Supercooled phase transitions and baryogenesis

Iason Baldes

Based partly on the paper:

- IB, Blasi, Turbang, Mariotti, Sevrin, Phys. Rev. D 104 (2021) 11, 115029, arXiv:2106.15602

CosmoChart
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LPENS
LABORATOIRE DE PHYSIQUE DE L'ÉCOLE NORMALE SUPÉRIEURE

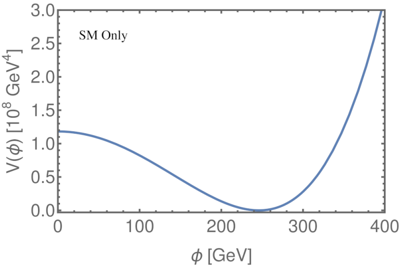
SORBONNE UNIVERSITÉ

LPTHE, 30 April 2024

Overview

- EWBG: review and status.
- Supercooled PTs.
- Baryogenesis in supercooled PTs.
- Relation to DM, PBHS?

SM H Potential

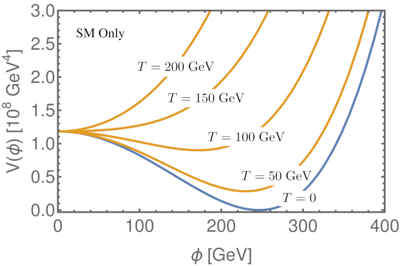


$$\langle H \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ \phi \end{pmatrix} \qquad V(\phi) = -\frac{1}{2}\mu_H^2\phi^2 + \frac{1}{4}\lambda_H\phi^4$$

All the parameters are known:

$\sqrt{2}\mu_H = m_h = 125$ GeV [LHC] $\qquad v_{\rm EW} = \sqrt{\frac{m_h^2}{2\lambda_H}} = 246$ GeV [Muon decay]

At finite temperature

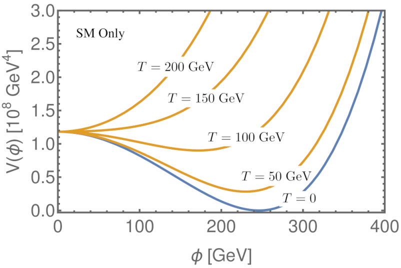


$$V(H) \approx -\frac{1}{2}\mu_H^2\phi^2 + \frac{1}{4}\lambda_H\phi^4 + \frac{1}{2}c_H T^2\phi^2$$

The thermal mass coefficient is related to other SM couplings:

$$c_H \approx \left(\frac{\lambda_H}{2} + \frac{3g_2^2}{16} + \frac{g_Y^2}{16} + \frac{y_t^2}{4}\right) \approx 0.4$$

At finite temperature



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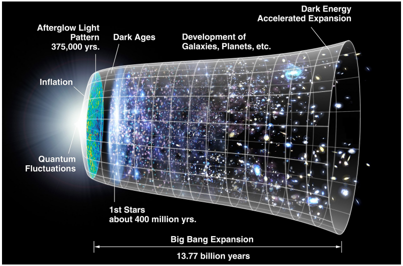
Remarkably: Symmetry is restored at high T and the vacuum energy is larger.

Cosmological Puzzles



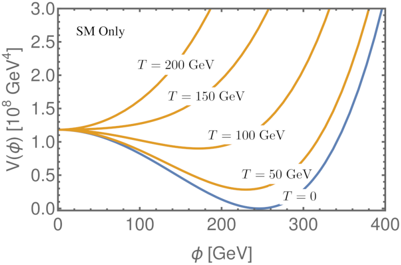
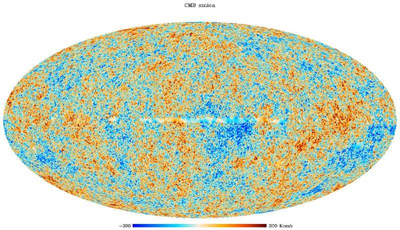


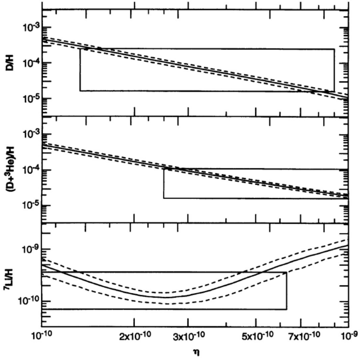
Image: NASA/Wikipedia

Cosmological puzzles which could be related to the EW or some BSM phase transition?

- Inflation
- Dark Energy
- Dark Matter
- Baryon Asymmetry → Ordinary Matter Density

The matter-antimatter asymmetry





CMB in agreement with BBN:

$$Y_B \equiv \frac{n_b - n_{\bar{b}}}{s} = (0.86 \pm 0.02) \times 10^{-10}$$

Baryogenesis

Sakharov Conditions

1. B violation
2. C and CP violation
3. Departure from thermal equilibrium (or spontaneously broken CPT)

SM + FLRW

1. (B+L) violation present in symmetric phase at $T \gtrsim 100$ GeV from non-perturbative EW sphaleron process.
2. CP violation observed in quark sector.
3. Can be driven by expansion.

