Next Frontiers in the Search for Dark Matter
GGI, 10/10/2019

Composite Dynamics in the Early Universe

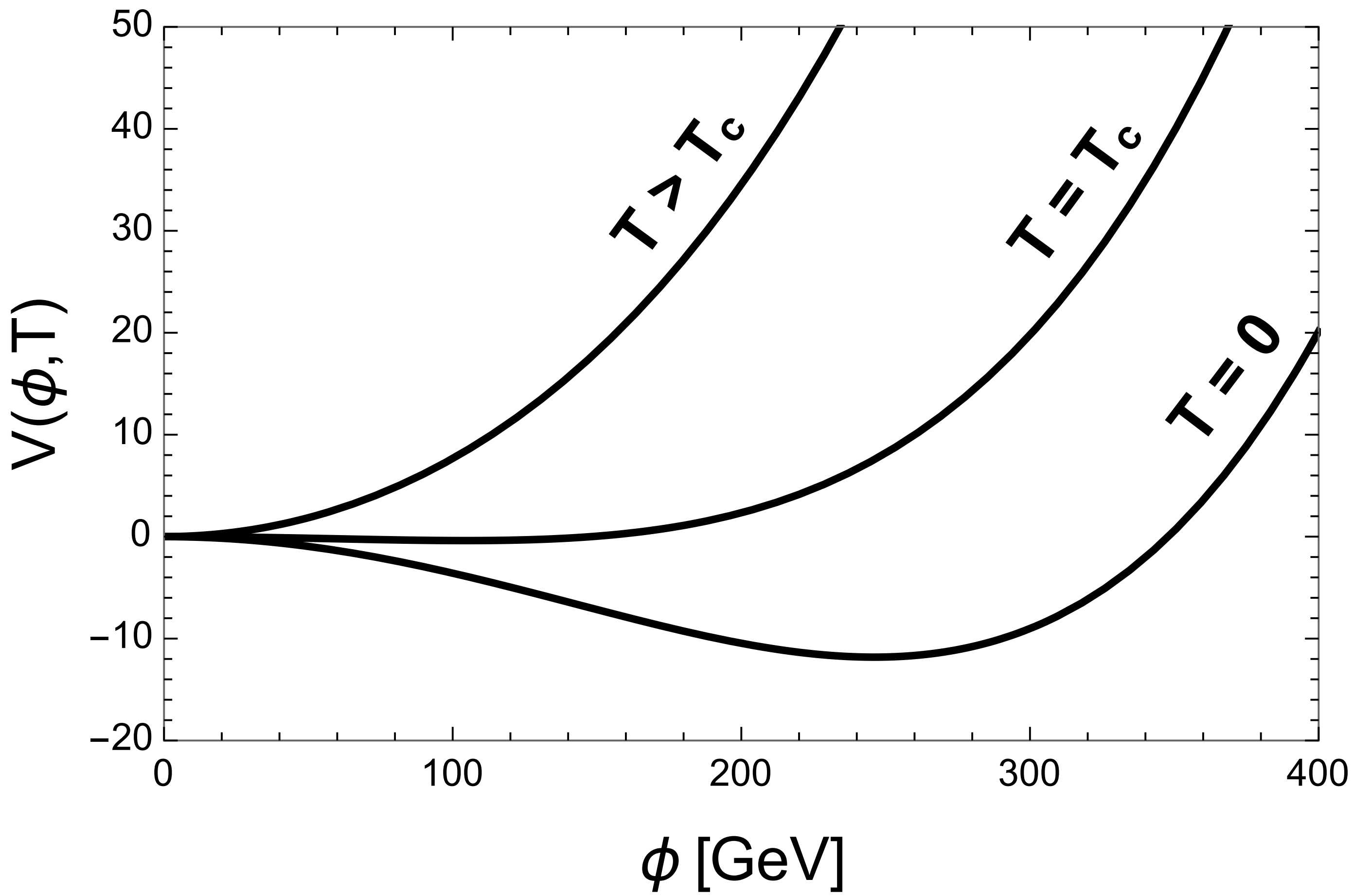
Luigi Delle Rose

S. De Curtis, LDR, G. Panico, arXiv:1909.07894

Outline

- ☑ The Standard Model (and beyond) at finite temperature
- ☑ The ElectroWeak Phase Transition
- ☑ Composite Higgs models at finite temperature
- ☑ Gravitational wave spectrum and baryogenesis

The Standard Model at finite temperature



- ☑ The SM phase transition is a smooth crossover
- ☑ The EW symmetry is restored at $T > T_c$
- ☑ Different scenario if $m_h \lesssim 70$ GeV

The effective potential at finite temperature

$$V_{eff}(\phi, T) = V_0(\phi) + V_1(\phi) + V_1^T(\phi, T) + V_{ring}^T(\phi, T)$$

finite temperature one-loop corrections

$$V_1^T(\phi, T) = \sum_b \frac{n_b T^4}{2\pi^2} J_B\left(\frac{m_b^2(\phi)}{T^2}\right) + \sum_f \frac{n_f T^4}{2\pi^2} J_F\left(\frac{m_f^2(\phi)}{T^2}\right)$$

the thermal integrals $J_{B,F}(y) = \pm \int_0^\infty dx\, x^2 \log\left[1 \mp e^{-\sqrt{x^2+y}}\right]$

resummation of daisy diagrams

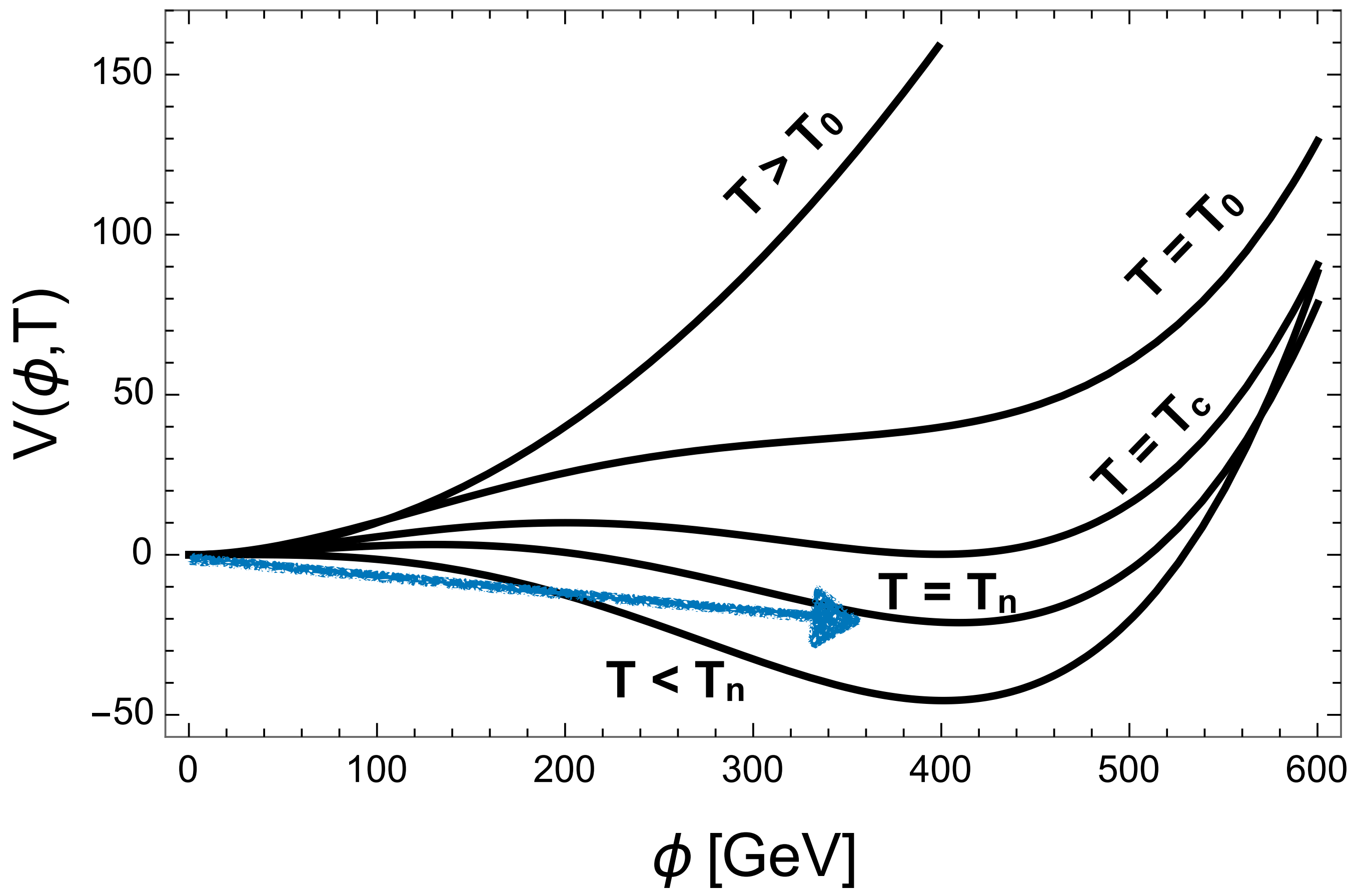
$$V_{ring}^T(\phi, T) = \sum_b \frac{n_b T}{12\pi}\left[m_b^3(\phi) - (m_b^2(\phi) + \Pi_b(T))^{3/2}\right]$$

high-temperature expansion

$$J_B(y) = -\frac{\pi^4}{45} + \frac{\pi^2}{12} y - \frac{\pi}{6} y^{3/2} + \dots$$

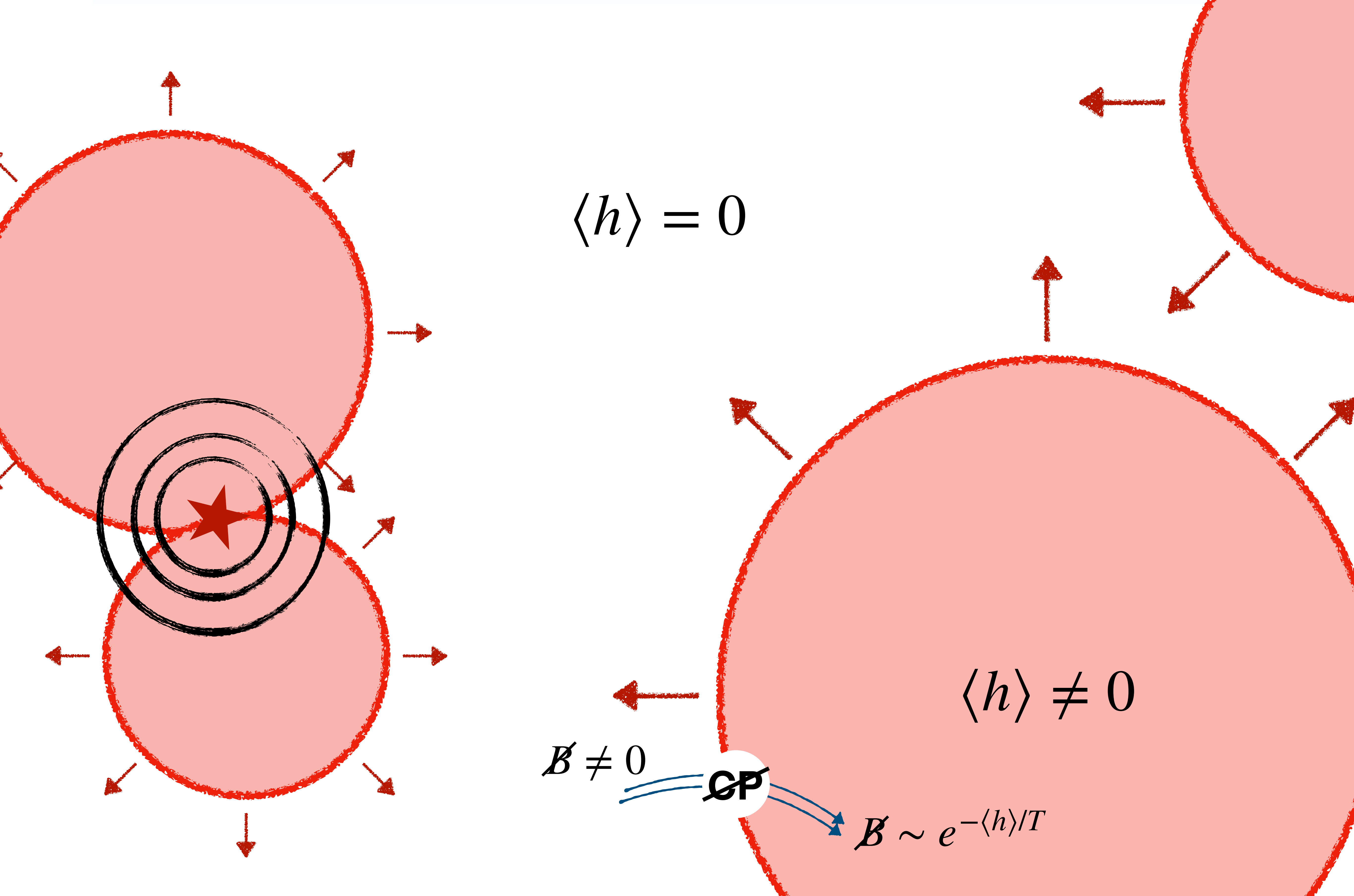
$$J_F(y) = -\frac{7\pi^4}{360} + \frac{\pi^2}{24} y + \dots$$

