A dilaton induced first order QCD PT and phenomenology of axion relic pockets

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Based on: 2507.01191 and 2605.XXXXX
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Dilatons and Axions

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

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

Dilatons and Axions

Motivated by no free parameters in Quantum Gravity

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

$$\langle\frac{\phi}{\Lambda}\rangle = \frac{1}{g^2}\Big|_{\mathrm{UV}}$$

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

Dilaton

Axion

Part 1: QCD and its Dilaton

Chatrchyan, Marsh, **CN**: 2507.01191

Focus on the QCD "dilaton"

$$\mathscr{L}_{\rm QCD} \supset -\frac{1}{2}\frac{\phi}{\Lambda}\,\mathrm{Tr}\left[G_{\mu\nu}G^{\mu\nu}\right]$$

$$\langle\frac{\phi}{\Lambda}\rangle = \frac{1}{g^2}\Big|_{\rm UV}$$

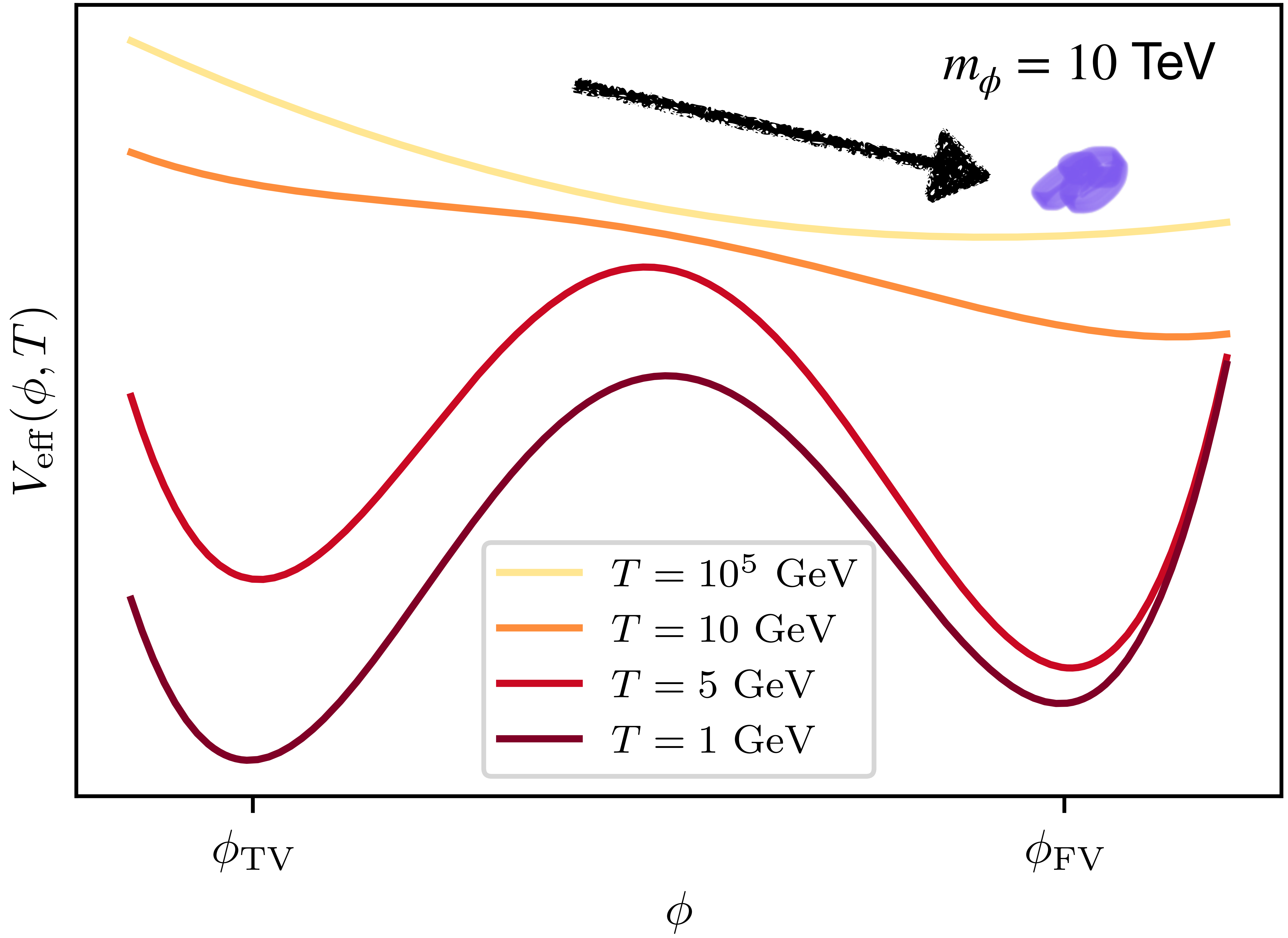
Confinement scale via
Dimensional Transmutation

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

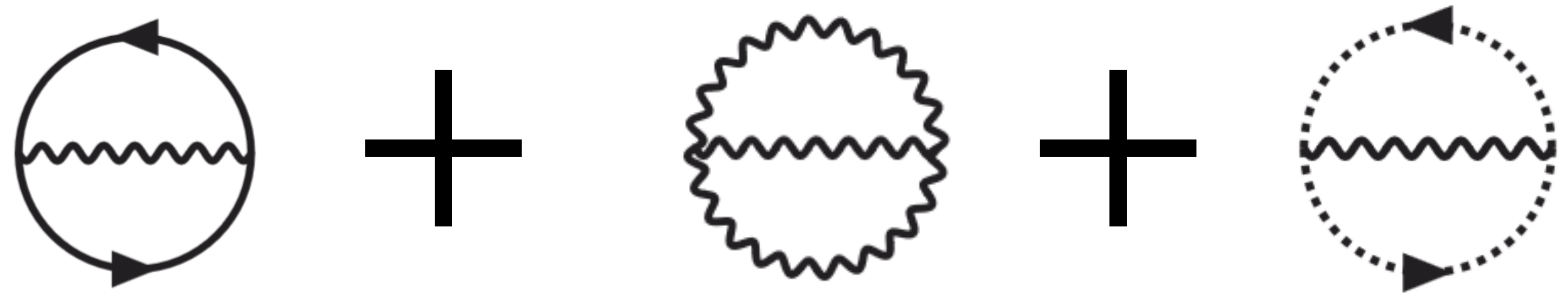
But the coupling depends on the dilaton:

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

Cosmology of field-dependent couplings



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



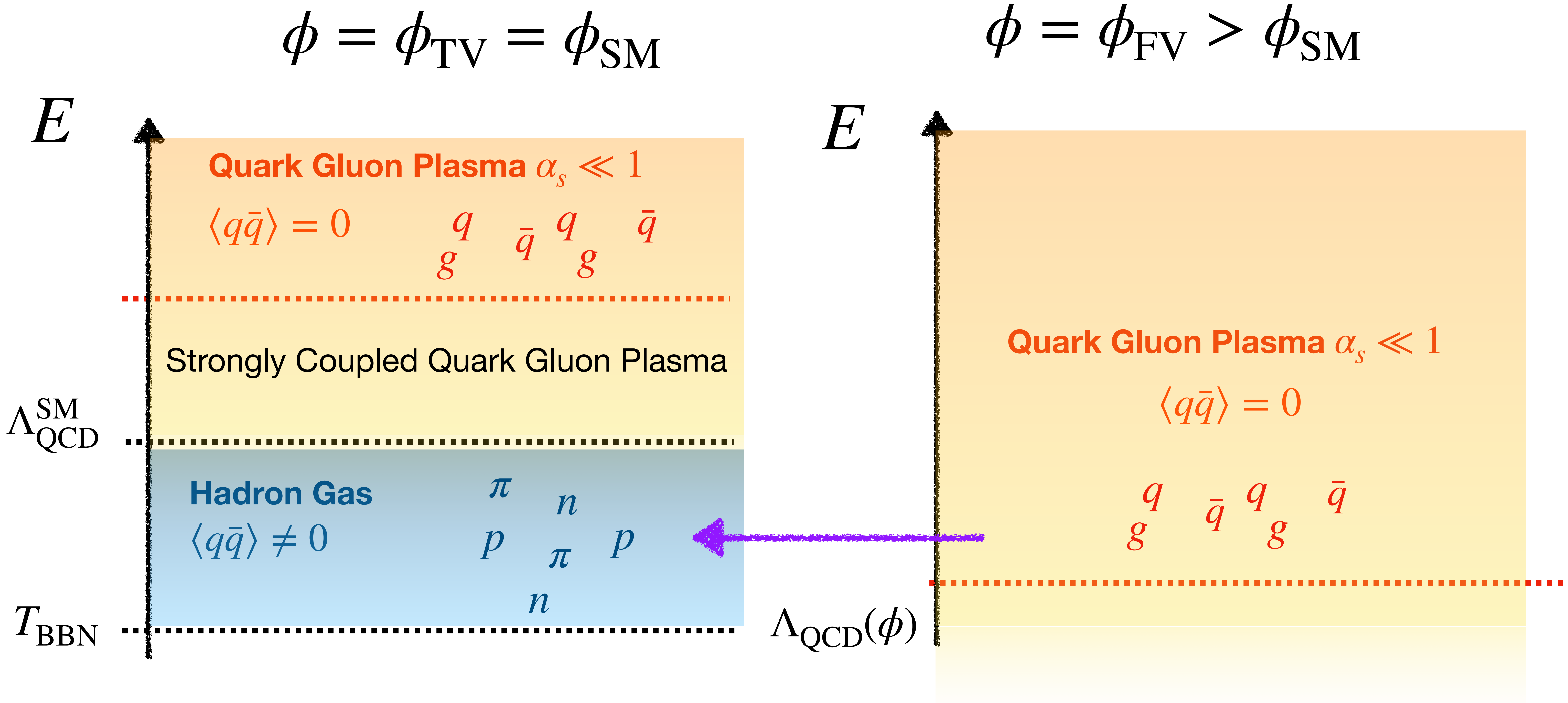
$$\propto g_s^2 = \left(\frac{\Lambda}{\phi}\right)$$