Electroweak baryogenesis - basic picture

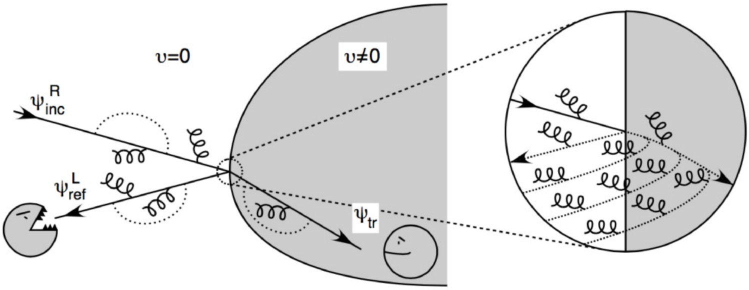
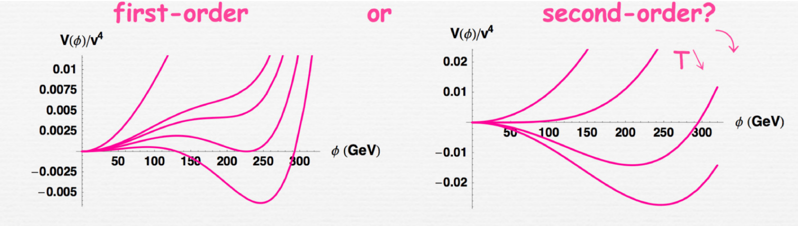


Image from - Gavela, Hernandez, Orloff, Pène, Quimbay [hep-ph/9406289]

- CP violating collisions with the bubble walls lead to a chiral asymmetry.
- Sphalerons convert this to a Baryon Asymmetry.
- This is swept into the expanding bubble where sphalerons are suppressed.

Electroweak baryogenesis - Requirements



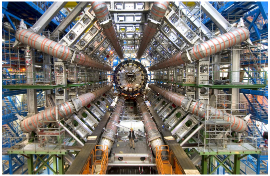
Electroweak baryogenesis requires:

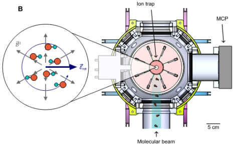
- A strong first order phase transition ($\phi_n / T_n \gtrsim 1$)
- Sufficient CP violation

However in the SM:

- The H boson mass is too large
- Quark masses are too small

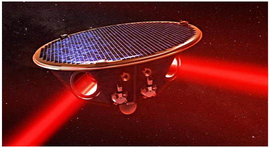
Requires new EW-scale physics.

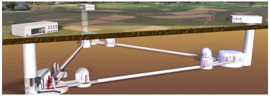




BSM Experimental signatures for EWBG

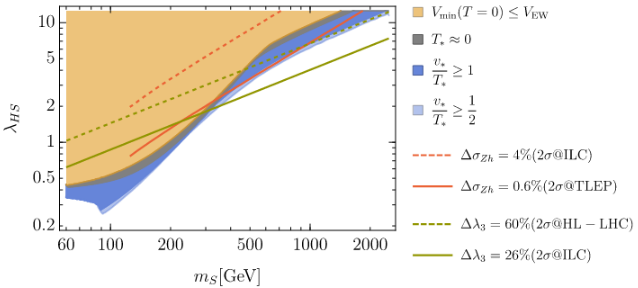
1. Collider signals associated with $V(H)$ modificiation.
2. Electric Dipole Moments associated with low scale CP violation.
3. Gravitational waves from the strong FOPT?





Singlet model

First order EW Phase Transition from a singlet - Choi, Volkas '93 + ...



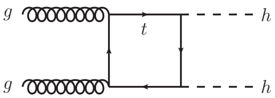
- Beniwal et al, 1702.06124

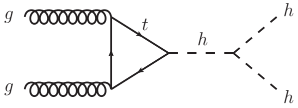
Modification of h^3 coupling

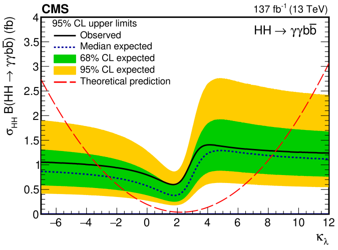
$$\lambda_3 \approx \frac{m_h^2}{2v_{\rm EW}} + \frac{\lambda_{HS}^3 v_{\rm EW}^3}{24\pi^2 m_S^2}$$

Collider signatures - Triple h coupling

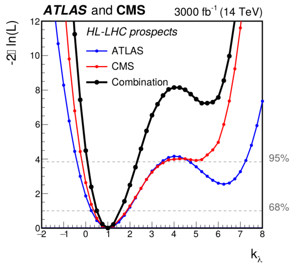
SM: $V(h) = \frac{1}{2}m_h^2 h^2 + \lambda_H v_{\rm EW} h^3 + \frac{1}{4}\lambda_H h^4$ with $v_{\rm EW} = \sqrt{\frac{m_h^2}{2\lambda_H}} = 246$ GeV.







- 2011.12373

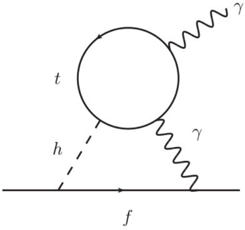


- 1902.00134

Measuring the cubic term is long term challenge.

Some, but not all, singlet models returning a strong FOPT can be excluded by HL-LHC.

Electron EDM constraint



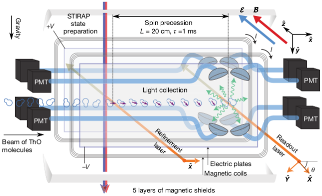
$$\frac{i}{2} d_e (\bar{e}\sigma^{\mu\nu}\gamma_5 e) F_{\mu\nu}$$

Rough estimate of the EDM - Glioti, Rattazzi, Vecchi, 1811.11740.

