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Probing the fate of the electroweak symmetry

Based on [2208.14466], [2103.12707] in collaboration with
Sven Heinemeyer, José Miguel No, María Olalla Olea Romacho, Georg Weiglein

ITP seminar

26th of January 2023

Thomas Biekötter

EW symmetry in the SM

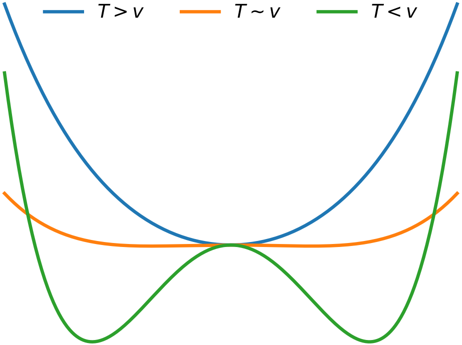
EW symmetry unbroken in early universe

$\downarrow$

Cross-over transition at $T \sim v$

$\downarrow$

EW symmetry broken at $T = 0$



Each step is a model-dependent feature!

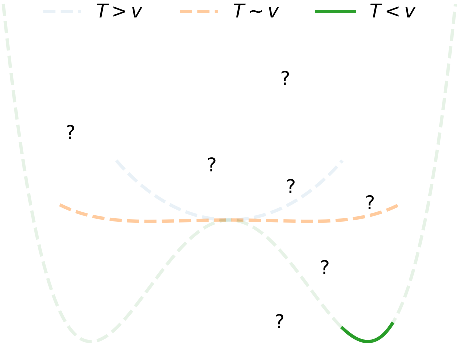
EW symmetry beyond SM

Other possiblities:

→ EW symmetry non-restoration

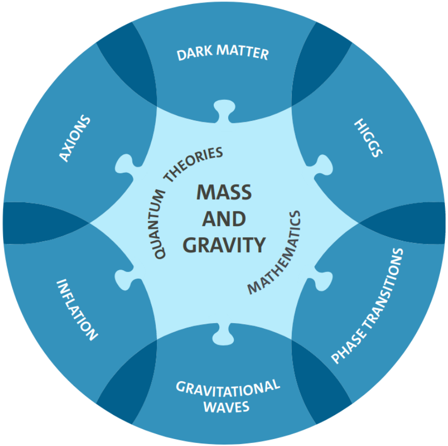
→ EW 1st-order phase transitions

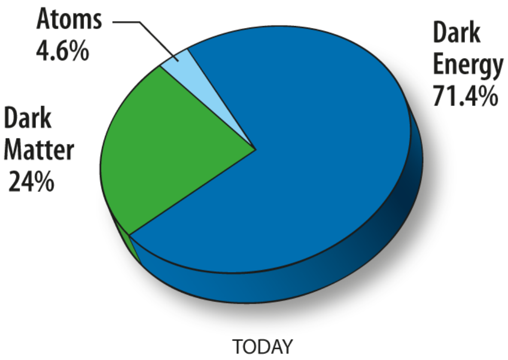
→ Vacuum trapping



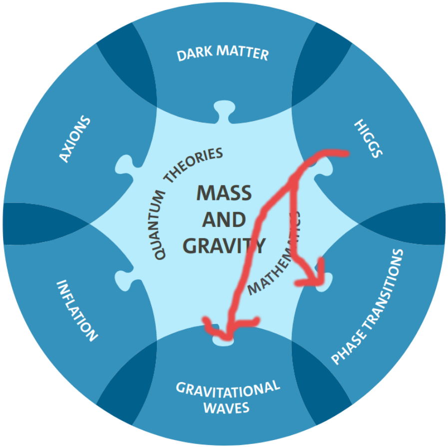
Phenomenological consequences?

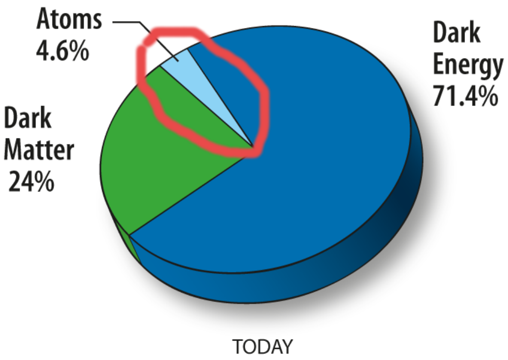
Why do we care?





Why do we care?





Matter-antimatter asym.

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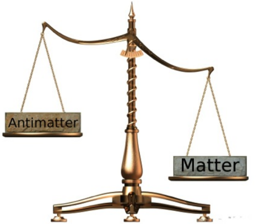
SM prediction: We do not exit: $\frac{n_b}{n_\gamma} \sim 6 \cdot 10^{-19}$

Observations: We exist: $\frac{n_b}{n_\gamma} \sim 6 \cdot 10^{-10}$



[D0, Fermilab]

Baryon Asymmetry of the Universe (BAU) $\rightarrow$ Sakharov conditions

1. B violation
2. Loss of thermal equilibrium
3. C and CP violation

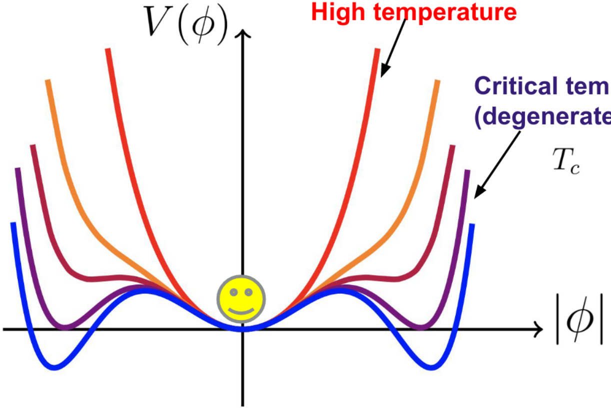
Electroweak baryogenesis: Requires BSM around the EW scale

Matter-antimatter asym.

