Baryogenesis and Gravitational Waves in two-Higgs-doublet models

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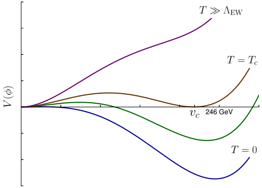
Outline

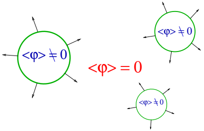
- BAU and GWs: relics from the electroweak epoch
- Baryogenesis with detectable GWs?
- 2HDMs: constraints and benchmark
- Gravitational wave spectrum
- Baryogenesis facing EDM constraints
- Conclusions and Outlook

Relics from the electroweak epoch

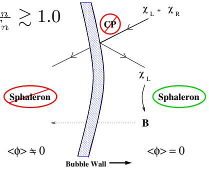
- A first order electroweak phase transition could lead to a BAU...



$$\frac{n_B}{s} \simeq 8.9 \times 10^{-11}$$

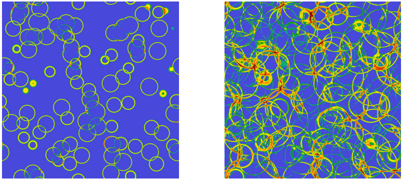


$$\frac{v_n}{T_n} \gtrsim 1.0$$



Morrisey and Ramsey-Musolf, New J. Phys. **14** *(2012) 125003*

- ...and source gravitational waves during bubble collision.



Hindmarsh, Huber, Rummukainen and Weir, Phys. Rev. D **92**, *123009*

- Red-shifted spectrum peaks at $f_{\rm GW} \sim 0.1 - 100$ mHz, in the range of **LISA**'s detectability.

Relics from the electroweak epoch

- Wall velocity is crucial for the BAU and the GW spectrum:
  - EWBG relies on diffusion in front of bubble wall ⇒ $\boxed{v_w < c_s}$
  - Detectable GWs predicated on very strong phase transitions, releasing large amount of energy → fast walls.
    Particularly true for the *envelope approximation*: $v_w \approx 1 \Rightarrow$ EWBG impossible!
- However, important recent developments!

Sensitivity curves for searches for gravitational-wave backgrounds

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(Dated: November 26, 2013)

We propose a graphical representation of detector sensitivity curves for stochastic gravitational-wave backgrounds that takes into account the increase in sensitivity that comes from *integrating over frequency* in addition to integrating over time. This method is valid for backgrounds that have a power-law spectrum in the analysis band. We call these graphs "power-law integrated curves." For simplicity, we consider cross-correlation searches for unpolarized and isotropic stochastic backgrounds using two sitivity curves for detectors such as L The code used to p for researchers inte

Numerical simulations of acoustically generated gravitational waves at a first order phase transition

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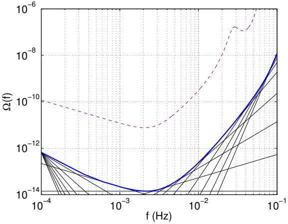
(Dated: January 7, 2016)

We present details of numerical simulations of the gravitational radiation produced by a first order thermal phase transition in the early universe. We confirm that the dominant source of gravitational waves is sound waves generated by the expanding bubbles of the low-temperature phase. We demonstrate that the sound waves have a power spectrum with a power-law form between the scales set by the average bubble separation (which sets the length scale of the fluid flow L_f) and the bubble wall width. The sound waves generate gravitational waves whose power spectrum also has a power-law form, at a rate proportional to L_f and the square of the fluid kinetic energy density. We identify a dimensionless parameter $\tilde{\Omega}_{GW}$ characterising the efficiency of this "acoustic" gravitational wave production whose value is $8\pi\tilde{\Omega}_{GW} \simeq 0.8 \pm 0.1$ across all our simulations. We compare the acoustic gravitational waves with the standard prediction from the envelope approximation. Not only is the power spectrum steeper (apart from an initial transient) but the gravitational wave energy density is generically larger by the ratio of the Hubble time to the phase transition duration, which can be 2 orders of magnitude or more in a typical first order electroweak phase transition.



$$\frac{\Omega_{\rm sw}}{\Omega_{\rm env}} \sim \frac{\tau_{\rm sw}}{\tau_{\rm env}} \sim \text{few} \times 10^2$$

Baryogenesis with gravitational waves?

- Could we get GW with deflagrating walls?
  GW + BAU simultaneously?
- Baryogenesis has its own "difficulties" to be overcome.
  SM fails to account for BAU because:
  - ✘ "phase transition" is not strongly first order (it's a cross-over!!!)
  - ✘ $\not{CP}$ from CKM matrix too small
- Begs for BSM physics with new particles in the plasma ($M \sim \Lambda_{\rm EW}$) and/or modified scalar sector.
  Also **new sources of $\not{CP}$**.
- Very stringent recent bounds on electron EDM:

$$\frac{d_e^{\rm ACME}}{d_e^{\rm prev}} \simeq \frac{8.7 \times 10^{-29} e \cdot {\rm cm}}{1.06 \times 10^{-27} e \cdot {\rm cm}} \approx 8.2 \times 10^{-2}.$$

