Strong Phase Transitions in the Early Universe

Giuliano Panico

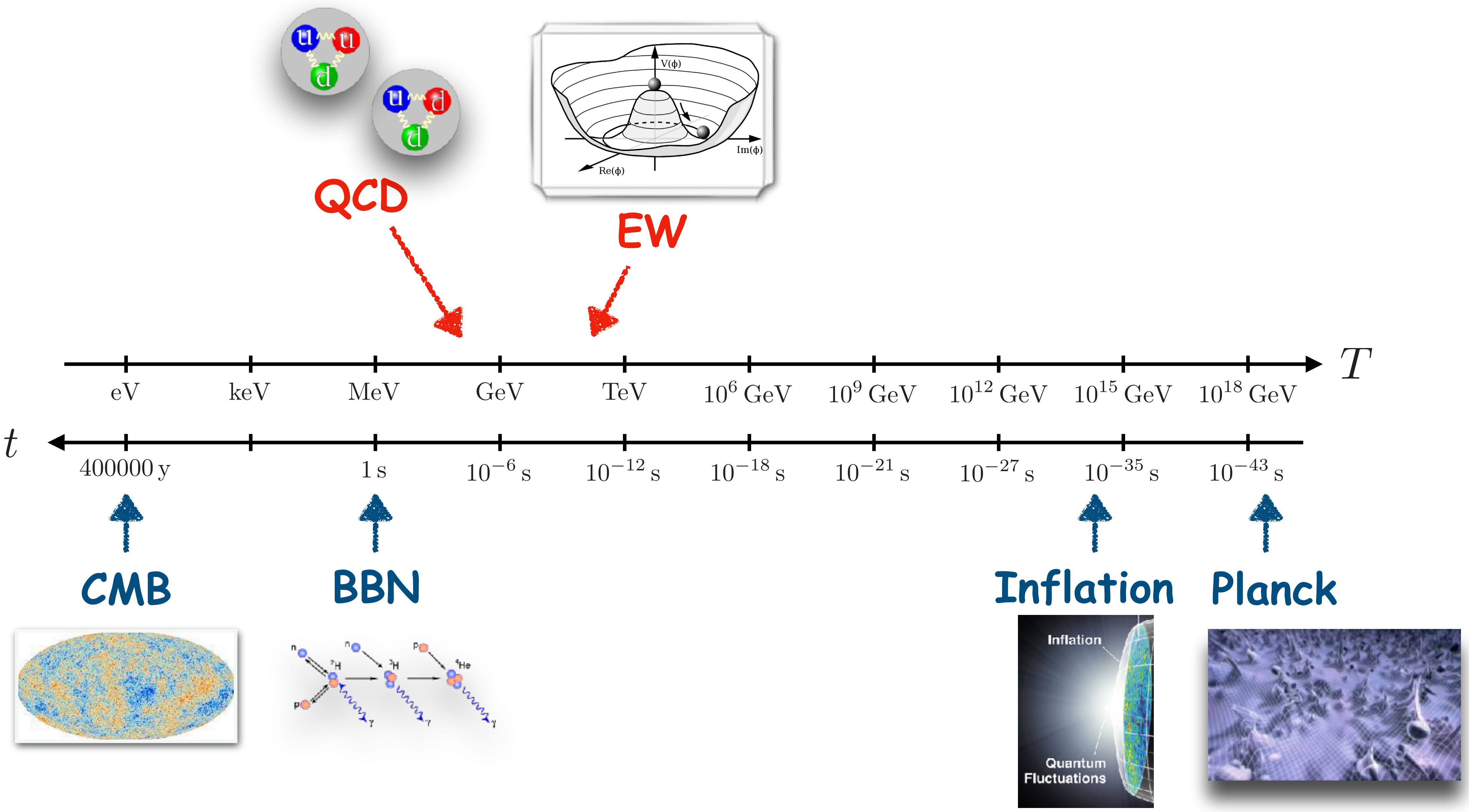
Università di Firenze and INFN Firenze

IFAE Barcelona — 3/12/2019

based on De Curtis, Delle Rose, GP '19,
Delle Rose, GP, Redi, Tesi in preparation

Thermal History of the Universe

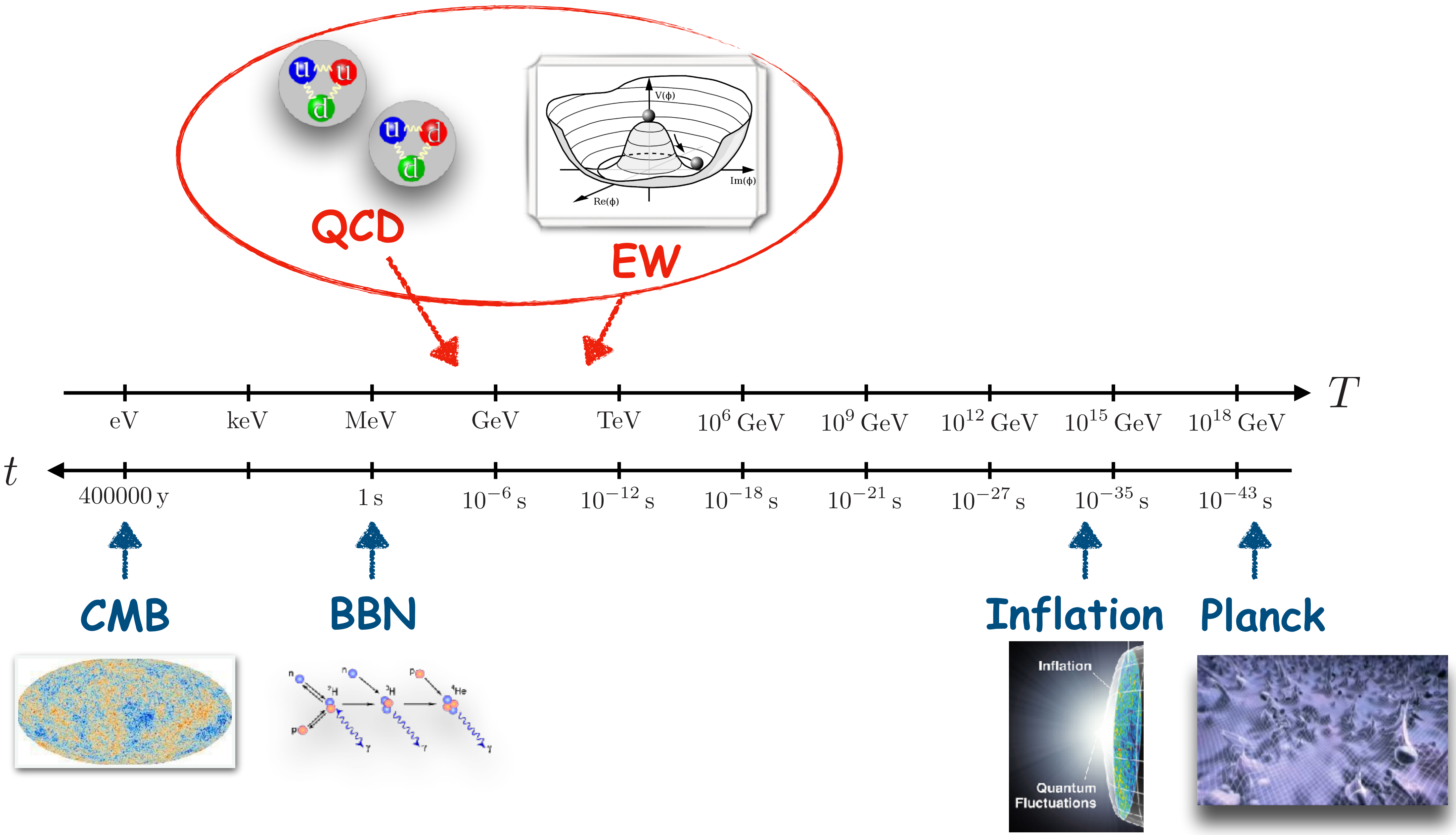
Phase transitions are important events in the evolution of the Universe



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

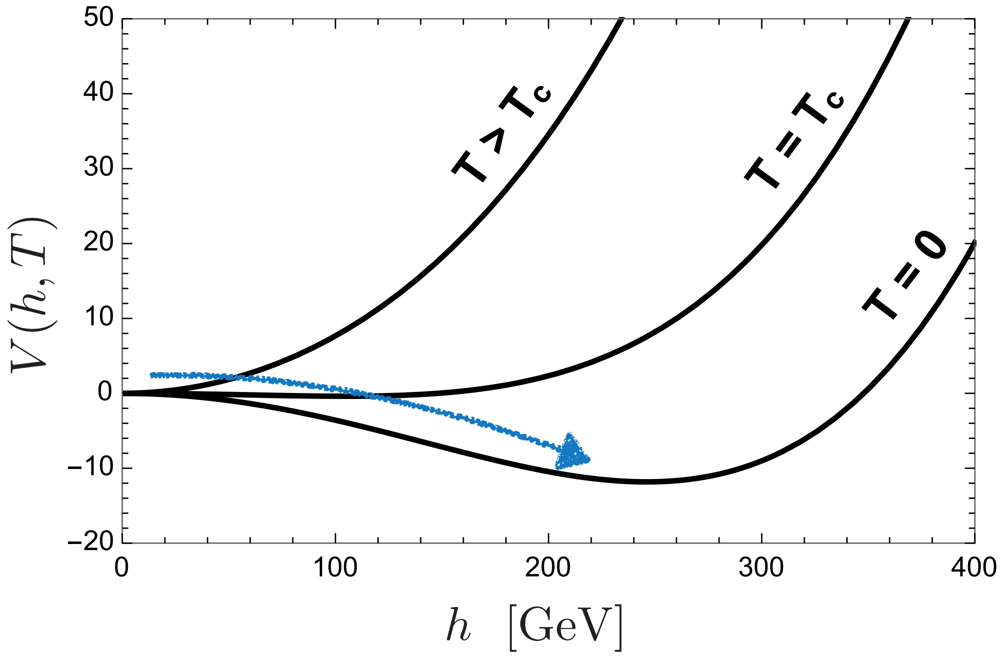
➔ the two phases are smoothly connected (cross over)

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 $T < T_c$



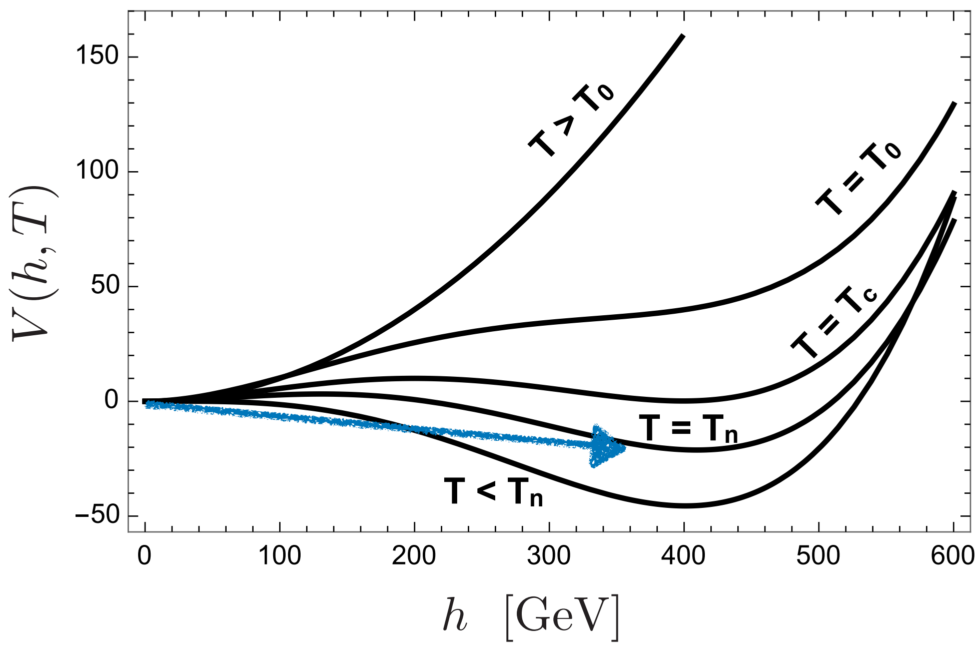
- no strong breaking of thermal equilibrium
- no distinctive experimental signatures

Weak EW PhT is an "accident"

The SM EW PhT is first-order for $m_h \lesssim 70\,\mathrm{GeV}$

- thermal corrections due to gauge bosons provide a barrier in the potential

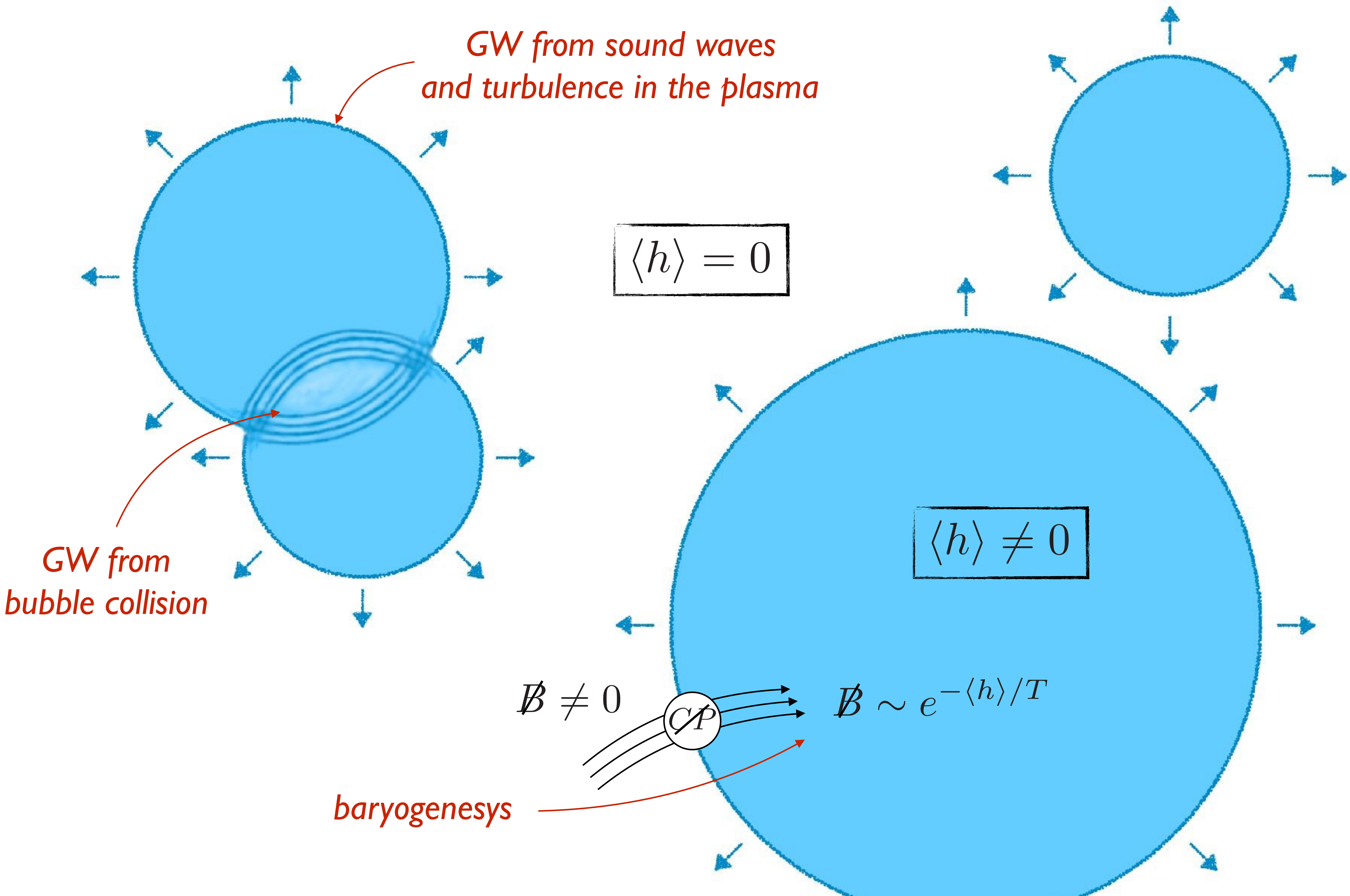
- the field tunnels from false to true minimum at $T = T_n < T_c$