1st-order electroweak phase transition

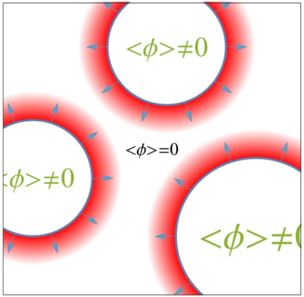
Necessary ingredient for EW baryogenesis

[Slide: Olalla Olea, Susy2021]



Baryon number preservation criterion:

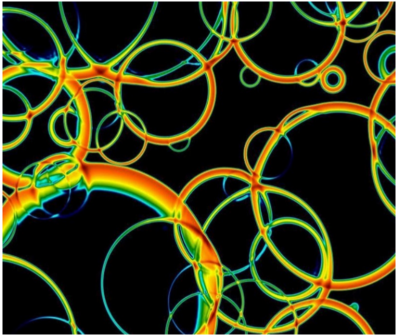
$$\frac{v}{T} \gtrsim 1$$

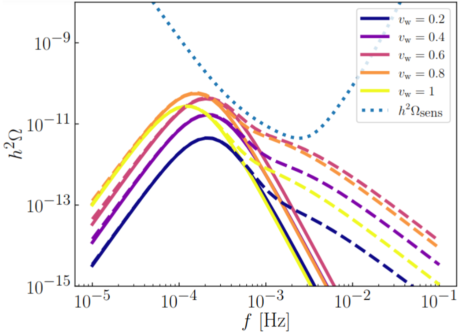


[José Miguel No]

Gravitational waves

1st-order EWPT gives rise to a primordial stochastic GW background





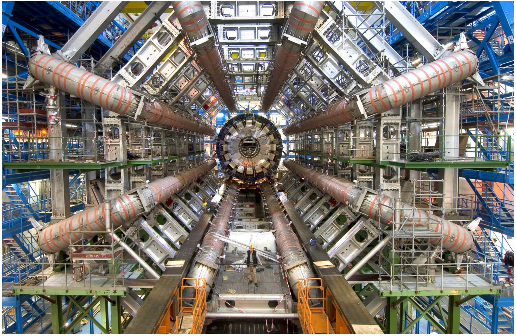
[D. Weir] [T.B., S. Heinemeyer, J.M. No, M.O. Olea Romacho, G. Weiglein: 2208.14466]

Characteristic wavelength: $T_{EW} \approx 100$ GeV $\leftrightarrow \lambda \approx 10^6$ km

Gravitational waves

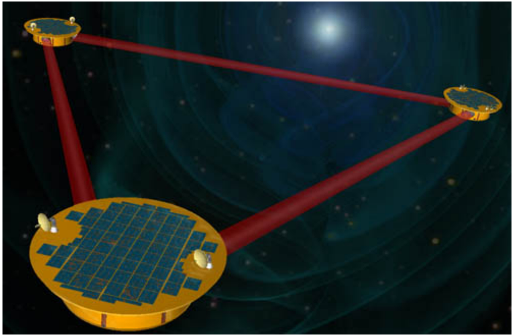
1st-order EWPT gives rise to a primordial stochastic GW background

LHC



[CERN]

LISA



[NASA]

Complementarity: Colliders $\leftrightarrow$ GW detectors

The very^2 early universe

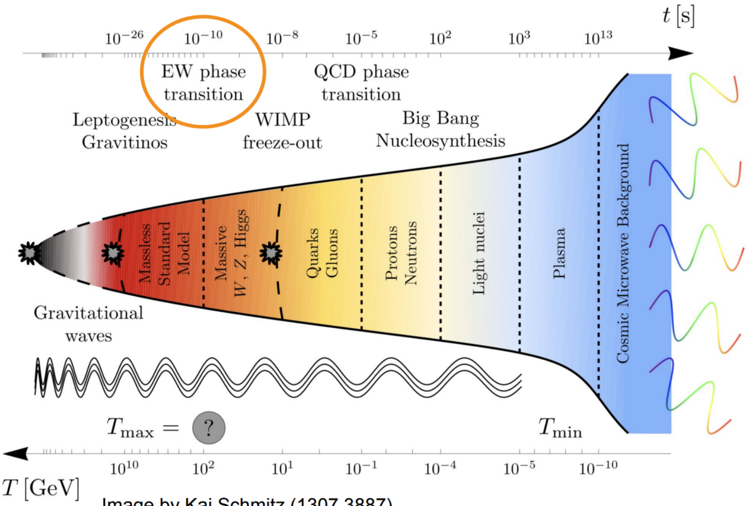


Image by Kai Schmitz (1307.3887)

