Dilaton Phase Transitions and Axion Relic Pockets

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Stockholm University

Swedish Research Council

20th Patras workshop on axions, WIMPs and WISPs

22 September, 2025

Dilaton Phase Transitions and Axion Relic Pockets

With
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A gauge theory has two parameters — quantum gravity has none

$$\mathcal{L} = -\frac{1}{2g^2}\,\mathrm{Tr}\left(F_{\mu\nu}F^{\mu\nu}\right) + \frac{\theta}{16\pi^2}\mathrm{Tr}\left(F_{\mu\nu}\tilde{F}^{\mu\nu}\right)$$

A gauge theory has two parameters — quantum gravity has none

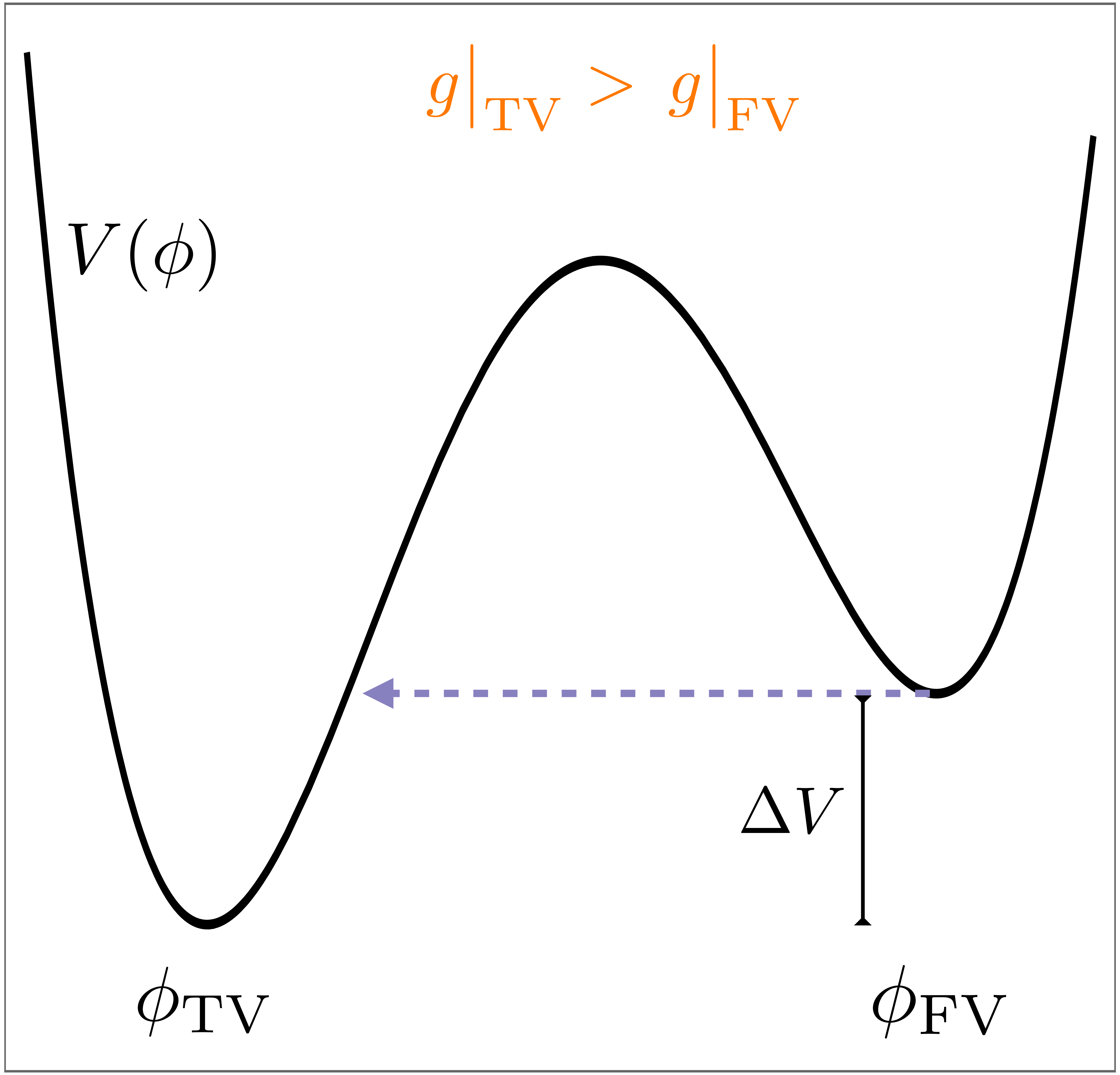
$$\mathcal{L} = -\tfrac{1}{2} f(\phi)\, \mathrm{Tr}\left(F_{\mu\nu}F^{\mu\nu}\right) + \frac{a}{16\pi^2 f_a} \mathrm{Tr}\left(F_{\mu\nu}\tilde{F}^{\mu\nu}\right)$$

ϕ : 'dilaton'

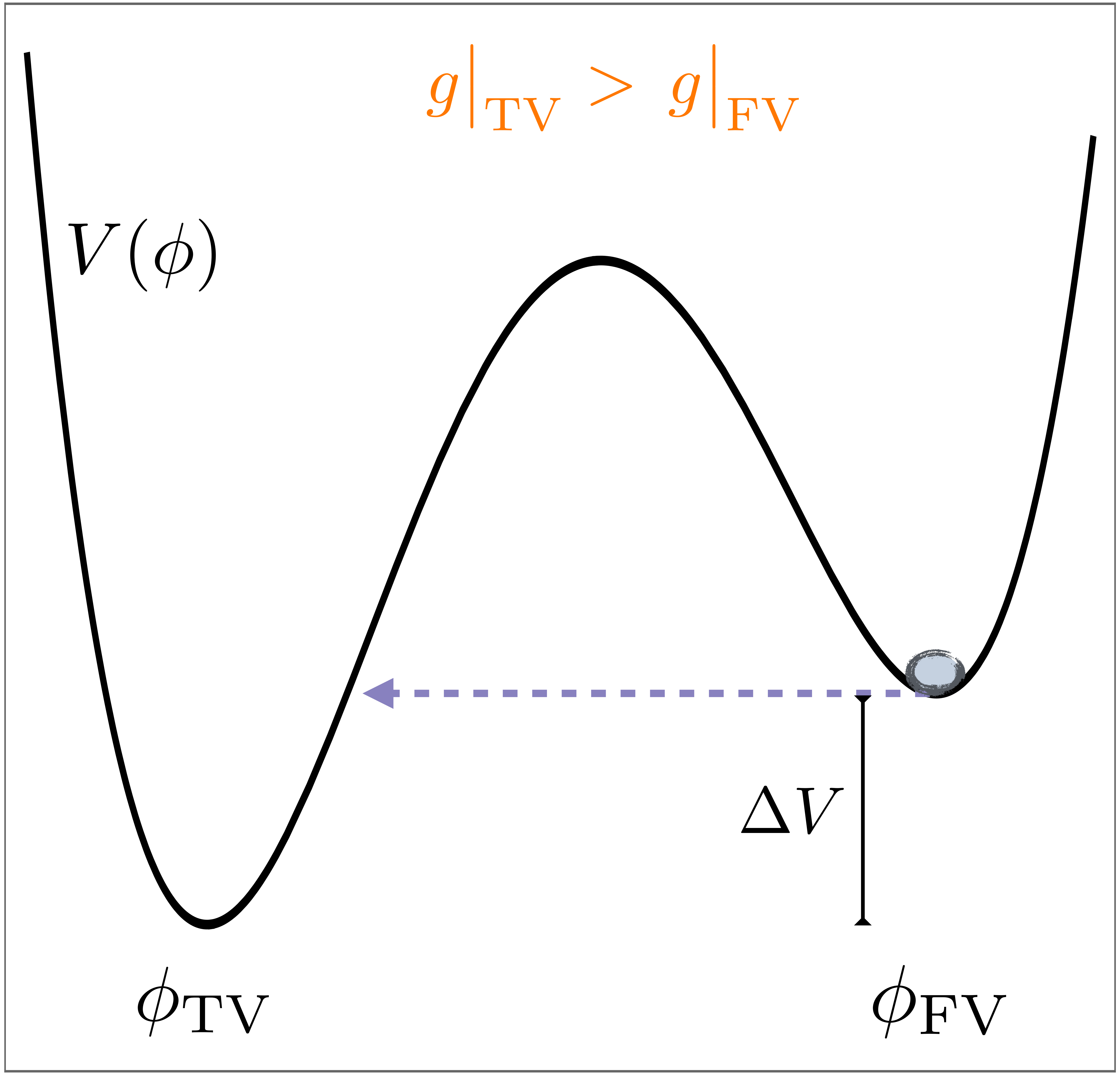
$$\langle f(\phi) \rangle = \frac{1}{g^2}\Big|_{\mathrm{UV}}$$

a : axion

$$\langle a/f_a \rangle = \theta$$



$g|_{\rm TV} > g|_{\rm FV}$
$V(\phi)$
ΔV
$\phi_{\rm TV}$
$\phi_{\rm FV}$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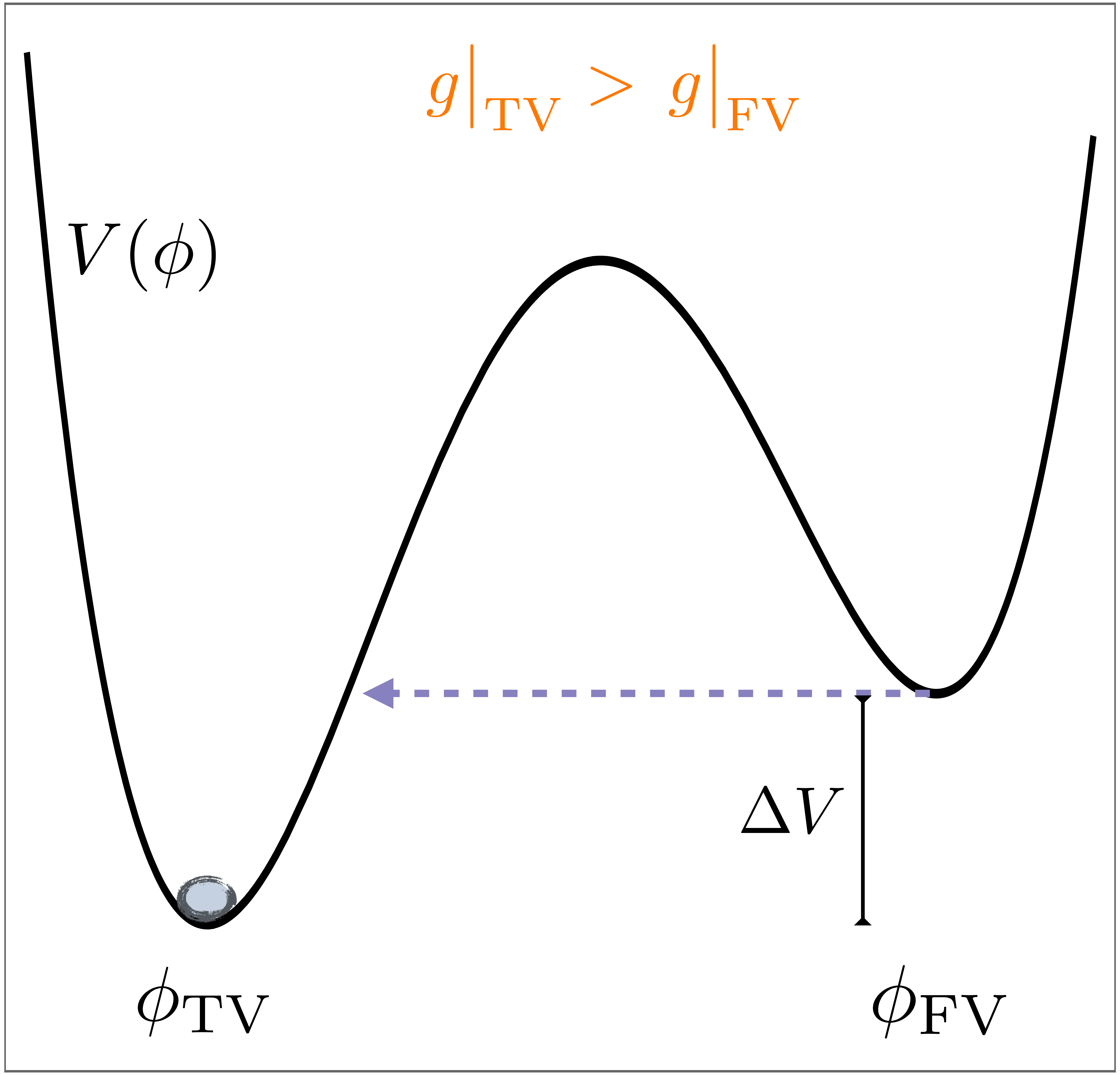

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Part I: the QCD dilaton

$$\mathscr{L} = -\frac{1}{2} f\left(\phi\right) \operatorname{tr}\left(G_{\mu\nu}G^{\mu\nu}\right) + \sum_i \bar{q}_i \left(i\not{D} - m_i\right) q_i + \frac{1}{2}(\partial\phi)^2 - V_0(\phi)$$

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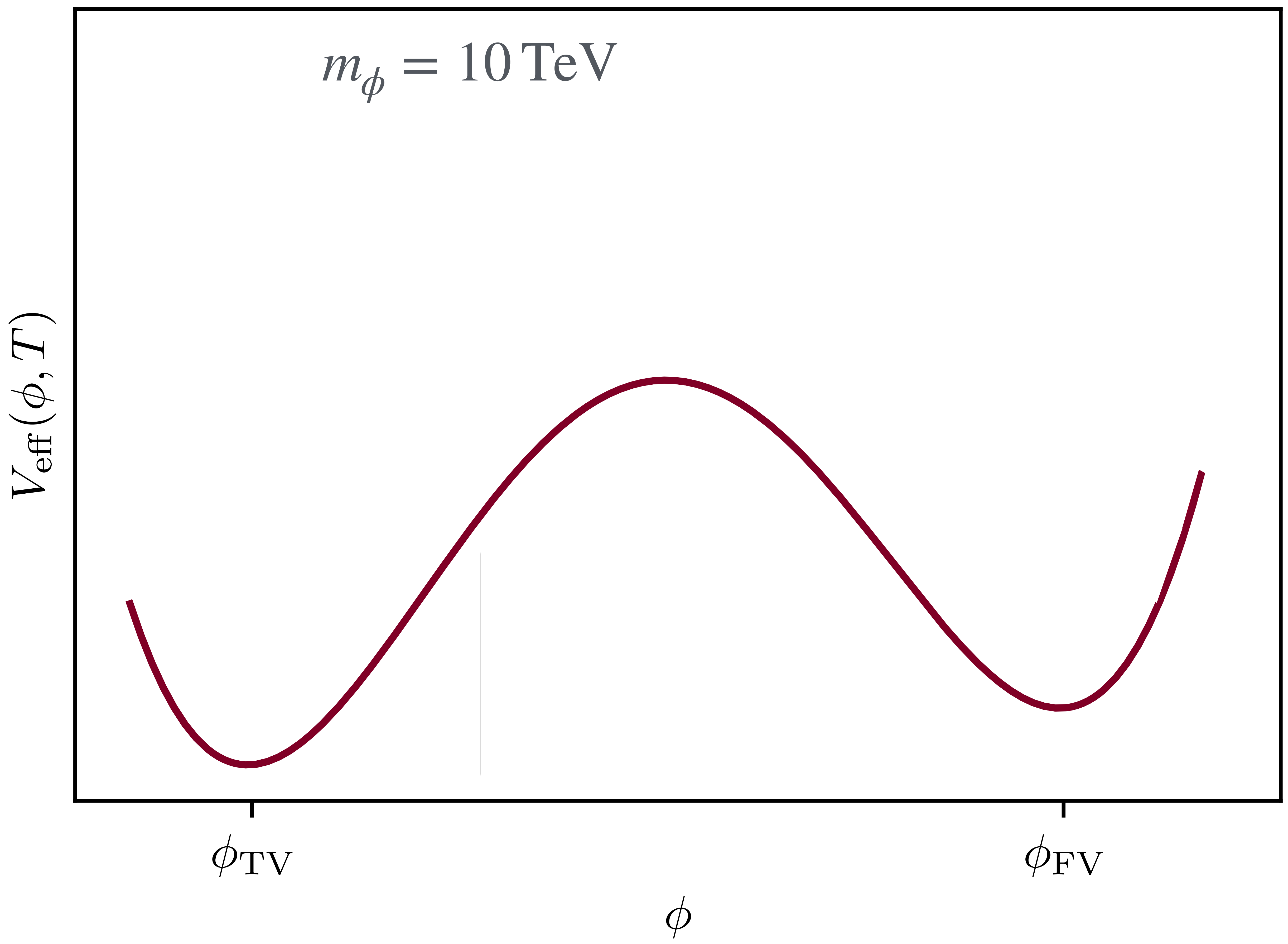
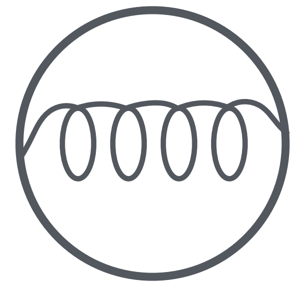


$$V_{\mathrm{eff}} = V_0 + V_T + V_{\mathscr{P}}$$

V_0 = tilted double well

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

$$V_{\mathscr{P}} = -\frac{8\pi^2 T^4}{45}\left(\frac{17}{3} - \frac{235}{16}\alpha_s + \mathscr{O}(\alpha_s^{3/2})\right)$$



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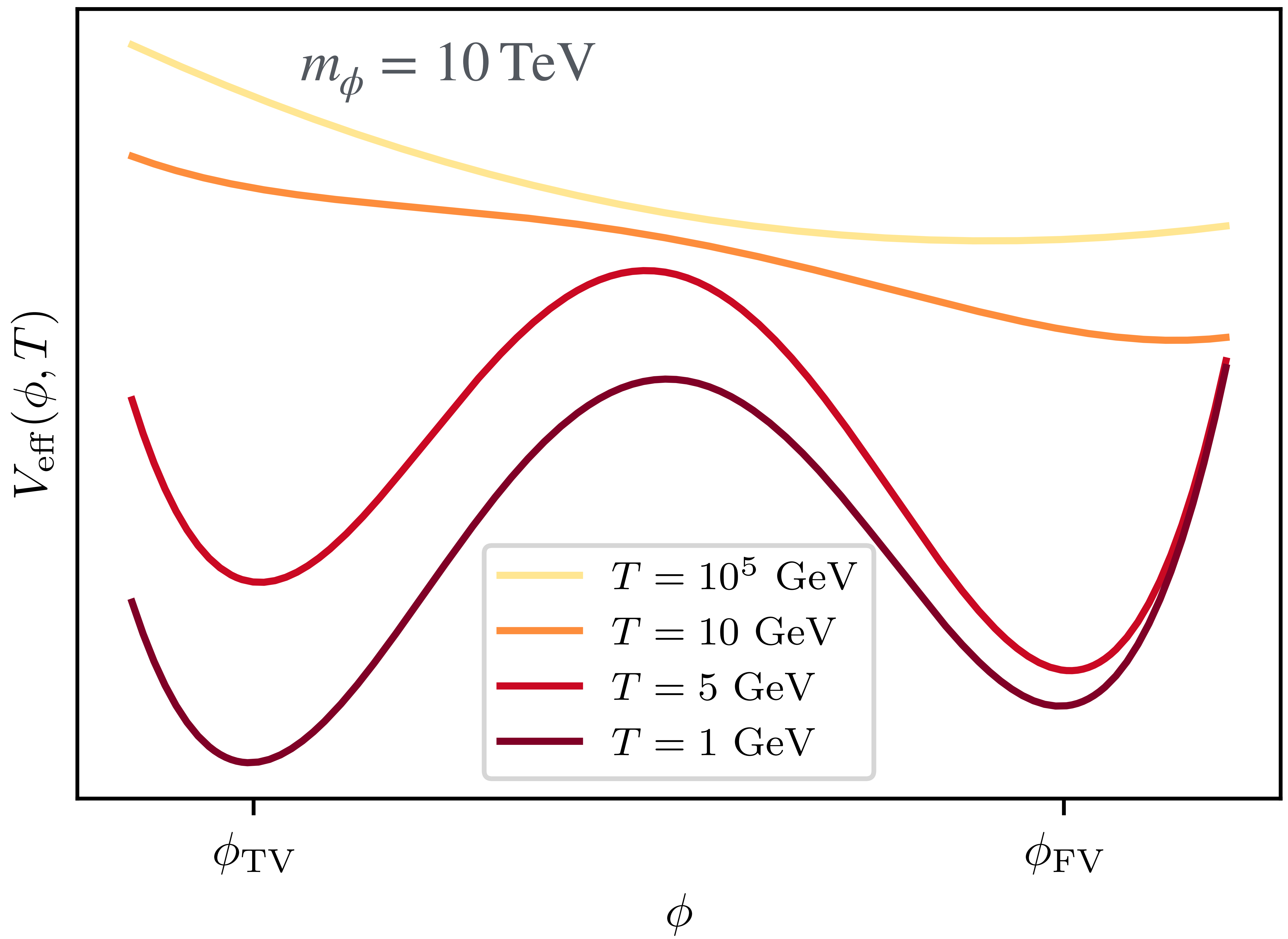

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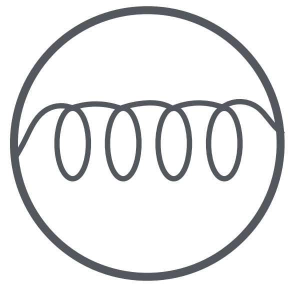

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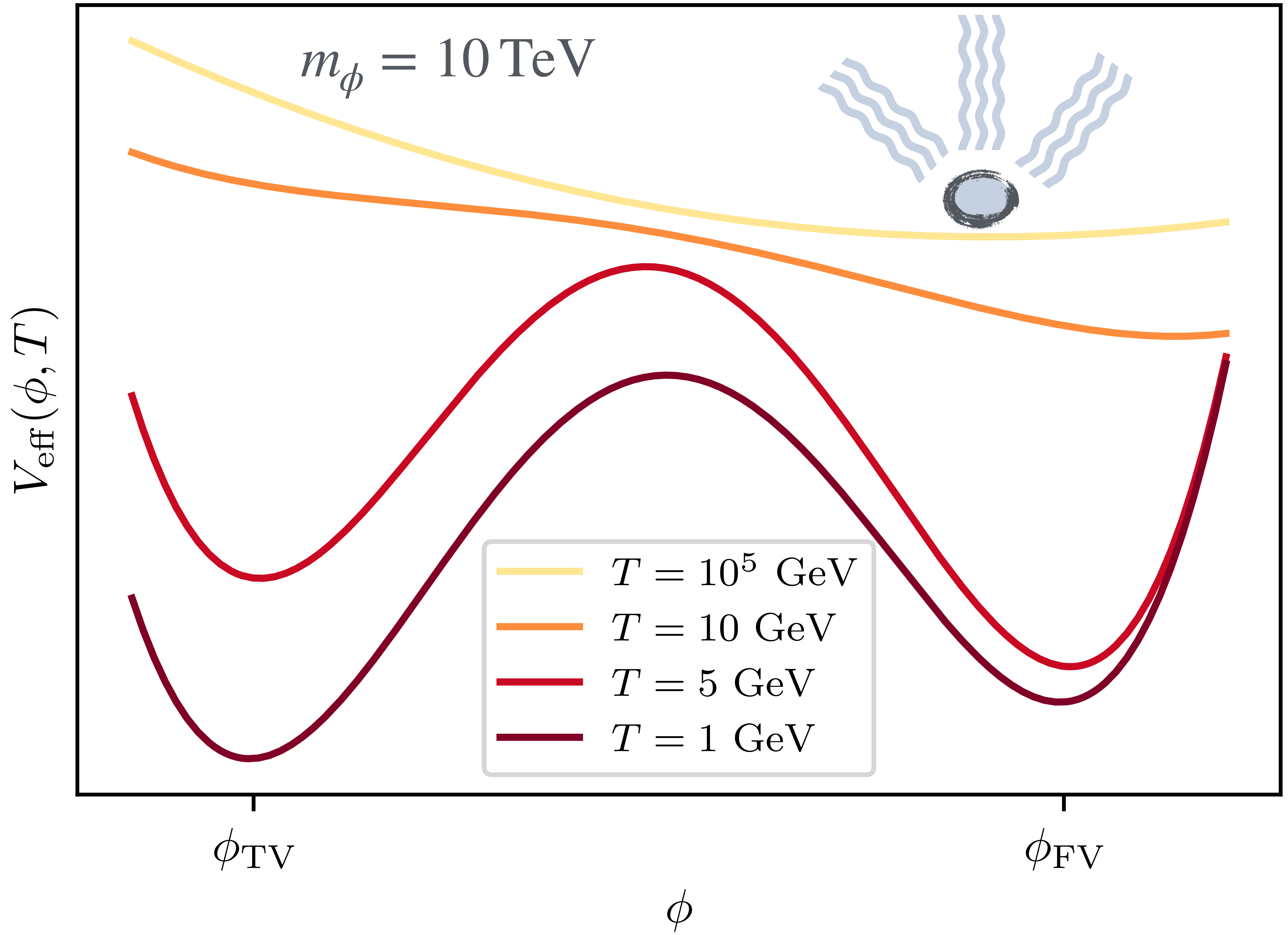

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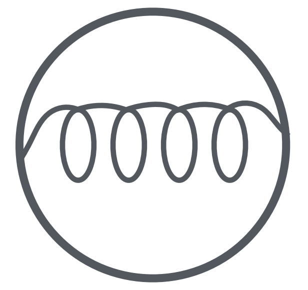