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

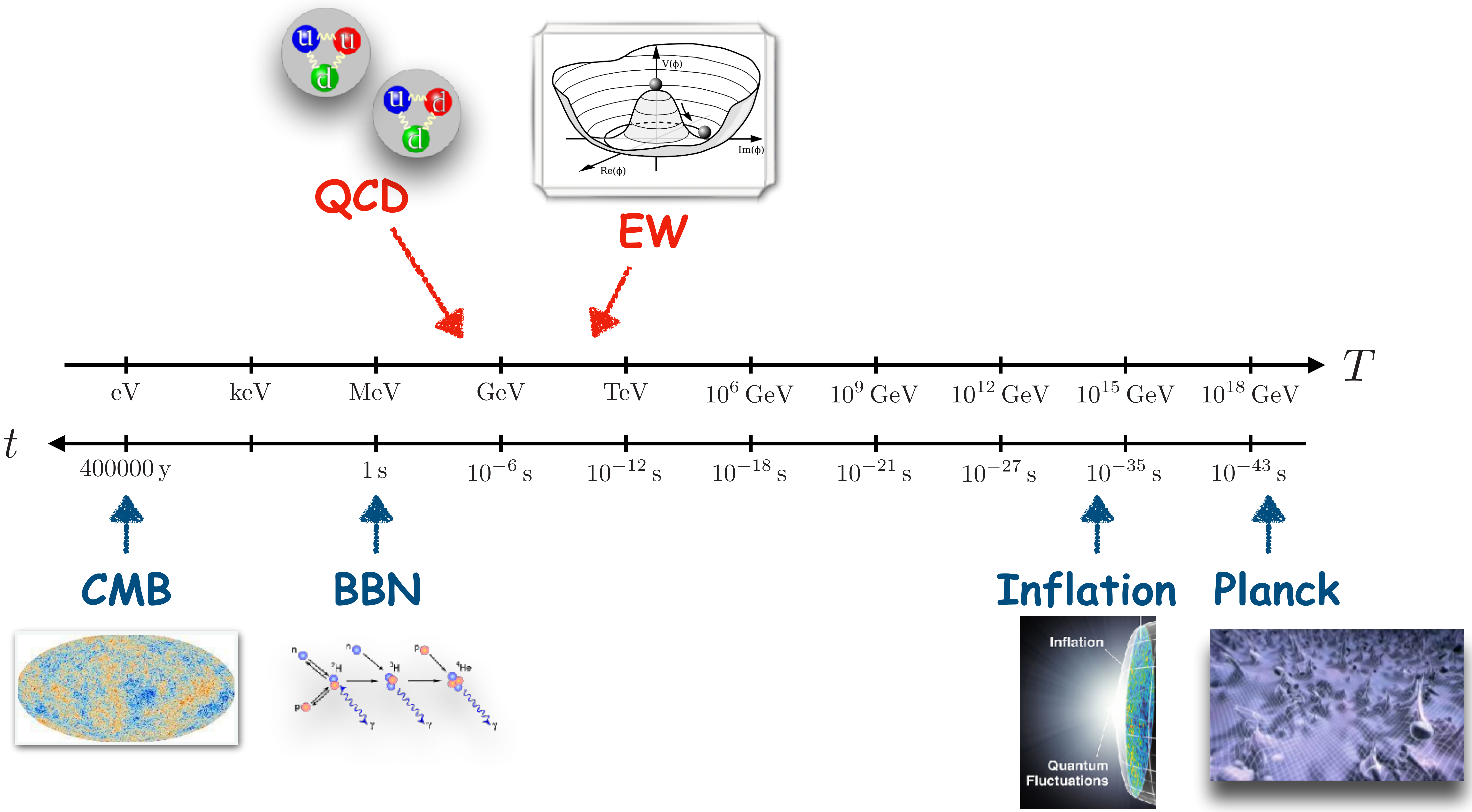
Bubble Nucleation

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



Phase transitions from BSM

Additional phase transitions could be present due to **new-physics**

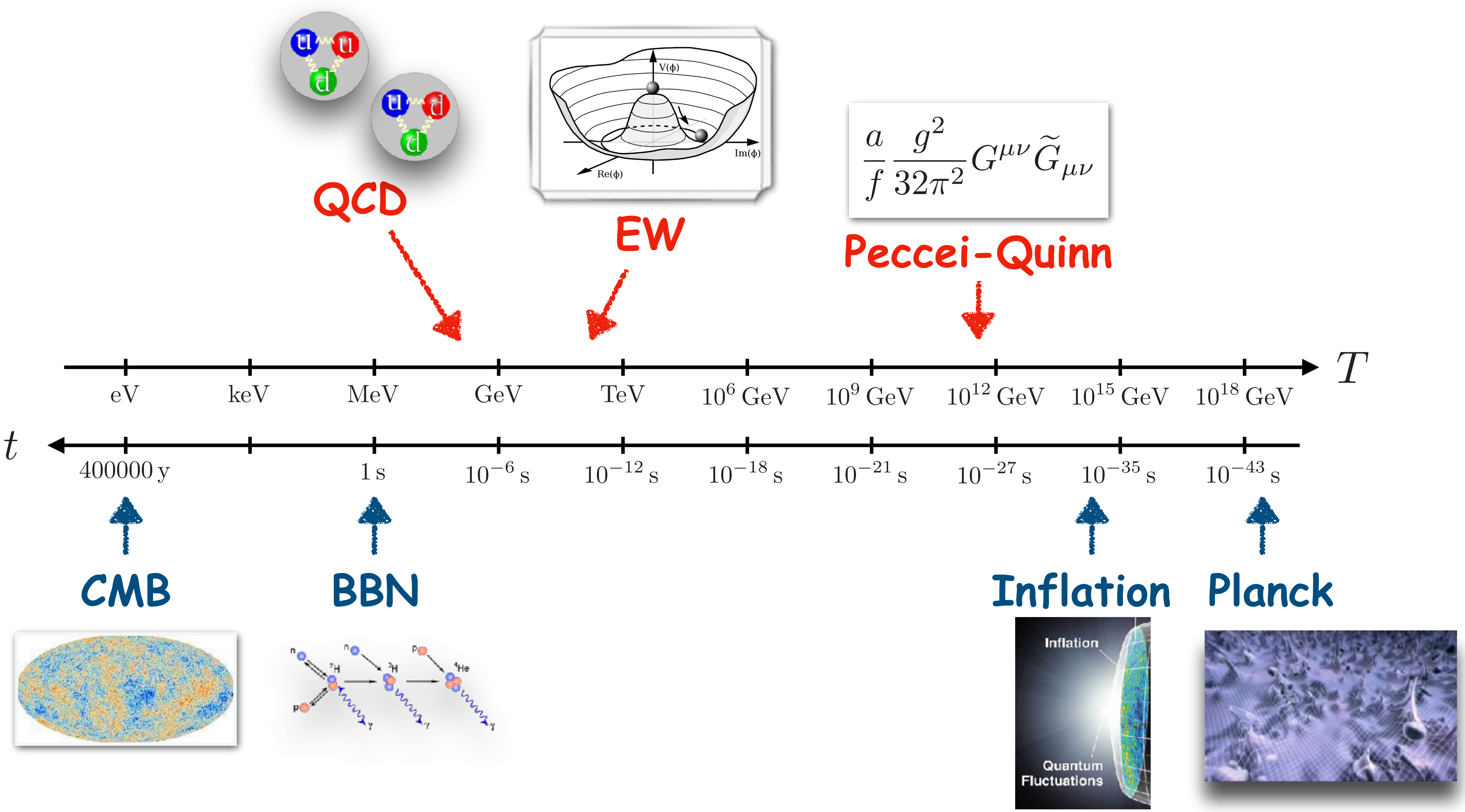


Phase transitions from BSM

Additional phase transitions could be present due to **new-physics**

well motivated example:

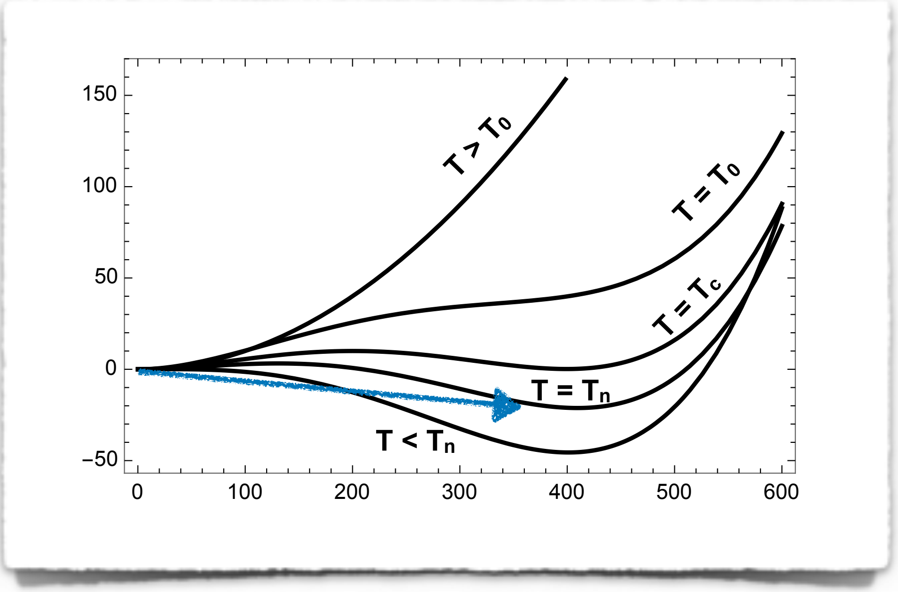
- Peccei-Quinn symmetry breaking connected to QCD axion



How to get a first-order PhT

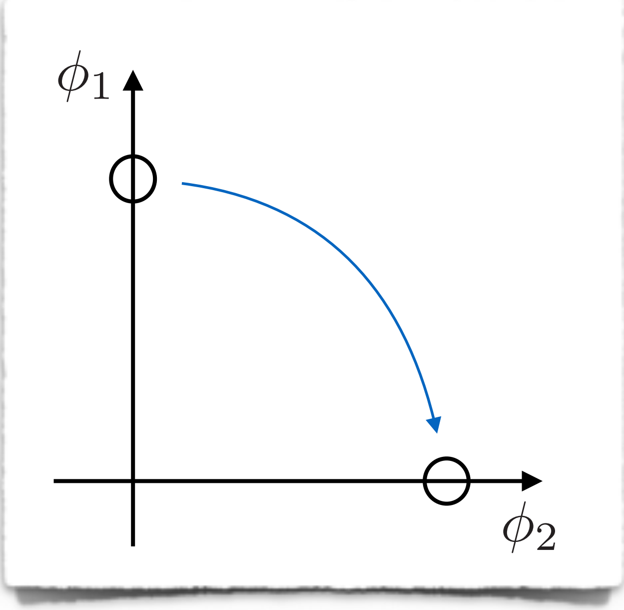
I. **“Single field”** transitions

- 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

Scalar singlet extension

Higgs + singlet scalar potential (Z_2 symmetric)

in the high-temperature limit

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

important to create
a barrier in the potential

with thermal masses

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

Scalar singlet extension

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

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

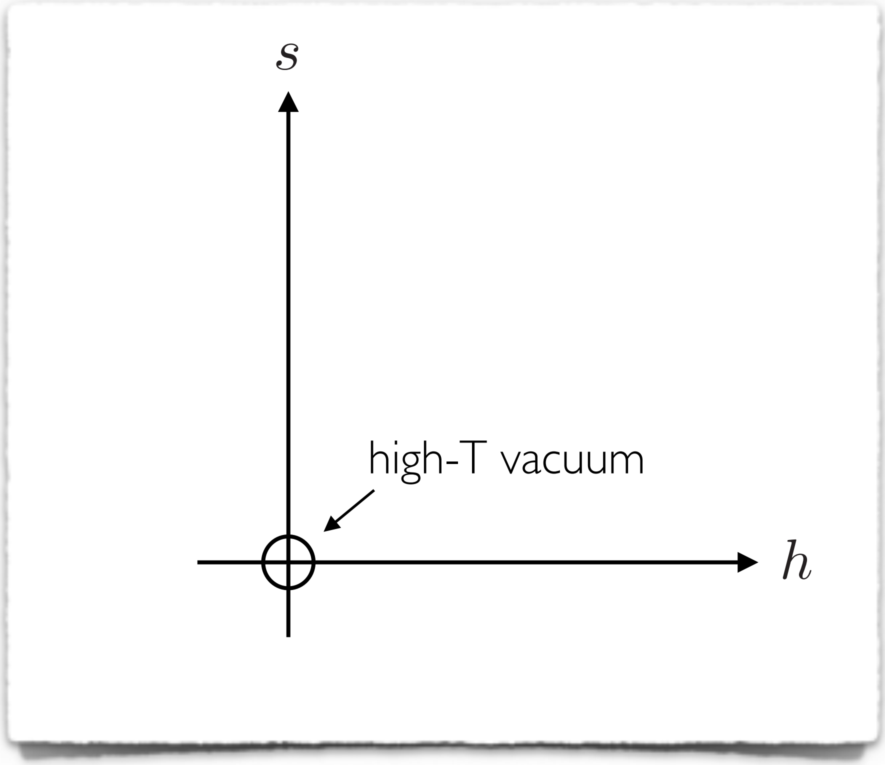
important to create
a barrier in the potential

with thermal masses

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

- ✦ EW symmetry is restored at very high T

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



Scalar singlet extension

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

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

important to create a barrier in the potential

with thermal masses

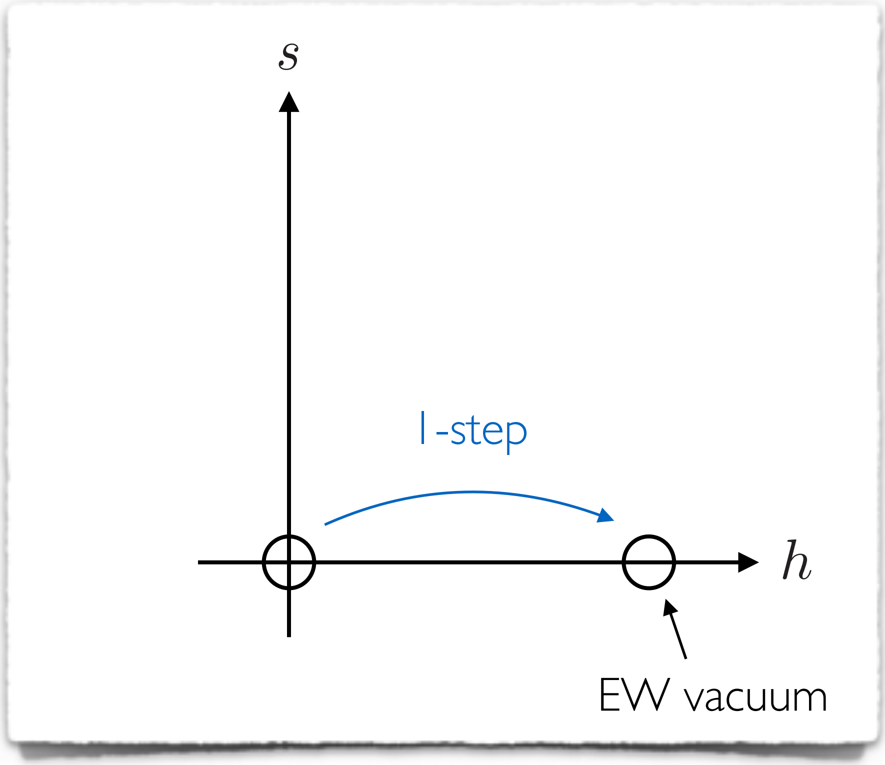
$$c_h = \frac{1}{48}\left(9g^2 + 3g'^2 + 12y_t^2 + 24\lambda_h + 2\lambda_{h\eta}\right) \qquad c_\eta = \frac{1}{12}\left(4\lambda_{h\eta} + \lambda_\eta\right)$$

- 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 $\quad (0,0) \to (v,0)$



Scalar singlet extension

Higgs + singlet scalar potential (Z_2 symmetric)

in the high-temperature limit

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

important to create
a barrier in the potential

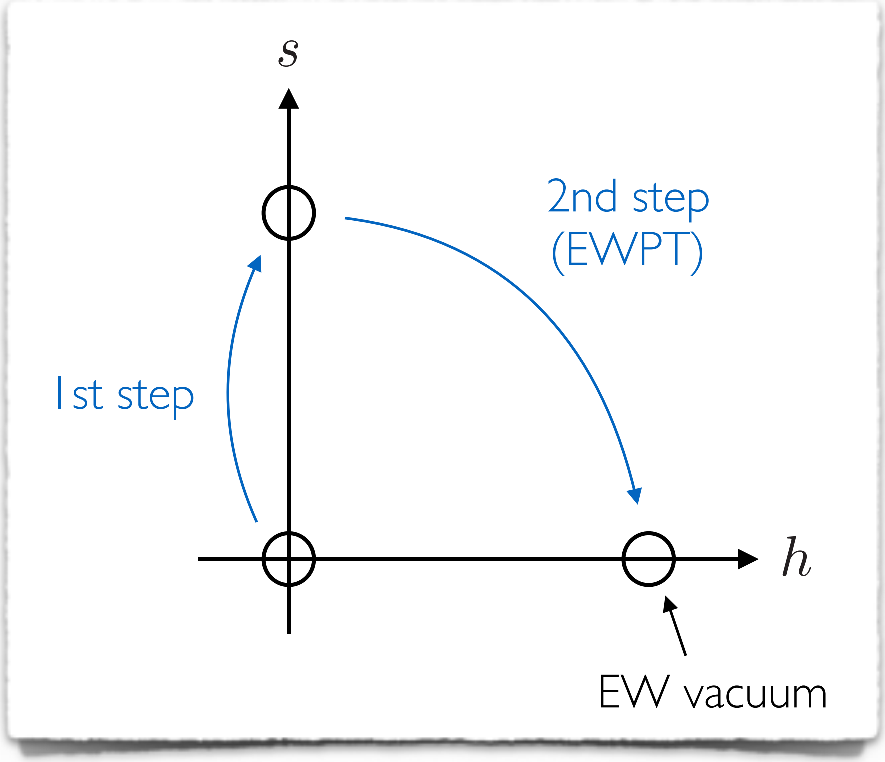
with thermal masses

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

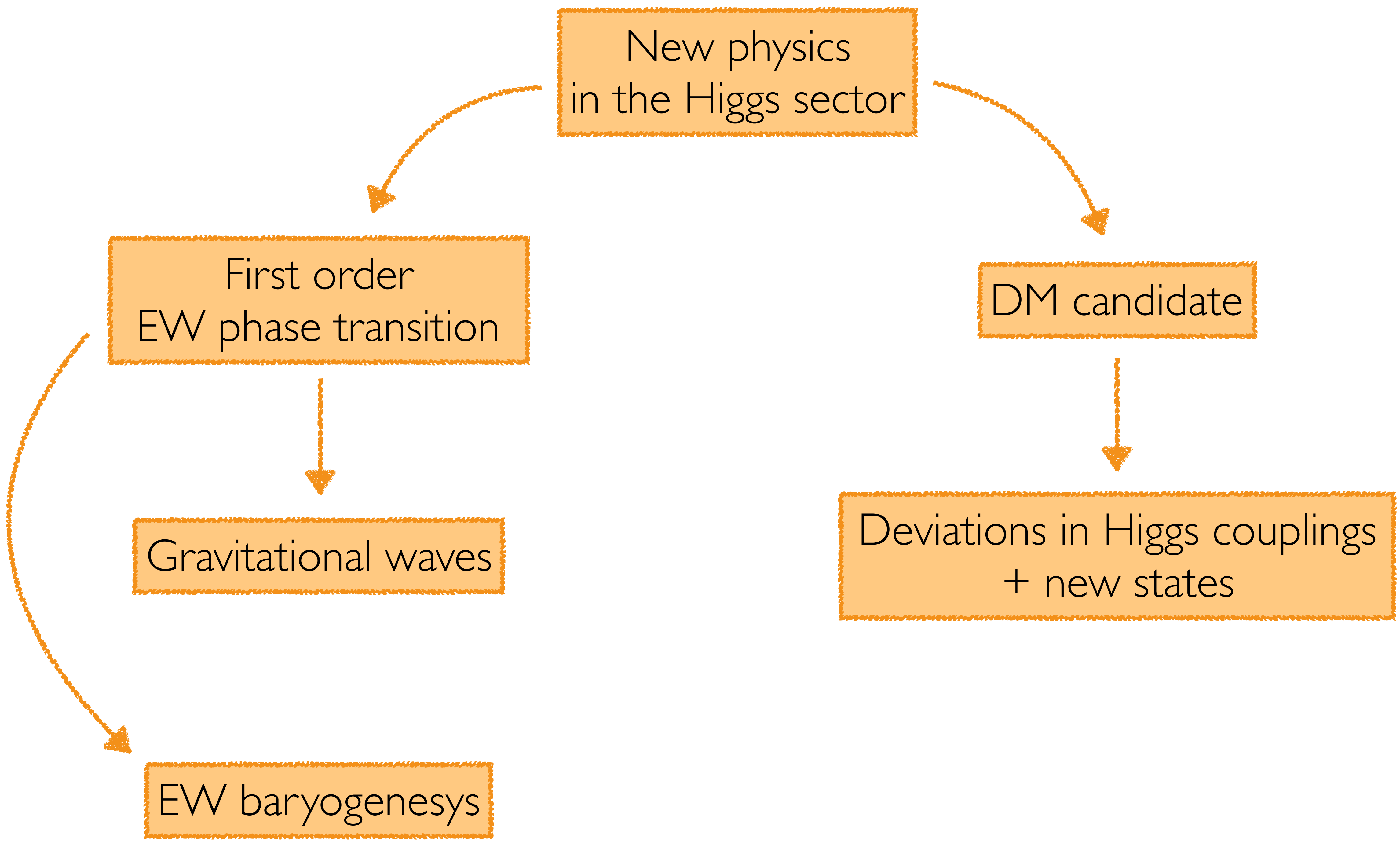
- ✦ EW symmetry is restored at very high T