Atlernative thermal histories

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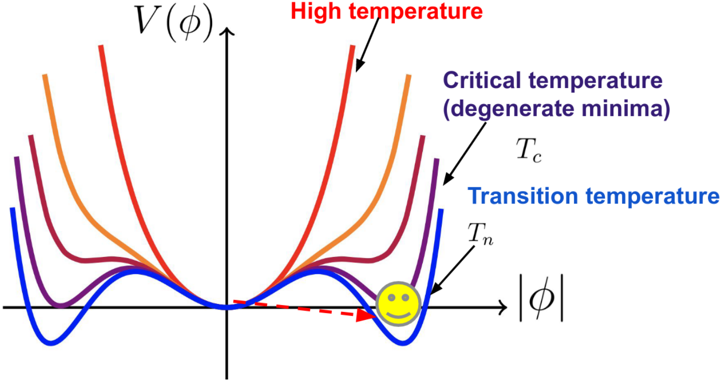
1st-order EW phase transition



Transition rate: (S_3: *bounce action*)

$$\Gamma \sim \exp\left(-S_3(T)/T\right)$$

Nucleation/transition temperature T_n:

$$\rightarrow \quad S_3(T_n)/T_n \sim 140$$

Strength (energy budget):

$$\alpha = \frac{1}{\rho_R}\left(\Delta V(T_n) - \left(\frac{T}{4}\frac{\partial \Delta V(T)}{\partial T}\right)\bigg|_{T_n}\right)$$

Inverse duration:

$$\frac{\beta}{H} = T_n \left(\frac{d}{dT}\frac{S_3(T)}{T}\right)\bigg|_{T_n}$$

Atlernative thermal histories

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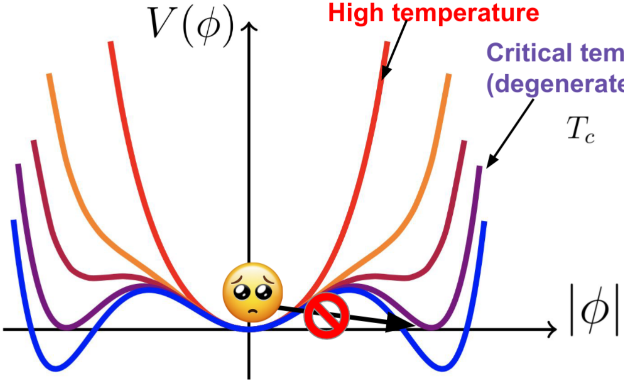
Vacuum trapping



Transition cannot complete:

$S_3/T > 140$ for all T

Reasons:

→ Potential is too shallow

→ Potential barrier is too large

→ Separation of minima is too large

Atlernative thermal histories

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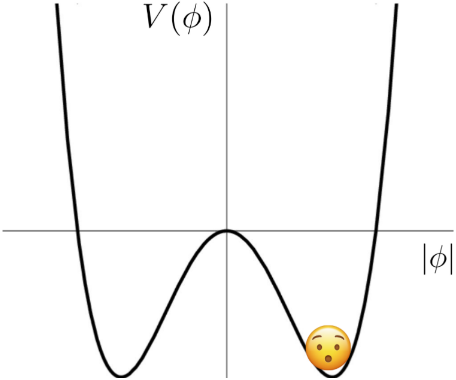
Electroweak symmetry non-restoration



Related to terms $\sim c\ \Phi^2 T^2$ with $c < 0$

- $\to$ Negative curvature in high-T limit
- $\to$ EW-conserving origin is saddle point

Phenomenological consequences:

- $\to$ Active (new) field of research*
- $\to$ Here: no GW signals at LISA
- $\to$ *High-scale EW baryogensis*

Generically:

- $\to$ EWSB scale can be $\gg$ EW scale

* [Carena, Krause, Liu, Wang: 2104.00638],
[Chang, Olea, Tanin: 2210.05680],
[Matsedonskyi, Unwin, Wang: 2107.07560],
[Matsedonskyi, Servant: 2002.05174], [Glioti, Rattazzi, Vecchi, 1811.11740],
[Baldes, Servant, 1807.08770]

The (next-to) 2HDM

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N2HDM $=$ **2HDM**(ϕ_1, ϕ_2) $+$ Real Scalar Singlet(ϕ_s)

Scalar tree-level potential

$$V_{\text{tree}} = m_{11}^2|\Phi_1|^2 + m_{22}^2|\Phi_2|^2 - m_{12}^2(\Phi_1^\dagger\Phi_2 + \text{h.c.}) + \frac{\lambda_1}{2}(\Phi_1^\dagger\Phi_1)^2 + \frac{\lambda_2}{2}(\Phi_2^\dagger\Phi_2)^2$$
$$+ \lambda_3(\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2) + \lambda_4(\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1) + \frac{\lambda_5}{2}[(\Phi_1^\dagger\Phi_2)^2 + h.c.]$$
$$\left(+ \frac{1}{2}m_S^2\Phi_S^2 + \frac{\lambda_6}{8}\Phi_S^4 + \frac{\lambda_7}{2}(\Phi_1^\dagger\Phi_1)\Phi_S^2 + \frac{\lambda_8}{2}(\Phi_2^\dagger\Phi_2)\Phi_S^2 \right)$$

