

Primordial black hole formation during supercooled phase transitions

Yann Gouttenoire (feat. Tomer Volansky)

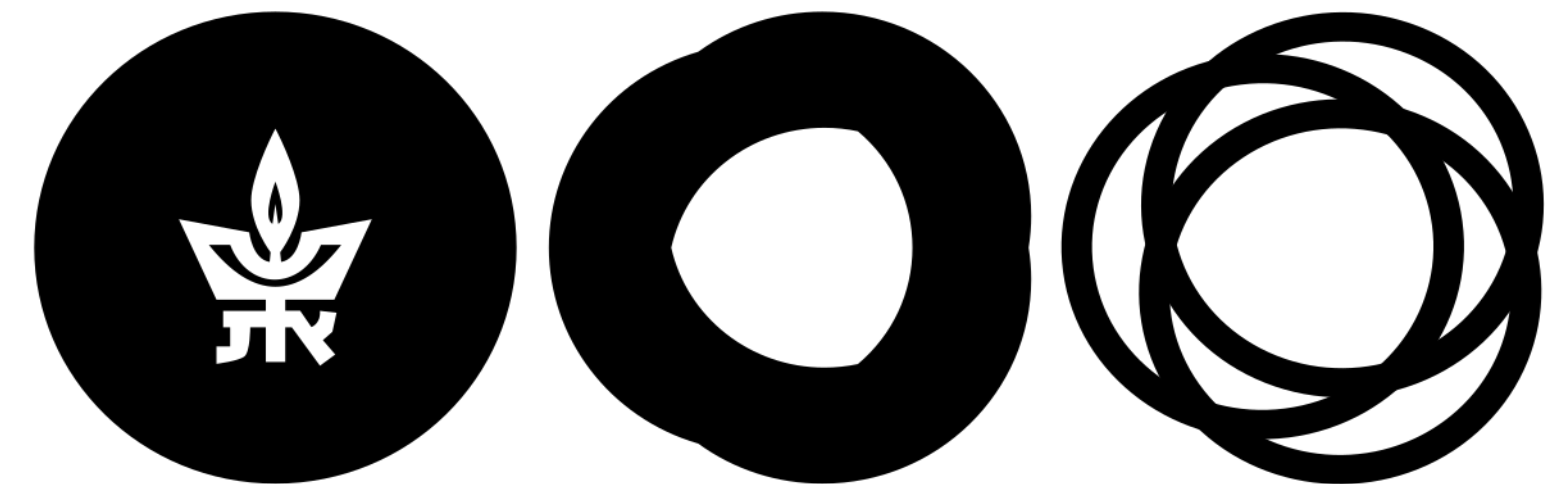


Instituto de
Física
Teórica
UAM-CSIC

IFT Madrid

10th October 2022

Postdoc in Tel Aviv U.

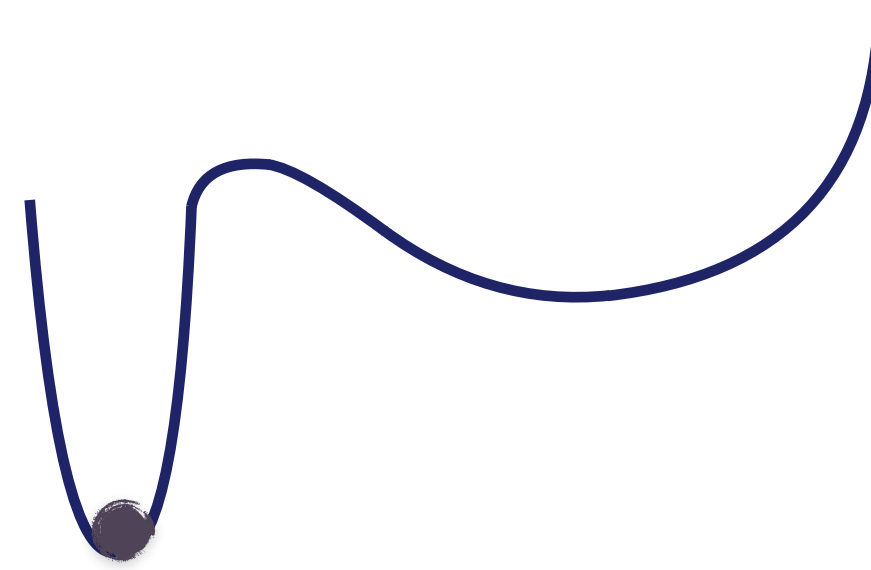
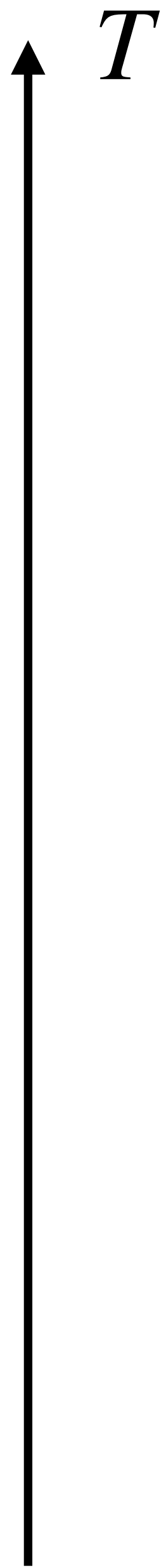


TEL AVIV UNIVERSITY

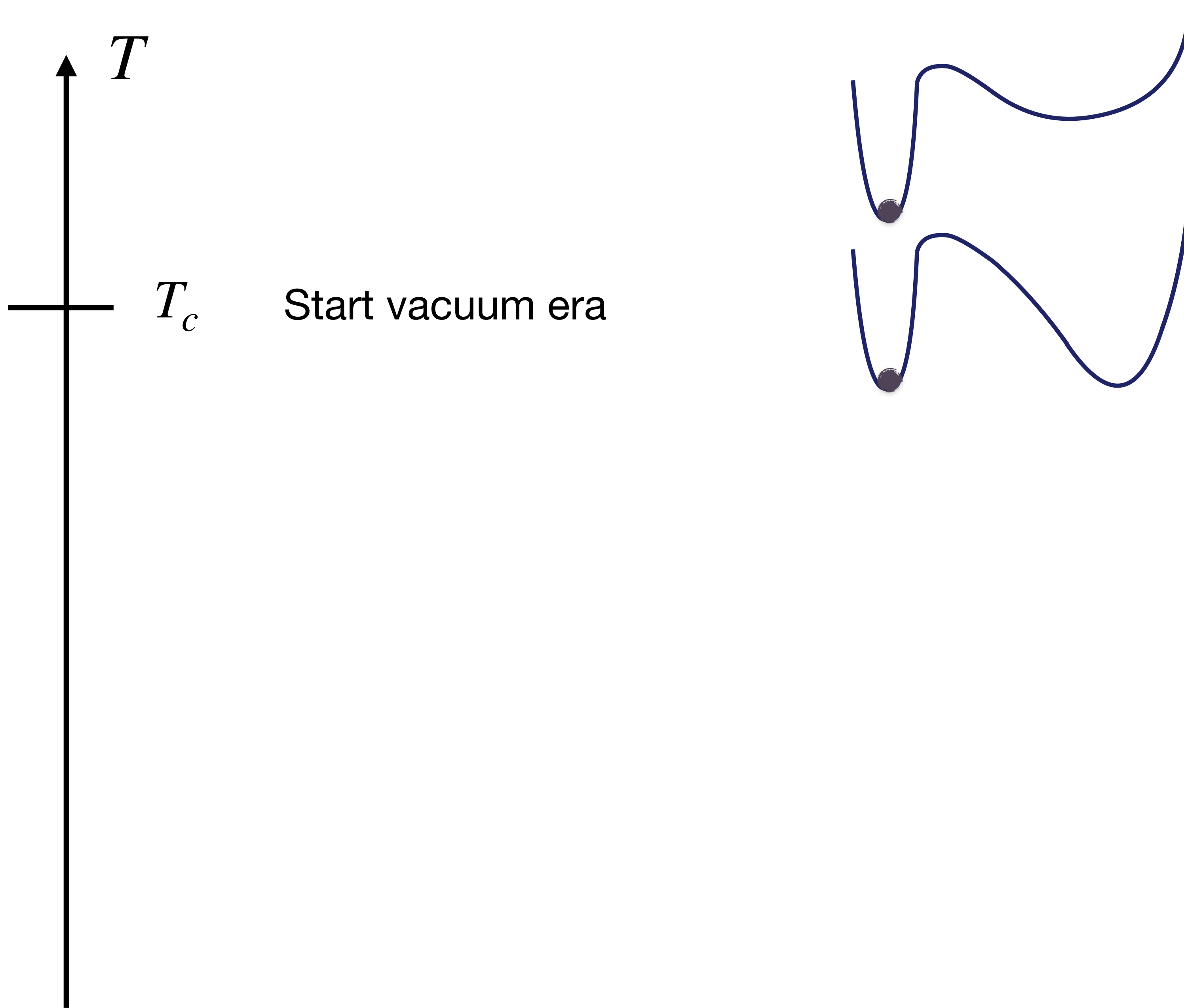
Supercooled 1stOPT

Supercooled 1stOPT = Hierarchical PT

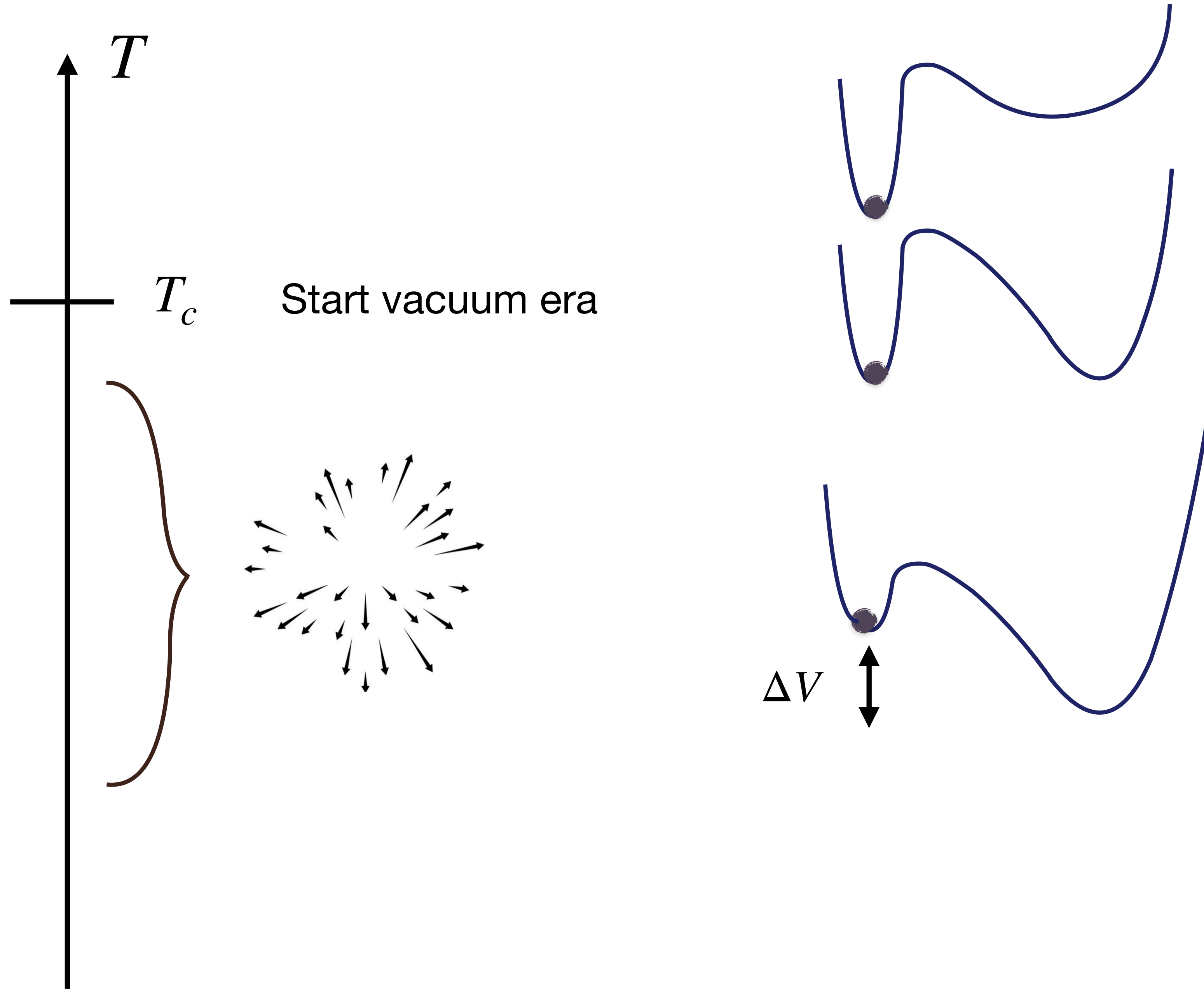
Supercooled 1stOPT = Hierarchical PT



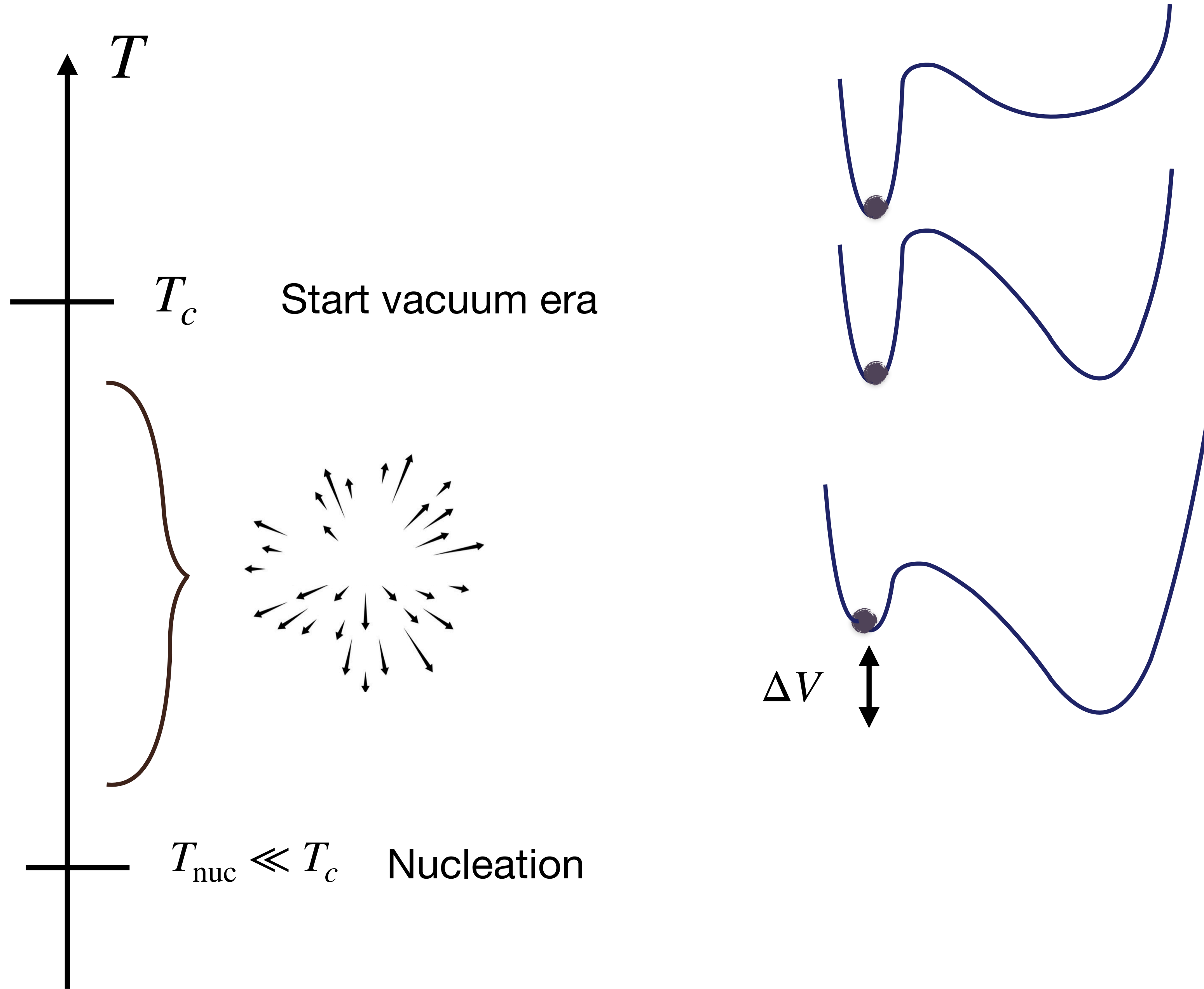
Supercooled 1stOPT = Hierarchical PT



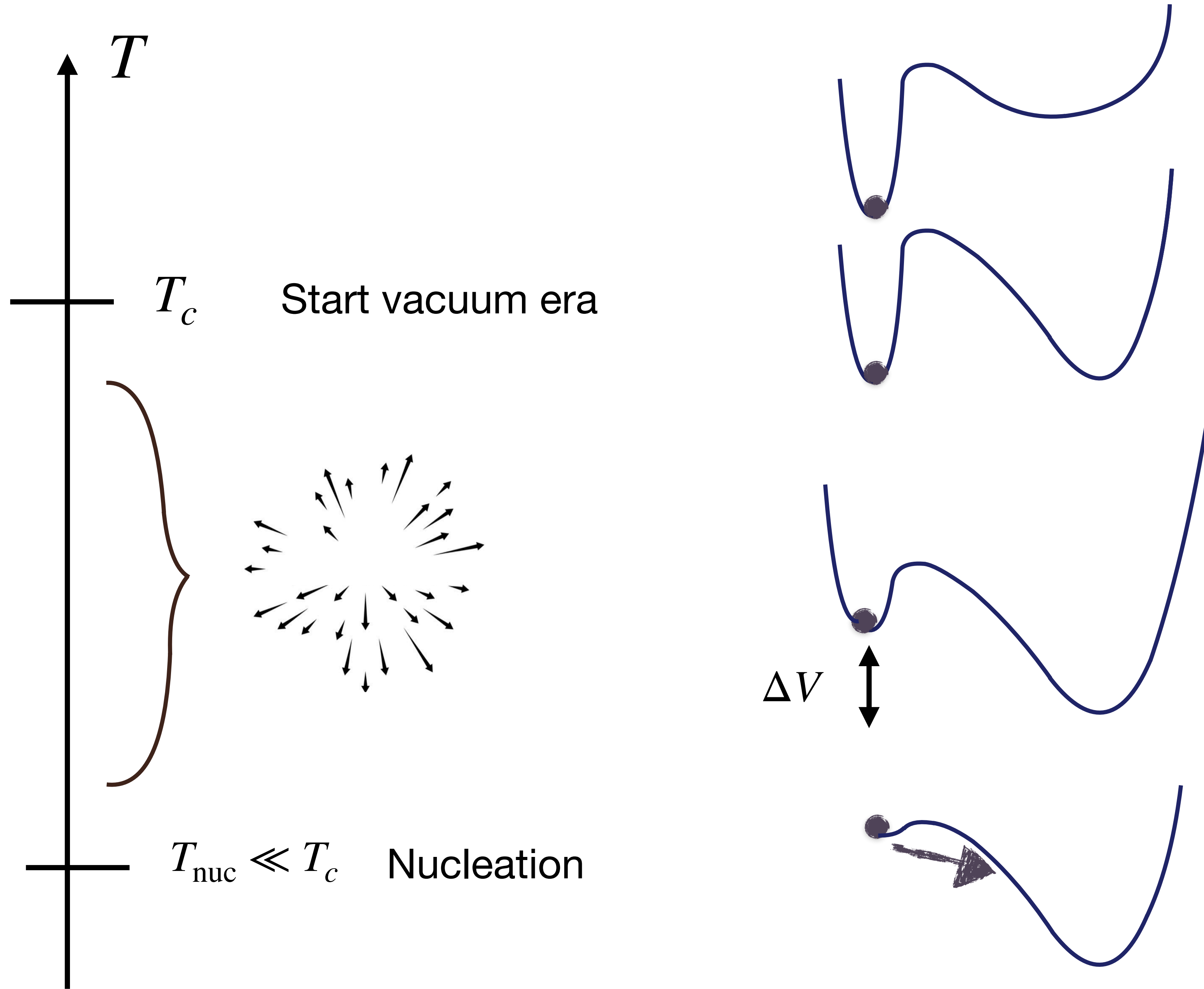
Supercooled 1stOPT = Hierarchical PT



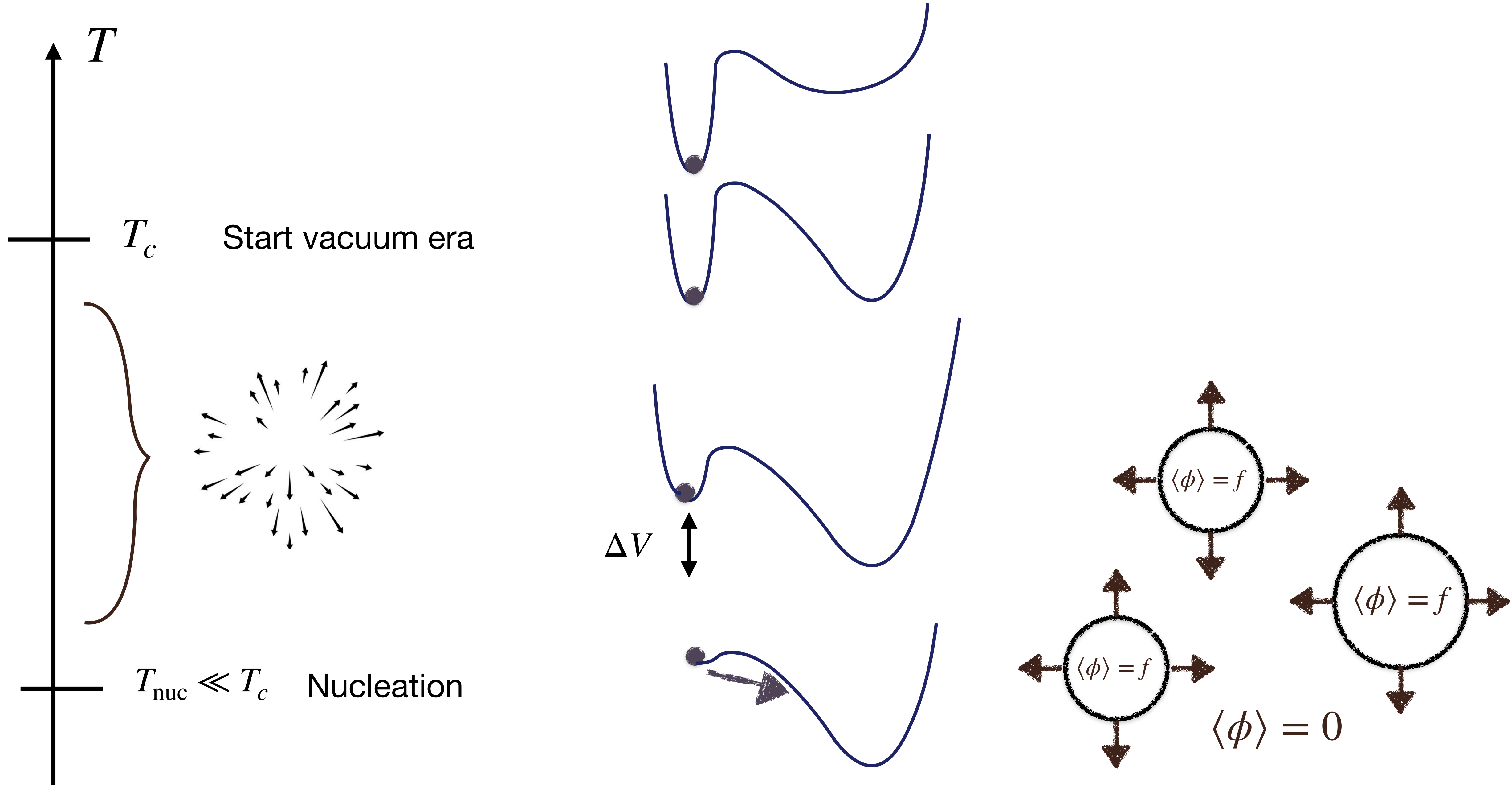
Supercooled 1stOPT = Hierarchical PT



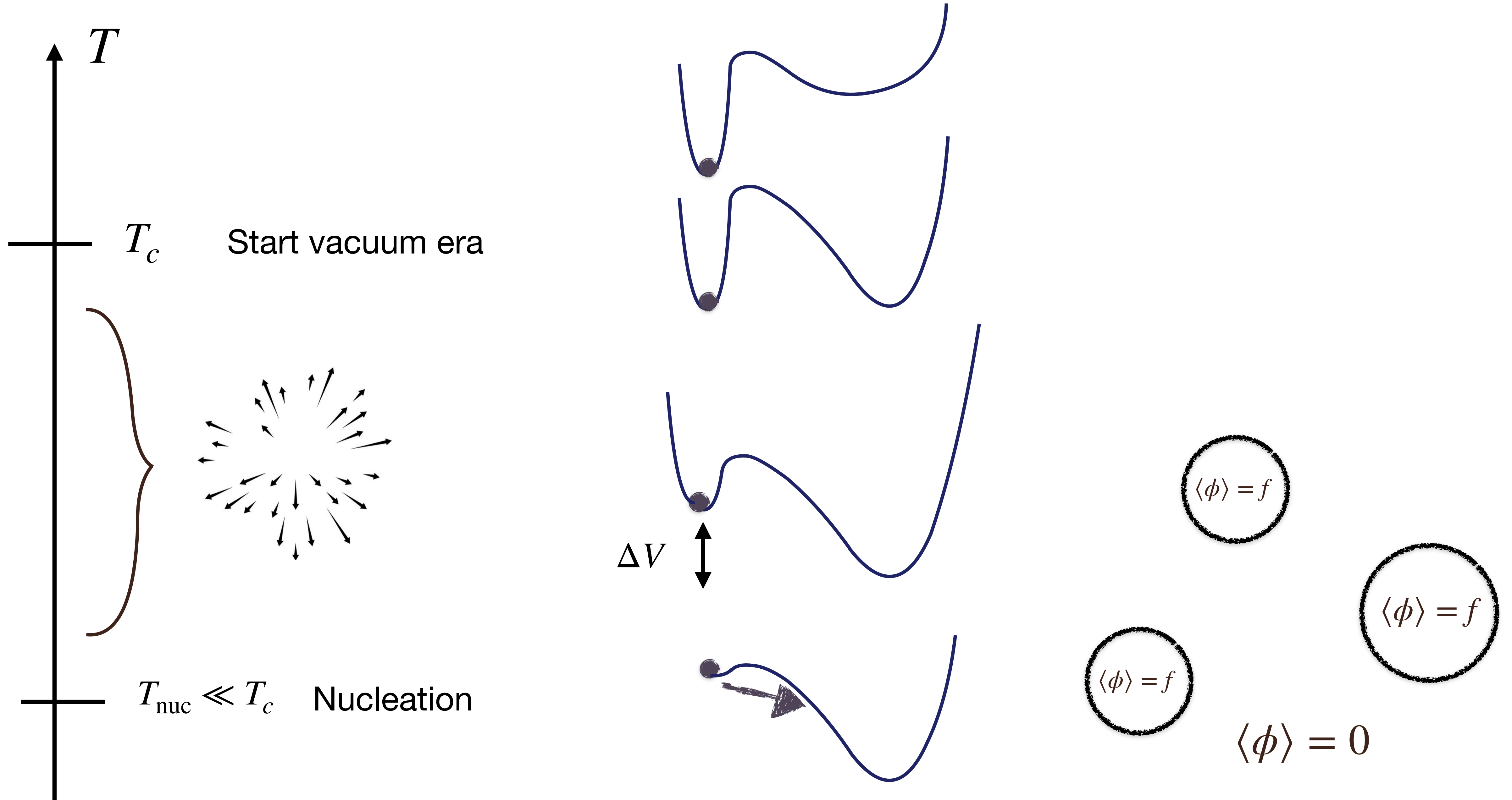
Supercooled 1stOPT = Hierarchical PT



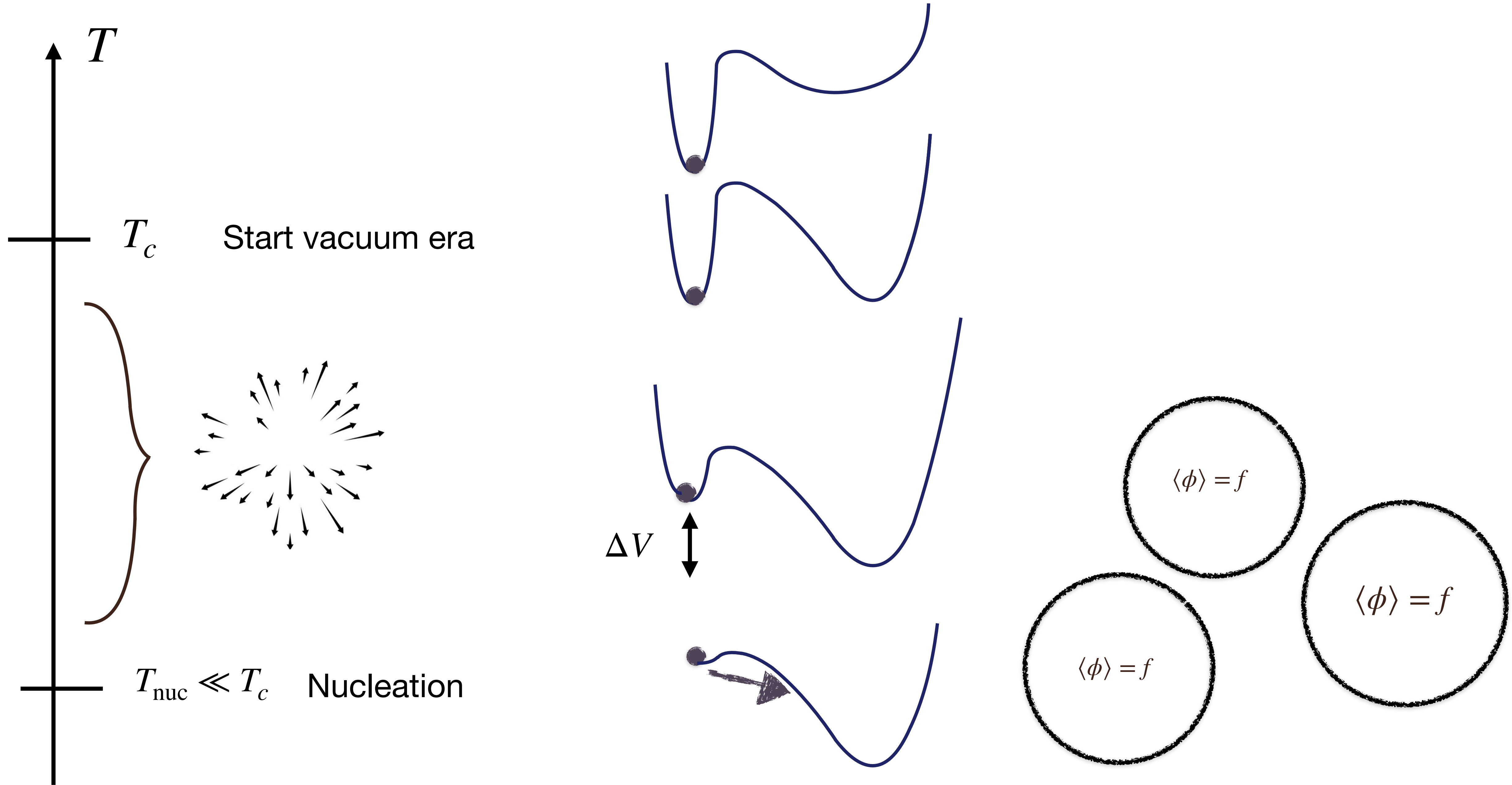
Supercooled 1stOPT = Hierarchical PT



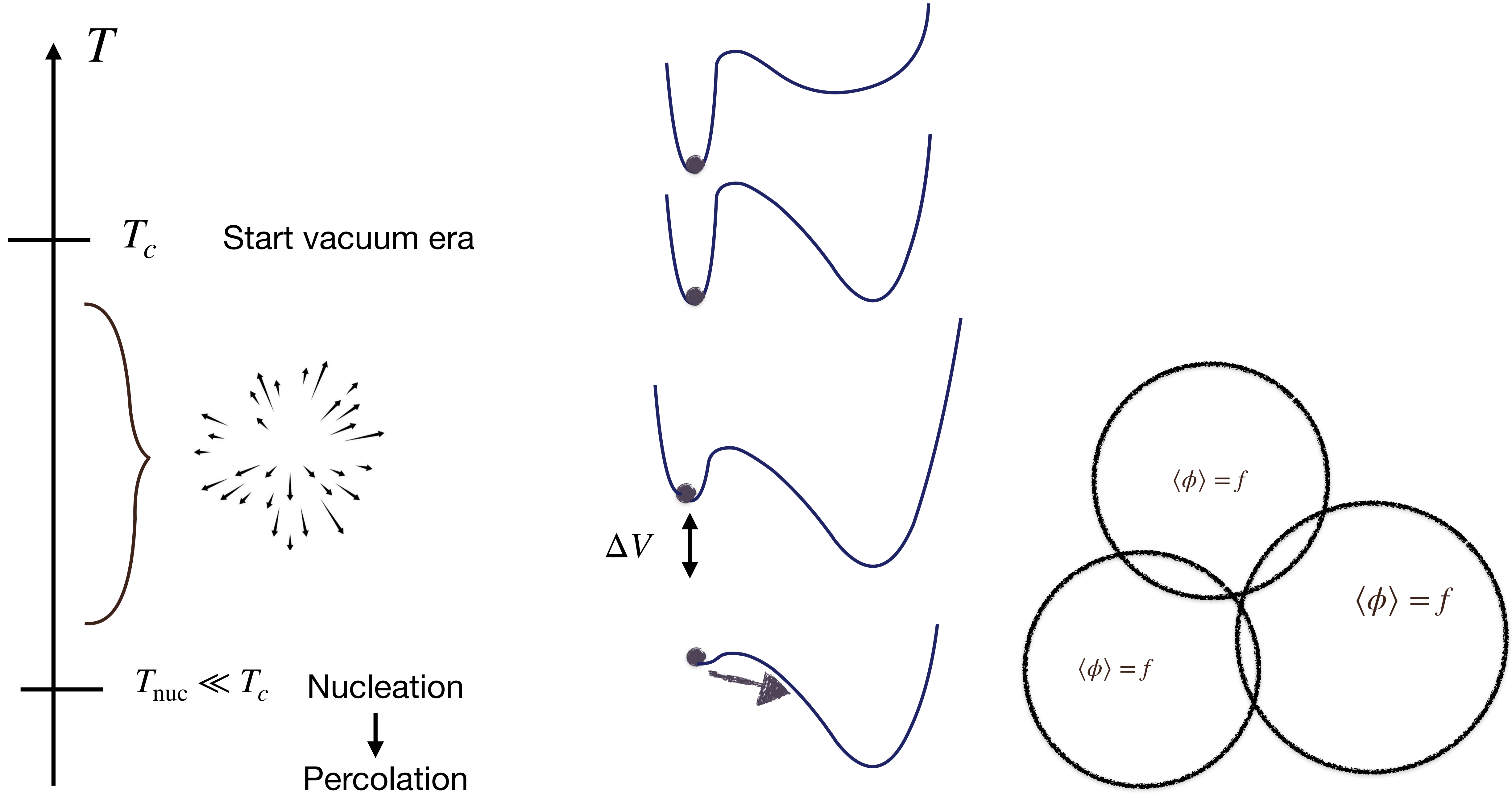
Supercooled 1stOPT = Hierarchical PT



Supercooled 1stOPT = Hierarchical PT



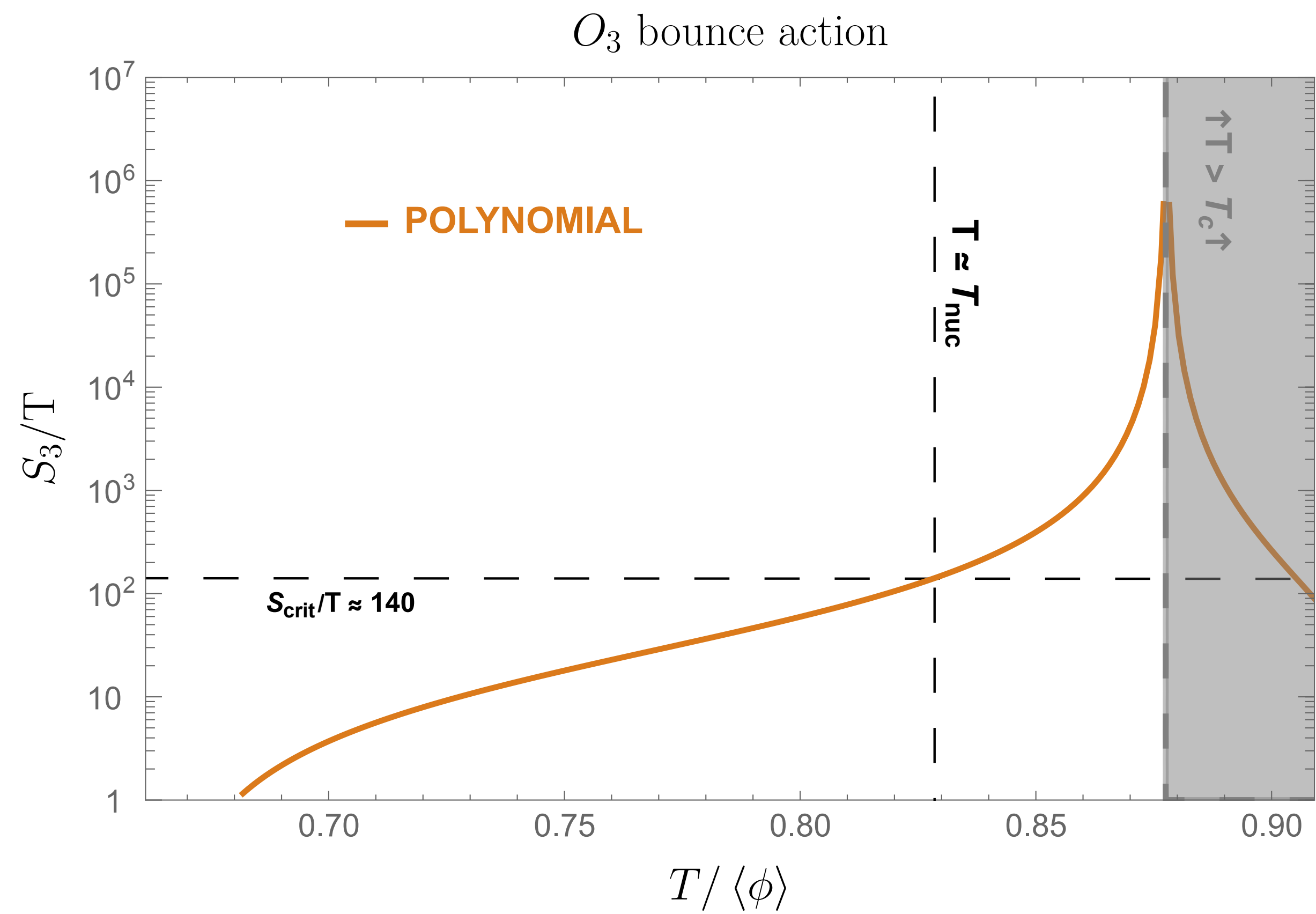
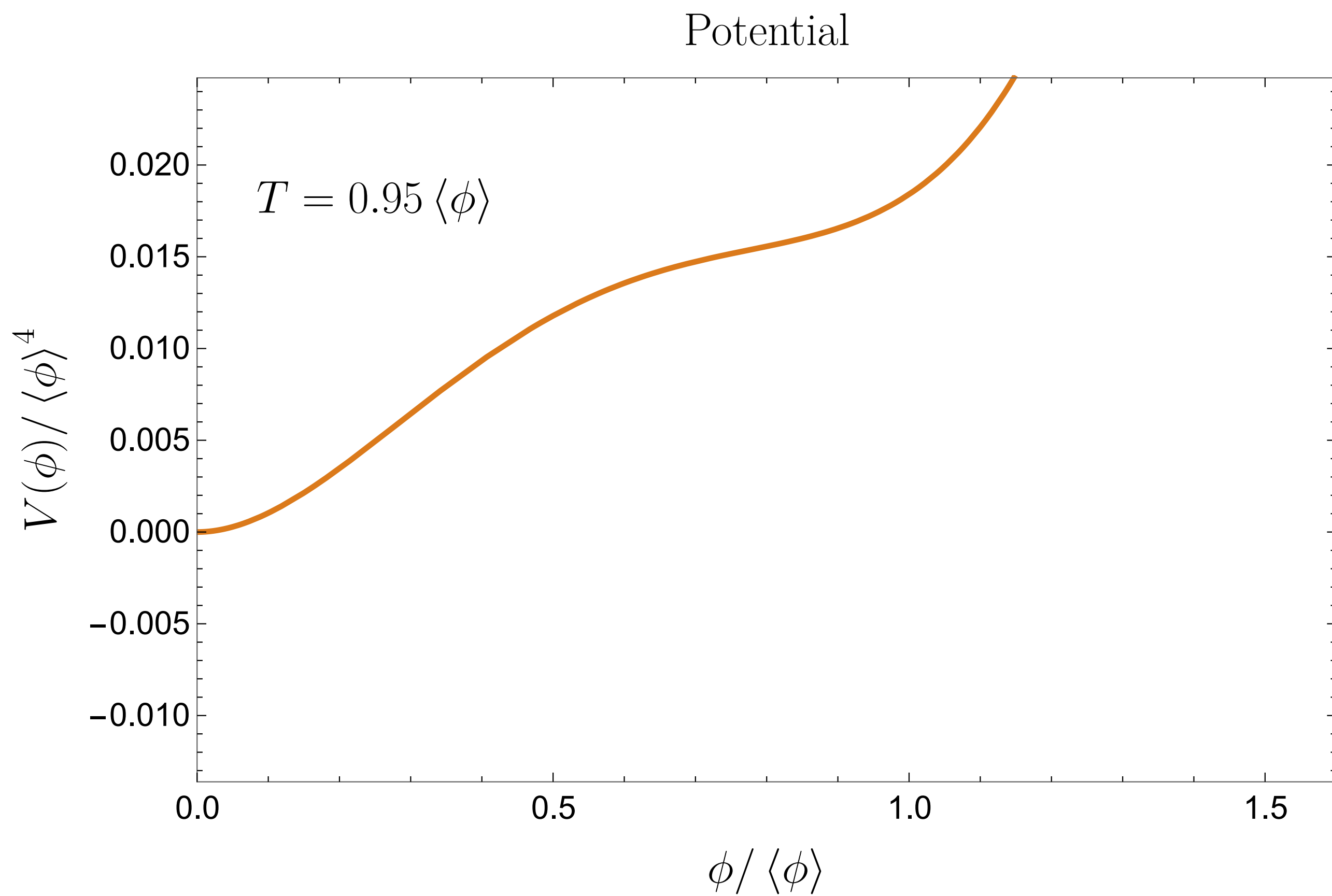
Supercooled 1stOPT = Hierarchical PT



What kind of particle physics model lead to supercooling ?

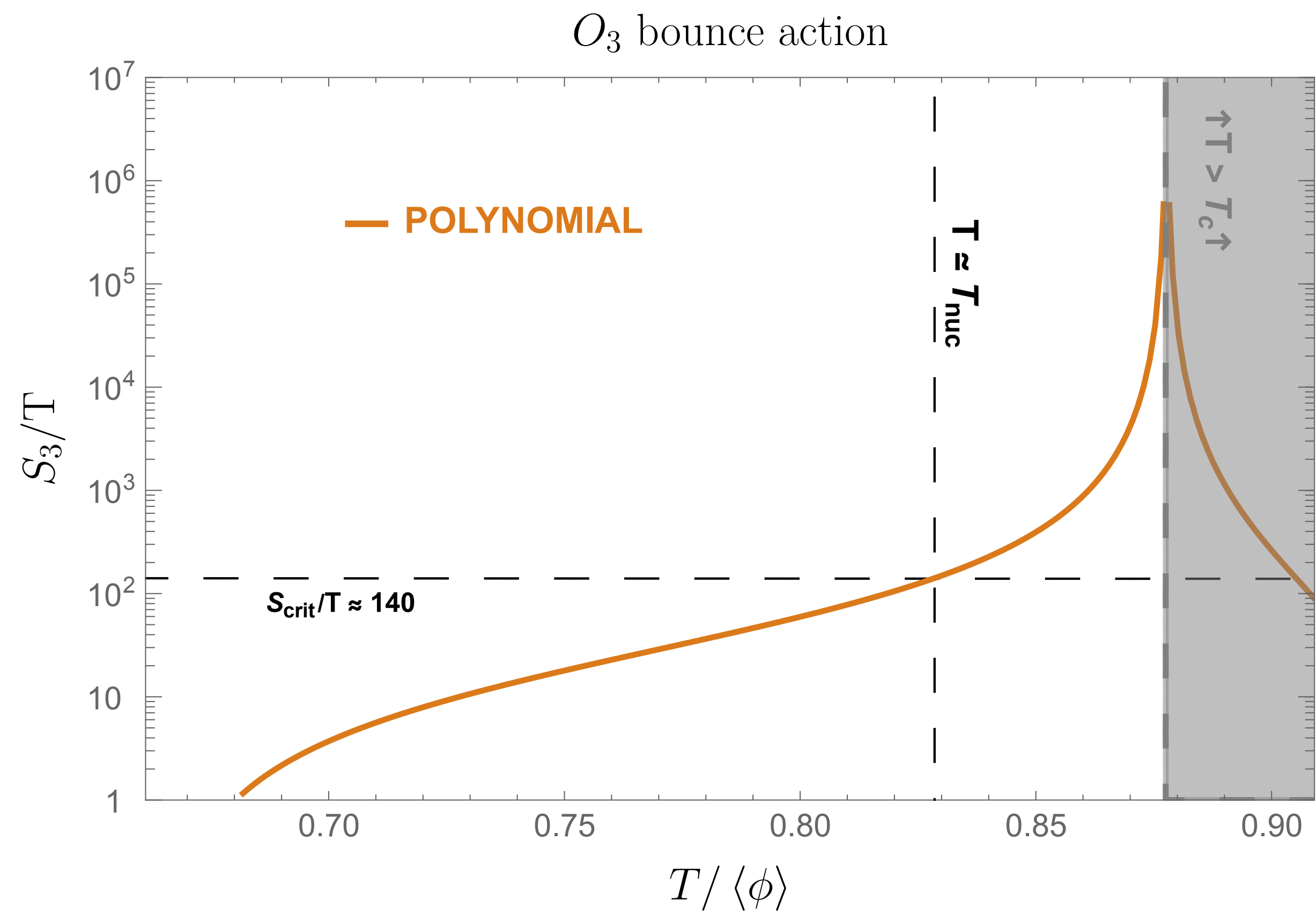
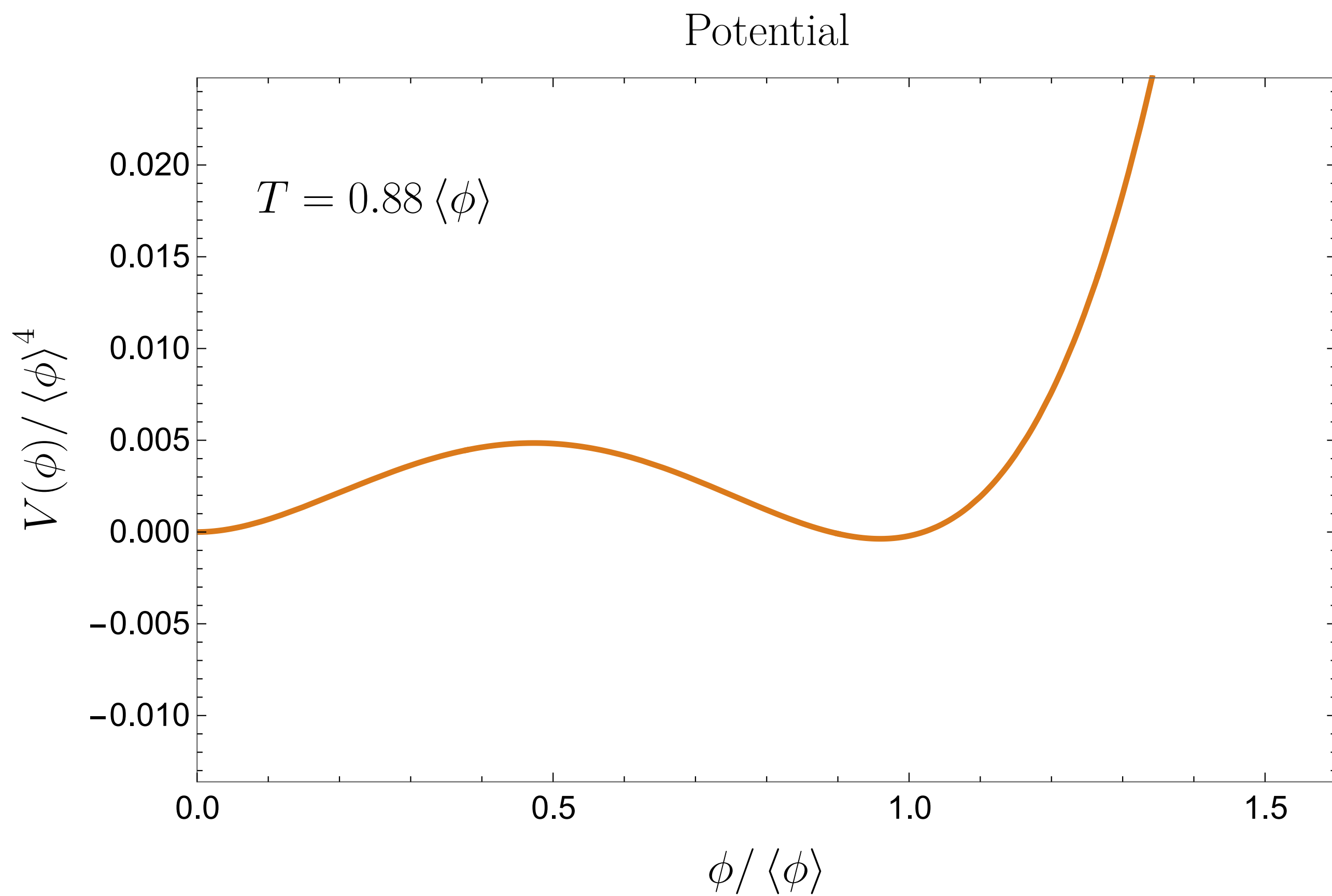
POLYNOMIAL POTENTIAL

$$V(\phi) = D(T^2 - T_0^2)\phi^2 - ET\phi^3 + \frac{\lambda}{4}\phi^4$$



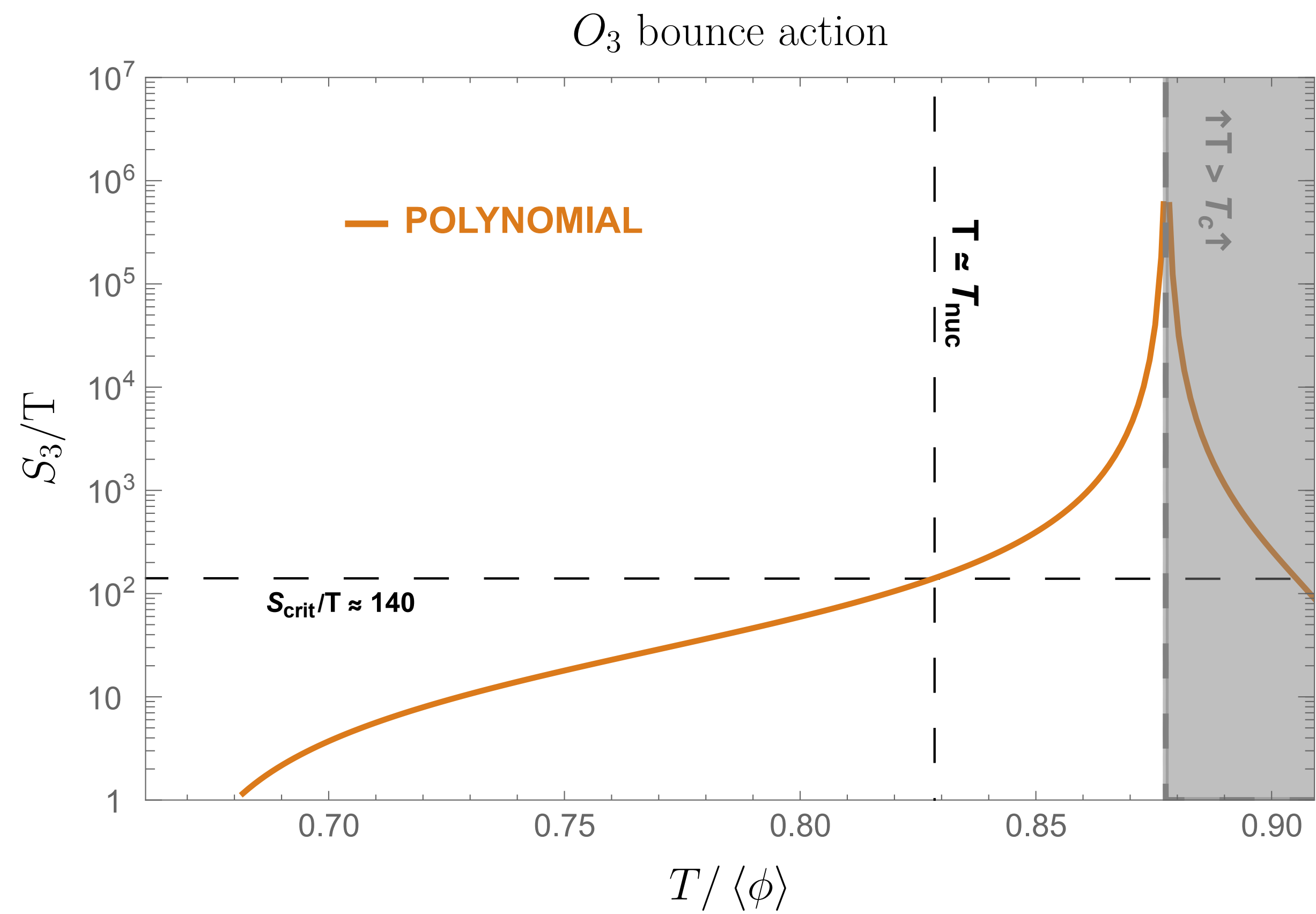
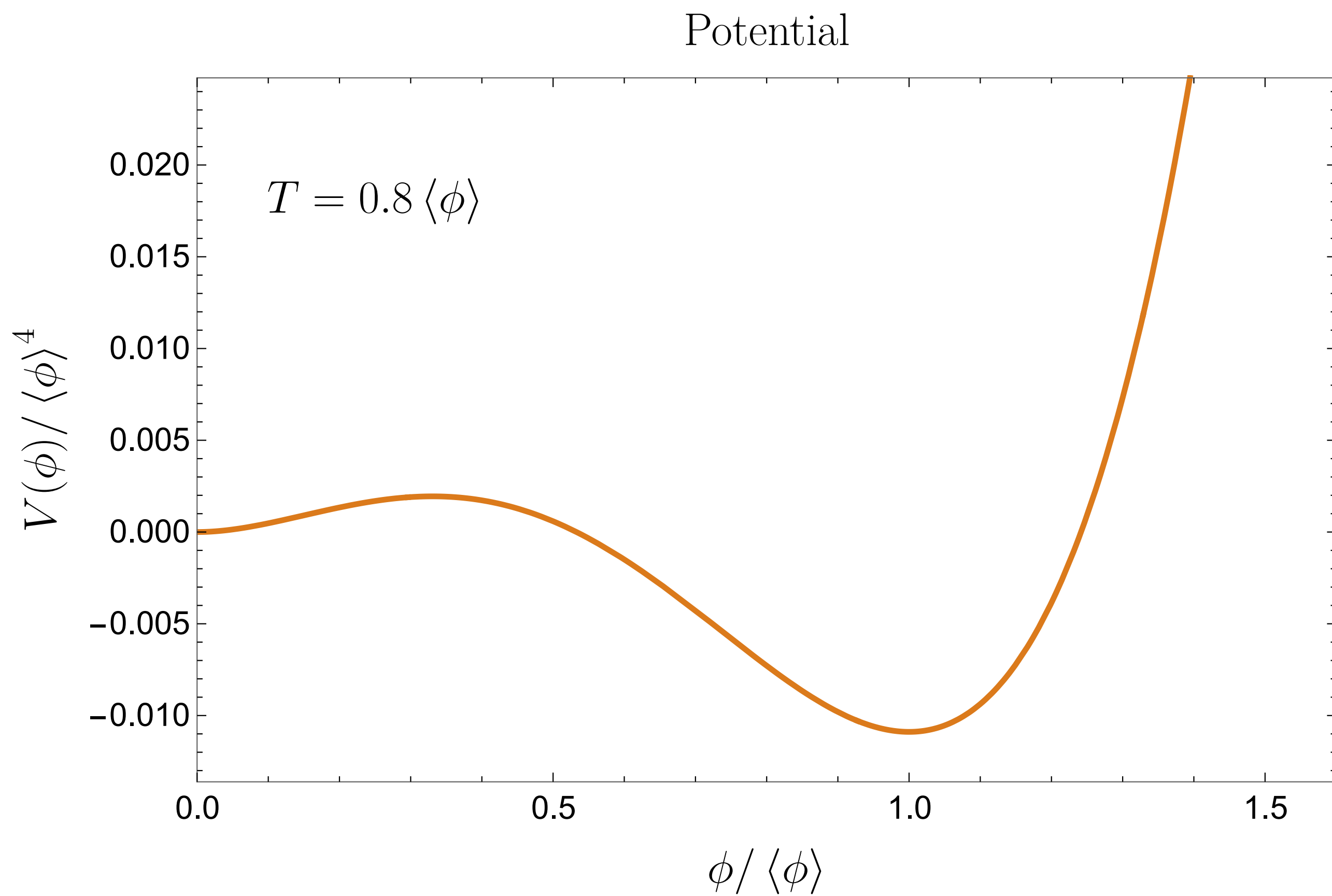
POLYNOMIAL POTENTIAL

$$V(\phi) = D(T^2 - T_0^2)\phi^2 - ET\phi^3 + \frac{\lambda}{4}\phi^4$$



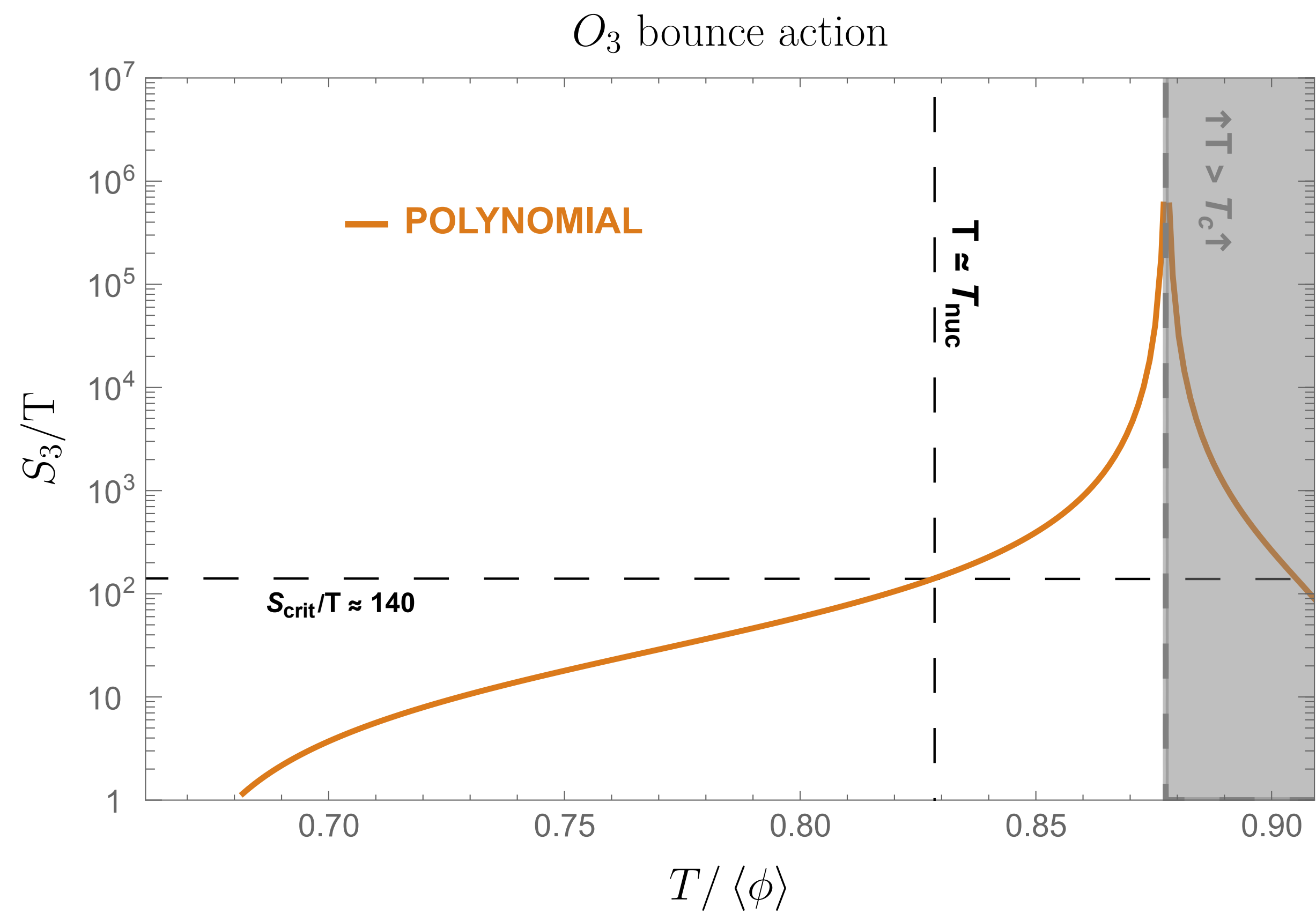
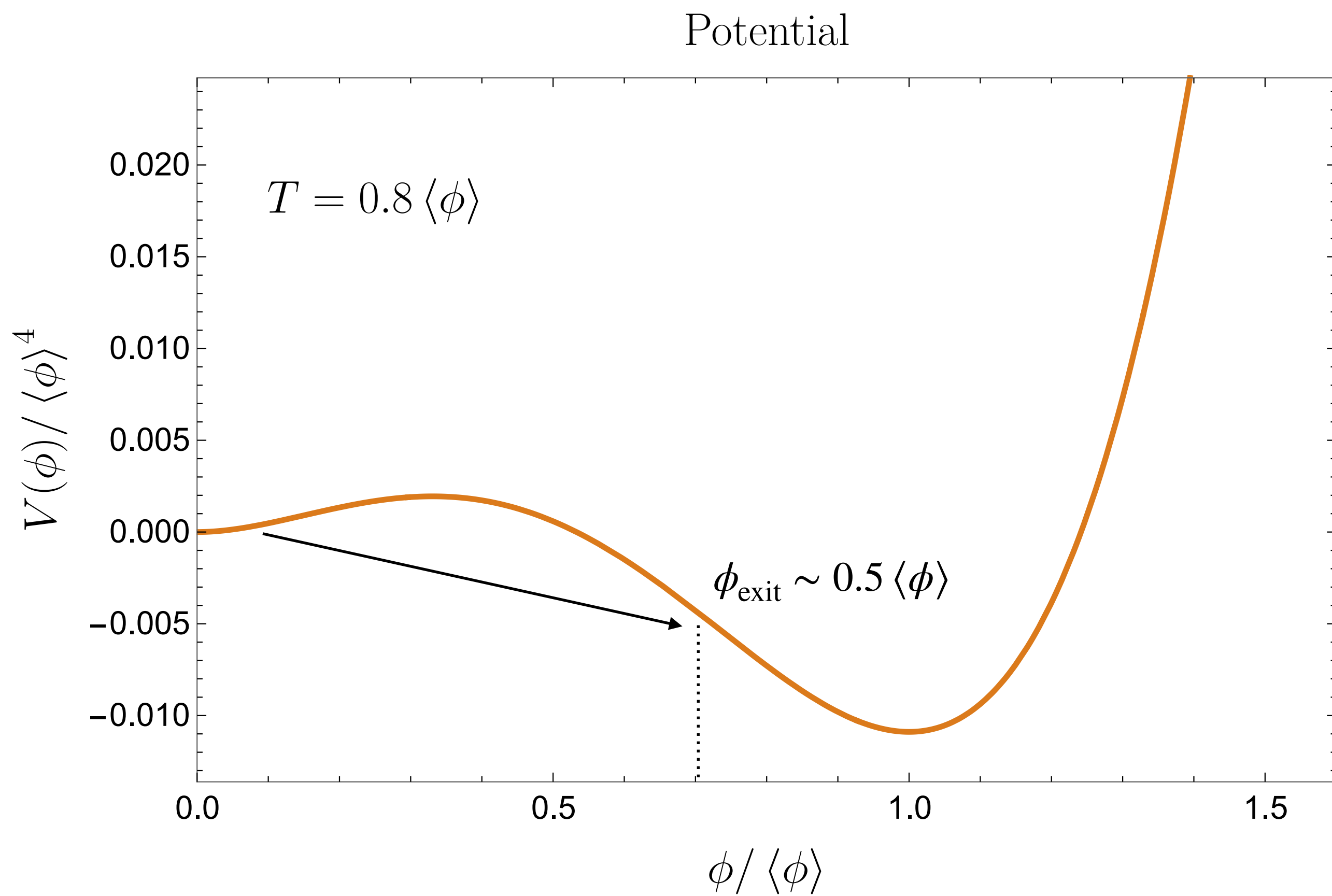
POLYNOMIAL POTENTIAL

$$V(\phi) = D(T^2 - T_0^2)\phi^2 - ET\phi^3 + \frac{\lambda}{4}\phi^4$$



POLYNOMIAL POTENTIAL

$$V(\phi) = D(T^2 - T_0^2)\phi^2 - ET\phi^3 + \frac{\lambda}{4}\phi^4$$



POLYNOMIAL POTENTIAL

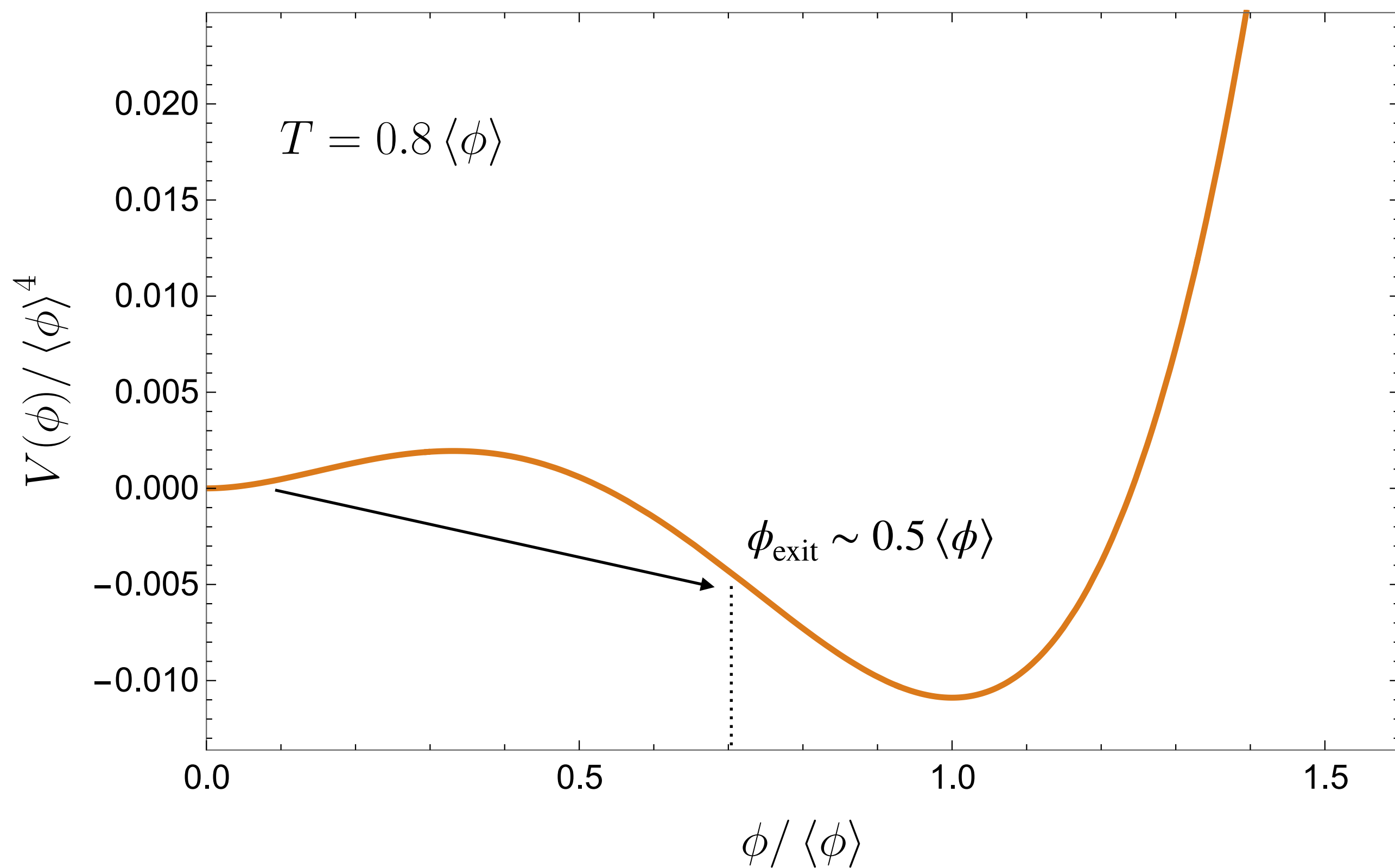
VS

NEARLY-CONFORMAL POTENTIAL

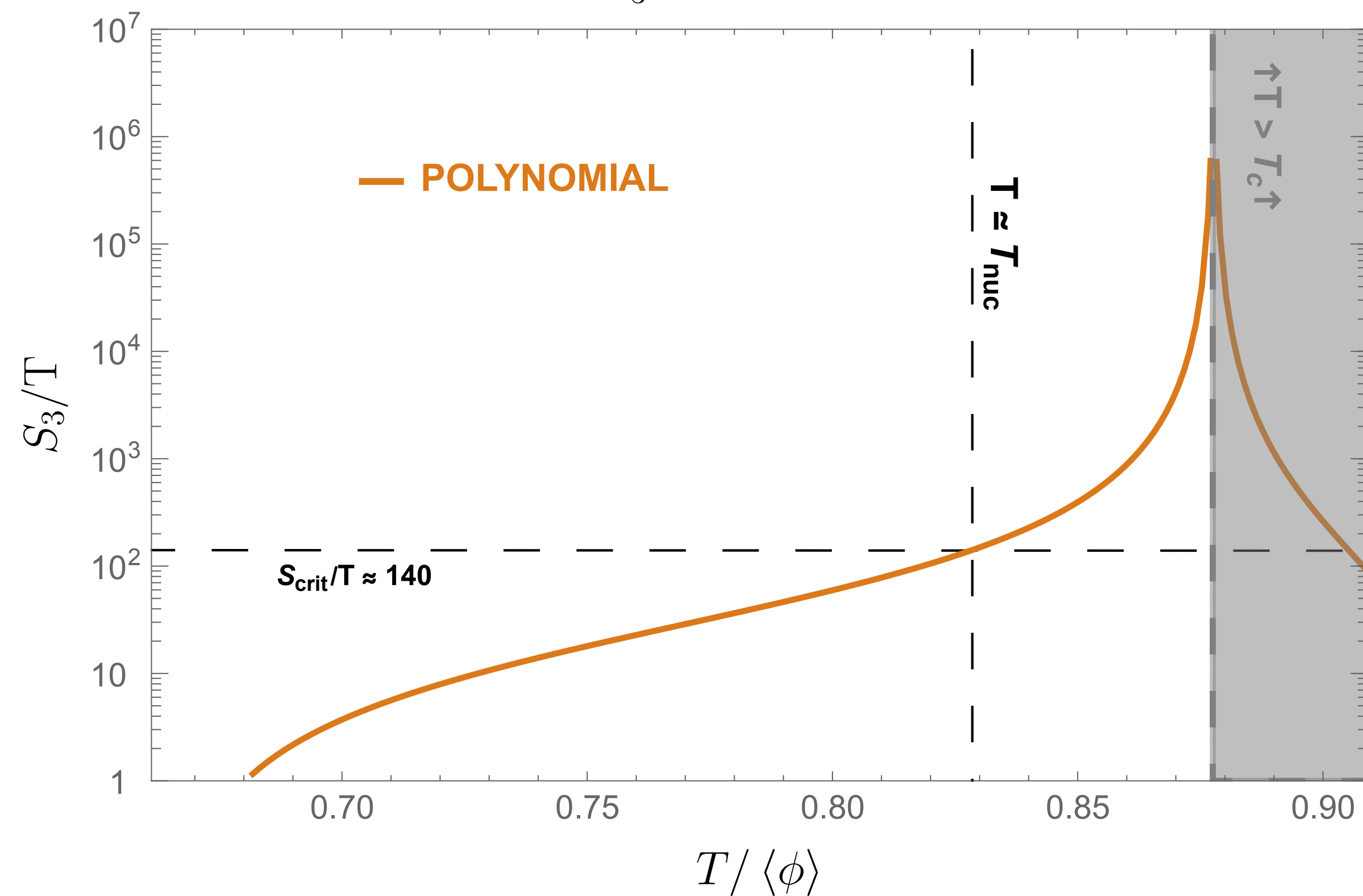
$$V(\phi) = D(T^2 - T_0^2)\phi^2 - ET\phi^3 + \frac{\lambda}{4}\phi^4$$

$$V(\phi) = D(T^2 - 0)\phi^2 - ET\phi^3 + \frac{\lambda}{4}\phi^4 \log\left(\frac{\phi}{\phi_*}\right)$$

Potential



O_3 bounce action



POLYNOMIAL POTENTIAL

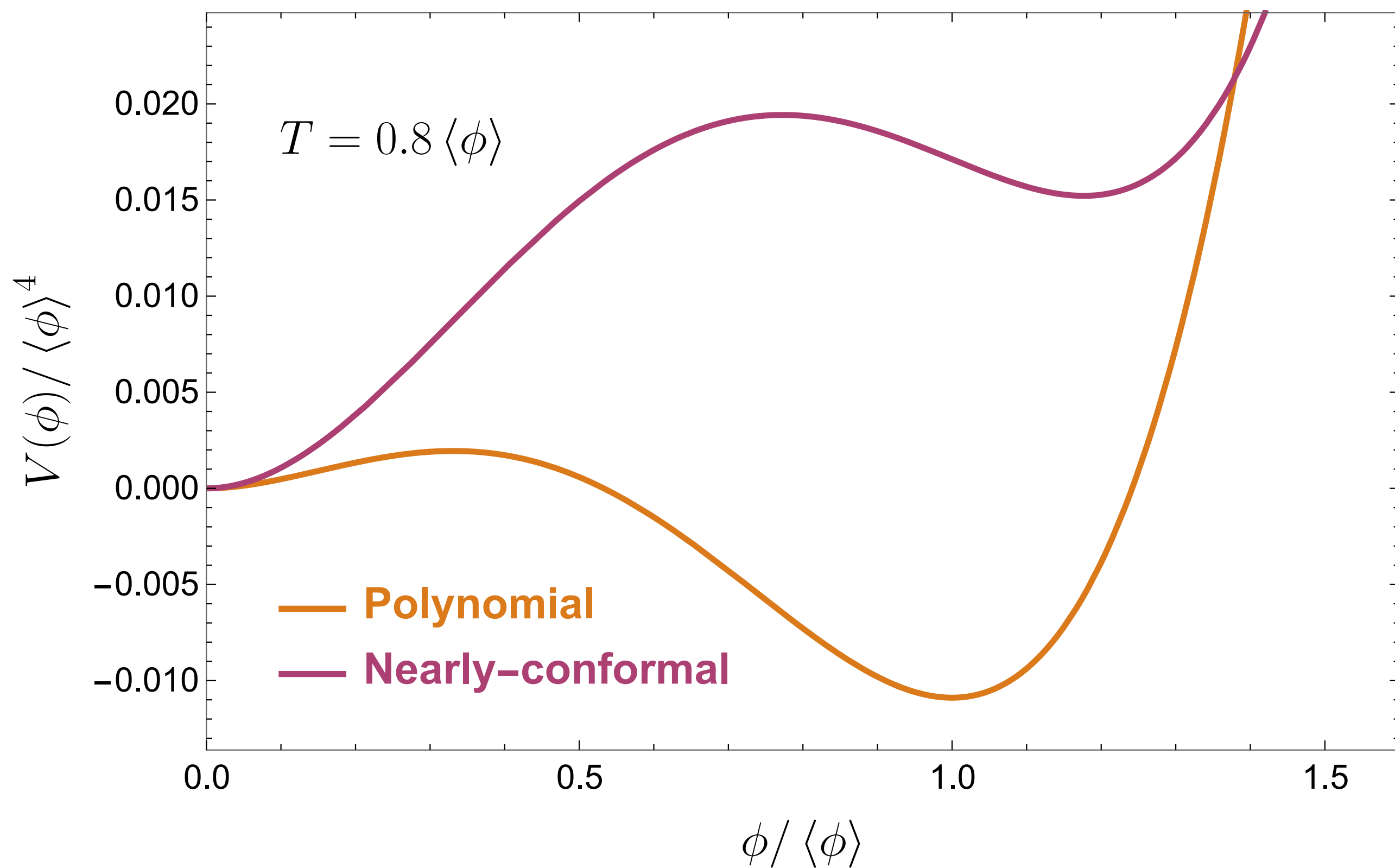
VS

NEARLY-CONFORMAL POTENTIAL

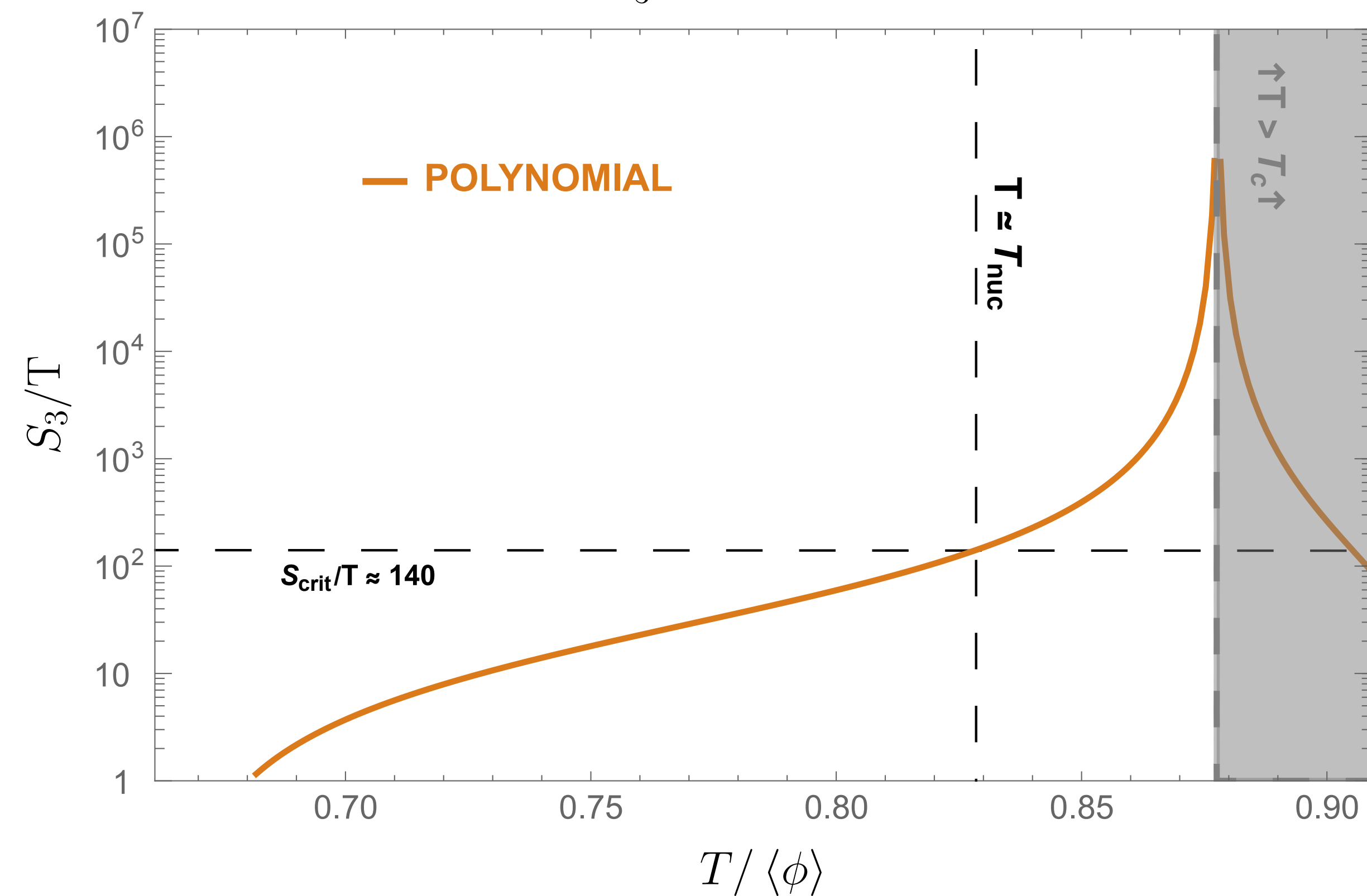
$$V(\phi) = D(T^2 - T_0^2)\phi^2 - ET\phi^3 + \frac{\lambda}{4}\phi^4$$

$$V(\phi) = D(T^2 - 0)\phi^2 - ET\phi^3 + \frac{\lambda}{4}\phi^4 \log\left(\frac{\phi}{\phi_*}\right)$$