Pushes theory to weaker couplings at high T

But then the confinement scale

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

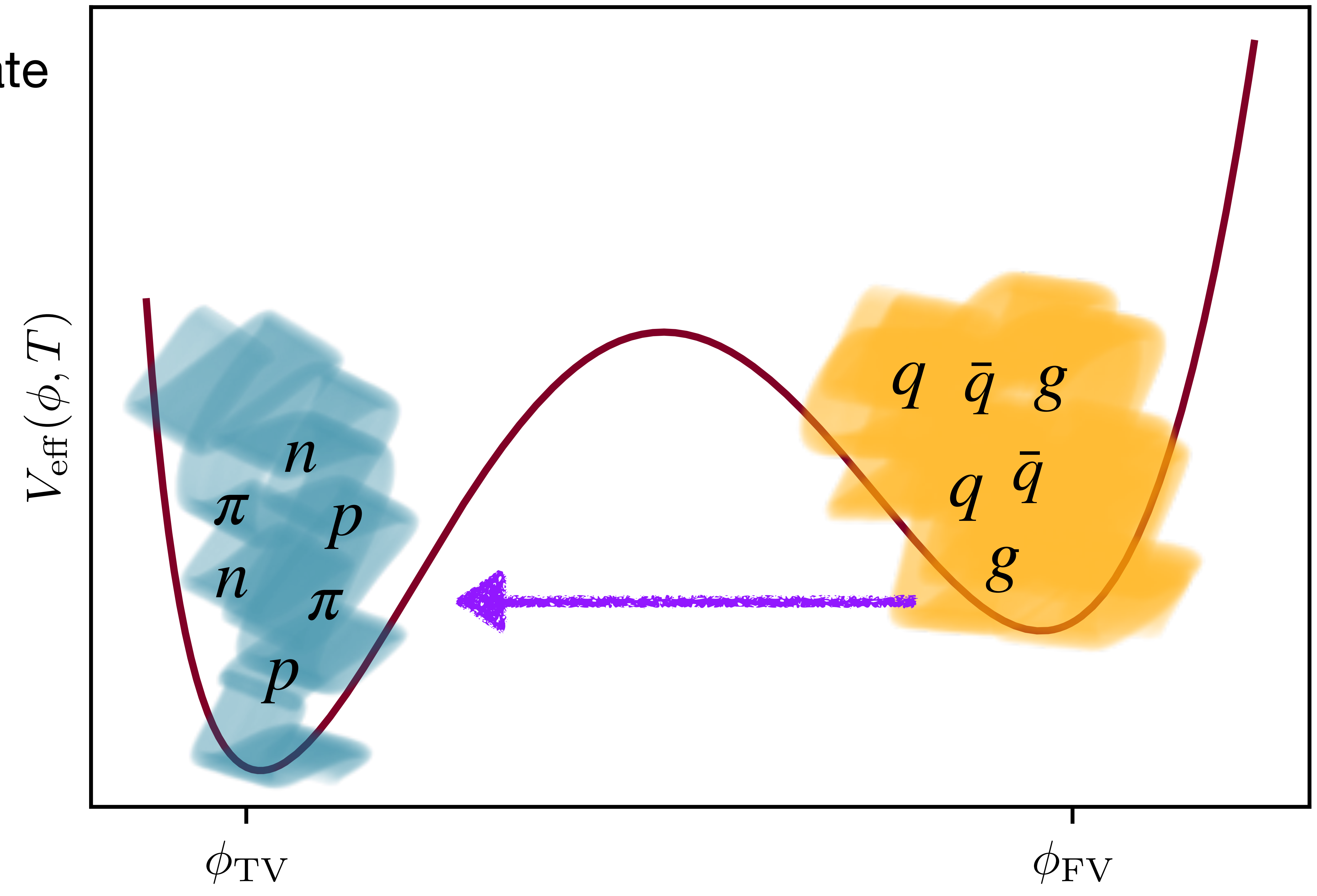
QCD confinement scale



A Dilaton First Order PT

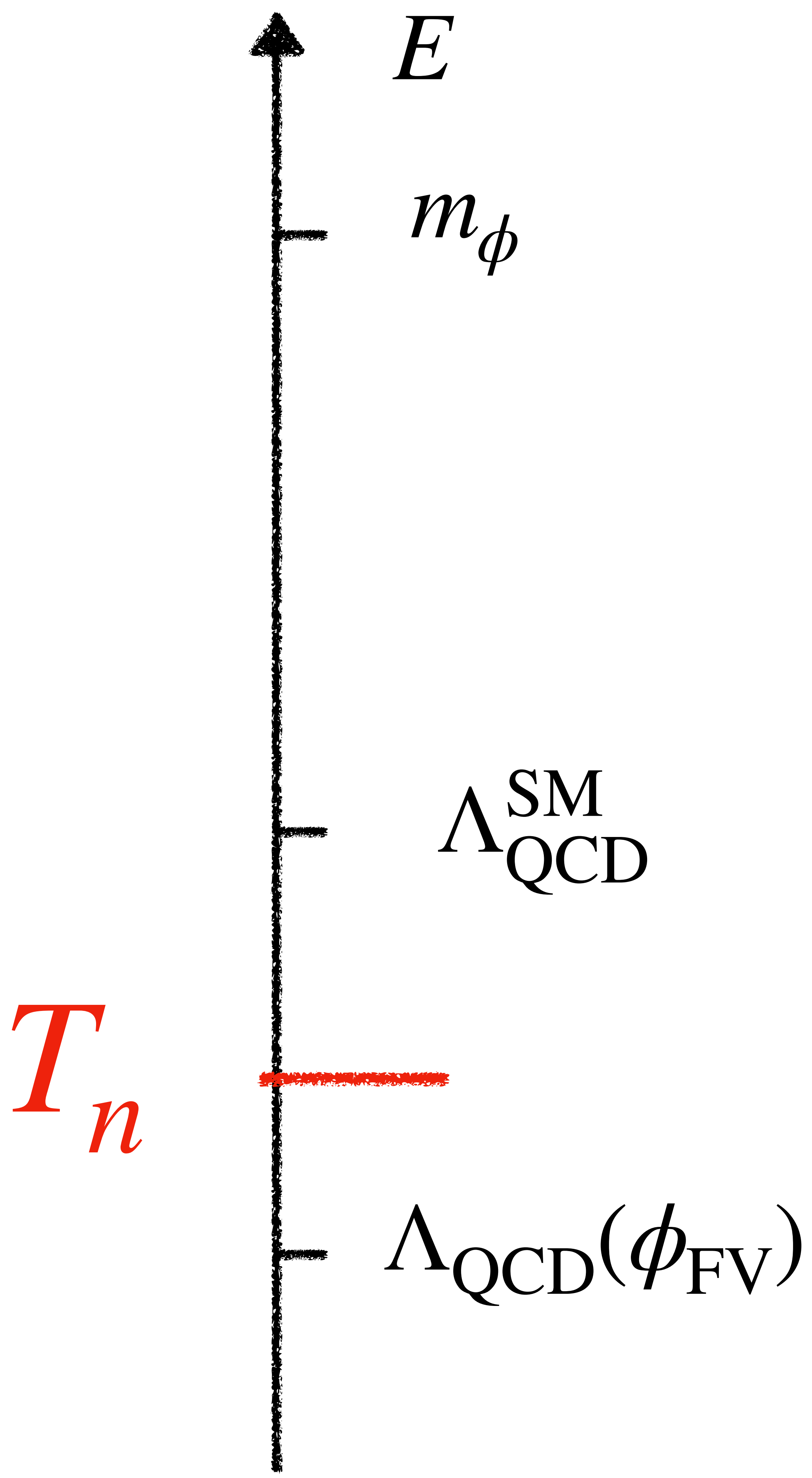
The field is naturally attracted
to the false vacuum

Tunneling from a QGP state
to a Hadron Gas state



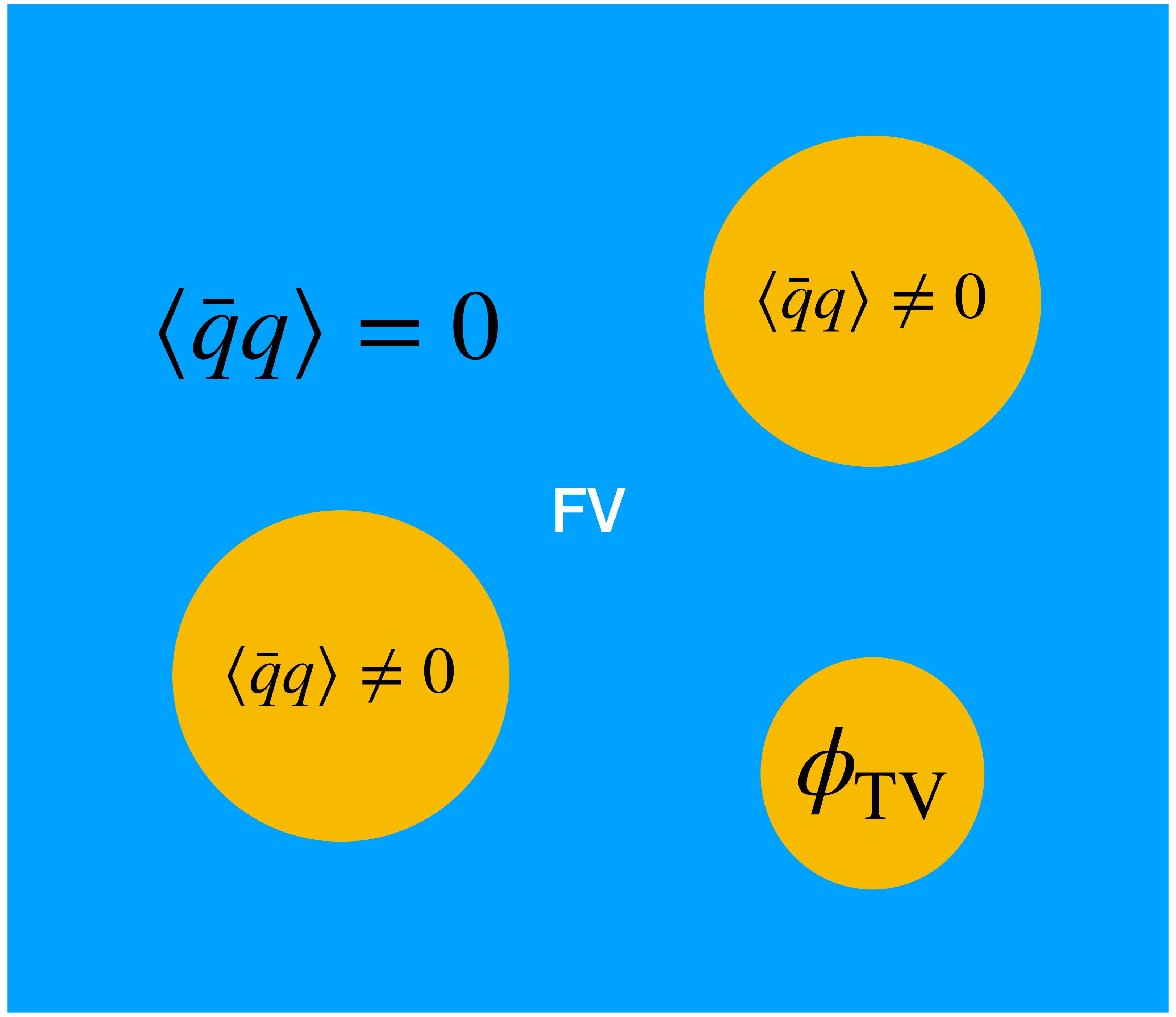
$\Lambda_{\rm QCD}(\phi_{\rm TV}) = \Lambda_{\rm QCD}^{\rm SM}$

