

First order phase transitions with ultra fast bubbles: dynamics and applications

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New Physics Directions in the LHC era and beyond

MPIK, Max Planck Institute for Nuclear Physics

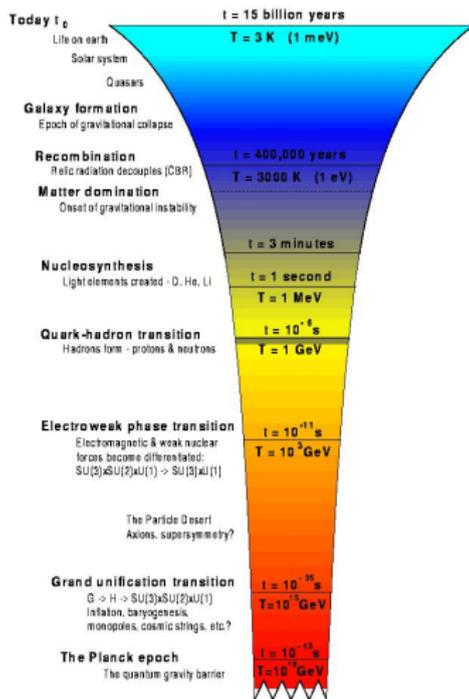
based on 2207.02230, 2106.14913, 2101.05721, 2010.02590, 2310.06972

with Barni, Chakraborty, Vanvlasselaer, Yin, Petrossian

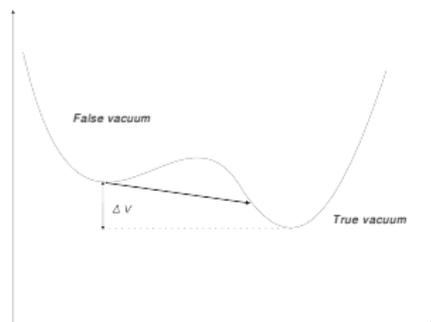
Phase transitions in the early universe

- ▶ Current temperature of the universe is $\sim 10^{-3}\text{eV}$
- ▶ $T \sim 160 \text{ MeV}$ QCD becomes deconfined, chiral symmetry is restored
- ▶ $T \sim 100 \text{ GeV}$ EW is restored

In SM both of the phase transitions are smooth crossovers, but in BSM first order phase transitions are ubiquitous



FOPT and tunneling

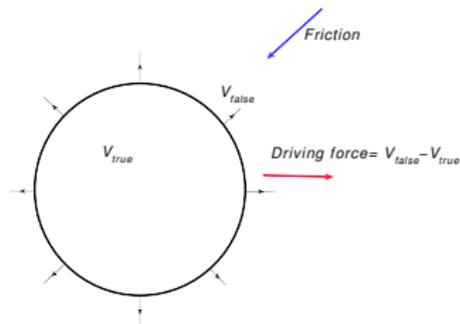


- ▶ False and true vacua are separated by the potential barrier
- ▶ Transition occurs by bubble nucleation (Coleman 77)

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

Bubbles of true vacua are formed, which later expand

Relativistic 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 $T \rightarrow 0$
- ▶ **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

Why it is important?

- ▶ Baryogenesis?
- ▶ Prediction for stochastic gravitational wave signal?

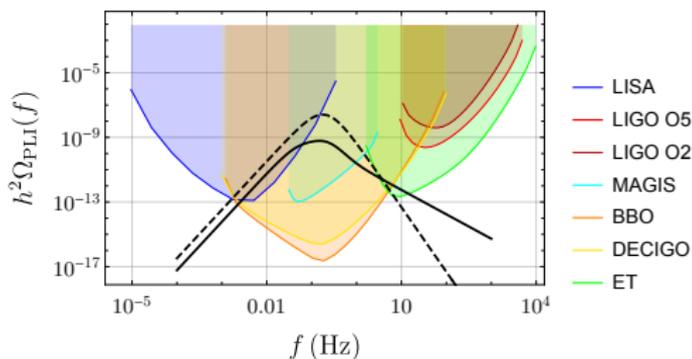


Figure: solid- runaway, dashed fixed velocity

- ▶ production of primordial Black holes? ...

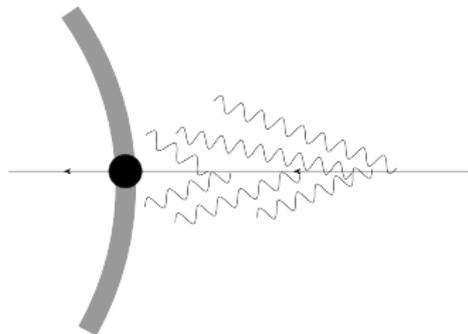
How fast?