Potential



O_3 bounce action



POLYNOMIAL POTENTIAL

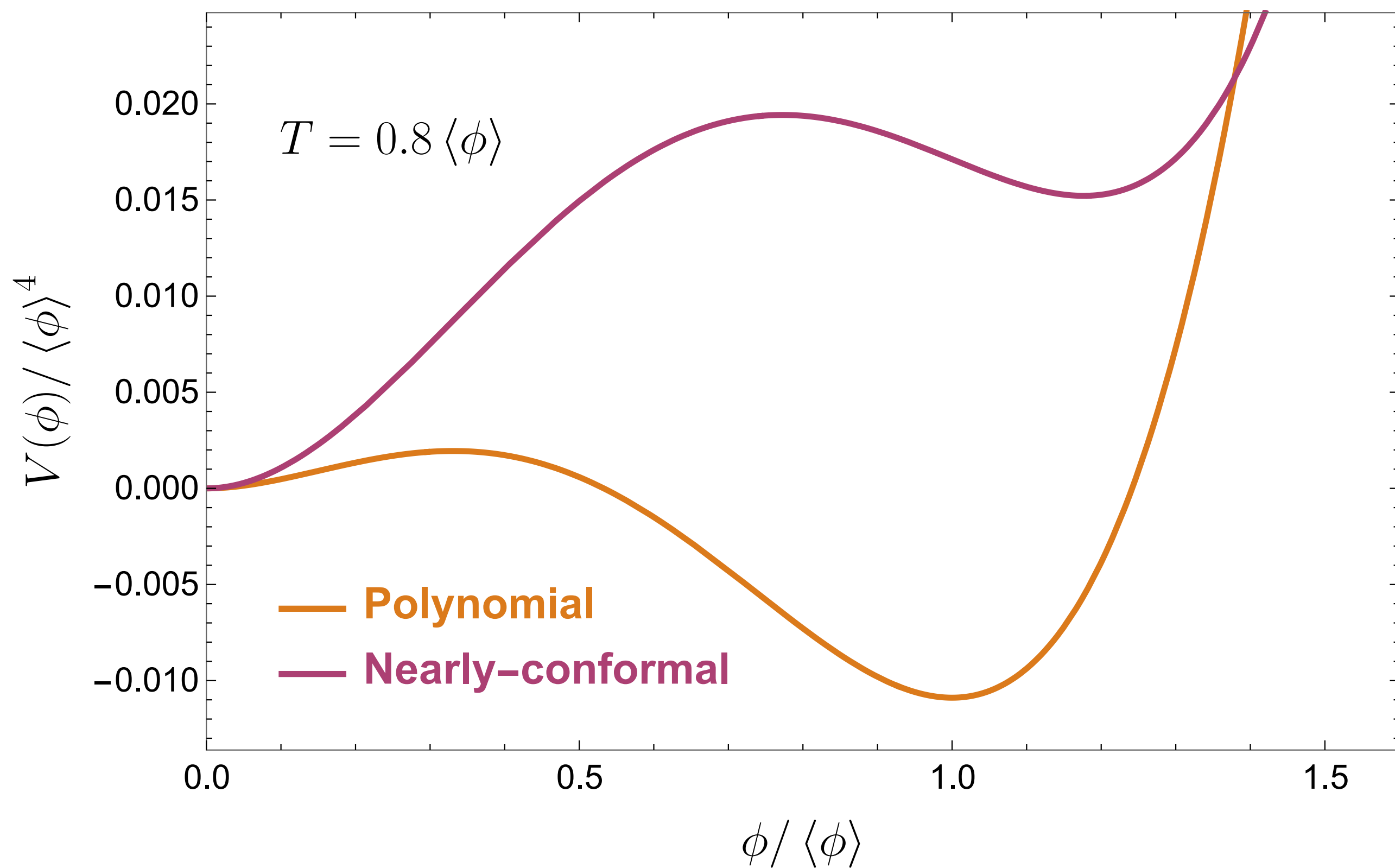
VS

NEARLY-CONFORMAL POTENTIAL

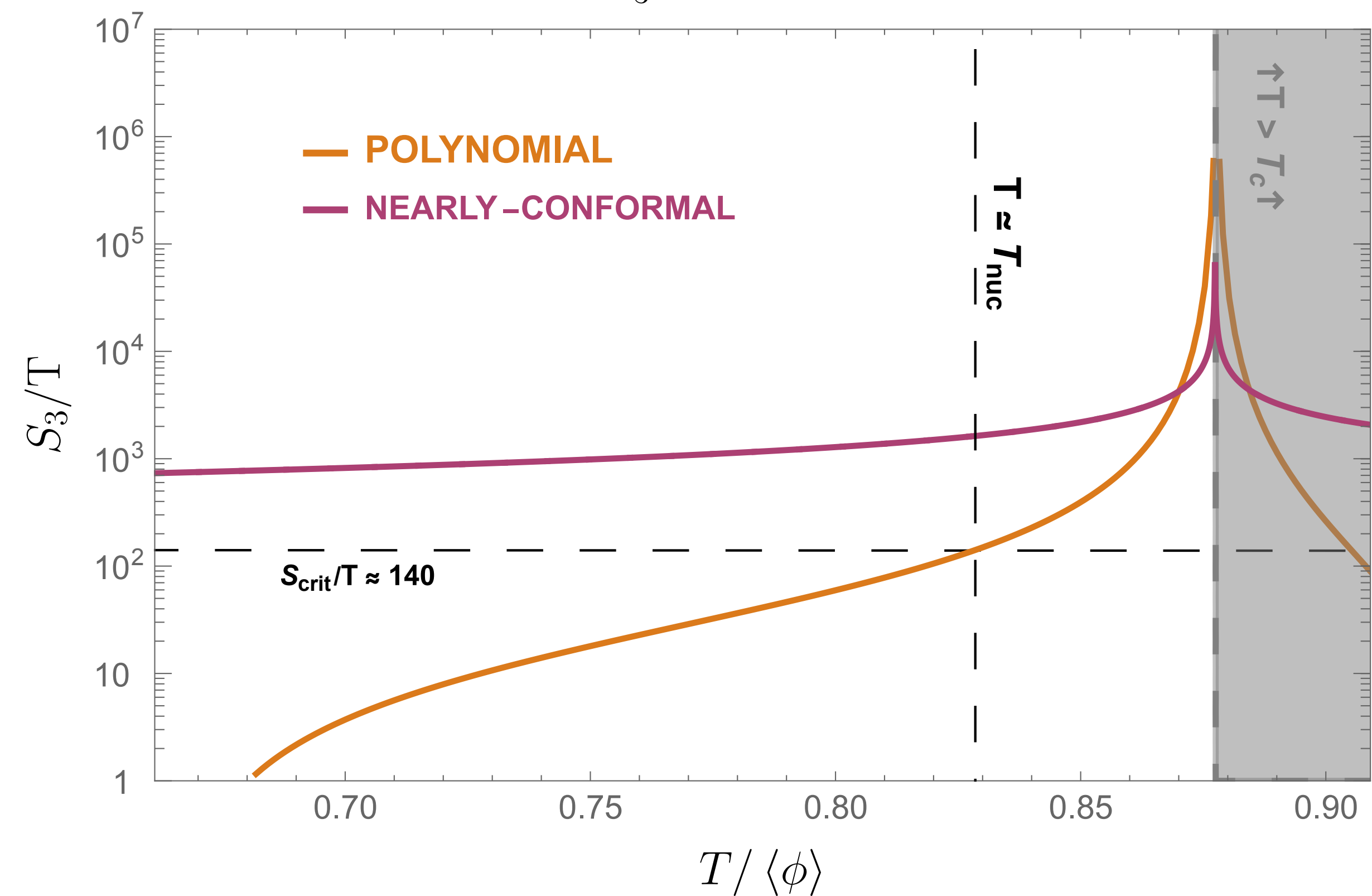
$$V(\phi) = D(T^2 - T_0^2)\phi^2 - ET\phi^3 + \frac{\lambda}{4}\phi^4$$

$$V(\phi) = D(T^2 - 0)\phi^2 - ET\phi^3 + \frac{\lambda}{4}\phi^4 \log\left(\frac{\phi}{\phi_*}\right)$$

Potential



O_3 bounce action



POLYNOMIAL POTENTIAL

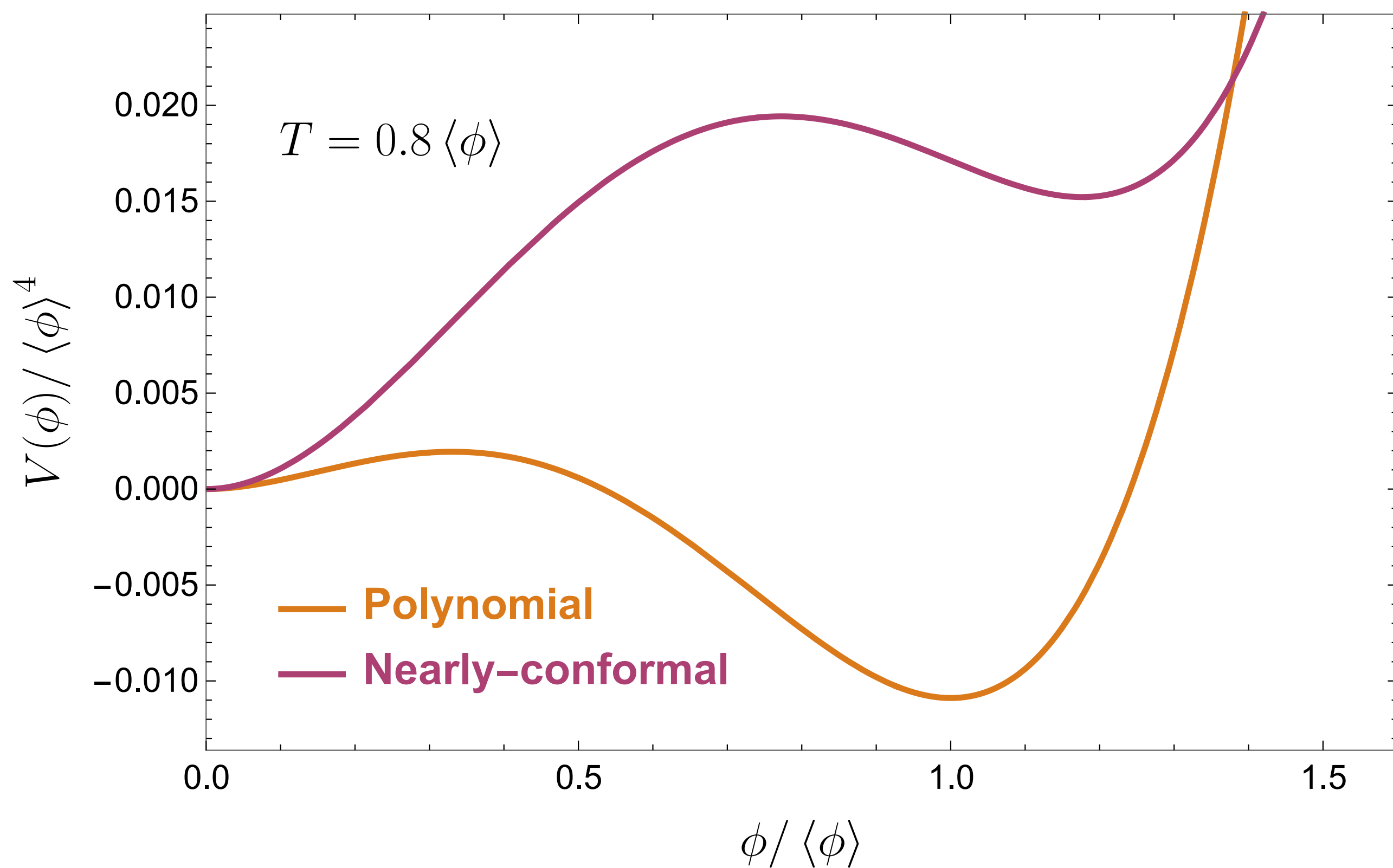
VS

NEARLY-CONFORMAL POTENTIAL

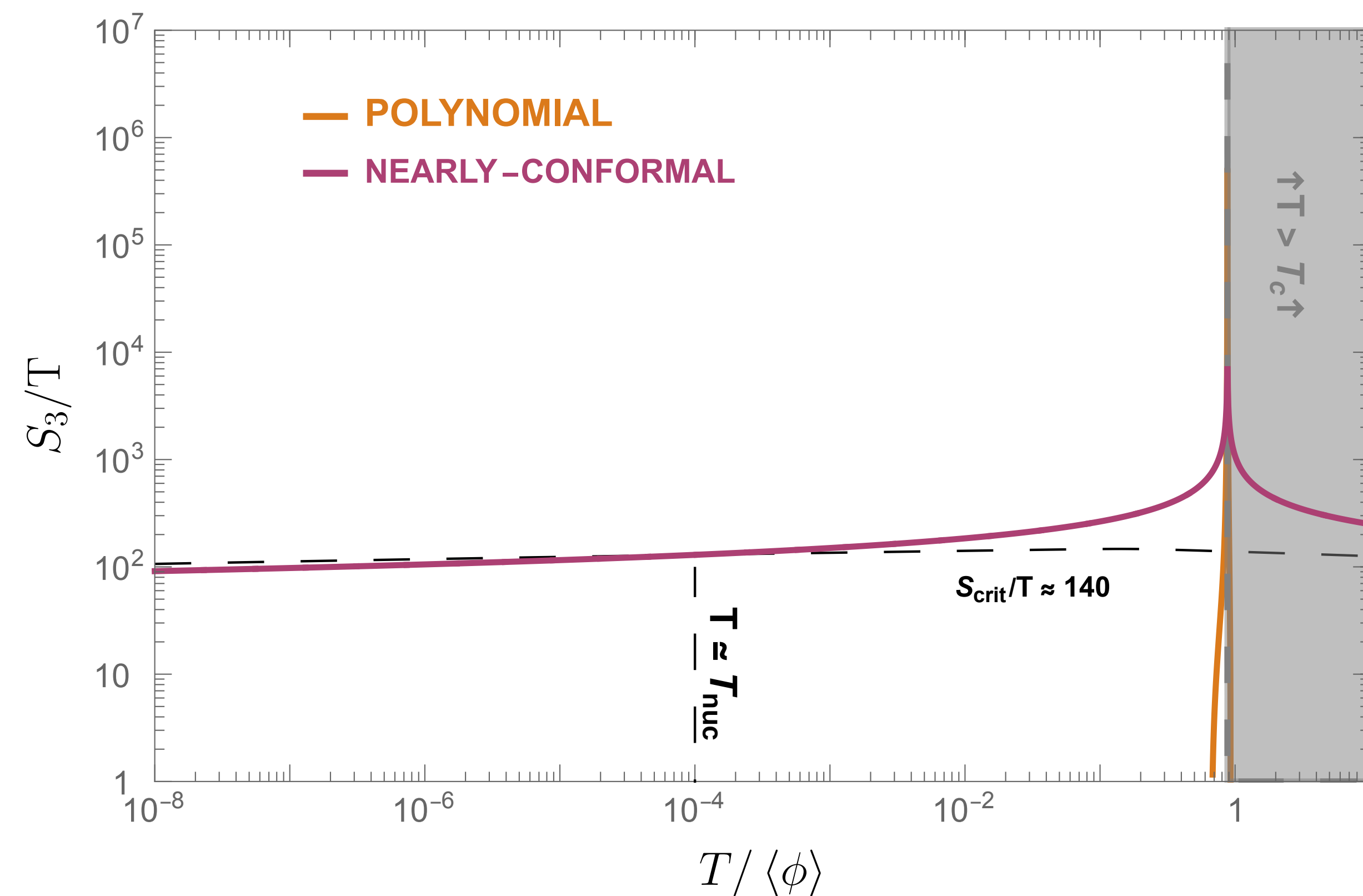
$$V(\phi) = D(T^2 - T_0^2)\phi^2 - ET\phi^3 + \frac{\lambda}{4}\phi^4$$

$$V(\phi) = D(T^2 - 0)\phi^2 - ET\phi^3 + \frac{\lambda}{4}\phi^4 \log\left(\frac{\phi}{\phi_*}\right)$$

Potential



O_3 bounce action



POLYNOMIAL POTENTIAL

VS

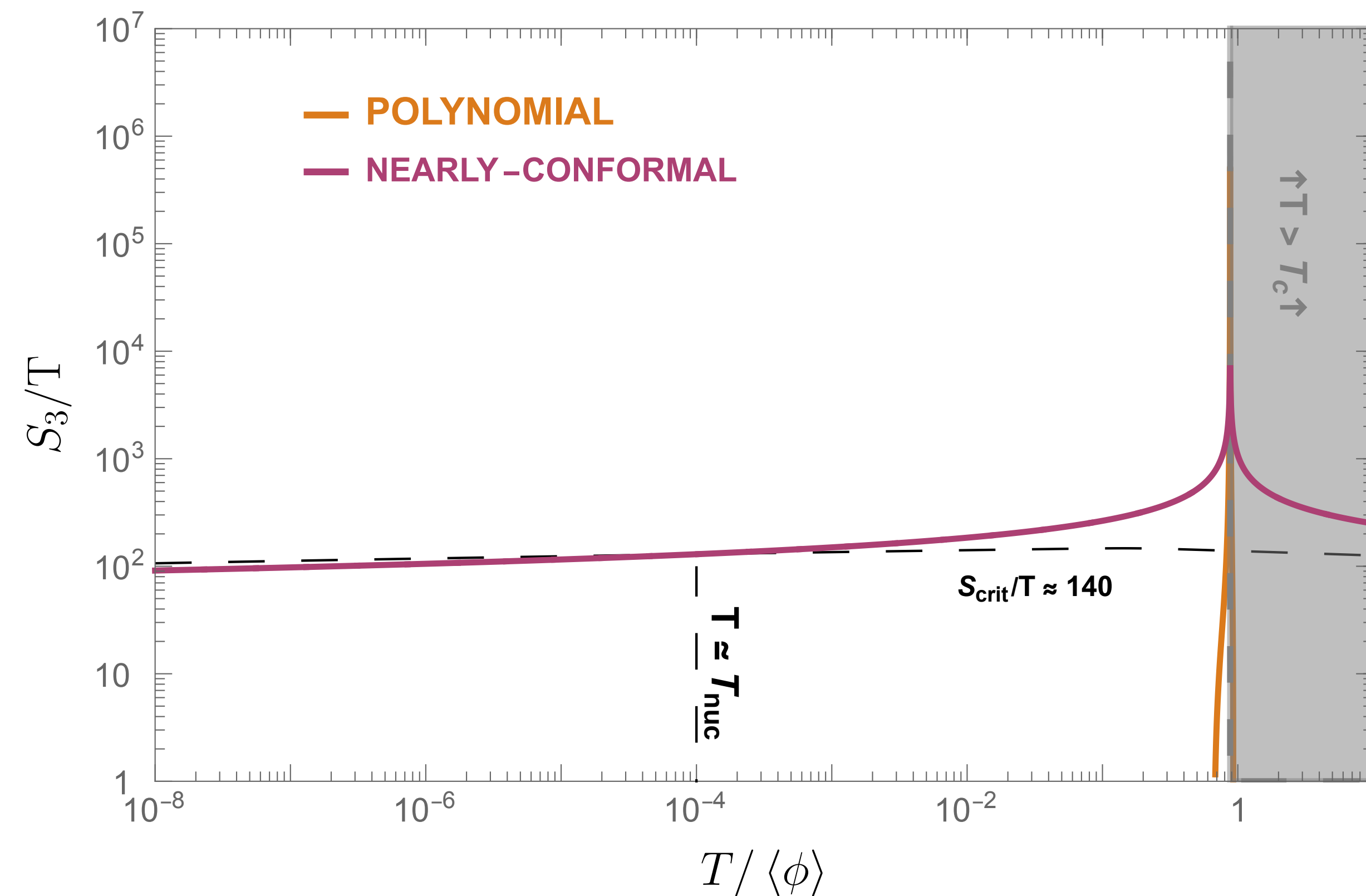
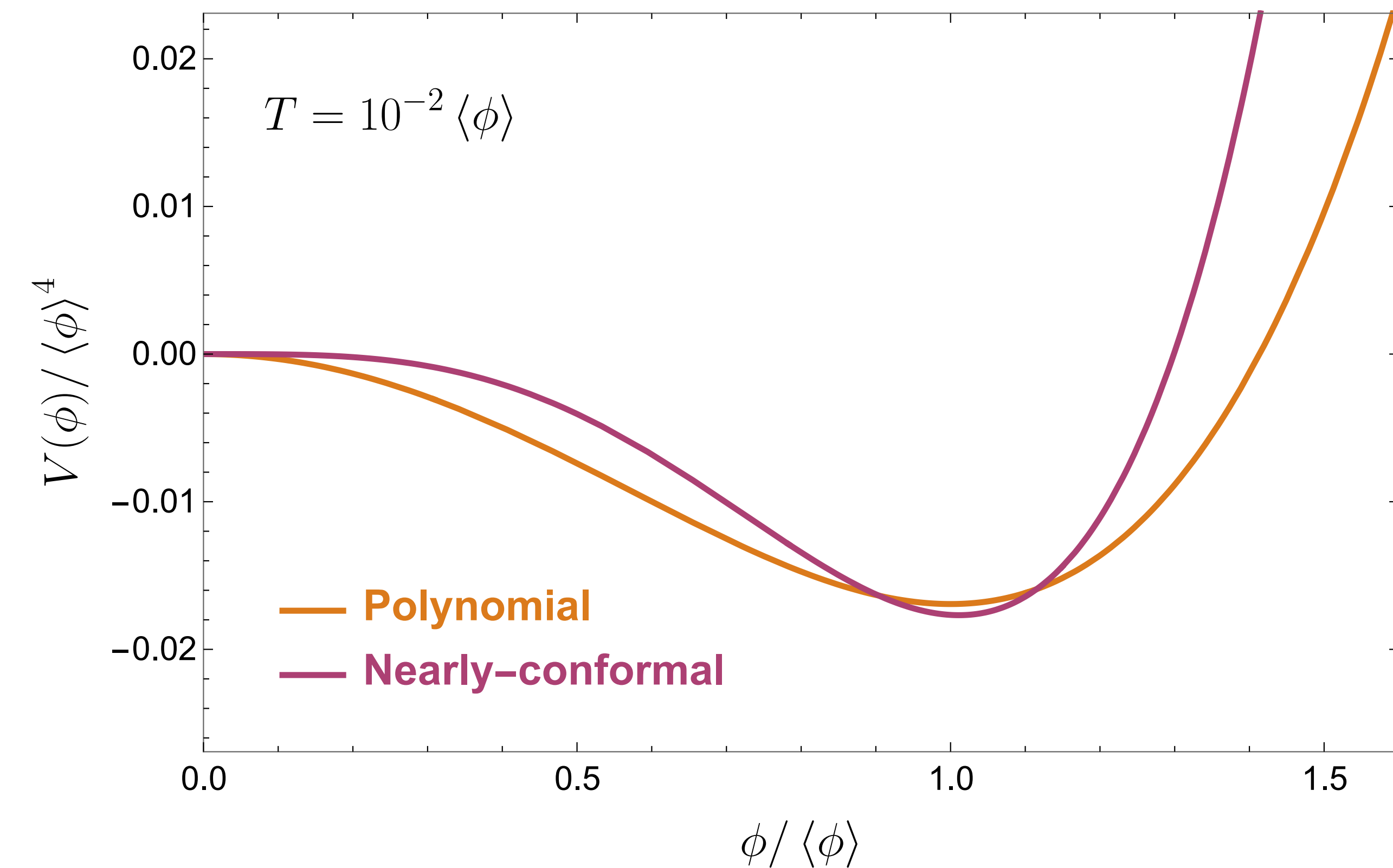
NEARLY-CONFORMAL POTENTIAL

$$V(\phi) = D(T^2 - T_0^2)\phi^2 - ET\phi^3 + \frac{\lambda}{4}\phi^4$$

$$V(\phi) = D(T^2 - 0)\phi^2 - ET\phi^3 + \frac{\lambda}{4}\phi^4 \log\left(\frac{\phi}{\phi_*}\right)$$

Potential

O_3 bounce action



POLYNOMIAL POTENTIAL

VS

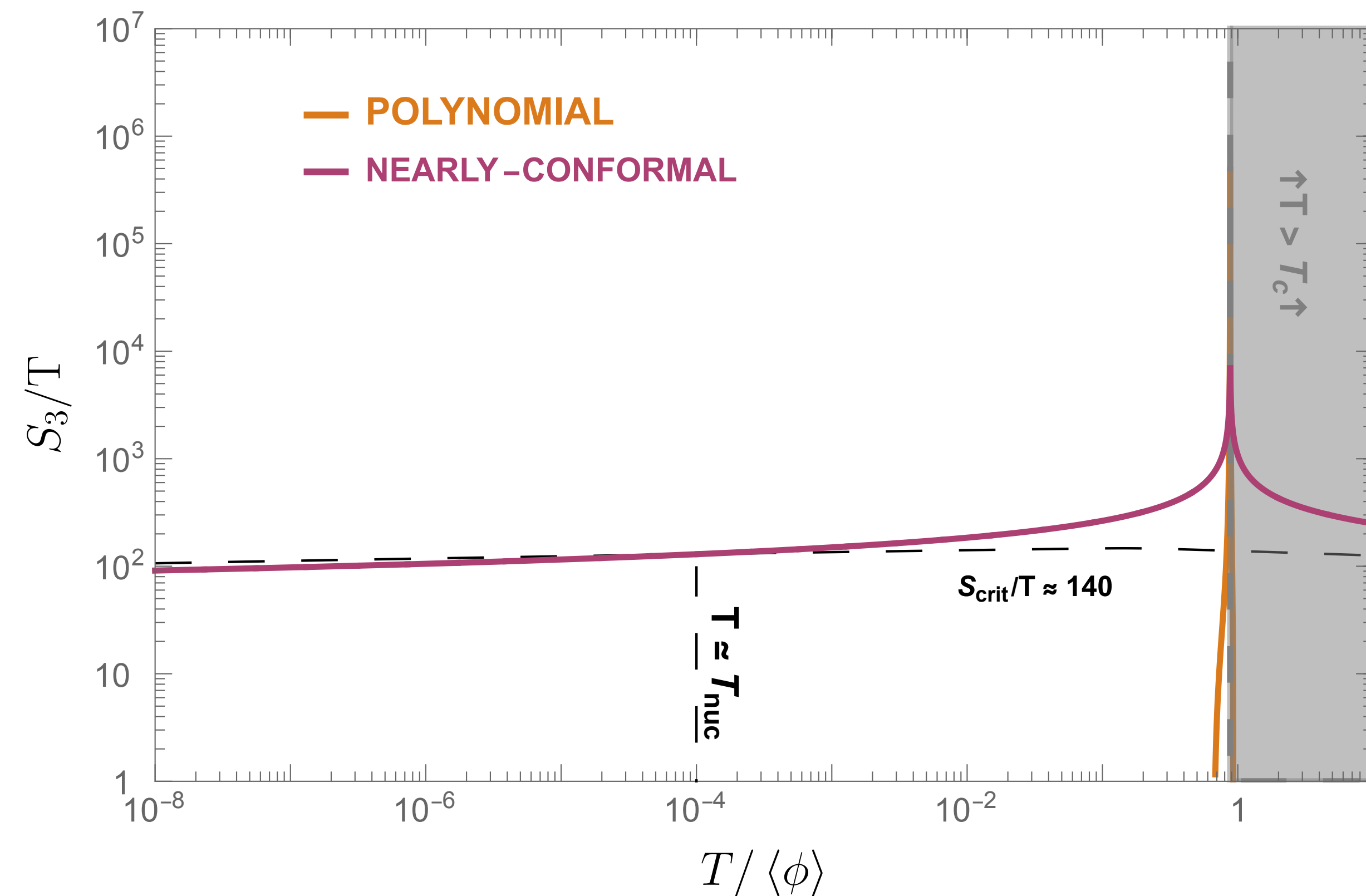
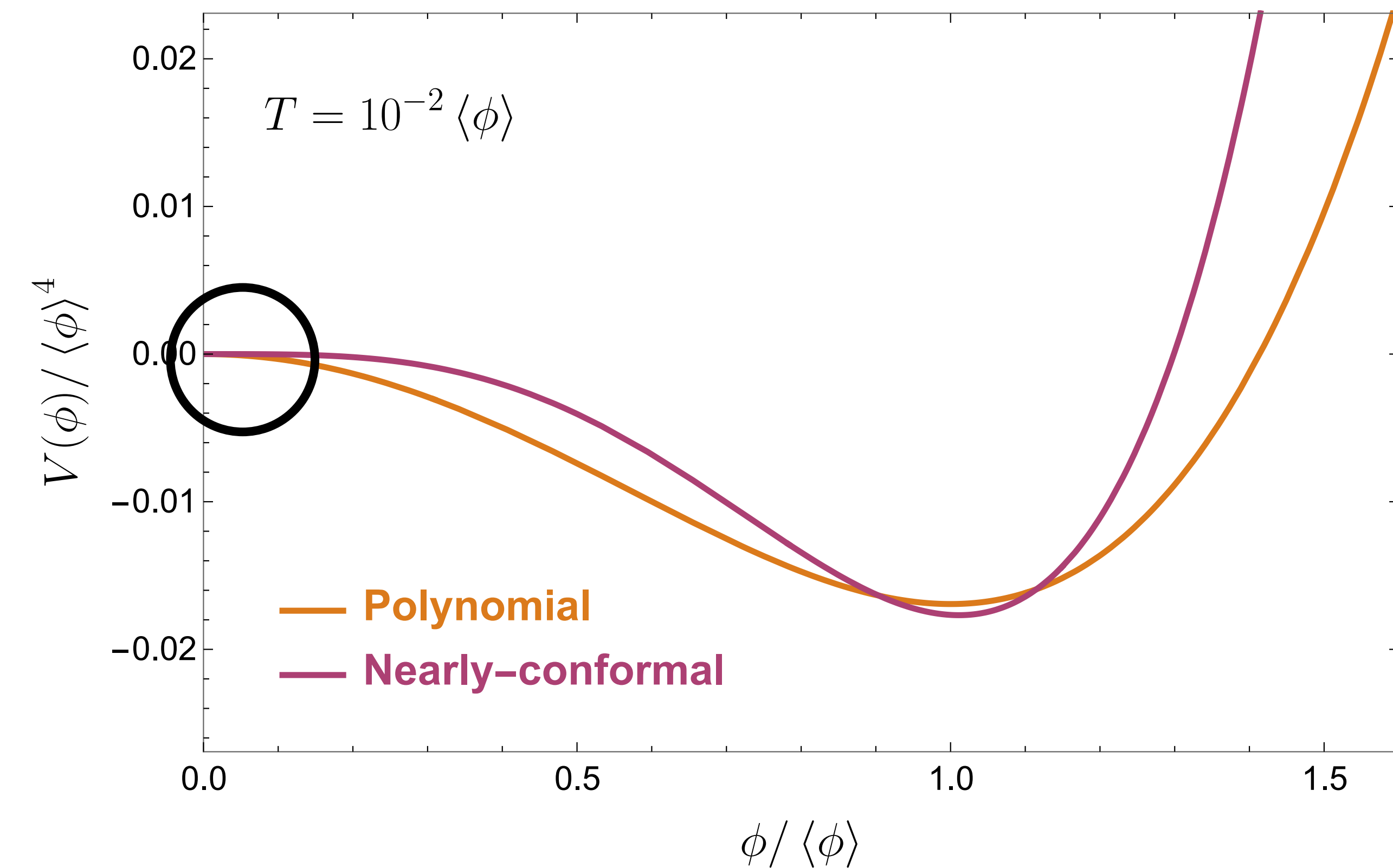
NEARLY-CONFORMAL POTENTIAL

$$V(\phi) = D(T^2 - T_0^2)\phi^2 - ET\phi^3 + \frac{\lambda}{4}\phi^4$$

$$V(\phi) = D(T^2 - 0)\phi^2 - ET\phi^3 + \frac{\lambda}{4}\phi^4 \log\left(\frac{\phi}{\phi_*}\right)$$

Potential

O_3 bounce action



POLYNOMIAL POTENTIAL

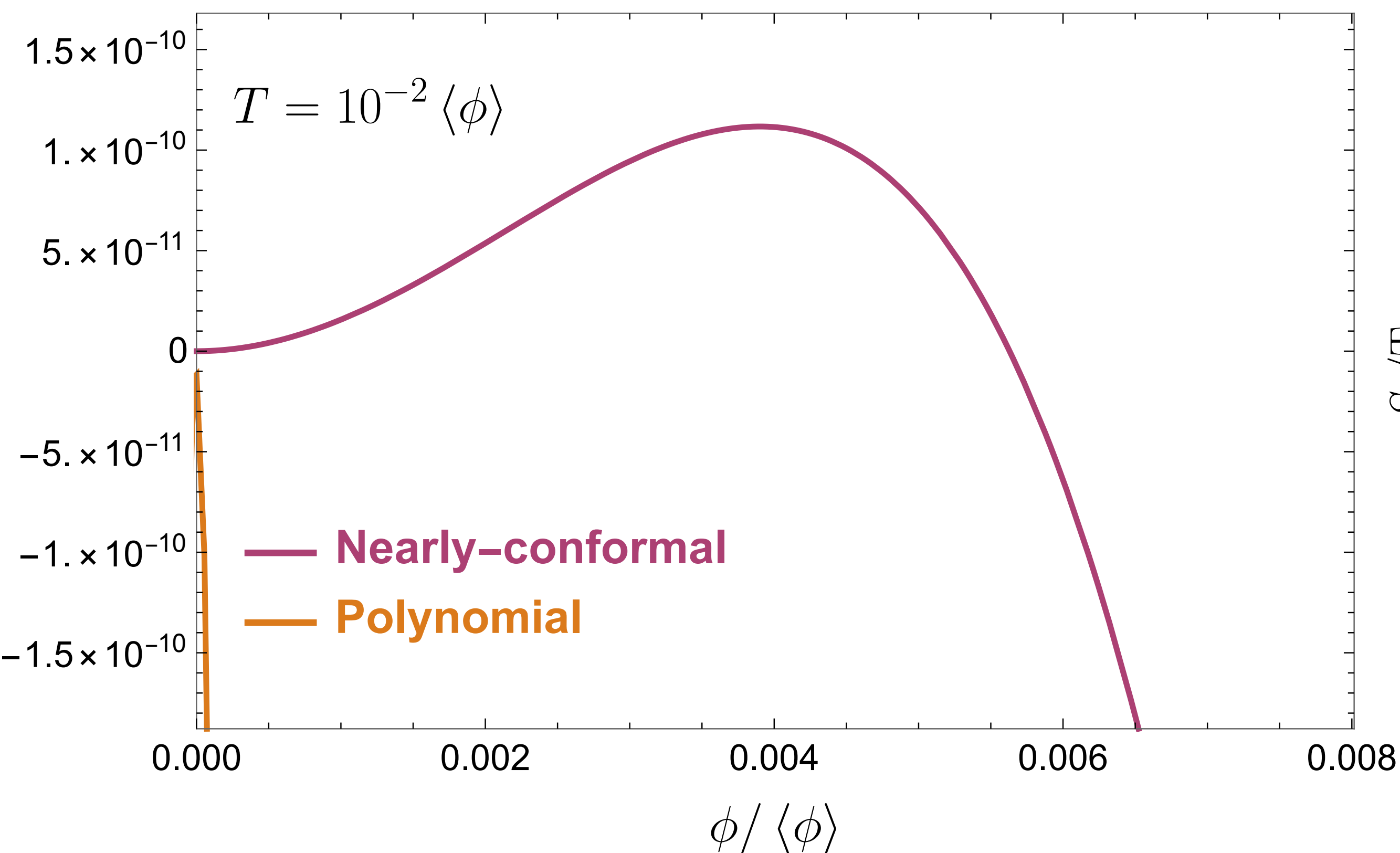
VS

NEARLY-CONFORMAL POTENTIAL

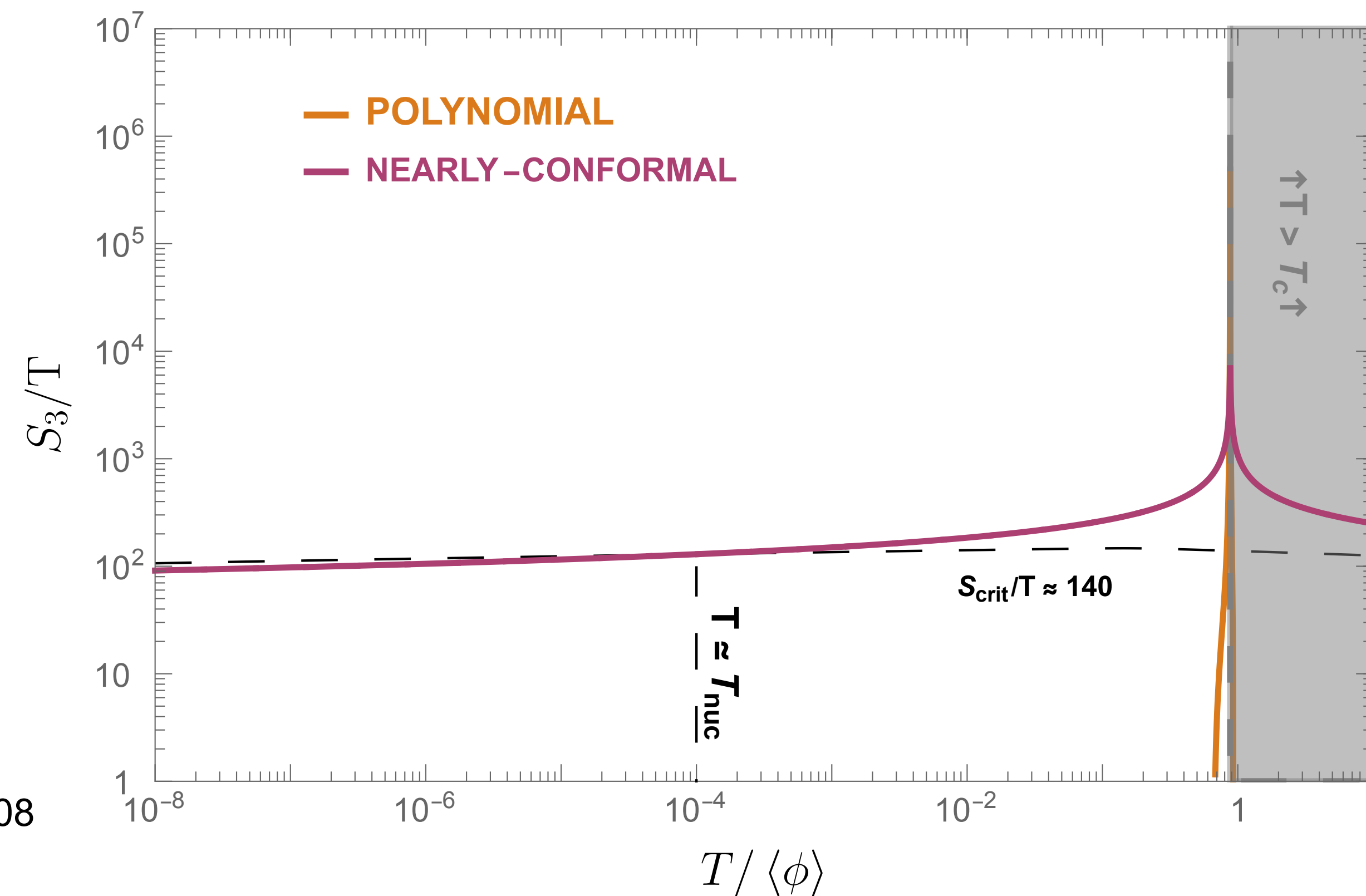
$$V(\phi) = D(T^2 - T_0^2)\phi^2 - ET\phi^3 + \frac{\lambda}{4}\phi^4$$

$$V(\phi) = D(T^2 - 0)\phi^2 - ET\phi^3 + \frac{\lambda}{4}\phi^4 \log\left(\frac{\phi}{\phi_*}\right)$$

Potential



O_3 bounce action



POLYNOMIAL POTENTIAL

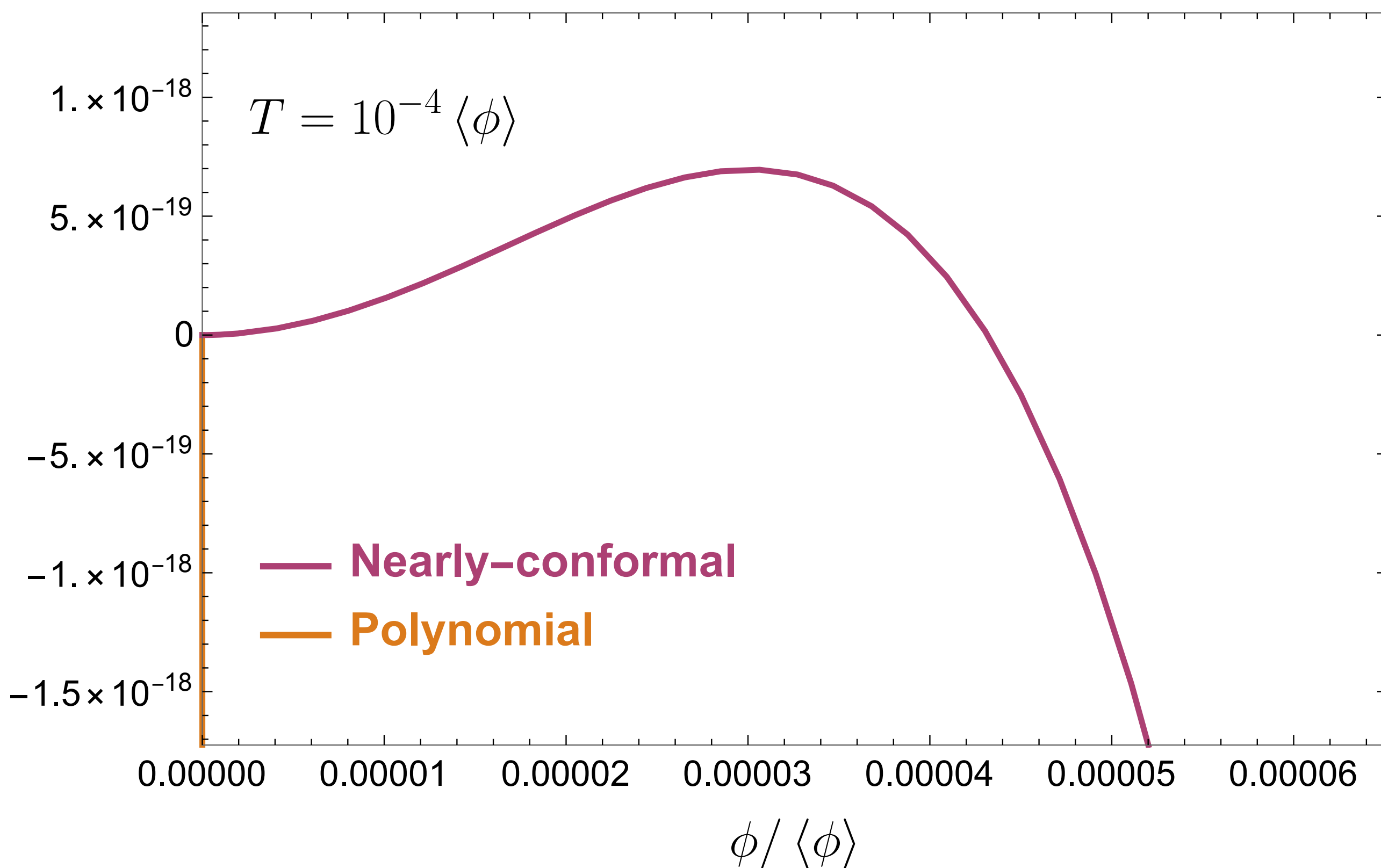
VS

NEARLY-CONFORMAL POTENTIAL

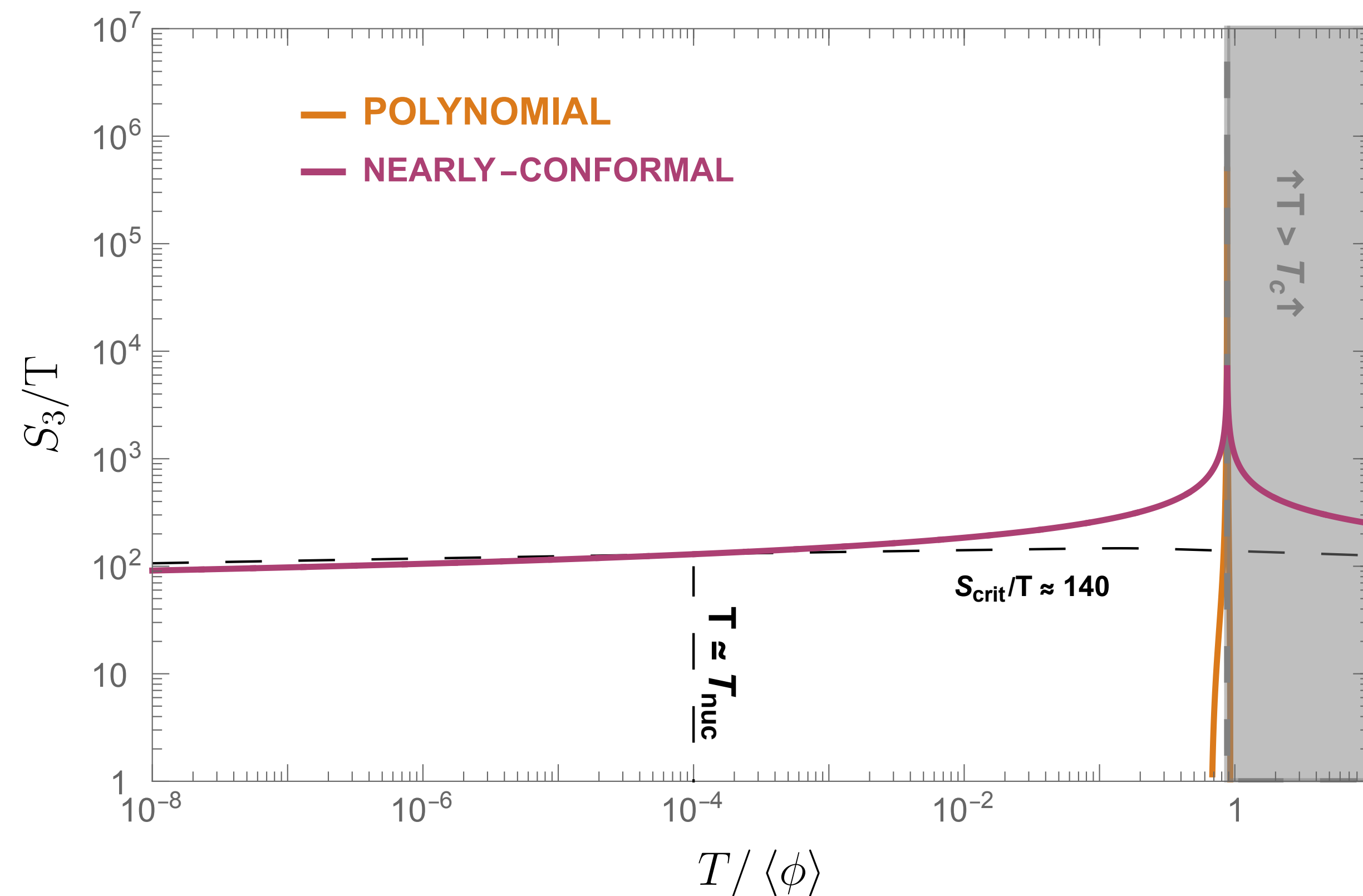
$$V(\phi) = D(T^2 - T_0^2)\phi^2 - ET\phi^3 + \frac{\lambda}{4}\phi^4$$

$$V(\phi) = D(T^2 - 0)\phi^2 - ET\phi^3 + \frac{\lambda}{4}\phi^4 \log\left(\frac{\phi}{\phi_*}\right)$$

Potential



O_3 bounce action



POLYNOMIAL POTENTIAL

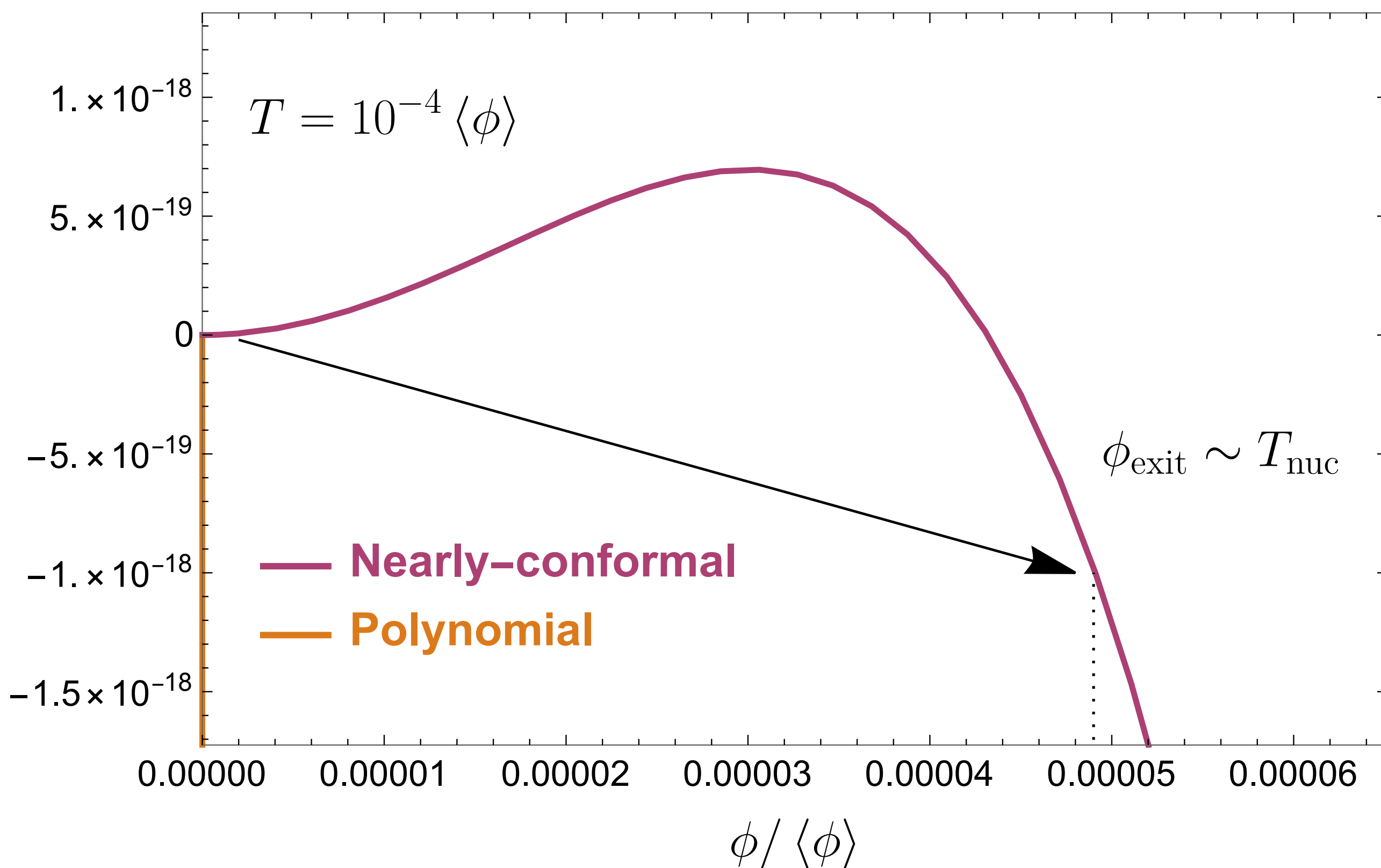
VS

NEARLY-CONFORMAL POTENTIAL

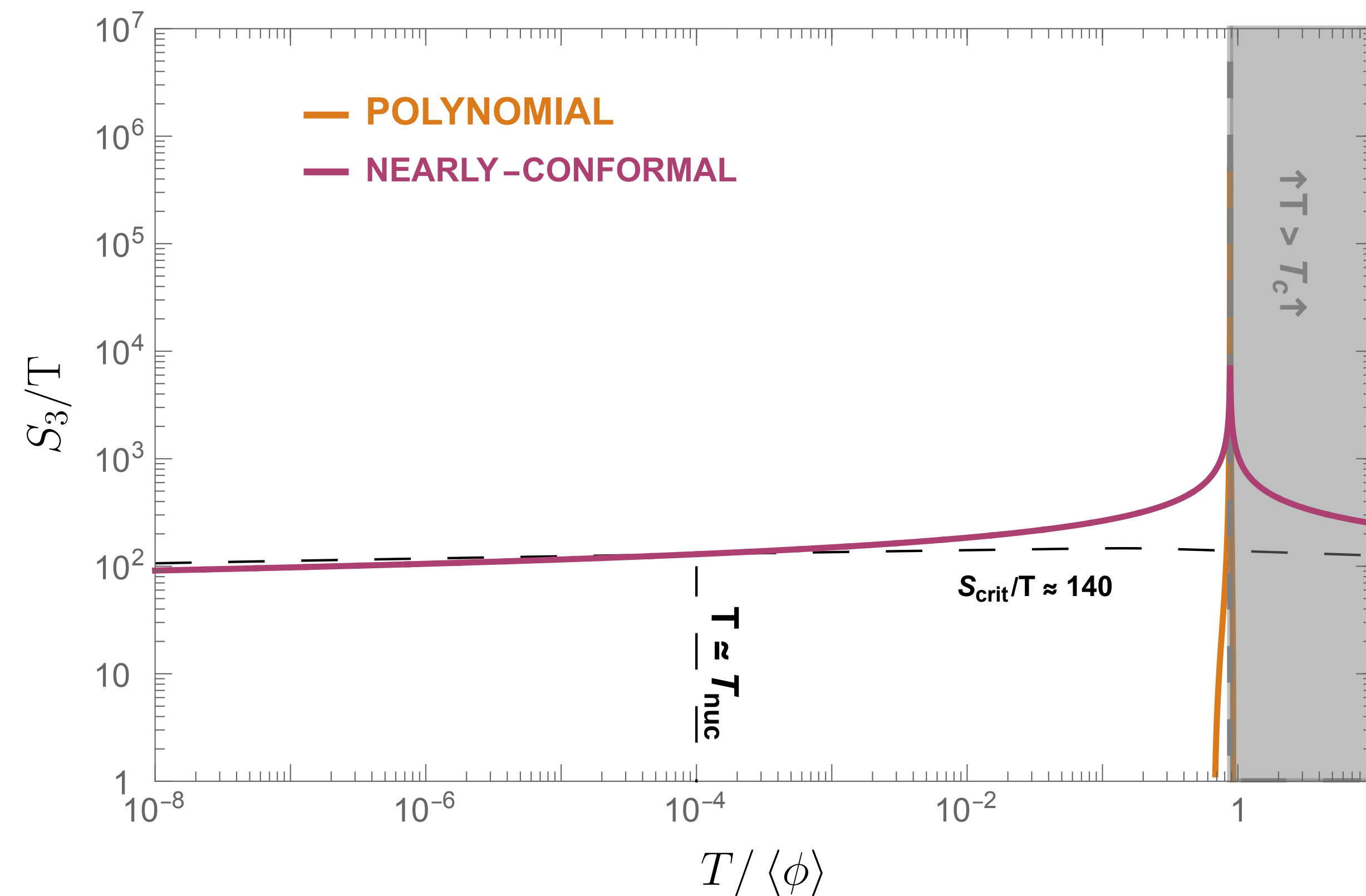
$$V(\phi) = D(T^2 - T_0^2)\phi^2 - ET\phi^3 + \frac{\lambda}{4}\phi^4$$

$$V(\phi) = D(T^2 - 0)\phi^2 - ET\phi^3 + \frac{\lambda}{4}\phi^4 \log\left(\frac{\phi}{\phi_*}\right)$$

Potential



O_3 bounce action



POLYNOMIAL POTENTIAL

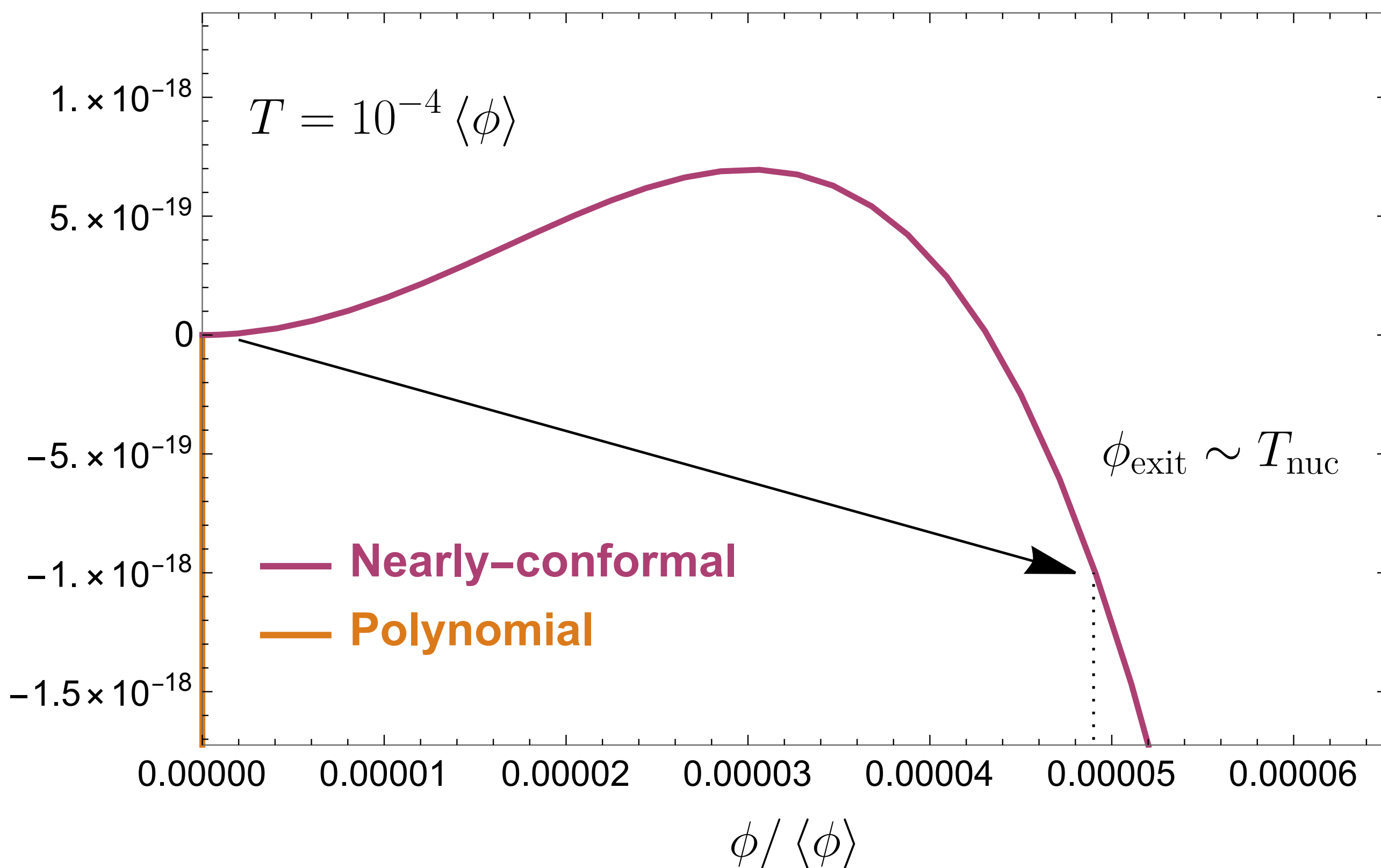
$$V(\phi) = D(T^2 - T_0^2)\phi^2 - ET\phi^3 + \frac{\lambda}{4}\phi^4$$

VS

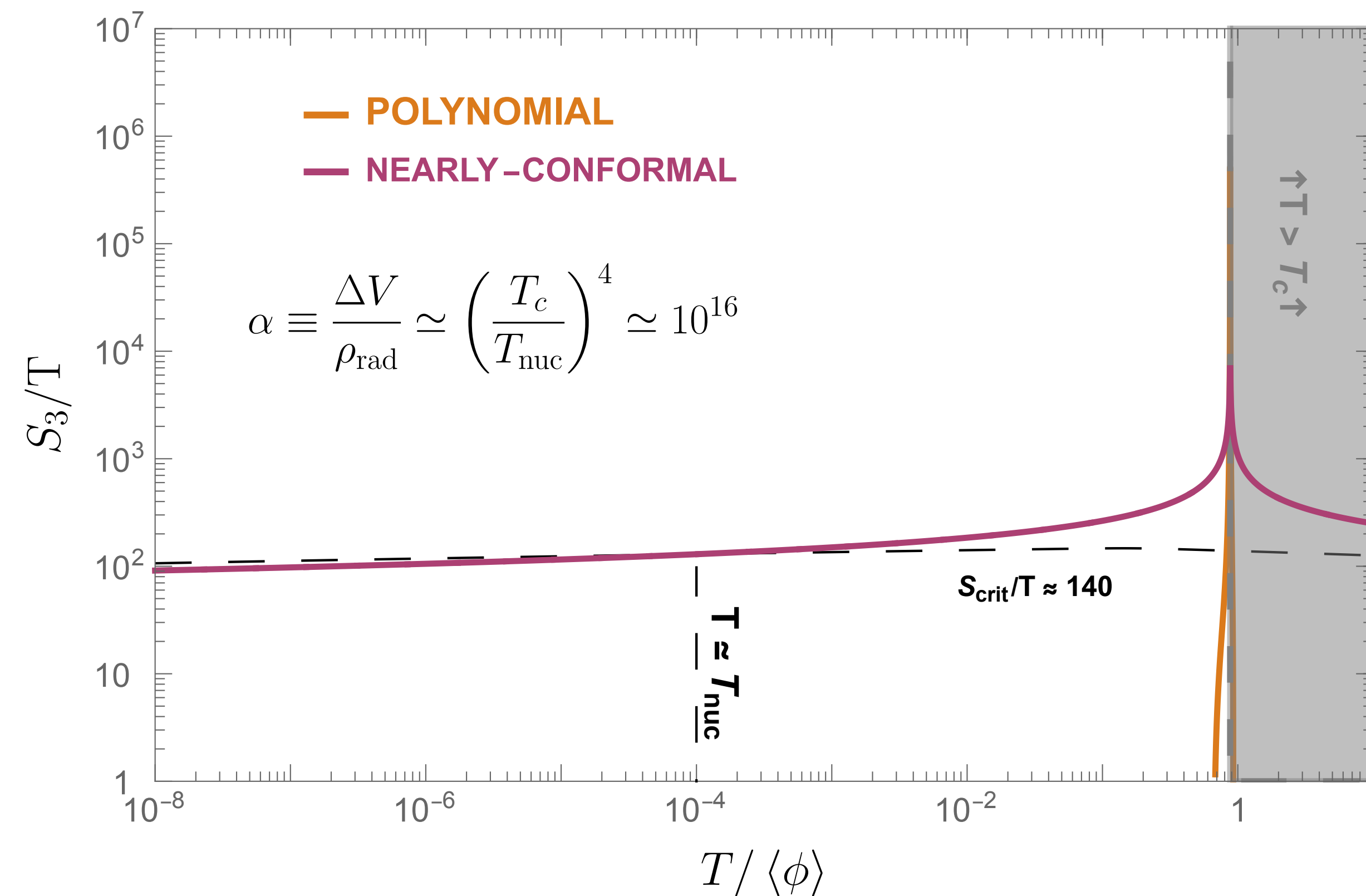
NEARLY-CONFORMAL POTENTIAL

$$V(\phi) = D(T^2 - 0)\phi^2 - ET\phi^3 + \frac{\lambda}{4}\phi^4 \log\left(\frac{\phi}{\phi_*}\right)$$

Potential



O_3 bounce action



POLYNOMIAL POTENTIAL

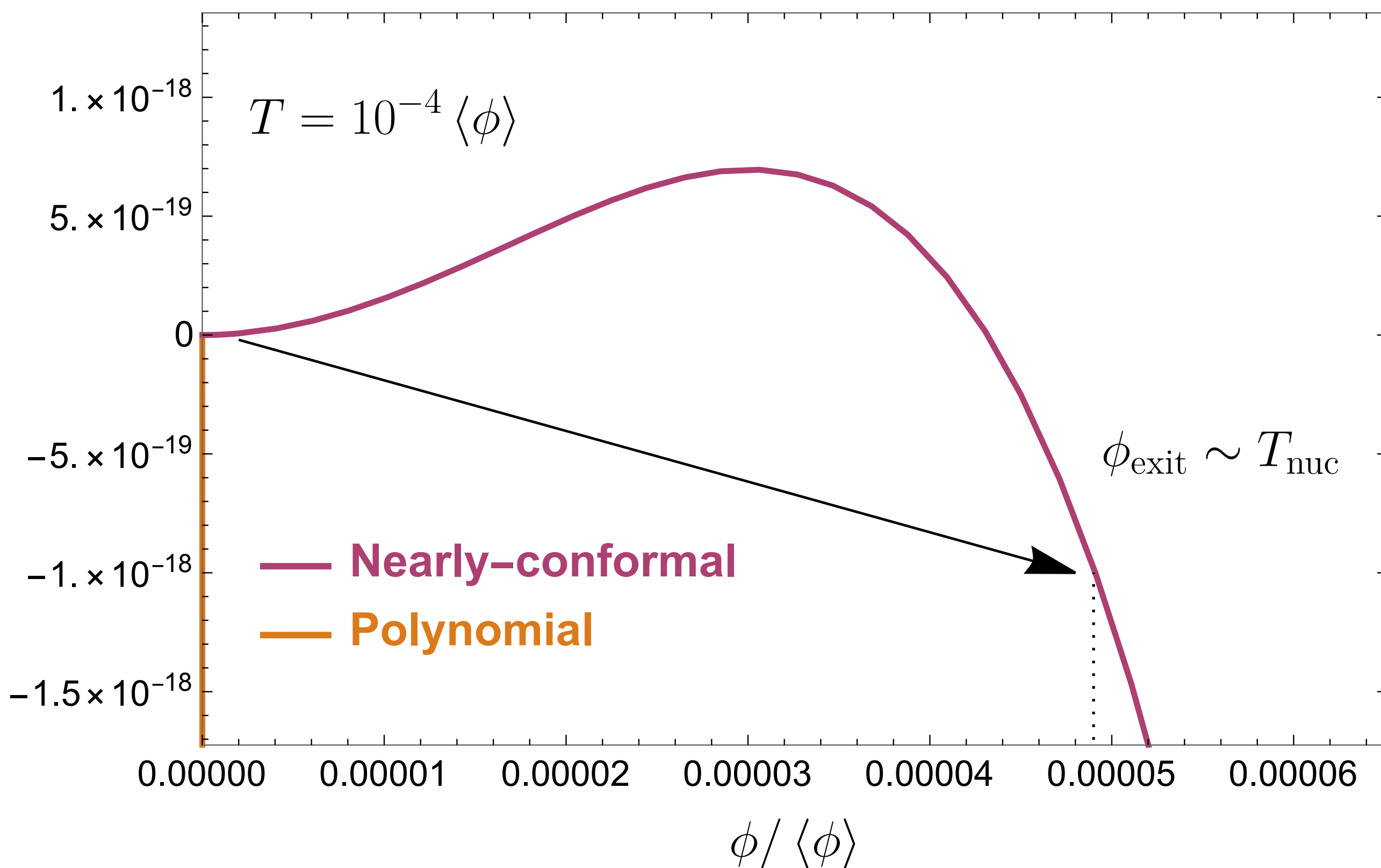
$$V(\phi) = D(T^2 - T_0^2)\phi^2 - ET\phi^3 + \frac{\lambda}{4}\phi^4$$

VS

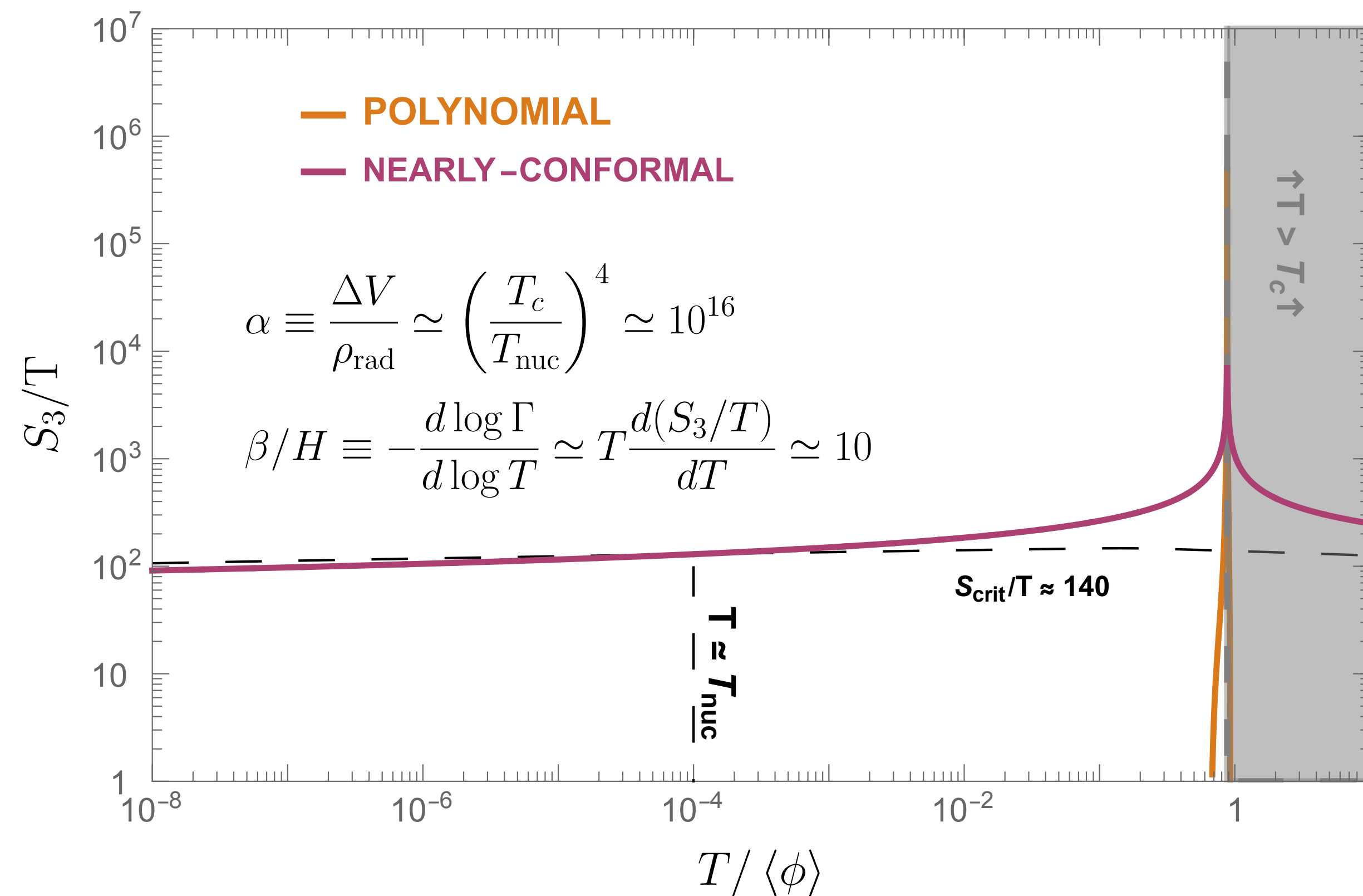
NEARLY-CONFORMAL POTENTIAL

$$V(\phi) = D(T^2 - 0)\phi^2 - ET\phi^3 + \frac{\lambda}{4}\phi^4 \log\left(\frac{\phi}{\phi_*}\right)$$

Potential



O_3 bounce action

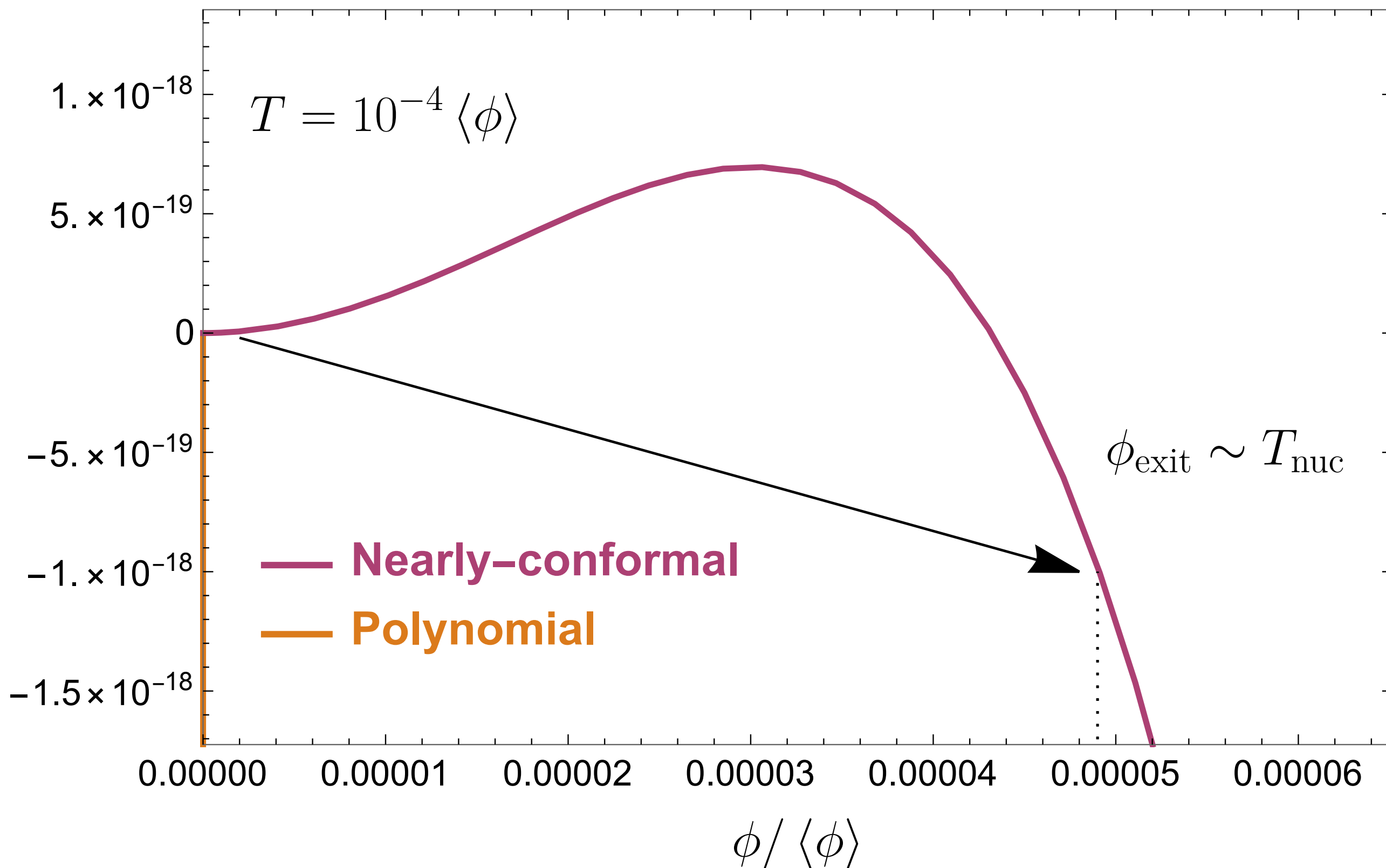


TAKE HOME : Supercooled phase transitions arises in presence of FLAT direction, are STRONG and SLOW

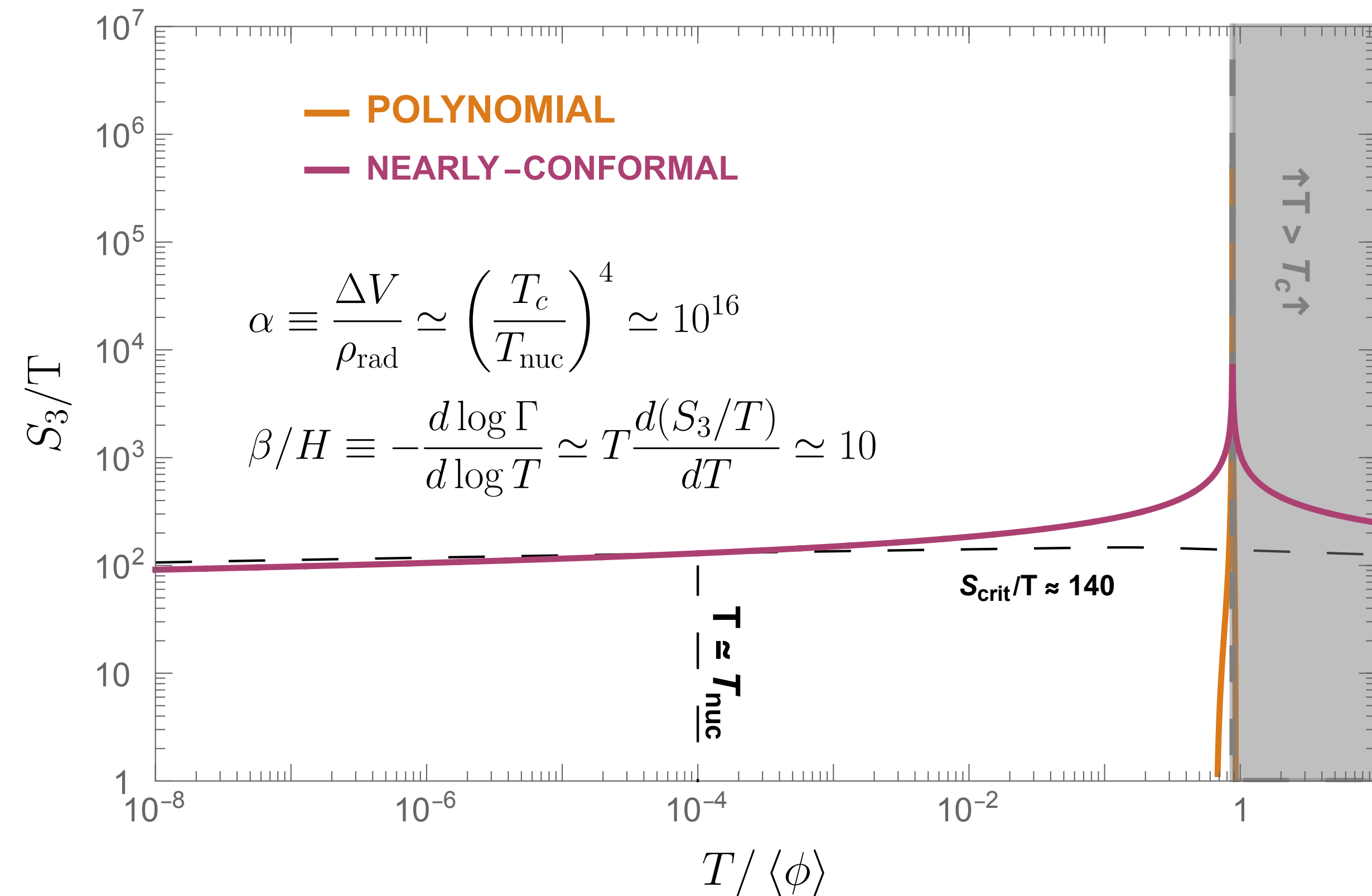
NEARLY-CONFORMAL POTENTIAL

$$V(\phi) = D(T^2 - 0)\phi^2 - ET\phi^3 + \frac{\lambda}{4}\phi^4 \log\left(\frac{\phi}{\phi_*}\right)$$

Potential



O_3 bounce action



Classes of nearly-conformal models

<i>Space-time dimension</i> <i>Strength coupling</i>	Weakly-coupled	Strongly-coupled
D = 4		
D = 5		

Classes of nearly-conformal models

Space-time dimension \ Strength coupling	Weakly-coupled	Strongly-coupled
D = 4	Coleman-Weinberg $V(\phi) = \beta_\lambda \frac{\phi^4}{4} \left[\log \left(\frac{\phi}{f} \right) - \frac{1}{4} \right]$	
D = 5		

Classes of nearly-conformal models

Strength coupling Space-time dimension	Weakly-coupled	Strongly-coupled
D = 4	Coleman-Weinberg $V(\phi) = \beta_\lambda \frac{\phi^4}{4} \left[\log \left(\frac{\phi}{f} \right) - \frac{1}{4} \right]$	Light-dilaton $V(\phi) = g_\chi^2 \frac{\sigma^4}{4} \left[1 - \frac{1}{1+\epsilon} \left(\frac{\sigma}{f} \right)^\epsilon \right]$
D = 5		

Classes of nearly-conformal models

Strength coupling Space-time dimension	Weakly-coupled	Strongly-coupled
D = 4	Coleman-Weinberg $V(\phi) = \beta_\lambda \frac{\phi^4}{4} \left[\log \left(\frac{\phi}{f} \right) - \frac{1}{4} \right]$	Light-dilaton $V(\phi) = g_\chi^2 \frac{\sigma^4}{4} \left[1 - \frac{1}{1+\epsilon} \left(\frac{\sigma}{f} \right)^\epsilon \right]$
D = 5		

$$V(\phi) = \beta_\lambda \frac{\phi^4}{4} \left[\log \left(\frac{\phi}{f} \right) - \frac{1}{4} \right] \xleftarrow{\epsilon \rightarrow 0} V(\phi) = g_\chi^2 \frac{\sigma^4}{4} \left[1 - \frac{1}{1+\epsilon} \left(\frac{\sigma}{f} \right)^\epsilon \right]$$

Classes of nearly-conformal models

Space-time dimension Strength coupling	Weakly-coupled	Strongly-coupled
D = 4	Coleman-Weinberg $V(\phi) = \beta_\lambda \frac{\phi^4}{4} \left[\log \left(\frac{\phi}{f} \right) - \frac{1}{4} \right]$	Light-dilaton $V(\phi) = g_\chi^2 \frac{\sigma^4}{4} \left[1 - \frac{1}{1+\epsilon} \left(\frac{\sigma}{f} \right)^\epsilon \right]$
D = 5	Warped fifth dimension $V(\mu) = v_{\text{IR}}^2 \mu^4 \left[(4 + 2\epsilon) \left(1 - \frac{v_{\text{UV}}}{v_{\text{IR}}} \left(\frac{\mu}{\mu_0} \right)^\epsilon \right)^2 + \delta \right]$	

Weakly-coupled

Strongly-coupled

Coleman-Weinberg

Light-dilaton

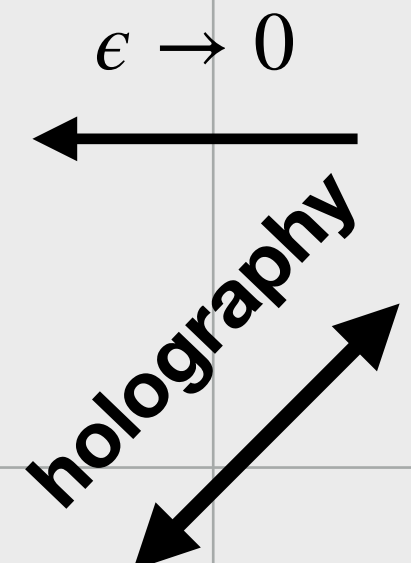
$$V(\phi) = \beta_\lambda \frac{\phi^4}{4} \left[\log \left(\frac{\phi}{f} \right) - \frac{1}{4} \right] \xleftarrow{\epsilon \rightarrow 0} V(\phi) = g_\chi^2 \frac{\sigma^4}{4} \left[1 - \frac{1}{1+\epsilon} \left(\frac{\sigma}{f} \right)^\epsilon \right]$$

Warped fifth dimension

$$V(\mu) = v_{\text{IR}}^2 \mu^4 \left[(4 + 2\epsilon) \left(1 - \frac{v_{\text{UV}}}{v_{\text{IR}}} \left(\frac{\mu}{\mu_0} \right)^\epsilon \right)^2 + \delta \right]$$

Classes of nearly-conformal models

Space-time dimension Strength coupling	Weakly-coupled	Strongly-coupled
D = 4	Coleman-Weinberg $V(\phi) = \beta_\lambda \frac{\phi^4}{4} \left[\log \left(\frac{\phi}{f} \right) - \frac{1}{4} \right]$	Light-dilaton $V(\phi) = g_\chi^2 \frac{\sigma^4}{4} \left[1 - \frac{1}{1+\epsilon} \left(\frac{\sigma}{f} \right)^\epsilon \right]$
D = 5	Warped fifth dimension $V(\mu) = v_{\text{IR}}^2 \mu^4 \left[(4 + 2\epsilon) \left(1 - \frac{v_{\text{UV}}}{v_{\text{IR}}} \left(\frac{\mu}{\mu_0} \right)^\epsilon \right)^2 + \delta \right]$	