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

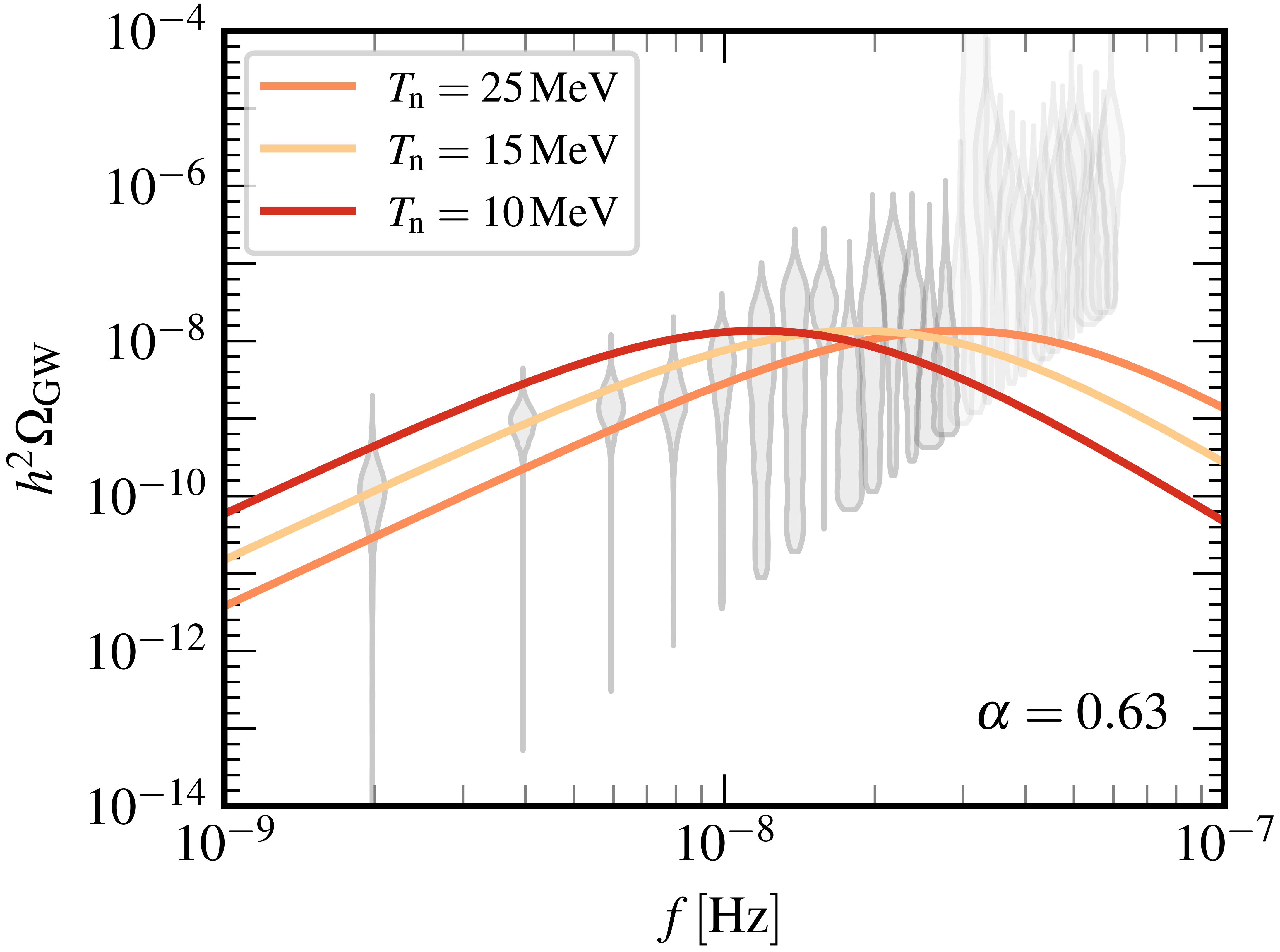


Gravitational Waves from the dilaton induced PT

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



Spectrum fits the signal detected by PTAs

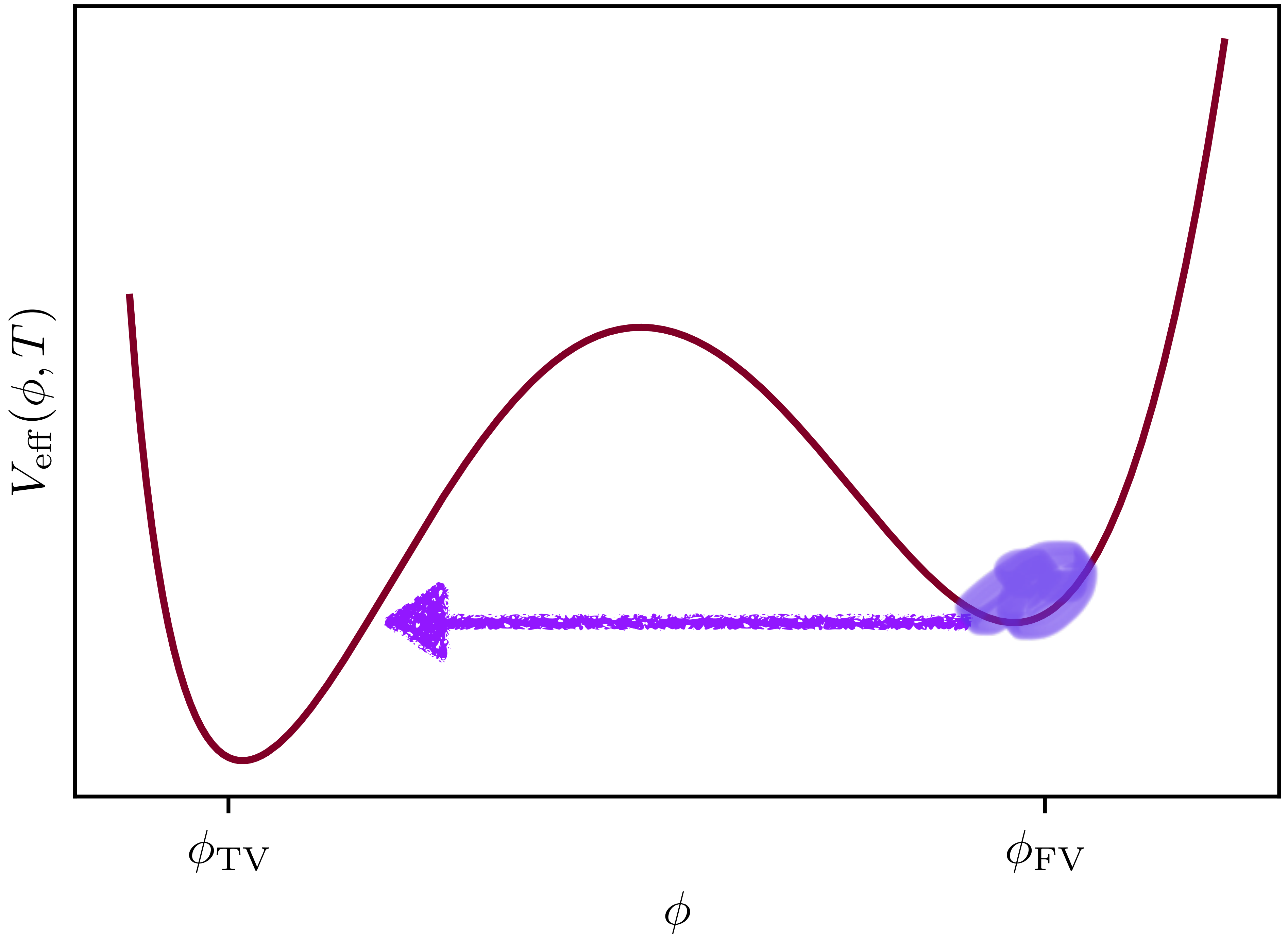


Model parameters $\Delta\phi$, ΔV, m determine the parameters α, T_n and how QCD changes across the wall

Part 2: Axion Relic Pockets

Carenza, Ebby, Iarygina, Marsh: 2407.01676
Khater, Marsh, **CN**: 2605.XXXXX

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



Axion potential sensitive to changes in ϕ

$$V(\phi, a) = M^4 \exp\left[-8\pi^2 \frac{\phi - \phi_{\rm TV}}{\Lambda}\right]\left(1 - \cos\left(a/f_a\right)\right)$$

Induces a mass change

$$m_a^2\Big|_{\rm TV} \gg m_a^2\Big|_{\rm FV}$$

Trapping of axions

True vacuum inaccessible for axions located in the false vacuum due to the huge mass difference in the two regimes.

True vacuum bubbles expand and fill space, compressing axions in smaller and smaller regions of false vacuum.

Pressure of hot gas of trapped axions stabilizes the pressure from the expanding bubbles,
resulting in “pockets” of
false vacuum filled with axions.

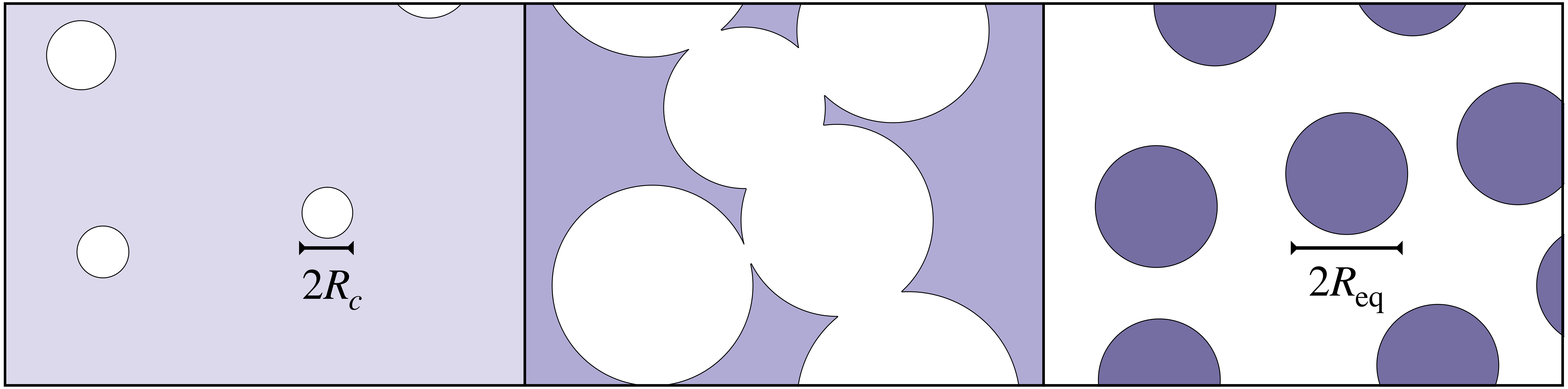


Figure from 2407.01676

Axion Relic Pockets as DM

ARPs are cosmologically stable and can comprise all of dark matter for a choice of ΔV

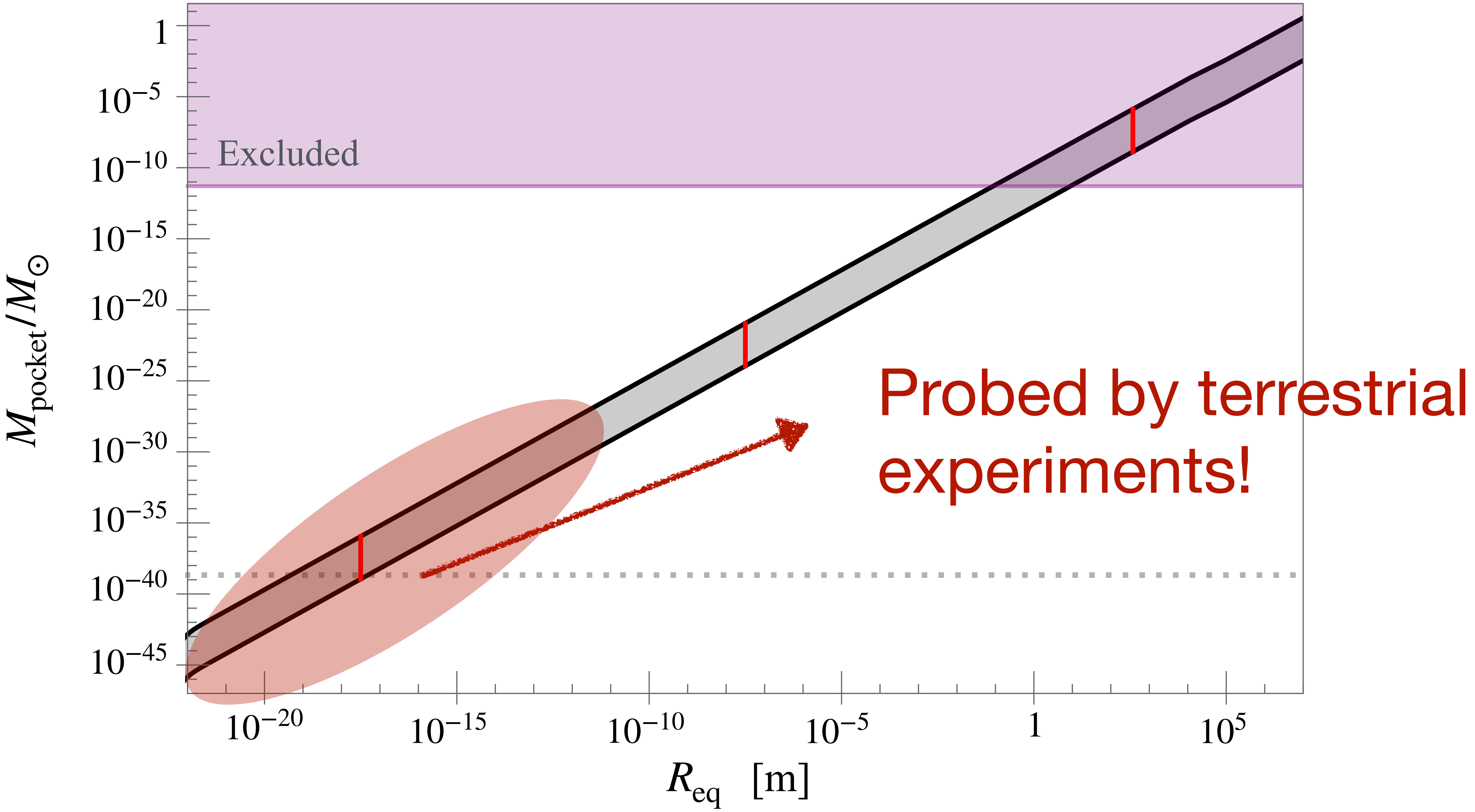
All their properties become a function of a **single** parameter: the transition temperature T_t

$$R_{\rm eq} \sim H^{-1}(T_t)$$

$$M_{\rm pocket} \sim 4\Delta V R_{\rm eq}^3$$

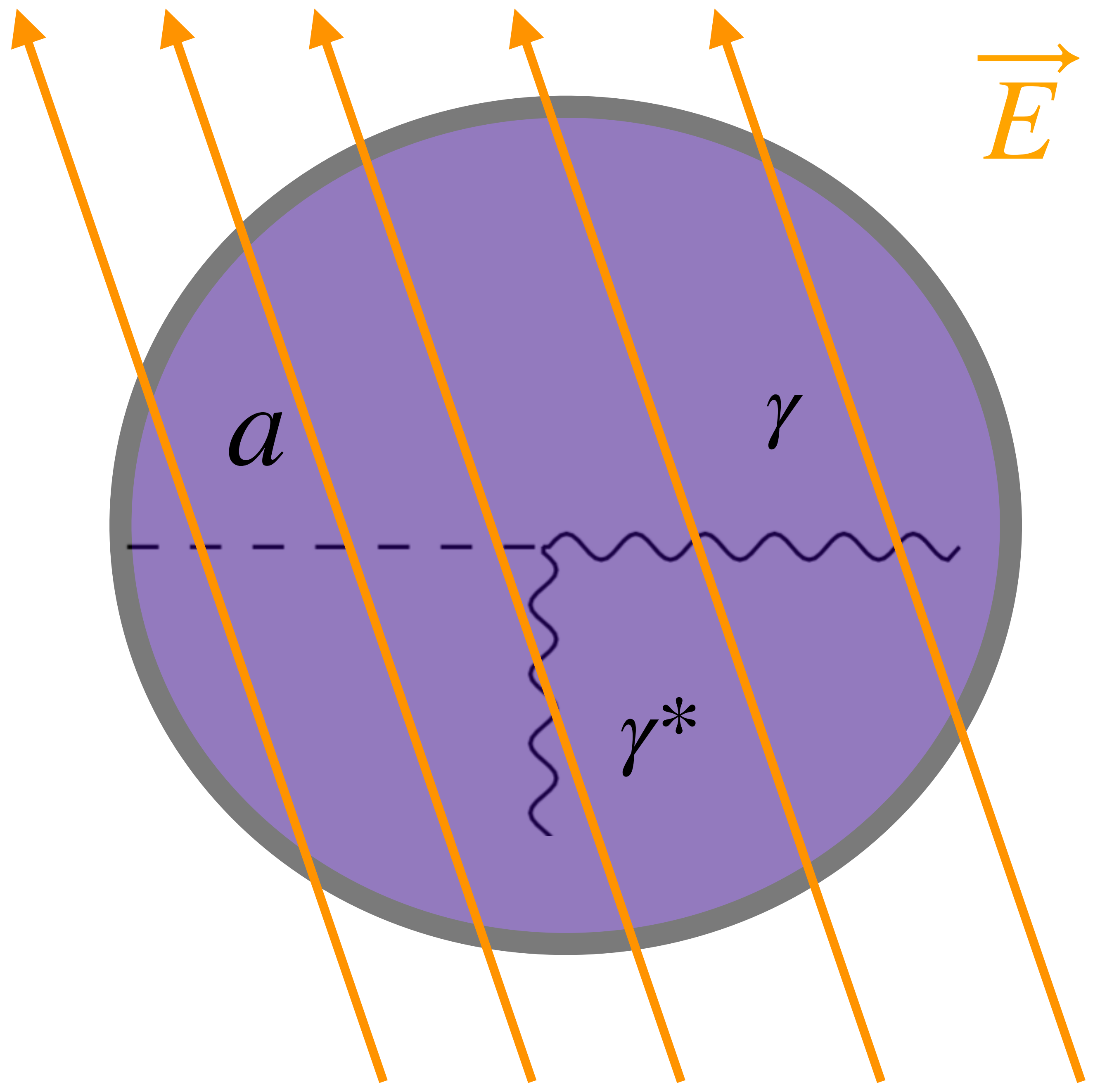
$$E_a \sim 5 \text{ GeV} \left(\frac{\rm T_t}{\rm TeV}\right)$$

