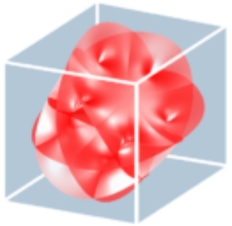
Cosmological implications of supercooled phase transitions

Yann Gouttenoire

Collaborators: Iason Baldes, Ryusuke Jinno, Filippo Sala, Geraldine Servant, Tomer Volansky

Harvard CMSA



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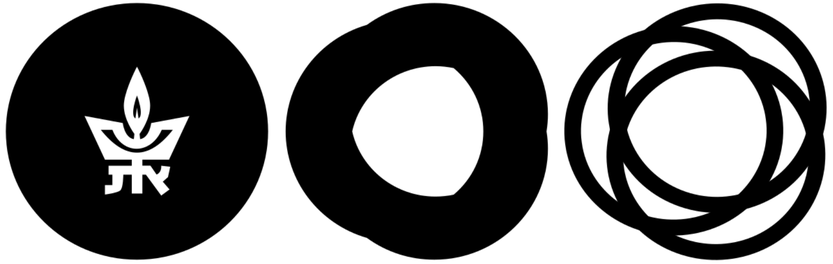

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Supercooled 1stOPT

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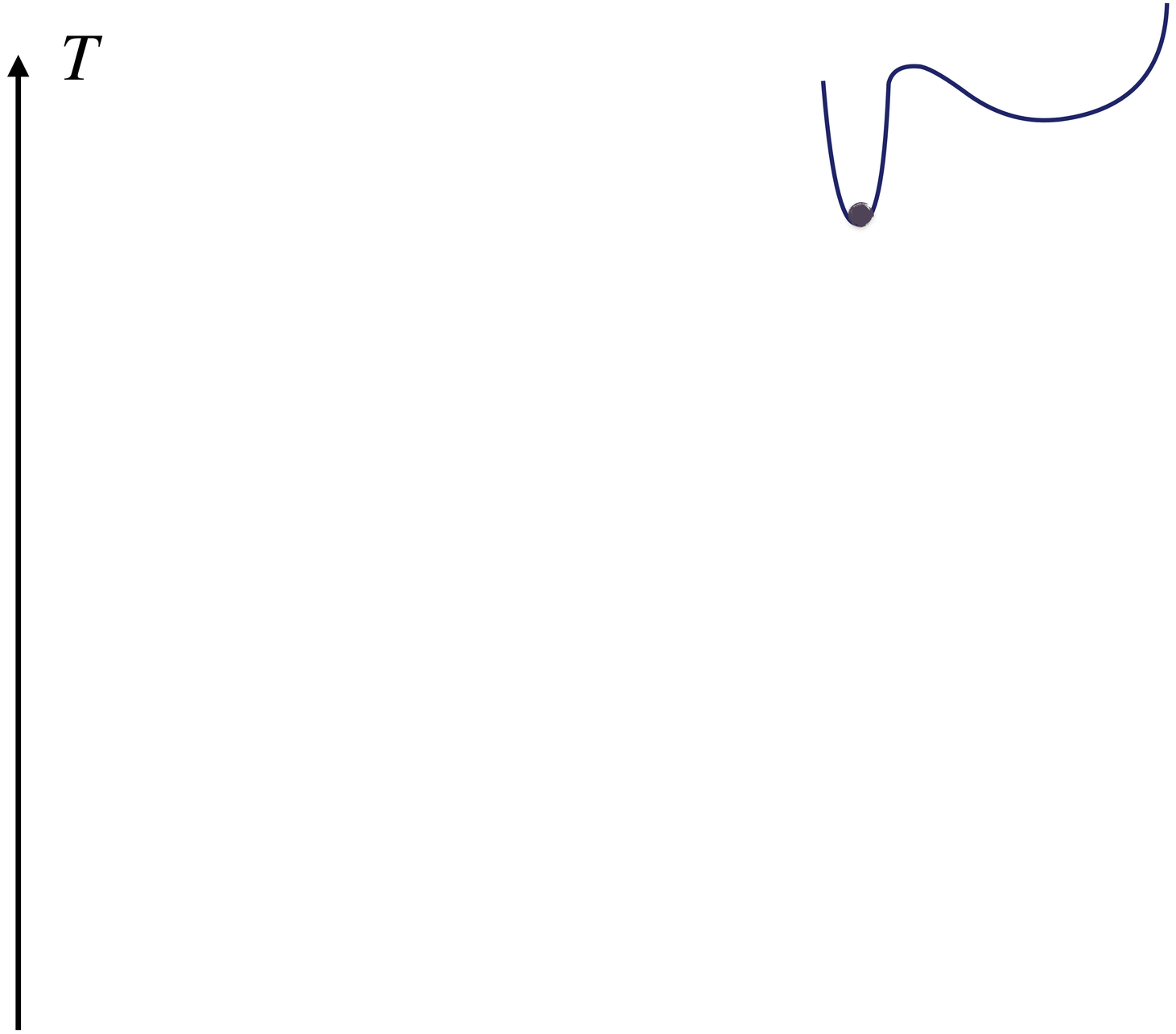

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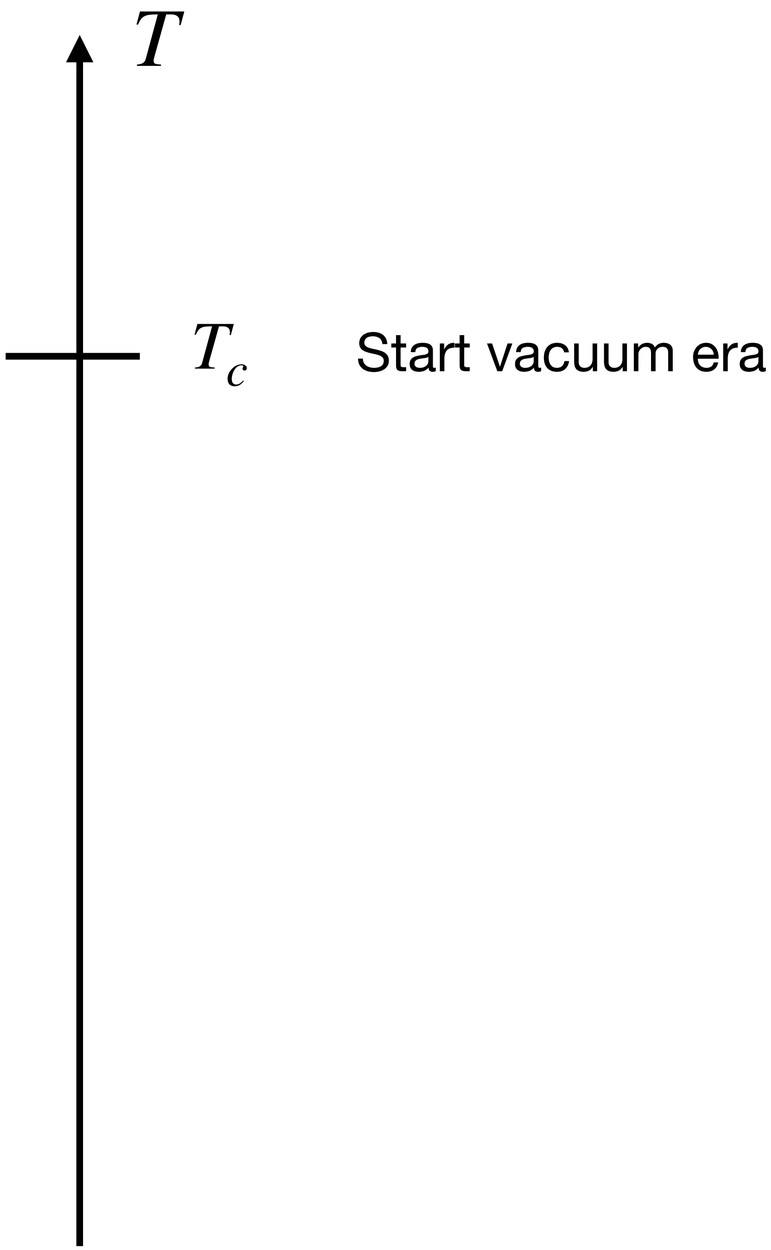
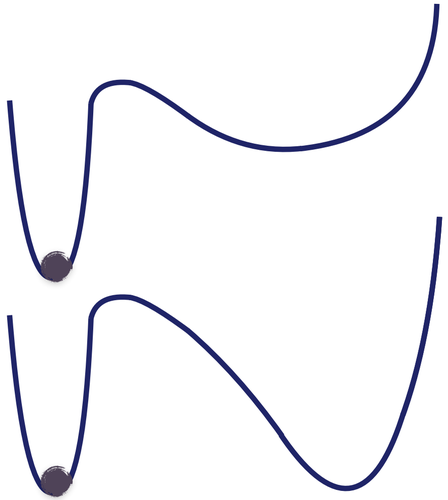


Start vacuum era



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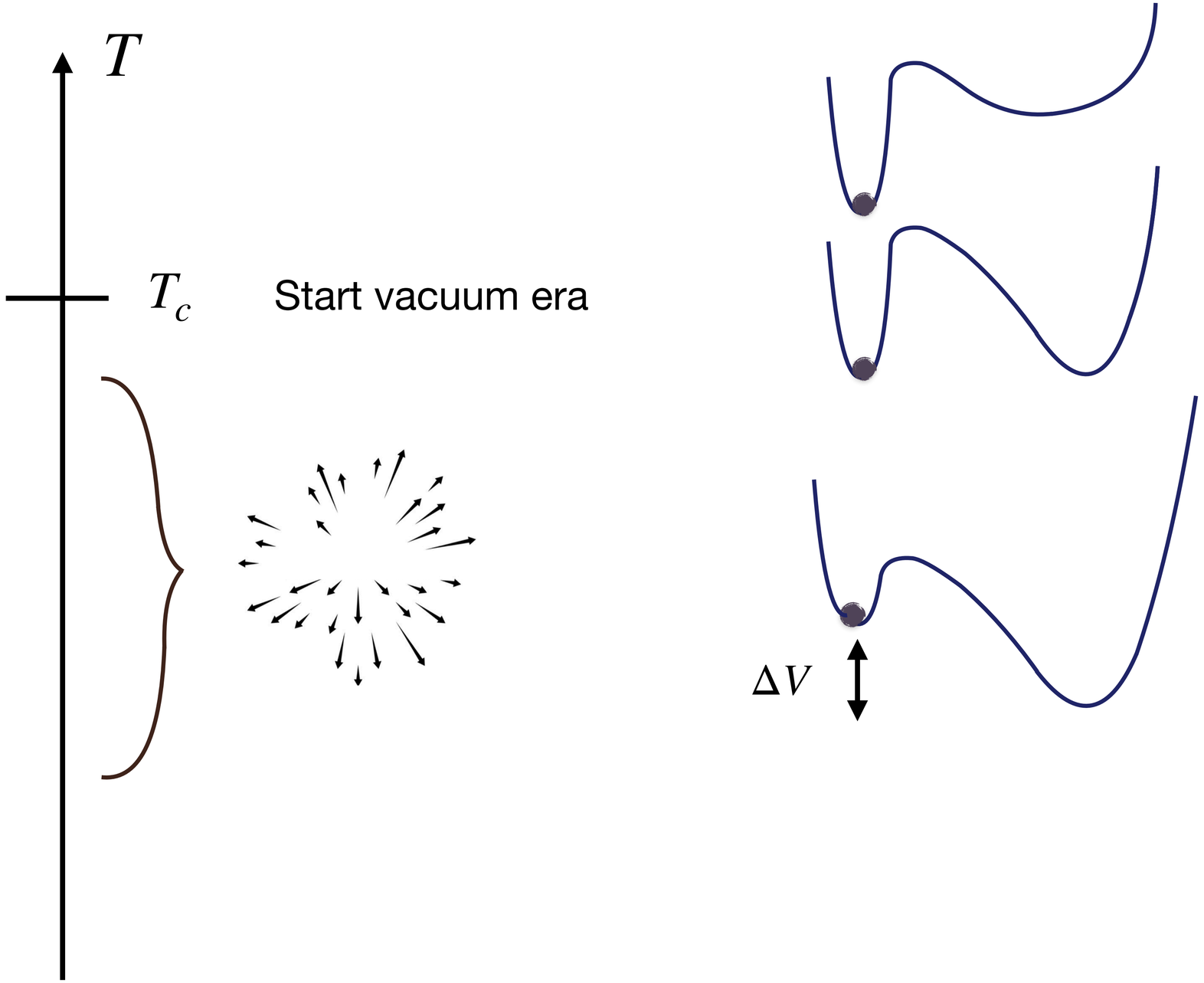

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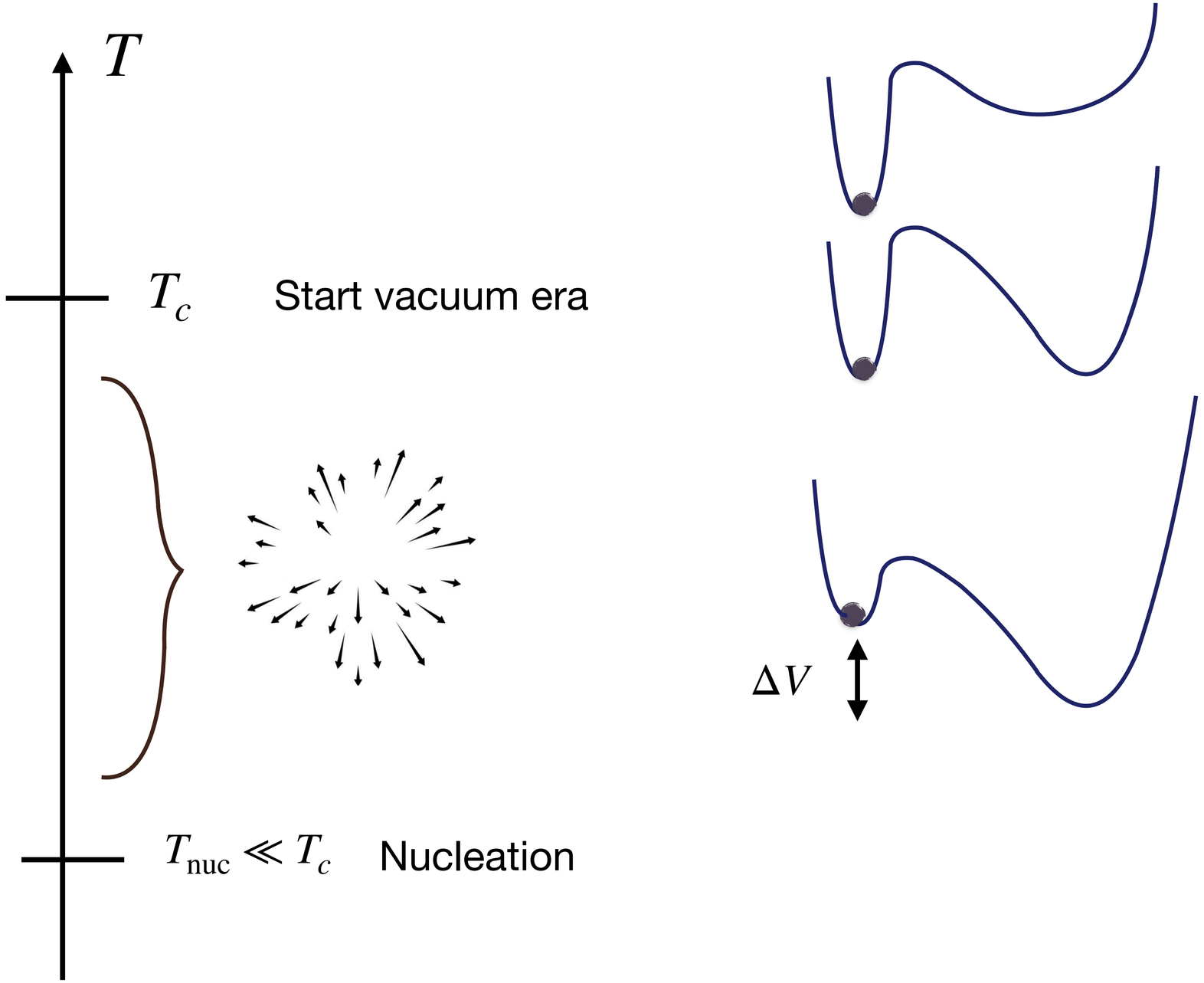

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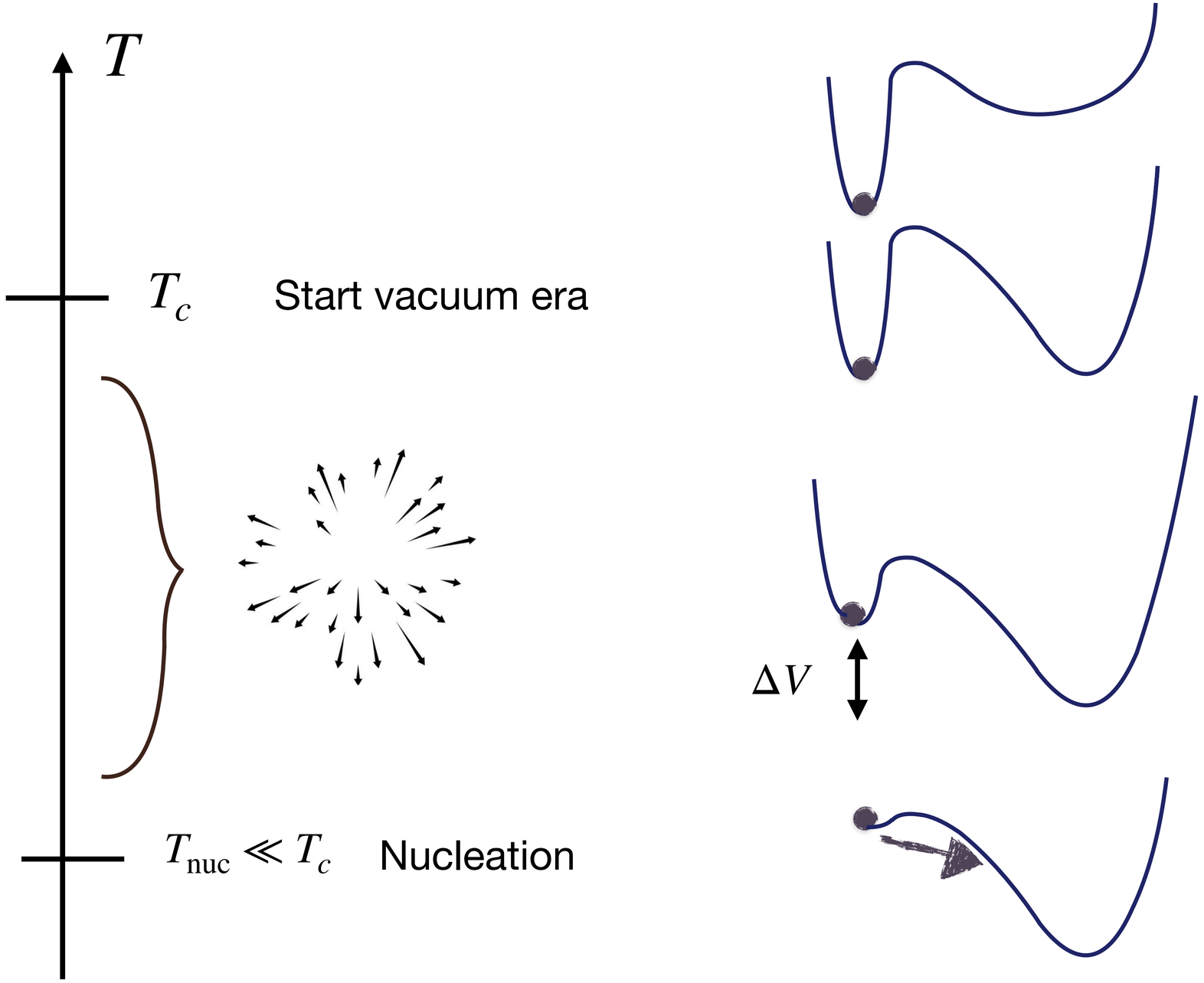

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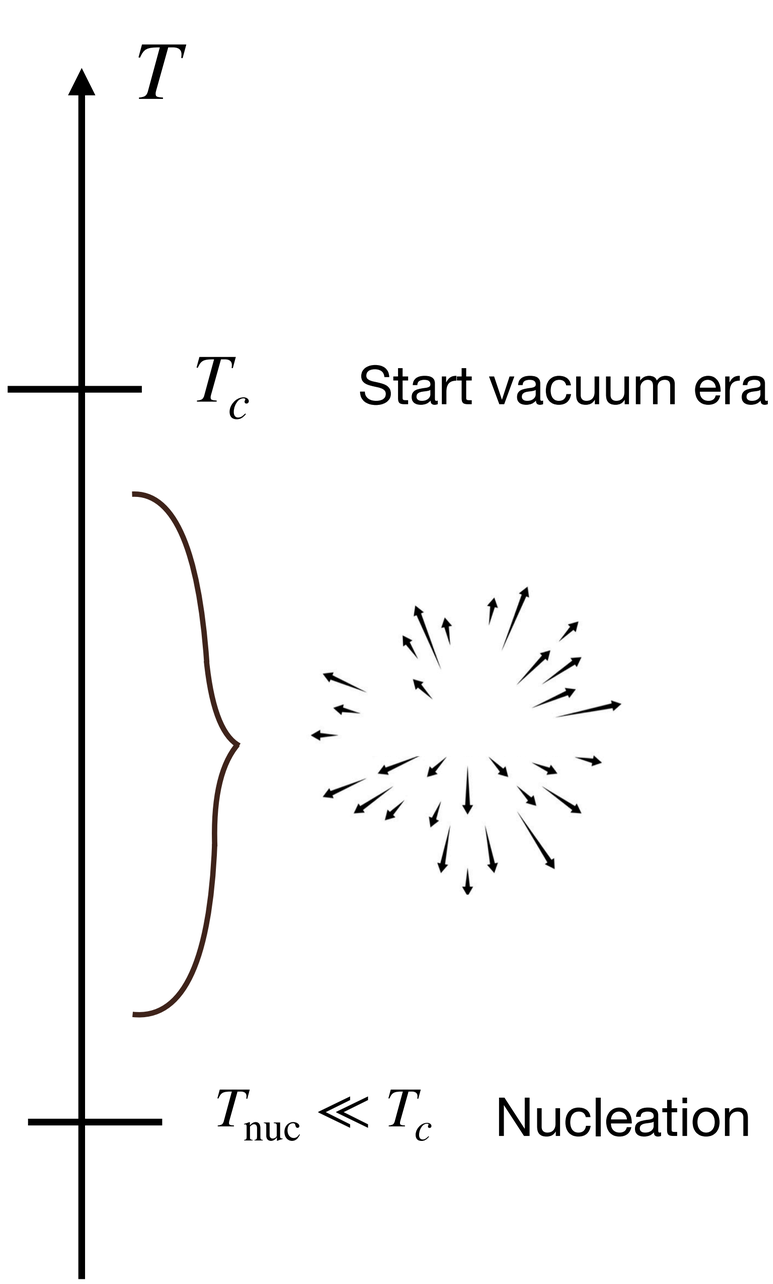

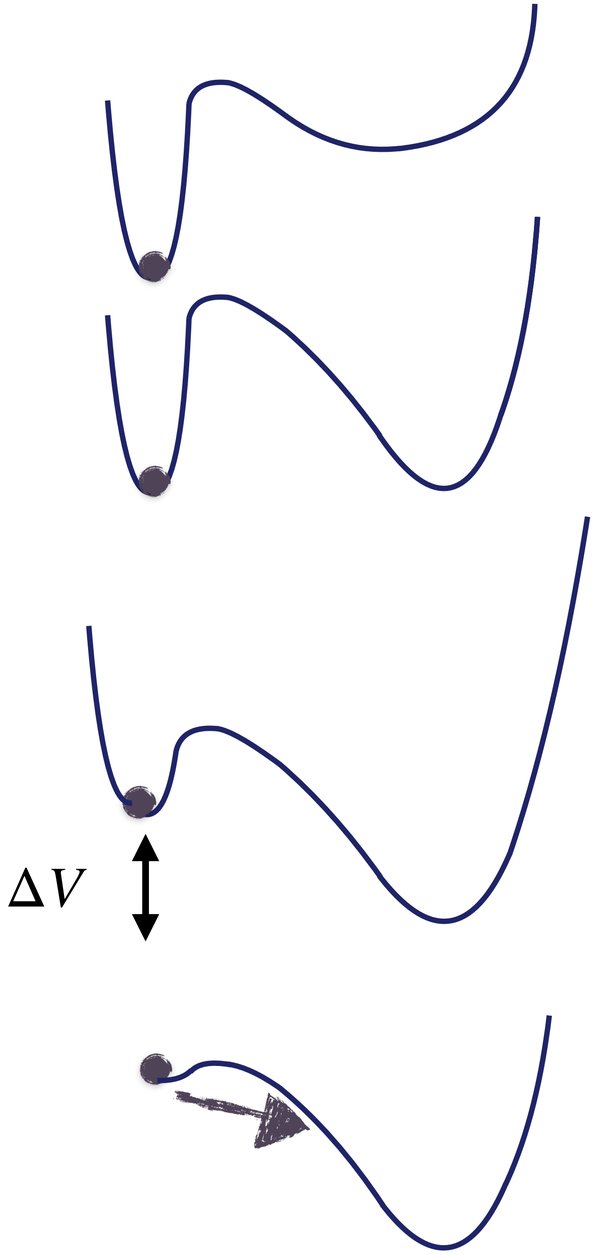

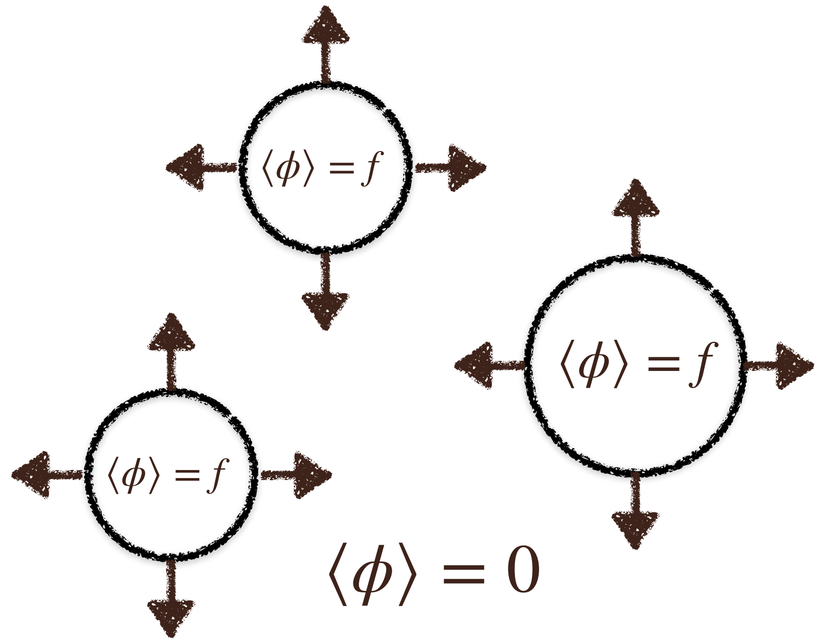

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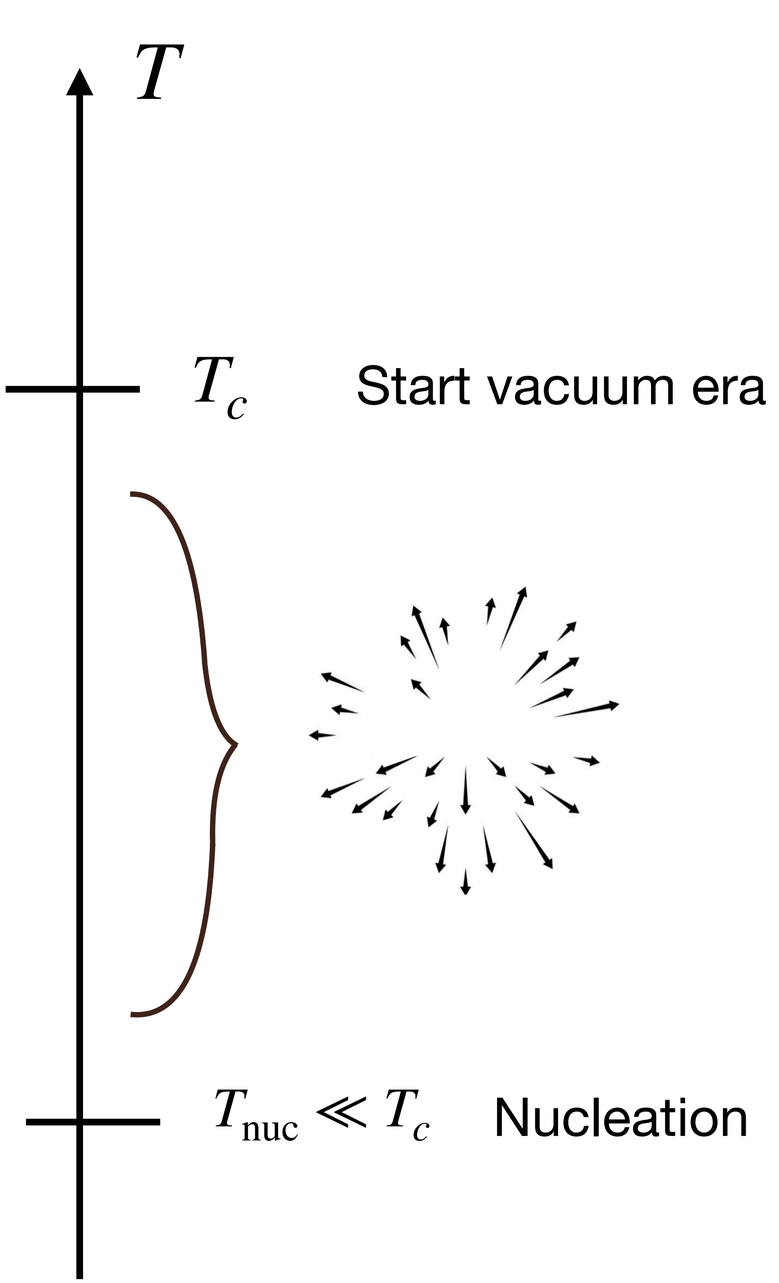

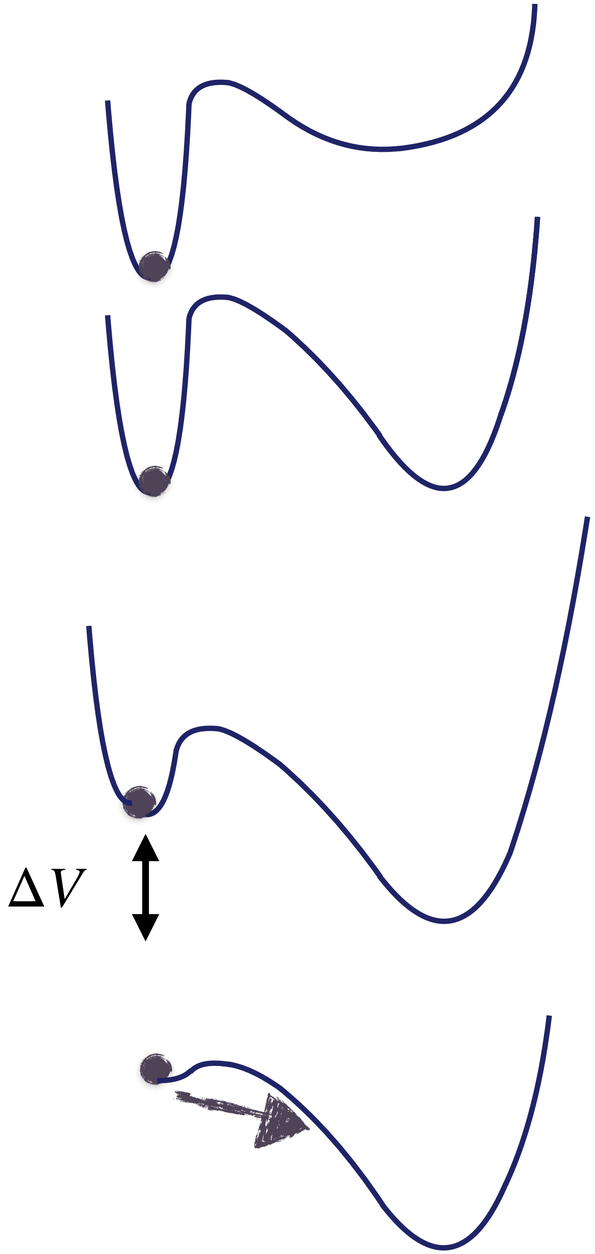

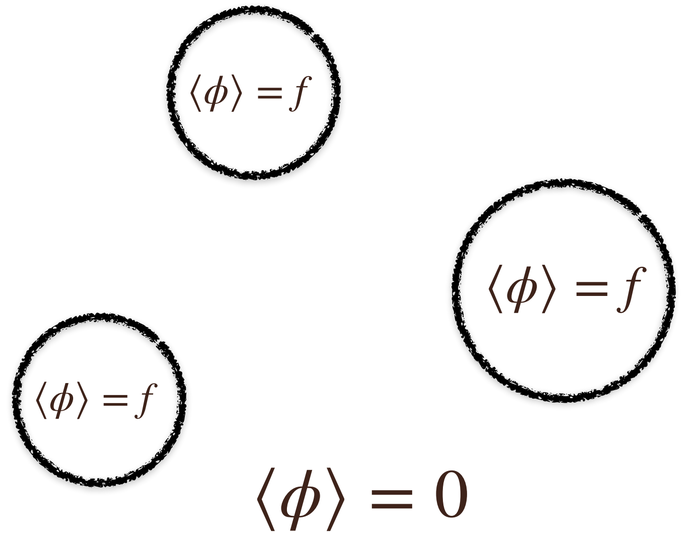

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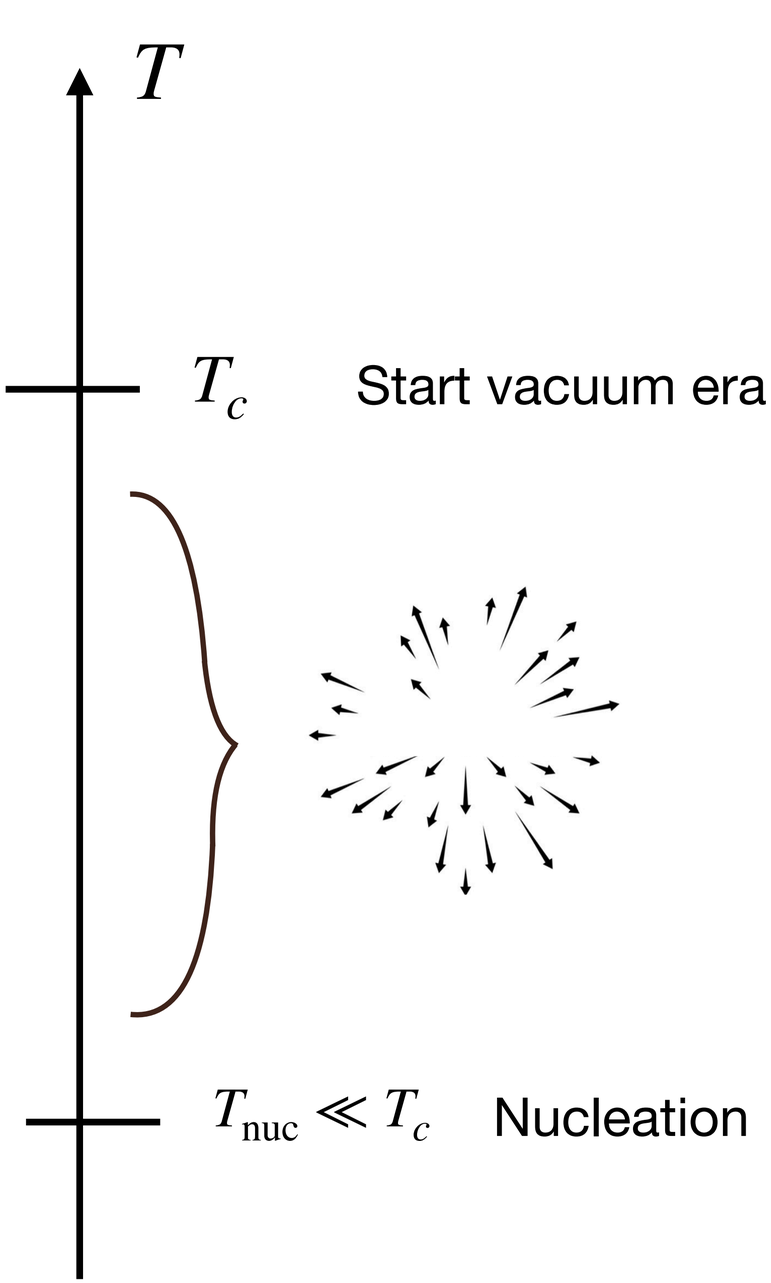

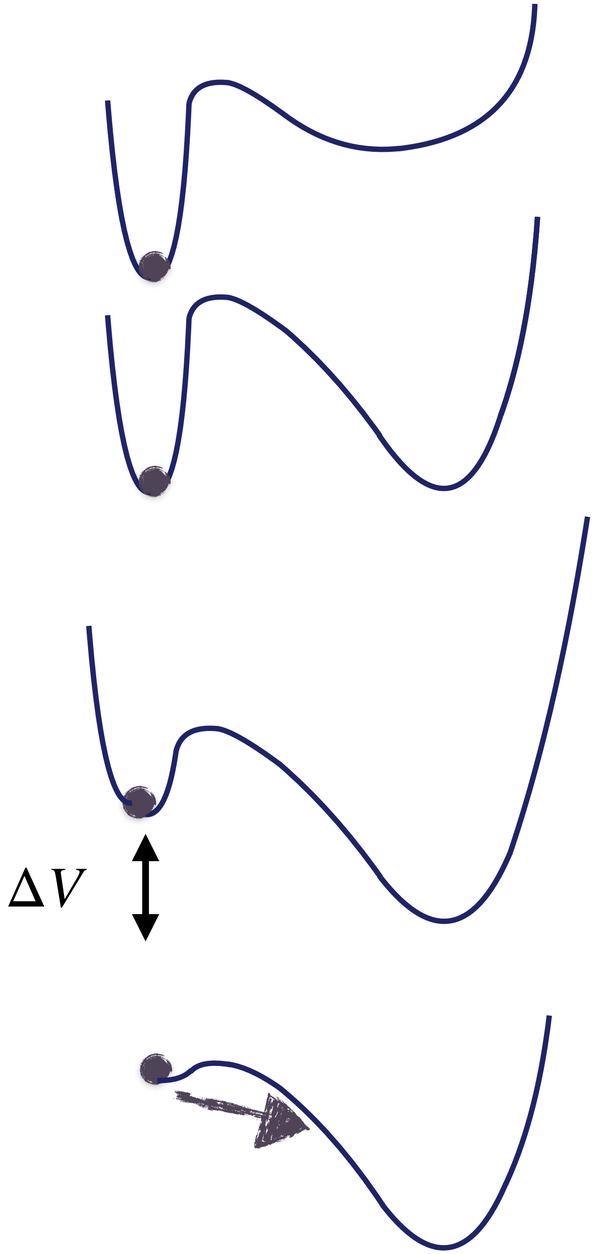

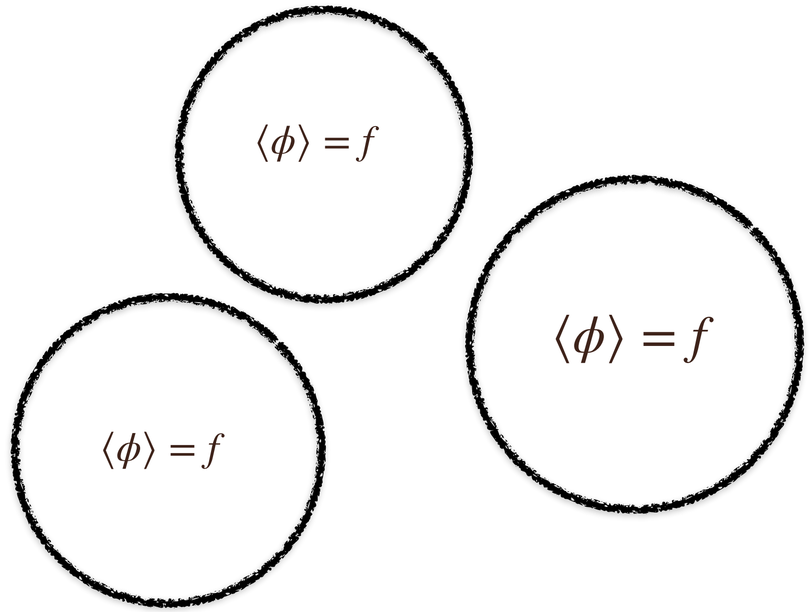

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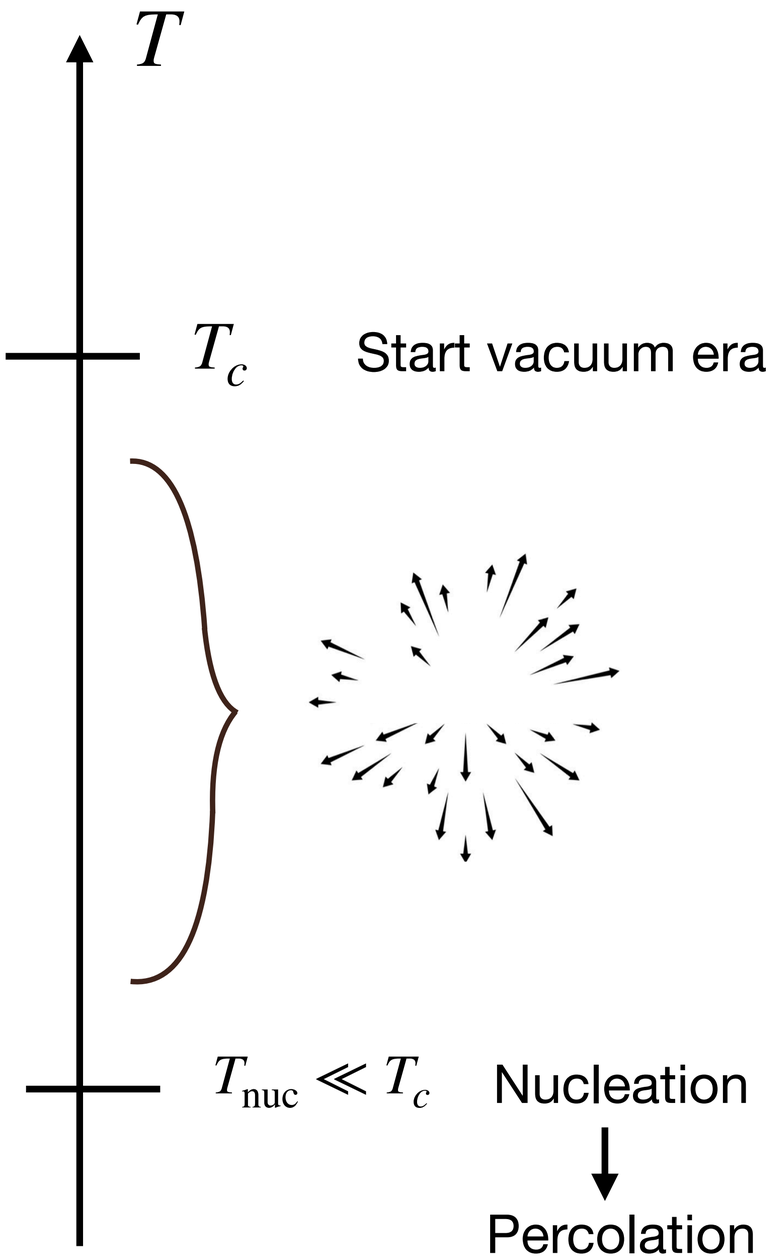

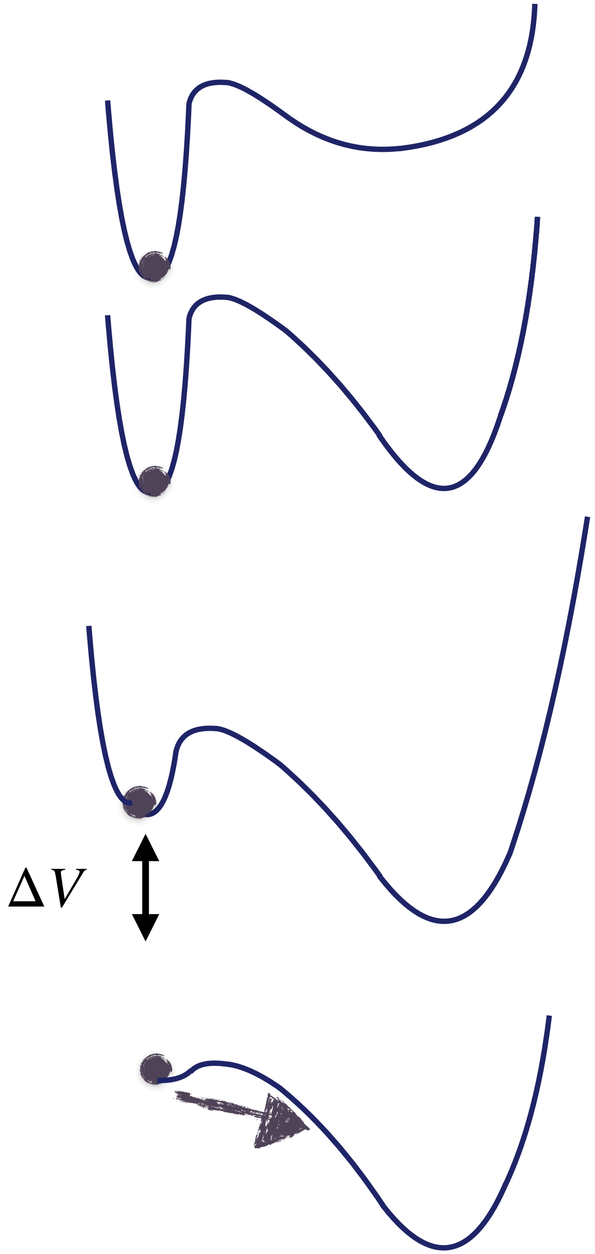

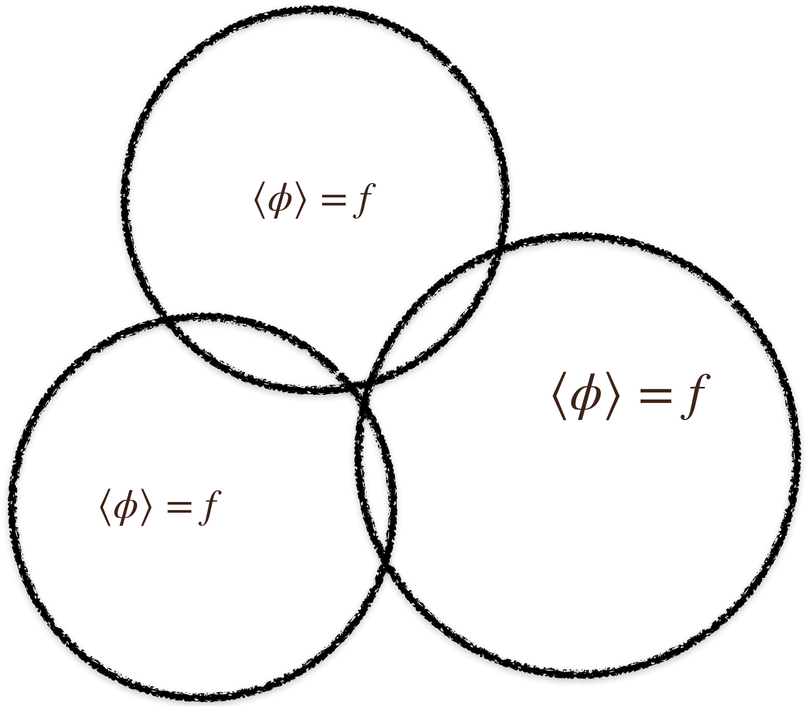

What kind of particle physics model lead to supercooling ?

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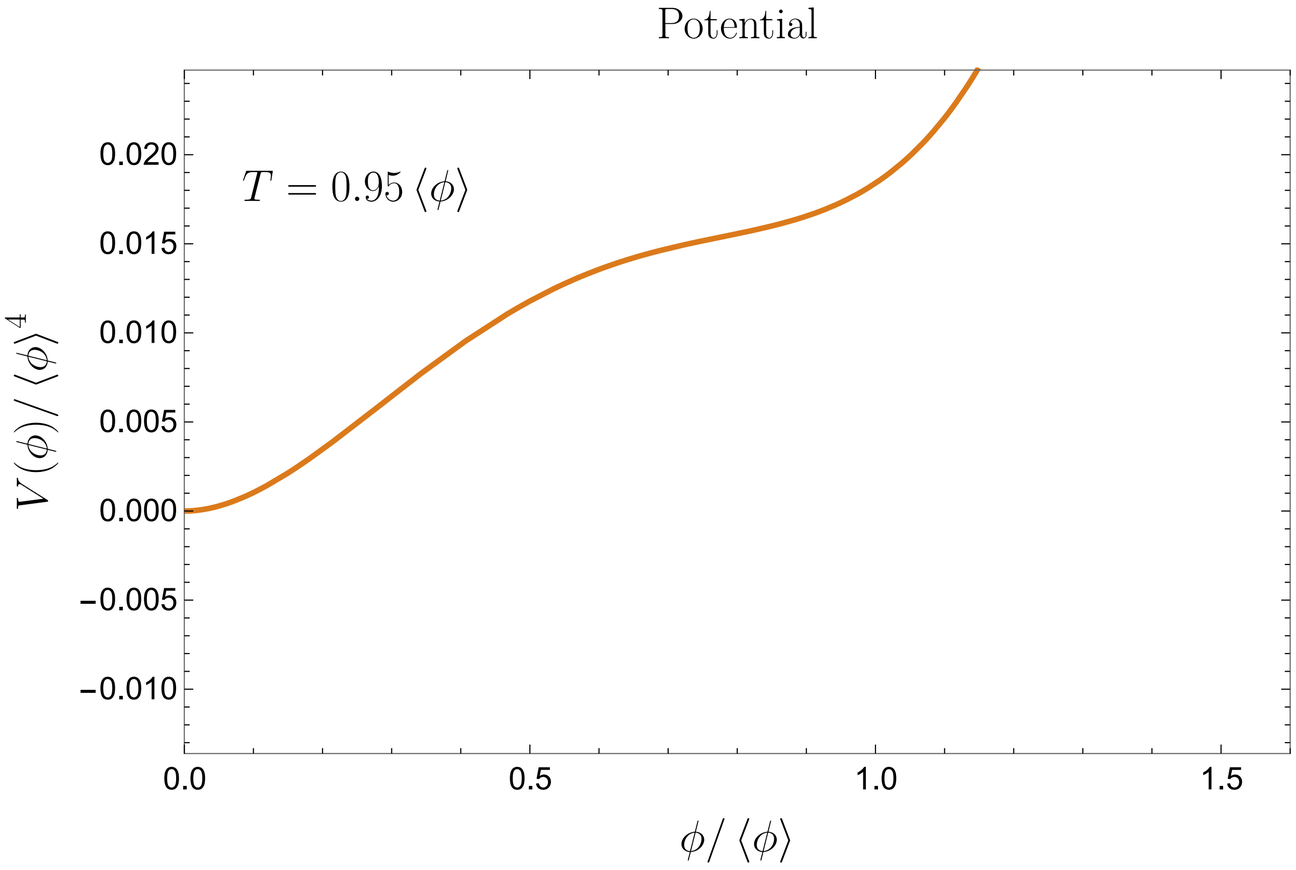
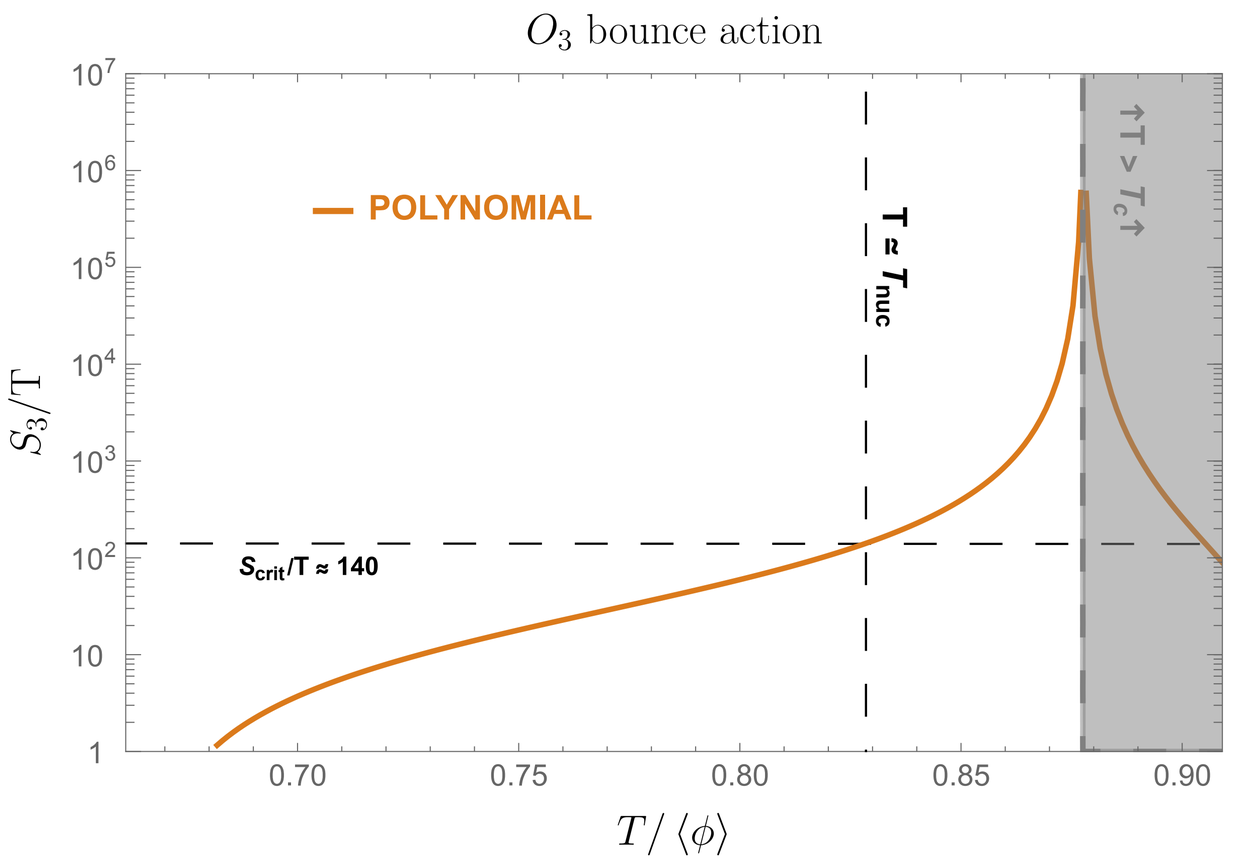
$$V(\phi) = D(T^2 - T_0^2)\phi^2 - ET\phi^3 + \frac{\lambda}{4}\phi^4$$





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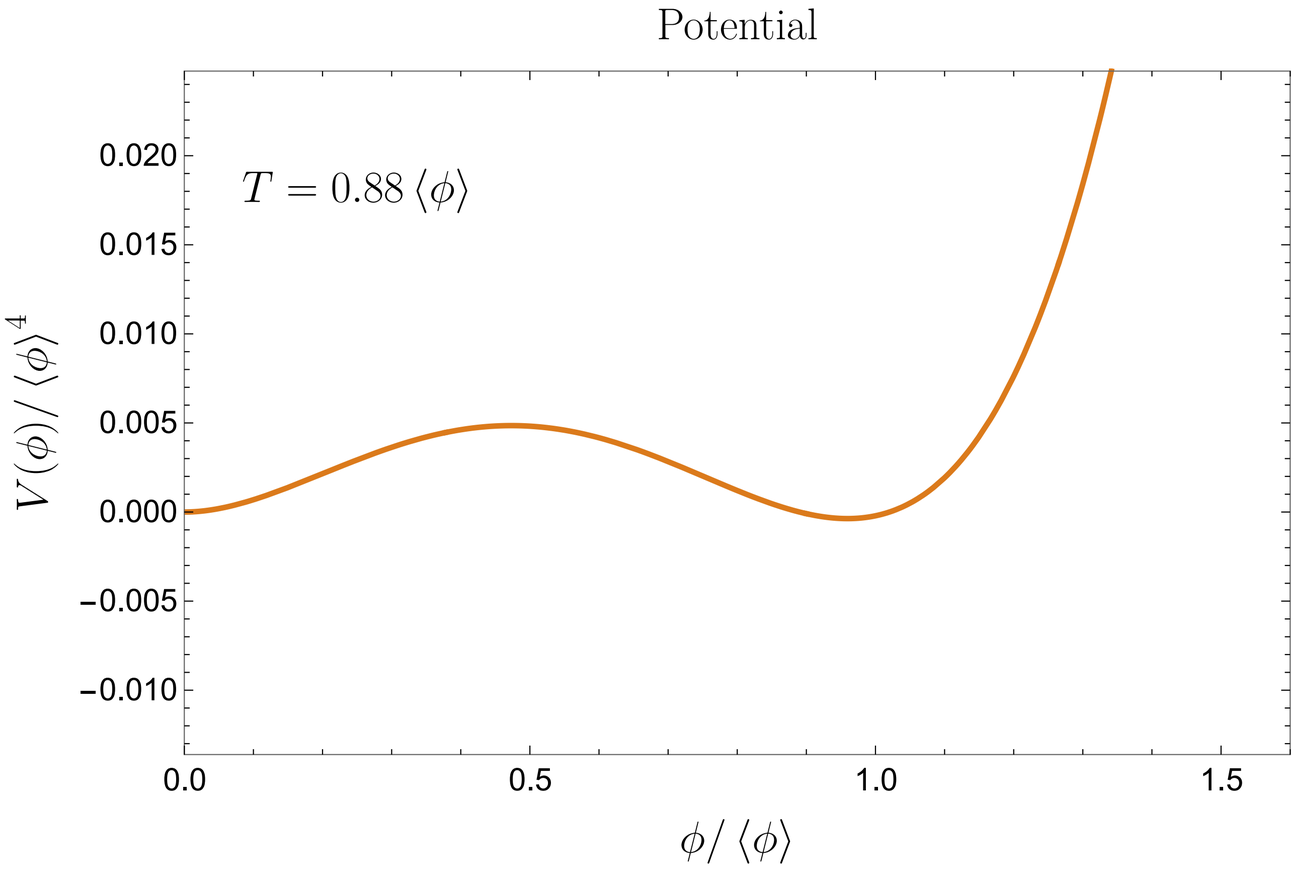

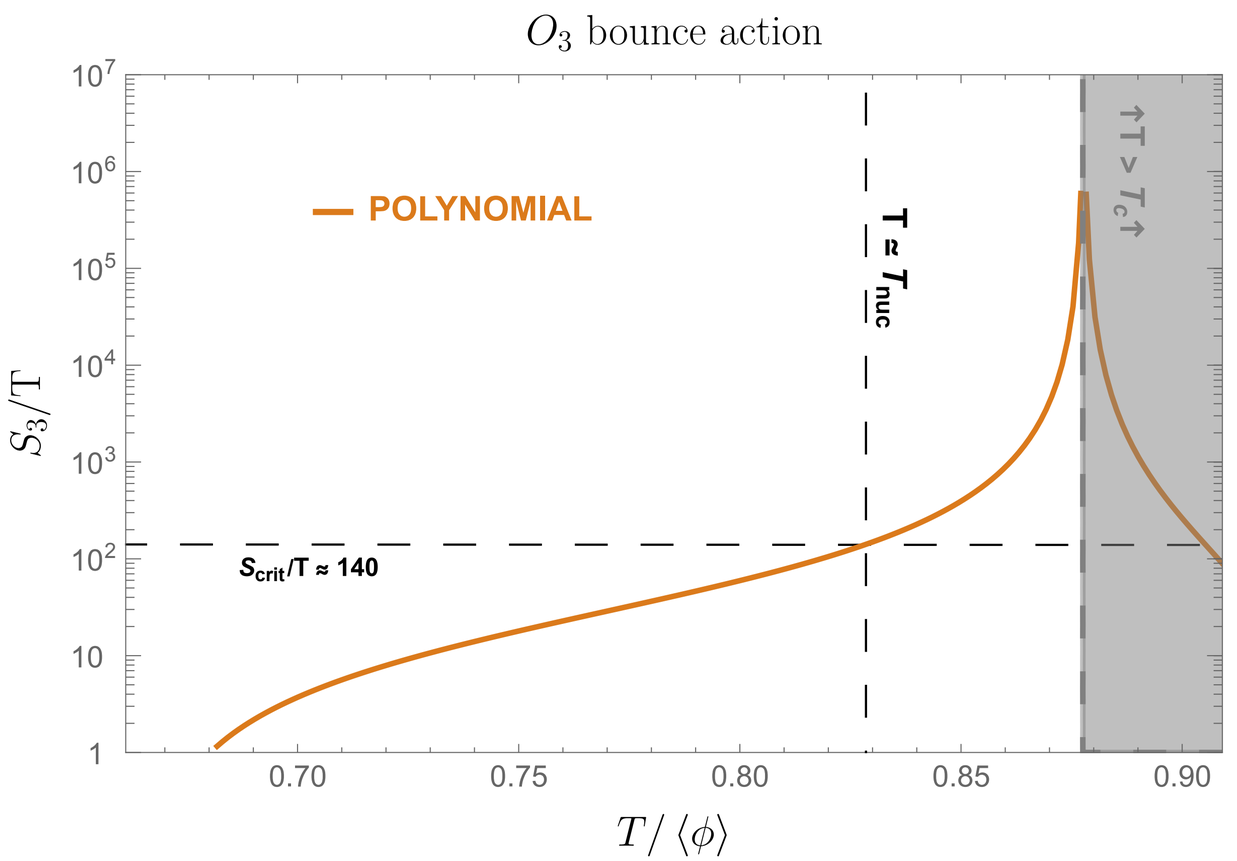

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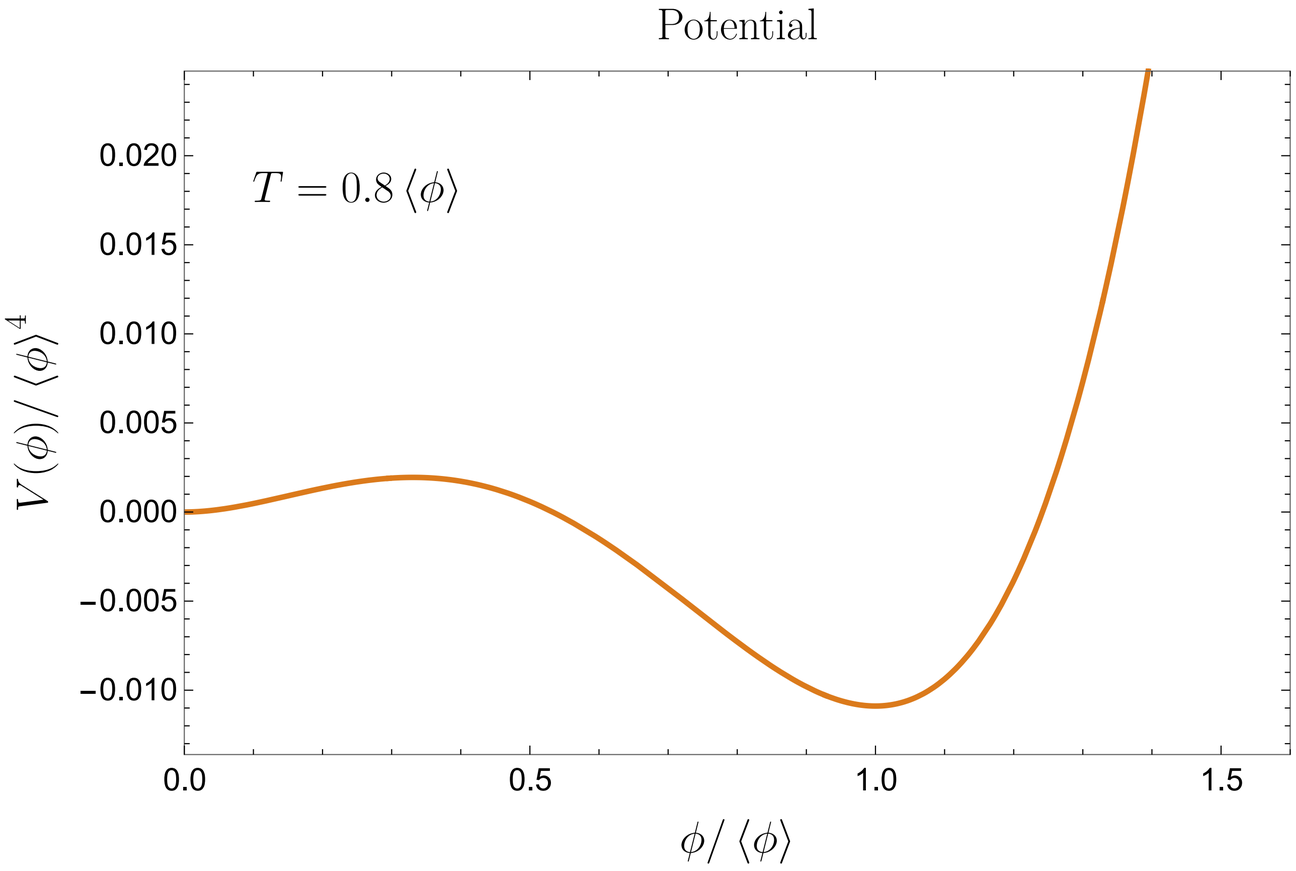

