Primordial black hole formation during supercooled phase transitions

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Supercooled 1stOPT

Supercooled 1stOPT = Hierarchical PT

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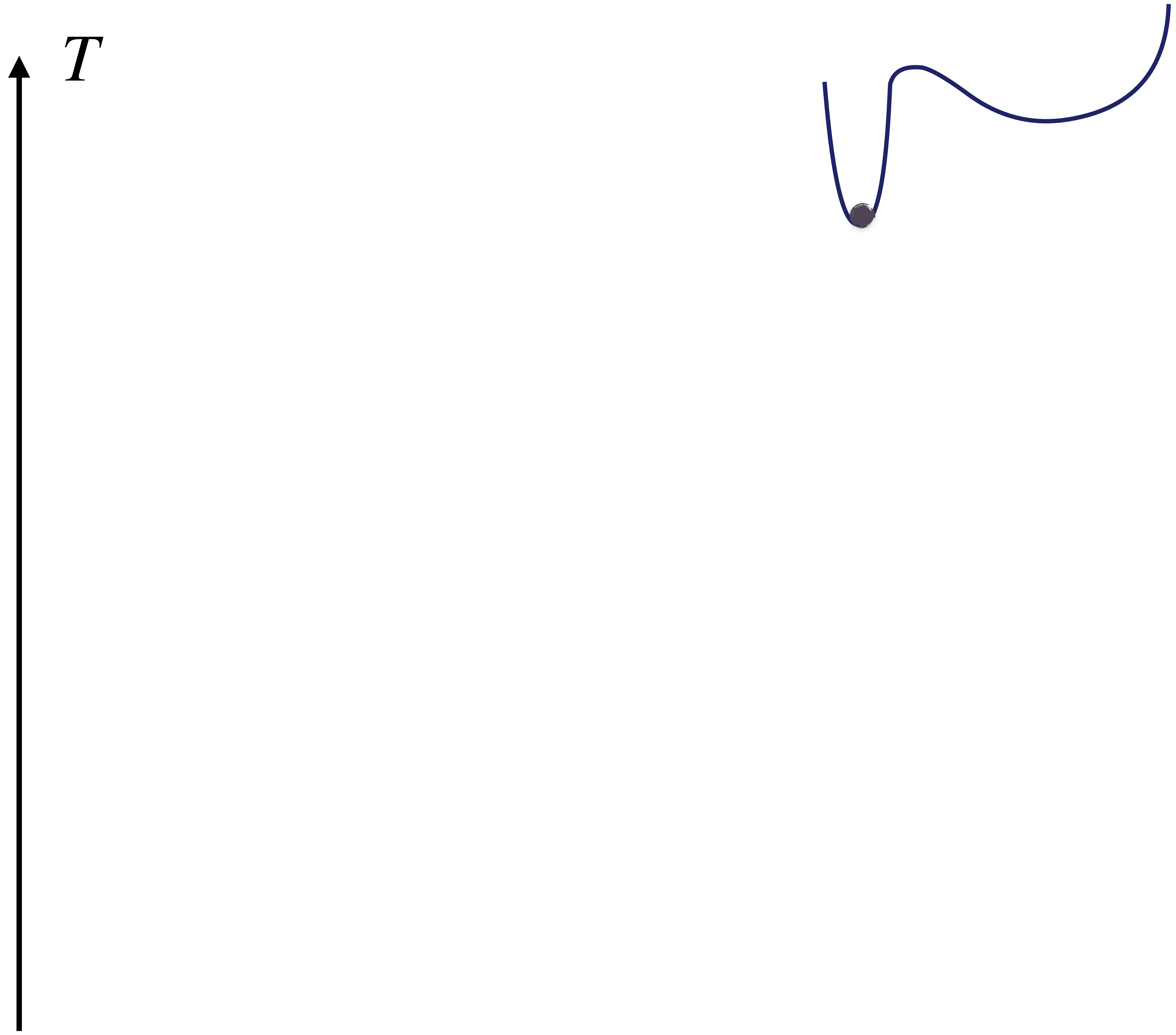

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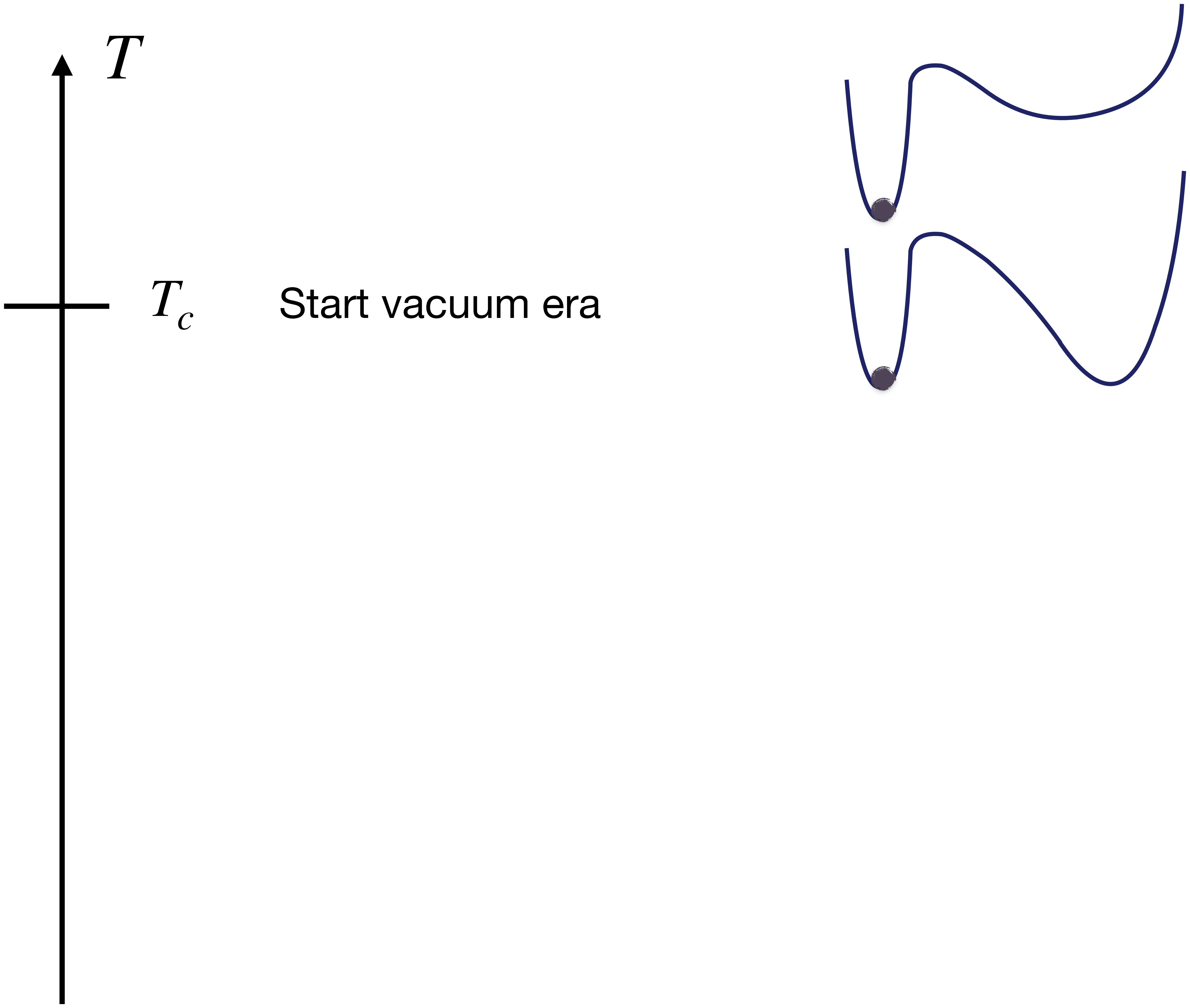

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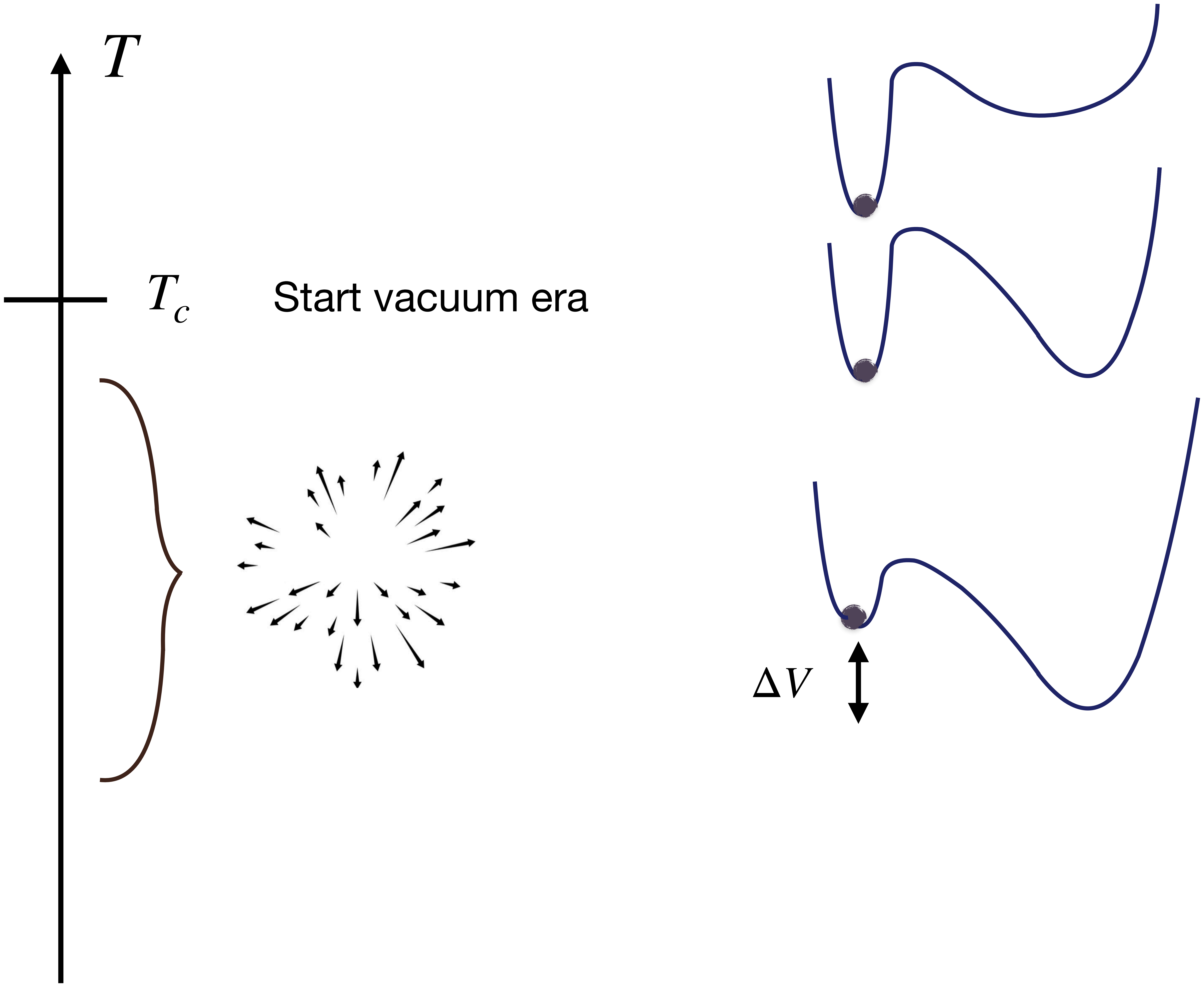

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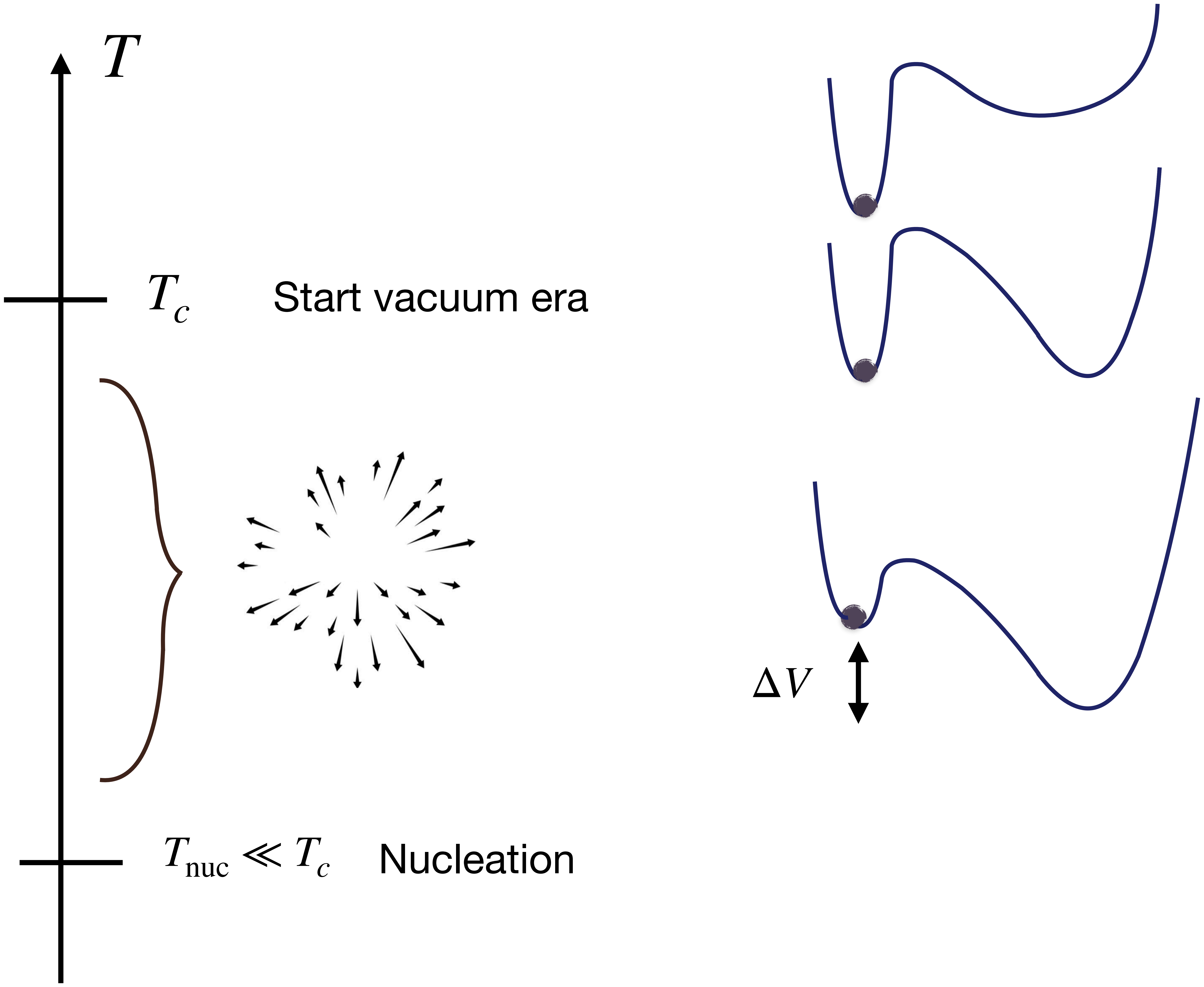

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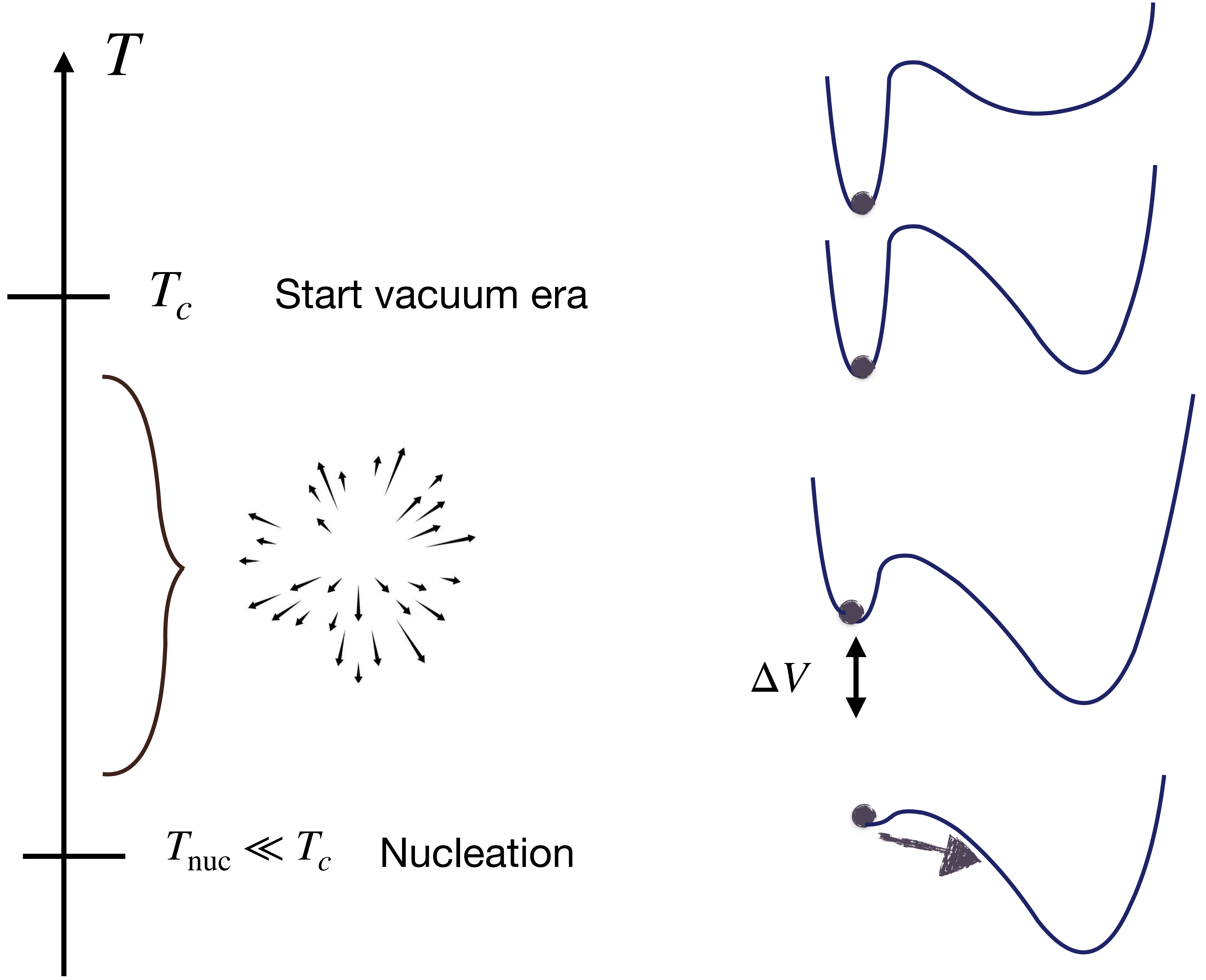

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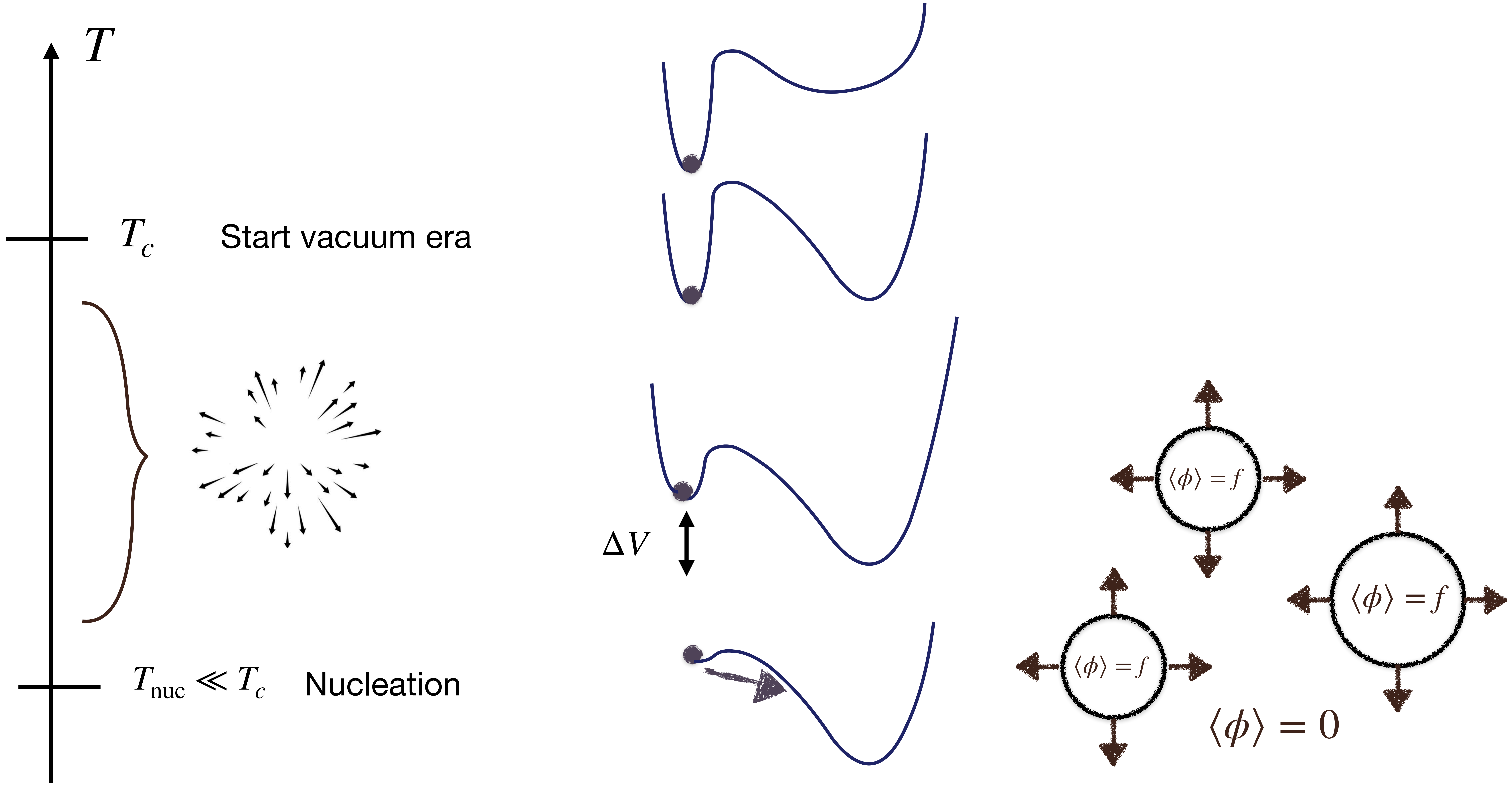

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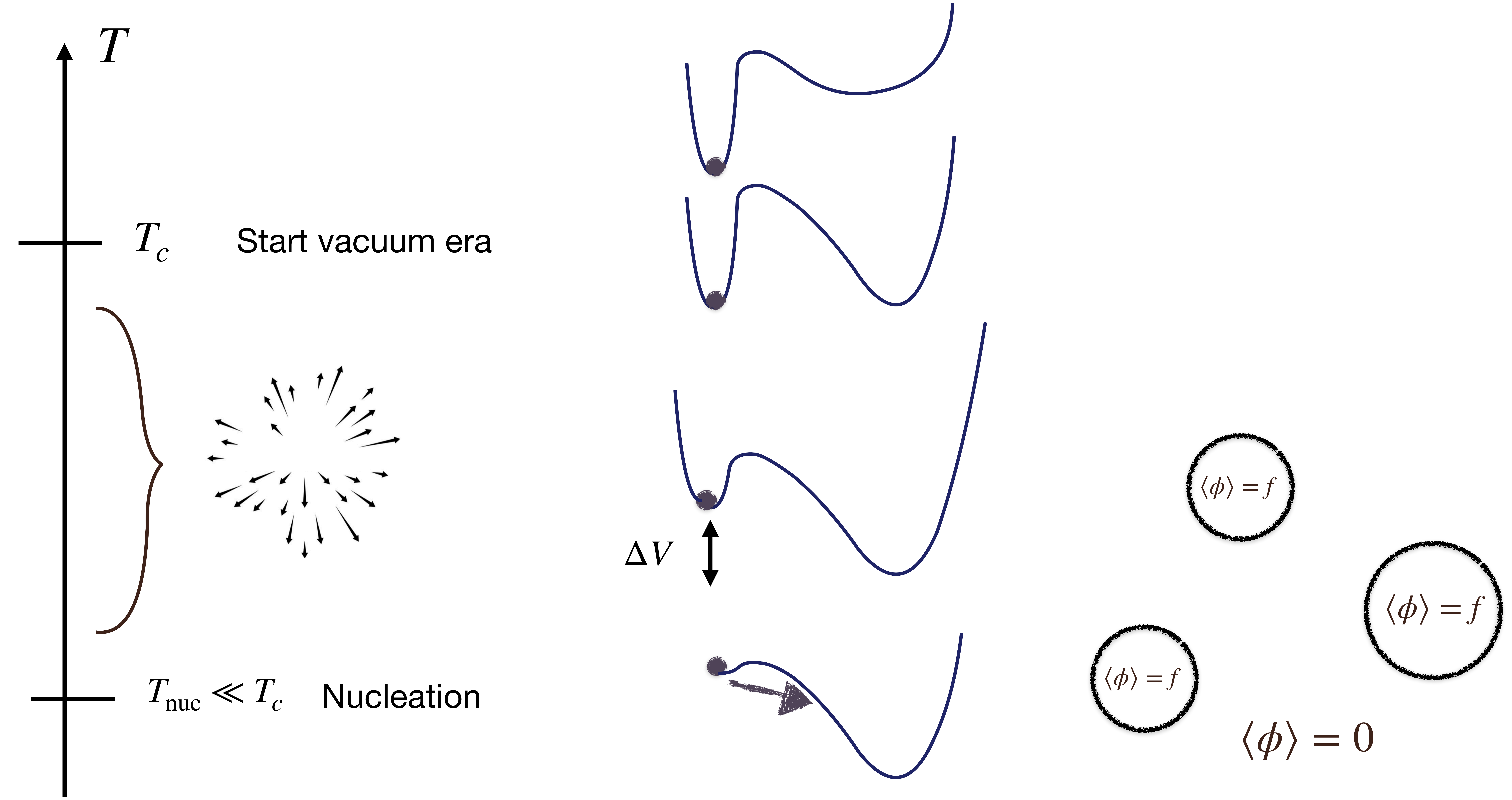

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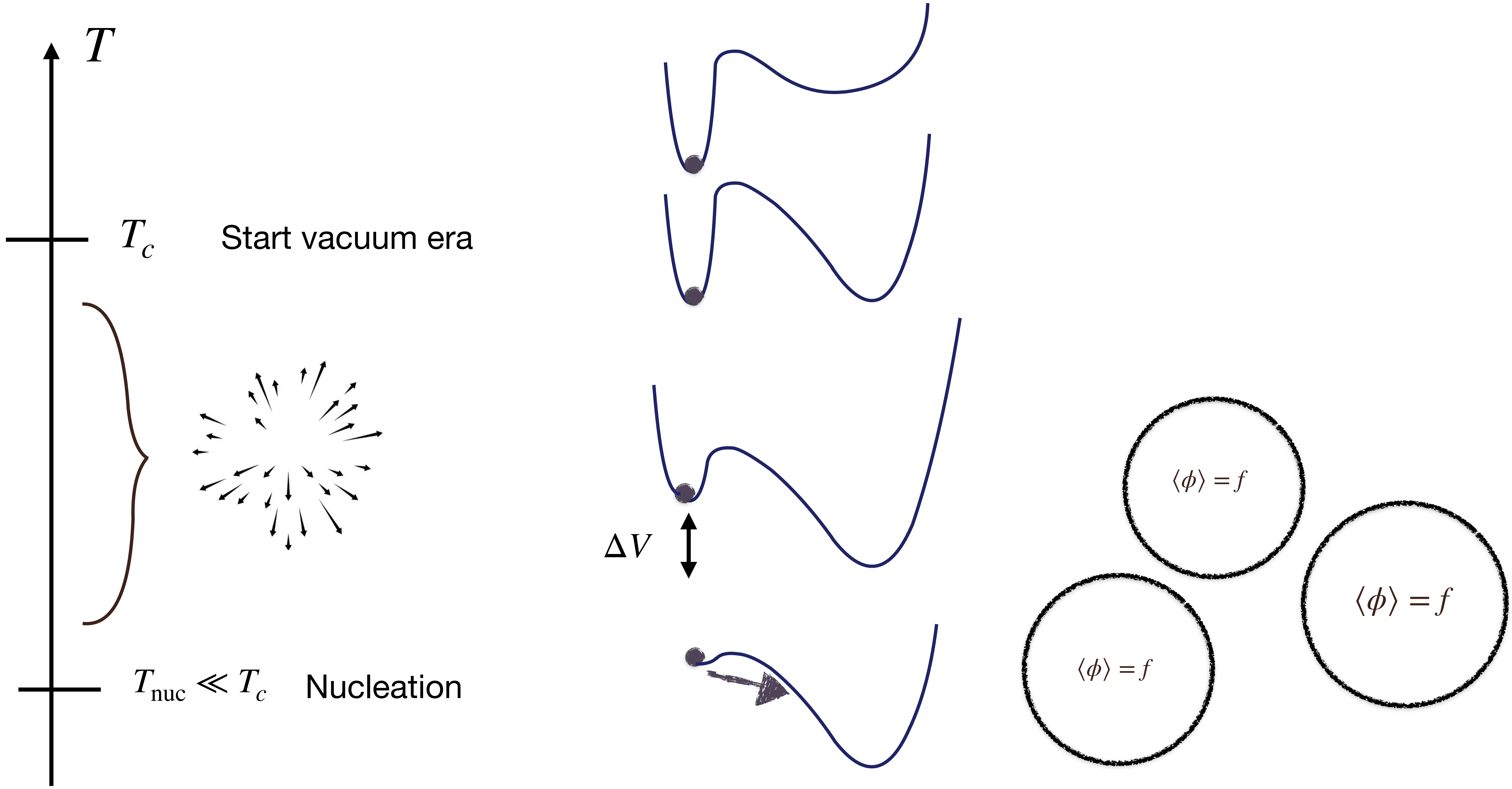

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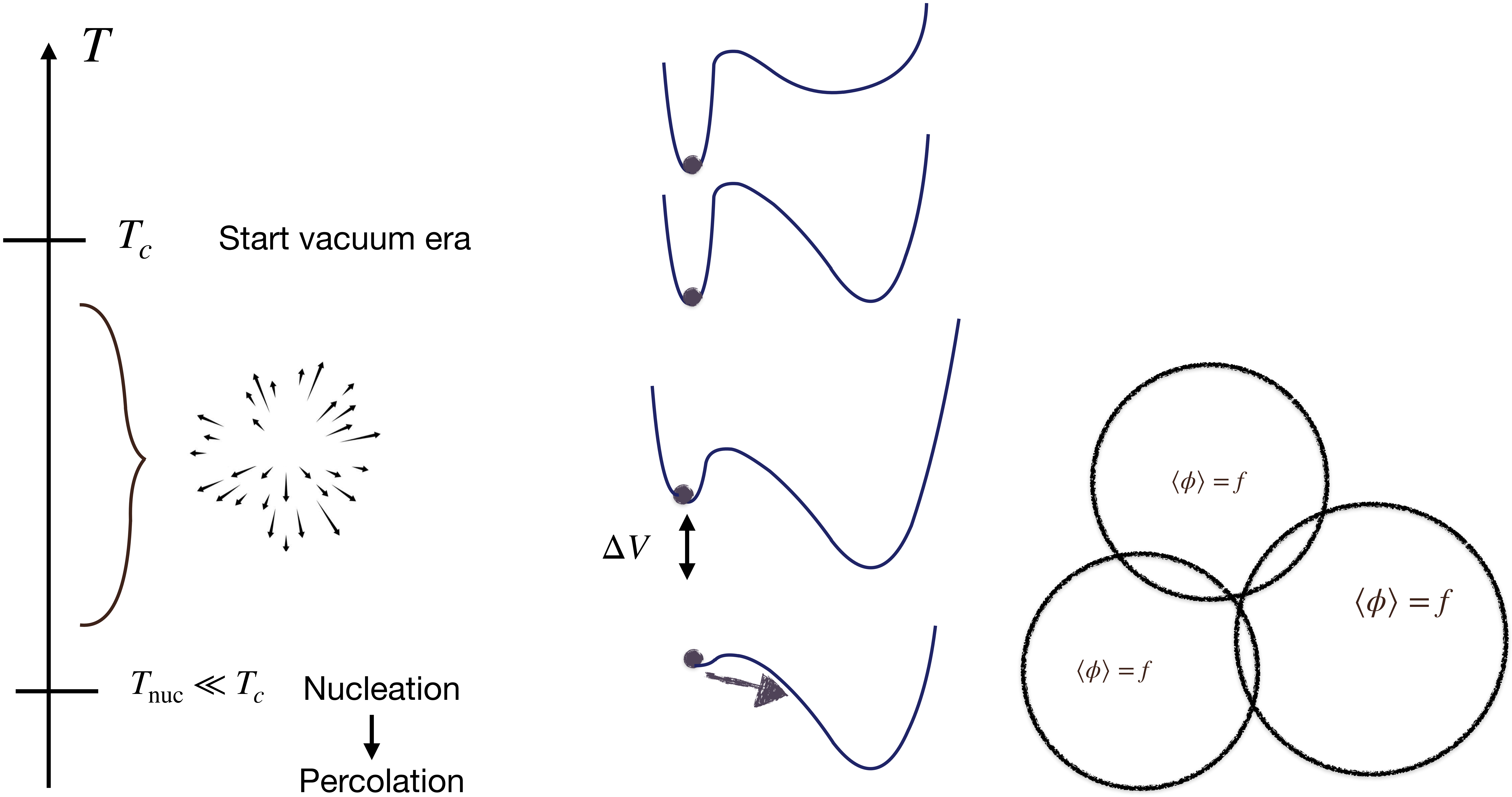
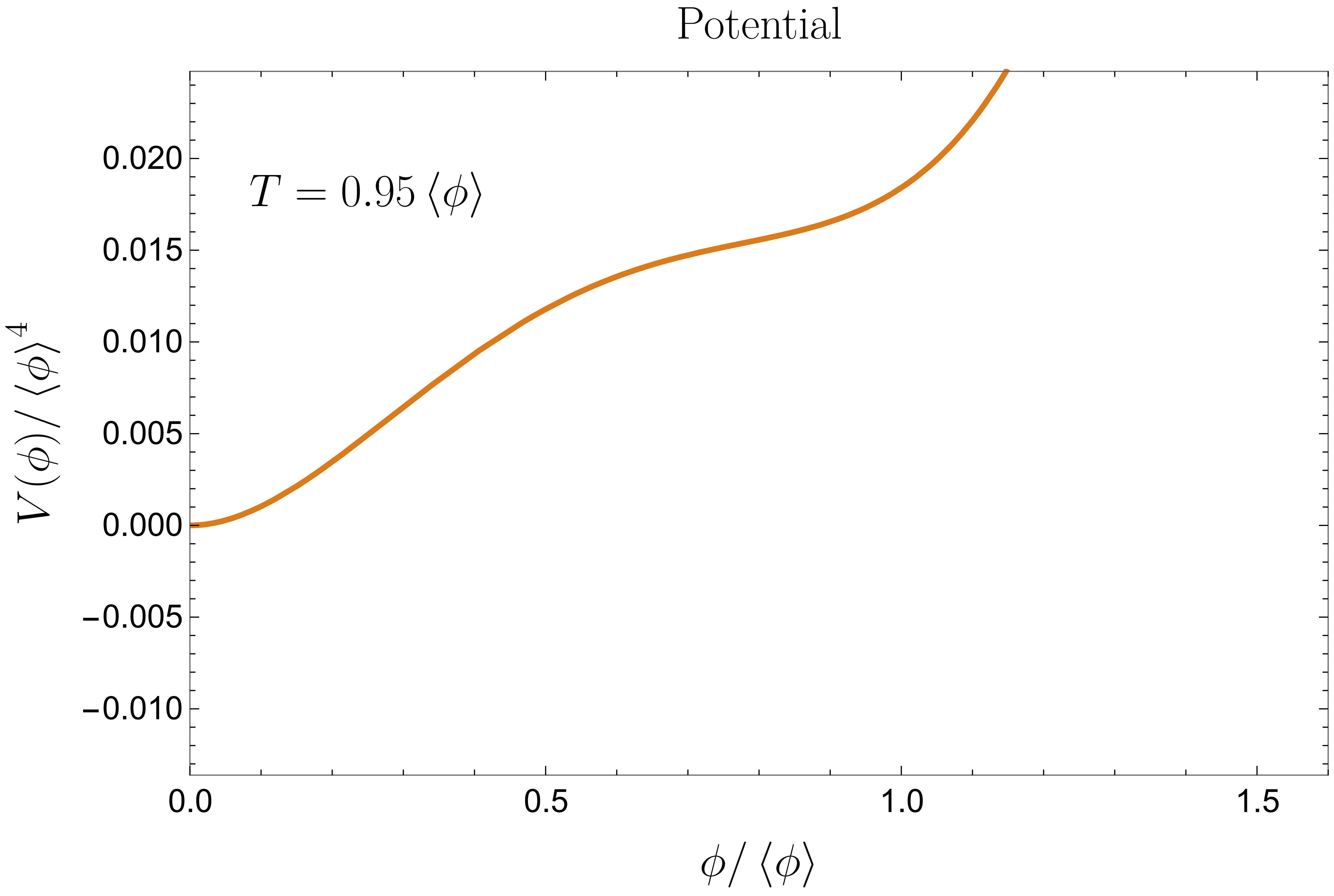
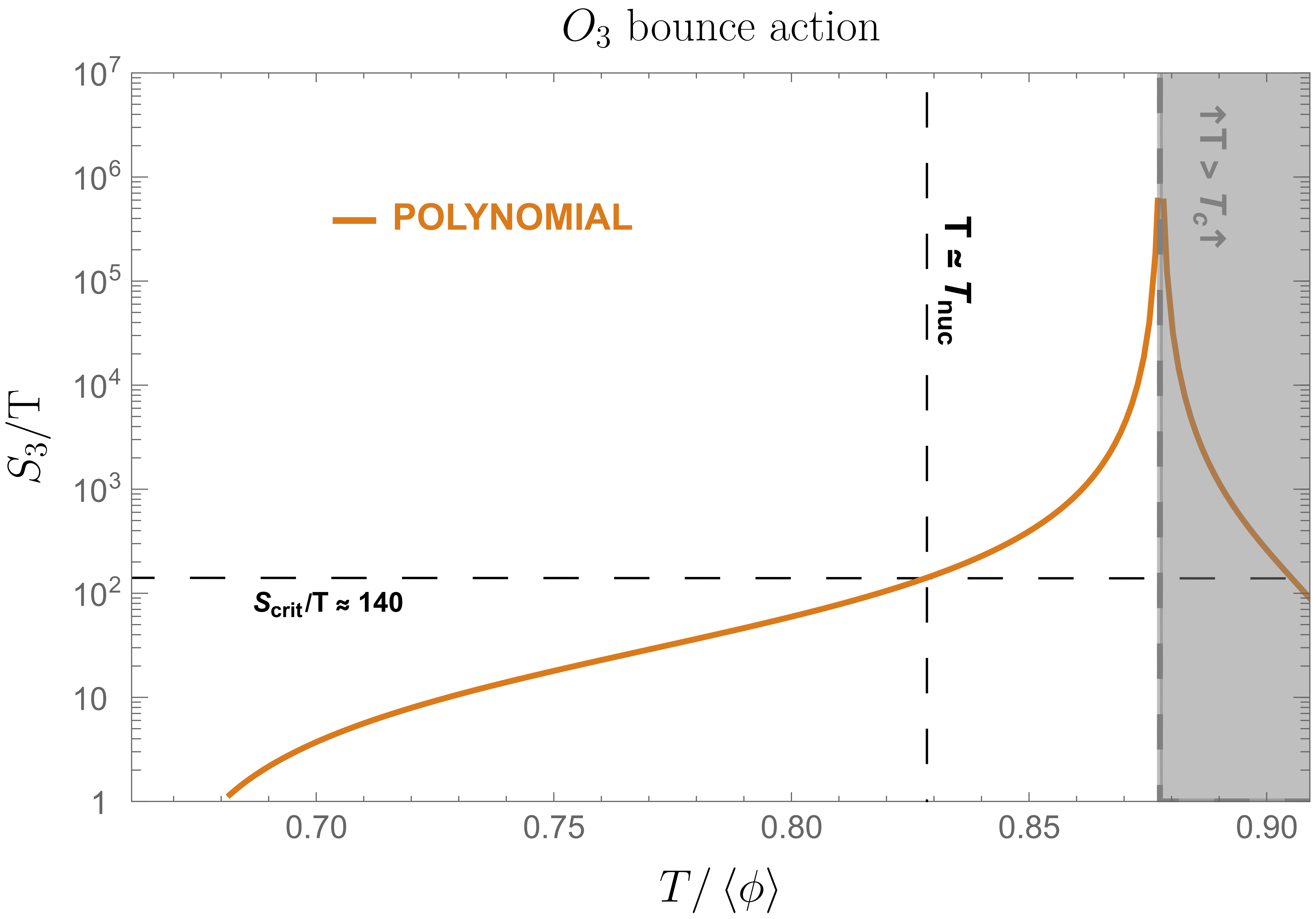


What kind of particle physics model lead to supercooling ?

POLYNOMIAL POTENTIAL

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





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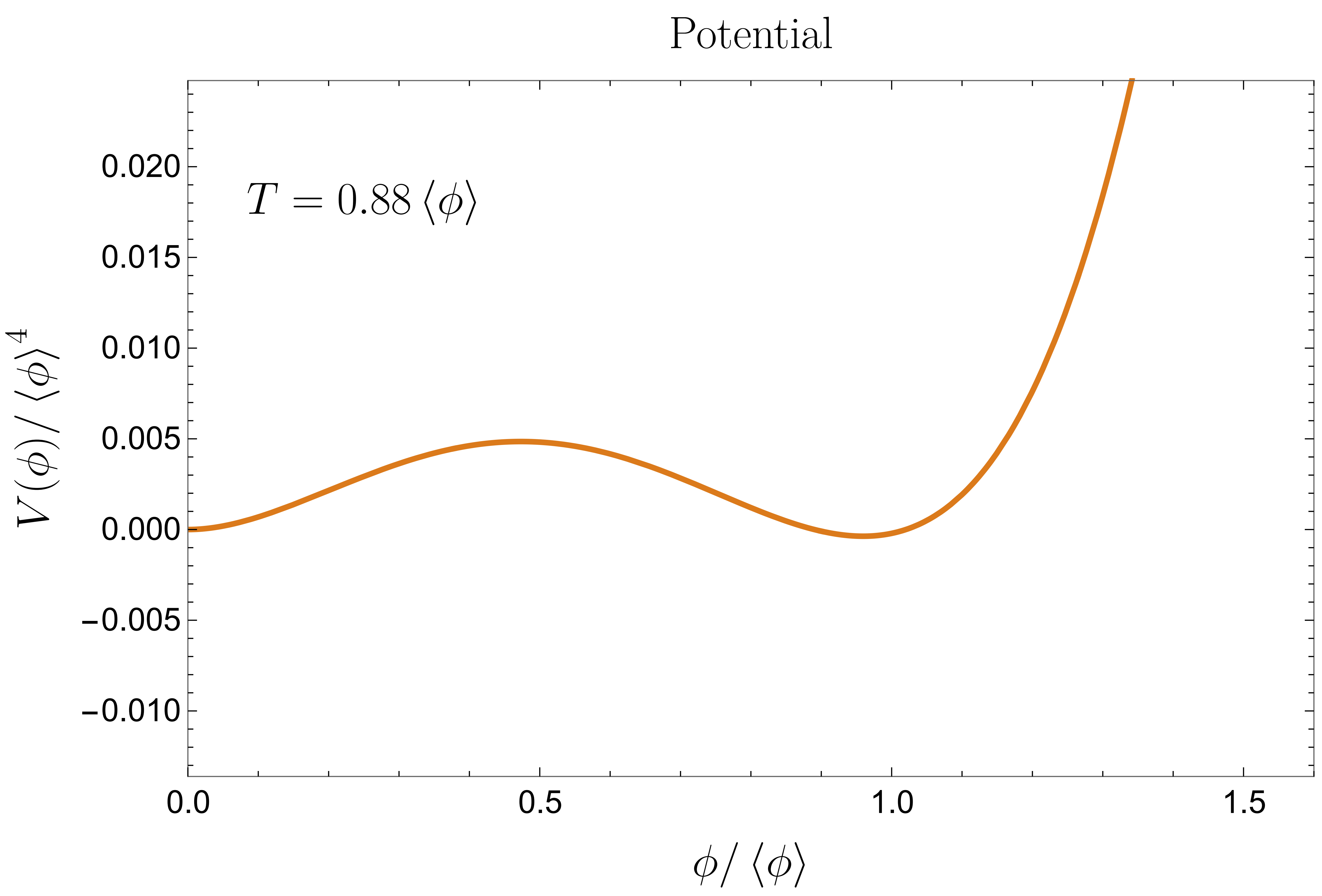

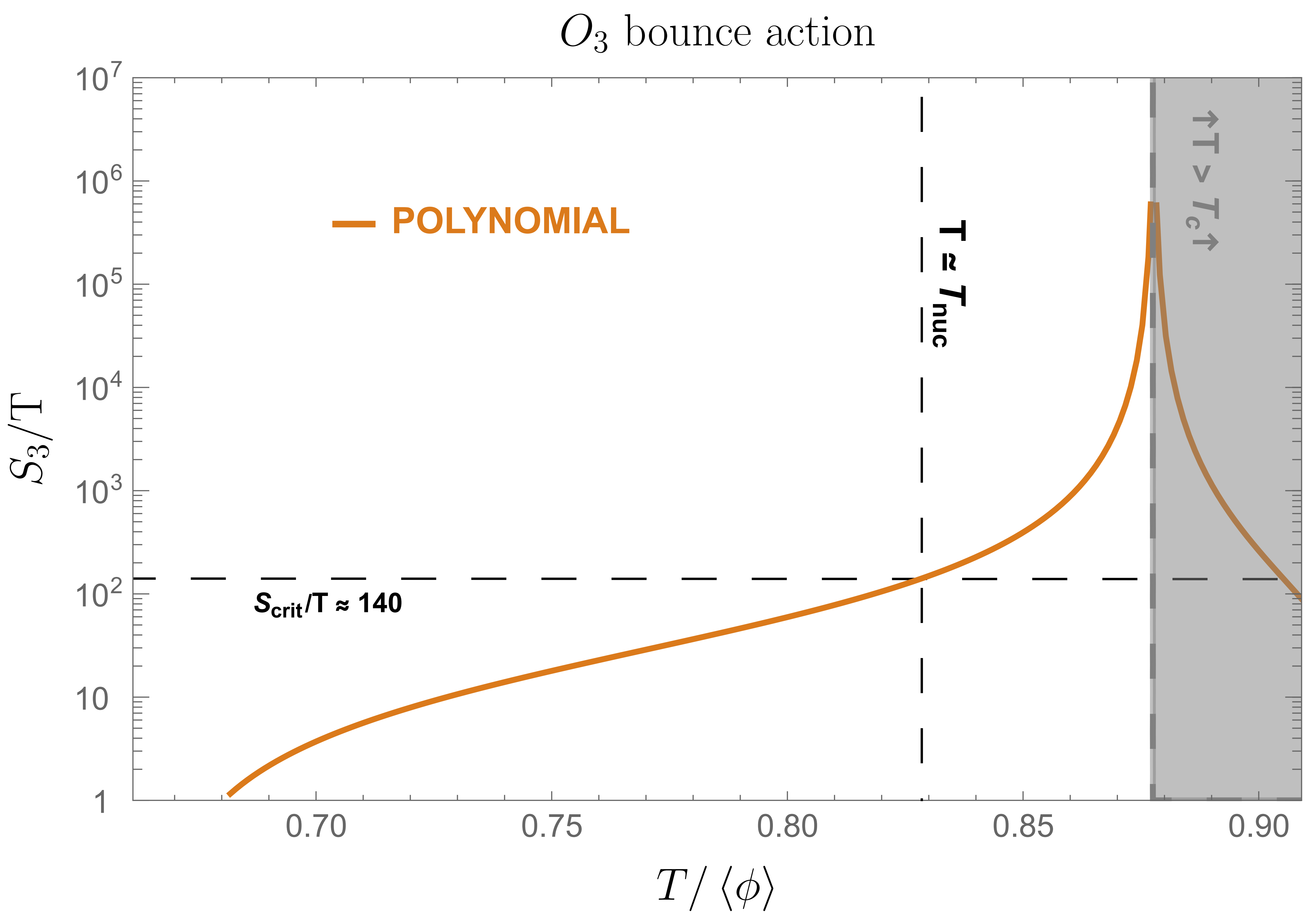

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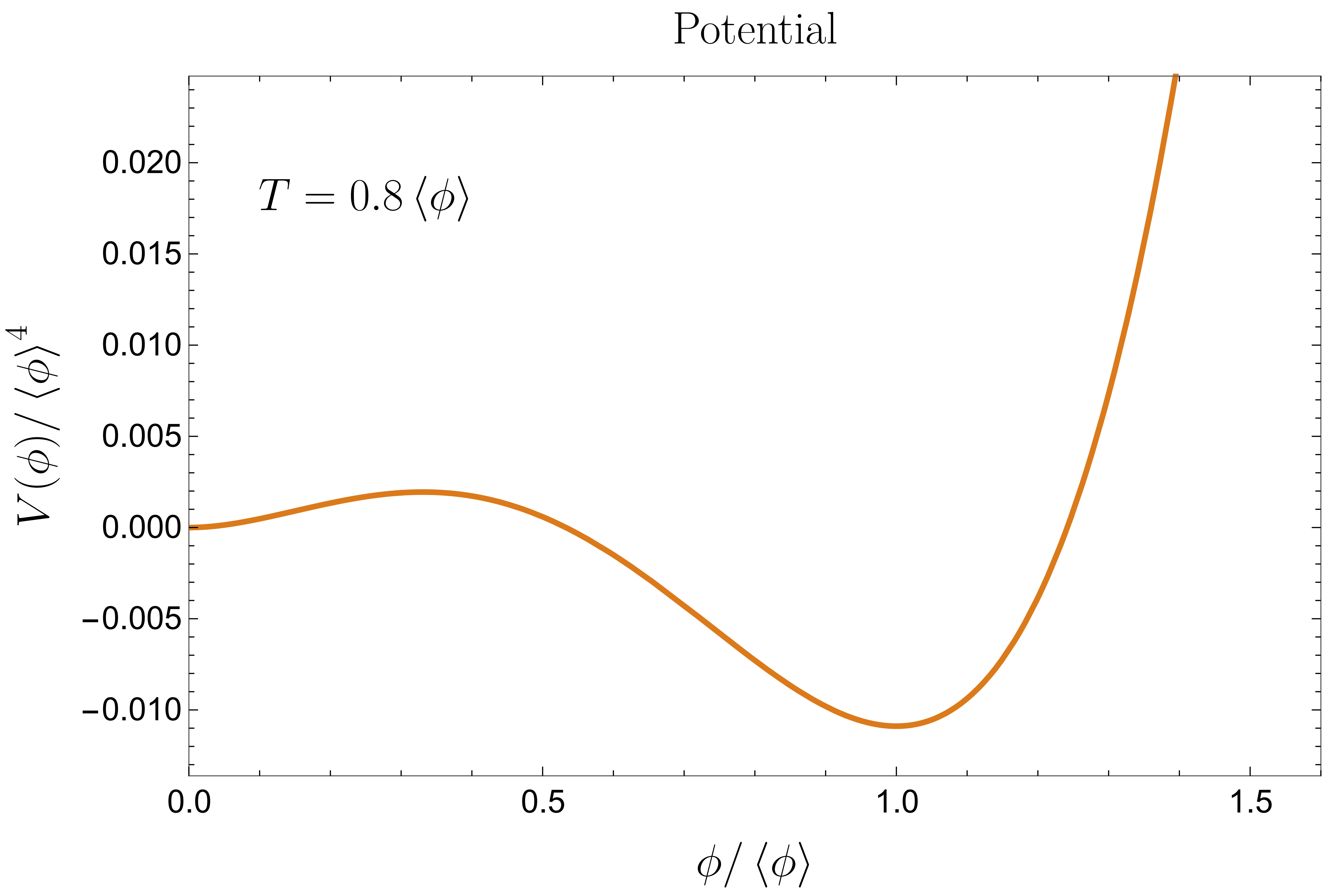

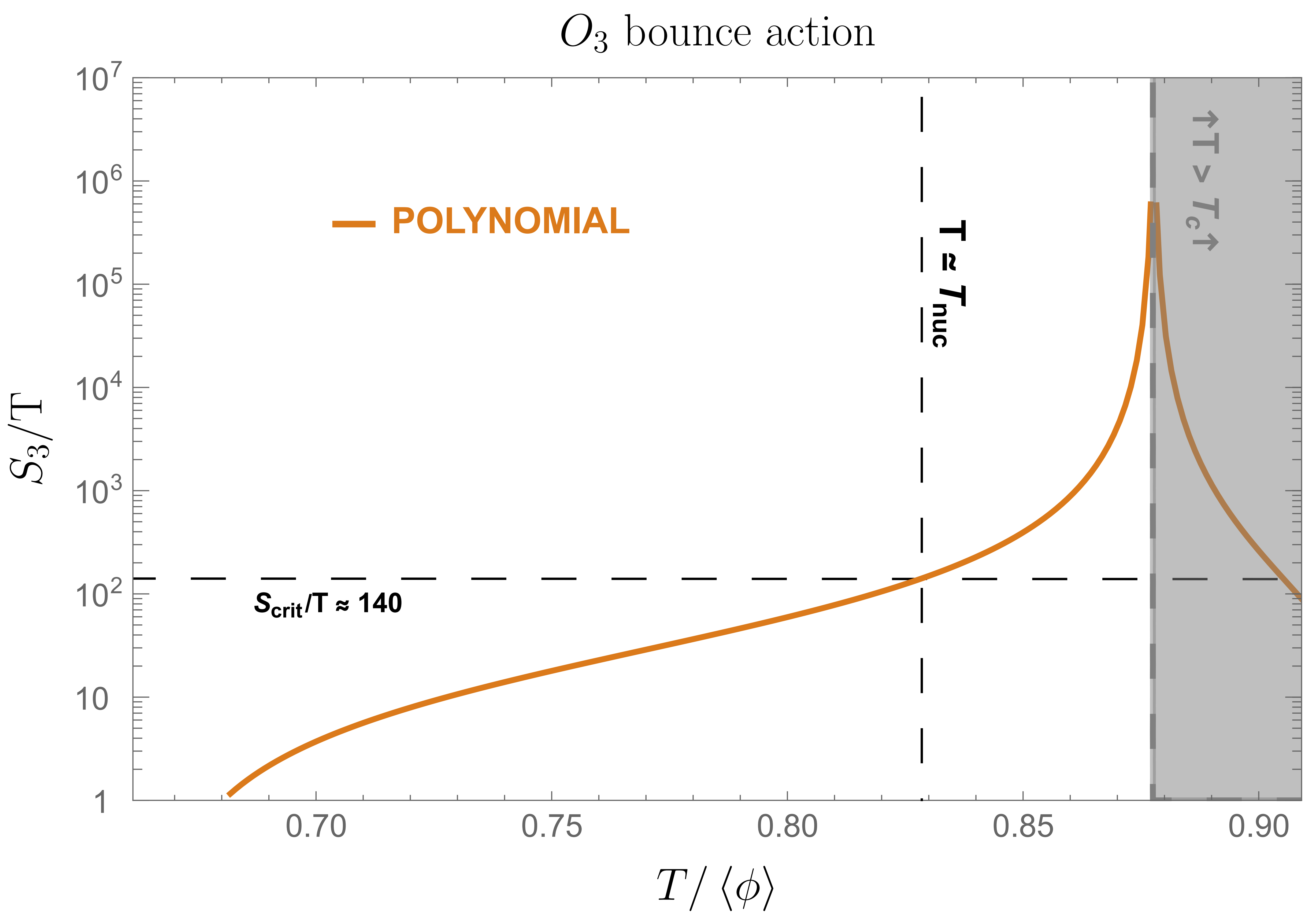

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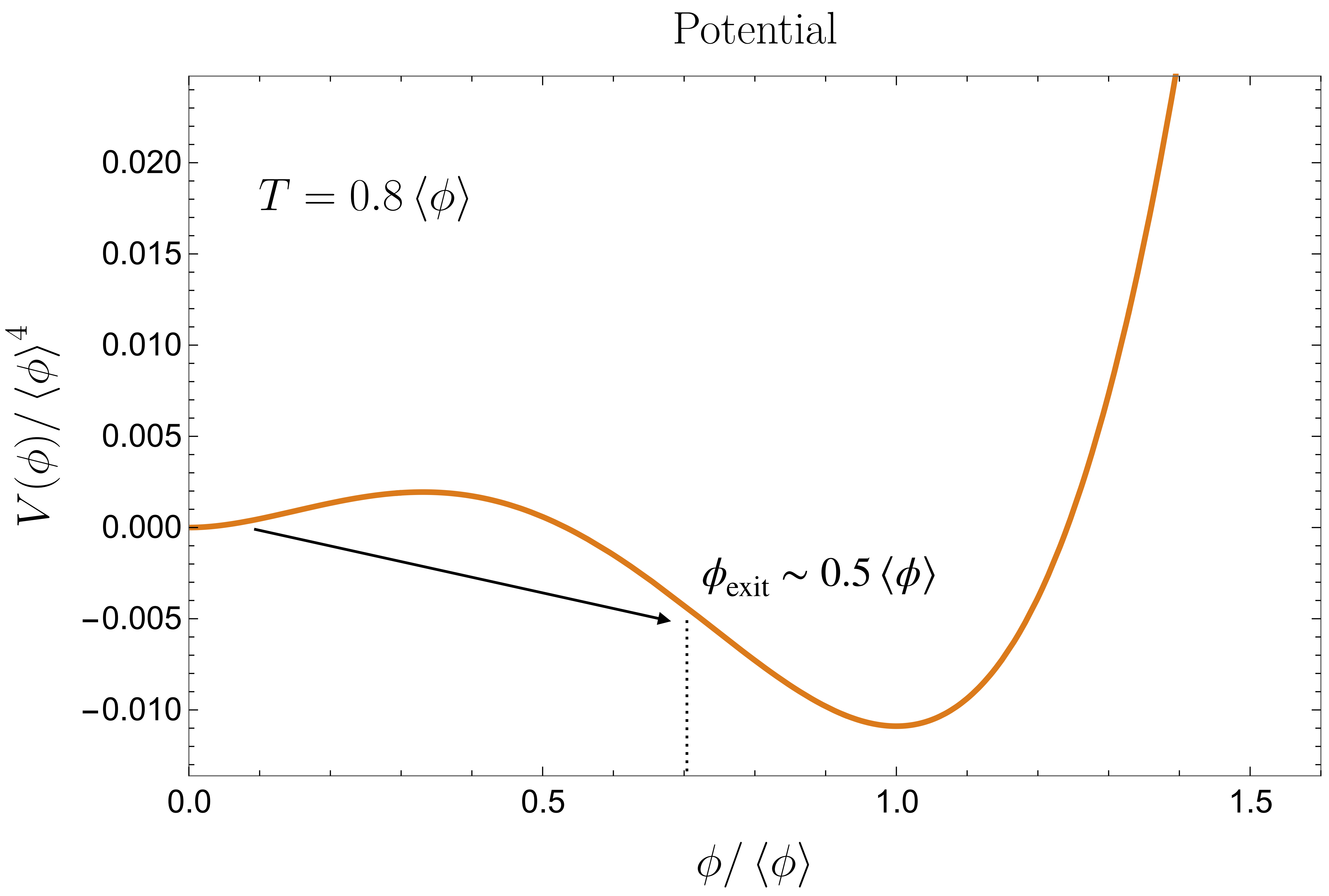

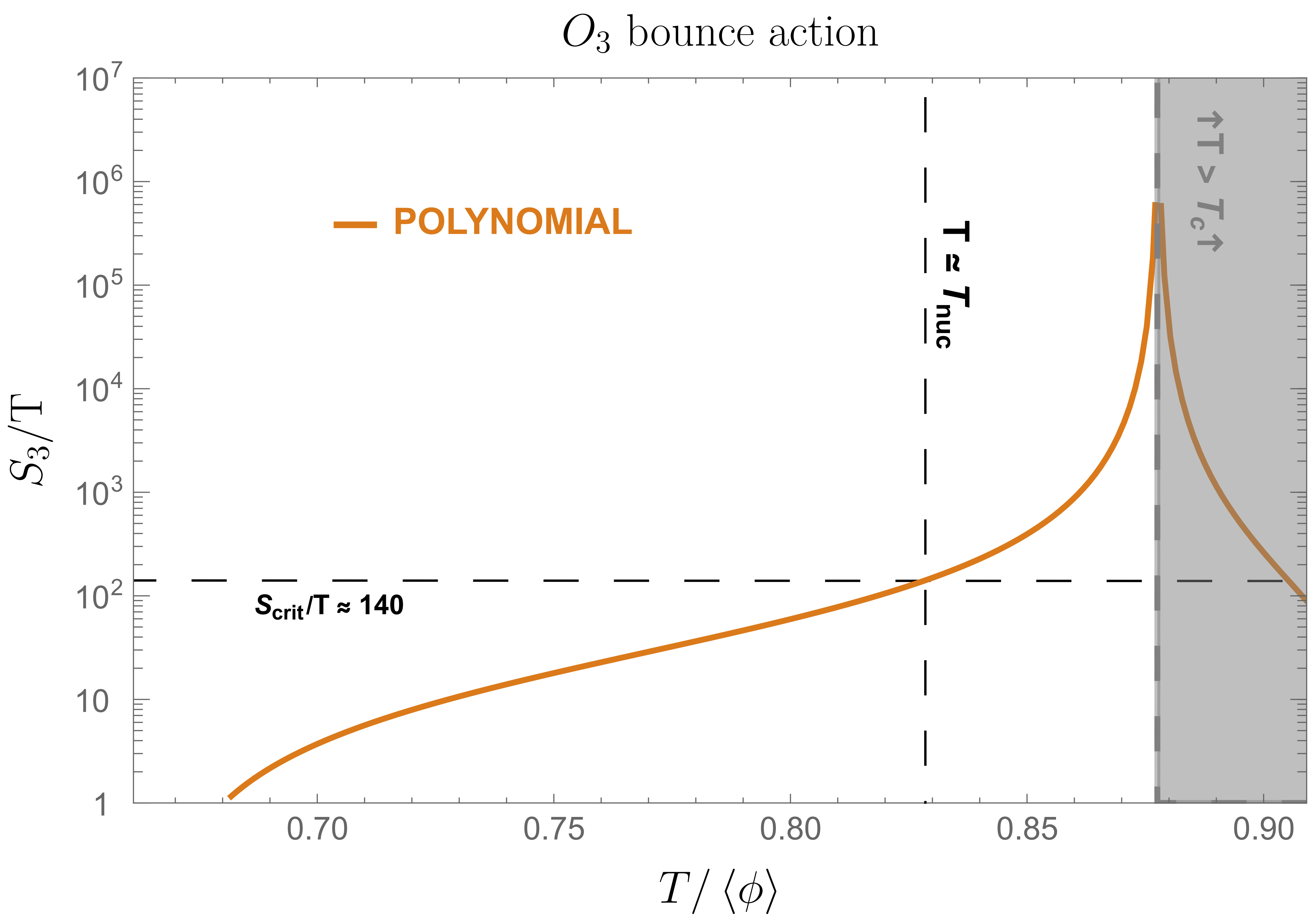

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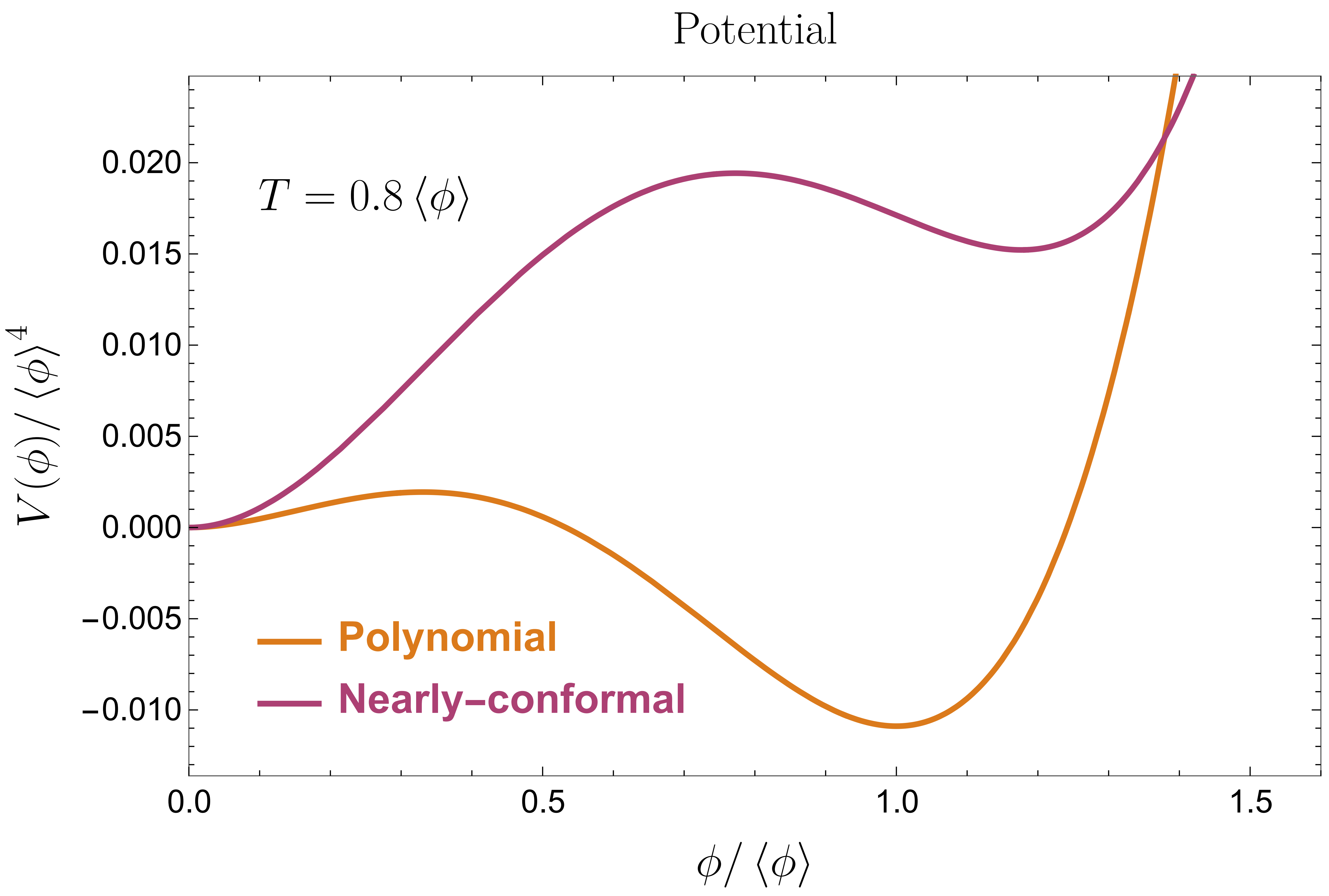

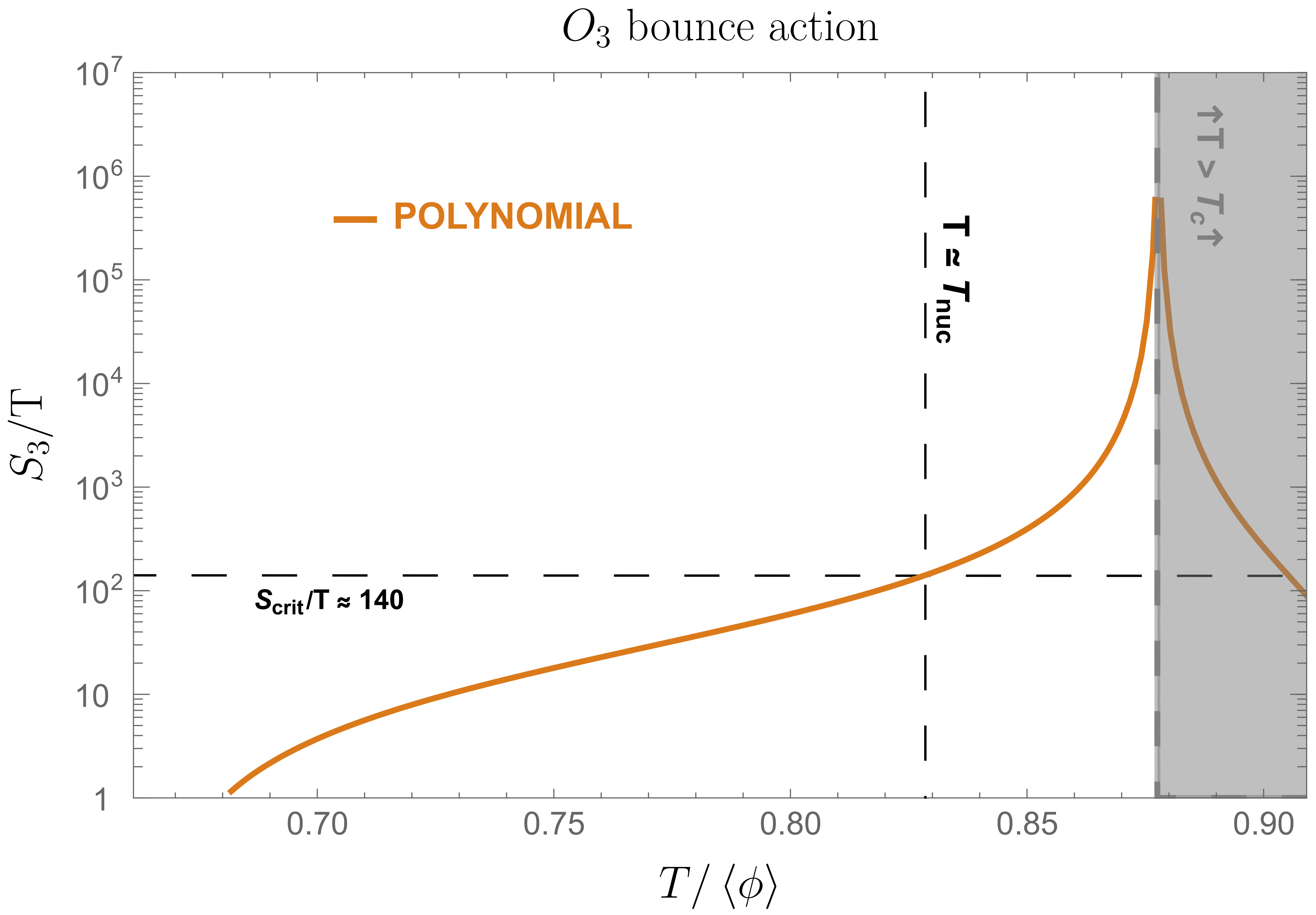

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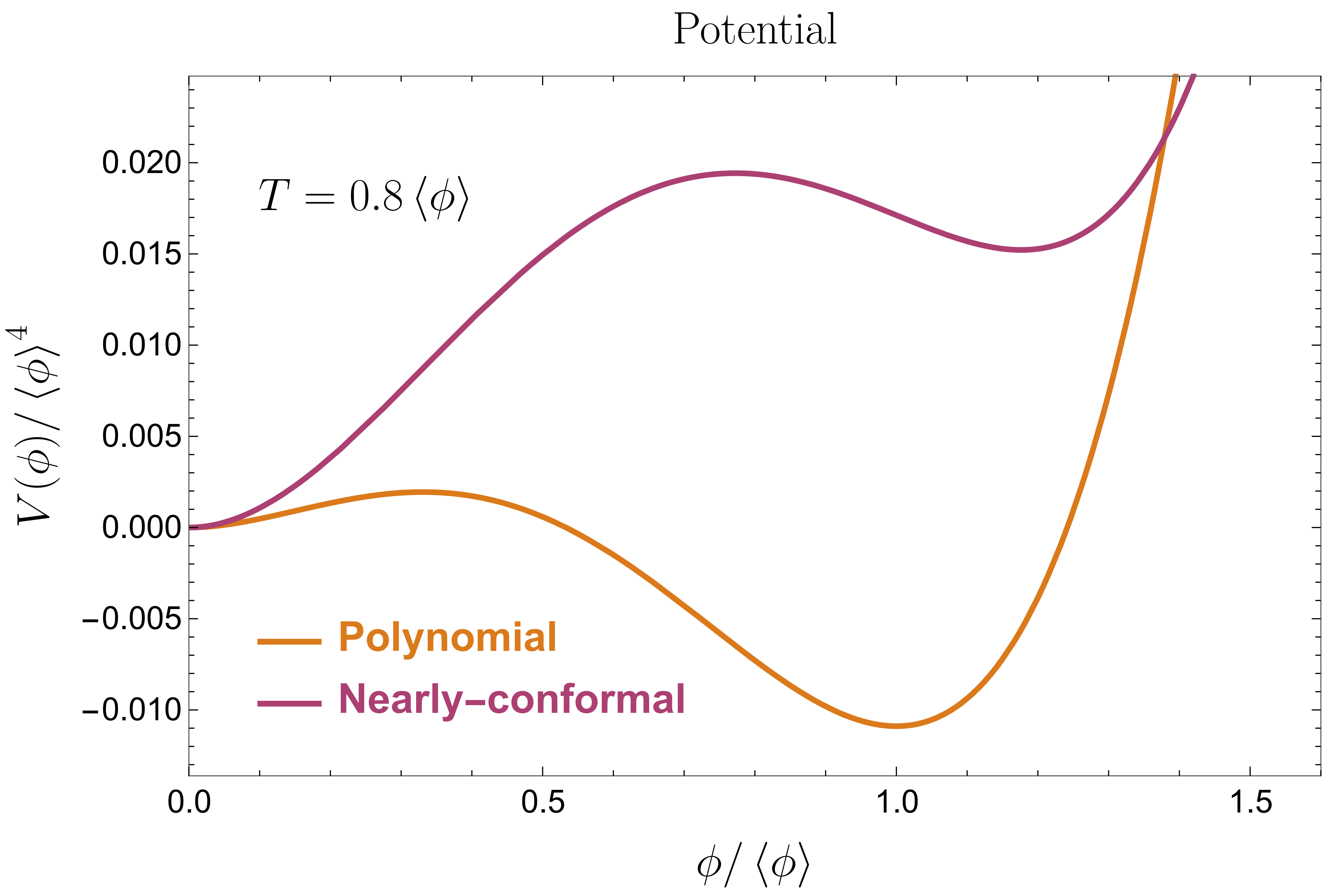