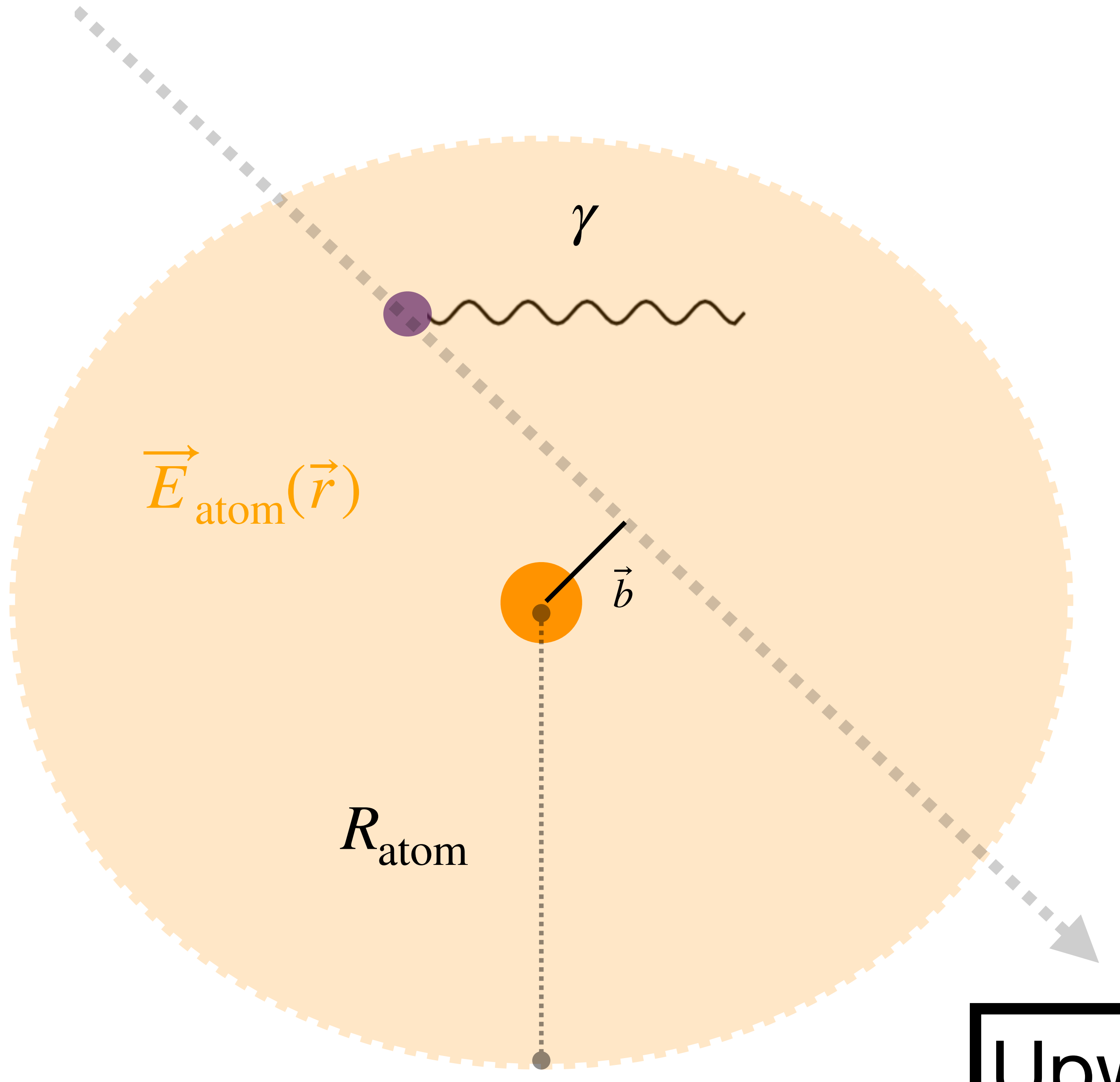
(For thermalized axions in the pocket)



Probing the ARP-photon coupling

$$\mathcal{L}_{\rm int} = -\frac{1}{4} g_{a\gamma\gamma}\, a F_{\mu\nu}\tilde{F}^{\mu\nu} = -\, g_{a\gamma\gamma} a \mathbf{E} \cdot \mathbf{B}$$





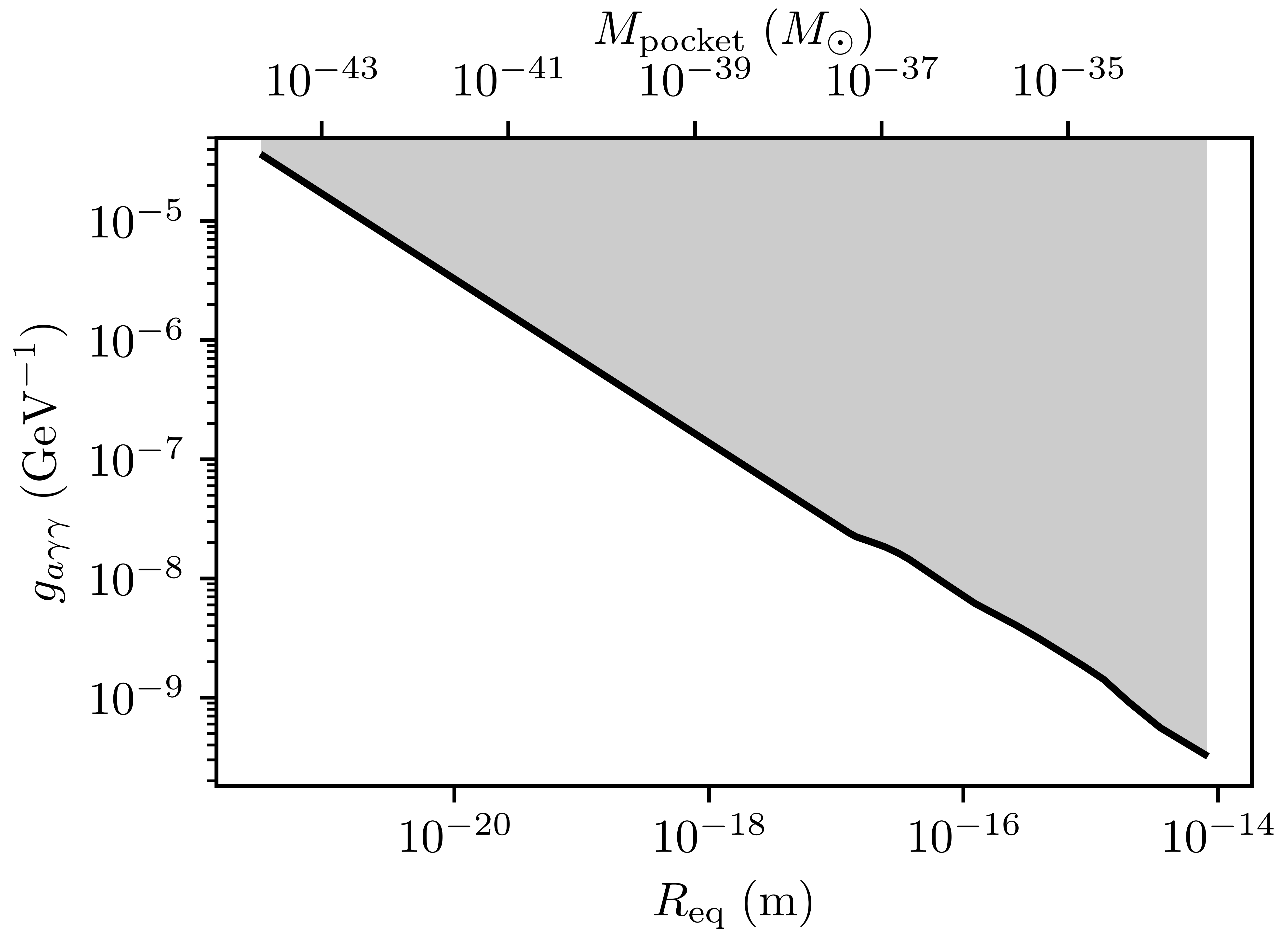
ARPs formed early in cosmic history have $R_{\rm pocket} \ll R_{\rm atom}$

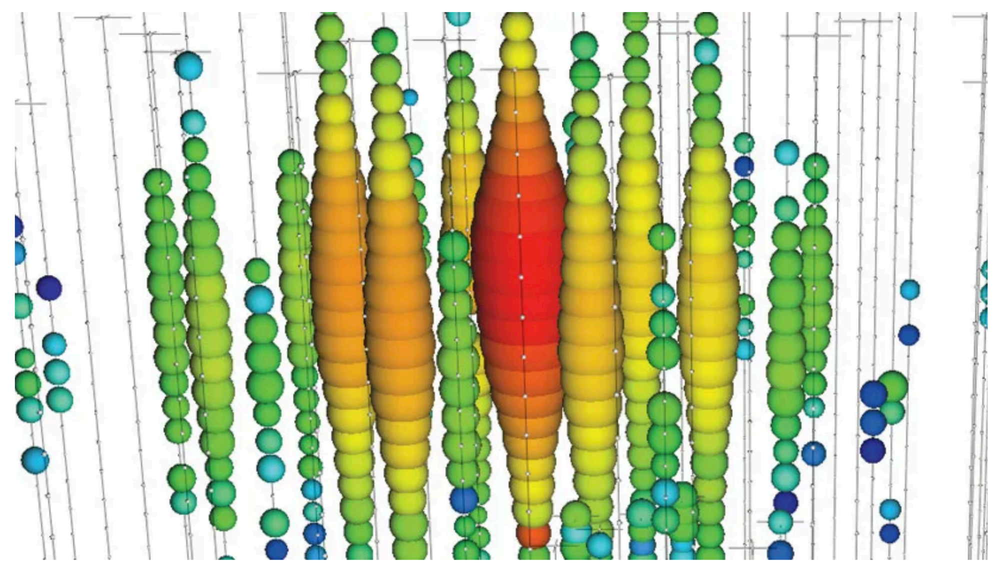
Passing through atoms, axion inside the pockets, convert into photons due to atomic electric fields.

The emitted photons are very energetic and induce isotropic E/M cascades that could be **both** going downwards and upwards

Upward going E/M showers is a smoking gun signal of the model and can be probed in large scale neutrino detectors and in the atmosphere !

First constraints from IceCube





ARPs convert into photons in the electric field of oxygen atoms in the ice, and induce E/M cascades that can be constrained by recent data samples of cascade events in IceCube.

Summary

- A Dilaton phase transition in the QCD sector could lead to an interesting alternative model of confinement based on multi field dynamics, with signatures potentially detected by PTAs.

- 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? What are the obstructions from the SM thermal plasma ?

- A Dilaton phase transition in a dark sector, confining gauge theory, could lead to stabilized pockets of hot axion gas that can comprise dark matter. This leads to exciting new phenomenology and novel dark matter signatures.

- Some future directions span theory and phenomenology, including embedding the theory to a concrete UV realization, include more ARP couplings to matter, a proper formulation of the quantum field theory of ARPs and exploring signatures in extreme astrophysical environments.

Back up

$$\mathscr{L}_{\text{int}} = -\frac{1}{4} g_{a\gamma\gamma}\, a F_{\mu\nu} F^{\mu\nu} = -\, g_{a\gamma\gamma} a \mathbf{E} \cdot \mathbf{B}$$

Axions can convert into photons in background magnetic fields, or background Coulomb electric fields

But

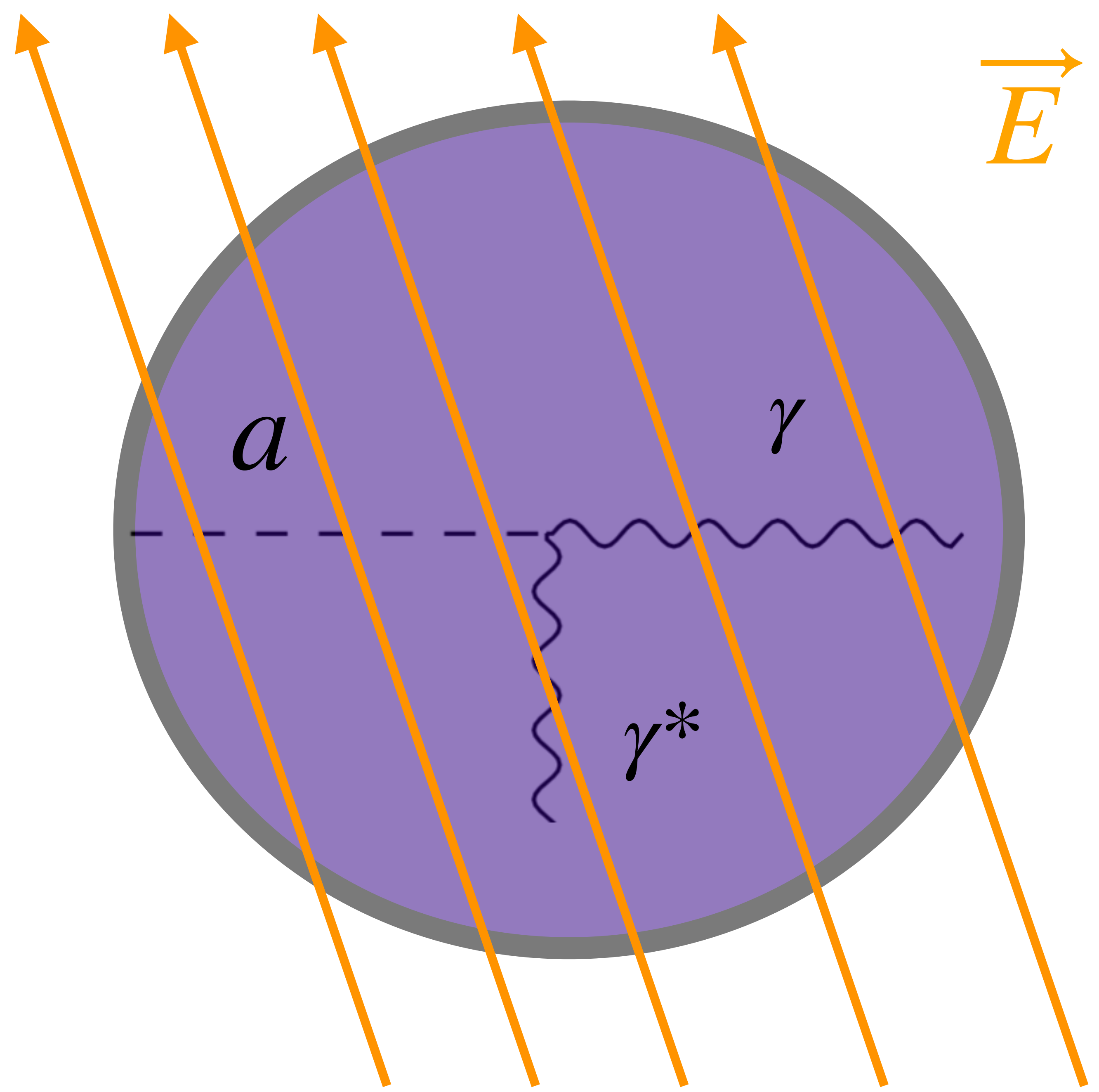
The axions are trapped in the pockets → the mode functions from the free EoM are **not** plane waves

$$a(r, \theta, \phi, t) = e^{i\omega t} u_{nlm}(r, \theta, \phi) + \text{h.c.}; \quad k_{a,nl} = \frac{\alpha_{nl}}{R_{\text{pocket}}}$$

Standard formulas for axion-photon conversion no longer apply!

