"la Caixa" Foundation

Institut de Física d'Altes Energies

Composite Dynamics in the Early Universe

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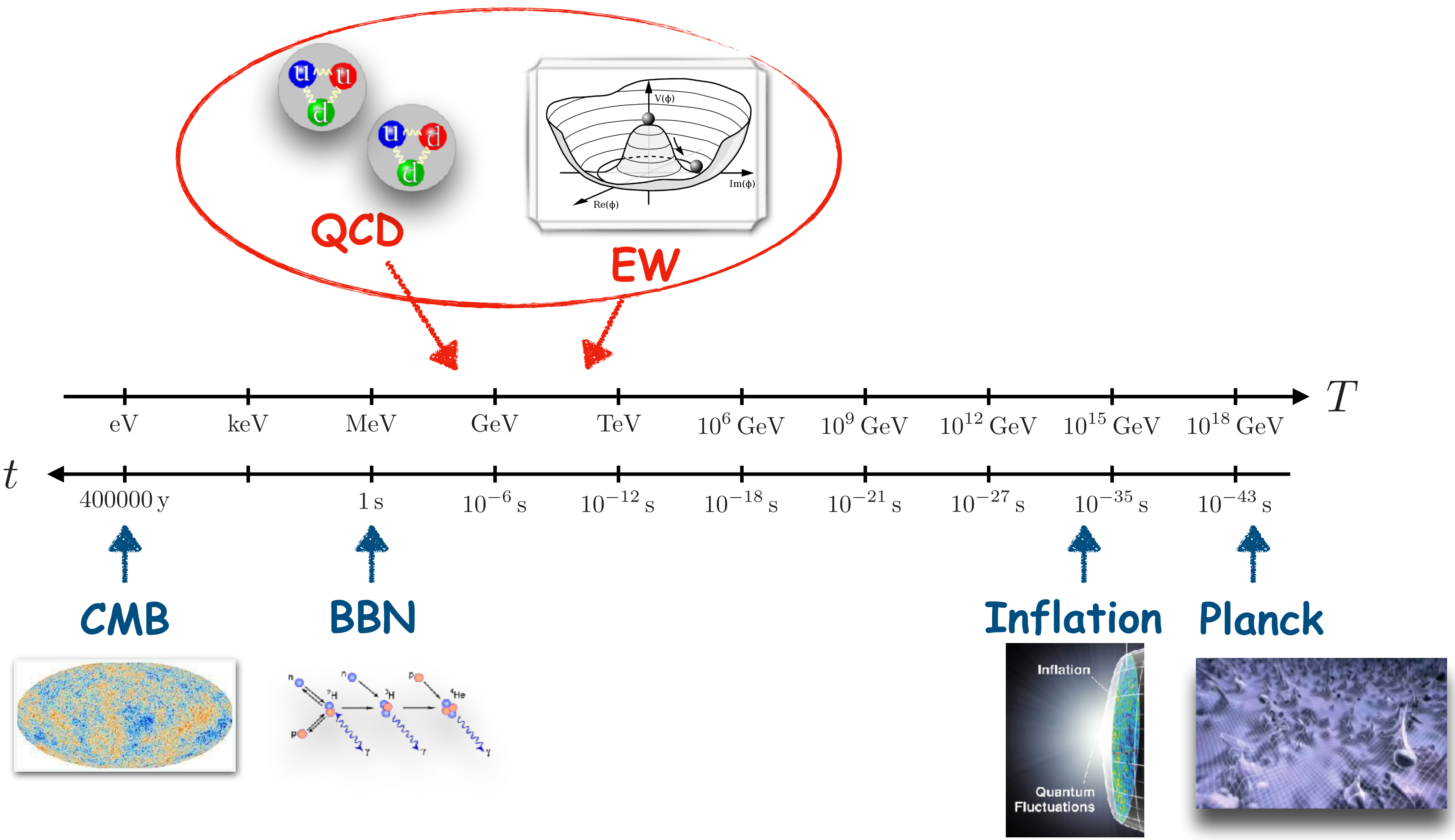
based on JHEP 12 (2019) 149 *arXiv:1909.07894*

Thermal History of the Universe

Phase transitions are important events in the evolution of the Universe

- the SM predicts two of them (QCD confinement and EW symmetry breaking)

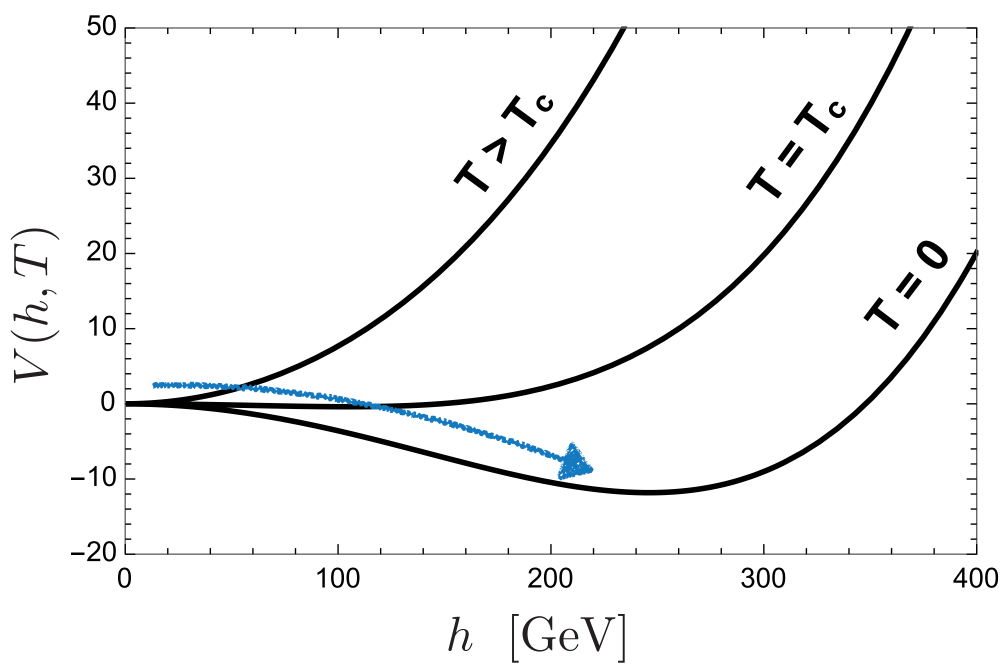


Phase transitions in the SM

In the SM the QCD and EW PhT are extremely weak

→ the two phases are smoothly connected (cross over)

