Cosmology with inverse phase transition

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Quantum Gravity and Cosmology

(dedicated to A.D. Sakharov's centennial)

talk is based on 2104.13772
and ongoing work by E.Babichev, D.G., S.Ramazanov and A.Vikman

The talk in brief

- Take any model where
  a symmetry is broken in the VERY early Universe
  but later it gets restored
- In the late Universe
  no problems with goldstones, topological defects, etc
- imprints like gravitational waves (GW) can be left...
- at phase transitions many particles can be produced,
  including dark matter (DM)
- GW signal (e.g. f_{GW}) and DM parameters (e.g. M)
  are related

Cosmic transitions in the Standard Model

Crossovers (if temperature was high enough)

- Electroweak (EW) transition
- confinement (QCD)

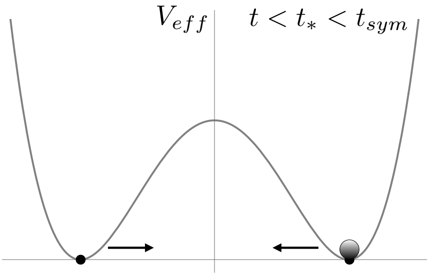
No any observables

Cosmic transitions in beyond the SM

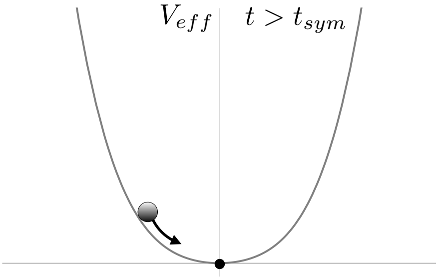
- axions, black holes, etc at QCD
- Ist order EW phase transition with extended Higgs sector
- GUT-like phase transitions:
  heavy stable (dangerous) stuff: topological defects
  light particles (dangerous): goldstone bosons

Symmetry is spontaneously broken at $T = 0$

Inverse phase transition



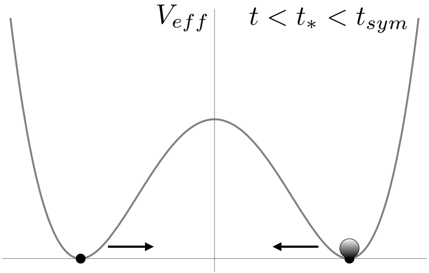
early times



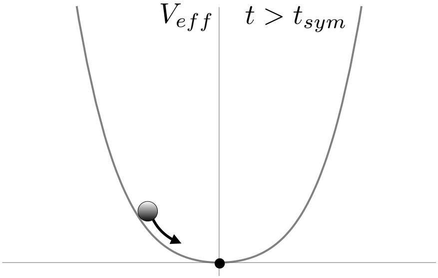
late times

It can be thermal or non-thermal

Inverse phase transition



early times

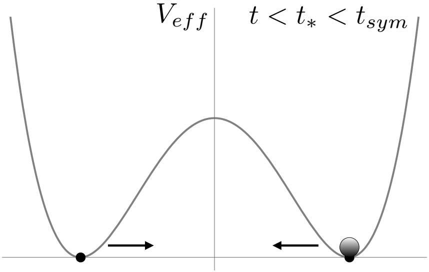


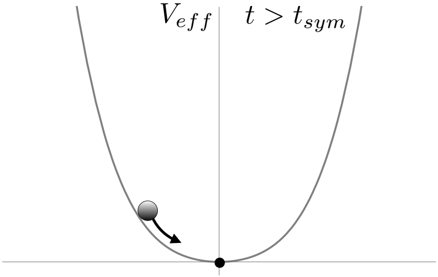
late times

$$\mathscr{V}_{eff}(\chi) = \frac{M^2\chi^2}{2} + \frac{\lambda\chi^4}{4} - \frac{g^2\chi^2\phi^\dagger\phi}{2}.$$

provided $\beta \equiv \lambda/g^4 > 1/\lambda_\phi > 1$

Phase transition in the plasma: $\langle\phi^\dagger\phi\rangle \propto T^2$, $\quad g \ll 1$