Probing the ARP-photon coupling

$$\mathscr{L}_{\text{int}} = -\frac{1}{4} g_{a\gamma\gamma}\, a F_{\mu\nu}\tilde{F}^{\mu\nu} = -\, g_{a\gamma\gamma} a \mathbf{E}\cdot\mathbf{B}$$



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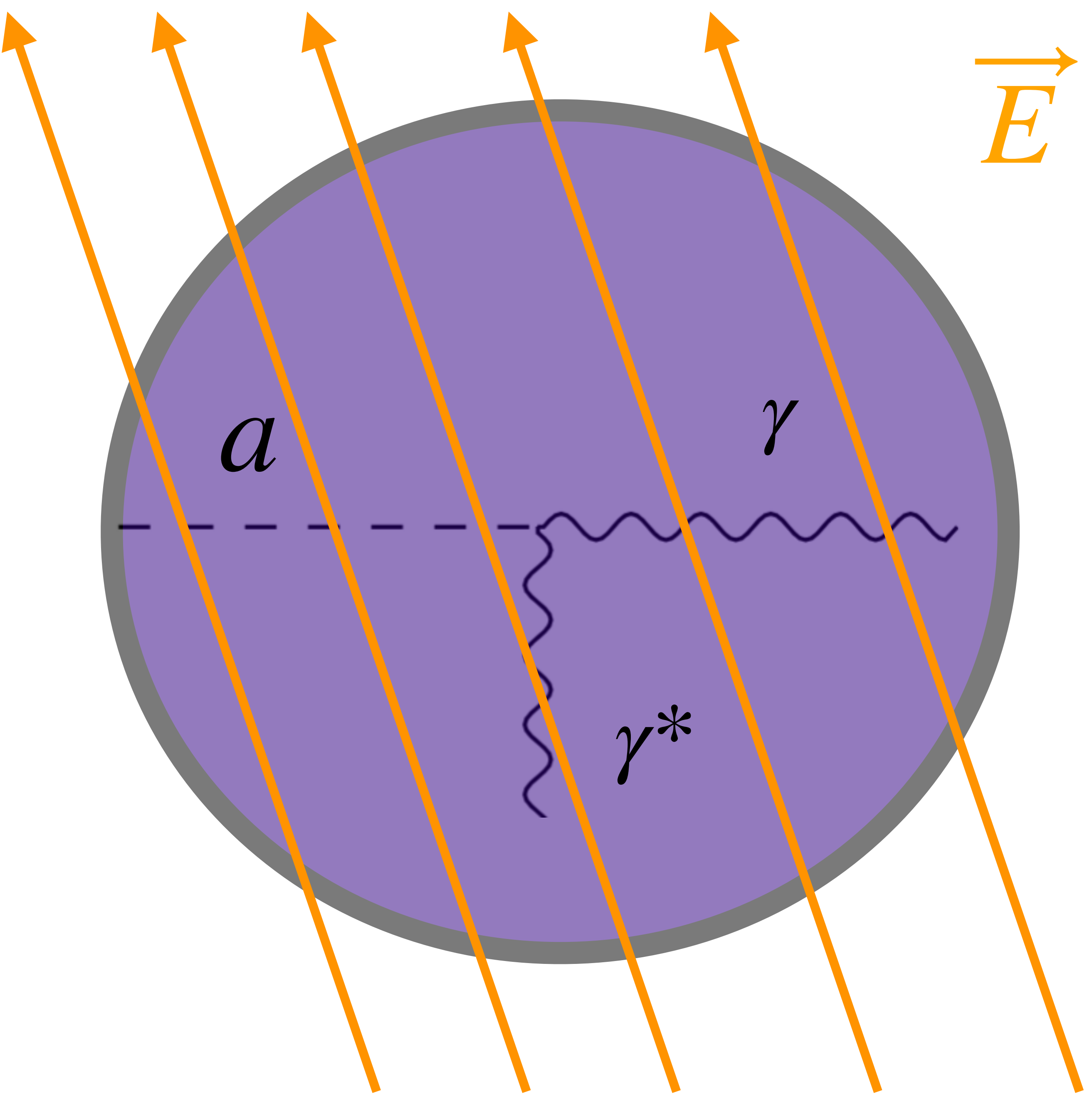
$$\mathscr{M} = \langle nlm \,|\, \mathbf{k}_\gamma \rangle \propto g_{a\gamma\gamma} \left(\mathbf{k}_\gamma \times \vec{\epsilon}^{\,*} \right) \cdot \int_{V_{\text{pocket}}} d^3 r\, e^{i\mathbf{k}_\gamma\cdot\mathbf{r}}\, \mathbf{E}(\mathbf{r}) u_{nlm}(\mathbf{r})$$



Back up

The calculation can be done both for classical (modified) E/M and tree-level QFT, and boils down to an overlap integral of the mode function wrt the background field

$$\mathscr{M} = \langle nlm \,|\, \mathbf{k}_\gamma \rangle \propto g_{a\gamma\gamma} \left(\mathbf{k}_\gamma \times \epsilon^* \right) \cdot \int_{V_{\rm pocket}} d^3 r e^{i\mathbf{k}_\gamma \cdot \mathbf{r}} \, \mathbf{E}(\mathbf{r}) u_{nlm}(\mathbf{r})$$

If the field does not vary much in pocket volume

$$\Gamma_{a\to\gamma} = \frac{2E_a}{3m_a^4} g_{a\gamma\gamma}^2 E_{\rm atom}^2 \mathscr{B}_{nl}^2 F_{nl}^2 \left(R_{\rm pocket} \right) \left(1 - \frac{l(l+1) - 3m^2}{(2l-1)(2l+3)} \right),$$

$$\Gamma_{a\to\gamma}^{nl} = \frac{g_{a\gamma\gamma}^2 E_{\rm atom}^2 R_{\rm pocket}}{3}$$

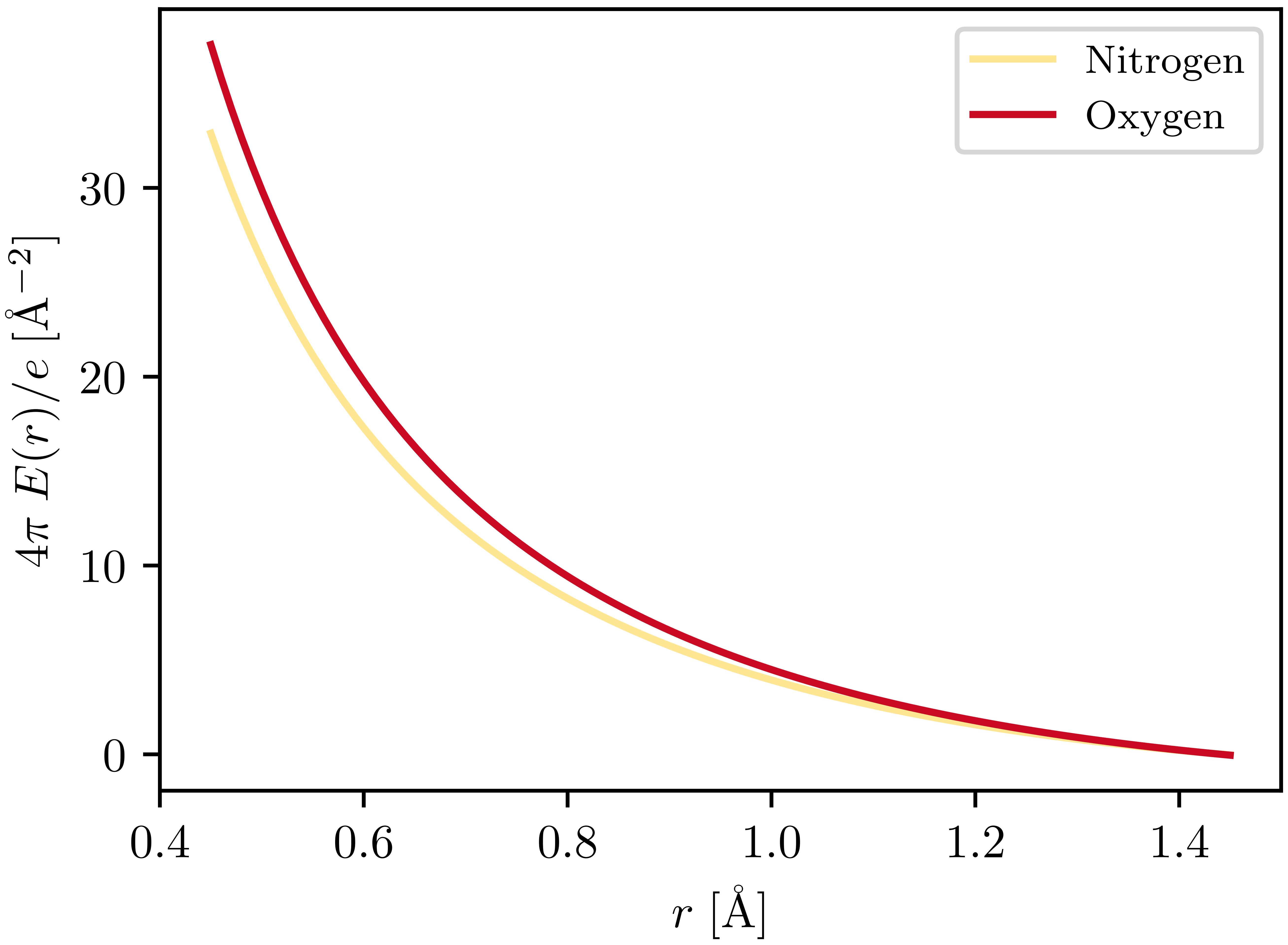
$$F_{nl}\left(R_{\rm pocket}\right) = R_{\rm pocket}^2 k_\gamma k_a \; j_{l-1}\left(k_{nl,a} R_{\rm pocket}\right) j_l(k_\gamma R_{\rm pocket})$$

Reconstructed Electric fields

$$F(q) = \sum_{i=1}^{4} a_i \exp\left[-b_i \left(\frac{|\mathbf{q}|}{4\pi}\right)^2\right] + c$$

$$n_e(r) = \frac{1}{2\pi^2} \int_0^{q_{\max}} dq \, \frac{q \sin(qr) F(q)}{r} \, .$$

