Cosmological phase transitions with fast bubbles

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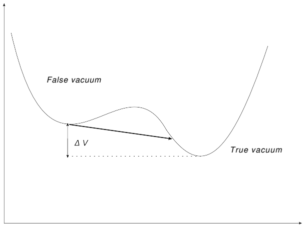
together with Barni, Chakraborty, Vanvlasselaer, Yin

- Congratulations Serguey on your 70th birthday!
- I wish you a lot and a lot of years of active research!

Introduction

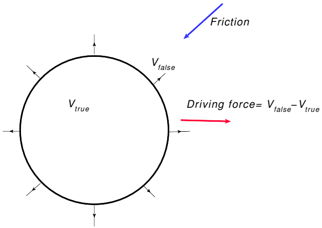


- False and true vacua are separated by the potential barrier
- Transition occurs by bubble nucleation (Coleman 77)

$$\Gamma(T) \sim \max\left[T^4\left(\frac{S_3}{2\pi T}\right)^{3/2} e^{-S_3/T}, R_0^{-4}\left(\frac{S_4}{2\pi}\right)^2 e^{-S_4}\right]$$

Bubbles of true vacua are formed, which later expand

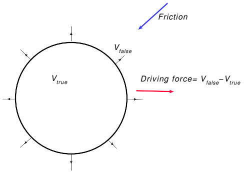
Fast bubbles



Forces acting on the bubble

- Driving force $\sim V_{true} - V_{false}$ due to the energy difference between true and false vacuum
- Friction forces due the bubble wall collision with plasma particles. These forces must vanish in the limit of zero temperature $T \to 0$
- **If $T \ll \Delta V^{1/4}$ the friction forces cannot prevent bubbles from reaching relativistic velocities**
- in the regime of supercooling i.e. $T \ll \Delta V^{1/4}$ bubble must be relativistic

How fast?

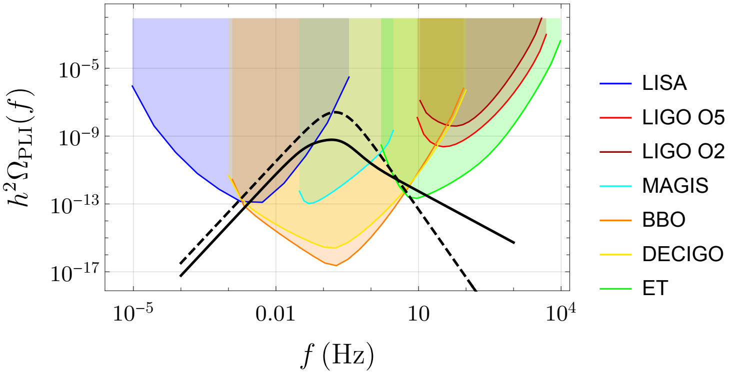


- the velocity is controlled by the balance of the forces acting on the bubble, calculation of the friction from plasma is a very complicated task, but for $\gamma \gg 1$ things simplify, since we can consider individual particle collision on the bubble
- $1 \to 1$ transition $\Delta P \sim \Delta m^2 T^2$ 0903.4099
- $1 \to 1+$ soft radiation $\Delta P \sim \gamma \Delta m T^3$ 1703.08215

If temperature is sufficiently low or/and there are no vectors changing their mass $\gamma \gg 1$

Why fast bubbles are interesting?

strong signals in stochastic GW background



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Collision energy between the bubble wall and the plasma particle can be much larger than the transition scale

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- Is it consistent to ignore all other degrees of freedom which are decoupled at the phase transition?
- What effect these heavy fields can have?

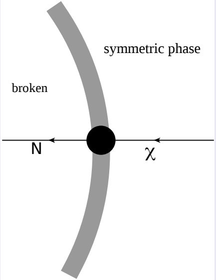
$1 \to 1$ transition, with mixing *2010.02590*

Consider the following lagrangian,

$$\mathcal{L}_{\text{fermion}} = i\bar{\chi}\partial\!\!\!/\chi + i\bar{N}\partial\!\!\!/ N + M\bar{N}N + Y_{\text{mixing}}\phi\bar{\chi}N$$
$$M \gg \langle\phi\rangle$$

N-field is decoupled at PT and its density is suppressed by $\exp(-M/T)$

Will N field during χ - wall scattering?