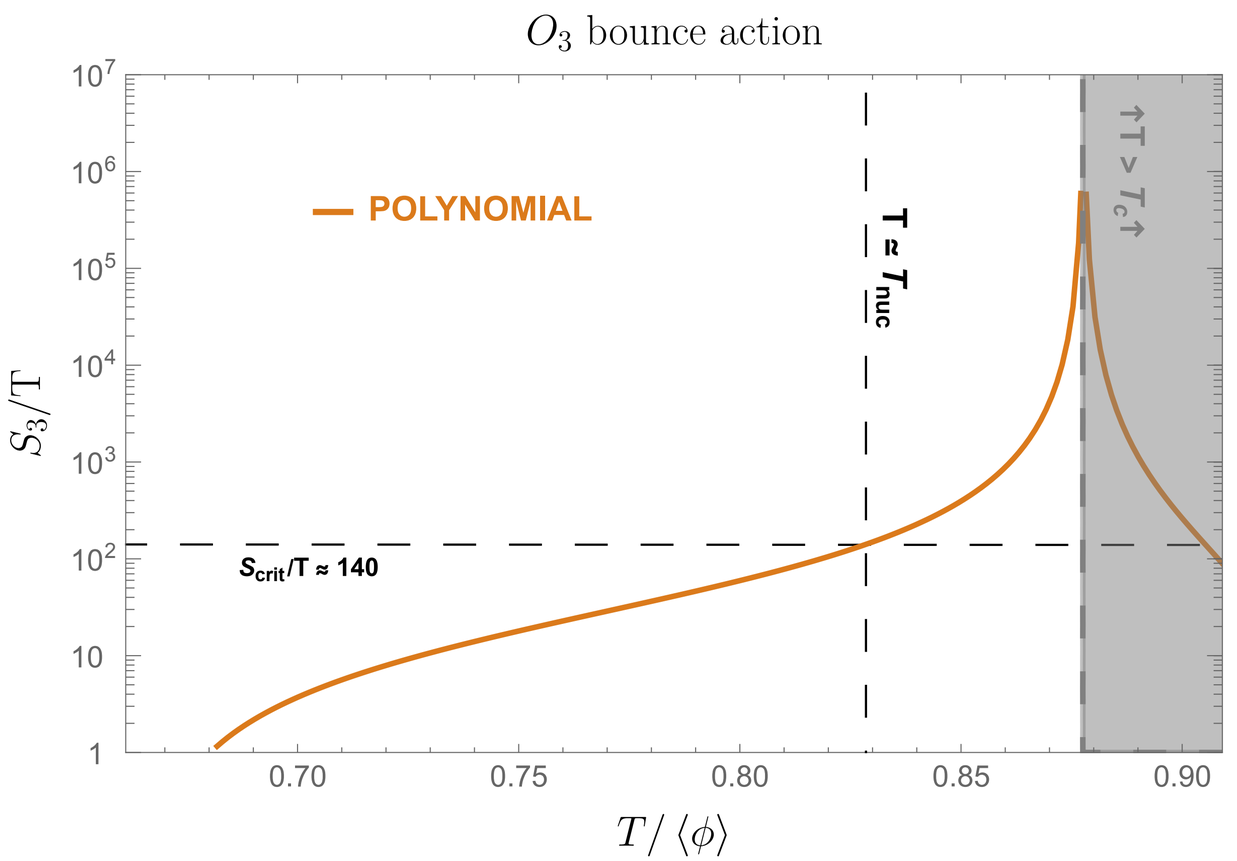

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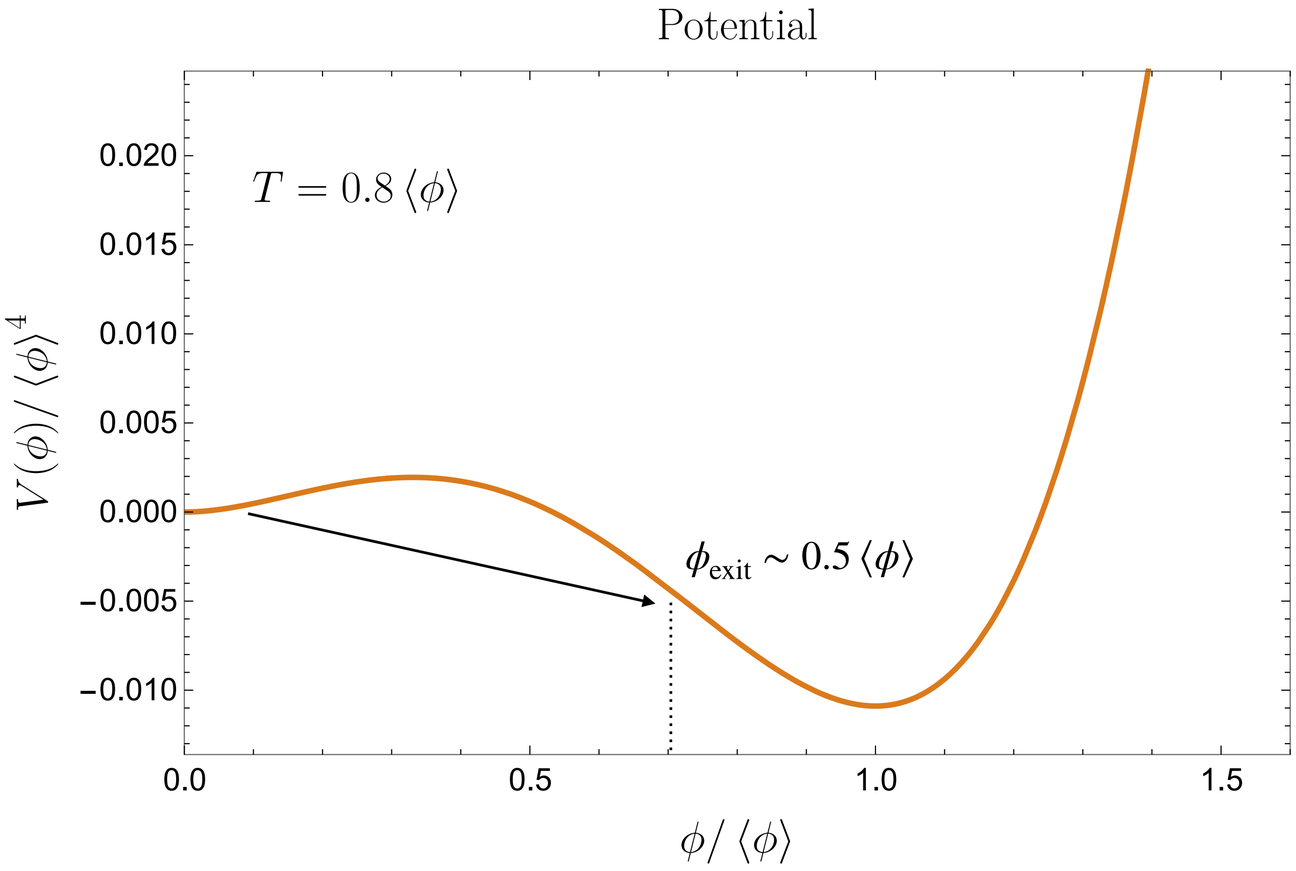

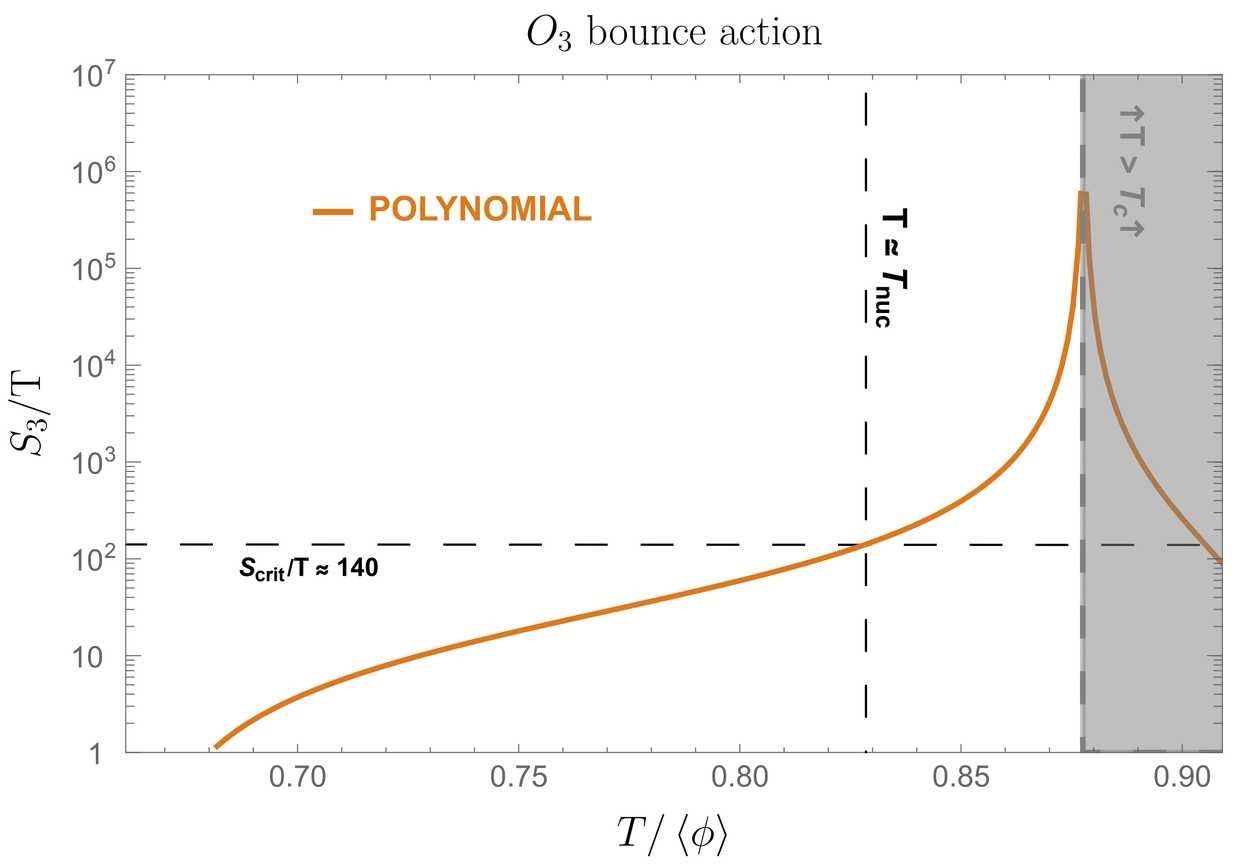

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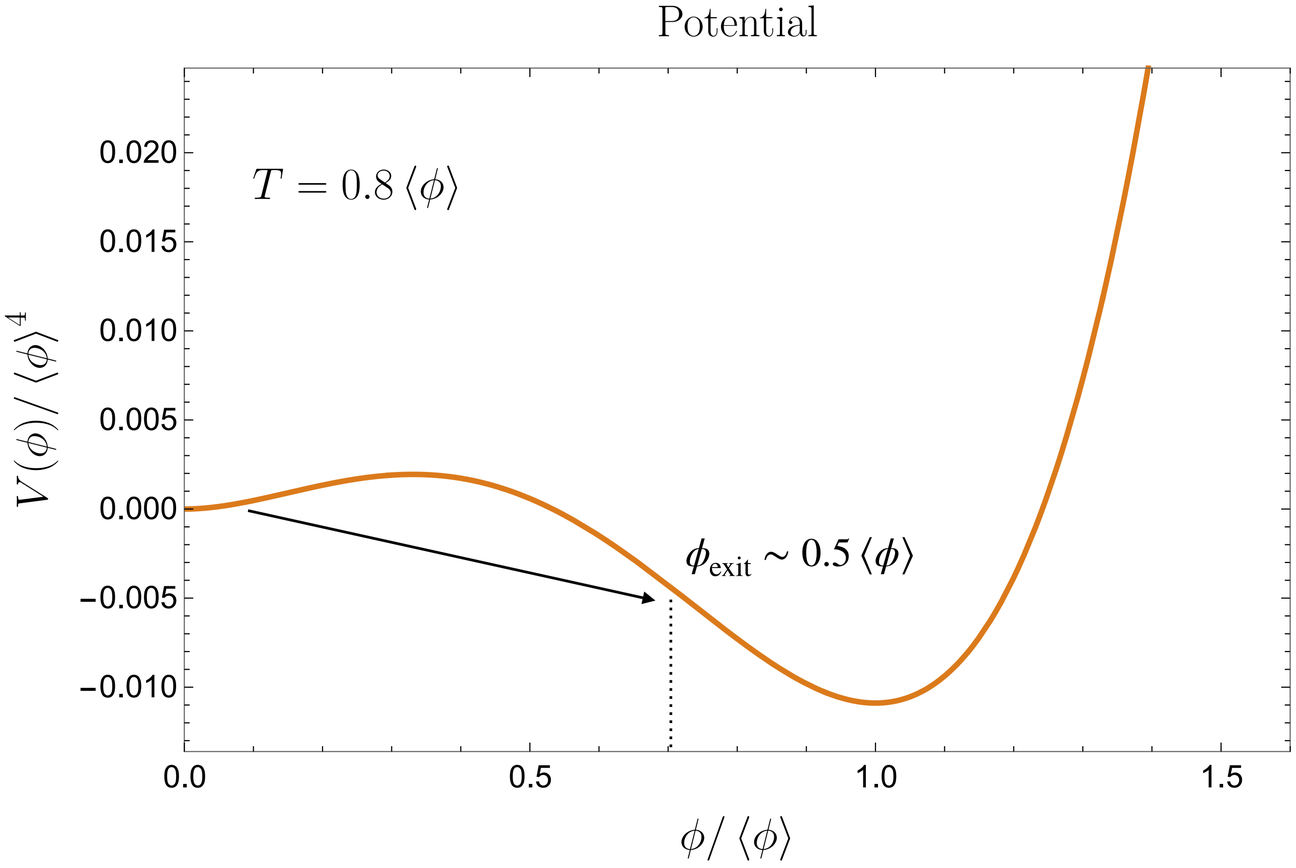

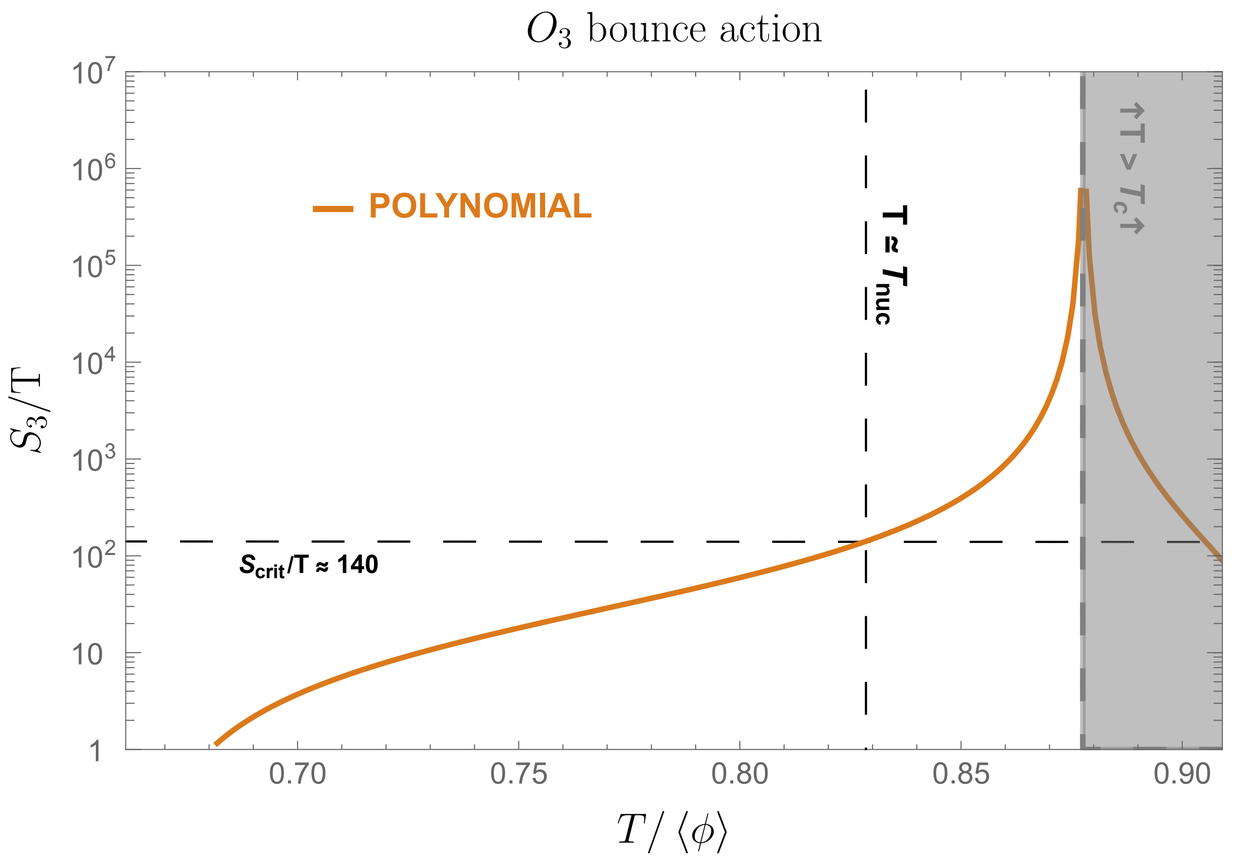

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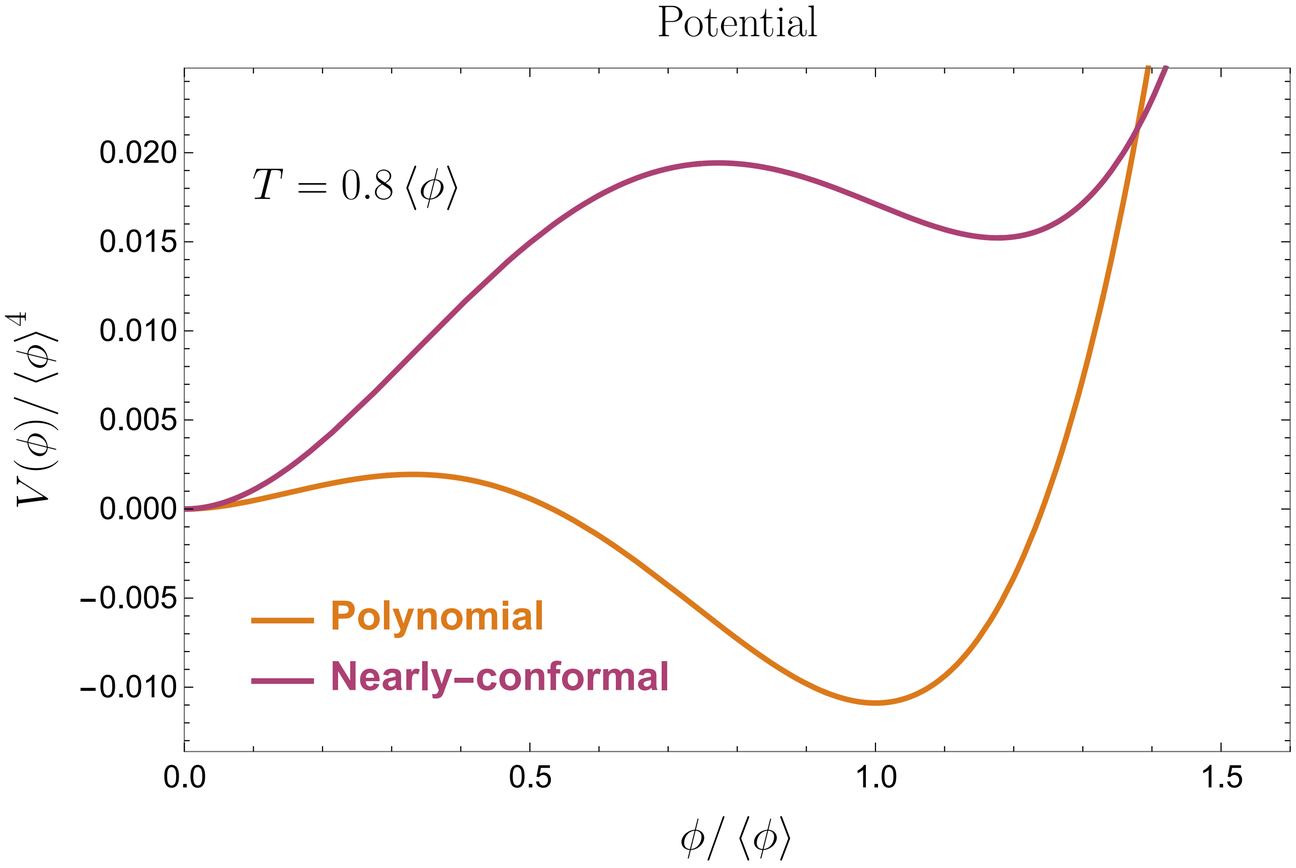

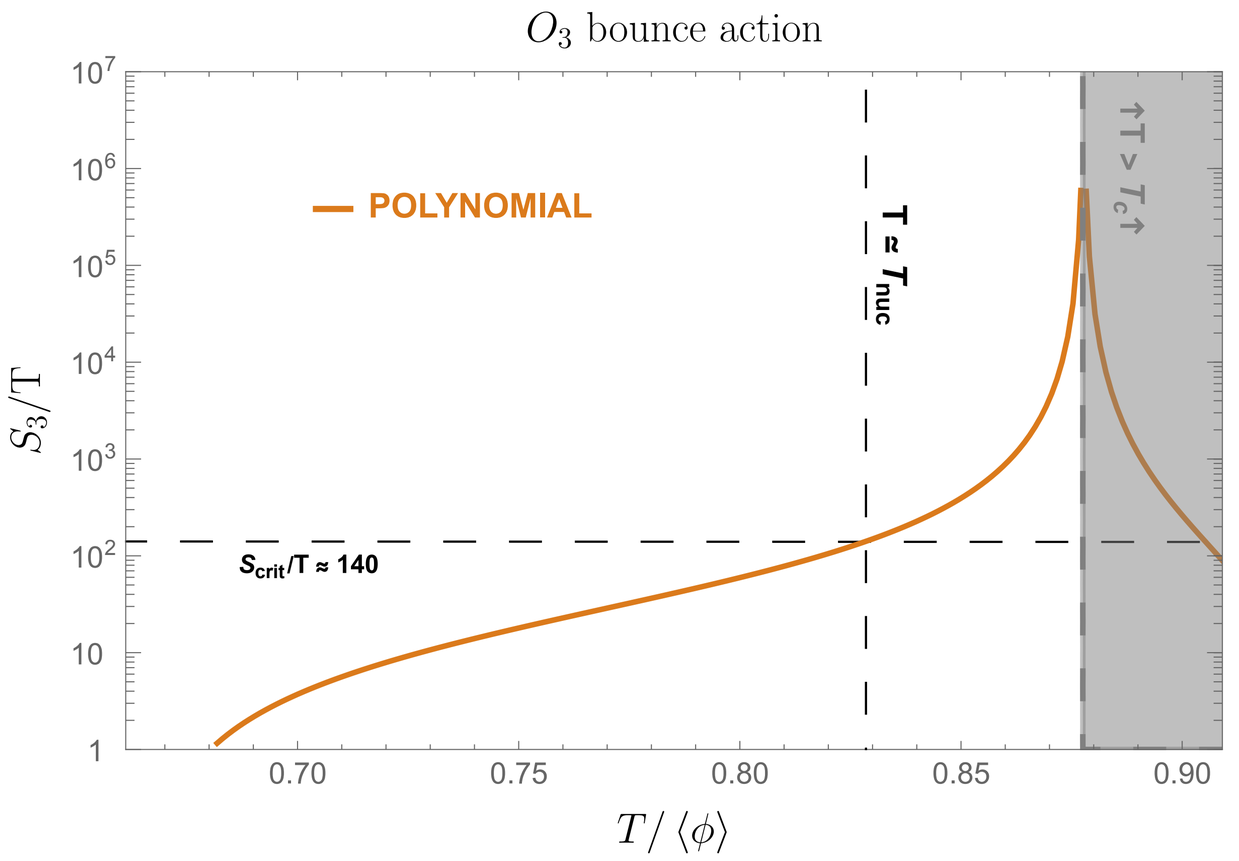

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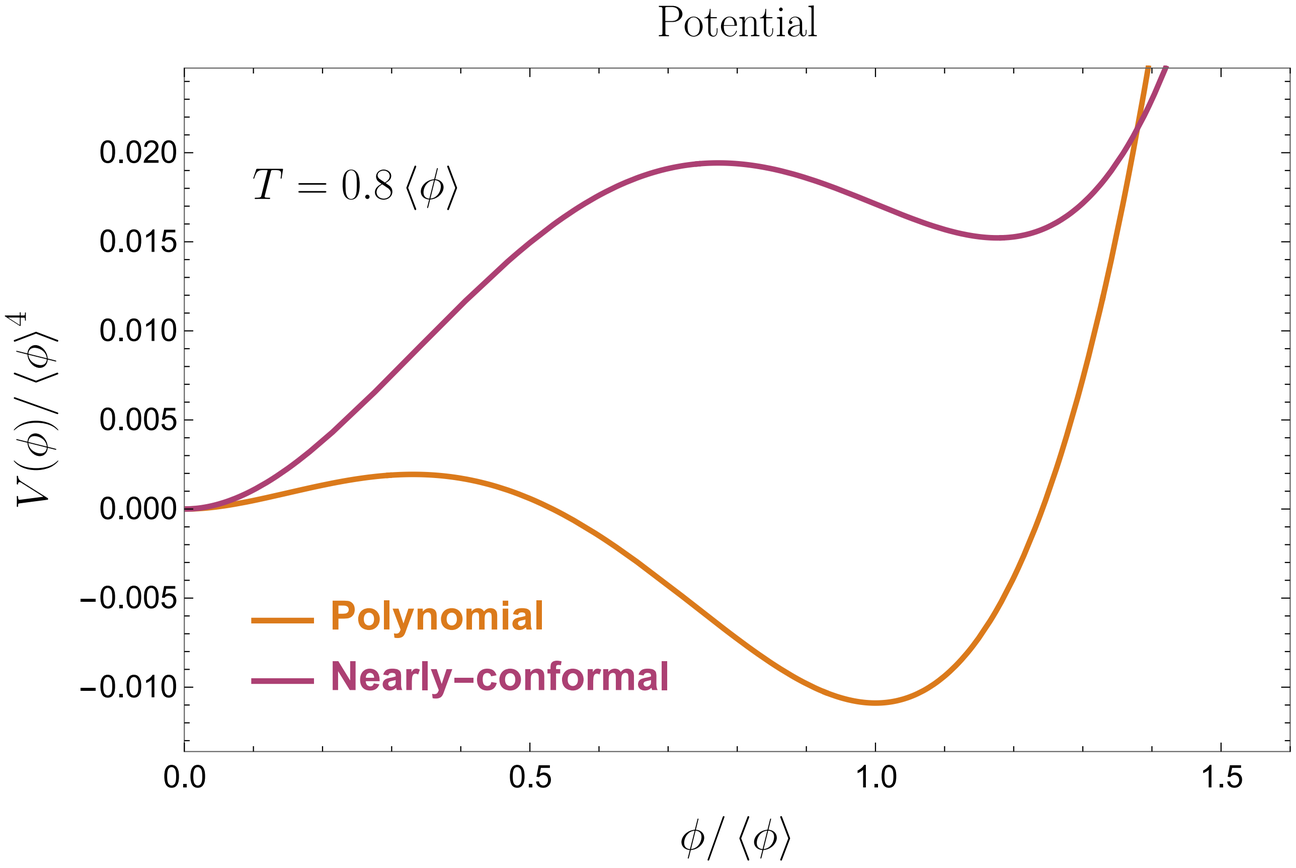

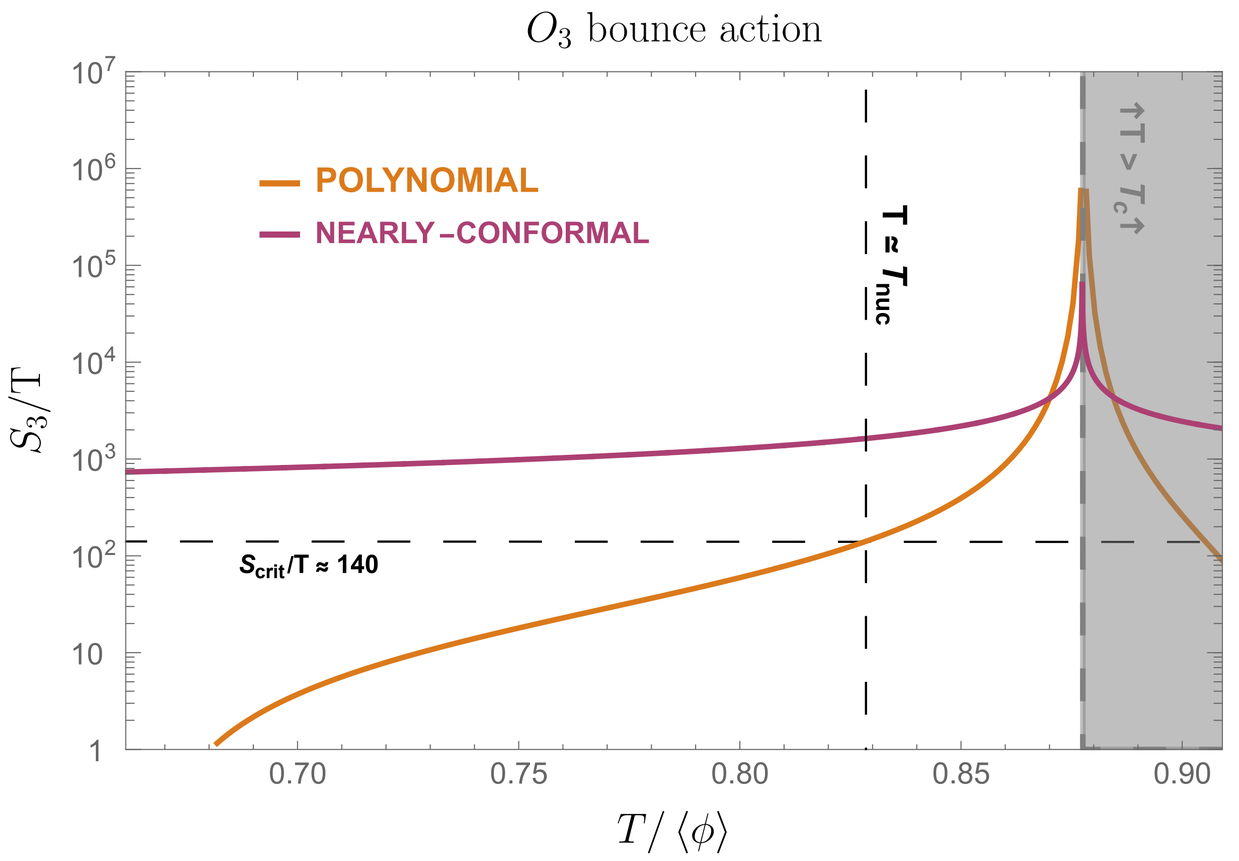

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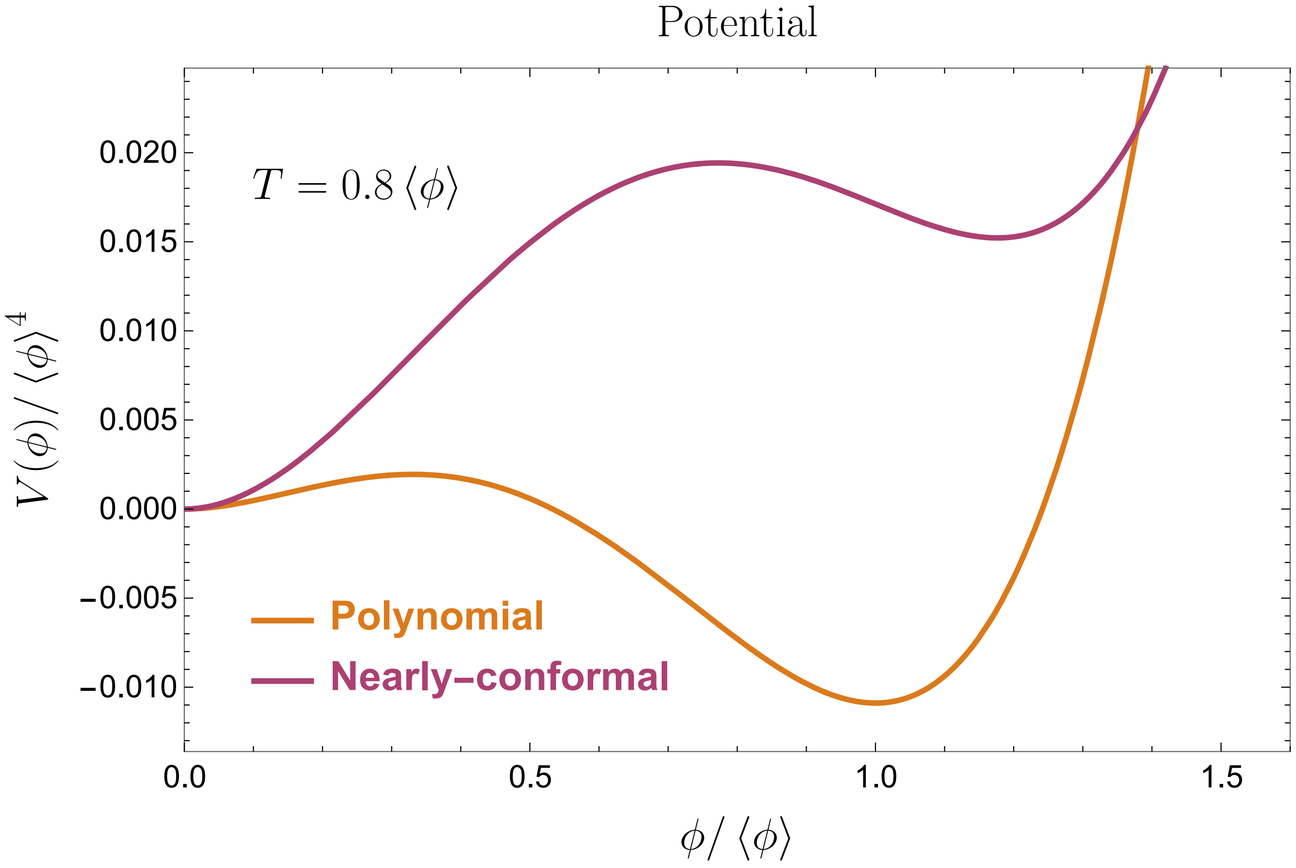

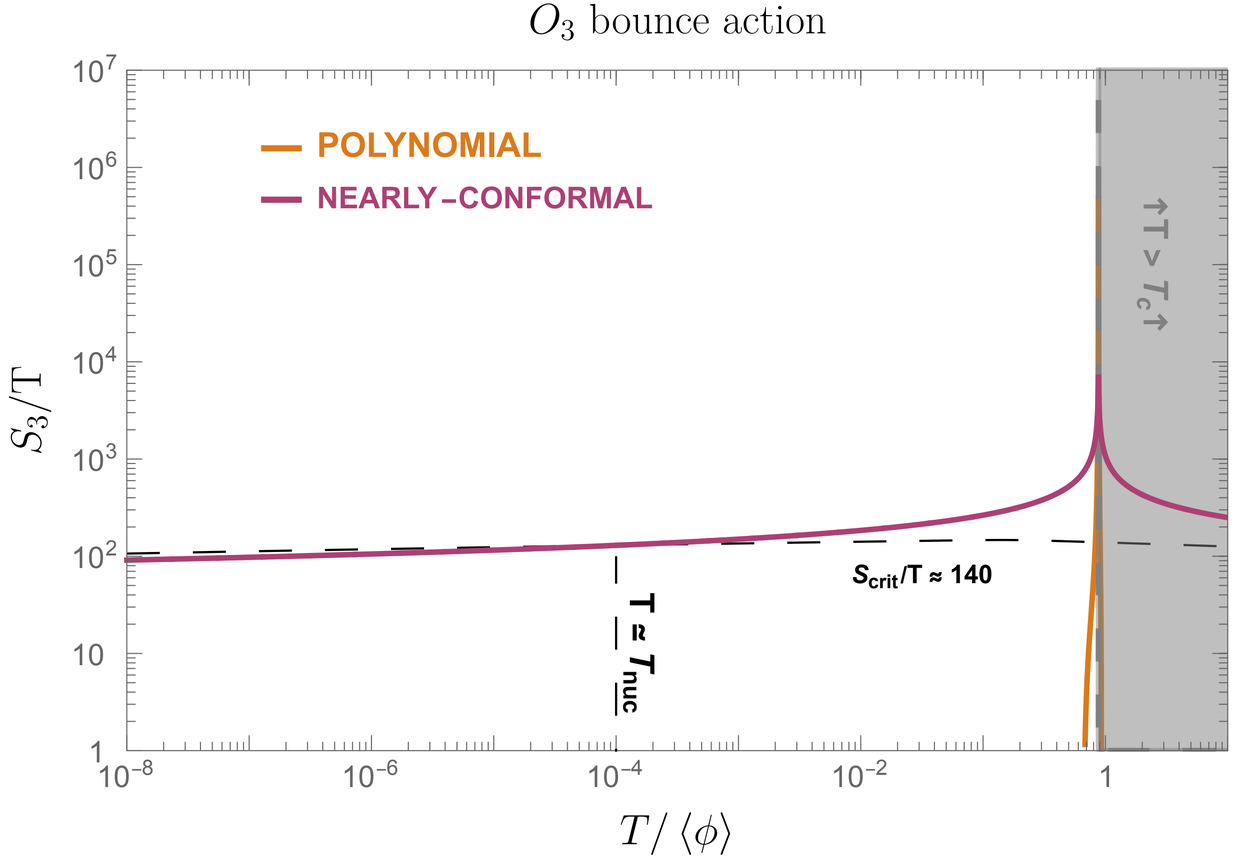

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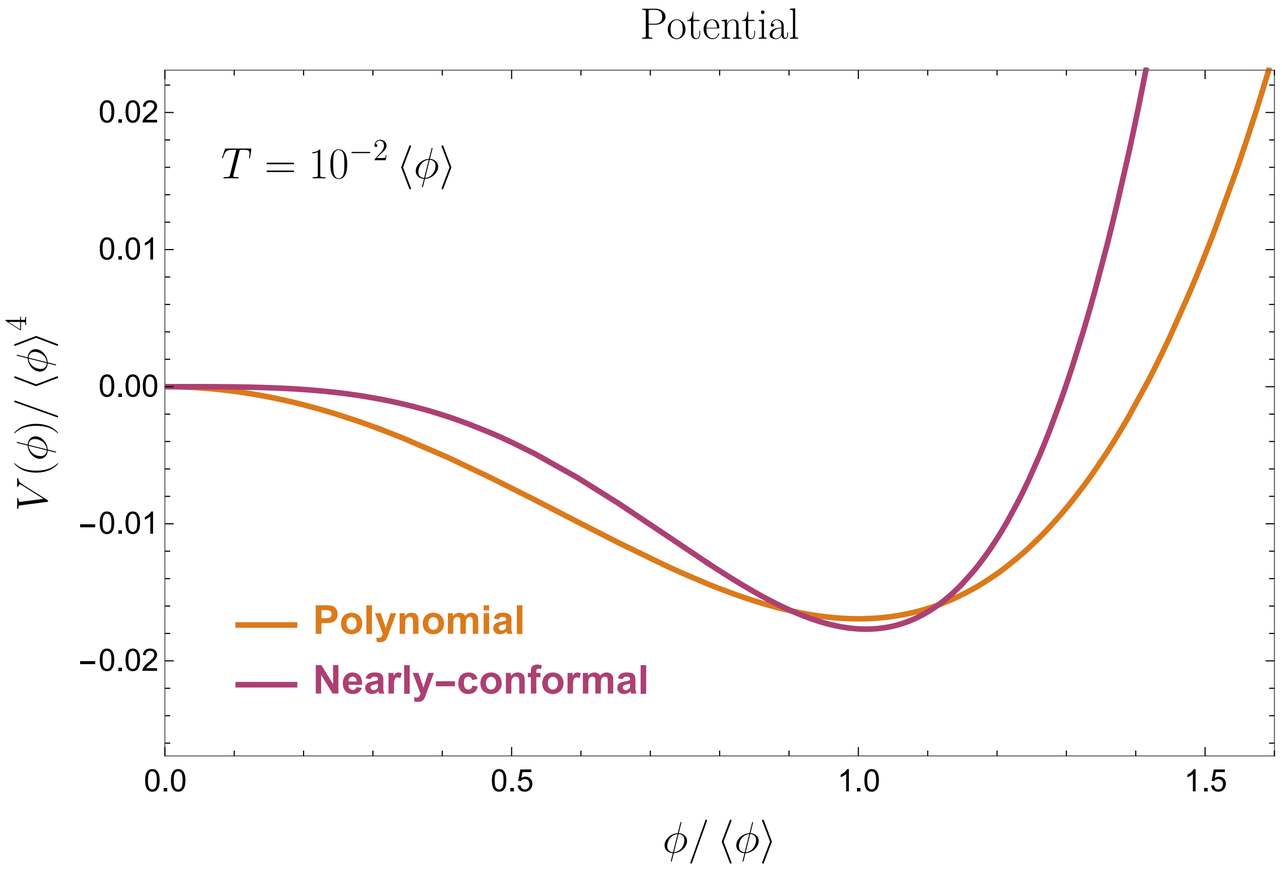

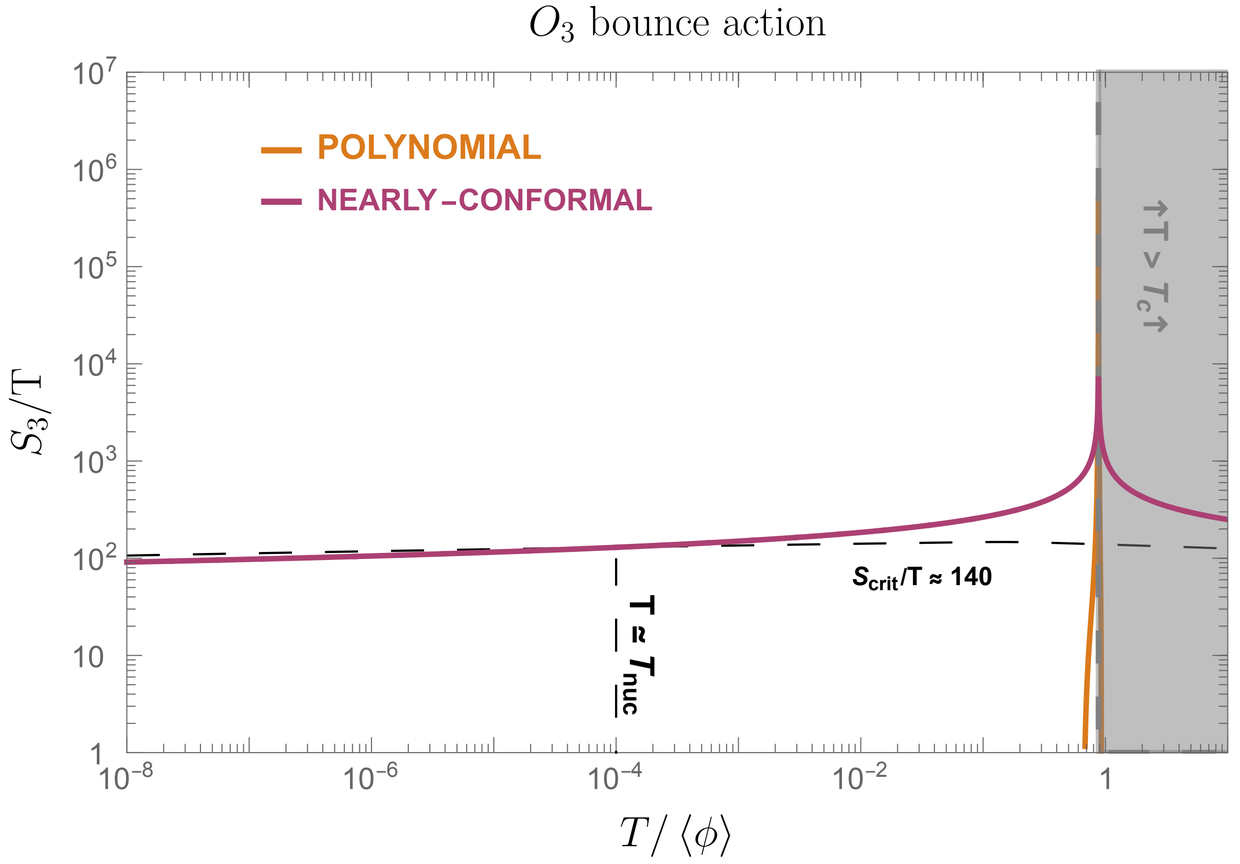

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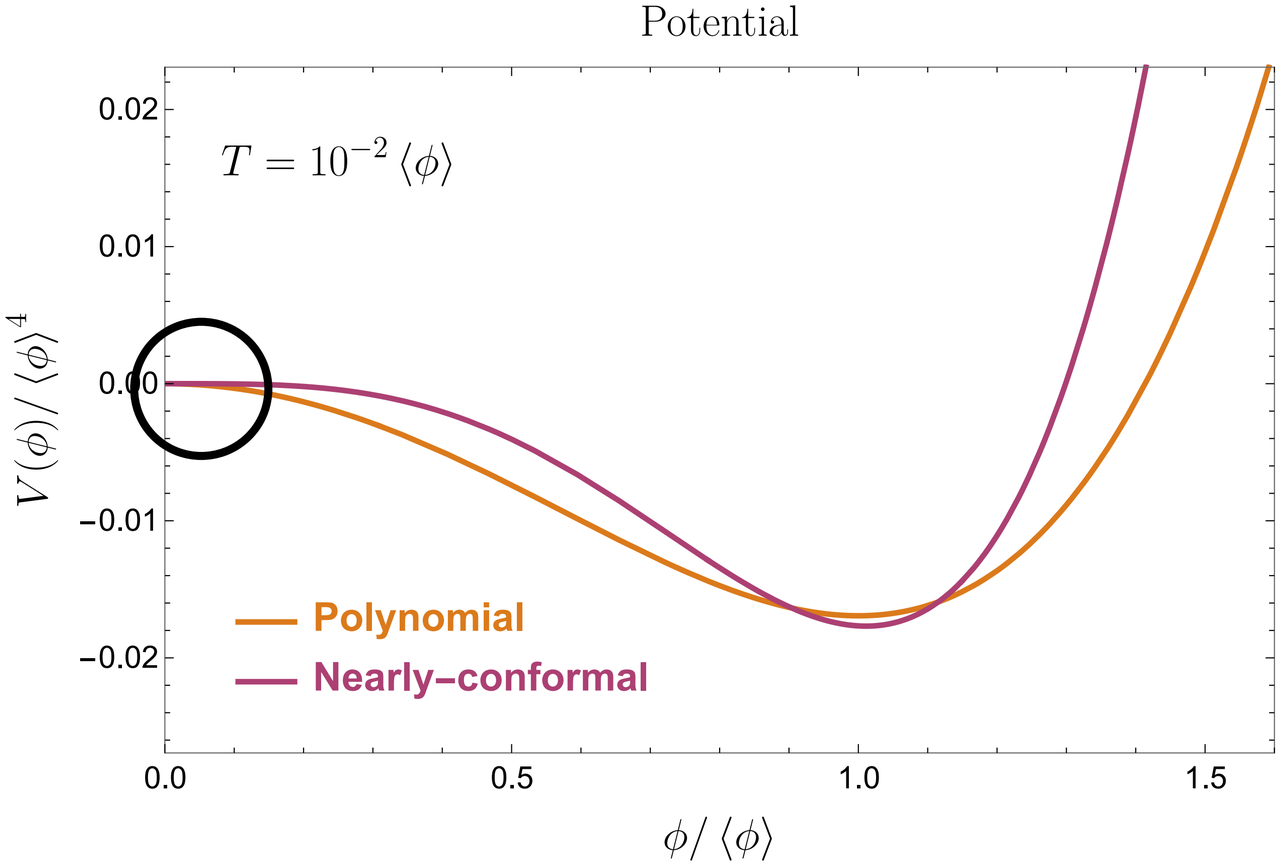

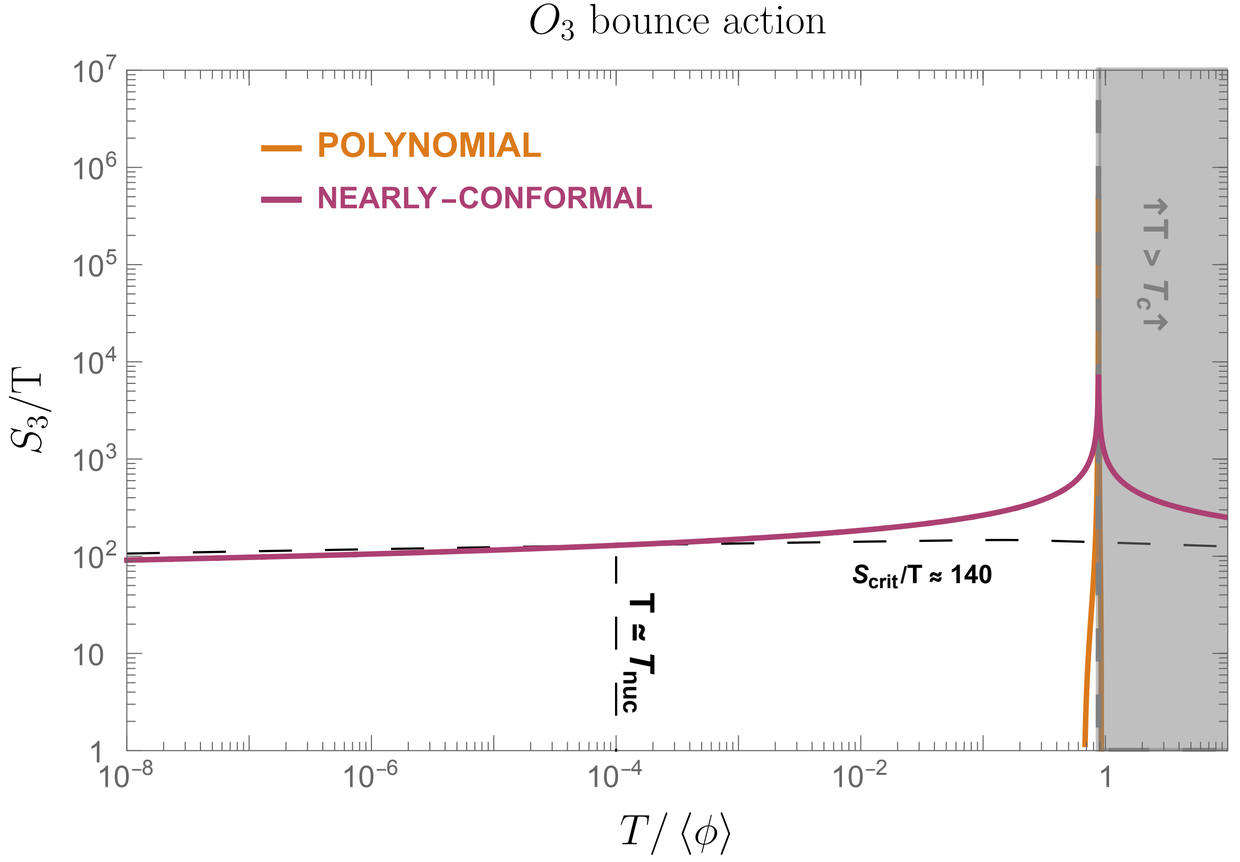

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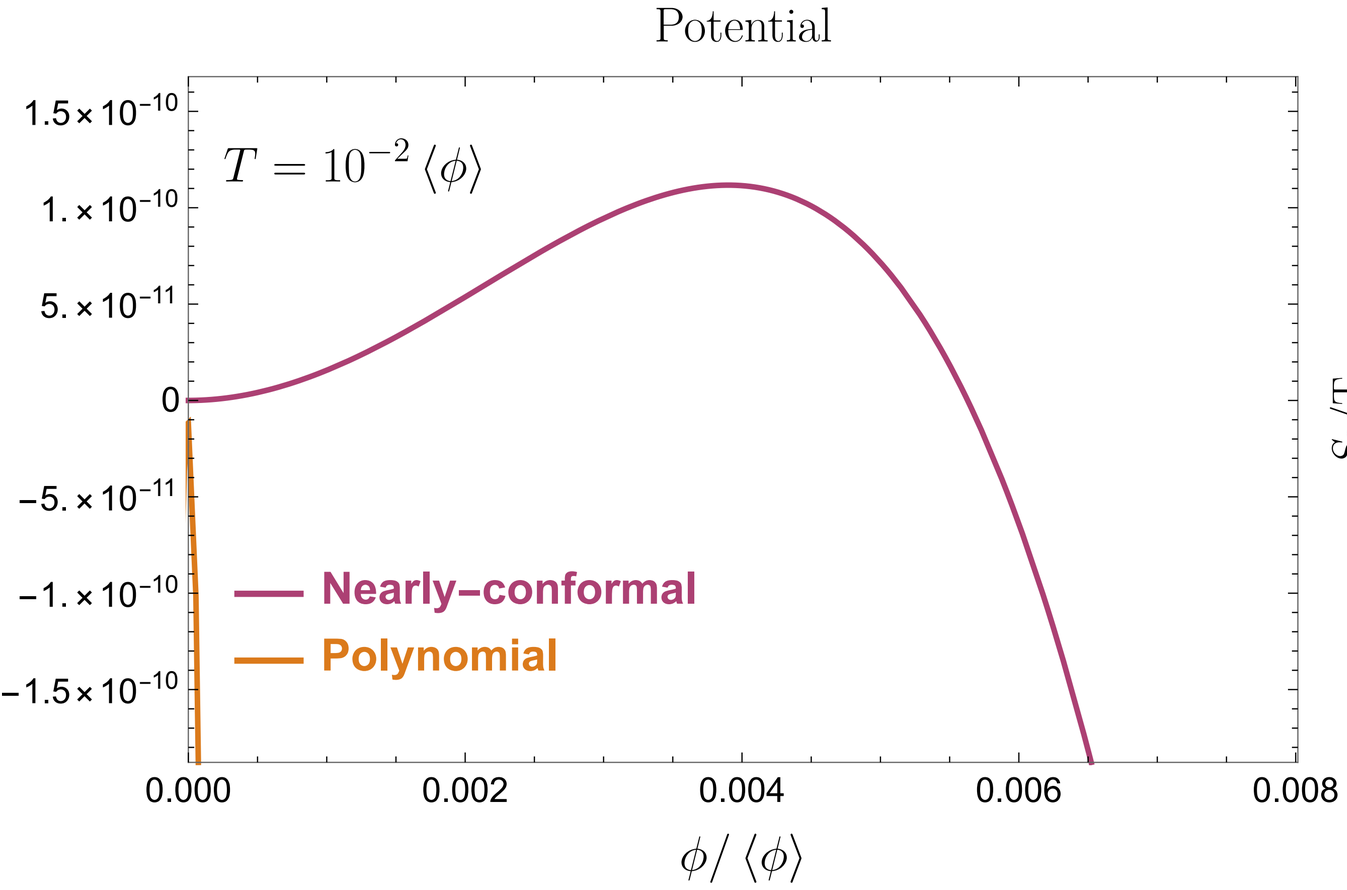

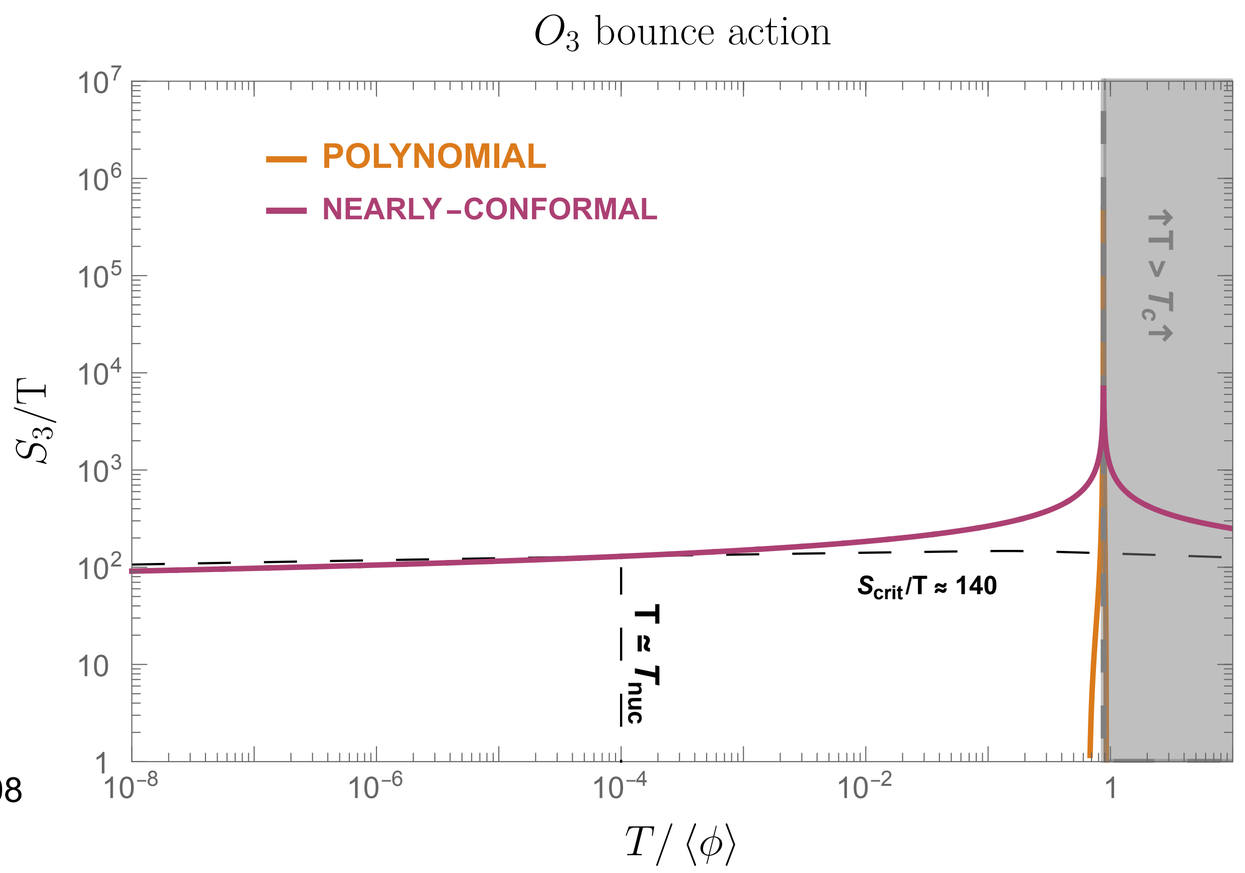

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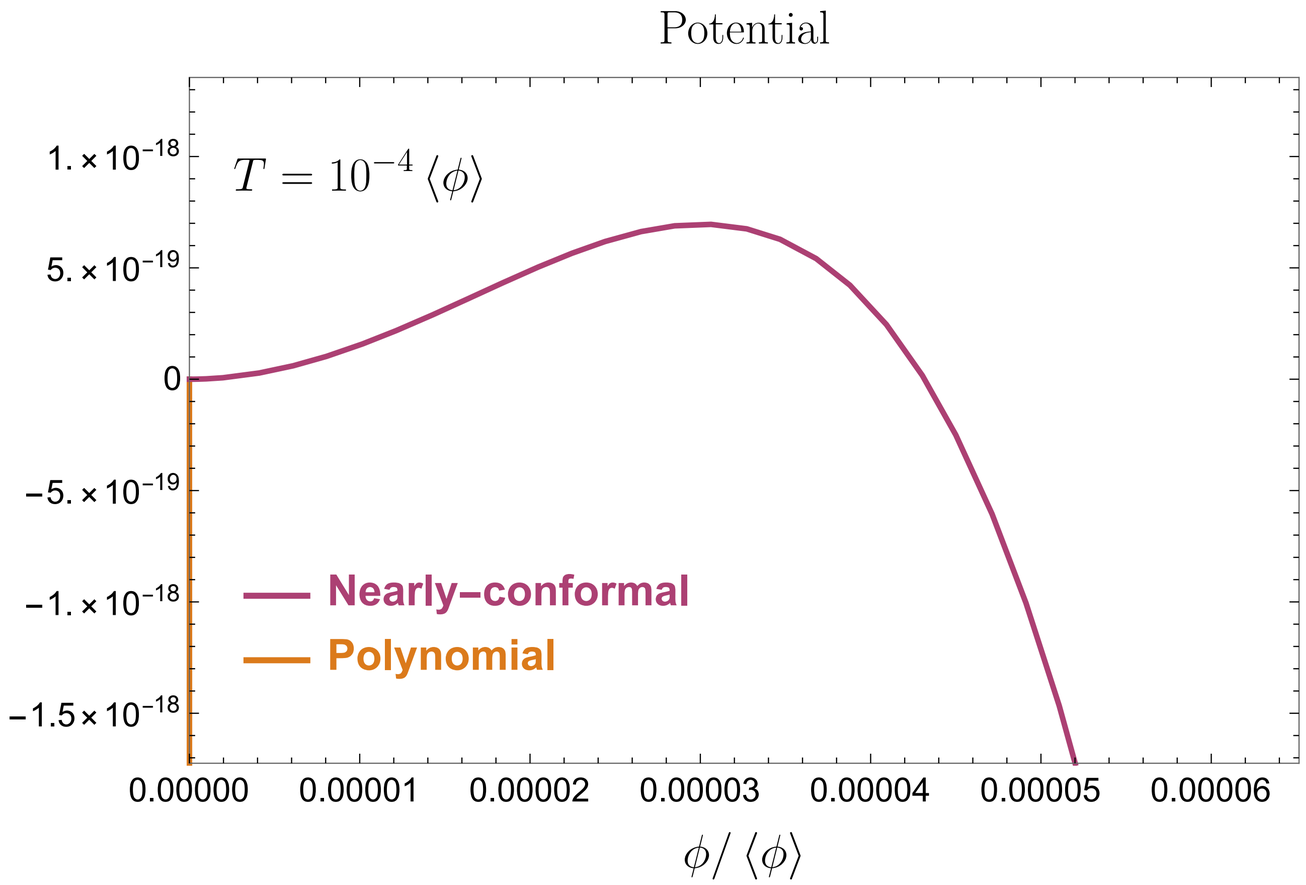

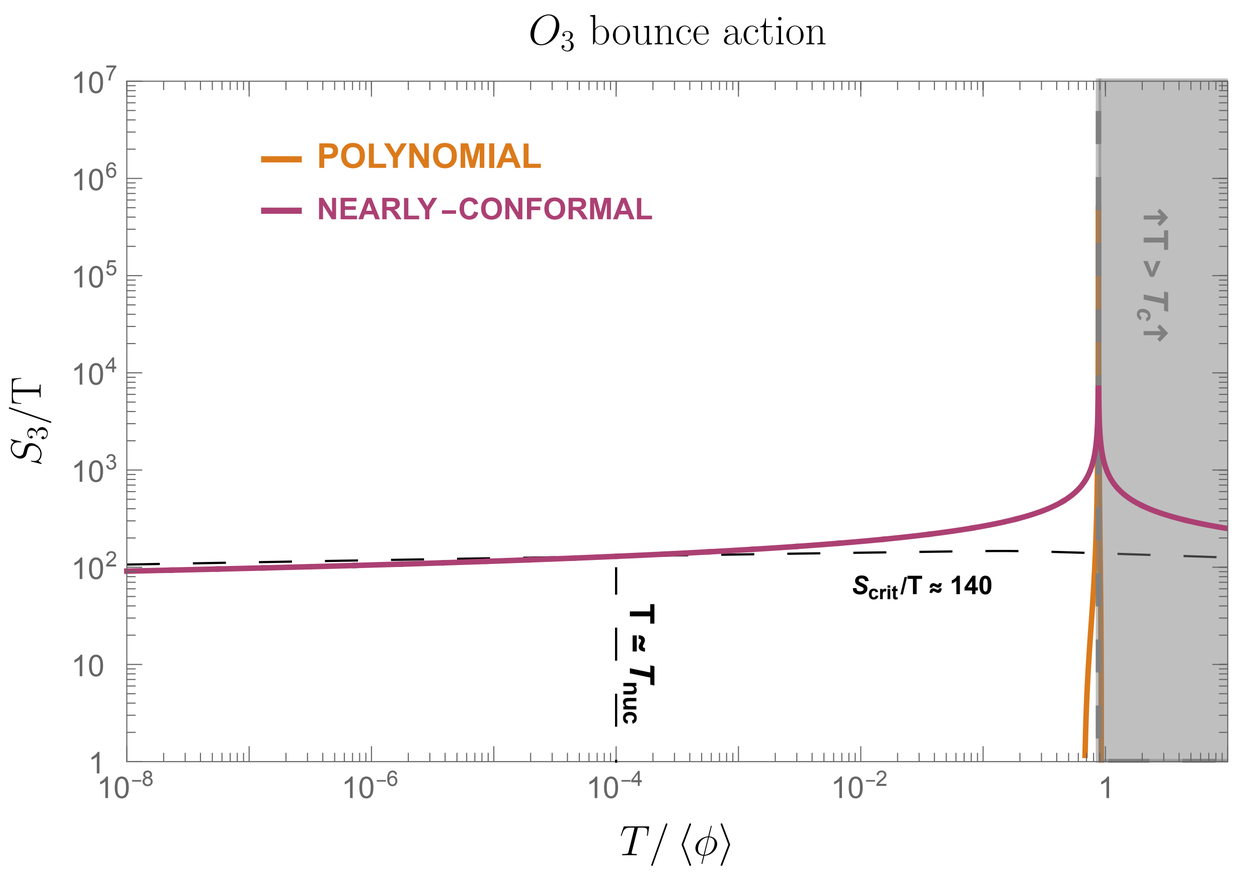

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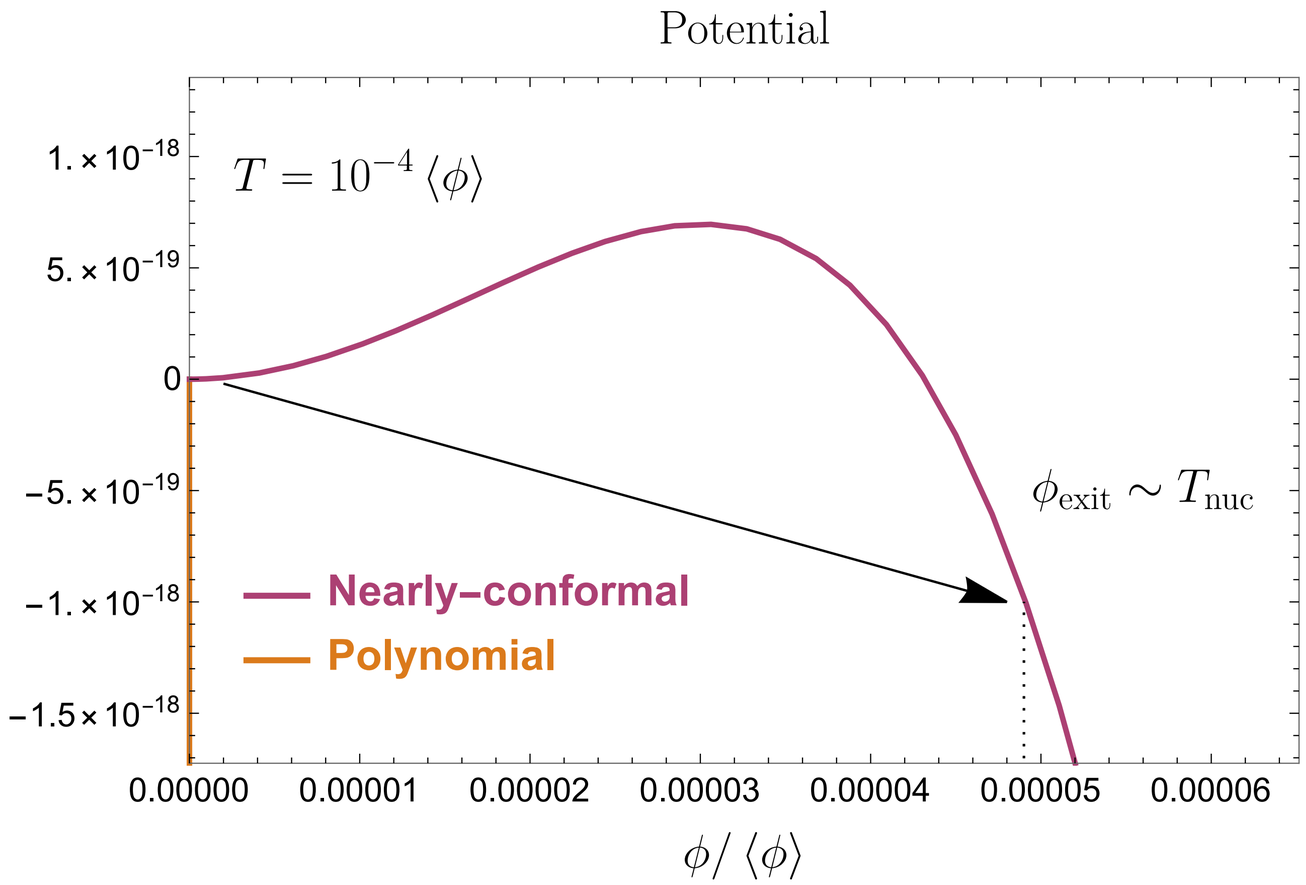

