Gravitational Waves from a dilaton induced first order QCD PT

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Based on arXiv: 2507.01191
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QCD and its Dilaton

$$\mathscr{L}_{\mathrm{QCD}} \supset -\frac{1}{2g^2}\mathrm{Tr}\left[G_{\mu\nu}G^{\mu\nu}\right] + \frac{\theta}{16\pi^2}\mathrm{Tr}\left[G_{\mu\nu}\tilde{G}^{\mu\nu}\right]$$

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2 Parameters : **coupling** and theta angle

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2 Parameters : **coupling** and **theta angle**

QCD and its Dilaton

Motivated by no free parameters in Quantum Gravity

$$\mathscr{L}_{\mathrm{QCD}} \supset -\frac{1}{2} f(\phi)\, \mathrm{Tr}\left[G_{\mu\nu}G^{\mu\nu}\right] + \frac{1}{16\pi^2}\frac{a}{f_a}\mathrm{Tr}\left[G_{\mu\nu}\tilde{G}^{\mu\nu}\right]$$

$$f\left(\langle\phi\rangle\right) = \frac{1}{g^2}\bigg|_{\mathrm{UV}}$$

$$\langle\frac{a}{f_a}\rangle = \theta$$

Dilaton

Axion

QCD and its Dilaton

Focus on the QCD “dilaton” in this talk

$$\mathcal{L}_{\mathrm{QCD}} \supset -\frac{1}{2} f(\phi)\ \mathrm{Tr}\left[G_{\mu\nu}G^{\mu\nu}\right]$$

$$f\left(\langle\phi\rangle\right) = \frac{1}{g^2}\bigg|_{\mathrm{UV}}$$

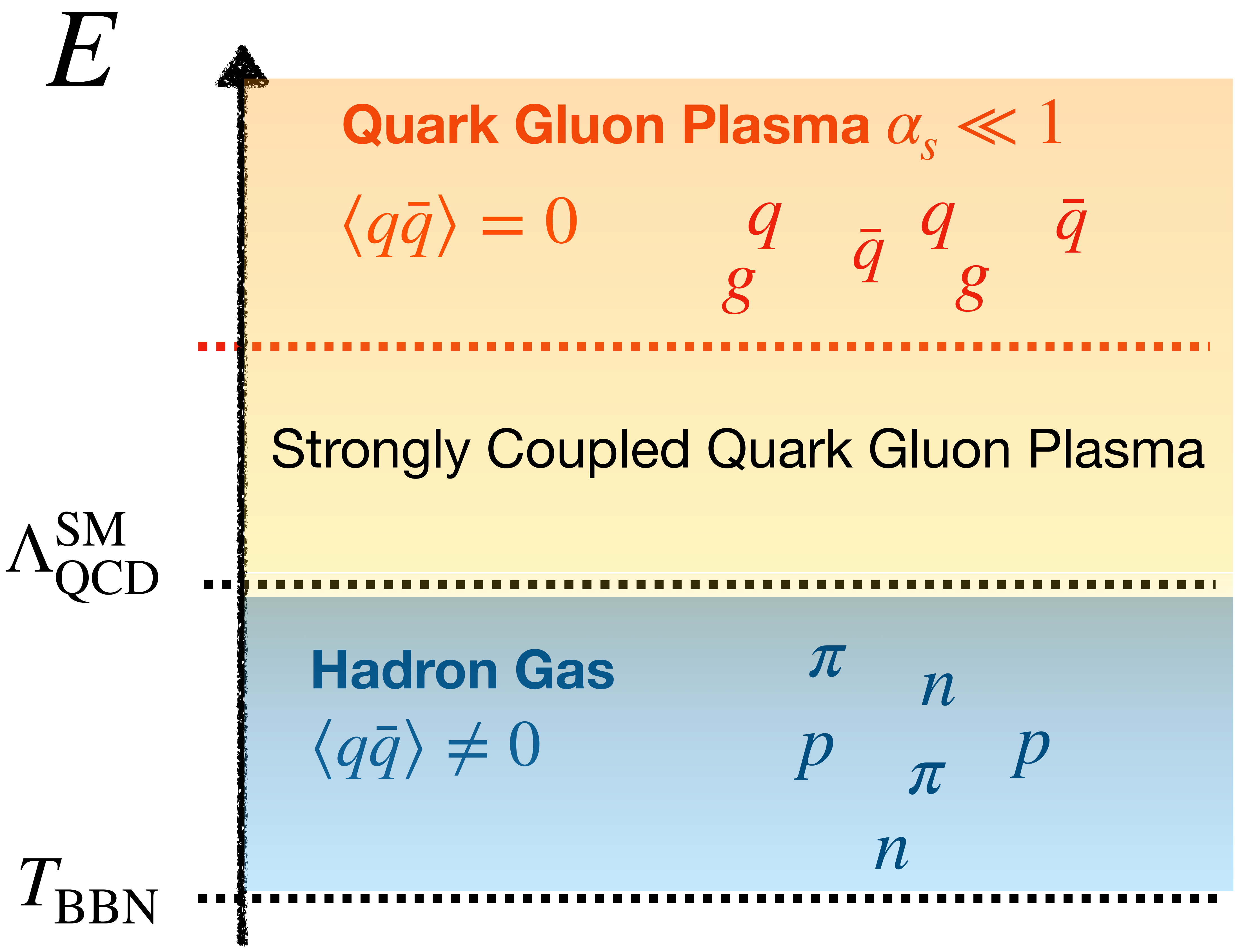
Dilaton

See arXiv:2407.01676 and upcoming works for possible implications of dilaton phase transitions on axion DM

QCD confinement scale

$$\phi = \bar{\phi}_{\mathrm{SM}}$$

Dimensional Transmutation $\Lambda_{\mathrm{QCD}} = \mu \exp\left(-\frac{8\pi^2}{\beta_0\, g^2(\mu)}\right)$



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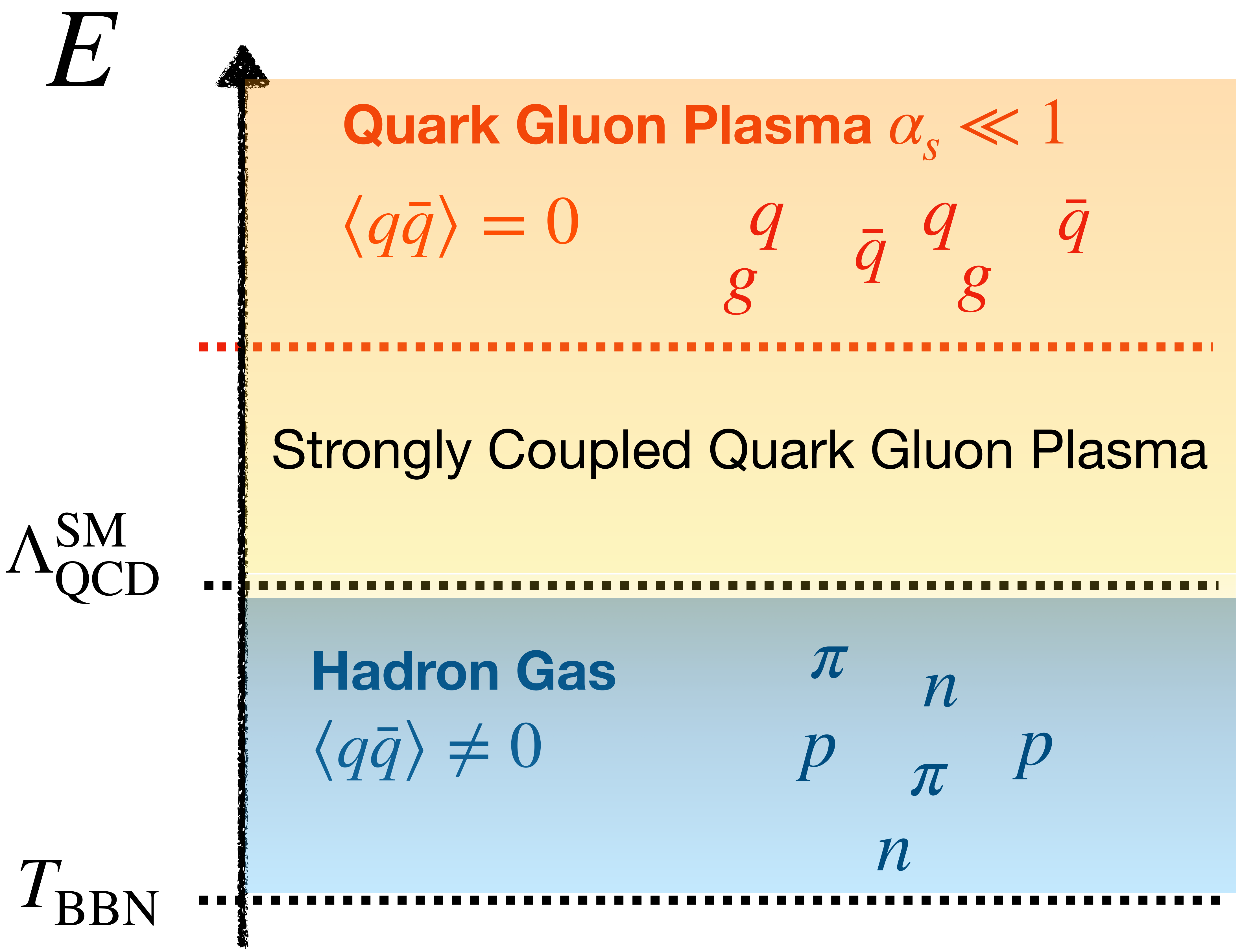


Dimensional Transmutation $\quad \Lambda_{\rm QCD} = \mu \exp\left(-\frac{8\pi^2}{\beta_0\, g^2(\mu)}\right)$