Extension of Z_2 ($\Phi_1 \to \Phi_1$ and $\Phi_2 \to -\Phi_2$) to Yukawa sector $\Rightarrow$ 4 types of the **(N)2HDM**

Type-II: u_R coupled to Φ_2, d_R and e_R coupled to Φ_1

EW vacuum:

$$\langle\Phi_1\rangle = \begin{pmatrix} 0 \\ v_1/\sqrt{2} \end{pmatrix}, \quad \langle\Phi_2\rangle = \begin{pmatrix} 0 \\ v_2 \end{pmatrix}, \quad \langle\Phi_S\rangle = v_S/\sqrt{2} \quad \in \mathbb{R} \quad \tan\beta := v_2/v_1$$

Scalar spectrum: CP-even scalars h_1/h, h_2/H, h_3, CP-odd scalar A, charged scalars $H^\pm$

Effective potential

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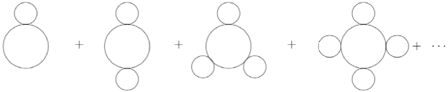
$$V_{\text{eff}} = \underbrace{V_{\text{tree}}(\phi_i) + V_{\text{CW}}(\phi_i) + V_{\text{CT}}(\phi_i) + V_{\text{T}}(\phi_i, T)}_{\text{tree-level + one-loop}} \quad \underbrace{+V_{\text{daisy}}(\phi_i, T)}_{\text{resummed n-loop daisy diagrams}}$$

V_{tree}: Classical (tree-level) potential
V_{CW}: One-loop radiative corrections (at $T = 0$) [S. R. Coleman, E. J. Weinberg (1973)]
V_{CT}: UV-finite counterterm potential (OS conditions)
V_{T}: One-loop thermal corrections [L. Dolan, R. Jackiw (1974)]
V_{daisy}: Resummation of daisy diagrams [P. Arnold, O. Espinosa (1996)]

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

$$V_T(\phi_i) = \sum_j \frac{n_j\, T^4}{2\pi^2} J_{\pm}\left(\frac{m_j^2(\phi_i)}{T^2}\right)$$

$$V_{\text{daisy}}(\phi_i) = -\sum_k \frac{T}{12\pi}\left(\left(\bar{m}_k^2(\phi_i, T)\right)^{\frac{3}{2}} - \left(m_k^2(\phi_i)\right)^{\frac{3}{2}}\right)$$



Daisy diagrams

[More details: M.Quiros, hep-ph/9901312]

Analysis strategy

1. $\mathbf{T = 0}$ analysis: Generate viable parameter points `[ScannerS]`

Hierarchical spectrum among the BSM scalar masses (facilitates a FOEWPT)

Theoretical constraints: (Meta-)stability of the EW vacuum `[EVADE]`, perturbativity, unitarity

Experimental constraints: flavour physics, EW precision observables

h_{125}, collider searches `[HiggsSignals, HiggsBounds, SusHi, N2HDECAY]`

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2. $\mathbf{T > 0}$ analysis: Track the vacuum as a function of T `[cosmoTransitions]`

Minimization problem: Find the (co-existing) minima of the potential at each T

Determine first-order phase transitions: Nucleation (transition) temperature T_n

$$\Gamma(T) = A(T)\, e^{-S_3(T)/T} \sim H^4(T) \quad \rightarrow \quad S_3(T_n)/T_n \sim 140$$

---

3. Categorize parameter space of the model

→ Strong 1st-order EW PT → EW SnR → Vacuum trapping

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Fate of electroweak symmetry in the early Universe: Non-restoration and trapped vacua in the N2HDM

Origin of EW SnR

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Toy model: BSM scalar ϕ getting mass from Higgs field h

$$\text{Debye mass:} \quad \Pi_\phi = \left(\frac{\partial^2}{\partial \phi^2} V_T^{T\to\infty} \Big|_{\phi=0} \right) / T^2$$

$$\text{Tree-level bkg-field-dependent mass of } \phi\text{:} \quad m_\phi^2(T=0) = \mu_\phi^2 + \lambda_{\phi h} h^2$$

The daisy diagrams add the following term to the effective potential:

$$V^{\text{full}}(T) \supset -\frac{T}{12\pi} \left[\mu_\phi^2 + \lambda_{\phi h} h^2 + \Pi_\phi T^2 \right]^{3/2} = -\frac{T}{12\pi} [3h^4 \lambda_{\phi h}^2 \Pi_\phi T^2 + \dots]^{1/2}$$

Thermal mass of h (curvature at the "origin"of field space) at high T:

$$m_h^2(T) = \frac{\partial^2 V^{\text{full}}}{\partial h^2} \Big|_{h=0} \approx m_h^2(0) + \Pi_h T^2 - \frac{\lambda_{\phi h} \sqrt{\Pi_\phi}}{4\pi} T^2$$

EW symmetry non-restoration if at high T:

$$\Pi_h - \lambda_{\phi h} \sqrt{\Pi_\phi} / (4\pi) < 0$$

Origin of FOEWPT

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Formation of **potential-barrier** is not possible at classical level
(symmetries $\rightarrow$ no terms with odd powers of fields)
$\downarrow$
Barrier sourced by **radiative and thermal corrections**

Source 1: $\mathbf{V}_{\mathrm{CW}}$

$$\rightarrow V_{\mathrm{eff}} \sim \frac{m_\phi^3}{m_h^2}(1 - \frac{M^2}{m_\phi^2})^3 \; h^3 \; ,$$

$$m_\phi^2 = M^2 + \lambda h^2$$

[Kanemura et al.]

