Probing extremely weakly coupled Dark Matter with GWs

Sabir Ramazanov (CEICO, Prague)
In collaboration with E. Babichev, D. Gorbunov, W. Emond, R. Samanta, A. Vikman

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Mechanisms of Dark Matter production

- Freeze-out: Dark Matter couplings to thermal bath are large enough to maintain early time thermal equilibrium.
- Freeze-in: feebly coupled Dark Matter.
  No equilibrium at any time. Out-of-equilibrium scatterings of particles in the primordial plasma into DM particles are sufficient to populate DM phase space.
  McDonald'02, Hall et al'10

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In the present talk: Dark Matter production through inverse phase transition.

Couplings are so weak that out-of-equilibrium scatterings are insufficient (beyond freeze-in).

Earlier discussions of inverse phase transitions:
S. Weinberg'74, Dodelson and Widrow'90.

Scalar portal coupling

$$\mathcal{L} = \frac{(\partial_\mu \chi)^2}{2} - \frac{M^2 \cdot \chi^2}{2} - \frac{\lambda \cdot \chi^4}{4} + \frac{g^2 \chi^2 \phi^\dagger \phi}{2} \, .$$

χ is Dark Matter field Z_2-symmetry protects stability

Assume that ϕ is in thermal equilibrium with hot plasma.
Could be Higgs field.

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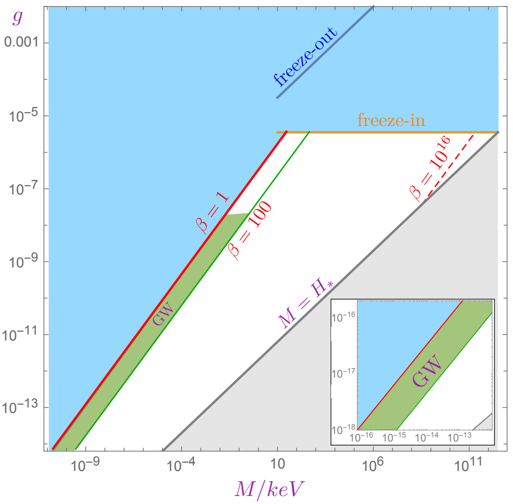
- $|g^2| \simeq 0.1 - 10^{-8} \Longrightarrow$ freeze-out
- $|g^2| \simeq 10^{-11} \Longrightarrow$ freeze-in

Chu, Hambye, Tytgat'11, Yaguna'11, Lebedev and Toma'19

- $0 < g^2 \lesssim 10^{-11} \Longrightarrow$ second order inverse phase transition



S. R., Babichev, Gorbunov, Vikman'21

$$\langle \phi^\dagger \phi \rangle_T = \frac{NT^2}{12}$$

$$V_{eff} = \frac{M^2 \cdot \chi^2}{2} + \frac{\lambda \cdot \chi^4}{4} - \frac{Ng^2 T^2 \chi^2}{24}$$

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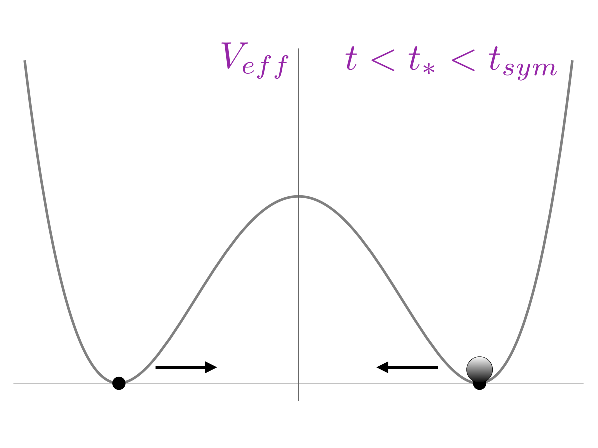
$$T^2(t) \propto \frac{1}{a^2(t)}$$