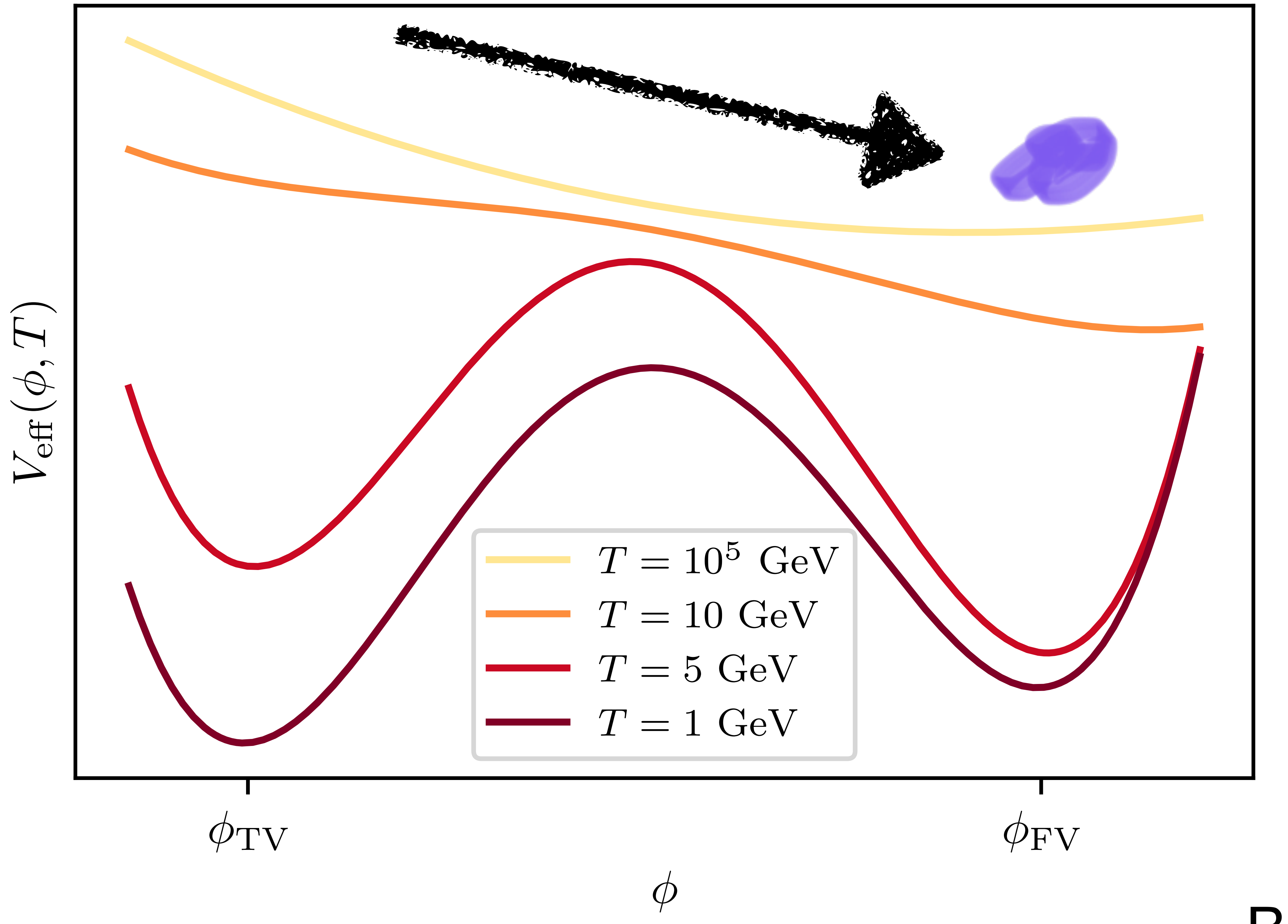
$$\nabla \mathbf{E}_{\text{atom}} = = Ze\delta^3(\mathbf{x}) - en_e(\mathbf{x}) \, .$$



Cosmology of field-dependent couplings

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

$m_\phi = 10$ 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

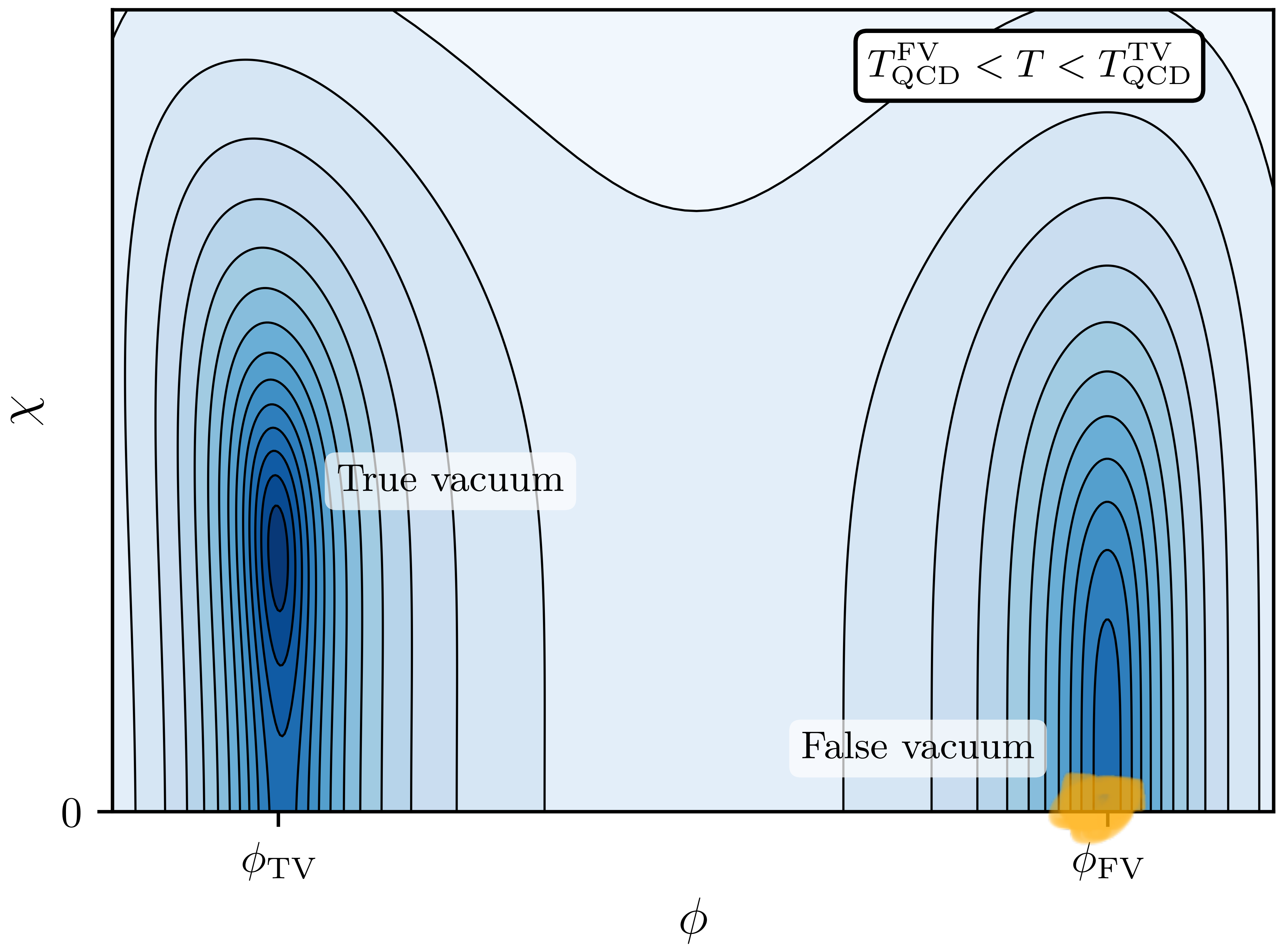
But then the confinement scale $\Lambda_{\rm QCD}(\phi_{\rm FV}) \ll \Lambda_{\rm QCD}^{\rm SM}$