Cosmological consequences of supercooling

Cosmological consequences of supercooling

1) Large GW spectrum

Cosmological consequences of supercooling

1) Large GW spectrum

2) Dilution of relics

Cosmological consequences of supercooling

1) Large GW spectrum

2) Dilution of relics

3) Relativistic bubble walls

Cosmological consequences of supercooling

- 1) Large GW spectrum**
- 2) Dilution of relics**
- 3) Relativistic bubble walls**
- 4) High energy particle production**

Cosmological consequences of supercooling

1) Large GW spectrum

2) Dilution of relics

3) Relativistic bubble walls

4) High energy particle production

5) Primordial black hole production

1) Large GW spectrum

Randall, Servant 06'

1) Large GW spectrum

Randall, Servant 06'

$$\Omega_{\text{GW}} h^2 \simeq \Omega_\gamma h^2 \times \left(\frac{\alpha}{1 + \alpha} \right)^2 \times \left(\frac{H}{\beta} \right)^2 \times v_w^3$$

1) Large GW spectrum

Randall, Servant 06'

$$\Omega_{\text{GW}} h^2 \simeq \Omega_\gamma h^2 \times \left(\frac{\alpha}{1 + \alpha} \right)^2 \times \left(\frac{H}{\beta} \right)^2 \times v_w^3$$

Normalisation

$$10^{-5}$$

1) Large GW spectrum

Randall, Servant 06'

$$\Omega_{\text{GW}} h^2 \simeq \Omega_\gamma h^2 \times \left(\frac{\alpha}{1 + \alpha} \right)^2 \times \left(\frac{H}{\beta} \right)^2 \times v_w^3$$

Normalisation

Scalar field fraction

$$10^{-5}$$

$$\alpha \gg 1$$

1) Large GW spectrum

Randall, Servant 06'

$$\Omega_{\text{GW}} h^2 \simeq \Omega_\gamma h^2 \times \left(\frac{\alpha}{1 + \alpha} \right)^2 \times \left(\frac{H}{\beta} \right)^2 \times v_w^3$$

Normalisation

Scalar field fraction

Bubble size

$$10^{-5}$$

$$\alpha \gg 1$$

$$\beta/H \sim 15$$

1) Large GW spectrum

Randall, Servant 06'

$$\Omega_{\text{GW}} h^2 \simeq \Omega_\gamma h^2 \times \left(\frac{\alpha}{1 + \alpha} \right)^2 \times \left(\frac{H}{\beta} \right)^2 \times v_w^3$$

Normalisation

Scalar field fraction

Bubble size

Bubble wall velocity

$$10^{-5}$$

$$\alpha \gg 1$$

$$\beta/H \sim 15$$

$$v_w \simeq 1$$

1) Large GW spectrum

Randall, Servant 06'

$$\Omega_{\text{GW}} h^2 \simeq \Omega_\gamma h^2 \times \left(\frac{\alpha}{1 + \alpha} \right)^2 \times \left(\frac{H}{\beta} \right)^2 \times v_w^3$$

Normalisation

Scalar field fraction

Bubble size

Bubble wall velocity

$$10^{-5}$$

$$\alpha \gg 1$$

$$\beta/H \sim 15$$

$$v_w \simeq 1$$

$$\Omega_{\text{GW}} h^2 \simeq 10^{-8}$$

1) Large GW spectrum

Randall, Servant 06'

$$\Omega_{\text{GW}} h^2 \simeq \Omega_\gamma h^2 \times \left(\frac{\alpha}{1 + \alpha} \right)^2 \times \left(\frac{H}{\beta} \right)^2 \times v_w^3$$

Normalisation

Scalar field fraction

Bubble size

Bubble wall velocity

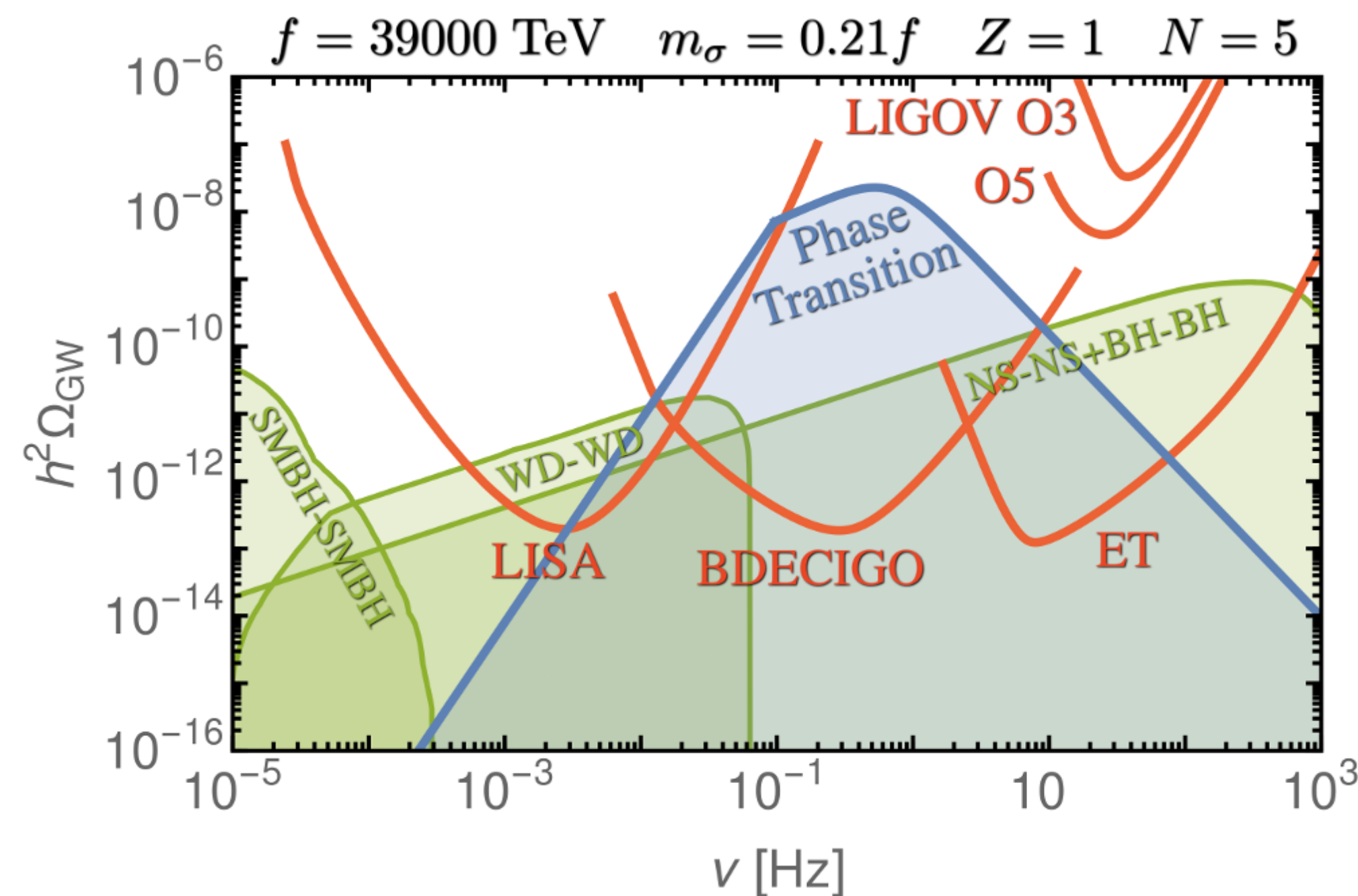
$$10^{-5}$$

$$\alpha \gg 1$$

$$\beta/H \sim 15$$

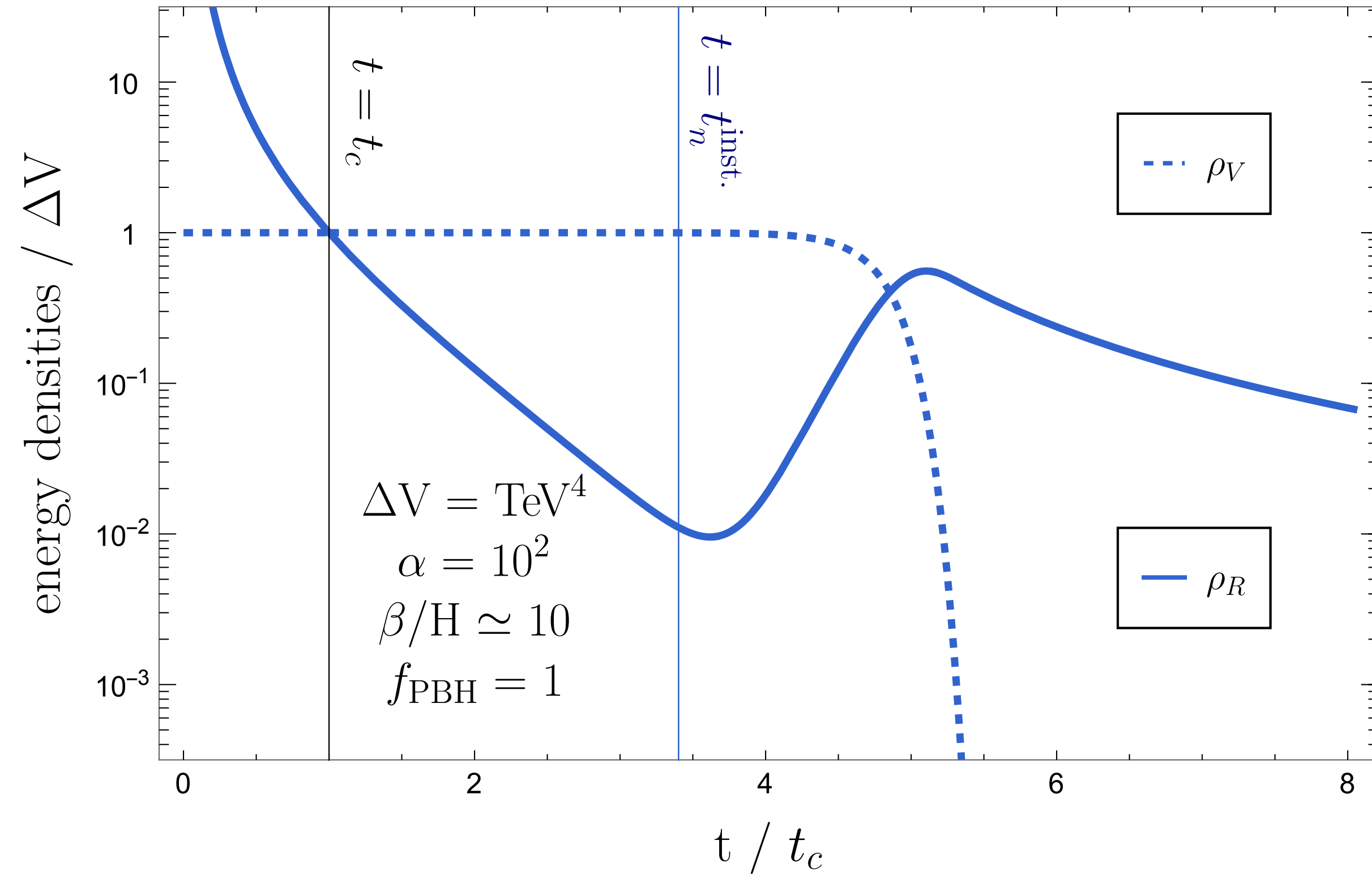
$$v_w \simeq 1$$

$$\Omega_{\text{GW}} h^2 \simeq 10^{-8}$$

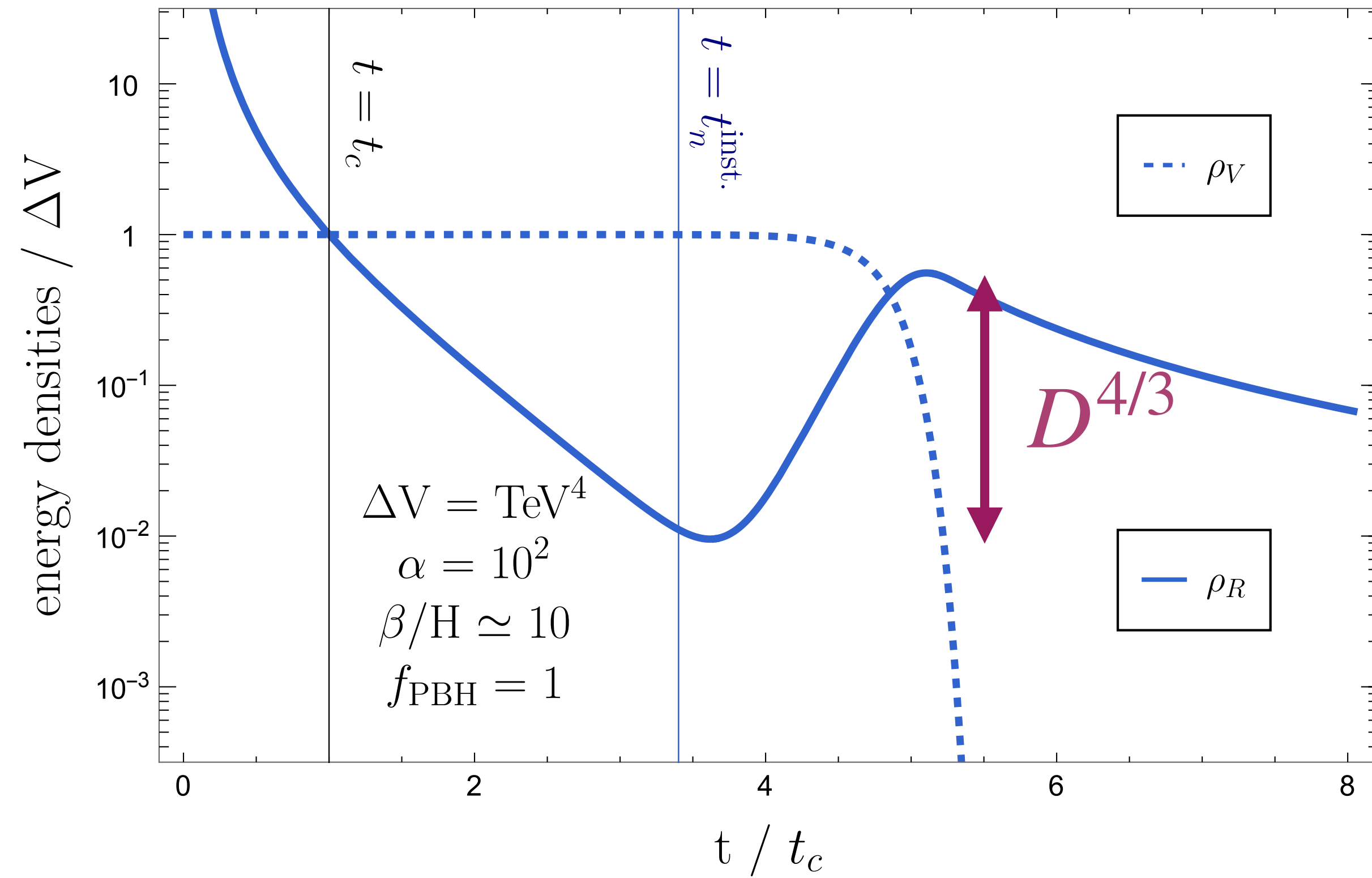


Baldes, YG, Sala, Servant 21'

2) Dilution of relics

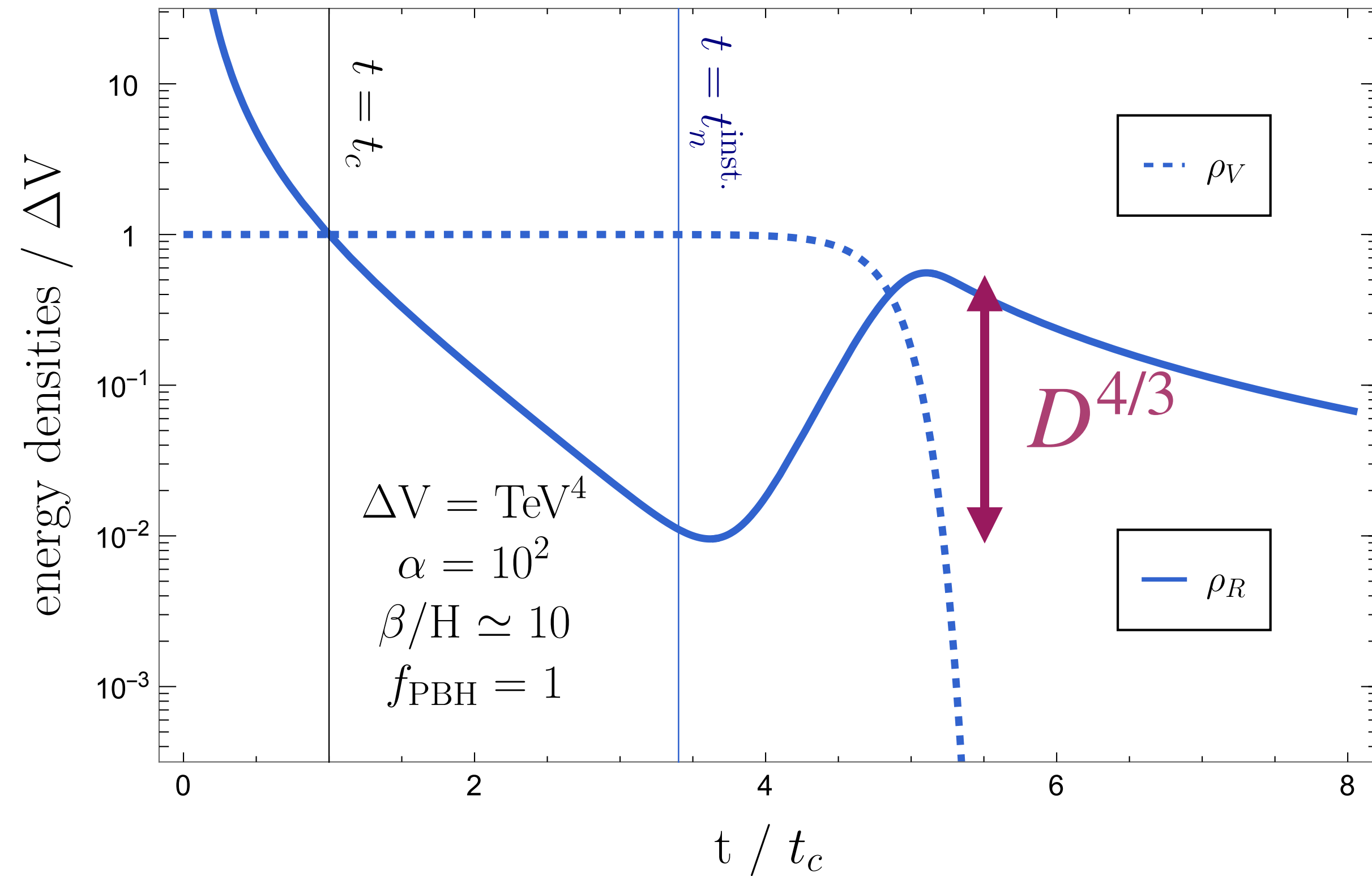


2) Dilution of relics



$$D = \frac{S_{\text{after}}}{S_{\text{before}}} = \left(\frac{T_c}{T_{\text{nuc}}} \right)^3$$

2) Dilution of relics



$$D = \frac{S_{\text{after}}}{S_{\text{before}}} = \left(\frac{T_c}{T_{\text{nuc}}} \right)^3$$

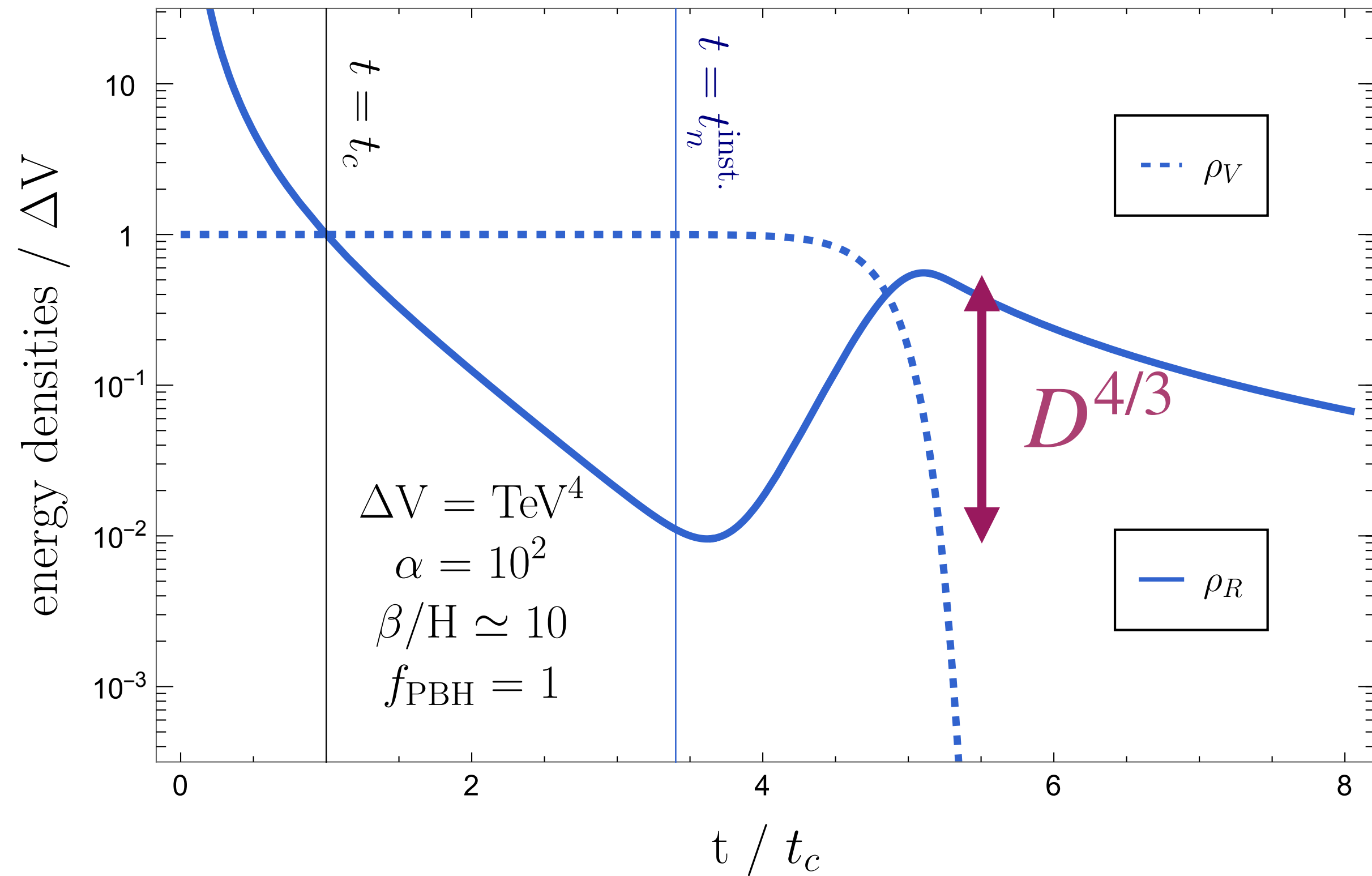
Evade unitarity bound on thermal DM

$\longrightarrow M_{\text{DM}} < 100 \text{ TeV} \times \sqrt{D}$

\nearrow Griest&Kamionkowski 91'

\nwarrow Reheating after PT

2) Dilution of relics



$$D = \frac{S_{\text{after}}}{S_{\text{before}}} = \left(\frac{T_c}{T_{\text{nuc}}} \right)^3$$

(Konstandin, Servant 11')

Warped fifth dimension

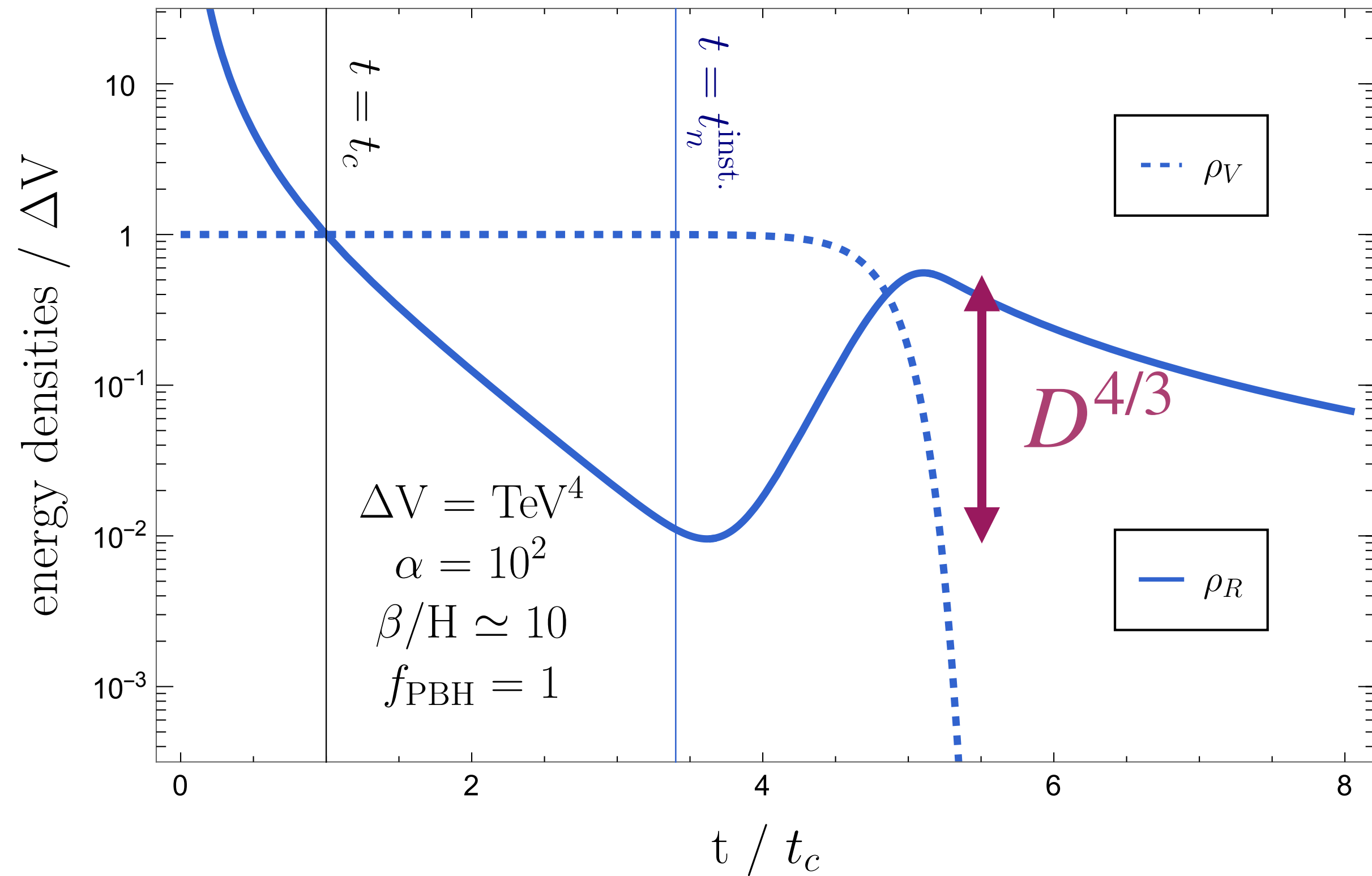
Evade unitarity bound on thermal DM

$\longrightarrow M_{\text{DM}} < 100 \text{ TeV} \times \sqrt{D}$

\nearrow Griest&Kamionkowski 91'

\nwarrow Reheating after PT

2) Dilution of relics



$$D = \frac{S_{\text{after}}}{S_{\text{before}}} = \left(\frac{T_c}{T_{\text{nuc}}} \right)^3$$

(Konstandin, Servant 11')

Warped fifth dimension

(Hambye, Strumia, Teresi 18')

Weakly-coupled

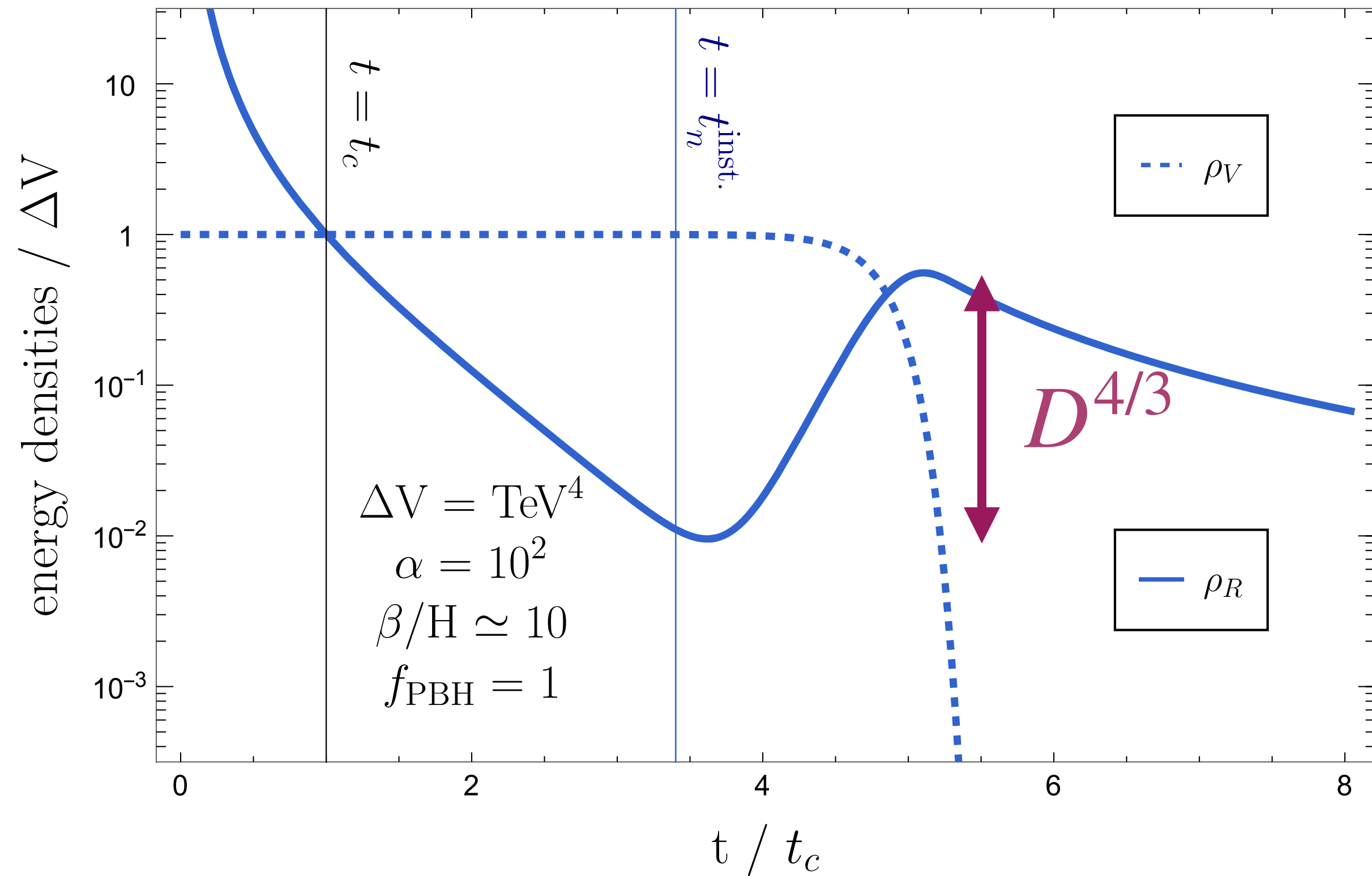
Evade unitarity bound on thermal DM

$\longrightarrow M_{\text{DM}} < 100 \text{ TeV} \times \sqrt{D}$

\nearrow Griest&Kamionkowski 91'

\nwarrow Reheating after PT

2) Dilution of relics



$$D = \frac{S_{\text{after}}}{S_{\text{before}}} = \left(\frac{T_c}{T_{\text{nuc}}} \right)^3$$

Evade unitarity bound on thermal DM

$\longrightarrow M_{\text{DM}} < 100 \text{ TeV} \times \sqrt{D}$

Griest&Kamionkowski 91' Reheating after PT

(Konstandin, Servant 11')

Warped fifth dimension

(Hambye, Strumia, Teresi 18')

Weakly-coupled

(Baratella, Pomarol, Rompineve 18')

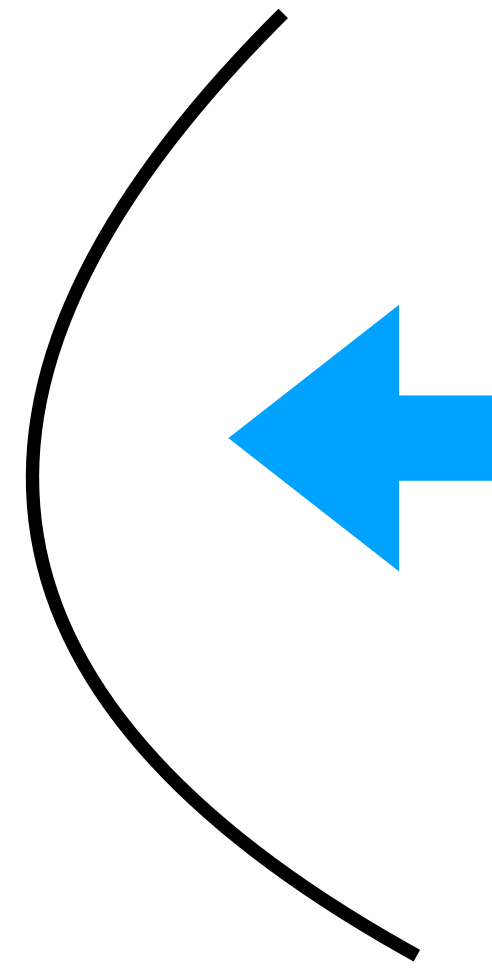
Baldes, YG, Sala 20'

Baldes, YG, Sala, Servant 21'

Strongly-coupled

3) Relativistic bubble walls

3) Relativistic bubble walls

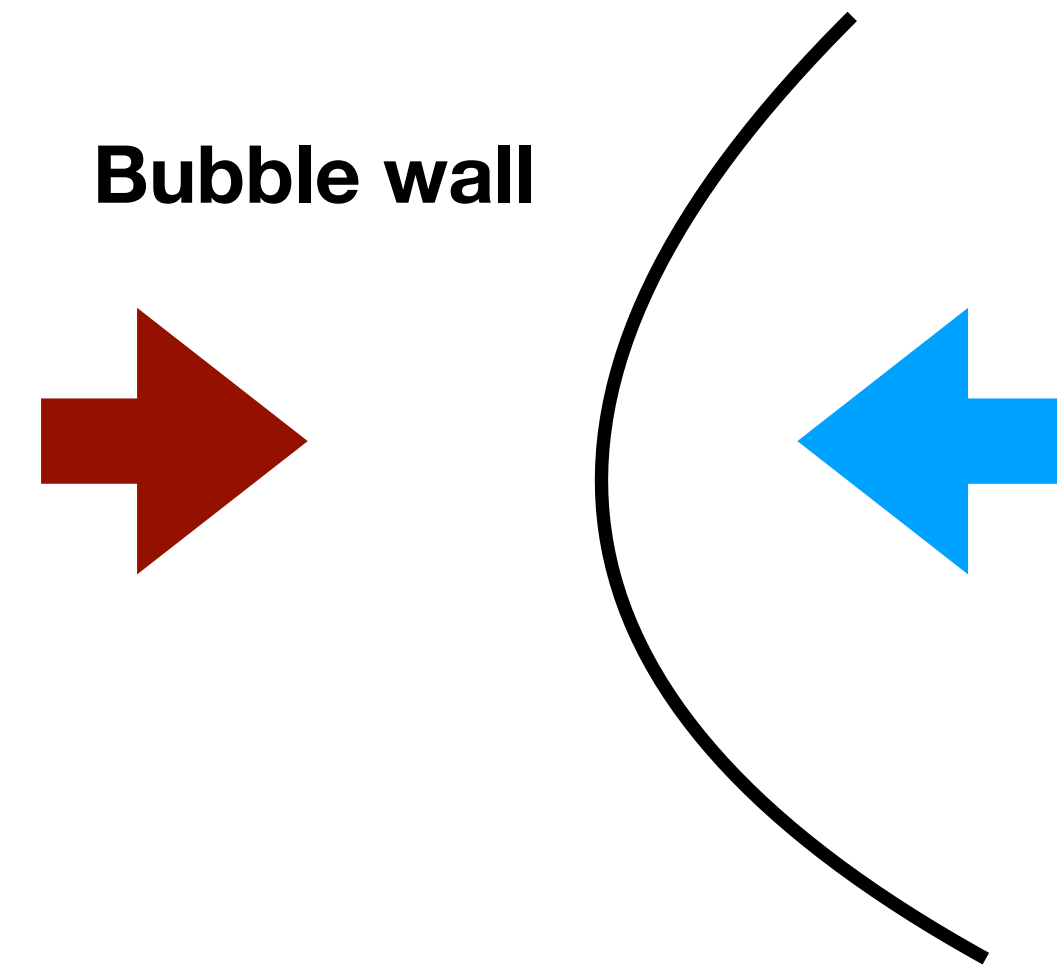


$$\Delta V_{\text{vac}} \simeq T_c^4$$

3) Relativistic bubble walls

$$\mathcal{P}_{\text{LO}} \simeq \Delta m^2 T_{\text{nuc}}^2$$

Bodeker, Moore 09'



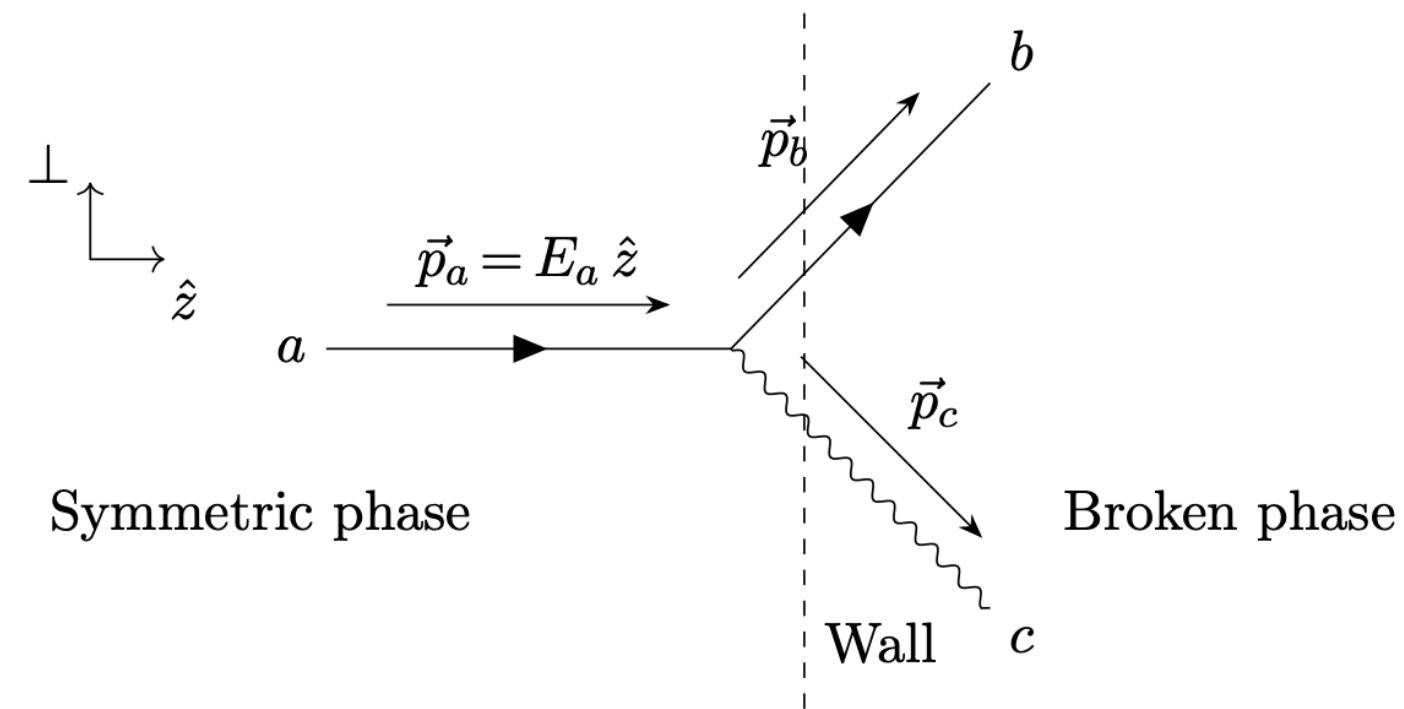
$$\Delta V_{\text{vac}} \simeq T_c^4$$

3) Relativistic bubble walls

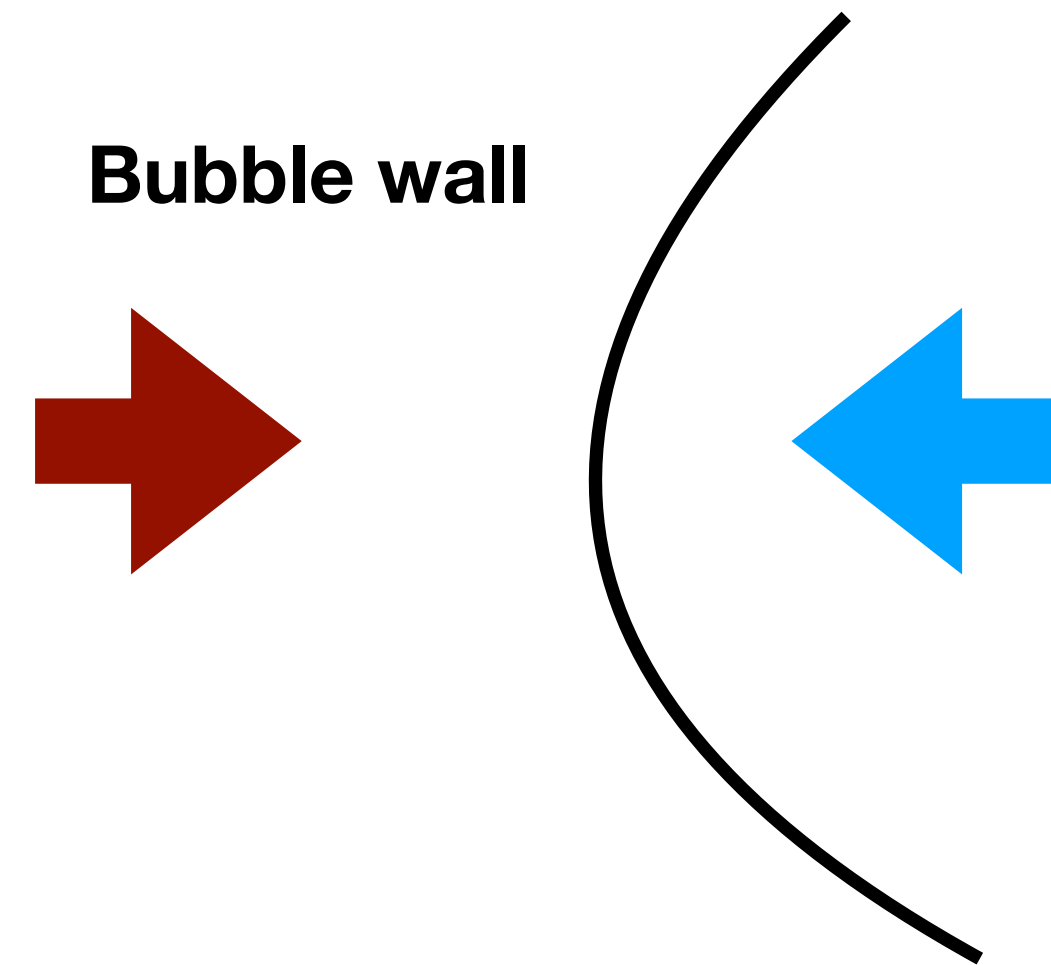
$$\mathcal{P}_{\text{LO}} \simeq \Delta m^2 T_{\text{nuc}}^2$$

Bodeker, Moore 09'

$$\mathcal{P}_{\text{NLO}} \simeq g_w \gamma \Delta m T_{\text{nuc}}^3$$



Bodeker, Moore 17' (Perturbative level)



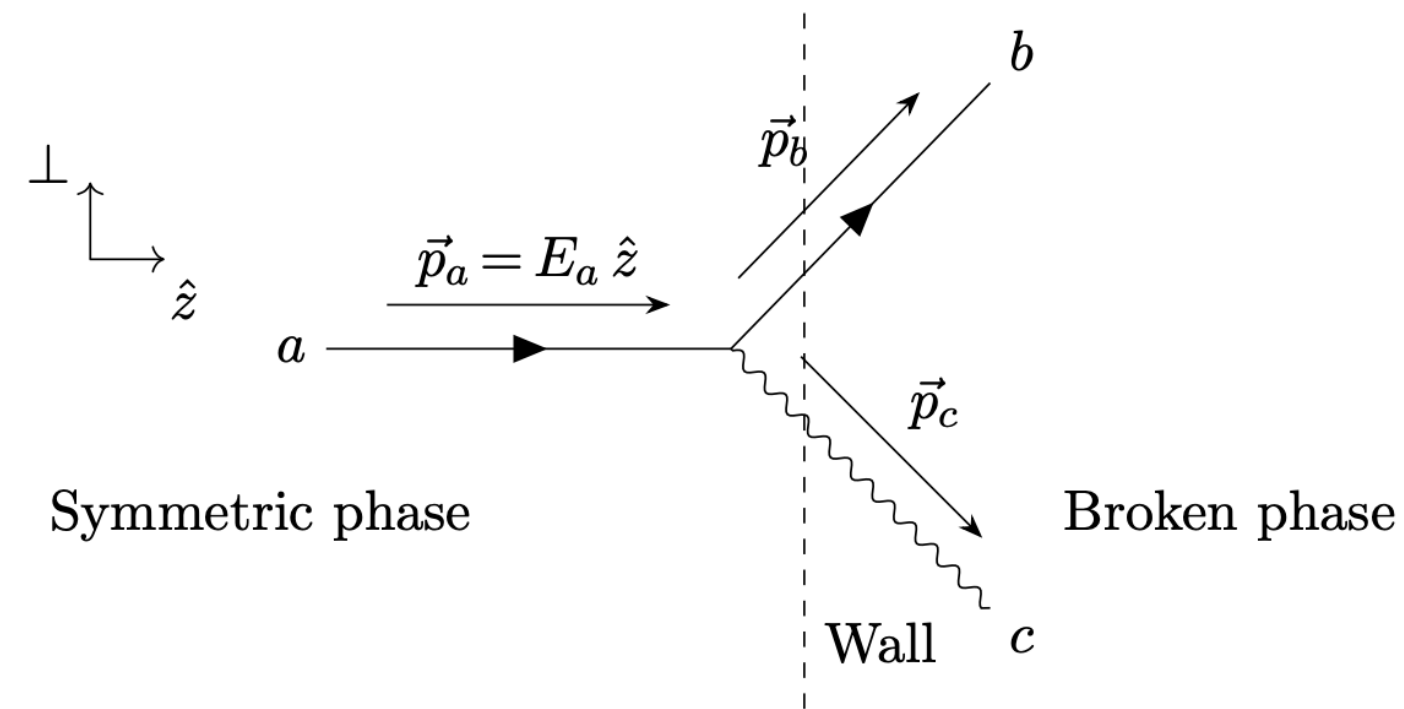
$$\Delta V_{\text{vac}} \simeq T_c^4$$

3) Relativistic bubble walls

$$\mathcal{P}_{\text{LO}} \simeq \Delta m^2 T_{\text{nuc}}^2$$

Bodeker, Moore 09'

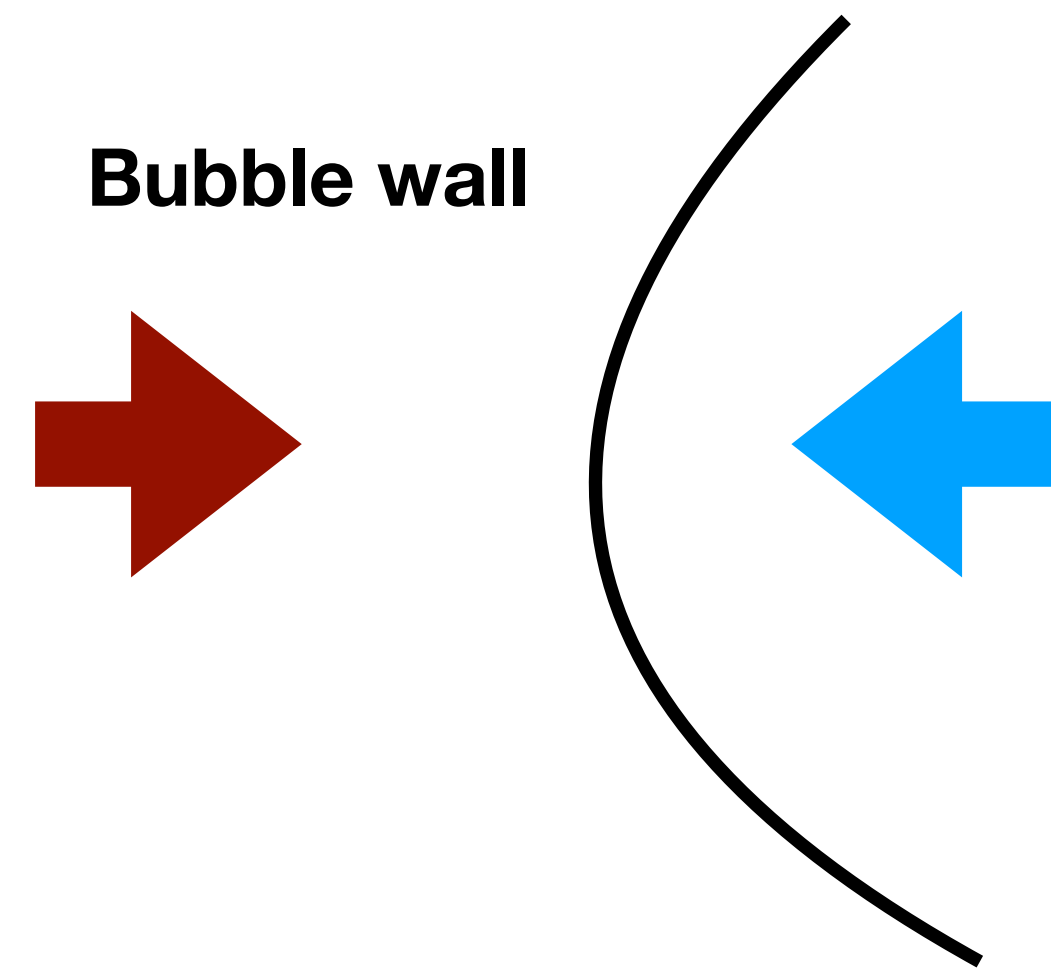
$$\mathcal{P}_{\text{NLO}} \simeq g_w \gamma \Delta m T_{\text{nuc}}^3$$



Bodeker, Moore 17' (Perturbative level)

YG, Jinno, Sala 21' (Sudakov resummation)

Baldes, YG, Sala 20' (Gluon string description)



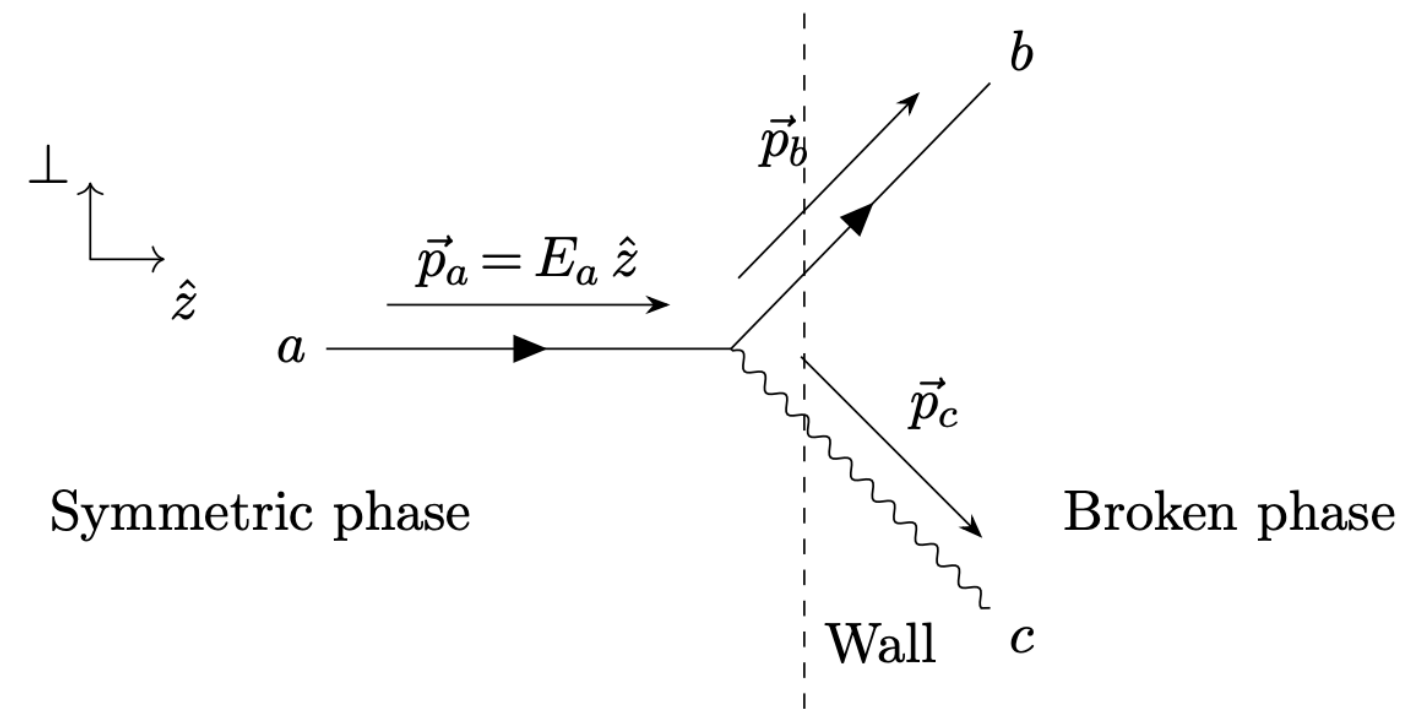
$$\Delta V_{\text{vac}} \simeq T_c^4$$

3) Relativistic bubble walls

$$\mathcal{P}_{LO} \simeq \Delta m^2 T_{\text{nuc}}^2$$

Bodeker, Moore 09'

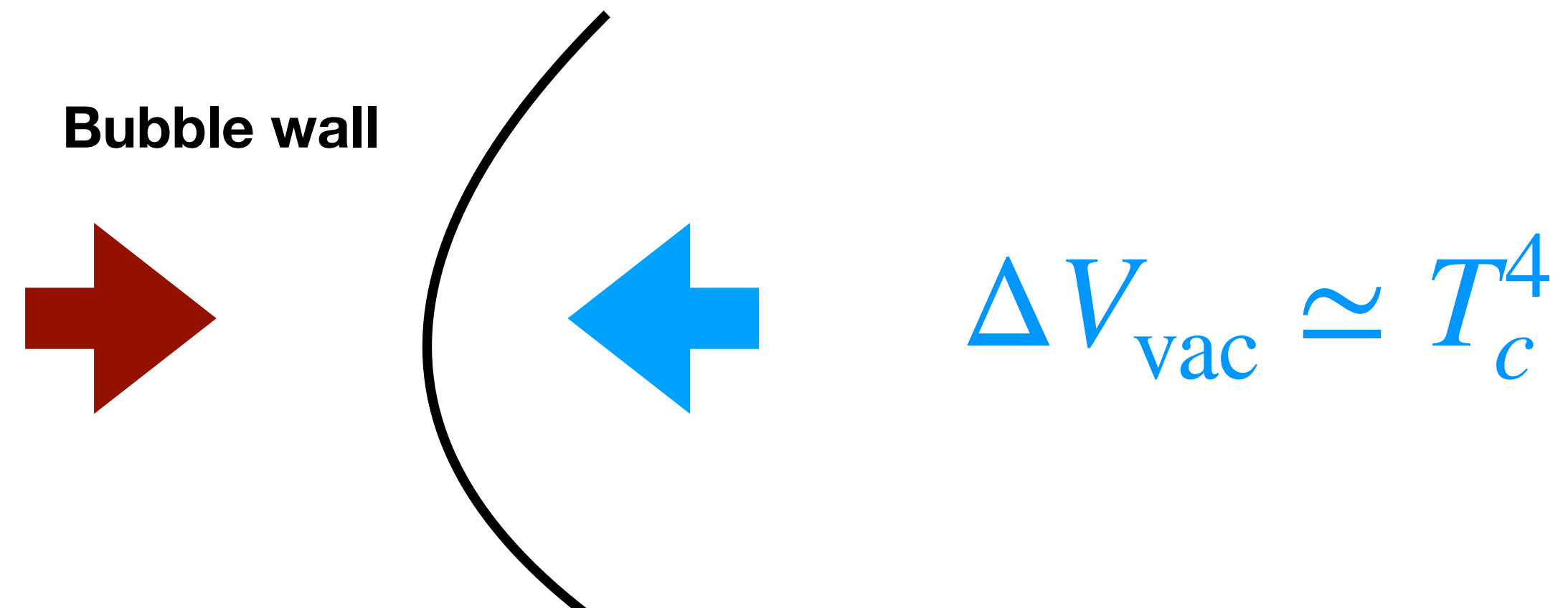
$$\mathcal{P}_{NLO} \simeq g_w \gamma \Delta m T_{\text{nuc}}^3$$



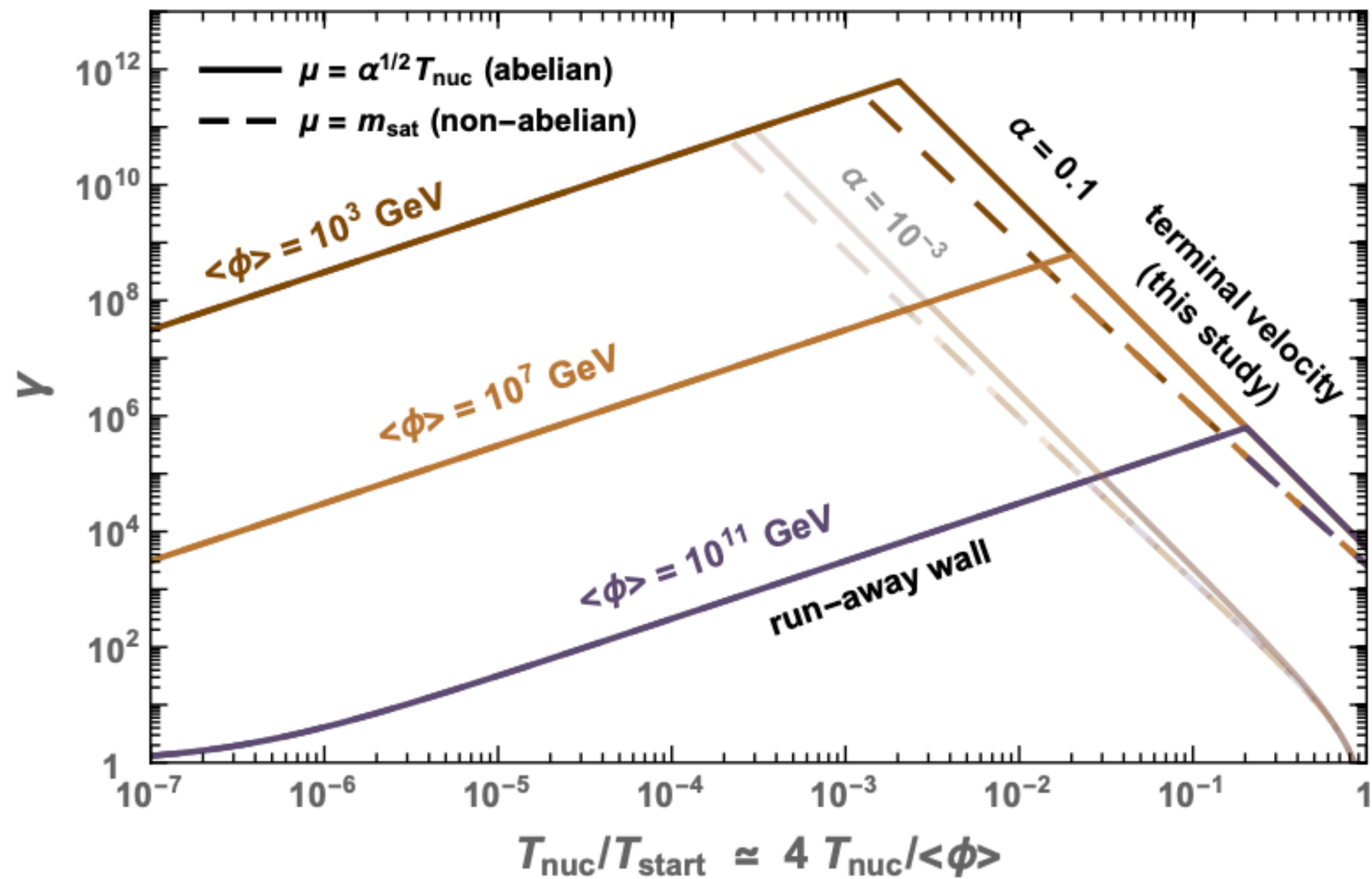
Bodeker, Moore 17' (Perturbative level)

YG, Jinno, Sala 21' (Sudakov resummation)

Baldes, YG, Sala 20' (Gluon string description)



Bubble wall Lorentz factor

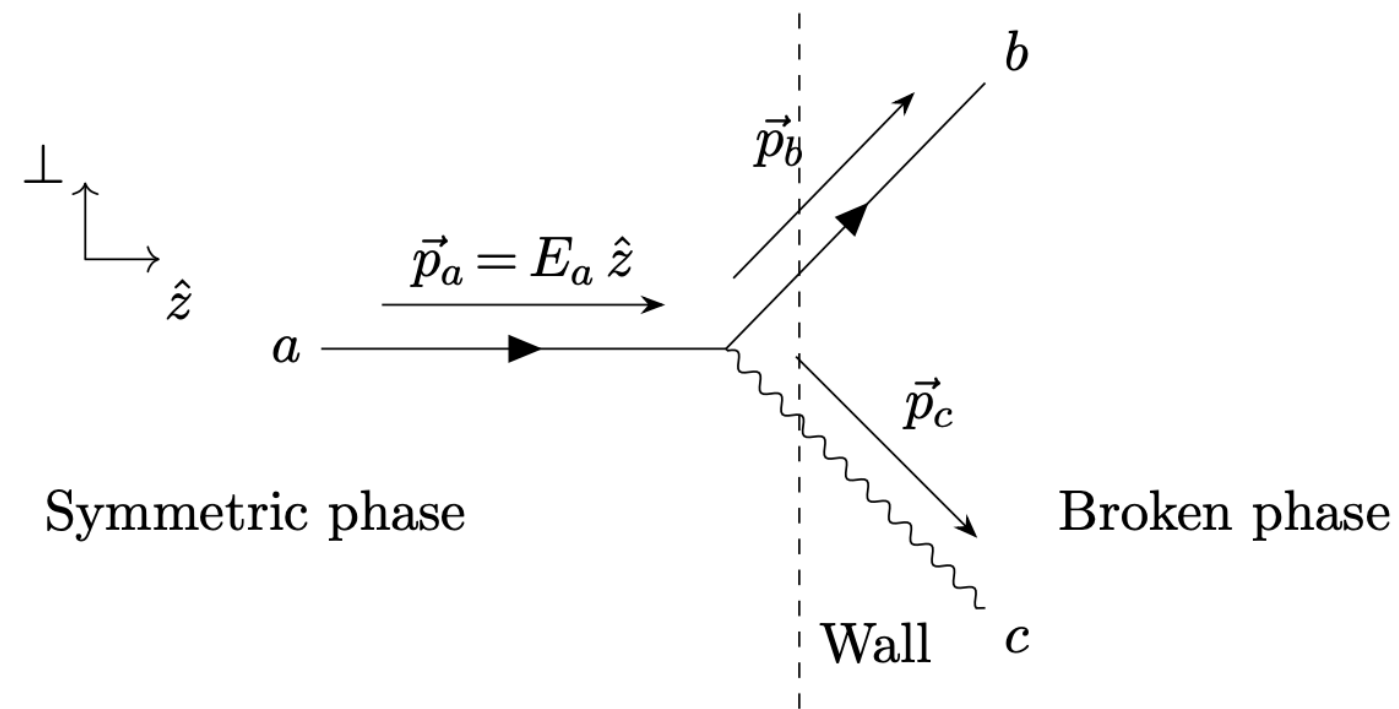


3) Relativistic bubble walls

$$\mathcal{P}_{LO} \simeq \Delta m^2 T_{\text{nuc}}^2$$

Bodeker, Moore 09'

$$\mathcal{P}_{NLO} \simeq g_w \gamma \Delta m T_{\text{nuc}}^3$$



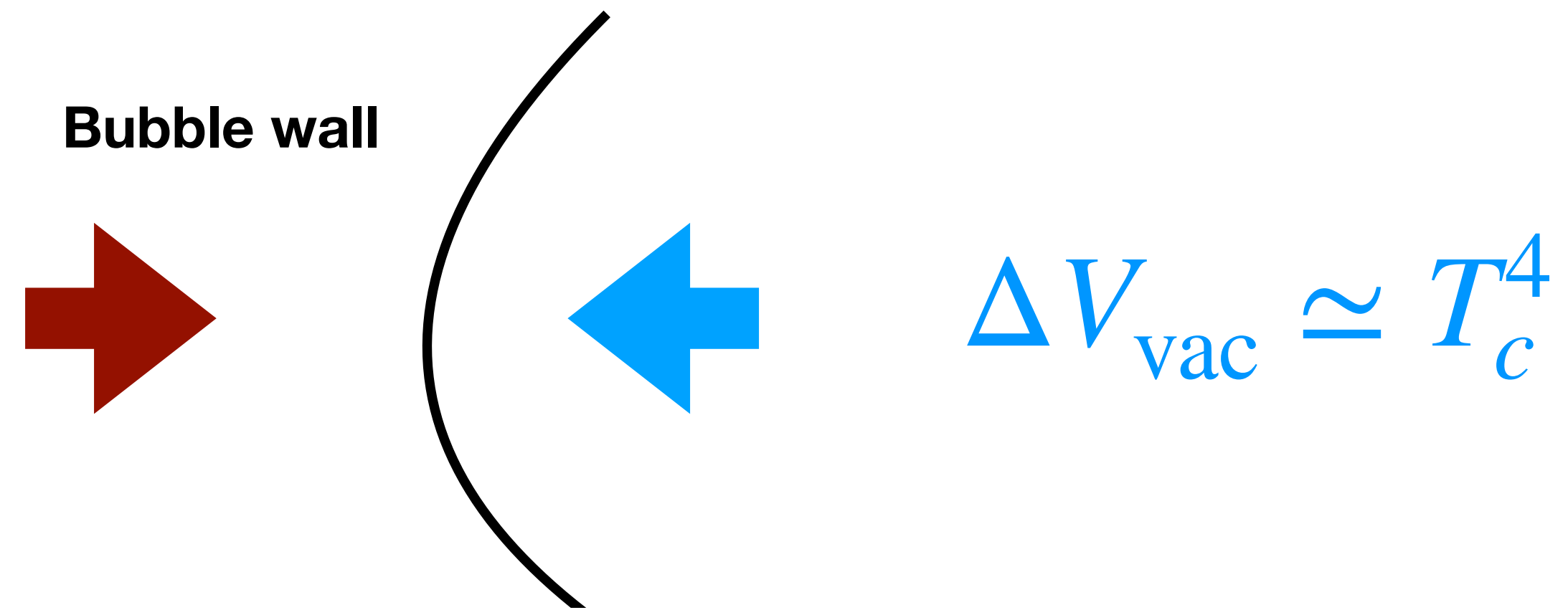
Bodeker, Moore 17' (Perturbative level)

YG, Jinno, Sala 21' (Sudakov resummation)

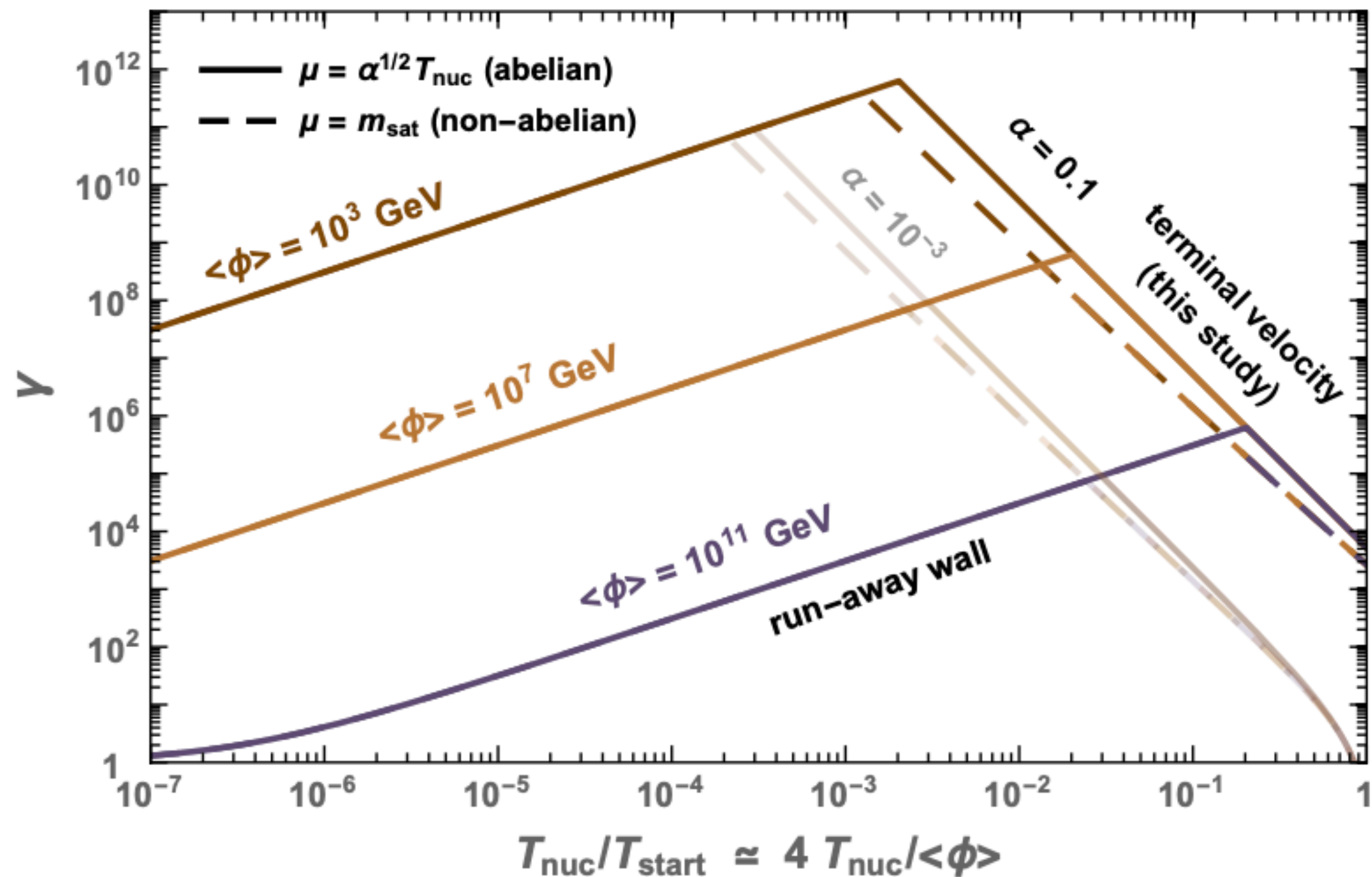
Baldes, YG, Sala 20' (Gluon string description)

There is still a gauge invariance problem

An attempt: Hoche, Kozaczuk, Long, Turner, Wang 20'



Bubble wall Lorentz factor

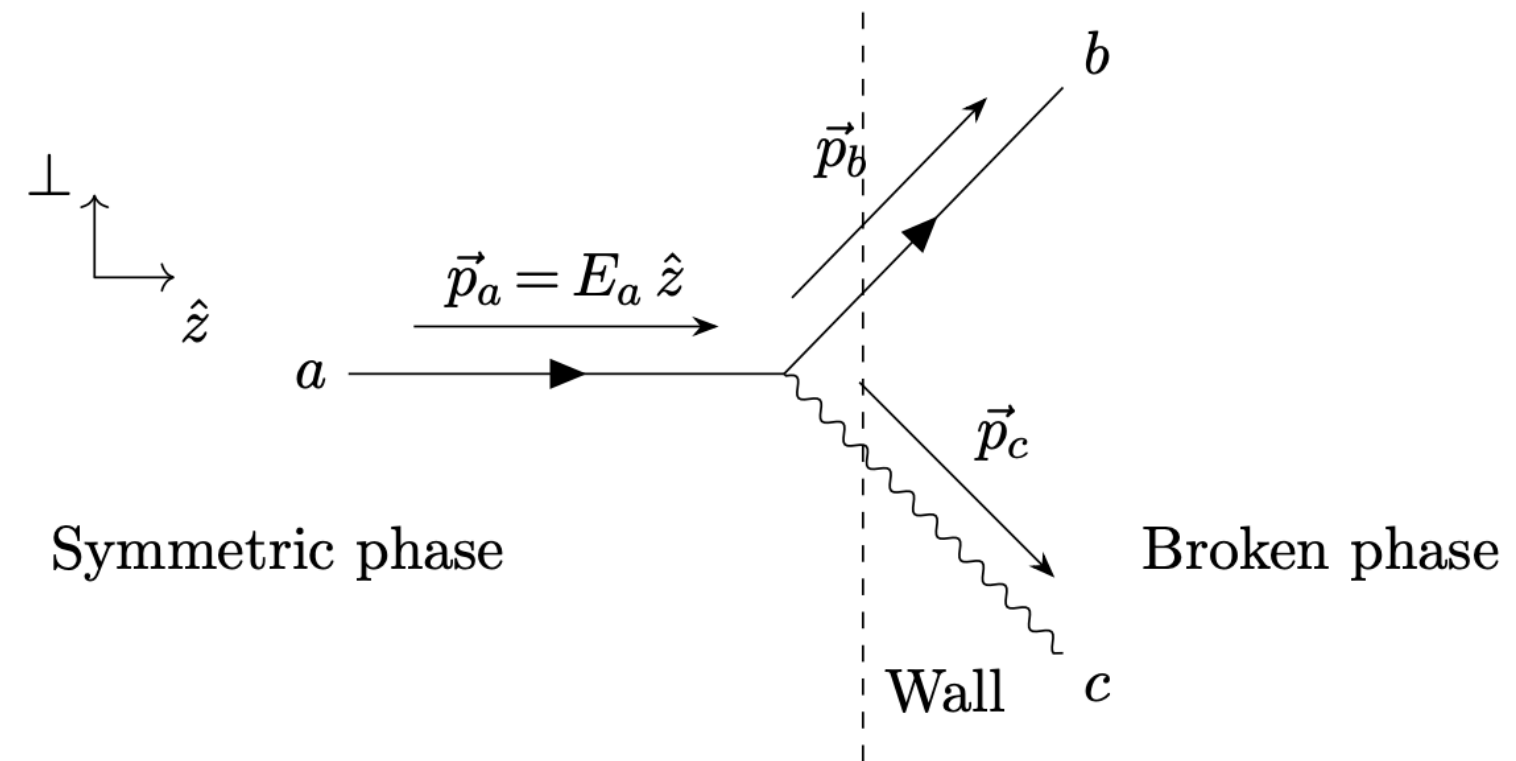


4) High energy particle production

4) High energy particle production

a) Weak interaction with plasma

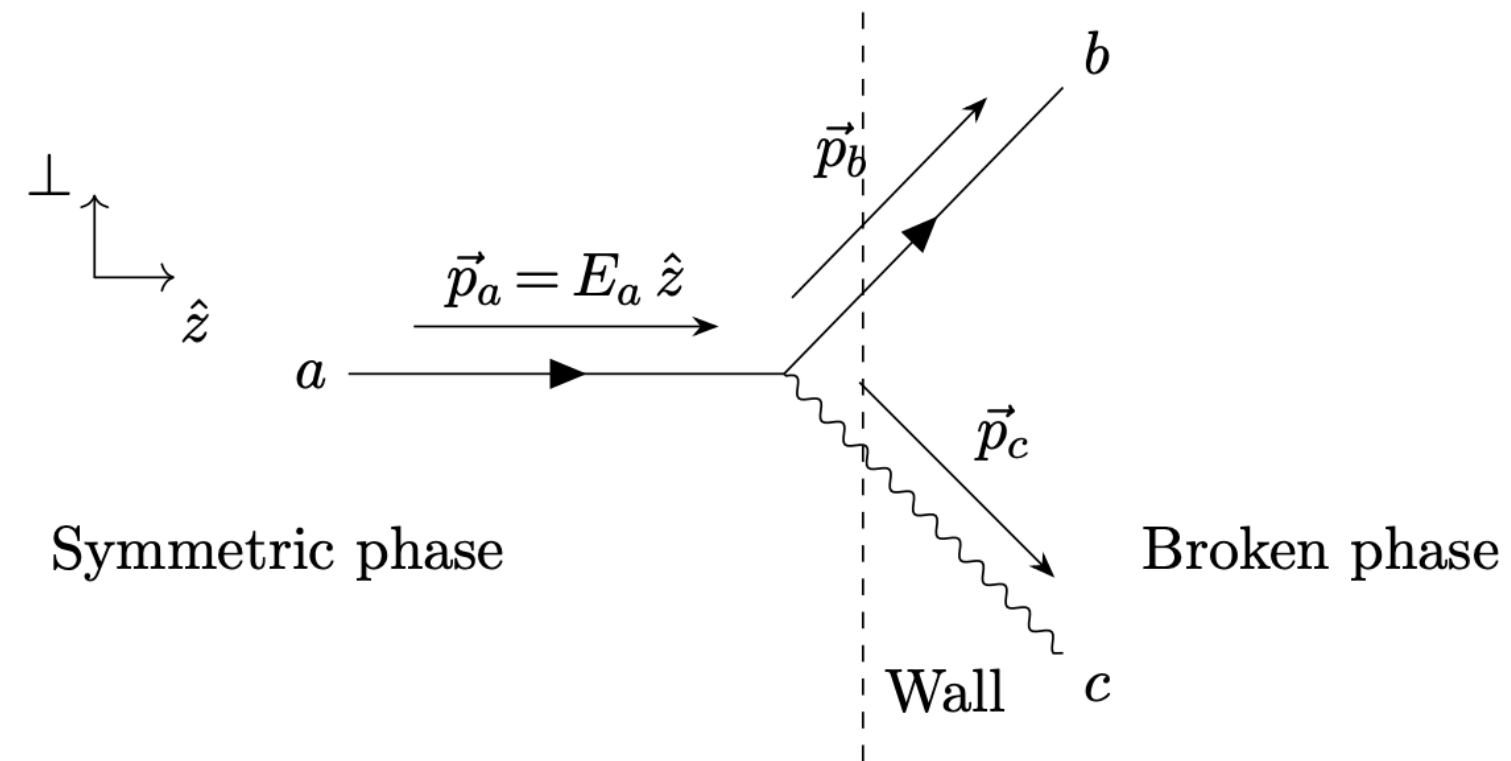
Bodeker, Moore 17'



4) High energy particle production

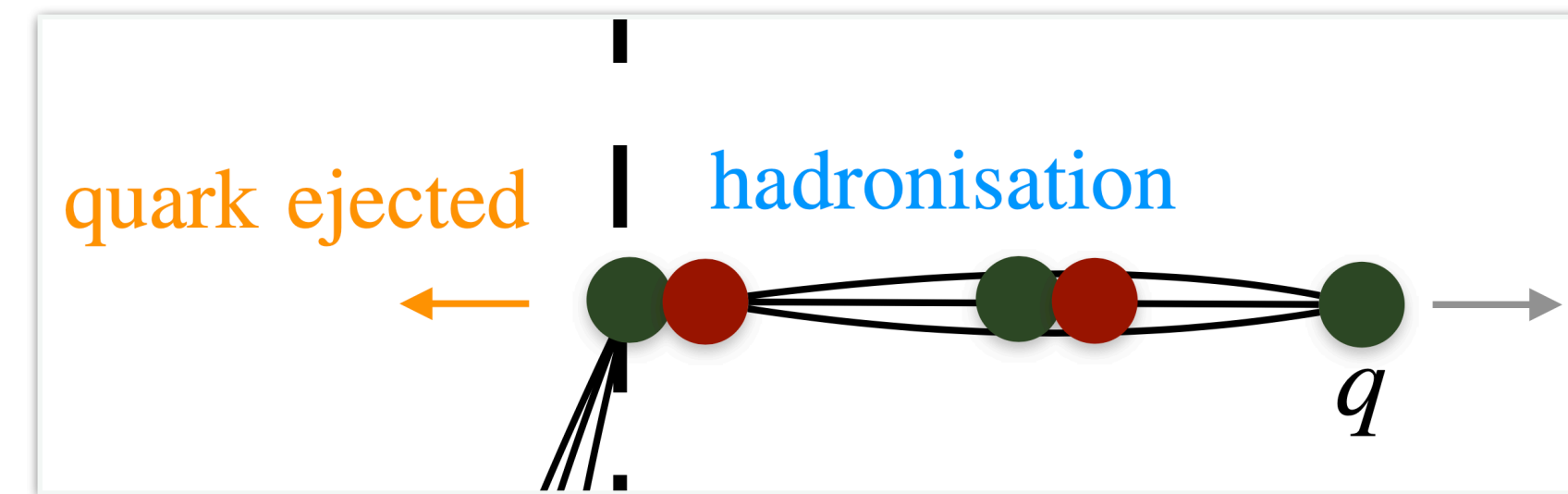
a) Weak interaction with plasma

Bodeker, Moore 17'



b) Strong interaction with plasma

Baldes, YG, Sala 20'

