中国科学院大学
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核科学与技术学院
School of Nuclear Science and Technology

Primordial Black Hole Dark Matter from Classically Conformal Cosmology

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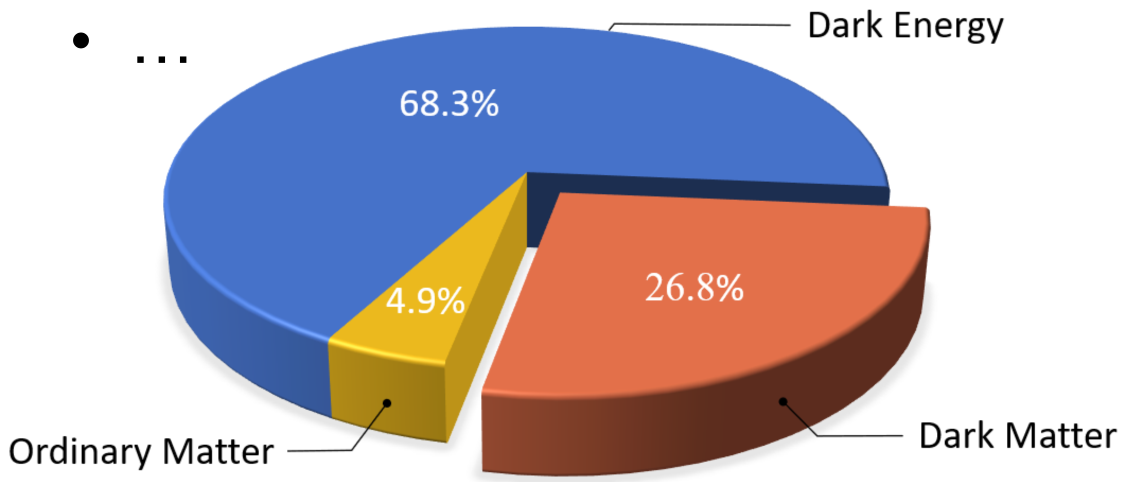
2026 年紫金山暗物质研讨会

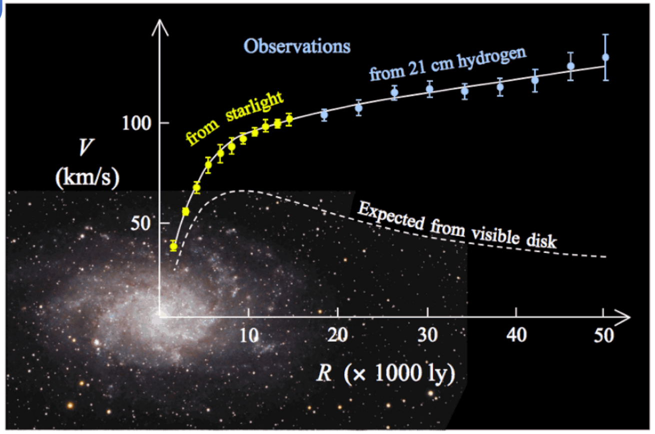
Xinjiang University, July 24, 2026

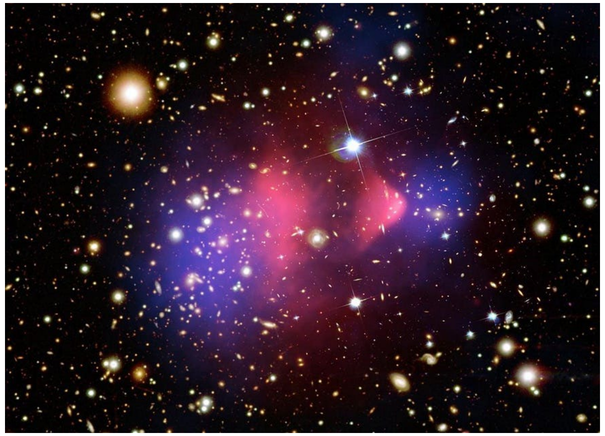
Dark Matter (DM)

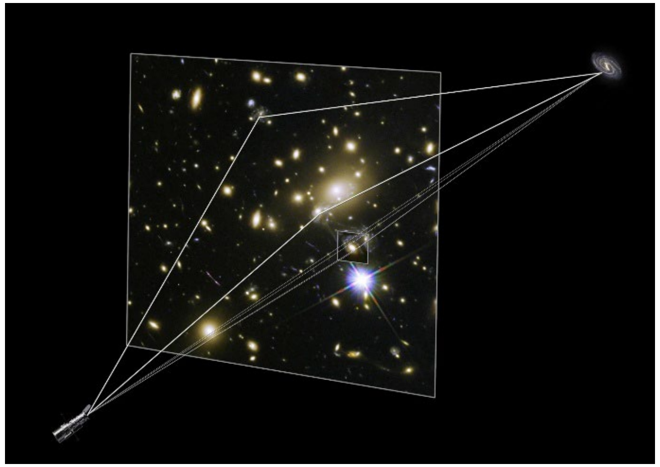
Observational evidence for DM:

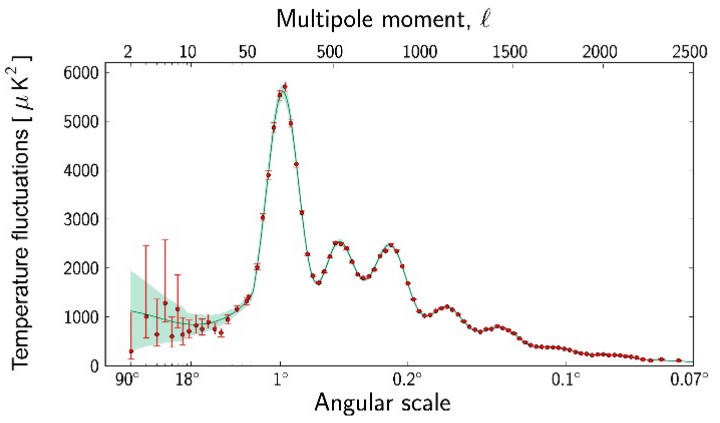
- Galaxy rotation curves
- Bullet cluster
- Gravitational lensing
- CMB anisotropies
- Structure formation
- …











We know it exists. But what is it?

PBHs as DM Candidates

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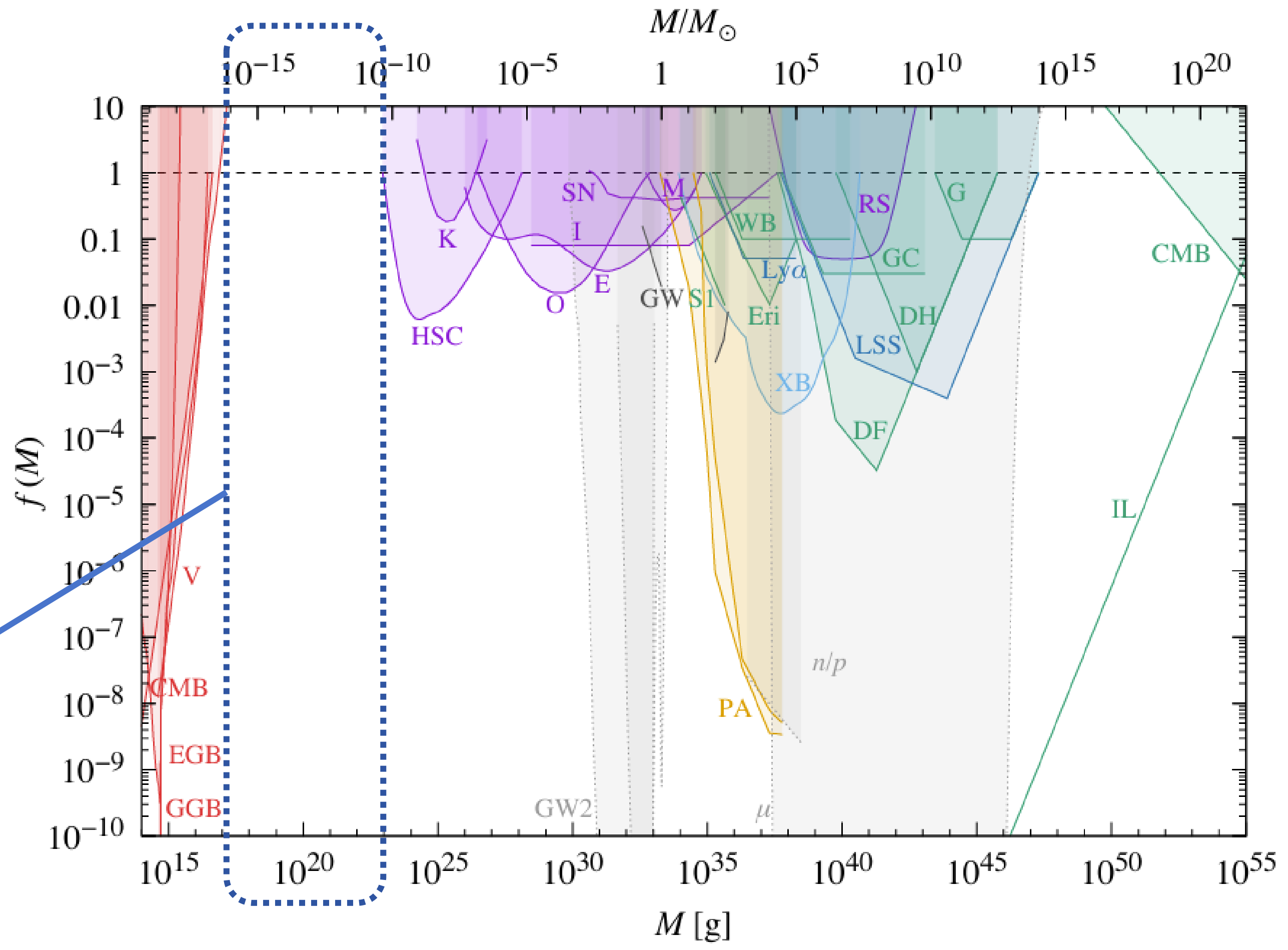
Why Primordial Black Holes:

- Non-baryonic
- Cold and matter-like
- No need for new particles
- Broad mass range
- …

Asteroid-mass window for PBHs: $10^{17}\text{g} \sim 10^{23}\text{g}$

- can account for all DM ($f_{\text{PBH}} = 1$)

Current constraints on the abundance of PBHs



[B. Carr, K. Kohri, Y. Sendouda, J. Yokoyama, 2002.12778]

Classically Scale-Invariant Models

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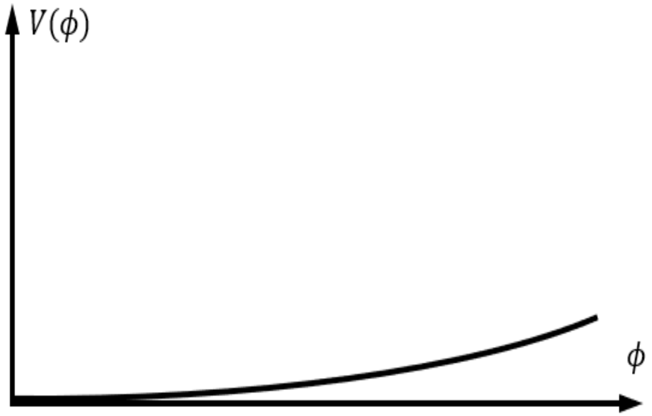
Consider a complex scalar Φ charged under a dark $U(1)$:

$$\mathcal{L} = \frac{1}{4} F_{\mu\nu} F^{\mu\nu} + |D_\mu \Phi|^2 - \lambda (\Phi^\dagger \Phi)^2, \qquad \Phi = \frac{\phi}{\sqrt{2}}$$

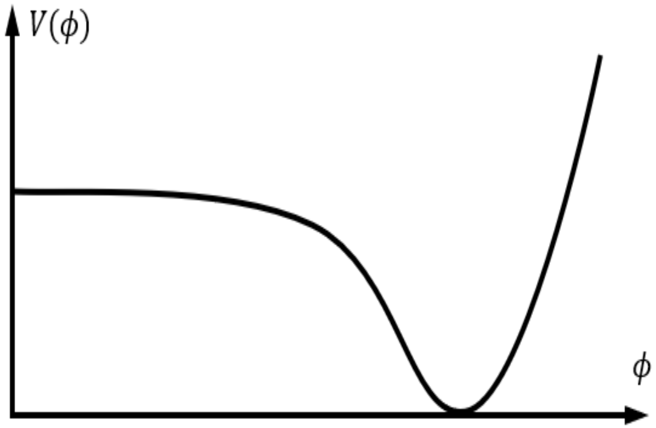
Tree-level potential:



$$V_{\rm tree}(\phi) = \frac{\lambda}{4}\phi^4$$

[No explicit mass scale]

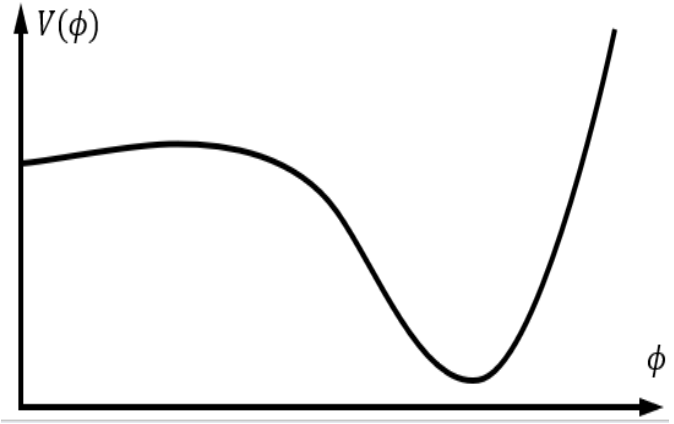
One-loop potential:



$$V_{\rm CW}(\phi) = \frac{3g_D^4}{4\pi^2}\phi^4\left(\ln\frac{\phi^2}{v_\phi^2} - \frac{1}{2}\right)$$

[Coleman-Weinberg mechanism]

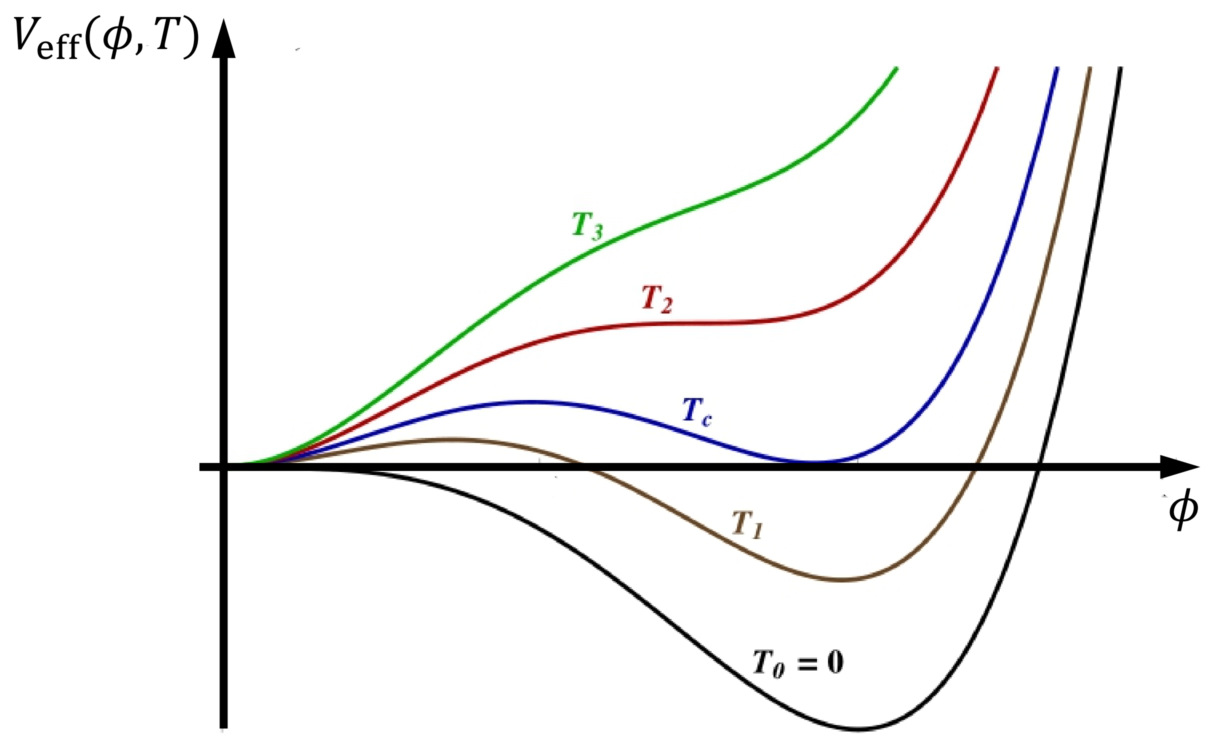
Finite-*T* effective potential:



$$V_{\rm eff}(\phi, T) \simeq \frac{g_D^2 T^2}{2}\phi^2 + \frac{3g_D^4}{4\pi^2}\phi^4\left(\ln\frac{\phi^2}{v_\phi^2} - \frac{1}{2}\right)$$

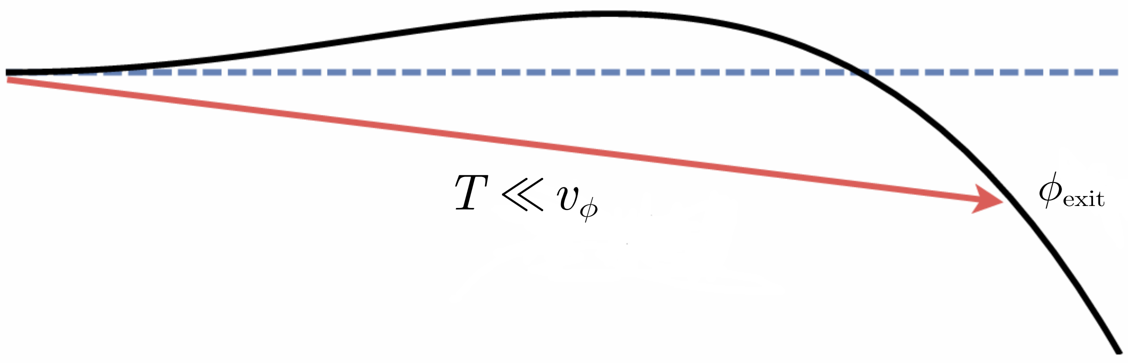
[Thermal corrections generate a barrier]

Classically Scale-Invariant Models



$$V_{\mathrm{eff}}(\phi,T)\simeq\frac{g_D^2T^2}{2}\phi^2+\frac{3g_D^4}{4\pi^2}\phi^4\left(\ln\frac{\phi^2}{v_\phi^2}-\frac{1}{2}\right)$$

$$\approx \# T^2\phi^2-\#_{\mathrm{loop}}\phi^4\log(v_\phi/T)$$



Bounce action: $\dfrac{S_3(T)}{T}\simeq\dfrac{430.72}{\sqrt{N_b}\,g_D^3}\dfrac{1}{\ln\frac{M}{T}}$

Nucleation rate: $\Gamma(T)\simeq T^4\left(\dfrac{S_3(T)}{2\pi T}\right)^{3/2}\exp\left(-\dfrac{S_3(T)}{T}\right)$

➡ ultra-supercooling

Escape from supercooling:

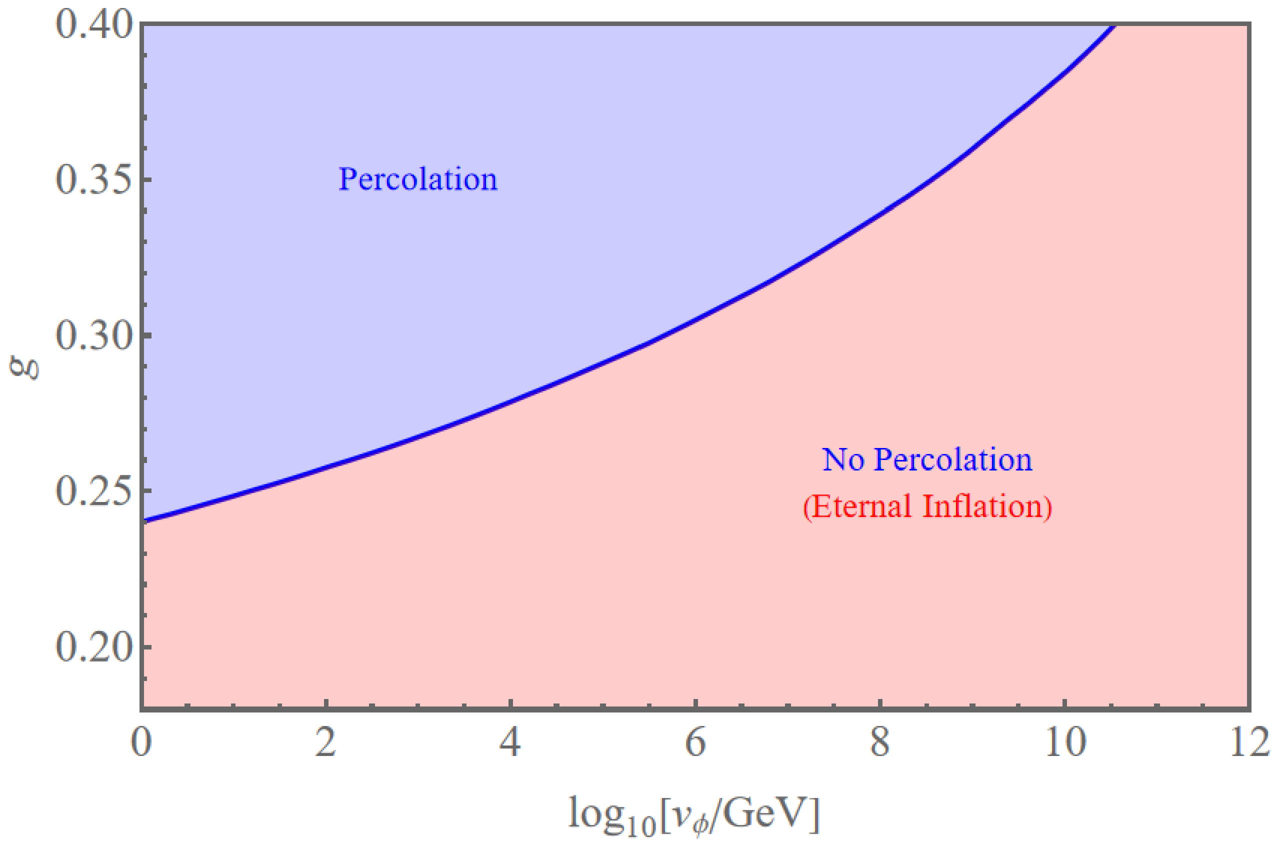


Fig. Schematic parameter space in the (g_D, v_ϕ) plane.

- Moderate g_D:
  - FOPT and bubble percolation
- Small g_D:
  - Percolation failure → eternal inflation?

$$V_{\text{false}} \propto a^3(t) e^{-I(t)}$$

$$\frac{1}{V_{\text{false}}} \frac{\mathrm{d}V_{\text{false}}}{\mathrm{d}t} = H(T)\left(3 + T\frac{\mathrm{d}I(T)}{\mathrm{d}T}\right) > 0$$

  - As T → 0, the thermal barrier disappears, seemingly enabling a classical-roll exit.

Mechanism I: Delayed Vacuum Phase Transitions

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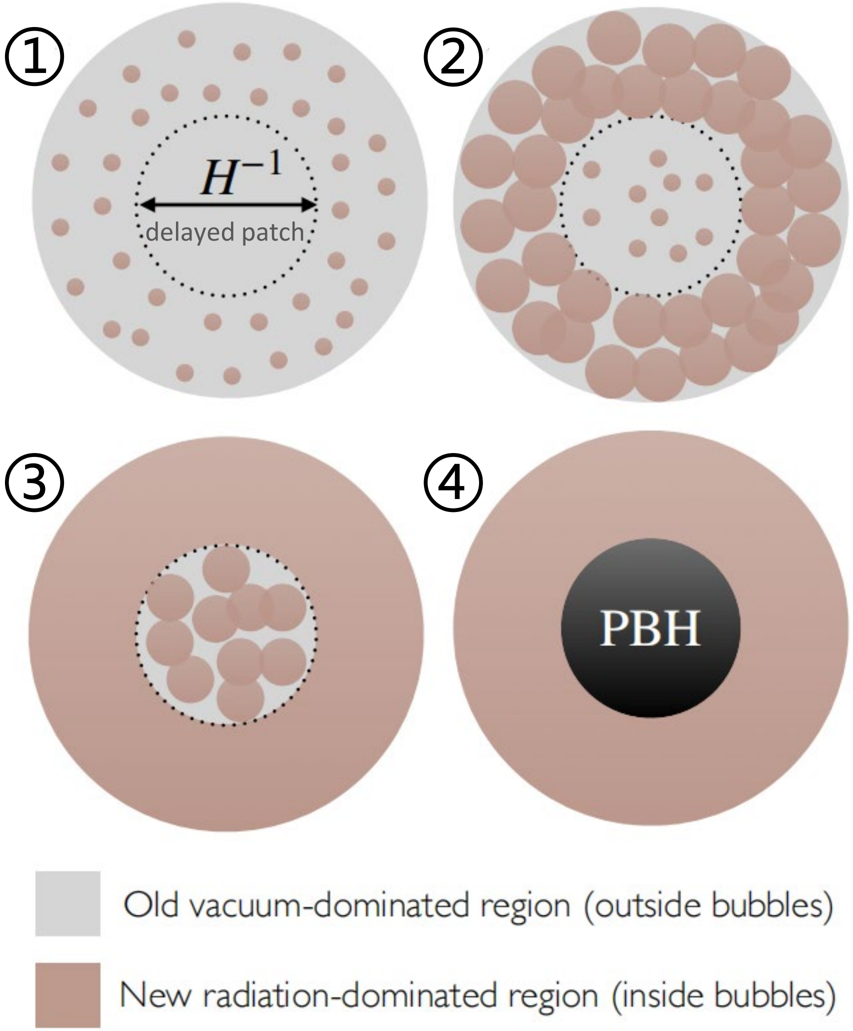
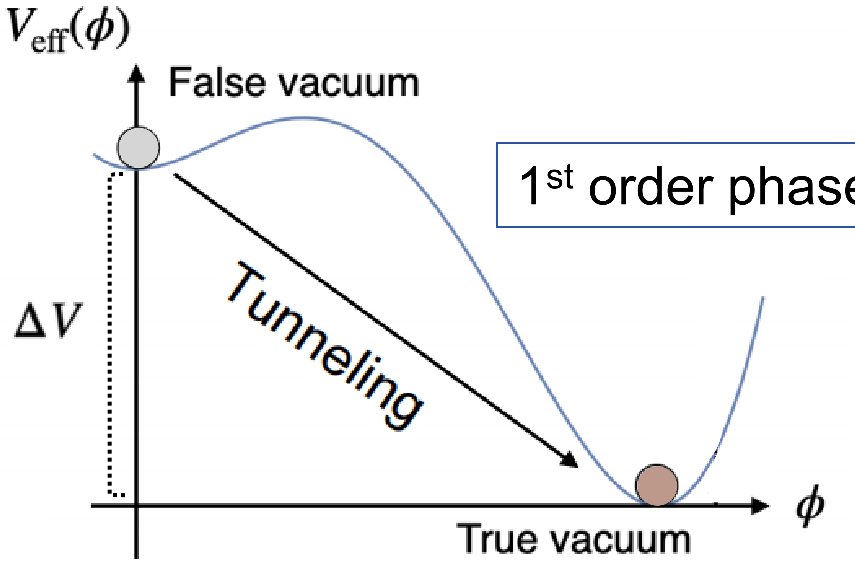
PBHs from FOPT:



[Y. Gouttenoire, T. Volansky, Phys.Rev.D 110 (2024)]

[Liu, Bian, Cai, Guo, Wang, PRD 105, L021303]

[Kodama et al, Prog. Theor. Phys. 68 (1982) 1979]



1st order phase transitions

- Energy densities scale as: $\rho_v(t) \propto a^0, \quad \rho_r(t) \propto a^{-4}$
- Energy contrast: $\delta(t) \equiv \dfrac{|\rho_{\rm in}(t) - \rho_{\rm out}(t)|}{\rho_{\rm in}(t)} > \delta_c = 0.45$

→ Slower supercooled PT:

✓ Leads to larger δ

✓ More delayed patches → enhances PBH production

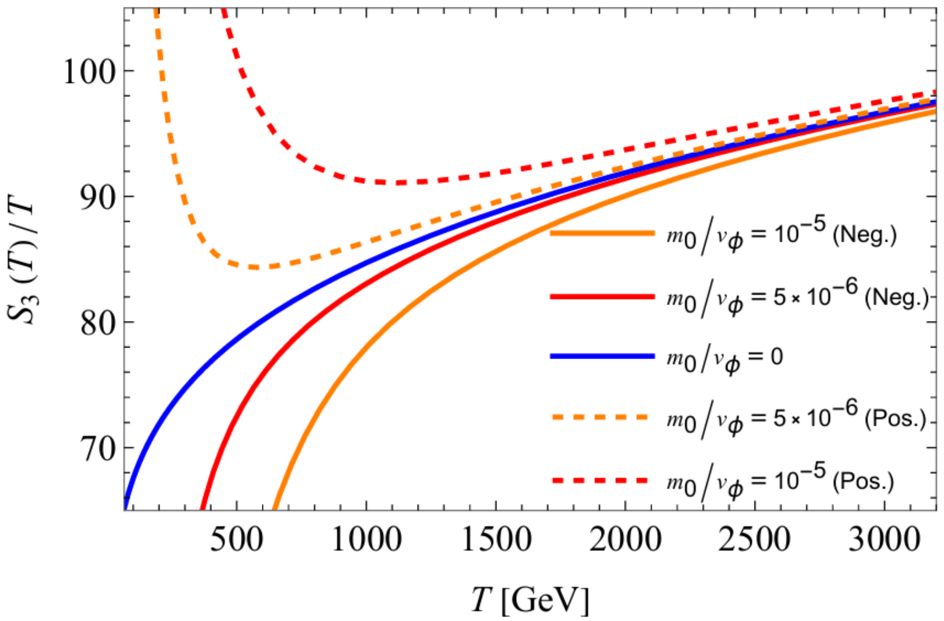
Departure from CW Models

Add a tiny source of soft-scale breaking, $\pm\frac{m_0^2}{2}\phi^2$

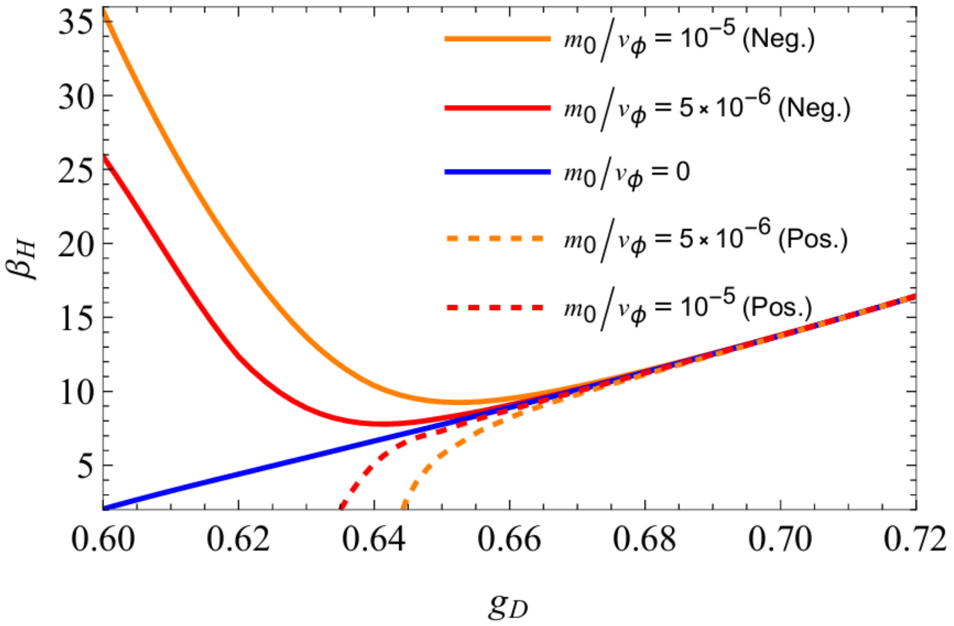
Bounce action: $$\frac{S_3(T)}{T} \simeq -4 + \frac{430.72}{\sqrt{N_b g_D^3}} \frac{1}{\ln\frac{M}{T}} \sqrt{1 \boxed{\pm\left(\frac{T_0}{T}\right)^2}}, \quad T_0 \equiv 2\sqrt{\frac{3}{N_b}}\frac{m_0}{g_D}.$$

Duration parameter: $$\beta_H \simeq -4 + \frac{\sqrt{N_b g_D^3}}{430.72}\left[1 \boxed{\mp\left(\frac{T_0}{T_n}\right)^2 \ln\frac{M}{T_n}}\right]\left(\frac{S_3}{T_n}\right)^2.$$

$g_D = 0.64,\ v_\phi = 10^7$ GeV



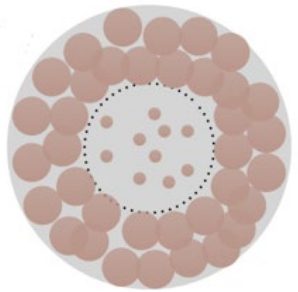
$v_\phi = 10^7$ GeV



PBH Formation

Evolution of radiation energy density: $$\frac{\mathrm{d}\rho_r(t)}{\mathrm{d}t} + 4H(t)\rho_r(t) = -\frac{\mathrm{d}\rho_v(t)}{\mathrm{d}t}$$

Normal patches initiate nucleation at $t_i = t_c$
Delayed patches initiate nucleation at $t_i > t_c$



$$\delta(t) \equiv \frac{|\rho_{\text{in}}(t) - \rho_{\text{out}}(t)|}{\rho_{\text{in}}(t)}$$

The fraction of causal patches collapsing into PBHs:

$$P_{\text{surv}}(t_i) = \exp\left[-\int_{t_c}^{t_i} \mathrm{d}t' \Gamma_{\text{in}}(t') a_{\text{in}}^3(t') V(t')\right], \quad V(t') = \frac{4\pi}{3}\left[\frac{1}{a_{\text{in}}(t_{\max}) H_{\text{in}}(t_{\max})} + r(t_{\max}, t')\right]^3.$$

The fraction of DM in the form of PBHs and the corresponding PBH mass:

$$M_{\text{PBH}} \simeq \frac{4\pi}{3} c_s^3 H_{\text{in}}^{-3}(t_{\max}^{\text{PBH}}) \rho_{\text{in}}(t_{\max}^{\text{PBH}}) \simeq M_{☽} \left(\frac{106.75}{g_\star(T_{\text{eq}})}\right)^{1/2} \left(\frac{500\text{GeV}}{T_{\text{eq}}}\right)^2$$

$$\boxed{M_{☽} \simeq 3.7 \times 10^{-8} M_\odot}$$

$$f_{\text{PBH}} \equiv \frac{\rho_{\text{PBH},0}}{\rho_{\text{DM},0}} \simeq \left(\frac{P_{\text{coll}}}{6.2 \times 10^{-12}}\right)\left(\frac{T_{\text{eq}}}{500\,\text{GeV}}\right)$$

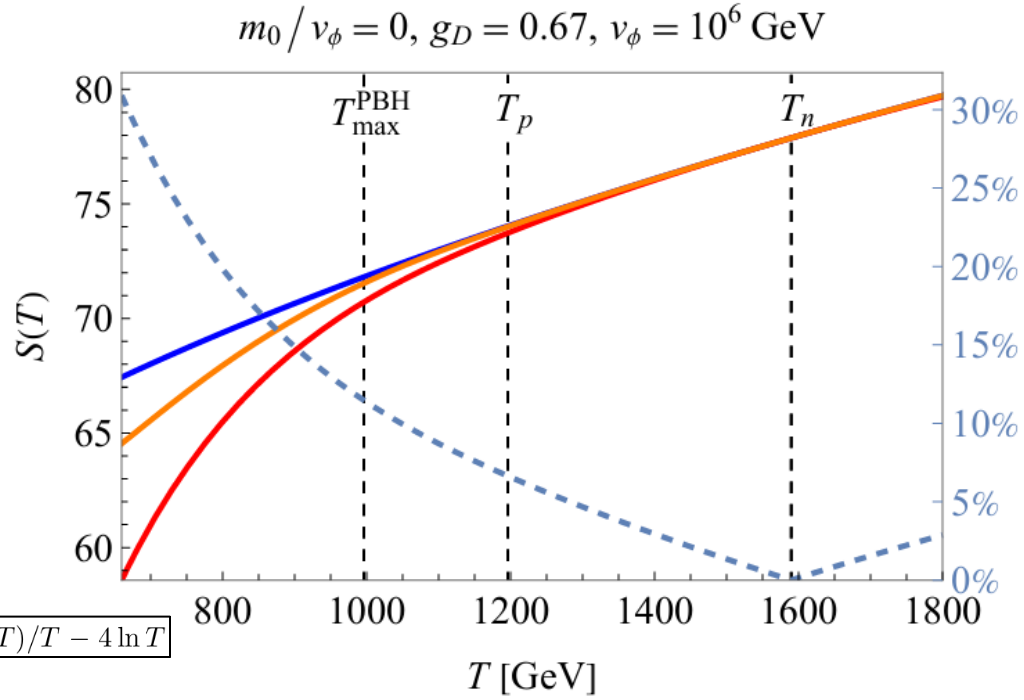
Impact of ESB on PBH Abundance

Case I: No soft-scale breaking

- Tangent-like bounce action curve
- Exponential nucleation

Case II: Negative soft-scale breaking

- Deeper tangent-like bounce action curve
- Exponential nucleation
- Speed up the PT
- Suppress the PBH production



$\boxed{S(T) \equiv S_3(T)/T - 4\ln T}$

TABLE II. The estimated numbers for $f_{\rm PBH}$ in the case with a negative soft-scale breaking mass term m_0: $-m_0^2\phi^2$, for $g_D = 0.64$ and $v_\phi = 10^7$ GeV, listed together with T_n, T_p, β_H. Here we have $M_{\rm PBH} \simeq 2.75 \times 10^{-14} M_\odot$ in all cases.

m_0/v_ϕ	T_n [GeV]	T_p [GeV]	β_H	$f_{\rm PBH}$
0	1690.44	1212.77	6.64	1.15×10^6
2×10^{-6}	1709.28	1227.1	6.85	1.94×10^5
4×10^{-6}	1762.26	1268.1	7.41	3.61×10^2
6×10^{-6}	1842.55	1331.76	8.28	6.11×10^{-4}
8×10^{-6}	1942.39	1412.81	9.27	4.38×10^{-15}
10×10^{-6}	2055.35	1506.42	10.41	2.37×10^{-35}

Impact of ESB on PBH Abundance

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Case III: Positive soft-scale breaking