- ▶ 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 (*talk by L.Delle Rose on Thursday*).
 - ▶ If $\gamma \gg 1$ interaction with the wall occur at distances $\sim \frac{L_0}{\gamma} \ll T \Rightarrow$ we can treat the particles colliding with the wall individually
- ▶ Pressure = Flux \times Momentum transfer
 - ▶ $1 \rightarrow 1$ transition $\Delta P \sim \Delta m^2 T^2$ 0903.4099 Bodeker Moore

Bubble motion @ NLO

Pressure effects at NLO in the presence of vector fields obtaining their mass during the phase transition leads to qualitatively different behaviour

(*Bodeker-Moore 1703.08215, 2112.07686, 2310.06972*) $P_{NLO} \propto \gamma T^3 m$



Effect is dominated by soft vector emission, since in this case the momentum transfer is most efficient (*lightning talk today by G. Barni*)

γ has upper bound!

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

Ultra fast bubbles: physics implications

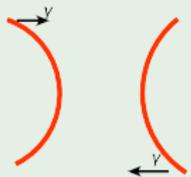
Collision of the bubble shell with plasma



$$\sqrt{s} \sim E_{CM} \sim \sqrt{\gamma T \langle \phi \rangle}$$

2207.02230, 2106.14913, 2101.05721, 2010.02590, 2306.15555, 2207.05096, 2106.15602

Two bubble shell collisions

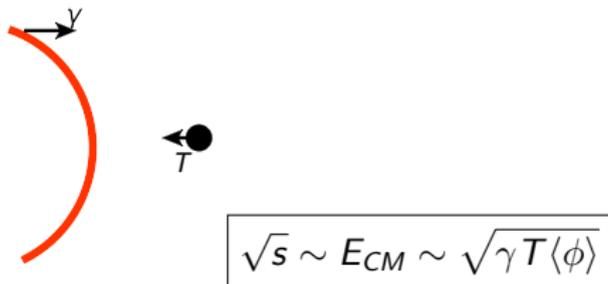


$$\sqrt{s} \sim E_{CM} \sim \gamma \langle \phi \rangle$$

Nucl. Phys. B 374 (1992) 446, 1211.5615, 1608.00583, 2306.15555, 2308.13070, 2308.16224, 2403.03252

We are testing energies which can be much larger than the scale of the phase transitions $E_{CM} \gg \langle \phi \rangle$!

Collision of the bubble shell with plasma



- ▶ New heavy degrees of freedom can be produced ! The process can be with single or pair production

$light + bubble \rightarrow heavy, light + bubble \rightarrow heavy + heavy$

$$M_{heavy}^{max} \lesssim \sqrt{\gamma T \langle \phi \rangle} \Leftrightarrow \Delta p_z \lesssim L_w^{-1} \sim \langle \phi \rangle$$

Physics implications?

This process can further effect the motion of the bubble, for example it can stop the accelerating expansion

New possibilities for baryogenesis, which can happen with fast bubble motion opposite to the usual EWBG regime

Non thermal Dark Matter production

New contribution to friction 2010.02590

$$\text{Pressure} \sim \underbrace{\int \frac{d^3 p}{(2\pi)^3} f_p}_{\text{Incident flux}} \times \underbrace{P(\text{Light} \rightarrow \text{Heavy})}_{\text{Probability of transition}} \times \underbrace{\frac{M^2}{2E}}_{\text{momentum transfer}}$$

$$P(\text{Light} \rightarrow \text{Heavy}) \sim \frac{Y^2 \langle \phi \rangle^2}{M^2} \Rightarrow$$

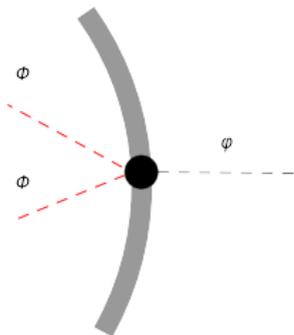
$$\text{Pressure} \sim Y_{\text{mixing}}^2 \langle \phi \rangle^2 T^2 \times \theta(\gamma T - M^2 L)$$

Friction is not suppressed by the heavy particle mass!

