Probing Features of a Strong First-Order Electroweak Phase Transition in correlation to the Alignment Limit in the Two-Higgs-Doublet Model of Type-I

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DESY, Hamburg and Universität Hamburg

In Collaboration with:
Francisco Arco, Georg Weiglein, Kateryna Radchenko,
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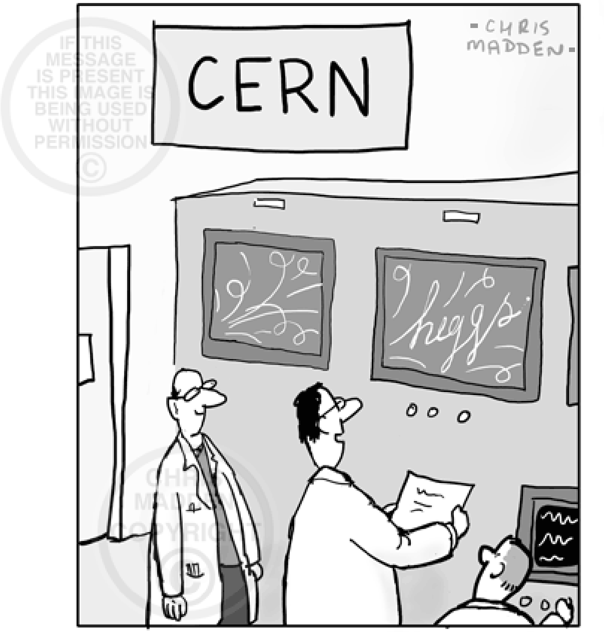
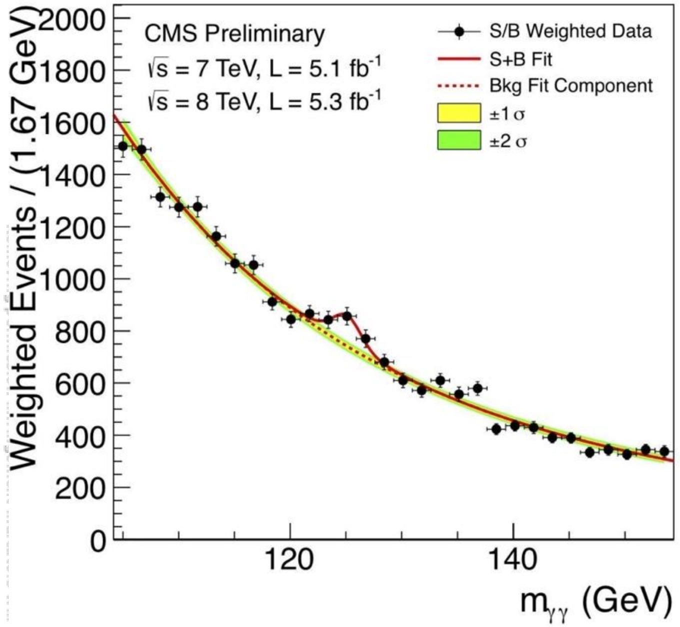
Outline

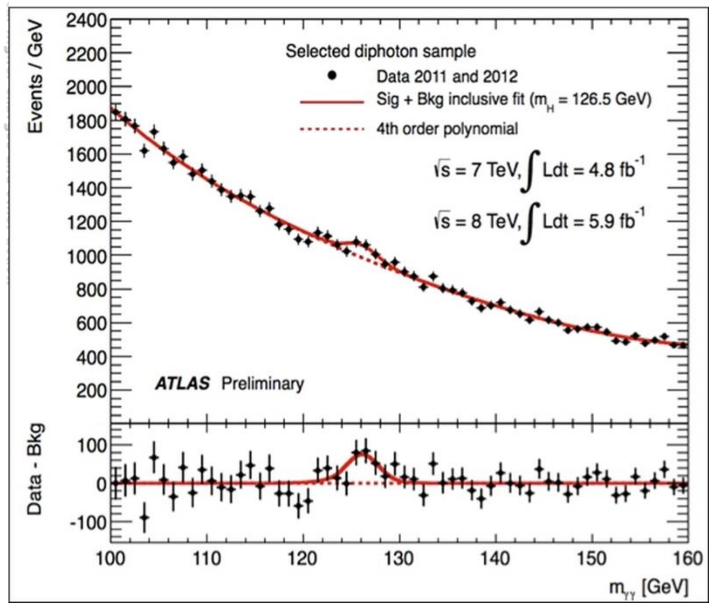
1. The Two-higgs-doublet model (2HDM)
2. Finite-temperature effective potential
3. Results and discussion:
   studying the 2HDM parameter space of type-I
4. Conclusions
5. Future prospects
6. references

2012



"Take a look at this everyone - it just could be the signature we've been looking for!"





The Premise of interest

Baryon asymmetry (BAU)

Observed value of BAU $\simeq 6 \cdot 10^{-10}$

insufficient !

The Standard Model ?

Smooth-crossover phase transition

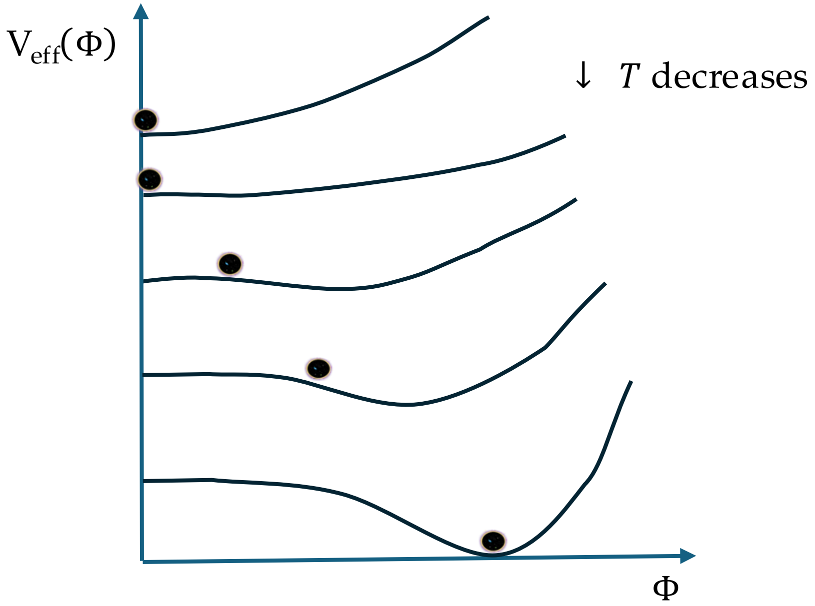


Figure 1.1: SM prediction of electroweak symmetry breaking as a smooth-crossover phase transition

EW Baryogenesis

✓ A strong first-order phase transition

Beyond the SM !

2 The Two-Higgs-Doublet Model (2HDM)

2HDM

RICHER POTENTIAL STRUCTURE!

SCALAR SECTOR → SM EXTENSION WITH A SCALAR DOUBLET → Φ_1 AND Φ_2

Z_2 SYMMETRY

$$\Phi_1 \to \Phi_1$$
$$\Phi_2 \to -\Phi_2$$

$$V(\Phi_1,\Phi_2) = m_{11}^2(\Phi_1^\dagger\Phi_1) + m_{22}^2(\Phi_2^\dagger\Phi_2) - m_{12}^2(\Phi_1^\dagger\Phi_2 + \Phi_2^\dagger\Phi_1) + \frac{\lambda_1}{2}(\Phi_1^\dagger\Phi_1)^2 + \frac{\lambda_2}{2}(\Phi_2^\dagger\Phi_2)^2 + \lambda_3(\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2) + \lambda_4(\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1) + \frac{\lambda_5}{2}\left[(\Phi_1^\dagger\Phi_2)^2 + (\Phi_2^\dagger\Phi_1)^2\right]$$

