Dark Matter Beyond Freeze-in

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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.

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In this talk:

Dark Matter production beyond freeze-in, or
Dark Matter via Inverse Phase Transition.

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

Scalar Portal Dark Matter

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

χ is DM field

ϕ is in thermal equilbrium with plasma

- Freeze-out: $10^{-8} \ll |g^2| \ll 1$

WIMPS: 1 MeV $\lesssim M \lesssim$ 100 TeV

Initially in thermal equilibrium by sufficiently large couplings $\Longrightarrow$ good prospects for testing.

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- For $0 < g^2 \lesssim 10^{-11}$ Dark Matter from inverse phase transition.

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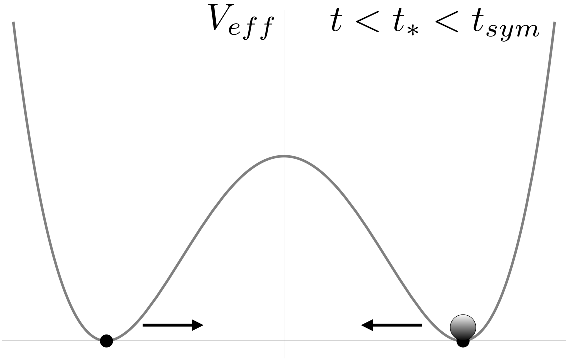
$T \propto \frac{1}{a(t)} \Longrightarrow Z_2$-symmetry breaking at early times

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

At very early times the field χ is tracking its vacuum value $\chi = \langle\chi\rangle$

$$\langle\chi\rangle \propto T(t) \Longrightarrow \frac{\dot{\langle\chi\rangle}}{\langle\chi\rangle} \sim H$$

No DM particles initially – same conditions as for freeze-in



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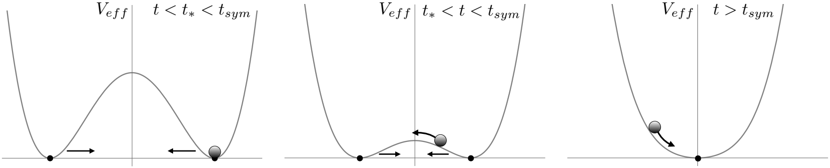
χ stops tracking minimum and starts oscillating at low T



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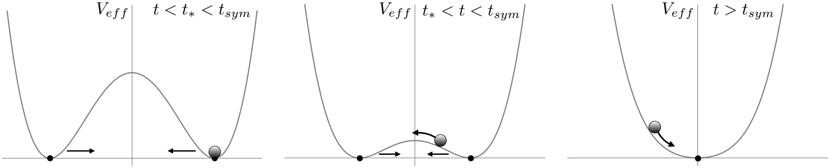
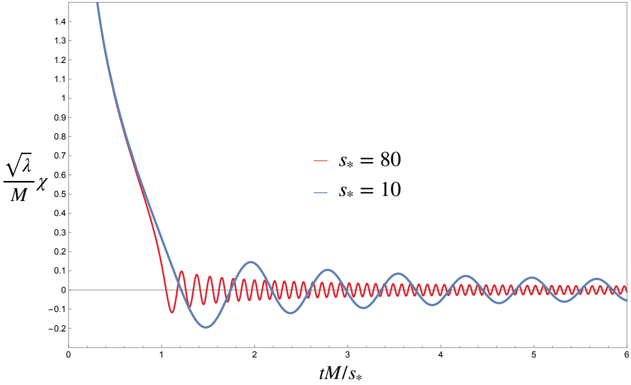


Z_2-symmetry + feeble couplings involved protect stability
$\Longrightarrow$ these oscillations naturally feed into Dark Matter