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

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



Phenomenology



Phenomenology

New physics
in the Higgs sector

First order
EW phase transition

DM candidate

Collider - Cosmology synergy

Gravitational waves

testable at
future interferometers

Deviations in Higgs couplings
+ new states

testable at
future colliders

EW baryogenesys

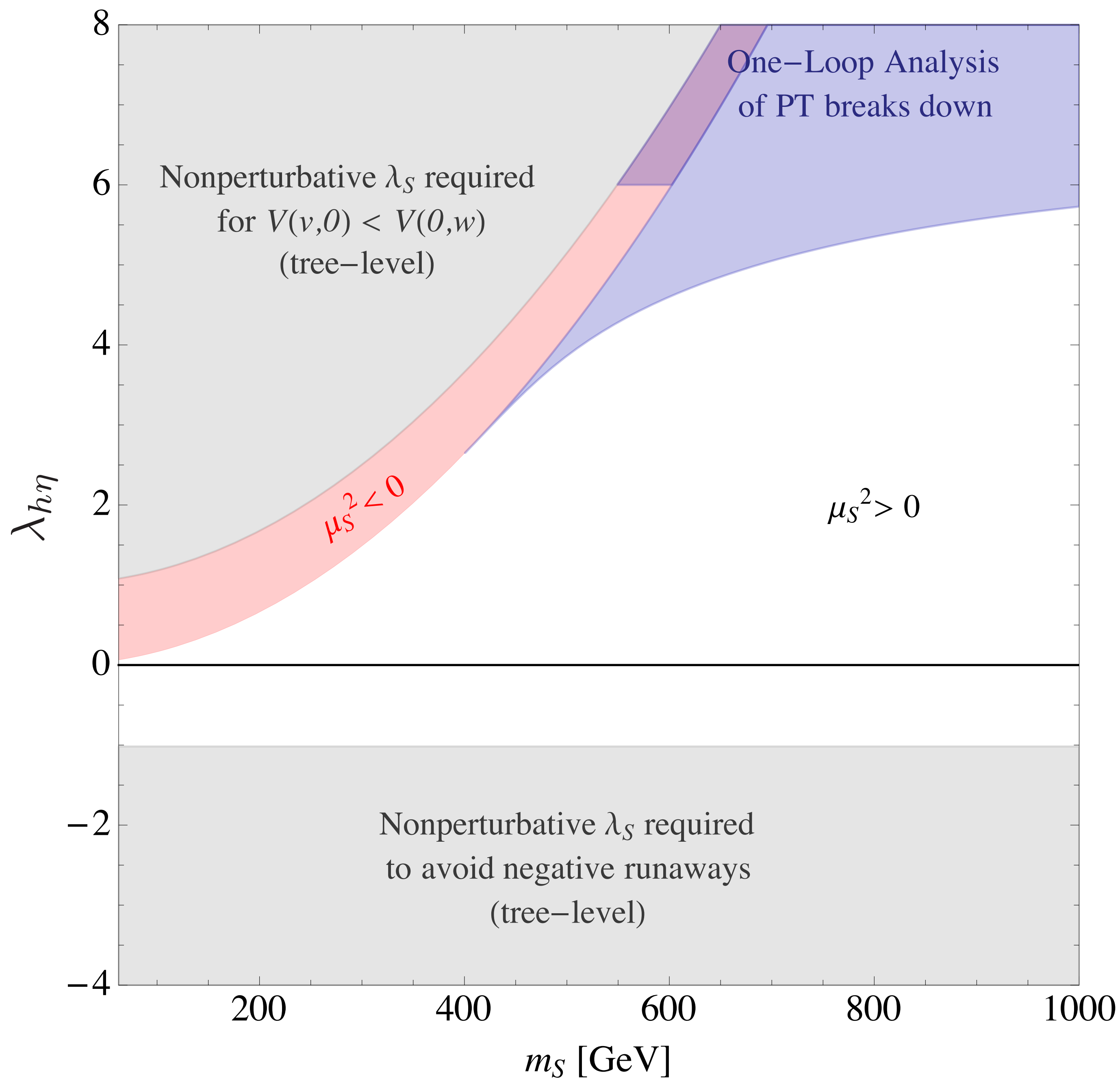
Phenomenology

Very weak constraints

- ✦ $m_\eta < m_h/2$ 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)

The parameter space

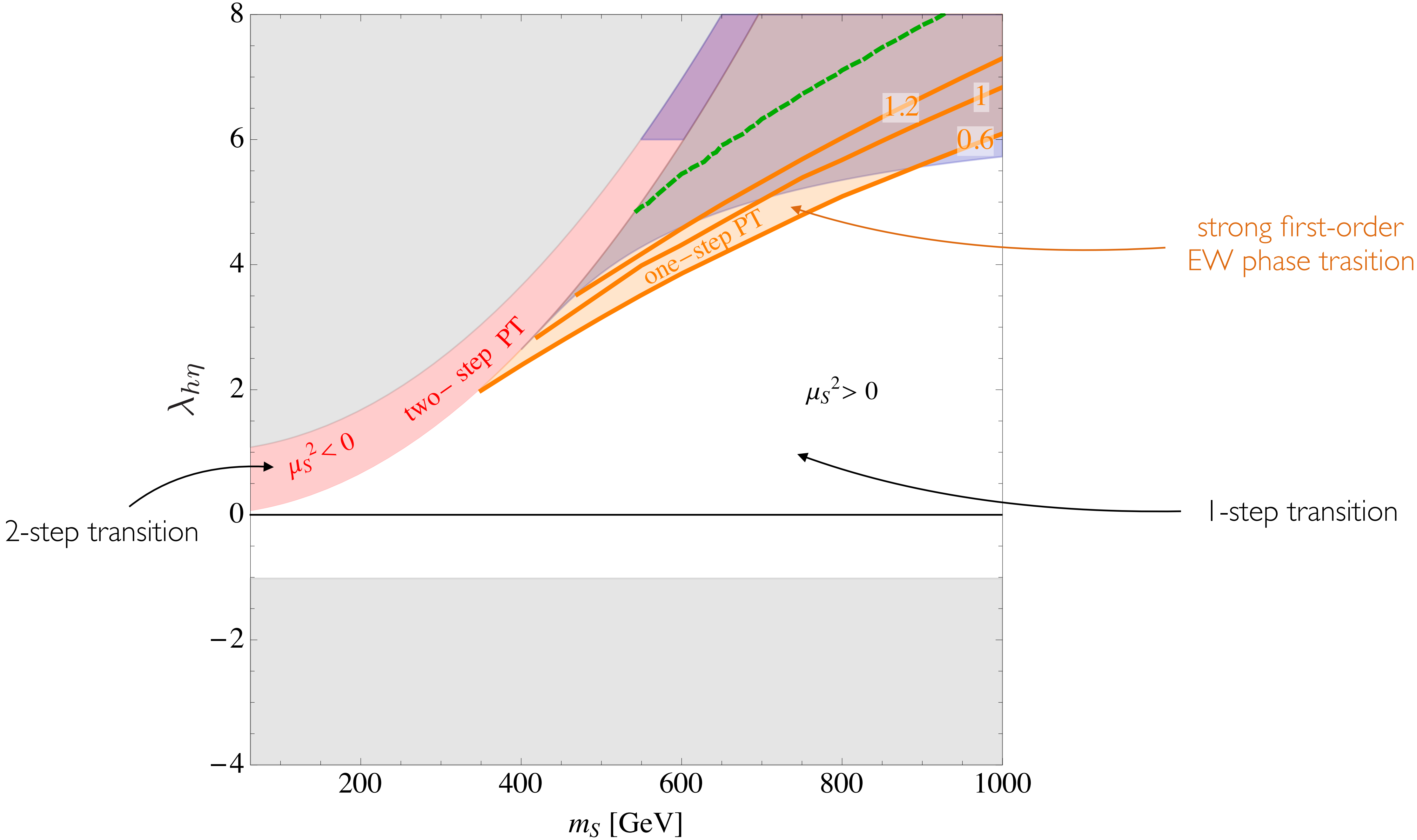
[Curtin, Meade, Yu '14]



Note: PhT parameter space shrinks if nucleation probability is taken into account

The parameter space

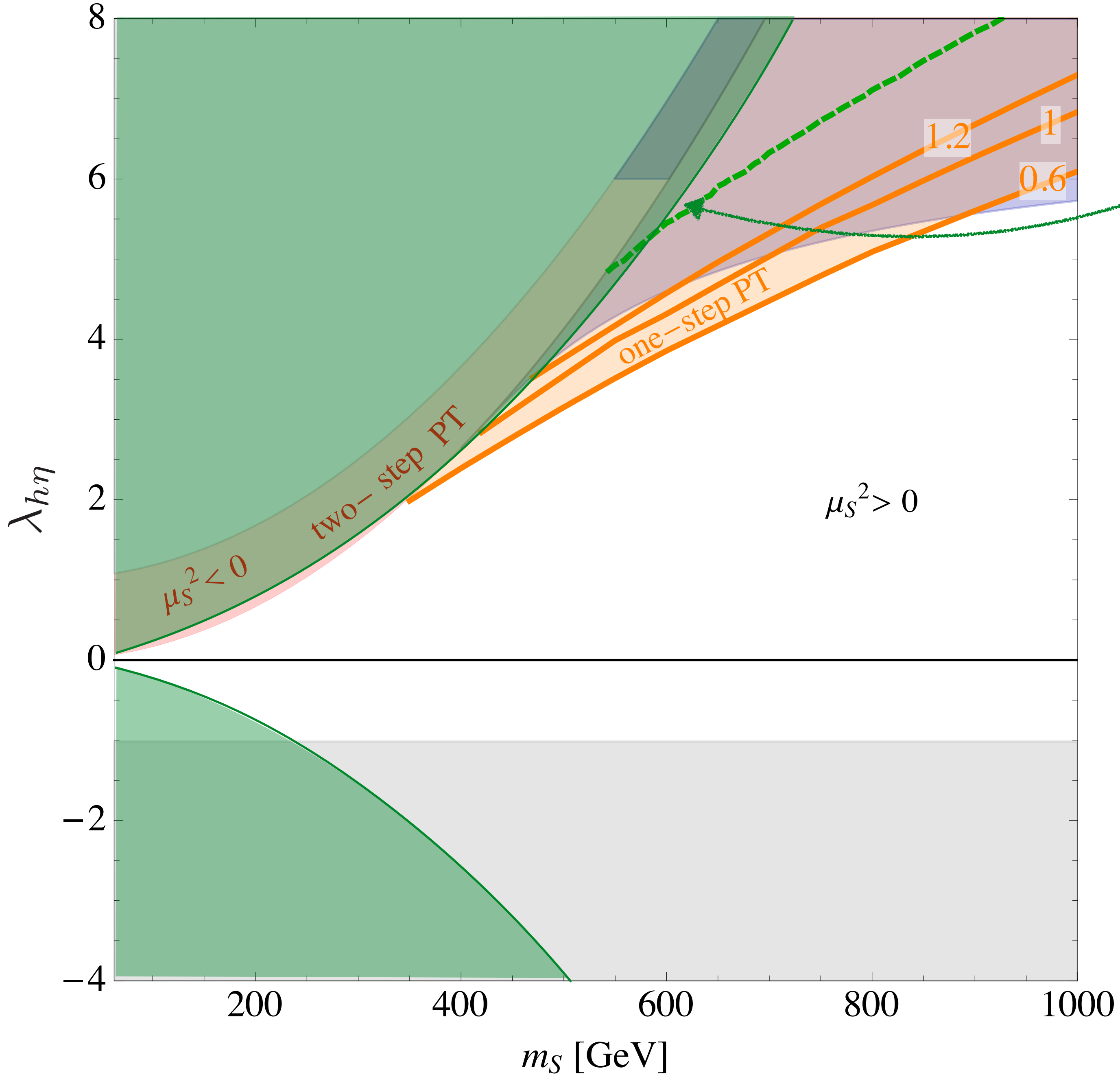
[Curtin, Meade, Yu '14]



Note: PhT parameter space shrinks if nucleation probability is taken into account

The parameter space

[Curtin, Meade, Yu '14]

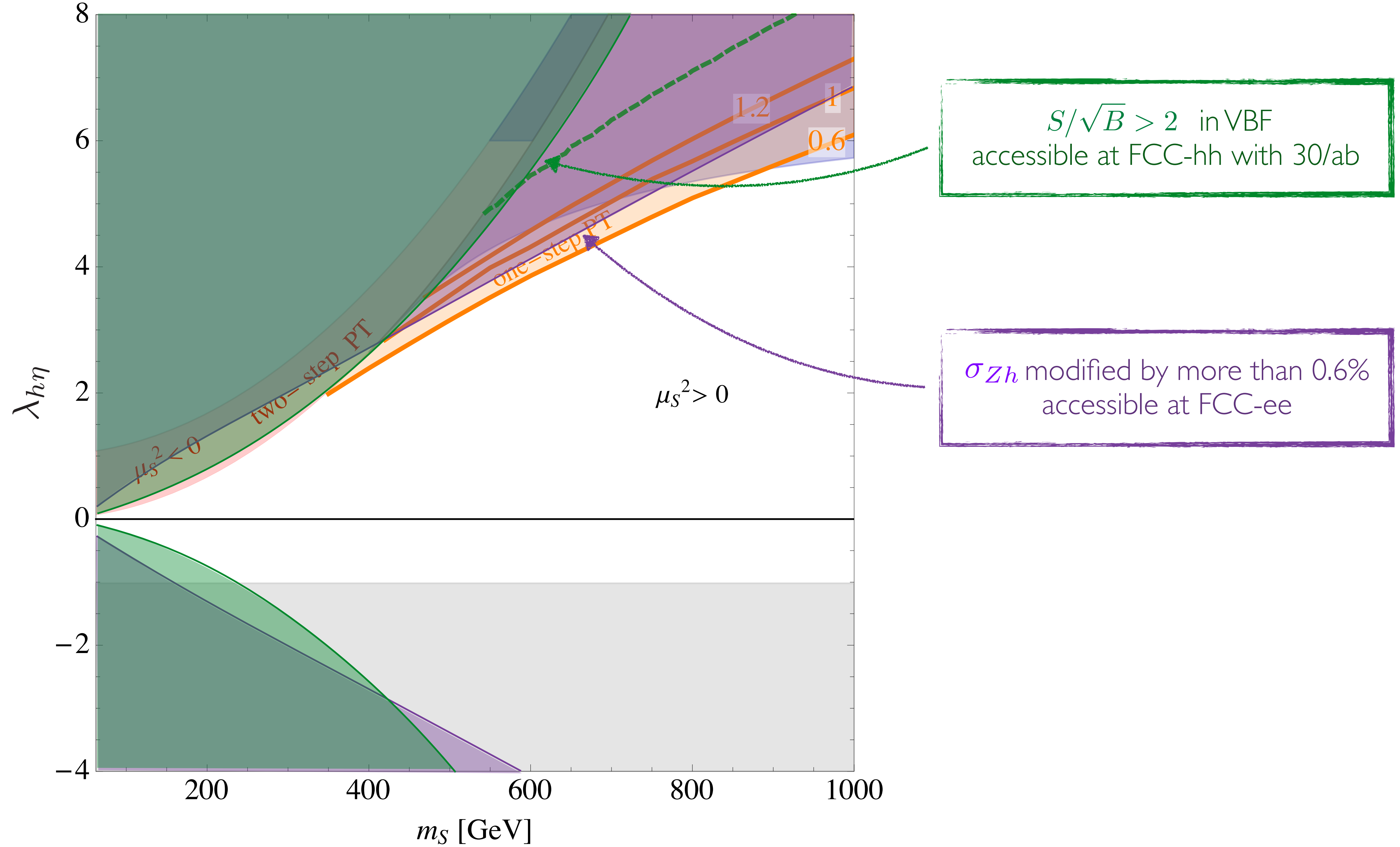


$S/\sqrt{B} > 2$ in VBF
accessible at FCC-hh with 30/ab

Note: PhT parameter space shrinks if nucleation probability is taken into account

The parameter space

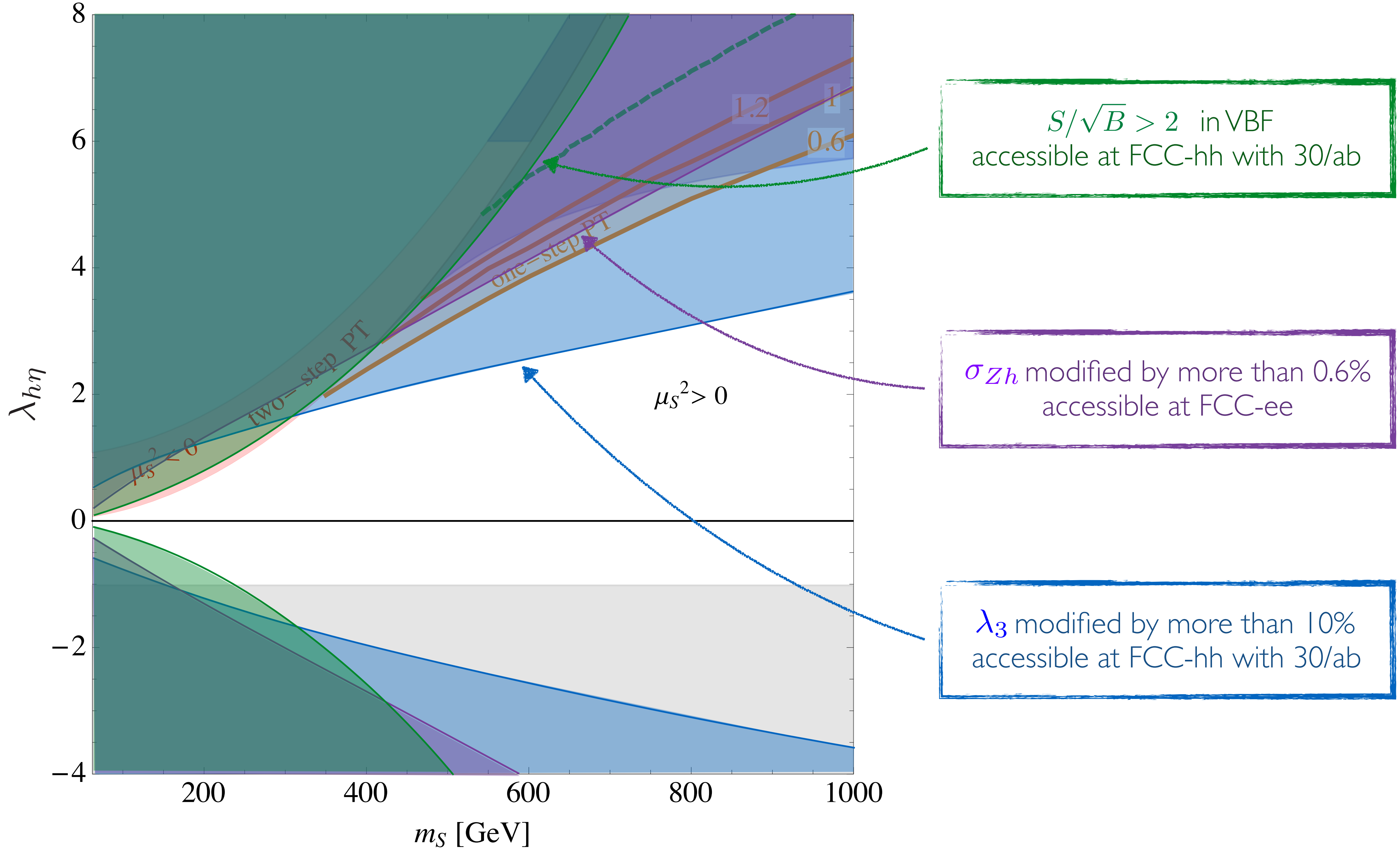
[Curtin, Meade, Yu '14]