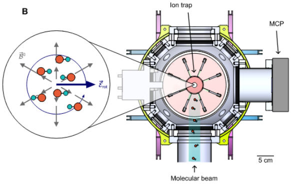
$$|d_e| \sim 10^{-29}\ e\,\mathrm{cm}\,\theta_{\mathrm{CP}} \left(\frac{50\ \mathrm{TeV}}{\Lambda}\right)^2 \qquad 1-\mathrm{loop}$$

$$|d_e| \sim 10^{-29}\ e\,\mathrm{cm}\,\theta_{\mathrm{CP}} \left(\frac{2.5\ \mathrm{TeV}}{\Lambda}\right)^2 \qquad 2-\mathrm{loop}$$

Experimental searches - EDMs

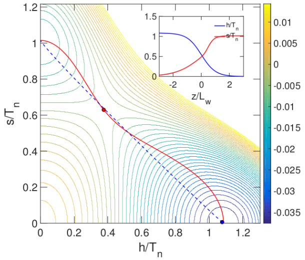


ACMEII (ThO): $|d_e| < 1.1 \times 10^{-29}$ $e\,\mathrm{cm}$ - Nature 562, 355–360 (2018)



Colorado ($\mathrm{Hf}F^{+}$): $|d_e| < 4.1 \times 10^{-30}$ $e\,\mathrm{cm}$ - 2212.11841

Hiding the CP violation



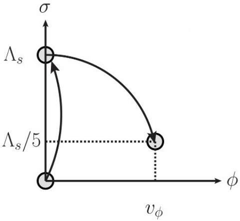
$\mathcal{L} \supset \frac{1}{2}\bar{\chi}\left((\eta P_R + \eta^* P_L)S + m_\chi\right)\chi + y\bar{L}_\tau H_2 P_R \chi + \mathrm{h.c.}$ - from [1] below.

One idea is to hide the CP violation in the dark sector

1. "Electroweak baryogenesis from a dark sector",
   Cline, Kainulainen, Tucker-Smith, 1702.08909.
2. "Electroweak Baryogenesis From Dark CP Violation,"
   Carena, Quirós, Zhang, 1811.09719 and 1908.04818.

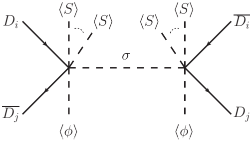
- eEDM at 3 or 4-loops (goes against the old appeal of EWBG).

Another option:



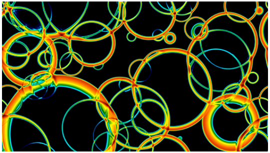
Large Yukawas before the EWPT as a source of CP violation
- IB, Konstandin, Servant 1608.03254.

Flavour observables such as $K - \bar{K}$ lead to severe constraints on the model.

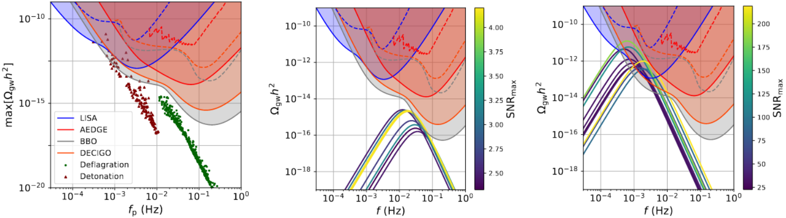


For overview and summary of other options in EWBG/flavour see: Servant 1807.11507

Experimental searches - GWs



From a simulation by Weir et al.

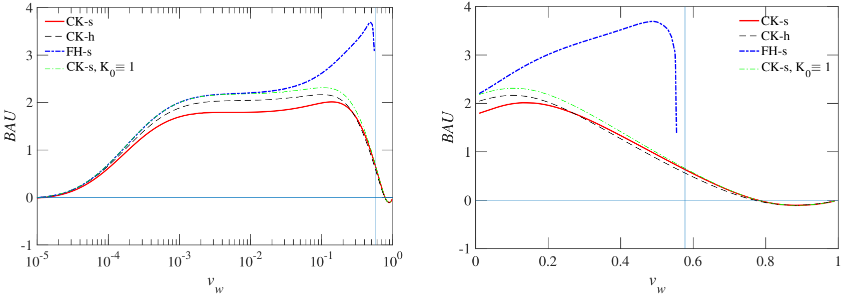


Singlet model - Cline et al. 2102.12490

Only the strongest transitions are detectable by LISA.

But: problem if $v_{\mathrm{wall}} \simeq 1$ (strongest transitions).

- Less of the plasma is pushed by the wall at high v_{wall}.
- This suppresses the BAU.
- EWBG typically occurs in a radiation dominated background.



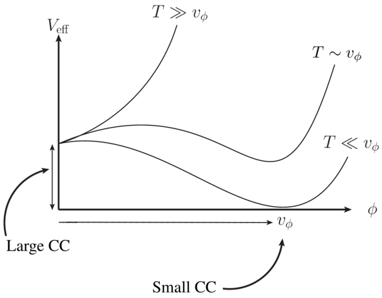
From: Cline, Kainulainen 2001.00568

Also see: Dorsch, Huber, Konstandin 2106.06547

What about baryogenesis with ultra-relativistic walls?

(Common in supercooled limit).

Supercooled Phase Transition

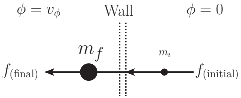


- Begin in radiation domination
- A scalar field becomes stuck behind a barrier
- We will be interested in supercooled phase transitions, where the universe becomes vacuum dominated (or close to it).
- Temperature evolution avoids graceful exit problem
- Bubbles accelerate and collide, reheating universe: $\rho_{\rm vac} \to$ Bubble walls $\to$ Oscillations $\to$ Radiation.

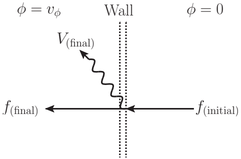
Ballistic limit

Processes of importance for us here:

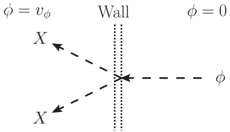
1. Particle crossing wall.