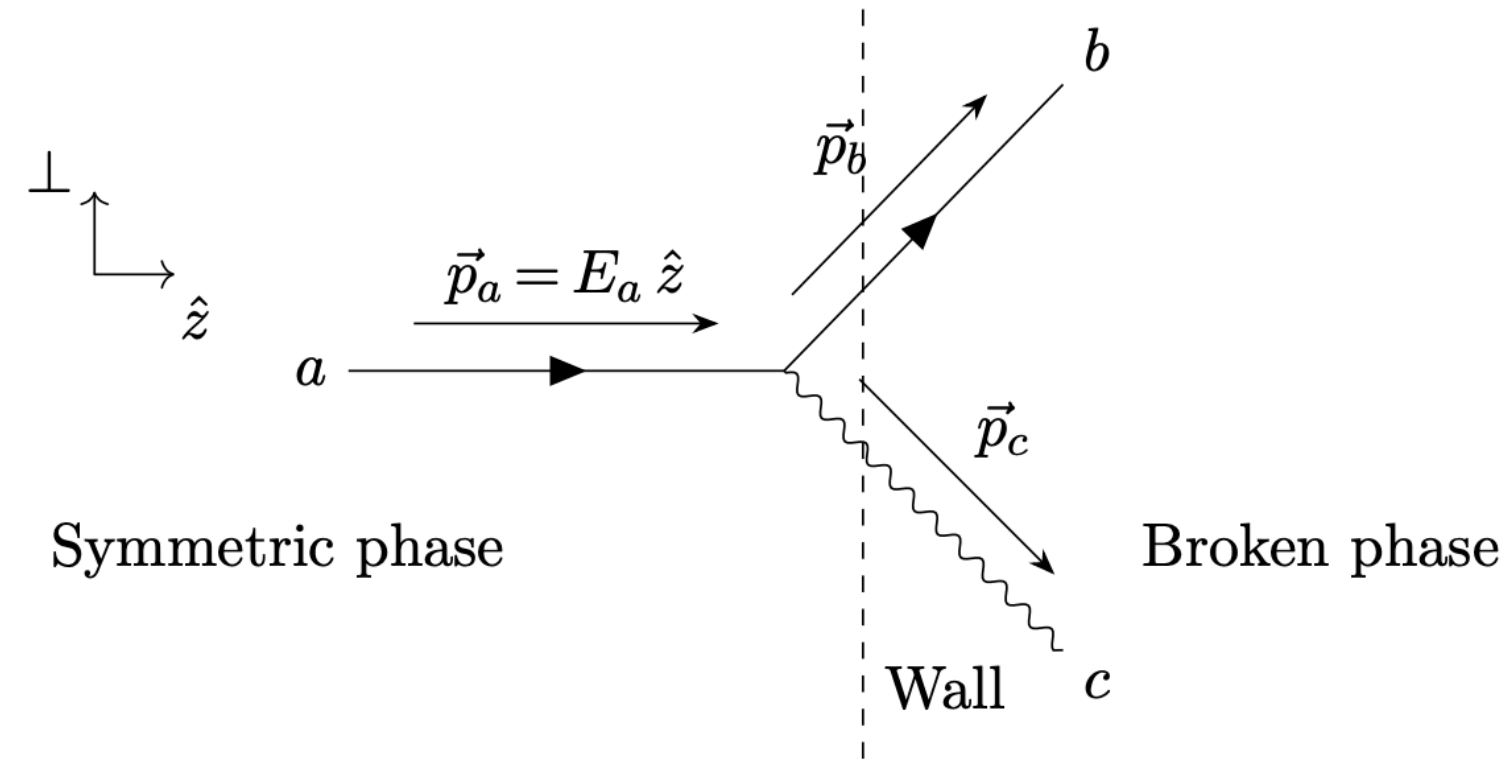


Maximilian Dichtl and Filippo Sala (to appear)

4) High energy particle production

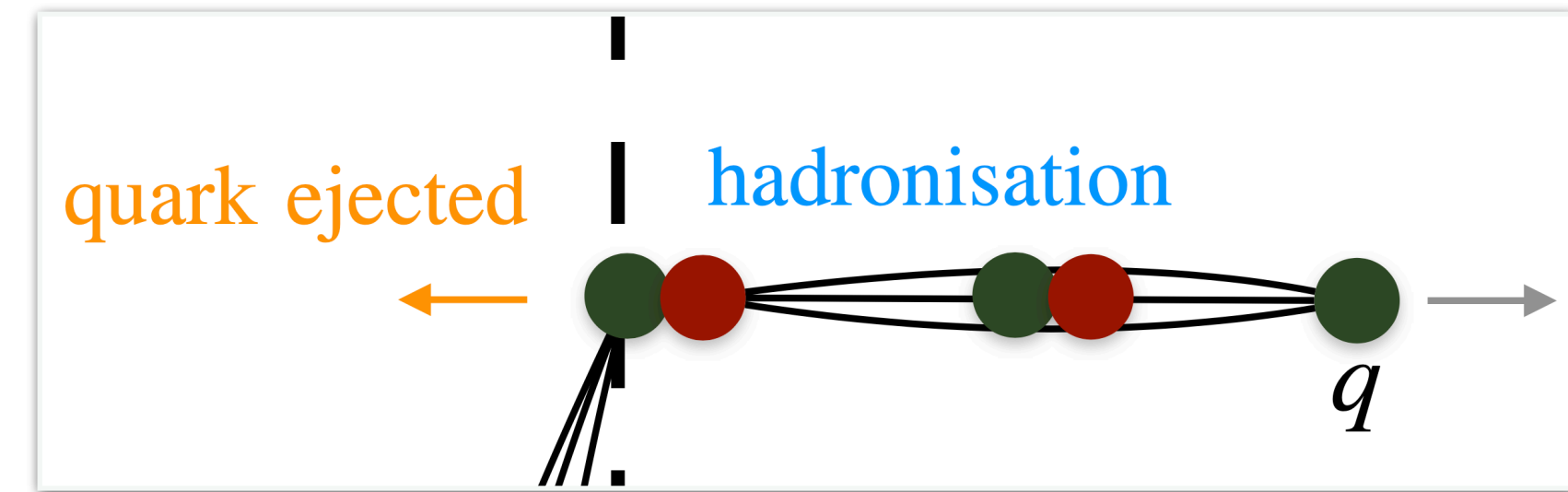
a) Weak interaction with plasma

Bodeker, Moore 17'



b) Strong interaction with plasma

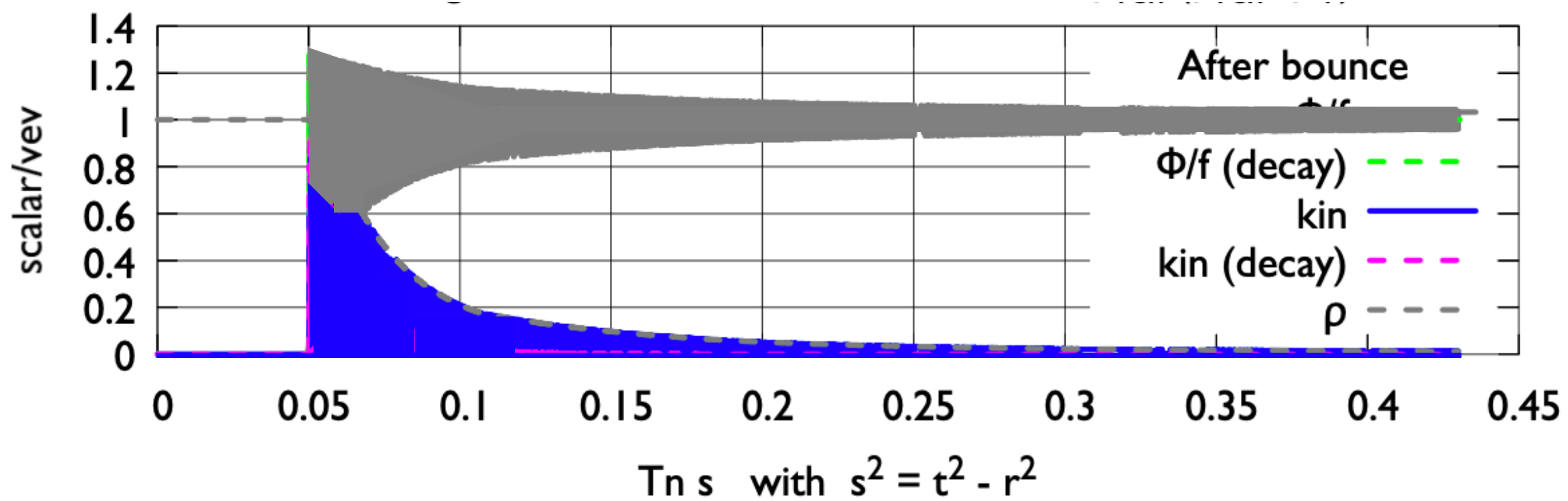
Baldes, YG, Sala 20'



Maximilian Dichtl and Filippo Sala (to appear)

c) Wall decay (YG)

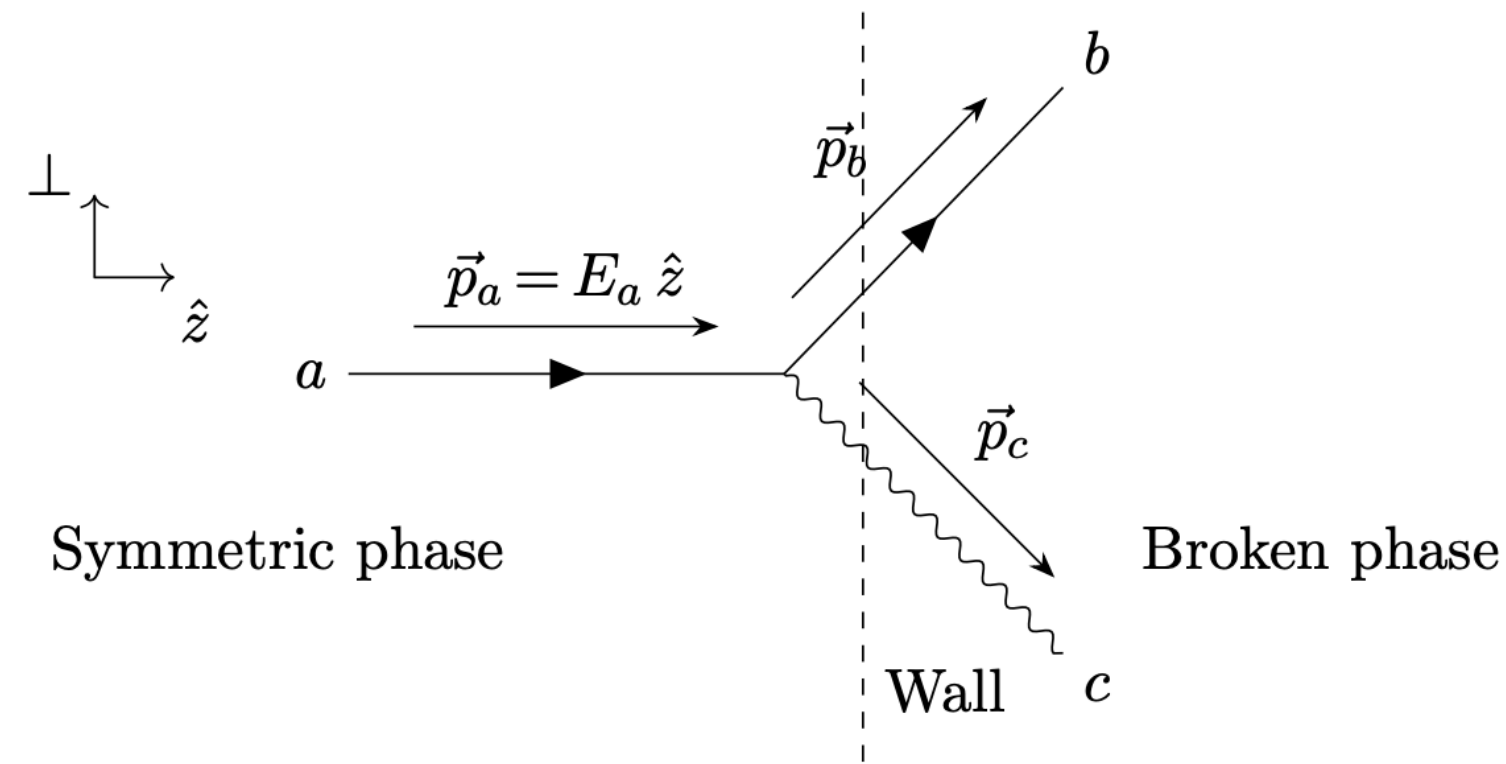
$$\frac{\partial^2 \phi}{\partial s^2} + \frac{3}{s} \frac{\partial \phi}{\partial s} + \frac{\partial V}{\partial \phi} = 0$$



4) High energy particle production

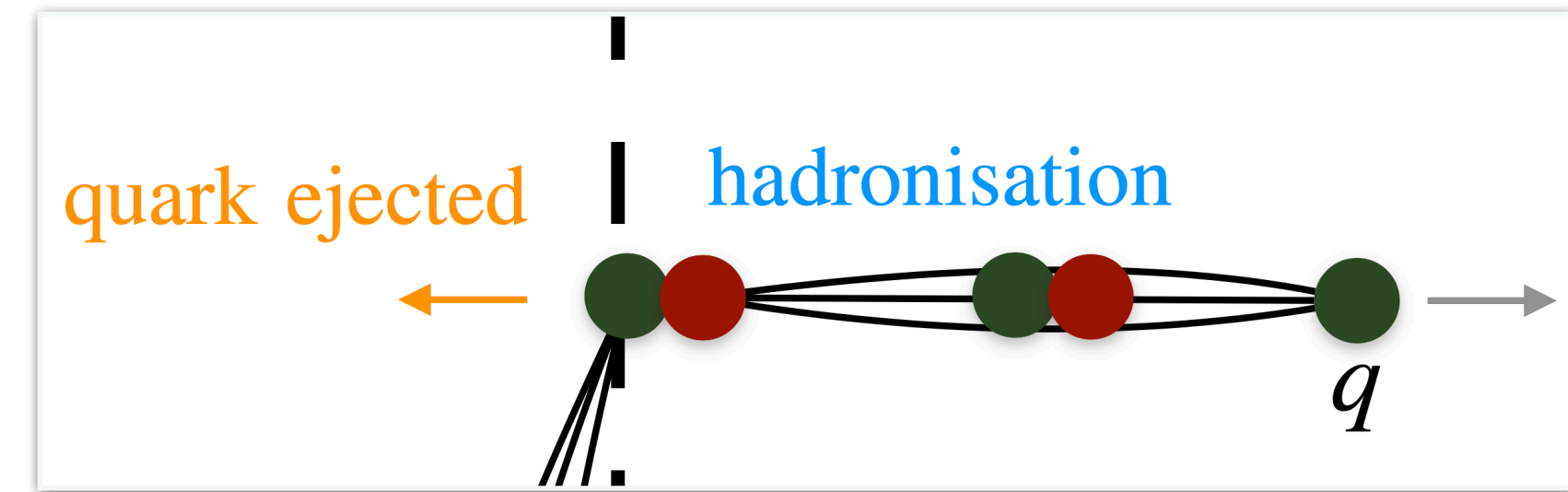
a) Weak interaction with plasma

Bodeker, Moore 17'



b) Strong interaction with plasma

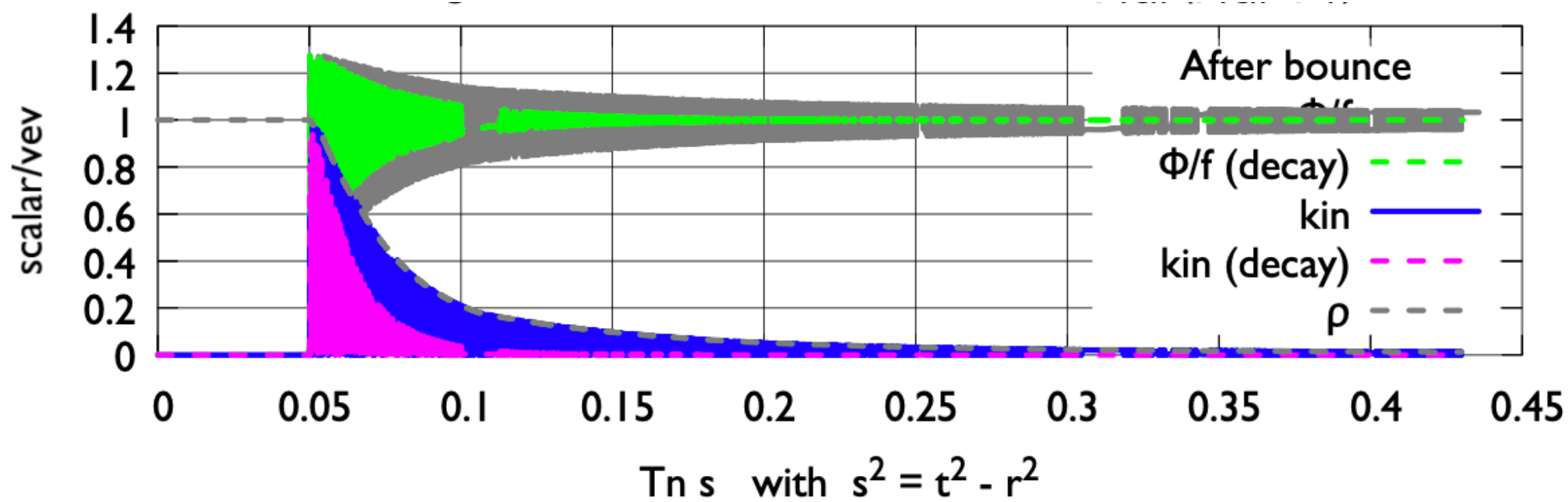
Baldes, YG, Sala 20'



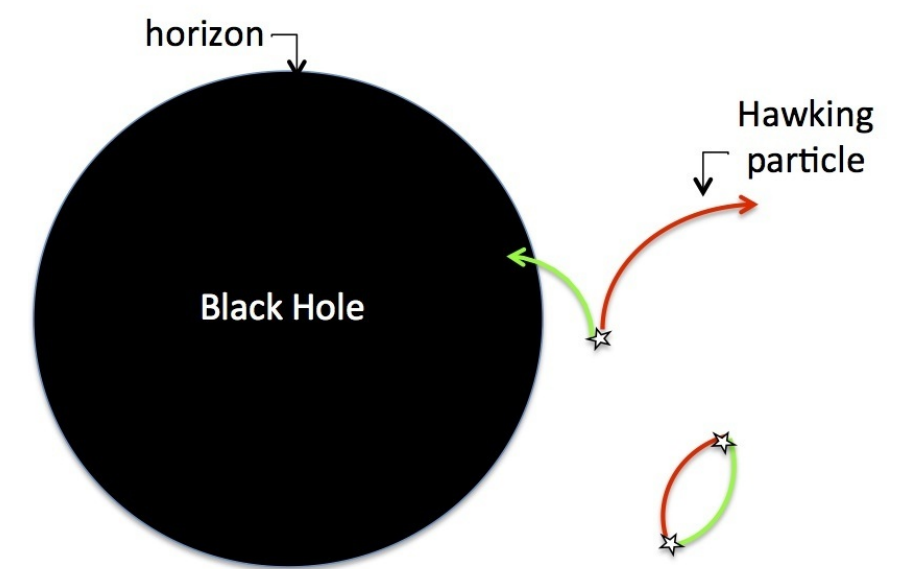
Maximilian Dichtl and Filippo Sala (to appear)

c) Wall decay (YG)

$$\frac{\partial^2 \phi}{\partial s^2} + \left(\frac{3}{s} + \Gamma_\phi \right) \frac{\partial \phi}{\partial s} + \frac{\partial V}{\partial \phi} = 0$$



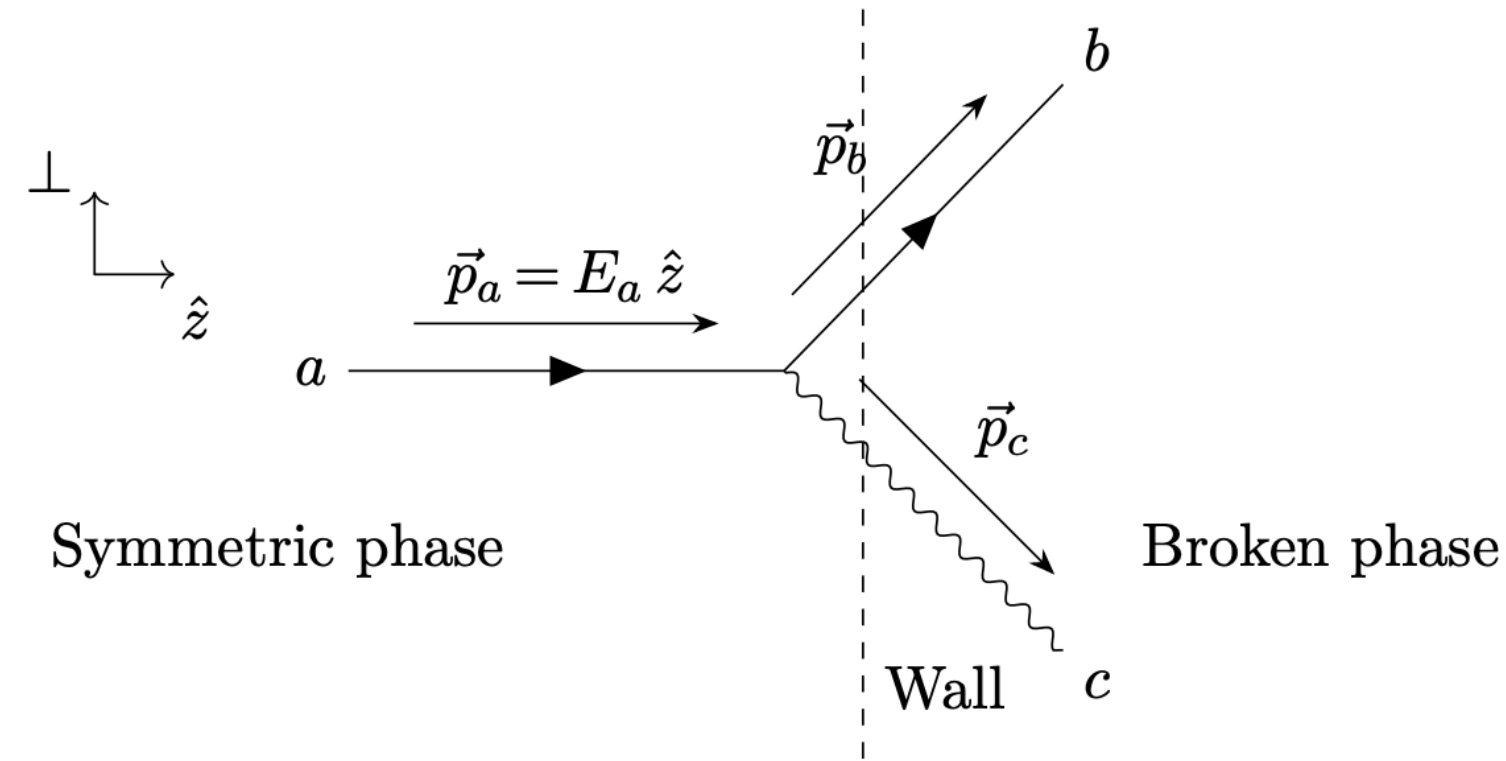
d) Unruh radiation (YG)



4) High energy particle production

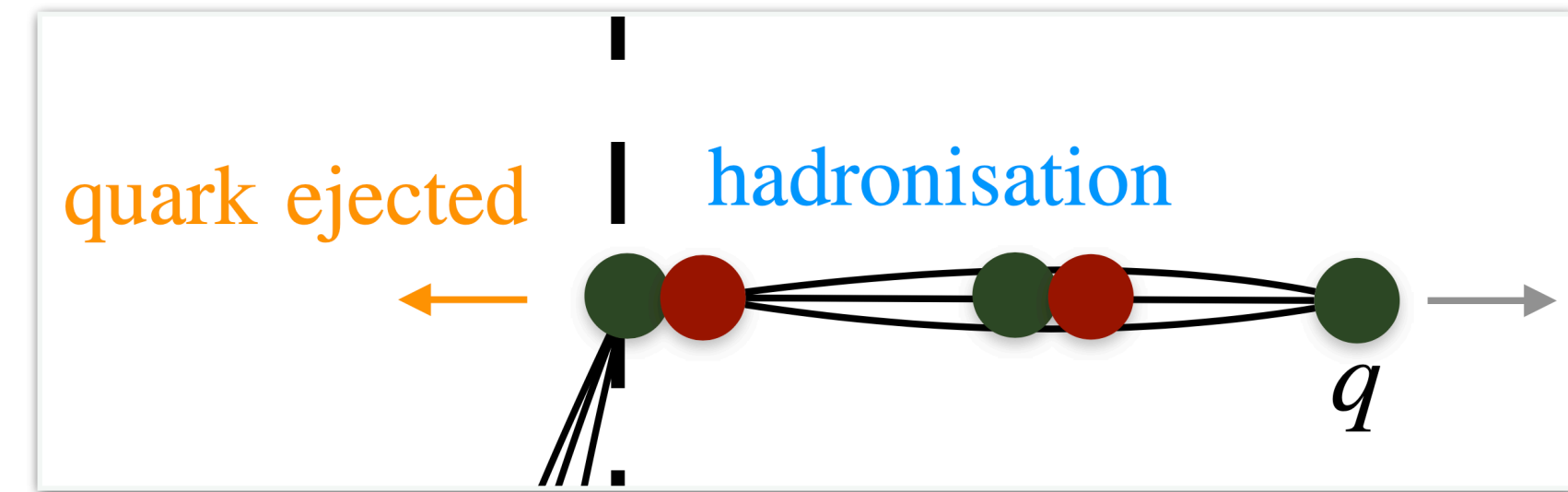
a) Weak interaction with plasma

Bodeker, Moore 17'



b) Strong interaction with plasma

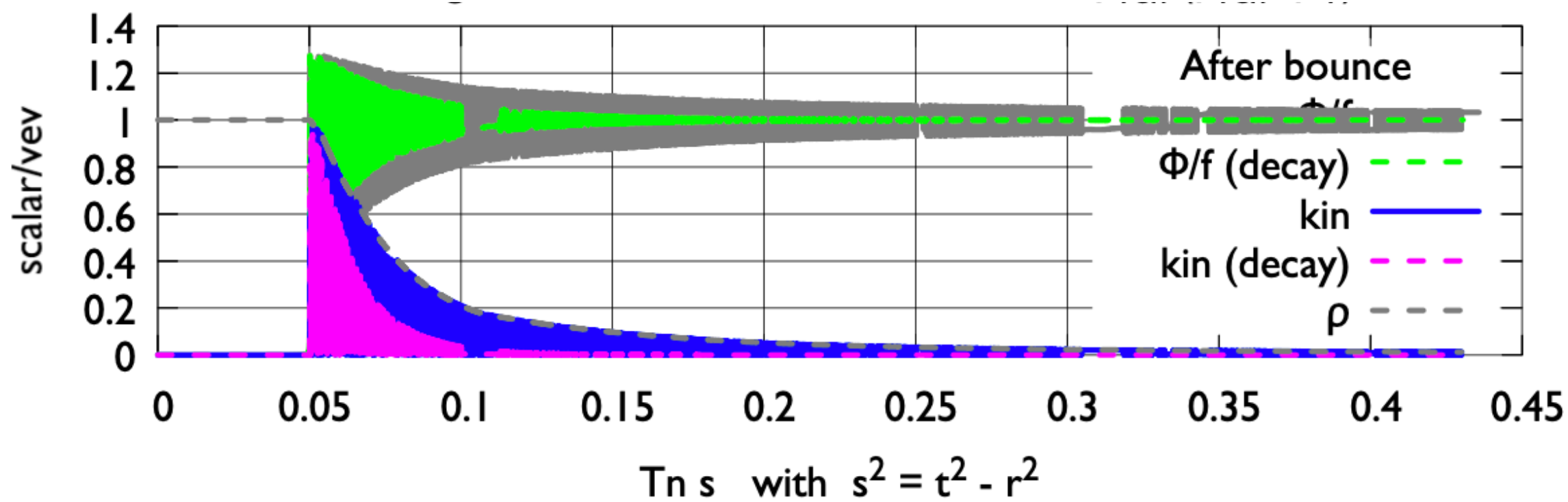
Baldes, YG, Sala 20'



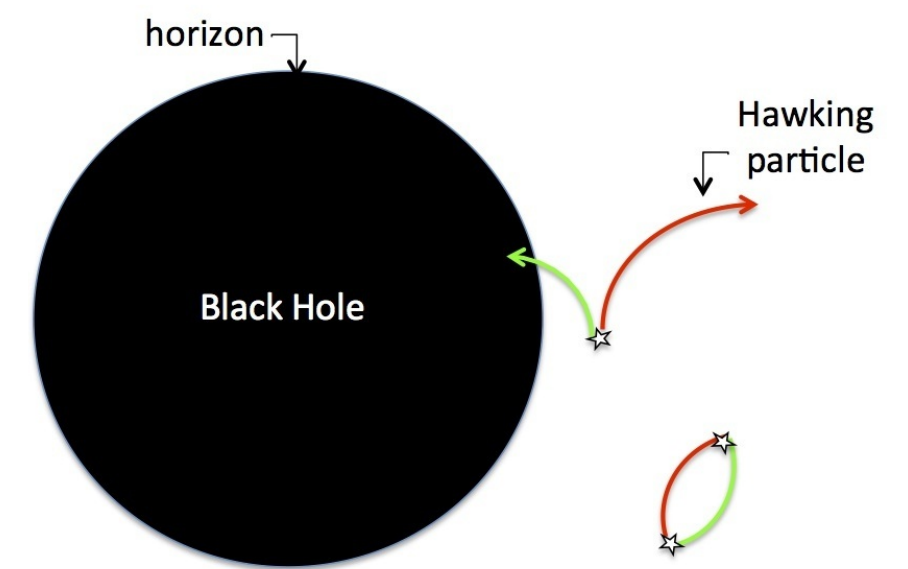
Maximilian Dichtl and Filippo Sala (to appear)

c) Wall decay (YG)

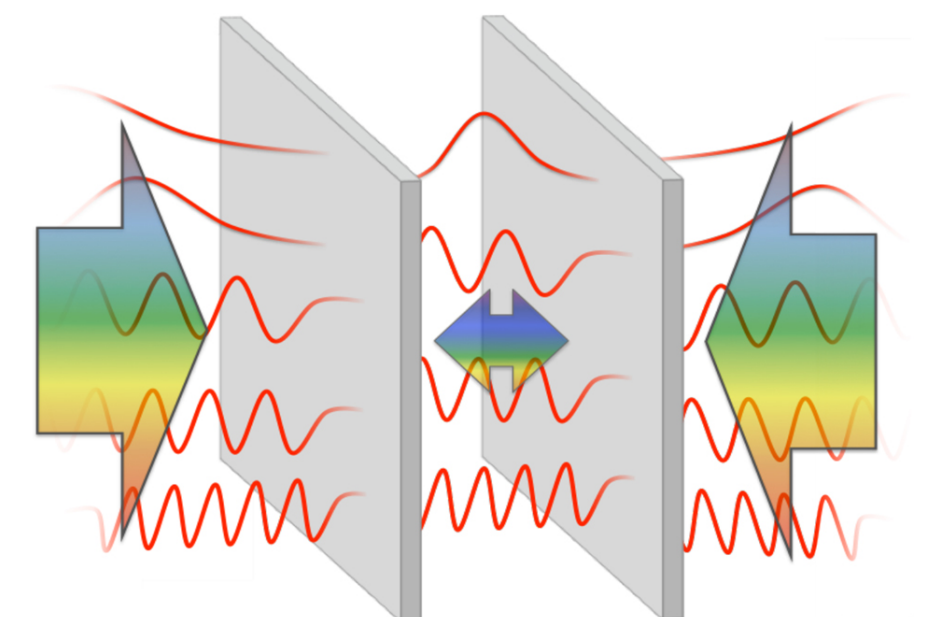
$$\frac{\partial^2 \phi}{\partial s^2} + \left(\frac{3}{s} + \Gamma_\phi \right) \frac{\partial \phi}{\partial s} + \frac{\partial V}{\partial \phi} = 0$$



d) Unruh radiation (YG)



e) Dynamical Casimir (YG)



4) High energy particle production

tevatron



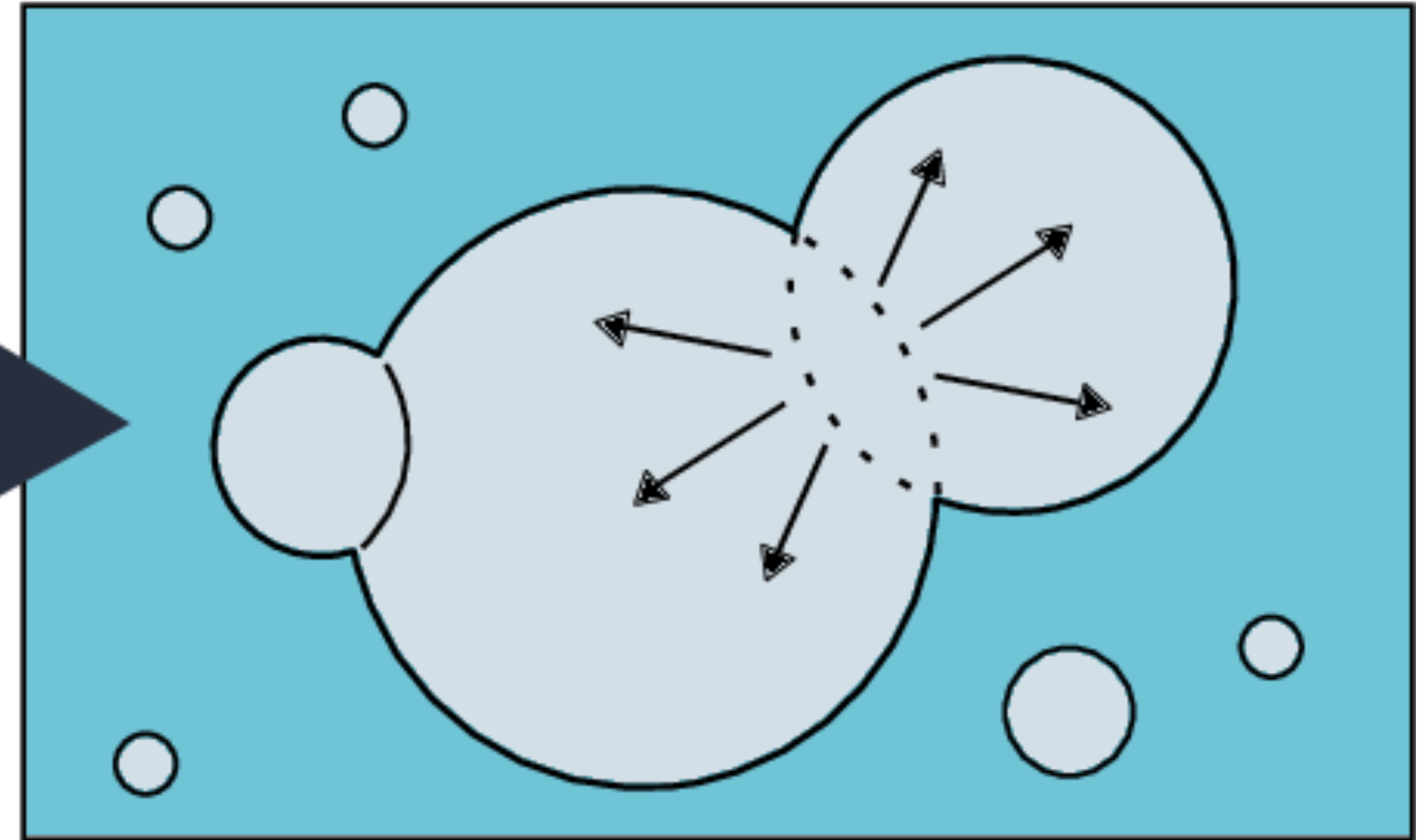
TeV scale

4) High energy particle production

tevatron



bubbletron



TeV scale

$$\sqrt{S} \sim \gamma T_c \sim 10^{16} \text{ GeV} \frac{\gamma}{10^{10}} \frac{T_c}{10^6 \text{ GeV}}$$

5) Primordial black hole production

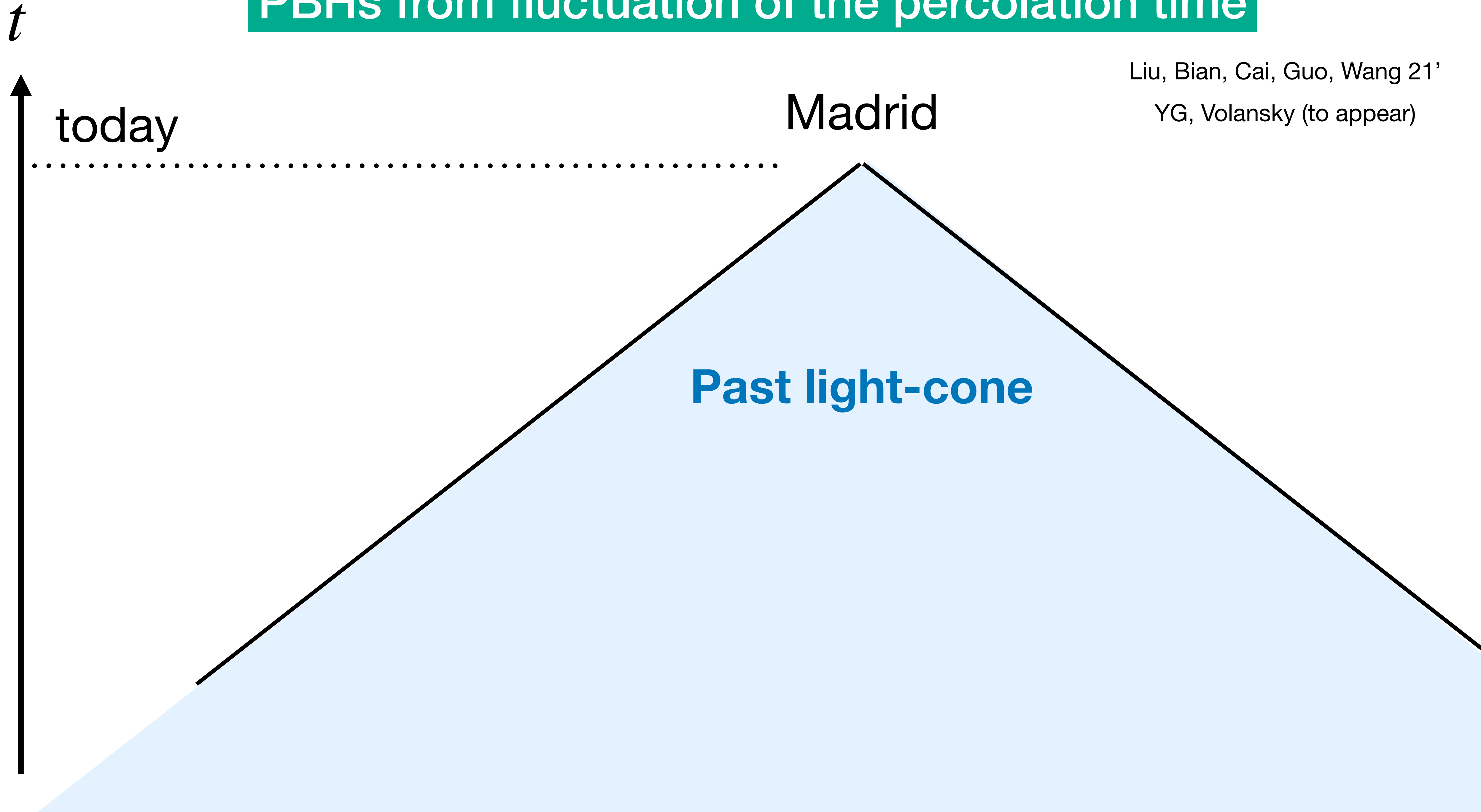
PBHs from fluctuation of the percolation time

Liu, Bian, Cai, Guo, Wang 21'

YG, Volansky (to appear)

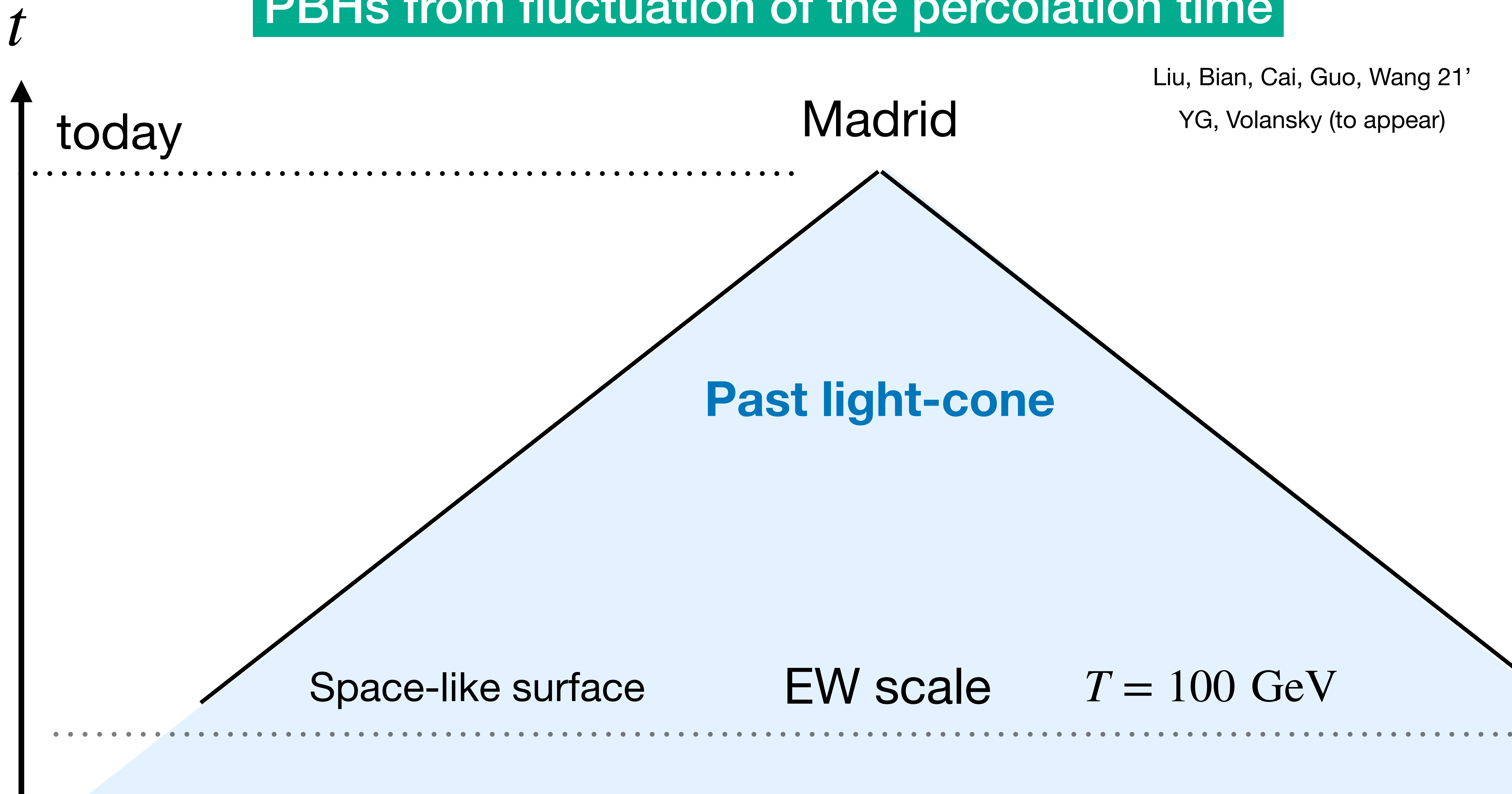
PBHs from fluctuation of the percolation time

Liu, Bian, Cai, Guo, Wang 21'
YG, Volansky (to appear)



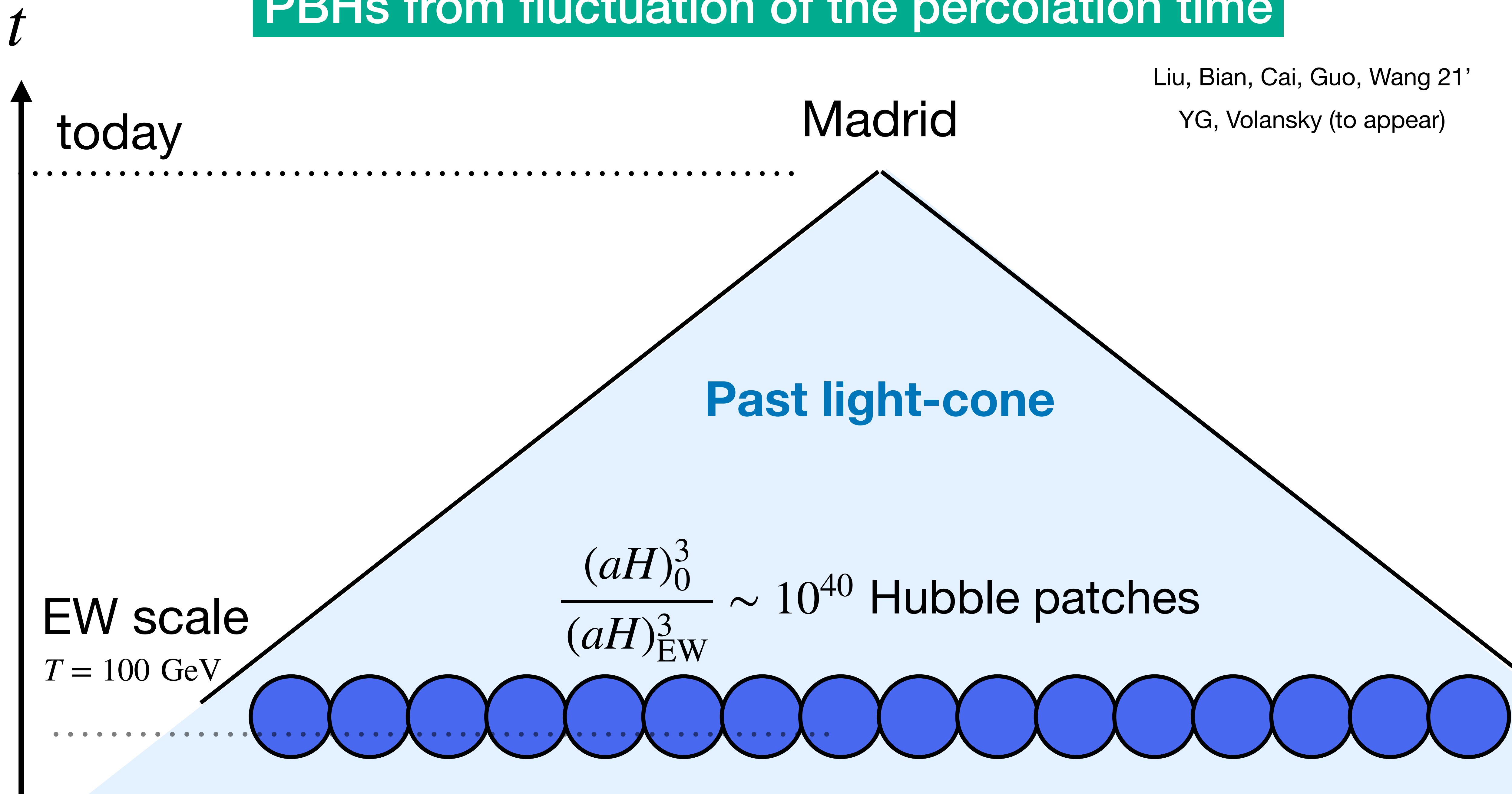
PBHs from fluctuation of the percolation time

Liu, Bian, Cai, Guo, Wang 21'
YG, Volansky (to appear)



PBHs from fluctuation of the percolation time

Liu, Bian, Cai, Guo, Wang 21'
YG, Volansky (to appear)



Madrid

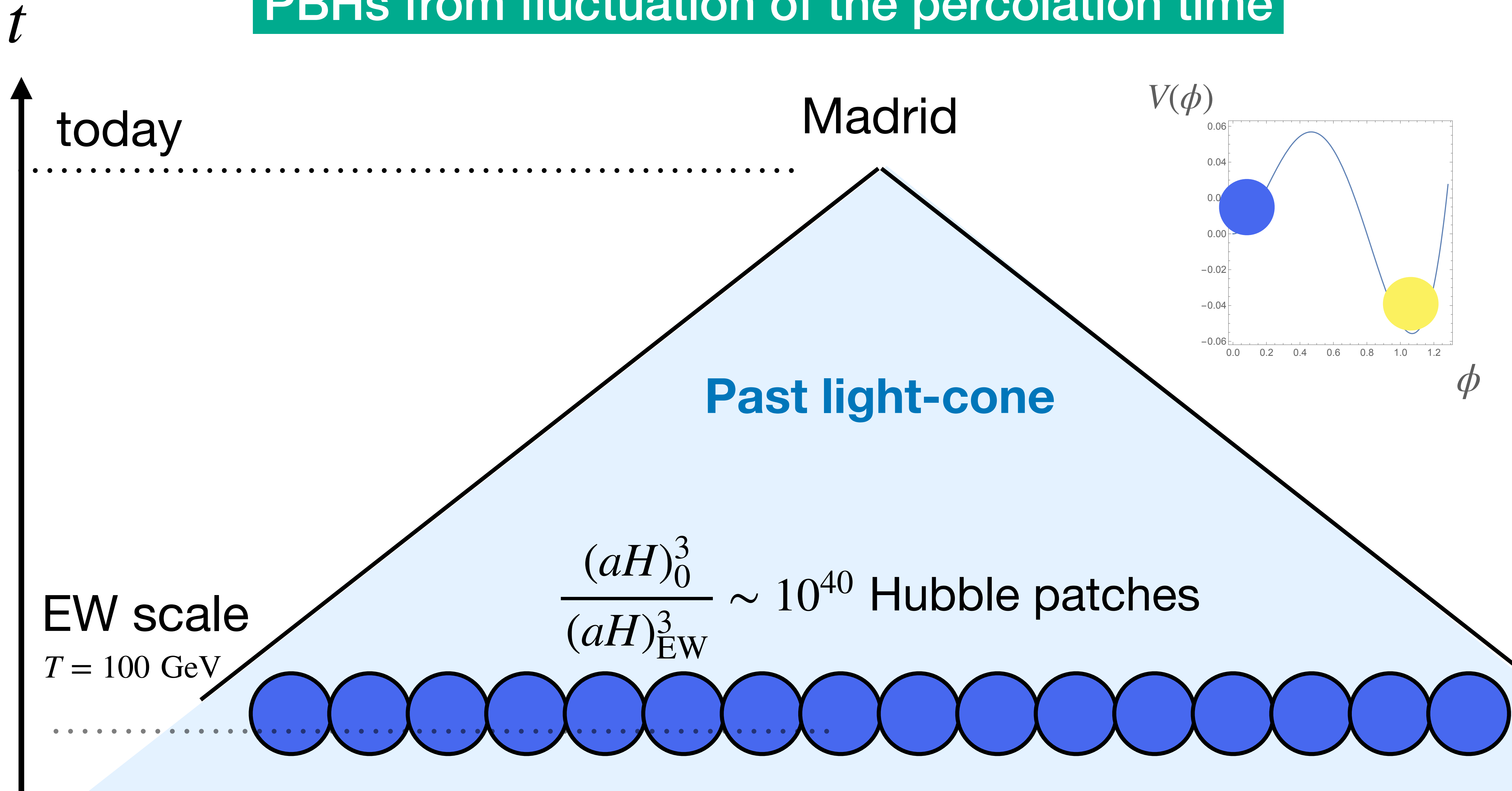
Past light-cone

today

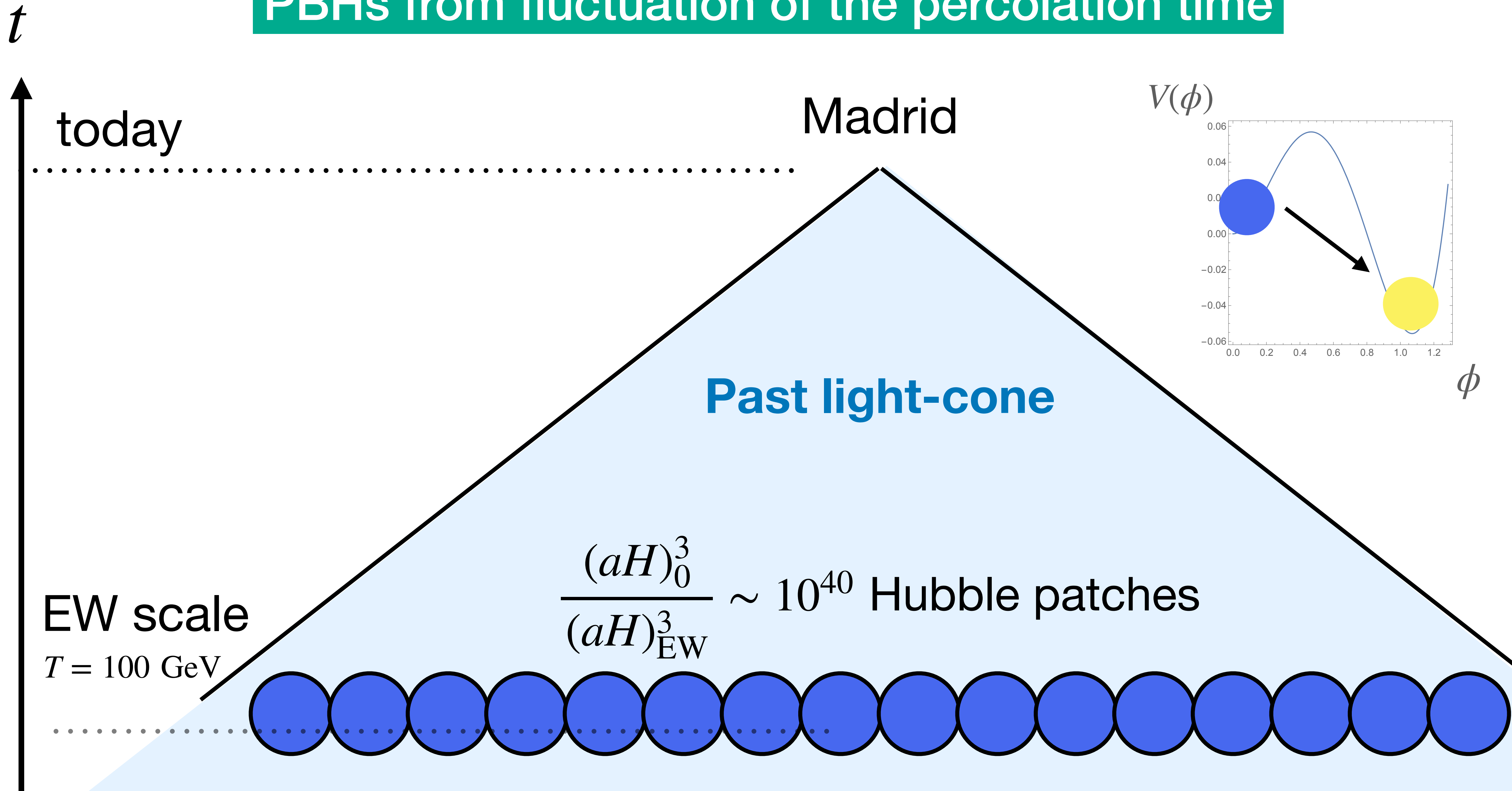
EW scale
 $T = 100 \text{ GeV}$

$$\frac{(aH)_0^3}{(aH)_{\text{EW}}^3} \sim 10^{40} \text{ Hubble patches}$$

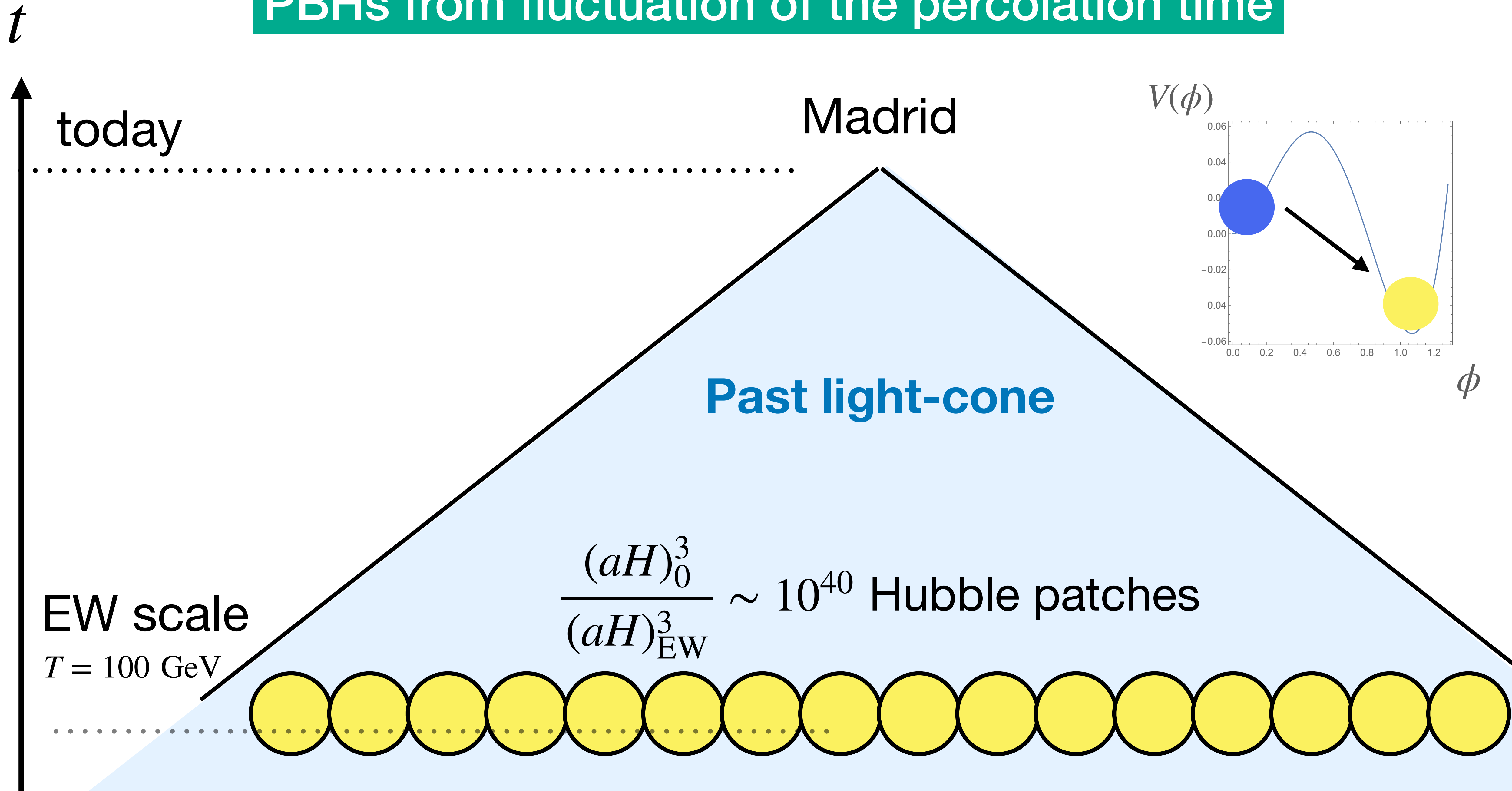
PBHs from fluctuation of the percolation time



PBHs from fluctuation of the percolation time

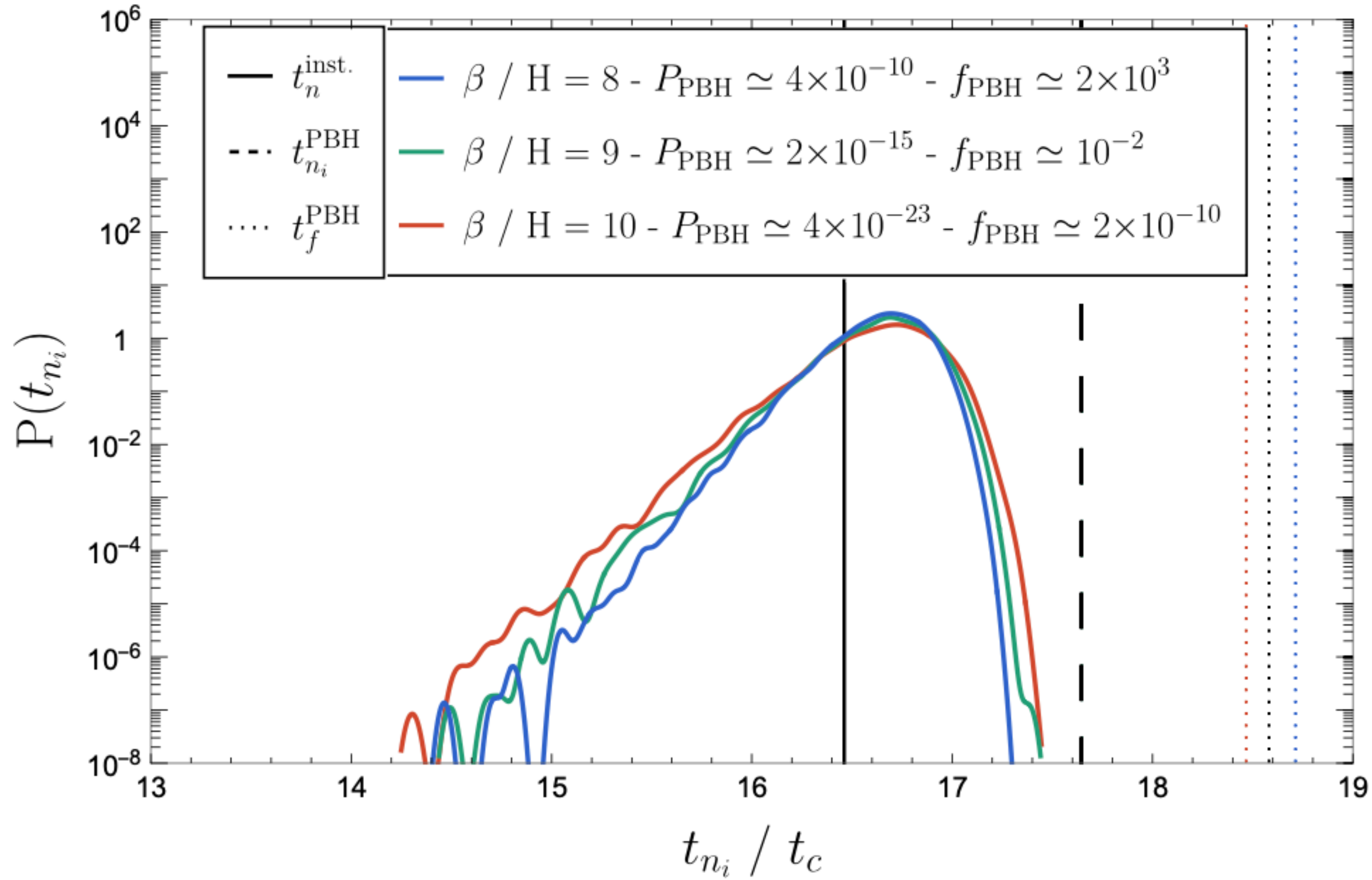


PBHs from fluctuation of the percolation time

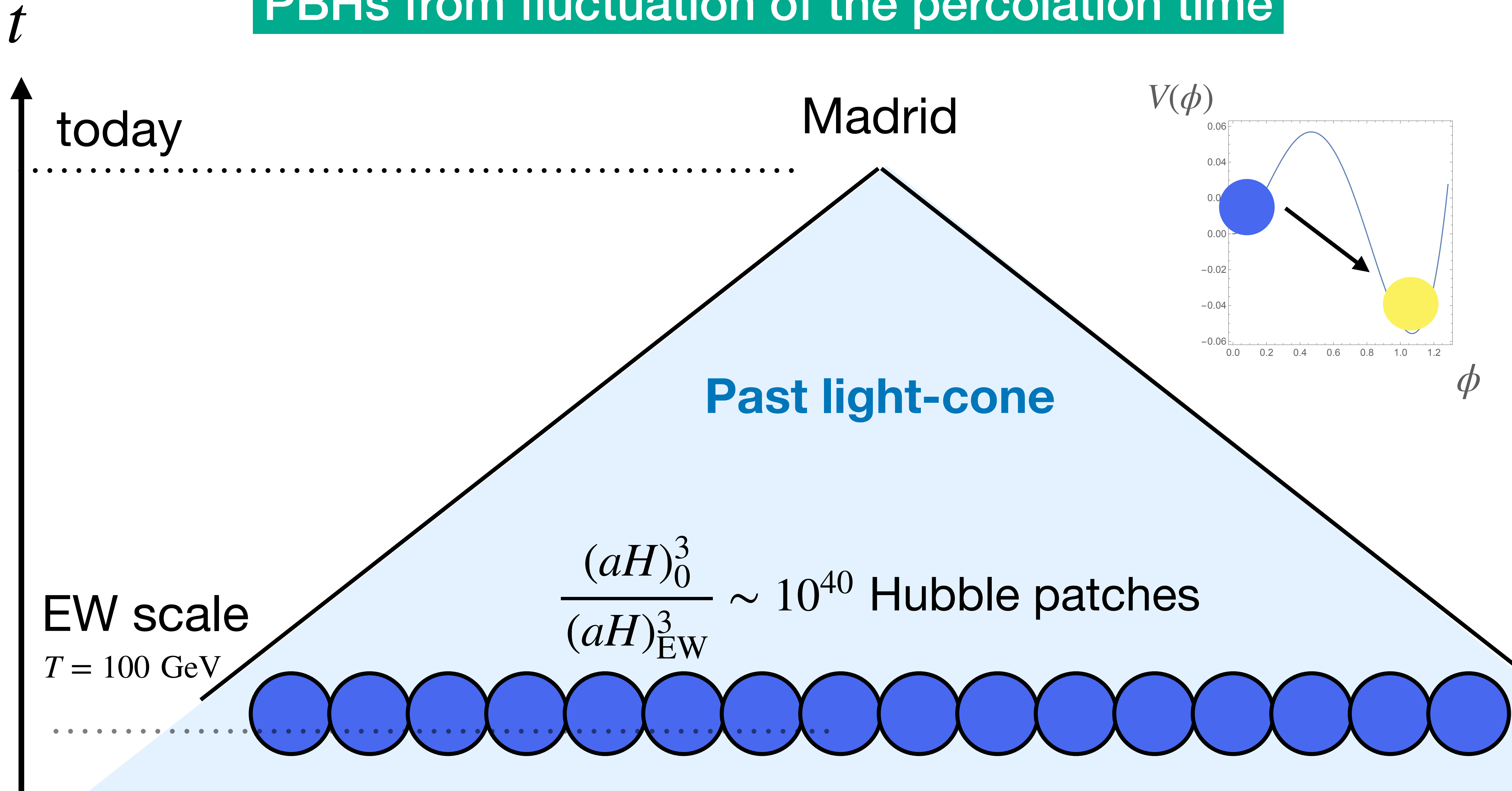


When phase transition takes place ?

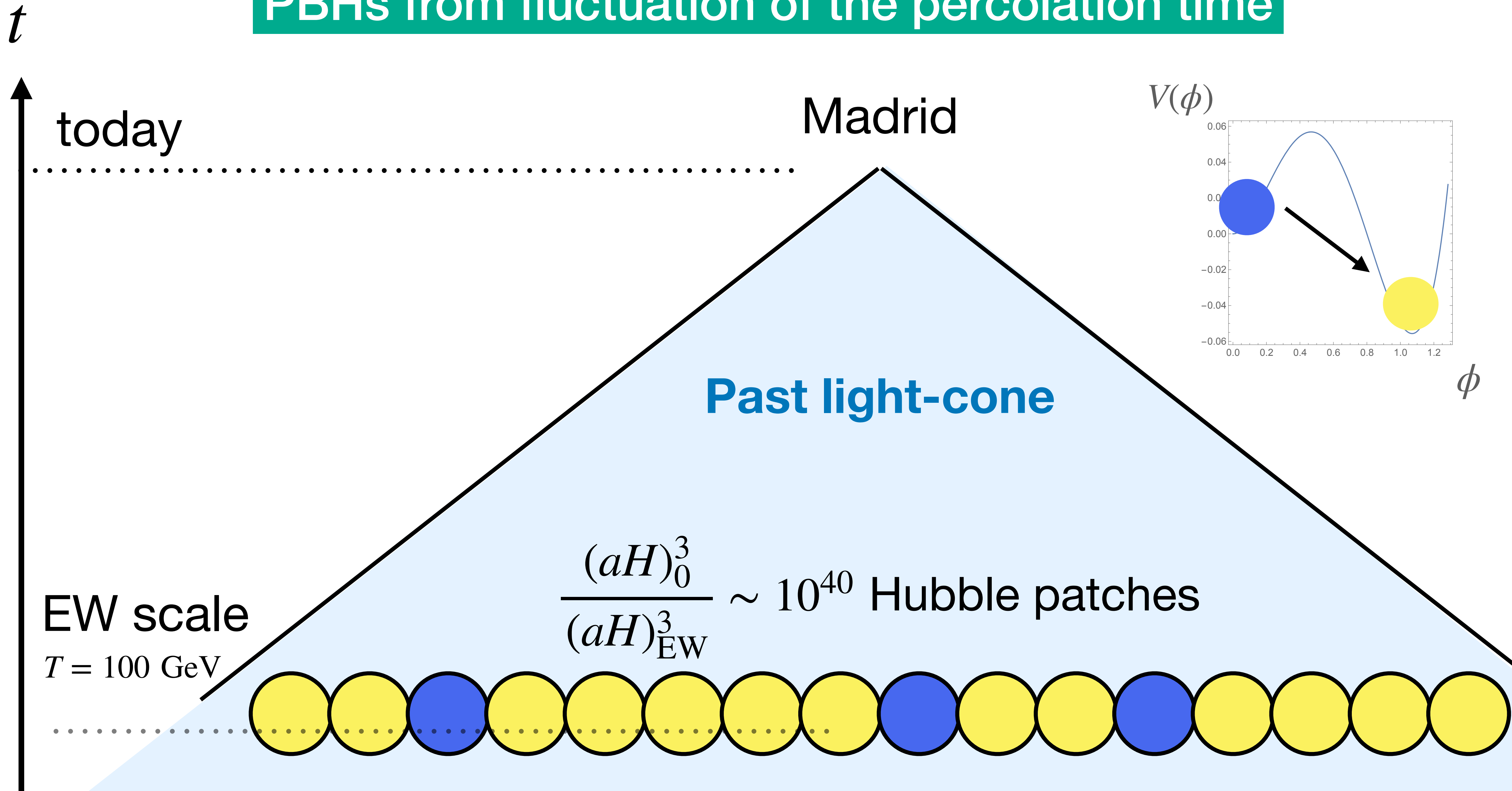
$$T_c = 100 \text{ GeV} - \alpha = 10^{12}$$



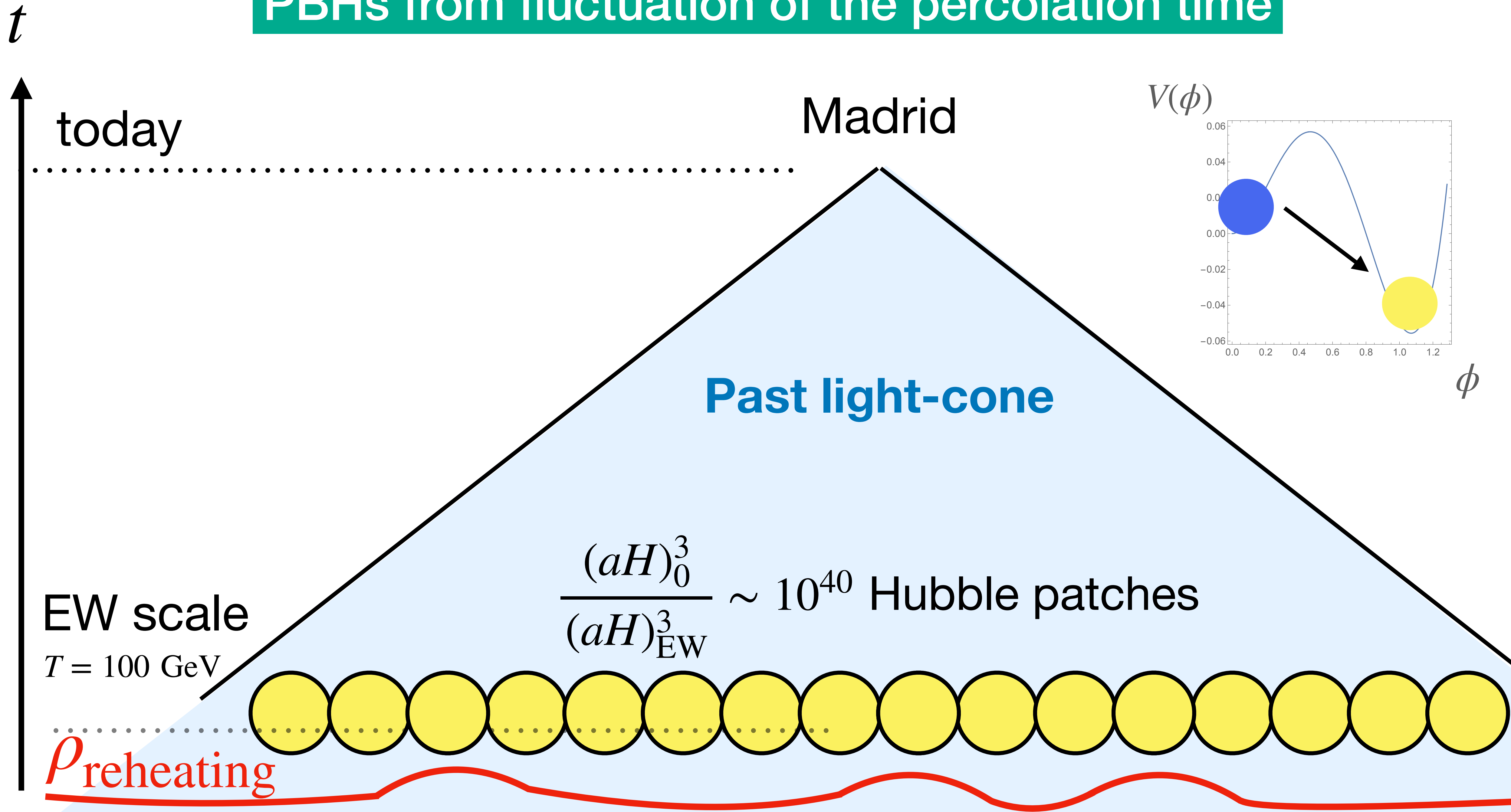
PBHs from fluctuation of the percolation time



PBHs from fluctuation of the percolation time



PBHs from fluctuation of the percolation time



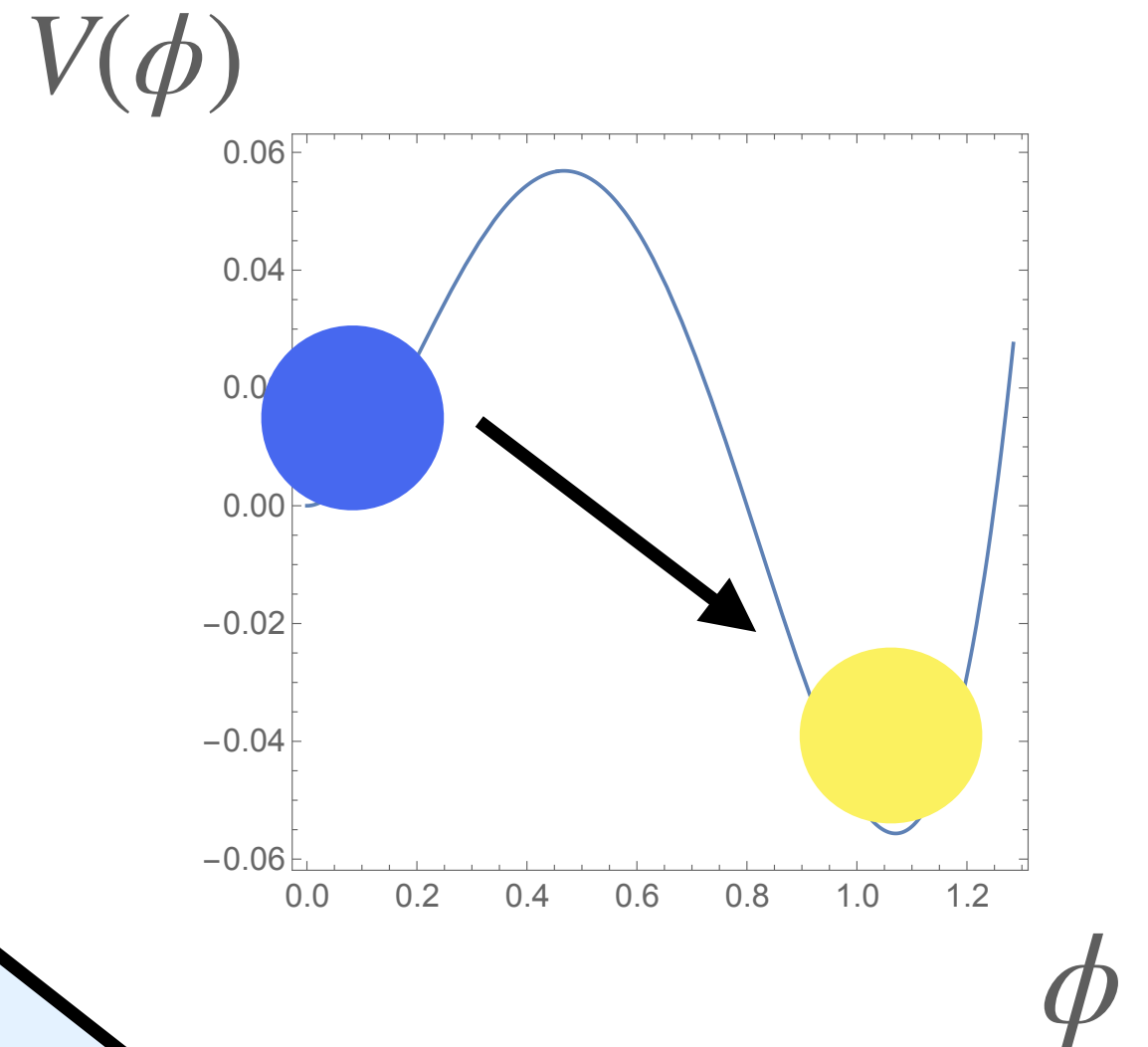
PBHs from fluctuation of the percolation time

t

today

Madrid

$$\delta = \frac{\rho_{\text{rad}} - \bar{\rho}_{\text{rad}}}{\bar{\rho}_{\text{rad}}} > \delta_c = 0.45$$