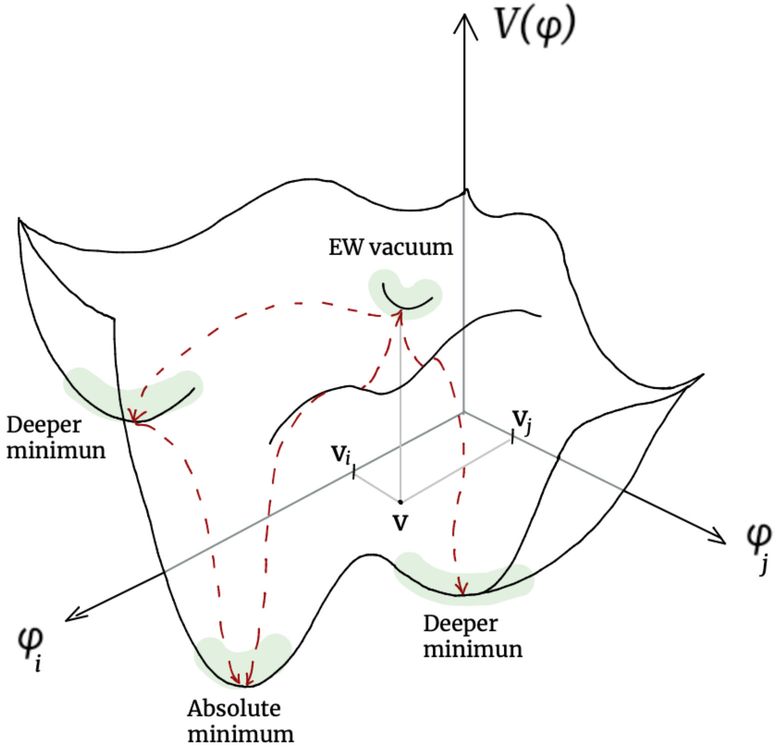
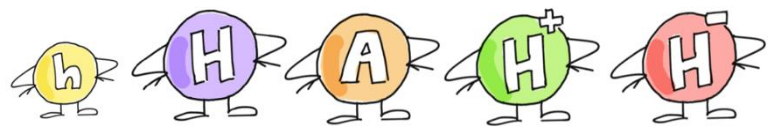


Figure 2.1:
Illustration* of the minima structure of the Higgs potential in the field space of the 2HDM.

$$\langle\Phi_1\rangle = \frac{1}{\sqrt{2}}\begin{pmatrix}0\\ v_1\end{pmatrix}$$
$$\langle\Phi_2\rangle = \frac{1}{\sqrt{2}}\begin{pmatrix}0\\ v_2\end{pmatrix}$$

5 PHYSICAL SCALAR FIELDS $(h,\ H,\ A,\ H^{\pm})$



*Art credit: Kateryna Radchenko

Figure 2.2:
Illustration* of the physical scalars in the 2HDM.

Free parameters

$\underbrace{\tan\beta,\ \cos(\beta - \alpha),\ v,}$ $\underbrace{m_h\ ,\ m_H,\ m_{H^\pm},\ m_A,}$ $\underbrace{m_{12}^2}$

Vev and vacuum direction | Physical scalar spectrum | Soft Z_2 breaking scale

Theoretical constraints:

- Vacuum stability and boundedness-from-below
- Perturbative unitarity

Experimental constraints:

- Electroweak precision observables
- Limits from BSM Higgs bosons searches
- Measurements of the properties of h_{125}
- Flavour Constraints

Do heavier scalars decouple?

$$\underbrace{M^2 = \frac{m_{12}^2}{\sin\beta\cos\beta}}$$

$$m_\varphi^2 = M^2 + \lambda_\varphi v^2 (+\mathcal{O}(v^2/M^4))$$

Enter loop corrections

In which direction EWS breaking occurs?

$$h_{SM} = h\ \sin(\alpha - \beta) - H\ \cos(\alpha - \beta)$$

If $\cos(\beta - \alpha) \to 0$

The alignment limit

EW vacuum aligns with the lighter state, h

$h \to h_{125}$

SM-like couplings at tree-level

HIGH TEMPERATURES $\Rightarrow$ **THERMAL EVOLUTION OF VACUUM** $\Rightarrow$ TODAY: $T=0$

THE EFFECTIVE POTENTIAL

FROM EFFECTIVE ACTION

$$V_{\text{eff}}(\phi, T) = \underbrace{\boxed{V_{\text{tree}} + V_{\text{CW}} + V_{\text{CT}}}}_{\text{Zero temperature scalar potential}} + \underbrace{\boxed{V_{\text{T}} + V_{\text{daisy}}}}_{\text{Finite temperature effects}}$$

ZERO TEMPERATURE SCALAR POTENTIAL

FINITE TEMPERATURE EFFECTS

First-order Phase Transition

EW SYMMETRY

DEGENERATE VACUA

EWS BREAKING

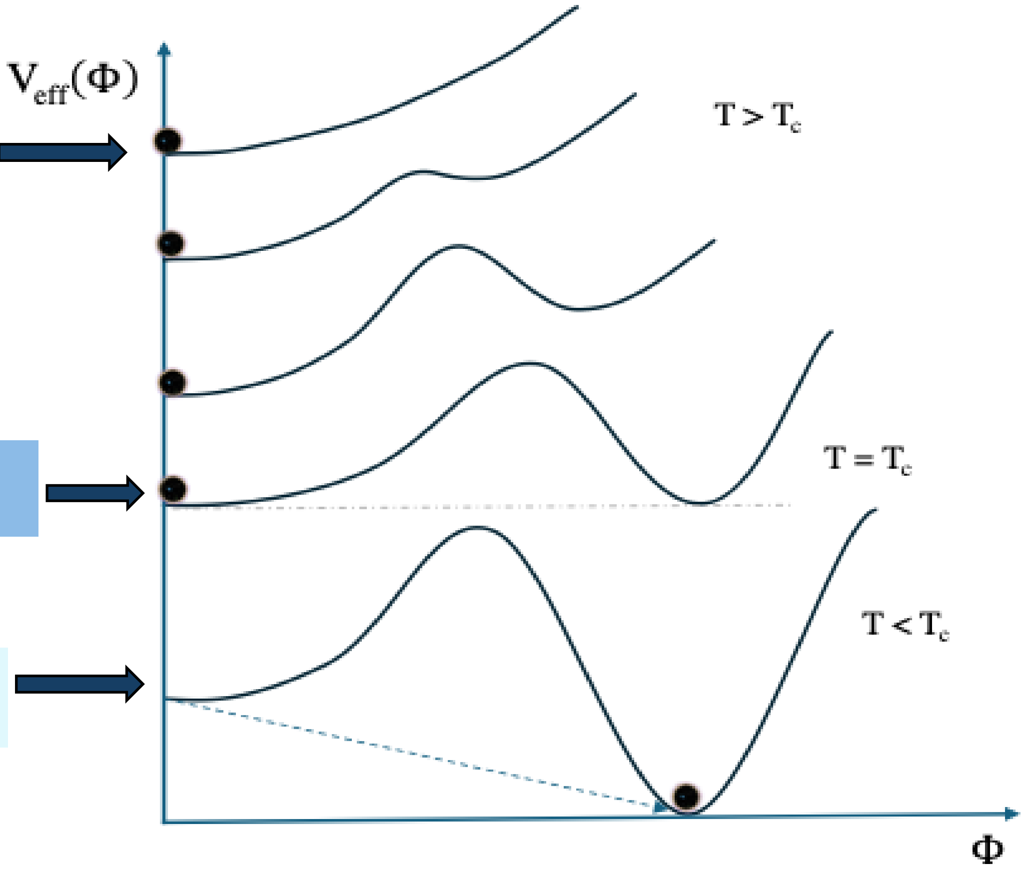


Figure 3.1:
Thermal evolution of the 2HDM potential leading to a strong first-order phase transition from the false vacuum to the true vacuum.

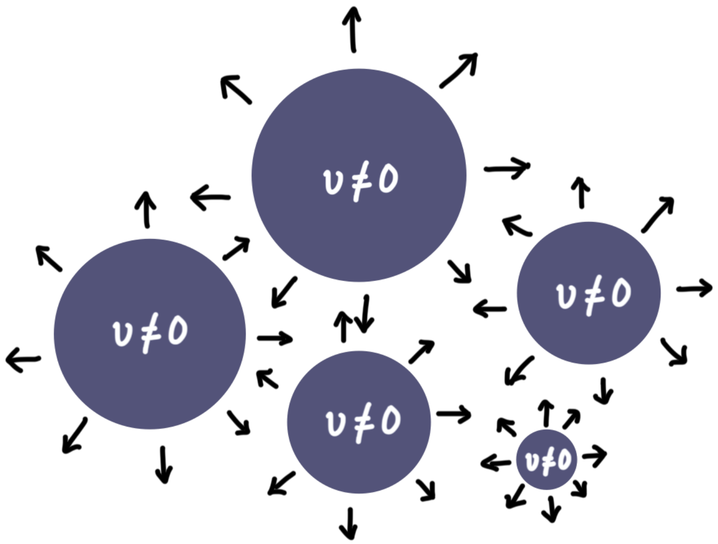


Figure 3.2:
Nucleation of broken bubbles as a result of SFOEWPT in the background space of unbroken phase.

