Istituto Nazionale di Fisica Nucleare
SEZIONE DI FIRENZE

Gravitational waves from Supercool Axions

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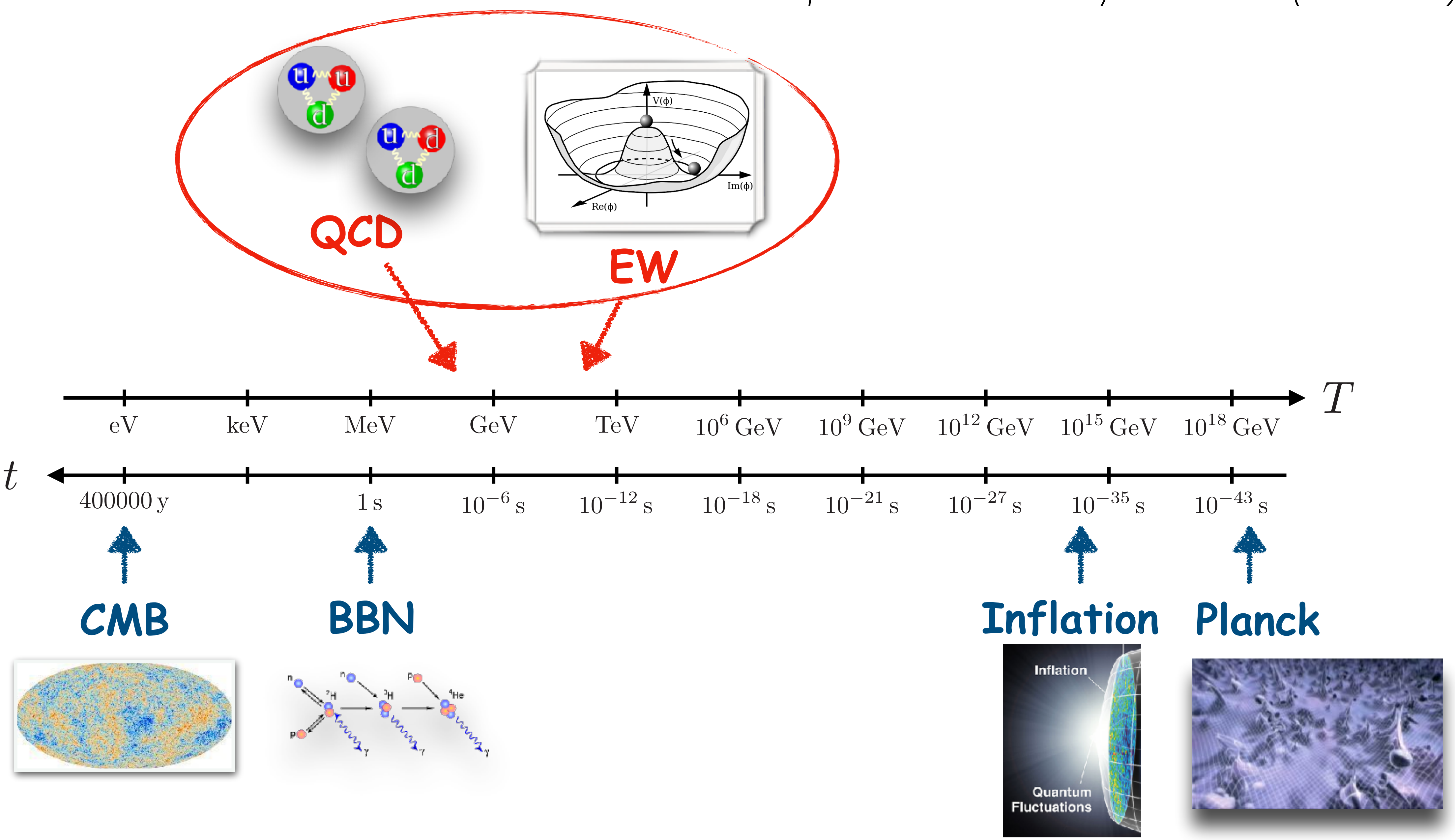
Thermal History of the Universe

Phase transitions are important events in the evolution of the Universe

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

  the two phases are smoothly connected (cross over)

