Cosmological consequences of supercooled confining phase transition

Yann Gouttenoire

With Iason Blades, Filippo Sala and Geraldine Servant

HPNP Tokyo

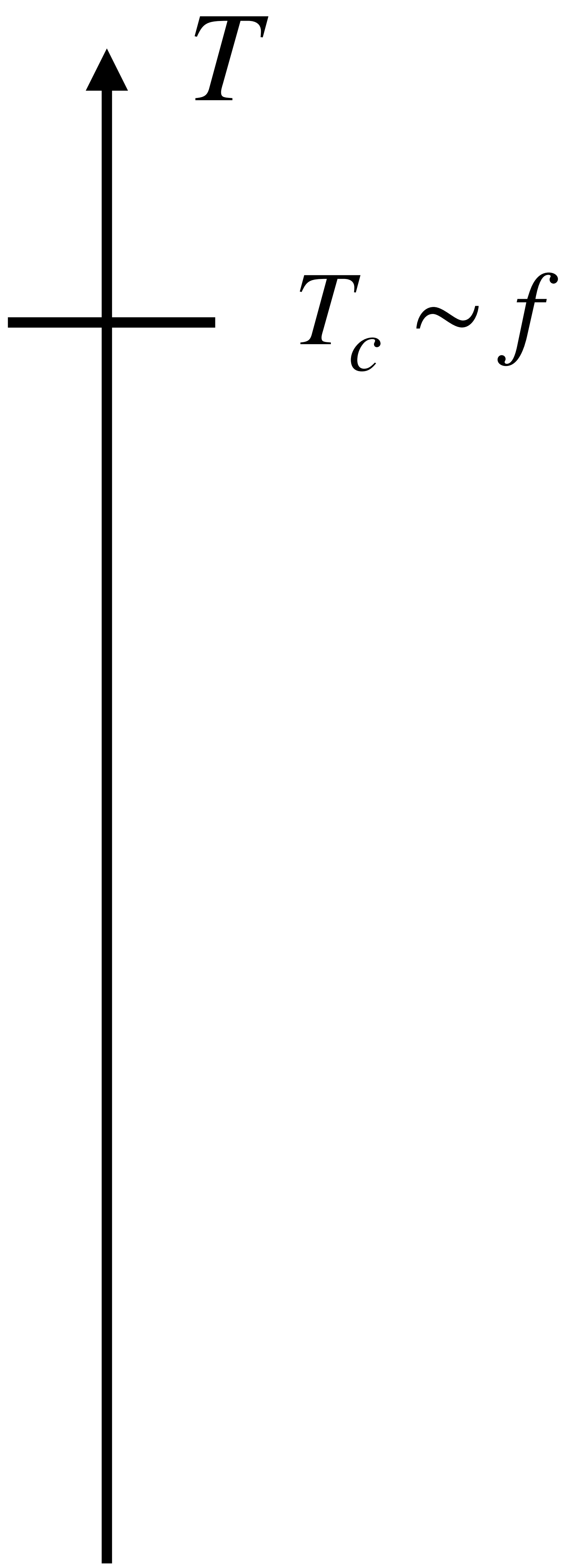
24th March 2021

2017-2020

2021-2023

Supercooled confinement

Baldes, YG, Sala, 2020



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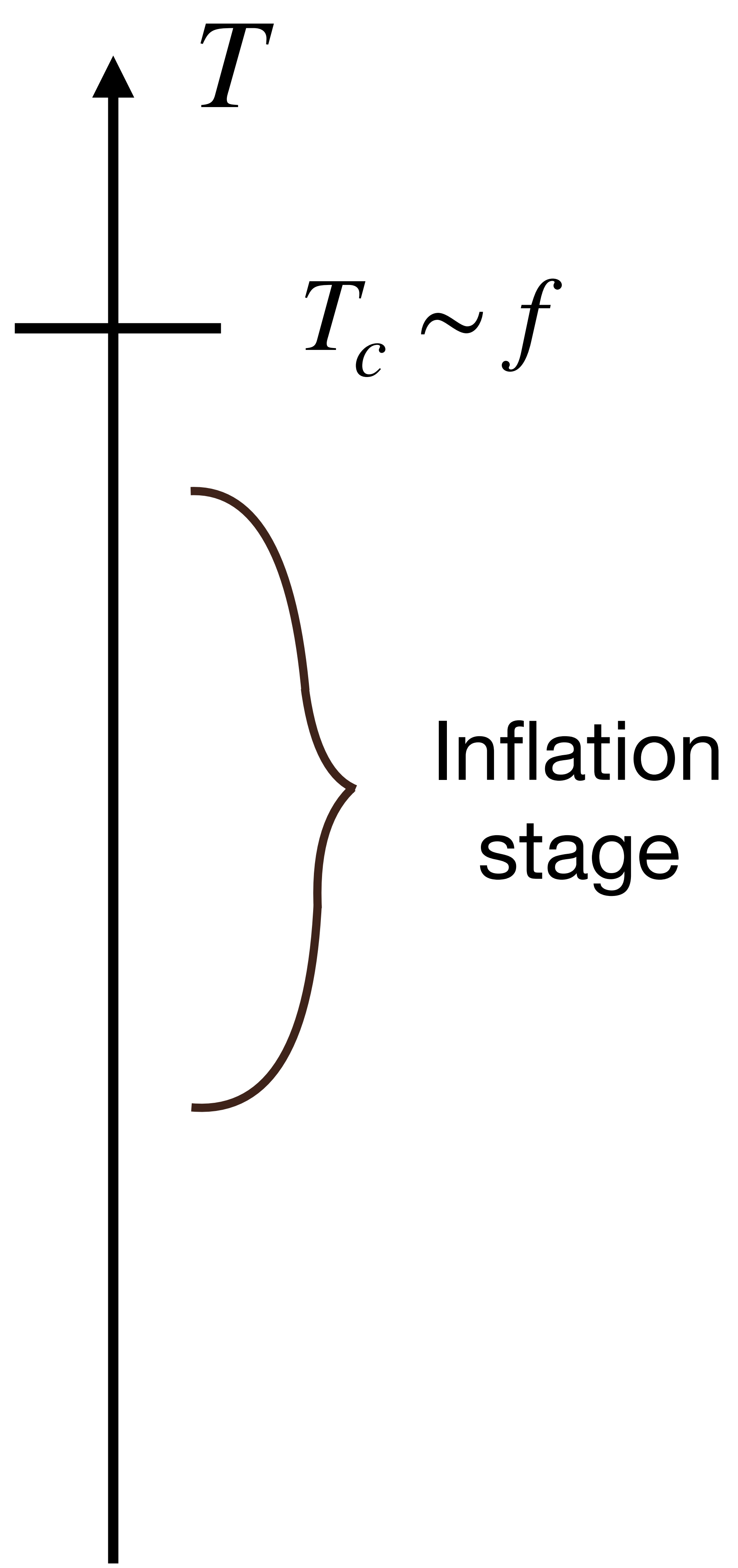

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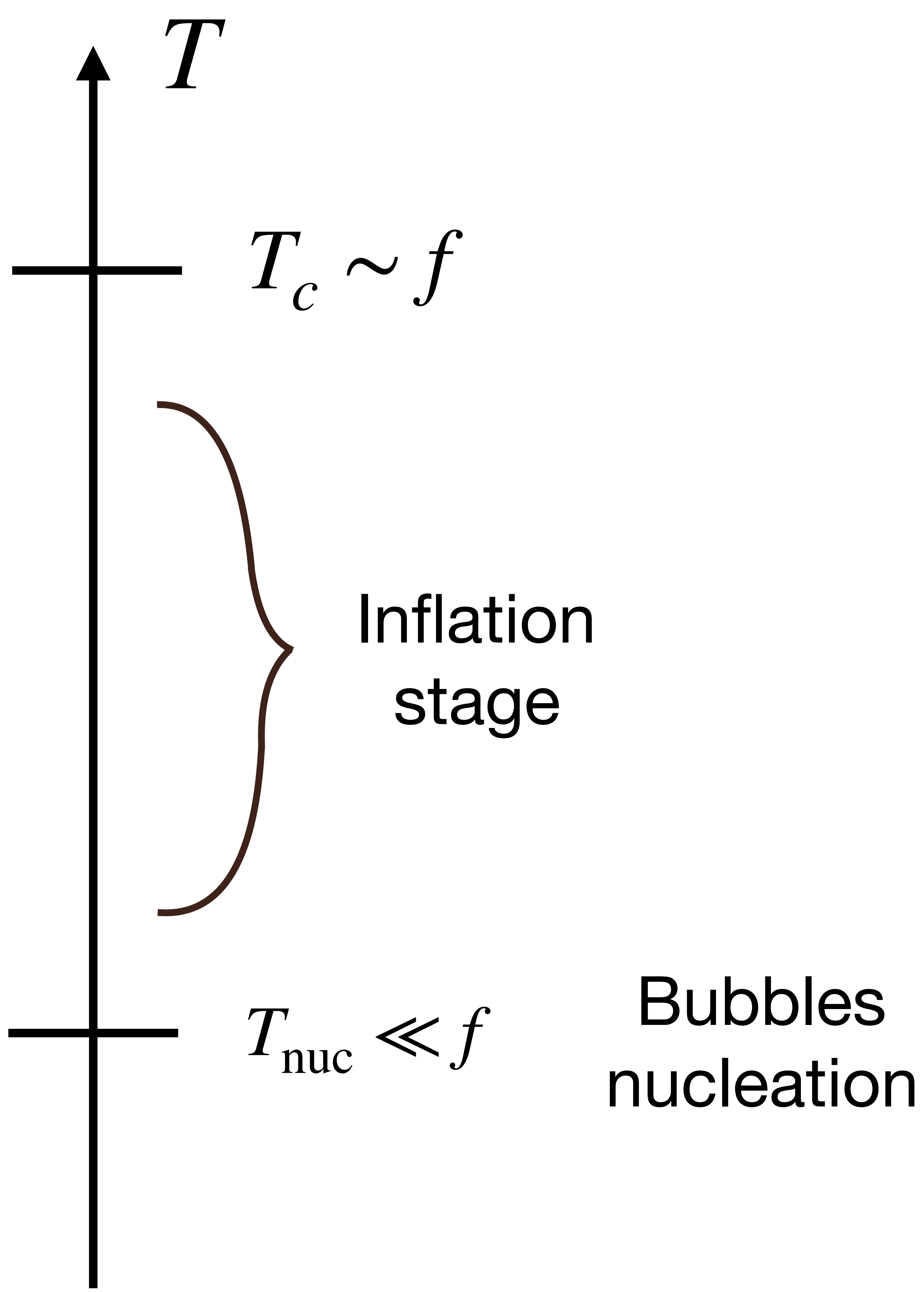

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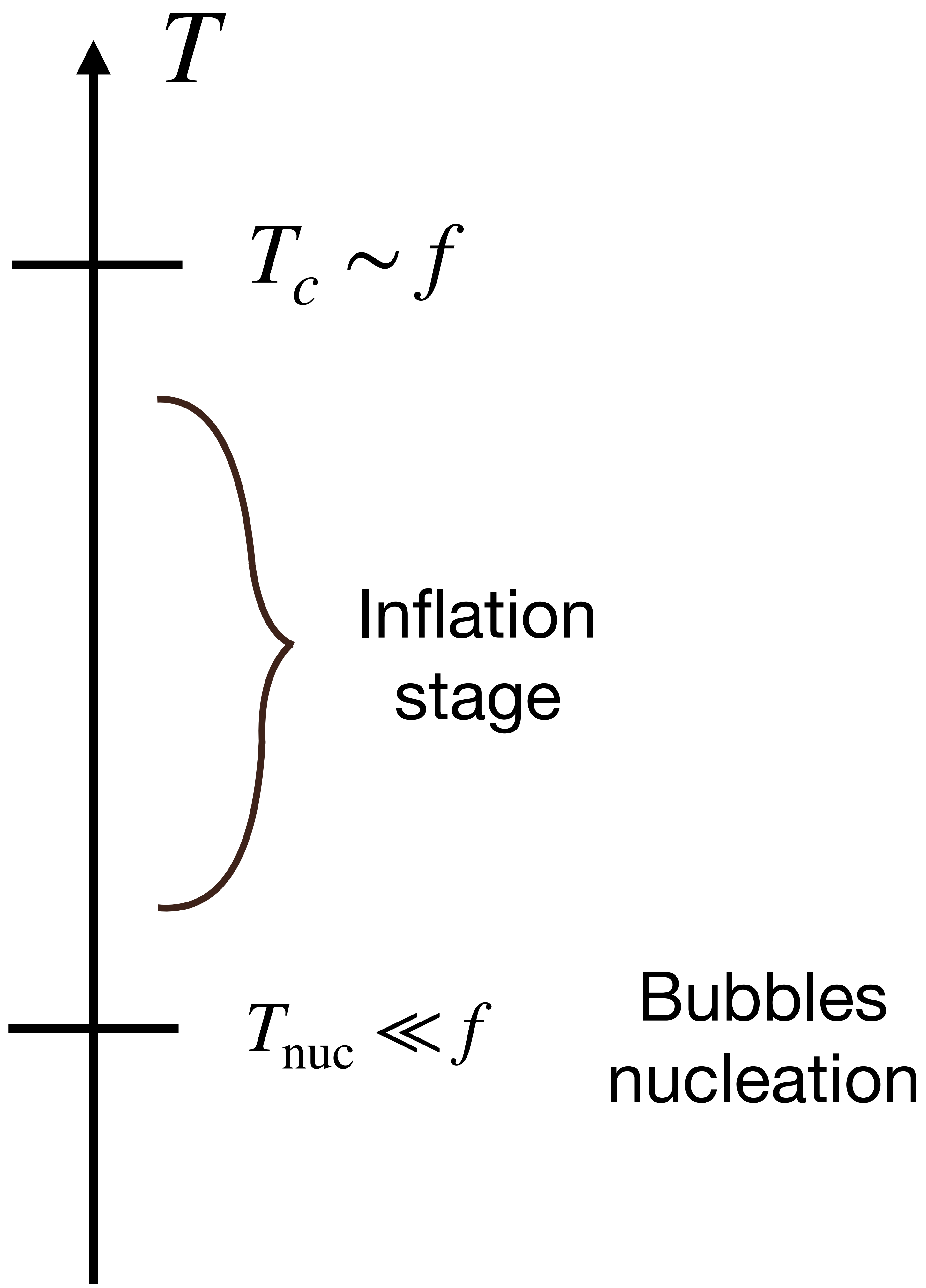
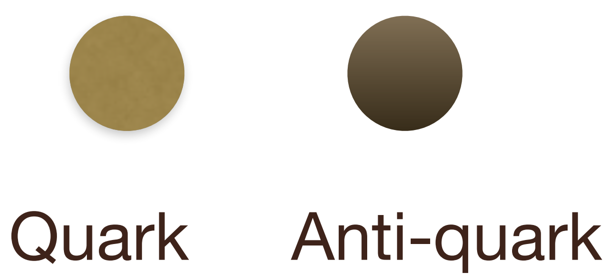


Naive picture



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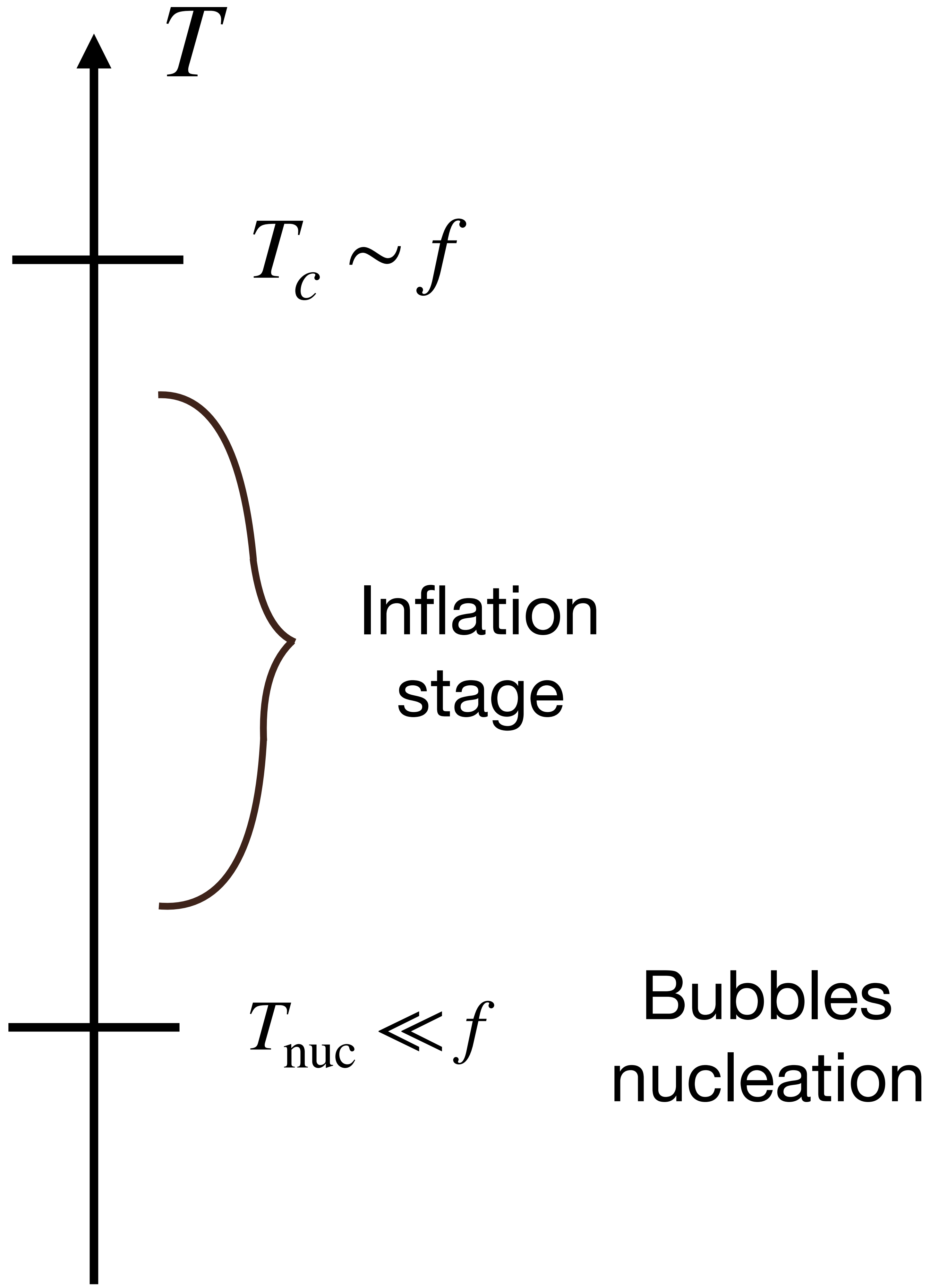

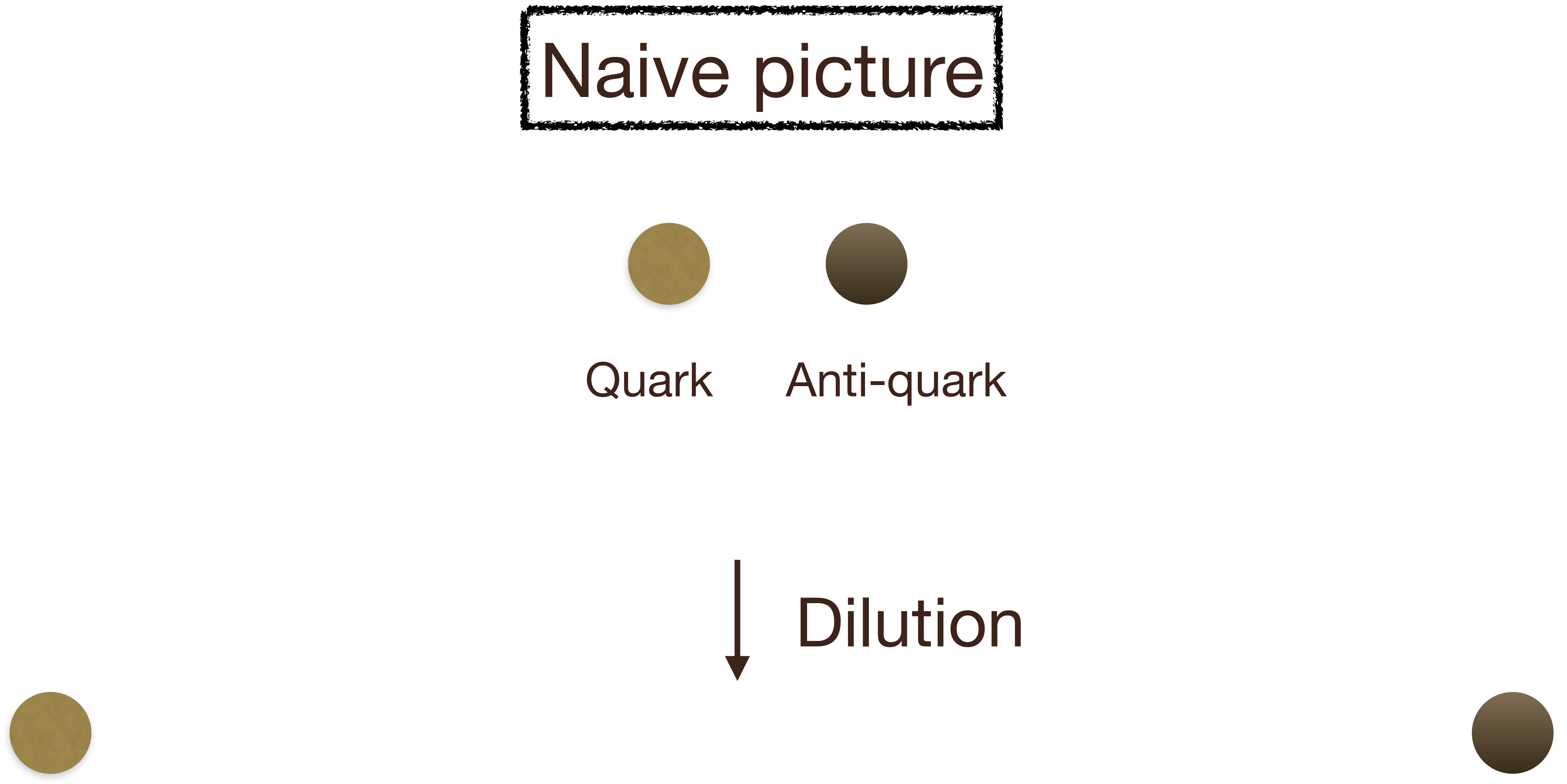

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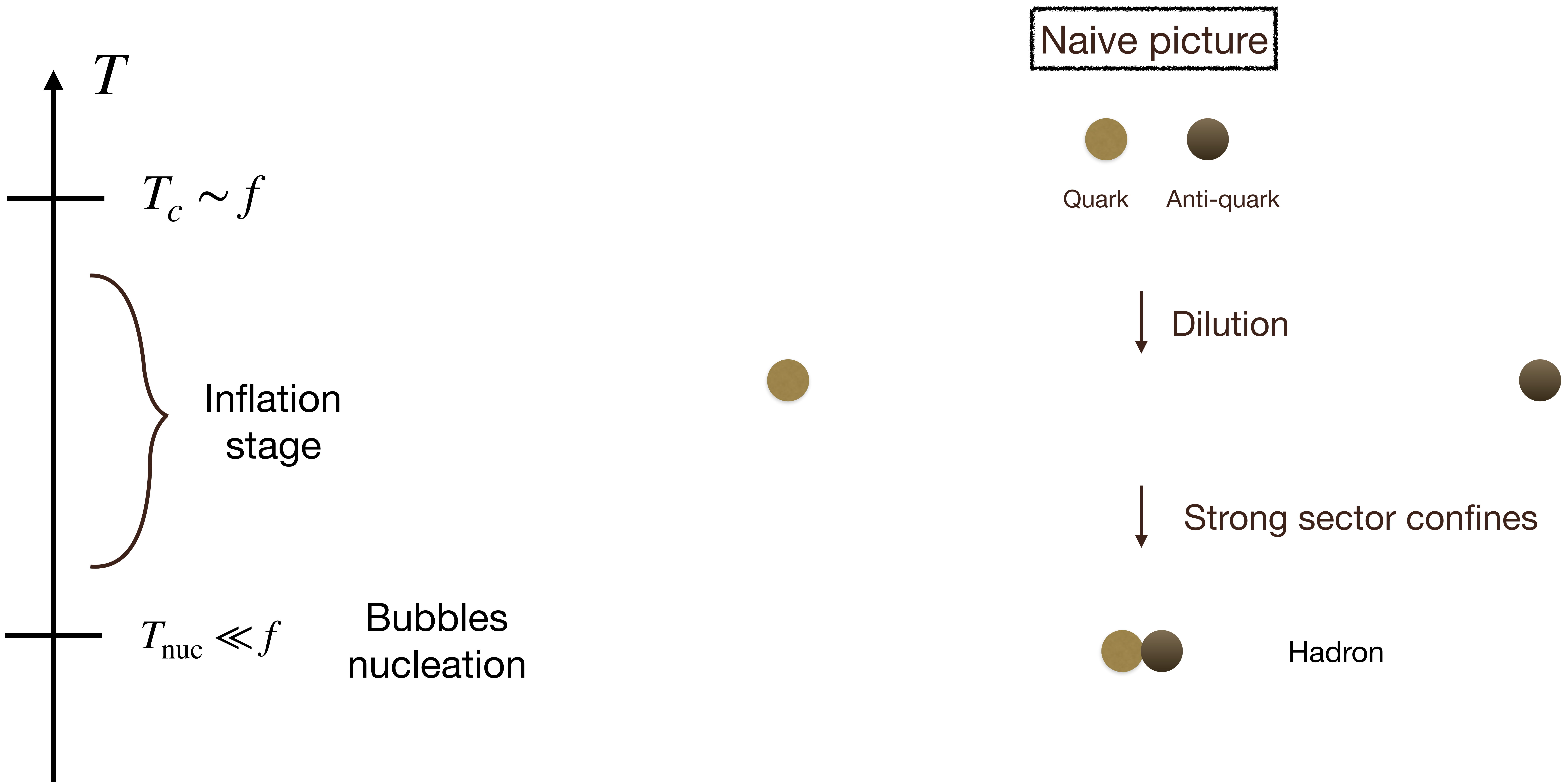

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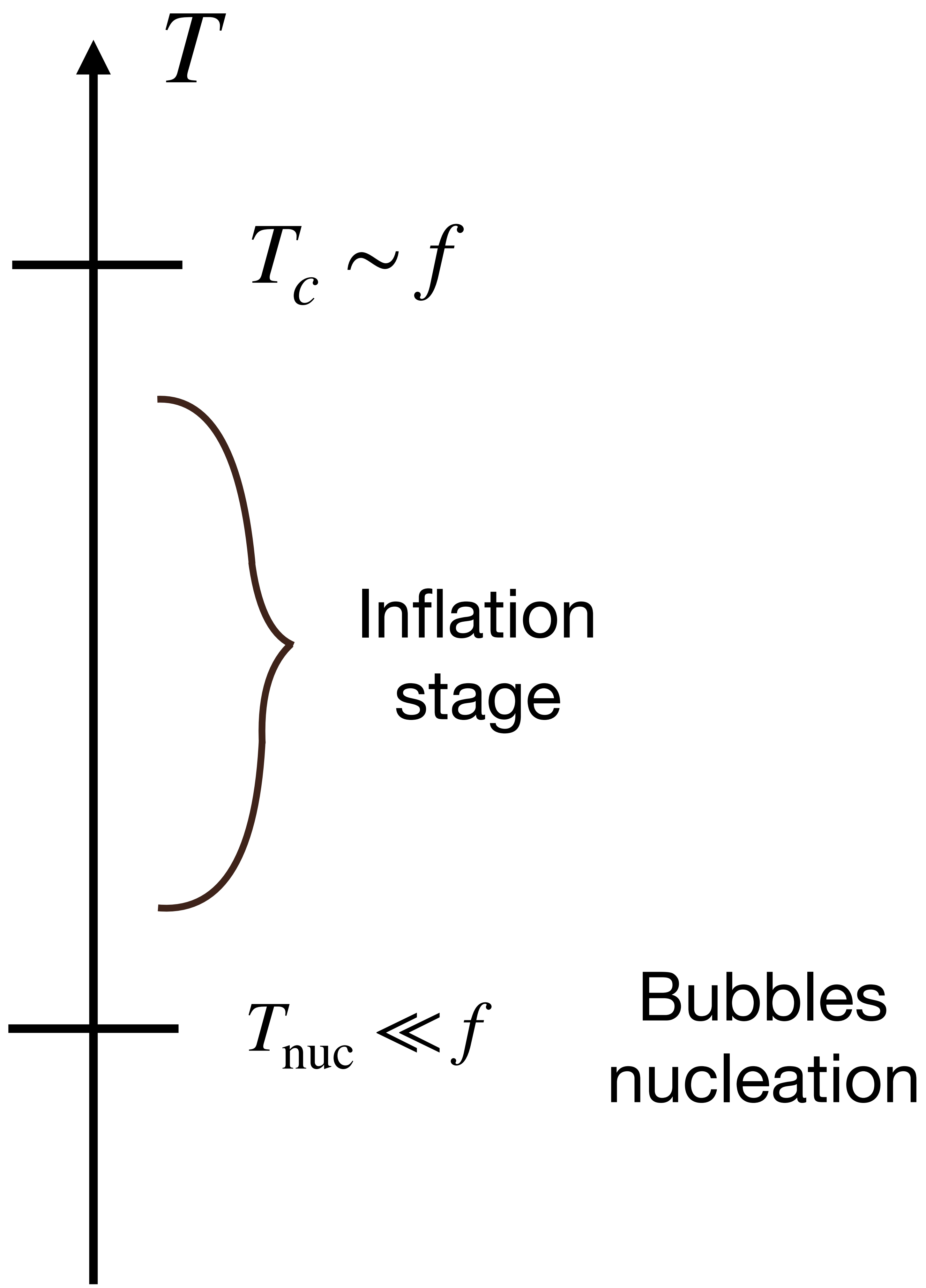
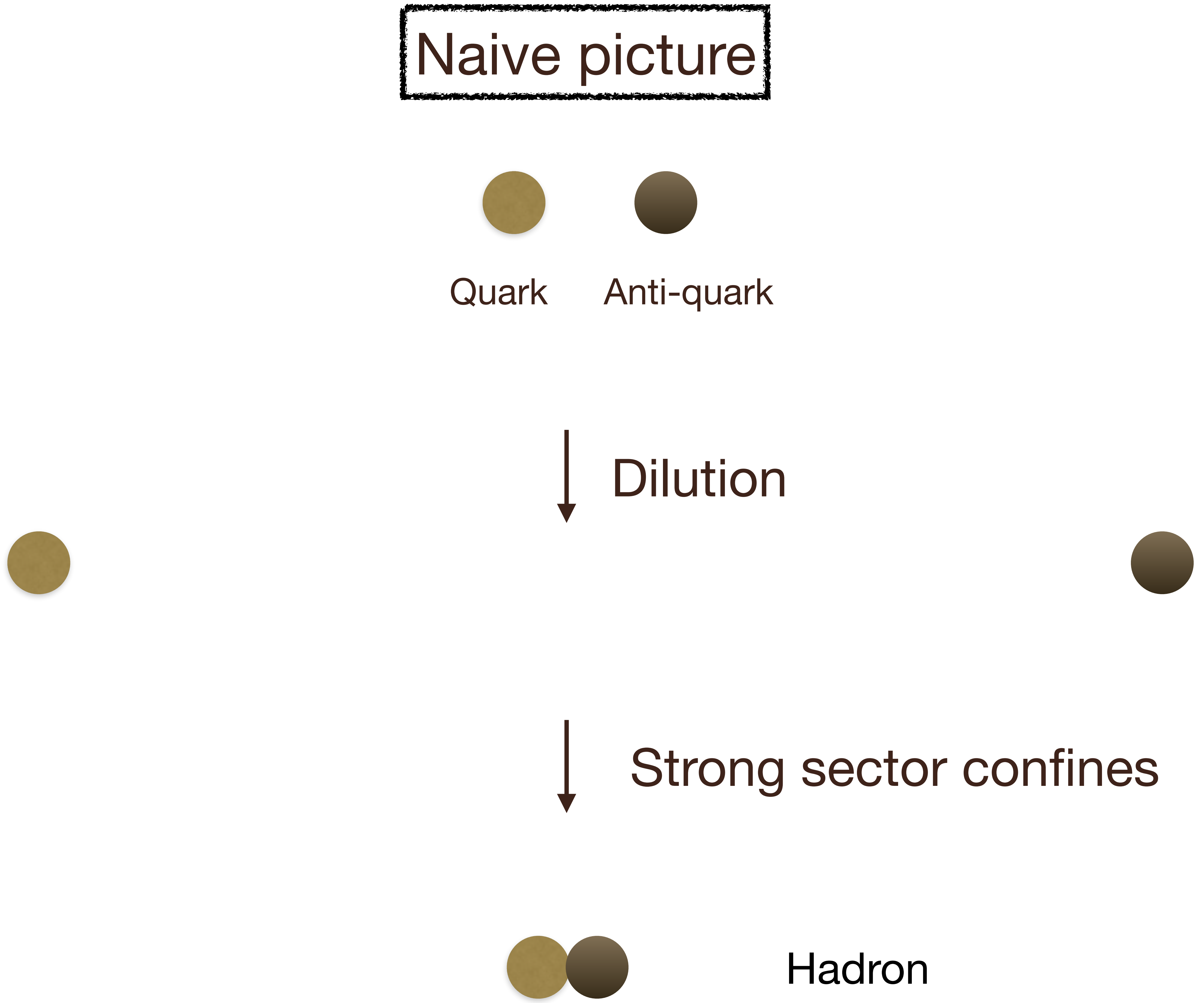
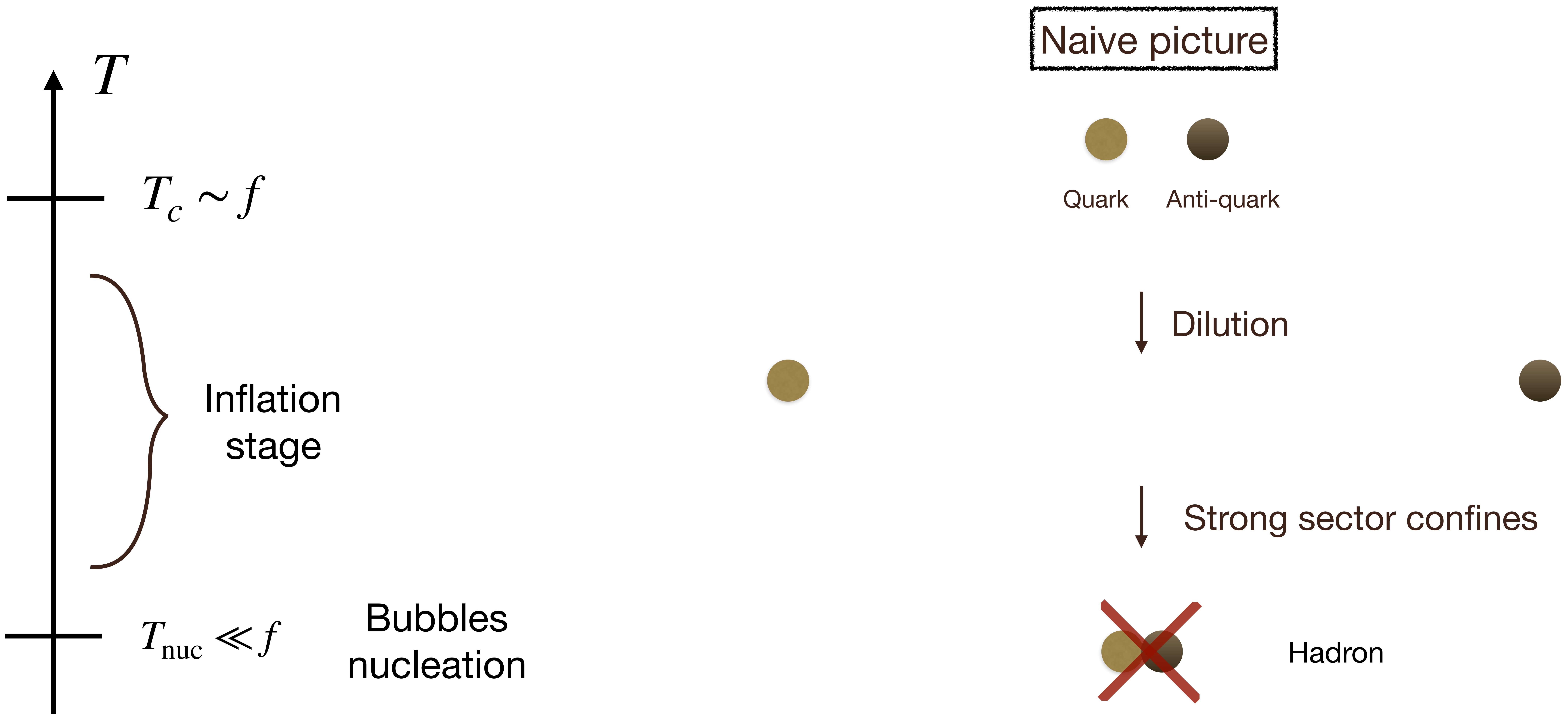




$$\longrightarrow \quad Y_{\rm DM} \propto \left(\frac{T_{\rm nuc}}{T_{\rm c}}\right)^3$$

Supercooled confinement

Baldes, YG, Sala, 2020



$$\longrightarrow \quad Y_{\text{DM}} \propto \cancel{\left(\frac{T_{\text{nuc}}}{T_{\text{c}}}\right)}^3$$

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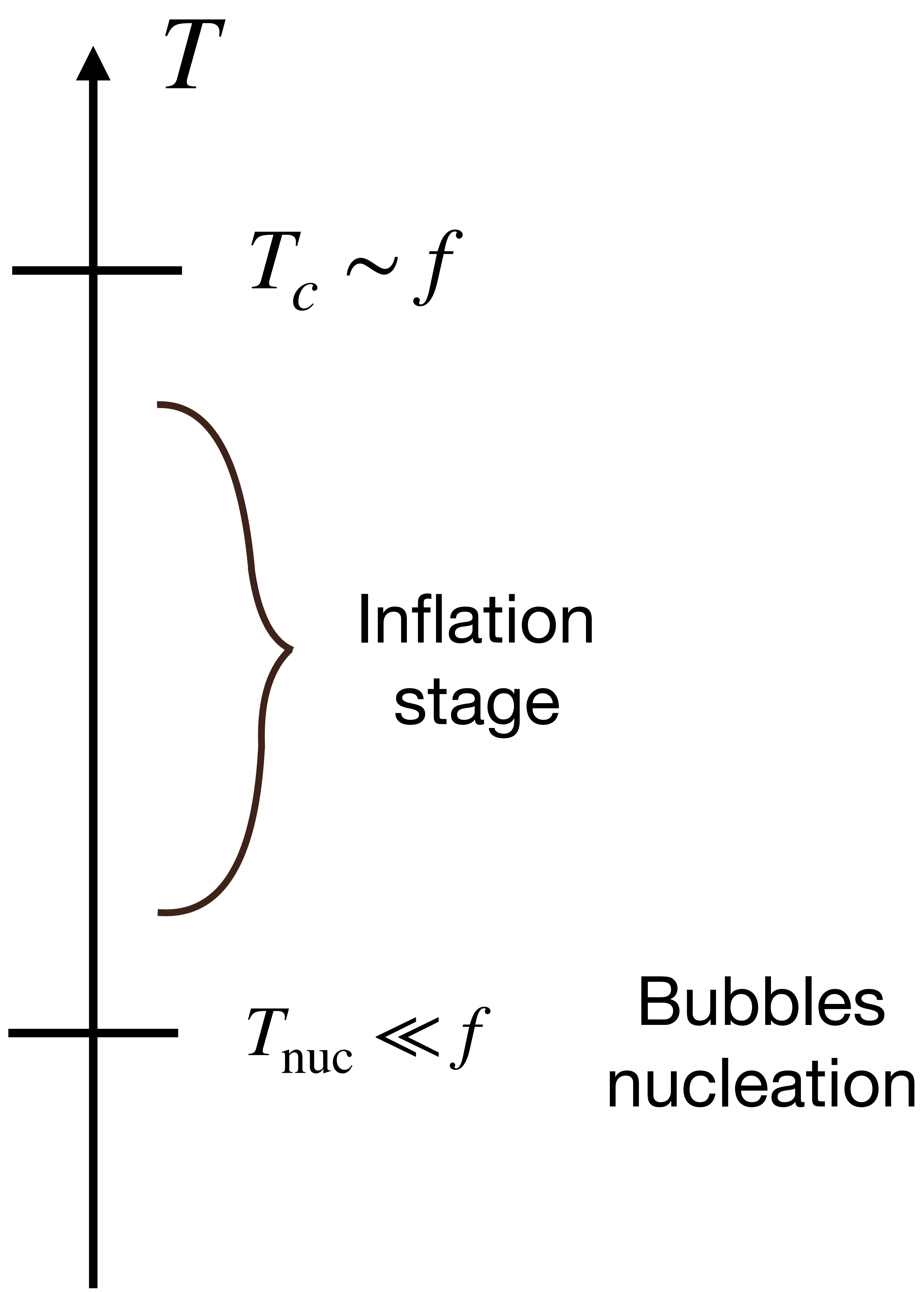

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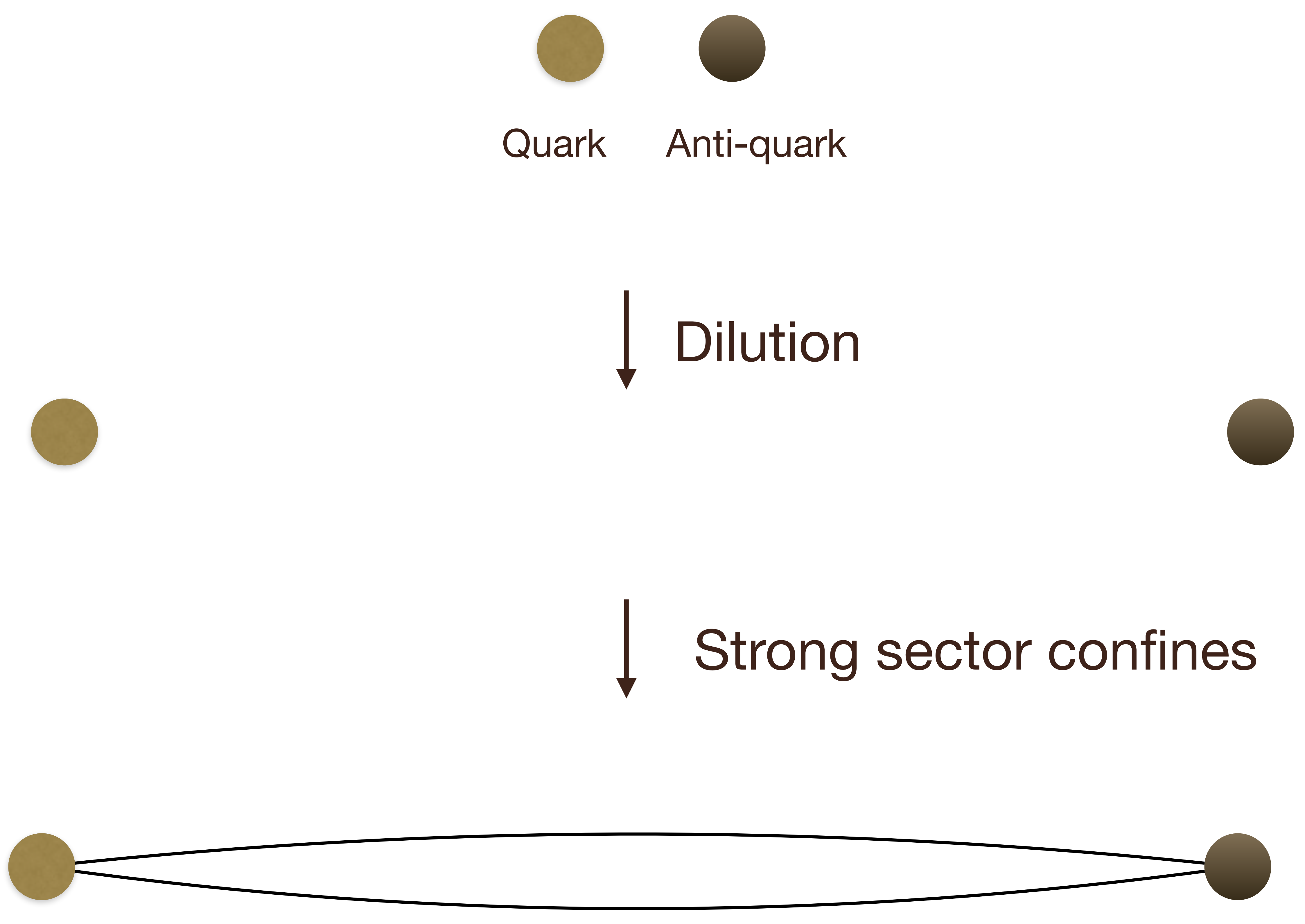

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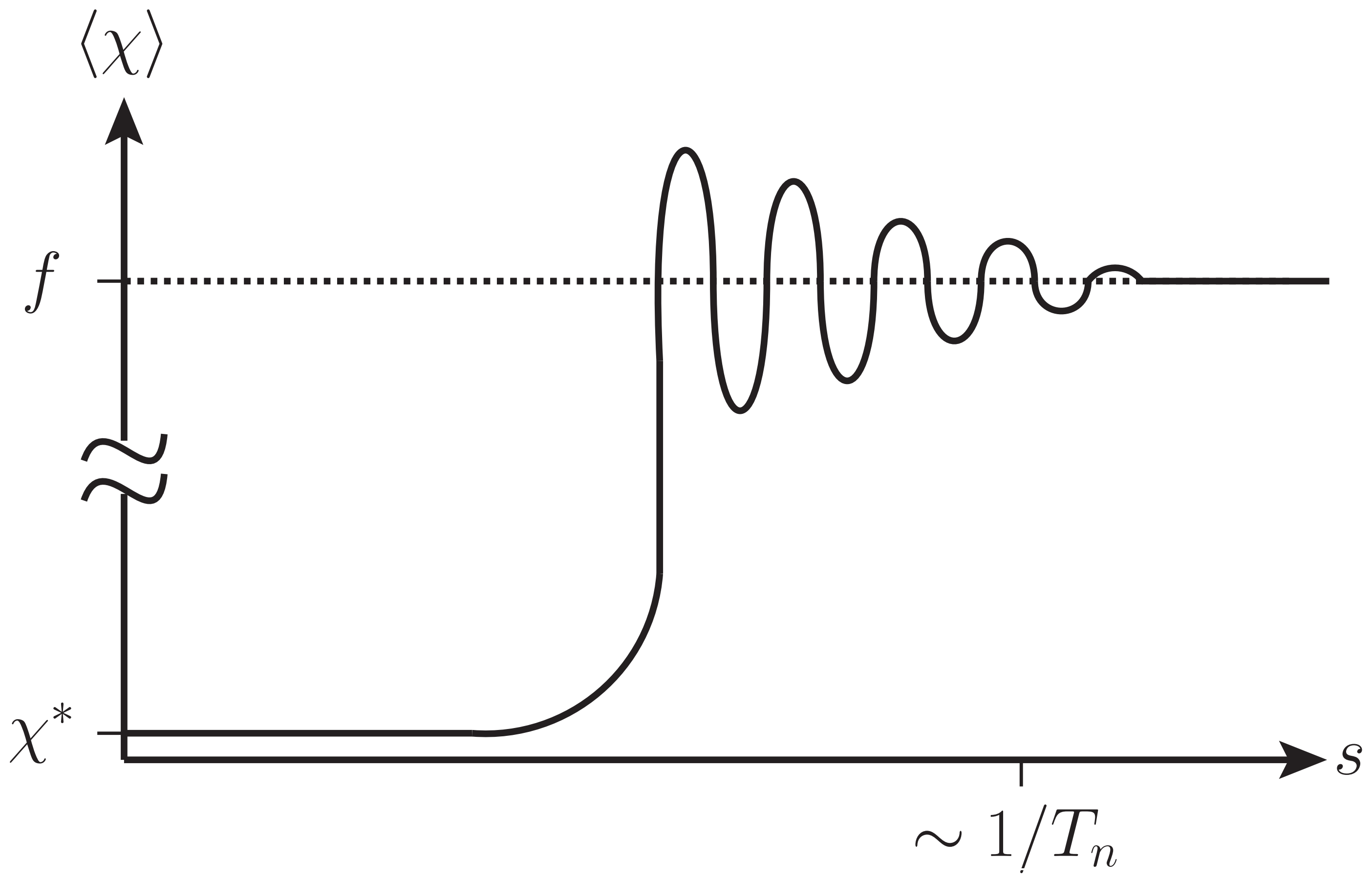
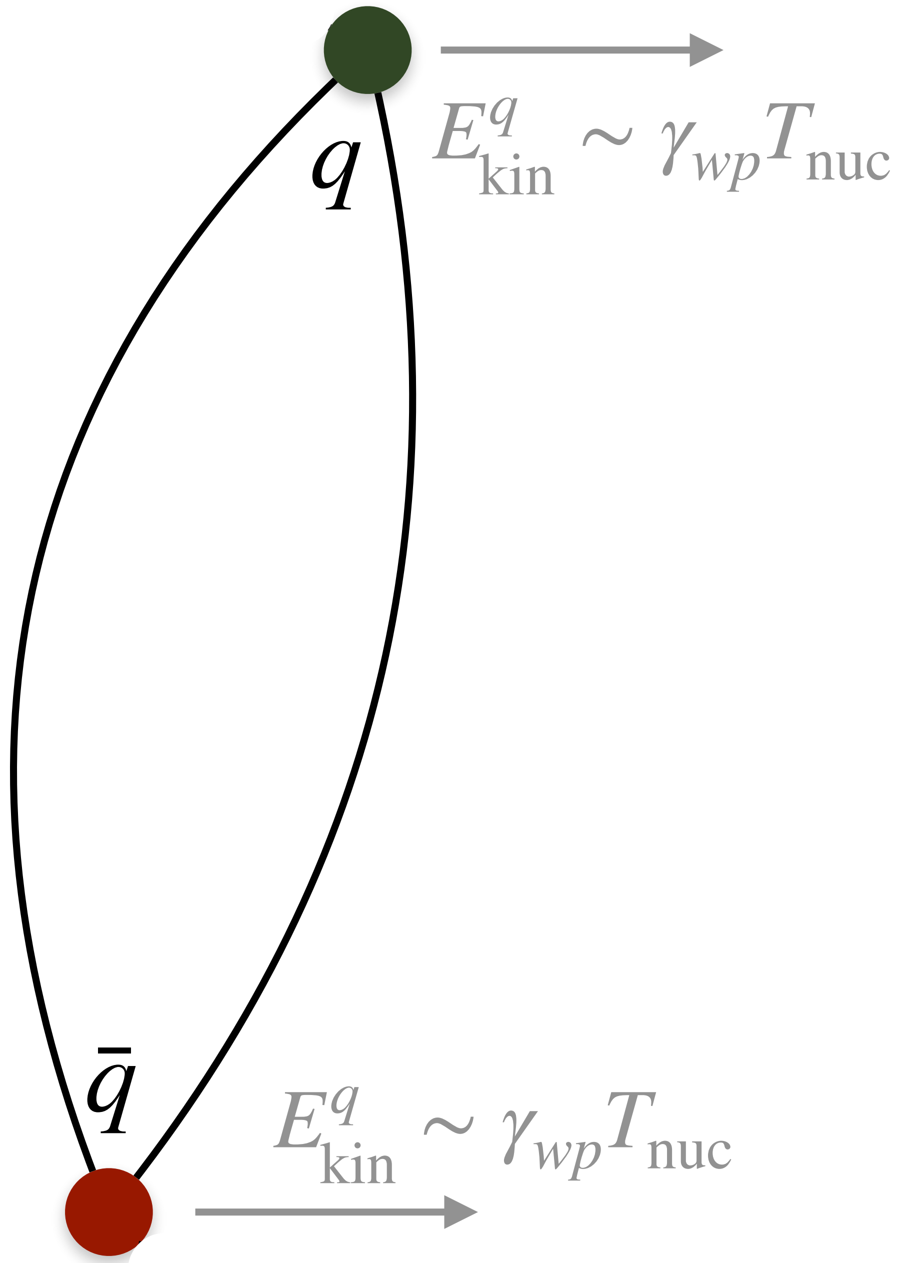
Hadrons formations



Bubble wall profile

Deconfined phase

$\chi = 0$



Confined phase

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Bubble wall frame

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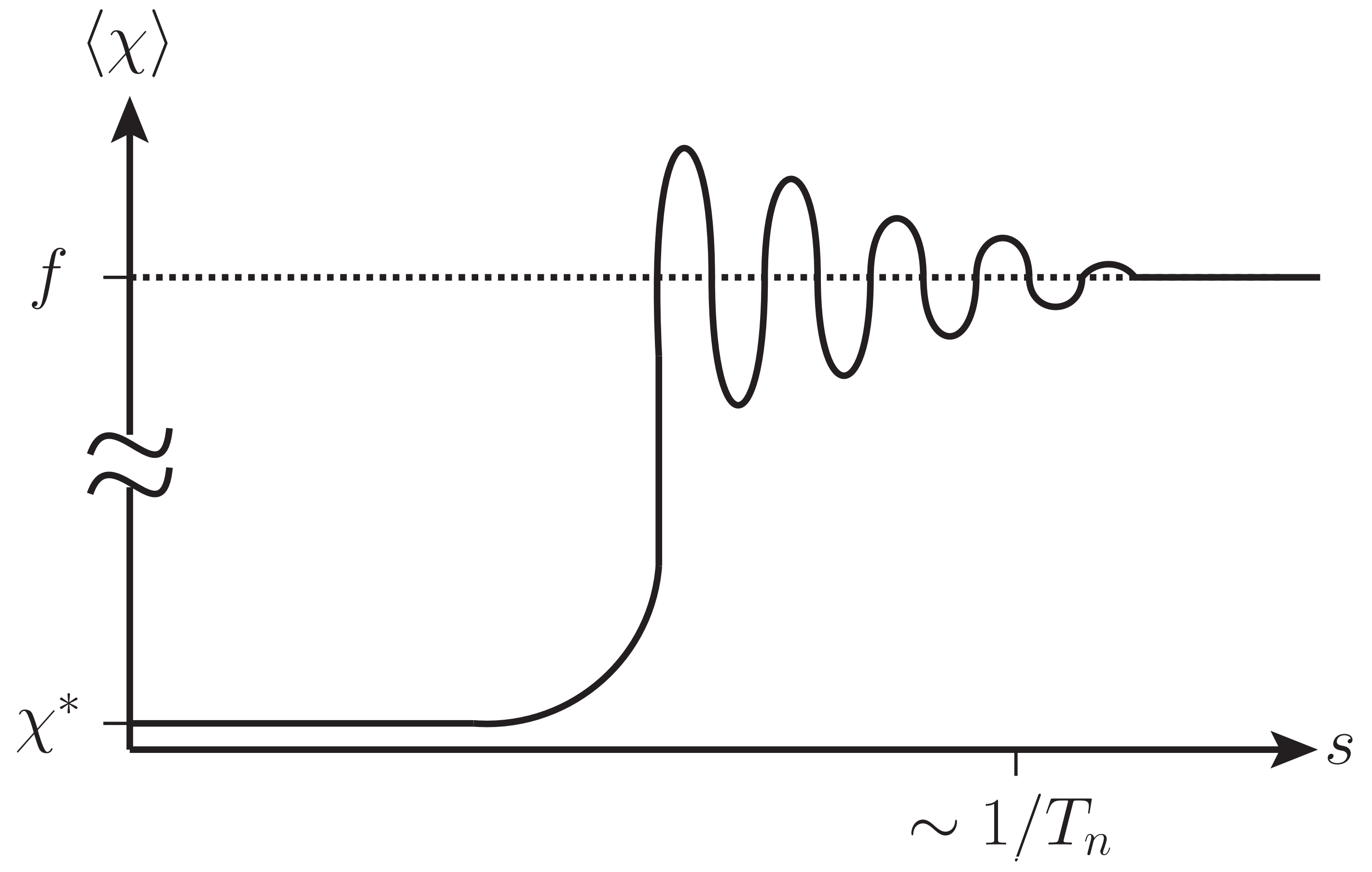

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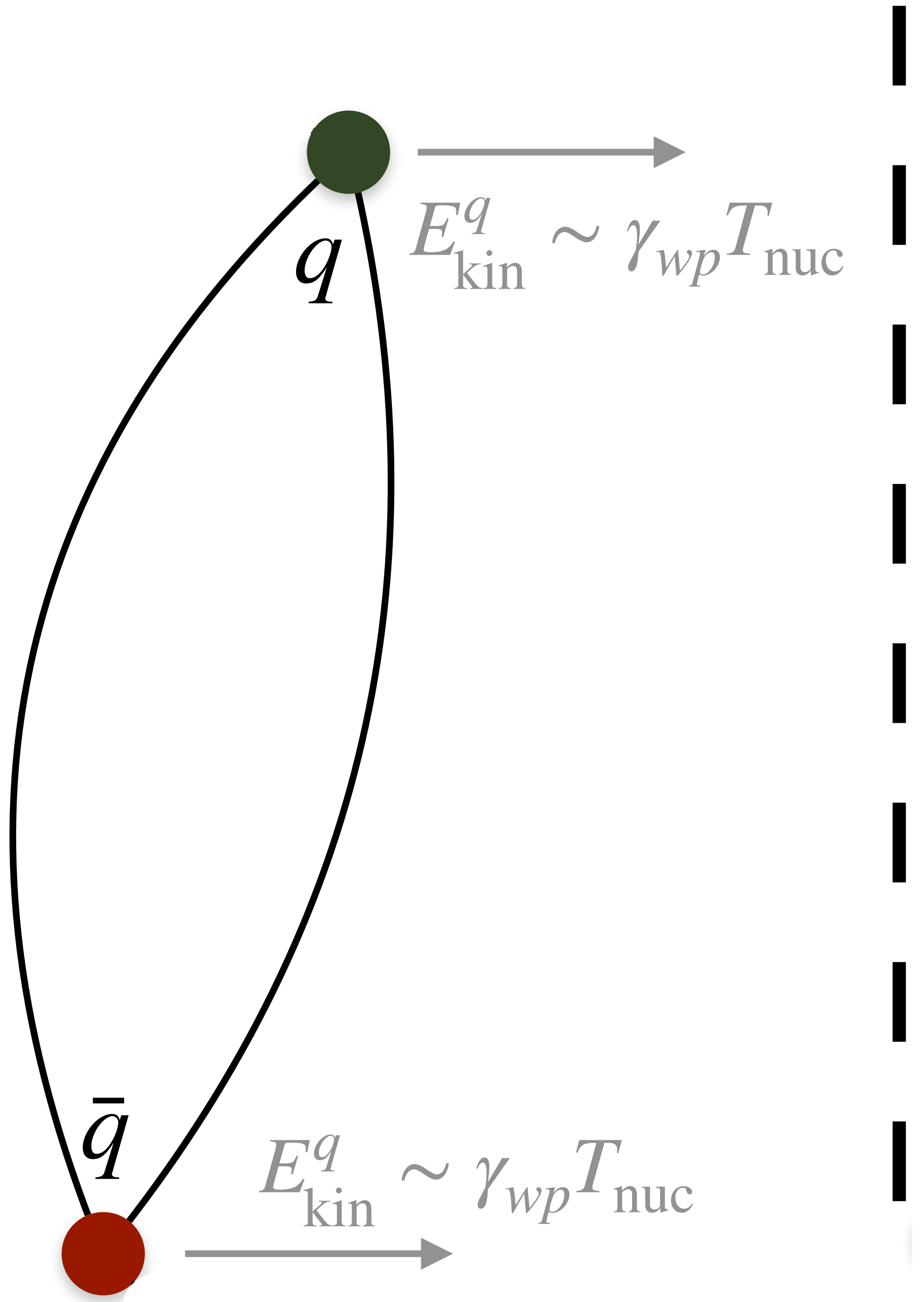