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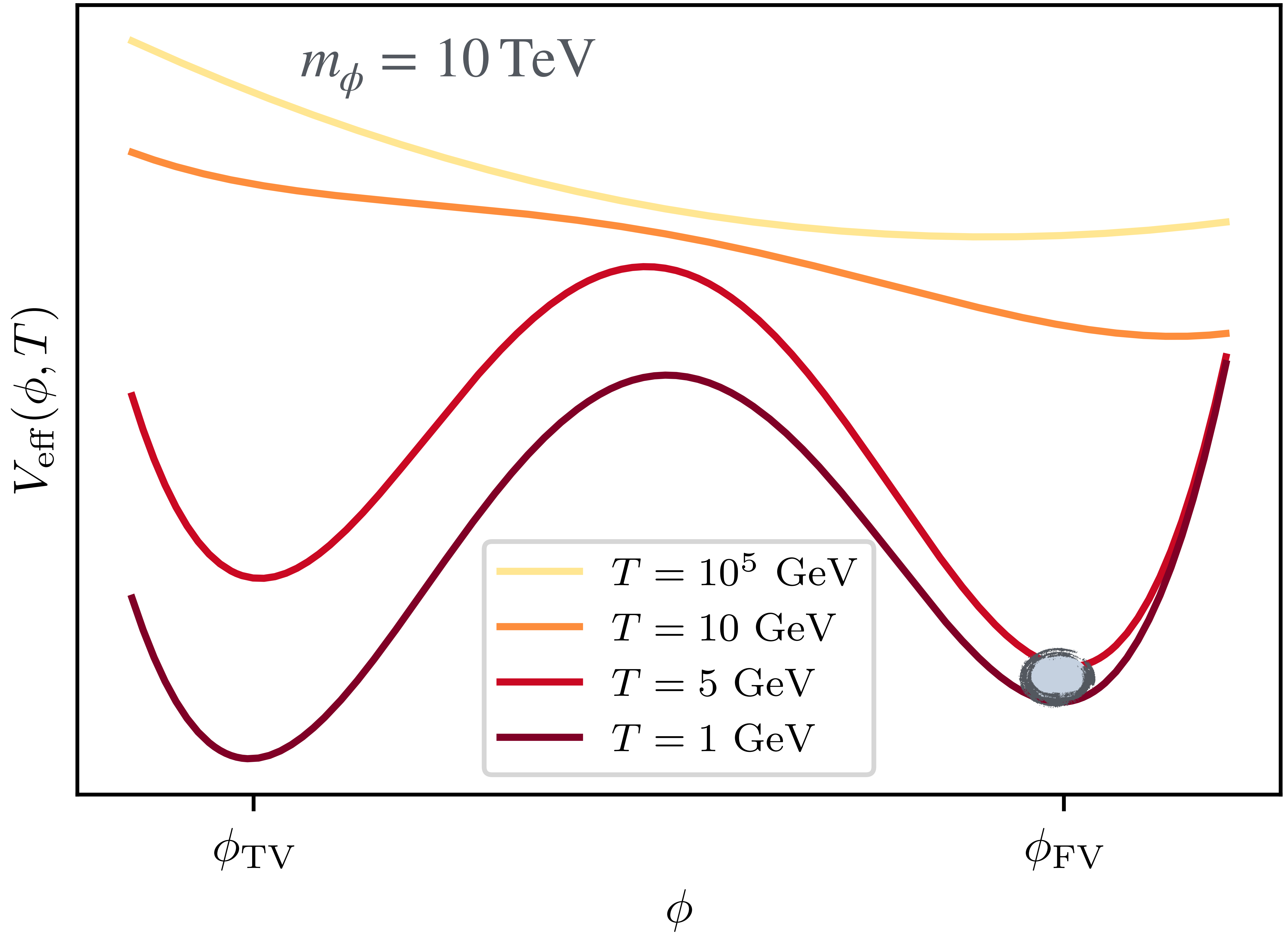

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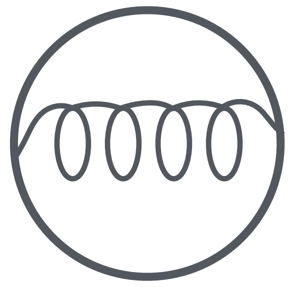

Big Bang Cosmology
of the first micro-second

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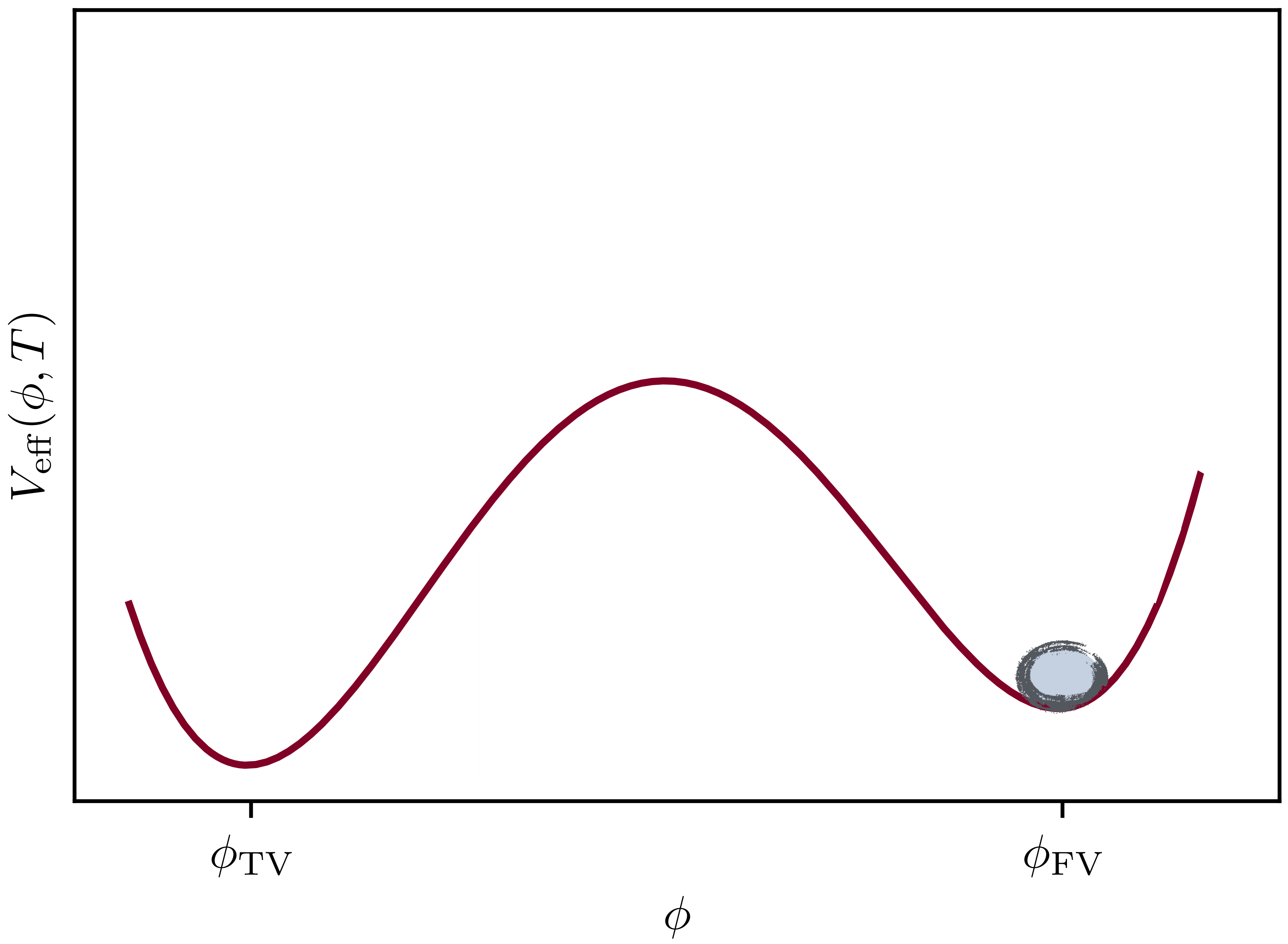
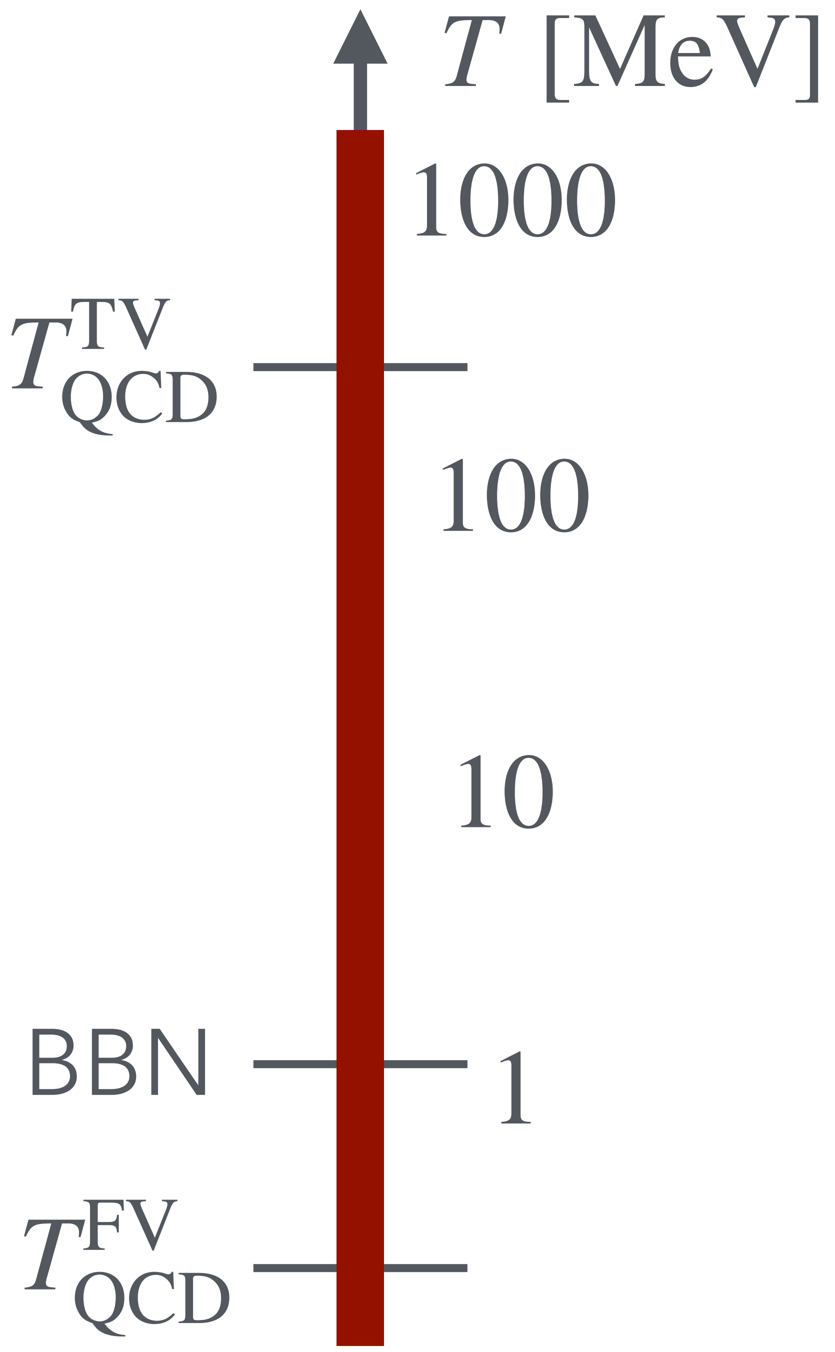
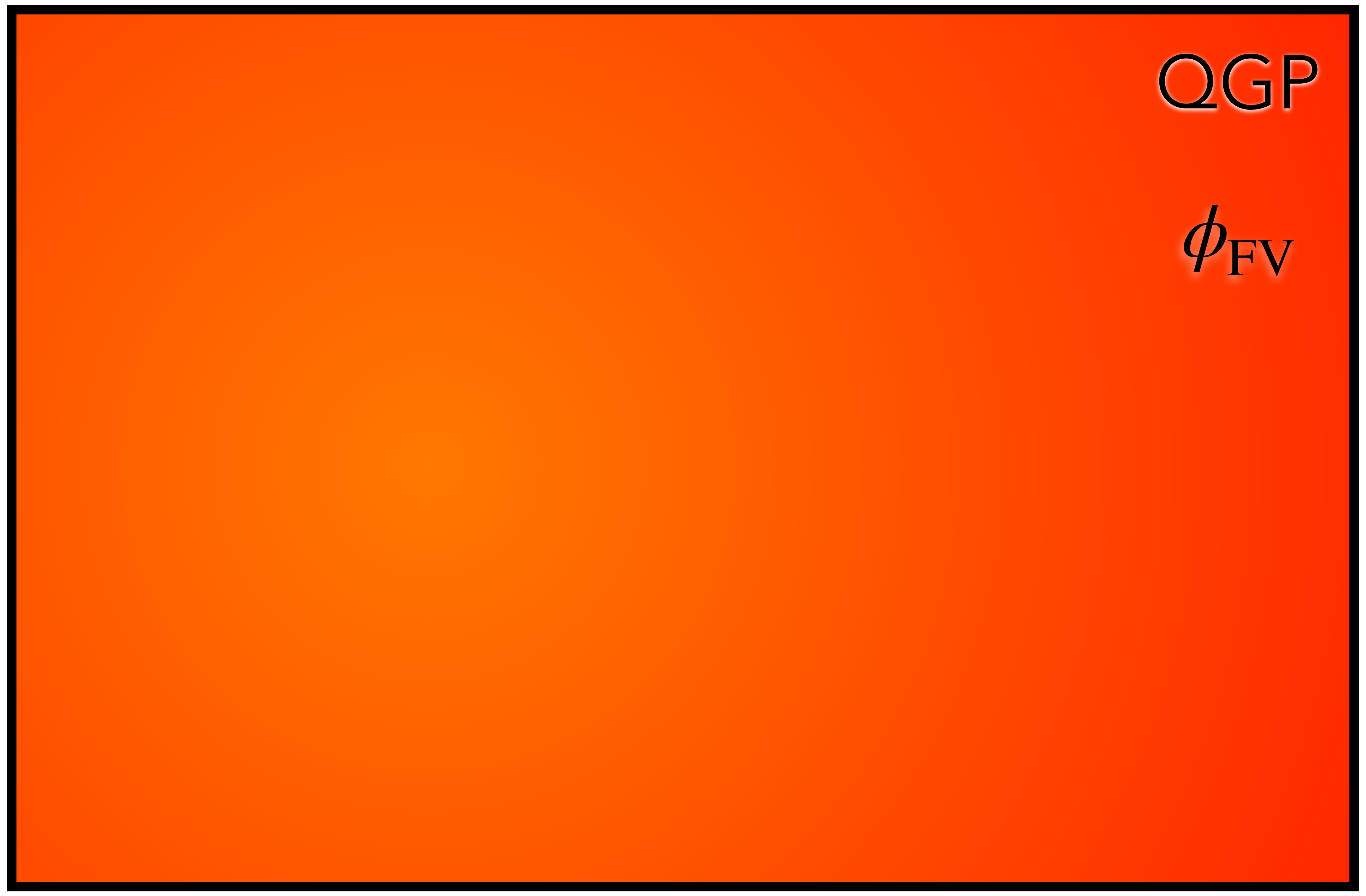
A dilton-induced first-order QCD Phase Transition

Dimensional transmutation: $$\Lambda_{\rm QCD} = \mu \exp\left[-\frac{8\pi^2}{\beta_0 g_3^2(\mu)}\right] \qquad \left(\beta_0 = 11 - \frac{2}{3}N_f\right)$$

$$\Lambda_{\rm QCD}^{\rm TV}/\Lambda_{\rm QCD}^{\rm FV} = \exp\left[\frac{8\pi^2 \Delta f}{\beta_0}\right]$$







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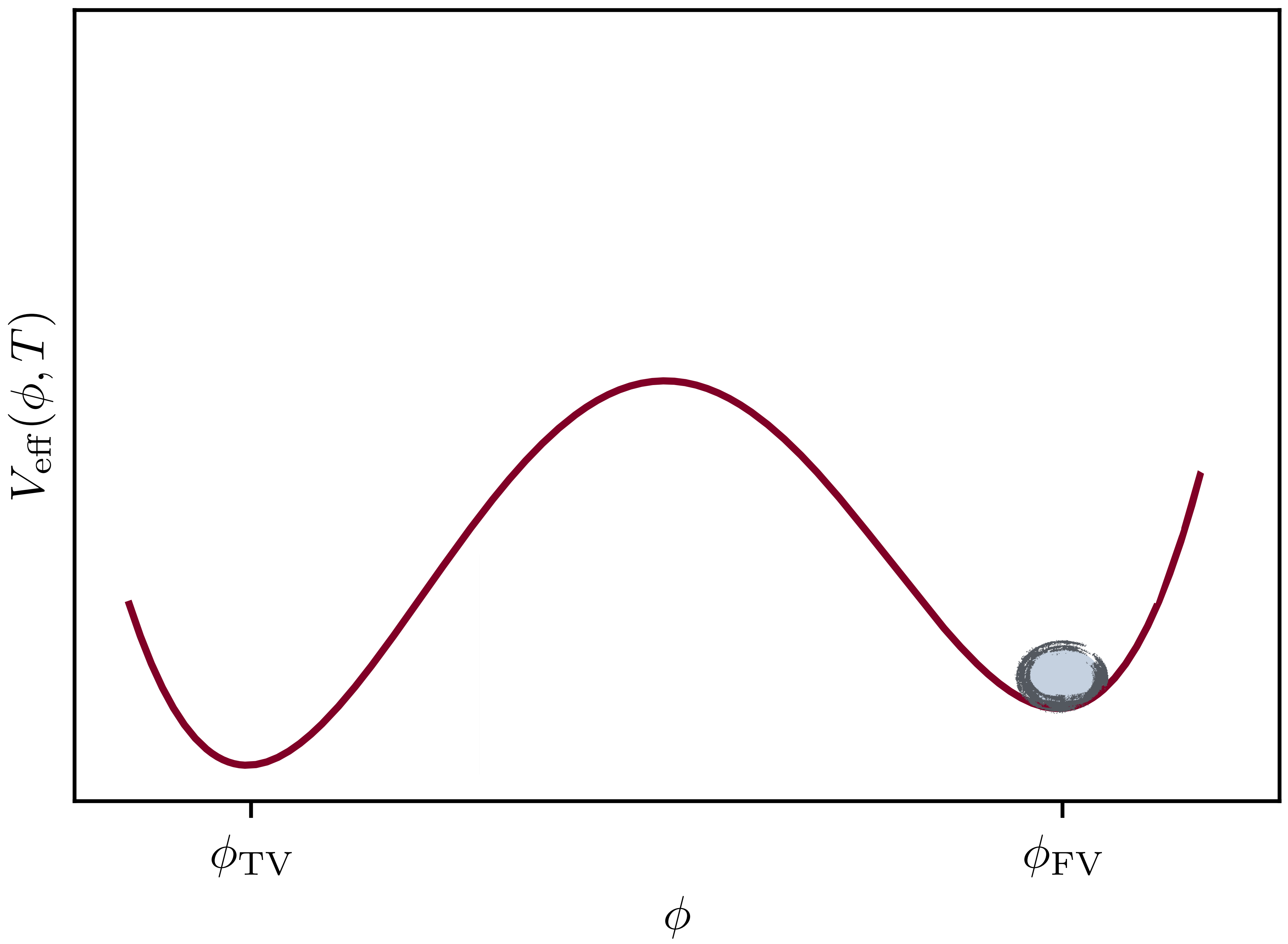

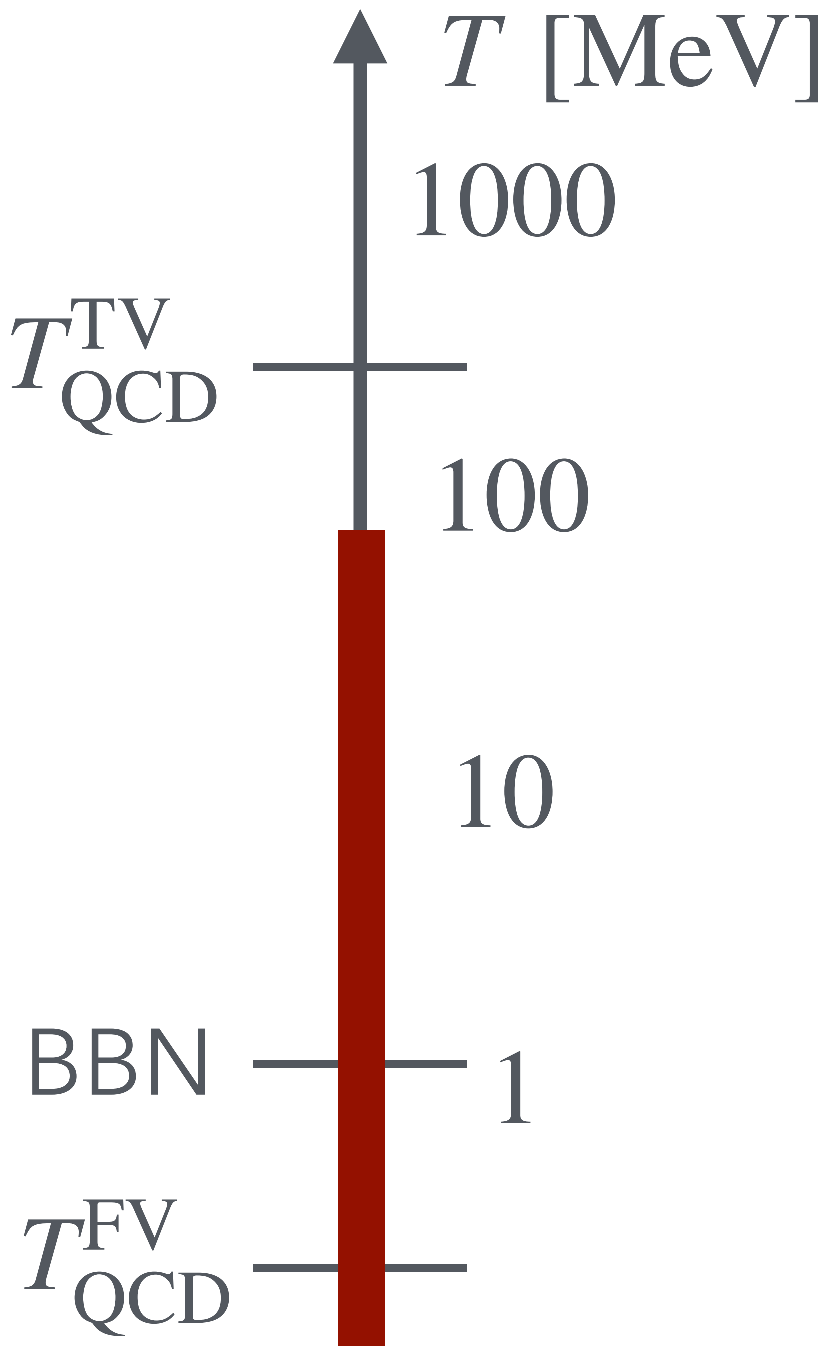

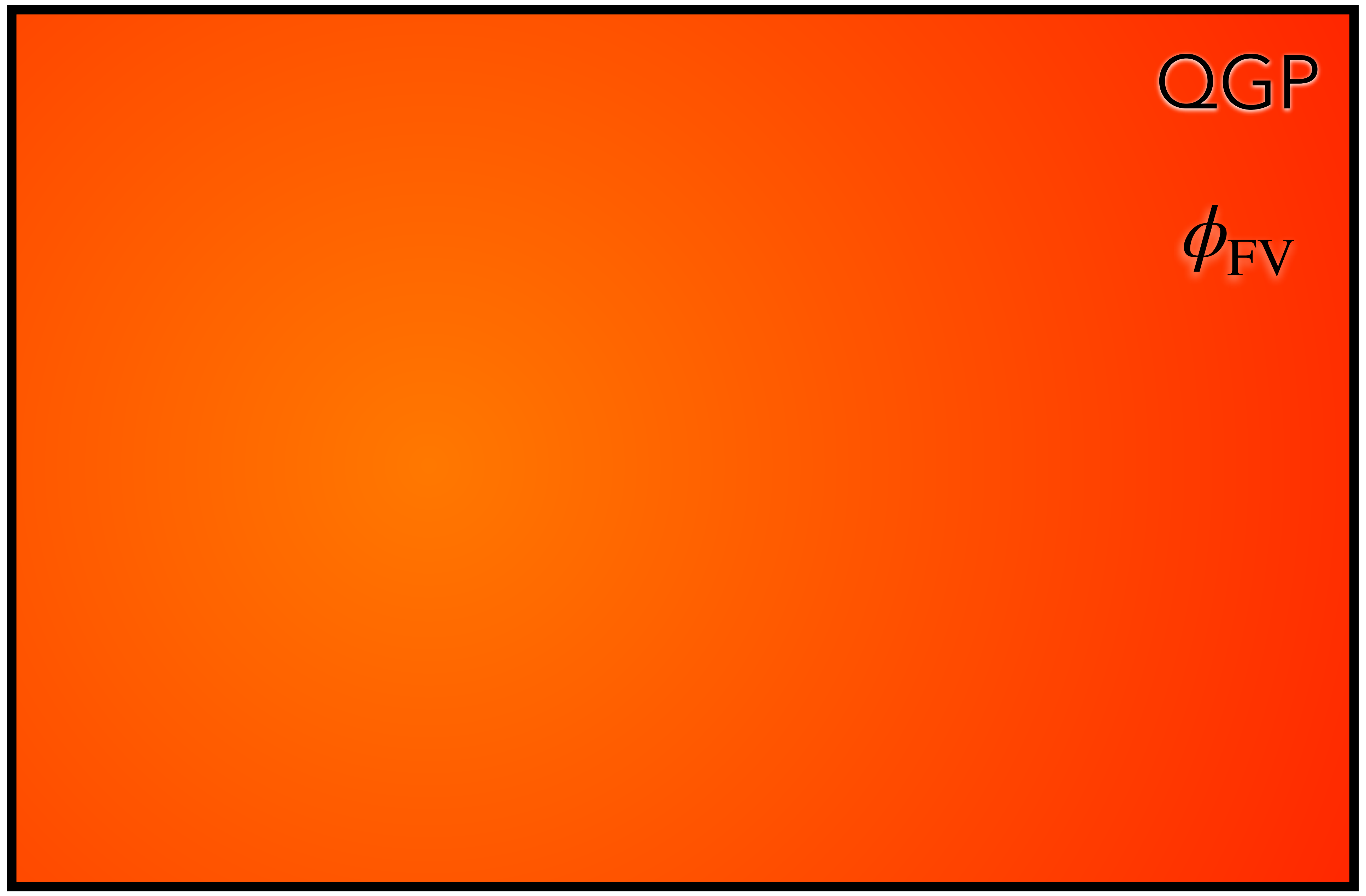

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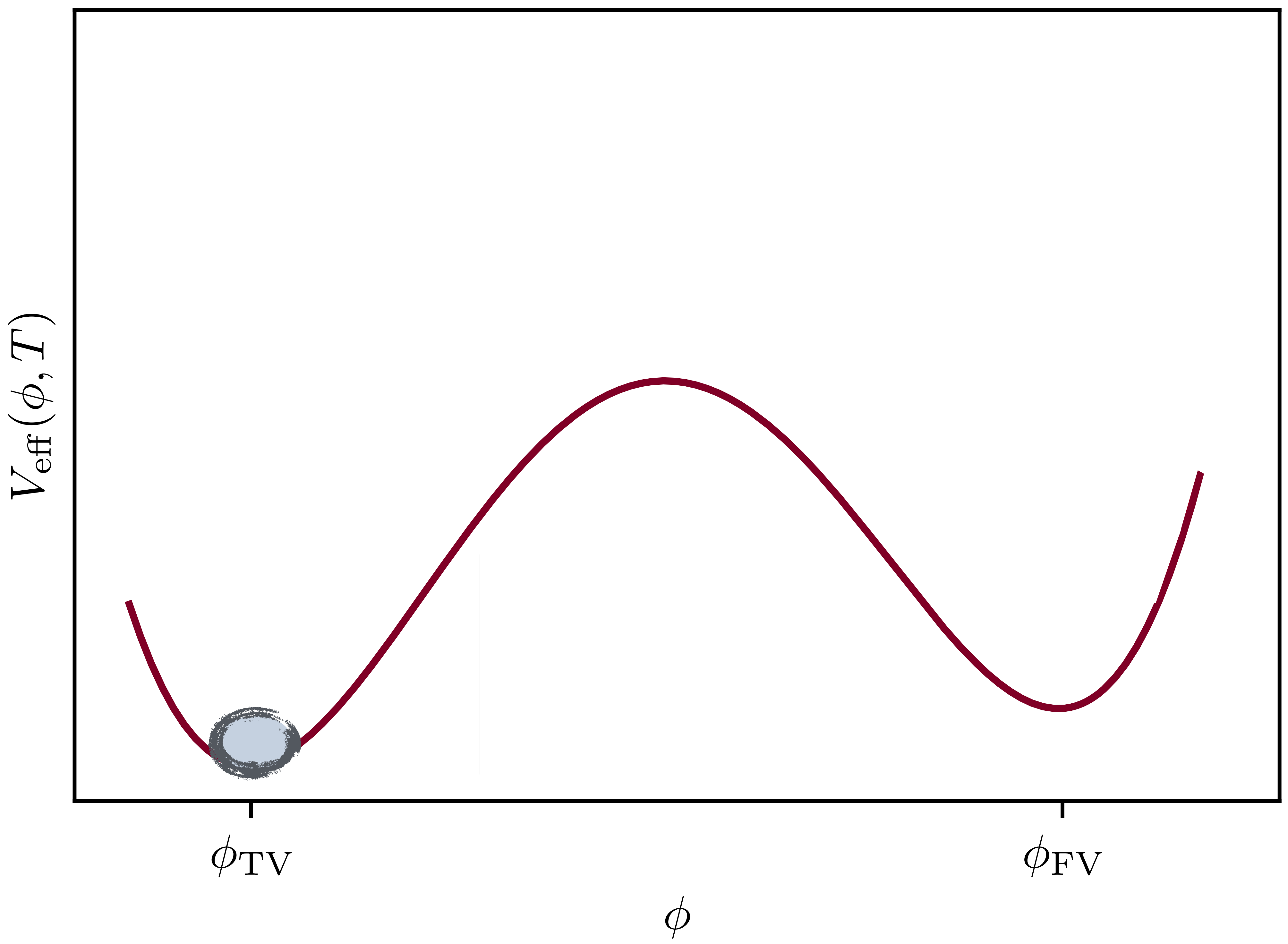