But the coupling depends on the dilaton

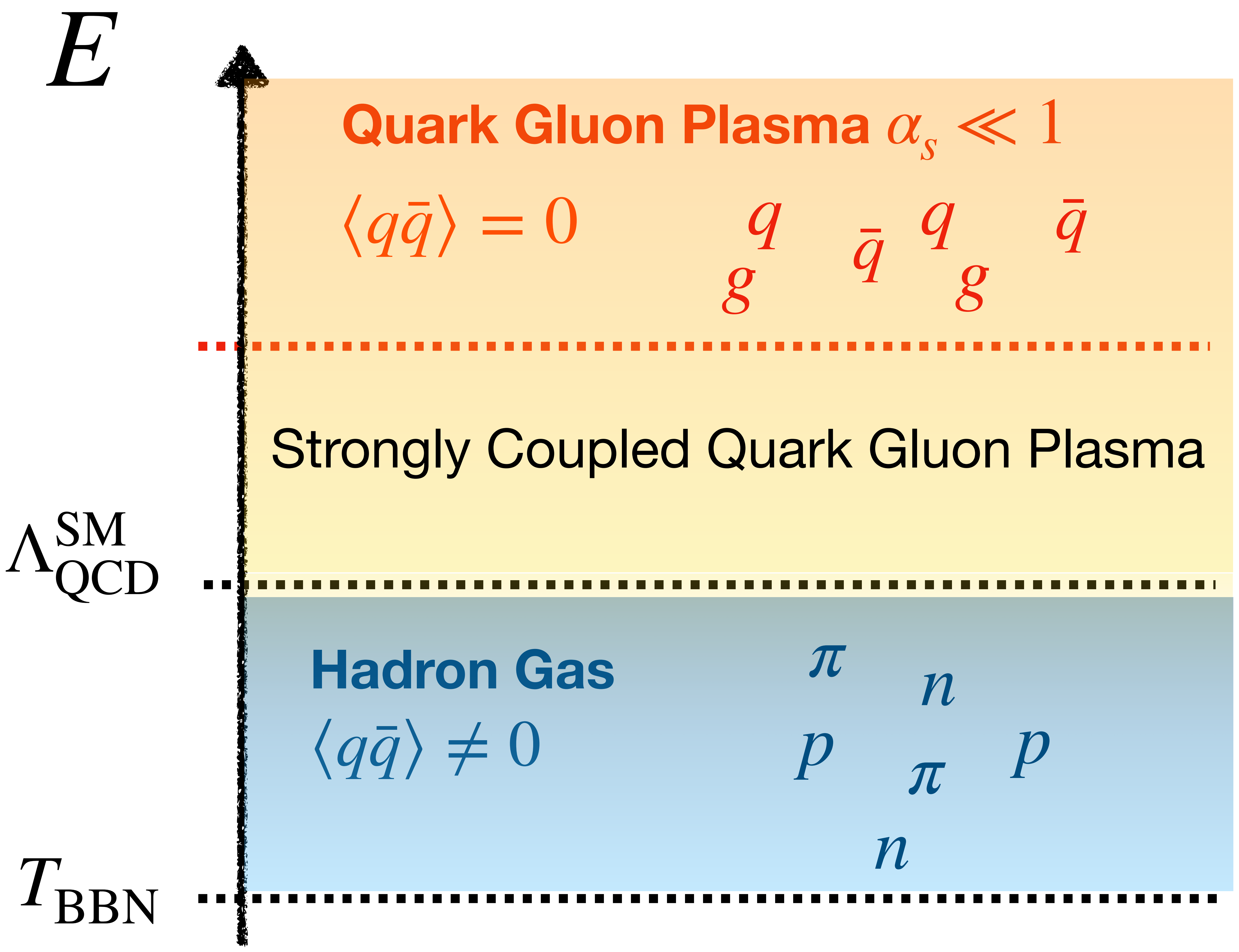
$$\Lambda_{\rm QCD}(\phi) = \Lambda_{\rm QCD}^{\rm SM} \exp\left[-\frac{8\pi^2}{\beta_0}\left(f(\phi) - f(\bar{\phi}_{\rm SM})\right)\right]$$

For $\quad f(\phi) - f(\bar{\phi}_{\rm SM}) \gg 1$,

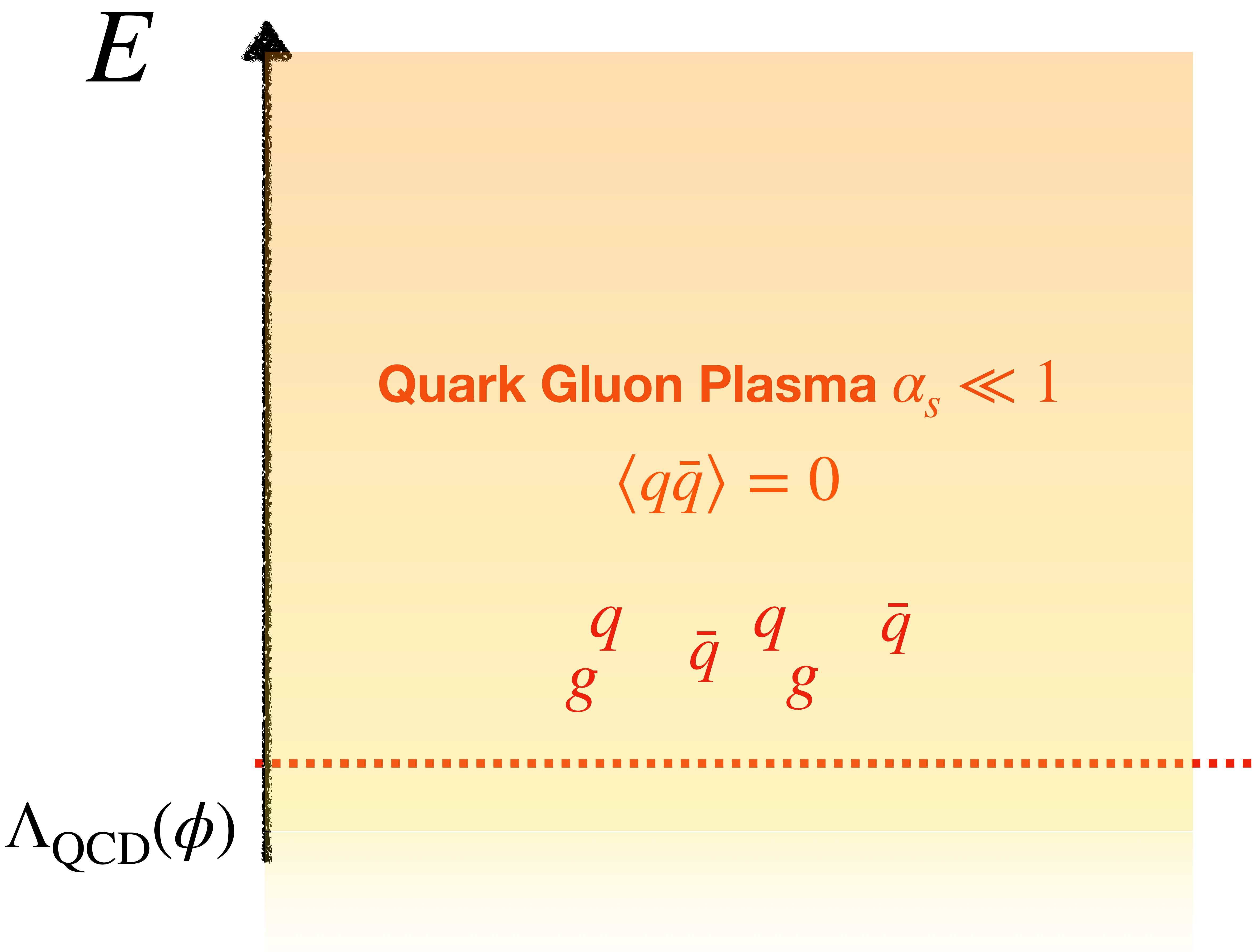
$$\Lambda_{\rm QCD}(\phi) \ll \Lambda_{\rm QCD}^{\rm SM}$$

QCD confinement scale

$\phi = \bar{\phi}_{\mathrm{SM}}$



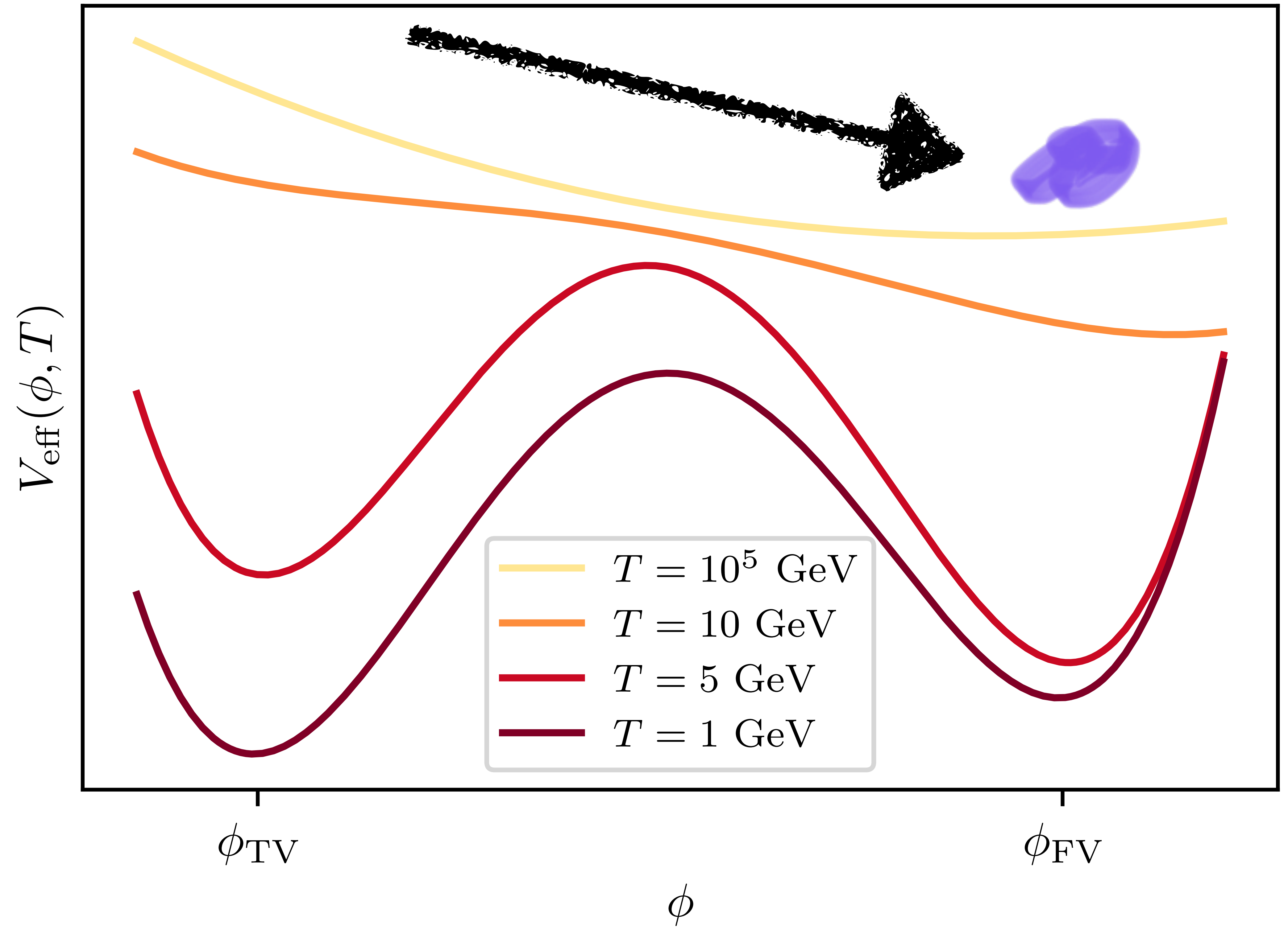
$\Lambda_{\mathrm{QCD}}(\phi) \ll \Lambda_{\mathrm{QCD}}^{\mathrm{SM}}$