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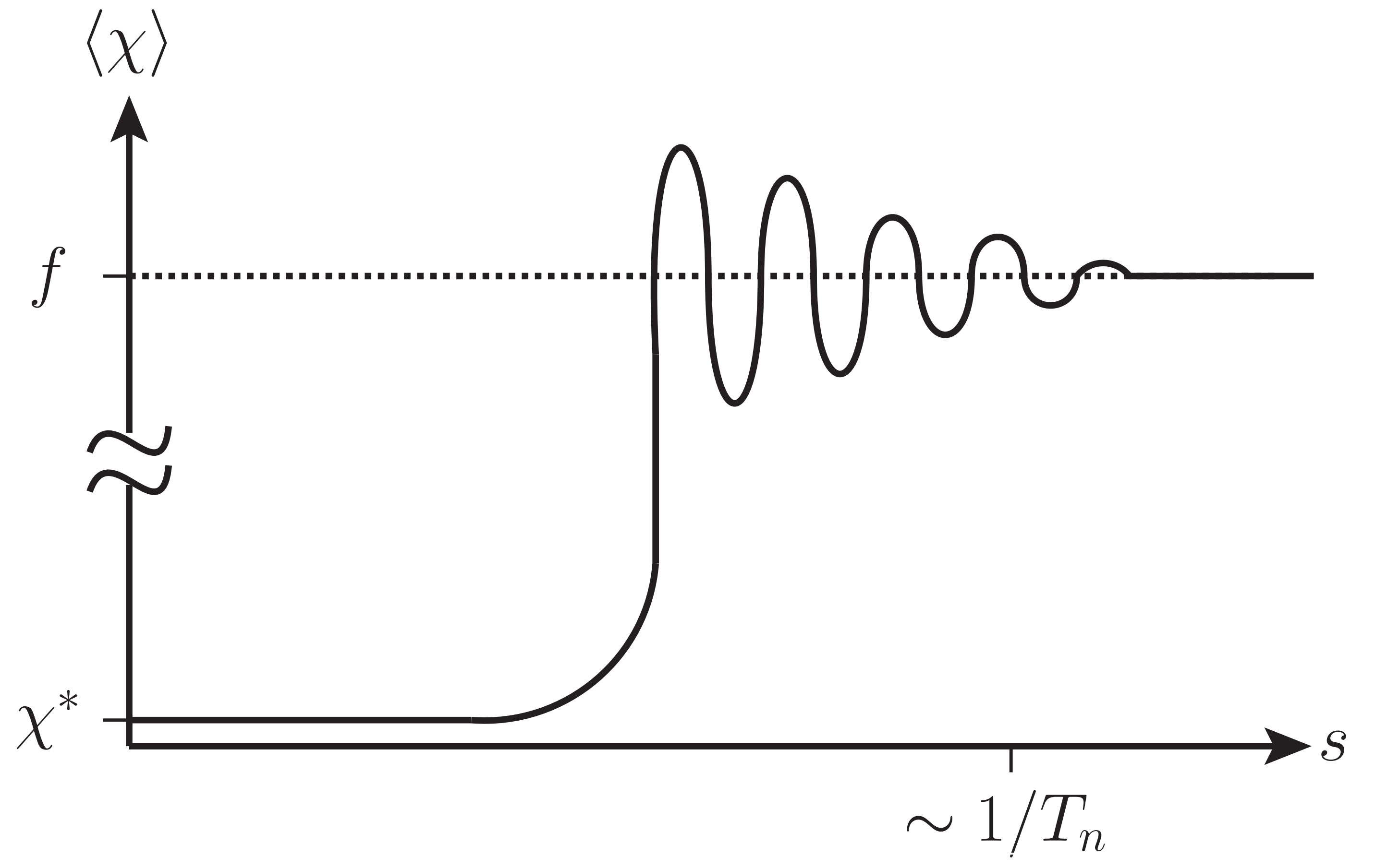

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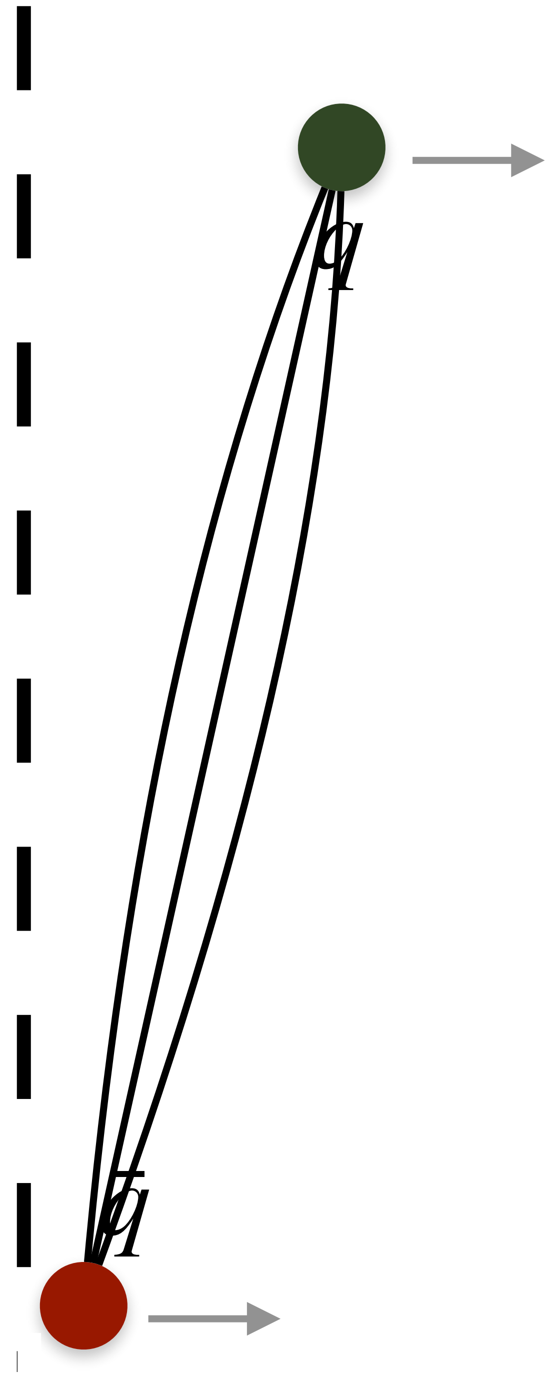
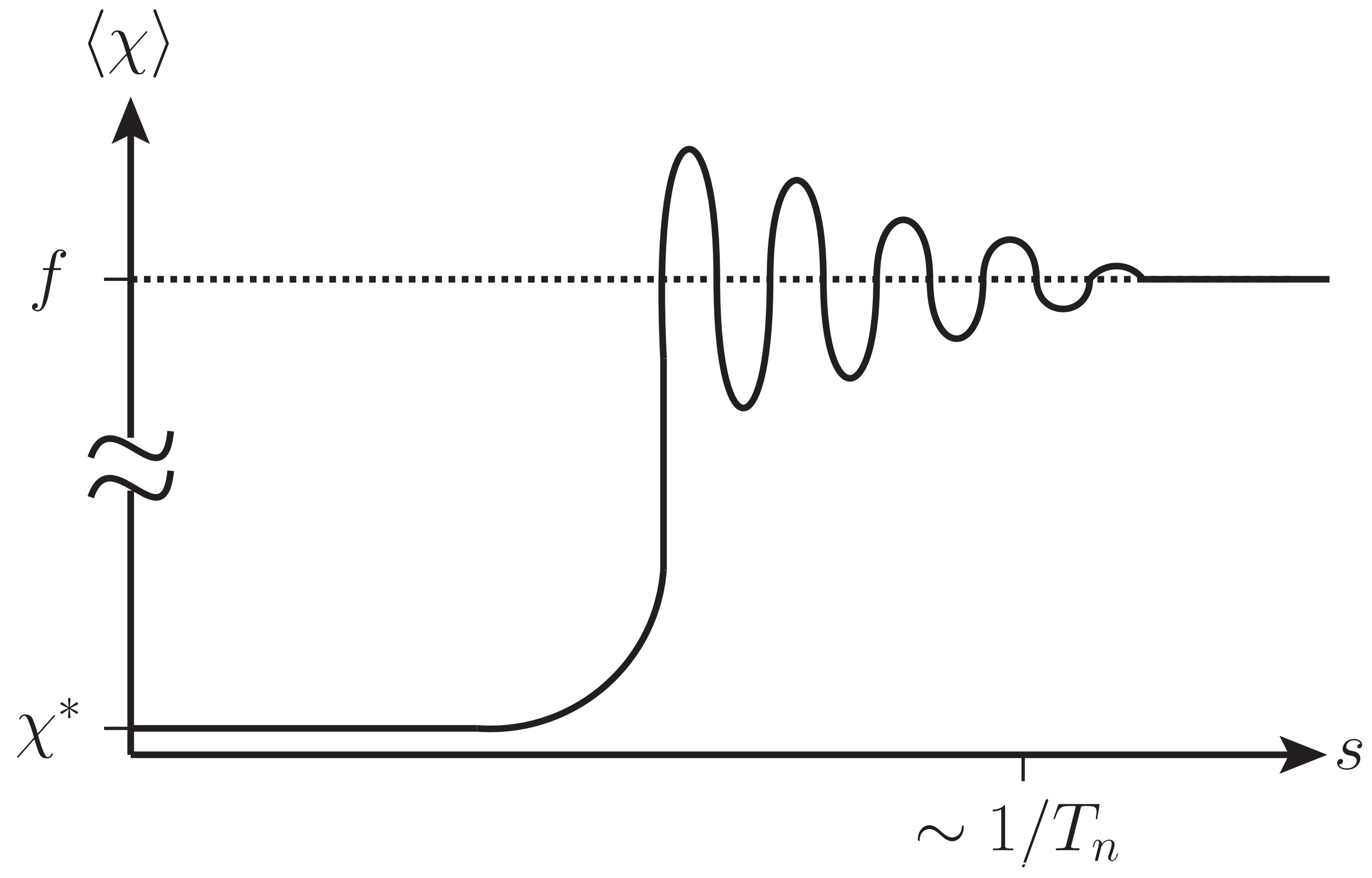


$V_{\text{string}} \simeq f^2 r$

Bubble wall frame

Hadrons formations



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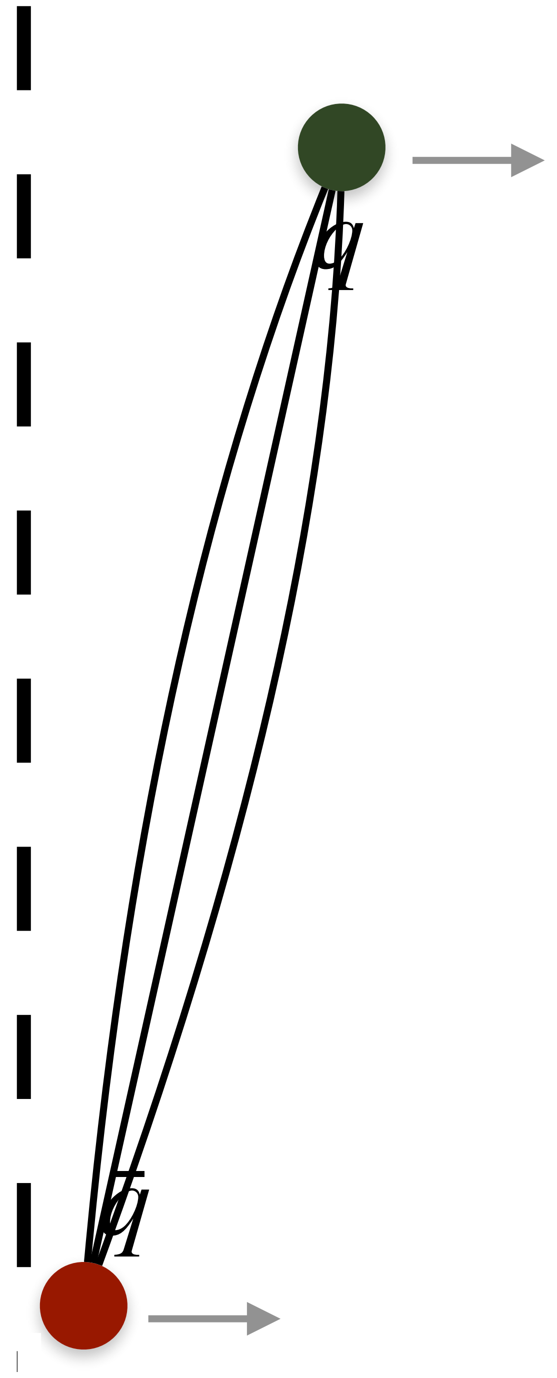
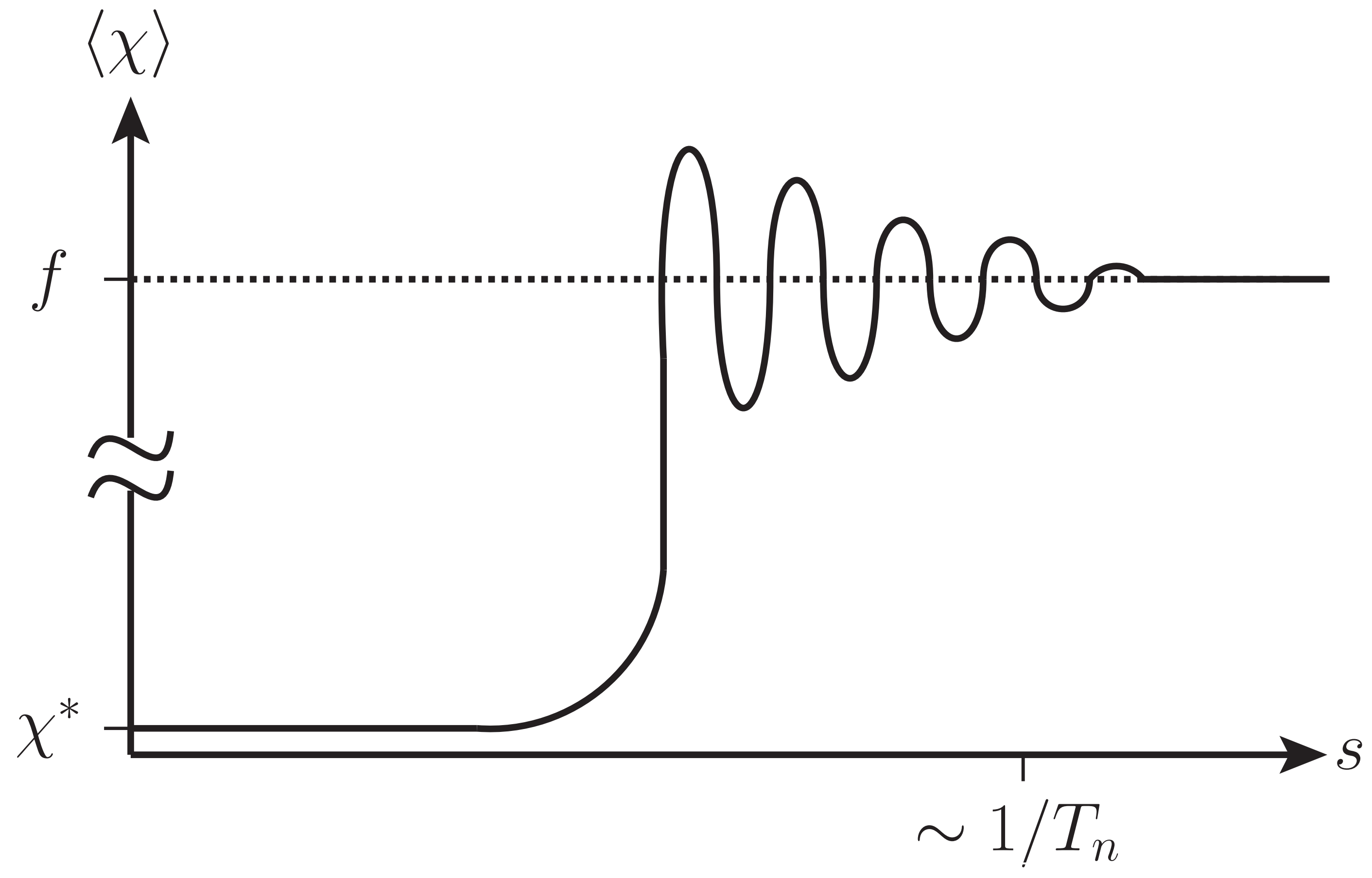


$$V_{\text{string}} \simeq f^2\, r \simeq \frac{f^2}{T_{\text{nuc}}}$$

Bubble wall frame

Hadrons formations



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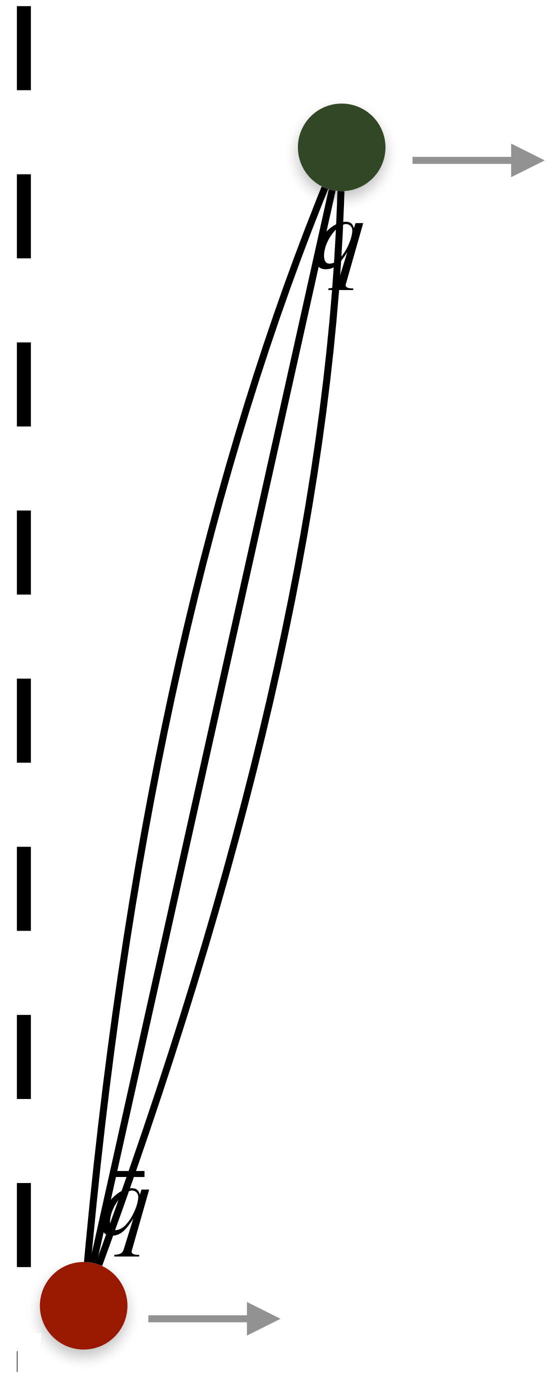


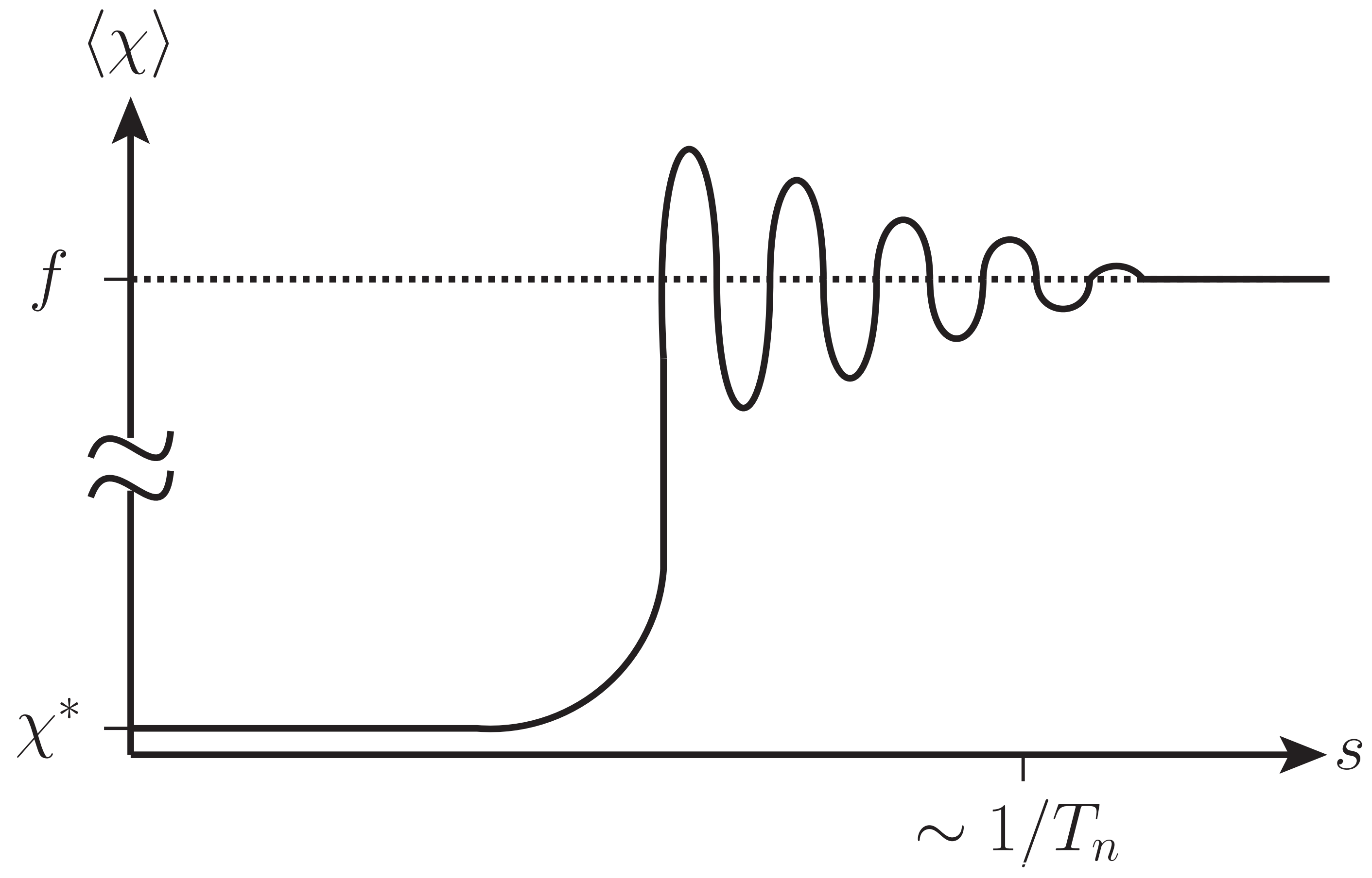
Confined phase

$$\chi = f$$

$$V_{\text{string}} \simeq f^2\, r \simeq \frac{f^2}{T_{\text{nuc}}} \gg f$$

Bubble wall frame

Hadrons formations



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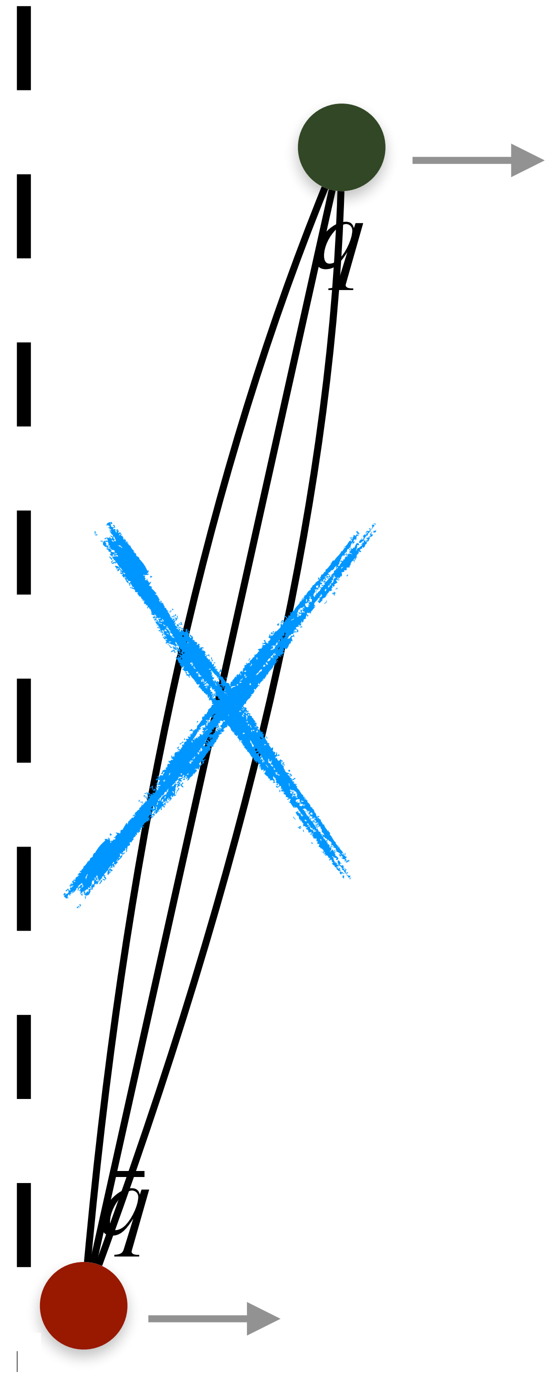
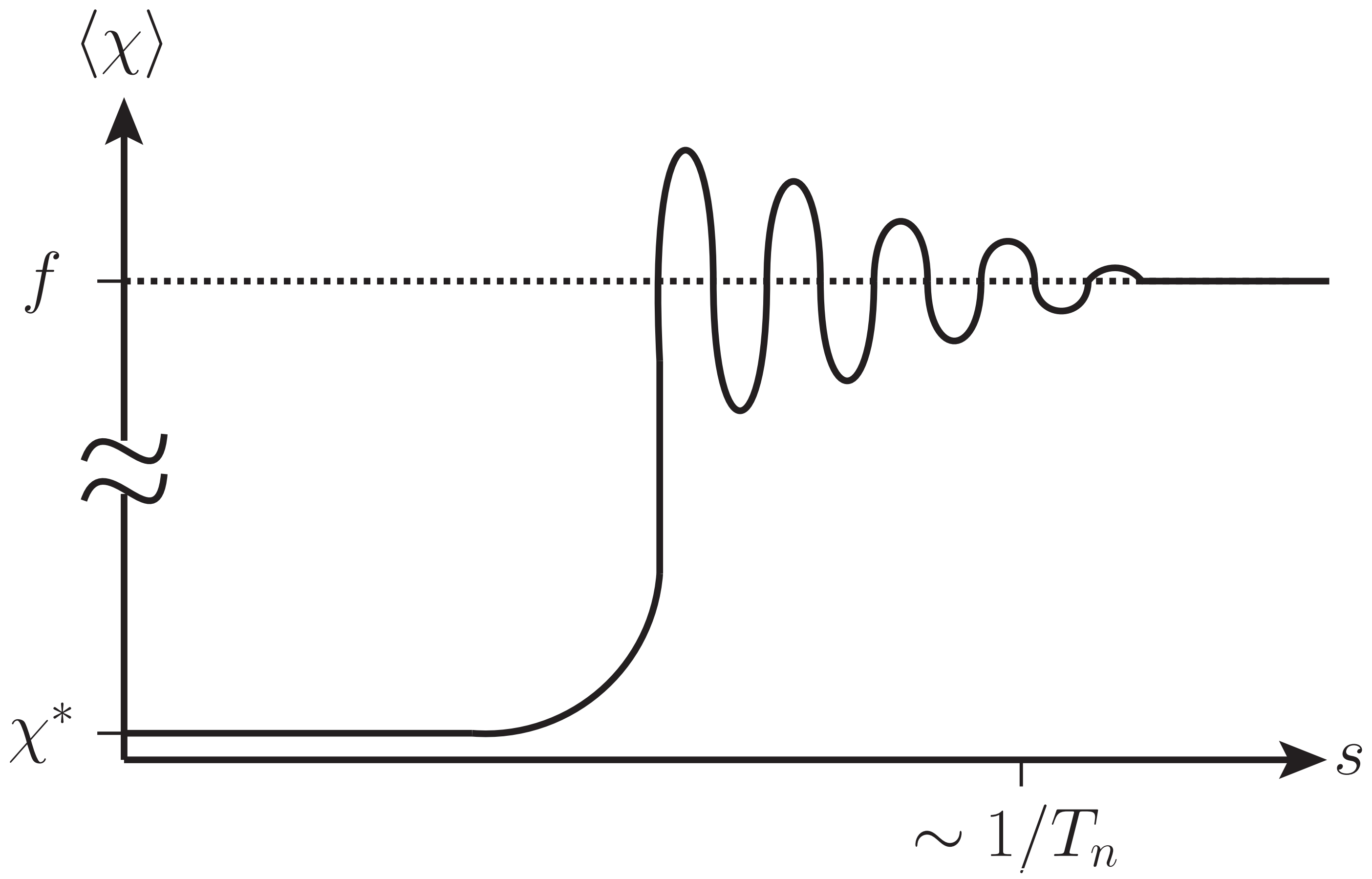


$$V_{\text{string}} \simeq f^2\, r \simeq \frac{f^2}{T_{\text{nuc}}} \gg f$$

Cost too much energy!

Bubble wall frame

Hadrons formations



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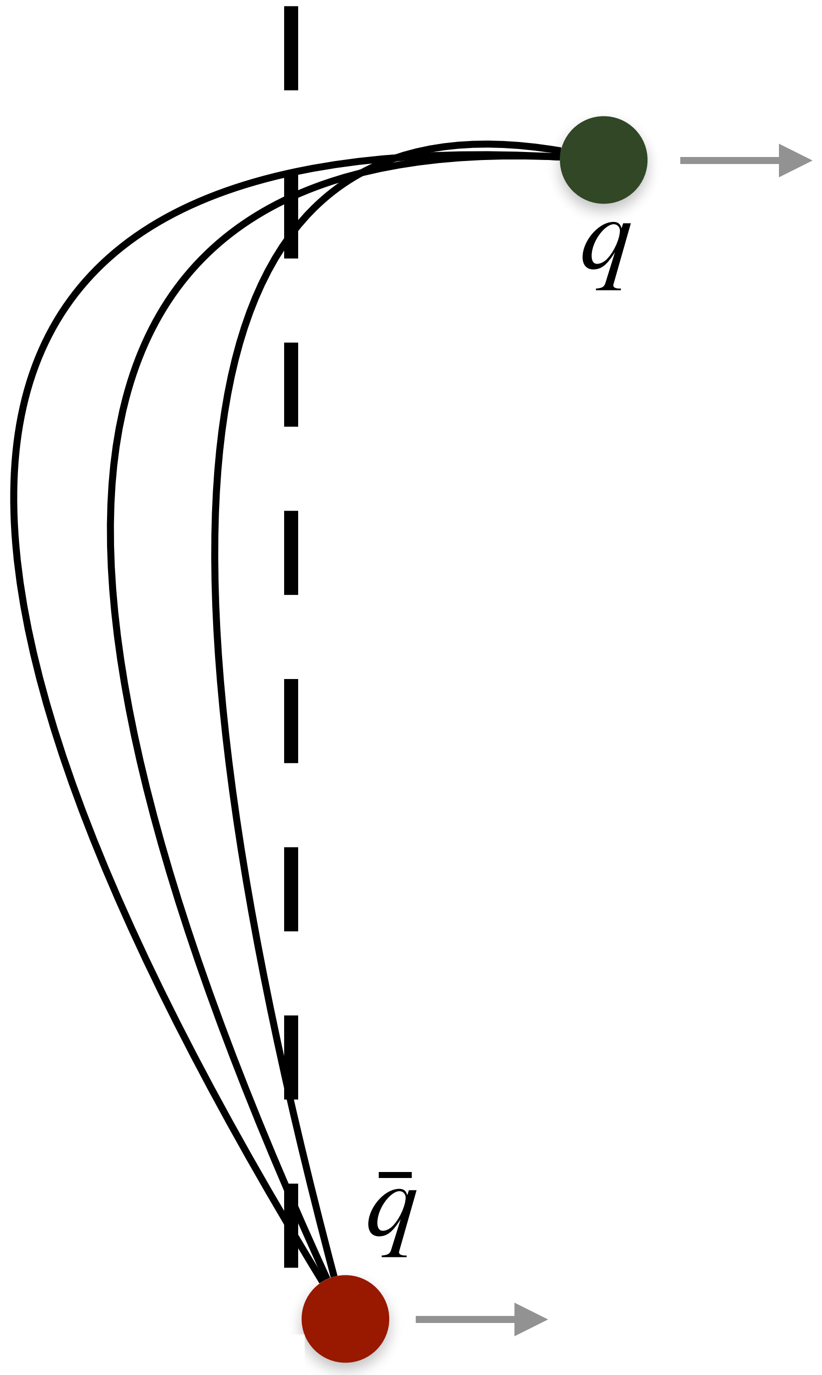
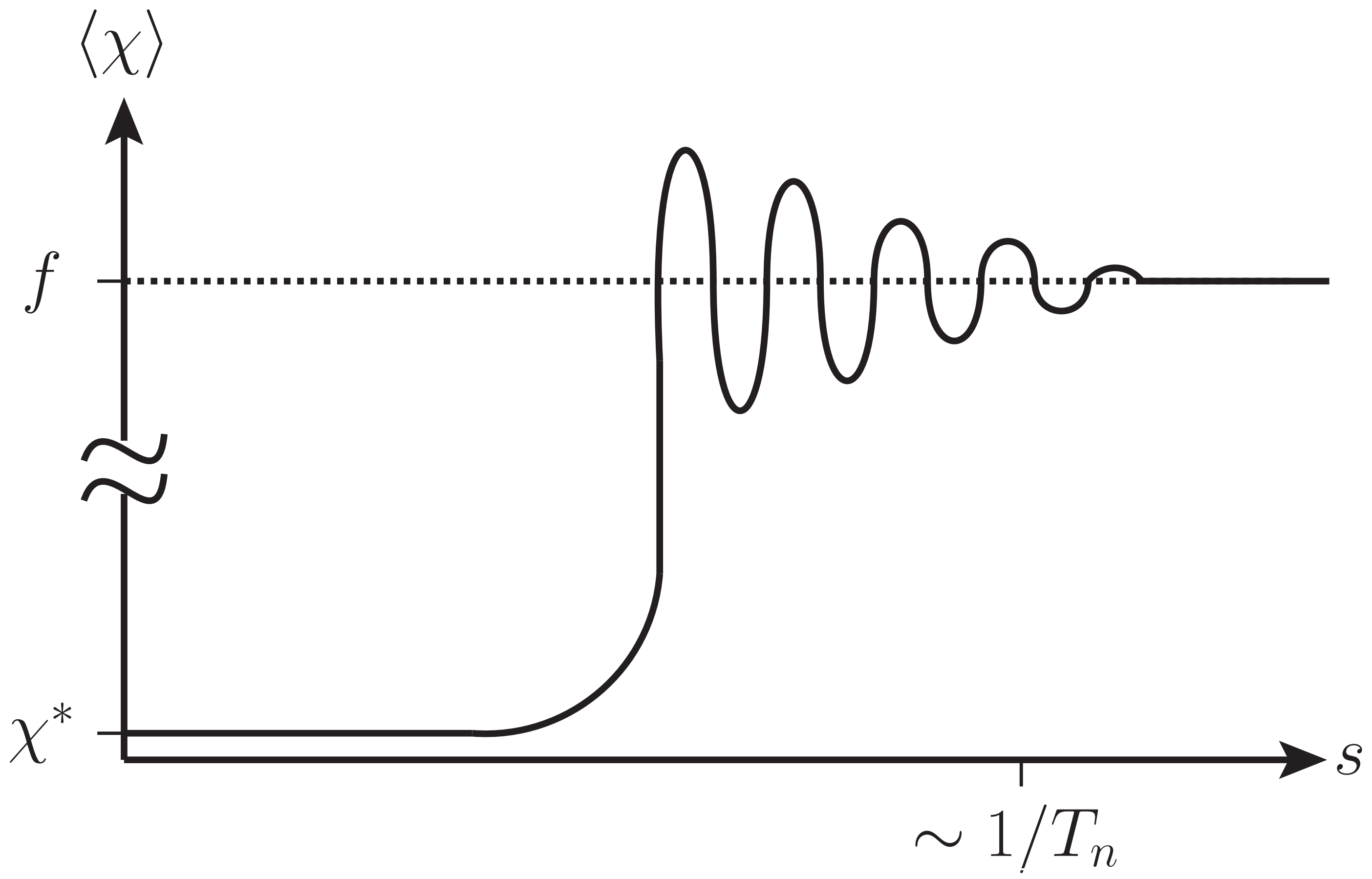


$$V_{\text{string}} \simeq f^2\, r \sim f$$

Flux tube minimises its energy !

Bubble wall frame

Hadrons formations



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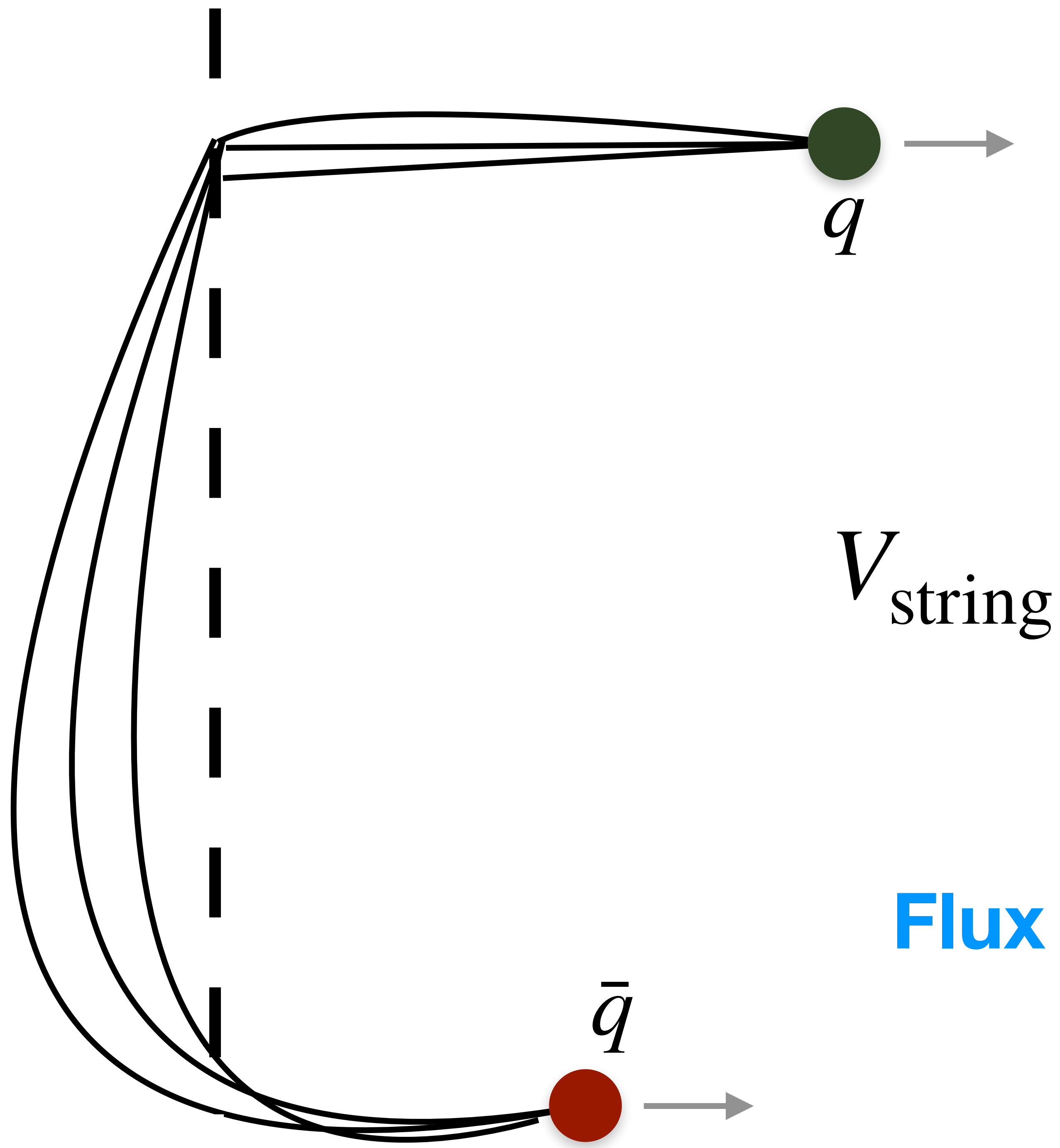

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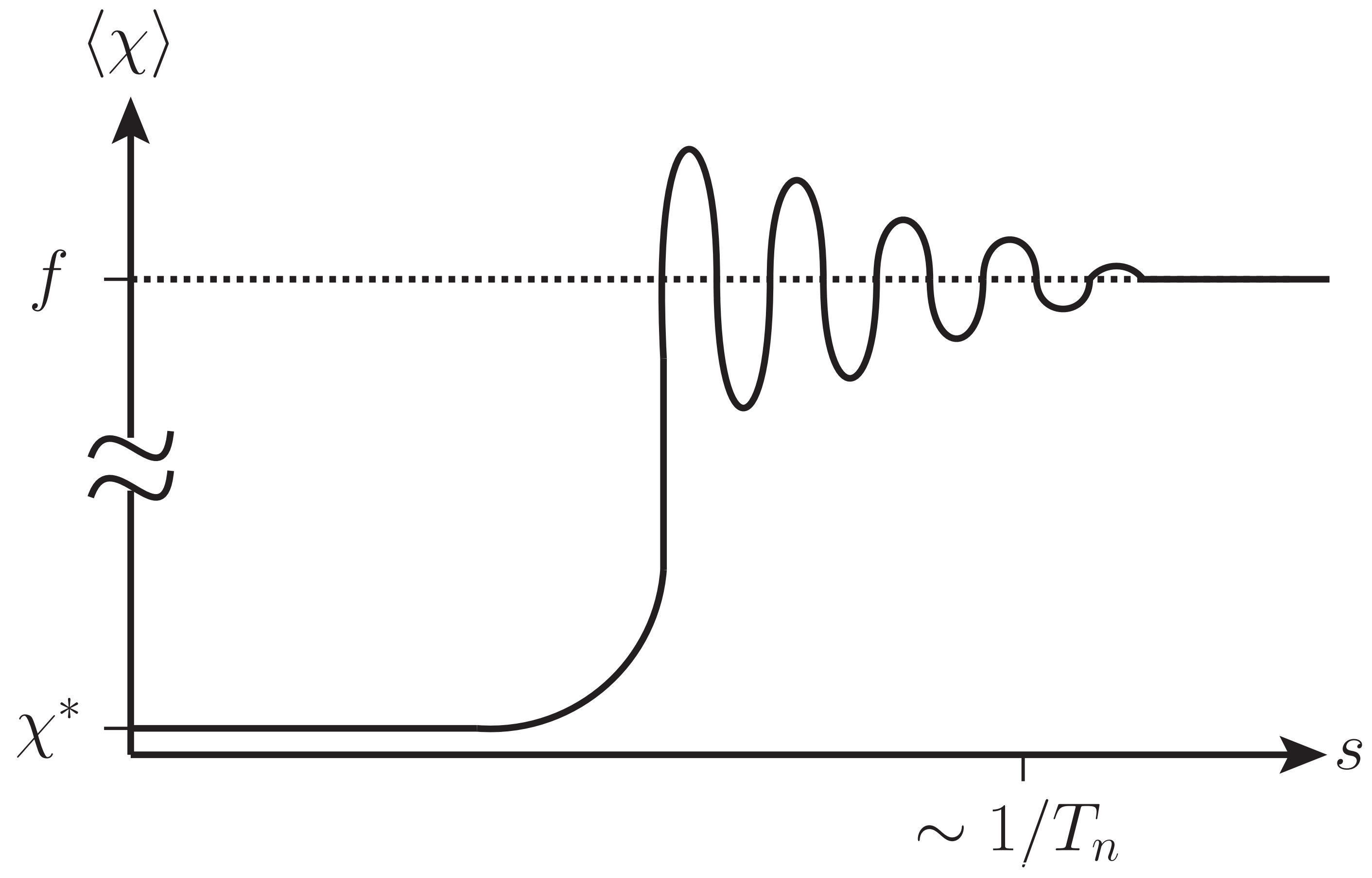

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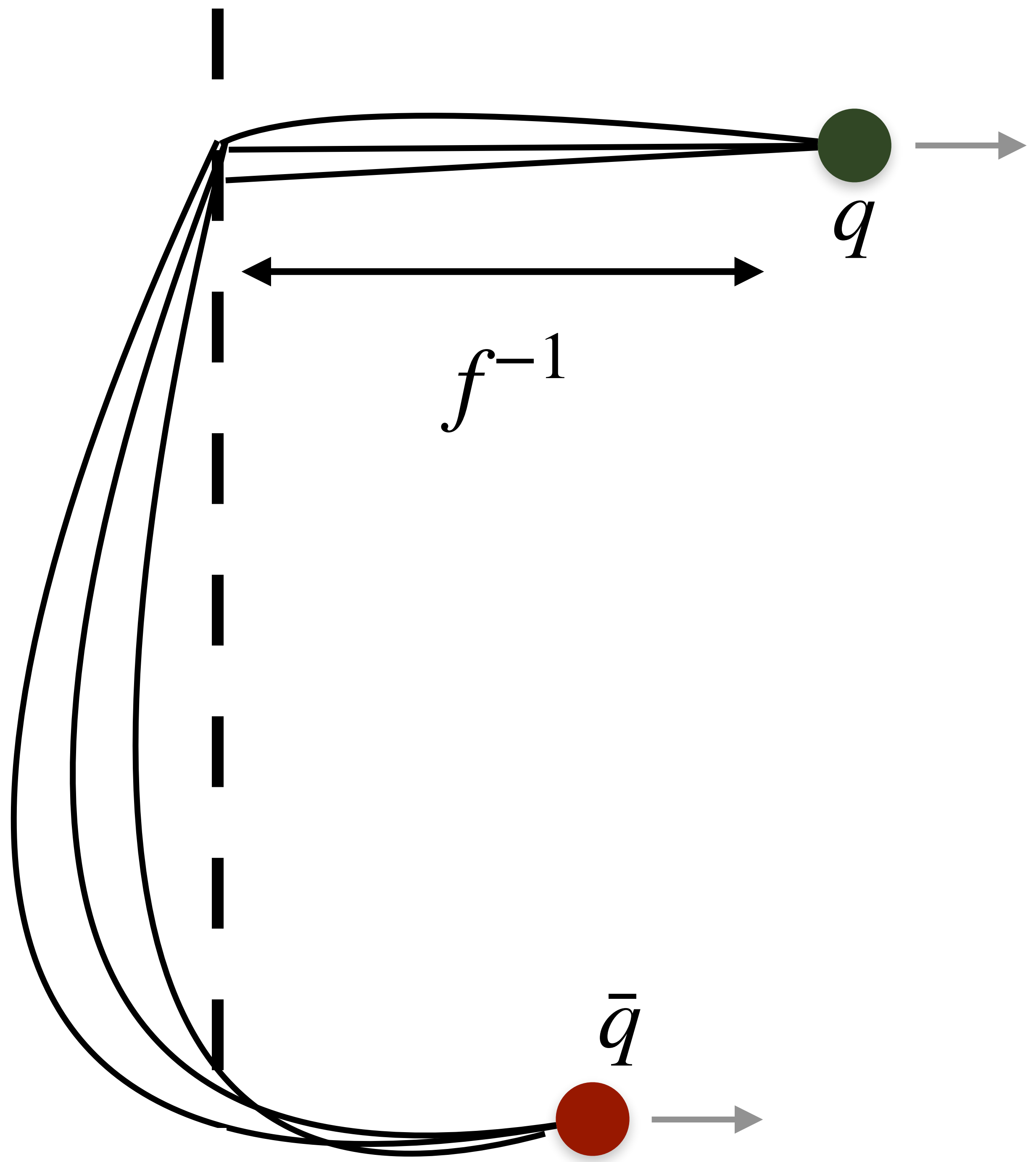

Confined phase

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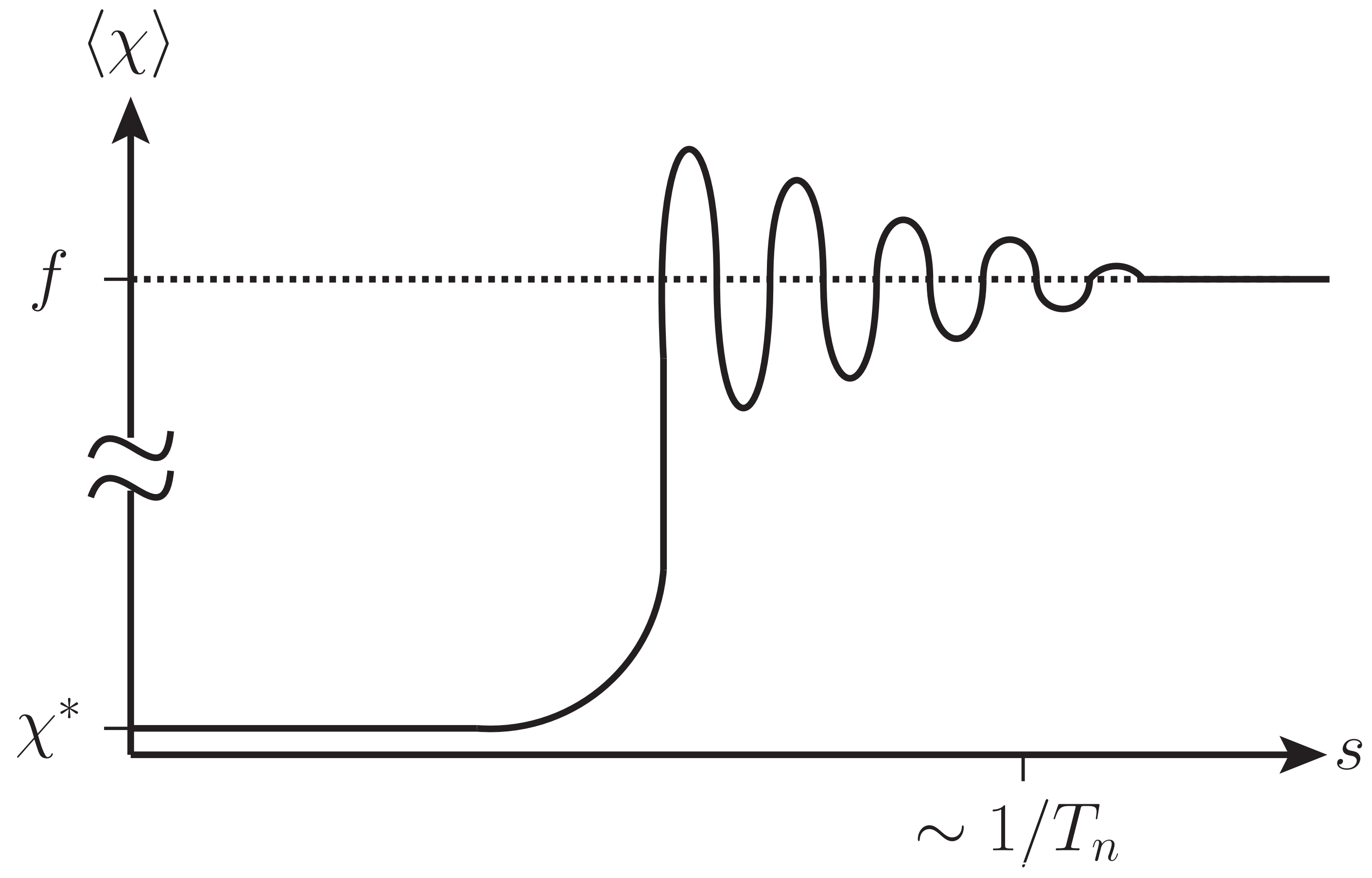
Bubble wall frame

String fragmentation



Bubble wall profile

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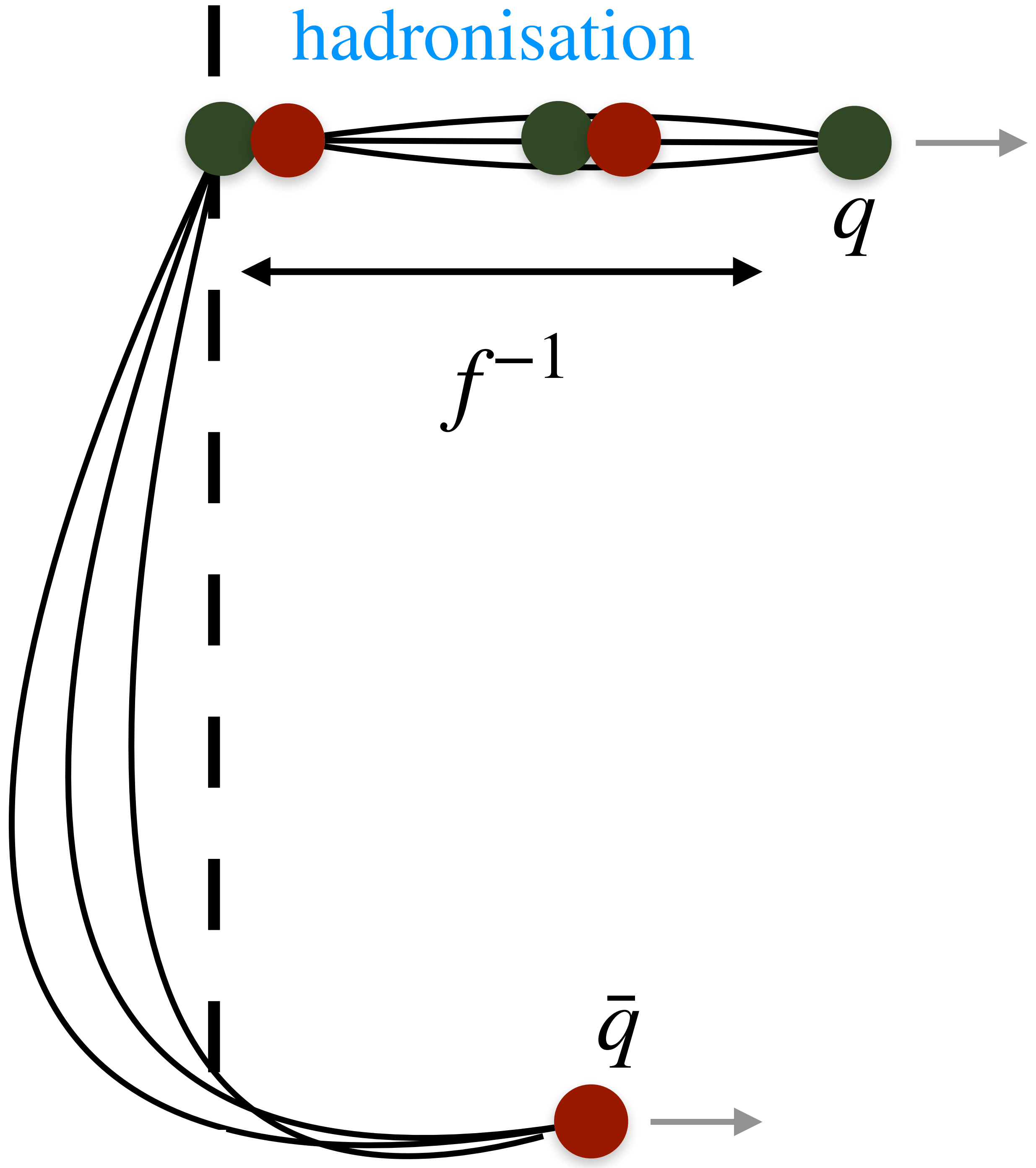

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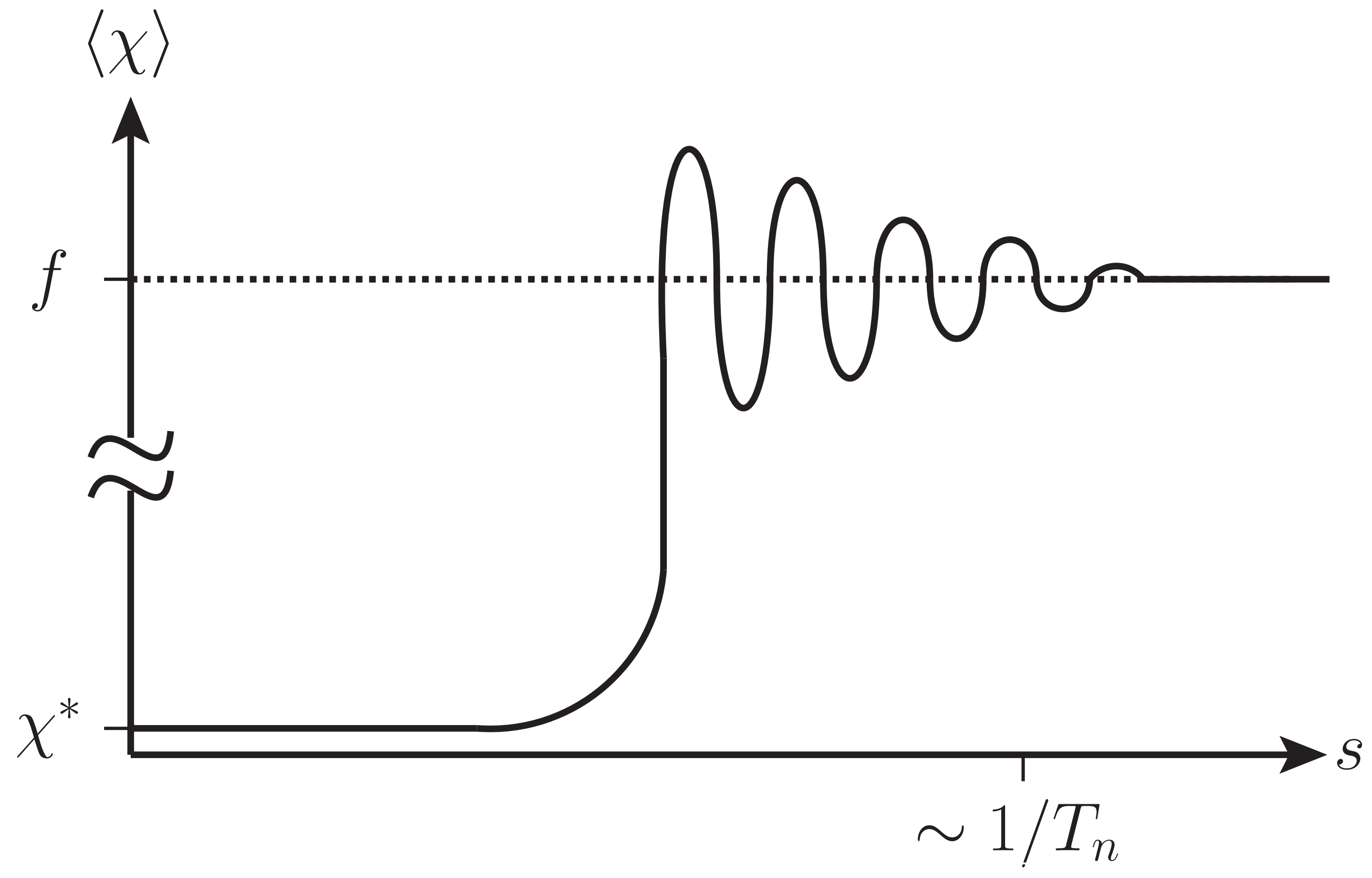

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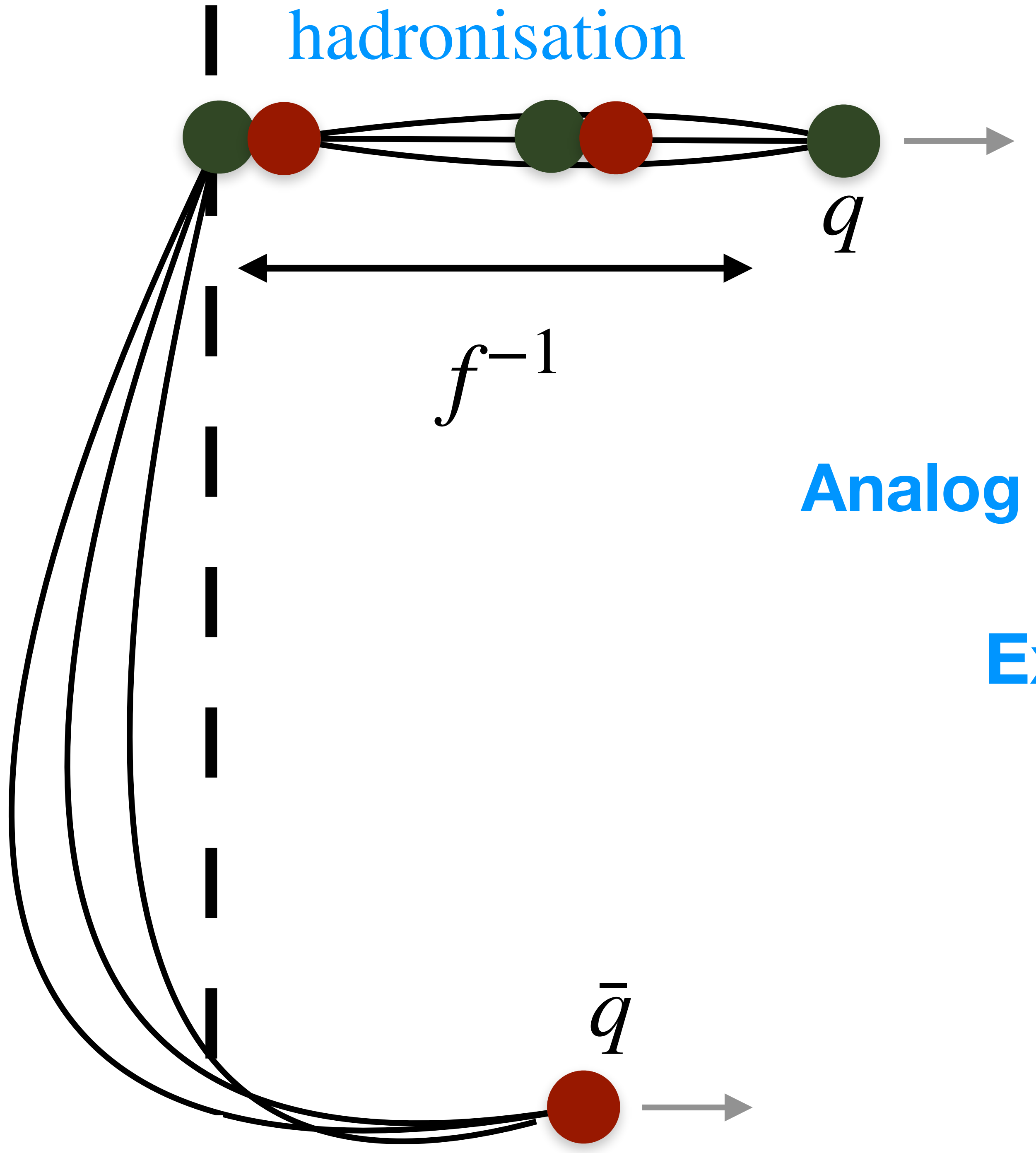


Confined phase

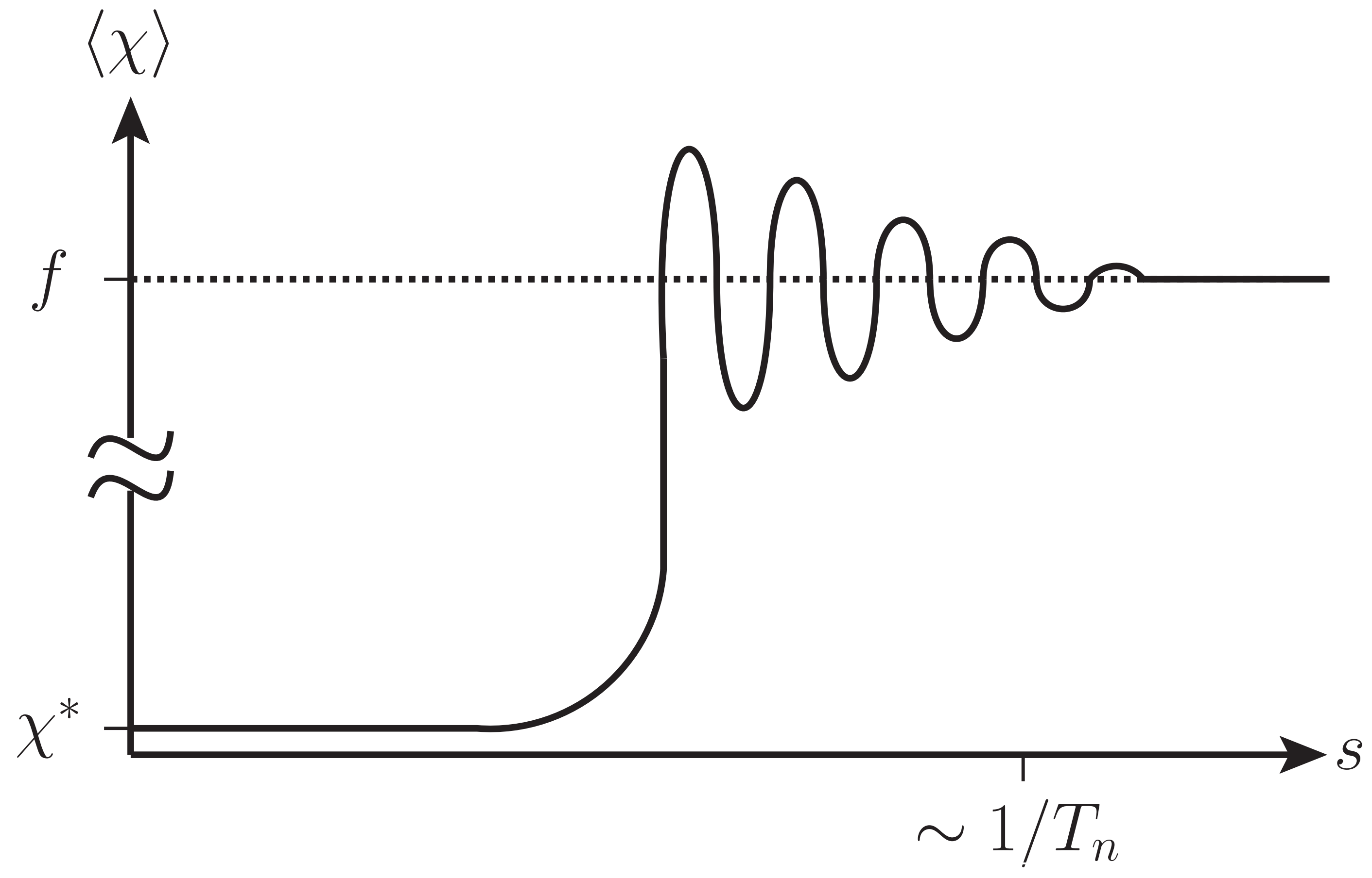
$\chi = f$

Analog to string fragmentation in QCD !