2. Transition radiation.



3. Pair production.



Wall velocity

Driving pressure:

$$\mathcal{P}_{\rm Driving} = V(\phi_{\rm symmetric}) - V(\phi_{\rm broken}) = c_{\rm vac} v_\phi^4$$

The LO friction pressure in the ballistic regime is:

$$\mathcal{P}_{\rm LO} \simeq \sum_a \Delta(m_a^2) \int \frac{d^3 p f_a^{\rm eq}}{(2\pi)^3 2E_a} \equiv g_a \frac{v_\phi^2 T_n^2}{24}$$

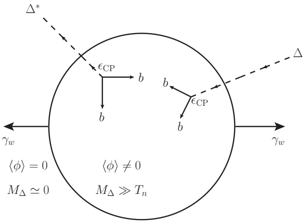
NLO friction pressure in case of gauged PTs:

$$\mathcal{P}_{\rm NLO} \approx \mathcal{O}(1) \times \alpha_X \gamma_w M_V T_n^3 \log\left(\frac{v_\phi}{T_n}\right)$$

For $\Delta V \gg \mathcal{P}_{\rm LO} + \mathcal{P}_{\rm NLO}$

$$\gamma_{\rm wall} \simeq \frac{1}{3}\frac{R}{R_{\rm nuc}} \sim \frac{T_n M_{\rm pl}}{v_\phi^2}$$

Baryogenesis sketch

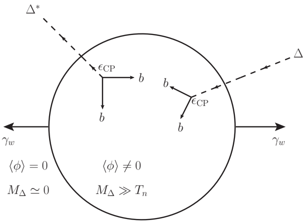


The idea - IB, Blasi, Turbang, Mariotti, Sevrin 2106.15602

- 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.
- Note no particle diffusion in front of wall needed.

Some commonality with: Lazarides et al., PRL 56 (1986) 557.

Very Strong Phase Transition



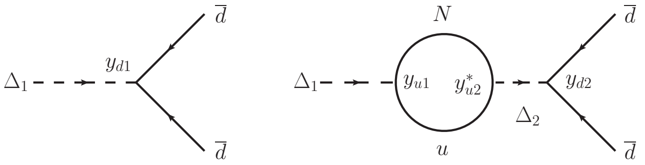
Generates Asymmetry

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

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

(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?

The Δ gains mass after wall crossing from a $\lambda\phi^2|\Delta|^2$ term.
Density in their own gas frame,

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

Can undergo Sommerfeld enhanced annihilations:

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

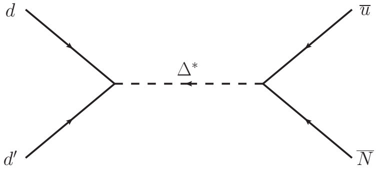
Annihilations into gauge bosons somewhat slower for our parameters.

B violating decay before annihilation for

$$y \gtrsim \frac{\lambda^{3/2}}{\pi}\sqrt{\frac{g_\Delta\zeta(3)}{432}}\sqrt{\frac{T_n}{M_\Delta}}$$

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

Thermal Washout



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

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

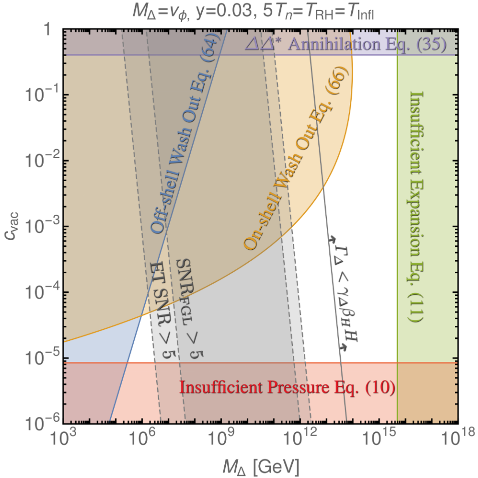
And washout via on-shell Δ's (inverse decays):

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

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

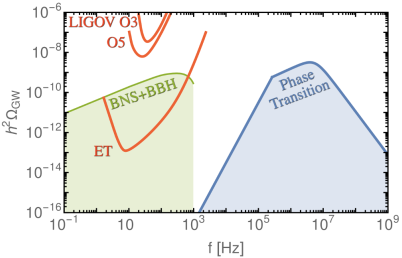
Summary

Putting everything together



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

Example Potential — GW signal



Simplest realisation for the potential

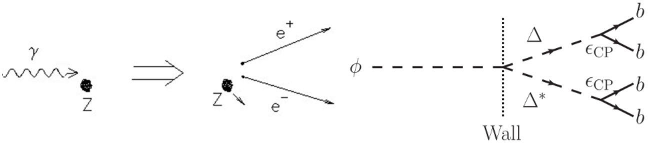
$$V_0(\phi, \Delta) = \frac{\lambda_\phi}{4}\phi^4 + \frac{\lambda}{2}\phi^2\Delta^2 + \frac{\lambda_\Delta}{4}\Delta^4.$$

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

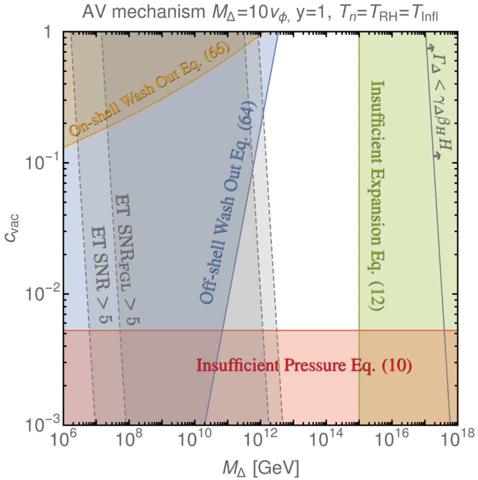
$\mathcal{L} \supset \frac{1}{2}\lambda\phi^2|\Delta|^2 + M_\Delta^2|\Delta|^2$. Now with $M_\Delta^2 \gg \lambda v_\phi^2$.