IS THE FOEWPT STRONG?

$$\xi_n \equiv \frac{v_n}{T_n} \geq 1$$

First-order Phase Transition

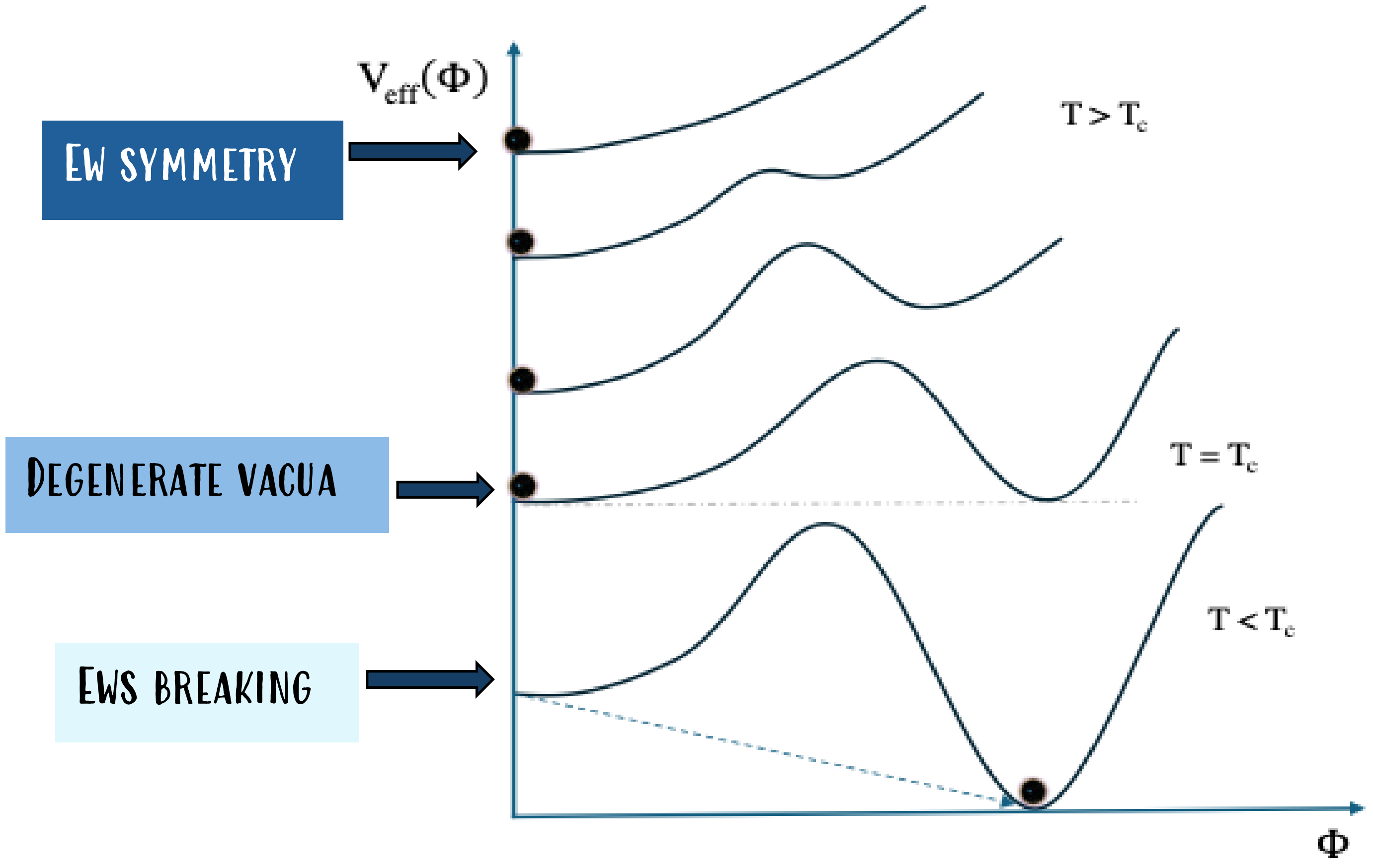


Figure 3.1:
Thermal evolution of the 2HDM potential leading to a strong first-order phase transition from the false vacuum to the true vacuum.

Source of GWs!

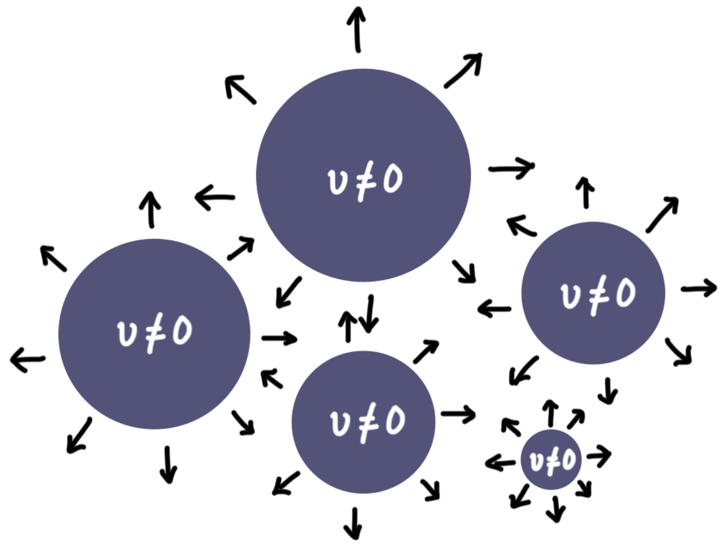


Figure 3.2:
Nucleation of broken bubbles as a result of SFOEWPT in the background space of unbroken phase.

IS THE FOEWPT STRONG?

$$\xi_n \equiv \frac{v_n}{T_n} \geq 1$$

4 RESULTS

How do the scalar masses influence SFOEWPT?

In relation to the alignment limit

SFOEWPT in (m_H , cos(β-α)) plane

For high masses: $m_H \gtrsim$ **400 GeV** :

- SFOEWPT occurs very close to the alignment limit
- EW symmetry breaking is preferred in the direction of the lighter state *h*, identified with the SM-like Higgs boson.

For low masses: $m_H \lesssim$ **400 GeV** :

- SFOEWPT occurs for larger deviations from the alignment limit
- EWPT driven by both *H* and *h*, broken vacuum preferred in non-SM-like Higgs direction.

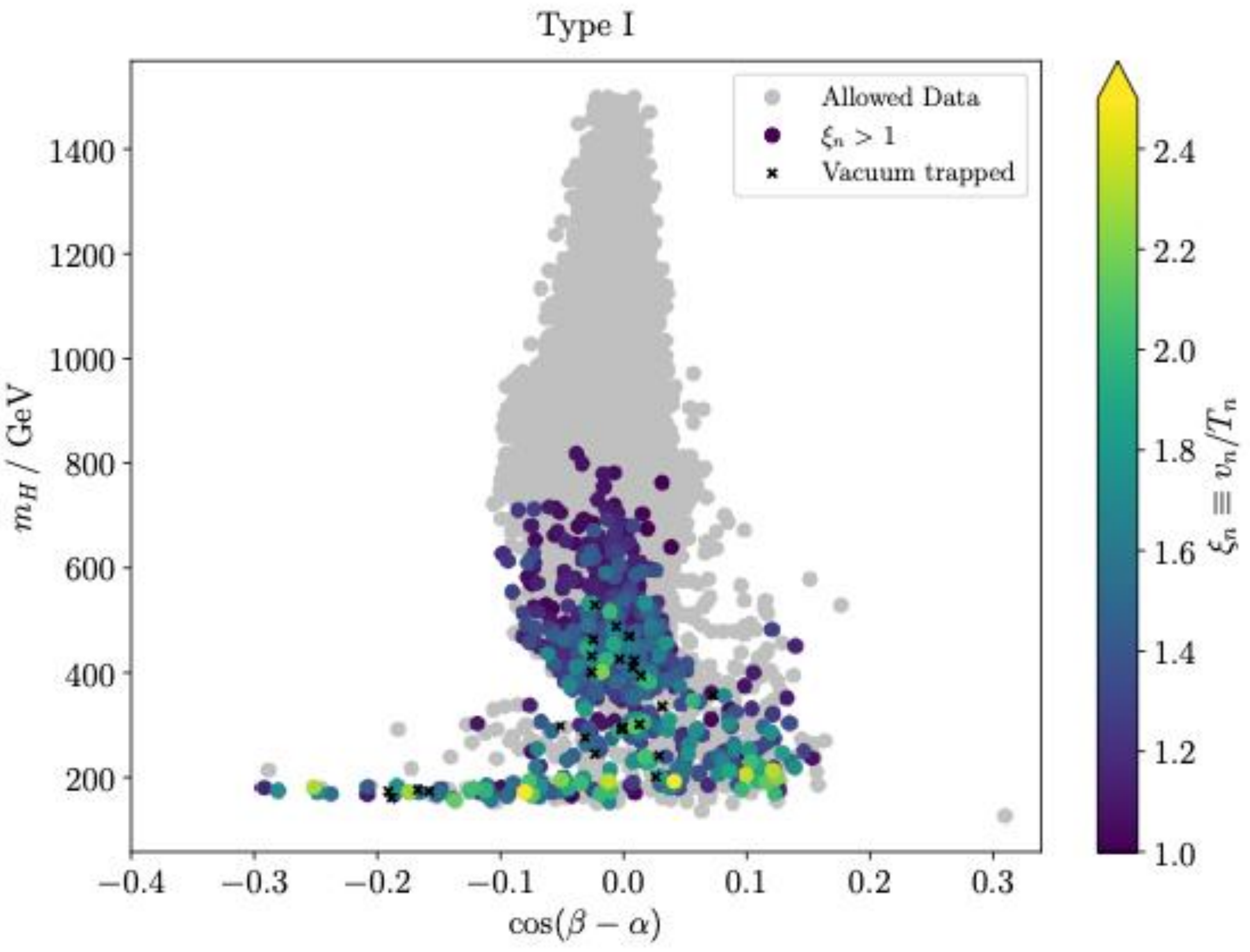


Figure 4.1:
Parameter points featuring an SFOEWPT in the plane of (m_H, cos(β − α)) that are allowed by the recent constraints within 2HDM of Type-I.