Note: PhT parameter space shrinks if nucleation probability is taken into account

The parameter space

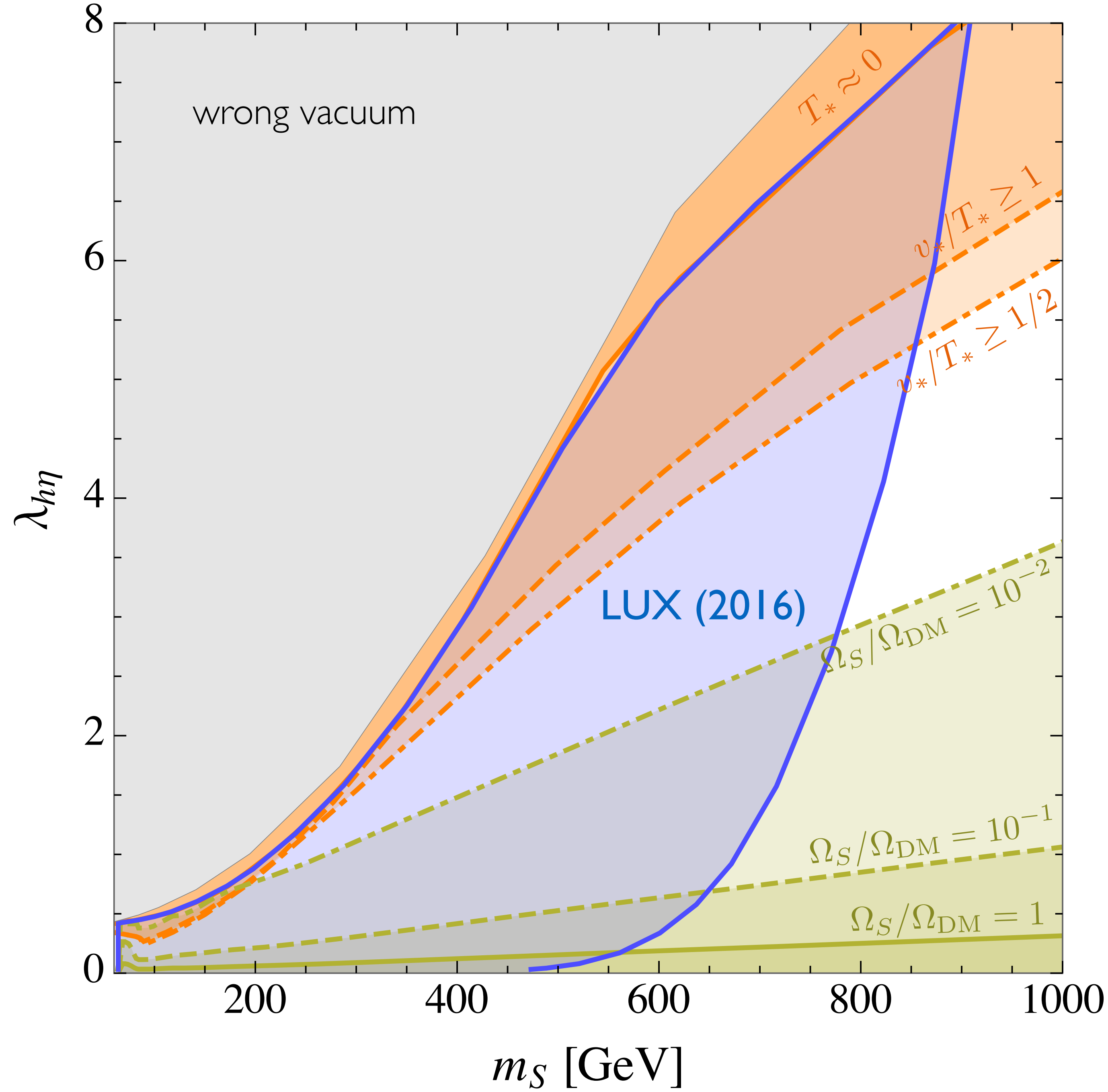
[Curtin, Meade, Yu '14]



Note: PhT parameter space shrinks if nucleation probability is taken into account

The parameter space: Dark Matter

In the Z_2 symmetric model the singlet can not account for the whole DM abundance



[Baniwal et al. '17]

A strongly-coupled realization

De Curtis, Delle Rose, GP '19

PhTs in composite Higgs

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

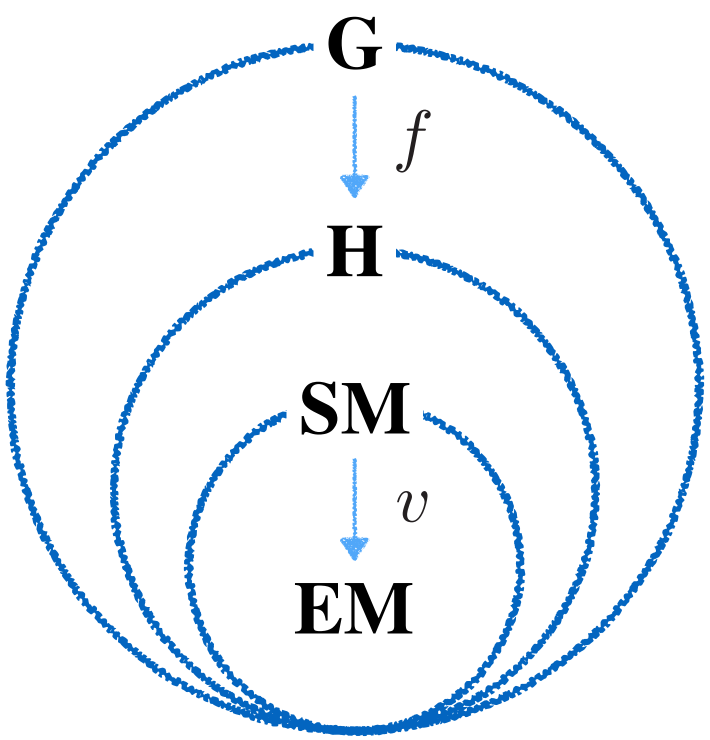
Multiple phase transitions expected:

- ✦ breaking of the global symmetry in the strong sector

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

- ✦ EW symmetry breaking

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



The EW PhT in composite Higgs

Minimal models have only one Higgs doublet

$\mathrm{SO}(5) \to \mathrm{SO}(4)$ ➔ 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

Extended models

Non-minimal models feature extended Higgs sector

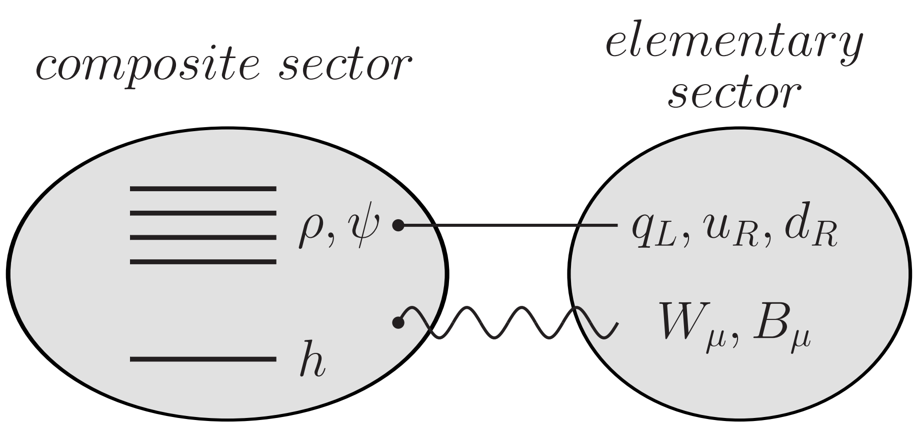
next-to-minimal construction:

$\mathrm{SO}(6) \to \mathrm{SO}(5)$ ➔ 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 break 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 corrections to $Z\bar{b}_L b_L$)

10 - no potential for the singlet

6, **15**, **20'** - viable representations for the top partners

---

(q_L, t_R) ~ (**6**, **6**) : typically predicts $\lambda_\eta \simeq 0$ and $\lambda_{h\eta} \simeq \lambda_h/2$

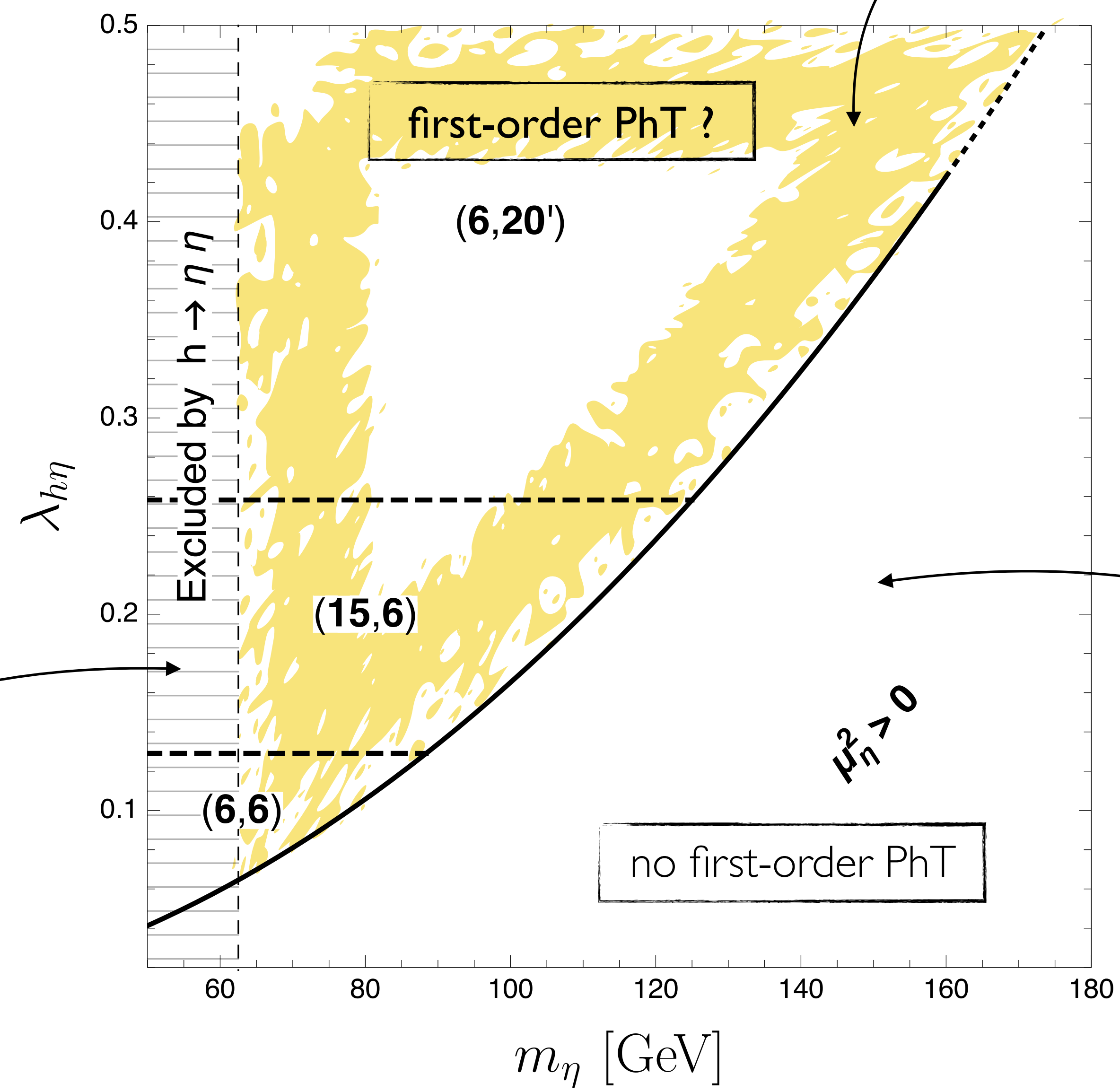
viable model require sizable bottom contributions and tuning

(q_L, t_R) ~ (**15**, **6**) : less-tuned scenario:

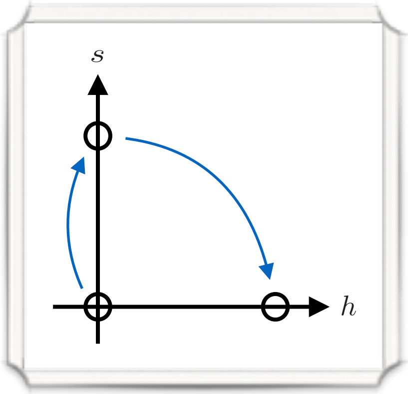
no need to rely on bottom partners, but λ_η is necessarily small

(q_L, t_R) ~ (**6**, **20'**) : large parameter space available without large tuning

The parameter space



singlet can get a VEV
(possible 2-step transition)



singlet does not get a VEV
(no 2-step transition)

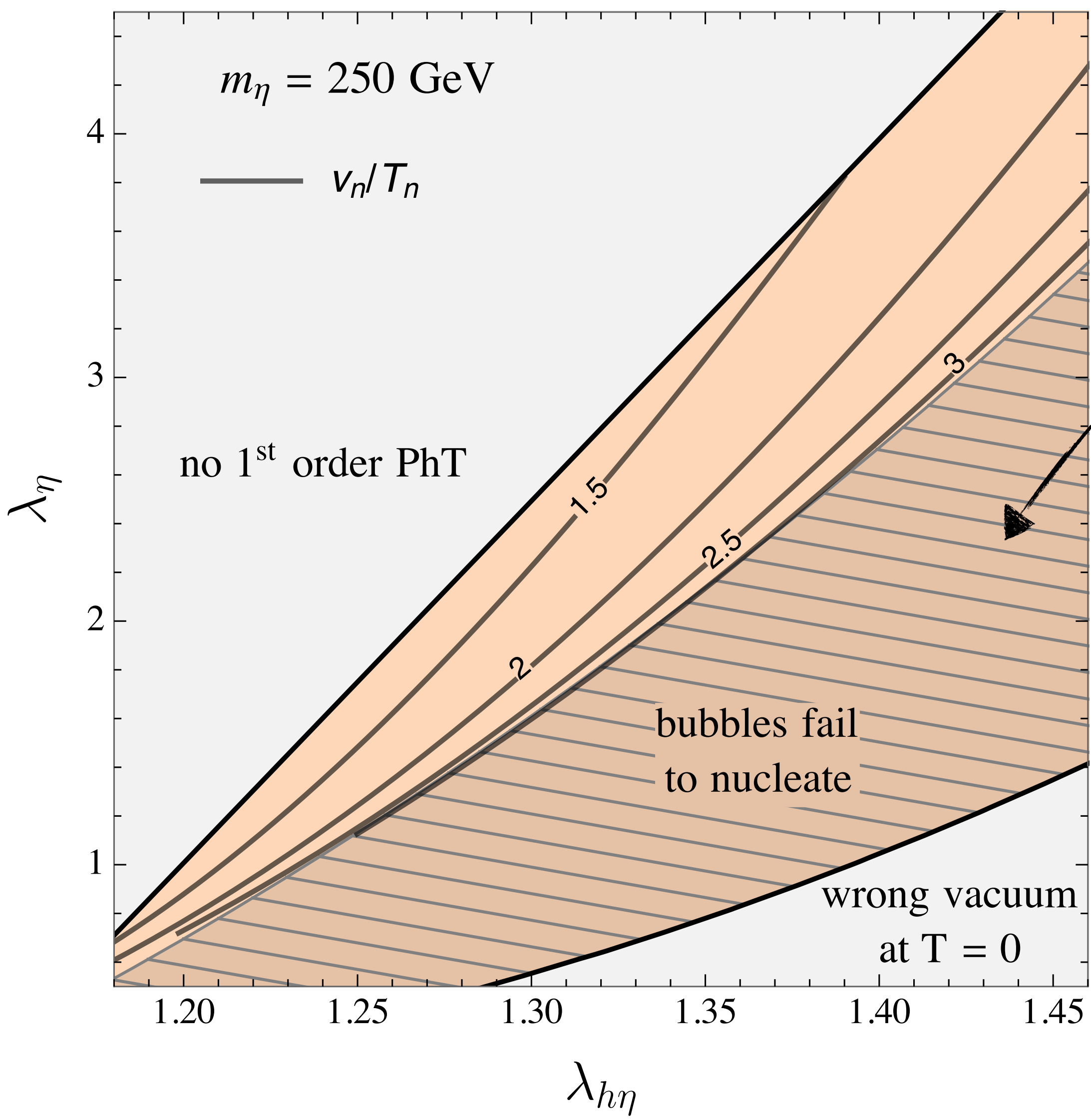
portal too small to induce barrier in Higgs potential

