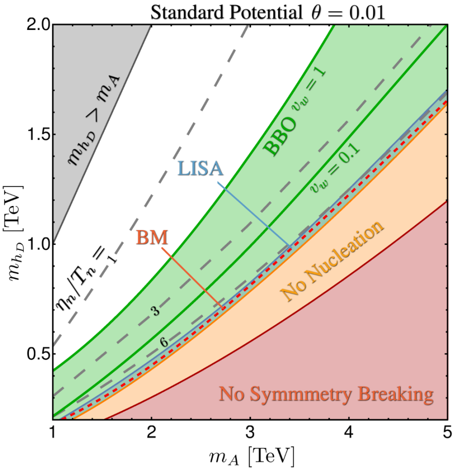
The SNR above is for power-law backgrounds.




With stronger signals also the shape can be reconstructed.

Caprini et al. 1906.09244

# 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.

## Part II.

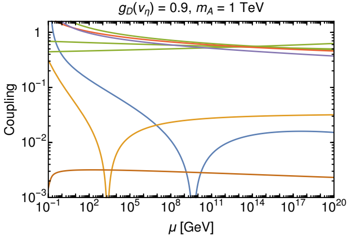
$SU(2)_D$ Vector Dark Matter with a Classically Scale Invariant Potential.

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

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

- Hambye, Strumia 1306.2329, - Hambye, Strumia, Teresi 1805.01473

# Radiative Symmetry Breaking




## We start with a classically scale invariant theory

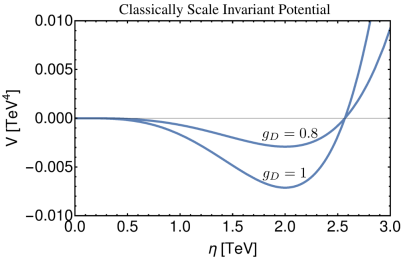
- The dark gauge coupling drives the exotic quartic negative in the IR

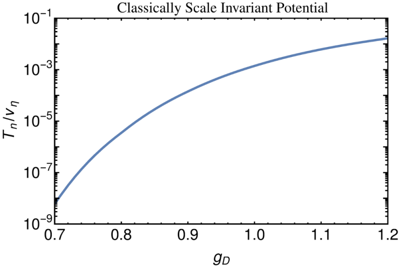
$$\beta_{\lambda_\eta} = \frac{1}{(4\pi)^2}\left(\frac{9}{8}g_D^4 - 9g_D^2\lambda_\eta + 2\lambda_{h\eta}^2 + 24\lambda_\eta^2\right)$$

- 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



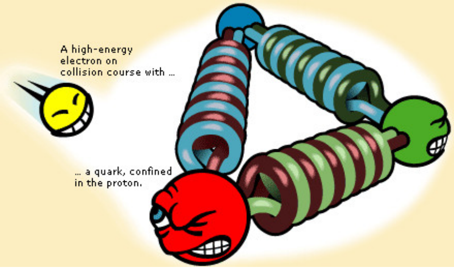



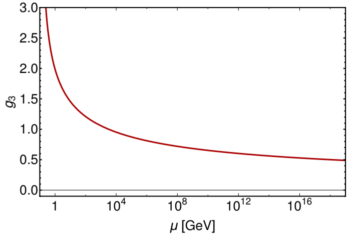

## Potential at $T = 0$

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

The thermal contribution of the gauge bosons is added to this.
The EW Higgs mass is generated through the portal.
Universe becomes vacuum dominated before PT, i.e. $\Lambda_{CC}^4 > g_* \pi^2 T^4/30$.