Non-thermal DM production

$$\lambda\phi^2\Phi_{\text{heavy}}^2 + M_{\text{heavy}}^2\Phi_{\text{heavy}}^2$$

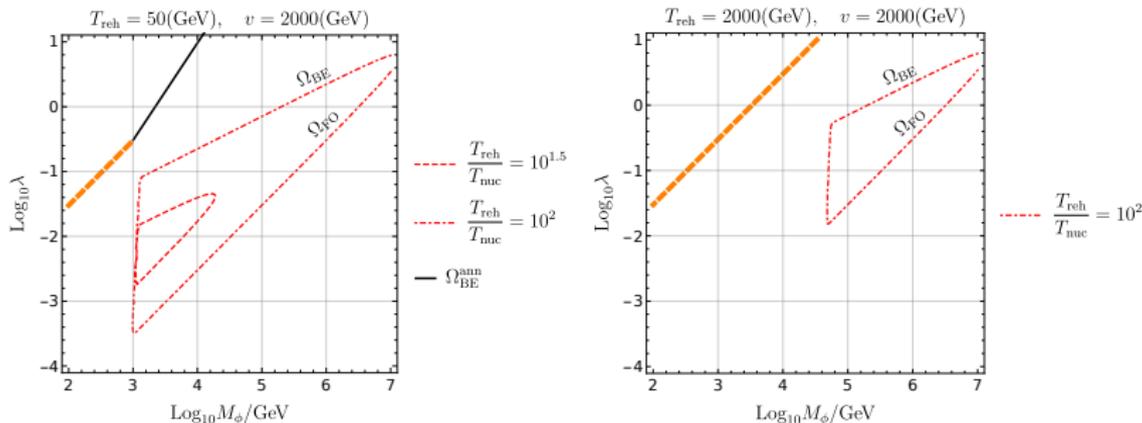
there will be $\phi \rightarrow \Phi_{\text{heavy}}\Phi_{\text{heavy}}$ production during the transition through the wall. Since the trilinear vertex $\phi\Phi\Phi$ is position dependent and momentum is not conserved.



$$n_{DM} \sim \frac{\lambda^2 \langle \phi \rangle^2 T^3}{12\pi^4 M_{\text{heavy}}^2} \times \exp \left[-\frac{M_{\text{heavy}}^2}{2\gamma \langle \phi \rangle T} \right]$$

Maximal mass is bounded by the c.o.m. energy $\sim \sqrt{\gamma \langle \phi \rangle T}$

DM production in phase transition



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

Properties of DM

- ▶ DM can be generically very heavy and is produced with the boost $\gamma_{DM} \sim \frac{M_{heavy}}{T} \gg 1$?

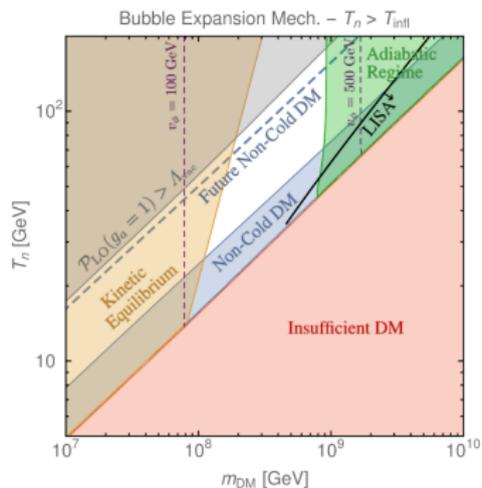
$$\Gamma_{DM+plasma \rightarrow DM+plasma} > H$$

In this case DM loses its energy quickly, and it becomes non-relativistic.

$$\Gamma_{DM+plasma \rightarrow DM+plasma} < H$$

Interactions with plasma are not strong enough, DM remains boosted.

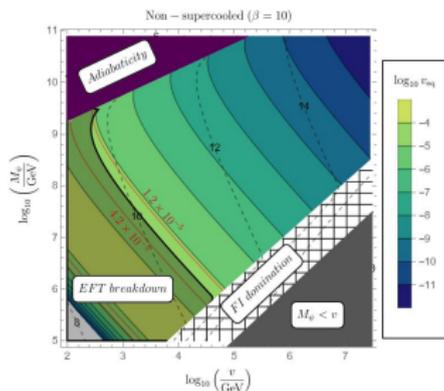
Hot and heavy Dark Matter



from Baldes et al 2207.05096

shaded region corresponds to $v(t_{\text{eq}}) \gtrsim 5 \times 10^{-5}$

Hot and heavy DM with higher dimensional portals:



$$\frac{\phi^2 \psi_{DM}^2}{\Lambda}$$

Dark matter is even stronger boosted

$$\gamma_{DM} \sim \frac{\gamma_{\text{wall}} \langle \phi \rangle}{M_{DM}}$$

Work in progress! with Nagels, Vanvlasselaer and Yin

Baryogenesis with fast bubbles: Sakharov's conditions

The process must be out of equilibrium: Heavy particle production in plasma wall collisions is always out of equilibrium