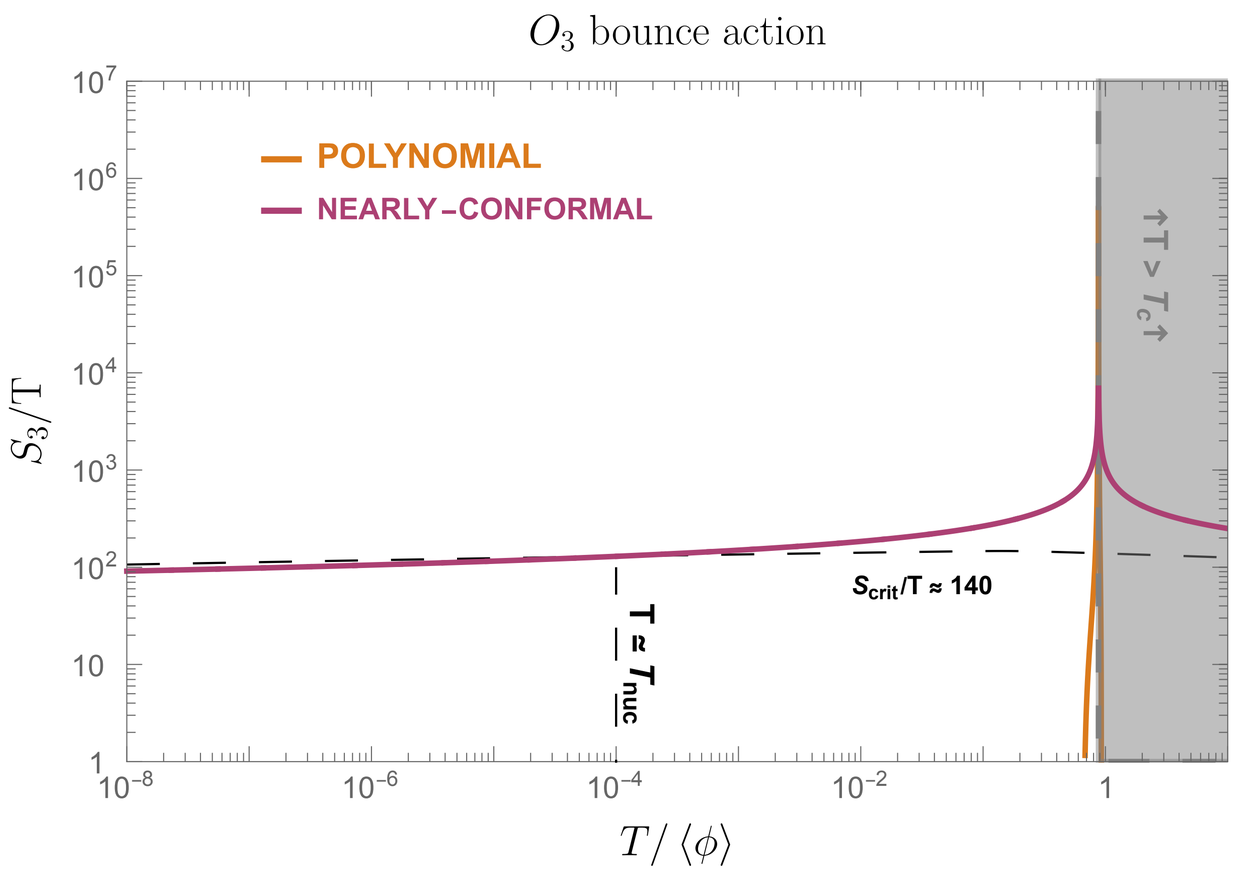

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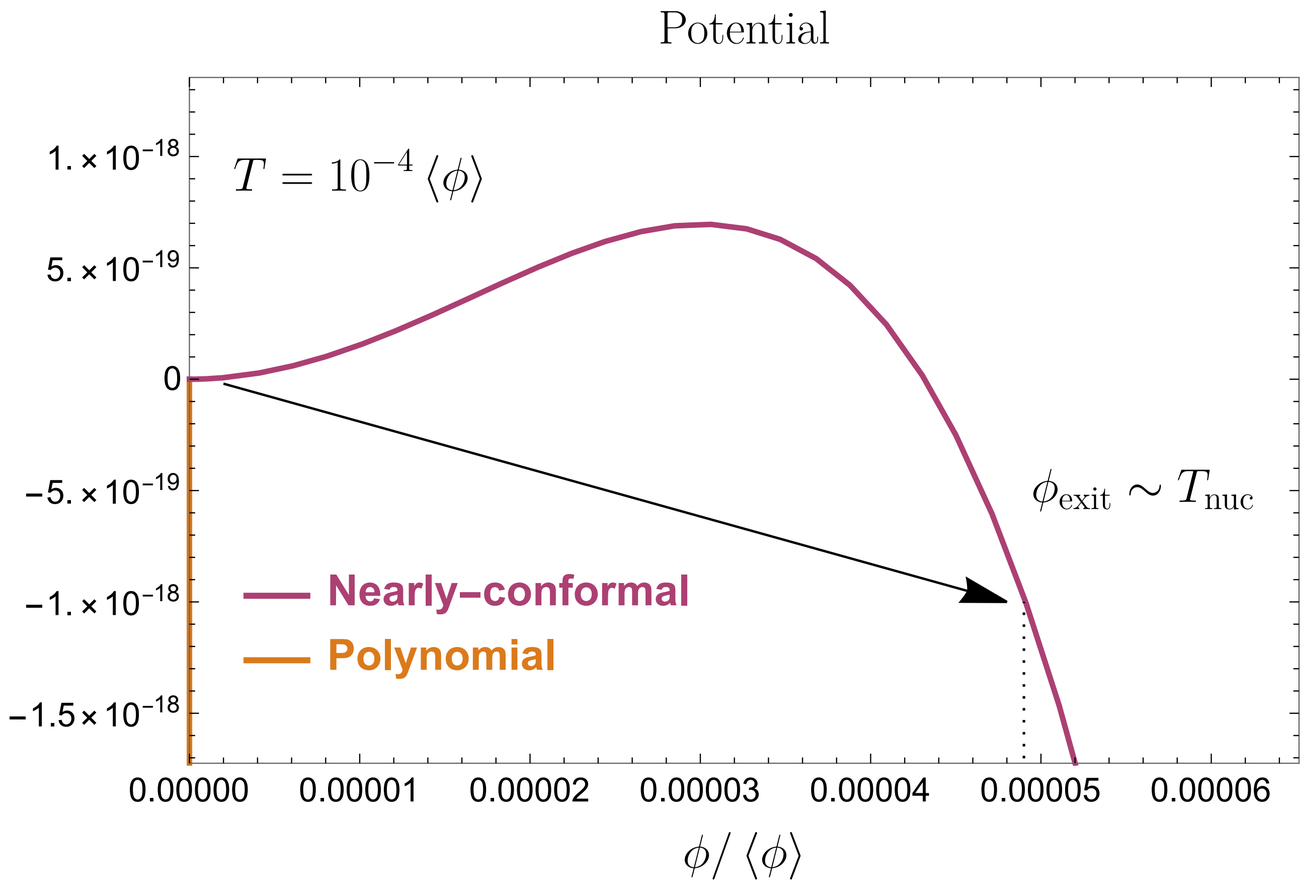

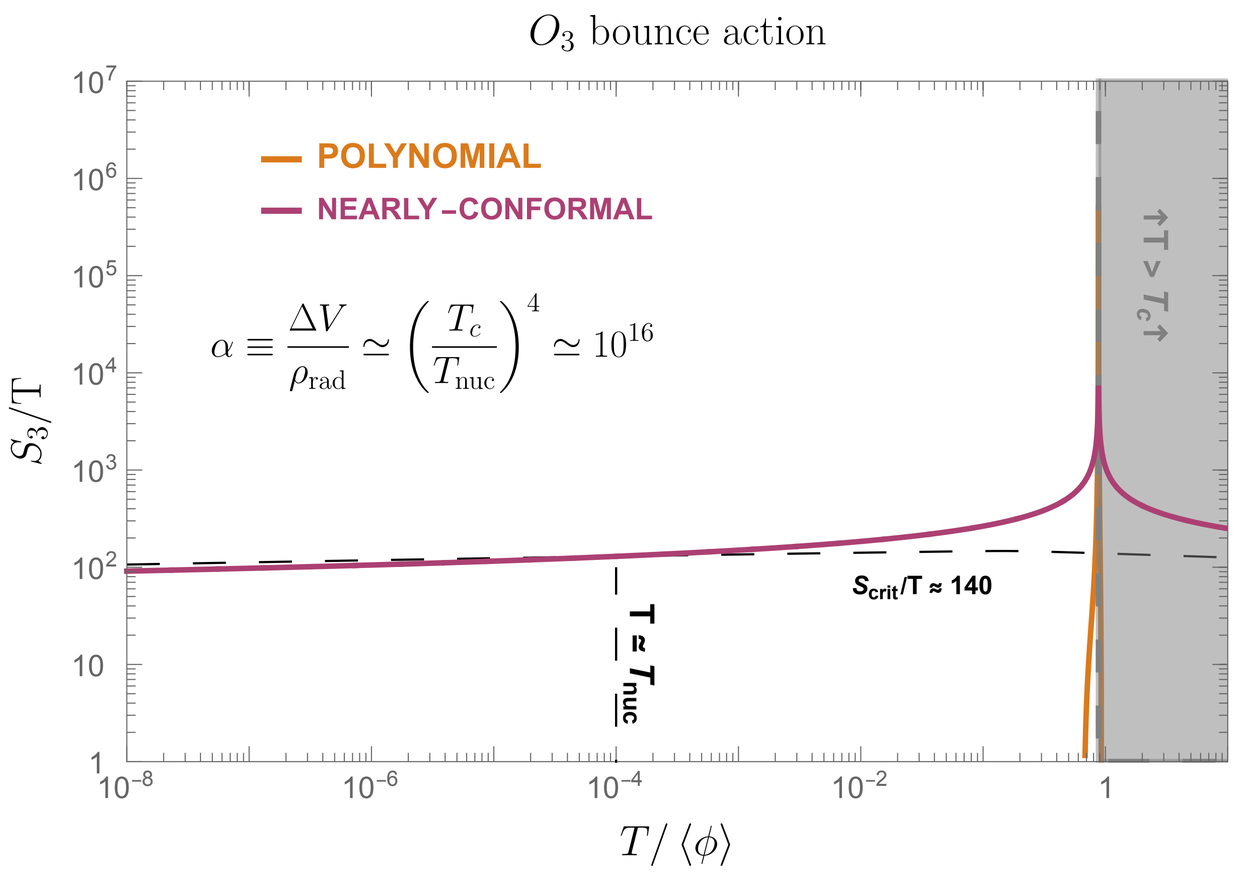

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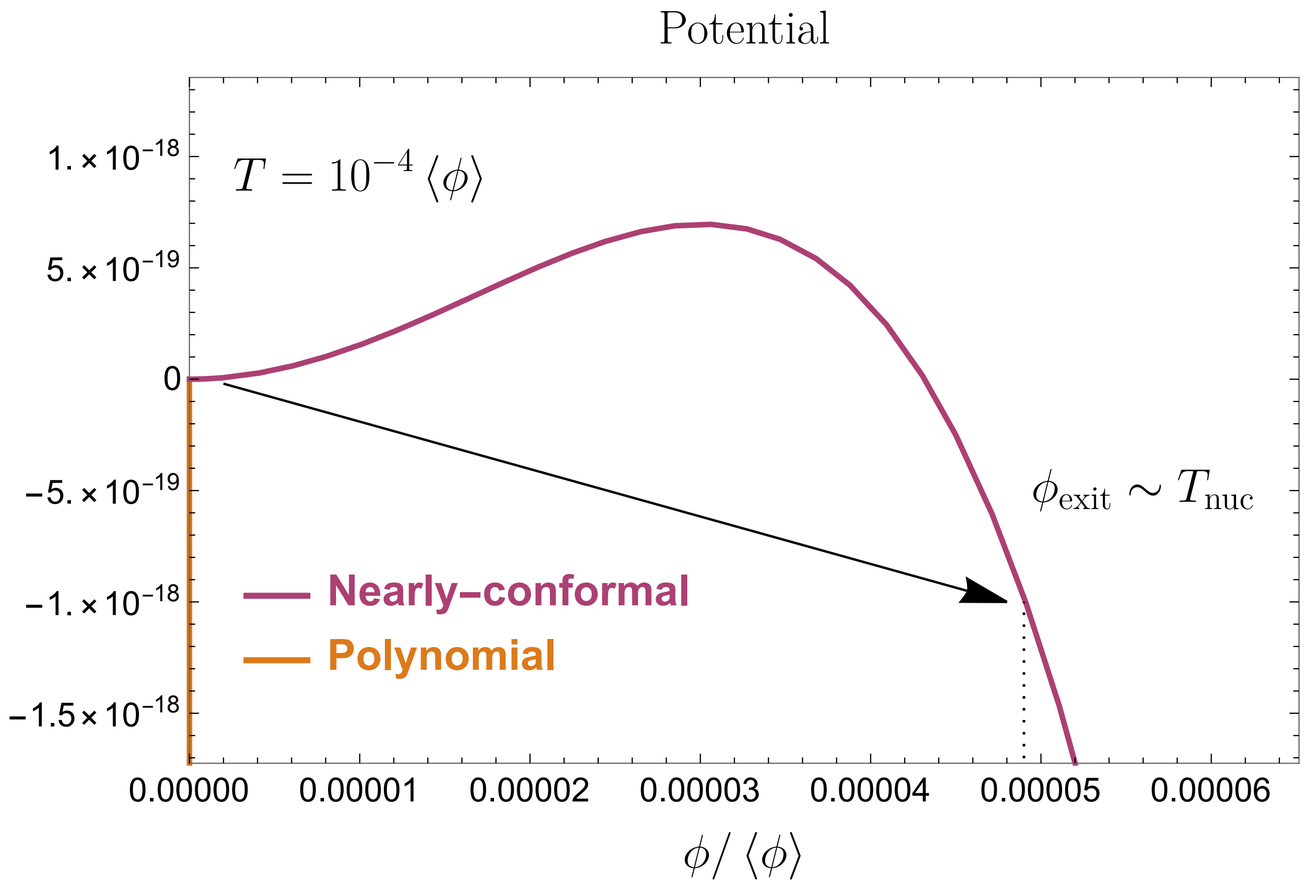
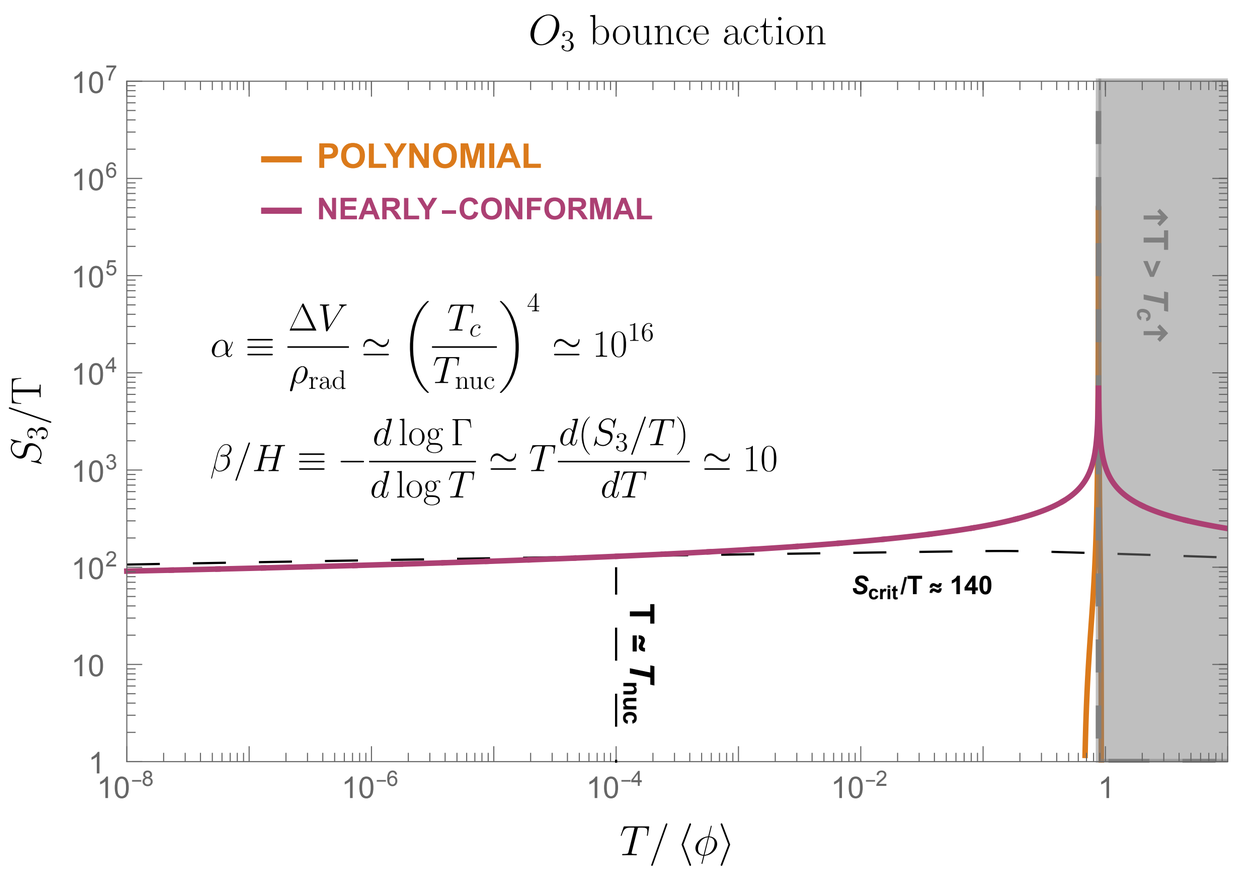
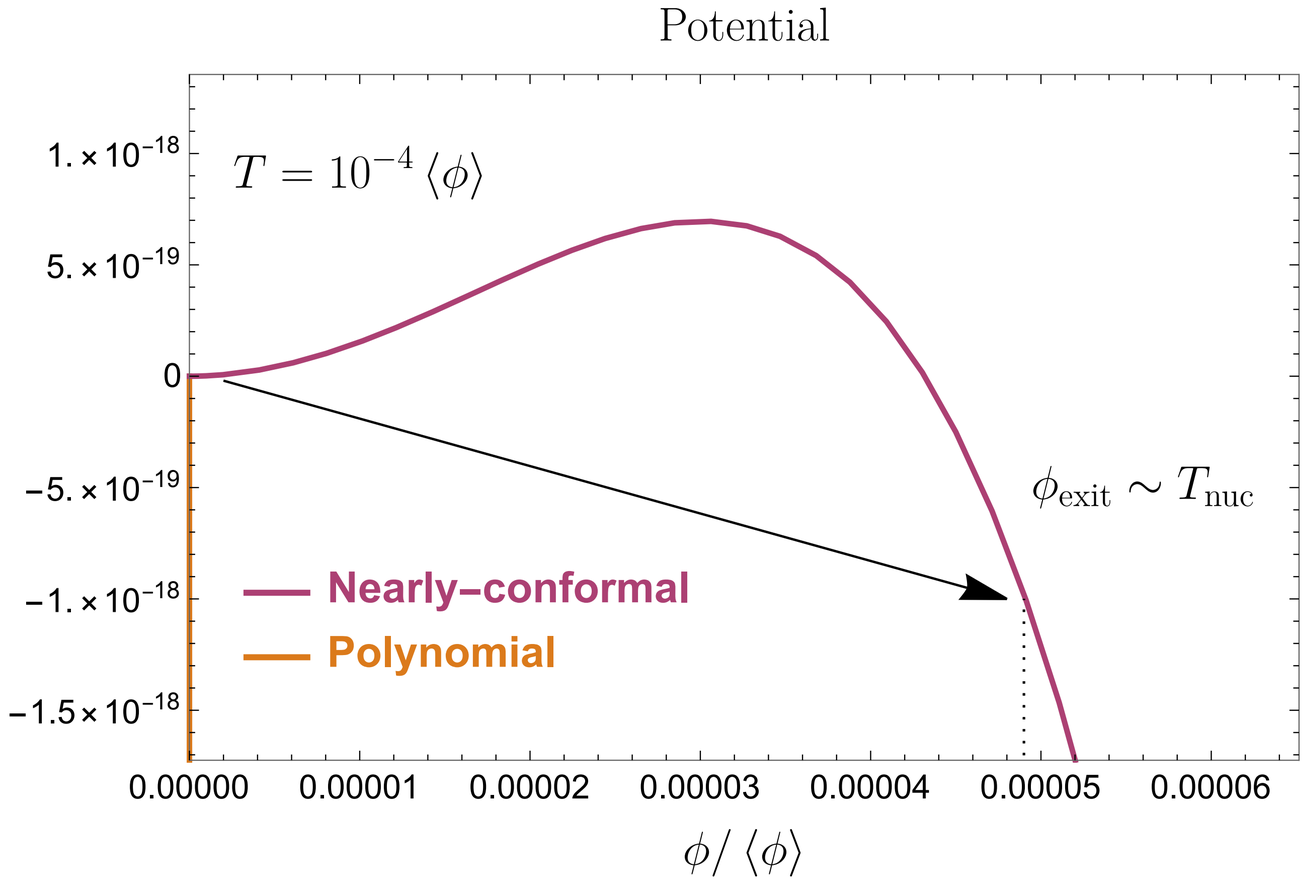


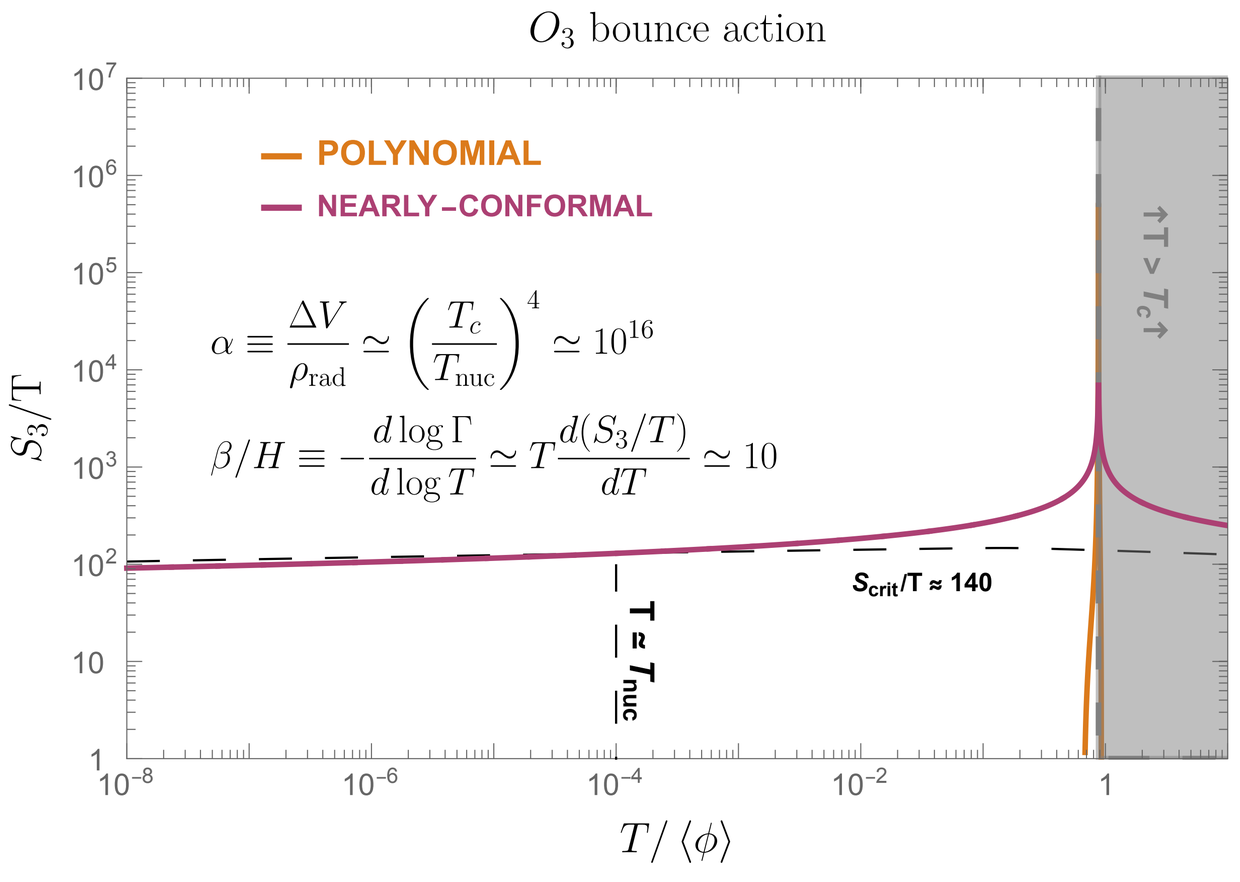


TAKE HOME : Supercooled phase transitions arises in presence of FLAT direction, are STRONG and SLOW

NEARLY-CONFORMAL POTENTIAL

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





Classes of nearly-conformal models

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

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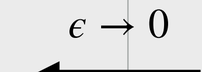

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$\epsilon \to 0$

holography

Cosmological consequences of supercooling

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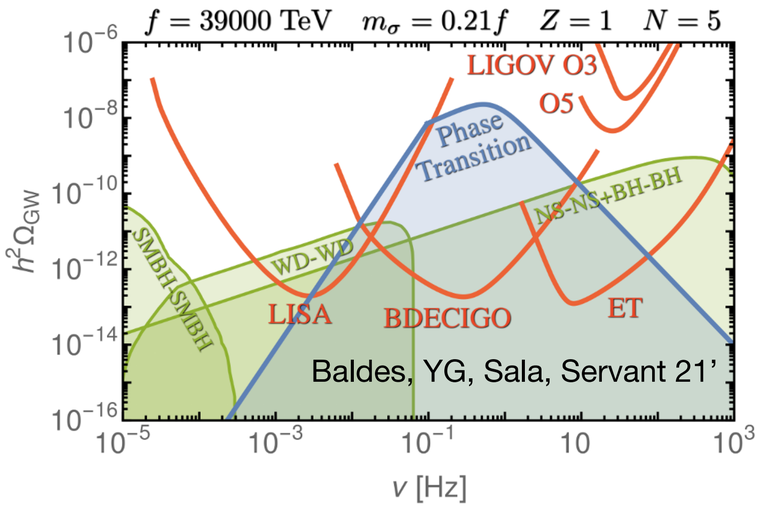
1) Large GW spectrum

Randall, Servant 06’



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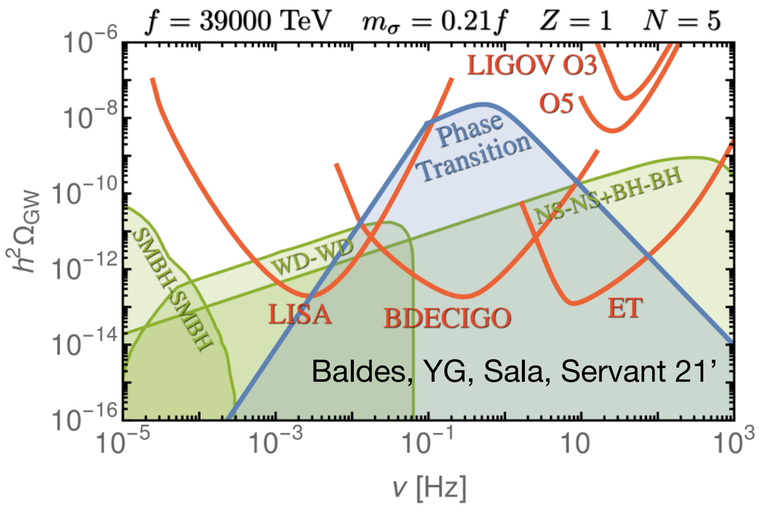

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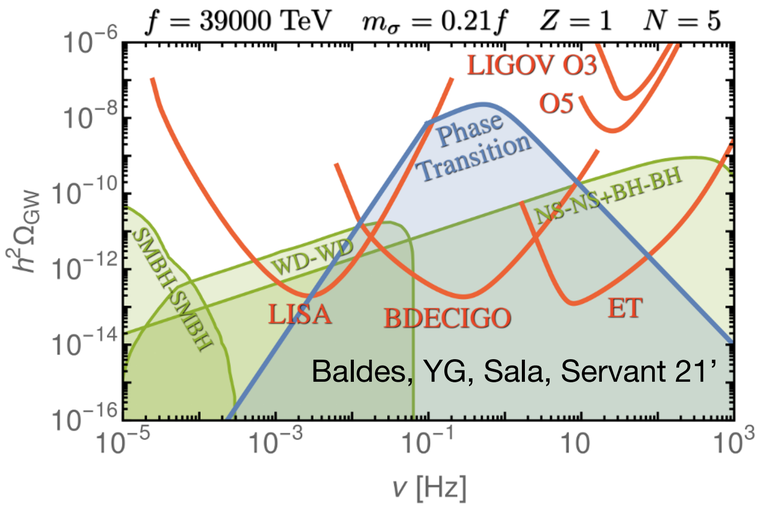

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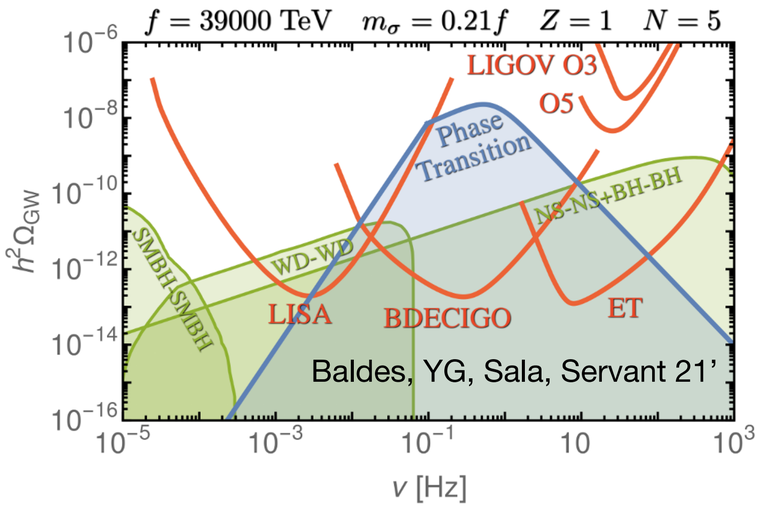

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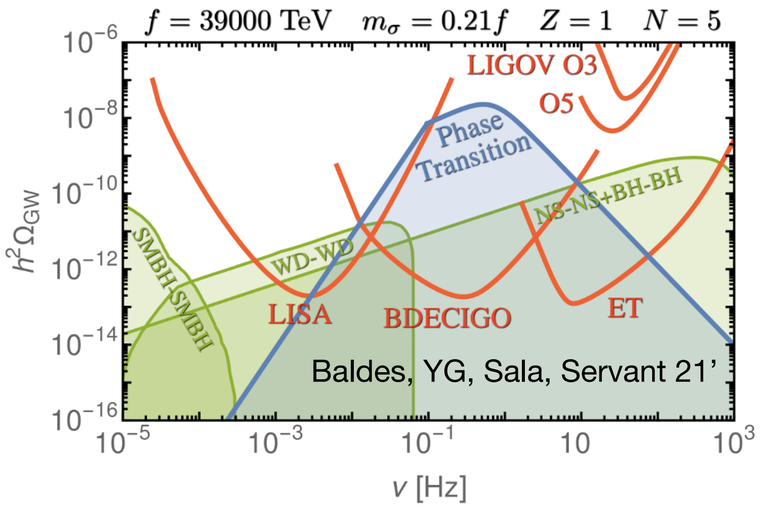

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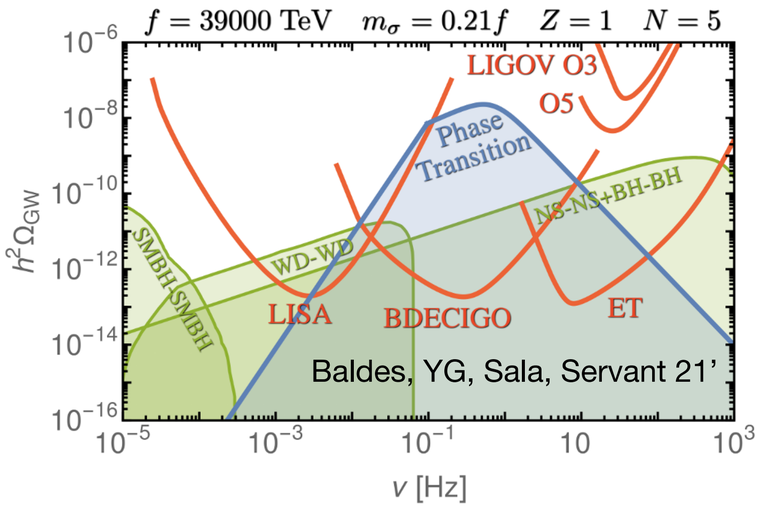

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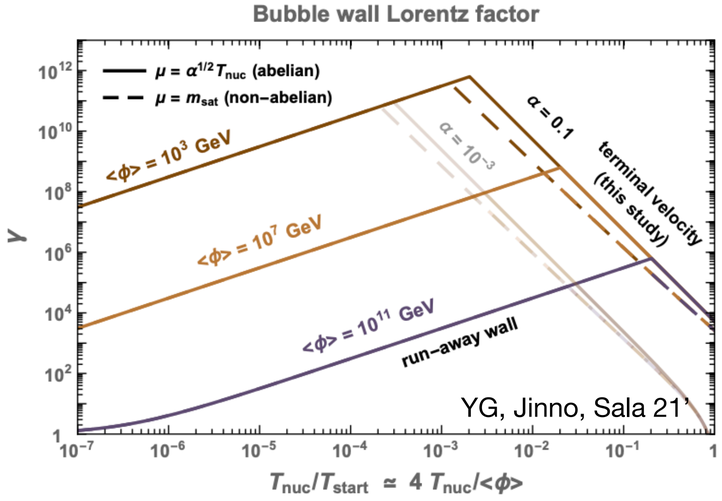

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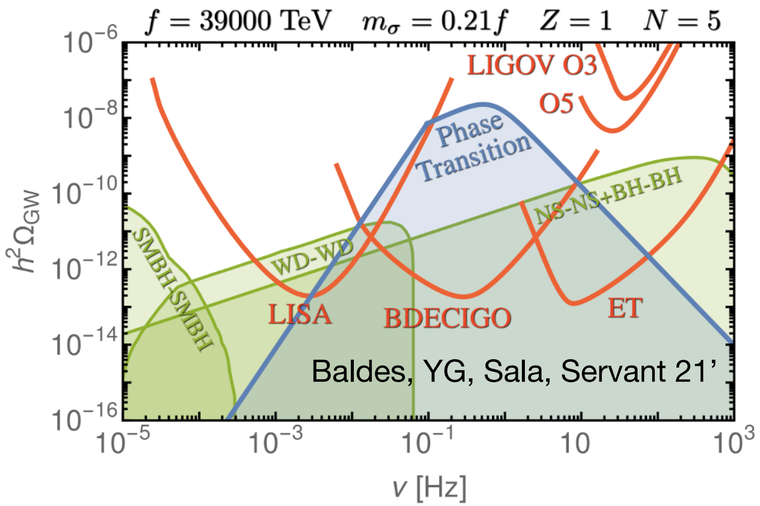

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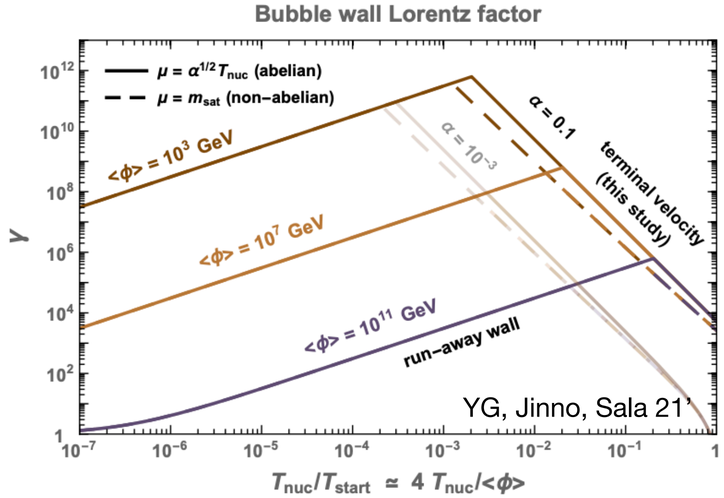

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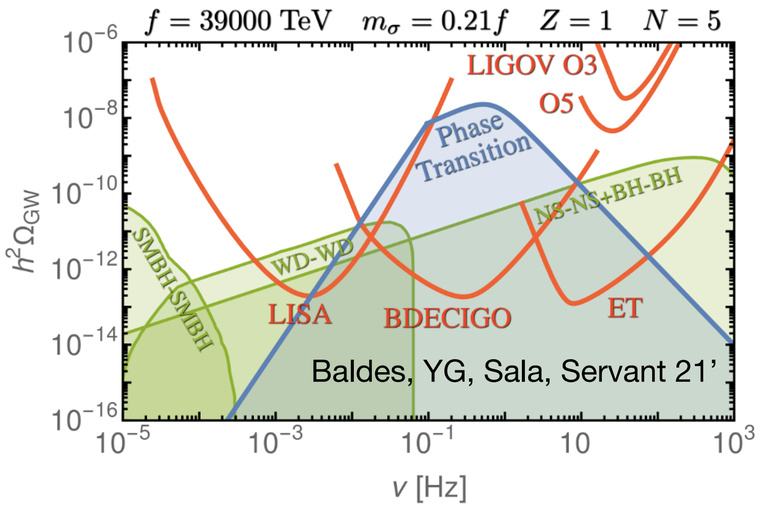

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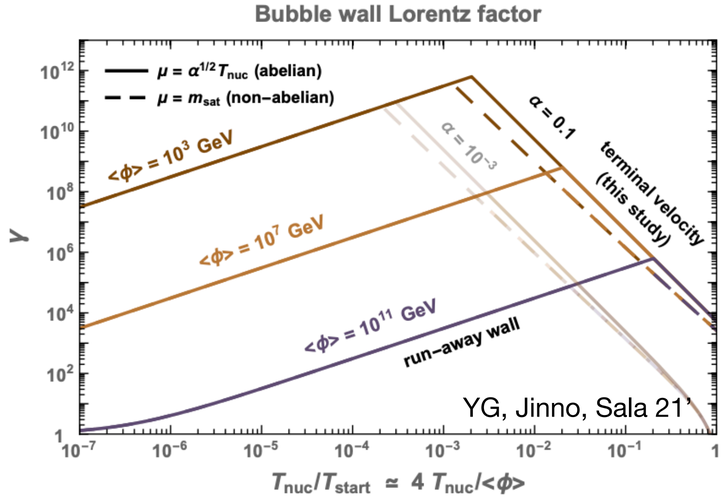

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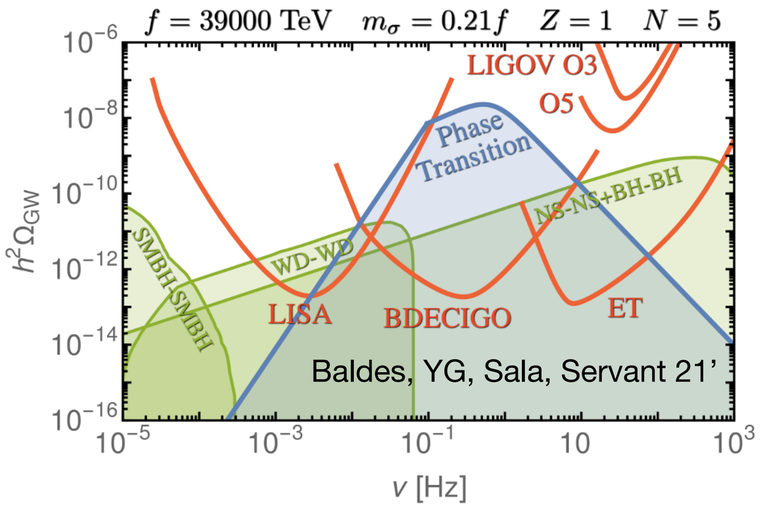

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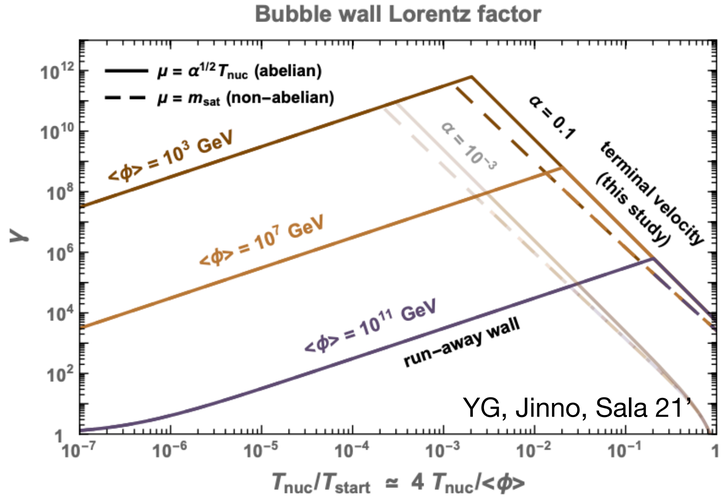

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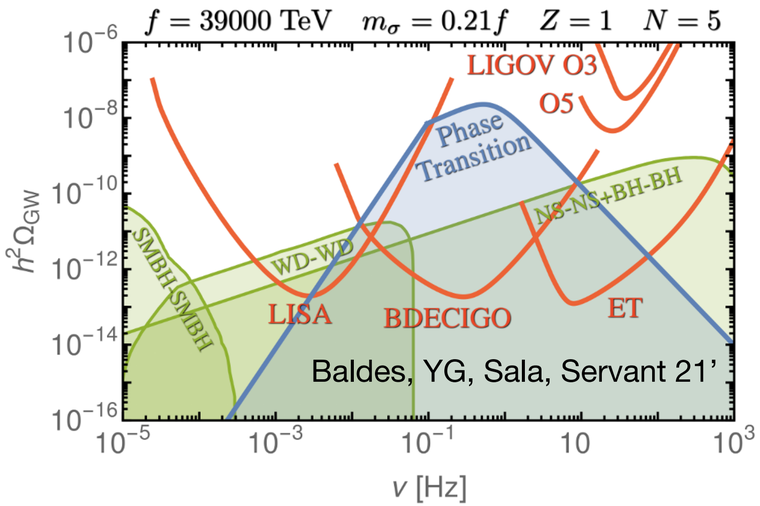

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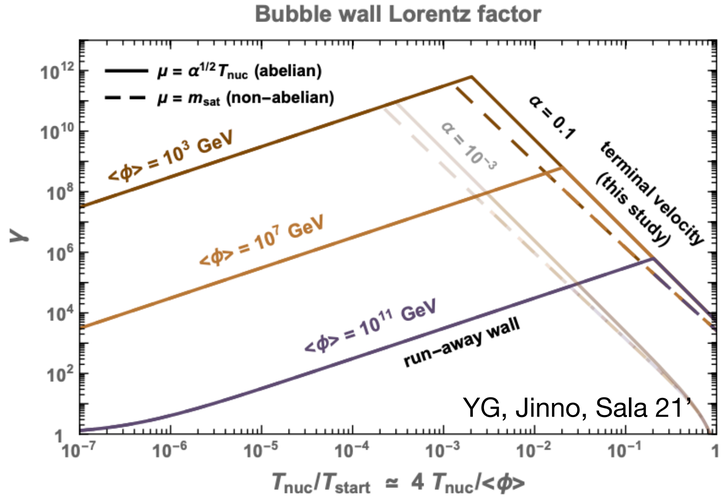

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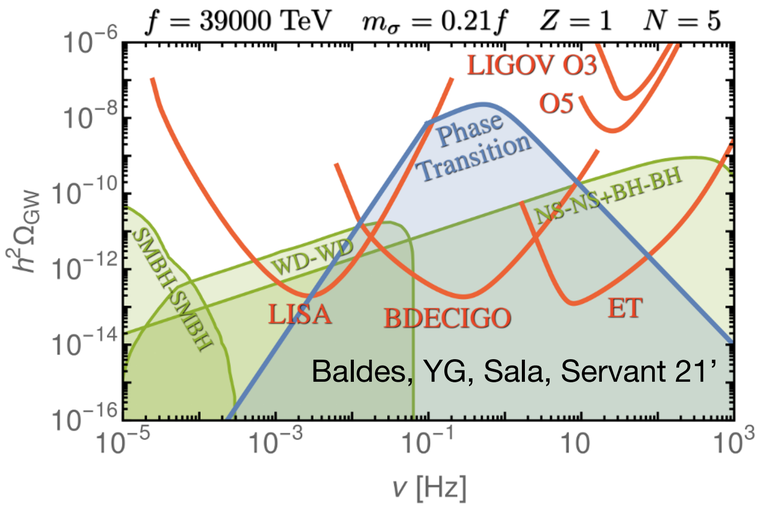

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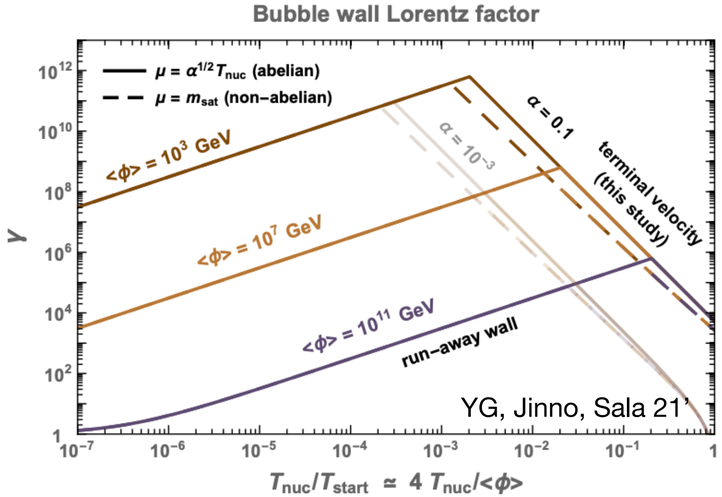

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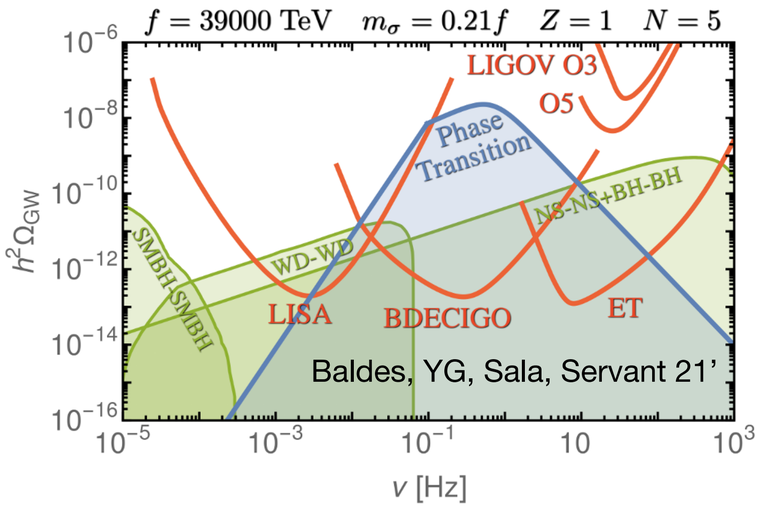

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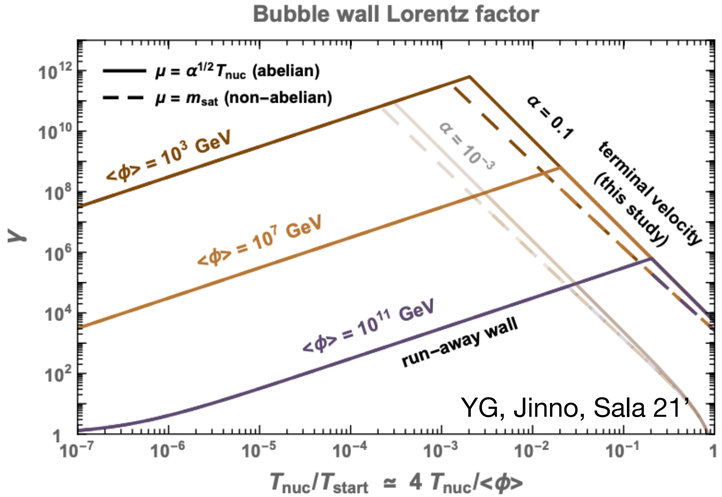

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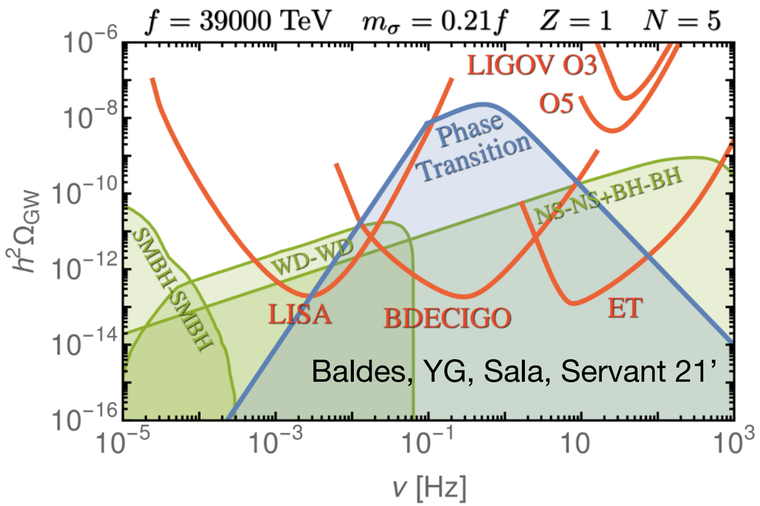

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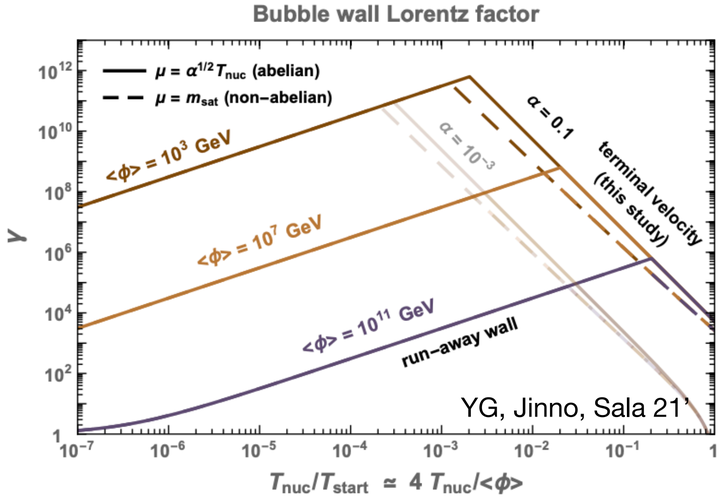

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Griest & Kamionkowski 91’

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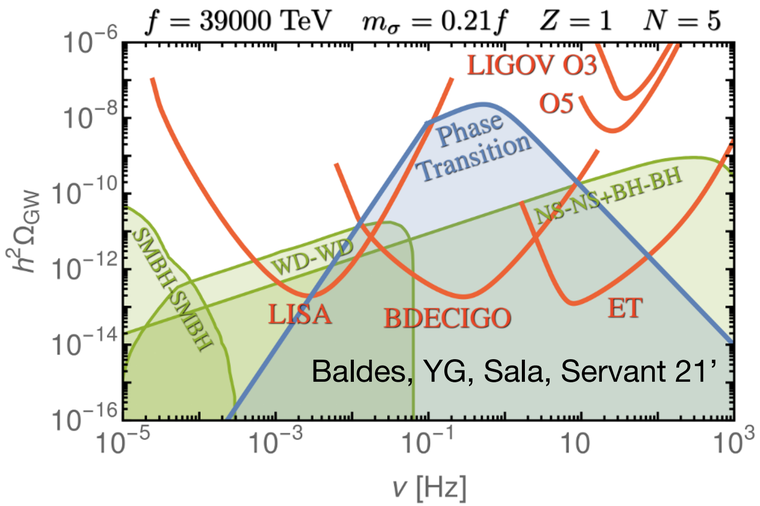

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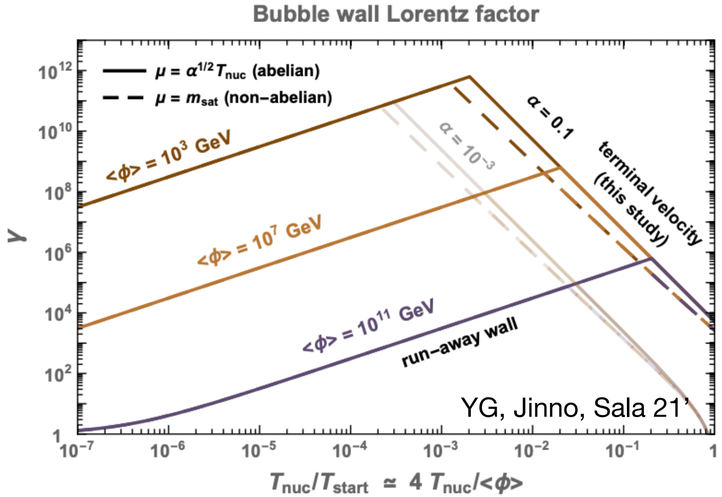

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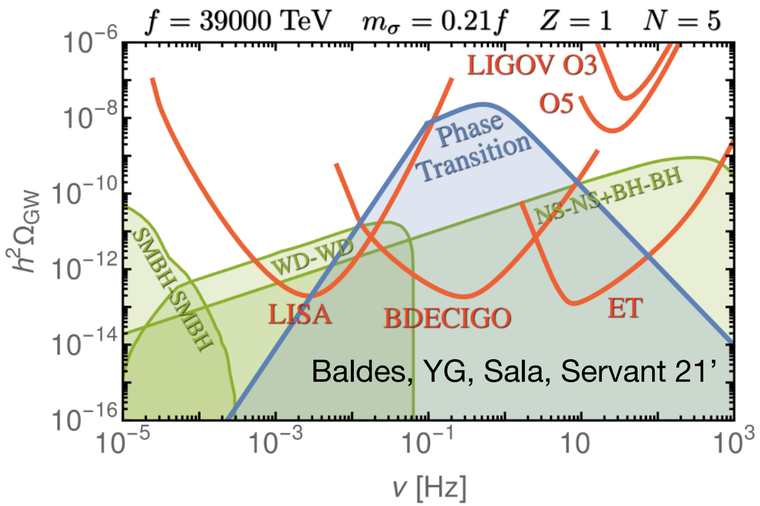

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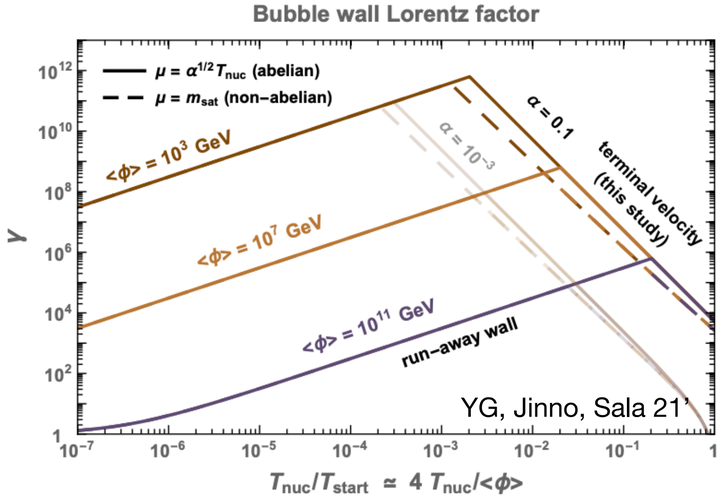

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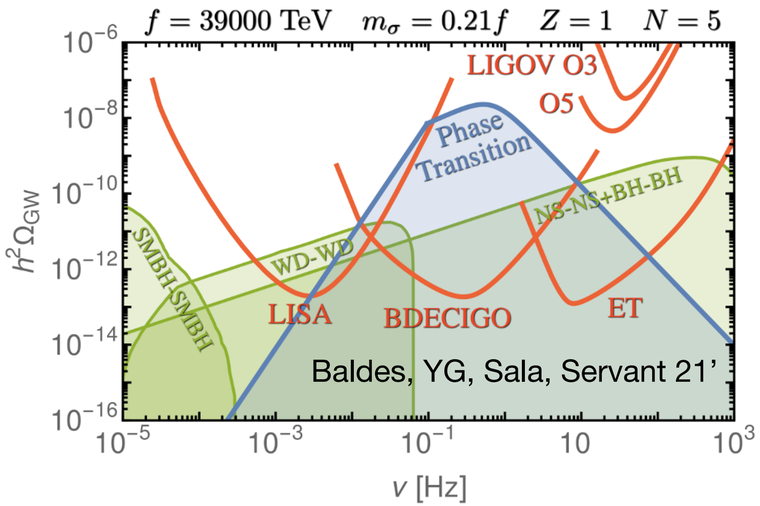

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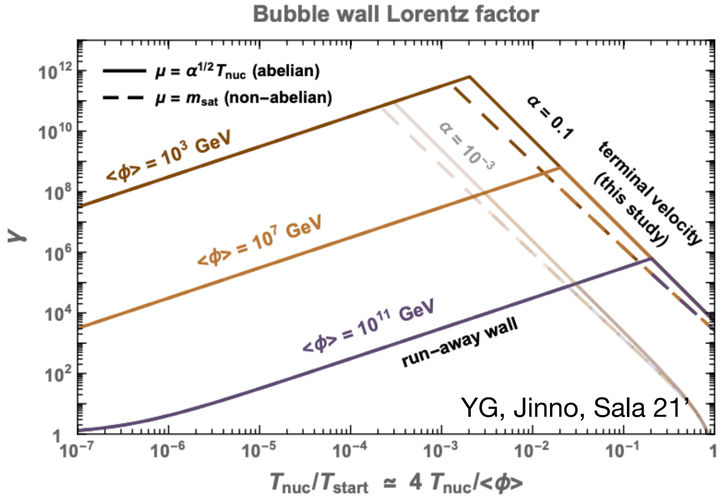

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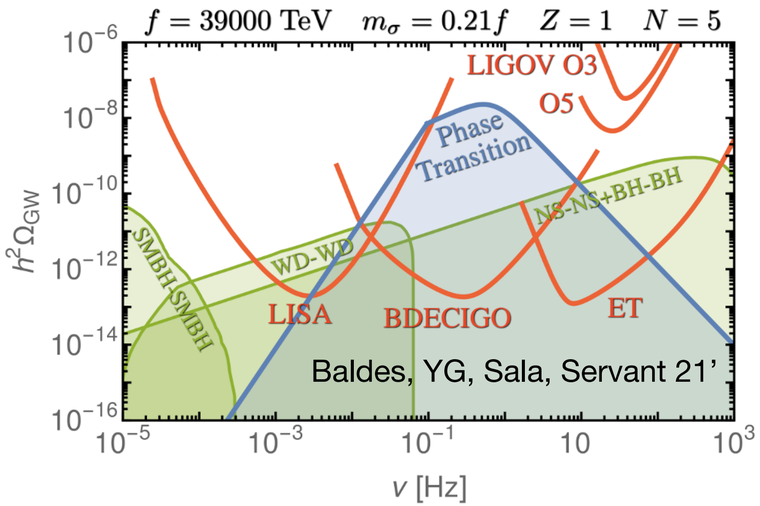

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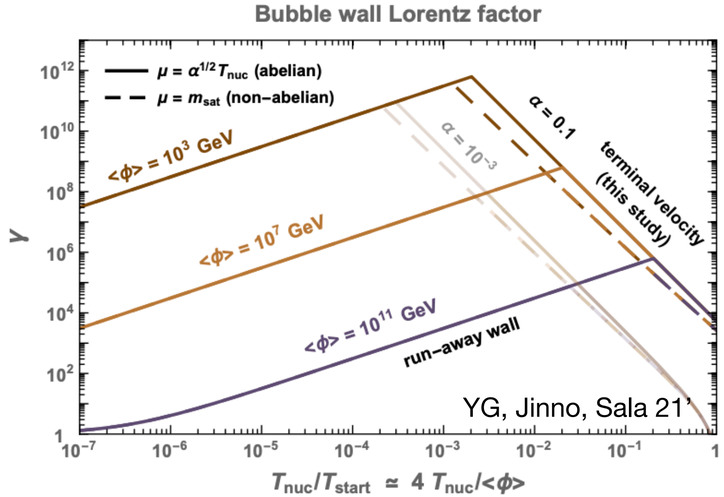

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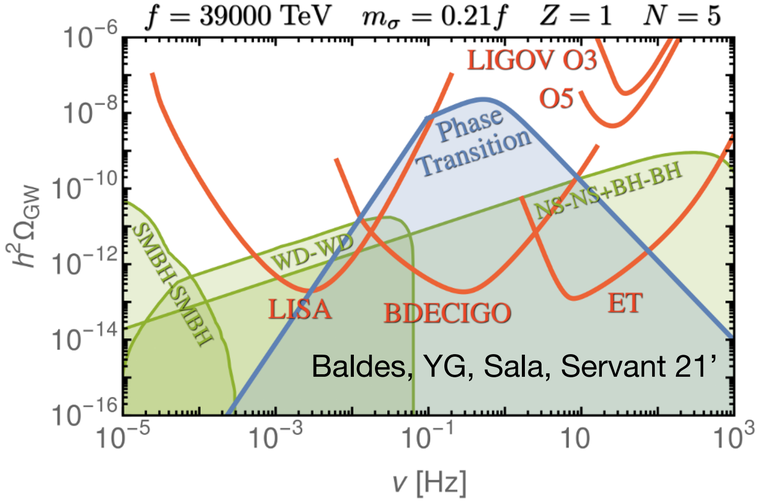

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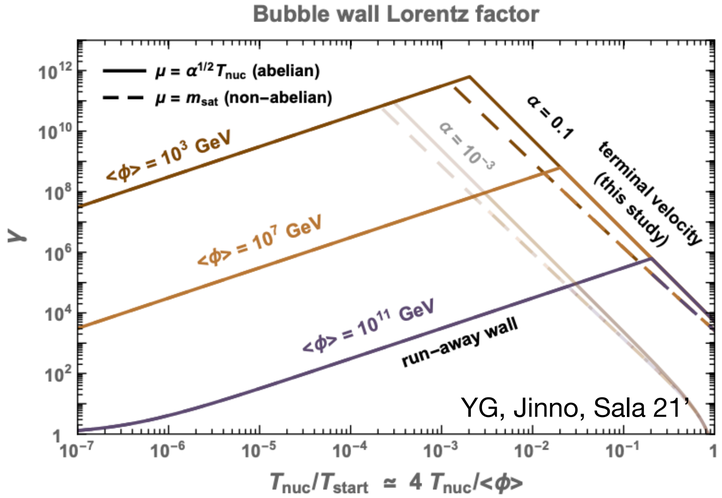

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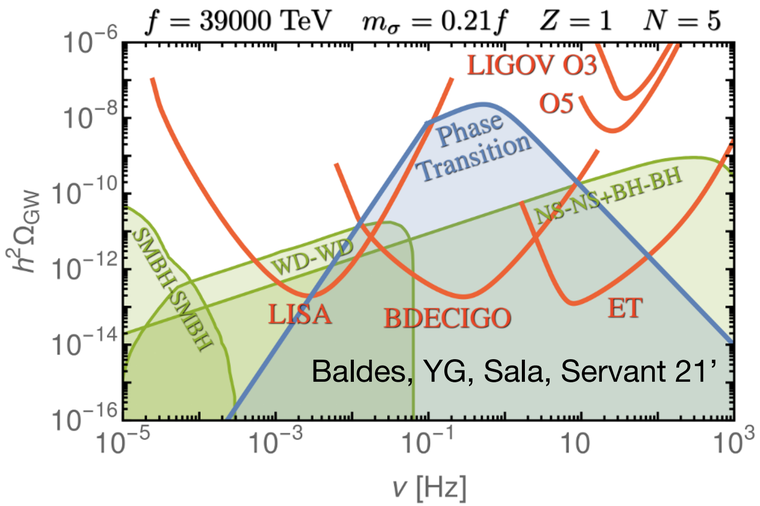
Randall, Servant 06’