Momentum is not conserved along z direction, $\chi \to N$ conversion is allowed

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N field production during χ - wall scattering

$$n_N \sim \underbrace{\int \frac{d^3p}{(2\pi)^3} f_p}_{\text{Incident } \psi \text{ density}} \underbrace{P(\chi \to N)}_{\text{Probability of transition}} \sim T^3 P(\chi \to N)$$

$$P(\psi \to N) \sim (\text{mixing angle})^2 \sim \frac{Y^2_{\text{mixing}}\langle\phi\rangle^2}{M^2}$$

$\boxed{T^3 \frac{Y^2_{\text{mixing}}\langle\phi\rangle^2}{M^2} \gg (MT)^{3/2} e^{-M/T}}$ This extra density will be much larger than the equilibrium value.

$1 \to 1$ transition, with mixing

Wall width is finite, $L \neq 0$!

processes with momentum loss $\Delta p_z L \gg 1$ must be suppressed, since L^{-1} is a typical energy scale of the interaction with the wall.

Situation is similar to the neutrino oscillations in matter. If the $\Delta p_z L \gg 1$ is satisfied the evolution is "adiabatic", so the state remains in the lightest flavour:

$$\chi \to \chi_{\langle\phi\rangle\neq 0}$$

$\psi_{\langle\phi\rangle\neq 0}$ is the lightest eigenstate in the broken phase (inside the bubble)

We need to be in the "anti-adiabatic" regime

$$\Delta p_z L \lesssim 1 \to \frac{M^2}{E} \lesssim L^{-1}$$

Effects from heavy particle production

New mechanism of heavy particle production

$$n_{heavy} \sim \frac{Y^2 \langle \phi \rangle^2}{M_{heavy}^2} T_{nuc}^3$$

Applications?

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- New contribution to the friction on the bubble wall
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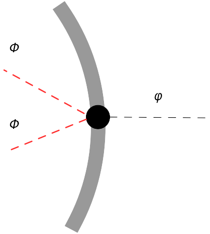
- Baryogenesis : the process of heavy particles production is out of equilibrium

DM production

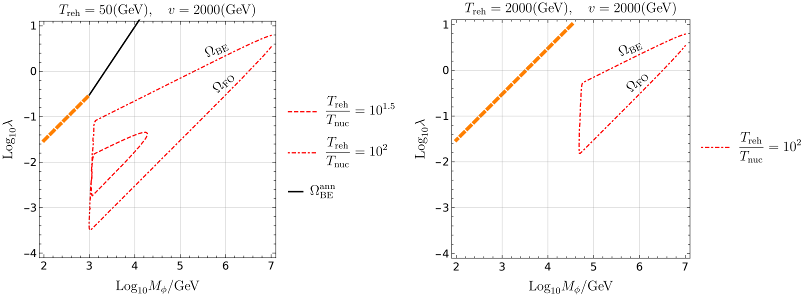
$$\lambda\phi^2\Phi^2_{\rm heavy} + M^2_{\rm heavy}\Phi^2_{\rm heavy}$$

there will be $\phi \to \Phi_{\rm heavy}\Phi_{\rm heavy}$ production during the transition through the wall. Since the trilinear vertex $\phi\Phi\Phi$ is position dependent and momentum is not conserved.



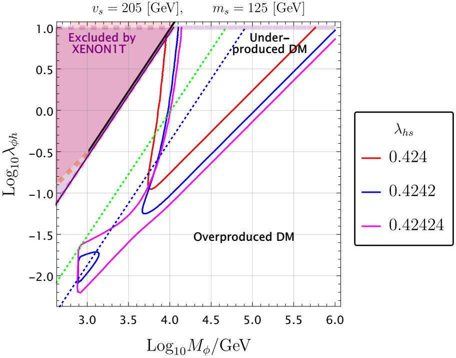
$$\Omega^{\rm today}_{\phi,\rm tot} h^2 \approx \left(\frac{T_{\rm nuc}}{T_{\rm reh}}\right)^3 \times \Bigg[\underbrace{0.1 \times \left(\frac{0.03}{\lambda}\right)^2 \left(\frac{M_\phi}{100\ \rm GeV}\right)^2}_{\rm FO} + \underbrace{5 \times 10^3 \times \lambda^2 \frac{v}{M_\phi}\left(\frac{v}{\rm GeV}\right)}_{\rm BE}\Bigg].$$

DM production in phase transition



DM production during the EW phase transition?

SM extended with a real singlet to achieve the first order phase transition



Summary

- First order phase transitions with ultra relativistic bubbles in the early universe lead to very interesting scenarios.
- Particles seemingly decoupled are playing an important role and can be produced abundantly. Important phenomenological consequences.
    - Modification of the bubble expansion velocity.
    - DM production
    - Models of baryogenesis
- **all of these must be accompanied with strong stochastic GW signal observable at current/future experiments.**