Cosmology of field dependent couplings

$$\mathscr{L} = -\frac{1}{2} f(\phi)\, \mathrm{tr}\left(G_{\mu\nu}G^{\mu\nu}\right) + \sum_i \bar{q}_i \left(i\gamma^\mu D_\mu - m_i\right) q_i + \frac{1}{2}(\partial\phi)^2 - V(\phi)$$

$m_\phi = 10$ TeV



With $V(\phi) = V_0(\phi) + V_T(\phi) + V_{\mathscr{P}}(\phi)$

$V_0(\phi)$ Assume a double well potential

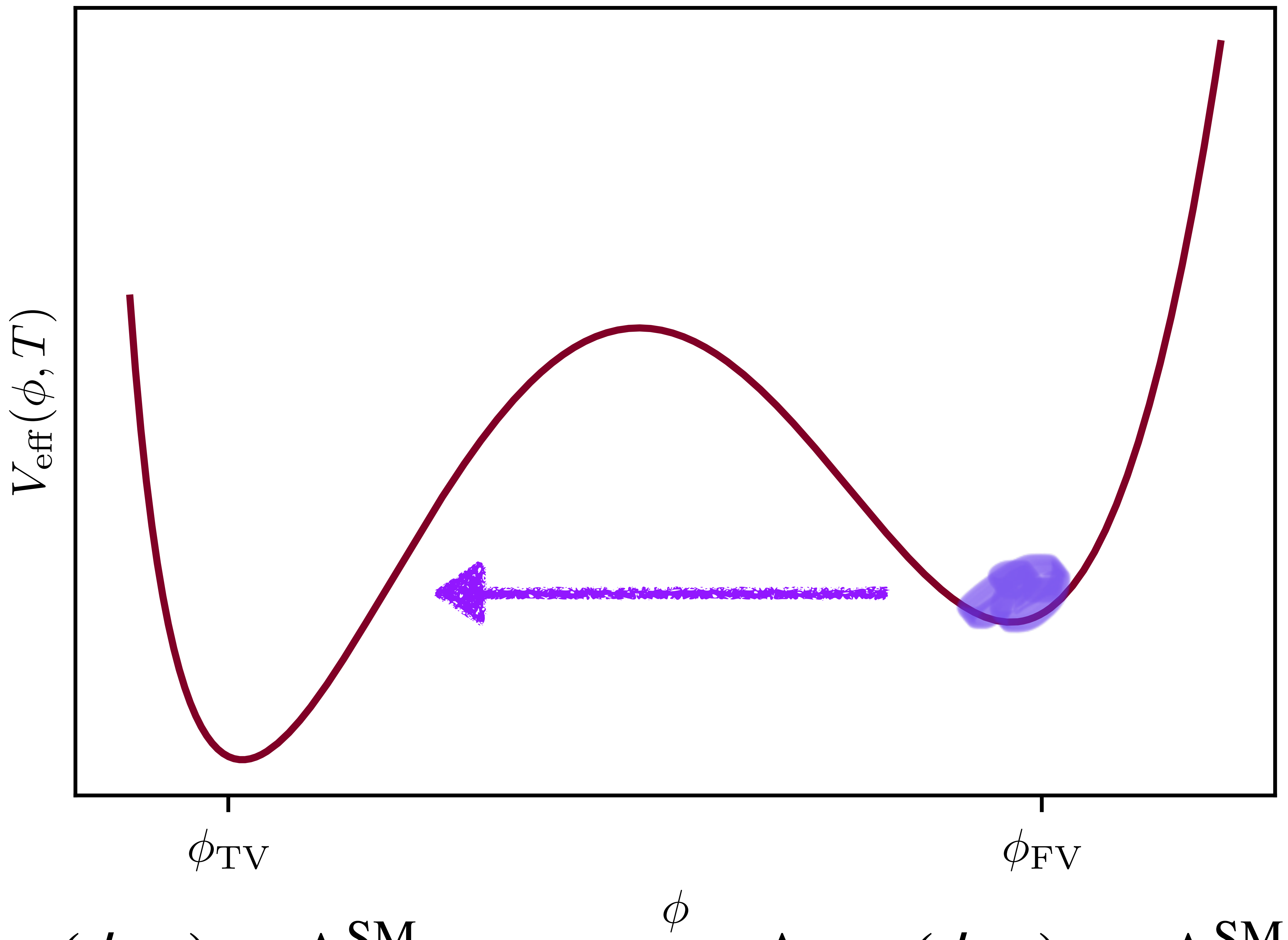
$$V_T(\phi) = \frac{T^4}{2\pi^2} J_B\left(\frac{m_\phi^2}{T^2}\right)$$

$$V_{\mathscr{P}}(\phi, T) = -\frac{8\pi^2}{45} T^4 \left(\left(1 + \frac{21N_f}{32}\right) - \frac{15\alpha_s(\phi, T)}{4\pi}\left(1 + \frac{5N_f}{12}\right)\right)$$

Pushes theory to weaker couplings at high T

A Dilaton First Order PT

$m_\phi = 10$ TeV



$T < m_\phi = 10$ TeV

The field is naturally attracted to the false vacuum

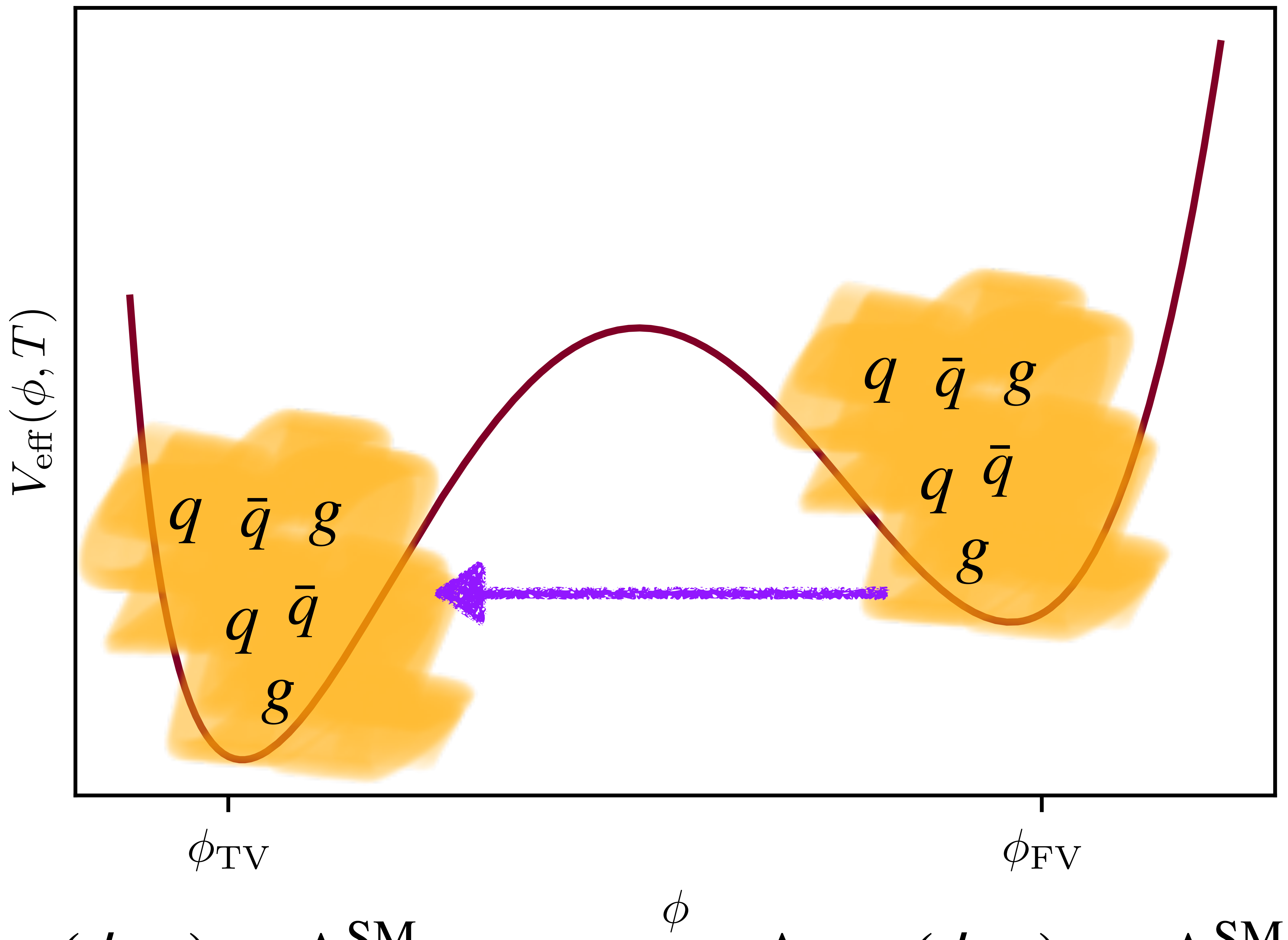
$\Lambda_{\rm QCD}(\phi_{\rm TV}) = \Lambda_{\rm QCD}^{\rm SM}$

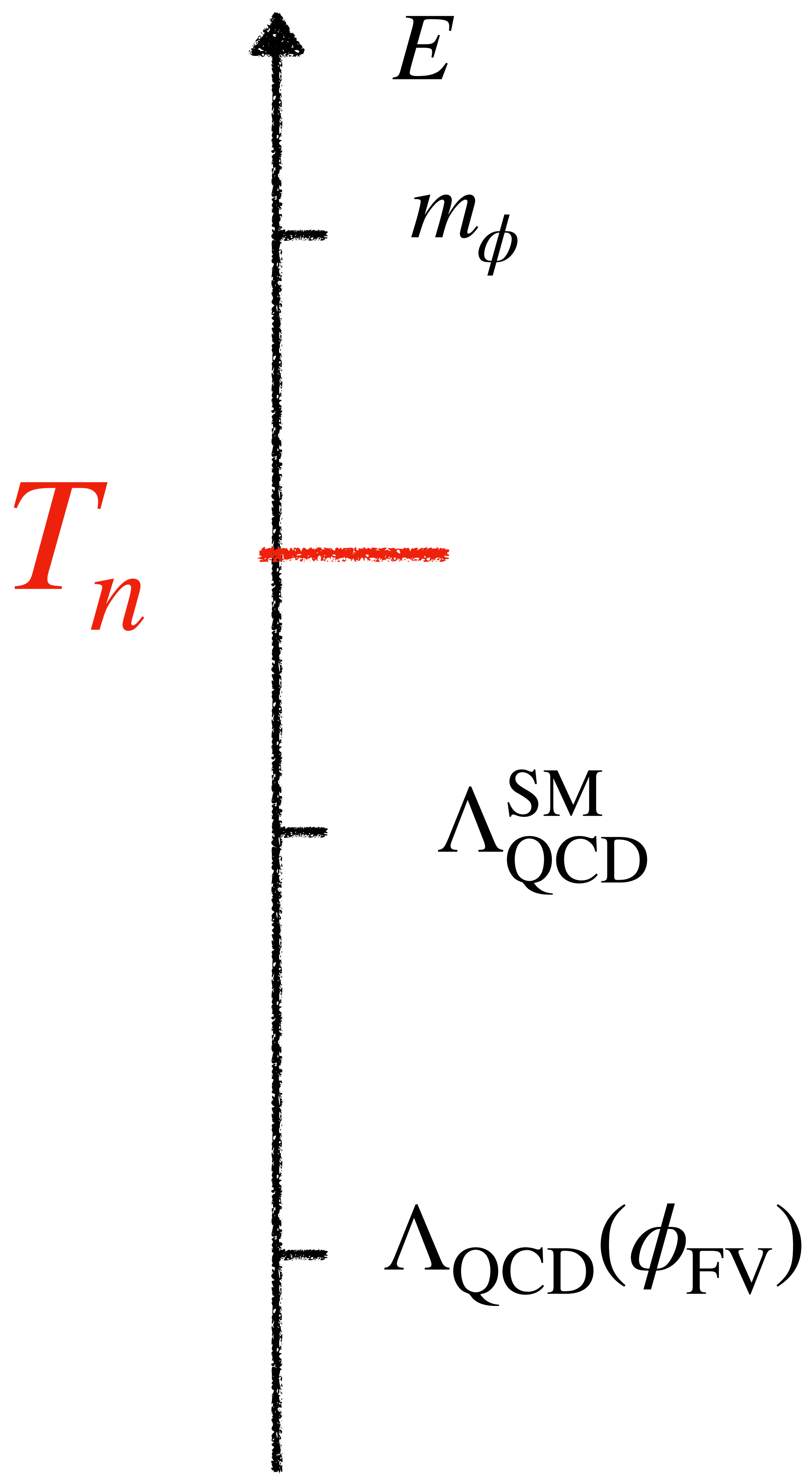
$\Lambda_{\rm QCD}(\phi_{\rm FV}) \ll \Lambda_{\rm QCD}^{\rm SM}$