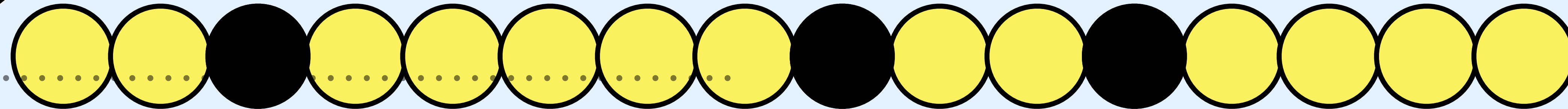
Past light-cone

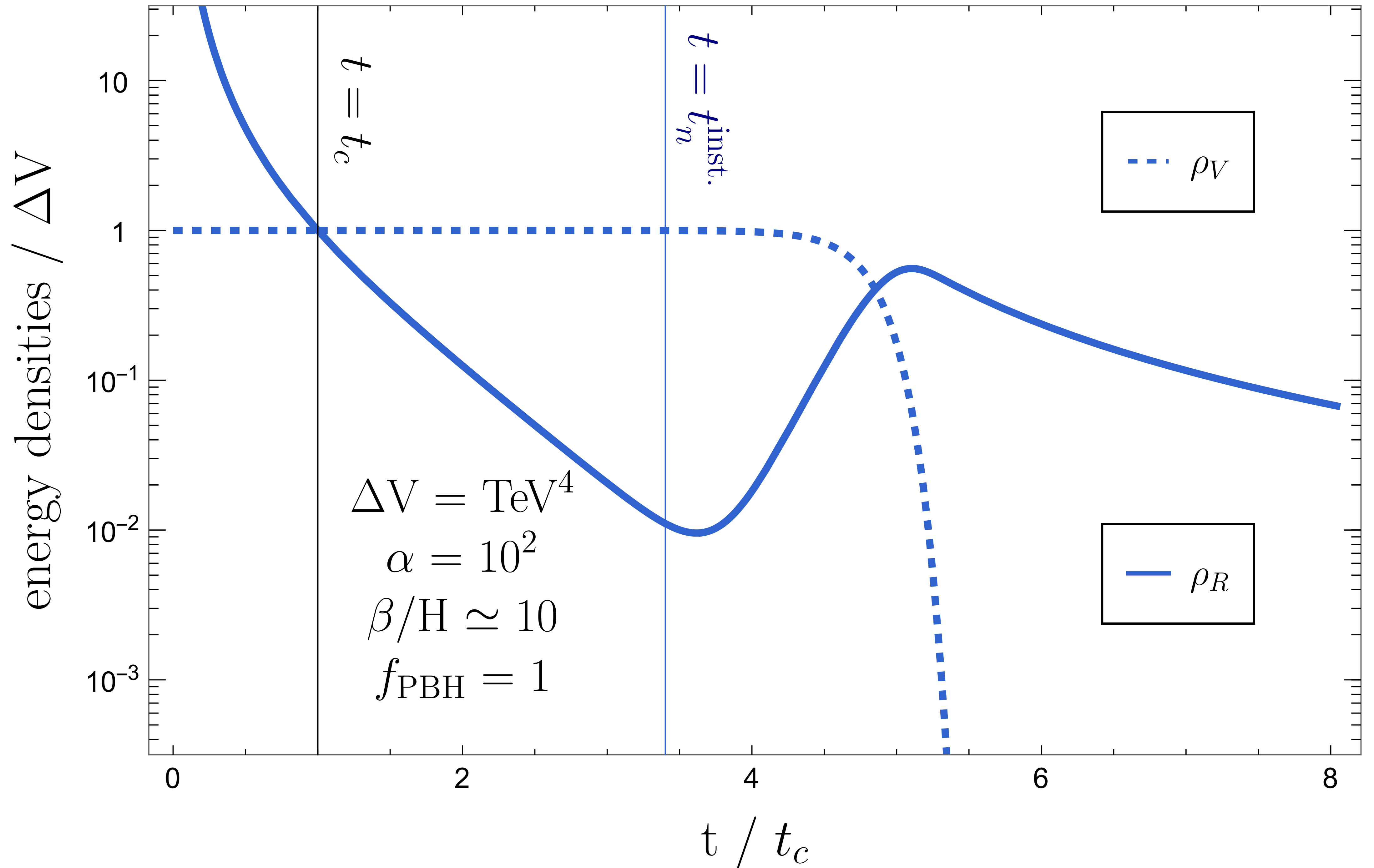
EW scale

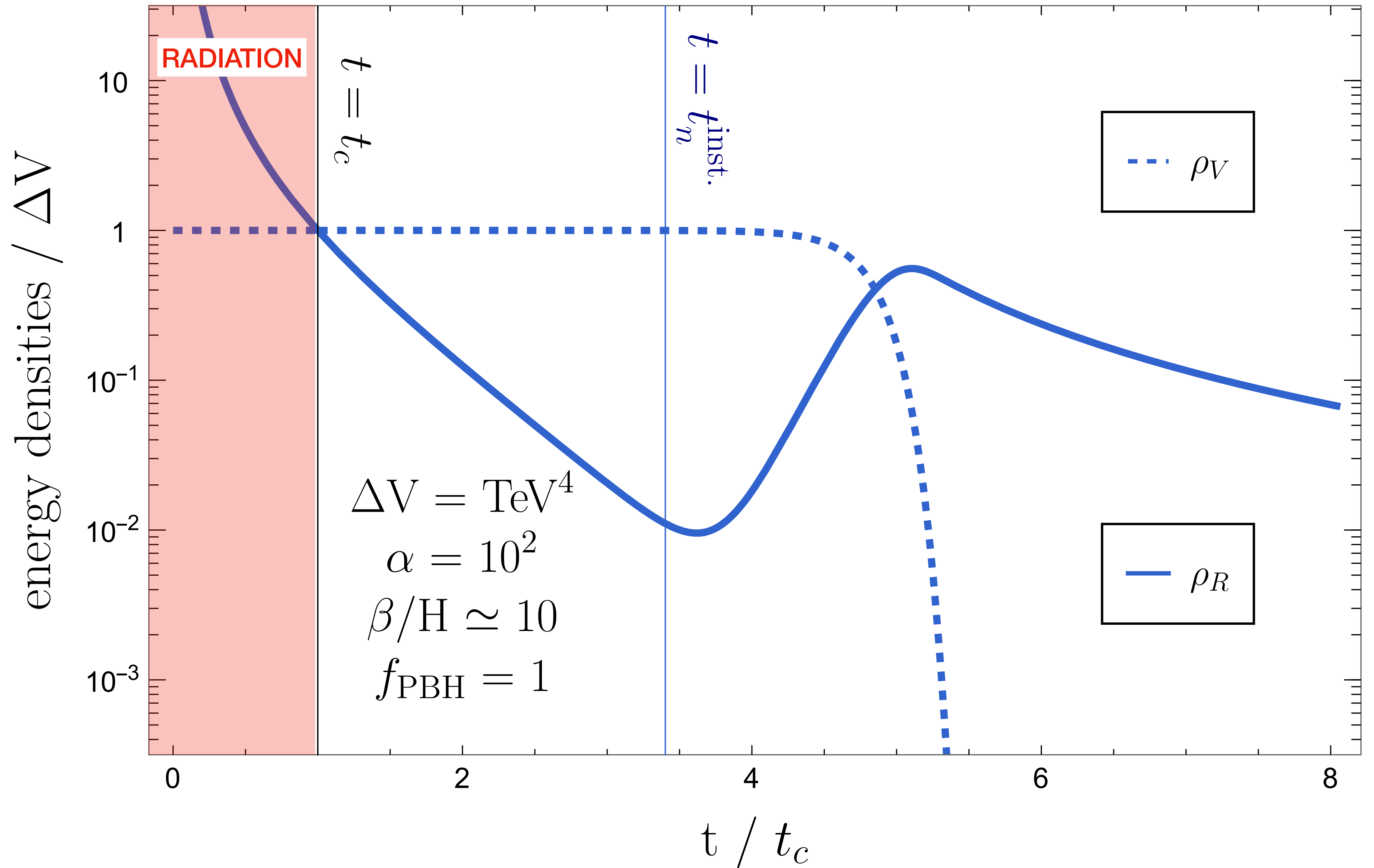
$T = 100 \text{ GeV}$

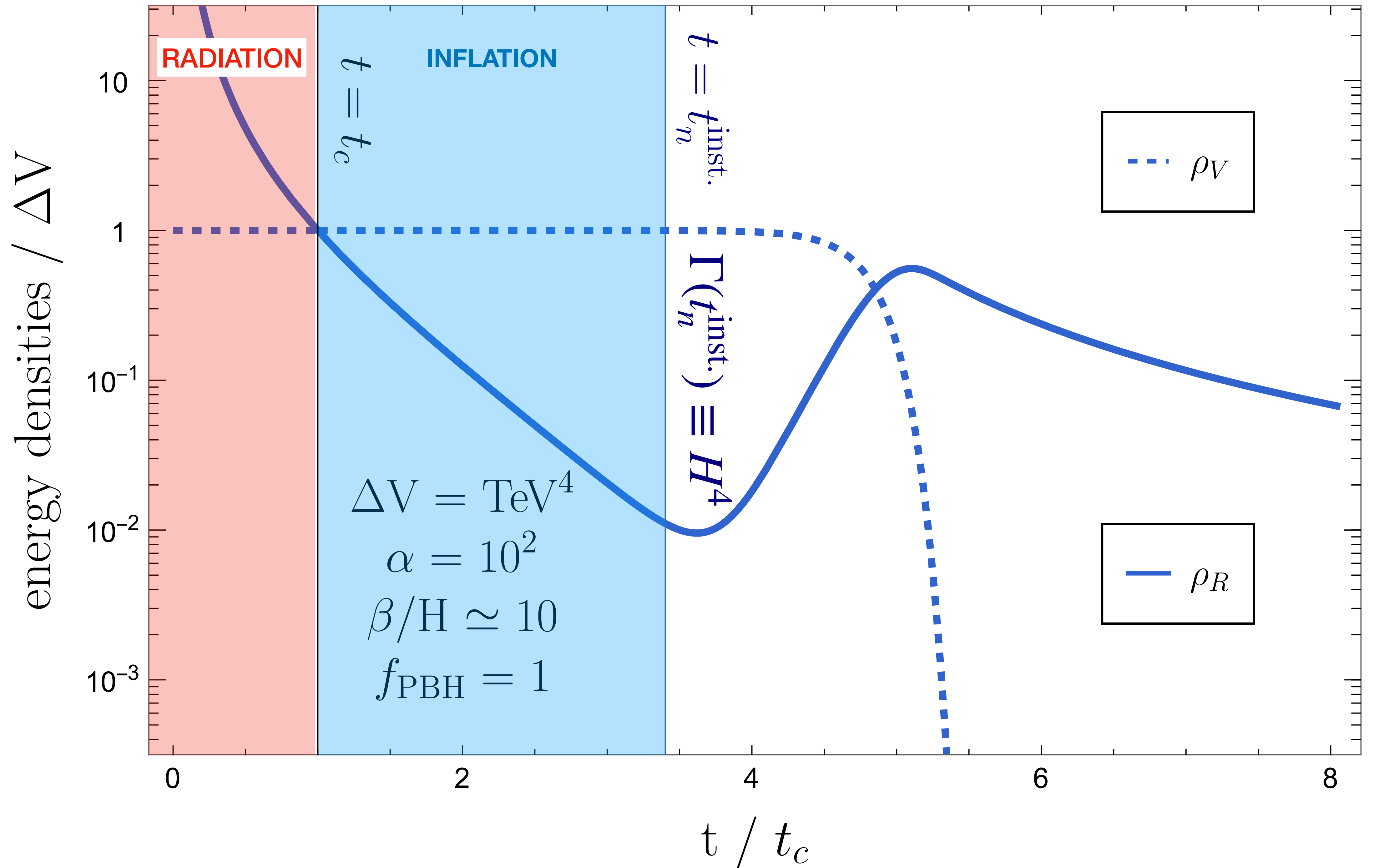
$$\frac{(aH)_0^3}{(aH)_{\text{EW}}^3} \sim 10^{40} \text{ Hubble patches}$$

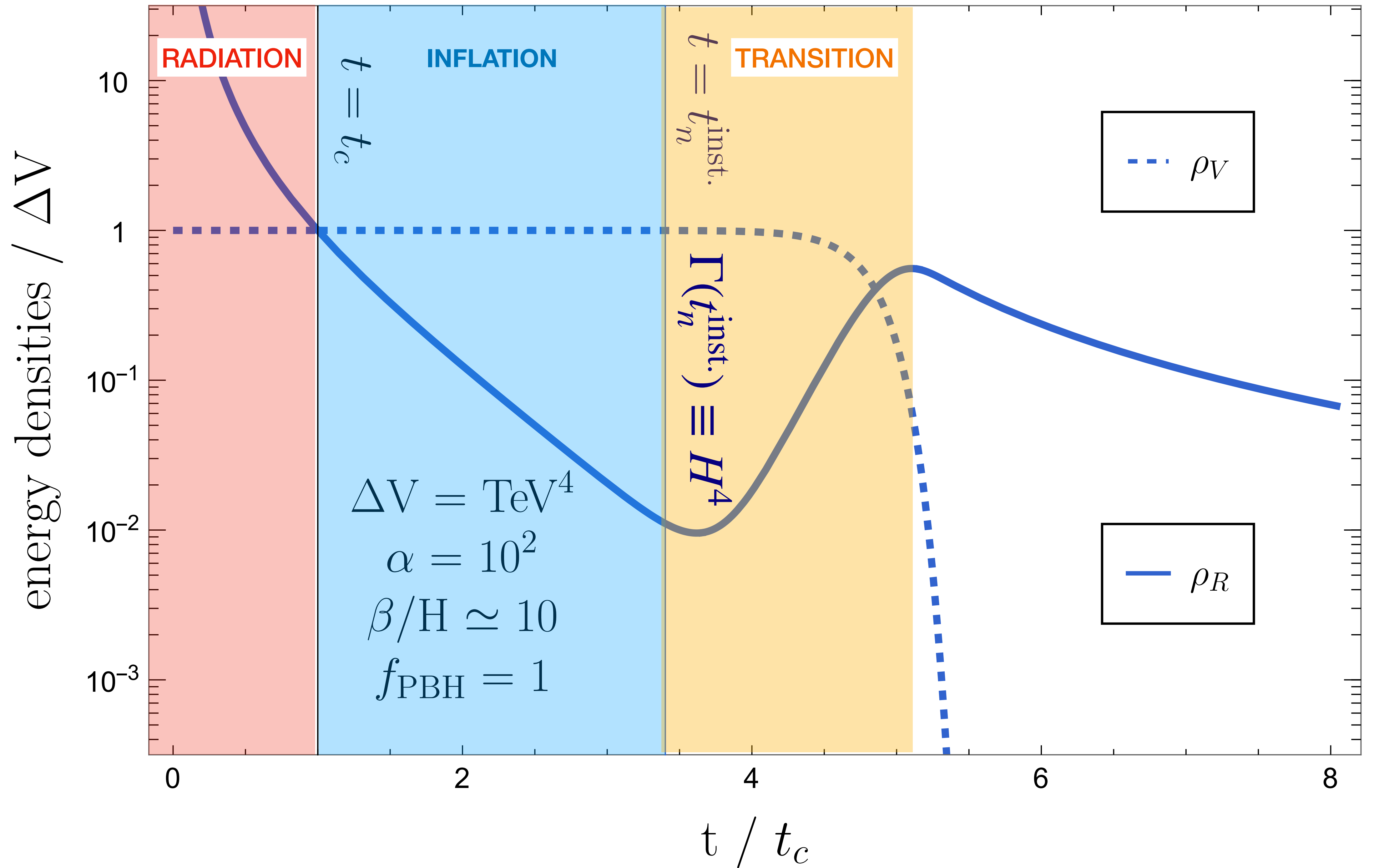
$\rho_{\text{reheating}}$

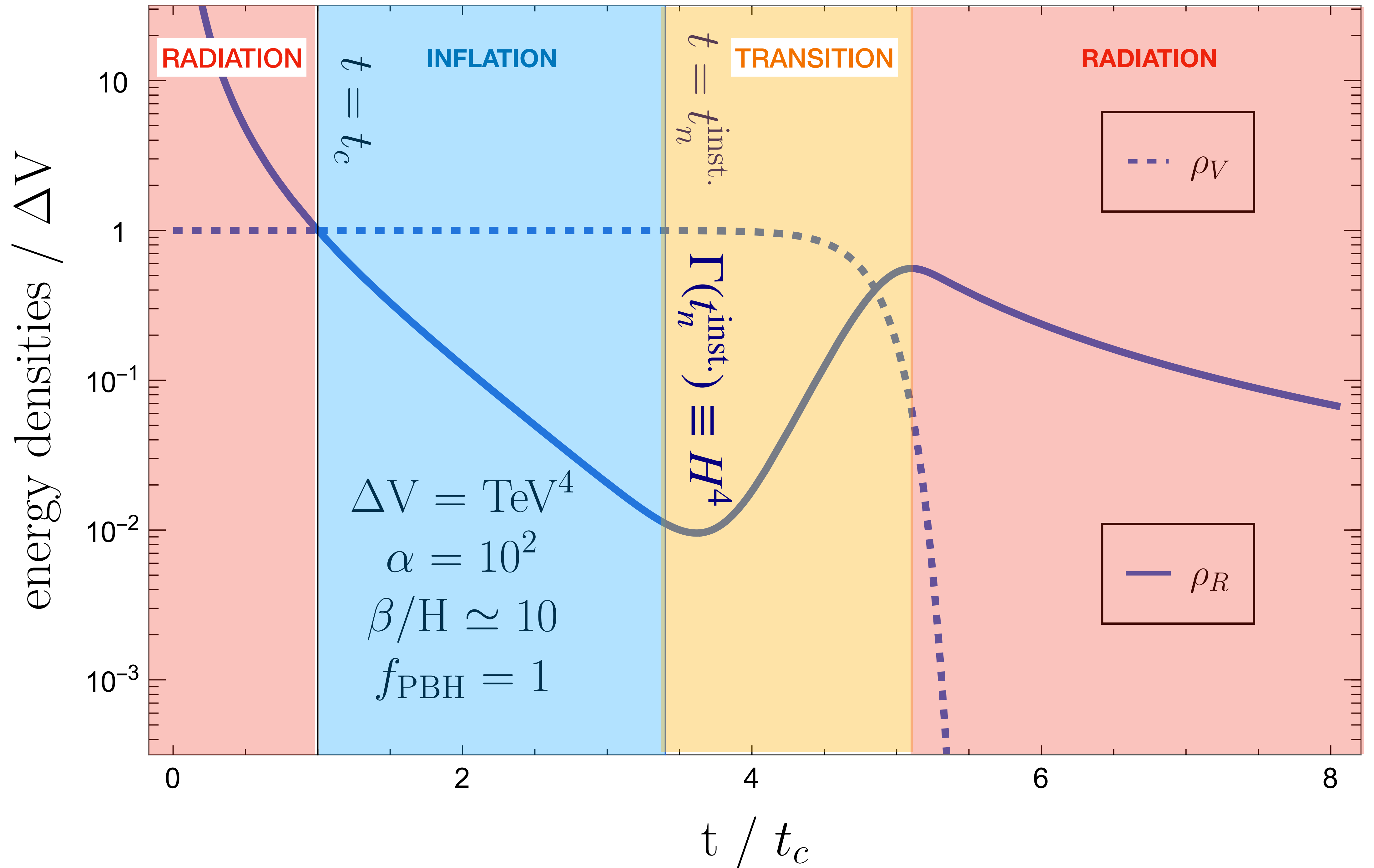


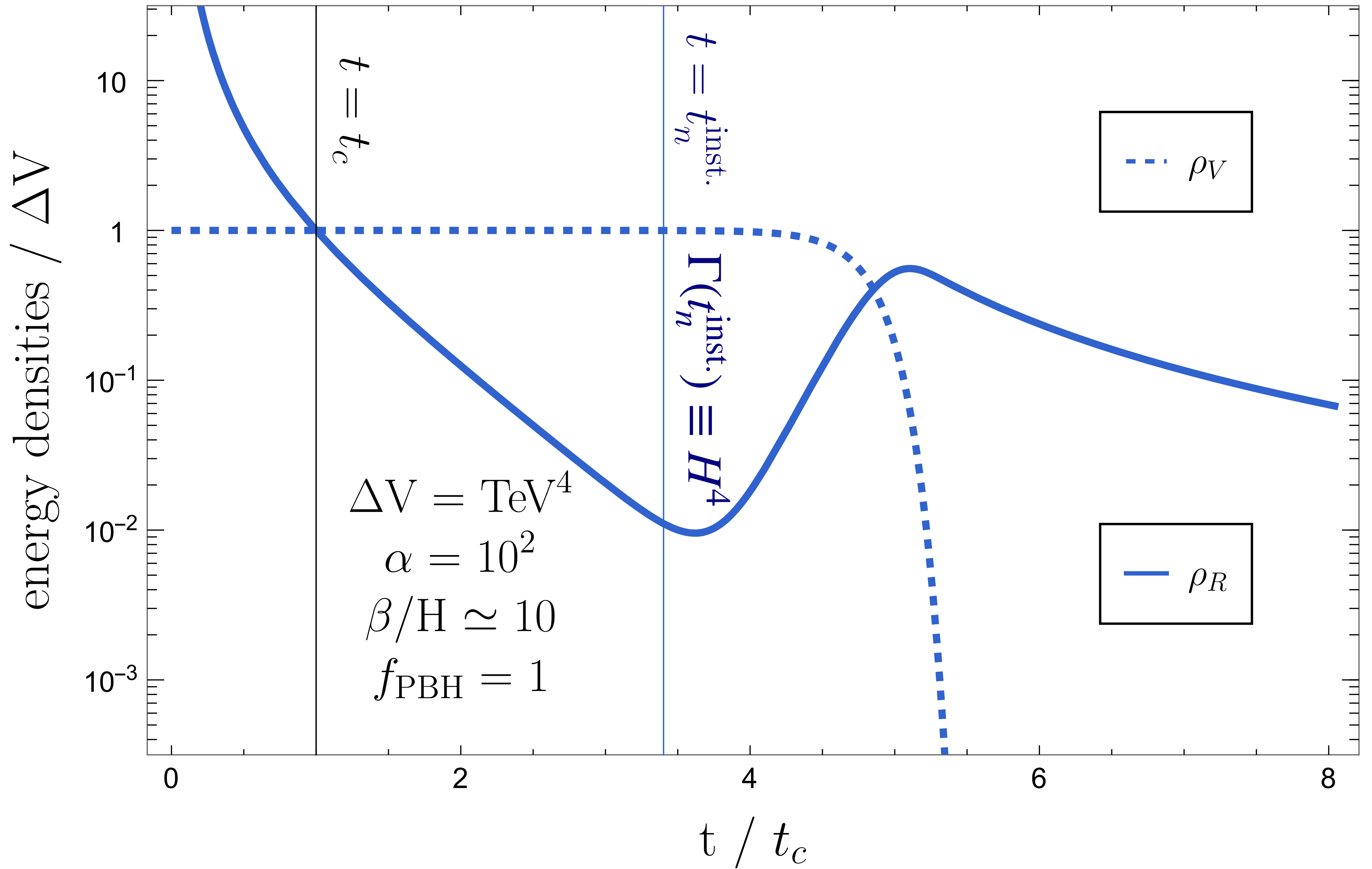


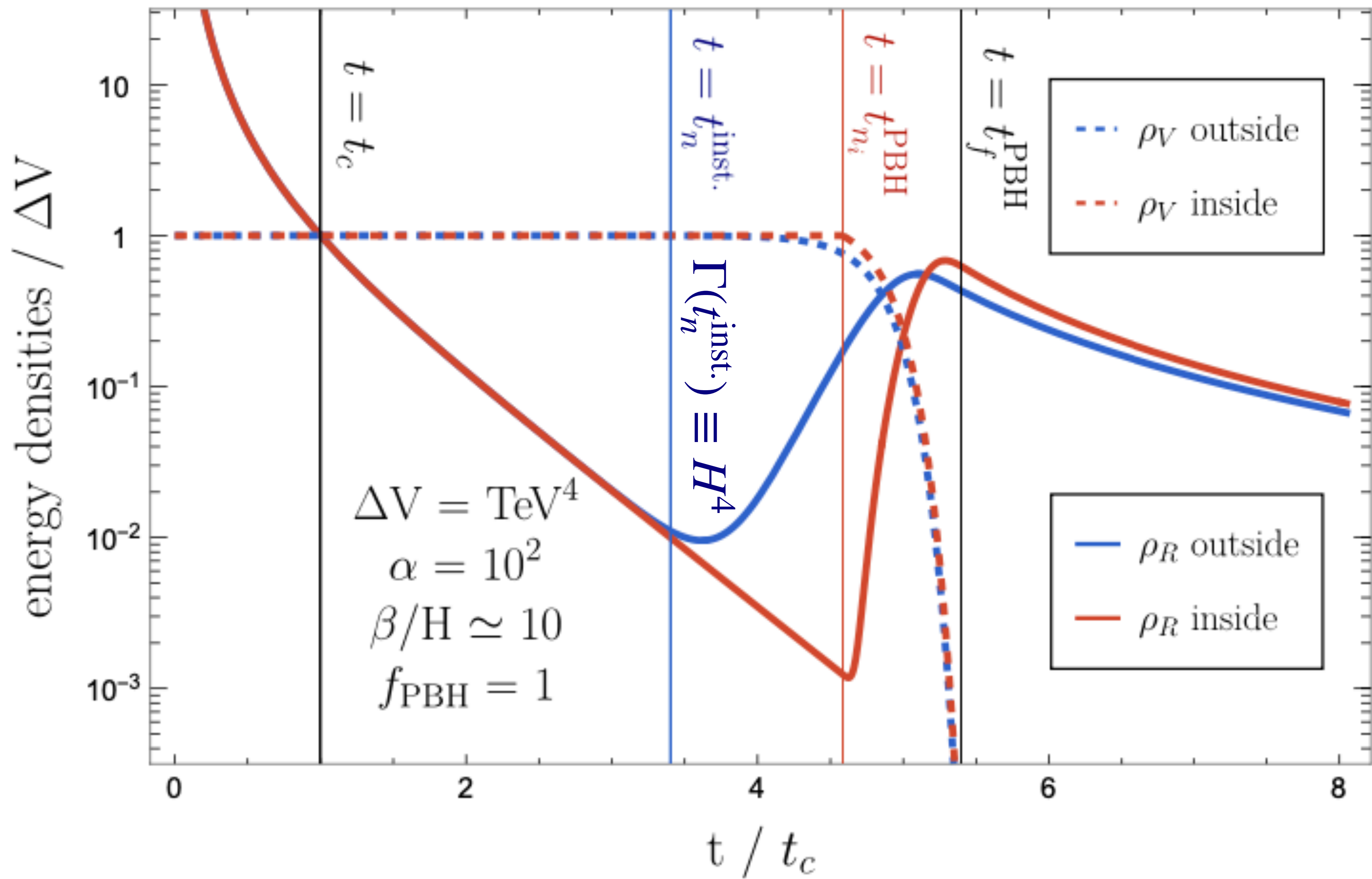


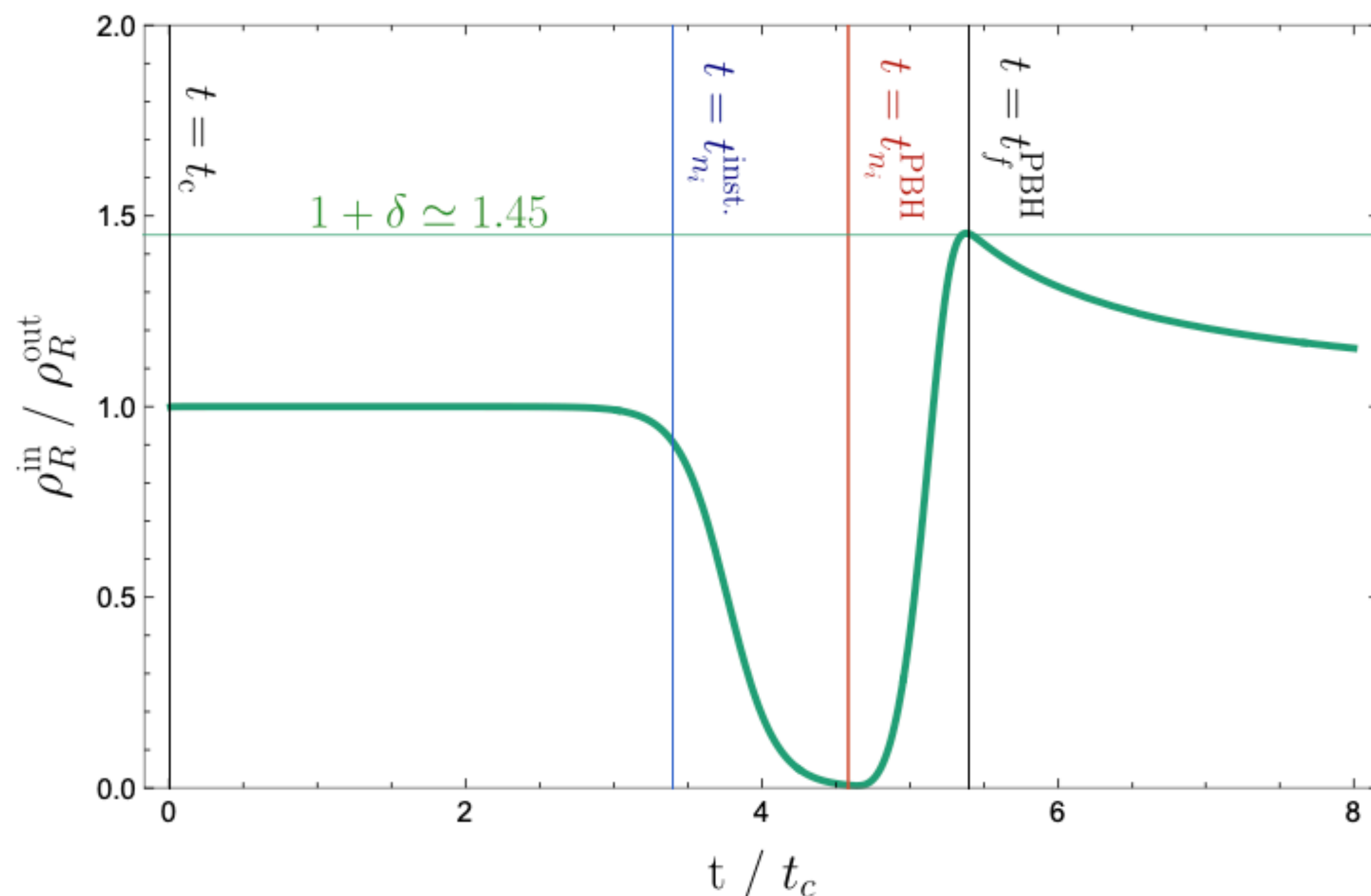
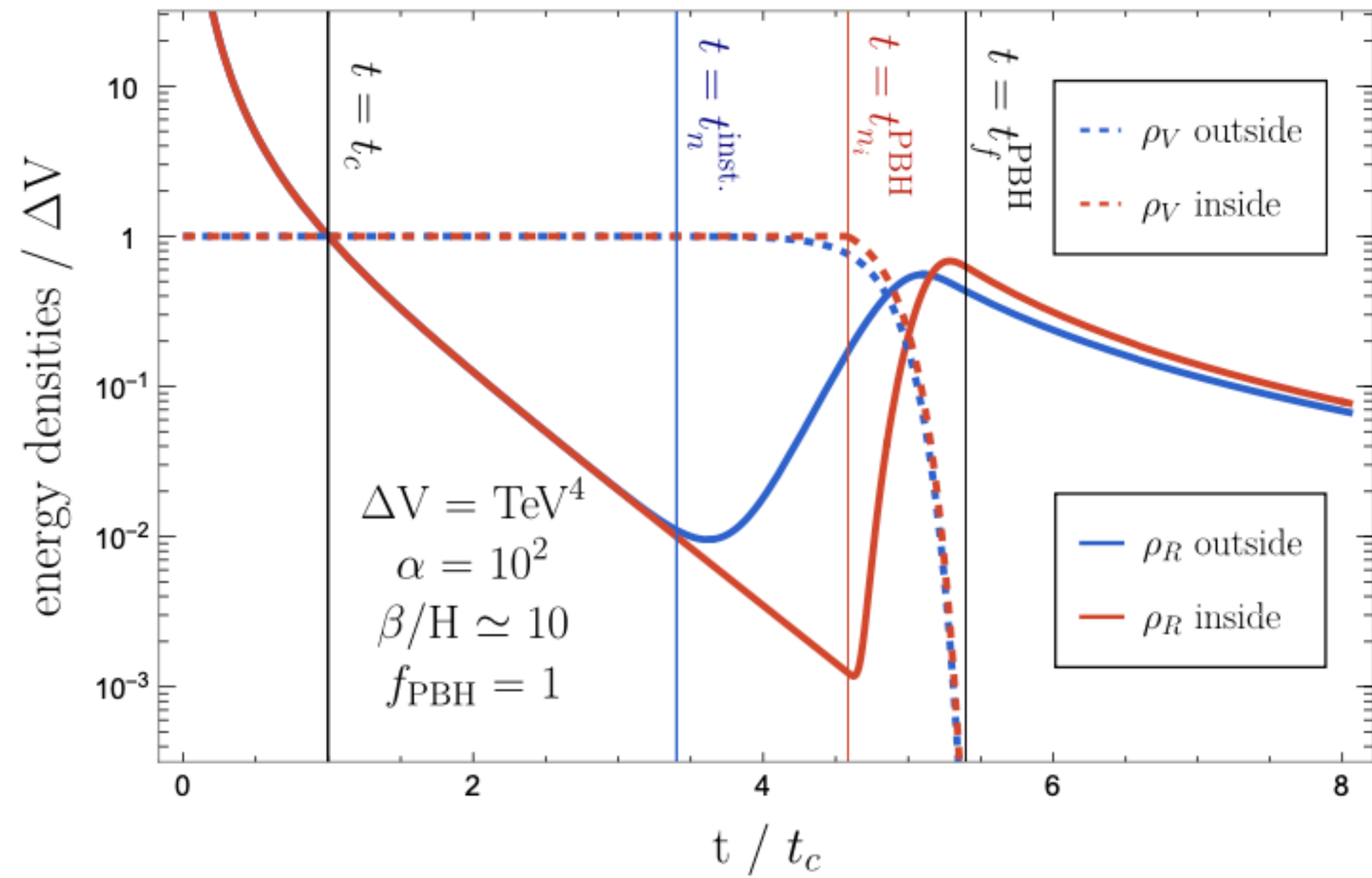






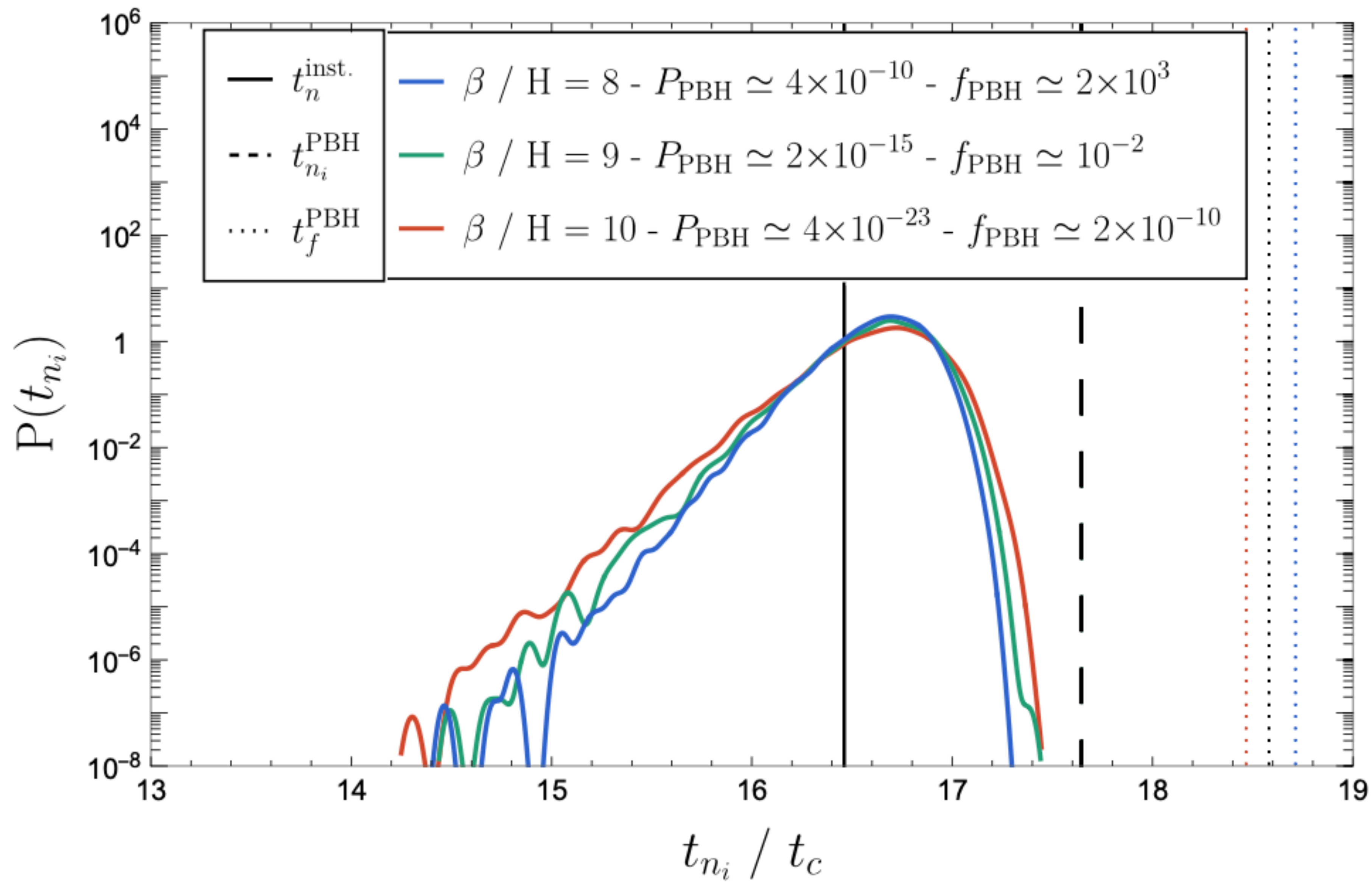






The survival probability

$$T_c = 100 \text{ GeV} - \alpha = 10^{12}$$



PBH abundance

$$f_{\text{PBH}} \equiv \frac{\rho_{\text{PBH}}}{\rho_{\text{DM}}} = P_{\text{PBH}} \frac{M_{\text{PBH}} \mathcal{N}_{\text{patches}}}{\frac{4\pi}{3} H_0^{-3}} \frac{1}{\rho_{\text{DM},0}} = \frac{P_{\text{PBH}}}{3 \times 10^{-11}} \left(\frac{T_c}{100 \text{ GeV}} \right)$$

PBH abundance

$$f_{\text{PBH}} \equiv \frac{\rho_{\text{PBH}}}{\rho_{\text{DM}}} = P_{\text{PBH}} \frac{M_{\text{PBH}} \mathcal{N}_{\text{patches}}}{\frac{4\pi}{3} H_0^{-3}} \frac{1}{\rho_{\text{DM},0}} = \frac{P_{\text{PBH}}}{3 \times 10^{-11}} \left(\frac{T_c}{100 \text{ GeV}} \right)$$

● with $P_{\text{PBH}} = P(t_{n_i}^{\text{PBH}}) = \exp \left[-\frac{4\pi}{3} \int_{t_c}^{t_{n_i}} dt' \Gamma(t') a(t')^3 \left(\frac{1}{a(t_f^{\text{PBH}}) H(t_f^{\text{PBH}})} \right)^3 \right]$

PBH abundance

$$f_{\text{PBH}} \equiv \frac{\rho_{\text{PBH}}}{\rho_{\text{DM}}} = P_{\text{PBH}} \frac{M_{\text{PBH}} \mathcal{N}_{\text{patches}}}{\frac{4\pi}{3} H_0^{-3}} \frac{1}{\rho_{\text{DM},0}} = \frac{P_{\text{PBH}}}{3 \times 10^{-11}} \left(\frac{T_c}{100 \text{ GeV}} \right)$$

- with $P_{\text{PBH}} = P(t_{n_i}^{\text{PBH}}) = \exp \left[-\frac{4\pi}{3} \int_{t_c}^{t_{n_i}} dt' \Gamma(t') a(t')^3 \left(\frac{1}{a(t_f^{\text{PBH}}) H(t_f^{\text{PBH}})} \right)^3 \right]$
- with $t_{n_i}^{\text{PBH}}$ the minimum value such that there is a t_f^{PBH} solution of :

$$\left(\frac{\rho_{\text{R}}(t, t_{n_i}^{\text{PBH}}) - \rho_{\text{R}}(t, t_c)}{\rho_{\text{R}}(t, t_c)} \right)_{t=t_f^{\text{PBH}}} \equiv \delta.$$

PBH abundance

$$f_{\text{PBH}} \equiv \frac{\rho_{\text{PBH}}}{\rho_{\text{DM}}} = P_{\text{PBH}} \frac{M_{\text{PBH}} \mathcal{N}_{\text{patches}}}{\frac{4\pi}{3} H_0^{-3}} \frac{1}{\rho_{\text{DM},0}} = \frac{P_{\text{PBH}}}{3 \times 10^{-11}} \left(\frac{T_c}{100 \text{ GeV}} \right)$$

- with $P_{\text{PBH}} = P(t_{n_i}^{\text{PBH}}) = \exp \left[-\frac{4\pi}{3} \int_{t_c}^{t_{n_i}} dt' \Gamma(t') a(t')^3 \left(\frac{1}{a(t_f^{\text{PBH}}) H(t_f^{\text{PBH}})} \right)^3 \right]$

- with $t_{n_i}^{\text{PBH}}$ the minimum value such that there is a t_f^{PBH} solution of :

$$\left(\frac{\rho_{\text{R}}(t, t_{n_i}^{\text{PBH}}) - \rho_{\text{R}}(t, t_c)}{\rho_{\text{R}}(t, t_c)} \right)_{t=t_f^{\text{PBH}}} \equiv \delta.$$

- with $\rho_{\text{R}}(t, t_{n_i})$ is solution of $\rho_{\text{R}}'(t) + 4H(t)\rho_{\text{R}}(t) = -\Delta V \frac{dF(t, t_{n_i})}{dt}$ $H^2(t) = \frac{\rho_{\text{R}}(t) + \Delta V F(t, t_{n_i})}{3M_{\text{pl}}^2}$

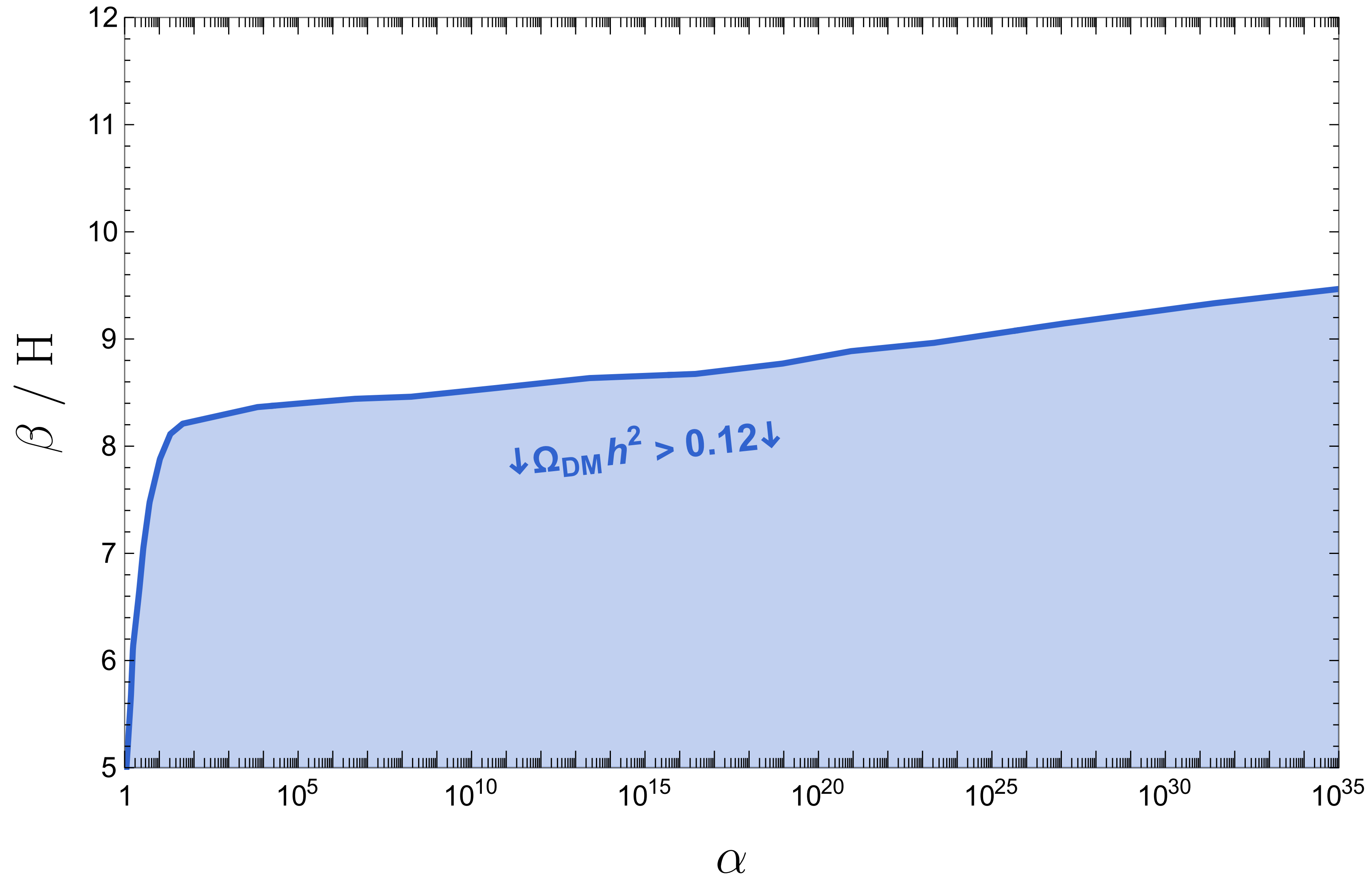
$$F(t, t_{n_i}) = \exp \left[-\int_{t_{n_i}}^t dt' \Gamma(t') a^3(t') \times \frac{4\pi}{3} \left(\int_{t'}^t \frac{d\tau}{a(\tau)} \right)^3 \right]$$

Latent heat:

$$\alpha \equiv \frac{\Delta V}{\frac{\pi^2}{30} g_* T_n^4} \simeq \left(\frac{T_{\text{eq}}}{T_n} \right)^4$$

Phase transition rate:

$$\Gamma(t) = \Gamma_0 e^{\beta t}, \quad \text{with} \quad \beta \equiv \frac{1}{\Gamma} \frac{d\Gamma}{dt}.$$

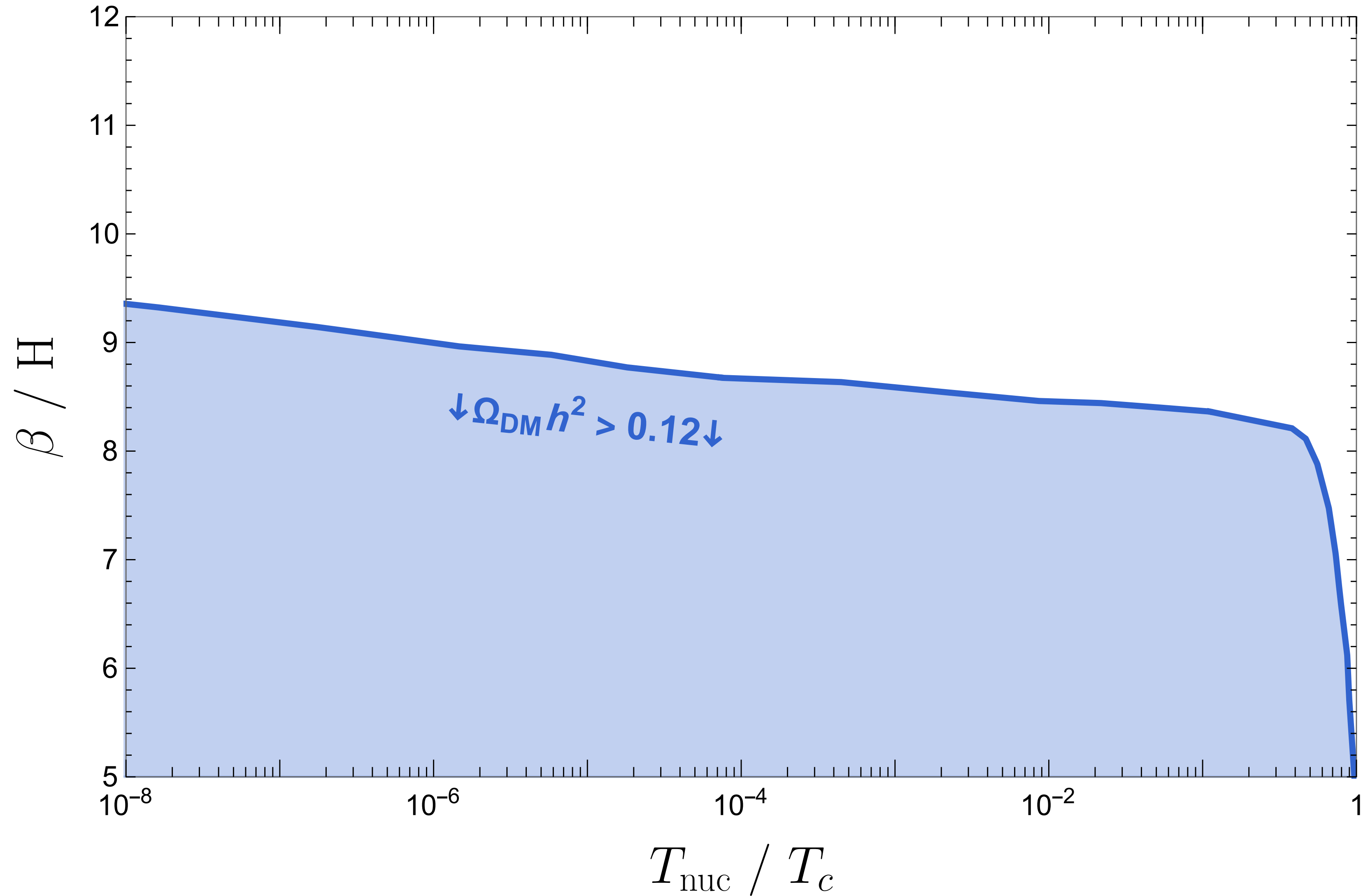


Latent heat:

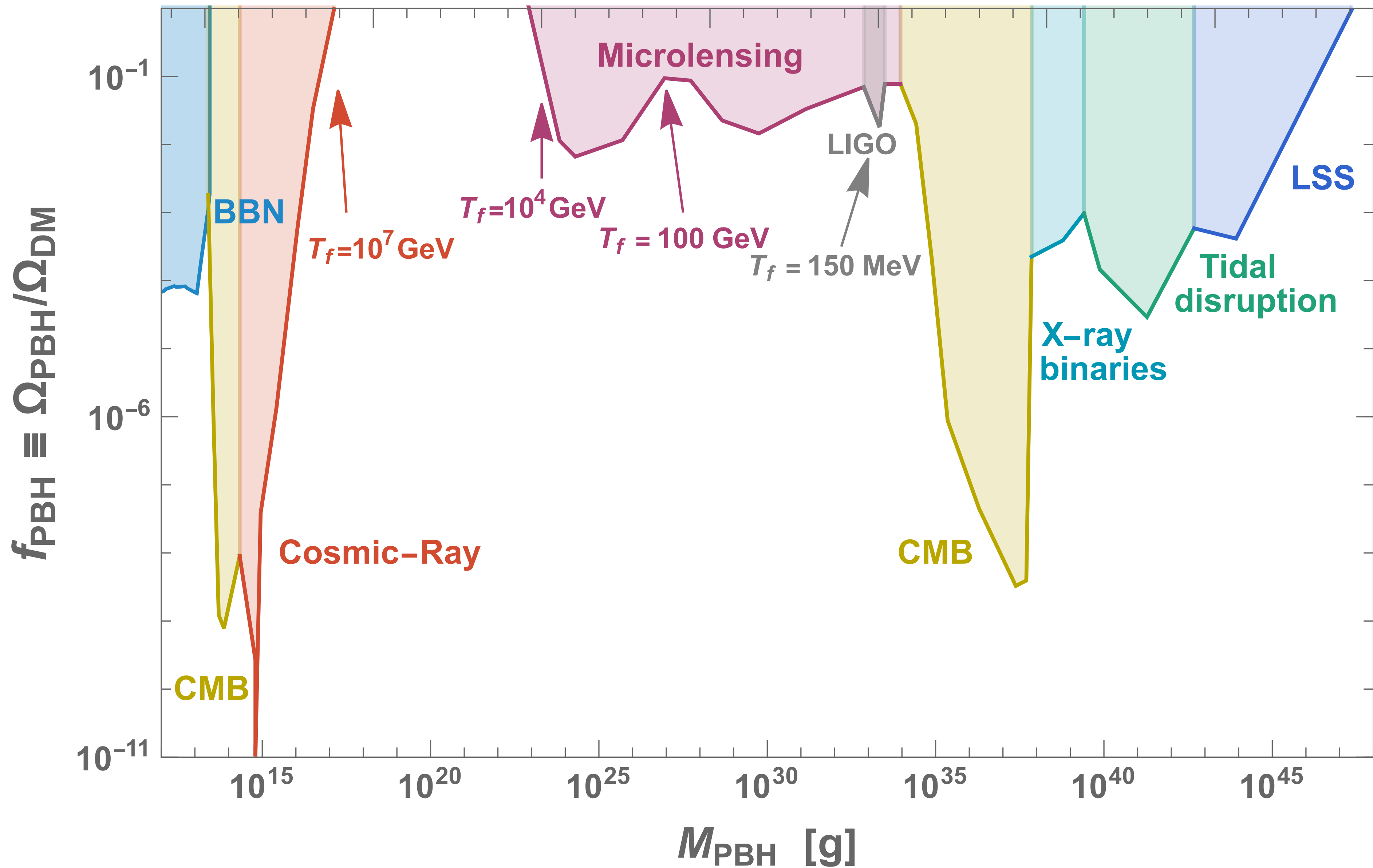
$$\alpha \equiv \frac{\Delta V}{\frac{\pi^2}{30} g_* T_n^4} \simeq \left(\frac{T_{\text{eq}}}{T_n} \right)^4$$

Phase transition rate:

$$\Gamma(t) = \Gamma_0 e^{\beta t}, \quad \text{with} \quad \beta \equiv \frac{1}{\Gamma} \frac{d\Gamma}{dt}.$$

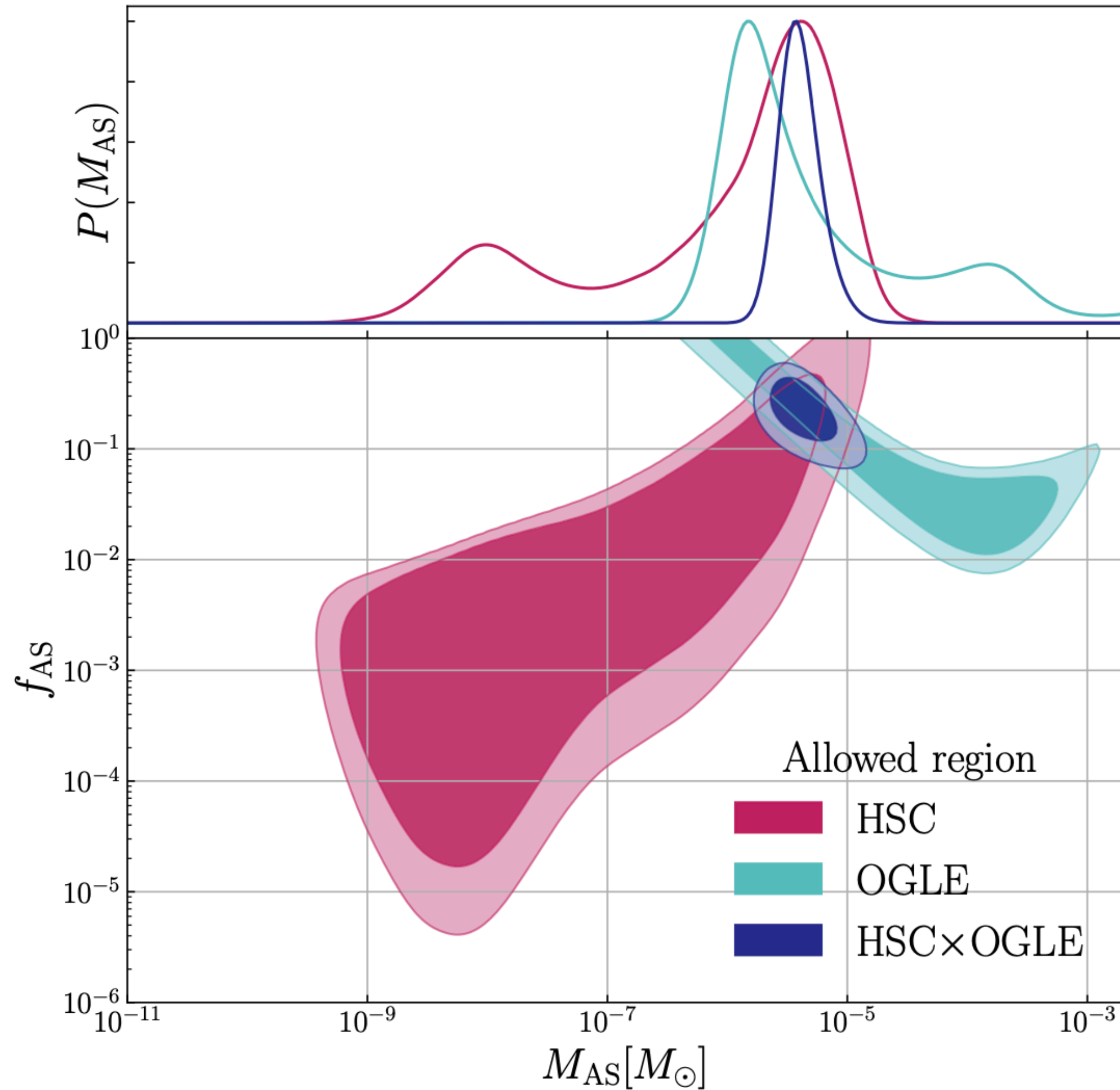


Supercooling from a nearly conformal sector

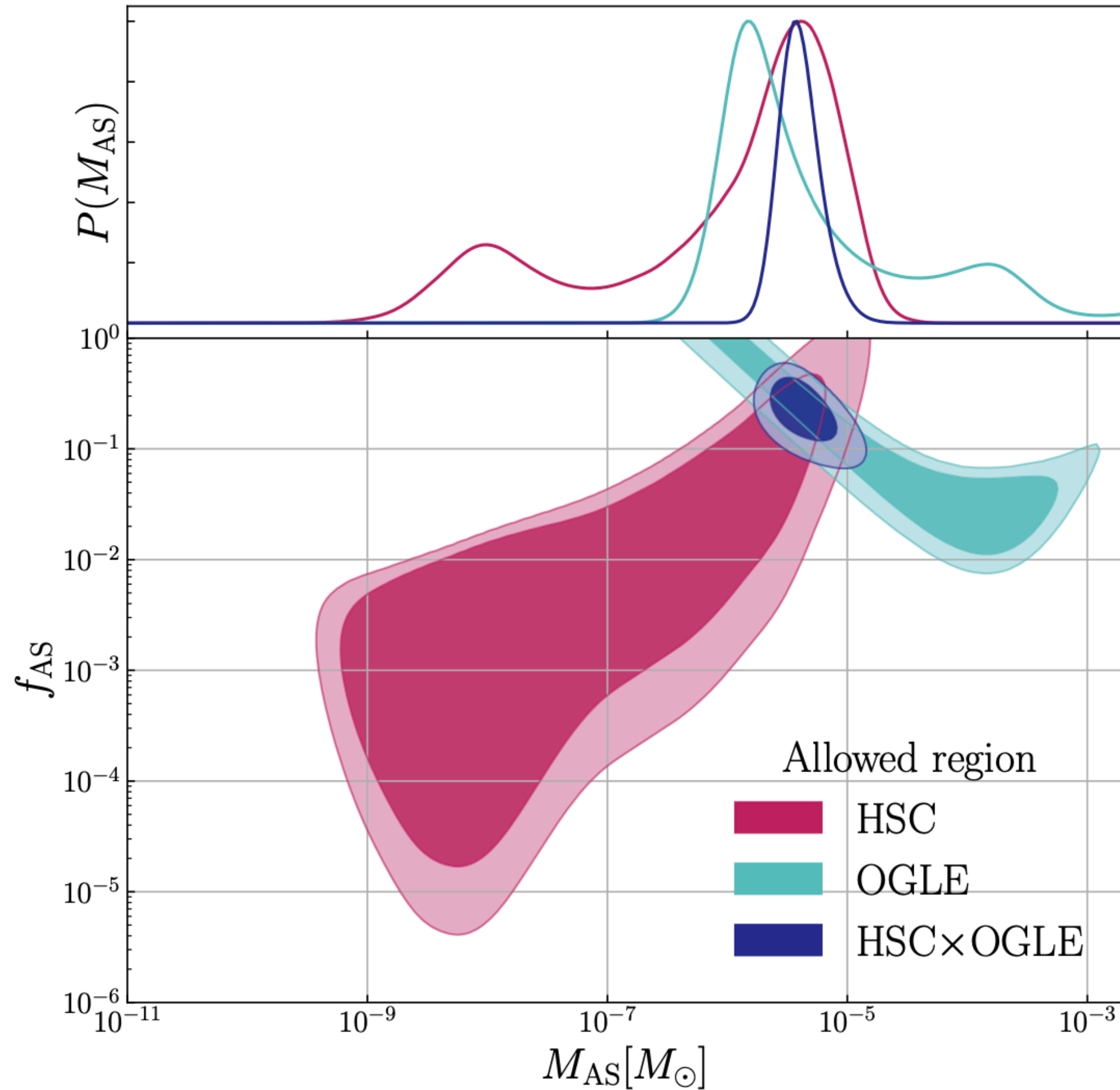


Have microlensing experiments detected remnants of the EWPT ?

Have microlensing experiments detected remnants of the EWPT ?



Have microlensing experiments detected remnants of the EWPT ?

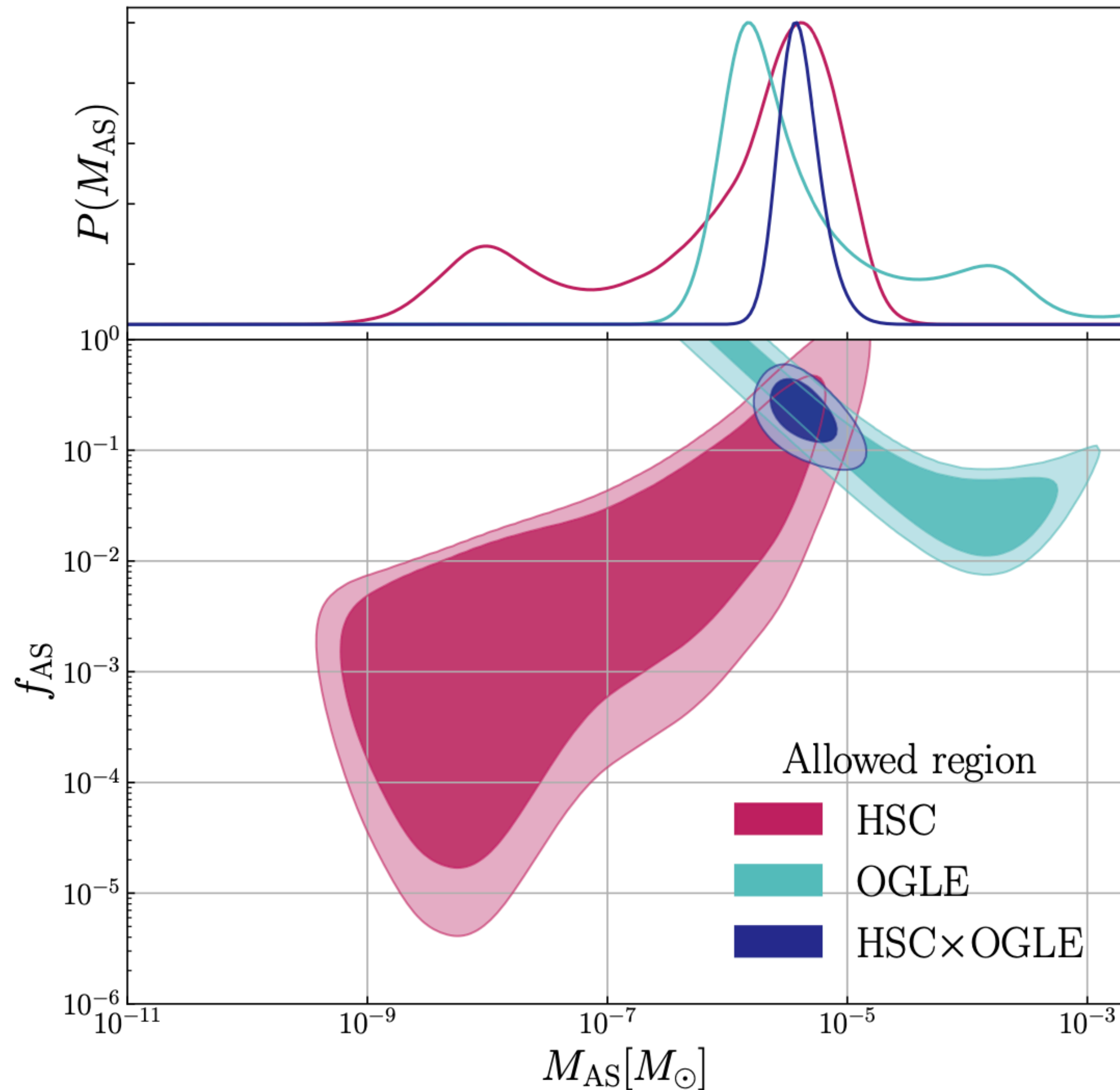


OGLE x HSC

$$M_{\text{PBH}} \simeq 10^{-6} M_{\odot} \left(\frac{100 \text{ GeV}}{T_c} \right)^2$$

$$\simeq M_{\text{earth}} \simeq 1 \text{ cm}$$

Have microlensing experiments detected remnants of the EWPT ?



OGLE x HSC

$$M_{\text{PBH}} \simeq 10^{-6} M_{\odot} \left(\frac{100 \text{ GeV}}{T_c} \right)^2$$

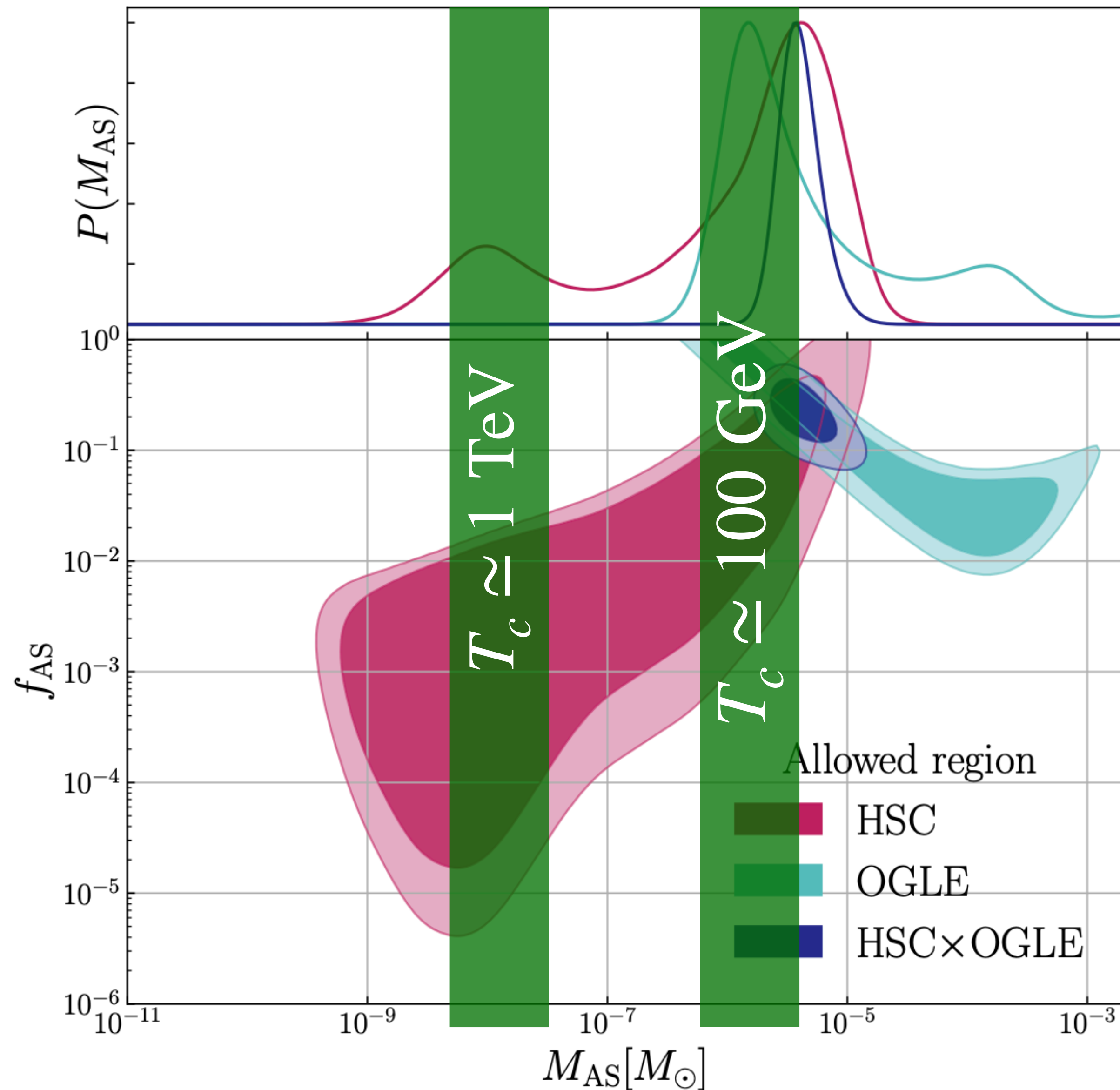
$$\simeq M_{\text{earth}} \simeq 1 \text{ cm}$$

HSC

$$M_{\text{PBH}} \simeq 10^{-8} M_{\odot} \left(\frac{1 \text{ TeV}}{T_c} \right)^2$$

$$\simeq M_{\text{moon}} \simeq 0.1 \text{ mm}$$

Have microlensing experiments detected remnants of the EWPT ?



OGLE x HSC

$$M_{\text{PBH}} \approx 10^{-6} M_{\odot} \left(\frac{100 \text{ GeV}}{T_c} \right)^2$$

$$\approx M_{\text{earth}} \approx 1 \text{ cm}$$

HSC

$$M_{\text{PBH}} \approx 10^{-8} M_{\odot} \left(\frac{1 \text{ TeV}}{T_c} \right)^2$$

$$\approx M_{\text{moon}} \approx 0.1 \text{ mm}$$

Nearly-conformal EW sector

YG, Volansky (to appear)

Nearly-conformal EW sector

YG, Volansky (to appear)

$$\mathcal{L}_{\text{tree}} = -\frac{1}{4} (F_{\mu\nu})^2 + |D_\mu \Phi|^2 - \lambda_h |H|^4 + \lambda_\sigma |\phi|^4 - \lambda_{h\sigma} \phi^2 H^2.$$

Nearly-conformal EW sector

YG, Volansky (to appear)

$$\mathcal{L}_{\text{tree}} = -\frac{1}{4} (F_{\mu\nu})^2 + |D_\mu \Phi|^2 - \lambda_h |H|^4 + \lambda_\sigma |\phi|^4 - \lambda_{h\sigma} \phi^2 H^2.$$

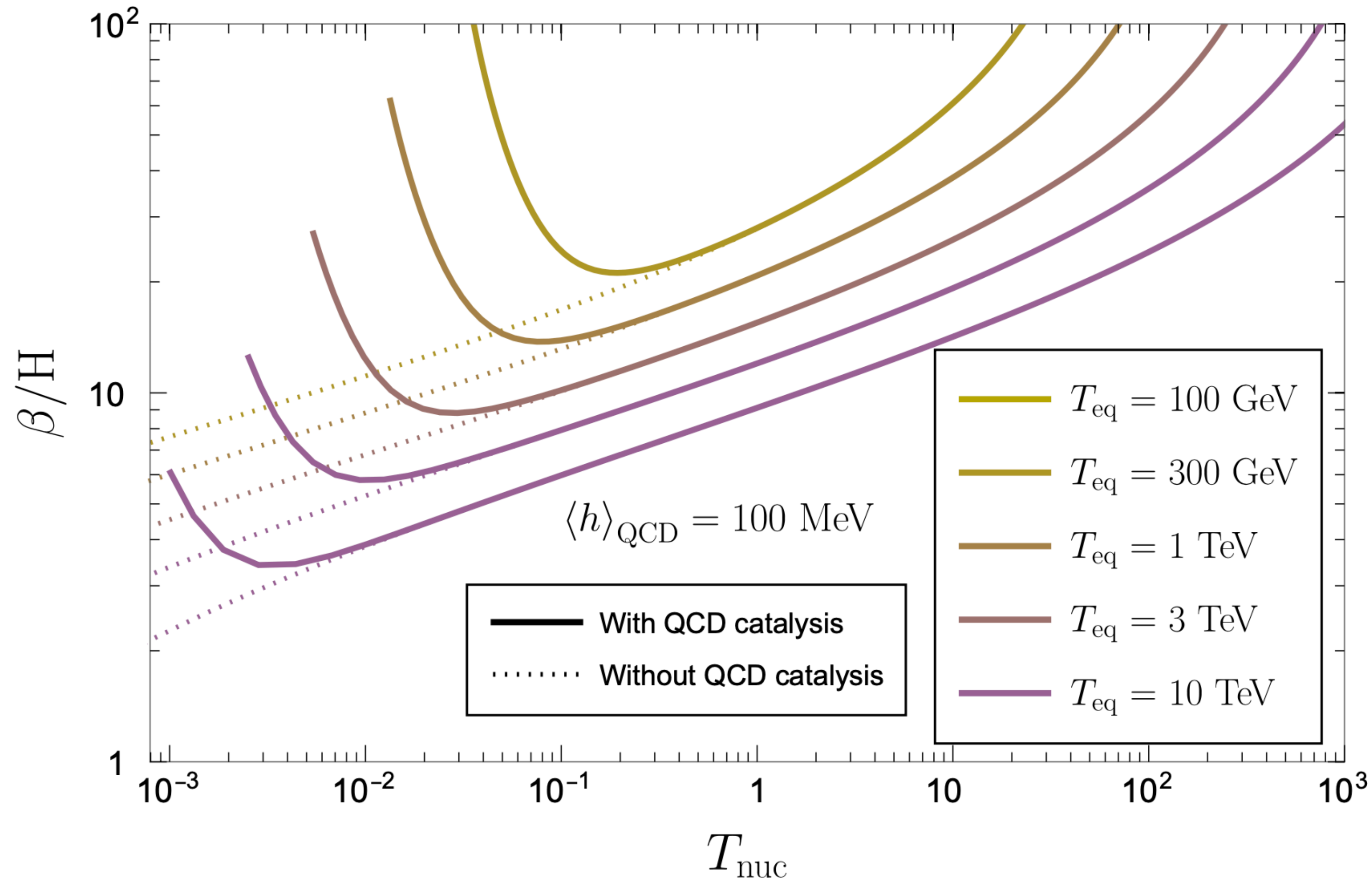
$$V(\phi) = \beta_\lambda \frac{\phi^4}{4} \left[\log \left(\frac{\phi}{f} \right) - \frac{1}{4} \right] \quad \beta_\lambda = \frac{1}{8\pi^2} \left(\frac{9g_D^4}{16} - \frac{9g_D^2 \lambda_\sigma}{2} + \lambda_{h\sigma}^2 + 12\lambda_\sigma^2 \right) \simeq \frac{9}{8} \alpha_D^2.$$

Nearly-conformal EW sector

YG, Volansky (to appear)

$$\mathcal{L}_{\text{tree}} = -\frac{1}{4} (F_{\mu\nu})^2 + |D_\mu \Phi|^2 - \lambda_h |H|^4 + \lambda_\sigma |\phi|^4 - \lambda_{h\sigma} \phi^2 H^2.$$

$$V(\phi) = \beta_\lambda \frac{\phi^4}{4} \left[\log \left(\frac{\phi}{f} \right) - \frac{1}{4} \right] \quad \beta_\lambda = \frac{1}{8\pi^2} \left(\frac{9g_D^4}{16} - \frac{9g_D^2 \lambda_\sigma}{2} + \lambda_{h\sigma}^2 + 12\lambda_\sigma^2 \right) \simeq \frac{9}{8} \alpha_D^2.$$

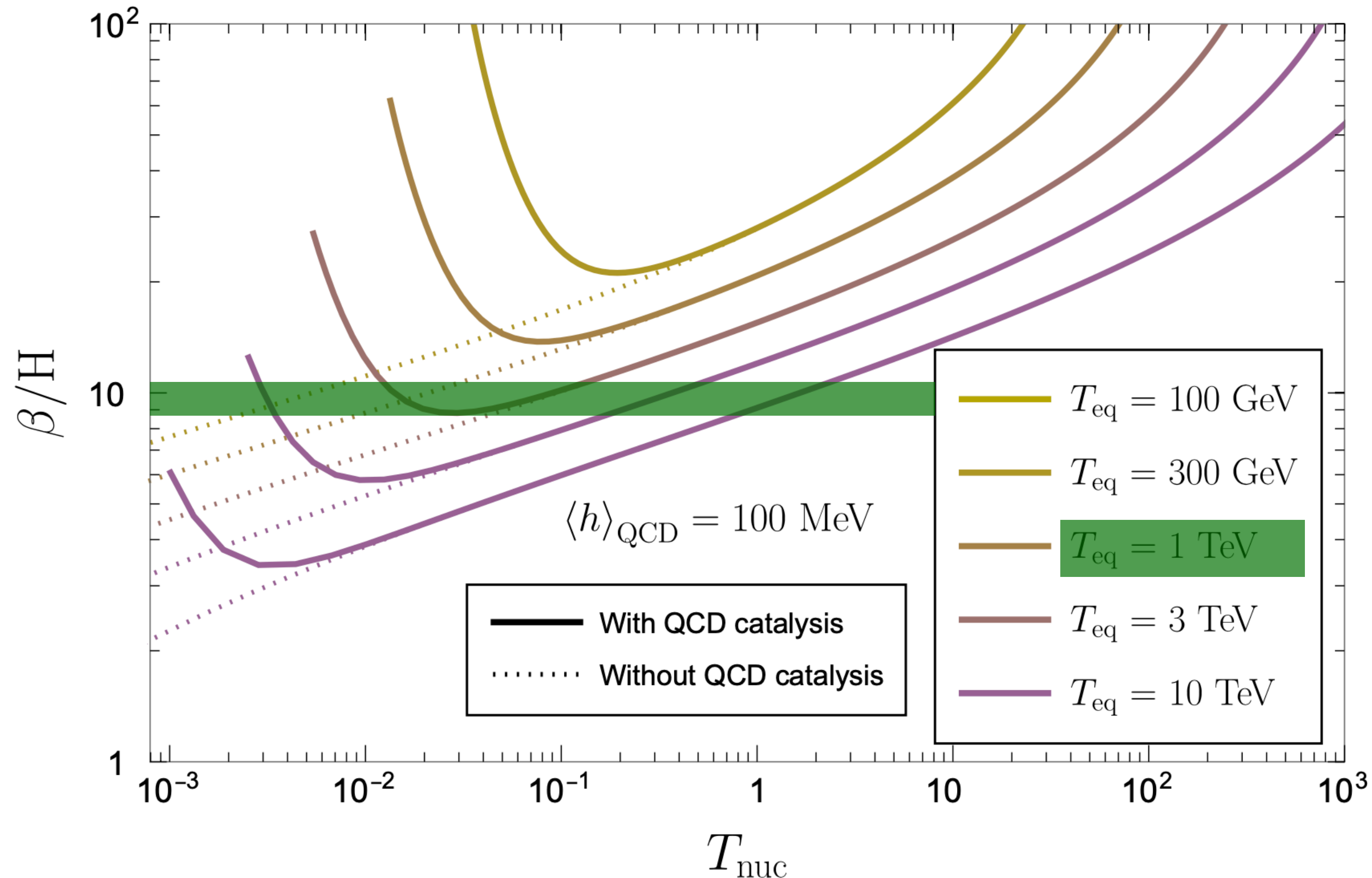


Nearly-conformal EW sector

YG, Volansky (to appear)

$$\mathcal{L}_{\text{tree}} = -\frac{1}{4} (F_{\mu\nu})^2 + |D_\mu \Phi|^2 - \left[\lambda_h |H|^4 + \lambda_\sigma |\phi|^4 - \lambda_{h\sigma} \phi^2 H^2 \right]$$

$$V(\phi) = \beta_\lambda \frac{\phi^4}{4} \left[\log \left(\frac{\phi}{f} \right) - \frac{1}{4} \right] \quad \beta_\lambda = \frac{1}{8\pi^2} \left(\frac{9g_D^4}{16} - \frac{9g_D^2 \lambda_\sigma}{2} + \lambda_{h\sigma}^2 + 12\lambda_\sigma^2 \right) \simeq \frac{9}{8} \alpha_D^2.$$



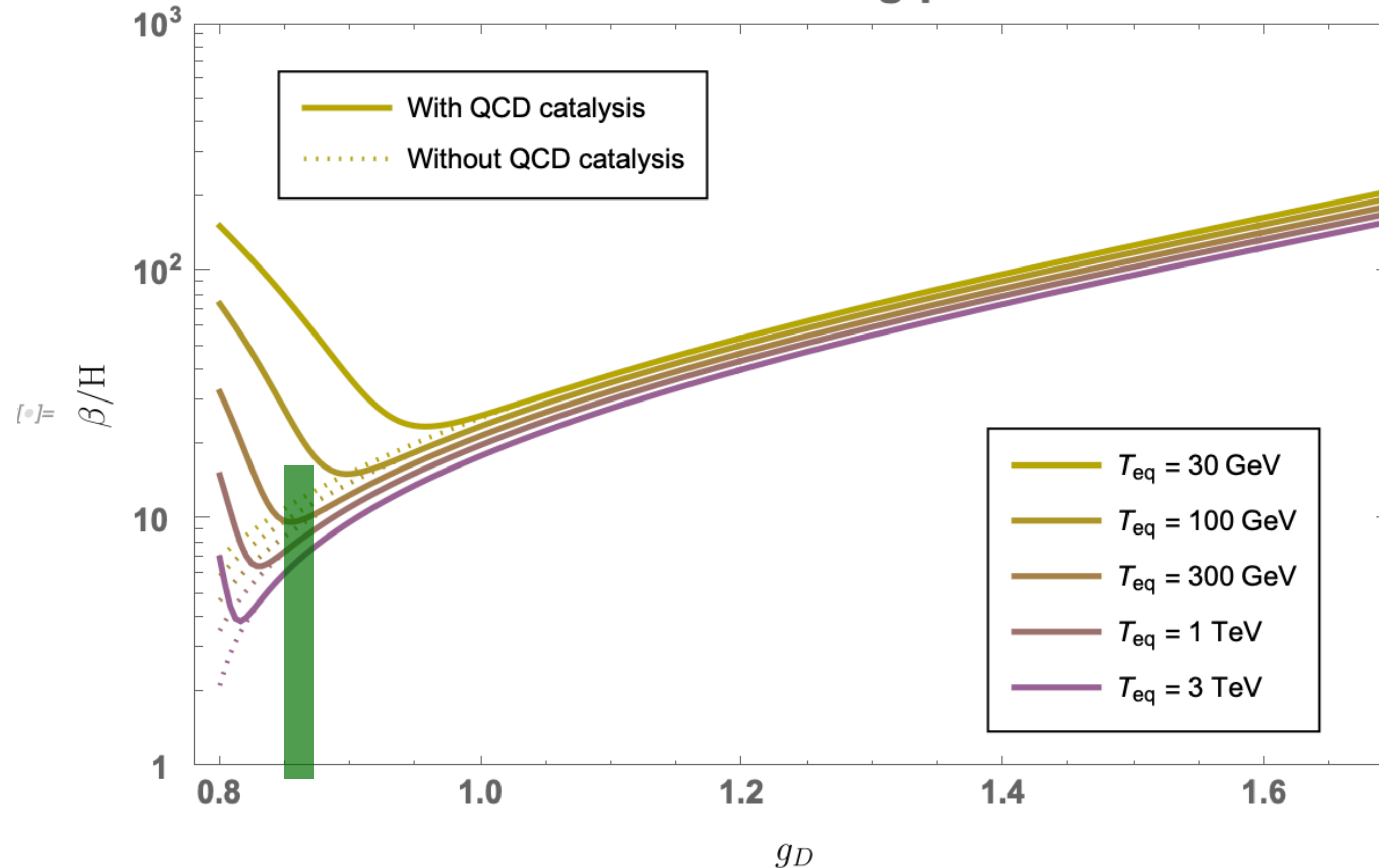
Nearly-conformal EW sector

YG, Volansky (to appear)

$$\mathcal{L}_{\text{tree}} = -\frac{1}{4} (F_{\mu\nu})^2 + |D_\mu \Phi|^2 - \lambda_h |H|^4 + \lambda_\sigma |\phi|^4 - \lambda_{h\sigma} \phi^2 H^2.$$

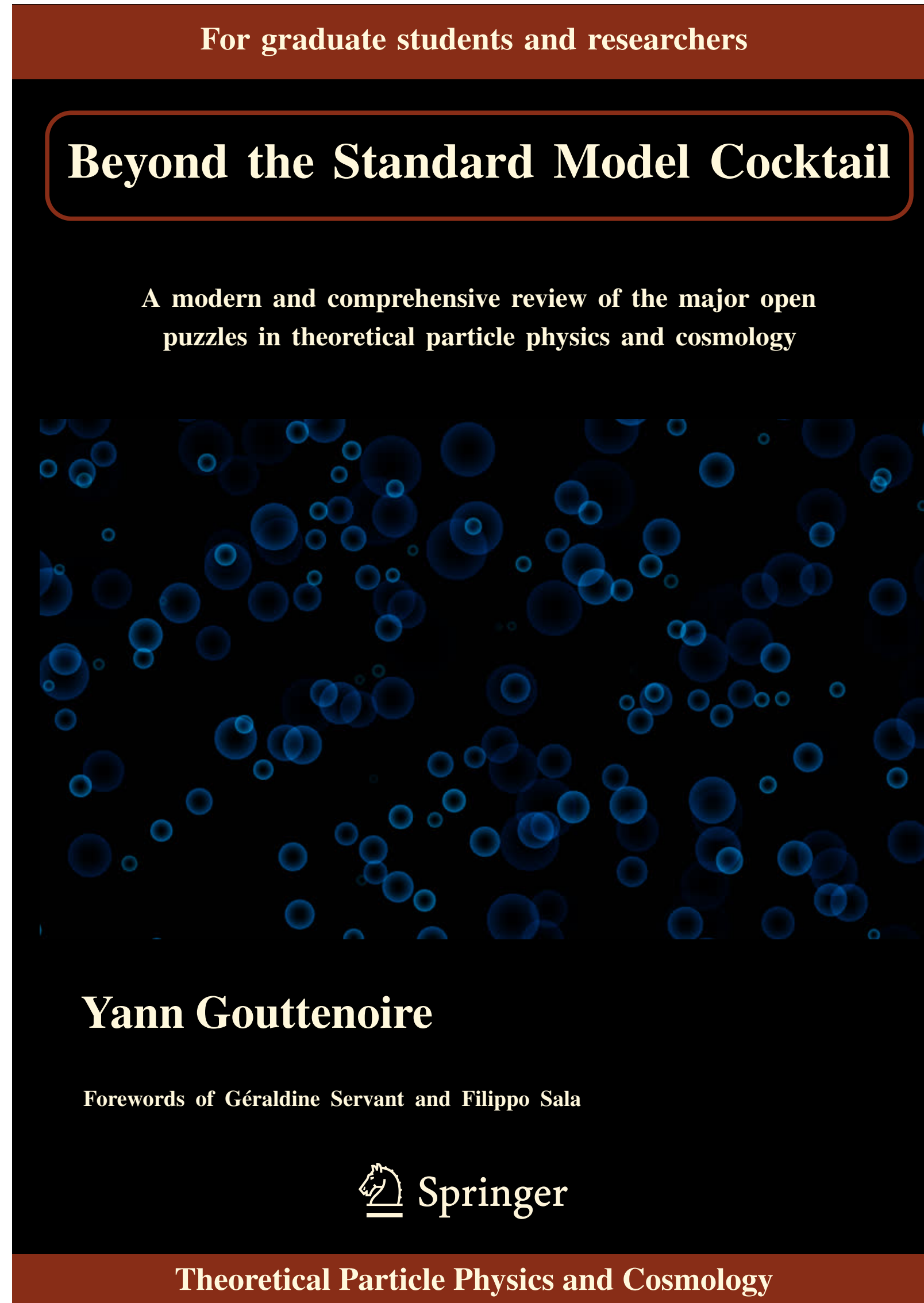
$$V(\phi) = \beta_\lambda \frac{\phi^4}{4} \left[\log \left(\frac{\phi}{f} \right) - \frac{1}{4} \right] \quad \beta_\lambda = \frac{1}{8\pi^2} \left(\frac{9g_D^4}{16} - \frac{9g_D^2 \lambda_\sigma}{2} + \lambda_{h\sigma}^2 + 12\lambda_\sigma^2 \right) \simeq \frac{9}{8} \alpha_D^2.$$