Example: $e^+e^- \to q\bar{q}$

Bubble wall frame

String fragmentation



Bubble wall profile

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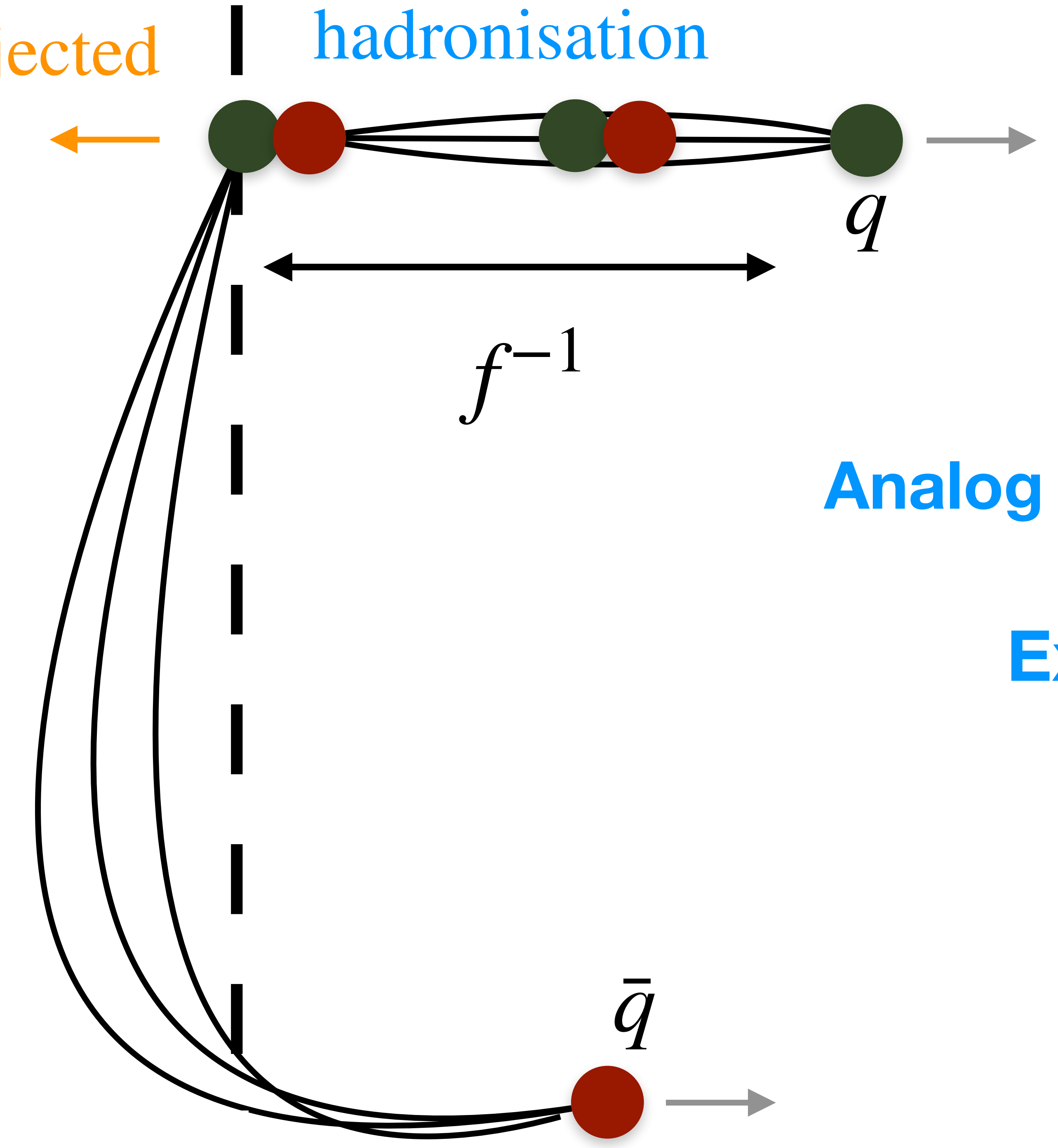


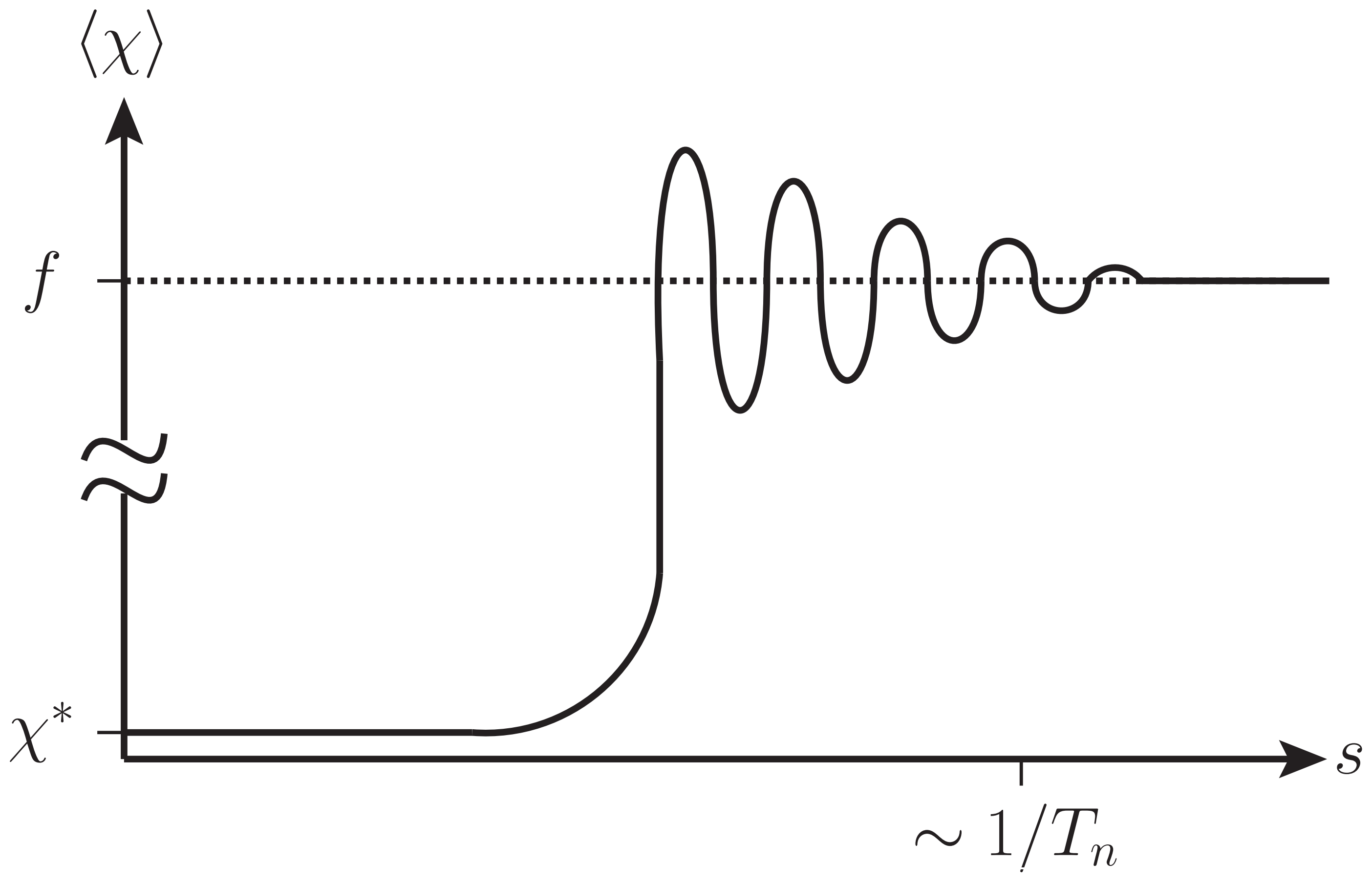
Due to color conservation

Analog to string fragmentation in QCD !

Example: $e^+e^- \to q\bar{q}$

Bubble wall frame

String fragmentation



Bubble wall profile

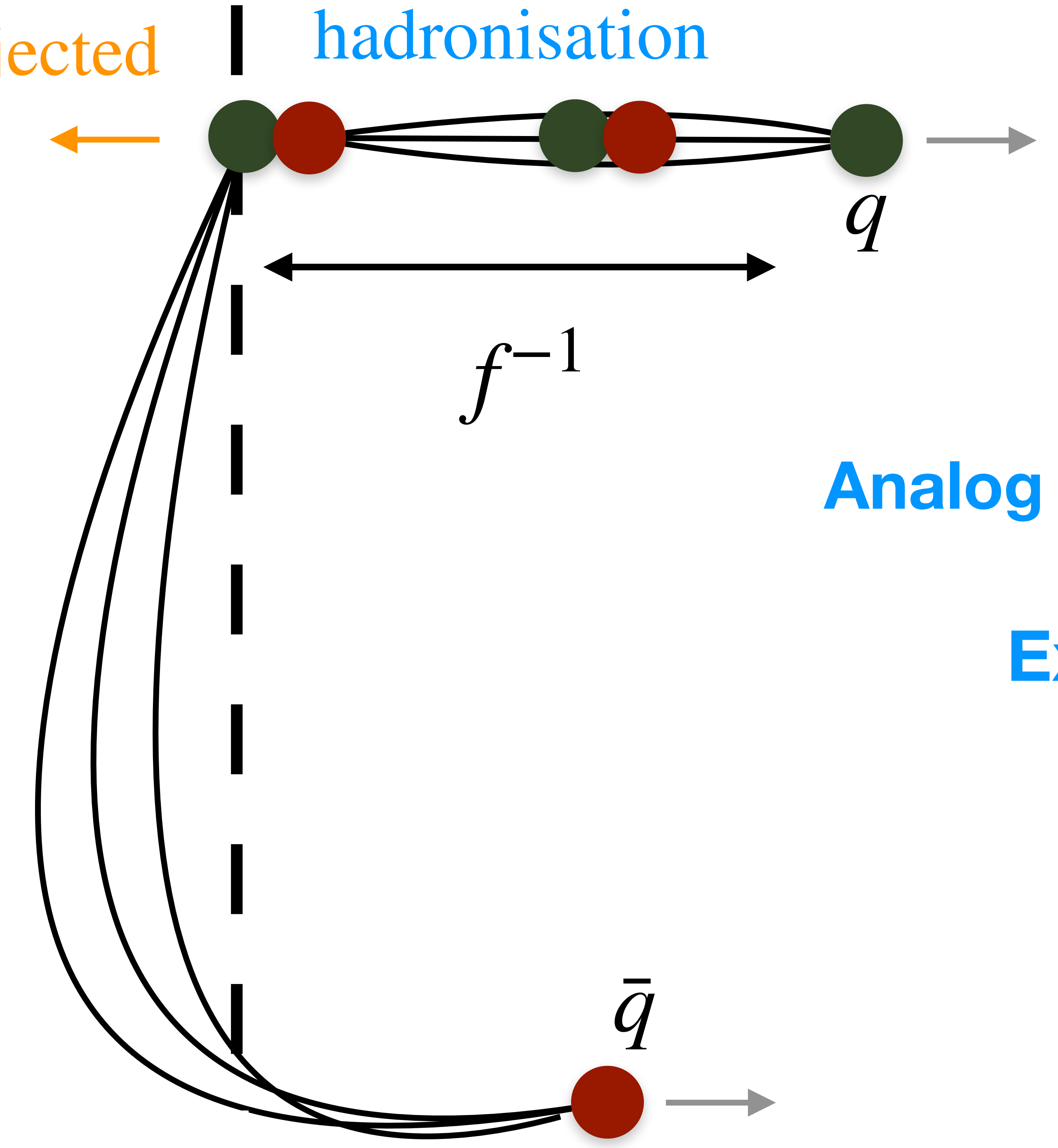
Deconfined phase

$$\chi = 0$$

Confined phase

$$\chi = f$$

quark ejected



Due to color conservation

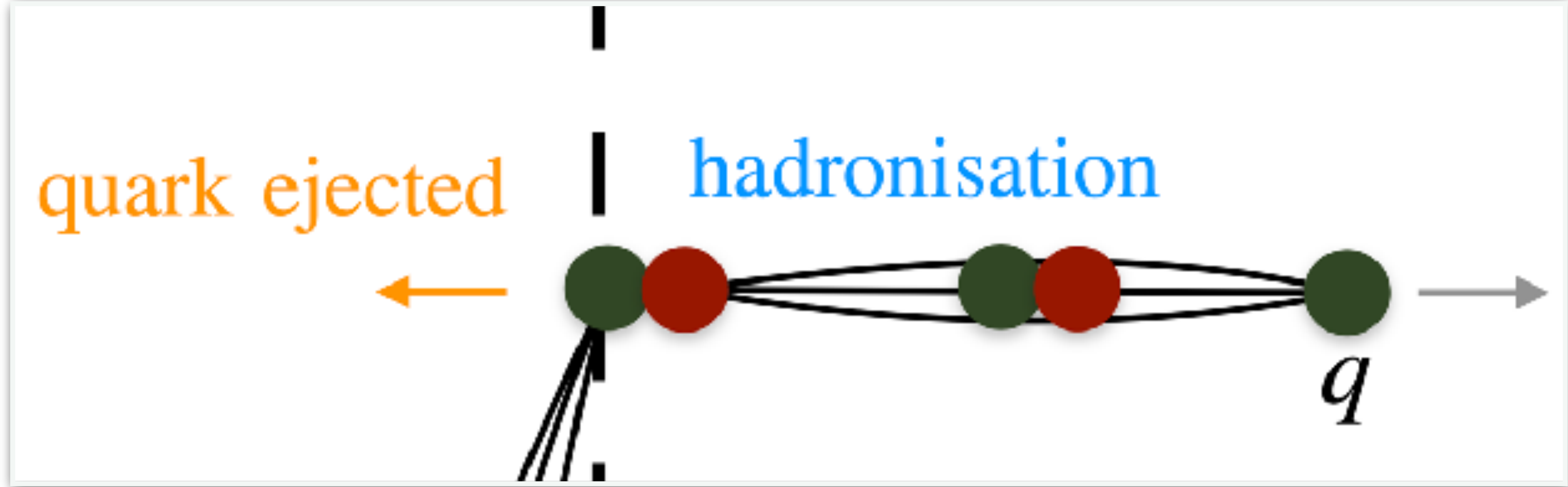
Analog to Hawking evaporation !

Analog to string fragmentation in QCD !

Example: $e^+e^- \to q\bar{q}$

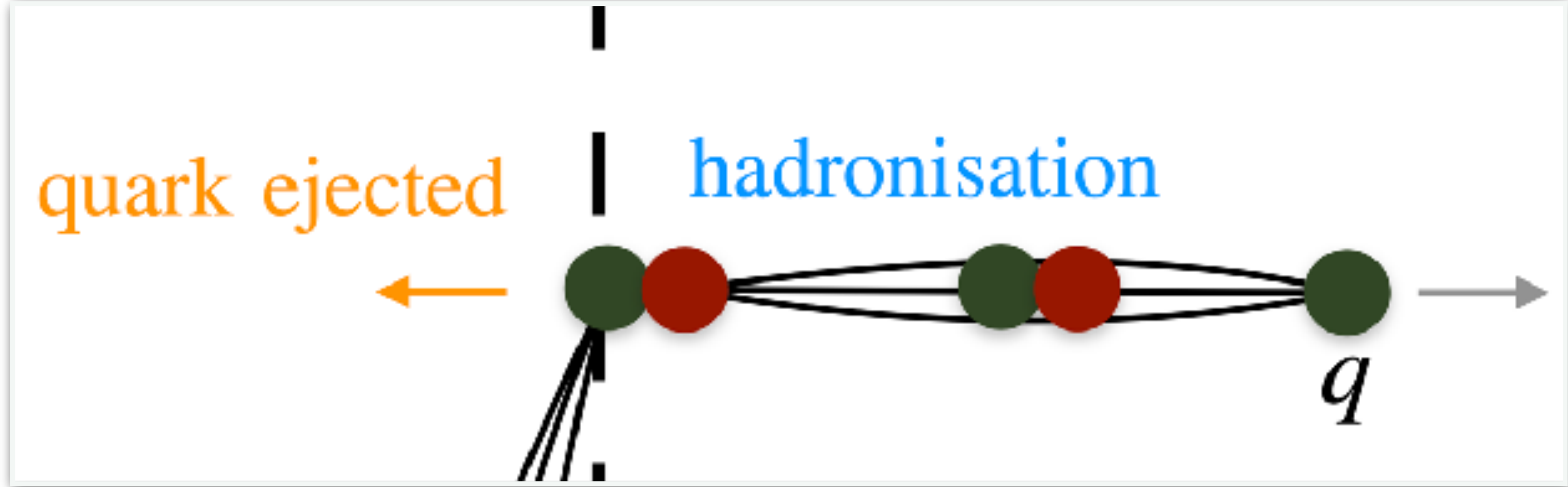
Bubble wall frame

Impact on DM



1. More hadrons per initial quark pair

Impact on DM



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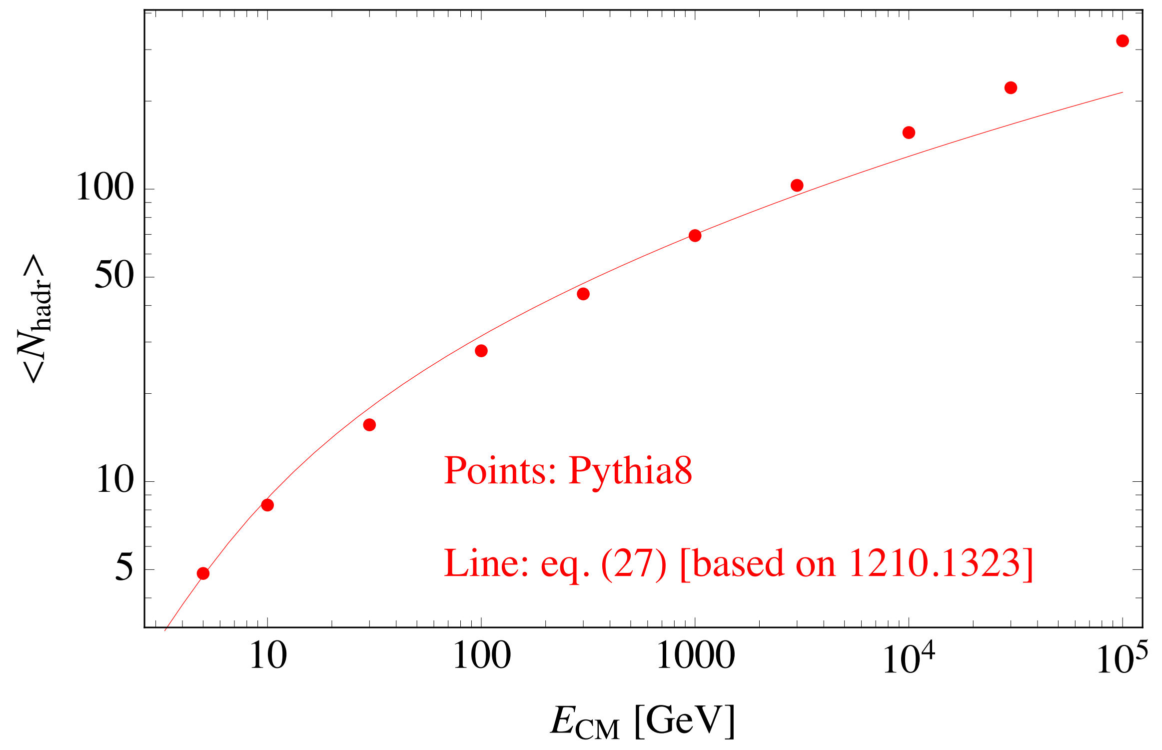
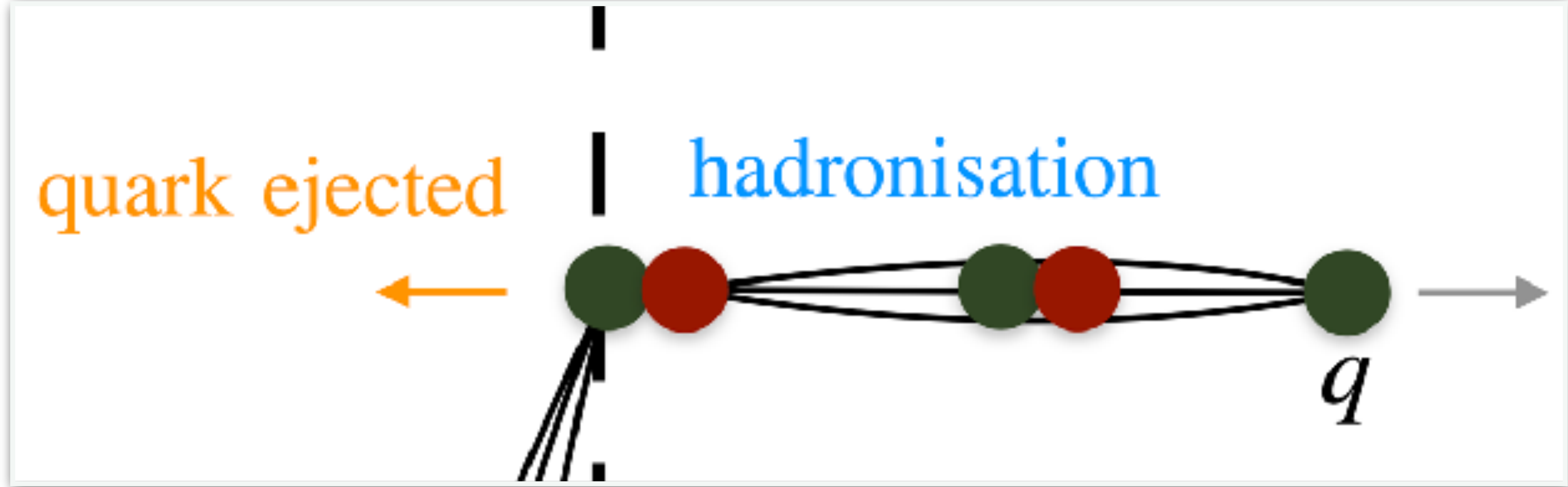


$$Y_{\text{DM}} / Y_{\text{DM}}^{\text{naive}} \propto \log^n\left(\gamma T_{\text{nuc}}/f\right)$$

$$Y_{\text{DM}}^{\text{naive}} \propto \left(\frac{T_{\text{nuc}}}{f}\right)^3$$

Impact on DM



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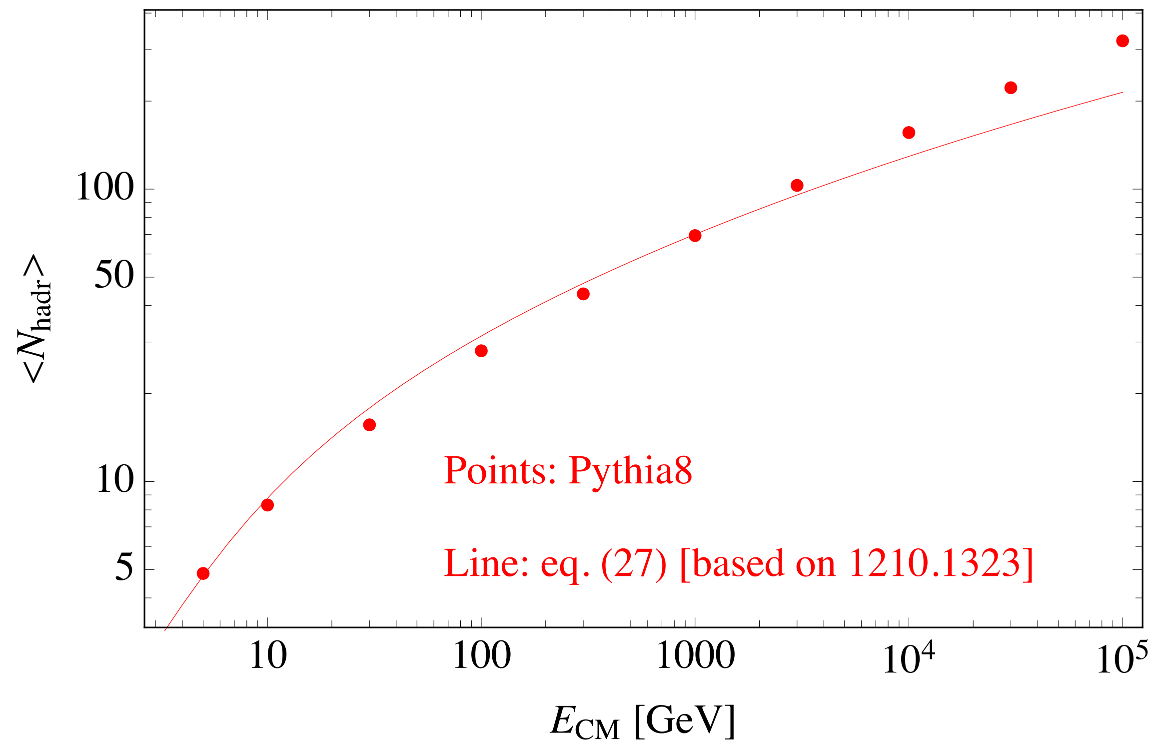

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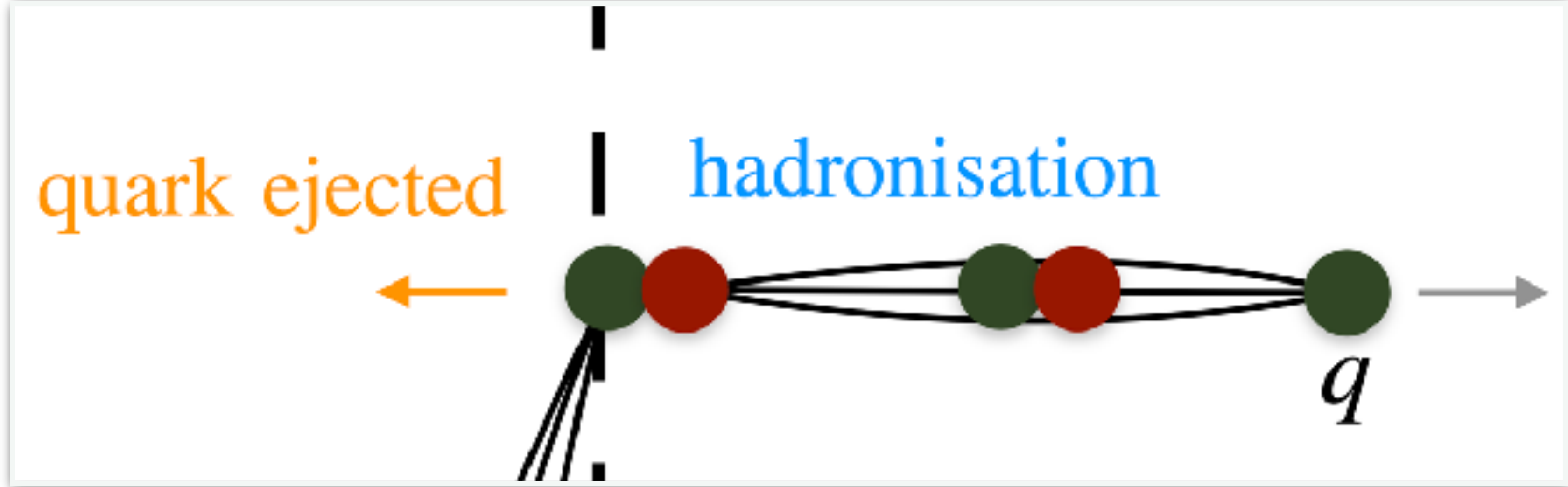
2. Cosmological catapult

Impact on DM



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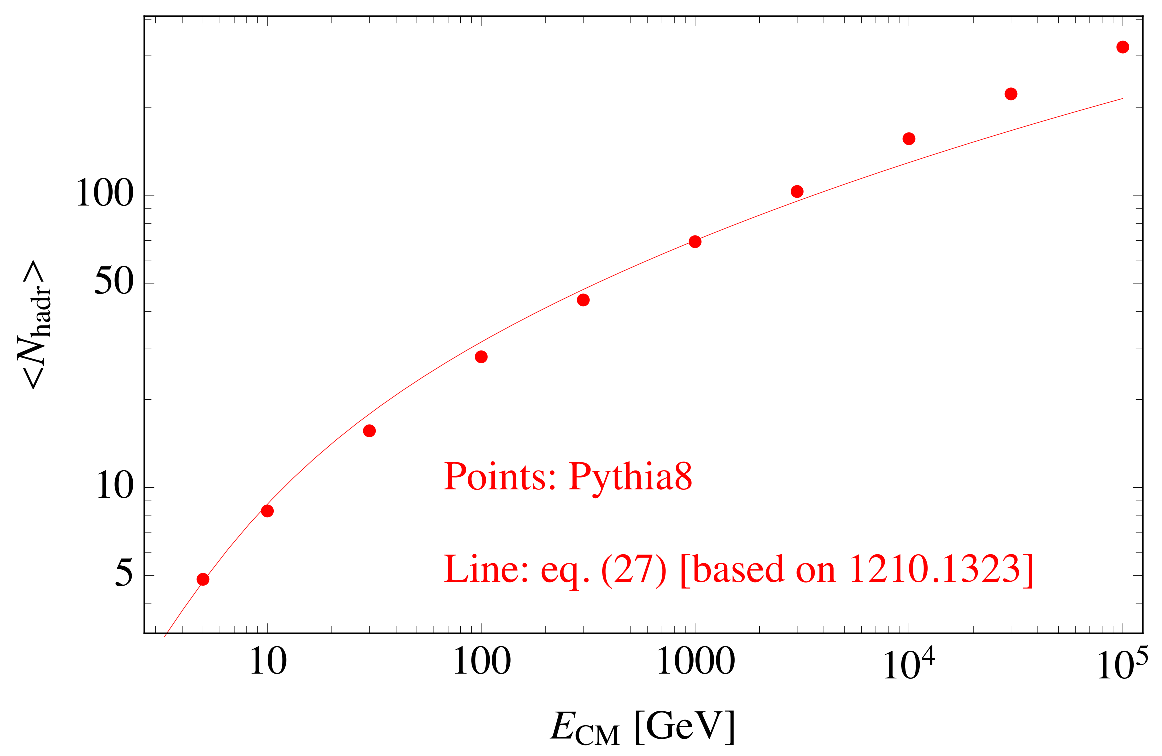

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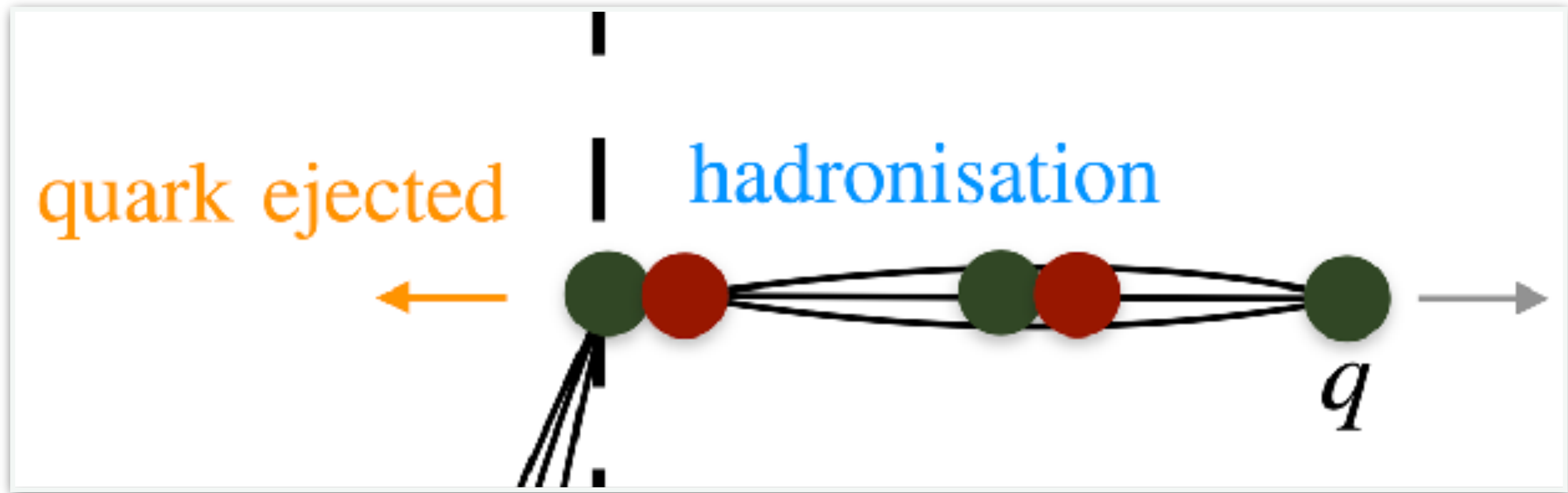
2. Cosmological catapult

$E_{hadron} \propto \gamma f \gg f$

Impact on DM



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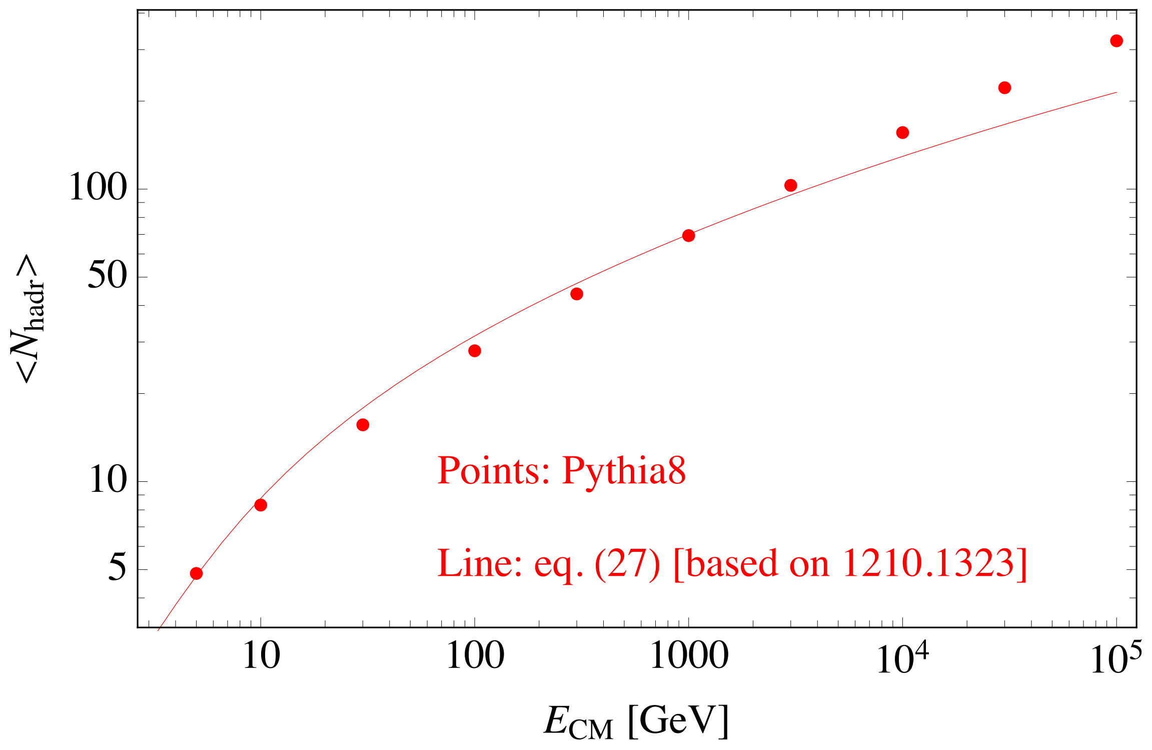

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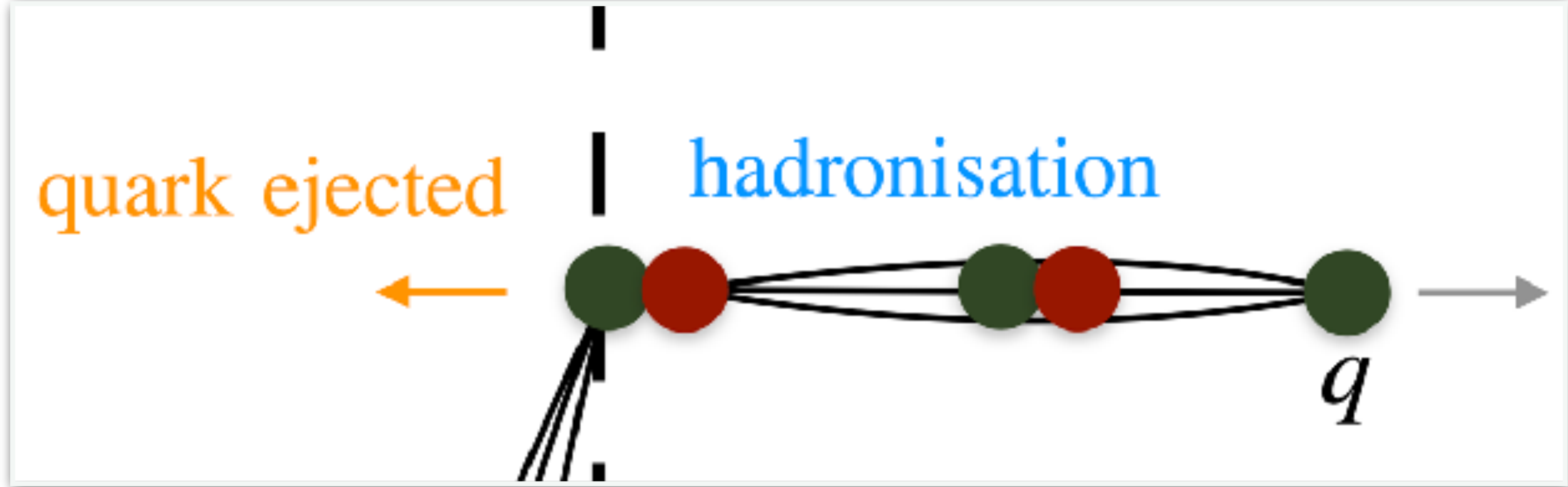
2. Cosmological catapult

$$s \sim E_{\rm hadron} E_{\rm bath} \gg 1$$

$E_{\rm hadron} \propto \gamma f \gg f$

$E_{\rm bath} \sim f$

Impact on DM



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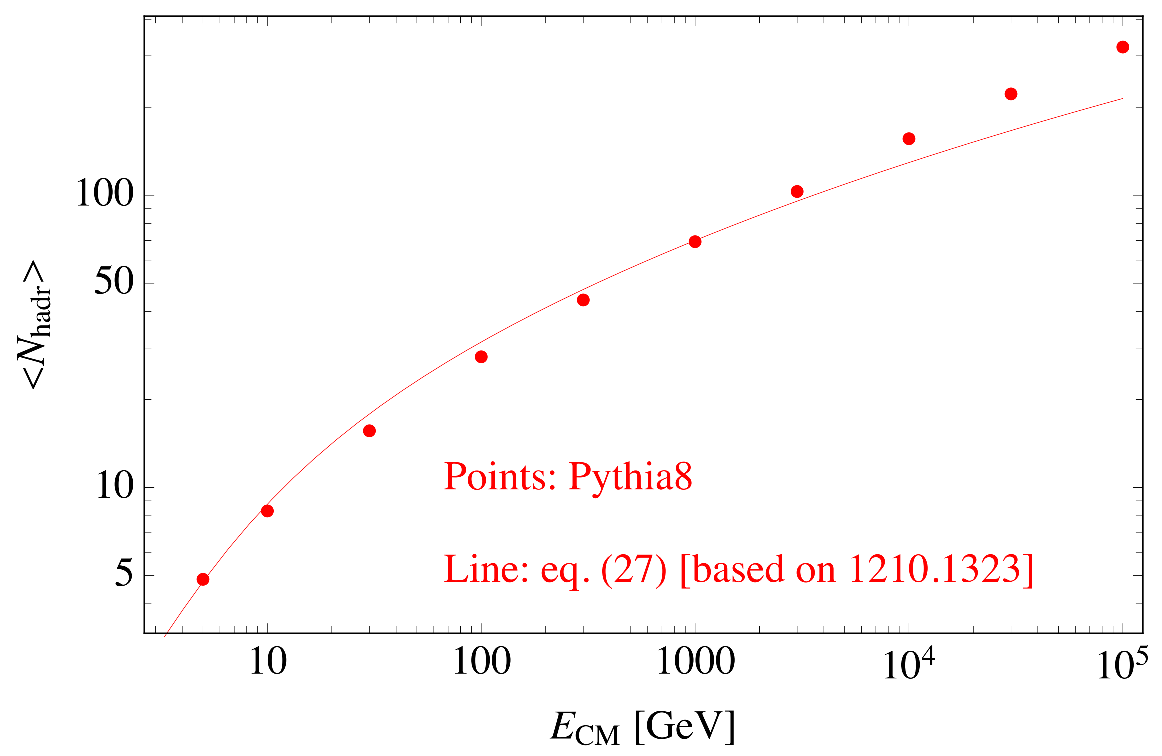

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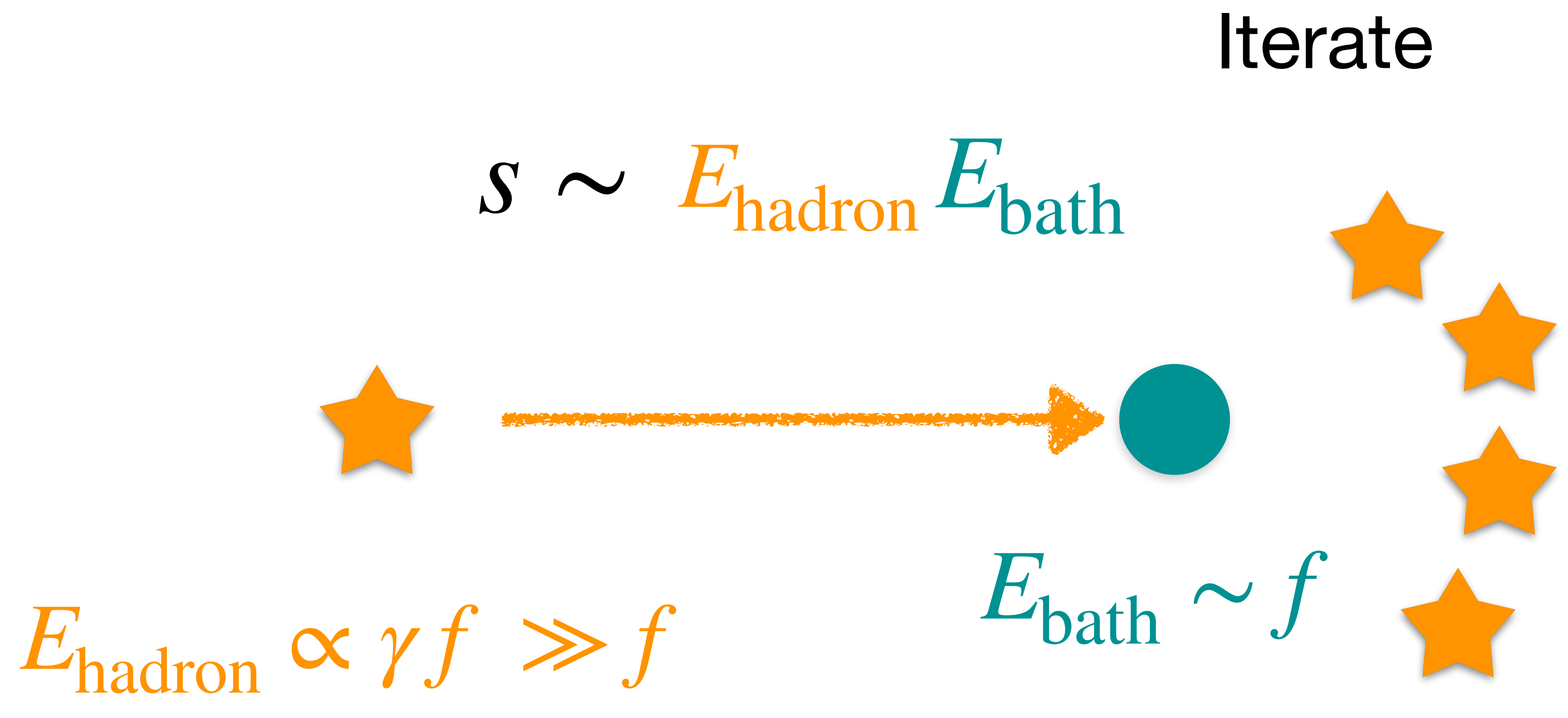

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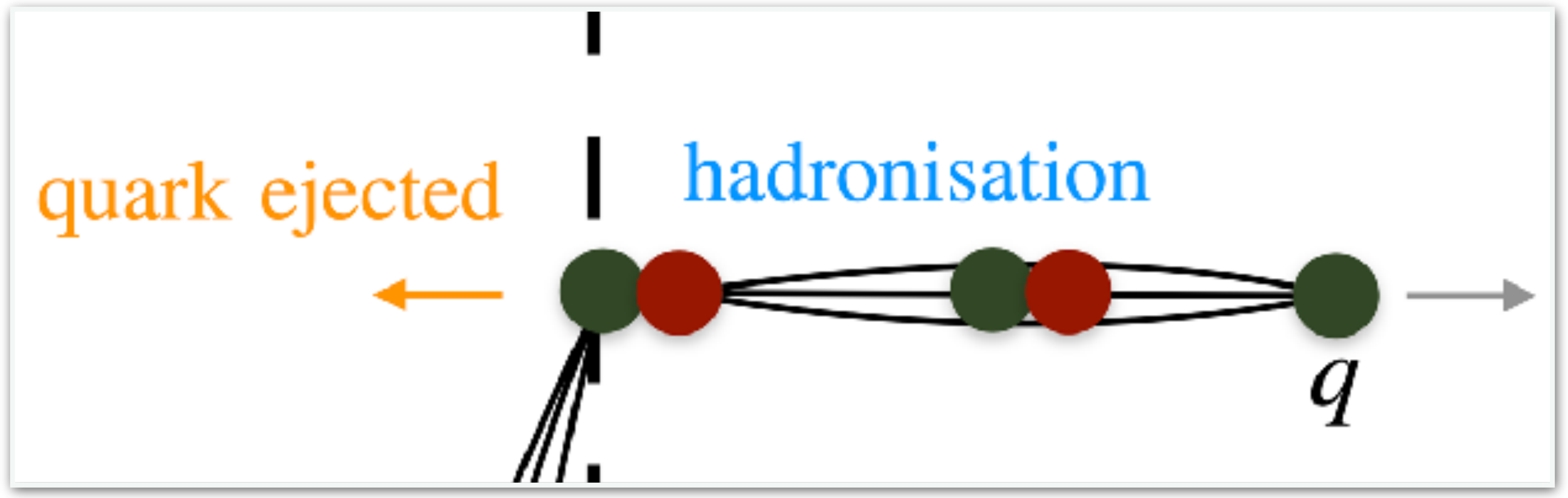

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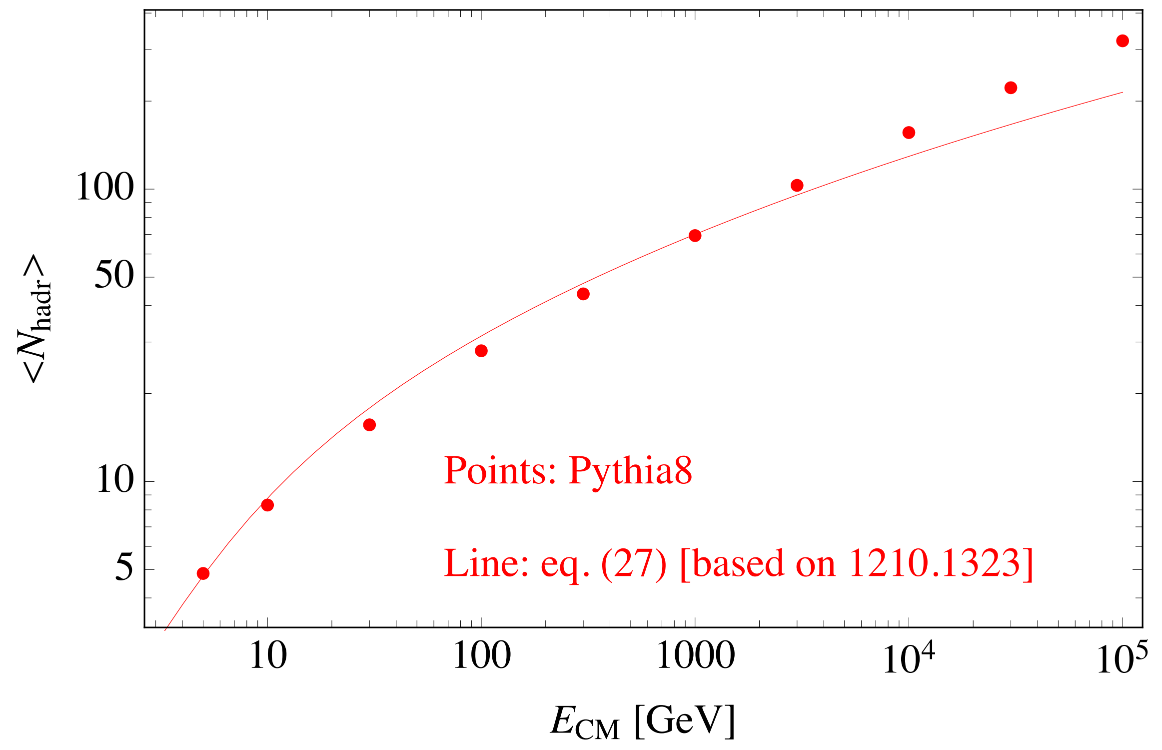

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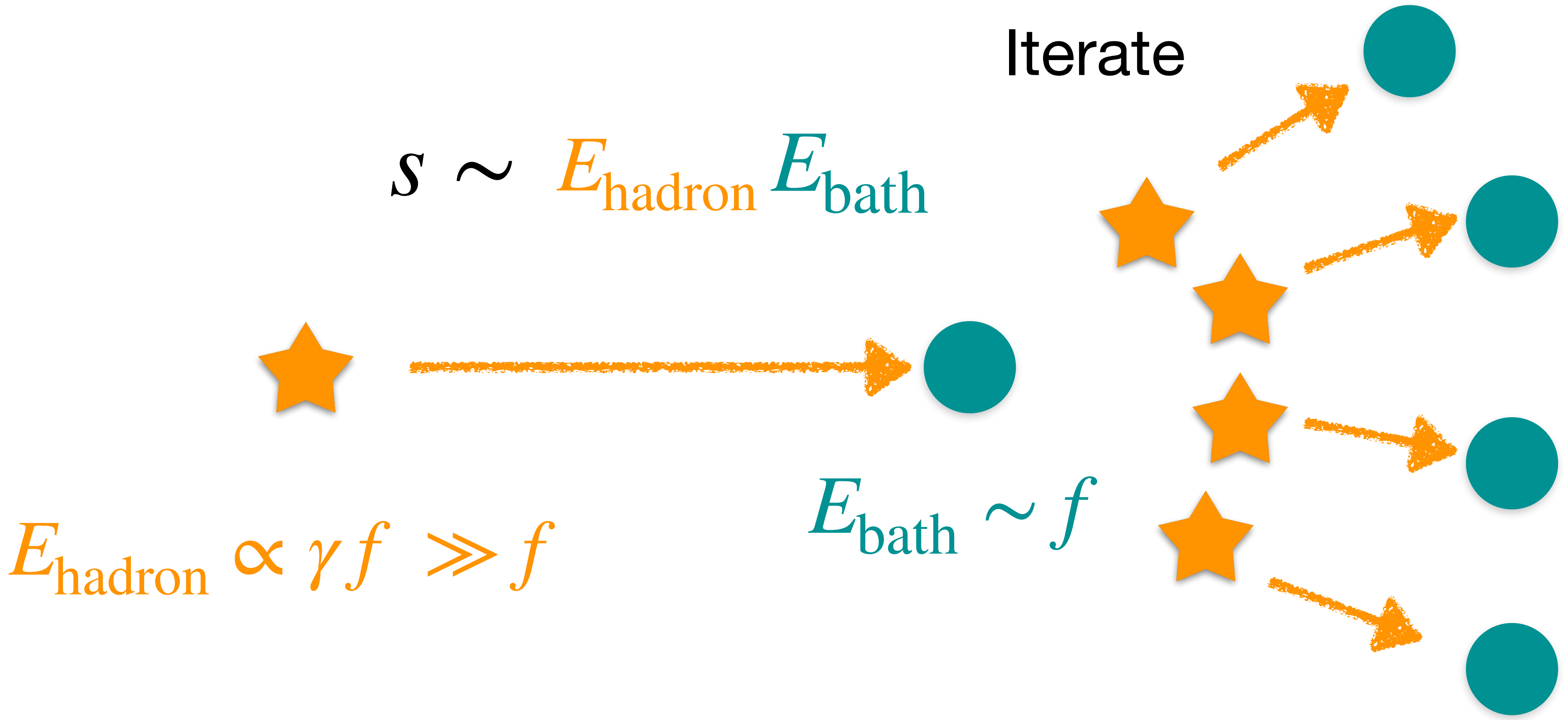

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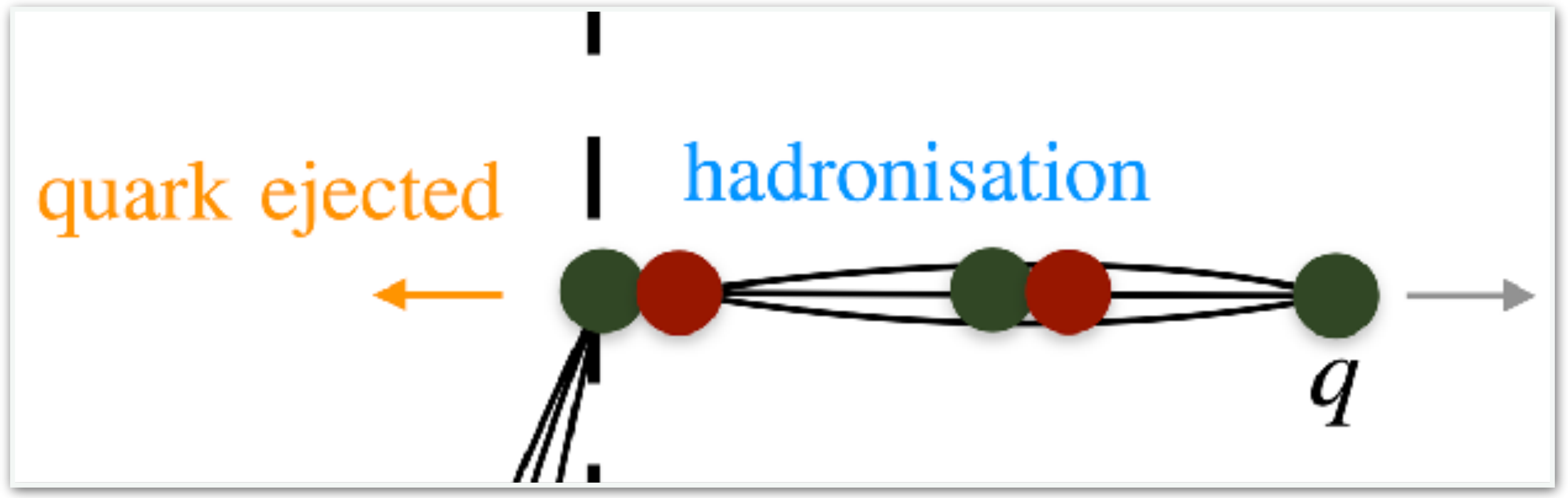