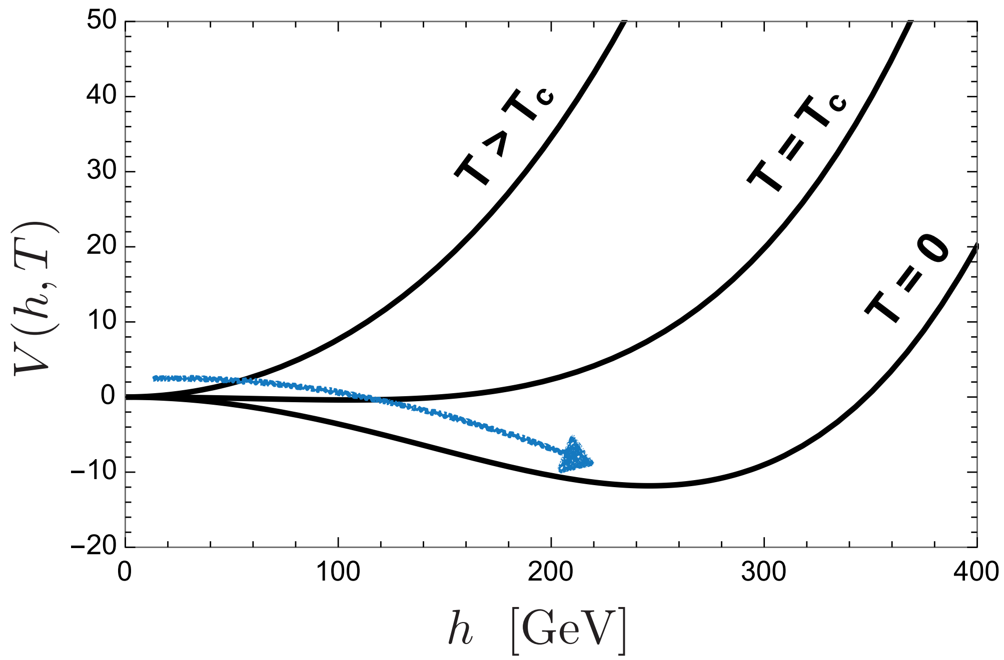


Phase transitions in the SM

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 $T < T_c$



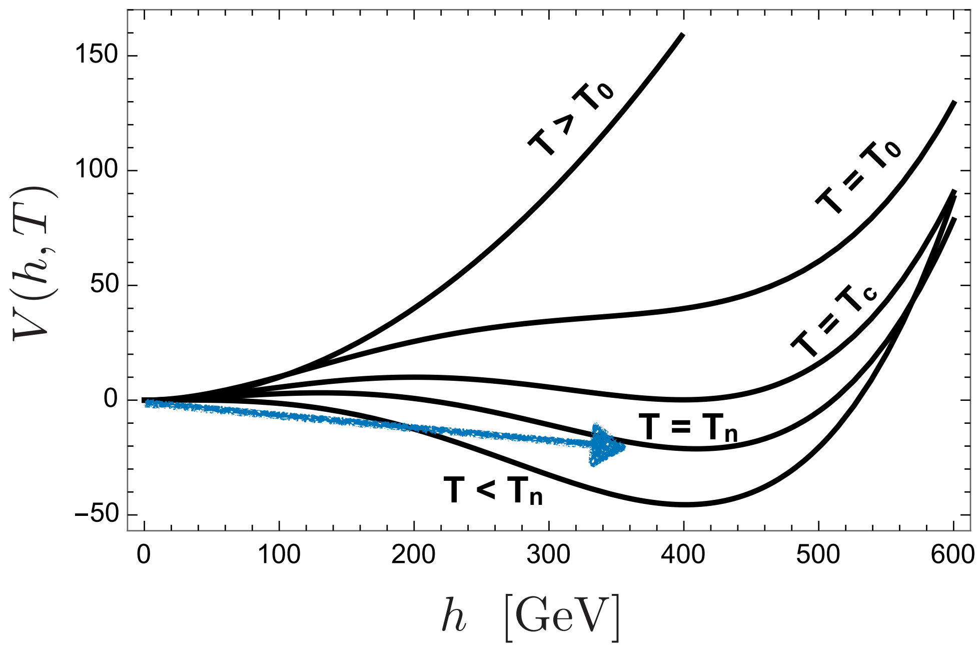
- no strong breaking of thermal equilibrium
- no distinctive experimental signatures

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

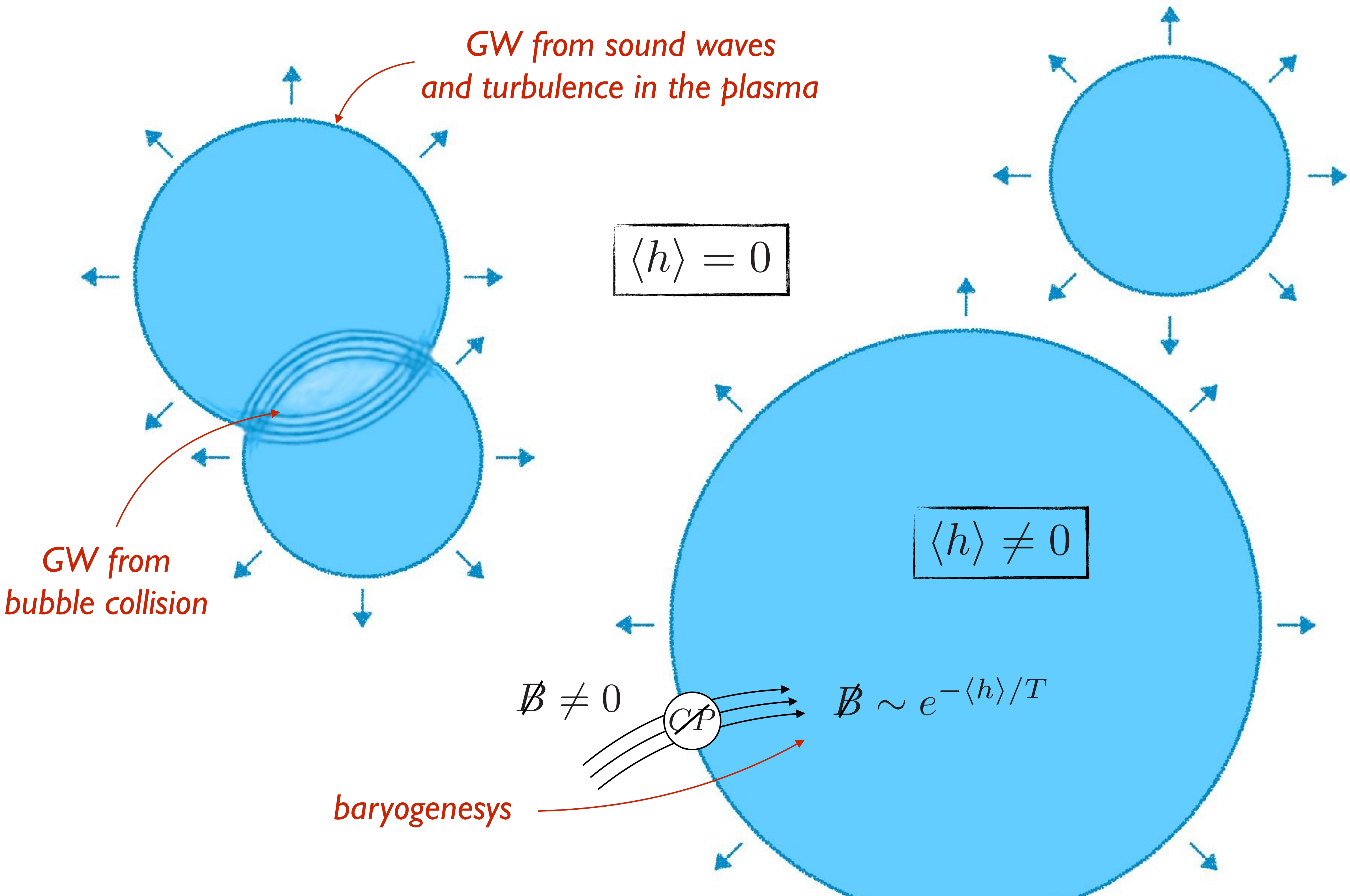
- the field tunnels from false to true minimum at $T = T_n < T_c$