Coleman-Weinberg potential



For more details on supercooled phase transitions

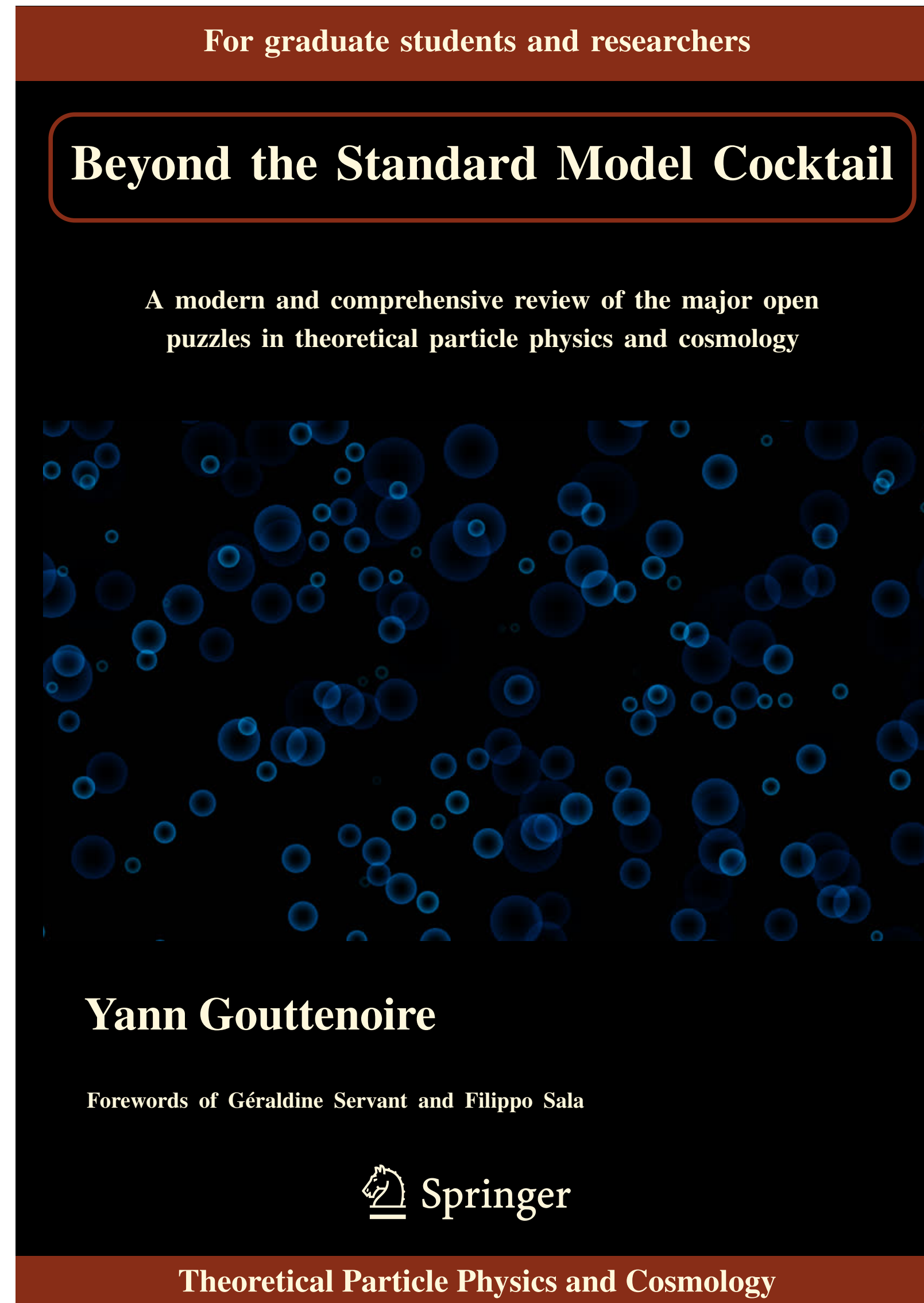
-> **Chap 6.4 of** Beyond the Standard Model Cocktail



For more details on supercooled phase transitions

-> Chap 6.4 of Beyond the Standard Model Cocktail

500 pages, 2400 references, review of numerous BSM topics

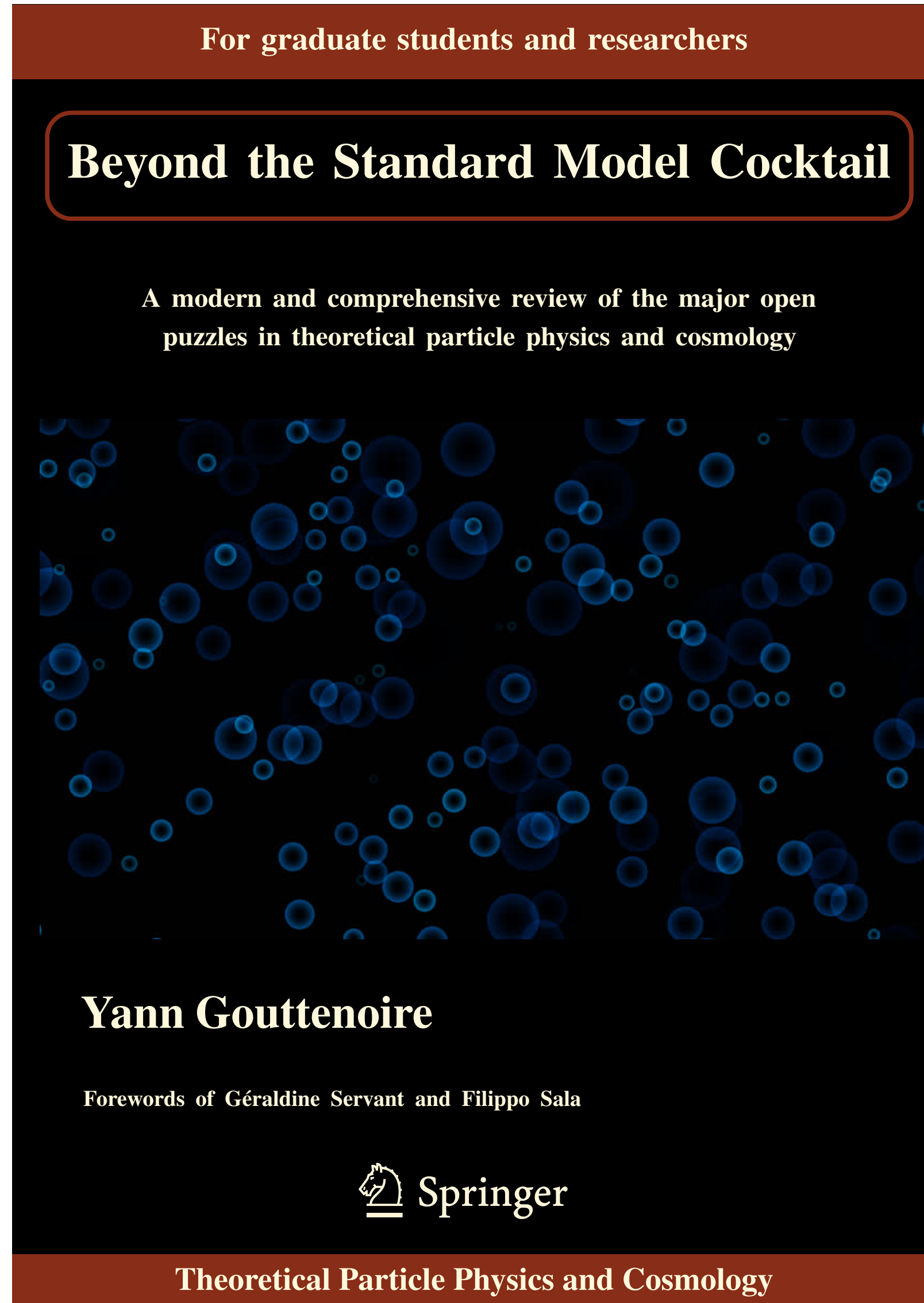


For more details on supercooled phase transitions

-> **Chap 6.4** of *Beyond the Standard Model Cocktail*

500 pages, 2400 references, review of numerous BSM topics

Available at Springer very soon (200\$) or for free on ArXiv

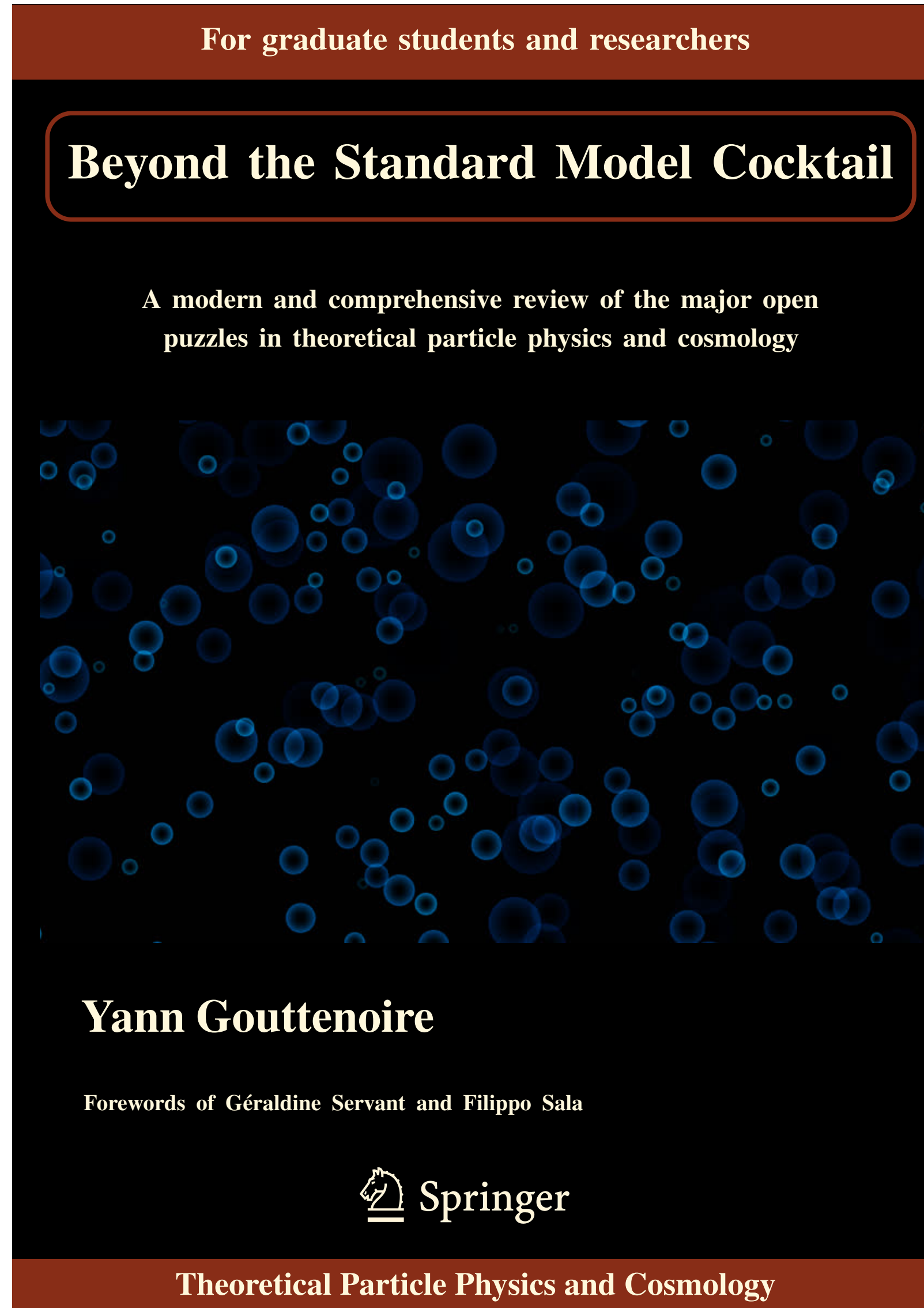


For more details on supercooled phase transitions

-> Chap 6.4 of Beyond the Standard Model Cocktail

500 pages, 2400 references, review of numerous BSM topics

Available at Springer very soon (200\$) or for free on ArXiv



2	Standard Model of Elementary Particles	23
2.1	Fields and symmetries	24
2.1.1	The Lorentz representations	24
2.1.2	The gauge interactions	25
2.1.3	The matter content	25
2.1.4	The Higgs field	26
2.2	The Standard Model in a nutshell	27
2.2.1	The Lagrangian	27
2.2.2	Quantum Chromodynamics	28
2.2.3	Electroweak Symmetry Breaking	32
2.2.4	Weak CP violation	35
2.2.5	Anomaly cancellation	38
2.2.6	Strong CP violation	39
2.3	Open problems	43
2.3.1	Hierarchy problem	43
2.3.2	Neutrino oscillations	52
2.3.3	Flavor hierarchy problem	56
2.3.4	Strong CP problem	57

For more details on supercooled phase transitions

-> Chap 6.4 of Beyond the Standard Model Cocktail

500 pages, 2400 references, review of numerous BSM topics

Available at Springer very soon (200\$) or for free on ArXiv

2	Standard Model of Elementary Particles	23
2.1	Fields and symmetries	24
2.1.1	The Lorentz representations	24
2.1.2	The gauge interactions	25
2.1.3	The matter content	25
2.1.4	The Higgs field	26
2.2	The Standard Model in a nutshell	27
2.2.1	The Lagrangian	27
2.2.2	Quantum Chromodynamics	28
2.2.3	Electroweak Symmetry Breaking	32
2.2.4	Weak CP violation	35
2.2.5	Anomaly cancellation	38
2.2.6	Strong CP violation	39
2.3	Open problems	43
2.3.1	Hierarchy problem	43
2.3.2	Neutrino oscillations	52
2.3.3	Flavor hierarchy problem	56
2.3.4	Strong CP problem	57
3	Standard Model of Cosmology	83
3.1	The ΛCDM cosmological model	85
3.1.1	A homogeneous and isotropic expanding universe	85
3.1.2	Energy content of the universe	86
3.2	The hot big-bang scenario	87
3.2.1	Thermal equilibrium	87
3.2.2	Beyond thermal equilibrium	89
3.3	Inflation	91
3.3.1	The homogeneity problem	91
3.3.2	The flatness problem	92
3.3.3	The solution: shrinking the comoving Hubble radius	92
3.3.4	Slow-roll inflation	93
3.4	Gravitational waves of primordial origin	97
3.4.1	Linearized wave solutions of Einstein equations	97
3.4.2	Energy of gravitational-waves	99
3.4.3	Cosmological signals	101
3.5	Open problems	104
3.5.1	Cosmological constant problem	105
3.5.2	Matter-anti-matter asymmetry	110
3.5.3	Dark Matter puzzle	115
3.5.4	The fragility of Λ CDM	120
3.5.5	The Hubble tension	131
3.5.6	The 21-cm anomaly	133

For graduate students and researchers

Beyond the Standard Model Cocktail

A modern and comprehensive review of the major open puzzles in theoretical particle physics and cosmology

Yann Gouttenoire

Forewords of Géraldine Servant and Filippo Sala

 Springer

Theoretical Particle Physics and Cosmology

For more details on supercooled phase transitions

-> Chap 6.4 of Beyond the Standard Model Cocktail

500 pages, 2400 references, review of numerous BSM topics

Available at Springer very soon (200\$) or for free on ArXiv

2	Standard Model of Elementary Particles	23
2.1	Fields and symmetries	24
2.1.1	The Lorentz representations	24
2.1.2	The gauge interactions	25
2.1.3	The matter content	25
2.1.4	The Higgs field	26
2.2	The Standard Model in a nutshell	27
2.2.1	The Lagrangian	27
2.2.2	Quantum Chromodynamics	28
2.2.3	Electroweak Symmetry Breaking	32
2.2.4	Weak CP violation	35
2.2.5	Anomaly cancellation	38
2.2.6	Strong CP violation	39
2.3	Open problems	43
2.3.1	Hierarchy problem	43
2.3.2	Neutrino oscillations	52
2.3.3	Flavor hierarchy problem	56
2.3.4	Strong CP problem	57
3	Standard Model of Cosmology	83
3.1	The ΛCDM cosmological model	85
3.1.1	A homogeneous and isotropic expanding universe	85
3.1.2	Energy content of the universe	86
3.2	The hot big-bang scenario	87
3.2.1	Thermal equilibrium	87
3.2.2	Beyond thermal equilibrium	89
3.3	Inflation	91
3.3.1	The homogeneity problem	91
3.3.2	The flatness problem	92
3.3.3	The solution: shrinking the comoving Hubble radius	92
3.3.4	Slow-roll inflation	93
3.4	Gravitational waves of primordial origin	97
3.4.1	Linearized wave solutions of Einstein equations	97
3.4.2	Energy of gravitational-waves	99
3.4.3	Cosmological signals	101
3.5	Open problems	104
3.5.1	Cosmological constant problem	105
3.5.2	Matter-anti-matter asymmetry	110
3.5.3	Dark Matter puzzle	115
3.5.4	The fragility of Λ CDM	120
3.5.5	The Hubble tension	131
3.5.6	The 21-cm anomaly	133
4	Thermal Dark Matter	189
4.1	Production mechanism	189
4.1.1	The Boltzmann equation	189
4.1.2	Freeze-in versus Freeze-out	191
4.1.3	Exceptions	194
4.2	The WIMP paradigm	196
4.2.1	Motivations	196
4.2.2	The WIMP abundance	196
4.2.3	Minimal WIMP under pressure	197
4.2.4	Warm Dark Matter	199
4.3	Heavy WIMP	202
4.3.1	Breakdown of perturbation theory	202
4.3.2	Sommerfeld enhancement	204
4.3.3	Bound-state-formation	206
4.3.4	The unitary bound	208

For graduate students and researchers

Beyond the Standard Model Cocktail

A modern and comprehensive review of the major open puzzles in theoretical particle physics and cosmology

Yann Gouttenoire

Forewords of Géraldine Servant and Filippo Sala

 Springer

Theoretical Particle Physics and Cosmology

For more details on supercooled phase transitions

-> Chap 6.4 of Beyond the Standard Model Cocktail

500 pages, 2400 references, review of numerous BSM topics

Available at Springer very soon (200\$) or for free on ArXiv

For graduate students and researchers

Beyond the Standard Model Cocktail

A modern and comprehensive review of the major open puzzles in theoretical particle physics and cosmology

Yann Gouttenoire

Forewords of Géraldine Servant and Filippo Sala



Theoretical Particle Physics and Cosmology

2	Standard Model of Elementary Particles	23
2.1	Fields and symmetries	24
2.1.1	The Lorentz representations	24
2.1.2	The gauge interactions	25
2.1.3	The matter content	25
2.1.4	The Higgs field	26
2.2	The Standard Model in a nutshell	27
2.2.1	The Lagrangian	27
2.2.2	Quantum Chromodynamics	28
2.2.3	Electroweak Symmetry Breaking	32
2.2.4	Weak CP violation	35
2.2.5	Anomaly cancellation	38
2.2.6	Strong CP violation	39
2.3	Open problems	43
2.3.1	Hierarchy problem	43
2.3.2	Neutrino oscillations	52
2.3.3	Flavor hierarchy problem	56
2.3.4	Strong CP problem	57
3	Standard Model of Cosmology	83
3.1	The ΛCDM cosmological model	85
3.1.1	A homogeneous and isotropic expanding universe	85
3.1.2	Energy content of the universe	86
3.2	The hot big-bang scenario	87
3.2.1	Thermal equilibrium	87
3.2.2	Beyond thermal equilibrium	89
3.3	Inflation	91
3.3.1	The homogeneity problem	91
3.3.2	The flatness problem	92
3.3.3	The solution: shrinking the comoving Hubble radius	92
3.3.4	Slow-roll inflation	93
3.4	Gravitational waves of primordial origin	97
3.4.1	Linearized wave solutions of Einstein equations	97
3.4.2	Energy of gravitational-waves	99
3.4.3	Cosmological signals	101
3.5	Open problems	104
3.5.1	Cosmological constant problem	105
3.5.2	Matter-anti-matter asymmetry	110
3.5.3	Dark Matter puzzle	115
3.5.4	The fragility of Λ CDM	120
3.5.5	The Hubble tension	131
3.5.6	The 21-cm anomaly	133
4	Thermal Dark Matter	189
4.1	Production mechanism	189
4.1.1	The Boltzmann equation	189
4.1.2	Freeze-in versus Freeze-out	191
4.1.3	Exceptions	194
4.2	The WIMP paradigm	196
4.2.1	Motivations	196
4.2.2	The WIMP abundance	196
4.2.3	Minimal WIMP under pressure	197
4.2.4	Warm Dark Matter	199
4.3	Heavy WIMP	202
4.3.1	Breakdown of perturbation theory	202
4.3.2	Sommerfeld enhancement	204
4.3.3	Bound-state-formation	206
4.3.4	The unitary bound	208
6	First-order Cosmological Phase Transition	277
6.1	Bubble nucleation	278
6.1.1	Effective potential at finite temperature	278
6.1.2	Tunneling rate	282
6.1.3	Thin-wall and thick-wall limits	285
6.1.4	Temperature at which the phase transition completes	288
6.2	Bubble propagation	289
6.2.1	Equation of motion for the scalar field	290
6.2.2	Friction pressure at local thermal equilibrium	292
6.2.3	Friction pressure close to local thermal equilibrium	294
6.2.4	Friction pressure in the ballistic approximation	295
6.2.5	Friction pressure at NLO	299
6.2.6	Speed of the wall	302
6.3	GW generation	305
6.3.1	The GW spectrum for a generic source	306
6.3.2	Contribution from the scalar field	308
6.3.3	Contributions from sound waves and turbulence	312
6.3.4	Energy transfer to sound-waves	313
6.4	Supercooling from a nearly-conformal sector	320
6.4.1	Weakly-coupled scenario: the Coleman-Weinberg potential	320
6.4.2	Strongly-coupled scenario: the light-dilaton potential	326

For more details on supercooled phase transitions

-> Chap 6.4 of Beyond the Standard Model Cocktail

500 pages, 2400 references, review of numerous BSM topics

Available at Springer very soon (200\$) or for free on ArXiv

For graduate students and researchers

Beyond the Standard Model Cocktail

A modern and comprehensive review of the major open puzzles in theoretical particle physics and cosmology

Yann Gouttenoire

Forewords of G eraldine Servant and Filippo Sala



Theoretical Particle Physics and Cosmology

2	Standard Model of Elementary Particles	23
2.1	Fields and symmetries	24
2.1.1	The Lorentz representations	24
2.1.2	The gauge interactions	25
2.1.3	The matter content	25
2.1.4	The Higgs field	26
2.2	The Standard Model in a nutshell	27
2.2.1	The Lagrangian	27
2.2.2	Quantum Chromodynamics	28
2.2.3	Electroweak Symmetry Breaking	32
2.2.4	Weak CP violation	35
2.2.5	Anomaly cancellation	38
2.2.6	Strong CP violation	39
2.3	Open problems	43
2.3.1	Hierarchy problem	43
2.3.2	Neutrino oscillations	52
2.3.3	Flavor hierarchy problem	56
2.3.4	Strong CP problem	57
3	Standard Model of Cosmology	83
3.1	The ΛCDM cosmological model	85
3.1.1	A homogeneous and isotropic expanding universe	85
3.1.2	Energy content of the universe	86
3.2	The hot big-bang scenario	87
3.2.1	Thermal equilibrium	87
3.2.2	Beyond thermal equilibrium	89
3.3	Inflation	91
3.3.1	The homogeneity problem	91
3.3.2	The flatness problem	92
3.3.3	The solution: shrinking the comoving Hubble radius	92
3.3.4	Slow-roll inflation	93
3.4	Gravitational waves of primordial origin	97
3.4.1	Linearized wave solutions of Einstein equations	97
3.4.2	Energy of gravitational-waves	99
3.4.3	Cosmological signals	101
3.5	Open problems	104
3.5.1	Cosmological constant problem	105
3.5.2	Matter-anti-matter asymmetry	110
3.5.3	Dark Matter puzzle	115
3.5.4	The fragility of Λ CDM	120
3.5.5	The Hubble tension	131
3.5.6	The 21-cm anomaly	133
4	Thermal Dark Matter	189
4.1	Production mechanism	189
4.1.1	The Boltzmann equation	189
4.1.2	Freeze-in versus Freeze-out	191
4.1.3	Exceptions	194
4.2	The WIMP paradigm	196
4.2.1	Motivations	196
4.2.2	The WIMP abundance	196
4.2.3	Minimal WIMP under pressure	197
4.2.4	Warm Dark Matter	199
4.3	Heavy WIMP	202
4.3.1	Breakdown of perturbation theory	202
4.3.2	Sommerfeld enhancement	204
4.3.3	Bound-state-formation	206
4.3.4	The unitary bound	208

6	First-order Cosmological Phase Transition	277
6.1	Bubble nucleation	278
6.1.1	Effective potential at finite temperature	278
6.1.2	Tunneling rate	282
6.1.3	Thin-wall and thick-wall limits	285
6.1.4	Temperature at which the phase transition completes	288
6.2	Bubble propagation	289
6.2.1	Equation of motion for the scalar field	290
6.2.2	Friction pressure at local thermal equilibrium	292
6.2.3	Friction pressure close to local thermal equilibrium	294
6.2.4	Friction pressure in the ballistic approximation	295
6.2.5	Friction pressure at NLO	299
6.2.6	Speed of the wall	302
6.3	GW generation	305
6.3.1	The GW spectrum for a generic source	306
6.3.2	Contribution from the scalar field	308
6.3.3	Contributions from sound waves and turbulence	312
6.3.4	Energy transfer to sound-waves	313
6.4	Supercooling from a nearly-conformal sector	320
6.4.1	Weakly-coupled scenario: the Coleman-Weinberg potential	320
6.4.2	Strongly-coupled scenario: the light-dilaton potential	326
8	Gravitational Waves from Cosmic Strings	403
8.1	Introduction	403
8.2	Recap on Cosmic Strings	405
8.2.1	Microscopic origin of Cosmic Strings	405
8.2.2	Cosmic-string network formation and evolution	407
8.2.3	Decay channels of Cosmic Strings	410
8.2.4	Constraints on the string tension $G\mu$ from GW emission	413
8.3	Gravitational waves from cosmic strings	413
8.3.1	Beyond the Nambu-Goto approximation	413
8.3.2	Assumptions on the loop distribution	415
8.3.3	The gravitational-wave spectrum	418
8.3.4	The frequency - temperature relation	419
8.3.5	The astrophysical foreground	422
8.A	Constraints on cosmic strings from BBN, gravitational lensing, CMB and cosmic rays	441
8.A.1	GW constraints from BBN	441
8.A.2	Gravitational lensing	443
8.A.3	Temperature anisotropies in the CMB	443
8.A.4	Non-gravitational radiation	443
8.F	GW spectrum from global strings	457
8.F.1	The presence of a massless mode	457
8.F.2	Evolution of the global network	458
8.F.3	The GW spectrum	458
8.F.4	Global versus local strings	460
8.F.5	As a probe of non-standard cosmology	461

For more details on supercooled phase transitions

-> Chap 6.4 of Beyond the Standard Model Cocktail

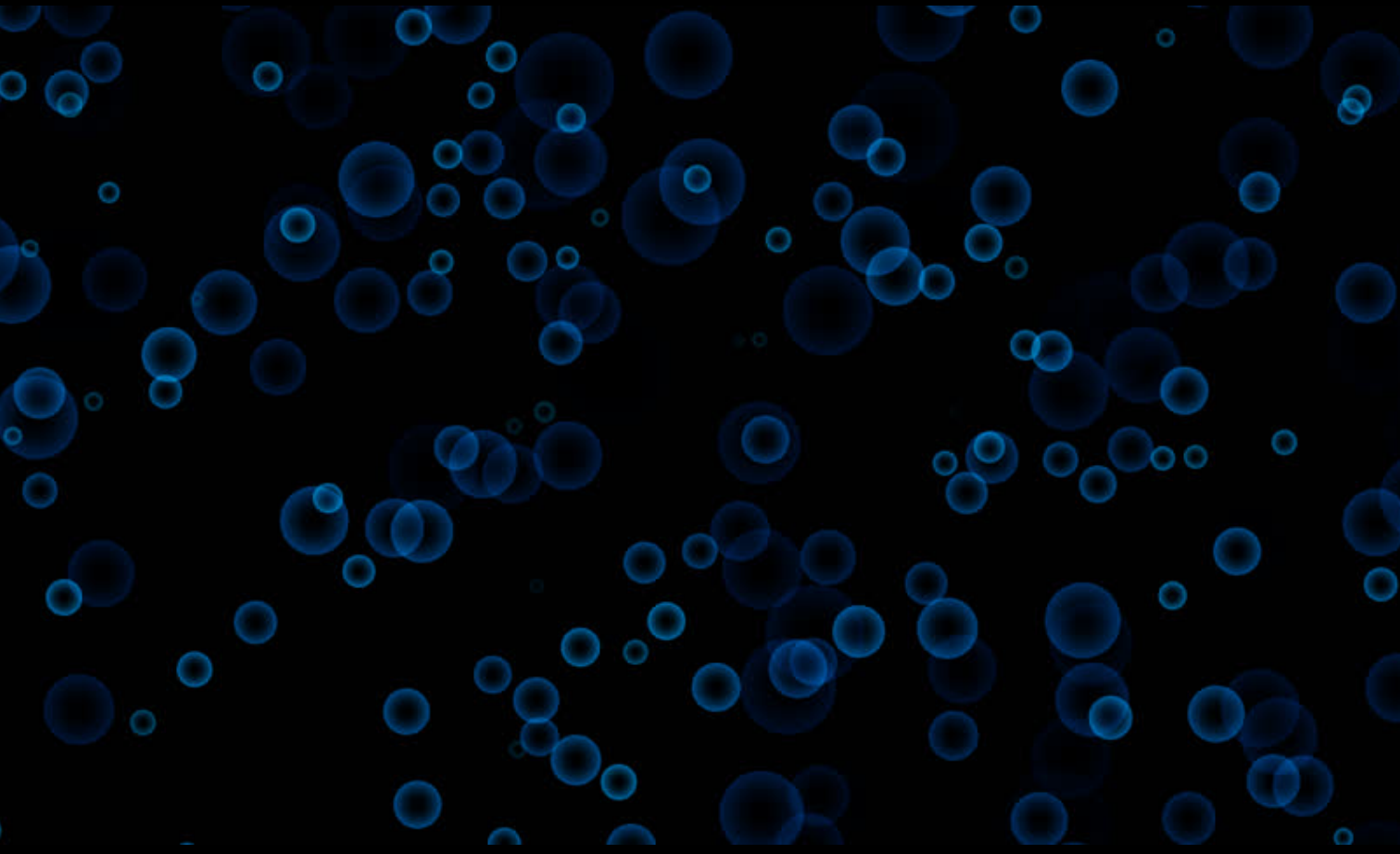
500 pages, 2400 references, review of numerous BSM topics

Available at Springer very soon (200\$) or for free on ArXiv

For graduate students and researchers


Beyond the Standard Model Cocktail

A modern and comprehensive review of the major open puzzles in theoretical particle physics and cosmology



Yann Gouttenoire

Forewords of Géraldine Servant and Filippo Sala



Theoretical Particle Physics and Cosmology

2	Standard Model of Elementary Particles	23
2.1	Fields and symmetries	24
2.1.1	The Lorentz representations	24
2.1.2	The gauge interactions	25
2.1.3	The matter content	25
2.1.4	The Higgs field	26
2.2	The Standard Model in a nutshell	27
2.2.1	The Lagrangian	27
2.2.2	Quantum Chromodynamics	28
2.2.3	Electroweak Symmetry Breaking	32
2.2.4	Weak CP violation	35
2.2.5	Anomaly cancellation	38
2.2.6	Strong CP violation	39
2.3	Open problems	43
2.3.1	Hierarchy problem	43
2.3.2	Neutrino oscillations	52
2.3.3	Flavor hierarchy problem	56
2.3.4	Strong CP problem	57
3	Standard Model of Cosmology	83
3.1	The ΛCDM cosmological model	85
3.1.1	A homogeneous and isotropic expanding universe	85
3.1.2	Energy content of the universe	86
3.2	The hot big-bang scenario	87
3.2.1	Thermal equilibrium	87
3.2.2	Beyond thermal equilibrium	89
3.3	Inflation	91
3.3.1	The homogeneity problem	91
3.3.2	The flatness problem	92
3.3.3	The solution: shrinking the comoving Hubble radius	92
3.3.4	Slow-roll inflation	93
3.4	Gravitational waves of primordial origin	97
3.4.1	Linearized wave solutions of Einstein equations	97
3.4.2	Energy of gravitational-waves	99
3.4.3	Cosmological signals	101
3.5	Open problems	104
3.5.1	Cosmological constant problem	105
3.5.2	Matter-anti-matter asymmetry	110
3.5.3	Dark Matter puzzle	115
3.5.4	The fragility of Λ CDM	120
3.5.5	The Hubble tension	131
3.5.6	The 21-cm anomaly	133
4	Thermal Dark Matter	189
4.1	Production mechanism	189
4.1.1	The Boltzmann equation	189
4.1.2	Freeze-in versus Freeze-out	191
4.1.3	Exceptions	194
4.2	The WIMP paradigm	196
4.2.1	Motivations	196
4.2.2	The WIMP abundance	196
4.2.3	Minimal WIMP under pressure	197
4.2.4	Warm Dark Matter	199
4.3	Heavy WIMP	202
4.3.1	Breakdown of perturbation theory	202
4.3.2	Sommerfeld enhancement	204
4.3.3	Bound-state-formation	206
4.3.4	The unitary bound	208

6	First-order Cosmological Phase Transition	277
6.1	Bubble nucleation	278
6.1.1	Effective potential at finite temperature	278
6.1.2	Tunneling rate	282
6.1.3	Thin-wall and thick-wall limits	285
6.1.4	Temperature at which the phase transition completes	288
6.2	Bubble propagation	289
6.2.1	Equation of motion for the scalar field	290
6.2.2	Friction pressure at local thermal equilibrium	292
6.2.3	Friction pressure close to local thermal equilibrium	294
6.2.4	Friction pressure in the ballistic approximation	295
6.2.5	Friction pressure at NLO	299
6.2.6	Speed of the wall	302
6.3	GW generation	305
6.3.1	The GW spectrum for a generic source	306
6.3.2	Contribution from the scalar field	308
6.3.3	Contributions from sound waves and turbulence	312
6.3.4	Energy transfer to sound-waves	313
6.4	Supercooling from a nearly-conformal sector	320
6.4.1	Weakly-coupled scenario: the Coleman-Weinberg potential	320
6.4.2	Strongly-coupled scenario: the light-dilaton potential	326
8	Gravitational Waves from Cosmic Strings	403
8.1	Introduction	403
8.2	Recap on Cosmic Strings	405
8.2.1	Microscopic origin of Cosmic Strings	405
8.2.2	Cosmic-string network formation and evolution	407
8.2.3	Decay channels of Cosmic Strings	410
8.2.4	Constraints on the string tension $G\mu$ from GW emission	413
8.3	Gravitational waves from cosmic strings	413
8.3.1	Beyond the Nambu-Goto approximation	413
8.3.2	Assumptions on the loop distribution	415
8.3.3	The gravitational-wave spectrum	418
8.3.4	The frequency - temperature relation	419
8.3.5	The astrophysical foreground	422
8.A	Constraints on cosmic strings from BBN, gravitational lensing, CMB and cosmic rays	441
8.A.1	GW constraints from BBN	441
8.A.2	Gravitational lensing	443
8.A.3	Temperature anisotropies in the CMB	443
8.A.4	Non-gravitational radiation	443
8.F	GW spectrum from global strings	457
8.F.1	The presence of a massless mode	457
8.F.2	Evolution of the global network	458
8.F.3	The GW spectrum	458
8.F.4	Global versus local strings	460
8.F.5	As a probe of non-standard cosmology	461

Conclusion

Supercooled phase transitions arises in presence of FLAT direction

1) Large GW spectrum: large α and small β/H

2) Dilution of relics due to entropy injection following reheating

3) Relativistic bubble walls because plasma is diluted

4) High energy particle production because relativistic bubble walls

5) Primordial black hole production because expansion of the universe controlled by low number of randomly nucleated bubbles

Additional slides

Supercooling from a nearly conformal sector

Nearly-conformal dark $U(1)_D$:

$$\mathcal{L}_{\text{tree}} = -\frac{1}{4} (F_{\mu\nu})^2 + |D_\mu \Phi|^2 + \bar{\psi} \not{D}_\mu \psi - (y \Phi \bar{\psi}_L \psi_R + \text{h.c.}) - V_{\text{tree}}(|\Phi|),$$

$$V_{\text{tree}}(|\Phi|) = \lambda |\Phi|^4 + \lambda_{\phi h} |H|^2 |\Phi|^2,$$

1-loop Coleman-Weinberg corrections at $T=0$:

$$V(\phi) = \beta_\lambda \frac{\phi^4}{4} \left[\log \left(\frac{\phi}{f} \right) - \frac{1}{4} \right]. \quad \beta_\lambda = \frac{d\lambda}{d \log \phi} = \frac{1}{8\pi^2} (12g_D^4 + 12\lambda^4 + 4\lambda_{hs}^4 - 4y^4)$$

1-loop Dolan-Jackiw corrections at finite- T :

$$V_T(\sigma, T) = V_{1\text{-loop}}^T + V_{\text{Daisy}} = \frac{3T^4}{2\pi^2} J_B \left(\frac{m_V^2}{T^2} \right) + \frac{T}{12\pi} \left[m_V^3 - (m_V^2 + \Pi_V)^{3/2} \right].$$

Supercooling from a nearly conformal sector

Thick-wall formula:

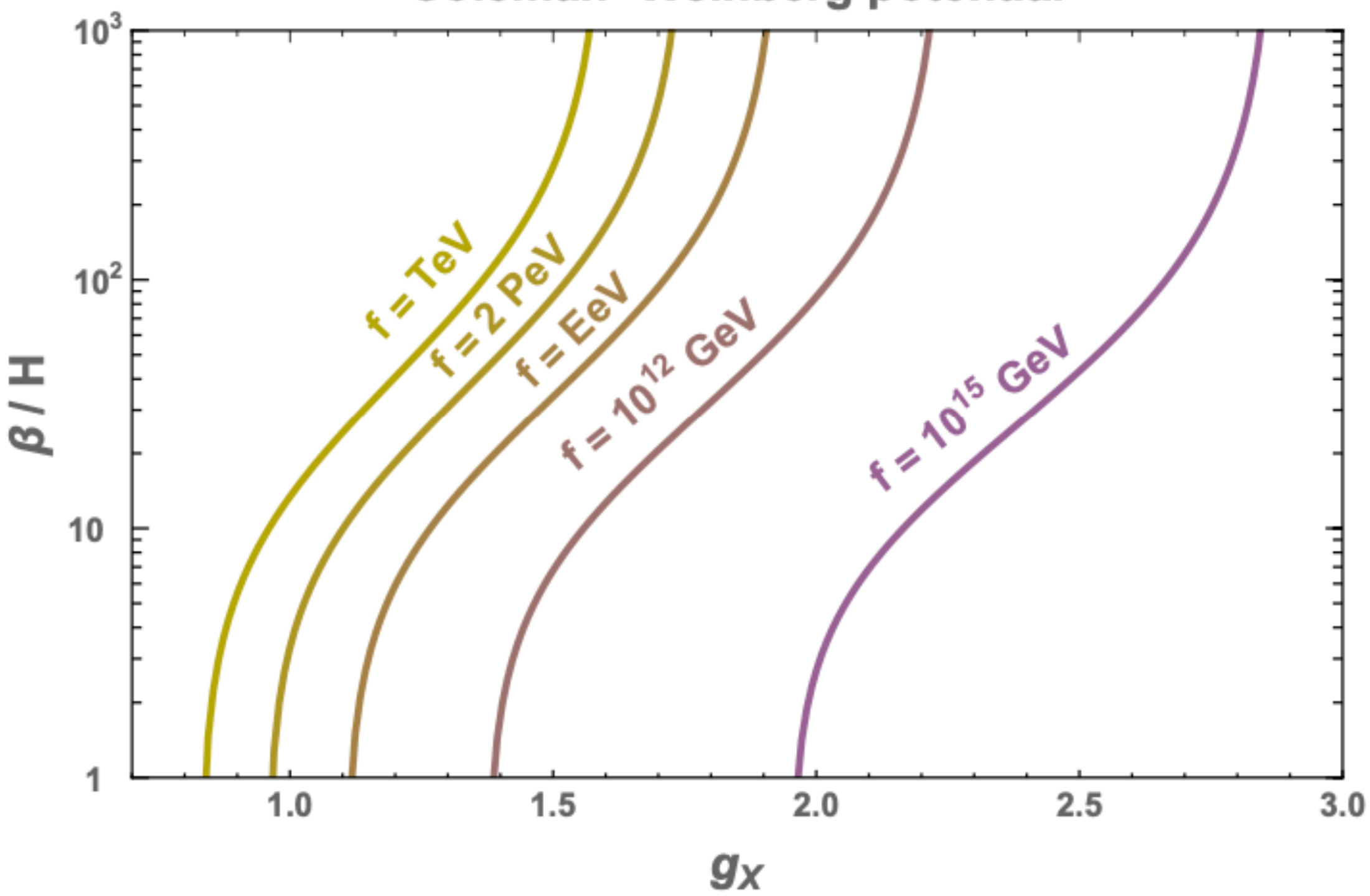
$$\frac{S_3}{T} \simeq \frac{A}{\log\left(\frac{M}{T}\right)} \quad \text{with} \quad A = \frac{78}{g_D^3} \quad \text{and} \quad M = 0.35 g_D f.$$

alpha and beta parameters:

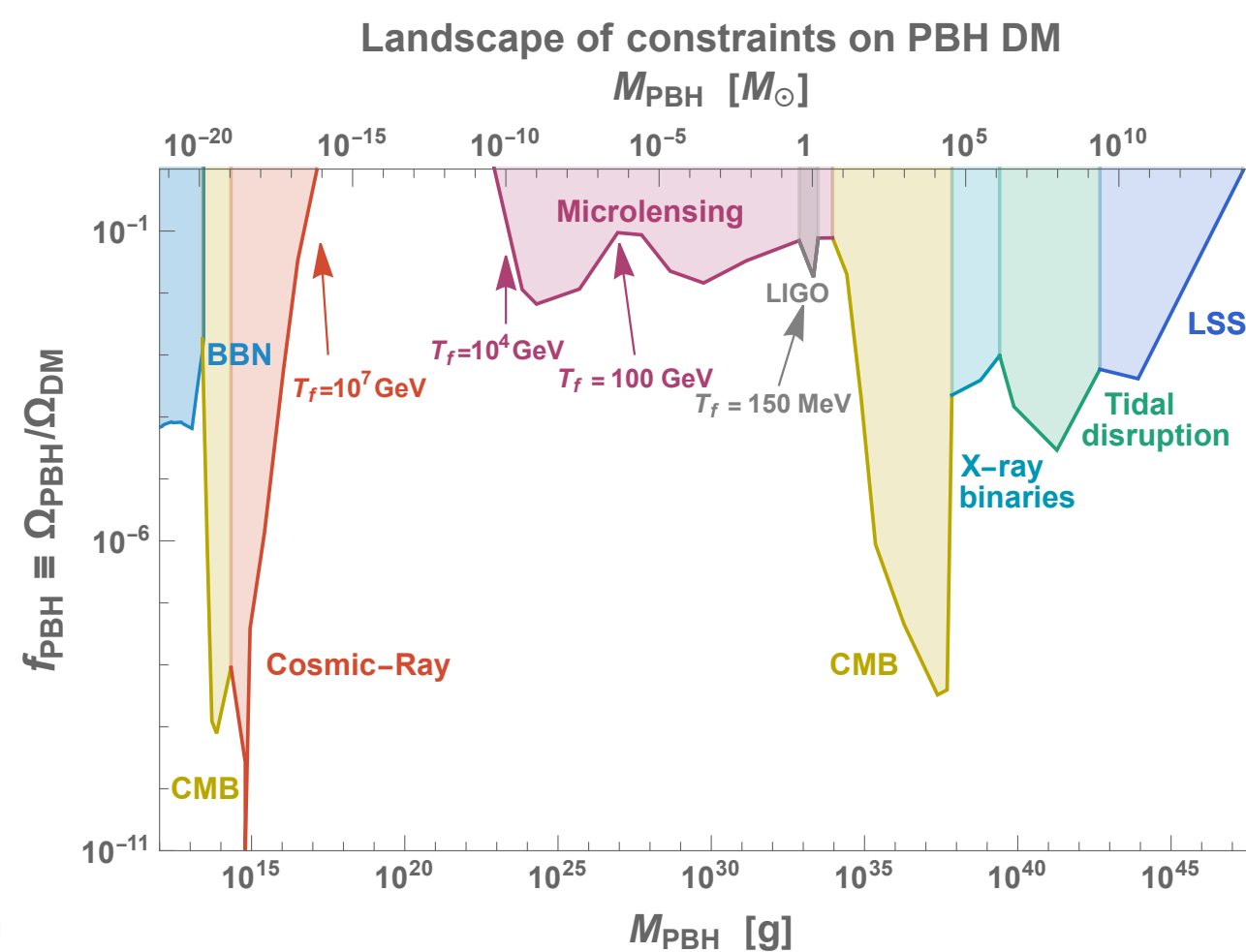
$$\alpha = \frac{\Delta V}{\rho_{\text{rad}}(T_{\text{nuc}})} \simeq 2 \times 10^{-4} \frac{100}{g_*} \left(\frac{M_X}{T_{\text{nuc}}}\right)^4,$$

$$\beta/H \simeq -4 + T \left. \frac{d(S_3/T)}{dT} \right|_{T_{\text{nuc}}} = -4 + \left. \frac{S_3/T}{\log\frac{M}{T}} \right|_{T_{\text{nuc}}} = -4 + \frac{A}{\log^2 \frac{M}{T}}$$

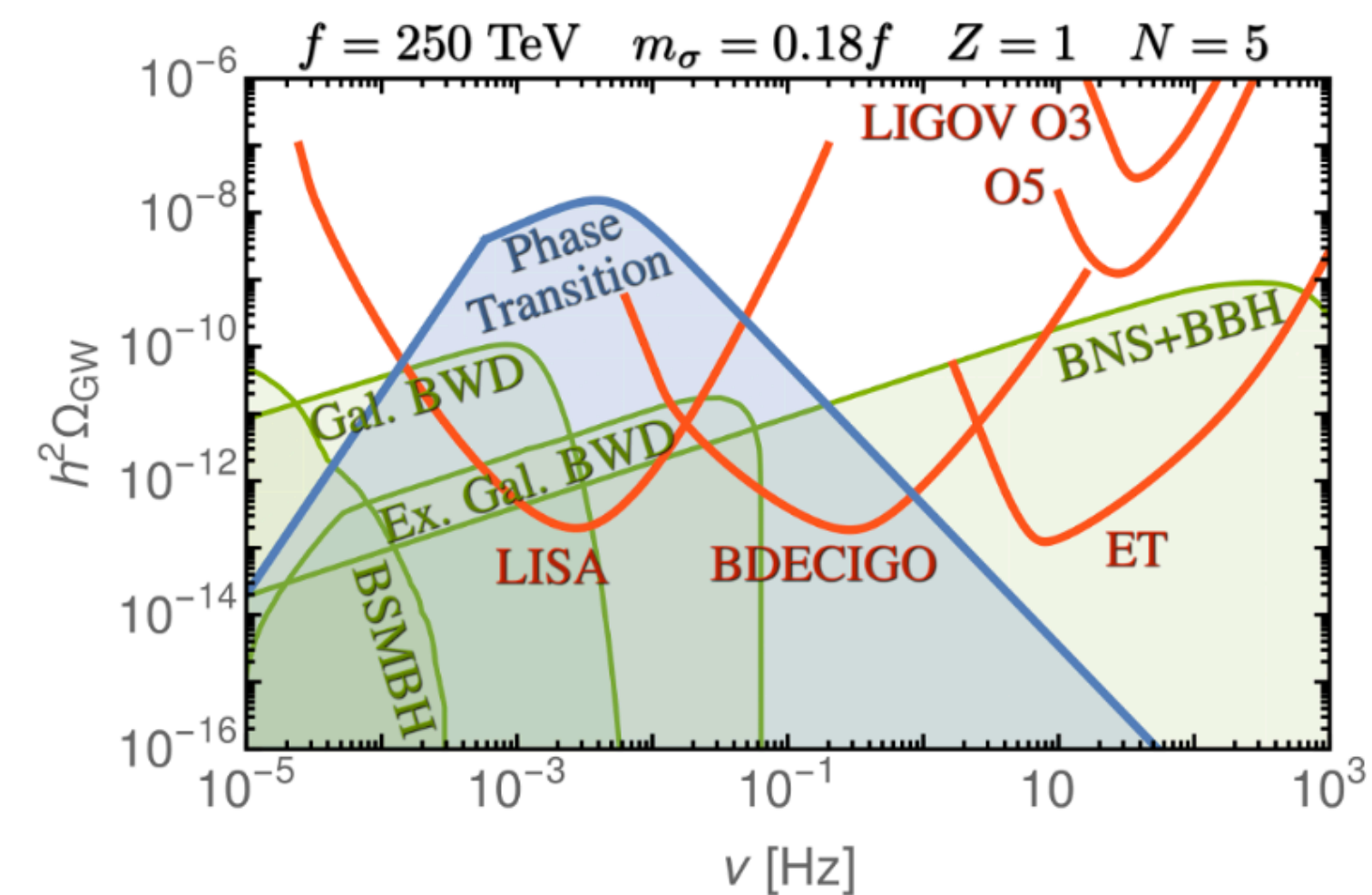
Coleman–Weinberg potential



PBH DM



Large GW signal



Classes of nearly-conformal models

<i>Space-time dimension</i> <i>Strength coupling</i>	Weakly-coupled	Strongly-coupled
D = 4		
D = 5		

Classes of nearly-conformal models

Space-time dimension \ Strength coupling	Weakly-coupled	Strongly-coupled
D = 4	Coleman-Weinberg $V(\phi) = \beta_\lambda \frac{\phi^4}{4} \left[\log \left(\frac{\phi}{f} \right) - \frac{1}{4} \right]$	
D = 5		

Classes of nearly-conformal models

Strength coupling Space-time dimension	Weakly-coupled	Strongly-coupled
D = 4	Coleman-Weinberg $V(\phi) = \beta_\lambda \frac{\phi^4}{4} \left[\log \left(\frac{\phi}{f} \right) - \frac{1}{4} \right]$	Light-dilaton $V(\phi) = g_\chi^2 \frac{\sigma^4}{4} \left[1 - \frac{1}{1+\epsilon} \left(\frac{\sigma}{f} \right)^\epsilon \right]$
D = 5		

Classes of nearly-conformal models

Strength coupling Space-time dimension	Weakly-coupled	Strongly-coupled
D = 4	Coleman-Weinberg $V(\phi) = \beta_\lambda \frac{\phi^4}{4} \left[\log \left(\frac{\phi}{f} \right) - \frac{1}{4} \right]$	Light-dilaton $V(\phi) = g_\chi^2 \frac{\sigma^4}{4} \left[1 - \frac{1}{1+\epsilon} \left(\frac{\sigma}{f} \right)^\epsilon \right]$
D = 5		

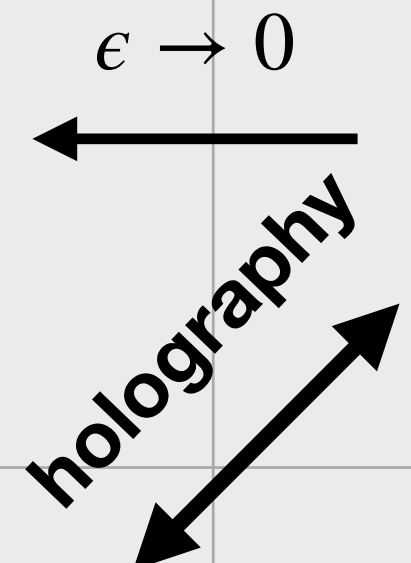
$$V(\phi) = \beta_\lambda \frac{\phi^4}{4} \left[\log \left(\frac{\phi}{f} \right) - \frac{1}{4} \right] \xleftarrow{\epsilon \rightarrow 0} V(\phi) = g_\chi^2 \frac{\sigma^4}{4} \left[1 - \frac{1}{1+\epsilon} \left(\frac{\sigma}{f} \right)^\epsilon \right]$$

Classes of nearly-conformal models

Space-time dimension Strength coupling	Weakly-coupled	Strongly-coupled
D = 4	Coleman-Weinberg $V(\phi) = \beta_\lambda \frac{\phi^4}{4} \left[\log \left(\frac{\phi}{f} \right) - \frac{1}{4} \right]$	Light-dilaton $V(\phi) = g_\chi^2 \frac{\sigma^4}{4} \left[1 - \frac{1}{1+\epsilon} \left(\frac{\sigma}{f} \right)^\epsilon \right]$
D = 5	Warped fifth dimension $V(\mu) = v_{\text{IR}}^2 \mu^4 \left[(4 + 2\epsilon) \left(1 - \frac{v_{\text{UV}}}{v_{\text{IR}}} \left(\frac{\mu}{\mu_0} \right)^\epsilon \right)^2 + \delta \right]$	

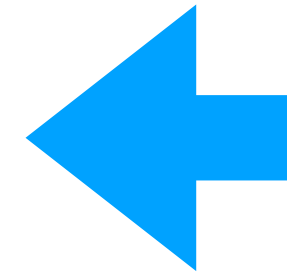
Classes of nearly-conformal models

Space-time dimension Strength coupling	Weakly-coupled	Strongly-coupled
D = 4	Coleman-Weinberg $V(\phi) = \beta_\lambda \frac{\phi^4}{4} \left[\log \left(\frac{\phi}{f} \right) - \frac{1}{4} \right]$	Light-dilaton $V(\phi) = g_\chi^2 \frac{\sigma^4}{4} \left[1 - \frac{1}{1+\epsilon} \left(\frac{\sigma}{f} \right)^\epsilon \right]$
D = 5	Warped fifth dimension $V(\mu) = v_{\text{IR}}^2 \mu^4 \left[(4 + 2\epsilon) \left(1 - \frac{v_{\text{UV}}}{v_{\text{IR}}} \left(\frac{\mu}{\mu_0} \right)^\epsilon \right)^2 + \delta \right]$	



Consequences on bubble wall velocity

Bubble wall

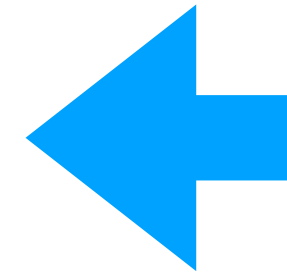
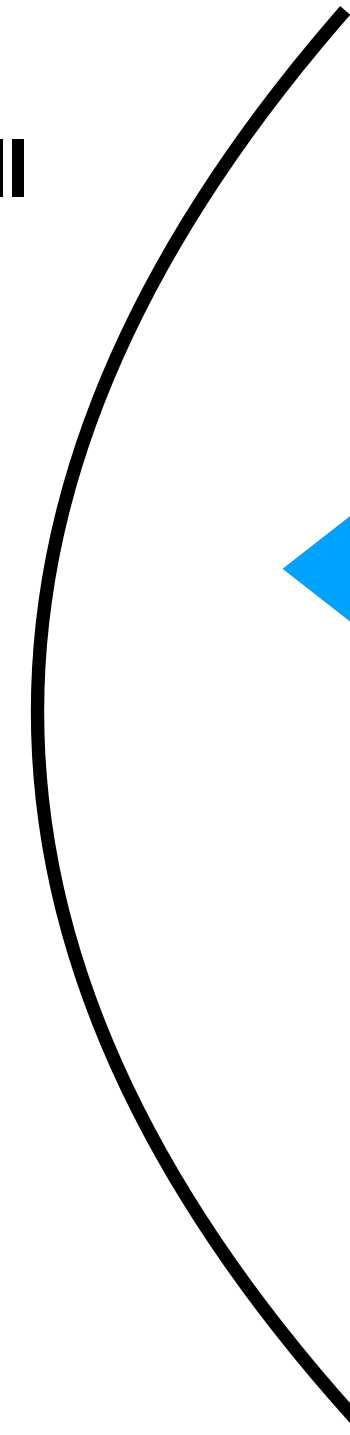
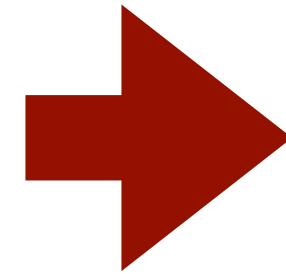


$$\Delta V_{\text{vac}} = c_{\text{vac}} f^4$$

Consequences on bubble wall velocity

$$\mathcal{P}_{\text{friction}} \simeq \gamma T_{\text{nuc}}^3 \times \Delta p$$

Bubble wall



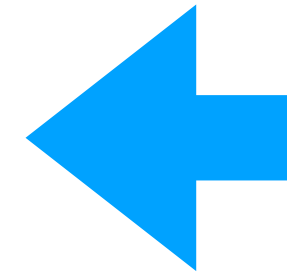
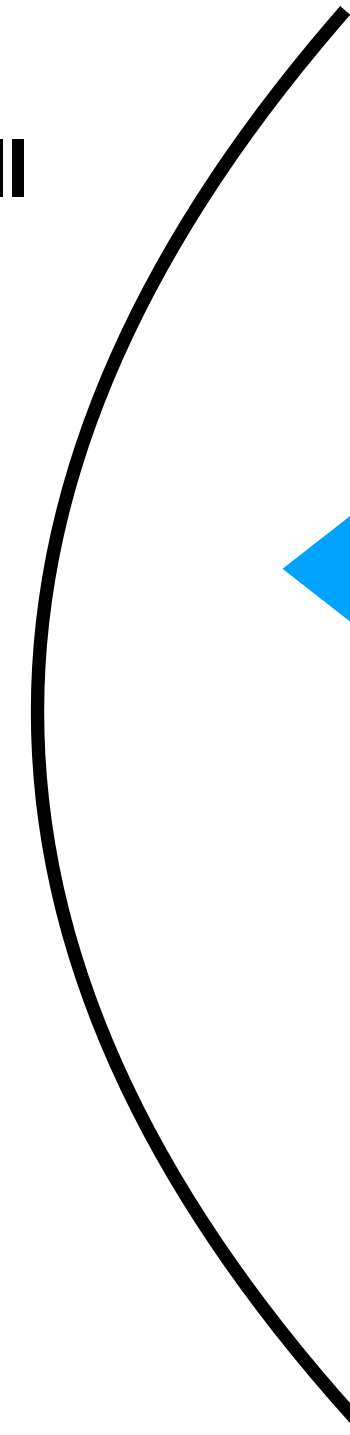
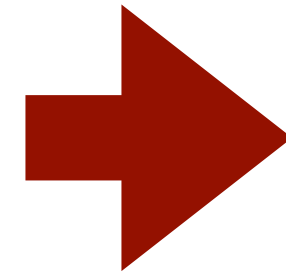
$$\Delta V_{\text{vac}} = c_{\text{vac}} f^4$$

Consequences on bubble wall velocity

$$\mathcal{P}_{\text{friction}} \simeq \gamma T_{\text{nuc}}^3 \times \Delta p$$

$$\Delta p = ?$$

Bubble wall



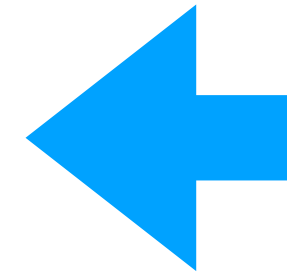
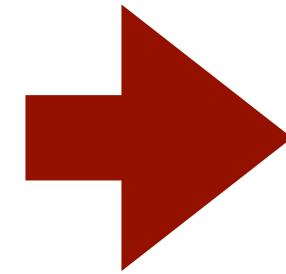
$$\Delta V_{\text{vac}} = c_{\text{vac}} f^4$$

Consequences on bubble wall velocity

$$\mathcal{P}_{\text{friction}} \simeq \gamma T_{\text{nuc}}^3 \times \Delta p$$

$$\Delta p = ?$$

Bubble wall



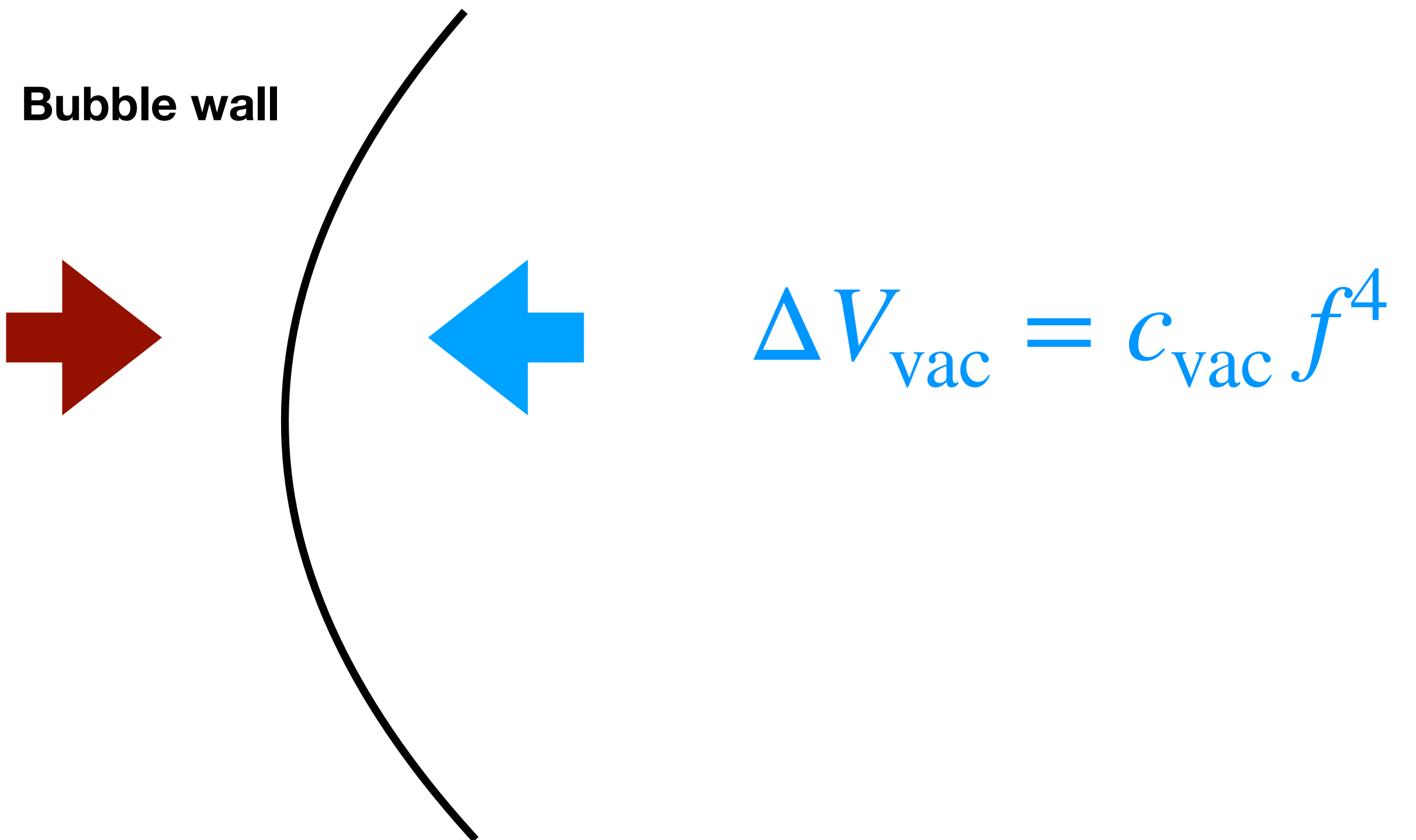
$$\Delta V_{\text{vac}} = c_{\text{vac}} f^4$$

Weakly-coupled PT

Consequences on bubble wall velocity

$$\mathcal{P}_{\text{friction}} \simeq \gamma T_{\text{nuc}}^3 \times \Delta p$$

$$\Delta p = ?$$



Weakly-coupled PT

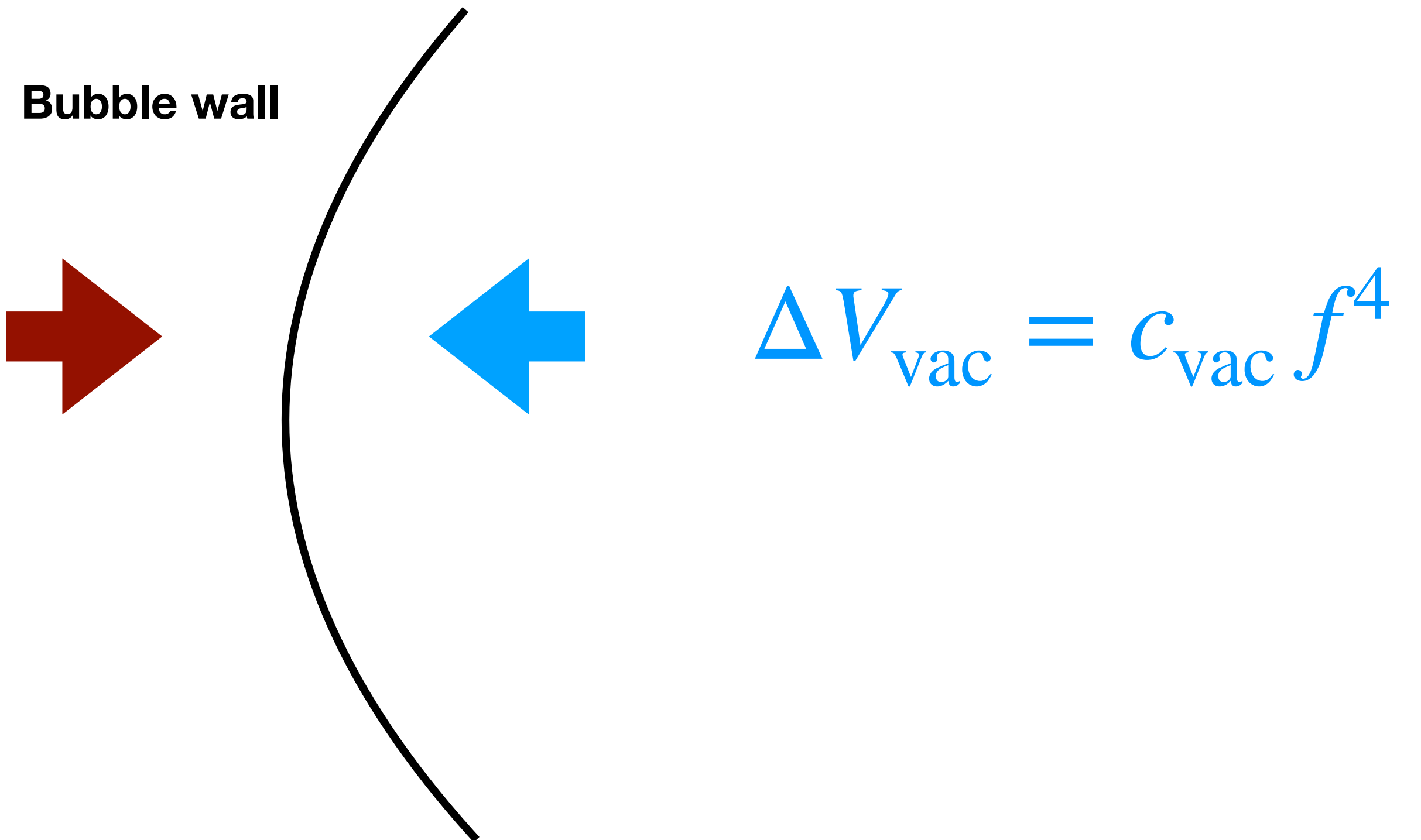
Bodeker&Moore (09' and 17')

Azatov+ 20'

Consequences on bubble wall velocity

$$\mathcal{P}_{\text{friction}} \simeq \gamma T_{\text{nuc}}^3 \times \Delta p$$

$$\Delta p = ?$$



Weakly-coupled PT

Bodeker&Moore (09' and 17')

Azatov+ 20'

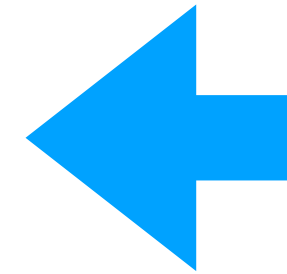
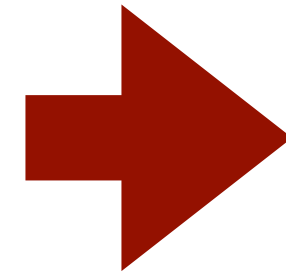
$$\mathcal{P}_{\text{LO}} \simeq \Delta m^2 T_{\text{nuc}}^2$$

Consequences on bubble wall velocity

$$\mathcal{P}_{\text{friction}} \simeq \gamma T_{\text{nuc}}^3 \times \Delta p$$

$$\Delta p = ?$$

Bubble wall



$$\Delta V_{\text{vac}} = c_{\text{vac}} f^4$$

Weakly-coupled PT

Bodeker&Moore (09' and 17')

Azatov+ 20'

$$\mathcal{P}_{\text{LO}} \simeq \Delta m^2 T_{\text{nuc}}^2 \quad \mathcal{P}_{\text{NLO}} \simeq g_w \gamma \Delta m T_{\text{nuc}}^3$$

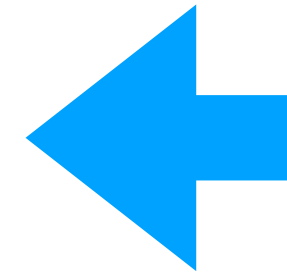
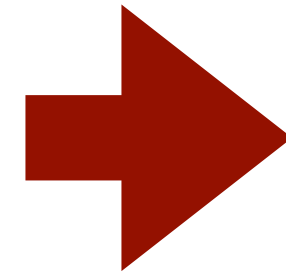
⋮

Consequences on bubble wall velocity

$$\mathcal{P}_{\text{friction}} \simeq \gamma T_{\text{nuc}}^3 \times \Delta p$$

$$\Delta p = ?$$

Bubble wall



$$\Delta V_{\text{vac}} = c_{\text{vac}} f^4$$

Weakly-coupled PT

Strongly-coupled PT

Bodeker&Moore (09' and 17')

Azatov+ 20'

$$\mathcal{P}_{\text{LO}} \simeq \Delta m^2 T_{\text{nuc}}^2 \quad \mathcal{P}_{\text{NLO}} \simeq g_w \gamma \Delta m T_{\text{nuc}}^3$$

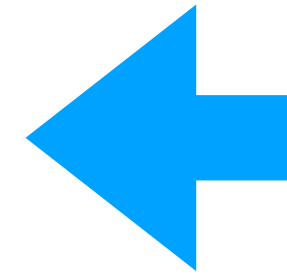
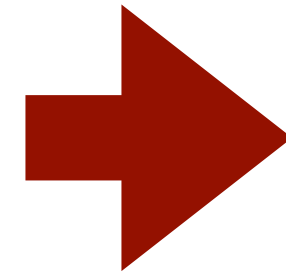
⋮

Consequences on bubble wall velocity

$$\mathcal{P}_{\text{friction}} \simeq \gamma T_{\text{nuc}}^3 \times \Delta p$$

$$\Delta p = ?$$

Bubble wall



$$\Delta V_{\text{vac}} = c_{\text{vac}} f^4$$

Weakly-coupled PT

Bodeker&Moore (09' and 17')

Azatov+ 20'

$$\mathcal{P}_{\text{LO}} \simeq \Delta m^2 T_{\text{nuc}}^2 \quad \mathcal{P}_{\text{NLO}} \simeq g_w \gamma \Delta m T_{\text{nuc}}^3$$

Strongly-coupled PT

Hoeche, Kozaczuk, Long, Turner, Wang 20'

$$\mathcal{P}_{\text{all-order}} \simeq \gamma^2 T_{\text{nuc}}^4$$

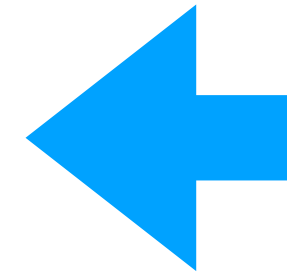
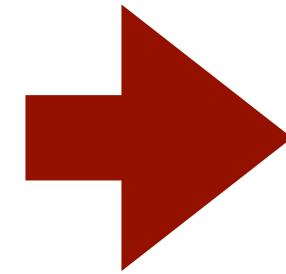
⋮

Consequences on bubble wall velocity

$$\mathcal{P}_{\text{friction}} \simeq \gamma T_{\text{nuc}}^3 \times \Delta p$$

$$\Delta p = ?$$

Bubble wall



$$\Delta V_{\text{vac}} = c_{\text{vac}} f^4$$

Weakly-coupled PT

Bodeker&Moore (09' and 17')

Azatov+ 20'

$$\mathcal{P}_{\text{LO}} \simeq \Delta m^2 T_{\text{nuc}}^2 \quad \mathcal{P}_{\text{NLO}} \simeq g_w \gamma \Delta m T_{\text{nuc}}^3$$

Strongly-coupled PT

Hoeche, Kozaczuk, Long, Turner, Wang 20'

$$\mathcal{P}_{\text{all-order}} \simeq \gamma^2 T_{\text{nuc}}^4$$

Baldes, YG, Sala 20'

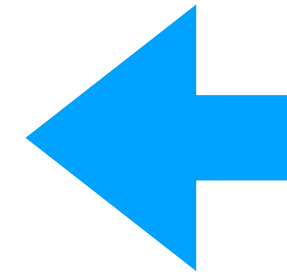
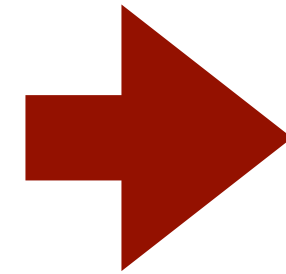
$$\mathcal{P}_{\text{flux-tube}} \simeq \gamma f T_{\text{nuc}}^3$$

Consequences on bubble wall velocity

$$\mathcal{P}_{\text{friction}} \simeq \gamma T_{\text{nuc}}^3 \times \Delta p$$

$$\Delta p = ?$$

Bubble wall



$$\Delta V_{\text{vac}} = c_{\text{vac}} f^4$$

Weakly-coupled PT

Bodeker&Moore (09' and 17')

Azatov+ 20'

$$\mathcal{P}_{\text{LO}} \simeq \Delta m^2 T_{\text{nuc}}^2 \quad \mathcal{P}_{\text{NLO}} \simeq g_w \gamma \Delta m T_{\text{nuc}}^3$$

Strongly-coupled PT

Hoeche, Kozaczuk, Long, Turner, Wang 20'