New Physics at finite temperature



- ☑ The EW symmetry is restored at $T > T_0$, below T_0 a new (local) minimum appears
- ☑ At a critical T_c the two minima are degenerate and separated by a barrier (two phases coexist)
- ☑ The transition starts at the nucleation temperature $T_n < T_c$

Bubble nucleation



A barrier in the effective potential

- ☑ Tree level effects
  - ☐ renormalizable terms: *new scalars coupling to the Higgs* $\lambda_{h\eta} h^2 \eta^2$
  - ☐ non-renormalizable operators: $c\,|H|^6$

- ☑ Thermal effects

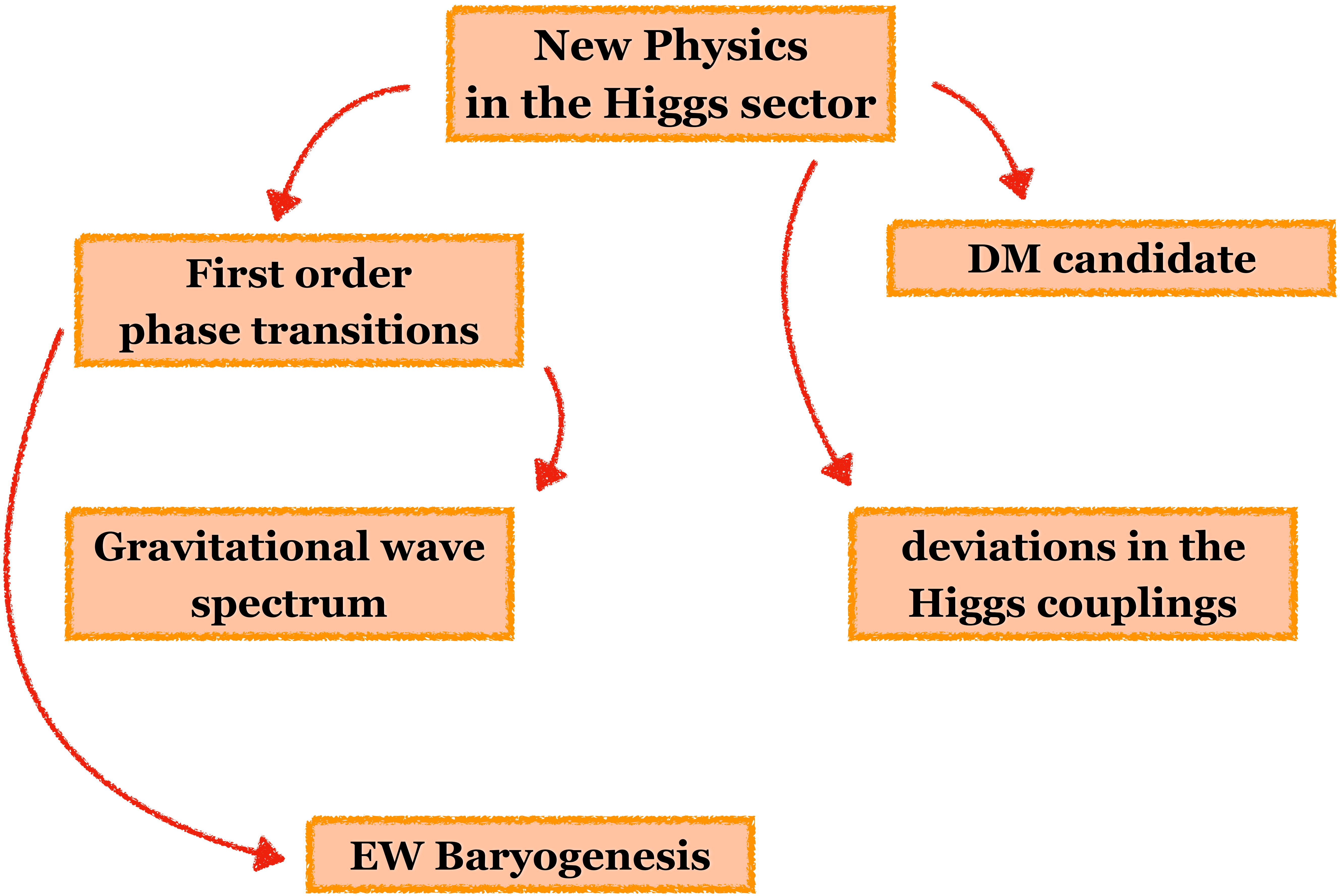
$$V(h,T) \simeq \frac{1}{2}(-\mu_h^2 + cT^2)h^2 + \frac{\lambda}{4}h^2 - ETh^3$$

- E gets contributions from all the bosonic dof coupled to the Higgs
- E arises from the non-analyticity of $J_B(y)$ at y = 0

typical BSM scenario realising 1st order EWPhT: light stops in the MSSM

- ☑ T = 0 loop effects:

large loop corrections from the Coleman-Weinberg potential can generate $h^4 \log h^2$


New Physics in the Higgs sector
First order phase transitions
DM candidate
Gravitational wave spectrum
deviations in the Higgs couplings
EW Baryogenesis

New Physics
in the Higgs sector

First order
phase transitions

DM candidate

Collider - cosmology synergy

Gravitational wave spectrum

observables at future interferometers

deviations in the Higgs couplings

observables at future colliders

EW Baryogenesis

First order phase transitions

key parameters

- ☑ Nucleation probability (per unit time and volume) **P**: $P = T^4 e^{-S_3/T}$
- ☑ Nucleation temperature **T_n**:

$$\int_{T_n}^{\infty} \frac{dT}{T} V_H^4 P \simeq O(1)$$

for phase transitions at the EW scale
$S_3/T_n \approx 140$

- ☑ Vacuum expectation value in the broken phase at T_n: **v_n**
- ☑ Vacuum energy released in the plasma: $\alpha = \epsilon/\rho_{rad}$
- ☑ Time duration of the phase transition: **β/H_n**

$$\frac{\beta}{H_n} = T \frac{d}{dT} \frac{S_3}{T}\Big|_{T_n}$$

extracted from the solution of the bounce equation

$$\frac{d^2\phi}{dr^2} + \frac{2}{r}\frac{d\phi}{dr} = \nabla V(\phi, T)$$

$$d\phi/dr|_{r=0} = 0 \quad \phi|_{r=\infty} = 0$$

- ☑ Bubble wall velocity: **v_w**

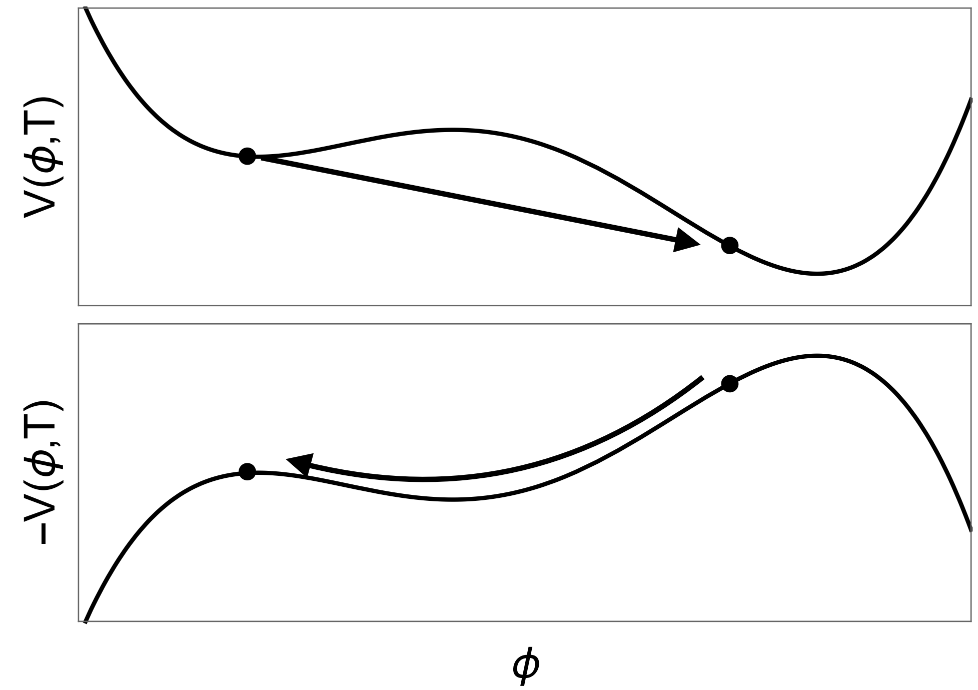
highly non-trivial: requires hydrodynamics
modelling of the bubble wall moving in the plasma

The bounce equation

single-field equation

can be solved with the
overshoot-undershoot method

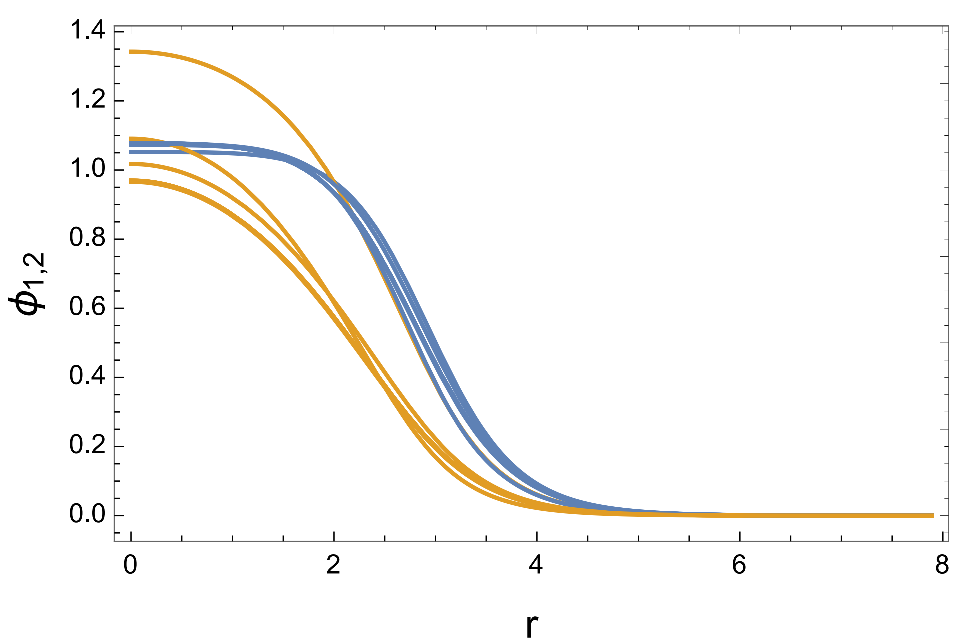
classical motion analogy:
particle at position ϕ moving in time *r*
under the potential -*V* and
a time-dependent friction term

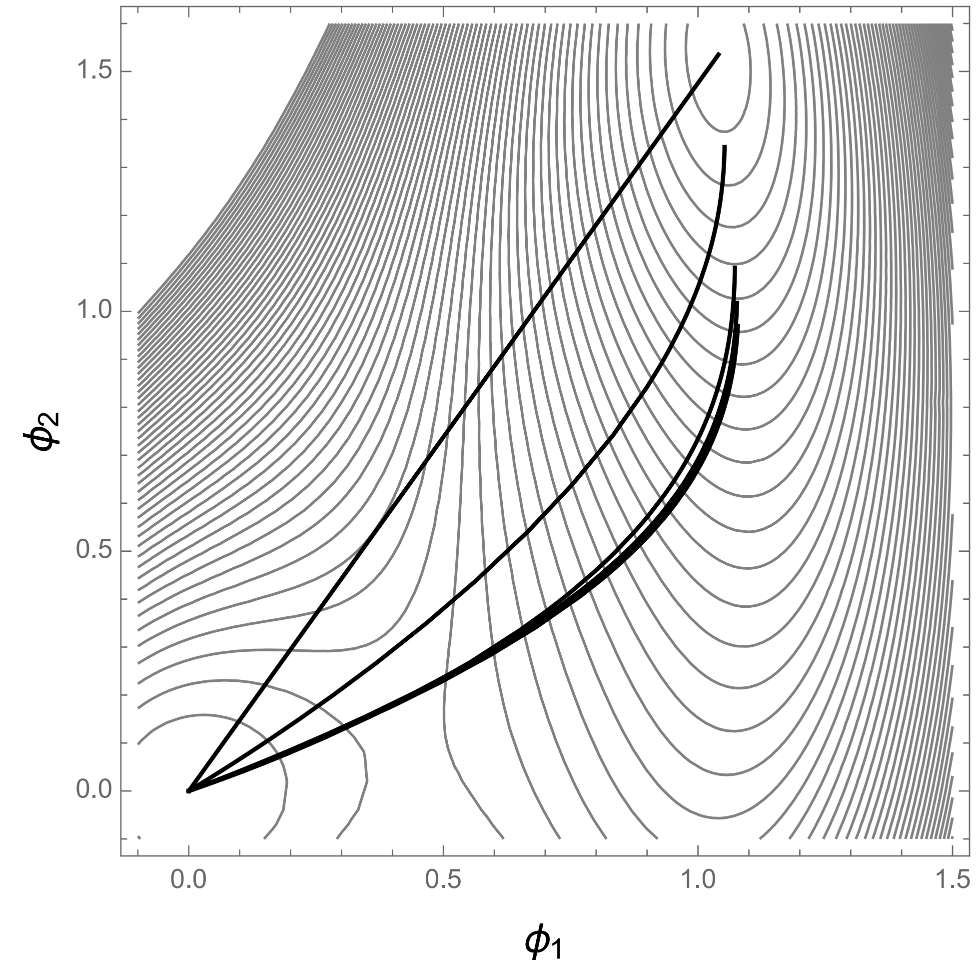


multi-field equation

trajectory not known:
the path is deformed from an initial guess
until convergence is reached

the bounce is
recomputed
along each path





The SM + scalar singlet

Higgs + singlet effective potential (Z_2 symmetric)
in the high-temperature limit

$$V(h,\eta,T) = \frac{\mu_h^2}{2}h^2 + \frac{\lambda_h}{4}h^4 + \frac{\mu_\eta^2}{2}\eta^2 + \frac{\lambda_\eta}{4}\eta^4 + \frac{\lambda_{h\eta}}{2}h^2\eta^2 + \left(c_h\frac{h^2}{2} + c_\eta\frac{\eta^2}{2}\right)T^2$$

thermal masses (count the dof coupled to the scalars)