Here: $M^2 = \dfrac{m_{12}^2}{\sin\beta\cos\beta}$,
with $m_\phi = m_{h_{2,3}}, m_A, m_{H^\pm}$

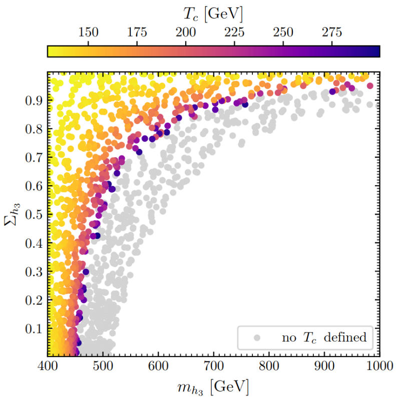
Source 2: $\mathbf{V}_{\mathbf{T}}$

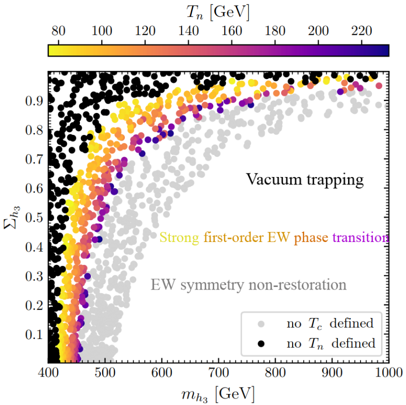
$$\rightarrow V_{\mathrm{eff}} \sim -\frac{T}{12\pi}(\mu_\phi^2 + \lambda h^2 + \lambda T^2)^{3/2}$$

In order to be sizable both sources require **large quartic couplings**
($\rightarrow$ **mass splittings** between BSM scalars)

N2HDM Type 2

Alignment limit, $\tan\beta = 2$, $m_{h_1} = 125\,\mathrm{GeV}$, $m_{h_2} = M = 400\,\mathrm{GeV}$, $m_A = m_{H^\pm} = 650\,\mathrm{GeV}$



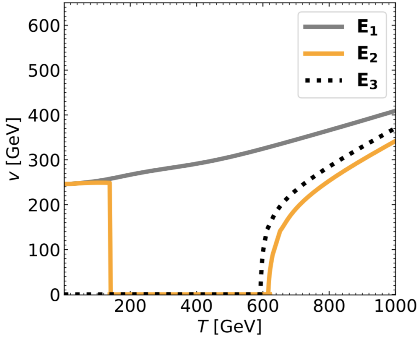


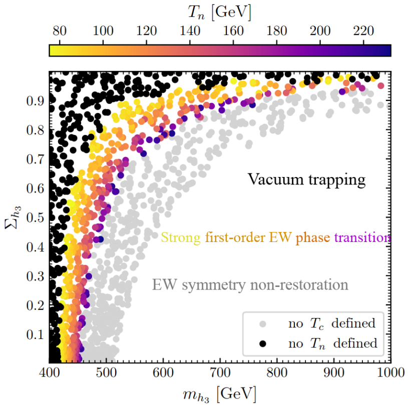
Σ_{h_3}: Singlet admixture of h_3

"Transition strength" $v_c/T_c > 1$ not a viable indicator of a strong FOEWPT

N2HDM Type 2

Alignment limit, $\tan\beta = 2$, $m_{h_1} = 125\,\mathrm{GeV}$, $m_{h_2} = M = 400\,\mathrm{GeV}$, $m_A = m_{H^\pm} = 650\,\mathrm{GeV}$





Σ_{h_3}: Singlet admixture of h_3

Black region unphysical | Grey region in principle allowed, but no FOEWPT

N2HDM Type 2

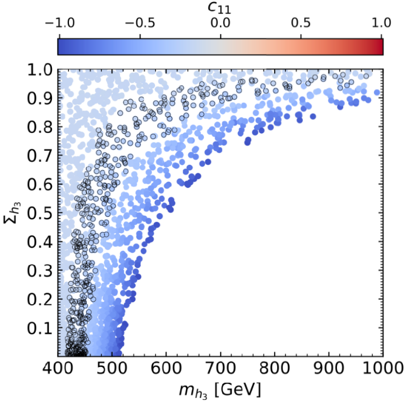
Alignment limit, $\tan\beta = 2$, $m_{h_1} = 125\,\mathrm{GeV}$, $m_{h_2} = M = 400\,\mathrm{GeV}$, $m_A = m_{H^\pm} = 650\,\mathrm{GeV}$

$$H^0_{ij} = \partial^2 V(\rho_k, T)/\partial\rho_i\partial\rho_j\big|_{(0,0,0)}$$

$$c_{ii} \equiv \lim_{T\to\infty} H^0_{ii}/T^2$$

$$c_{11} \simeq -0.025 + c_1 - \frac{1}{2\pi}\left(\frac{3}{2}\lambda_1\sqrt{c_1} + \lambda_3\sqrt{c_2} + \frac{1}{2}\lambda_4\sqrt{c_2} + \frac{1}{4}\lambda_7\sqrt{c_3}\right)$$

$$c_1 = \frac{1}{16}(g'^2 + 3g^2) + \frac{\lambda_1}{4} + \frac{\lambda_3}{6} + \frac{\lambda_4}{12} + \frac{\lambda_7}{24}$$