- 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**

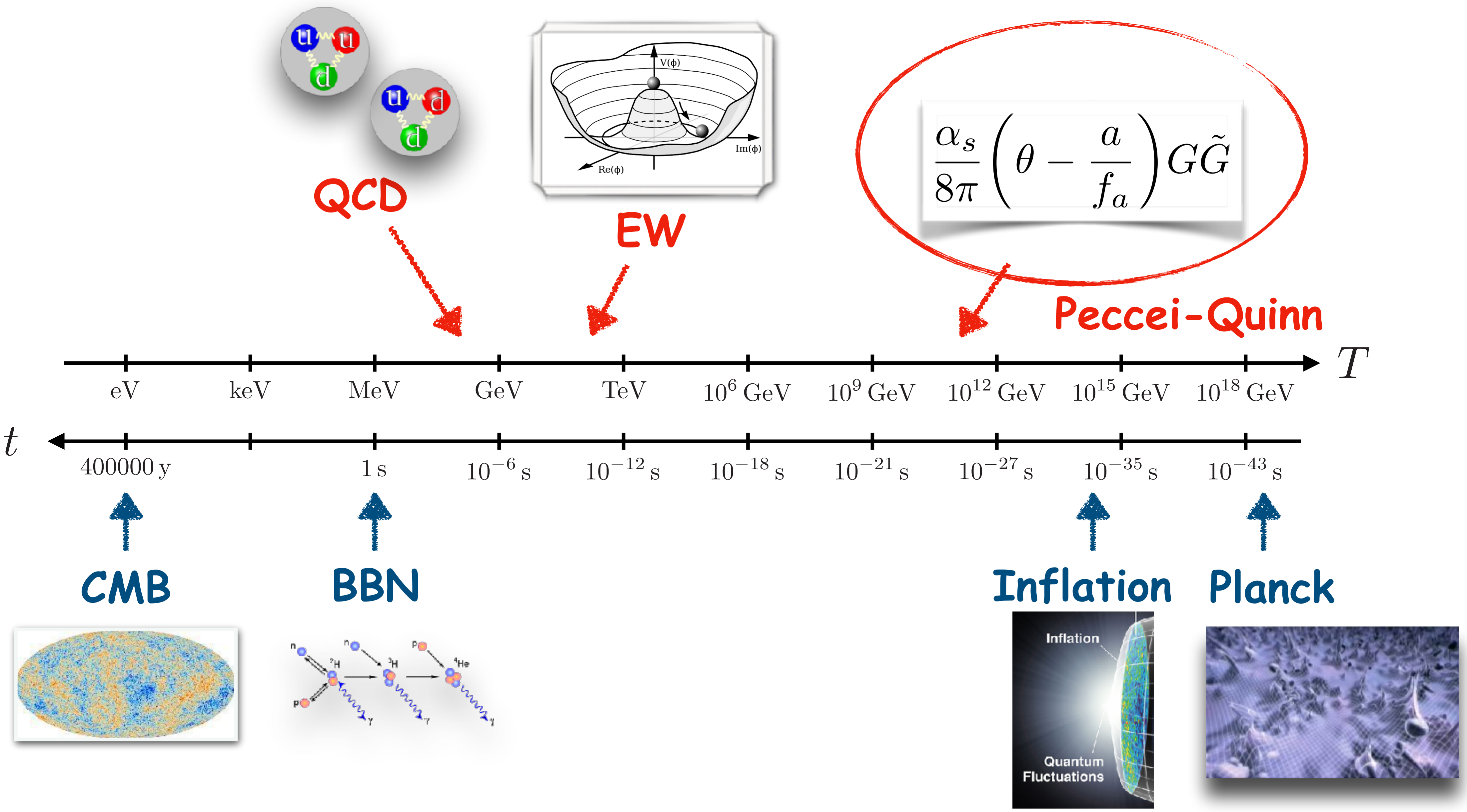


Thermal History of the Universe

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

well motivated example:

- Peccei-Quinn symmetry breaking connected to QCD axion



The axion

The **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 $f_a \gtrsim 10^9\,\mathrm{GeV}$

- **Is the phase transition of the PQ symmetry first order?**
- **Is there any signal of gravity waves?**

The minimal PQ model

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

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

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

exploiting the portal coupling with the Higgs is not enough!

[Dev, Ferrer, Zhang,Zhang '19]

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)