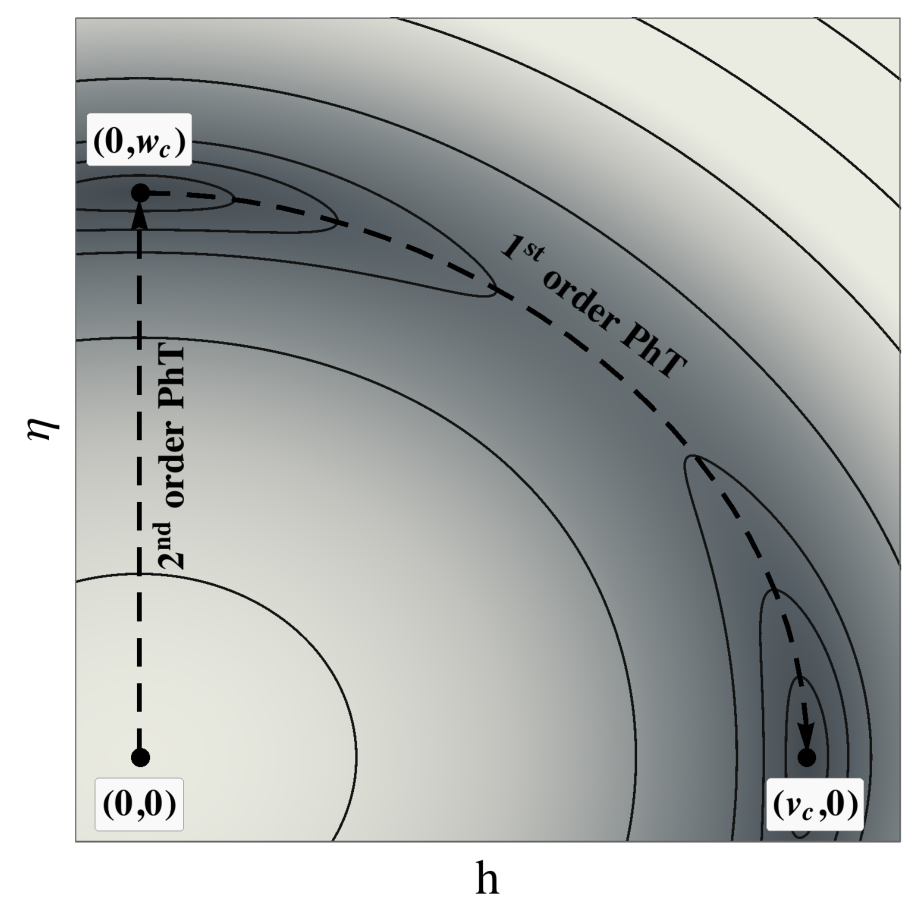
$$c_h = \frac{1}{48}(9g^2 + 3g'^2 + 12y_t^2 + 24\lambda_h + 2\lambda_{h\eta}) \qquad c_\eta = \frac{1}{12}(4\lambda_{h\eta} + \lambda_\eta)$$

- ☑ EW symmetry restored at very high T:
  $\langle h, \eta \rangle = (0,0)$

- ☑ two interesting patterns of symmetry breaking
  (as the Universe cools down)

  1. (0,0) -> (v,0) 1-step PhT
  2. (0,0) -> (0,w) -> (v, 0) 2-step PhT

2-step more natural as, typically, $c_\eta < c_h$
and the singlet is destabilised before the Higgs



The SM + scalar singlet

phenomenology

Higgs + singlet (with Z_2 symmetry and $m_\eta > m_h/2$) poorly constrained

- ☑ $m_\eta < m_h/2$ excluded by the invisible Higgs decay

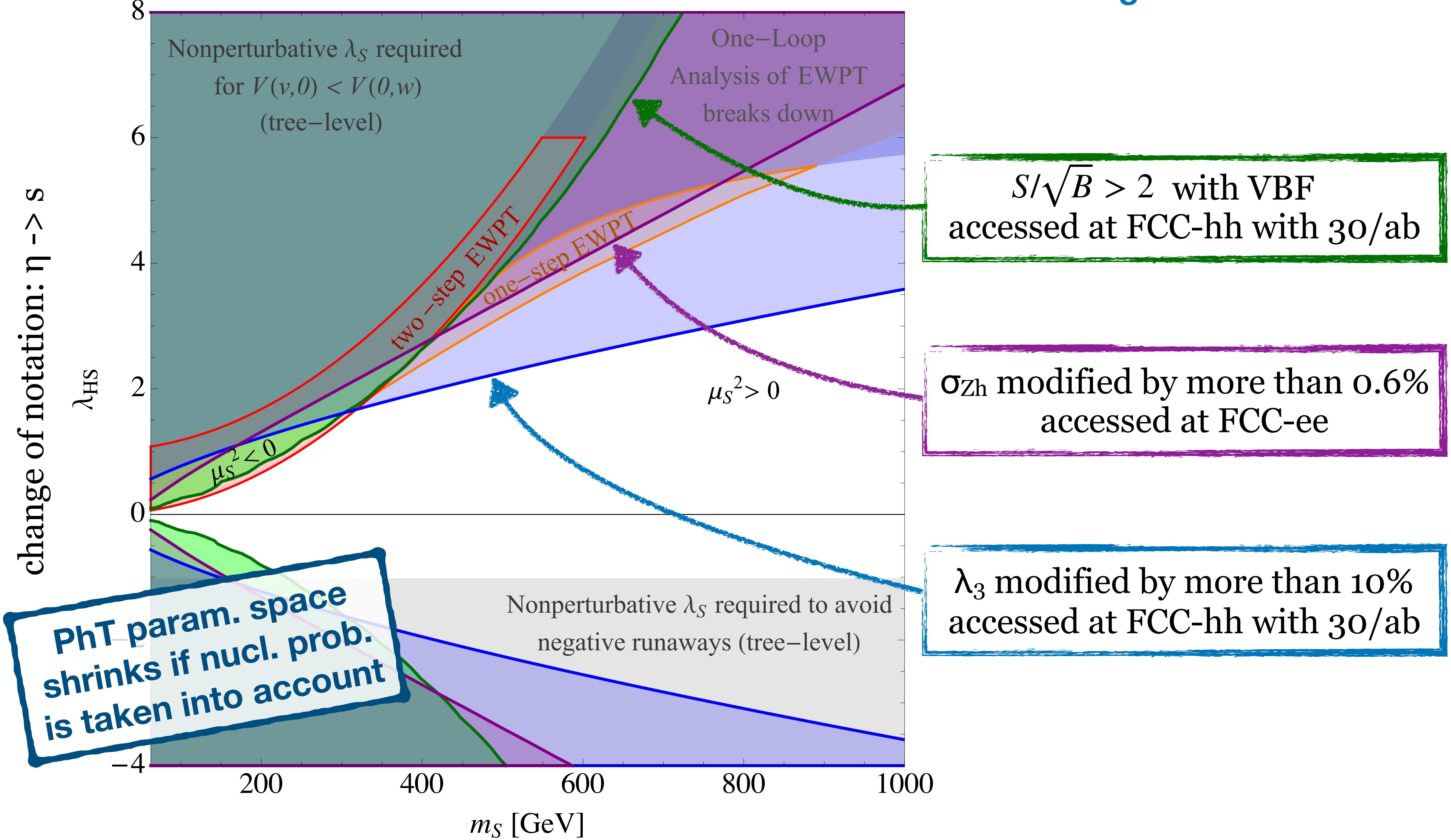
- ☑ direct searches very challenging: need for a 100TeV collider.
  interesting channel: qq -> qq ηη (VBF)

- ☑ indirect searches:
  - modification to the triple Higgs coupling $$\lambda_3 = \frac{m_h^2}{2v} + \frac{\lambda_{h\eta}^3}{24\pi^2}\frac{v^3}{m_\eta^2} + \ldots$$
  - corrections to the Zh cross section at lepton colliders

- ☑ dark matter direct detection
  - the singlet can be a DM candidate
  - constraints are very model dependent.
    the cosmological history depends on the hidden sector