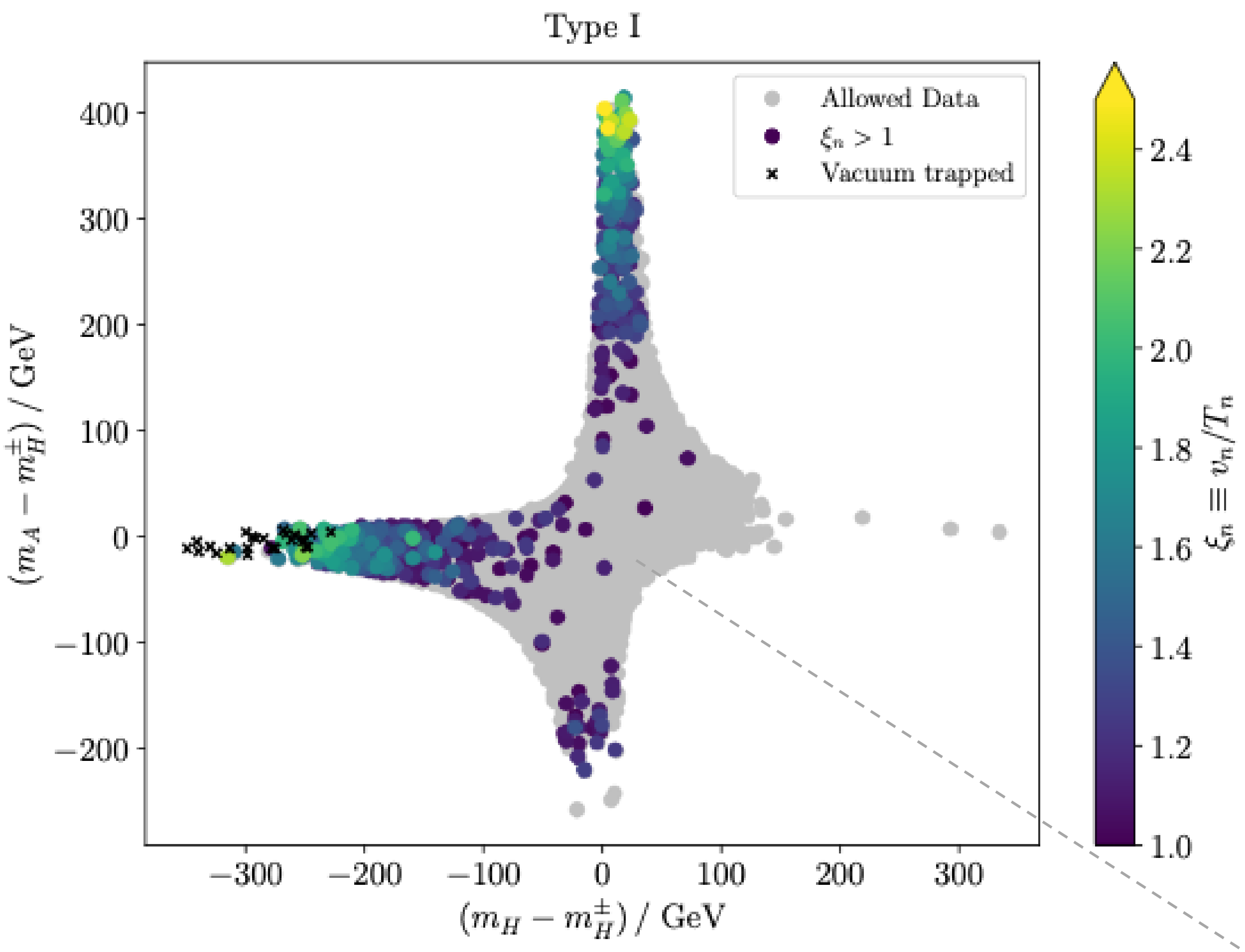


Figure 4.4:
Parameter points featuring an SFOEWPT in the $(m_A - m_{H^\pm}, m_H - m_{H^\pm})$ plane allowed by the recent constraints within 2HDM of Type-I.

Mass splittings

$E_\varphi \propto m_\varphi^3$

Cubic contribution

Mass splittings (driven by λ_ϕ) are correlated to an SFOEWPT occurence

Larger mass splittings → stronger FOPTs
→ constrained by perturbative unitarity

An average mass splitting of 200 - 400 GeV observed for the two regions, $m_A = m_{H^\pm}$ and $m_H = m_{H^\pm}$. Cross-shaped region is mainly constraints from electroweak precision observables.

Note: No SFOEWPTs occur in the region with degenerate masses $m_A = m_{H^\pm} = m_H$

MASS SPLITTINGS PLANES FOR m_H

$m_A = m_{H^\pm}$: $\Delta m \lesssim 300$ GeV

$m_H = m_{H^\pm}$: $\Delta m \lesssim 400$ GeV

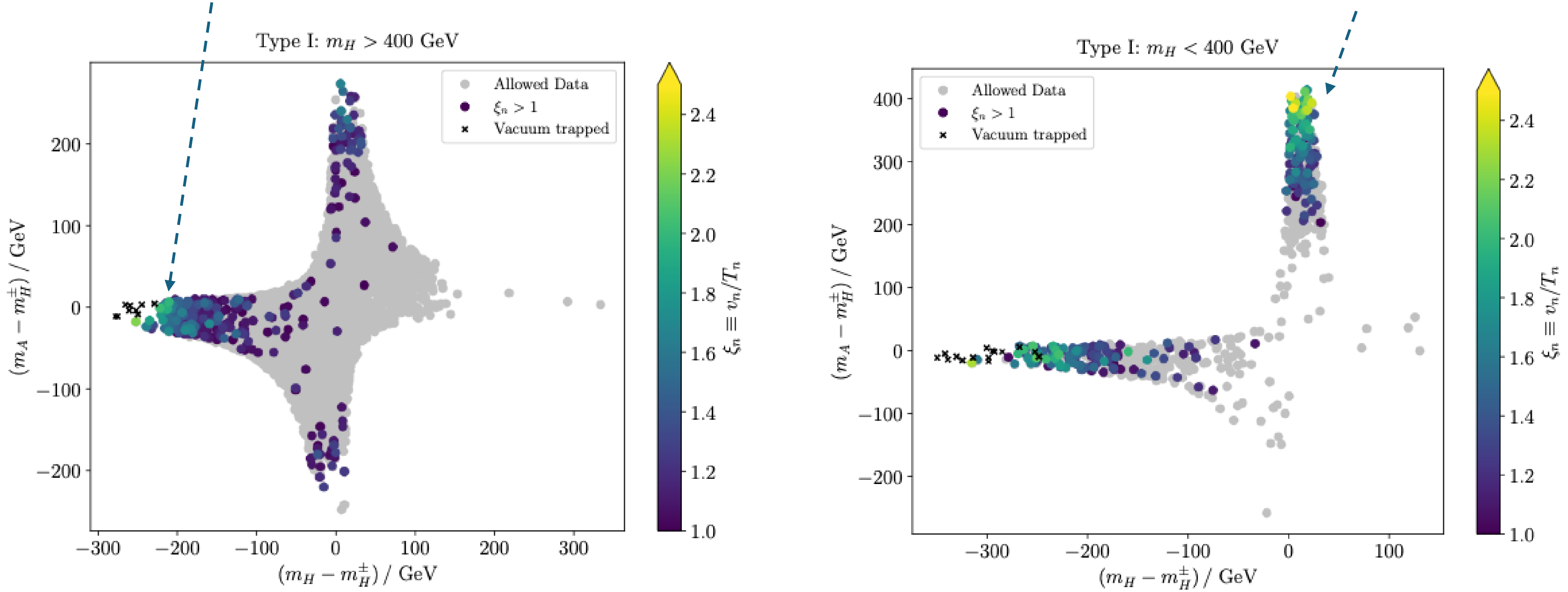


Figure 4.5:
Parameter points featuring an SFOEWPT in the $(m_A - m_{H^\pm}, m_H - m_{H^\pm})$ plane allowed by the recent constraints within 2HDM of Type-I for (a) high m_H and (b) low m_H.