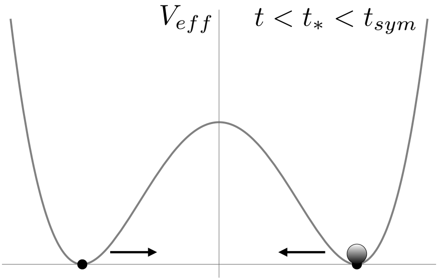


eff potential for χ

T-dependent mass term

$$V_{eff} = \frac{M^2\chi^2}{2} + \frac{\lambda\cdot(\chi^2 - \eta^2(T))^2}{4}\,, \qquad \eta^2(T) \approx \frac{Ng^2T^2}{12\lambda}$$

Thermal transition: Domain Walls for Z_2



$$T_i \simeq \sqrt{\frac{100}{g_*(T_i)}}\,\frac{\sqrt{N} g M_{Pl}}{10}$$

T-dependent tension

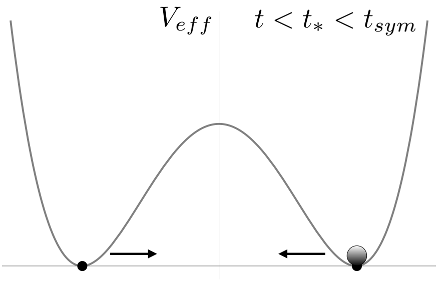
$$\sigma_{wall} = \frac{2\sqrt{2\lambda}\,\eta^3(T)}{3}$$

Broken symmetry when $M < M_{th} \sim \sqrt{\lambda}\,\eta$

DWs formation starts after: $M_{th} \sim \sqrt{\lambda}\,\eta(T) \gtrsim H(T)$

$$V_{eff} = \frac{M^2\chi^2}{2} + \frac{\lambda\cdot\left(\chi^2 - \eta^2(T)\right)^2}{4}\,, \qquad \eta^2(T) \approx \frac{N g^2 T^2}{12\lambda}$$

Domain Walls evolution



$$T_i \simeq \sqrt{\frac{100}{g_*(T_i)}}\,\frac{\sqrt{N} g M_{Pl}}{10}$$

T-dependent tension

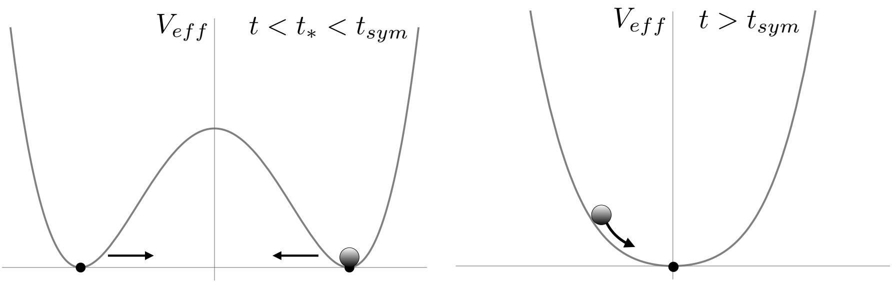
$$\sigma_{wall} = \frac{2\sqrt{2\lambda}\,\eta^3(T)}{3}$$

Entering scaling regime: a few DWs per horizon W.Press, B.Ryden, D.Spergel (1989)

$$M_{wall} \sim \sigma_{wall} \times l_H^2\,, \quad \rho_{DW} \sim \frac{M_{wall}}{l_H^3} \sim \sigma_{wall} H$$

At RD-satge $$\frac{\rho_{wall}}{\rho_{rad}} \sim \frac{N^2}{30 g_*(T)\beta} \cdot \frac{T}{T_i} < 1$$

Domain Walls evolution with decreasing temperature

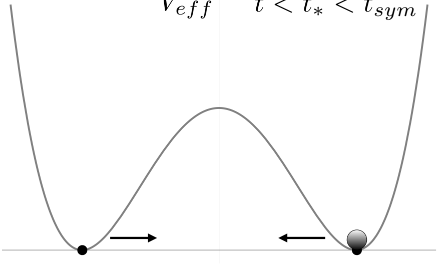


$$\sigma_{wall} = \frac{2\sqrt{2\lambda}\,\eta^3(T)}{3} \propto T^3 \to 0$$

DWs disappear…

but leave imprints in gravitational waves !!