Σ_{h_3}: Singlet admixture of h_3

EW SnR driven by Daisy resummation $\rightarrow \lambda_i \gtrsim 1$ instead of $\lambda_i < 0$ required

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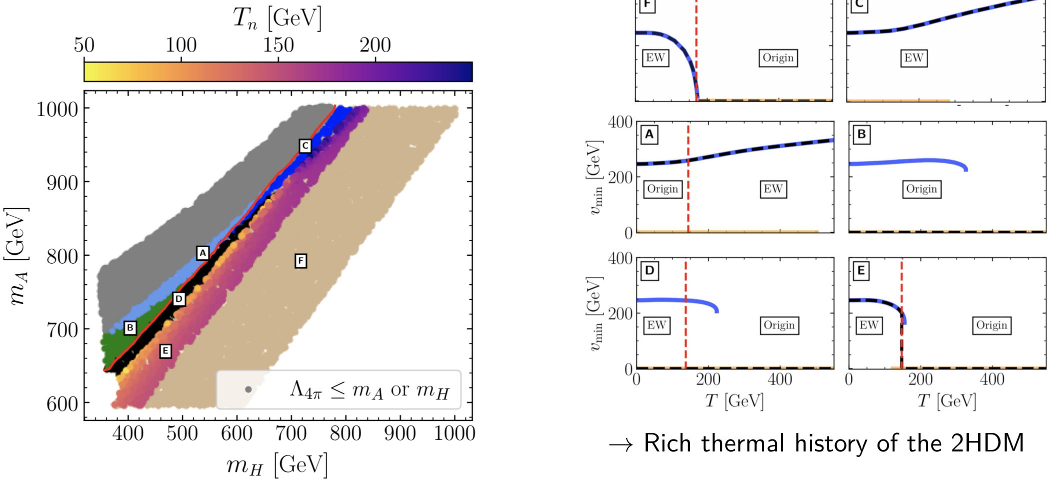
The trap in the early Universe: impact on the interplay between gravitational waves and LHC physics in the 2HDM

2HDM Type 2

2HDM: $c_{\beta-\alpha} = 0$, $t_\beta = 3$, $m_H = M$, $m_A = m_{H^\pm}$

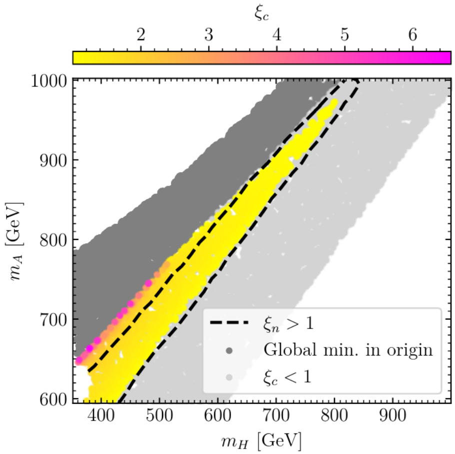


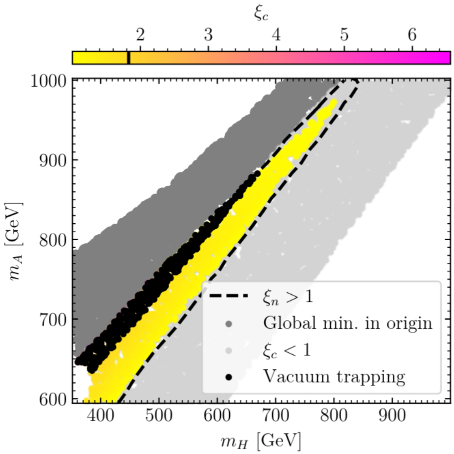
→ Rich thermal history of the 2HDM

2HDM Type 2

2HDM: $c_{\beta-\alpha} = 0$, $t_\beta = 3$, $m_H = M$, $m_A = m_{H^\pm}$

Vacuum trapping!





2HDM Type 2

2HDM: $c_{\beta-\alpha} = 0$, $t_\beta = 3$, $m_H = M$, $m_A = m_{H^\pm}$

Phenomenology

How to probe the thermal history at experiments?*

1. Direct searces for additional Higgs bosons at the LHC
2. Stochastic gravitational-wave backgrounds at LISA
3. Non-resonant pair production of h_{125} at LHC and ILC

*We only considered currently existing experiments or approved/non-fantasy future facilities

2HDM Type 2

1. Direct searches at the (HL-)LHC:

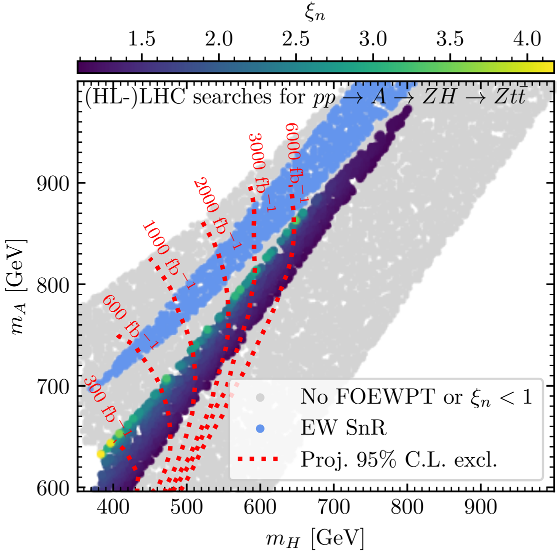
$pp \to A \to ZH \to \ell^+\ell^- t\bar{t}$

Vital to exploit the $H \to t\bar{t}$ channel

No limits yet!