A Dilaton First Order PT

$m_\phi = 10$ TeV

Runaway bubbles
when QCD is perturbative
on both sides





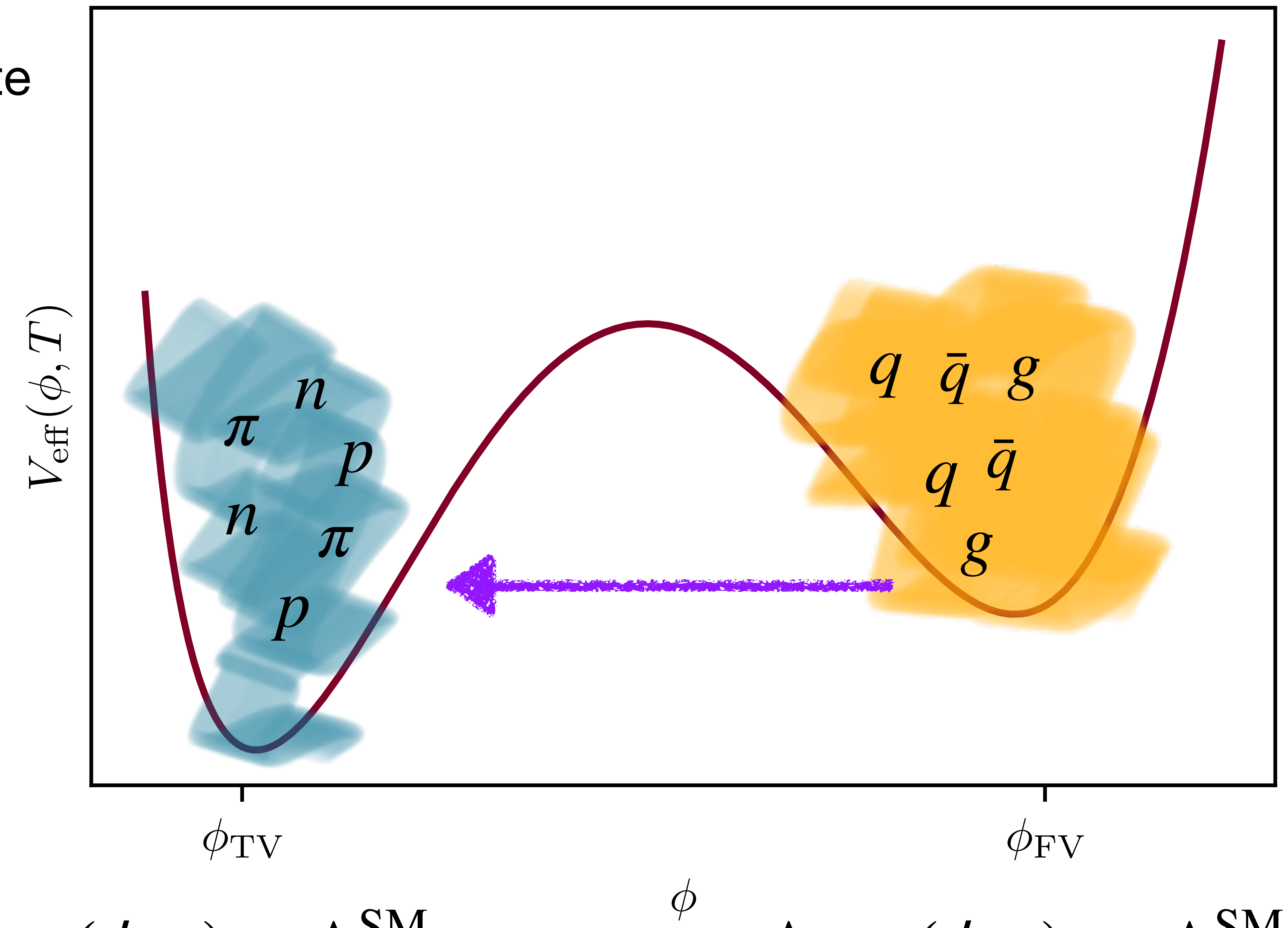
$\Lambda_{\rm QCD}(\phi_{\rm TV}) = \Lambda_{\rm QCD}^{\rm SM}$