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

$$P(\phi \to \Delta\Delta^*) \approx \frac{g_\Delta \lambda^2 v_\phi^2}{96\pi^2 M_\Delta^2}$$

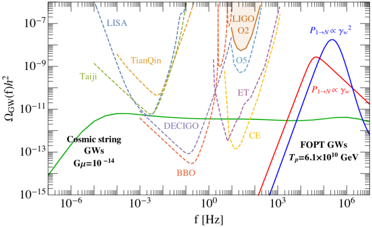
No Boltzmann suppression in anti-adiabatic regime $\gamma_w > M_\Delta^2/(v_\phi T_n)$!

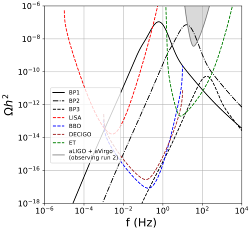
Azatov/Vanvlasslear Option — Summary



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.

Follow up studies - Mass gain mechanism

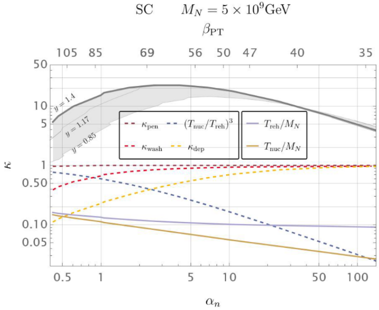


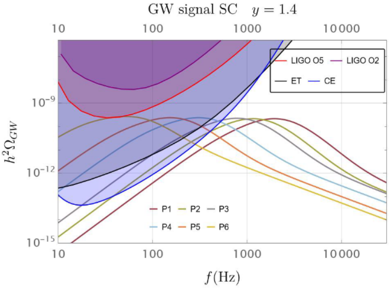


- $U(1)_{B-L}$ leptogenesis - Peisi Huang, Ke-Pan Xie 2206.04691
- Resonant leptogenesis - Dasgupta et al. 2206.07032

Larger range of GW signals possible.

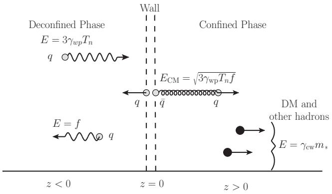
Follow up studies





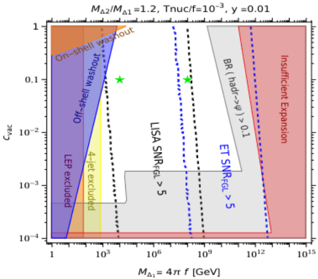
- Inclusion of thermal leptogenesis processes. Finds PT reduces washout for $M_N \gtrsim 10^7$ GeV. - Chun et al., 2305.10759
- Flavoured leptogenesis - Zhao, Wu, 2403.18630

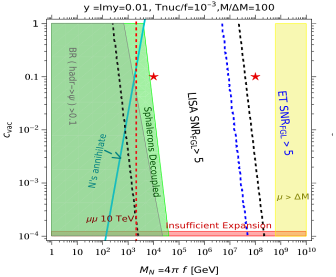
Realization in supercooled confinement



Using string fragmentation/DIS picture developed in:

- IB, Gouttenoire, Sala 2007.08440





- Dichtl, Nava, Pascoli, Sala, 2312.09282

Supercooled PTs and DM/PBHs

Supercooled PTs can also:

- Set the DM abundance

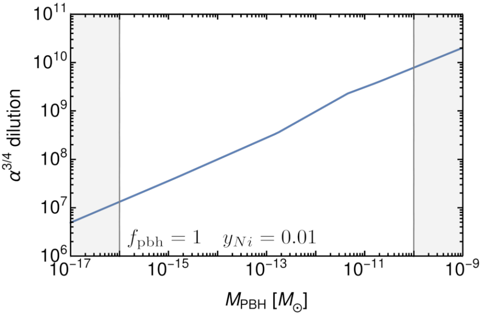
  e.g. Hambye et al., 1805.01473, IB et al., 2110.13926
- Or produce PBHs

  e.g. Liu, et al., arXiv:2106.05637

In both cases the PTs are typically very strong $\rightarrow$ significant entropy production.

Dilution effect

Example of dilution factor after the PT:



- B dilution in $U(1)_{\rm B-L}$ model for PBH production - IB, M.O. Olea-Romacho, 2307.11639

Entropy production precludes our baryogenesis mechanism
$\rightarrow$ baryogenesis should take place sometime after the PT.