~~$$\mathcal{P}_{\text{all-order}} \simeq \gamma^2 T_{\text{nuc}}^4$$~~

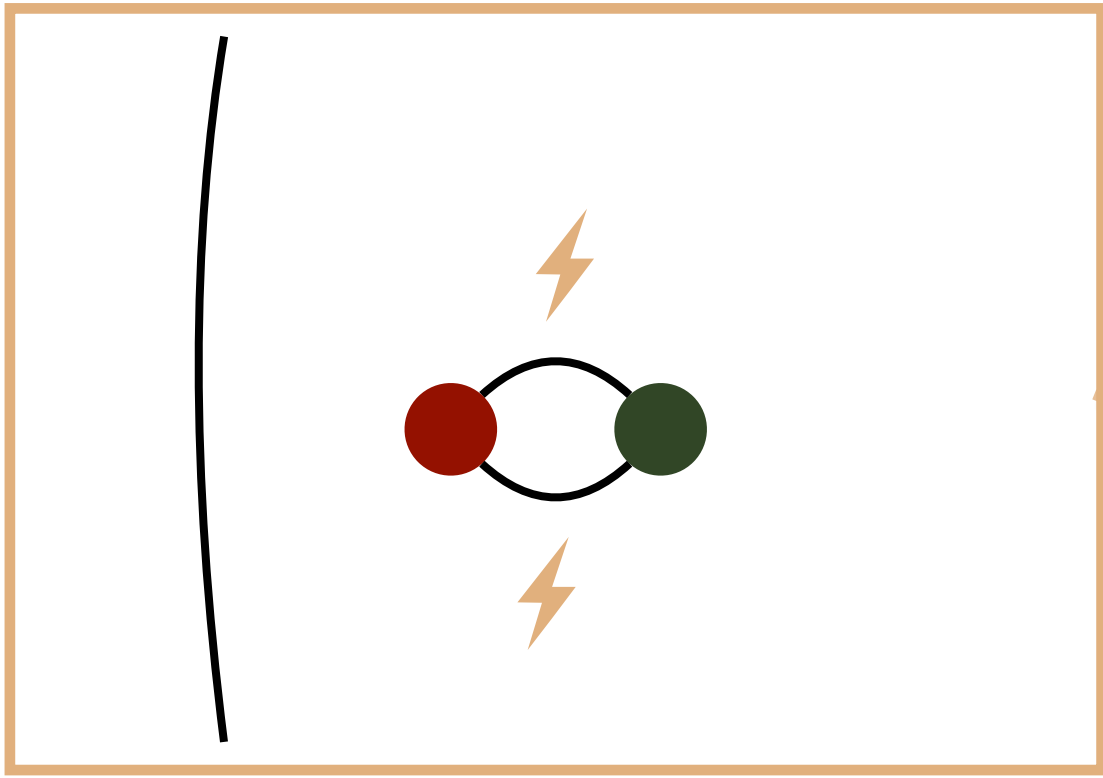
Baldes, YG, Sala 20'

$$\mathcal{P}_{\text{flux-tube}} \simeq \gamma f T_{\text{nuc}}^3$$

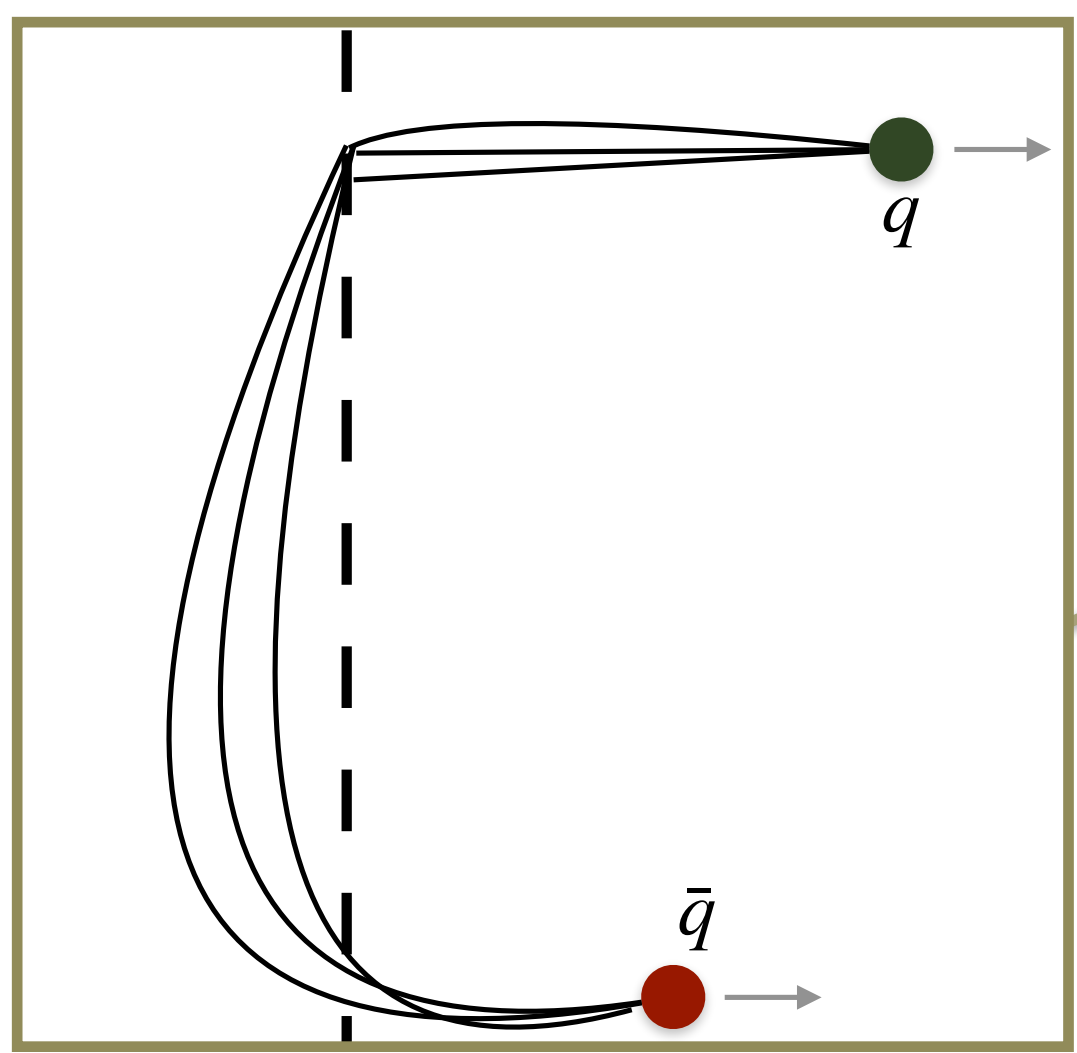
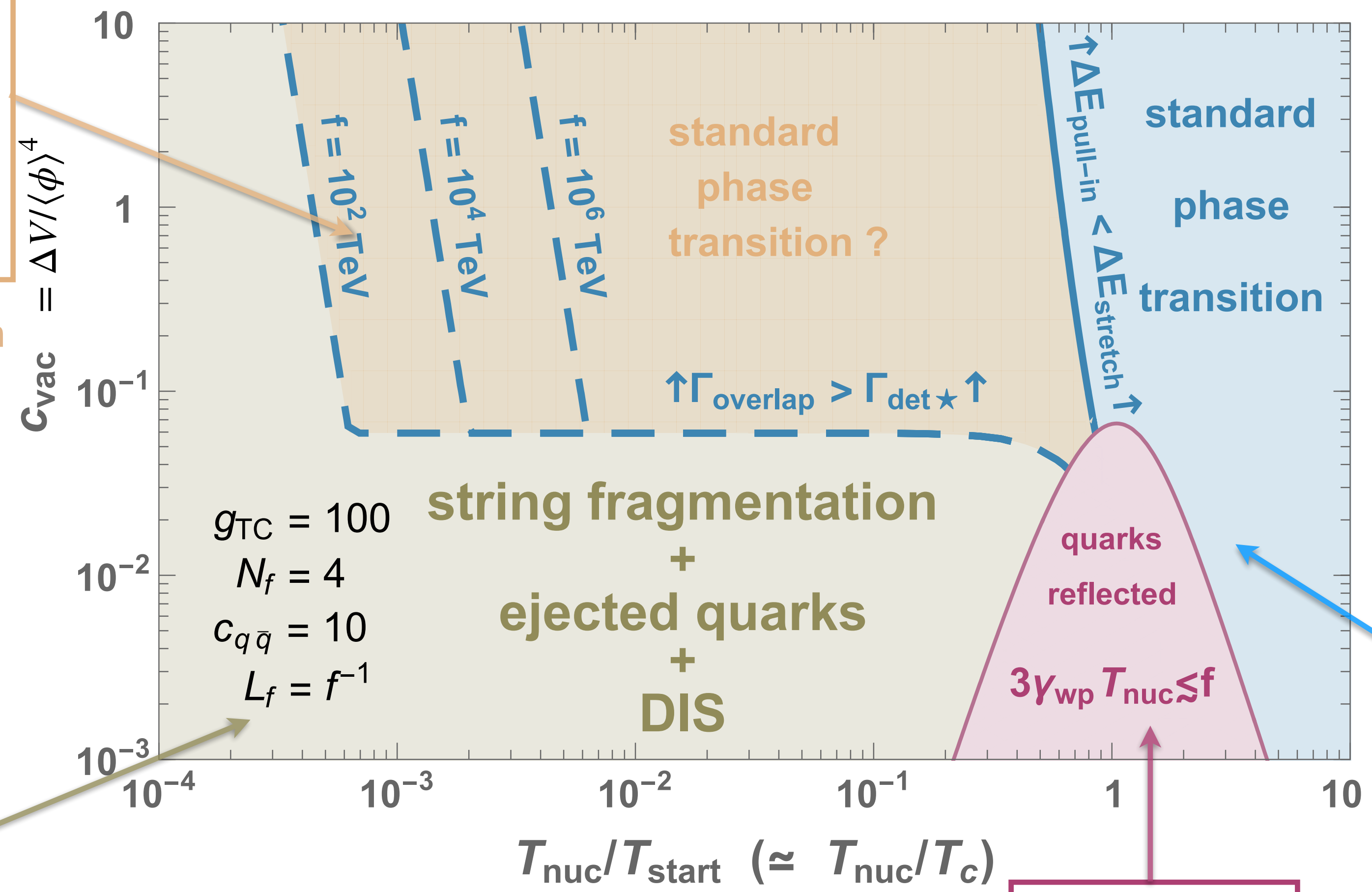
YG, Jinno, Sala 21'

$$\mathcal{P}_{\text{all-order}} \simeq \gamma f T_{\text{nuc}}^3$$

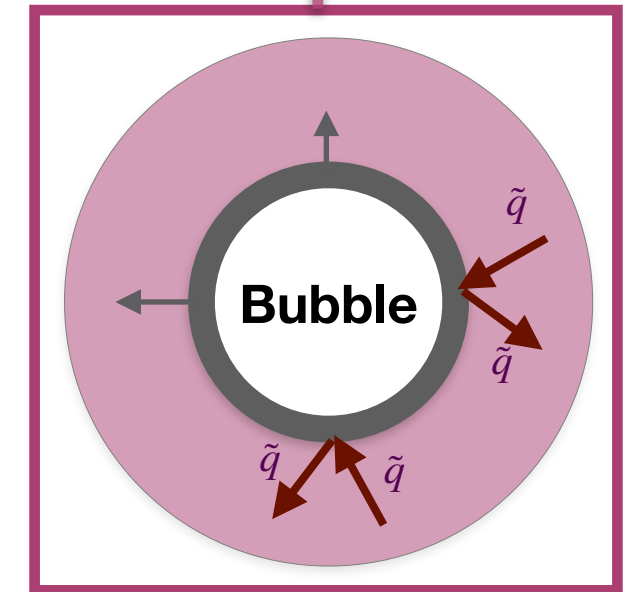
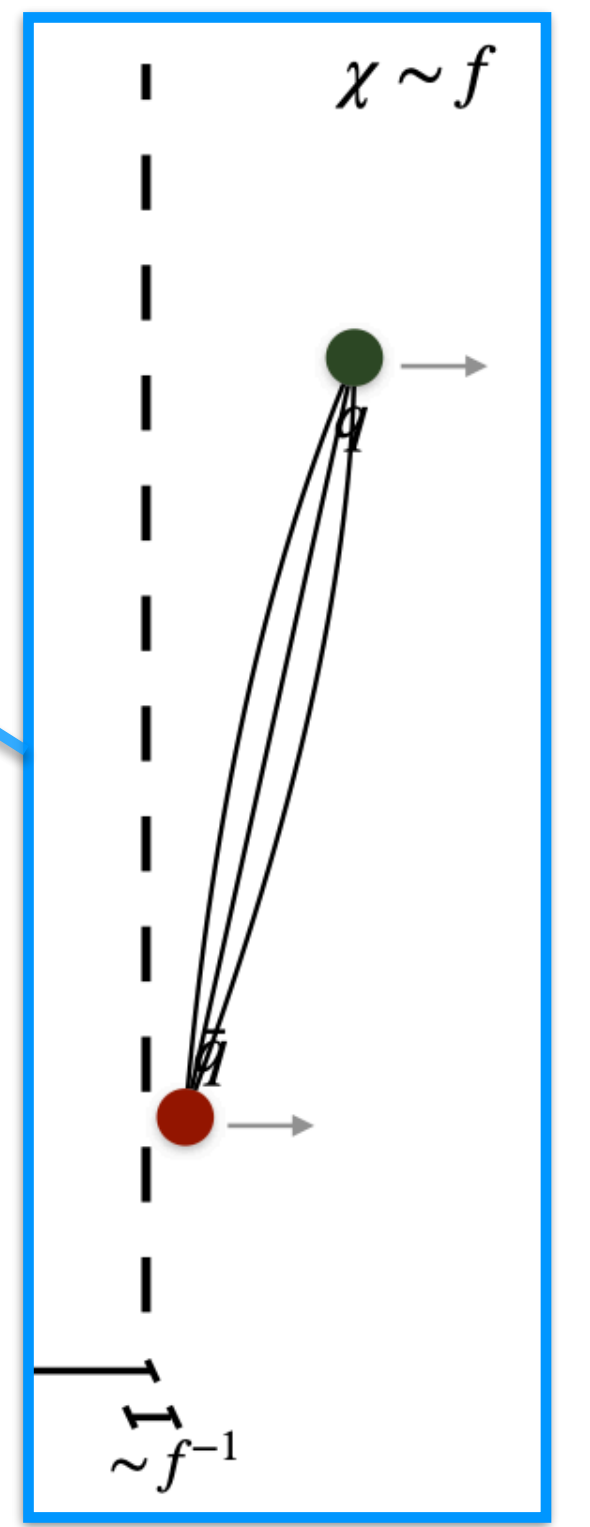
How much supercooling is needed ?



quark-string interaction win



No line distortion



Quark nuggets Witten 1984

Filtered DM. 1912.02830

Thermal Squeezeout of DM. 2103.09827

Snow ball effect

Ping-pong effect

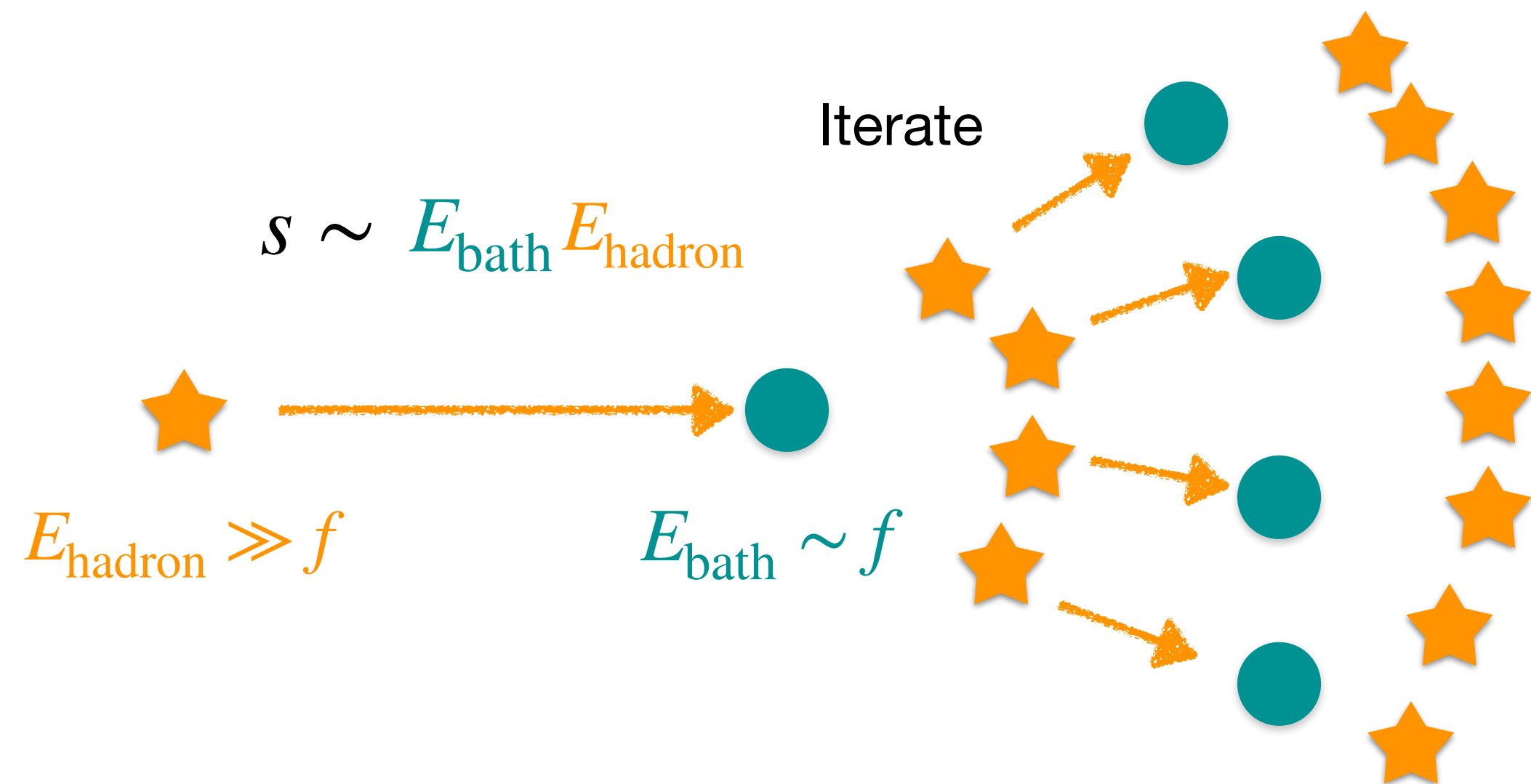
Deep Inelastic Scattering in the Early Universe

Hadron energy in plasma (= CMB) frame

$$\langle E_{\text{hadron}} \rangle = \frac{E_{\text{cm}}^{q\bar{q}}}{\langle N_{\text{hadron}} \rangle} \sim \frac{\sqrt{\gamma_{\text{wp}} f / T_{\text{nuc}}}}{\langle N_{\text{hadron}} \rangle} \gg f$$

We find dominant scatterers in (p)reheated bath at

$$E_{\text{bath}} \sim f$$



$$E_{\text{cm}}^{q\bar{q}} = |p_q + p_{\bar{q}}| \simeq \sqrt{E_q E_{\bar{q}}} \simeq \sqrt{\gamma_{\text{wp}} f T_{\text{nuc}}}$$

$$\gamma_{\text{cp}} \simeq \frac{\gamma_{\text{wp}}}{\gamma_{\text{wc}}} \quad \gamma_{\text{wc}} \simeq \frac{E_{\text{cm}}^{q\bar{q}}}{f} \simeq \sqrt{\gamma_{\text{wp}} \frac{T_{\text{nuc}}}{f}}$$

$$\dots \quad E_{\text{hadrons, p}} \simeq \gamma_{\text{cp}} \frac{E_{\text{cm}}^{q\bar{q}}}{\langle N_{\text{hadron}} \rangle} \simeq \frac{\gamma_{\text{wp}}}{E_{\text{cm}}^{q\bar{q}}/f} \frac{E_{\text{cm}}^{q\bar{q}}}{\langle N_{\text{hadron}} \rangle} \simeq \frac{\gamma_{\text{wp}} f}{\langle N_{\text{hadron}} \rangle}$$

$$Y_{\text{DM}} / Y_{\text{DM}}^{\text{naive}} \propto \langle N_{\text{hadron}} \rangle \frac{s}{f^2} \propto \langle N_{\text{hadron}} \rangle \frac{E_{\text{bath}} E_{\text{hadrons, p}}}{f^2} \propto \gamma_{\text{wp}} \propto \frac{T_{\text{nuc}}}{f} \frac{M_{\text{Pl}}}{f}$$

Dark Matter candidates

(WIMPs=Weakly-Interacting Massive Particles)



Two motivations for the WIMPs:

1) Connection with Hierarchy problem

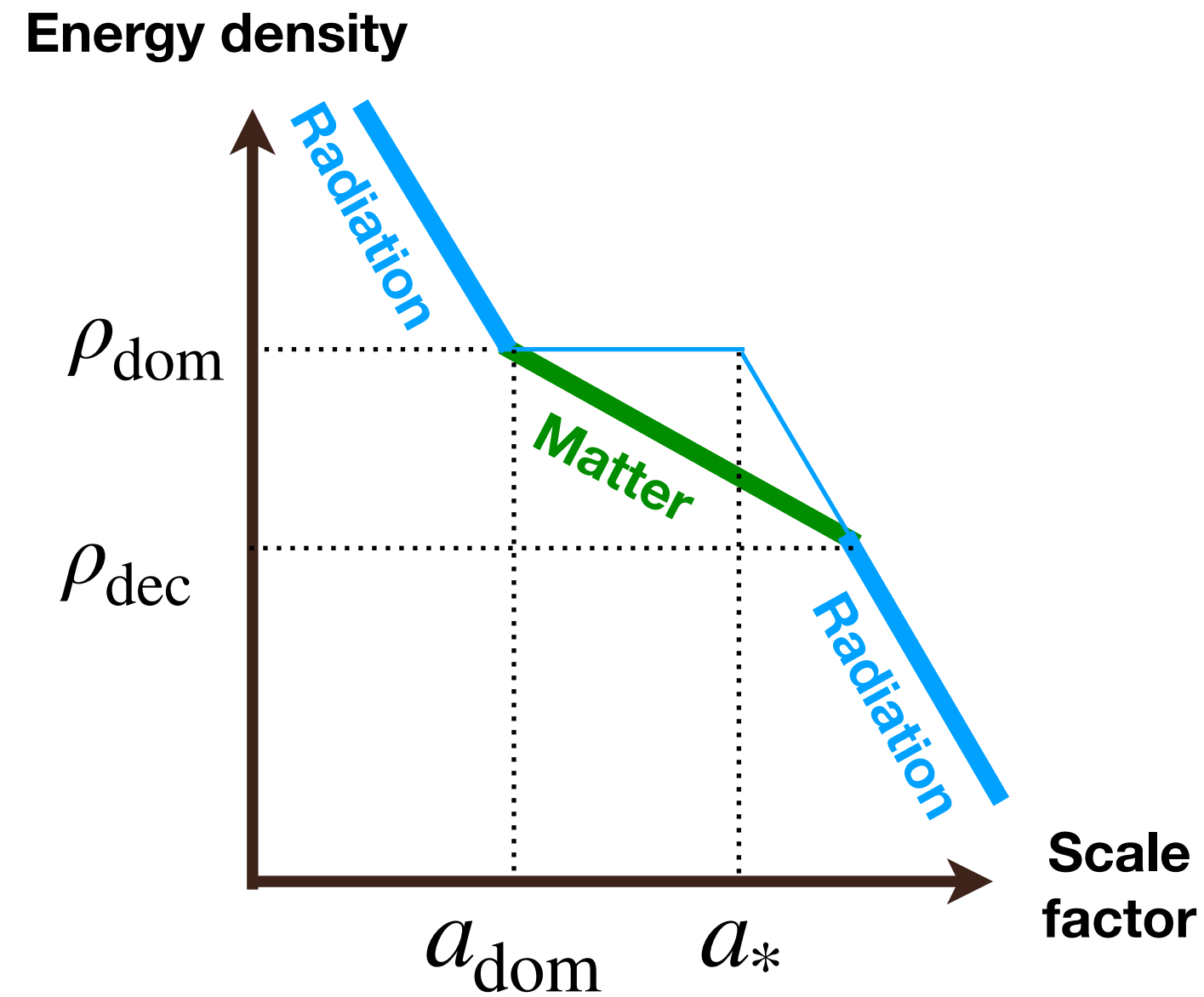
$$M_{\text{DM}} \sim 1 \text{ TeV}, \quad \alpha \sim \alpha_{\text{weak}}$$

2) Thermal Dark Matter

$$\frac{\Omega_{\text{DM}} h^2}{0.1186} \simeq \frac{4.4 \times 10^{-26} \text{ cm}^3/\text{s}}{\langle \sigma v \rangle},$$

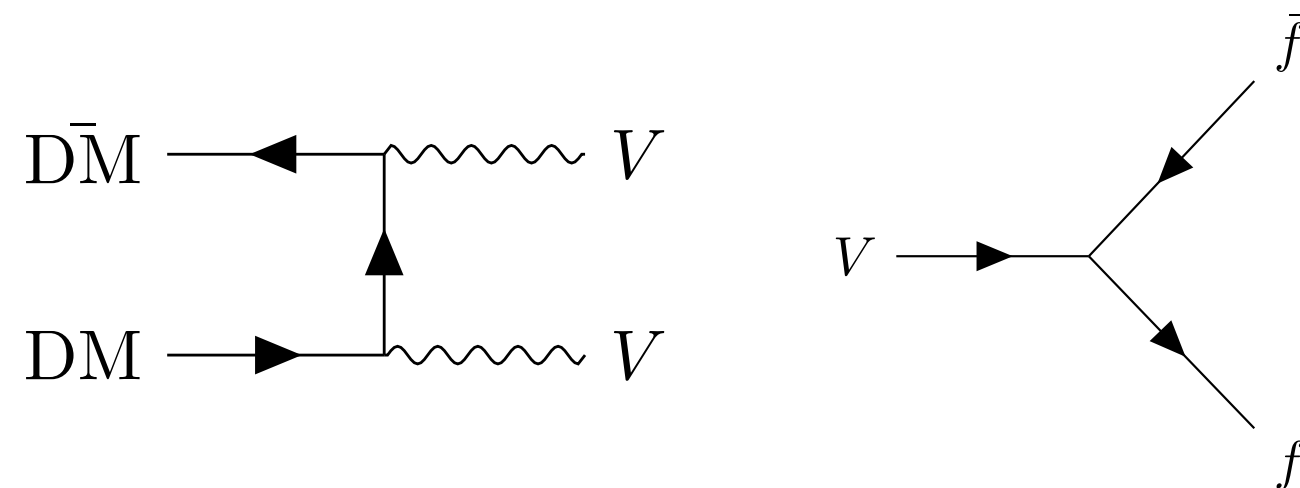
Entropy injection

1) After a matter era



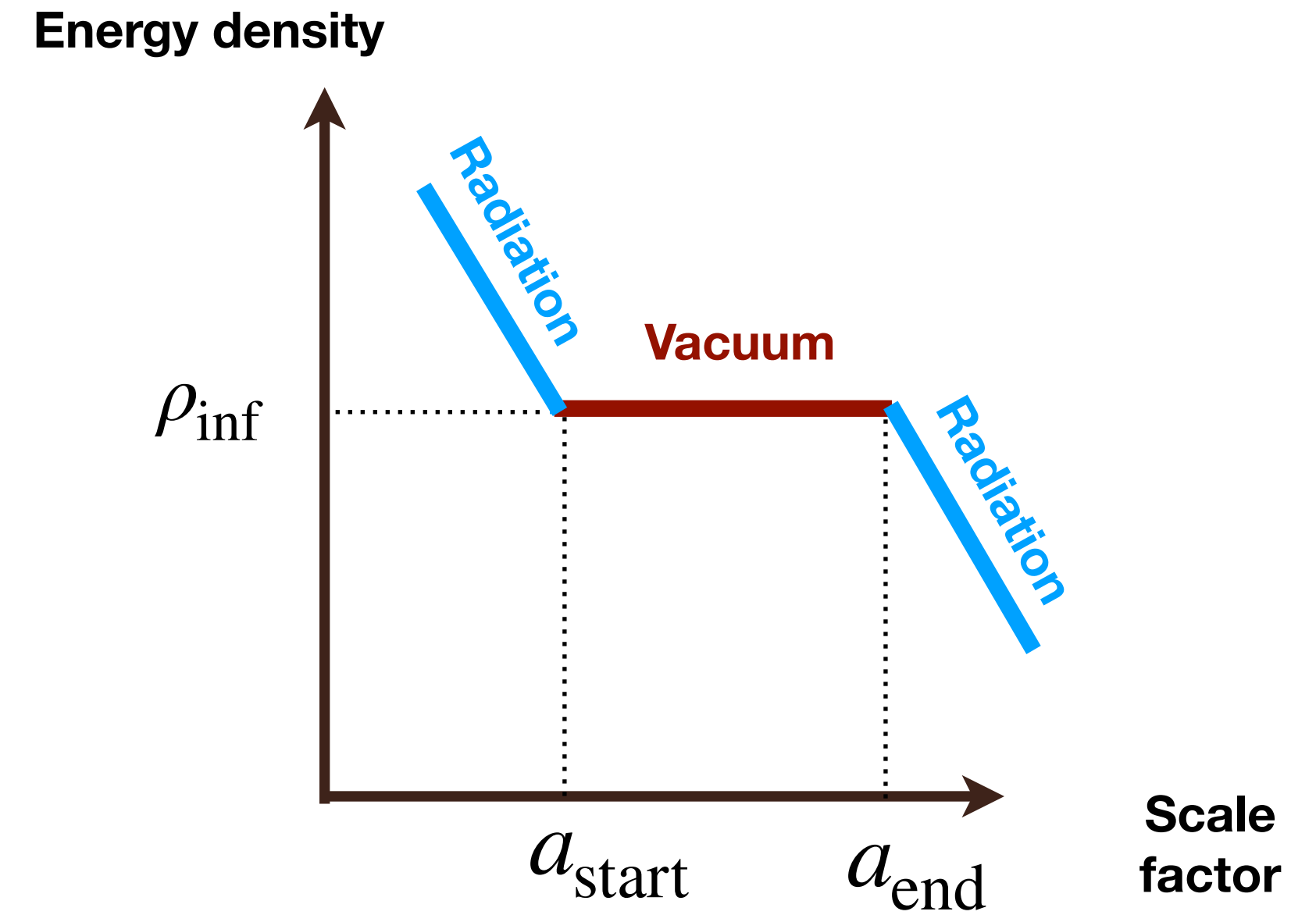
$$D = \left(\frac{a_{\text{dom}}}{a_*} \right)^3 = \frac{T_{\text{dom}}}{T_{\text{dec}}} \simeq \frac{m_V}{\sqrt{M_{\text{pl}} \Gamma_V}}$$

Homeopathic DM



Cirelli, Gouttenoire, Petraki, Sala, 2018

2) After an inflationary era



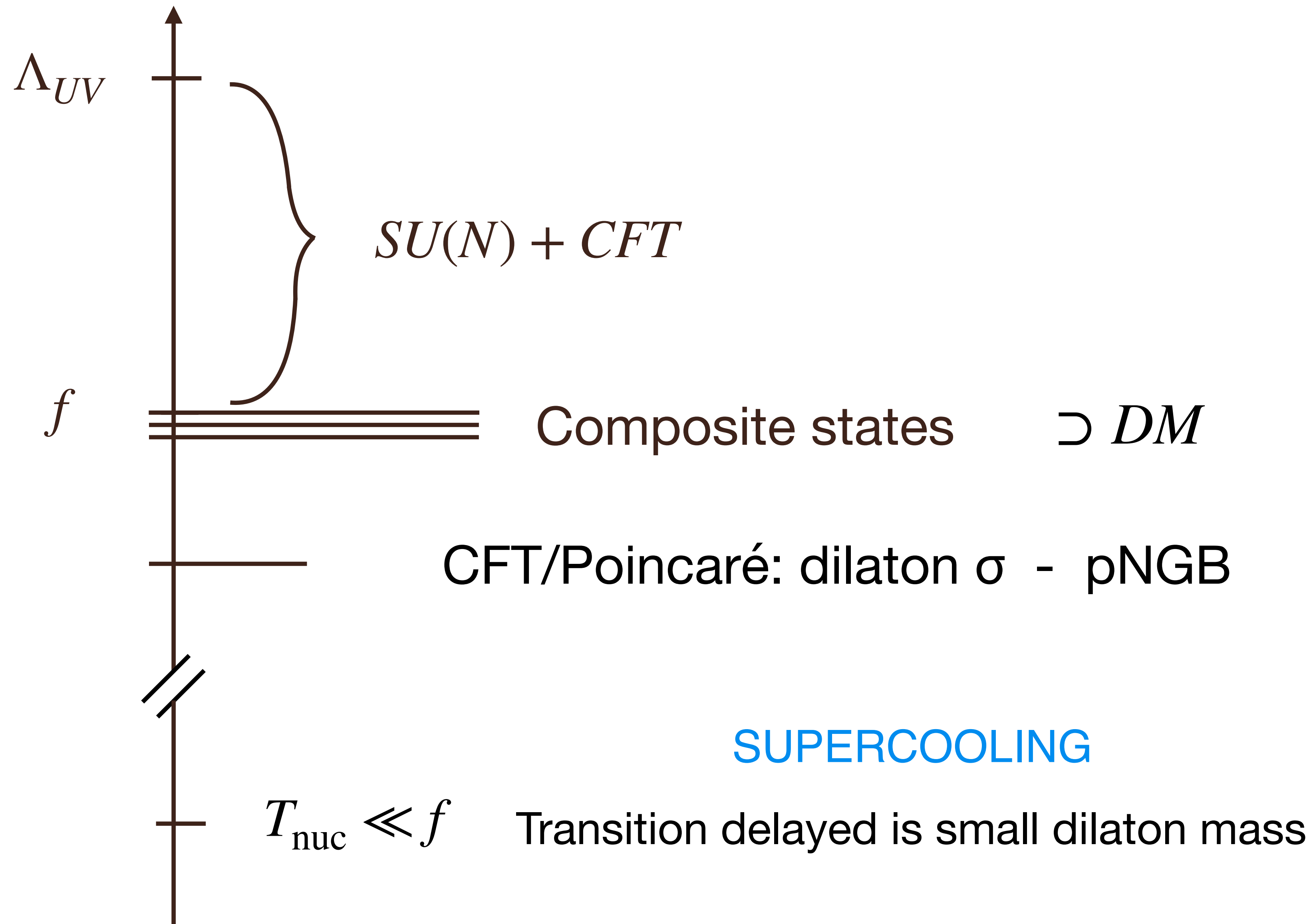
$$D = \left(\frac{a_{\text{end}}}{a_{\text{start}}} \right)^3 = e^{3 N_e} = \left(\frac{f}{T_{\text{nuc}}} \right)^3$$

Supercooled confinement

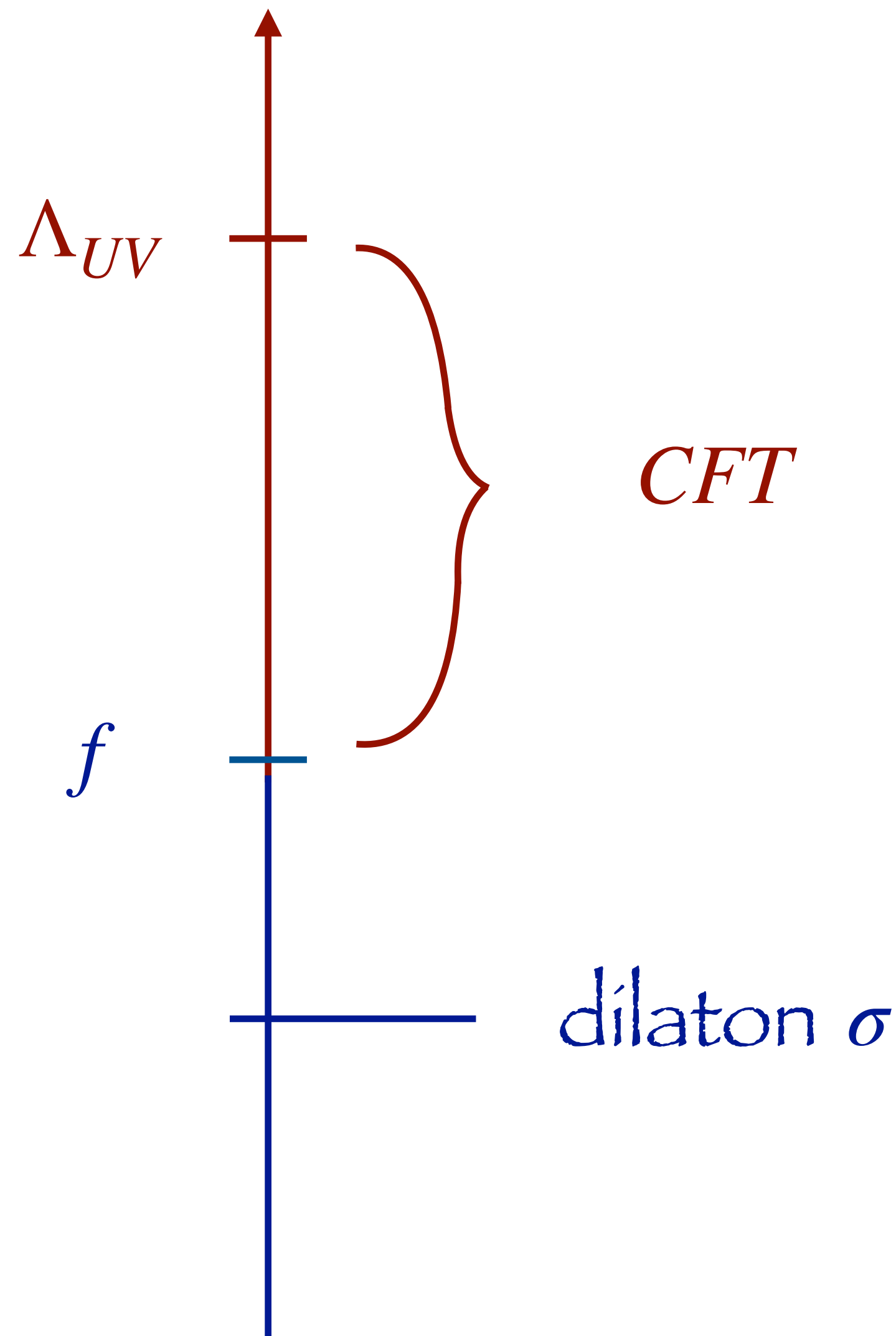
$$N_e = \log \frac{f}{T_{\text{nuc}}}$$

Baldes, Gouttenoire, Sala, 2020

Nearly-conformal strong sector



Nearly-conformal strong sector



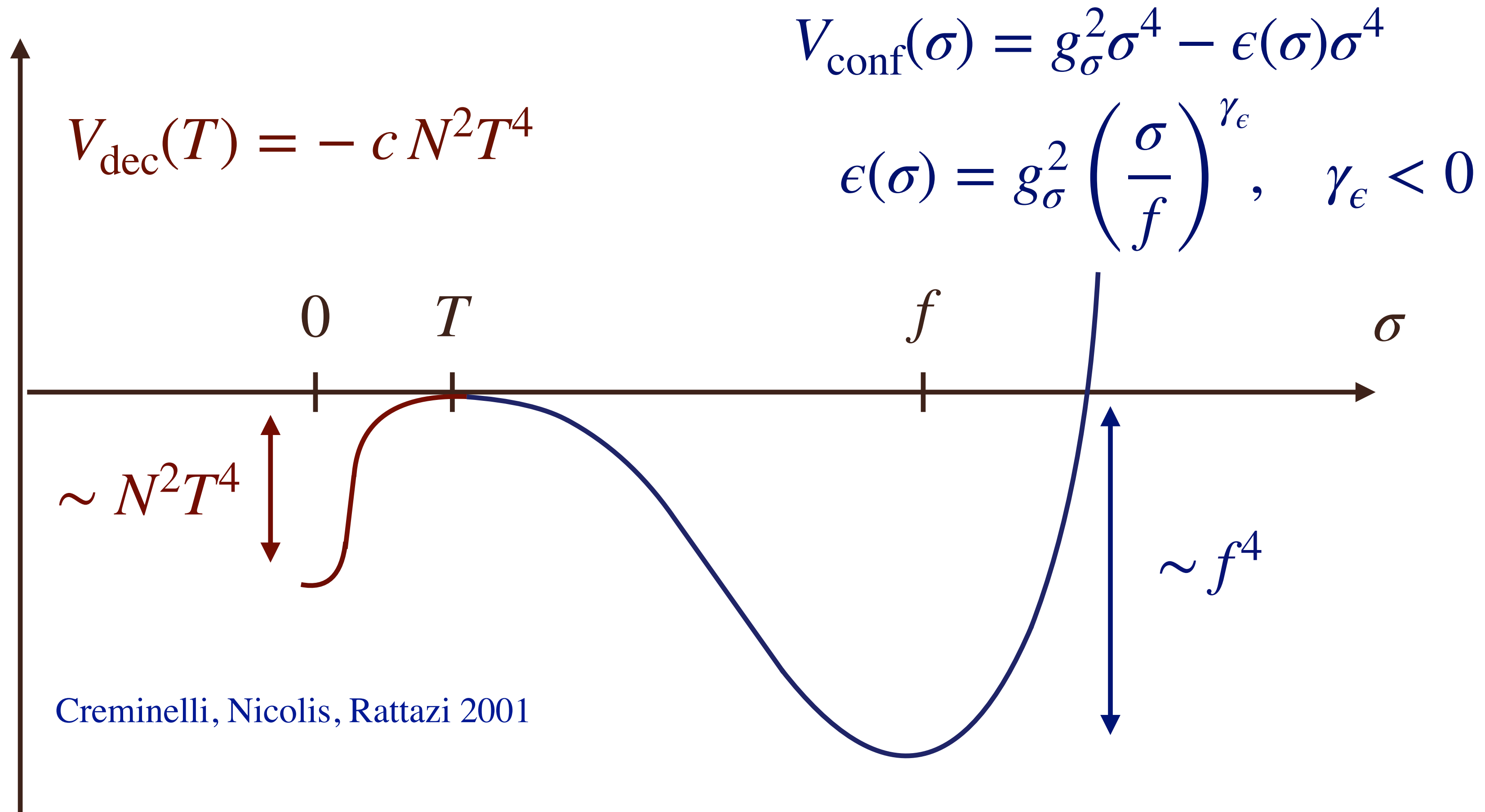
Deconfined phase

$$V_{\text{dec}}(T) = -c N^2 T^4$$

Confined phase

$$V_{\text{conf}}(\sigma) = g_\sigma^2 \sigma^4 - \epsilon(\sigma) \sigma^4$$

$$\epsilon(\sigma) = g_\sigma^2 \left(\frac{\sigma}{f} \right)^{\gamma_\epsilon}, \quad \gamma_\epsilon < 0$$



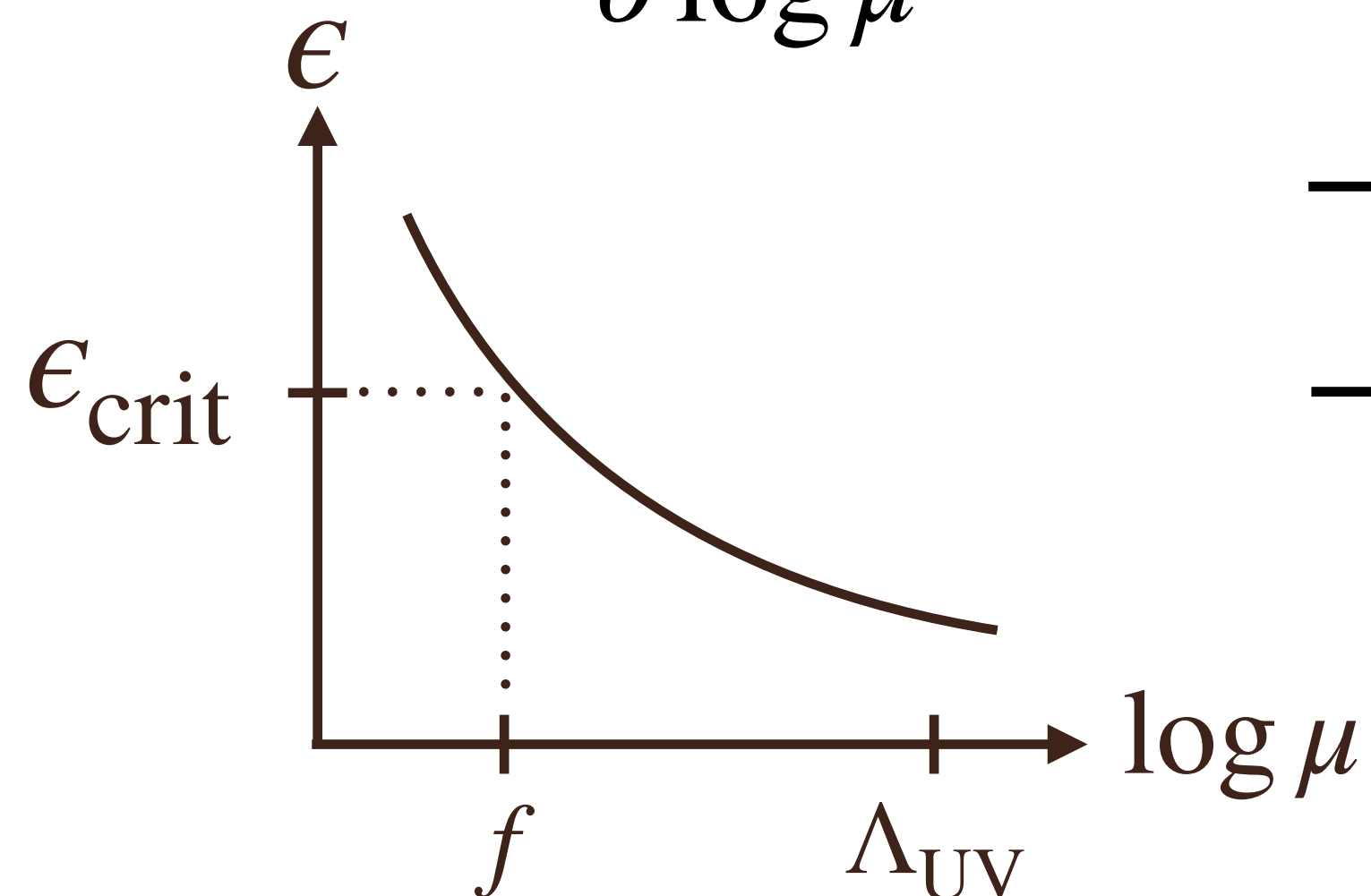
Super-cooling starts for: $T_{\text{start}} \sim f$

ends for: $T_{\text{nuc}} \sim c_1 f \text{Exp} - c_2 \frac{f^2}{m_\sigma^2}$

Nearly-conformal strong sector

- Hyp:
- strong sector conformally invariant in the UV
 - Scale invariance explicitly broken by a slightly relevant operator $\mathcal{L} \supset \epsilon O_\epsilon$, $[O_\epsilon] = 4 + \gamma_\epsilon$

RGE: $\frac{\partial \epsilon}{\partial \log \mu} \simeq \gamma_\epsilon \epsilon \quad \rightarrow \quad \epsilon = g_\sigma^2 \left(\frac{\mu}{f} \right)^{\gamma_\epsilon}, \quad \gamma_\epsilon < 0$



→ Scale inv. spontaneously broken

→ pNGB: the dilation σ

$$V_{\text{conf}}(\sigma) = \left(1 - \left(\frac{\sigma}{f} \right)^{\gamma_\epsilon} \right) g_\sigma^2 \sigma^4$$

Gravitational Waves from Supercool Phase Transition

Randall Servant hep-ph/0607158,...

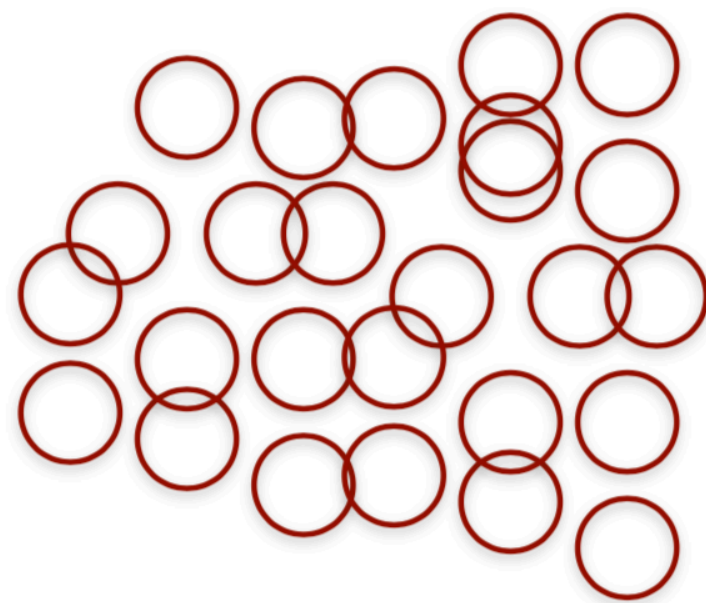
$$\Omega_{\text{GW}} \propto (H/\beta) \times (H/\beta)$$

Bubble size \times Collision time

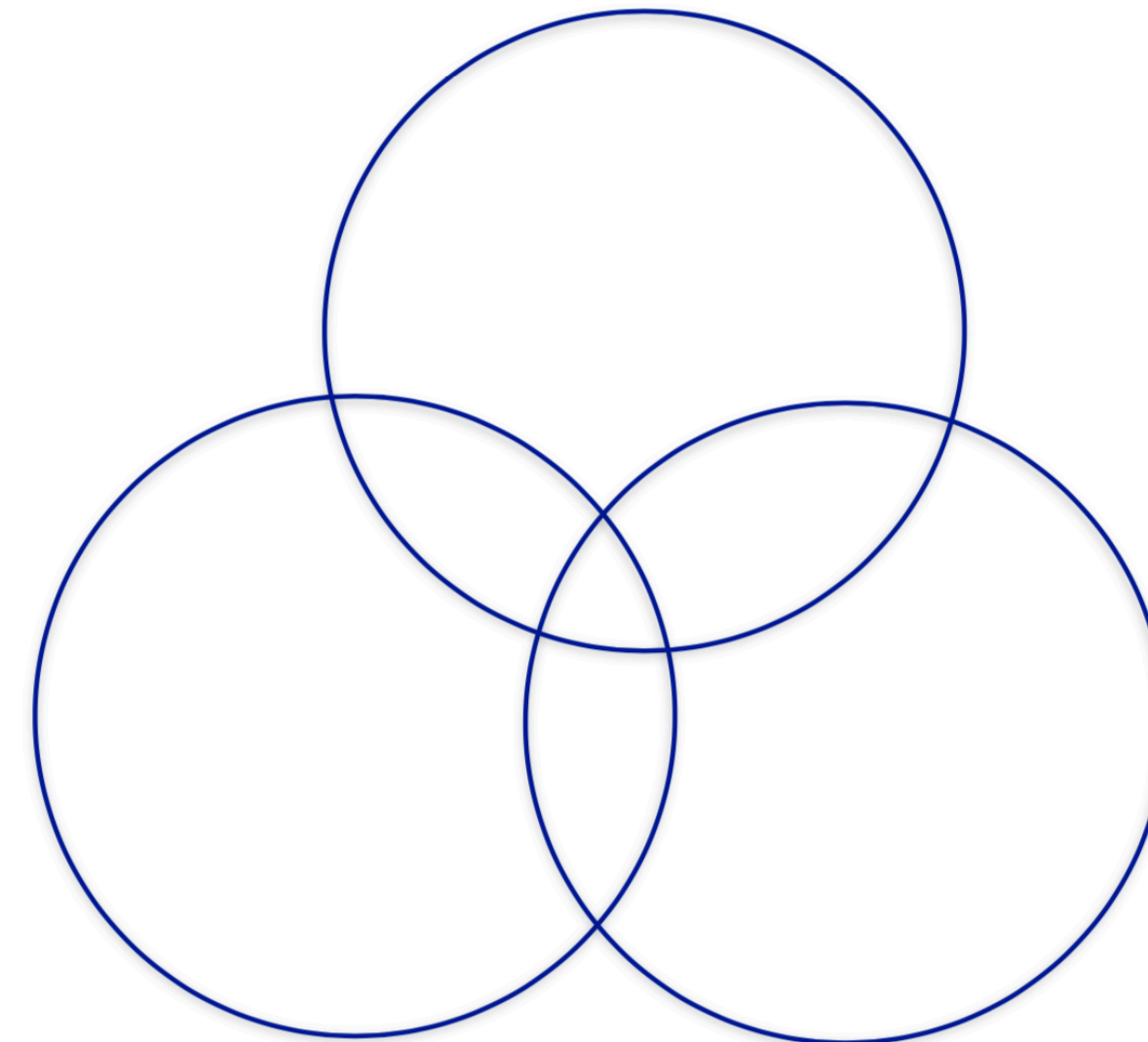
$$\frac{\beta}{H} \simeq T \left. \frac{dS_4}{dT} \right|_{T_{\text{nuc}}} \simeq 15 \left(\frac{10}{N_{\text{e-fold}}} \right)^2$$

Standard 1st order PT

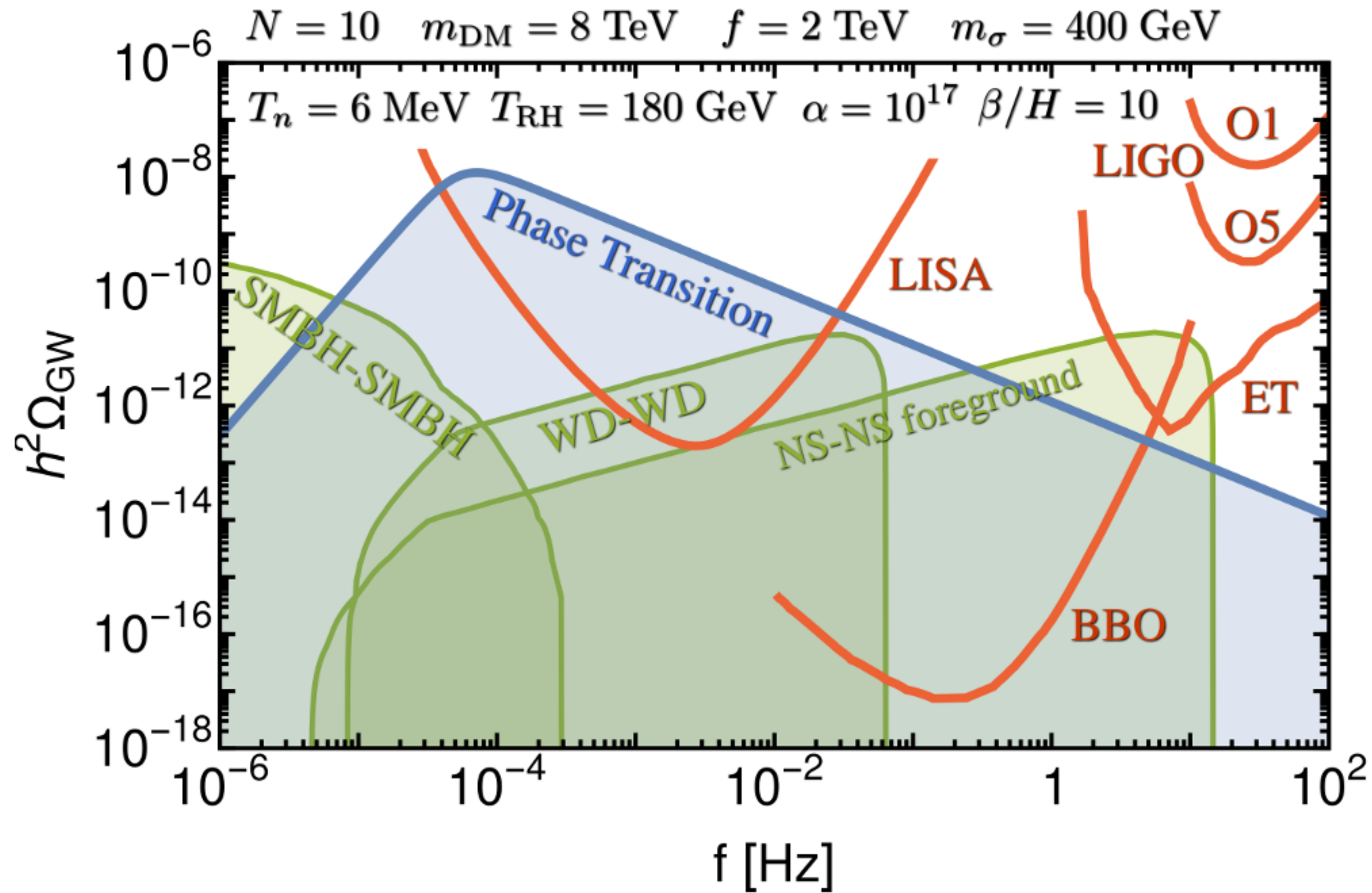
$\beta/H \sim 100$



Supercooled PT
 $\beta/H \sim 10$



Gravitational Waves from Phase Transition



Nucleation Temperature

Supercooling begins at

$$T_{\text{start}} \sim f$$

Bubble nucleation ends SC at

$$T_{\text{nuc}} \sim f \exp\left(-c \frac{f^2}{m_\sigma^2}\right)$$

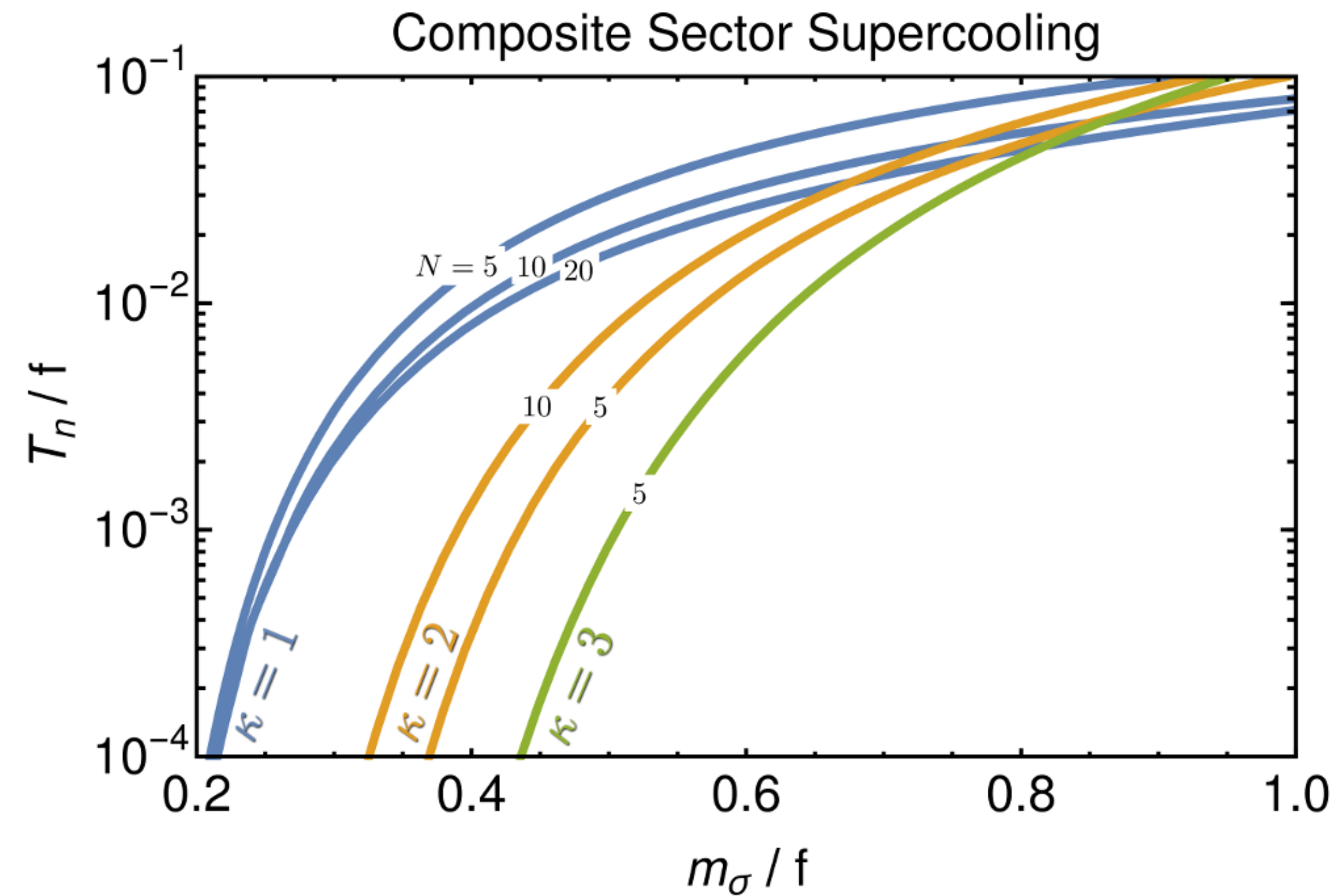
Nucleation happens when tunnelling rate \sim Hubble

$$\Gamma(T_{\text{nuc}}) \sim H^4(T_{\text{nuc}})$$

Bounce action $S_4 \approx 100$

Tunneling rate $\Gamma \sim T^4 \left(\frac{S_4}{2\pi}\right)^2 e^{-S_4}$

Nucleation Temperature



For small m_σ PT seem to never complete!



But then it can be triggered by QCD

Iso Serpico Shimada 1704.04955

von Harling Servant 1711.11554

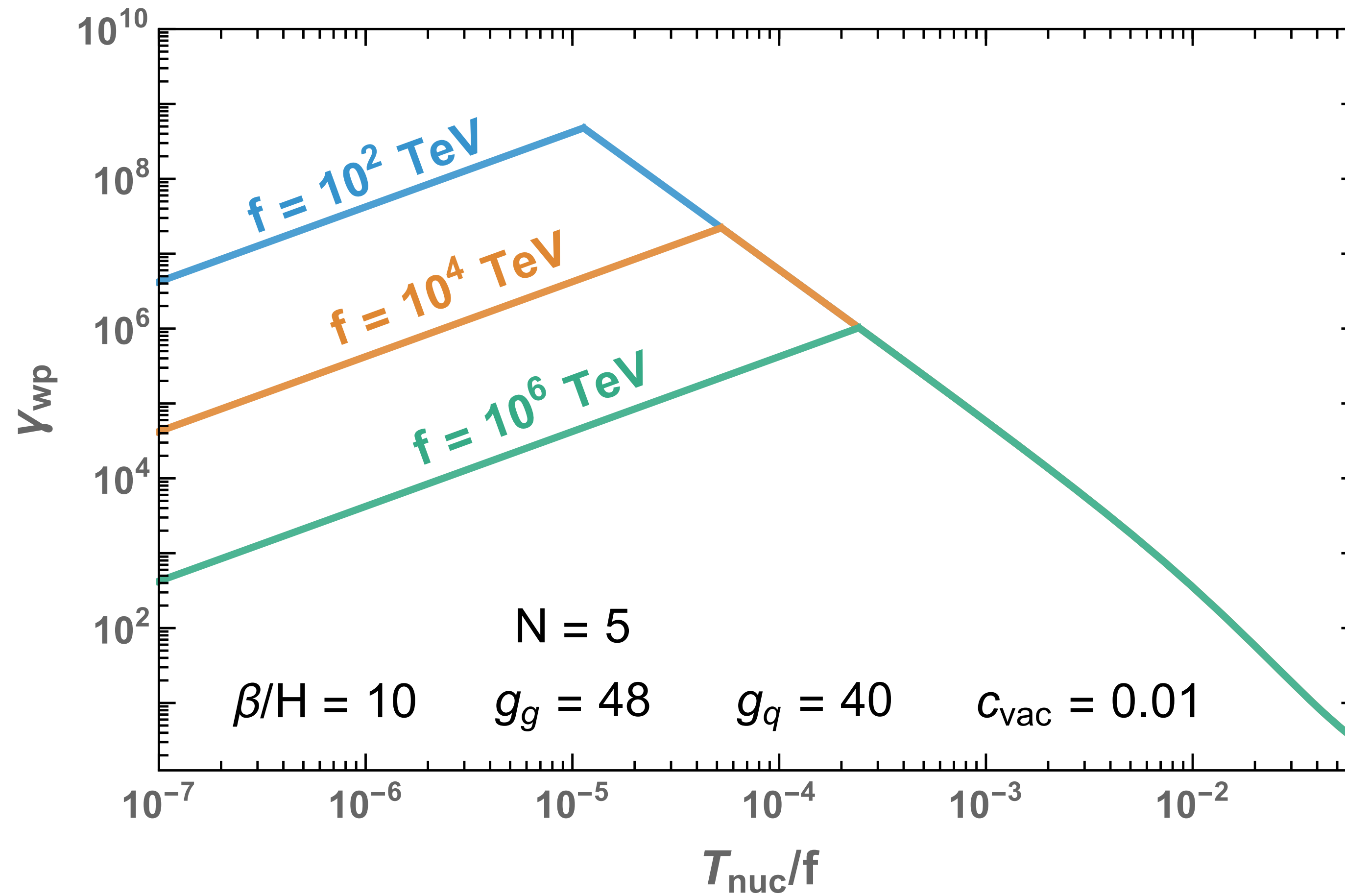


Catalysed by black holes ?

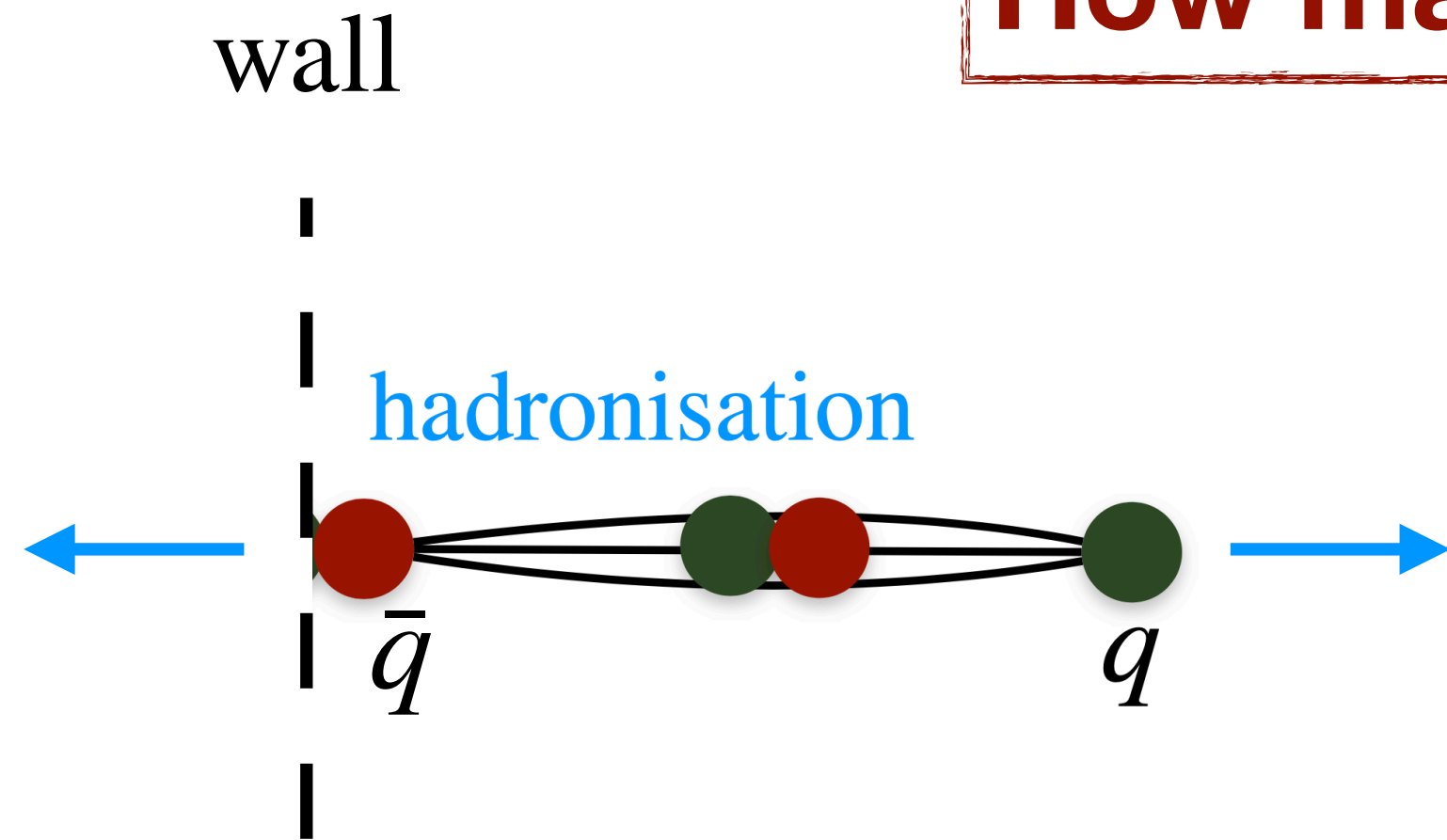
Gregory, Moss, Withers 15

Mukaïda, Yamada 17

Bubble wall Lorentz factor



How many hadrons ?



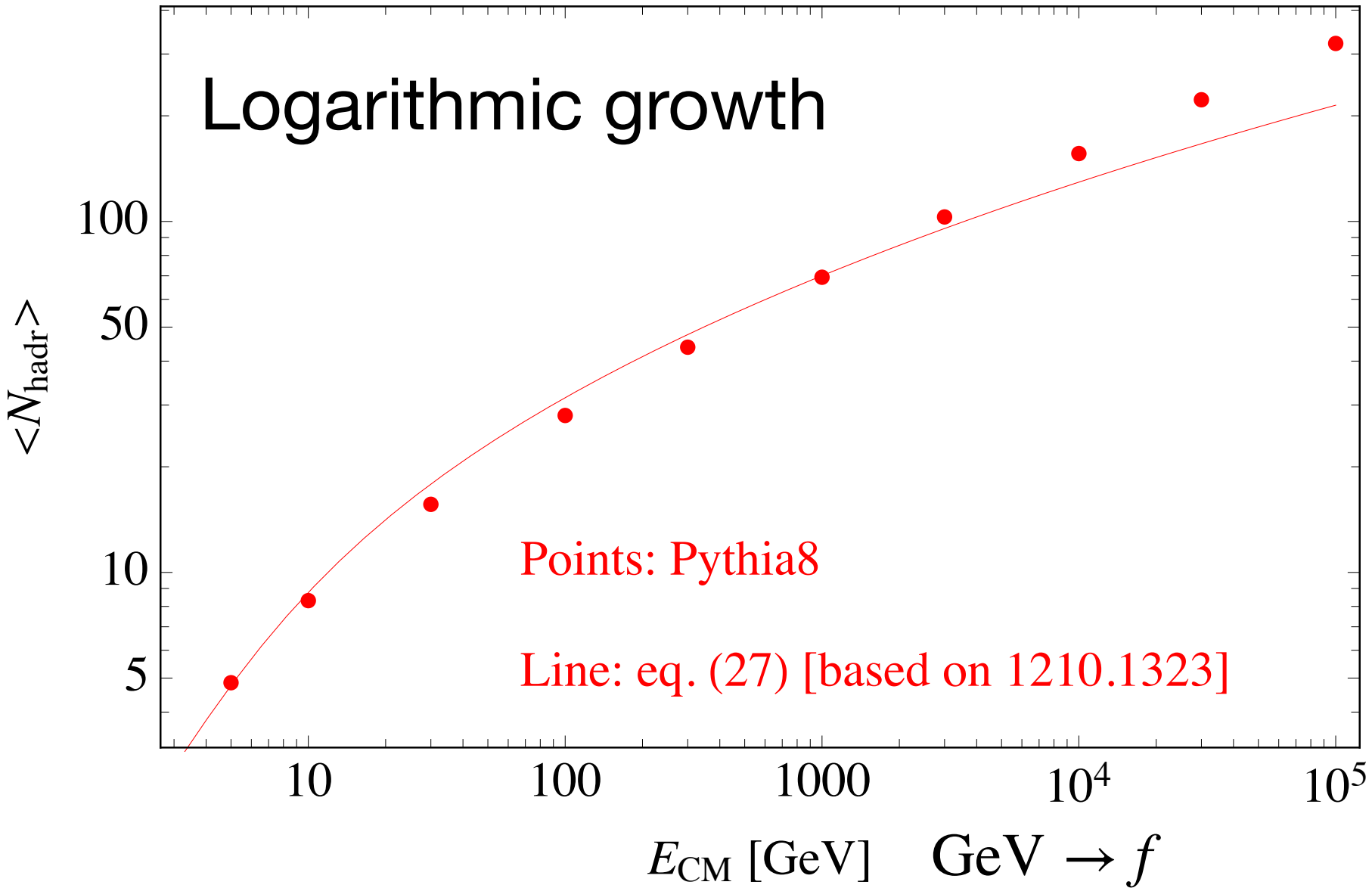
Center of mass frame of $q\bar{q}$

Analogous to $e^+e^- \rightarrow q\bar{q}$ in QCD

Use Pythia with

$$E_{\text{cm}}^{q\bar{q}} = |p_q + p_{\bar{q}}|$$

$$\approx \sqrt{E_q E_{\bar{q}}}$$

$$\approx \sqrt{\gamma_{wp} f T_{\text{nuc}}}$$


DM abundance after supercooling

Hambye, Strumia, Teresi 18 \rightarrow Baldes, Gouttenoire, Sala, Servant 19

$$Y_{\text{SC}} \propto \left(\frac{T_{\text{nuc}}}{f} \right)^3 \times BR \times N_{\text{frag}}$$

Standard Supercooling Branching ratio quark \rightarrow DM String fragmentation

2 possibilities:

Combinatoric

Thermal distrib.

DM: light meson

DM: heavy baryon

e.g. $BR \simeq 2/N_f^2$

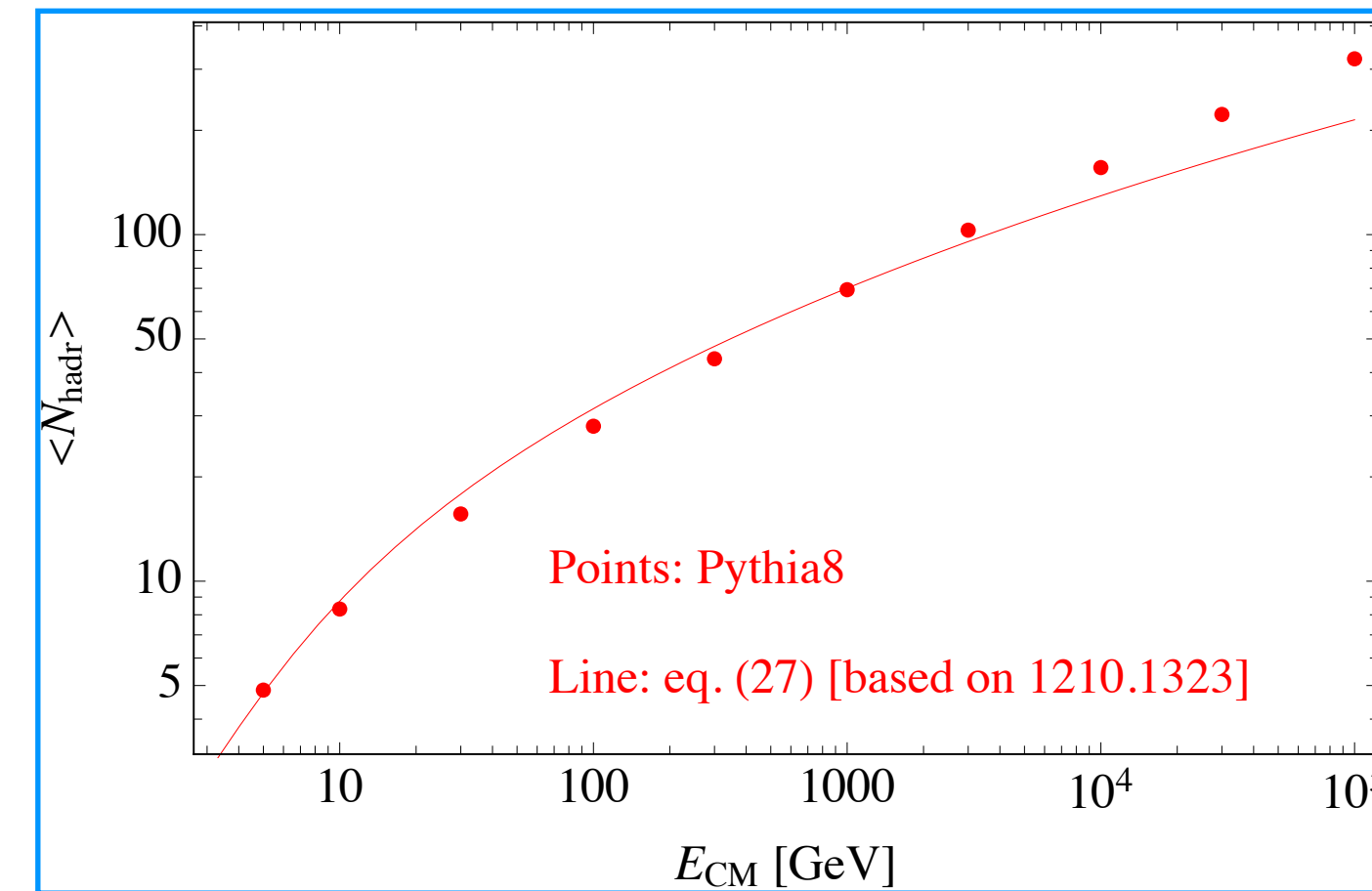
$$BR \propto \exp - m_{\text{DM}}/f$$

DIS in the Sky: result



Brute force: iterate this \longrightarrow

until $E_{\text{CM}} \sim \sqrt{TE_{\text{hadron}}} = f$



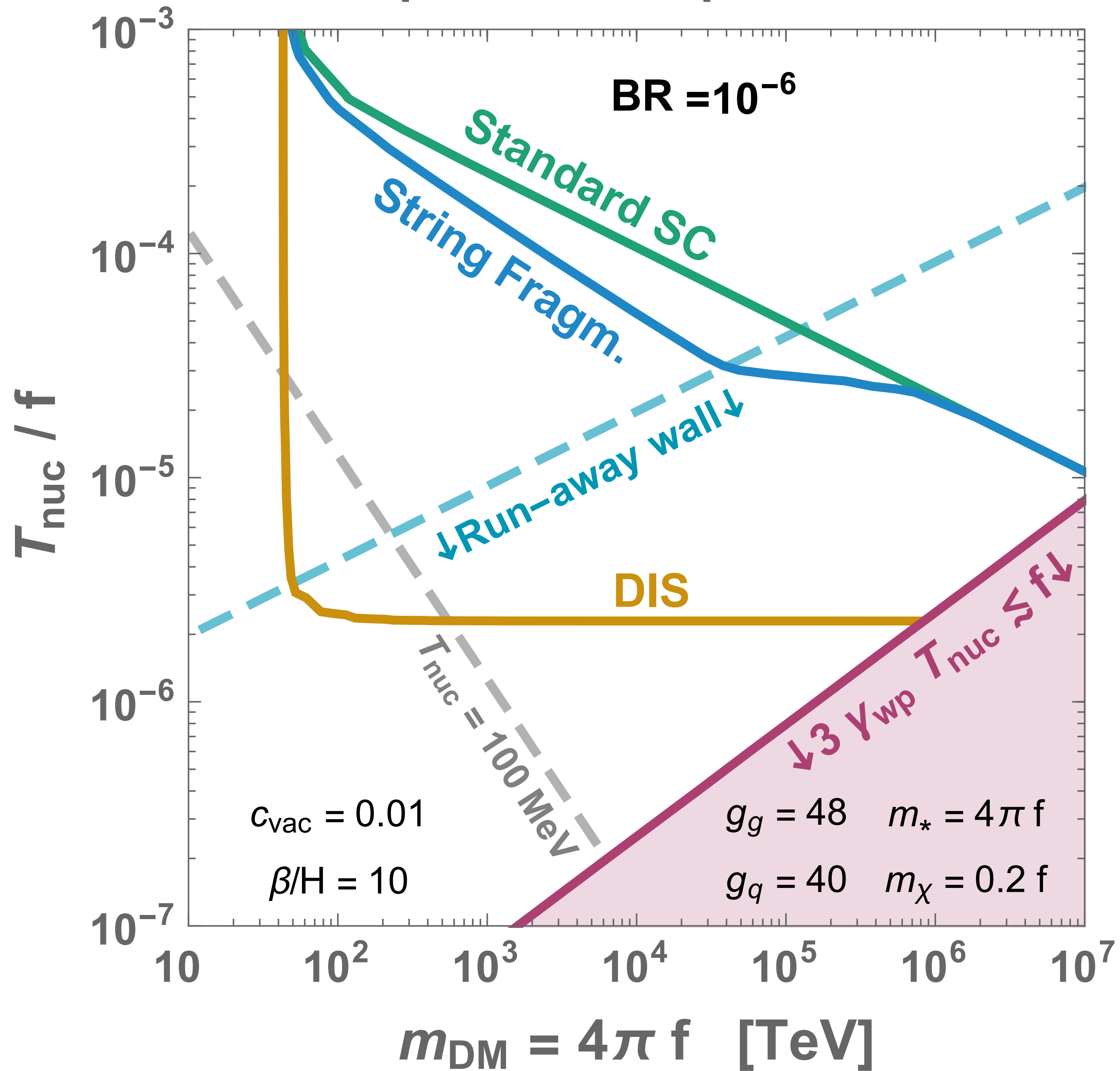
O(1) fraction of initial hadron energy converted into hadron masses

$$Y_{\text{SC+string+DIS}} \sim \frac{T E_{\text{hadr}}}{m_*^2} Y_{\text{SC+string}}$$

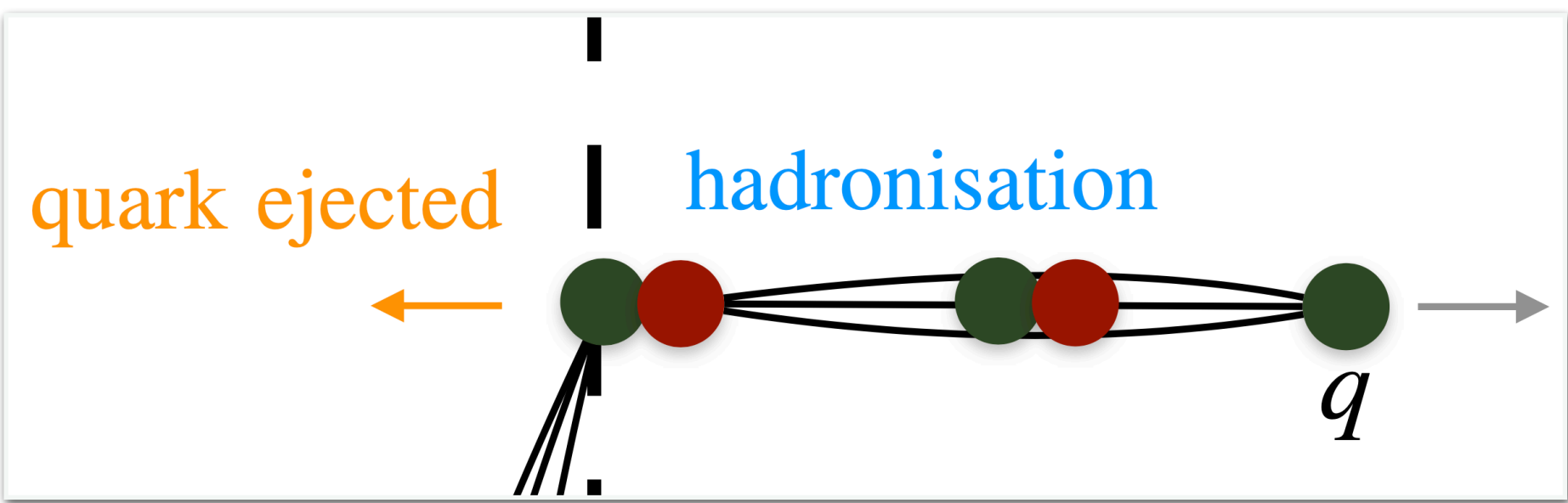
$$\frac{\gamma_{cp} E_{q\bar{q}}^{\text{CM}}}{\langle N_{\text{hadr}} \rangle} \quad \langle N_{\text{hadr}} \rangle Y_{\text{SC}} \longrightarrow \langle N_{\text{hadr}} \rangle \text{ simplifies!}$$

$$\langle E_{\text{hadron}} \rangle = \frac{E_{\text{cm}}^{q\bar{q}}}{\langle N_{\text{hadron}} \rangle} \sim \frac{\sqrt{\gamma_{wp} f / T_{\text{nuc}}}}{\langle N_{\text{hadron}} \rangle} \gg f$$

Supercool Composite DM



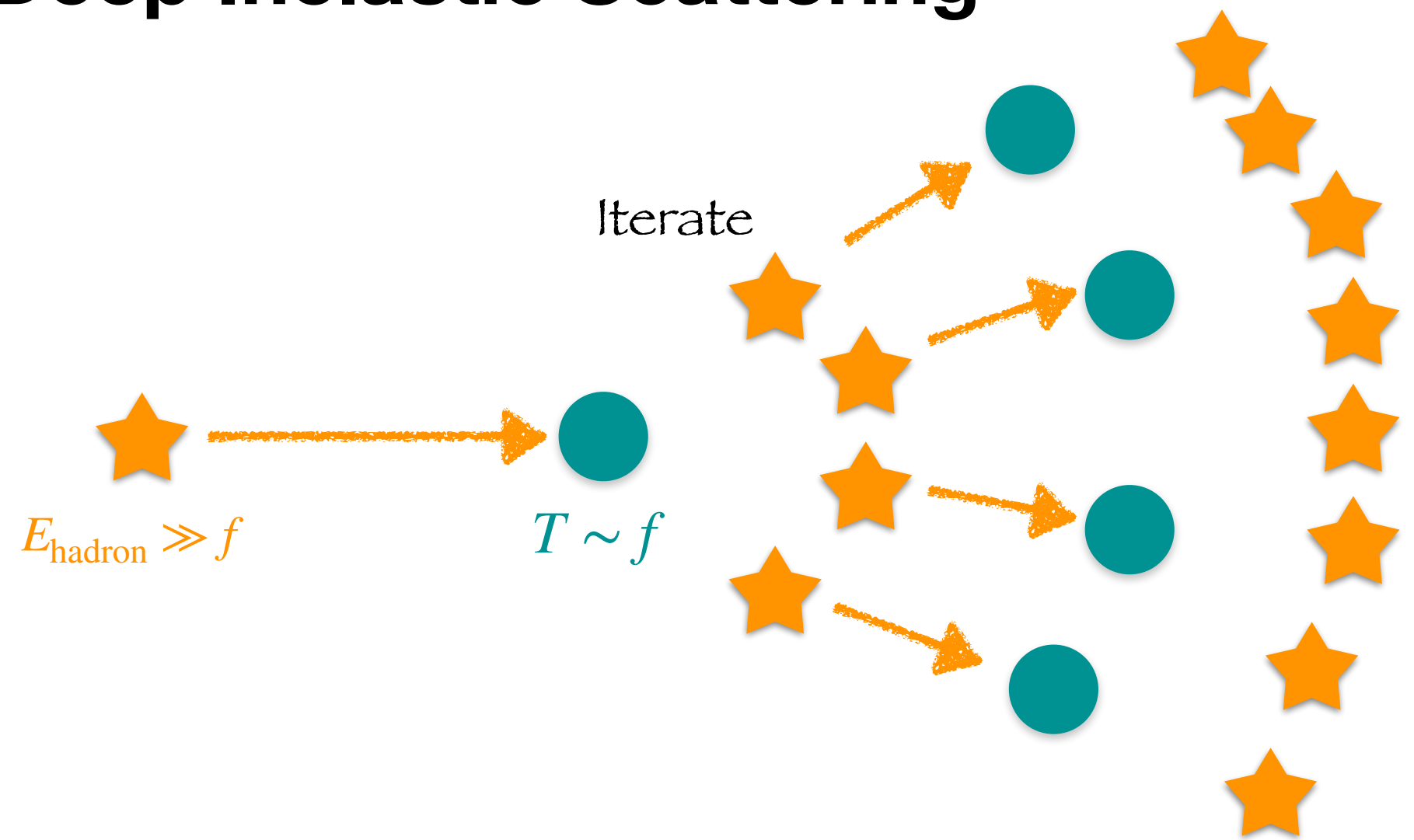
Consequences on DM abundance



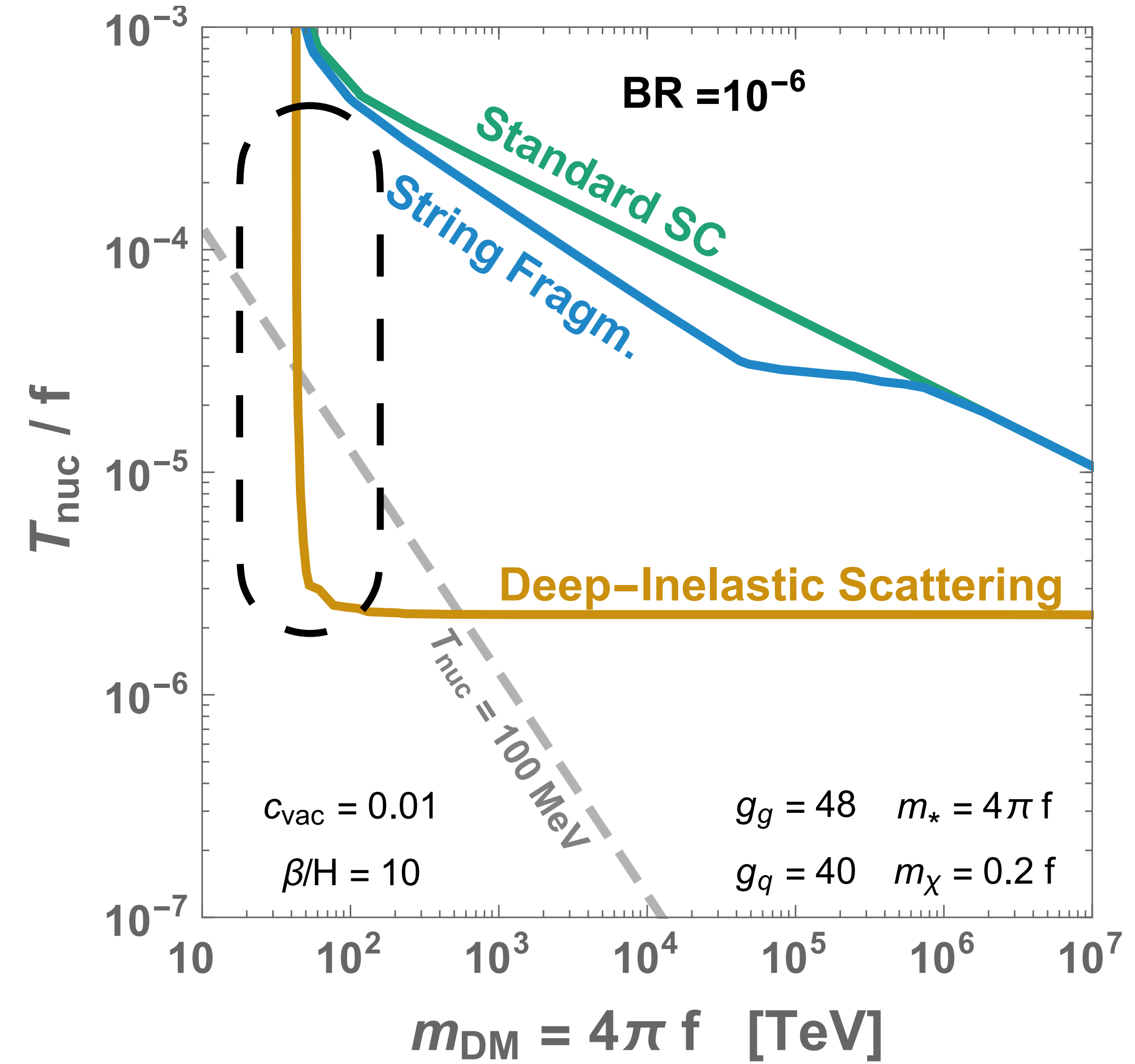
1. String fragmentation + quark ejection

$$Y_{\text{DM}} / Y_{\text{DM}}^{\text{naive}} \propto \log^n(\gamma_{\text{wp}} T_{\text{nuc}} / f)$$