- no barrier is present in the effective potential
- the field gently "rolls down" towards the global minimum when $T < T_c$



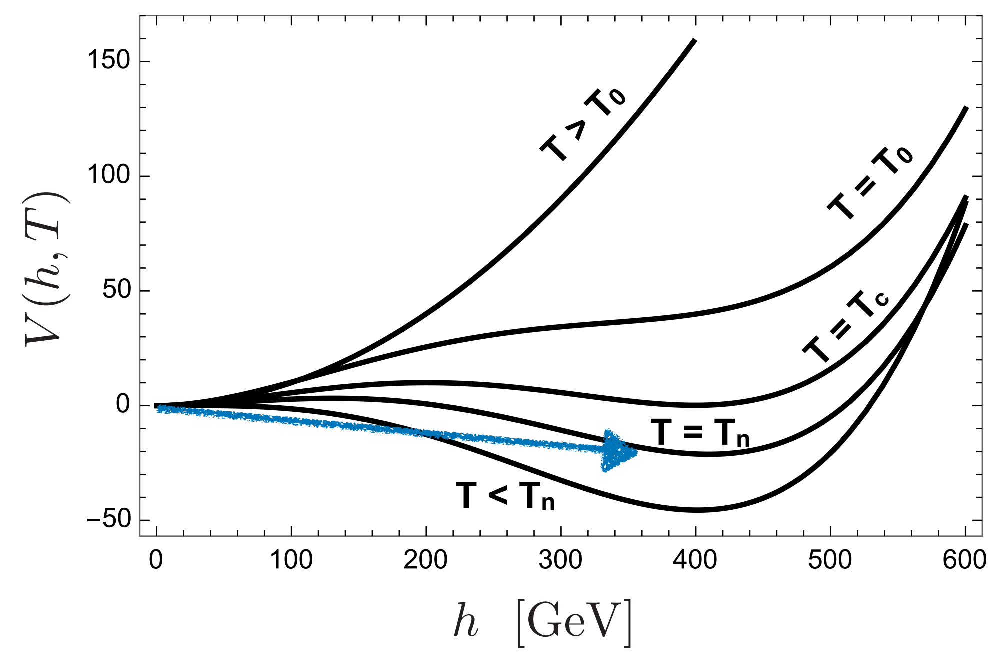
- no strong breaking of thermal equilibrium
- no distinctive experimental signatures

Phase transitions beyond the SM

New physics may provide **first order** phase transitions

- a barrier in the potential may be generated from tree-level deformations, thermal or quantum effects

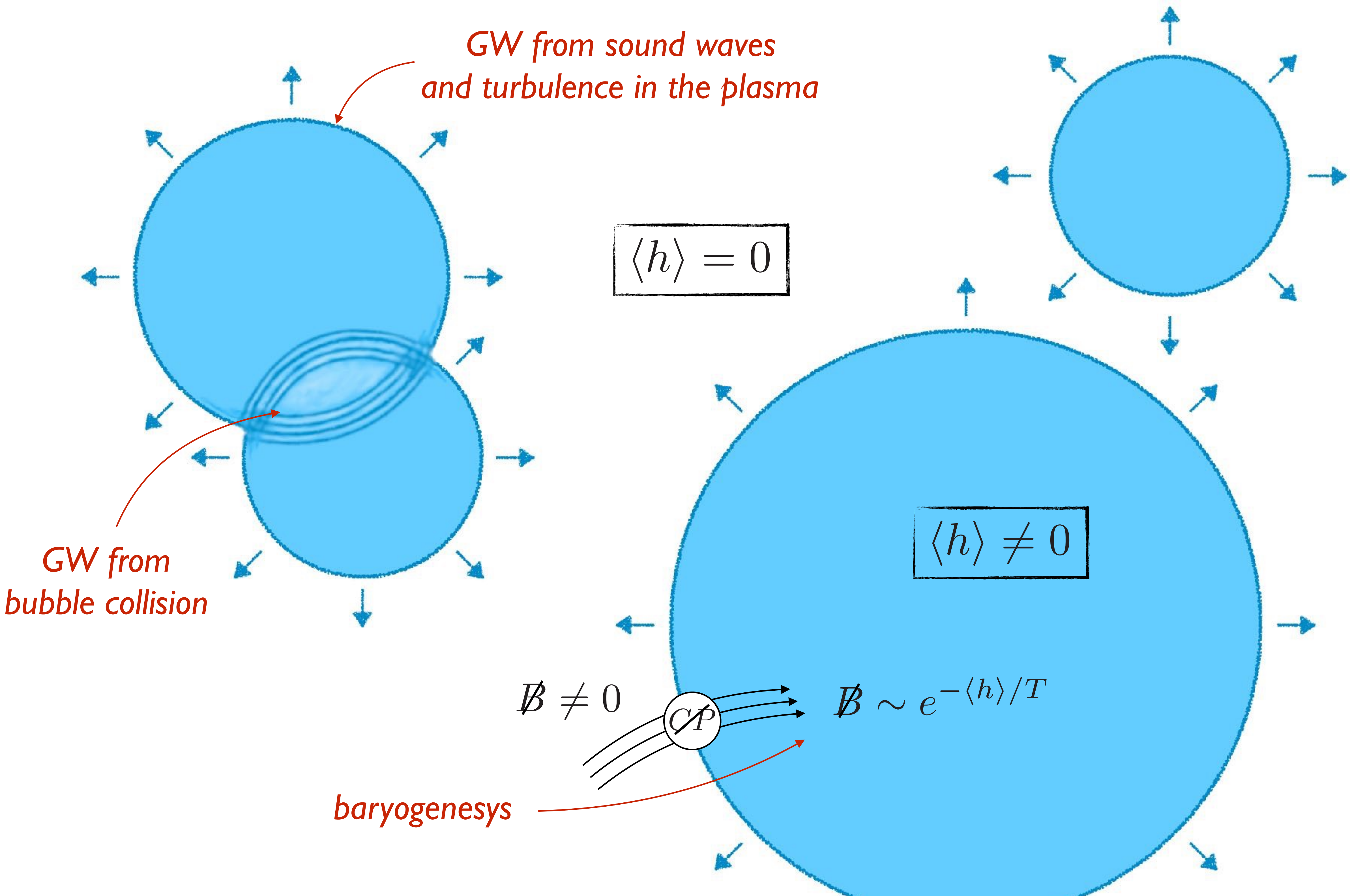
- the field tunnels from false to true minimum at $T = T_n < T_c$