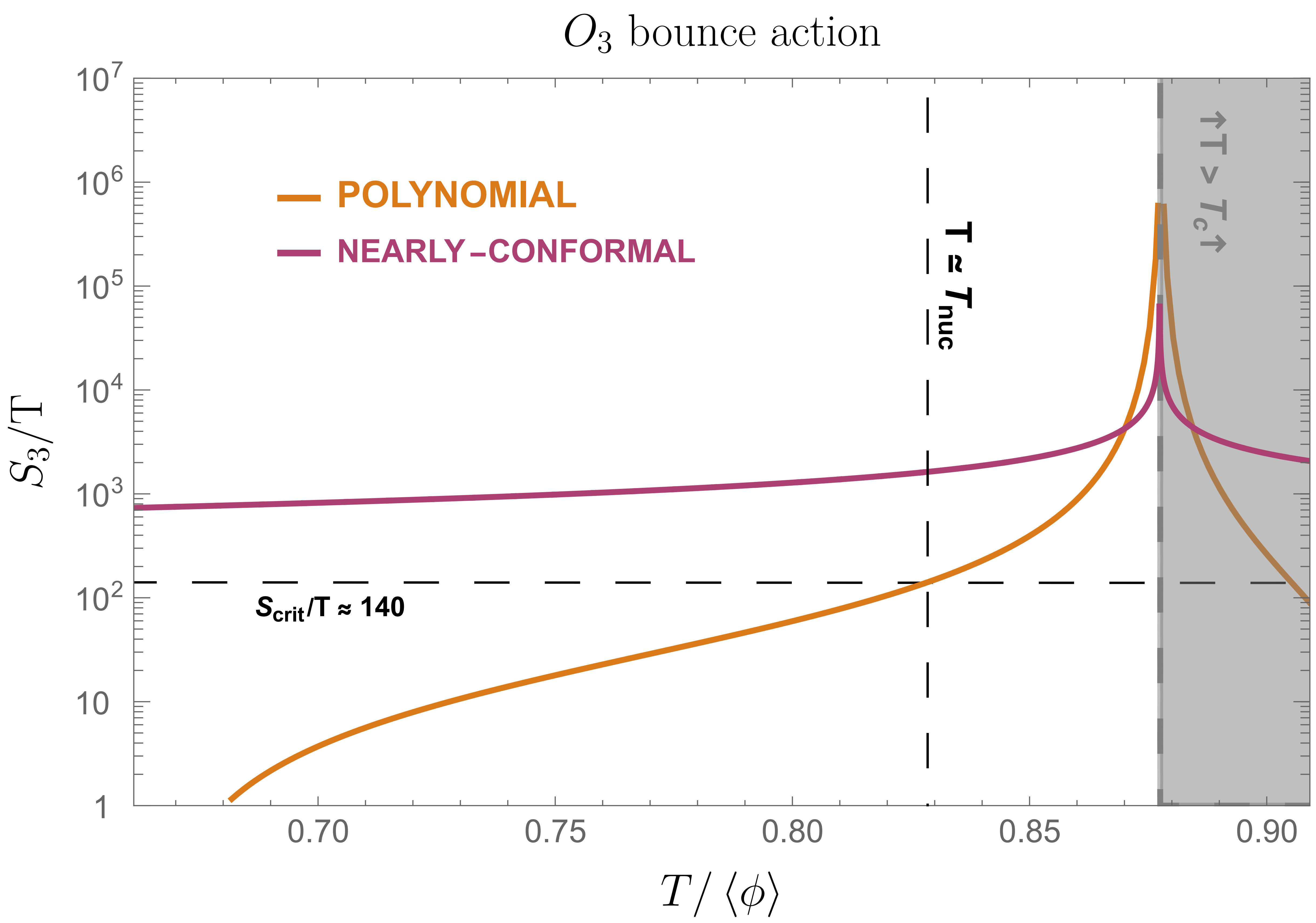

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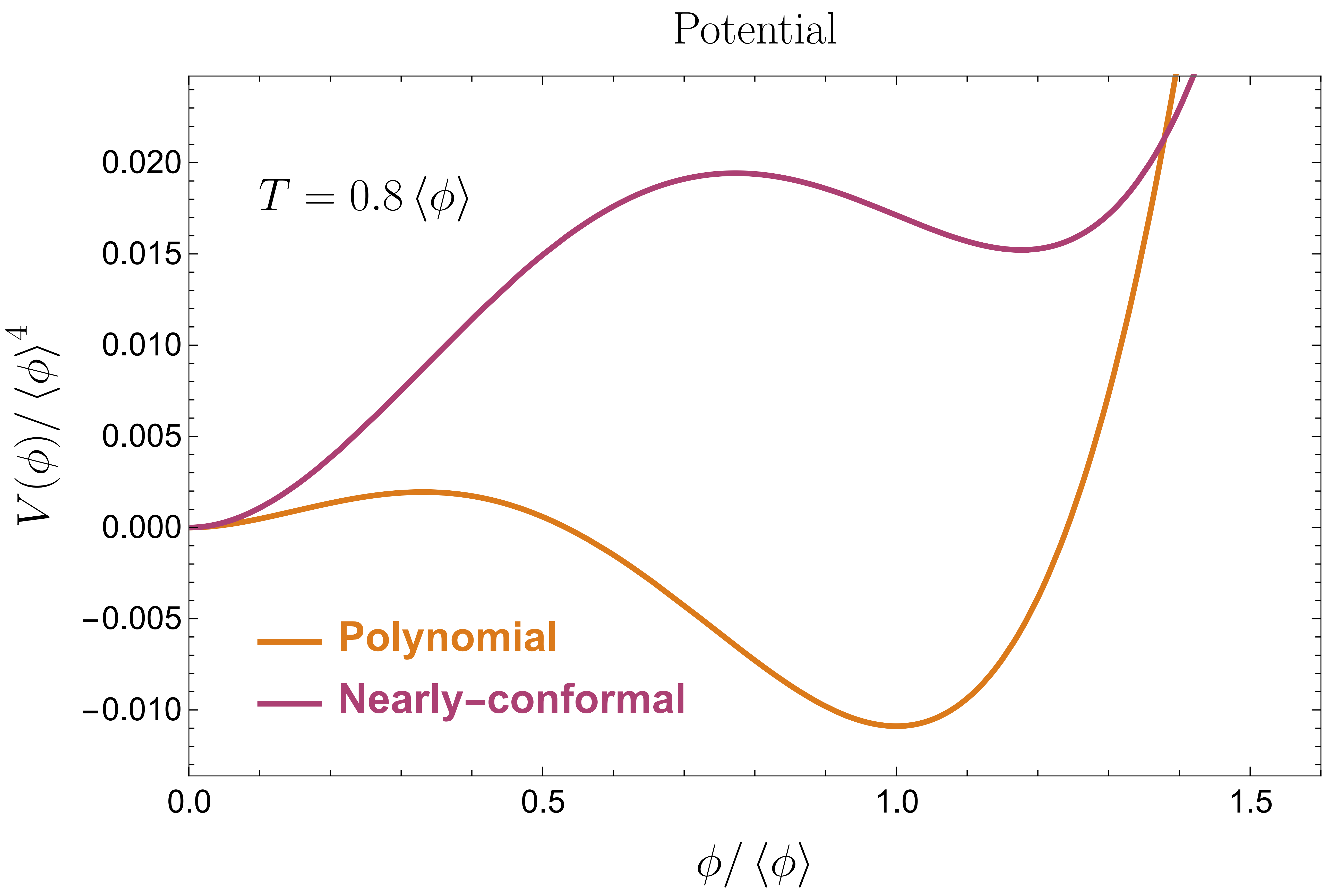

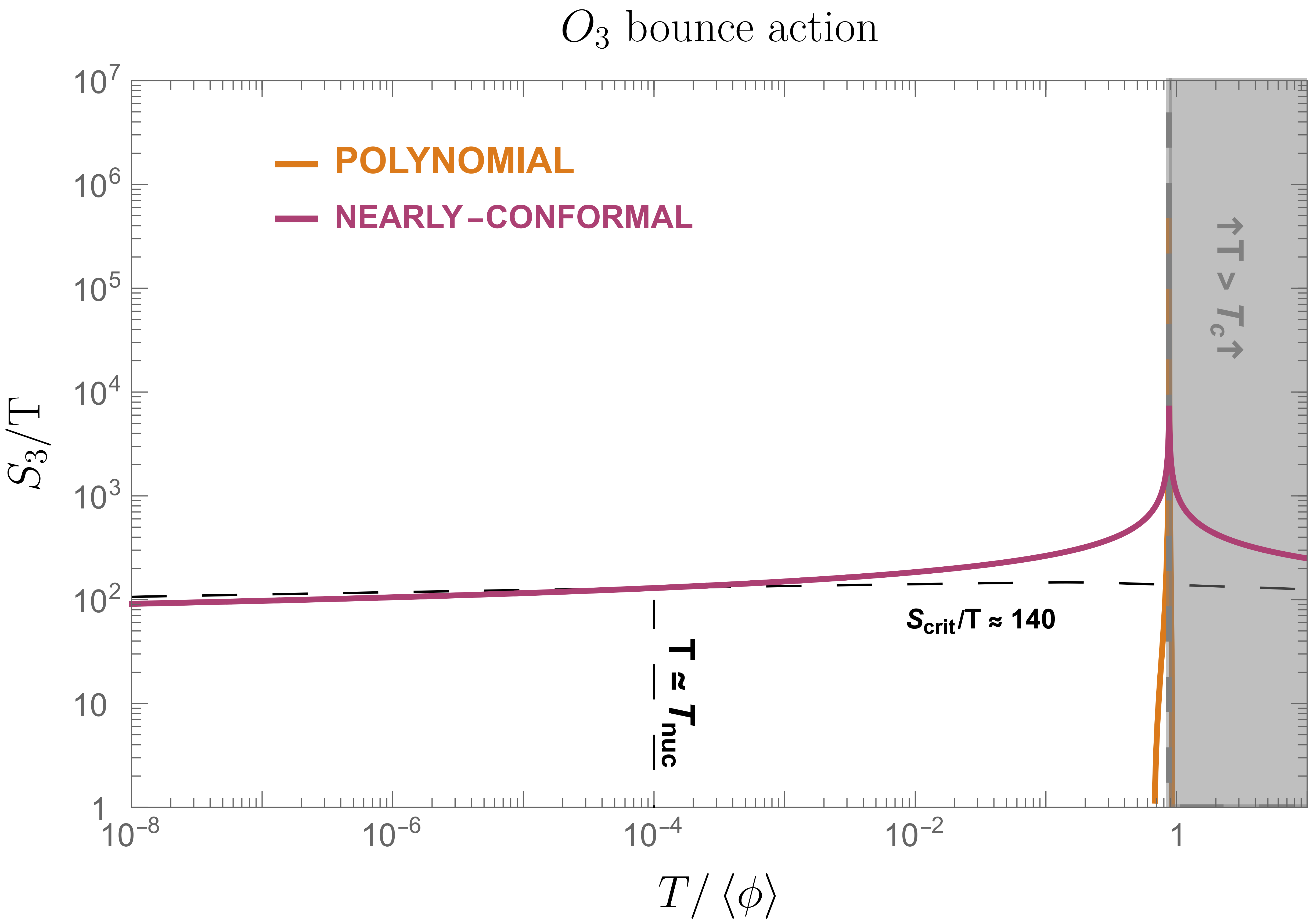

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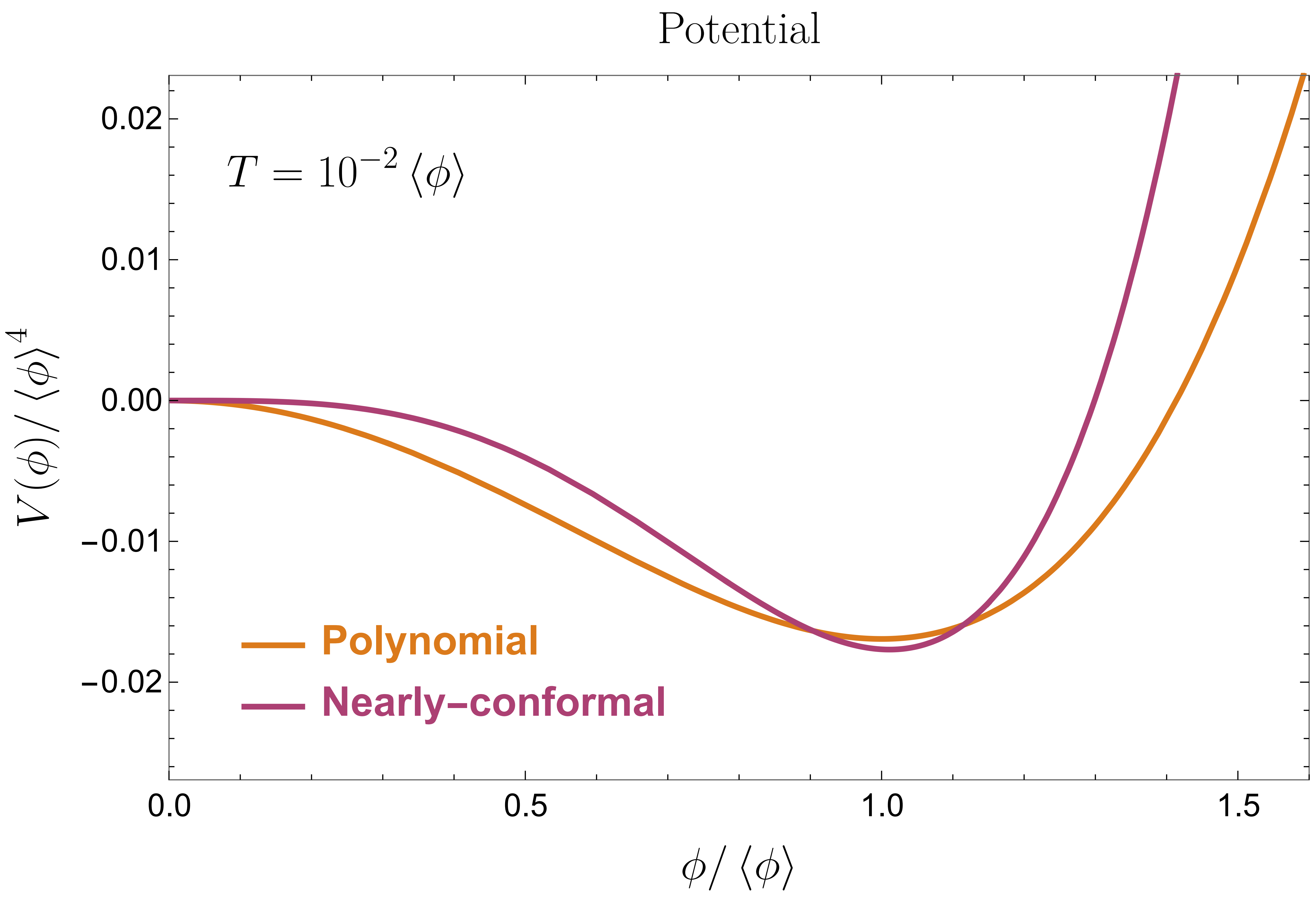

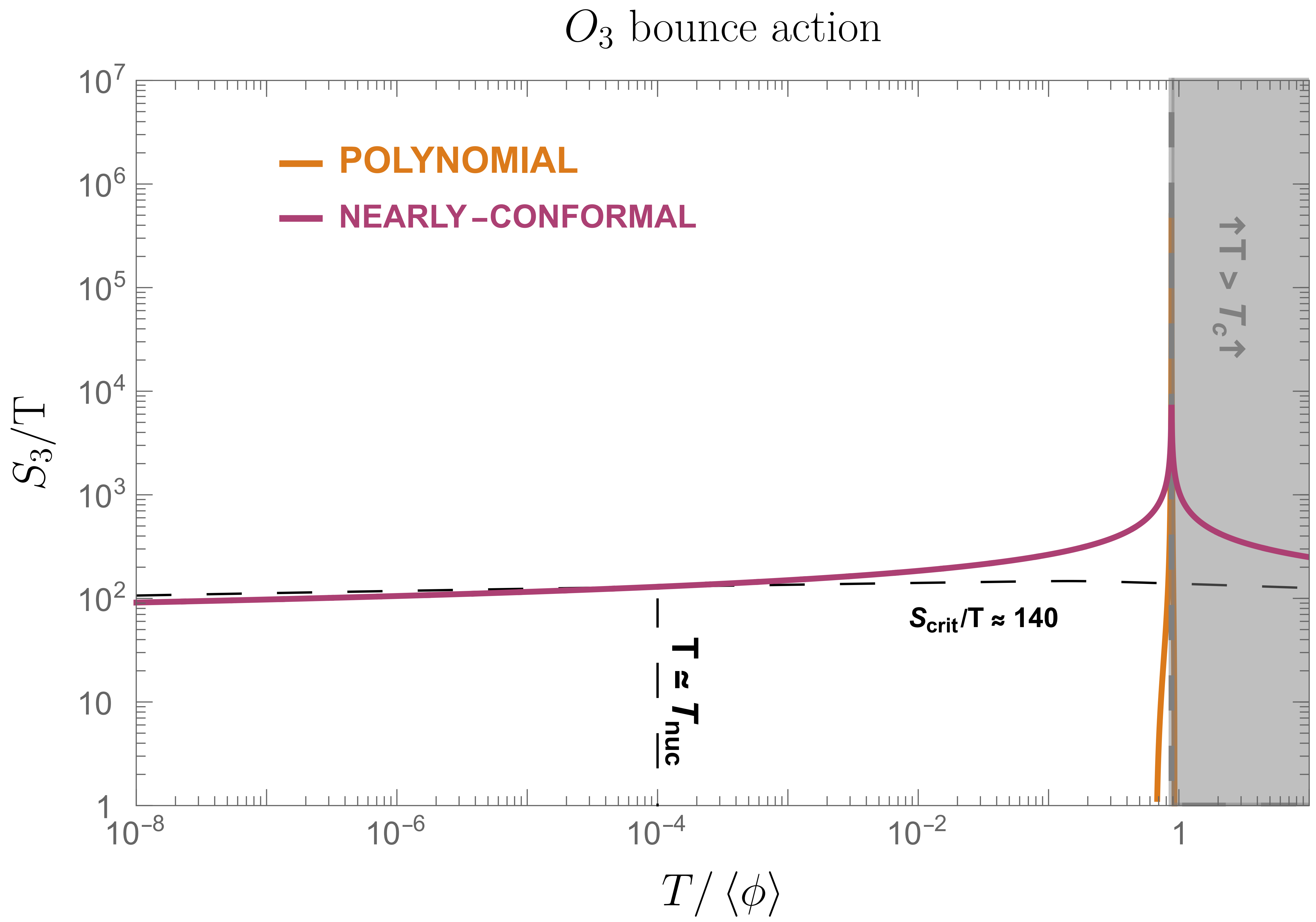

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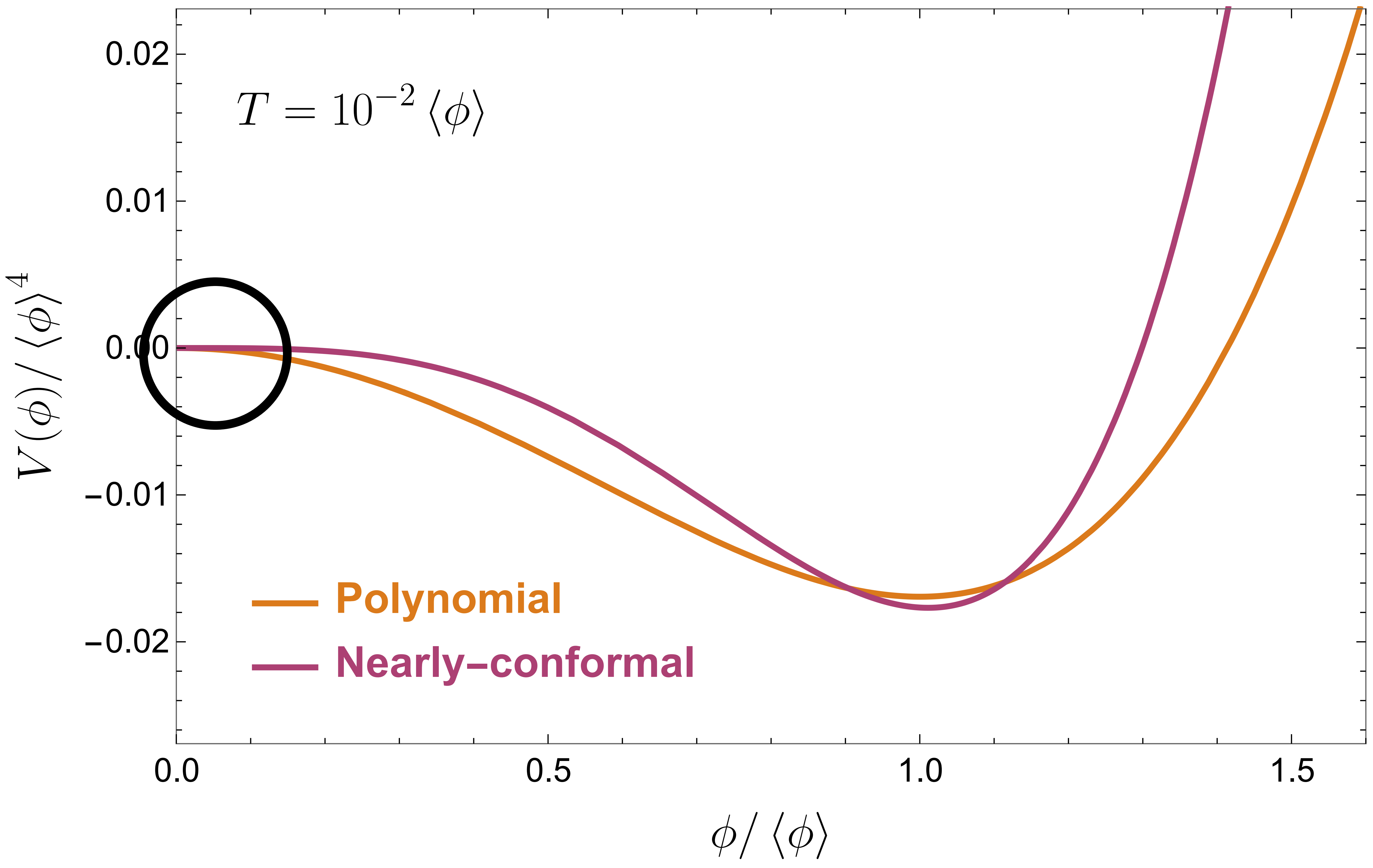
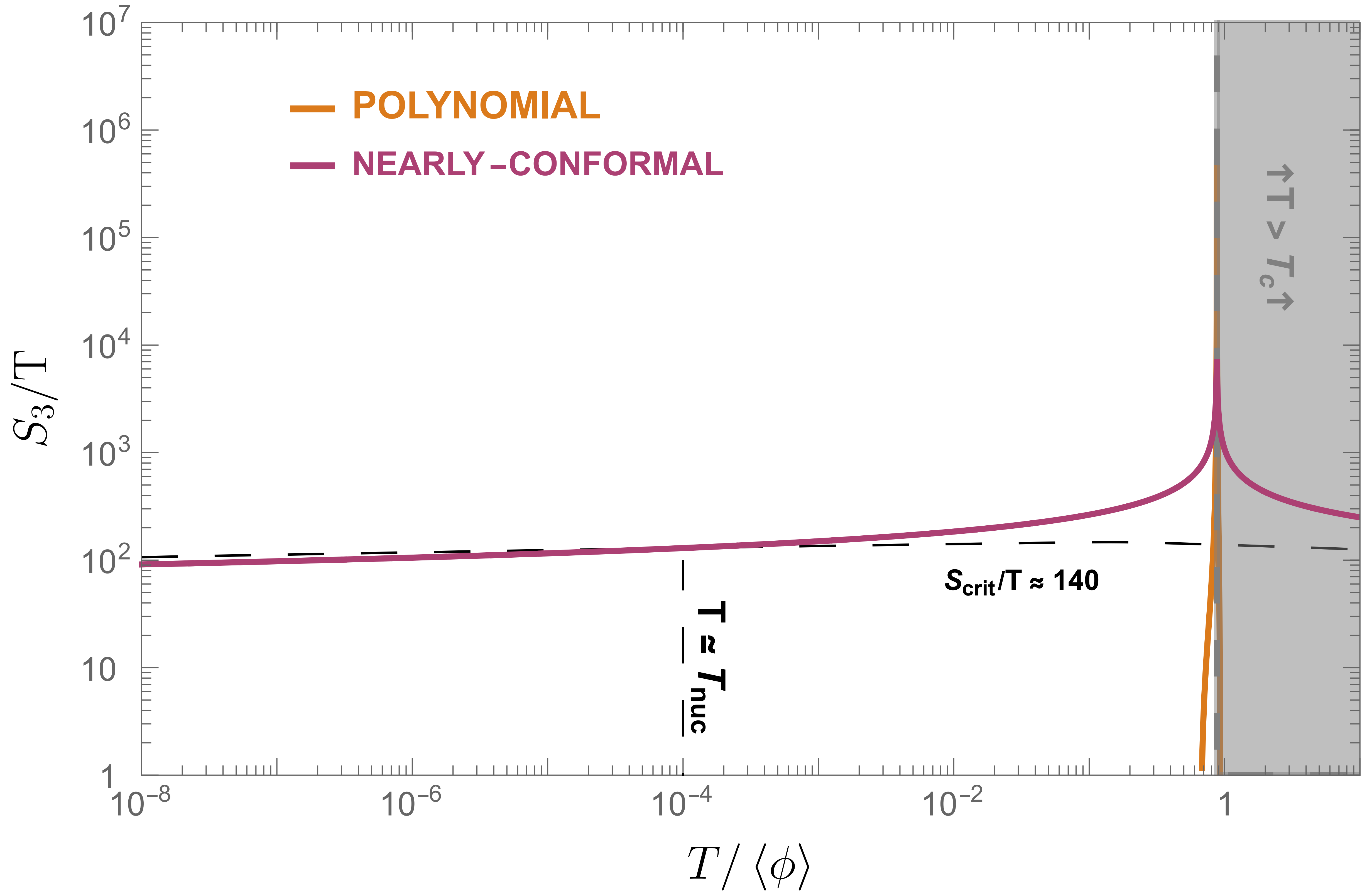
Potential



O_3 bounce action



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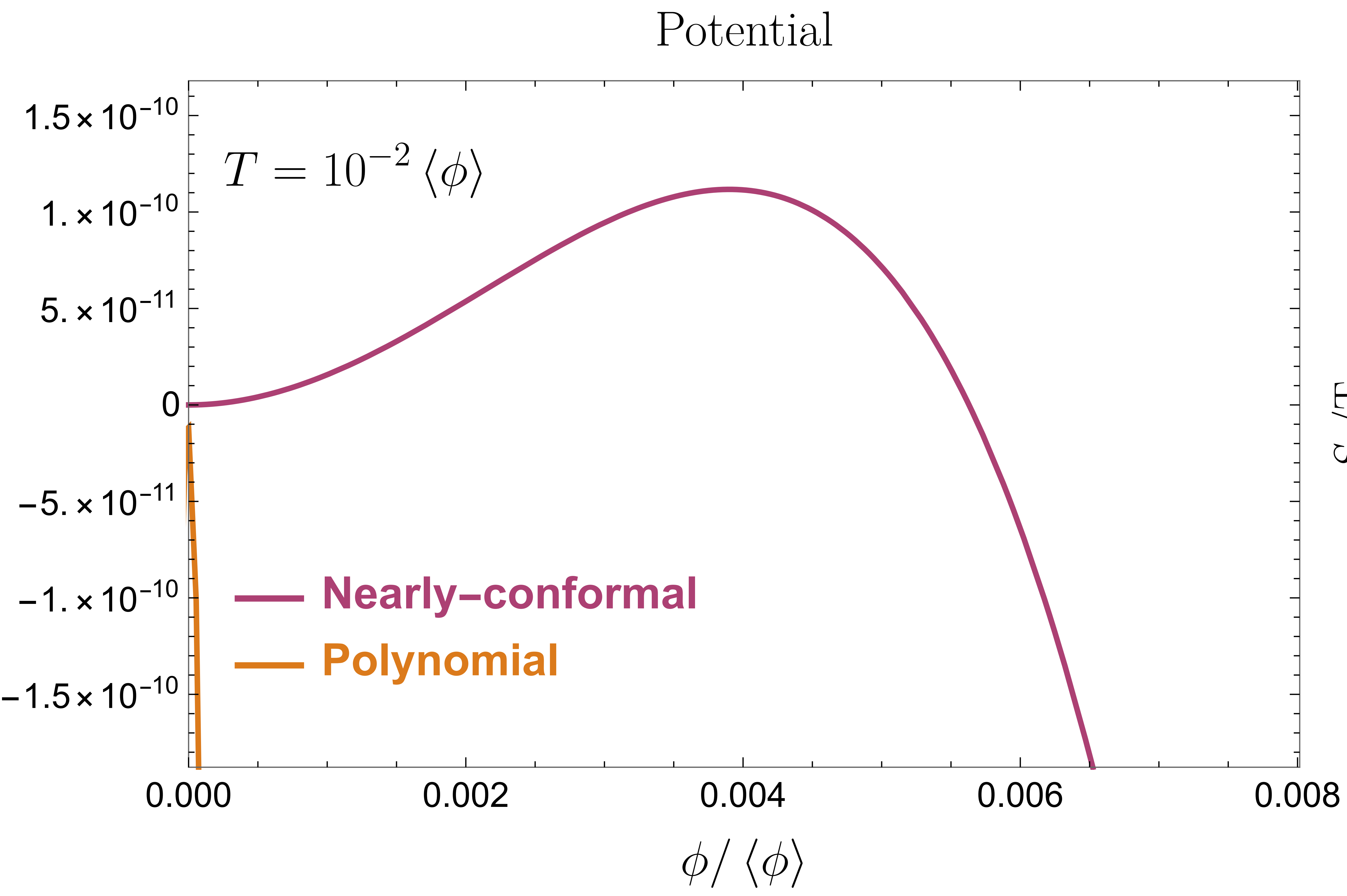

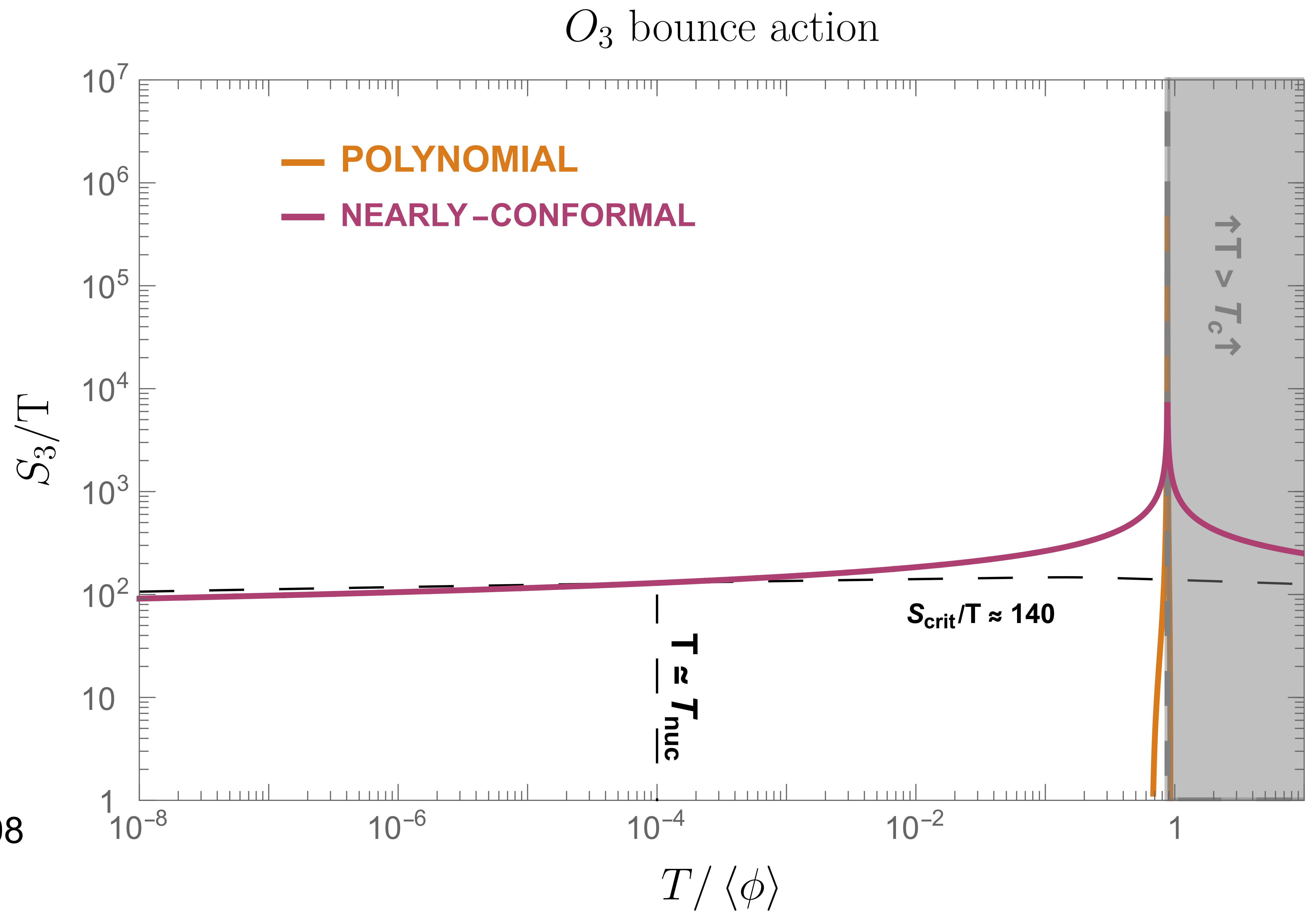

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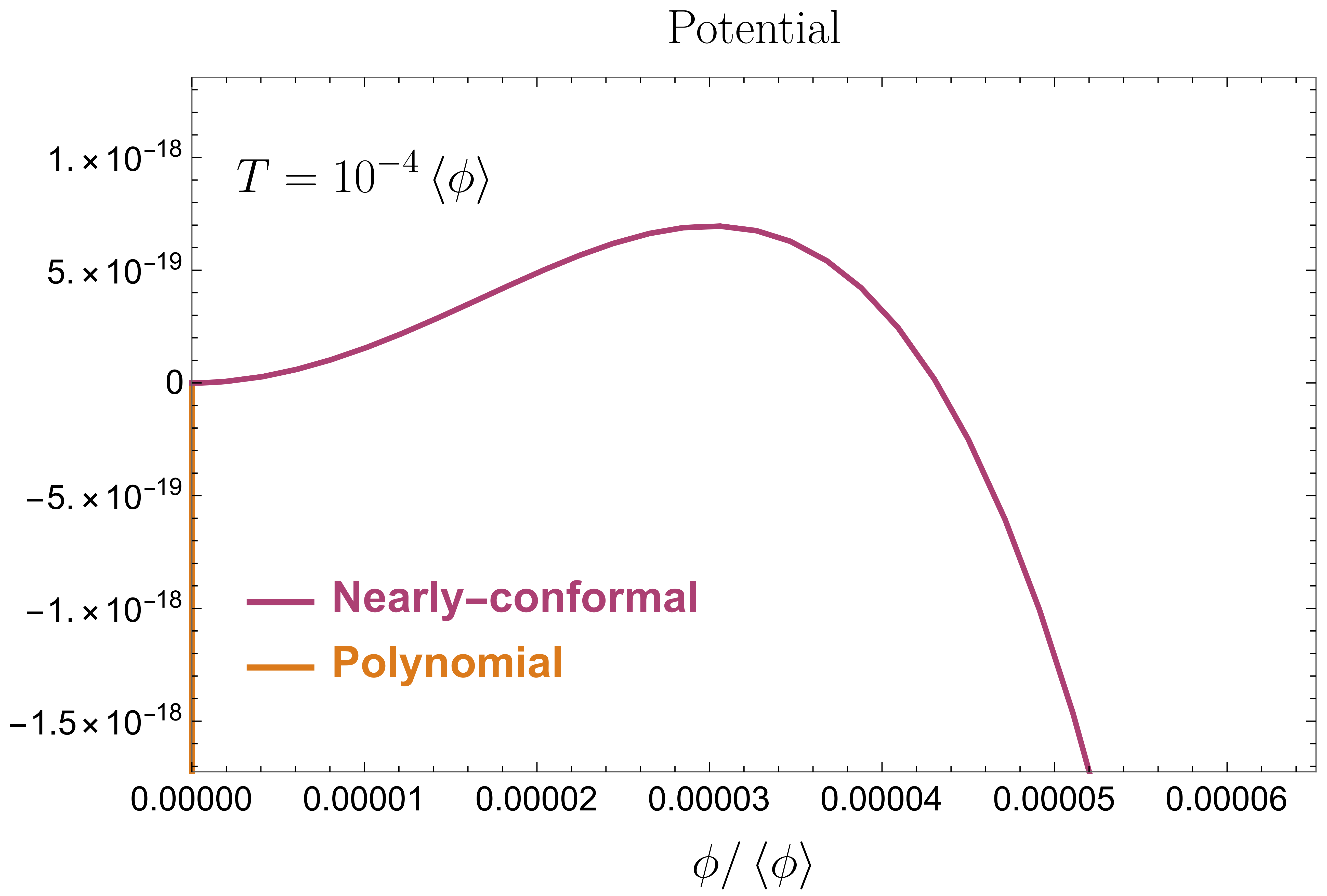

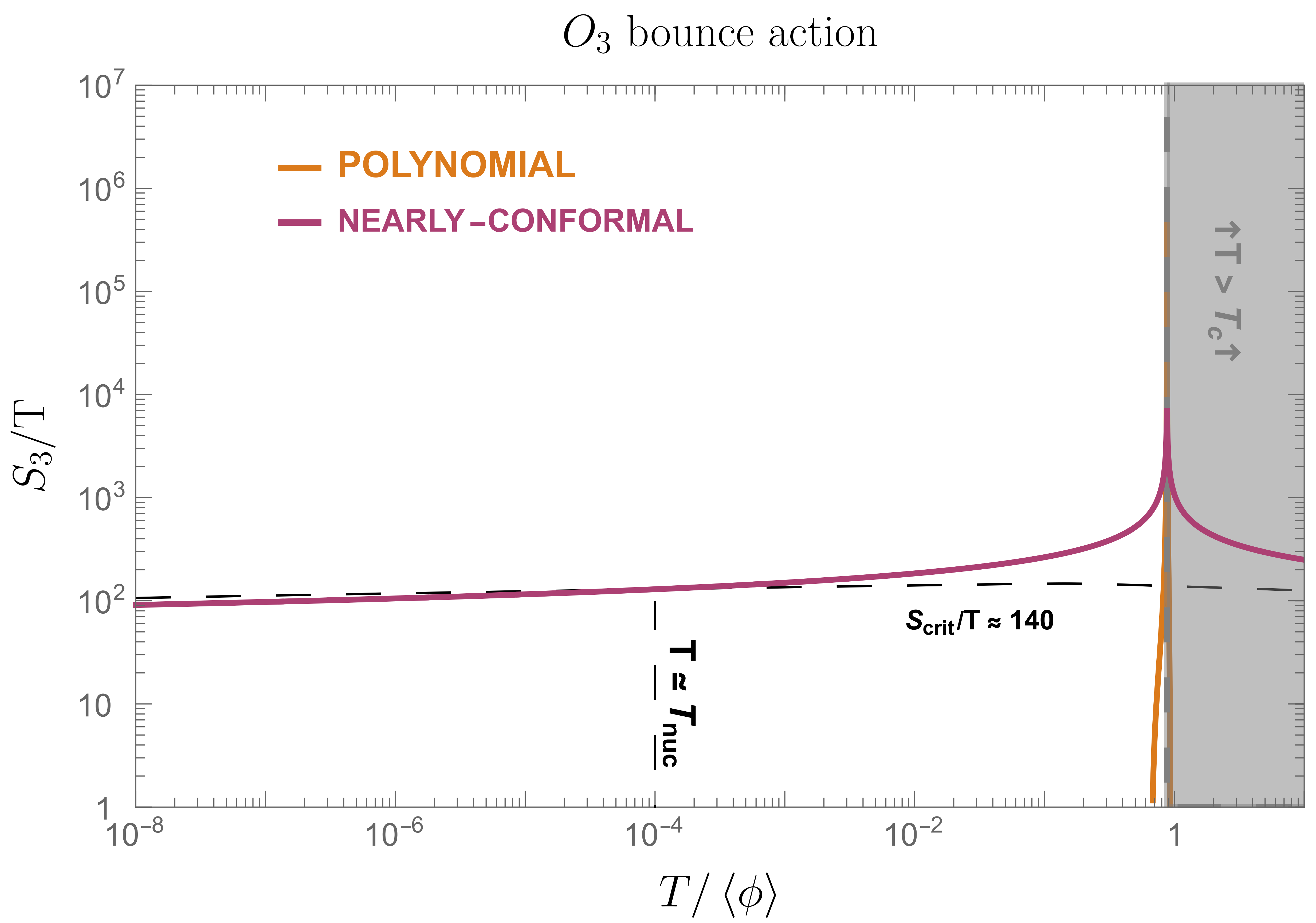

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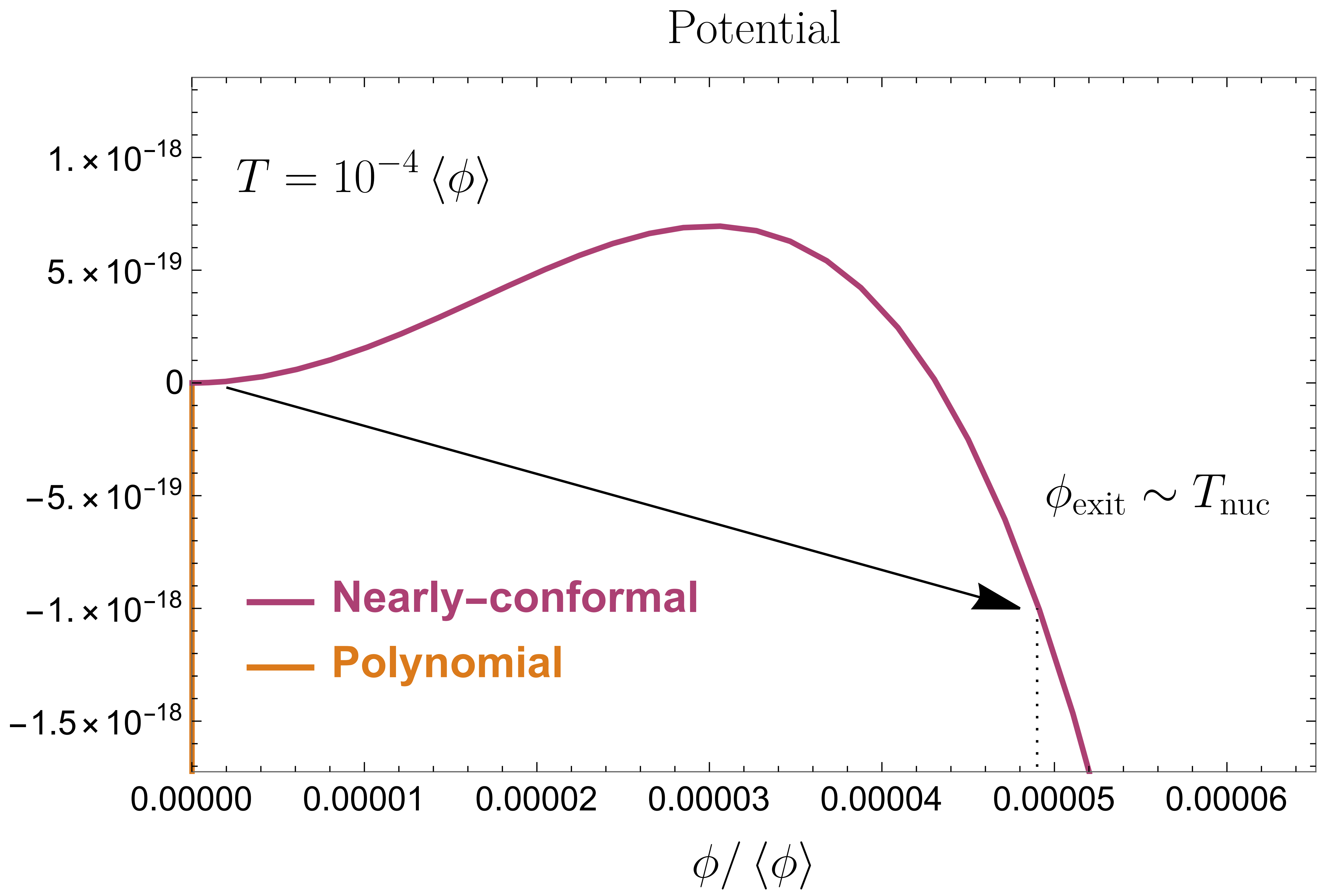

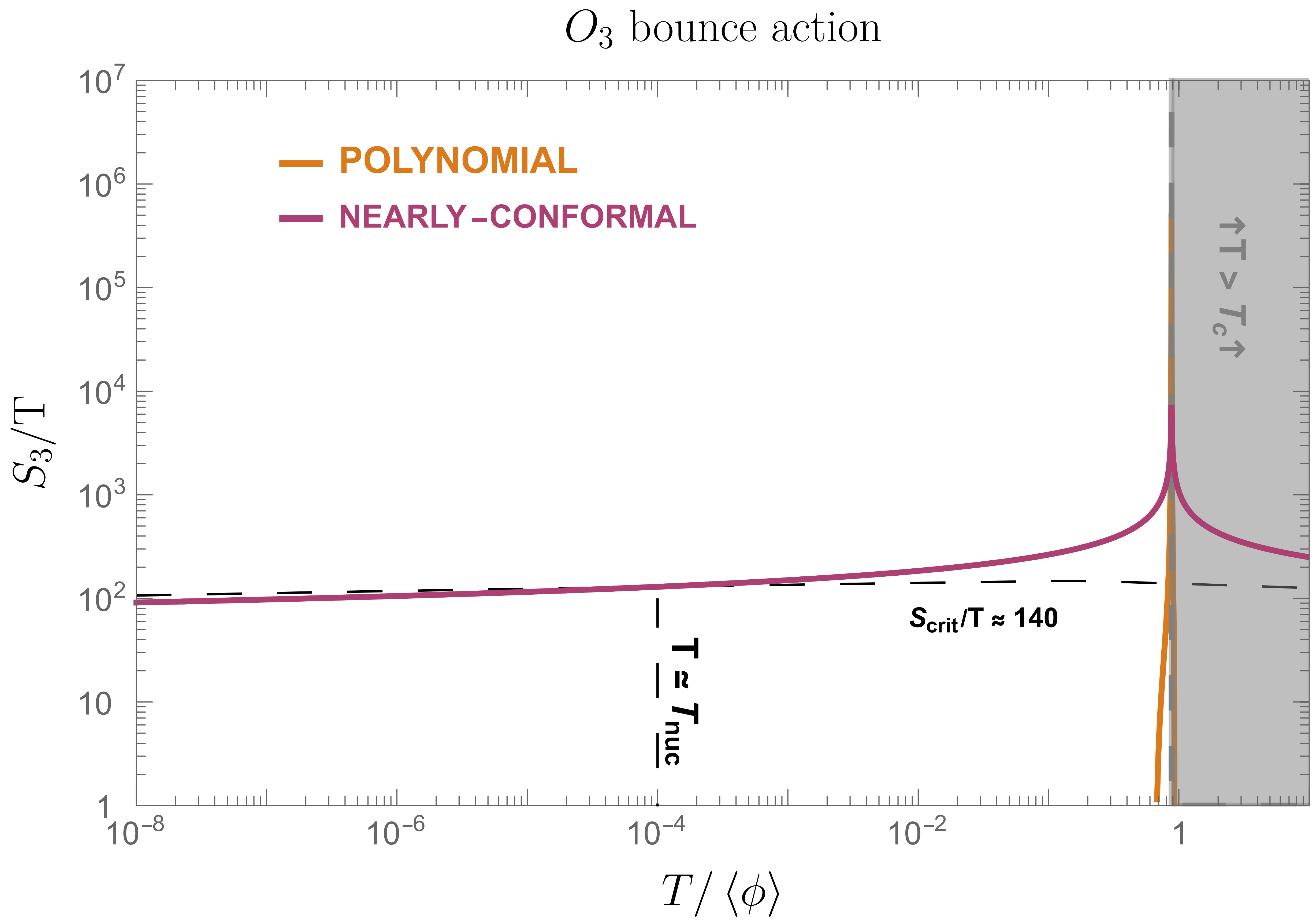

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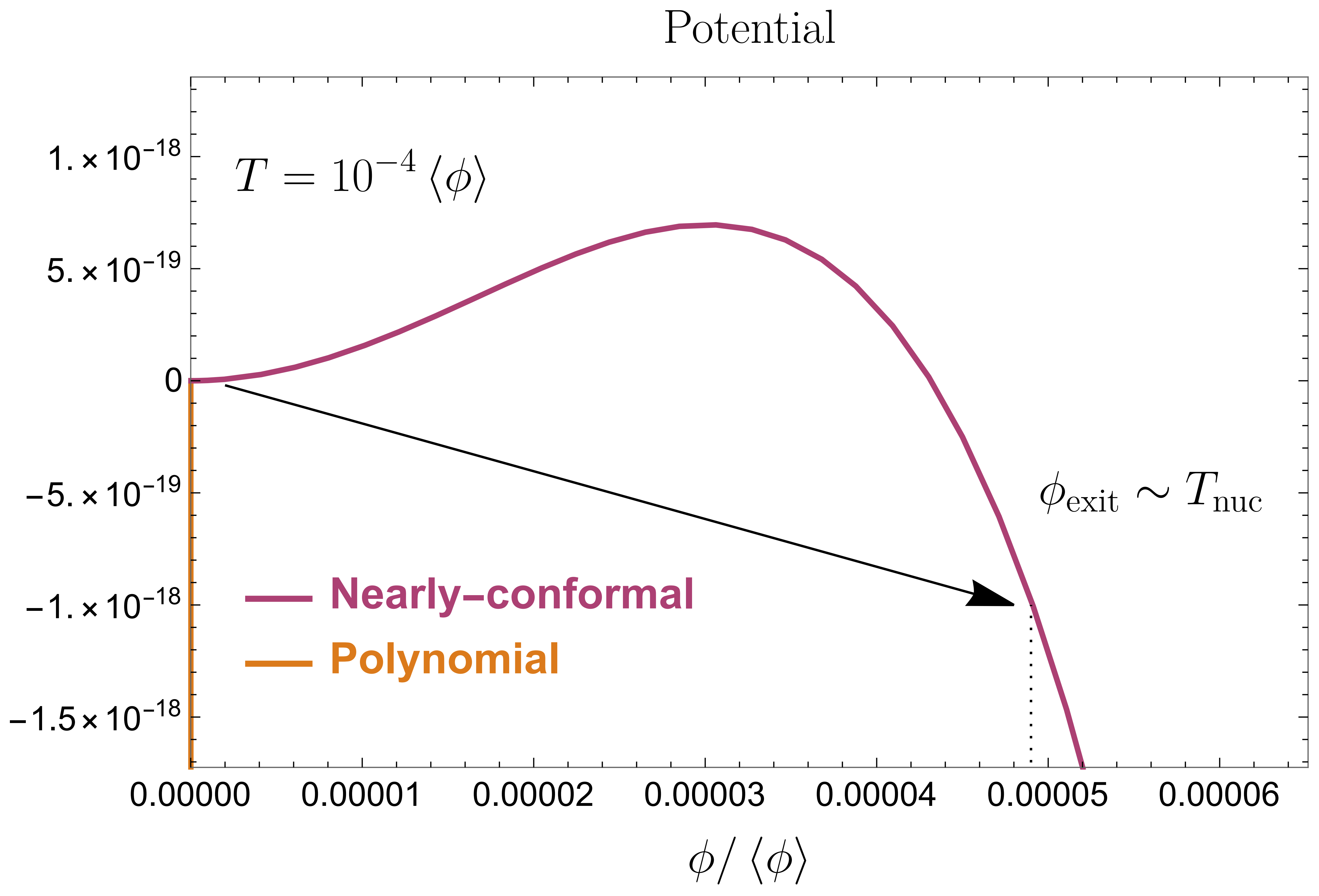

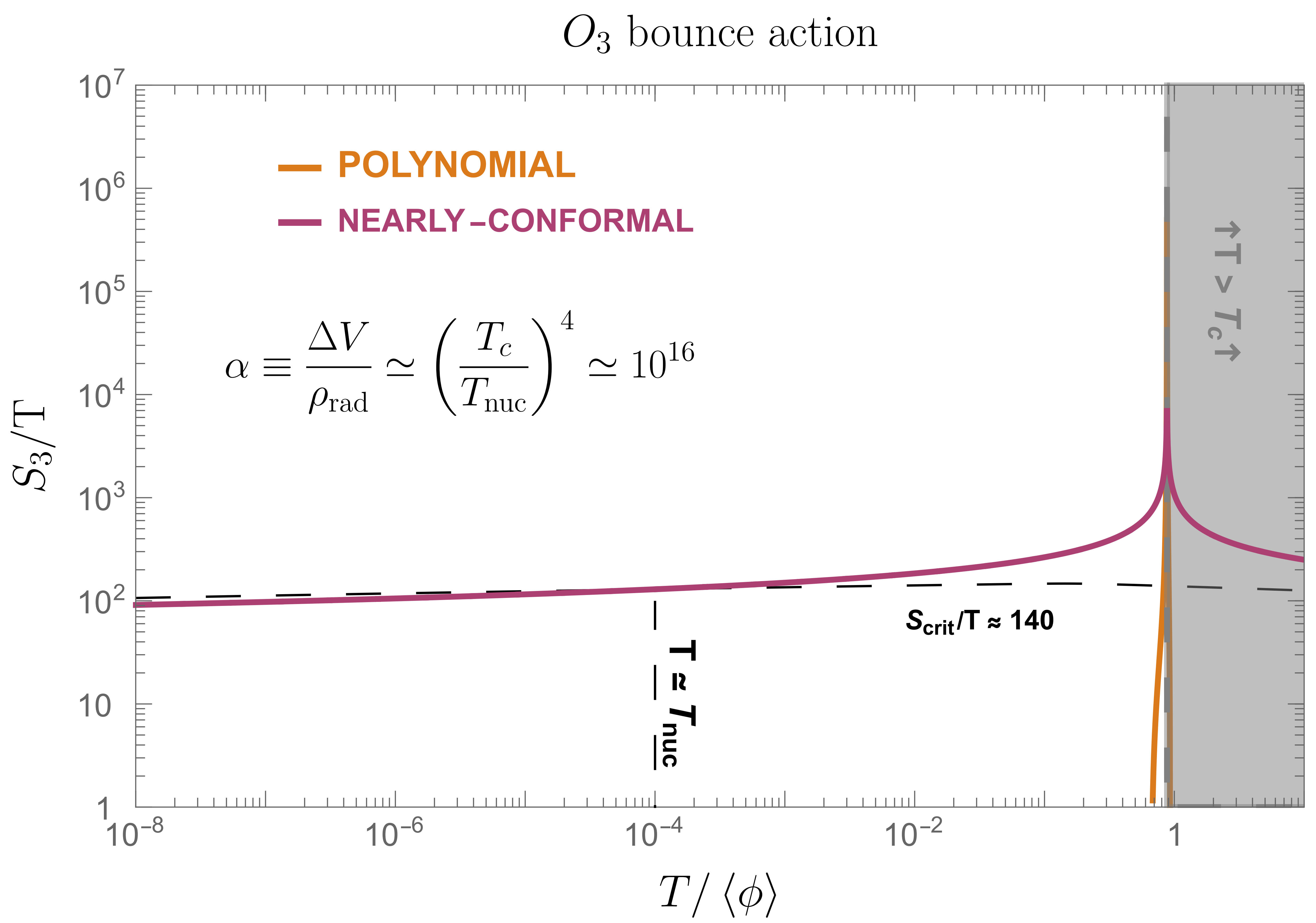

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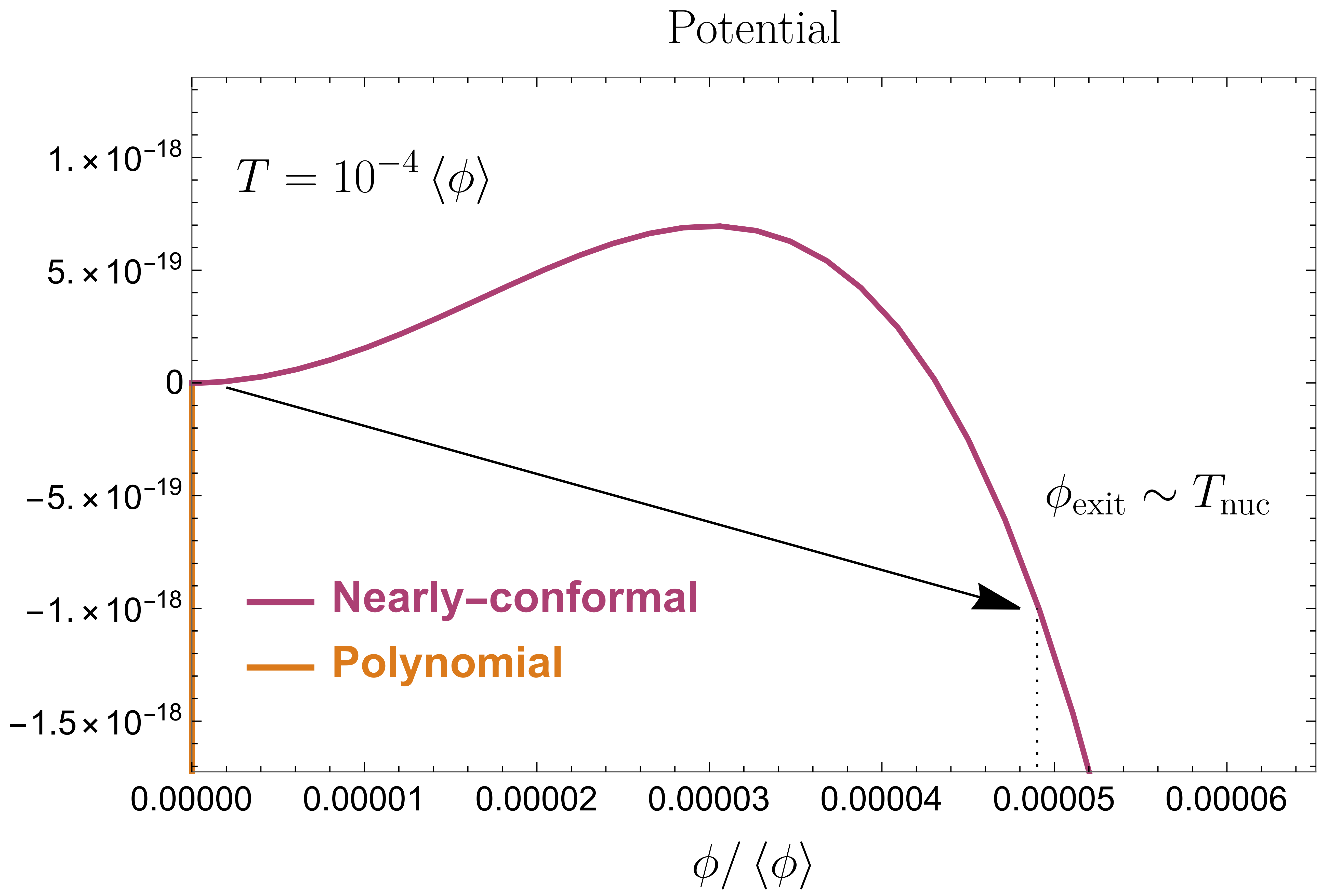

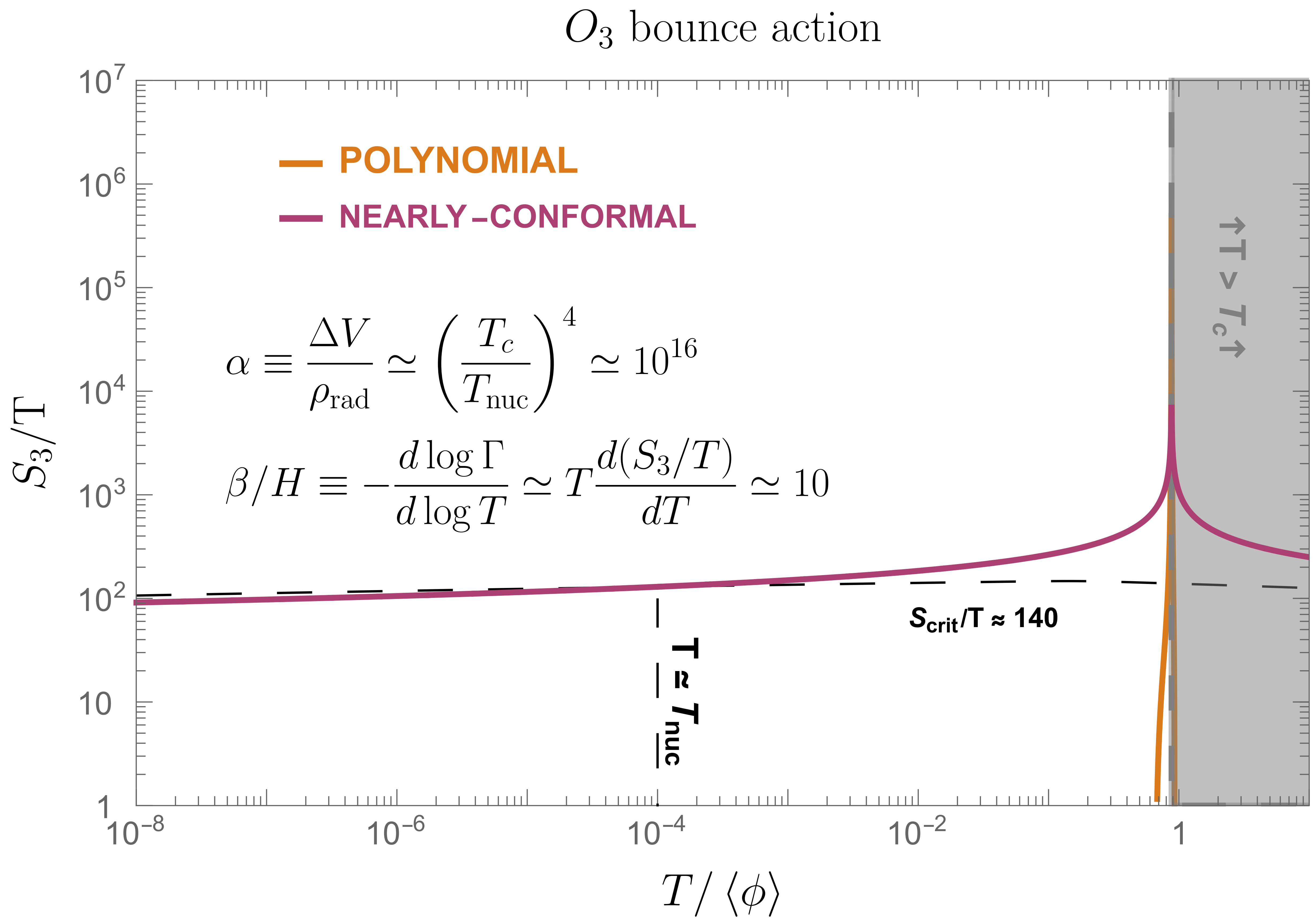

TAKE HOME : Supercooled phase transitions arises in presence of FLAT direction, are STRONG and SLOW

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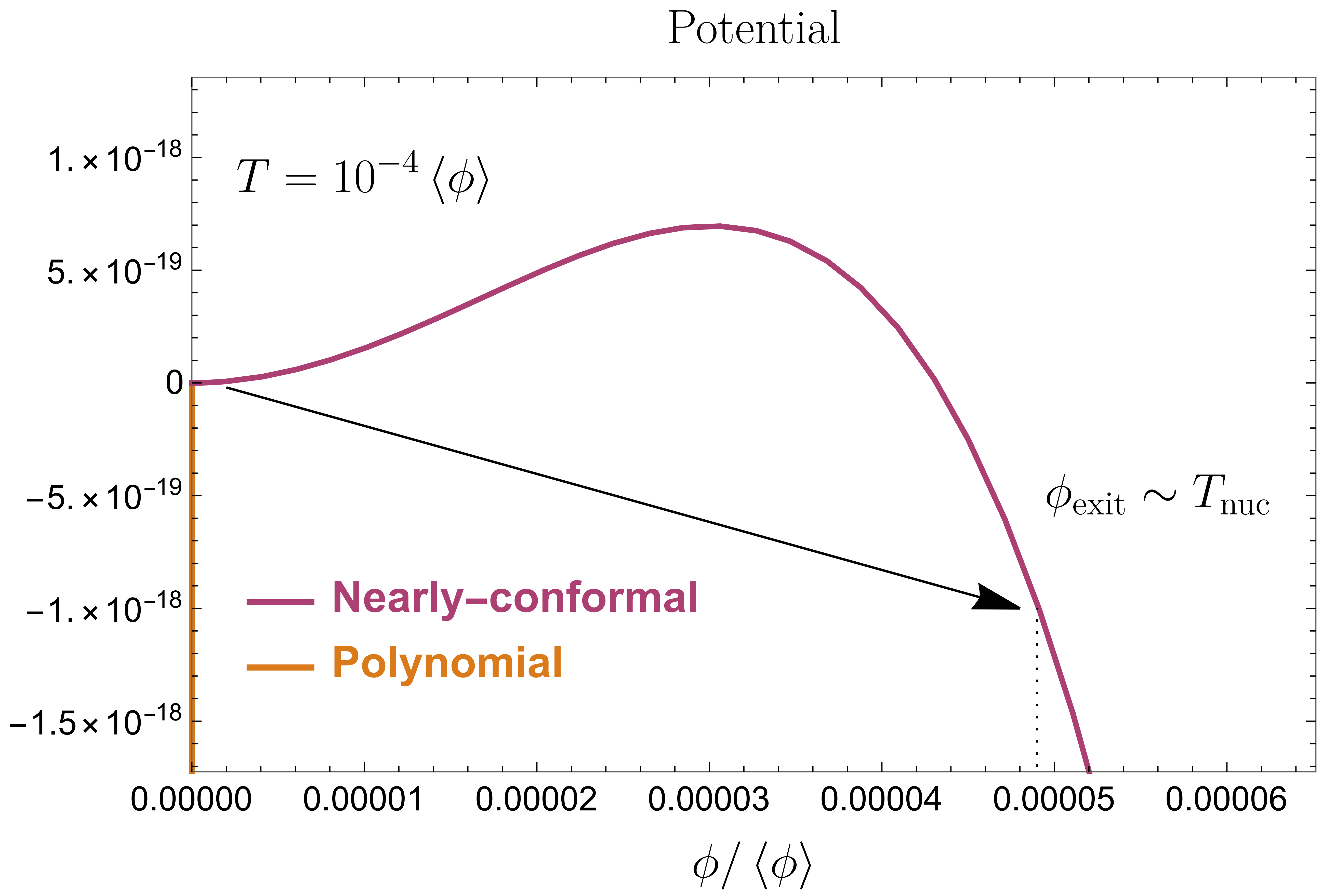

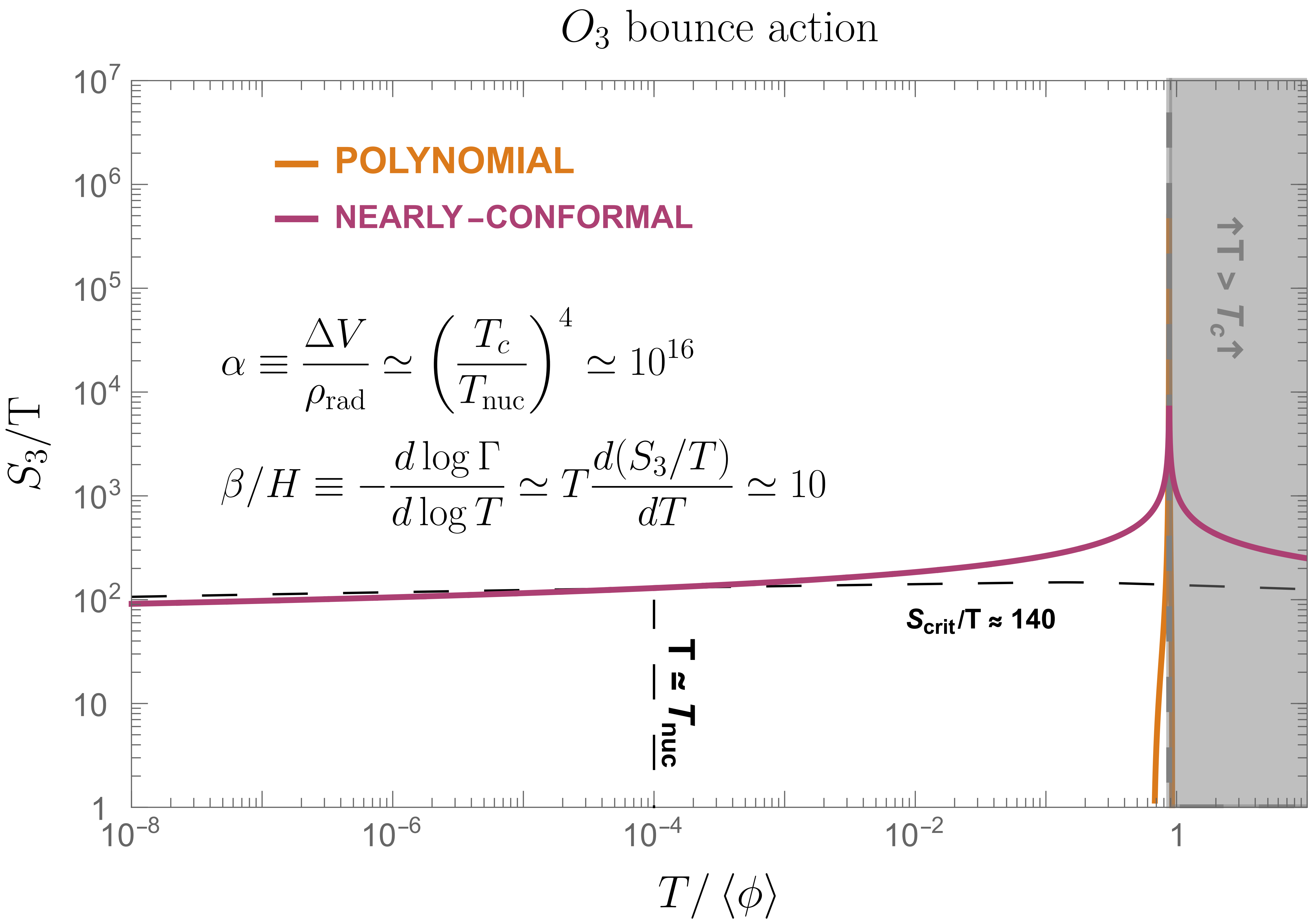

Classes of nearly-conformal models

Strength coupling / Space-time dimension	**Weakly-coupled**	**Strongly-coupled**
D = 4		
D = 5		

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$\epsilon \to 0$ (arrow from Light-dilaton to Coleman-Weinberg)

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D = 5	**Warped fifth dimension** $$V(\mu) = v_{\rm IR}^2 \mu^4 \left[(4+2\epsilon)\left(1 - \frac{v_{\rm UV}}{v_{\rm IR}}\left(\frac{\mu}{\mu_0}\right)^\epsilon\right)^2 + \delta\right]$$	

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$\epsilon \to 0$

holography

Cosmological consequences of supercooling

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1) Large GW spectrum

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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’

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

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Normalisation

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Normalisation **Scalar field fraction**

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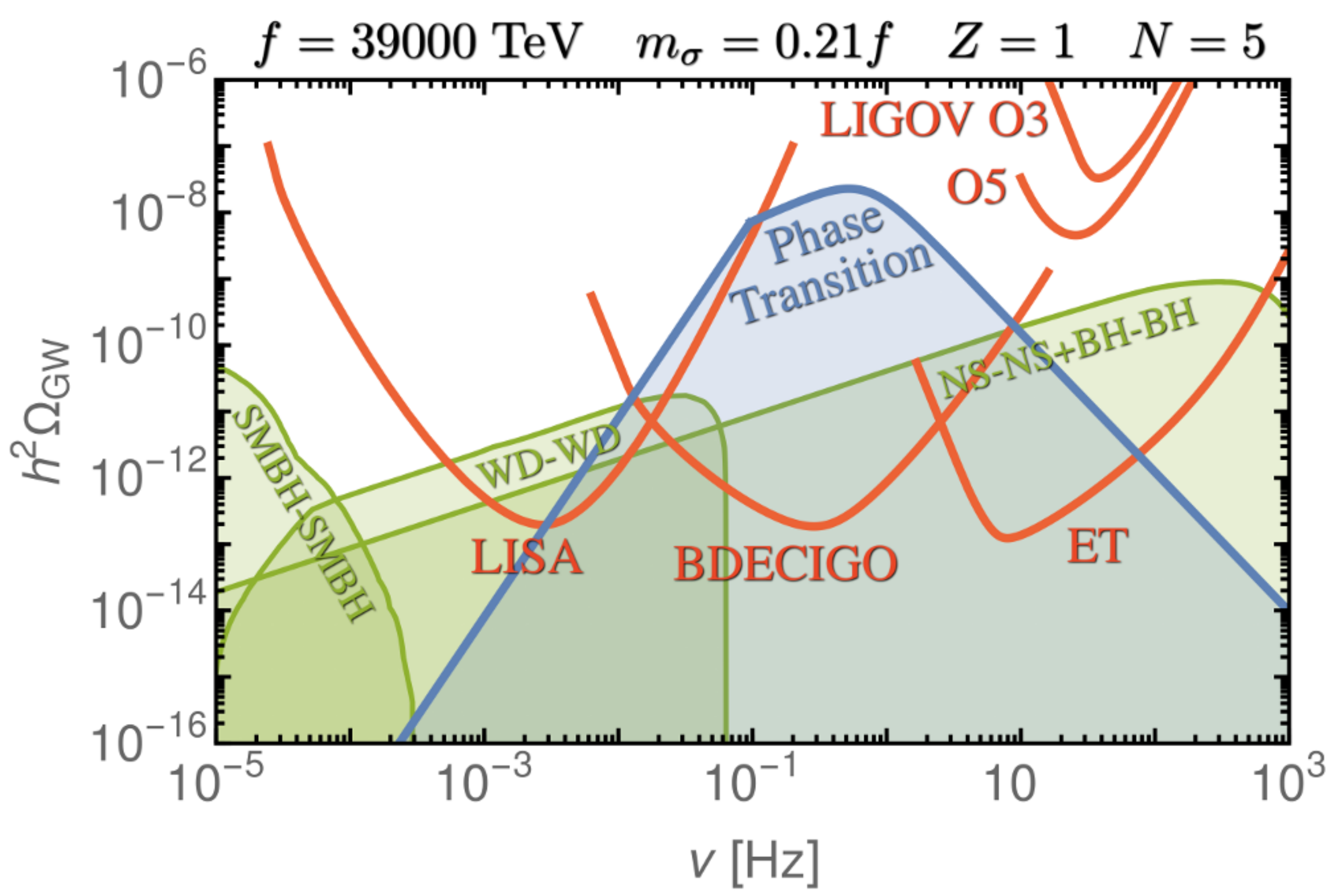
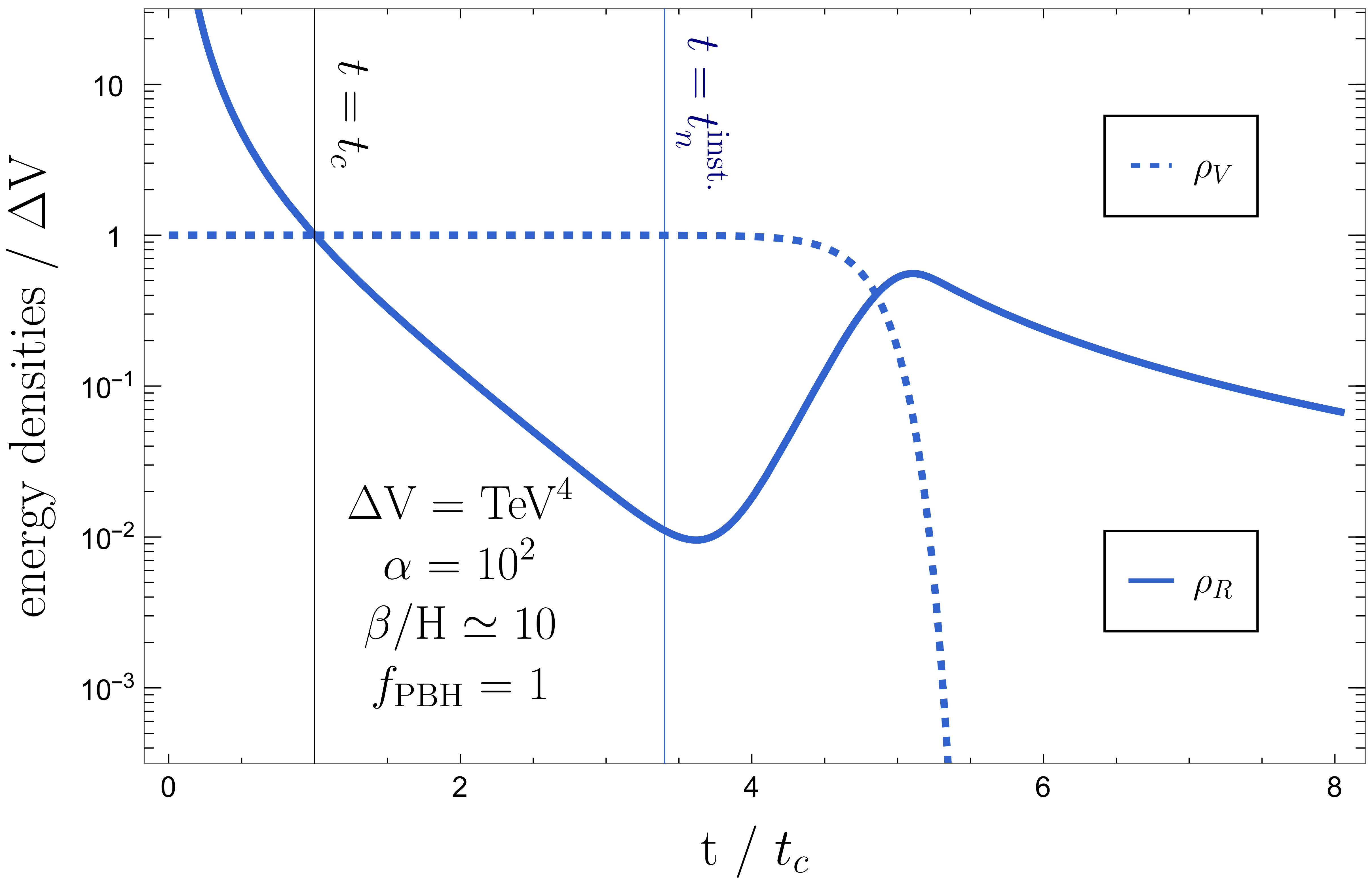


Baldes, YG, Sala, Servant 21'

2) Dilution of relics



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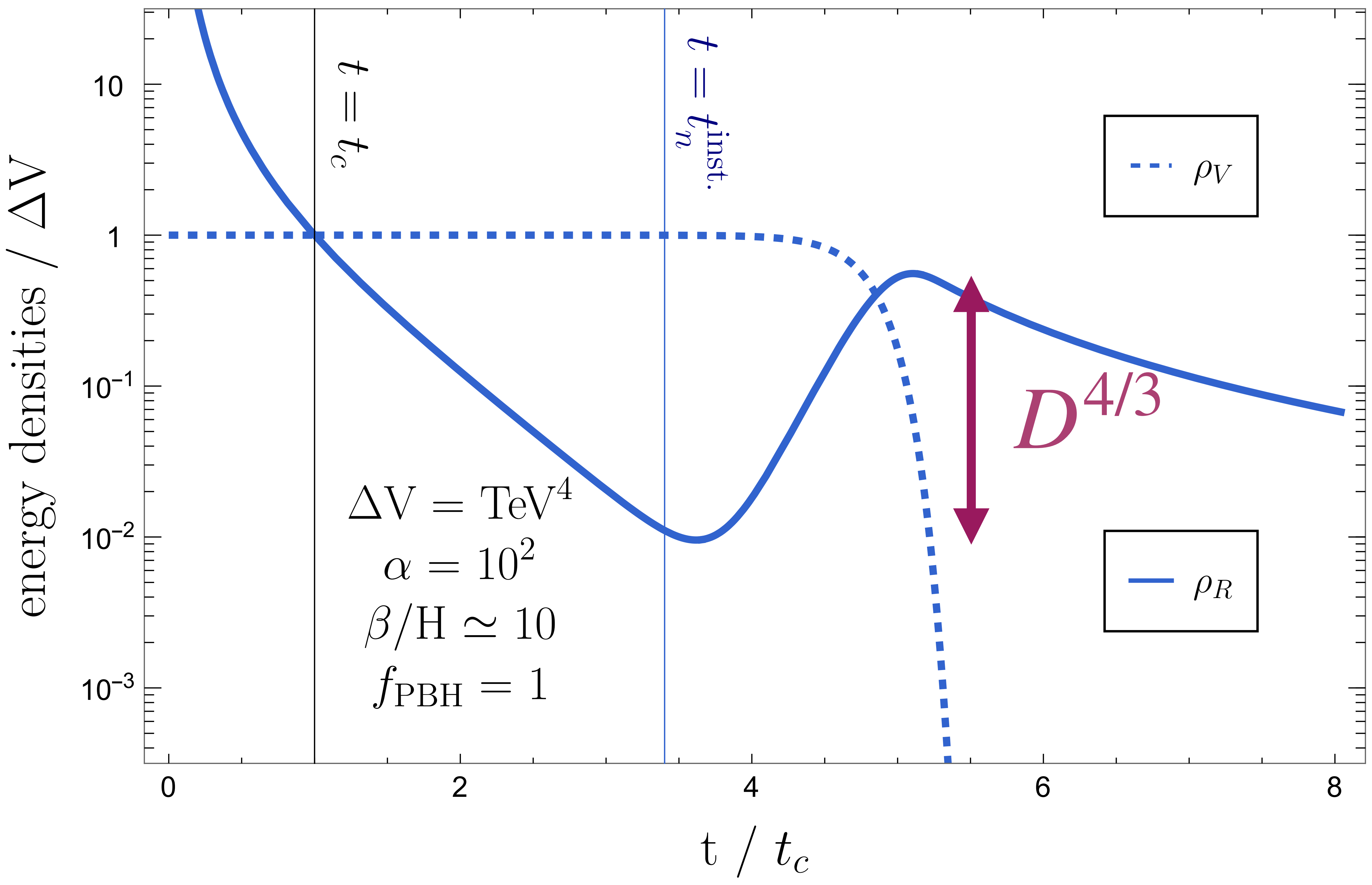

$$D = \frac{S_{\text{after}}}{S_{\text{before}}} = \left(\frac{T_c}{T_{\text{nuc}}}\right)^3$$