# Taking into account QCD

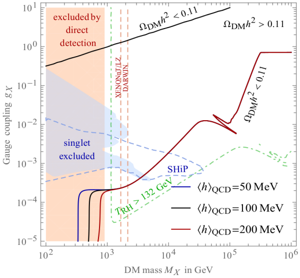



## If $T_n \lesssim \Lambda_{\rm QCD}$, QCD confinement must be taken into account.

- 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

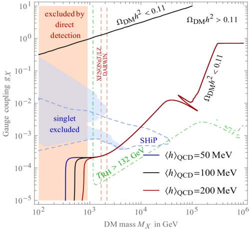



## Super-cool DM - Hambye, Strumia, Teresi 1805.01473

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

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

# 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 $V_{\rm eff}$.)

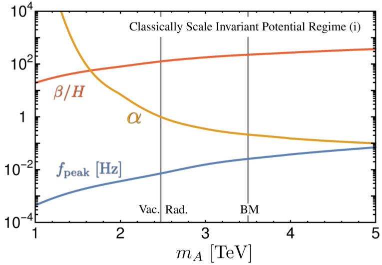
Regime (ia) and (iia) are amenable for testing using GWs!

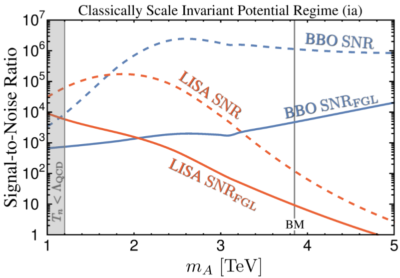
# Why is the signal suppressed for $T_n < \Lambda_{\rm QCD}$?

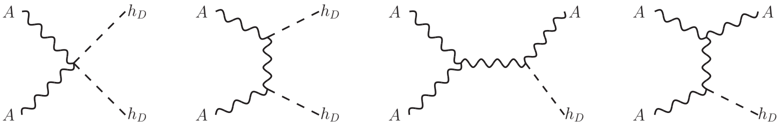
- With massless quarks QCD PT is first order at $T \sim \Lambda_{QCD}$: GW signal
  - Helmboldt, Kubo, van der Woude 1904.07891
- However inflation continues until $T \sim m_h \Lambda_{QCD}/m_A$
  $\to$ suppresses signal.
- $SU(2)_D$ PT is also first order.
- But due to mass term $V_{\rm eff} \supset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

