Baryogenesis via relativistic bubble expansion

Iason Baldes
In collaboration with
S. Blasi, A. Mariotti, A. Sevrin, K. Turbang

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Intro/Overview

In order to generate the matter-antimatter asymmetry

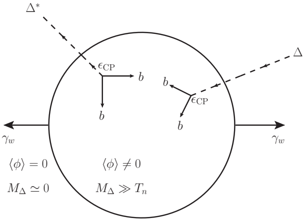
Sakharov Conditions

1. B violation
2. C and CP violation
3. Departure from Equilibrium

- I will present a new way of achieving $\#3$ using a phase transition.
- It can be applied to many models of decay baryogenesis.
- It relies on the decaying particle gaining a mass in a very strong PT.
- In principle testable using gravitational waves.

Conceptually it seems the simplest way of generating Y_B from a PT.
Seems to have been missed.

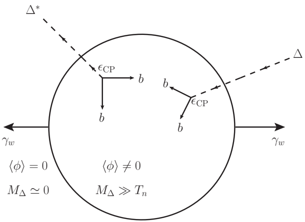
Very Strong Phase Transition



The idea

- Consider a very strong phase transition for ϕ with $v_\phi/T_n \gg 1$.
- We can generate some mass for another field: $\mathcal{L} \supset \lambda\phi^2|\Delta|^2$
- Δ out of equilibrium, $\gamma_\Delta \sim M_\Delta/T_n$, after crossing wall.
- Δ Decays in CPV and $B - L$ violating way.
- Friction pressure: $P_{\rm LO} \sim g_\Delta M_\Delta^2 T_n^2/24 < \Lambda_{\rm vac} = c_{\rm vac} v_\phi^4$.
- Wall can reach $\gamma_w \sim T_n M_{\rm Pl}/v_\phi^2$.
- Note no particle diffusion in front of wall needed.

Very Strong Phase Transition



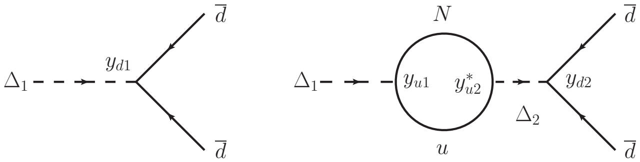
Generates Asymmetry

$$\frac{Y_B}{Y_B^{\mathrm{Obs.}}} = \epsilon_\Delta \kappa_{\mathrm{Sph.}} \frac{Y_\Delta^{\mathrm{MG}}}{Y_B^{\mathrm{Obs.}}} \left(\frac{T_n}{T_{\mathrm{RH}}}\right)^3$$

$$\approx 2.3 \times 10^5 g_\Delta \left(\frac{100}{g_*}\right) \left(\frac{\epsilon_\Delta}{1/16\pi}\right) \left(\frac{T_n}{T_{\mathrm{RH}}}\right)^3$$

(Assuming no washout — to be examined carefully below)

Detailed Model



We consider $\Delta_i \sim (3, 1, 2/3)$ under SM gauge group.

$$\mathcal{L} \supset y_{di}\Delta_i \overline{d^c_R} d'_R + y_{ui}\Delta_i \overline{N_R} u^c_R + \mathrm{H.c.}$$

Here N is a SM gauge singlet fermion.

Decay is CPV

$$\epsilon_\Delta = \frac{1}{4\pi}\frac{2\,\mathrm{Im}(y^*_{d1}y_{u1}y^*_{u2}y_{d2})}{|y_{u1}|^2 + 2|y_{d1}|^2}\frac{M^2_{\Delta 1}}{M^2_{\Delta 2} - M^2_{\Delta 1}} \sim \frac{\mathrm{Im}[y^2]}{6\pi}\left(\frac{M_{\Delta 1}}{M_{\Delta 2}}\right)^2$$

Wall Crossing — Do the Δ's annihilate before decay?

After wall crossing, in their own gas frame,

$$n_\Delta \approx \left(\frac{M_\Delta}{T_n}\right) n_\Delta^{\text{eq}}(M_\Delta \simeq 0) \qquad \text{with } v_{\text{rel}} \sim T_n/M_\Delta \ll 1.$$

Can undergo Sommerfeld enhanced annihilations:

$$v_{\text{rel}}\sigma(\Delta\Delta^* \to \phi\phi) \simeq \frac{\pi\alpha_\phi^2}{M_\Delta^2} S_0$$

Annihilations into gauge bosons somewhat slower for our parameters.