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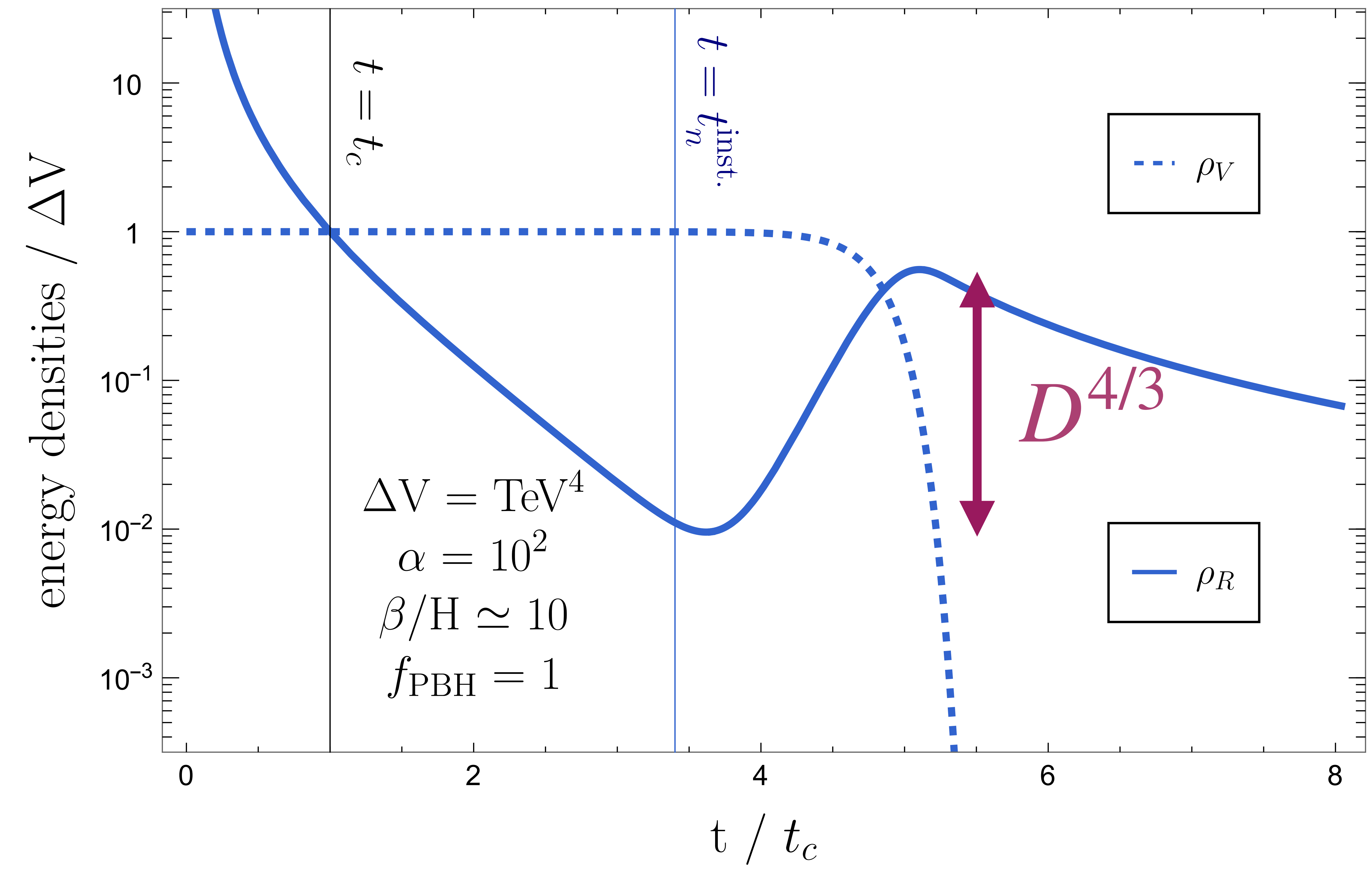


$$D = \frac{S_{\text{after}}}{S_{\text{before}}} = \left(\frac{T_c}{T_{\text{nuc}}}\right)^3$$

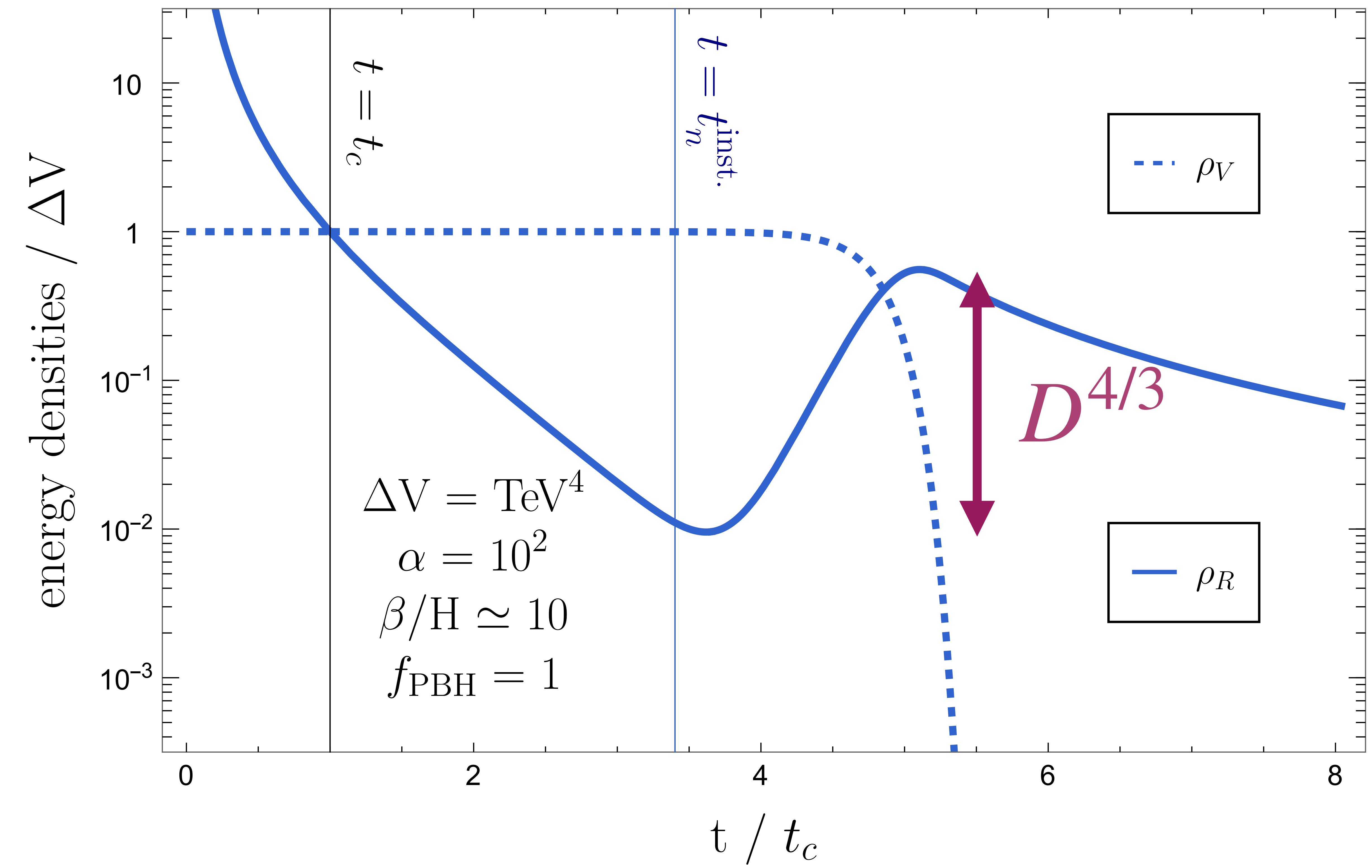
Evade unitarity bound on thermal DM

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

Griest&Kamionskowski 91'

Reheating after PT

2) Dilution of relics



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(Konstandin, Servant 11') Warped fifth dimension

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Griest&Kamionskowski 91'

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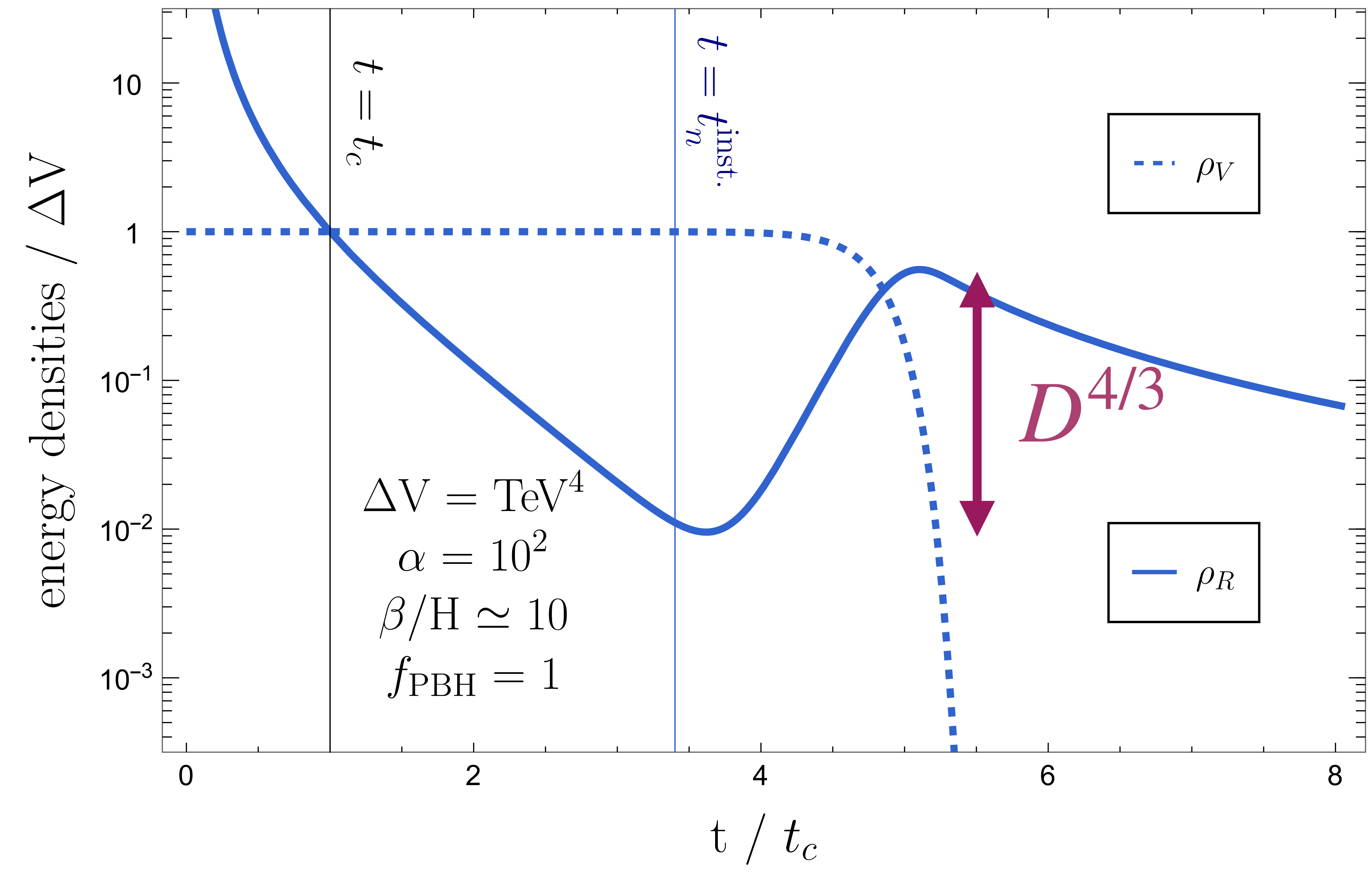

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(Hambye, Strumia, Teresi 18') Weakly-coupled

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Griest&Kamionskowski 91'

Reheating after PT

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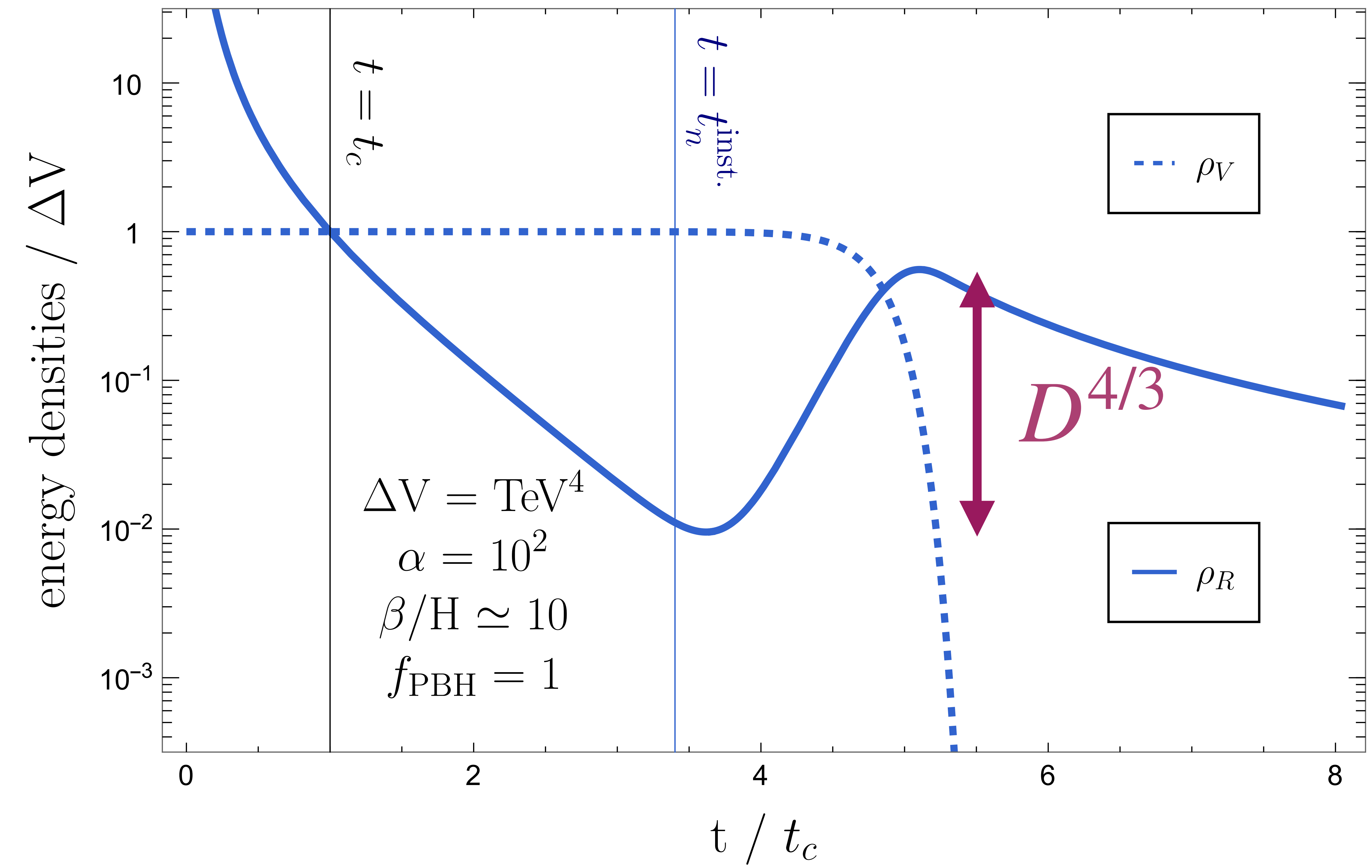

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(Konstandin, Servant 11') Warped fifth dimension

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(Baratella, Pomarol, Rompineve 18')

Baldes, YG, Sala 20'

Baldes, YG, Sala, Servant 21' Strongly-coupled

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Griest&Kamionskowski 91'

Reheating after PT

3) Relativistic bubble walls

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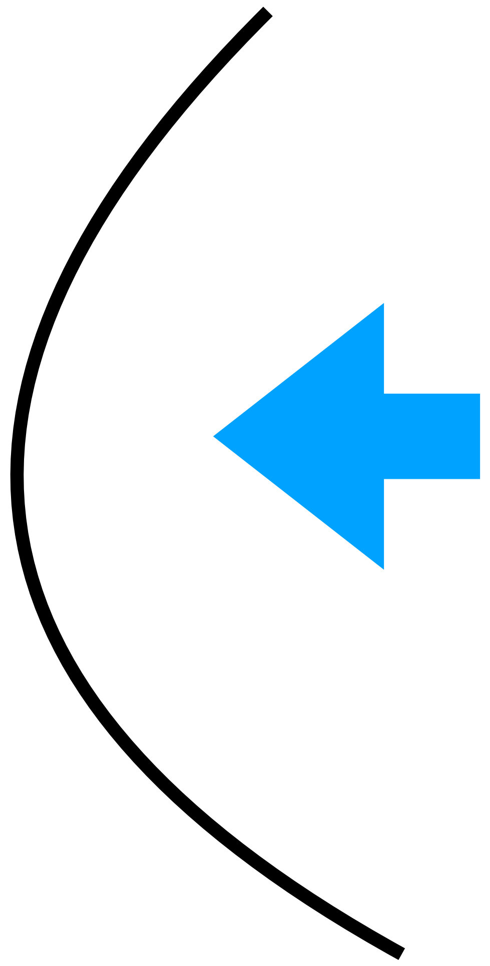
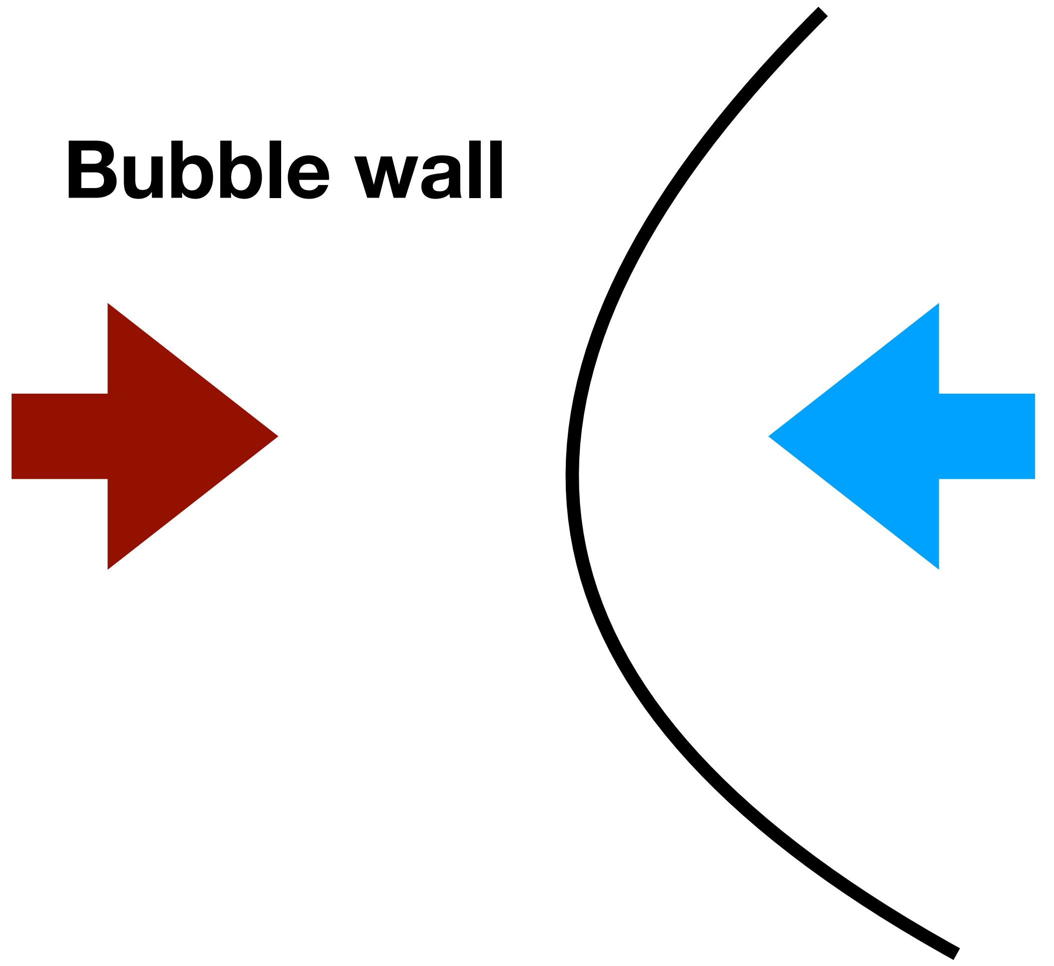


$$\Delta V_{\rm vac} \simeq T_c^4$$

3) Relativistic bubble walls

$$\mathscr{P}_{\rm LO} \simeq \Delta m^2 T_{\rm nuc}^2$$

Bodeker, Moore 09’



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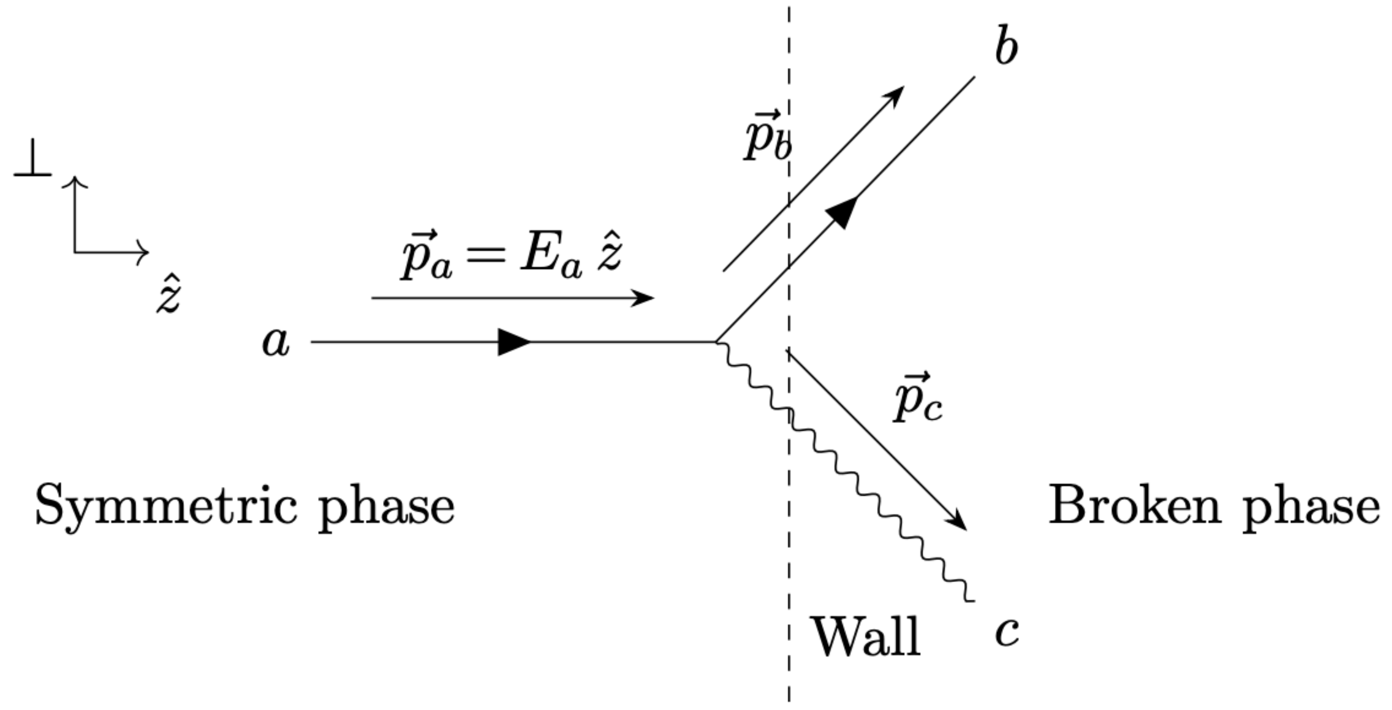
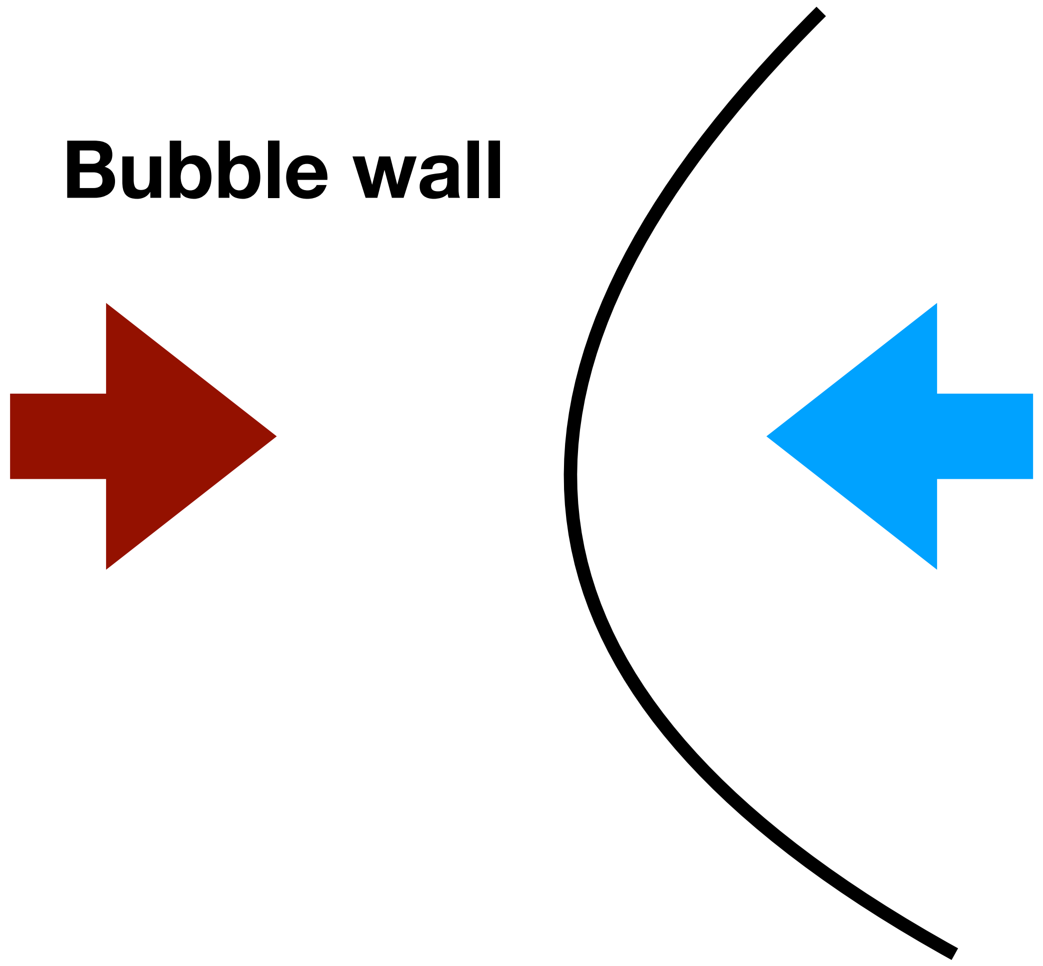
Bodeker, Moore 09’

$$\mathscr{P}_{\mathrm{NLO}} \simeq g_{\mathrm{W}} \gamma \, \Delta m T_{\mathrm{nuc}}^3$$



Bodeker, Moore 17’ (Perturbative level)



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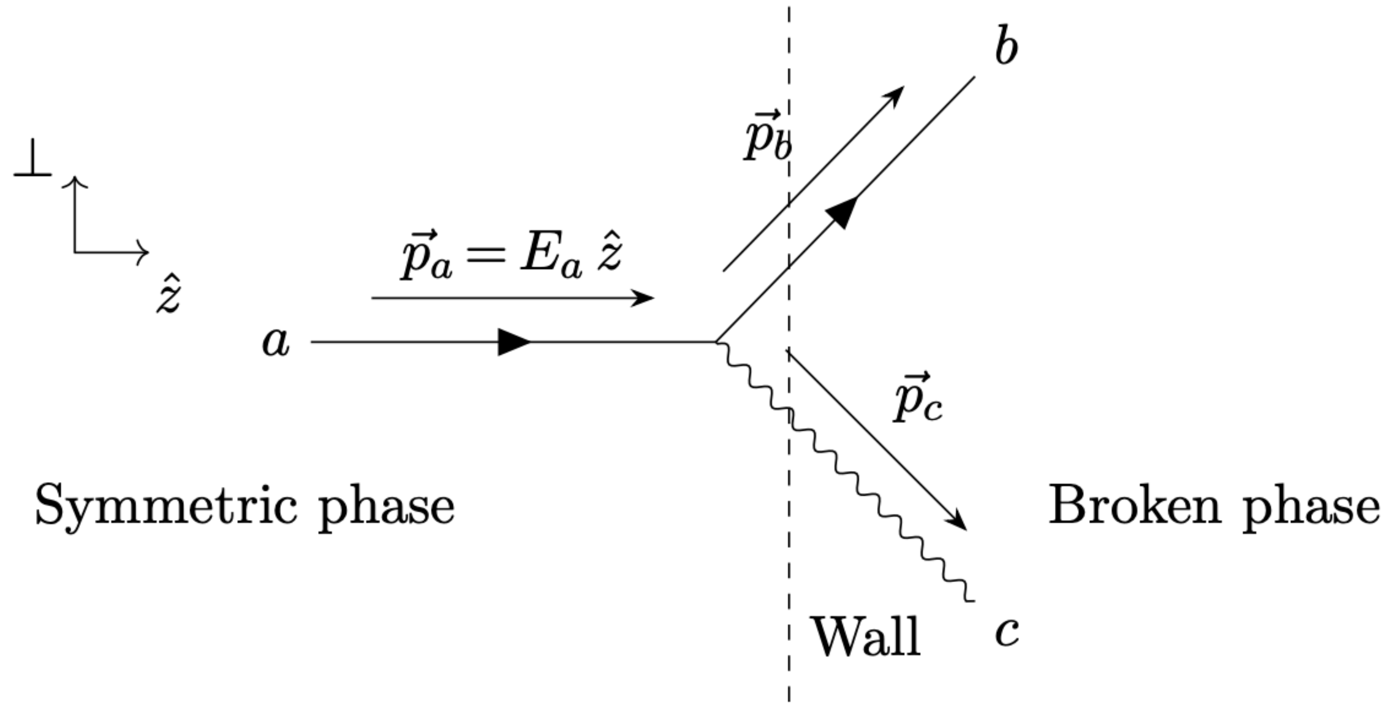
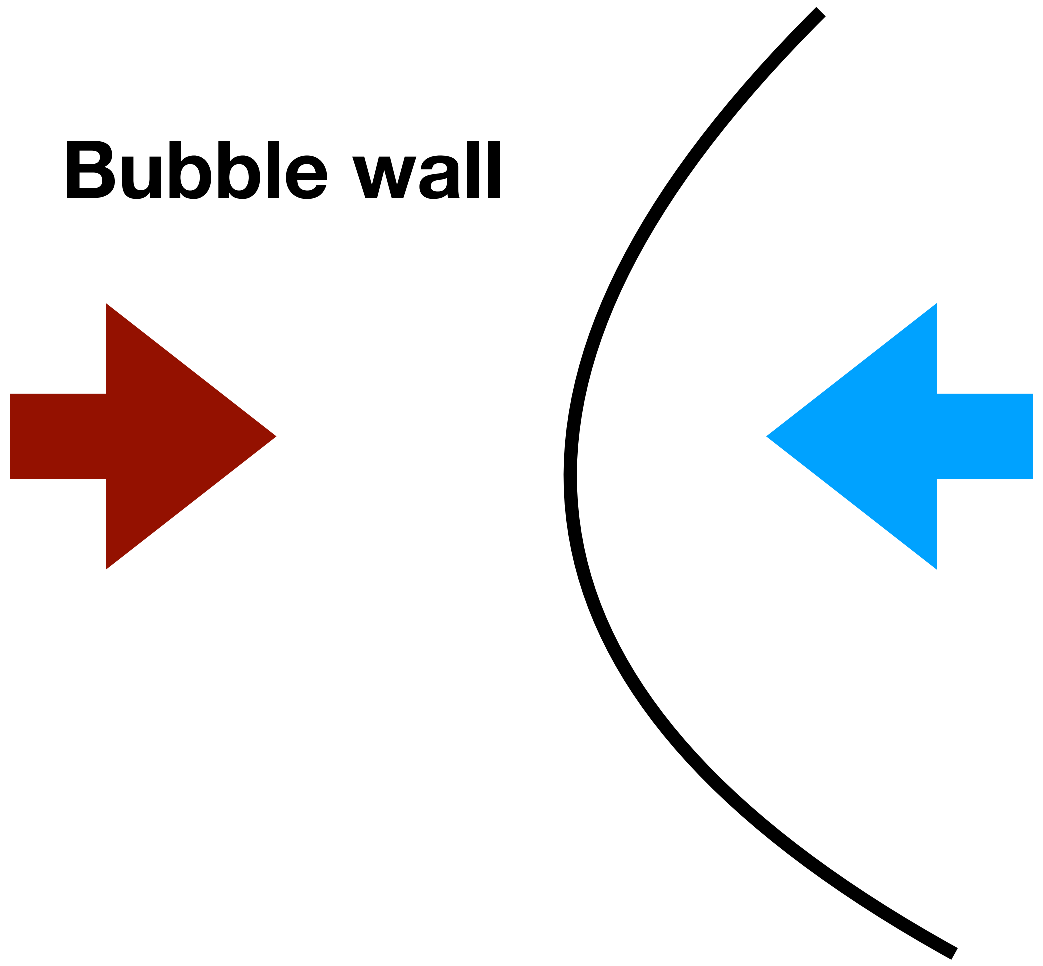


Bodeker, Moore 17’ (Perturbative level)

YG, Jinno, Sala 21’ (Sudakov resummation)
Baldes, YG, Sala 20’ (Gluon string description)



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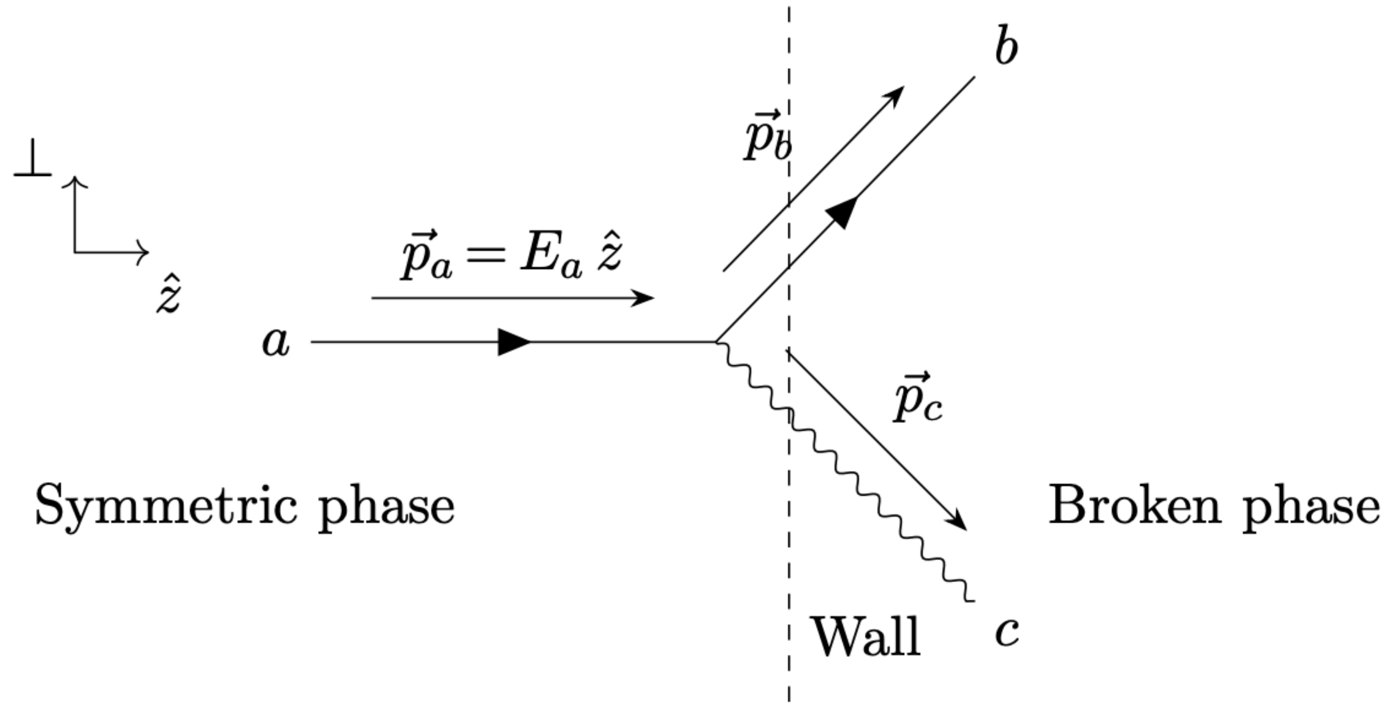

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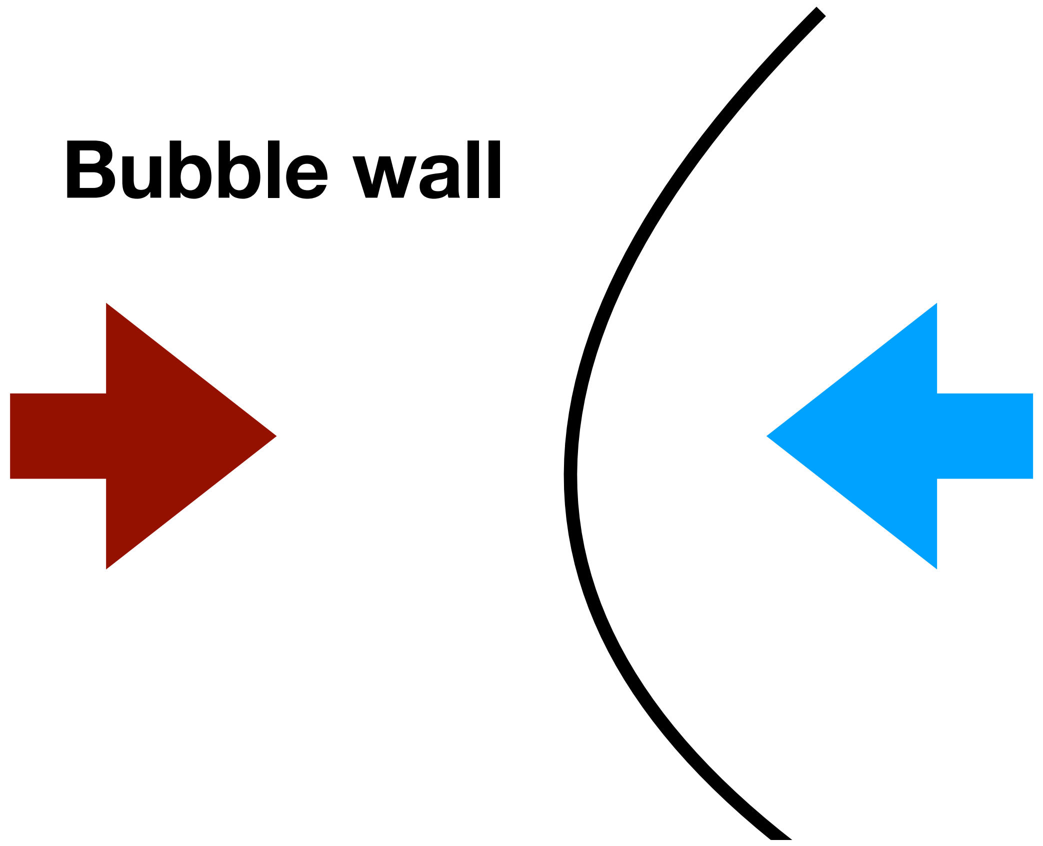

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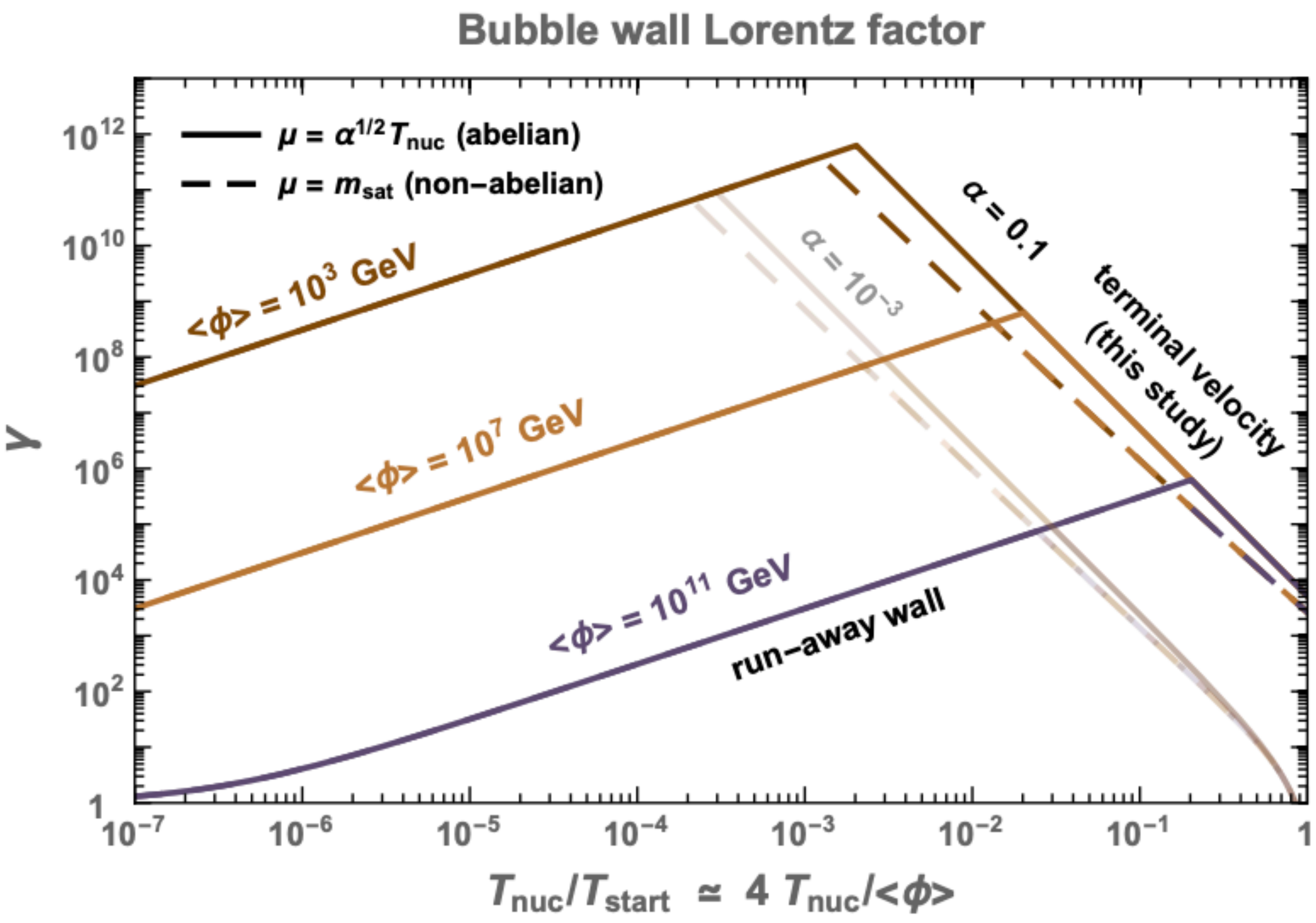

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Bodeker, Moore 09’

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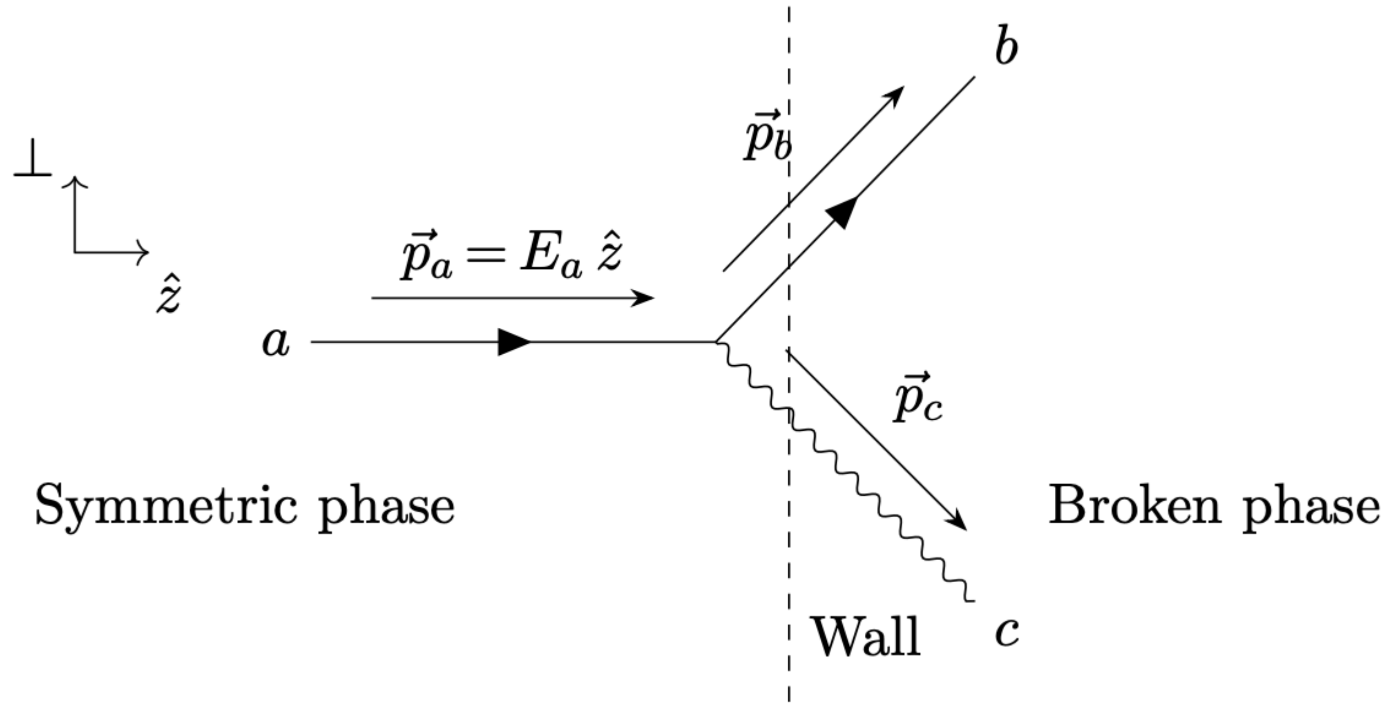

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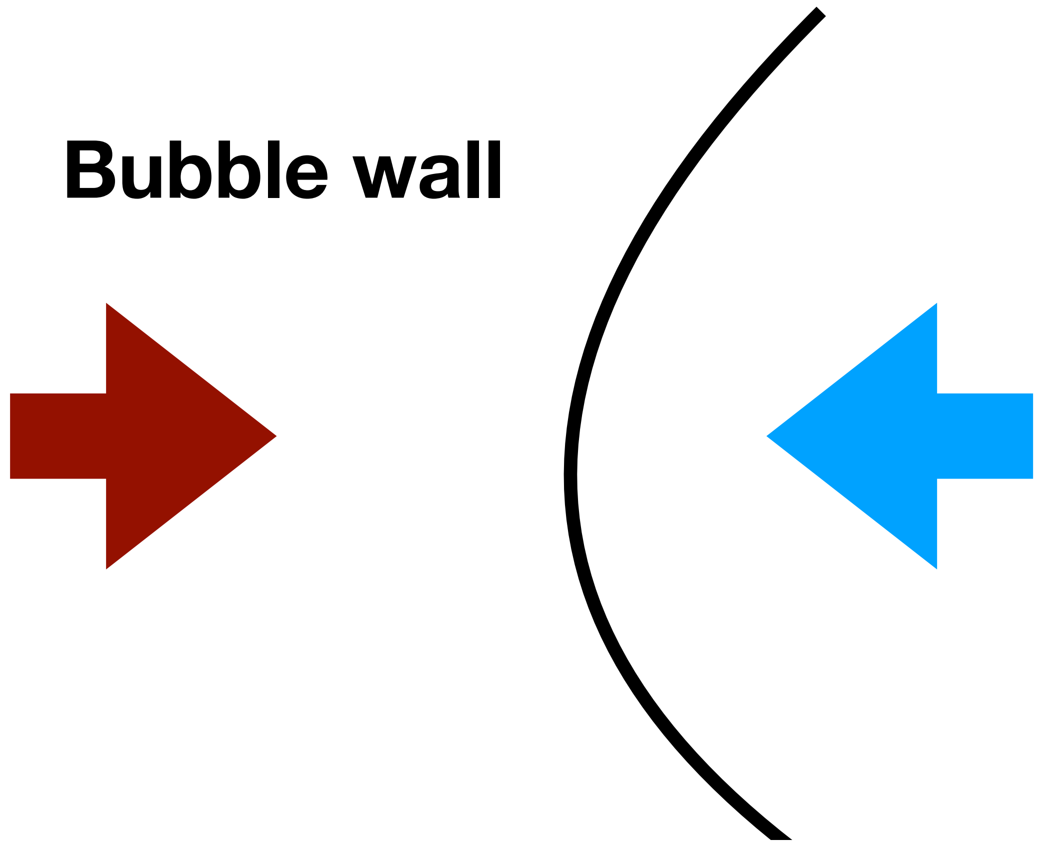
There is still a gauge invariance problem

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



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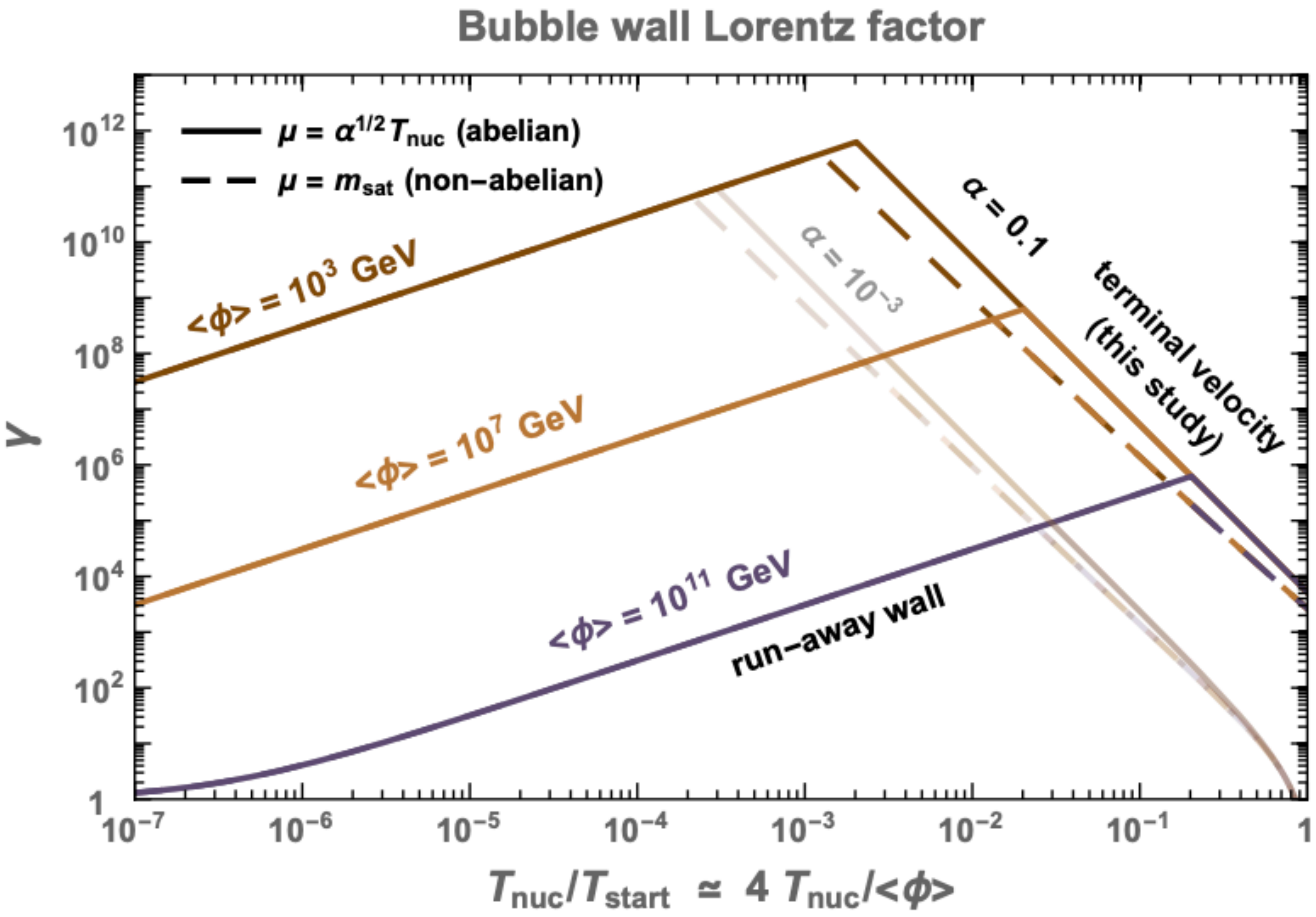

4) High energy particle production

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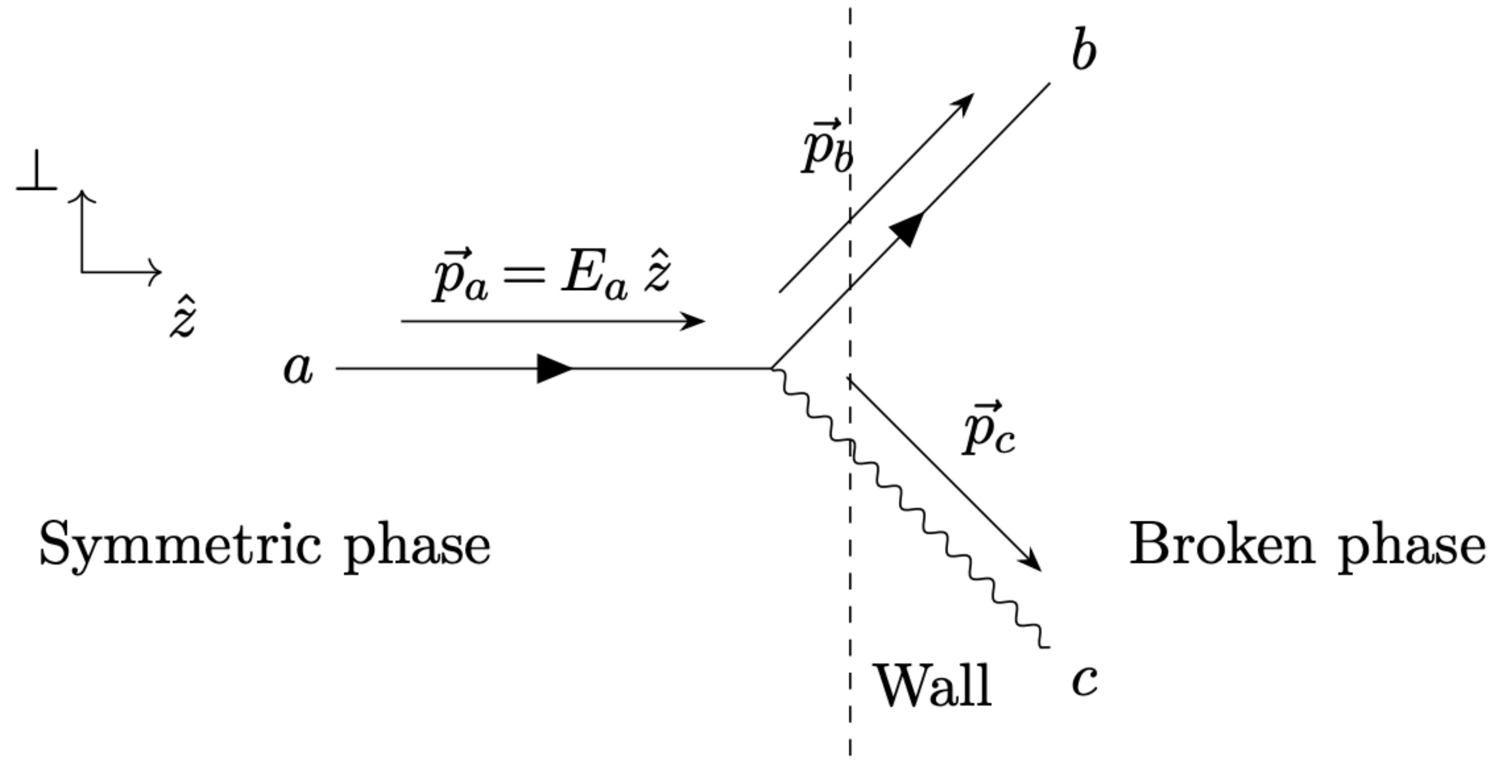
a) Weak interaction with plasma

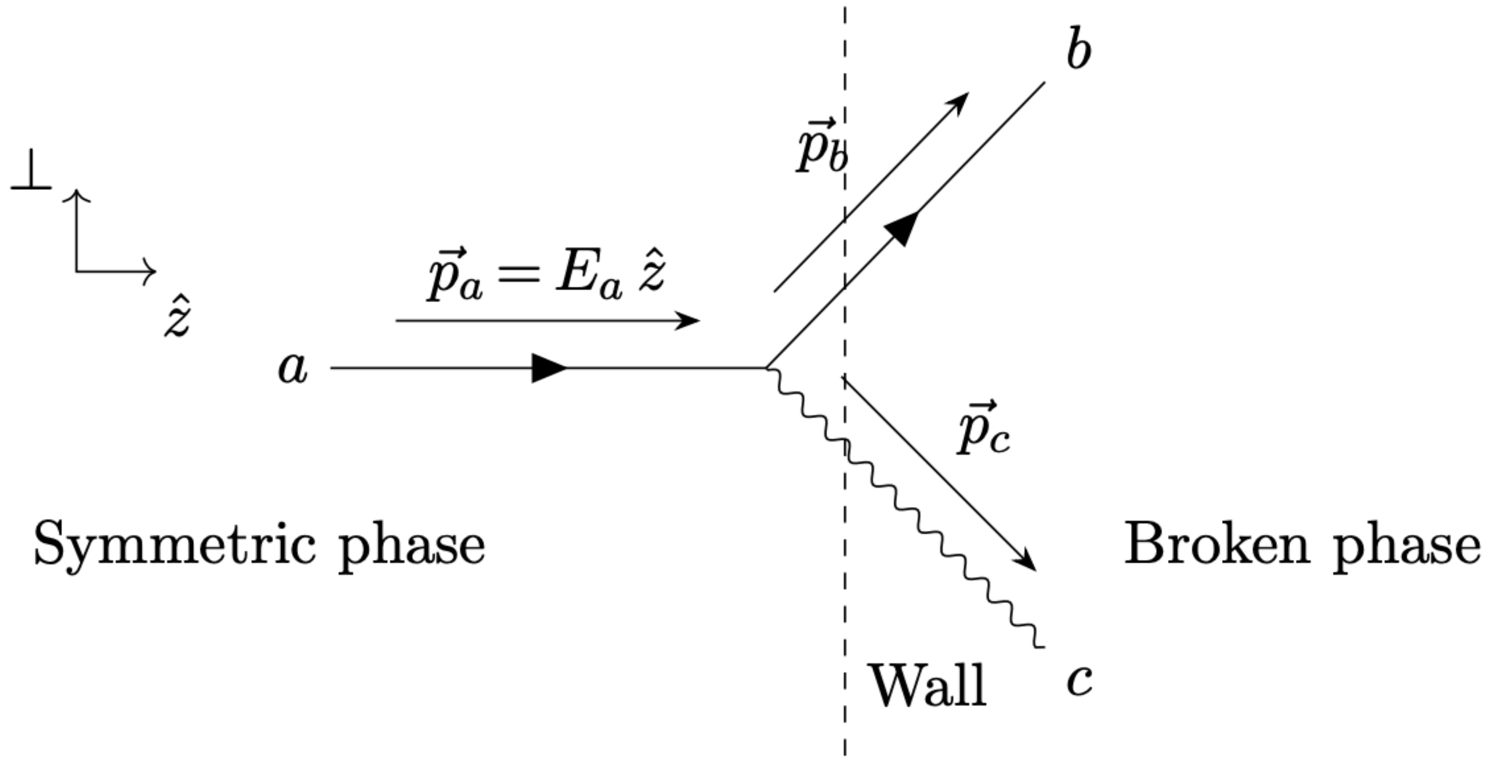
Bodeker, Moore 17'



4) High energy particle production

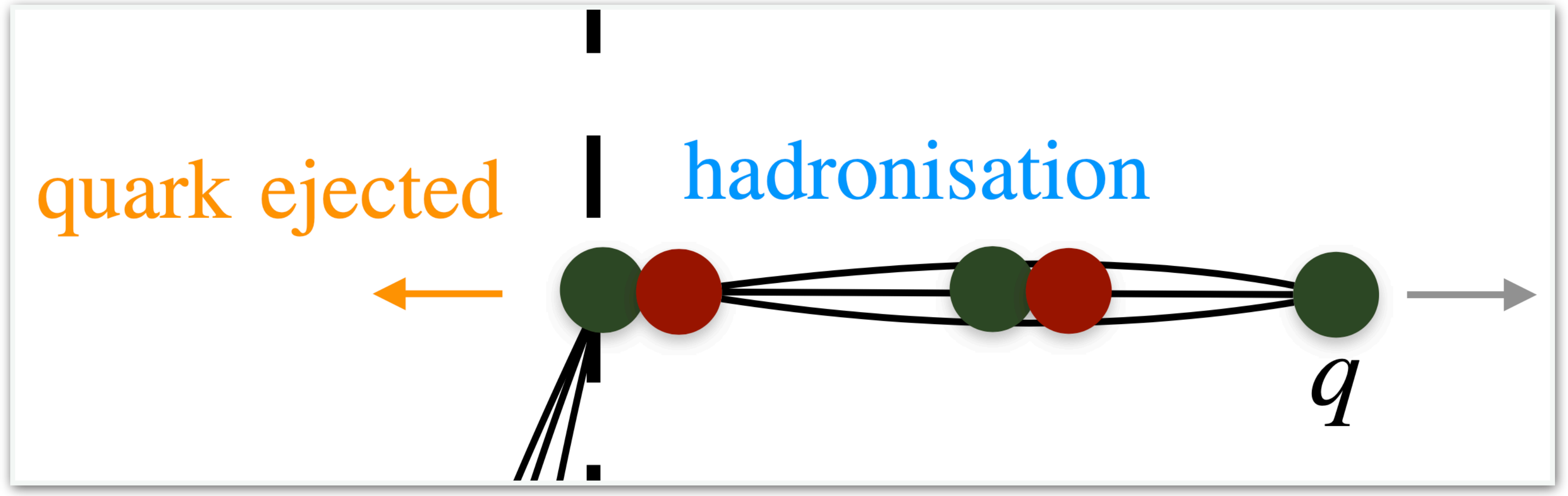
a) Weak interaction with plasma

Bodeker, Moore 17'



b) Strong interaction with plasma

Baldes, YG, Sala 20'

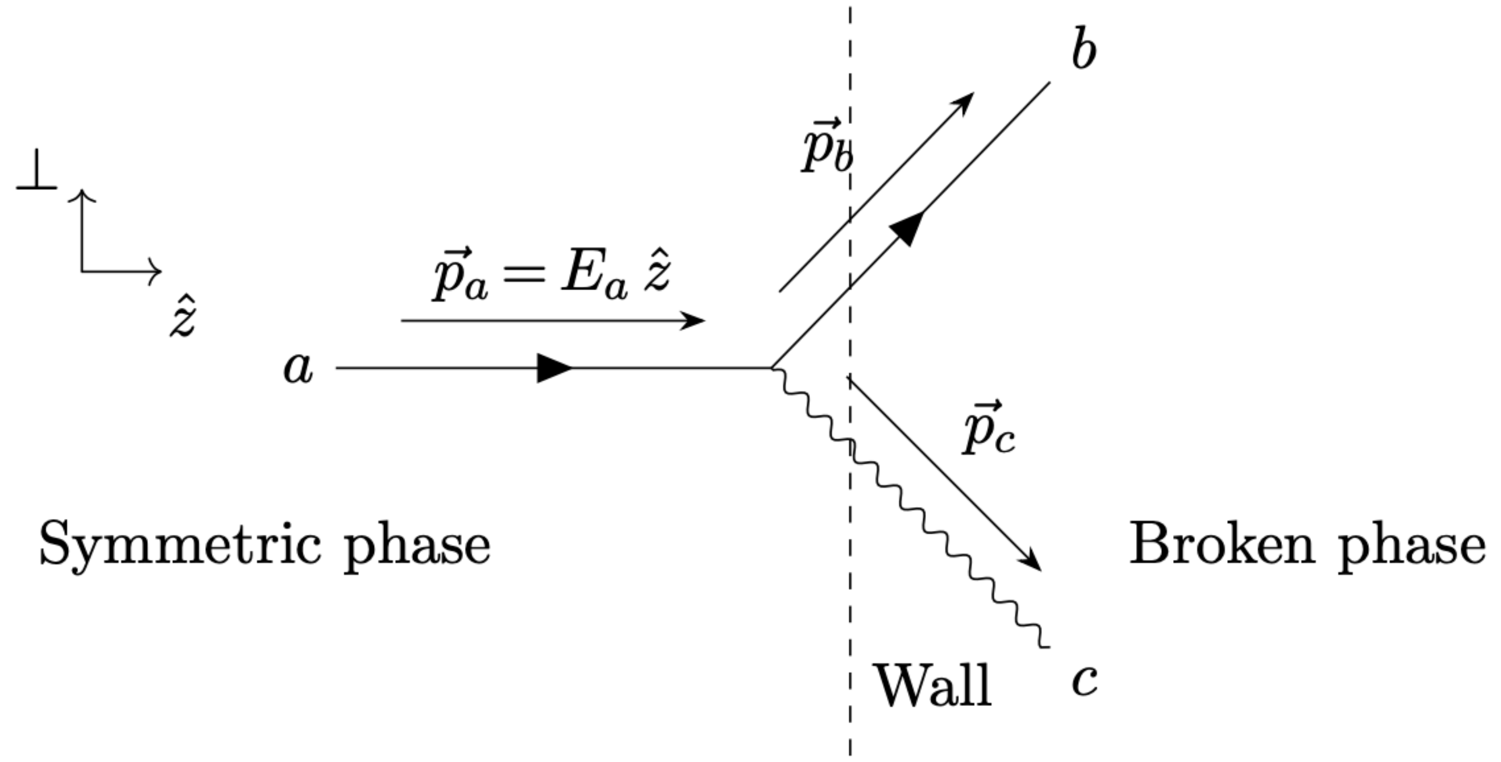


Maximilian Dichtl and Filippo Sala (to appear)

4) High energy particle production

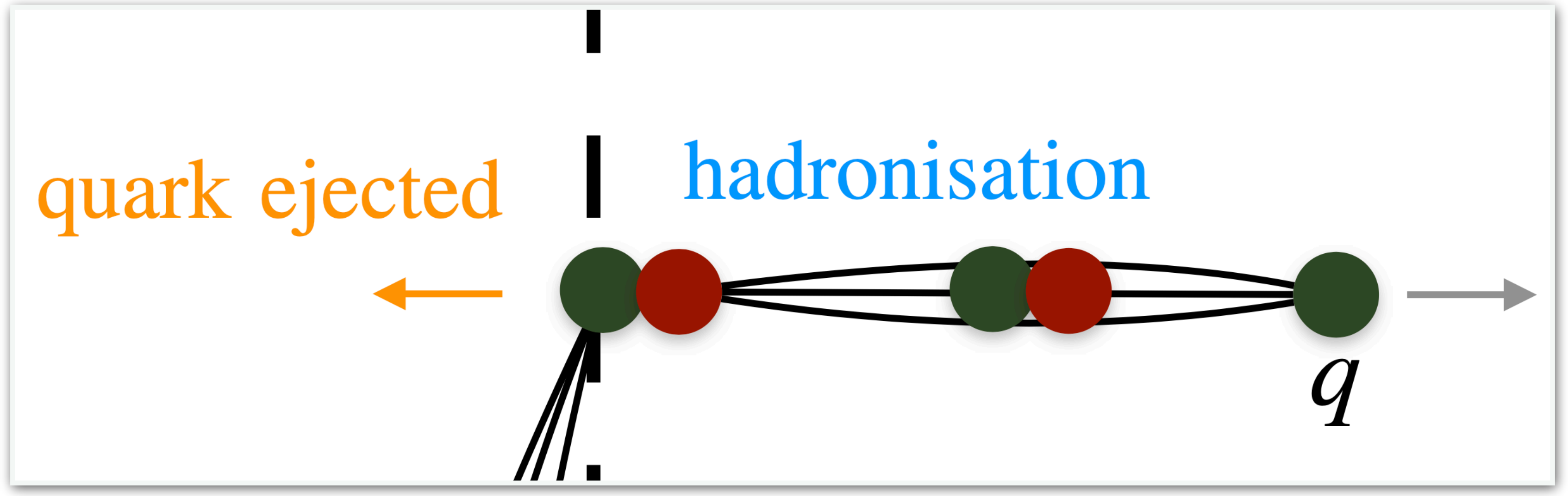
a) Weak interaction with plasma

Bodeker, Moore 17'



b) Strong interaction with plasma

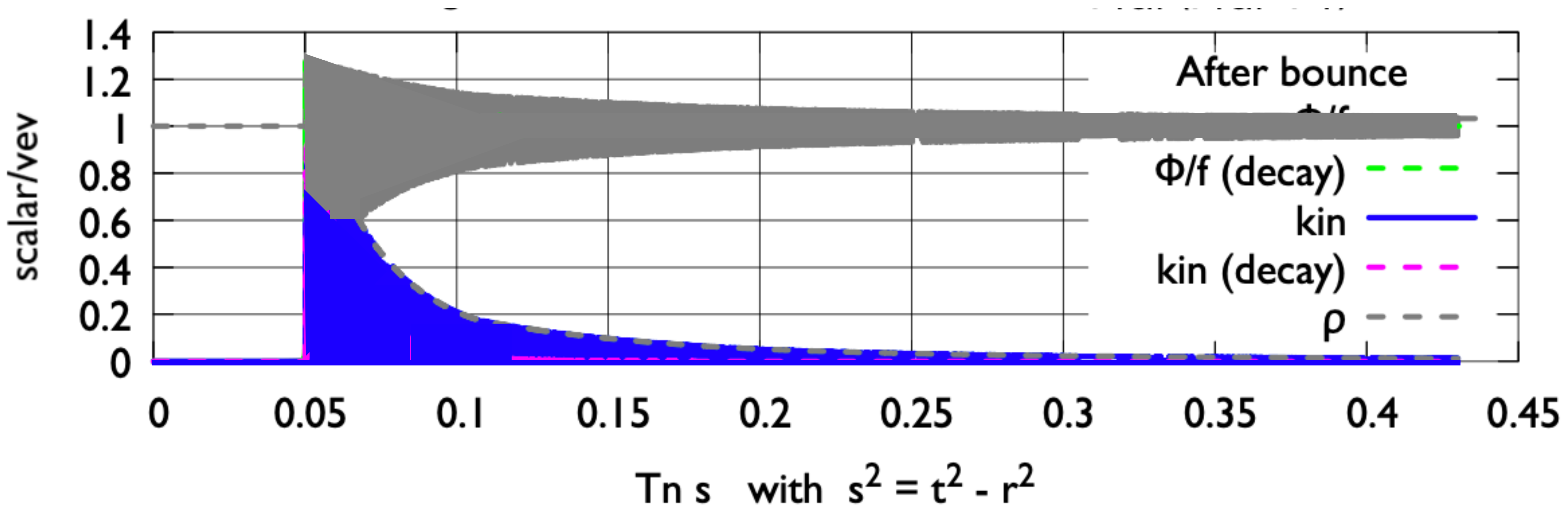
Baldes, YG, Sala 20'



Maximilian Dichtl and Filippo Sala (to appear)

c) Wall decay (YG)

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



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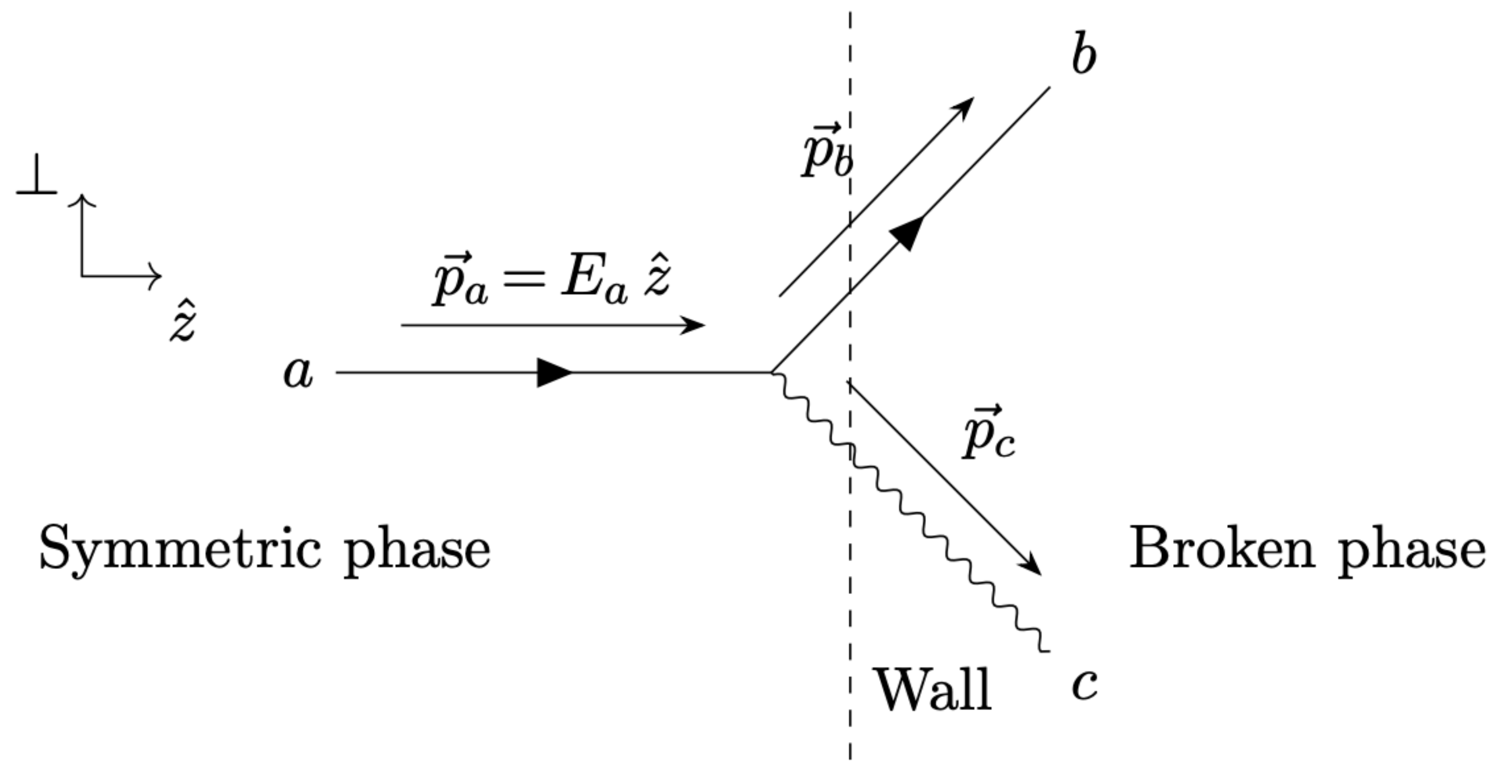
Bodeker, Moore 17'