THERMAL EVOLUTION OF VACUUM

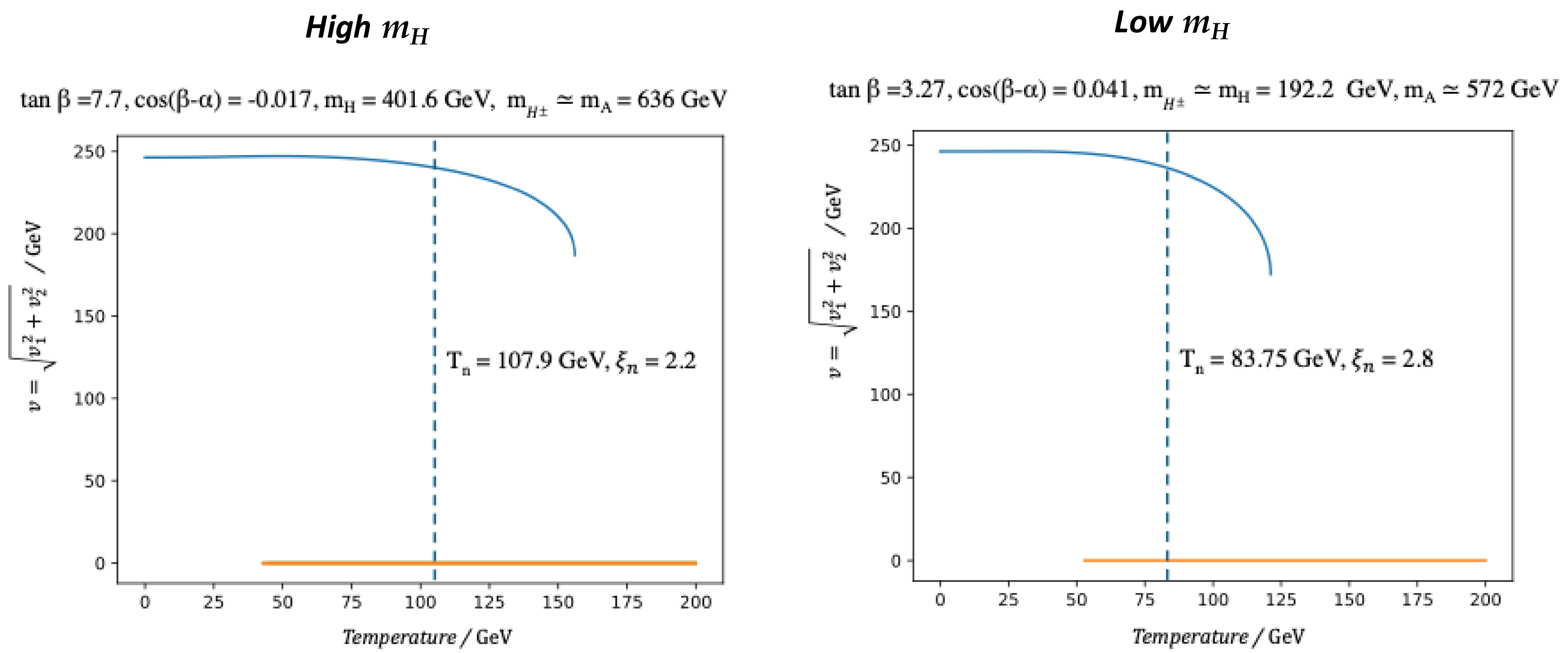


Figure 4.3: Thermal evolution of the vacuum from high *T* to low *T*, indicating a discontinuous phase transition from the false vacuum to the true vacuum for (**a**) high CP-even Higgs mass and (**b**) for low CP-even Higgs mass.

CONCLUSIONS

- Extended Higgs sectors can feature a **SFOEWPT**, necessary for EW baryogenesis, can potentially lead to detectable GW signals.

- Heavier scalars enter **loop corrections** and enhance the barrier for a strongly first-order EWPT.

- **Thermal effects** play a crucial role in generating the barrier, featuring SFOEWPTs within the model.

- **Higher the mass splitting** between scalars, **stronger the transitions** induced.

- For **higher $\boldsymbol{m_H}$**, SFOEWPTs occur **close to the alignment limit**. *But*, for **lower $\boldsymbol{m_H}$**, it occurs **away** from this limit and in non-SM-like direction.

FUTURE PROSPECTS

- To analyse these correlations in other 2HDM types, especially more constrained parameter space in Type II.
- To check for κ_λ variation for the above parameter regions showing SFOEWPT in correlation to the alignment limit
- To investigate the prospects for possible GW signals from an SFOEWPT

REFERENCES

1) Biekötter, T., Heinemeyer, S., No, J.M., Radchenko, K., Olea Romacho, M.O. and Weiglein, G., 2024. First shot of the smoking gun: probing the electroweak phase transition in the 2HDM with novel searches for A→ ZH in $${\ell}^{+}{\ell}^{-} t\overline {t} $$ and $$\nu\nu b\overline {b} $$ final states. *Journal of high energy physics*, *2024*(1), pp.1-44.

2) Coleman, S. and Weinberg, E., 1973. Radiative corrections as the origin of spontaneous symmetry breaking. Physical Review D, 7(6), p.1888.

3) Arnold, P. and Espinosa, O., 1993. Effective potential and first-order phase transitions: Beyond leading order. Physical Review D, 47(8), p.3546.

4) GWs studies: Athron, P., Balázs, C., Fowlie, A., Morris, L. and Wu, L., 2024. Cosmological phase transitions: From perturbative particle physics to gravitational waves. *Progress in Particle and Nuclear Physics*, *135*, p.104094.

5) Biekötter, T., Heinemeyer, S., No, J.M., Olea, M.O. and Weiglein, G., 2021. Fate of electroweak symmetry in the early Universe: Non-restoration and trapped vacua in the N2HDM. *Journal of Cosmology and Astroparticle Physics*, *2021*(06), p.018.

6) Cline, J.M. and Lemieux, P.A., 1997. Electroweak phase transition in two Higgs doublet models. *Physical Review D*, *55*(6), p.3873.

7) Fromme, L., Huber, S.J. and Seniuch, M., 2006. Baryogenesis in the two-Higgs doublet model. *Journal of High Energy Physics*, *2006*(11), p.038.

8) Dorsch, G.C., Huber, S.J., Konstandin, T. and No, J.M., 2017. A second Higgs doublet in the early universe: baryogenesis and gravitational waves. *Journal of Cosmology and Astroparticle Physics*, *2017*(05), p.052.

9) Dorsch, G.C., Huber, S., Mimasu, K. and No, J.M., 2014. Echoes of the Electroweak Phase Transition: Discovering a second Higgs doublet through $ A_0\rightarrow H_0 Z$. *arXiv preprint arXiv:1405.5537*.

10) Dorsch, G.C., Huber, S.J., Mimasu, K. and No, J.M., 2017. The Higgs vacuum uplifted: revisiting the electroweak phase transition with a second Higgs doublet. *Journal of high energy physics*, *2017*(12), pp.1-32.

11) Su, Wei, Anthony G. Williams, and Mengchao Zhang. "Strong first order electroweak phase transition in 2HDM confronting future Z & Higgs factories." Journal of High Energy Physics 2021, no. 4 (2021): 219.

Thank you

Backup slides

2HDM

$$\Phi_1 = \begin{pmatrix} \phi_1^+ \\ \frac{1}{\sqrt{2}}(v_1 + \rho_1 + i\eta_2) \end{pmatrix}, \quad \Phi_2 = \begin{pmatrix} \phi_2^+ \\ \frac{1}{\sqrt{2}}(v_2 + \rho_2 + i\eta_2) \end{pmatrix}$$