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

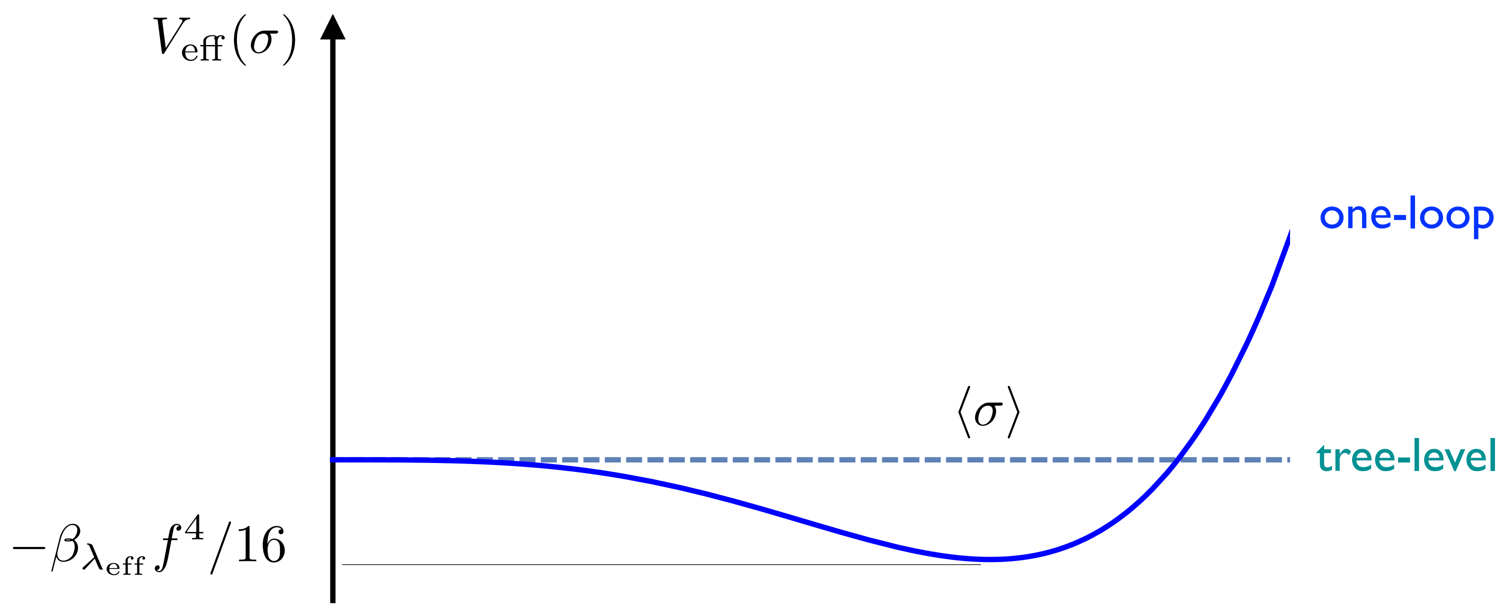
Dynamics mainly controlled by field σ

Radiative PQ breaking

Radiative corrections can lift the flat direction and stabilize the field

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

- beta function needs to be positive at the reference scale



Thermal corrections

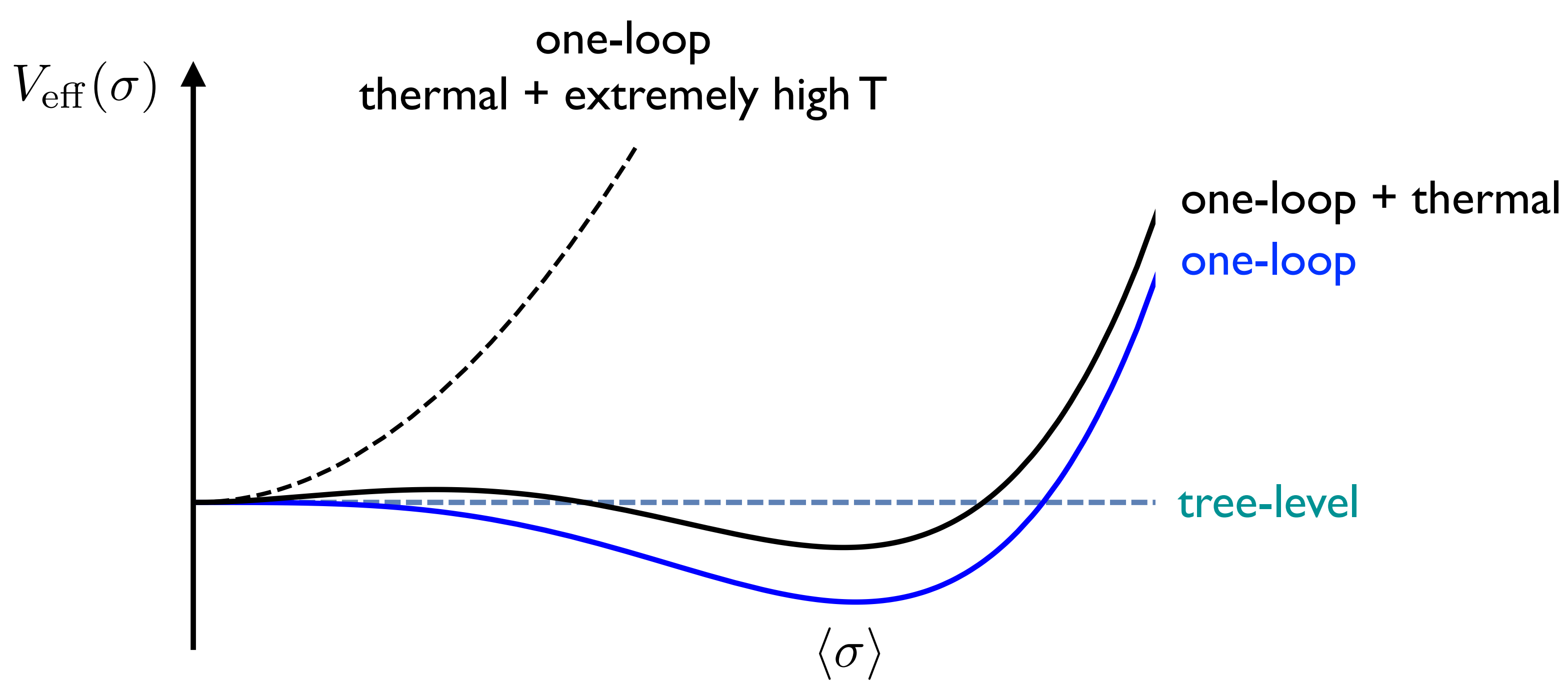
Due to flatness of the potential thermal corrections are always important

[Witten '81]

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

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!

Nucleation and supercooling

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

- the integral of the bounce action can be done exactly

[Brézin, Parisi '78]

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

S_3/T scales logarithmically with the temperature

- 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

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

this scenario has the maximal effect on the amplitude of gravitational wave power spectrum generated during the bubble collisions

An explicit realisation

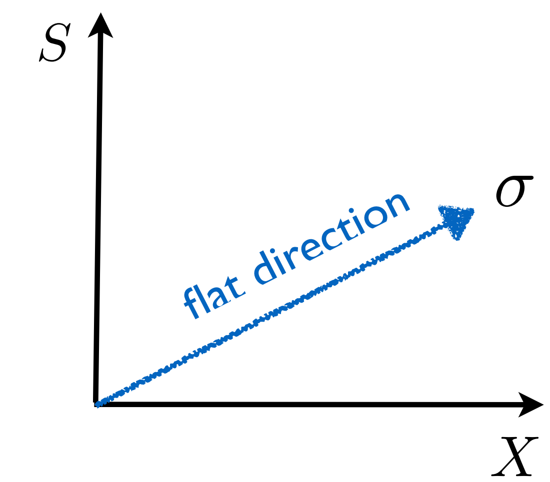
Two complex scalars: one charged under PQ and one with U(1) gauge charge

