Confronting the W mass anomaly with a possible observation of primordial gravitational waves

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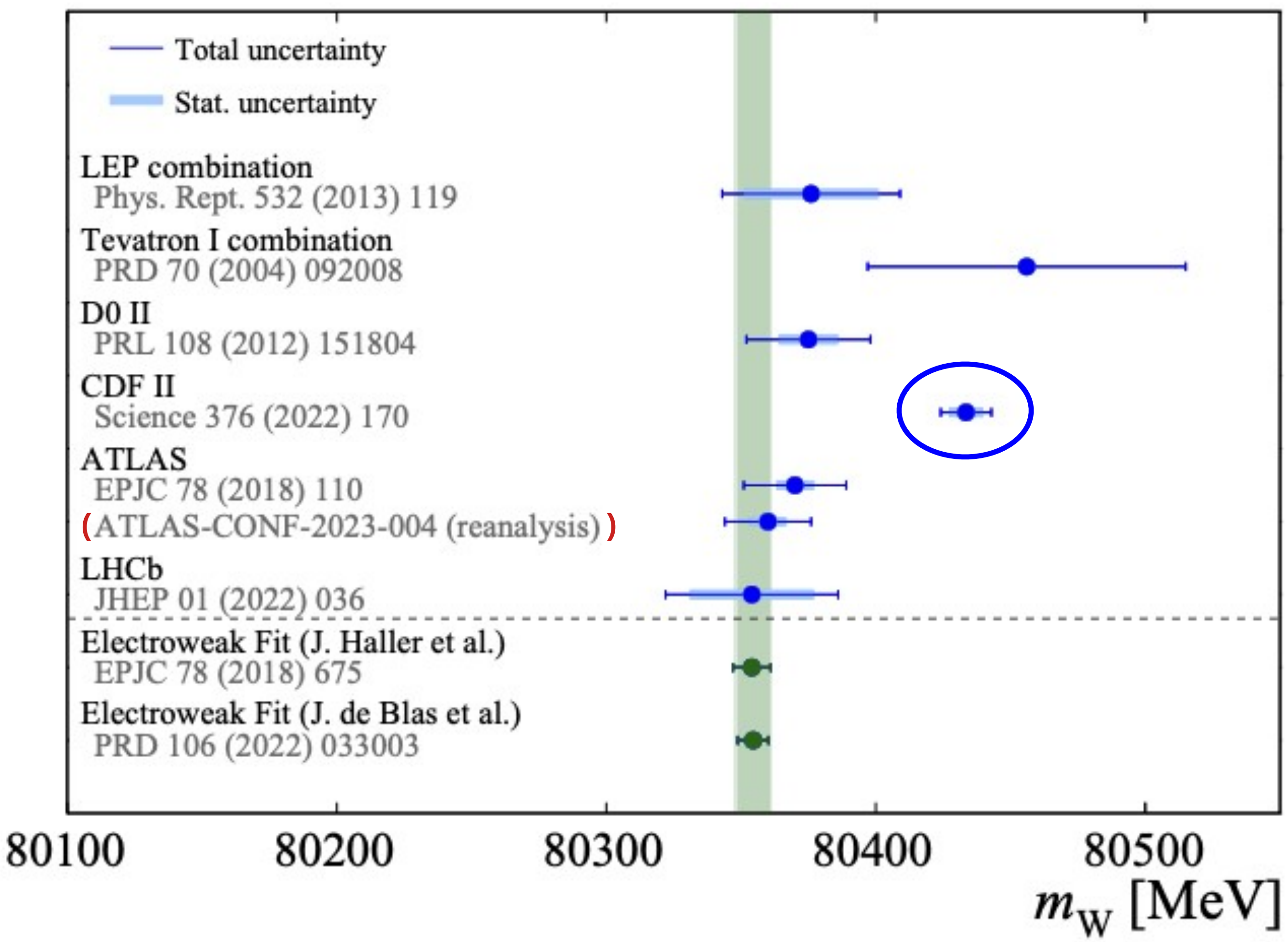
Outline



talk by Maarten Boonekamp

- Surprising CDF II measurement of W mass lies >7σ away from the Standard Model
- Many scenarios beyond the SM have been deployed in the literature to explain this measurement (over 300 publications so far!)
- A large class of BSM scenarios offering such an explanation features the existence of a new SU(2) adjoint (triplet) scalar which provides a tree-level corrections to the SM W mass value
- Existence of such scalars may impact the Electro Weak phase transition in early Universe, possibly rendering such models testable in future gravitational-wave detectors

