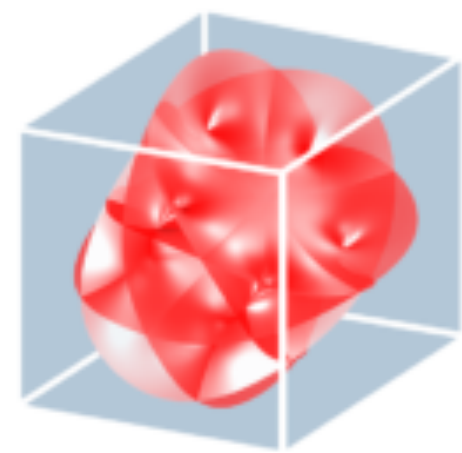


# Cosmological implications of supercooled phase transitions

Yann Gouttenoire

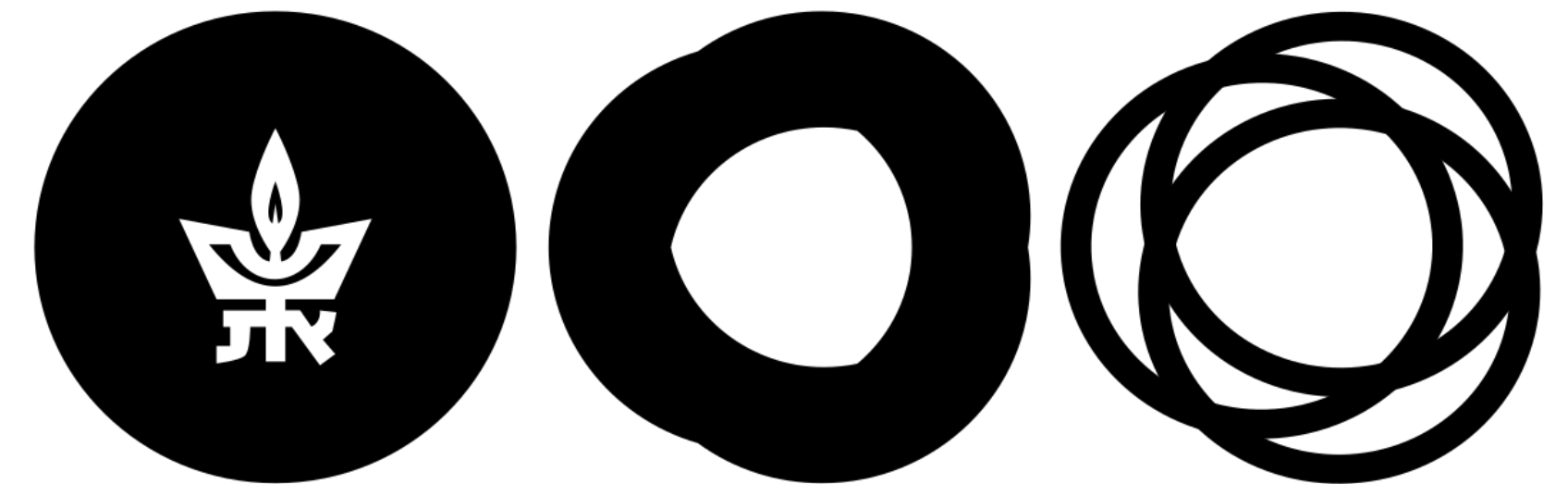
Collaborators: Iason Baldes, Ryusuke Jinno, Filippo Sala, Geraldine Servant, Tomer Volansky

Harvard CMSA



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**CENTER OF MATHEMATICAL  
SCIENCES AND APPLICATIONS**

5th August 2022

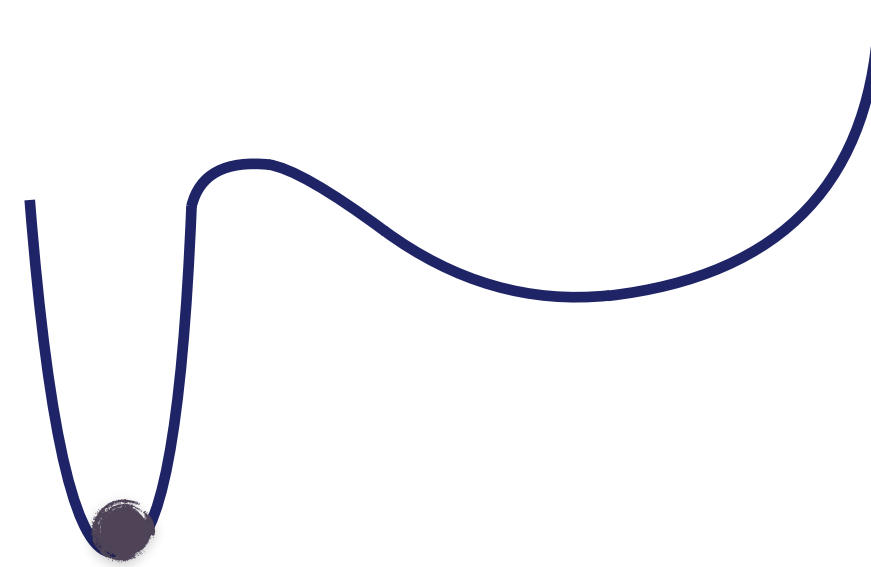
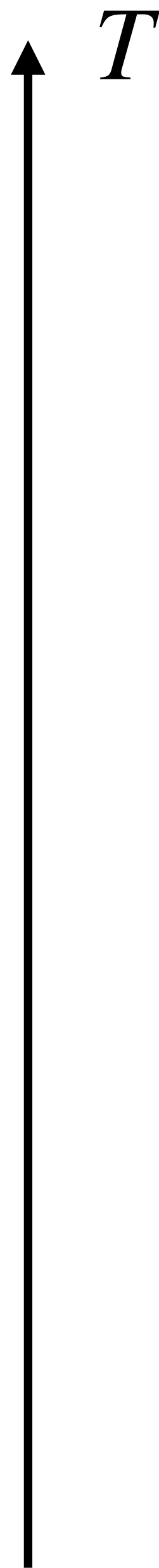