GW production by Domain Walls



$$P \sim \frac{\dddot{Q}_{ij}^2}{M_{Pl}^2}, \quad |Q_{ij}| \sim M_{wall} \times l_H^2$$

GW energy density

$$\rho_{gw} \sim \frac{P \cdot t}{l_H^3} \sim \frac{\sigma_{wall}^2}{M_{Pl}^2} \propto T^6$$

In the scaling regime we use simulations

T.Hiramatsu, M.Kawasaki, K.Saikawa (2014)

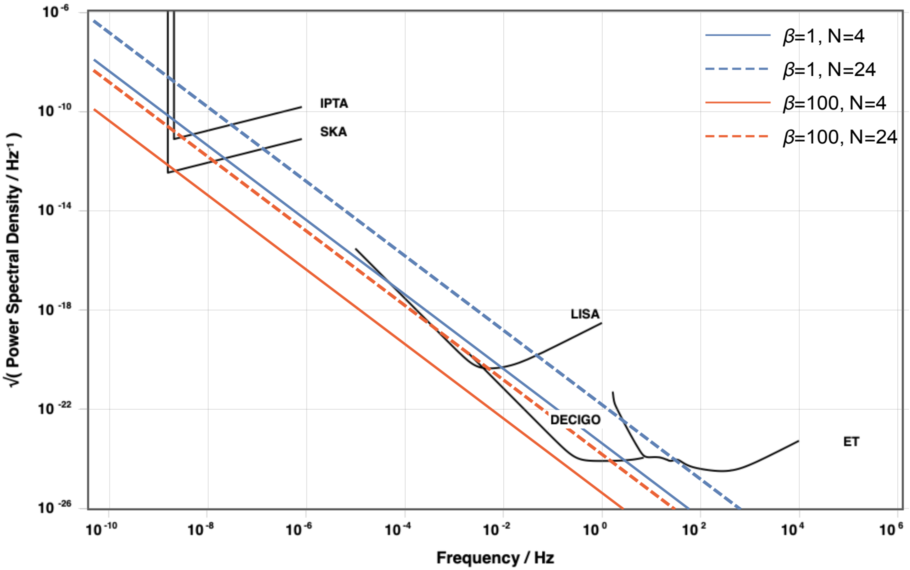
$$\Omega_{gw}(t_i) \approx \frac{\lambda \tilde{\varepsilon}_{gw} \mathscr{A}^2 \eta_i^6}{27\pi H_i^2 M_{Pl}^4} \to \Omega_{gw}(t_0) \approx \frac{4 \cdot 10^{-14} \cdot N^4}{\beta^2} \cdot \left(\frac{100}{g_*(T_i)}\right)^{7/3}$$

fractional energy density per log-frequency at peak

$f_{gw}(t_i) \simeq H_i/(2\pi)$

$$f_{gw} \equiv f_{gw}(t_0) \simeq 60\ \text{Hz} \cdot \sqrt{N} \cdot \frac{g}{10^{-8}} \cdot \left(\frac{100}{g_*(T_i)}\right)^{1/3}$$

Power spectral density S_h: $\Omega_{gw}(t_0)H_0^2 \equiv S_h 2\pi^2 f_{gw}^3/3$



GW signal reflects the early-time dynamics

Why is it interesting... ?

with Z_2-symmetry... χ can form Dark Matter component

Tesing DM model with GW signal !!

Three options for the DM production, recall $g \ll 1$

- Thermal production in plasma: freeze-out

$$\langle\sigma_{\chi\chi\to\phi\phi} v\rangle \simeq \frac{Ng^4}{8\pi E^2}\,, \quad \Omega_\chi \simeq \frac{3\times 10^{-11}\,\text{GeV}^{-2}}{\langle\sigma_{\chi\chi\to\phi\phi} v\rangle} \quad \to \quad g \approx \frac{2\cdot 10^{-2}}{N^{1/4}}\sqrt{\frac{M}{\text{GeV}}}$$

requires thermalization and sufficiently large coupling g

- Non-thermal production in plasma: freeze-in

$$\frac{dn_\chi}{dt} + 3Hn_\chi \approx \sum_i \langle\sigma_{\phi_i\phi_i\to\chi\chi} v\rangle \cdot n^2_{\phi_i,eq}\,, \qquad \Omega_\chi \propto M\cdot n_\chi\,, \quad \to \quad g \approx \frac{5\cdot 10^{-6}}{N^{1/4}}$$