B violating decay before annihilation for

$$y \gtrsim \frac{\lambda^{3/2}\sqrt{g_\Delta\zeta(3)}}{4\pi}\sqrt{\frac{T_n}{M_\Delta}}.$$

Similarly safe from bound states: $[\Delta\Delta^*]_{\text{Bound}} \to \phi\phi, gg, YY$, provided $y \gtrsim 10^{-3}$.

Boosted Washout

The Δ's decay with their boost intact for

$$y \gtrsim \left(\frac{\alpha_s}{0.03}\right)^{3/4} \left(\frac{g_{\mathrm{QCD}*}}{79}\right)^{1/2} \frac{T_n}{M_\Delta}$$

Decay products also boosted, with $E \sim M_\Delta^2/2T_n$ in the plasma frame.

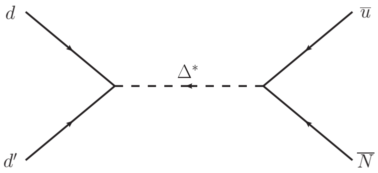
The danger is: $(B-L)$ violating interactions in the return to kinetic equilibrium!

Compare hard scattering $ds \to \overline{u}\overline{N}$ to thermalisation rate for the quarks

$$\frac{\Gamma_{\mathrm{q.th.}}}{\Gamma_{\mathrm{Hd.}}} \approx \frac{64\pi^3 g_{\mathrm{QCD}*} \alpha_s^{3/2}}{3\sqrt{2\pi^3} y^4} \approx \frac{34}{y^4} \left(\frac{\alpha_s}{0.03}\right)^{3/2}$$

However, N, do not have gauge interactions. For small $y \lesssim 0.1$ can have $\Gamma_{Hd.} < H$. For large y some additional interactions are needed.

Thermal Washout



After reheating we have washout via off-shell Δ's:

$$\Gamma_{\mathrm{WO}} \approx \frac{y^4 T_{\mathrm{RH}}^5}{8\pi M_\Delta^4}$$

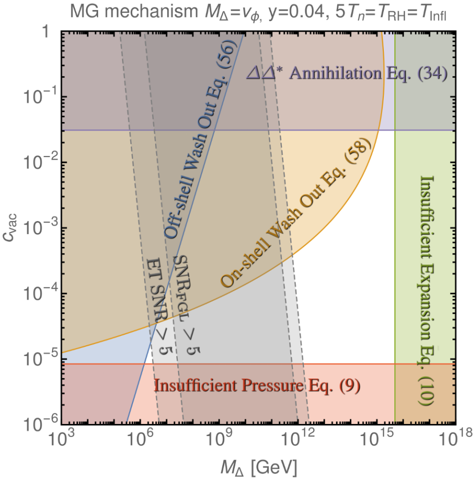
And washout via on-shell Δ's (inverse decays):

$$\Gamma_{\mathrm{ID}} \approx \frac{3y^2}{16\pi} M_\Delta \left(\frac{M_\Delta}{T_{\mathrm{RH}}}\right)^{3/2} \mathrm{Exp}\left[-\frac{M_\Delta}{T_{\mathrm{RH}}}\right].$$

For sufficiently large T_{RH} or small y these are safely smaller than $H \sim T_{\mathrm{RH}}^2/M_{\mathrm{Pl}}$.

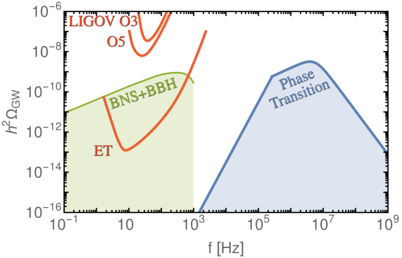
Summary

Putting everything together



Can avoid washout for large M_Δ or for small $\Lambda_{vac} \equiv c_{vac} v_\phi^4$.

Example Potential — GW signal



Simplest realisation for the potential

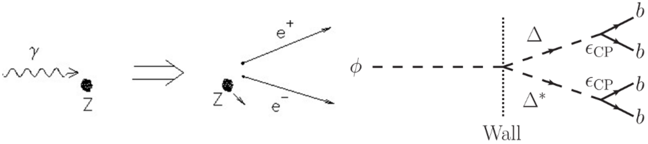
$$V_0(\phi, \Delta) = \frac{\lambda_\phi}{4}\phi^4 + \frac{\lambda}{2}\phi^2\Delta^2 + \frac{\lambda_\Delta}{4}\Delta^4 .$$

The scale invariance is broken by the running of the couplings.

$$\beta_{\lambda_\phi} = \frac{1}{16\pi^2}\left(3\lambda^2 + 18\lambda_\phi^2\right) .$$

Returns desired bulk parameters for $\lambda \sim 1$ and $v_\phi \gtrsim 10^{13}$ GeV.