- the transition proceeds through bubble nucleation
- significant breaking of thermal equilibrium
- interesting experimental signatures (eg. gravitational waves)

Bubble nucleation

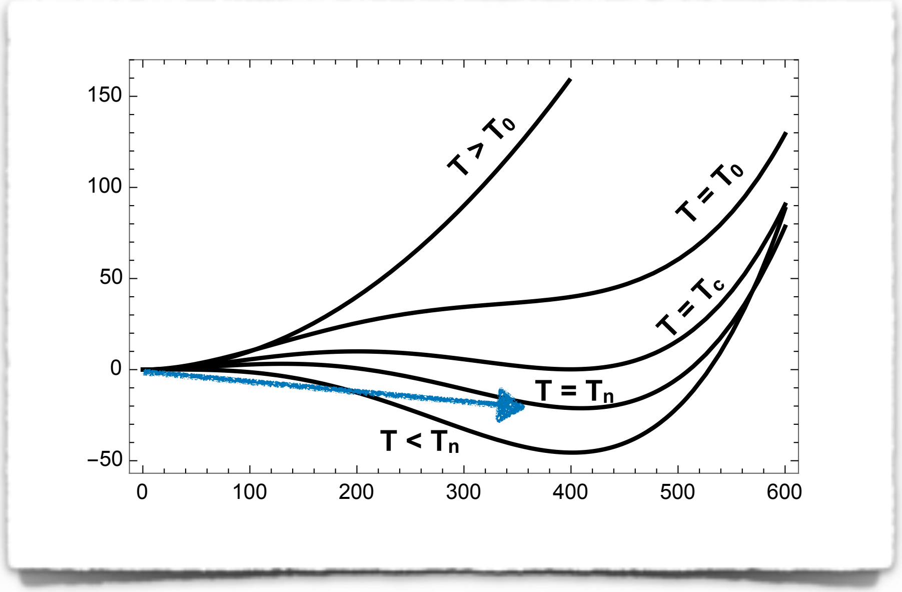
Bubble dynamics can produce **gravitational waves** and **baryogenesys**



How to get a first-order PhT

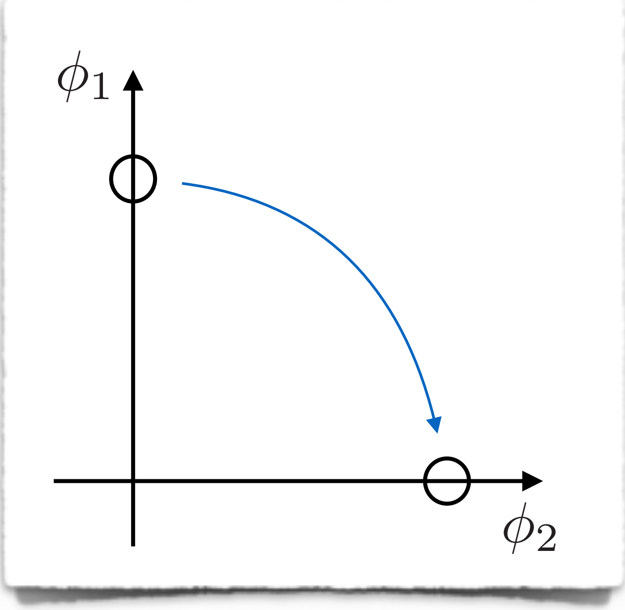
I. **“Single field”** transitions

- barrier coming from:
  - quantum corrections due to additional fields
  - thermal effects



II. **“Multiple field”** transitions

- barrier can be present already at tree-level and T=0
- minima in different directions in field space



Extended Higgs sectors

SM + singlet scalar

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

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

with thermal masses

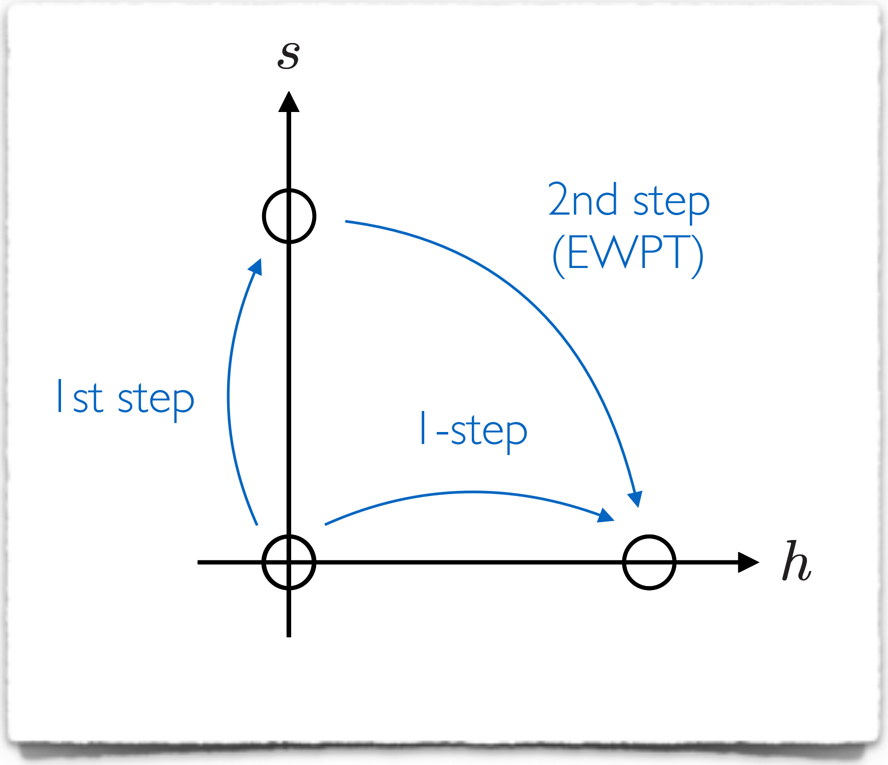
important to create
a barrier in the potential