singlet too light

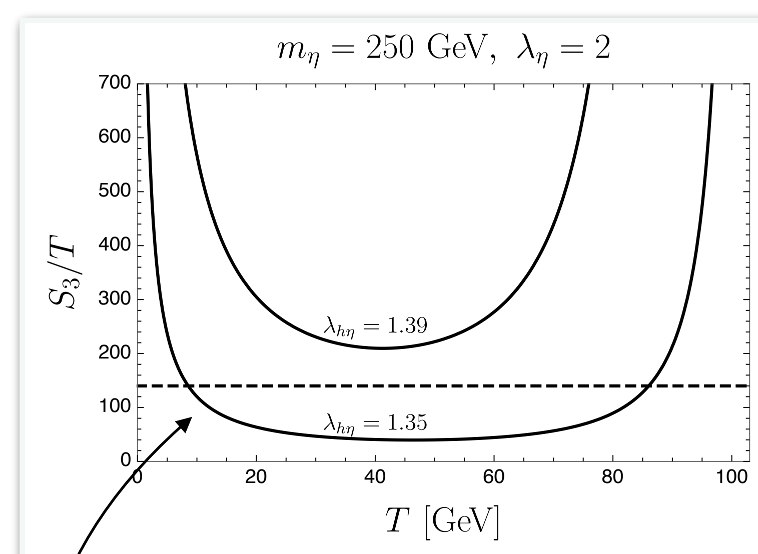
Properties of the EW PhT

Results for the (q_L, t_R) ~ (**6**, **20'**) model

strength of the phase transition



bubbles fail to nucleate:
the system is trapped in the
metastable vacuum



bounce action has
minimal value

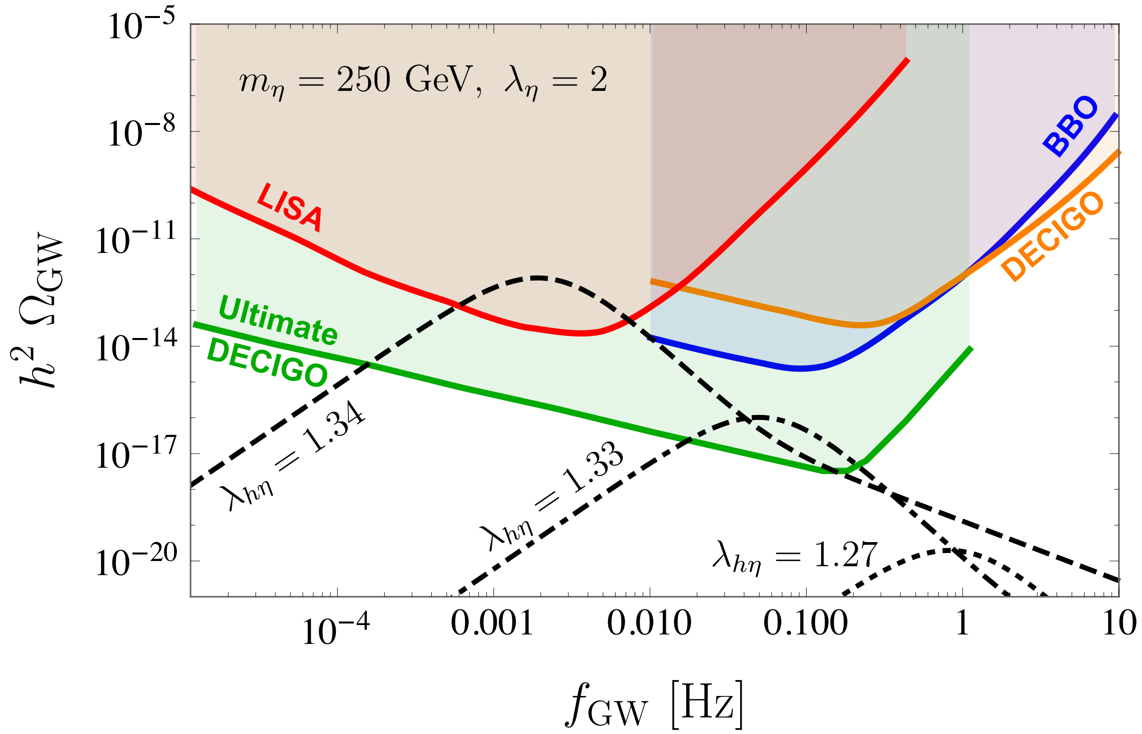
Gravitational waves

First-order PhTs produce stochastic background of gravitational waves

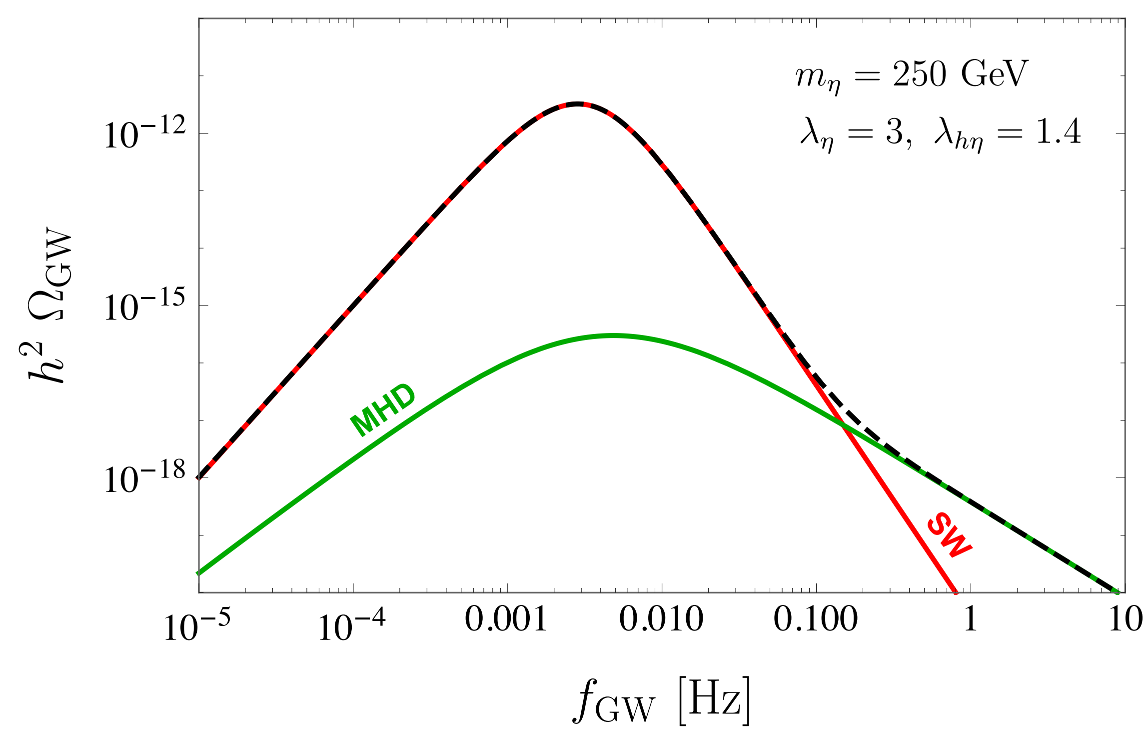
three main components:

- sound waves in the plasma (SW)
- turbulence in the plasma (MHD)
- bubble collisions (negligible in our case)

$$f_{\rm peak} \sim 10^{-5}{\rm Hz}\,\underbrace{\frac{1}{v_w}}_{\text{bubble velocity}}\overbrace{\left(\frac{\beta}{H_n}\right)}^{\mathcal{O}(100-1000)}\left(\frac{T_n}{100\,{\rm GeV}}\right)\left(\frac{g_*}{100}\right)^{\frac{1}{6}}$$



peak frequency within the range
of future experiments for a significant fraction
of the parameter space



spectra with non-trivial shape
(due to multiple components)

EW baryogenesys

Sakharov's conditions

	SM		SO(6)/SO(5)	
✦ B violation	✔	EW sphaleron processes violate B+L	✔	same as in the SM
✦ Out of equilibrium dynamics	✘	EW PhT not first order	✔	EW PhT can be first-order and sufficiently strong
✦ C and CP violation	✘	CP violation too small	✔	CP violation in the $\eta h \bar{t} t$ coupling

EW baryogenesys: CP violation

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

the singlet coupling to the fermions can have a complex coefficient:

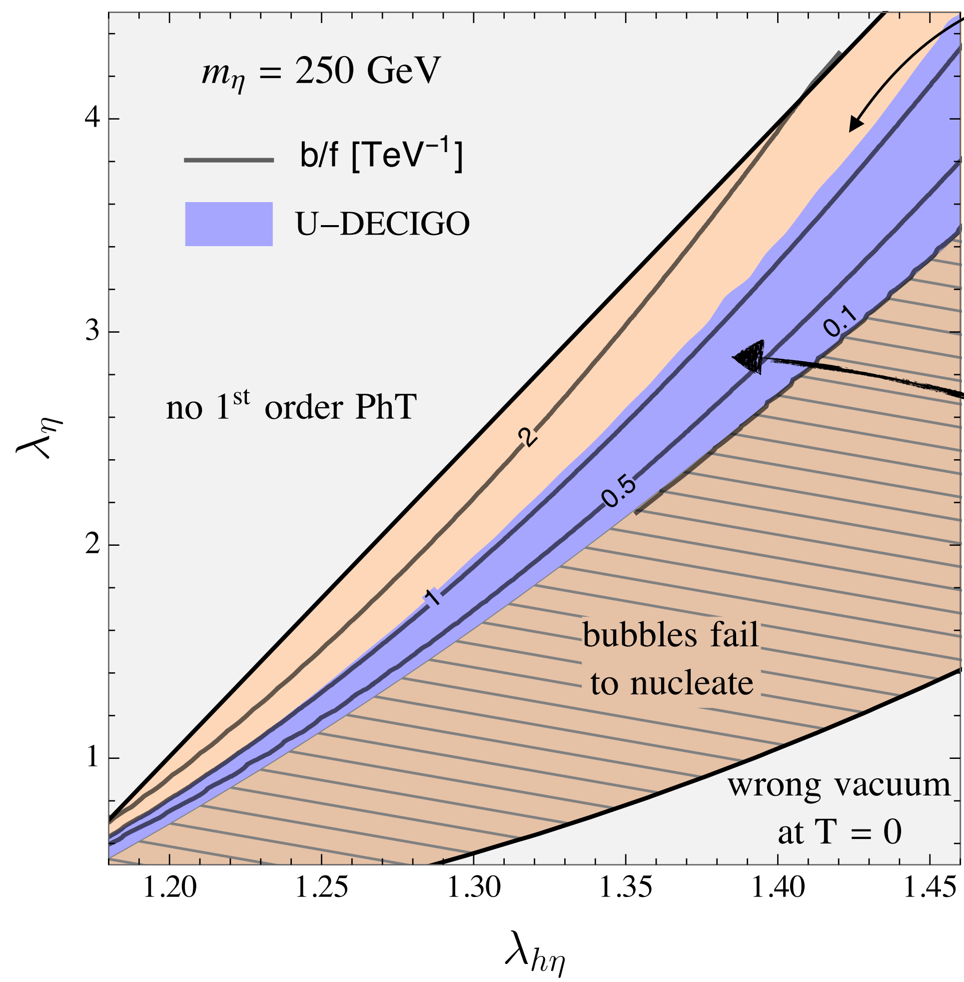
$$\mathcal{O}_t = y_t \left(1 + i\frac{b}{f}\eta\right) \frac{h}{\sqrt{2}} \bar{t}_L t_R + \text{h.c.}$$

A phase in the quark mass term is generated when both the Higgs and the singlet acquire a VEV

The phase becomes physical during the 2-step phase transition

$$(0,0) \to (0,w) \to (v,0)$$

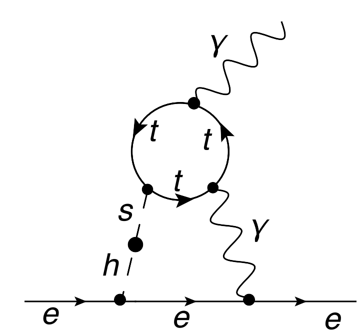
EW baryogenesys



$b/f \lesssim 1/\mathrm{TeV}$ is enough to reproduce the observed baryon asymmetry

EWBG and observable GW spectrum can be achieved simultaneously

Note: if Z_2 is broken at T=0, constraints from EDM can challenge EWBG



The Peccei-Quinn phase transition

Delle Rose, GP, Redi, Tesi in preparation

The Peccei-Quinn axion

The Peccei-Quinn **axion** offers an elegant solution to the strong CP problem

$$\mathscr{L} \supset -\frac{\alpha_s}{8\pi}\left(\frac{a}{f_a} - \theta\right) G^A_{\mu\nu}\tilde{G}^{A\mu\nu}$$

[Peccei-Quinn; Weinberg-Wilczek]

Small size of θ angle explained dynamically

- Goldstone boson of a spontaneously broken U(1) anomalous under QCD
- symmetry breaking at very high scale $\longrightarrow$ weak coupling

  $f_a \gtrsim 10^9 \mathrm{GeV}$

The minimal PQ sector

Single scalar field (the **axion**) coupled to colored fermions

$$\mathcal{L} = -\lambda_X(|X|^2 - f^2/2)^2 + (yXQQ^c + \text{h.c.})$$

It displays a **second order** phase transition for several reasons:

I. No massless bosonic states coupled to X where PQ is restored

II. Fermion contribution to 1-loop Coleman-Weinberg has "wrong" sign

III. Potential is always well approximated by $m^2(T)|X|^2 + \lambda(T)|X|^4$

Peccei-Quinn breaking must be **non-minimal**
to have first-order phase transition

The Higgs portal

Coupling with the Higgs boson is typically present

$$V = -\mu^2|H|^2 + \lambda|H|^4 + \lambda_{XH}|X|^2|H|^2 + \lambda_X(|X|^2 - f^2/2)^2$$

[Dev, Ferrer, Zhang, Zhang '19]

Lagrangian similar to the Higgs + singlet case, but with crucial differences:

I. huge **hierarchy** of scales $v \lll f$

- tuning of parameters: $\mu^2 = \lambda_{XH}/2f^2 + O((100\mathrm{GeV})^2)$
- matching to the Higgs mass: $\frac{M_h^2}{2v^2} = \lambda - \frac{\lambda_{XH}^2}{4\lambda_X}$

II. both fields must have VEV at T=0

- two step transition not possible (due to minimum structure of tree-level potential)

The Higgs portal

Differences from minimal PQ case can arise for **large portal** $\lambda_{XH} \gg \lambda_X$

Expanding the potential in the limit $h, v \ll f\,, \quad \lambda_{XH} \gg \lambda_X$

$$V_{eff} = \frac{1}{2}\frac{\lambda_{XH}T^2}{6}s^2 + \frac{\lambda_X}{4}s^4 + \frac{\lambda_{XH}^2 s^4}{64\pi^2}\log\left(\frac{\lambda_X H}{2\bar{\mu}^2}s^2\right)$$

$s^2 \equiv |X|^2 - f^2$

Can deviate from quadratic + quartic potential only if

$$\lambda_{XH}^2 \sim 16\pi^2\lambda_X \quad \longrightarrow \quad \lambda \gtrsim 16\pi^2$$

strong coupling ! ☹

The Higgs portal

Differences from minimal PQ case can arise for **large portal** $\lambda_{XH} \gg \lambda_X$

Expanding the potential in the limit $h, v \ll f\,, \quad \lambda_{XH} \gg \lambda_X$

$$V_{eff} = \frac{1}{2}\frac{\lambda_{XH} T^2}{6} s^2 + \frac{\lambda_X}{4} s^4 + \frac{\lambda_{XH}^2 s^4}{64\pi^2} \log\left(\frac{\lambda_X H}{2\bar{\mu}^2} s^2\right)$$

$s^2 \equiv |X|^2 - f^2$

Can deviate from quadratic + quartic potential only if

$\lambda_{XH}^2 \sim 16\pi^2 \lambda_X \longrightarrow \lambda \gtrsim 16\pi^2$ **strong coupling !** ☹

many more possibilities open if the additional scalar is not the Higgs !

Radiative PQ breaking at weak coupling

Radiative PQ breaking

Collection of scalar fields (some of which charged under PQ)

[Gildener, Weinberg '76]

$$V = \frac{\lambda_{ijkl}}{4}\phi_i\phi_j\phi_k\phi_l$$

Flat direction in the potential at scale Λ (generic feature due to RG running)

$$\lambda_{\rm eff}(\mu) = \lambda_{ijkl}(\mu) n_i n_j n_k n_l \,, \qquad \lambda_{\rm eff}(\Lambda) = 0\,, \qquad \phi_i = n_i \sigma$$

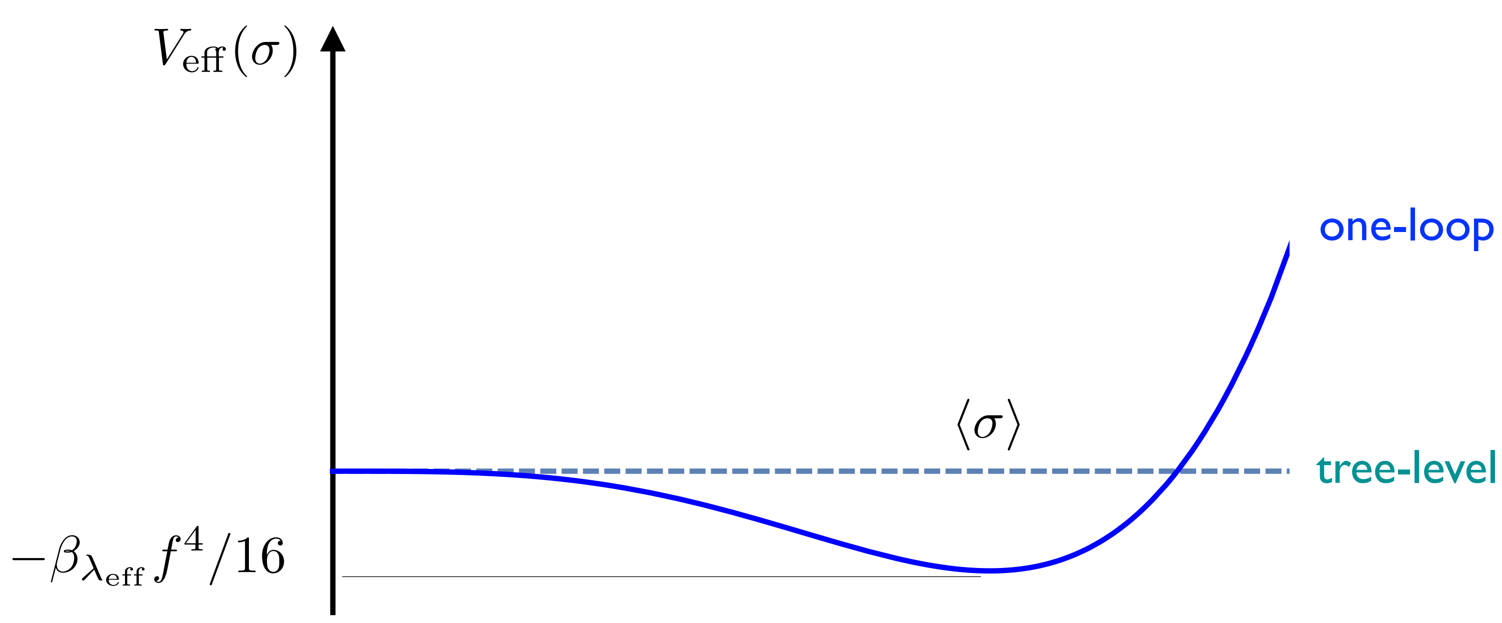
Dynamics mainly controlled by field σ

Radiative PQ breaking

Radiative corrections can lift the flat direction and stabilize the field

$$V_{\text{eff}}(\sigma) \approx \frac{\beta_{\lambda_{\text{eff}}}}{4}\sigma^4\left(\log\frac{\sigma}{f} - \frac{1}{4}\right) \qquad \langle\sigma\rangle \equiv f \approx \Lambda$$