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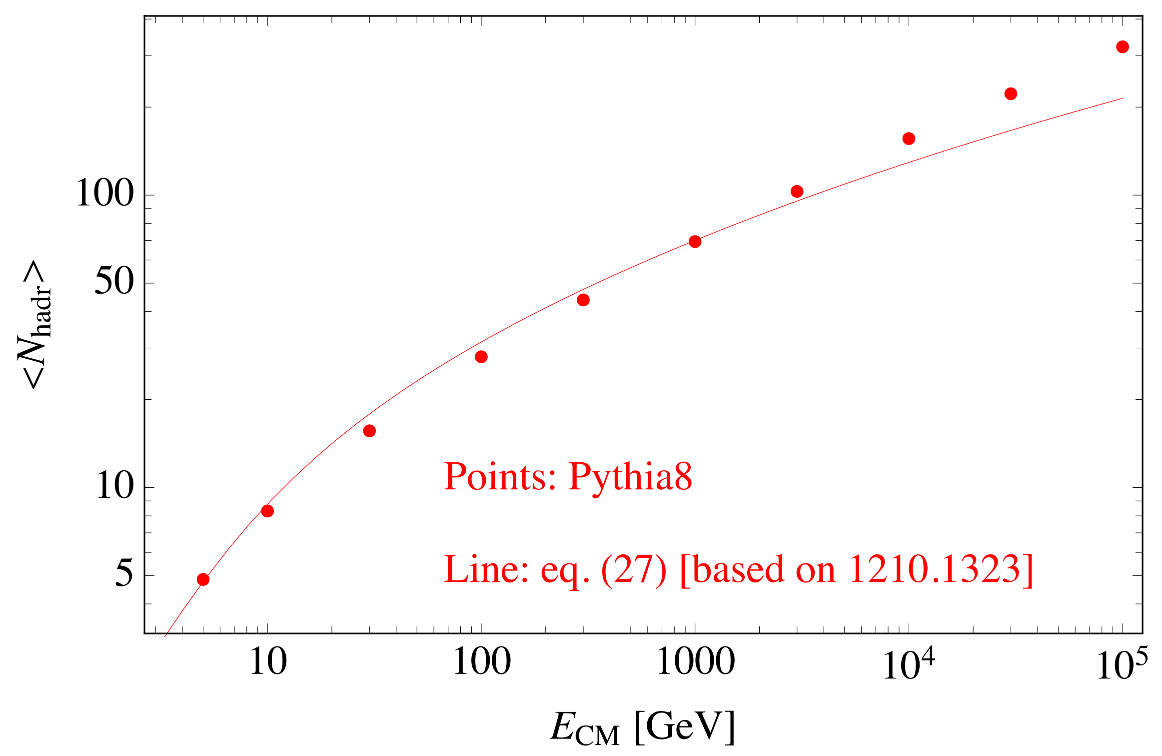

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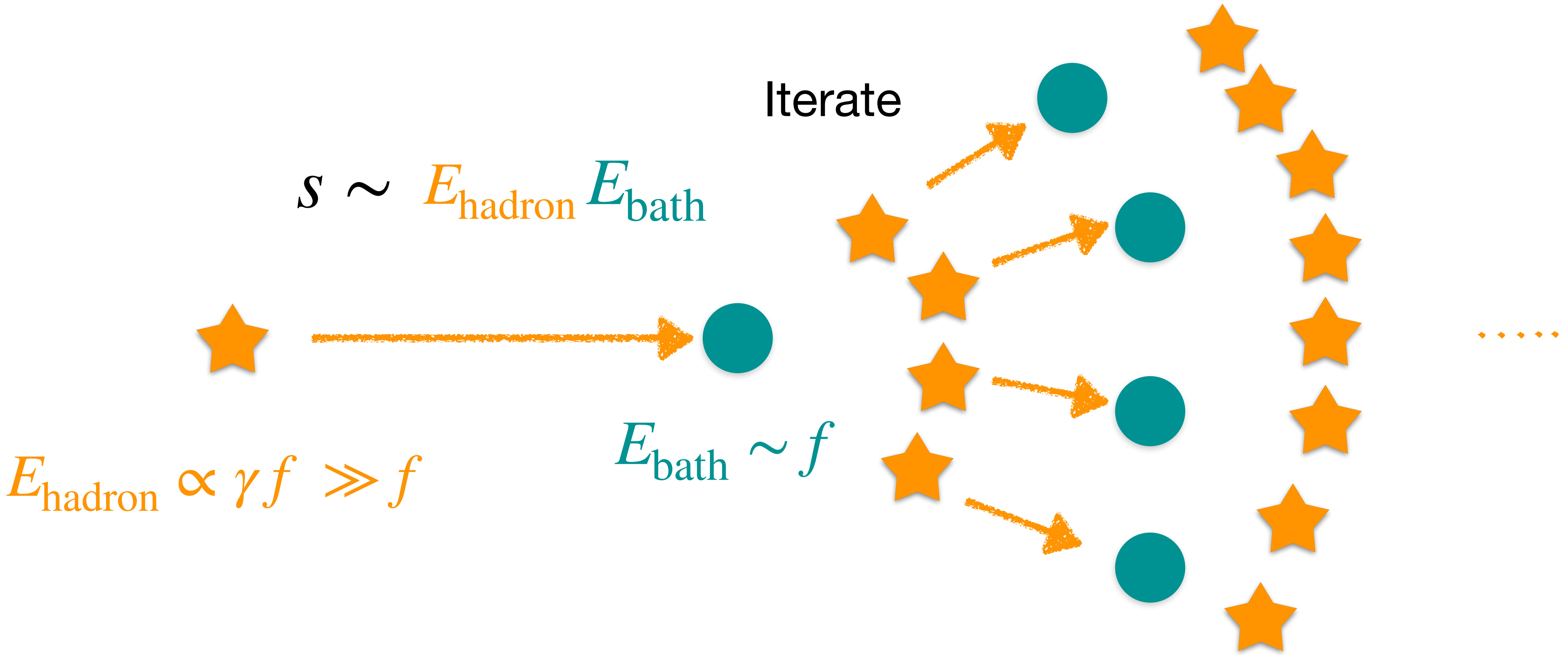

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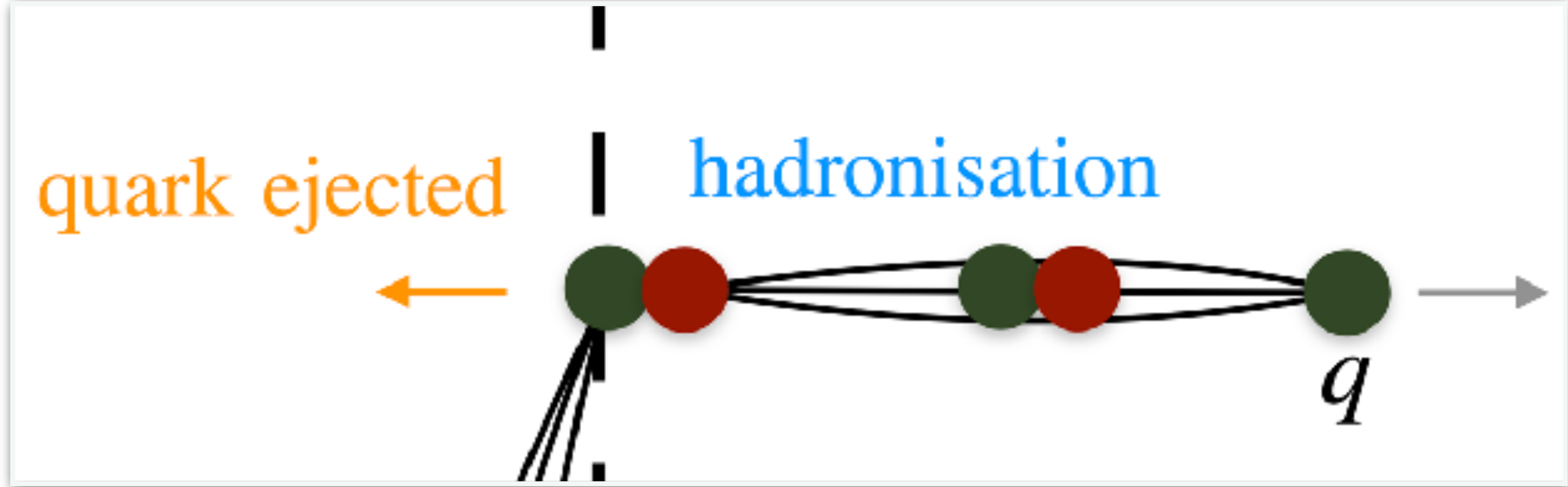

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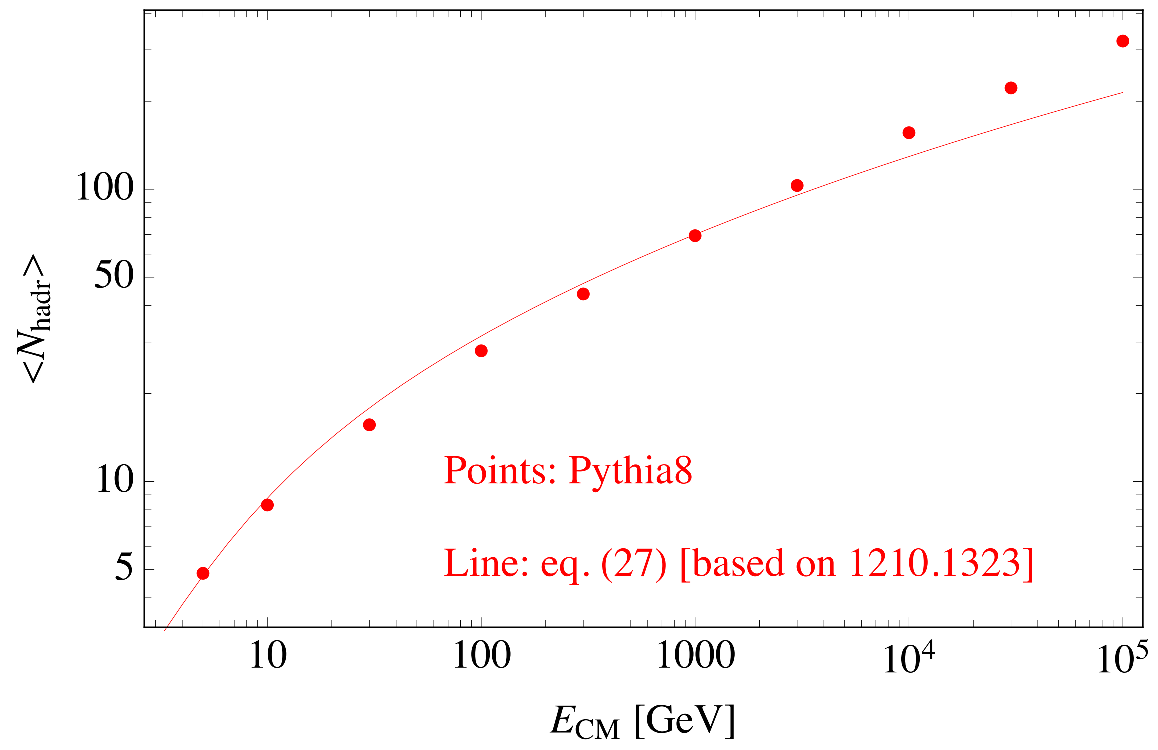

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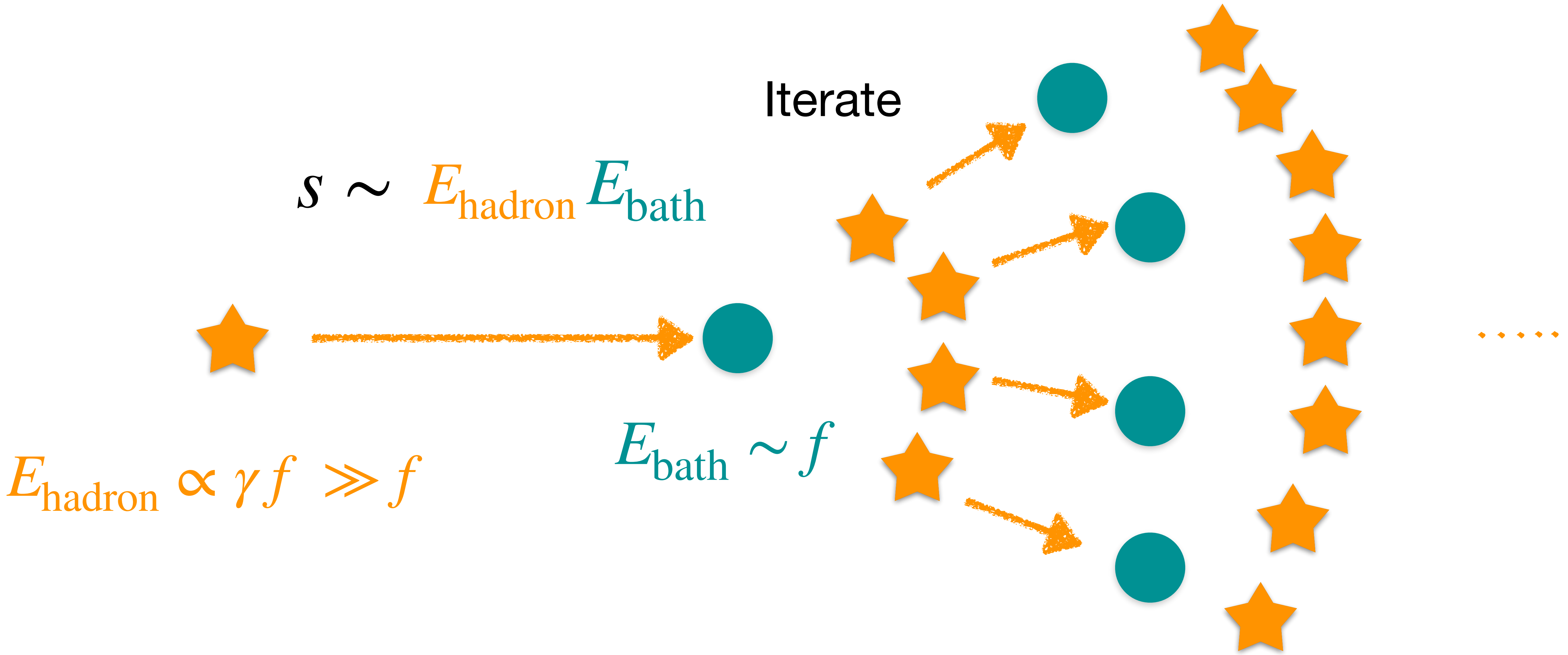
2. Cosmological catapult

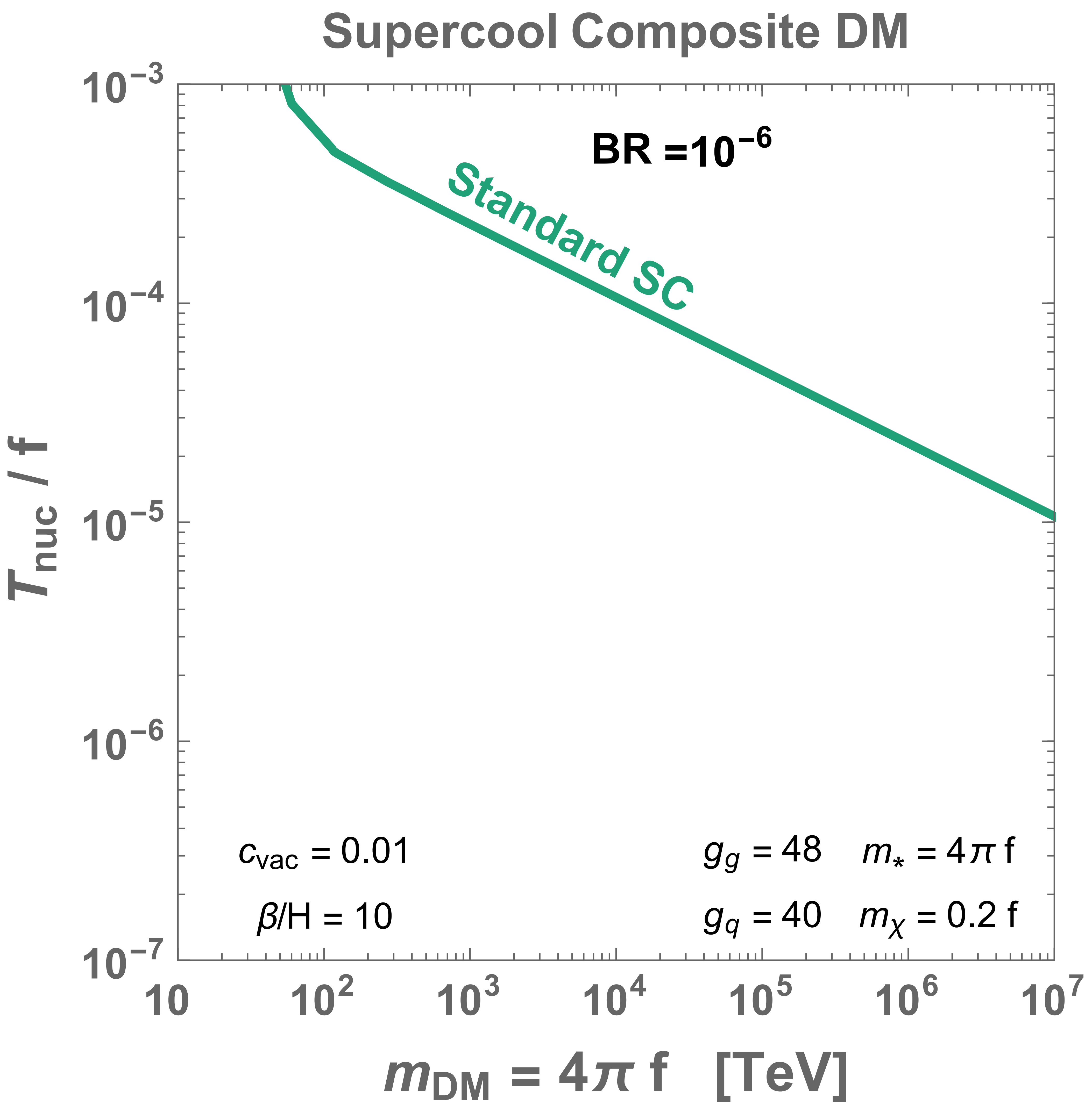


$$Y_{\mathrm{DM}} / Y_{\mathrm{DM}}^{\mathrm{naive}} \propto \gamma \propto \frac{T_{\mathrm{nuc}}}{f} \frac{M_{\mathrm{Pl}}}{f}$$

runaway regime

Consequences on DM abundance

$$Y_{\rm DM}^{\rm naive} \propto \left(\frac{T_{\rm nuc}}{f}\right)^3$$



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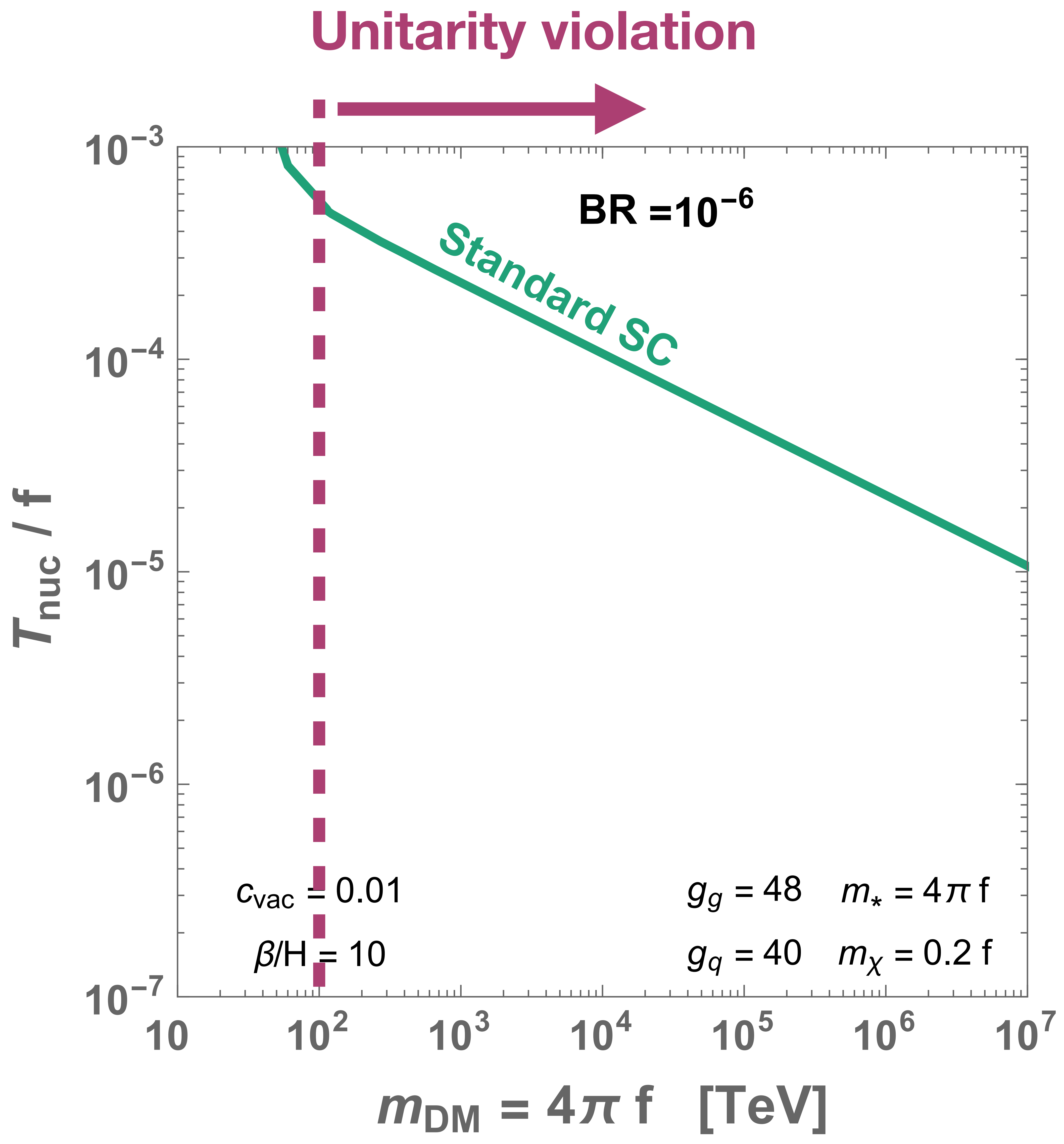
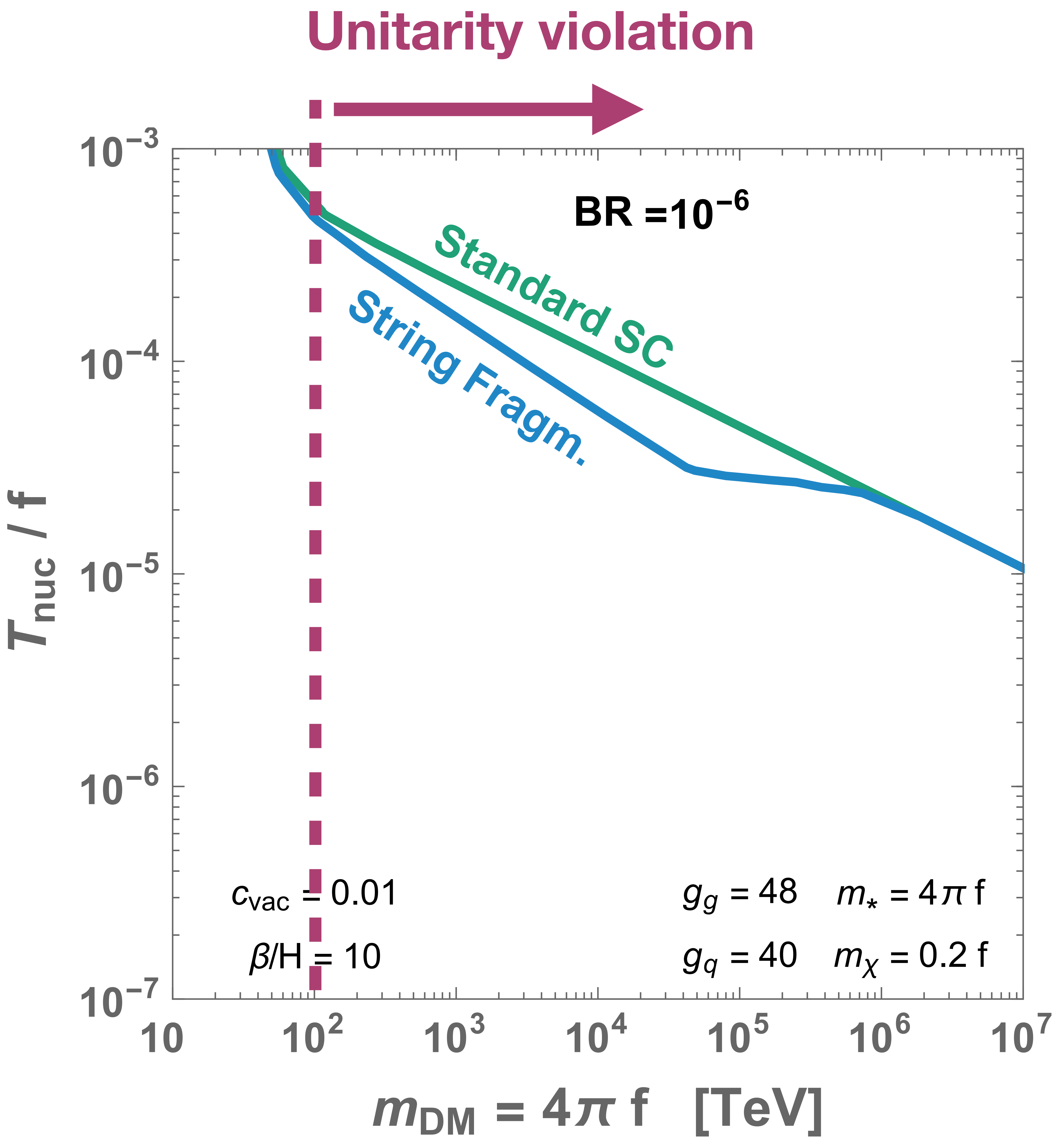


Consequences on DM abundance

$$Y^{\text{naive}}_{\text{DM}} \propto \left(\frac{T_{\text{nuc}}}{f}\right)^3$$

$$Y_{\text{DM}} / Y^{\text{naive}}_{\text{DM}} \propto \log^n\left(\gamma T_{\text{nuc}}/f\right)$$



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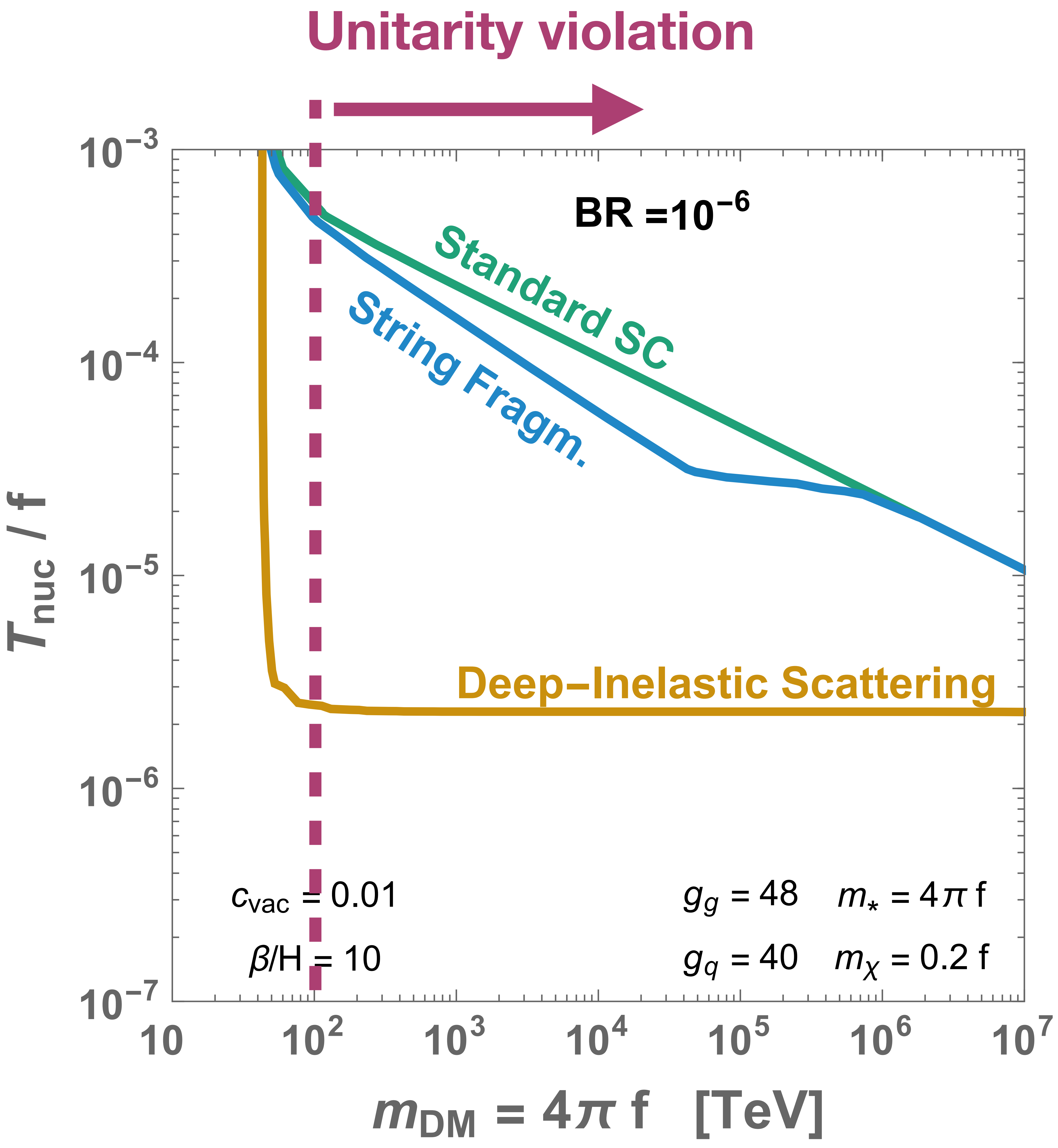

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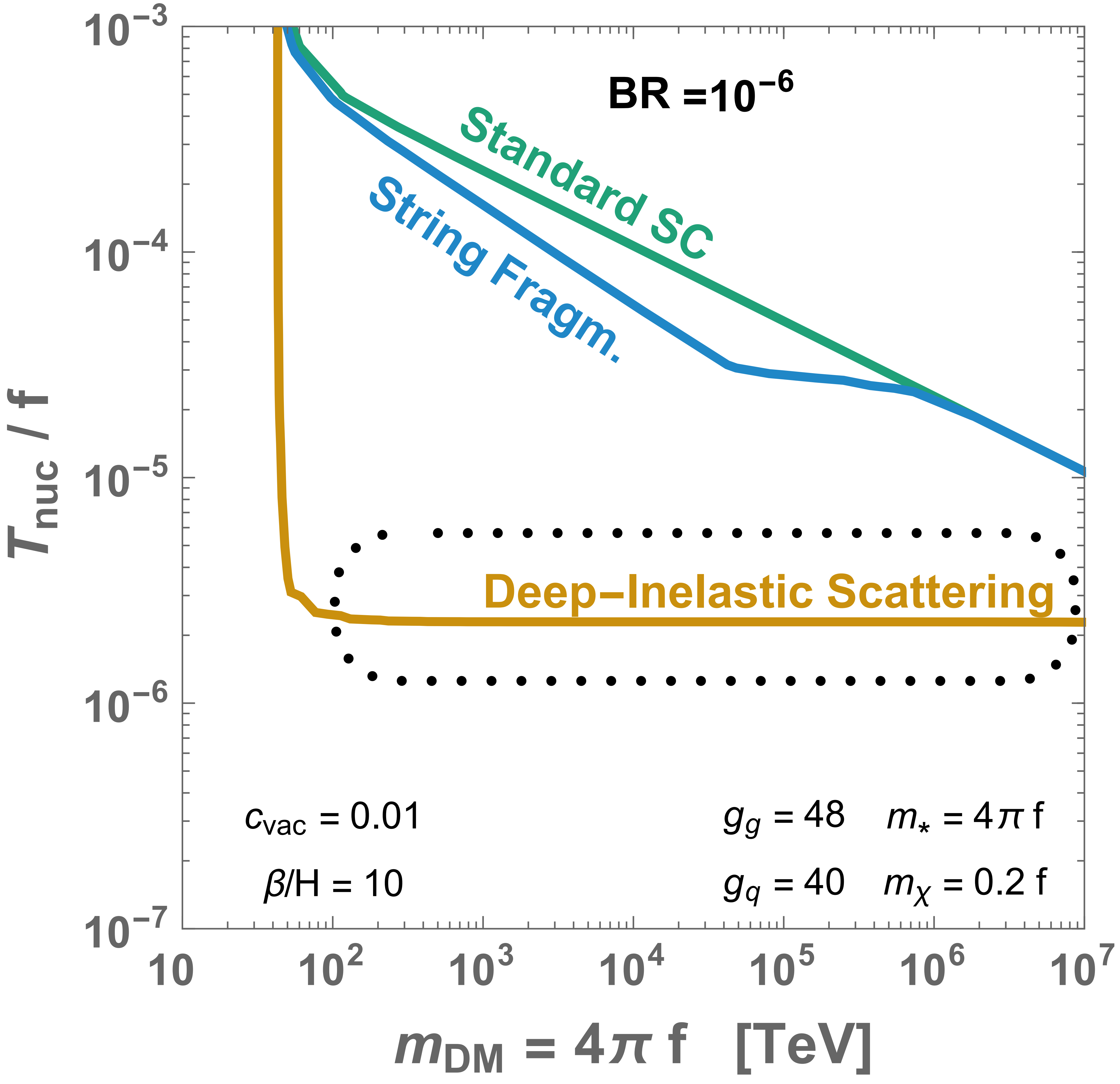

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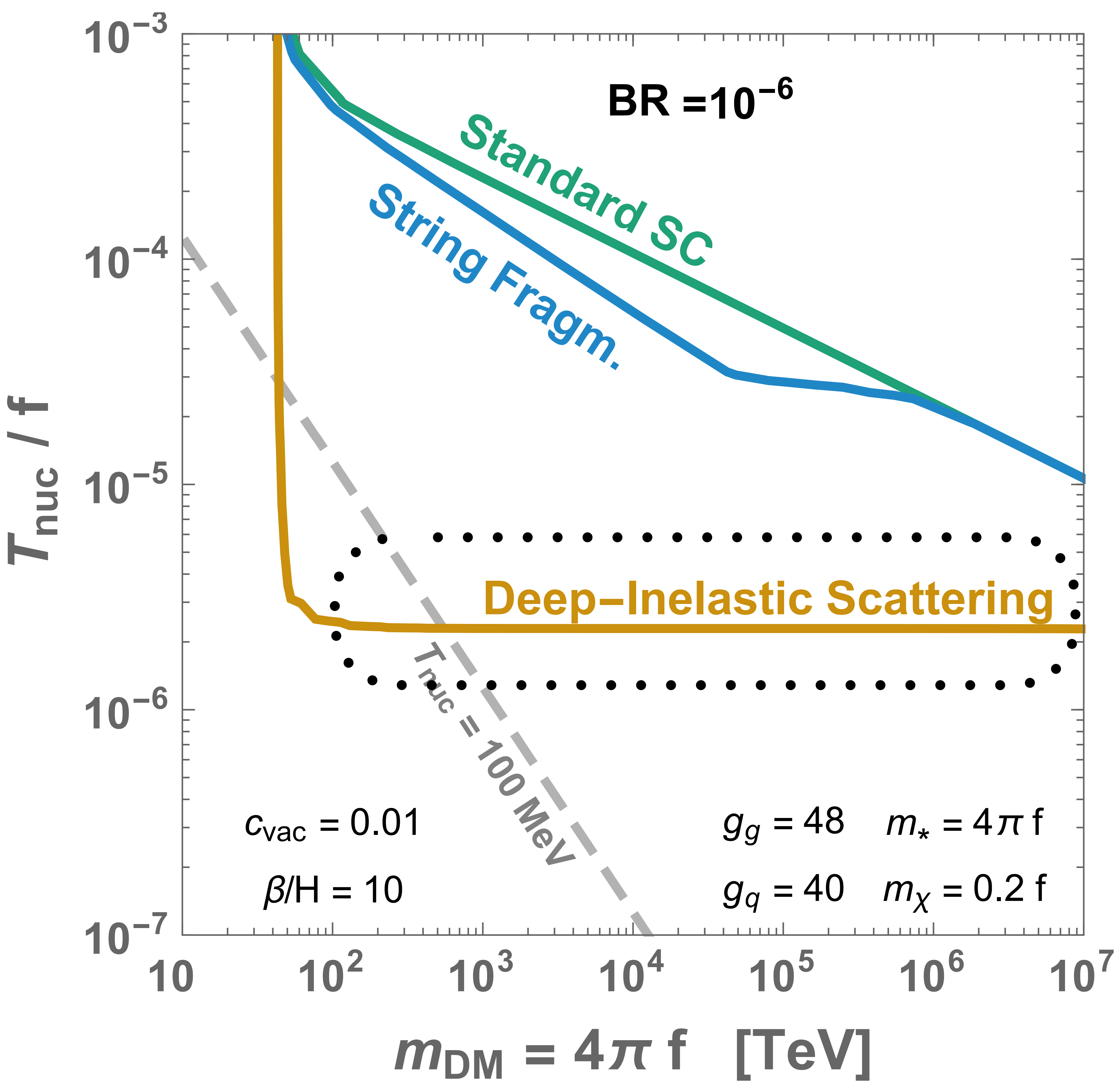

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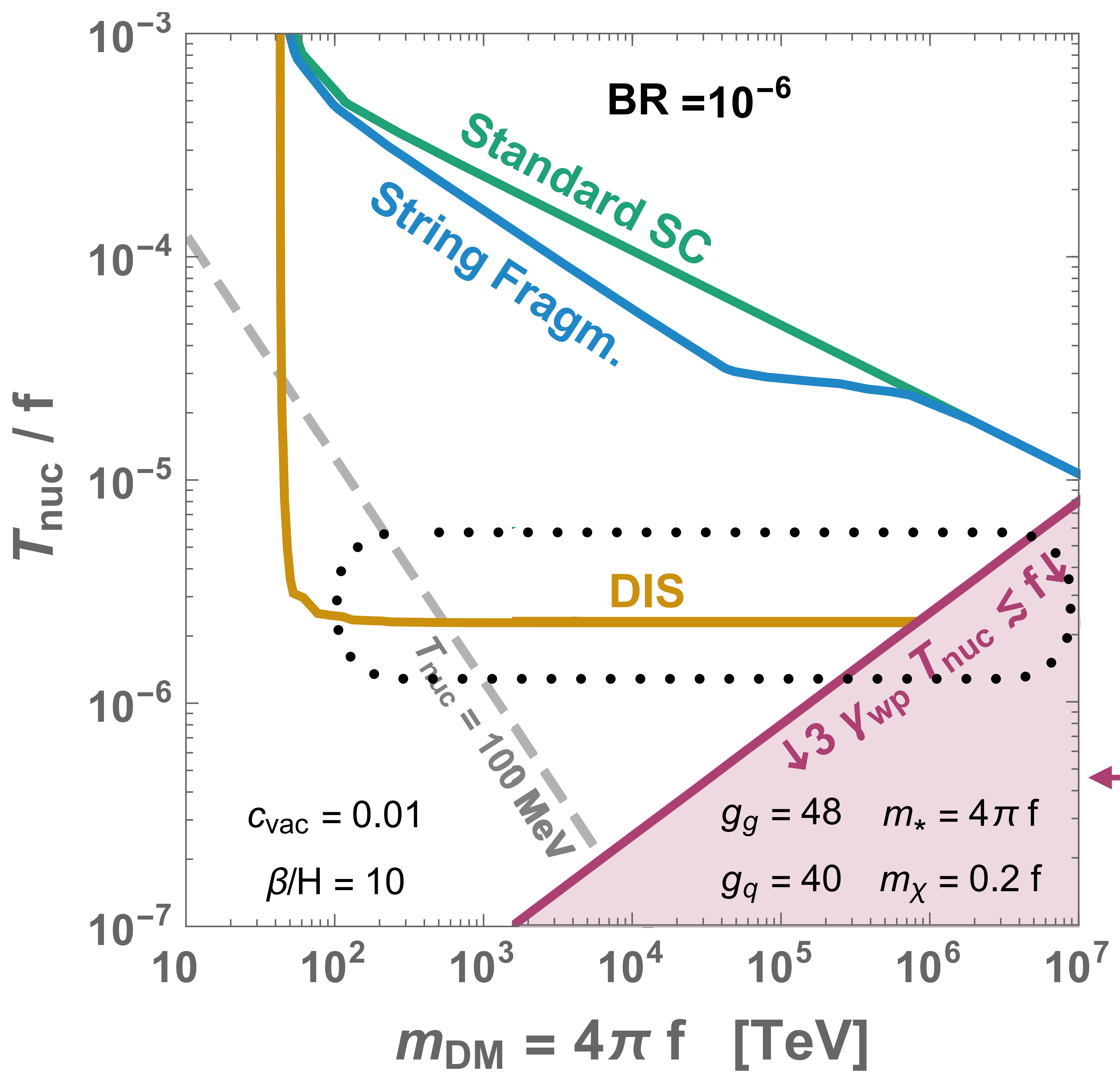
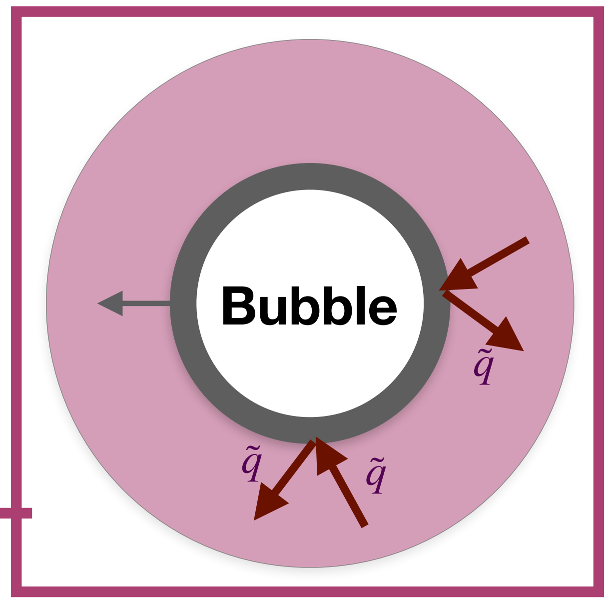


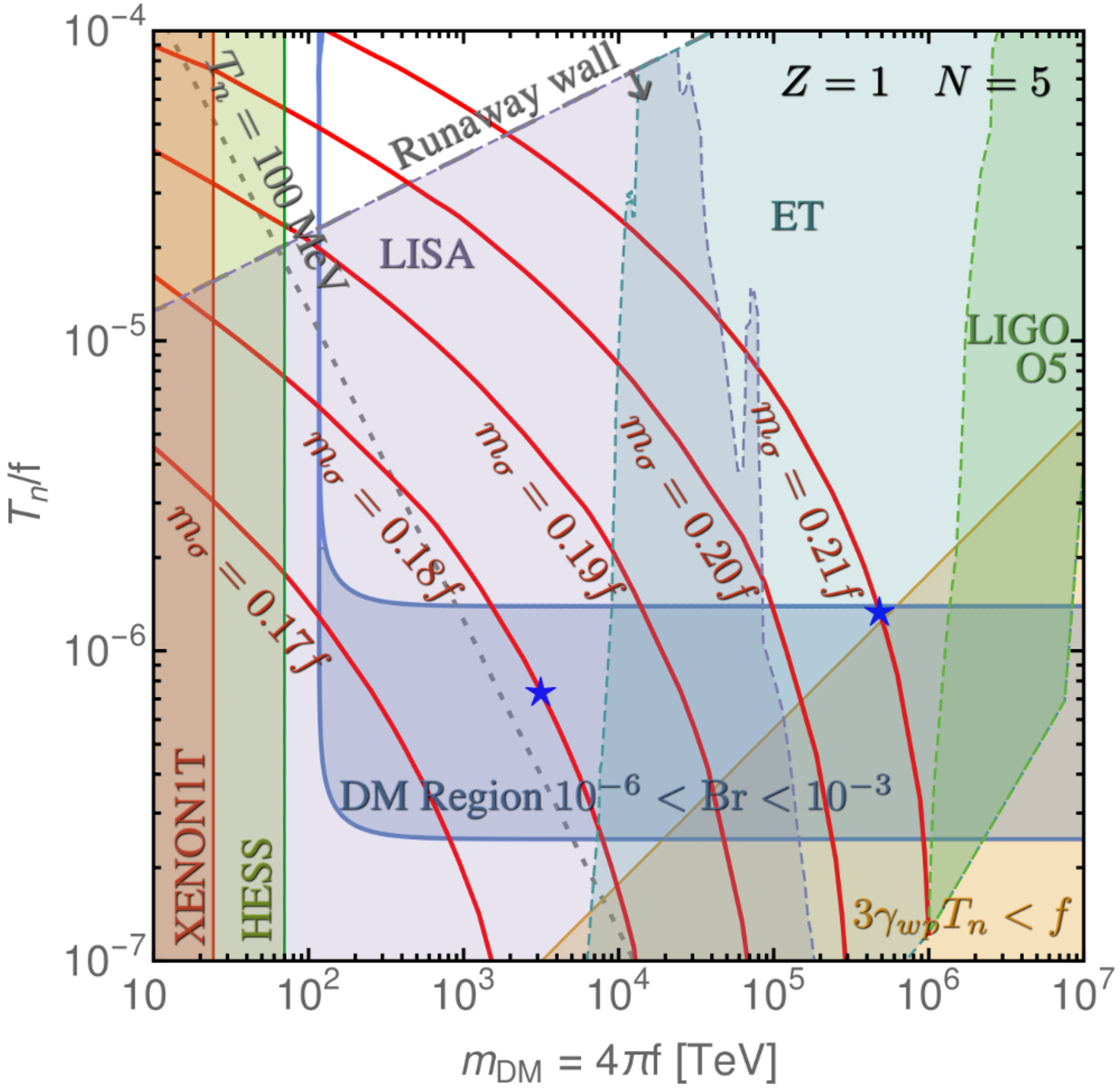
Quarks can not enter



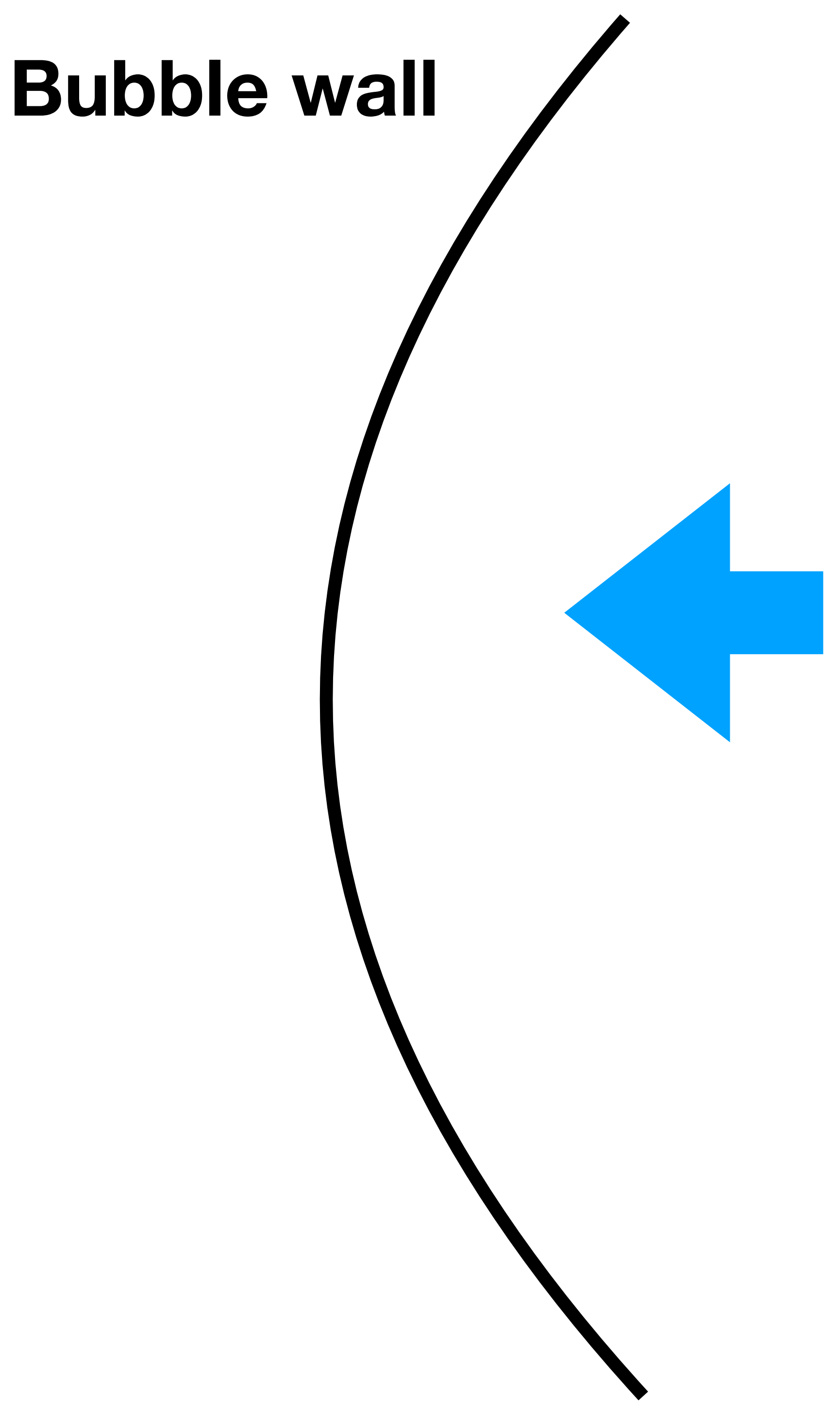
Snow ball effect

Ping-pong effect

Gravitational waves signature



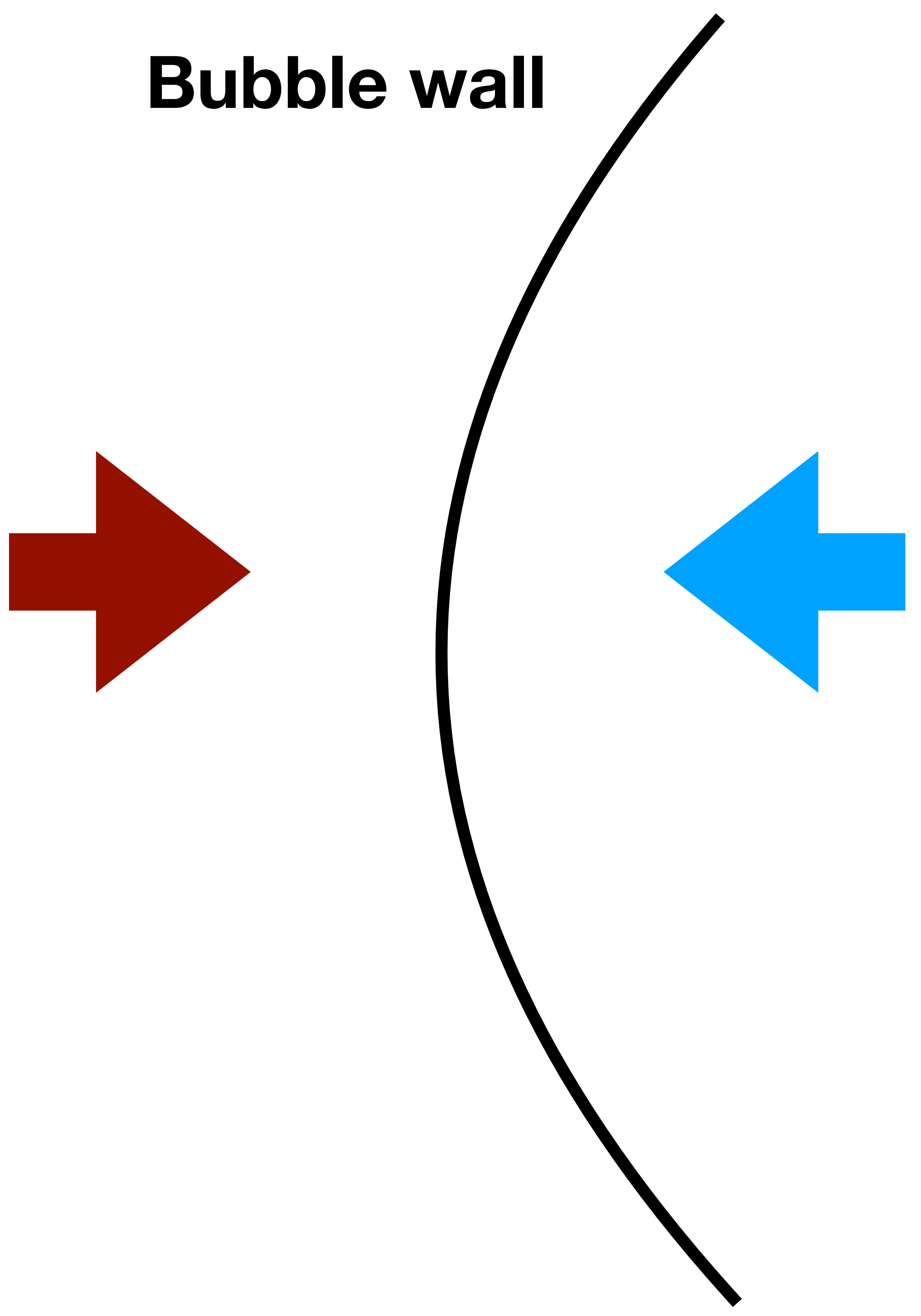
Consequences on bubble wall velocity



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

Consequences on bubble wall velocity

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



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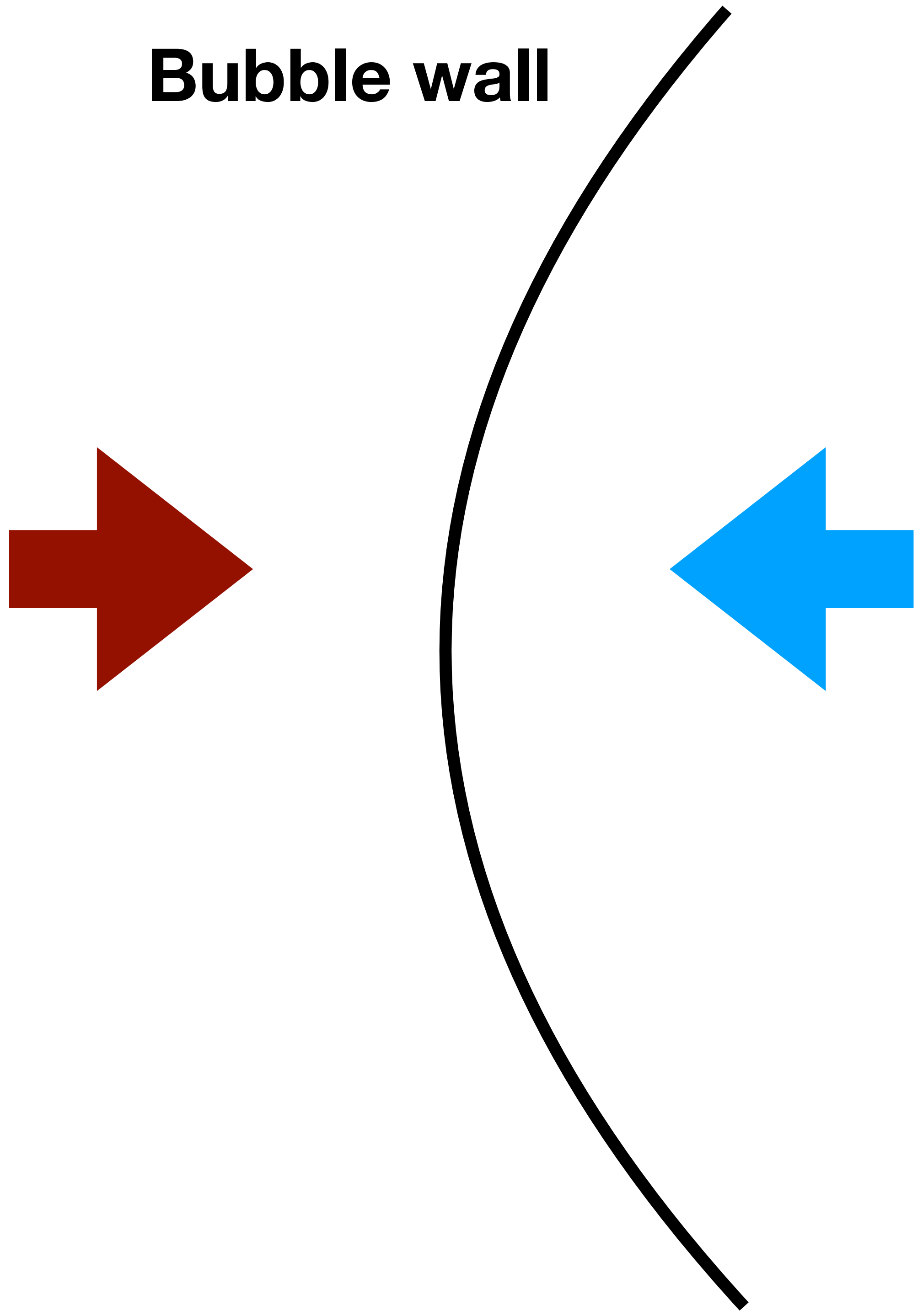
$$\mathscr{P}_{\text{friction}} \simeq \gamma T_{\text{nuc}}^3 \times \Delta p$$

$$\Delta p = ?$$



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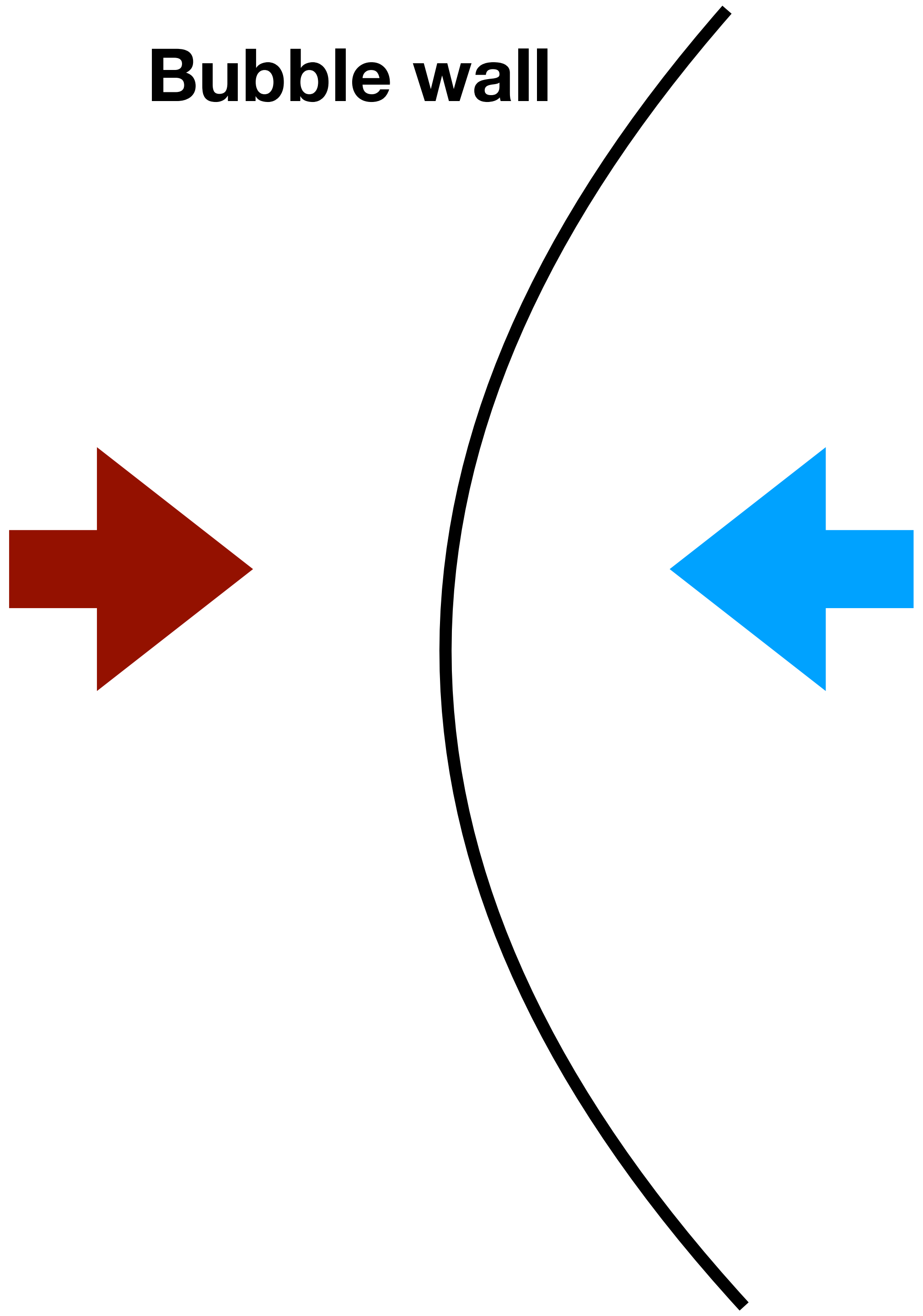