EMEFT approach

L. Di Luzio, R. Gröber and P. Paradisi,
"Higgs physics confronts the m_W anomaly" Phys.Lett.B 832 (2022) 137250

SMEFT Lagrangian (Warsaw):

$$\mathcal{L}_{\rm SMEFT} = \mathcal{L}_{\rm SM} + \sum_i c_i \mathcal{O}_i$$

Universal "bosonic" operators:

$$\mathcal{O}_{HWB} = (H^\dagger \tau^a H) W^a_{\mu\nu} B^{\mu\nu} ,$$

$$\mathcal{O}_{HD} = (H^\dagger D_\mu H)((D_\mu H)^\dagger H) ,$$

Leading EW oblique corrections:

$$\hat{S} \equiv \frac{c_W}{s_W} \Pi'(0)_{W_3 B} = \frac{c_W}{s_W} v^2 c_{HWB} ,$$

$$\hat{T} \equiv \frac{1}{M_W^2} (\Pi_{W_3 W_3}(0) - \Pi_{W^+ W^-}(0)) = -\frac{v^2}{2} c_{HD} ,$$

EFT d=6 operator generates W mass shift

A. Strumia, JHEP 08 (2022) 248

W mass anomaly ⟷ **Anomaly in T-parameter (assuming U=0)**

$$\hat{T} \simeq (0.84 \pm 0.14) \times 10^{-3}$$

$$c_{HD} \ = \ -(0.17 \pm 0.07/\mathrm{TeV})^2$$

$$\hat{S} \sim 10^{-3} \qquad c_{HWB} \sim (0.07/\mathrm{TeV})^2$$

compatible with zero

What can generate a positive shift in T?

L. Di Luzio, R. Gröber and P. Paradisi,
"Higgs physics confronts the m_W anomaly" Phys.Lett.B 832 (2022) 137250

New Physics states generating tree-level contribution to T via renormalisable interactions with SM states:

our focus →

Field	Spin	$SU(3)_C$	$SU(2)_L$	$U(1)_Y$	$\text{sign}(\hat{T})$	$\hat{S}$
Δ	0	1	3	0	$+$	$\times$
Δ_1	0	1	3	1	$-$	$\times$
Θ_1	0	1	4	1/2	$+$	$\times$
Θ_3	0	1	4	3/2	$-$	$\times$
$\mathcal{B}$	1	1	1	0	$+$	$\times$
$\mathcal{B}_1$	1	1	1	1	$-$	$\times$
$\mathcal{W}$	1	1	3	0	$-$	$\times$
$\mathcal{W}_1$	1	1	3	1	$+$	$\times$
$\mathcal{L}$	1	1	2	1/2	$+/-$	✓

Let us focus on a simplified framework that relates the characteristics of EW phase transitions to a possible explanation of the W mass anomaly

A minimal scalar SU(2) triplet extension

Interaction Lagrangian with Higgs:

$$\mathcal{L}_{\Delta}^{\text{int}} \ni -\kappa_{\Delta} H^{\dagger} \Delta^a \sigma^a H - \frac{\lambda_{H\Delta}}{2} (H^{\dagger} H) \Delta^a \Delta^a$$

$$\Delta = (1, 3, 0)$$

Integrating out heavy triplet:

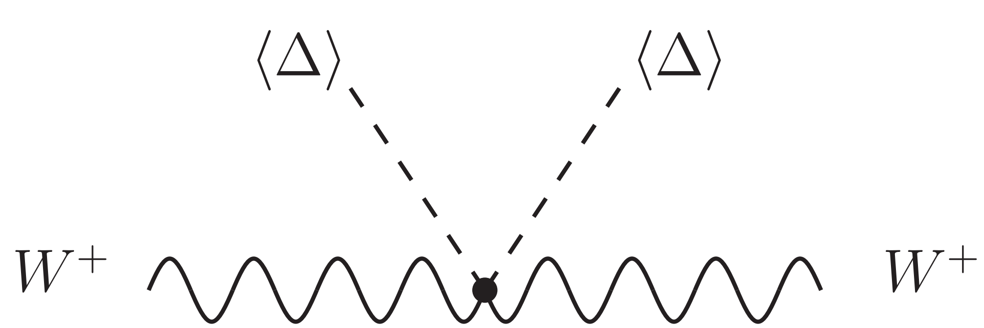
$$c_{HD} = -2 \frac{\kappa_{\Delta}^2}{M_{\Delta}^4}$$

negative effective coupling!

$$\hat{T} = \frac{\kappa_{\Delta}^2 v^2}{M_{\Delta}^4} = 0.84 \times 10^{-3} \left(\frac{|\kappa_{\Delta}|}{M_{\Delta}} \right)^2 \left(\frac{8.5\,\text{TeV}}{M_{\Delta}} \right)^2$$

the same effect in T can be recast in terms of the adjoint VEV

$$\langle \Delta \rangle \equiv v_{\Delta} = \kappa_{\Delta} v^2 / (2 M_{\Delta}^2)$$



L. Di Luzio, R. Gröber and P. Paradisi, Phys.Lett.B 832 (2022) 137250

Saturating the perturbativity bound $|k_{\Delta}|/M_{\Delta} \leq 4\pi$ the mass scale cannot exceed 100 TeV