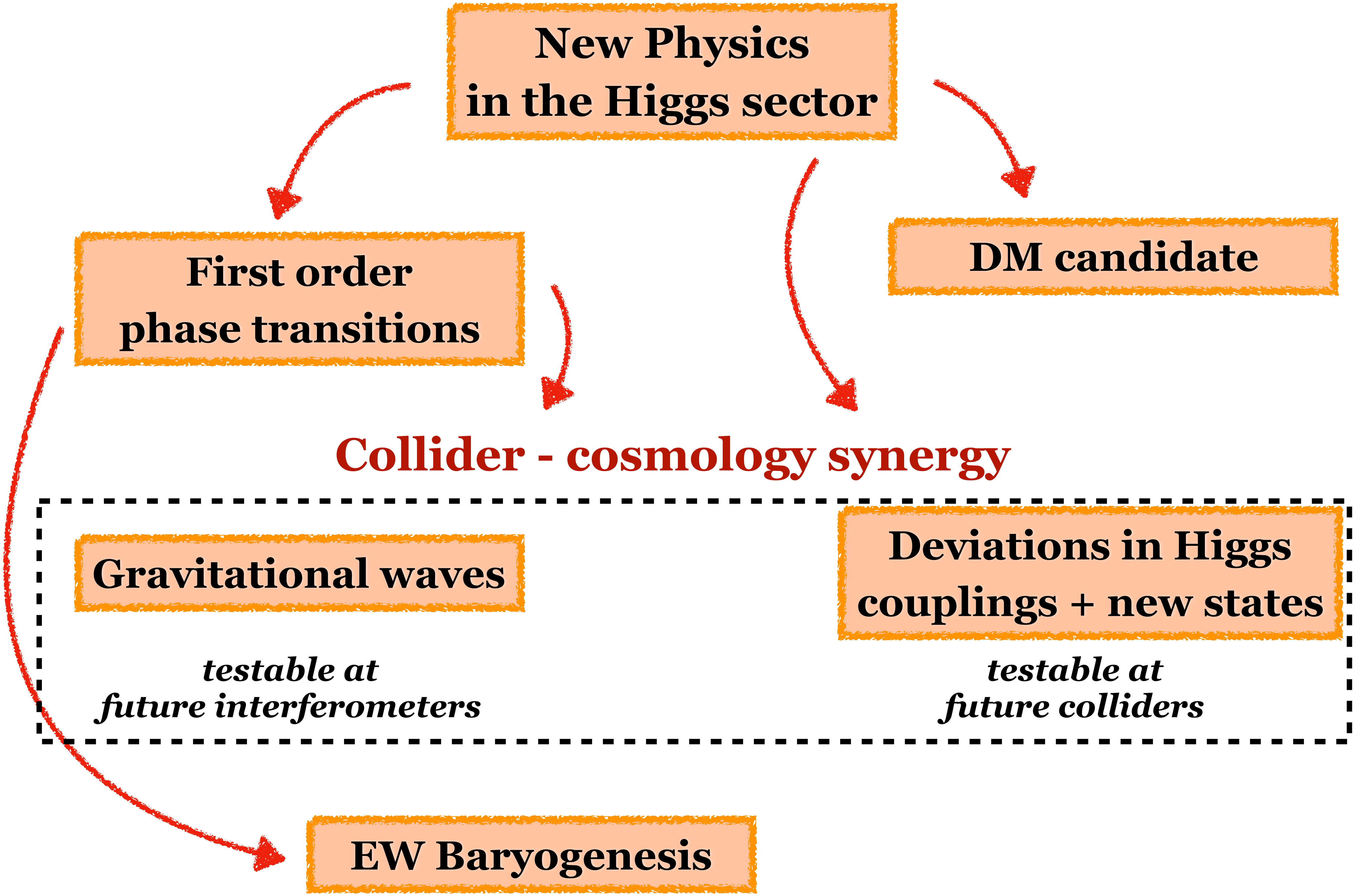
$$c_h = \frac{1}{48}\left(9g^2 + 3g'^2 + 12y_t^2 + 24\lambda_h + 2\lambda_{h\eta}\right) \qquad c_\eta = \frac{1}{12}\left(4\lambda_{h\eta} + \lambda_\eta\right)$$

- ✦ EW symmetry is restored at very high T

$$\langle h,\eta\rangle = (0,0)$$

- ✦ Two interesting patterns of symmetry breaking (as the Universe cools down)
  - i. 1-step PhT $(0,0)\to(v,0)$
  - ii. 2-step PhT $(0,0)\to(0,w)\to(v,0)$
    - ‣ 2-step naturally realized since singlet is destabilized before the Higgs ($c_\eta < c_h$)




New Physics
in the Higgs sector
First order
phase transitions
DM candidate
Collider - cosmology synergy
Gravitational waves
Deviations in Higgs
couplings + new states
testable at
future interferometers
testable at
future colliders
EW Baryogenesis

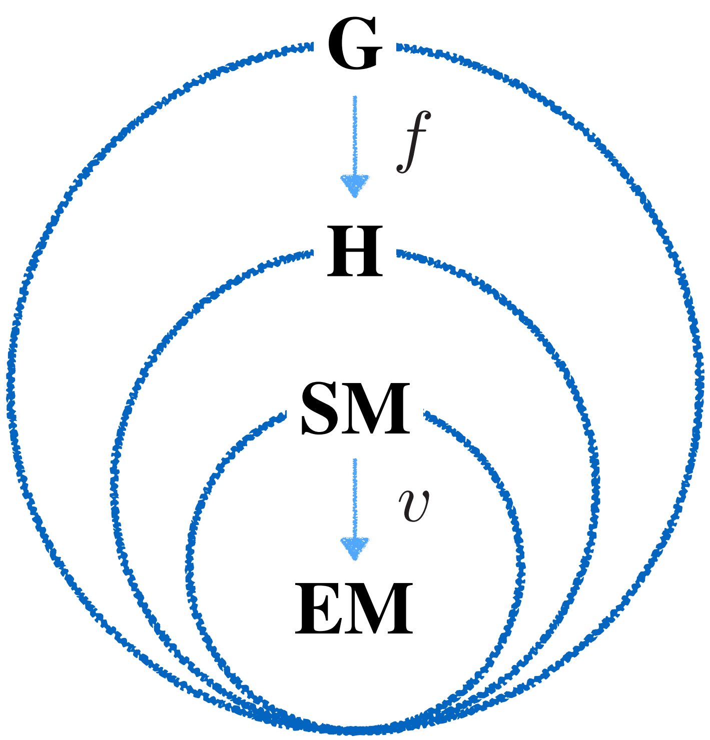
A strongly coupled realisation

with S. De Curtis and G. Panico
JHEP 12 (2019) 149, *arXiv:1909.07894*

Phase transitions in Composite Higgs

Higgs as a **Goldstone** from spontaneously broken global symmetry in a strongly-coupled sector