- Is electroweak baryogenesis still viable?
  Yes! Recently shown e.g. for 2HDM+Singlet
  Alanne, Kainulainen, Tuominen and Vaskonen, JCAP **1608** *(2016) no.08, 057*
  See also Marek's talk

Two-Higgs-doublet model

- Two-Higgs-doublet models are minimal candidates for baryogenesis
- **Softly broken** $\mathbb{Z}_2$ suppresses FCNCs while allowing for CP violation and avoiding domain wall problems.

$$
\begin{aligned}
V_{\text{tree}} = & -\mu_1^2 \Phi_1^\dagger \Phi_1 - \mu_2^2 \Phi_2^\dagger \Phi_2 - \frac{1}{2}\left(\mu^2 e^{i\phi}\, \Phi_1^\dagger \Phi_2 + H.c.\right) \\
& + \frac{\lambda_1}{2}\left(\Phi_1^\dagger \Phi_1\right)^2 + \frac{\lambda_2}{2}\left(\Phi_2^\dagger \Phi_2\right)^2 + \lambda_3 \left(\Phi_1^\dagger \Phi_1\right)\left(\Phi_2^\dagger \Phi_2\right) \\
& + \lambda_4 \left(\Phi_1^\dagger \Phi_2\right)\left(\Phi_2^\dagger \Phi_1\right) + \frac{1}{2}\left[\lambda_5\, e^{i\psi}\left(\Phi_1^\dagger \Phi_2\right)^2 + H.c.\right]
\end{aligned}
$$

$$
\langle \Phi_1 \rangle = \begin{pmatrix} 0 \\ v_1 \end{pmatrix}, \qquad \langle \Phi_2 \rangle = \begin{pmatrix} 0 \\ v_2\, e^{i\xi} \end{pmatrix}
$$

- Two field-redefinition-independent complex phases related by a minimization condition:

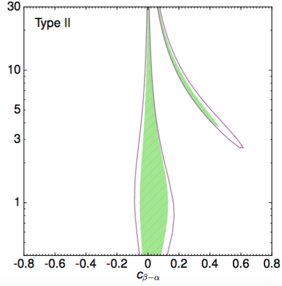
$$
\delta_1 = 2\phi - \psi, \qquad \delta_2 = \phi - \psi - \xi,
$$
$$
|\mu^2| \sin(\delta_1 - \delta_2) = v^2 \sin\beta \cos\beta\, |\lambda_5| \sin(\delta_1 - 2\delta_2).
$$

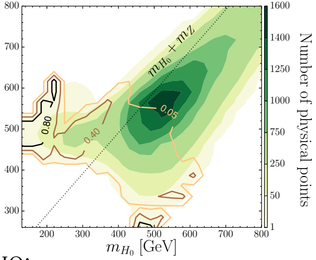
- Important parameters:

$\not{C}\not{P}$ phase:	$\delta_1 - \delta_2$
Scalar masses:	$m_{h^0} = 125$ GeV, m_{H^0}, m_{A^0}, $m_{H^\pm}$
Mass scale of Φ_2:	$M^2 \equiv \text{Re}(\mu^2)/\sin(2\beta)$
Mixing angles:	$\tan\beta$, $\beta - \alpha$ (sets departure of h^0 from h_{SM})

Constraints and phase transition in 2HDMs

- Higgs signals constraints requires approximate *alignment* ($h^0 \approx h_{SM}$)
  This also favors a strong EWPT.
- EW precision observables enforce an approx. degeneracy, $\boxed{m_{H^\pm} \approx m_{A^0} \text{ or } m_{H^0}}$
- For Type II, $\overline{B} \to X_s \gamma$ constrains $m_{H^\pm} \geq 480$ GeV
  Misiak et al., PRL **114** *(2015) no. 22 221801*
- A strongly first order phase transition prefers a large mass splitting
  $m_{A^0} \gtrsim m_{H^0} + m_Z$ with $m_{A_0} \gtrsim 300$ GeV
  GCD, Huber, No, JHEP 1310 (2013) 029
  GCD, Huber, Mimasu, No, PRL 113 (2014) 21, 211802





Benchmark scenario:

$$\boxed{M = m_{H^0} = 200 \text{ GeV}, \quad m_{A^0} = m_{H^\pm} \simeq 480 \text{ GeV}}$$

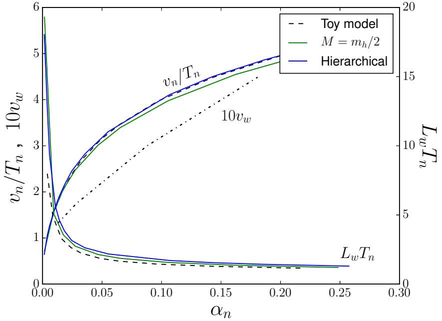
Estimating the wall velocity

- Estimate the wall velocity using a simplified model.
  Four additional scalars get their masses from the Higgs according to

$$m_s^2 = \kappa^2 \frac{\langle h \rangle^2}{2} \quad \text{(no self-interactions).}$$

  Comparable to a 2HDM in alignment limit, $\tan\beta = 1$ and $M = m_h/\sqrt{2}$.