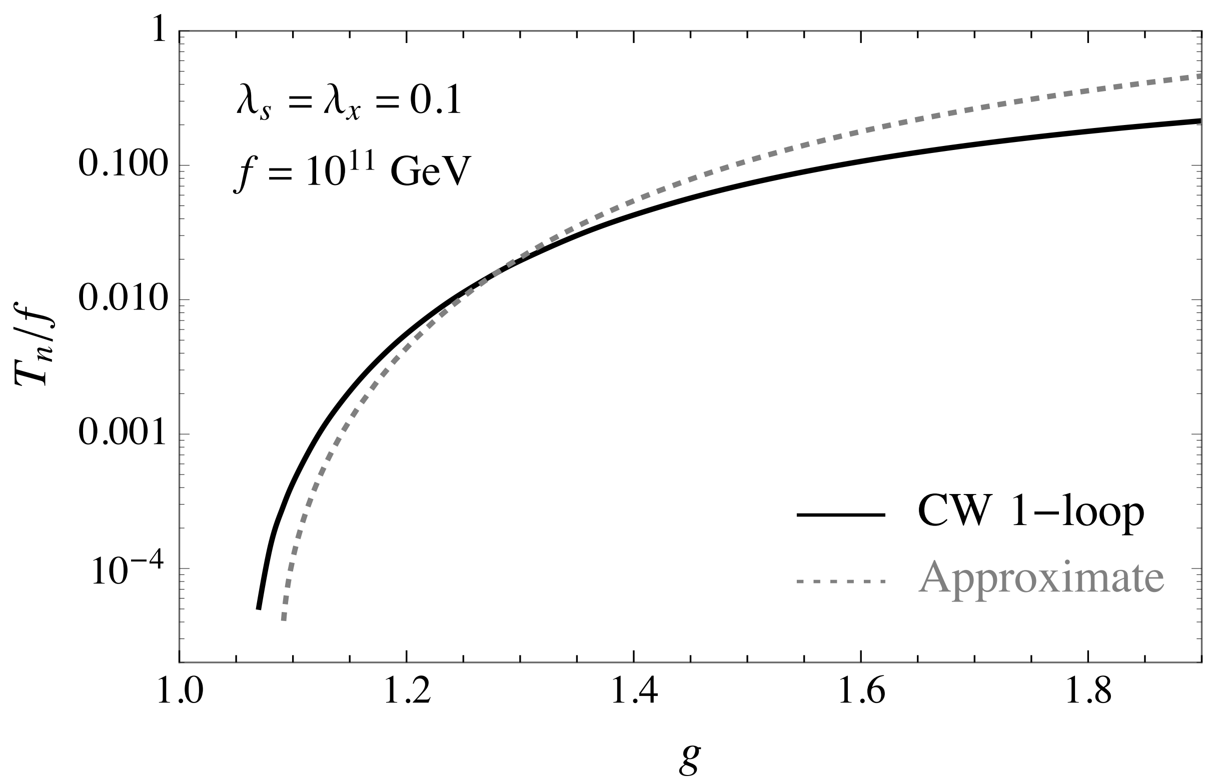
$$\mathcal{L} = -\frac{1}{4g^2}F^2 + |D_\mu S|^2 + |\partial_\mu X|^2 + (yXQQ^c + \text{h.c.}) - \lambda_S|S|^4 - \lambda_X|X|^4 - \lambda_{XS}|S|^2|X|^2$$

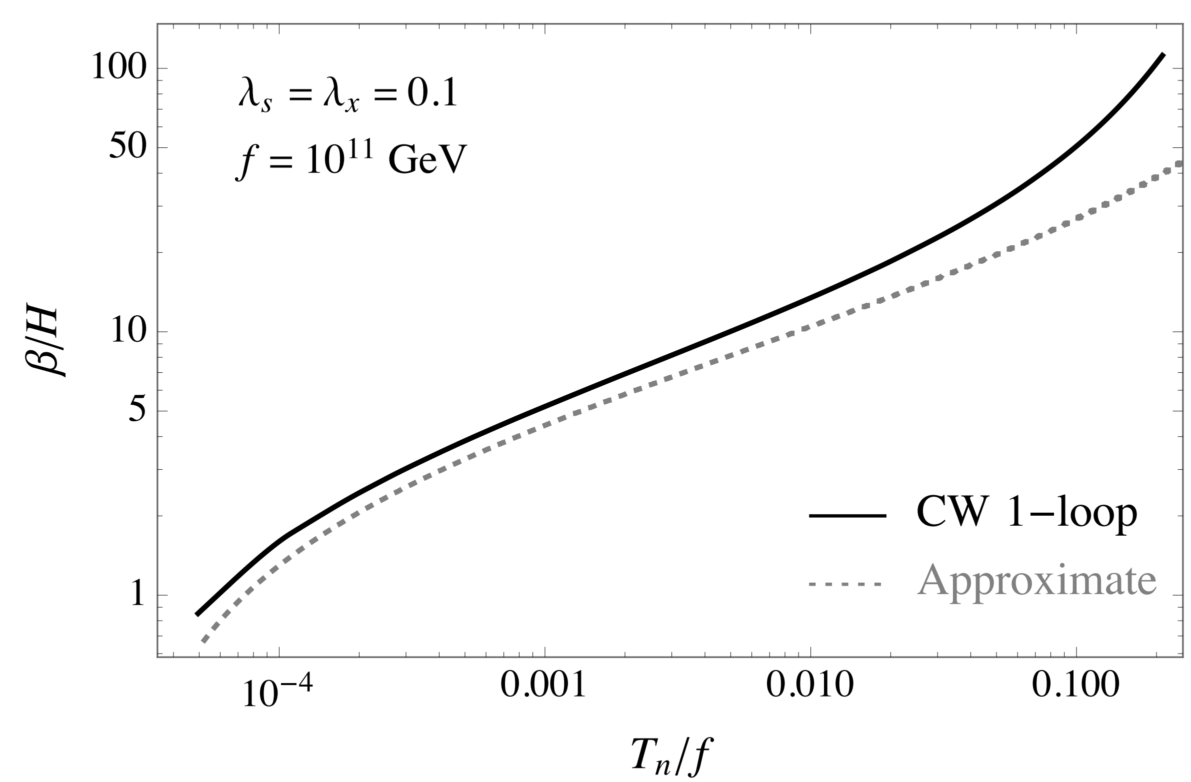
[see related Hambye, Strumia, Teresi '18]