Multiple phase transitions expected:



- breaking of the global symmetry in the strong sector

$$G \to H \quad \text{at} \quad T \sim \mathrm{TeV}$$

- EW symmetry breaking

$$\mathrm{SU}(2)_L \times \mathrm{U}(1)_Y \to \mathrm{U}(1)_{\mathrm{EM}} \quad \text{at} \quad T \sim 100\,\mathrm{GeV}$$

EWPhT in Composite Higgs

Minimal models have only one Higgs doublet

$\mathrm{SO}(5) \rightarrow \mathrm{SO}(4)$ ➔ 4 Goldstone bosons

Experimental data strongly constrain this scenario

$$\xi \equiv v^2/f^2 \lesssim 0.1$$

- only mild deviations in Higgs couplings allowed (<10%)
- EW phase transition similar to the SM one (no first order)

Extended models

Non-minimal models feature extended Higgs sector

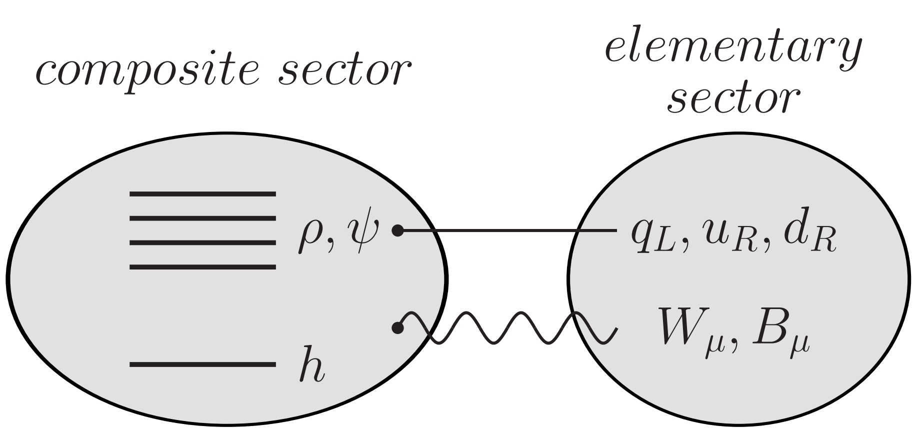
next-to-minimal construction:

$\mathrm{SO}(6) \to \mathrm{SO}(5)$ ➔ 5 Goldstone bosons: Higgs doublet + singlet

Scalar potential induced by the coupling to SM fields

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

- couplings explicitly breaks the global symmetry ➔ Higgs as a pseudo NGB
- structure of the potential fixed by quantum numbers under G/H
- main contributions from top mixing



Top partners

The quantum numbers of the fermionic top partners under SO(6) control the Higgs potential

- ☑ 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

☑ $(q_L, t_R) \sim (\mathbf{6}, \mathbf{6})$

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

it requires large tuning in bottom quark sector

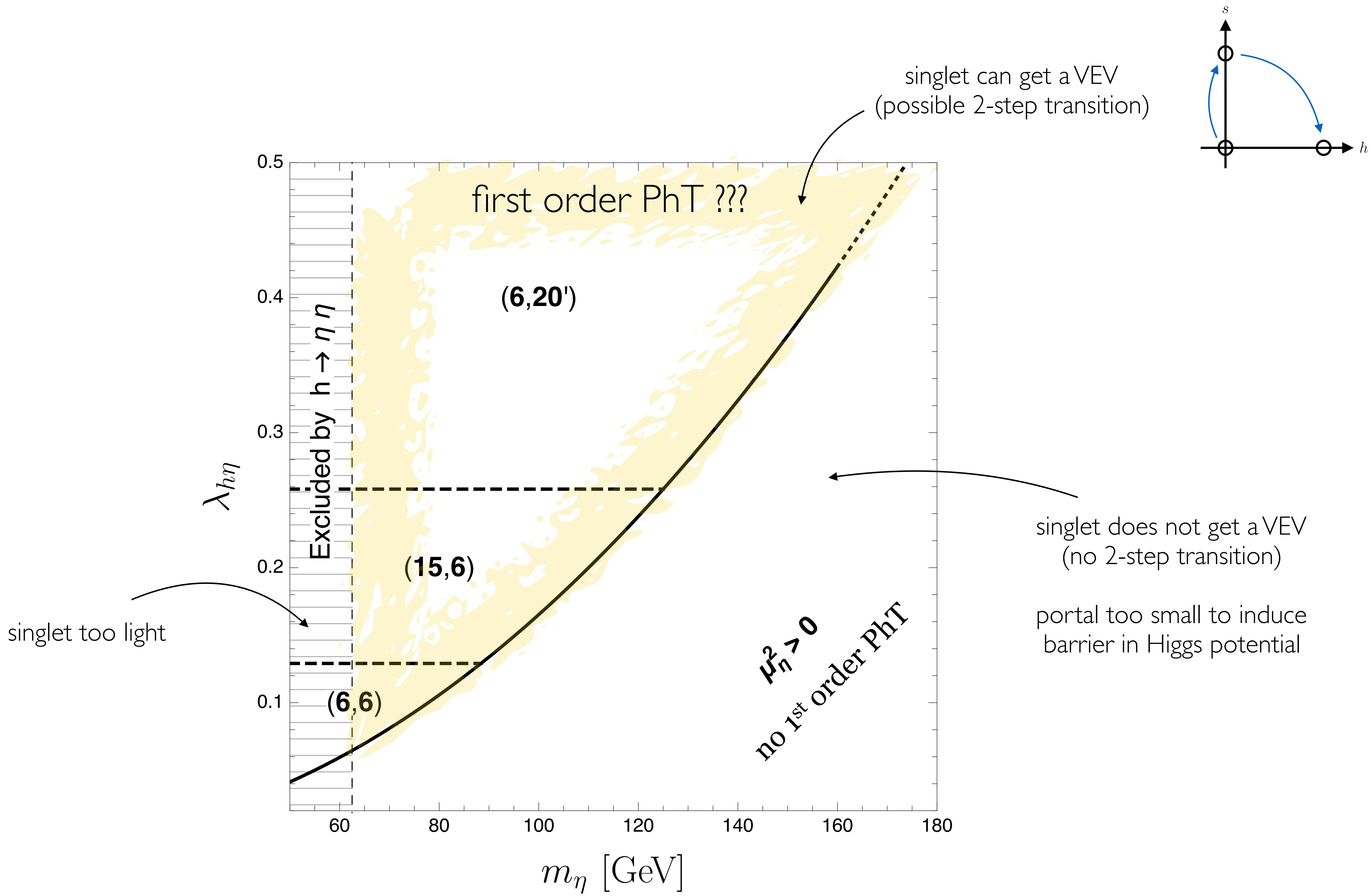
☑ $(q_L, t_R) \sim (\mathbf{15}, \mathbf{6})$