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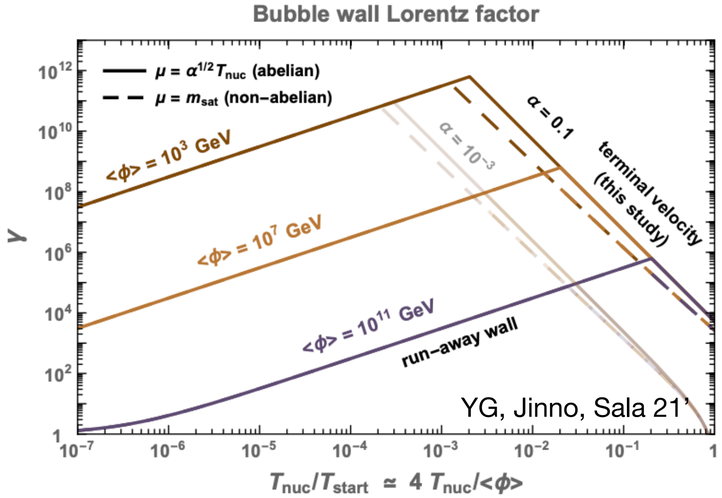

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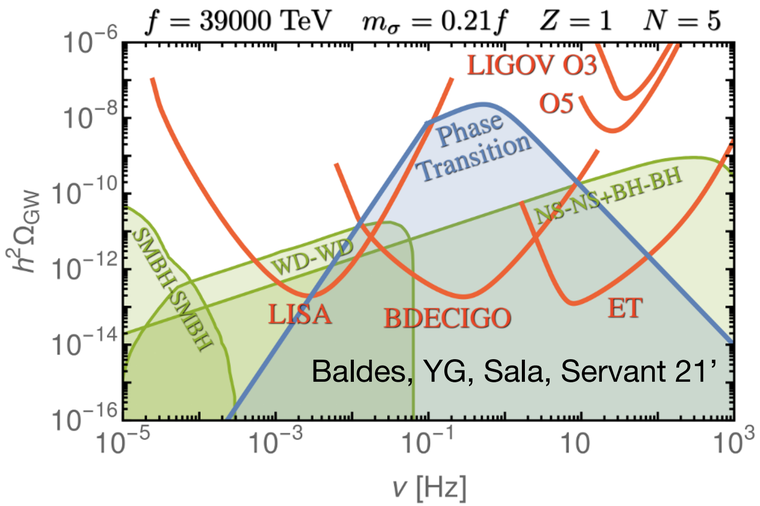

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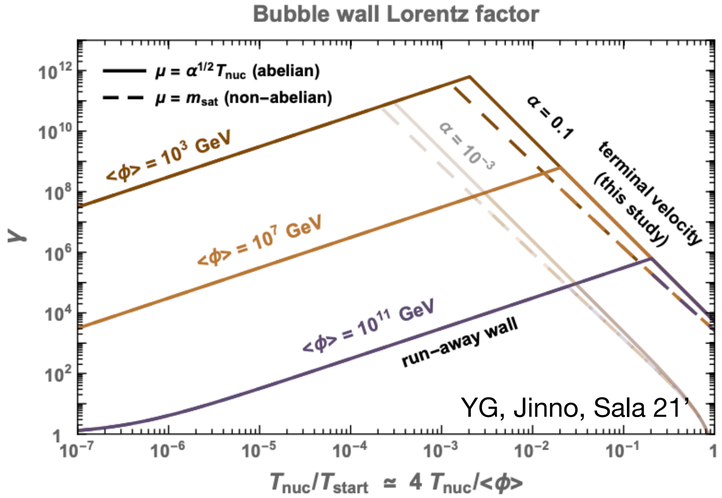

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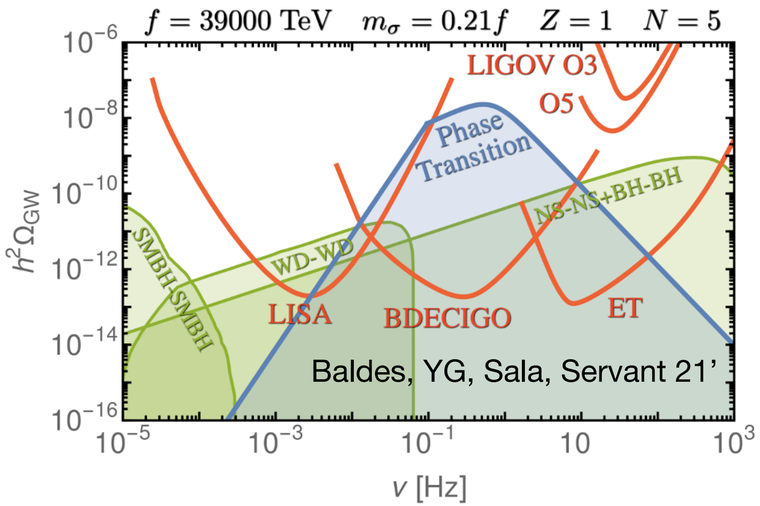

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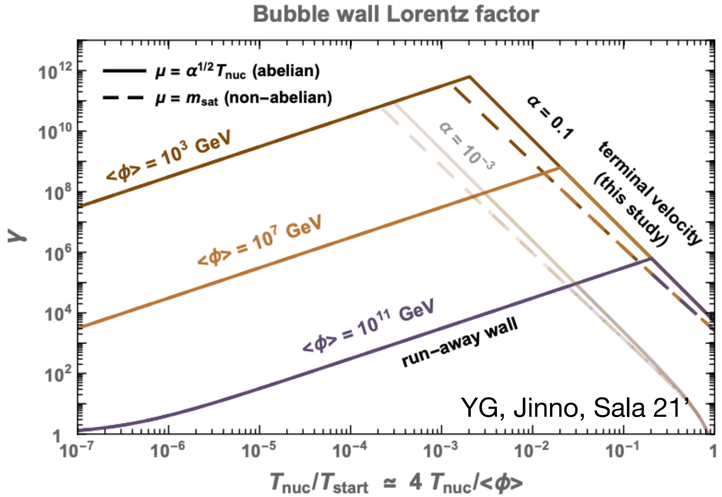

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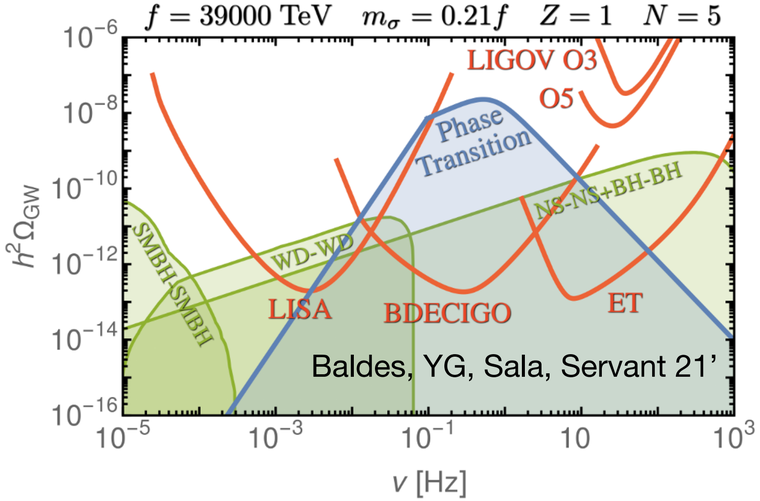

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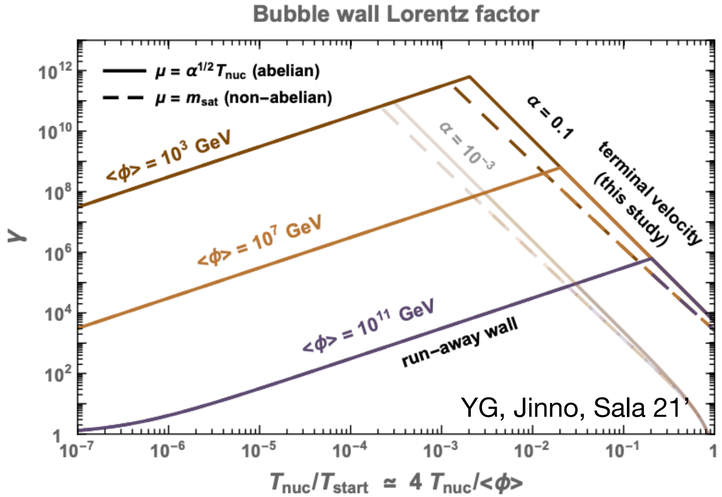

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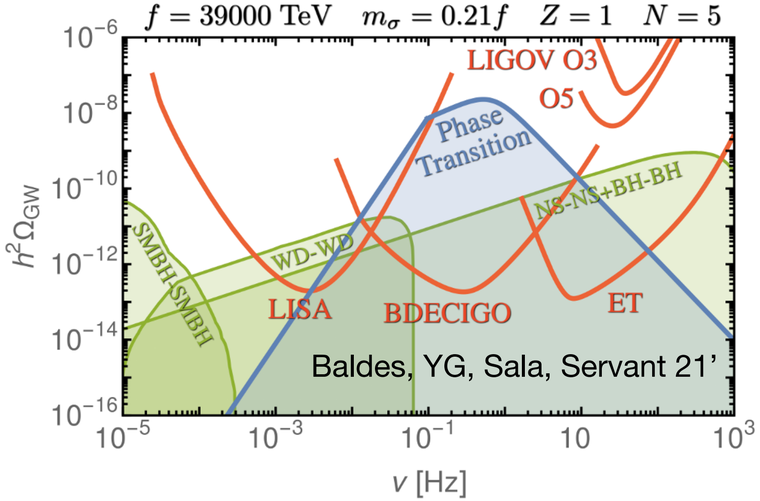

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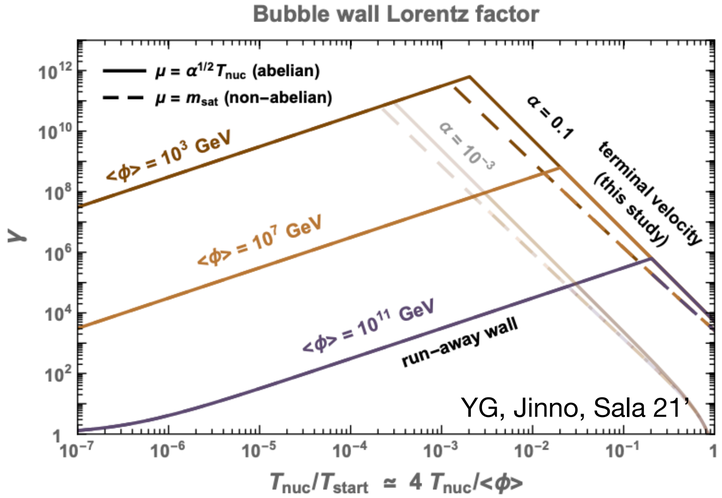

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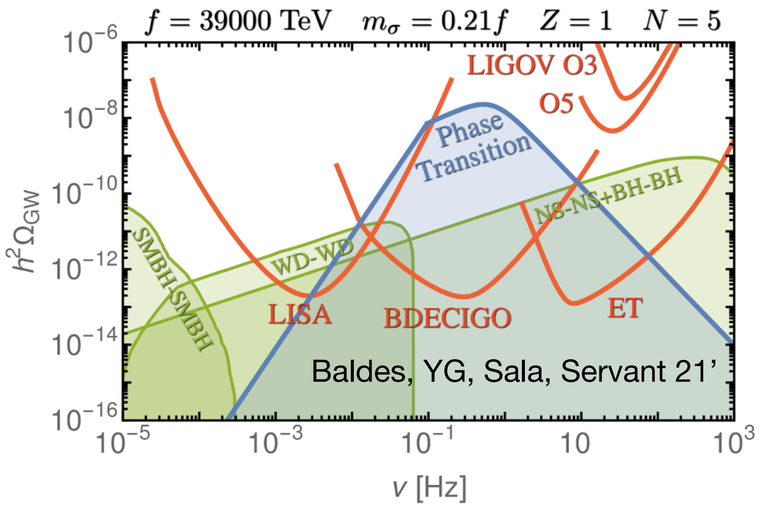

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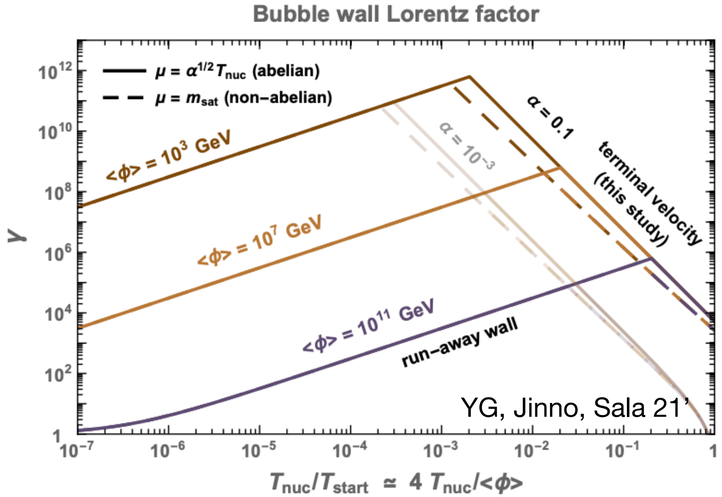

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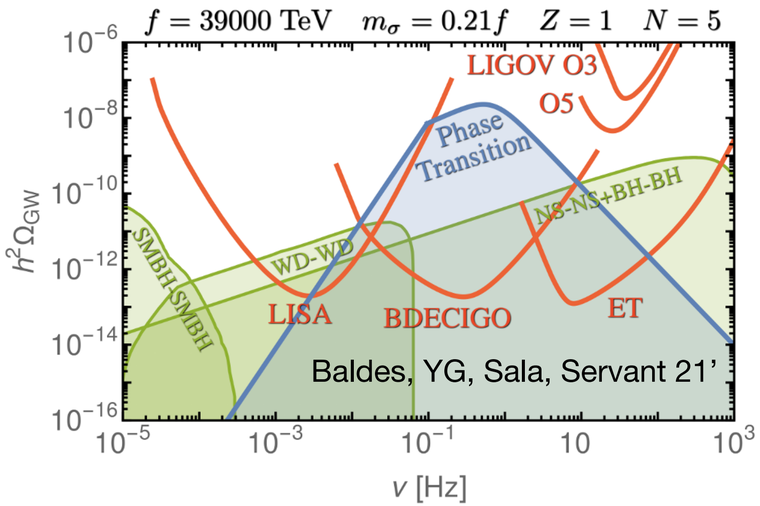

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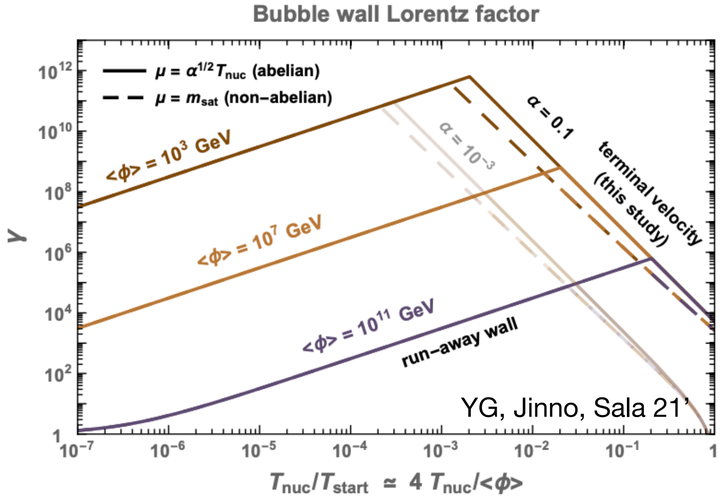

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More details soon

4) Particle production

a) Strongly-coupled case

More details soon

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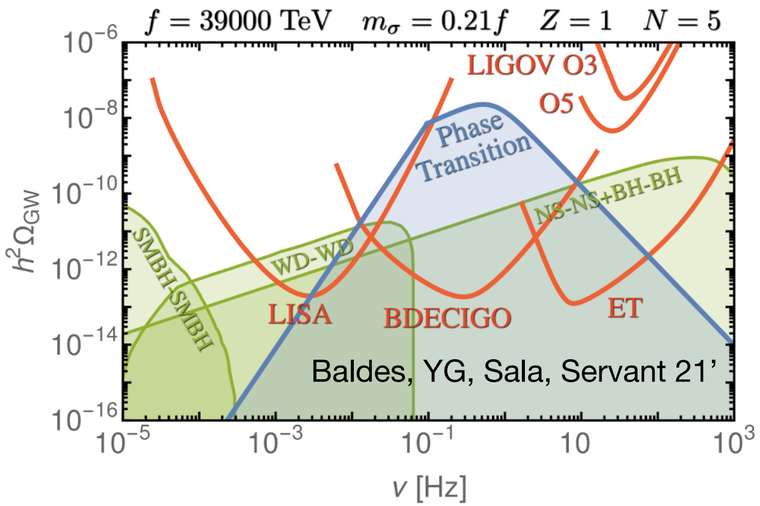

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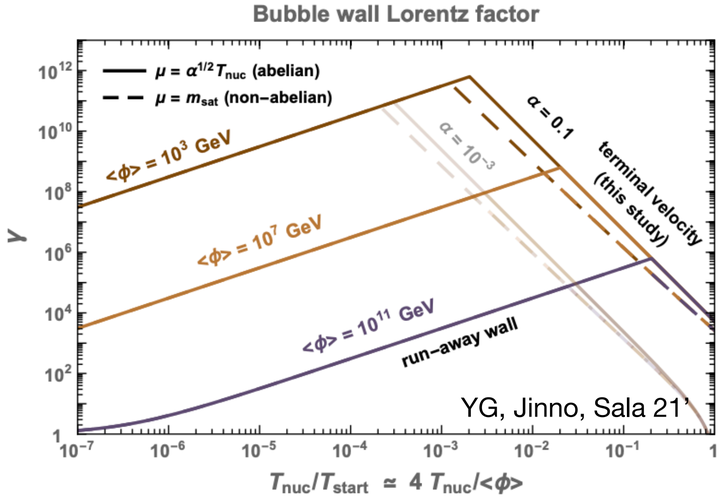

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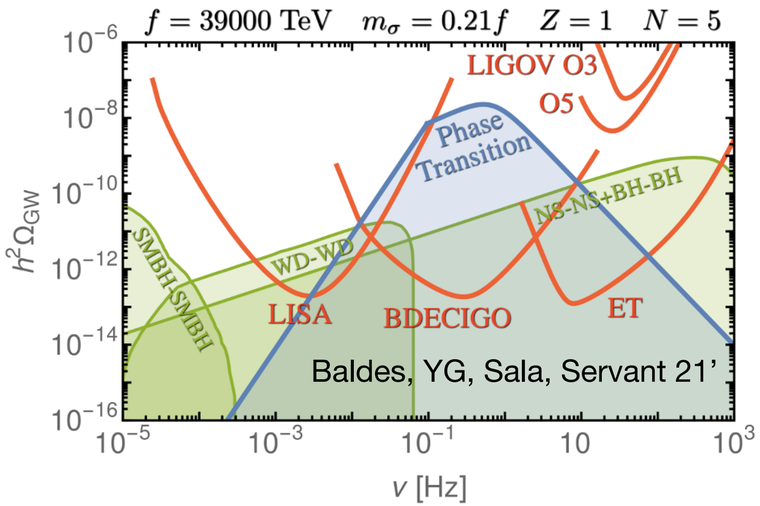

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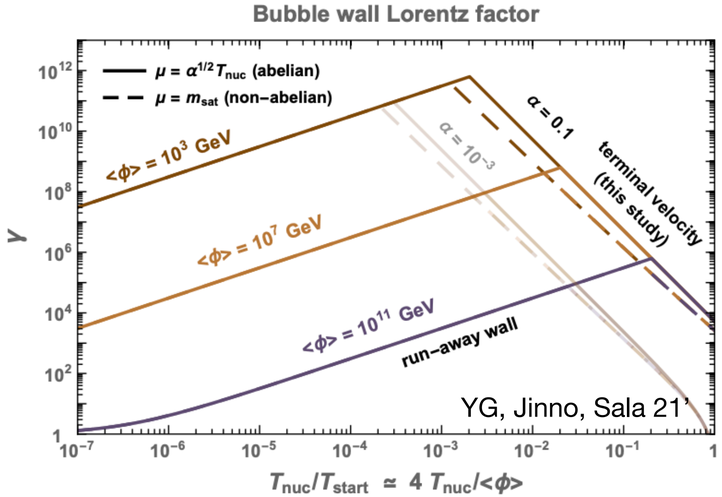

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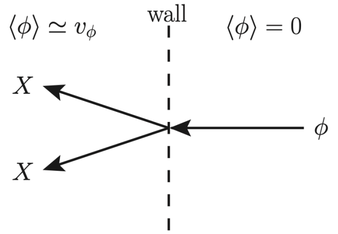

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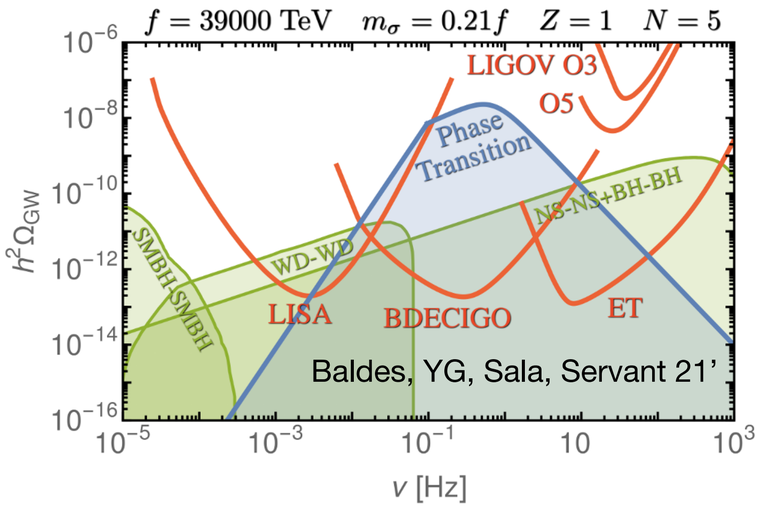

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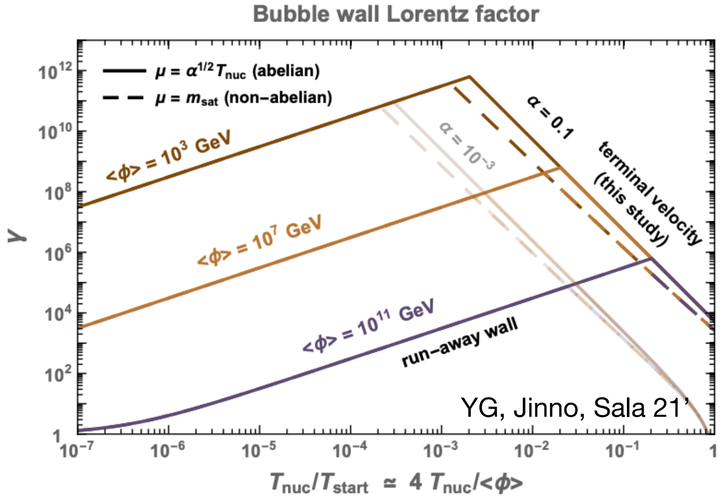

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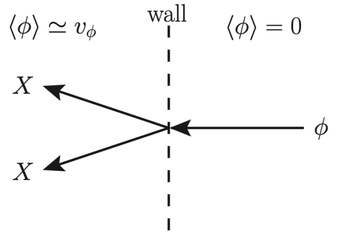

Baldes, YG, Sala 22’

$M_{DM} \sim 10^8$ GeV

$v(t_{eq}) \sim 10^{-4}$ with PT at the weak scale

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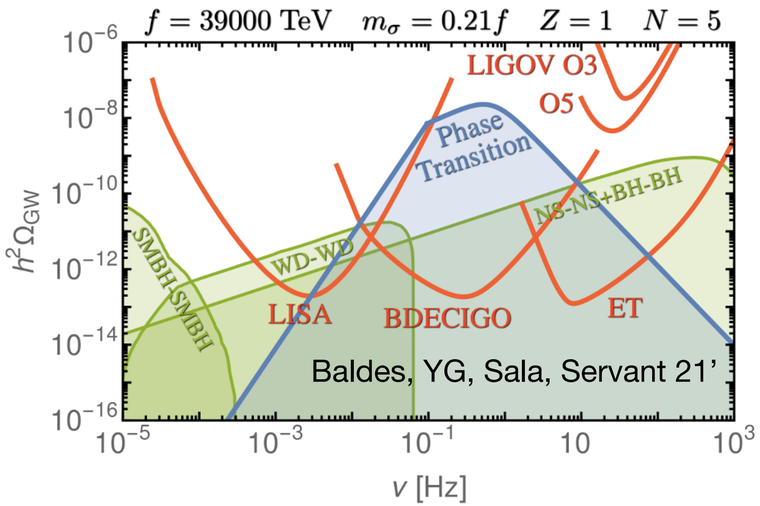

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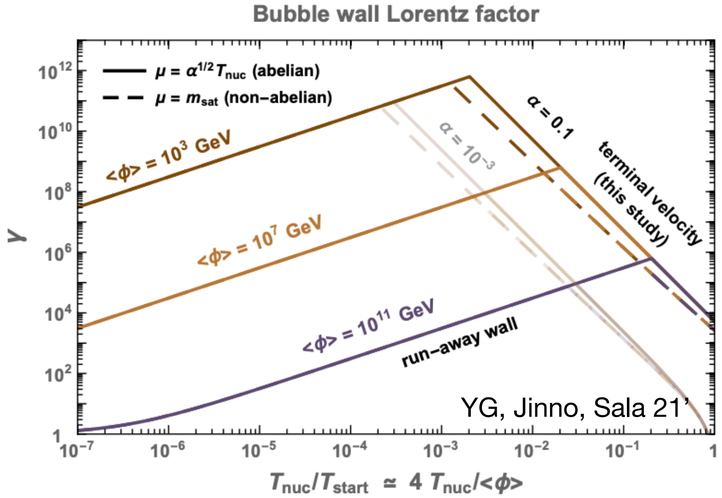

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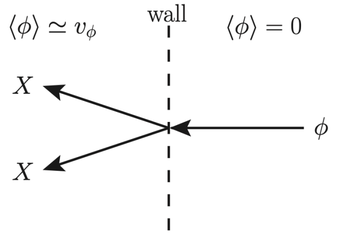

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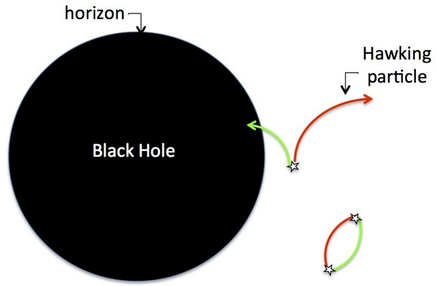
c) Unruh radiation

YG (to appear)



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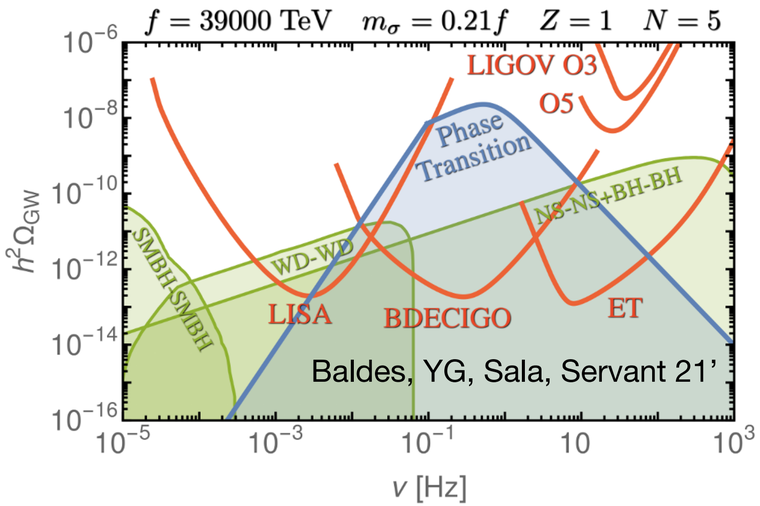

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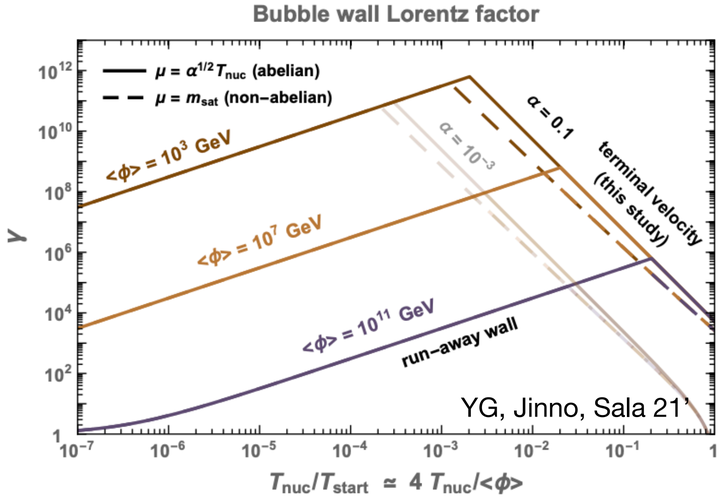

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(Baratella, Pomarol, Romponeve 18’) Strongly-coupled

Baldes, YG, Sala 20’

Baldes, YG, Sala, Servant 21’ DM production at the wall due to flux tube formation

More details soon

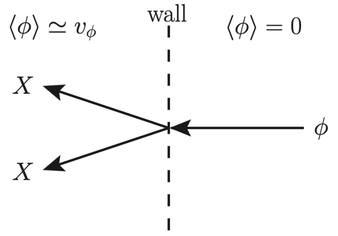
4) Particle production

a) Strongly-coupled case

More details soon

b) Weakly-coupled case

Azatov, Vanvlasselaer, Yin 21’



Baldes, YG, Sala 22’

$M_{DM} \sim 10^8$ GeV

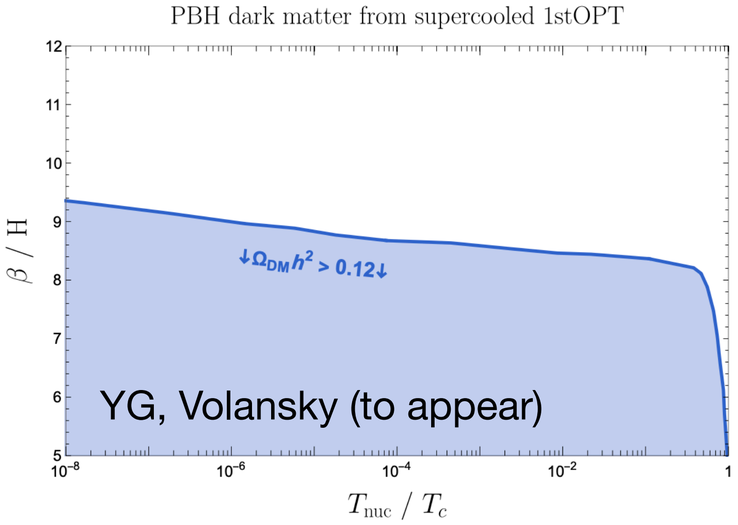
$v(t_{eq}) \sim 10^{-4}$

with PT at the weak scale

5) Black hole production

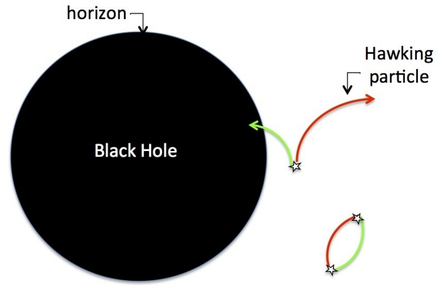
Liu, Bian, Cai, Guo, Wang 21’

YG, Volansky (to appear)



c) Unruh radiation

YG (to appear)



Heavy Dark Matter from supercool confinement

Baldes, YG, Sala 20’

Baldes, YG, Sala, Servant 21’

Supercool confinement ?

Super-uncool confinement

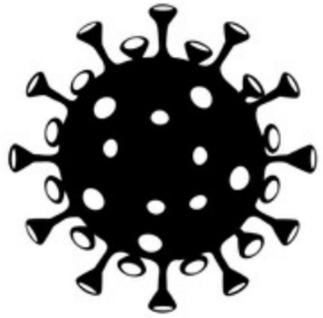
Super-uncool confinement

Early 2020 Virus outbreak

time

Super-uncool confinement

Early 2020 Virus outbreak

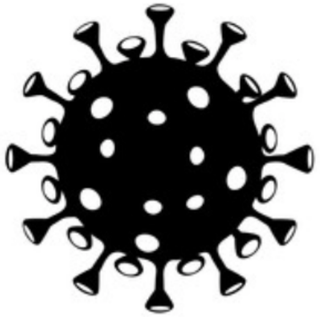


Confinement stage

time

Super-uncool confinement

Early 2020 Virus outbreak



Confinement stage

Mid 2021 Vaccination

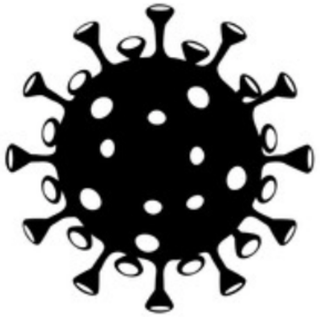
time

~~Super-uncool~~ confinement

Baldes, YG, Sala 20’
Baldes, YG, Sala, Servant 21’

Super-cool

Early 2020 Virus outbreak



Confinement stage

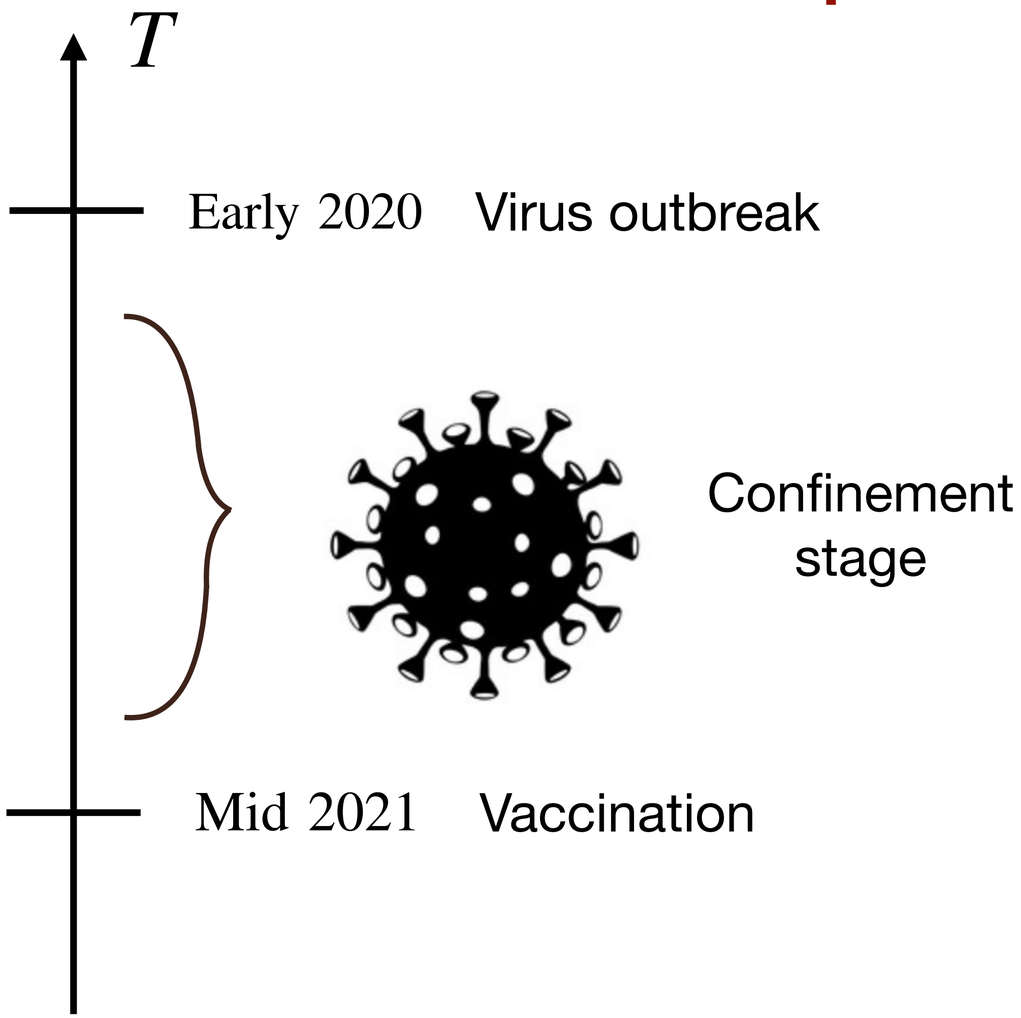
Mid 2021 Vaccination

time

~~Super-uncool~~ confinement

Baldes, YG, Sala 20’
Baldes, YG, Sala, Servant 21’

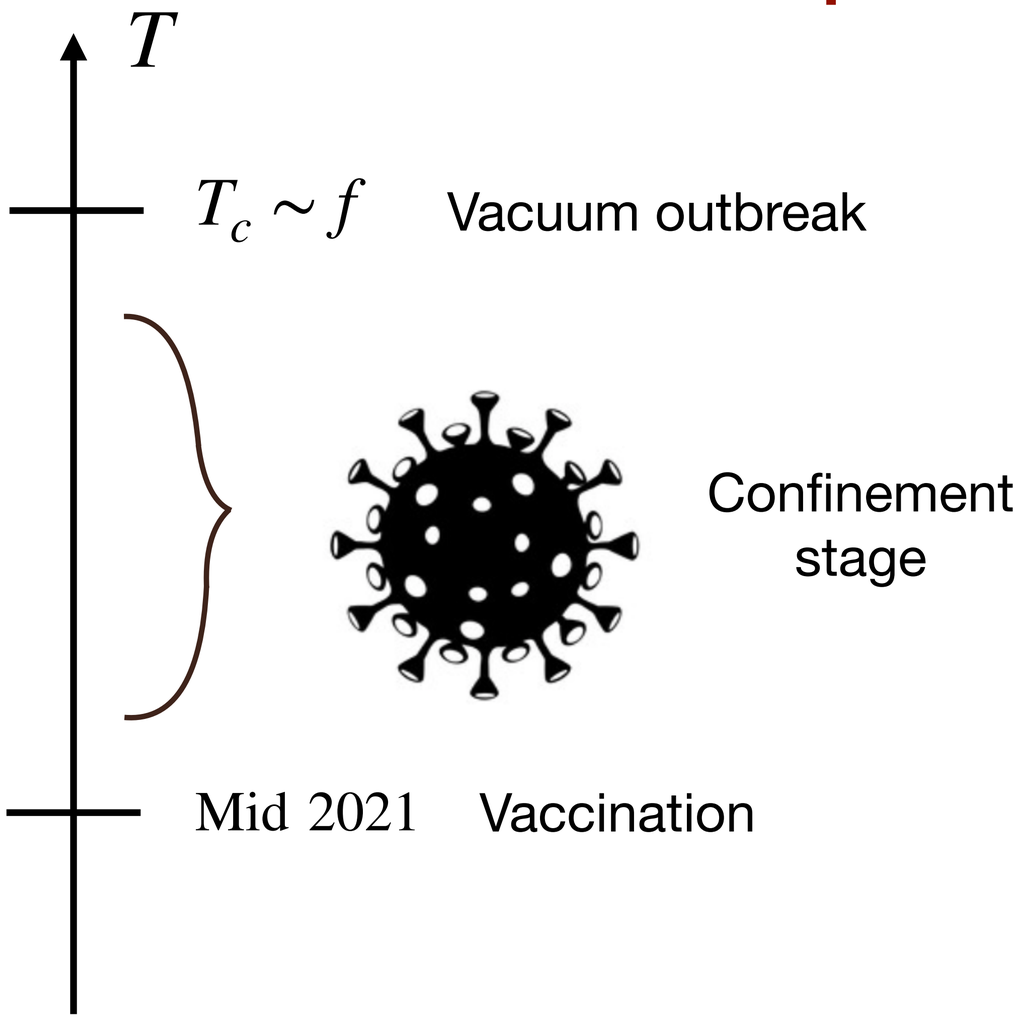
Super-cool



~~Super-uncool~~ confinement

Baldes, YG, Sala 20’
Baldes, YG, Sala, Servant 21’

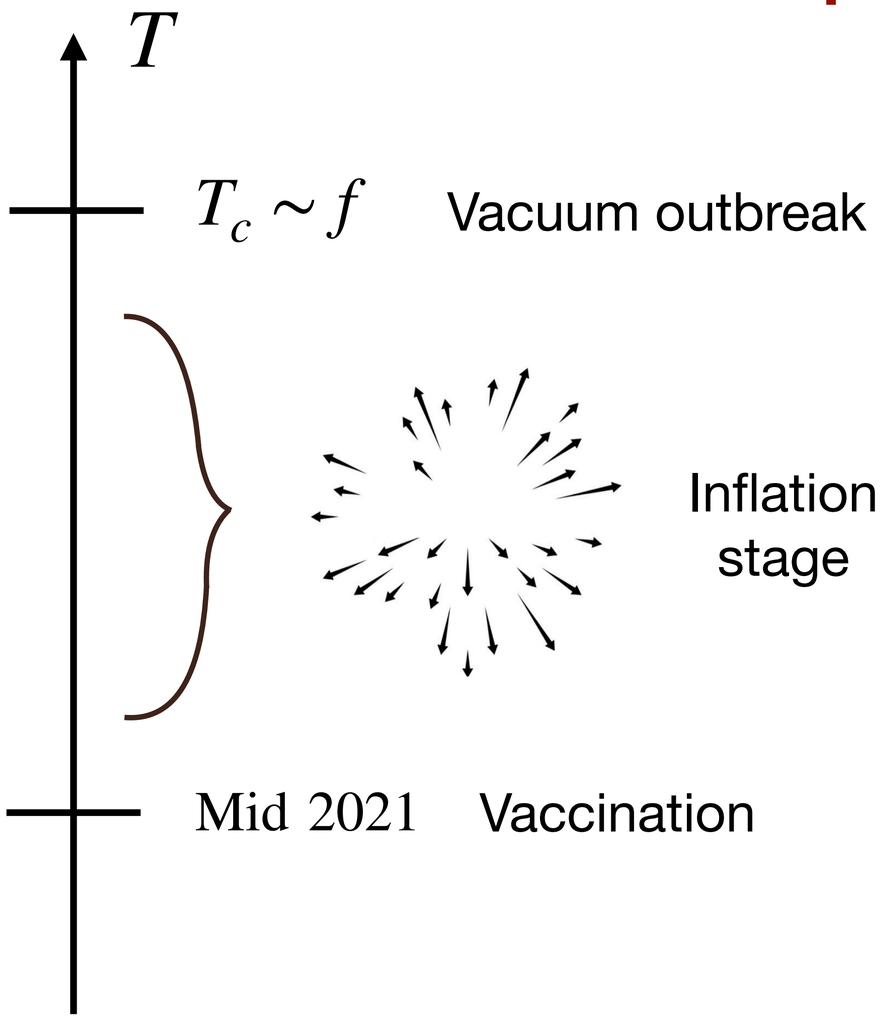
Super-cool



~~Super-uncool~~ confinement

Baldes, YG, Sala 20’
Baldes, YG, Sala, Servant 21’

Super-cool

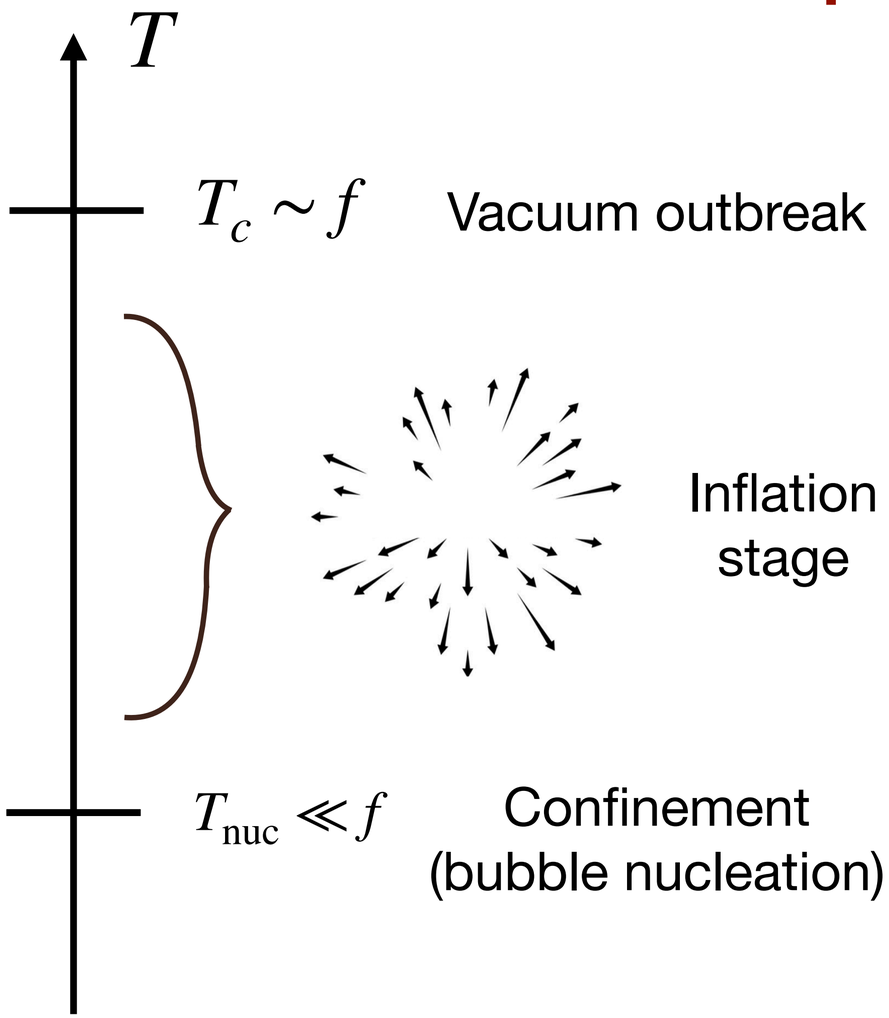


~~Super-uncool~~ confinement

Baldes, YG, Sala 20’

Baldes, YG, Sala, Servant 21’

Super-cool



~~Super-uncool~~ confinement

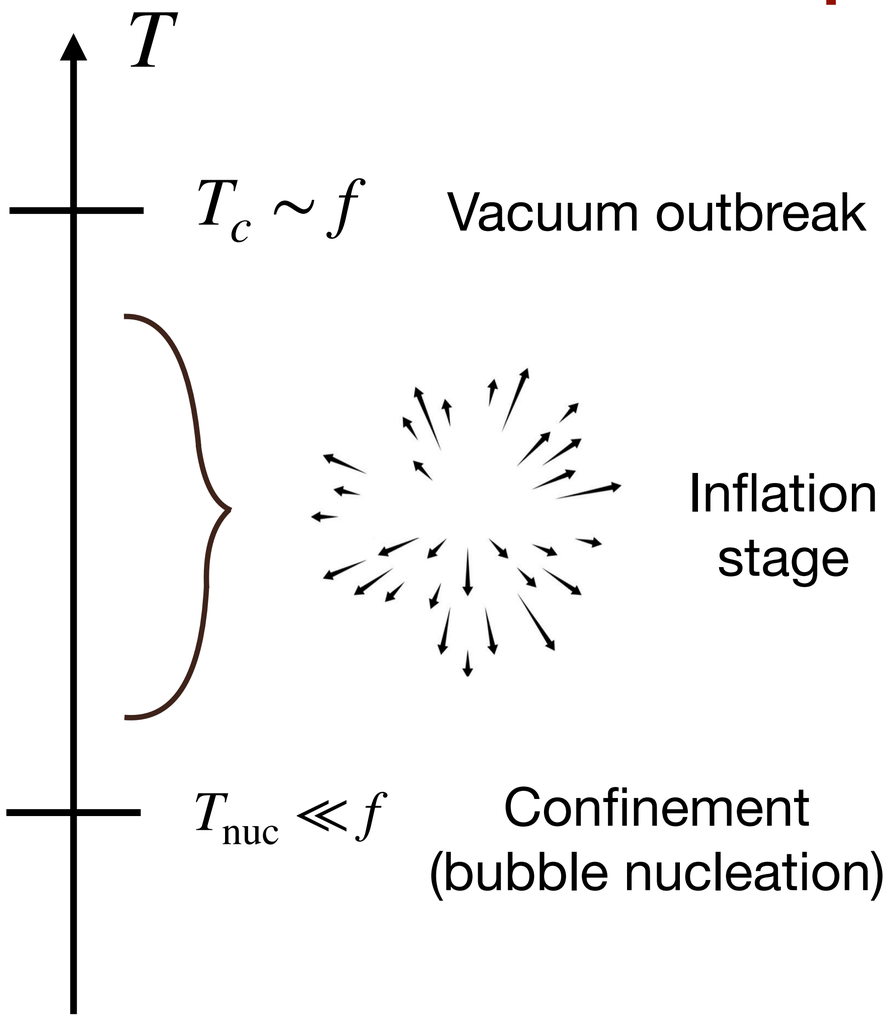
Baldes, YG, Sala 20’

Baldes, YG, Sala, Servant 21’

Super-cool

Naive picture

Quark Anti-quark

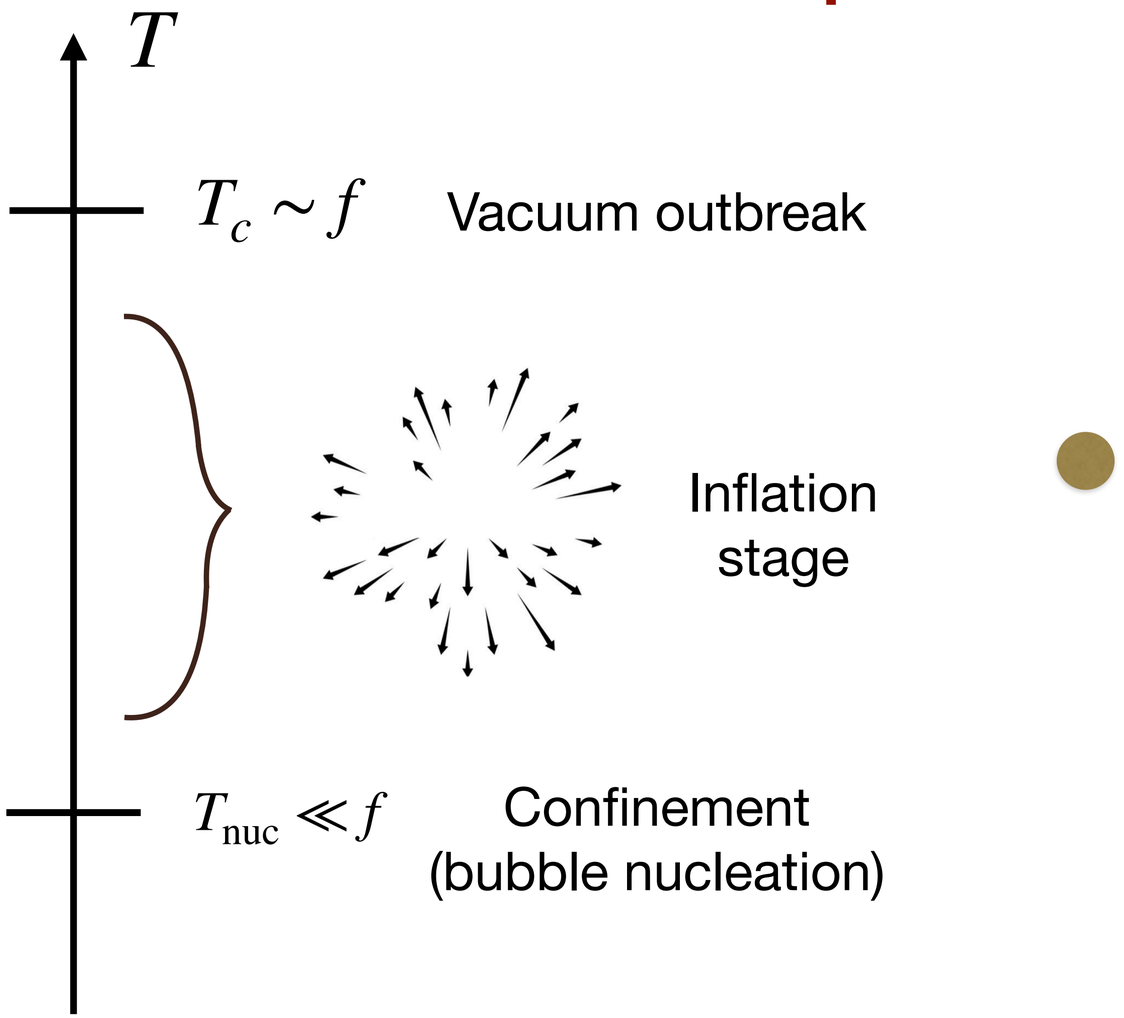


~~Super-uncool~~ confinement

Baldes, YG, Sala 20’

Baldes, YG, Sala, Servant 21’

Super-cool



Naive picture

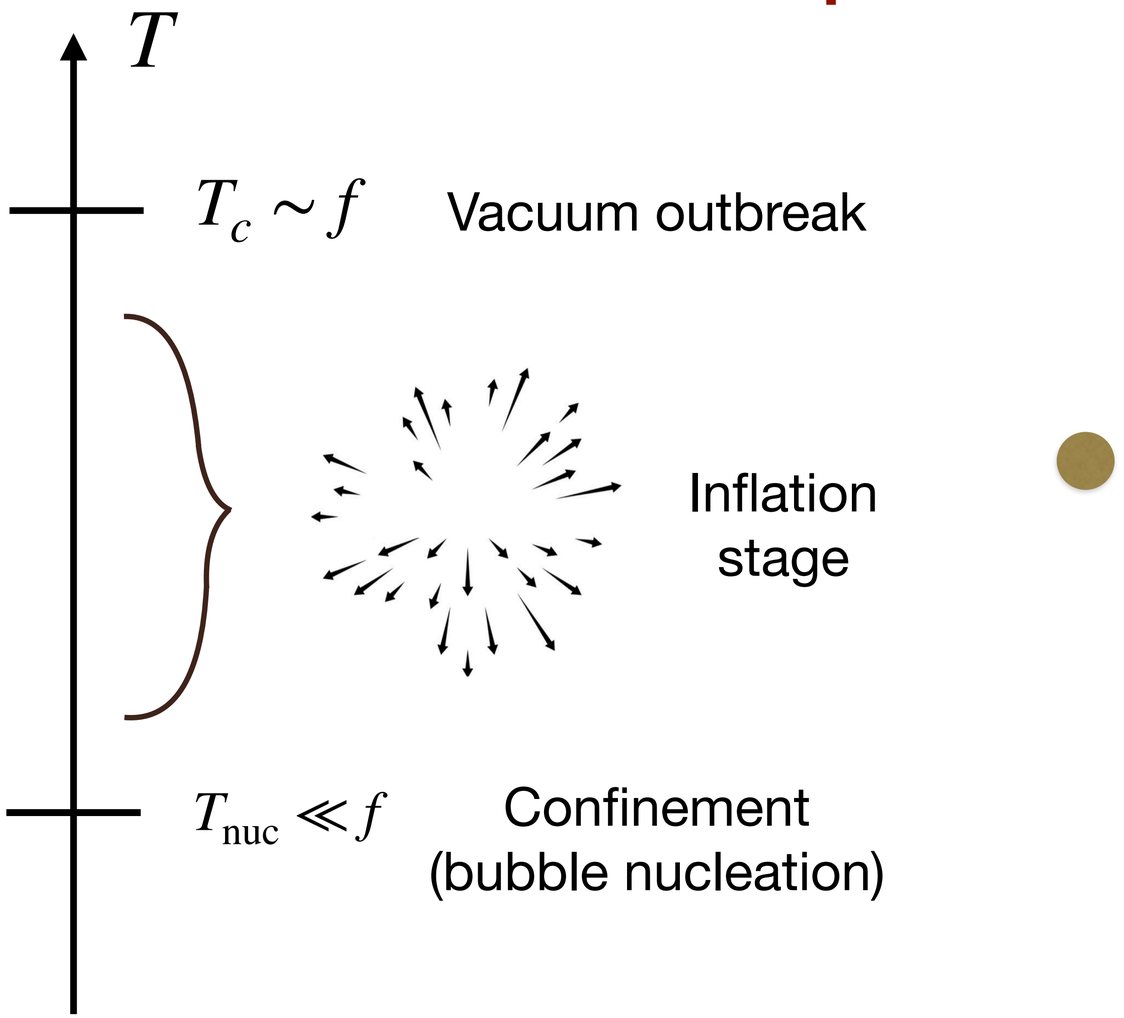
Quark Anti-quark

Dilution

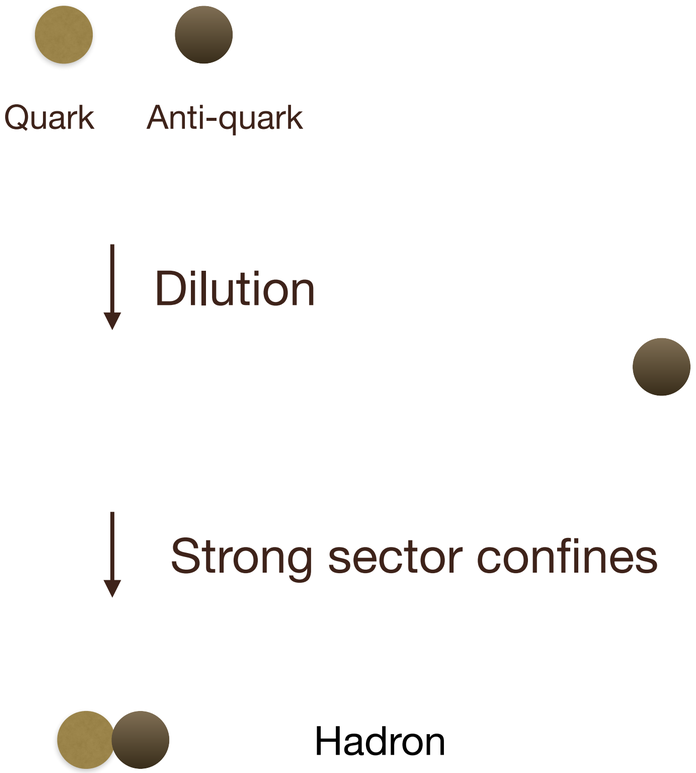
~~Super-uncool~~ confinement

Baldes, YG, Sala 20’
Baldes, YG, Sala, Servant 21’

Super-cool



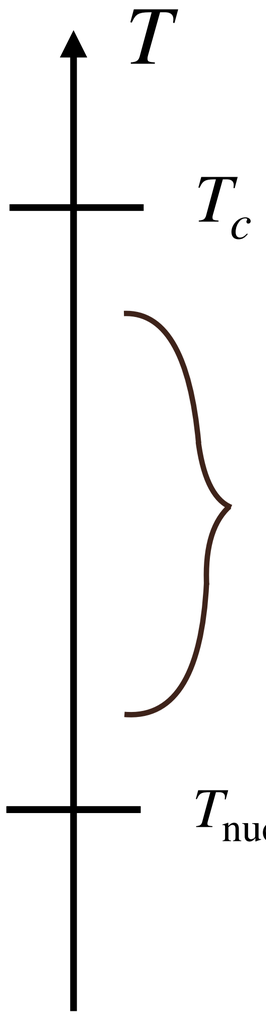
Naive picture



~~Super-uncool~~ confinement

Baldes, YG, Sala 20’
Baldes, YG, Sala, Servant 21’

Super-cool



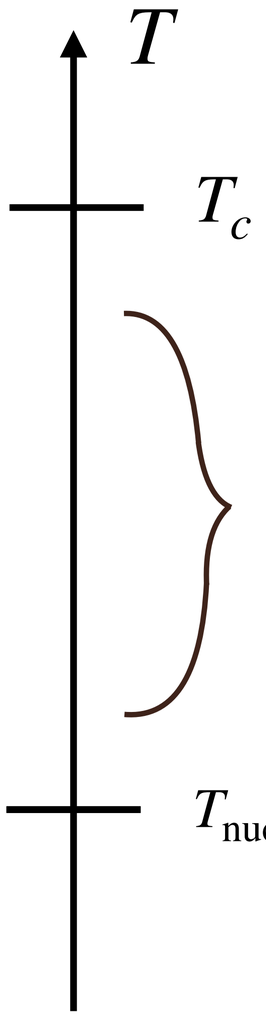
Naive picture

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

~~Super-uncool~~ confinement

Baldes, YG, Sala 20’
Baldes, YG, Sala, Servant 21’

Super-cool



Naive picture

Dilution

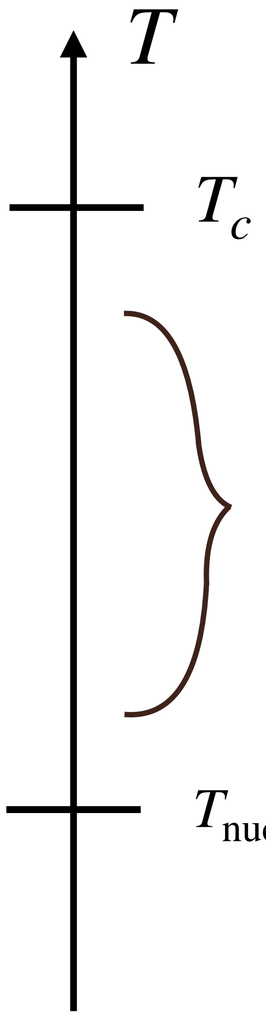
Strong sector confines

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

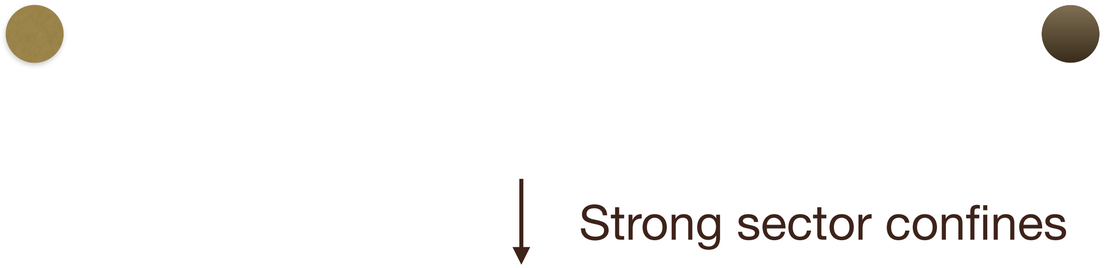
~~Super-uncool~~ confinement

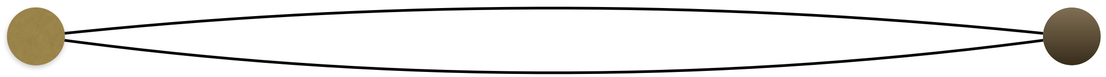
Baldes, YG, Sala 20’
Baldes, YG, Sala, Servant 21’

Super-cool



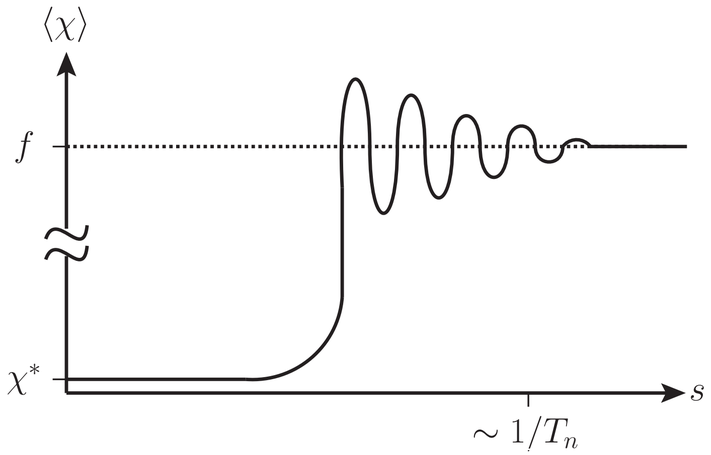
Naive picture





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

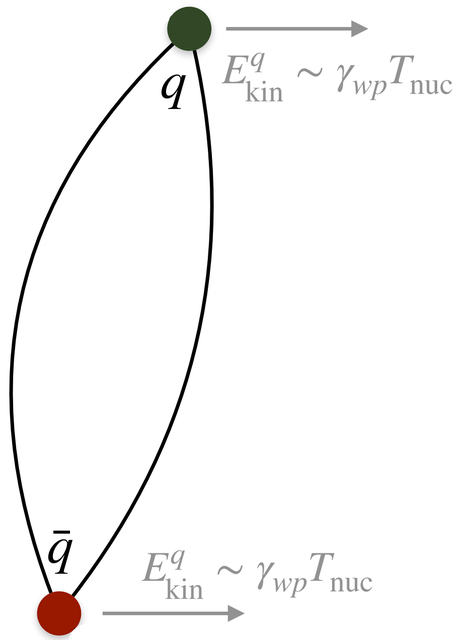
Confinement



Bubble wall profile

Deconfined phase

$\chi = 0$

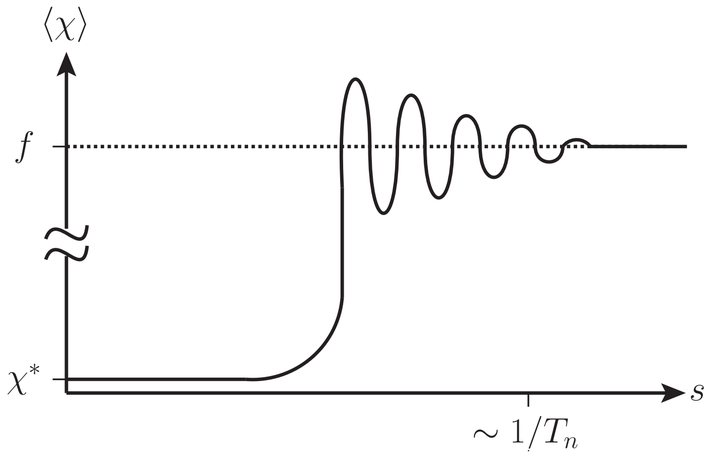


Confined phase

$\chi = f$

Bubble wall frame

Confinement



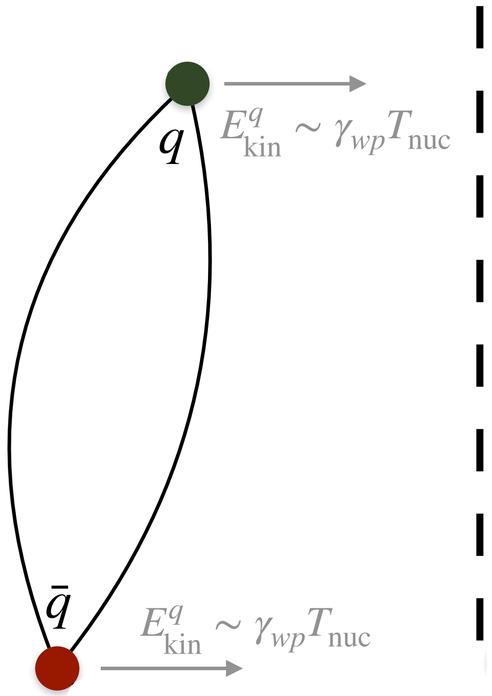
Bubble wall profile

Deconfined phase

$\chi = 0$

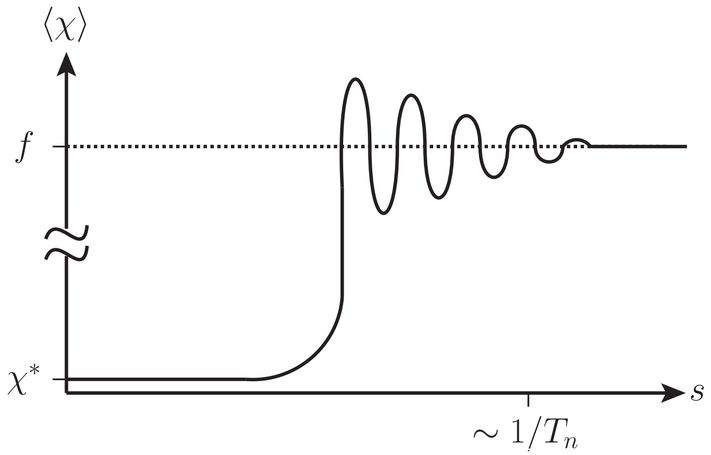
Confined phase

$\chi = f$



Bubble wall frame

Confinement



Bubble wall profile

Deconfined phase

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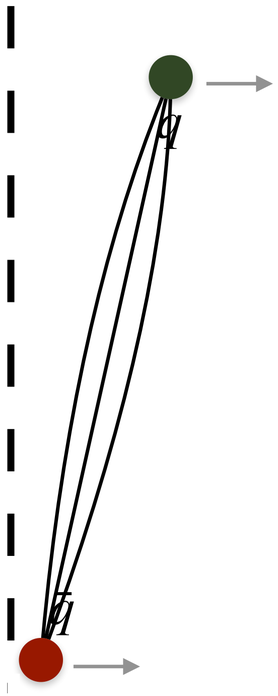
Confined phase

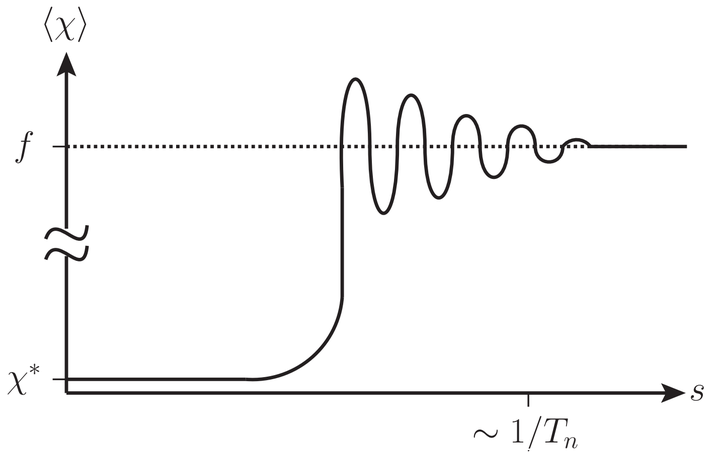
$$\chi = f$$



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

Bubble wall frame

Confinement



Bubble wall profile

Deconfined phase

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Confined phase

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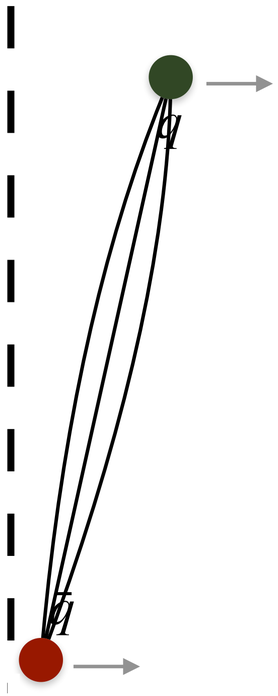
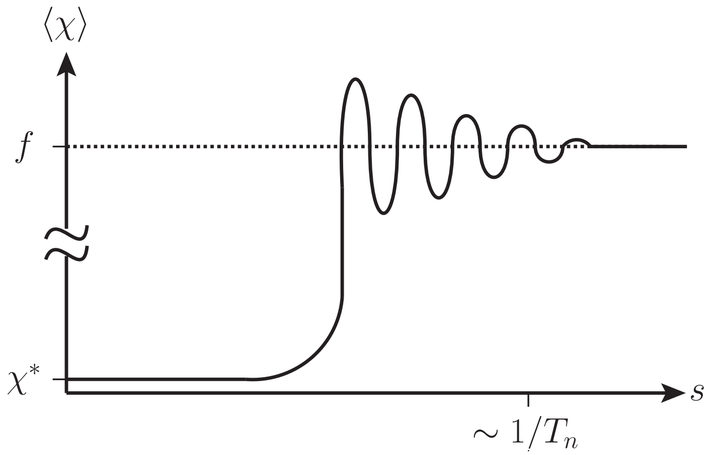


$$V_{\text{string}} \simeq f^2\, r \simeq \frac{f^2}{T_{\text{nuc}}}$$

Bubble wall frame

Confinement



Bubble wall profile

Deconfined phase

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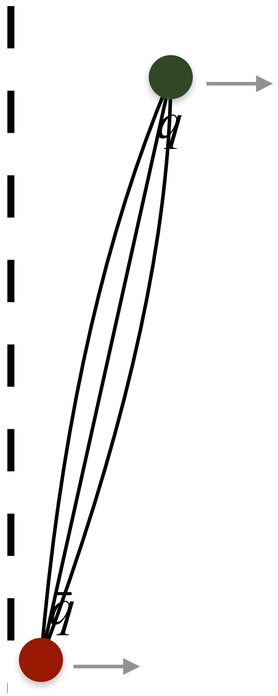
Confined phase

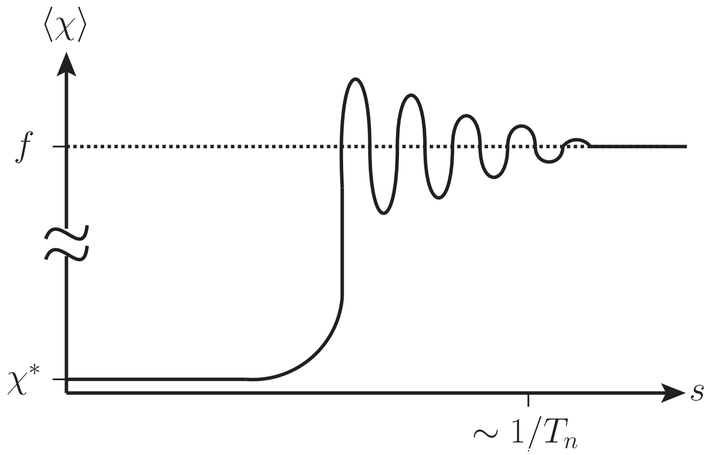
$$\chi = f$$



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

Bubble wall frame

Confinement



Bubble wall profile

Deconfined phase

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Confined phase

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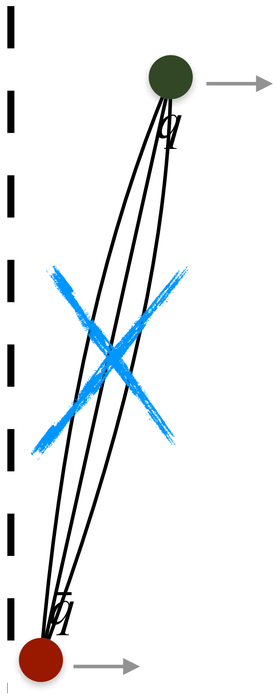
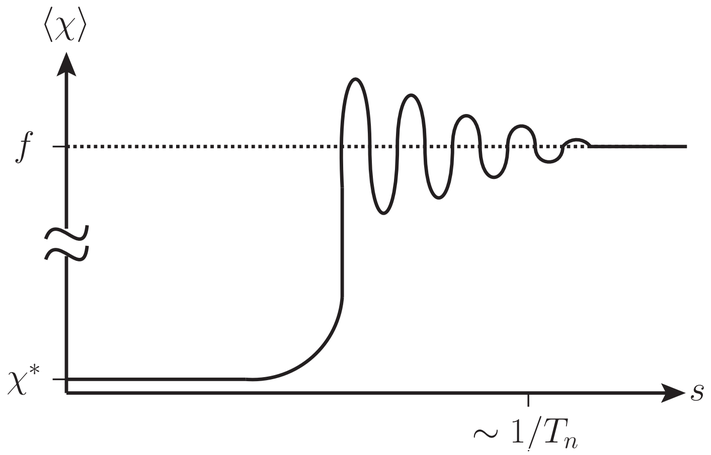


$$V_{\text{string}} \simeq f^2\, r \simeq \frac{f^2}{T_{\text{nuc}}} \gg f$$

Cost too much energy!