- beta function needs to be positive at the reference scale



Thermal corrections

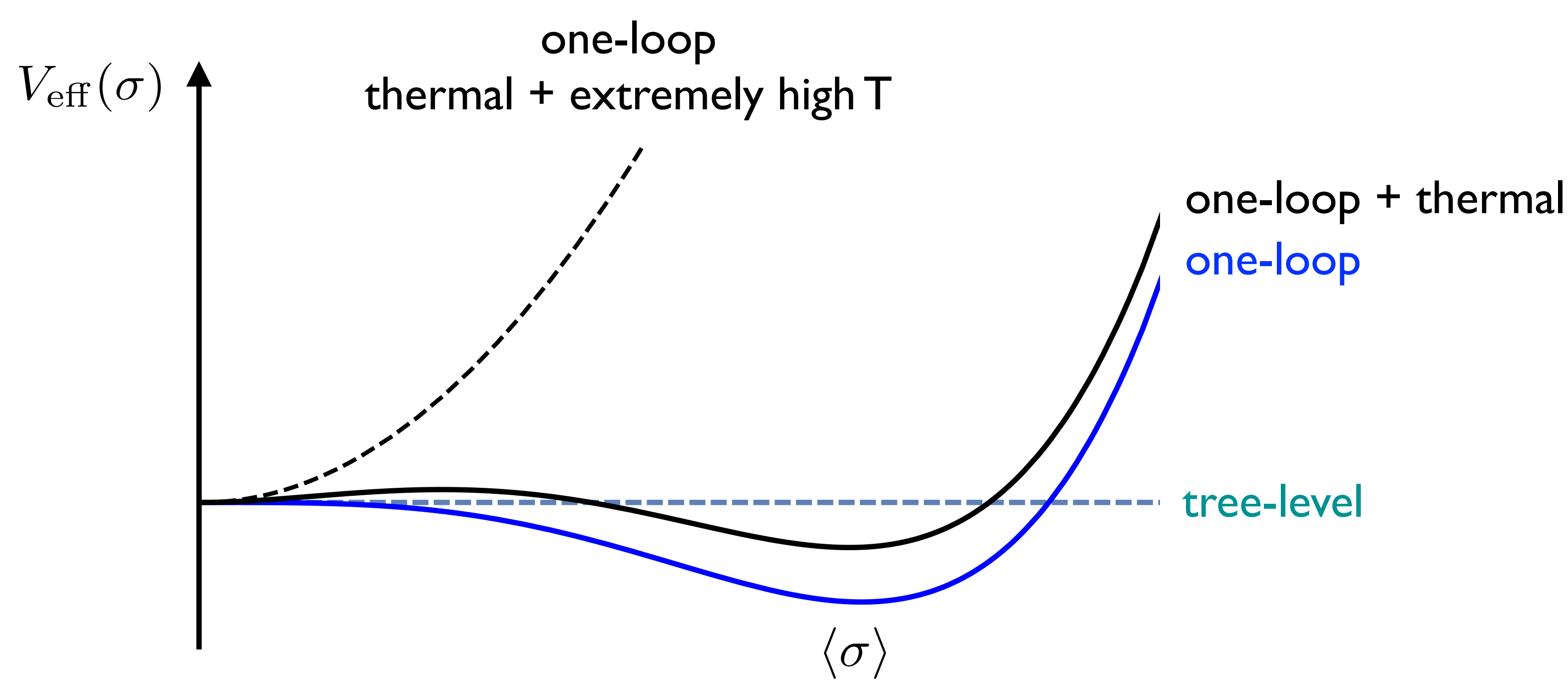
Due to flatness of the potential thermal corrections are always important

[Witten '81]

$$F(\sigma;T) \simeq \frac{N}{24}\hat{g}^2\sigma^2T^2 + \sum_i \frac{m_i^4}{64\pi^2}\log\frac{T^2}{m_i^2} + V_{\text{eff}}(\sigma)$$

even for $T \ll f$
one can formally expand at hight-T
close to the origin

$m_i \sim \hat{g}\sigma$
where $\hat{g}$ is a typical coupling of σ
to other light fields

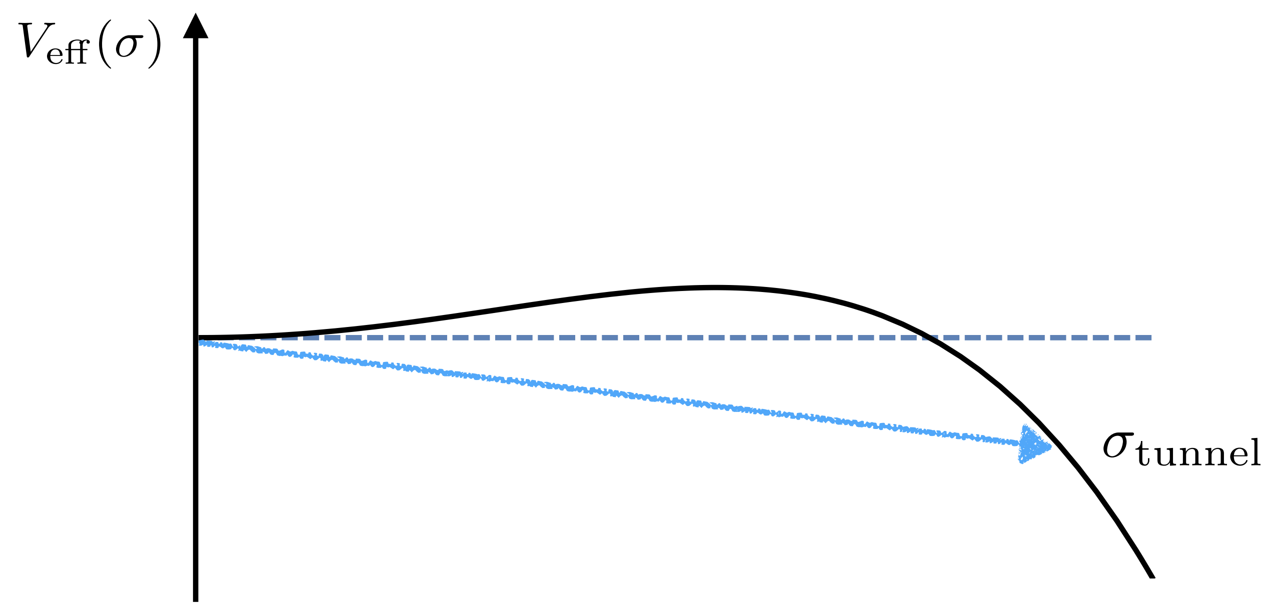


- barrier lasts for arbitrarily low temperatures

The bounce: Analytic approximation

When supercooling is present the barrier is very close to the origin and the potential can be approximated as

$$V_{eff}(\sigma;T) \simeq \frac{N}{24}\hat{g}^2\sigma^2T^2 - \frac{\beta_{\lambda_{\rm eff}}}{4}\sigma^4 \log\frac{M}{T}$$



The integral of the bounce solution can be done exactly [Brézin, Parisi '78]

$$\frac{S_3}{T} \approx 18.9\frac{\sqrt{N/12}}{\hat{g}^3}\frac{16\pi^2/b_{\rm eff}}{\log(M/T)}\,, \qquad \beta \equiv b_{\rm eff}\hat{g}^4/(16\pi^2)$$

S3/T scales logarithmically with the temperature

Nucleation and Supercooling

Due to small deviation from conformal invariance we expect **significant supercooling**

The nucleation temperature is determined by the equation

$$\Gamma(T_n) \approx T_n^4 \left(\frac{S_3/T}{2\pi}\right)^{\frac{3}{2}} \exp(-S_3/T) = H_I^4$$

- given the peculiar form of the bounce action $S_3/T = \#/\log(M/T)$ we find **lower bound** on the nucleation temperature

$$T_n \gtrsim \sqrt{M H_I} \sim 0.1 f \left(\frac{f}{M_{\rm Pl}}\right)^{\frac{1}{2}}$$

- the beta parameter in minimized for large supercooling

$$\beta/H = \#/\log^2(M/T)$$

An explicit realization

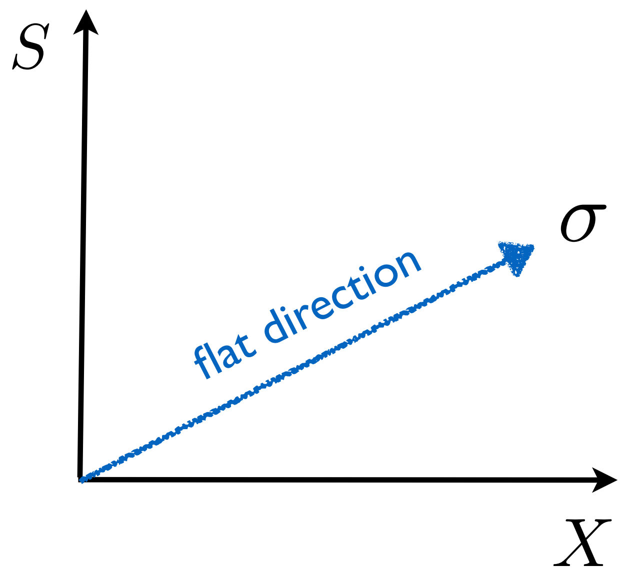
Two complex scalars: one charged under PQ and one with U(1) gauge charge

$$\mathcal{L} = -\frac{1}{4g^2}F^2 + |D_\mu S|^2 + |\partial_\mu X|^2 + (yXQQ^c + \text{h.c.}) - \lambda_S|S|^4 - \lambda_X|X|^4 - \lambda_{XS}|S|^2|X|^2$$

[see related Hambye, Strumia, Teresi '18]

A tree-level flat direction is realized for $\lambda_{XS} = -2\sqrt{\lambda_S\lambda_X}$

… lifted by the running induced by the quartic couplings and by the gauge interactions



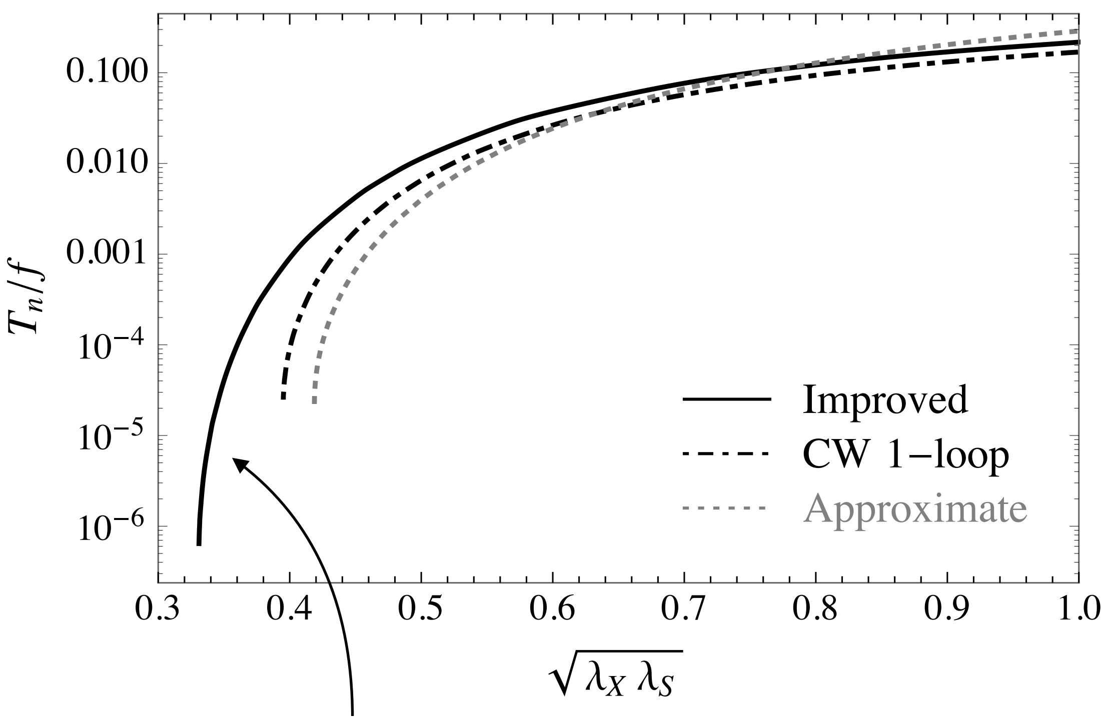
$$V_{T=0} = \frac{2\lambda_S\lambda_X + \frac{3}{2}g^4\sin^4\alpha - \frac{3}{2}y^4\cos^4\alpha}{16\pi^2}\sigma^4\left(\log\frac{\sigma}{f} - \frac{1}{4}\right)$$

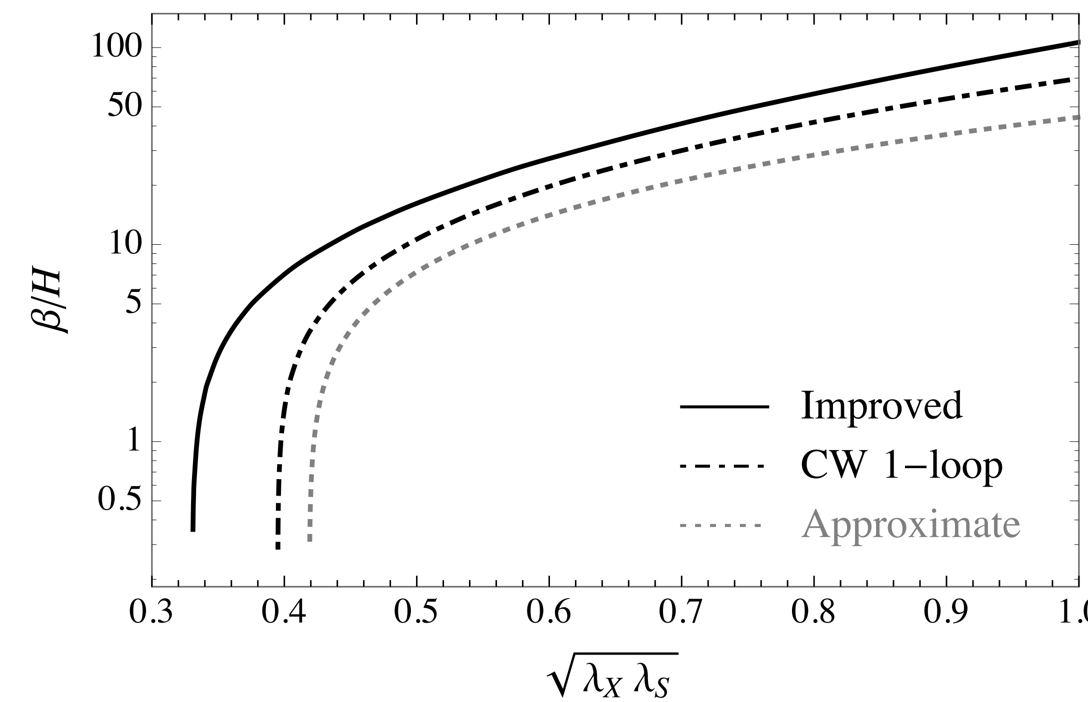
$$(S\,,X) = (\sin\alpha\,,\cos\alpha)\frac{\sigma}{\sqrt{2}}\,,\qquad \sin^2\alpha = \frac{\sqrt{\lambda_X}}{\sqrt{\lambda_X}+\sqrt{\lambda_S}}$$

Results: Pure quartics

Limit with **only quartic couplings**

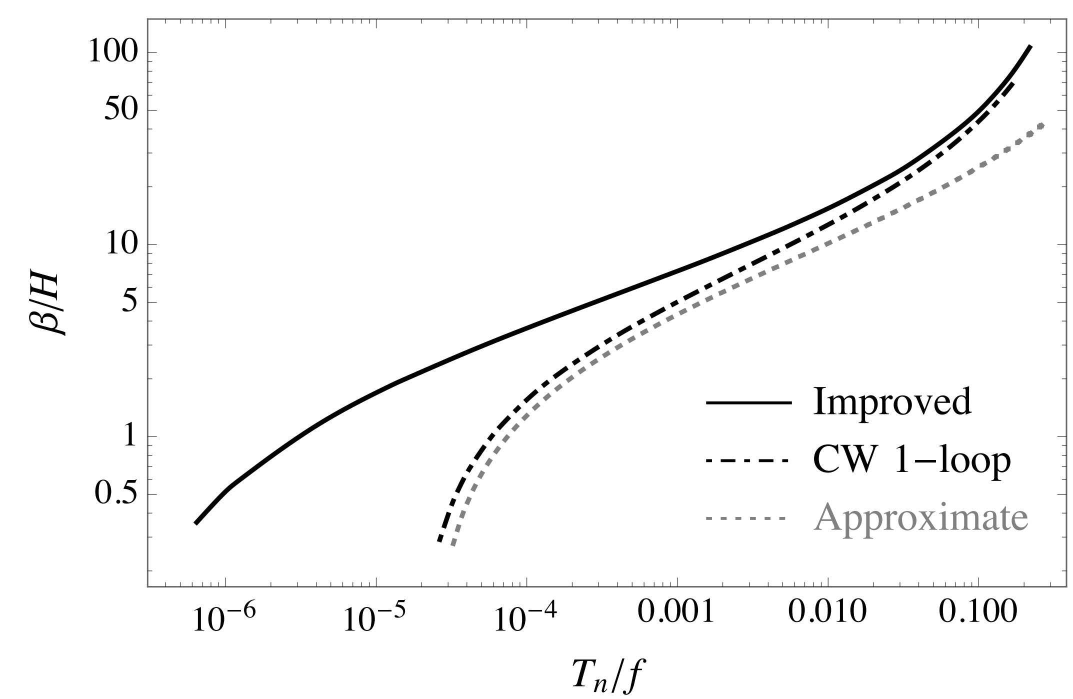
$f = 10^{11}\,\mathrm{GeV},\ g = 0$





improvement of the potential due to running has sizable impact impact

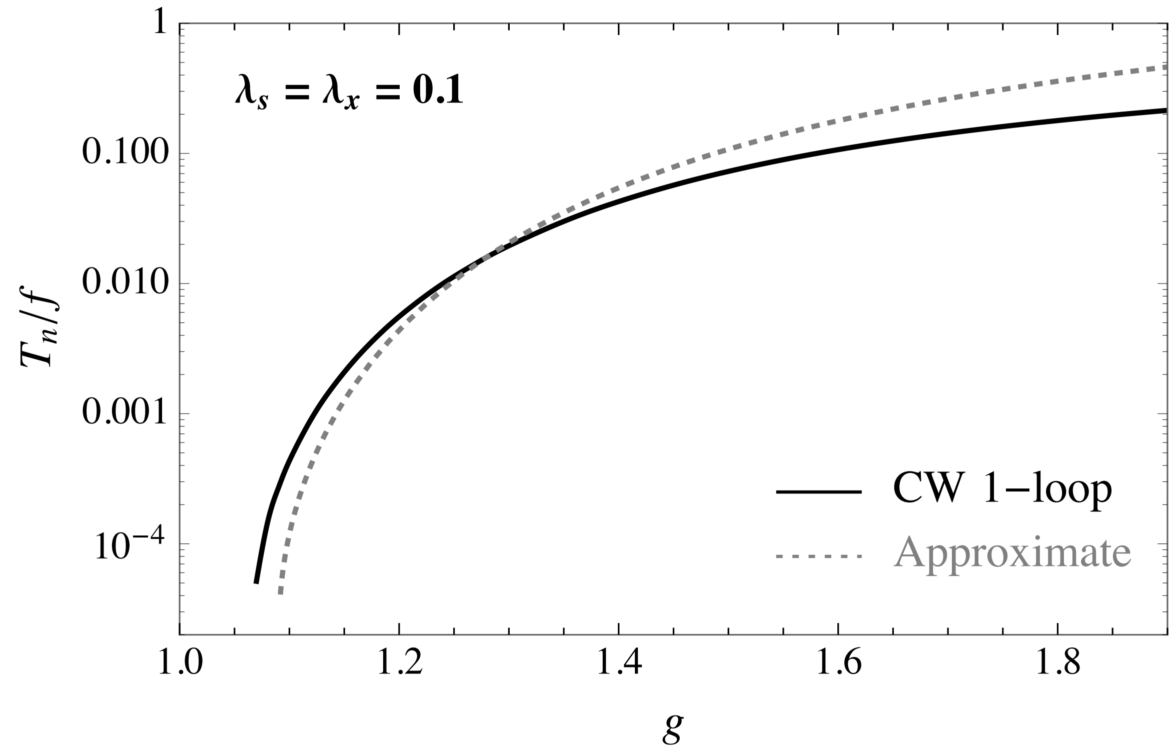
- a sizable region wit large supercooling and $\beta/H \sim few$
- approximate analytic results work remarkably well!