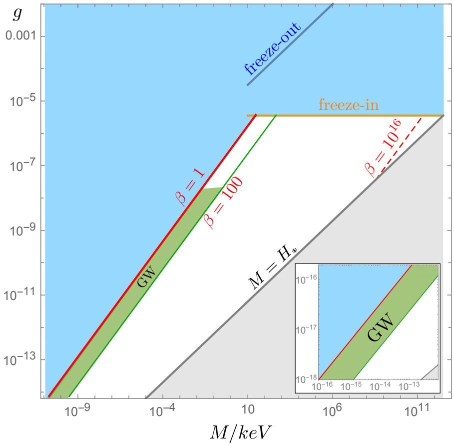


Dark Matter abundance is fulfilled provided that

$$M \simeq 25 \text{ eV} \cdot \frac{\beta^{3/5}}{\sqrt{N}} \cdot \left(\frac{g}{10^{-8}}\right)^{7/5} \qquad \beta \equiv \frac{\lambda}{g^4} \gtrsim 1/\lambda_\phi \gtrsim 1$$

Why being interested in so small masses and/or feeble couplings?

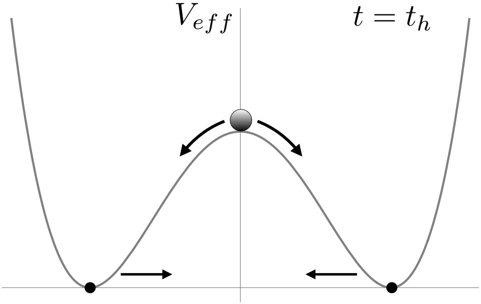
Is there a life beyond freeze-in?



$$\beta \equiv \frac{\lambda}{g^4} \qquad\qquad 1 \lesssim \frac{1}{\lambda_\phi} \lesssim \beta \lesssim 10^{18}$$

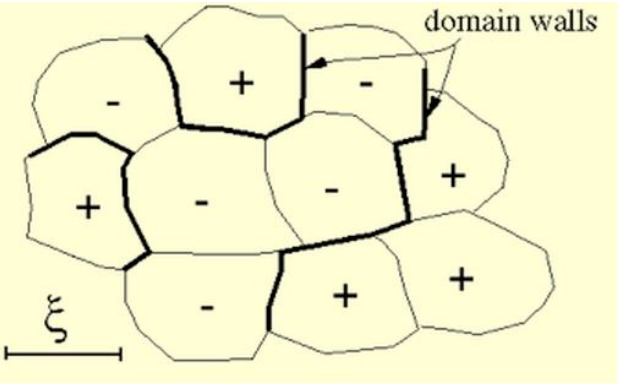
How to probe very small couplings?- Gravitational waves from domain walls

Domain walls are common in models with spontaneous breaking of Z_2-symmetry Zel'dovich et al'74



NB Setting to zero through $\xi R\chi^2/2$ for $\xi \gtrsim 1$

Domain walls separate regions, where $\chi = \pm\langle\chi\rangle$



The picture is taken from http://www.ctc.cam.ac.uk/

Domain wall problem

$$\text{Kink}: \quad \chi(z) = \langle\chi\rangle \cdot \tanh\left(\sqrt{\frac{\lambda}{2}} \cdot \langle\chi\rangle \cdot z\right)$$

$$\text{Domain wall tension:} \quad \sigma_{wall} = \frac{M_{wall}}{S} = \frac{2\sqrt{2\lambda}\langle\chi\rangle^3}{3}$$

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In the scaling regime: one or a few domain walls in the horizon volume.

Ryden, Press, Spergel'89

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$$\rho_{wall} \sim M_{wall} H^3 \sim \sigma_{wall} H$$

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

$$\frac{\rho_{wall}}{\rho_{rad}} \propto \frac{1}{T^2(t)} \propto a^2(t) \Longrightarrow$$ domain walls overclose the Universe!

No domain wall problem in our case

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

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

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Energy density of domain walls redshifts faster than radiation

Domain walls completely vanish at inverse phase transition

Vilenkin'81

Do melting domain walls leave any trace?