**TEL AVIV UNIVERSITY**

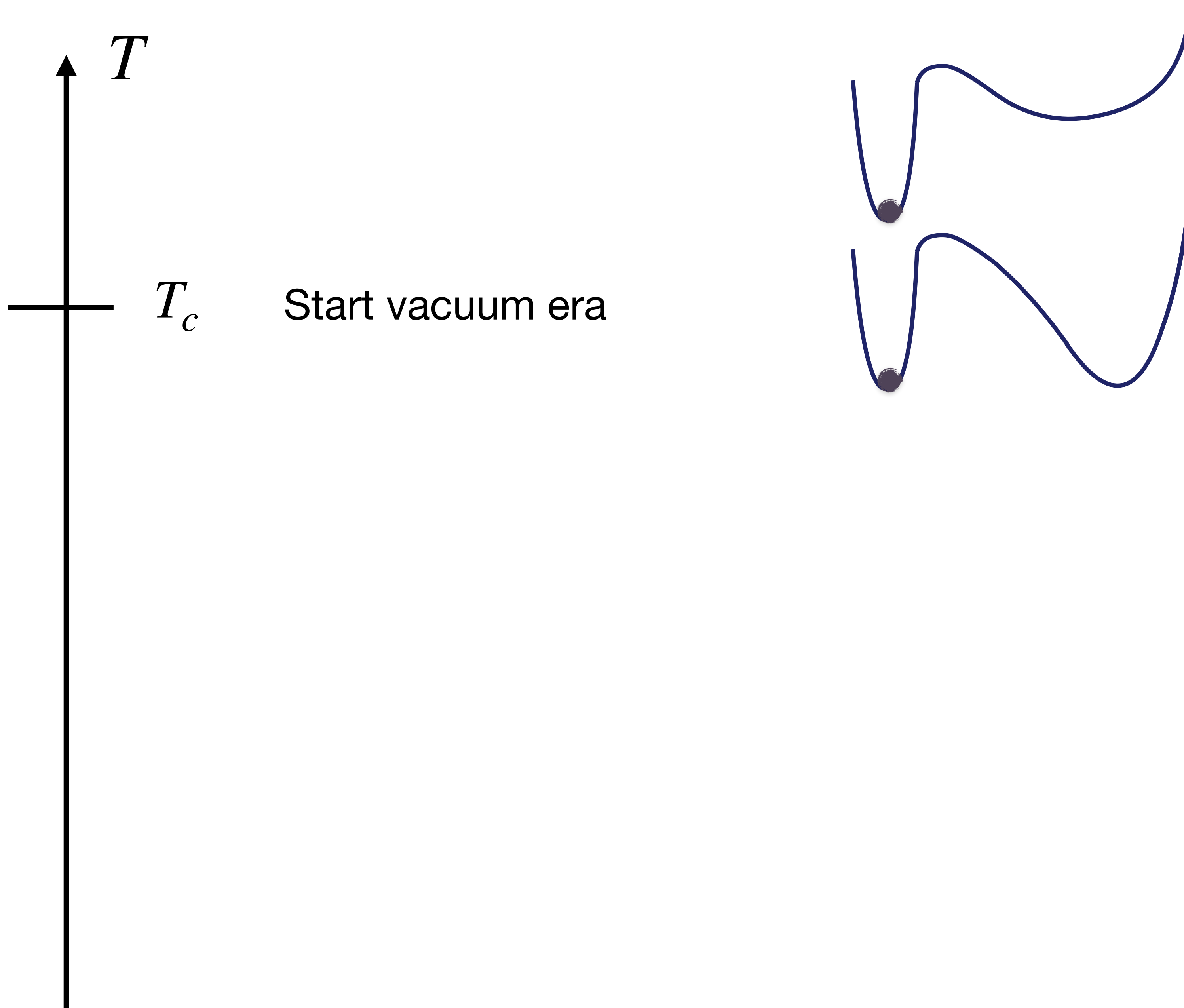
# Supercooled 1stOPT

**Supercooled 1stOPT = Hierarchical PT**

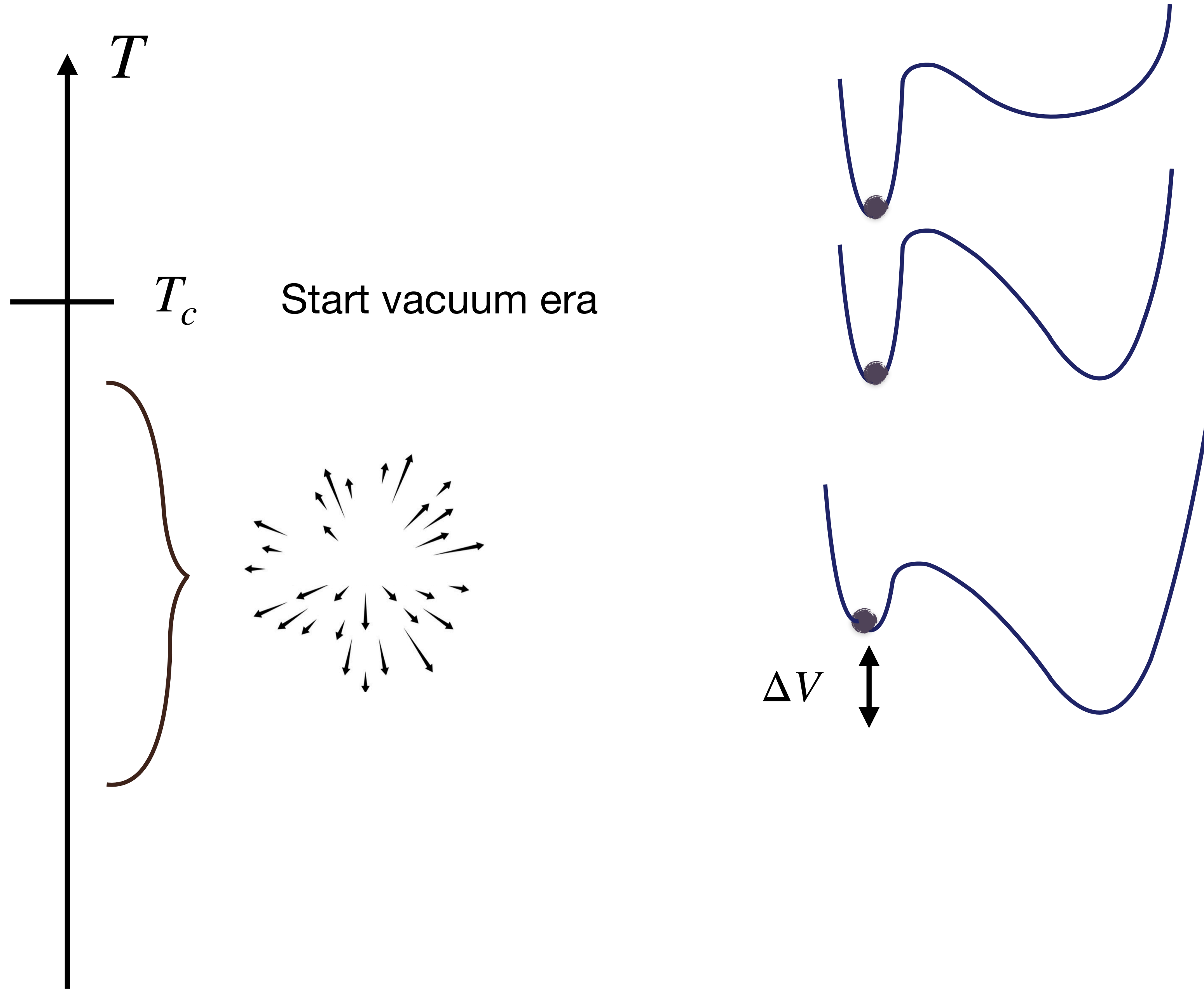