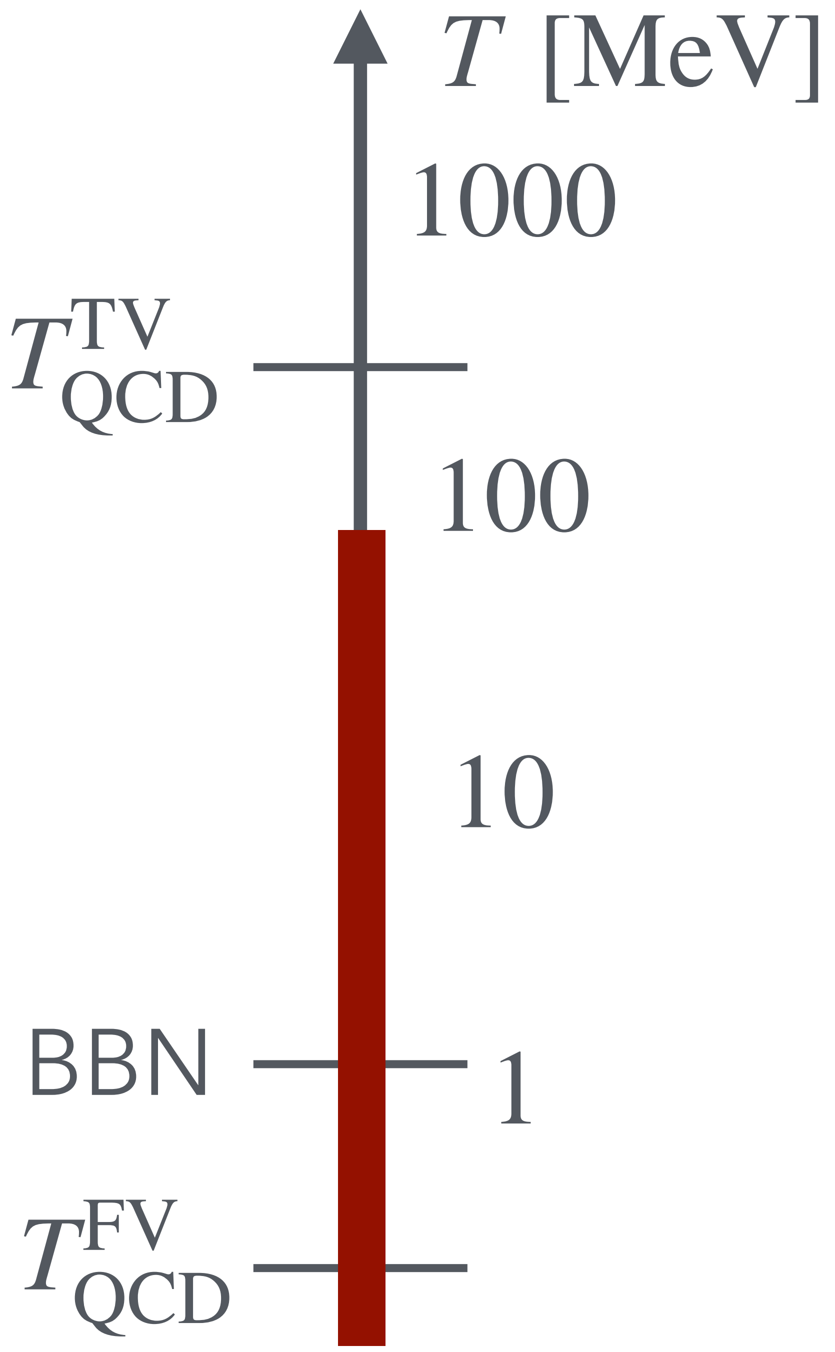

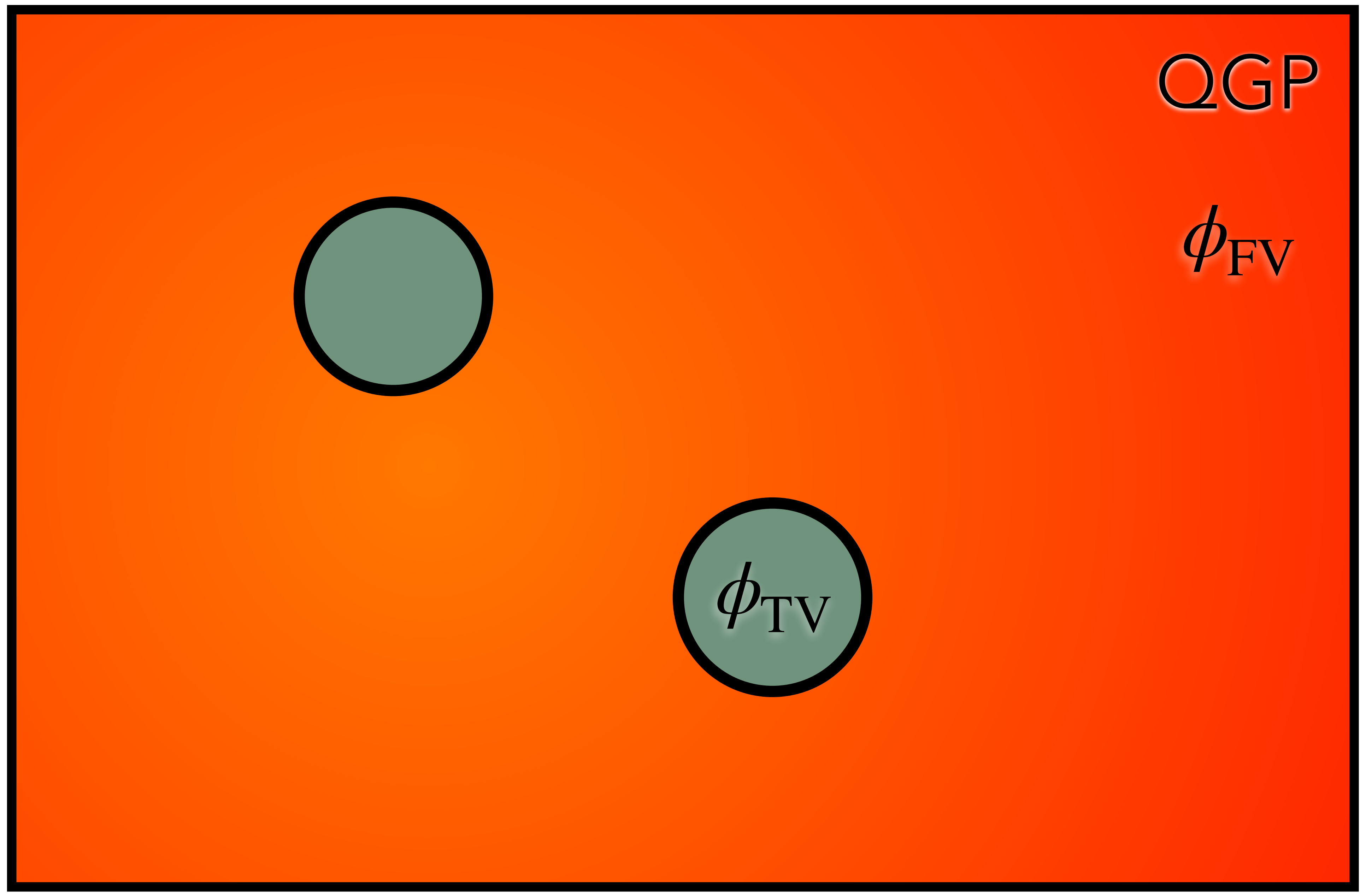

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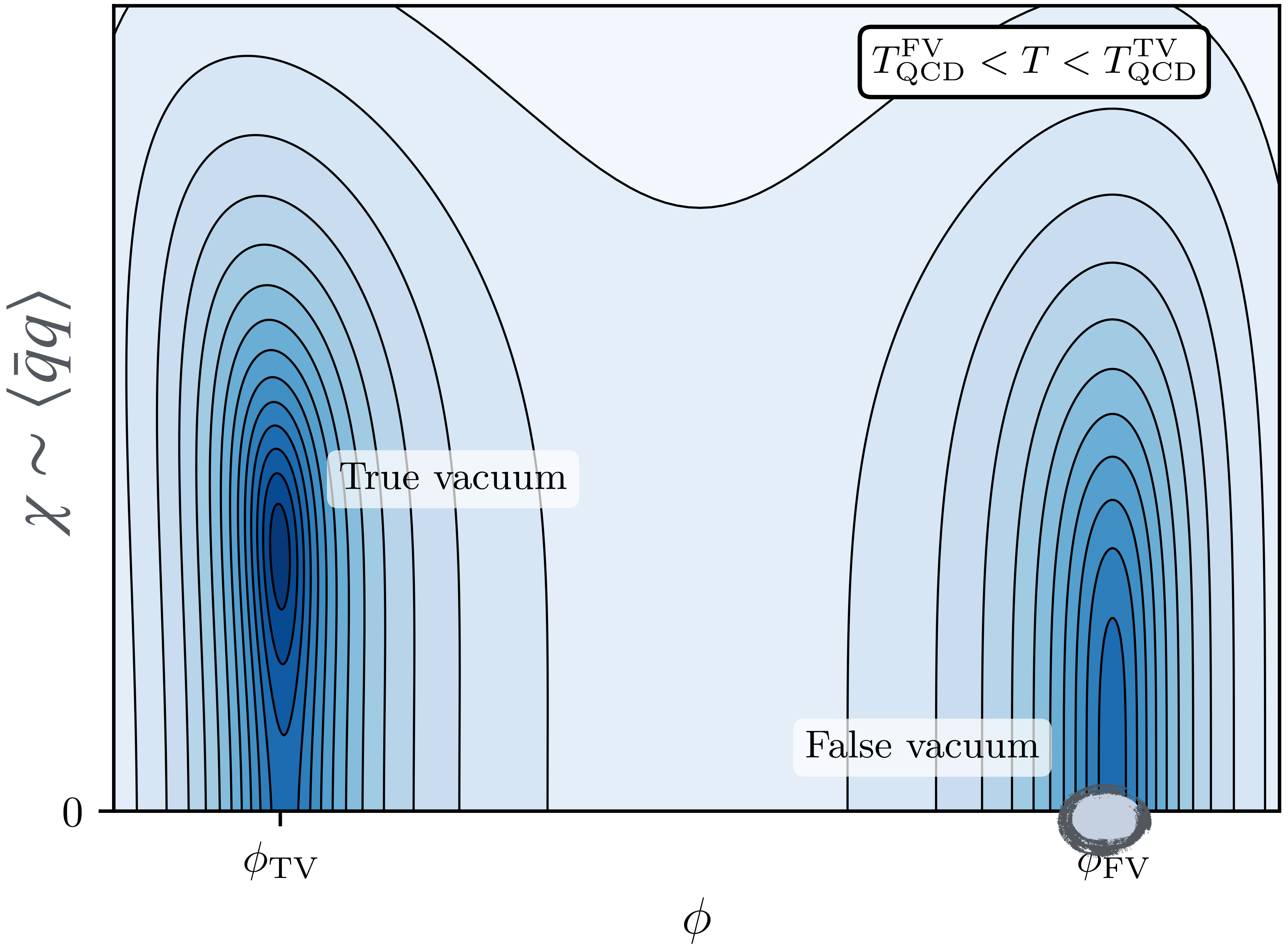

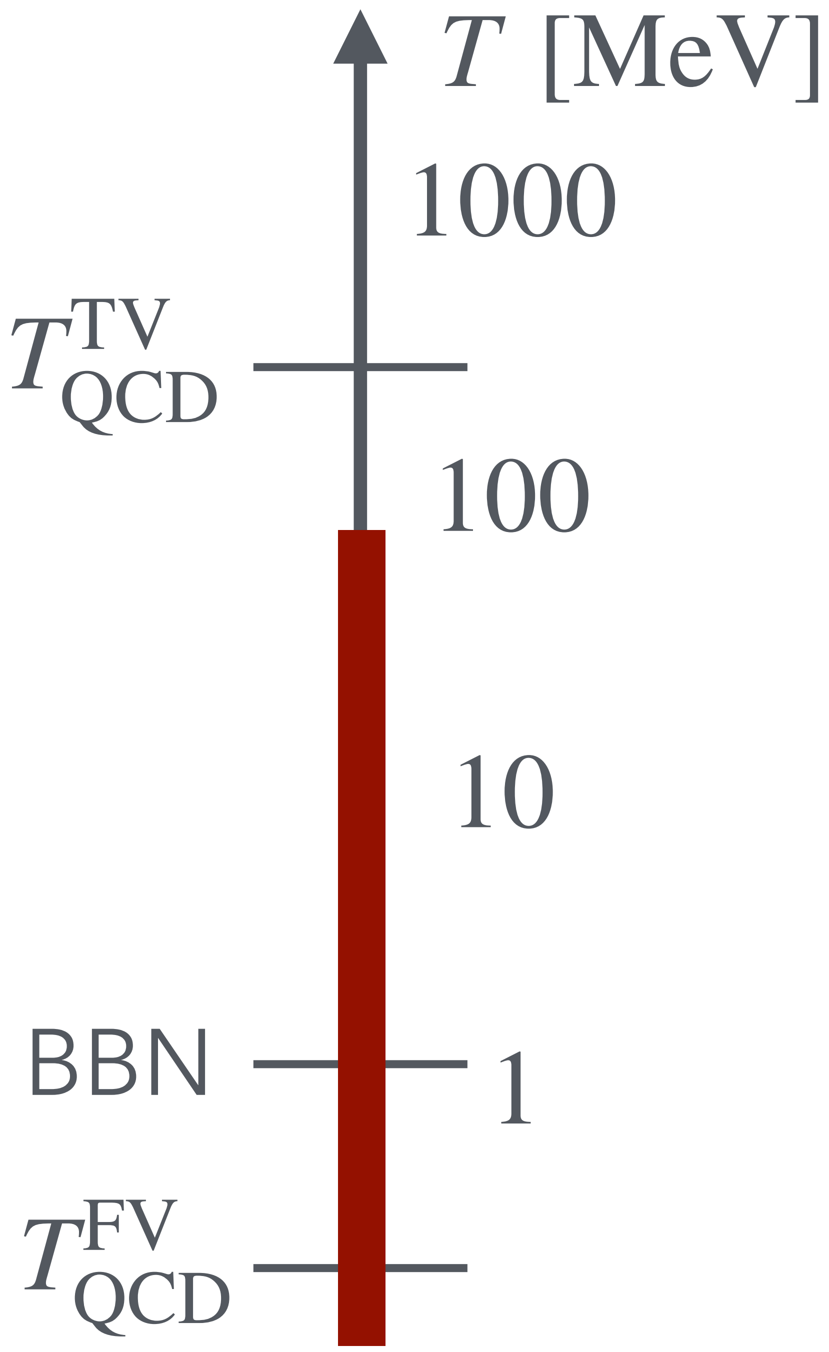

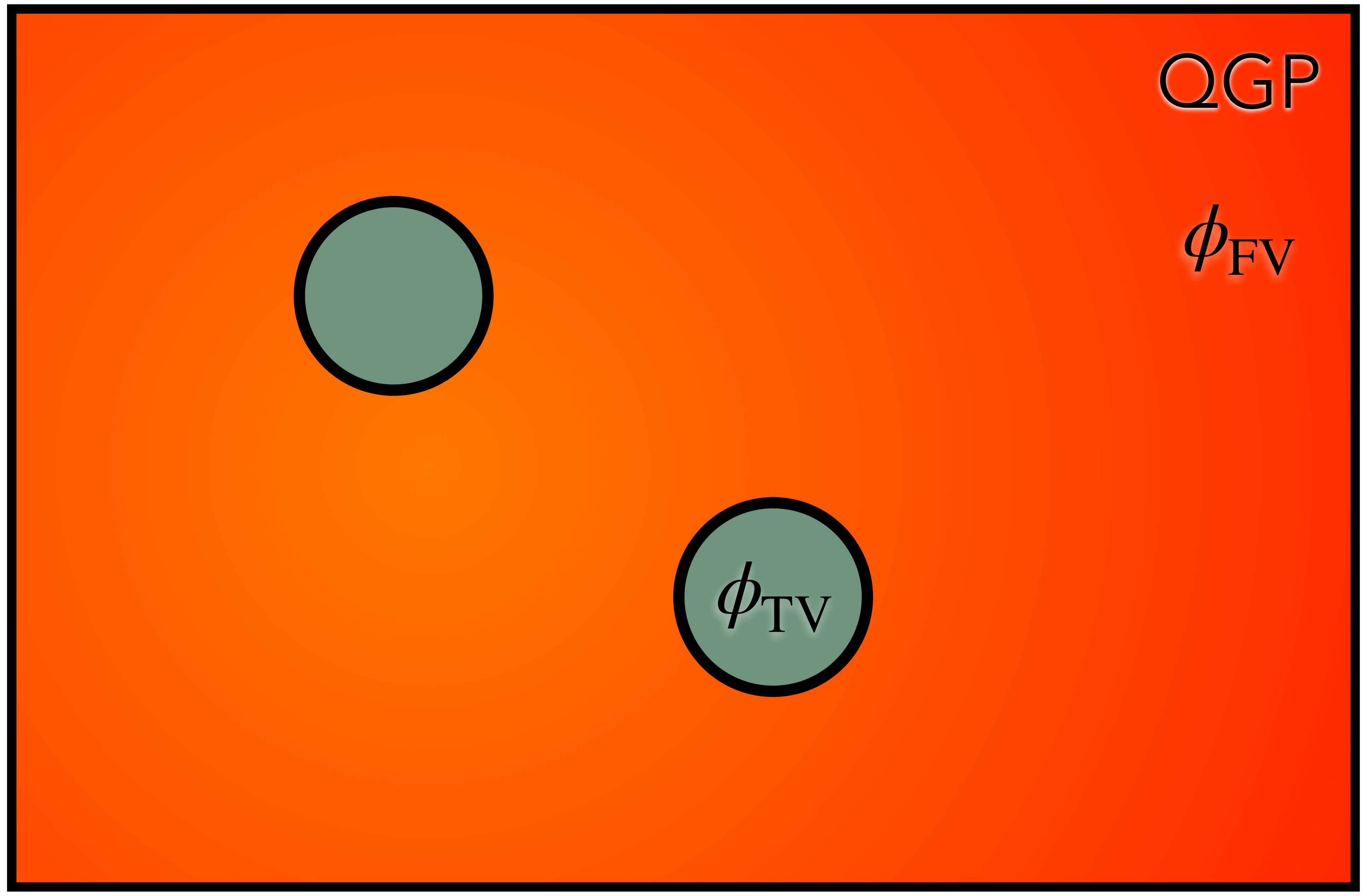

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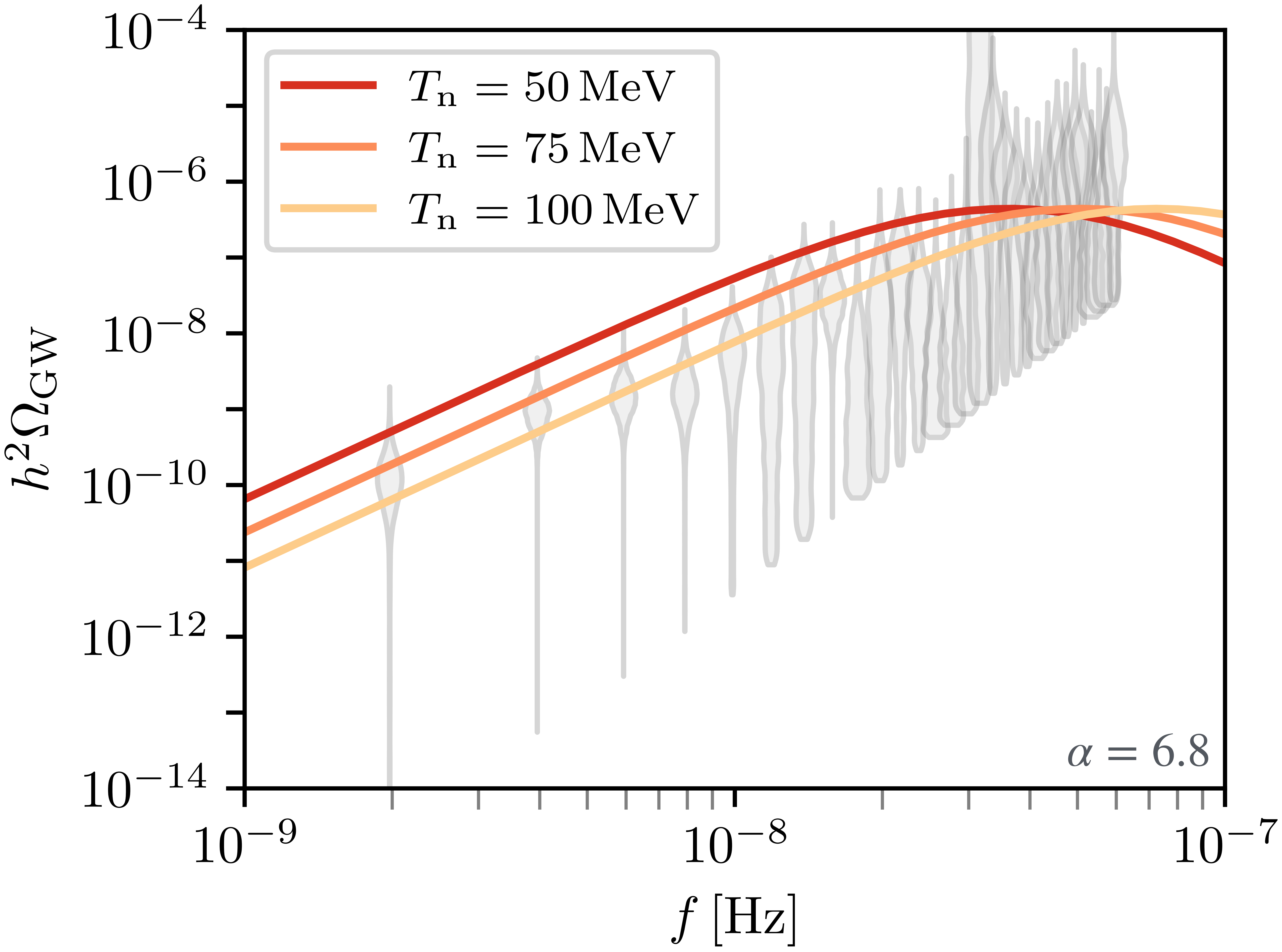
Gravitational Wave Spectrum



Bubble walls expand as detonations; QGP exerts pressure, but terminal velocity is relativistic.