Red: Extrapolations of CMS projections for $41\ \mathrm{fb}^{-1}$

Huge discovery potential (low $\tan\beta$)



2HDM Type 2

Gravitational waves from cosmological phase transitions

2HDM: Two relevant contribution

→ Soundwaves

→ Turbulances

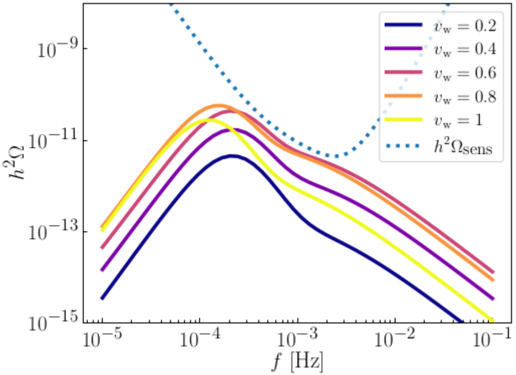
$$h^2\Omega_{\rm GW}(f) = h^2\Omega_{\rm sw}(f) + h^2\Omega_{\rm turb}(f)$$

$h^2\Omega_{\rm sw,turb}$ obtained from numerical simulations

→ Approximations as functions of α, β/H, T_n, $g_{\rm eff}$ and bubble wall velocity $v_{\rm w}$ (unknown)

Signal-to-noise ratio (SNR):

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



[More details: Caprini et al., 1910.13125]

2HDM Type 2

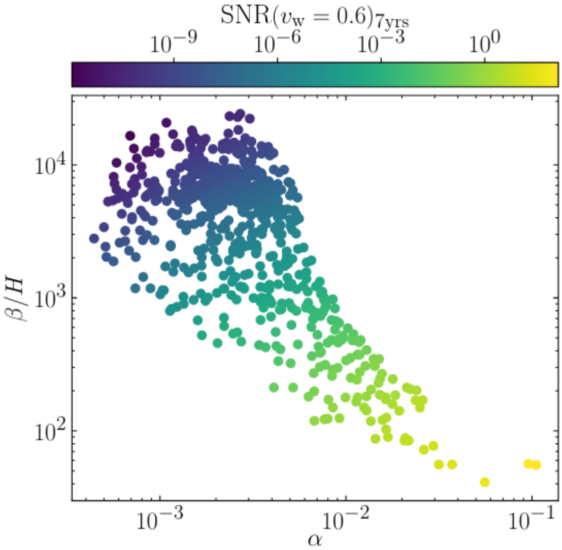
2. GW signals at LISA:

Detectable signals only in corners of parameter space

Limitations for interplay between LISA and (HL-)LHC

Vacuum trapping impedes stronger GW signals

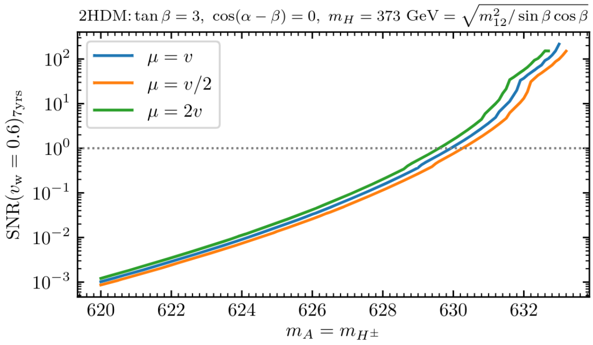
Focus on region with detectable GWs

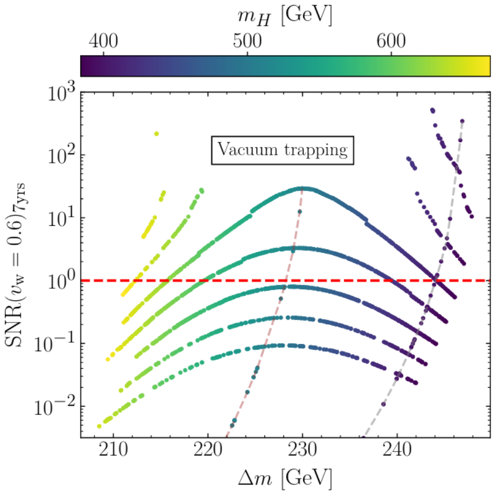


2HDM Type 2

2. GW signals at LISA:

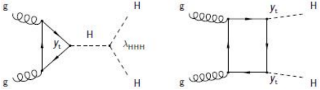
Changing masses of a few GeV has a drastic effect on the SNR