CP & C violation: CP violation in the light-heavy coupling \Rightarrow number of the heavy particles and antiparticles produced is different

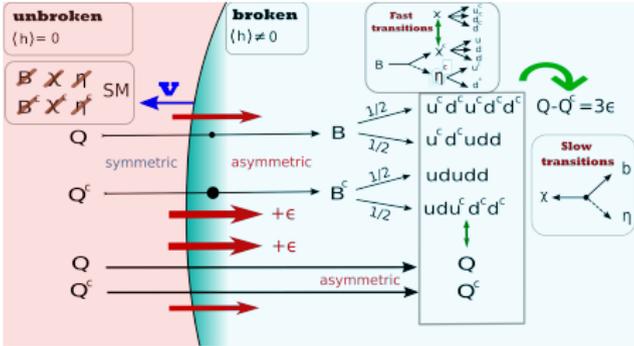
B violation: EW sphalerons might not be enough, maybe need a new source of B violation.

Prototype model: EW baryogenesis with fast bubbles

$$\mathcal{L} = \mathcal{L}_{SM} + m_\eta^2 |\eta|^2 + \sum_{I=1,2} M_I \bar{B}_I B_I + \left(\sum_{I=1,2} Y_I (\bar{B}_I H) P_L Q + y_I \eta^* \bar{B}_I P_R \chi + \kappa \eta^c du + \frac{1}{2} m_\chi \bar{\chi}^c \chi + h.c. \right)$$

- ▶ B_I vector like quark with charge $-1/3$, singlet under $SU(2)$
- ▶ η scalar with $Q(\eta) = 1/3$, χ - Majorana fermion
- ▶ $B(\eta) = 2/3$, $B(\chi) = 1$
- ▶ Baryon number violation is coming from χ mass and Baryon number violated by 2, proton will be stable.

Model at work



- ▶ $M_B \gg v_{EW}$ so at the moment of PT there are no B in the universe
- ▶ These fields are produced in bubble expansion $Q + wall \rightarrow B$
- ▶ This production can be CP violating \Rightarrow we have $B - B^c$ and $Q - Q^c$ asymmetry inside the bubble

Baryon asymmetry

$$\frac{\Delta n_{\text{Baryon}}}{s} \approx \frac{135\zeta(3)}{8\pi^4} \sum_{I,J} \theta_I^2 \frac{|y_I|^2}{|y_I|^2 + |Y_I|^2} \times \frac{g_b}{g_\star} \left(\frac{T_{\text{nuc}}}{T_{\text{reh}}} \right)^3 \times \text{Im}(Y_I Y_J^* y_I^* y_J) \left(-\frac{2\text{Im}[f_B^{IJ}]}{|Y_I|^2} + \frac{4\text{Im}[f_B^{IJ}]}{|y_I|^2} \right).$$

- ▶ θ_I^2 suppression from mixing between QB
- ▶ $\left(\frac{T_{\text{nuc}}}{T_{\text{reh}}} \right)^3$ dilution of asymmetry during the reheating after the phase transition
- ▶ $\frac{|y_I|^2}{|y_I|^2 + |Y_I|^2}$ - branching ratio of the decay into $B \rightarrow \chi\eta^c$, which can lead to baryon number violation.

Baryon asymmetry

$$\frac{\Delta n_{Baryon}}{s} \approx \frac{135\zeta(3)}{8\pi^4} \sum_{I,J} \theta_I^2 \frac{|y_I|^2}{|y_I|^2 + |Y_I|^2} \times \frac{g_b}{g_*} \left(\frac{T_{nuc}}{T_{reh}} \right)^3 \\ \times \text{Im}(Y_I Y_J^* y_I^* y_J) \left(-\frac{2\text{Im}[f_B^{IJ}]}{|Y_I|^2} + \frac{4\text{Im}[f_B^{IJ}]}{|y_I|^2} \right).$$

assuming order one complex phases and requiring $\frac{\Delta n_{Baryon}}{s} \sim 8.8 \times 10^{-11}$

$$\theta_I^2 \left(\frac{T_{nuc}}{T_{reh}} \right)^3 \sim 10^{-(6-7)}$$

$\theta_I \sim \frac{Y_V}{M}$ cannot be too small, need new physics in the 1-100 TeV range

CAN WE REALISE SUCH MECHANISMS
IN THE EW PHASE TRANSITION?