- Skewed U-shaped action curve
- Quadratic approximation
- Slow down the PT
- Enhance the PBH production

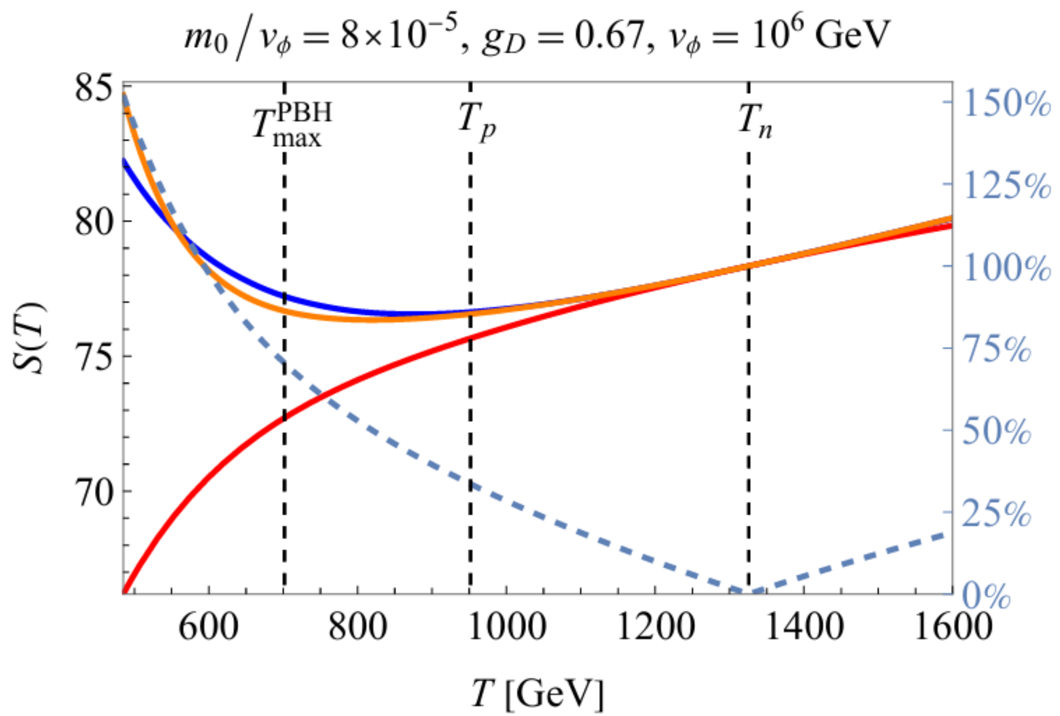

TABLE III. The estimated numbers for $f_{\rm PBH}$ in the case with a positive soft-scale breaking mass term m_0: $+m_0^2\phi^2$, for $g_D = 0.67$ and $v_\phi = 10^7$ GeV, listed together with T_n, T_p, β_H. Here we have $M_{\rm PBH} \simeq 2.51 \times 10^{-14} M_\odot$ in all cases.

m_0/v_ϕ	T_n [GeV]	T_p [GeV]	β_H	$f_{\rm PBH}$
0	7587.35	5529.61	10.06	1.01×10^{-16}
0.5×10^{-5}	7567.94	5512.56	9.99	9.63×10^{-16}
1.0×10^{-5}	7508.90	5460.82	9.79	2.58×10^{-13}
1.5×10^{-5}	7407.63	5372.43	9.43	1.75×10^{-9}
2.0×10^{-5}	7259.19	5243.79	8.90	7.99×10^{-5}
2.5×10^{-5}	7055.00	5068.97	8.14	5.71×10^{0}

Scenario 1 – Positive soft-scale breaking

Many-flavor QCD:

$\bar{F}_{L,R}$: *dark quarks* ϕ: *composite dilaton(dark meson)* S: *pseudoscalar*

Yukawa coupling: $iy_S \overline{F}_L S F_R + \text{h.c.}$

Dilaton-portal: $V = -\kappa S^2 |\phi|^2 + \lambda_S S^4, \quad \kappa, \lambda_S > 0$

$$\boxed{\kappa \sim \mathcal{O}\left(\frac{g_{\phi FF}^2 y_s^2 N_C}{(4\pi)^2}\right), \quad g_{\phi FF} \sim m_F / f_\phi}$$

Time fluctuation $\partial_t \theta(t) \sim \mu_5$ in a local CP-odd domain of the hot dark-QCD plasma:

$$|D_\mu S|^2 = |(\partial_\mu - i\mu_5 \delta_\mu^0) S|^2 \Longrightarrow V_{\mu_5}(S) = -\frac{\mu_5^2}{2}|S|^2 \Longrightarrow \langle S \rangle = \sqrt{\frac{\mu_5^2}{\lambda_S}}$$

$$V \supset +\kappa \langle S \rangle^2 |\phi|^2 \Longrightarrow m_0^2 |\phi|^2, \quad \text{with} \quad m_0^2 = \frac{\kappa \mu_5^2}{\lambda_S}.$$

Benchmark Scenarios

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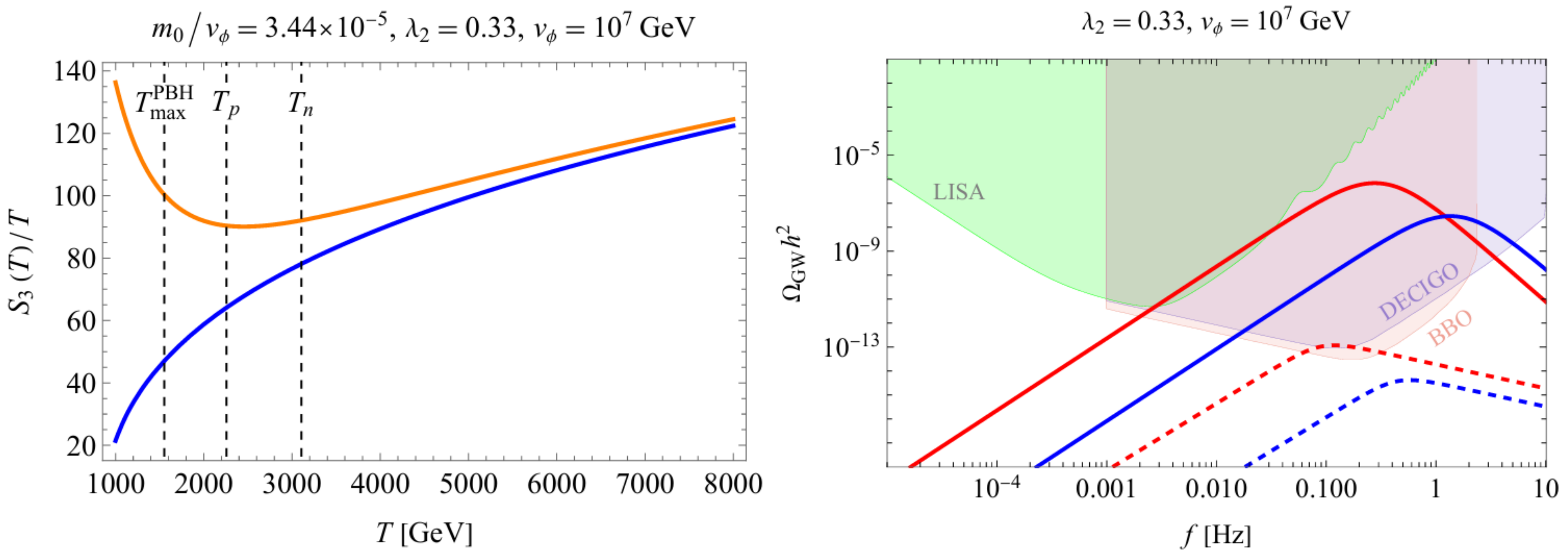
Scenario 1 – Positive soft-scale breaking

TABLE IV. Predicted parameters related to the supercooling phase transition and PBH production for two benchmark points (BPs) for the many-flavor QCD scenario with $N_f = 8$.

	m_0/v_ϕ	T_n[GeV]	T_p[GeV]	α	β_H	$M_{\rm PBH}$	$f_{\rm PBH}$
BP A	0	4272.8	3598	6.38×10^7	40.55	$2.975 \times 10^{-14} M_\odot$	~ 0
BP A′	3.44×10^{-5}	3105.1	2257.4	4.12×10^8	11.75	$2.975 \times 10^{-14} M_\odot$	~ 1