Sound waves produce GWs.

Curiously, the amplitude and spectrum match the nHz GW background reported by Pulsar Timing Arrays (PTAs).

Parameters:

$0 < \alpha = \Delta V/\rho_{\mathrm{rad}} \lesssim 20,\ 8 \geq \beta/H \geq 3$

$$f_{\mathrm{peak}} \simeq 17\,\mathrm{nHz}\frac{\beta}{H}\frac{T_n}{100\,\mathrm{MeV}}$$

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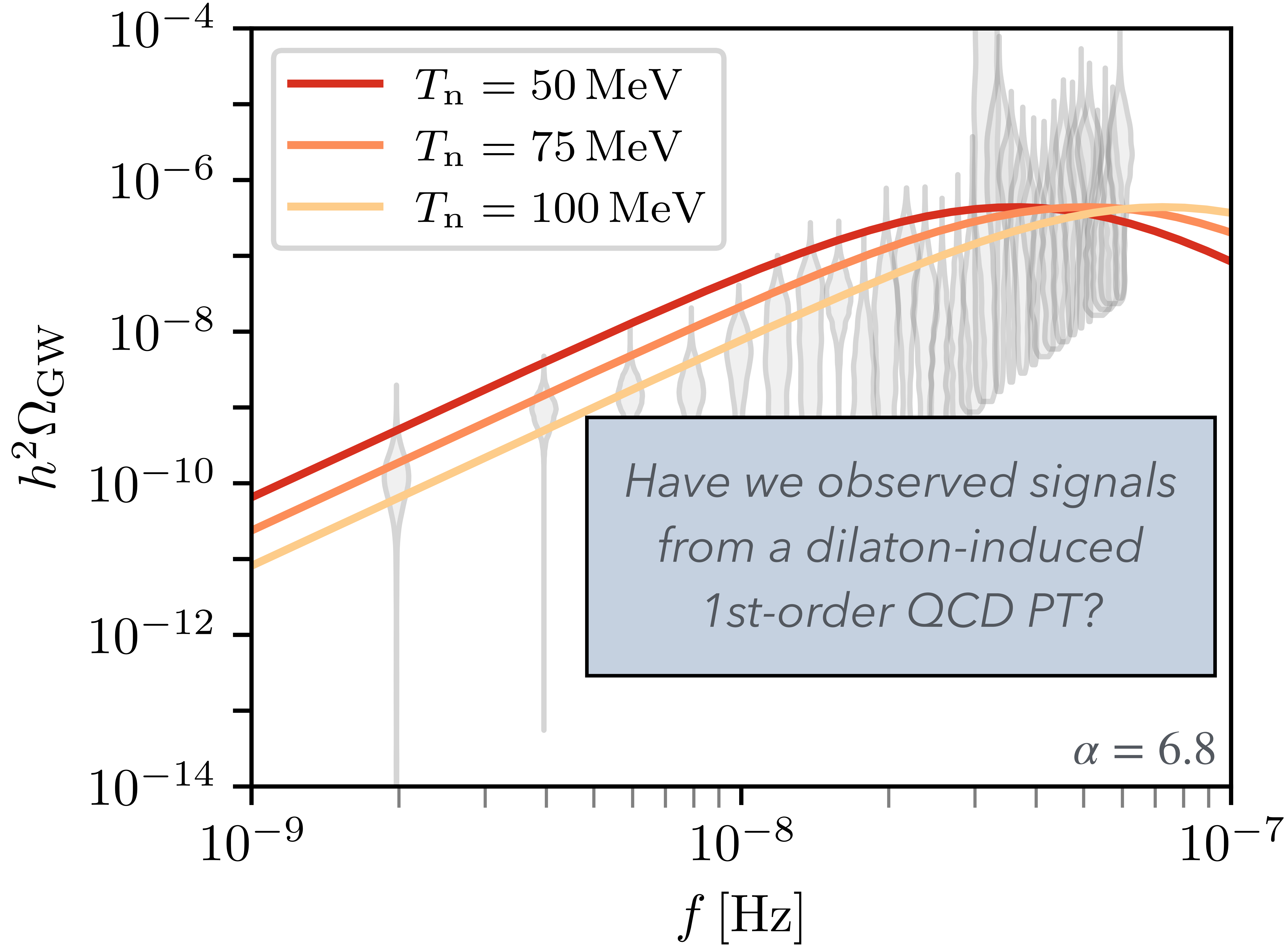

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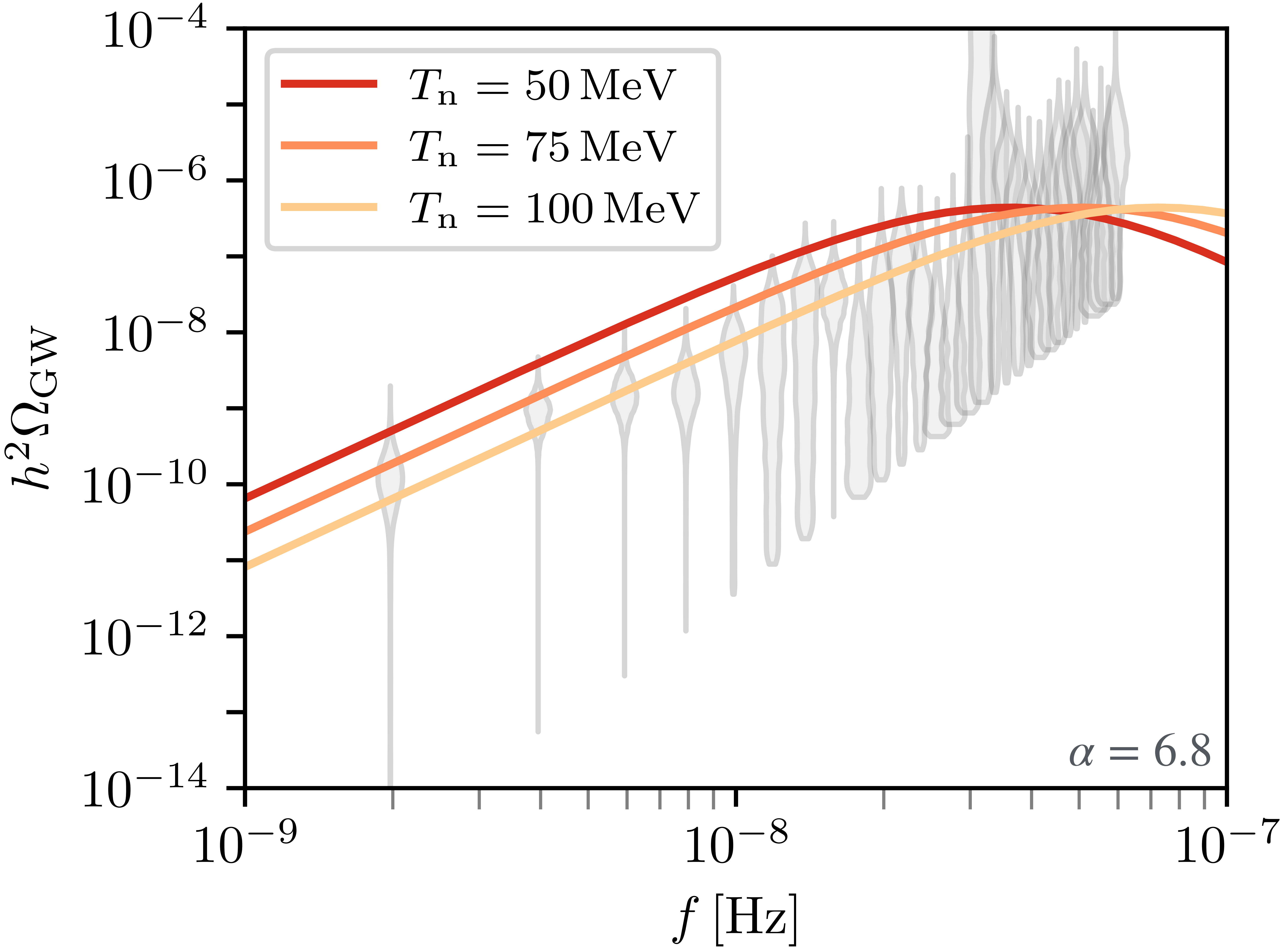

Testable:

Dilaton is probed at colliders through dijet resonances.

Probed cosmologically through inhomogeneous BBN.

The GW signal should reach 5σ with the upcoming IPTA DR3.

Part II: dilatons and axions

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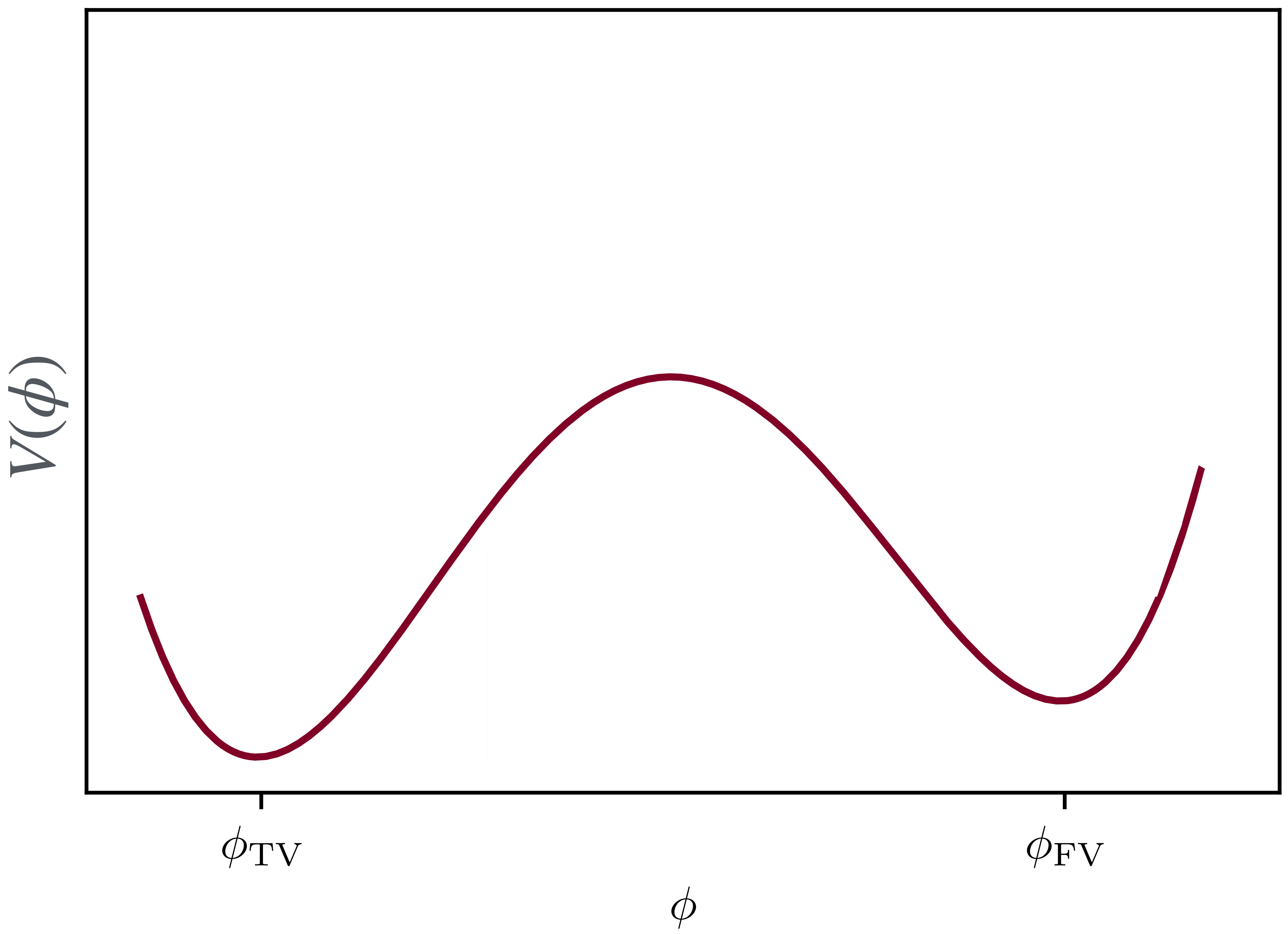
Hidden sector confining gauge theory

Initial seed density of axions present (e.g. from dark radiation or misalignment)



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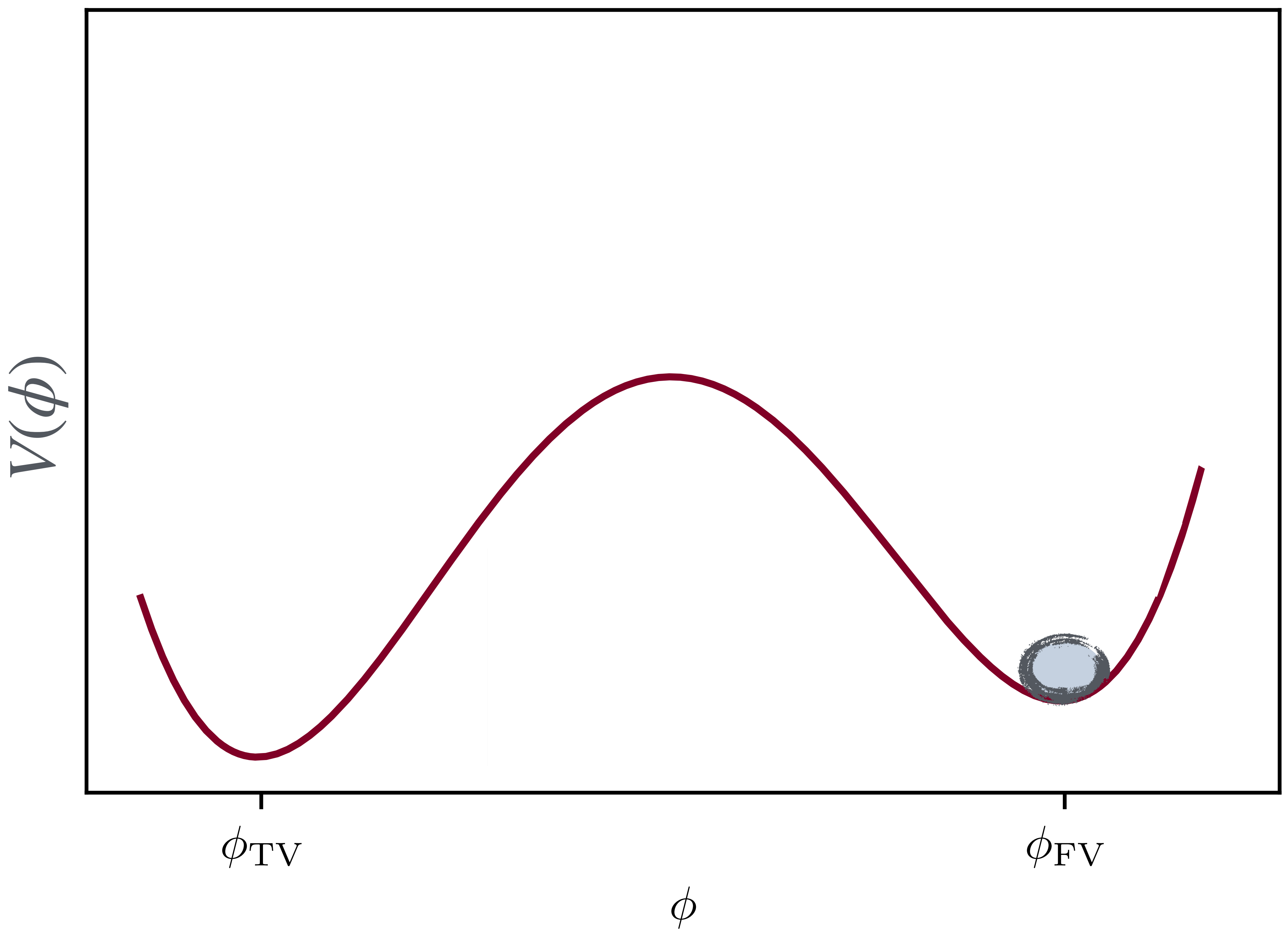

The axion potential is exponentially sensitive to ϕ .

$$V(\phi, a) = M^4 e^{-S(\phi)} \left(1 - \cos\left(\frac{a}{f_a}\right)\right)$$

$$m_a^2\Big|_{\mathrm{TV}} = m_a^2\Big|_{\mathrm{FV}} \exp\left(S_{\mathrm{FV}} \cdot \frac{|\Delta f|}{f_{\mathrm{FV}}}\right)$$

Often $\mathcal{O}(100 - 1000)$

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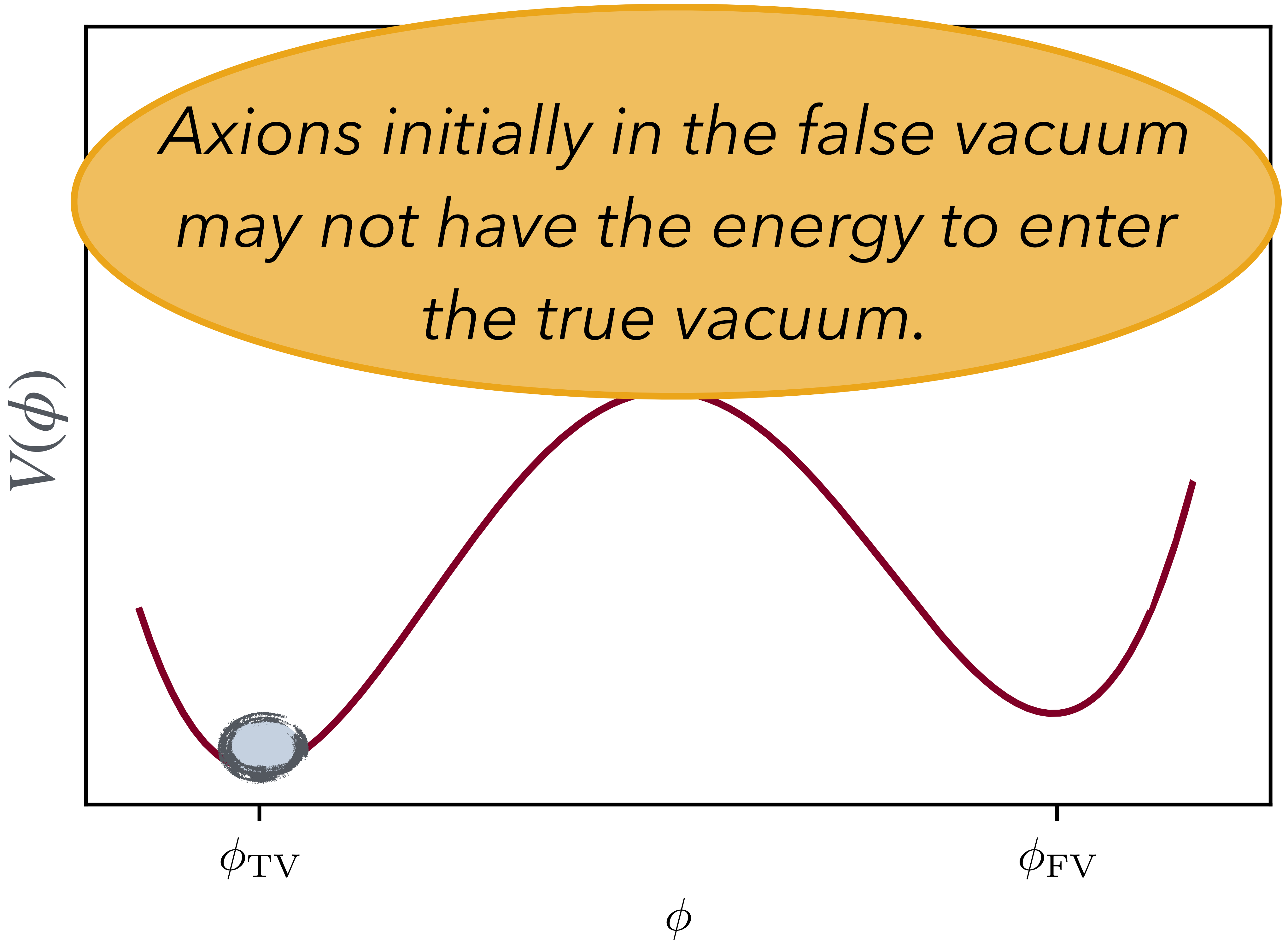

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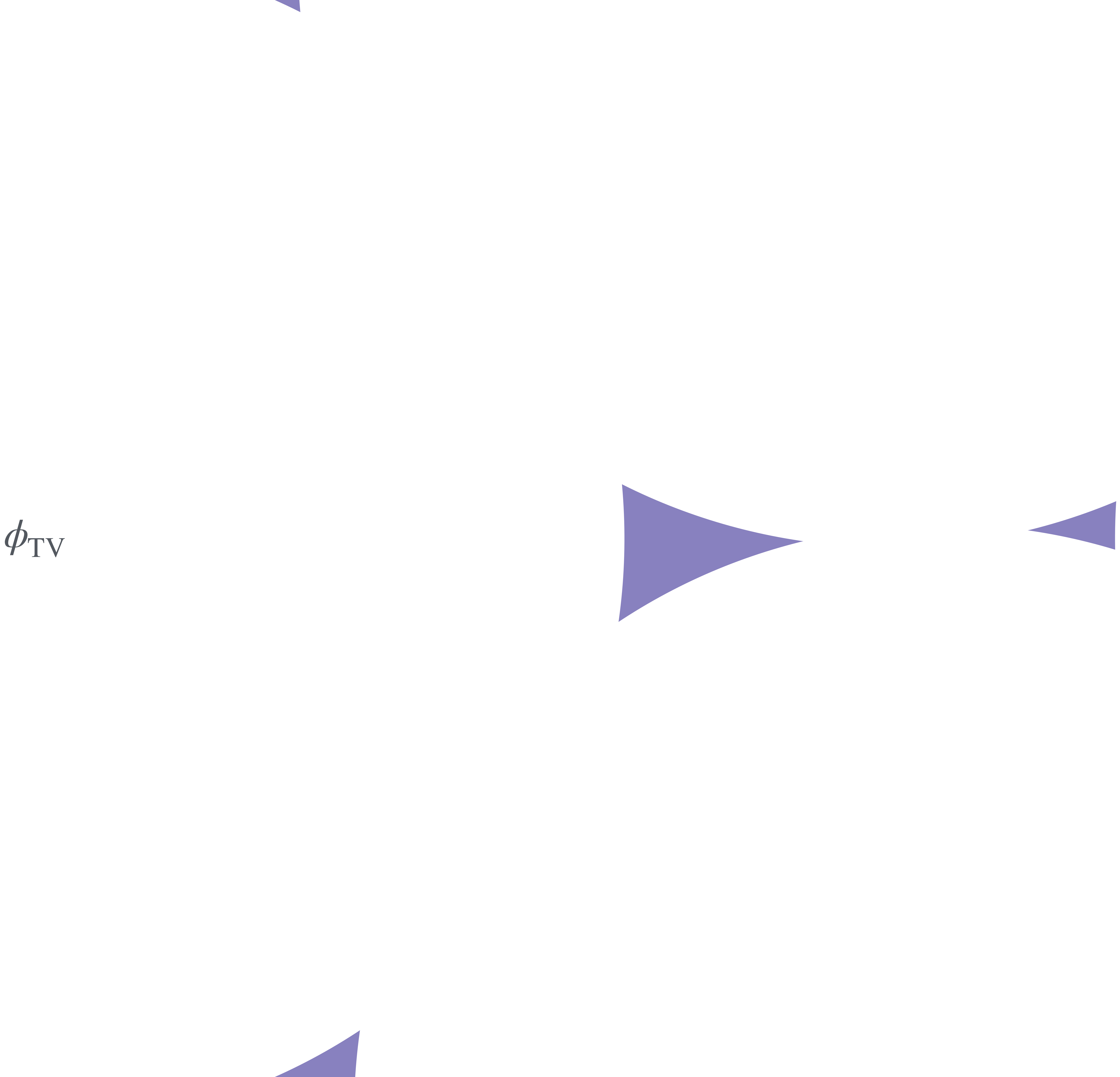
$$\phi_{\mathrm{FV}}$$