Large T at early times $\Longrightarrow$ spontaneous breaking of Z_2-symmetry

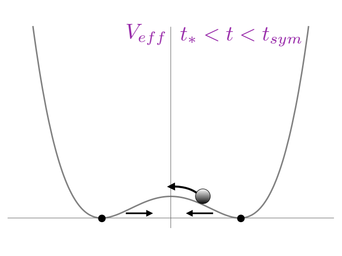
$$\langle \chi \rangle = \sqrt{\frac{Ng^2T^2}{12\lambda} - \frac{M^2}{\lambda}}$$

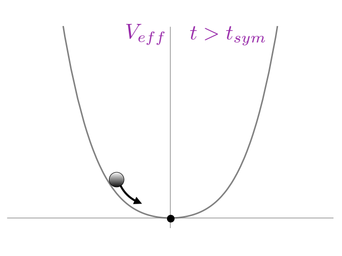
$g^2T^2 \ll M^2$ at late times $\Longrightarrow$ symmetry is restored $\langle \chi \rangle = 0$



$$\frac{d\langle\chi\rangle}{dt} \propto \frac{1}{\sqrt{Ng^2T^2/12 - M^2}} \to \infty \qquad \text{as} \qquad \frac{Ng^2T^2}{12} \to M^2$$

The field χ stops to track the minimum $\langle \chi \rangle$!!!





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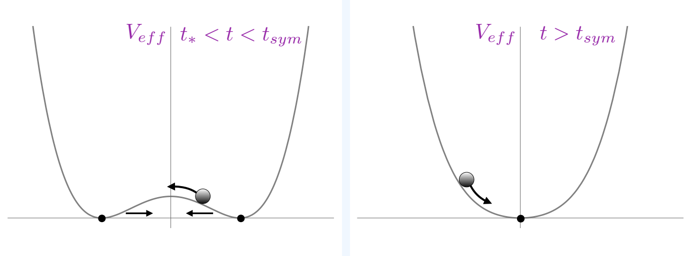
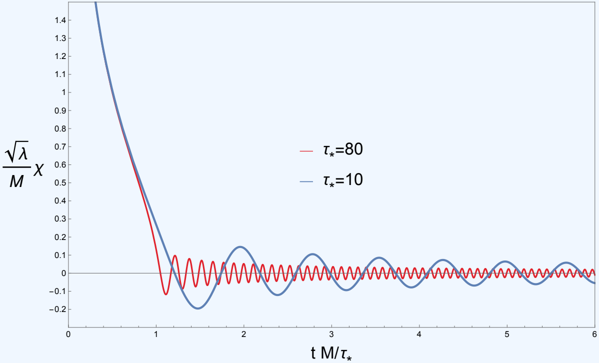


NB Similar to misalignment mechanism in case of axions.

Axions are offset from zero because they are massless (prior to phase transition).

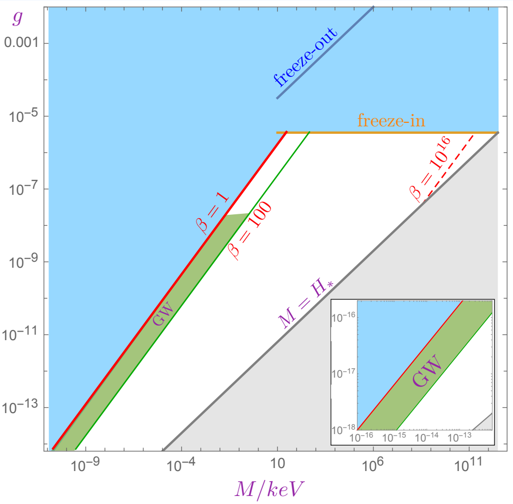
In our case: the offset is due to the temperature-dependent tachyonic mass.