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

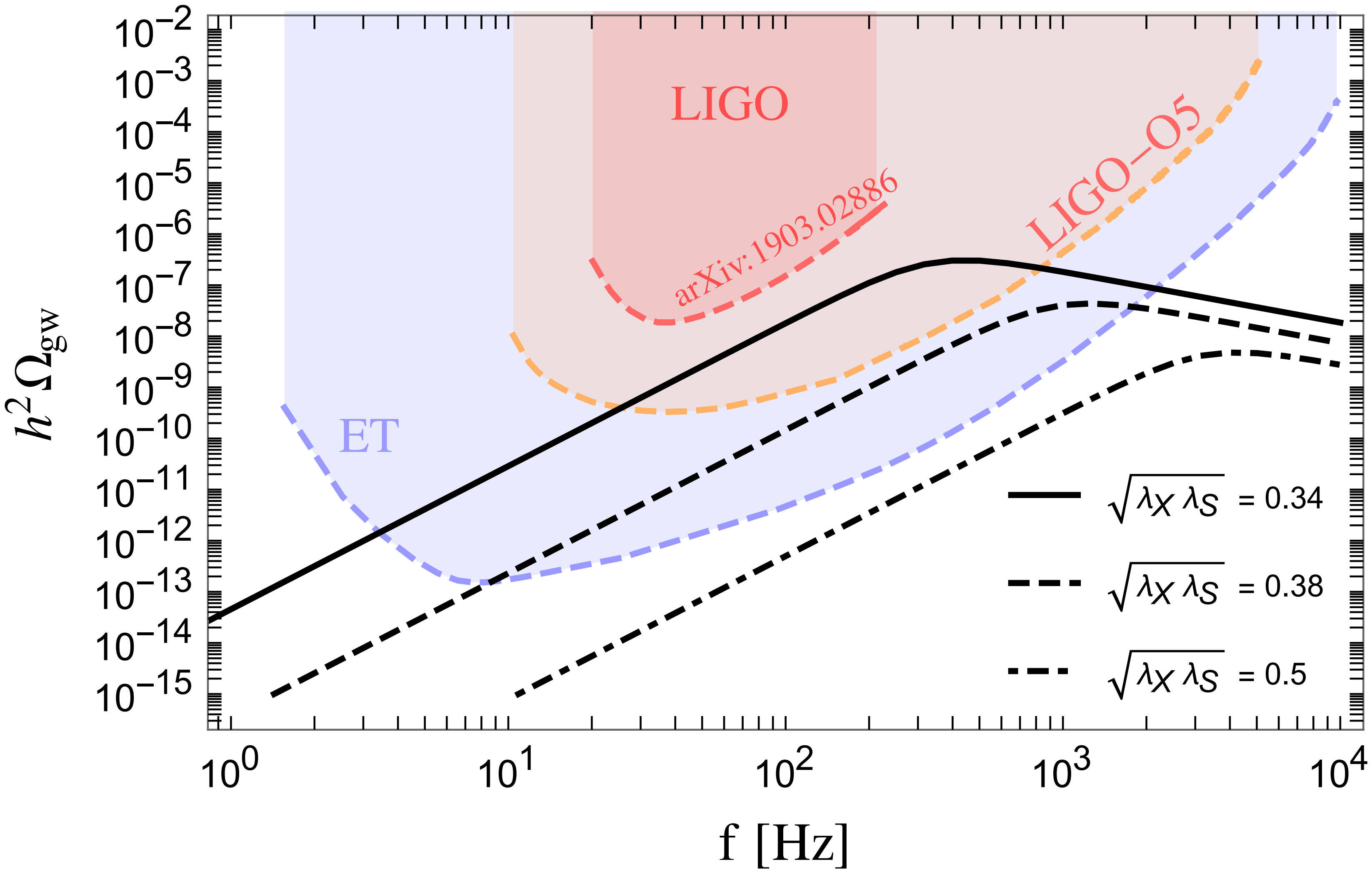
… lifted by the running induced by the quartic couplings and by the gauge interactions







Gravitational waves



For large supercooling spectrum within the range of ground based experiments

Portion of the parameter space accessible at LIGO

$$h^2\Omega_{\rm gw}\big|_{\rm peak} \simeq 1.27 \times 10^{-10} \left(\frac{100}{\beta/H}\right)^2 \qquad f_{\rm peak} \simeq 3.83 \times 10^5\,{\rm Hz} \left(\frac{\beta/H}{100}\right)\left(\frac{T}{10^{11}{\rm GeV}}\right)$$

Radiative PQ breaking at strong coupling

Confinement phase transition

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

strongly coupled large-N CFT at finite temperature with global Peccei-Quinn U(1)

tiny deviation from scale invariance realises a 1st order phase transition with a large amount of supercooling
(in the same spirit as in the weakly coupled case)