$\Lambda_{\rm QCD}(\phi_{\rm FV}) \ll \Lambda_{\rm QCD}^{\rm SM}$

A Dilaton First Order PT

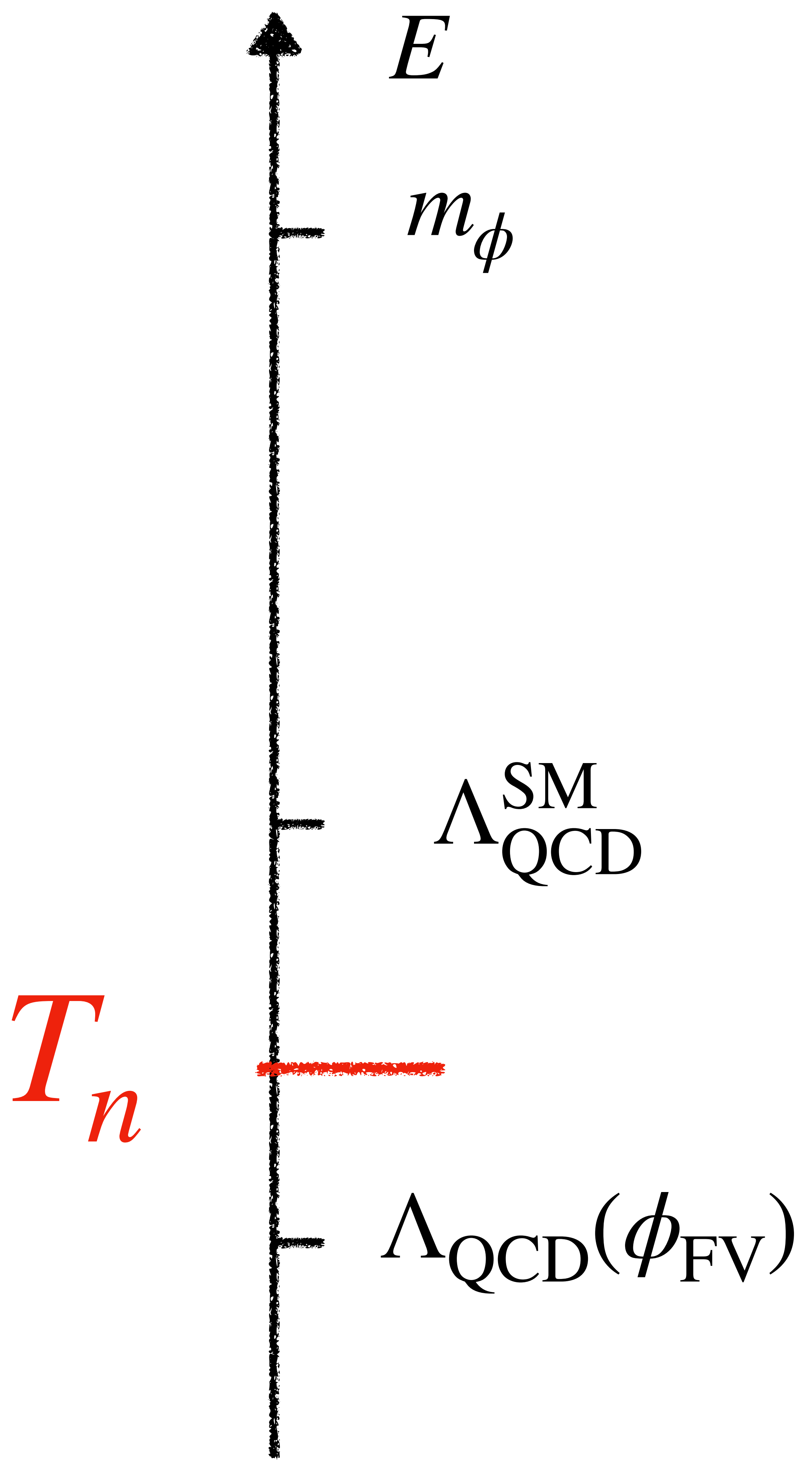
$m_\phi = 10$ TeV

Tunneling from a QGP state to a Hadron Gas state



$\Lambda_{\rm QCD}(\phi_{\rm TV}) = \Lambda^{\rm SM}_{\rm QCD}$

$\Lambda_{\rm QCD}(\phi_{\rm FV}) \ll \Lambda^{\rm SM}_{\rm QCD}$

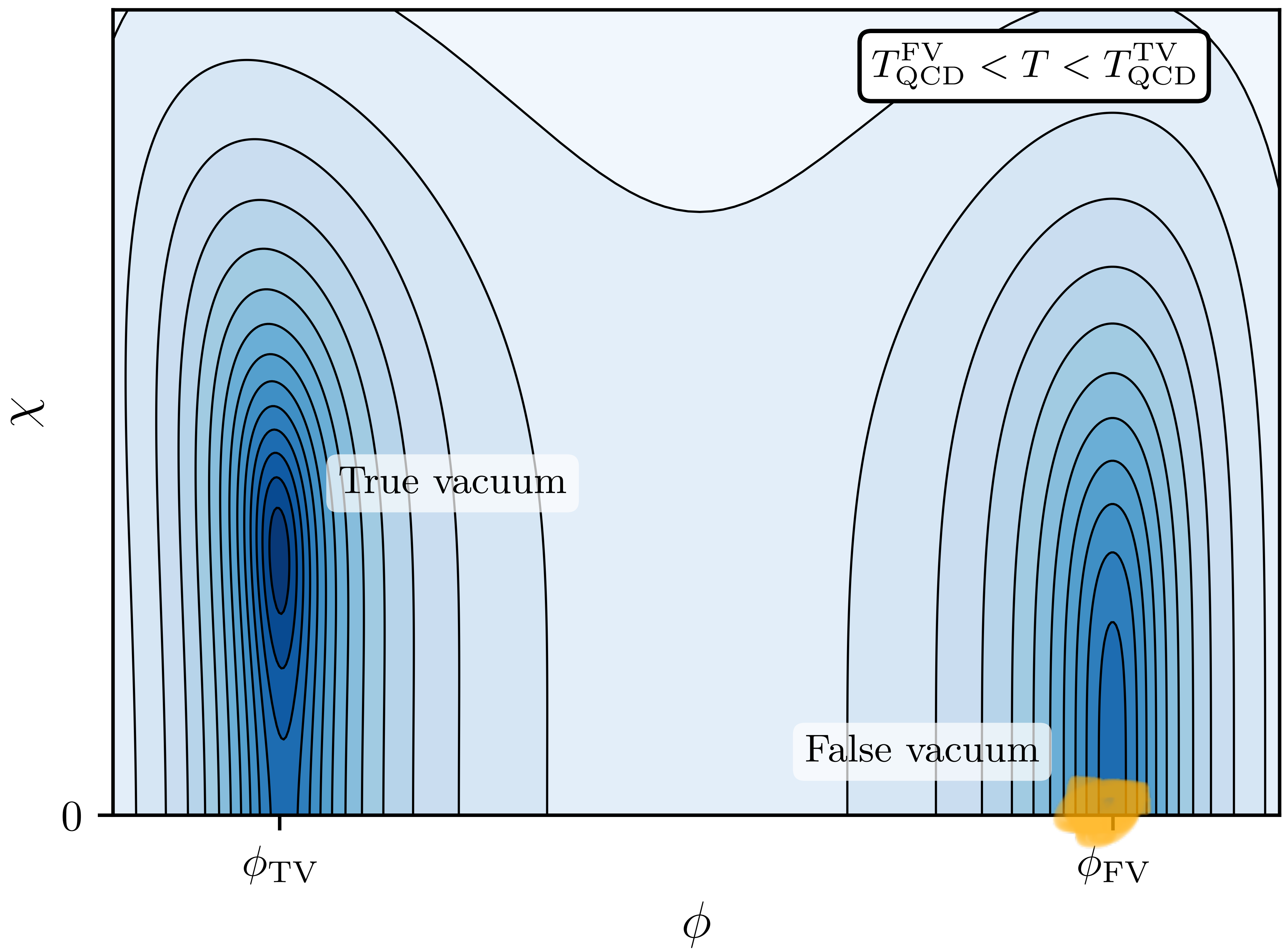


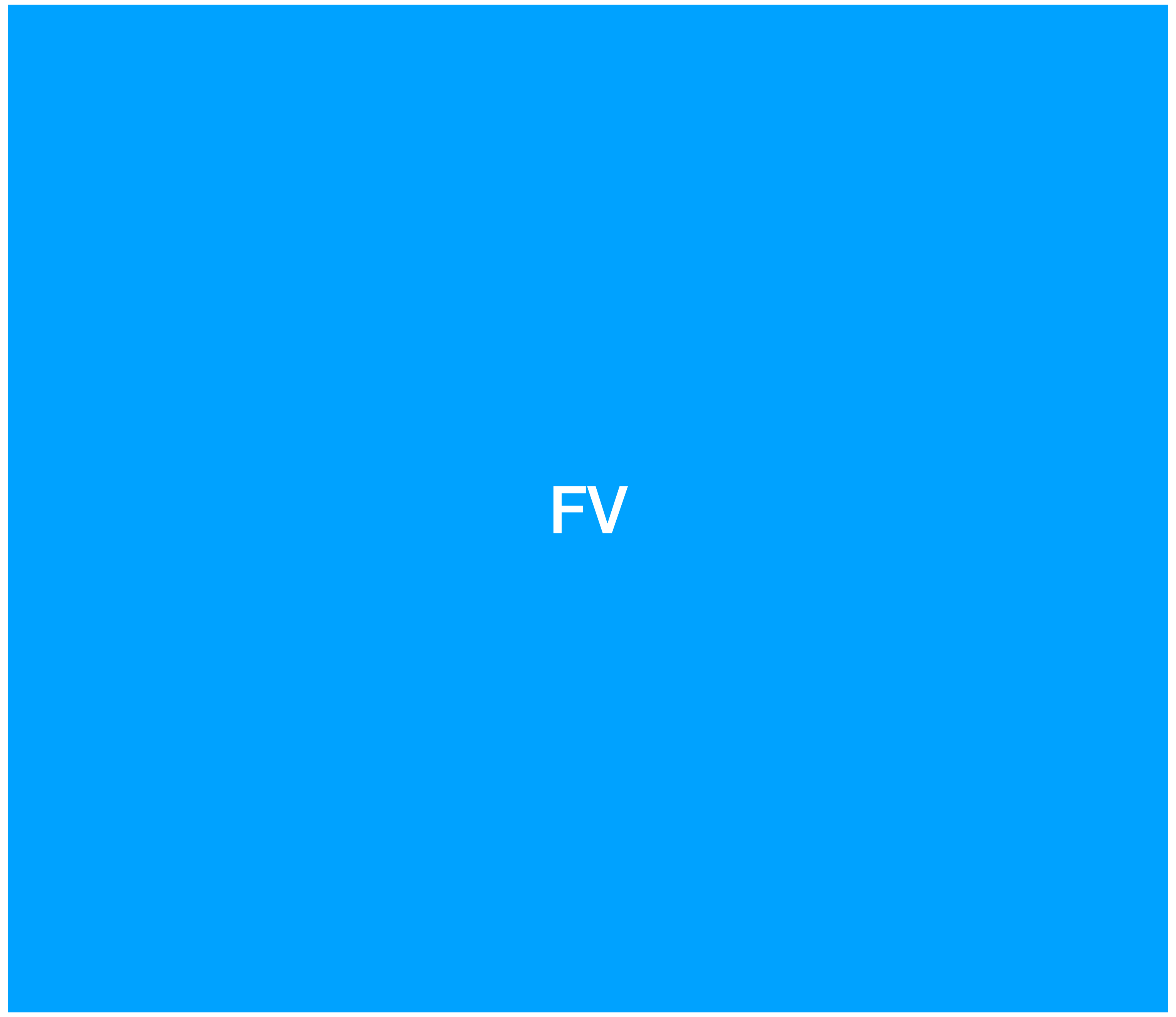
Two field transition involving QCD

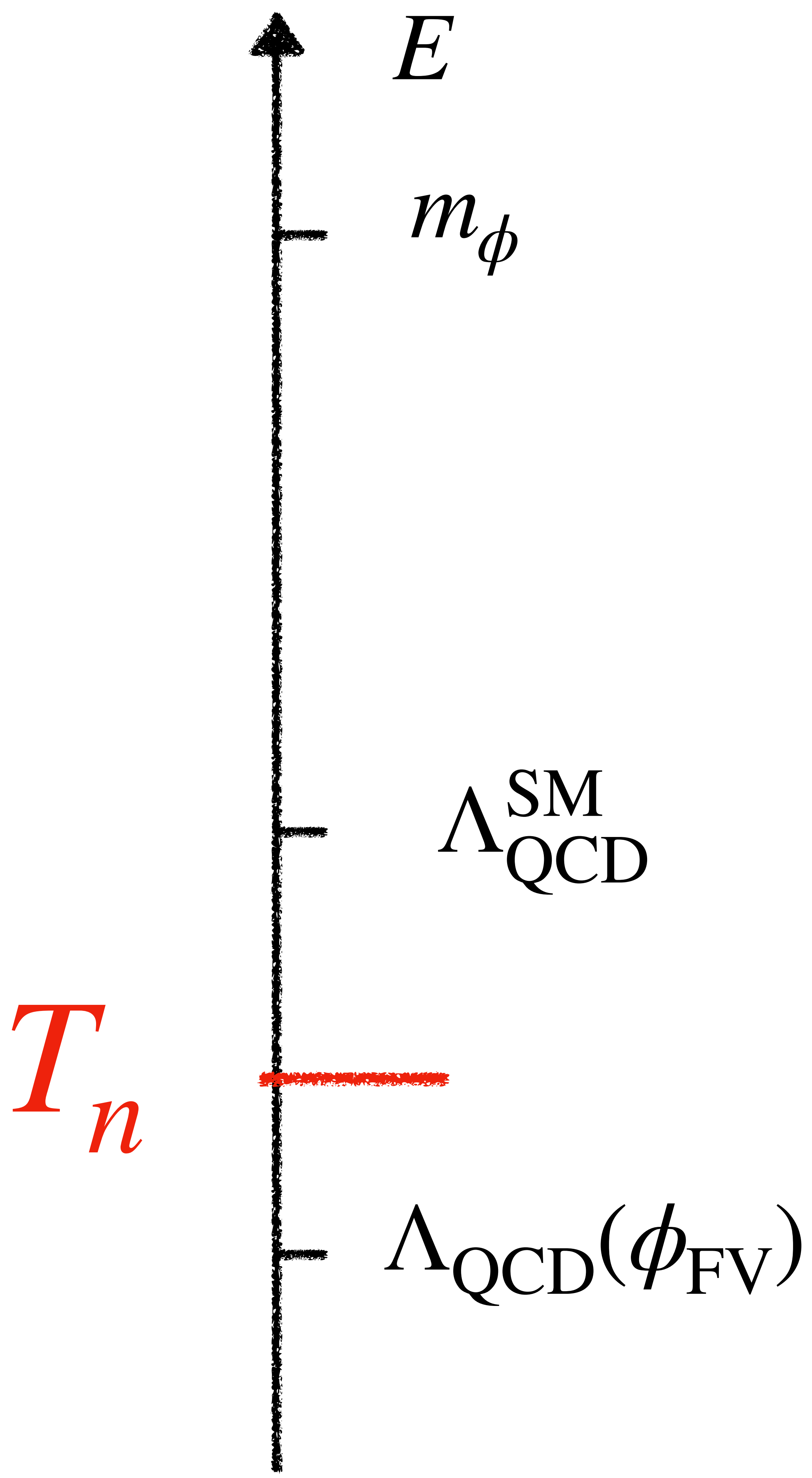
$m_\phi = 10$ TeV

$V(\chi, \phi)$, linear sigma model for $\chi \sim \langle \bar{q} q \rangle$

$V_{\rm tot}(\phi) + V(\chi, \phi)$







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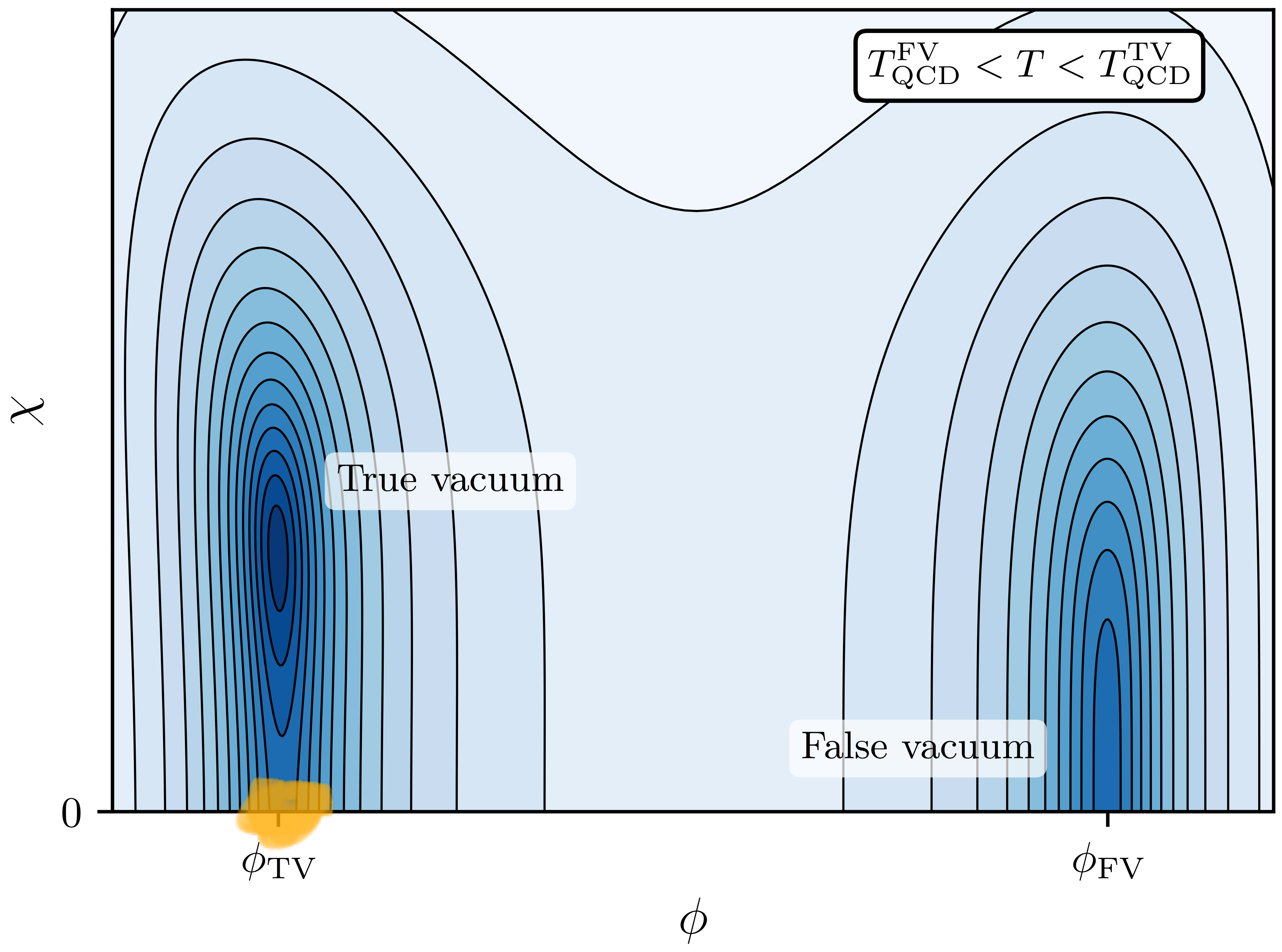