2HDM Type 2

3. Non-res. h_{125} pair production:

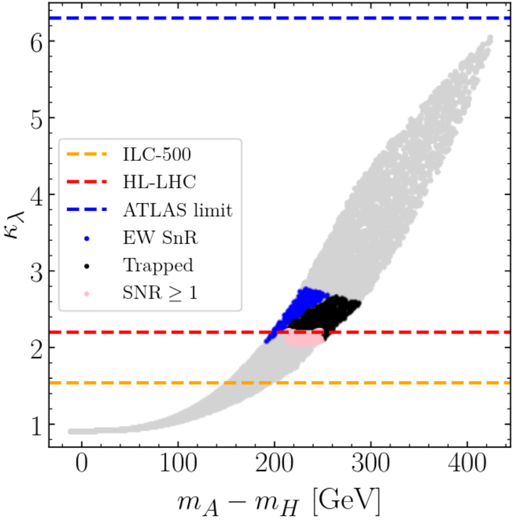


$$\kappa_\lambda = \frac{(\lambda_{hhh}^{\mathrm{2HDM}})^{(1)}}{(\lambda_{hhh}^{\mathrm{SM}})^{(0)}}$$

Expectations at LISA will be shaped by (HL-)LHC results

For points with potentially detectable GW signals:

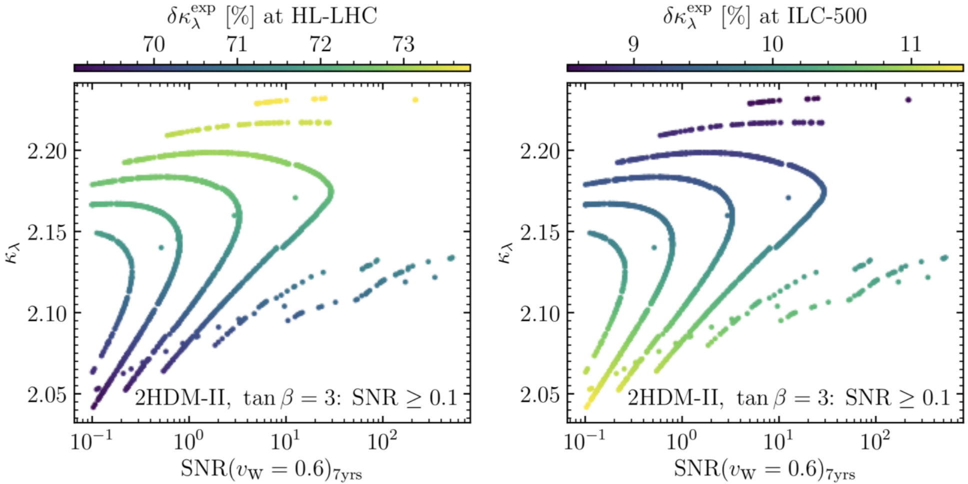
$\kappa_\lambda \sim 2 \sim$ exp. HL-LHC limit



2HDM Type 2

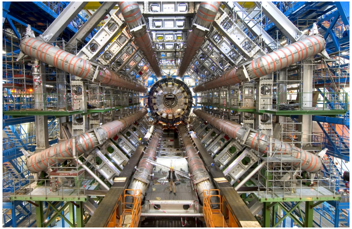
3. Non-res. h_{125} pair production:

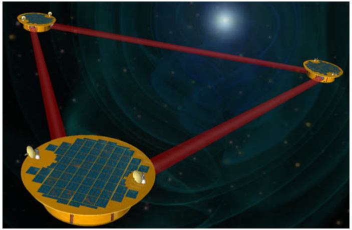
(For $\kappa_\lambda = 1 : \delta\kappa_\lambda^{\rm exp} = 60\%/27\%$ at HL-LHC/ILC-500)

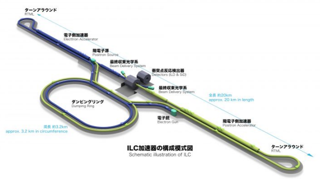


Conclusions

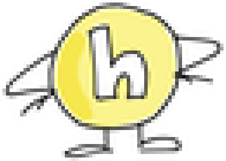
Higgsciting times ahead







Thanks!



Bounce action

Karlsruher Institut für Technologie

$$\Gamma(T) = A(T)\, e^{-S_3(T)/T}, \tag{15}$$

where S_3 denotes the three-dimensional action for the "bounce" (multi-)field configuration $\phi_{\rm B}$ that interpolates between the metastable and EW vacua for $T < T_c$,

$$S_3(T) = 4\pi \int r^2 dr \left[\frac{1}{2} \left(\frac{d\phi_{\rm B}}{dr} \right)^2 + V_{\rm eff}\left(\phi_{\rm B}, T\right) \right] . \tag{16}$$

Specifically, the bounce $\phi_{\rm B}$ is the configuration of scalar fields ϕ that solves the equations of motion derived from the action (16) with boundary conditions $d\phi/dr|_{r=0} = 0$ and approaching the false vacuum at $r \to \infty$. Physically, $\phi_{\rm B}$ describes a bubble of the true vacuum phase nucleating in the false vacuum background. The prefactor $A(T)$ is a functional determinant [69] given approximately by $A(T) \sim T^4 \left(S_3/2\pi T\right)^{3/2}$ [70]. The onset of the FOEWPT occurs when the time integral of the transition rate (15) within a Hubble volume H becomes of order one. This defines the nucleation temperature T_n (see e.g. [72]) as

$$\int_{T_n}^{T_c} \frac{T^4}{H^4} \frac{A(T)}{T}\, e^{-S_3(T)/T}\, dT \sim 1 \ , \tag{17}$$