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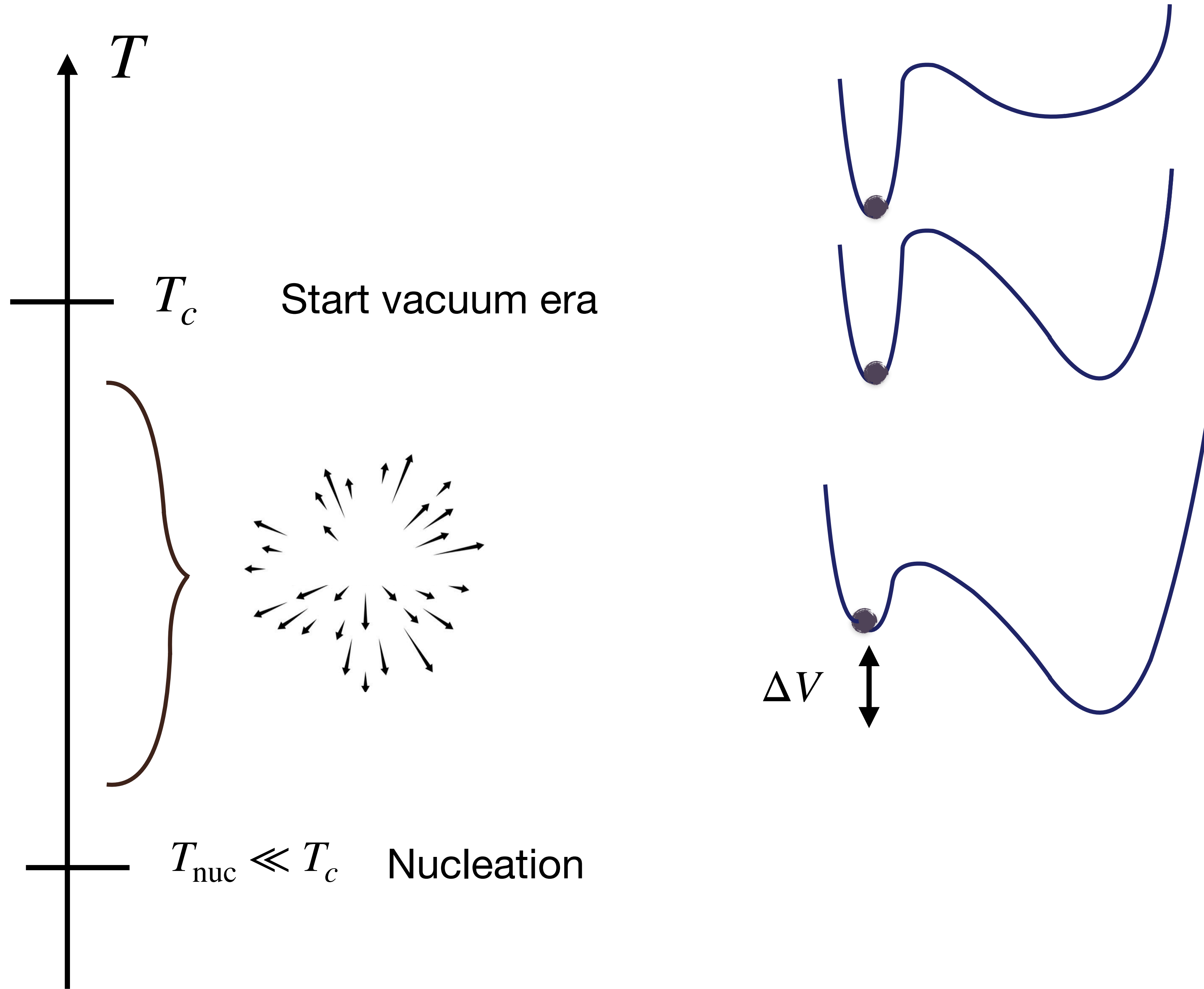
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