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

# GW signal Regime (ia) - Standard Freezeout



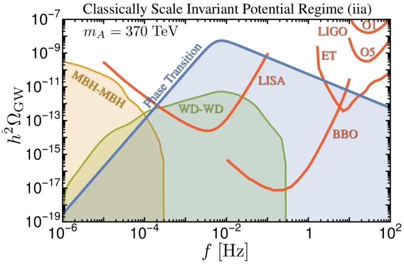



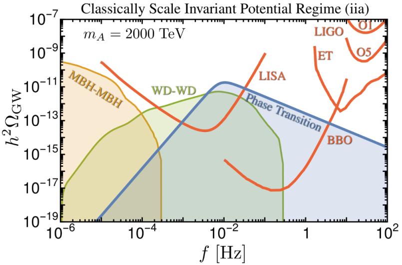




## Standard Freezeout

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

# GW signal Regime (iia) - Super-cool DM



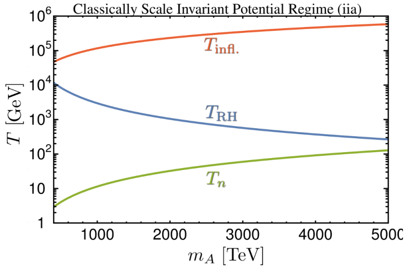



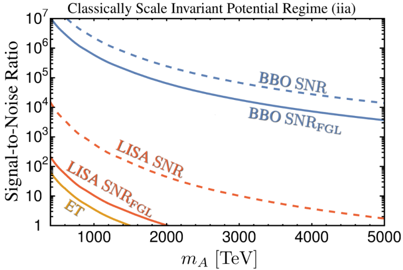

## Super-cool DM

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

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

# GW signal Regime (iia) - Super-cool DM

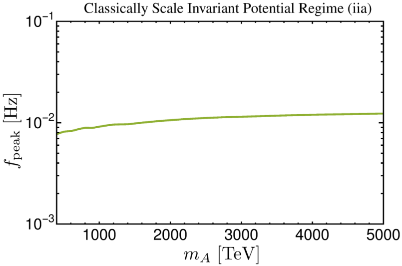



**We correct for the period of matter domination after the PT.**

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

# Peak Frequency Regime (iia) - Super-cool DM

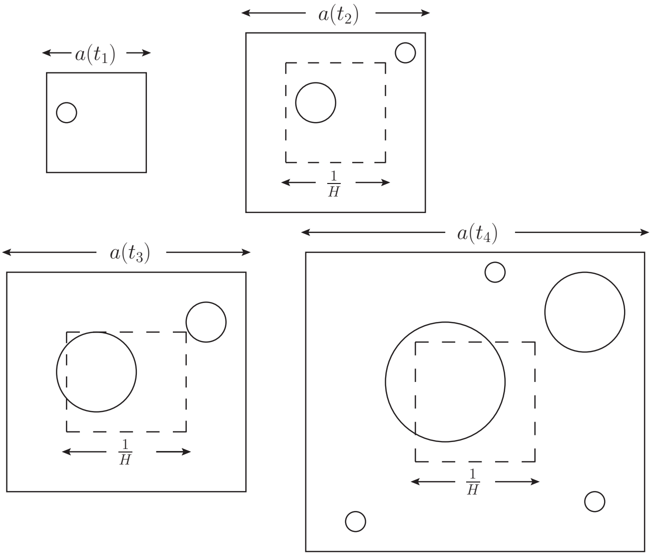



**Key prediction of the model**

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

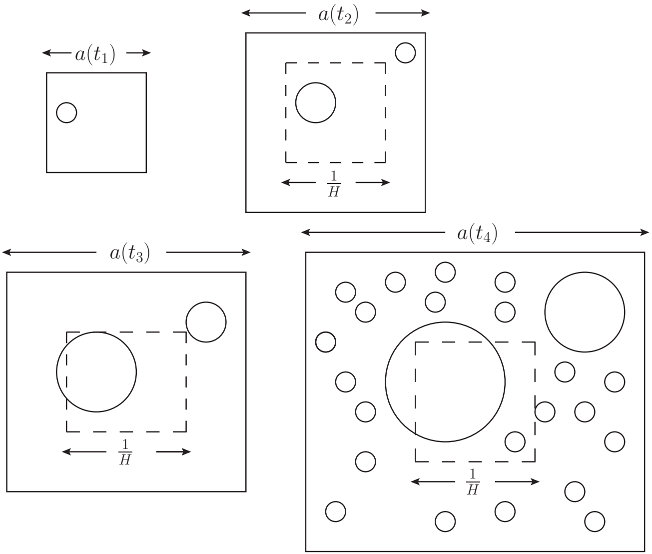
Caveat: calculation can be improved as the running of $g_D$ potentially important.

# Completion of the Phase Transtion



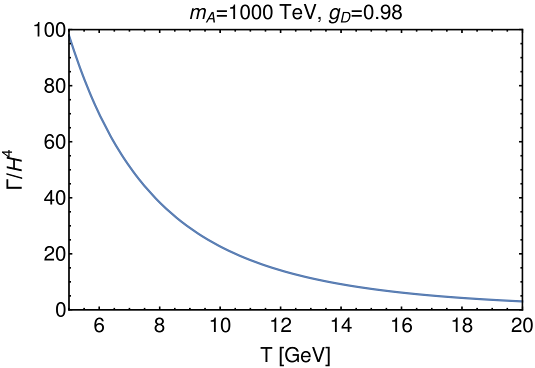

If nucleation rate is low, we can form bubbles which never meet.