$$n_a \neq 0$$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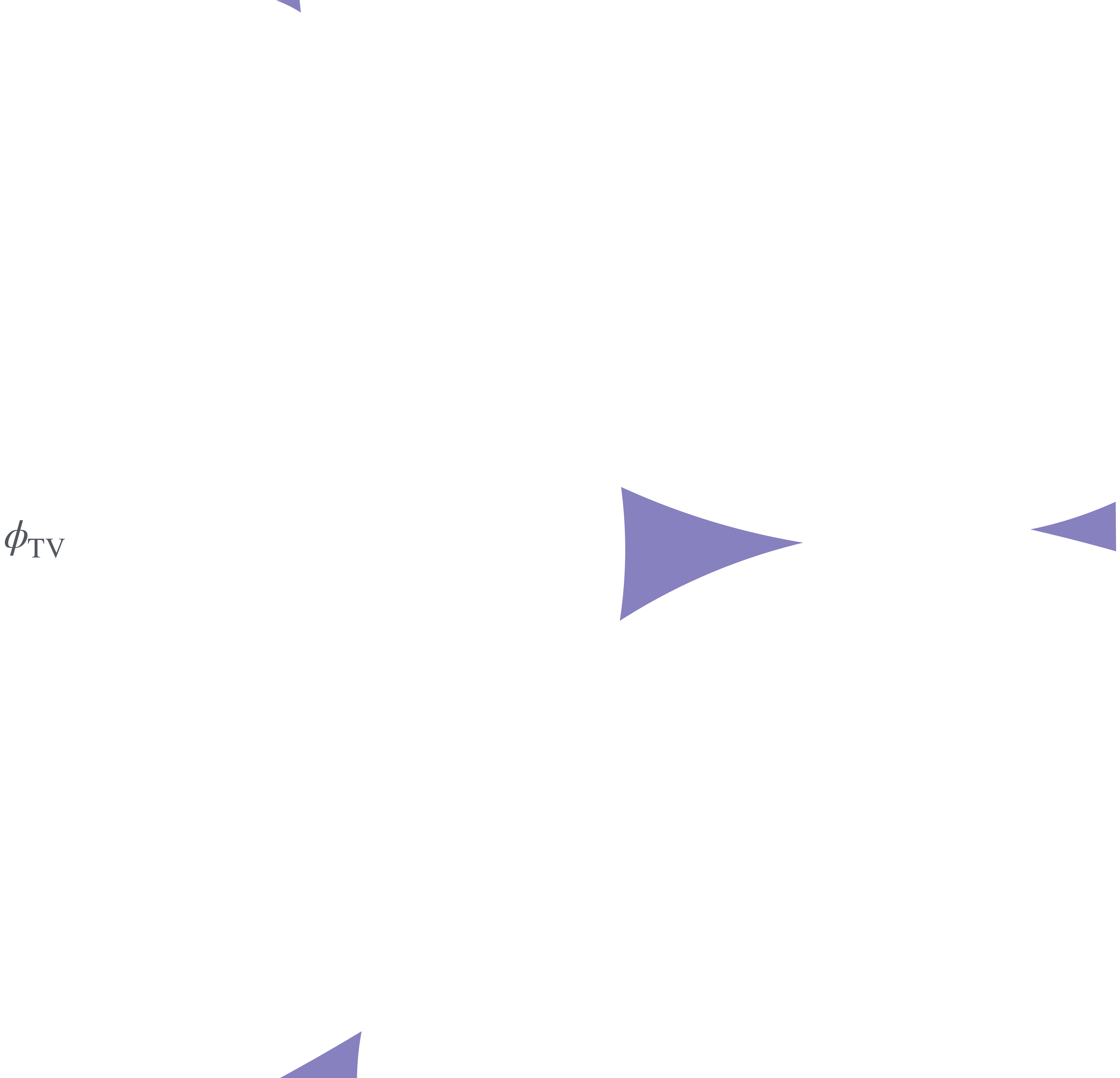
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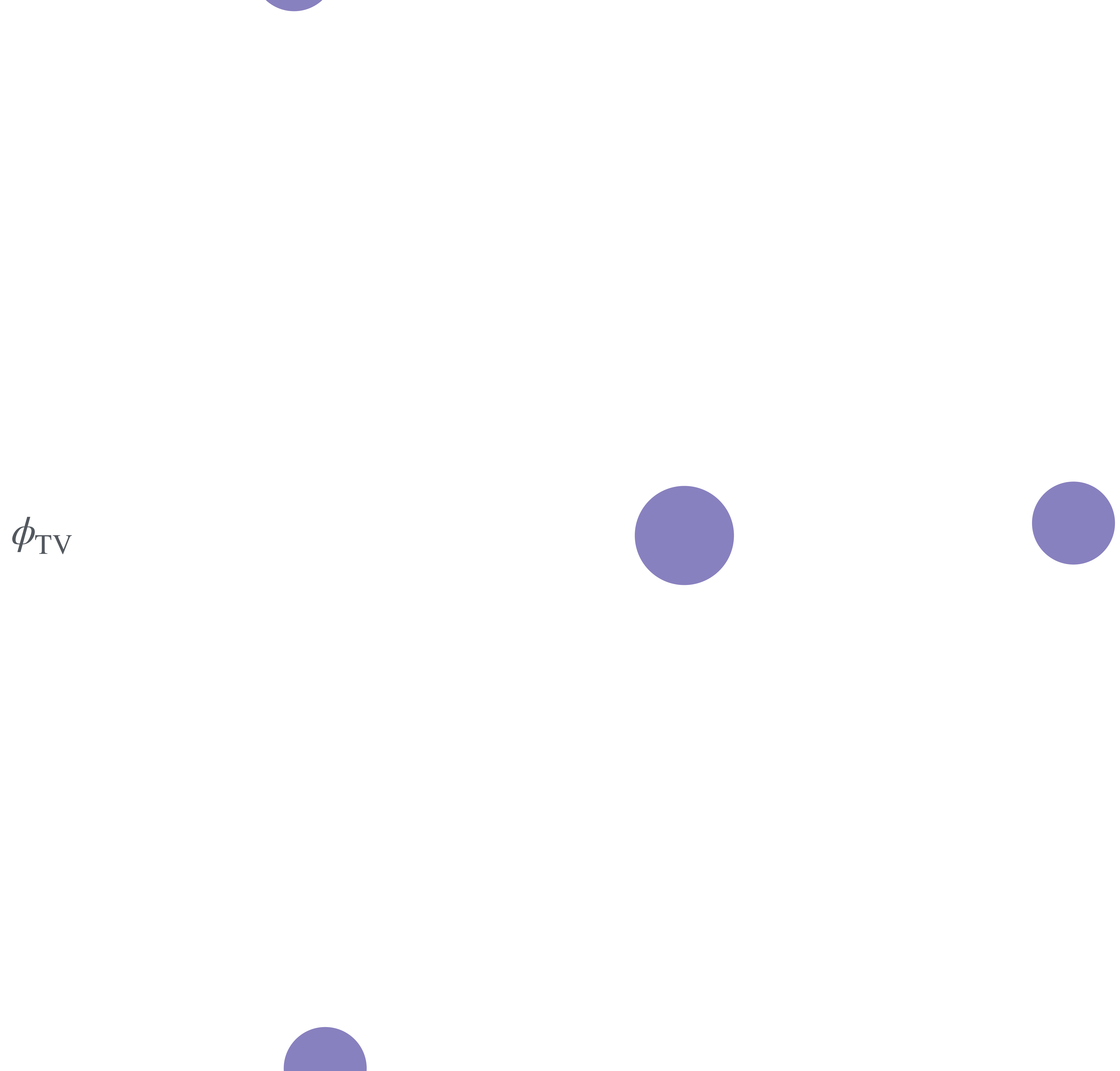
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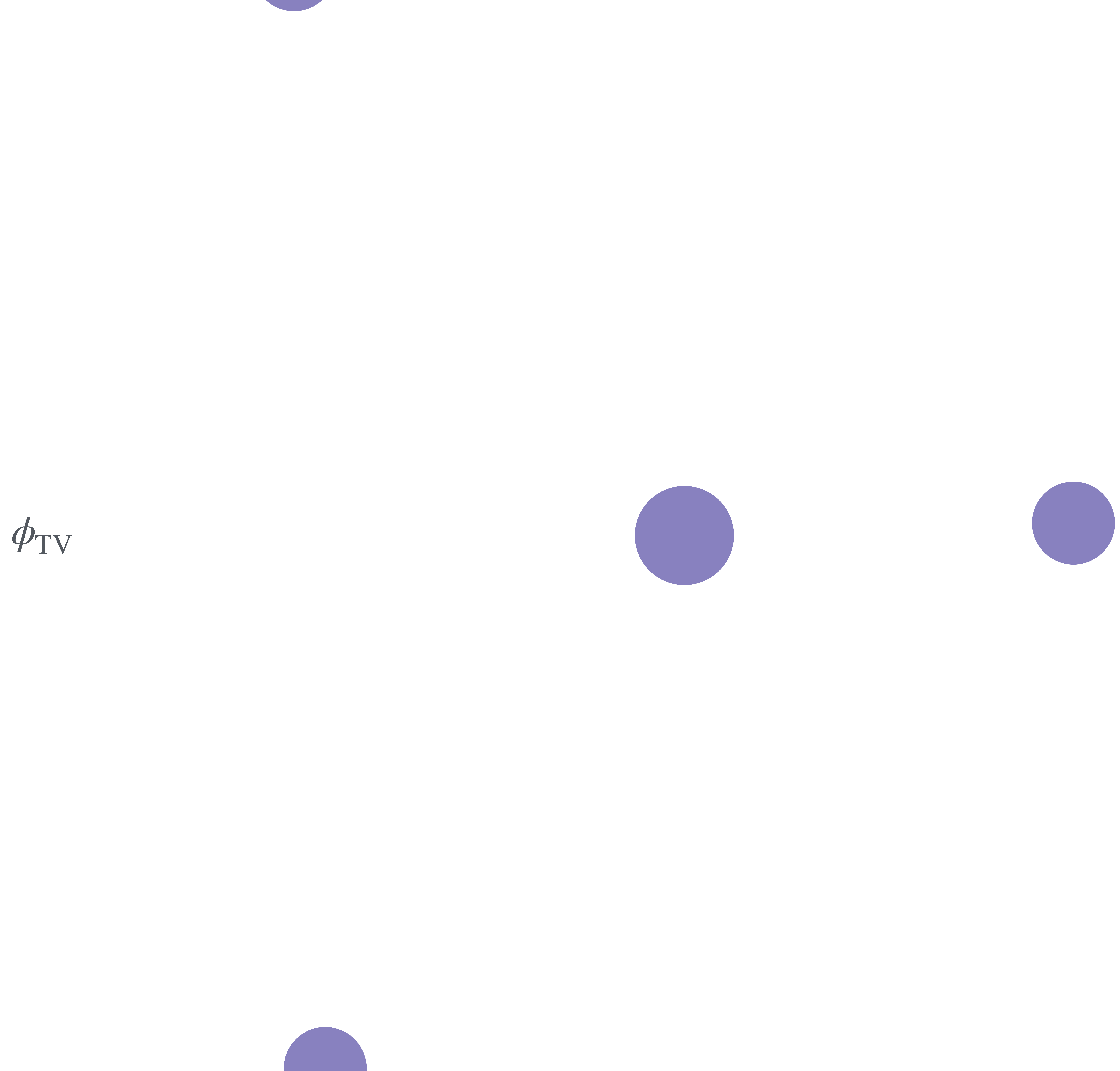
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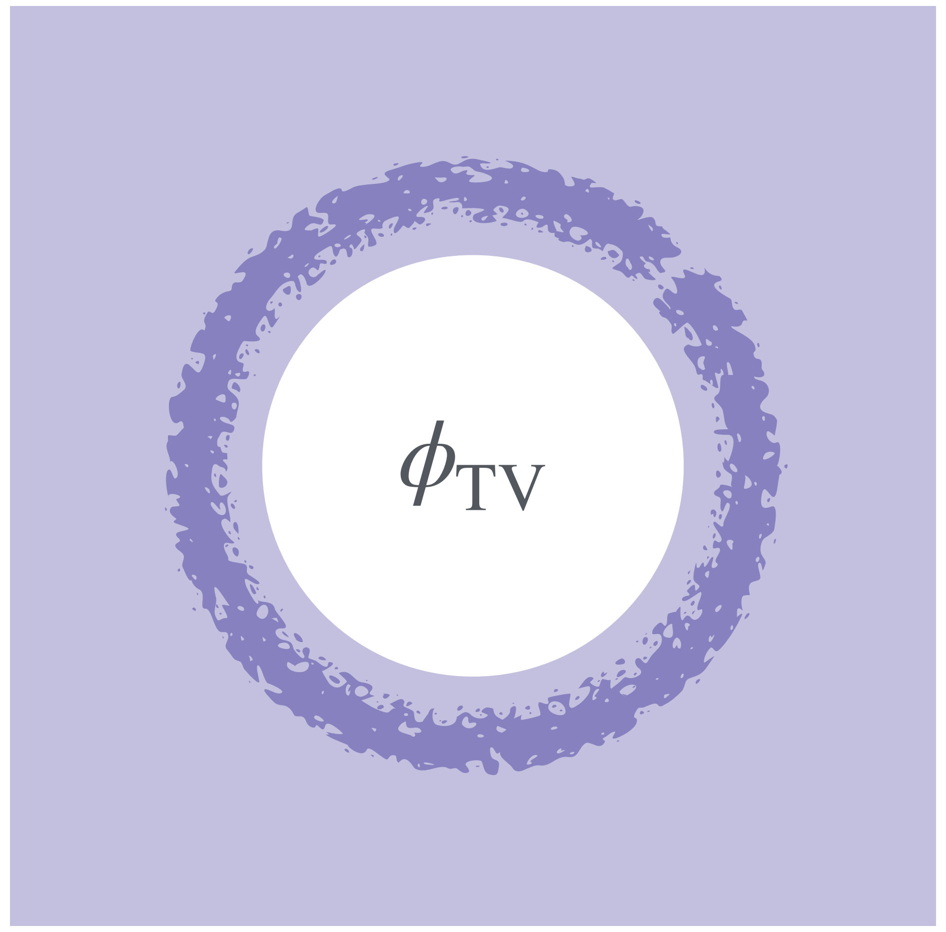
$\phi_{\rm TV}$

Axion Relic Pockets

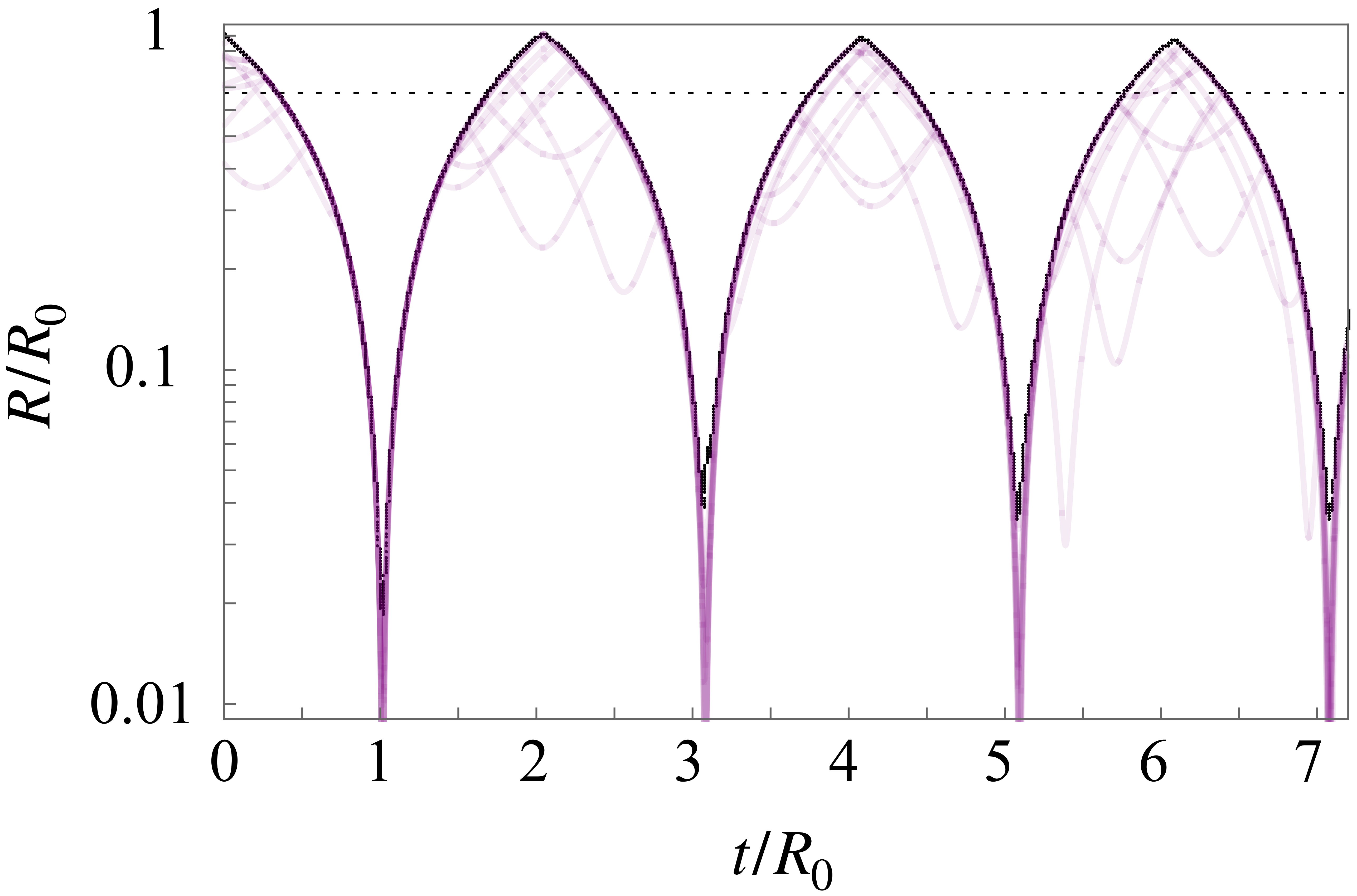
Pressure from axions on wall



Initial axion pressure is negligible, but grows like $\Delta p \sim \gamma_w^2$.

Colliding bubbles are highly relativistic: $\gamma_w \sim R_H/R_c$

N-body simulations of spherical pockets show that they pulsate with a period $2R_0 \approx 2R_H$.



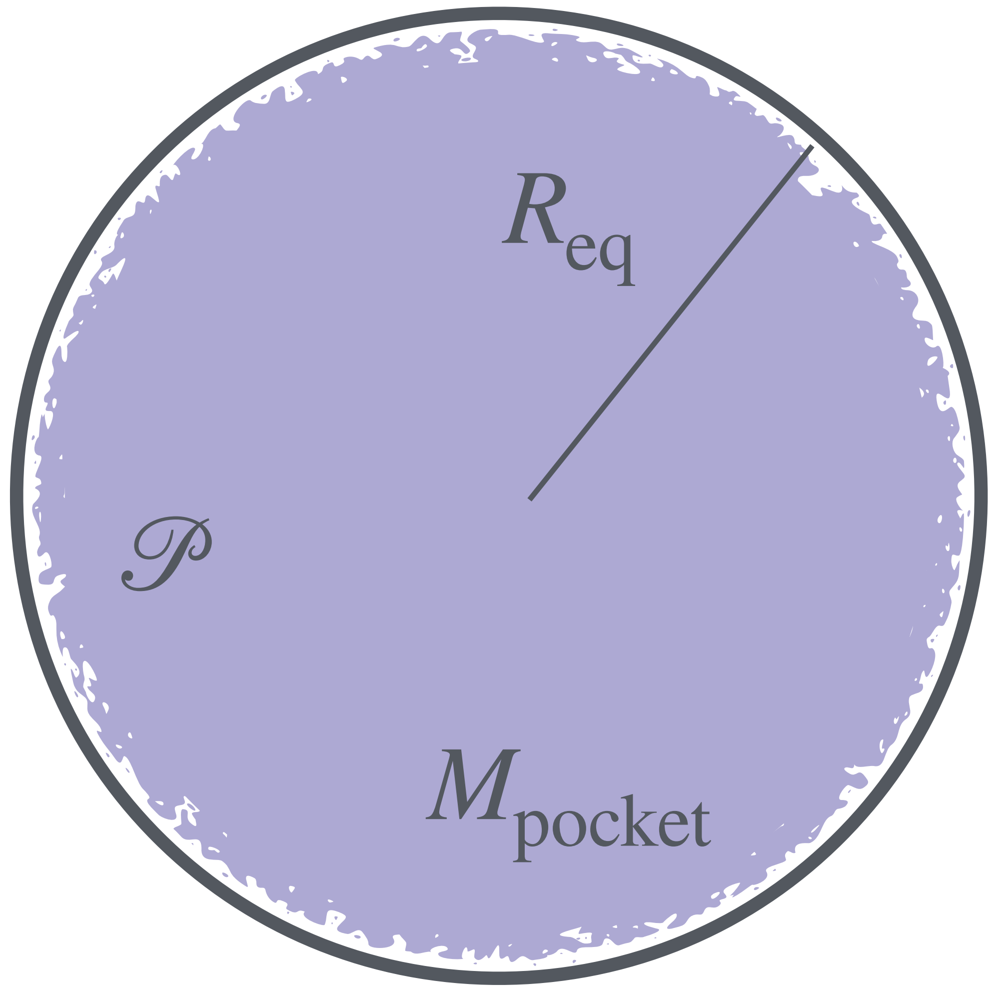
Equilibrium properties

Model independently:

$$R_{\rm eq} = \mathcal{O}(1) \times R_H$$

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

$$M_{\rm pocket} \approx \left(\Delta V + 3\mathscr{P}\right) {\rm Vol}_{\rm eq}$$



Axion gas temperature (thermal)**:**

$$T_{\rm eq} \sim 5\ {\rm GeV} \left(\frac{T_t}{\rm TeV}\right)^{3/4}$$

If gas *thermalises*, all properties become independent of initial axion abundance.

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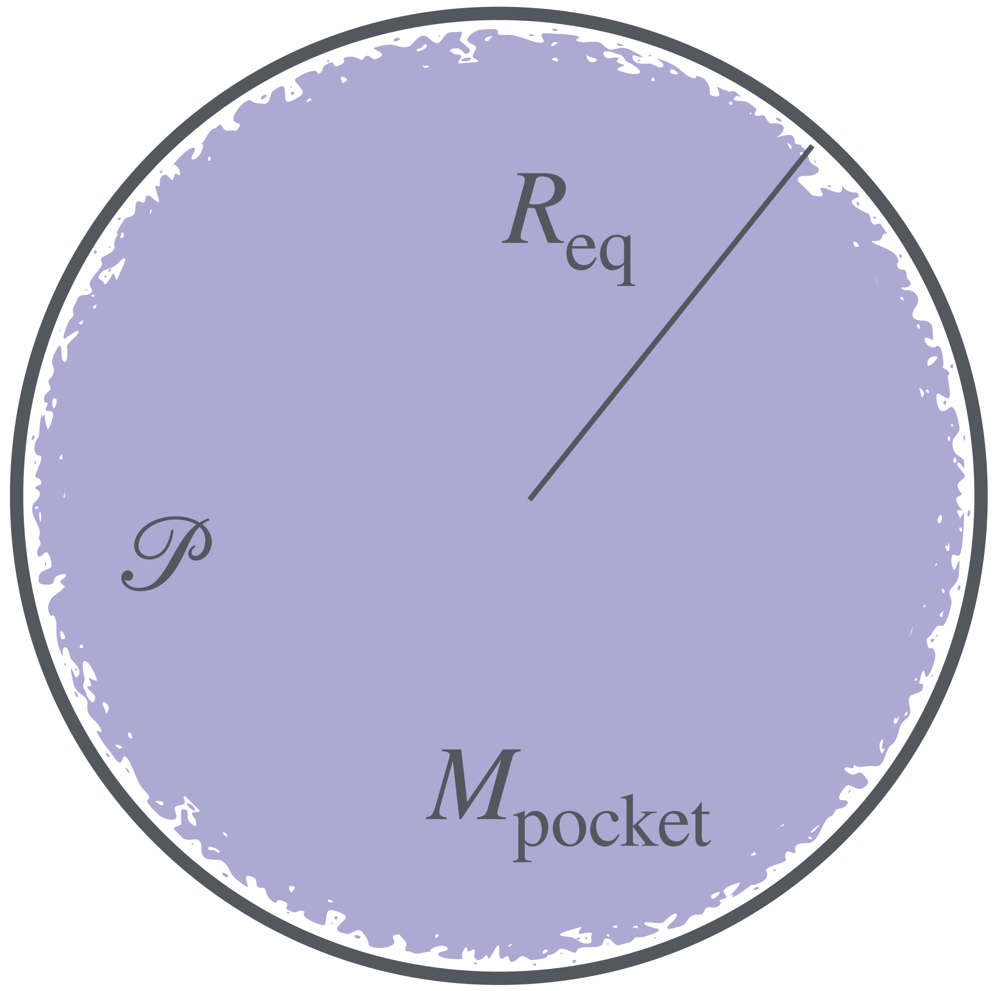

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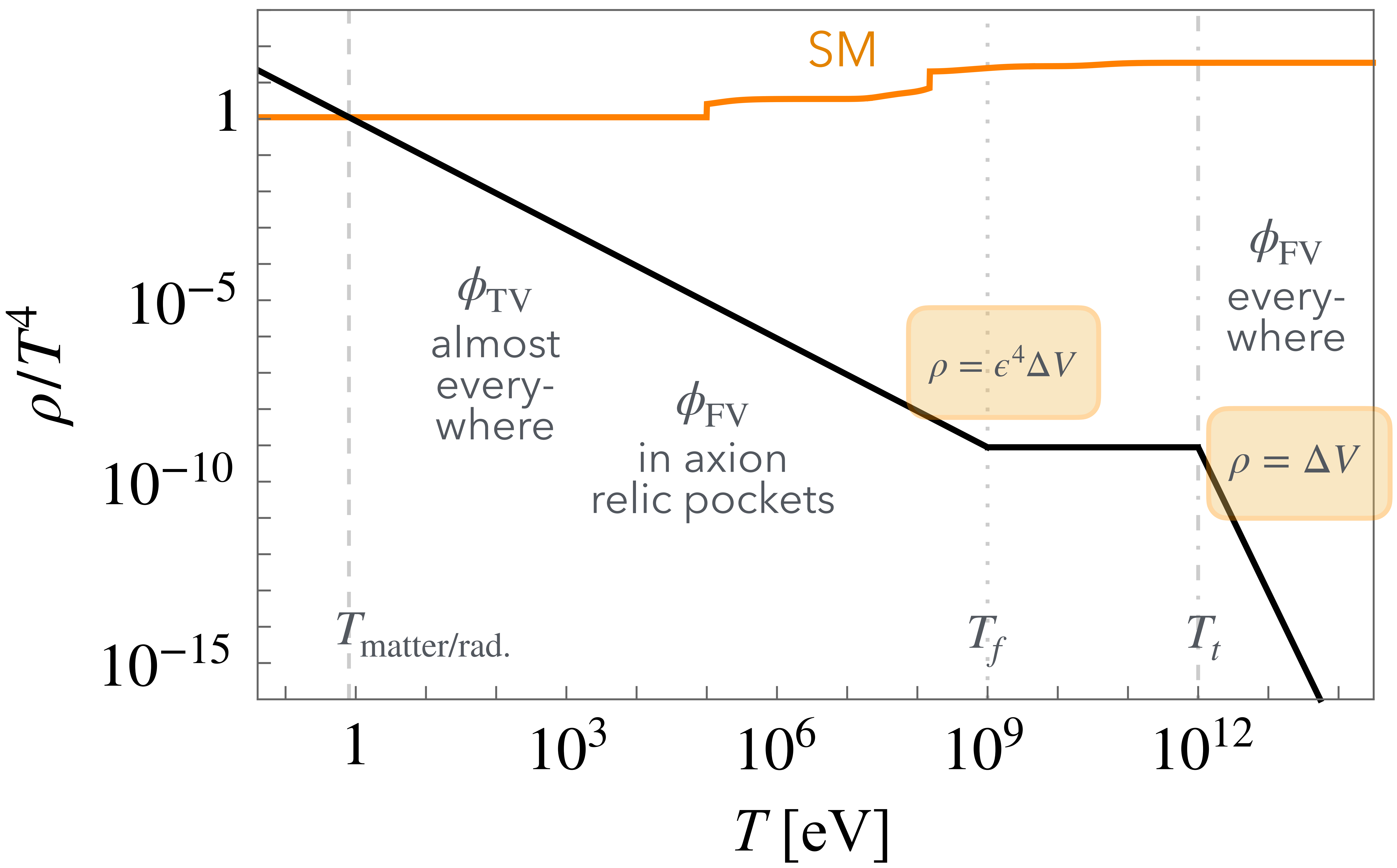
Axion Relic Pocket Cosmology



The pockets can (rather easily) be cosmologically stable.