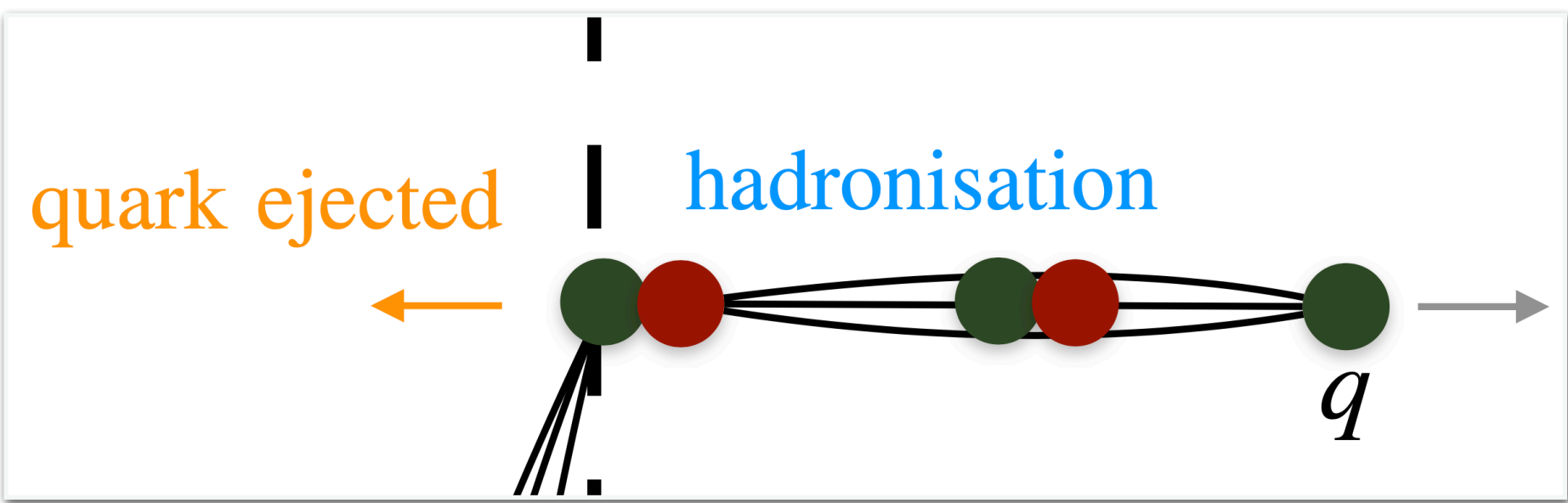
2. Deep Inelastic Scattering



$$Y_{\text{DM}} / Y_{\text{DM}}^{\text{naive}} \propto \gamma_{\text{wp}} \propto \frac{T_{\text{nuc}}}{f} \frac{M_{\text{Pl}}}{f}$$



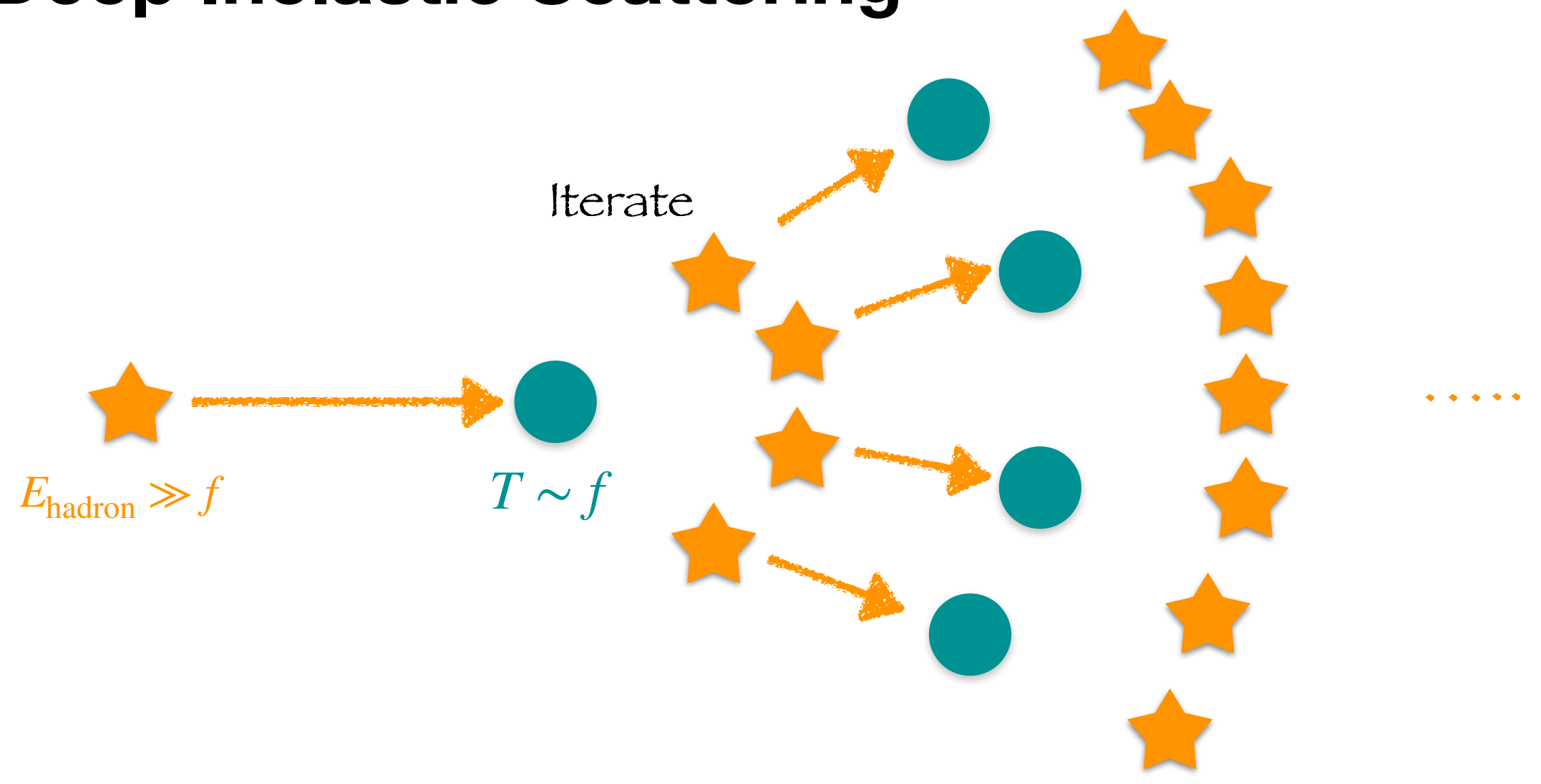
Consequences on DM abundance



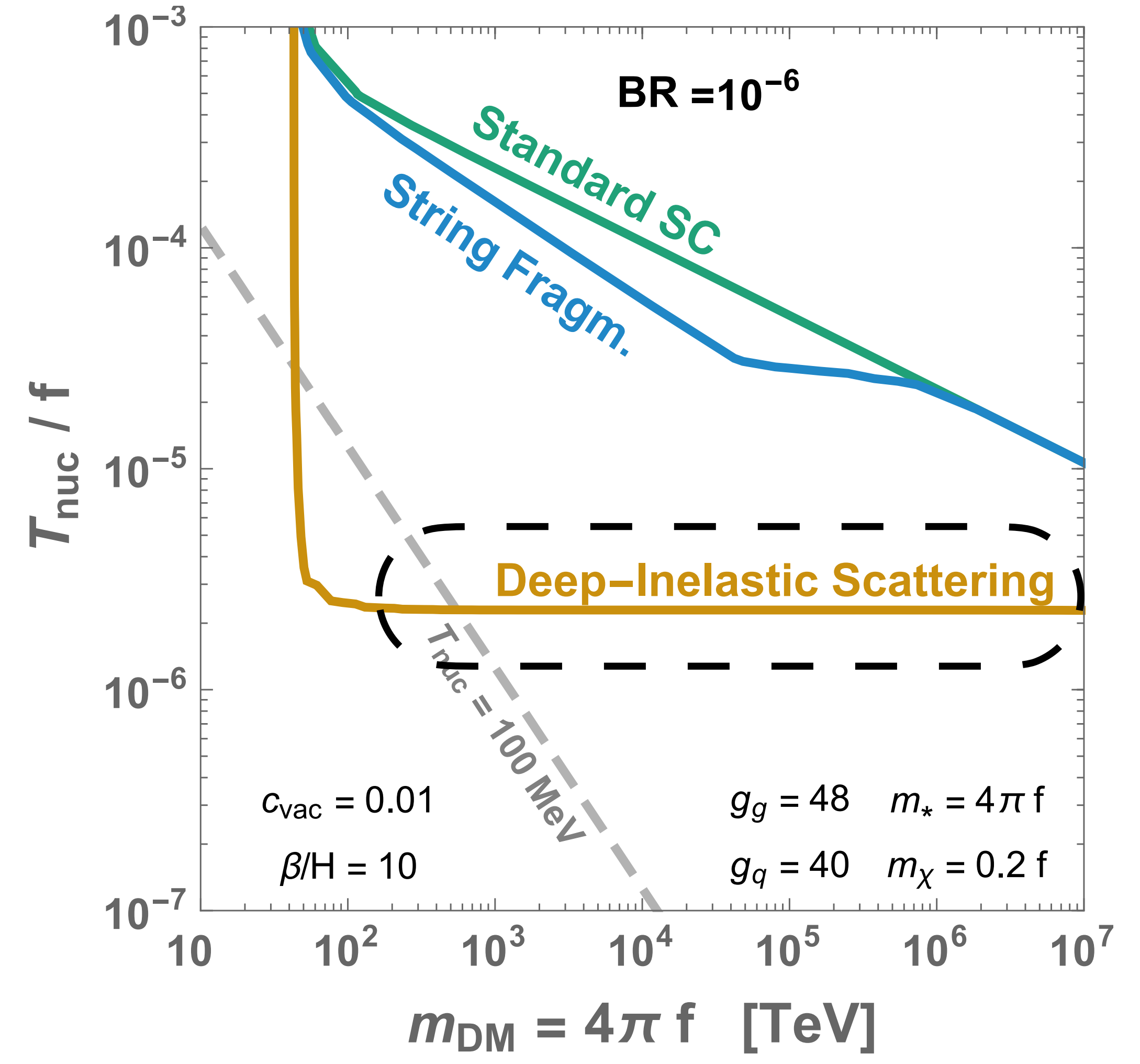
1. String fragmentation + quark ejection

$$Y_{\text{DM}} / Y_{\text{DM}}^{\text{naive}} \propto \log^n(\gamma_{\text{wp}} T_{\text{nuc}} / f)$$

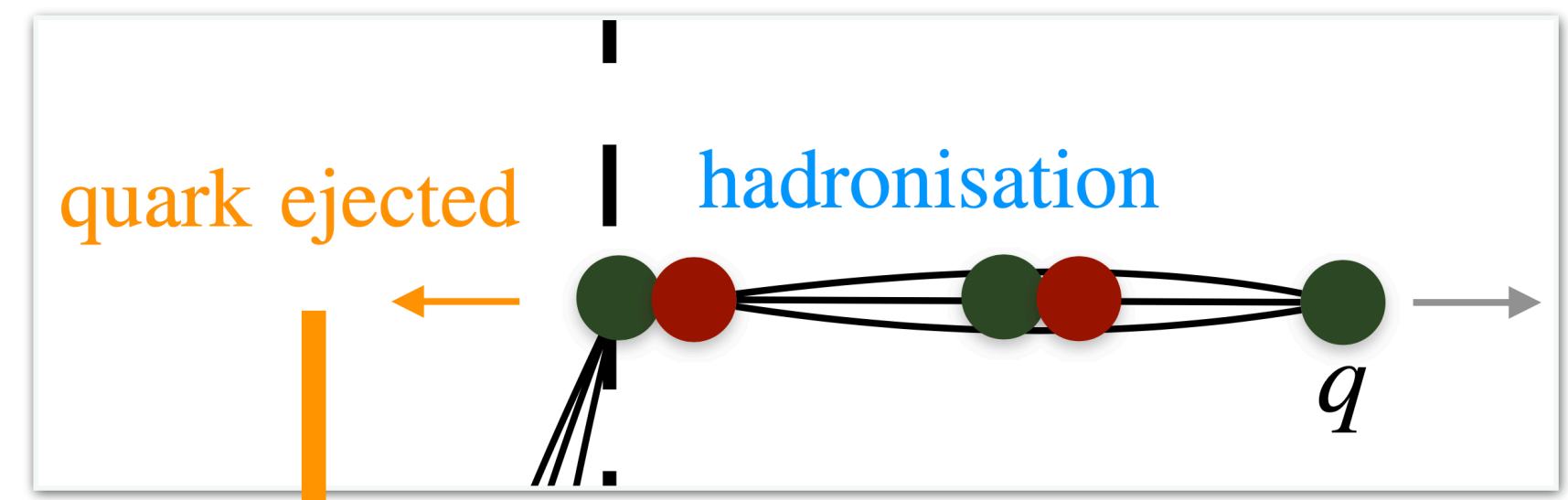
2. Deep Inelastic Scattering



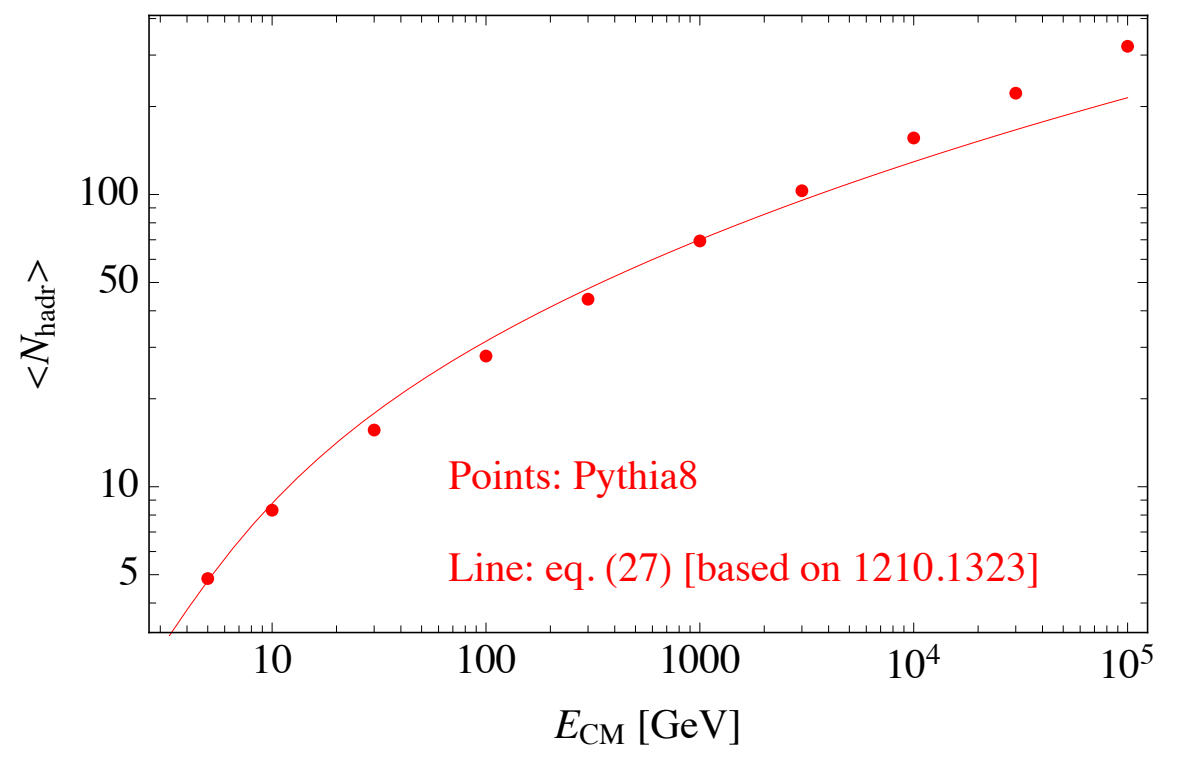
$$Y_{\text{DM}} / Y_{\text{DM}}^{\text{naive}} \propto \gamma_{\text{wp}} \propto \frac{T_{\text{nuc}} M_{\text{Pl}}}{f f}$$



Cosmological consequences



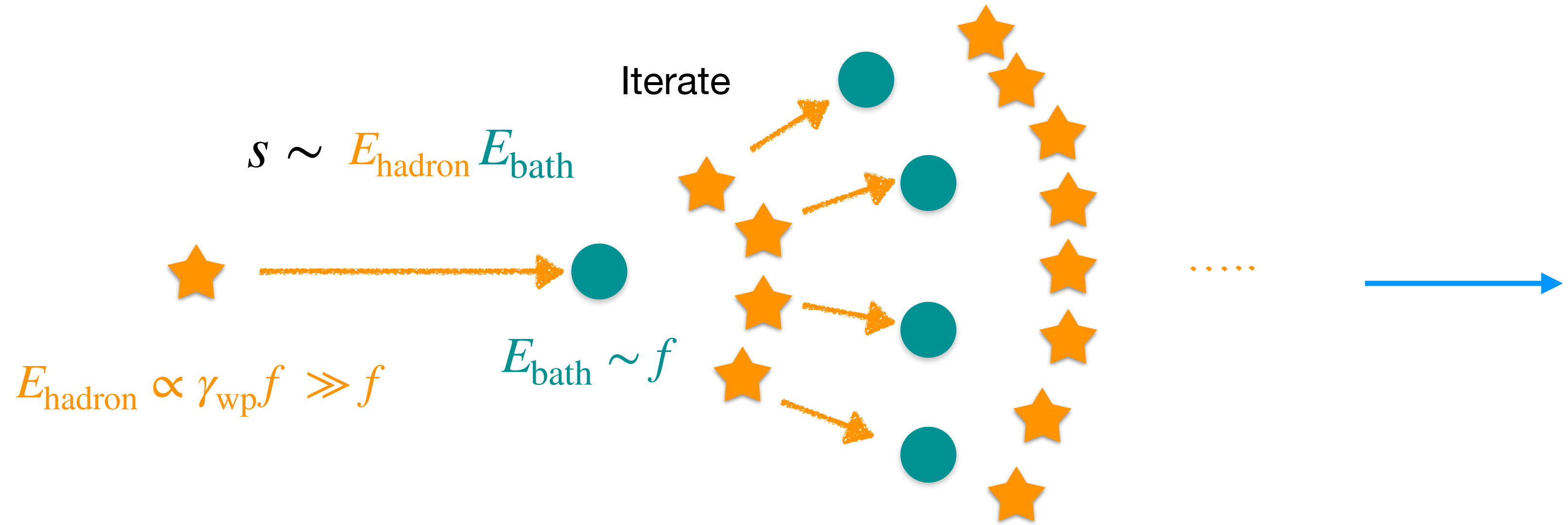
1. More hadrons per initial quark pair



Y_{D}

Ejected quarks give contribution of same order of magnitude

2. Cosmological catapuit

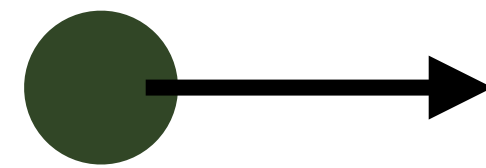


runaway regime

$$Y_{\text{DM}} / Y_{\text{DM}}^{\text{naive}} \propto \gamma_{\text{wp}} \propto \frac{T_{\text{nuc}}}{f} \frac{M_{\text{Pl}}}{f}$$

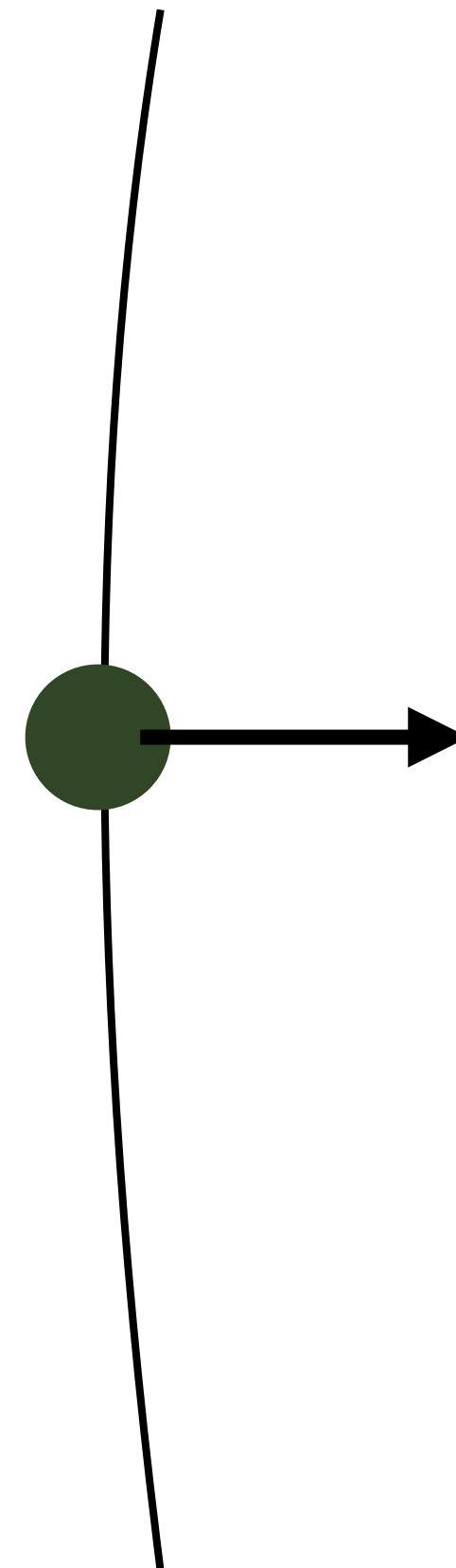
Interaction with other quarks ?

Bubble wall



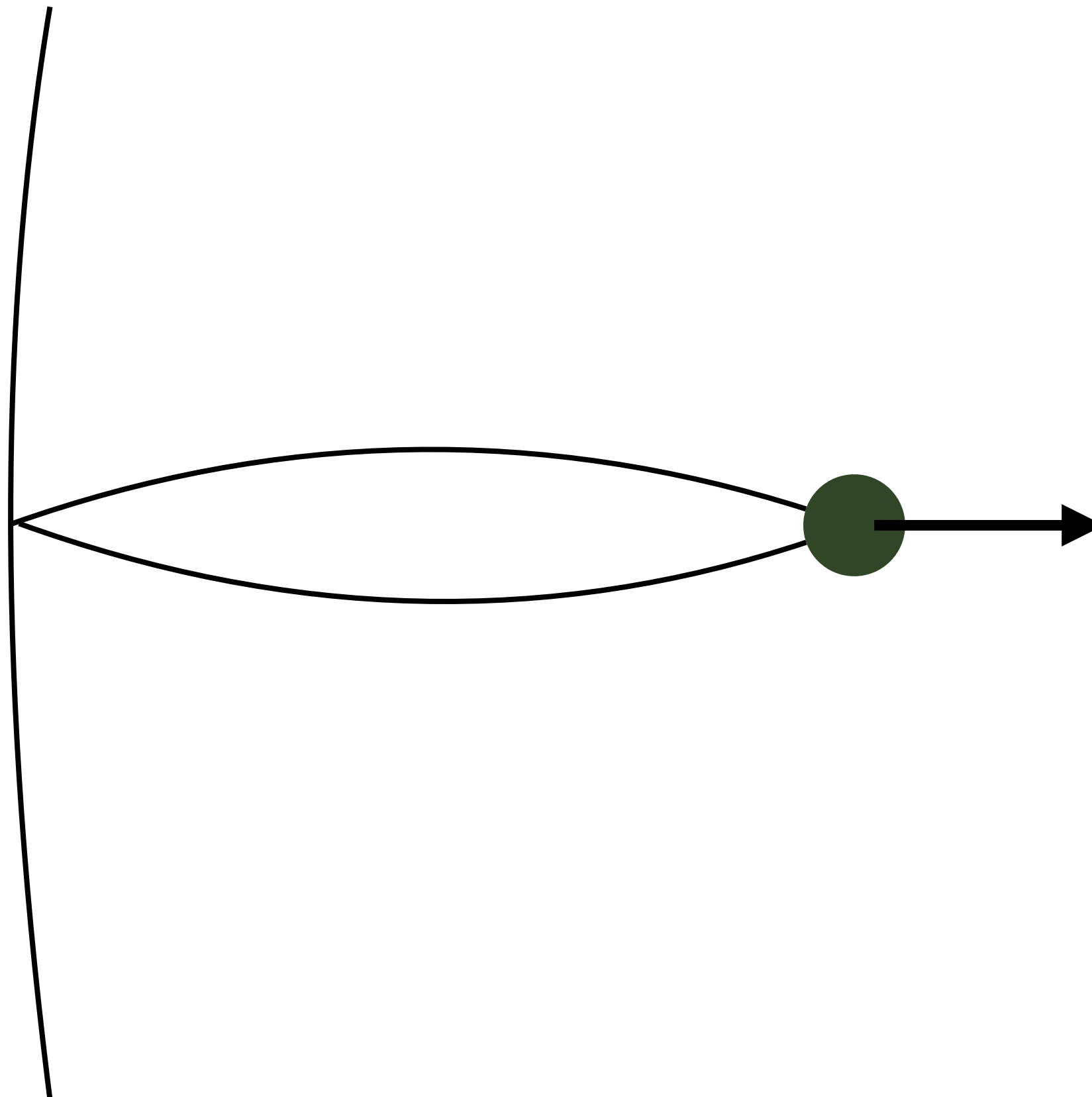
Interaction with other quarks ?

Bubble wall



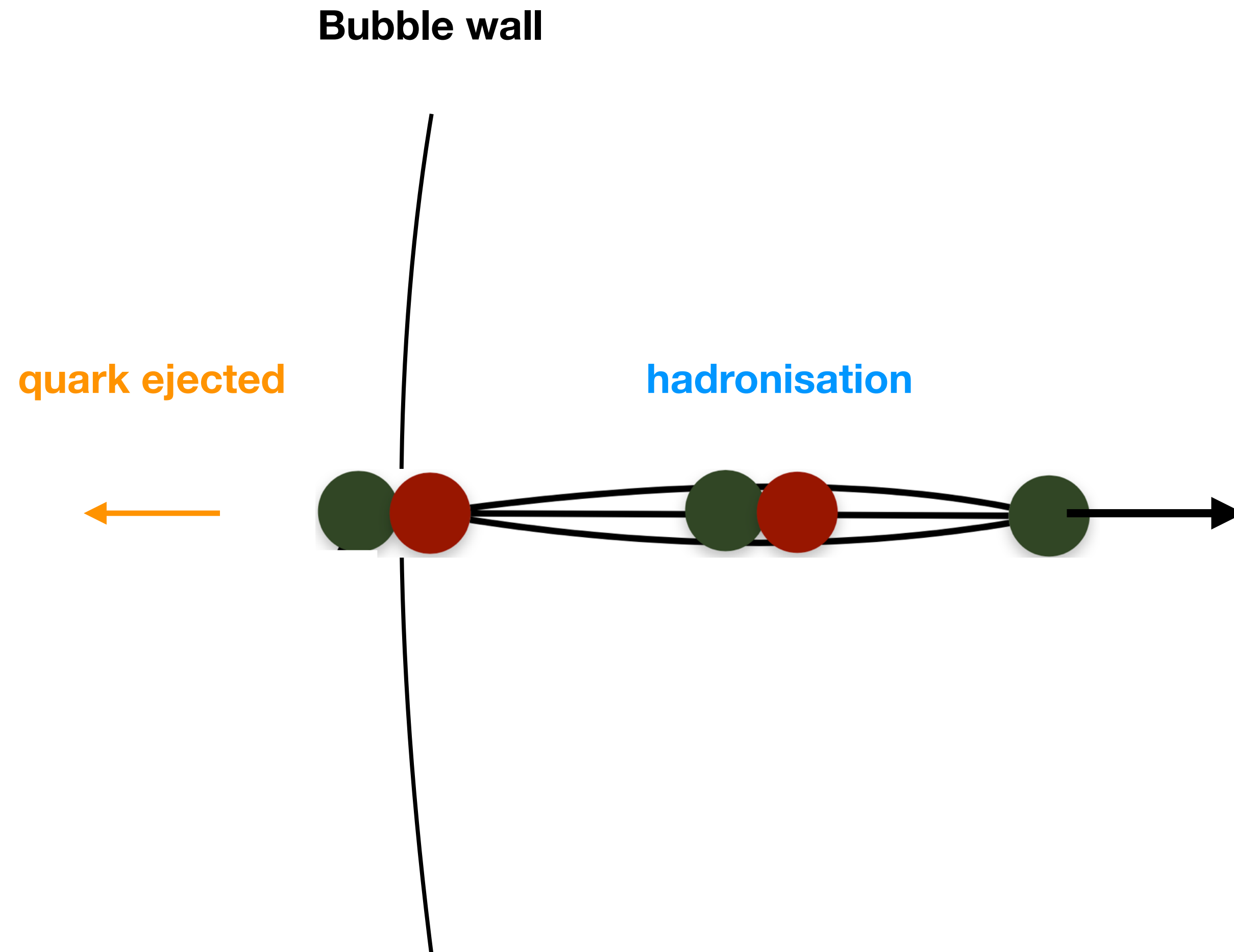
Interaction with other quarks ?

Bubble wall



Interaction with other quarks ?

$$\Gamma_{\text{nucl}} \sim f/N$$

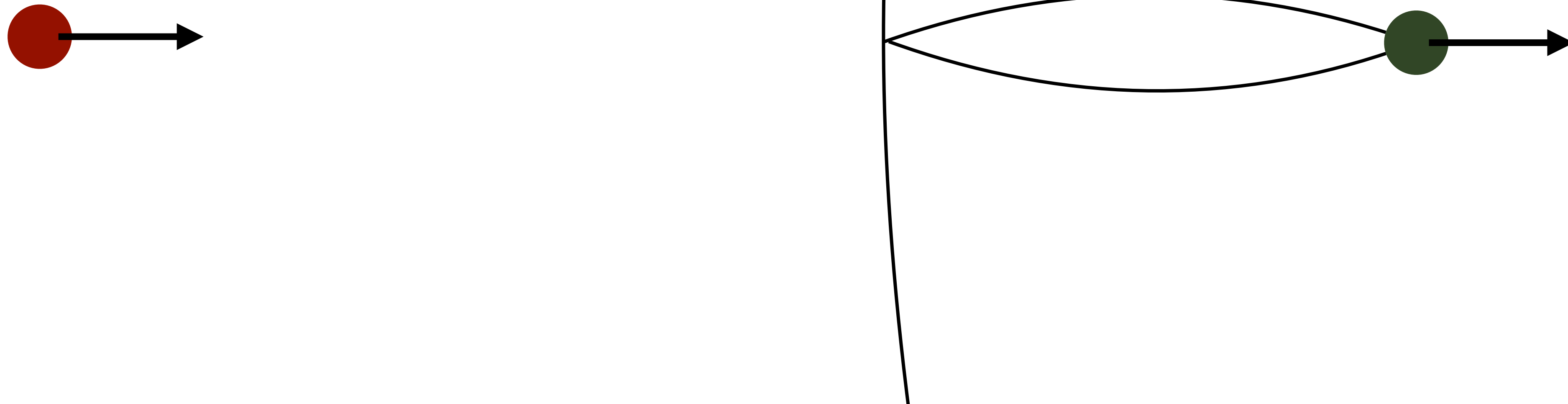


Interaction with other quarks ?

$$\Gamma_{\text{q-string}} \sim \pi f^{-2} \times \gamma_{\text{wp}} T_{\text{nuc}}^3$$

$$\Gamma_{\text{nucl}} \sim f/N$$

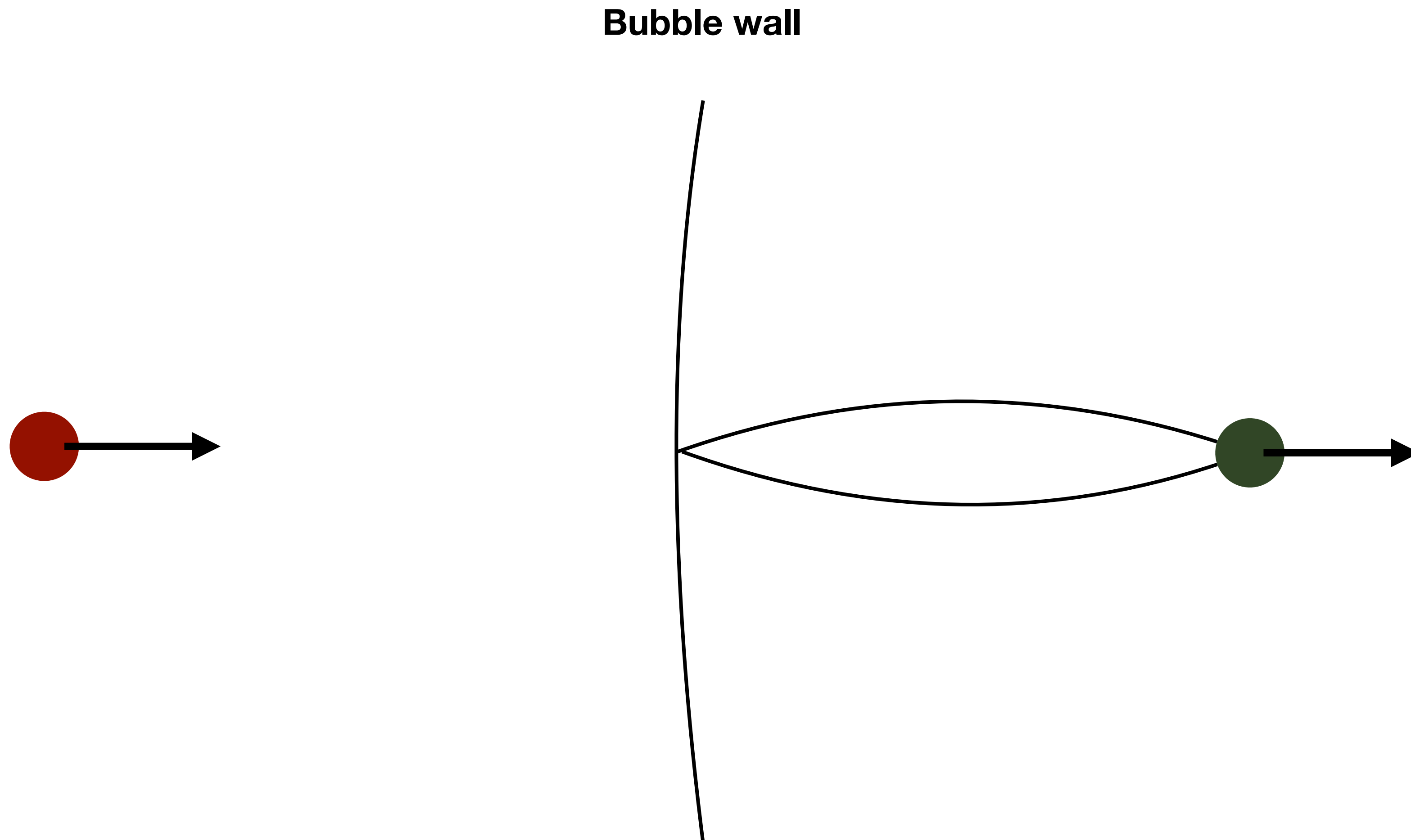
Bubble wall



Interaction with other quarks ?

$$\Gamma_{\text{q-string}} \sim \pi f^{-2} \times \gamma_{\text{wp}} T_{\text{nuc}}^3$$

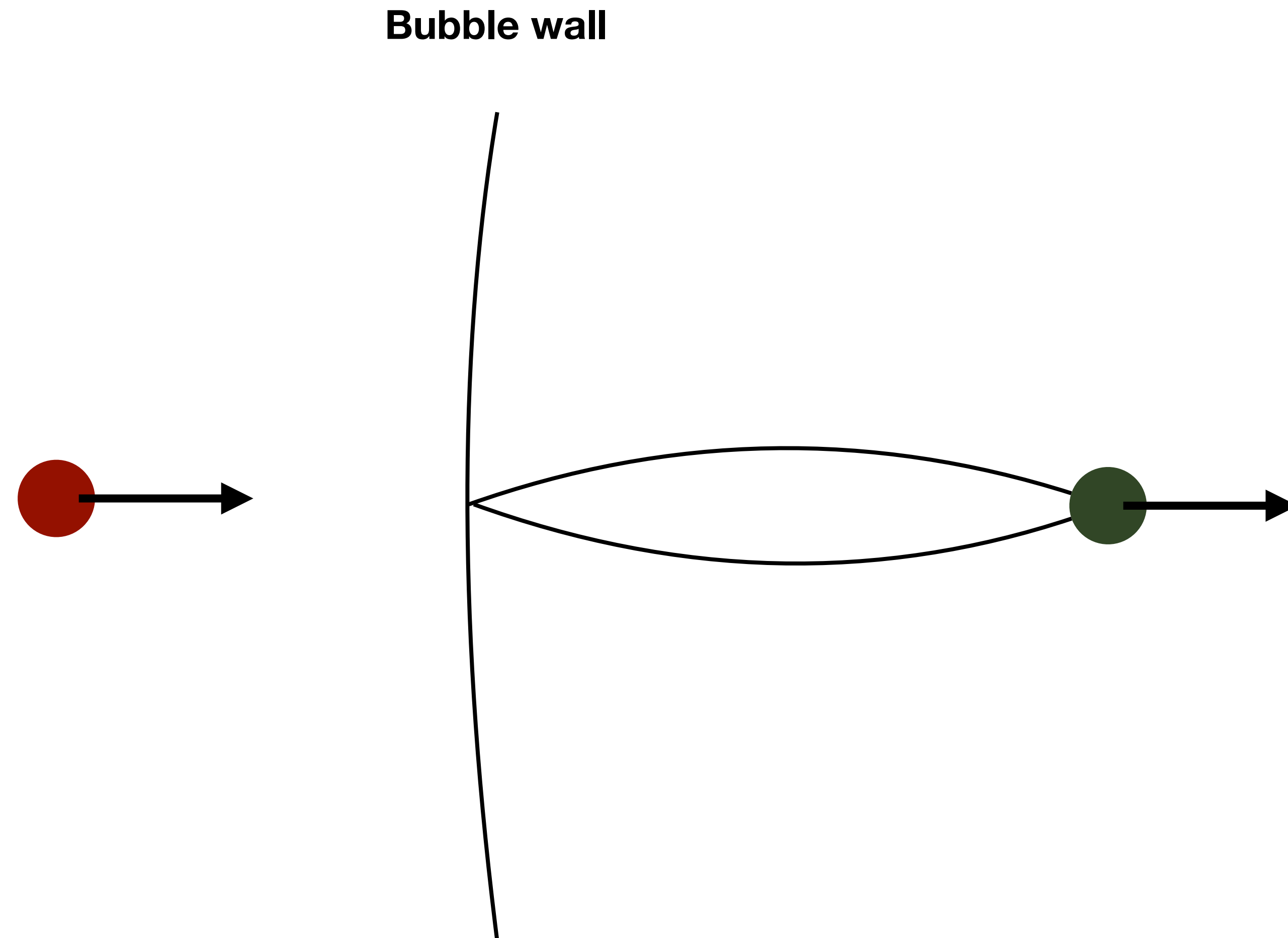
$$\Gamma_{\text{nucl}} \sim f/N$$



Interaction with other quarks ?

$$\Gamma_{\text{q-string}} \sim \pi f^{-2} \times \gamma_{\text{wp}} T_{\text{nuc}}^3$$

$$\Gamma_{\text{nucl}} \sim f/N$$

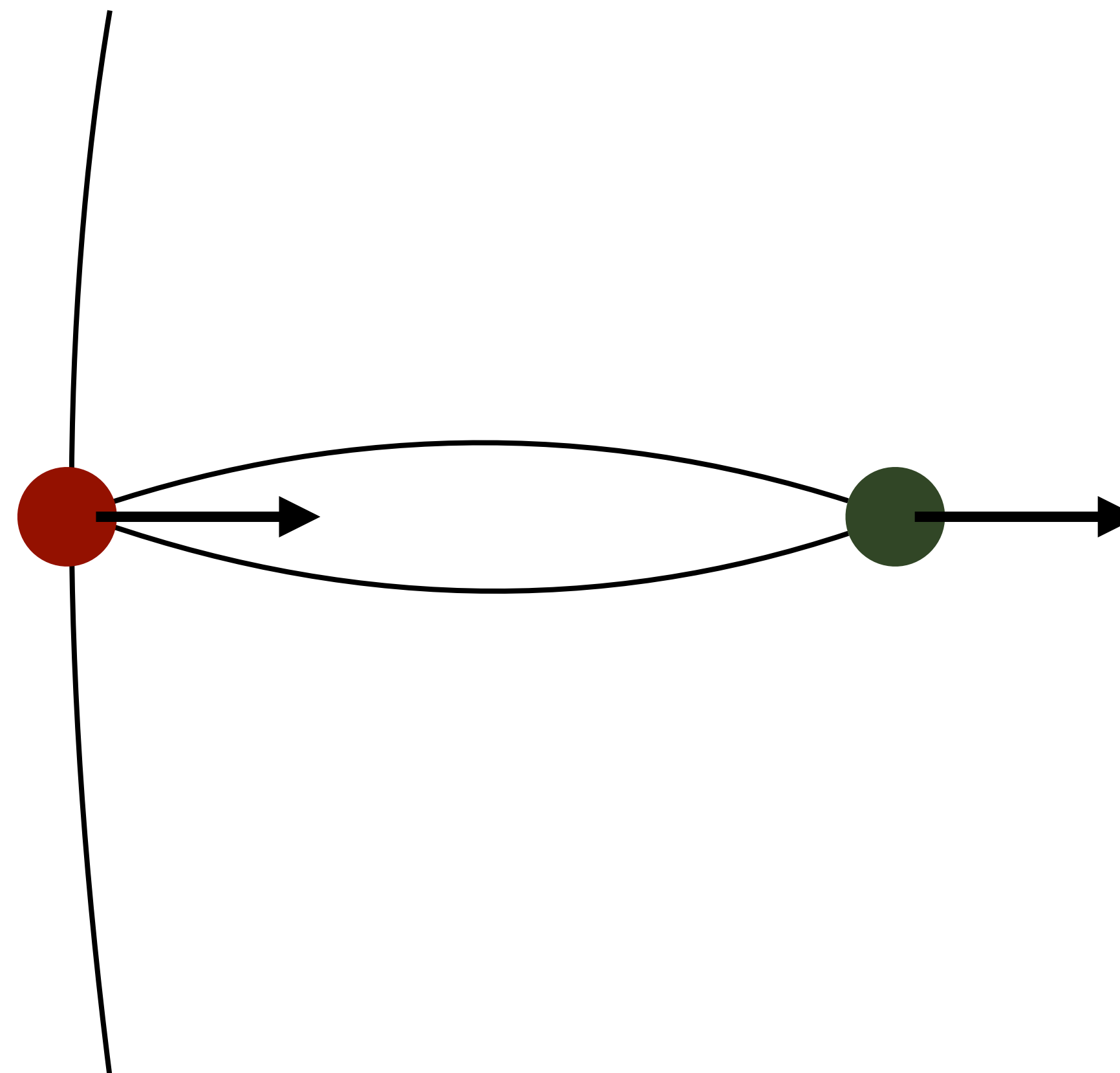


Interaction with other quarks ?

$$\Gamma_{\text{q-string}} \sim \pi f^{-2} \times \gamma_{\text{wp}} T_{\text{nuc}}^3$$

$$\Gamma_{\text{nucl}} \sim f/N$$

Bubble wall



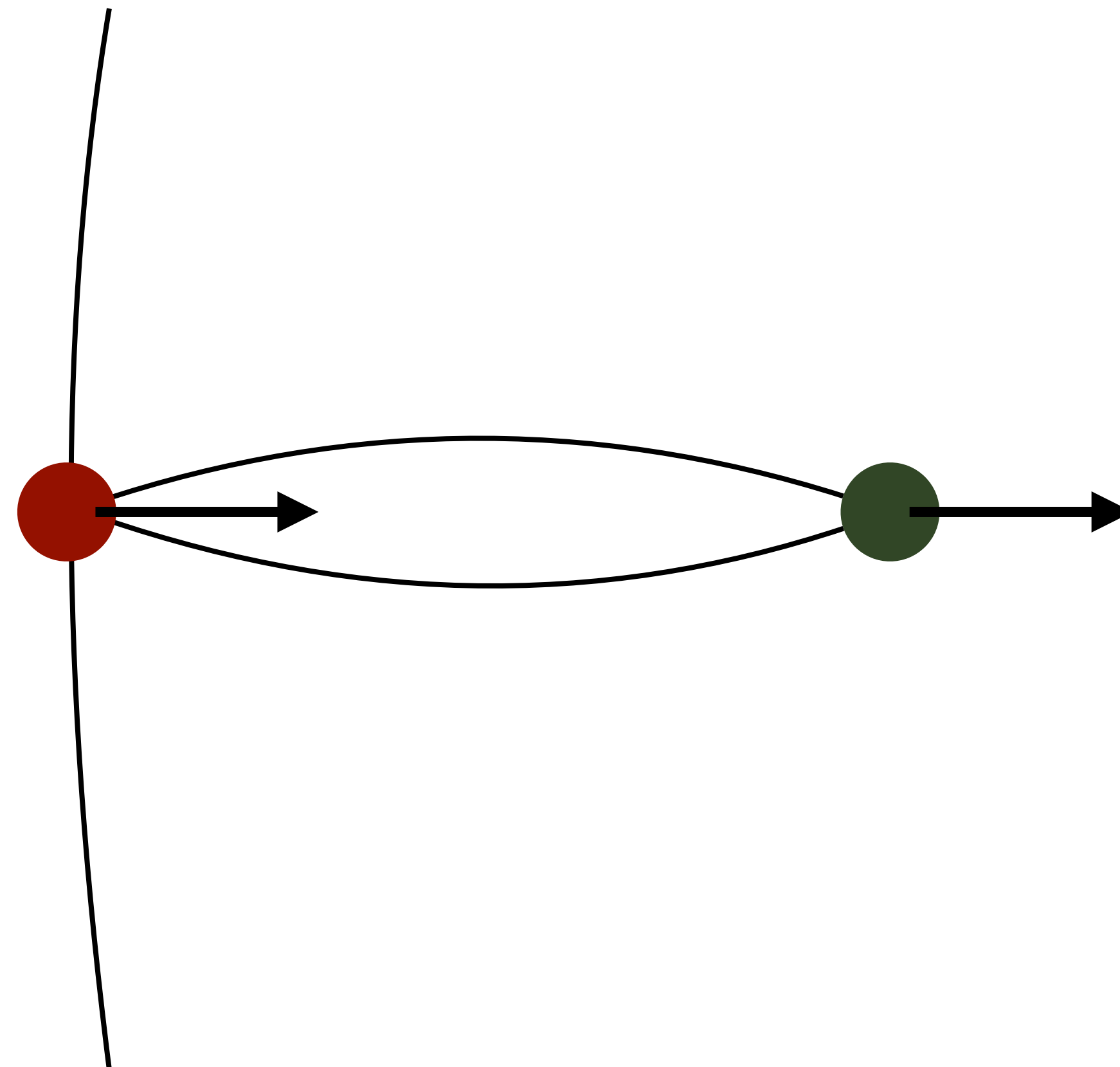
Interaction with other quarks ?

$$\Gamma_{\text{q-string}} \sim \pi f^{-2} \times \gamma_{\text{wp}} T_{\text{nuc}}^3$$

\gg

$$\Gamma_{\text{nucl}} \sim f/N$$

Bubble wall



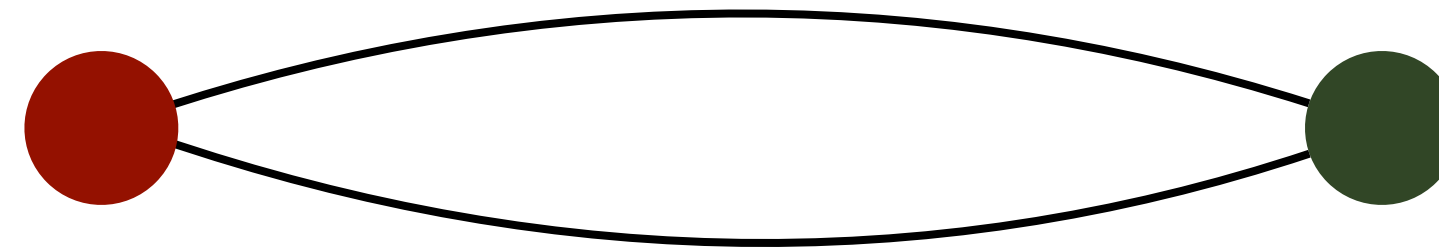
Interaction with other quarks ?

$$\Gamma_{\text{q-string}} \sim \pi f^{-2} \times \gamma_{\text{wp}} T_{\text{nuc}}^3$$

\sim

$$\Gamma_{\text{nucl}} \sim f/N$$

Bubble wall



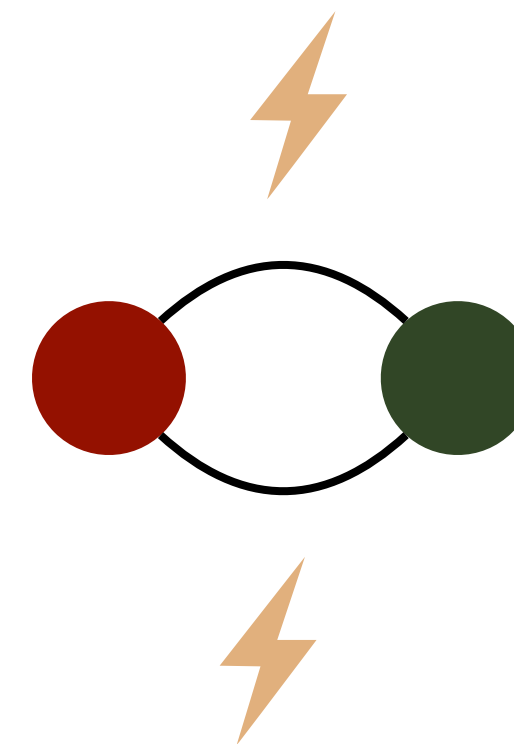
Interaction with other quarks ?

$$\Gamma_{\text{q-string}} \sim \pi f^{-2} \times \gamma_{\text{wp}} T_{\text{nuc}}^3$$

\gg

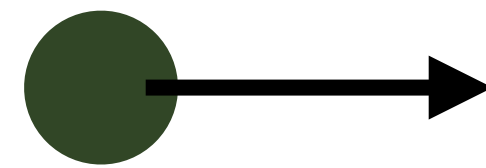
$$\Gamma_{\text{nucl}} \sim f/N$$

Bubble wall



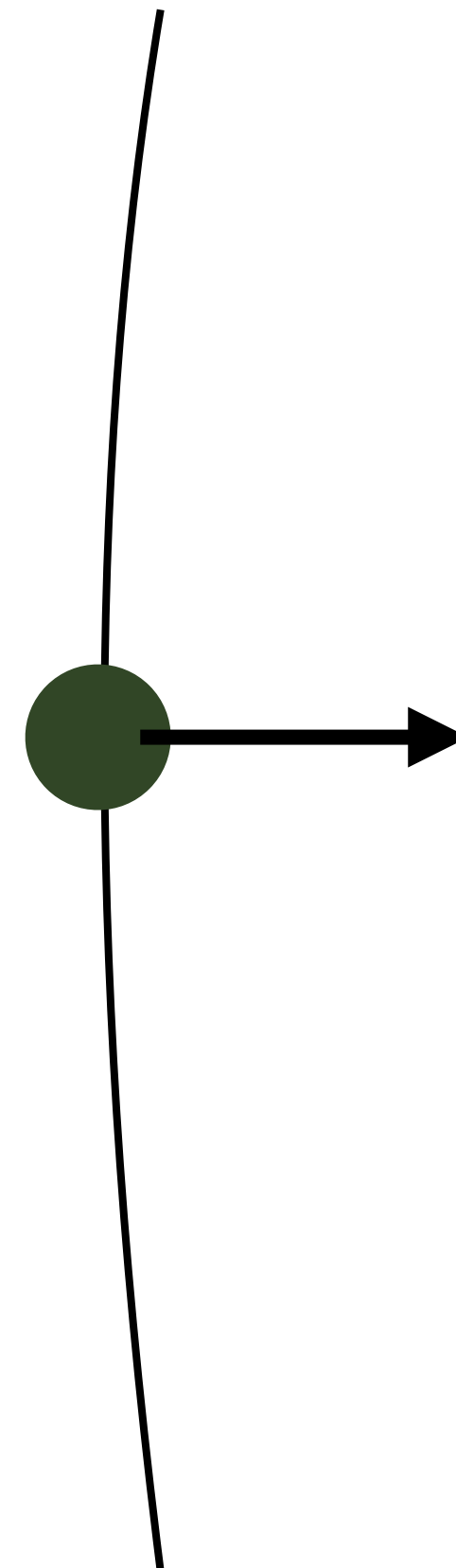
Interaction with other quarks ?

Bubble wall



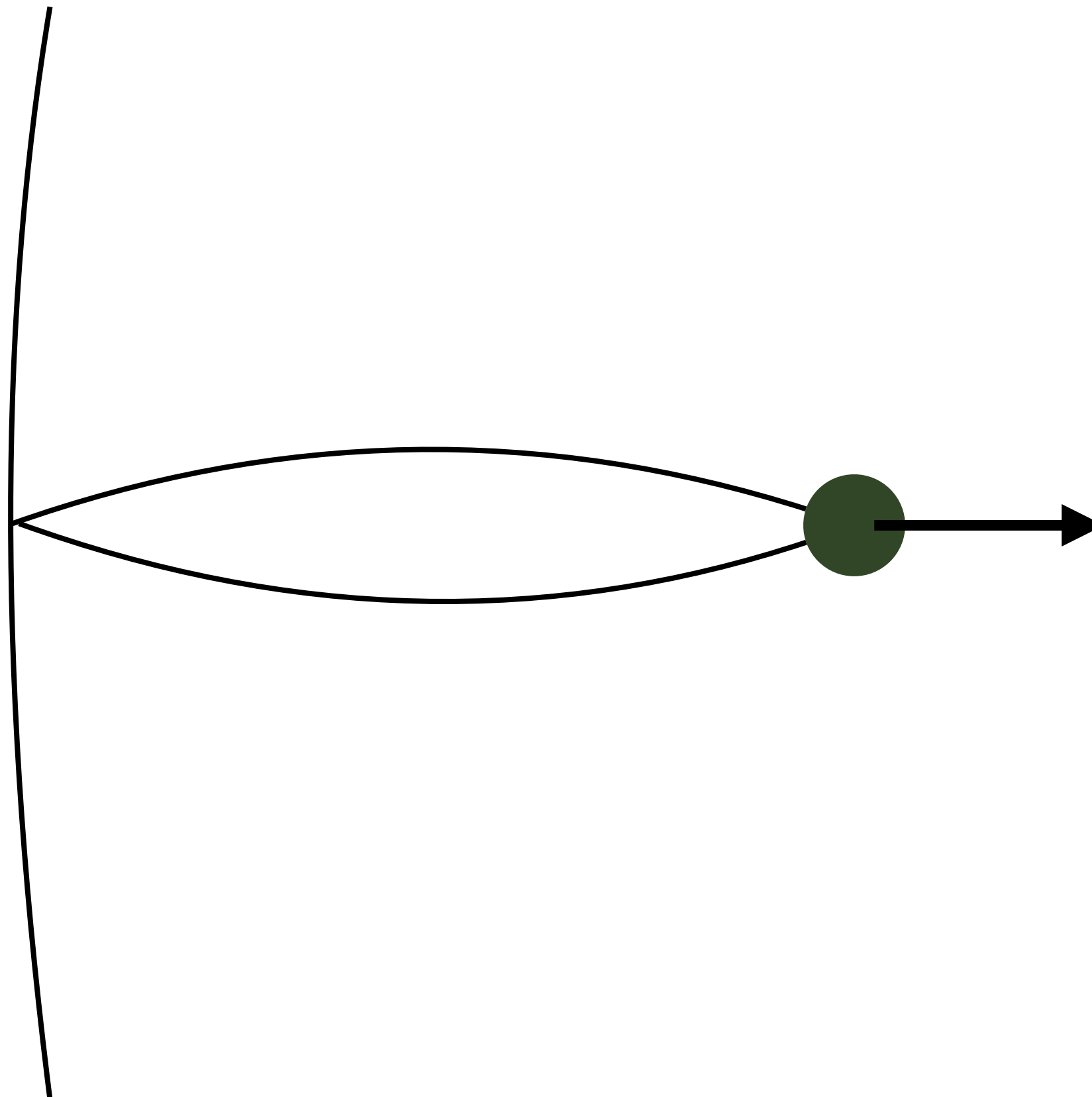
Interaction with other quarks ?

Bubble wall



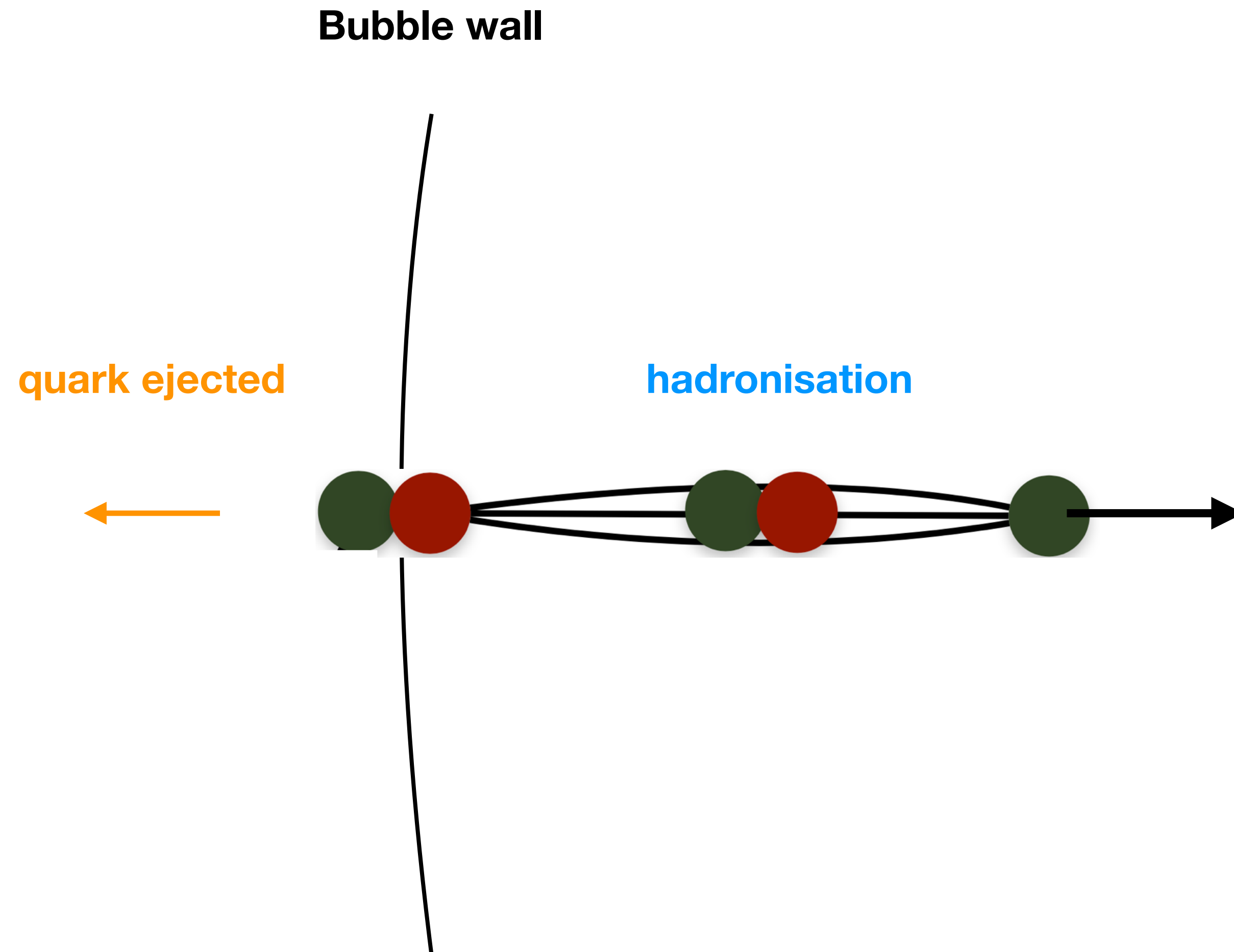
Interaction with other quarks ?

Bubble wall



Interaction with other quarks ?

$$\Gamma_{\text{nucl}} \sim f/N$$

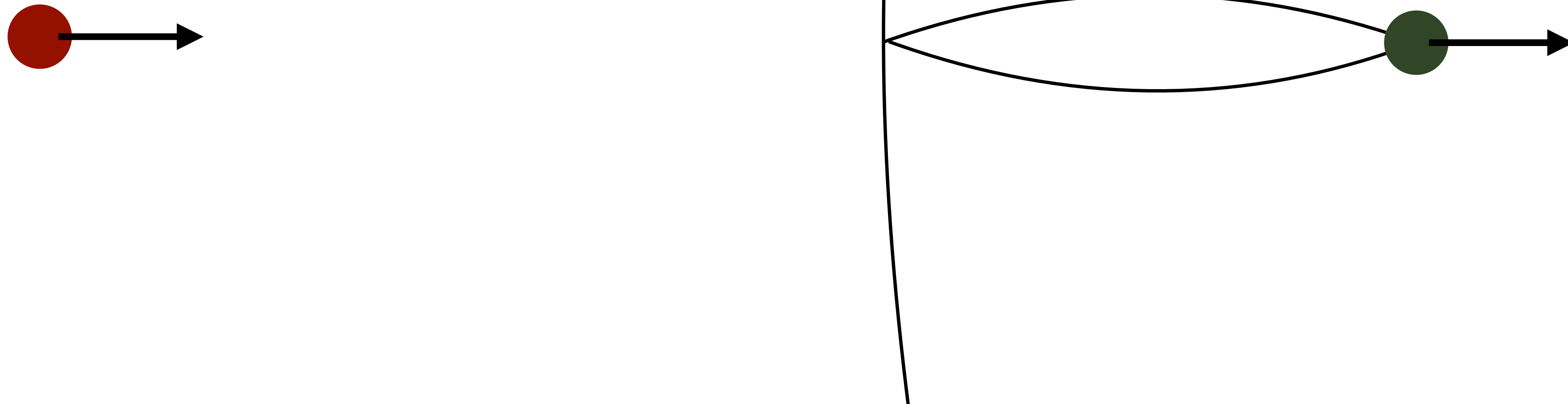


Interaction with other quarks ?

$$\Gamma_{\text{q-string}} \sim \pi f^{-2} \times \gamma_{\text{wp}} T_{\text{nuc}}^3$$

$$\Gamma_{\text{nucl}} \sim f/N$$

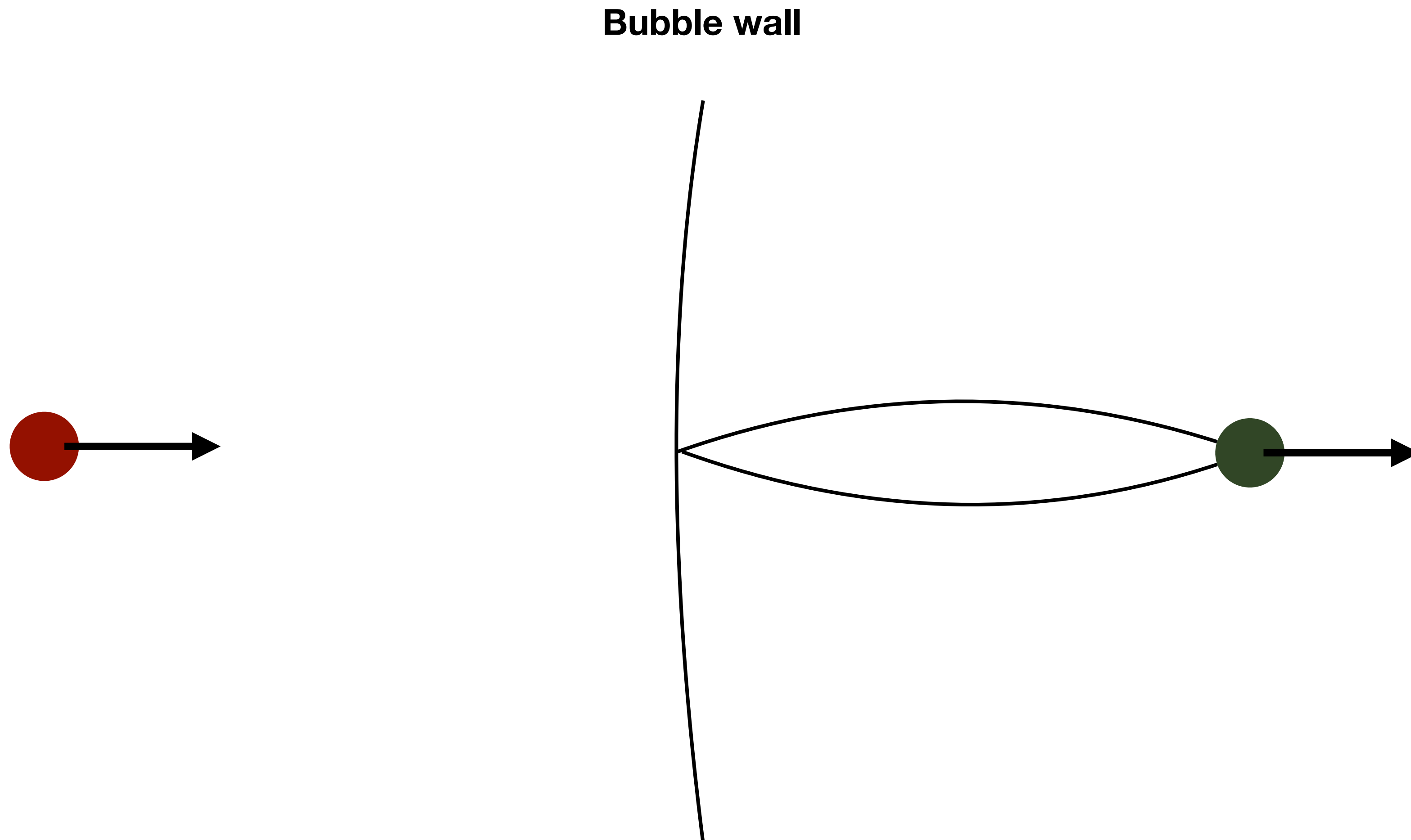
Bubble wall



Interaction with other quarks ?

$$\Gamma_{\text{q-string}} \sim \pi f^{-2} \times \gamma_{\text{wp}} T_{\text{nuc}}^3$$

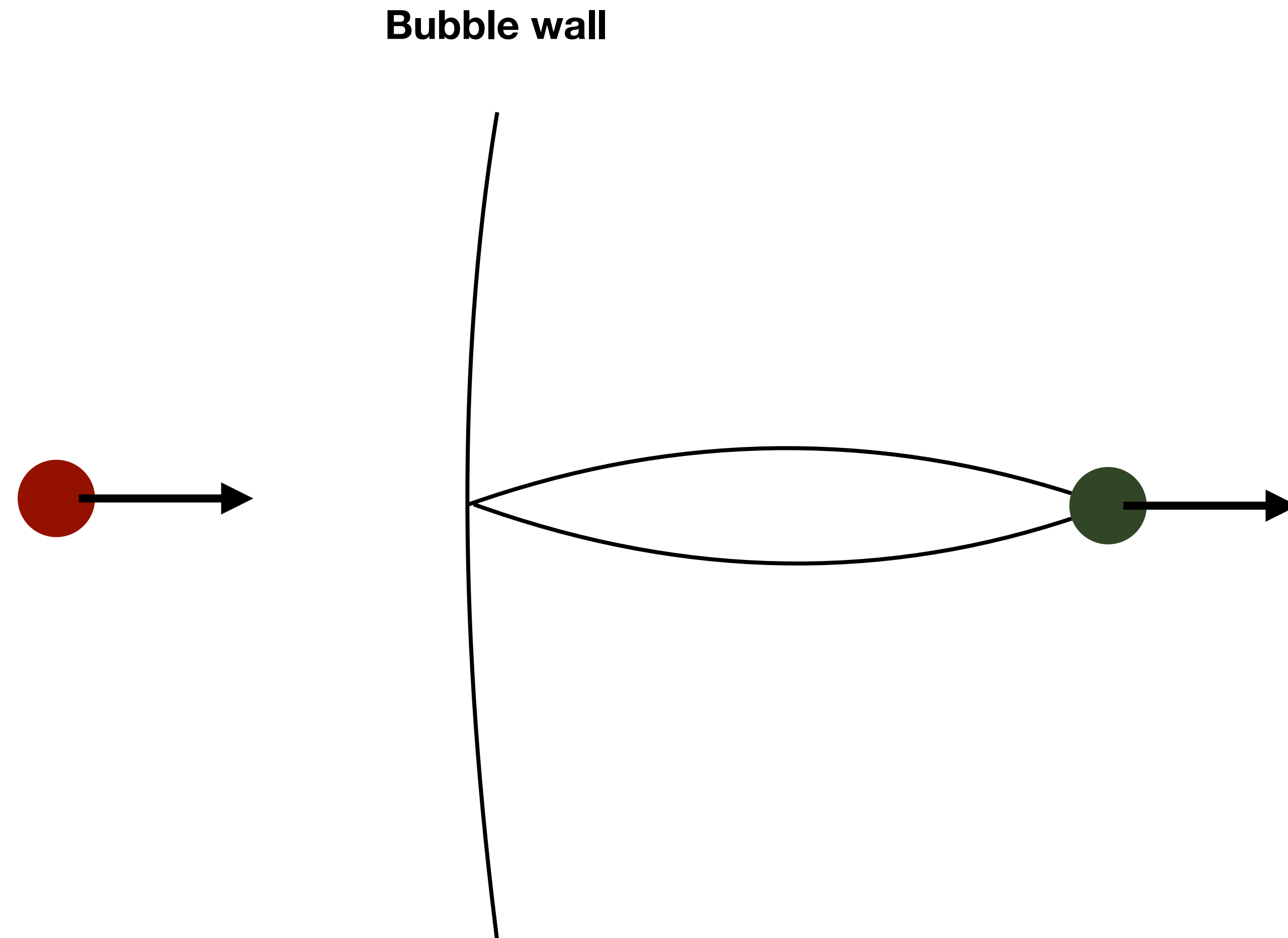
$$\Gamma_{\text{nucl}} \sim f/N$$



Interaction with other quarks ?

$$\Gamma_{\text{q-string}} \sim \pi f^{-2} \times \gamma_{\text{wp}} T_{\text{nuc}}^3$$

$$\Gamma_{\text{nucl}} \sim f/N$$

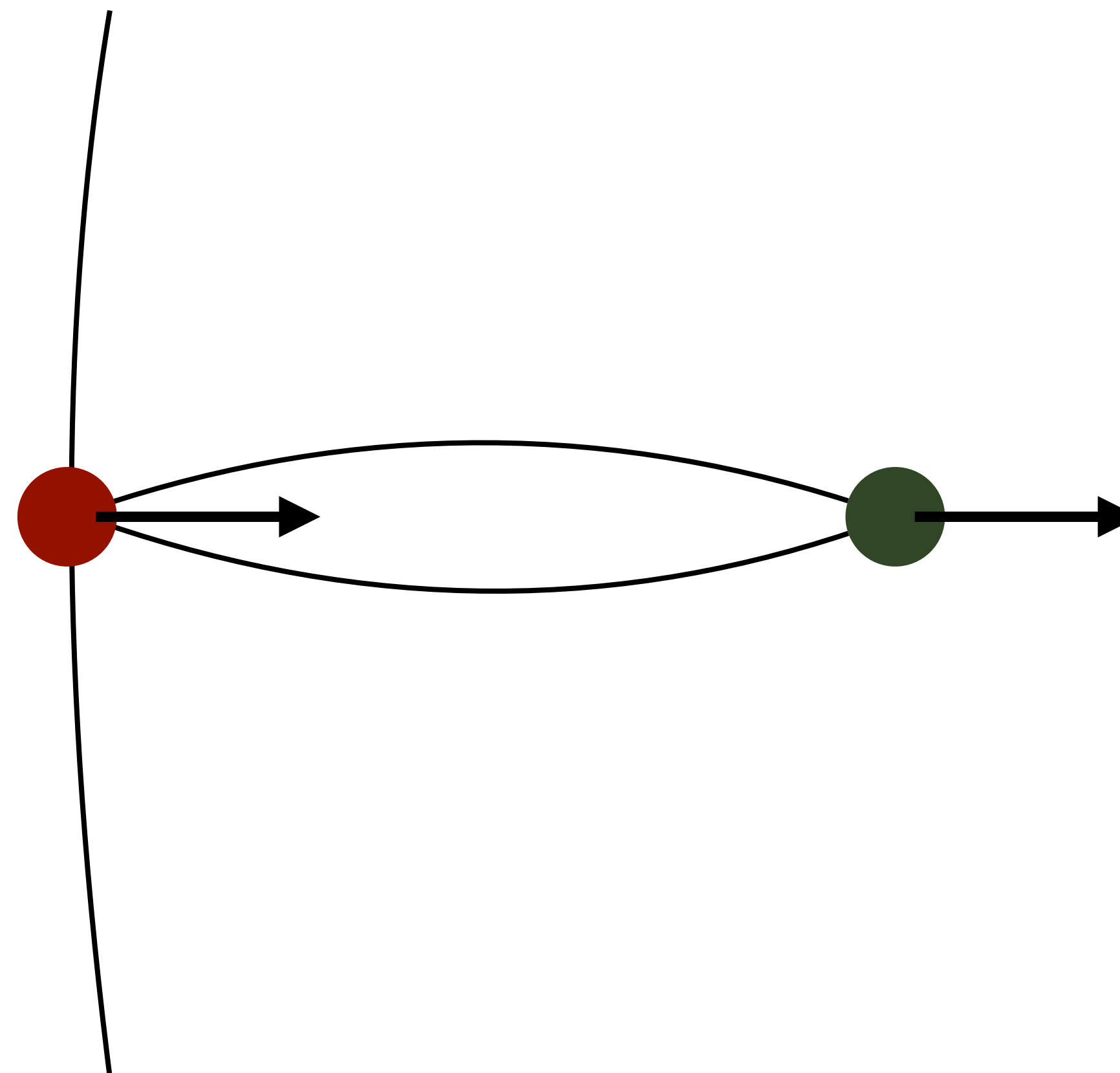


Interaction with other quarks ?

$$\Gamma_{\text{q-string}} \sim \pi f^{-2} \times \gamma_{\text{wp}} T_{\text{nuc}}^3$$

$$\Gamma_{\text{nucl}} \sim f/N$$

Bubble wall



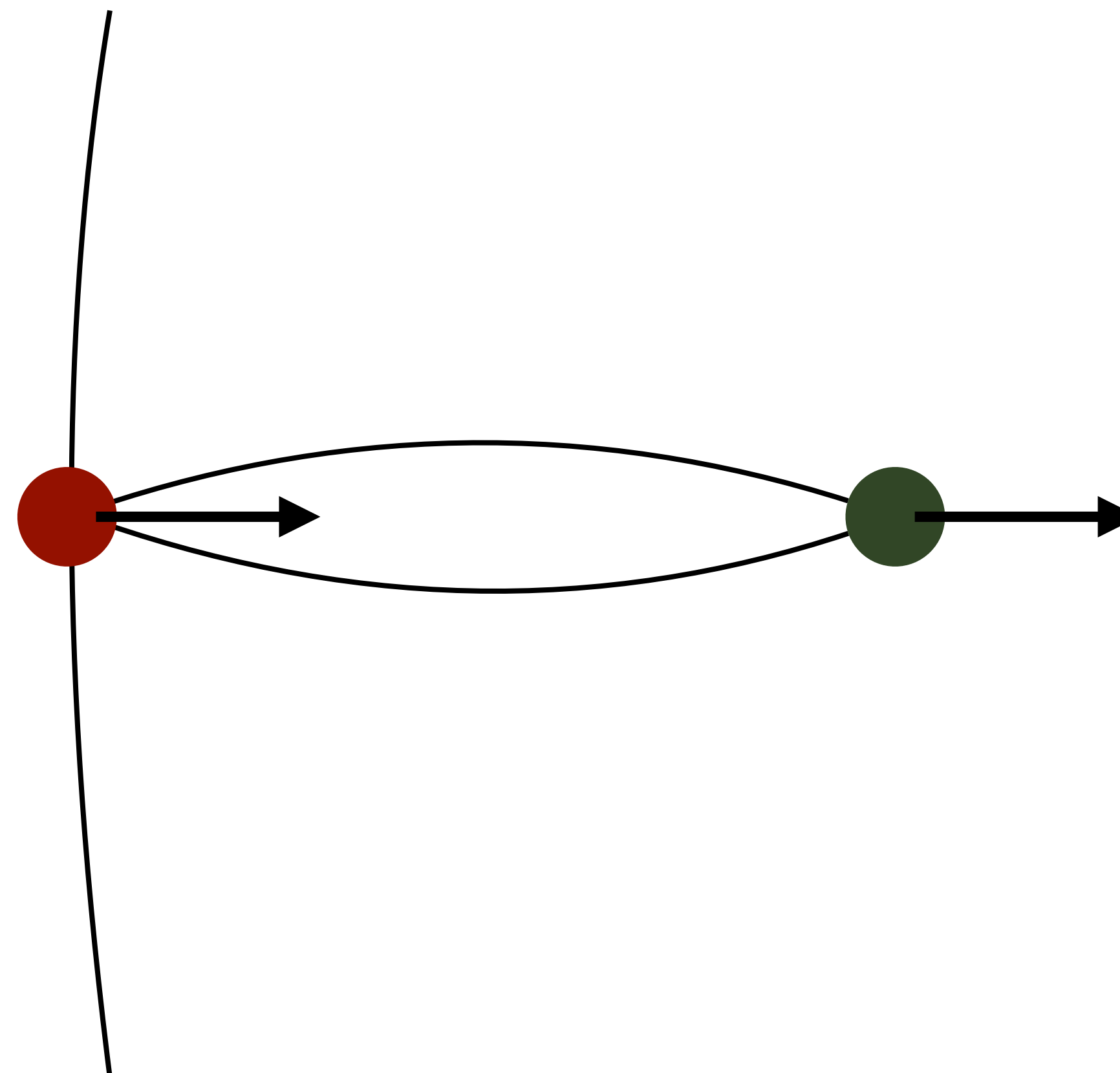
Interaction with other quarks ?

$$\Gamma_{\text{q-string}} \sim \pi f^{-2} \times \gamma_{\text{wp}} T_{\text{nuc}}^3$$

\gg

$$\Gamma_{\text{nucl}} \sim f/N$$

Bubble wall



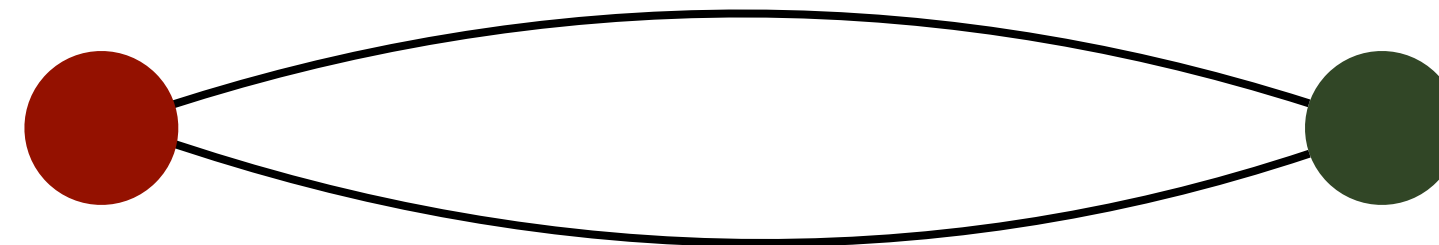
Interaction with other quarks ?

$$\Gamma_{\text{q-string}} \sim \pi f^{-2} \times \gamma_{\text{wp}} T_{\text{nuc}}^3$$

\sim

$$\Gamma_{\text{nucl}} \sim f/N$$

Bubble wall



Interaction with other quarks ?

$$\Gamma_{\text{q-string}} \sim \pi f^{-2} \times \gamma_{\text{wp}} T_{\text{nuc}}^3$$

\gg

$$\Gamma_{\text{nucl}} \sim f/N$$

Bubble wall