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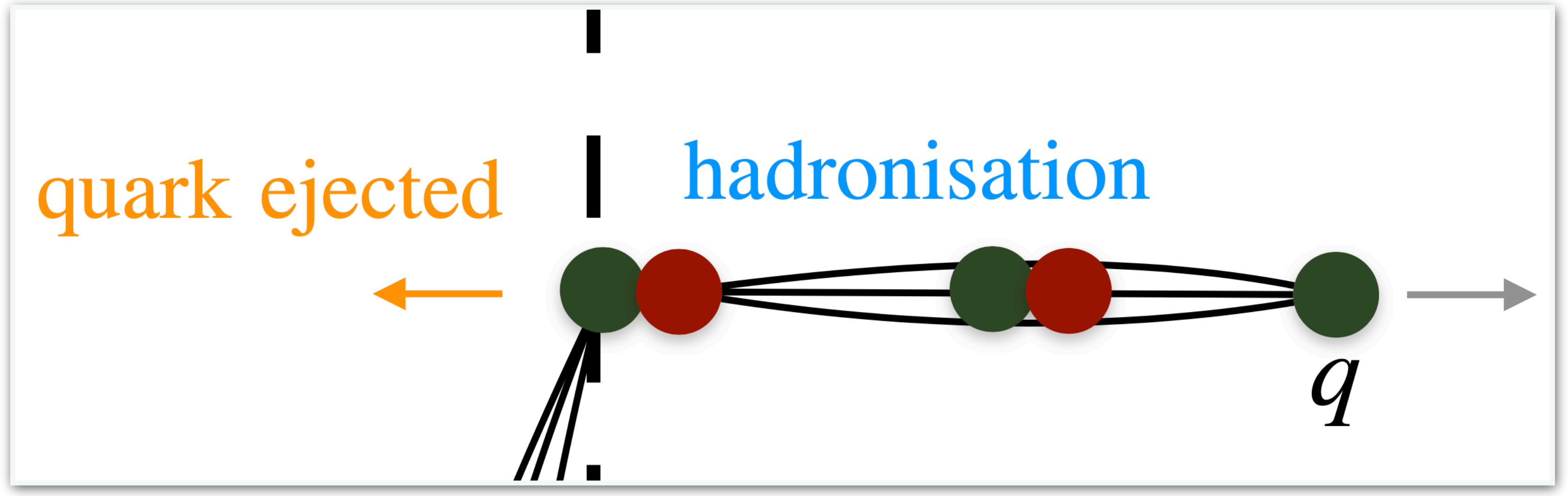
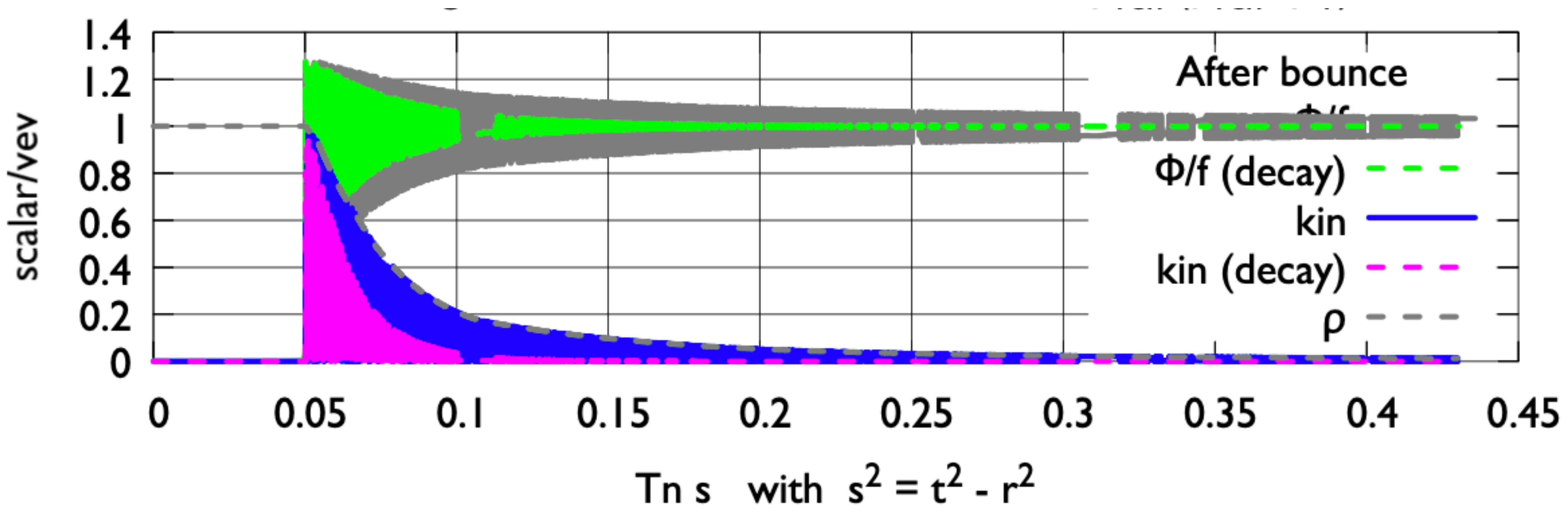


Maximilian Dichtl and Filippo Sala (to appear)

c) Wall decay (YG)

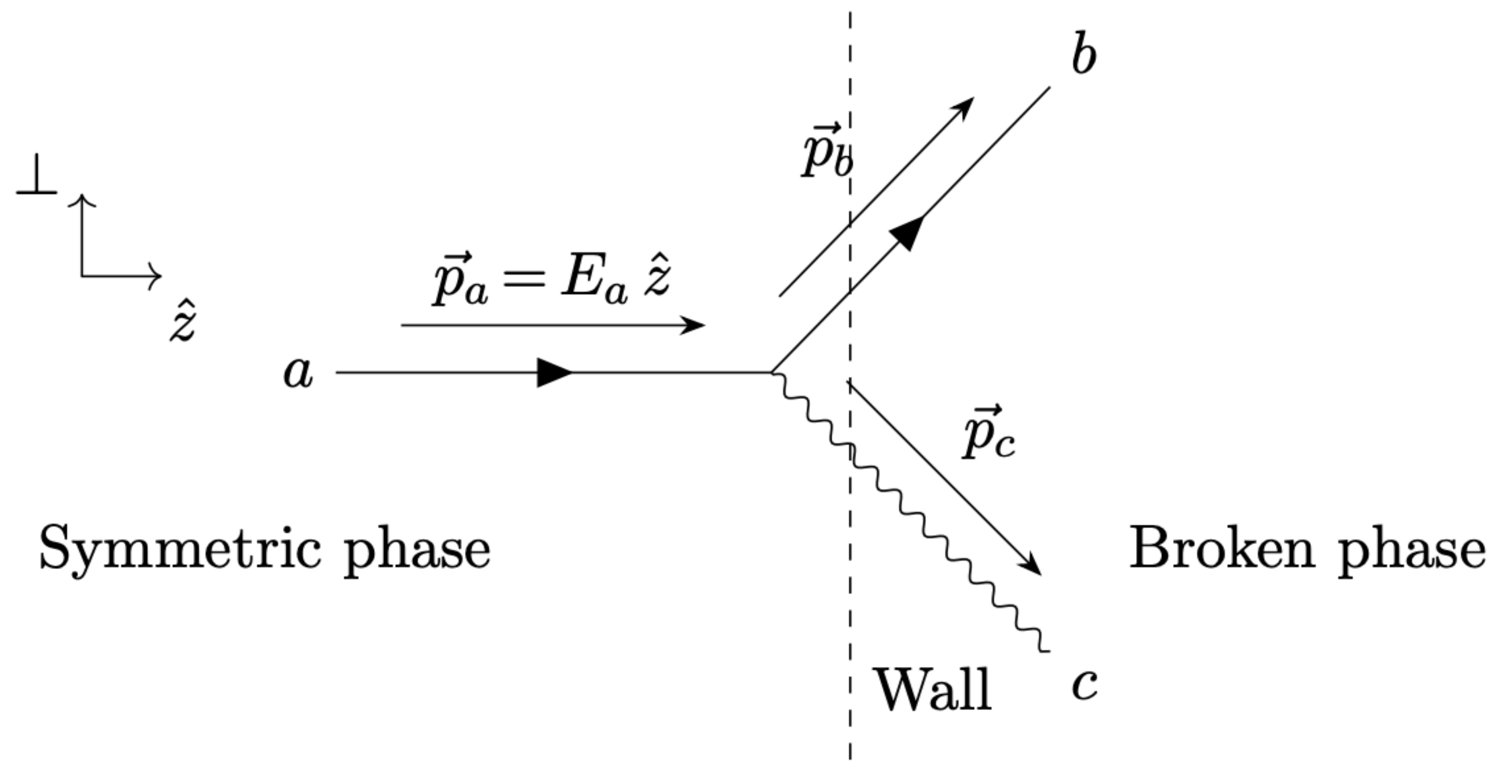
$$\frac{\partial^2 \phi}{\partial^2 s} + \left(\frac{3}{s} + \Gamma_\phi\right)\frac{\partial \phi}{\partial s} + \frac{\partial V}{\partial \phi} = 0$$



4) High energy particle production

a) Weak interaction with plasma

Bodeker, Moore 17'



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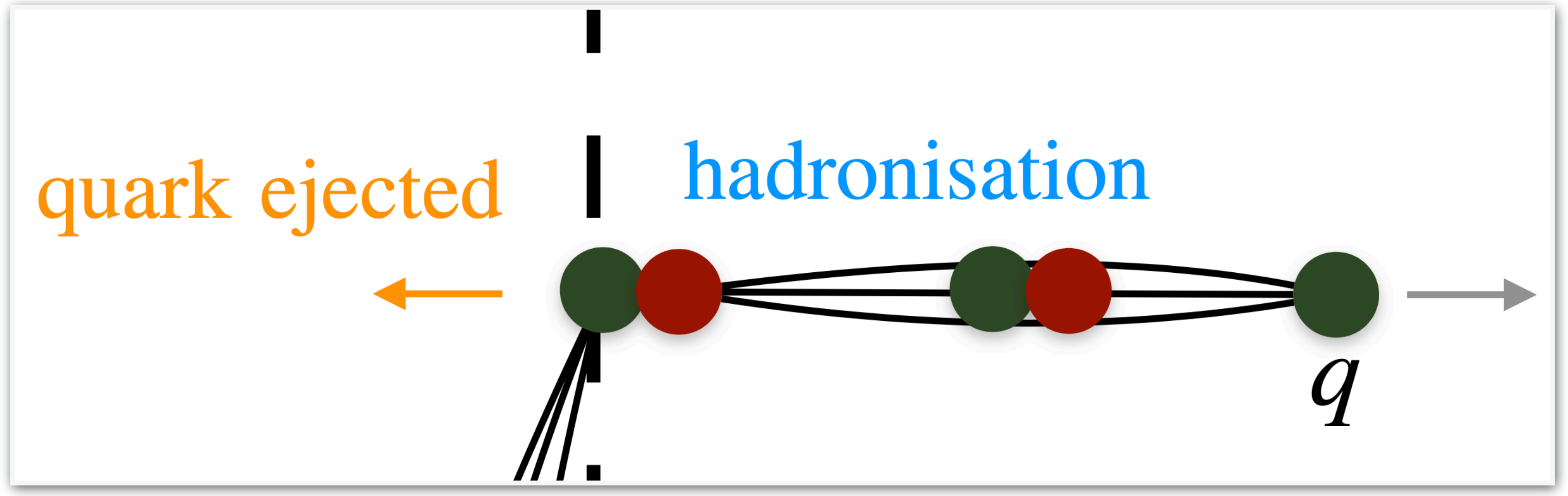

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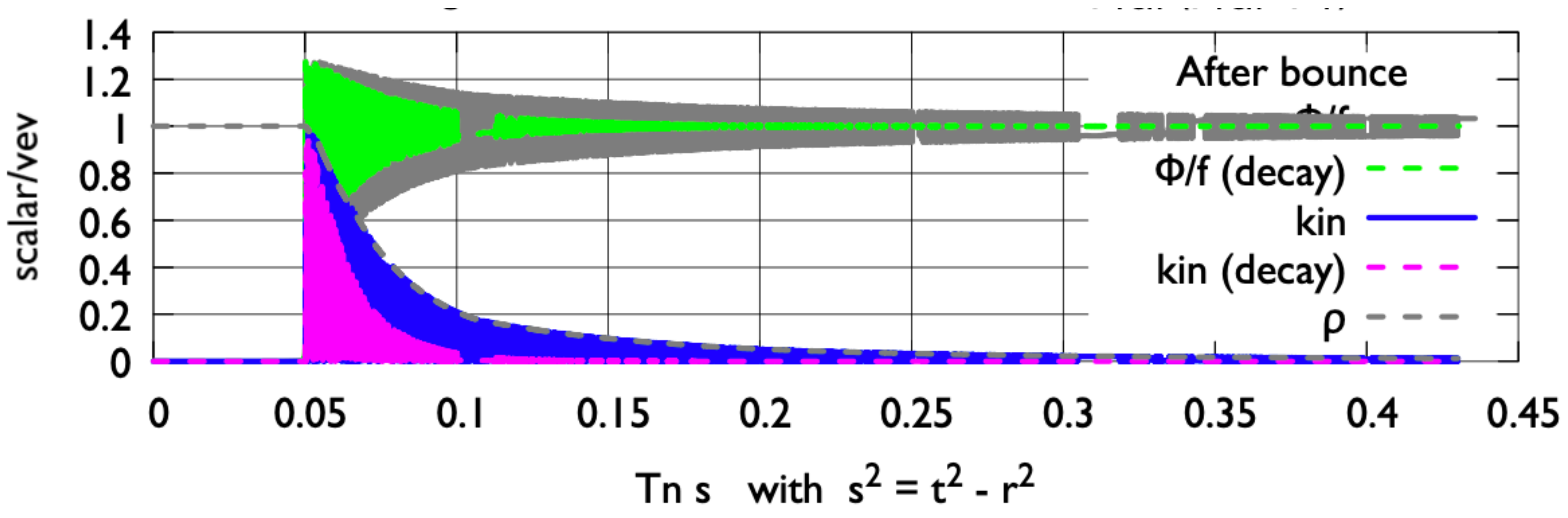
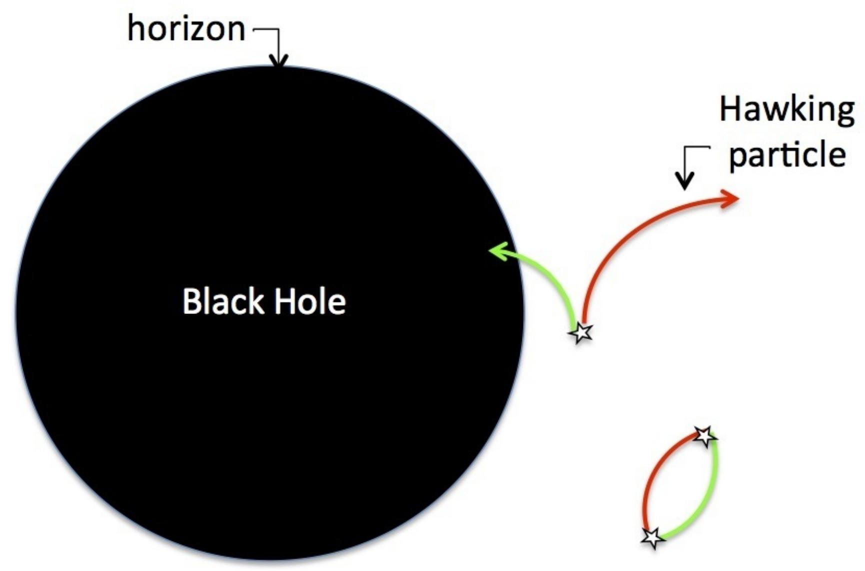


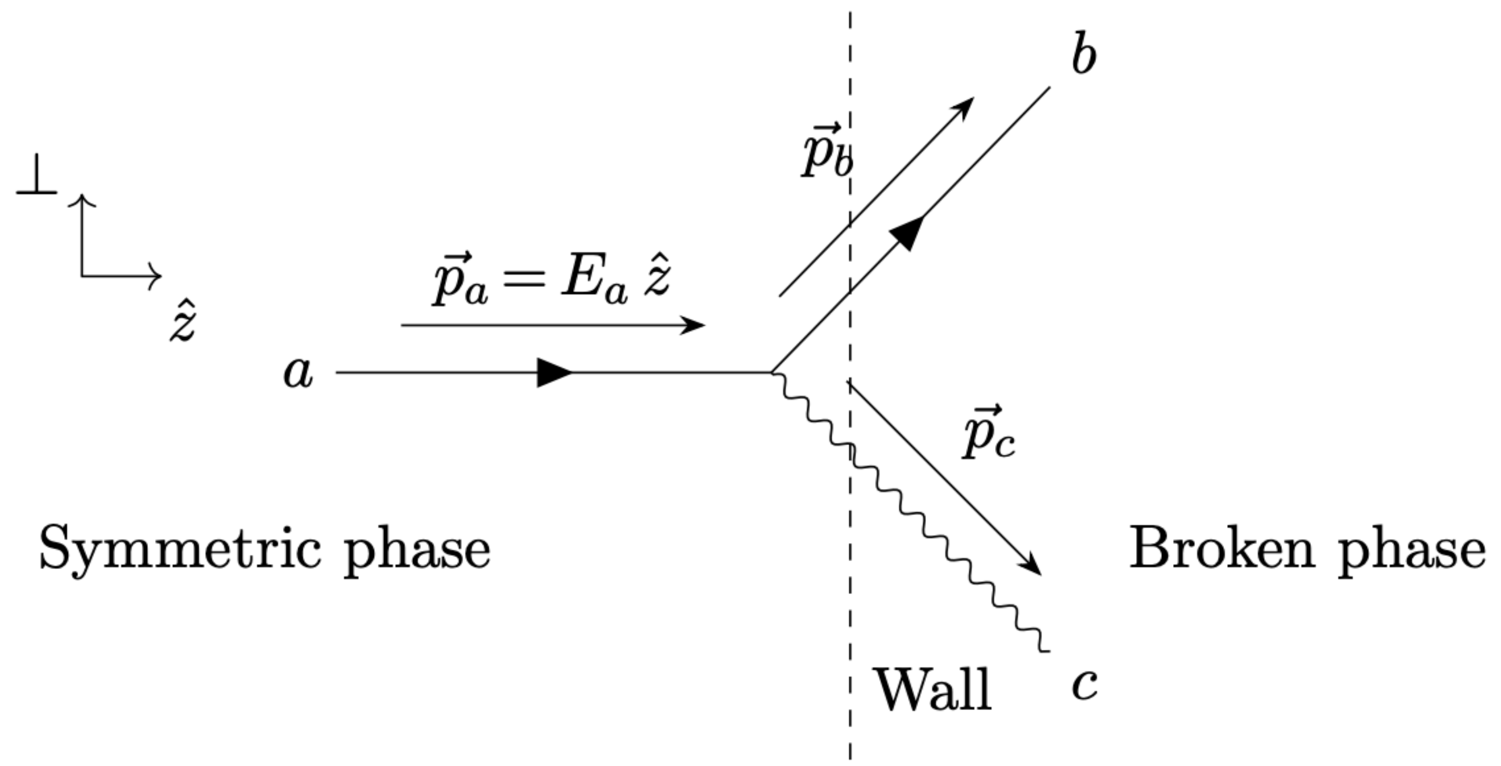
d) Unruh radiation (YG)



4) High energy particle production

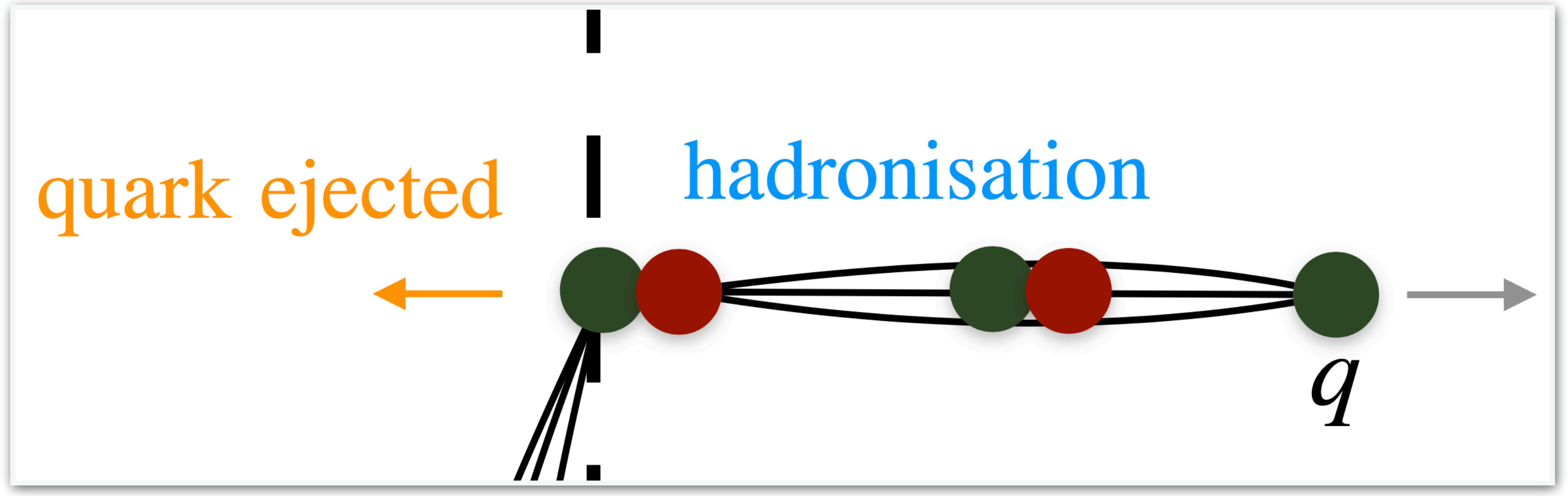
a) Weak interaction with plasma

Bodeker, Moore 17'



b) Strong interaction with plasma

Baldes, YG, Sala 20'



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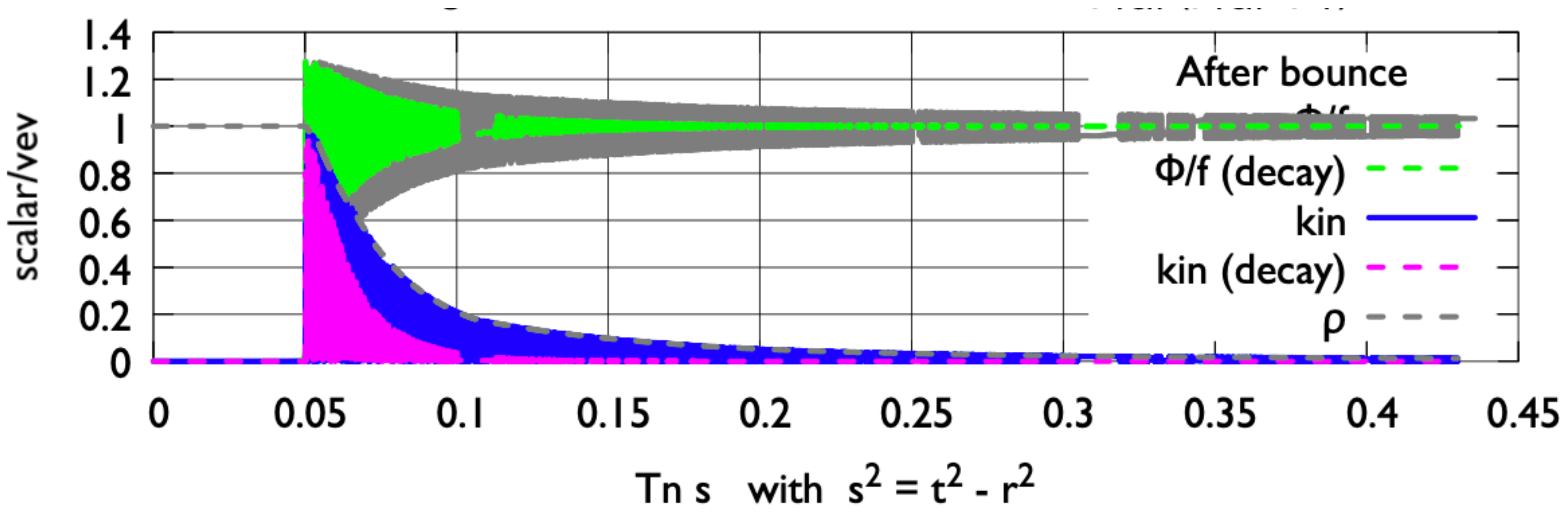

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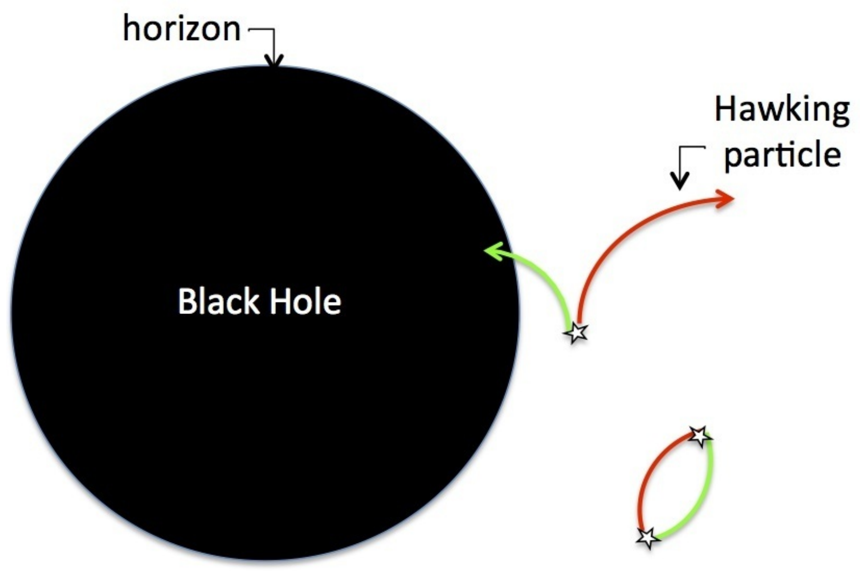
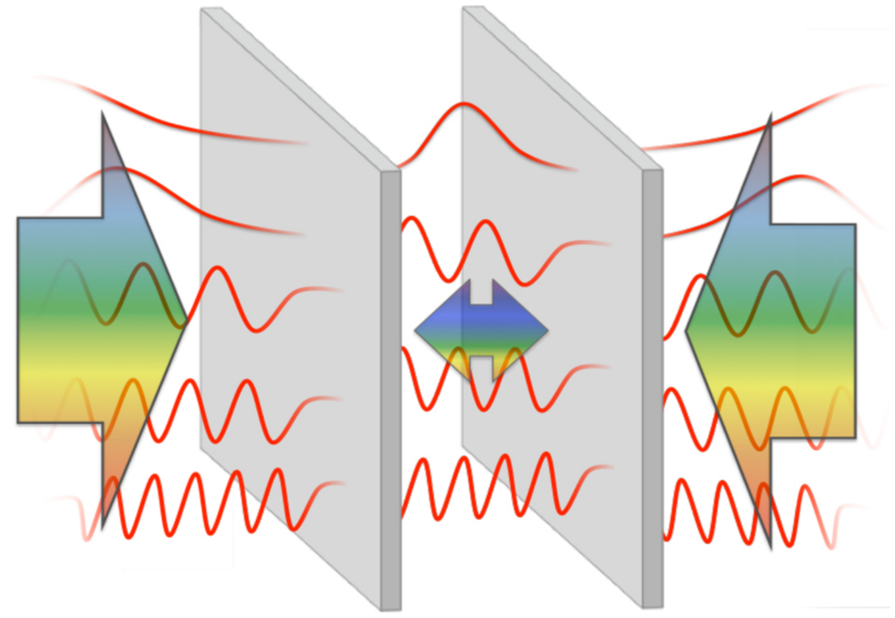


e) Dynamical Casimir (YG)



4) High energy particle production

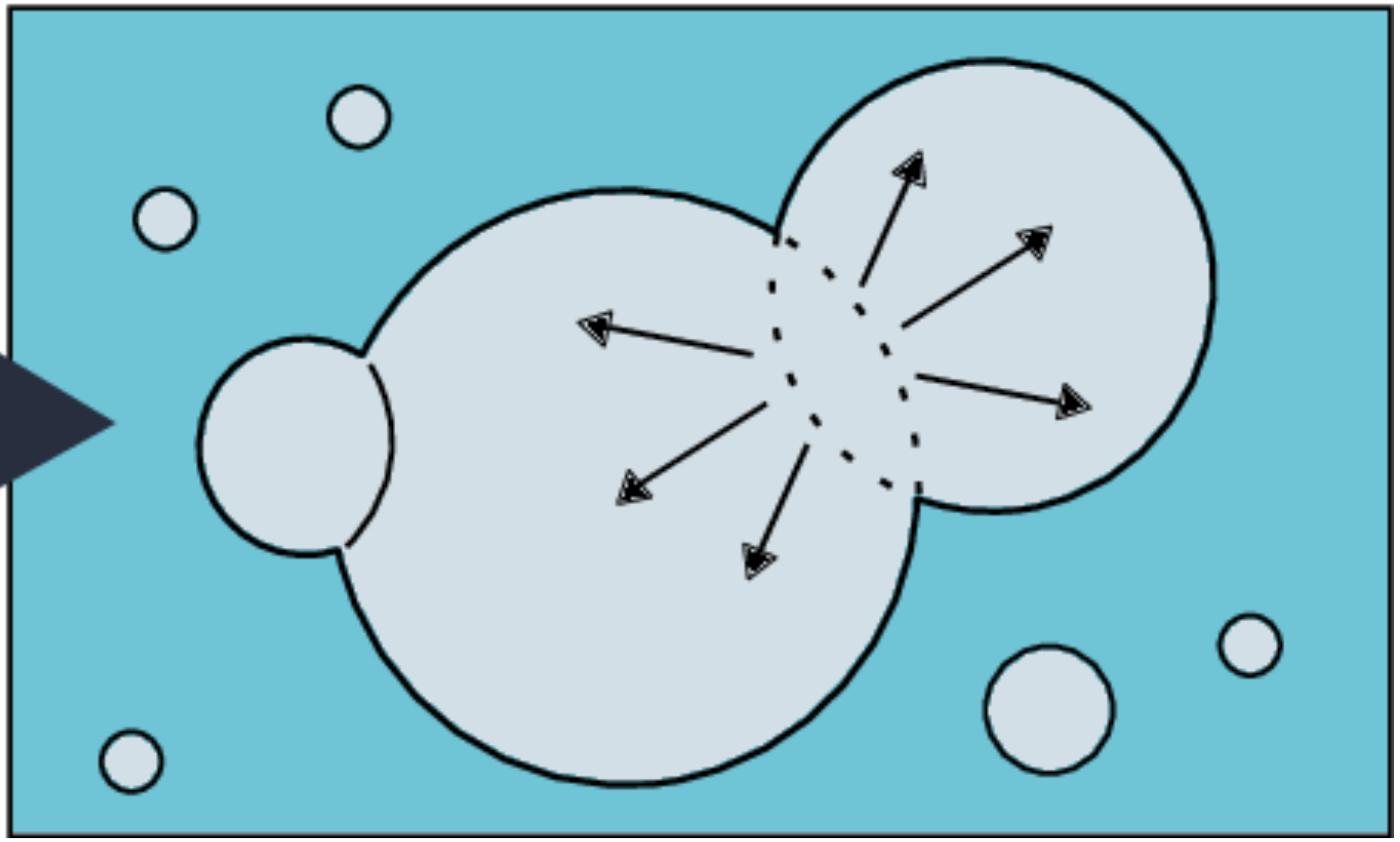
tevatron

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

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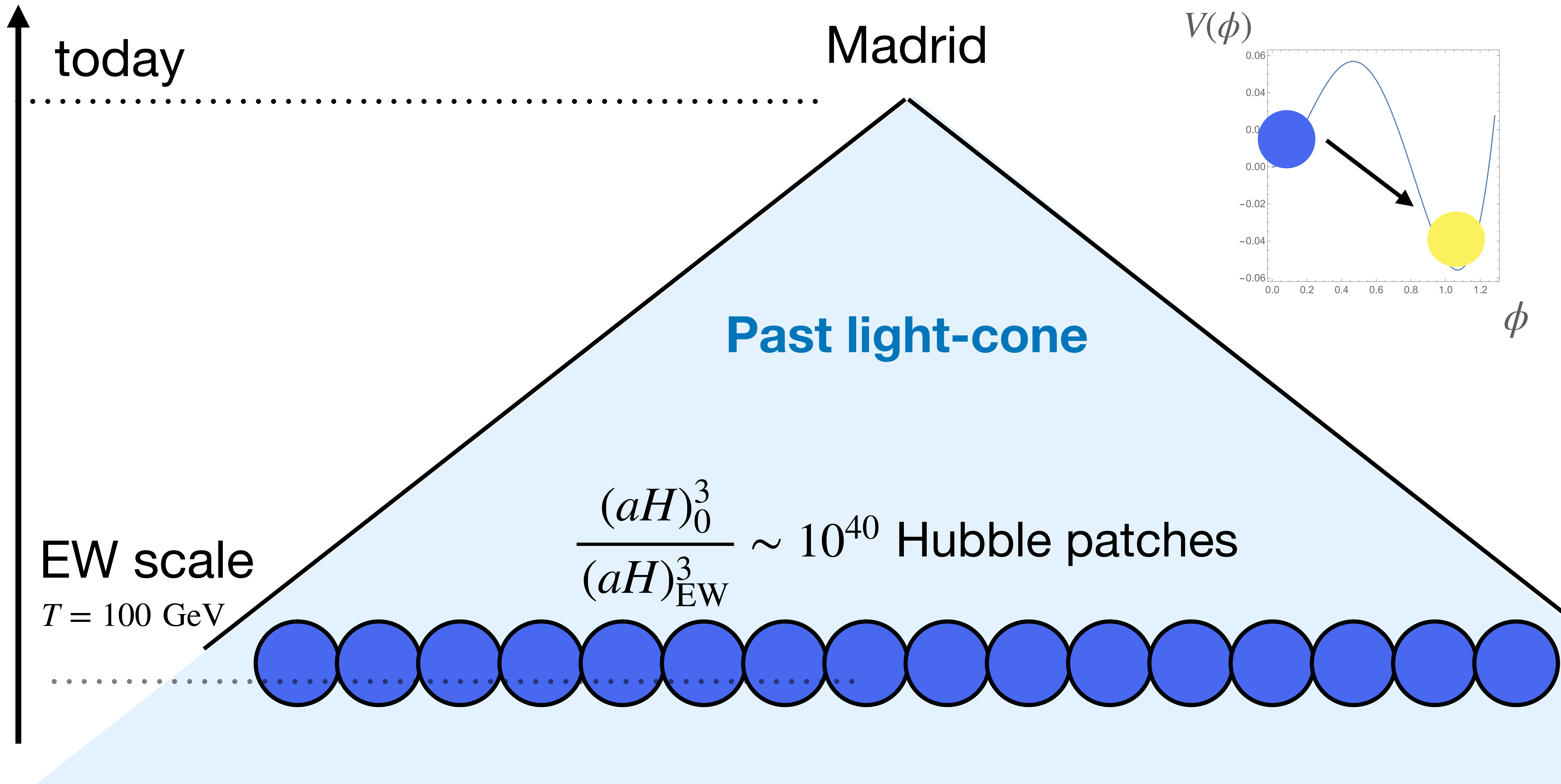
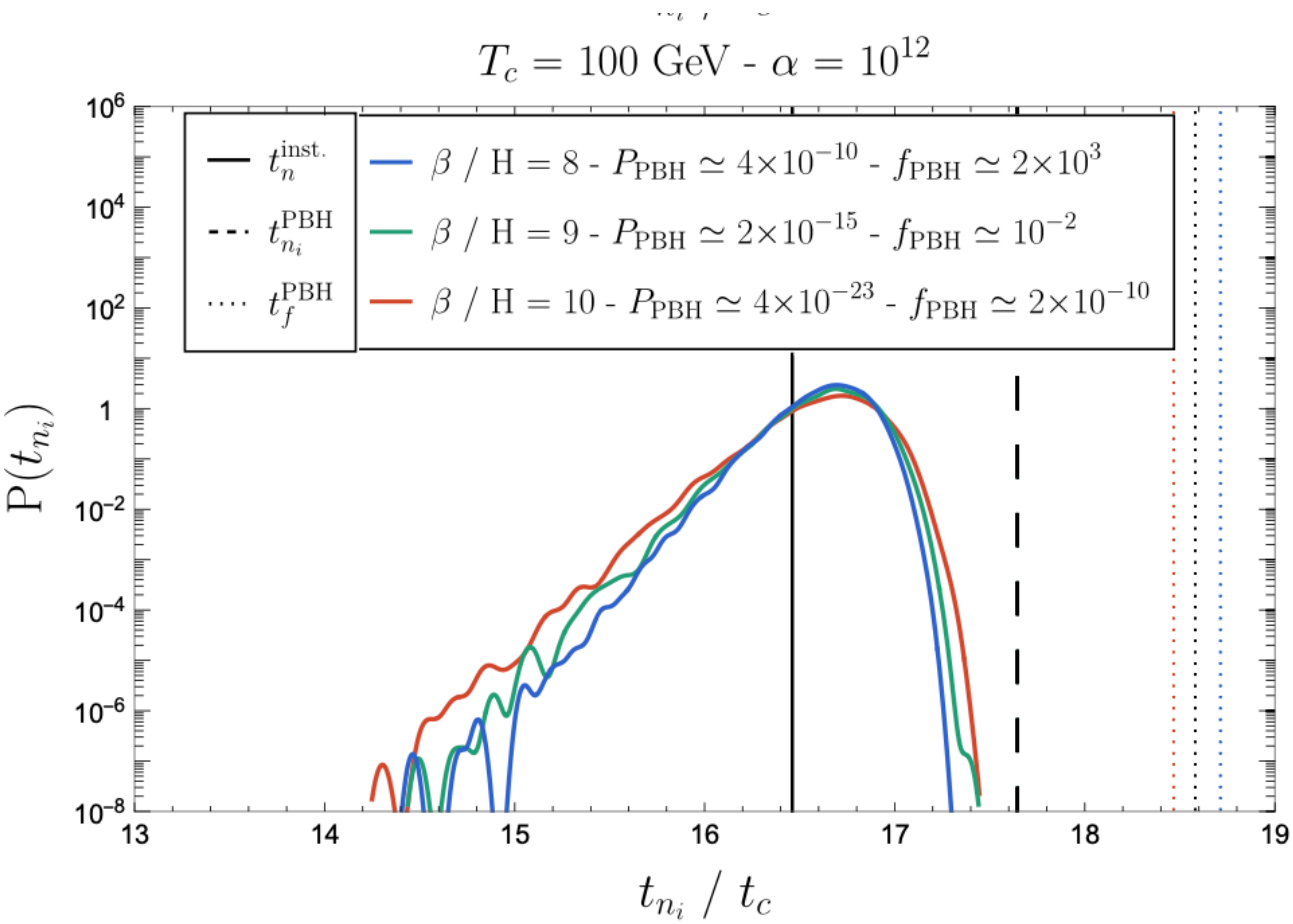


PBHs from fluctuation of the percolation time

When phase transition takes place ?



PBHs from fluctuation of the percolation time

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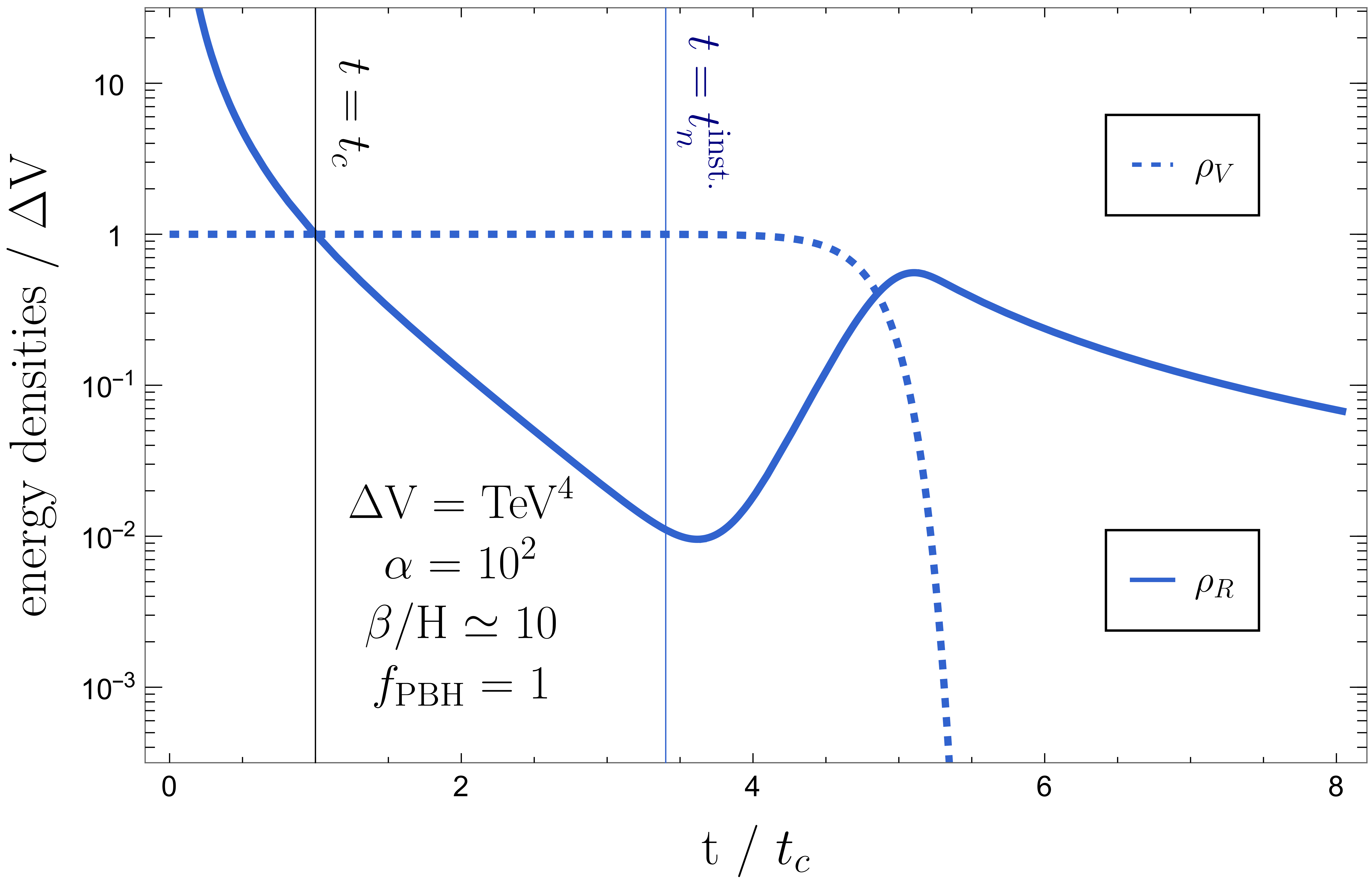
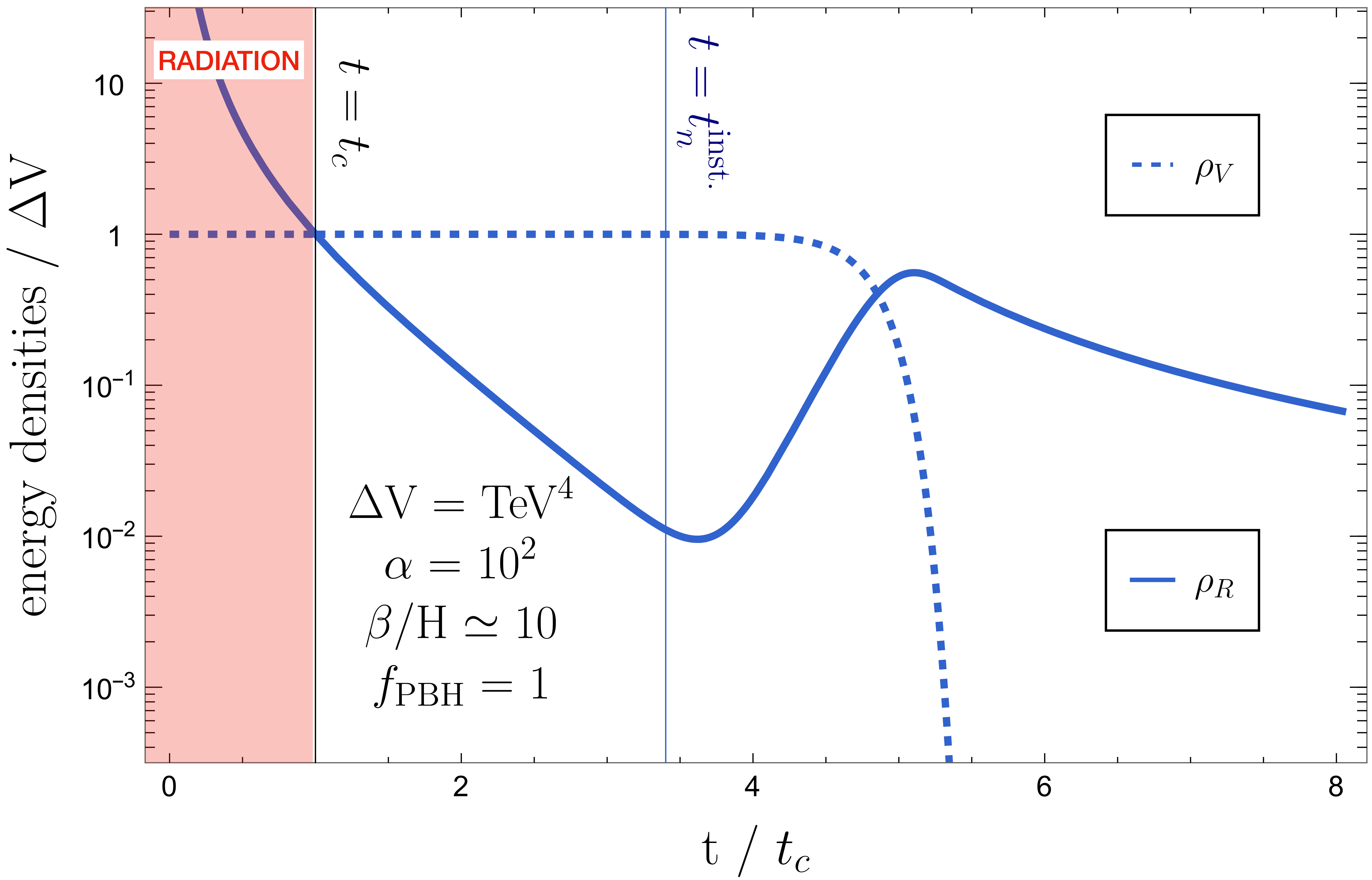


energy densities / ΔV
t / t_c
$t = t_c$
$t = t_n^{\text{inst.}}$
ρ_V
ρ_R
$\Delta V = \text{TeV}^4$
$\alpha = 10^2$
$\beta/\text{H} \simeq 10$
$f_{\text{PBH}} = 1$
10
1
10^{-1}
10^{-2}
10^{-3}
0
2
4
6
8



RADIATION
$t = t_c$
$t = t_n^{\text{inst.}}$
ρ_V
ρ_R
$\Delta V = \text{TeV}^4$
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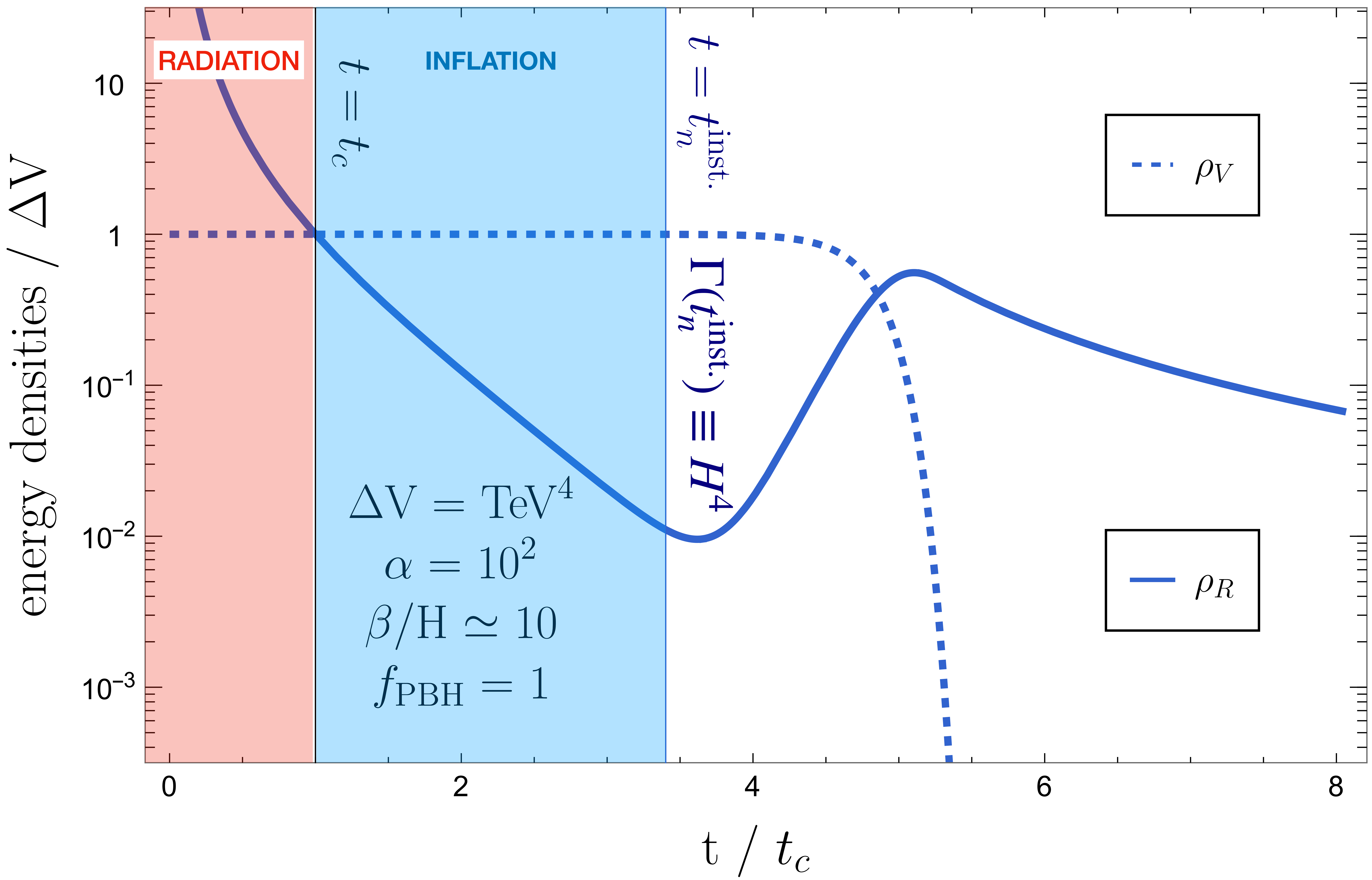

RADIATION
INFLATION
$t = t_c$
$t = t_n^{\rm inst.}$
$\Gamma(t_n^{\rm inst.}) \equiv H^4$
$\Delta V = {\rm TeV}^4$
$\alpha = 10^2$
$\beta/H \simeq 10$
$f_{\rm PBH} = 1$
ρ_V
ρ_R
energy densities / ΔV
t / t_c
10
1
10^{-1}
10^{-2}
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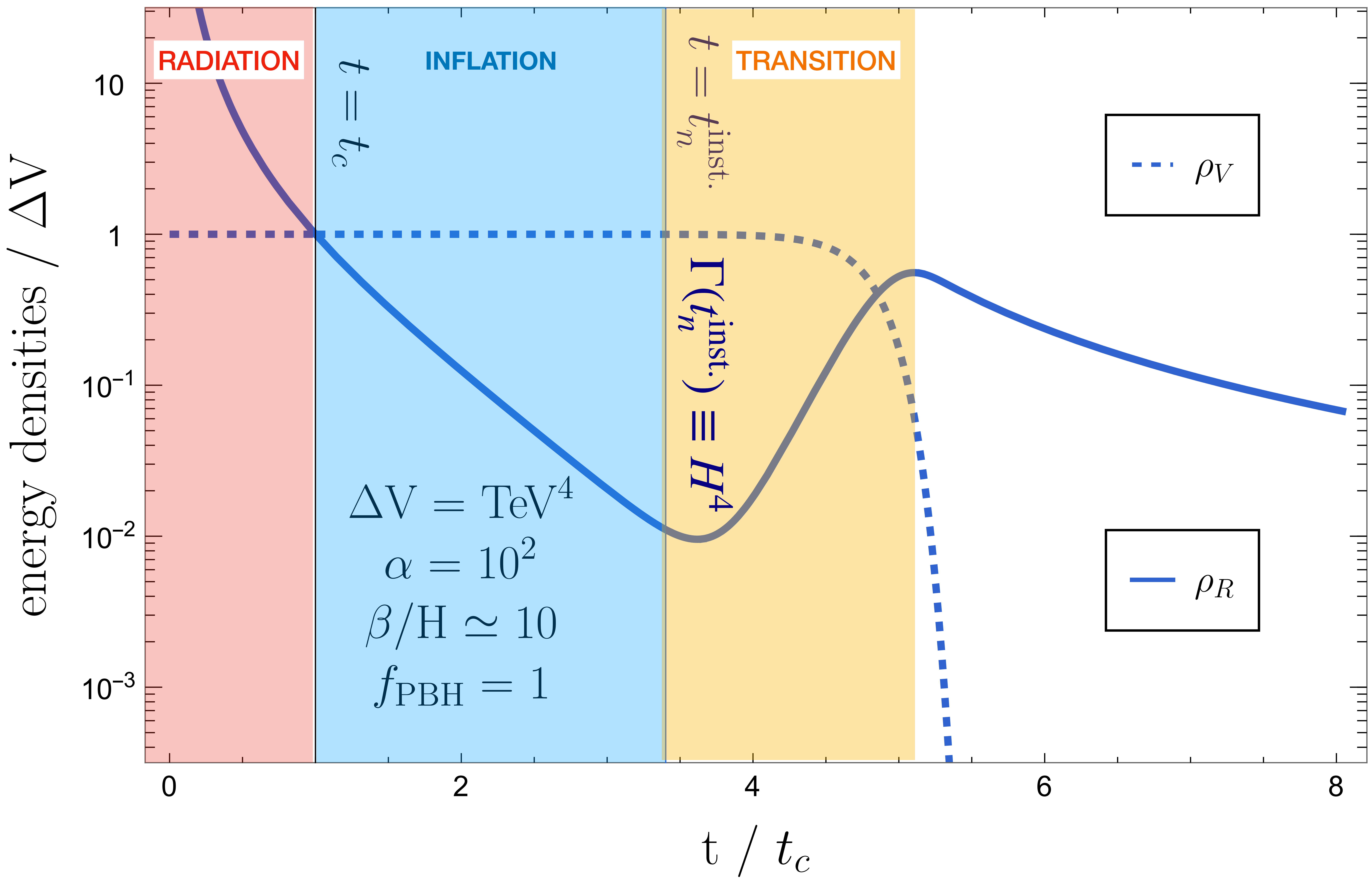
RADIATION
INFLATION
TRANSITION
$t = t_c$
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$\Gamma(t_n^{\text{inst.}}) \equiv H^4$
$\Delta V = \text{TeV}^4$
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$\beta/\text{H} \simeq 10$
$f_{\text{PBH}} = 1$
ρ_V
ρ_R
energy densities / ΔV
t / t_c
10
1
10^{-1}
10^{-2}
10^{-3}
0
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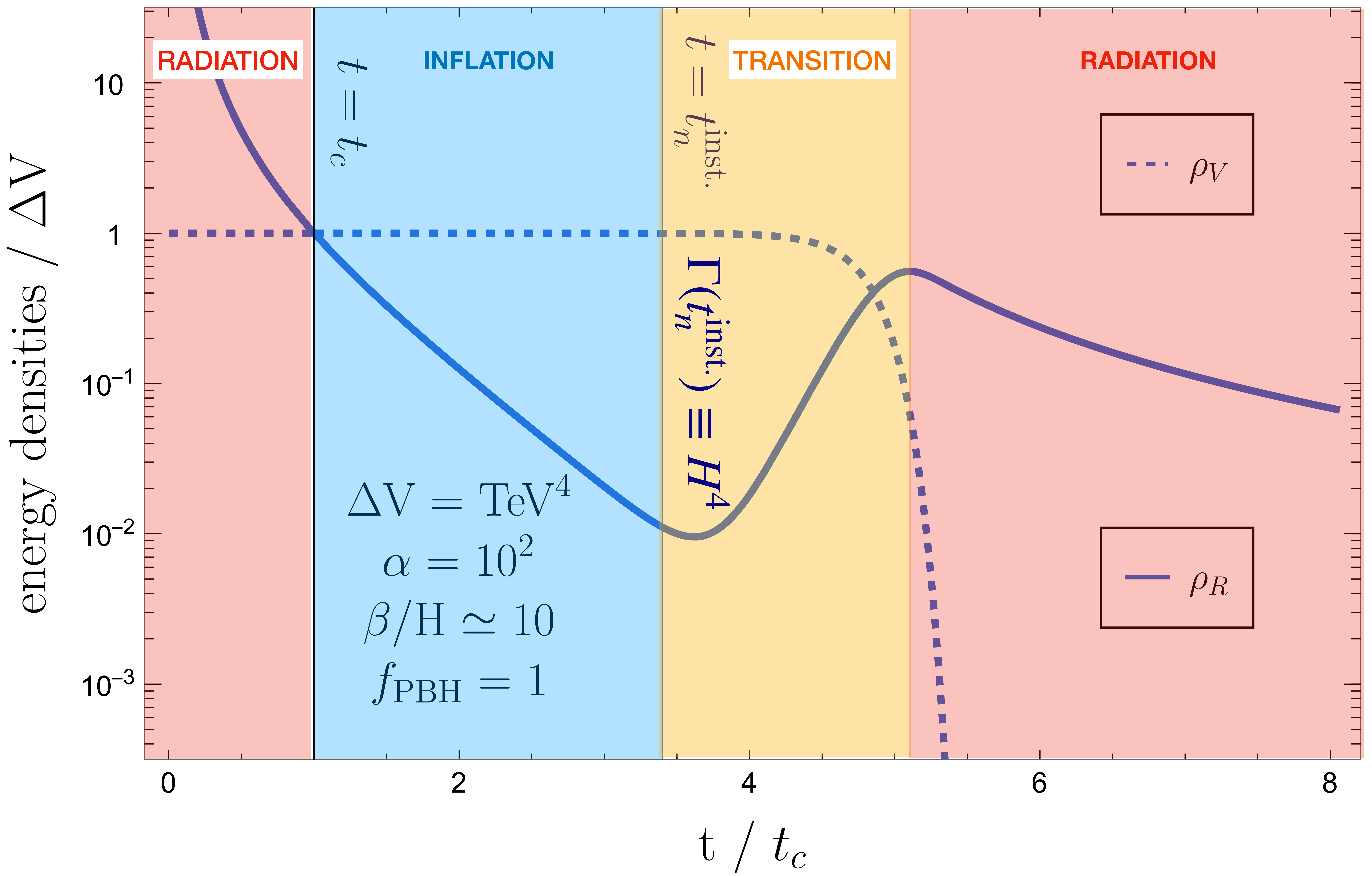
4
6
8



RADIATION
INFLATION
TRANSITION
RADIATION
$t = t_c$
$t = t_n^{\text{inst.}}$
$\Gamma(t_n^{\text{inst.}}) \equiv H^4$
ρ_V
ρ_R
$\Delta V = \text{TeV}^4$
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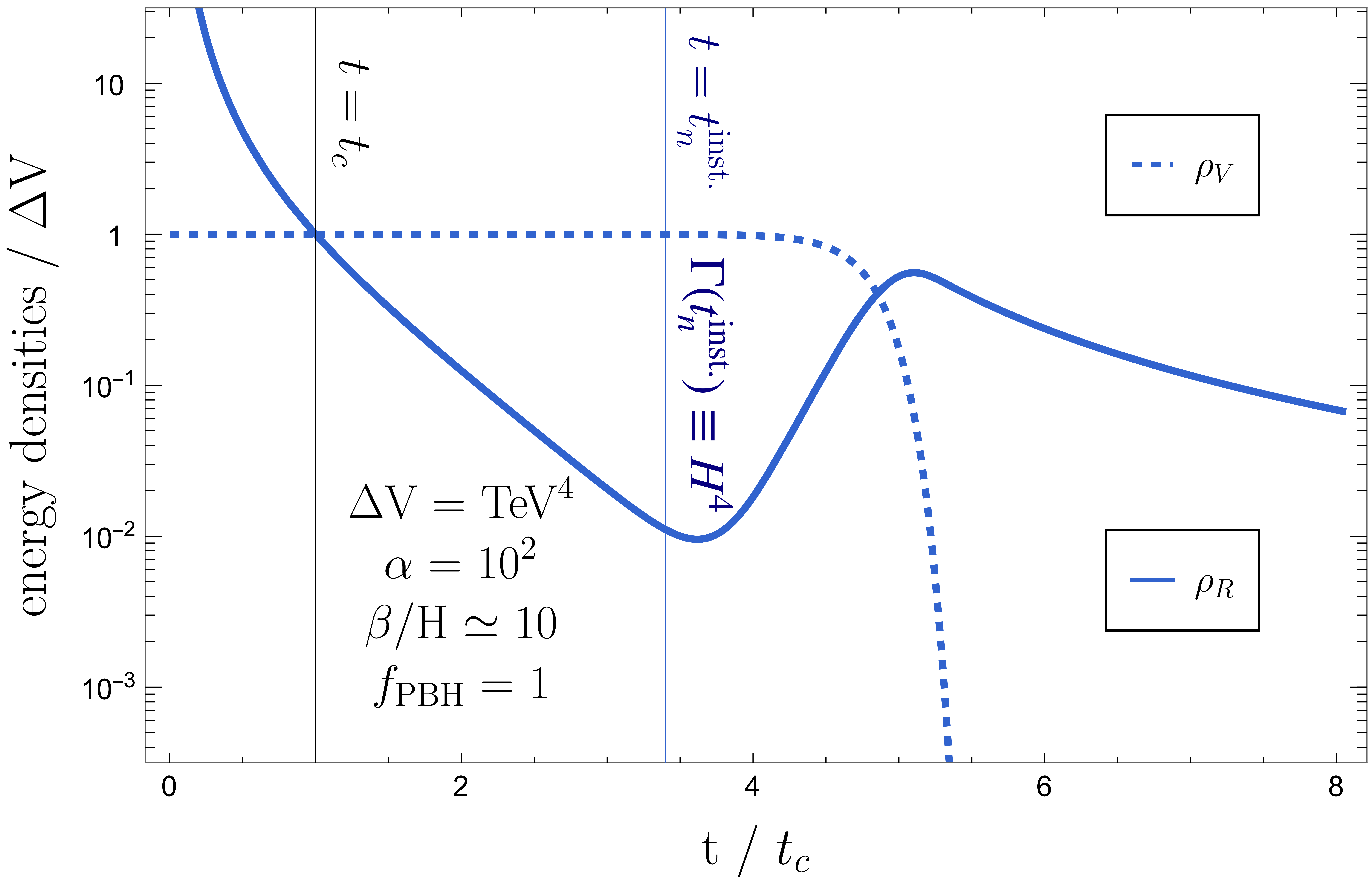
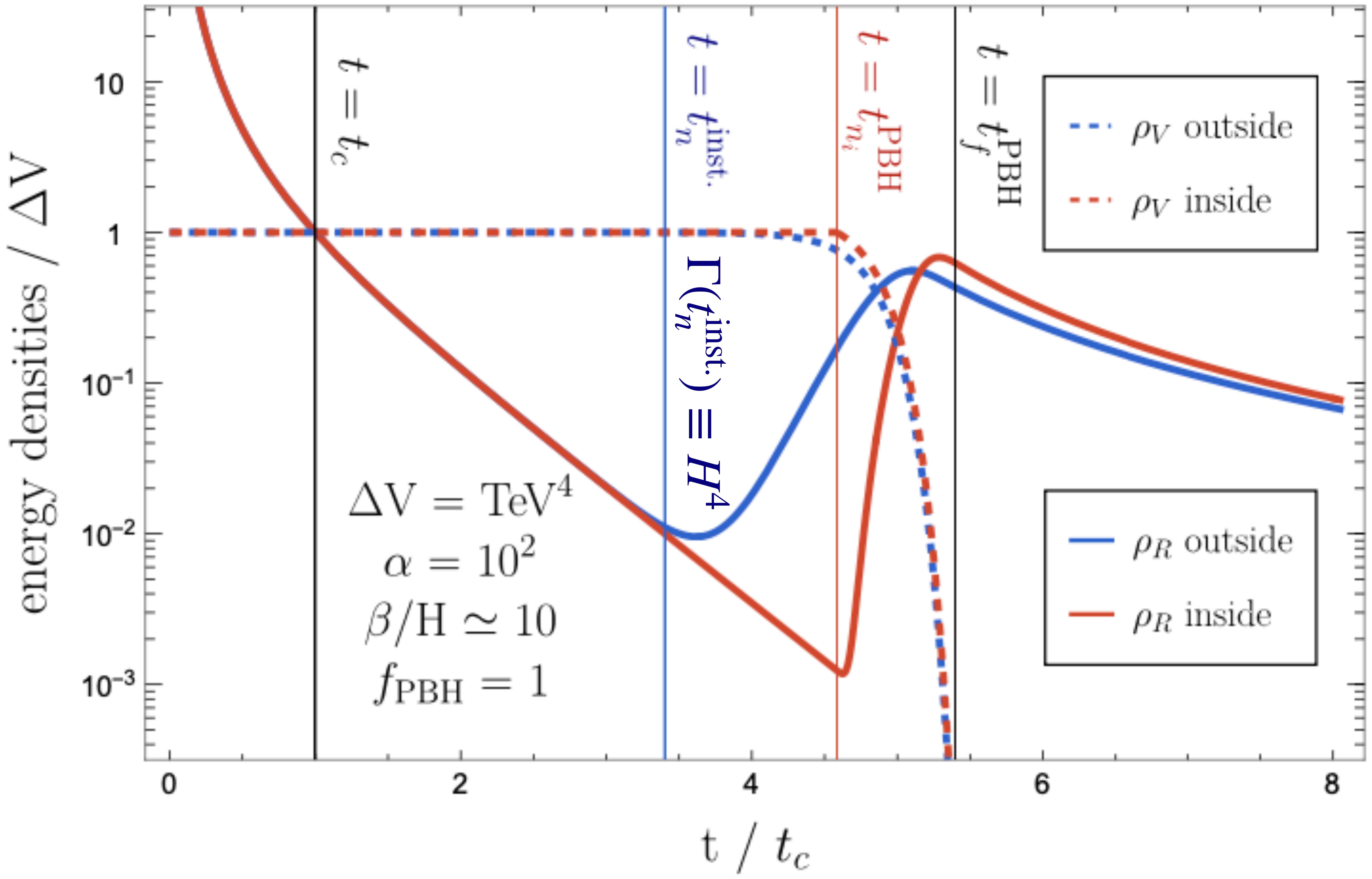
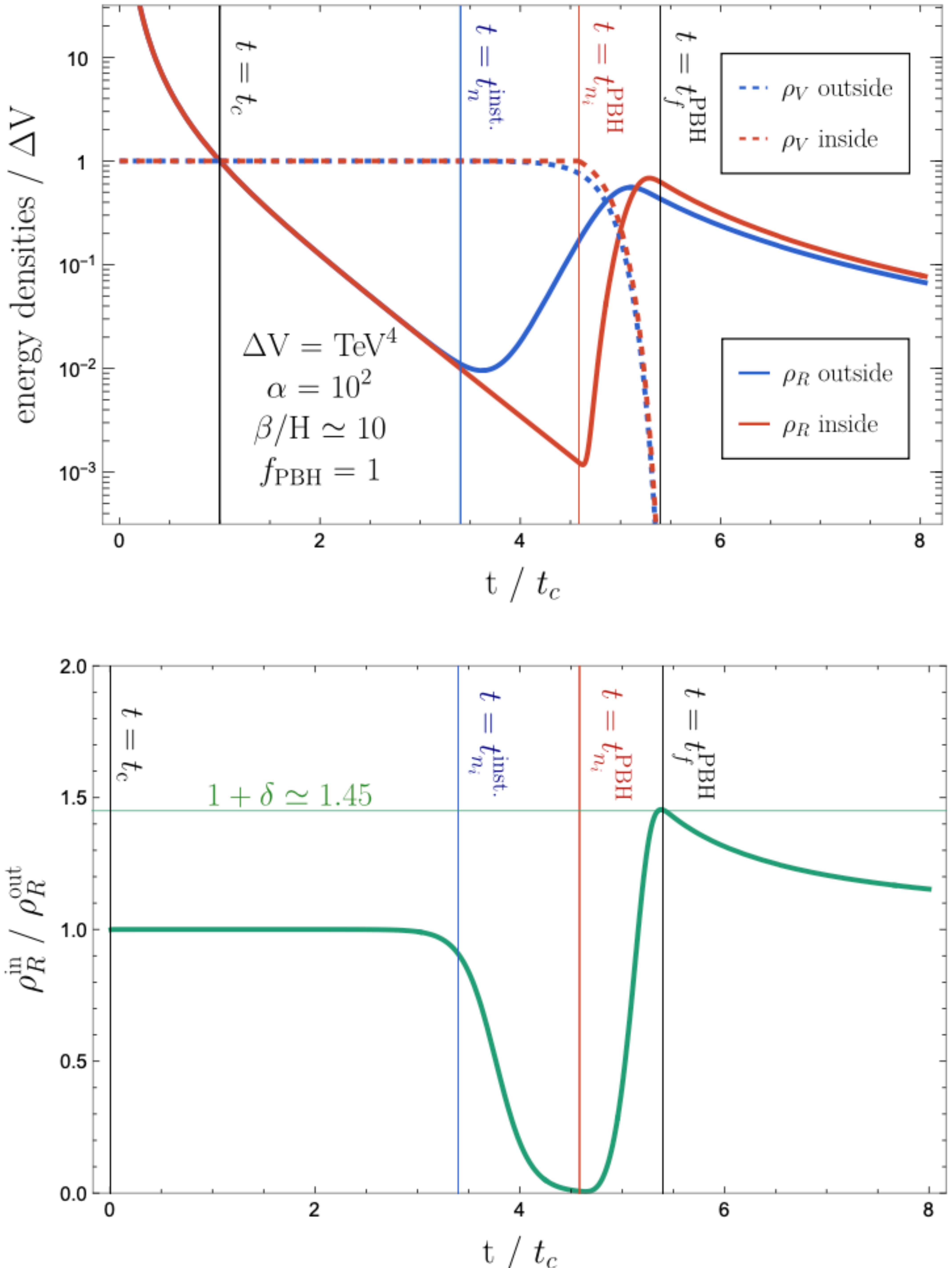
energy densities / ΔV
10
1
10^{-1}
10^{-2}
10^{-3}
0
2
4
6
8
t / t_c



energy densities / ΔV
10
1
10^{-1}
10^{-2}
10^{-3}
0
2
4
6
8
t / t_c
$t = t_c$
$t = t_n^{\rm inst.}$
$\Gamma(t_n^{\rm inst.}) \equiv H^4$
$\Delta V = \mathrm{TeV}^4$
$\alpha = 10^2$
$\beta/\mathrm{H} \simeq 10$
$f_{\rm PBH} = 1$
ρ_V
ρ_R

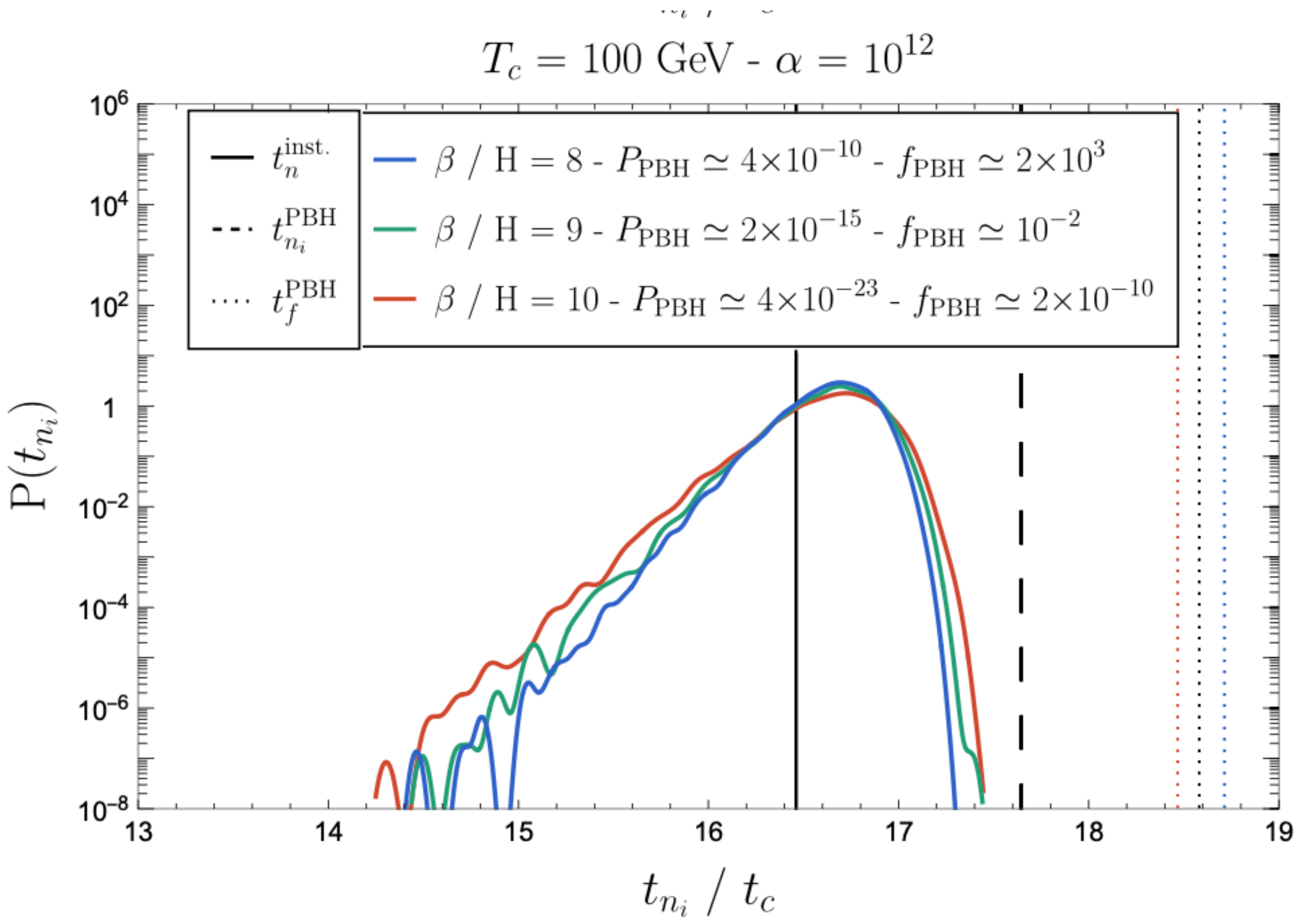


energy densities / ΔV
t / t_c
10
1
10^{-1}
10^{-2}
10^{-3}
0
2
4
6
8
$t = t_c$
$t = t_n^{\rm inst.}$
$t = t_{n_i}^{\rm PBH}$
$t = t_f^{\rm PBH}$
$\Gamma(t_n^{\rm inst.}) \equiv H^4$
ρ_V outside
ρ_V inside
ρ_R outside
ρ_R inside
$\Delta V = {\rm TeV}^4$
$\alpha = 10^2$
$\beta/{\rm H} \simeq 10$
$f_{\rm PBH} = 1$



energy densities / ΔV
t / t_c
$t = t_c$
$t = t_n^{\rm inst.}$
$t = t_{n_i}^{\rm PBH}$
$t = t_f^{\rm PBH}$
ρ_V outside
ρ_V inside
ρ_R outside
ρ_R inside
ΔV = TeV^4
$\alpha = 10^2$
$\beta/H \simeq 10$
$f_{\rm PBH} = 1$
$\rho_R^{\rm in} / \rho_R^{\rm out}$
$t = t_{n_i}^{\rm inst.}$
$1 + \delta \simeq 1.45$
t / t_c

The survival probability



PBH abundance

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

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

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

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

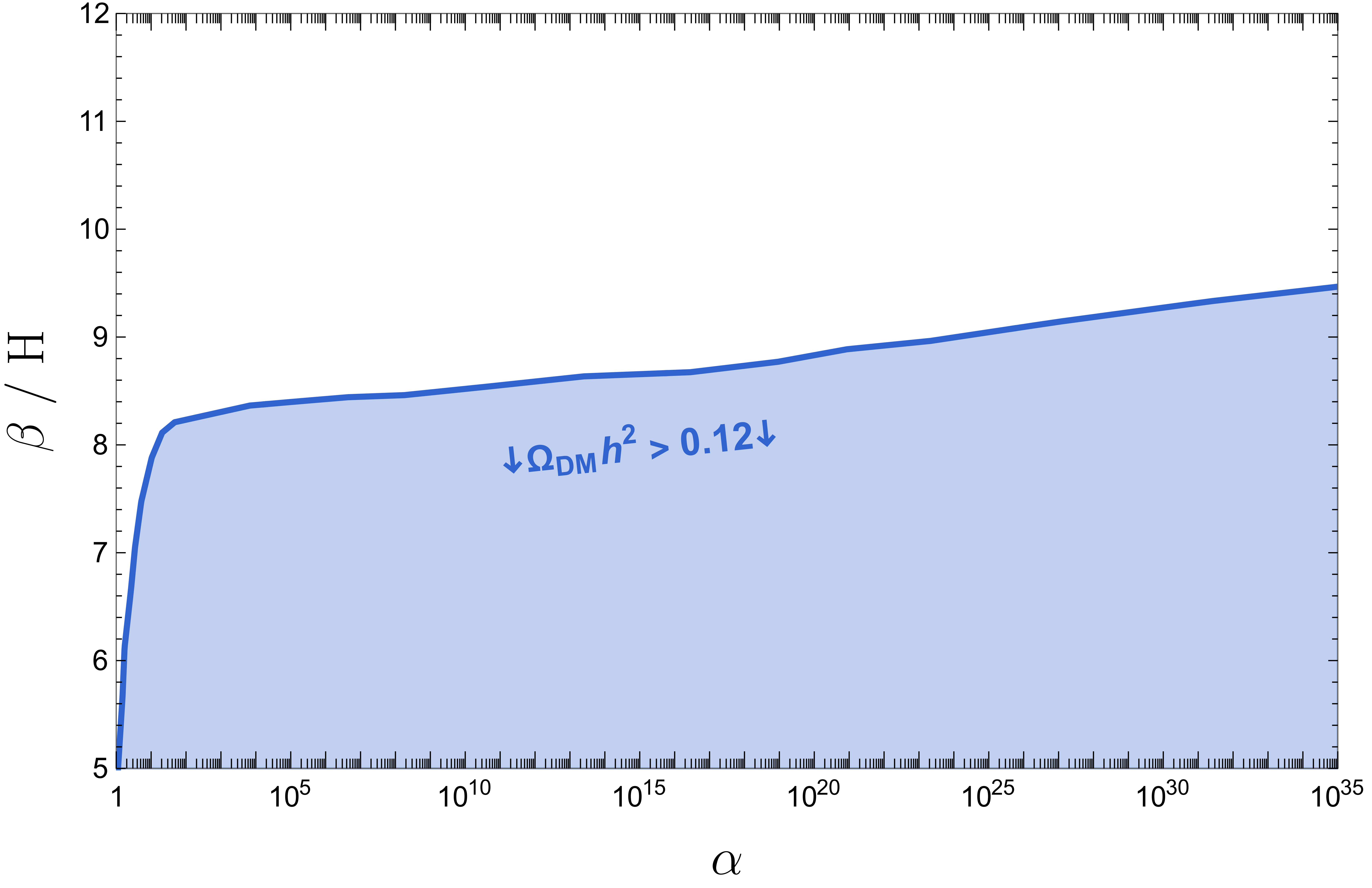
$$F(t,t_{n_i}) = \exp\left[-\int_{t_{n_i}}^{t} dt^{'}\,\Gamma(t^{'})\,a^3(t^{'})\times\frac{4\pi}{3}\left(\int_{t^{'}}^{t}\frac{d\tau}{a(\tau)}\right)^3\right]$$