Ultra-relativistic particle shells - more generally

Channel		Multiplicity $\mathcal{N}$ per incoming particle	Momentum of shell particles (p_c or p_X)	$\bar{L}_b = (L_b^2 - \frac{1}{p_X^2})^{\frac{1}{2}}$ (L_b = effective shell thickness)
Leading-order interaction (LO): $a \to a$ Particles acquiring a mass [43, 50]		1	$\Delta m^2/T_n$	$\frac{R_c}{2(\Delta m/T_n)^2}$
Gauge interaction $\alpha_D \ll 4\pi$: Bremsstrahlung radiation $a \to bc$ [44–47] and App. A.1	transmitted	$2\frac{\alpha_D}{\pi} L_m L_E$	$\gamma_w\, m_{c,h}$	$\frac{R_c}{2\gamma_w^2}$
	reflected	$\frac{\alpha_D}{\pi} L_m^2$		
Gauge interaction $\alpha_D \simeq 4\pi$: Hadronization [23]	string fragmentation ejected quarks	$\frac{\alpha_D}{\pi} L_E$	$\gamma_w\, v_\phi$	$\frac{R_c}{2\gamma_w^2}$
Scalar interaction $\lambda\phi^4/4!$: Scalar Bremsstrahlung $a \to bc$ App. A.3	transmitted	$\lambda^2 v_\phi^2/192\pi^2 m_{c,h}^2$	$\gamma_w\, m_{c,h}^2/E_a$	$\frac{R_c}{2\gamma_w^2}$
	reflected	$\lambda^2 v_\phi^2/32\pi^2 E_a^2$	$\gamma_w m_{c,h}$	
Heavier particle production $\lambda\phi^2 X^2/4$ (Azatov-Vanvlasselaer mechanism $\phi \to XX$) $M_X \gg v_\phi$ [45]		$\lambda^2 v_\phi^2/192\pi^2 M_X^2 \times \Theta\left(\gamma_w - M_X^2/T_n v_\phi\right)$	M_X^2/T_n	$\frac{R_c}{2(M_X/T_n)^2}$

Shell properties and free streaming conditions - IB, Dichtl, Gouttenoire, Sala, 2403.05615

Particle production from shell collisions - IB, Dichtl, Gouttenoire, Sala, 2306.15555

Conclusion

- Early Universe PTs: No guarantee, but provide fruitful BSM physics.
- Offer unique links to realizations of baryogenesis, dark matter or primordial black holes.
- Related phenomenology: Ultra-heavy DM in indirect/direct detection, GWs (improved predictions...) well worth studying
- Questions of particle-physics/QFT: shell free-streaming, particle production at/from bubble walls also well worth studying.

Conclusion

- Early Universe PTs: No guarantee, but provide fruitful BSM physics.
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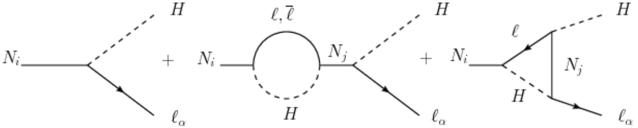
Thanks.

Backup slides

In contrast: Leptogenesis

$$m_\nu \sim \frac{y_\nu^2 v_{\rm EW}^2}{M_N} \sim 0.1\ {\rm eV}$$



Leptogenesis

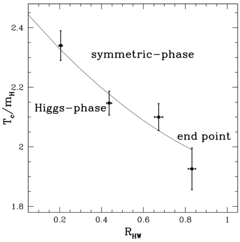
- Very minimal. Tied to $M_N \gtrsim 10^9$ GeV in the vanilla scenario.
- This introduces a calculable hierarchy problem.
- Scale can be lowered, while remaining rather minimal.
  Price: degeneracies or other complications.
- Typically only indirect tests: m_ν and $0\nu\beta\beta$.

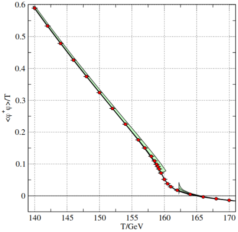
The matter-antimatter asymmetry

Textbook Argument for Baryogenesis

- In a symmetric universe $n_b/s = n_{\bar{b}}/s \approx 10^{-20}$
- The post-inflation causal volume is too small for baryons/antibaryons to be sufficiently separated
- $n_b/s = n_{\bar{b}}/s \approx 10^{-10}$ would be reached at $T \approx 40$ MeV when $M_{H^{-3}} \approx 10^{-7} M_{\odot}$
- Need a mechanism to generate the asymmetry

Electroweak phase transition - Lattice Studies





- Csikor, Fodor, Heitger, hep-ph/9809291, D'Onofrio, Rummukainen 1508.07161

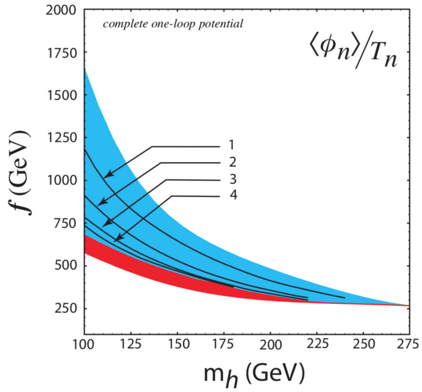
SM with $m_h = 125$ GeV predicts a crossover.
Nevertheless, only the minimum (VEV) of the potential, and the 2nd derivative there (m_h), is known if we allow for BSM physics.

The SM scalar potential can be modified.