Axion relic pockets can comprise all of dark matter.

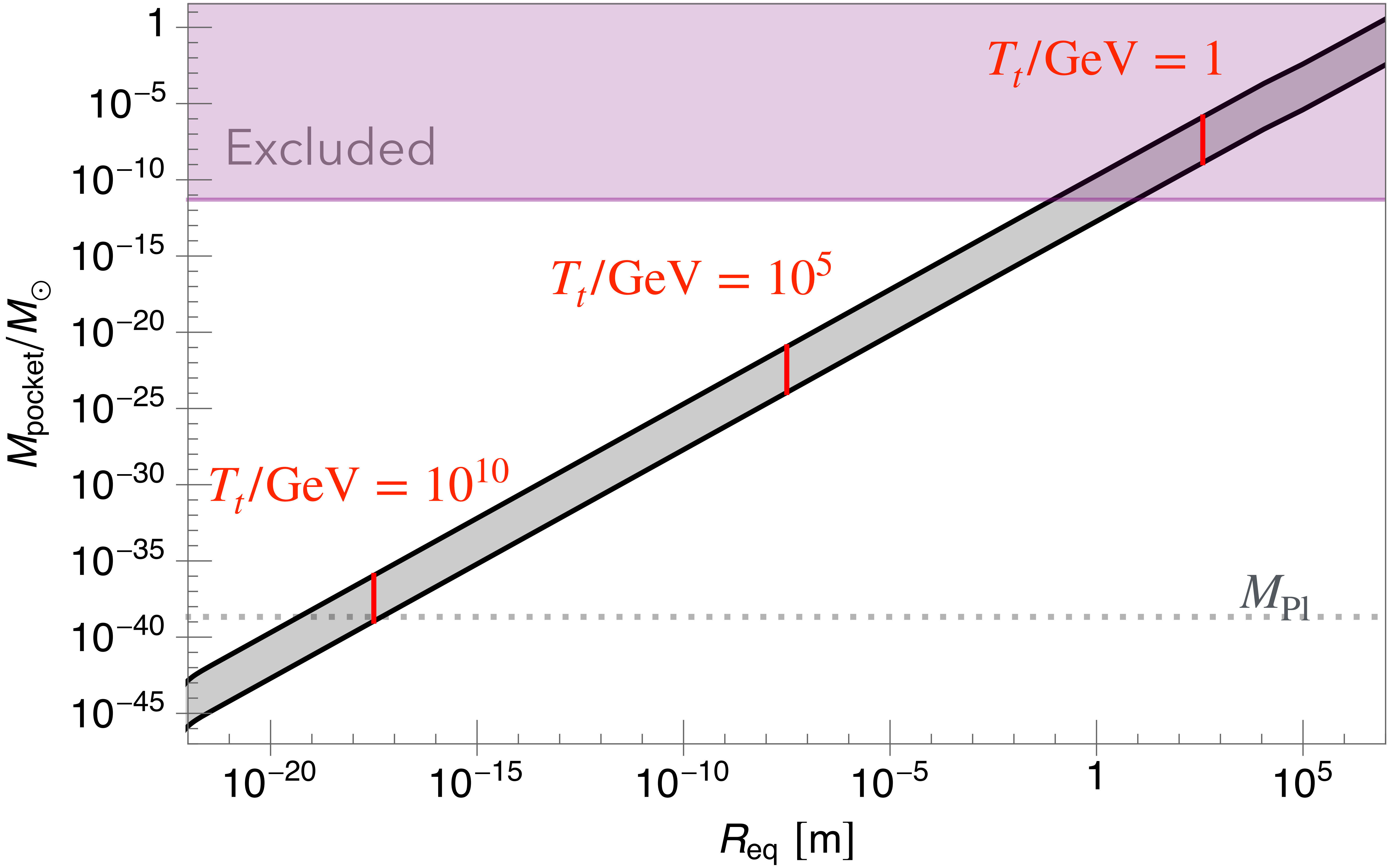
$$\Delta V\Big|_{\rm DM} \simeq 20\ {\rm GeV}^4\ \epsilon^{-4} \left(\frac{T_t}{\rm TeV}\right)^3$$

Transition must (naively) happen between inflation and matter/rad. equality:

$$1\ {\rm eV} \lesssim T_t \lesssim 10^{16}\,{\rm GeV}$$

Mass v. Radius

Single-parameter solution, but with a broad range.



A priori, radius may run from point-like to galactic.

Microlensing constraints: $T_t \gtrsim 13\,\mathrm{GeV}$.

Viable range:

$$10^{10}\,\mathrm{GeV} < M_{\mathrm{pocket}} \lesssim 5 \cdot 10^{-12}\,\mathrm{M}_\odot$$

$$10^{-25}\,\mathrm{m} \lesssim R_{\mathrm{pocket}} \lesssim 20\,\mathrm{cm}$$

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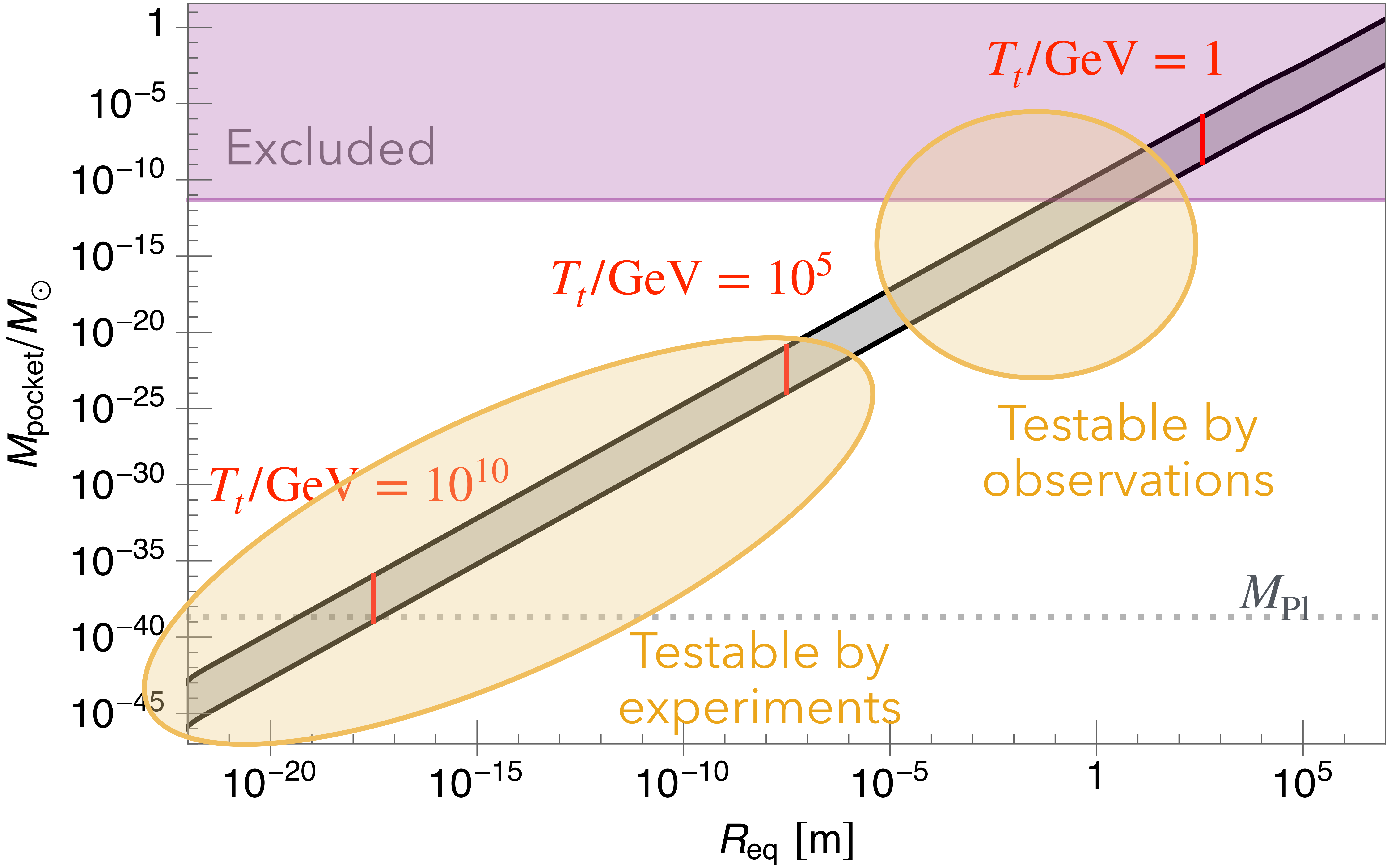

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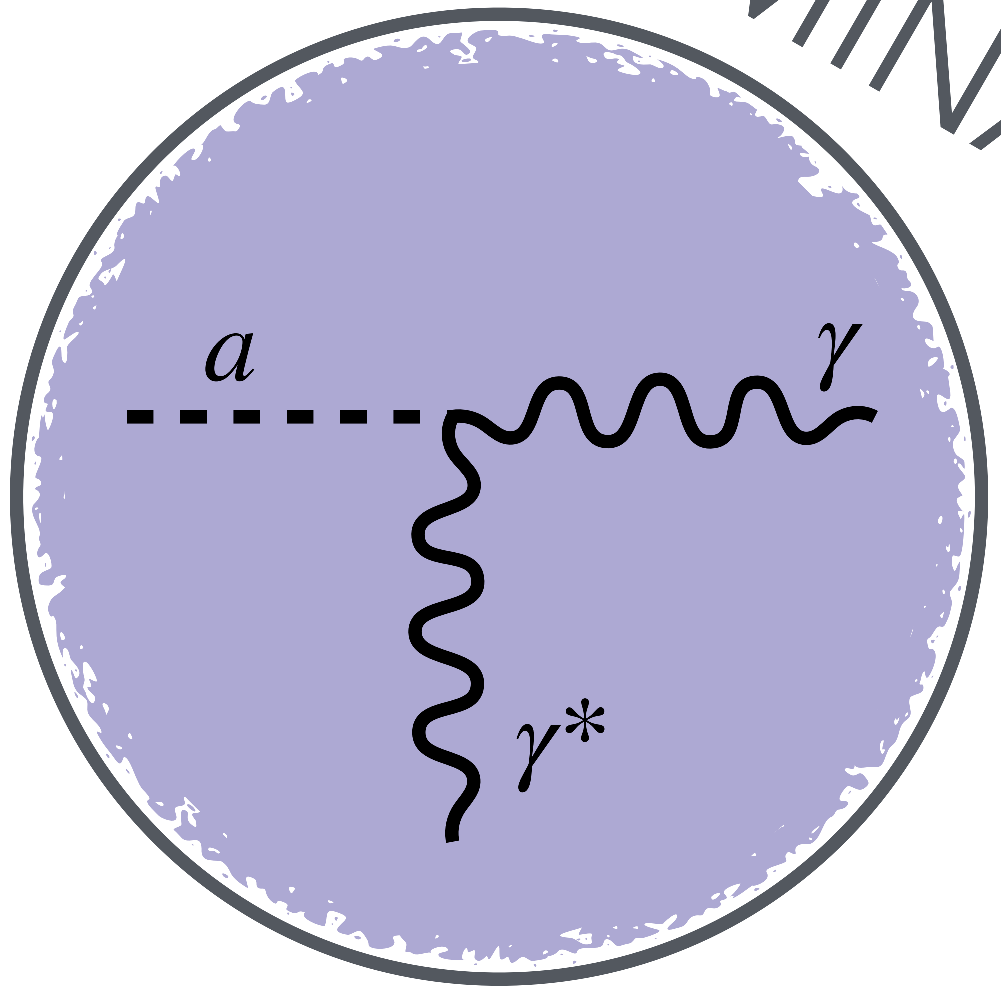
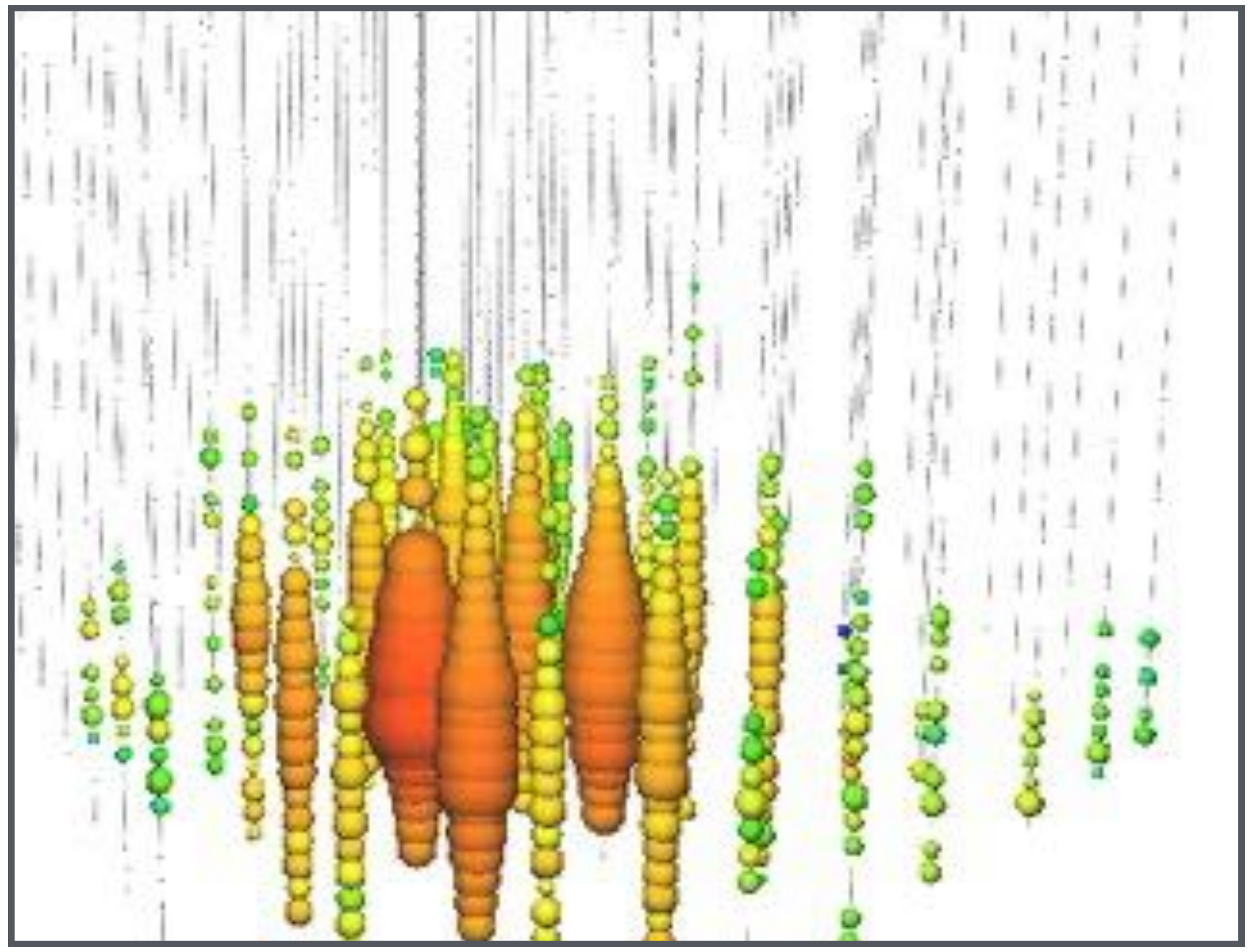
Terrestrial Axion Relic Pockets searches

PRELIMINARY

Event rate (single-axion processes): $\dot{N}_{\rm event} = \frac{3}{4}\frac{\sigma}{E_a}\rho_{\rm DM} N_{\rm target}$

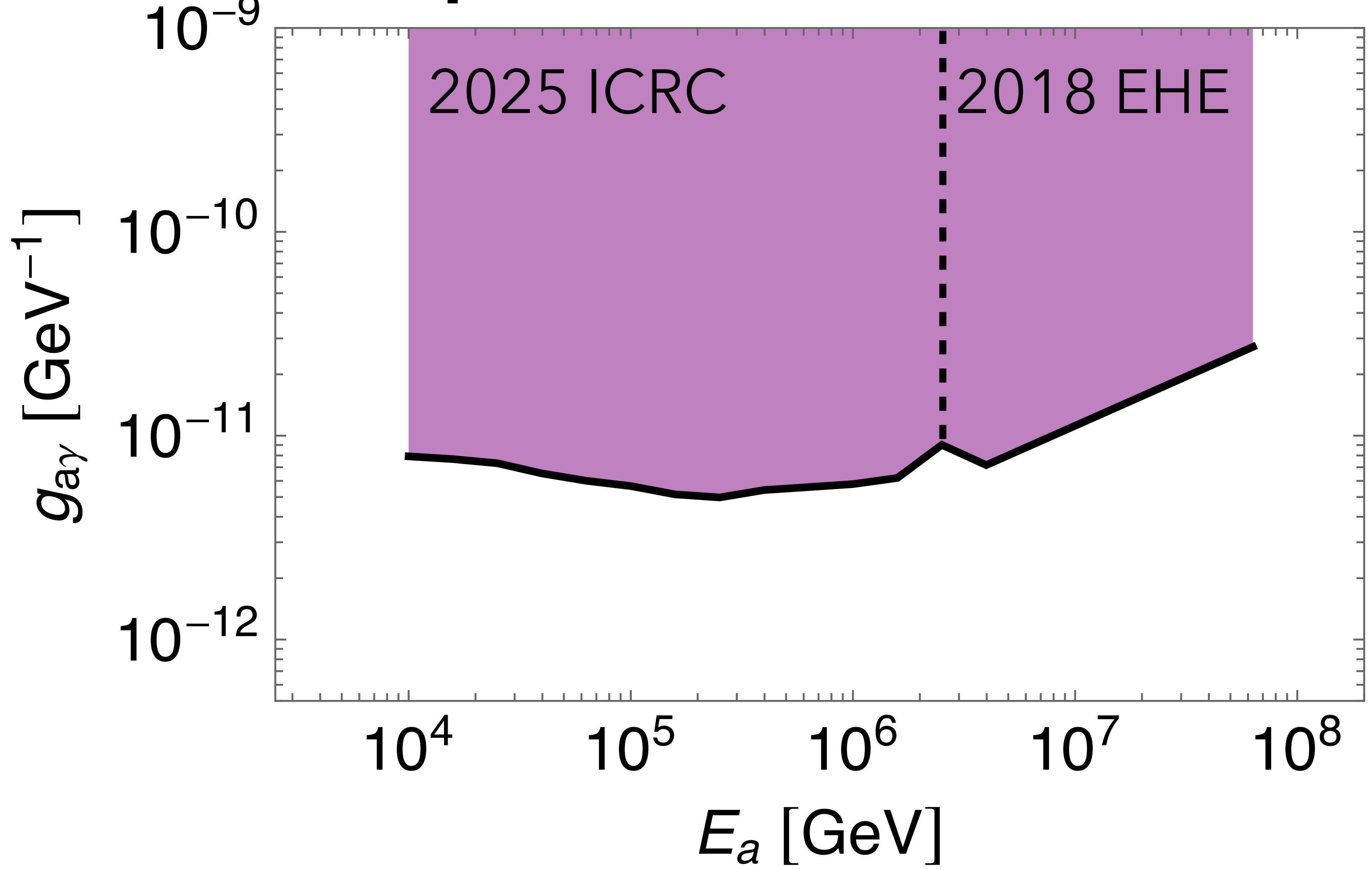
targets (e.g. atoms) in detector





Smoking gun: high-energy upward-going cascades.

Example: IceCube



Summary

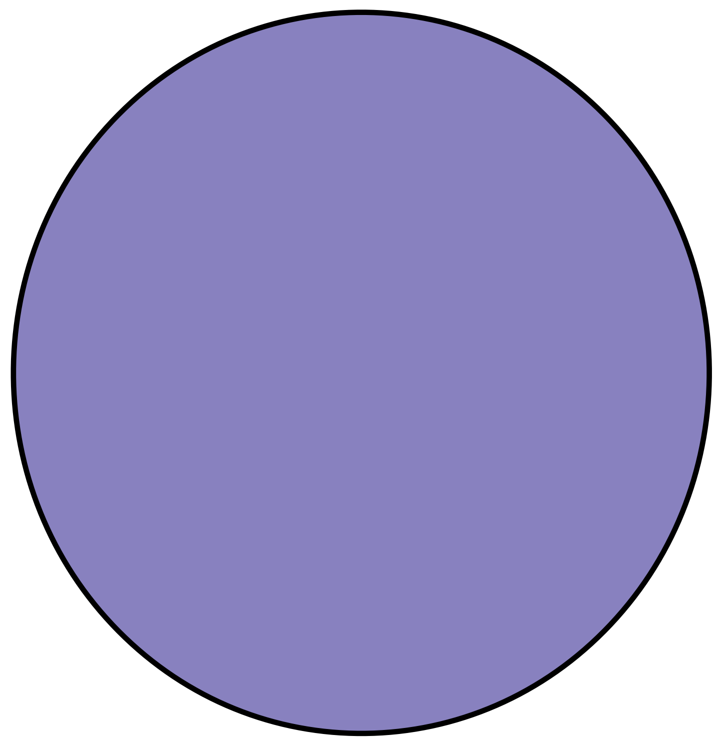
Dilatons and axions are both highly motivated by high-energy physics.
Cosmic dilaton phase transitions can lead to:

- **1st order QCD PT:** with GW signals curiously close to those reported by PTAs.
- **Axion relic pockets:** a dark matter theory with phenomenology distinct from existing paradigms.

Thanks for your attention!

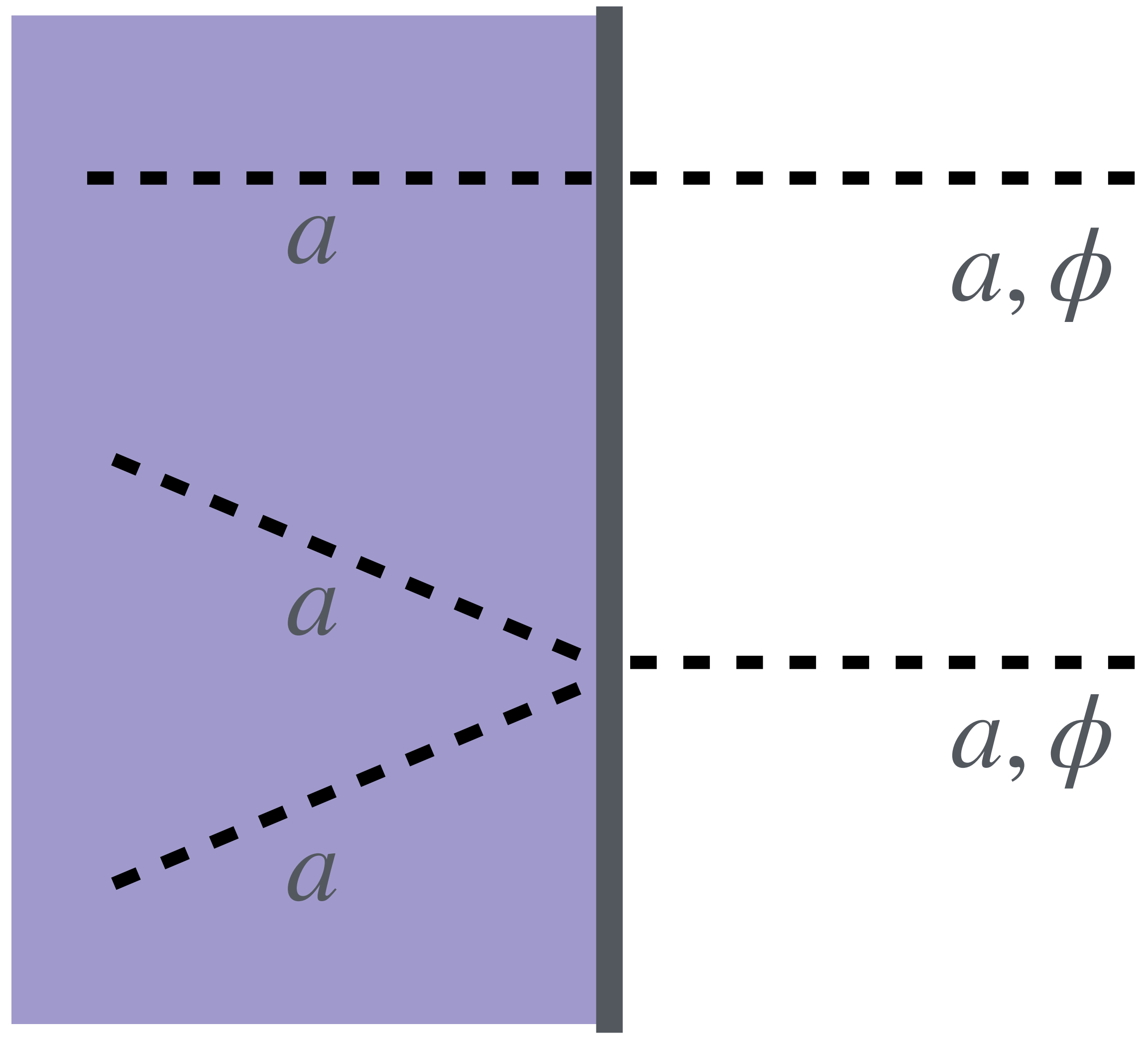
Extra slides

Pocket stability

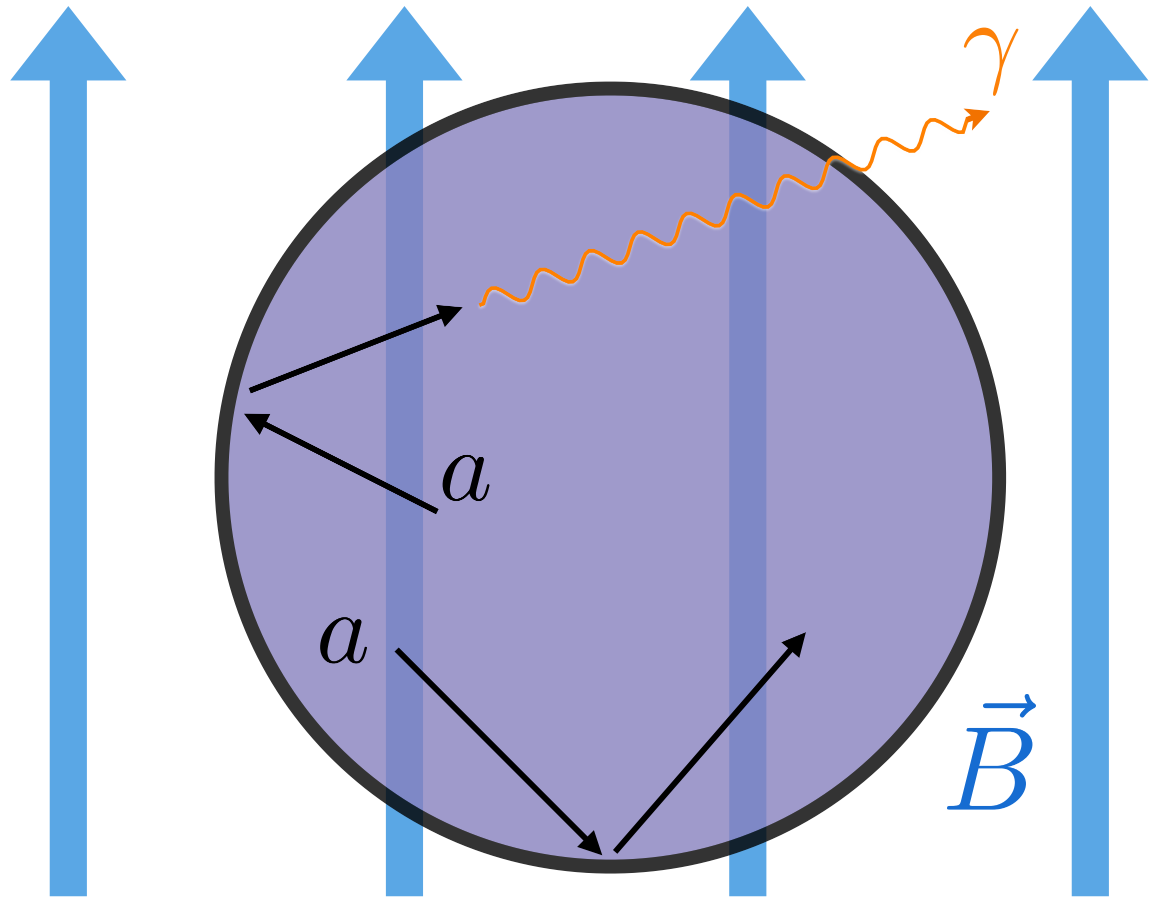


Since $R_{\text{eq}} \gg R_c$, bubble formation doesn't stop. However, TV bubbles collapse due to gas pressure.