Dark Matter abundance is fulfilled provided that

$$M \simeq 15\ \text{eV} \cdot \frac{\beta^{3/5}}{\sqrt{N}} \cdot \left(\frac{g}{10^{-8}}\right)^{7/5} \qquad \beta \equiv \frac{\lambda}{g^4}$$

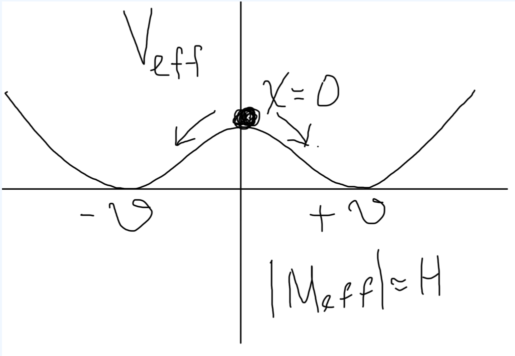
Practically infinite capacity of decreasing g: only for $g \lesssim 10^{-20}$, one has $T_* \lesssim 10$ keV.



$$\beta \equiv \frac{\lambda}{g^4}$$

$$1 \lesssim \frac{1}{\lambda_\phi} \lesssim \beta \lesssim 10^{18}$$

Spontaneous breaking of Z_2-symmetry $\Longrightarrow$ domain wall formation in the early Universe.



$$|M_{eff}| = \frac{N^{1/2} g T_i}{\sqrt{12}} \simeq H(T_i) \Longrightarrow T_i \simeq \sqrt{\frac{100}{g_*(T_i)}} \cdot \frac{N^{1/2} g M_{Pl}}{10}$$

Domain walls are melting

Domain walls are harmless, because their tension decreases as the cube of the temperature.

$$\sigma_{wall} \propto \sqrt{\lambda}\langle\chi\rangle^3 \propto T^3$$

$$\rho_{wall} \simeq \sigma_{wall} H \propto T^5 \qquad \frac{\rho_{wall}}{\rho_{rad}} \propto T(t) \propto \frac{1}{a(t)}$$

Domain walls vanish completely at the inverse phase transition.

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NB Constant tension domain walls: $\rho_{wall} \simeq \sigma_{wall} H \propto T^2$

$$\frac{\rho_{wall}}{\rho_{rad}} \propto \frac{1}{T^2(t)} \propto a^2(t)$$

More weakly coupled means more visible!

Domain walls emit gravitational waves!

See the analysis in Hiramatsu, Kawasaki, Saikawa'2013

$$\rho_{gw} \simeq \frac{\sigma_{wall}^2(t)}{M_{Pl}^2} \qquad F_{gw,peak} \simeq H(t)$$

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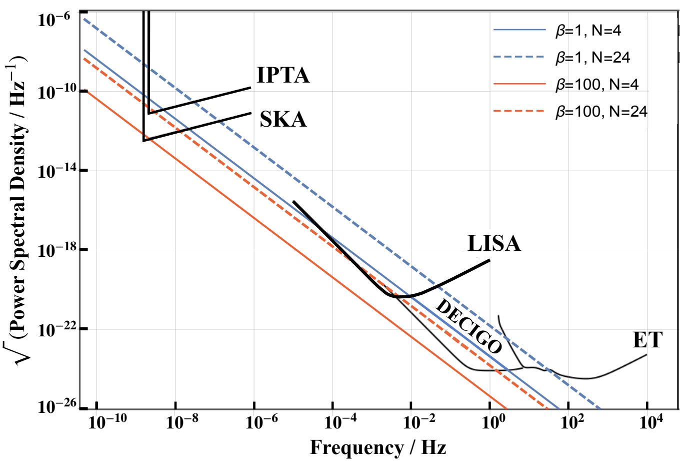
$$\Omega_{gw,peak} \cdot h^2(t_0) \approx \frac{4 \cdot 10^{-14} \cdot N^4}{\beta^2}$$

Vanilla region:

$$\beta \equiv \frac{\lambda}{g^4} \simeq 1 \qquad N \gg 1$$

Gravitational waves



gwplotter.com Moore, Cole, and Berry'14

Z_2-symmetry $\to$ $U(1)$-symmetry

$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}^2 + |D_\mu \chi|^2 - M^2 \cdot |\chi|^2 - \frac{1}{4}\lambda \cdot |\chi|^4 + \frac{1}{2}g^2|\chi|^2|\phi|^2 \,.$$

Melting domain walls $\to$ melting cosmic strings

Emond, S. R., Samanta'21

$$\mu \propto \langle \chi \rangle^2 \propto T^2$$

Existing limits on $G\mu$ assuming constant string tension μ are not applicable!!