Require a modification of the SM Scalar potential

Successful electroweak baryogenesis requires suppressed washout:

$$\frac{\Gamma_{\rm sph}}{V} \sim 10^{1\div 4}\left(\frac{\alpha_W T}{4\pi}\right)^4\left(\frac{2M_W(\phi)}{\alpha_W T}\right)^7 {\rm Exp}\left[-\frac{3.2M_W(\phi)}{\alpha_W T}\right] \Rightarrow \frac{\phi_n}{T_n} \gtrsim 1$$



- Delaunay, Grojean, Wells [0711.2511]

$V(\Phi) =$
$m^2|\Phi|^2 + \lambda|\Phi|^4 + \frac{1}{f^2}|\Phi|^6$

Other options:

- Singlet models/tree level barriers
- Multi-step transitions
- Thermal barriers from bosonic loops

CPV and The Baryonic Yield

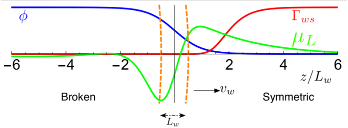


Image from 1706.08534 - Bruggisser, Konstandin, Servant

Diffusion equation

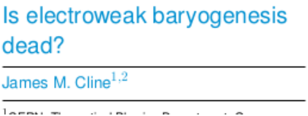
$$\partial_z\, n_B = \frac{3}{2} v_w^{-1} \Gamma_{ws} \left(N_c \mu_L T^2 - \mathcal{A}\ n_B \right) , \qquad \Gamma_{ws} = 10^{-6}\ T\ \exp(-a\phi(z)/T)$$

$$\eta_B = \frac{n_B(-\infty)}{s} = \frac{135\ N_c}{4\pi^2 v_w g_* T} \int_{-\infty}^{+\infty} dz\ \Gamma_{ws}\ \mu_L\ e^{-\frac{3}{2}\mathcal{A}\frac{1}{v_w}\int_{-\infty}^{z} dz_0 \Gamma_{ws}}$$

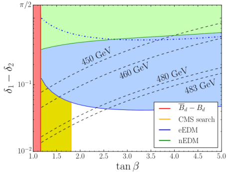
$$\eta_B \sim \frac{\Gamma_{ws}\mu_L L_w}{g_* T} \sim \frac{10^{-8}\mu_L}{T} \quad \text{for} \quad L_w \sim \frac{1}{T}$$

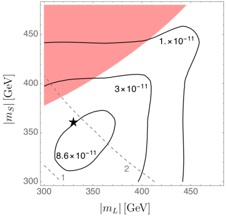
EDMs - Situation 2013-2018

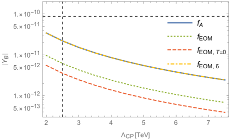
ACME: $|d_e| < 8.7 \times 10^{-29}\, e\,\mathrm{cm}$ (2013) $|d_e| < 9.4 \times 10^{-29}\, e\,\mathrm{cm}$ (2017)


Is electroweak baryogenesis dead?

James M. Cline[1,2]

1. 

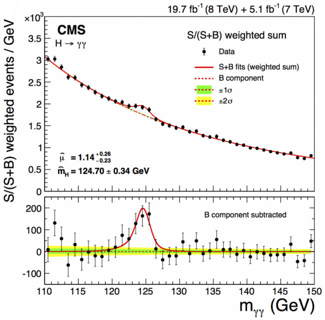
2. 

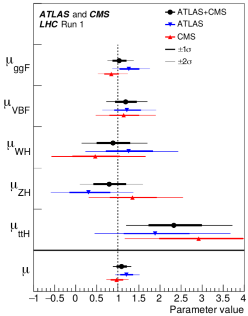
3. 

1. 1611.05874 - Dorsch, Huber, Konstandin, No
2. 1707.02306 - Egana-Ugrinovic
3. 1710.04061 - de Vries, Postma, van de Vis, White

Severe constraint on EWBG!

LHC constraints - Limit on Mixing



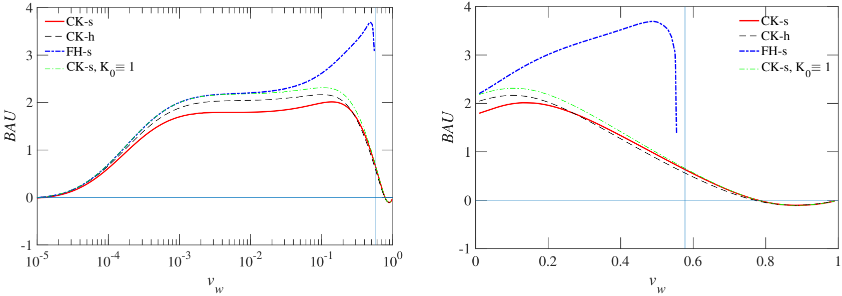


$\mu = 1.09 \pm 0.11$	LHC Run 1	$7 + 8$ TeV	1606.02266
$\mu = 1.10 \pm 0.06$	LHC Run 2	13 TeV	1810.02521

$$\theta \lesssim \mathcal{O}(0.1)$$

But: problem if $v_{\mathrm{wall}} \simeq 1$.

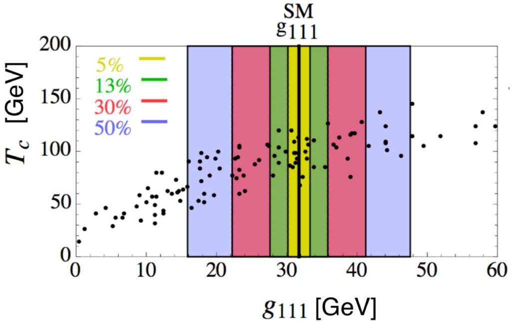
- Less of the plasma is pushed by the wall at high v_{wall}.
- This suppresses the BAU.
- EWBG typically occurs in a radiation dominated background.



From: Cline, Kainulainen 2001.00568

Also see: Dorsch, Huber, Konstandin 2106.06547

Collider signatures - Singlet models difficult to detect



Somewhat optimistically:

$\sim 30 - 50\%$ HL-LHC or TLEP

$\sim 13\%$ ILC

$\sim 3 - 8\%$ 100 TeV pp

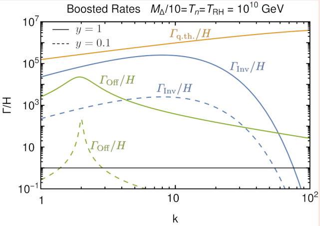
- Correlation between T_c and triple Higgs couplings $g_{111} h^3$ in a singlet model. - Profumo, Ramsey-Musolf, Wainwright, Winslow [1407.5342]
- And/or: mixing reducing the signal strength.
  Currently LHC: $\theta \lesssim \mathcal{O}(0.1)$ compatible with singlet models of EWBG.
- And/or: direct searches for heavy singlet states.