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Weakly-coupled PT

Consequences on bubble wall velocity

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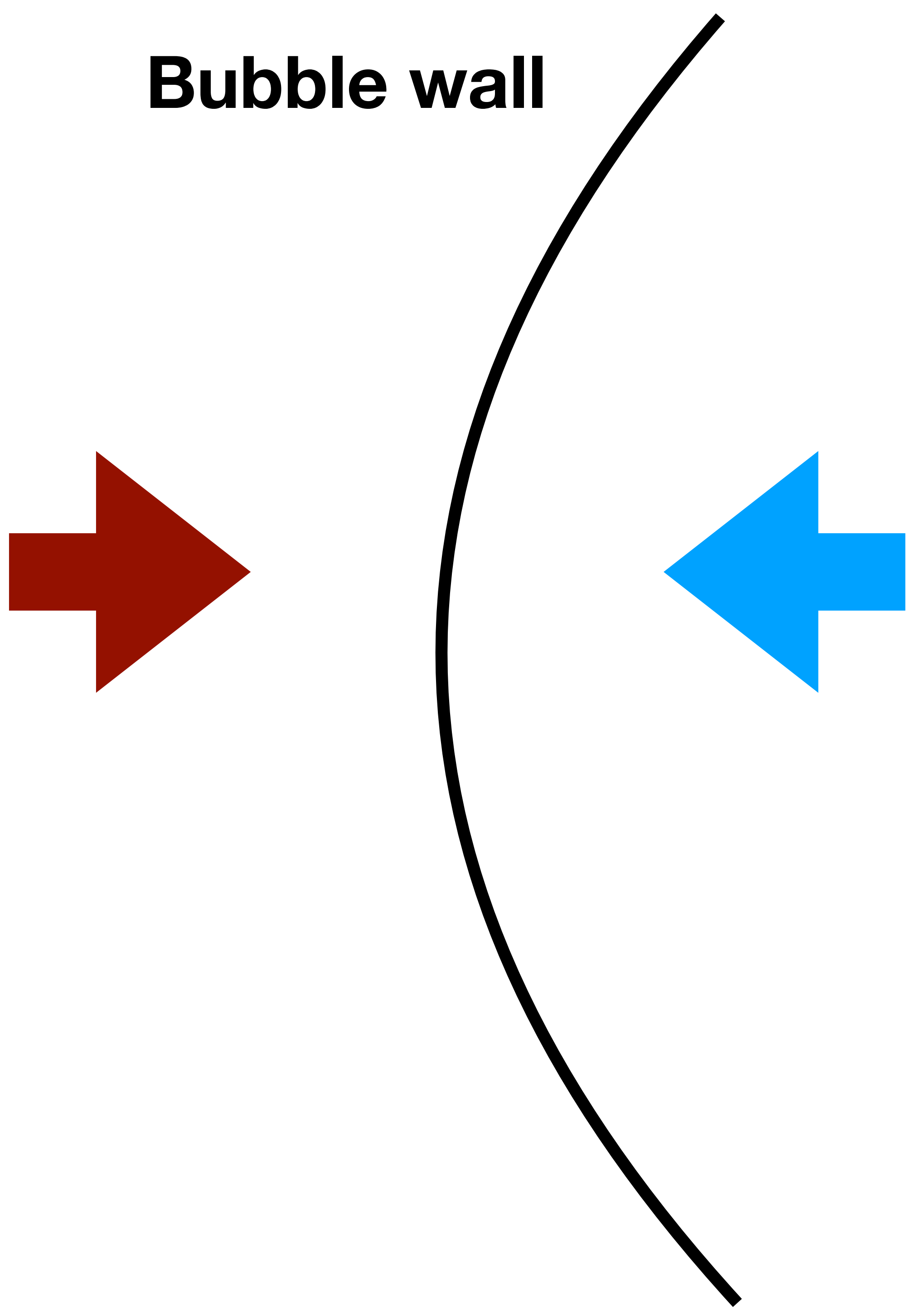

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Weakly-coupled PT

Bodeker&Moore (09' and 17')

Azatov+ 20'

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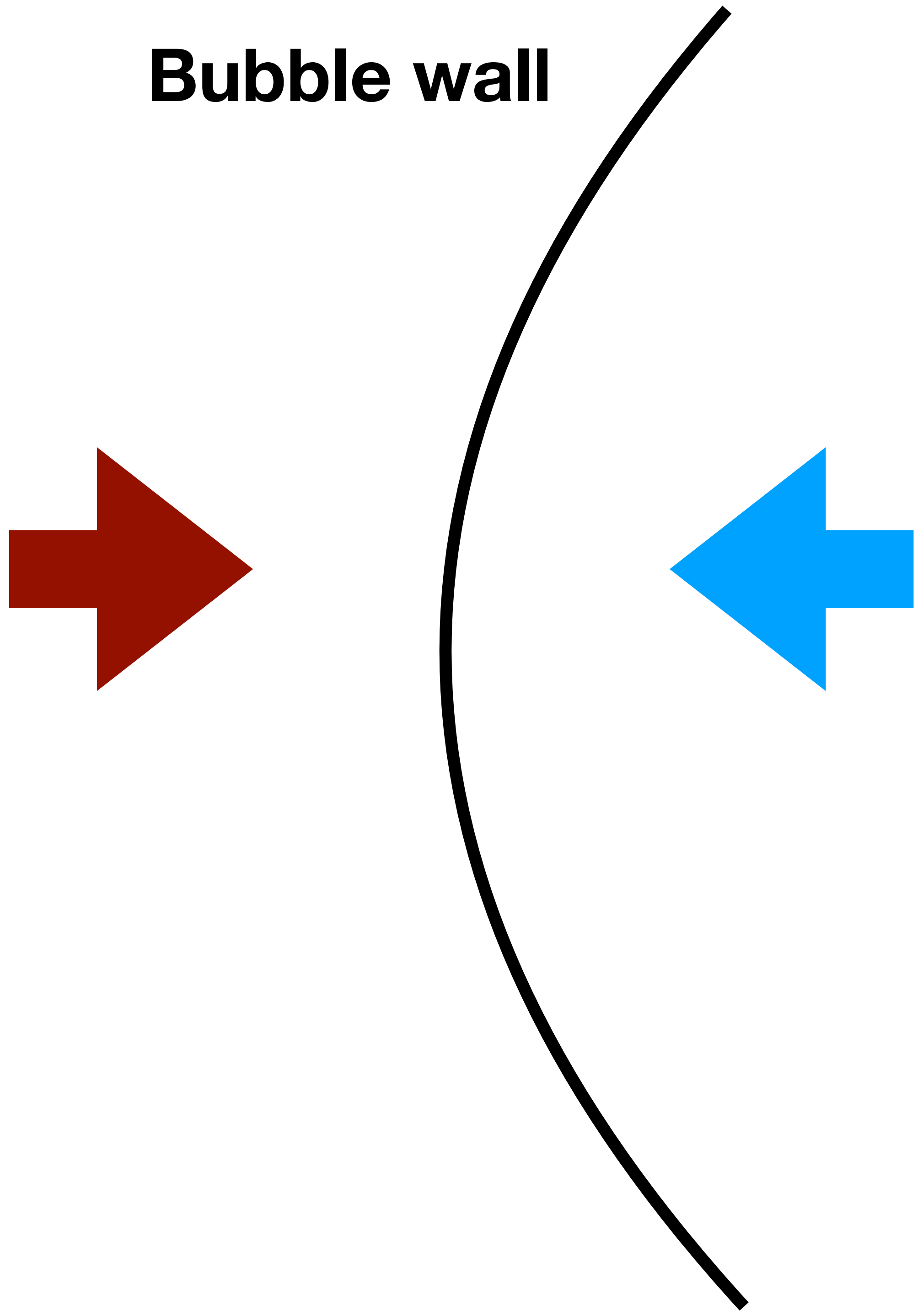

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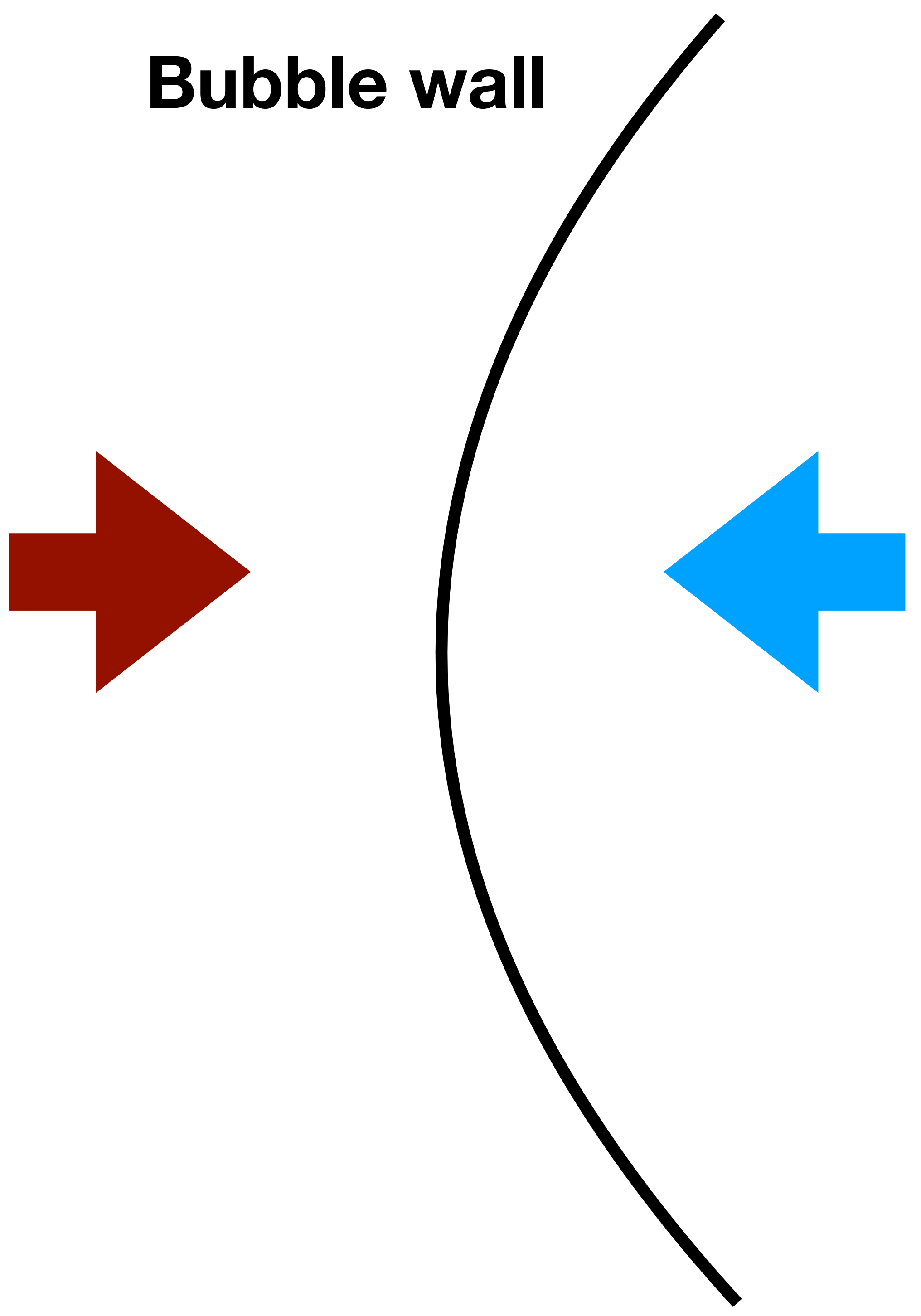
Weakly-coupled PT

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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Weakly-coupled PT

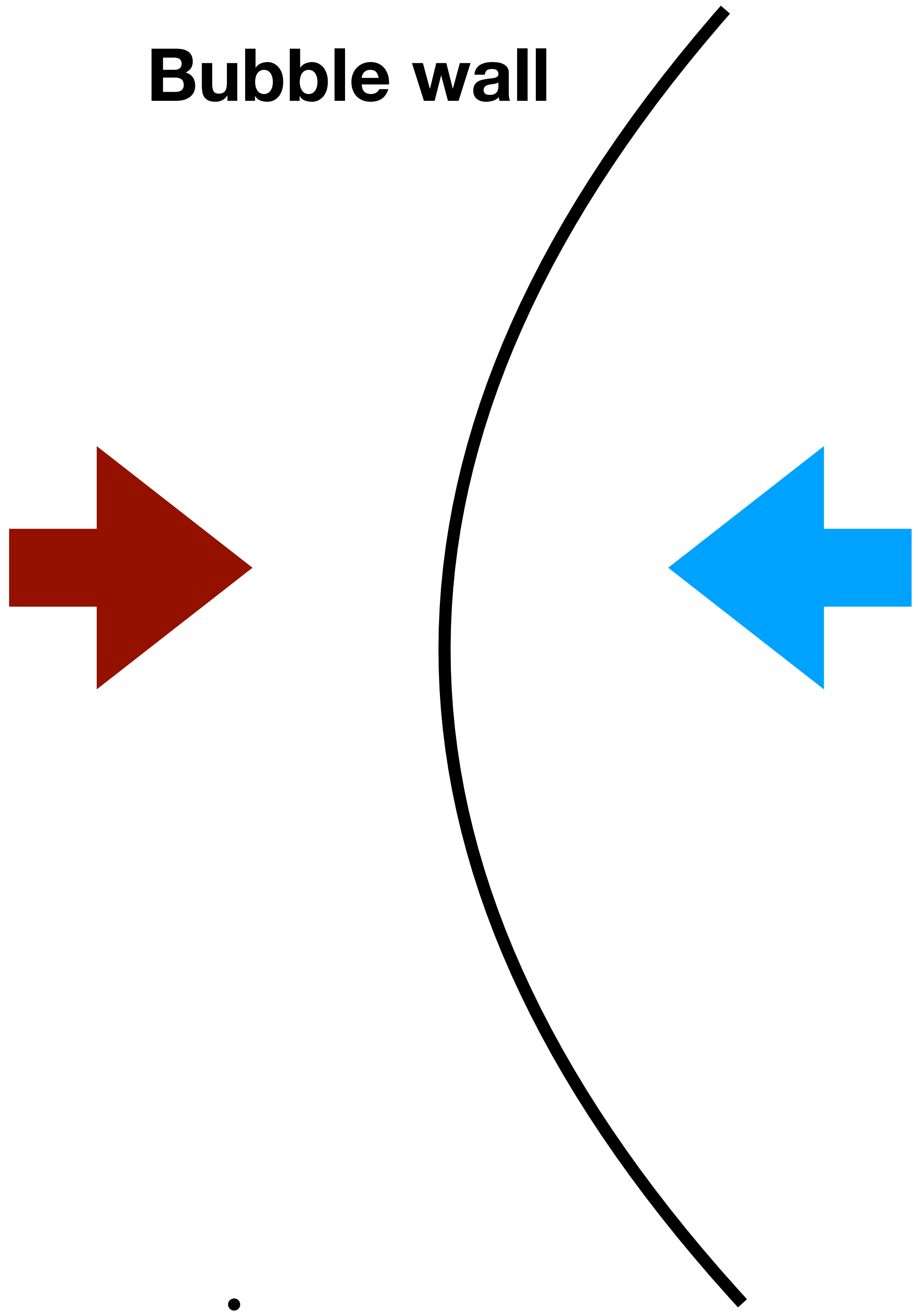
Bodeker&Moore (09’ and 17’)

Azatov+ 20’

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

Consequences on bubble wall velocity

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



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

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Weakly-coupled PT

Strongly-coupled PT

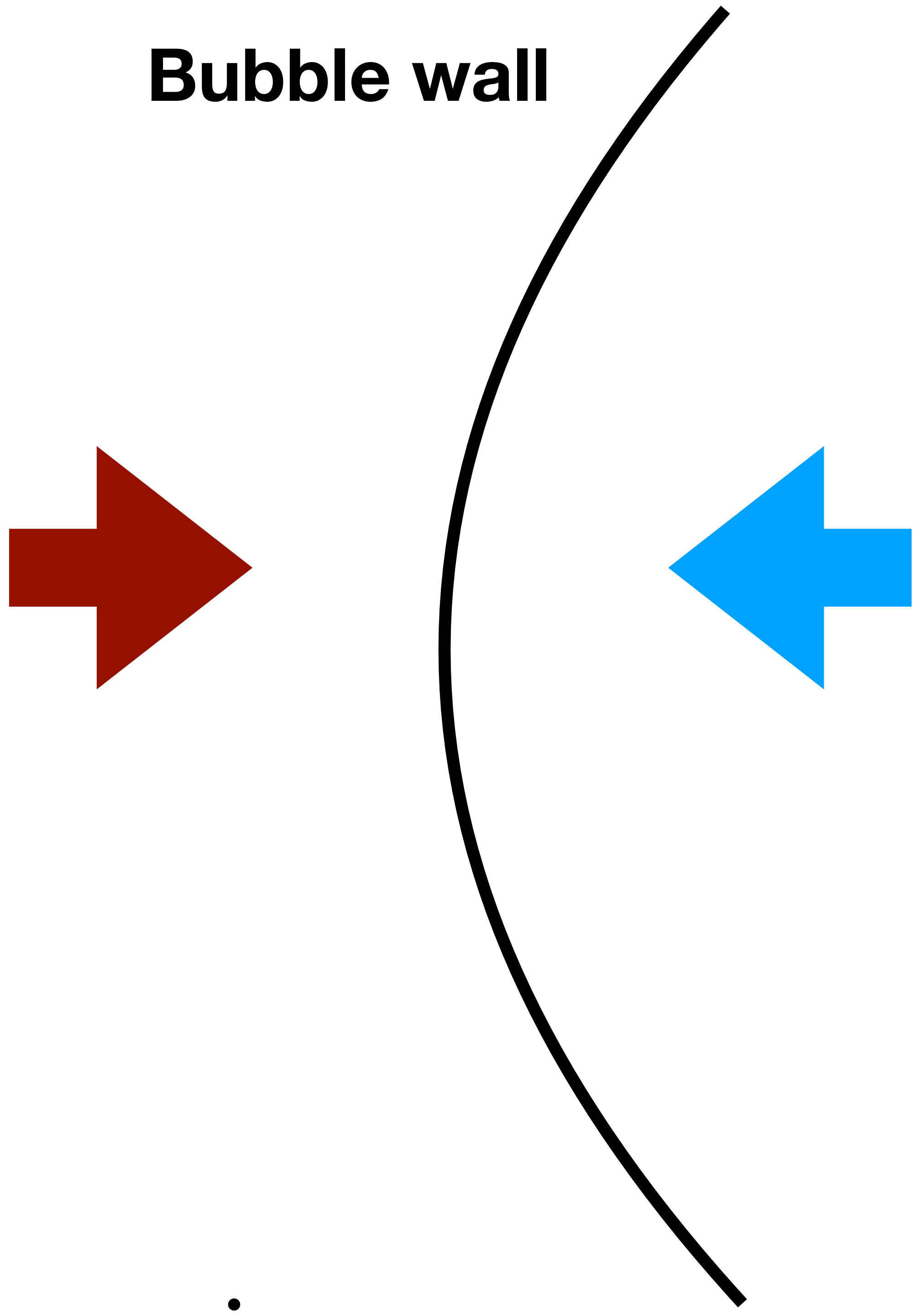
Bodeker&Moore (09' and 17')

Azatov+ 20'

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

Consequences on bubble wall velocity

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



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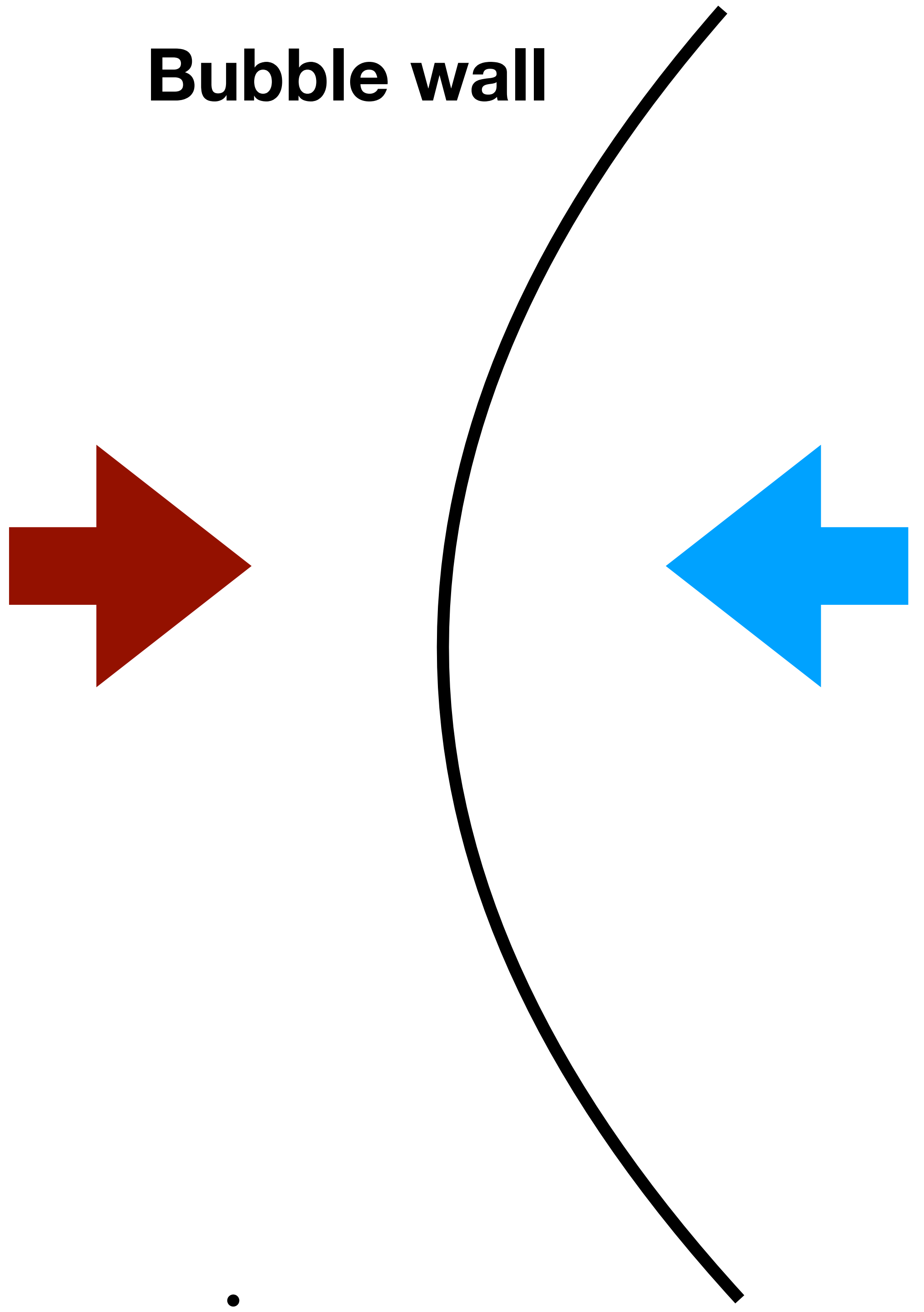
Strongly-coupled PT

Hoeche, Kozaczuk, Long, Turner, Wang 20'

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

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

Bodeker&Moore (09' and 17')

Azatov+ 20'

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

Strongly-coupled PT

Hoeche, Kozaczuk, Long, Turner, Wang 20'

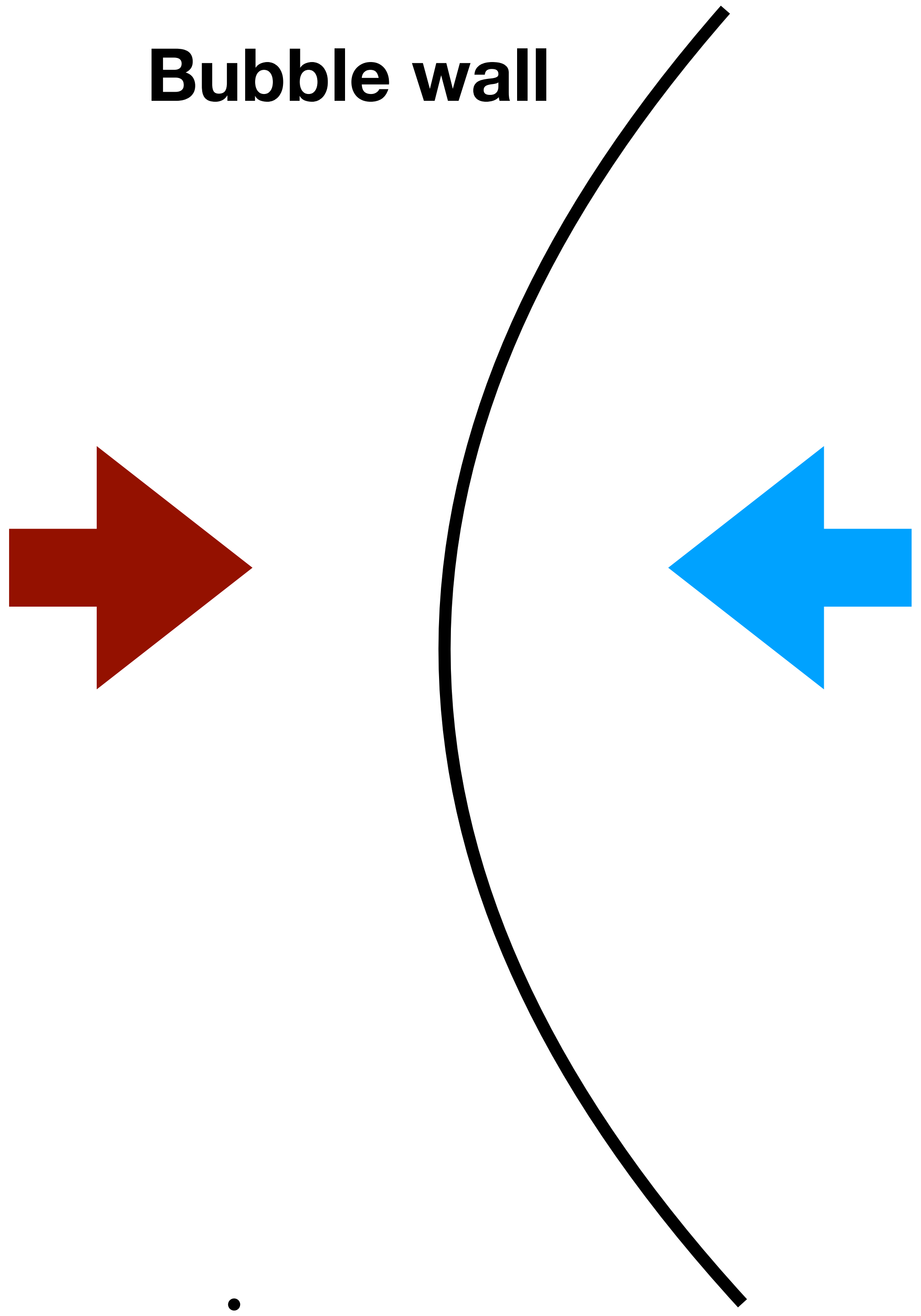
$$\mathscr{P}_{\text{all-order}} \simeq \gamma^2 T_{\text{nuc}}^4$$

Baldes, YG, Sala 20'

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

Consequences on bubble wall velocity

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



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Baldes, YG, Sala 20'

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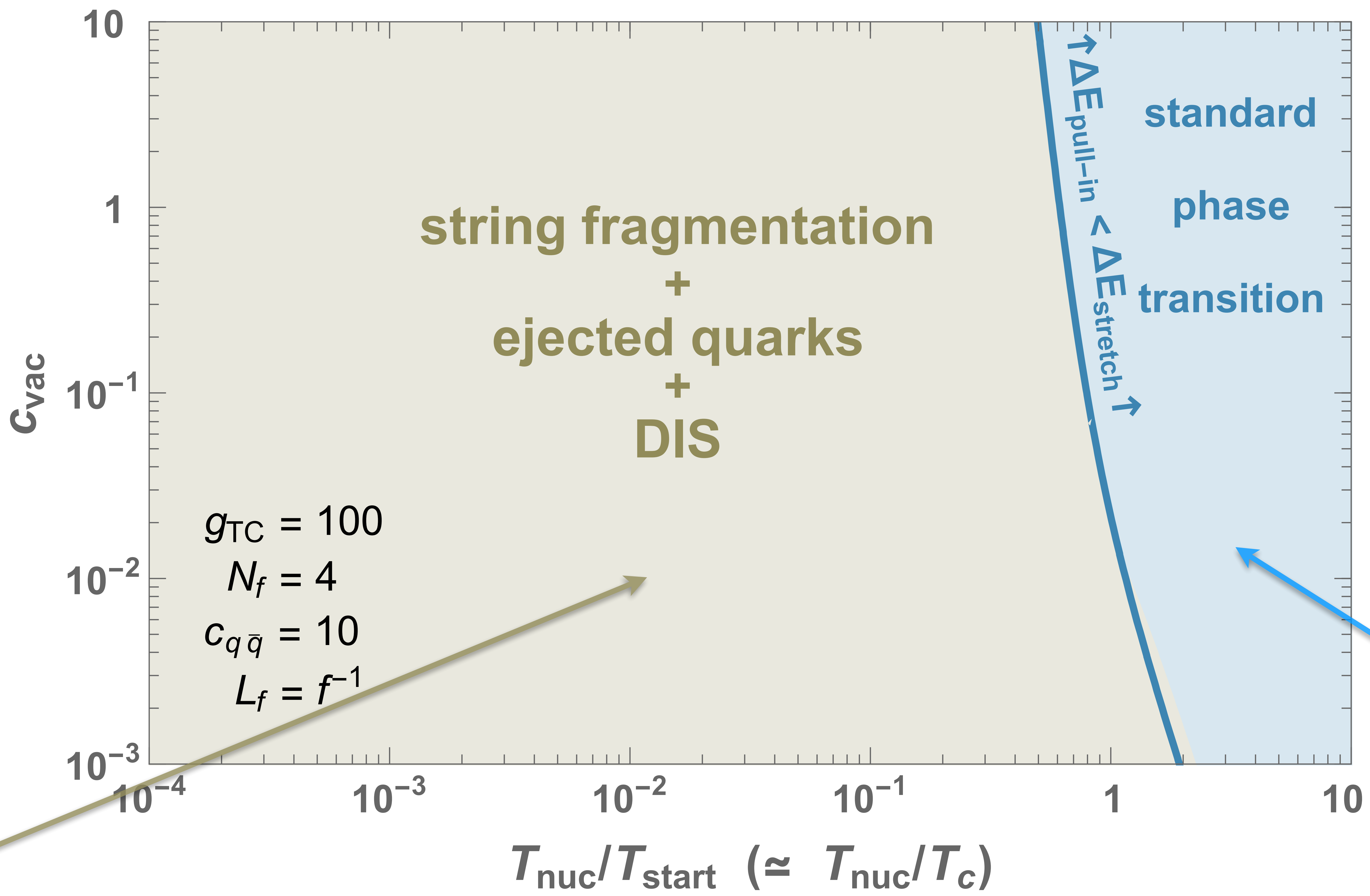
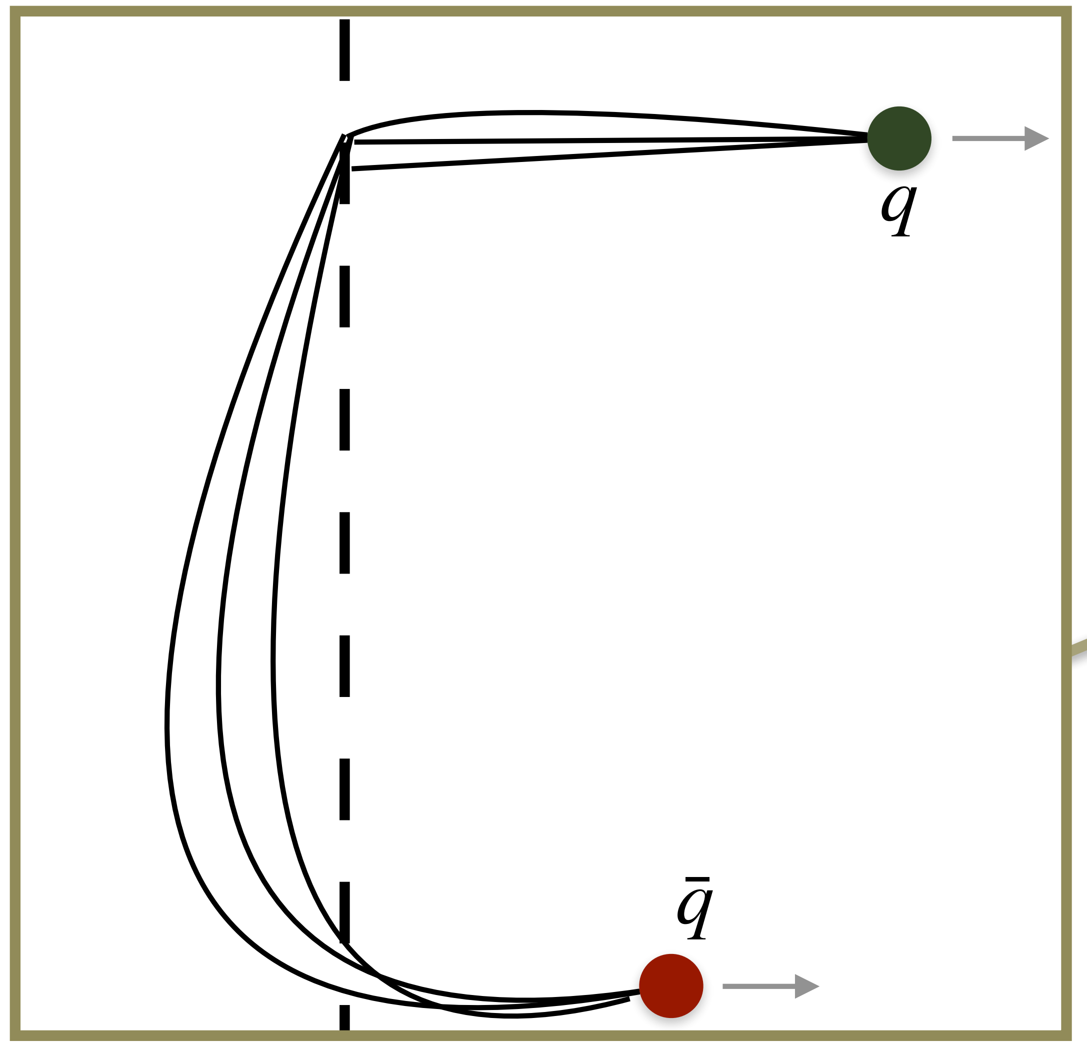
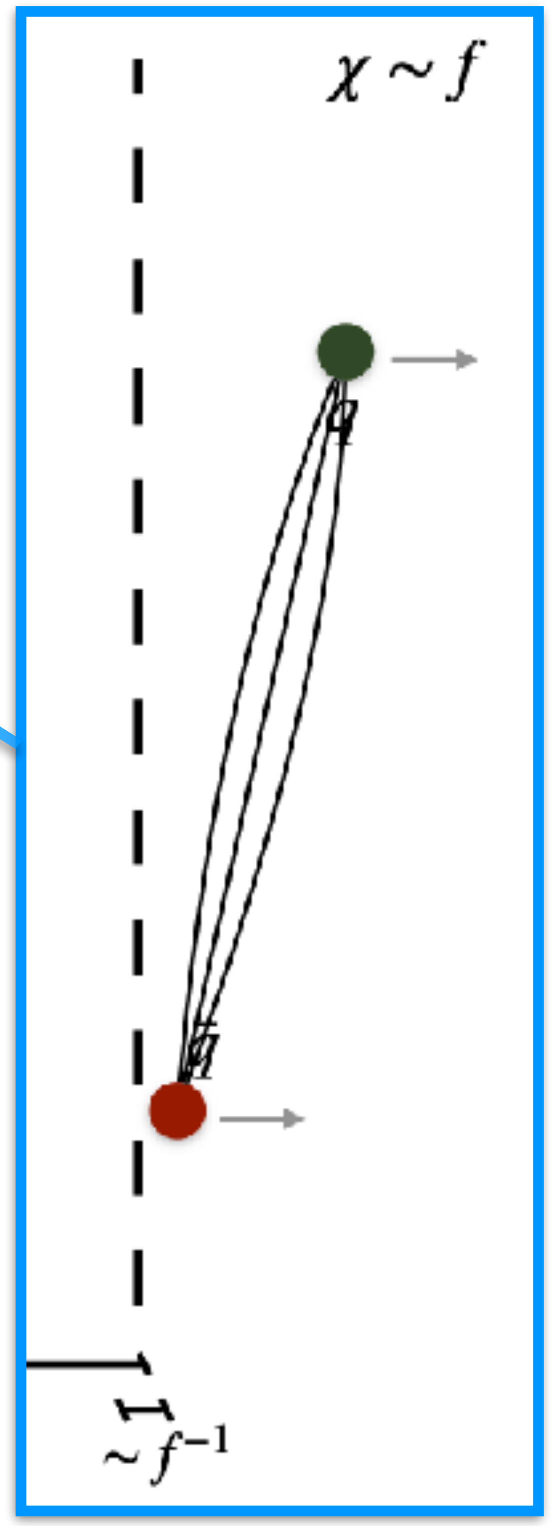
How much supercooling is needed ?





No line distortion



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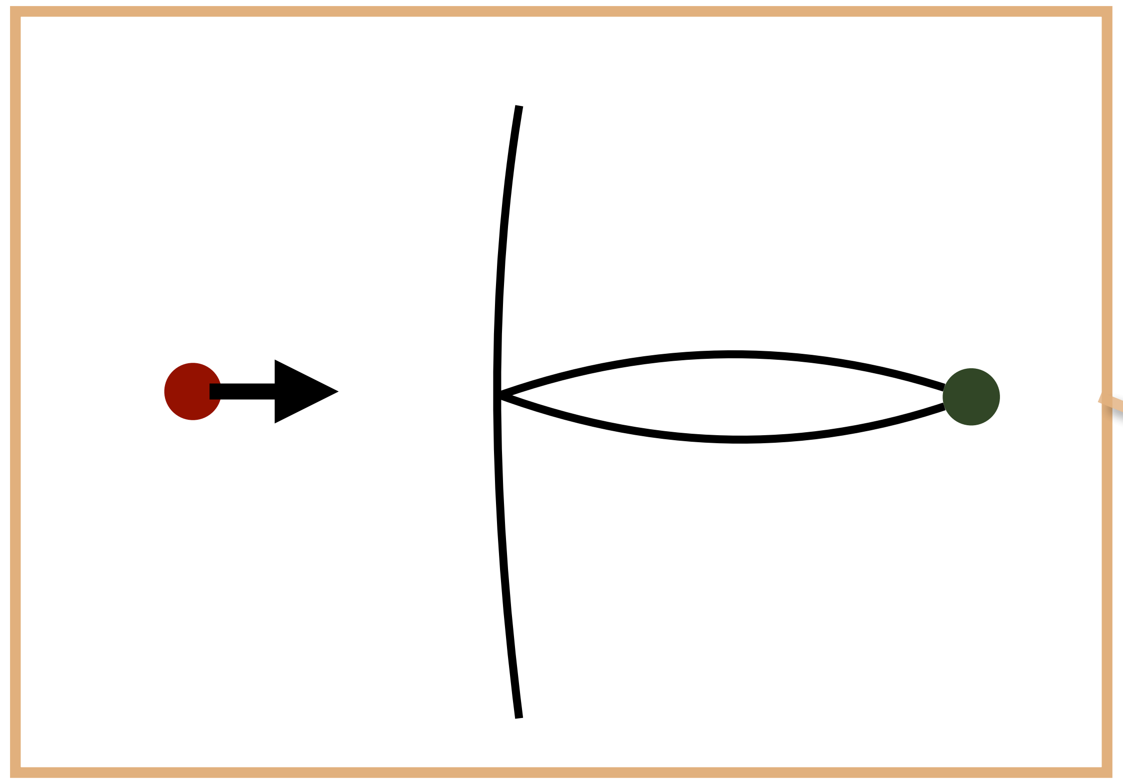

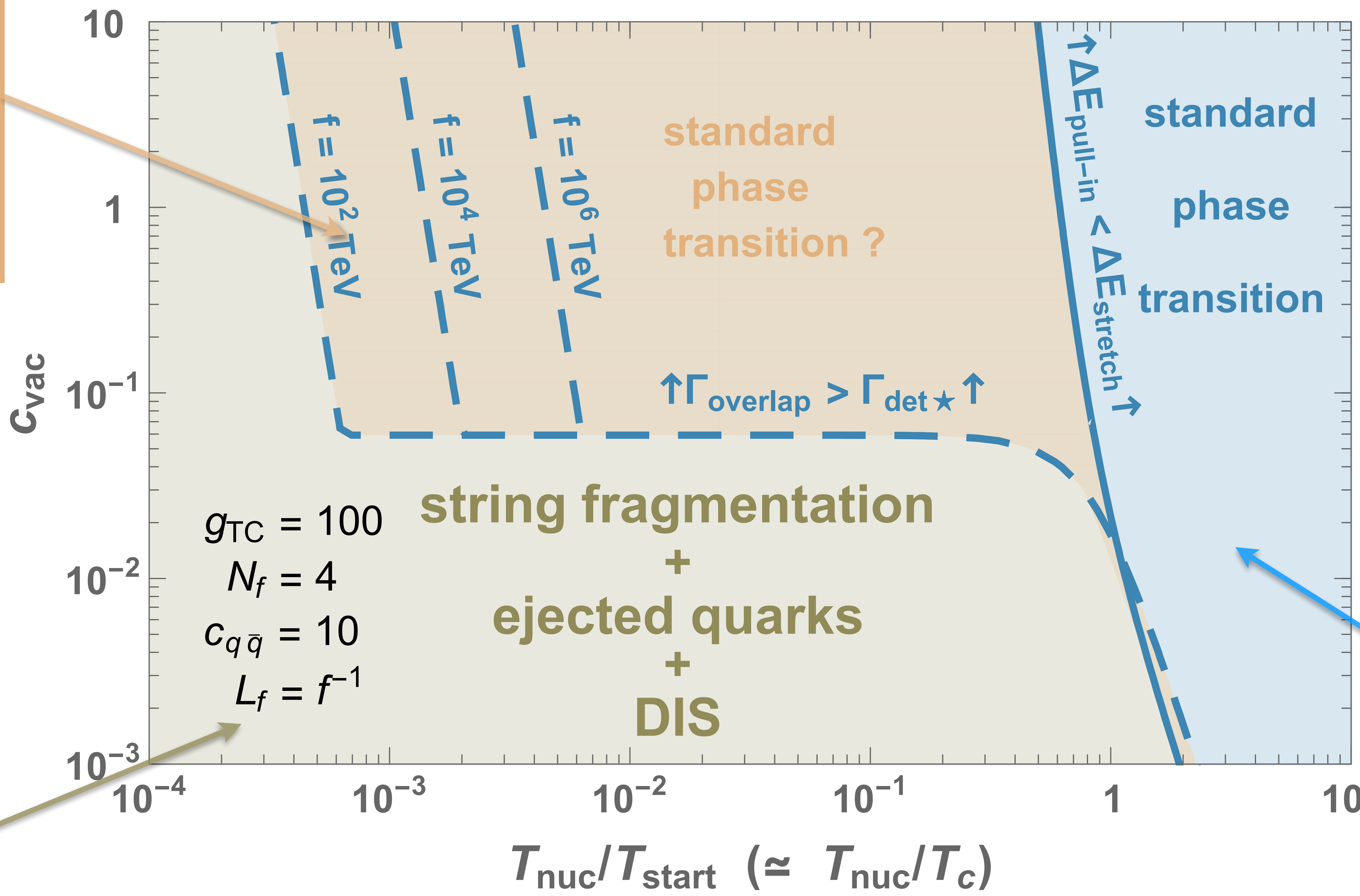

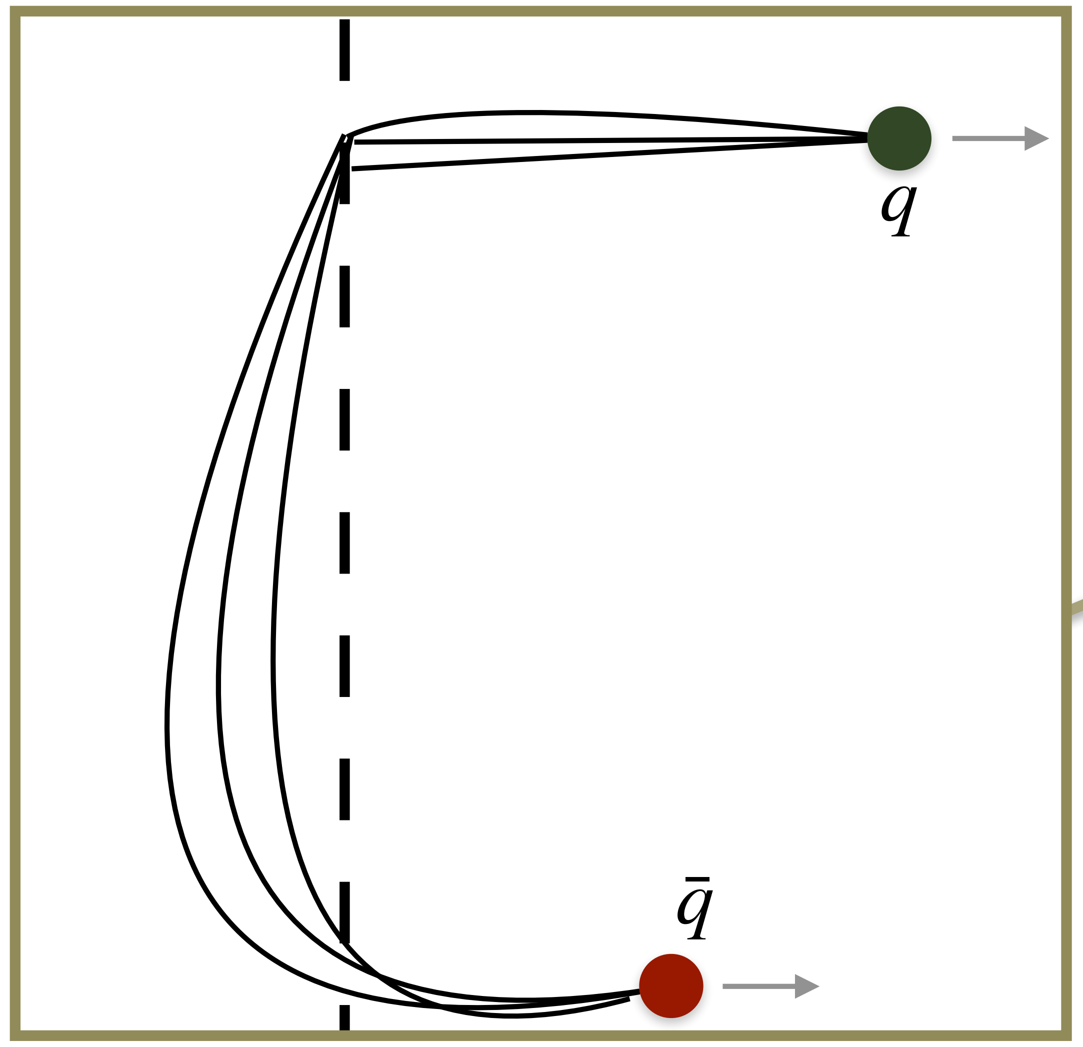

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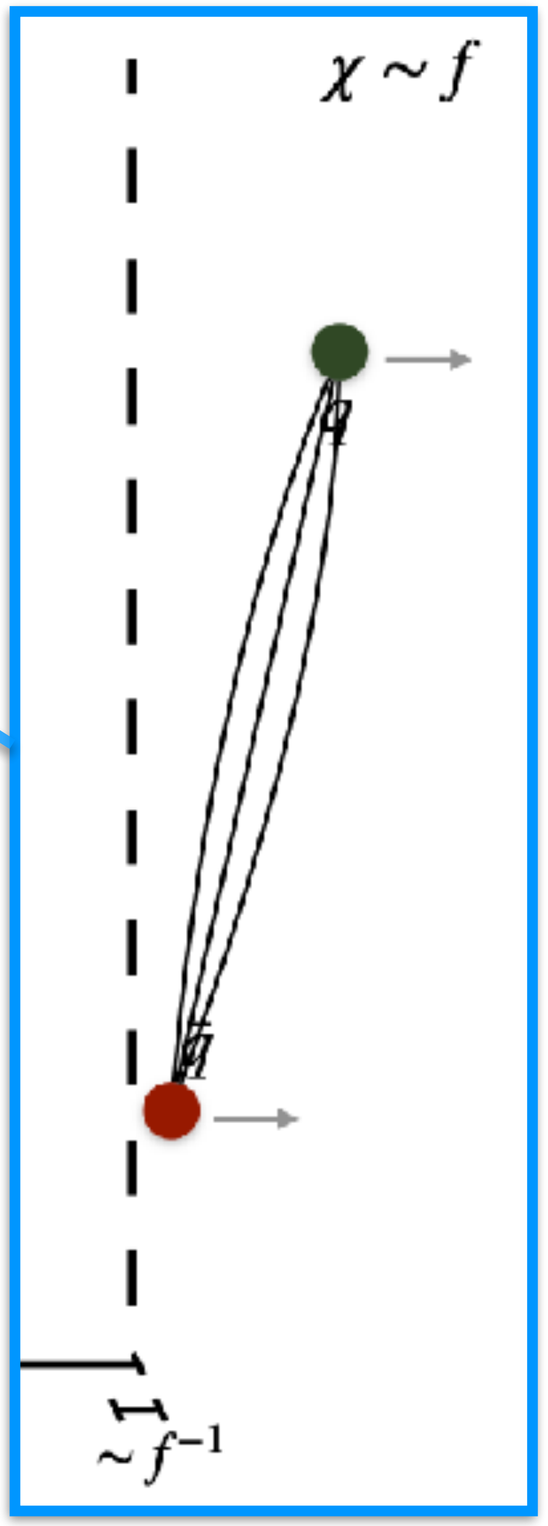

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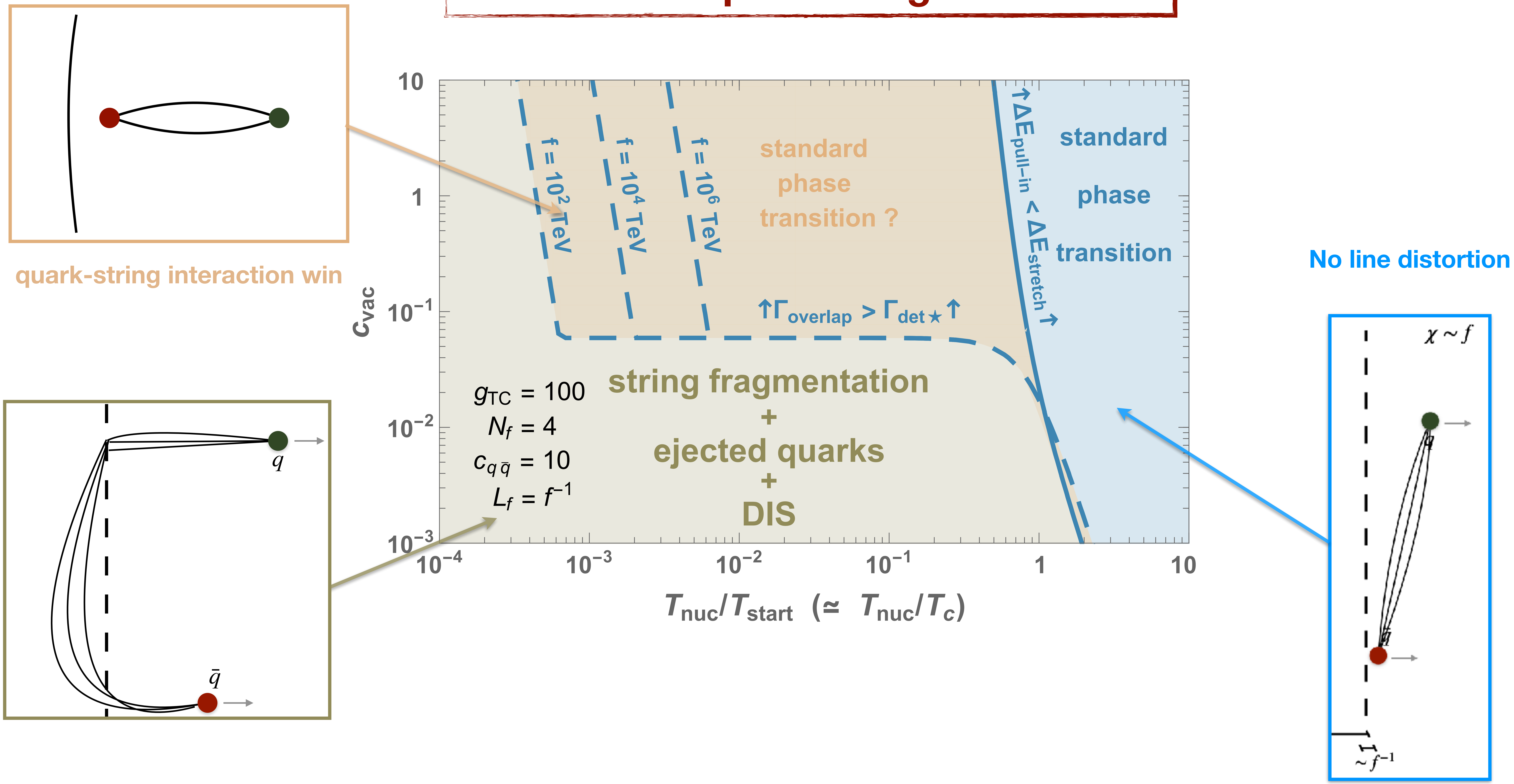