The SM + scalar singlet

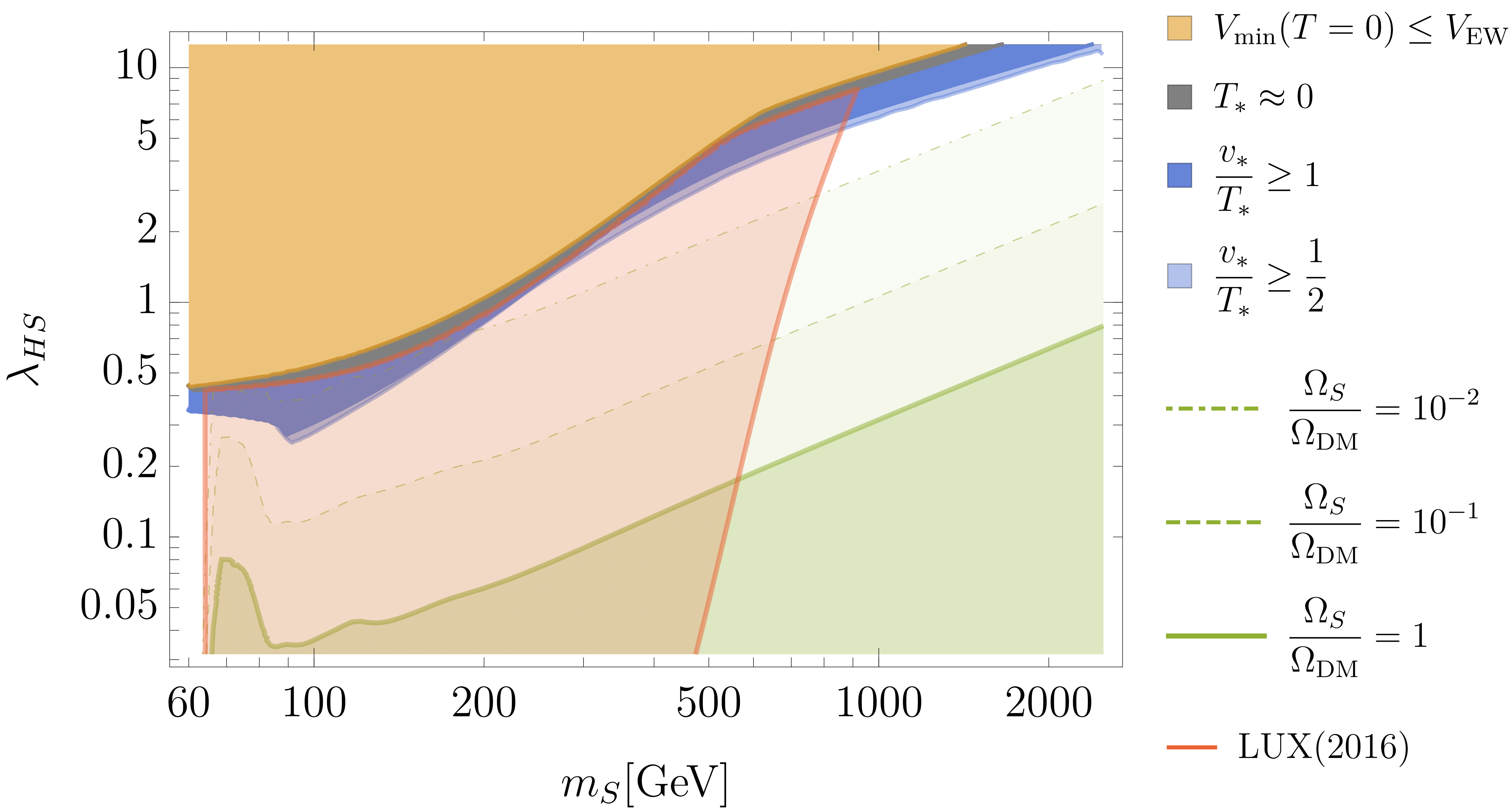
nightmare scenario



Curtin, Meade, Yu, 2015

The SM + scalar singlet

change of notation: η -> s



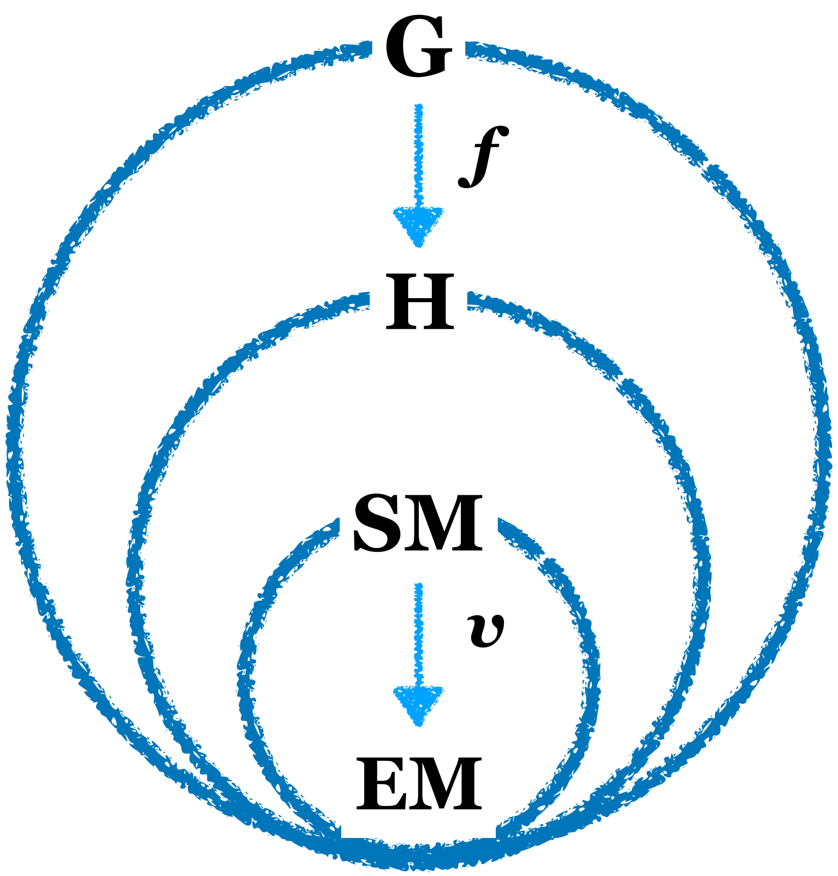
In the Z_2 symmetric model, the singlet scalar cannot account for all the DM without any new dark sector

Beniwal et al., 2017

EWPhT in Composite Higgs models

the basic idea:
Higgs as Goldstone boson of G/H of a strong sector

PhTs in Composite Higgs models

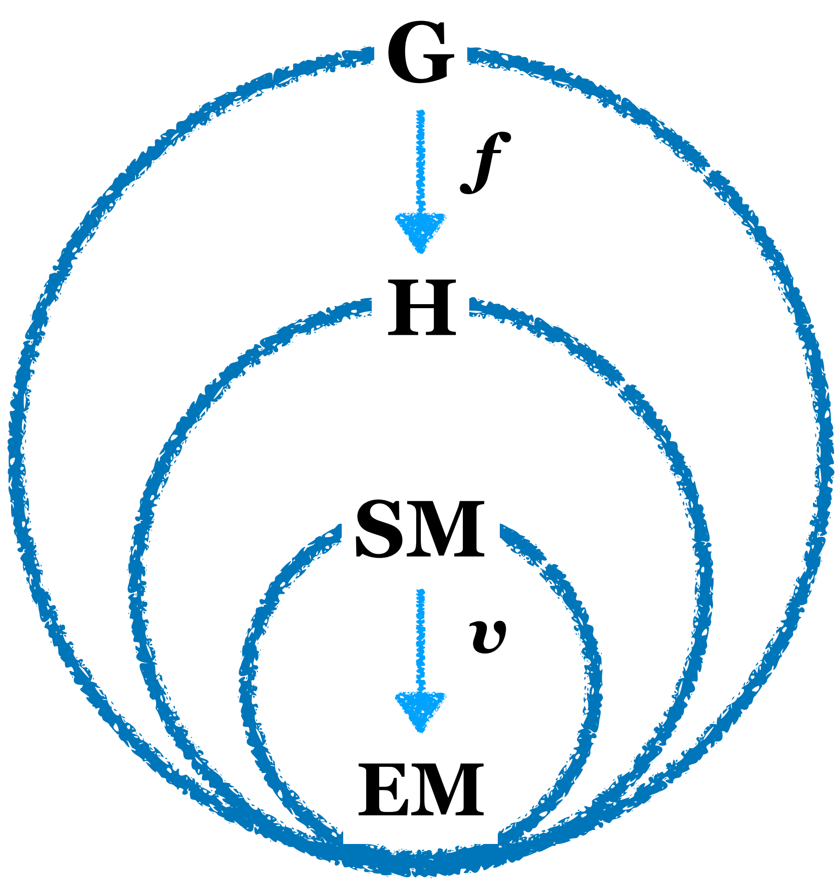


* *phase transition G -> H in the strongly coupled sector*

* ***EW phase transition***

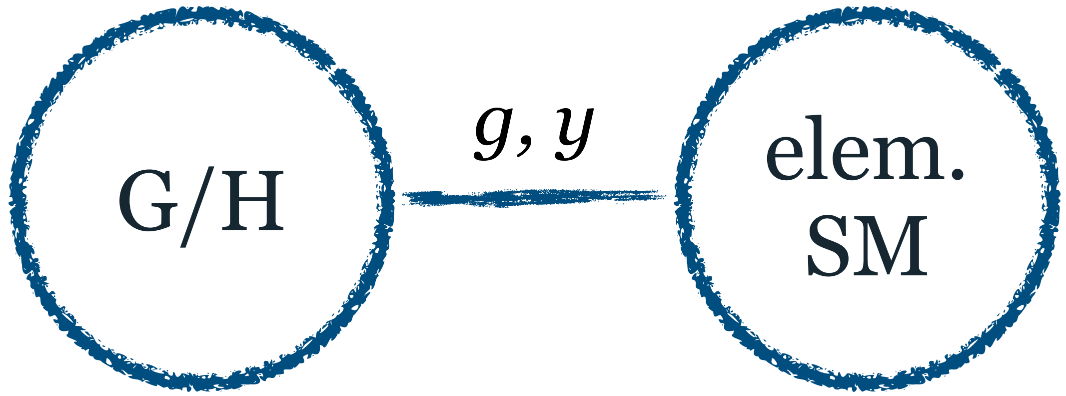
multiple peaks in the GW spectrum?

Basic rules for Composite Higgs models

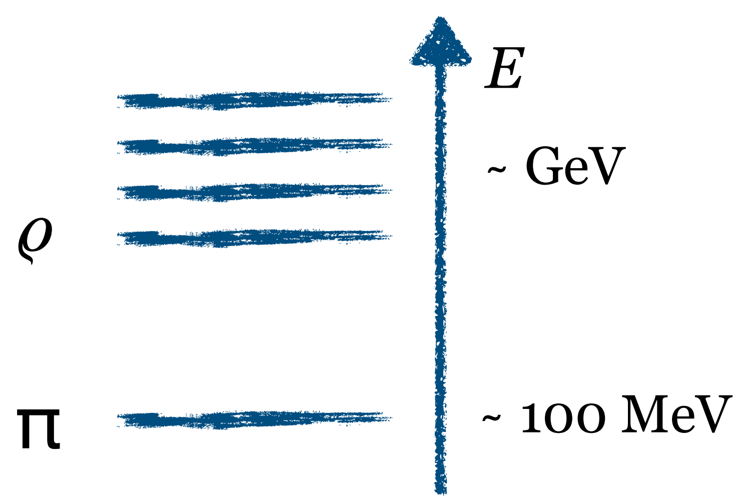


- ☑ a global symmetry G above f (~ TeV) is spontaneously broken down to a subgroup H
- ☑ the structure of the Higgs sector is determined by the coset G/H
- ☑ H should contain the custodial group
- ☑ the number of NGBs (dim G - dim H) must be larger than (or at least equal to) 4
- ☑ the symmetry G must be explicitly broken to generate the mass for the (otherwise massless) NGBs

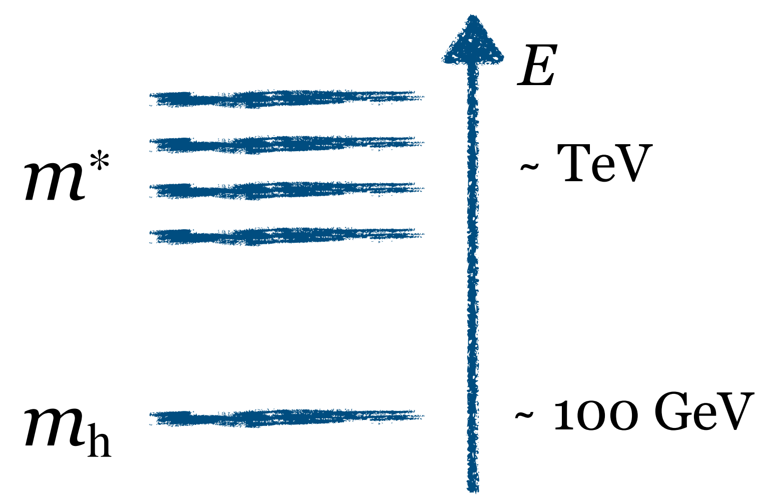
Mass spectra

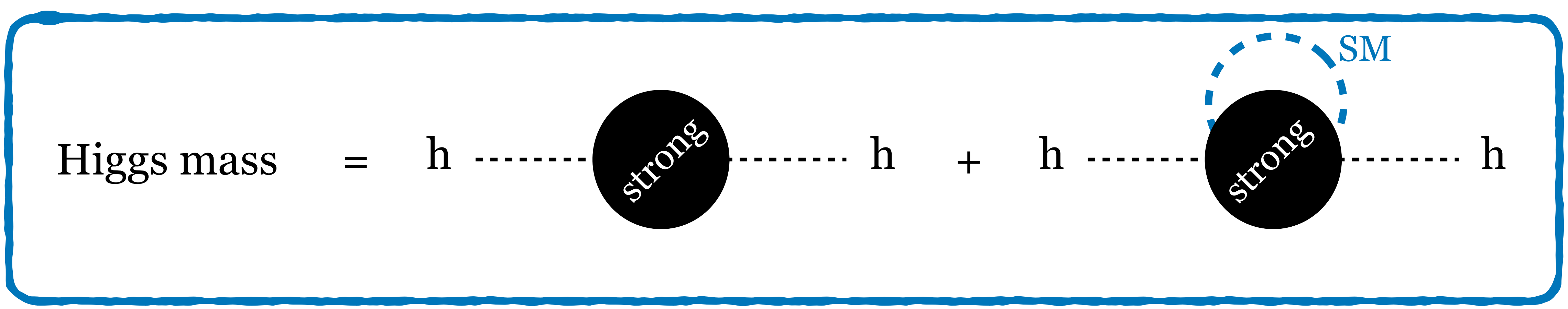


we borrow the idea from QCD
where we observe that the
(pseudo) scalars are the lightest states



the Higgs could be a kind of pion
arising from a new strong sector





Symmetry structure of the strong sector

G	H	N_G	NGBs rep.$[H]$ = rep.$[\mathrm{SU}(2)\times\mathrm{SU}(2)]$
SO(5)	SO(4)	4	$\mathbf{4} = (\mathbf{2},\mathbf{2})$
SO(6)	SO(5)	5	$\mathbf{5} = (\mathbf{1},\mathbf{1}) + (\mathbf{2},\mathbf{2})$
SO(6)	SO(4) × SO(2)	8	$\mathbf{4_{+2}} + \mathbf{\bar{4}_{-2}} = 2\times(\mathbf{2},\mathbf{2})$
SO(7)	SO(6)	6	$\mathbf{6} = 2\times(\mathbf{1},\mathbf{1}) + (\mathbf{2},\mathbf{2})$
SO(7)	G_2	7	$\mathbf{7} = (\mathbf{1},\mathbf{3}) + (\mathbf{2},\mathbf{2})$
SO(7)	SO(5) × SO(2)	10	$\mathbf{10_0} = (\mathbf{3},\mathbf{1}) + (\mathbf{1},\mathbf{3}) + (\mathbf{2},\mathbf{2})$
SO(7)	$[\mathrm{SO}(3)]^3$	12	$(\mathbf{2},\mathbf{2},\mathbf{3}) = 3\times(\mathbf{2},\mathbf{2})$
Sp(6)	Sp(4) × SU(2)	8	$(\mathbf{4},\mathbf{2}) = 2\times(\mathbf{2},\mathbf{2}), (\mathbf{2},\mathbf{2}) + 2\times(\mathbf{2},\mathbf{1})$
SU(5)	SU(4) × U(1)	8	$\mathbf{4}_{-5} + \mathbf{\bar{4}_{+5}} = 2\times(\mathbf{2},\mathbf{2})$
SU(5)	SO(5)	14	$\mathbf{14} = (\mathbf{3},\mathbf{3}) + (\mathbf{2},\mathbf{2}) + (\mathbf{1},\mathbf{1})$