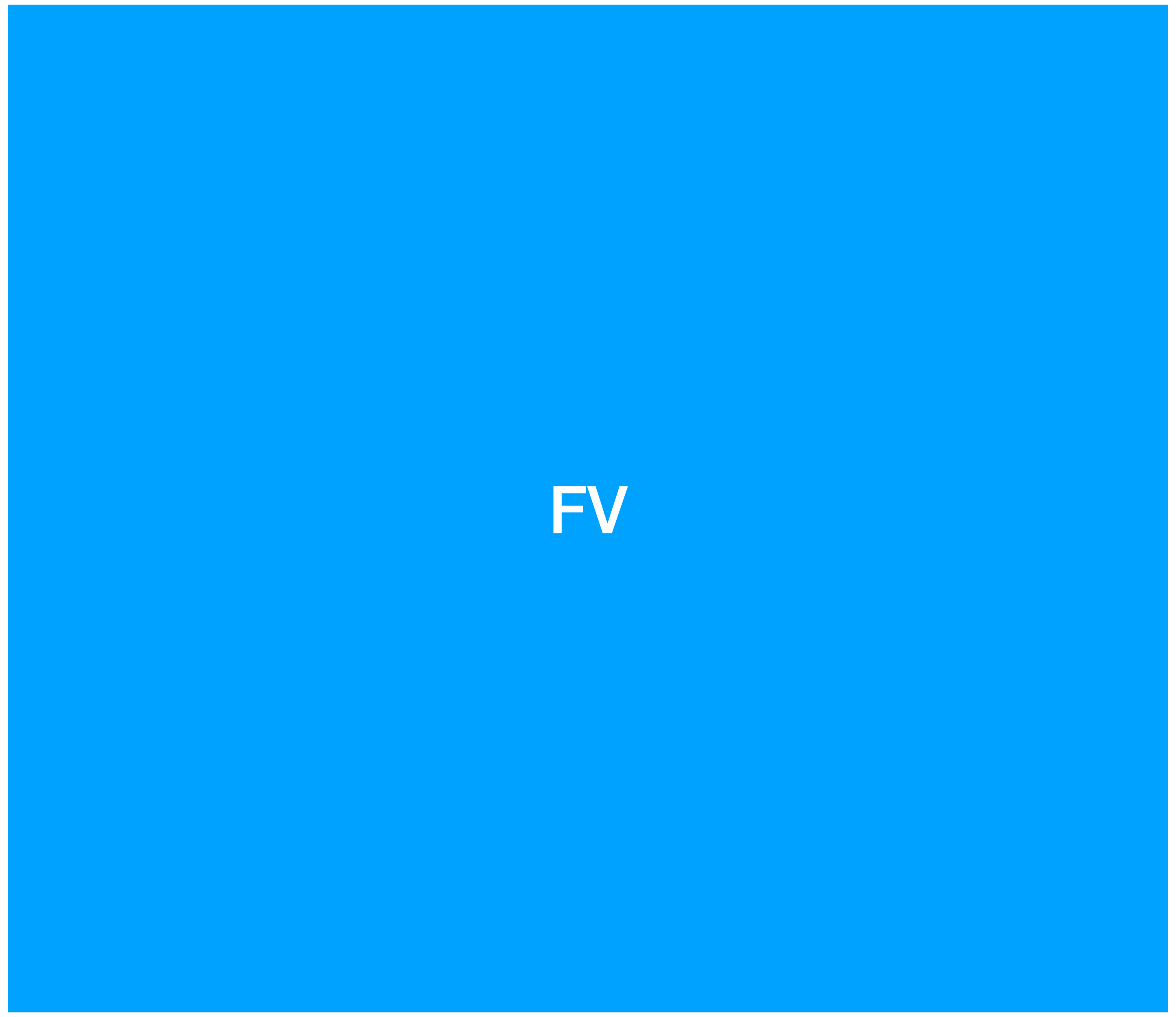
Two field transition involving QCD

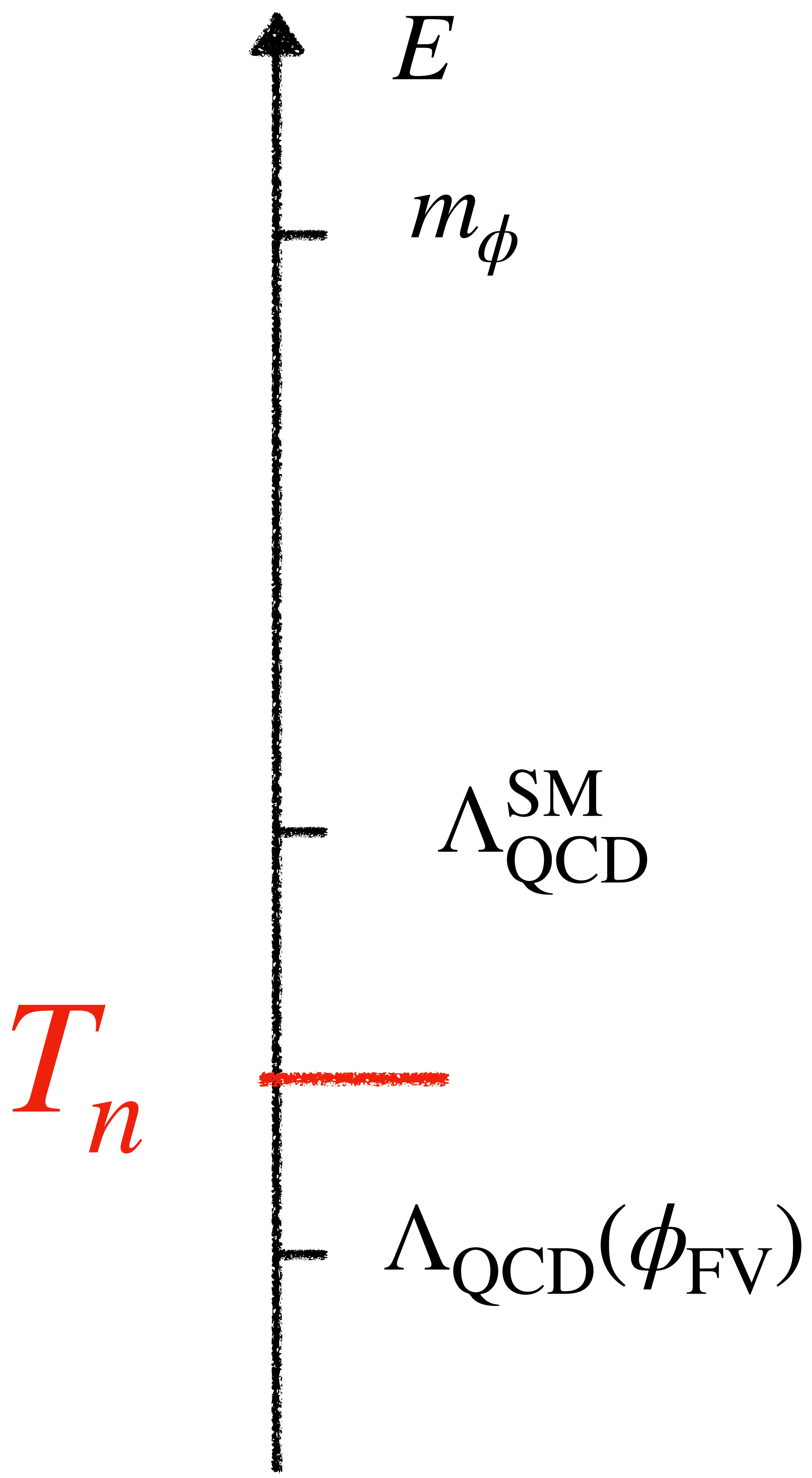
$m_\phi = 10$ TeV

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

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







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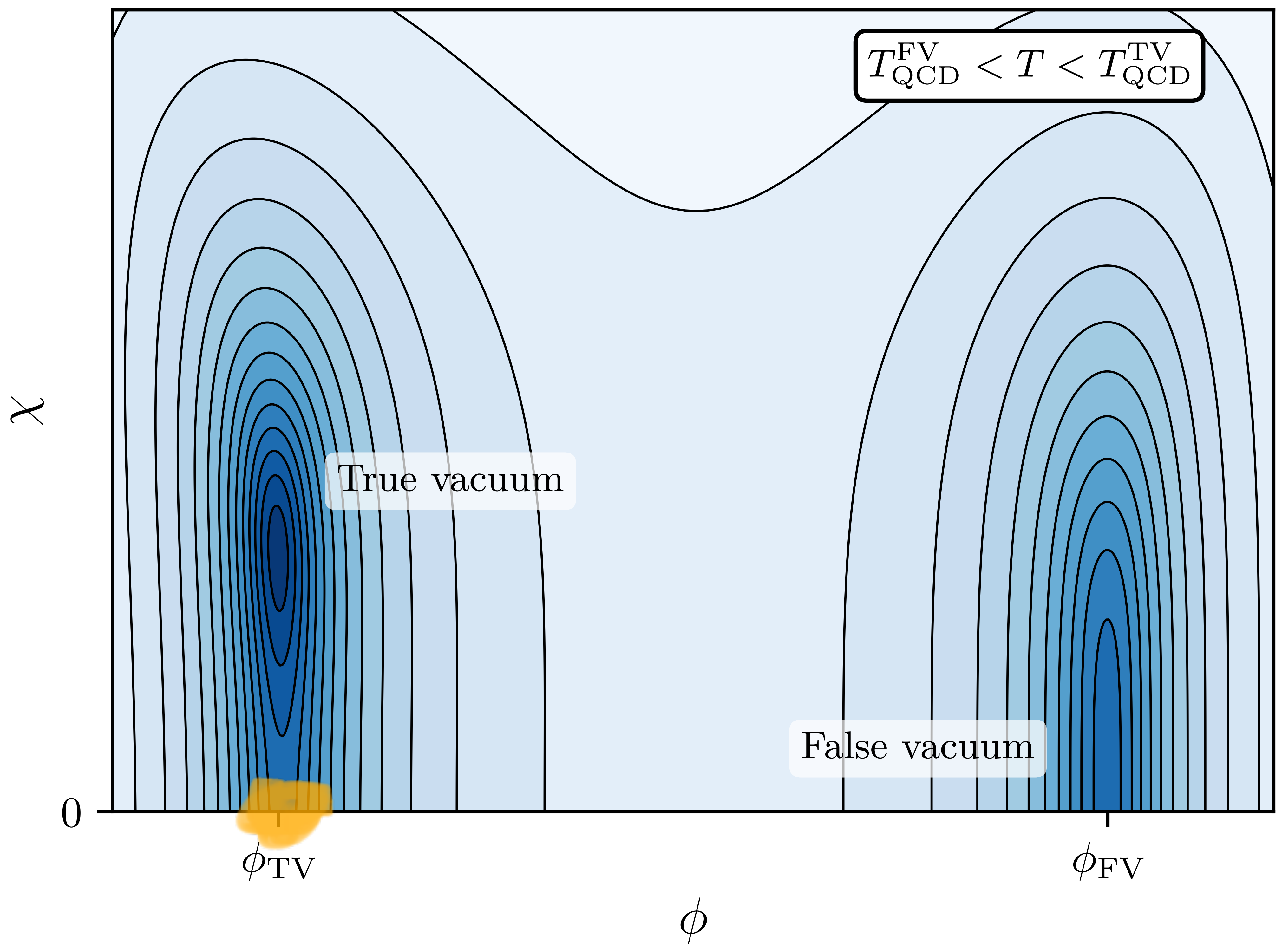