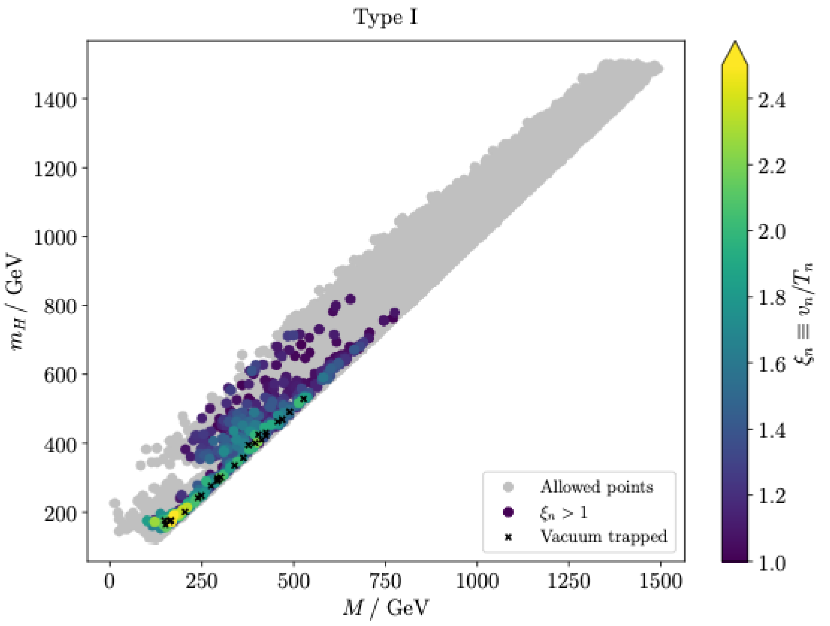
$$m_H^2 = M^2 s^2_{(\alpha-\beta)} + \left(\lambda_1\, c_\alpha^2 c_\beta^2 + \lambda_2\, s_\alpha^2 s_\beta^2 + \frac{1}{2}\lambda_{345}\, s_{2\alpha}s_{2\beta}\right)v^2,$$

$$m_h^2 = M^2 c^2_{(\alpha-\beta)} + \left(\lambda_1\, s_\alpha^2 c_\beta^2 + \lambda_2\, c_\alpha^2 s_\beta^2 - \frac{1}{2}\lambda_{345}\, s_{2\alpha}s_{2\beta}\right)v^2$$

$$m_A^2 = M^2 - \lambda_5 v^2$$

$$m_{H^\pm}^2 = M^2 - \frac{1}{2}(\lambda_4 + \lambda_5)v^2$$

2HDM Type	Φ_1 Coupling	Φ_2 Coupling
Type I	-	All fermions
Type II	down-type quarks, leptons	up-type quarks
Type III (lepton-specific)	leptons	quarks
Type IV (flipped)	down-type quarks	up-type quarks, leptons



Higgs basis

$$H_1 = \cos\beta\, \Phi_1 + \sin\beta\, \Phi_2 \equiv \begin{pmatrix} G^\pm \\ \frac{1}{\sqrt{2}}[v + S_1 + iG^0] \end{pmatrix}$$

$$H_2 = -\sin\beta\, \Phi_1 + \cos\beta\, \Phi_2 \equiv \begin{pmatrix} H^\pm \\ \frac{1}{\sqrt{2}}[S_2 + iS_3] \end{pmatrix}$$

The S_1 and S_2 fields in Higgs basis can be written as,

$$\begin{pmatrix} S_1 \\ S_2 \end{pmatrix} = R_\beta \begin{pmatrix} \rho_1 \\ \rho_2 \end{pmatrix} = R_\beta\, R_\alpha^{-1} \begin{pmatrix} H \\ h \end{pmatrix}$$
$$= \begin{pmatrix} \cos(\beta-\alpha) & \sin(\beta-\alpha) \\ -\sin(\beta-\alpha) & \cos(\beta-\alpha) \end{pmatrix} \begin{pmatrix} H \\ h \end{pmatrix}$$

Gauge sector

$$\mathcal{L}_H \supset \sum_{\varphi=h,H}\left[g_{WW\varphi}W_\mu^+W^{\mu-}\varphi+\frac{1}{2}g_{ZZ\varphi}Z_\mu Z^\mu\varphi\right]$$

$$\supset \sum_{\varphi=h,H}\left[\frac{2m_W^2}{v}\xi_\varphi^W\; W_\mu^+W^{\mu-}\varphi+\;\frac{m_Z^2}{v}\xi_\varphi^Z\; Z_\mu Z^\mu\varphi\right]$$

where, $\xi_h^V=\sin(\beta-\alpha)$ and $\xi_H^V=\cos(\beta-\alpha)$

	Type I	Type II
ξ_h^u	$\cos\alpha/\sin\beta$	$\cos\alpha/\sin\beta$
ξ_h^d	$\cos\alpha/\sin\beta$	$-\sin\alpha/\cos\beta$
ξ_h^ℓ	$\cos\alpha/\sin\beta$	$-\sin\alpha/\cos\beta$
ξ_H^u	$\sin\alpha/\sin\beta$	$\sin\alpha/\sin\beta$
ξ_H^d	$\sin\alpha/\sin\beta$	$\cos\alpha/\cos\beta$
ξ_H^ℓ	$\sin\alpha/\sin\beta$	$\cos\alpha/\cos\beta$
ξ_A^u	$\cot\beta$	$\cot\beta$
ξ_A^d	$-\cot\beta$	$\tan\beta$
ξ_A^ℓ	$-\cot\beta$	$\tan\beta$

Yukawa sector

$$\mathcal{L}_Y^{\rm 2HDM}=-\sum_{f=u,d,\ell}\frac{m_f}{v}\left(\xi_h^f\,\bar{f}f\,h+\xi_H^f\,\bar{f}f\,H-i\,\xi_A^f\,\bar{f}\gamma_5 f\,A\right)$$

$$-\left[\frac{\sqrt{2}\,V_{CKM}}{v}\,\bar{u}\left(m_u\xi_A^u P_L+m_d\xi_A^d P_R\right)d\,H^+ +\frac{\sqrt{2}\,m_\ell\xi_A^\ell}{v}\,\bar{\nu}_L\ell_R\,H^+ +\text{h.c.}\right].$$

Thermal field formalism

$$\Gamma[\phi_{\min}] = -\int d^4x\,[-V(\phi_{\min}) + \delta V\,] := -\int d^4x\, V_{\text{eff}}(\phi_{\min})$$

$$\begin{aligned}\mathcal{Z}[H] &= \text{Tr}\; e^{-\beta H} \\ &= \sum_a \langle \phi_a | e^{-\beta H} | \phi_a \rangle \\ &= \int \mathcal{D}\pi \int \mathcal{D}\phi\; \exp\Big[\int_0^\beta d\tau \int d^3x \Big(i\pi\, \partial_\tau \phi - H(\pi,\phi)\Big)\Big]\end{aligned}$$

$$\phi(\tau,\vec{x}) = \frac{1}{\sqrt{\beta}} \sum_{n=-\infty}^{\infty} \phi(i\omega_n,\vec{x})\, e^{i\omega_n \tau}$$

$$\omega^2(\vec{p},\phi_{\min}) = \boldsymbol{p^2} + m^2(\phi_{\min}),$$

where, $m^2(\phi_{\min}) = \left.\dfrac{\partial^2 V_{\text{tree}}}{\partial \phi^2}\right|_{\phi_{\min}}$

The Fourier transform of the Green's function

$$\tilde{G}(\omega_n,\vec{p}) = \int_{\alpha-\beta}^{\alpha} d\tau \int d^3x\, e^{i\omega_n\tau - i\vec{x}\cdot\vec{p}}\, G(\tau,\vec{x}) \tag{A.1}$$

where Matsubara frequencies for bosons and fermions are $\omega_n = 2n\pi\beta^{-1}$ and $\omega_n = (2n+1)\pi\beta^{-1}$, respectively. So, the propagator in momentum space is,

$$\tilde{G}(\omega_n,\vec{p}) = \frac{1}{\vec{p}^2 + m^2 + \omega_n^2}. \tag{A.2}$$

Introducing the Euclidean propagator $\Delta(i\tau,\vec{x}) = -iG(\tau,\vec{x})$, the inverse Fourier transform is obtained as,

$$\Delta(x) = \frac{1}{\beta}\sum_{n=-\infty}^{\infty} \int \frac{d^3p}{(2\pi)^3}\, e^{-i\omega_n\tau + i\vec{p}\cdot\vec{x}} \frac{-i}{\vec{p}^2 + m^2 + \omega_n^2}. \tag{A.3}$$

From the above equation, we obtain propagators for the Feynman diagrams as,

$$\text{Boson propagator:}\quad \frac{i}{p^2 - m^2},\quad p^\mu = \left[2ni\pi\beta^{-1},\vec{p}\right], \tag{A.4}$$

$$\text{Fermion propagator:}\quad \frac{i}{\gamma\cdot p - m},\quad p^\mu = \left[(2n+1)i\pi\beta^{-1},\vec{p}\right], \tag{A.5}$$

$$\text{Loop integral:}\quad \frac{i}{\beta}\sum_{n=-\infty}^{\infty}\int \frac{d^3p}{(2\pi)^3}, \tag{A.6}$$

$$\text{Vertex function:}\quad -i\beta(2\pi)^3 \delta_{\sum \omega_i}\, \delta^{(3)}\Big(\sum_i \vec{p}_i\Big). \tag{A.7}$$

$$V_{\text{eff}}^{(1)}(\phi) = V_0^{(1)}(\phi) + V_T^{(1)}(\phi),$$

$$V_0^{(1)}(\phi) = \int \frac{d^3p}{(2\pi)^3}\,\frac{\omega_p}{2}, \quad V_T^{(1)}(\phi) = T\int \frac{d^3p}{(2\pi)^3}\log\left(1 - e^{-\omega_p/T}\right)$$

1-LOOP COLEMAN-WEINEBERG POTENTIAL

$$V_{\text{CW}}(\phi_1,\phi_2) = \sum_j \frac{n_j}{64\pi^2}(-1)^{2s_j}\, m_j^4(\phi_1,\phi_2)\left[\ln\left(\frac{m_j^2(\phi_1,\phi_2)}{\mu^2}\right) - c_j\right]$$