Too dilute to collapse into black holes. Lewicki++ 2022

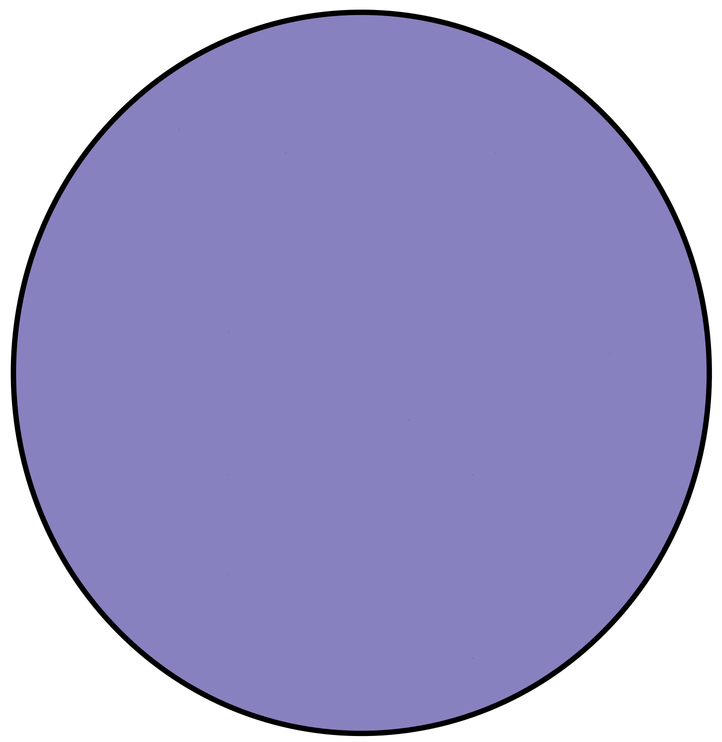


If $m_a|_{\text{TV}}$ and $m_\phi|_{\text{TV}}$ are sufficiently large ($\gg T_{\text{eq}}$), then axions can't escape by scattering through wall.



Interactions with Standard Model typically harmless for stability, but can give interesting signals.

Pocket stability



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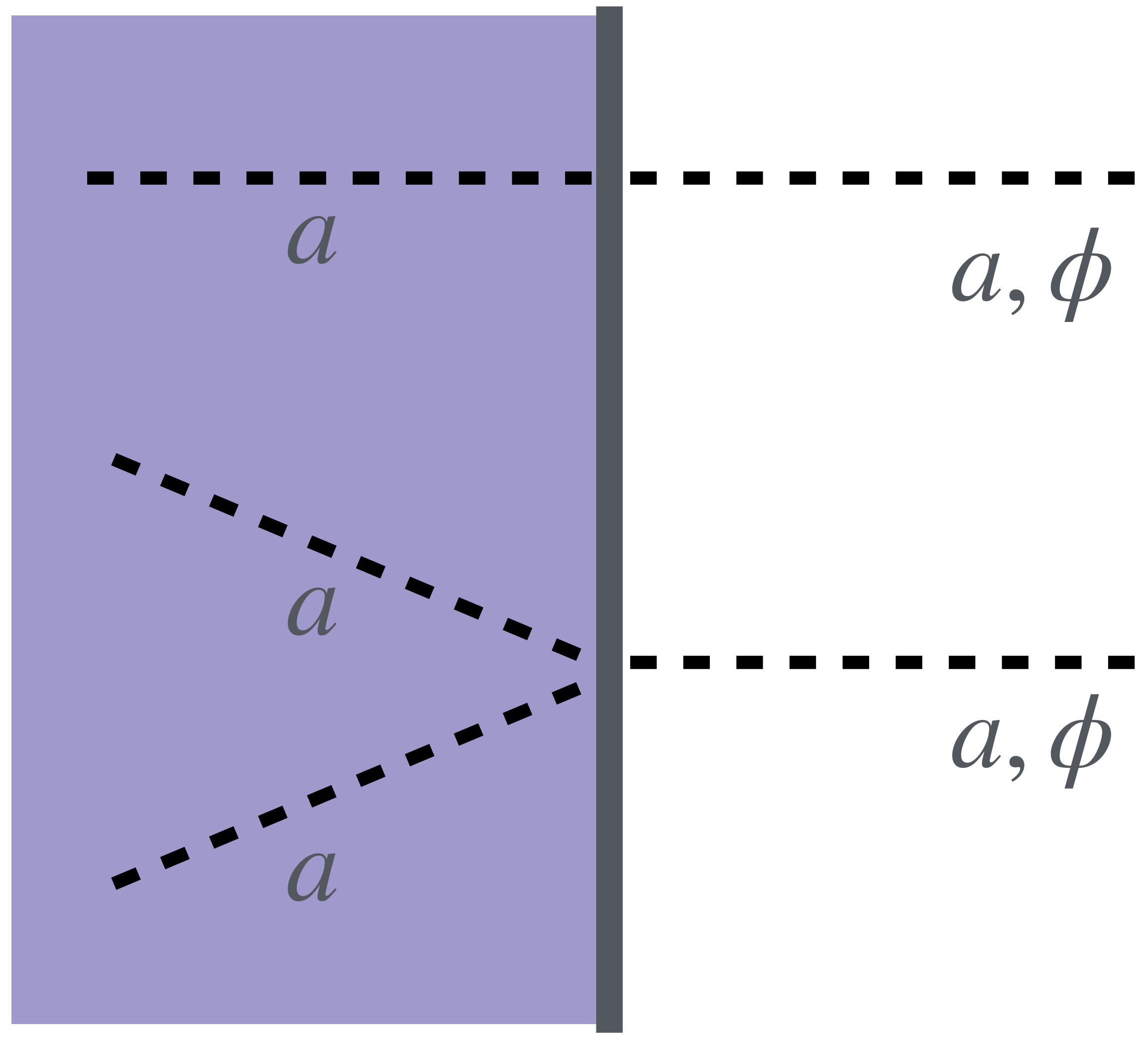

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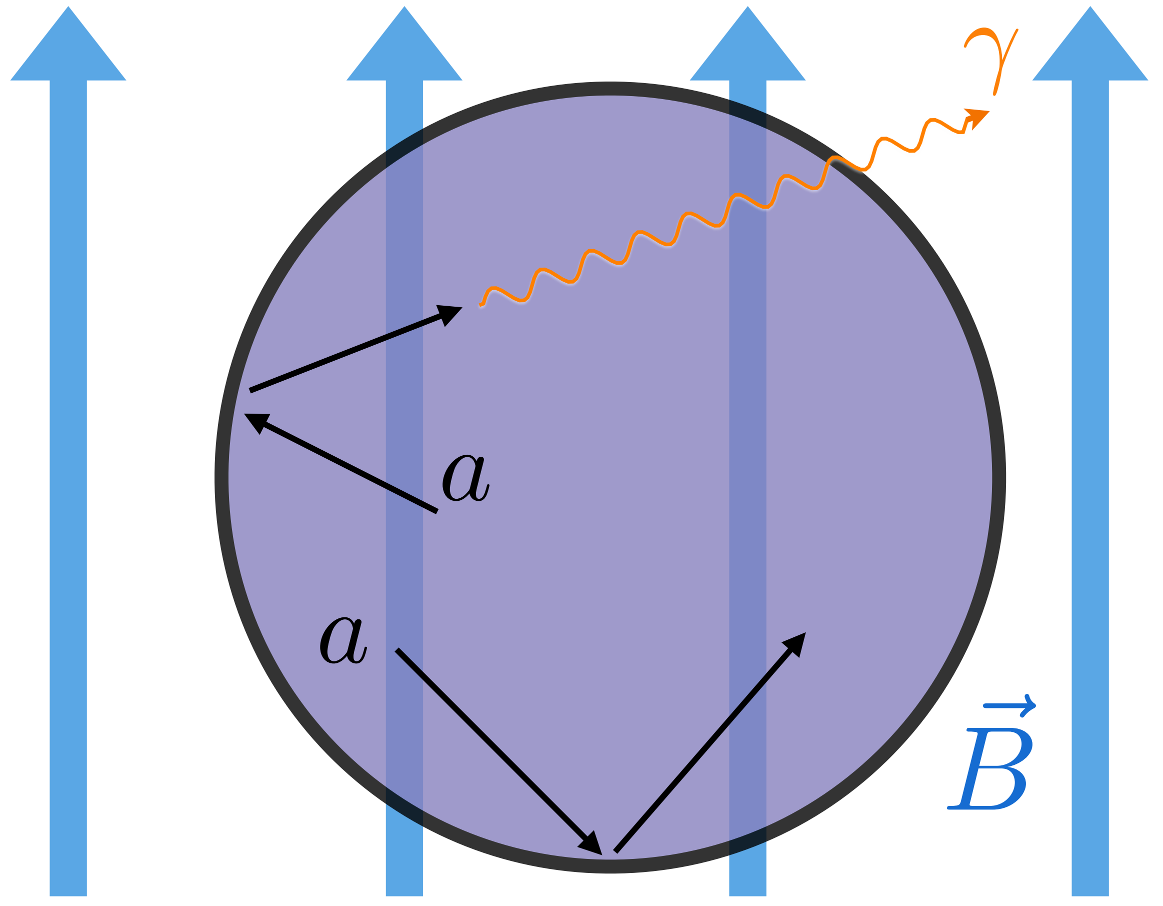


Interactions with Standard Model typically harmless for stability, but can give interesting signals.

Equilibrium properties

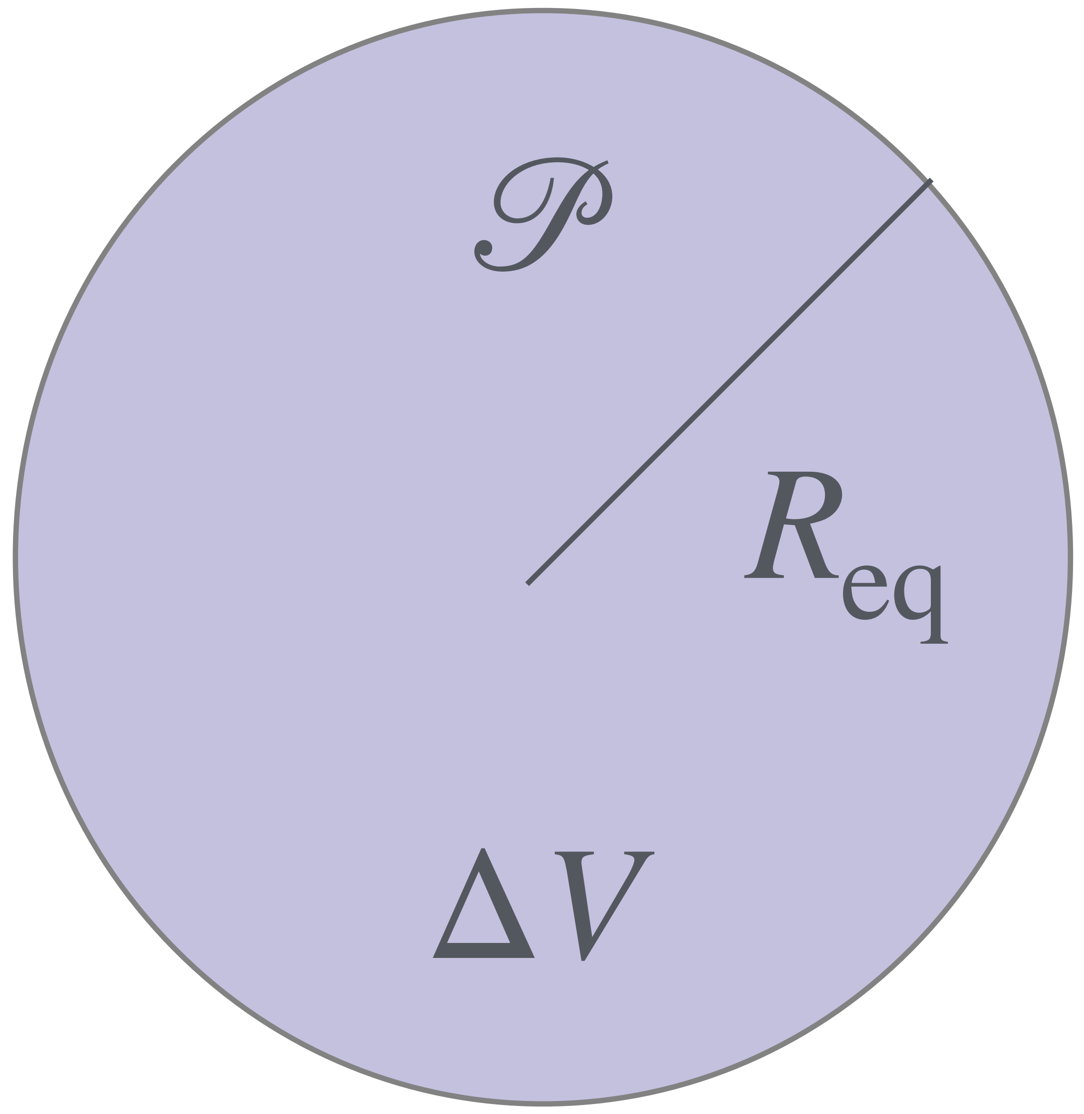
$$\dot{R} = \ddot{R} = 0$$

Spherical EoM:

$$\ddot{R} + \frac{2(1-\dot{R}^2)}{R} = -\frac{3(1-\dot{R}^2)^{3/2}}{R_c}\left(1 - \frac{\mathscr{P}}{\Delta V}\right)$$

Equilibrium radius:

$$R_{\text{eq}} = \frac{2}{3}\frac{R_c}{\mathscr{P}/\Delta V - 1}$$



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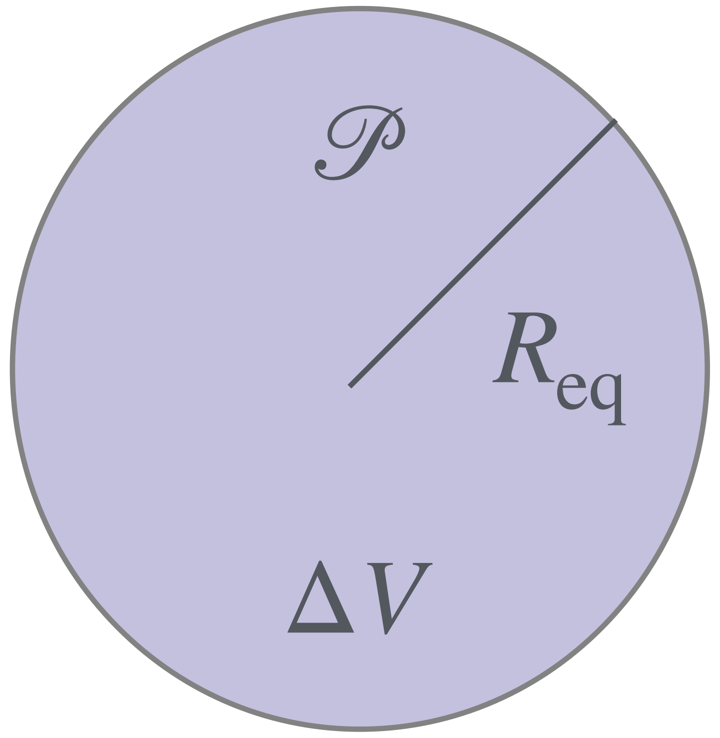


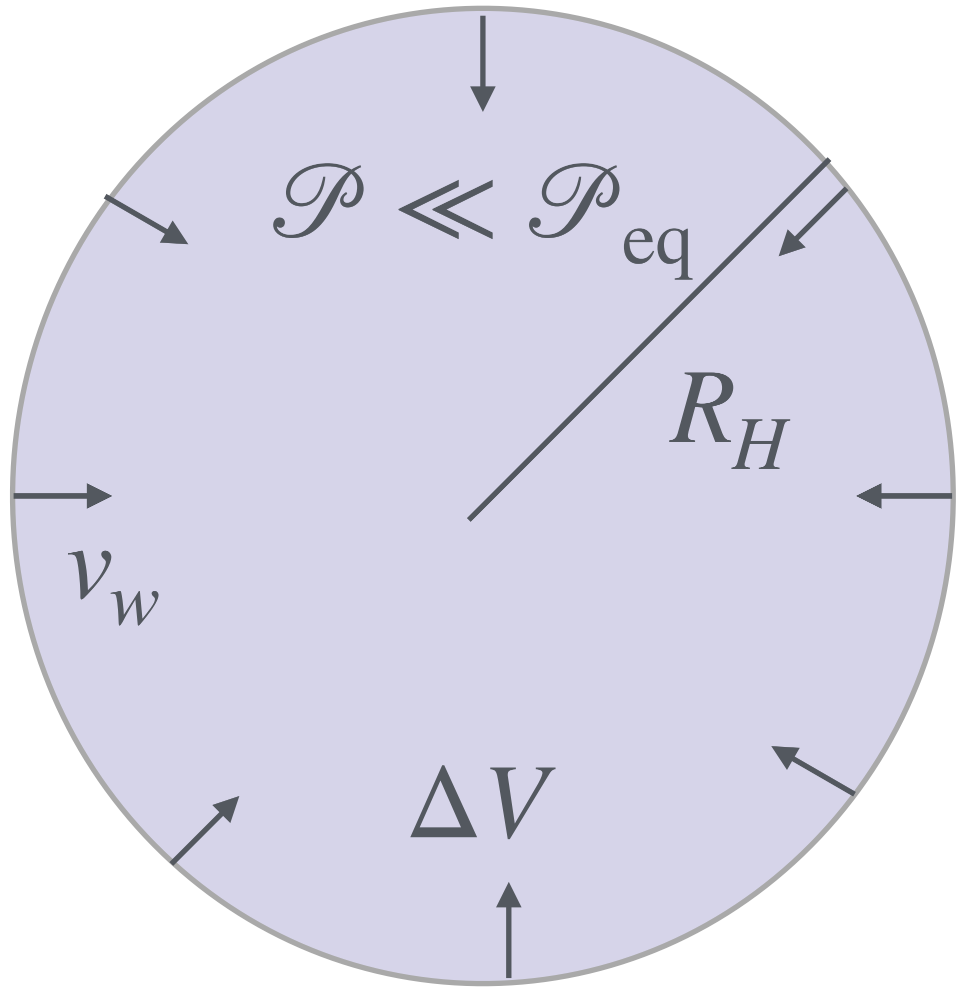
Equilibrium radius: $$R_{\rm eq} = \frac{2}{3}\frac{R_c}{\mathscr{P}/\Delta V - 1}$$

Equilibrium mass: $$M_{\rm pocket} = \sigma A_{\rm eq} + \left(\Delta V + 3\mathscr{P}\right) V_{\rm eq} \quad = \Delta V V_{\rm eq}\left(4 + \frac{R_c}{R_{\rm eq}}\right) \approx 4\Delta V V_{\rm eq}$$

Mass =3/4 Axion gas
+ 1/4 vacuum energy

Energy conservation

$E_{\text{tot}}($



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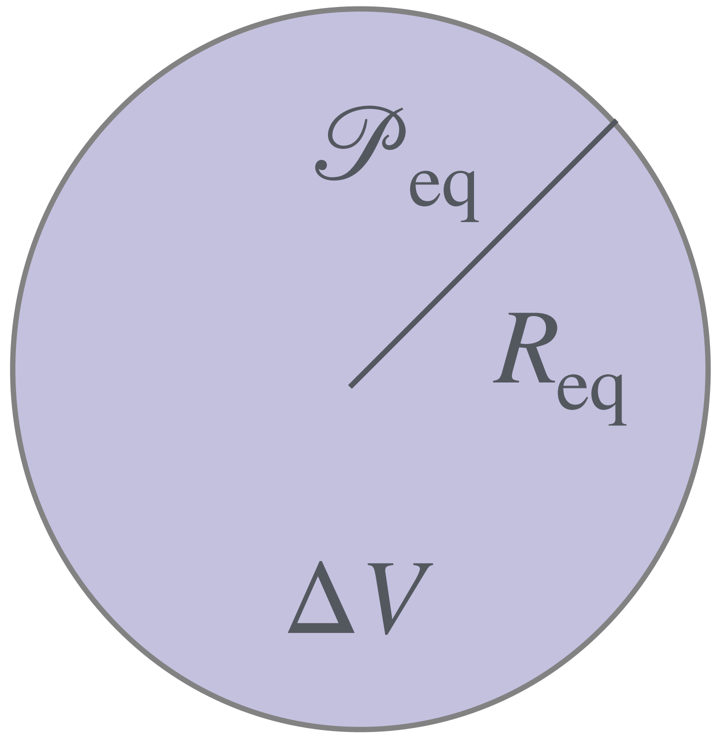


$)$

Model independently:

$$R_{\text{eq}} = \mathscr{O}(1) \times R_H$$

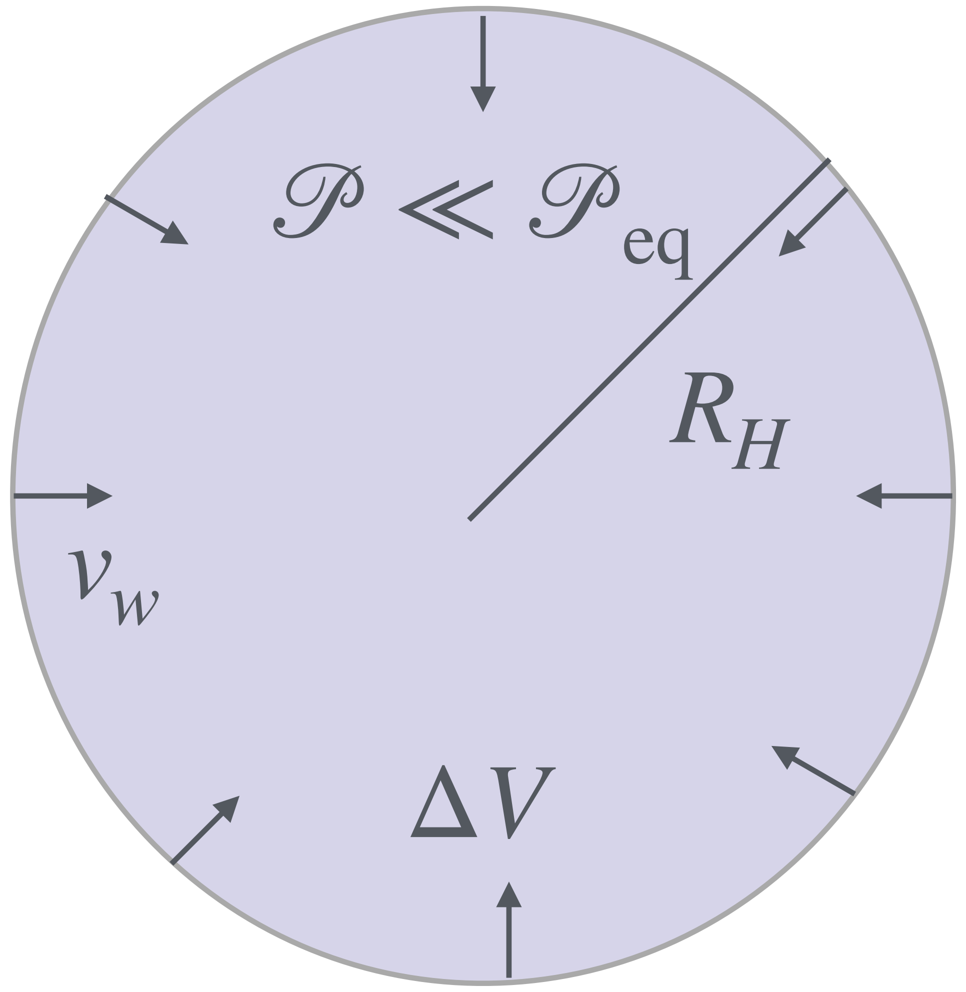
$$\mathscr{P}_{\text{eq}} = \Delta V \left(1 + \text{small}\right)$$

$$M_{\text{pocket}} \approx \left(\Delta V + 3\mathscr{P}\right) V_{\text{eq}} \; = \; 4 \Delta V V_{\text{eq}}$$

Axion gas temperature (thermal)**:**

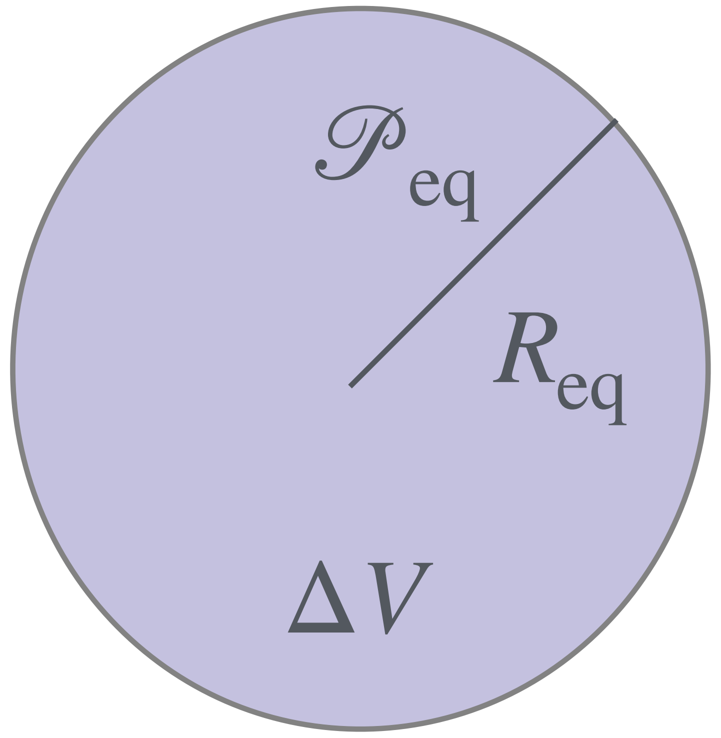
$$T_{\text{eq}} \sim 5 \text{ GeV} \left(\frac{T_t}{\text{TeV}}\right)^{3/4}$$

If gas *thermalises*, all properties become independent of initial axion abundance.