breaking of scaling invariance at a scale f also triggers PQ breaking

$$\langle 0 | j^{\mu}_{\rm PQ}(p) | a \rangle \sim \frac{N}{4\pi} f \, p^{\mu}$$

Explicit realization in 5D through AdS/CFT duality

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

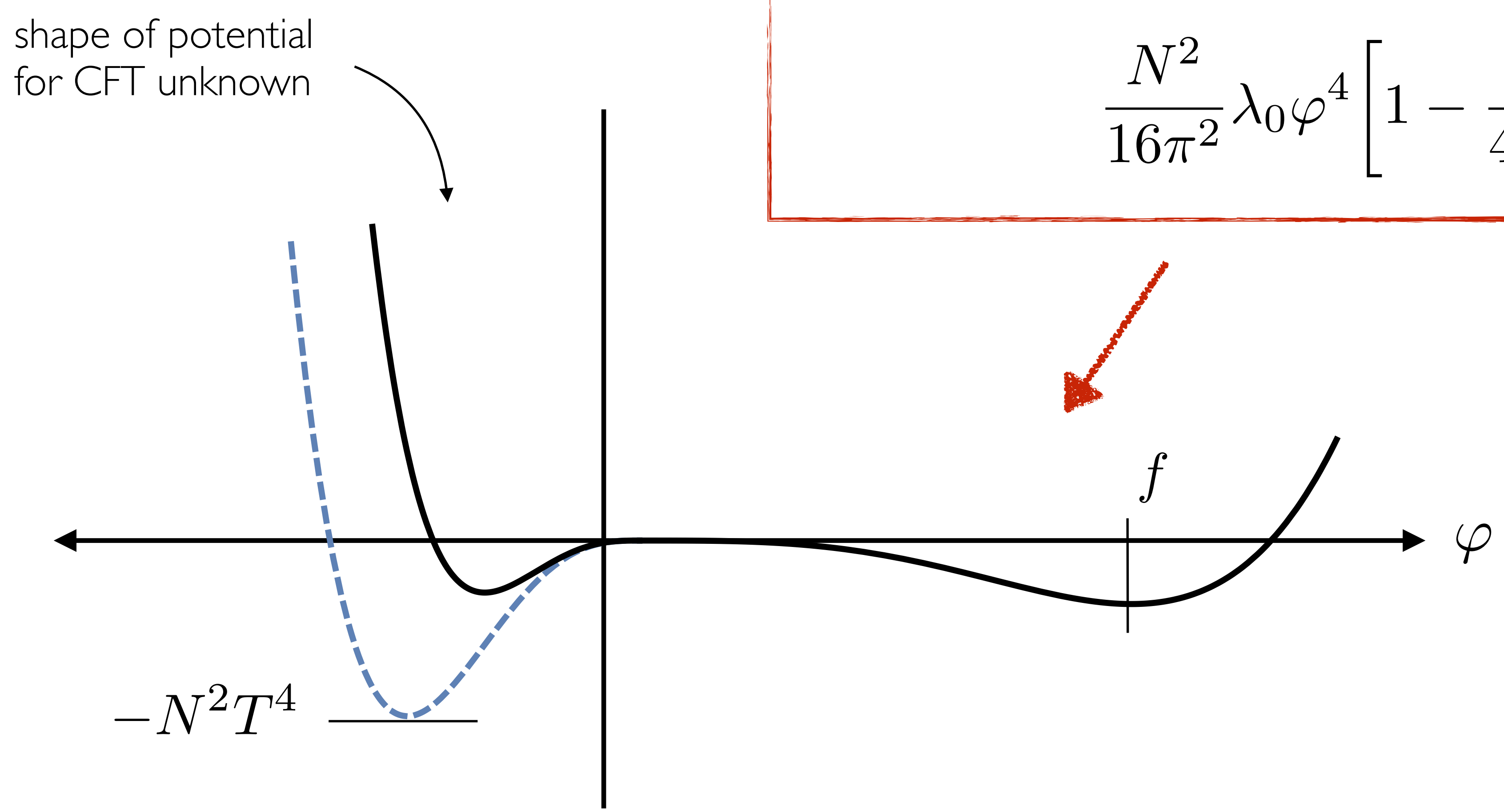
The dilaton potential

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

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



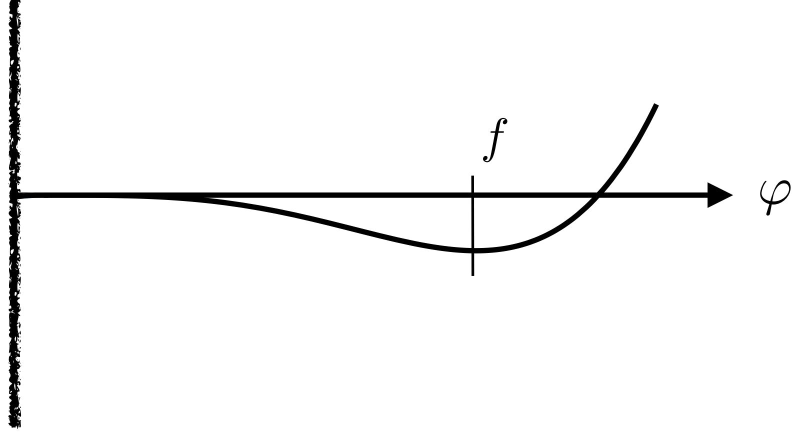
deconfined phase
unbroken PQ

confined phase
spontaneously broken PQ

Analytic approximations

At large supercooling tunnelling happens very close to the origin

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



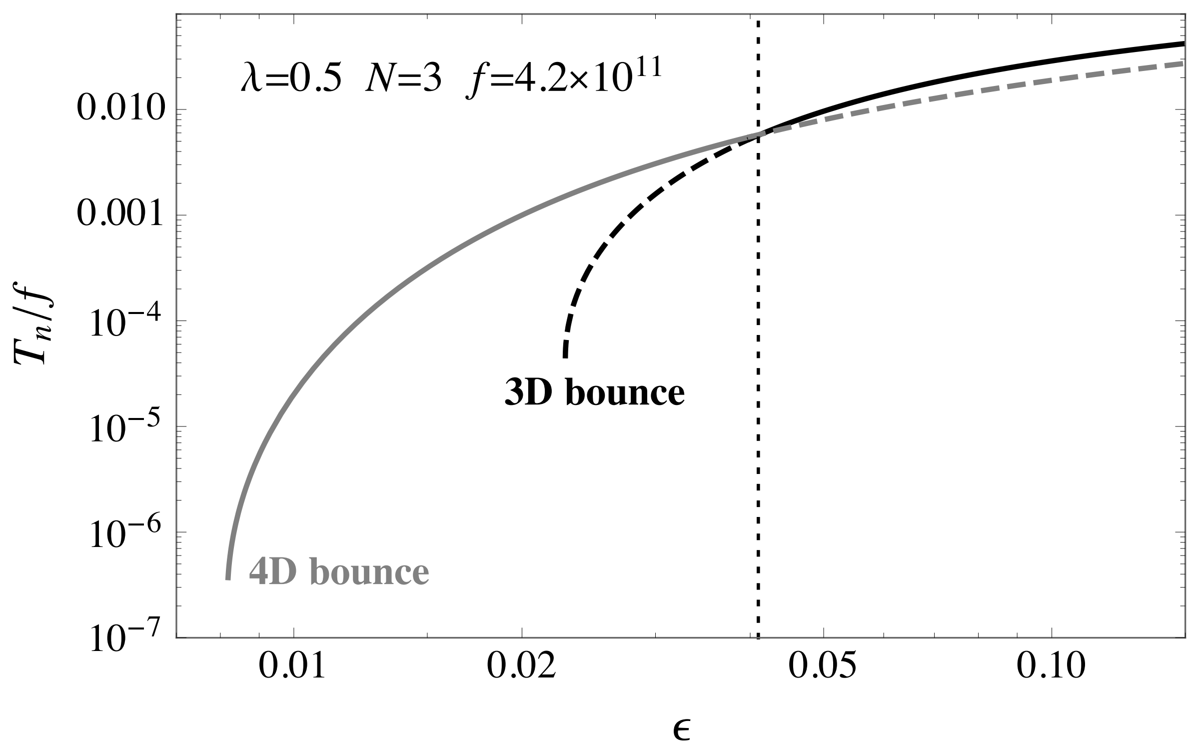
simple evolution of the quartic coupling
with the temperature