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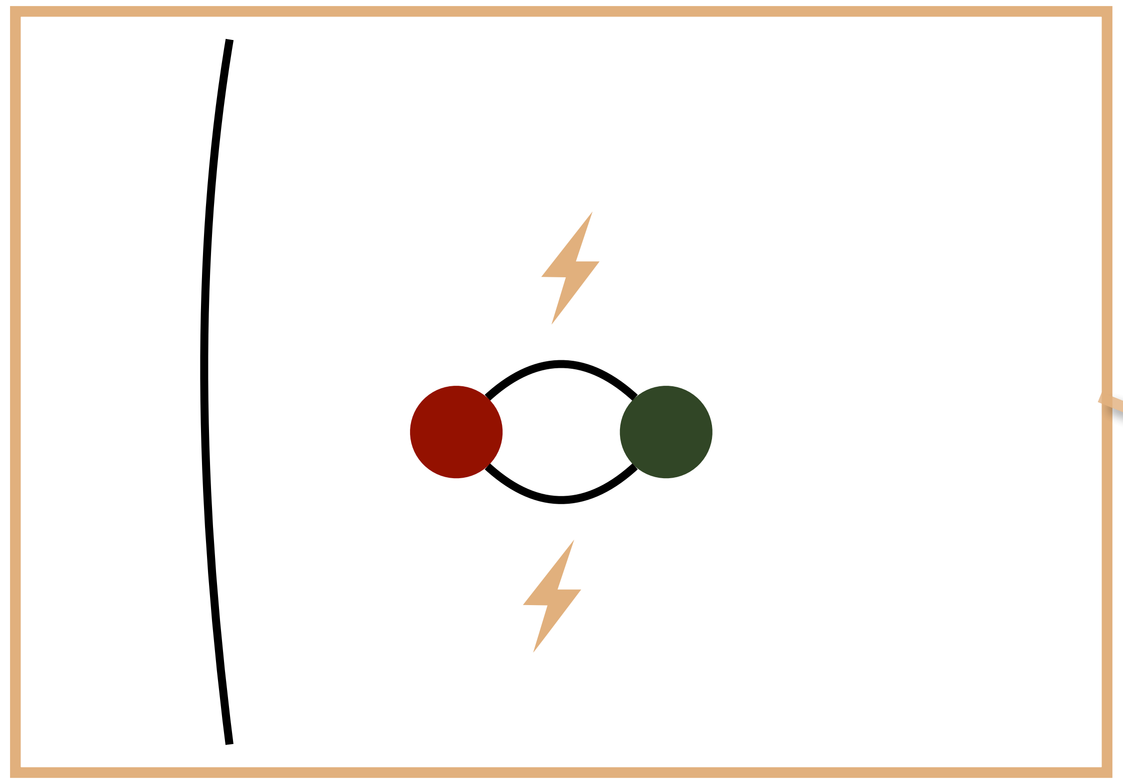
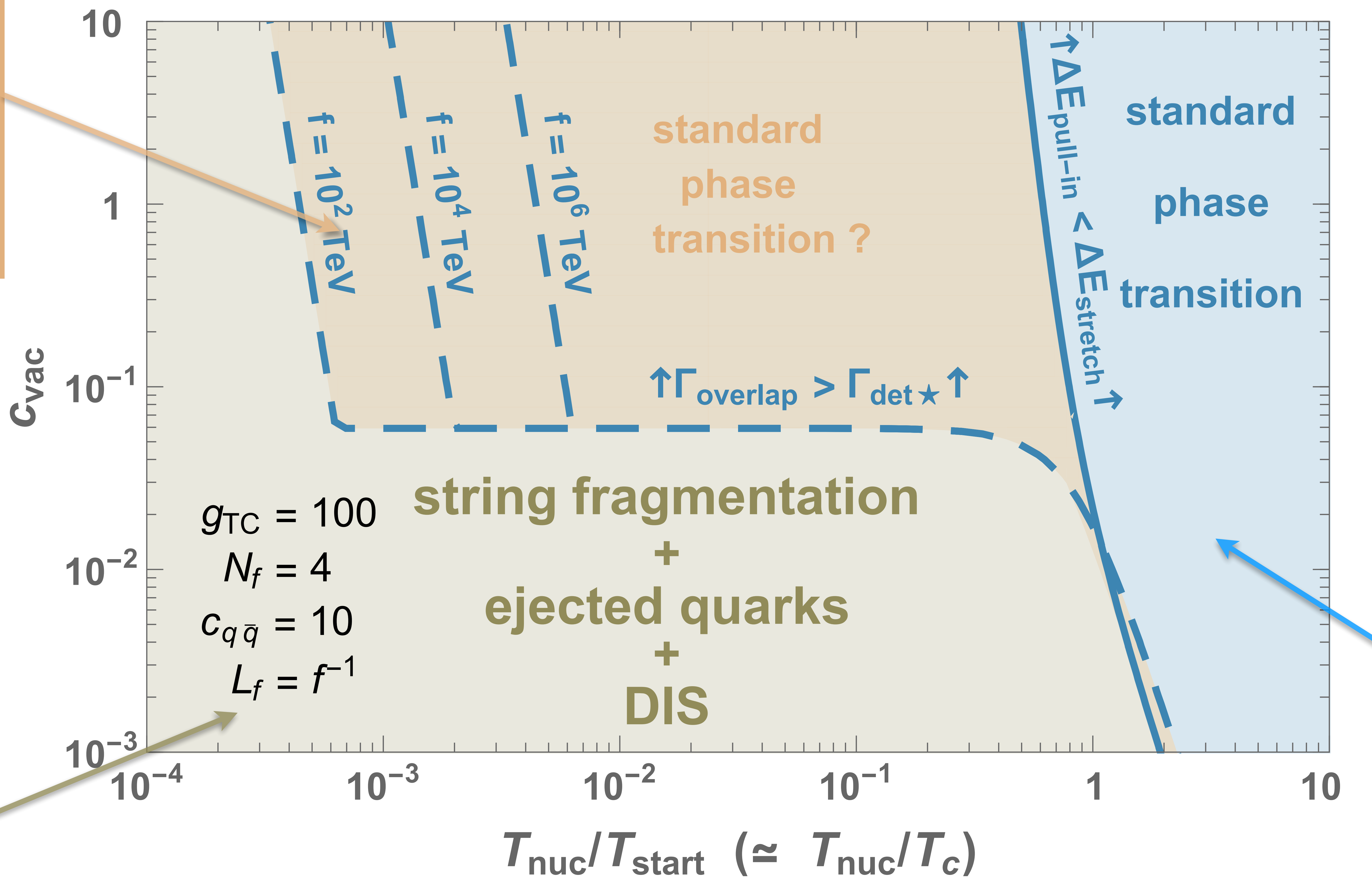
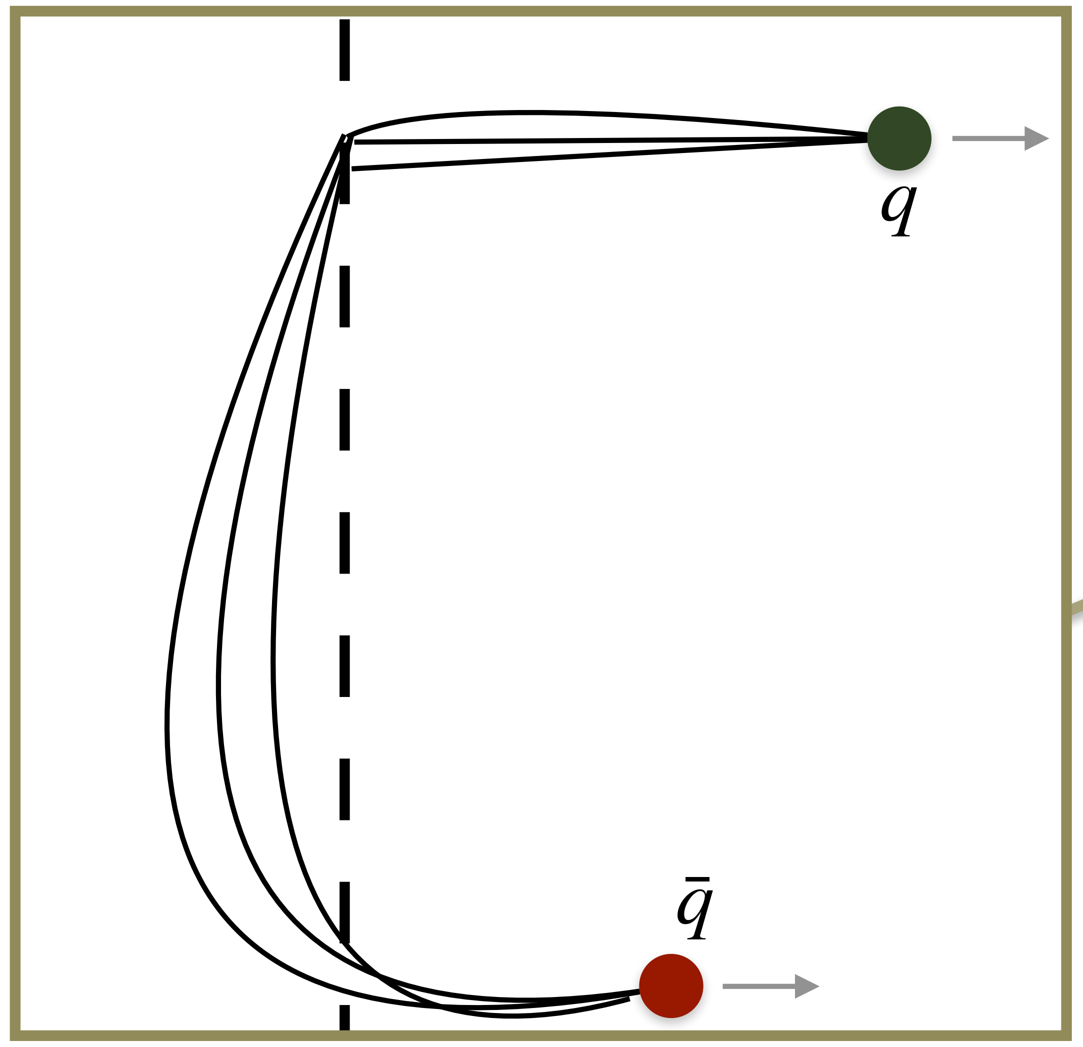


quark-string interaction win





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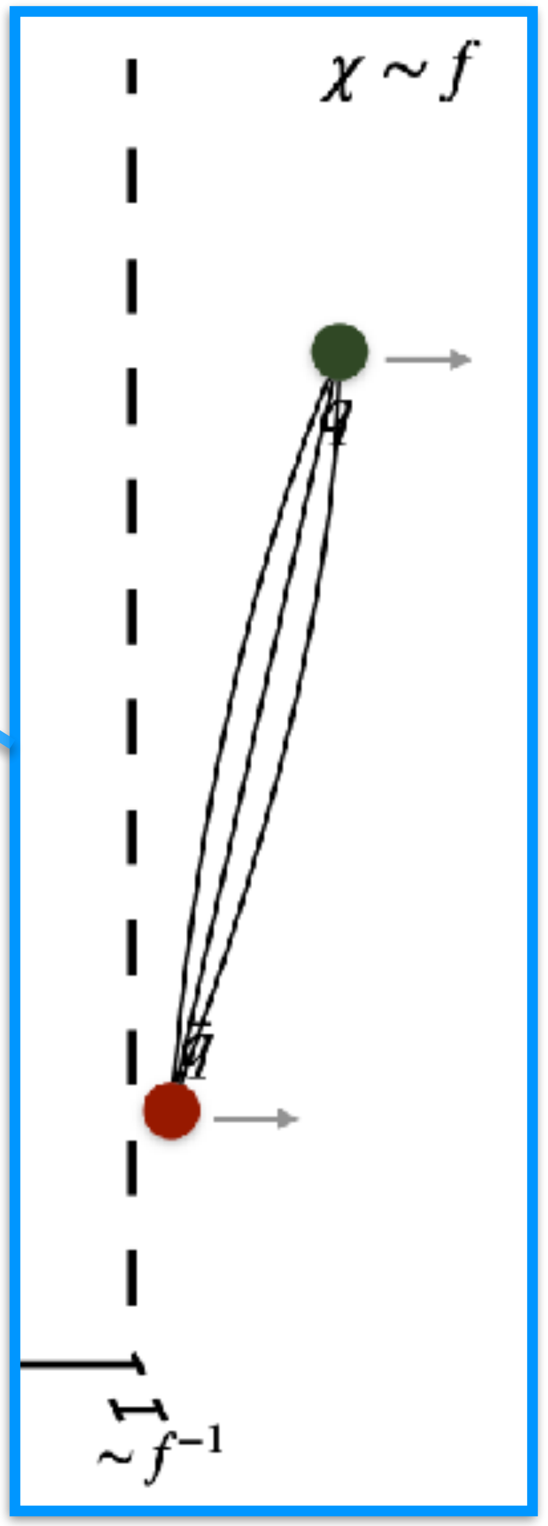

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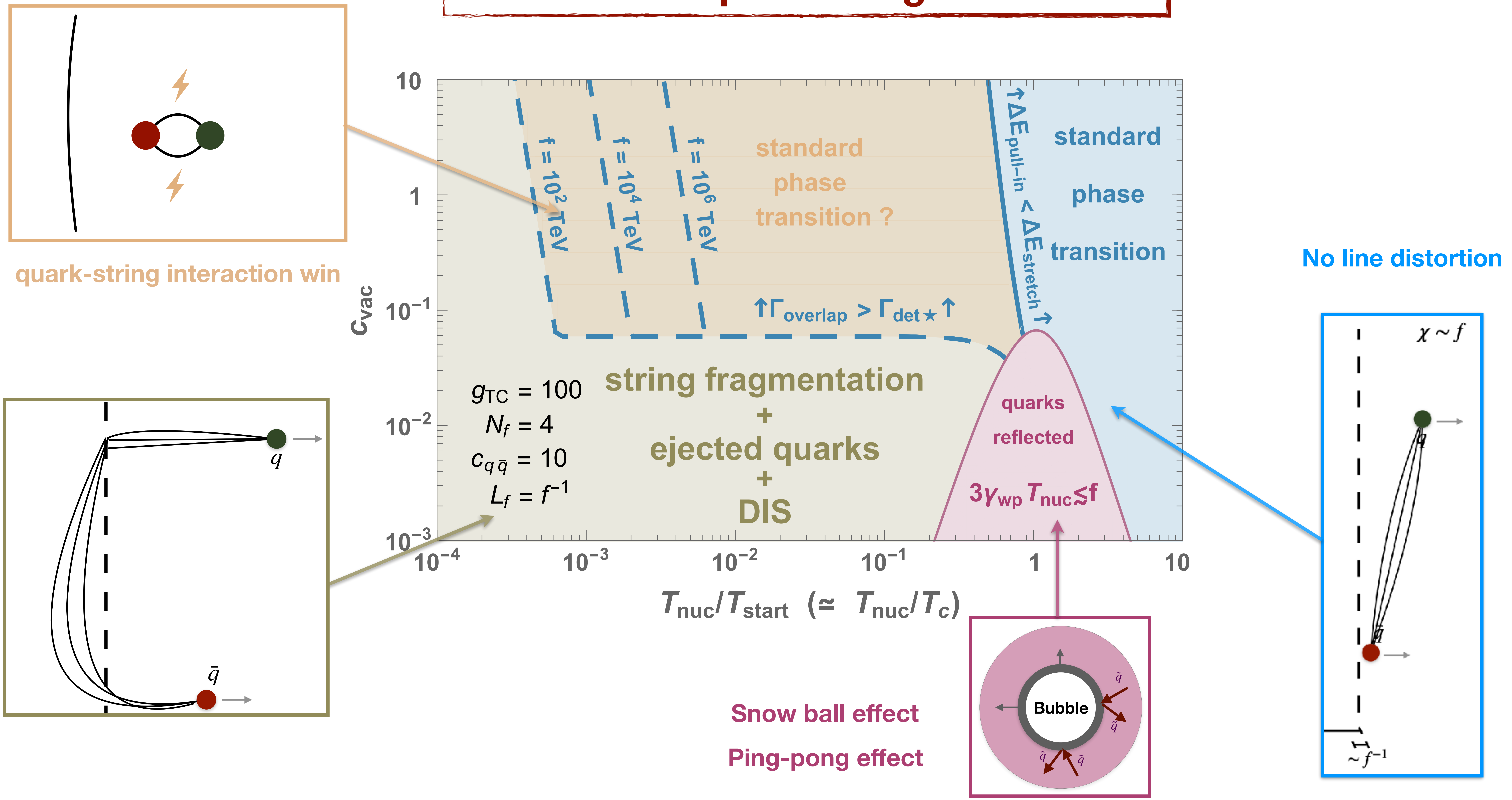


Conclusion

Supercooled confinement:

1. **Dilution + string fragmentation + cosmological catapult followed by DIS**

2. **Friction pressure grows linearly with** γ

3. **Should apply already for moderate Supercooling** $T_{\rm nuc} \lesssim T_{\rm c}$

Next directions:

- **Snowball effect ?**
- **Ping-Pong effect ?**
- **QCD phase transition ?**
- **Supercool PT in SU(N)/SUSY/Composite Higgs?**

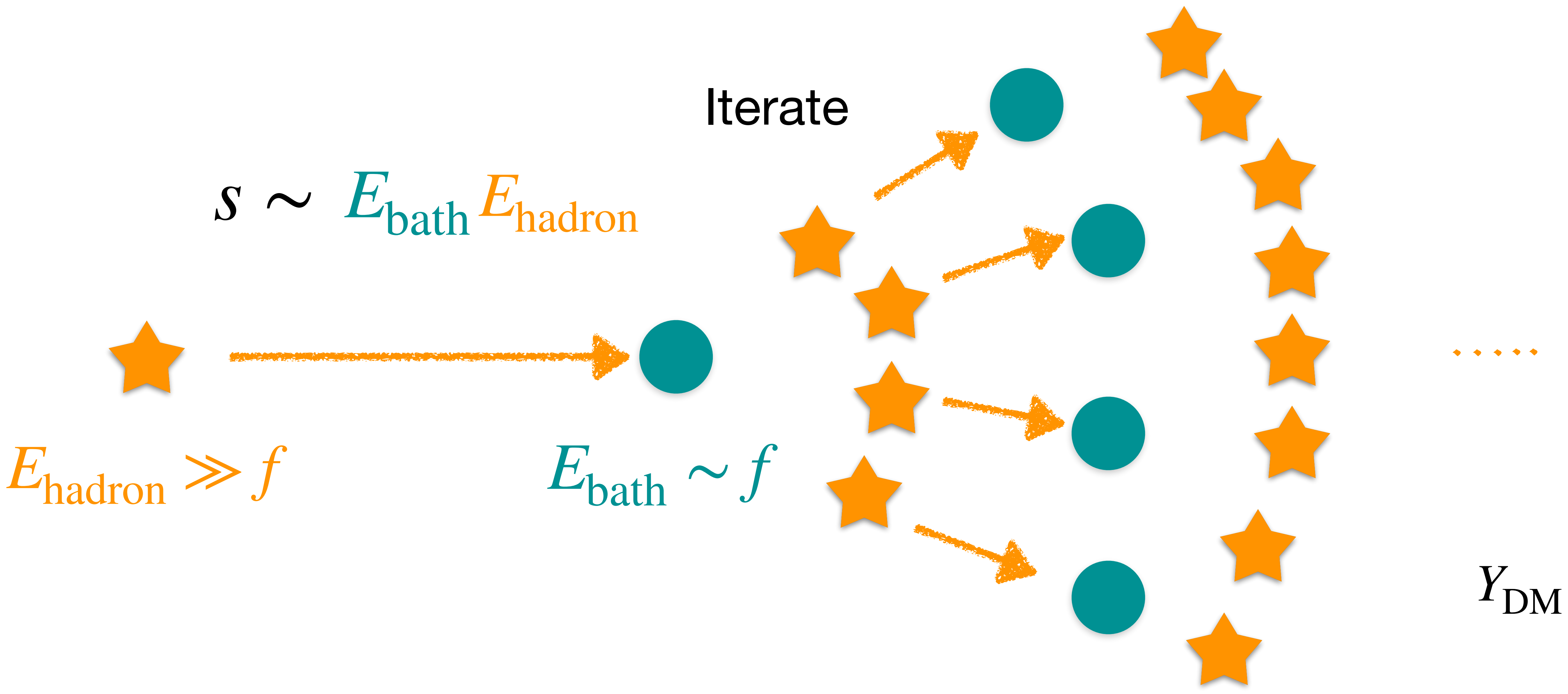
Additional slides

Deep Inelastic Scattering in the Early Universe

Hadron energy in plasma (= CMB) frame

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

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



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

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

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

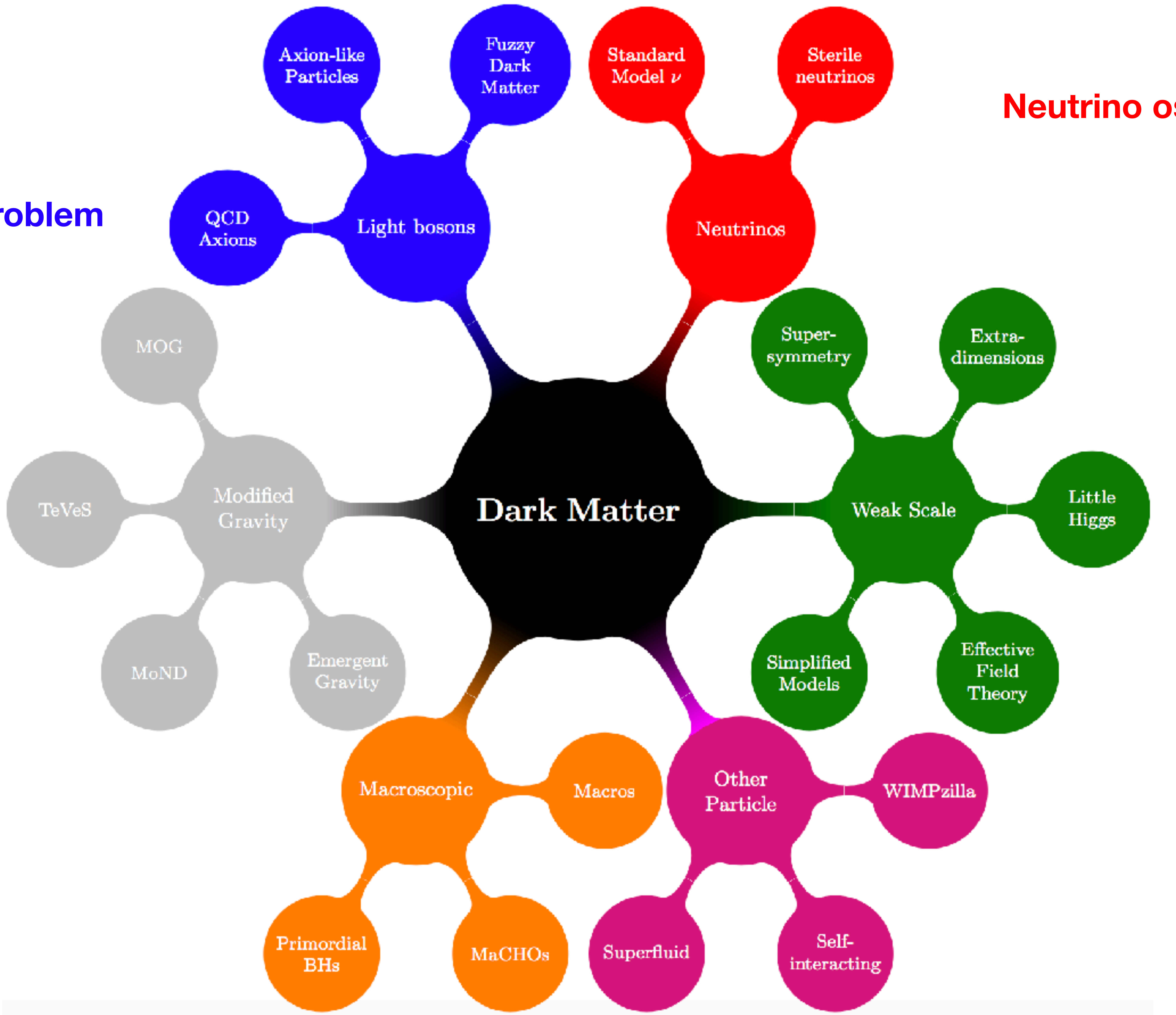
$$Y_{\rm DM} / Y_{\rm DM}^{\rm naive} \propto \langle N_{\rm hadron}\rangle \frac{s}{f^2} \propto \langle N_{\rm hadron}\rangle \frac{E_{\rm bath} E_{\rm hadrons,\,p}}{f^2} \propto \gamma_{\rm wp} \propto \frac{T_{\rm nuc}}{f} \frac{M_{\rm Pl}}{f}$$

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

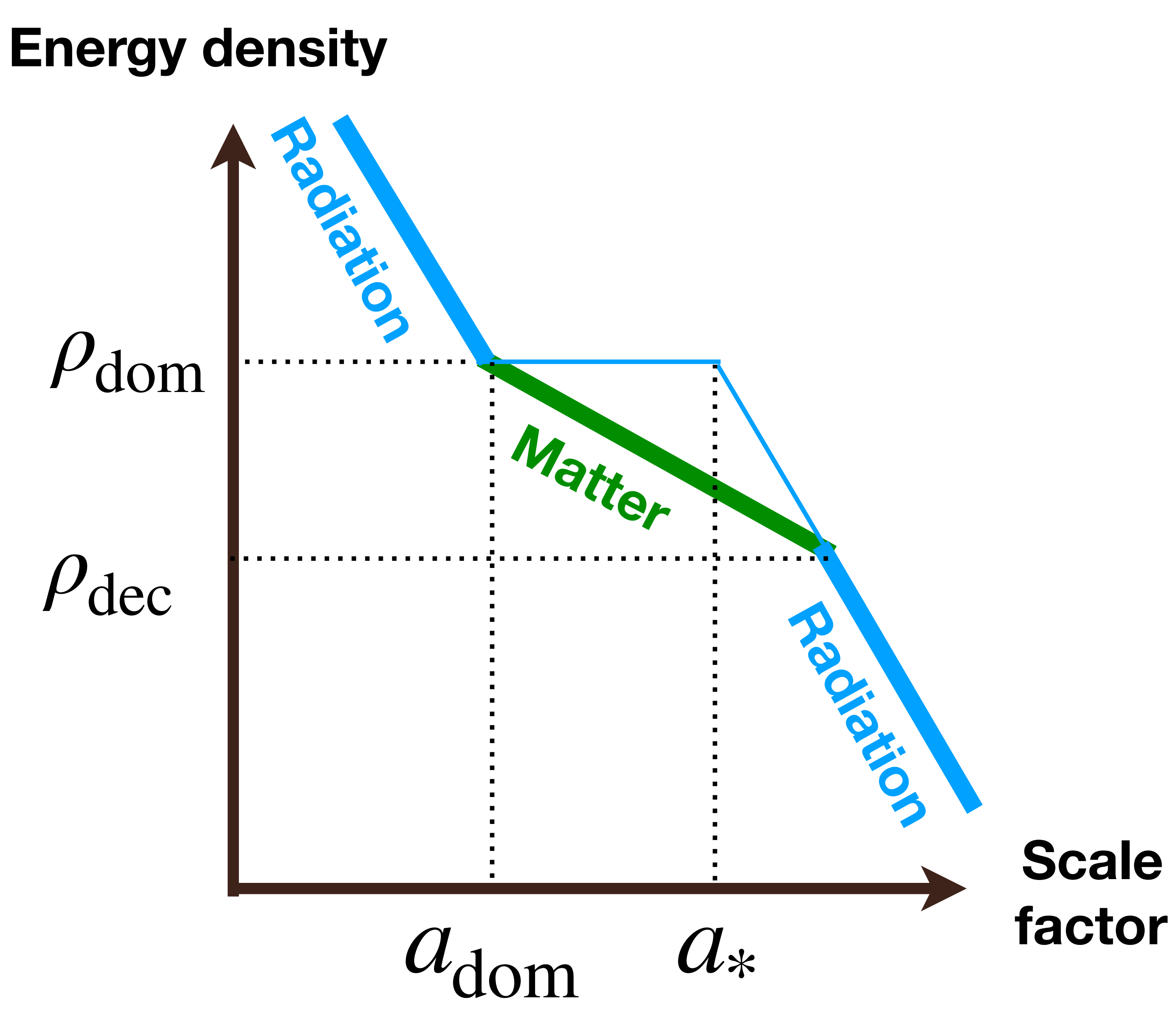
$$M_{\rm DM} \sim 1\ \text{TeV}, \qquad \alpha \sim \alpha_{\rm weak}$$

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

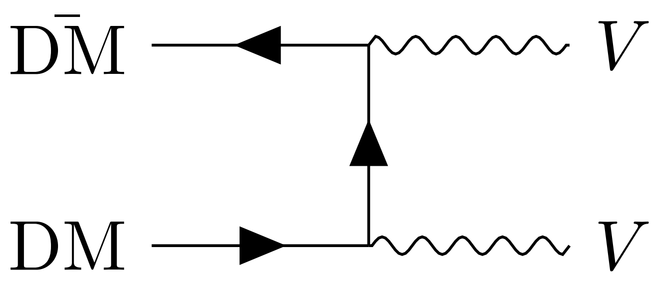
1) After a matter era

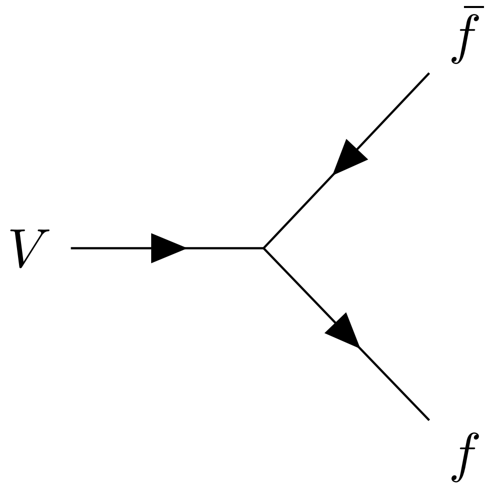


$$D = \left(\frac{a_{\rm dom}}{a_*}\right)^3 = \frac{T_{\rm dom}}{T_{\rm dec}} \simeq \frac{m_V}{\sqrt{M_{\rm pl}\Gamma_V}}$$

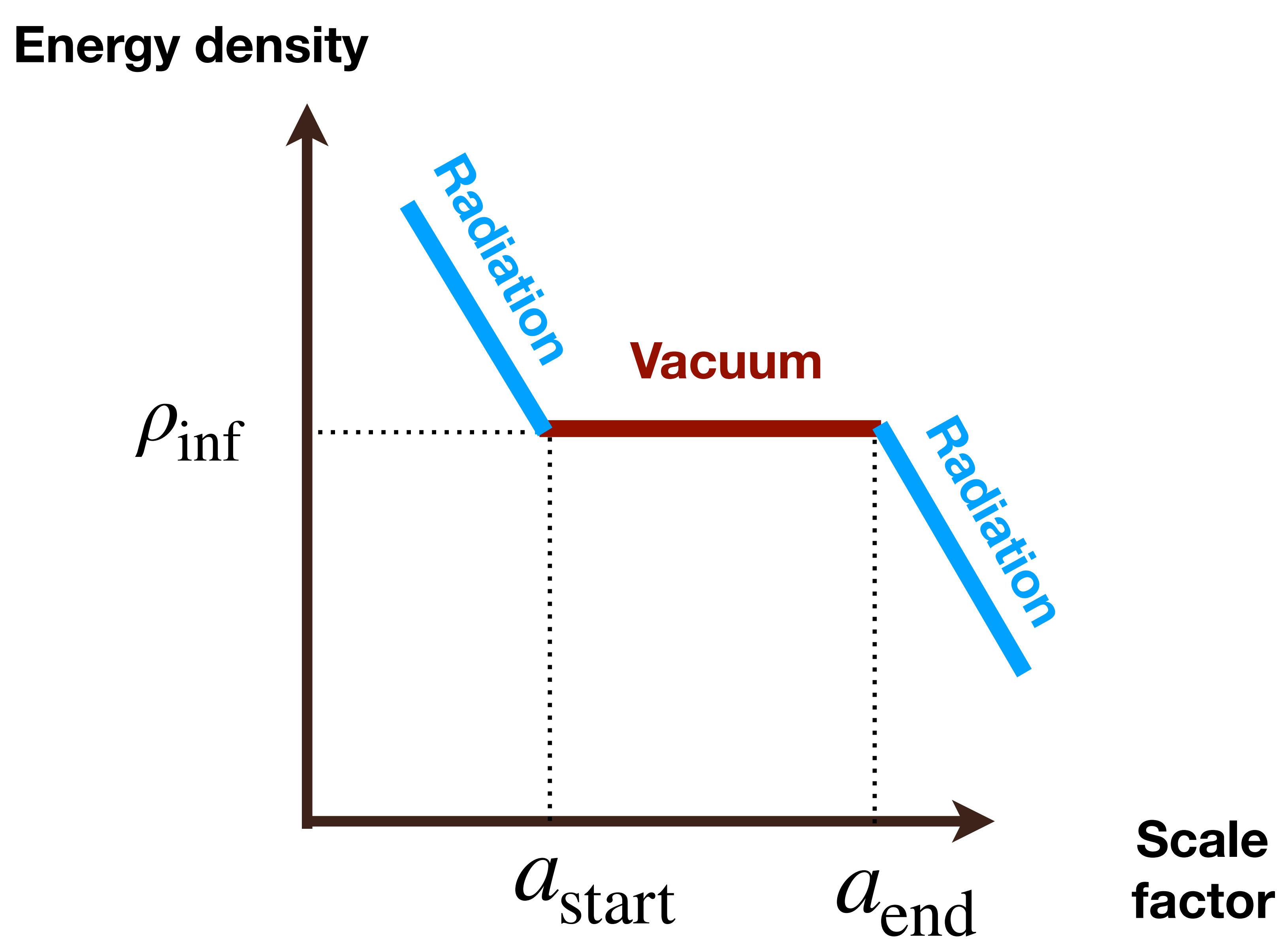
Homeopathic DM

Cirelli, Gouttenoire, Petraki, Sala, 2018





2) After an inflationary era



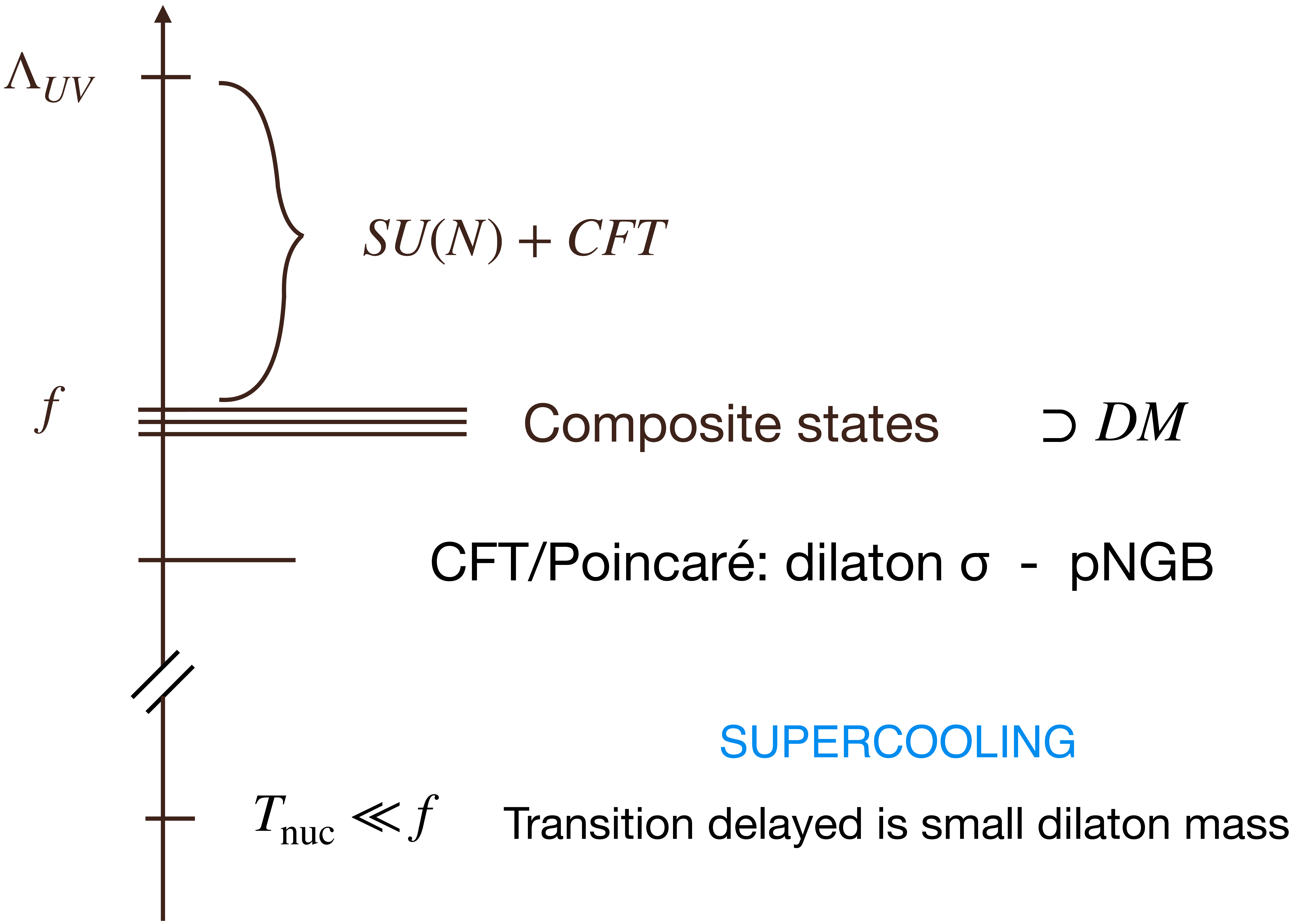
$$D = \left(\frac{a_{\rm end}}{a_{\rm start}}\right)^3 = e^{3\,N_e} = \left(\frac{f}{T_{\rm nuc}}\right)^3$$

Supercooled confinement

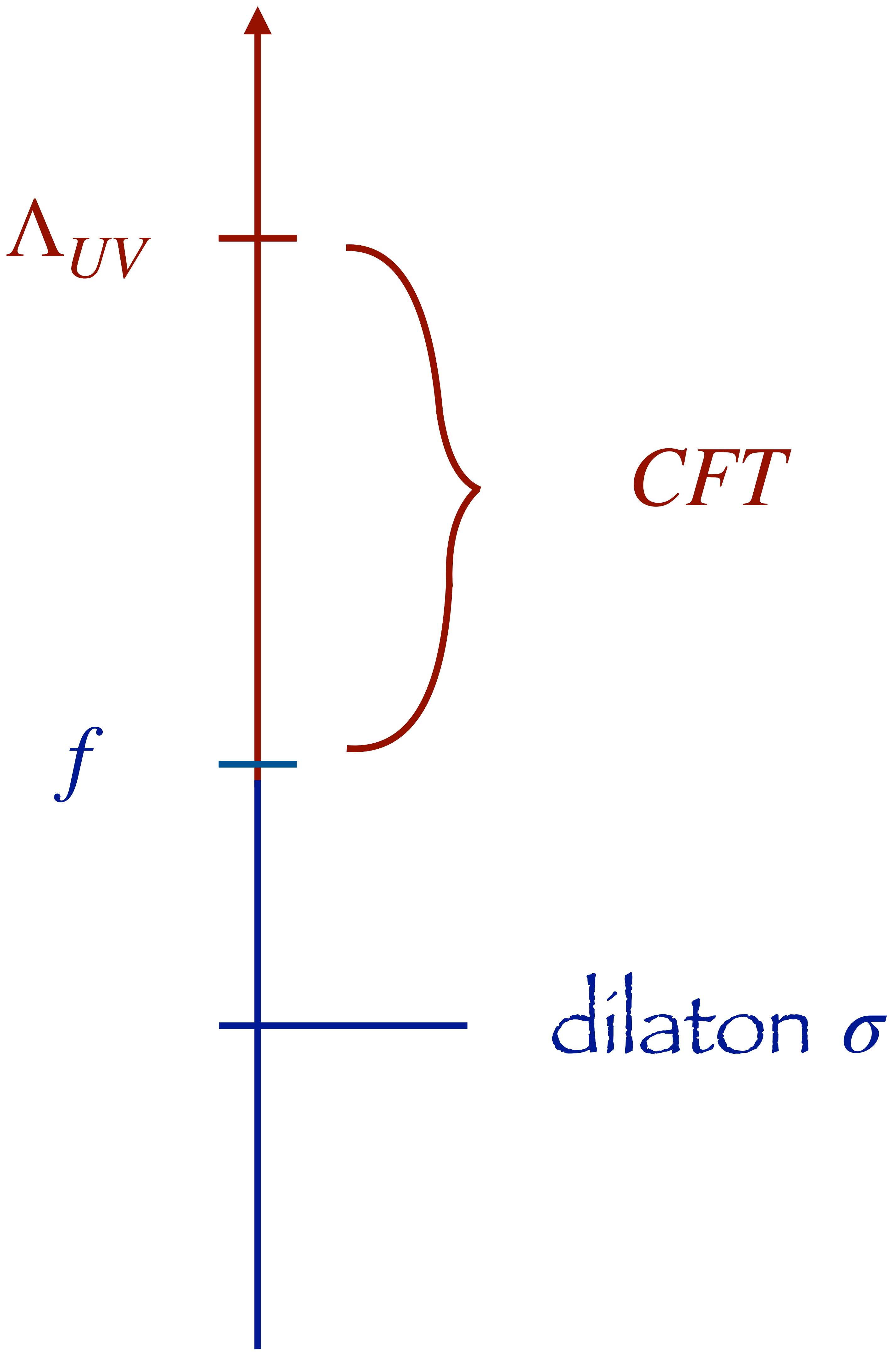
Baldes, Gouttenoire, Sala, 2020

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

Nearly-conformal strong sector



Nearly-conformal strong sector



Deconfined phase

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

Confined phase

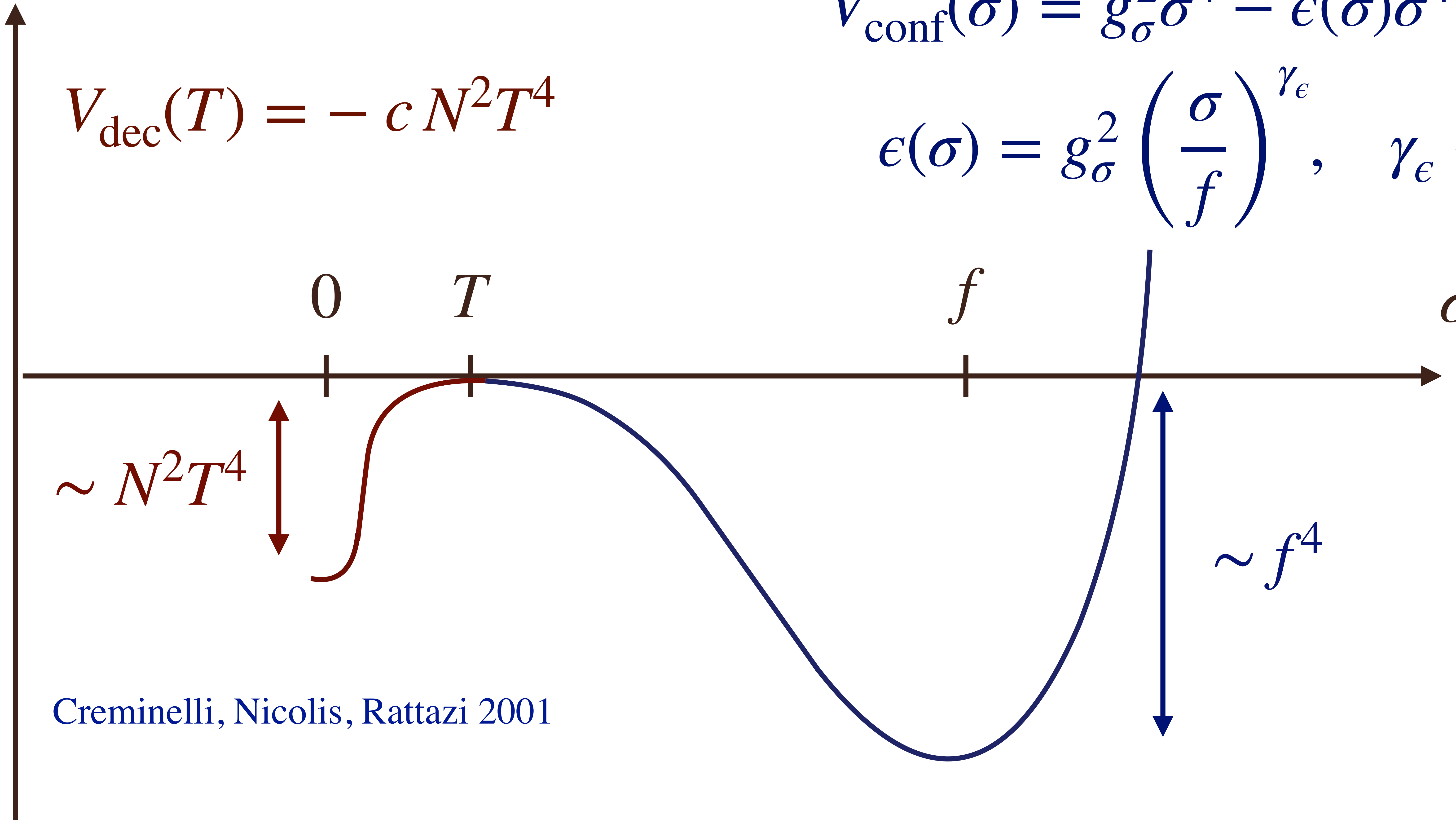
$$V_{\text{conf}}(\sigma) = g_\sigma^2\sigma^4 - \epsilon(\sigma)\sigma^4$$

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

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

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

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



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

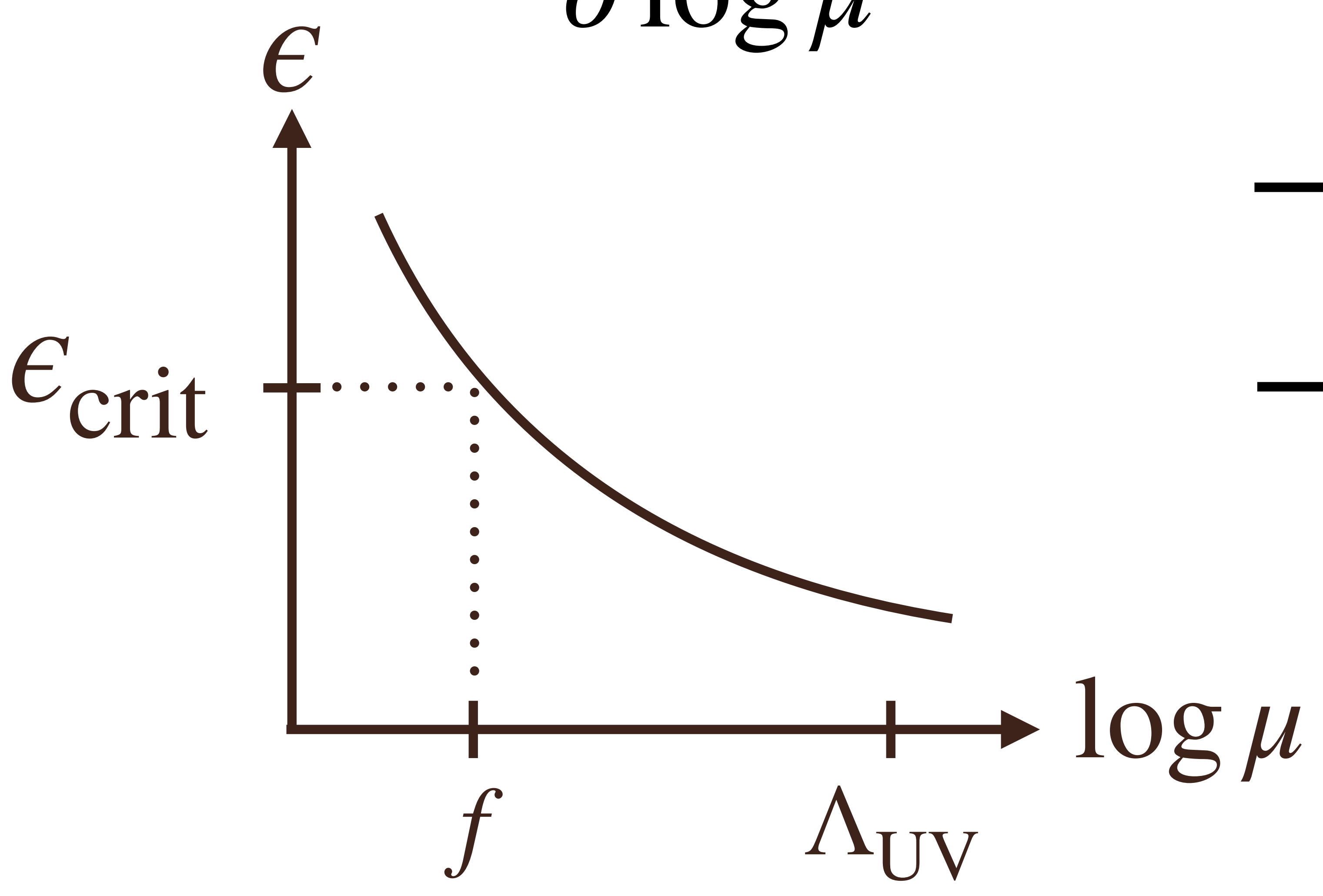
ends for: $T_{\rm nuc} \sim c_1 f \ \mathrm{Exp} - \mathrm{c}_2 \dfrac{\mathrm{f}^2}{\mathrm{m}_\sigma^2}$

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

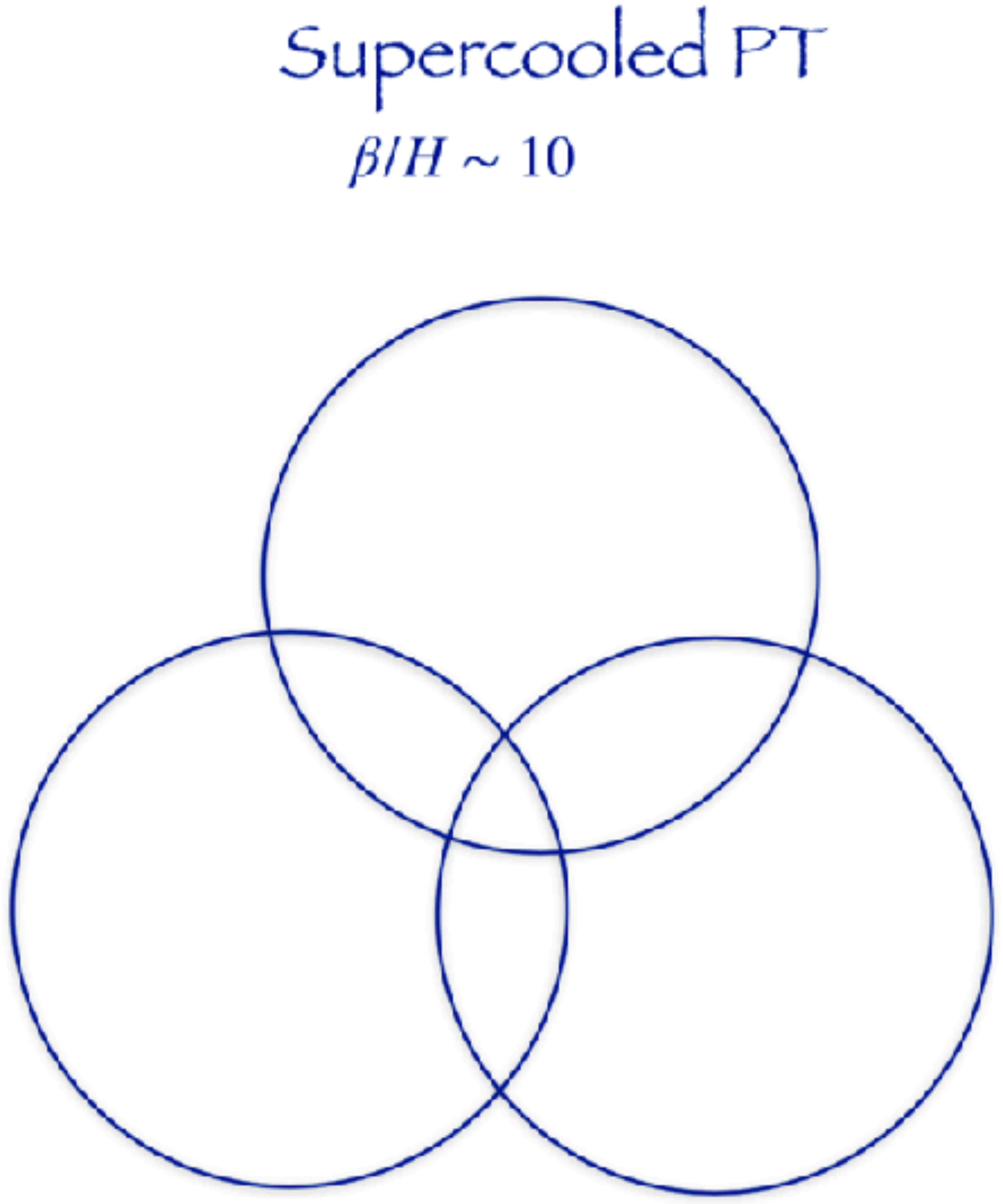
$$V_{\rm conf}(\sigma) = \left(1 - \left(\frac{\sigma}{f}\right)^{\gamma_\epsilon}\right) g_\sigma^2 \sigma^4$$

Gravitational Waves from Phase Transition

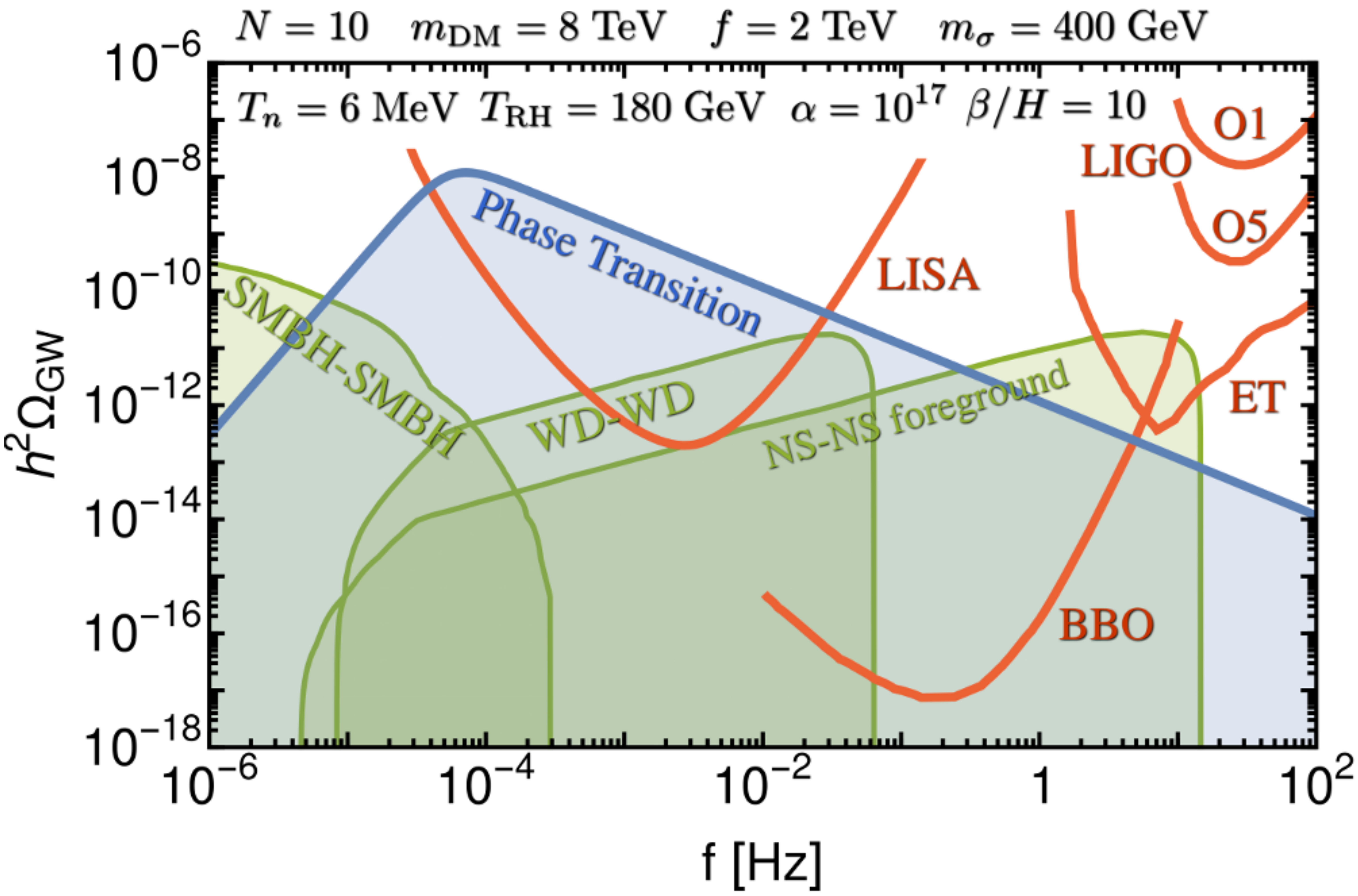
Randall Servant hep-ph/0607158,…

$$\Omega_{\mathrm{GW}} \propto \left(H/\beta\right)^2 \qquad \beta^{-1} \sim \text{duration of PT}$$

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



Gravitational Waves from Phase Transition



Nucleation Temperature

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

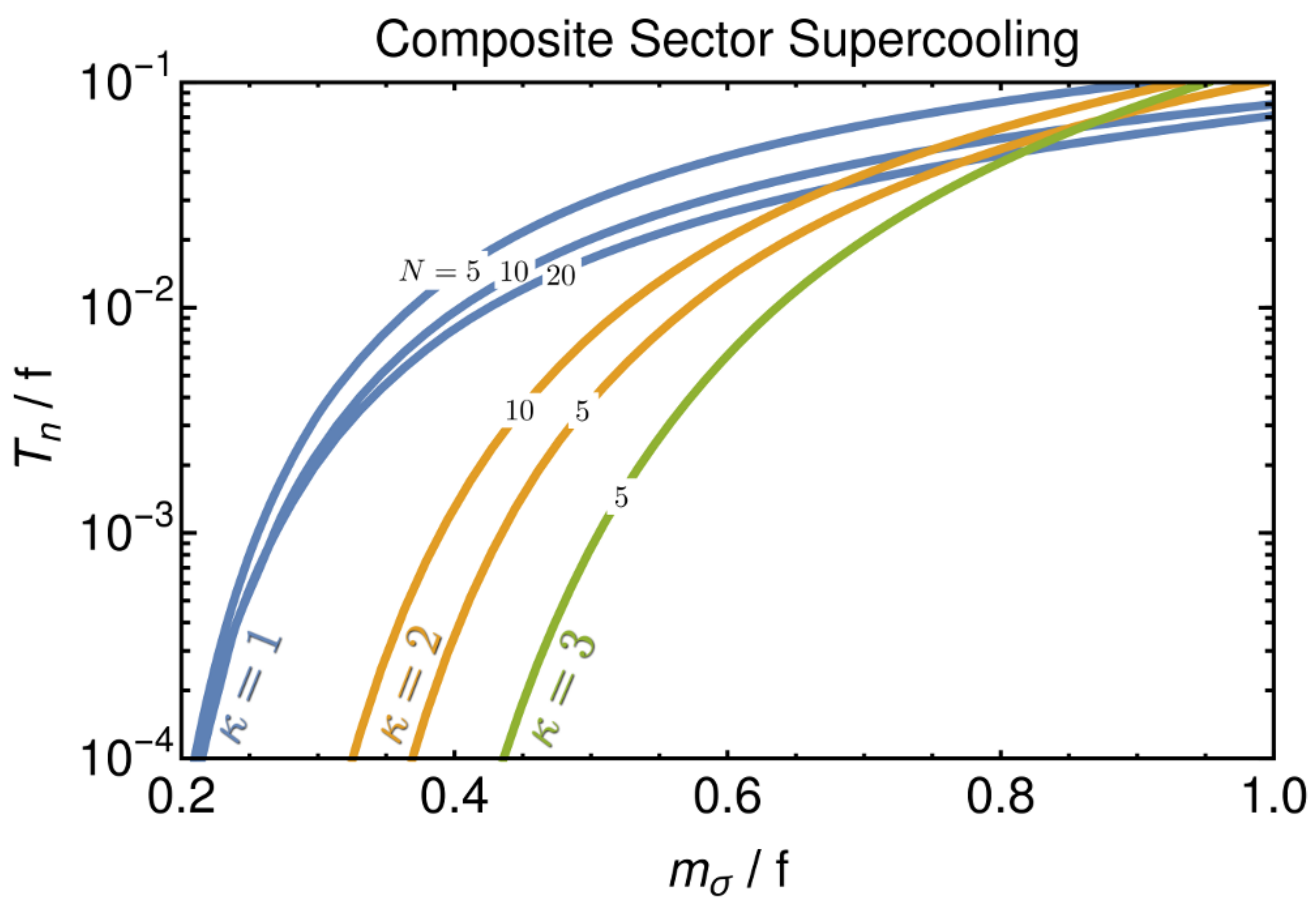
Bubble nucleation ends SC at $$\boxed{T_{\text{nuc}} \sim f \exp\left(-c\,\frac{f^2}{m_\sigma^2}\right)}$$

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

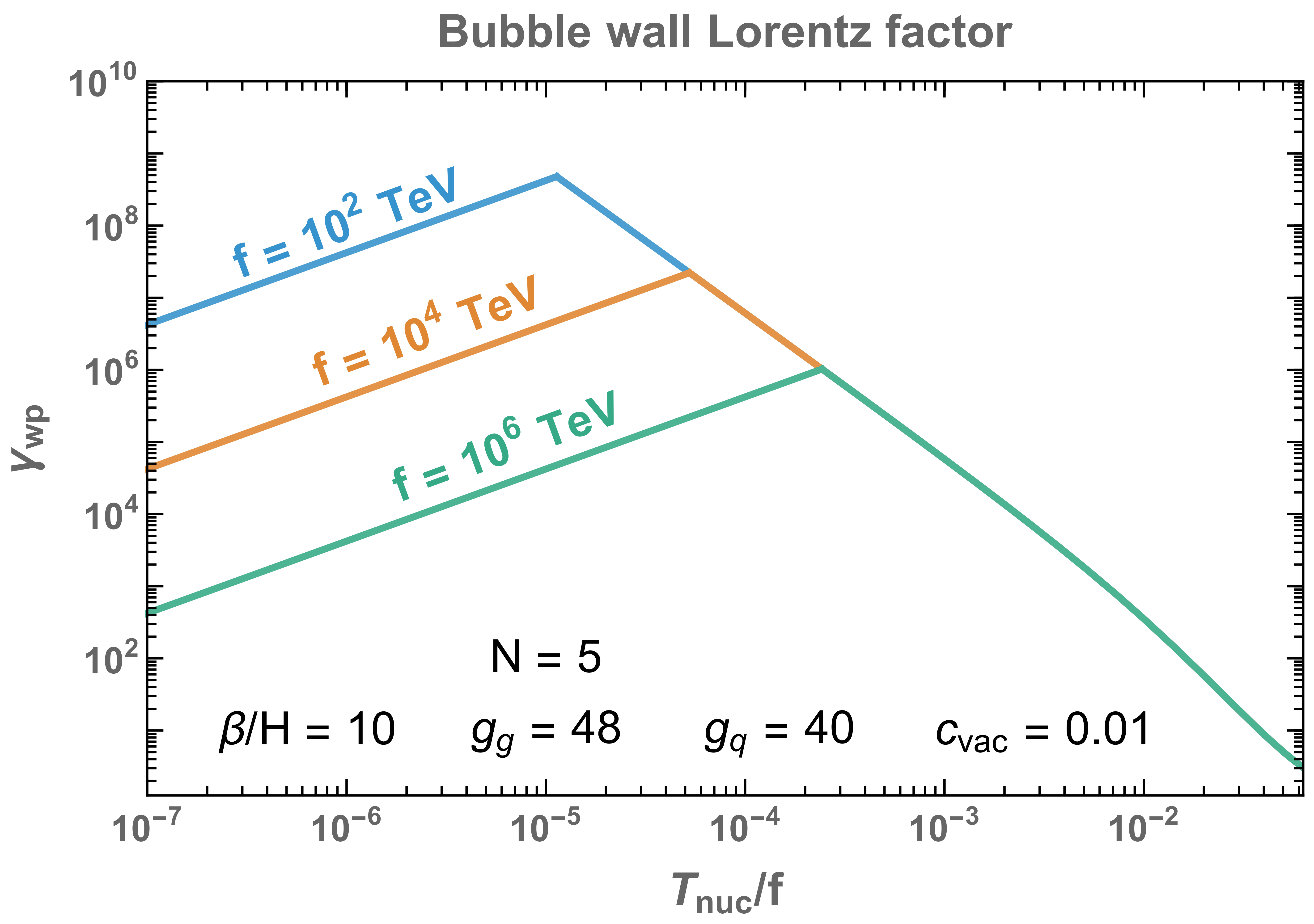
Iso Serpico Shimada 1704.04955

von Harling Servant 1711.11554

→ Catalysed by black holes ?