# Completion of the Phase Transtion




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

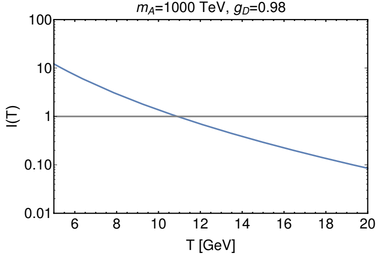
# Completion of the Phase Transtion

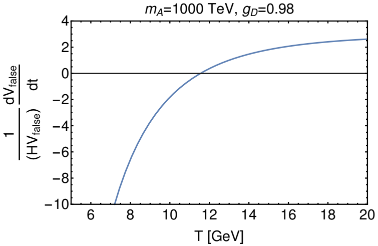



In the classically scale invariant potential we have a slow transition but an exponentially growing nucleation rate.

# Completion of the Phase Transtion

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




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

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

Also see Ellis, Lewicki, No 1809.08242 Ellis, Lewicki, No, Vaskonen 1903.09642

# Part III.

Supercooled Composite DM from a Confining Phase Transition.

All results here are preliminary. Digitize the plots at your own risk.

IB, Yann Gouttenoire, Filippo Sala, Geraldine Servant `arXiv:2ymm.nnnnn`

# The Setup

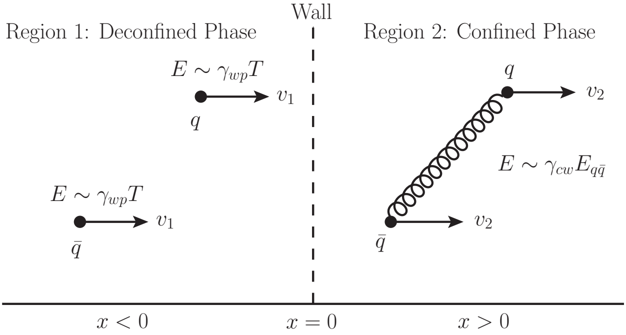
**Assume for now**

- The strong sector could arises from some $SU(N)$.
- Strong sector confines at a scale $f$.
- Along with the gluons there are a number of massless quarks.
- The DM is a hadron stable due to some underlying global symmetry of one of its constituent quarks.*
- The DM is a composite state with $m_{\rm DM} \sim f$.

* In analogy with proton/antiproton stability or $K$ mesons which would be stable in the absence of strangeness violating weak interactions.

# Quark Confinement

Now consider if the strong sector phase transition is supercooled.




## Cornell potential at large distances*

$$E_{q\bar{q}} \approx f^2 \langle d_c \rangle \approx \frac{f^2}{T_{\mathrm{nuc}}} \left( \frac{\gamma_{\mathrm{cw}}}{\gamma_{\mathrm{wp}}} \right)^{1/3} \approx \left( \frac{f^3}{T_{\mathrm{nuc}}} \right)^{1/2}$$

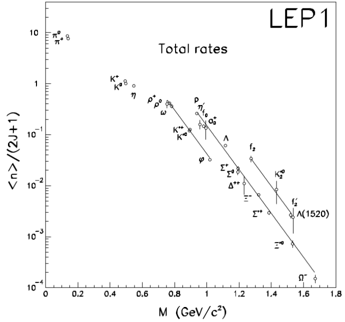
* Cf lattice QCD: compared to the confining distance of 1 fm, this has been tested out to 3 fm. Here we extrapolate further.

# DM from string breaking

1. The quarks are diluted by the supercooling to
$$Y_q^{SC} = Y_q^{eq} \left( \frac{T_{nuc}}{T_{start}} \right)^3 .$$
2. The gluons and quarks can enter the bubbles when
$$\gamma_{wp} \gtrsim \left( \frac{f}{T} \right)^{3/2}$$
which can easily be achieved in a supercooled transition.
3. The string hadronization yields an additional number of DM particles
$$N_{string}^{DM} \sim \frac{r\, E_{q\bar{q}}}{f}$$
where $r$ is a model dependent branching fraction.
4. DM again possibly reaches kinetic equilibrium with thermal bath following reheating. work in progress – further hadronization (?).