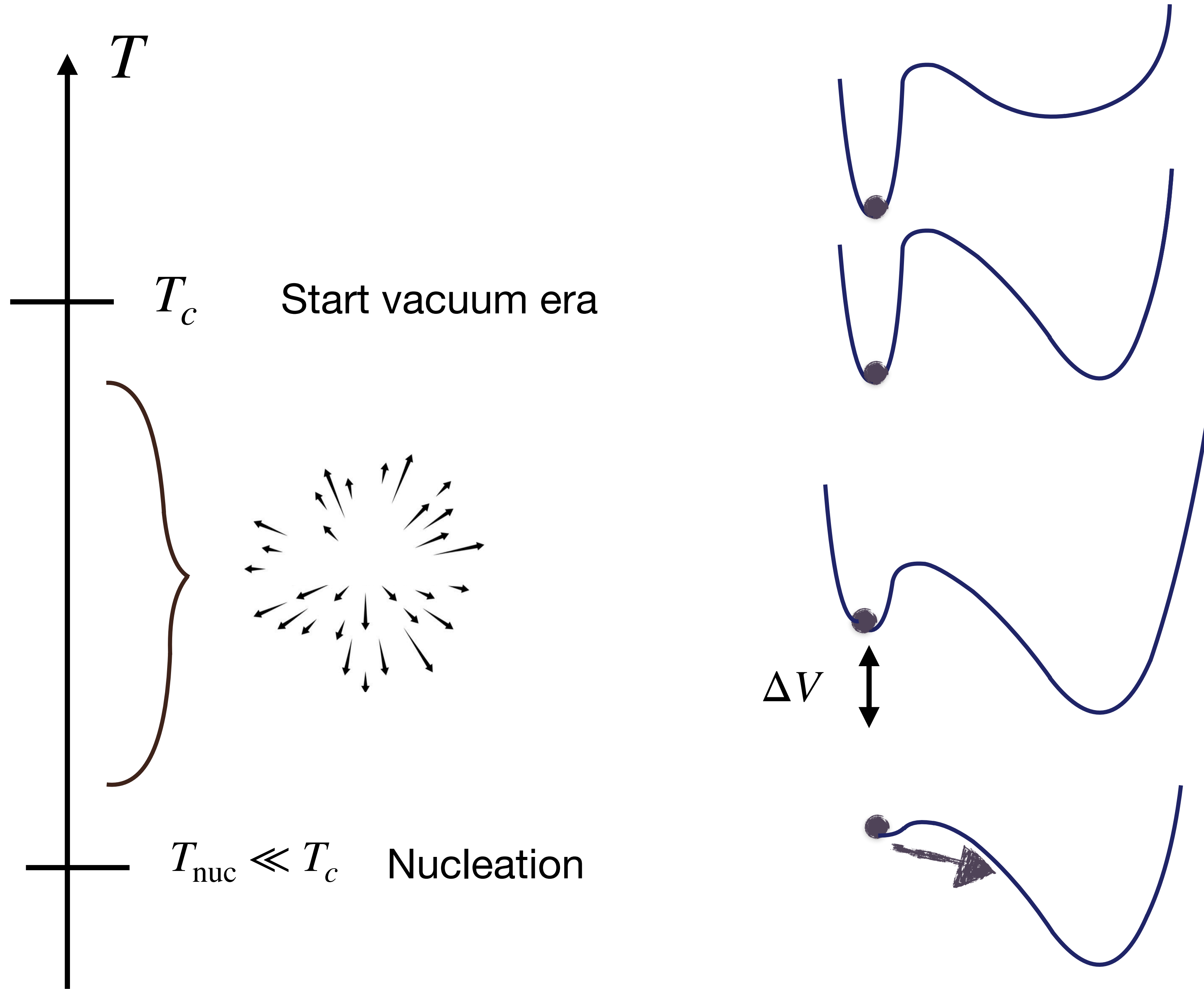
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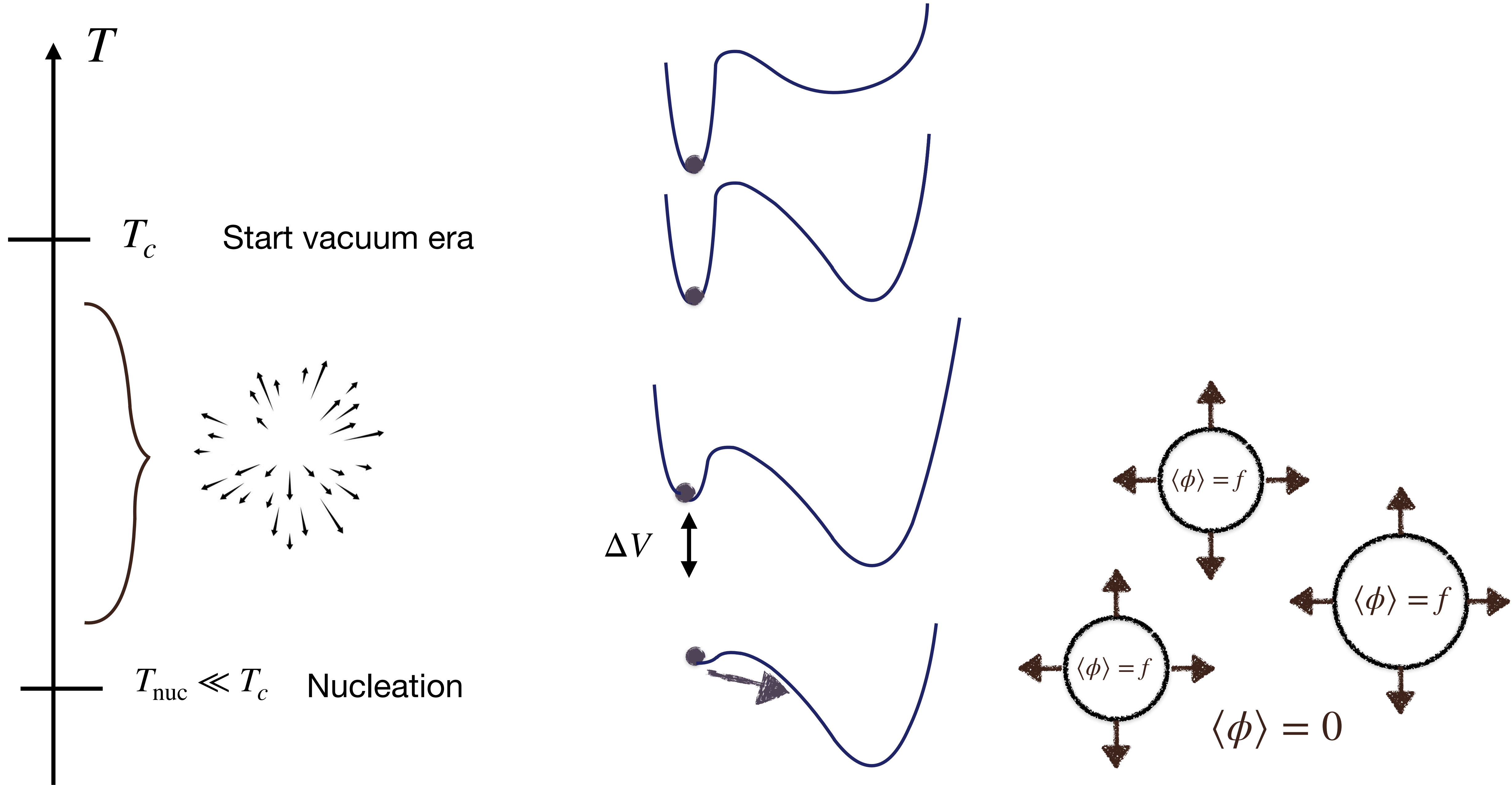