Latent heat:

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

Phase transition rate:

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



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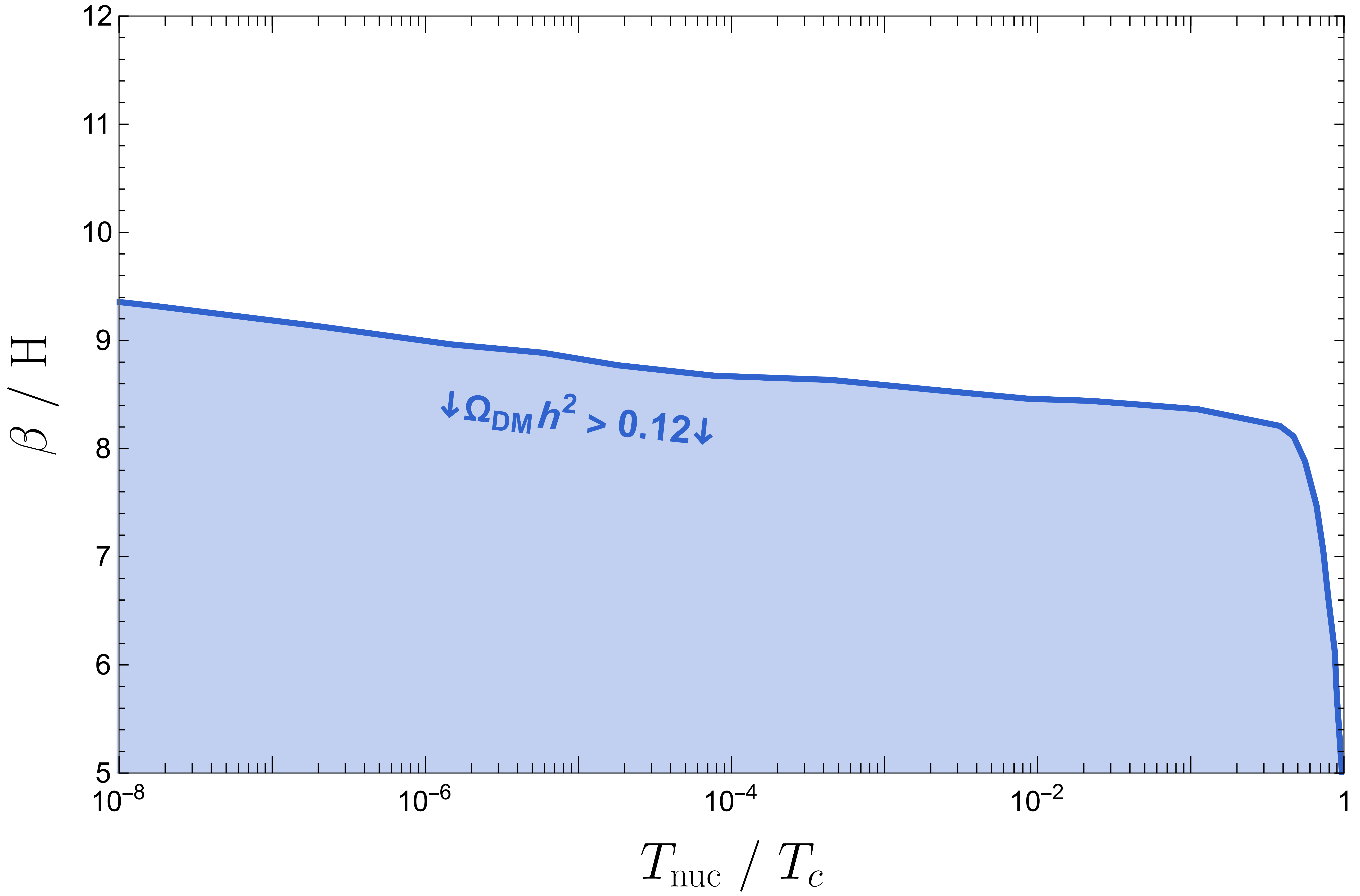
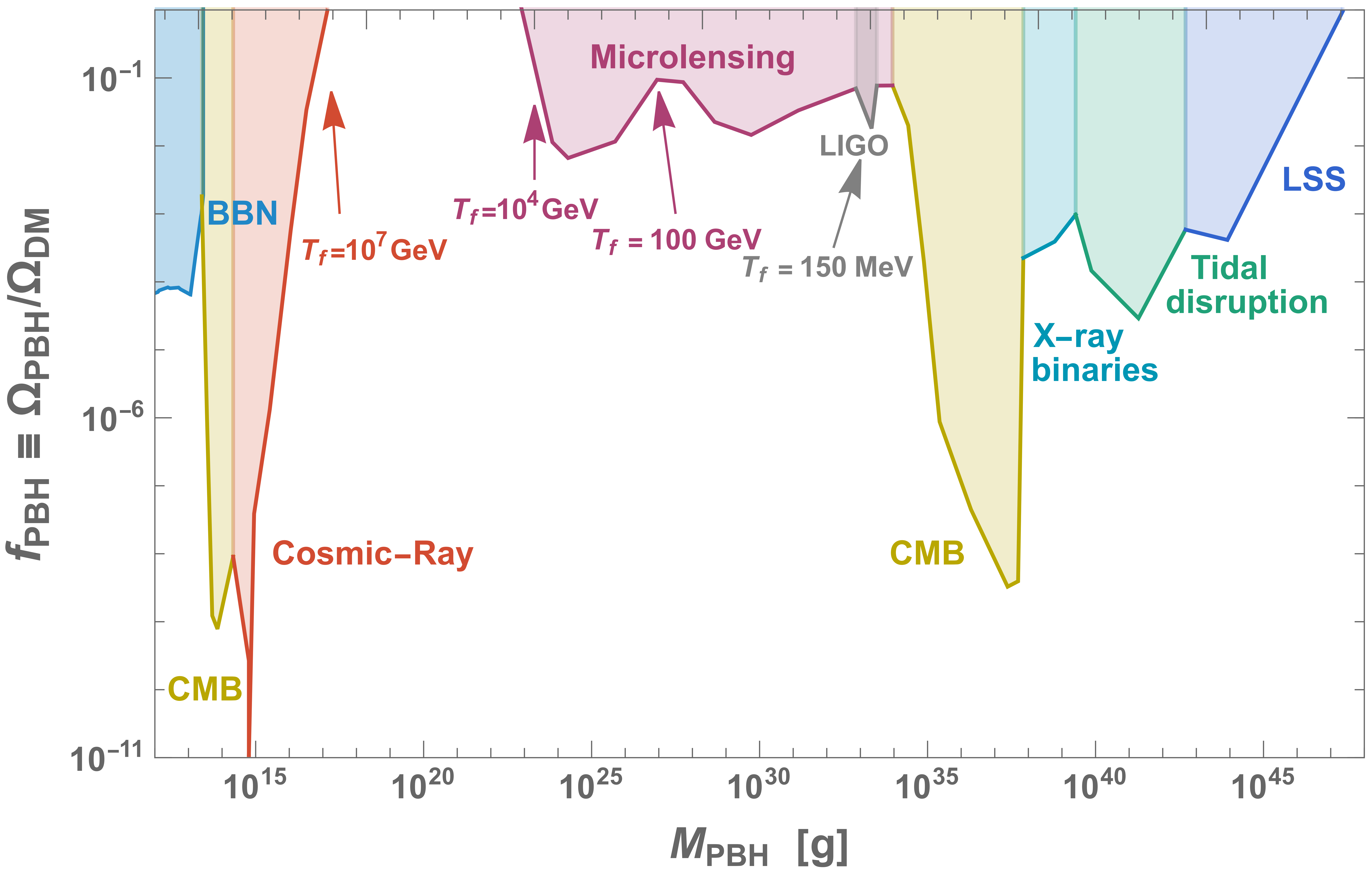


Supercooling from a nearly conformal sector



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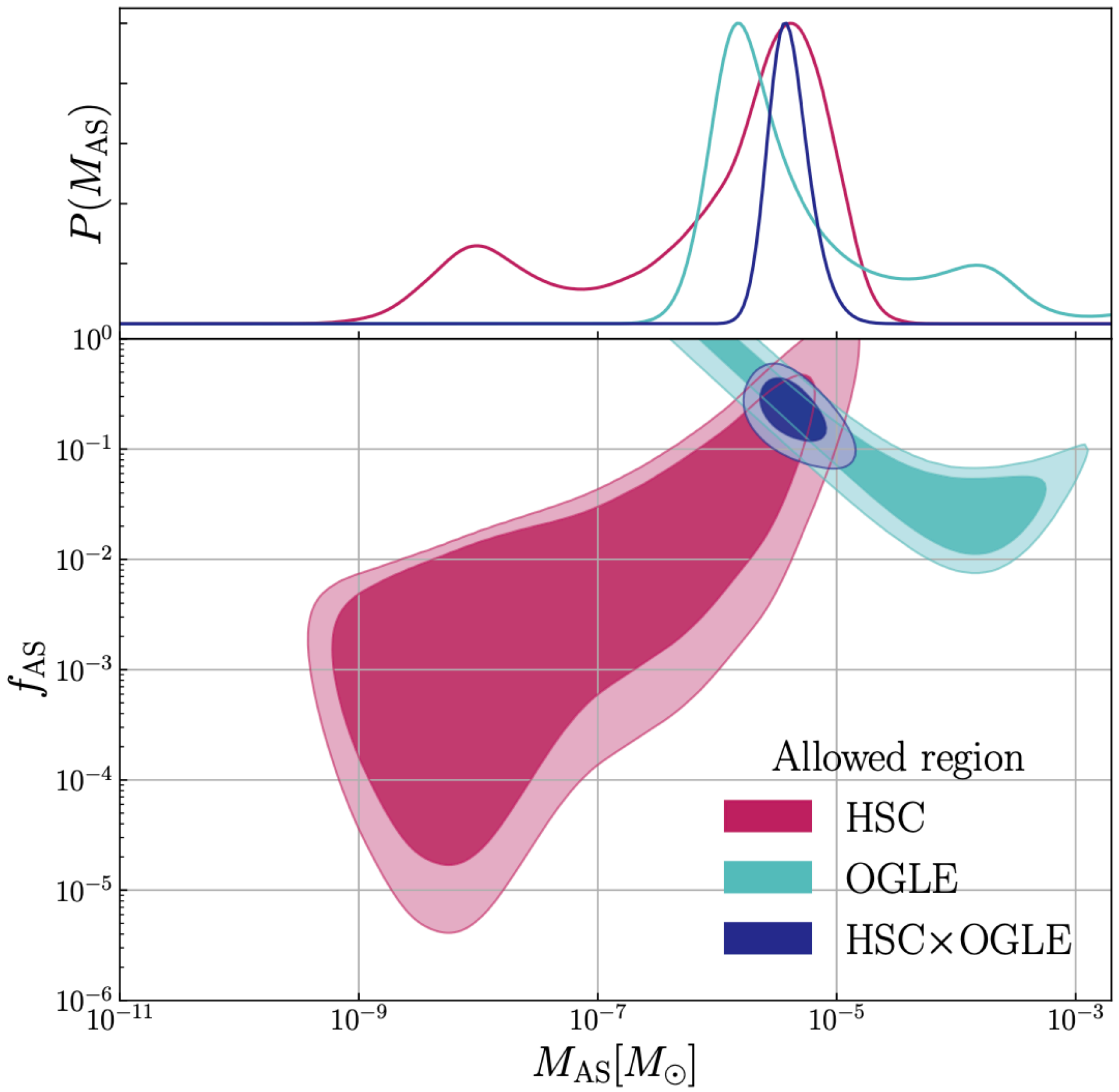

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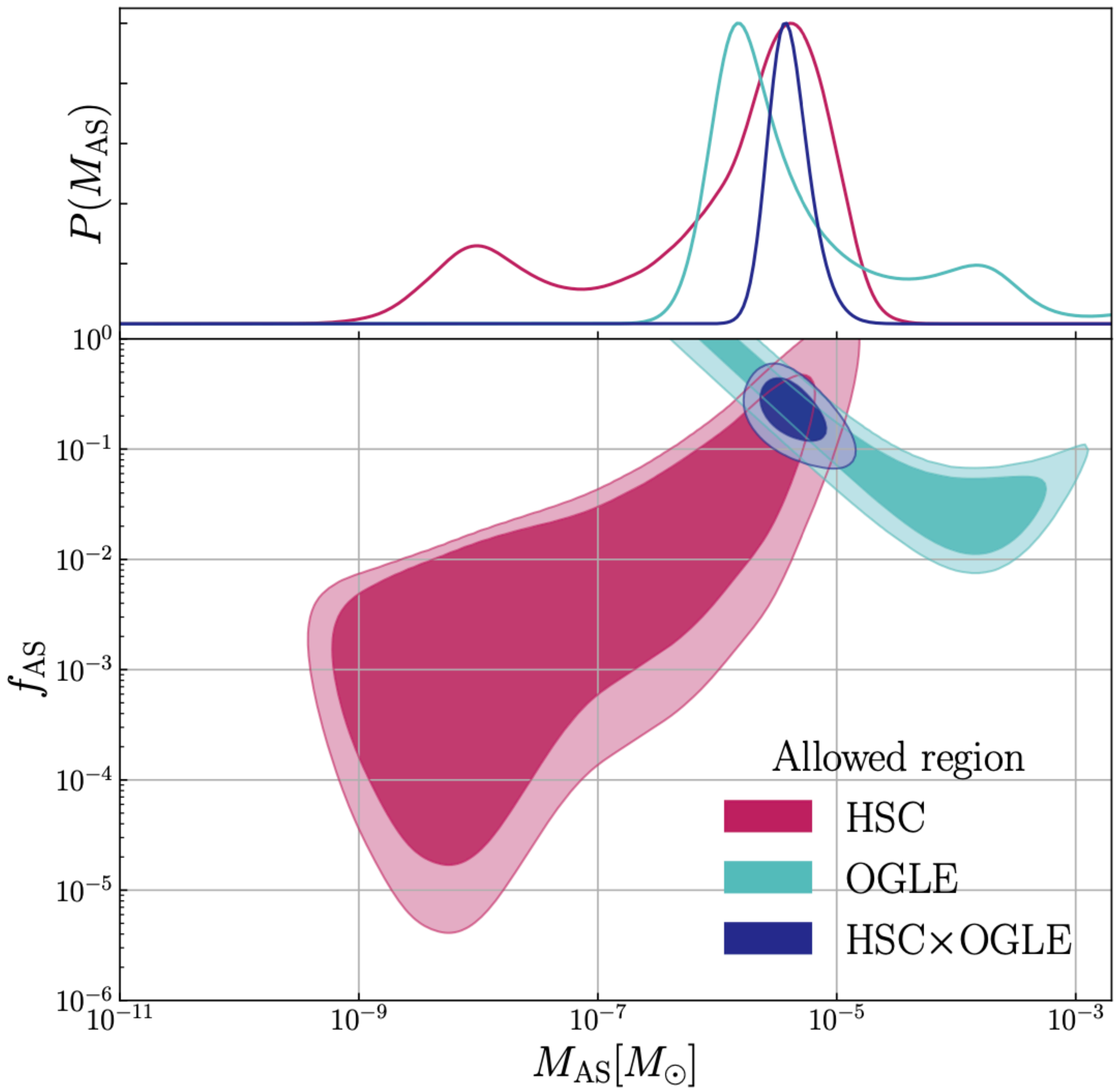

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$$M_{PBH} \simeq 10^{-6}\, M_\odot \left(\frac{100\ \text{GeV}}{T_c}\right)^2$$

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

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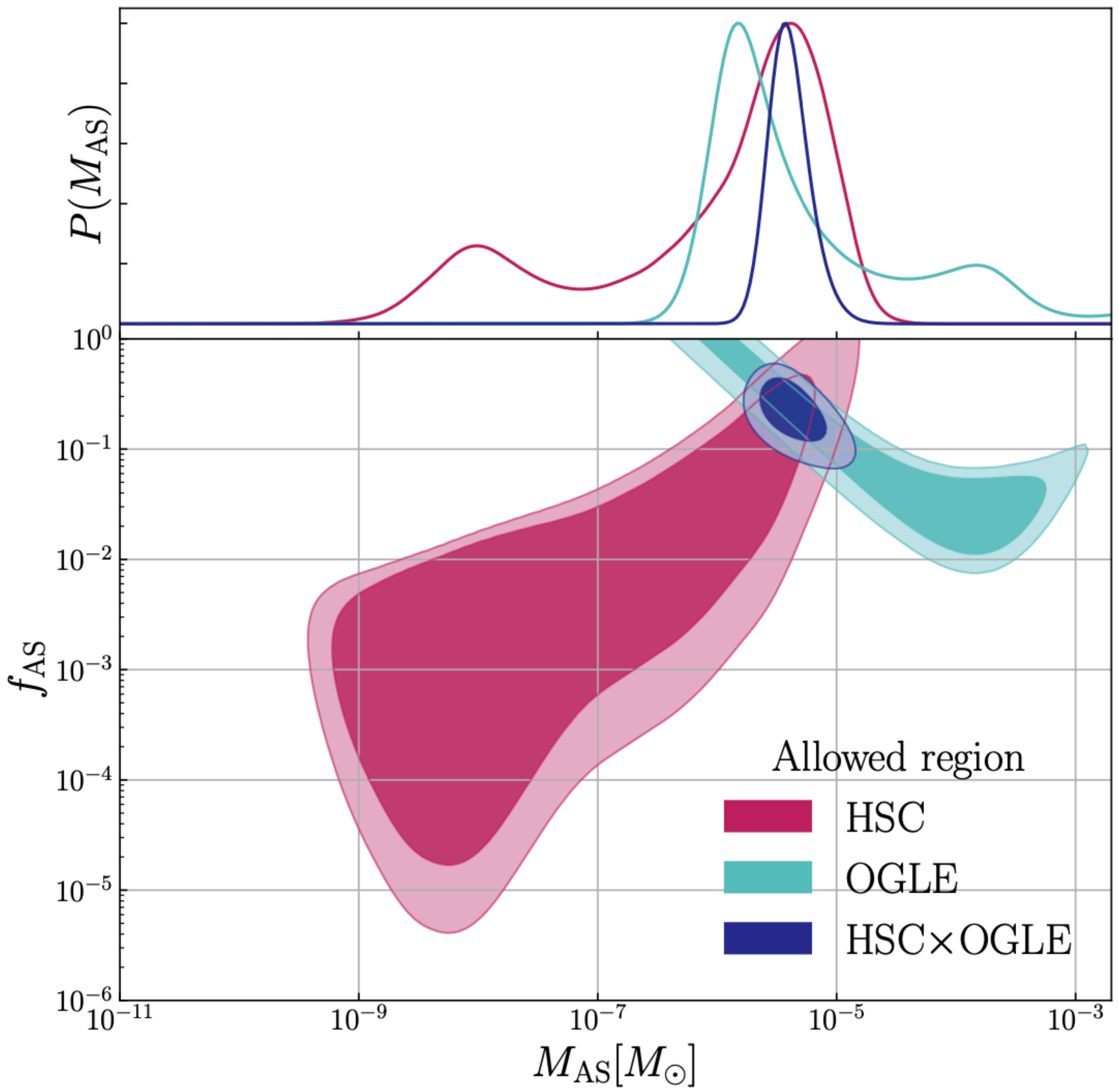

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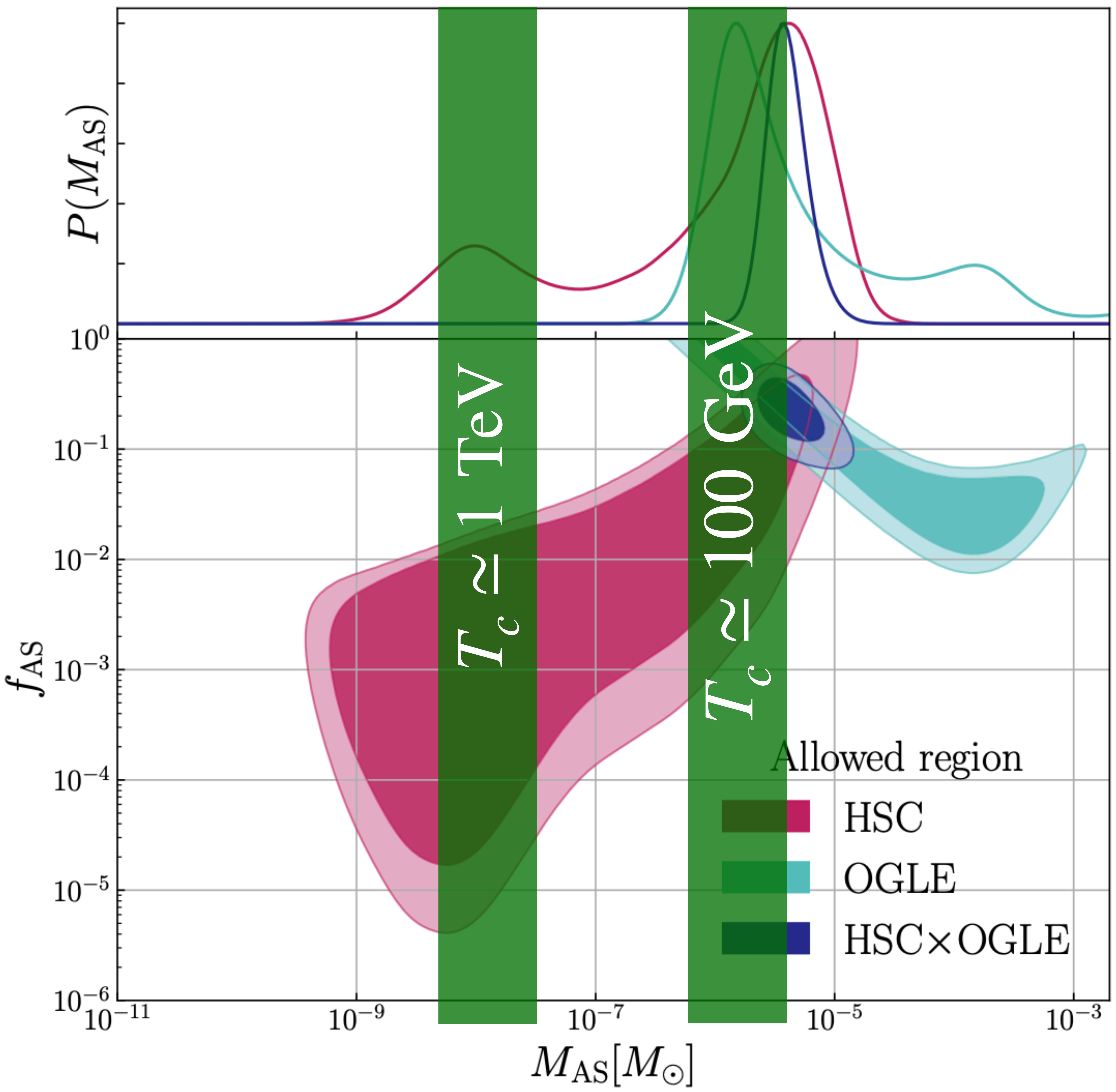

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Nearly-conformal EW sector

YG, Volansky (to appear)

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

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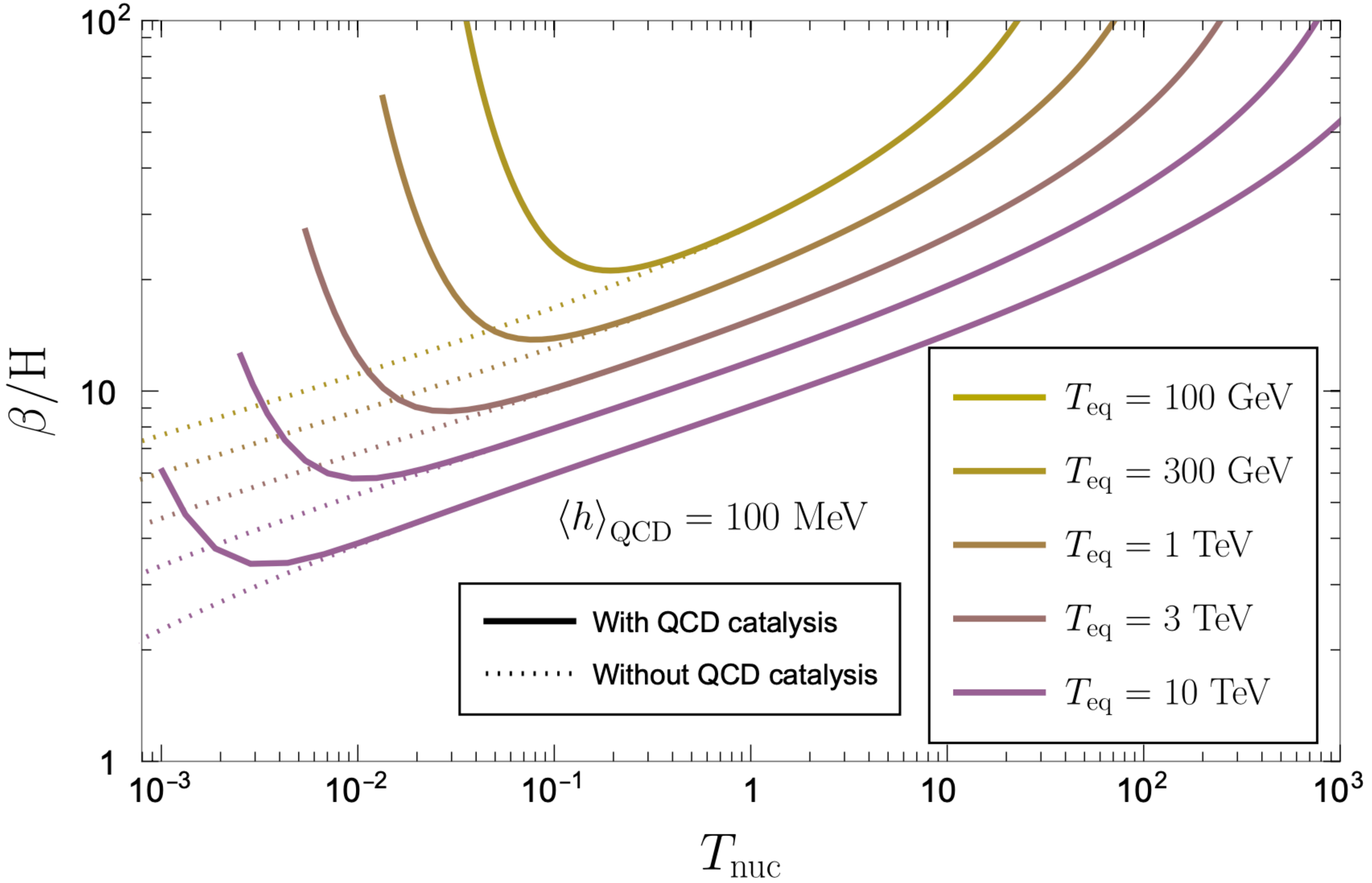

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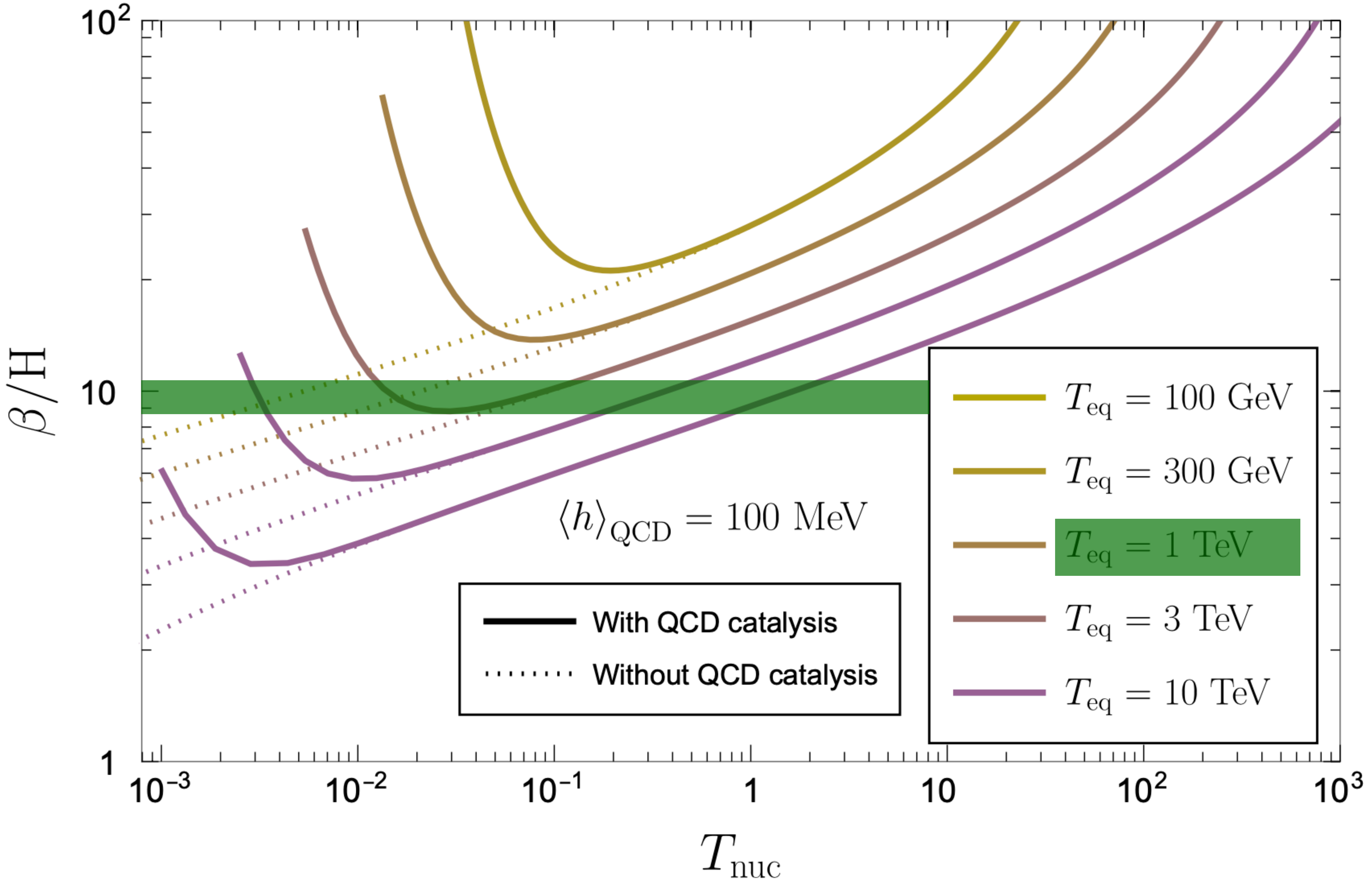

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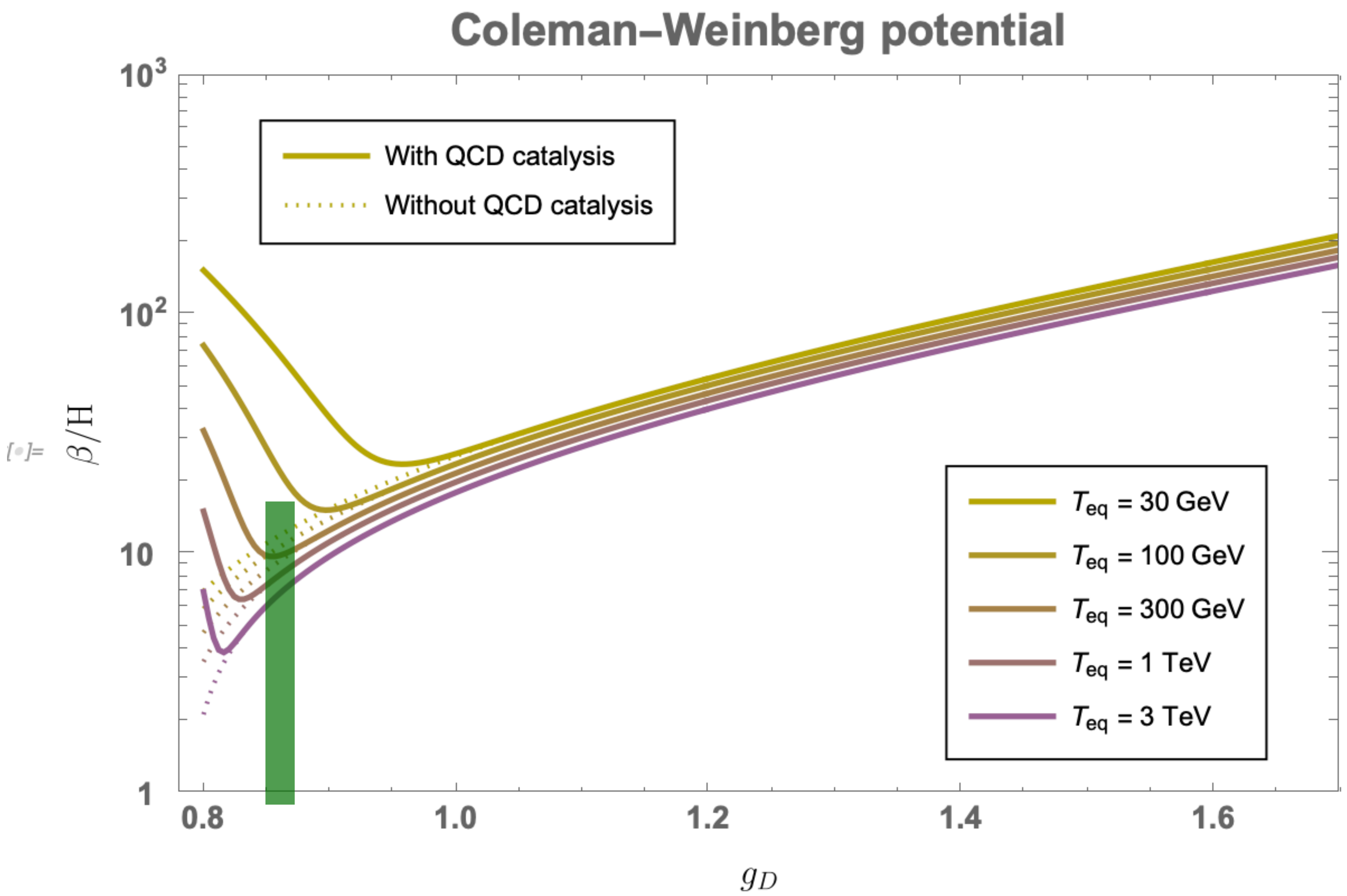
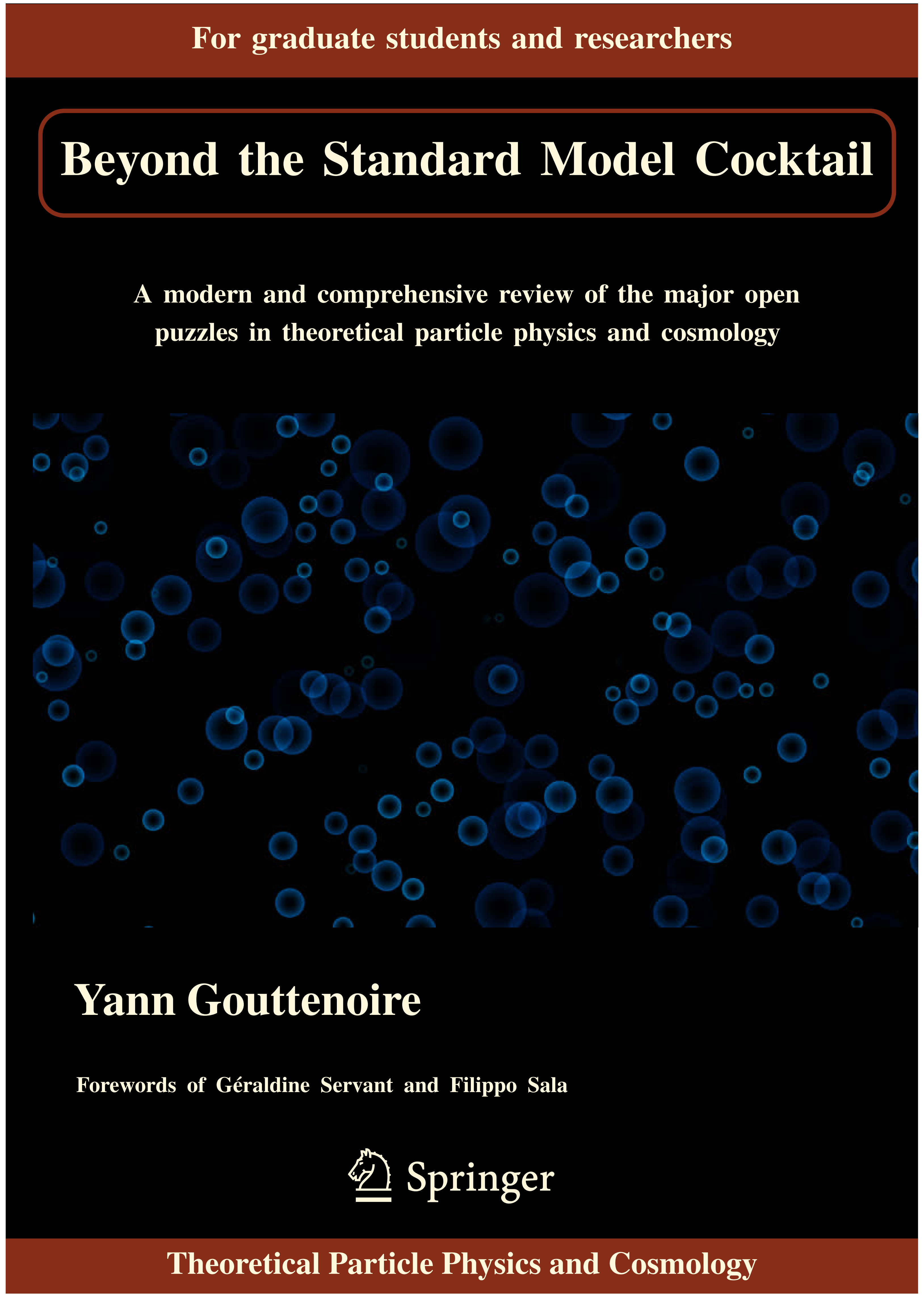


For more details on supercooled phase transitions
-> Chap 6.4 of Beyond the Standard Model Cocktail



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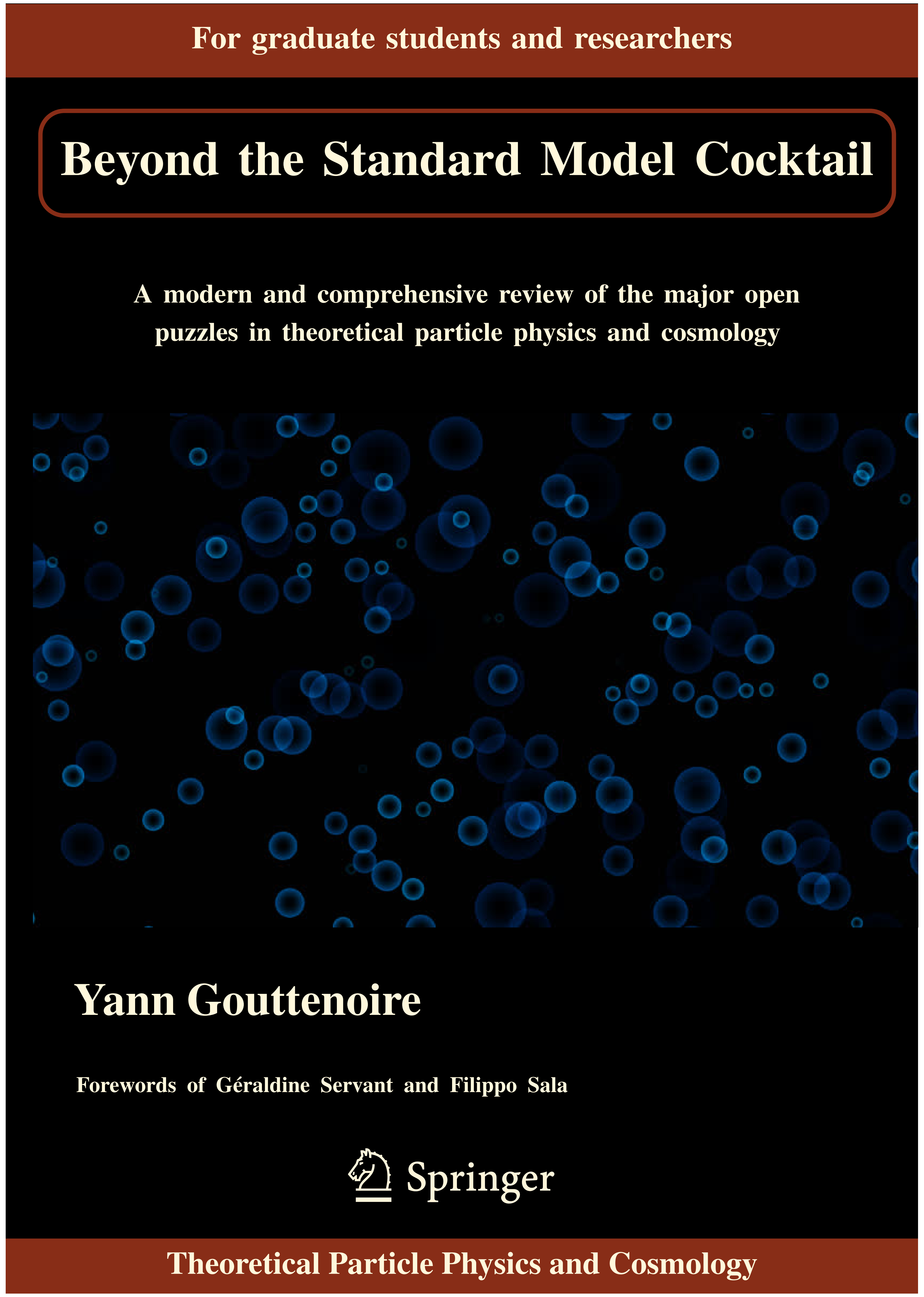

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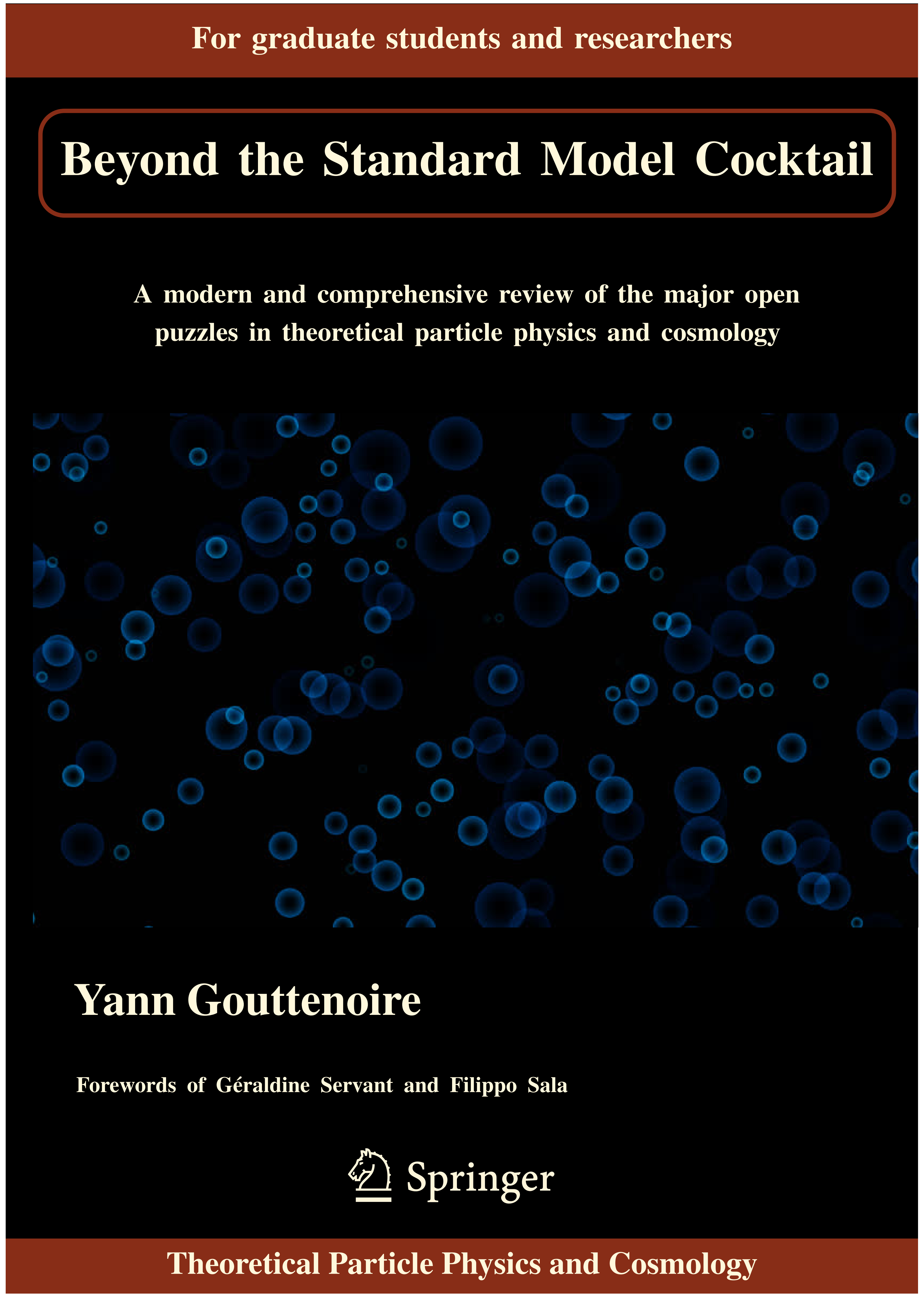

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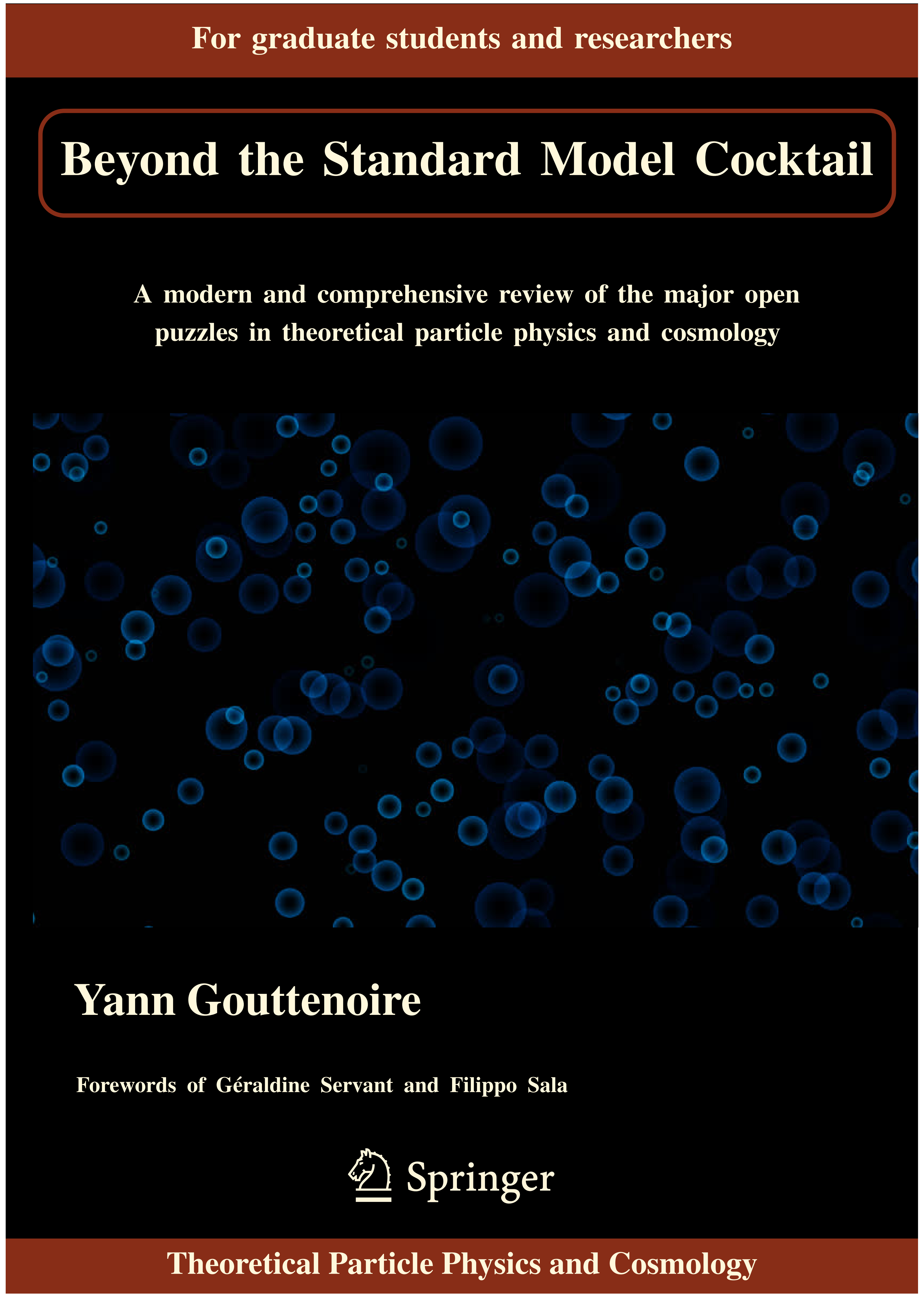

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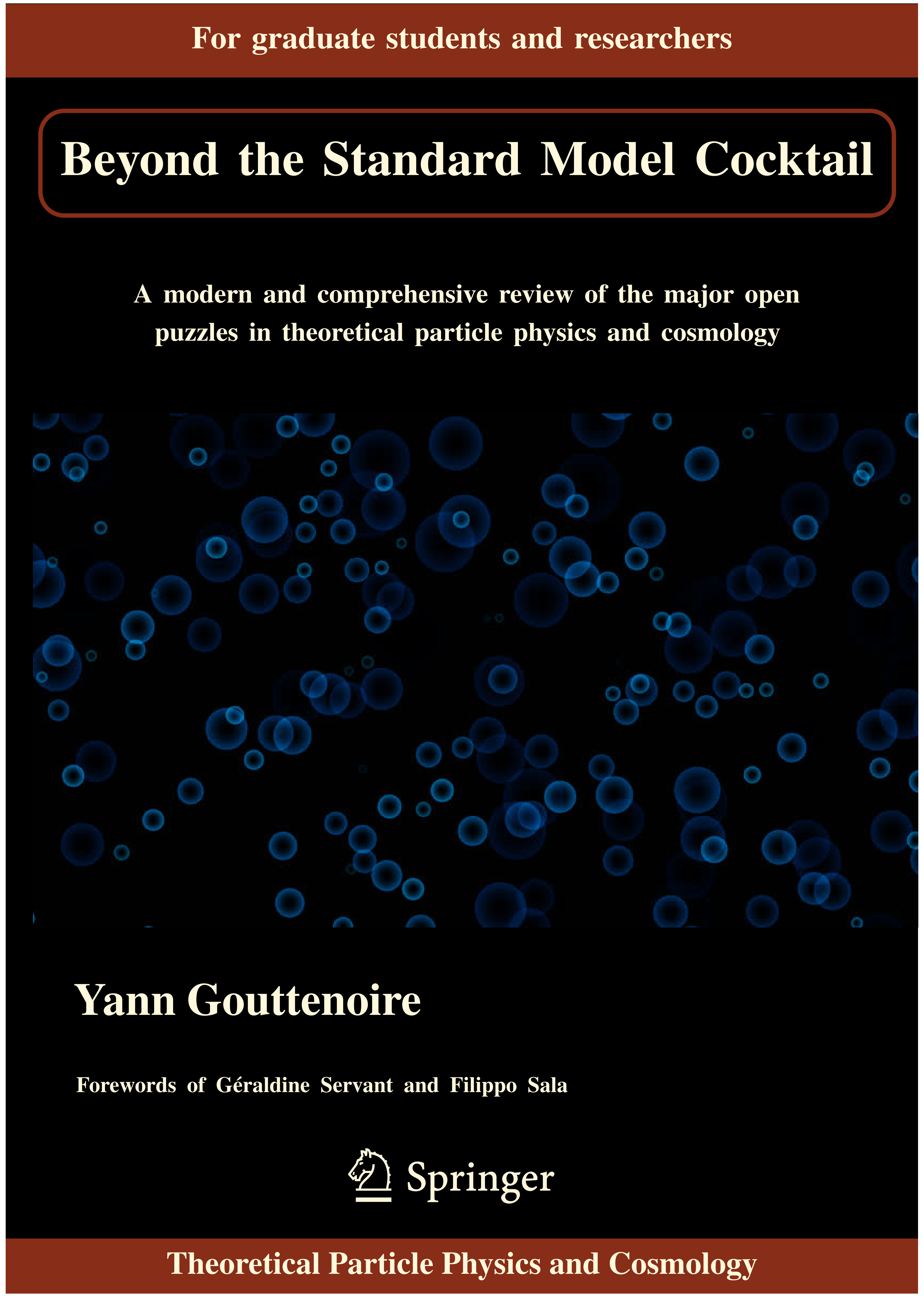

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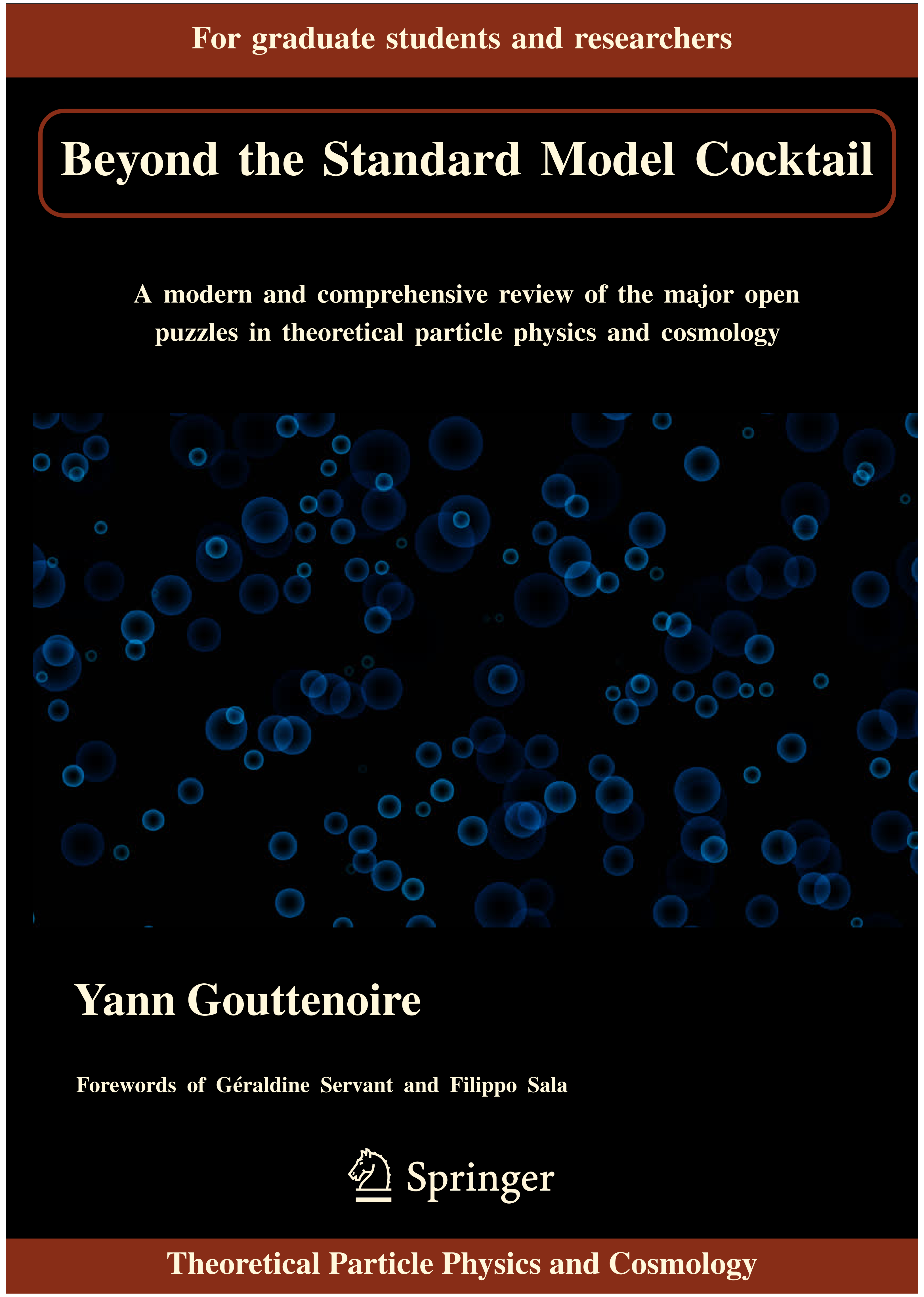

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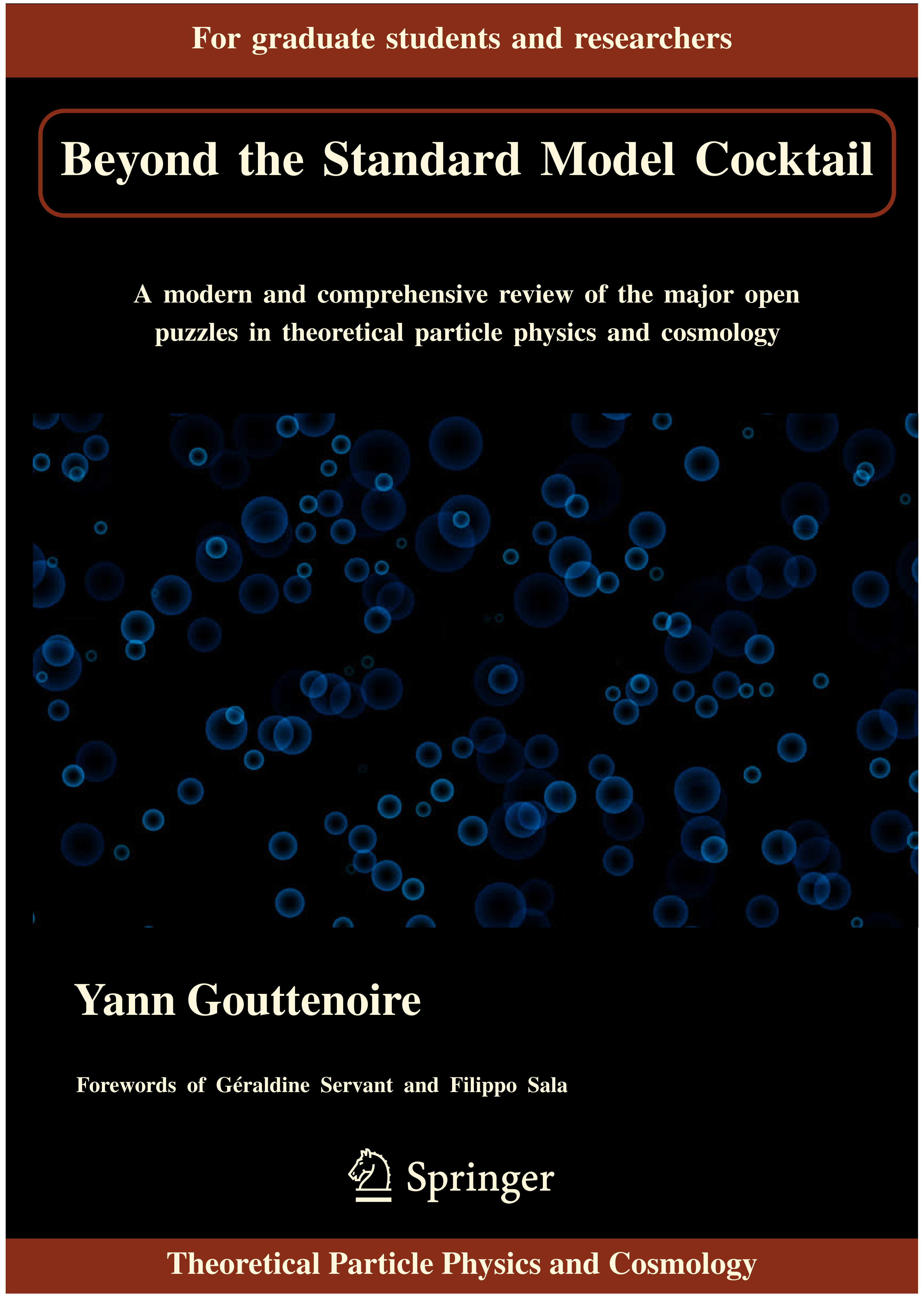

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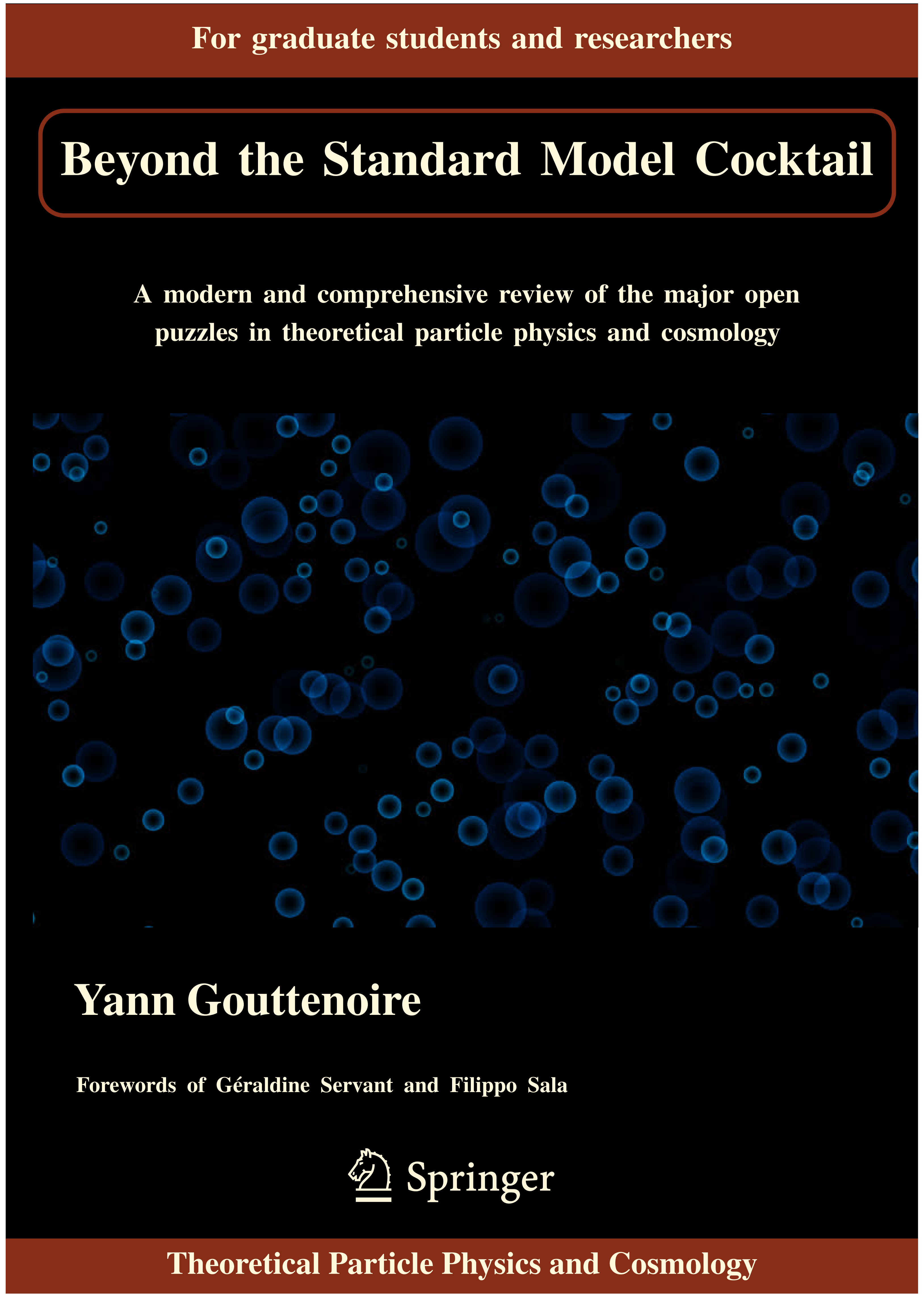

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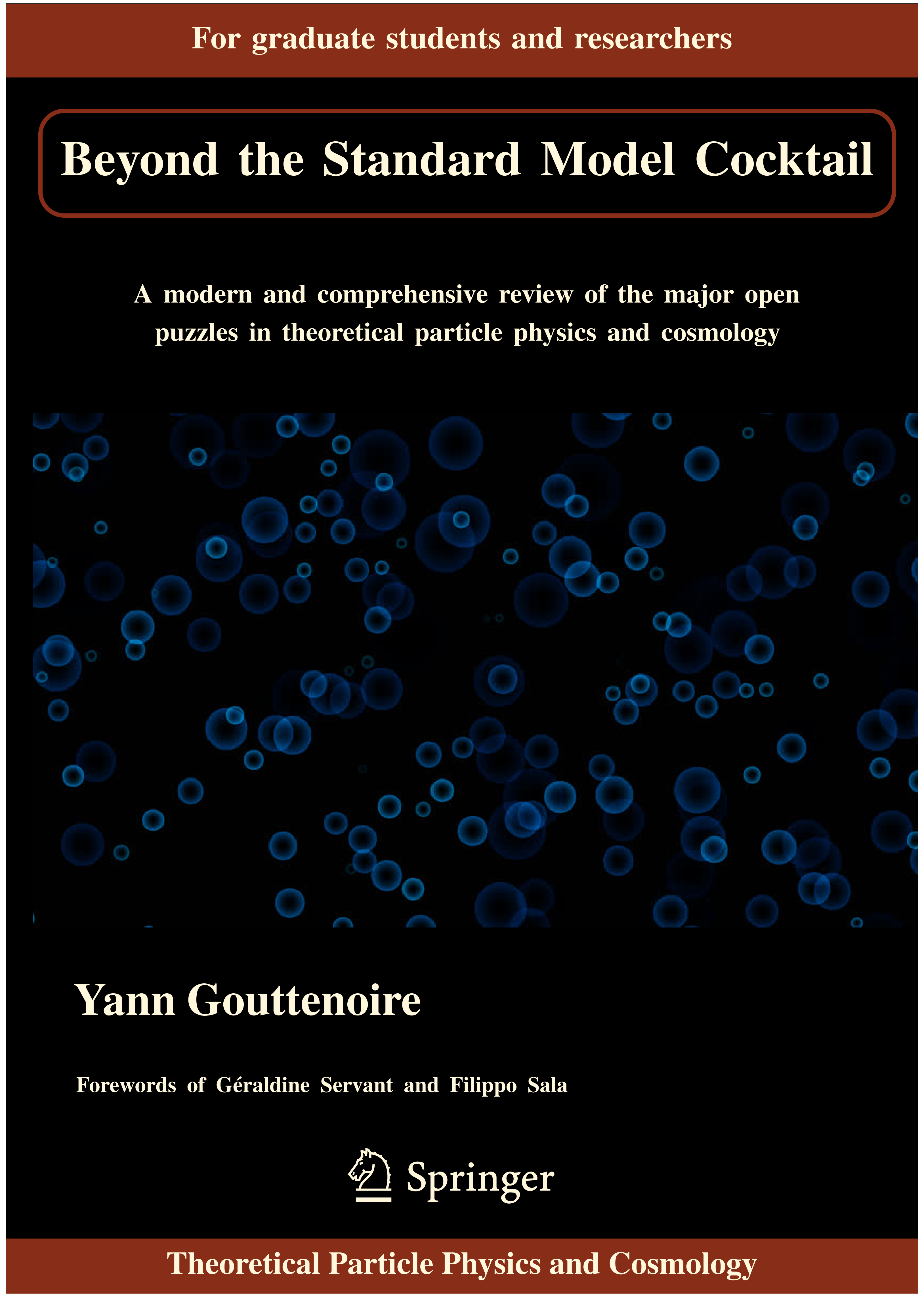


Conclusion

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 $U(1)_D$:

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

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

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

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

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

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

Supercooling from a nearly conformal sector

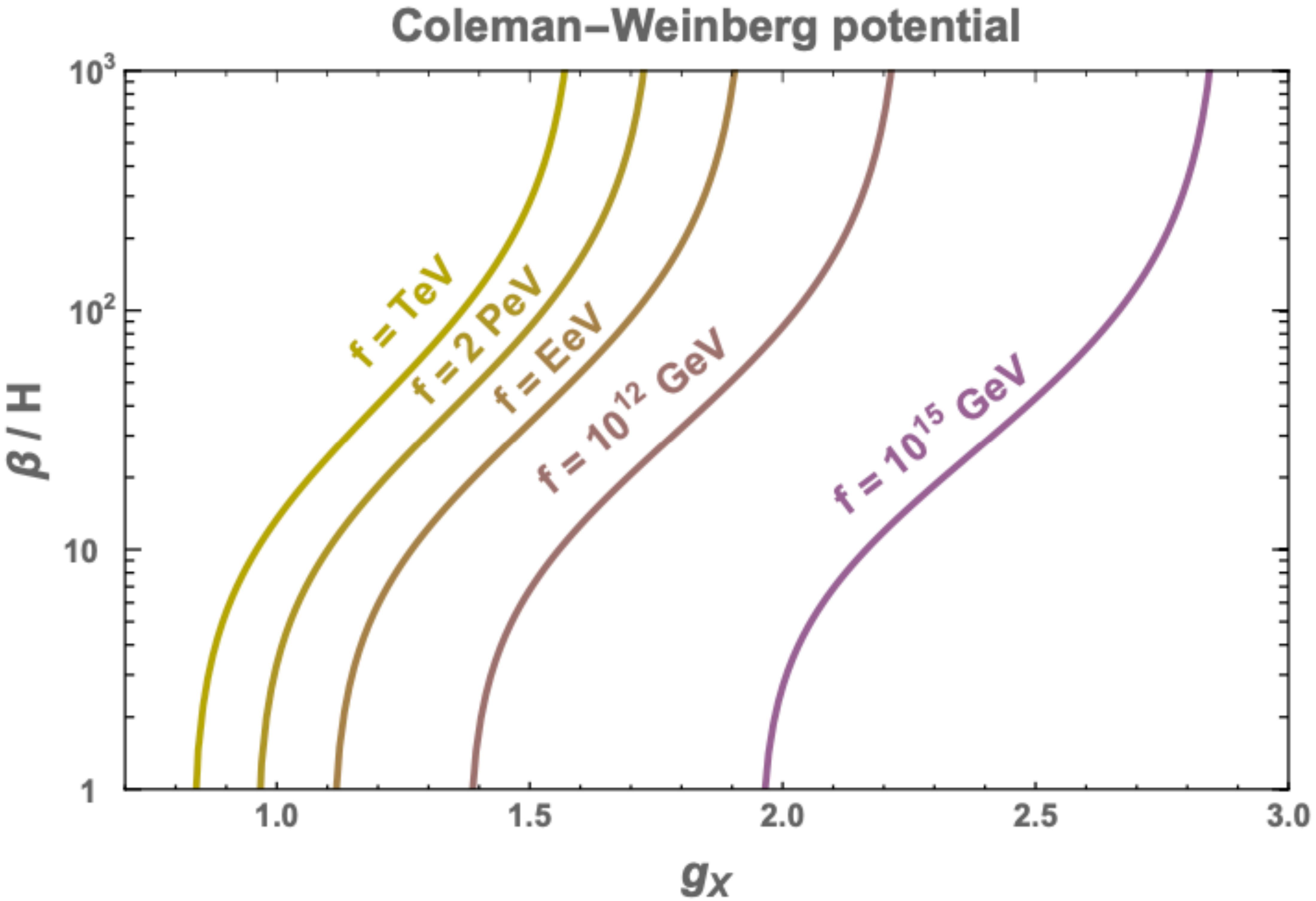
Thick-wall formula:

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

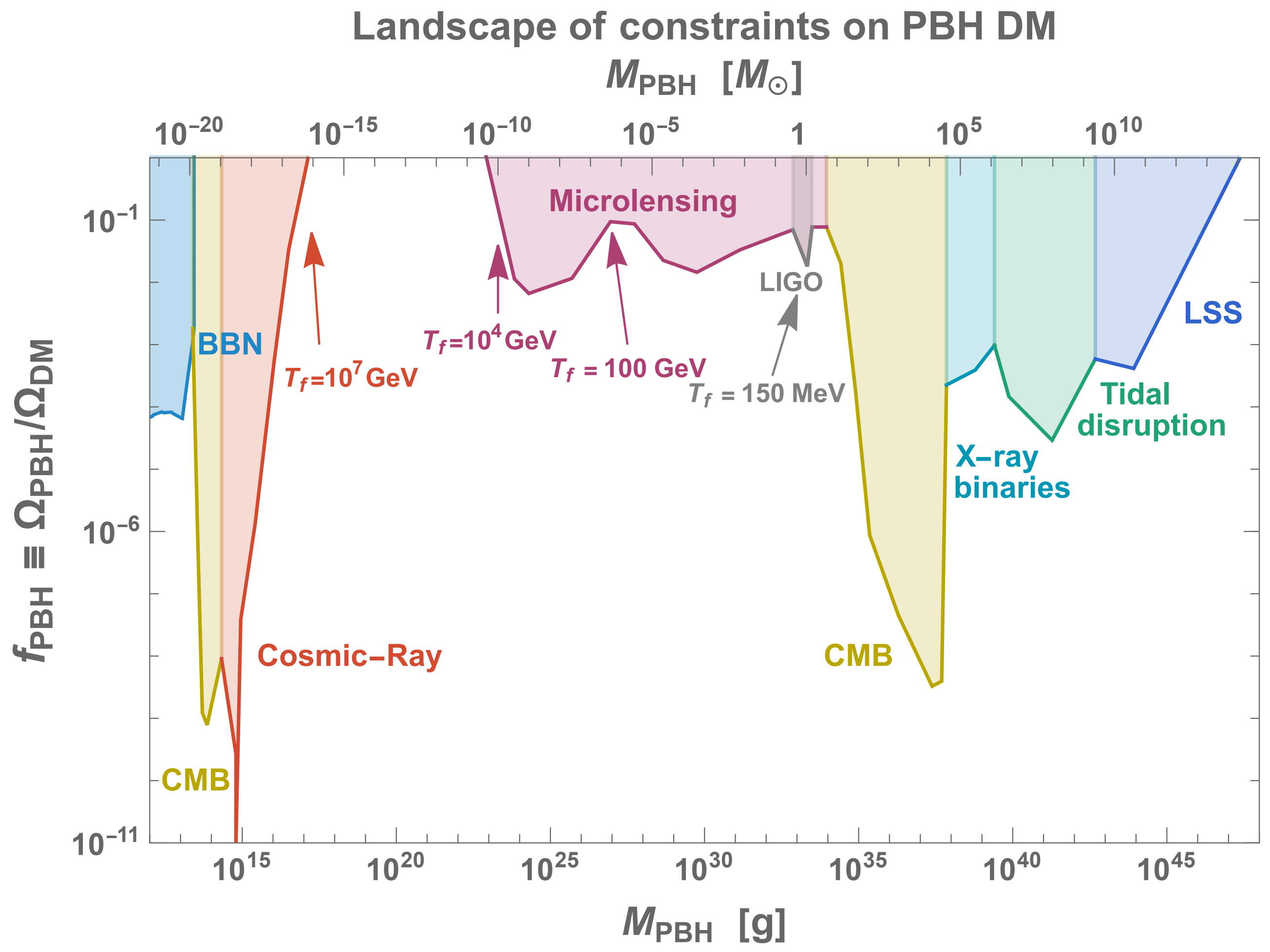
alpha and beta parameters:

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

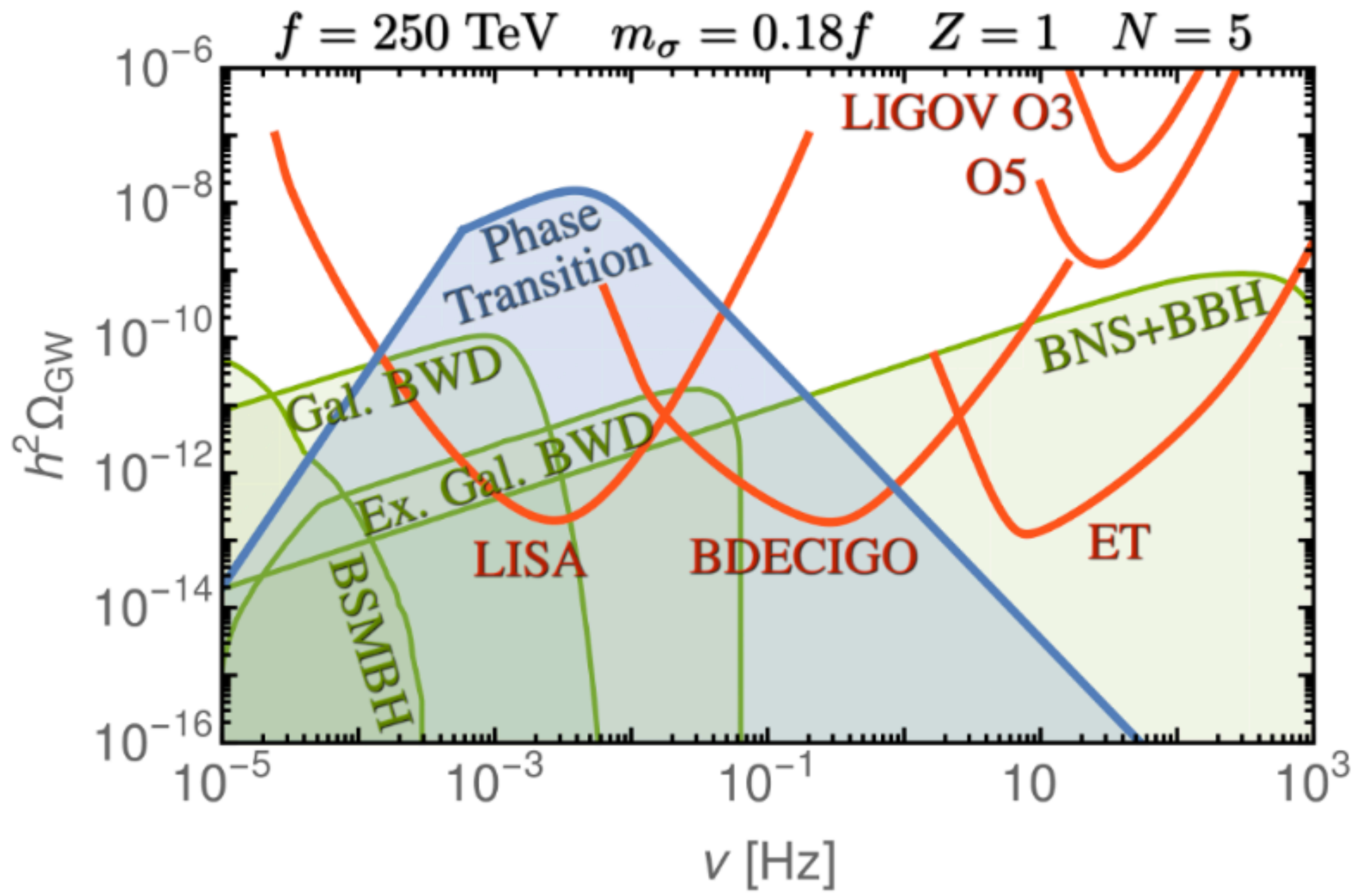
$$\beta/H \simeq -4 + T \frac{d(S_3/T)}{dT}\bigg|_{T_{\rm nuc}} = -4 + \frac{S_3/T}{\log \frac{M}{T}}\bigg|_{T_{\rm nuc}} = -4 + \frac{A}{\log^2 \frac{M}{T}}$$