# The string branching fraction

- If DM is a heavy resonance - additional suppression.

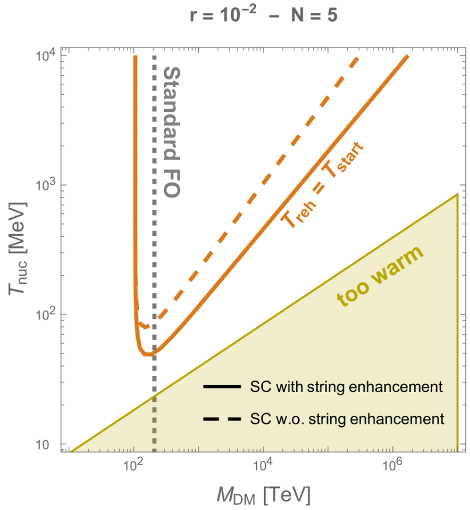



Thermal Model - Chliapnikov, Phys. Lett. B462, 341 (1999)

$$\langle r \rangle \propto (2J+1)\mathrm{Exp}\left[-\frac{M}{f}\right]$$

- Alternatively if $m_{\rm DM} \approx f$ we may have democratic production $r \sim 10^{-2} - 10^{-1}$.
- An $\mathcal{O}(1)$ fraction of $E_{q\bar{q}}$ also ends up in kinetic energy.

# The DM Yield



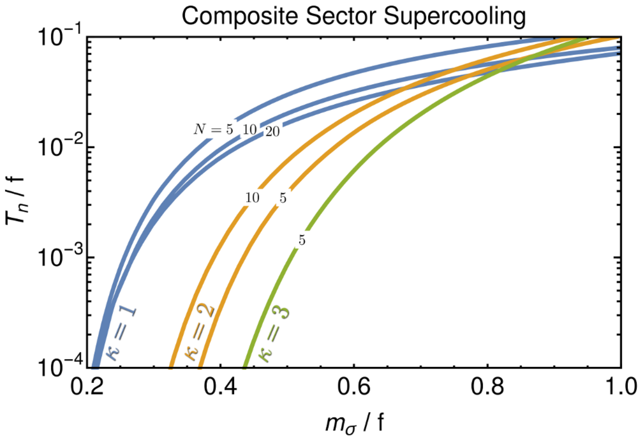

Here we assume $T_{\rm start} = 10^{-2} m_{\rm DM}$ and $\langle \sigma v \rangle = 100/m_{\rm DM}^2$.

# Composite Higgs

## Composite Higgs Scenario

- Possible solution to the hierarchy problem.
- Here we assume the DM is also composite.
- Along with the Higgs, the theory contains the Dilaton
  - a pNGB of the scale symmetry.
- The dilaton acts as a portal because it couples to the SM particles and to DM.
- For example, the DM can annihilate through the dilaton into the SM.
  - Bai et al. 0909.1319, Blum et al. 1410.1873, Efrati et al. 1410.2225

# Composite Higgs with a Light Dilaton

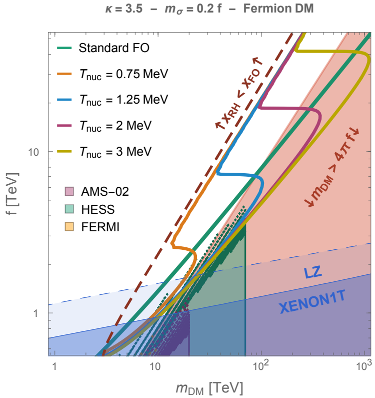


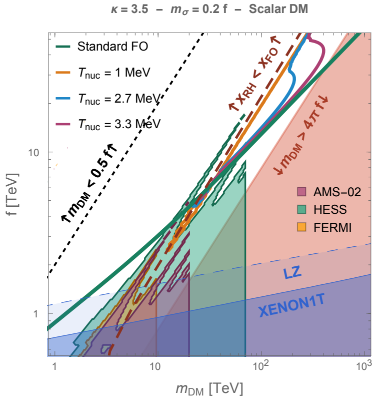

A light dilaton arises if the beta function of the strong sector is small when the theory confines.