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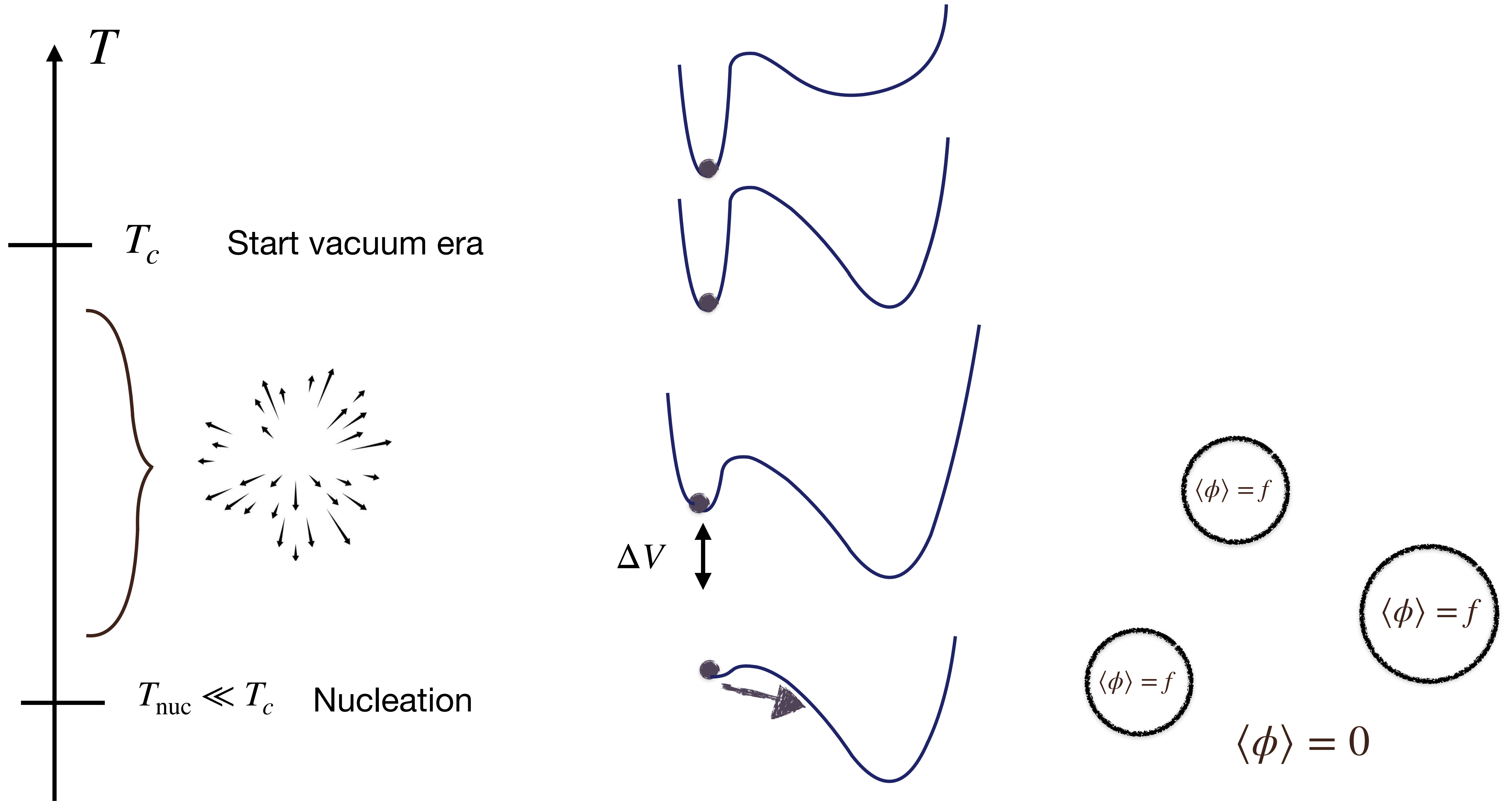