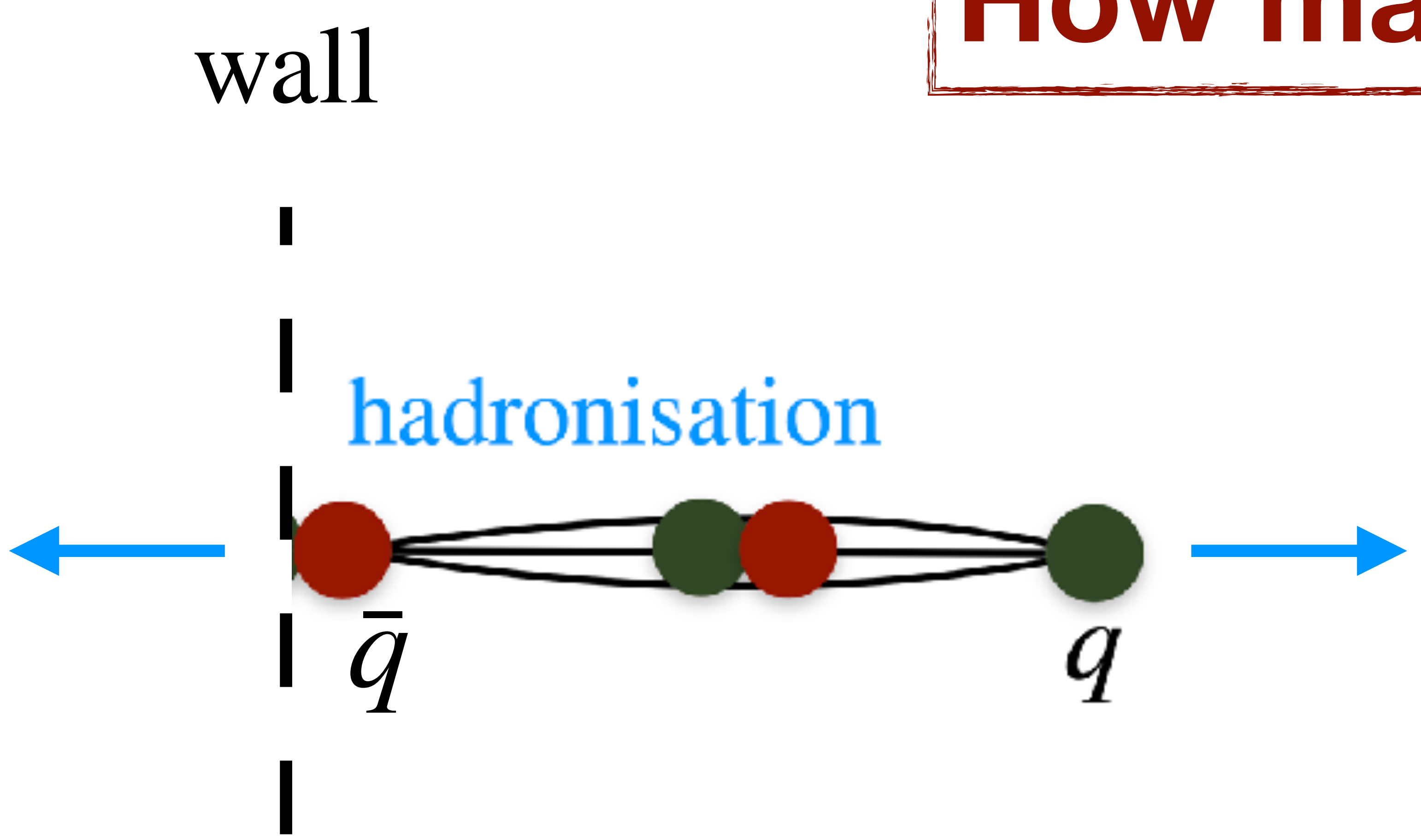
Gregory, Moss, Withers 15

Mukaida, Yamada 17



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

How many hadrons ?



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

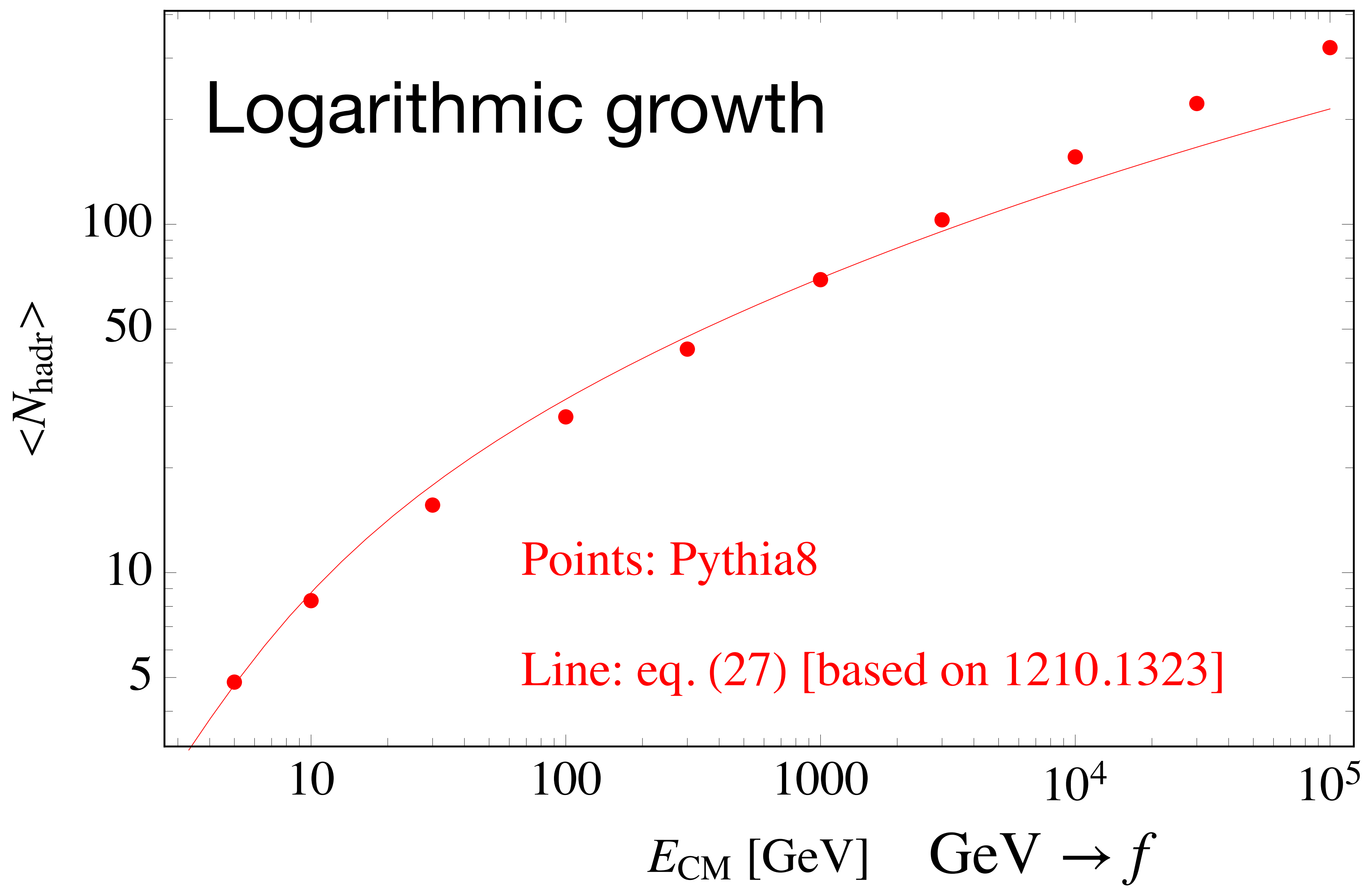
Analogous to $e^+e^- \to q\bar{q}$ in QCD

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

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

Standard Supercooling

Branching ratio quark -> DM

String fragmentation

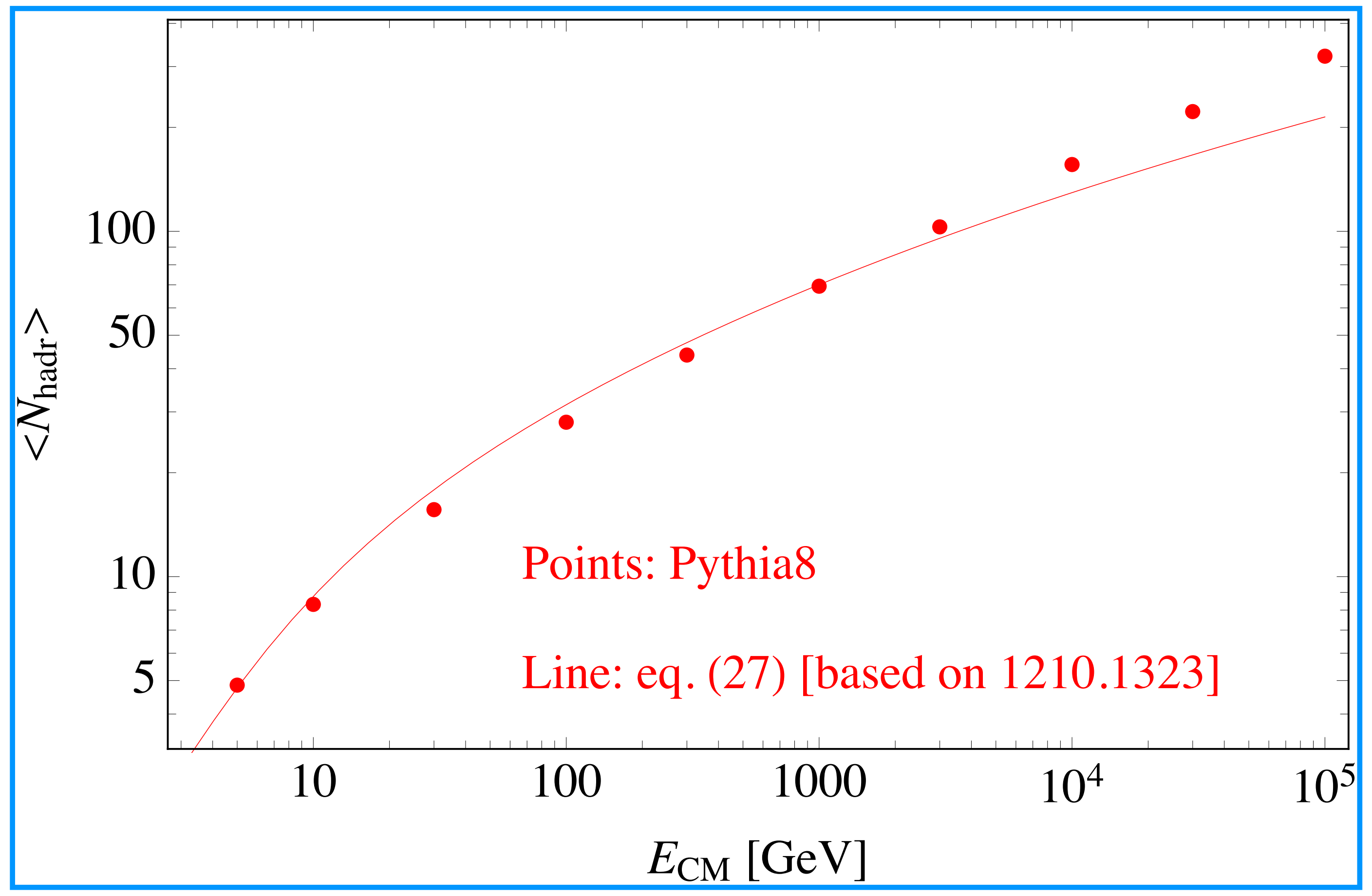
2 possibilities:

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



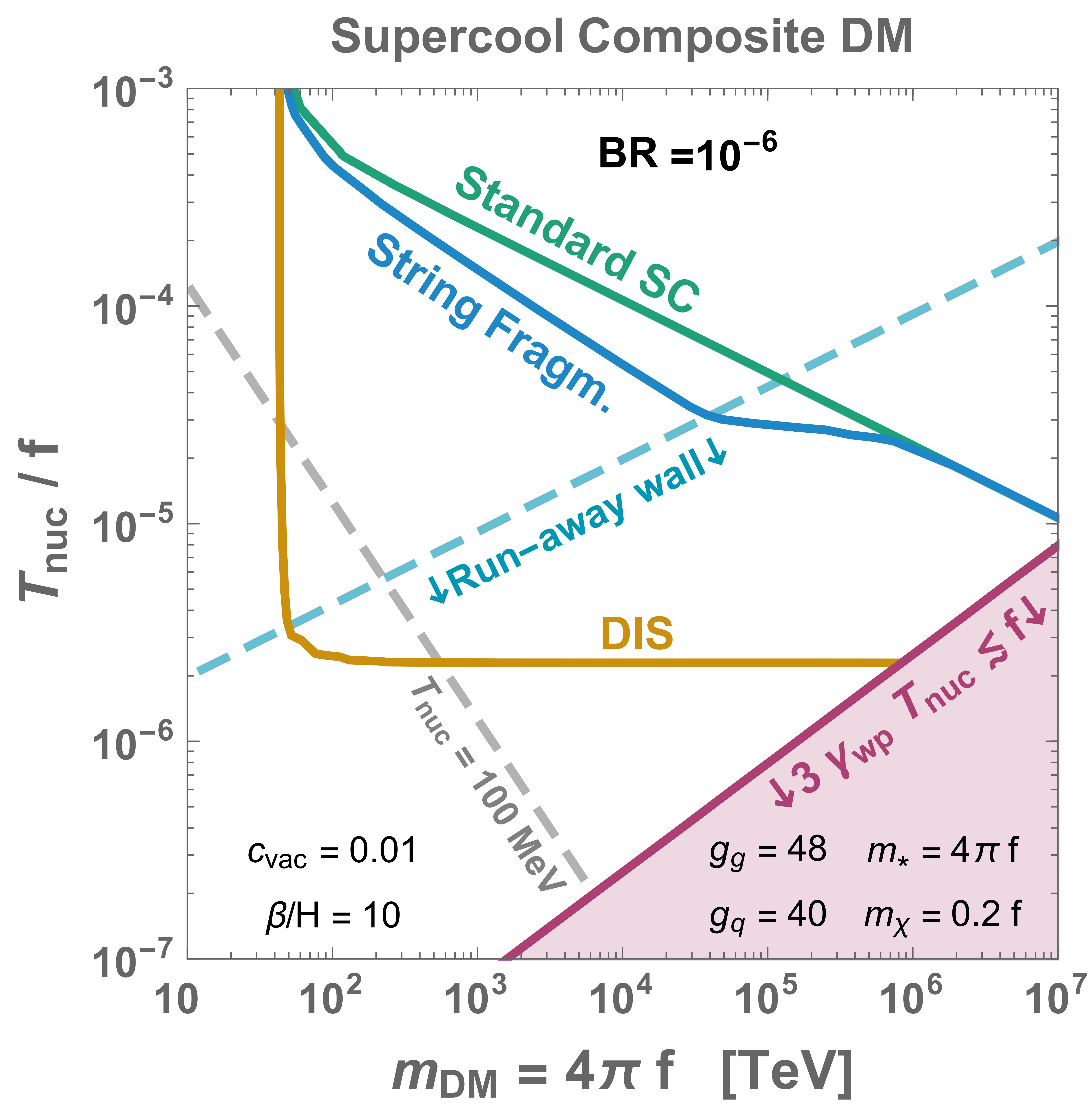
O(1) fraction of initial hadron energy converted into hadron masses

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

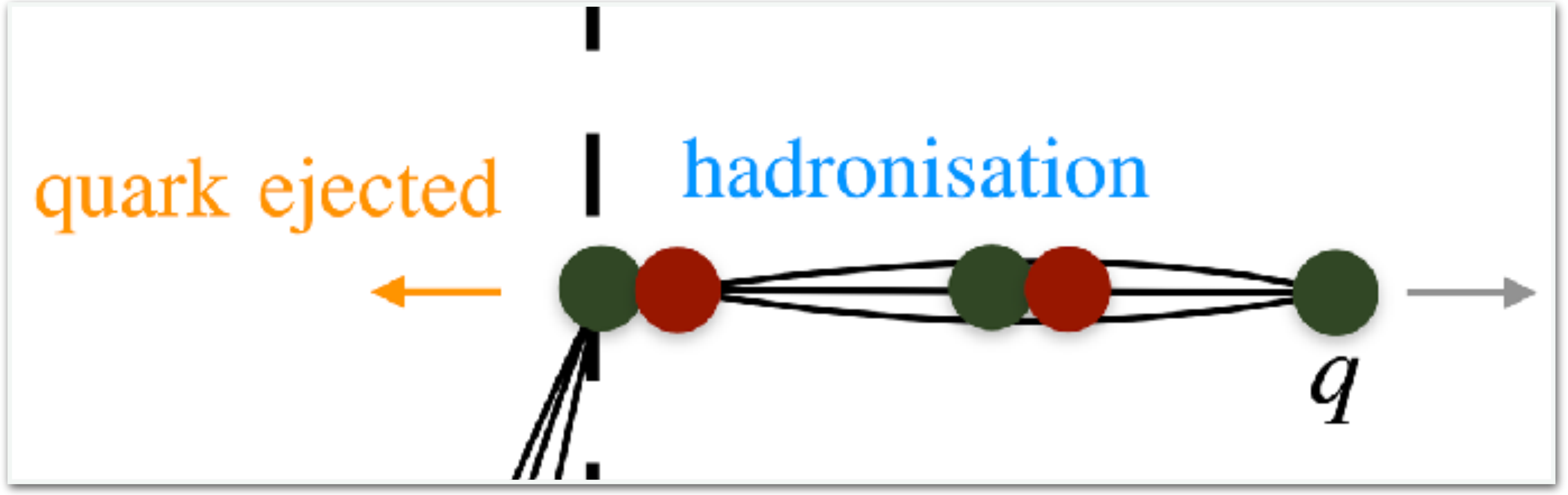
$$\langle E_{\rm hadron}\rangle = \frac{E_{\rm cm}^{q\bar q}}{\langle N_{\rm hadron}\rangle} \sim \frac{\sqrt{\gamma_{wp} f / T_{\rm nuc}}}{\langle N_{\rm hadron}\rangle} \gg f$$

$$\frac{\gamma_{cp} E_{q\bar q}^{\rm CM}}{\langle N_{\rm hadr}\rangle}$$

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



Supercool Composite DM
BR =10^{-6}
Standard SC
String Fragm.
↓Run–away wall↓
DIS
T_{nuc} = 100 MeV
↓3 γ_{wp} $T_{nuc} \lesssim$ 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]
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10
10^2
10^3
10^4
10^5
10^6
10^7

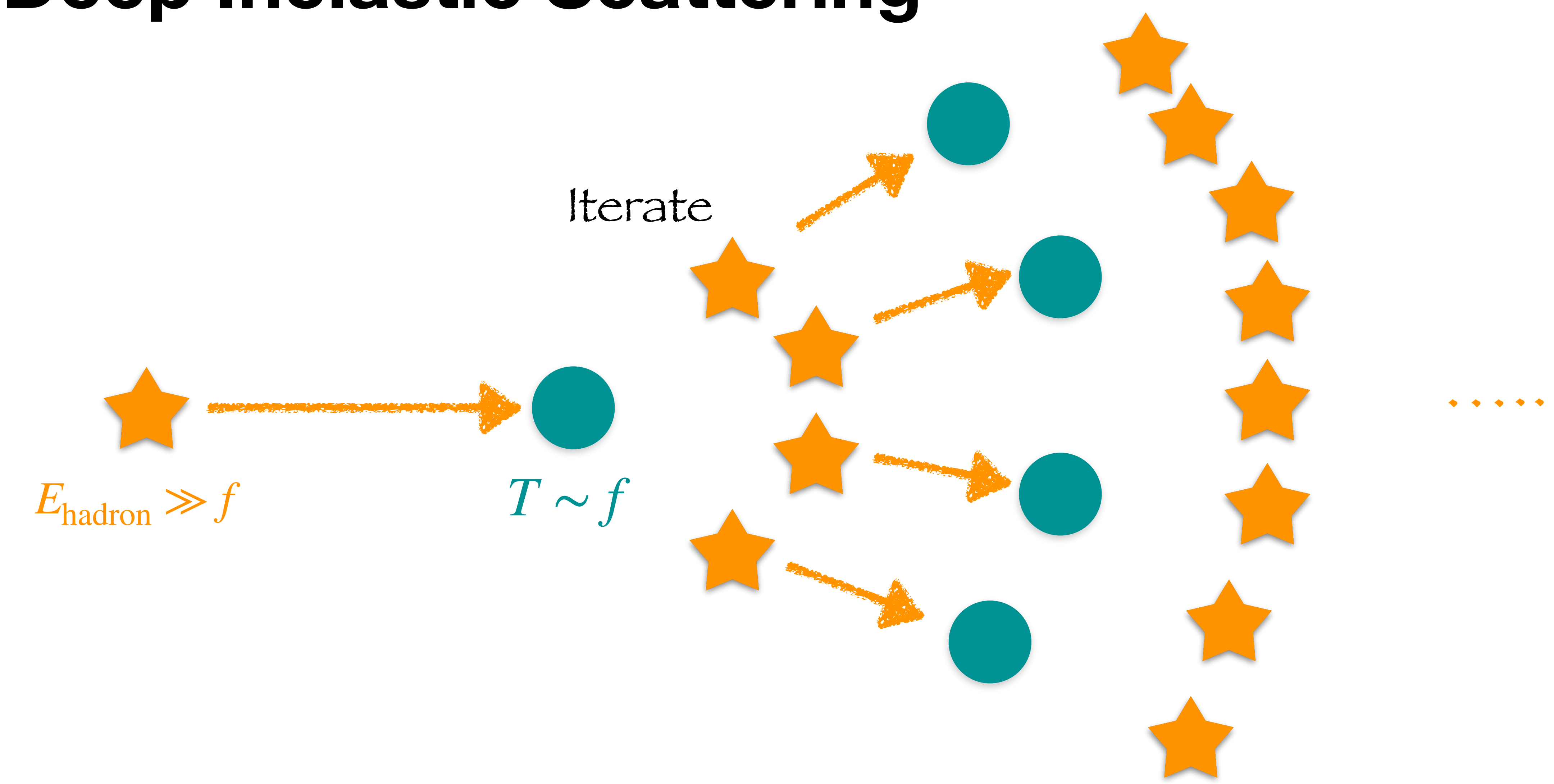


Consequences on DM abundance

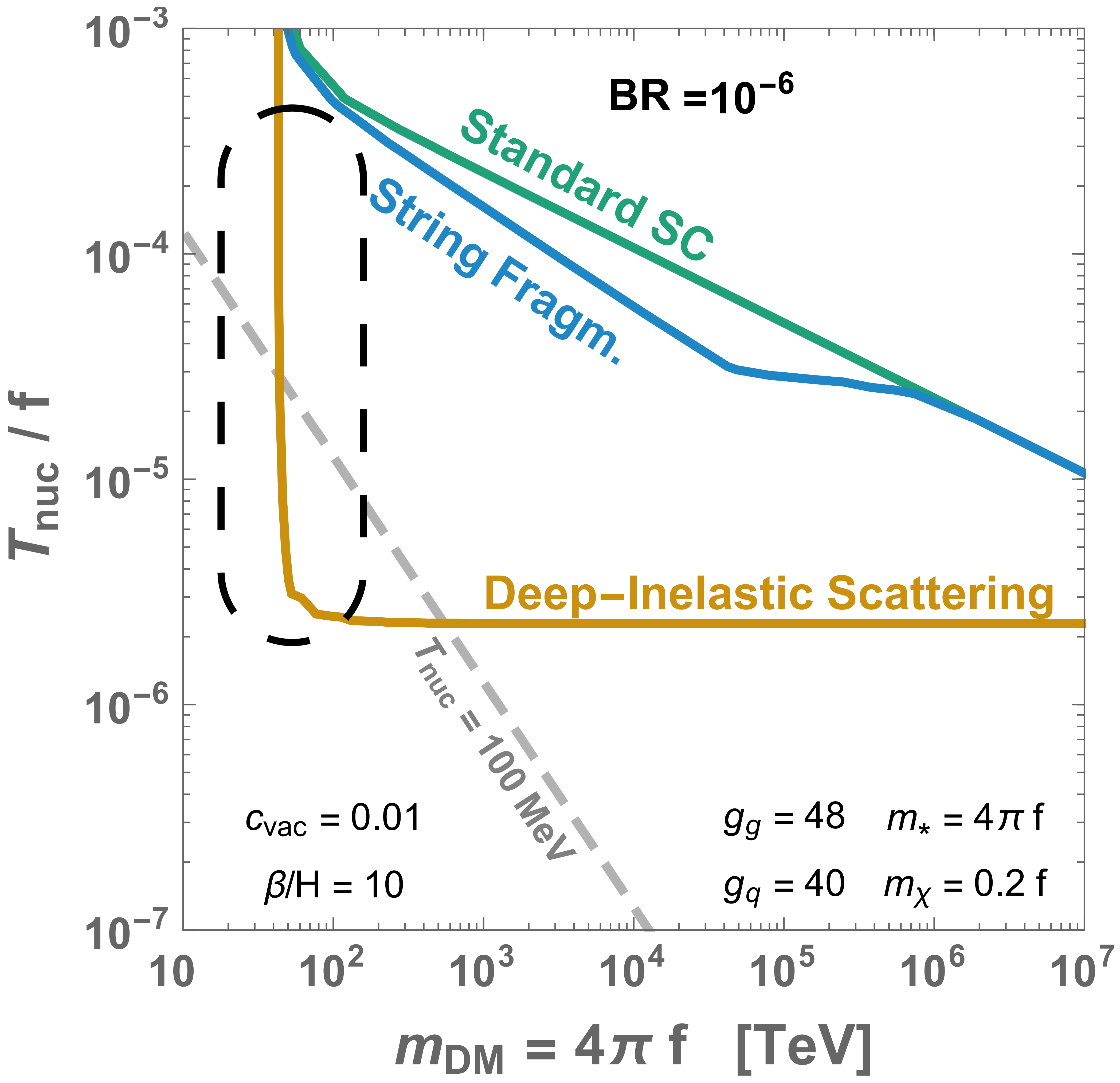
1. String fragmentation + quark ejection

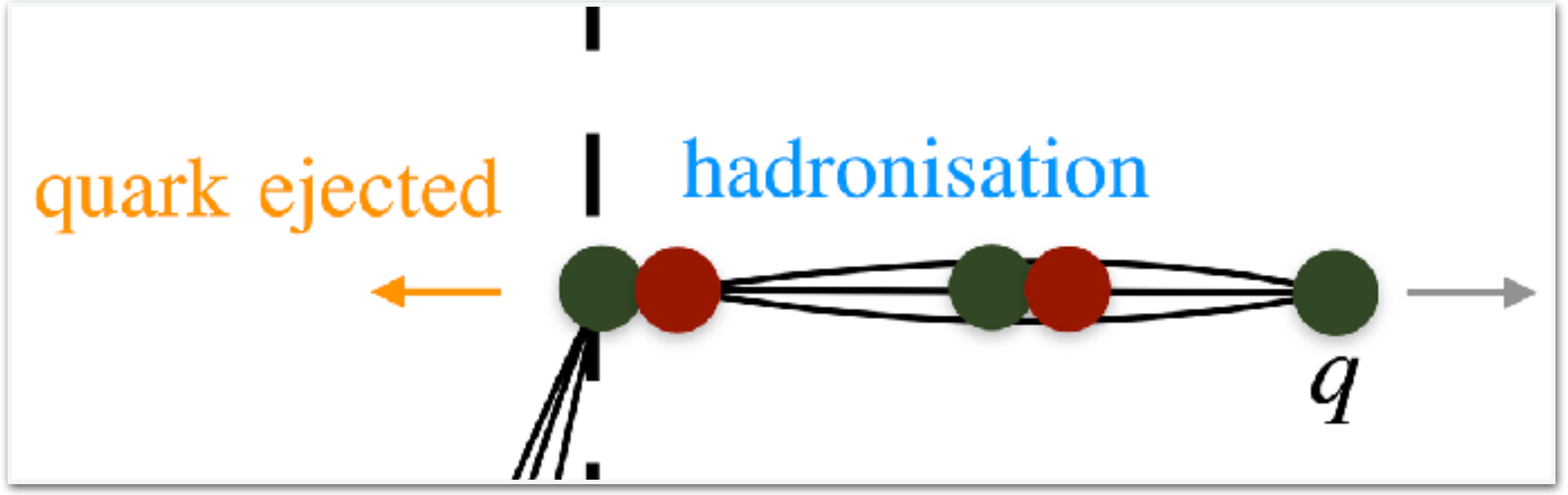
$$Y_{\rm DM} / Y_{\rm DM}^{\rm naive} \propto \log^n\left(\gamma_{wp} T_{\rm nuc}/f\right)$$

2. Deep Inelastic Scattering



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





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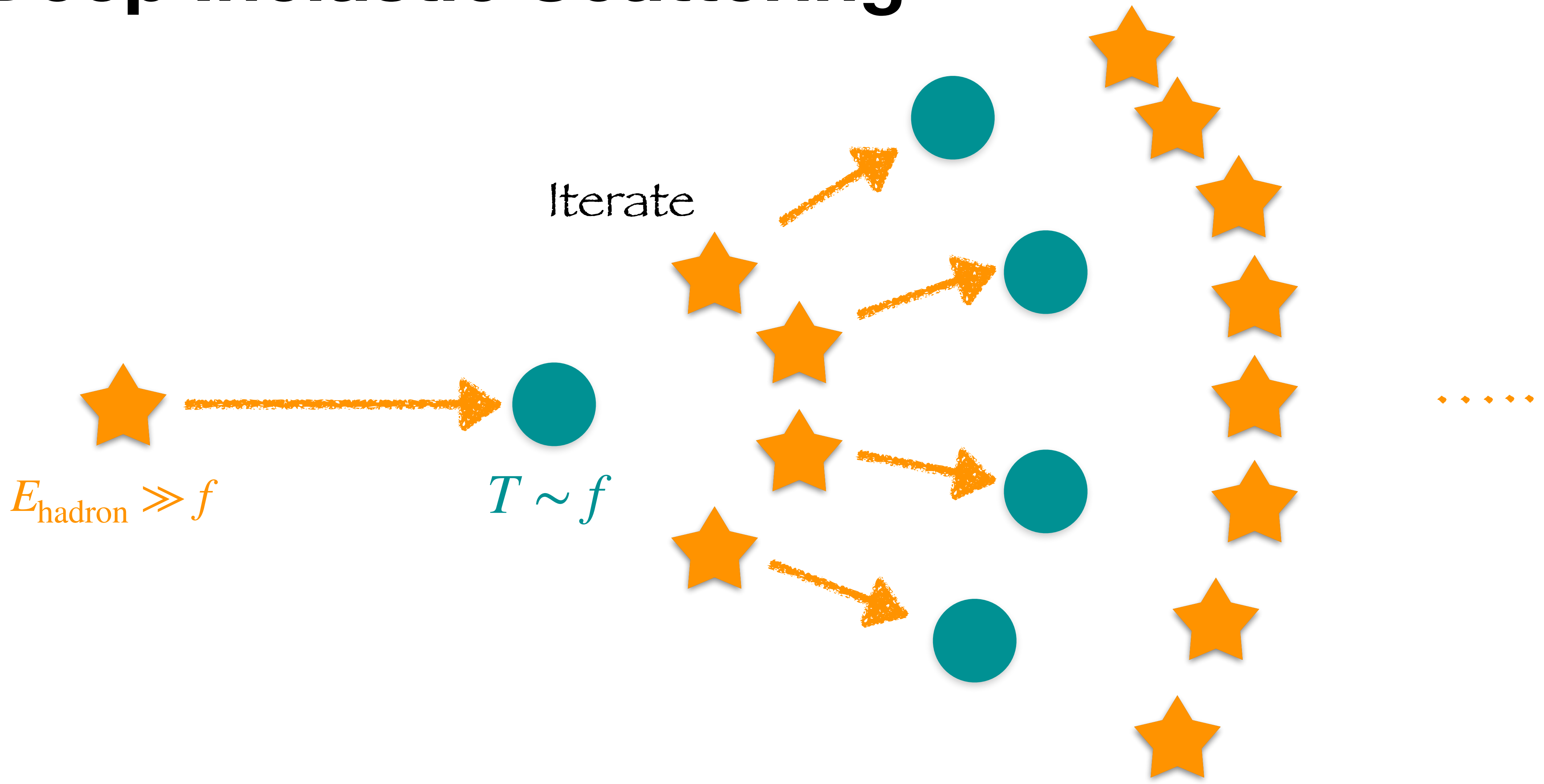
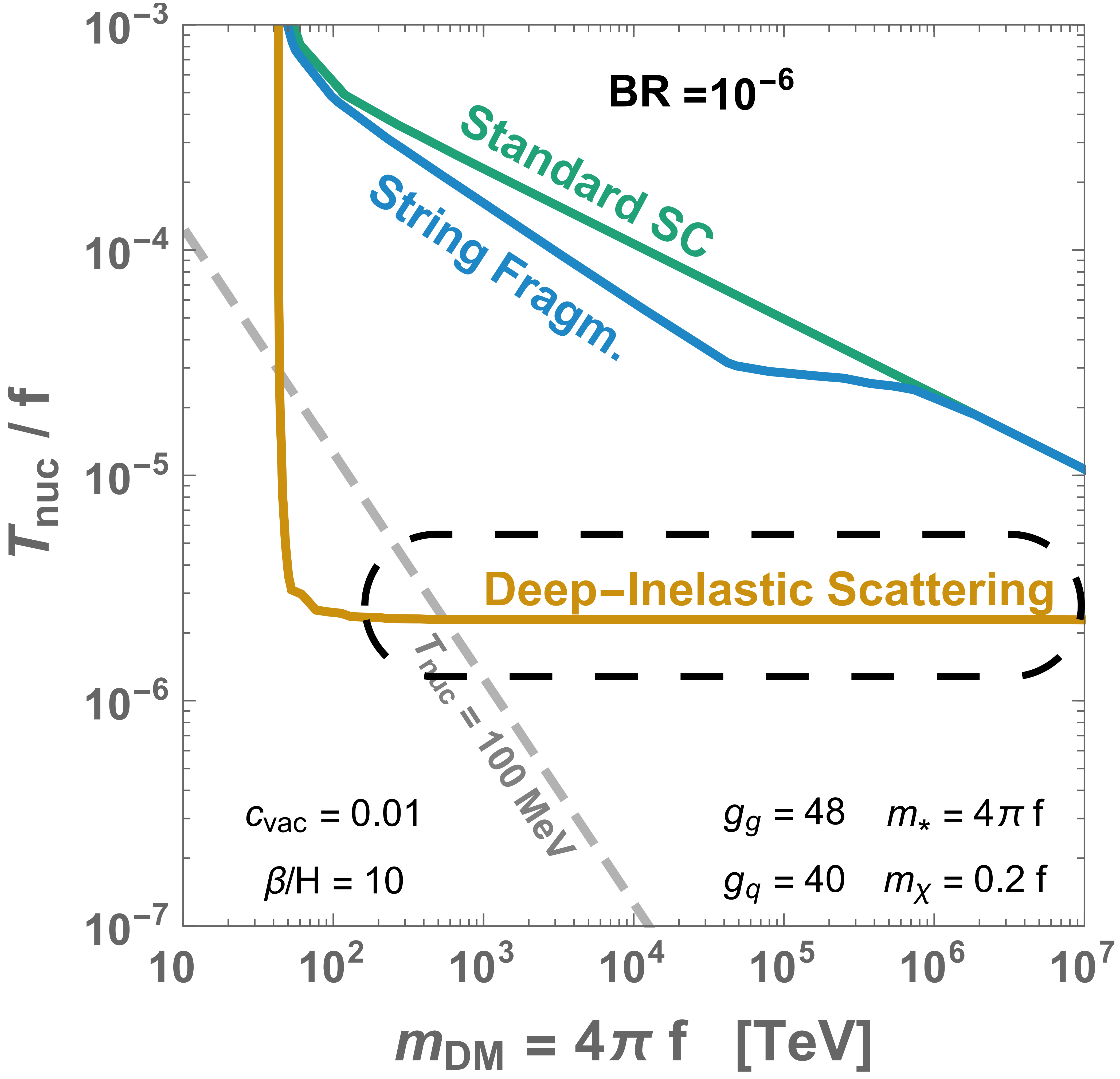
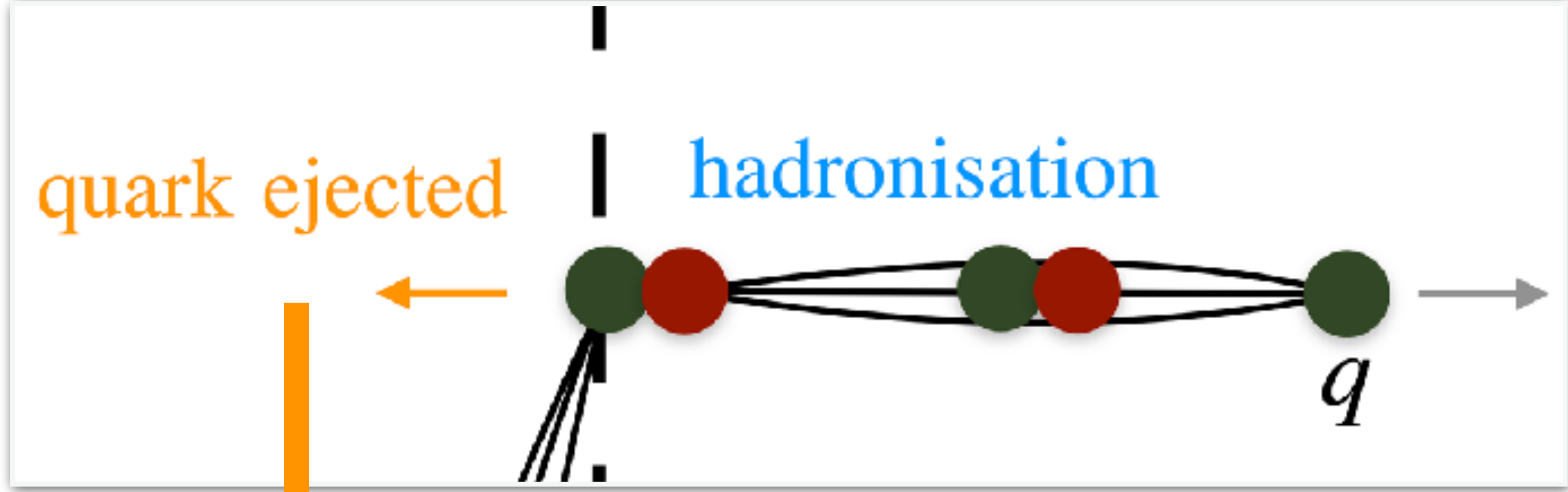


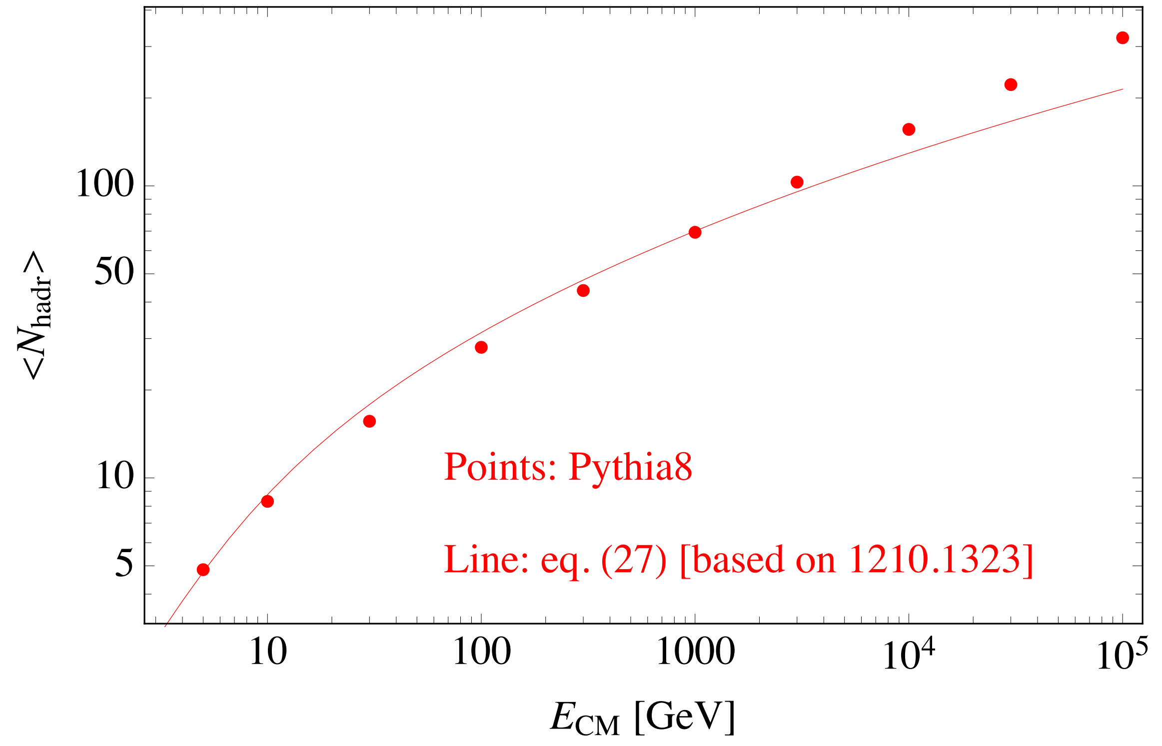
$$Y_{\rm DM} / Y_{\rm DM}^{\rm naive} \;\propto\; \gamma_{\rm wp} \;\propto\; \frac{T_{\rm nuc}}{f}\frac{M_{\rm Pl}}{f}$$





Cosmological consequences

1. More hadrons per initial quark pair



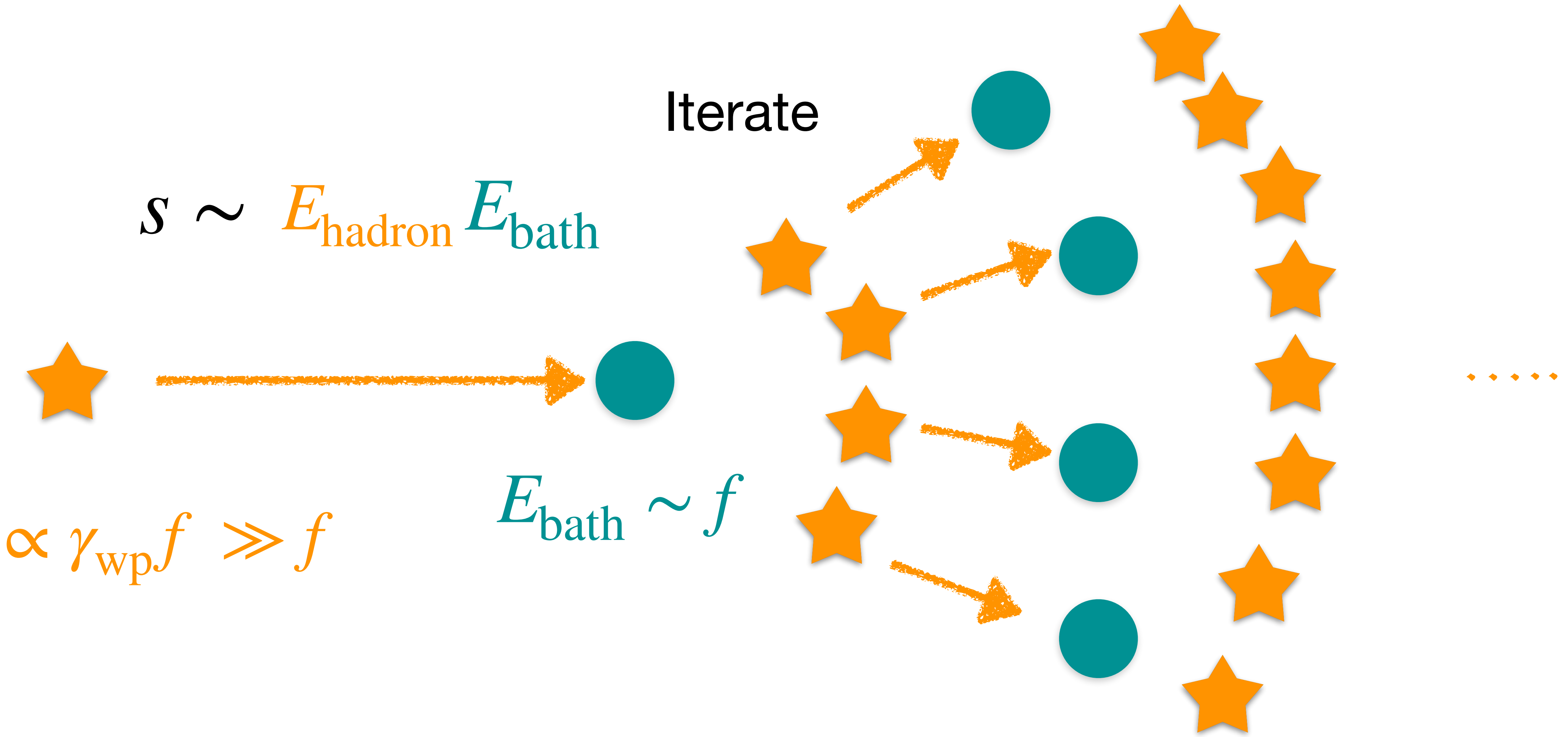
$Y_{\rm D}$

Ejected quarks give contribution of same order of magnitude

2. Cosmological catapult

$s \sim E_{\rm hadron} E_{\rm bath}$

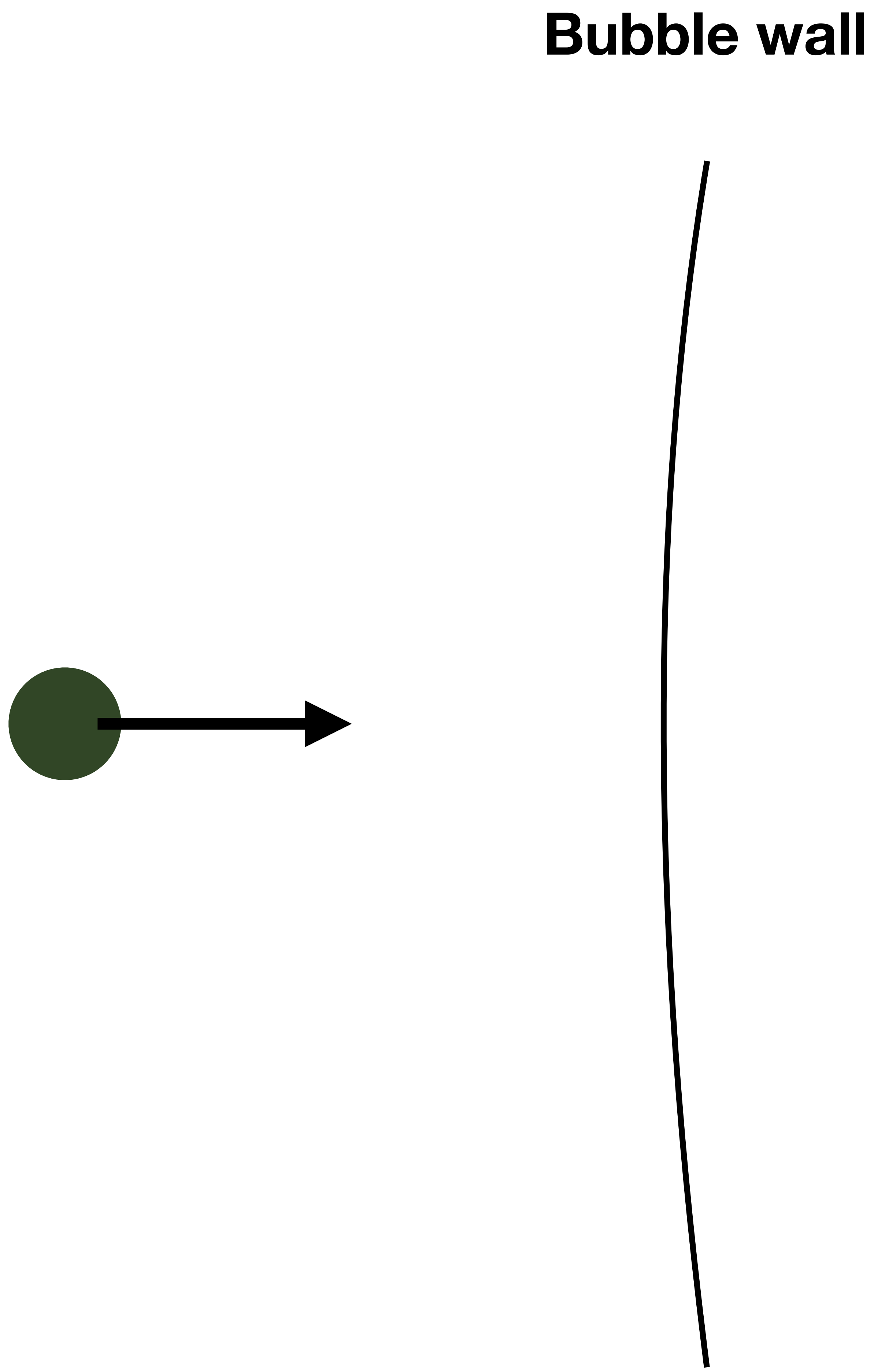
$E_{\rm hadron} \propto \gamma_{\rm wp} f \gg f$



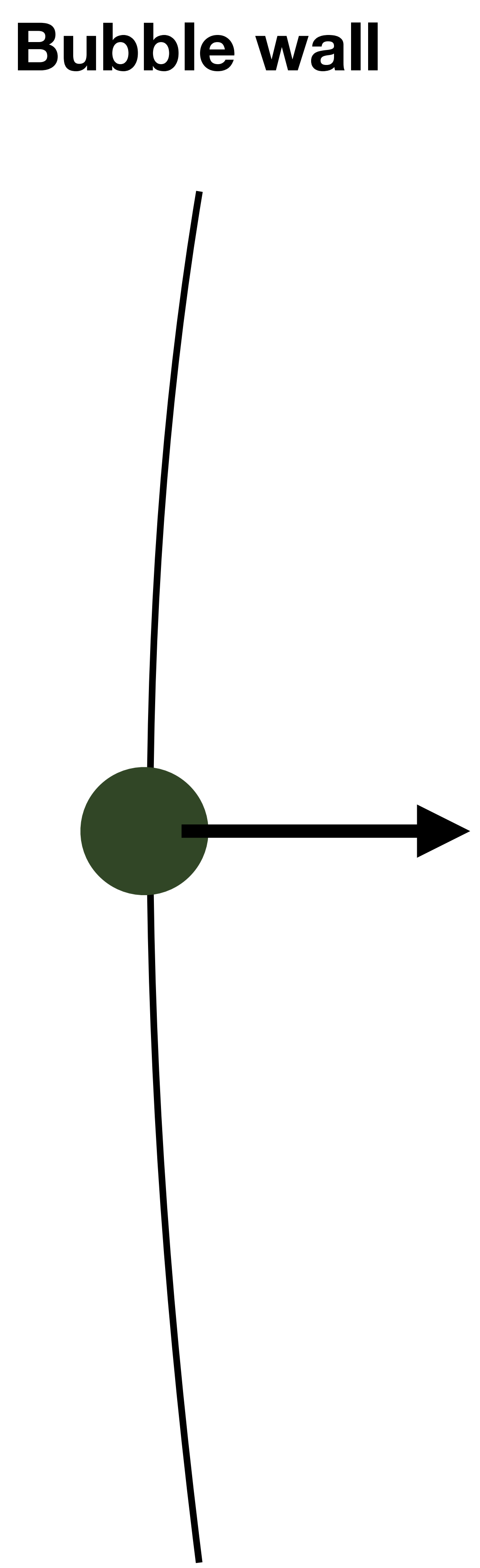
$$\boxed{Y_{\rm DM} / Y_{\rm DM}^{\rm naive} \propto \gamma_{\rm wp} \propto \frac{T_{\rm nuc}}{f}\frac{M_{\rm Pl}}{f}}$$

runaway regime

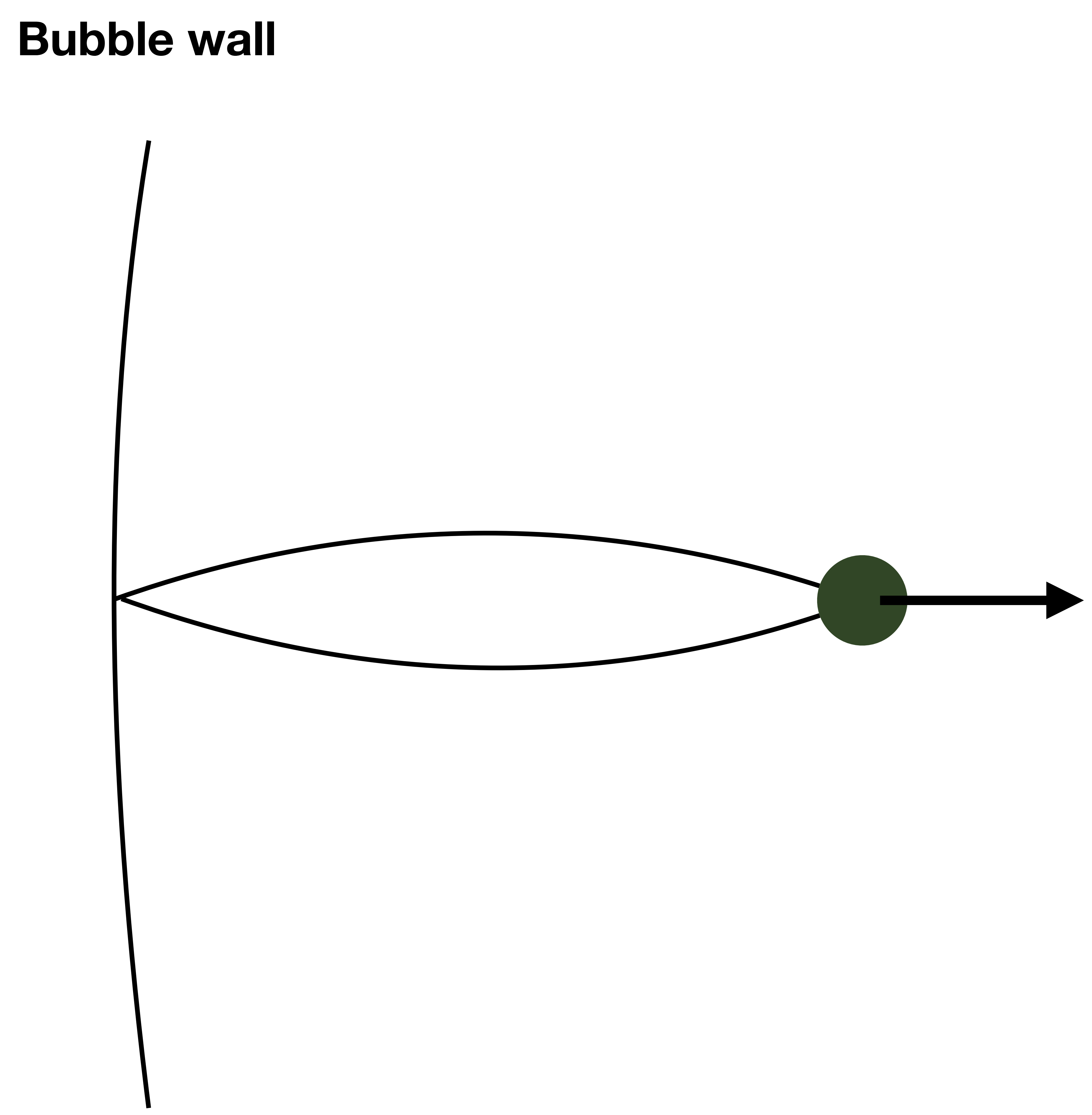
Interaction with other quarks ?



Interaction with other quarks ?

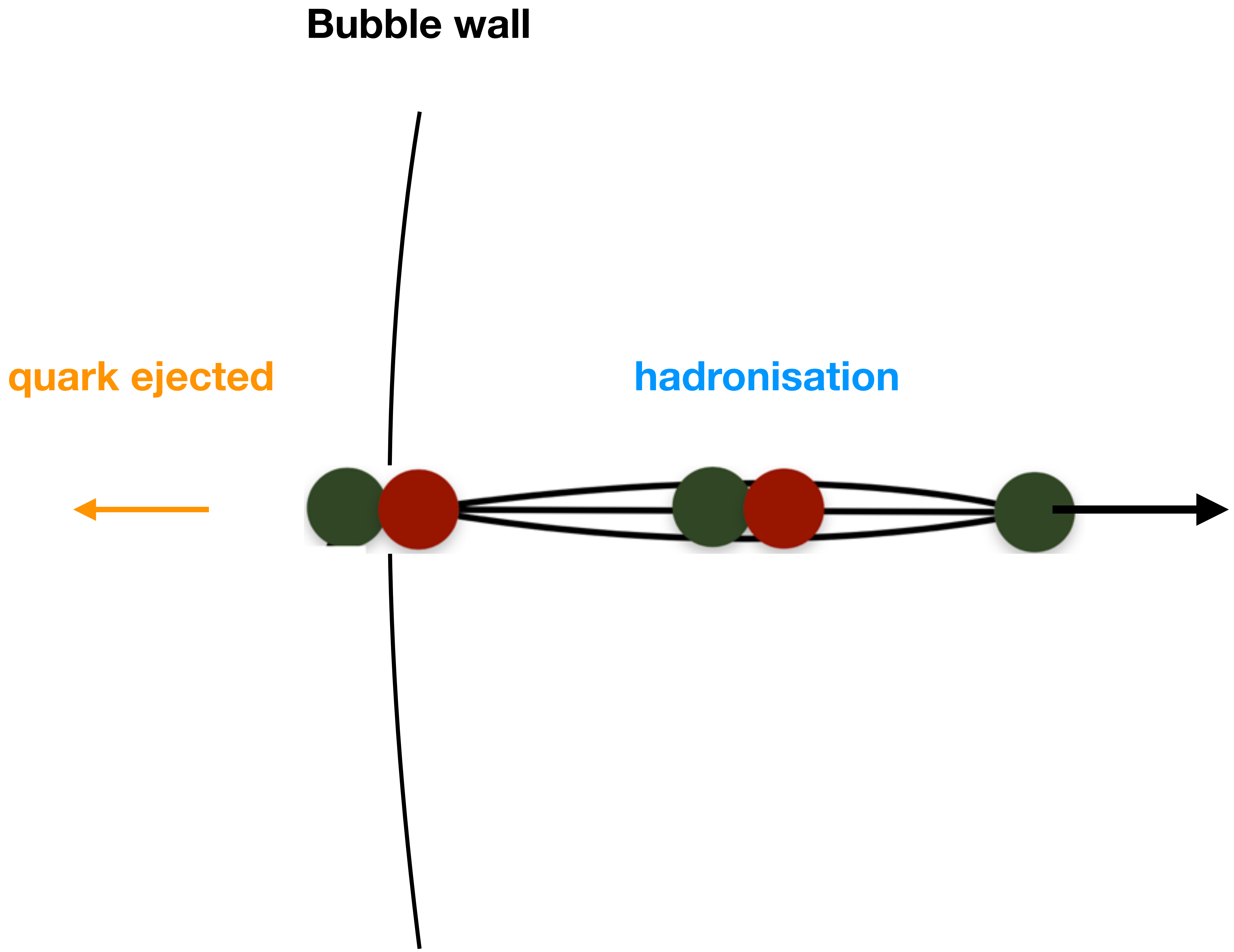


Interaction with other quarks ?



Interaction with other quarks ?

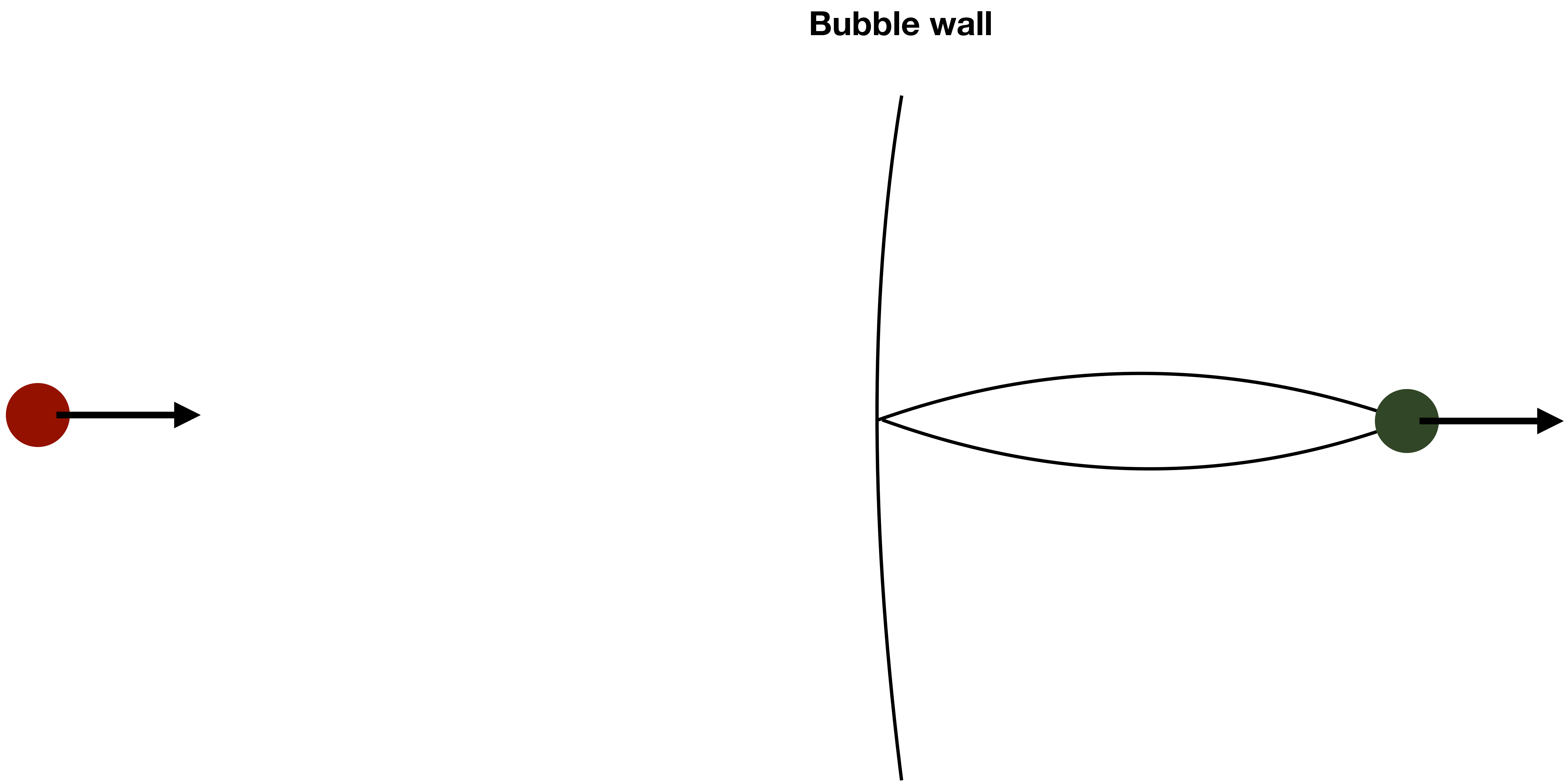
$$\Gamma_{\text{nucl}} \sim f/N$$



Interaction with other quarks ?