Another option: Azatov/Vanvlasslear Mechanism



Consider now a similar PT, but starting with

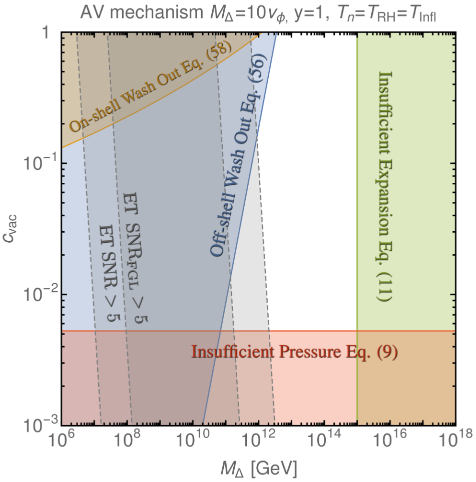
$\mathcal{L} \supset \lambda\phi^2|\Delta|^2 + M_\Delta^2|\Delta|^2$. Now with $M_\Delta^2 \gg \lambda v_\phi^2$.

- n_Δ negiligible in unbroken phase for $M_\Delta \gg T_n$.
- Azatov/Vanvlasselaer [2010.02590]: pair production across wall

$$P(\phi \to \Delta\Delta^*) \approx \frac{g_\Delta \lambda^2 v_\phi^2}{24\pi^2 M_\Delta^2}$$

No Boltzmann suppression in anti-adiabatic regime $\gamma_w > M_\Delta^2/(v_\phi T_n)$!

Azatov/Vanvlasslear Option — Summary



Y_B analysis very similar, except need for larger γ_w, and some suppression from $P(\phi \to \Delta\Delta^*) \ll 1$, $M_\Delta \gg v_\phi \gg T_{\rm RH}$ hierarchy can mean less washout.

Conclusions

- We studied decay baryogenesis during a strong first order phase transition which induces the required departure from equilibrium.
- For low dimensional operators we have considered (i.e. two body decays), mechanism works best at high scales $M_\Delta \gtrsim 10^{12}$ GeV. Central result of this study.
- If $c_{\rm vac}$ is somehow suppressed, can be pushed to lower M_Δ scales. Need to further study bubble nucleation in this regime.
- Prediction is a large amplitude GW background at high frequencies (can be in ET range for lower scales.) Safe from suppression of Y_B at large $v_{\rm wall}$ in EWBG (no diffusion necessary).
- Also studied Azatov/Vanvlasselaer pair production effect*. Works in a largely similar fashion.

*Also see: Azatov/Vanvlasselaer/Yin, 2106.14913, Baryogenesis via relativistic bubble walls, which appeared on the same day as our paper. This is complementary work: they consider CP violation in the production of the heavy states.

Third Sakharov Condition

- Sakharov 1+2: To generate $Y_B^{\text{Obs.}} \sim 10^{-10}$ we need B violation and CPV.
- Sakharov 3: Also need a departure from equilibrium.
- Consider a semi-classical Boltzmann equation approach. Then one has:

CPT+Unitarity relation

$$\sum_\beta |\mathcal{M}(\alpha \to \beta)|^2 = \sum_\beta |\mathcal{M}(\beta \to \alpha)|^2$$
$$= \sum_\beta |\mathcal{M}(\overline{\beta} \to \overline{\alpha})|^2 = \sum_\beta |\mathcal{M}(\overline{\alpha} \to \overline{\beta})|^2$$

- In thermal equilibrium similar relation also holds for reaction rate densities.
- These lead to manifestation of generating no Y_B in equilibrium.

Boltzmann Equations

For decay baryogenesis:

One typically has some equations of the form

$$\frac{dN_X}{dt} \sim -\Gamma(N_X - N_X^{\rm eq}) - \langle \sigma v \rangle (N_X^2 - [N_X^{\rm eq}]^2)$$

And for the asymmetry:

$$\frac{dN_B}{dt} \sim -\epsilon\Gamma(N_X - N_X^{\rm eq}) - \frac{N_B}{N_\gamma}\{N_X^{\rm eq}\Gamma - [N_X^{\rm eq}]^2\langle \sigma v \rangle\}$$

- The source term is proportional to $N_X - N_X^{\rm eq}$ due to CPT/unitarity.
- If CP violating decays (or annihilations) are efficient: some suppression because same factor enters into both equations.
- If CP conserving annihilations are very efficient: can have lots of suppression.