assuming $M \gtrsim m_\phi$

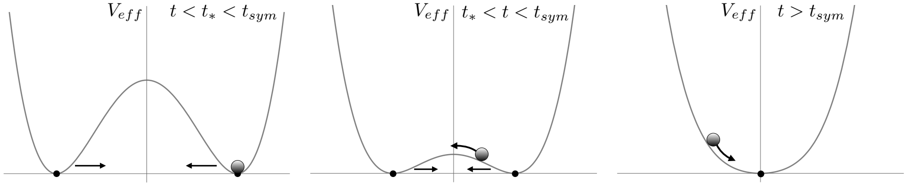
- Production by starting the scalar field oscillations: a variant of vacuum misalignment

$$\rho_\chi(t) \simeq \frac{M^2\chi_*^2}{2}\cdot\left(\frac{a_*}{a(t)}\right)^3\,.$$

stop field tracking the vacuum...

Initiating oscillations: departure from tracking

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



Departure from adiabaticity as $T \searrow$

$$M_{eff}^2 \approx 2\lambda\langle\chi\rangle^2\,, \qquad \left|\frac{\dot{M}_{eff}}{M_{eff}^2}\right| \ll 1 \quad \to \quad \left|\frac{\dot{M}_{eff}}{M_{eff}^2}\right| \simeq 1 \quad \text{at} \quad \chi_* \simeq \frac{(2M^2H_*)^{1/3}}{\sqrt{2\lambda}}\,.$$

$$\Omega_\chi = \Omega_{DM} \quad \to \quad M \simeq 15\,\text{eV}\cdot\frac{\beta^{3/5}}{\sqrt{N}}\cdot\left(\frac{g}{10^{-8}}\right)^{7/5}\cdot\left(\frac{g_*(T_*)}{100}\right)^{2/5}\,,$$

The mechanism is generic, e.g.

a stage with

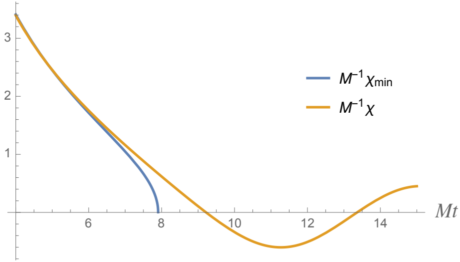
E.Babichev,D.G.,S.Ramazanov (2020)

$$p = w\rho\,, \quad R = -3\cdot(1-3w)\cdot H^2$$

DM with selfcoupling

$$\mathscr{L} = \frac{(\partial_\mu\chi)^2}{2} - \frac{M^2\chi^2}{2} - \frac{\lambda\chi^4}{4} - \frac{\zeta}{2}\cdot\chi^2\cdot R$$

χ is in the false vacuum at large H

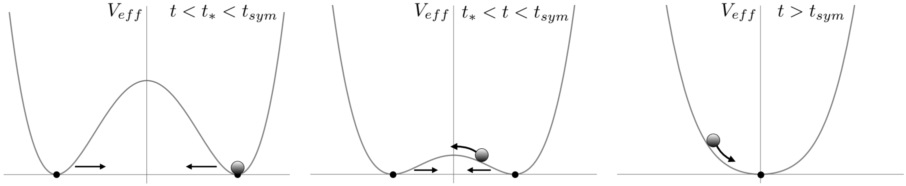


at $-\zeta R(t_*) \simeq M^2$ it changes and χ starts to oscillate gravitational misalignment

$$\rho_{DM}(t_*) = \frac{M^2\cdot\chi_*^2}{2} \simeq \frac{\left(M^5 H_*\right)^{2/3}}{4\lambda}$$