Bubble wall frame

Confinement



Bubble wall profile

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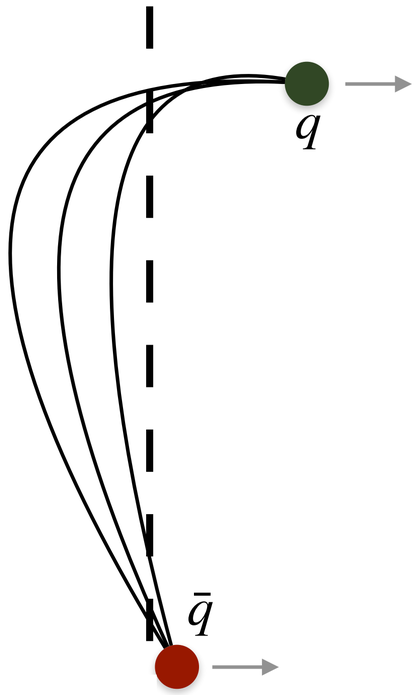
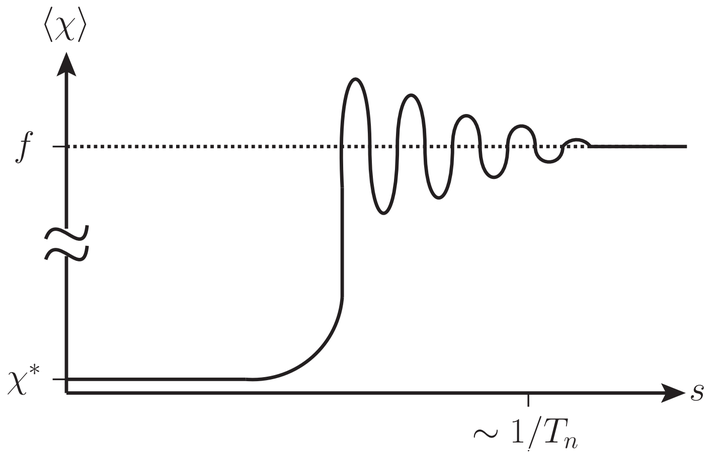


Bubble wall frame

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

Flux tube minimises its energy !

Confinement



Bubble wall profile

Deconfined phase

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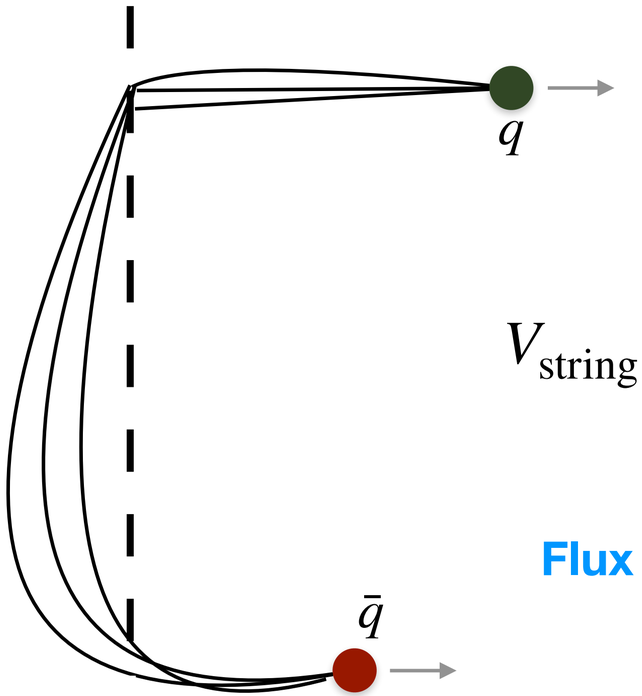
Confined phase

$$\chi = f$$



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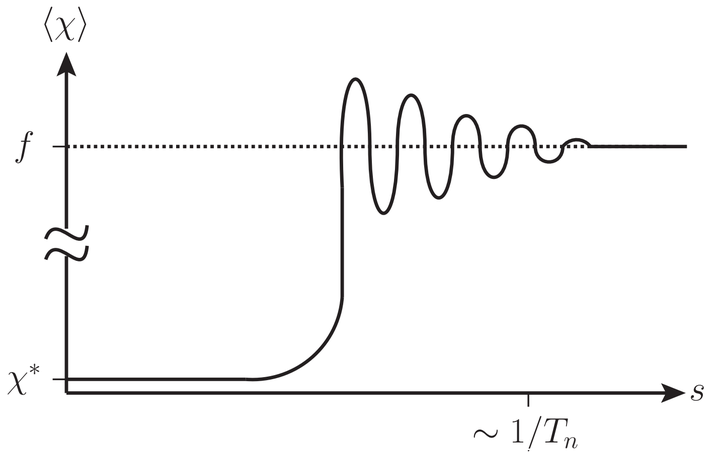
Flux tube minimises its energy !

Bubble wall frame

Confinement



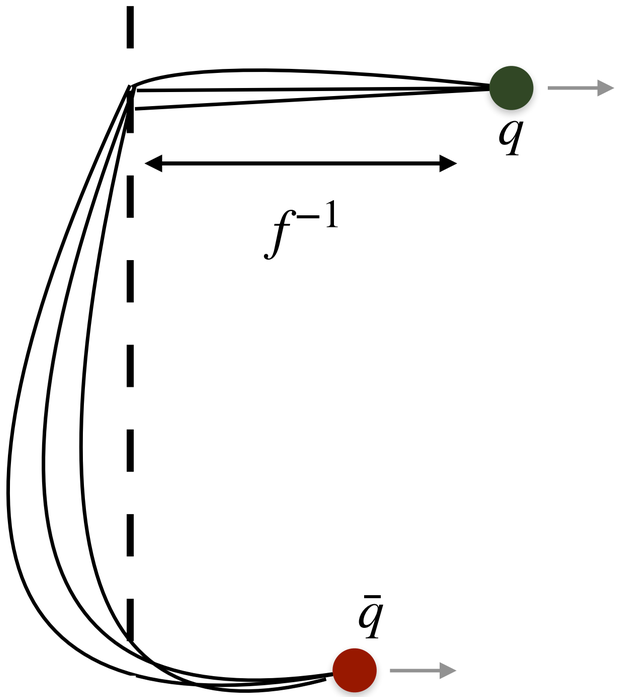
Bubble wall profile

Deconfined phase

$\chi = 0$

Confined phase

$\chi = f$



Bubble wall frame

Confinement

Deconfined phase

$\chi = 0$

Confined phase

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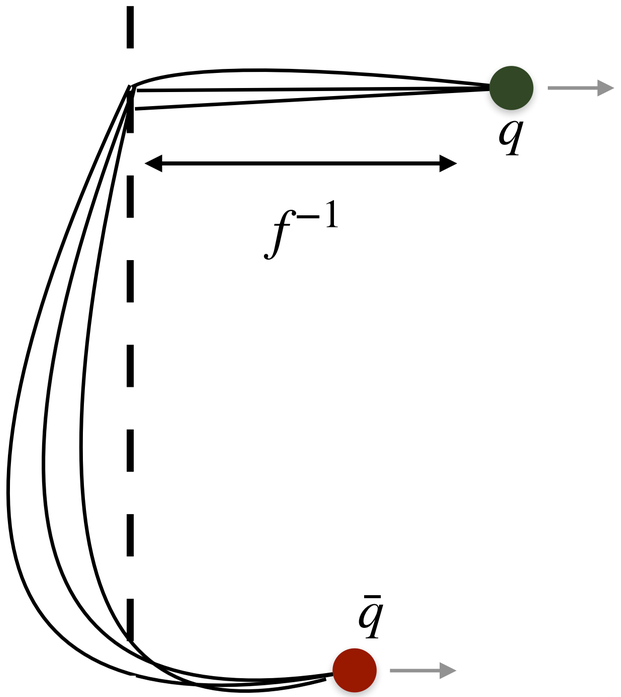

Bubble wall frame

Confinement

Deconfined phase

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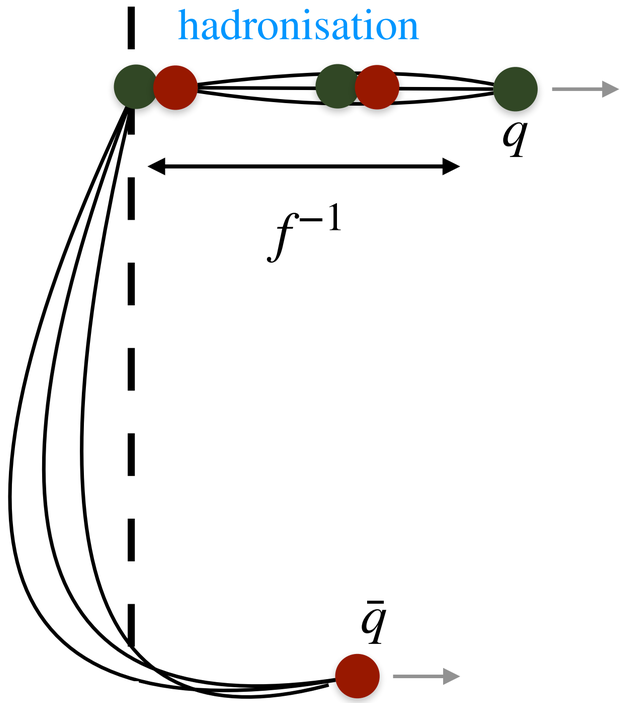
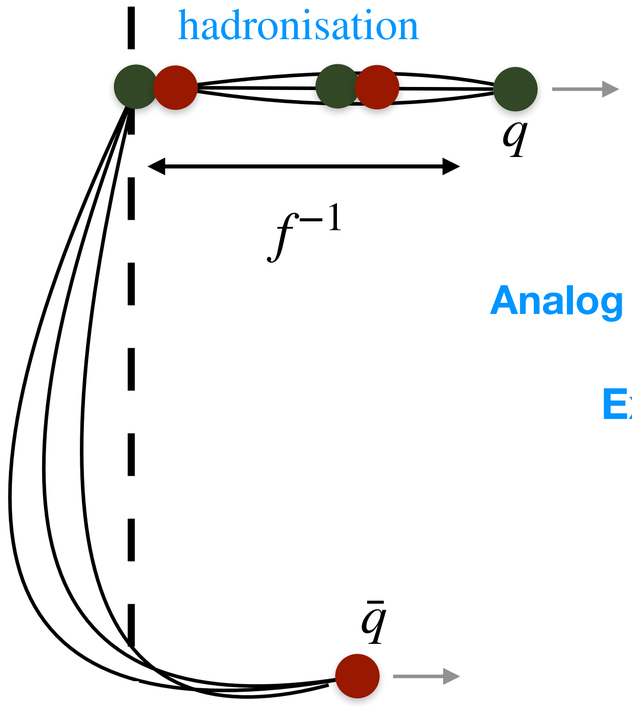


Bubble wall frame

Confinement

Deconfined phase

$\chi = 0$



Bubble wall frame

Confined phase

$\chi = f$

Analog to string fragmentation in QCD !

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

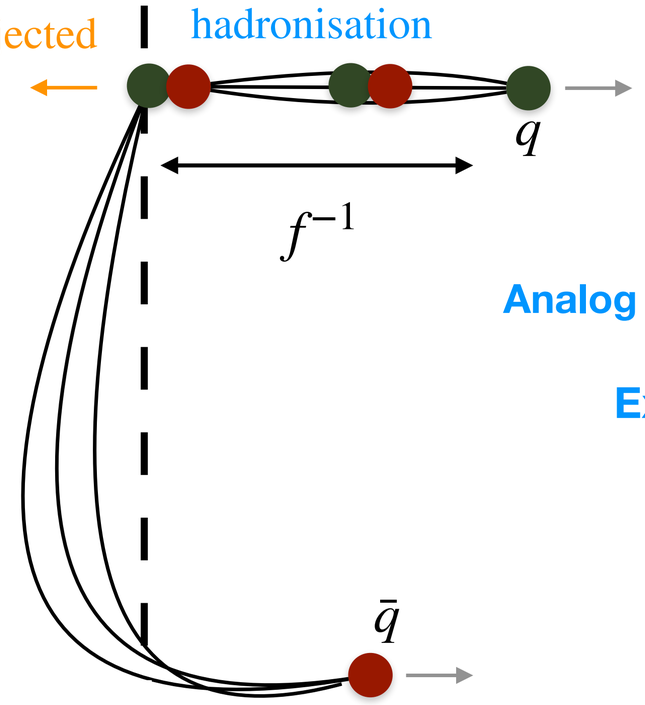
Confinement

Deconfined phase

$\chi = 0$

Confined phase

$\chi = f$



Due to color conservation

Analog to string fragmentation in QCD !

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

Bubble wall frame

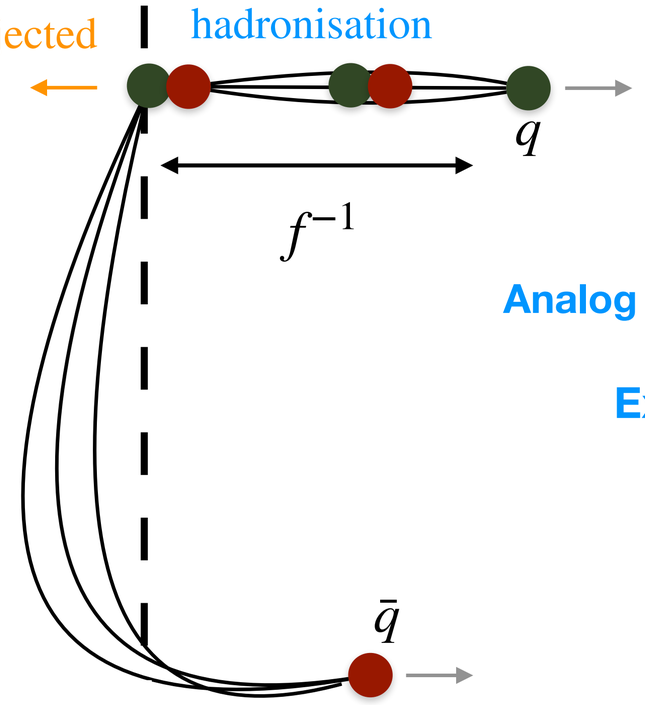
Confinement

Deconfined phase

$\chi = 0$

Confined phase

$\chi = f$



Due to color conservation

Analog to Hawking evaporation !

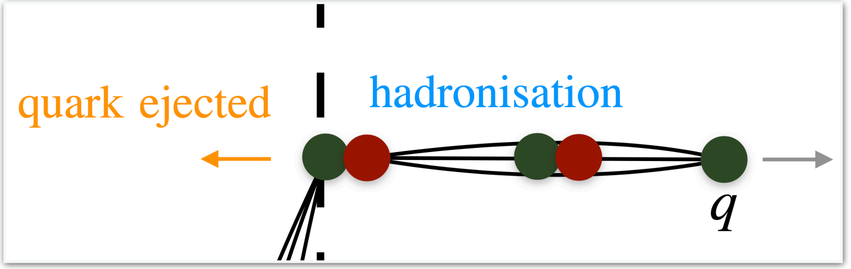
‘’Color radiation”

Analog to string fragmentation in QCD !

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

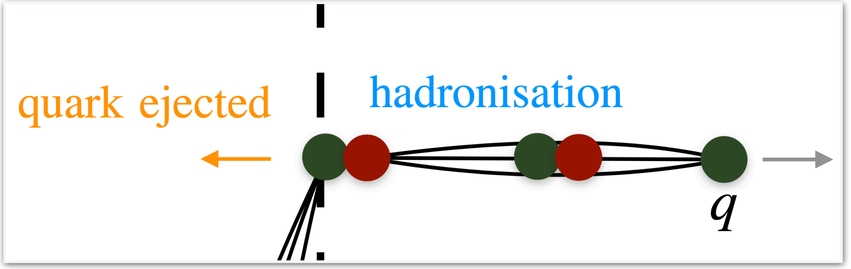
Bubble wall frame

Impact on DM



1. More hadrons per initial quark pair

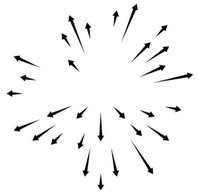
Impact on DM



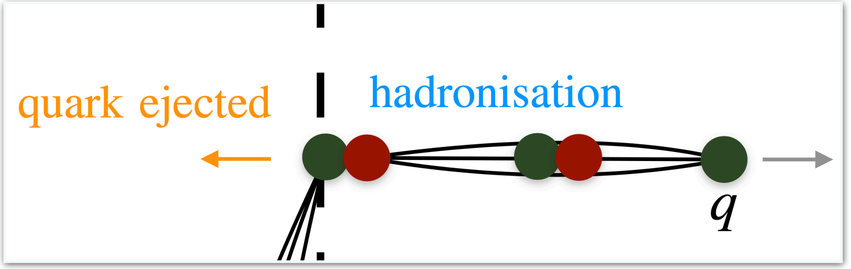
1. More hadrons per initial quark pair

DM abundance dilution

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



Impact on DM



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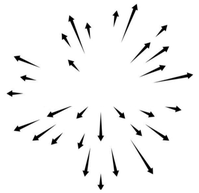
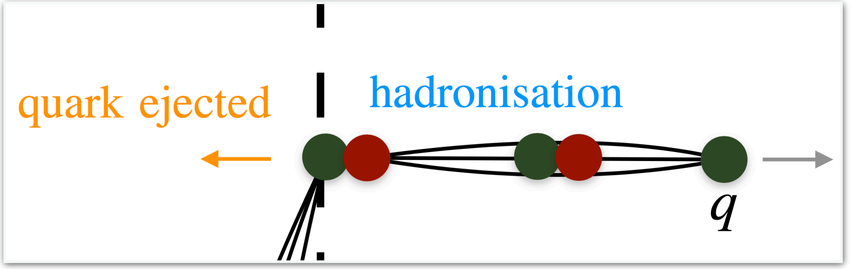


DM abundance enhancement

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

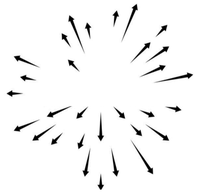
Impact on DM



1. More hadrons per initial quark pair

DM abundance dilution

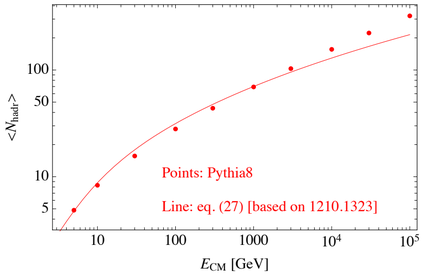
$$Y_{\rm DM}^{\rm naive} \propto \left(\frac{T_{\rm nuc}}{f}\right)^3$$



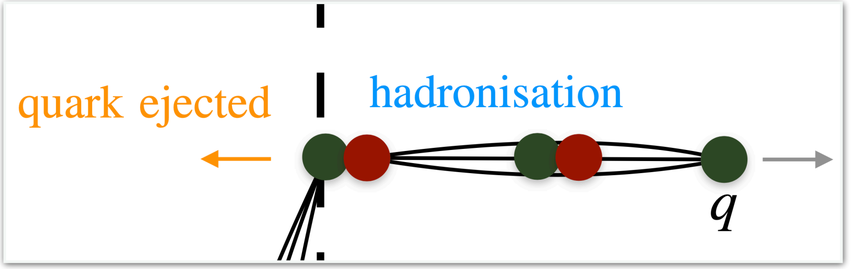
DM abundance enhancement

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

Pythia



Impact on DM



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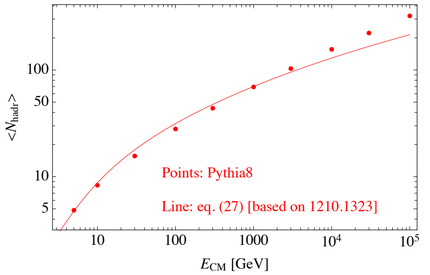
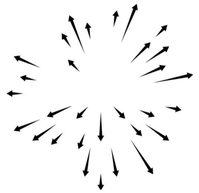
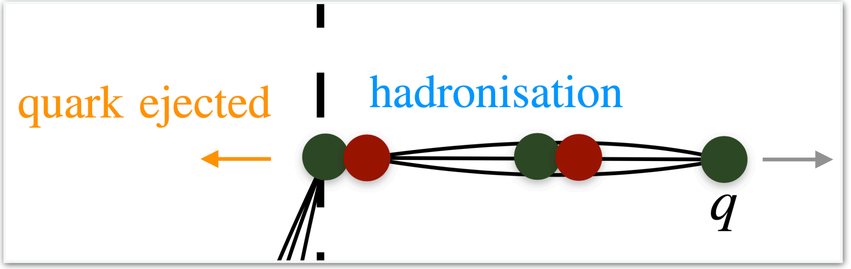




2. Cosmological catapult

Impact on DM



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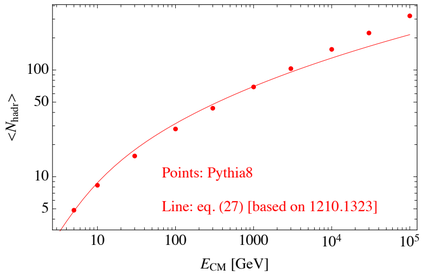
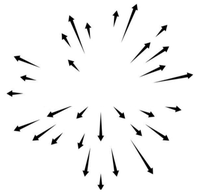
Pythia

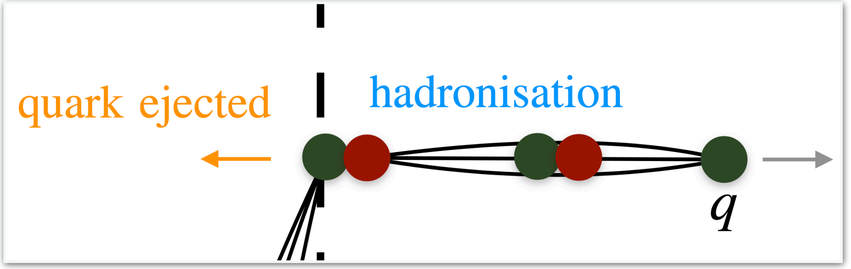




2. Cosmological catapult

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

Impact on DM



1. More hadrons per initial quark pair

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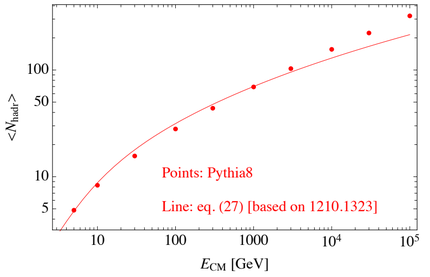
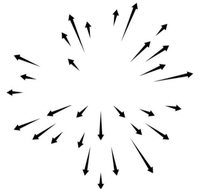
Pythia



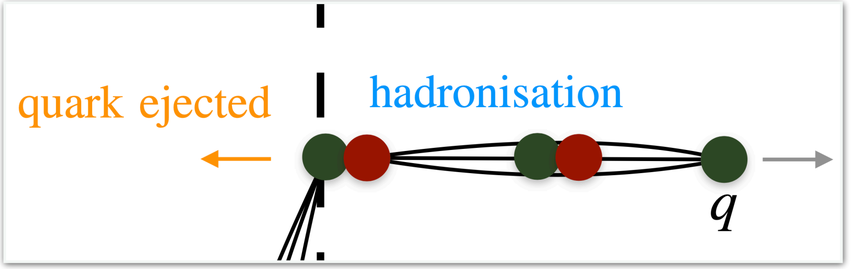


2. Cosmological catapult

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

$E_{\rm bath} \sim f$

Impact on DM



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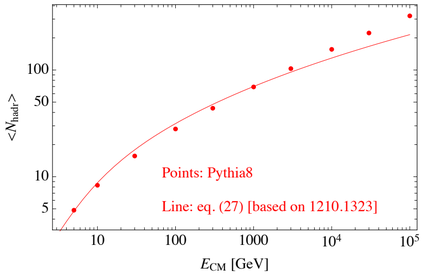
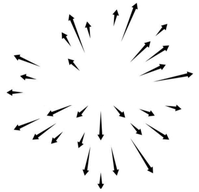




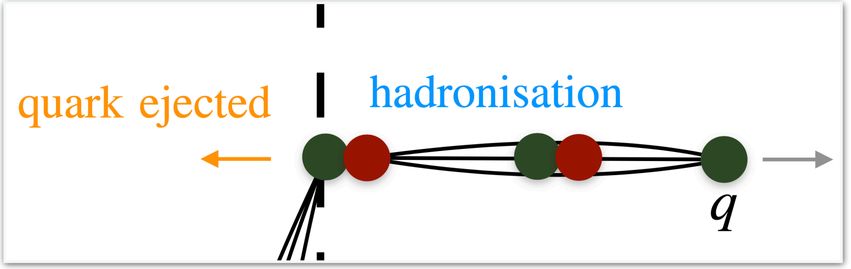
2. Cosmological catapult

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

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

$E_{\rm bath} \sim f$

Impact on DM



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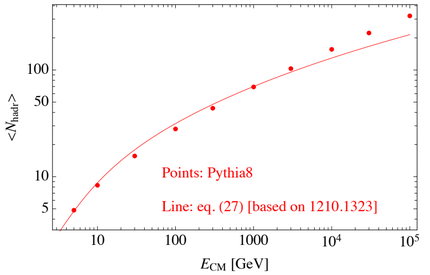
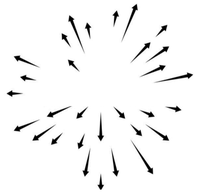
Pythia





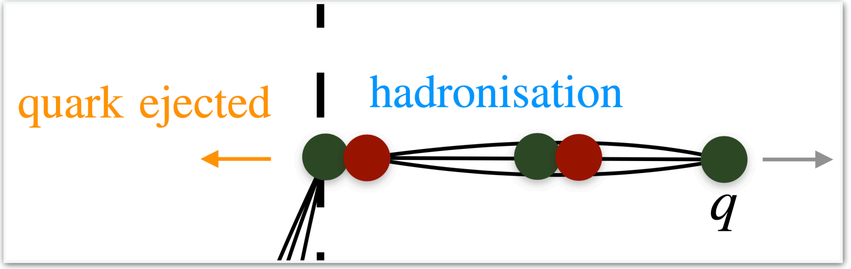
2. Cosmological catapult

$$s \sim E_{\rm hadron} E_{\rm bath} \gg f^2$$

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

$E_{\rm bath} \sim f$

Impact on DM



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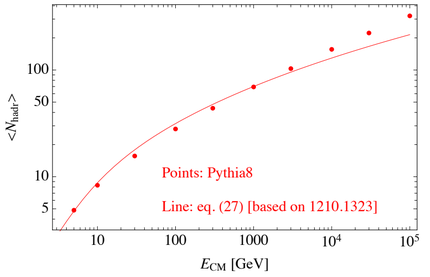
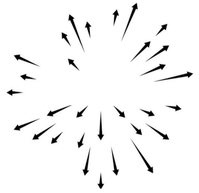
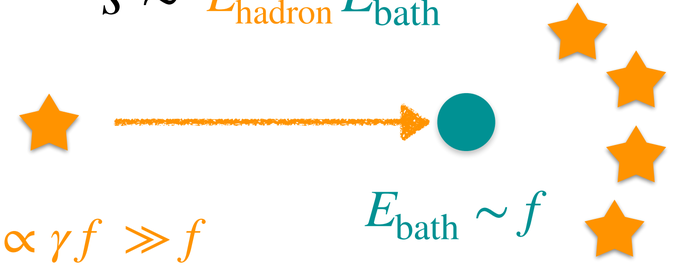




2. Cosmological catapult

Iterate

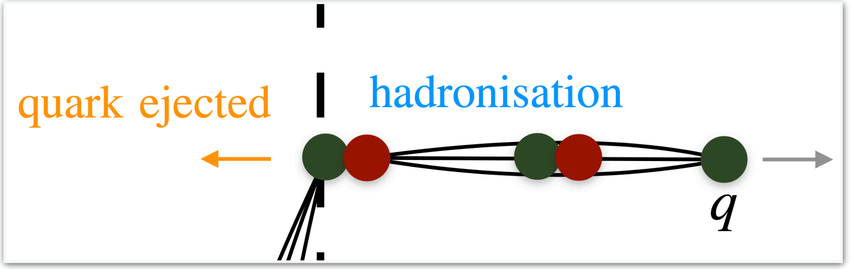
$s \sim E_{\rm hadron} E_{\rm bath}$



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

$E_{\rm bath} \sim f$

Impact on DM



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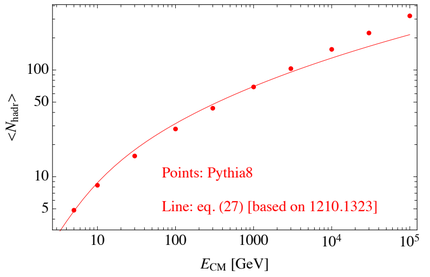
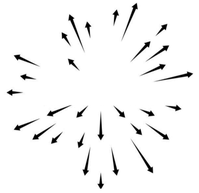
Pythia





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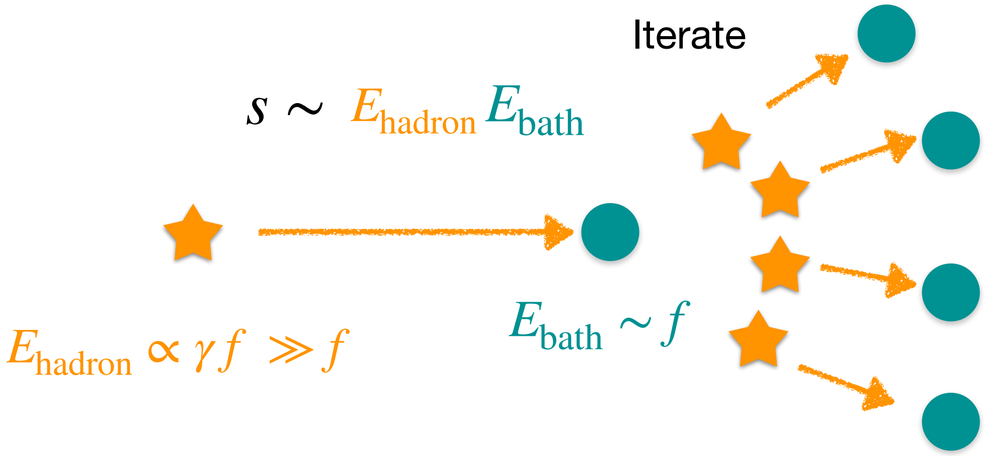
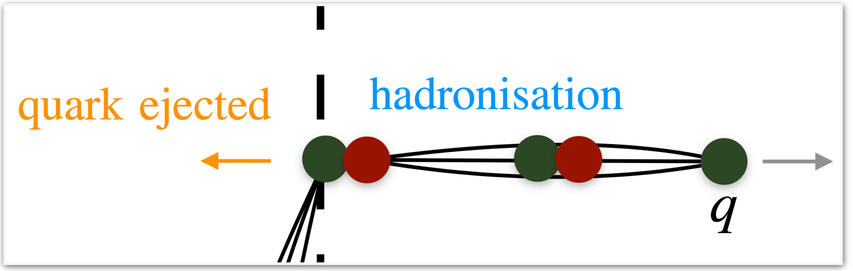


Impact on DM



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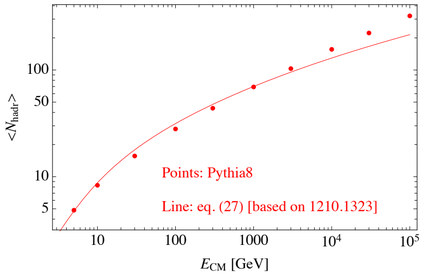

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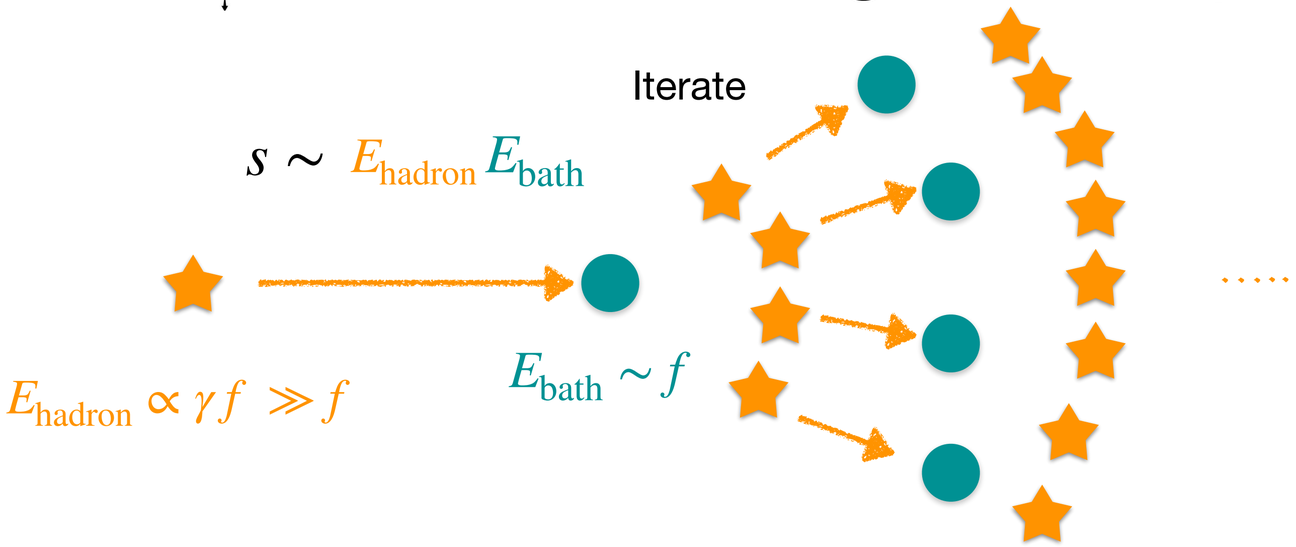
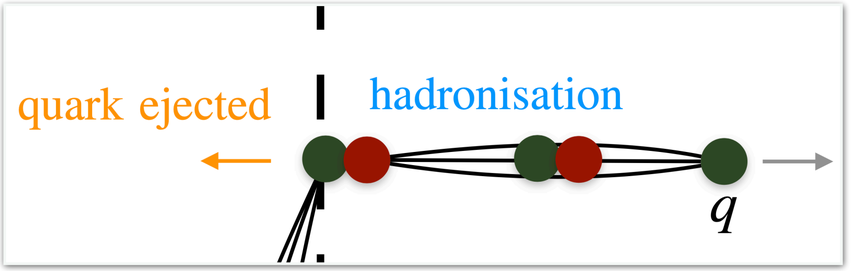


Impact on DM



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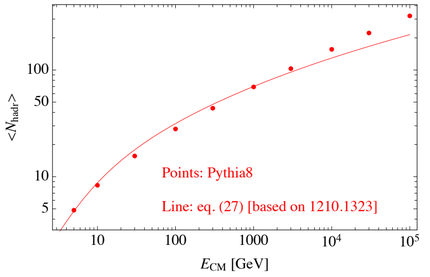

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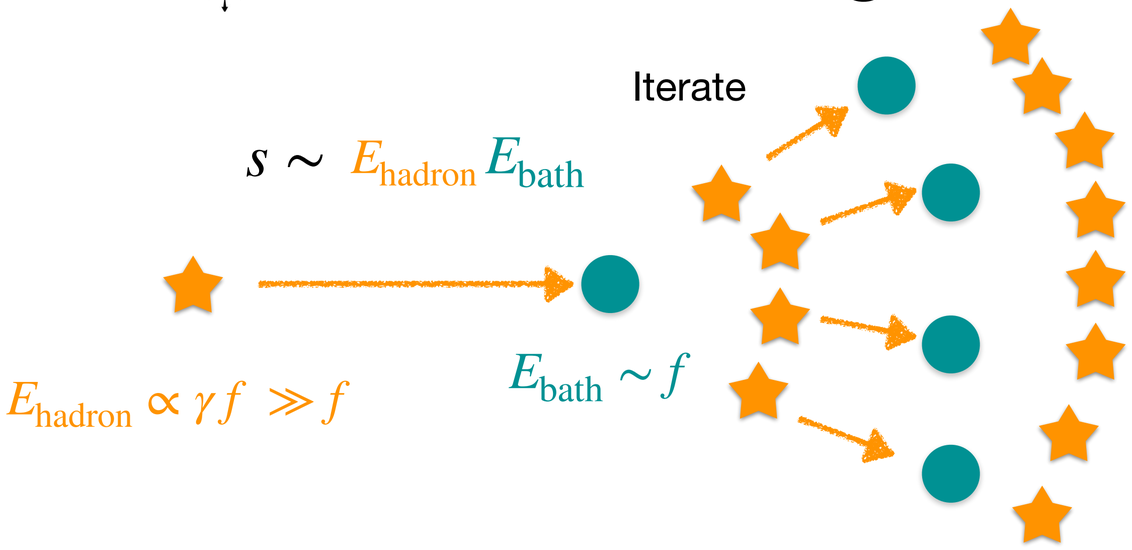


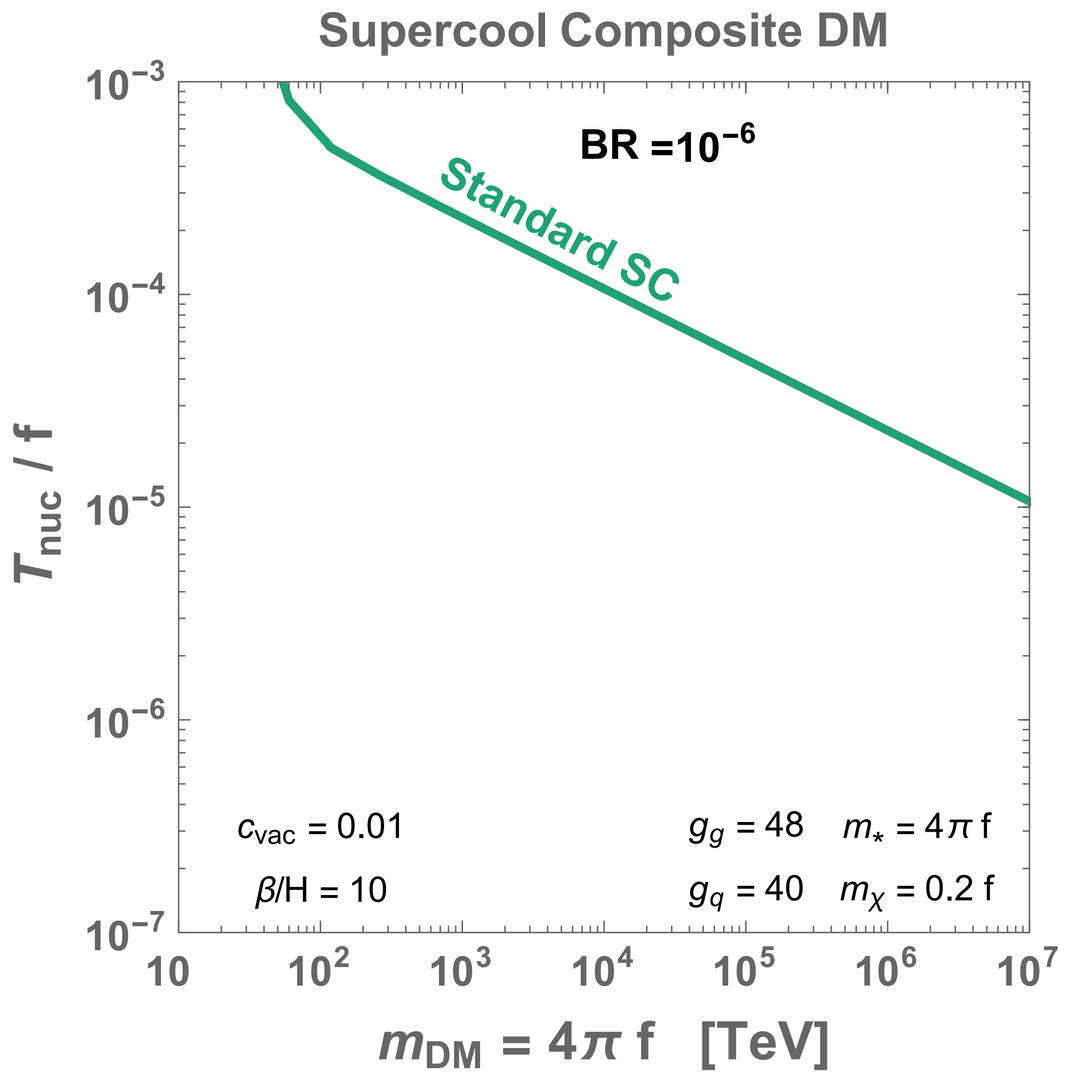
DM abundance enhancement

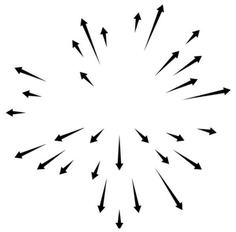
$$Y_{\rm DM} / Y_{\rm DM}^{\rm naive} \propto \gamma \propto \frac{T_{\rm nuc}}{f}\frac{M_{\rm Pl}}{f}$$

runaway regime

Consequences on DM abundance

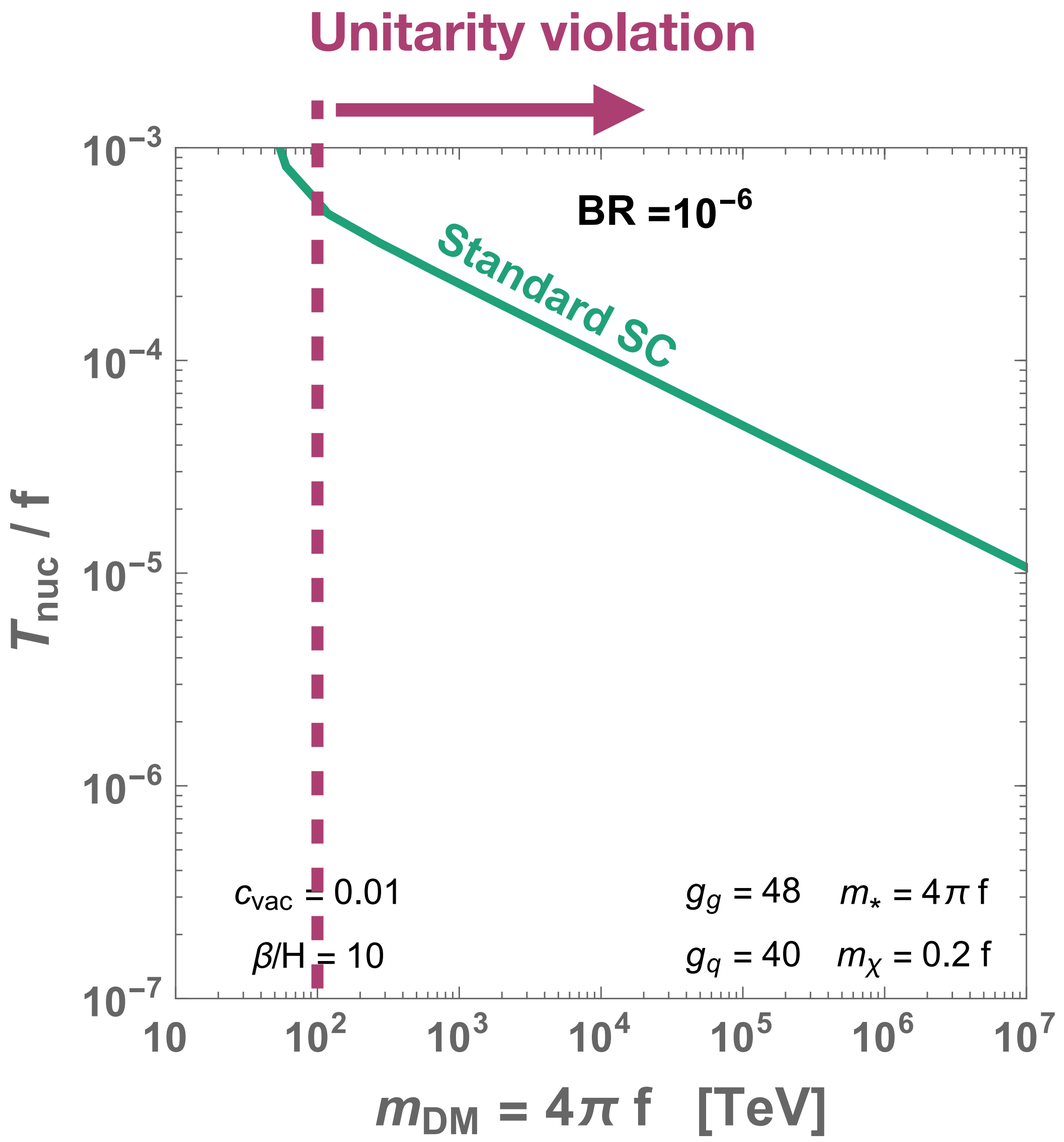
$$Y_{\rm DM}^{\rm naive} \propto \left(\frac{T_{\rm nuc}}{f}\right)^3$$



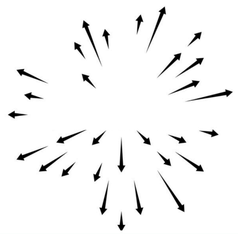


$$Y_{\mathrm{DM}}^{\mathrm{naive}} \propto \left(\frac{T_{\mathrm{nuc}}}{f}\right)^3$$

Consequences on DM abundance



Consequences on DM abundance



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

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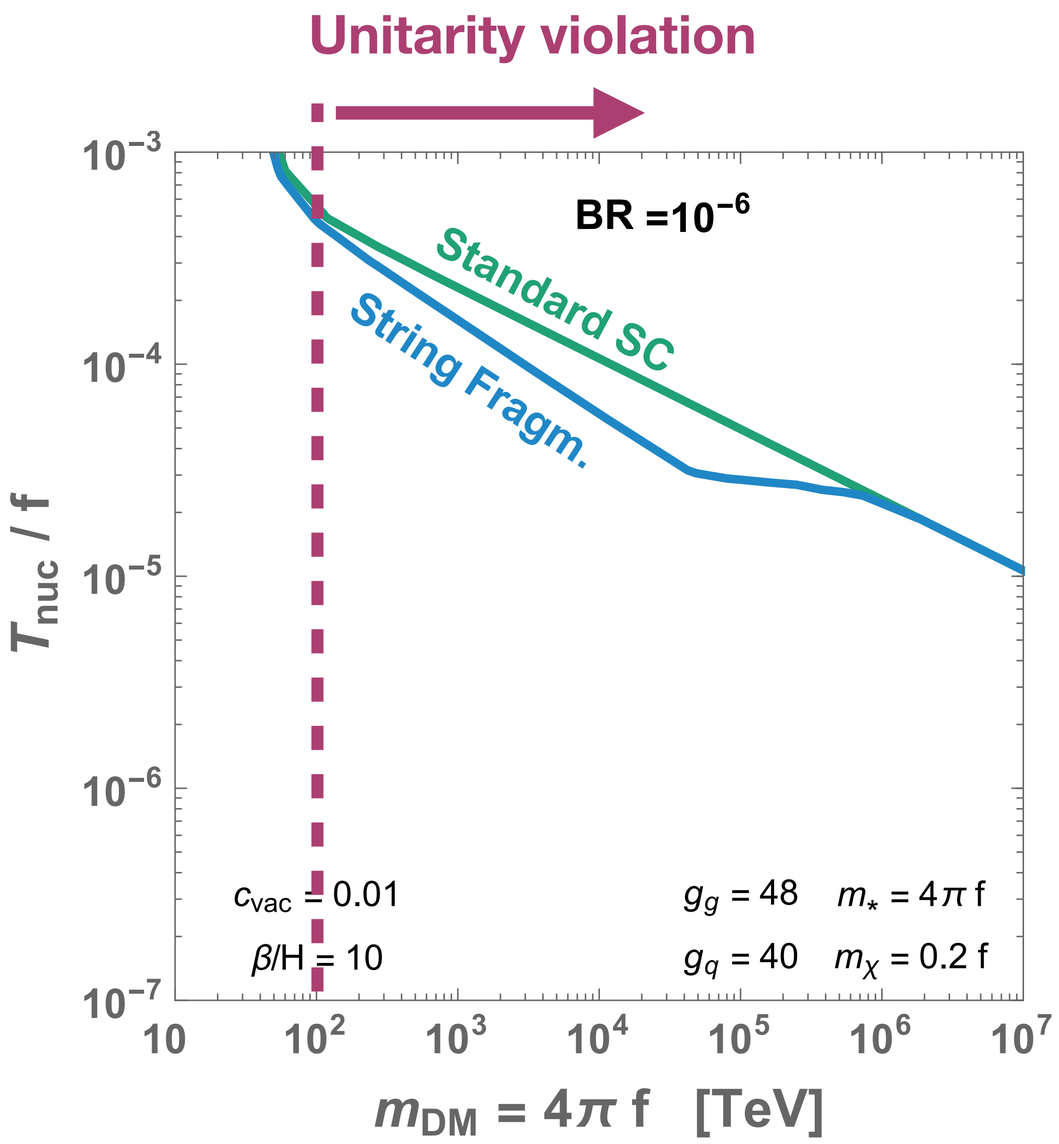
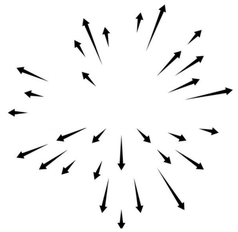


Consequences on DM abundance



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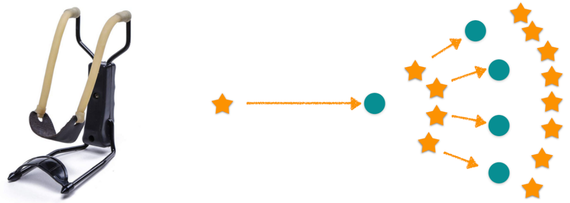

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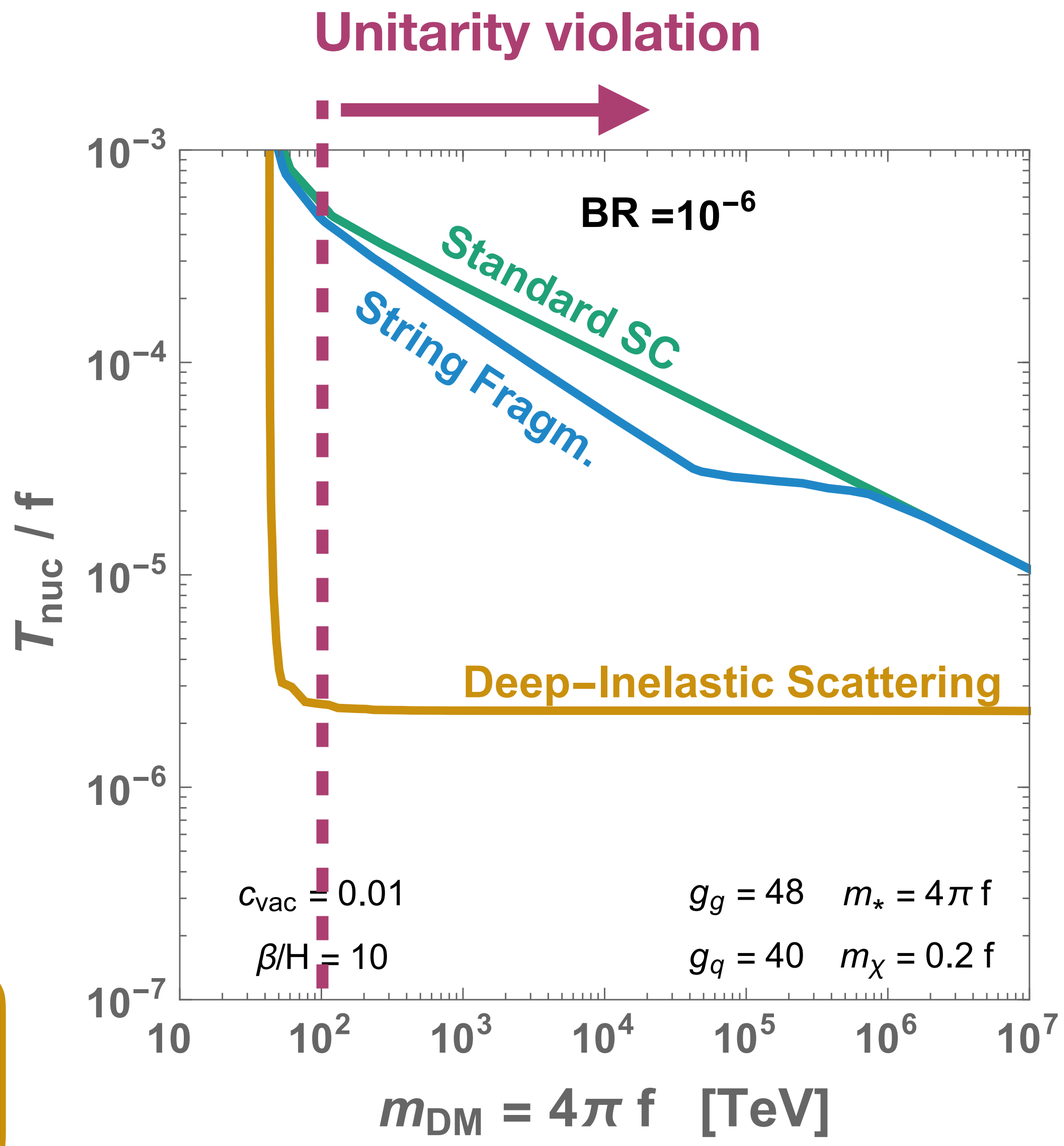
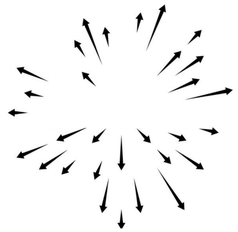


Consequences on DM abundance



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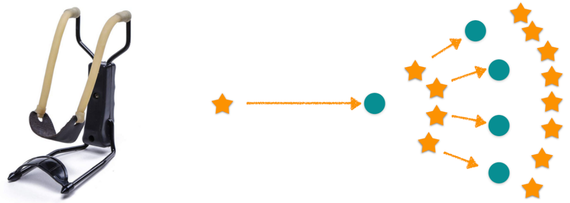

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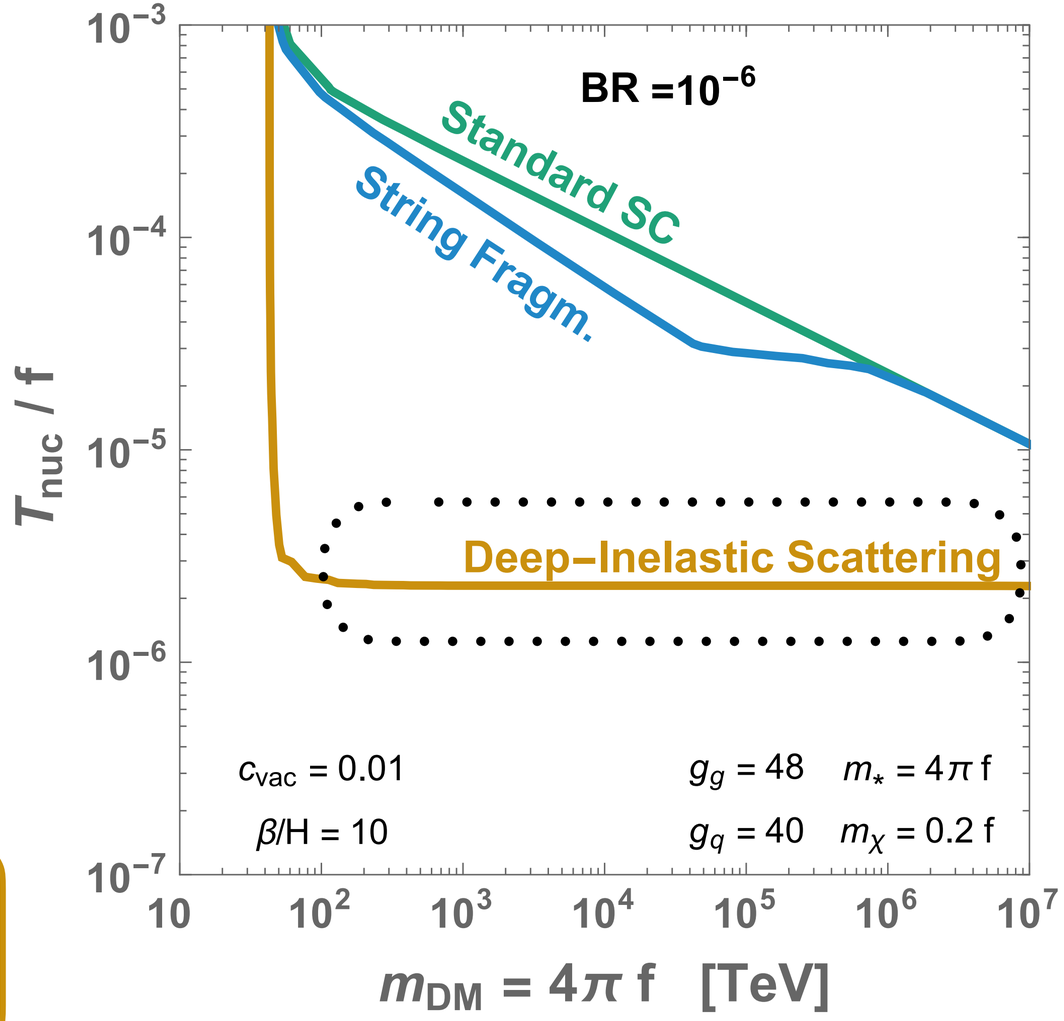