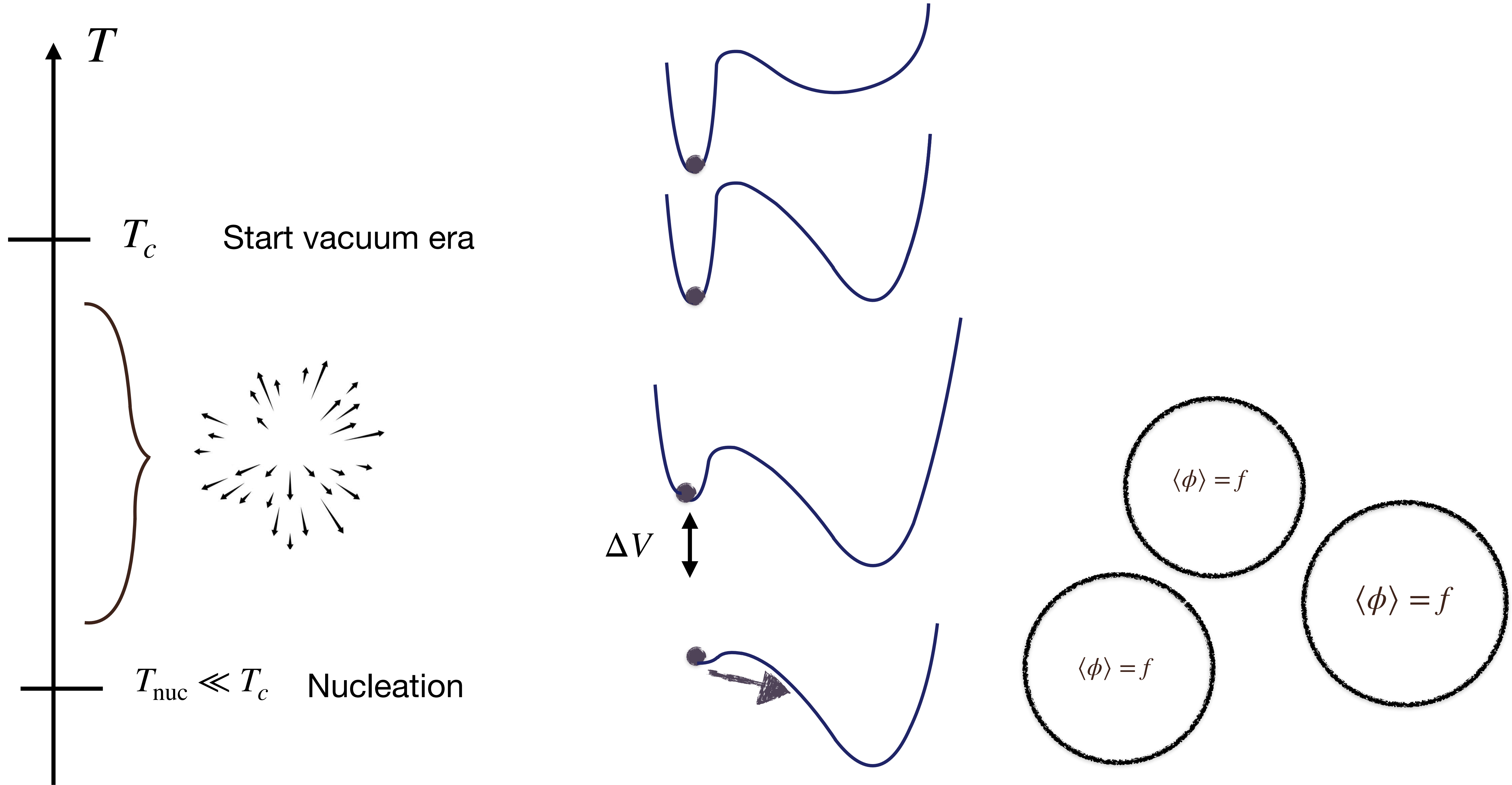
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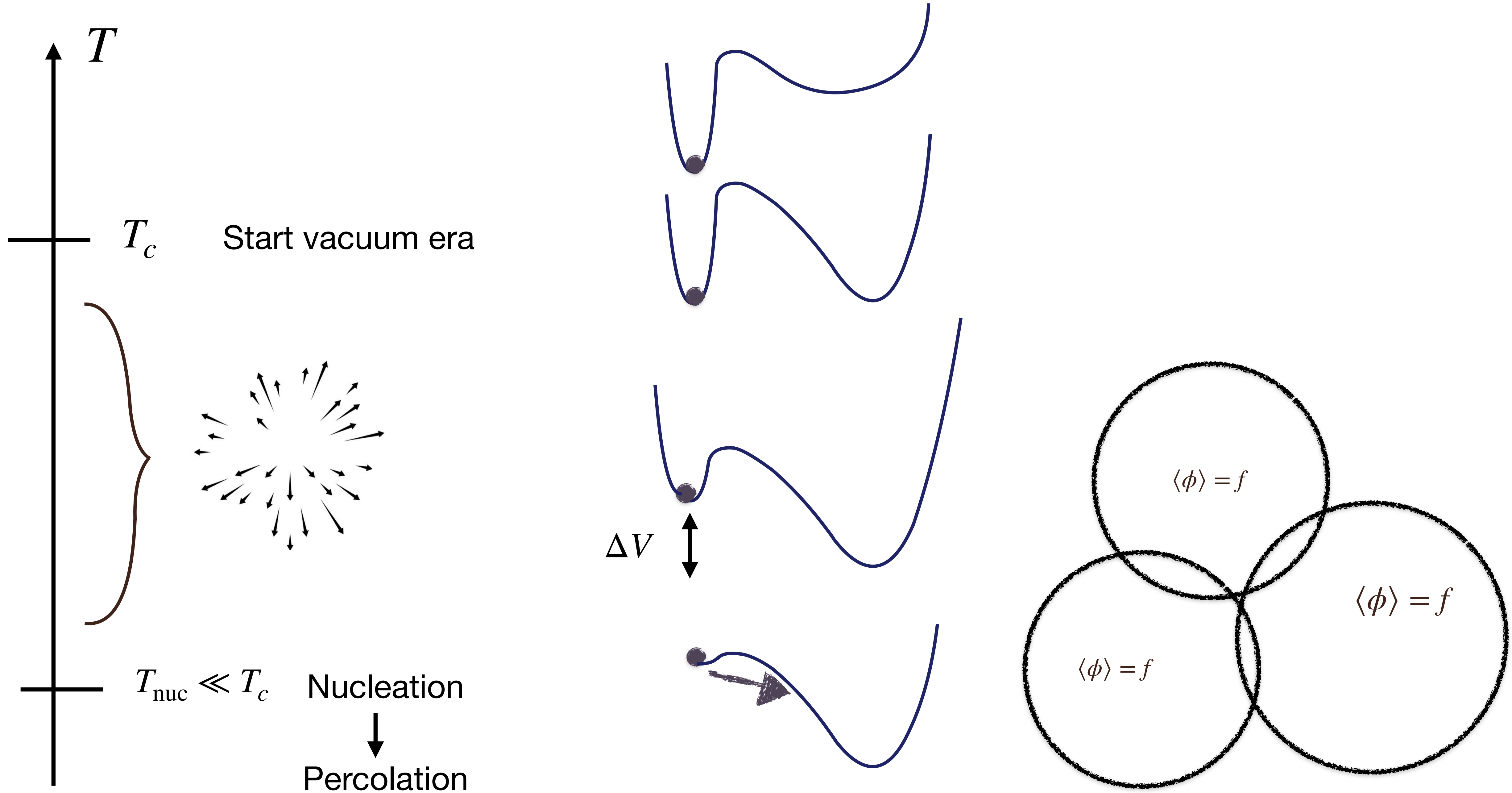