PBH DM



Large GW signal



Classes of nearly-conformal models

Space-time dimension \ Strength coupling	Weakly-coupled	Strongly-coupled
D = 4		
D = 5		

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D = 5	**Warped fifth dimension** $V(\mu) = v_{\rm IR}^2 \mu^4 \left[(4+2\epsilon)\left(1 - \frac{v_{\rm UV}}{v_{\rm IR}}\left(\frac{\mu}{\mu_0}\right)^\epsilon\right)^2 + \delta\right]$	

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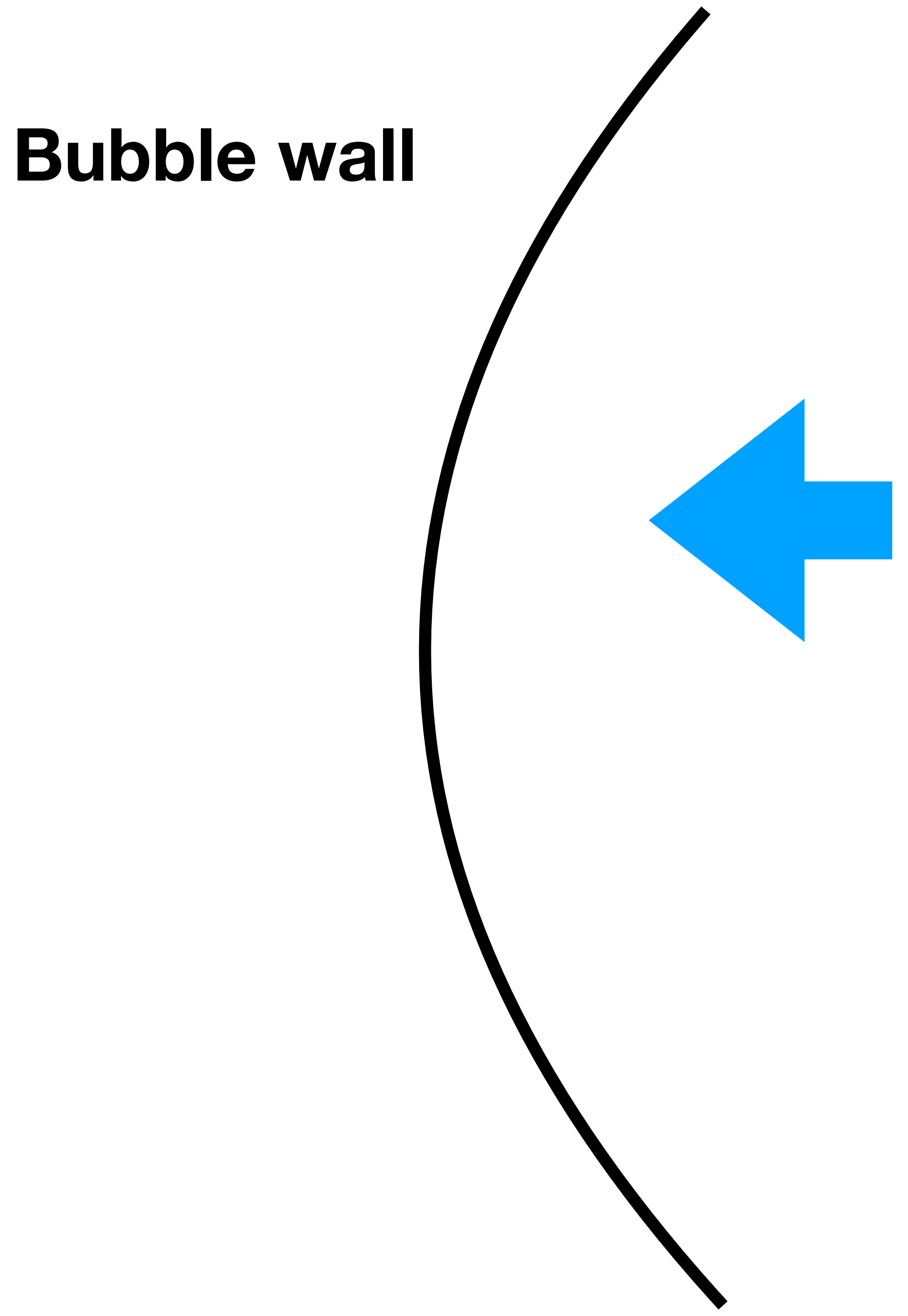
$\epsilon \to 0$ (Light-dilaton → Coleman-Weinberg)

holography (Light-dilaton ↔ Warped fifth dimension)

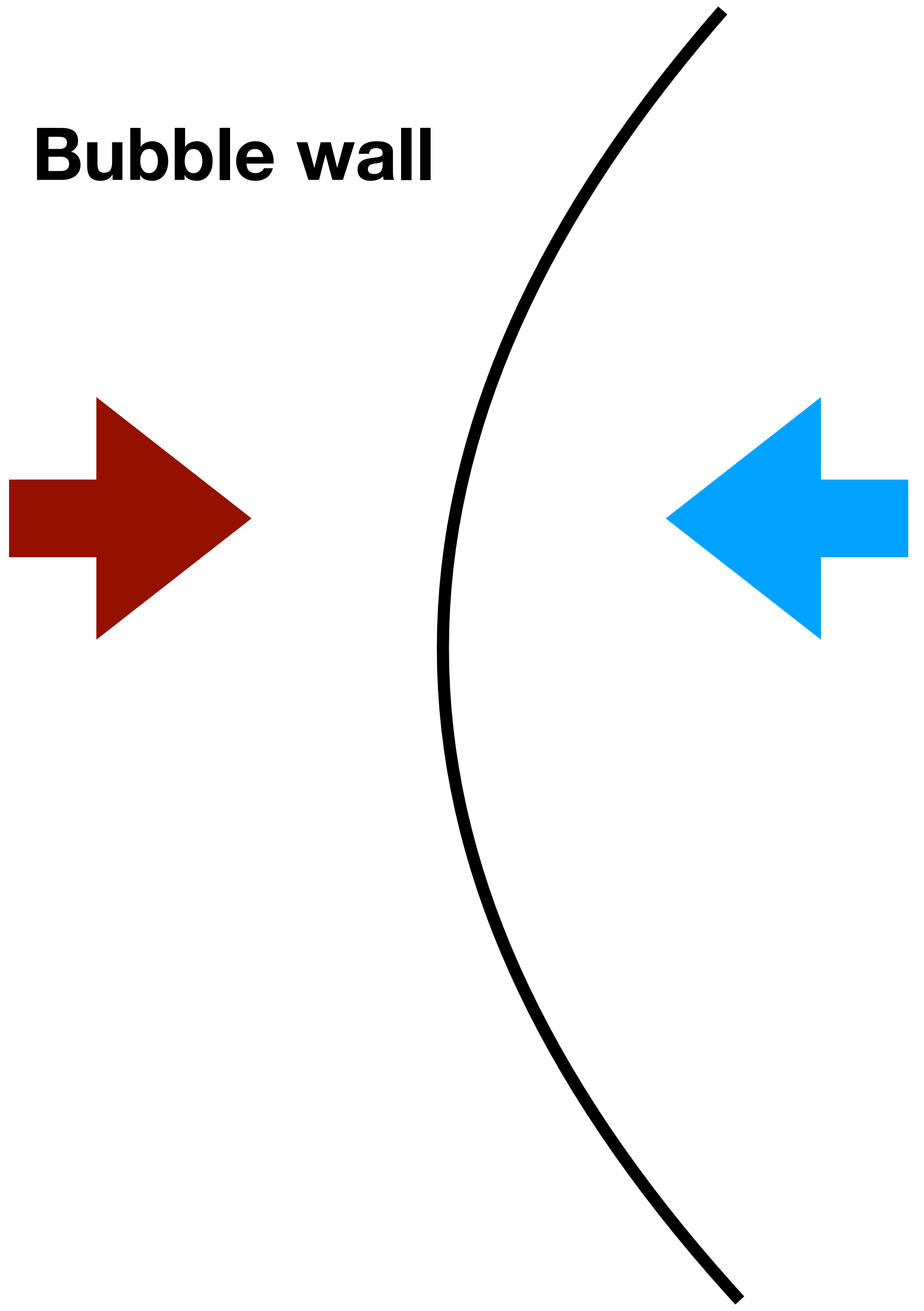
Consequences on bubble wall velocity



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

Consequences on bubble wall velocity

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



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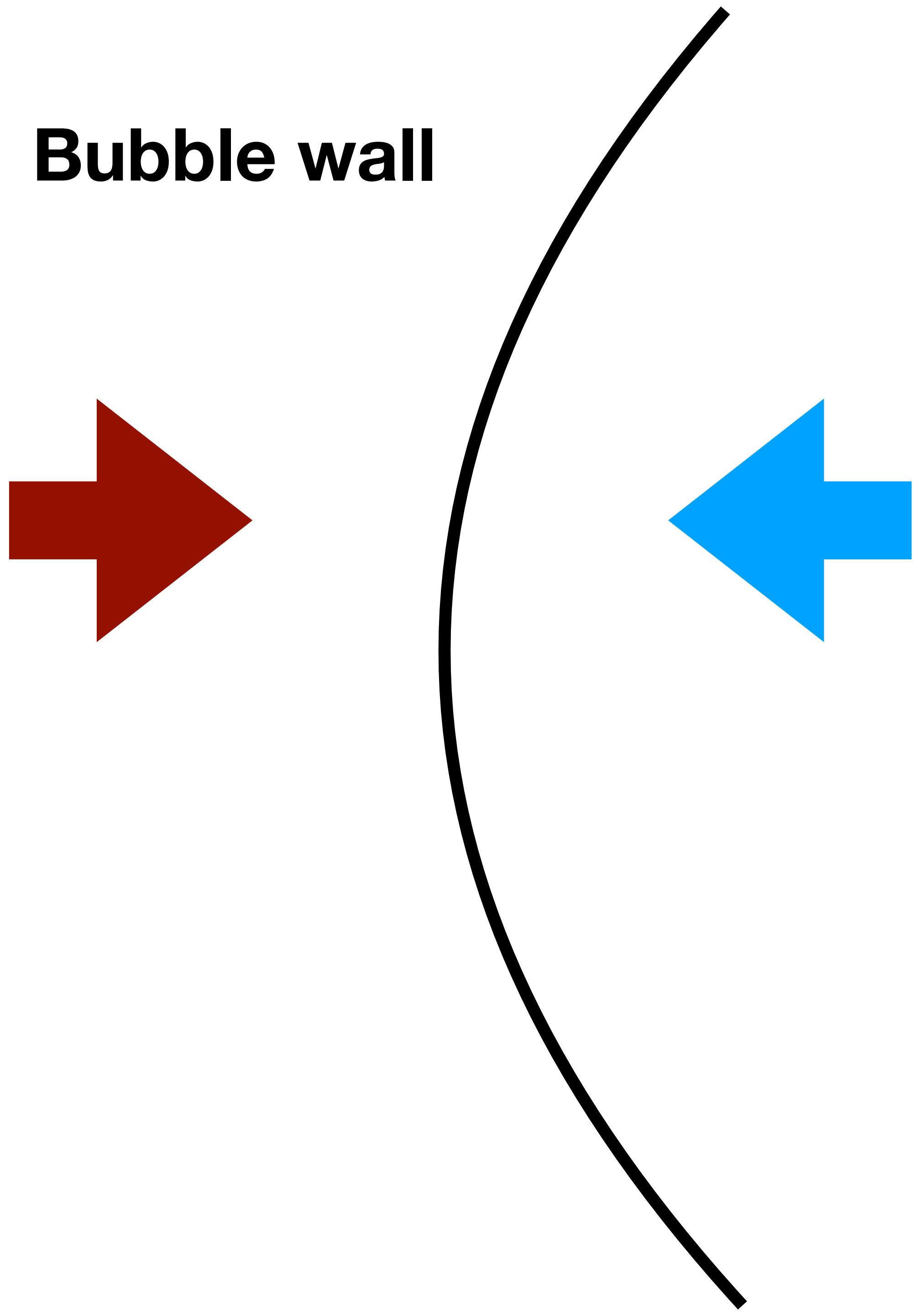

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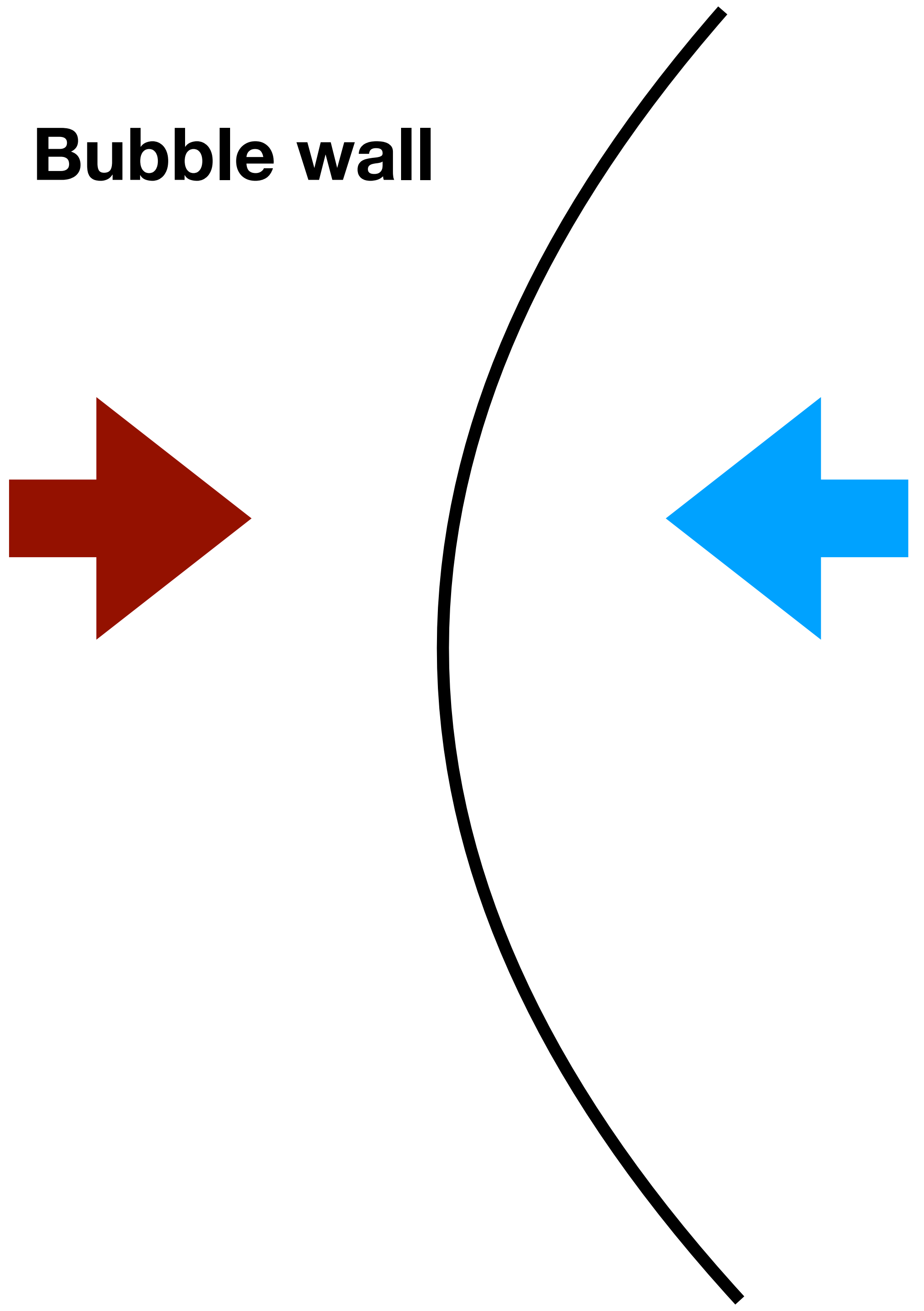

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Weakly-coupled PT

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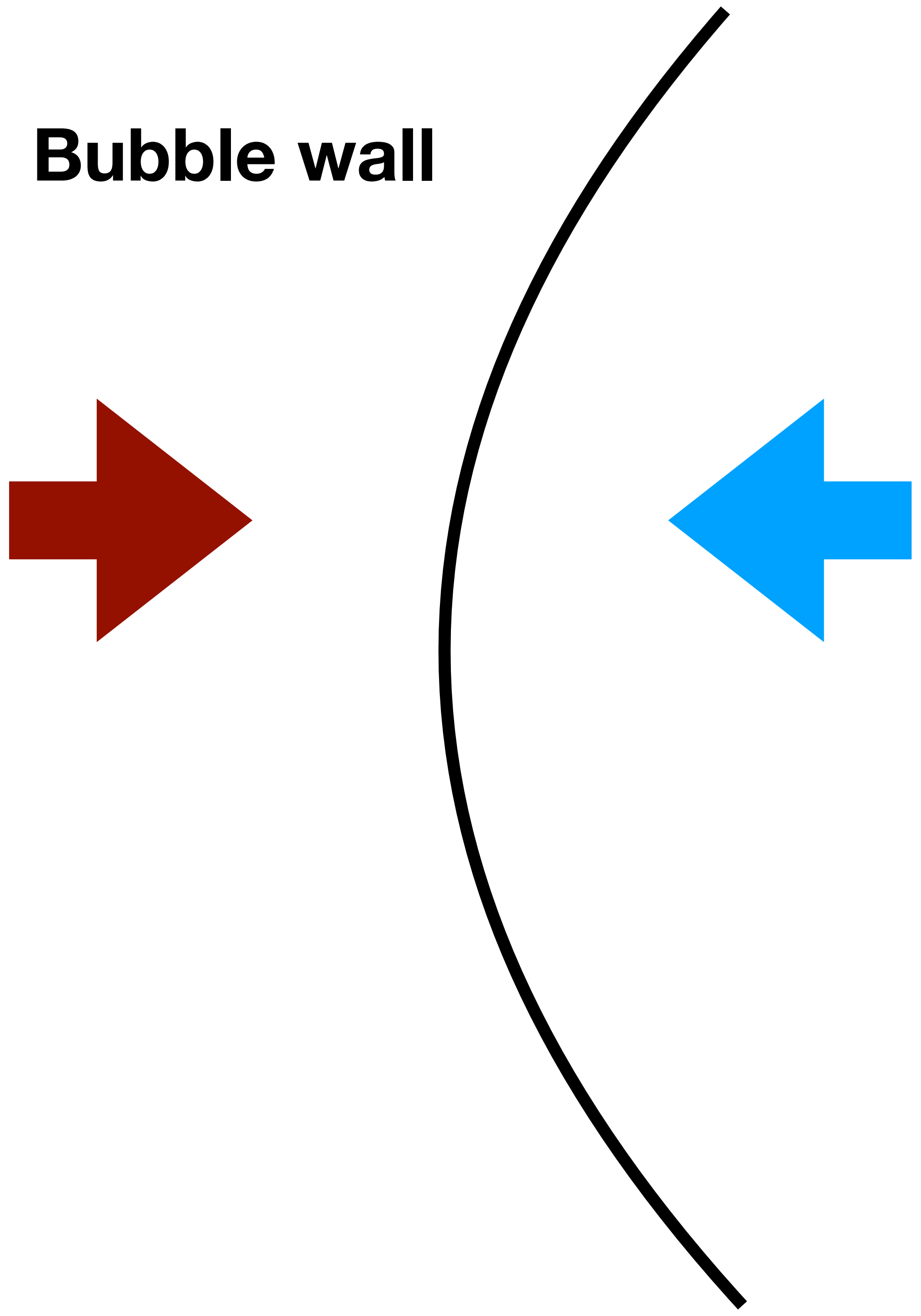

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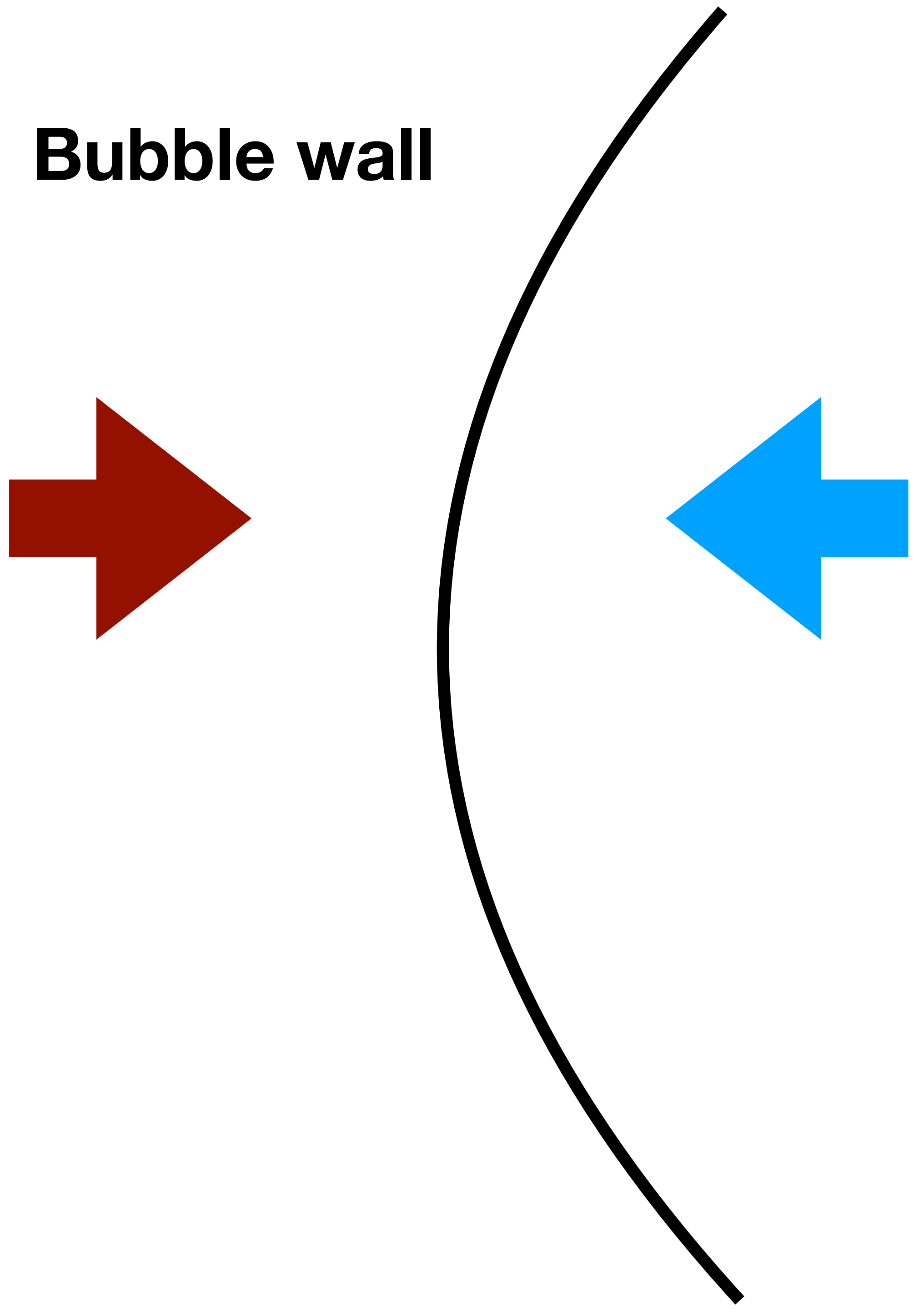
Weakly-coupled PT

Bodeker&Moore (09' and 17')

Azatov+ 20'

Consequences on bubble wall velocity



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

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

$$\Delta p = \,?$$

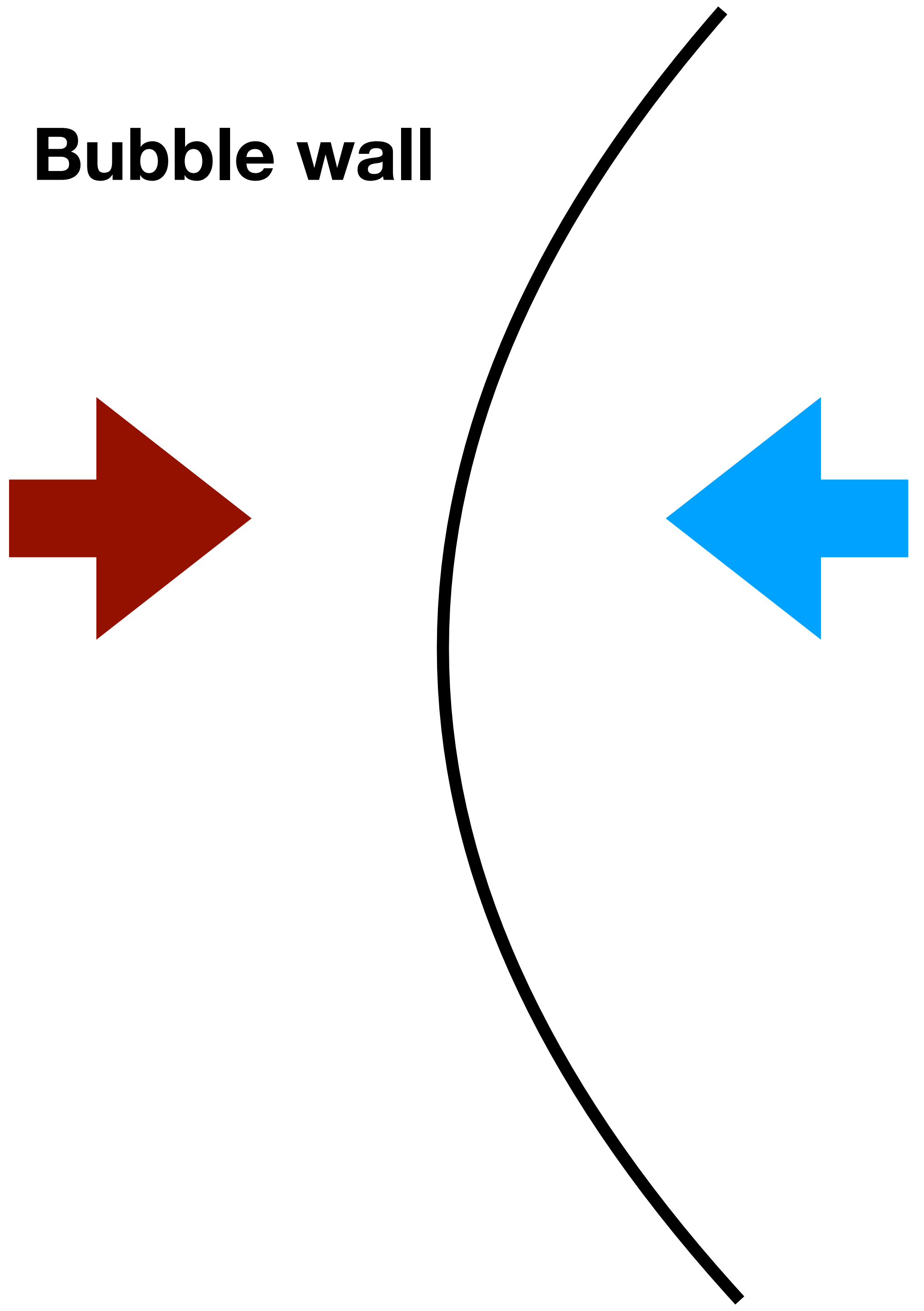
Weakly-coupled PT

Bodeker&Moore (09' and 17')

Azatov+ 20'

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

Consequences on bubble wall velocity



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Bodeker&Moore (09' and 17')

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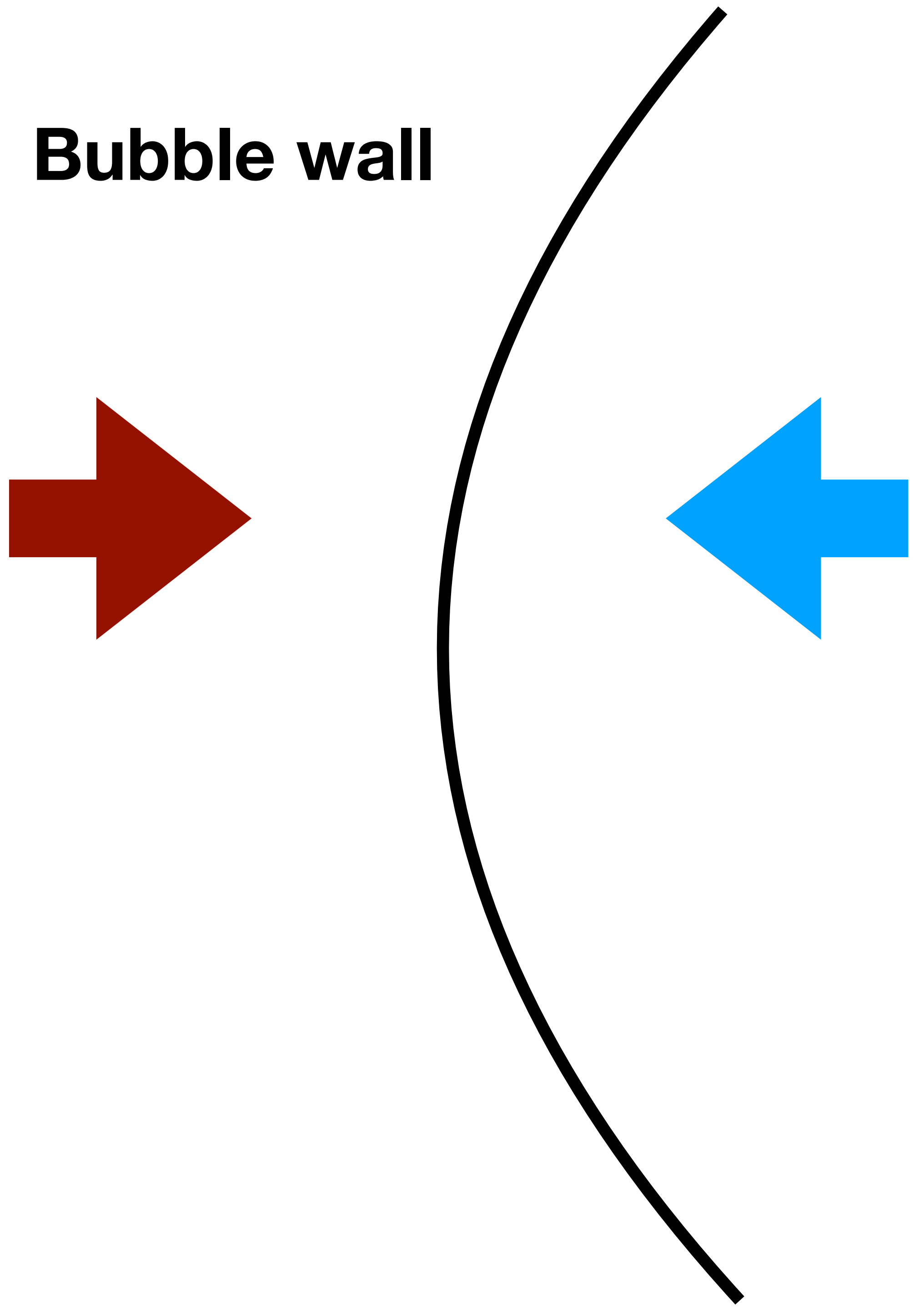
$$\mathscr{P}_{\text{LO}} \simeq \Delta m^2 T_{\text{nuc}}^2 \qquad \mathscr{P}_{\text{NLO}} \simeq g_{\text{w}} \gamma \, \Delta m T_{\text{nuc}}^3$$

Consequences on bubble wall velocity

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



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Weakly-coupled PT

Strongly-coupled PT

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Azatov+ 20'

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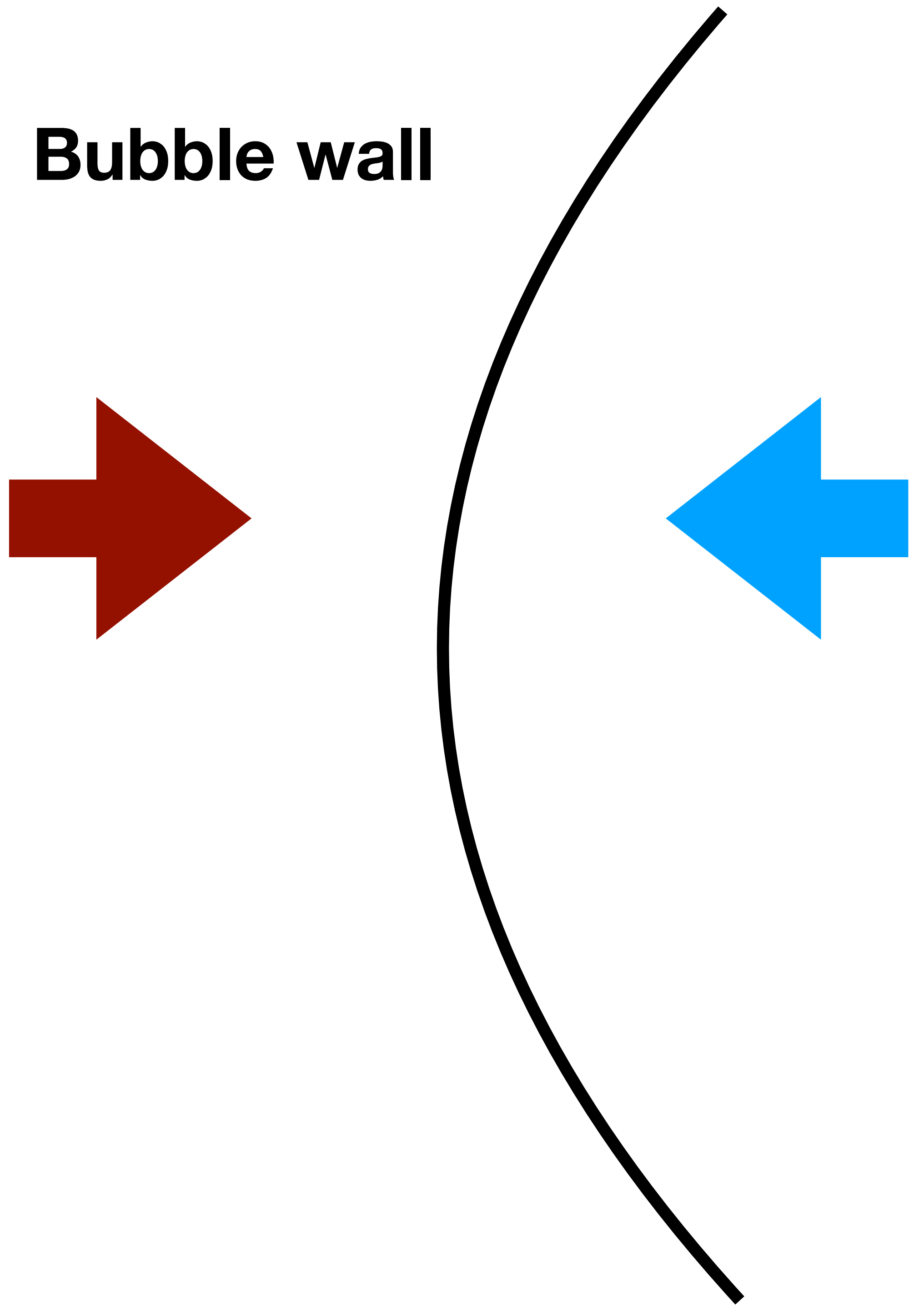
Consequences on bubble wall velocity



$$\mathscr{P}_{\rm friction} \simeq \gamma T^3_{\rm nuc} \times \Delta p$$

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Weakly-coupled PT

Bodeker&Moore (09' and 17')

Azatov+ 20'

$$\mathscr{P}_{\rm LO} \simeq \Delta m^2 T^2_{\rm nuc} \qquad \mathscr{P}_{\rm NLO} \simeq g_{\rm w}\gamma\, \Delta m T^3_{\rm nuc}$$

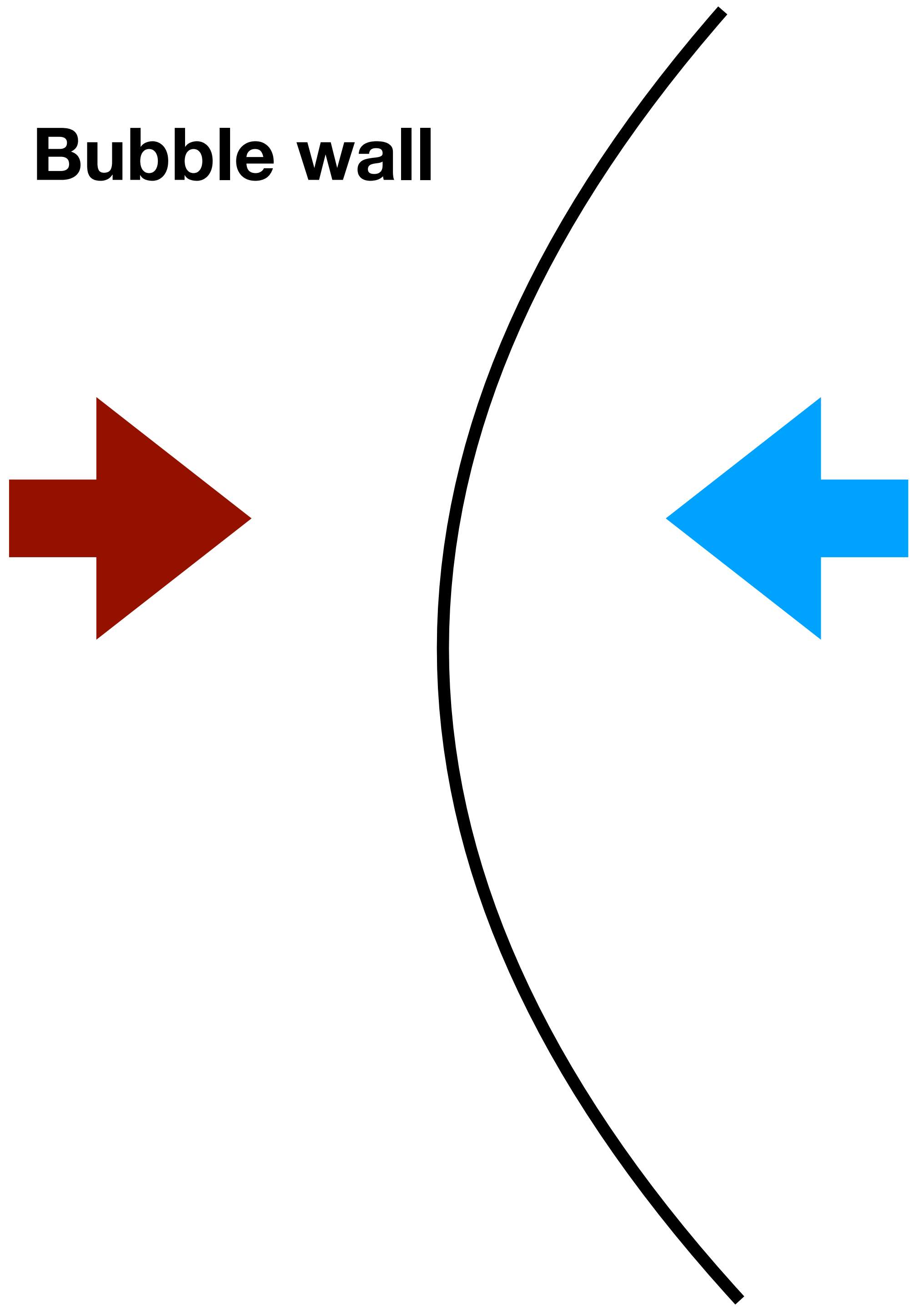
Strongly-coupled PT

Hoeche, Kozaczuk, Long, Turner, Wang 20'

$$\mathscr{P}_{\rm all-order} \simeq \gamma^2\, T^4_{\rm nuc}$$

Consequences on bubble wall velocity

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



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Hoeche, Kozaczuk, Long, Turner, Wang 20'

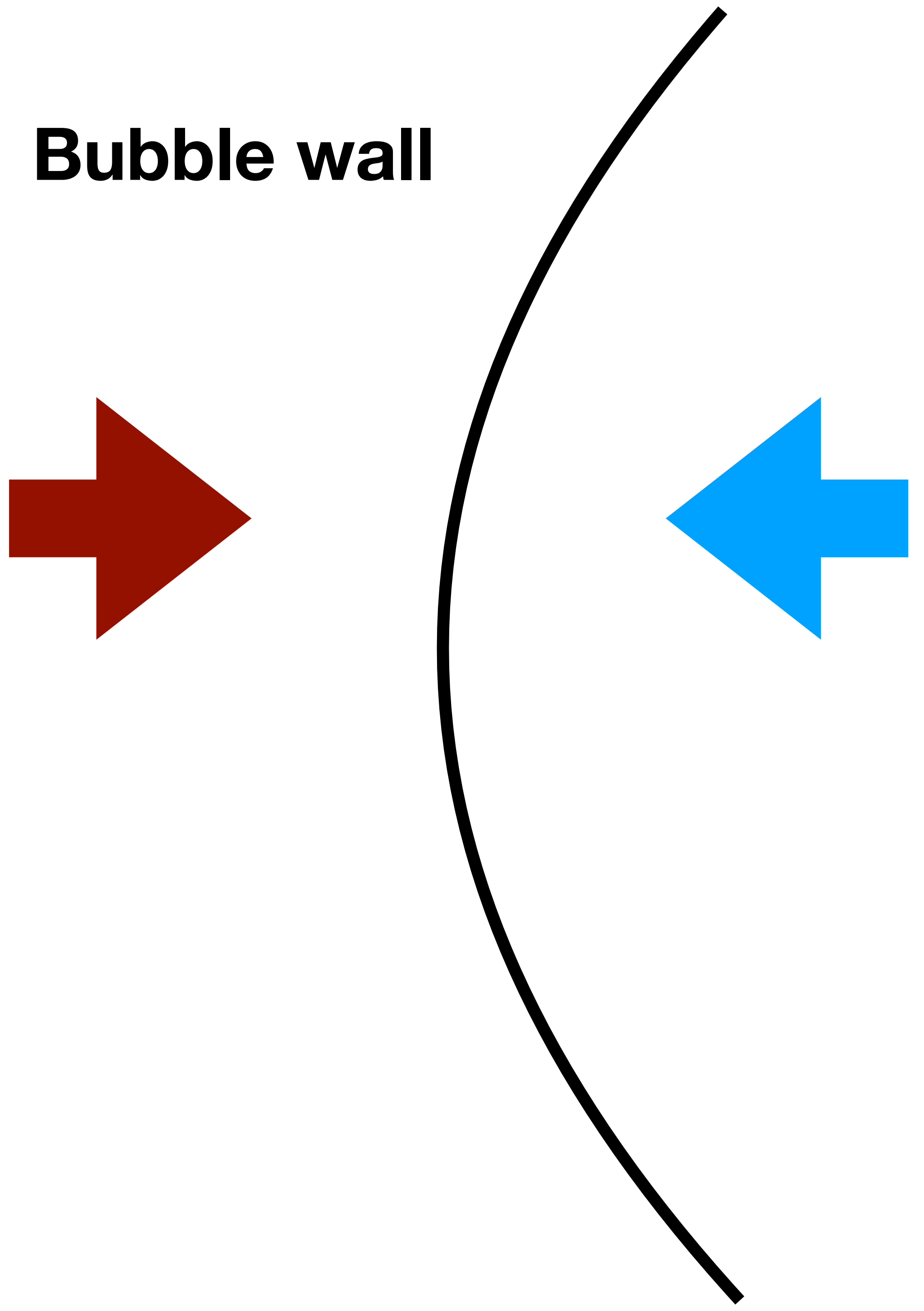
$$\mathscr{P}_{\rm all-order} \simeq \gamma^2\, T_{\rm nuc}^4$$

Baldes, YG, Sala 20'

$$\mathscr{P}_{\rm flux-tube} \simeq \gamma\, f\, T_{\rm nuc}^3$$

Consequences on bubble wall velocity

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



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Strongly-coupled PT

Hoeche, Kozaczuk, Long, Turner, Wang 20'

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

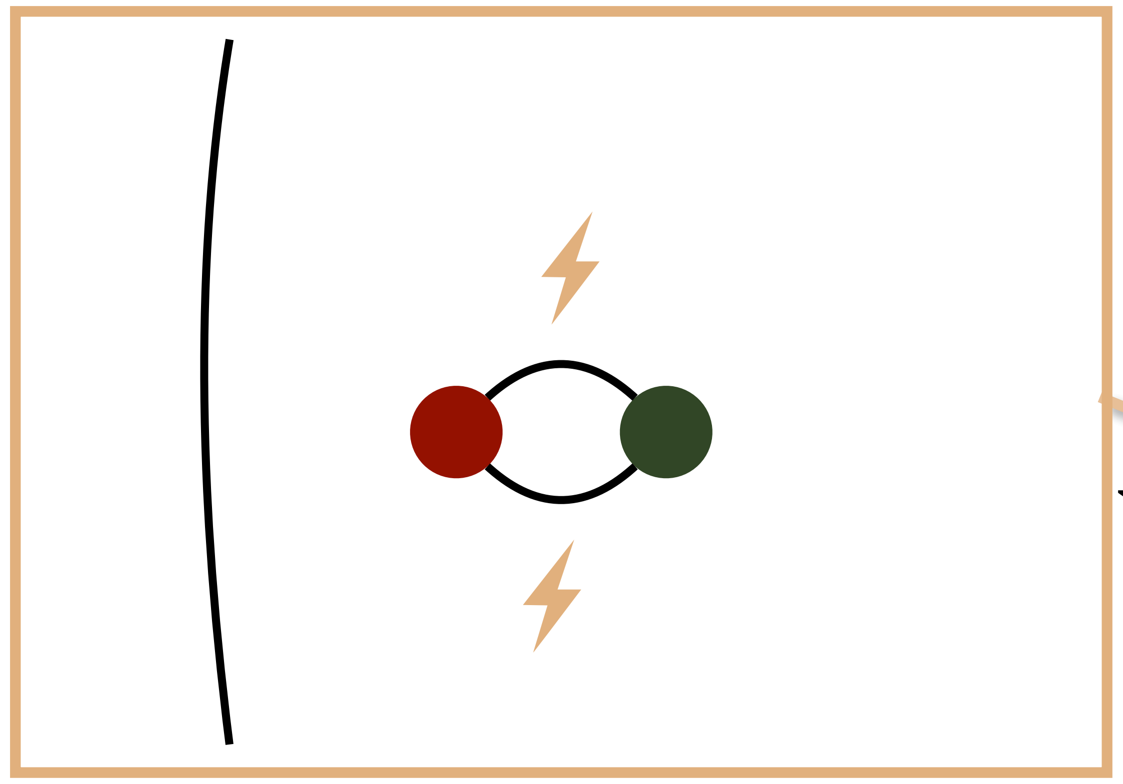
Baldes, YG, Sala 20'

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

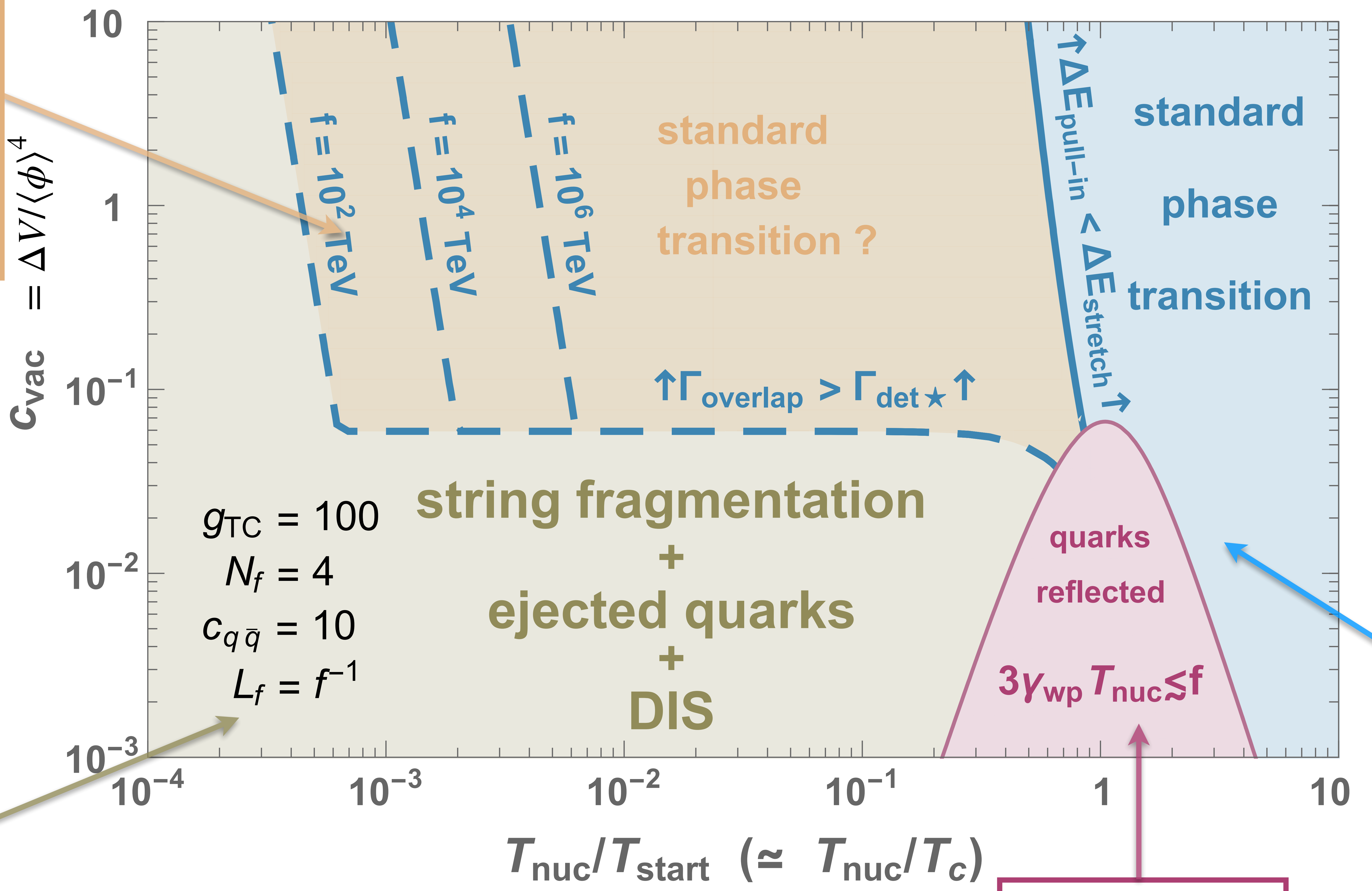
YG, Jinno, Sala 21'

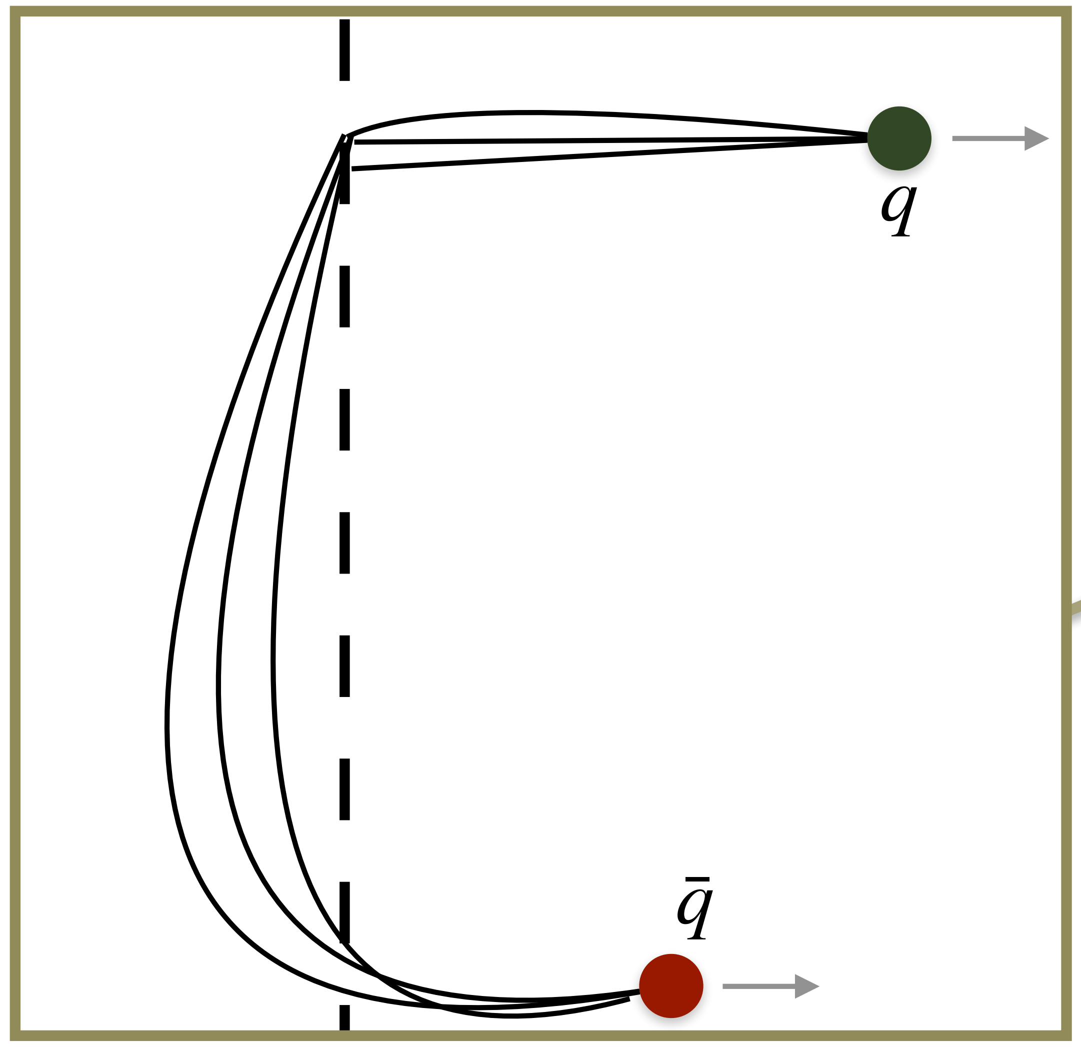
$$\mathscr{P}_{\text{all-order}} \simeq \gamma f T_{\text{nuc}}^3$$

How much supercooling is needed ?

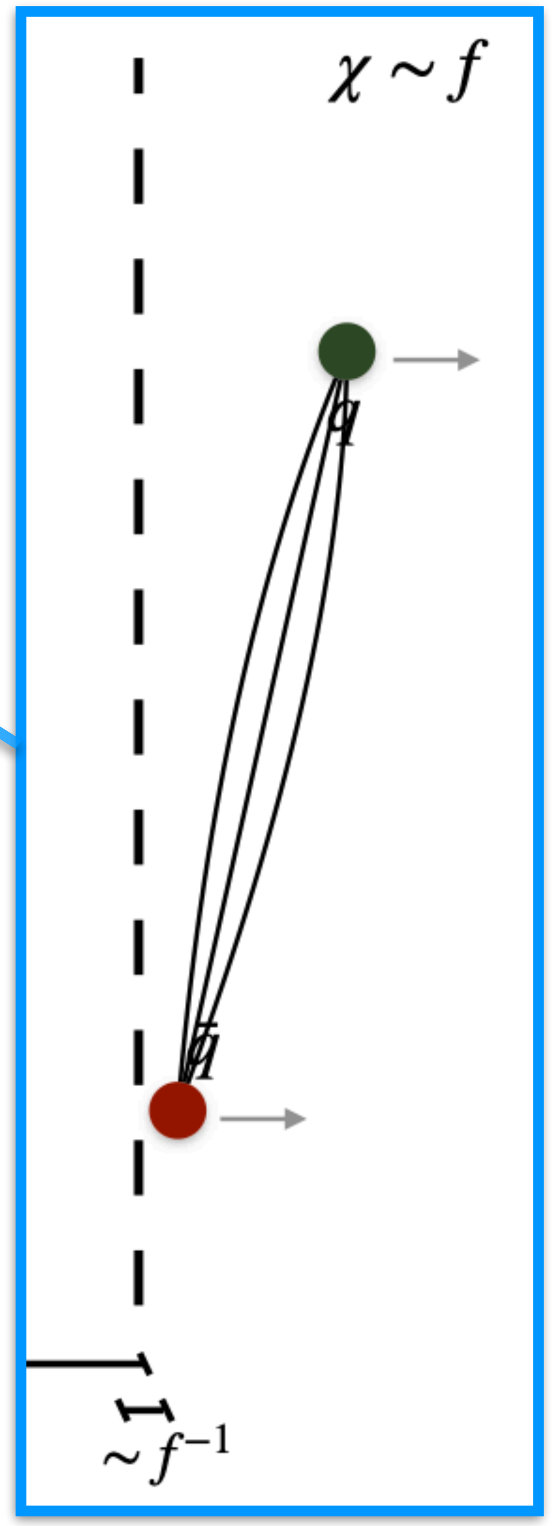


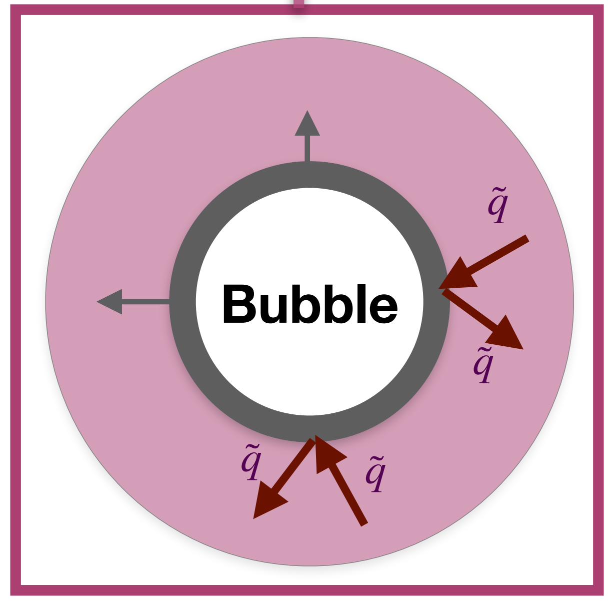
quark-string interaction win





No line distortion





Snow ball effect

Ping-pong effect

Quark nuggets Witten 1984

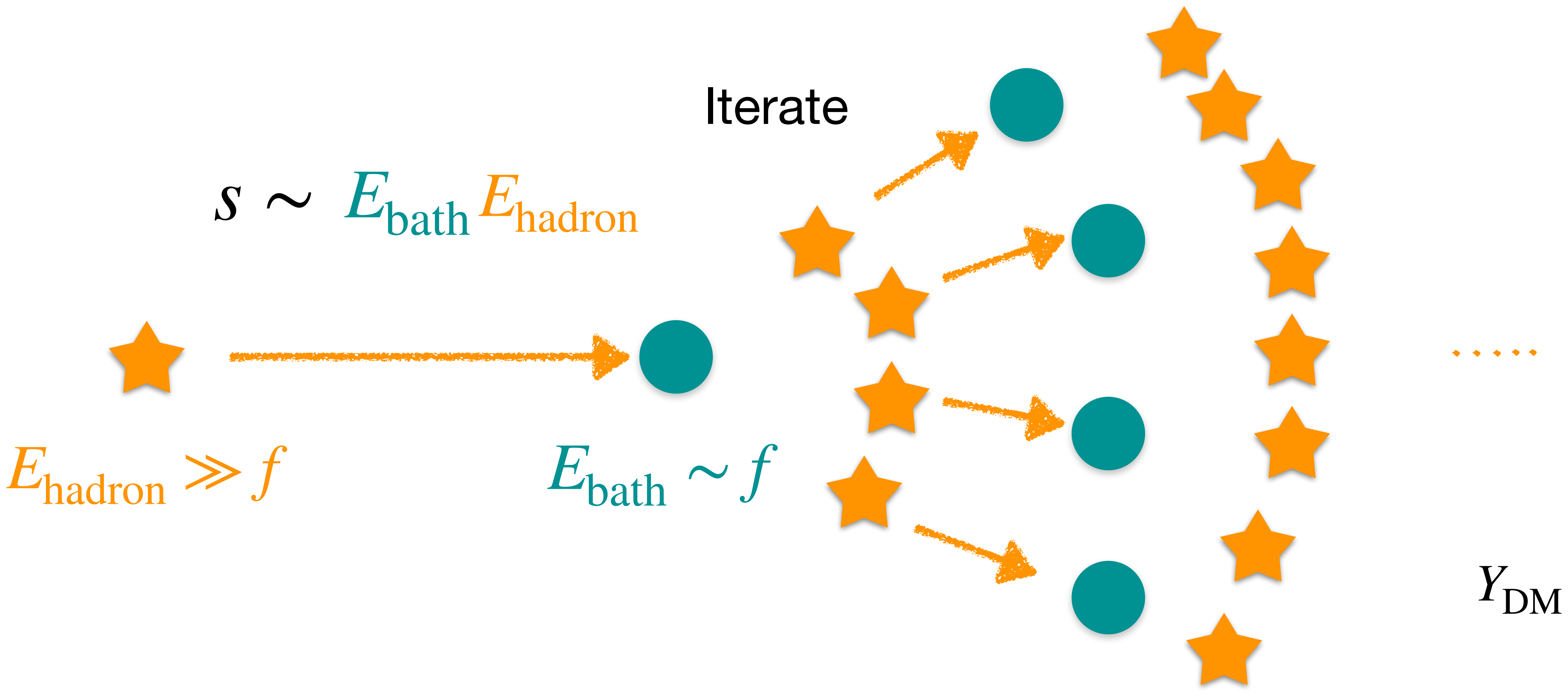
Filtered DM. 1912.02830

Thermal Squeezeout of DM. 2103.09827

Deep Inelastic Scattering in the Early Universe

Hadron energy in plasma (= CMB) frame
$$\langle E_{\rm hadron}\rangle = \frac{E^{q\bar q}_{\rm cm}}{\langle N_{\rm hadron}\rangle} \sim \frac{\sqrt{\gamma_{\rm wp} f/T_{\rm nuc}}}{\langle N_{\rm hadron}\rangle} \gg f$$

We find dominant scatterers in (p)reheated bath at $E_{\rm bath} \sim f$



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

$$\gamma_{\rm cp} \simeq \frac{\gamma_{\rm wp}}{\gamma_{\rm wc}} \qquad \gamma_{\rm wc} \simeq \frac{E^{q\bar q}_{\rm cm}}{f} \simeq \sqrt{\gamma_{\rm wp}\frac{T_{\rm nuc}}{f}}$$

$$E_{\rm hadrons,\,p} \simeq \gamma_{\rm cp}\frac{E^{q\bar q}_{\rm cm}}{\langle N_{\rm hadron}\rangle} \simeq \frac{\gamma_{\rm wp}}{E^{q\bar q}_{\rm cm}/f}\frac{E^{q\bar q}_{\rm cm}}{\langle N_{\rm hadron}\rangle} \simeq \frac{\gamma_{\rm wp} f}{\langle N_{\rm hadron}\rangle}$$

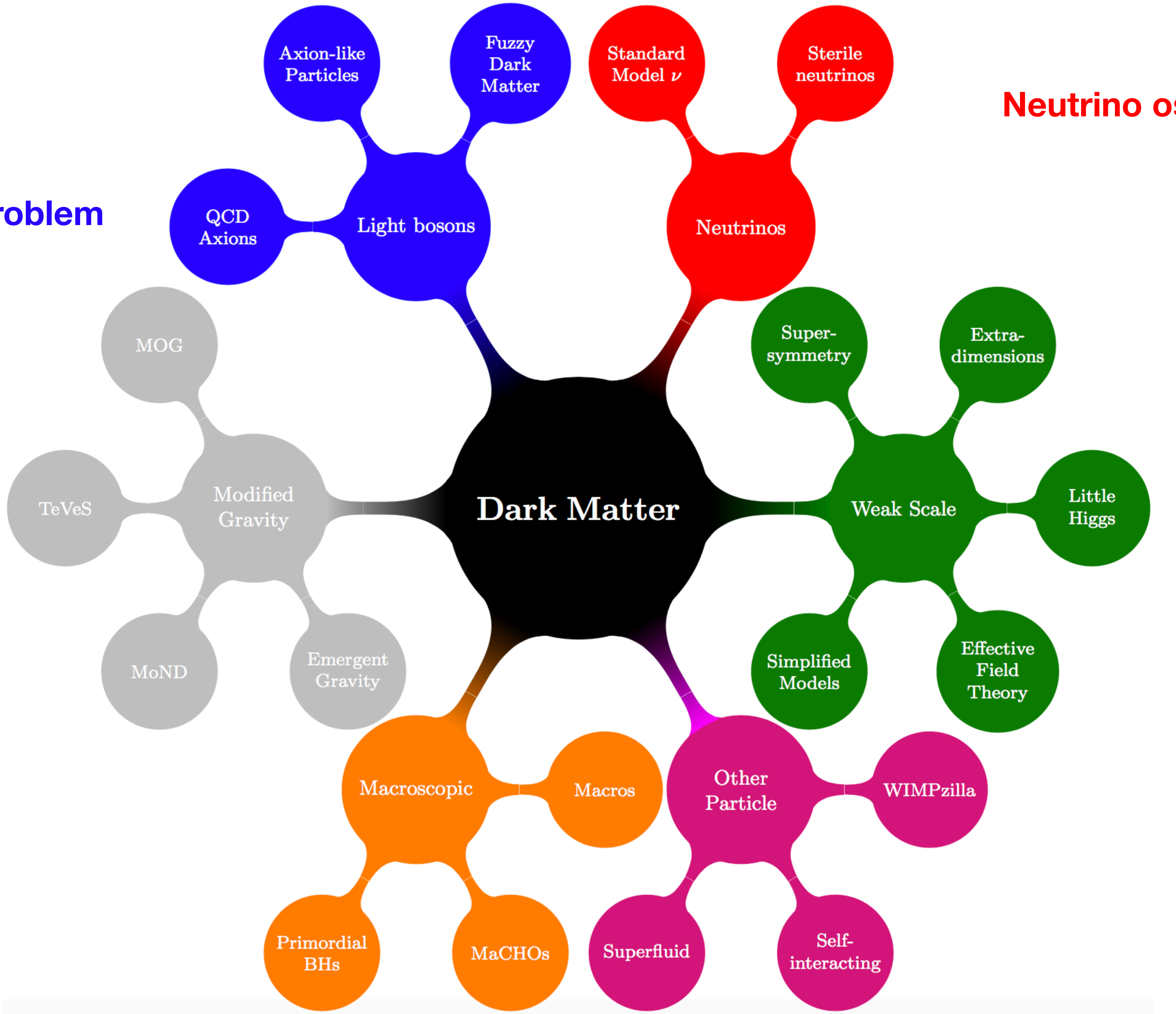
$$Y_{\rm DM}\,/\,Y^{\rm naive}_{\rm DM} \propto \langle N_{\rm hadron}\rangle \frac{s}{f^2} \propto \langle N_{\rm hadron}\rangle \frac{E_{\rm bath}E_{\rm hadrons,\,p}}{f^2} \propto \gamma_{\rm wp} \propto \frac{T_{\rm nuc}}{f}\frac{M_{\rm Pl}}{f}$$

Dark Matter candidates

(WIMPs=Weakly-Interacting Massive Particles)

Strong CP problem

Neutrino oscillations puzzle



Hierarchy problem

Two motivations for the WIMPs:

1) Connection with Hierarchy problem

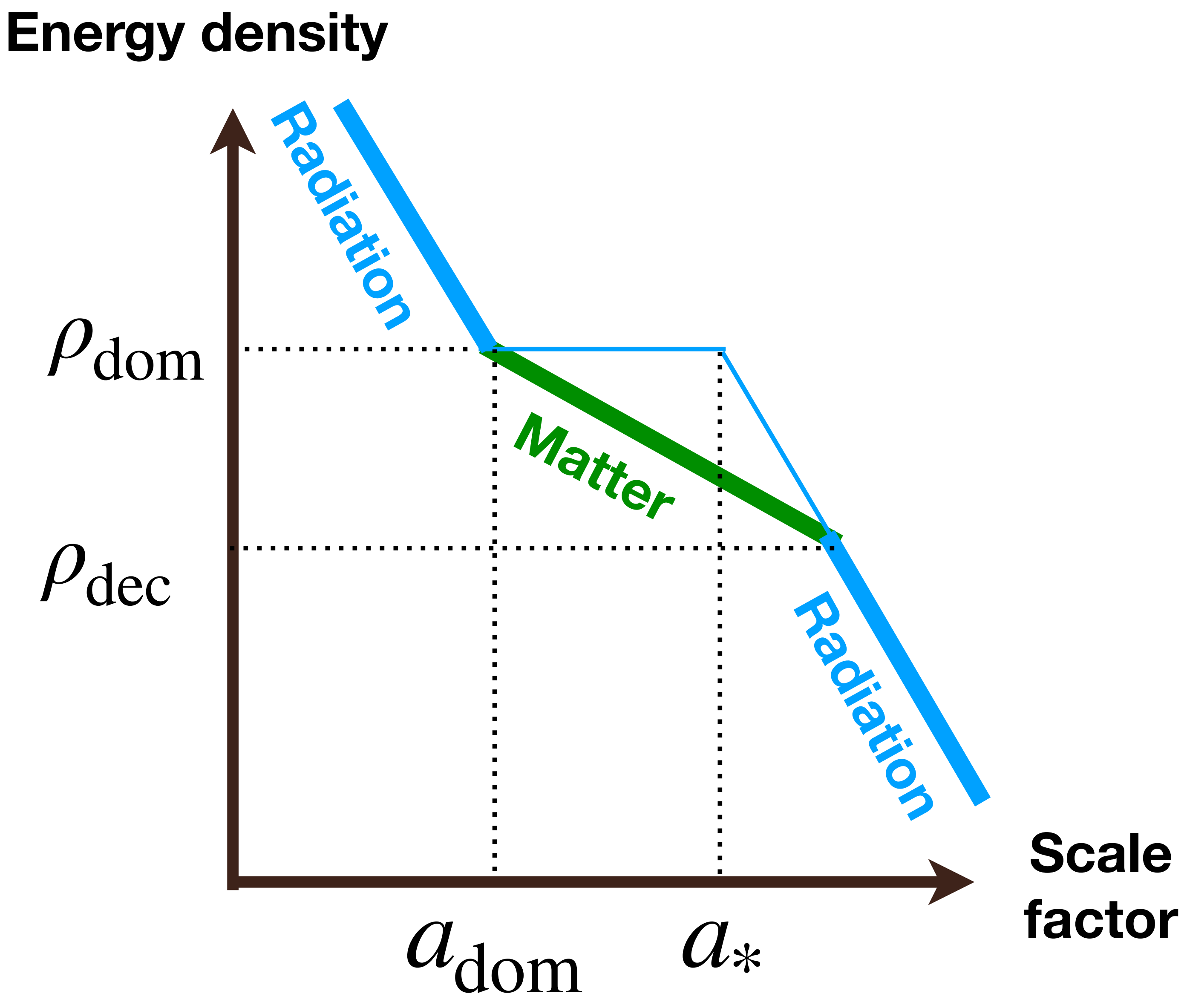
$$M_{\rm DM} \sim 1 \text{ TeV}, \qquad \alpha \sim \alpha_{\rm weak}$$

2) Thermal Dark Matter

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

Entropy injection

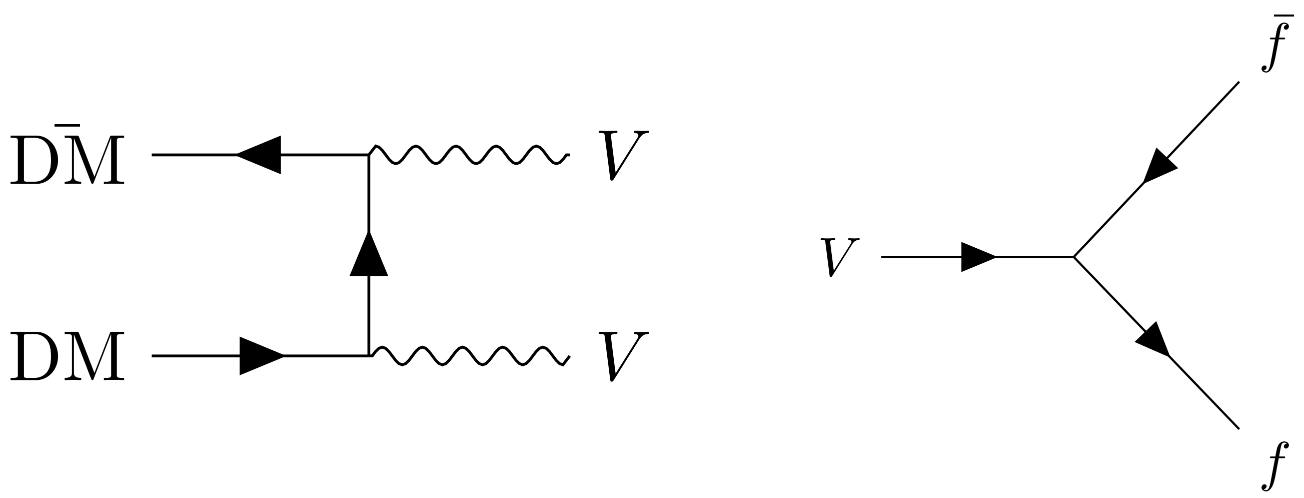
1) After a matter era



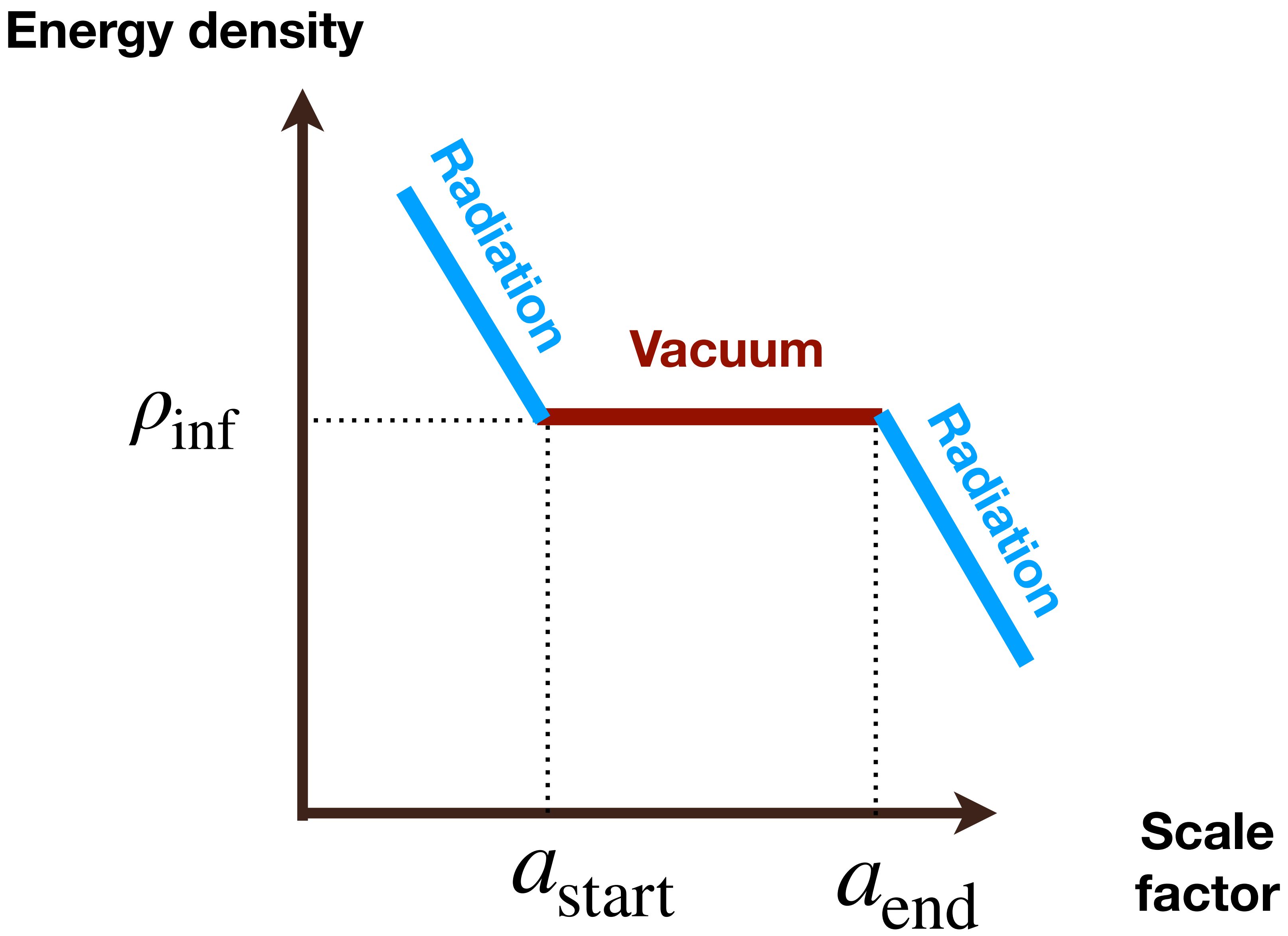
$$D = \left(\frac{a_{\rm dom}}{a_*}\right)^3 = \frac{T_{\rm dom}}{T_{\rm dec}} \simeq \frac{m_V}{\sqrt{M_{\rm pl}\Gamma_V}}$$