Main phenomenology is due to GWs.

GWs emitted by the loops are defined by the number density of the string loops.

Approximate scale-invariance of the model

$$\Longrightarrow$$

dynamics of melting cosmic strings in the radiation-dominated Universe is equivalent to the dynamics of cosmic strings with a constant tension in the flat spacetime.

Vanchurin, Olum, Vilenkin'05

Number density of loops in the flat spacetime:

$$n(t,l) = \frac{1}{l^4}\int_{l/t}^{l/t_s} dx' x'^3 f(x')$$

In the one-scale approach Kibble'85

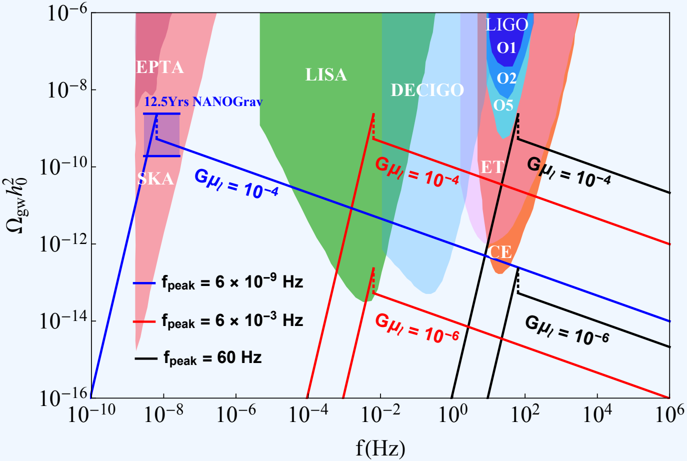
$$f(x) = C\delta(x-\alpha) \qquad C \approx 150 \qquad \alpha \approx 0.1$$

$$P_{gw}^{(j)}(l,F) \approx \frac{\Gamma G\mu^2(t)}{\zeta\left(\frac{4}{3},\infty\right)} \cdot \frac{1}{j^{4/3}} \cdot \delta\left(F - \frac{2j}{l(t)}\right)$$

Vachaspati and Vilenkin'84

One can define $\Omega_{gw} h_0^2$

Low-frequency range: $\Omega_{gw} \cdot h_0^2 \propto f^4$ $\quad f_{gw,peak} \propto g$



High frequency range: $\Omega_{gw} \cdot h_0^2 \propto f^{-1/3}$

DM production at inverse phase transition is generic.

$$V_{eff} = \frac{M^2|\chi|^2}{2} + \frac{\lambda|\chi|^4}{4} - \frac{\mu^2(t)|\chi|^2}{2}$$

$$\mu^2(t) \propto \frac{1}{a^n(t)} \qquad \mu^2(t) \propto T^2(t), R, \mathbf{B}^2 \; \ldots.$$

E. Babichev, D. Gorbunov, S. R.'20   S. R., F. Urban, A. Vikman'20

We deal with the class of models.

Summary

- Thermal fluctuations of hot primordial plasma can lead to abundant Dark Matter production even for extremely weak coupling constants $g^2 \ll 10^{-11}$.
- Weak couplings can be tested through GWs emitted by domain walls or cosmic strings. The peak frequency is pinned to the constant g, i.e., $f_{gw} \propto g$.
- Domain walls are melting and do not overclose the Universe.
- Spectrum of GWs has been estimated for the case of melting cosmic strings.

Thanks for listening!!!

Ευχαριστω