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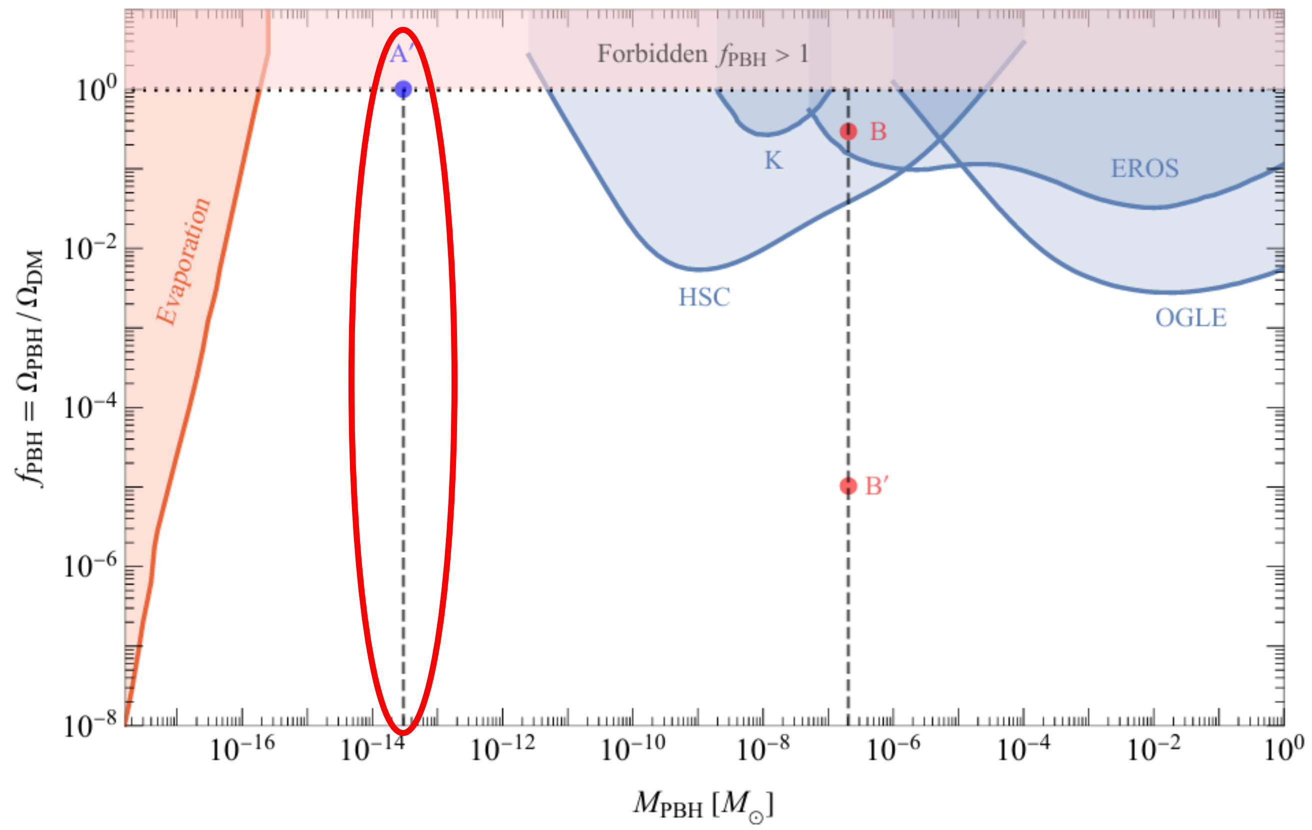

Scenario 2 – Negative soft-scale breaking

Classically conformal $B-L$ extension of the SM:

New particles:

$B-L$ gauge boson Z'

Complex scalar field ϕ, $Q_{B-L}=-2$

Right-handed neutrinos N_{Ri}, $Q_{B-L}=-1$

Tree-level effective potential:

$$V(H,\Phi)=\lambda_h|H|^4+\lambda_\phi|\Phi|^4-\lambda_{h\phi}|H|^2|\Phi|^2$$

In the unitary gauge,

$$H=\frac{1}{\sqrt{2}}\begin{pmatrix}0\\h\end{pmatrix},\quad \Phi=\frac{\phi}{\sqrt{2}}$$

→ Exist a flat direction at a certain RG scale.

1-loop effective potential (dominated by Z'):

$$V_{\rm eff}^{B-L}(\phi,T)\simeq\frac{96g_{B-L}^4}{64\pi^2}\phi^4\left[\ln\left(\frac{\phi}{v_\phi}\right)-\frac{1}{4}\right]+\frac{3T^4}{2\pi^2}J_B\left(\frac{m_{Z'}^2}{T^2}\right)+\frac{3T}{12\pi}\left[m_{Z'}^3-(m_{Z'}^2+\Pi_{Z'})^{3/2}\right],\quad m_{Z'}=2g_{B-L}\phi$$

A negative mass-squared explicit breaking term emerges due to the conformal nature:

$$T_p\lesssim T_{\rm QCD}\;\Rightarrow\;\langle h\rangle=v_{\rm QCD}\sim\left(y_t\langle tt\rangle/(\sqrt{2}\lambda_h)\right)^{1/3}\sim\Lambda_{\rm QCD}\;\Rightarrow\;-\frac{1}{4}\lambda_{h\phi}v_{\rm QCD}^2\phi^2$$

Benchmark Scenarios

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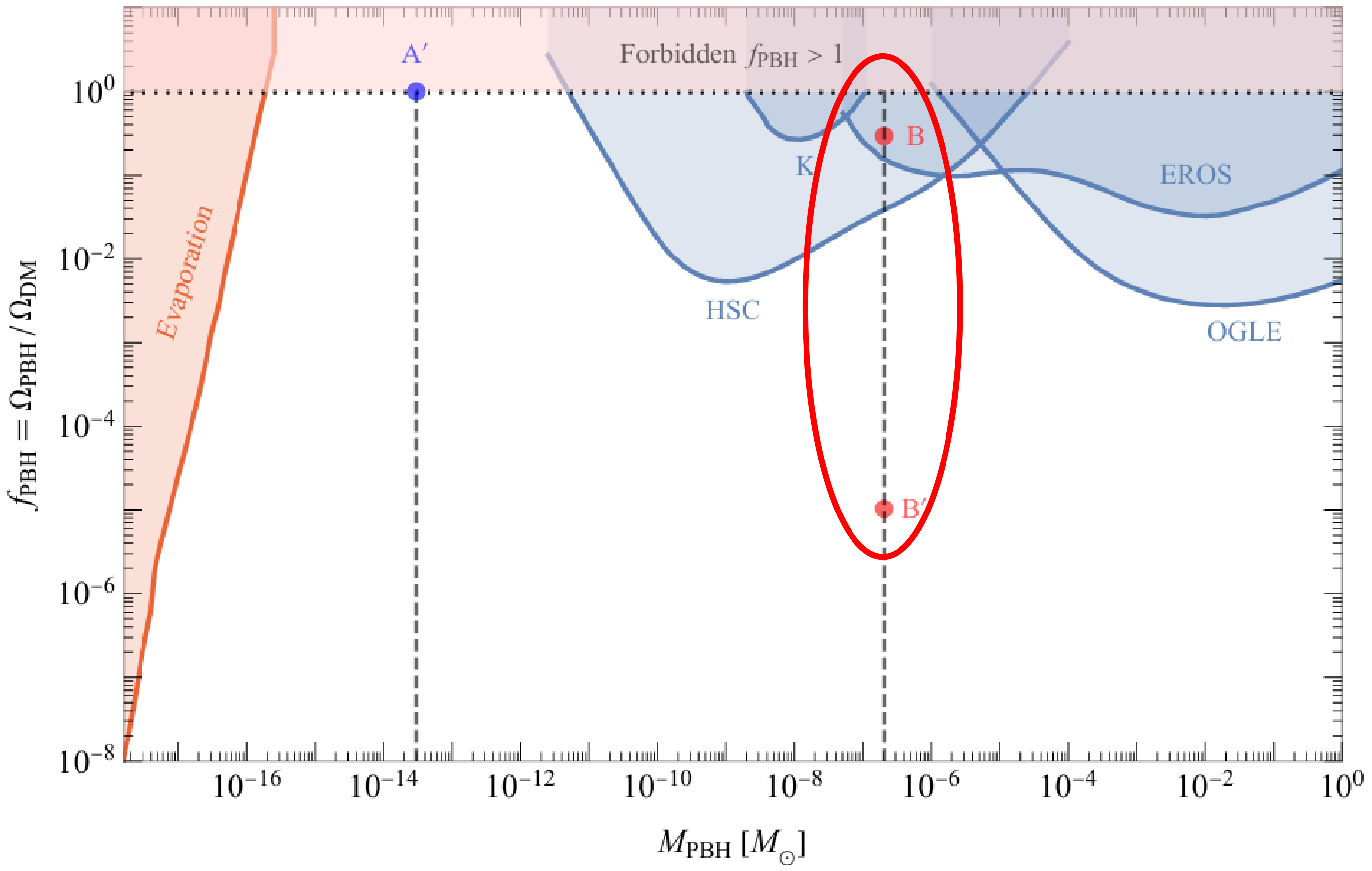
Scenario 2 – Negative soft-scale breaking

TABLE V. Predicted quantities, the same ones as those listed in Table IV, for the $U(1)_{B-L}$ gauge extension of the SM with the CSI.

	m_0/v_ϕ	T_n[MeV]	T_p[MeV]	α	β_H	$M_{\rm PBH}$	$f_{\rm PBH}$
BP B	0	145.12	104.37	1.8×10^6	7.53	$2.041\times10^{-7}M_\odot$	0.29
BP B′	5.4×10^{-7}	145.12	104.37	1.8×10^6	7.53	$2.041\times10^{-7}M_\odot$	1.03×10^{-5}



Mechanism 2: Tachyonic Instability

PBHs from Thermal Inflation:

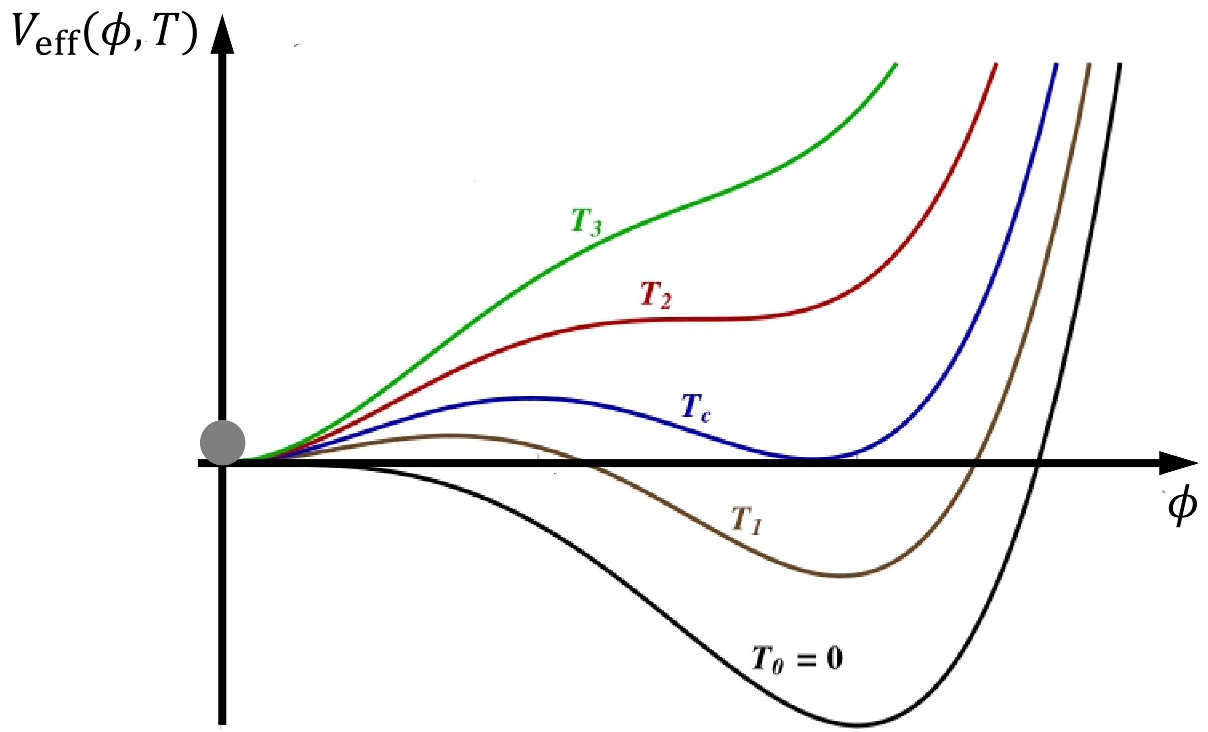


FIG. Schematic temperature evolution of the finite-T effective potential.