The simplest BSM with the FOPT

- ▶ Need to modify the potential of the SM, simplest extension real singlet field

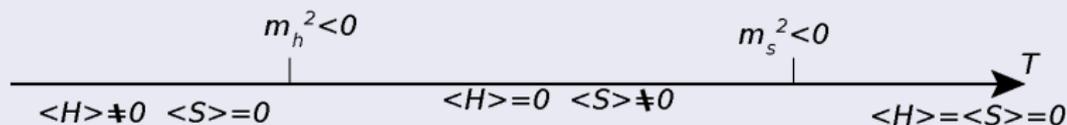
$$V(\mathcal{H}, s) = -\frac{m_h^2}{2}(\mathcal{H}^\dagger \mathcal{H}) + \lambda(\mathcal{H}^\dagger \mathcal{H})^2 - \frac{m_s^2}{4}s^2 + \frac{\lambda_{hs}}{2}s^2(\mathcal{H}^\dagger \mathcal{H}) + \frac{\lambda_s}{4}s^4$$

- ▶ Need very fast bubbles $\gamma \gg 1 \Rightarrow$ low nucleation temperature
 $T_N \ll T_c$

Possible phase transition

- ▶ Two-step phase transition
 $(\langle S \rangle|_{=0}, \langle H \rangle|_{=0}) \rightarrow (\langle S \rangle|_{\neq 0}, \langle H \rangle|_{=0}) \rightarrow (\langle S \rangle|_{=0}, \langle H \rangle|_{\neq 0})$

Two step phase transition



The needed pattern of the symmetry breaking is easy to achieve, by balancing the thermal corrections vs tree level potential

$$\blacktriangleright V_{\text{tree}}(h, s) = -\frac{m_h^2}{4}h^2 + \frac{m_h^2}{8v_{EW}^2}h^4 - \frac{m_s^2}{4}s^2 + \frac{\lambda_{hs}}{4}s^2h^2 + \frac{m_s^2}{8v_s^2}s^4$$

$$V_{\text{thermal}} \sim T^2 \left[h^2 \left(\frac{g'^2}{32} + \frac{3g^2}{32} + \frac{m_h^2}{8v_{EW}^2} + \frac{y_t^2}{8} + \frac{\lambda_{hs}}{48} \right) + s^2 \left(\frac{m_s^2}{16v_s^2} + \frac{\lambda_{hs}}{12} \right) \right]$$

Results

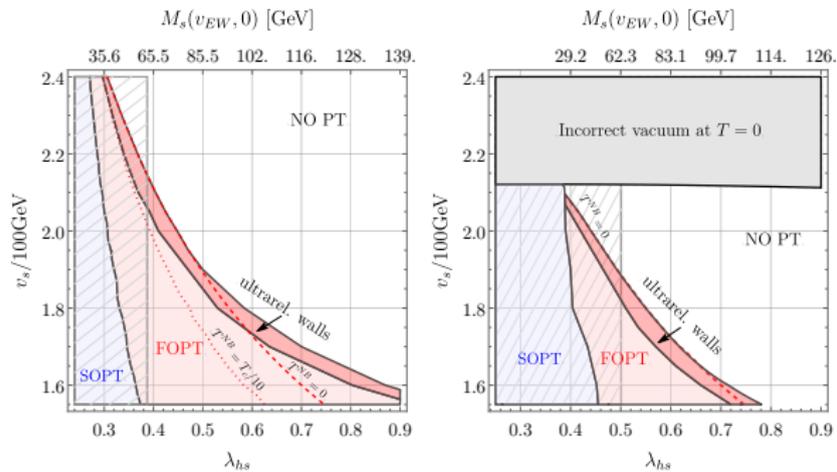
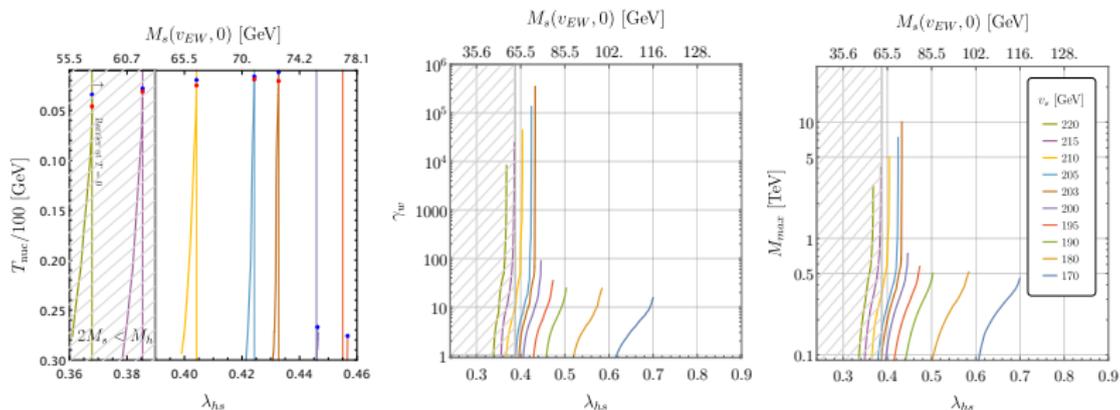