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

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



Interaction with other quarks ?

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

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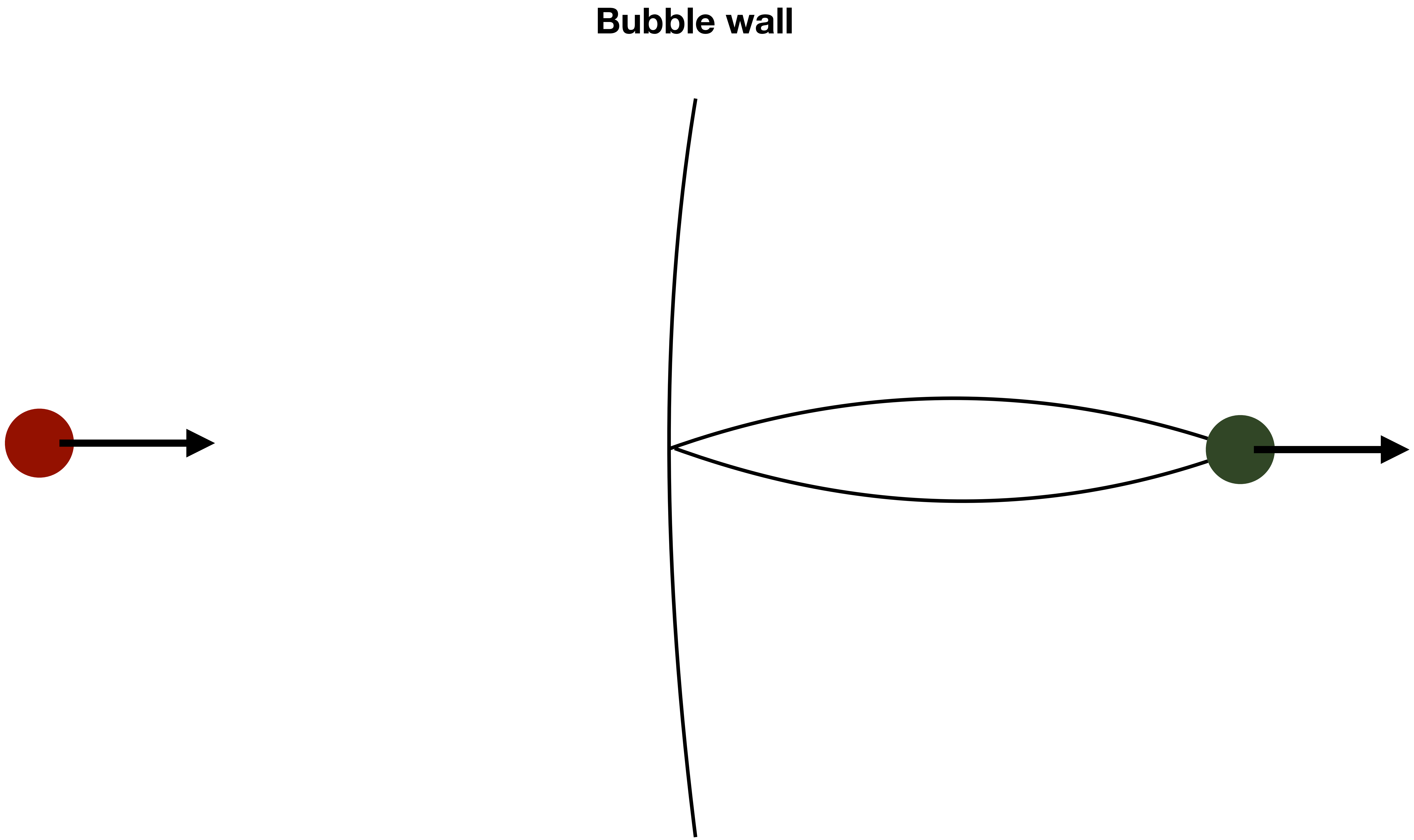

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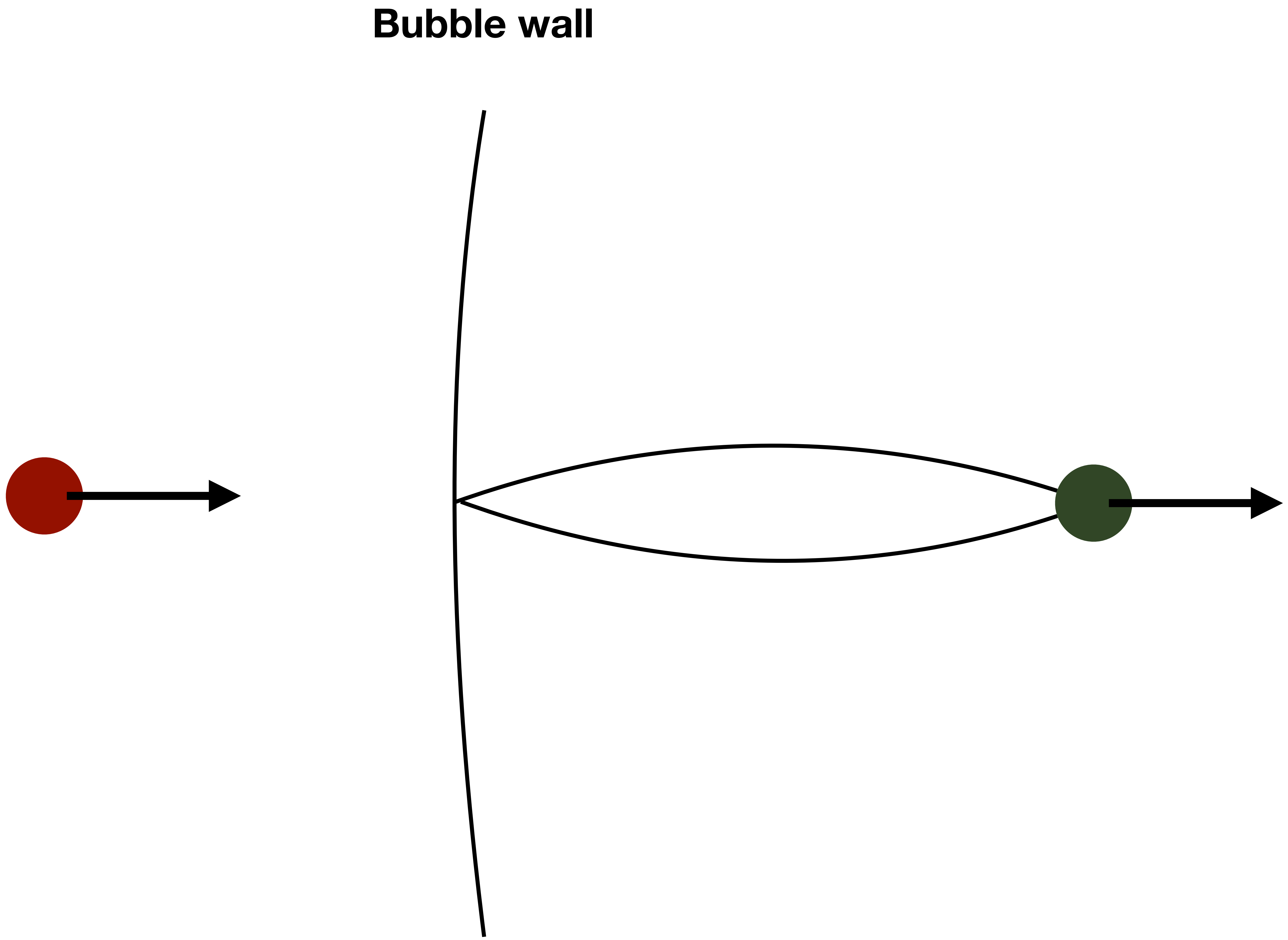

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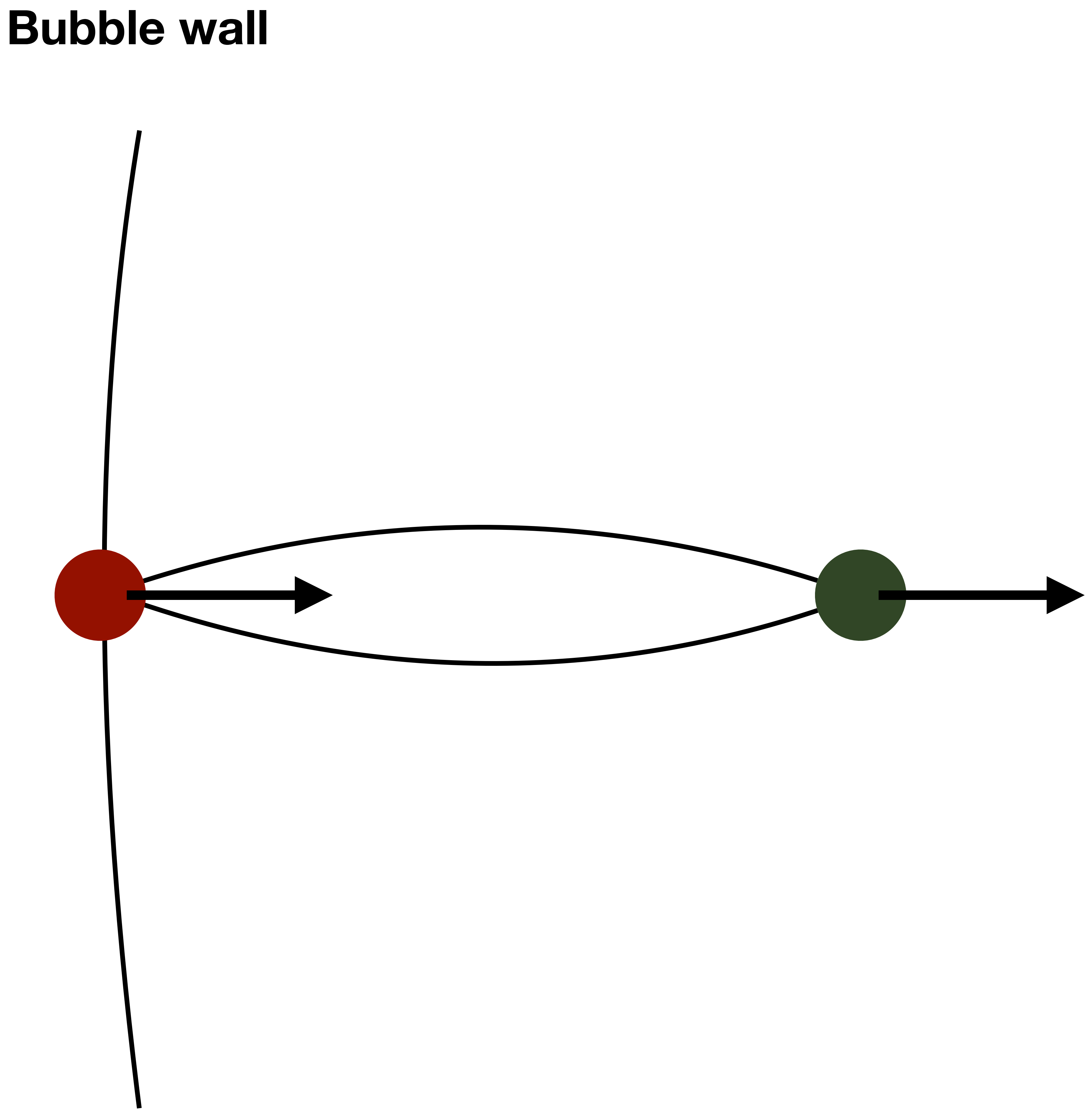
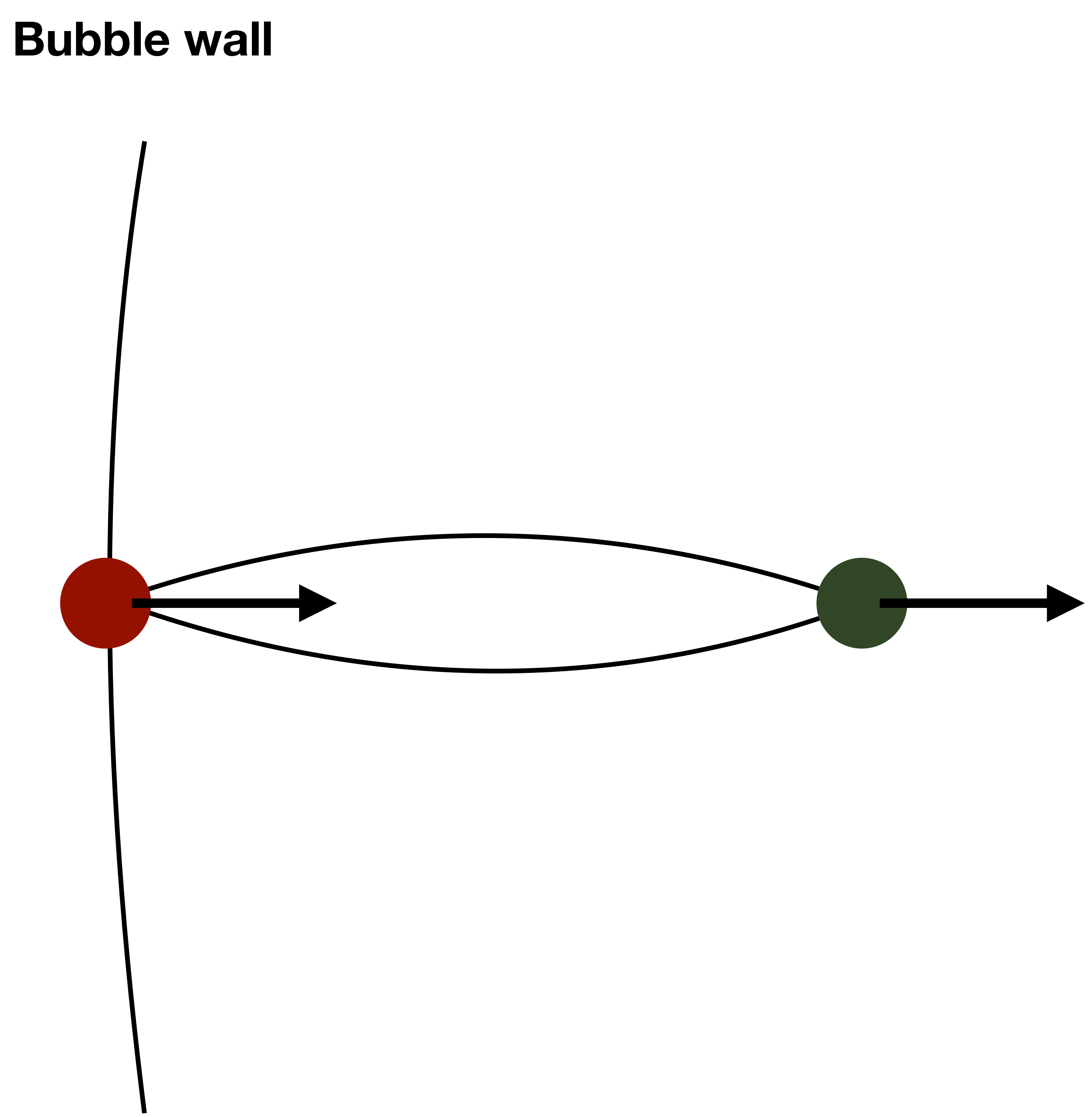


Interaction with other quarks ?

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



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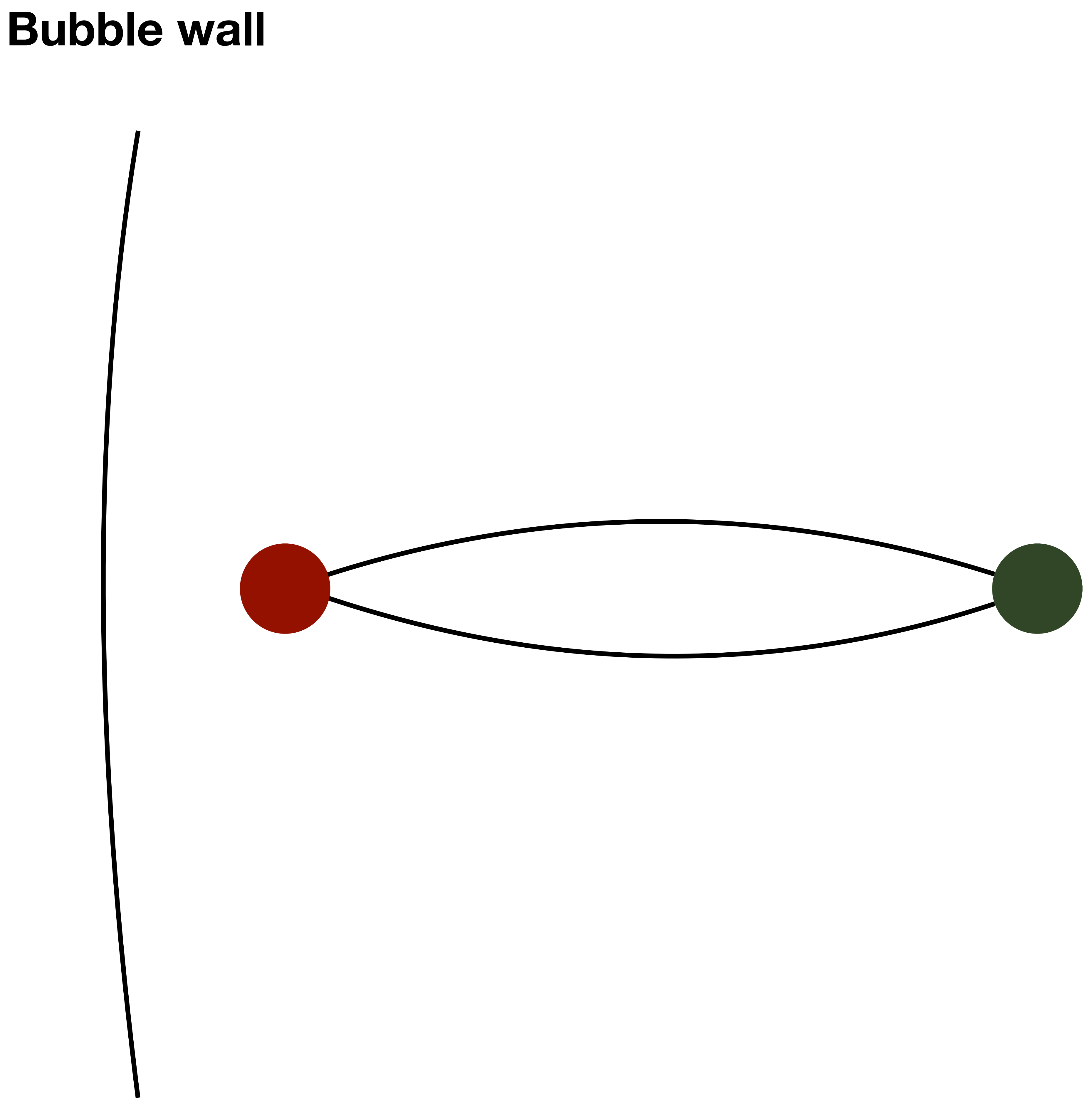

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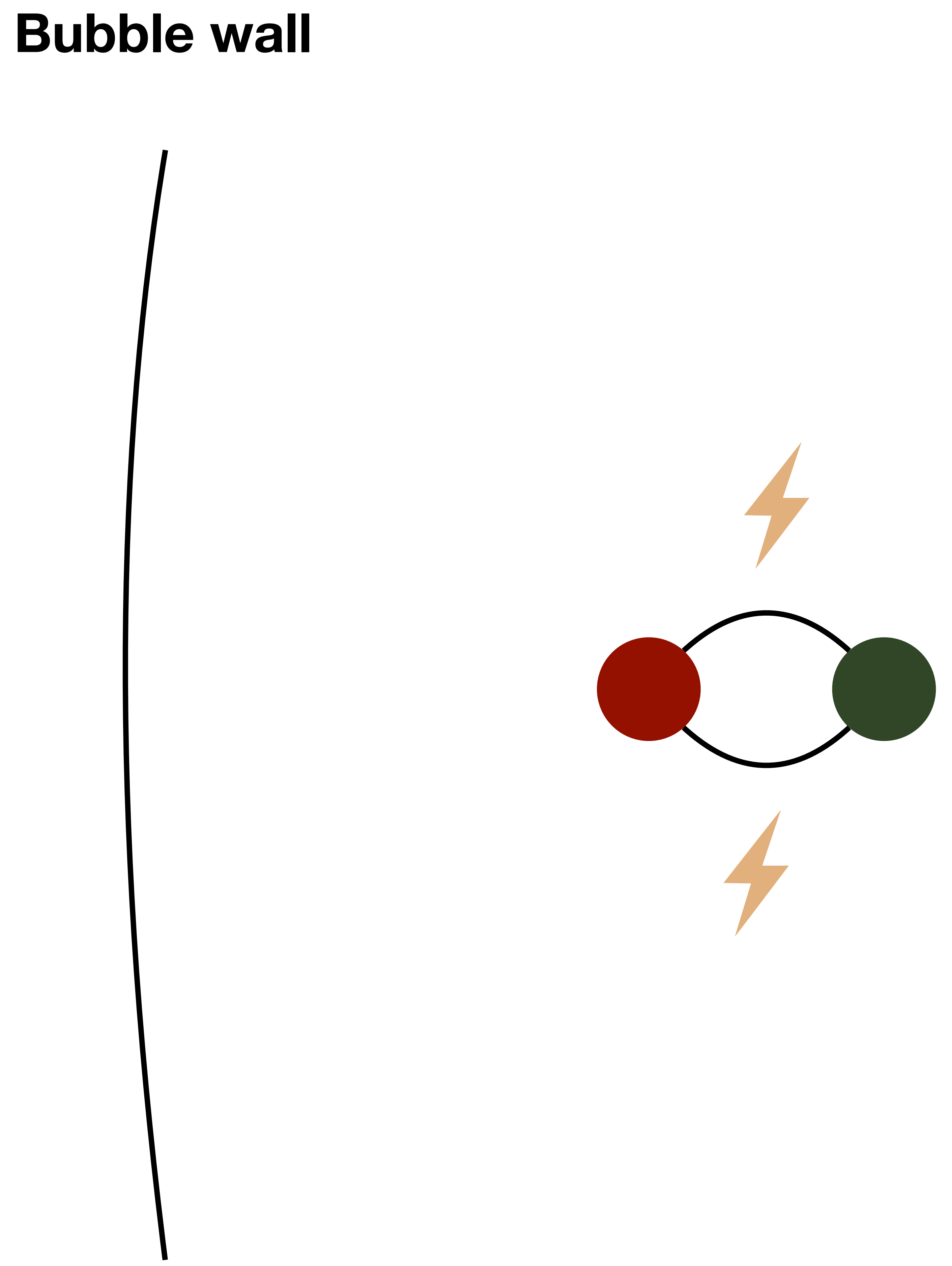

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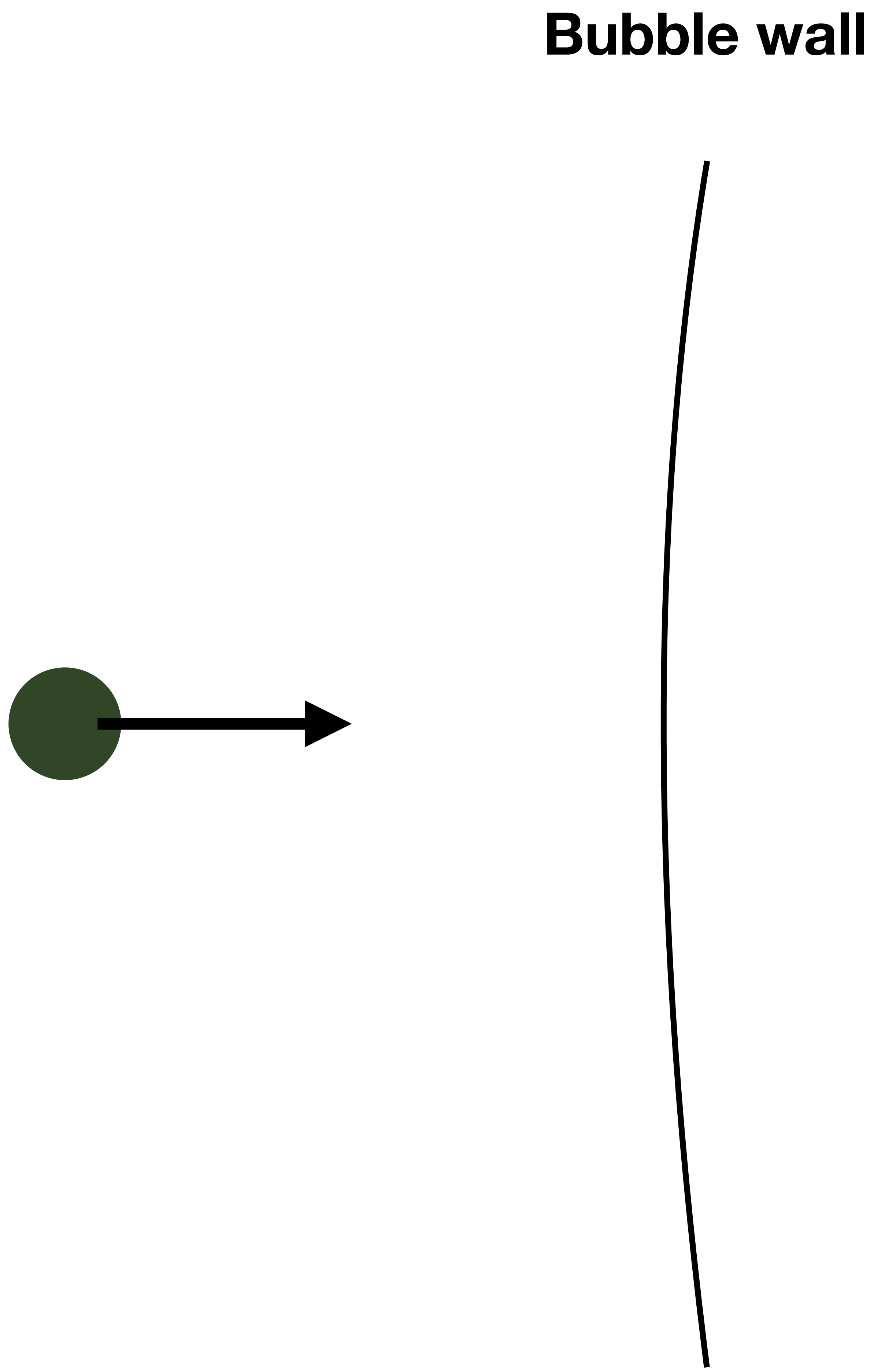

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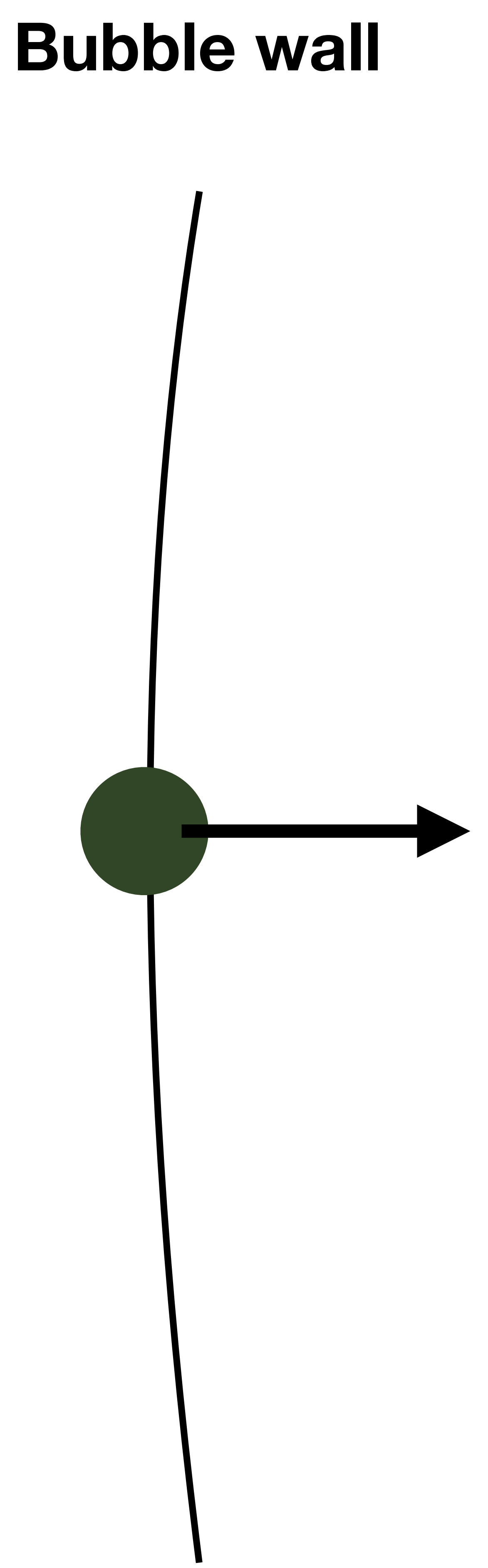

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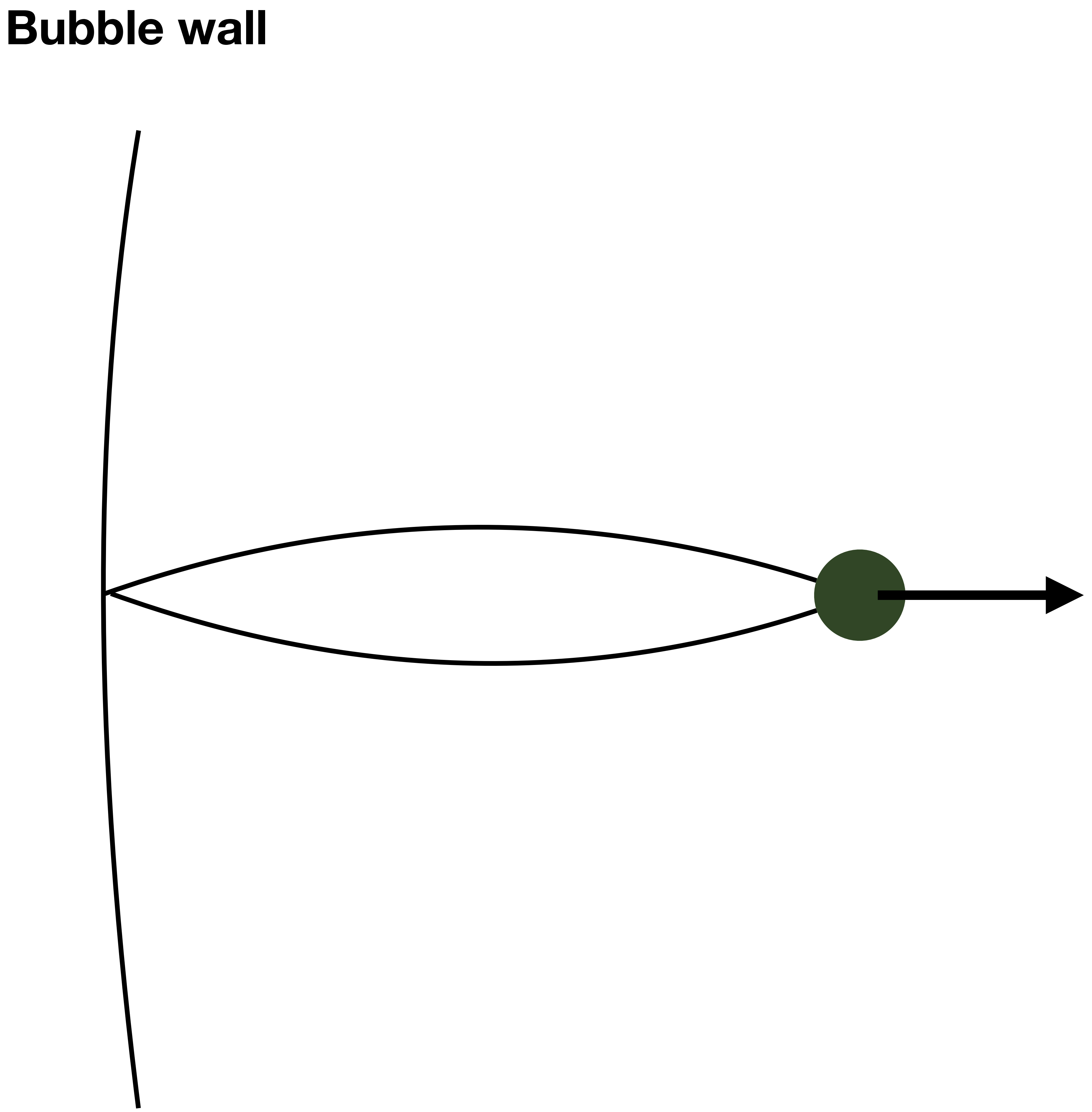

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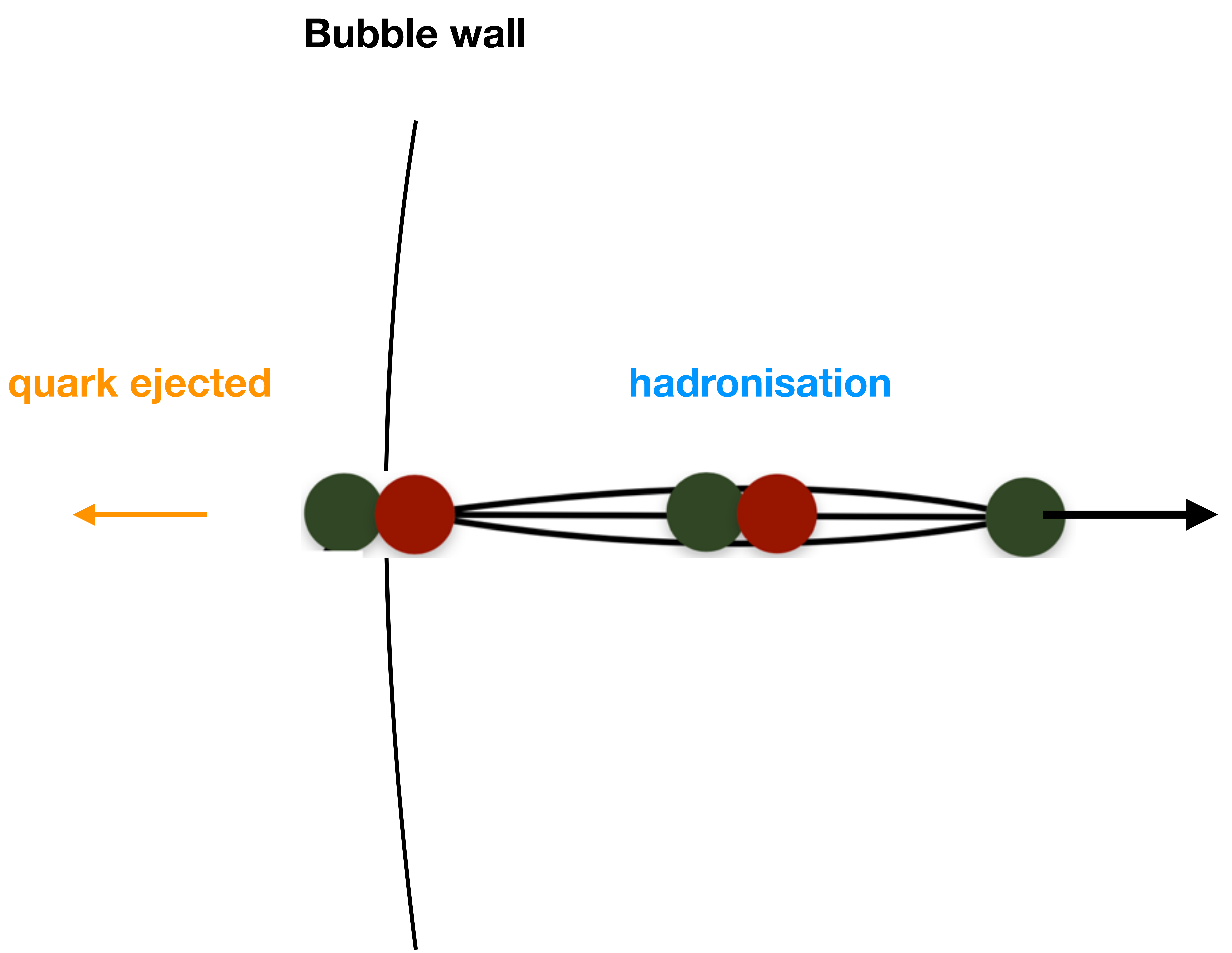

Interaction with other quarks ?

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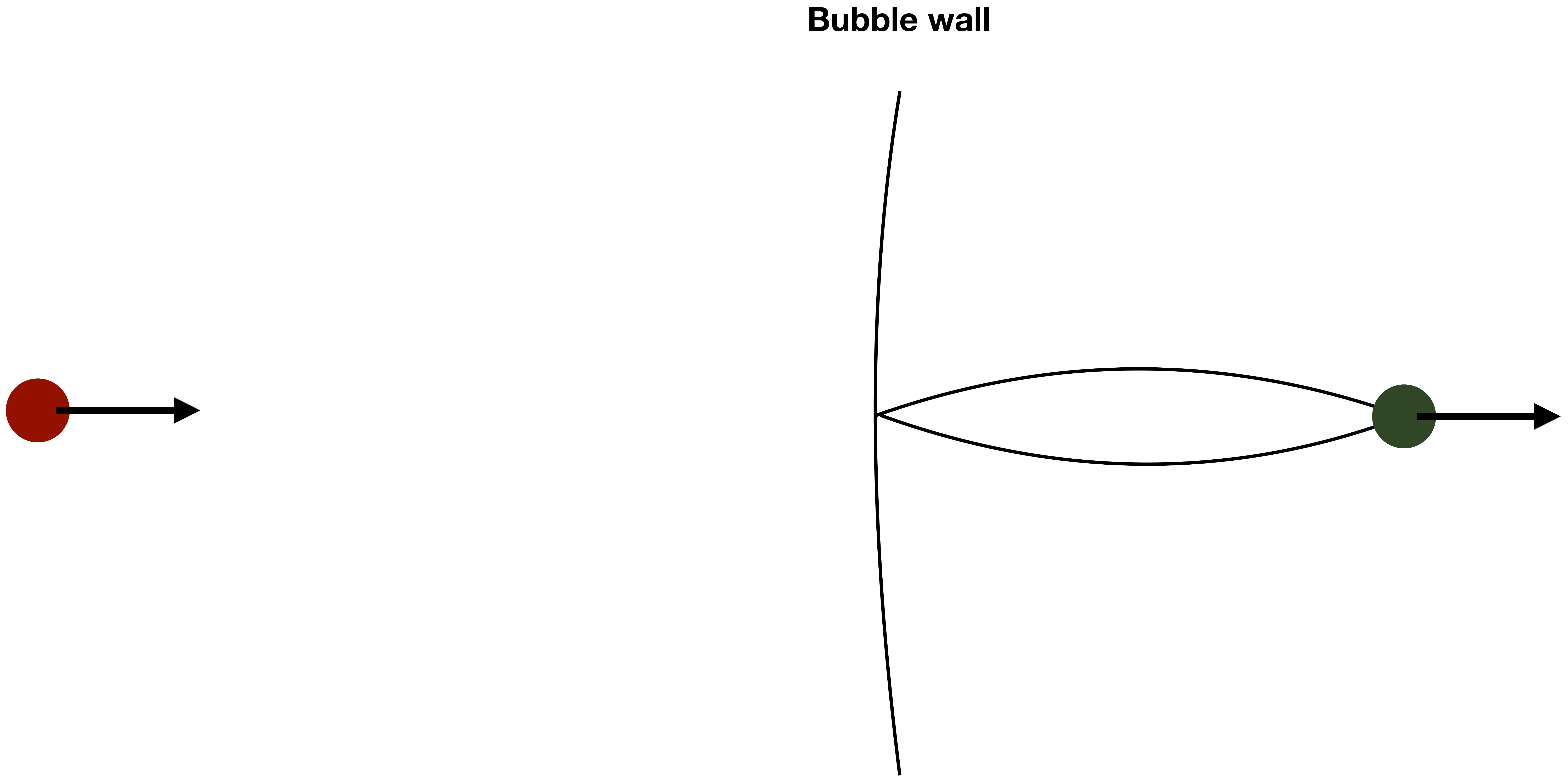

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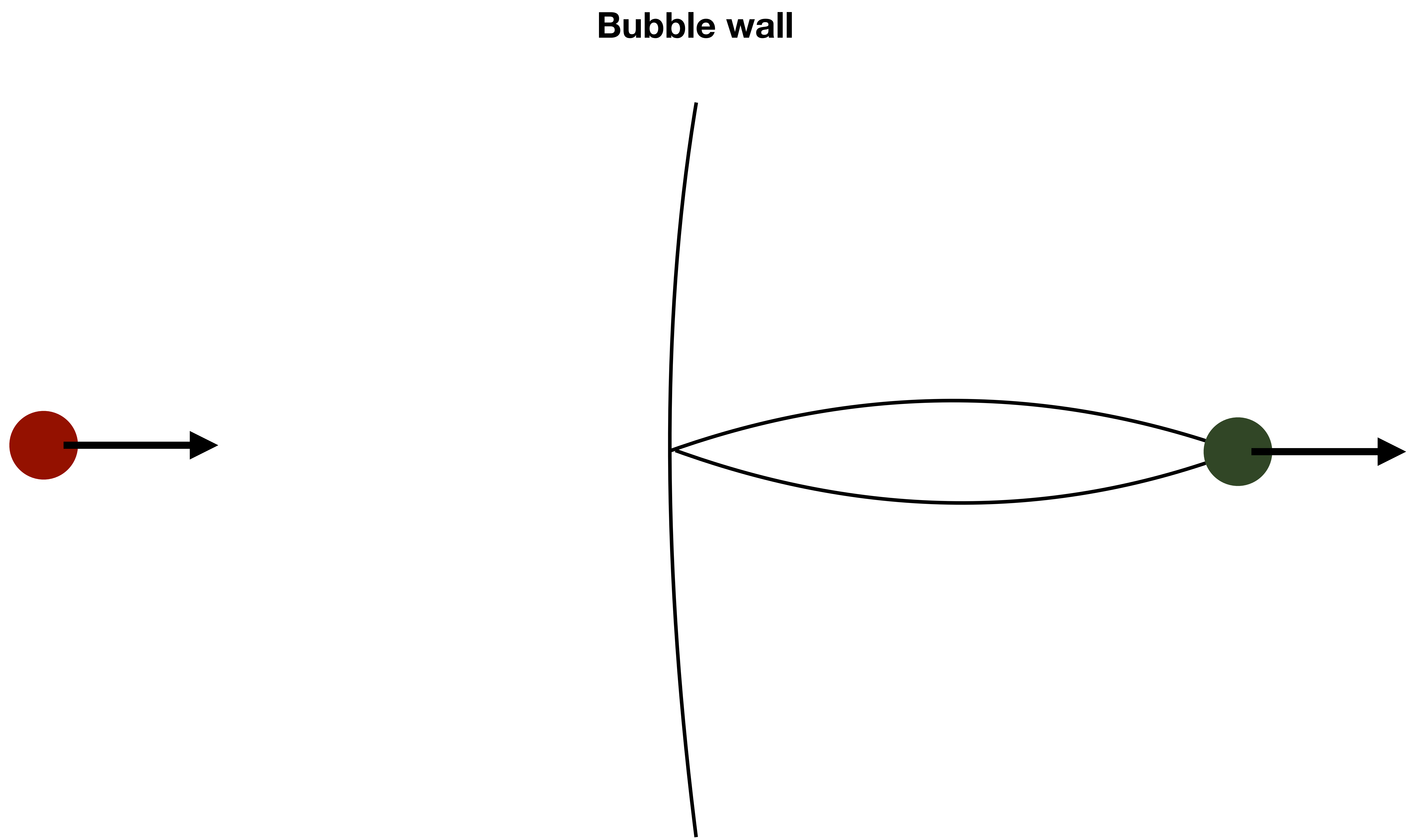

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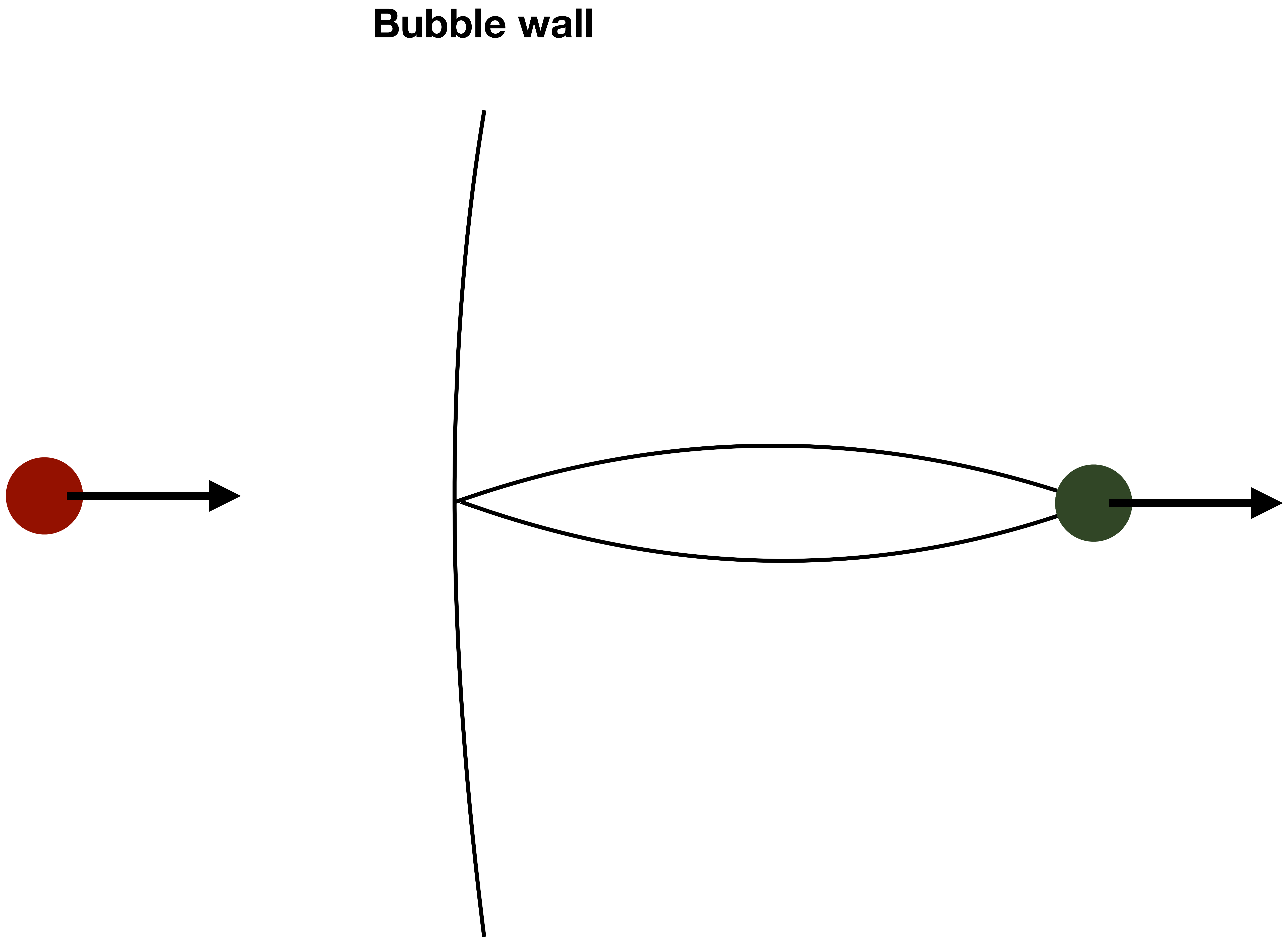

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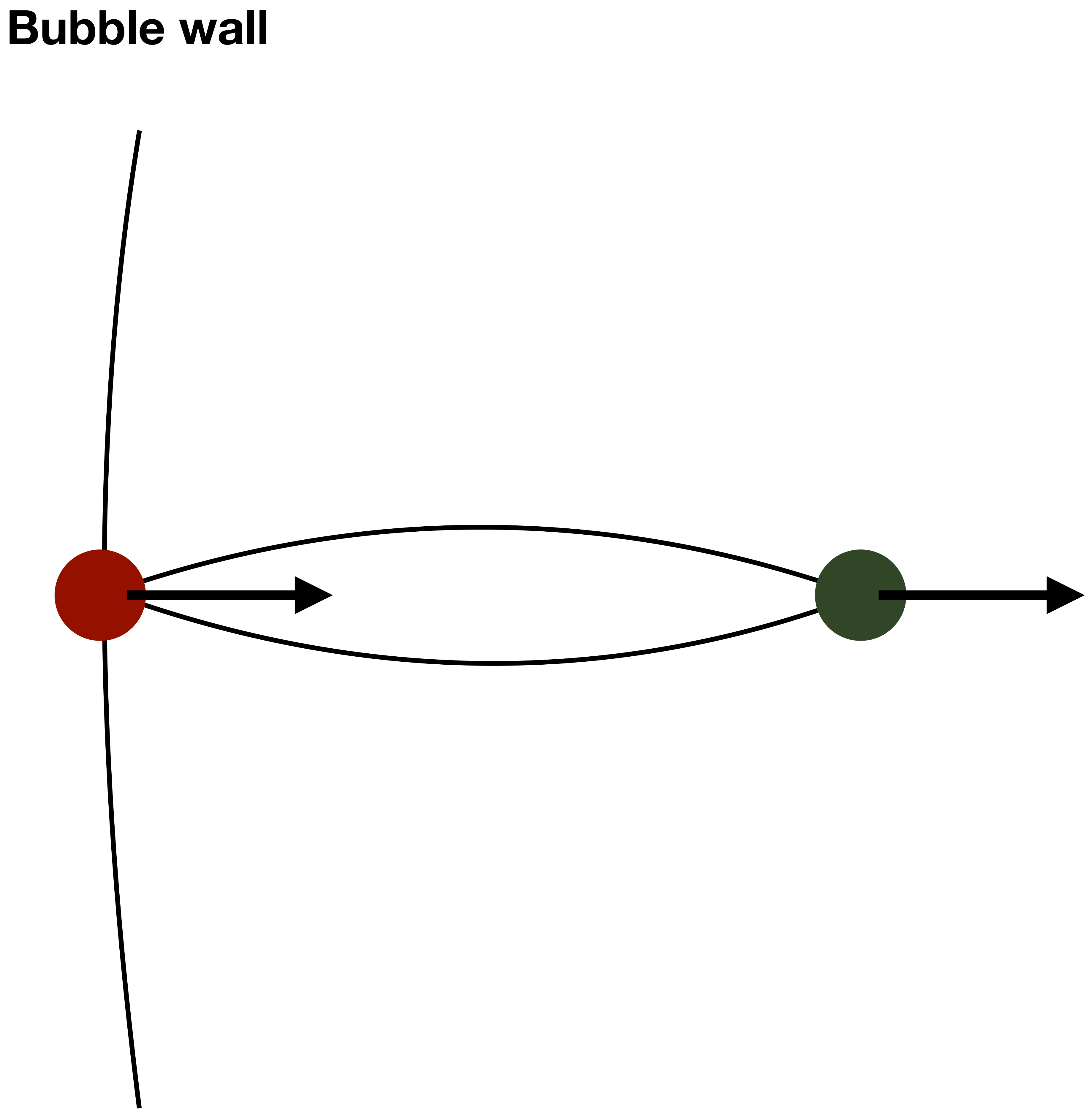

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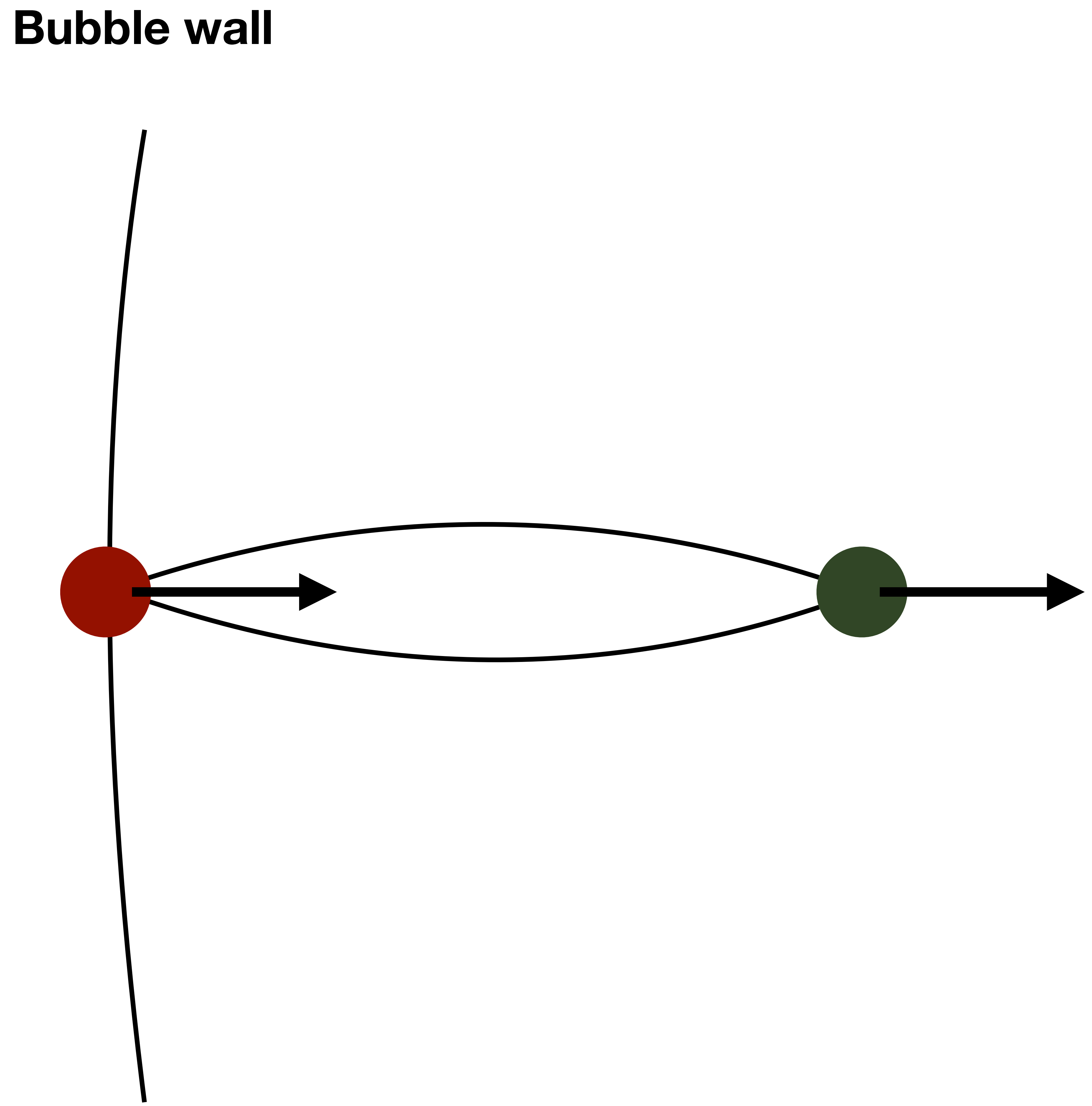

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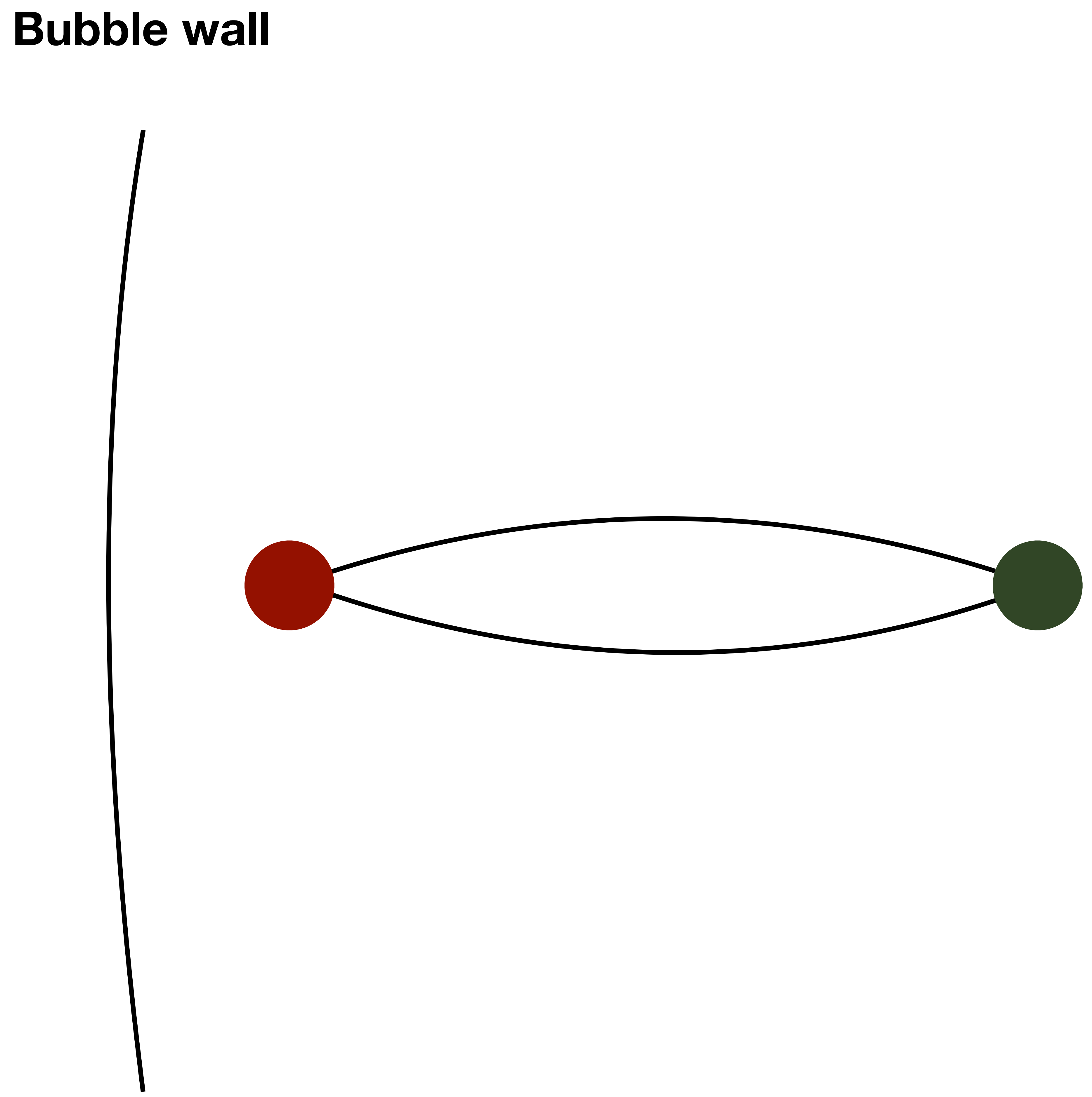

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