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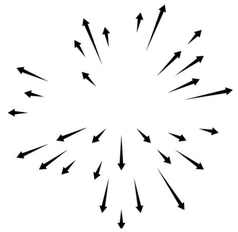

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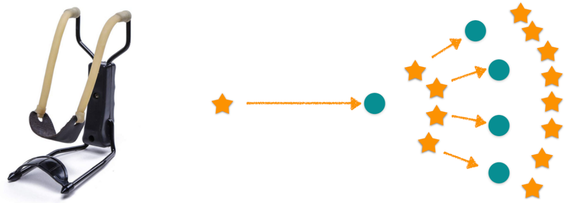

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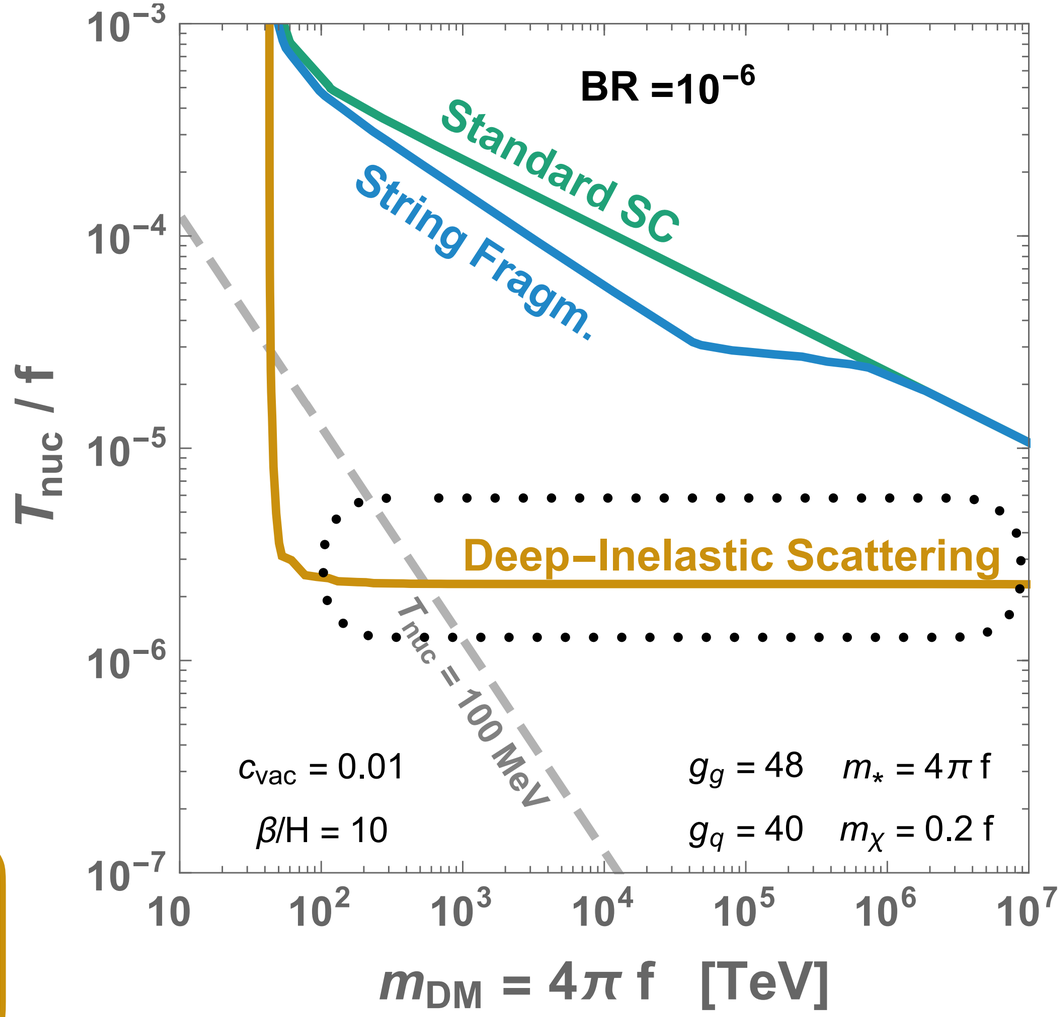
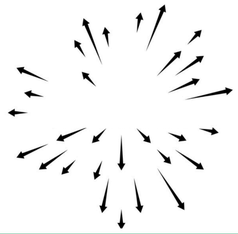


Consequences on DM abundance



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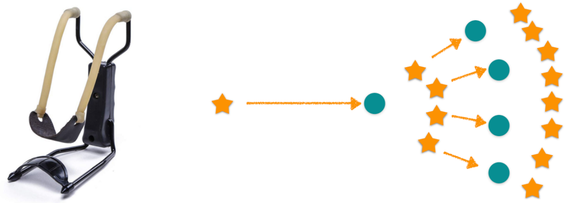

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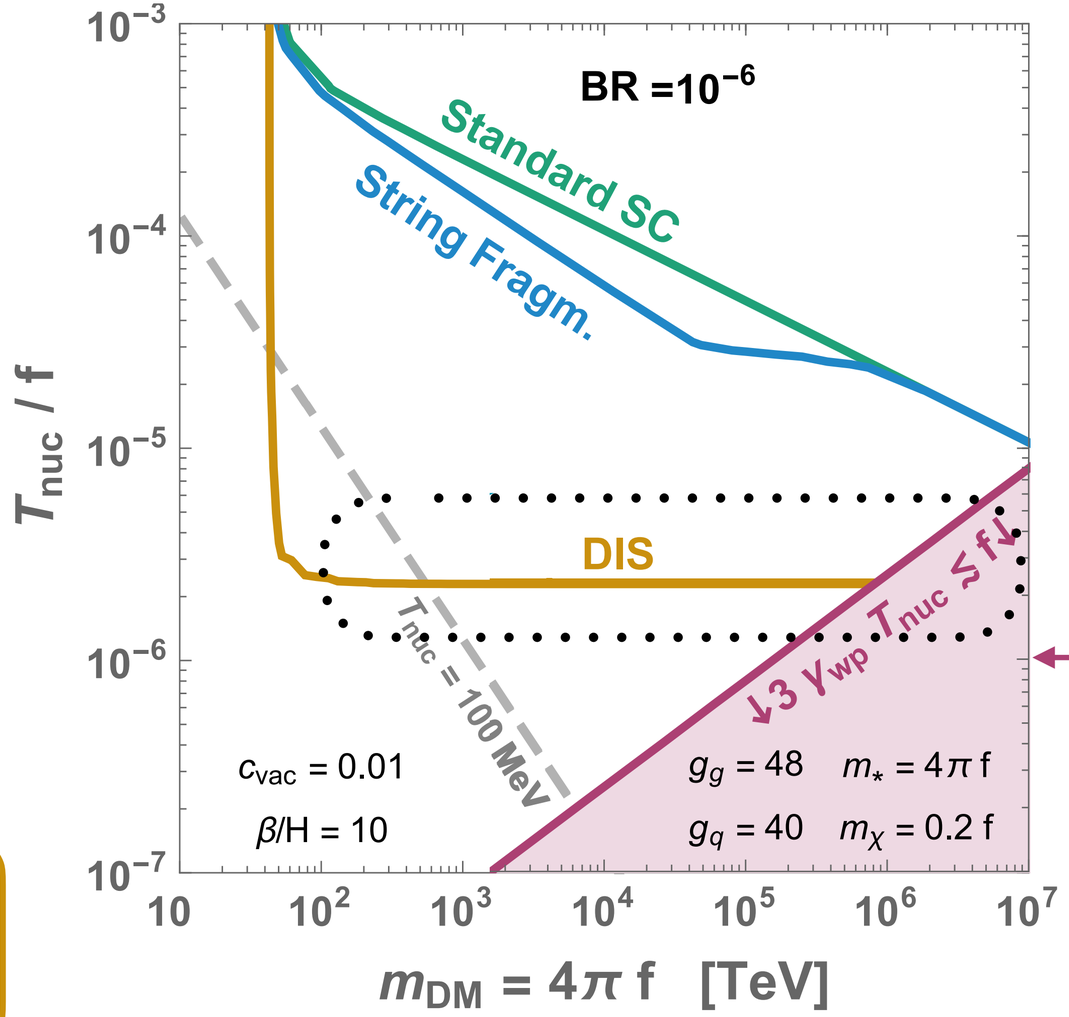
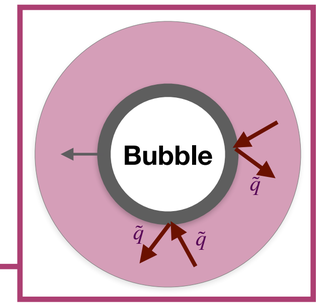
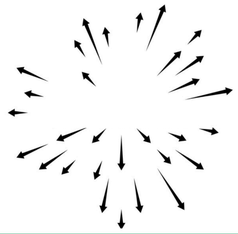


Quarks can not enter

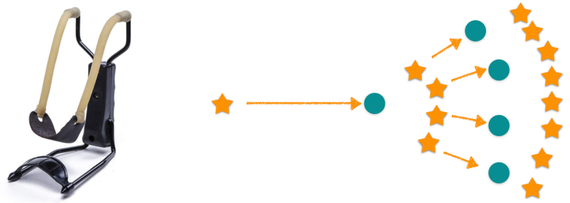


Consequences on DM abundance

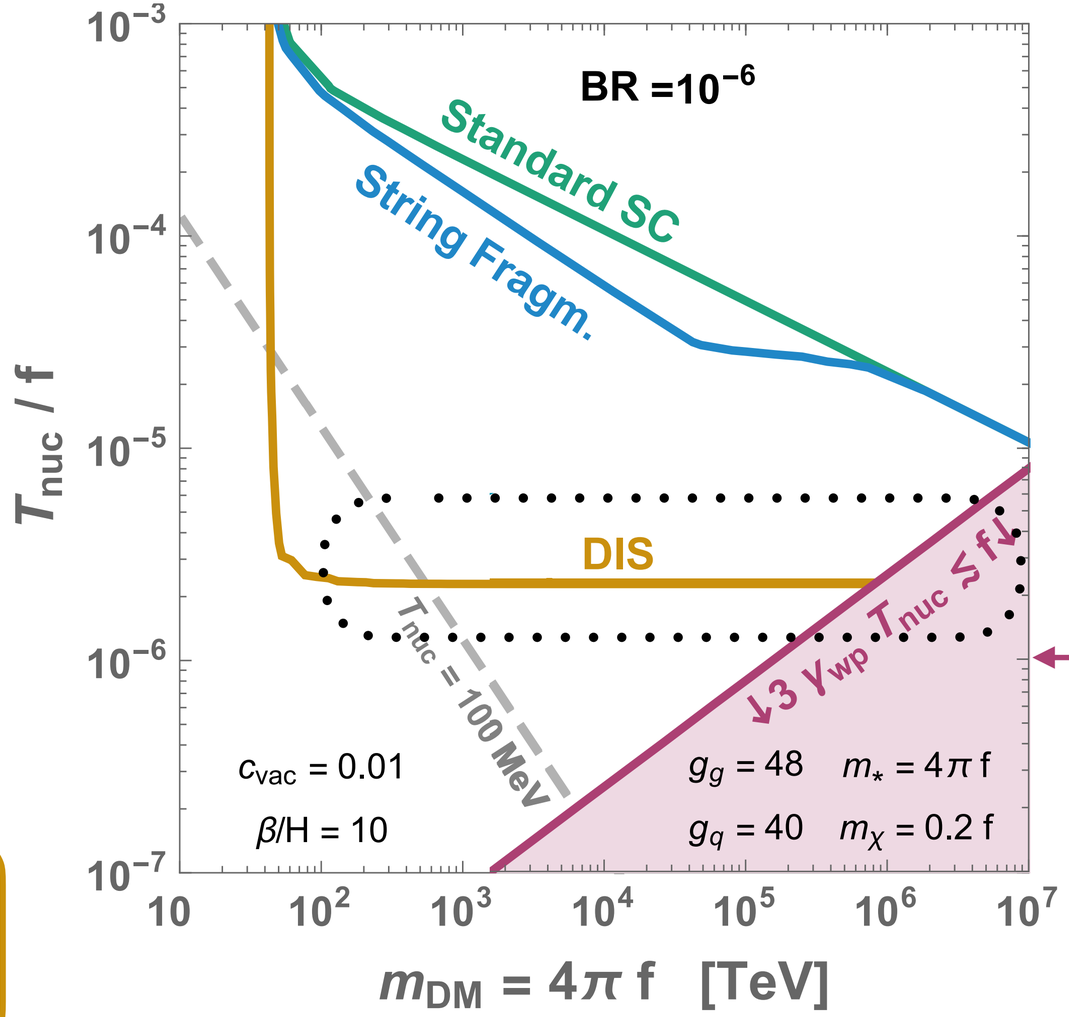


$$Y_{\rm DM}^{\rm naive} \propto \left(\frac{T_{\rm nuc}}{f}\right)^3$$

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



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



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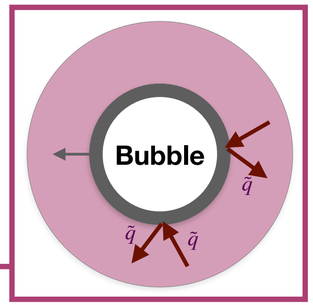
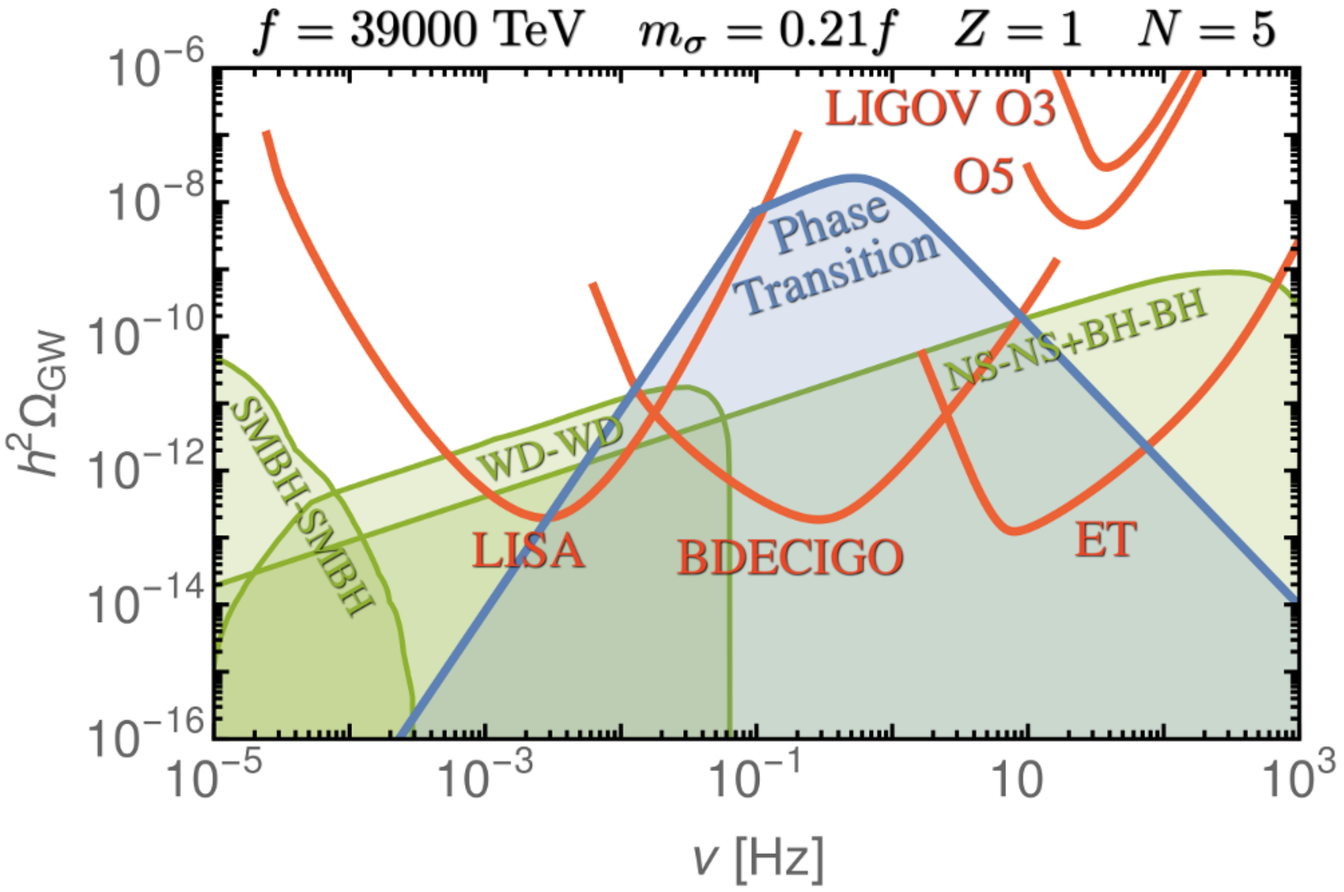


Supercool version of

Asadi, Kramer, Kuflik, Ridgway, Slatyer, Smirnov 21

Squeeze-out DM

Gravitational waves signature



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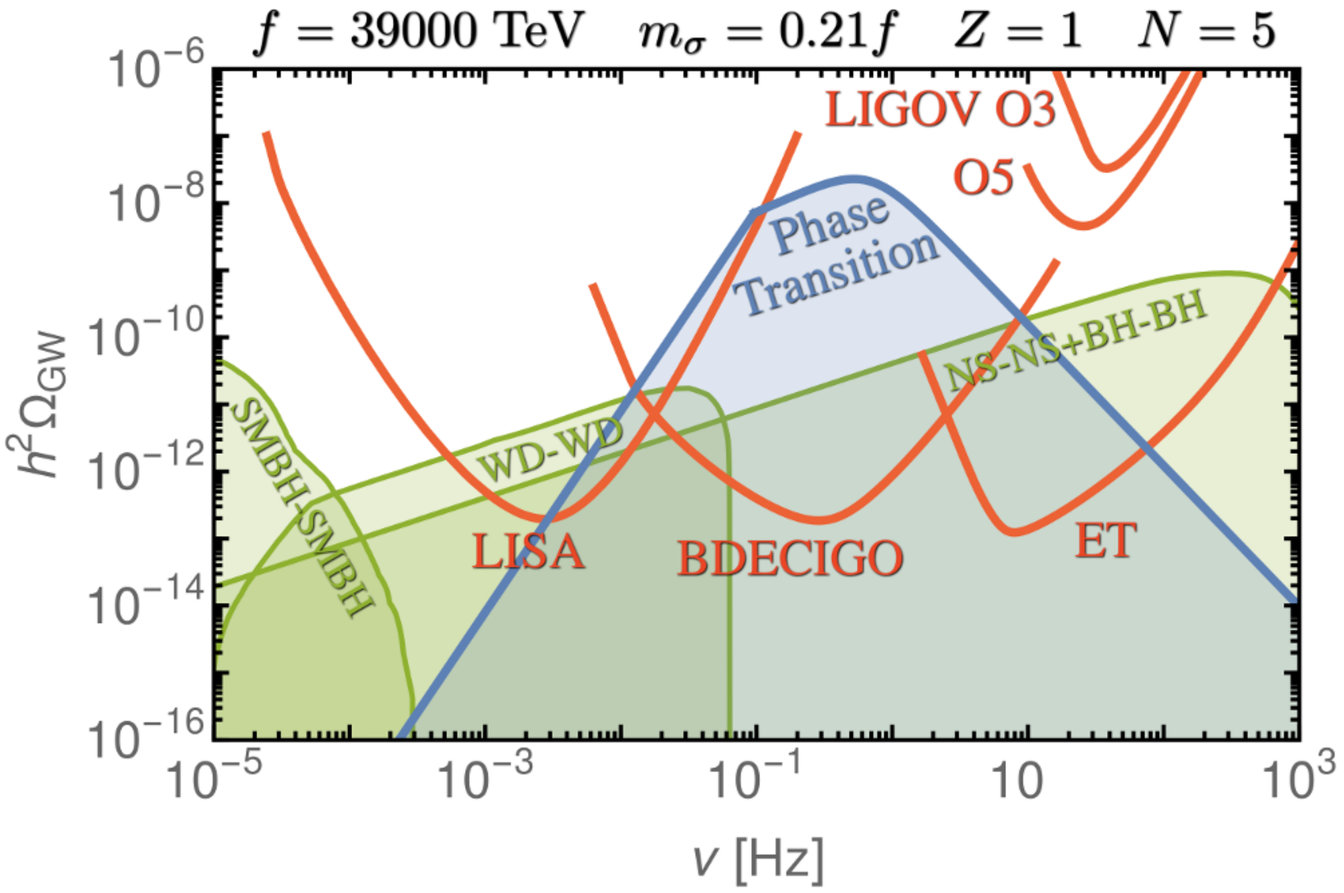

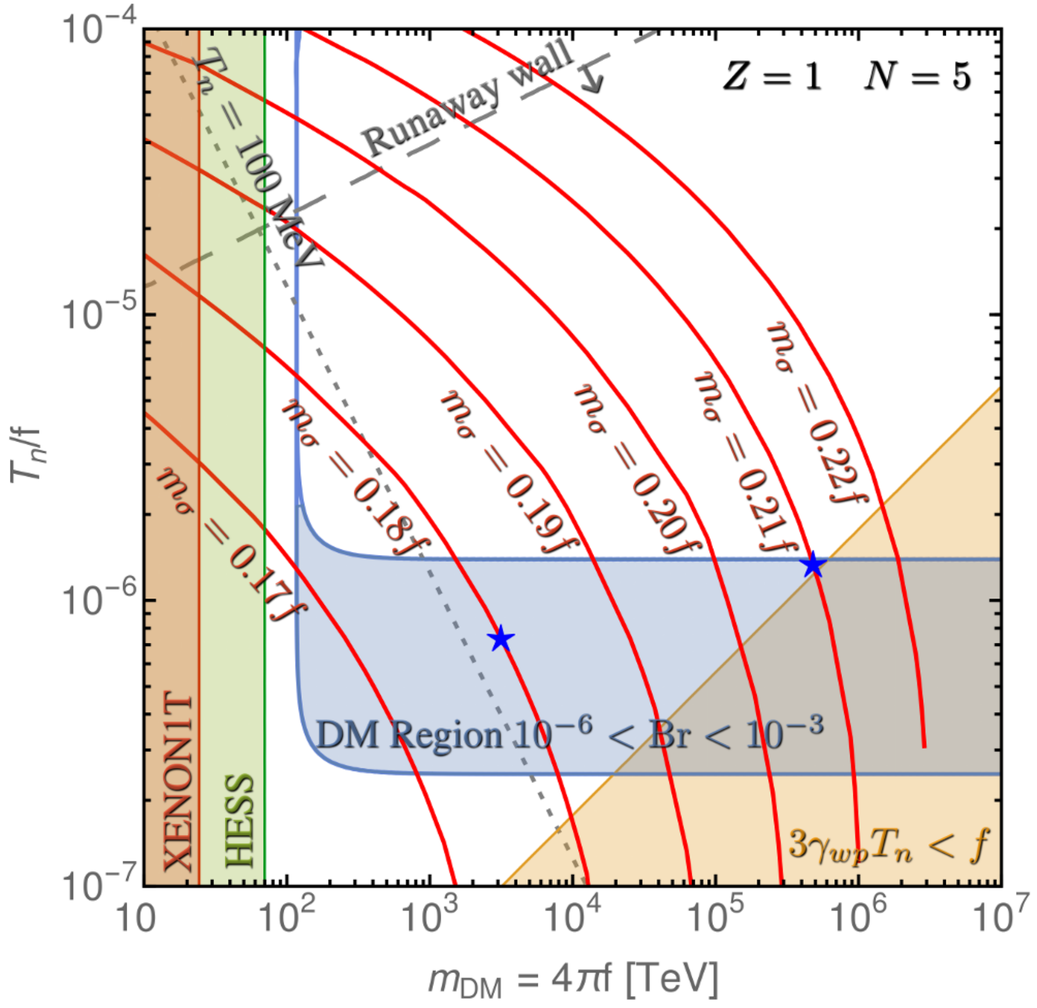

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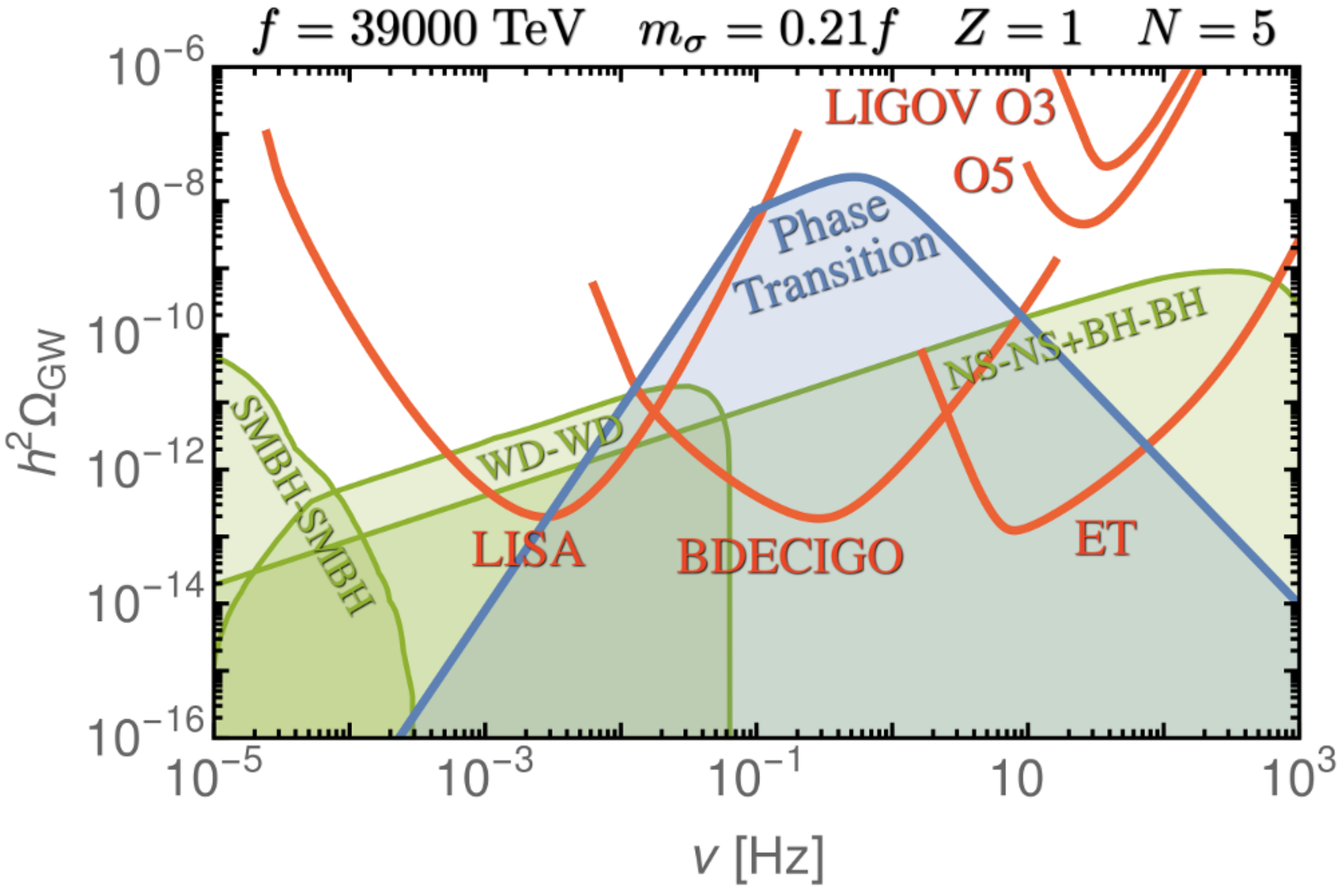

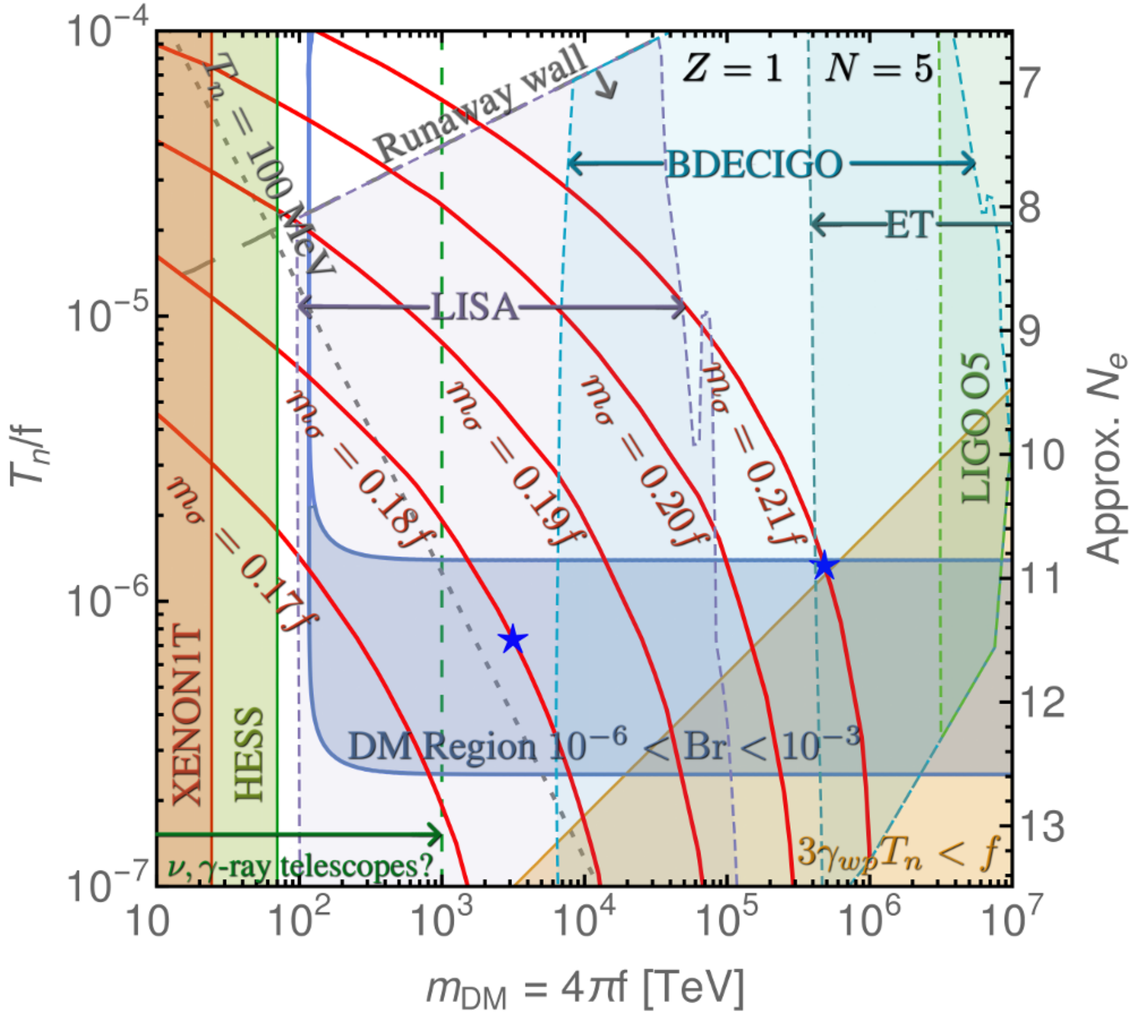

Conclusion

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Supercooled confinement:

Flux tubes dynamics at the wall boundary produce a lot of particles (e.g. Dark Matter)

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Other consequences of supercooling:

1. **Other particle production:**
   - i) **Off-shell decay**
   - ii) **Unruh radiation**

Conclusion

Supercooled confinement:

Flux tubes dynamics at the wall boundary produce a lot of particles (e.g. Dark Matter)

Other consequences of supercooling:

1. **Other particle production:**
   - i) **Off-shell decay**
   - ii) **Unruh radiation**
2. **Black hole formation**

For more details on supercooled phase transitions

-> Chap 6.4 of Beyond the Standard Model Cocktail

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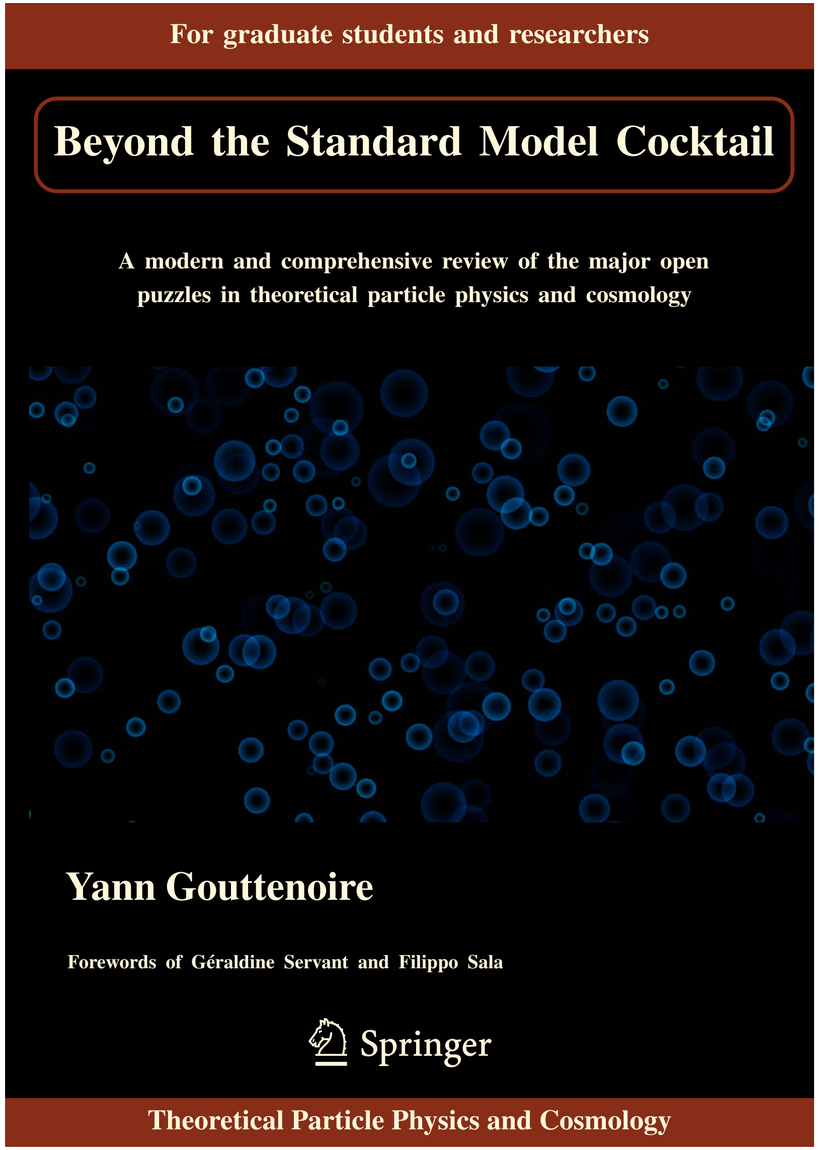

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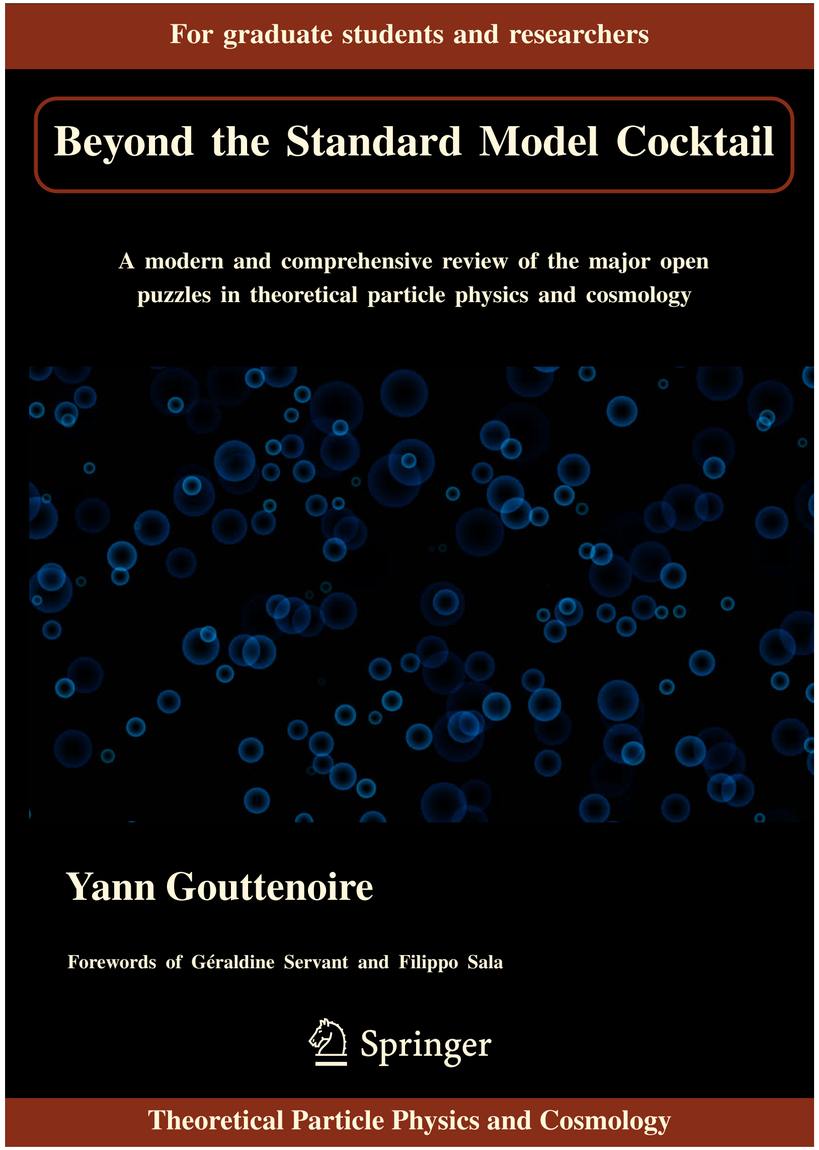

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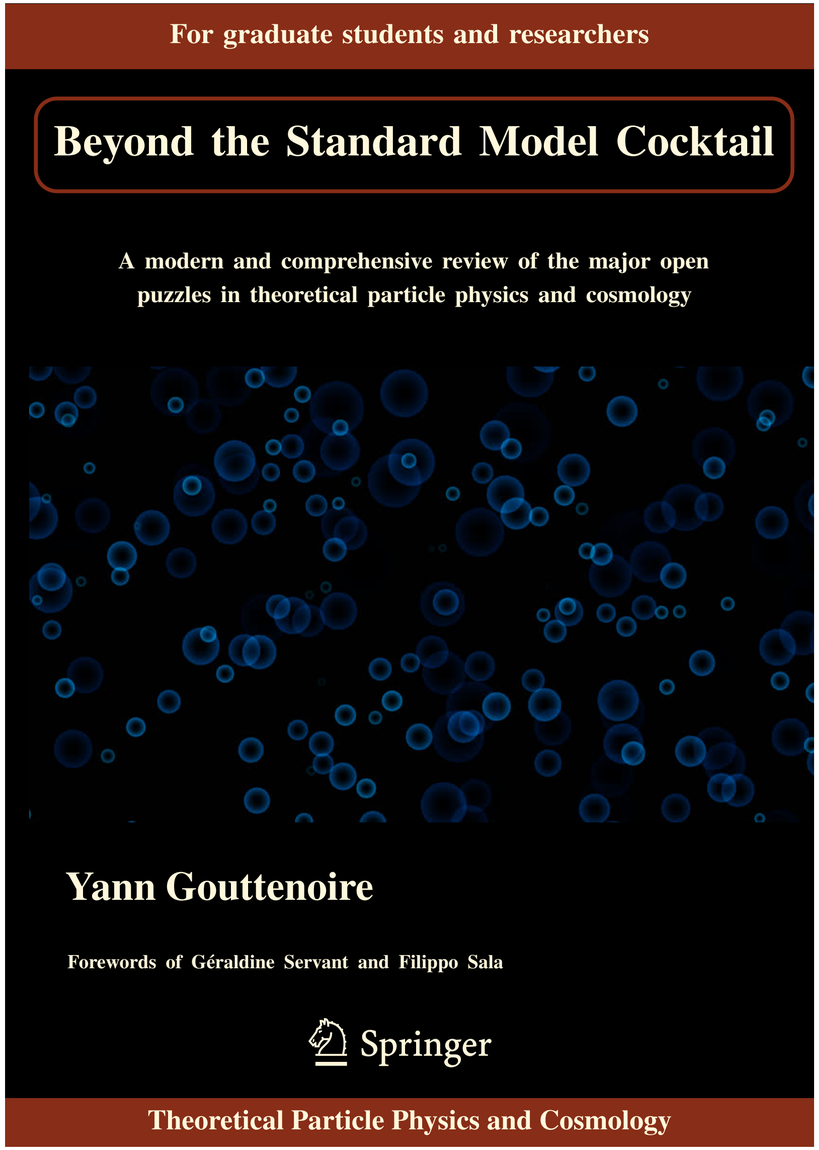

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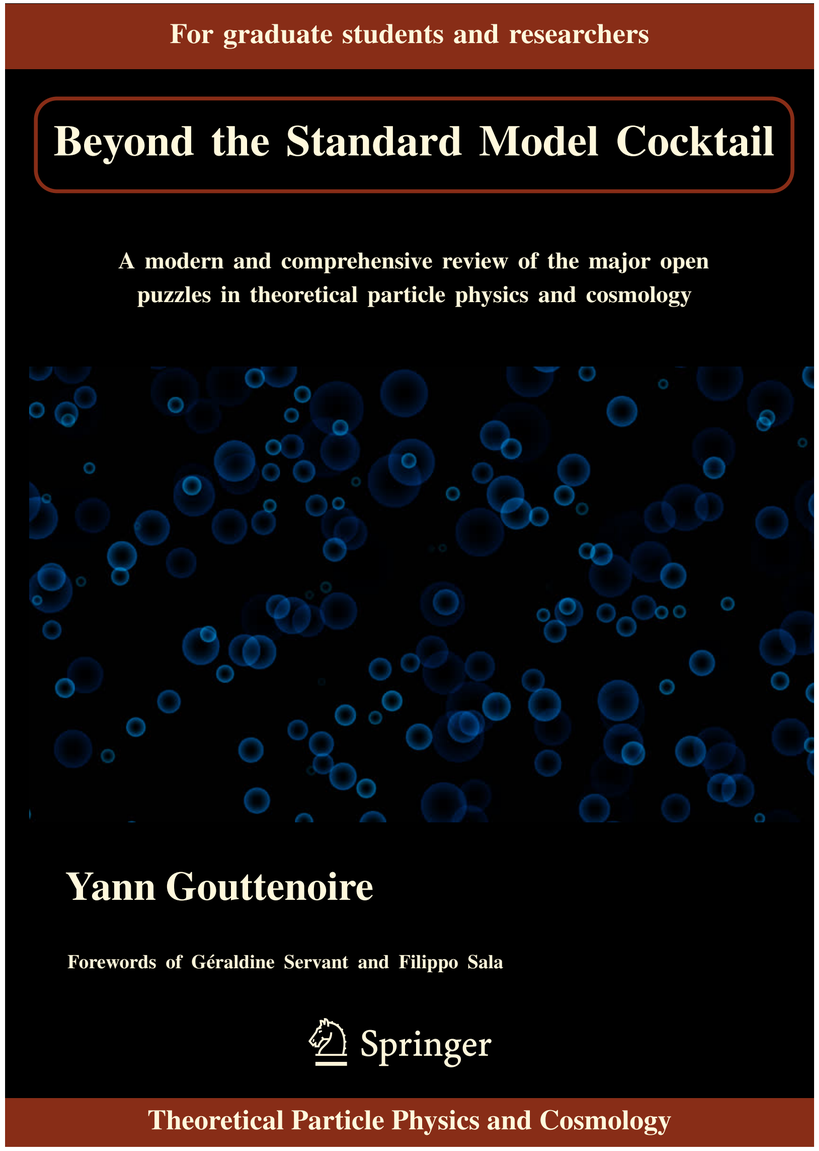

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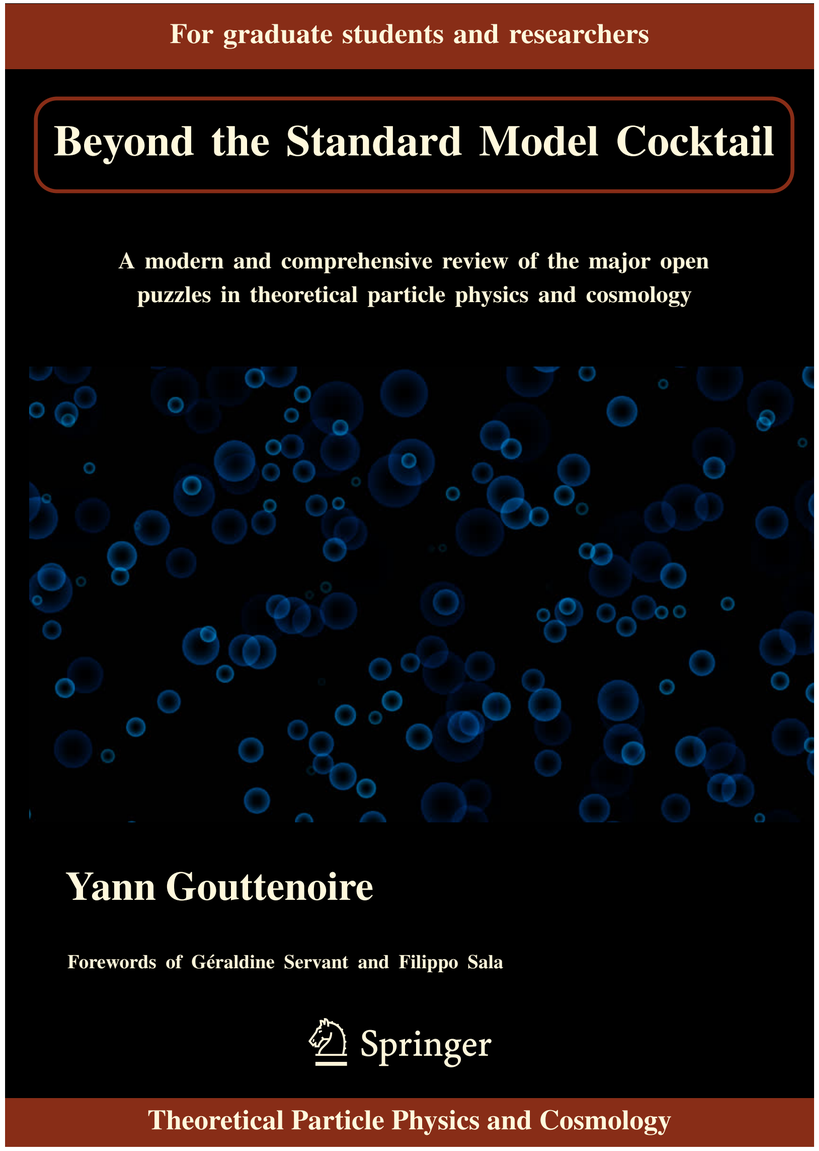

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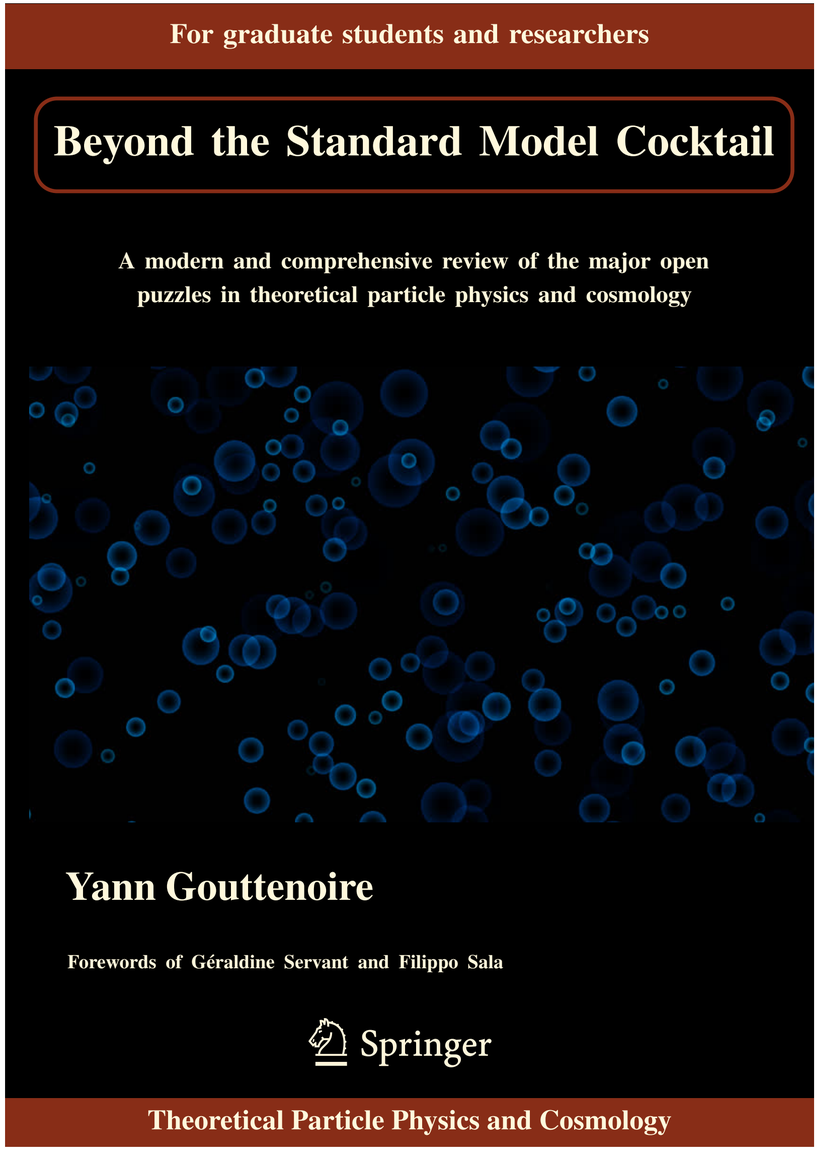

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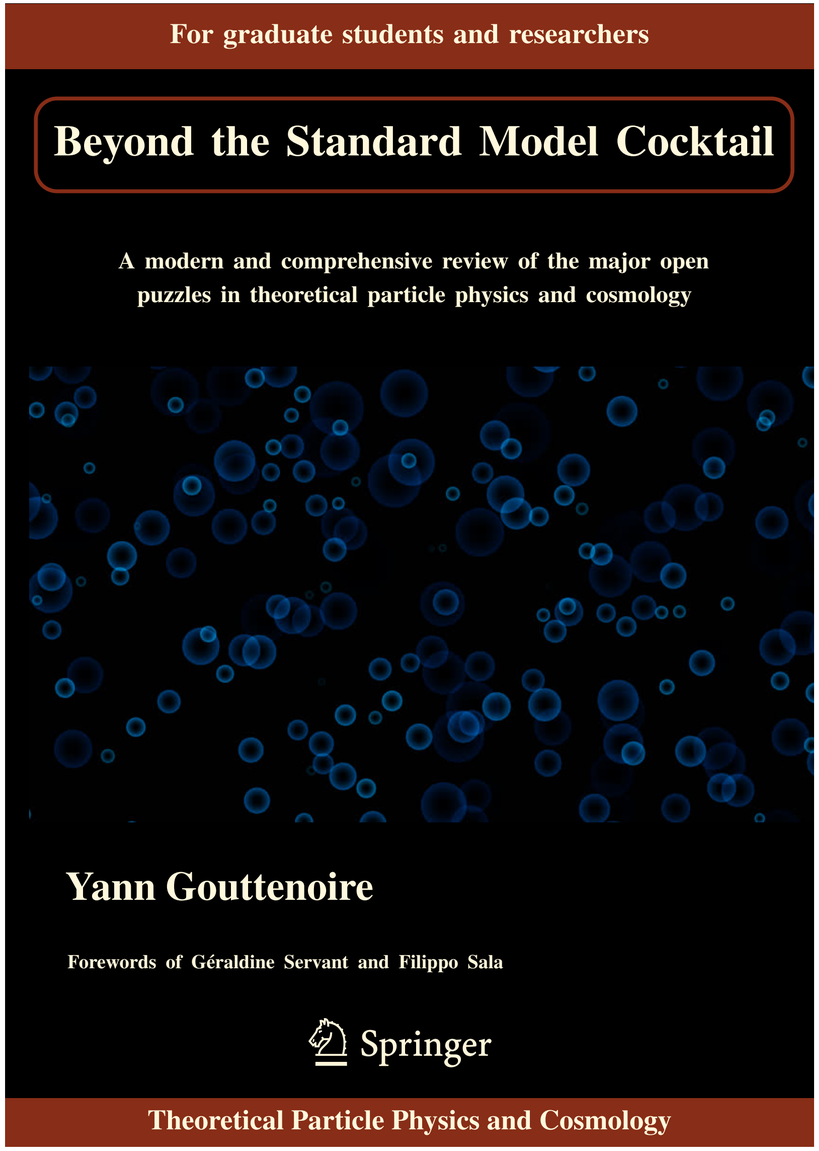

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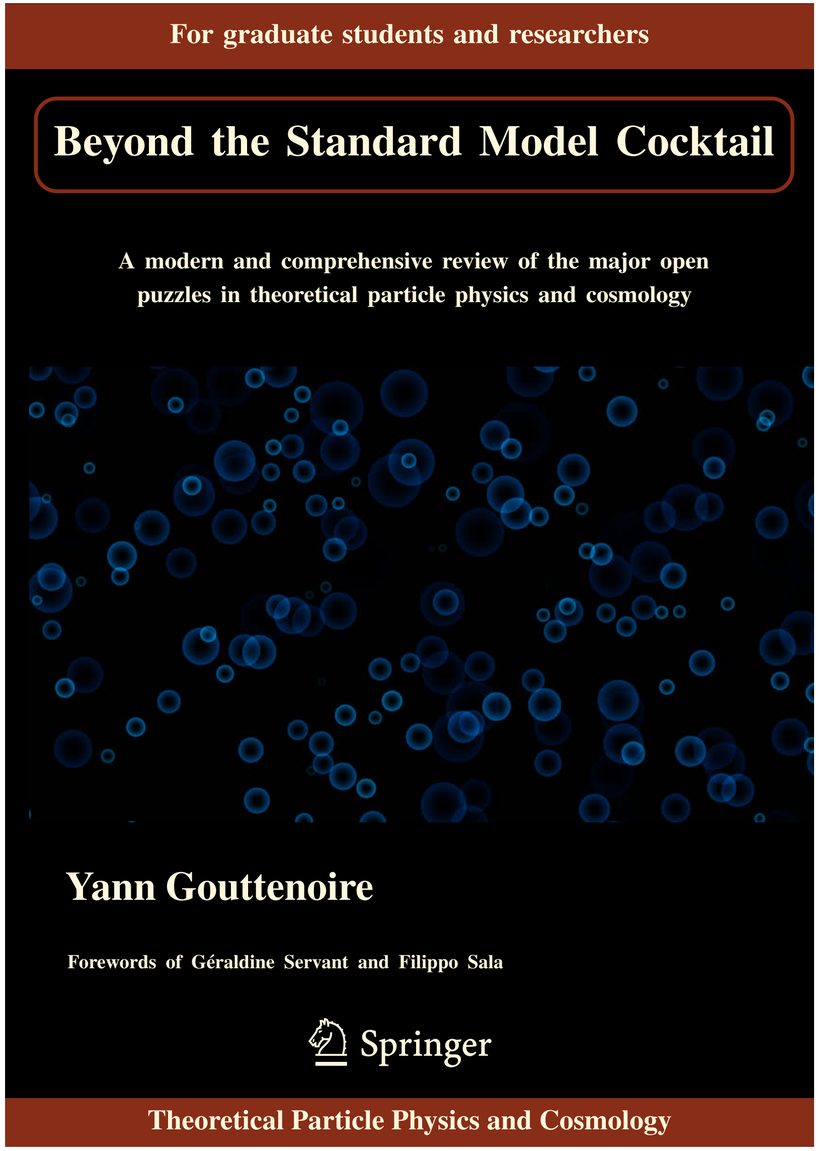

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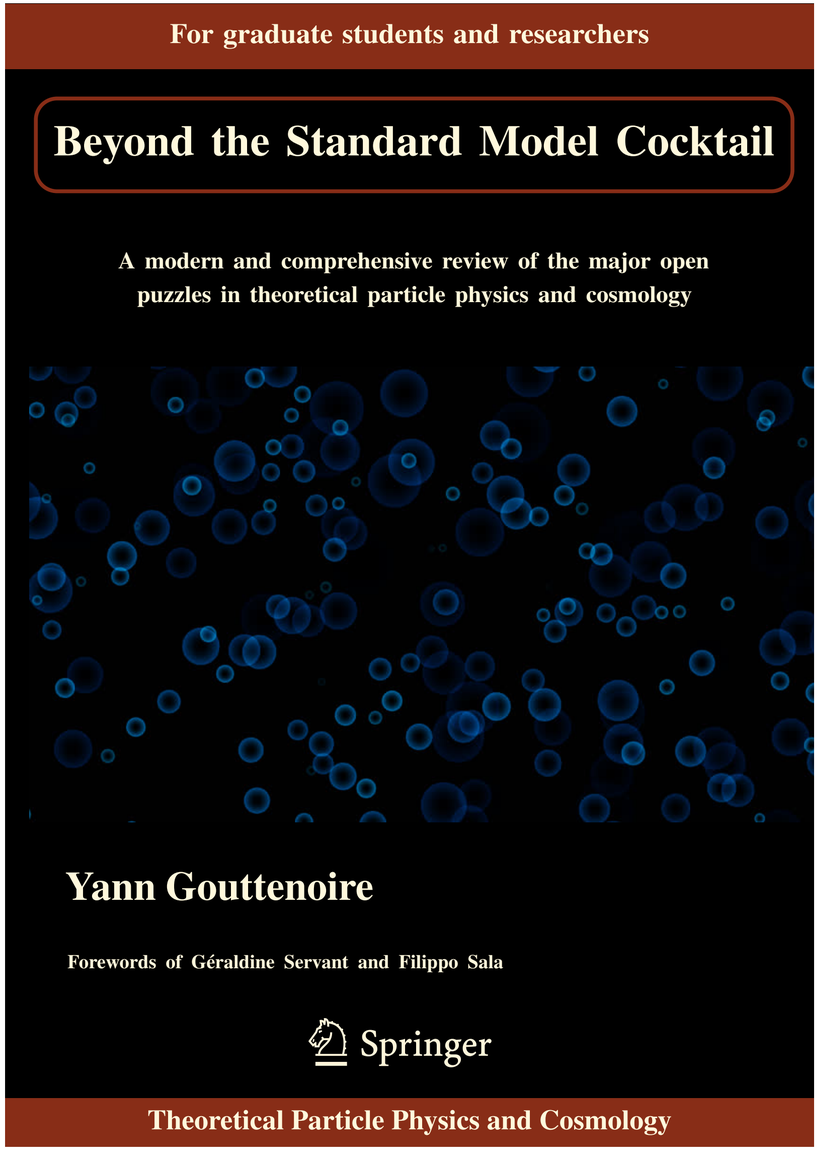
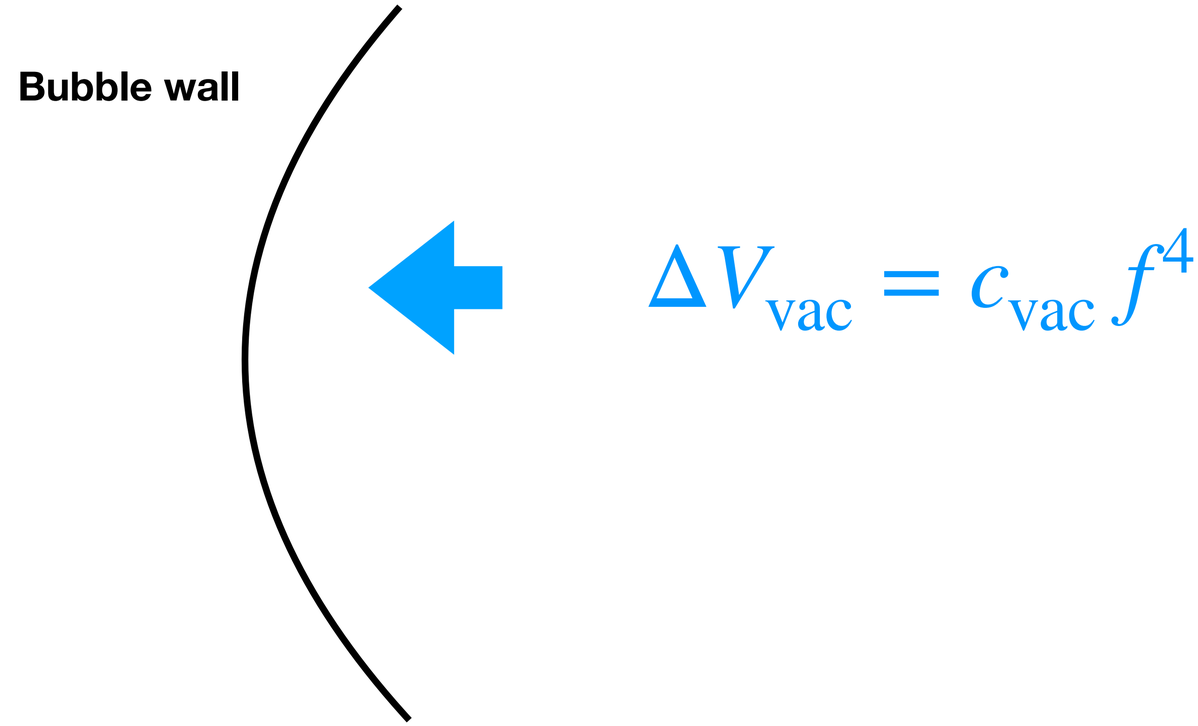


Additional slides

Consequences on bubble wall velocity



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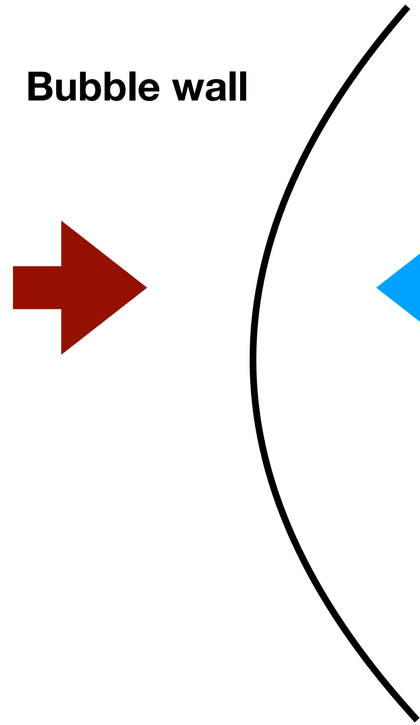
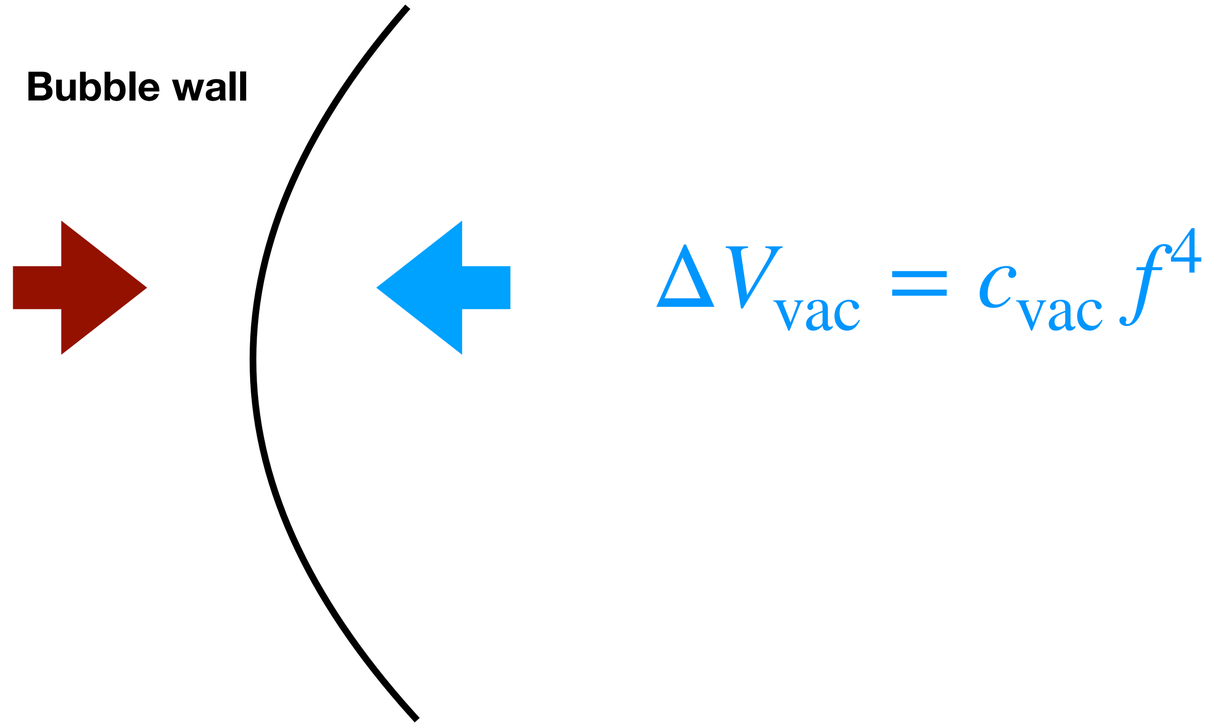


$$\mathscr{P}_{\text{friction}} \simeq \gamma T_{\text{nuc}}^3 \times \Delta p$$

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

Consequences on bubble wall velocity



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

$$\Delta p = ?$$

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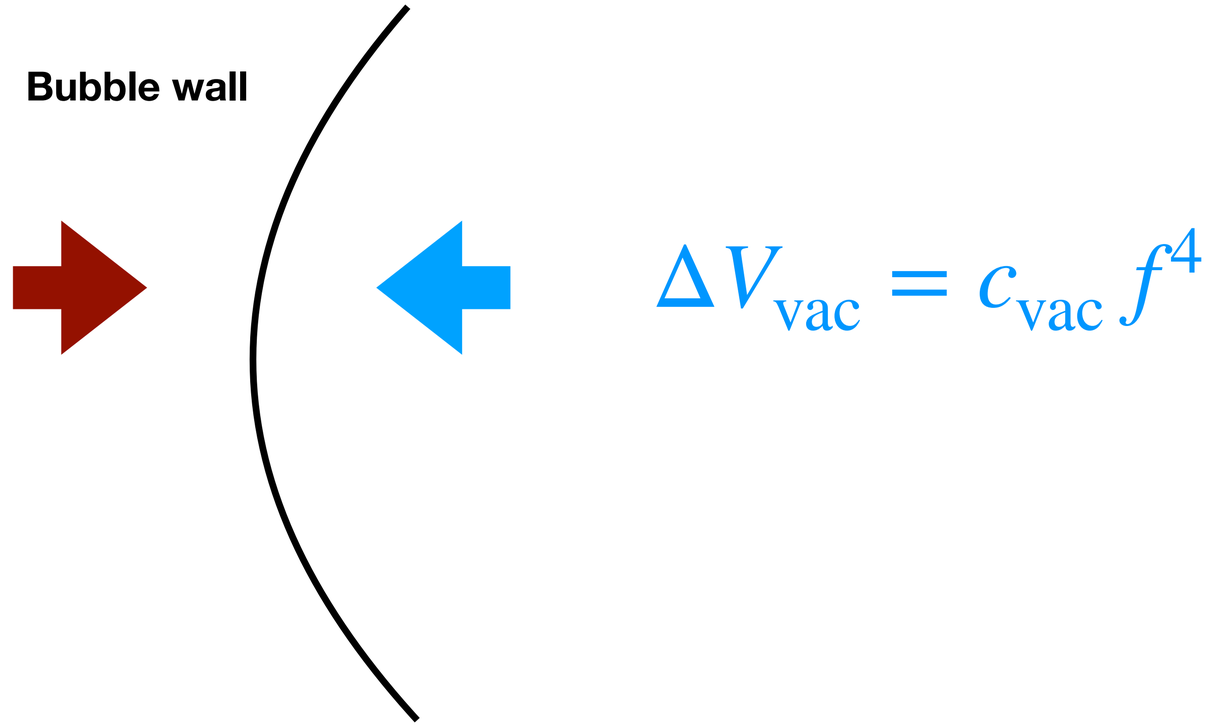
Consequences on bubble wall velocity