This implies strong supercooling.

# Supercooled composite DM and composite Higgs

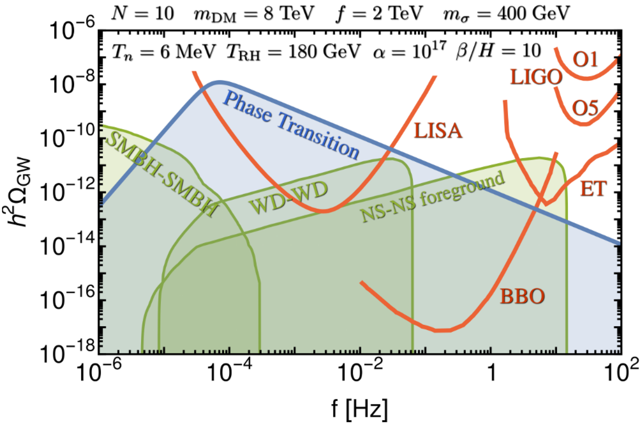
The composite DM confines upon entering the bubbles.



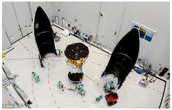

The light dilaton portal gives an interplay of direct, indirect, and gravitational wave signatures!
For colliders: see Ahmed, Mariotti, Najjari (to appear).

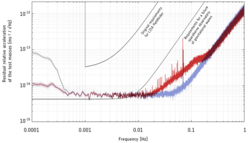
# GW signature




No precise prediction is available for this model yet. But as it relies on supercooling, we expect some sizable GW spectrum.

# Summary






## Summary

- Extensively studied the PTs for spin-one DM as a 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.
- Work is underway in studying the novel aspects of supercooled composite DM.
- This has a direct realisation in composite Higgs models, which are tied to the hierarchy problem, and offer a variety of other pheno.

# The terms of the one-loop effective potential

## Effective Potential

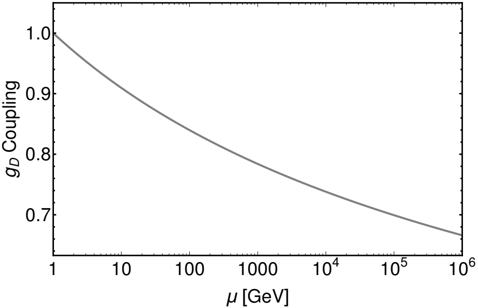
$$V_{\text{eff}} = V_{\text{tree}}(\phi) + V_1^0(\phi) + V_1^T(\phi, T) + V_{\text{Daisy}}(\phi, T)$$

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

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

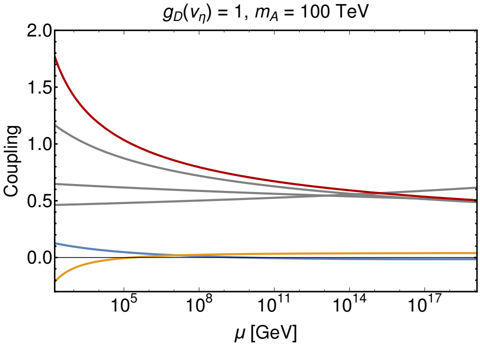
$$V_{\text{Daisy}}^{\phi}(\phi, T) = \frac{T}{12\pi}\left\{m_\phi^3(\phi) - \left[m_\phi^2(\phi) + \Pi_\phi(\phi, T)\right]^{3/2}\right\}$$