Homeopathic DM

Cirelli, Gouttenoire, Petraki, Sala, 2018



2) After an inflationary era



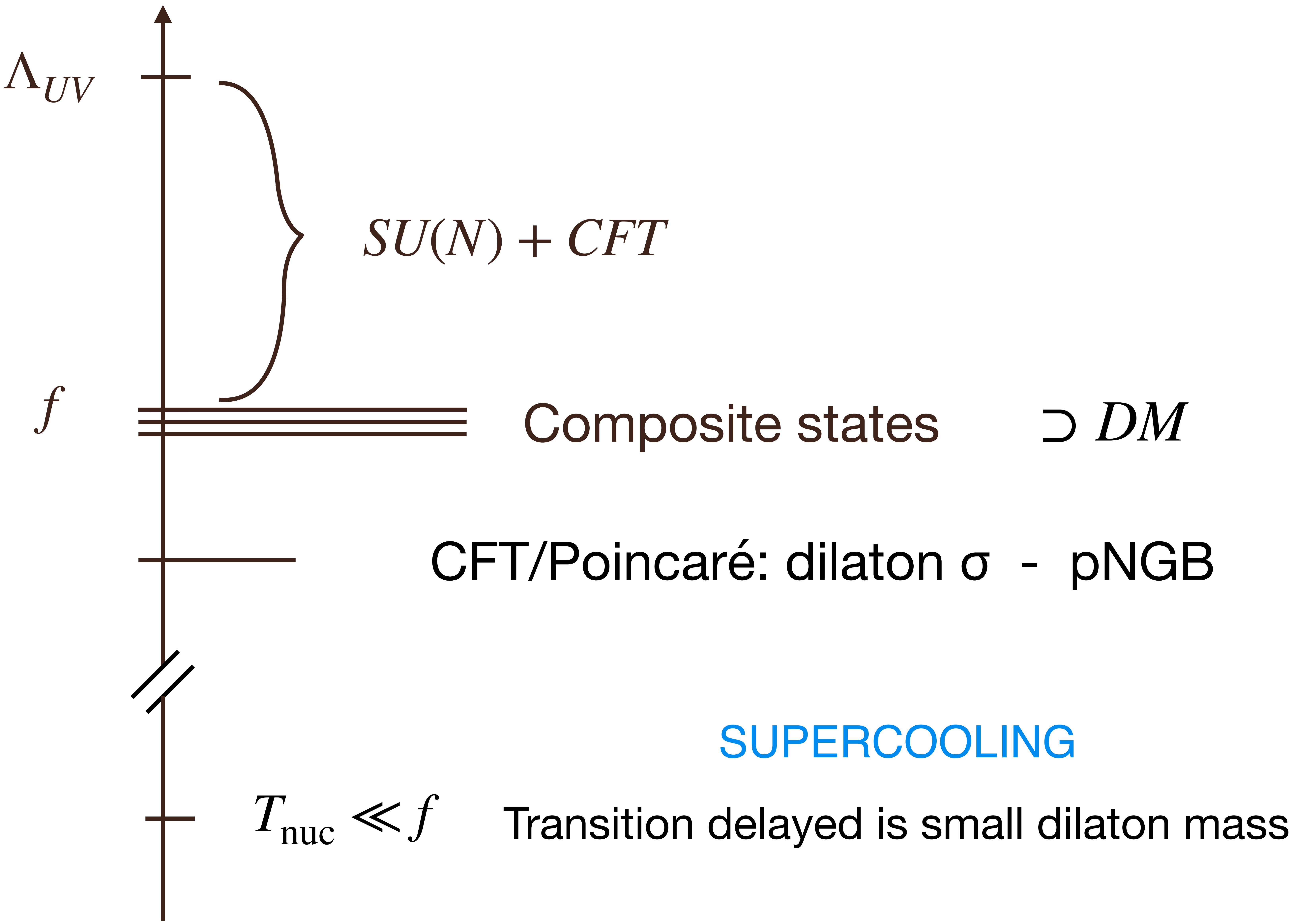
$$D = \left(\frac{a_{\rm end}}{a_{\rm start}}\right)^3 = e^{3\,N_e} = \left(\frac{f}{T_{\rm nuc}}\right)^3$$

Supercooled confinement

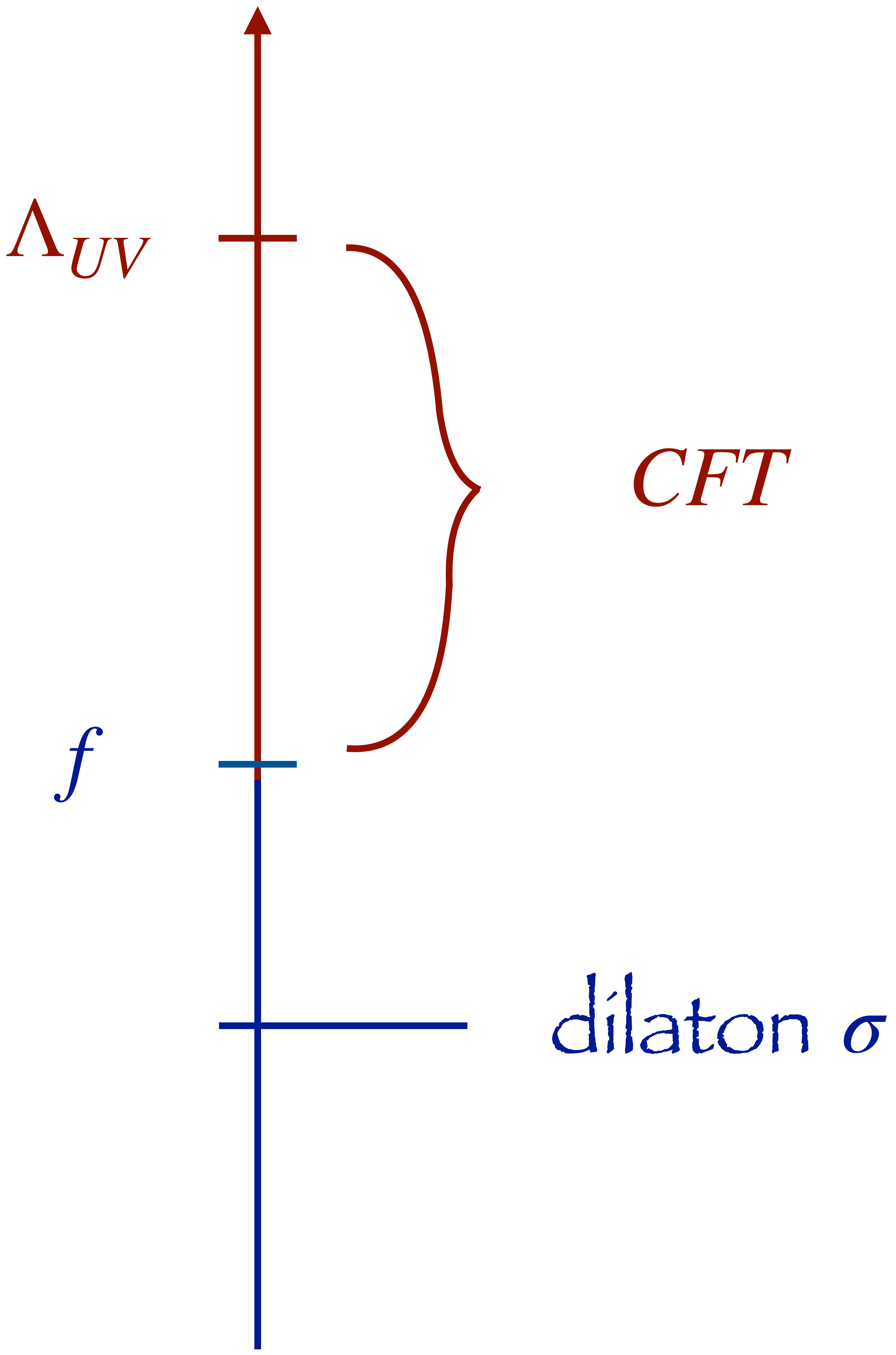
$$N_e = \log\frac{f}{T_{\rm nuc}}$$

Baldes, Gouttenoire, Sala, 2020

Nearly-conformal strong sector



Nearly-conformal strong sector



Deconfined phase

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

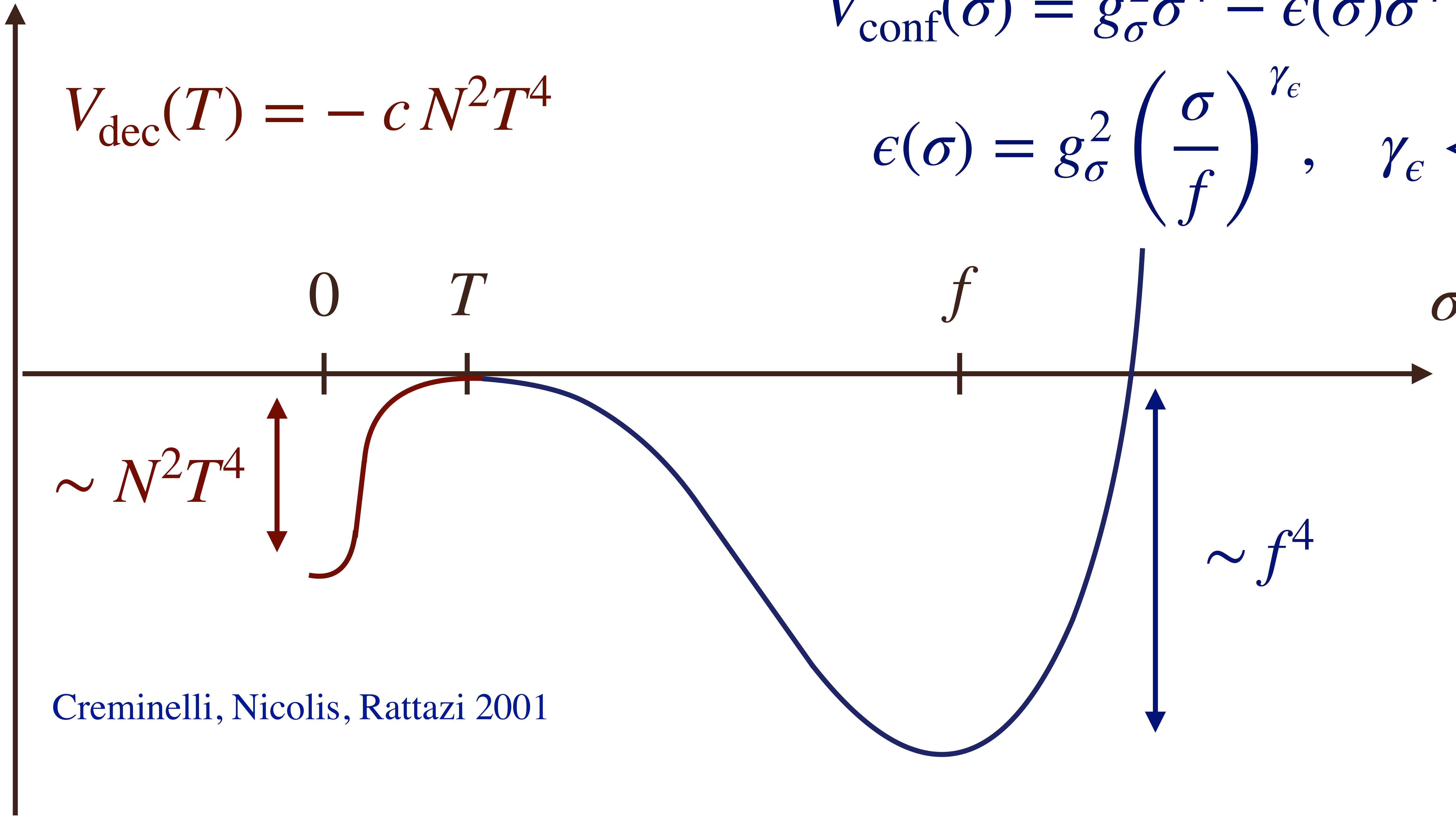
Confined phase

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

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

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

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



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

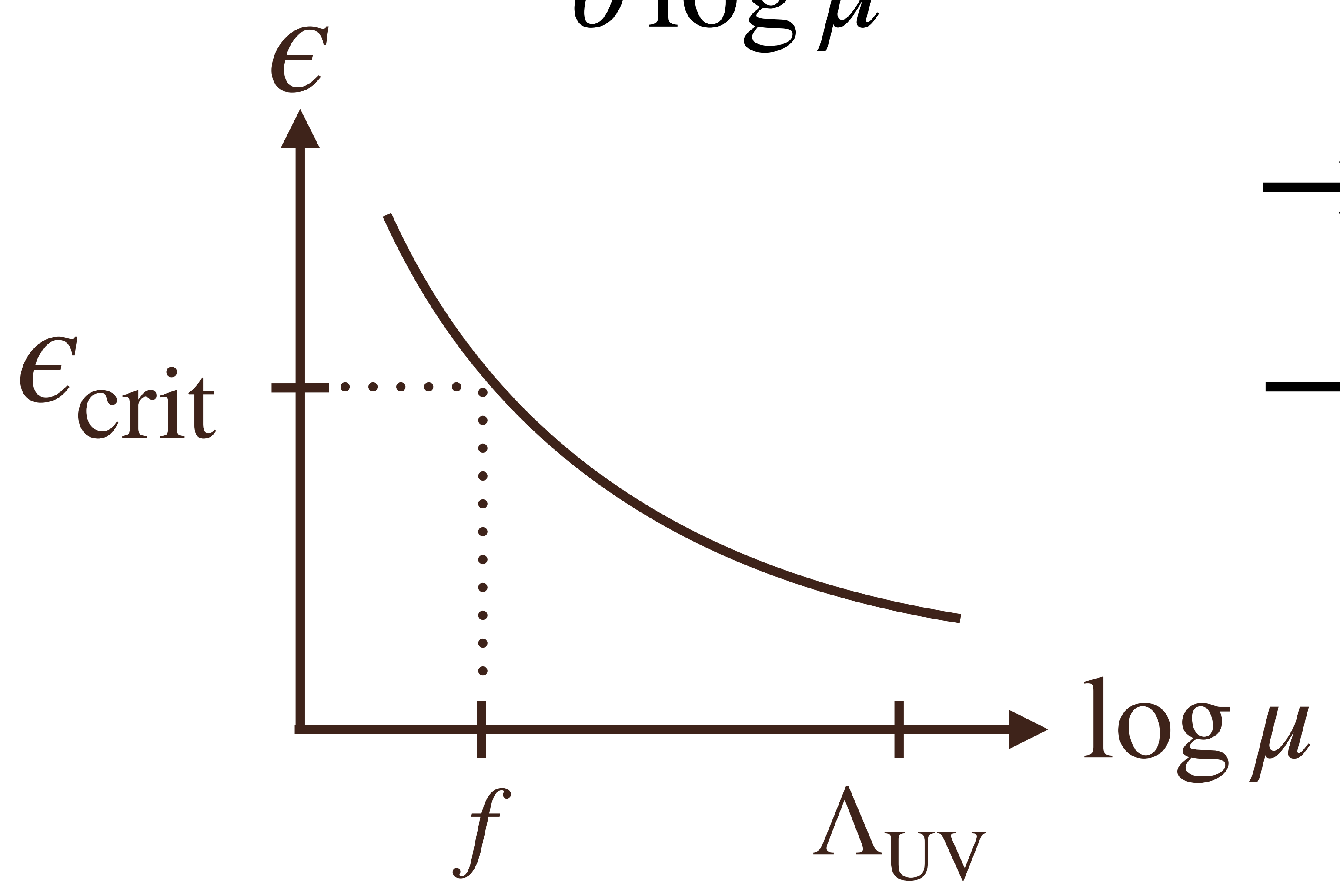
ends for: $T_{\rm nuc} \sim c_1 f\ \mathrm{Exp} - \mathrm{c}_2\,\frac{\mathrm{f}^2}{\mathrm{m}_\sigma^2}$

Nearly-conformal strong sector

Hyp: • strong sector conformally invariant in the UV

• Scale invariance explicitly broken by a slightly relevant operator $\mathscr{L} \supset \epsilon\, O_\epsilon, \quad [O_\epsilon] = 4 + \gamma_\epsilon$

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. spontanously broken

→ pNGB: the dilation σ

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

Gravitational Waves from Supercool Phase Transition

Randall Servant hep-ph/0607158,…

$$\Omega_{\rm GW} \propto \left(H/\beta\right) \times \left(H/\beta\right)$$

Bubble size × **Collision time**

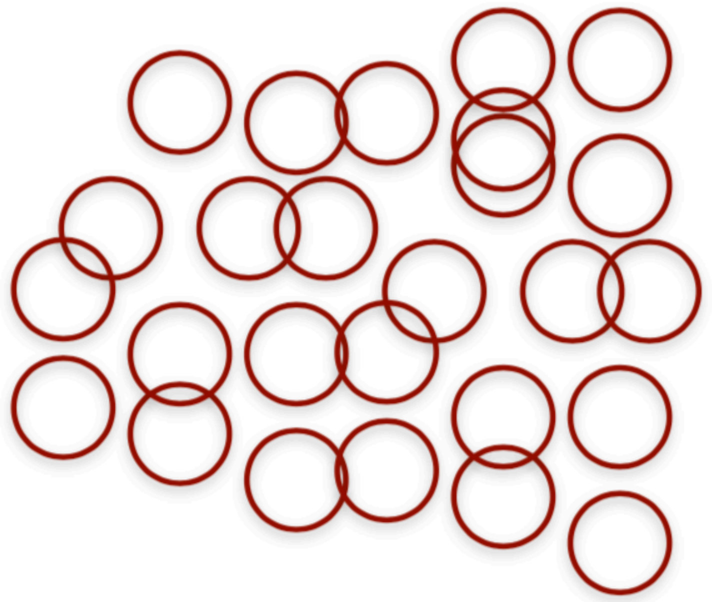
$$\frac{\beta}{H} \simeq T\frac{dS_4}{dT}\bigg|_{T_{\rm nuc}} \simeq 15\left(\frac{10}{N_{\rm e-fold}}\right)^2$$

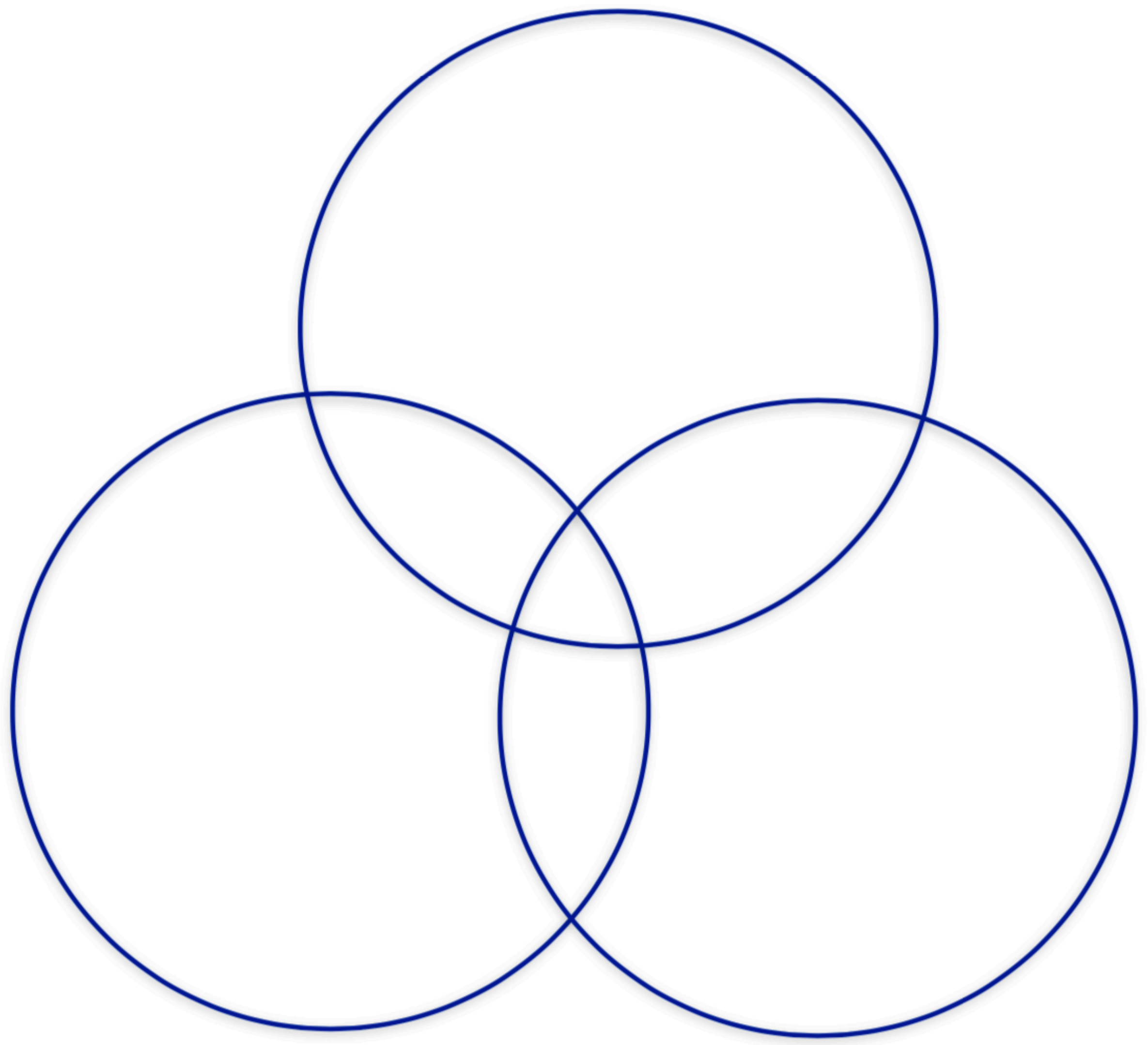
Supercooled PT

$\beta/H \sim 10$

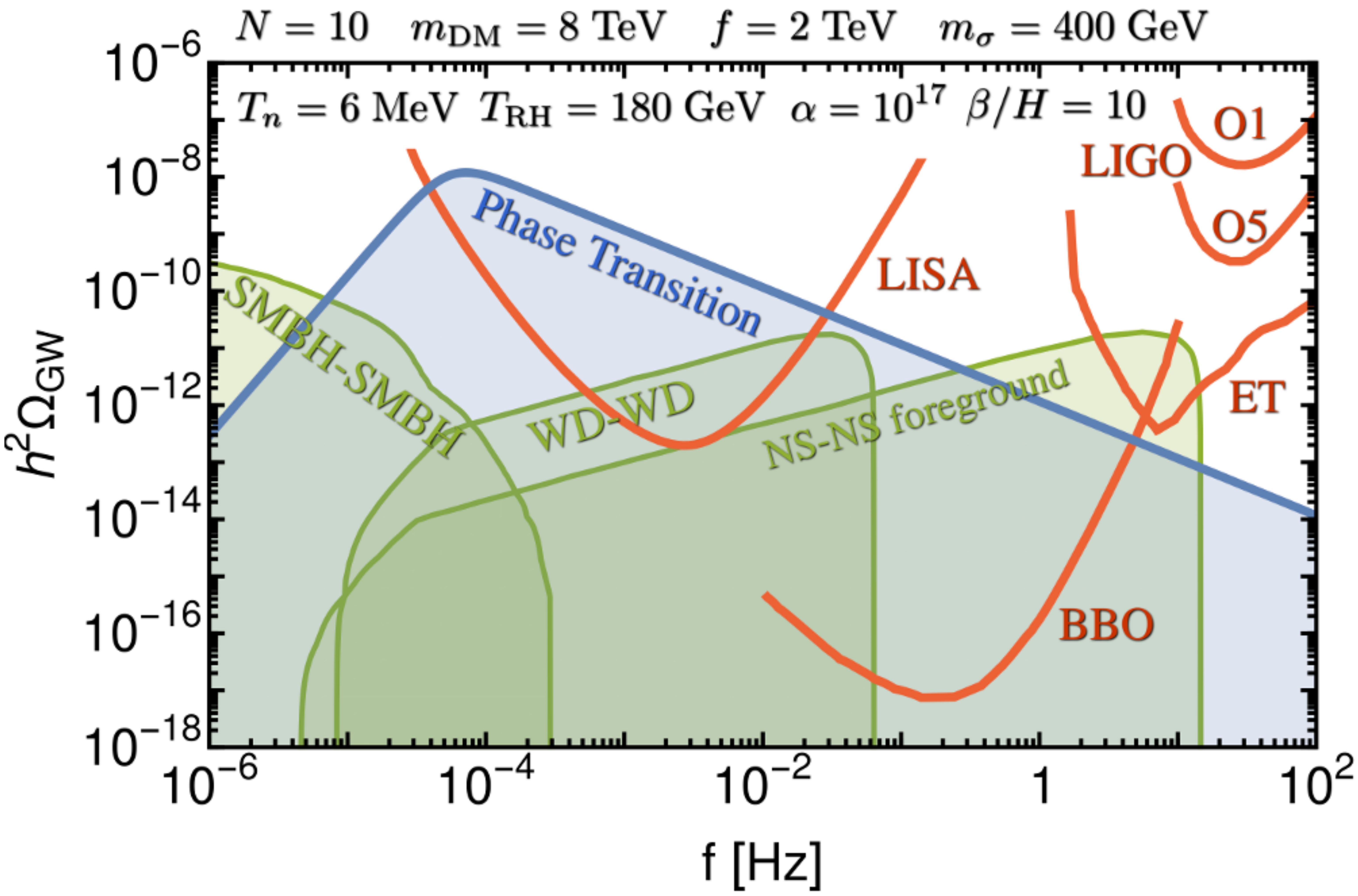
Standard 1st order PT

$\beta/H \sim 100$





Gravitational Waves from Phase Transition



Nucleation Temperature

Supercooling begins at $T_{\text{start}} \sim f$

Bubble nucleation ends SC at $T_{\text{nuc}} \sim f \exp\left(-c\,\frac{f^2}{m_\sigma^2}\right)$

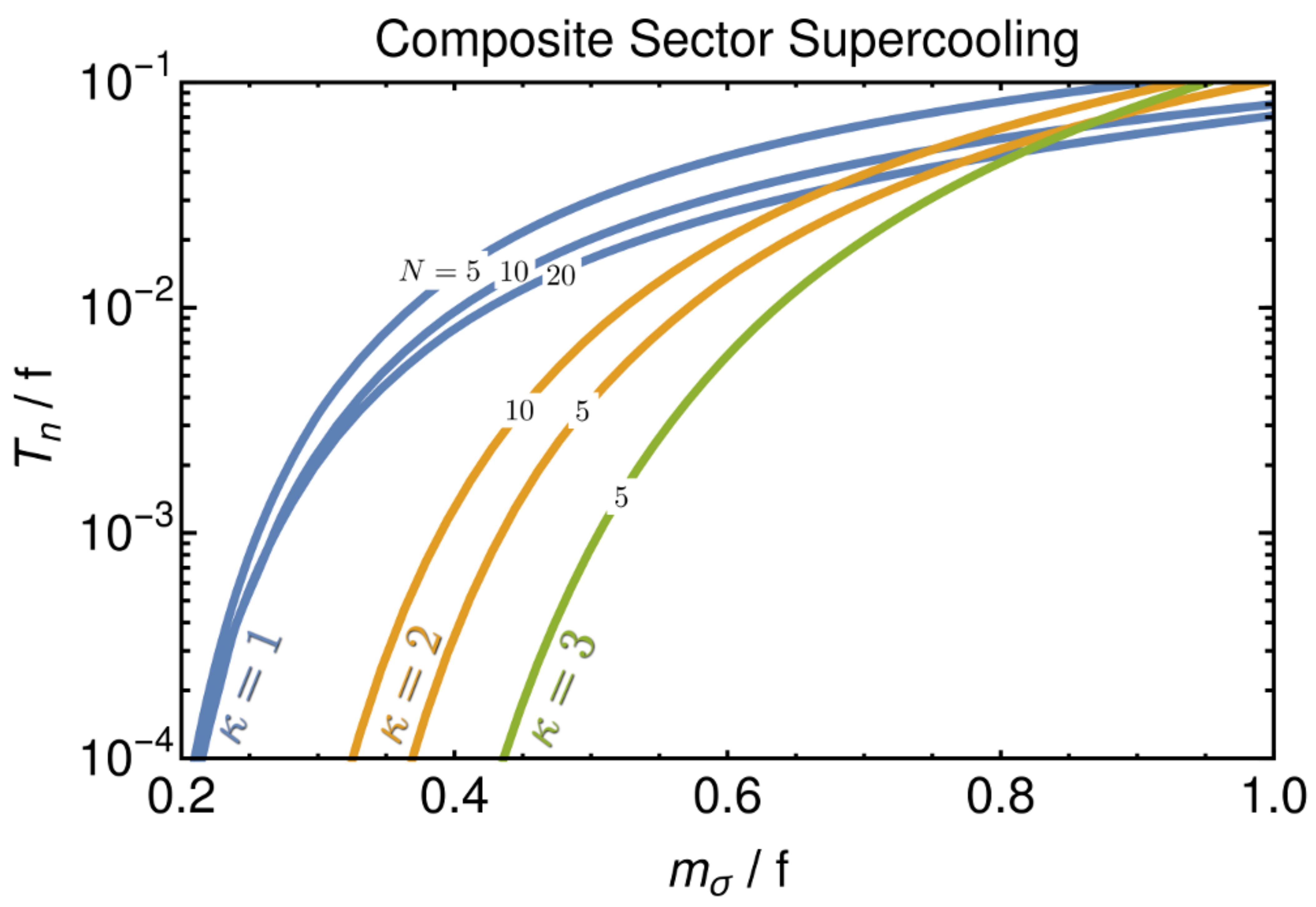
Nucleation happens when tunnelling rate ~ Hubble

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

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

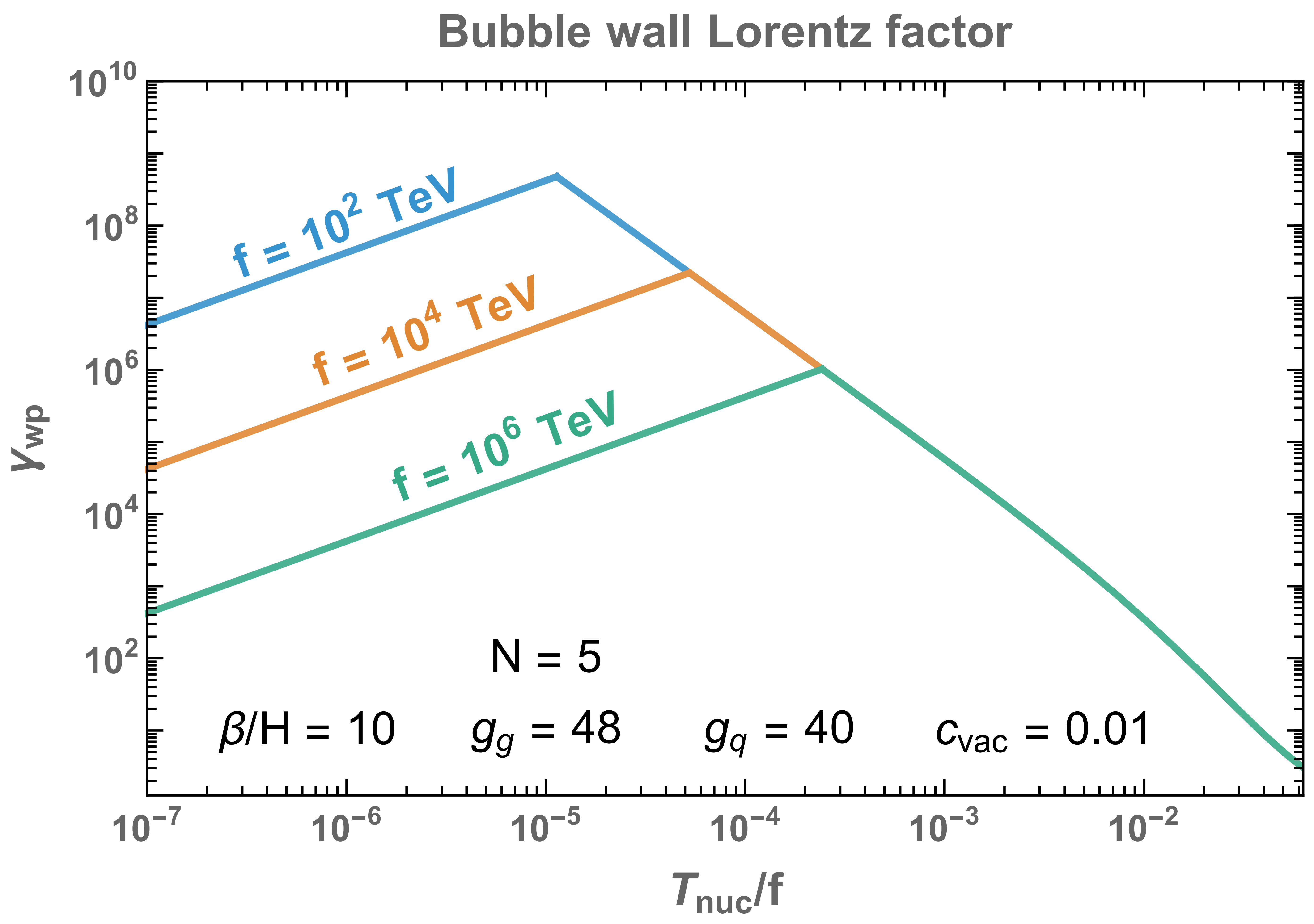
Iso Serpico Shimada 1704.04955

von Harling Servant 1711.11554

→ Catalysed by black holes ?

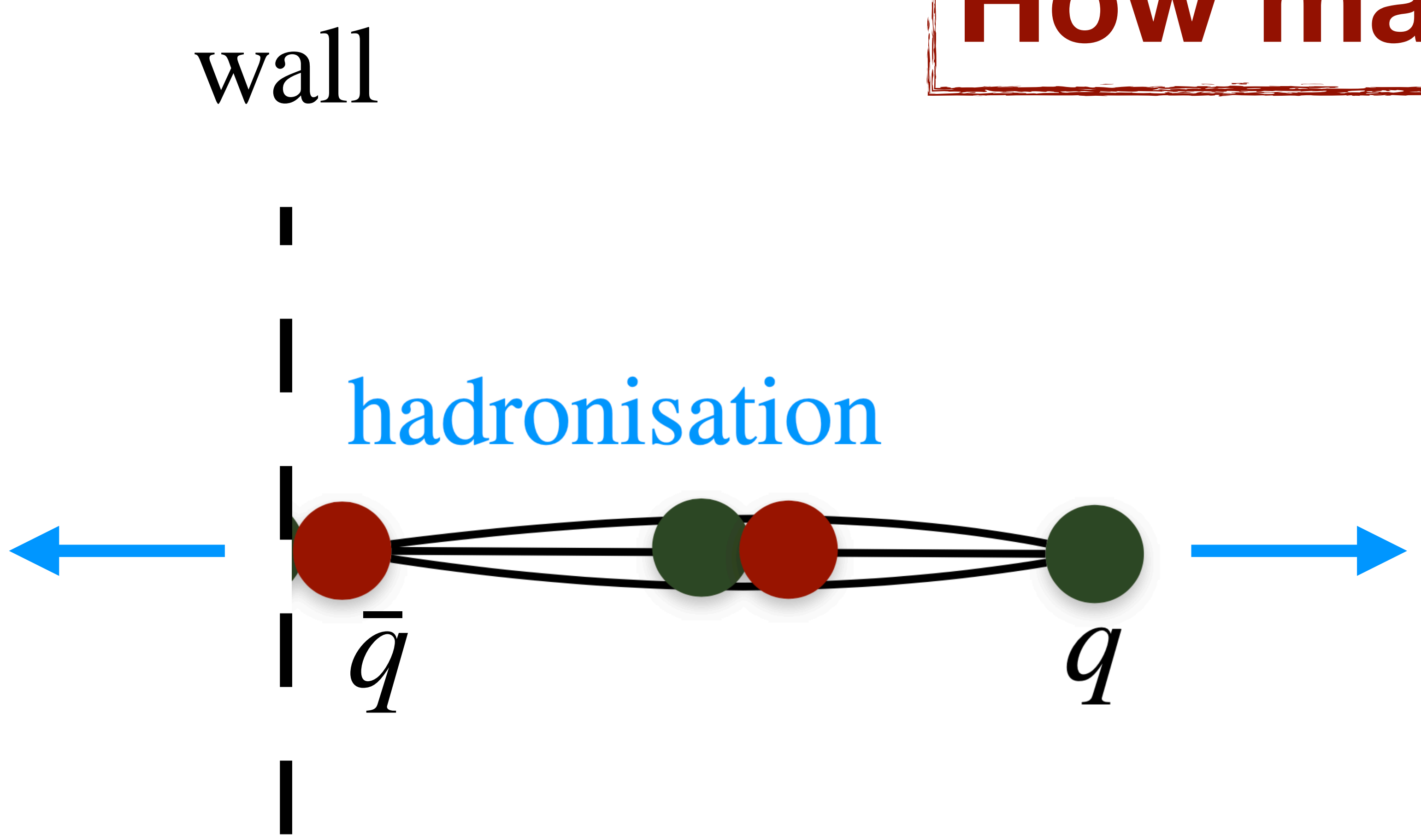
Gregory, Moss, Withers 15

Mukaida, Yamada 17



Bubble wall Lorentz factor
10^{10}
10^{8}
10^{6}
10^{4}
10^{2}
γ_{wp}
f = 10^2 TeV
f = 10^4 TeV
f = 10^6 TeV
N = 5
$\beta/H = 10$
$g_g = 48$
$g_q = 40$
$c_{vac} = 0.01$
10^{-7}
10^{-6}
10^{-5}
10^{-4}
10^{-3}
10^{-2}
T_{nuc}/f

How many hadrons ?



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

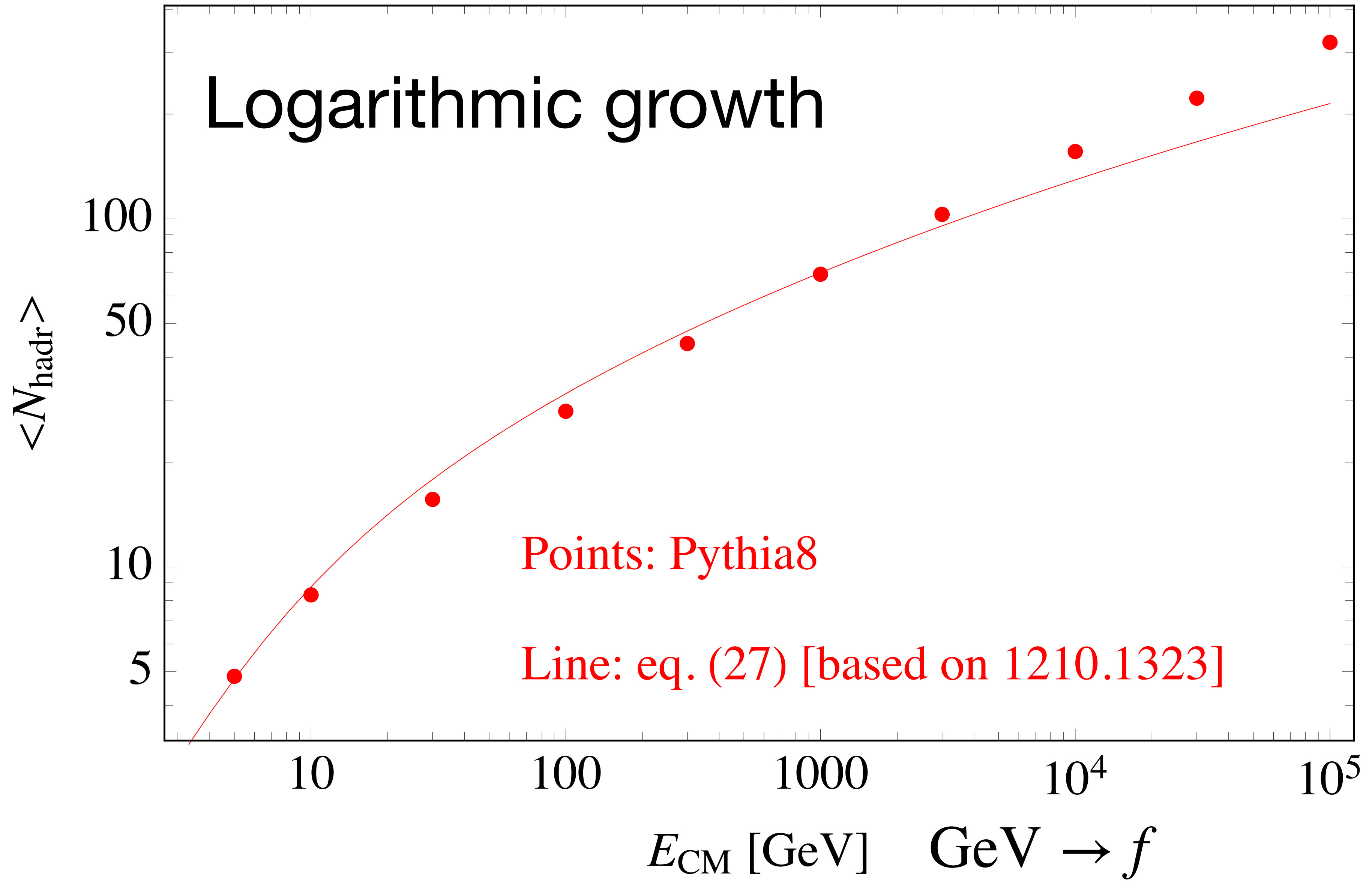
Analogous to $e^+e^- \to q\bar{q}$ in QCD

Use Pythia with

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

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

$$\simeq \sqrt{\gamma_{wp} f\, T_{\rm nuc}}$$



GeV $\to f$

DM abundance after supercooling

Hambye, Strumia, Teresi 18 —> Baldes, Gouttenoire, Sala, Servant 19

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

Standard Supercooling — **Branching ratio quark -> DM** — **String fragmentation**

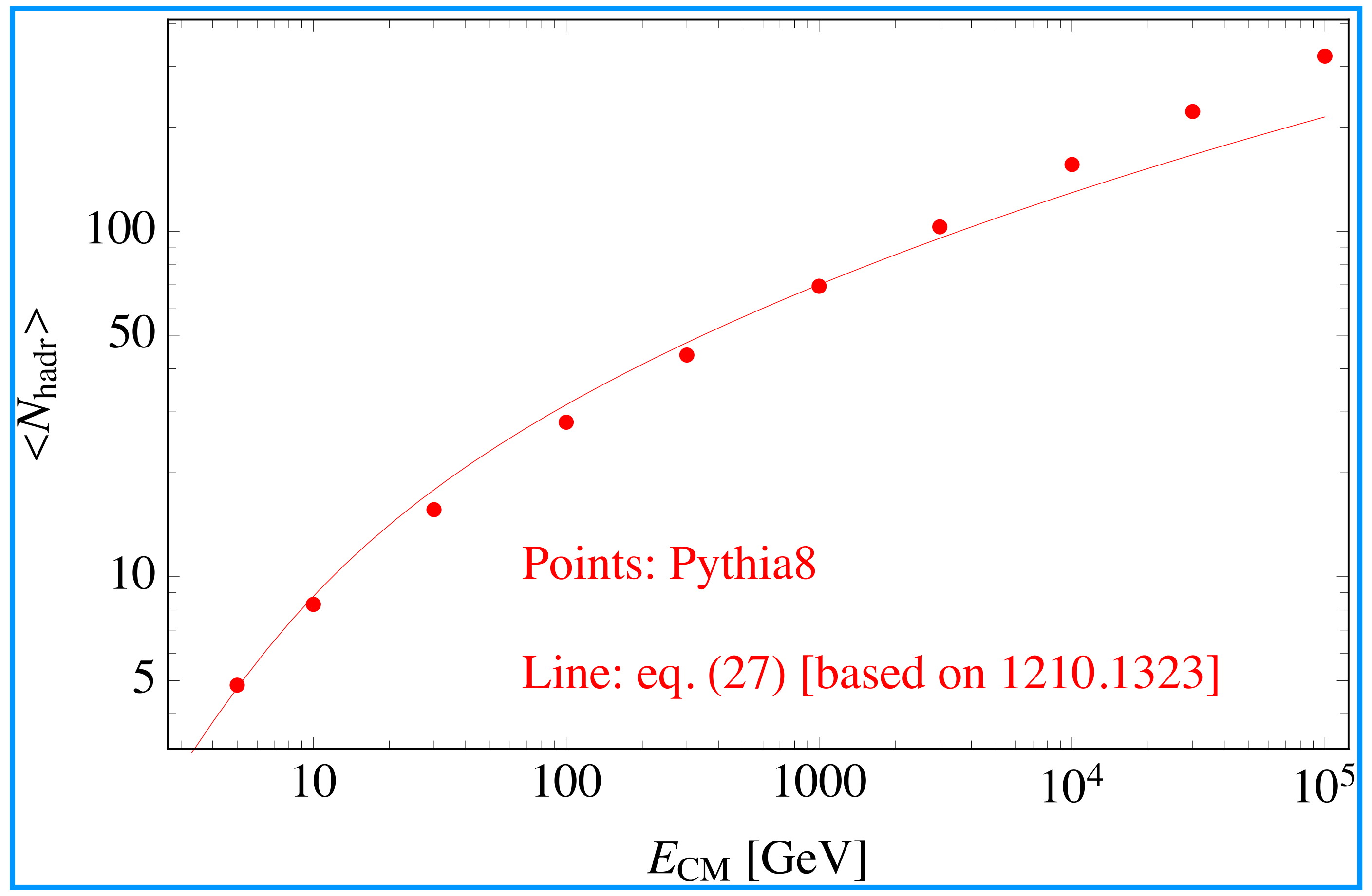
2 possibilities:

Combinatoric	Thermal distrib.
DM: light meson	DM: heavy baryon
e.g. $BR \simeq 2/N_f^2$	$BR \propto \exp - m_{DM}/f$

DIS in the Sky: result

Brute force: iterate this

until $E_{\rm CM} \sim \sqrt{T E_{\rm hadron}} = f$

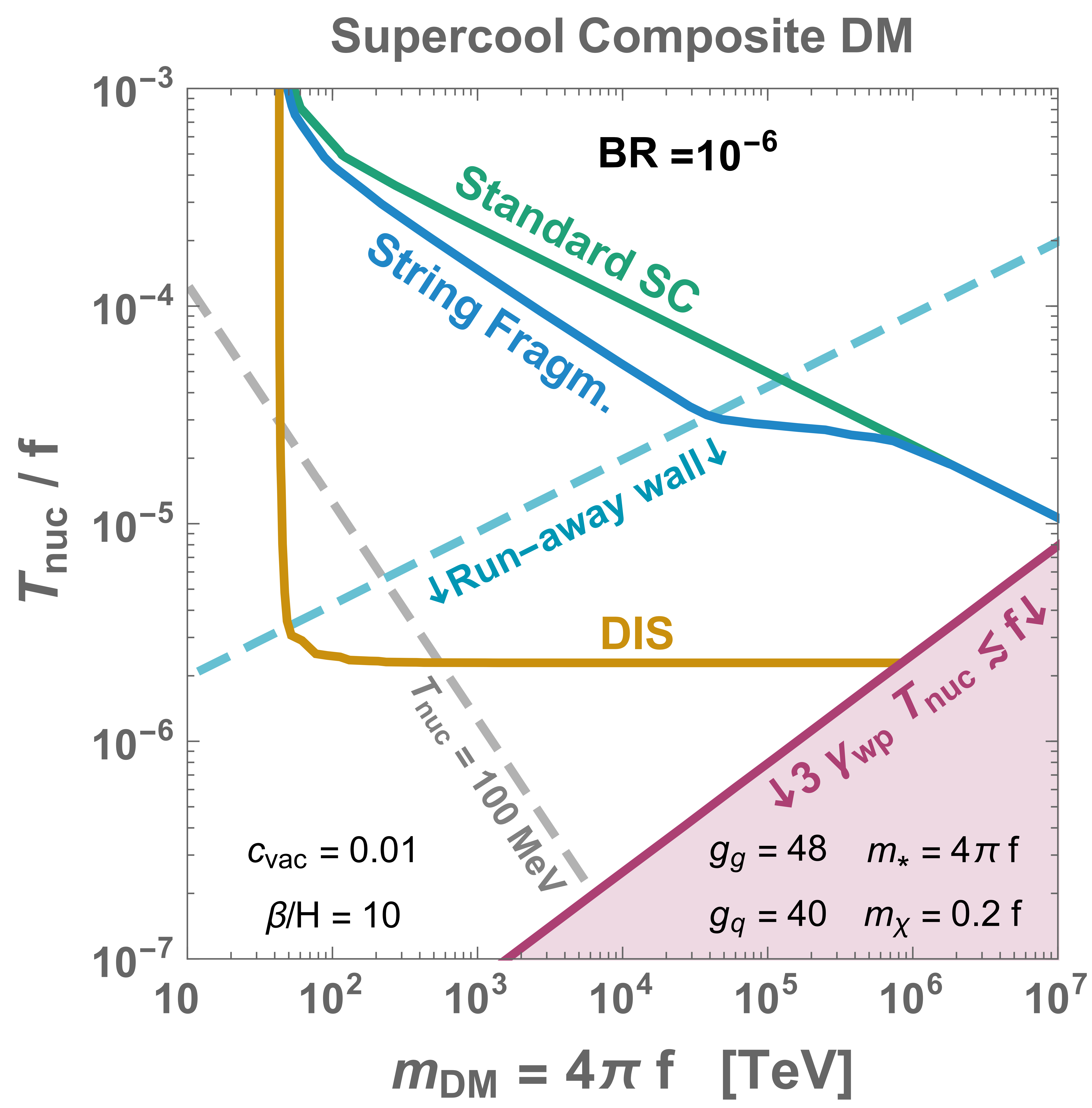


O(1) fraction of initial hadron energy converted into hadron masses

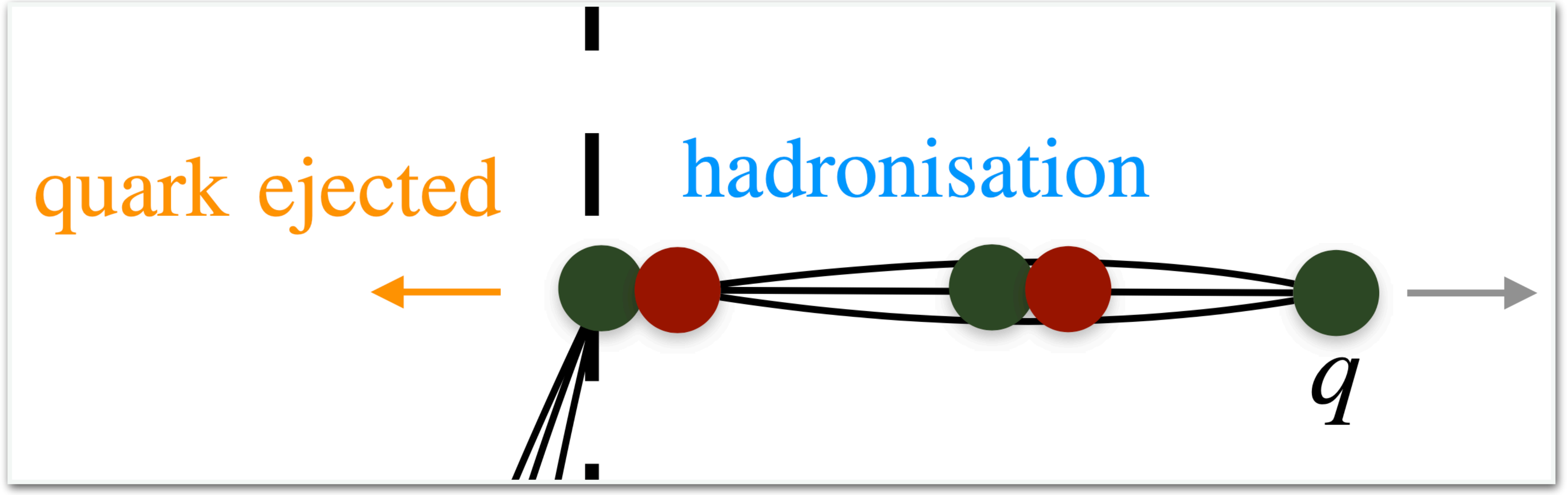
$$Y_{\rm SC+string+DIS} \sim \frac{T E_{\rm hadr}}{m_*^2} Y_{\rm SC+string} \qquad \langle E_{\rm hadron}\rangle = \frac{E^{q\bar q}_{\rm cm}}{\langle N_{\rm hadron}\rangle} \sim \frac{\sqrt{\gamma_{wp} f / T_{\rm nuc}}}{\langle N_{\rm hadron}\rangle} \gg f$$

$E_{\rm hadr} \to \dfrac{\gamma_{cp} E^{\rm CM}_{q\bar q}}{\langle N_{\rm hadr}\rangle}$

$Y_{\rm SC+string} \to \langle N_{\rm hadr}\rangle Y_{\rm SC} \longrightarrow \langle N_{\rm hadr}\rangle$ simplifies!



Supercool Composite DM
BR =10^−6
Standard SC
String Fragm.
↓Run–away wall↓
DIS
T_nuc = 100 MeV
↓3 γ_wp T_nuc ≲ f↓
c_vac = 0.01
β/H = 10
g_g = 48 m_* = 4π f
g_q = 40 m_χ = 0.2 f
T_nuc / f
m_DM = 4π f [TeV]

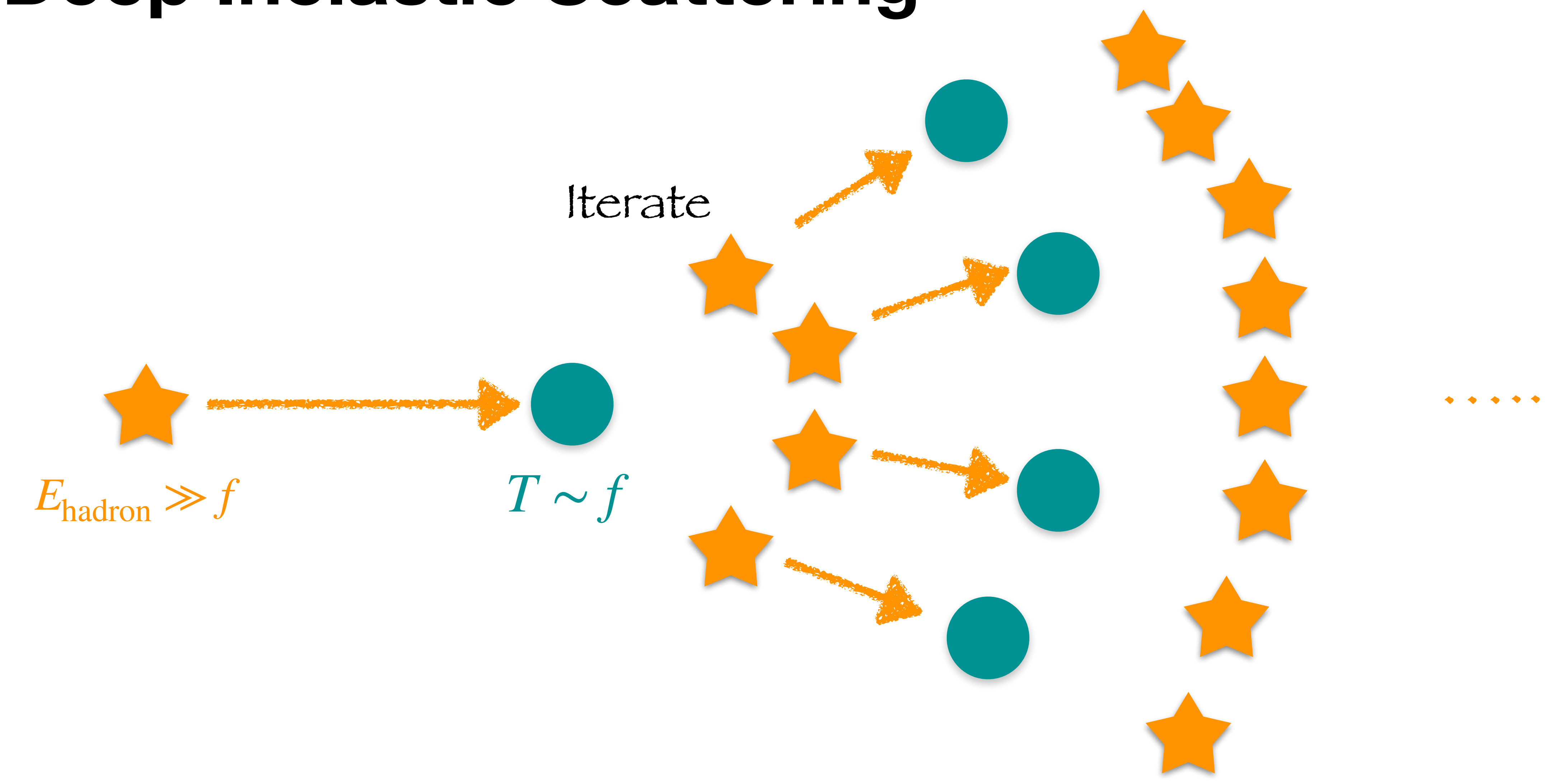


Consequences on DM abundance

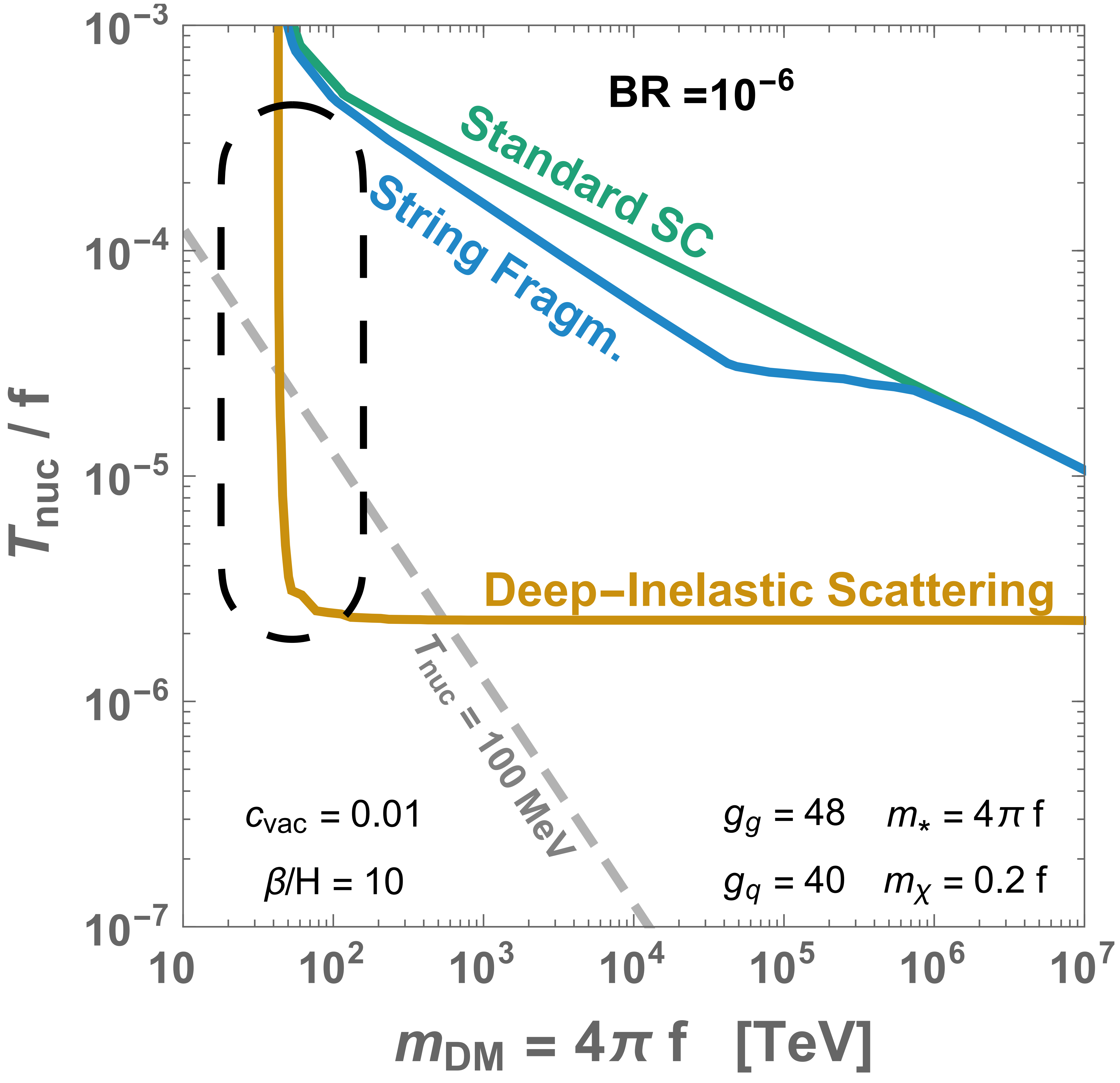
1. String fragmentation + quark ejection

$$Y_{\rm DM} \,/\, Y_{\rm DM}^{\rm naive} \;\propto\; \log^n\!\left(\gamma_{wp} T_{\rm nuc}/f\right)$$

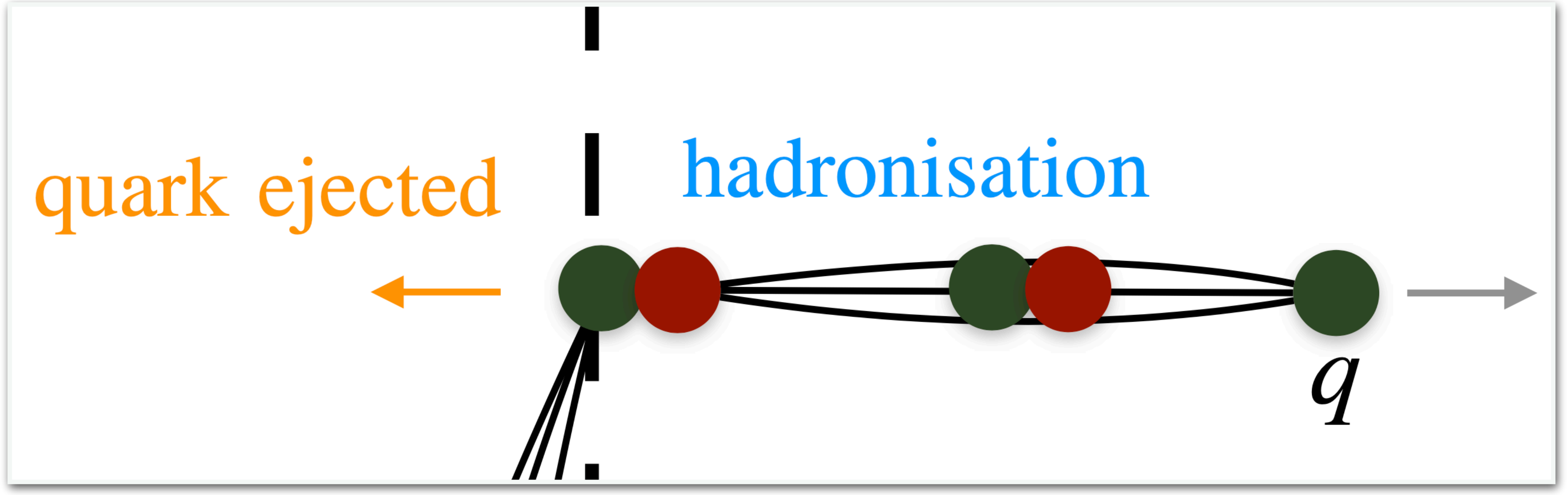
2. Deep Inelastic Scattering



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



Consequences on DM abundance



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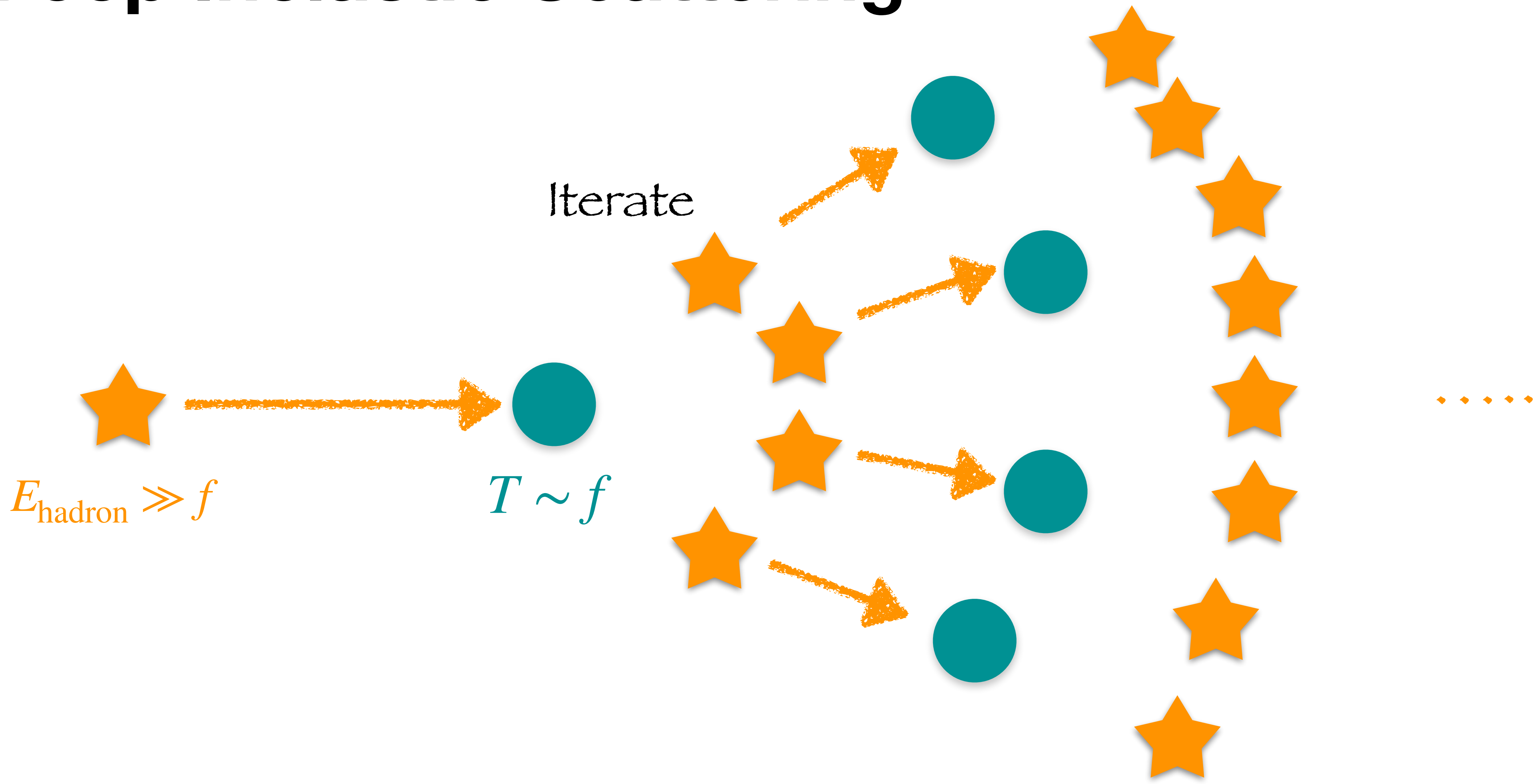
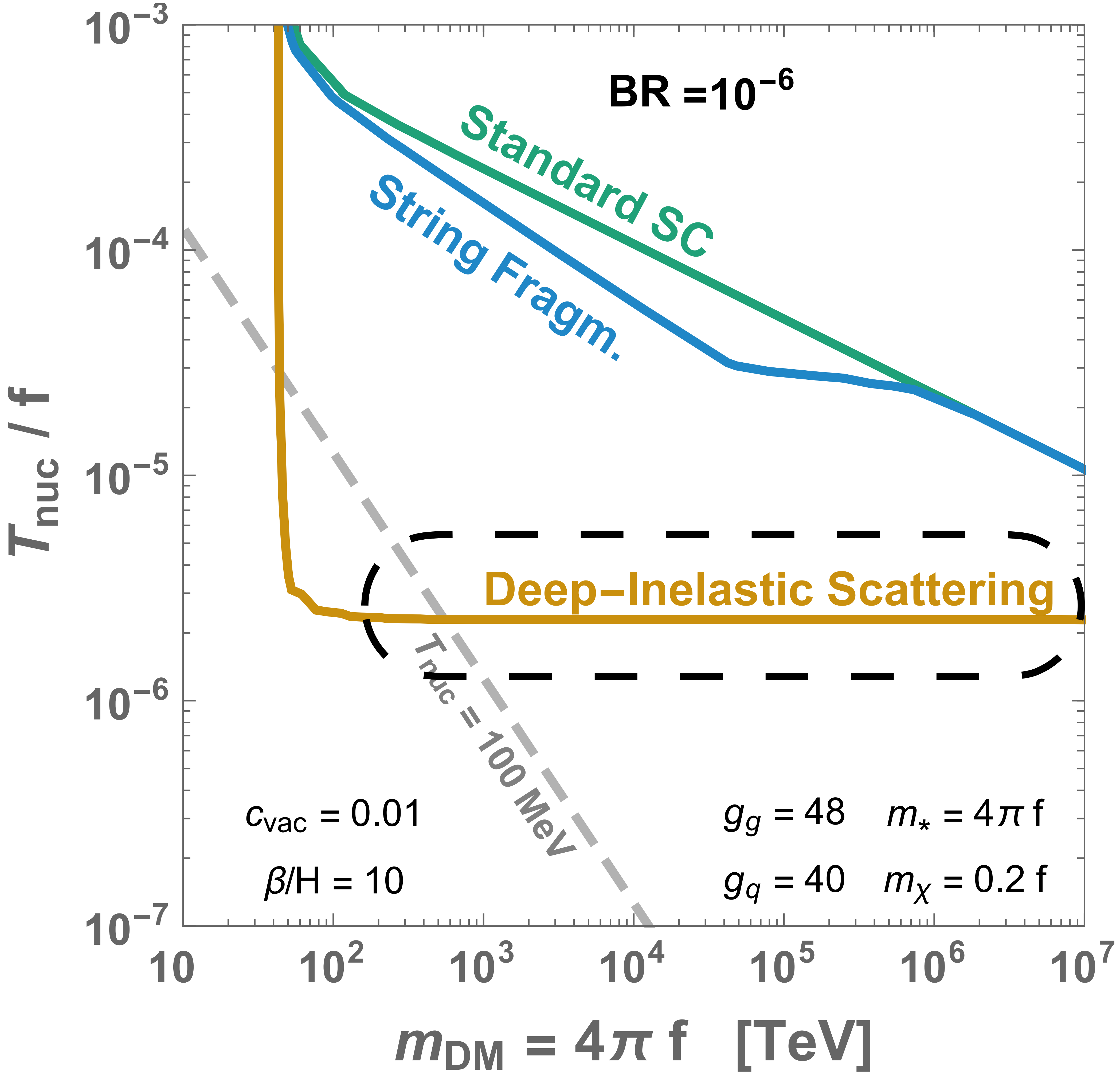
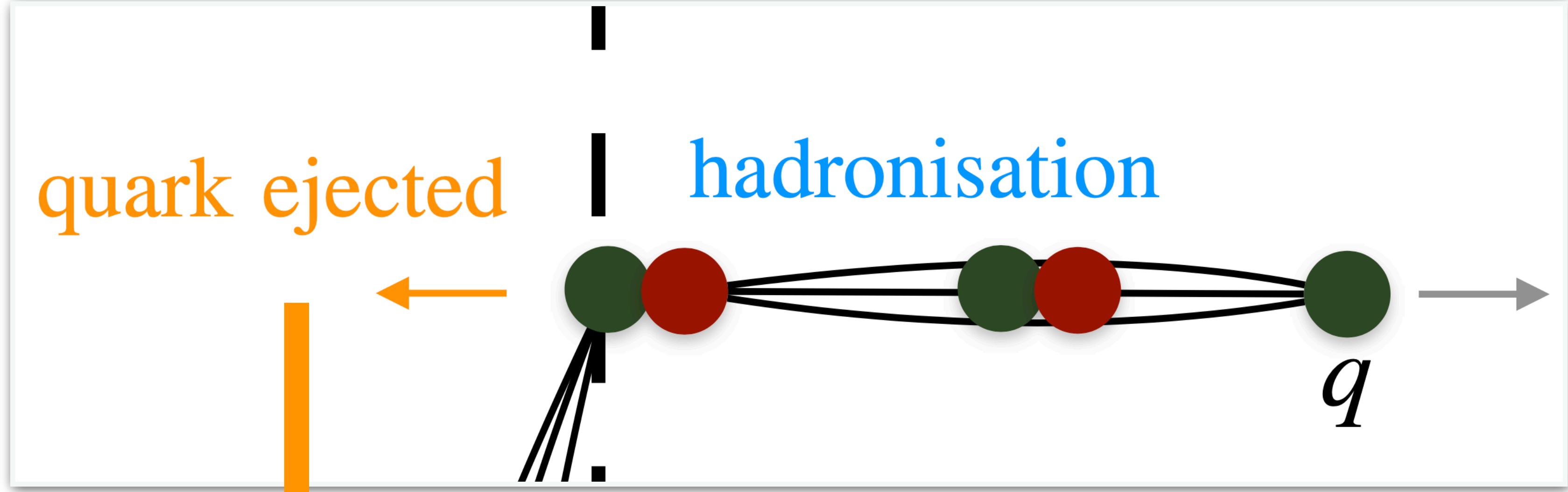


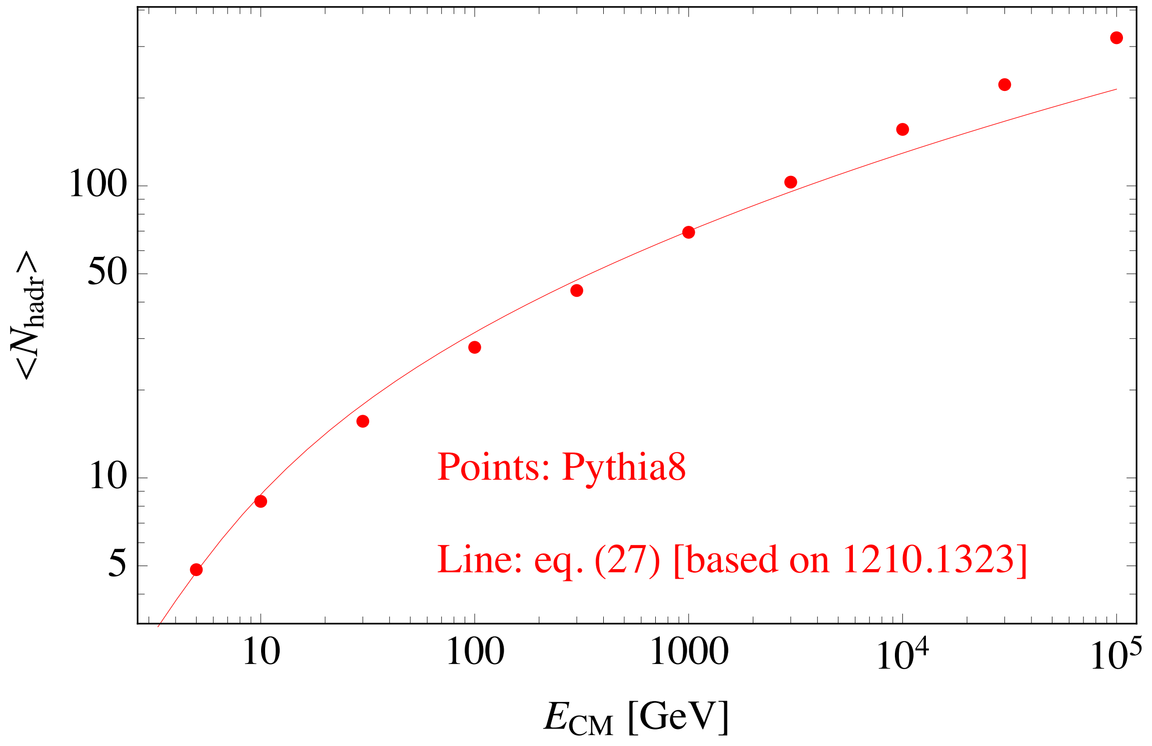
$$Y_{\rm DM} / Y_{\rm DM}^{\rm naive} \;\propto\; \gamma_{\rm wp} \;\propto\; \frac{T_{\rm nuc}}{f}\frac{M_{\rm Pl}}{f}$$



Cosmological consequences



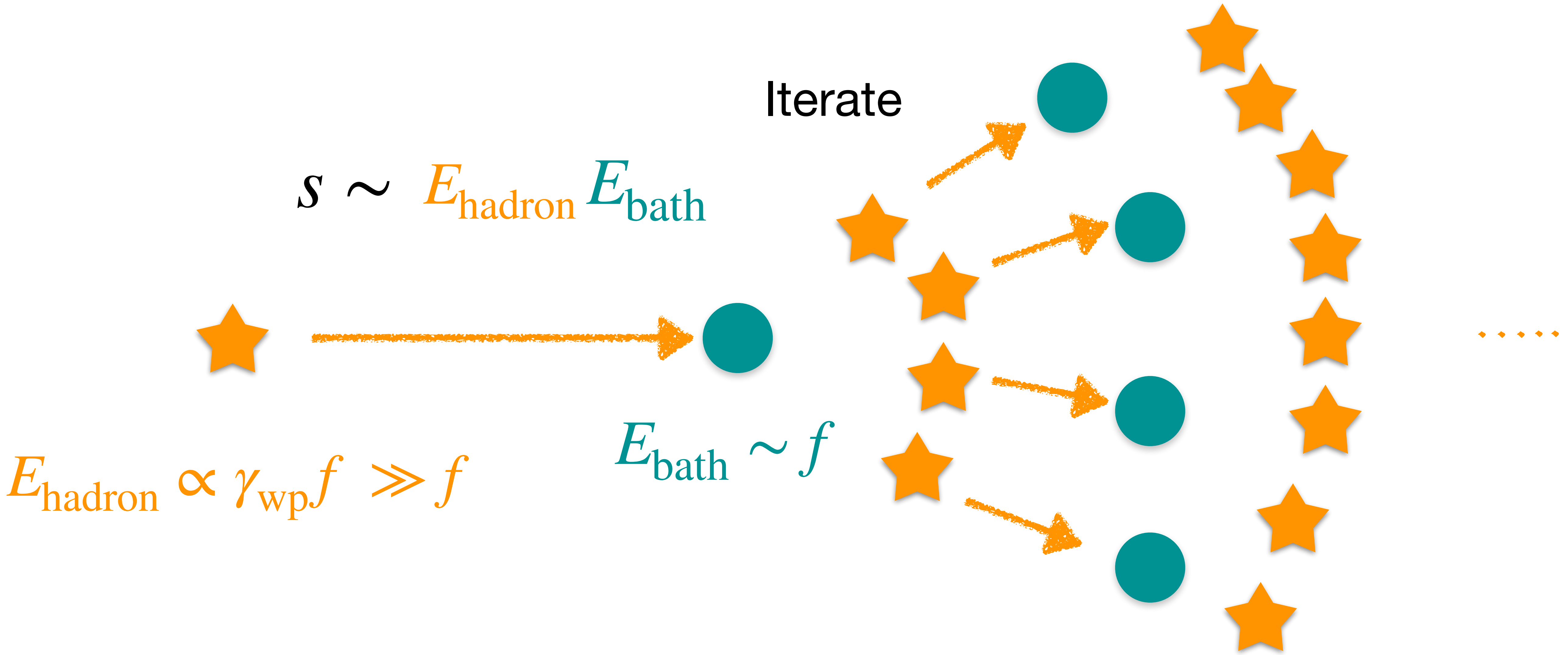
1. More hadrons per initial quark pair



Y_{D}

Ejected quarks give contribution of same order of magnitude

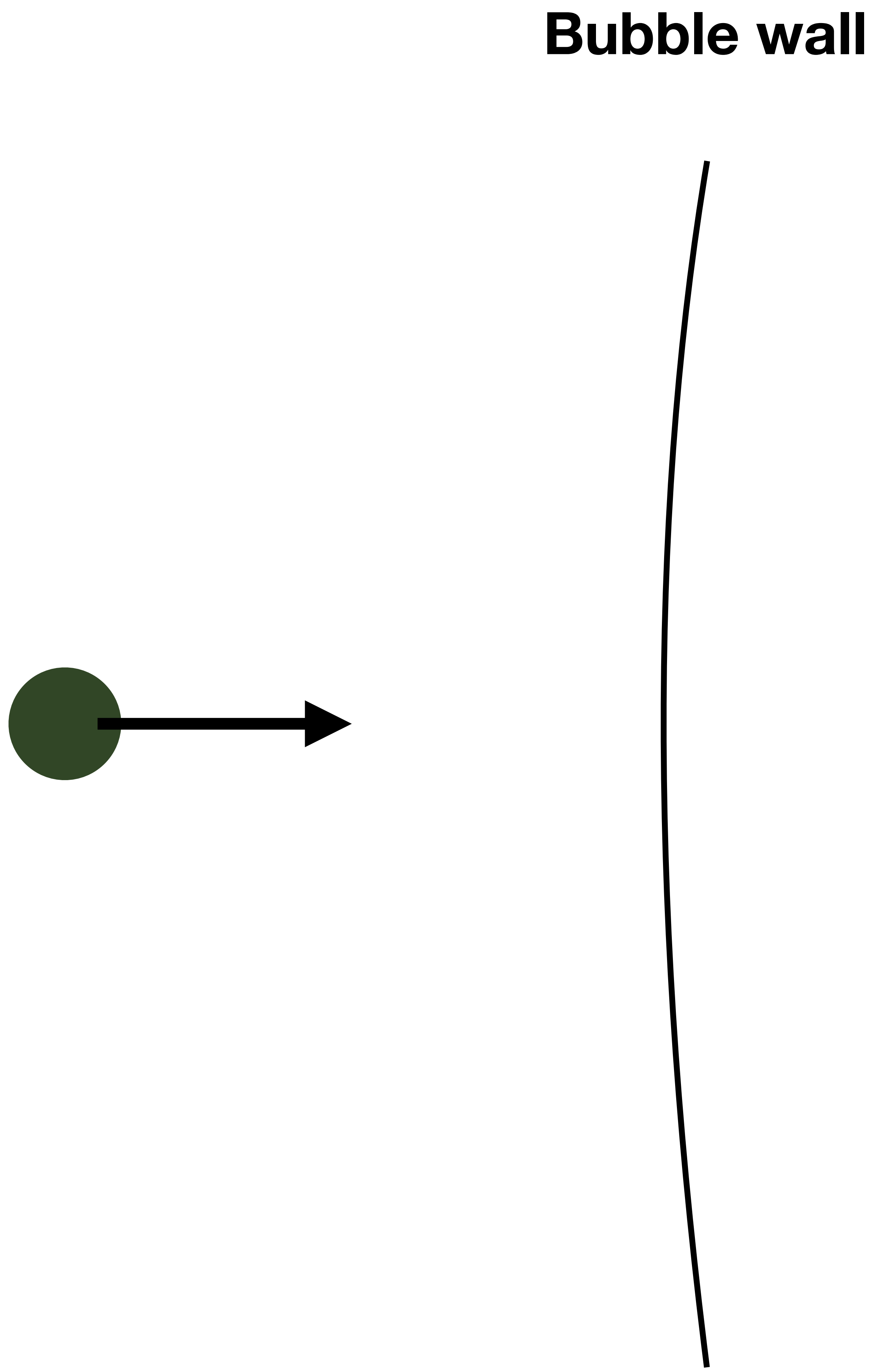
2. Cosmological catapult



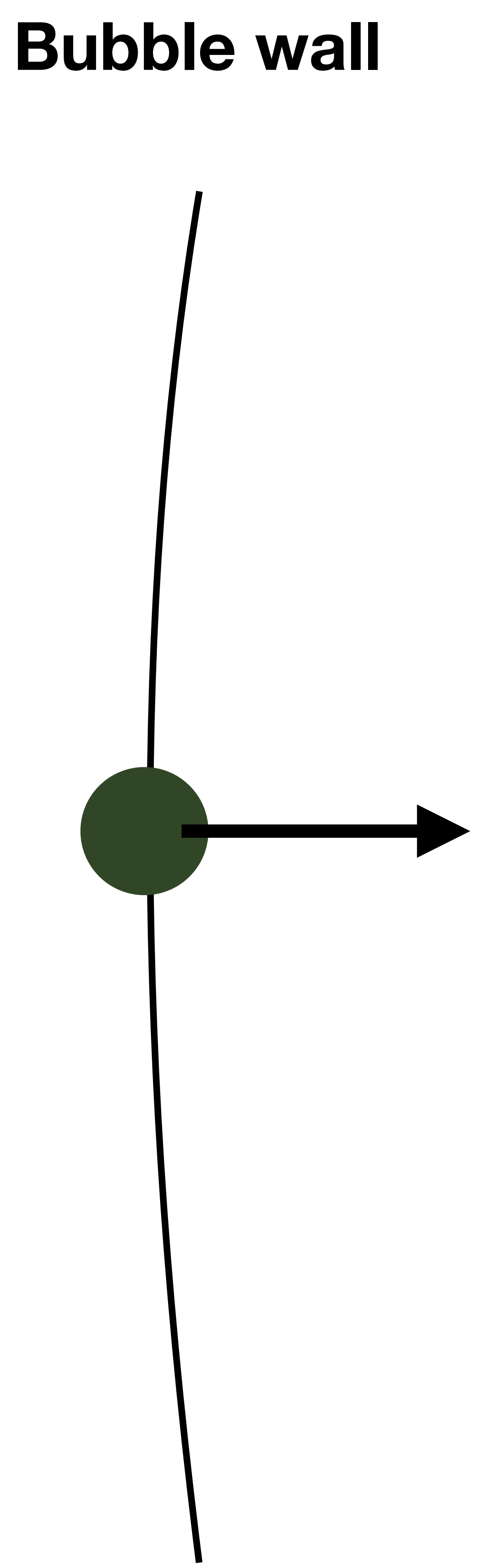
$$Y_{DM} / Y_{DM}^{naive} \propto \gamma_{wp} \propto \frac{T_{nuc}}{f} \frac{M_{Pl}}{f}$$

runaway regime

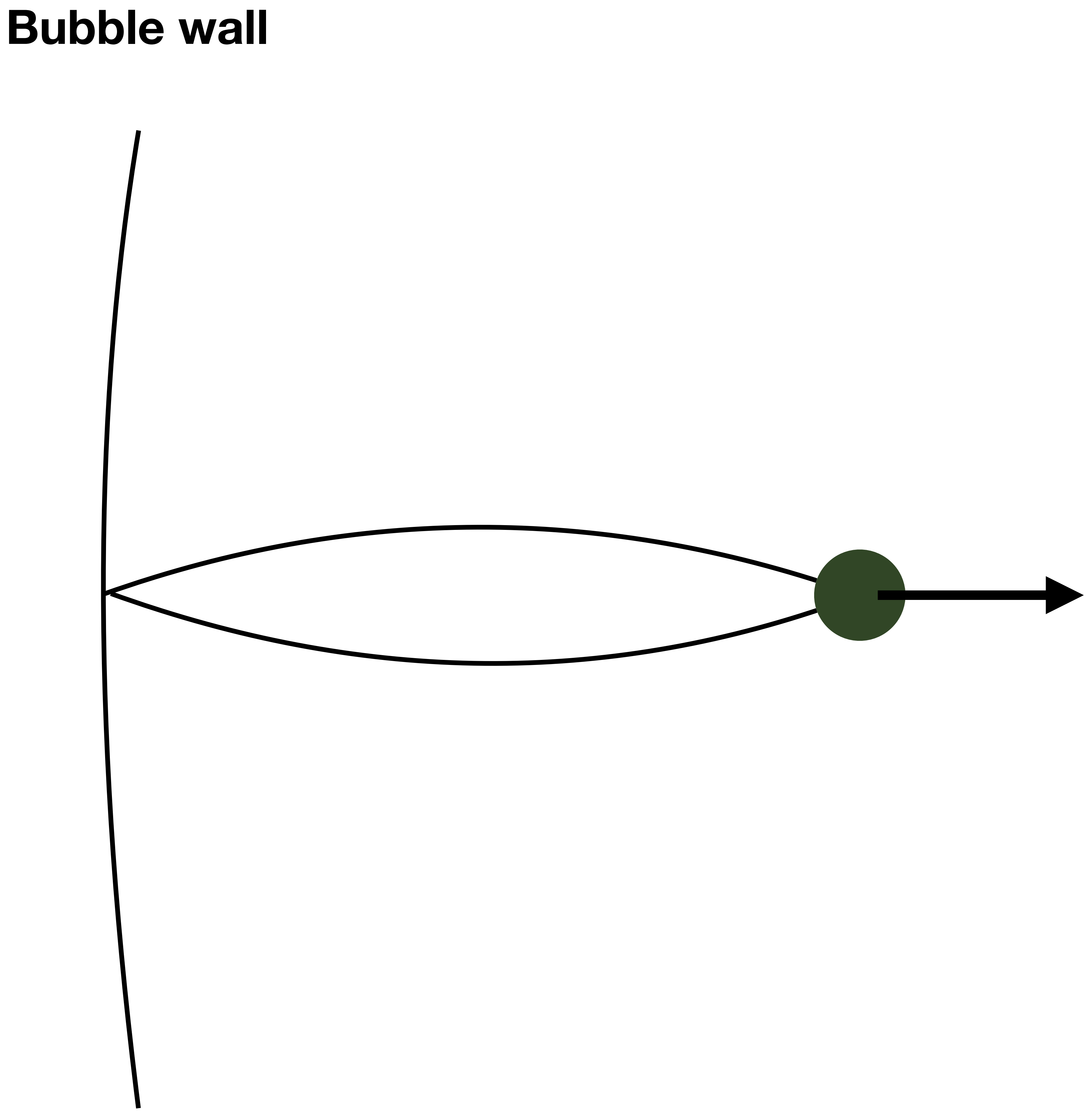
Interaction with other quarks ?