Mrazek et al., 2011

Symmetry structure of the strong sector

Minimal scenario: SO(5)/SO(4) *one Higgs doublet*

G	H	N_G	NGBs rep.$[H]$ = rep.$[SU(2) \times SU(2)]$
SO(5)	SO(4)	4	$\mathbf{4} = (\mathbf{2}, \mathbf{2})$
SO(6)	SO(5)	5	
SO(6)	SO(4) × SO(2)	8	
SO(7)	SO(6)	6	
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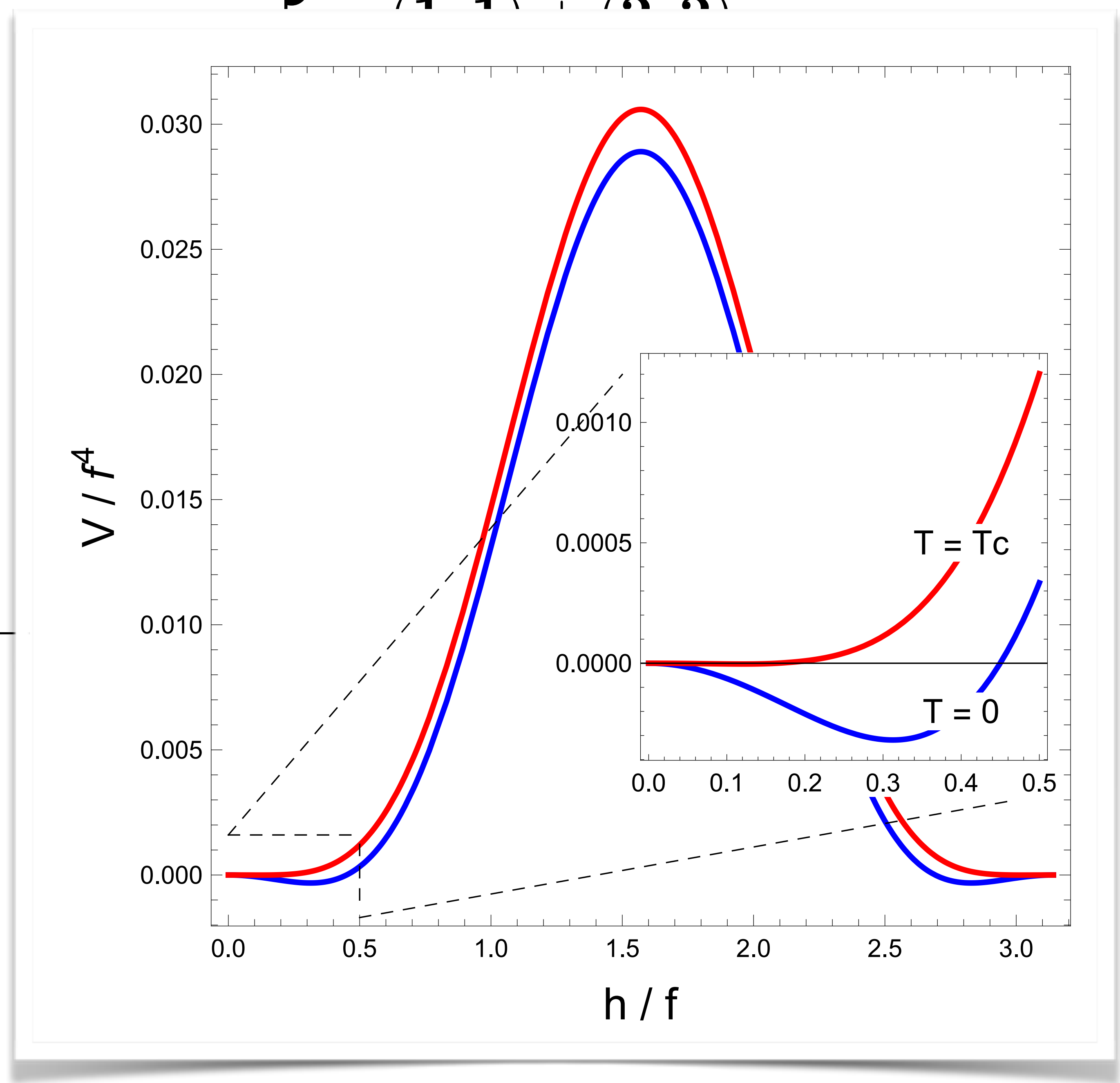
Sp(6)	Sp(4) × SU(2)	8	
SU(5)	SU(4) × U(1)	8	
SU(5)	SO(5)	14	



PhT similar to the SM
due to the pheno constraint

$\xi = v^2/f^2 \lesssim 0.1$ no 1st order PhT

unless one allows for a small tilt

Di Luzio et al., 2019

Symmetry structure of the strong sector

Next to minimal scenario: SO(6)/SO(5)

one Higgs doublet + a scalar singlet

G	H	N_G	NGBs rep.$[H]$ = rep.$[\mathrm{SU}(2)\times\mathrm{SU}(2)]$
SO(5)	SO(4)	4	$\mathbf{4}=(\mathbf{2},\mathbf{2})$
SO(6)	SO(5)	5	$\mathbf{5}=(\mathbf{1},\mathbf{1})+(\mathbf{2},\mathbf{2})$
SO(6)	SO(4) × SO(2)	8	$\mathbf{4_{+2}}+\mathbf{\bar{4}_{-2}}=2\times(\mathbf{2},\mathbf{2})$
SO(7)	SO(6)	6	$\mathbf{6}=2\times(\mathbf{1},\mathbf{1})+(\mathbf{2},\mathbf{2})$
SO(7)	G_2	7	$\mathbf{7}=(\mathbf{1},\mathbf{3})+(\mathbf{2},\mathbf{2})$
SO(7)	SO(5) × SO(2)	10	$\mathbf{10_0}=(\mathbf{3},\mathbf{1})+(\mathbf{1},\mathbf{3})+(\mathbf{2},\mathbf{2})$
SO(7)	$[\mathrm{SO}(3)]^3$	12	$(\mathbf{2},\mathbf{2},\mathbf{3})=3\times(\mathbf{2},\mathbf{2})$
Sp(6)	Sp(4) × SU(2)	8	$(\mathbf{4},\mathbf{2})=2\times(\mathbf{2},\mathbf{2}),(\mathbf{2},\mathbf{2})+2\times(\mathbf{2},\mathbf{1})$
SU(5)	SU(4) × U(1)	8	$\mathbf{4}_{-5}+\mathbf{\bar{4}_{+5}}=2\times(\mathbf{2},\mathbf{2})$
SU(5)	SO(5)	14	$\mathbf{14}=(\mathbf{3},\mathbf{3})+(\mathbf{2},\mathbf{2})+(\mathbf{1},\mathbf{1})$

the scalar potential

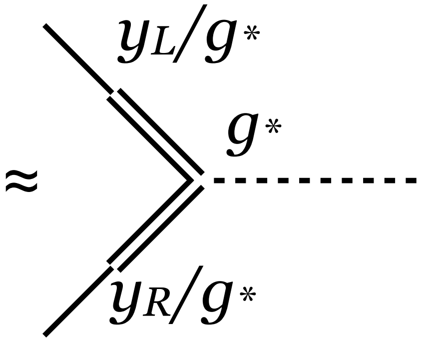
$$V(h,\eta)=\frac{\mu_h^2}{2}h^2+\frac{\lambda_h}{4}h^4+\frac{\mu_\eta^2}{2}\eta^2+\frac{\lambda_\eta}{4}\eta^4+\frac{\lambda_{h\eta}}{2}h^2\eta^2$$

Partial compositeness

linear interactions between composite and elementary operators

$$\mathcal{L}_{\text{int}} = g J_\mu W^\mu$$
$$\mathcal{L}_{\text{int}} = y_L\, q_L\, \mathcal{O}_L + y_R\, t_R\, \mathcal{O}_R$$

$y_{top} \approx$



in the IR $\quad -\mathcal{L} = m^* \bar{T}\, T + y\, f\, \bar{t}\, T$ $\longrightarrow$ ***partial compositeness***

SO(6) *representation decompositions under*
$SU(2)_L \otimes SU(2)_R \otimes U(1)_\eta$

$$\begin{aligned}
\mathbf{4} &= (\mathbf{2},\mathbf{1})_{+1} \oplus (\mathbf{1},\mathbf{2})_{-1}\ , \\
\mathbf{6} &= (\mathbf{2},\mathbf{2})_{0} \oplus (\mathbf{1},\mathbf{1})_{+2} \oplus (\mathbf{1},\mathbf{1})_{-2}\ , \\
\mathbf{10} &= (\mathbf{2},\mathbf{2})_{0} \oplus (\mathbf{3},\mathbf{1})_{+2} \oplus (\mathbf{1},\mathbf{3})_{-2}\ , \\
\mathbf{15} &= (\mathbf{1},\mathbf{3})_{0} \oplus (\mathbf{3},\mathbf{1})_{0} \oplus (\mathbf{1},\mathbf{1})_{0} \oplus (\mathbf{2},\mathbf{2})_{+2} \oplus (\mathbf{2},\mathbf{2})_{-2}\ , \\
\mathbf{20'} &= (\mathbf{3},\mathbf{3})_{0} \oplus (\mathbf{2},\mathbf{2})_{+2} \oplus (\mathbf{2},\mathbf{2})_{-2} \oplus (\mathbf{1},\mathbf{1})_{+4} \oplus (\mathbf{1},\mathbf{1})_{-4} \oplus (\mathbf{1},\mathbf{1})_{0}\ .
\end{aligned}$$

Classification of representations

☑ **4** — not suitable for the top quark: large Zb_Lb_L coupling

☑ **10** — no potential for the scalar singlet η

☑ **6, 15, 20'** — viable representations for the top quark

☑ (q_L, t_R) ~ **(6, 6)**

typically predicts $\lambda_\eta \simeq 0, \quad \lambda_{h\eta} \simeq \lambda_h/2$ unless we consider:

- ✱ large tuning in bottom quark and gauge sectors
- ✱ elementary-composite mixings λ_{qL}, λ_{tR}, up to the fourth power

☑ (q_L, t_R) ~ **(15, 6)**

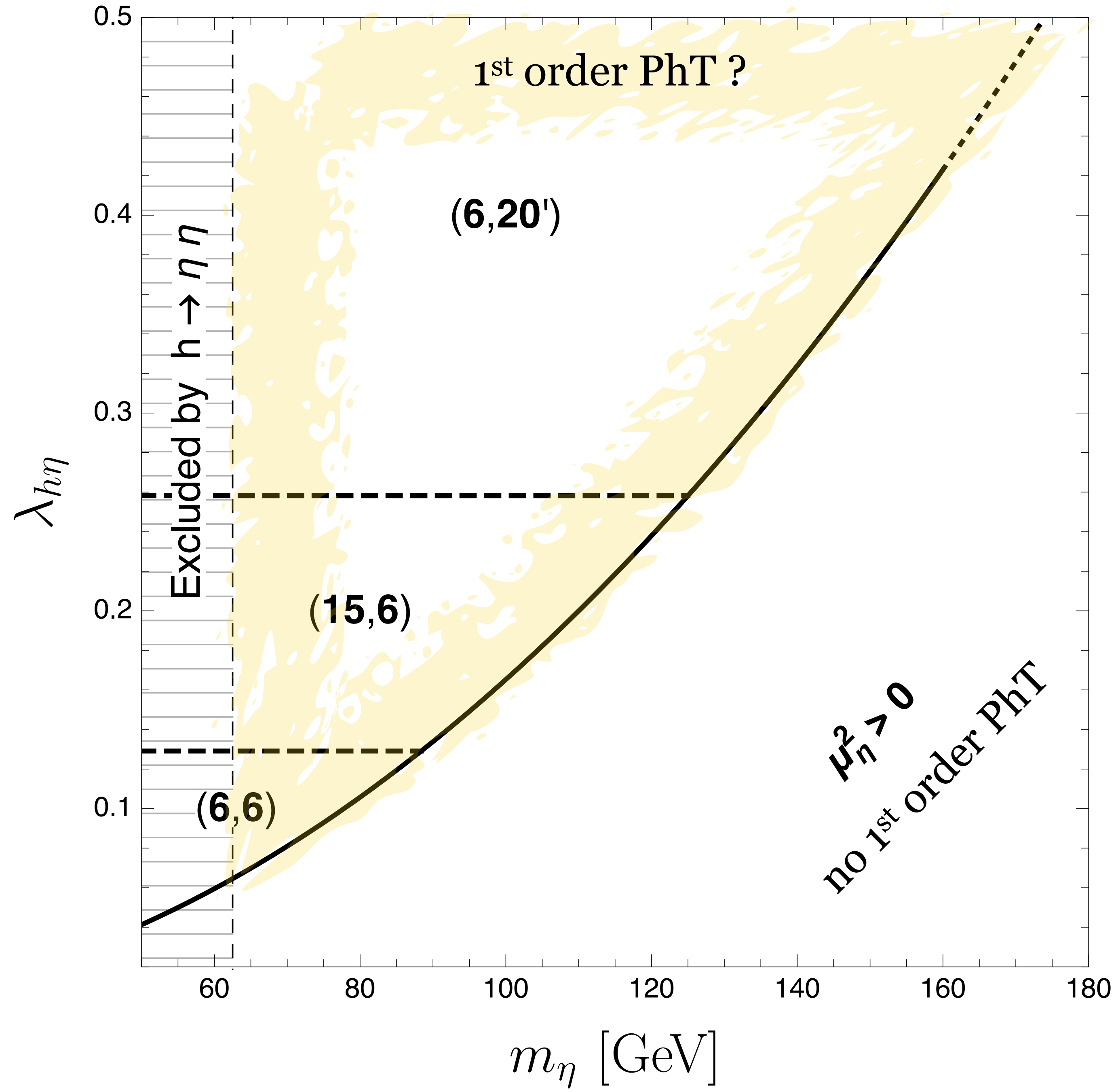
less-tuned scenario: no need to rely on bottom and gauge but λ_ψ still at the fourth power