- Determine friction coefficient η at runaway point and extrapolate using $\eta \sim \exp(-\sqrt{v/T})$ as found in MSSM scenarios.



$$\alpha_n \equiv \frac{\rho_{\text{released}}}{\rho_{\text{rad}}}$$

v_n/T_n	α_n	v_w
1.819	0.013	0.132
2.535	0.029	0.175
3.727	0.088	0.300
4.599	0.181	0.449

We can *exclude detonations* even for very strong transitions!

Gravitational wave spectrum

- For deflagrations the dominant contribution to GWs comes from acoustic oscillations in the plasma after collision.
- Active even after phase transition is complete.
- Relevant parameters: energy released (α_n) and duration of source activity

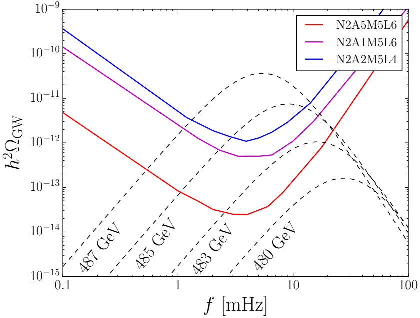
$$\frac{\Gamma}{\mathcal{V}} \sim e^{-S_3/T_n + \beta\,(t-t_n)}, \qquad \frac{\beta}{H_*} = T_n \left.\frac{dS_3}{dT}\right|_{T_n}.$$

- From numerical simulations the spectrum is estimated to behave as:

$$h^2\Omega_{\rm sw} \simeq 2.65 \times 10^{-6}\, v_w \left(\frac{H_*}{\beta}\right)\left(\frac{\kappa_v\,\alpha}{1+\alpha}\right)^2 \left(\frac{100}{g_*}\right)^{\frac{1}{3}}$$

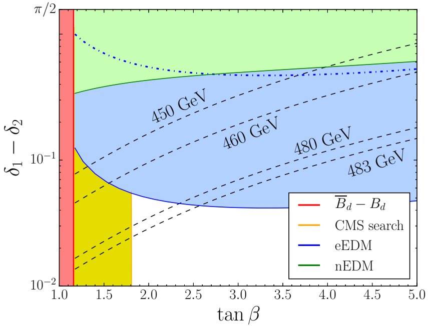
$$f_{\rm sw} \simeq 1.9 \times 10^{-2}\,{\rm mHz}\,\frac{1}{v_w}\left(\frac{\beta}{H_*}\right)\left(\frac{T}{100\,{\rm GeV}}\right)\left(\frac{100}{g_*}\right)^{\frac{1}{6}}$$

m_{A^0} [GeV]	v_n/T_n	$L_w T_n$	α_n	β/H^*	v_w
480	4.00	1.72	0.11	757.32	0.3
483	4.36	1.56	0.14	564.24	0.35
485	4.68	1.44	0.18	439.55	0.45
487	5.12	1.31	0.25	316.08	$\approx c_s$



EDM constraints and the BAU

- In 2HDMs, contributions to EDMs enter already at 2-loop (Barr-Zee diagrams, Weinberg 3-gluon operator)
  Experimental bounds place tight constraints on $\not{CP}$ phase.



- Regarding the BAU, full computation involves solving Boltzmann eqs. including all relevant scattering rates.
- The results are expected to scale as

$$\frac{\eta}{\eta_{\rm obs}} \sim \left(\frac{v_n}{T_n}\right)^4 \frac{1}{L_w T_n} \frac{\Delta\theta_{\rm CP}}{(1+\tan^2\beta)}$$

$$\theta_{\rm CP} \equiv {\rm Arg}(v_1^* v_2)$$

- A couple of sources of uncertainties must be mentioned:
  - v_w only estimated, but its impact is probably not drastic as long as we have deflagrations;
  - for such strong transitions, we find $L_w T_n \sim 1.5$.
    What's the impact on validity of gradient expansion $(L_w T_n \gg 1)$?

Conclusions and Outlook

- Recent developments in our understanding of GWs from EWPT opened the possibility of having a detectable signal even for *deflagrations*, $v_w < c_s$.
- Using these results, we show that the EWPT in 2HDMs could lead to **successful baryogenesis as well as a gravitational wave spectrum detectable in the near-future (LISA)!**
- Incidentally, we show that baryogenesis is viable in this model even after taking into account the tight ACME eEDM bounds.

Room for improvement:

- Full computation of wall velocity $\Rightarrow$ microscopic computation of friction and solution of the full set of hydrodynamical field equations.
- How to deal with very thin walls?
- Can numerical simulations of GWs be extrapolated beyond $\alpha \sim 0.1$? Does turbulence also play a role?

Perturbativity

- A strong PT typically requires large couplings.
  The most extreme case here considered has

$$\lambda_1 = \lambda_2 \simeq 0.2578, \qquad \lambda_3 \simeq 6.762, \qquad \lambda_4 = \lambda_5 \simeq -3.252.$$

- Solve RGE $\Rightarrow$ Landau pole and $\max(\lambda_i(\Lambda)) \geq 4\pi$.