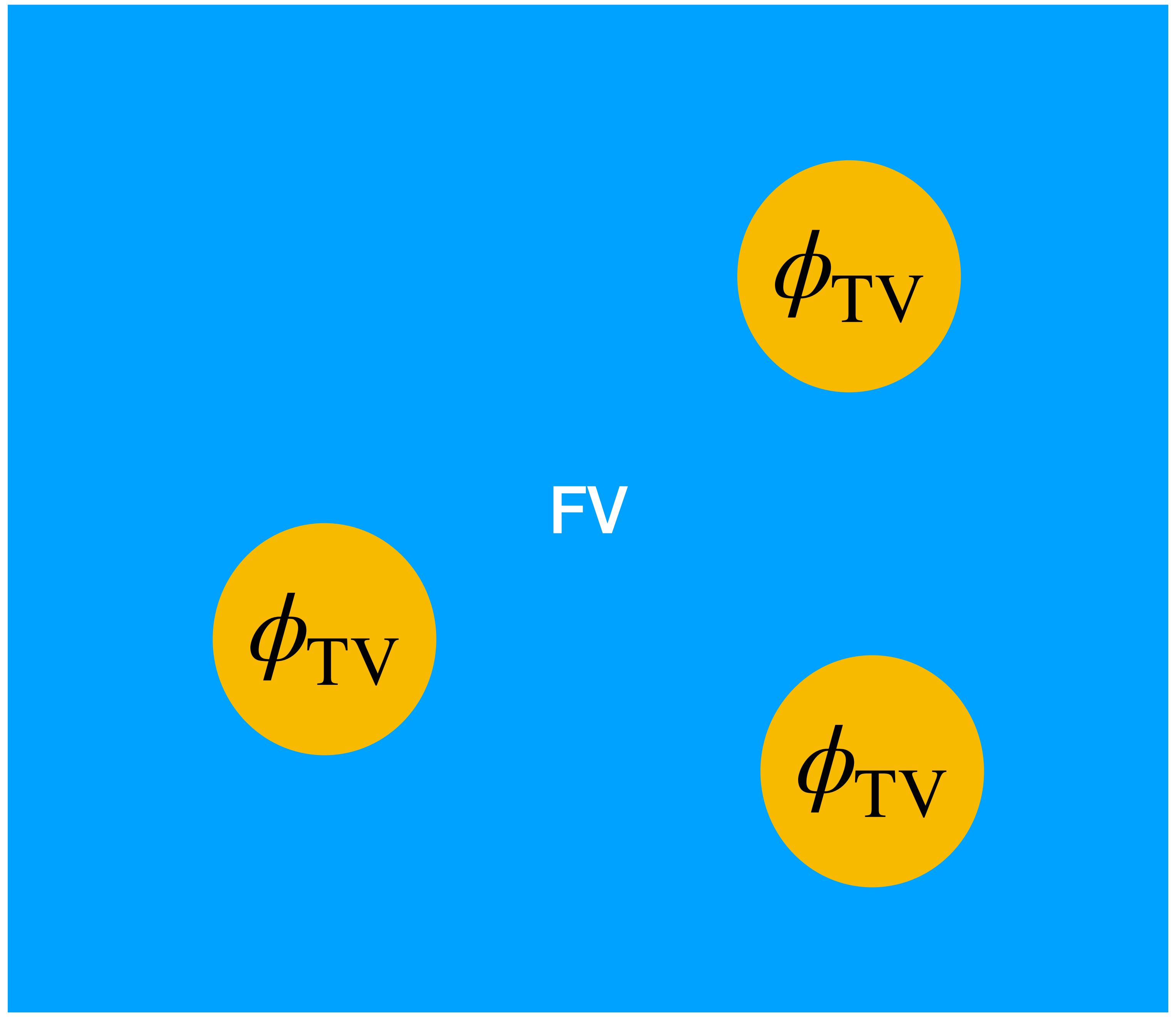

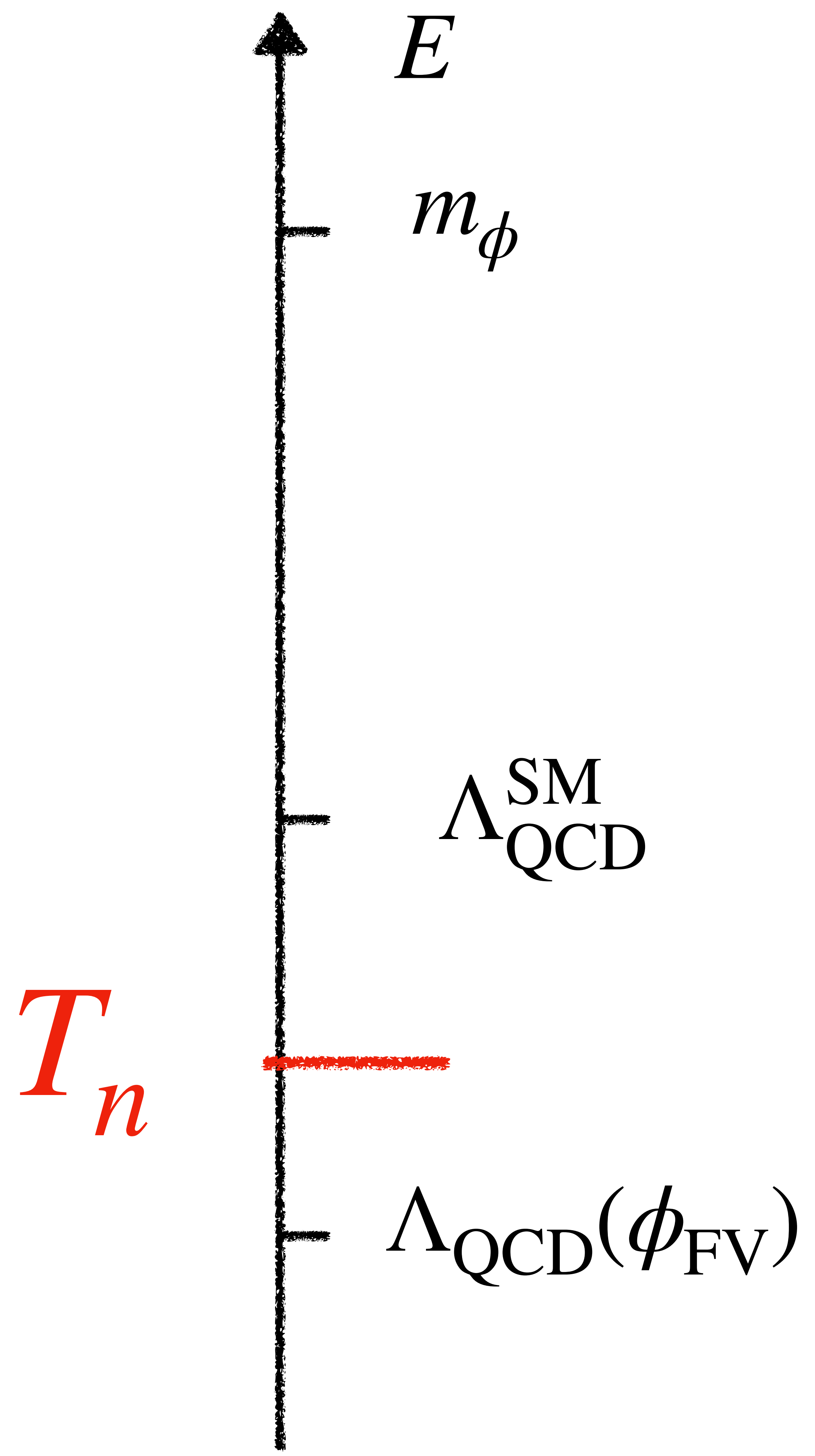

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