less-tuned scenario: no need to rely on bottom partners
but λ_η still small

☑ $(q_L, t_R) \sim (\mathbf{6}, \mathbf{20'})$

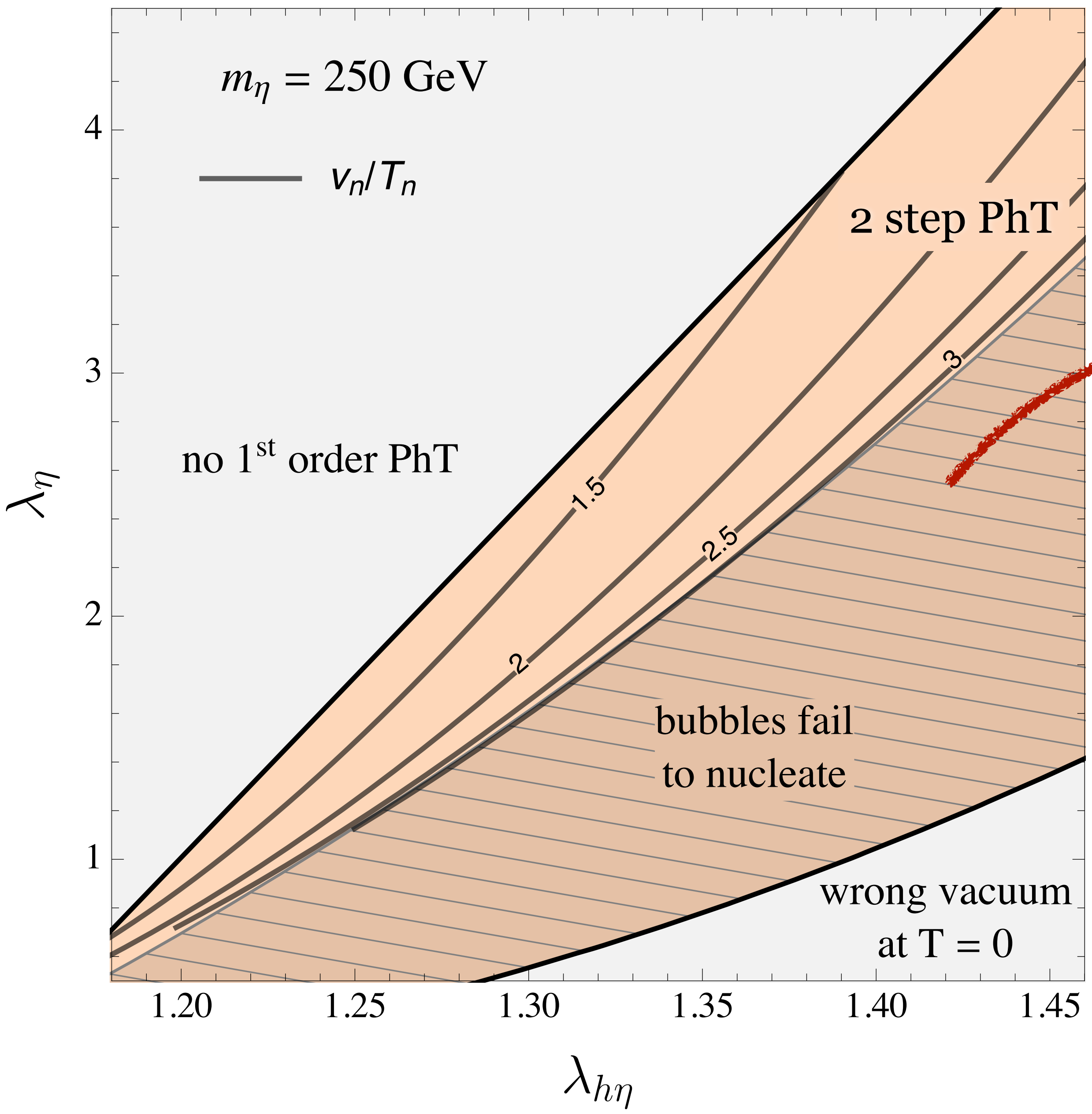
large parameter space available without large tuning

Parameter space



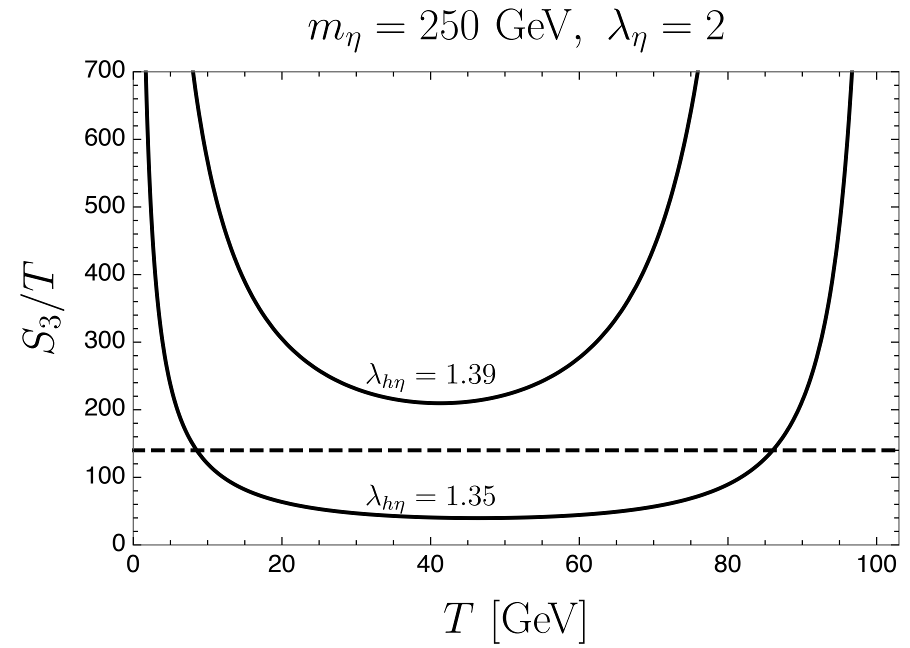
Properties of the EWPhT

(q_L, t_R) ~ (6, 20')