Figure: left $m_s = 125$ GeV, right $m_s = 150$ GeV

- ▶ Red- region where LO pressure cannot stop the bubble acceleration
- ▶ T_{NB} temperature when the potential barrier disappears

$$T_{NB} = 0 \Rightarrow \lambda_{hs} \lesssim \frac{m_h^2}{v_s^2} - \frac{n_t y_t^4}{32\pi^2} \frac{v_{EW}^2}{v_s^2}$$

Maximal γ



- ▶ λ_{hs} is varied with the step 10^{-6}
- ▶ **Heavy particles with the masses 5 – 10 TeV can be produced.**
☺
- ▶ **Need tuning of the coupling λ_{hs} of $10^{-5} - 10^{-6}$** ☹

DM production during the phase transition

- ▶ Same PT to produce DM? Simplest model and additional scalar field coupled to SM via Higgs portal

$$\mathcal{L}_{DM} = \frac{1}{2}(\partial_\mu\phi)^2 - \frac{M_\phi^2\phi^2}{2} - \frac{\lambda_{\phi h}}{2}h^2\phi^2$$

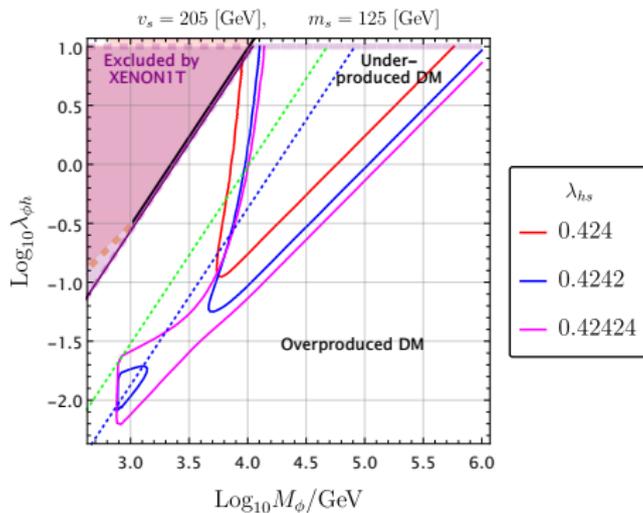


$$\Omega_{\phi,\text{tot}}^{\text{today}} h^2 = \Omega_{\phi,\text{BE}}^{\text{today}} h^2 + \Omega_{\phi,\text{FO}}^{\text{today}} h^2 .$$

$$\Omega_{\phi,\text{FO}}^{\text{today}} h^2 \approx 0.1 \times \left(\frac{T_{\text{nuc}}}{T_{\text{reh}}}\right)^3 \times \left(\frac{0.03}{\lambda_{\phi h}}\right)^2 \left(\frac{M_\phi}{100 \text{ GeV}}\right)^2$$

$$\Omega_{\phi,\text{BE}}^{\text{today}} h^2 \approx 5.4 \times 10^5 \times \left(\frac{C_{\text{eff}} \lambda_{h\phi}^2 v_{EW}}{M_\phi g_{*S}(T_{\text{reh}})}\right) \left(\frac{v_{EW}}{\text{GeV}}\right) \left(\frac{T_{\text{nuc}}}{T_{\text{reh}}}\right)^3 \times e^{-\frac{M_\phi^2}{2\gamma_w v_{EW} T_{\text{nuc}}}}$$

DM production during the phase transition



Summary

- ▶ First order phase transitions with fast bubbles work like colliders in the early universe
 - ▶ Bubble-plasma collisions are very efficient in heavy particle production
 - ▶ Non thermal DM production, hot and heavy DM production
 - ▶ Possibilities for baryogenesis
- ▶ Less tuned models?
 - ▶ Addressing Higgs hierarchy problem simultaneously?
 - ▶ Applications for strong dynamics?