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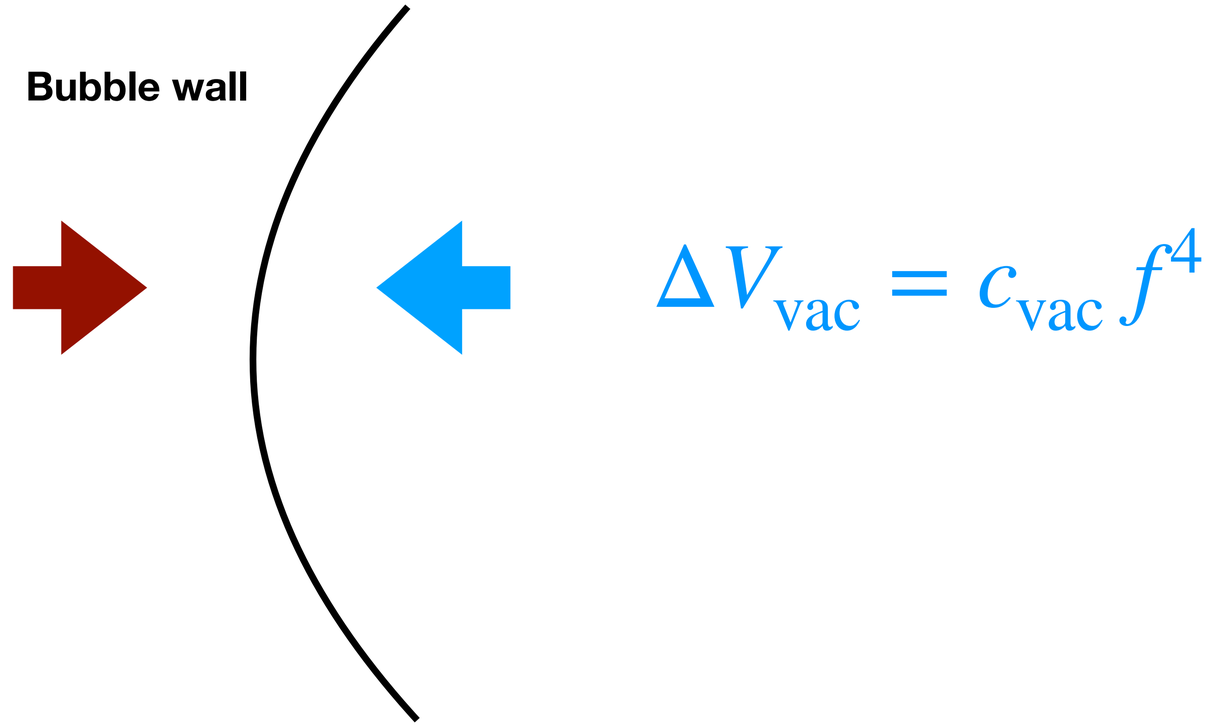
Weakly-coupled PT

Consequences on bubble wall velocity



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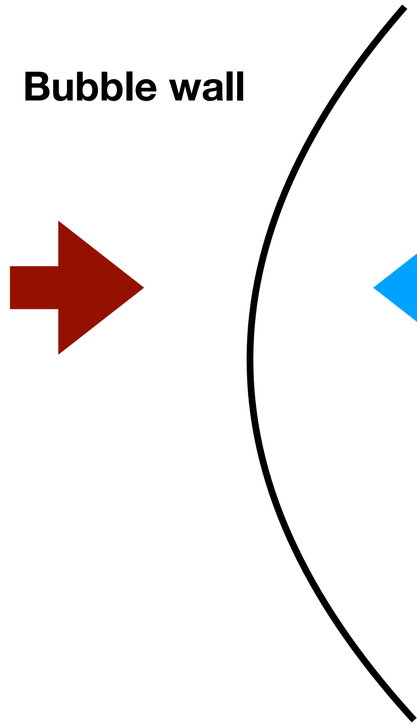
Weakly-coupled PT

Bodeker&Moore (09' and 17')

Azatov+ 20'

Consequences on bubble wall velocity



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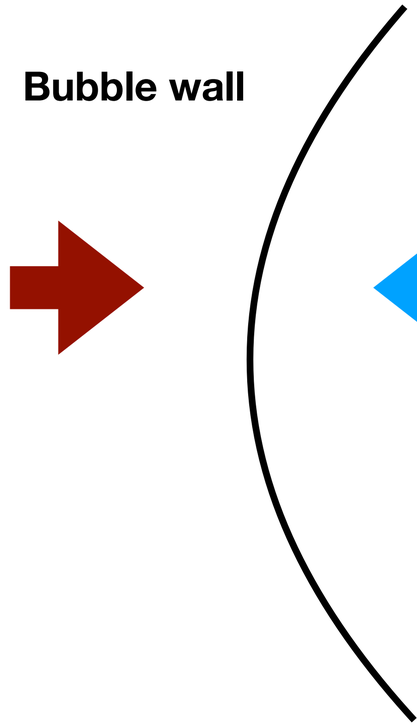
$$\mathscr{P}_{\rm LO} \simeq \Delta m^2 T_{\rm nuc}^2$$

Consequences on bubble wall velocity



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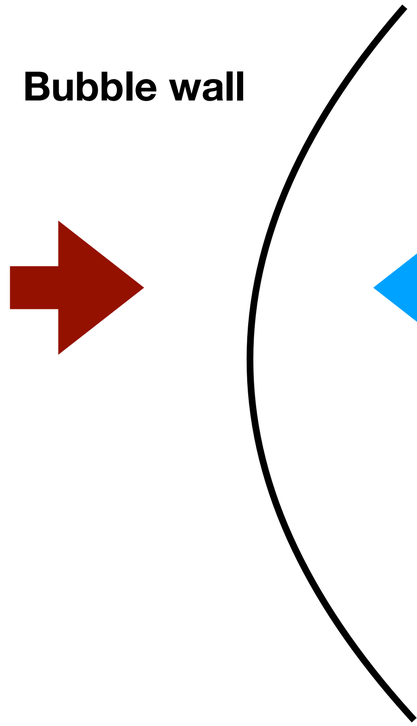
$$\mathscr{P}_{\rm LO} \simeq \Delta m^2 T_{\rm nuc}^2 \qquad \mathscr{P}_{\rm NLO} \simeq g_{\rm w} \gamma \, \Delta m T_{\rm nuc}^3$$

Consequences on bubble wall velocity



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Strongly-coupled PT

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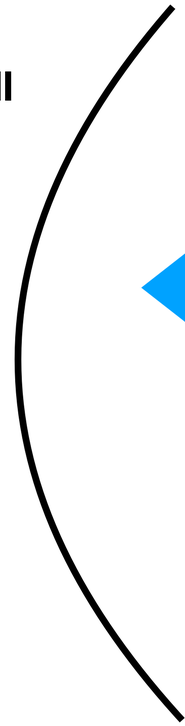

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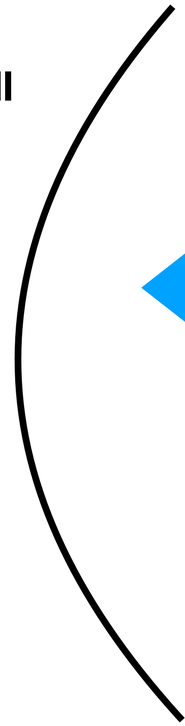
Strongly-coupled PT

Hoeche, Kozaczuk, Long, Turner, Wang 20'

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

Consequences on bubble wall velocity



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

Baldes, YG, Sala 20'

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

Consequences on bubble wall velocity

Bubble wall

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

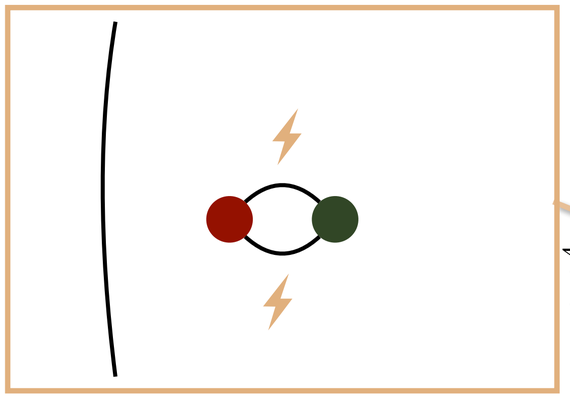
Baldes, YG, Sala 20'

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

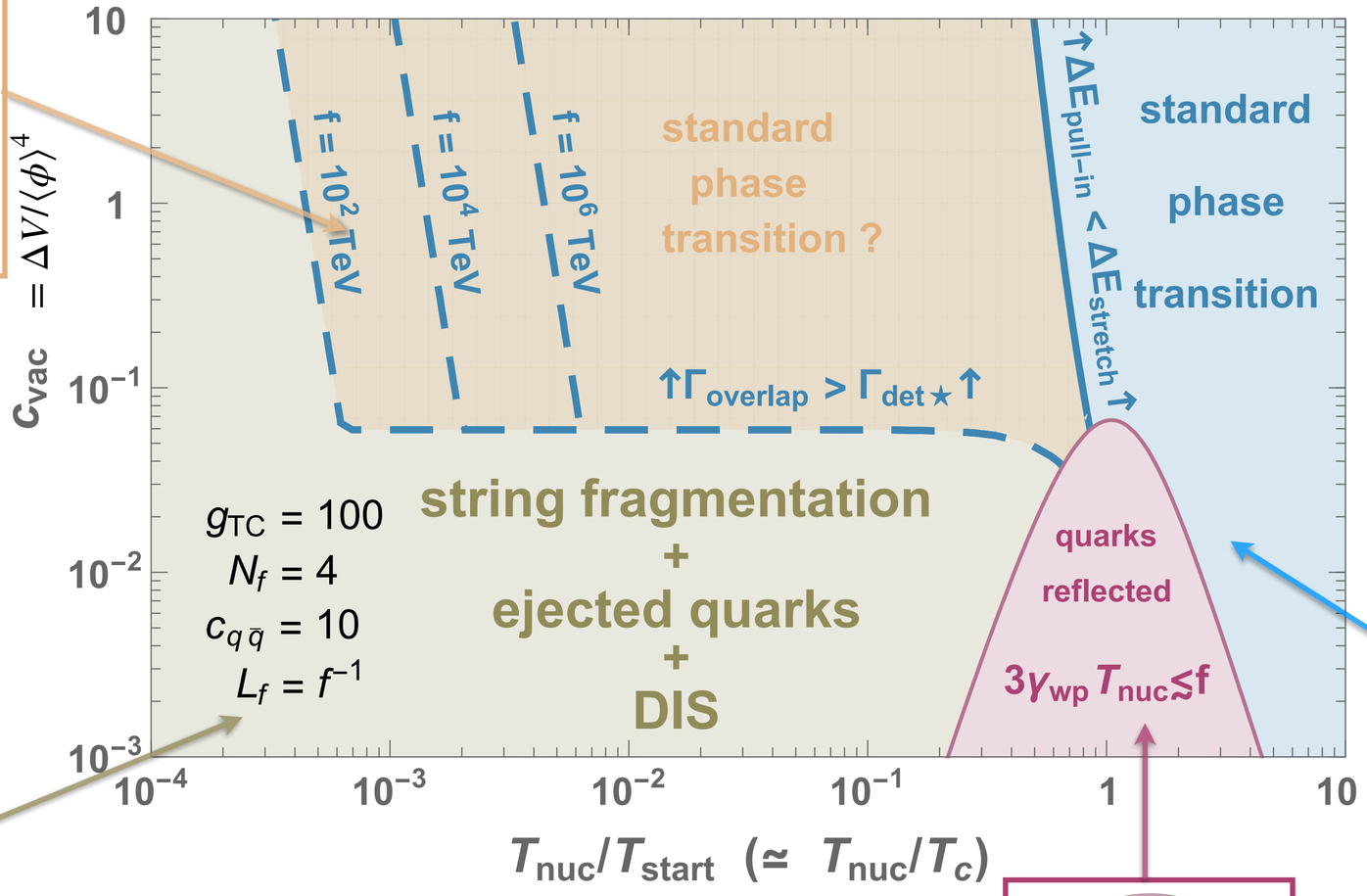
YG, Jinno, Sala 21'

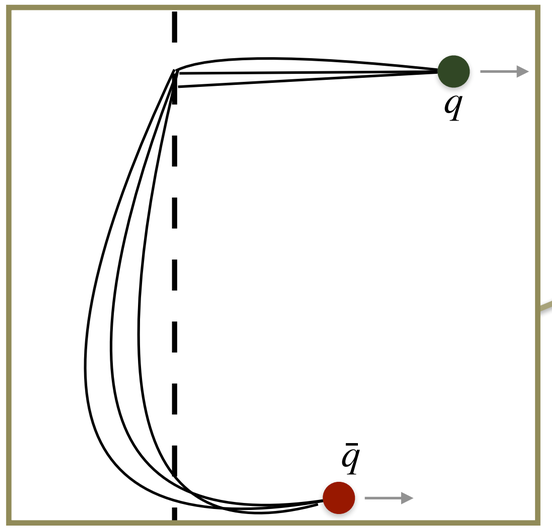
$$\mathscr{P}_{\rm all-order} \simeq \gamma f T_{\rm nuc}^3$$

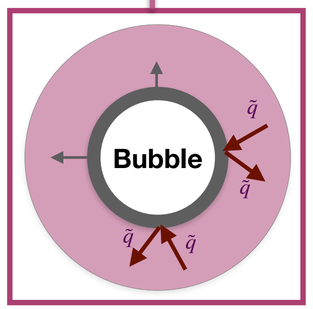
How much supercooling is needed ?



quark-string interaction win



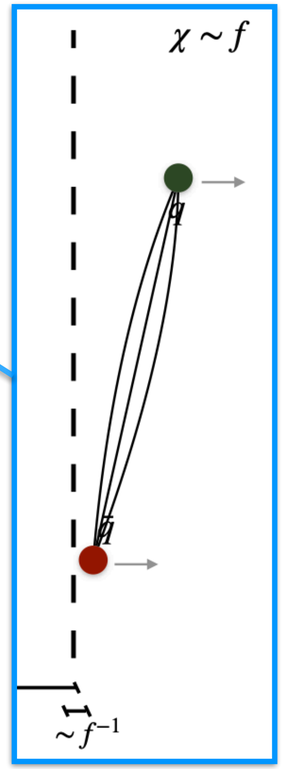




Snow ball effect

Ping-pong effect

No line distortion



Quark nuggets Witten 1984

Filtered DM. 1912.02830

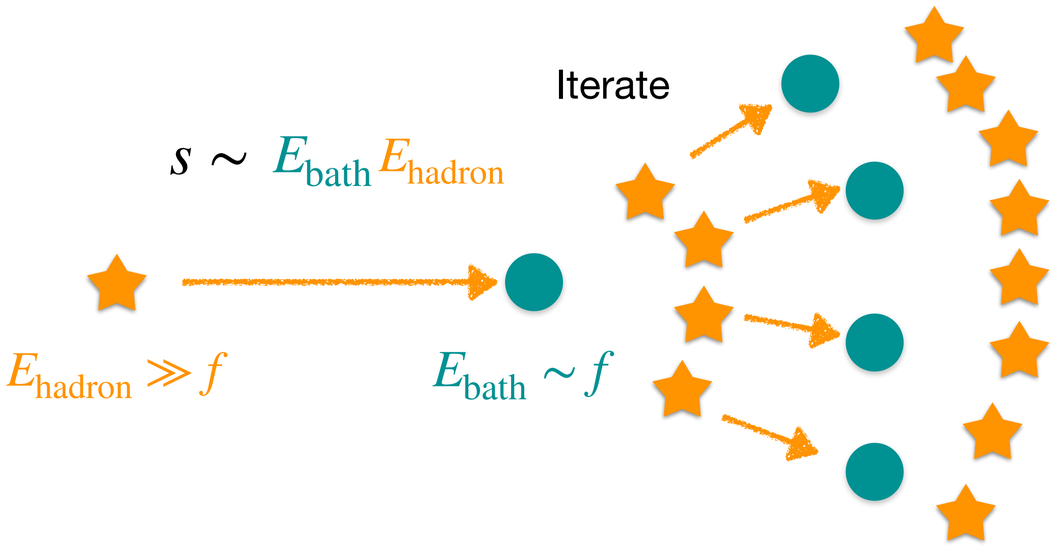
Thermal Squeezeout of DM. 2103.09827

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 $E_{\rm bath} \sim f$



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

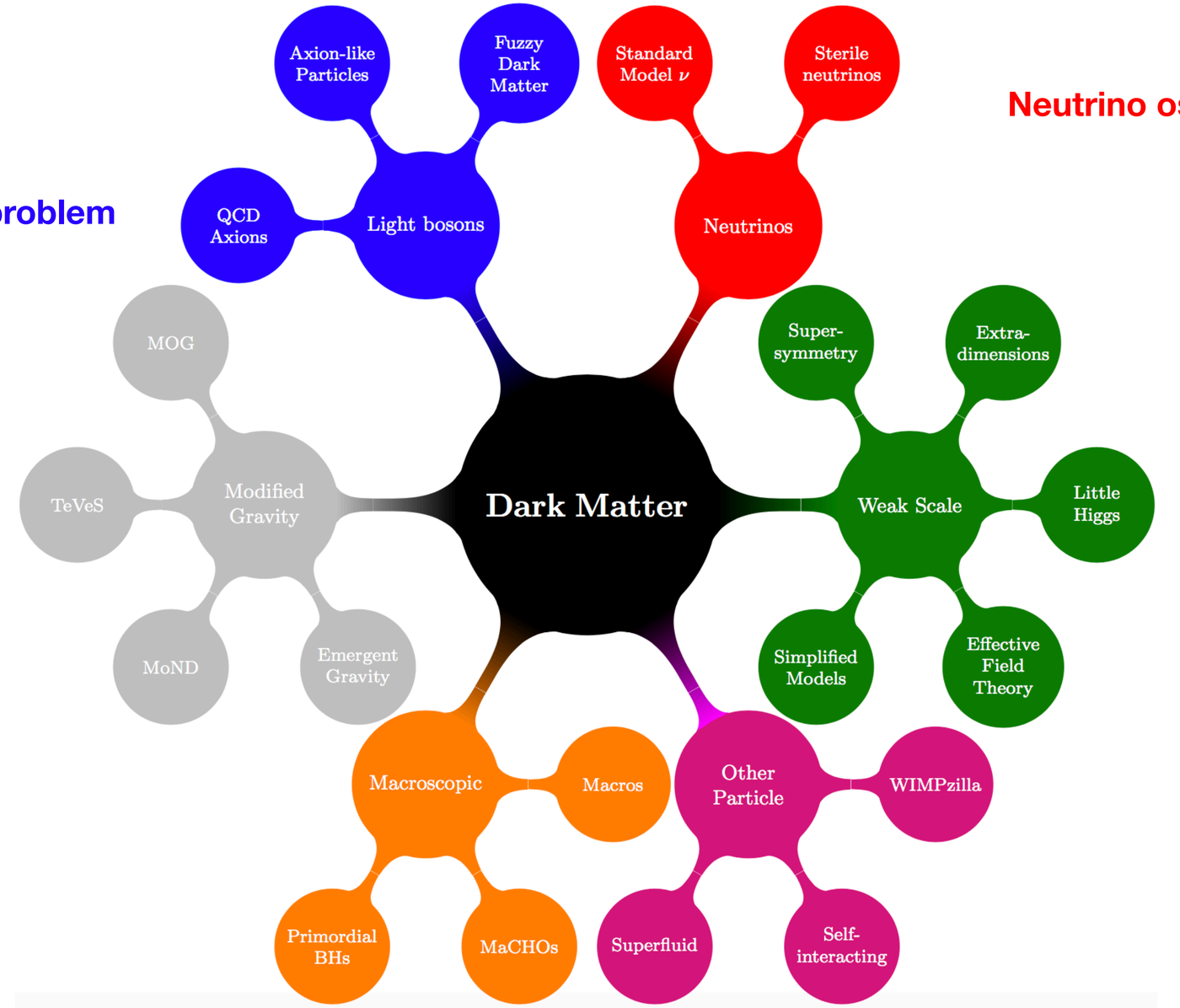
$$\gamma_{\rm cp} \simeq \frac{\gamma_{\rm wp}}{\gamma_{\rm wc}} \qquad \gamma_{\rm wc} \simeq \frac{E^{q\bar{q}}_{\rm cm}}{f} \simeq \sqrt{\gamma_{\rm wp}\frac{T_{\rm nuc}}{f}}$$

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

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

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

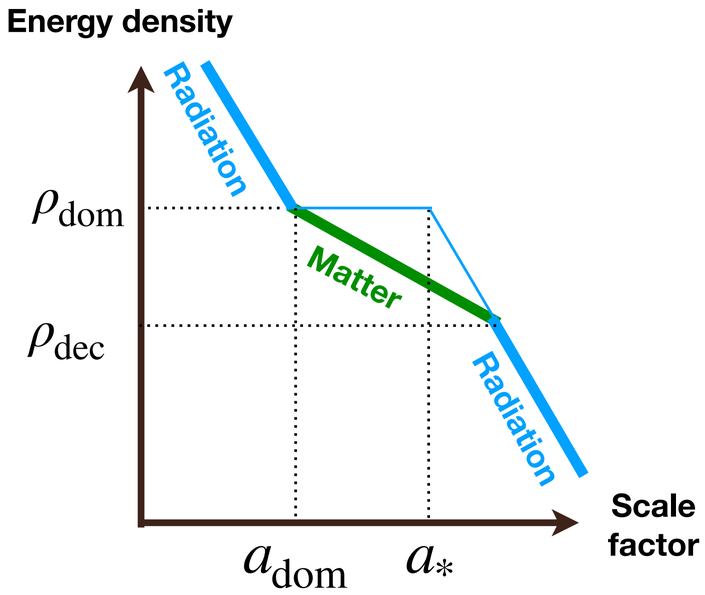
$$M_{\rm DM} \sim 1 \text{ TeV}, \qquad \alpha \sim \alpha_{\rm weak}$$

2) Thermal Dark Matter

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

Entropy injection

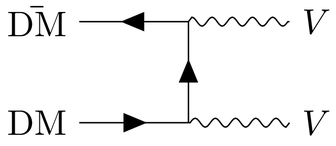
1) After a matter era

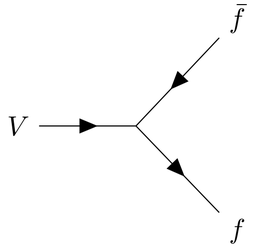


$$D = \left(\frac{a_{\rm dom}}{a_*}\right)^3 = \frac{T_{\rm dom}}{T_{\rm dec}} \simeq \frac{m_V}{\sqrt{M_{\rm pl}\,\Gamma_V}}$$

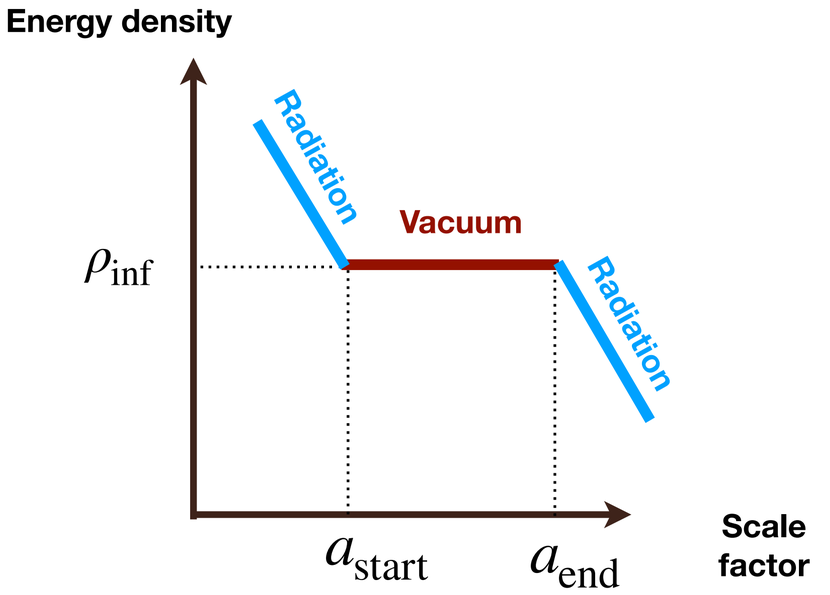
Homeopathic DM

Cirelli, Gouttenoire, Petraki, Sala, 2018





2) After an inflationary era



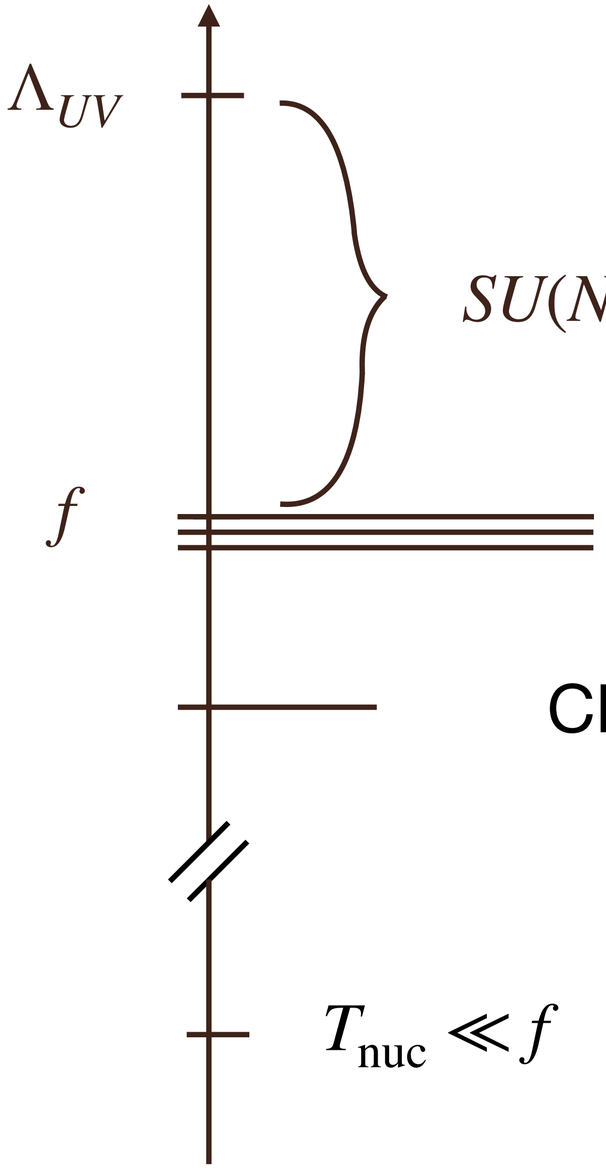
$$D = \left(\frac{a_{\rm end}}{a_{\rm start}}\right)^3 = e^{3\,N_e} = \left(\frac{f}{T_{\rm nuc}}\right)^3$$

Supercooled confinement

Baldes, Gouttenoire, Sala, 2020

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

Nearly-conformal strong sector



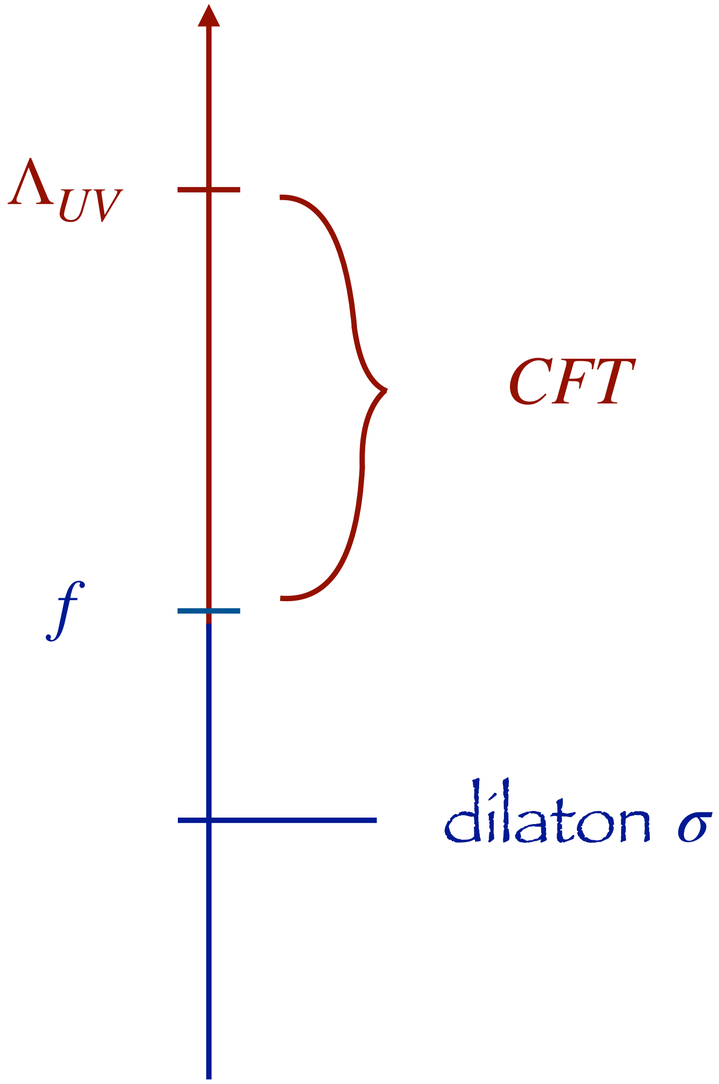
Composite states $\supset DM$

CFT/Poincaré: dilaton σ - pNGB

SUPERCOOLING

$T_{\rm nuc} \ll f$ Transition delayed is small dilaton mass

Nearly-conformal strong sector



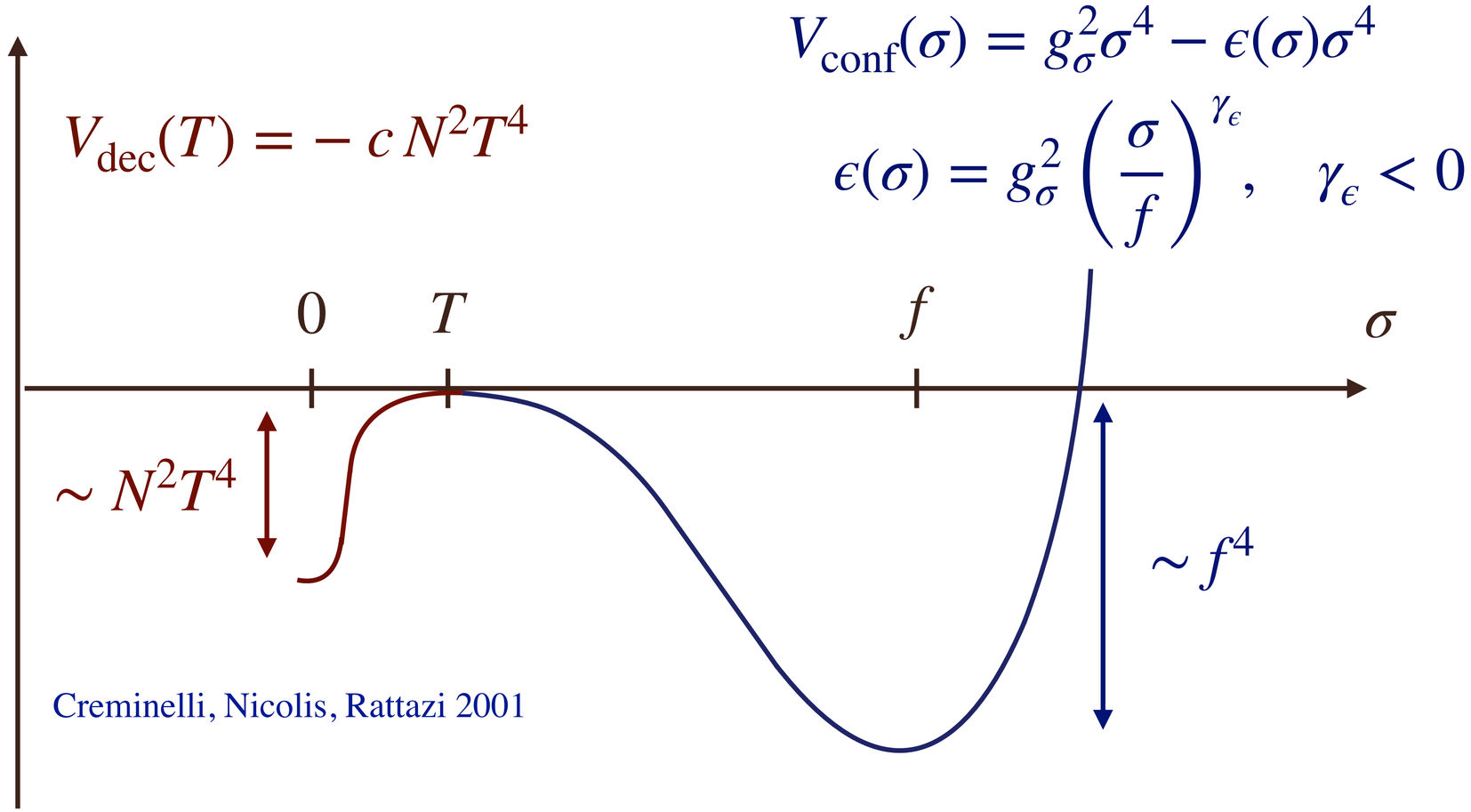
Deconfined phase

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

Confined phase

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

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



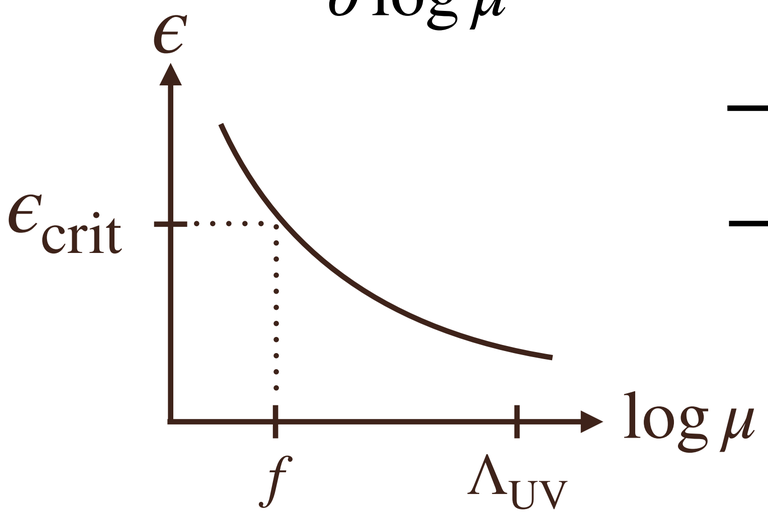
Super-cooling starts for: $T_{\rm start} \sim f$

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

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



→ 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 Supercool Phase Transition

Randall Servant hep-ph/0607158,…

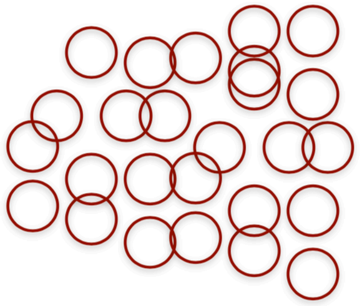
$$\Omega_{\rm GW} \propto \left(H/\beta\right) \times \left(H/\beta\right)$$

Bubble size × **Collision time**

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

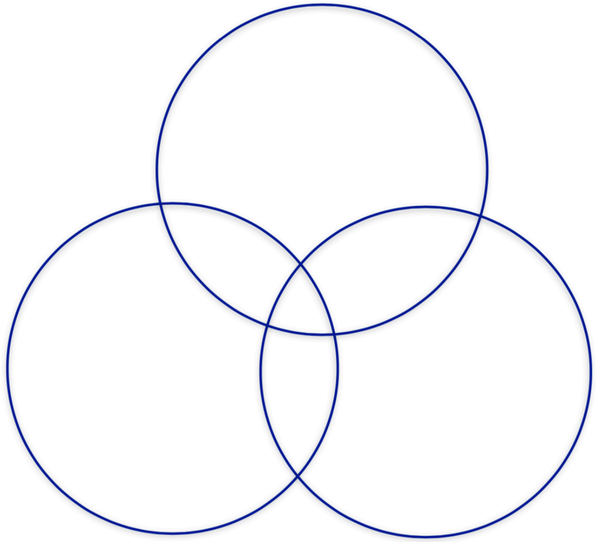
Standard 1st order PT

$\beta/H \sim 100$

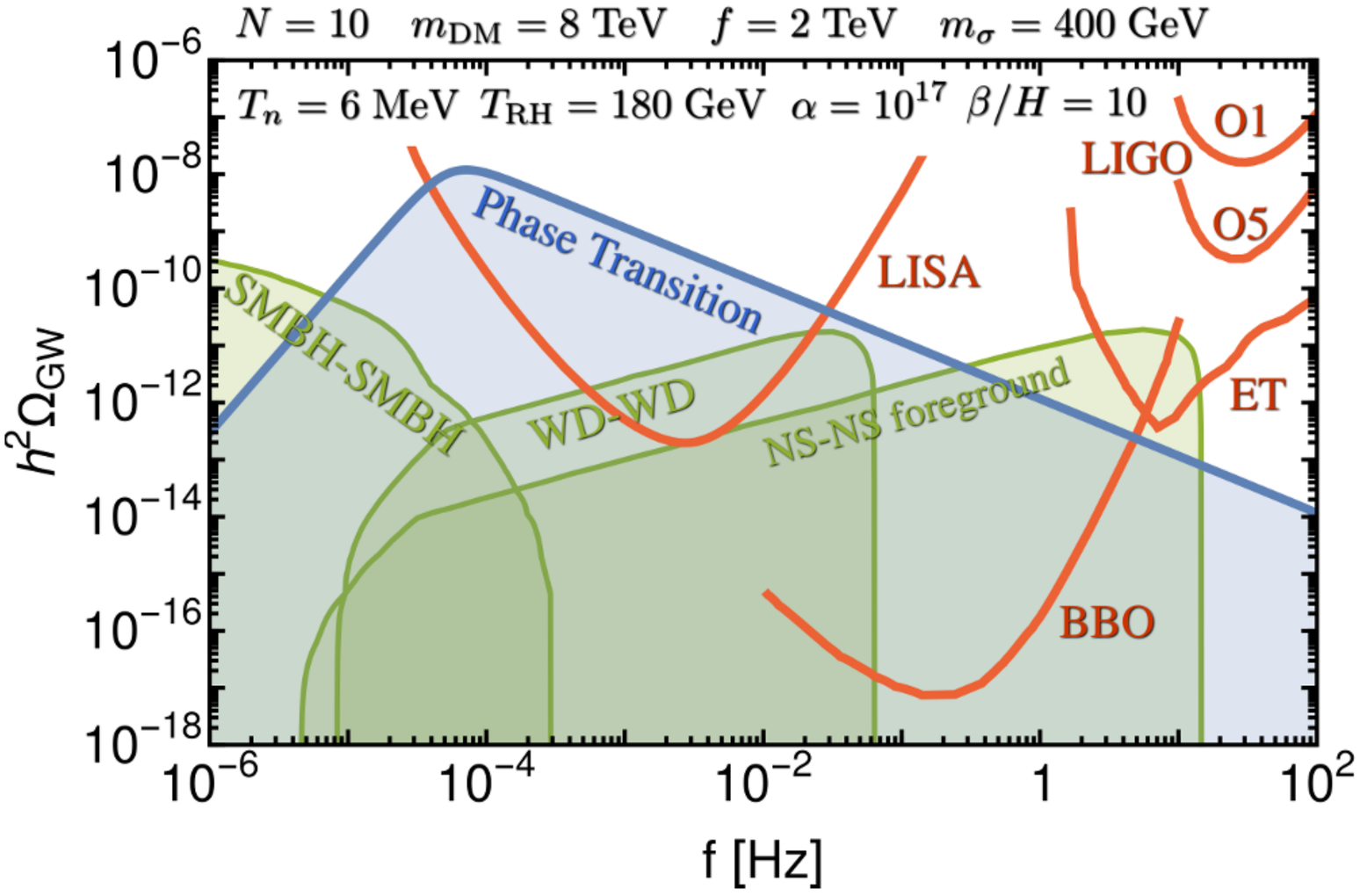


Supercooled PT

$\beta/H \sim 10$



Gravitational Waves from Phase Transition



Nucleation Temperature

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

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

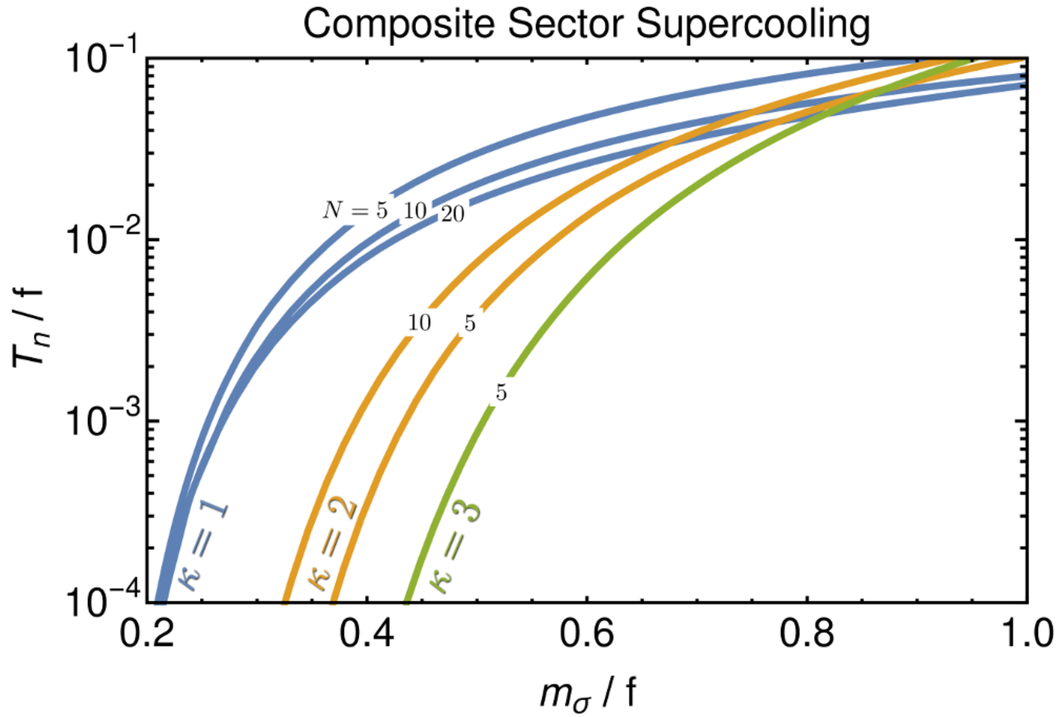
Nucleation happens when tunnelling rate ~ Hubble

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

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

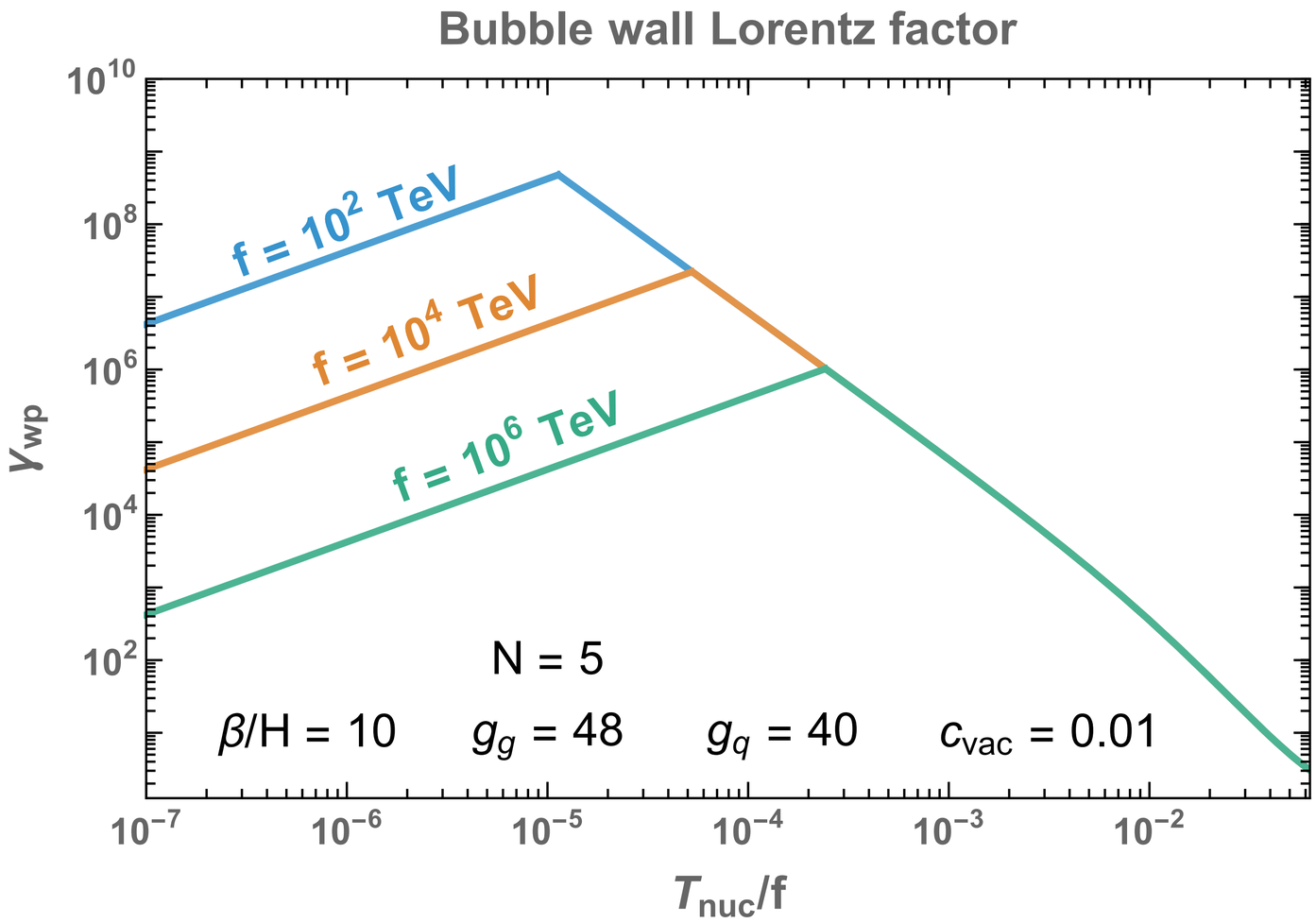
Iso Serpico Shimada 1704.04955

von Harling Servant 1711.11554

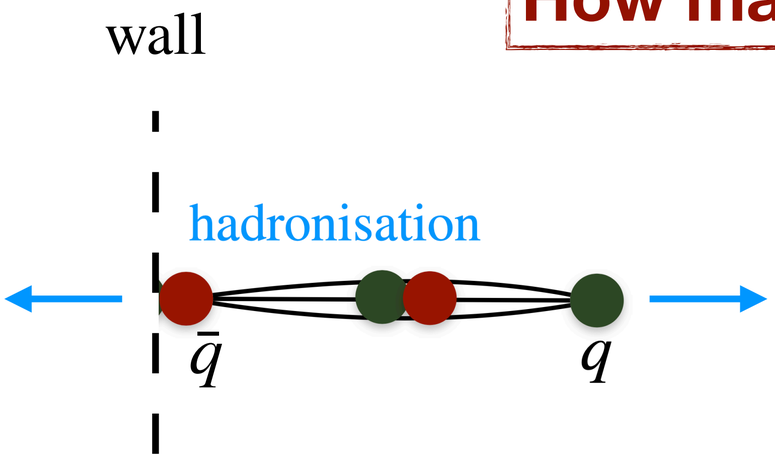
→ Catalysed by black holes ?

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
β/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 $q\bar{q}$

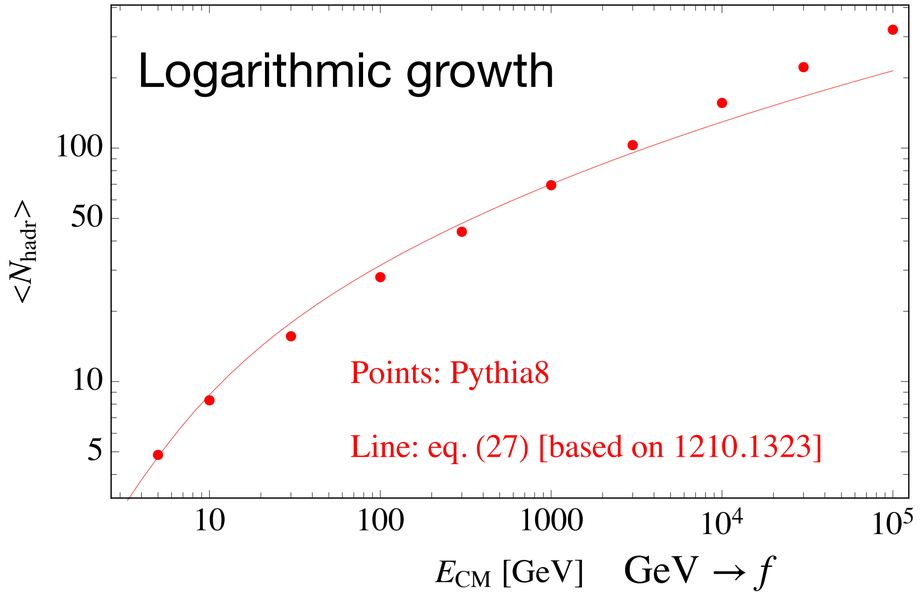
Analogous to $e^+e^- \to q\bar{q}$ in QCD

Use Pythia with

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

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

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



DM abundance after supercooling

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

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

Standard Supercooling

Branching ratio quark -> DM

String fragmentation

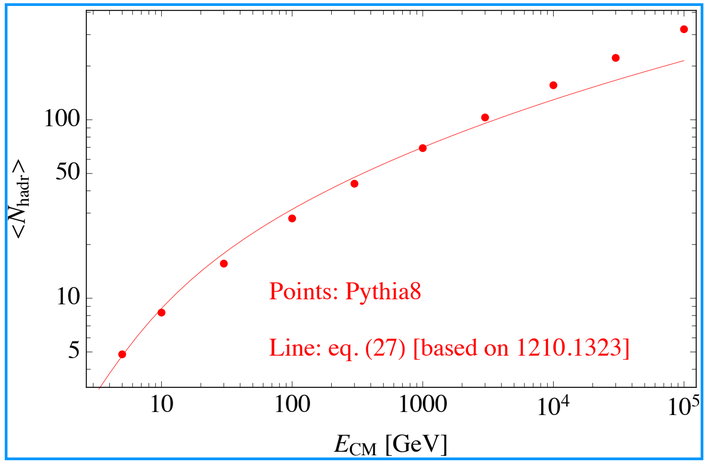
2 possibilities:

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



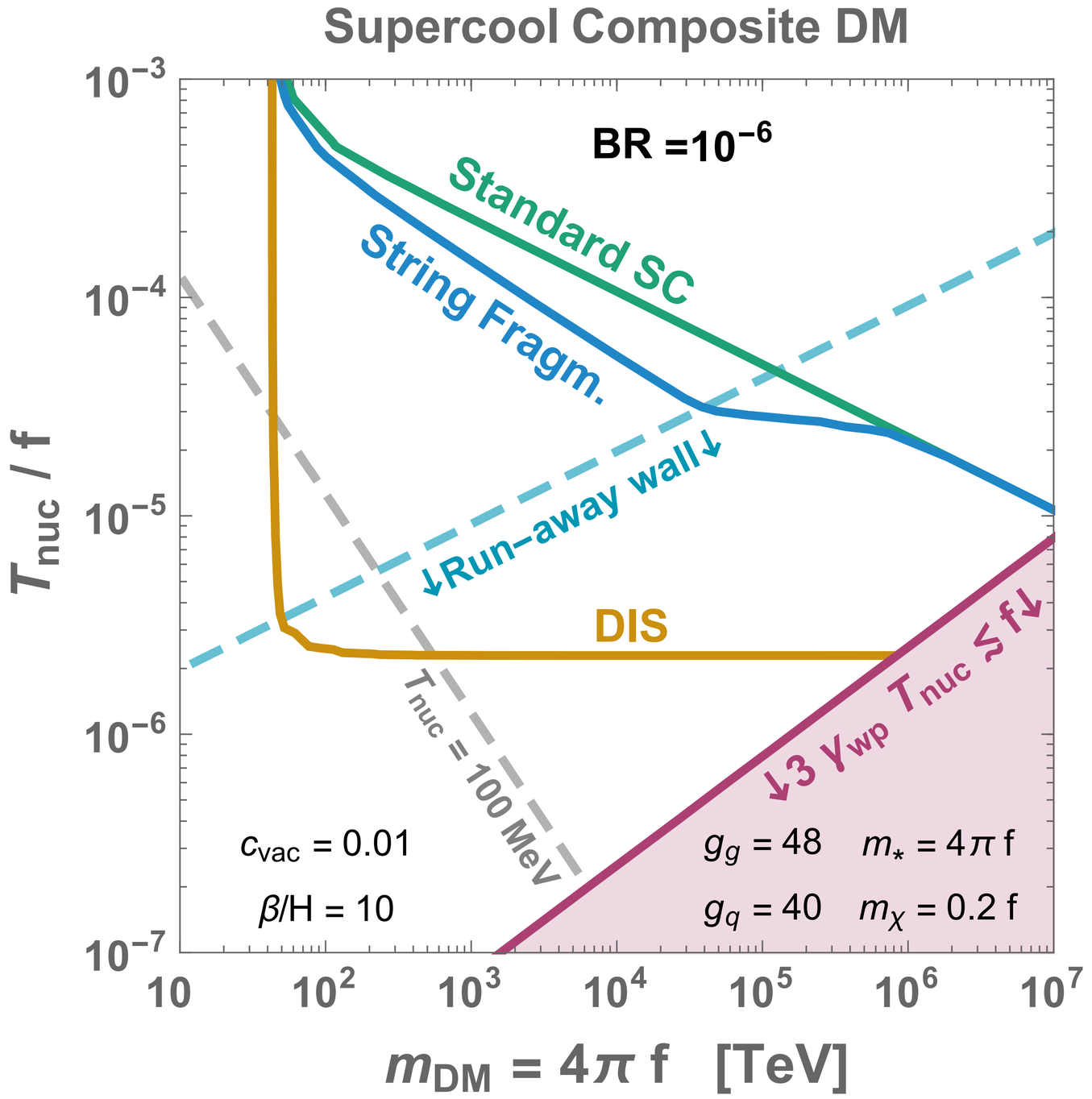
O(1) fraction of initial hadron energy converted into hadron masses

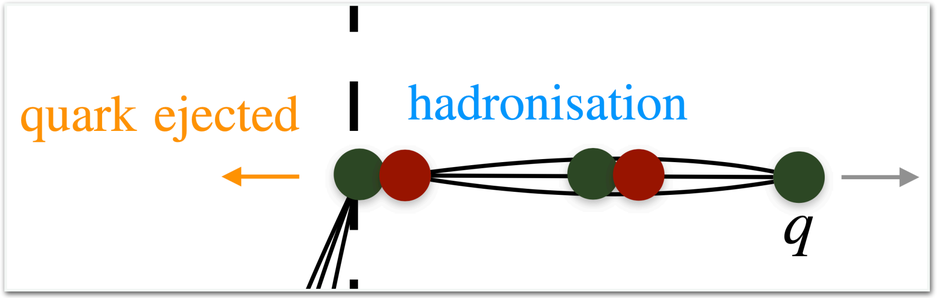
$$Y_{\rm SC+string+DIS} \sim \frac{T E_{\rm hadr}}{m_*^2} Y_{\rm SC+string}$$

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

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

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


Supercool Composite DM
BR =10^−6
Standard SC
String Fragm.
↓Run−away wall↓
DIS
T_nuc = 100 MeV
↓3 y_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]
10^−3
10^−4
10^−5
10^−6
10^−7
10
10^2
10^3
10^4
10^5
10^6
10^7

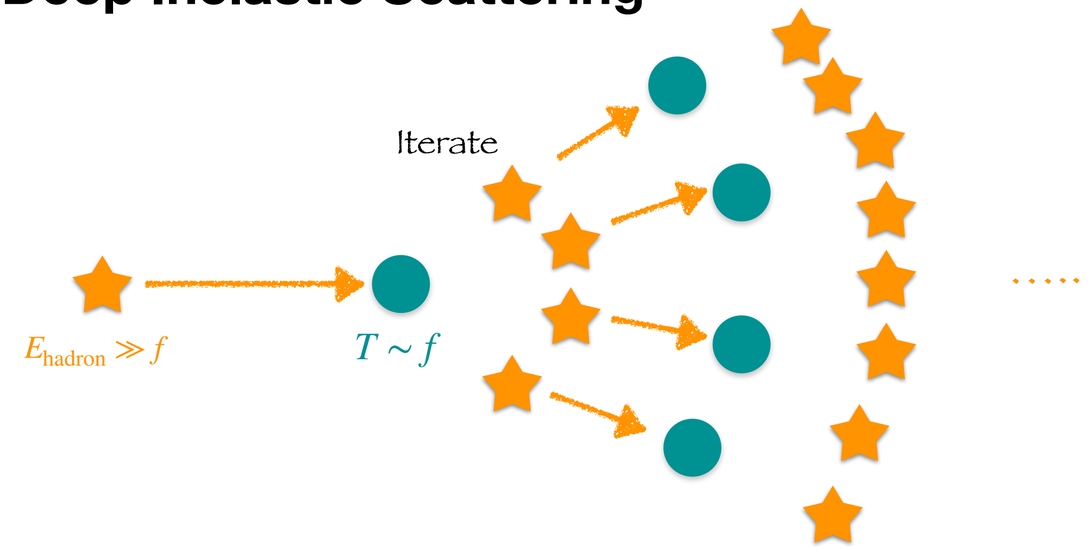


Consequences on DM abundance

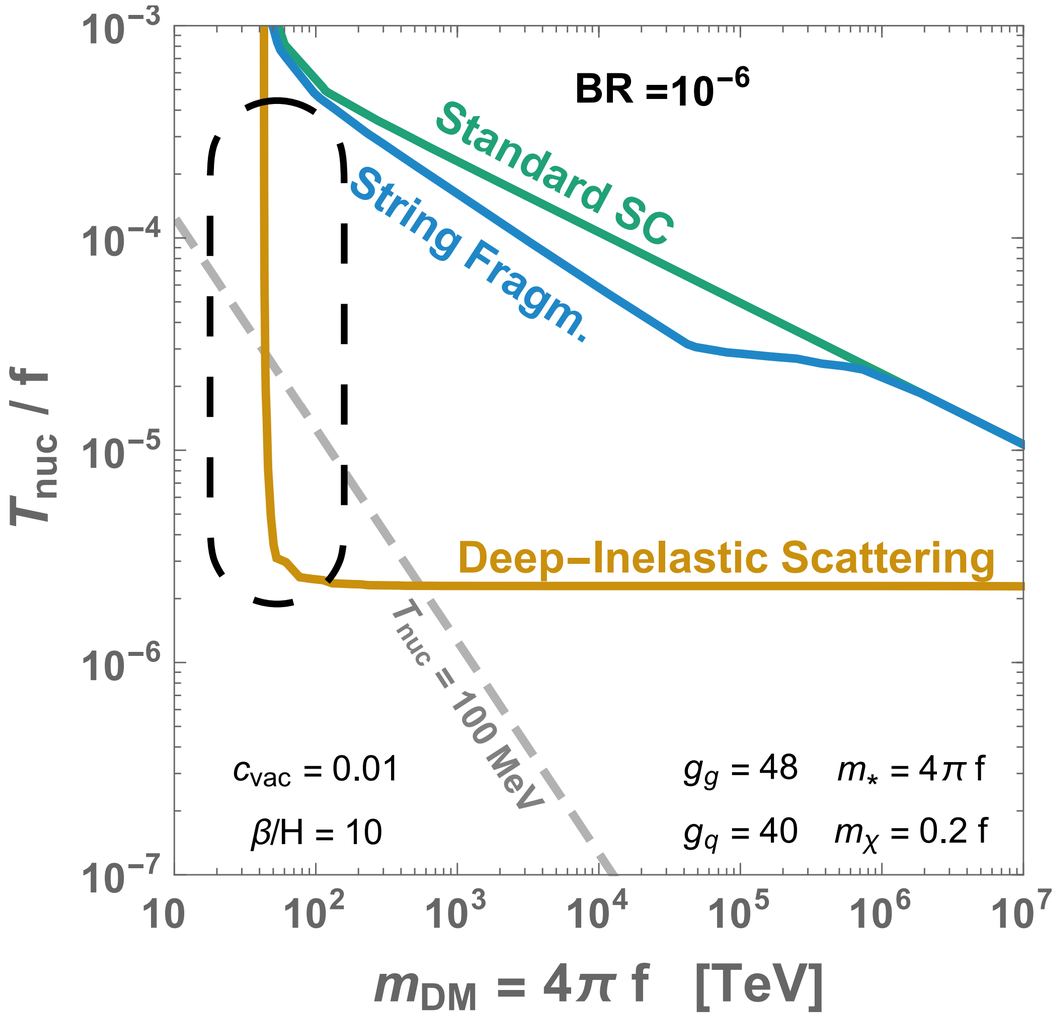
1. String fragmentation + quark ejection

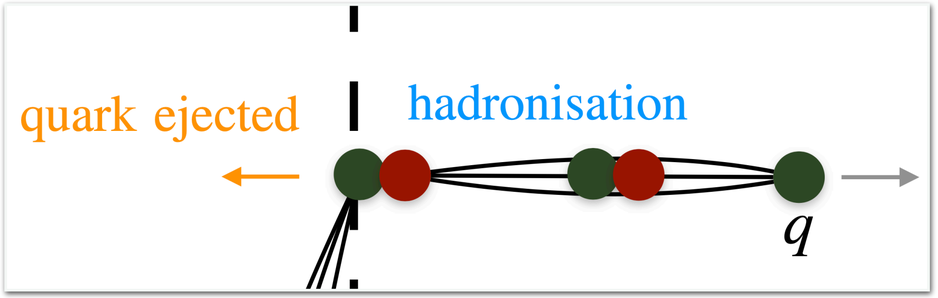
$$Y_{\rm DM} / Y_{\rm DM}^{\rm naive} \propto \log^n\left(\gamma_{wp} T_{\rm nuc}/f\right)$$

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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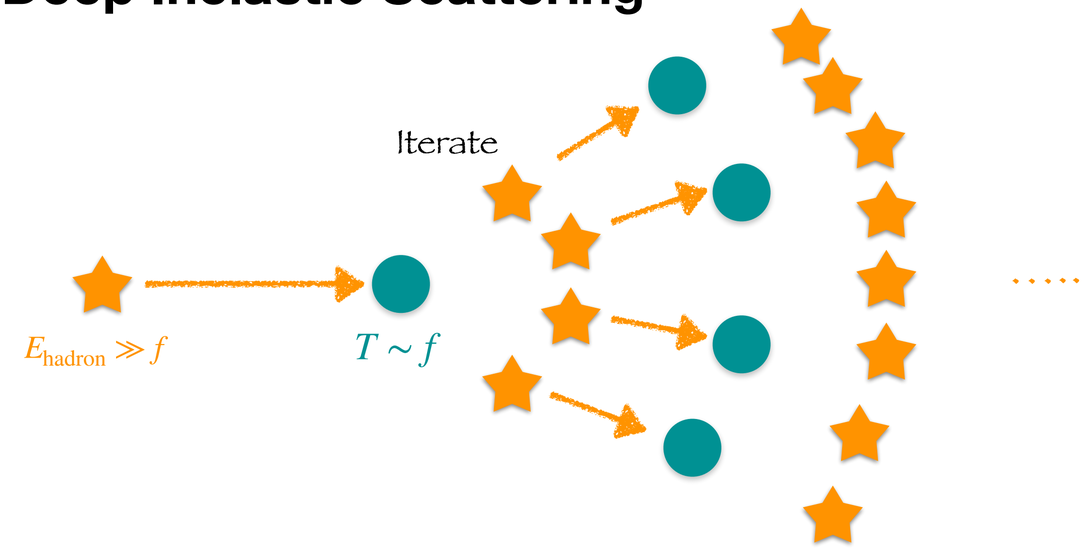

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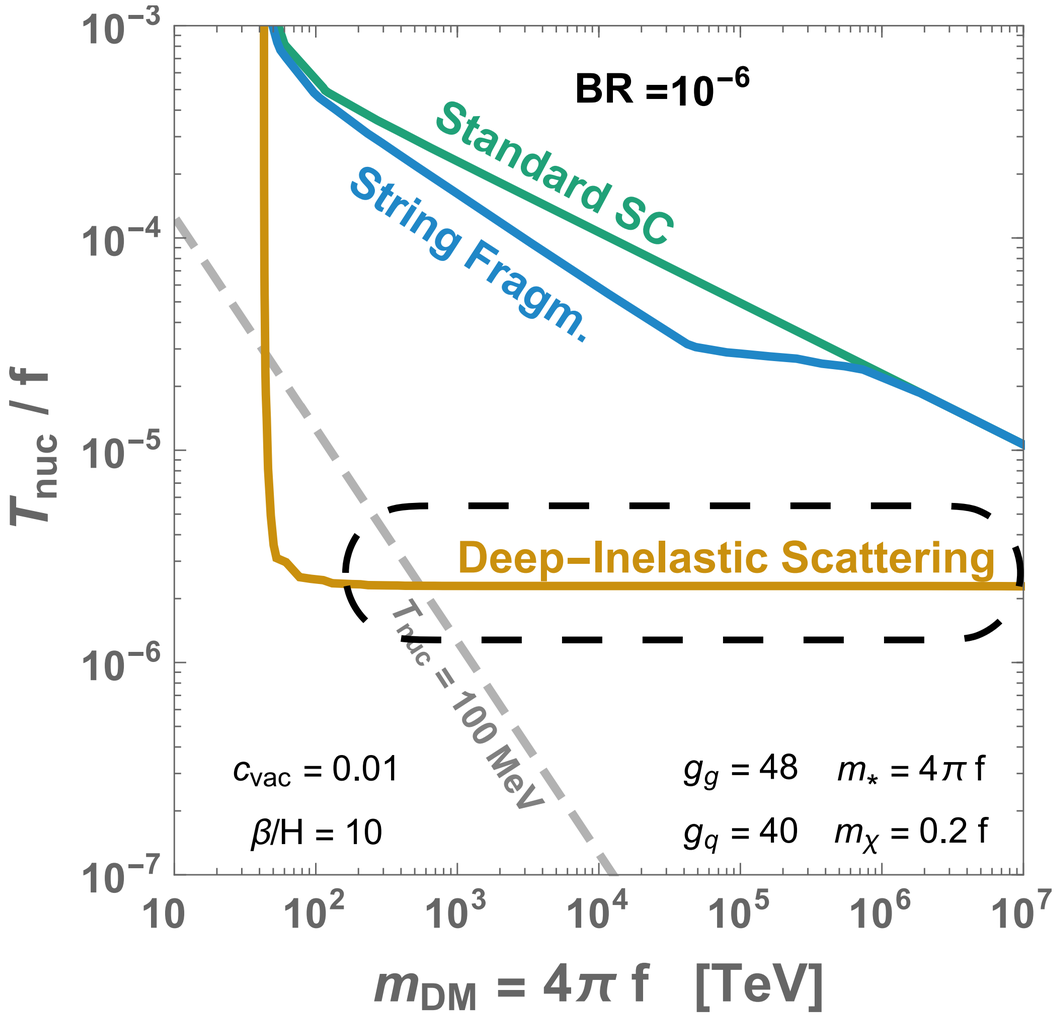
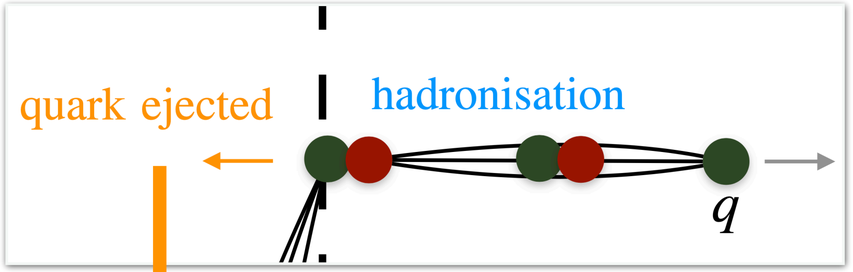
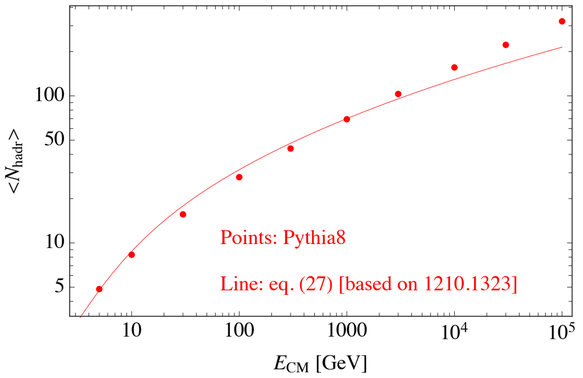


Cosmological consequences



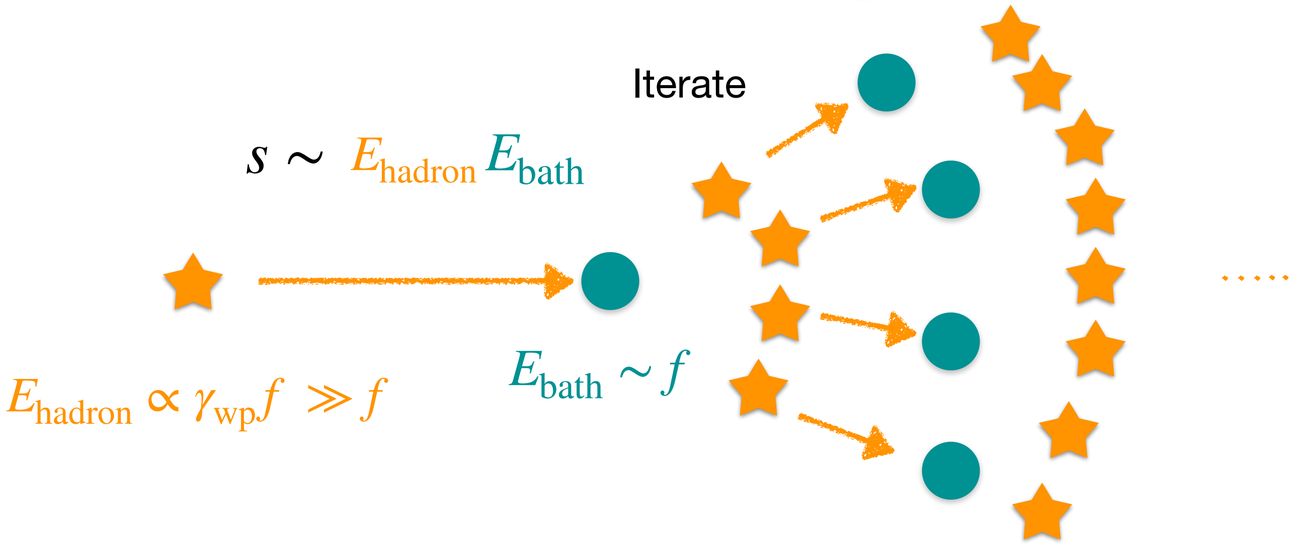
1. More hadrons per initial quark pair



Y_D

Ejected quarks give contribution of same order of magnitude

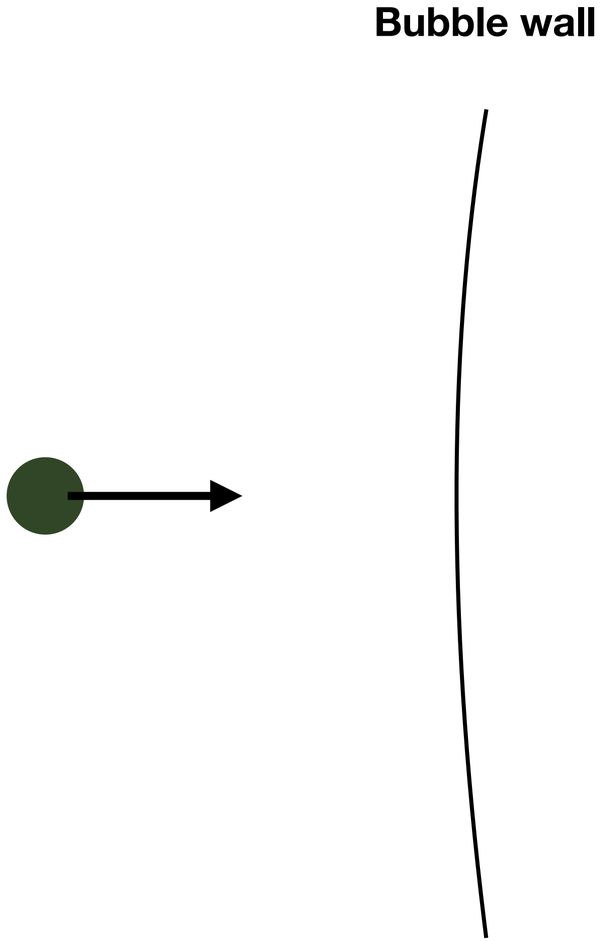
2. Cosmological catapult



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

runaway regime

Interaction with other quarks ?