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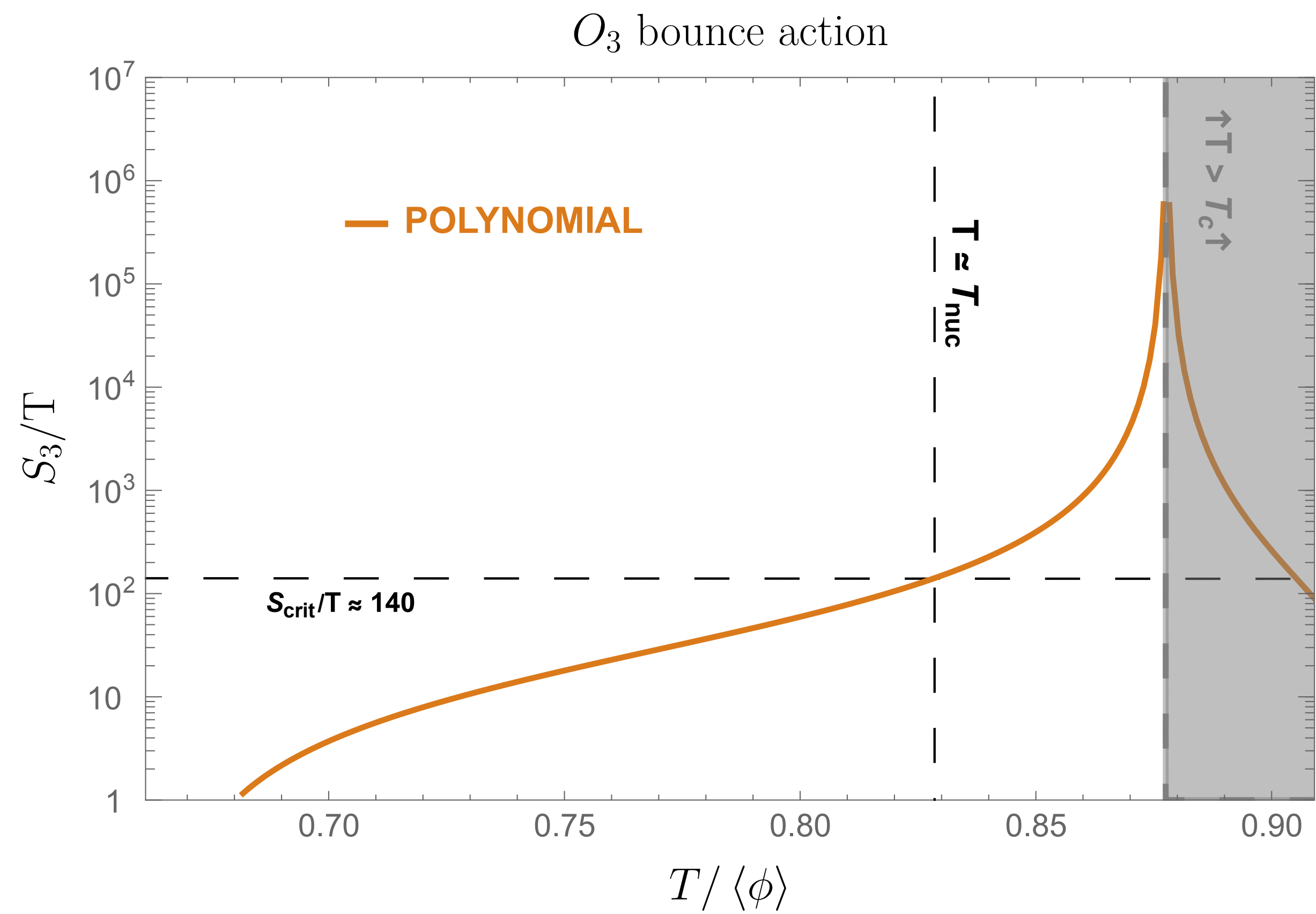
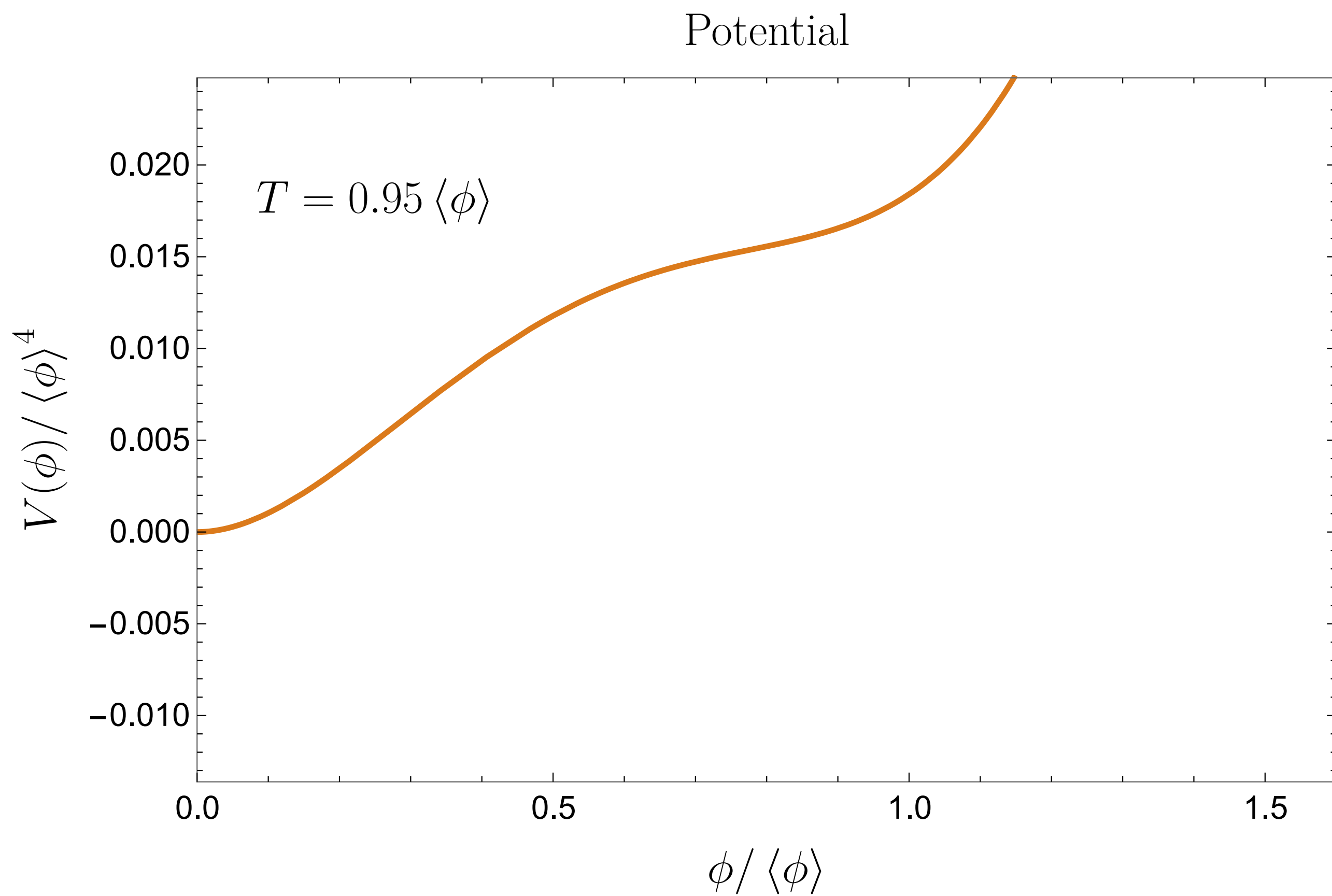
# Supercooled 1stOPT = Hierarchical PT