Maximal mass which can be produced?



$$M_{\max} = \sqrt{\gamma_{\max} \frac{T_{\text{nuc}}}{L}} \sim \sqrt{\gamma_{\max} T_{\text{nuc}} \langle \phi \rangle}$$

- ▶ If there are no gauge fields, Lorentz expansion factor for runaway bubbles can reach $\gamma_{\max} \sim \frac{R_*}{R_0}$

$$R_0 \sim \frac{1}{T_{\text{nuc}}}, \quad R_* \sim H^{-1} \sim \frac{M_{\text{pl}}}{\text{scale}^2},$$

- ▶ The maximal mass which can be probed is :

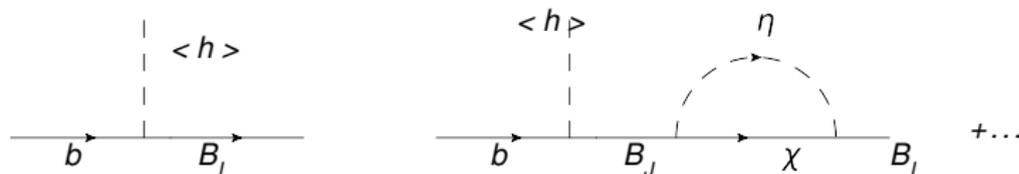
$$M^{\text{MAX}} \sim \text{Min} \left[\frac{4\pi}{g_{\text{gauge}}^{3/2}} \frac{\langle \phi \rangle^2}{T_{\text{nuc}}}, \frac{M_{\text{p}}^{1/2} T_{\text{nuc}}}{\langle \phi \rangle^{1/2}} \right]$$

Asymmetry in production

- ▶ We need to calculate the asymmetry generation in production
- ▶ Calculation simplifies in $E \gg M$

$$\langle B|b \rangle = \left[(2\pi)^3 \delta^{(3)}(k - q) \int dze^{-iz\Delta p_z} \langle h(z) \rangle \right] \mathcal{M}_{b(k) \rightarrow B(q)h(\Delta p_z)}$$

- ▶ Calculation is the same as in the vacuum, to generate CP asymmetry we need a strong phase, which can come from the diagrams:



$$\langle B|b \rangle \propto Y_I + Y_{JY_J^* y_I} f_{JI}, \quad \epsilon_{CP} \propto \frac{\text{Im}[Y_I^* Y_{JY_J^* y_I}] \text{Im}[f_{JI}]}{Y_I^2}$$

There will be asymmetry between number of $B(\bar{B})$ inside the bubble. But total baryon number is conserved $n_B + n_b = n_{\bar{B}} + n_{\bar{b}}$

Model at work

$$\sum_{I=1,2} Y_I (\bar{B}_I H) P_L Q + y_I \eta^* \bar{B}_I P_R \chi + \kappa \eta^c d u + \frac{1}{2} m_\chi \bar{\chi}^c \chi + h.c.$$

- ▶ Need to convert asymmetry in B to baryon asymmetry.
- ▶ $B \rightarrow H Q_{SM}$ is preserving B number.
- ▶ the other decay channel: $B_I \rightarrow \chi \eta^* \rightarrow \chi d^c u^c$

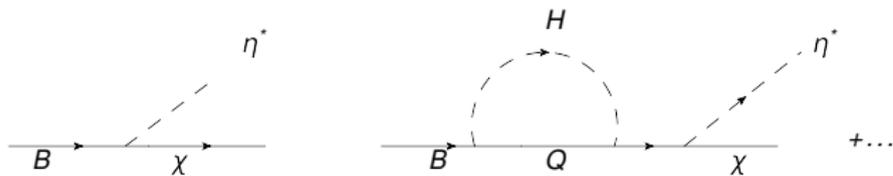
χ decay

- ▶ In the broken phase $B - b$ are mixed \Rightarrow there will be an interaction $y_I \eta^* \bar{b} P_R \chi$
- ▶ χ is Majorana fermion, thus $\chi \rightarrow b \eta \rightarrow b d u$ and $\chi \rightarrow b^c \eta^c \rightarrow b^c d^c u^c$