Effective d=6 Higgs self-interaction

Integrating out heavy new scalar triplet state yields both:
a positive contribution to the T-parameter and a modification of the Higgs potential

Higgs quartic couplings receives a tree-level correction

$$\lambda = \lambda_{\rm bare} + (k_\Delta / m_\Delta)^2$$

$$\lambda = m^2/2v^2$$

due to an adjoint VEV, we have

$$\lambda_\Delta {\rm Tr}[\Delta^\dagger \Delta \Delta^\dagger \Delta] \rightarrow \frac{\mu_\Delta}{3} \Delta^3 \qquad \mu_\Delta \sim \lambda_\Delta v_\Delta$$

effective operator below the cutoff scale:

d=6 Higgs self-interaction term:

$$c_H (H^\dagger H)^3 \qquad c_H \equiv \frac{\kappa}{\Lambda^2} \sim v_\Delta$$

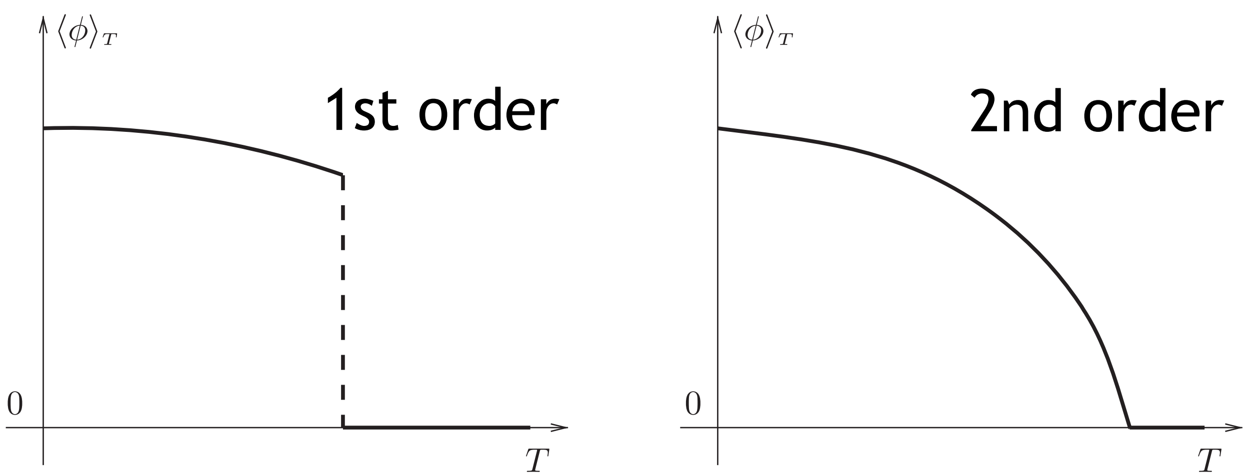
Other contributions to this operator come from quartics:

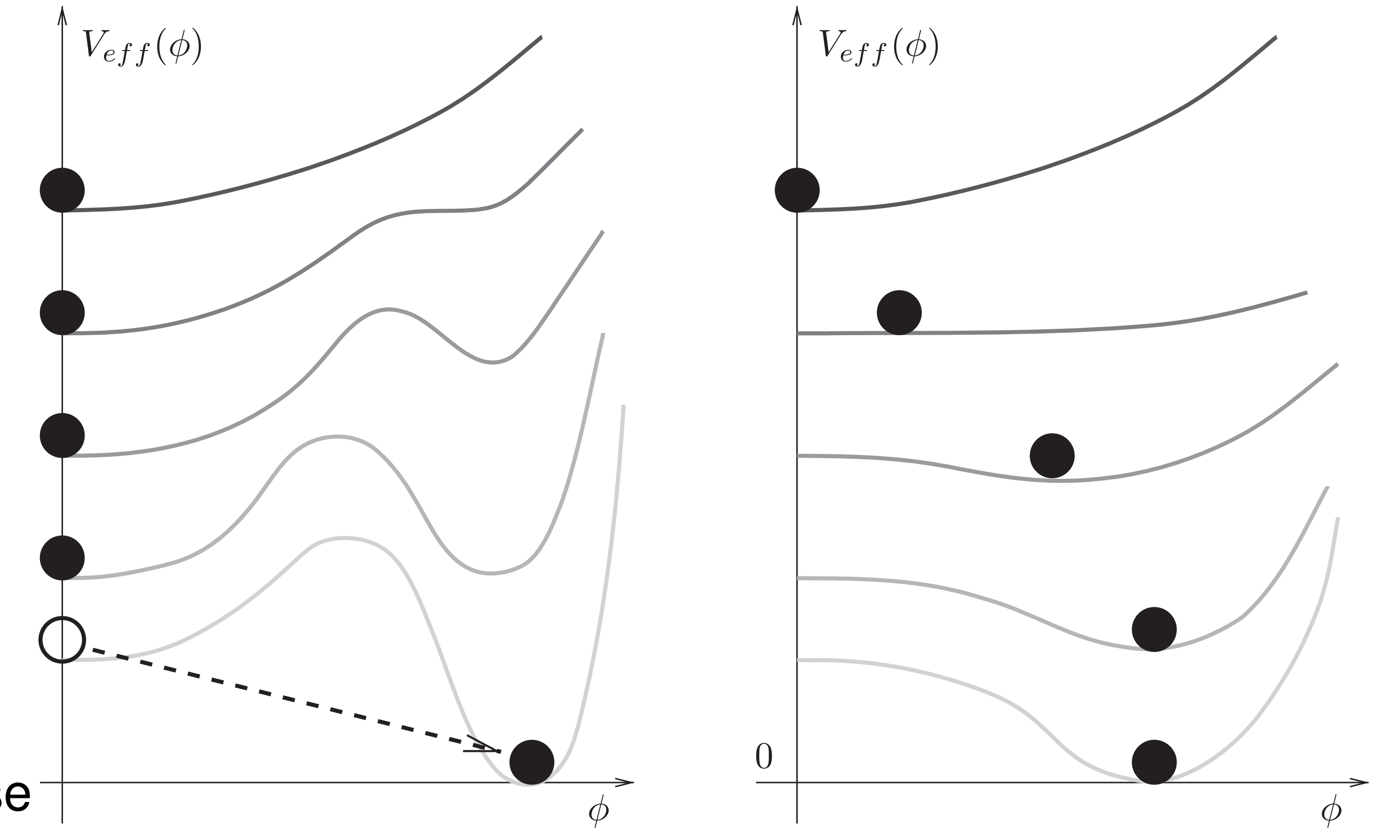
$$\frac{k_\Delta^2}{M_\Delta^4} \lambda' \rightarrow c_H \qquad \lambda' \equiv 4\lambda - \frac{\lambda_{H\Delta}}{2}$$

$$\mu_\Delta \rightarrow 0 \qquad c_H = -4 \frac{\hat{T}}{v^2} \left(\frac{\lambda_{H\Delta}}{8} - \lambda \right) \sim v_\Delta^2 \rightarrow 0$$

d=6 contribution to the Higgs potential is important for the nature and the strength of the EW phase transition

EW phase transitions





Strong cosmological phase transitions (PTs) $\rightarrow$
by expanding and colliding vacuum bubbles of new phase

Stochastic Gravitational Wave (GW) background
as a gravitational probe for New Physics

$$\frac{n_B - n_{\overline{B}}}{s} \sim 10^{-11}$$

Why strong FOPTs?

Sakharov'67

(i) B violation

(ii) C and CP violation

(iii) Departure from thermal equilibrium $\rightarrow$ **strong 1st-order PT**

Nucleation of expanding broken-phase vacuum bubbles $\rightarrow$ sphaleron suppression

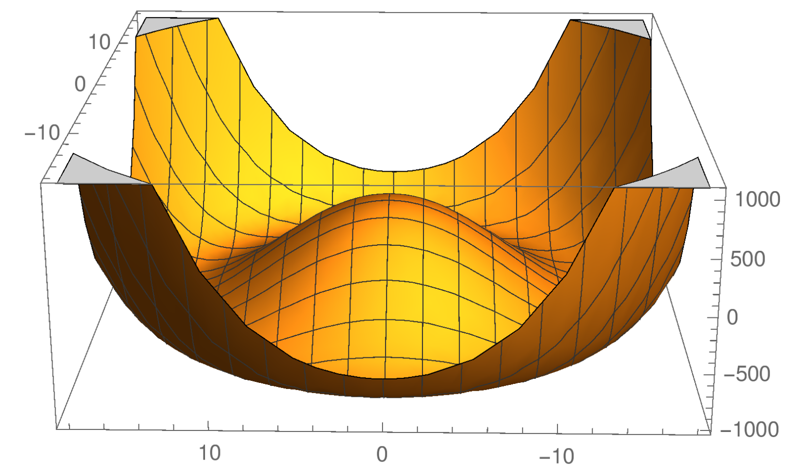
$$\frac{\phi(T_c)}{T_c} \gtrsim 1.1 \qquad \rightarrow \qquad 1^{st} \text{ order PT}$$

Standard Model (SM) does not explain the BA $\rightarrow$ **the need to go beyond the SM**

Basics of Strong First Order PTs (SFOPTs)

Consider a the scalar potential: $V(\phi) = \mu^2 \phi^* \phi + \lambda(\phi^* \phi)^2$