☑ (q_L, t_R) ~ **(6, 20')**

large parameter space available without large tuning

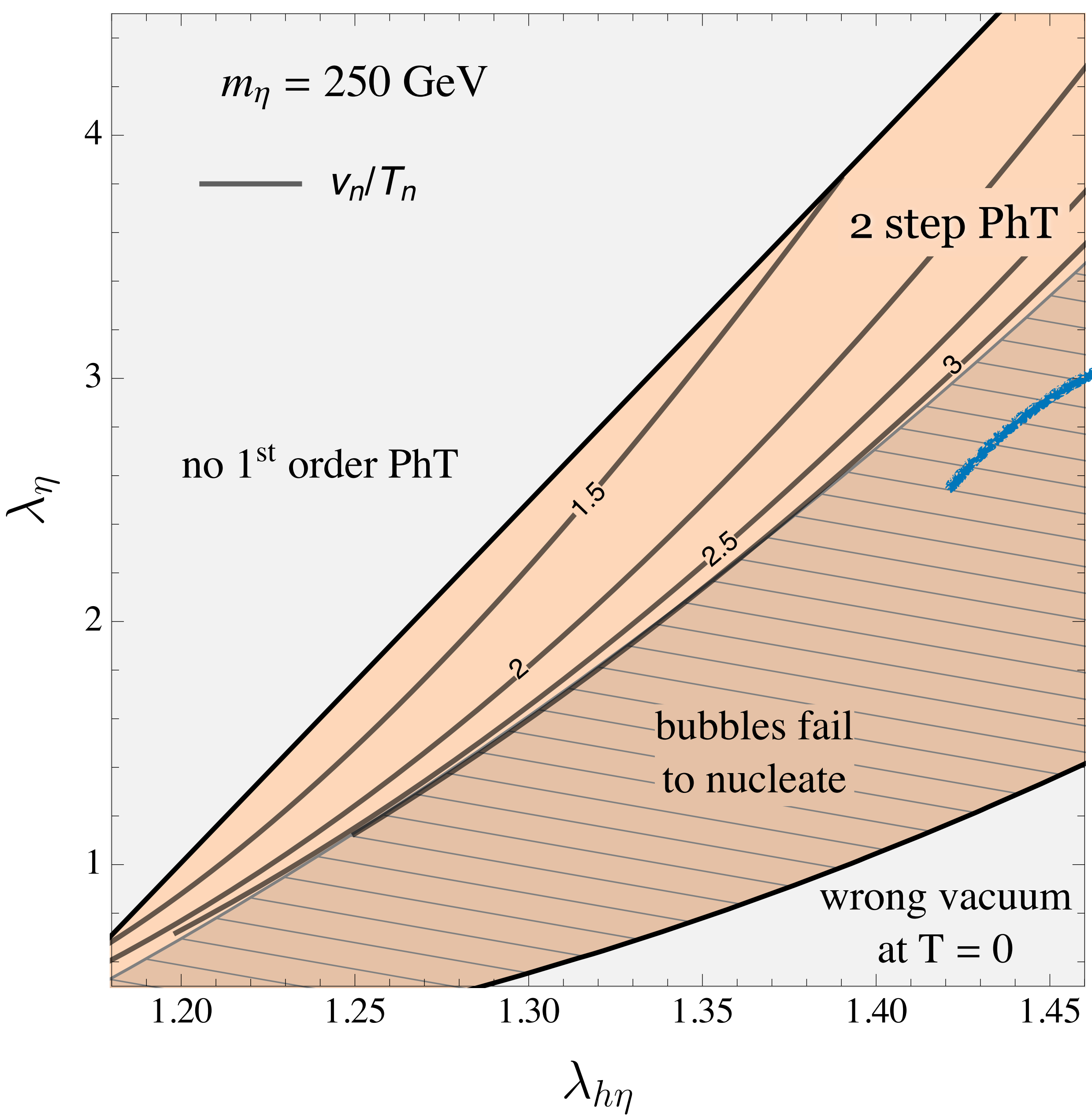
Classification of representations

Parameter space



Properties of the EWPhT

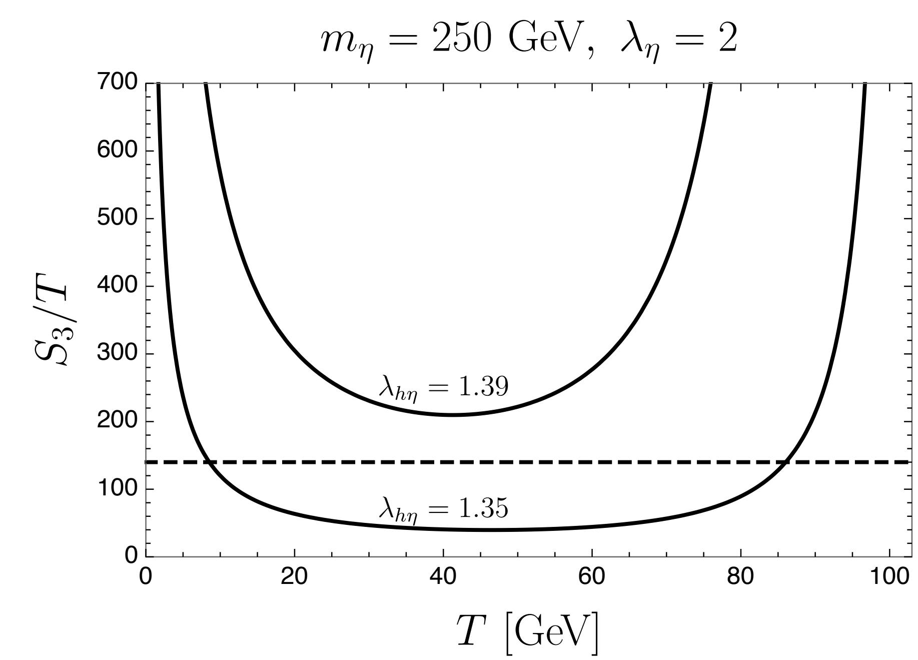
$(q_L, t_R) \sim (6, 20')$



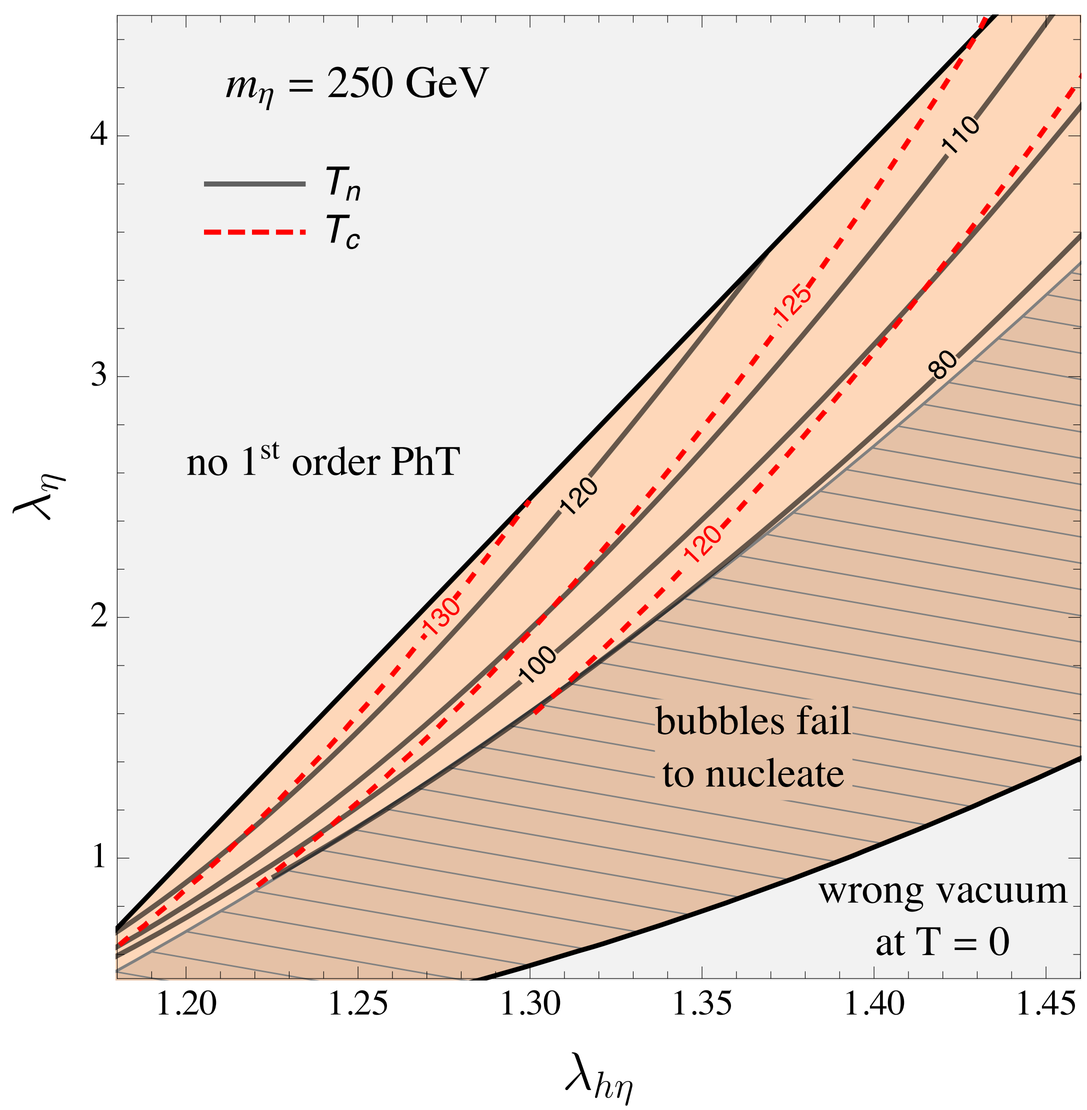
v_n/T_n: strength of the PhT
a crucial parameter for EWBG