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



v_n/T_n: strength of the PhT

Gravitational waves

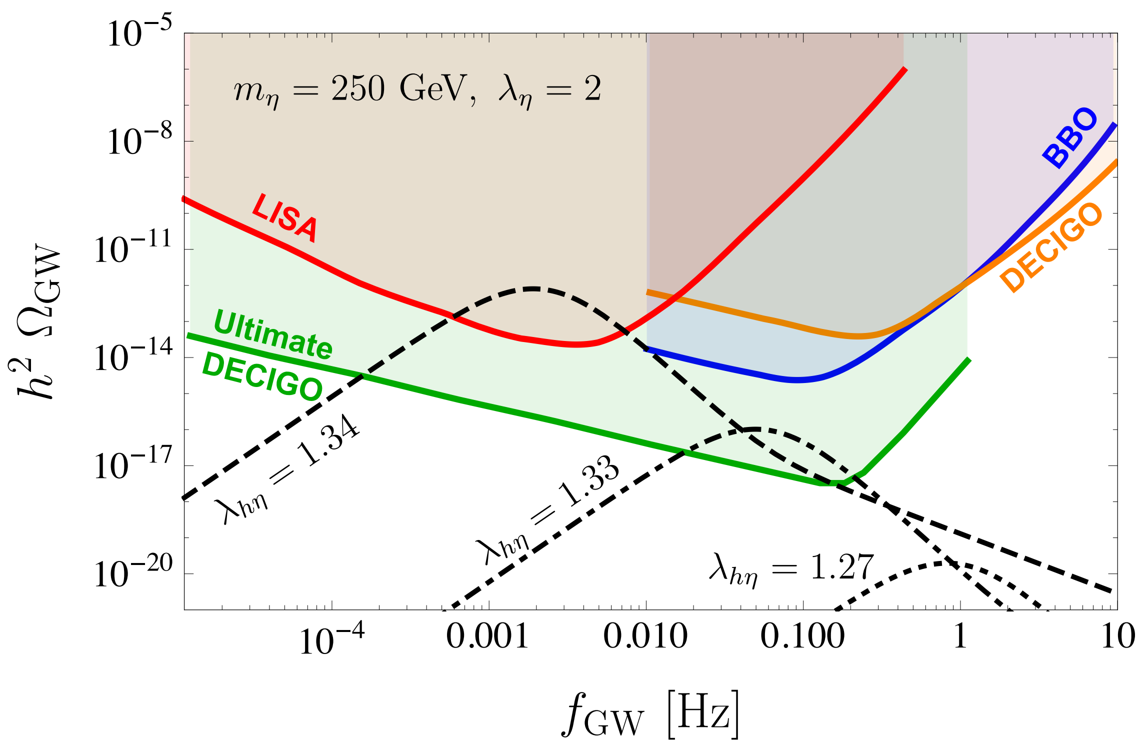
1st order phase transitions are sources of a stochastic background of GW:

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

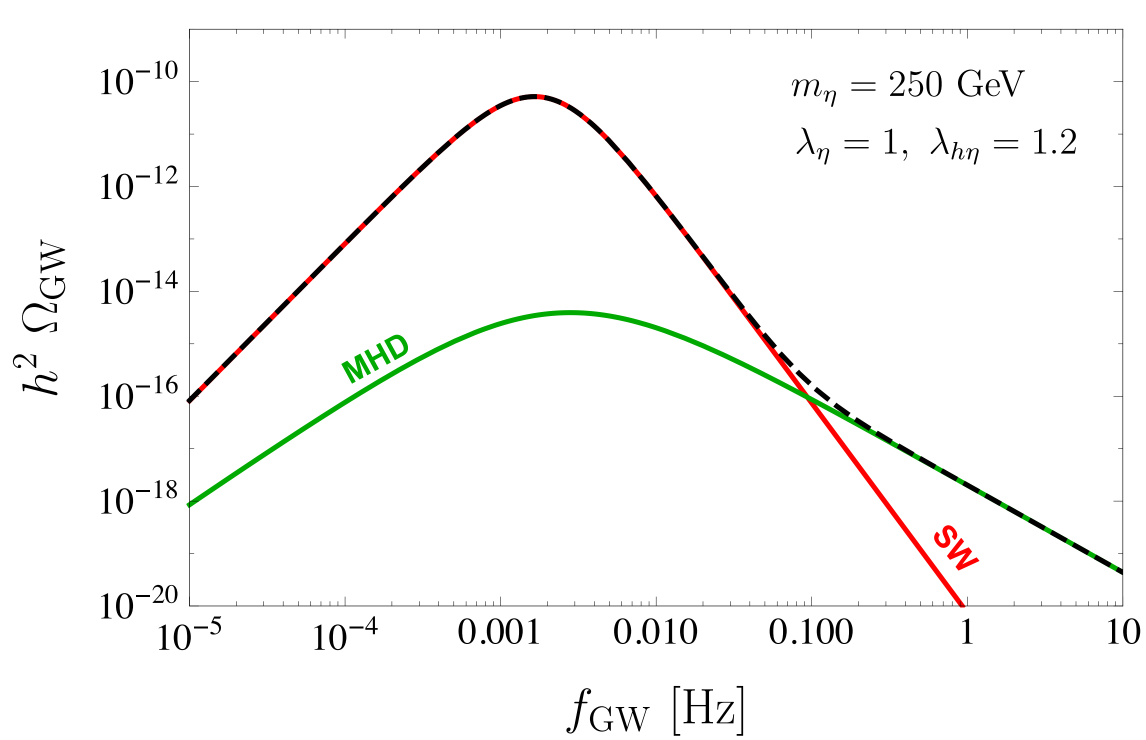
$$f_{\rm peak} = f_* \frac{a_*}{a_0} \sim 10^{-3}\,{\rm mHz} \left(\frac{f_*}{\beta}\right)\left(\frac{\beta}{H_*}\right)\left(\frac{T_*}{100\,{\rm GeV}}\right)\left(\frac{g_*}{100}\right)^{1/6}$$