Boosted Washout

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

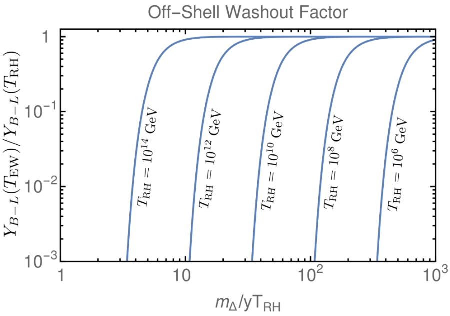
The danger is: $(B-L)$ violating interactions in the return to kinetic equilibrium!

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

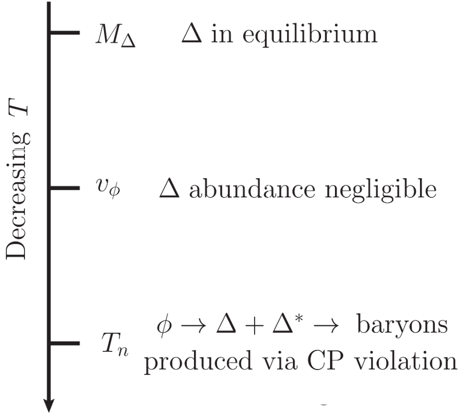


However, N, do not have gauge interactions. Some additional interactions are needed.

Numerical treatment of washout



Timeline of the AV option



Bubble collisions

End of the phase transition

- The phase transition completes through bubble nucleation/percolation.
- The bubble collisions lead to a gravitational wave signal.

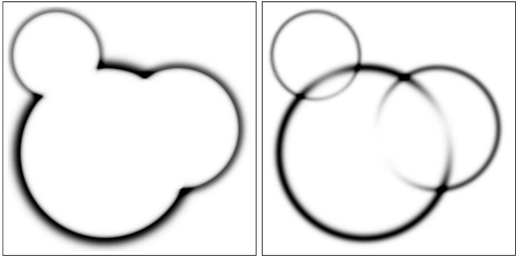
$$\Omega_{\mathrm{GW}}(\nu) \equiv \frac{d\Omega_{\mathrm{GW}}}{d\log\nu}$$

The spectra depend on the macroscopic properties

1. Latent heat $\alpha \approx \rho_{\mathrm{vac}}/\rho_{\mathrm{rad}}$.
2. Inverse timescale of the transition $\beta = -\frac{dS}{dt}$. (Sets bubble size).
3. The Hubble scale (determines redshifting).
4. The wall velocity v_w. For us $v_w \simeq 1$.

We can calculate these quantities from microphysics and then match onto results from simulations/semi-analytic studies.

Bubble collisions



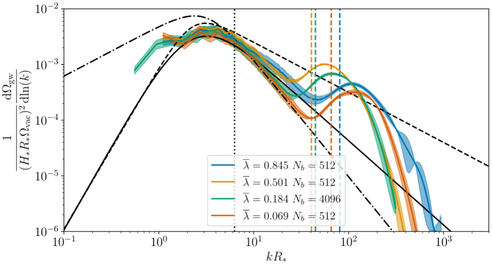
Left: envelope approximation. Right: bulk flow model.
Image from Konstandin 1712.06869

The GW spectrum

For such supercooled PTs: seems to be captured by the *bulk flow* model.

See: Ryusuke Jinno, Masahiro Takimoto 1707.03111,
Thomas Konstandin 1712.06869

Comparison of bulk flow to simulations.

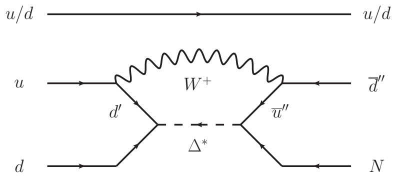


Cutting et al. 2005.13537 (also see Lewicki, Vaskonen 2007.04967)

- Amplitude scales as $(R_* H_*)^2 \approx (H_*/\beta)^2$.
- The peak frequency is set by the redshifted mean bubble size.
- Below the peak: region of $\Omega_{\rm GW}(\nu) \propto \nu^{0.9}$.
  $\rightarrow$ Eventually $\Omega_{\rm GW}(\nu) \propto \nu^3$ for superhorizon modes.
- Above the peak: $\Omega_{\rm GW}(\nu) \propto \nu^{-2.1}$.
- Second peak: suppressed by $\sim n_b/H_*^3 (m_\phi/M_{\rm Pl})^2$.

Possibilities for the N

1. Super light N. Gives Dirac leptogenesis with $y_\nu \overline{l_L} H N_R$ and $y_\nu \sim 10^{-12}$.



$$\Gamma(N \to \pi/K + \nu) \sim \frac{y^4 g_2^4 |V^*_{ud'} V_{u''d''}|^2 m_{d'}^2 m_{u''}^2 M_N^5}{\mathrm{Max}[M_W^4, M_{u''}^4] \times M_\Delta^4}$$

$M_\Delta \gtrsim y \times (10^{12} - 10^{13})\ \mathrm{GeV}$

Possibilities for the N

2. Massive N. Both Dirac and Majorana mass options give issues with washout.
3. Portal to asymmetric DM. Decay into a hidden sector $\sigma N \bar{f}$.