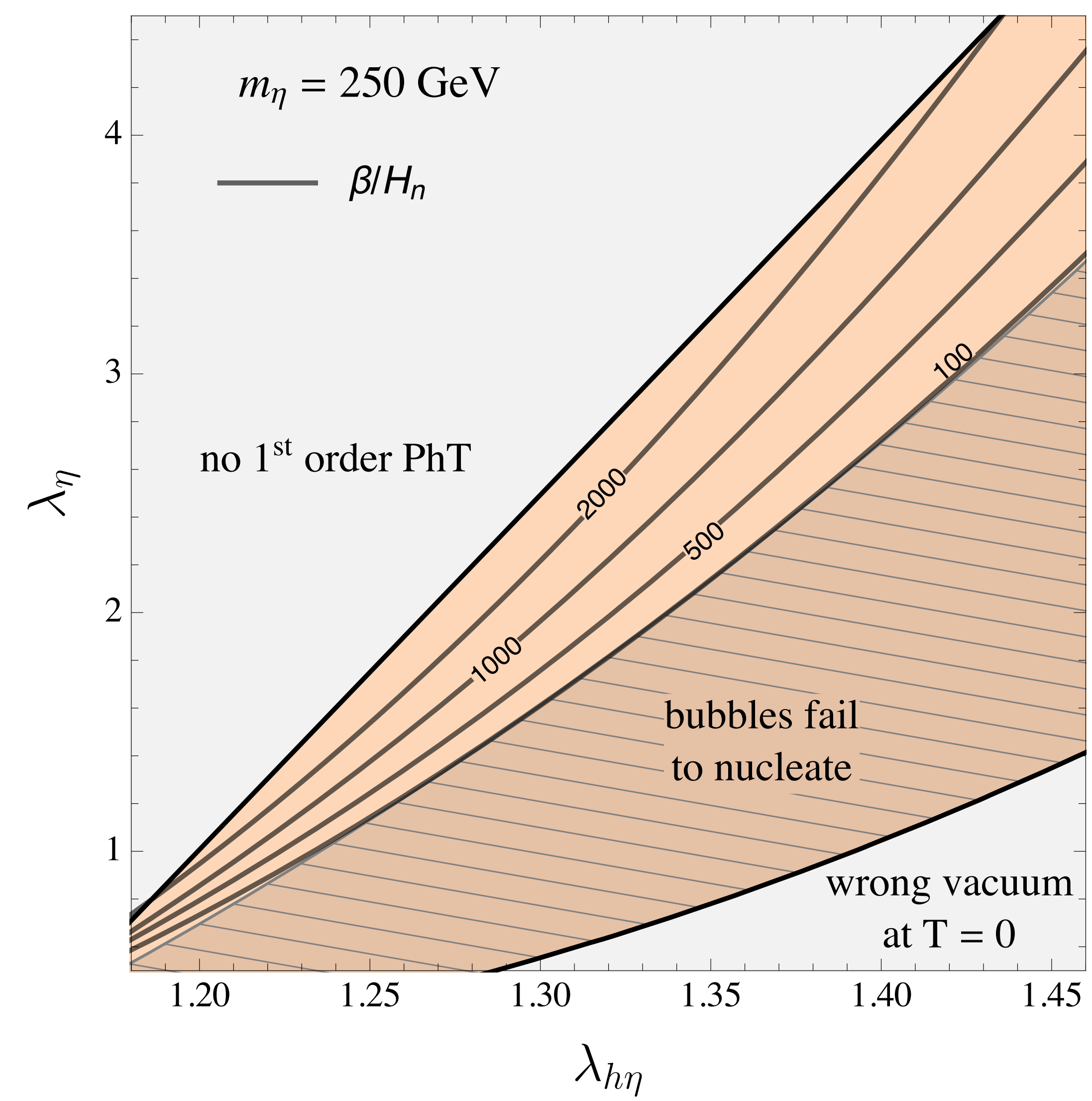
bubbles fail to nucleate:
the system is trapped in the false metastable vacuum
(it may decay to the true EW vacuum at zero temperature)

the bounce action is bounded from below



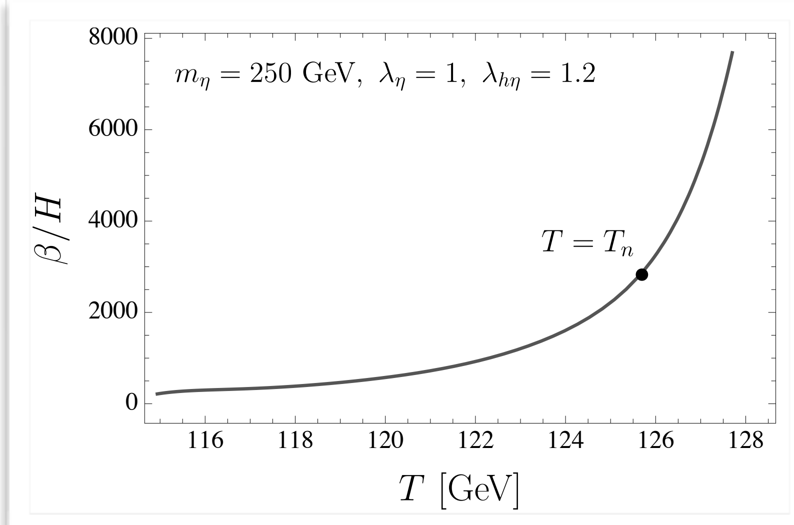
Properties of the EWPhT





Nucleation and critical temperatures

Inverse time duration of the phase transition



Gravitational waves

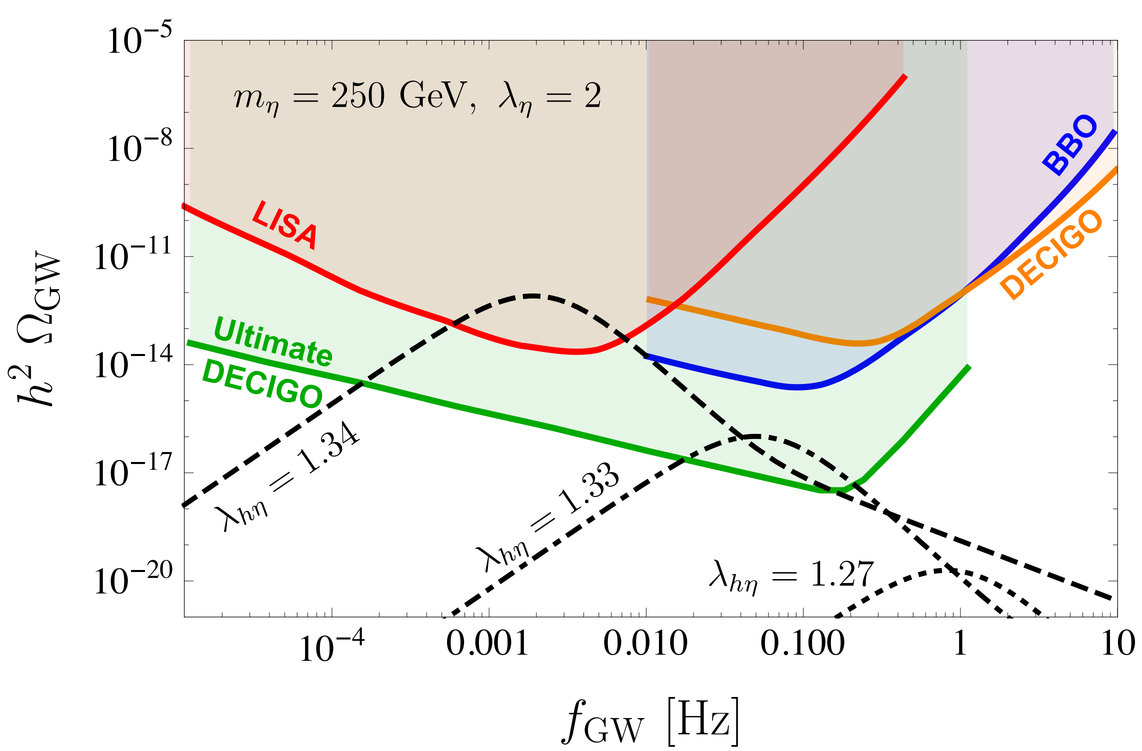
1st order phase transitions are sources of a stochastic background of GW:

- *bubble collision*
- *sound waves in the plasma*
- *turbulence in the plasma*

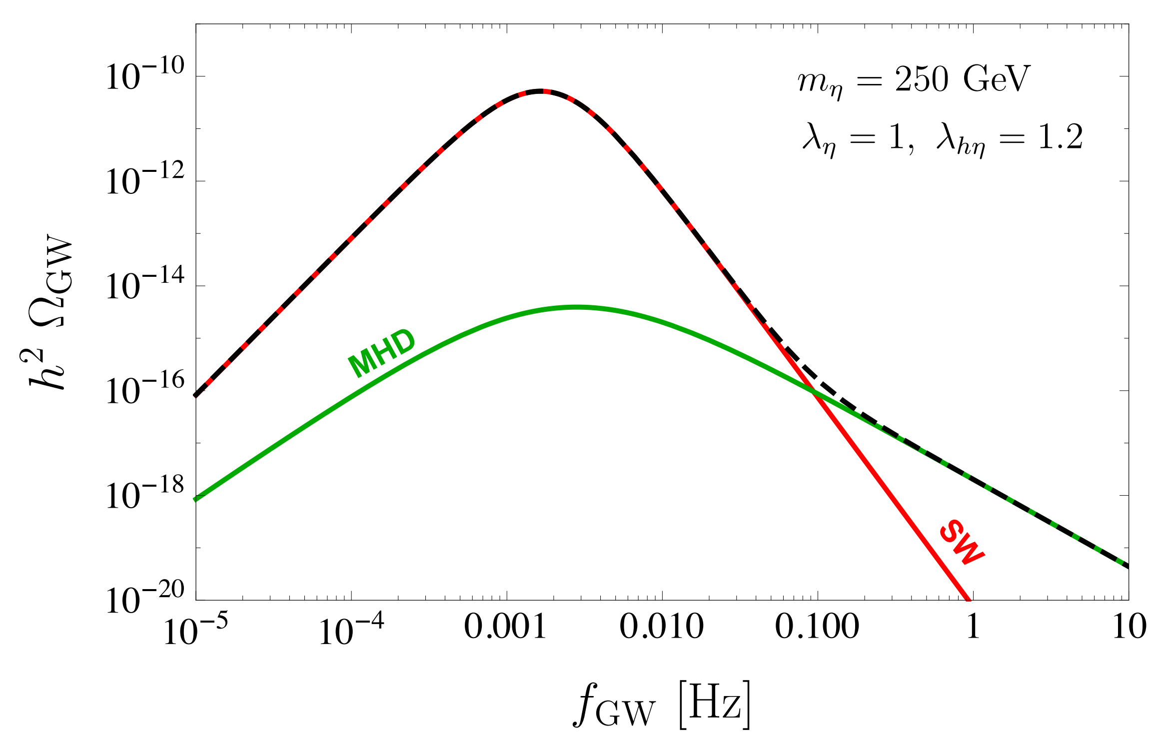
$$f_{\rm peak} = f_* \frac{a_*}{a_0} \sim 10^{-3}\,{\rm mHz} \left(\frac{f_*}{\beta}\right)\left(\frac{\beta}{H_*}\right)\left(\frac{T_*}{100\,{\rm GeV}}\right)\left(\frac{g_*}{100}\right)^{1/6}$$

$$f_*/\beta \equiv (f_*/\beta)(v_w)$$

$$\beta/H_* \simeq \mathcal{O}(10^2) - \mathcal{O}(10^3)$$



peak frequencies within the sensitivity reach of future experiments for a significant part of the parameter space



GW spectra with non trivial structure

bubble velocity v_w taken from
Dorsch, Huber, Konstandin, No, 2017

EW Baryogenesis

- ☑ explain matter - antimatter asymmetry $\eta = \frac{n_B - n_{\bar{B}}}{n_\gamma} \simeq 6 \times 10^{-10}$
- ☑ baryogenesis at the EW scale is testable (by definition)

Sakharov's conditions

	SM		SO(6)/SO(5)	
* **B violation**	✓	*EW sphaleron processes violate B+L*	✓	*as in the SM, η is a gauge singlet*
* **Out of equilibrium dynamics**	✗	*EWPhT not first order*	✓	*EWPhT can be 1st order and sufficiently strong*
* **C and CP violation**	✗	δ_{CKM} *not enough*	✓	*CP violation in the* $\eta \bar{t} t$ *coupling*

CP violation from the scalar singlet

an additional source of CPV is present in CHMs due to the non-linear dynamics of the GBs: dim-5 operator can have a complex coefficient

$$\mathcal{O}_t = y_t \left(1 + i\frac{b}{f}\eta\right) \frac{h}{\sqrt{2}}\, \bar{t}_L t_R + \text{h.c.}$$

A phase in the quark mass is generated. The phase becomes physical during the EW phase transition at T ≠ 0, when η changes its vev

this is realised in the two-step phase transition

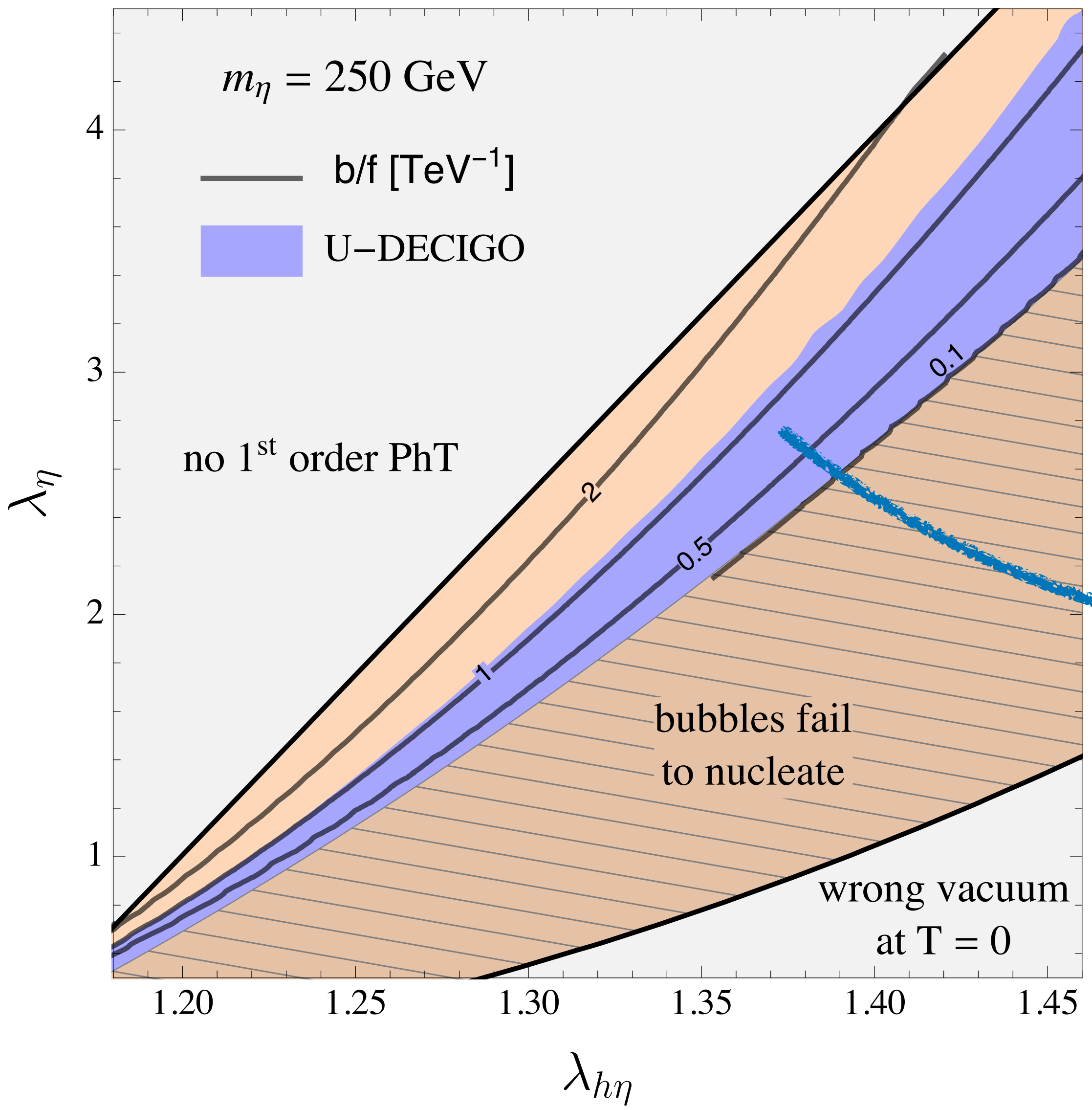
(0,0) -> (0,w) -> (v, 0)