$$\hat{\phi}(\eta,\mathbf{x}) = \int \frac{\mathrm{d}^3 k}{\sqrt{(2\pi)^3 a^2}} \left[a_{\mathbf{k}} u_k(\eta) + a^{\dagger}_{-\mathbf{k}} u_k^*(\eta)\right] e^{i\mathbf{k}\cdot\mathbf{x}}$$

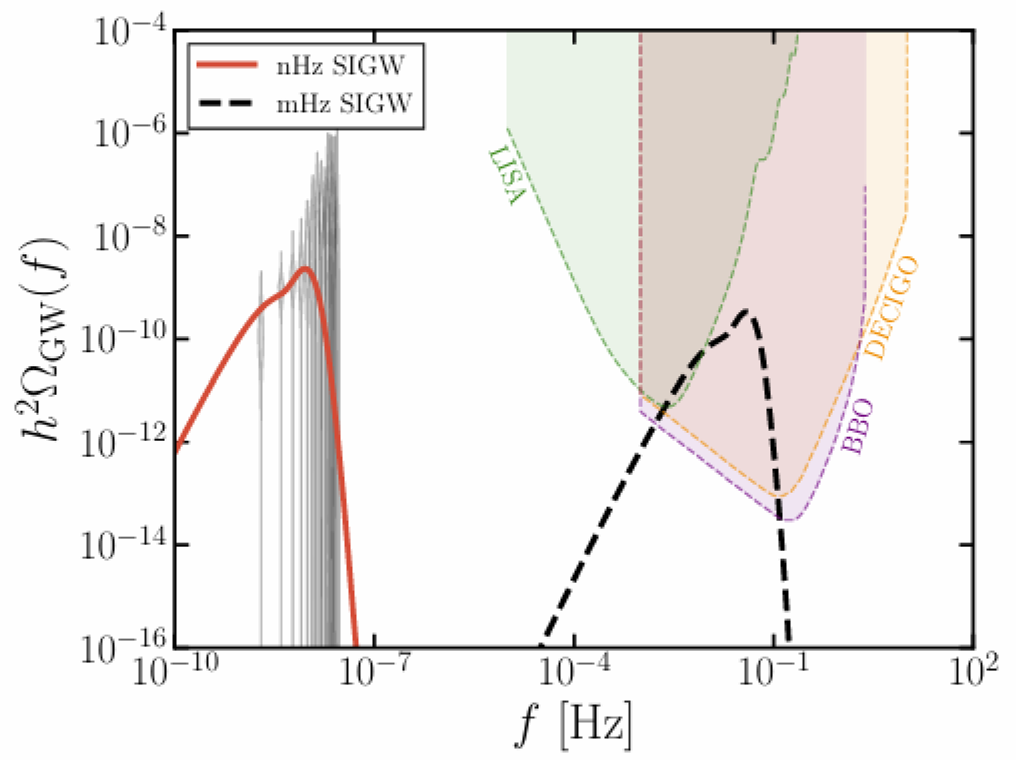
$$\ddot{u}_k(\eta) + \left[\omega_k^2 - \frac{\nu^2 - 1/4}{\eta^2}\right] u_k(\eta) = 0$$

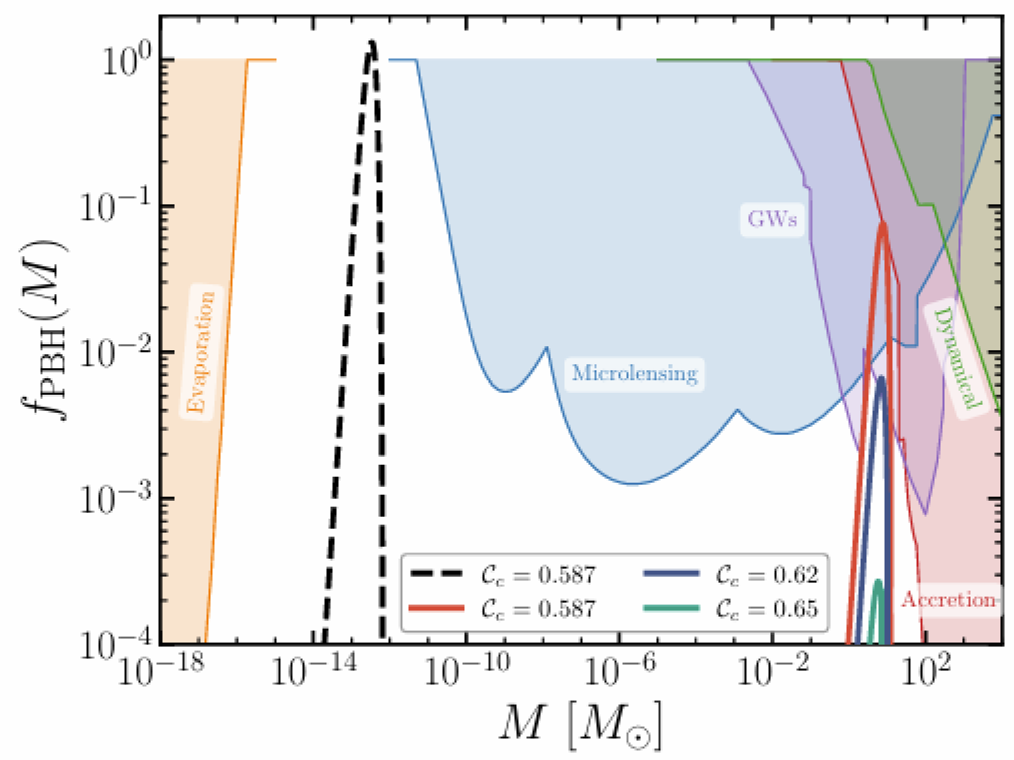
$$\zeta = -H\frac{\delta\rho}{\dot{\rho}} \simeq -\frac{\langle V''\rangle}{\eta\,\partial_\eta\left[\langle V''\rangle\,\langle\phi^2\rangle\right]}\,\delta\hat{\phi}^2$$

$$\mathcal{P}_\zeta(k) = \left[\frac{\langle V''\rangle}{\eta\,\partial_\eta\left[\langle V''\rangle\,\langle\phi^2\rangle\right]}\right]^2 \mathcal{P}_{\delta\phi^2}(k)$$

Mechanism 2: Tachyonic Instability

PBHs from Thermal Inflation: $f_{\mathrm{PBH}} \propto \exp[-\mathcal{O}(1)/\mathcal{P}_\zeta]$, $P_\zeta \sim \mathcal{O}(10^{-2})$

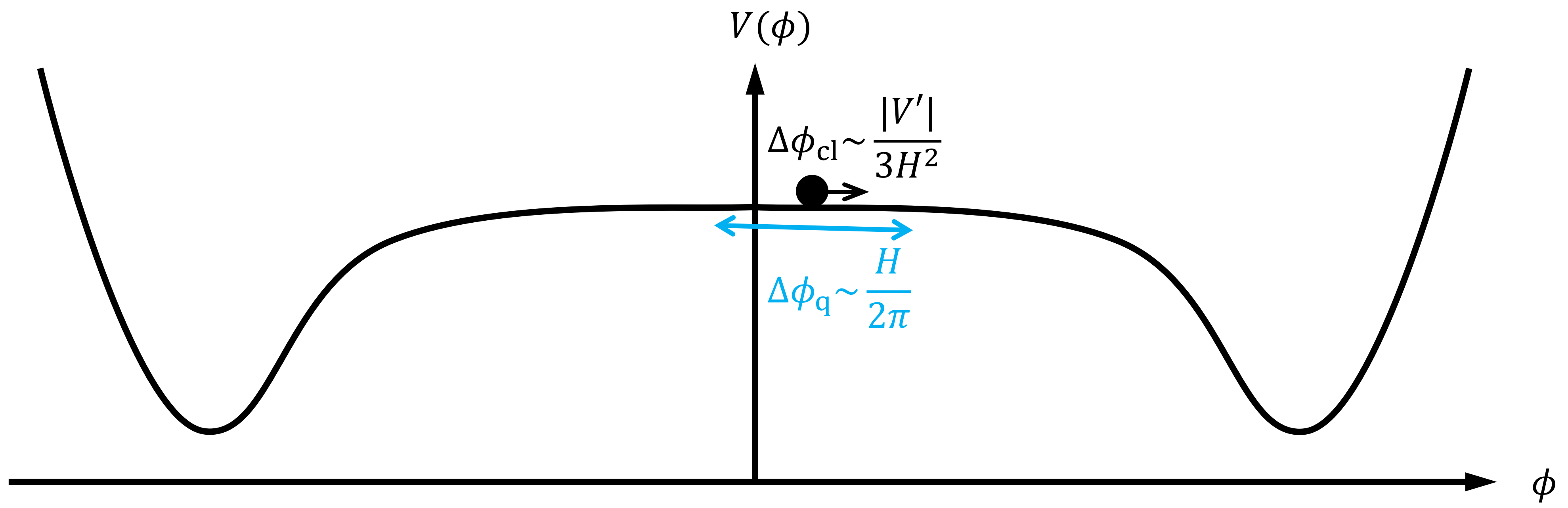




$$h^2\Omega_{\mathrm{GW}}(k) = 4.2\times10^{-5}\times\frac{1}{2}\int_{-1}^{1}\mathrm{d}x\int_{1}^{\infty}\mathrm{d}y\,\mathcal{T}(x,y)\mathcal{P}_\zeta\left(\frac{y-x}{2}k\right)\mathcal{P}_\zeta\left(\frac{x+y}{2}k\right)$$

However, the CW-type potential leads to eternal inflation.