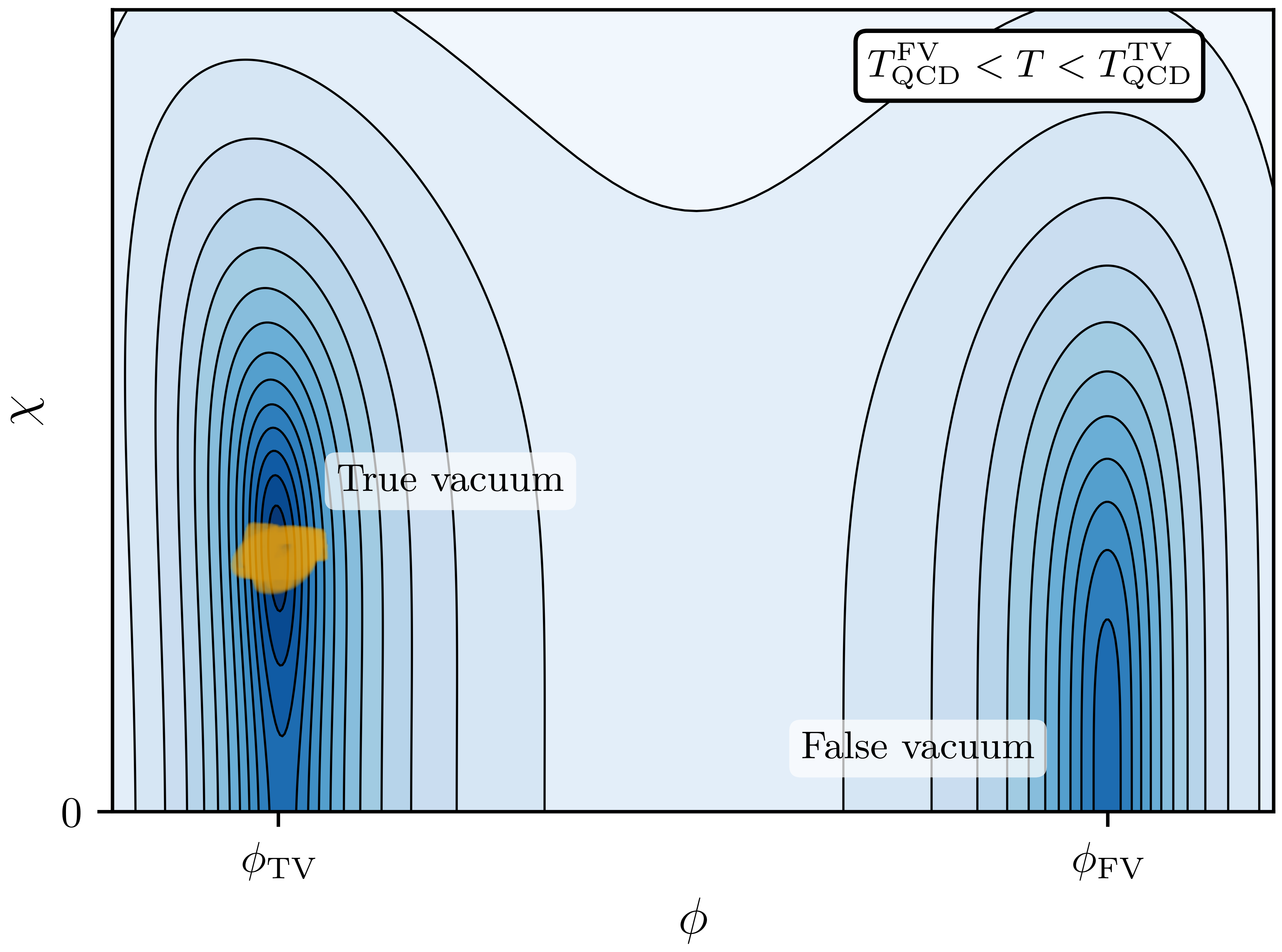
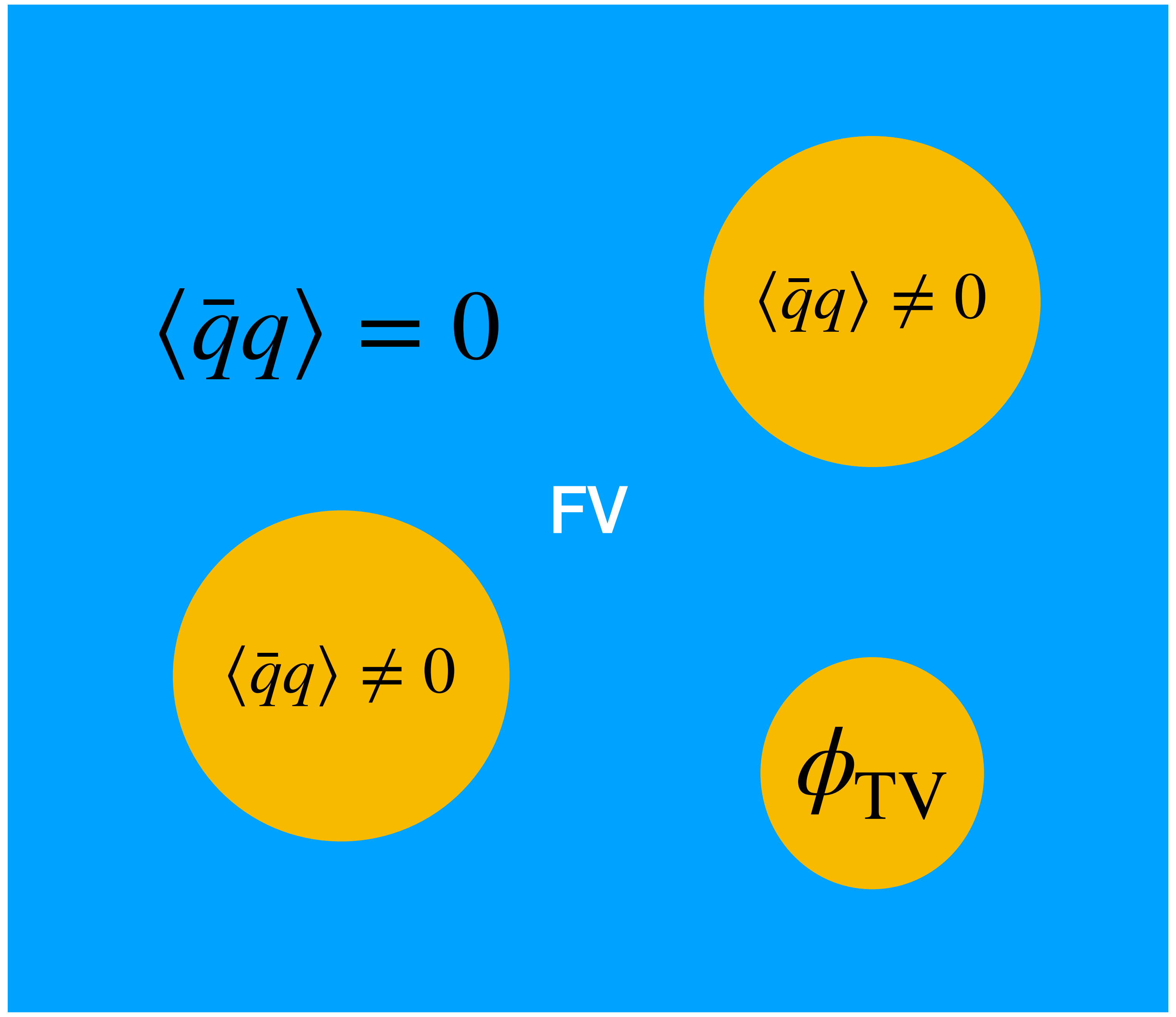
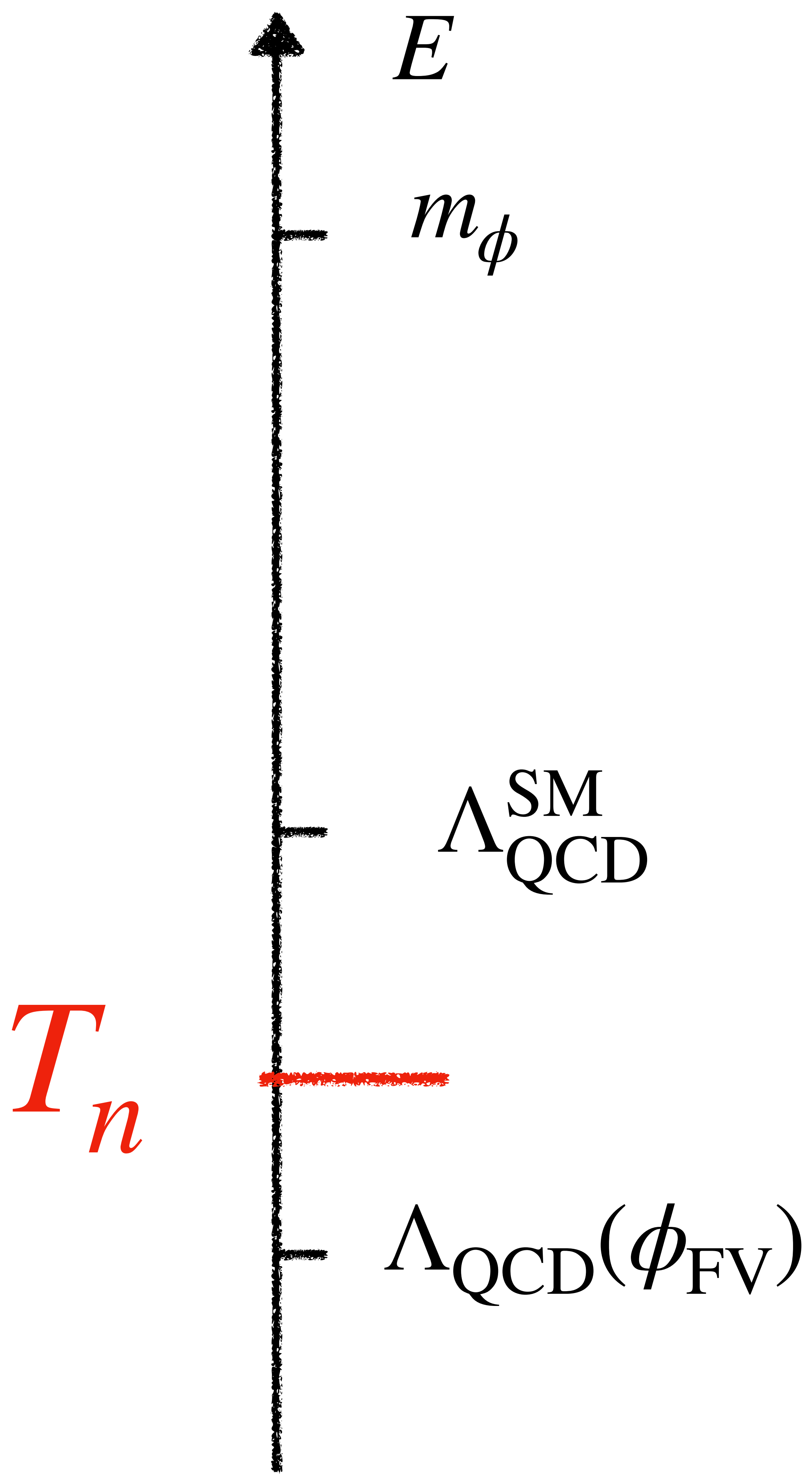
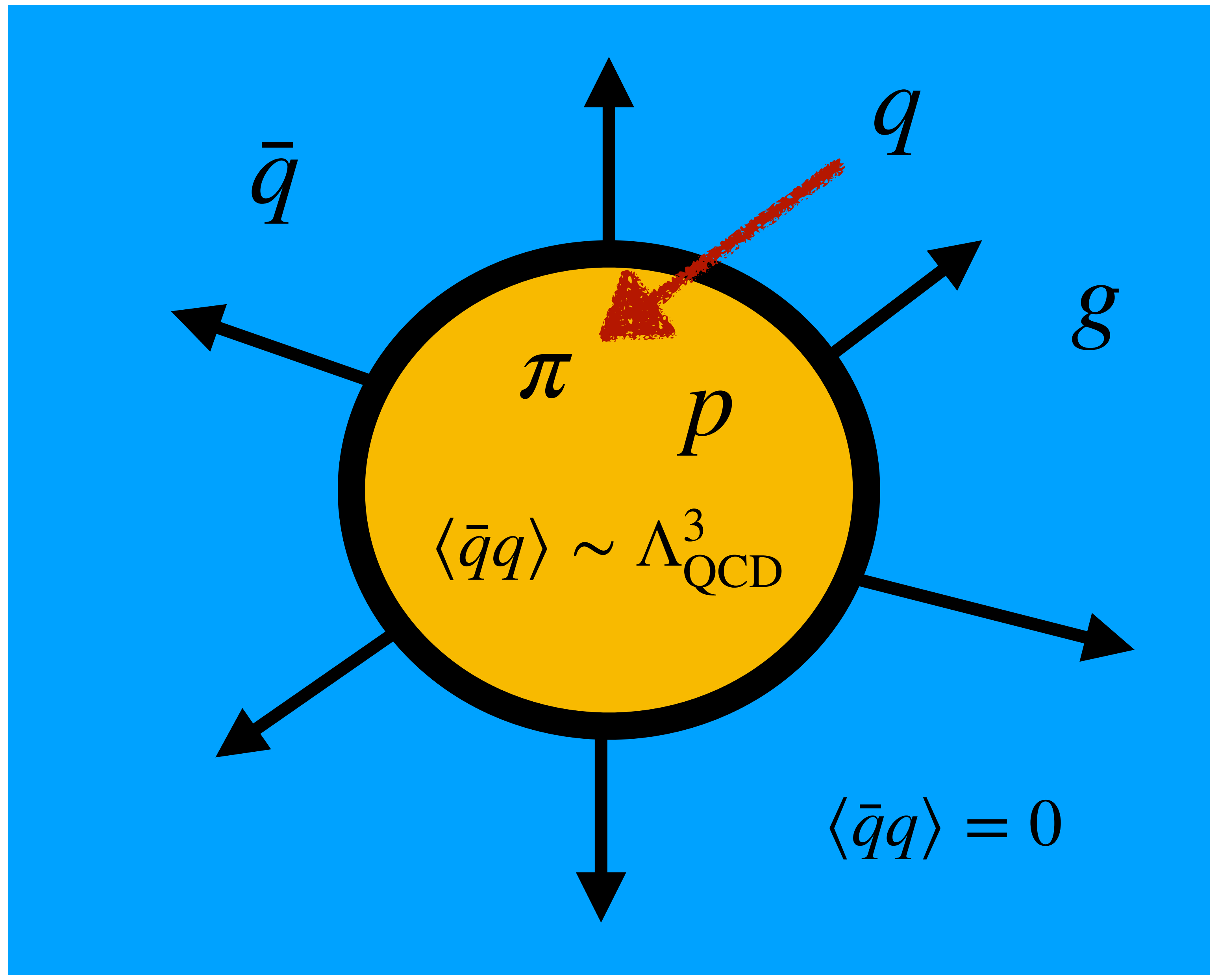