# Dark Running

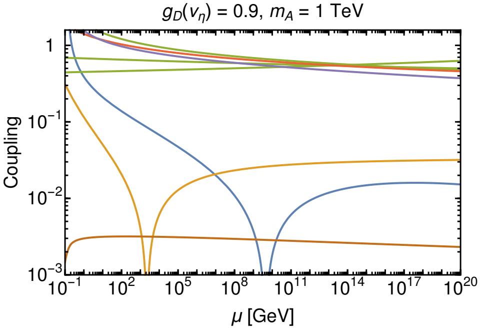



$$\frac{dg_D}{d\,ln(\mu)} = \frac{g_D^3}{(4\pi)^2}\left(-\frac{22}{3} + \frac{1}{6}\right)$$

# 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
Coupling
1
$10^{-1}$
$10^{-2}$
$10^{-3}$
$10^{-1}$
$10^{2}$
$10^{5}$
$10^{8}$
$10^{11}$
$10^{14}$
$10^{17}$
$10^{20}$
$\mu$ [GeV]

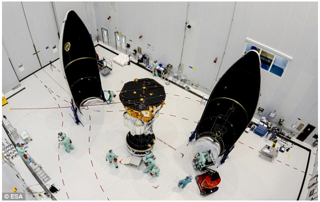
## Quick review of future experimental prospects

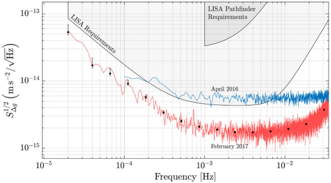
# LISA Pathfinder. 3/12/15 - 30/6/17

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

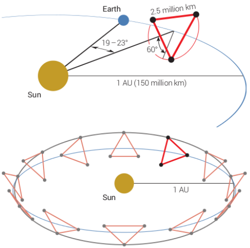
Editors' Suggestion | Featured in Physics

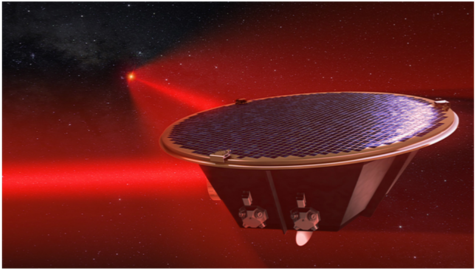
**Beyond the Required LISA Free-Fall Performance: New LISA Pathfinder Results down to 20 $\mu$Hz**



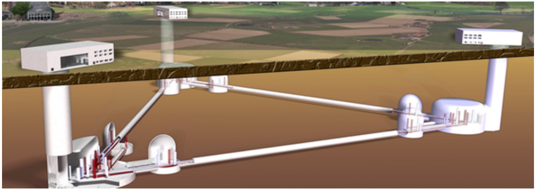
# LISA

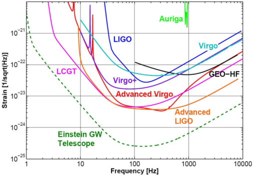


Proposal submitted to ESA - 1702.00786.
Planned launch: 2034.

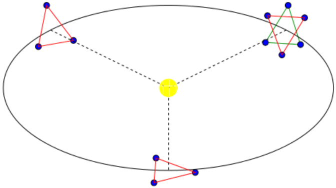
## Underground LISA






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

# BBO

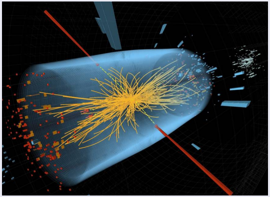


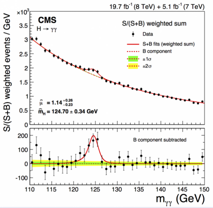
## Big Bang Observer: a super LISA

- 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

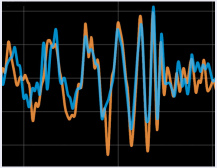
# Two big discoveries in the past decade

## 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, ...

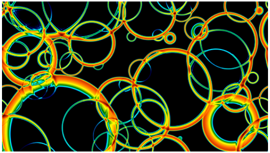
PHYSICAL REVIEW D VOLUME 30, NUMBER 2 15 JULY 1984

**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.