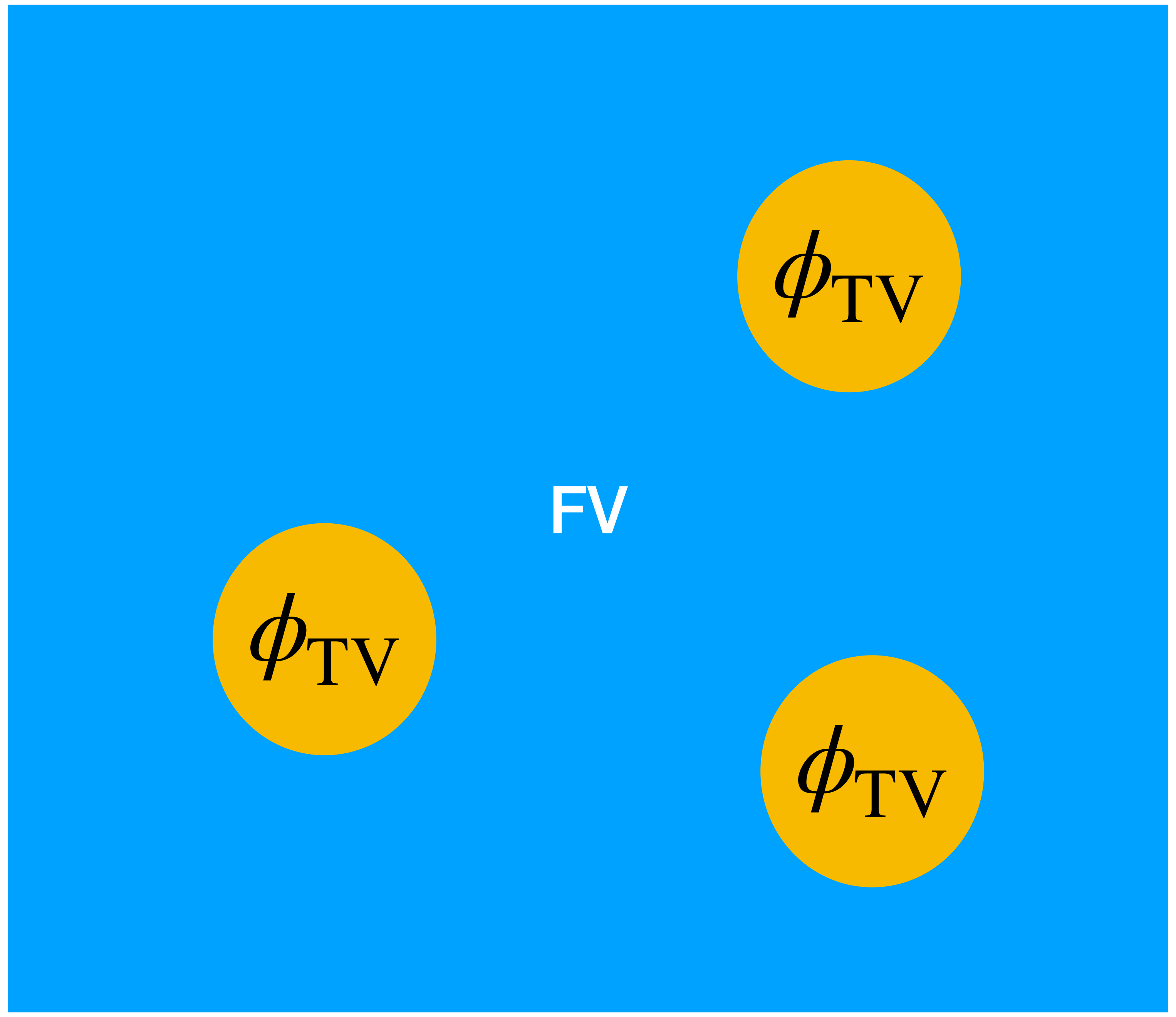

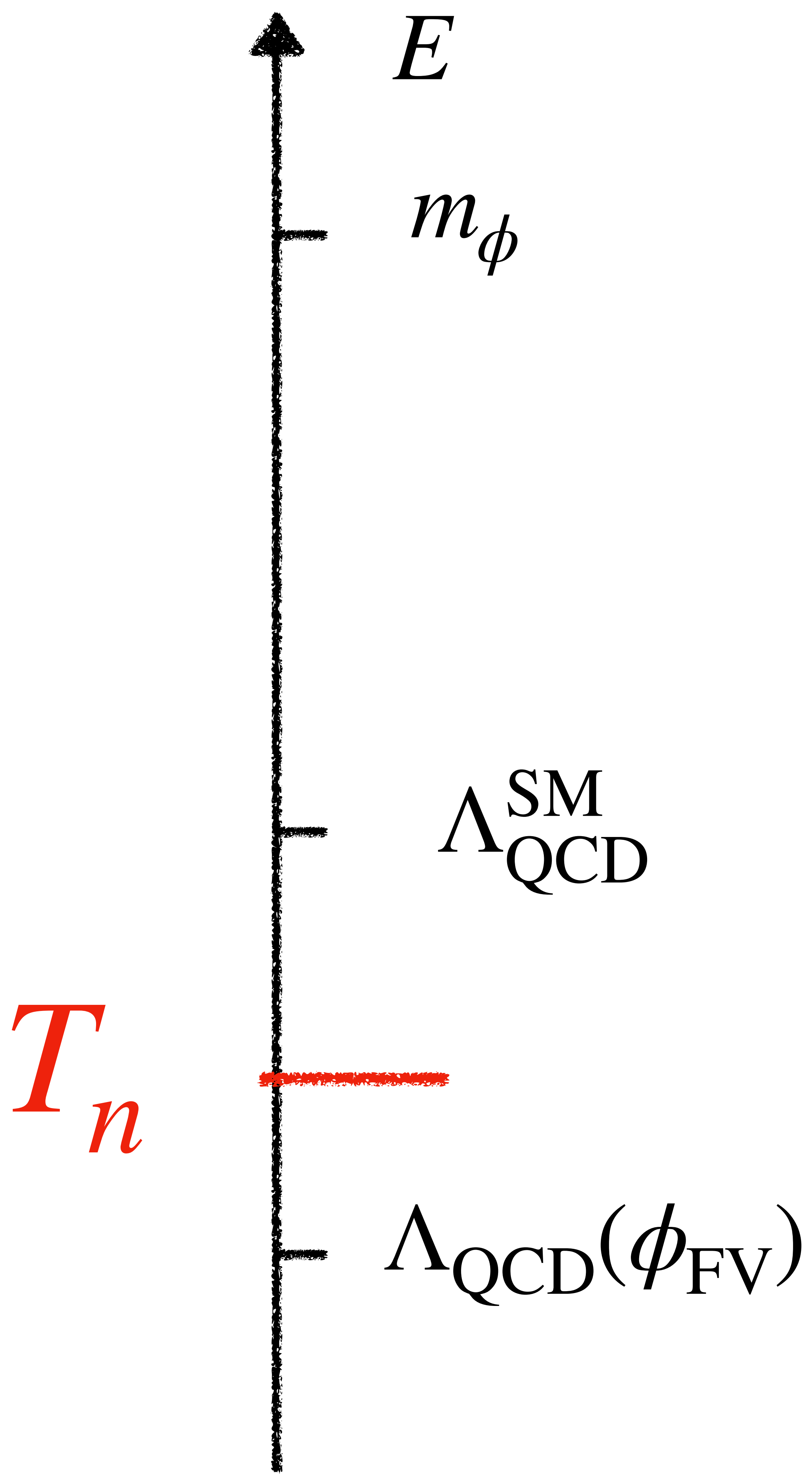

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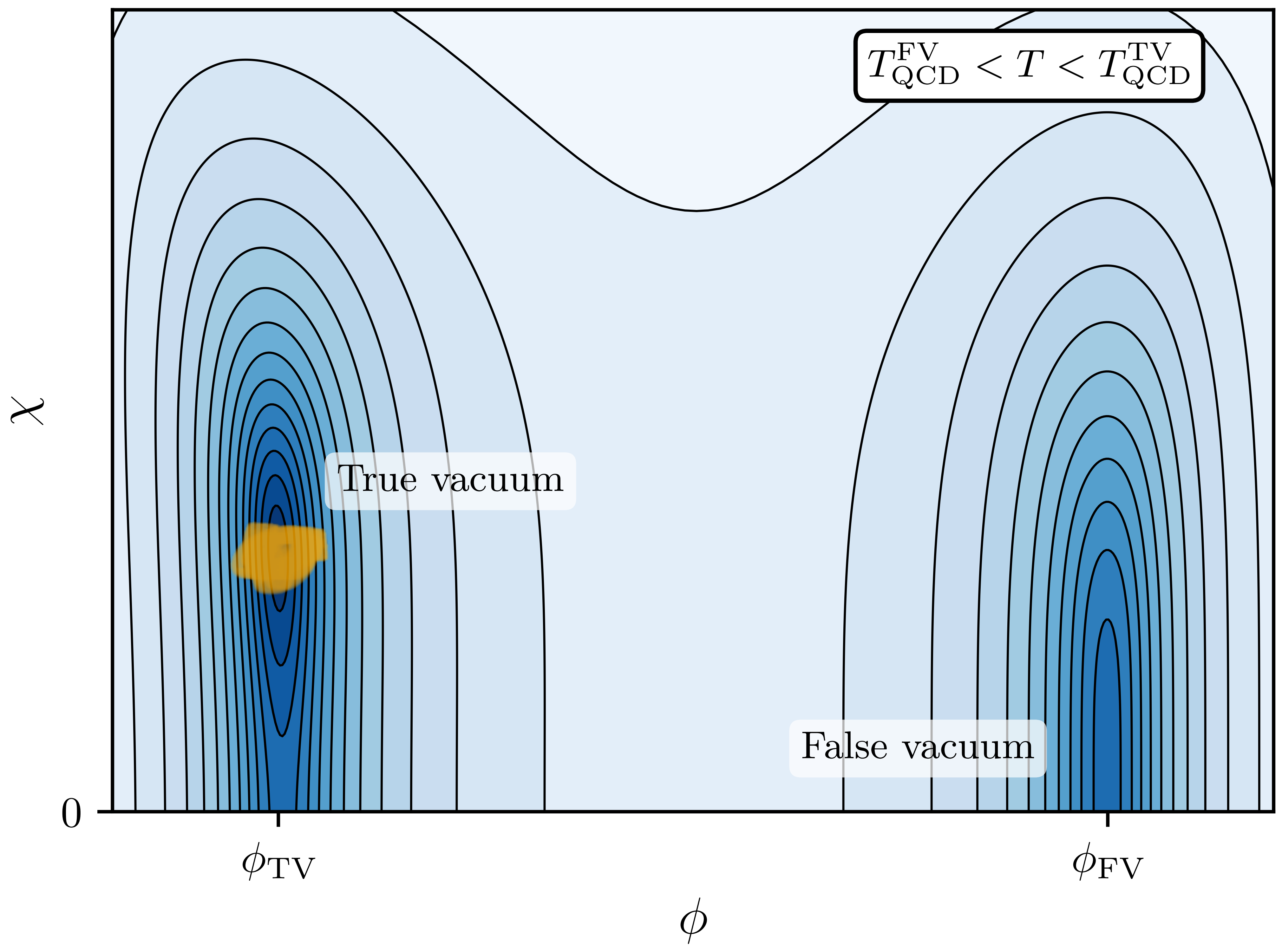
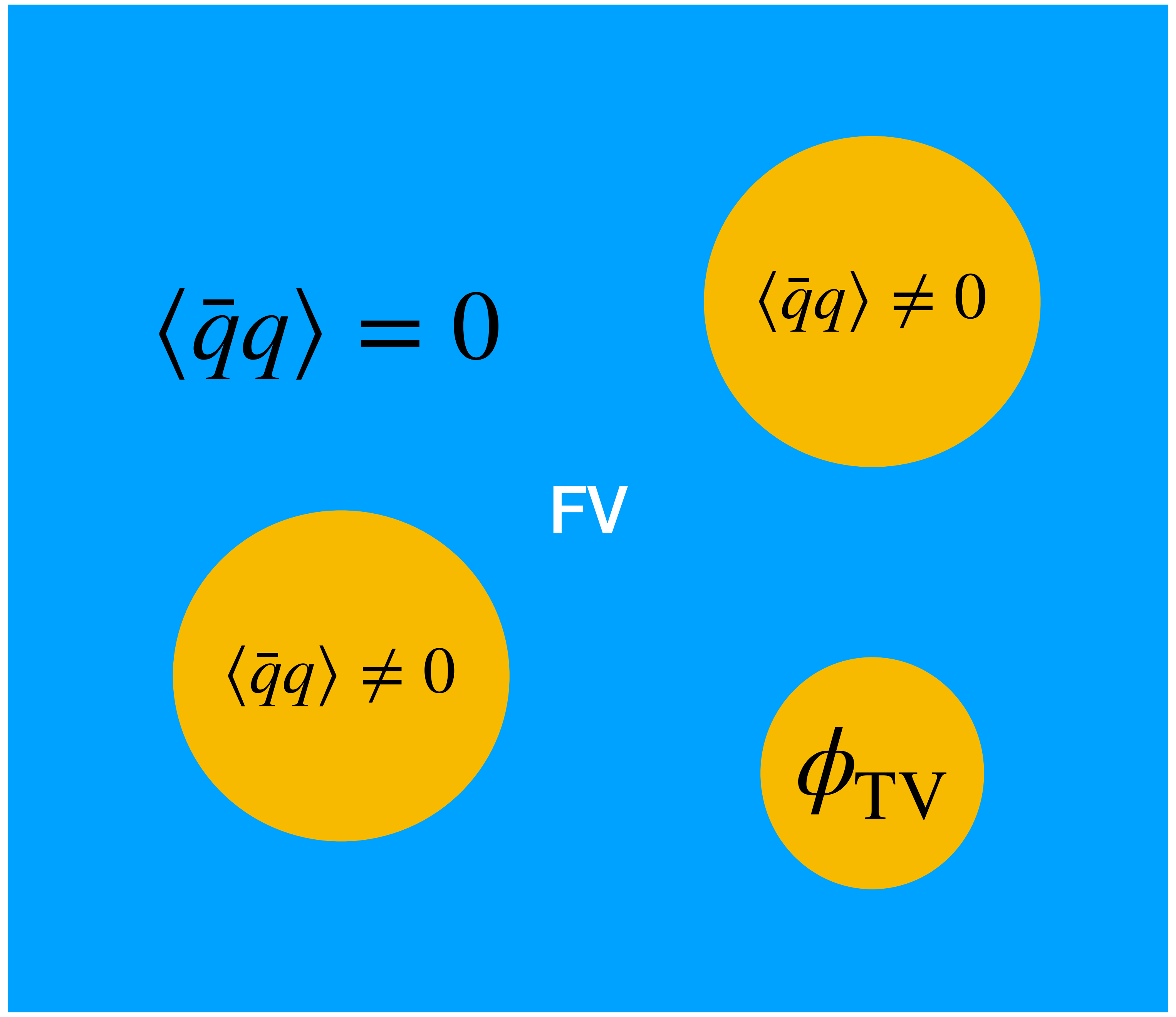
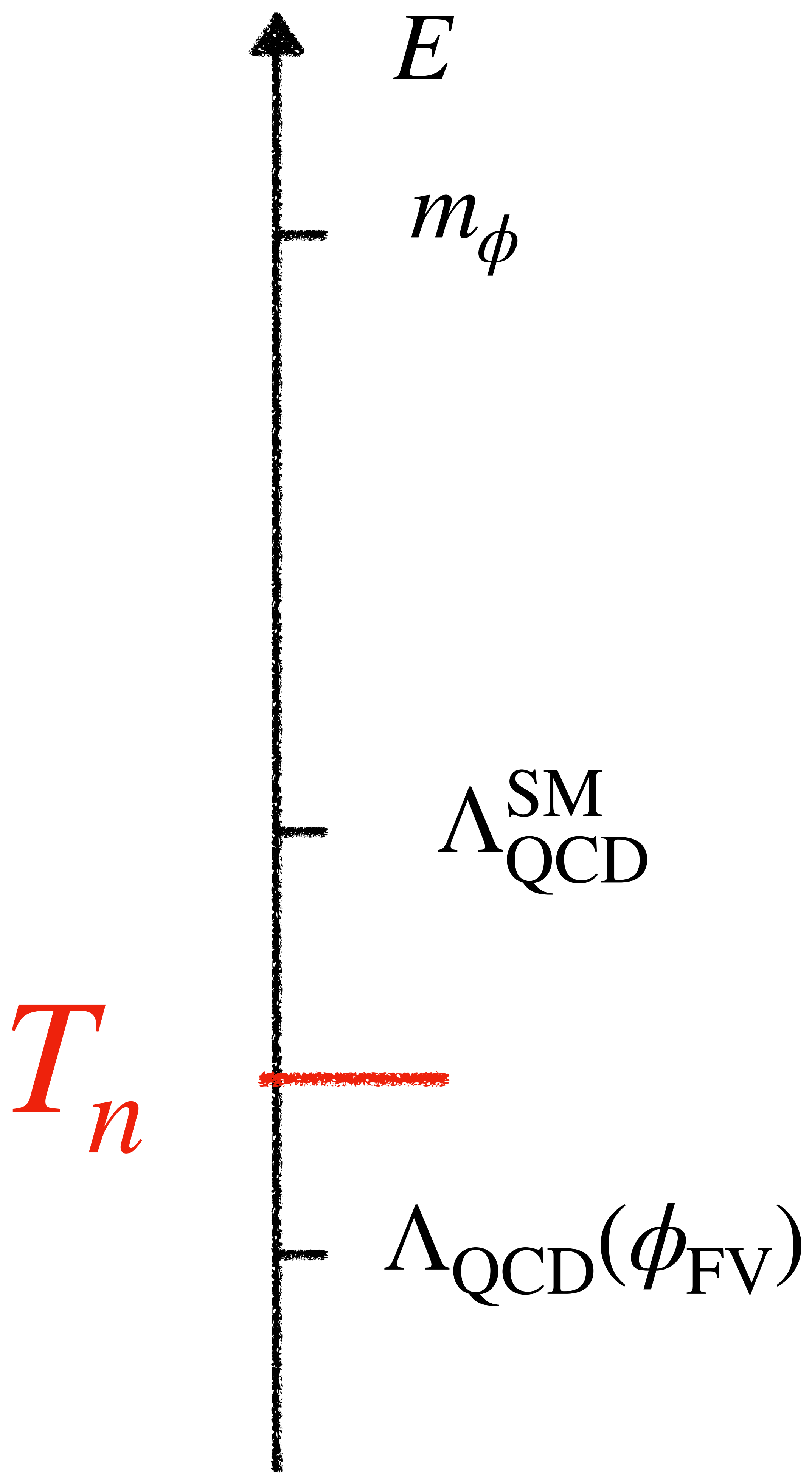
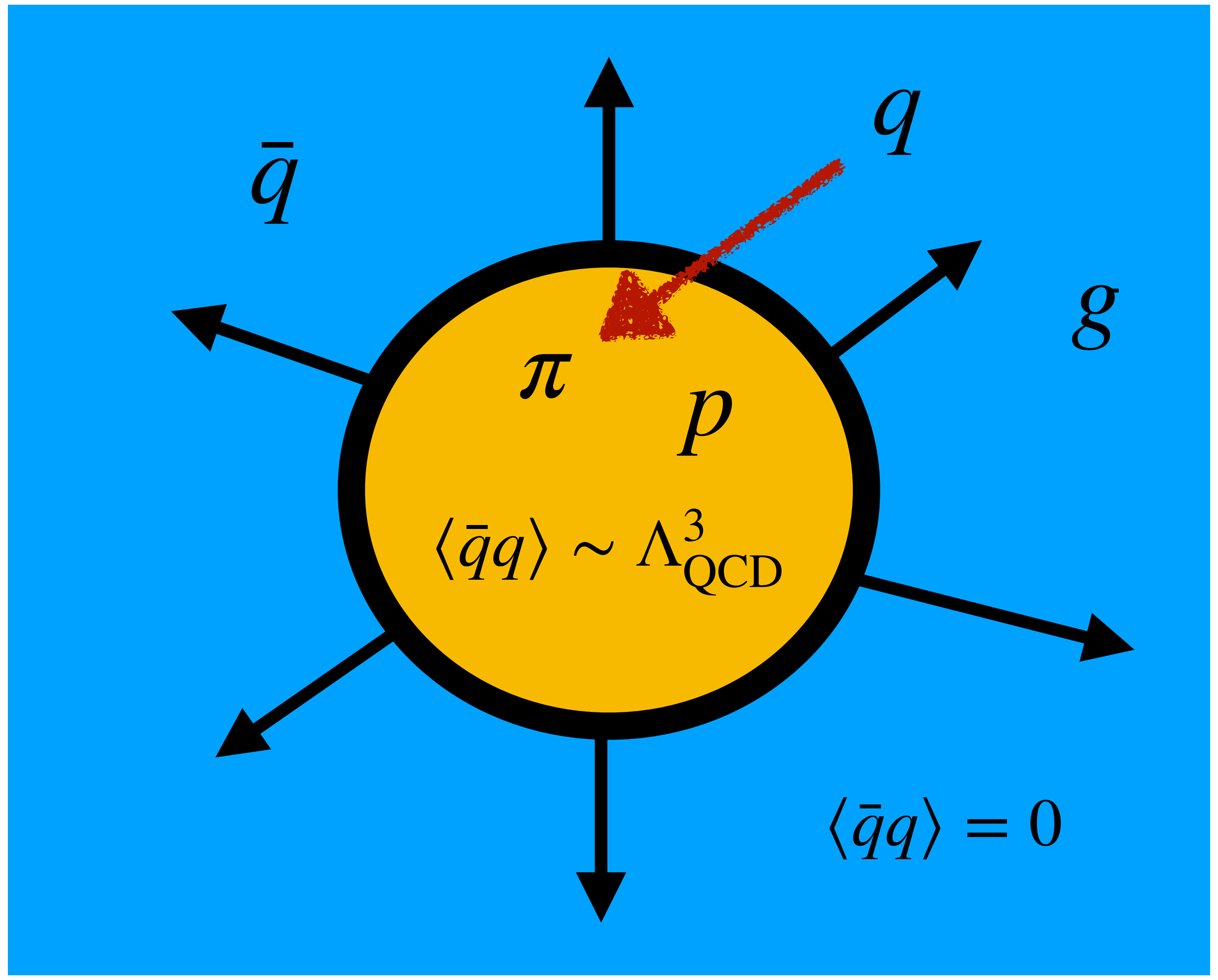






Gravitational Waves from the dilaton induced PT



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

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

$$\mathscr{P} = \mathscr{P}_{1\to1} + \mathscr{P}_{1\to2} \sim \frac{\Lambda^2_{\rm QCD} T_n^2}{24} + \Lambda_{\rm QCD}\, \gamma \alpha_s(\phi_{\rm w})\, T_n^3$$

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.

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