Gravitational Waves from the dilaton induced PT



Transition is driven by the dilaton and not by the QCD degrees of freedom

↓

QCD exerts pressure by forming bound states inside the wall

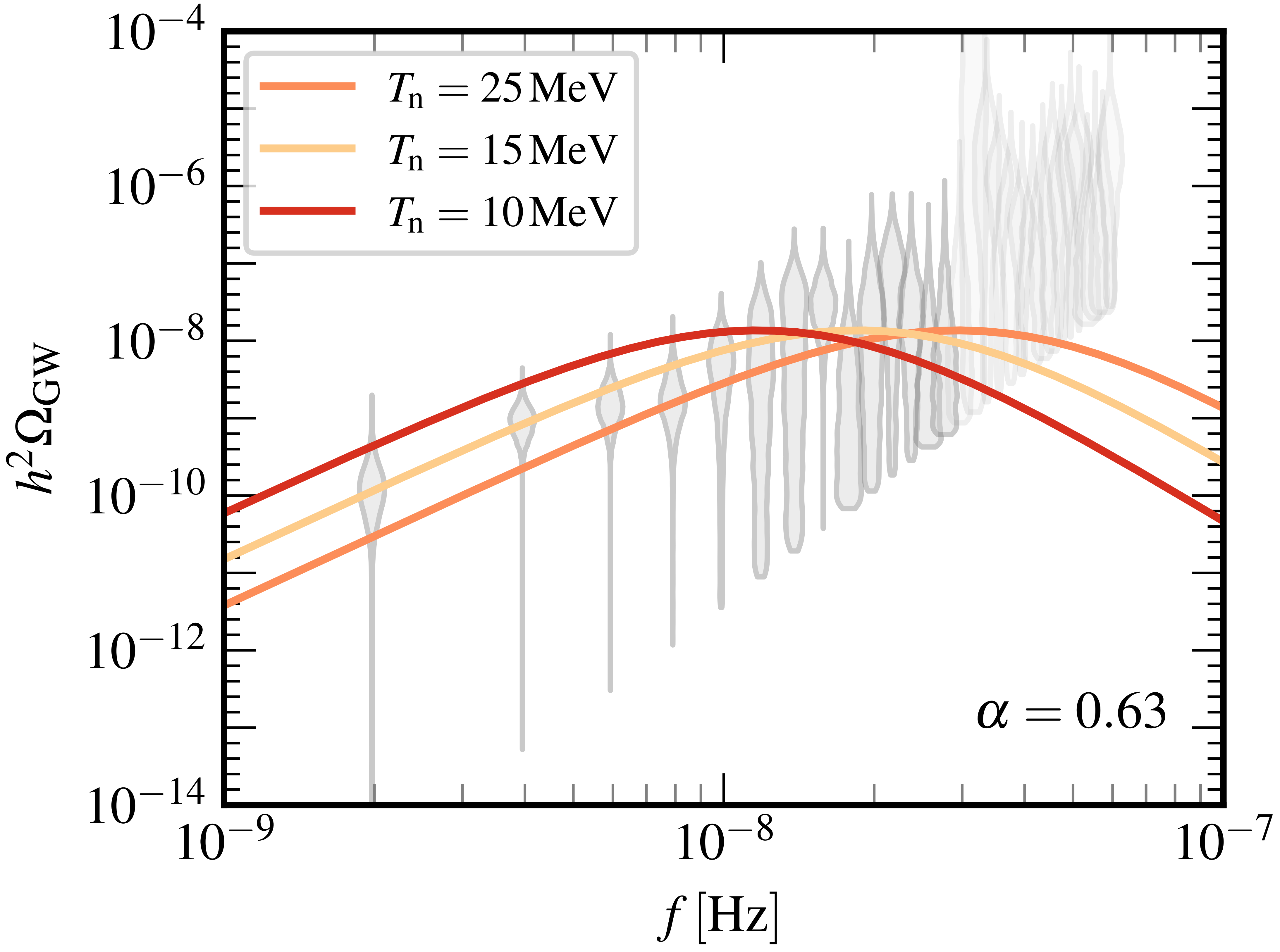
↓

Bubble reaches relativistic terminal velocity determined by the balance

$$\Delta V - \mathscr{P}$$

$$\mathscr{P} = \mathscr{P}_{1\to 1} + \mathscr{P}_{1\to 2} \sim \frac{\Lambda^2_{\rm QCD} T_n^2}{24} + \Lambda_{\rm QCD}\, \gamma \alpha_s(\phi_{\rm w})\, T_n^3$$

Gravitational Waves from the dilaton induced PT



Relativistic terminal velocity

↓

GWs from sound waves with
$3 \leq \beta/H \leq 8$ and $0 \leq \alpha \leq 20$

↓ As in Freese, Winkler: 2208.033

Spectrum fits the signal detected by PTAs

Model parameters $\Delta\phi$, ΔV, m determine the parameters α, T_n and how QCD changes across the wall

Summary and Caveats

- A model for confinement based on a multi-field first order phase transition, where the coupling of QCD is promoted to a dynamical field.

- For zero temperature potentials such that the nucleation temperature $T_n < \Lambda_{\text{QCD}}$, the gravitational wave spectrum seems to fit the PTA signal.

- Theories with field dependent couplings are naturally attracted to a weakly coupled state at high temperatures due to the 1-loop pressure term from the SM plasma. Can we make general statements about such theories when the dilaton (or moduli) fields exhibit multiple minima?

- Need a zero temperature potential that exhibits a PT for $T \sim \Lambda_{\text{QCD}}$. Used a toy double well potential to showcase the idea, but for a realistic construction one might need more complicated dynamics involved (multiple scalar fields, topological defects or other mechanisms).

Back-up slides

To calculate the QCD pressure near the confined vacuum we used the Lattice fit to the QCD pressure from the HotQCD collaboration, arXiv:1407.6387.

$$\mathscr{P}_{\text{QCD}} = \frac{T^4}{2}\Big(1 + \tanh\left(c_t(t - t_0)\right)\Big) \times \frac{p_{\text{id}} + a_n/t + b_n/t^2 + d_n/t^4}{1 + a_d/t + b_d/t^2 + d_d/t^4}\,.$$