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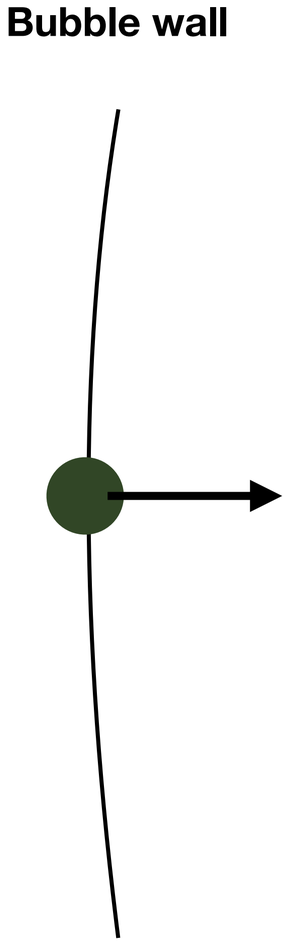

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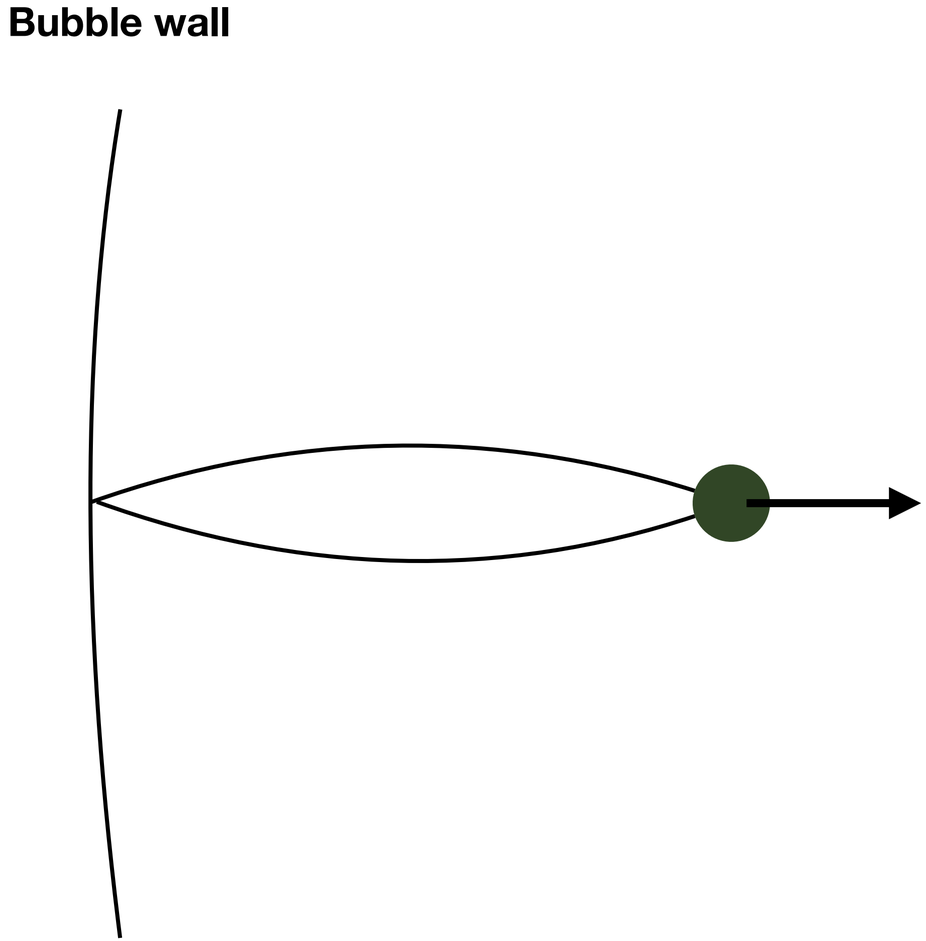
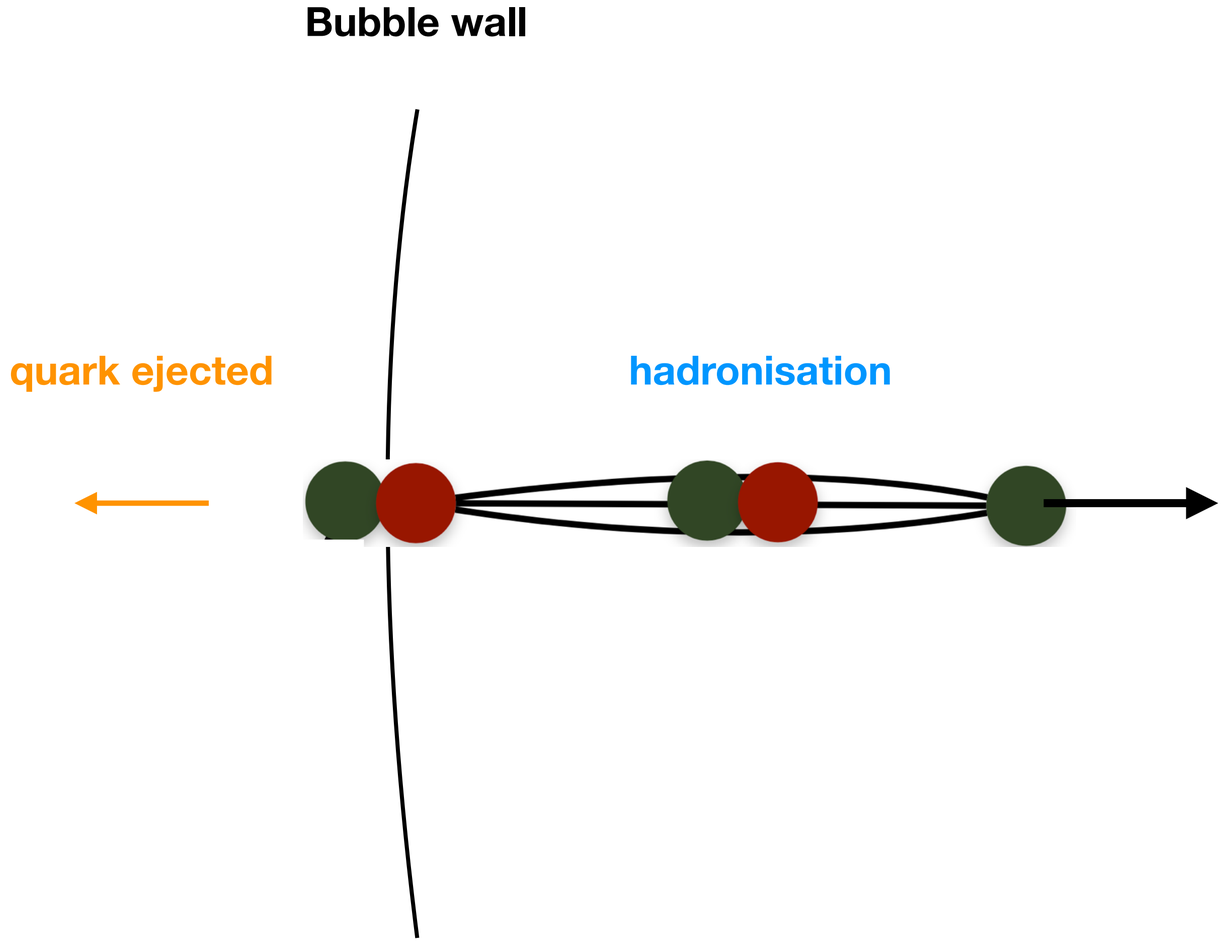


Interaction with other quarks ?

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



Interaction with other quarks ?

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

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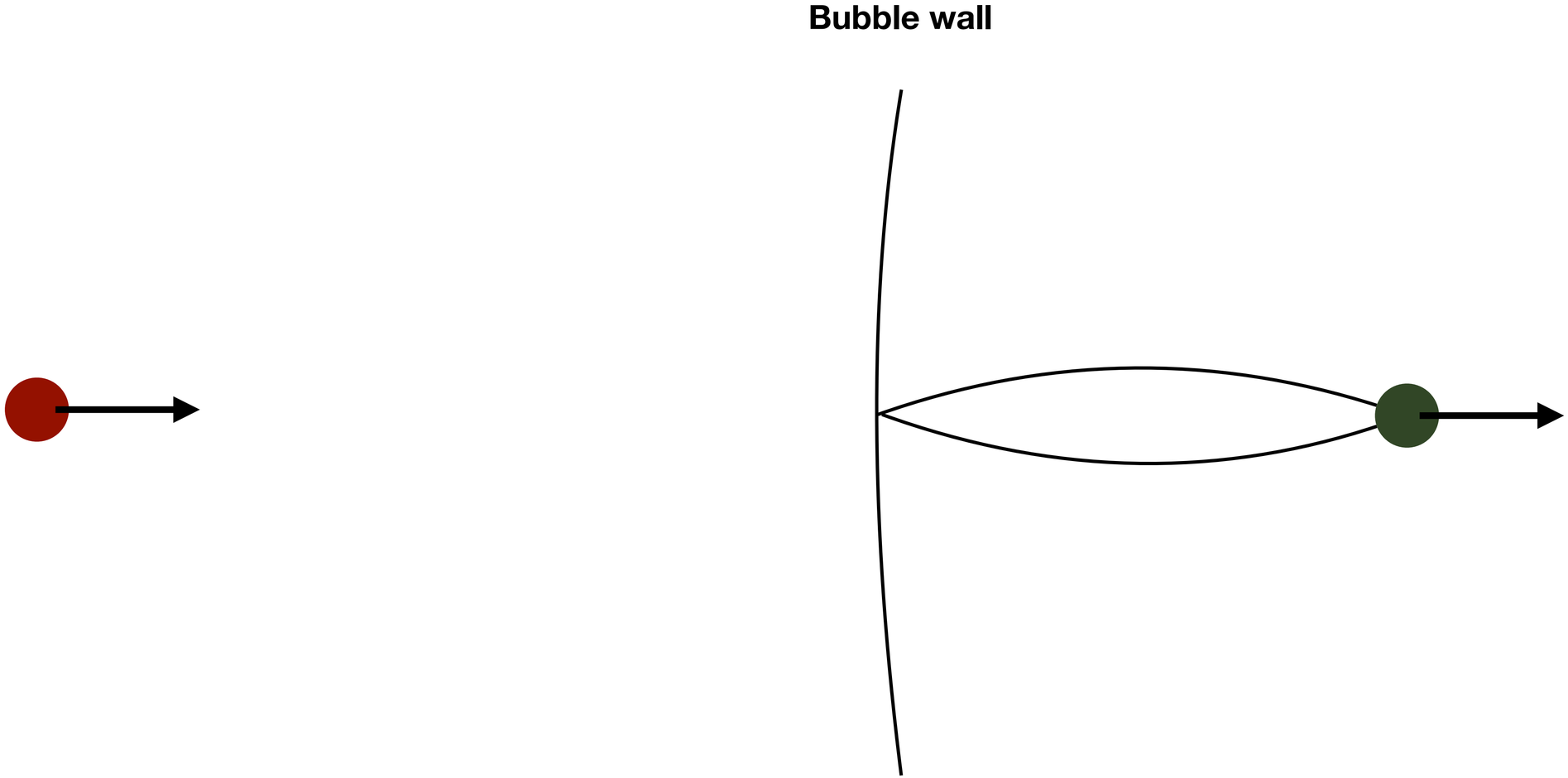

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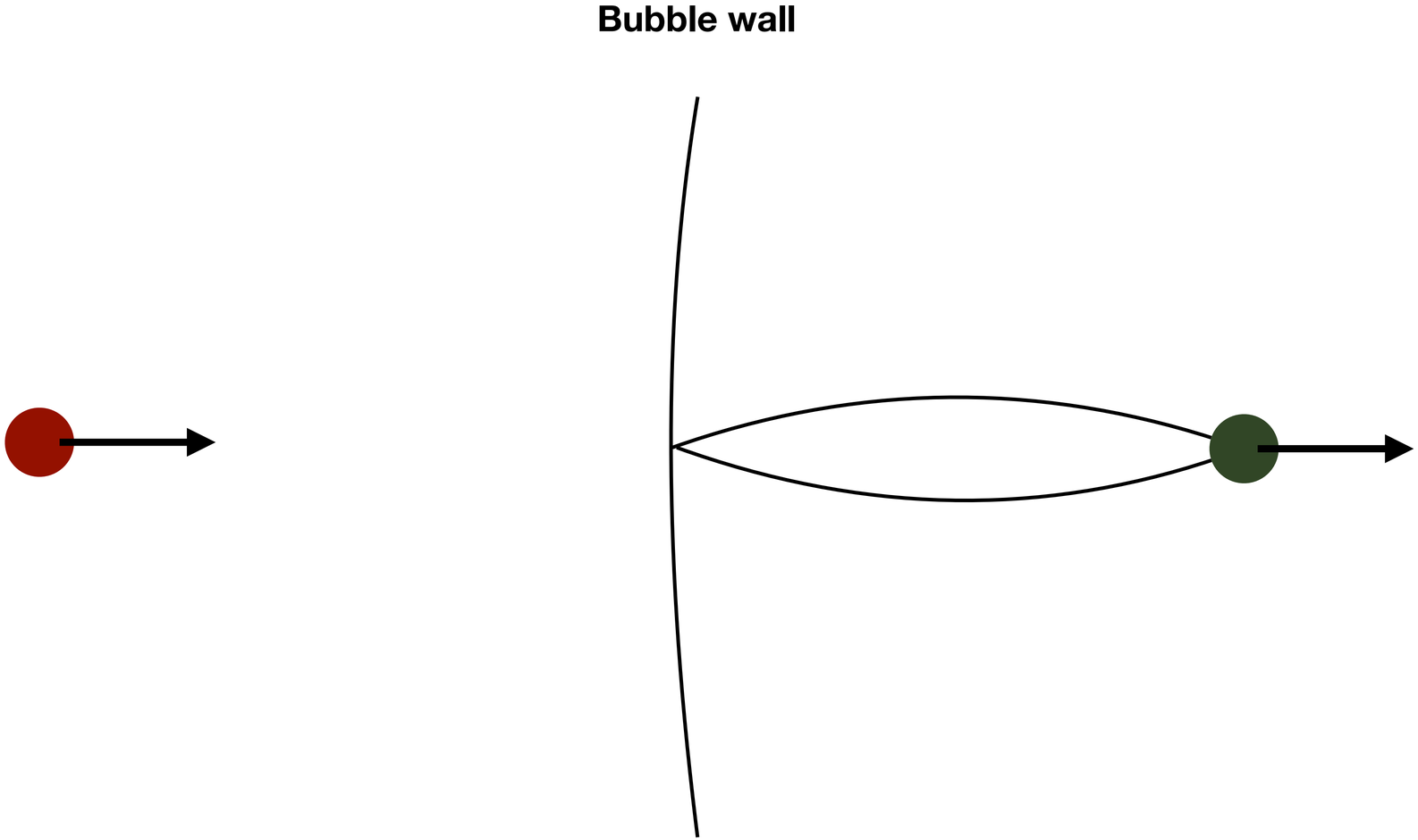

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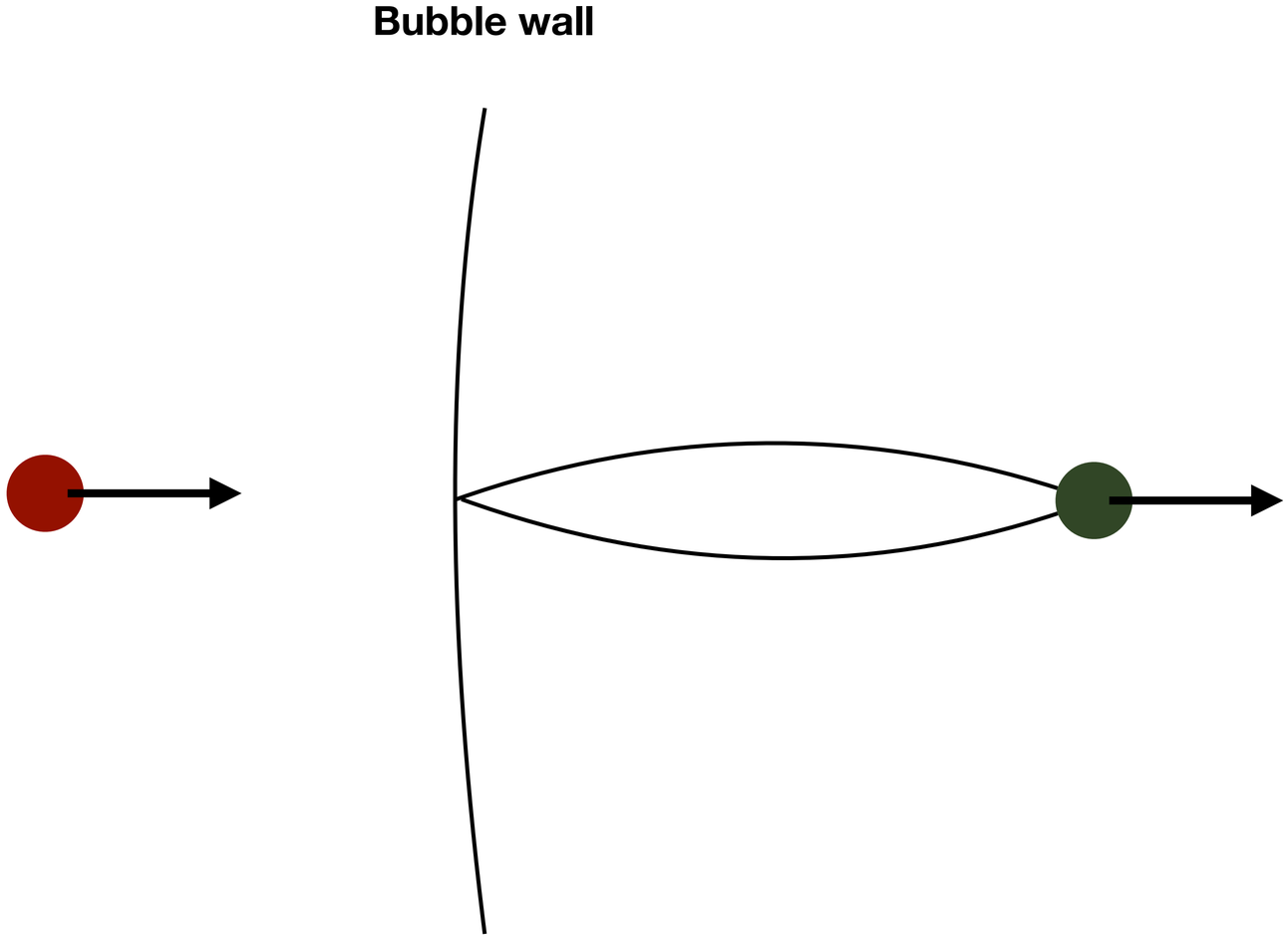

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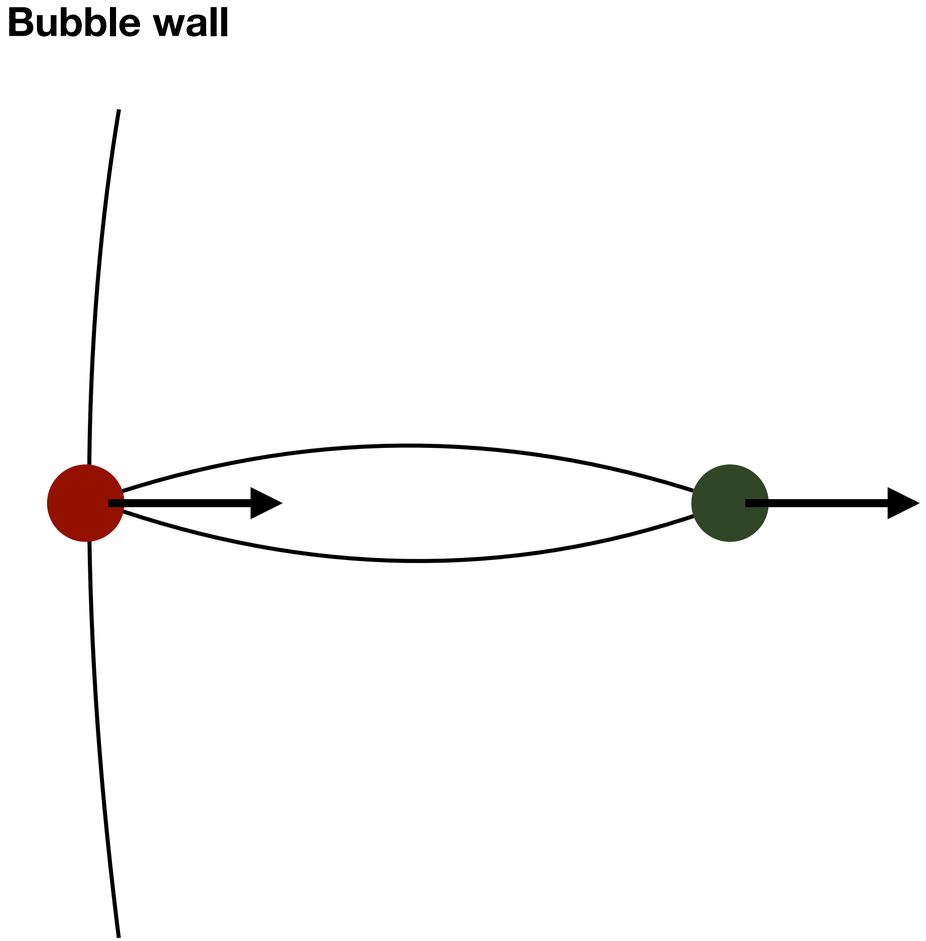

Interaction with other quarks ?

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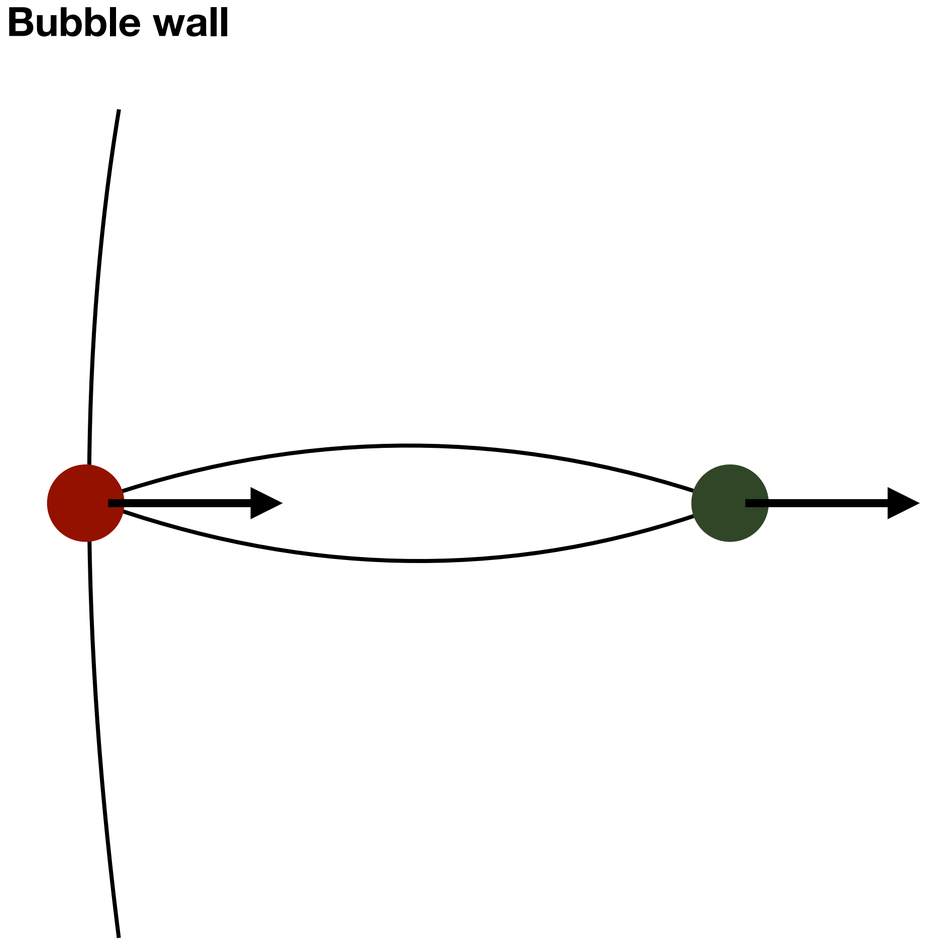

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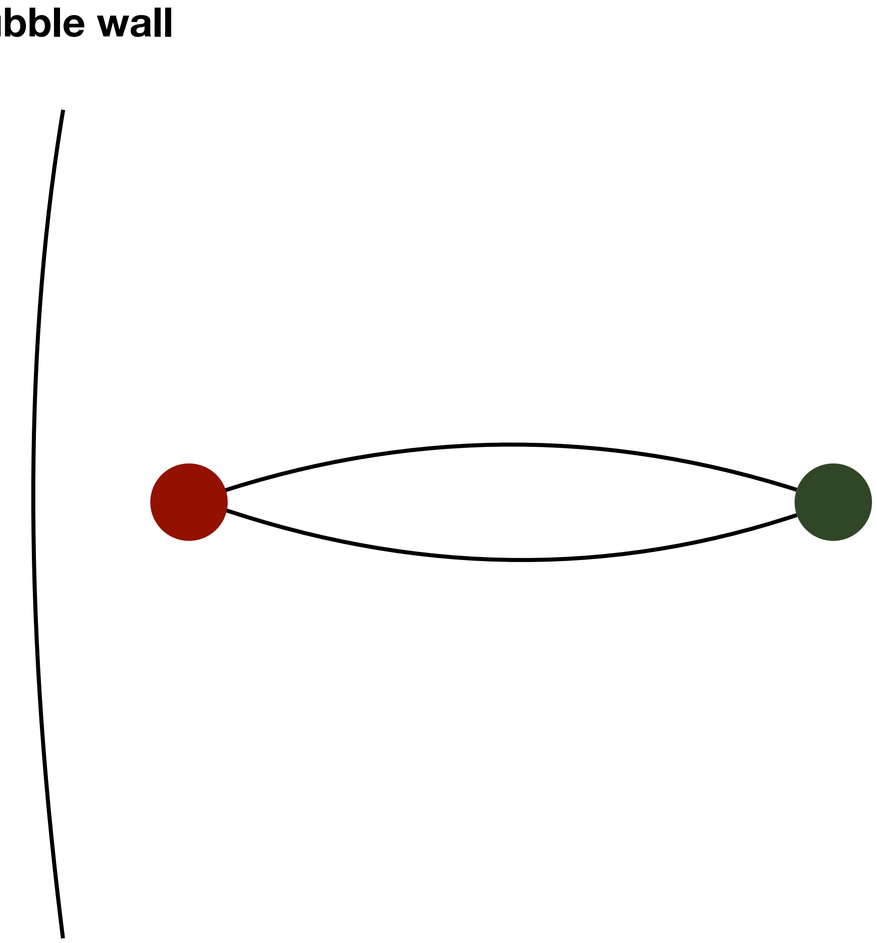

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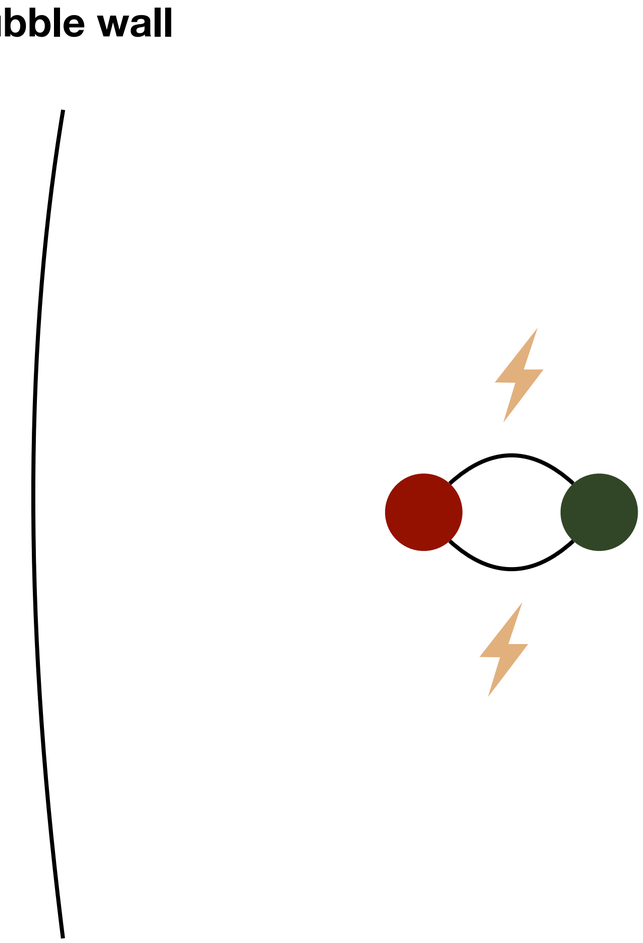

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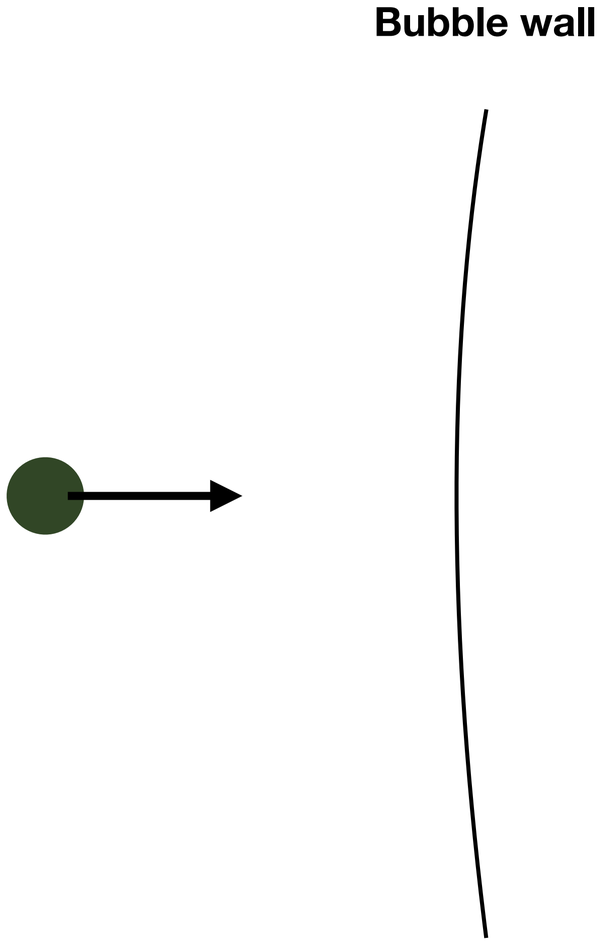

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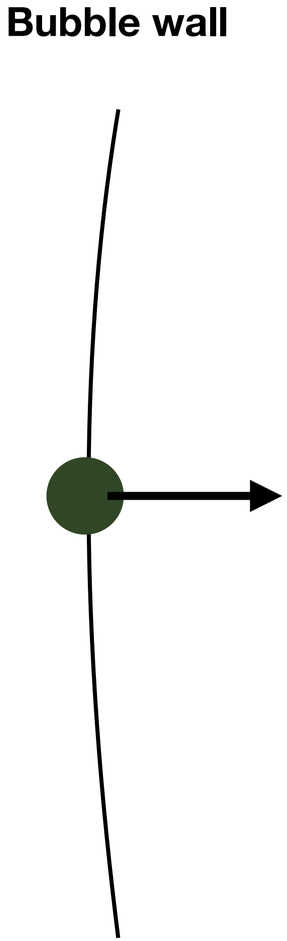

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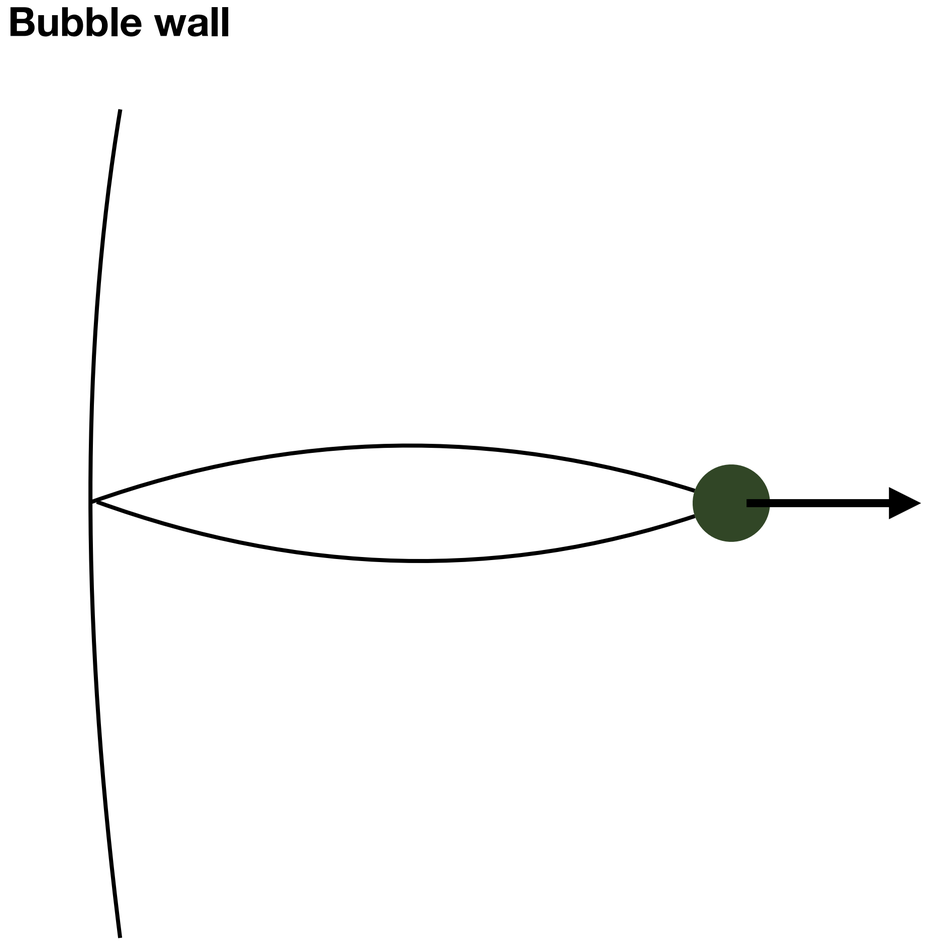

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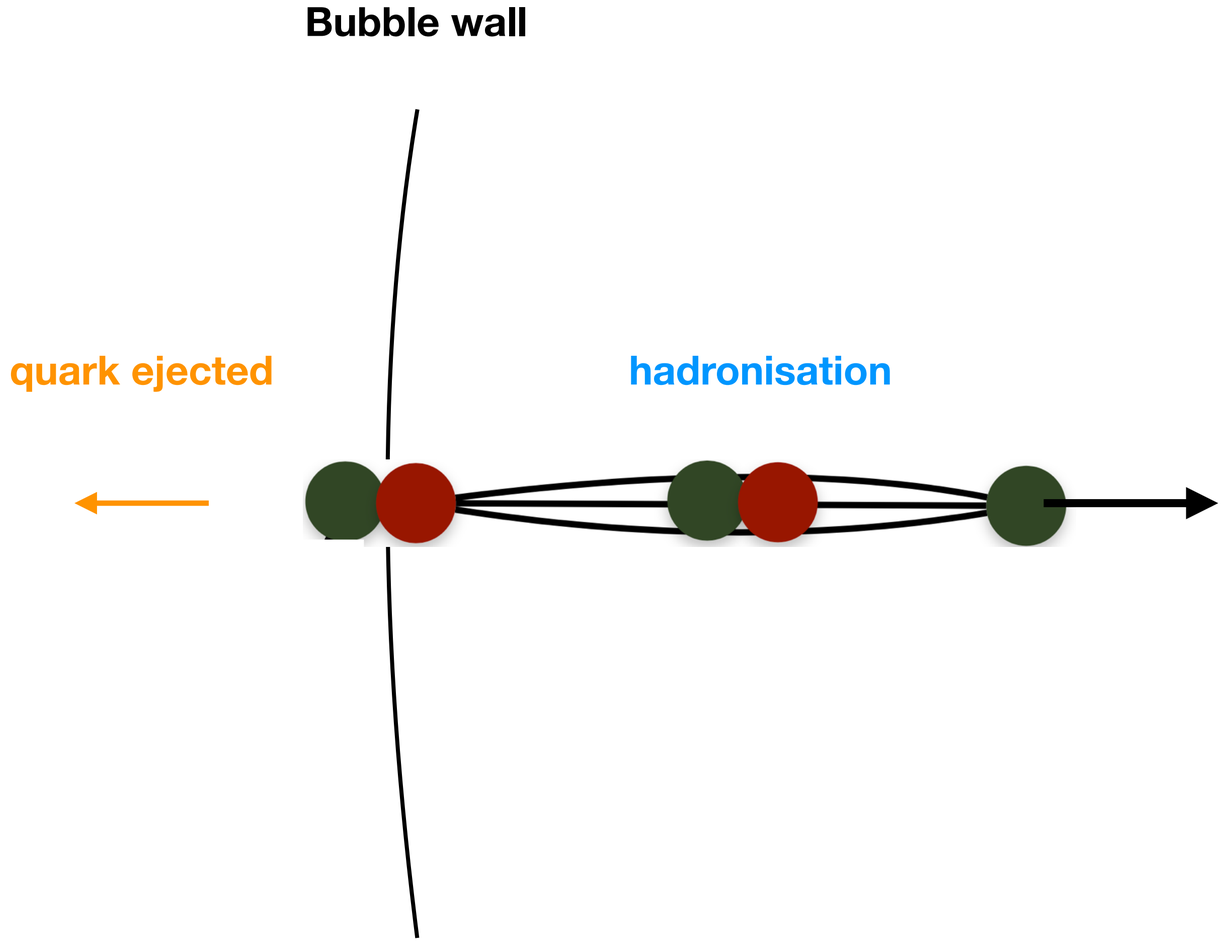

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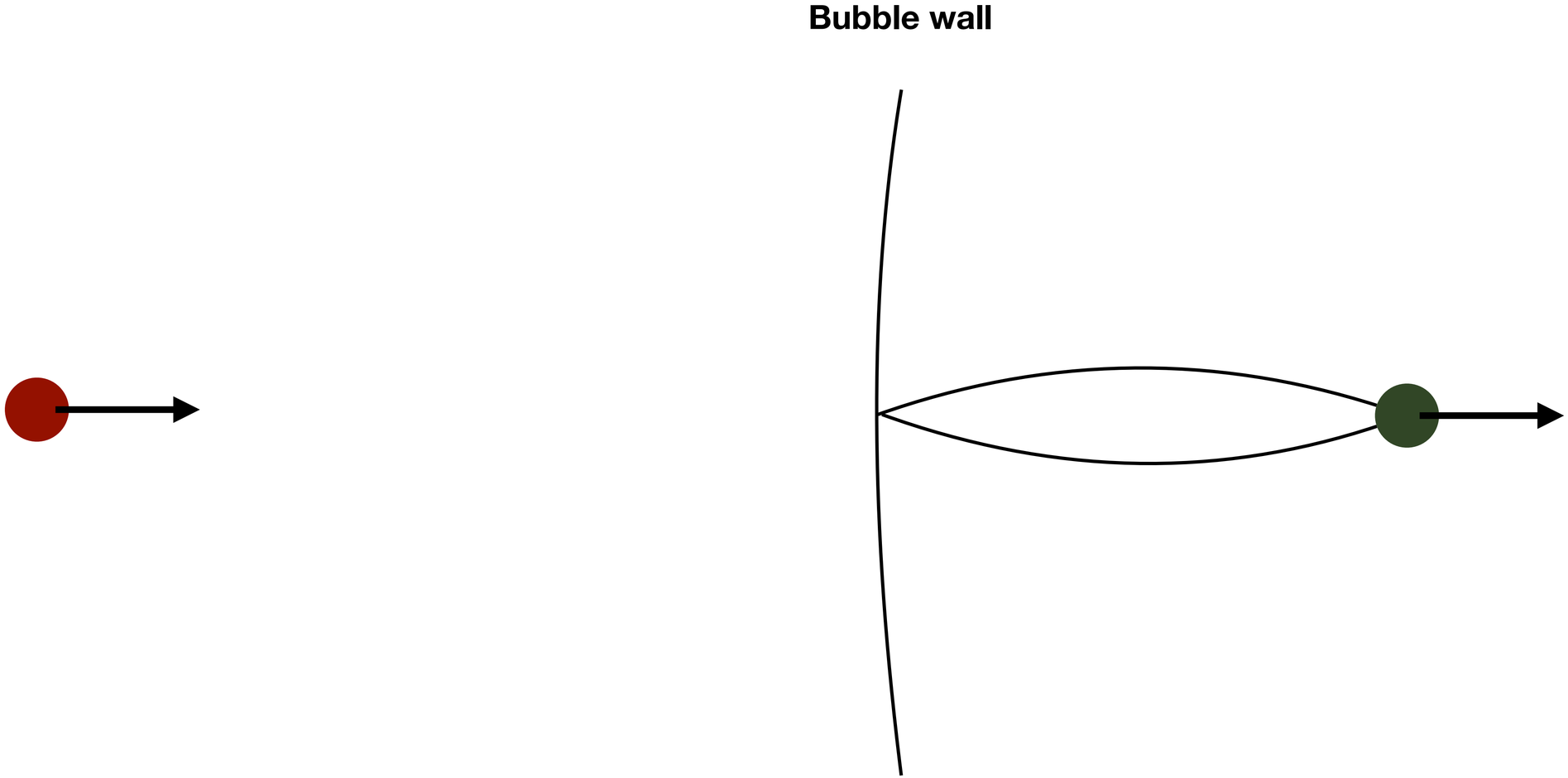

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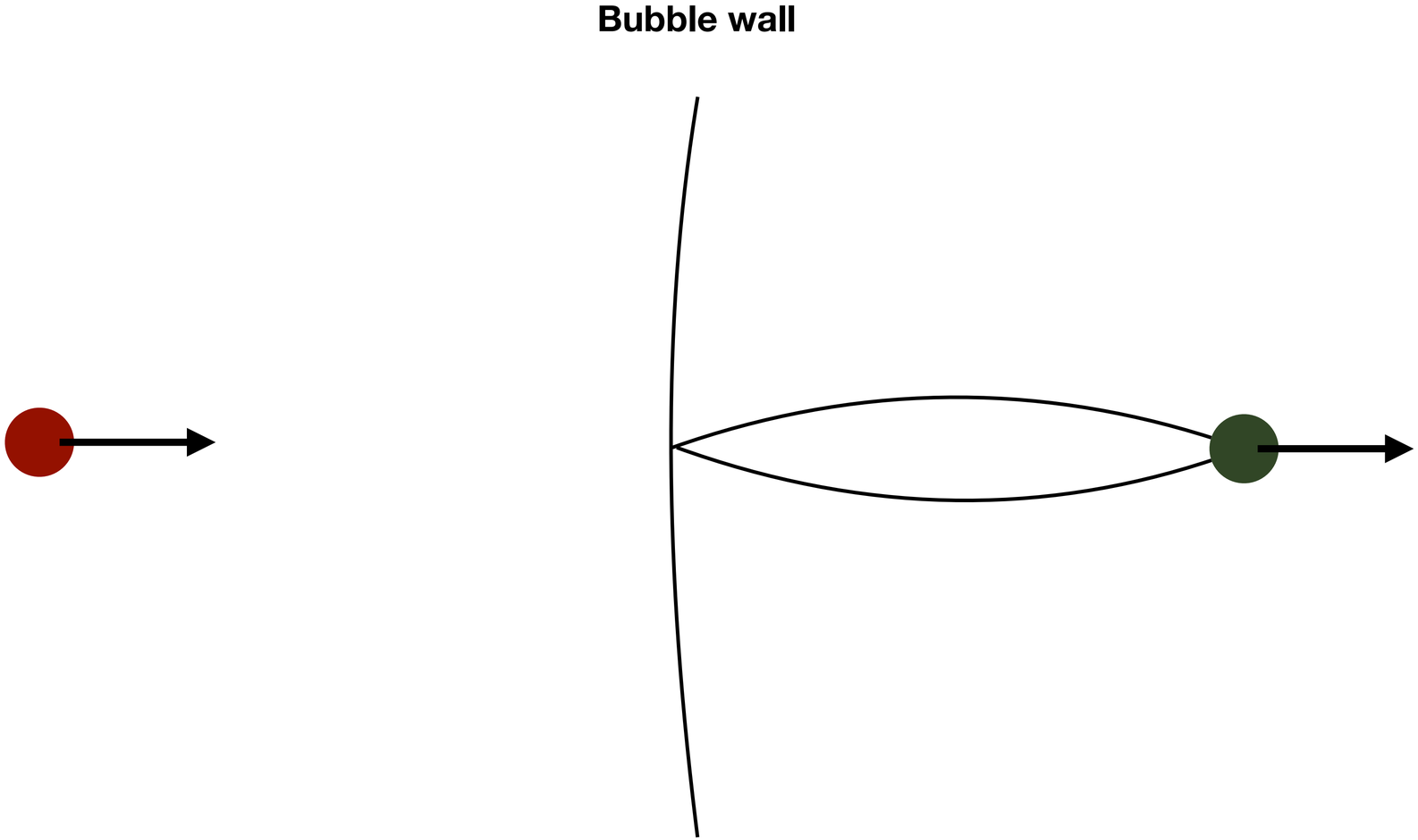
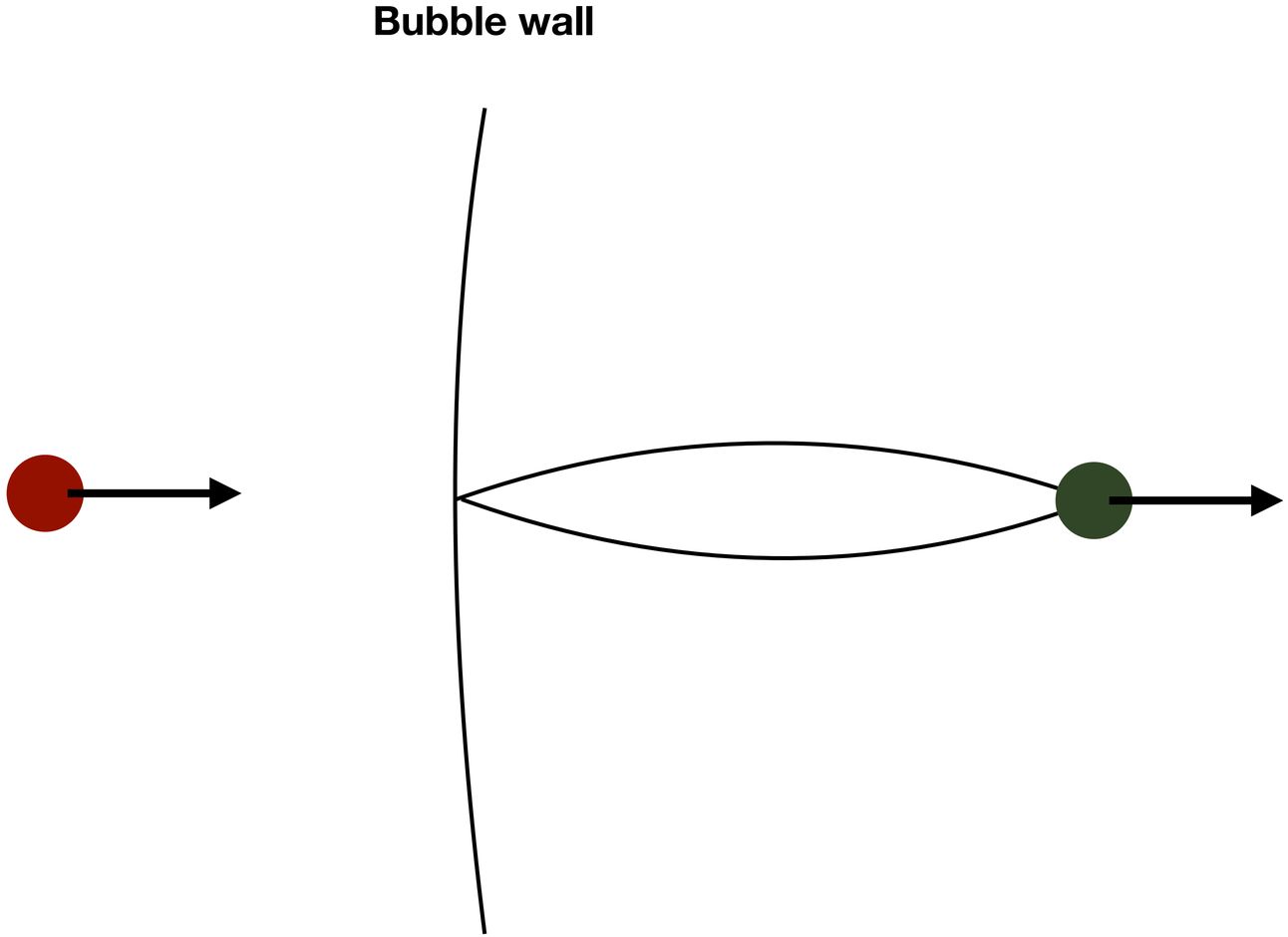


Interaction with other quarks ?

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

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



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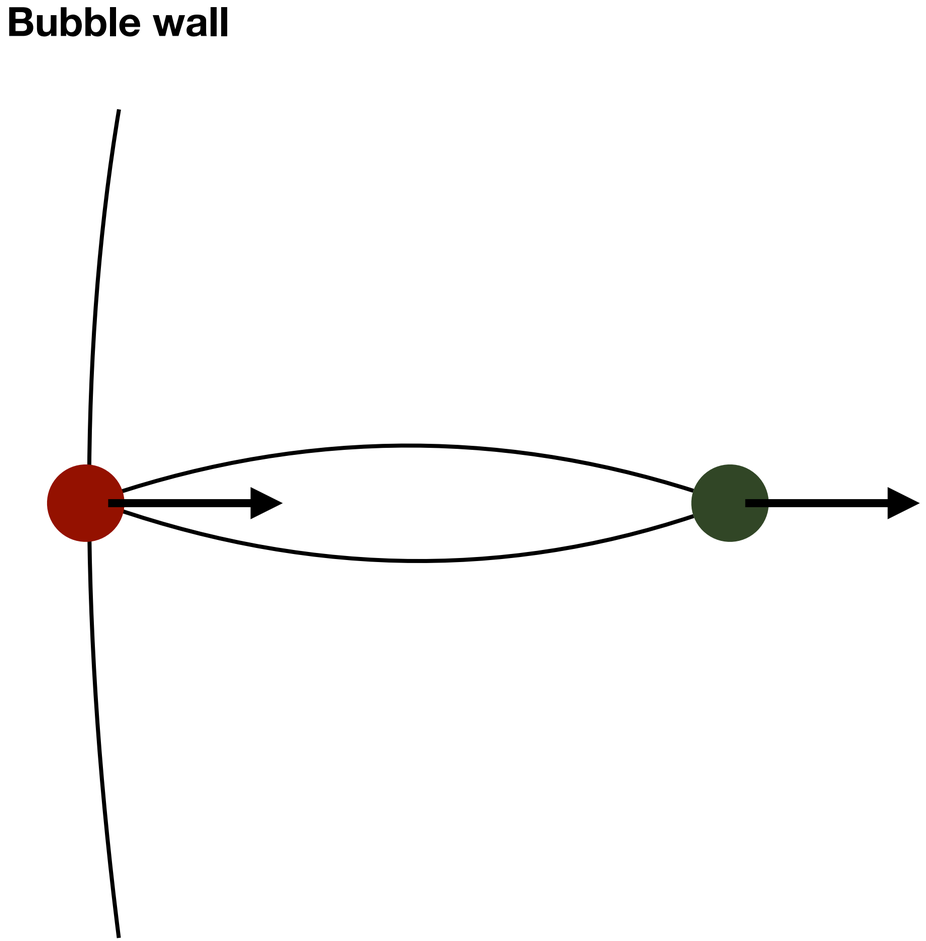

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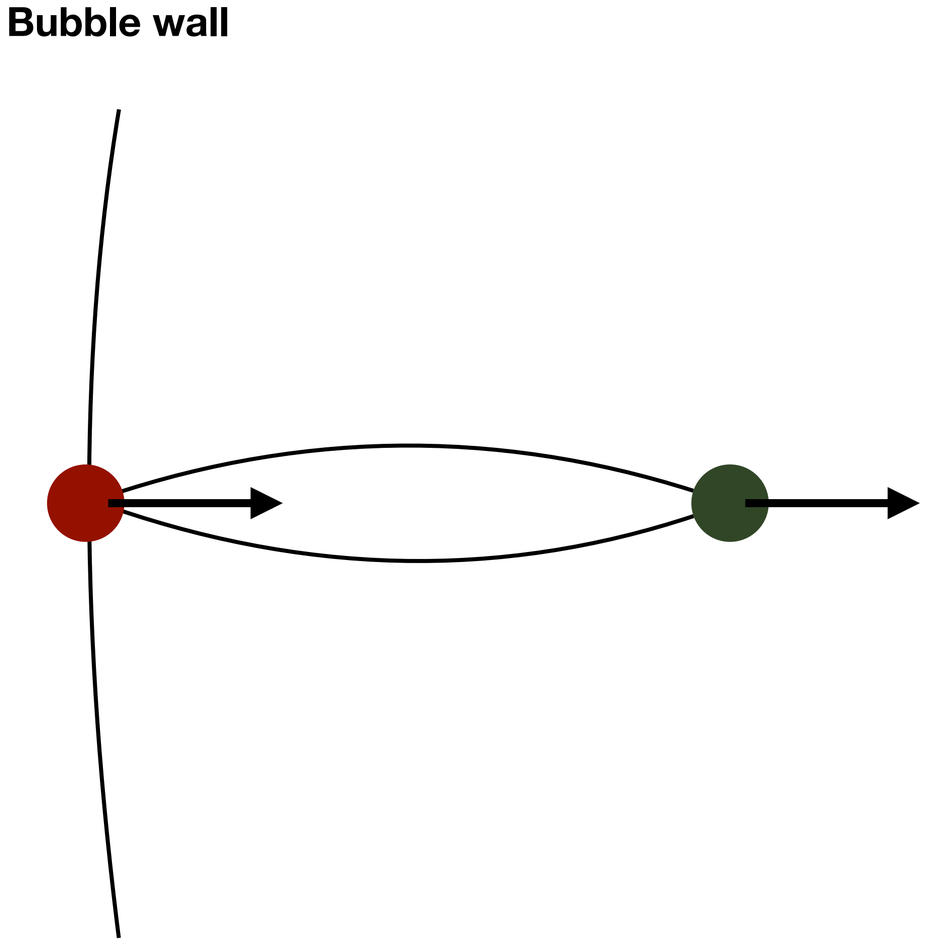

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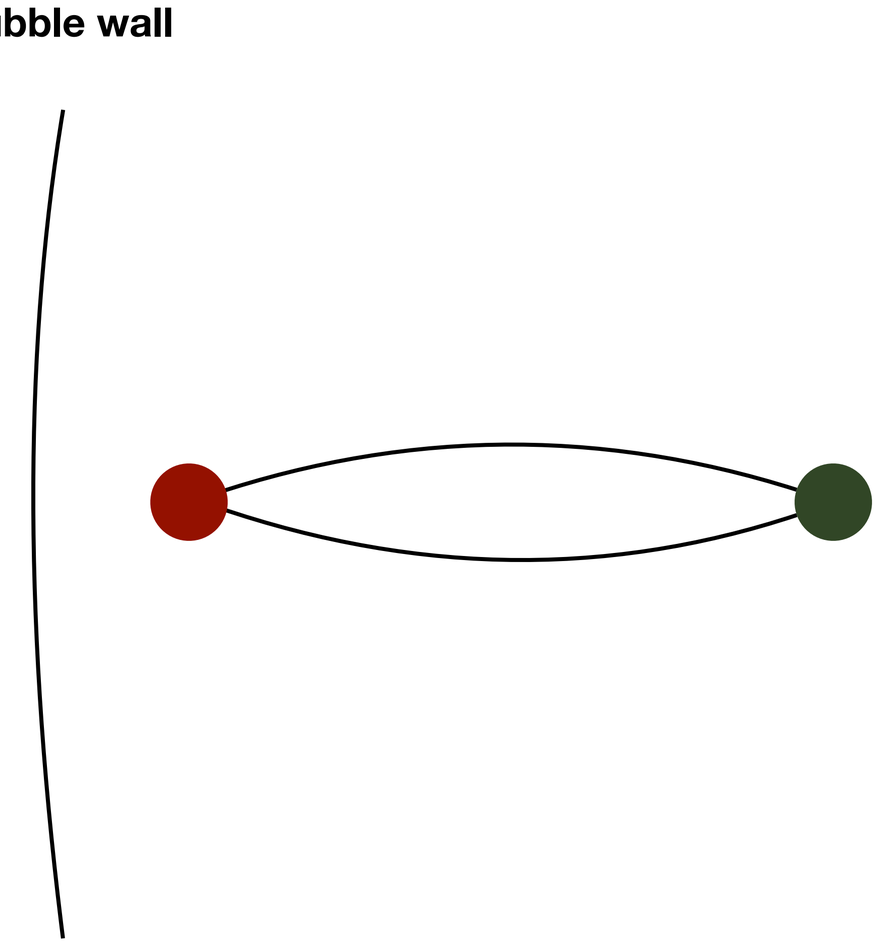

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