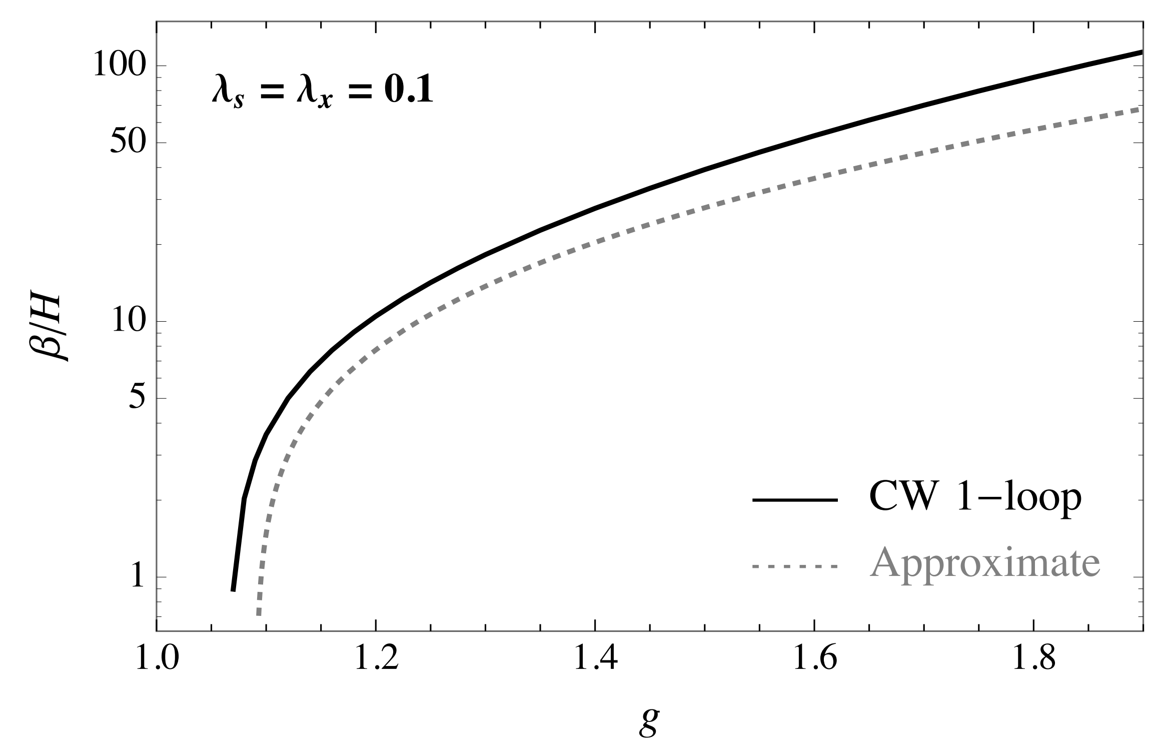


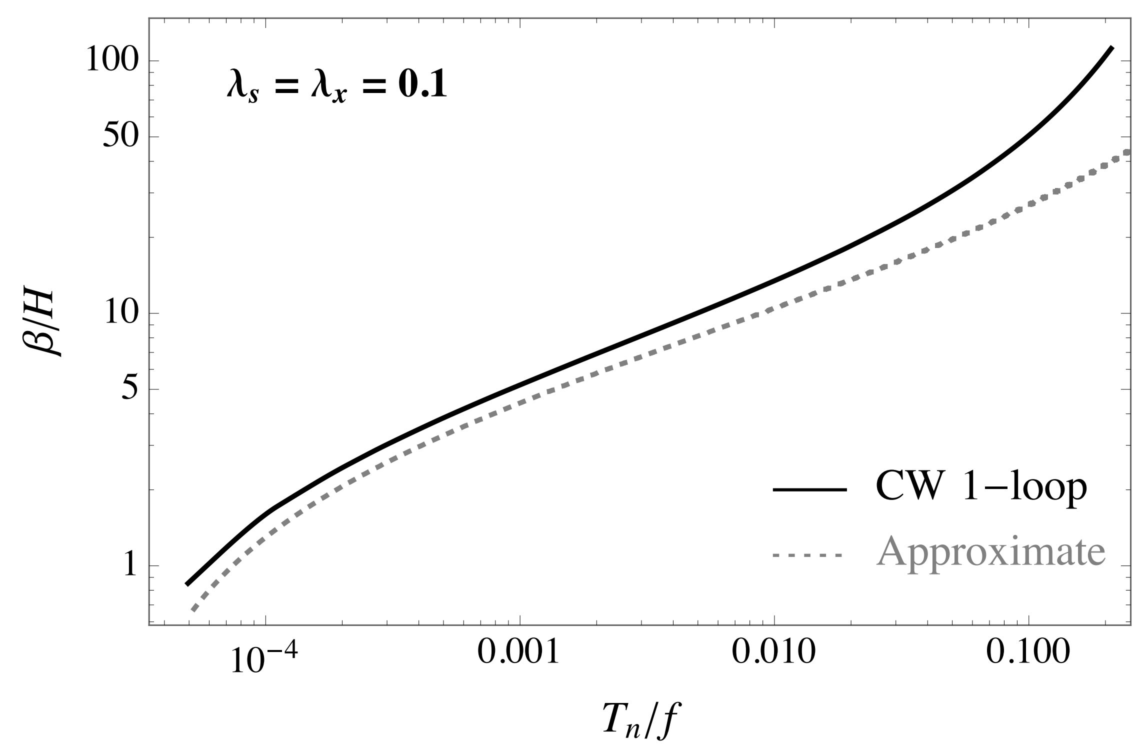
Results: Gauge coupling dominance

Limit with **gauge coupling** dominance

$f = 10^{11}\mathrm{GeV}$

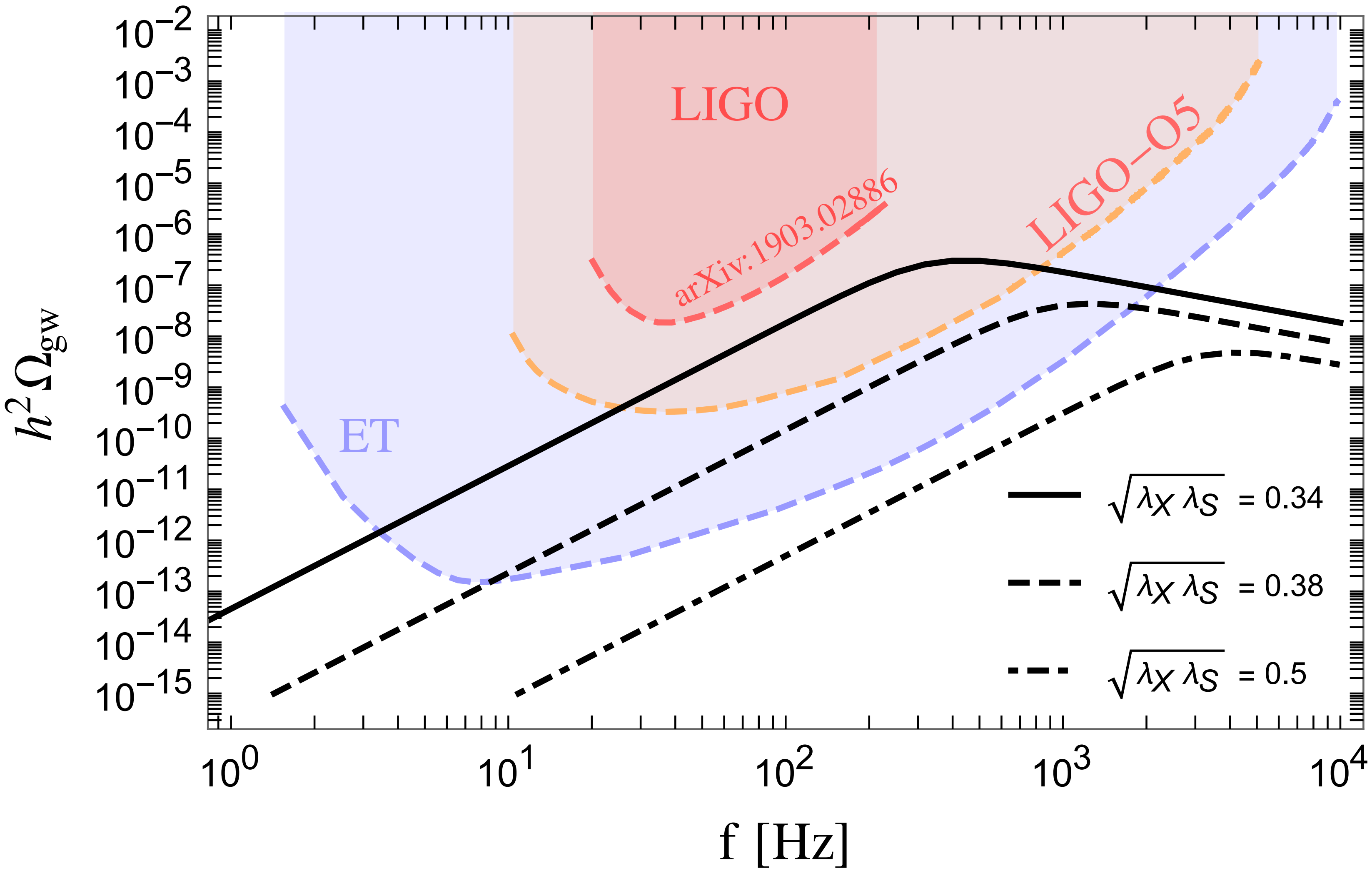






results insensitive to improvement (small running)

Gravitational waves



For large supercooling spectrum within the range of ground based experiments

Portion of the parameter space accessible at LIGO

Radiative PQ breaking at strong coupling

Confinement PhT

We consider a model with the **axion** together with a **dilaton**:
PQ breaking linked to **confinement PhT**

Explicit realization in 5D through AdS/CFT duality

[Creminelli, Nicolis, Rattazzi; Randall, Servant;…]

High T	**Low T**
AdS - Schwarzschild geometry	Randall-Sundrum geometry
Conformal invariance + unbroken $U(1)_{PQ}$	Conformal invariance broken by IR brane + broken $U(1)_{PQ}$

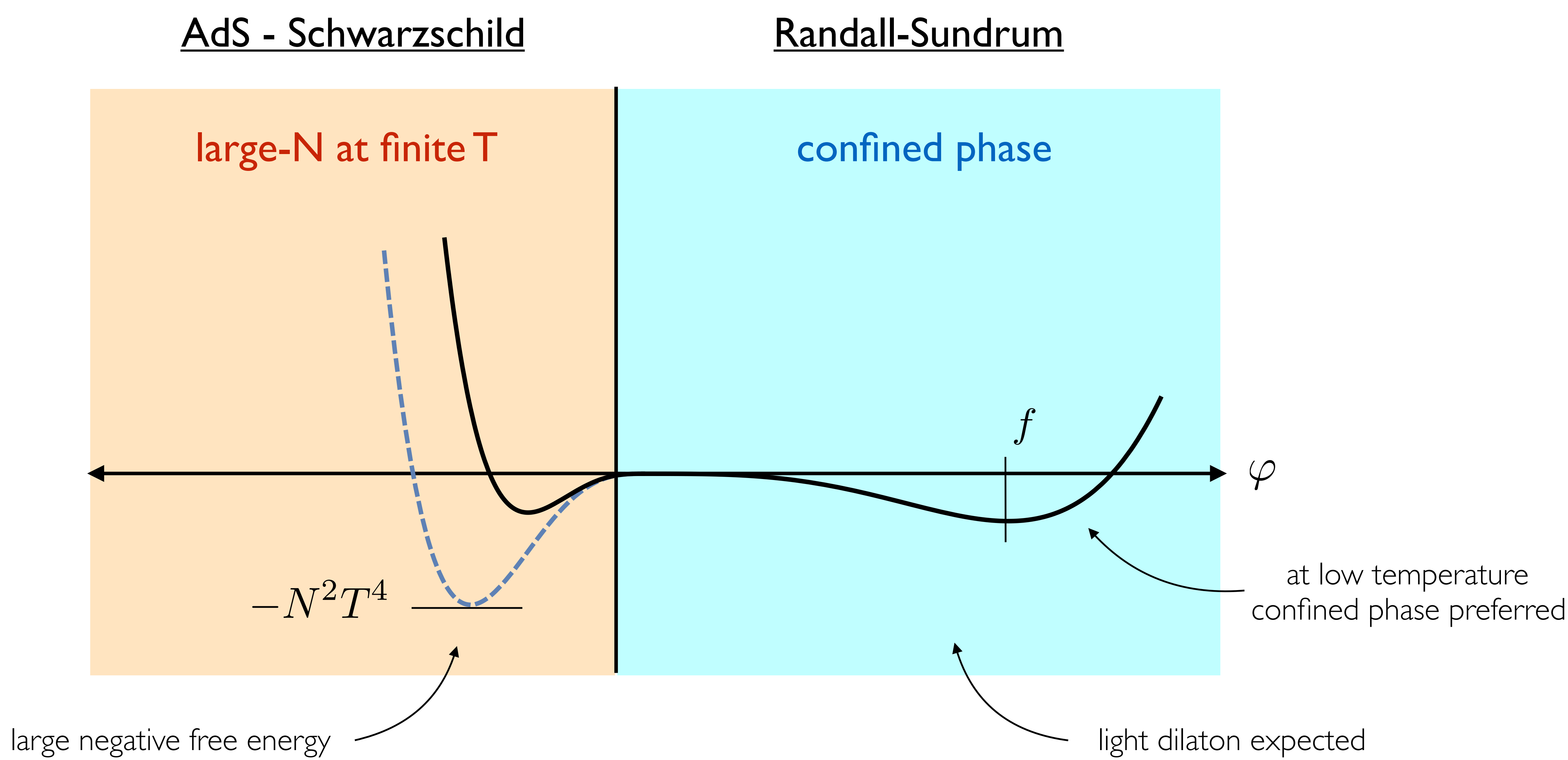
dual to gauge symmetry in 5D

Confinement PhT

We consider a model with the **axion** together with a **dilaton**:
PQ breaking linked to **confinement PhT**

Explicit realization in 5D through AdS/CFT duality

[Creminelli, Nicolis, Rattazzi; Randall, Servant;…]



The dilaton potential

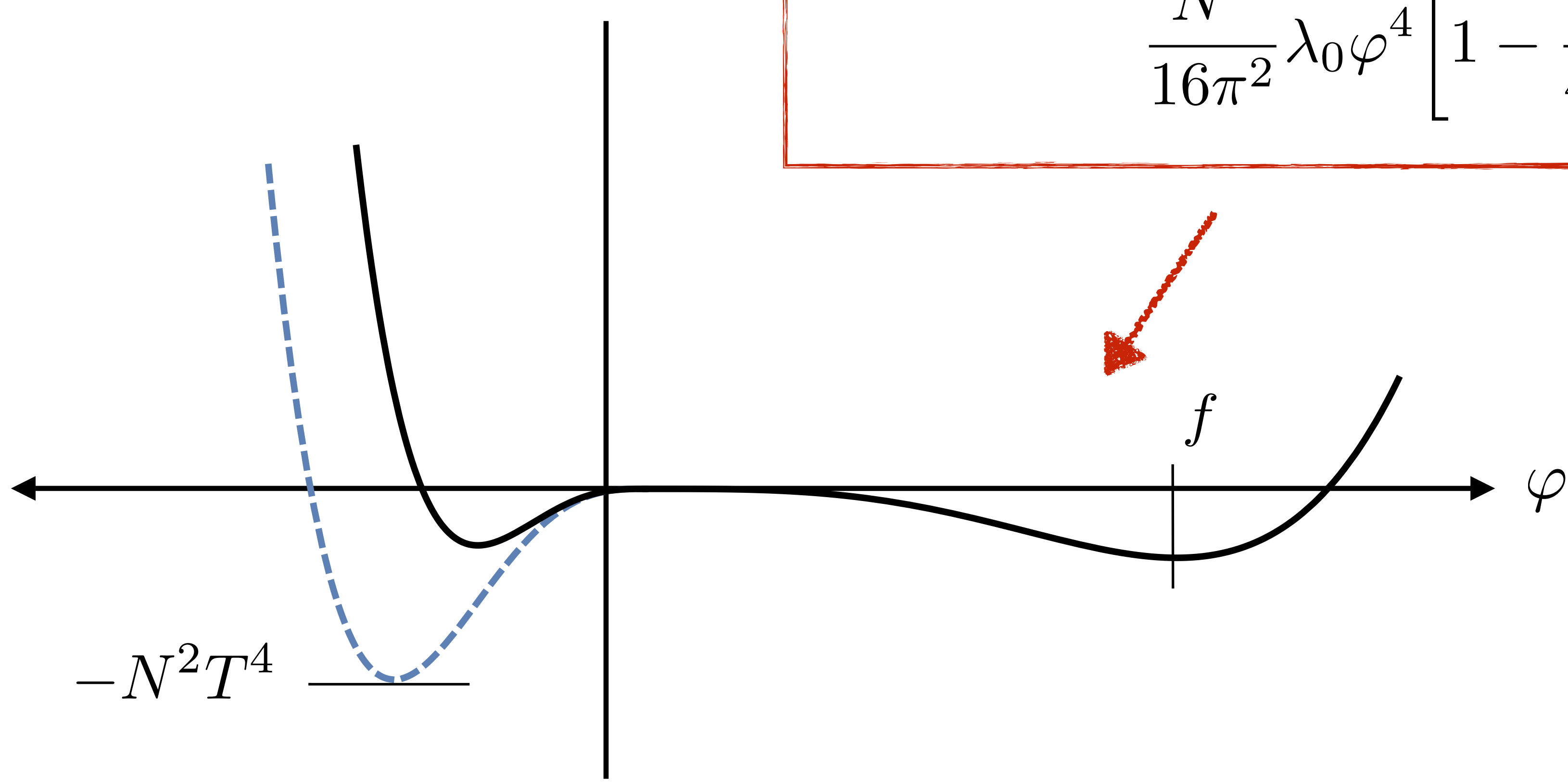
Simple parametrization for the dilaton potential