UV-finite counter terms to the zero-temperature one-loop scalar potential:

$$\begin{aligned} V_{\text{CT}}(\Phi_1,\Phi_2) = {} & \delta m_{11}^2\,\Phi_1^\dagger\Phi_1 + \delta m_{22}^2\,\Phi_2^\dagger\Phi_2 - \delta m_{12}^2\left(\Phi_1^\dagger\Phi_2 + h.c.\right) + \frac{\delta\lambda_1}{2}\left(\Phi_1^\dagger\Phi_1\right)^2 \\ & + \frac{\delta\lambda_2}{2}\left(\Phi_2^\dagger\Phi_2\right)^2 + \delta\lambda_3\left(\Phi_1^\dagger\Phi_1\right)\left(\Phi_2^\dagger\Phi_2\right) + \delta\lambda_4\left(\Phi_1^\dagger\Phi_2\right)\left(\Phi_2^\dagger\Phi_1\right) \\ & + \frac{\delta\lambda_5}{2}\left[\left(\Phi_1^\dagger\Phi_2\right)^2 + h.c.\right] + \delta t_1\phi_1 + \delta t_2\phi_2. \end{aligned}$$

OS-RENORMLISATION CONDITIONS:

$$\partial_{\psi_i}\left\{\, V_{\text{CT}}(\Phi_1,\Phi_2) + V_{\text{CW}}(\Phi_1,\Phi_2)\,\right\}\Big|_{\langle\Phi_i\rangle_{T=0}} = 0$$

$$\partial_{\psi_i}\partial_{\psi_j}\left\{\, V_{\text{CT}}(\Phi_1,\Phi_2) + V_{\text{CW}}(\Phi_1,\Phi_2)\,\right\}\Big|_{\langle\Phi_i\rangle_{T=0}} = 0$$

Daisy ring resummations

- Infrared (IR) breakdown of the perturbation theory by soft bosonic modes

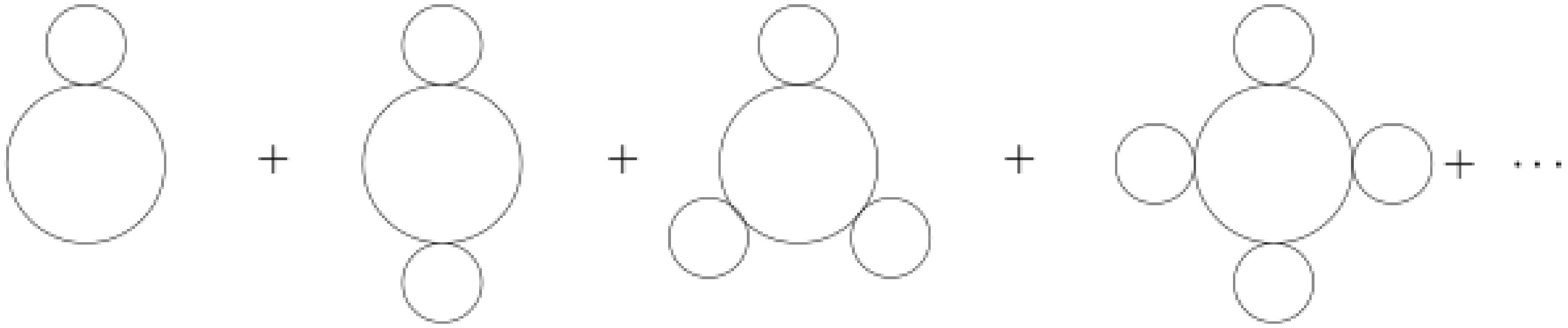


Image from Ref. Delaunay, Cedric, Christophe Grojean, and James D. Wells. "Dynamics of non-renormalizable electroweak symmetry breaking." *Journal of High Energy Physics* 2008, no. 04 (2008): 029-029.

$$V_{\text{eff}}^{1+\text{Parwani}} = \sum_j \frac{n_j T}{2} \sum_{n=-\infty}^{+\infty} \int \frac{d^3\vec{p}}{(2\pi)^3} \log\left(\omega_n + \vec{p}^2 + m_j^2(\phi_i) + \Pi_j(T)\right).$$

$$V_{\text{eff}}^{1+\text{AE}} = \sum_j \frac{n_j T}{2} \left\{ \sum_{n=-\infty\backslash\{0\}}^{+\infty} \int \frac{d^3\vec{p}}{(2\pi)^3} \log\left(\omega_n + \vec{p}^2 + m_j^2(\phi_i)\right) + \int \frac{d^3\vec{p}}{(2\pi)^3} \log\left(\vec{p}^2 + m_j^2(\phi_i) + \Pi_j(T)\right) \right\} \equiv V_{\text{eff}}^1 + V_{\text{daisy}}.$$

1-loop thermal potential

$$V_T(\phi_1,\phi_2,T) = \frac{T^4}{2\pi^2}\sum_i n_i\, J_B\left(\frac{m_i^2(\phi_1,\phi_2)}{T^2}\right) + \frac{T^4}{2\pi^2}\sum_j n_j\, J_F\left(\frac{m_j^2(\phi_1,\phi_2)}{T^2}\right) - \frac{T^4}{12\pi}\sum_k n_k \left\{\left(\frac{\tilde{m}_k^2(\phi_1,\phi_2,T)}{T^2}\right)^{3/2} - \left(\frac{m_k^2(\phi_1,\phi_2)}{T^2}\right)^{3/2}\right\}.$$

$$J_B(x) = \int_0^\infty dk\ \ k^2\ \ln\left[1 - e^{-\sqrt{k^2+x}}\right]$$

$$J_F(x) = \int_0^\infty dk\ \ k^2\ \ln\left[1 + e^{-\sqrt{k^2+x}}\right]$$

with, $\quad x \equiv \dfrac{m^2_{i,j,k}(\phi_1,\phi_2)}{T^2}$

Thermal loop integrals:

High T expansion

$$J_B(x) = -\frac{\pi^4}{45} + \frac{\pi^2}{12}x - \frac{\pi}{6}x^{3/2} - \frac{1}{32}x^2\log\frac{x}{a_b} - 2\pi^{7/2}\sum_{\ell=1}^{\infty}(-1)^{\ell}\frac{\zeta(2\ell+1)}{(\ell+1)!}\,\Gamma\left(\ell+\frac{1}{2}\right)\left(\frac{x}{4\pi^2}\right)^{\ell+2}$$

$$J_F(x) = \frac{7\pi^4}{360} - \frac{\pi^2}{24}x - \frac{1}{32}x^2\log\frac{x}{a_f} - \frac{\pi^{7/2}}{4}\sum_{\ell=1}^{\infty}(-1)^{\ell}\frac{\zeta(2\ell+1)}{(\ell+1)!}\,\Gamma\left(\ell+\frac{1}{2}\right)\left(\frac{x}{\pi^2}\right)^{\ell+2}$$

where, $\quad a_b = 16\pi^2 e^{(3/2-2\gamma_E)}\quad$ and $\quad a_f = \pi^2 e^{(3/2-2\gamma_E)}$

HIGGS VACUUM UPLIFTMENT

HOW UPLIFTED IS THE HIGGS VACUUM RELATIVE TO THE SM?

$$\mathcal{F}_T = \mathcal{F}_0 + \Delta V_T$$

where, $\mathcal{F}_T, \mathcal{F}_0$: free energy density and vacuum energy difference between symmetric and broken phases at finite T and $T = 0$, respectively,

ΔV_T: thermal contributions shaping the zero-temperature potential.

$$\boxed{\frac{\Delta\mathcal{F}_0}{\mathcal{F}_0^{\rm SM}} \equiv \frac{\mathcal{F}_0 - \mathcal{F}_0^{\rm SM}}{\mathcal{F}_0^{\rm SM}}}$$

$$\left[\ \mathcal{F}_0^{\rm SM} \simeq -1.25 \times 10^8 \ \ {\rm GeV}^4\ \right]$$

SHALLOWER SCALAR POTENTIAL → EASIER BARRIER FORMATION → STRONGER FOPTs

CORRELATING ξ_n WITH $\Delta\mathcal{F}_0\,/\mathcal{F}_0^{SM}$

- SFOEWPT occurs for $\Delta\mathcal{F}_0\,/\mathcal{F}_0^{SM} \leq -0.14$
- ξ_n **directly correlated** to the amount of Higgs vacuum upliftment relative to SM i.e. a more negative value of $\Delta\mathcal{F}_0\,/\mathcal{F}_0^{SM}$ favours a stronger FOPT, however this correlation declines for higher masses m_H.