$\mu^2 < 0$ and $\lambda > 0$

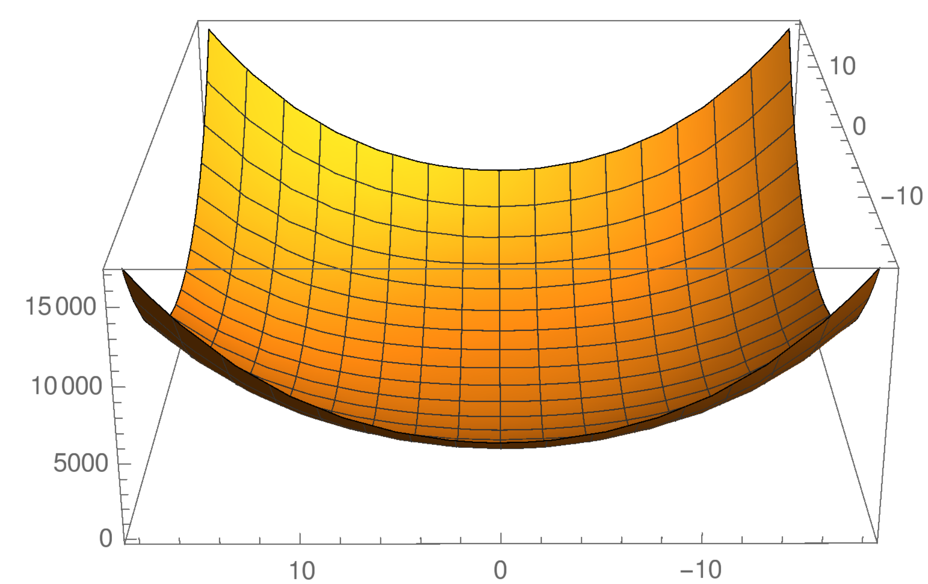


Add thermal corrections:

$$V(\phi, T) = (\mu^2 + C_\phi T^2)\phi^* \phi + \lambda(\phi^* \phi)^2$$

For $C_\phi > 0$, after a certain $T > 0$, $\mu_{eff} \equiv \mu^2 + C_\phi T^2 > 0$

Restored symmetry



Euclidean effective action

- High $T \to$ classical motion in Euclidean space described by action $\hat{S}_3$

$$\hat{S}_3 = 4\pi \int_0^\infty \mathrm{d}r\, r^2 \left\{ \frac{1}{2} \left(\frac{\mathrm{d}\hat{\phi}}{\mathrm{d}r} \right)^2 + V_{\mathrm{eff}}(\hat{\phi}) \right\} ,$$

- Effective potential: loop and thermal corrections

$$\begin{aligned} V_{\mathrm{eff}}^{(1)}(\hat{\phi}) &= V_{\mathrm{tree}} + V_{\mathrm{CW}} + \Delta V^{(1)}(T) \\ V_{\mathrm{CW}} &= \sum_i (-1)^F n_i \frac{m_i^4}{64\pi^2} \left(\log \left[\frac{m_i^2(\hat{\phi}_\alpha)}{\Lambda^2} \right] - c_i \right) \\ \Delta V^{(1)}(T) &= \frac{T^4}{2\pi^2} \left\{ \sum_b n_b J_B \left[\frac{m_b^2(\hat{\phi}_\alpha)}{T^2} \right] - \sum_f n_f J_F \left[\frac{m_f^2(\hat{\phi}_\alpha)}{T^2} \right] \right\} , \end{aligned}$$

- $\hat{\phi} \to$ solution of the e.o.m. found by the path that minimizes the energy.

$$\Delta V^{(1)}(T)|_{\mathrm{L.O.}} = \frac{T^2}{24} \left\{ \mathrm{Tr}\left[M^2_{\alpha\beta}(\phi_\alpha) \right] + \sum_{i=W,Z,\gamma} n_i m_i^2(\phi_\alpha) + \sum_{i=t,b,\tau} \frac{n_i}{2} m_i^2(\phi_\alpha) \right\}$$

Characteristics of phase transitions

- Nucleation temperature $T_n \to$ the PT does effectively occur $\to$ vacuum bubble nucleation processes
- Satisfies $T_n < T_c$, where T_c is the critical temperature $\to$ degenerate minima
- Corresponds to probability to realize one transition per cosmological horizon volume equal one

- The phase transition rate

$$\Gamma \sim T^4 \left(\frac{\hat{S}_3}{2\pi T} \right)^{3/2} \exp\left(-\hat{S}_3/T\right)$$

$$\frac{\Gamma}{H^4} \sim 1 \qquad \Rightarrow \qquad \frac{\hat{S}_3}{T_n} \sim 140$$

Inverse time-scale of the PTs:

$$\frac{\beta}{H} = T_* \frac{\partial}{\partial T} \left(\frac{\hat{S}_3}{T} \right) \Bigg|_{T_*}$$