Interaction with other quarks ?

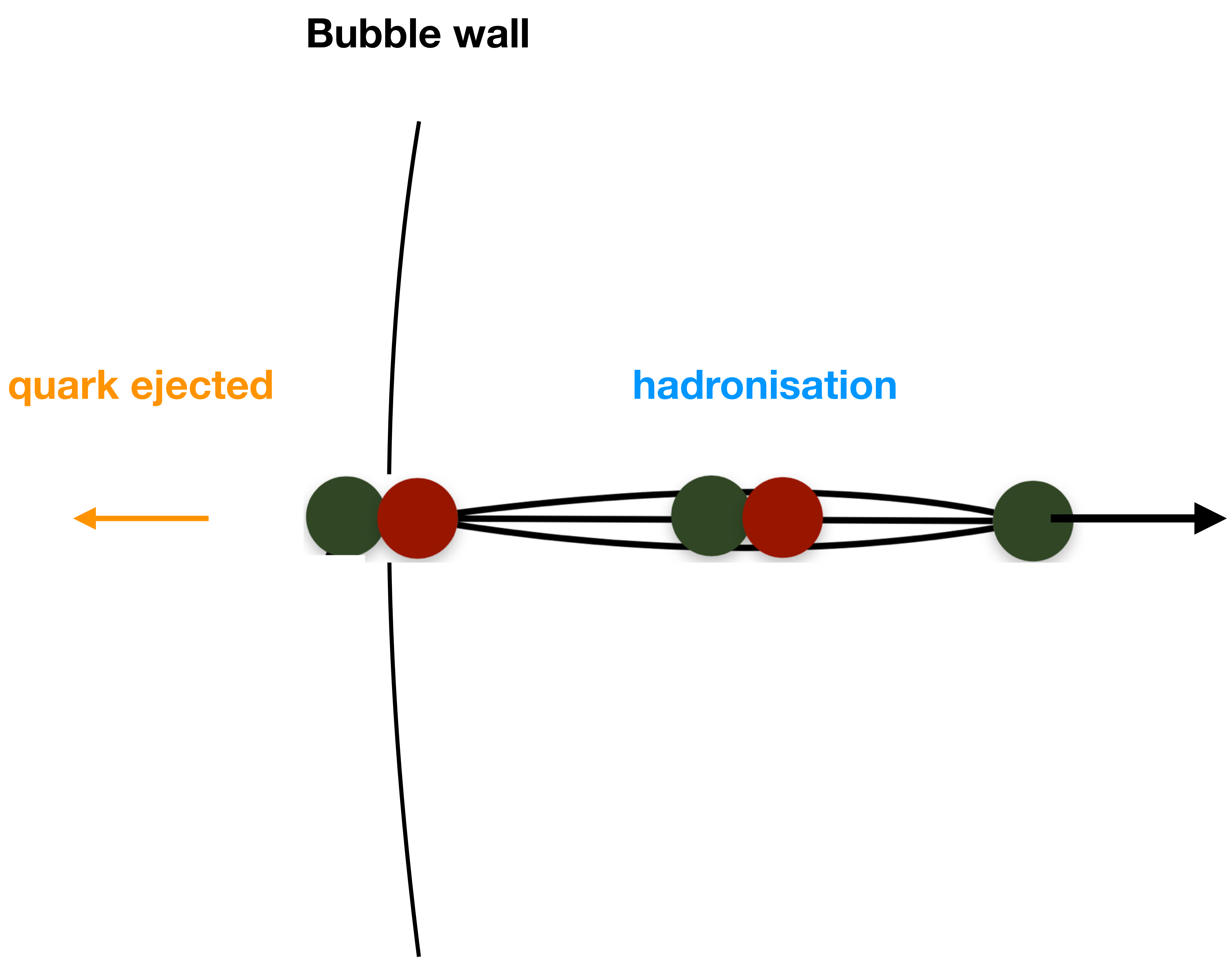


Interaction with other quarks ?



Interaction with other quarks ?

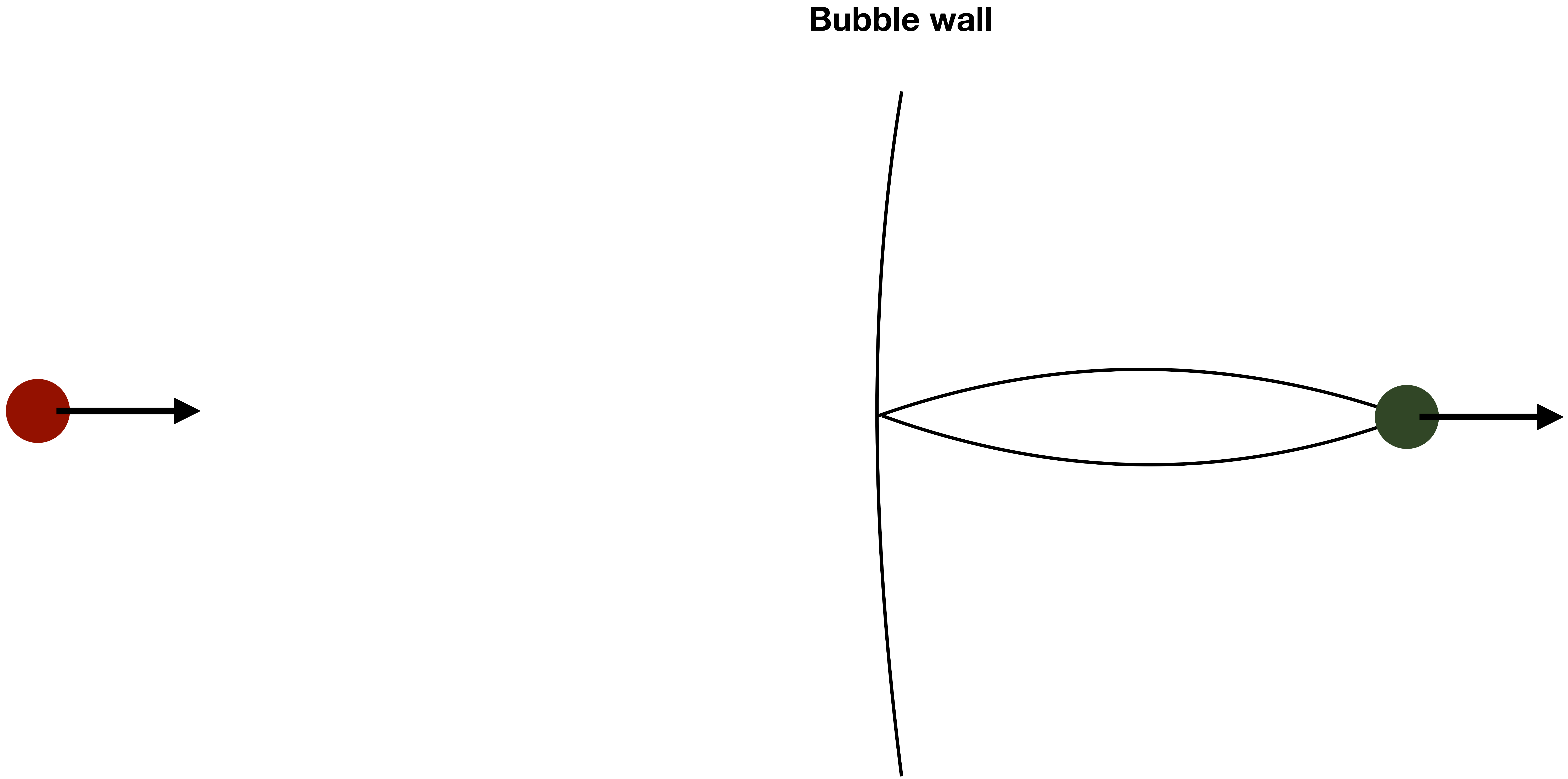
$$\Gamma_{\rm nucl} \sim f/N$$



Interaction with other quarks ?

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

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



Interaction with other quarks ?

$$\Gamma_{\rm q-string} \sim \pi f^{-2} \times \gamma_{\rm wp} T^3_{\rm nuc}$$

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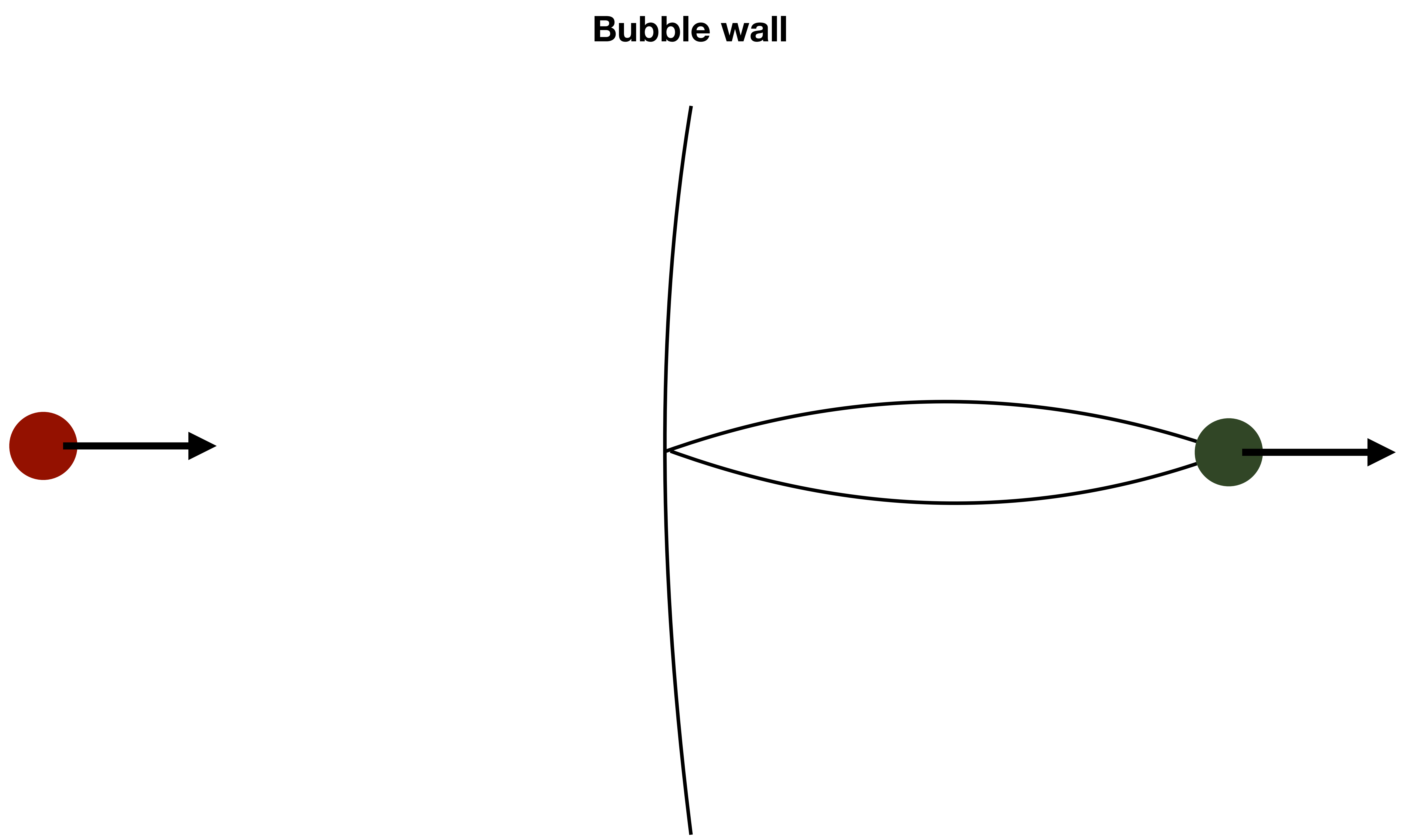

Interaction with other quarks ?

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

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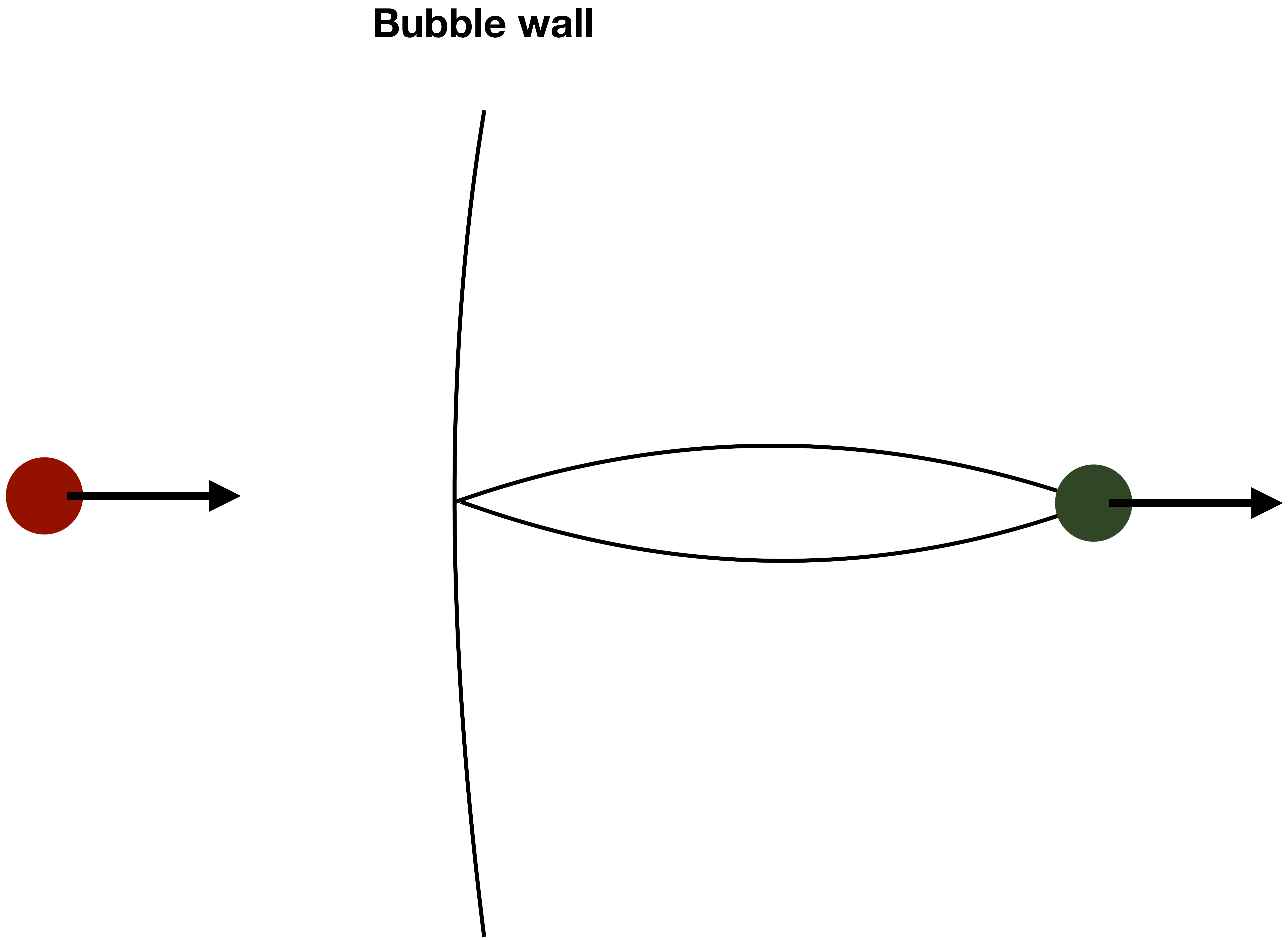

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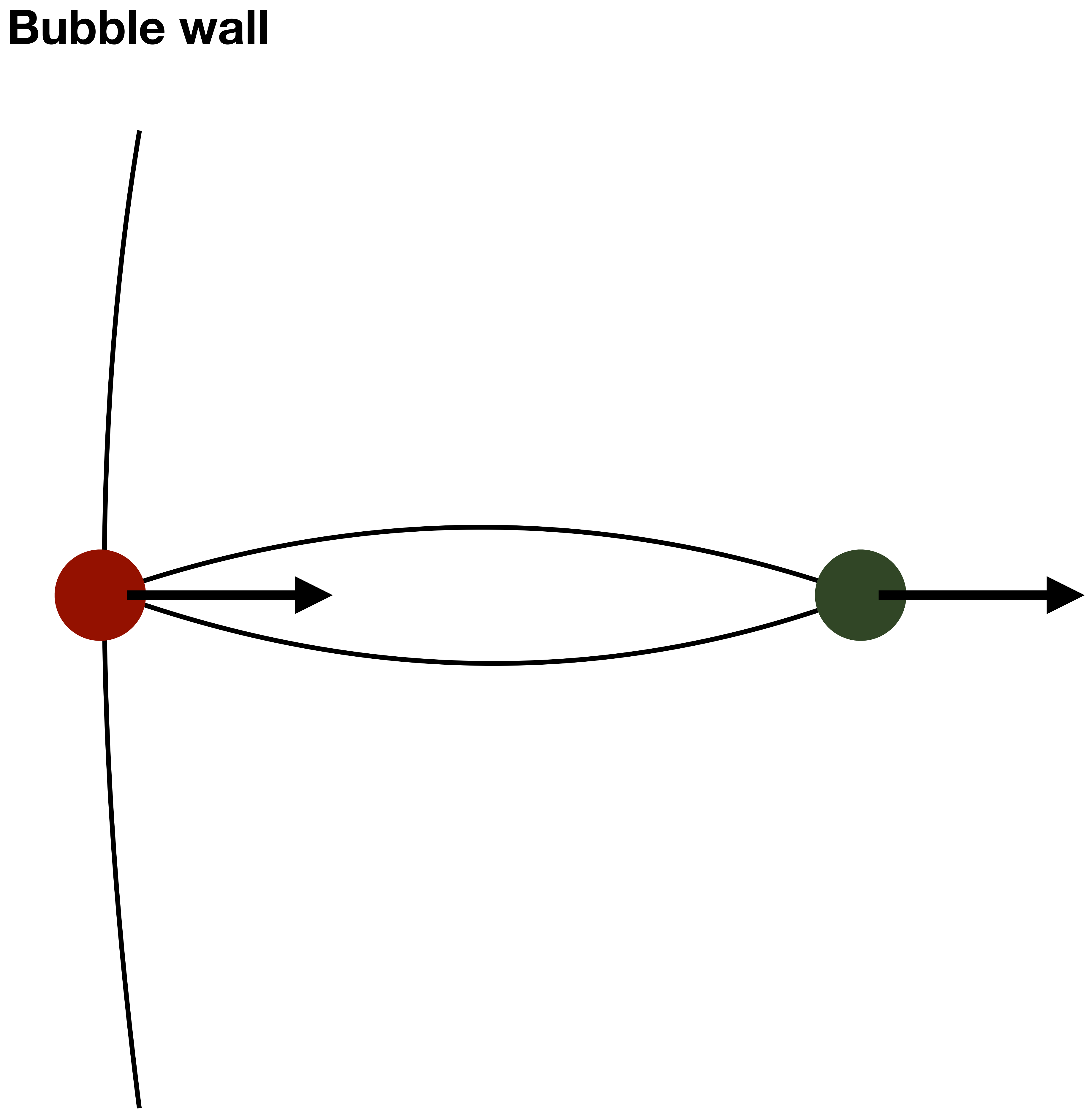
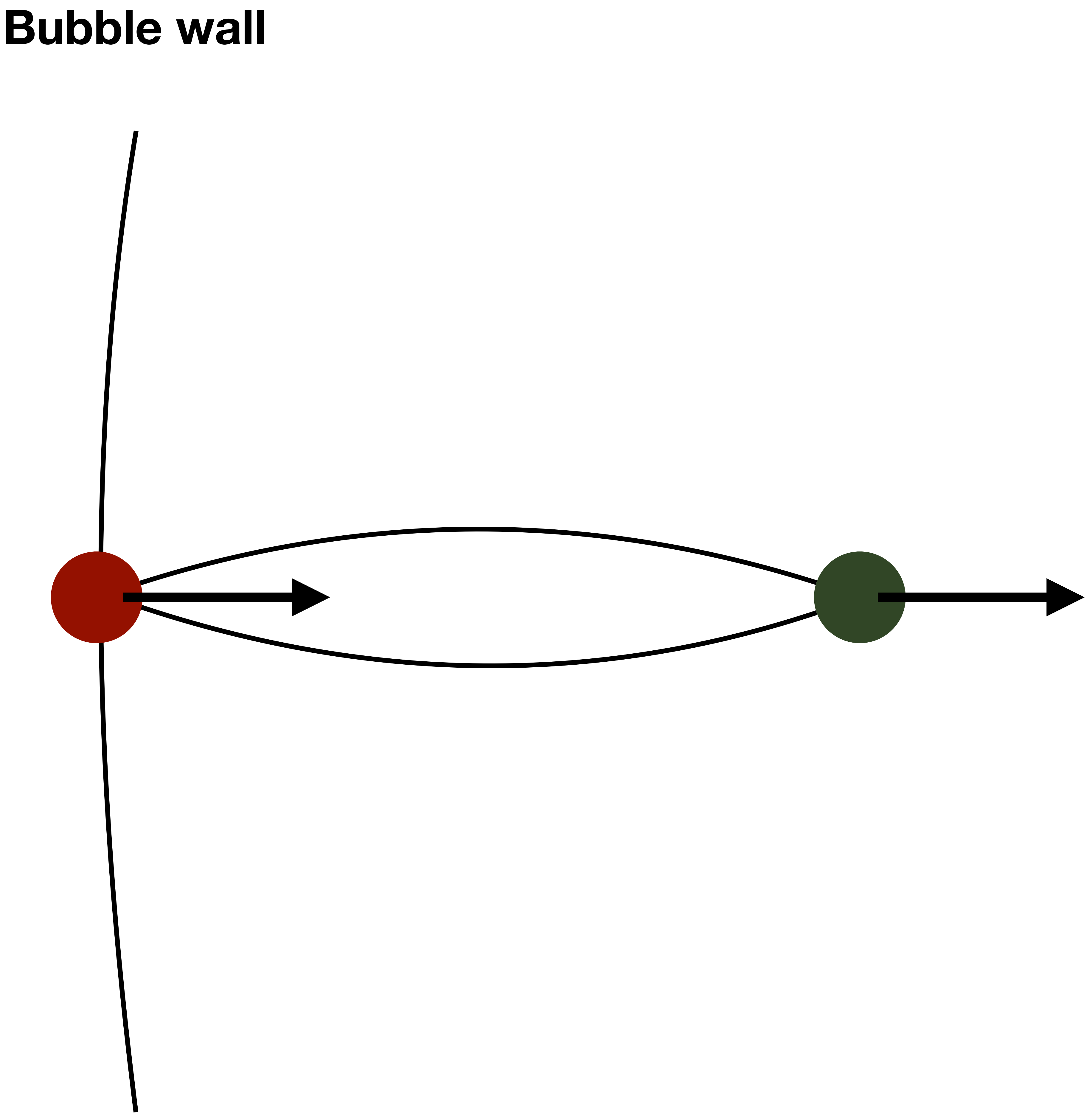


Interaction with other quarks ?

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



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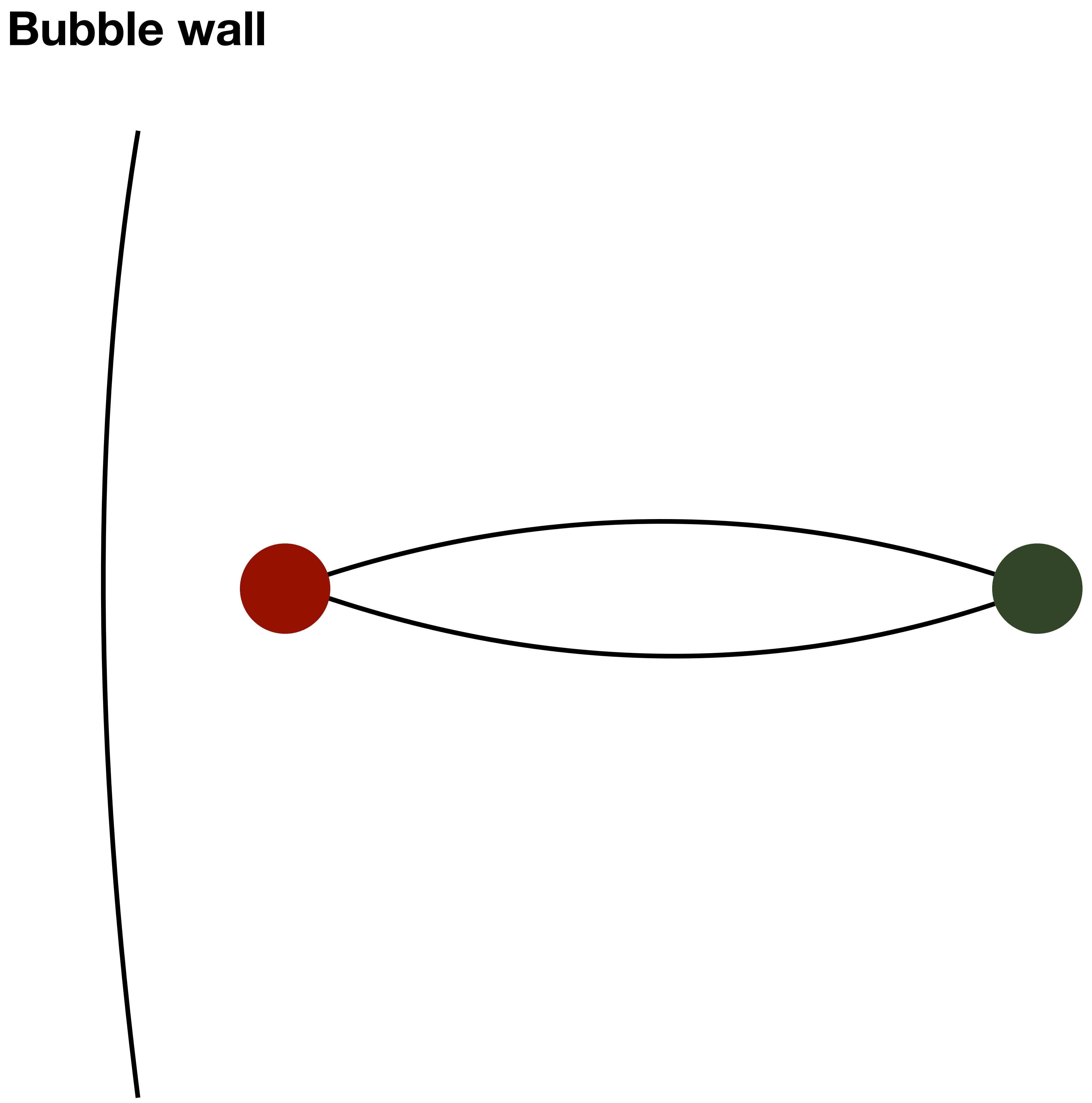

Interaction with other quarks ?

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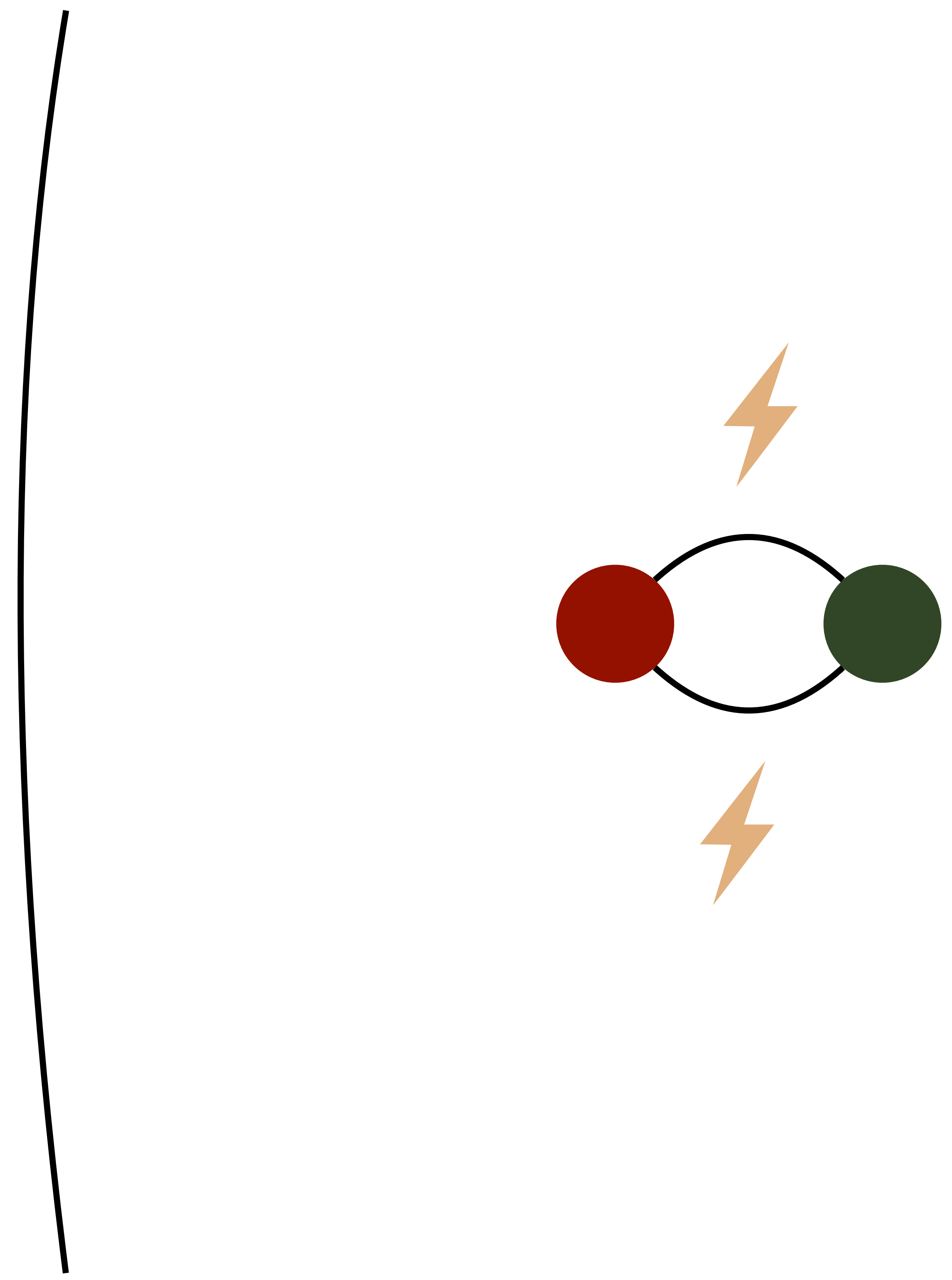
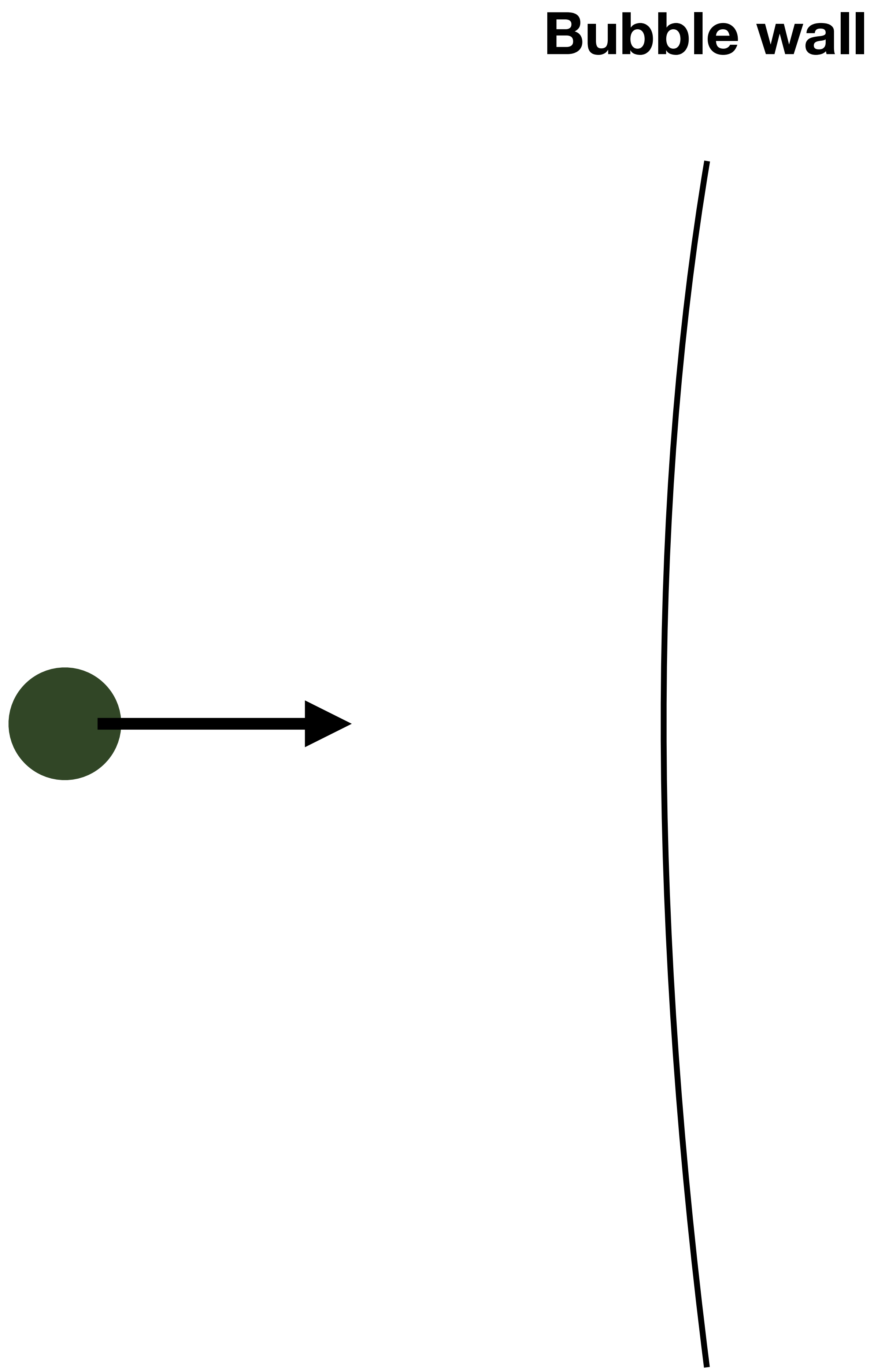
Bubble wall

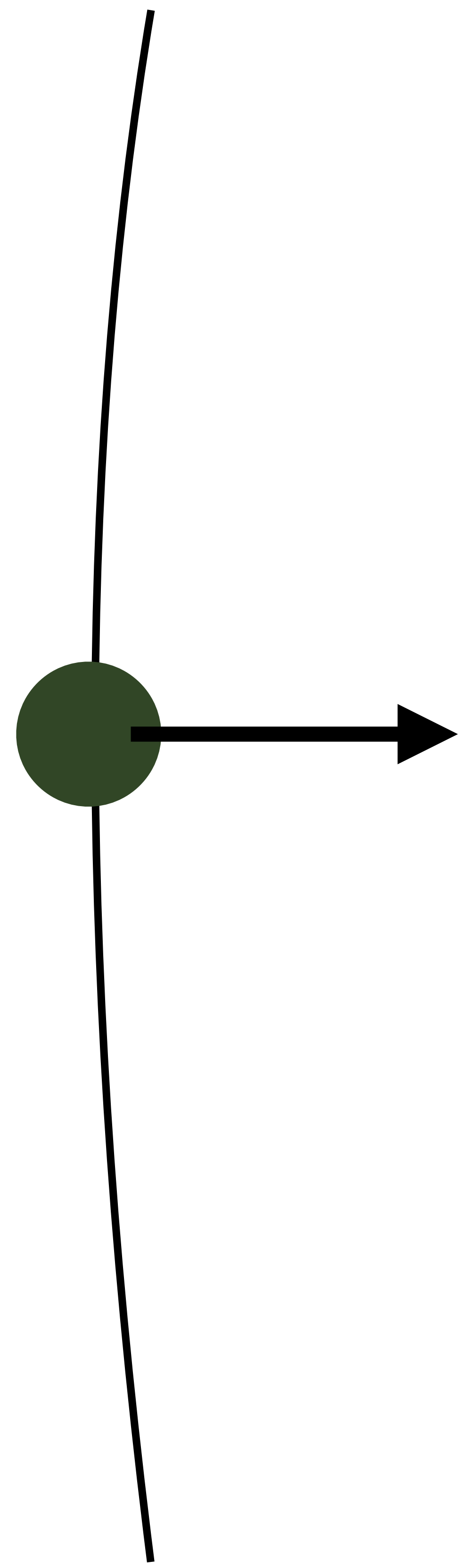


Interaction with other quarks ?

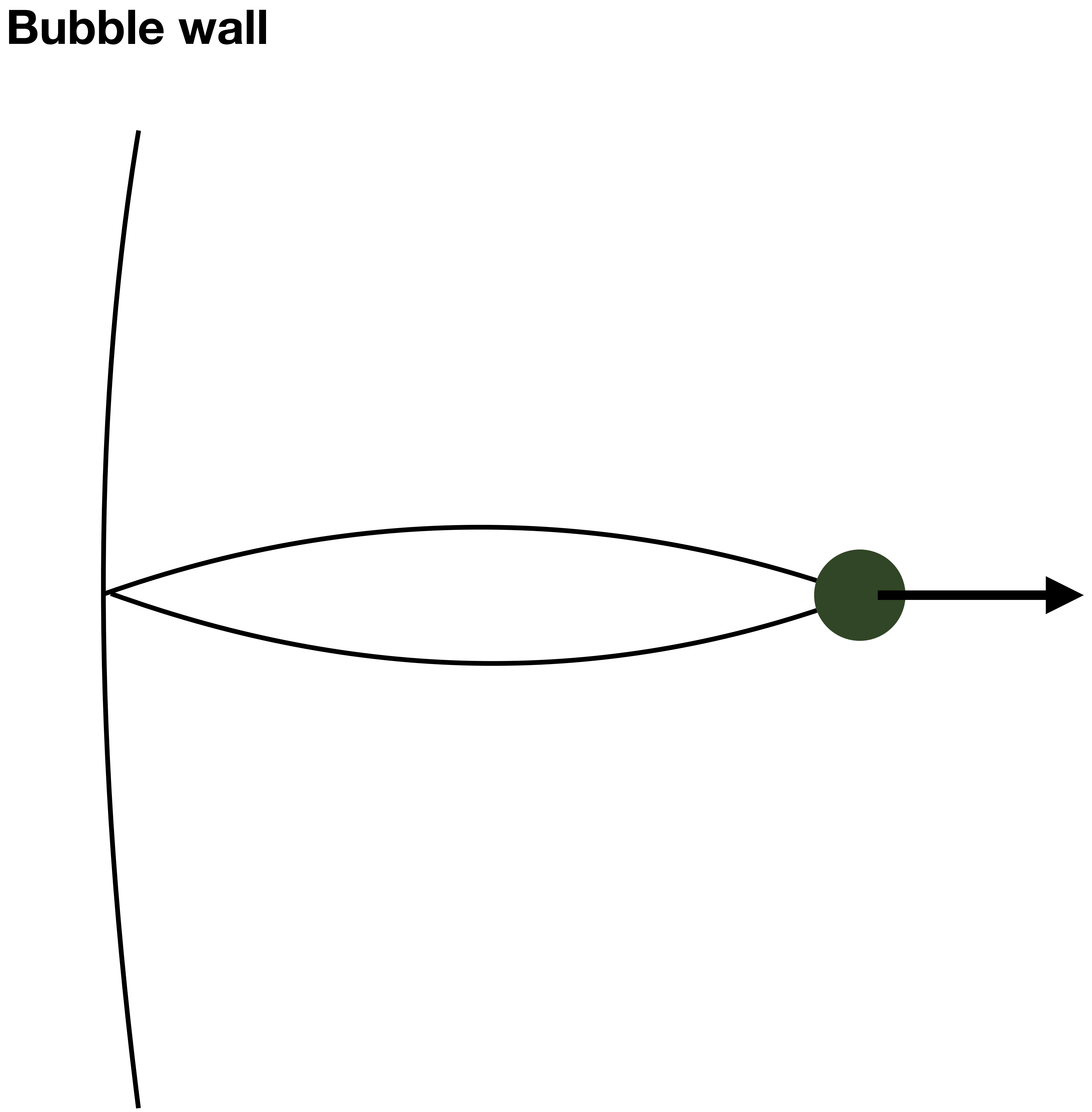


Interaction with other quarks ?

Bubble wall



Interaction with other quarks ?



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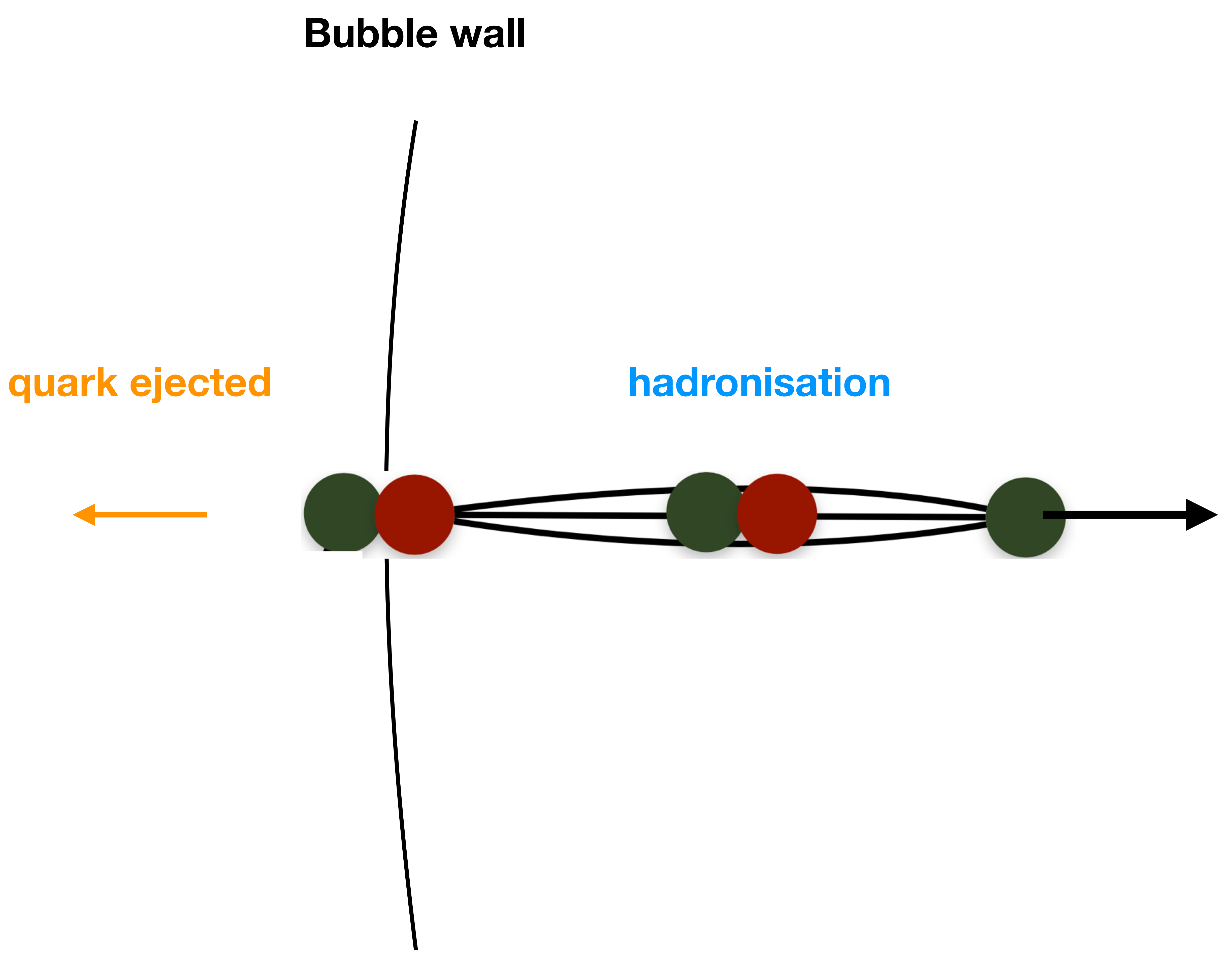

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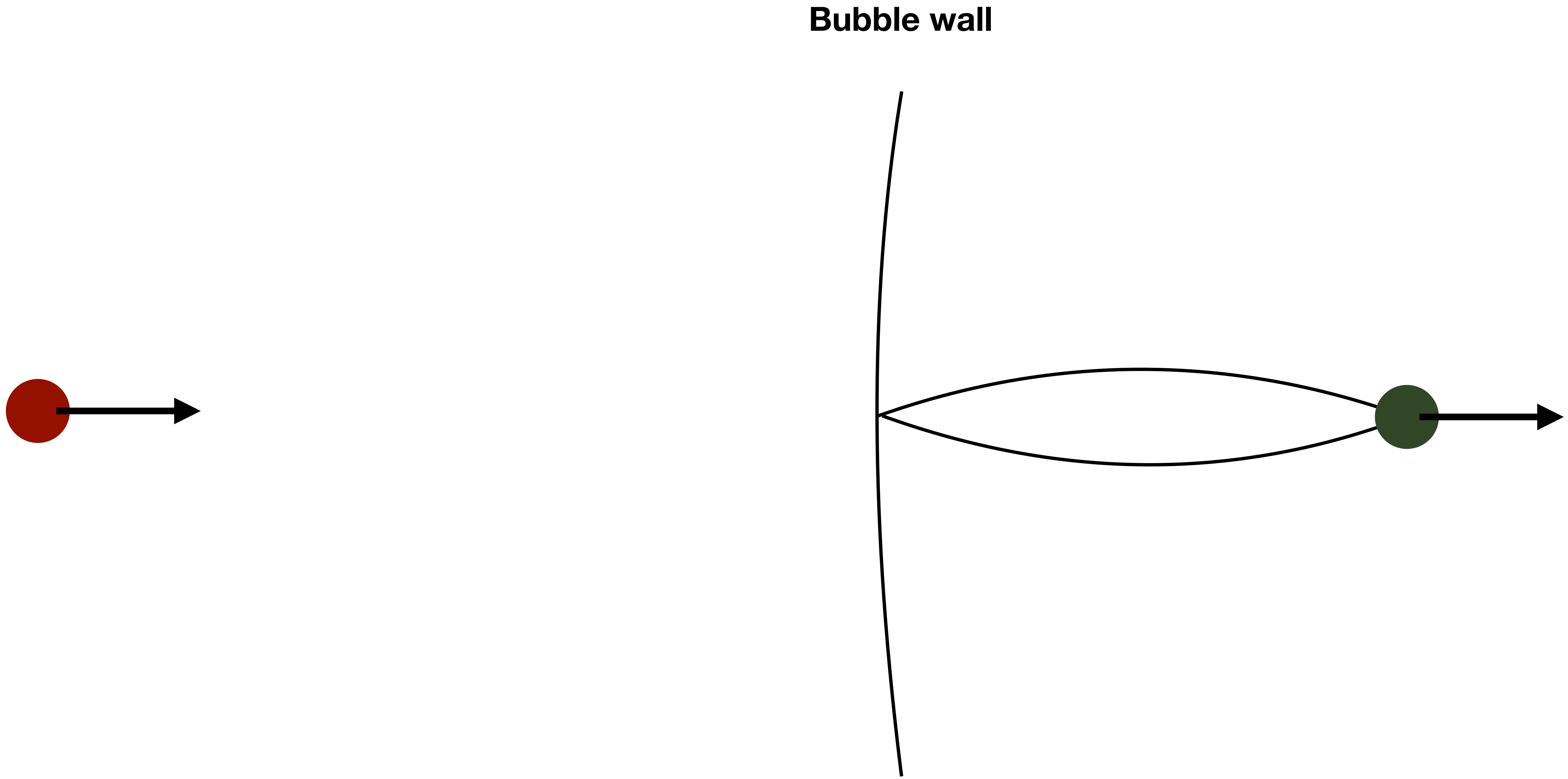

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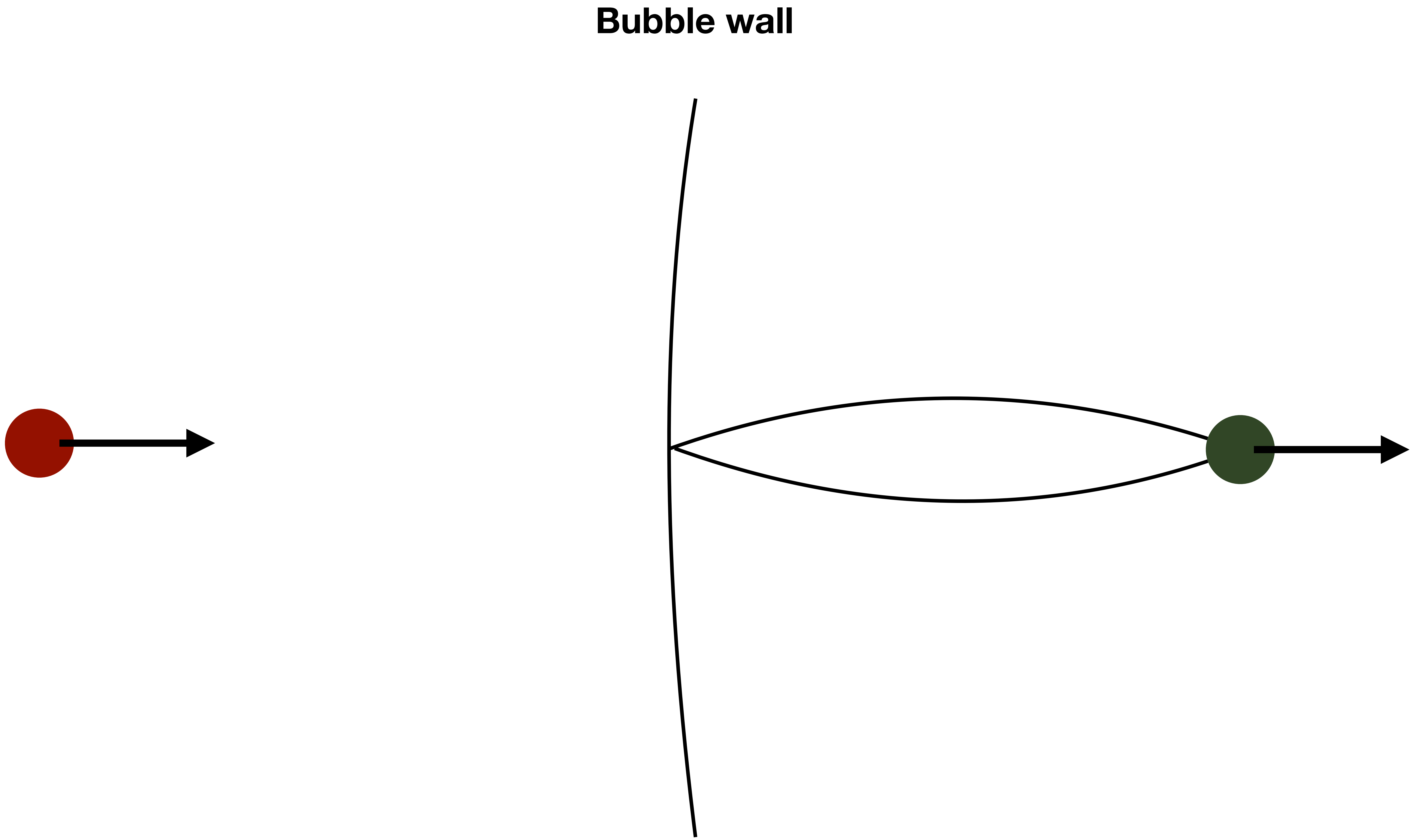
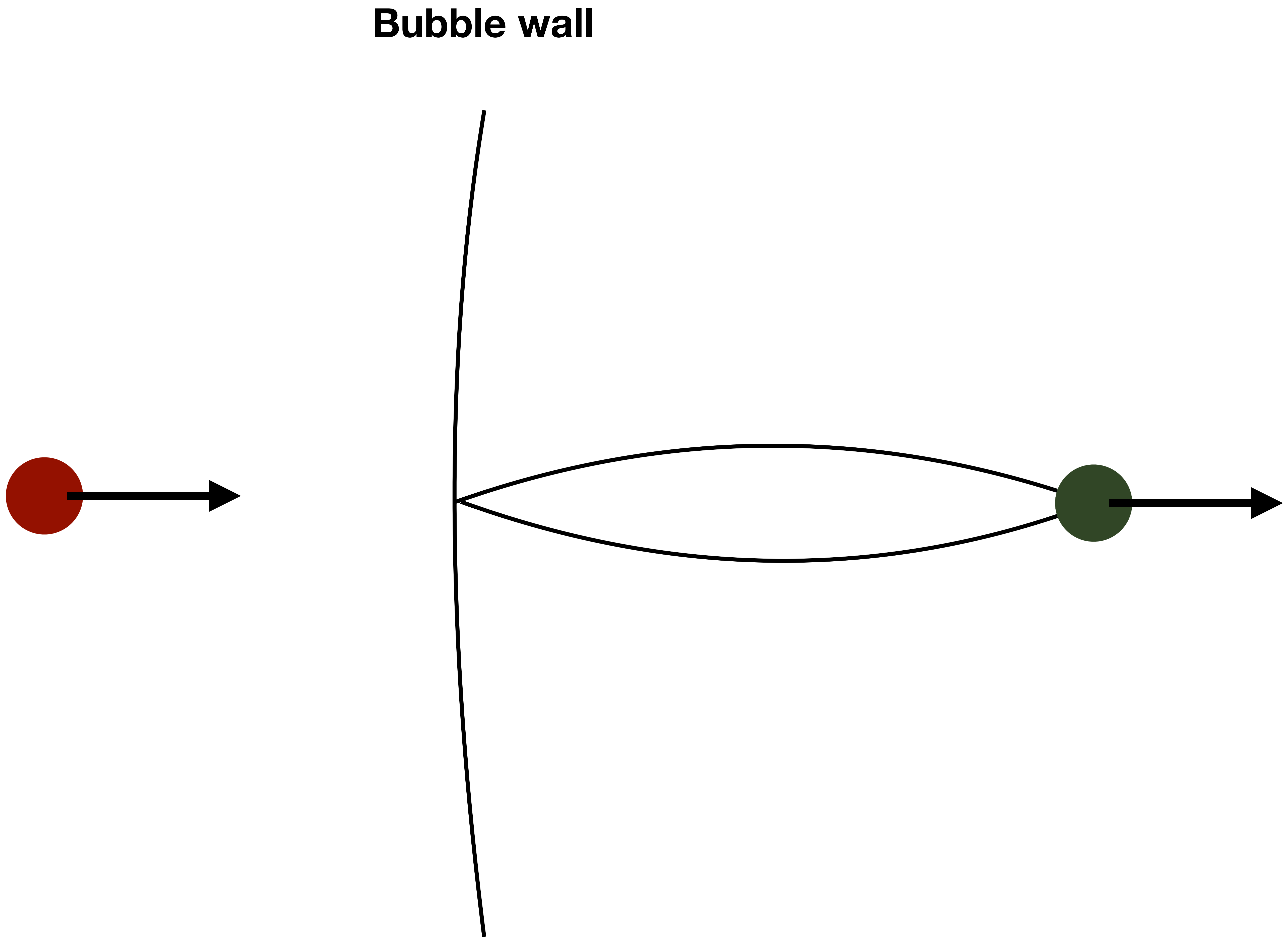


Interaction with other quarks ?

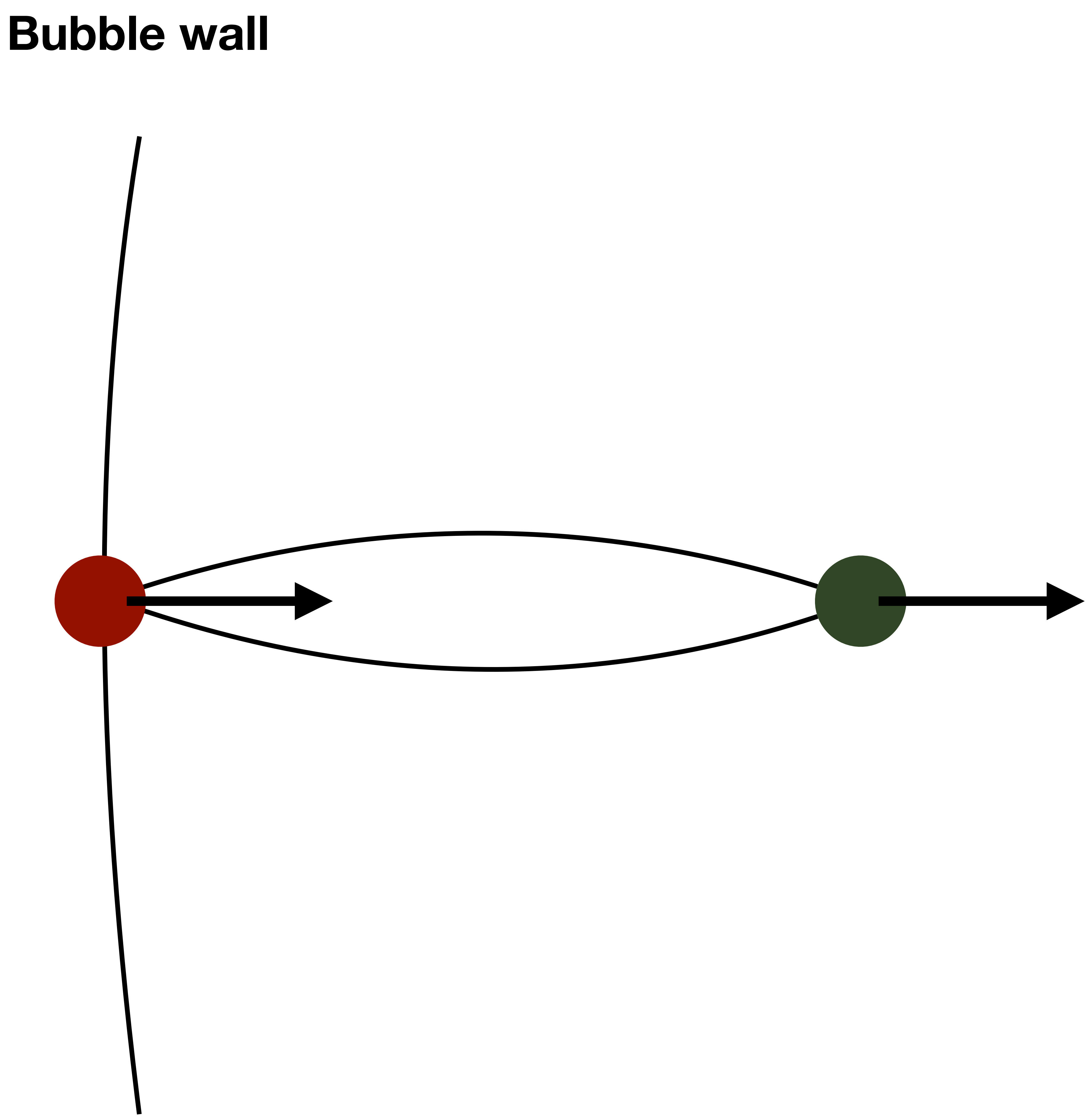
$$\Gamma_{\text{q-string}} \sim \pi f^{-2} \times \gamma_{\text{wp}} T_{\text{nuc}}^3$$

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



Interaction with other quarks ?

$$\Gamma_{\rm q-string} \sim \pi f^{-2} \times \gamma_{\rm wp} T_{\rm nuc}^3 \qquad \Gamma_{\rm nucl} \sim f/N$$



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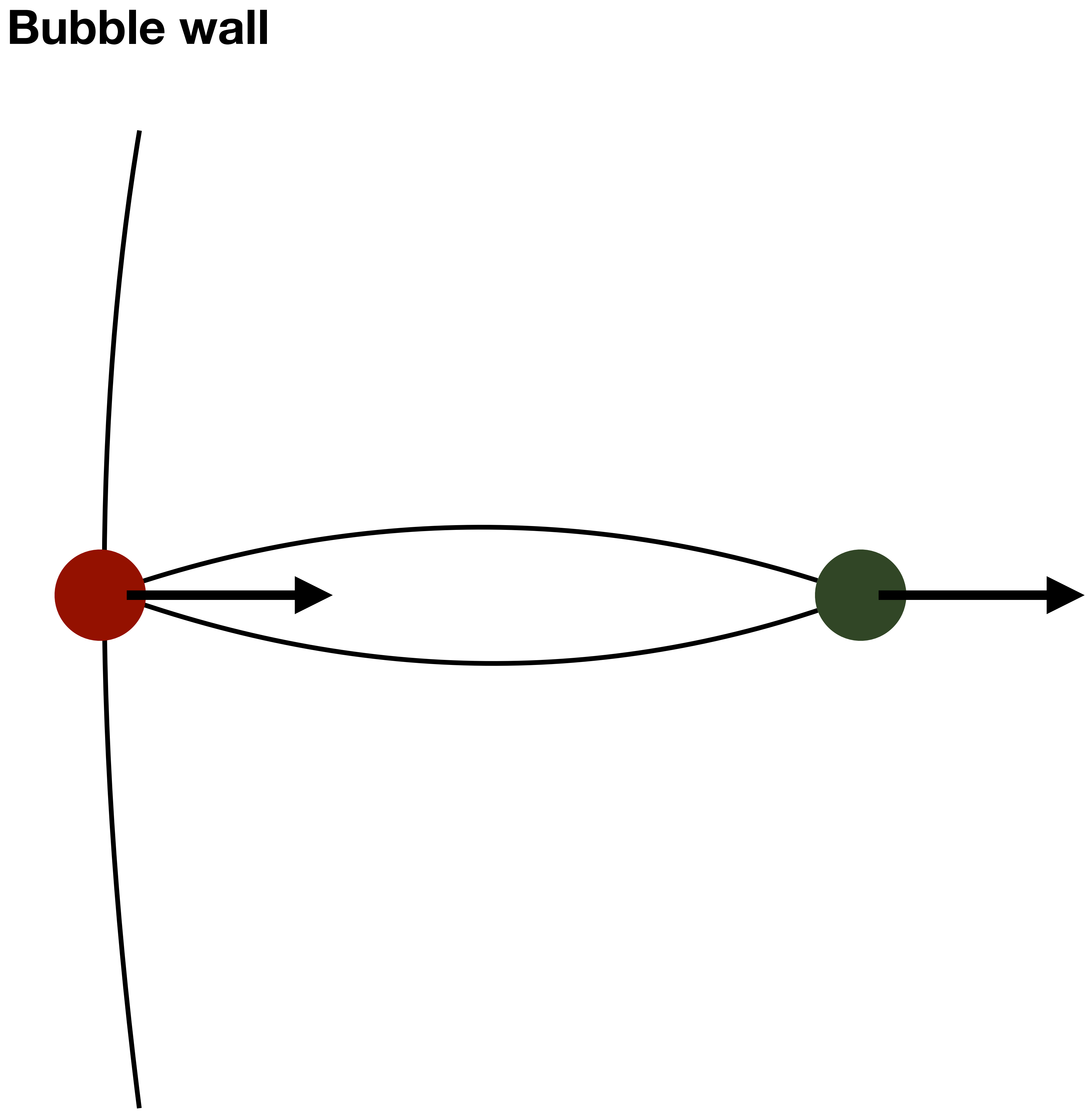

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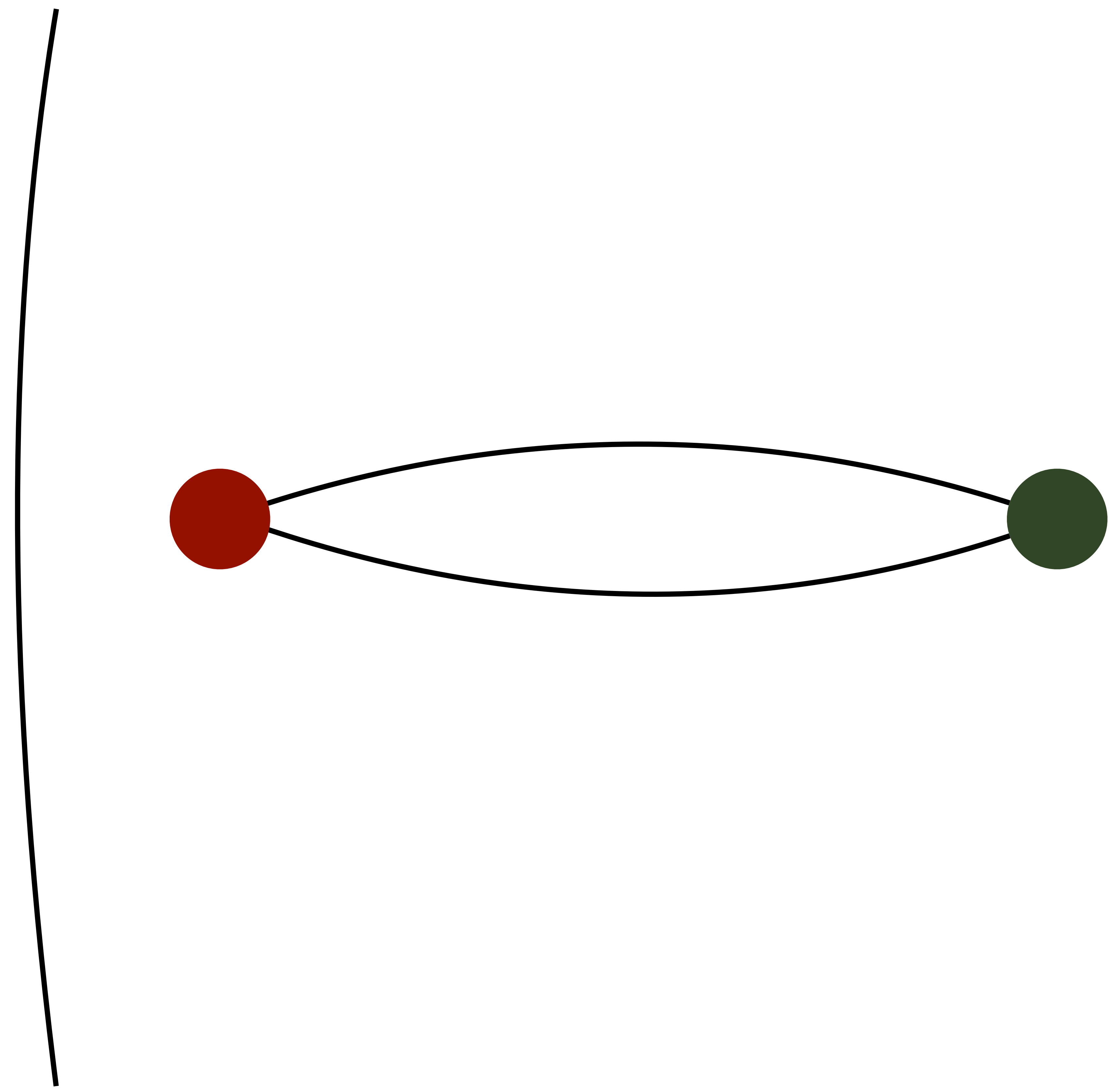
Bubble wall



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Bubble wall