Gravitational waves from domain walls

Numerical simulations: Hiramatsu, Kawasaki, Saikawa'13

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

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$$\boxed{f_{gw,peak} \simeq 60 \text{ Hz} \cdot \sqrt{\frac{N}{B}} \cdot \left(\frac{g}{10^{-8}}\right)} \qquad \boxed{\Omega_{gw,peak} \cdot h_0^2 \approx \frac{4 \cdot 10^{-14} \cdot N^4}{B \cdot \beta^2}}$$

$B = \ln^2 \frac{2\,\langle\chi\rangle}{\delta\chi} \simeq 1 - 100$ takes into account finite time of roll

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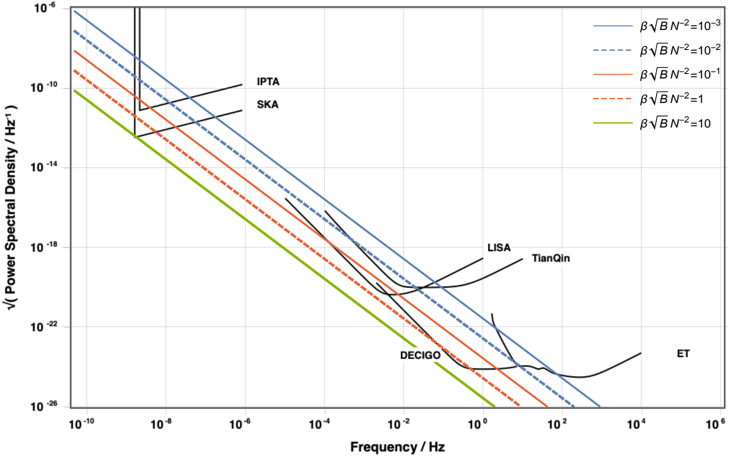
Vanilla region: $\boxed{g^2 \lesssim 10^{-16}}$ $\boxed{\beta \equiv \frac{\lambda}{g^4} \simeq 1}$ $\boxed{N \gg 1}$

Weaker coupled means more visible!

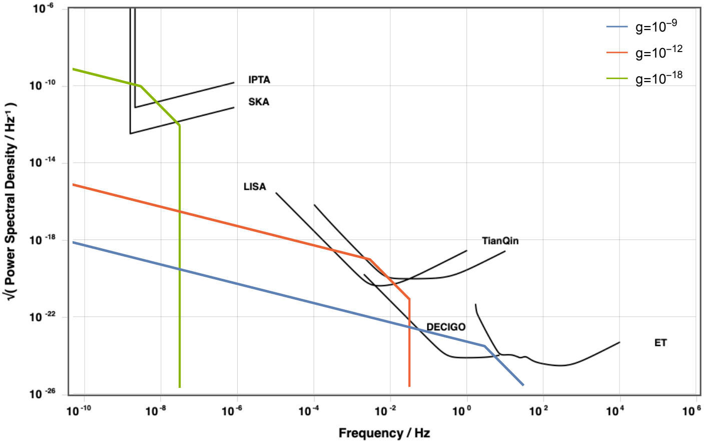
Gravitational waves vs sensitivity curves



Strain $\sqrt{S_h}$ $\qquad \Omega_{gw}H_0^2 = \frac{2\pi^2 f^3}{3} S_h$

gwplotter.com Moore, Cole, and Berry'14

Preliminary spectrum of GWs



$$\sqrt{S_h} \sim \frac{1}{\sqrt{f}} \ (f < f_{gw,peak}) \qquad \sqrt{S_h} \sim \frac{1}{f^2} \ \ (f_{gw,peak} < f < f_{cutoff})$$

Different spectrum compared to the case of constant tension domain walls.

Summary

- Dark Matter can be produced via inverse phase transition even for tiny portal couplings $g^2 \ll 10^{-11}$.
- Weak couplings can be tested through GWs emitted by domain walls. 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.

Merci Beaucoup! Thanks for your attention!!!