$B \rightarrow d^c d^c u^c u^c u^c$ and $B \rightarrow d^c u^c d d u$ violates B by factor of 2

Asymmetry in decay

- ▶ The decay rates $\Gamma(B \rightarrow \chi\eta^*) \neq \Gamma(\bar{B} \rightarrow \chi\eta)$, some asymmetry will be generated in decay as well.



$$\epsilon_{decay}^I = \frac{\Gamma(B^I \rightarrow \chi\eta^c) - \Gamma(B^{I,c} \rightarrow \chi^c\eta)}{\Gamma(B^{I,c} \rightarrow \chi\eta^c) + \Gamma(B^I \rightarrow \chi^c\eta)} = -\frac{4\text{Im}(Y_I Y_J^* y_I^* y_J) \text{Im}[f_B^{IJ}]|_{m_\eta, \chi \rightarrow 0}}{|y_I|^2}$$

Baryon asymmetry

$$\frac{\Delta n_{Baryon}}{s} \approx \frac{135\zeta(3)}{8\pi^4} \sum_{I,J} \theta_I^2 \frac{|y_I|^2}{|y_I|^2 + |Y_I|^2} \times \frac{g_b}{g_\star} \left(\frac{T_{nuc}}{T_{reh}} \right)^3 \\ \times \text{Im}(Y_I Y_J^* y_I^* y_J) \left(-\frac{2\text{Im}[f_B^{IJ}]}{|Y_I|^2} + \frac{4\text{Im}[f_B^{IJ}]|_{m_{\chi,\eta} \rightarrow 0}}{|y_I|^2} \right).$$

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- ▶ $\left(\frac{T_{nuc}}{T_{reh}} \right)^3$ dilution of asymmetry during the reheating after the phase transition
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assuming order one complex phases and requiring $\frac{\Delta n_{\text{Baryon}}}{s} \sim 8.8 \times 10^{-11}$

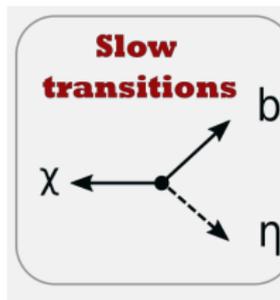
$$\theta_I^2 \left(\frac{T_{\text{nuc}}}{T_{\text{reh}}} \right)^3 \sim 10^{-(6-7)}$$

$\theta_I \sim \frac{Y_V}{M}$ cannot be too small, need new physics in the 1-100 TeV range

Constraints/signatures

- ▶ **avoiding wash out:** need to suppress baryon number violating interactions after the phase transition

$$\frac{M_{B,T,\chi}}{T_{reh}} \gtrsim 30$$



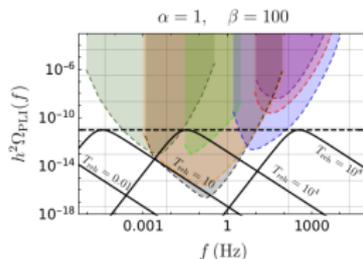
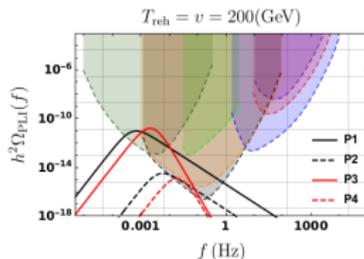
$n - \bar{n}$ oscillation

- ▶ The model contains the term violating the baryon number by two units, so neutron -antineutron oscillations are allowed. The operator

will scale as $\frac{(\sum \kappa \theta_I y_I)^2}{M_\eta^4 m_\chi} u^c d^c d^c u d d$ generated, for $\theta \sim 10^{-(1-2)}$

we will get $M_{\eta, m_\chi} \gtrsim 10^5$ GeV. If new physics couples only to the third generation the bound relaxes by the factor

$$(V_{td}^4 V_{ub}^2)^{1/5} \sim 10^{-2} \Rightarrow M_{\eta, \chi} \gtrsim 10^3 \text{ GeV}$$



$$f \sim 10^{-5} \left(\frac{T}{100 \text{ GeV}} \right) \text{ Hz}$$

$$10^{-6} - 10^9 \text{ GeV} \tag{1}$$