details depend on the fermion embeddings, for instance in the (q_L, t_R) ~ (**6**, **6**) case

$$\frac{y_t}{\sqrt{2}} h\, \bar{t} \left(\cos\theta \sqrt{1 - \frac{h^2}{f^2} - \frac{\eta^2}{f^2}} + i \sin\theta \frac{\eta}{f} \gamma^5 \right) t$$

a phase in the top mass is generated only when η gets a vev

EW Baryogenesis



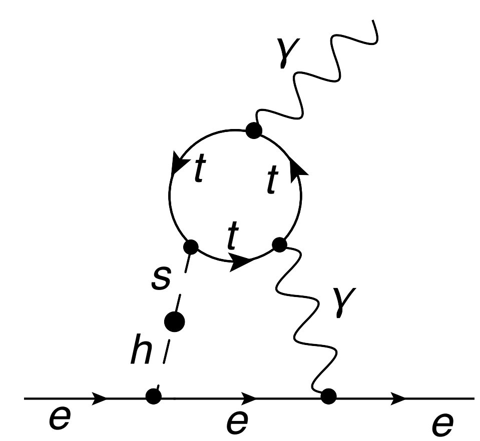
b/f ~ phase in the top mass needed to guarantee the amount of CPV for EWBG

b/f ≲ TeV^{-1} is enough to reproduce the observed baryon asymmetry

there is a region where EWBG and an observable GW spectrum can be achieved simultaneously

this crucially depends on the bubble wall velocity

caution: if Z_2 is broken ($w \neq 0$) at T = 0 constrains on the EDM can challenge EWBG



Some future developments

Next to minimal scenario: SO(6)/SO(4)xSO(2) *2 Higgs doublets*

G	H	N_G	NGBs rep.$[H]$ = rep.$[\mathrm{SU}(2)\times\mathrm{SU}(2)]$
SO(5)	SO(4)	4	$\mathbf{4} = (\mathbf{2},\mathbf{2})$
SO(6)	SO(5)	5	$\mathbf{5} = (\mathbf{1},\mathbf{1}) + (\mathbf{2},\mathbf{2})$
SO(6)	SO(4) × SO(2)	8	$\mathbf{4_{+2}} + \mathbf{\bar{4}_{-2}} = 2\times(\mathbf{2},\mathbf{2})$
SO(7)	SO(6)	6	$\mathbf{6} = 2\times(\mathbf{1},\mathbf{1}) + (\mathbf{2},\mathbf{2})$
SO(7)	G_2	7	$\mathbf{7} = (\mathbf{1},\mathbf{3}) + (\mathbf{2},\mathbf{2})$
SO(7)	SO(5) × SO(2)	10	$\mathbf{10_0} = (\mathbf{3},\mathbf{1}) + (\mathbf{1},\mathbf{3}) + (\mathbf{2},\mathbf{2})$
SO(7)	$[\mathrm{SO}(3)]^3$	12	$(\mathbf{2},\mathbf{2},\mathbf{3}) = 3\times(\mathbf{2},\mathbf{2})$
Sp(6)	Sp(4) × SU(2)	8	$(\mathbf{4},\mathbf{2}) = 2\times(\mathbf{2},\mathbf{2}), (\mathbf{2},\mathbf{2}) + 2\times(\mathbf{2},\mathbf{1})$
SU(5)	SU(4) × U(1)	8	$\mathbf{4}_{-5} + \mathbf{\bar{4}_{+5}} = 2\times(\mathbf{2},\mathbf{2})$
SU(5)	SO(5)	14	$\mathbf{14} = (\mathbf{3},\mathbf{3}) + (\mathbf{2},\mathbf{2}) + (\mathbf{1},\mathbf{1})$

Composite 2HDM

Custodial symmetry

The predicted leading order correction to the T parameter arises from the non-linearity of the GB Lagrangian. In the SO(6)/SO(4)xSO(2) model is

$$\hat{T} \propto 16 \times \frac{v^2}{f^2} \times \frac{\mathrm{Im}[\langle H_1 \rangle^\dagger \langle H_2 \rangle]^2}{(|\langle H_1 \rangle|^2 + |\langle H_2 \rangle|^2)^2}$$

no freedom in the coefficient, fixed by the coset

possible solutions:

- CP (*assumed here*)
- C_2: ($H_1 \to H_1$, $H_2 \to -H_2$) which forbids H_2 to acquire a vev

need to be relaxed for EWBG

Higgs-mediated FCNCs

FCNCs can be removed by

1. assuming C_2 in the strong sector and in the mixings

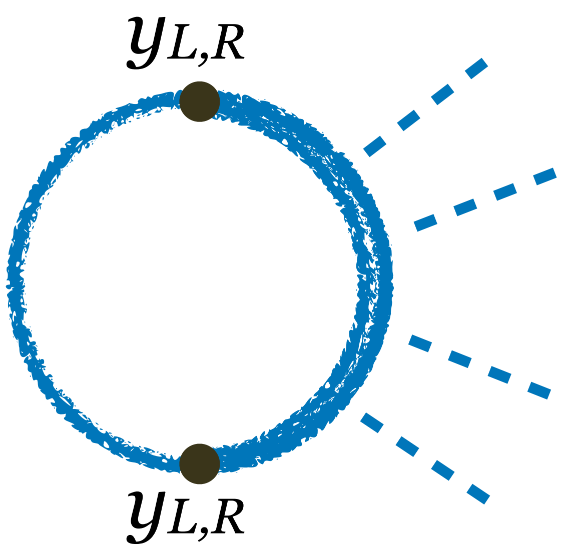
   inert C2HDM *(not considered here)*

2. requiring (flavour) alignment in the Yukawa couplings $Y_1^{IJ} \propto Y_2^{IJ}$

$$Y_u^{ij} Q^i u^j (a_{1u} H_1 + a_{2u} H_2) + Y_d^{ij} Q^i d^j (a_{1d} H_1 + a_{2d} H_2) + Y_e^{ij} L^i e^j (a_{1e} H_1 + a_{2e} H_2) + h.c.$$

the ratio a_1/a_2 is predicted by the strong dynamics

C2HDM - the scalar potential



the potential up to the fourth order in the Higgs fields:

$$V = m_1^2 H_1^\dagger H_1 + m_2^2 H_2^\dagger H_2 - \left[m_3^2 H_1^\dagger H_2 + \text{h.c.} \right]$$
$$+ \frac{\lambda_1}{2}(H_1^\dagger H_1)^2 + \frac{\lambda_2}{2}(H_2^\dagger H_2)^2 + \lambda_3 (H_1^\dagger H_1)(H_2^\dagger H_2) + \lambda_4 (H_1^\dagger H_2)(H_2^\dagger H_1)$$
$$+ \frac{\lambda_5}{2}(H_1^\dagger H_2)^2 + \lambda_6 (H_1^\dagger H_1)(H_1^\dagger H_2) + \lambda_7 (H_2^\dagger H_2)(H_1^\dagger H_2) + \text{h.c.}$$

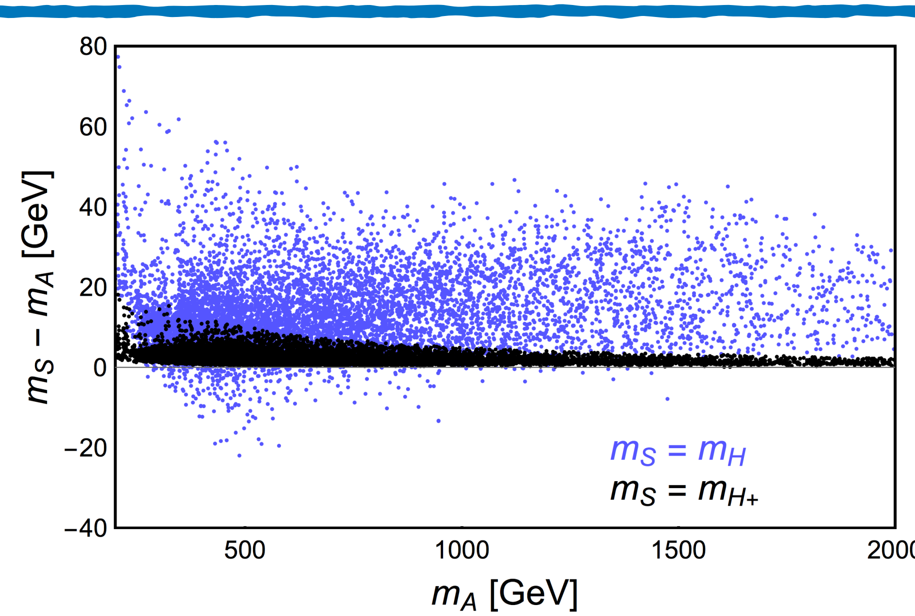
the entire effective potential is fixed by the parameters of the strong sector and the scalar spectrum is entirely predicted by the strong dynamics

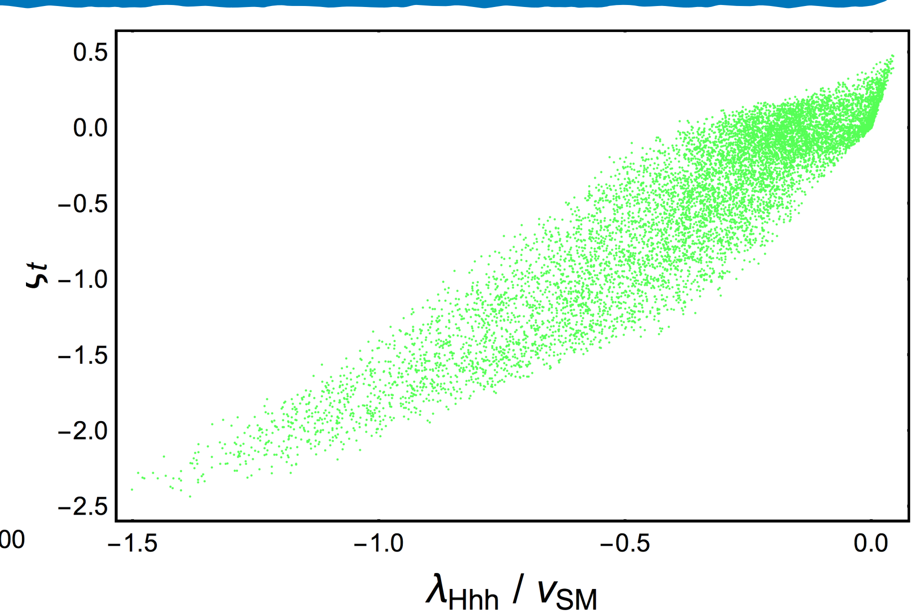
$$m_3^2 \neq 0, \lambda_6 \neq 0, \lambda_7 \neq 0$$

C_2 breaking in the strong sector induces: $\lambda_6 = \lambda_7 = \frac{5}{3}\frac{m_3^2}{f^2}$

it is not possible to realise a 2HDM-like scenario with a softly broken Z_2

very strong correlations among several parameters





Conclusions

- Higgs as a pseudo Nambu-Goldstone Boson is a compelling possibility for stabilising the EW scale

- Non-minimal CHMs can link the dynamics of a strong first order EWPhT to the structure of GW spectrum and the possibility to realise EW Baryogenesis

- Future collider and space-based gravitational interferometry experiments can provide complementary ways to test the Higgs sector