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

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



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



GW spectra with non trivial structure

EW Baryogenesis

Sakharov's conditions

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

EW Baryogenesis: CP violation

an additional source of CP violation is naturally present due to the non-linear dynamics of the Goldstones

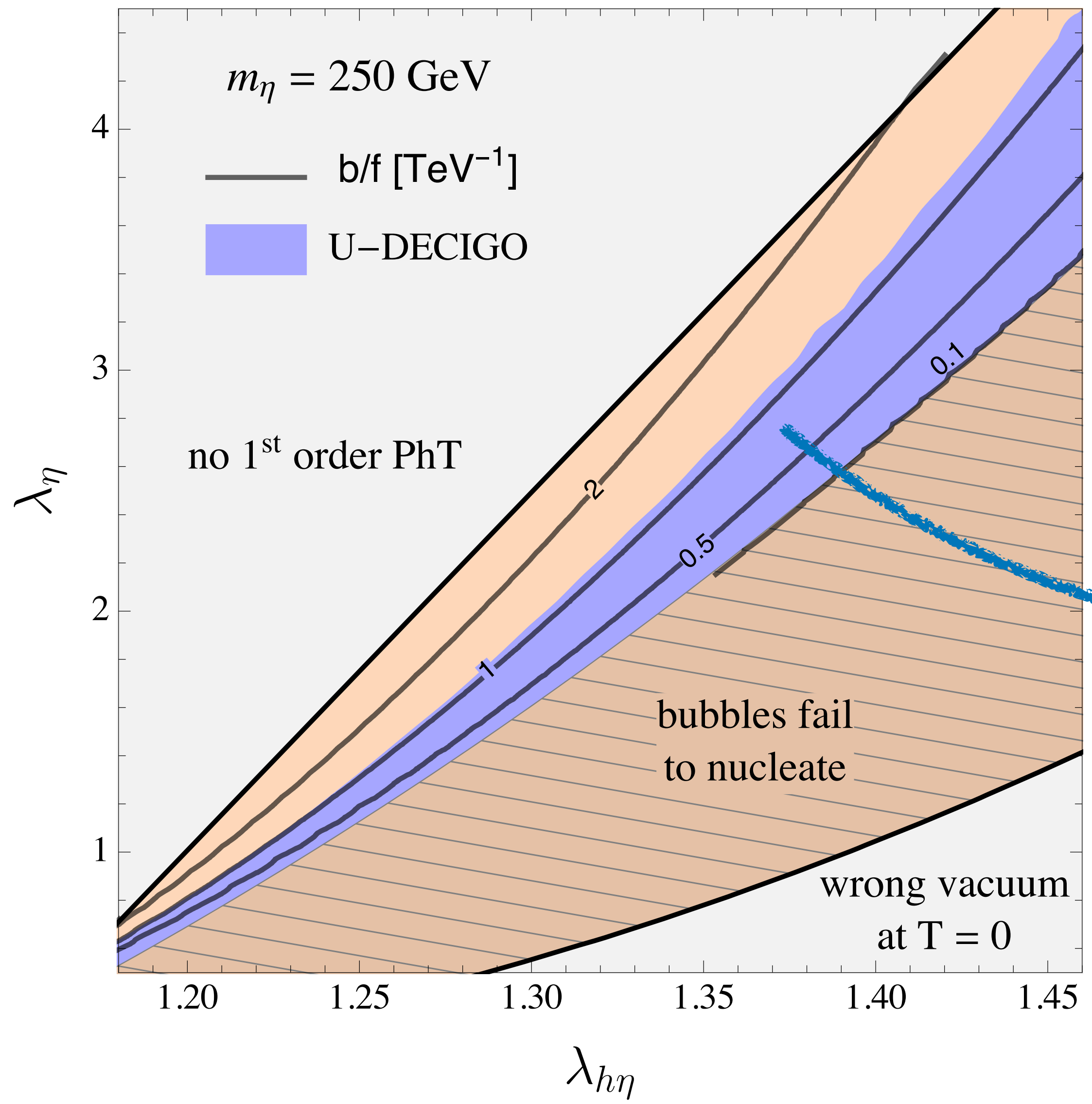
$$\mathcal{O}_t = y_t \left(1 + i\frac{b}{f}\eta\right) \frac{h}{\sqrt{2}}\, \bar{t}_L t_R + \text{h.c.}$$

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

this is realised in the two-step phase transition

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

EW Baryogenesis

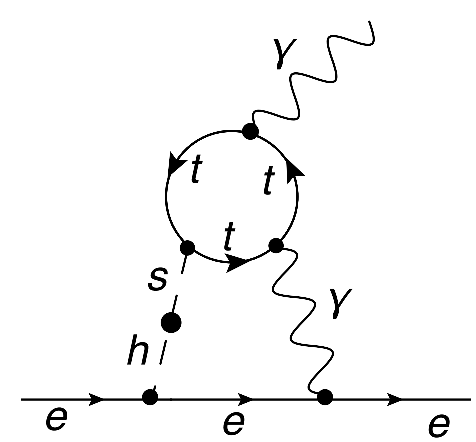


b/f ~ phase in the top mass needed to guarantee the amount of CPV for EWBG

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

note: if Z_2 is broken (w ≠ 0) at T = 0 constrains from EDM can challenge EWBG



Conclusions

Phase transitions are important events in the evolution of the Universe

New physics can significantly modify the SM predictions and open appealing scenarios:

- strong first-order **EW phase transition** from extended Higgs sector
  - possibility to achieve EW baryogenesys
  - collider signatures (at future machines)
  - detectable gravitational wave signal (at space-based interferometers)

Backup

Phenomenology

<u>Very weak constraints</u>

- $m_\eta < m_h/2$ excluded by invisible Higgs decays

- direct searches very challenging: only possible at FCC 100 TeV
  (interesting channel: $pp \to \eta\eta jj$ (VBF))

- indirect searches:
  - modification of Higgs self couplings $\left(\lambda_3 = \frac{m_h^2}{2v} + \frac{\lambda_{h\eta}^3}{24\pi^2}\frac{v^3}{m_\eta^2} + \cdots \right)$
  - corrections to Zh cross section at lepton colliders

- dark matter direct detection
  - the singlet can contribute to DM abundance (but can not provide all DM)
  - constraints are very model dependent
    (cosmological history depends on hidden sector details)