Energy conservation

Consider the (spherical) pocket just as it was formed



$$E_{\rm tot} = \gamma(t_{\rm coll})\sigma A_H + \Delta V V_H + E_{\rm gas}^{(0)} \approx (1+\alpha)\,\Delta V\, V_H$$

$\gamma(t_{\rm coll})\sigma A_H \equiv \alpha \dfrac{R_H}{R_c}$

$E_{\rm gas}^{(0)} \ll \Delta V V_H$

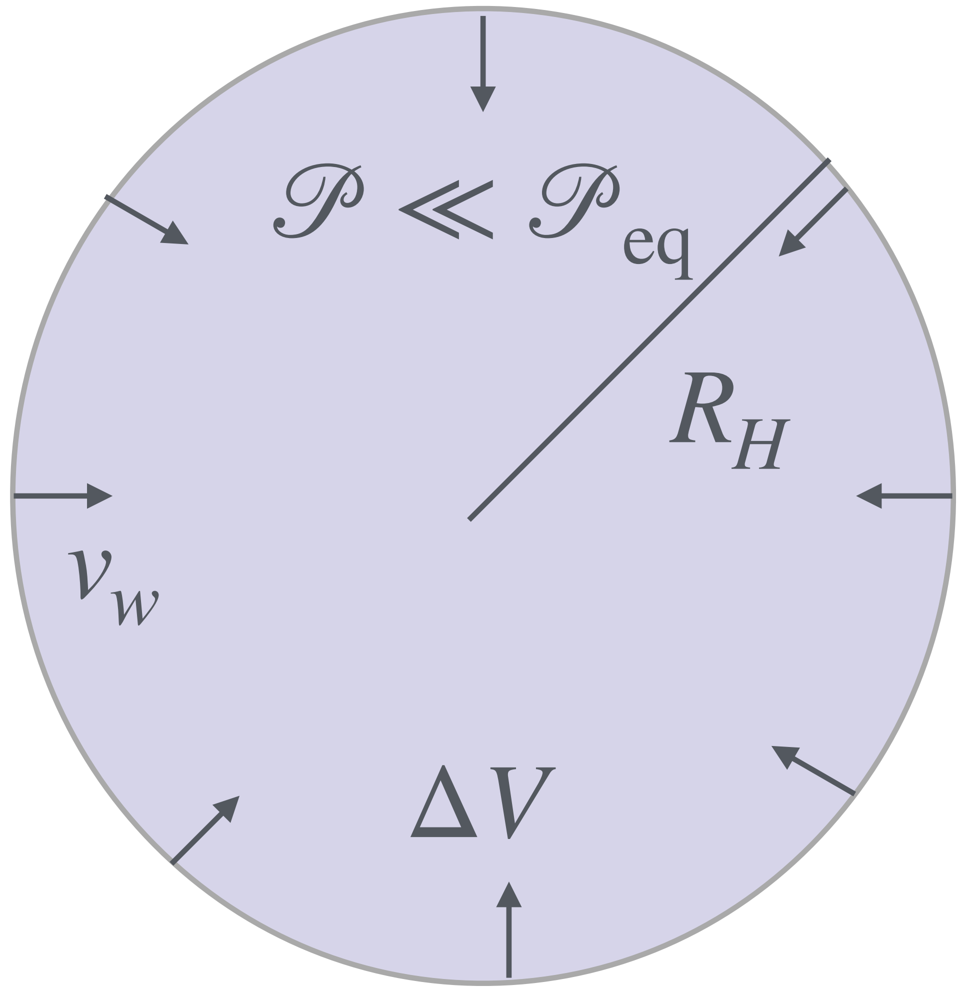
Energy conservation: $E_{\rm tot} = M_{\rm pocket} \approx 4\Delta V\, V_{\rm eq}$

$$R_{\rm eq} = \left(\frac{1+\alpha}{4}\right)^{1/3} R_H$$

Pocket radius ~ Hubble radius at time of creation

Gas pressure: $\mathscr{P}_{\rm eq} = \Delta V\left(1 + \mathscr{O}(R_c/R_H)\right)$

Axion gas temperature (thermal)**:**



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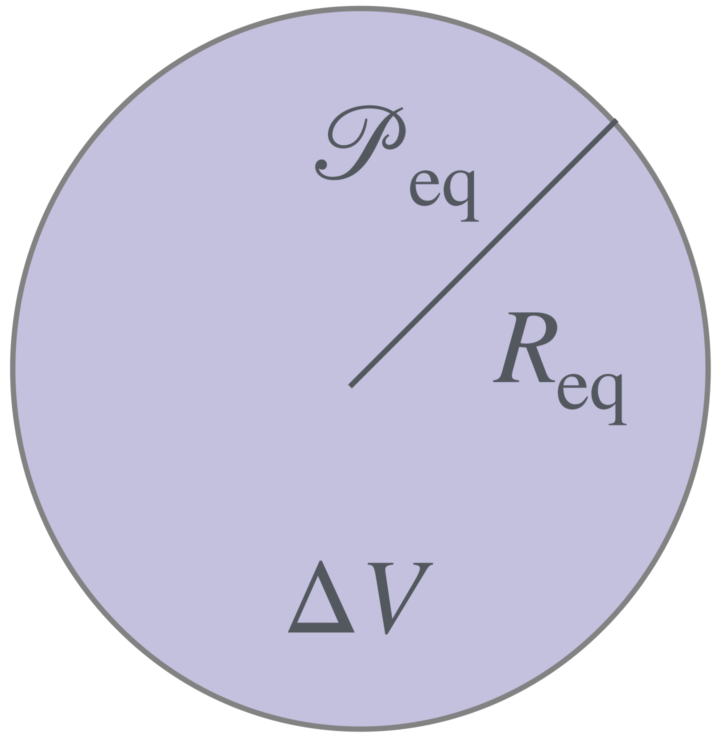

$$E_{\rm tot} = \gamma(t_{\rm coll})\sigma A_H + \Delta V V_H + E^{(0)}_{\rm gas} \approx (1+\alpha)\,\Delta V\, V_H$$

$\gamma(t_{\rm coll}) \equiv \alpha \dfrac{R_H}{R_c}$; $E^{(0)}_{\rm gas} \ll \Delta V V_H$

Energy conservation: $E_{\rm tot} = M_{\rm pocket} \approx 4\Delta V\, V_{\rm eq}$

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Axion gas temperature (thermal)**:**

$$T_{\rm eq} \sim 5\ {\rm GeV}\ \frac{1}{\epsilon^{1/4}}\left(\frac{T_t}{\rm TeV}\right)^{3/4}$$

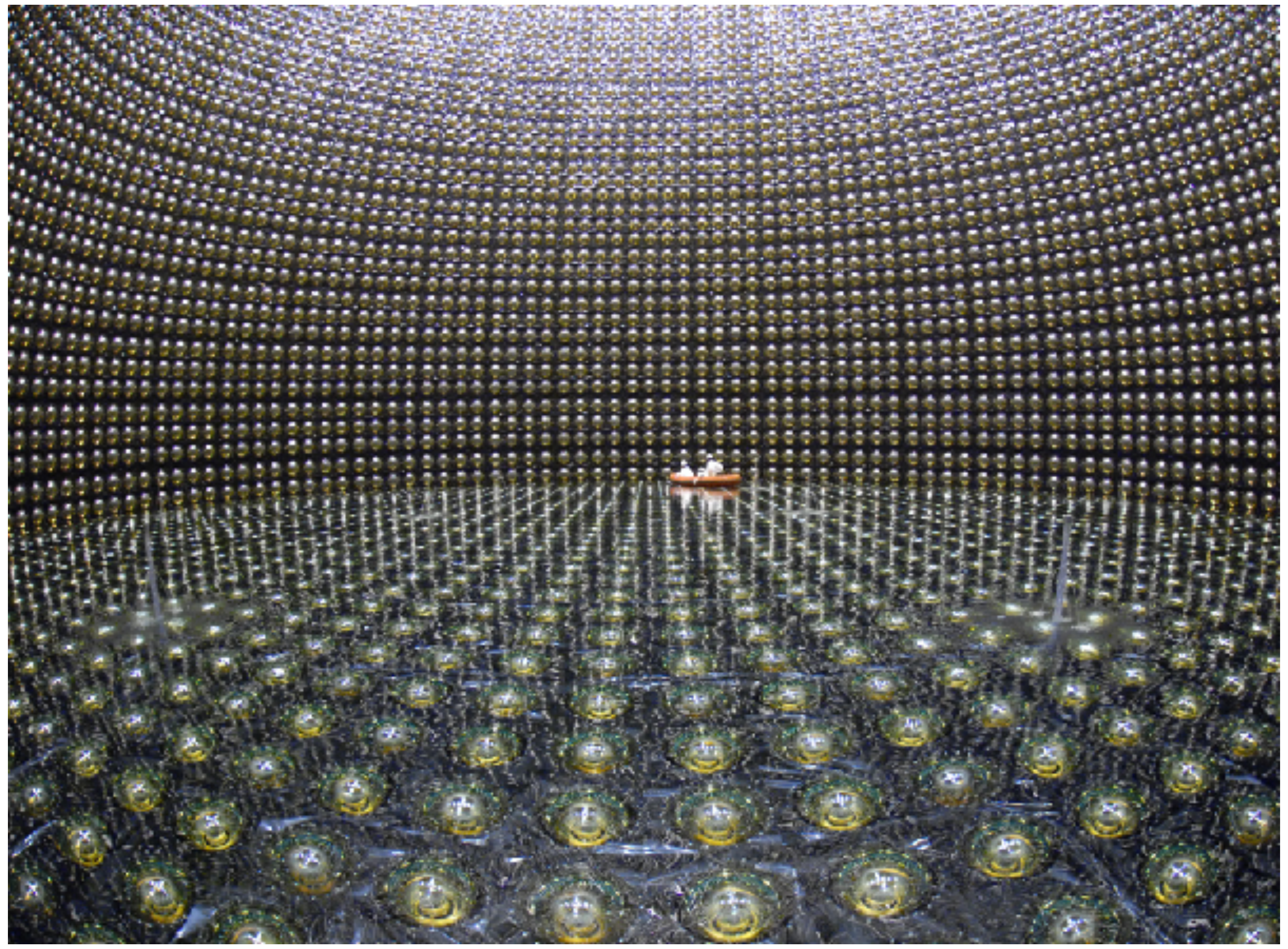
If gas *thermalises*, all properties become independent of initial axion abundance.

Laboratory searches for Axion Relic Pockets

Encounter rate:

$$\Gamma_{\text{encounter}} \sim n_{\text{pocket}}\sigma v_{\text{pocket}} = 10^{-6}\epsilon\ \text{year}^{-1}\left(\frac{R}{R_\oplus}\right)^2\left(\frac{T_t}{\text{TeV}}\right)^3$$

For $T_t \gtrsim 10^{12}\,\text{GeV}$, a detector volume of $1\,\text{m}^3$ would encounter 1 pocket/second.
Gas temperature ~$10^{10}\,\text{GeV}$, and #axions/pocket $\sim 10^5$.



Super-Kamiokande

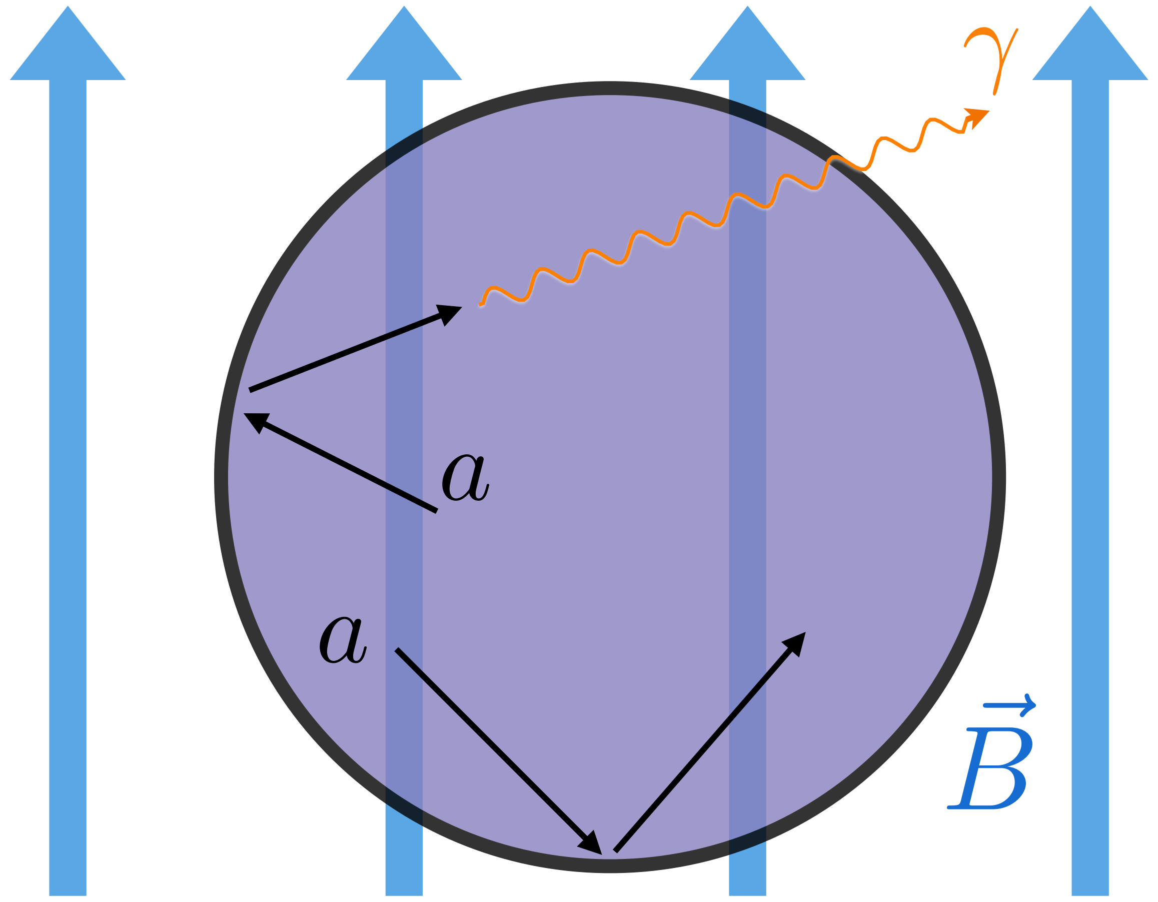
XENONnT

LHAASO, WCDA

Astronomical searches for Axion Relic Pockets

Axion-photon conversion rate:

$$\left|\frac{dN_{a\,\text{pocket}}}{dt}\right| = \Gamma_{a\to\gamma} N_{a\,\text{pocket}} = 200\ \text{s}^{-1}\ \epsilon^{-3/4}\left(\frac{g_{a\gamma}}{10^{-10}\,\text{GeV}^{-1}}\right)^2\left(\frac{B}{\mu\text{G}}\right)^2\left(\frac{\text{TeV}}{T_t}\right)^{23/4}$$



Rate is small enough for relic pockets to be long-lived.

Number flux is greatly enhanced at low temperatures. E.g., for $T_t = 15\,\text{GeV}$ and $B_\perp = 15\,\text{G}$,

$$\left|\frac{dN_{a\,\text{pocket}}}{dt}\right| \sim 10^{37}\ \text{s}^{-1}\left(\frac{g_{a\gamma}}{10^{-10}\,\text{GeV}^{-1}}\right)^2$$

with photon energy set by $T_{\text{eq}} \sim 230\ \text{MeV}$.

Moderate-to-highly magnetised regions (e.g. magnetars with $B \sim 10^{15}\,\text{G}$) may generate observable, characteristic signals.

Theory requirements

Initial axion population particle-like: $m_a\big|_{\rm FV} \gtrsim 3H(T_t)$ if produced by misalignment mech. no restriction if seed is dark radiation

Reflective boundary condition: $m_a\big|_{\rm TV} > E_a$

Required field displacement: $\dfrac{|\Delta\phi|}{\phi_{\rm FV}} \gtrsim 0.1 - 0.5$ for $S_{\rm FV} \sim \mathcal{O}(100)$

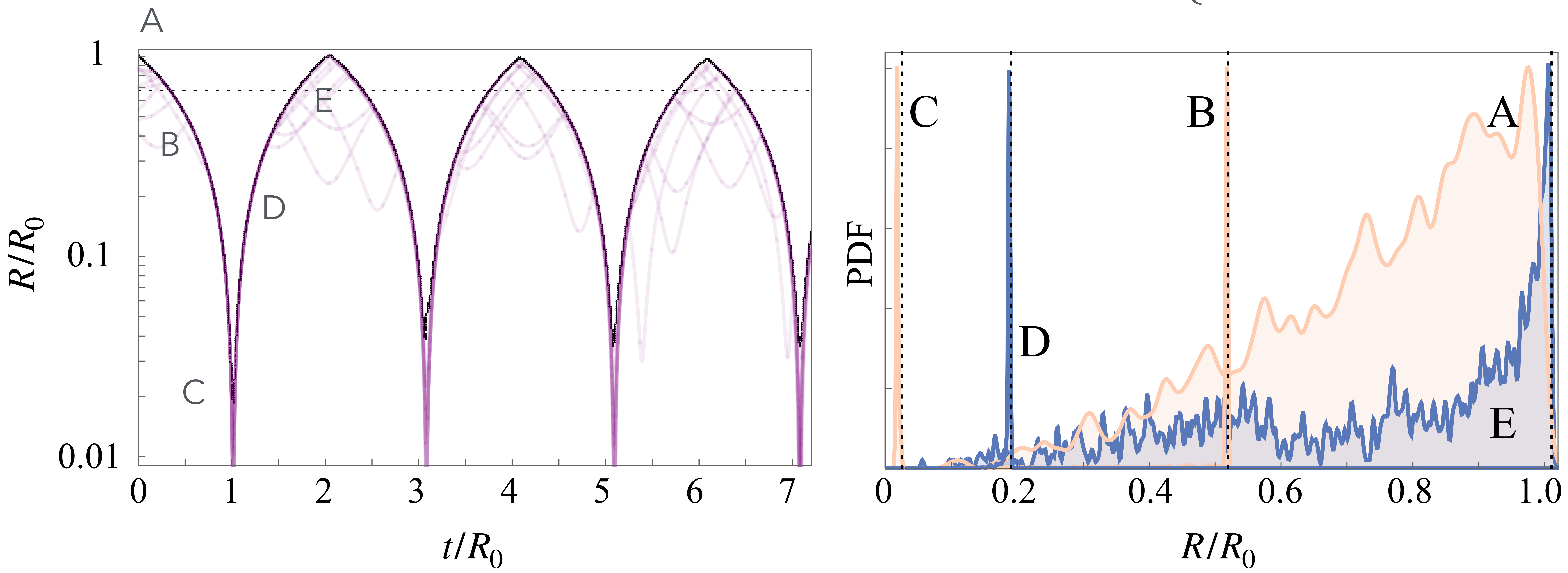
Dilaton potential: $V_{\rm dil}(\phi)$ should support a quantum phase transition during radiation domination.

$m_\phi \gg E_a$ in both phases, in simplest case.

Couplings to the Standard Model can make ϕ unstable.

Pulsating pockets

$$\begin{cases} N_{\text{particles}} & = 1{,}000 \\ \dot{R}(0) & = -0.999 \\ R_0/R_c & = 100 \end{cases}$$



Radial oscillations for some time.

Context: Previous work

Transient false-vacuum pockets ("droplets") are observed in more general PT's, even without large mass hierarchy.

Weir++ 2019

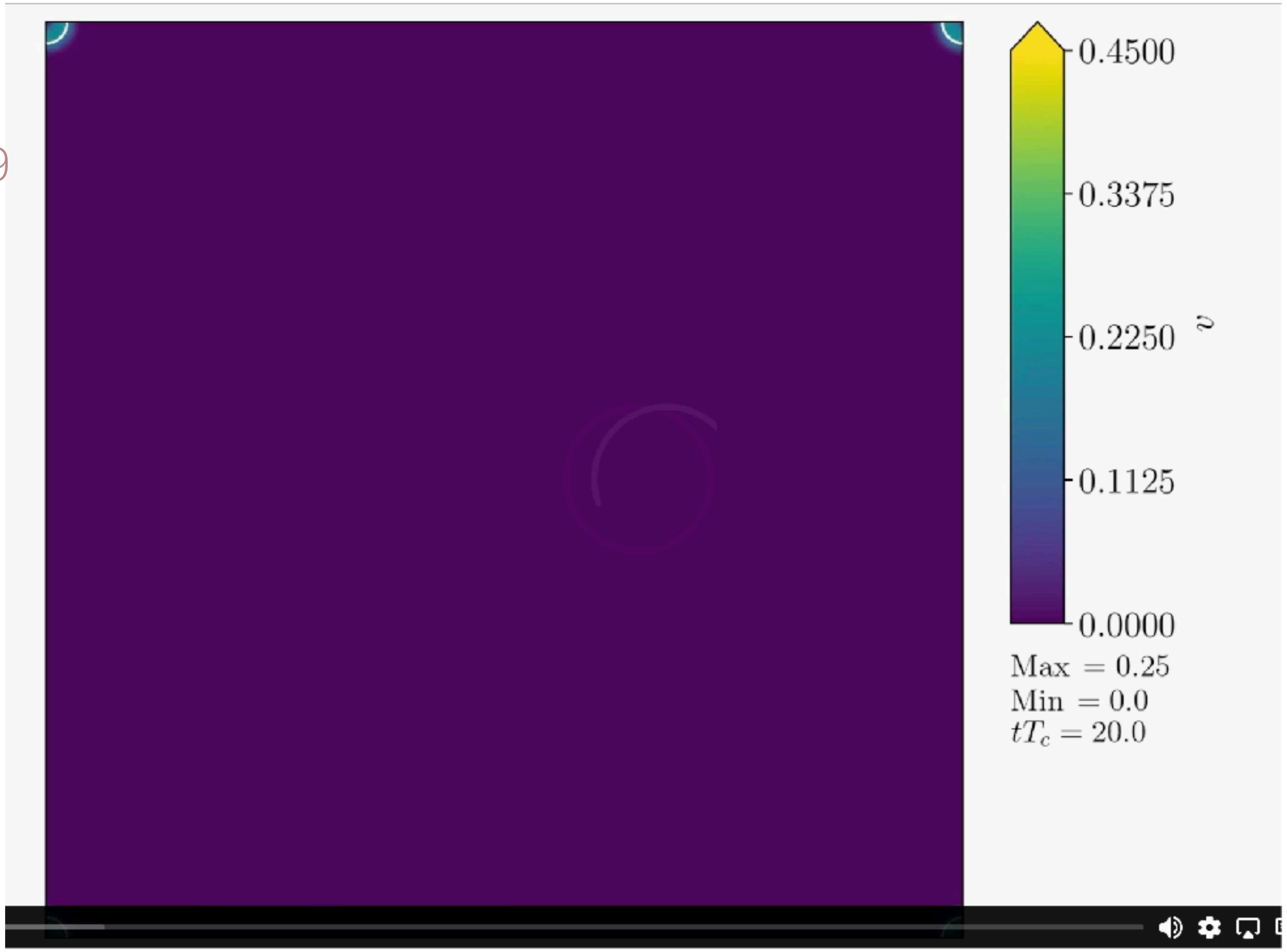
Quark nuggets are pockets that could have formed if the QCD phase transition was first order and "strange quark matter" is the true ground state of baryonic matter.

Witten '84

Generalisations: Axion Quark Nuggets, Dark Quark Nuggets, Fermi balls, Thermal balls

See talk by Ariel Zhitnitsky this afternoon.

Zhitnitsky 2002; Bai 2018; Gross++ 2021; Lewicki++ 2023; Kawana++ 2024; Xie++ 2025



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