Initiating oscillations: departure from tracking

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

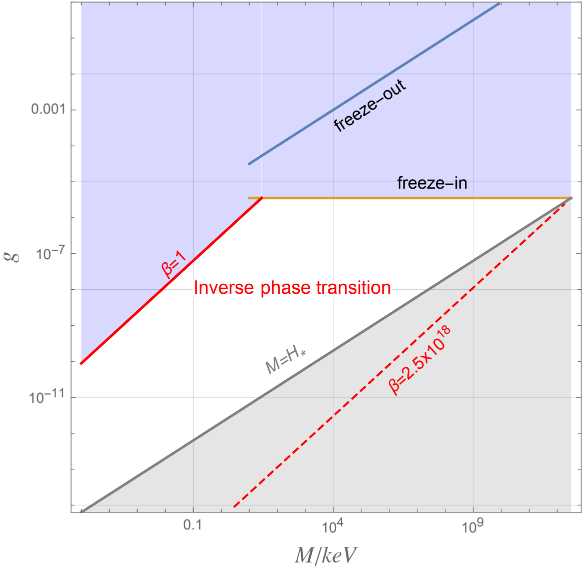


Departure from adiabaticity as $T \searrow$

$$M_{\rm eff}^2 \approx 2\lambda\langle\chi\rangle^2\,, \qquad \left|\frac{\dot M_{\rm eff}}{M_{\rm eff}^2}\right| \ll 1 \qquad \to \qquad \left|\frac{\dot M_{\rm eff}}{M_{\rm eff}^2}\right| \simeq 1 \quad \text{at} \quad \chi_* \simeq \frac{(2M^2H_*)^{1/3}}{\sqrt{2\lambda}}\,.$$

$$\Omega_\chi = \Omega_{DM} \qquad \to \qquad M \simeq 15\ \text{eV}\cdot\frac{\beta^{3/5}}{\sqrt{N}}\cdot\left(\frac{g}{10^{-8}}\right)^{7/5}\cdot\left(\frac{g_*(T_*)}{100}\right)^{2/5}\,,$$

Dark Matter



model potential:

$$\frac{M^2\chi^2}{2} + \frac{\lambda\chi^4}{4} - \frac{g^2\chi^2\phi^\dagger\phi}{2}$$

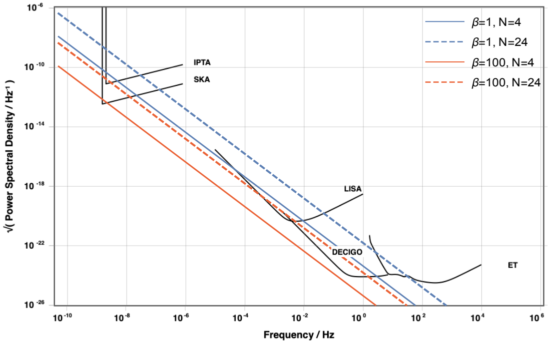
vacuum stability:

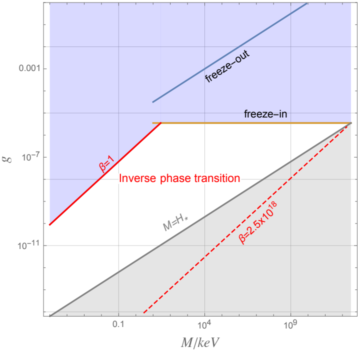
$$\beta \equiv \frac{\lambda}{g^4} > 1$$

beginning of oscillations:

$$M > H_* \equiv H(t_*)$$

Gravitational Wave probe of Dark Matter





$$f_{gw}(t_0) \simeq 60\text{ Hz} \cdot \sqrt{N} \cdot \frac{g}{10^{-8}} \cdot \left(\frac{100}{g_*(T_i)}\right)^{1/3}$$

$$\Omega_{gw}(t_0) \approx \frac{4 \cdot 10^{-14} \cdot N^4}{\beta^2} \cdot \left(\frac{100}{g_*(T_i)}\right)^{7/3}$$

$$M \simeq 15\text{ eV} \cdot \frac{\beta^{3/5}}{N^{6/5}} \cdot \left(\frac{\sqrt{N}g}{10^{-8}}\right)^{7/5} \cdot \left(\frac{g_*(T_*)}{100}\right)^{2/5}$$

Summary

- Inverse phase transitions in the early Universe have imprints in Gravitational Waves
- Inverse phase transitions may have other impacts on cosmology, like Dark Matter production
- GW signals can help to check forother impacts (e.g. Dark Matter)

It's a generic setup,
however, there are issues to be addressed in each particular model, e.g.:

– DW: relaxation to the scalinng solution
– GW: numerical results exist for constant tensions only
– DM: initial conditions (symmetric state, no isocurvature modes, onset of oscillations)
– ϕ should not spoil cosmology

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