Relative latent heat (PT strength):

$$\alpha = \frac{1}{\rho_\gamma} \left[V_i - V_f - \frac{T_*}{4} \left(\frac{\partial V_i}{\partial T} - \frac{\partial V_f}{\partial T} \right) \right]$$

- This formalism is implemented in CosmoTransitions package (Wainwright'12)

$$\rho_\gamma = g_* \frac{\pi^2}{30} T_n^4 \,, \qquad g_* \simeq 106.75$$

Probability to find a point in the false vacuum:

$$P(T) = e^{-I(T)},$$

$$I(T) = \frac{4\pi v_b^3}{3} \int_T^{T_c} \frac{\Gamma(T') dT'}{T'^4 H(T')} \left(\int_T^{T'} \frac{d\tilde{T}}{H(\tilde{T})} \right)^3$$

Percolation temperature

(temperature at which at least 34% of the false vacuum has tunnelled into the true vacuum)

$$I(T_*) = 0.34$$

J. Ellis, M. Lewicki, and V. Vaskonen, Journal of Cosmology and Astroparticle Physics **2020**, 020–020 (2020).

Gravitational-wave power spectrum

- GW energy density per logarithmic frequency

$$h^2\Omega_{\rm GW} \equiv \frac{h^2}{\rho_c}\frac{d\rho_{\rm GW}}{d\log f} \simeq h^2\Omega_{\rm col} + h^2\Omega_{\rm sw} + h^2\Omega_{\rm MHD}$$

C. Caprini *et al.*, JCAP **2003**, 024 (2020), 1910.13125

$$\text{signal} \;\sim\; \text{amplitude} \;\times\; \text{spectral shape}\;(f/f_{\rm peak})$$

Primordial GWs power spectrum:

$$h^2\Omega_{\rm GW} = h^2\Omega_{\rm GW}^{\rm peak}\left(\frac{4}{7}\right)^{-\frac{7}{2}}\left(\frac{f}{f_{\rm peak}}\right)^3\left[1+\frac{3}{4}\left(\frac{f}{f_{\rm peak}}\right)\right]^{-\frac{7}{2}}$$

Peak amplitude — Spectral function

peak frequency $f_{\rm peak} \propto (\beta/H)T_*$

$$h^2\Omega_{\rm GW}^{\rm peak} \propto T_*^2 K(\alpha) f_{\rm peak}^{-2}$$

Finite-T effective potential & EW FOPTs

In unitary gauge, one-loop effective Higgs potential:

$$V_{\rm eff}(T,h) = V_{\rm tree}(h) + V^{(1)}_{T=0}(h) + \Delta V_T(h,T)$$

$$V_{\rm tree}(h) = \frac{1}{2}m^2h^2 + \frac{\lambda}{4}h^4 + \frac{\kappa}{8\Lambda^2}h^6$$

The dominant thermal correction to the Higgs mass:

$$CT^2/2$$

$$C \simeq \frac{1}{16}\left(g'^2 + 3g^2 + 4y_{\rm t}^2 + 4\frac{m_{\rm h}^2}{v^2} + 36\frac{\kappa v^2}{\Lambda^2}\right)$$

modification of EW parameters

$$m^2 = m^2_{\rm SM}(1 - \Lambda^2_{\rm M}/2\Lambda^2)$$

$$\lambda = \lambda_{\rm SM}(1 - \Lambda^2_{\rm M}/\Lambda^2)$$

$$\Lambda_{\rm M} = \sqrt{3}\Lambda_{\rm m} = \sqrt{3\kappa}v^2/m^2$$

$$\Lambda_{\rm m} \le \Lambda \le \Lambda_{\rm M}$$ cutoff scale

$$m_{\rm h}^2 = 2\lambda v^2 + 3v^4\kappa/\Lambda^2 \qquad m_{\rm h} = 125\,{\rm GeV}$$

Limit on the d=6 operator imposed by the strongly 1st order EW phase transition requirement yields:

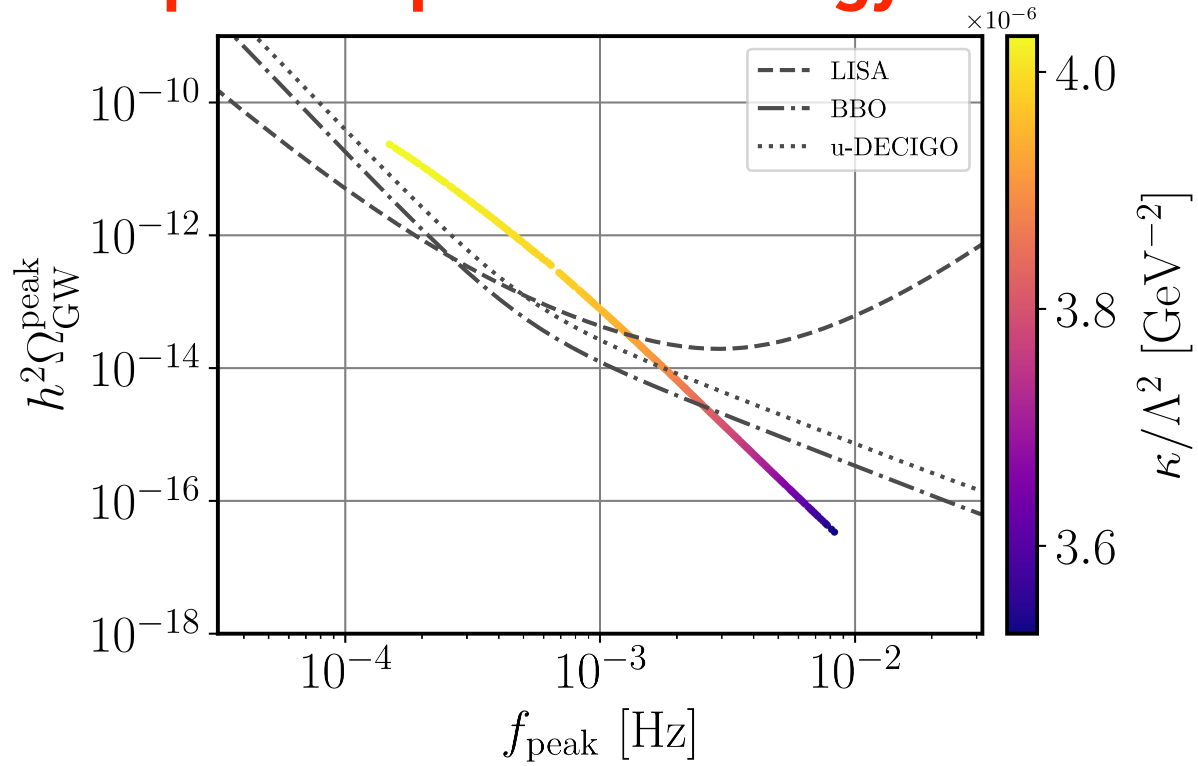
$$480\,{\rm GeV} \lesssim \frac{1}{\sqrt{|c_H|}} \lesssim 840\,{\rm GeV}$$

$$v(T_{\rm c})/T_{\rm c} > 1$$

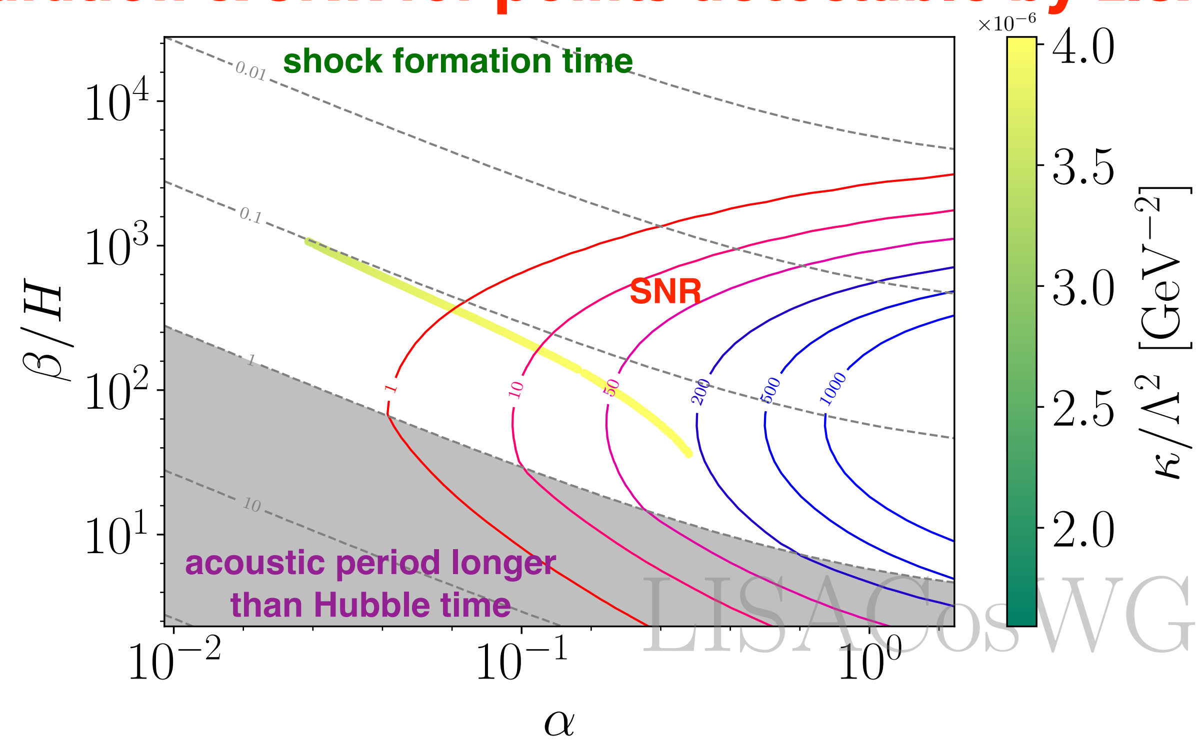
F. Huang et al, Phys. Rev. D94 (2016) 041702 [arXiv:1601.01640 [hep-ph]]