CFT explicitly broken by (almost) marginal deformation

$$\mathrm{CFT} + \frac{g}{\Lambda^\epsilon}\,\mathcal{O} \longrightarrow \beta_g = \epsilon g + a\,N\frac{g^3}{16\pi^2} + \ldots$$

Dilaton potential from running of quartic coupling

$$\frac{N^2}{16\pi^2}\lambda_0\varphi^4\left[1 - \frac{4}{4+\epsilon}\left(\frac{\varphi}{f}\right)^\epsilon\right]$$



The dilaton potential

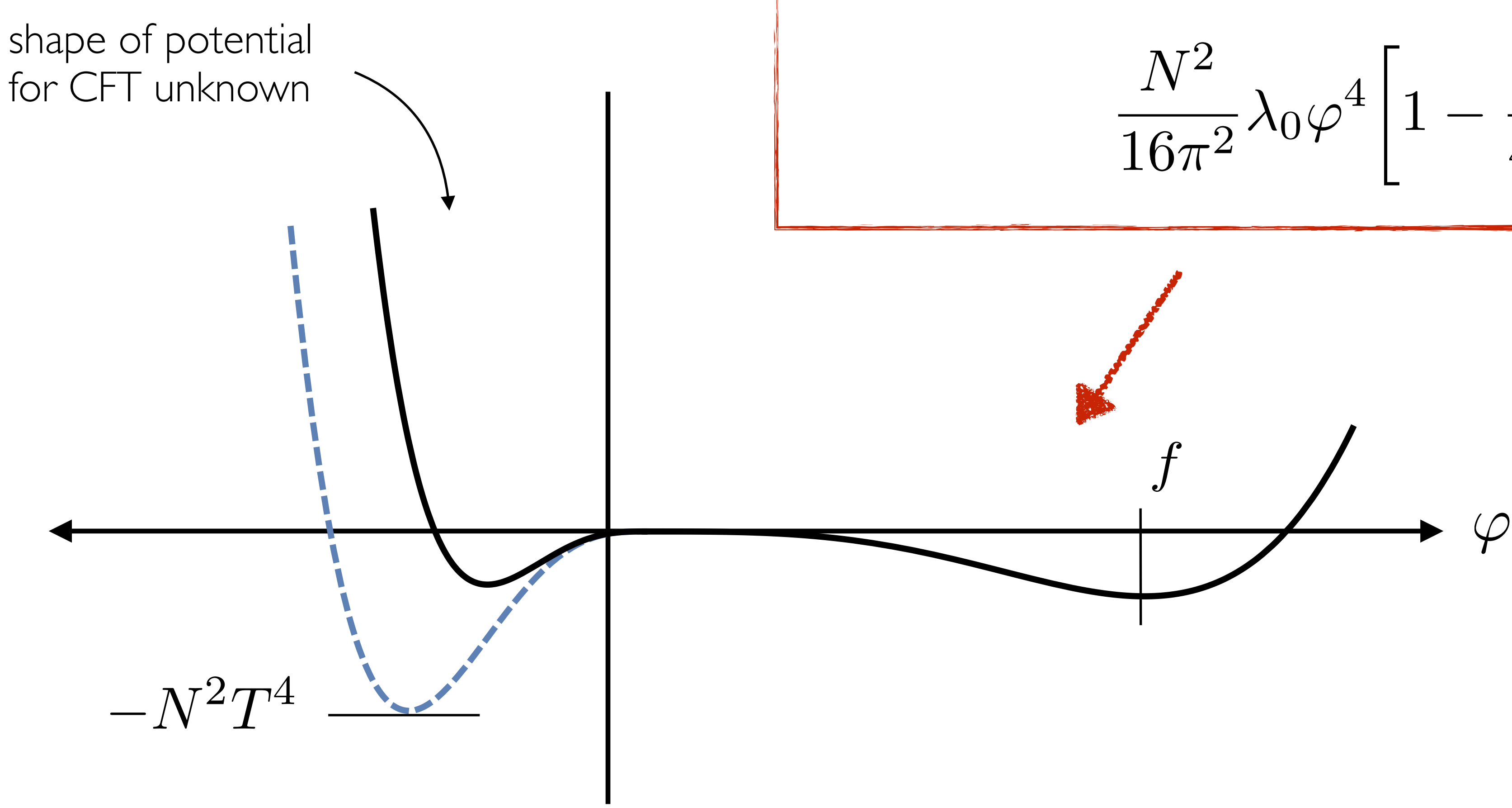
Simple parametrization for the dilaton potential

CFT explicitly broken by (almost) marginal deformation

$$\mathrm{CFT} + \frac{g}{\Lambda^\epsilon}\,\mathcal{O} \quad \longrightarrow \quad \beta_g = \epsilon g + a\,N\frac{g^3}{16\pi^2} + \ldots$$

Dilaton potential from running of quartic coupling

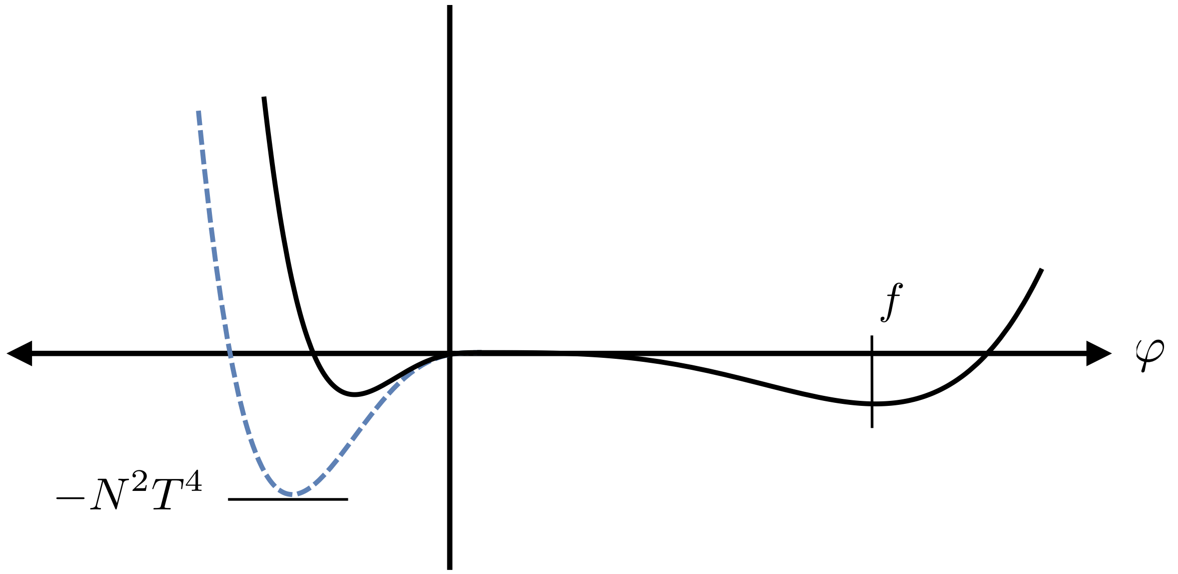
$$\frac{N^2}{16\pi^2}\lambda_0\varphi^4\left[1 - \frac{4}{4+\epsilon}\left(\frac{\varphi}{f}\right)^\epsilon\right]$$



How to compute the bounce

Use a “guess” for the potential
in the CFT phase

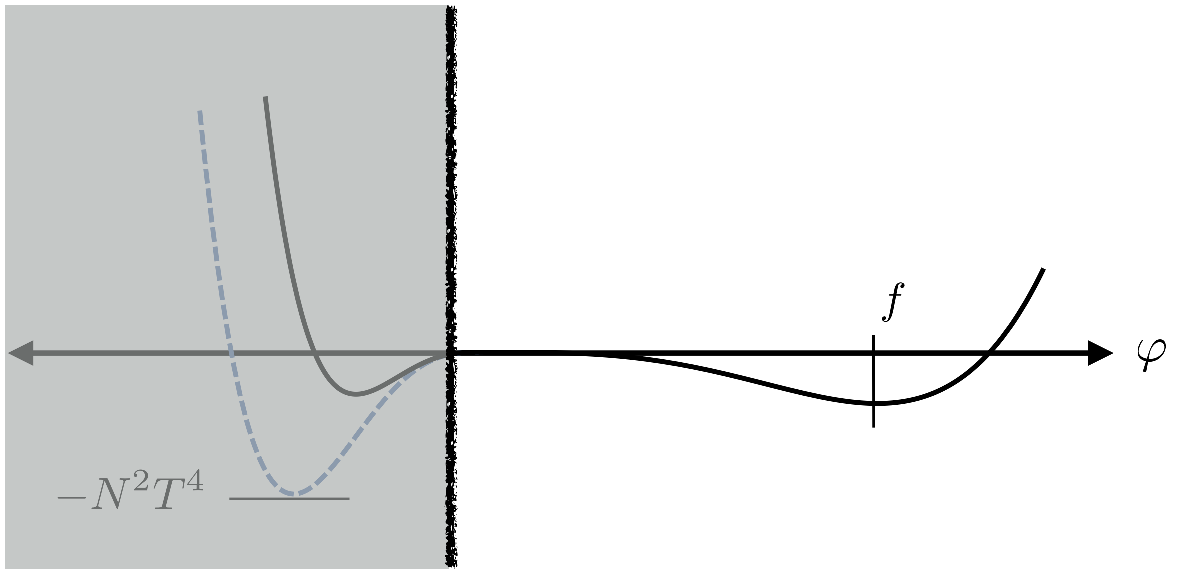
[Creminelli, Nicolis, Rattazzi;
Servant, Von Harling; Brussiger et al;
Baratella, Rompineve, Pomarol]



Neglect the CFT part and match the
gradient energy to the free energy

[Konstandin, Nardini, Quiros '10;
Agashe et al '19]

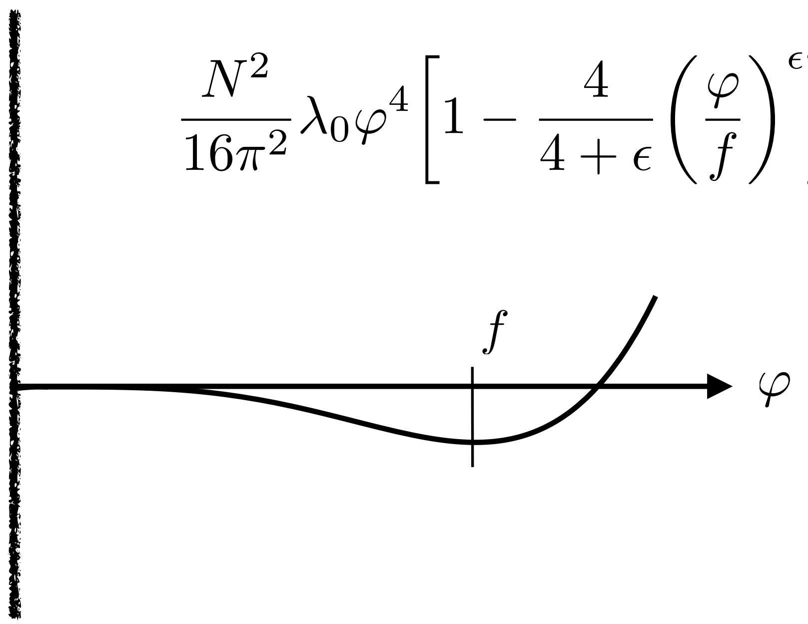
$$\dot{\varphi}^2|_{\varphi=0} \sim 16\pi^2 T^4$$



- the two methods give similar results

Analytic approximations

At large supercooling tunnelling happens very close to the origin



$$\frac{N^2}{16\pi^2}\lambda_0\varphi^4\left[1-\frac{4}{4+\epsilon}\left(\frac{\varphi}{f}\right)^{\epsilon}\right] \longrightarrow \frac{N^2}{16\pi^2}\phi^4\lambda_0\left(1-\frac{4}{4+\epsilon}\left[\frac{T}{c|\lambda_0/(16\pi^2)|^{1/4}f}\right]^{\epsilon}\right)$$

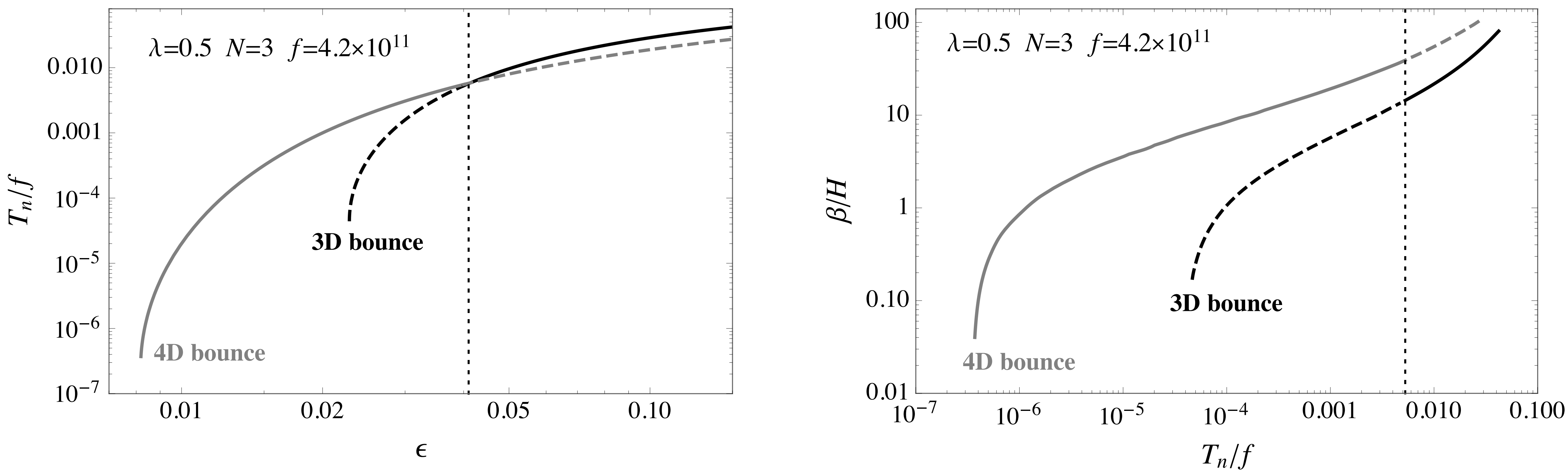
simple evolution of the quartic coupling with the temperature

- the 3D bounce action is given by $$\frac{S_3}{T}=28.5\,\frac{N^2}{16\pi^2}\times\frac{(16\pi^2)^{1/4}}{|\lambda_0|^{3/4}}\times\frac{1}{|g(T,\epsilon)|^{3/4}}$$

- 4D bounce can also be relevant (dominant at low T) $$S_4\sim 26\,\frac{N^2}{16\pi^2}\times\frac{1}{|\lambda_0|}\frac{1}{|g(T,\epsilon)|}$$

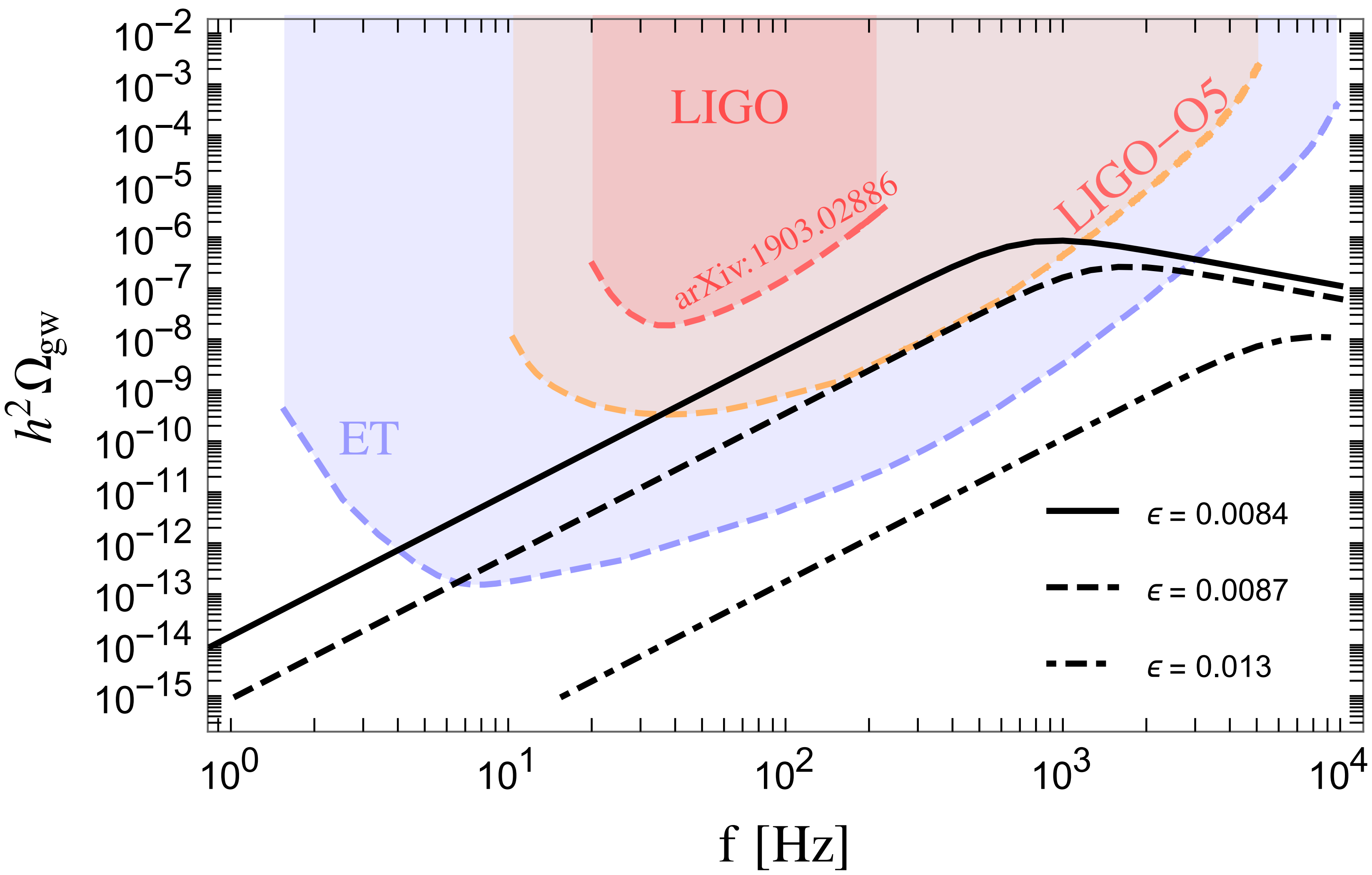
PhT properties

Most of the effects controlled by the size of the free energy
(shape of the CFT potential almost irrelevant)



- $\beta/H \sim few$ can be obtained but only in small portion of the parameter space

Gravitational waves



Portion of the parameter space accessible at LIGO

Conclusions

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)
- **Peccei-Quinn phase transition**
  - minimal scenarios predict second-order transition
  - possible first order for axion + scalar and axion + dilaton systems
  - detectable gravitational wave signal (at ground-based interferometers)