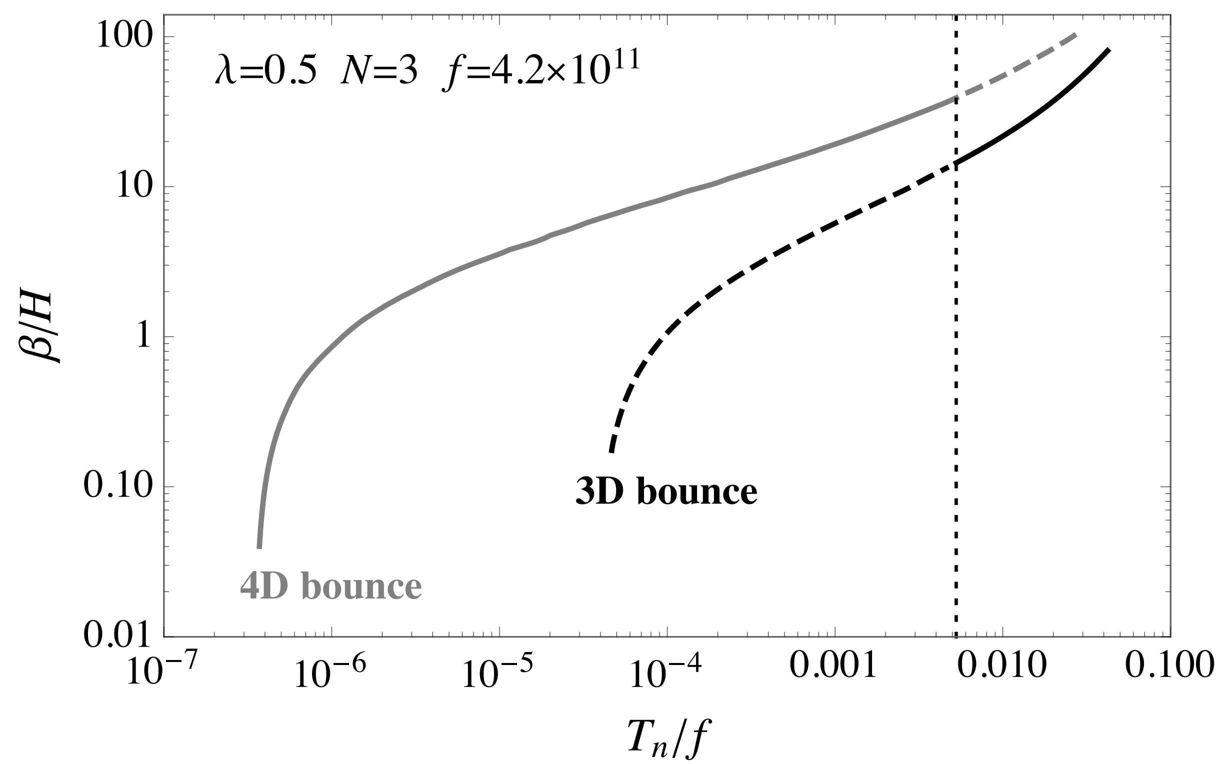
- the 3D bounce action is given by
$$\frac{S_3}{T} = 28.5\,\frac{N^2}{16\pi^2}\times\frac{(16\pi^2)^{1/4}}{|\lambda_0|^{3/4}}\times\frac{1}{|g(T,\epsilon)|^{3/4}}$$

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

Properties of the phase transition

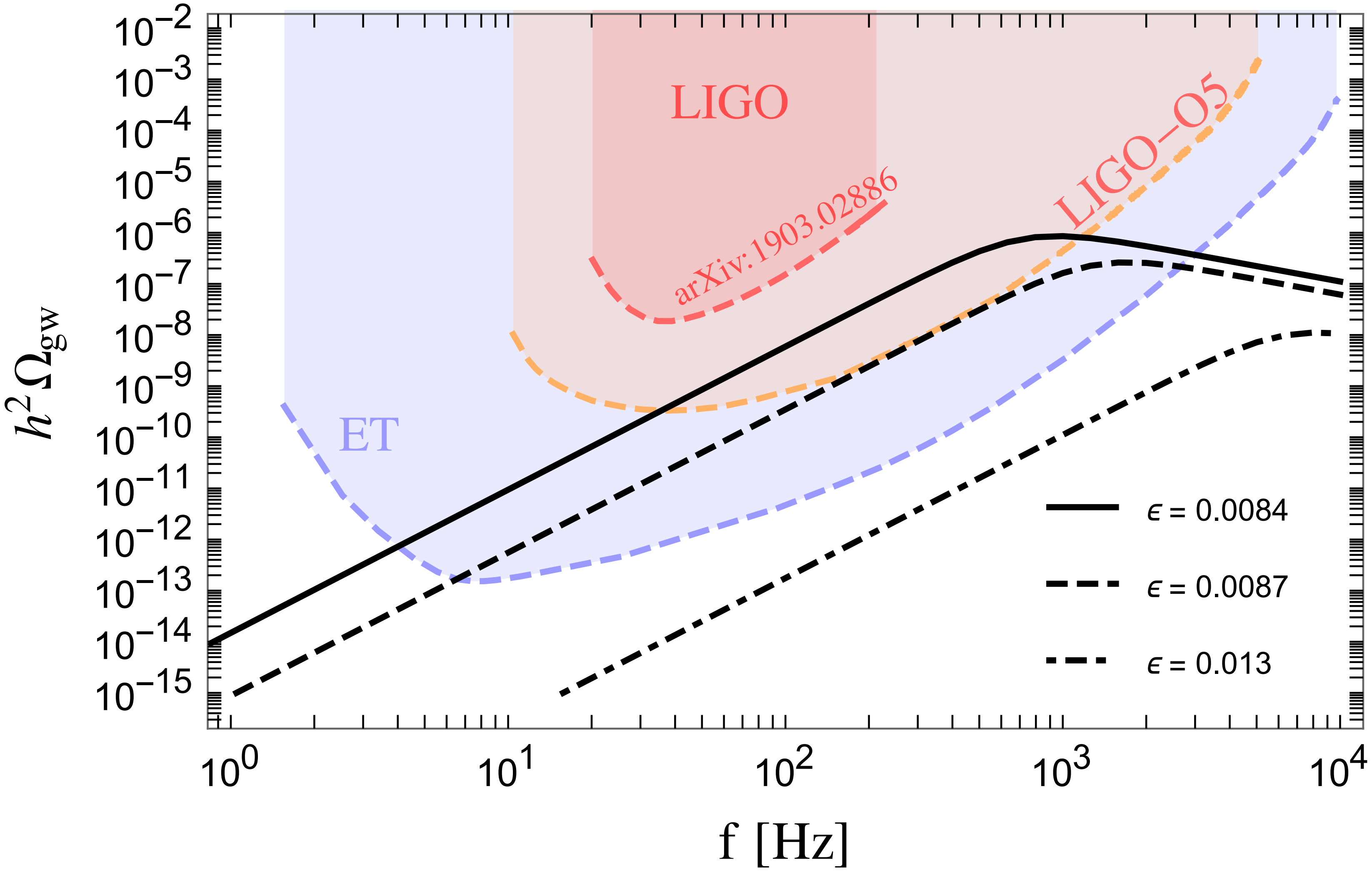
Most of the effects controlled by the size of the free energy
(shape of the CFT potential almost irrelevant)





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

Gravitational waves



Portion of the parameter space accessible at LIGO

Conclusions

Peccei-Quinn phase transition:

- minimal scenarios predict a second-order phase transition
- possible first order phase transitions with large supercooling in (axion, scalar) and (axion, dilaton) systems
- detectable gravitational waves at ground-based interferometers