Primordial GWs in a minimal triplet model

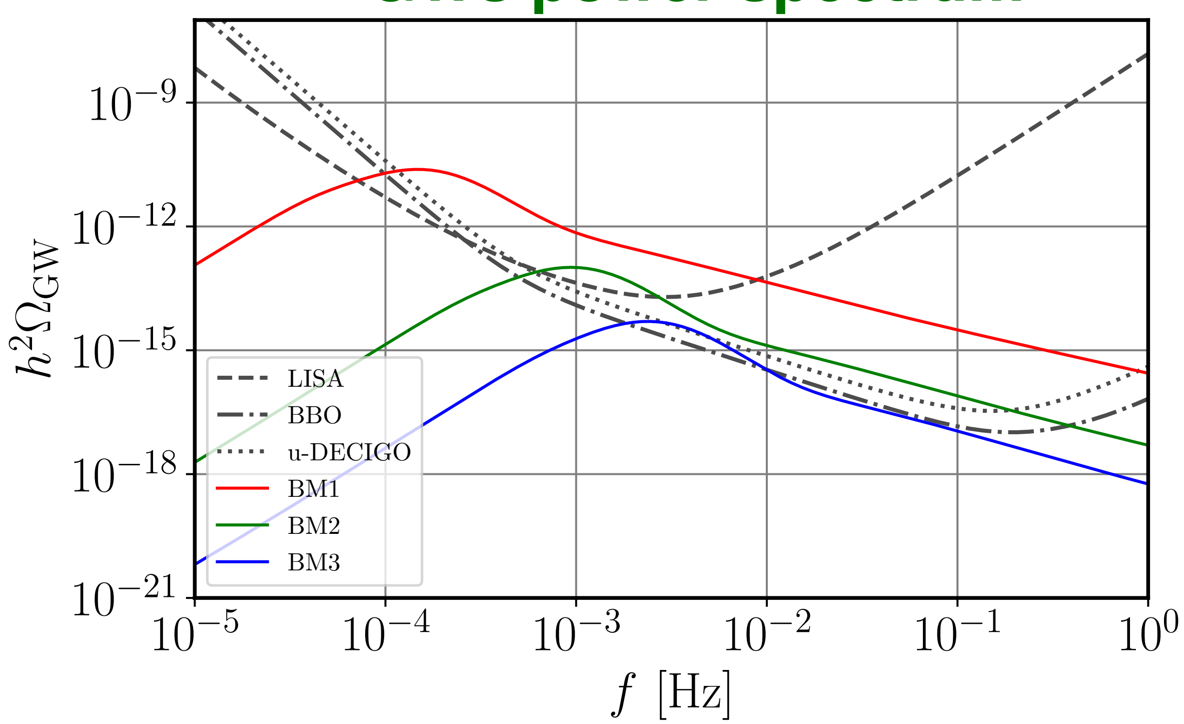
peak-amplitude vs energy scale



duration & SNR for points detectable by LISA



GWs power spectrum



Benchmarks:

T_*(GeV)	α	β/H_*	$\kappa^{-1/2}\Lambda$(GeV)	$\delta_{\sigma_{hz}}$(%)
43.8	0.30	36.37	498.12	1.8
55.6	0.12	180.94	502.40	2.1
64.2	0.07	394.14	508.38	2.2

- Consistent with LHC bounds
- Can be probed in future measurements of trilinear Higgs coupling:

$$\lambda_{3h} = -(1+\delta_h)\frac{Ah^3}{6} \qquad A = 3m_h^2/v$$

$$\delta_h = 2\Lambda_m/\Lambda \in (2/3, 2) \qquad \delta_{\sigma_{hZ}} = \delta\sigma_{hZ}/\sigma_{hZ} \simeq 1.6\%\ \delta_h \text{ at } \sqrt{s} = 240 \text{ GeV}$$

CEPC collider: $10\ \text{ab}^{-1}$ $\quad \delta_{\sigma_{hZ}} \sim 0.4\%$ $\quad |\delta_h| \sim 25\%$

Summary

- A simple model with heavy scalar triplet provides potentially observable new signatures (W mass correction, triple-Higgs coupling, FOPTs & GWs) and addresses some of the fundamental questions (e.g. neutrino mass)
- Primordial gravitational waves represent a complimentary source of information to the collider measurements (such as HE-LHC and Circular e+e- Collider)
- Combining W mass, future measurements of triple Higgs coupling and primordial GWs would provide strong case of probing such a class of models BSM