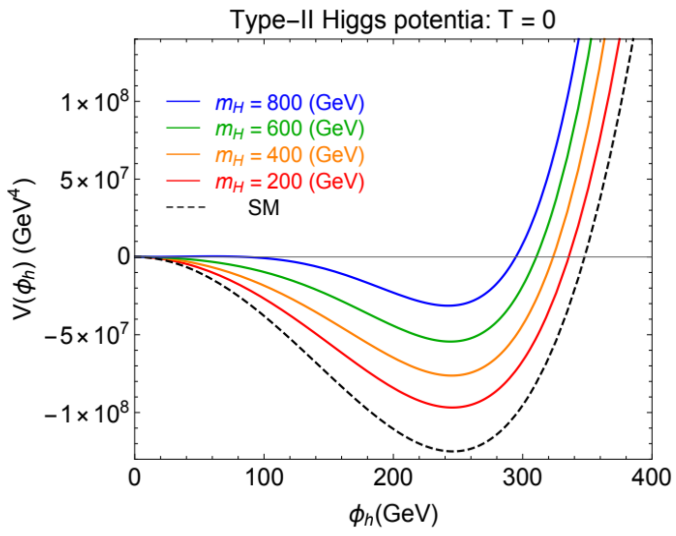


Figure: The zero-temperature Higgs potential with different m_H.

Ref: [11] arXiv:2011.04540v1

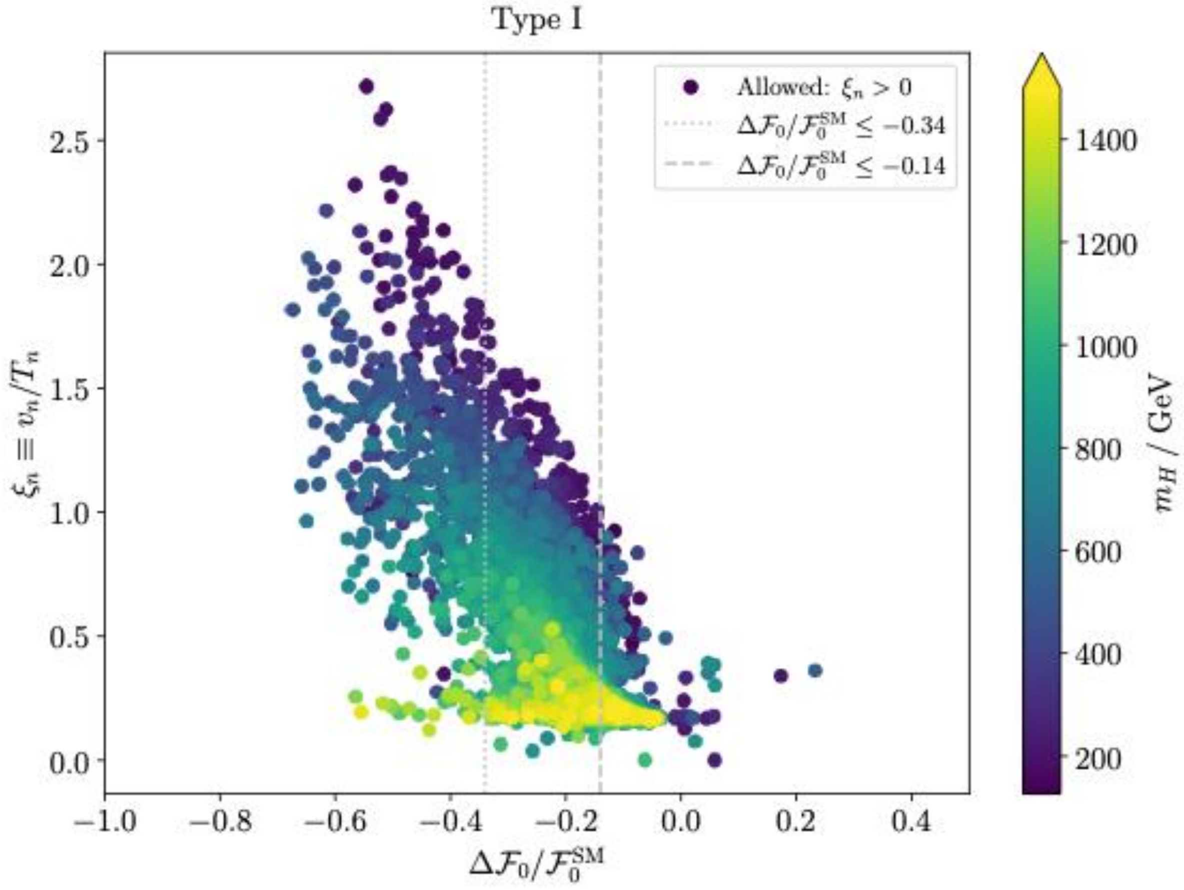


Figure 4.6:
The strength of the transition in the 2HDM of Type I in relation to the vacuum uplifting variable $\Delta F_0/F_{SM}$. The colour coding indicates the value of the mass m_H.

ΛCDM and EW Baryogenesis

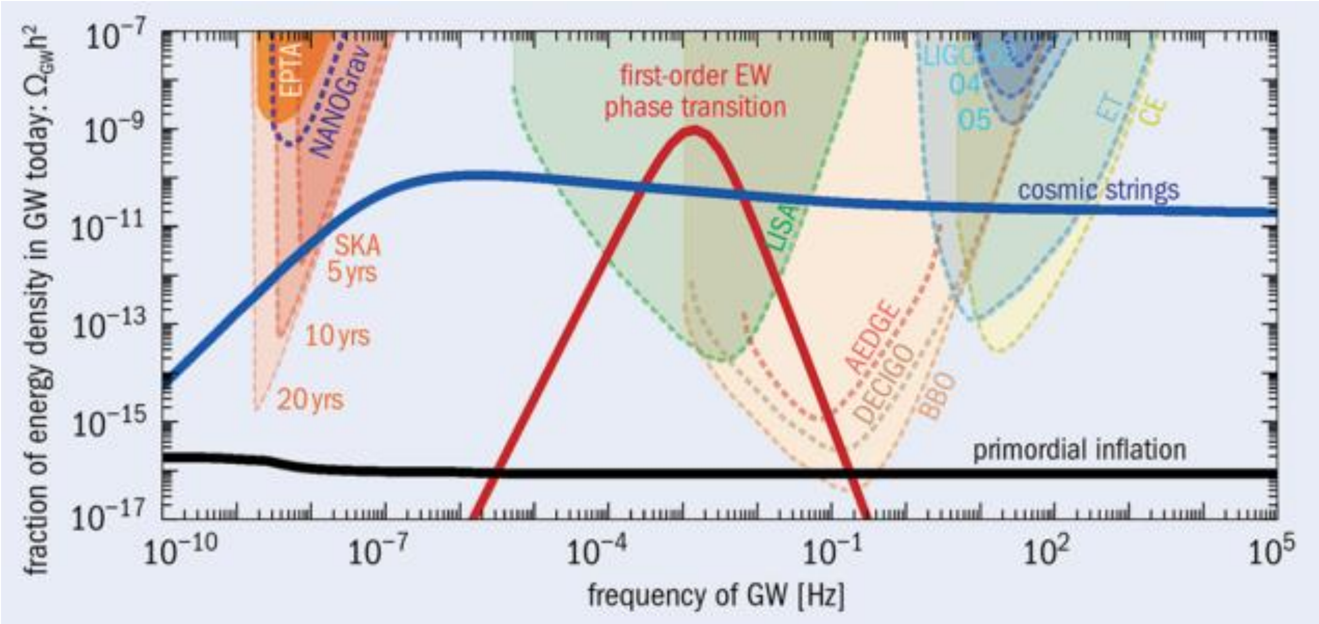
$$\Gamma(T) = A(T)e^{-S_3(T)/T},$$

$$\text{with,} \quad S_3(T) = 4\pi \int r^2\, dr \left[\frac{1}{2}\left(\frac{d\phi}{dr}\right)^2 + V(\phi, T)\right].$$

GW Density and SNR

$$h^2\Omega_{\rm GW}(f) = h^2\Omega_{\rm sw}(f) \; + \; h^2\Omega_{\rm turb}(f) \; + \; h^2\Omega_{\rm collision}(f)$$

$$\mathrm{SNR} = \sqrt{\mathcal{T}\int_{-\infty}^{+\infty} df \, \left[\frac{h^2\Omega_{\rm GW}(f)}{h^2\Omega_{\rm sens}(f)}\right]^2}$$



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Direct searches

- bbH with $H \to b\bar{b}$ [44, 45]
- $pp \to H/A \to AZ/HZ \to b\bar{b}\ell^+\ell^-$ [46, 47]
- $pp \to A \to Zh \to \ell^+\ell^-\tau^+\tau^-$ [48]
- bbA with $A \to Zh \to Zb\bar{b}$ [49]
- $pp \to A/H \to ZH/A \to \ell^+\ell^-W^+W^-/\ell^+\ell^-b\bar{b}$ [50]
- bbH with $H \to hh \to bb\bar{b}\bar{b}$ [51]