Graceful-exit problem



Quantum diffusion dominates over classical drift $(\Delta\phi_{\rm q} > \Delta\phi_{\rm cl})$

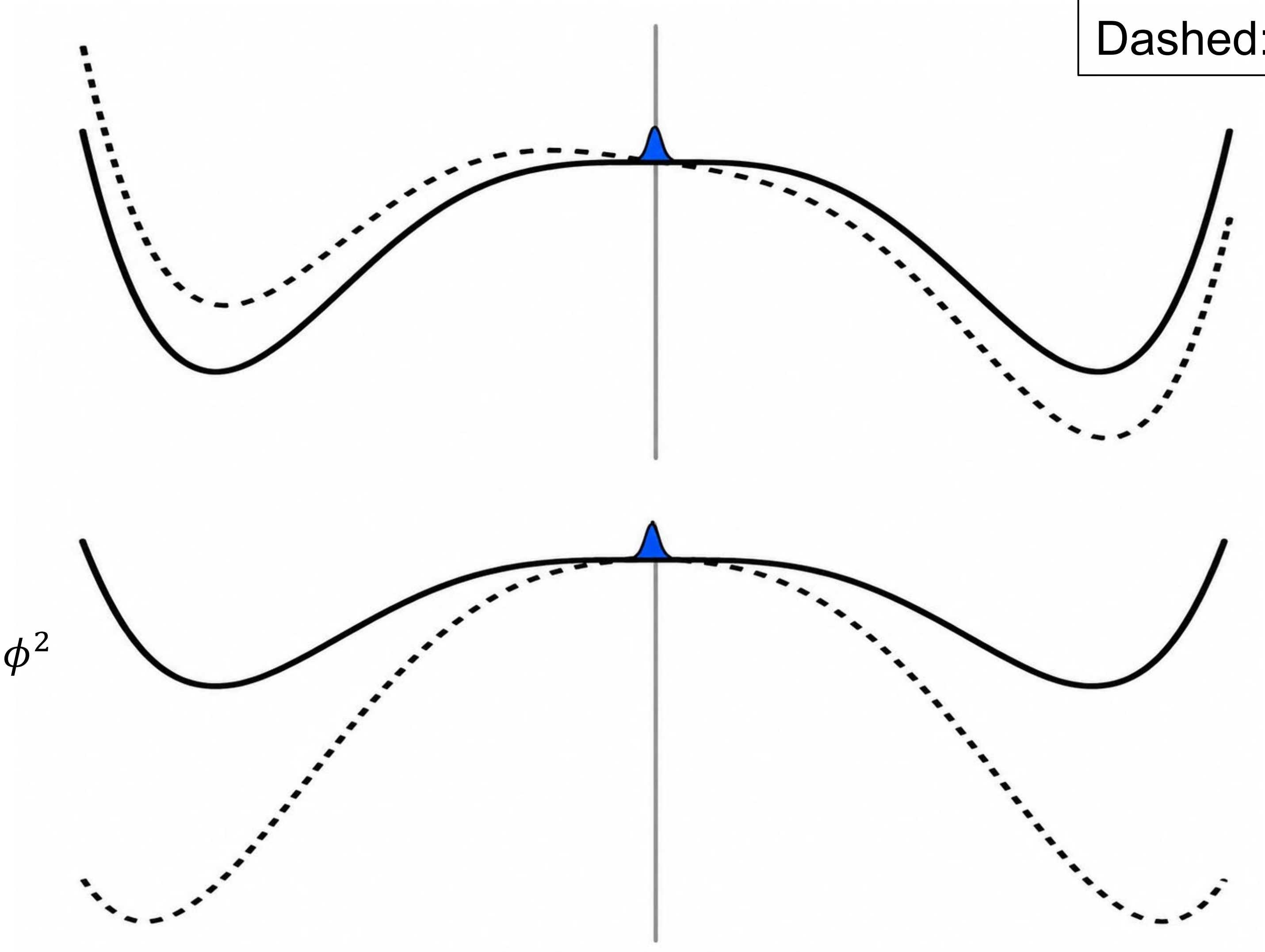
Eternal Inflation

Graceful Exit: Two Possible Ways

Solid: original potential
Dashed: deformed potential

① $V(\phi) - \alpha\,\phi$

② $V(\phi) - \frac{1}{2}m^2\,\phi^2$



No-Eternal-Inflation Condition:

Fokker-Planck equation:

$$\frac{\partial P(\phi,t)}{\partial t} = \frac{\partial}{\partial \phi}\left[\frac{V'(\phi)}{3H} P(\phi,t)\right] + \frac{1}{2}\left(\frac{H^3}{4\pi^2}\right)\frac{\partial^2 P(\phi,t)}{\partial \phi^2}$$

Probability of remaining inflating:

$$\mathrm{Pr}_{\mathrm{inf}}(t) = \int_{-\infty}^{\phi_e} \mathrm{d}\phi\, P(\phi,t) = \frac{1}{2}\mathrm{erfc}\left[\frac{\mu(t)-\phi_e}{\sqrt{2}\sigma(t)}\right]$$

For a locally linear potential, $V(\phi) = V_0 - \alpha\phi$

$$\mathcal{V}_{\mathrm{inf}}(t) \propto e^{3Ht}\,\mathrm{Pr}_{\mathrm{inf}}(t) \propto \exp\left[\left(3H - \frac{2\pi^2\alpha^2}{9H^5}\right)t\right] \Rightarrow \boxed{\alpha^2 > \frac{27H^6}{2\pi^2}}$$

For a tachyonic potential, $V(\phi) = V_0 - \frac{1}{2}m^2\phi^2$

$$\Rightarrow \boxed{m^2 > 9H^2}$$

Exit scenario I:

QCD-Induced Tachyonic Exit:

$$V(h) \supset -\frac{y_t}{\sqrt{2}}\langle \bar{t}\, t\rangle h$$

$$\Rightarrow \quad v_{\rm QCD} \equiv \langle h\rangle \sim \left(y_t \langle \bar{t}\, t\rangle / (\sqrt{2}\,\lambda_h)\right)^{1/3} \sim \Lambda_{\rm QCD}$$

$$V_{\rm eff}(\phi, T) \supset -\frac{1}{2} m_{\rm QCD}^2 \phi^2, \qquad \text{with} \quad m_{\rm QCD} \equiv \frac{m_h}{\sqrt{2}}\left(\frac{v_{\rm QCD}}{v_\phi}\right)\Theta(T_{\rm QCD} - T)$$

No-eternal-inflation condition: $g_D^2 v_\phi^3 \lesssim \dfrac{2\pi M_{\rm pl}}{3} m_h v_{\rm QCD}$

Exit scenario II:

Tadpole-Induced Exit:

$$-\mathcal{L}_{\Phi X}=\frac{1}{2}y_{\mathcal{N}}\Phi\;\epsilon_{ab}\epsilon^{\alpha\beta}\epsilon^{AB}\mathcal{N}^a_{A\alpha}\mathcal{N}^b_{B\beta}+\frac{1}{2}y_\chi\Phi^\dagger\;\epsilon_{ab}\epsilon^{\alpha\beta}\epsilon^{AB}\chi^a_{A\alpha}\chi^b_{B\beta}+\text{h.c.}$$

Particles	$SU(3)_c$	$SU(2)_L$	$U(1)_Y$	$U(1)_{B-L}$	$SU(2)_X$
q_L^i	**3**	**2**	$+1/6$	$+1/3$	**1**
u_R^i	**3**	**1**	$+2/3$	$+1/3$	**1**
d_R^i	**3**	**1**	$-1/3$	$+1/3$	**1**
ℓ_L^i	**1**	**2**	$-1/2$	-1	**1**
e_R^i	**1**	**1**	-1	-1	**1**
ν_R^i	**1**	**1**	0	-1	**1**
H	**1**	**2**	$+1/2$	0	**1**
Φ	**1**	**1**	0	$+2$	**1**
$\mathcal{N}_A^a$	**1**	**1**	0	-1	**2**
χ_A^a	**1**	**1**	0	$+1$	**2**

$$V_{\text{tad}}(\phi)=-2\sqrt{2}\,c_X f_X^3(y_{\mathcal{N}}+y_\chi)\,\phi$$

$$G=SU(3)_c\times SU(2)_L\times U(1)_Y\times U(1)_{B-L}\times \boxed{SU(2)_X}$$

Summary

- **Classically conformal dynamics** generates a physical scale through radiative symmetry breaking and naturally allows strongly supercooled PTs.
- **Mechanism I — Delayed vacuum PTs:** delayed patches develop a large density contrast and collapse into PBHs. Tiny soft-scale breaking can strongly modify the transition duration and hence the PBH abundance.
- **Mechanism II — Tachyonic amplification:** the end of thermal inflation amplifies curvature perturbations, producing PBHs together with SIGWs.
- **Graceful exit is essential:** the minimal Coleman–Weinberg potential may lead to eternal inflation, while linear or tachyonic deformations can provide viable exit routes.

Thank you for your attention!