**What kind of particle physics model lead to supercooling ?**

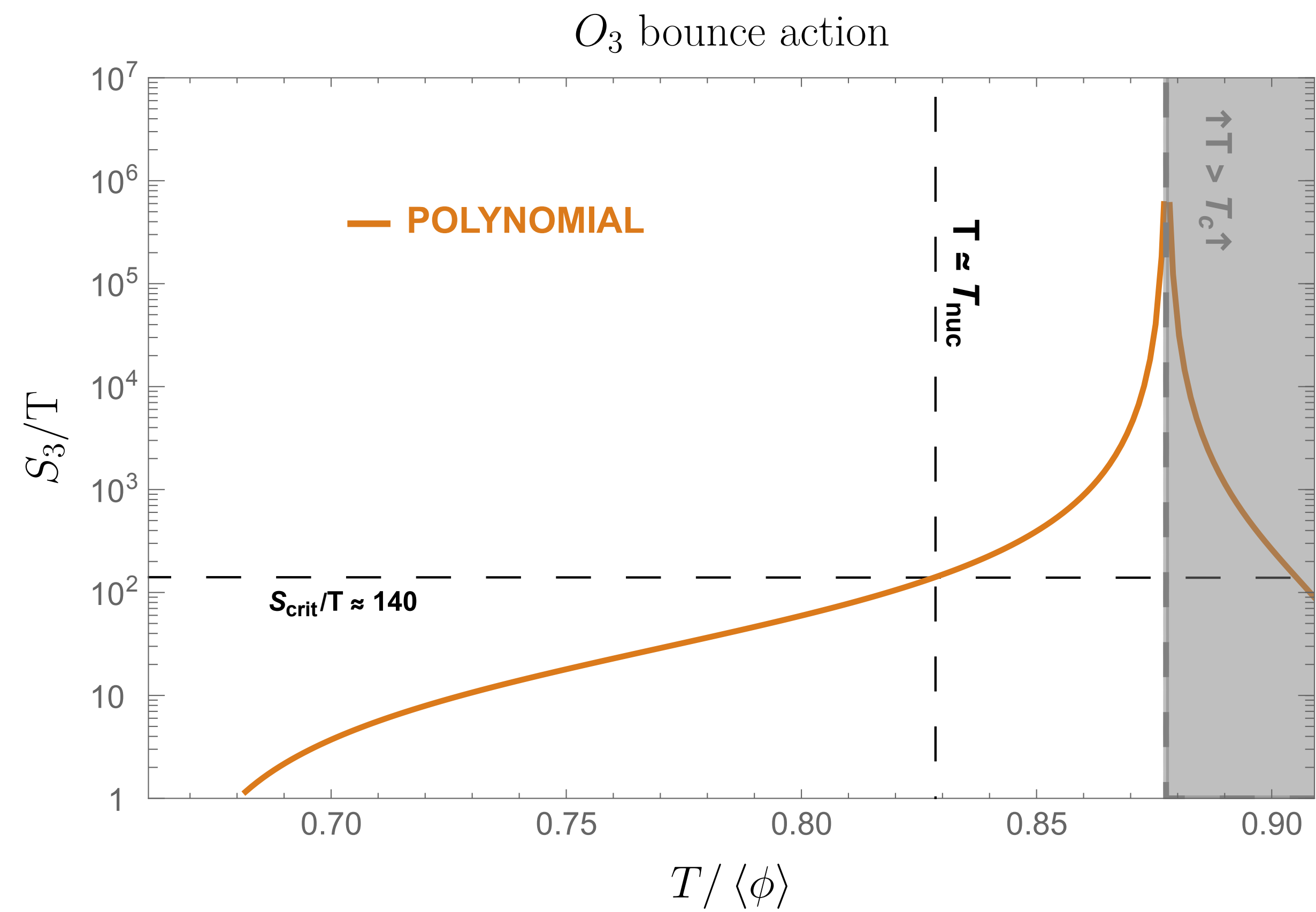
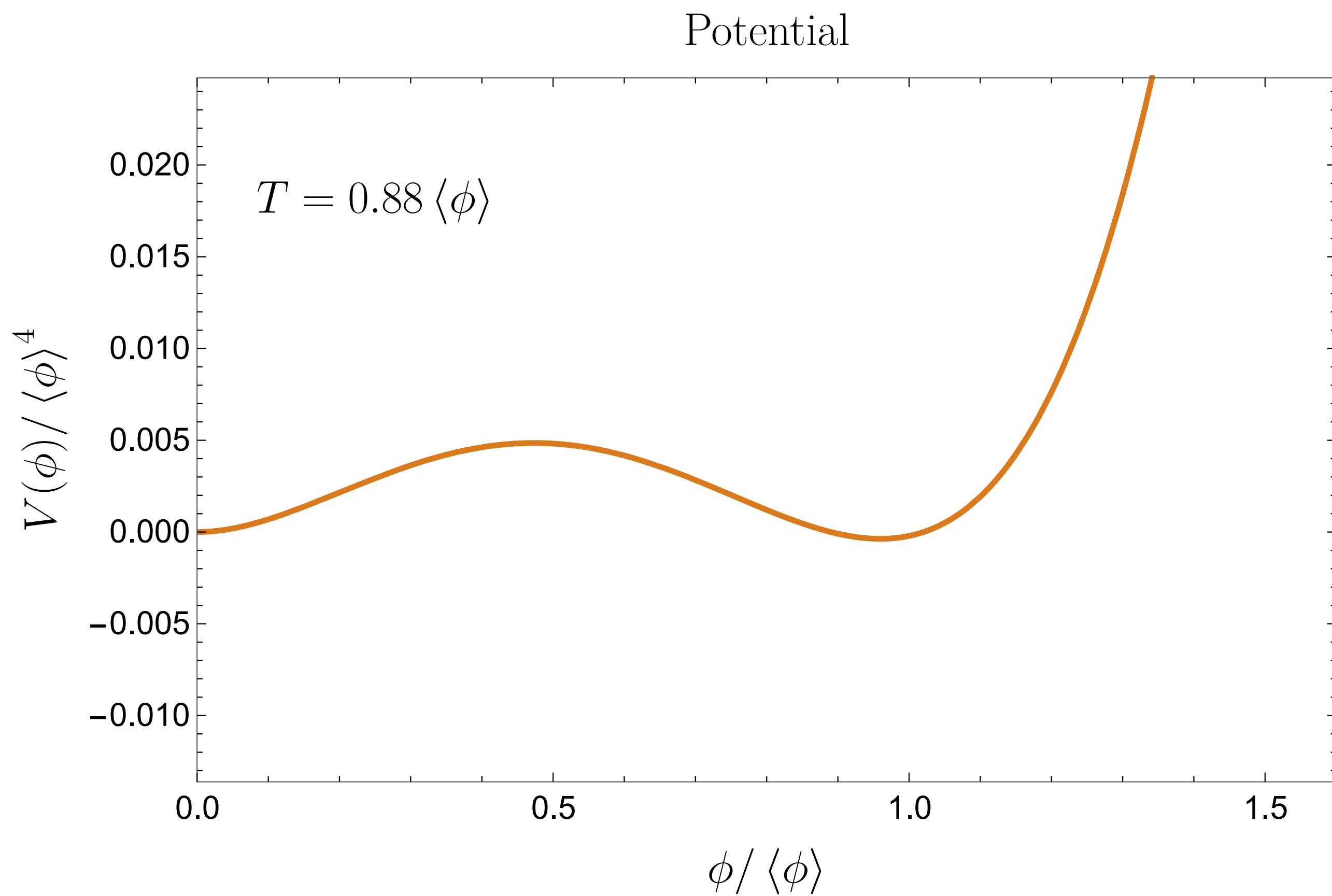
# POLYNOMIAL POTENTIAL

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



# POLYNOMIAL POTENTIAL

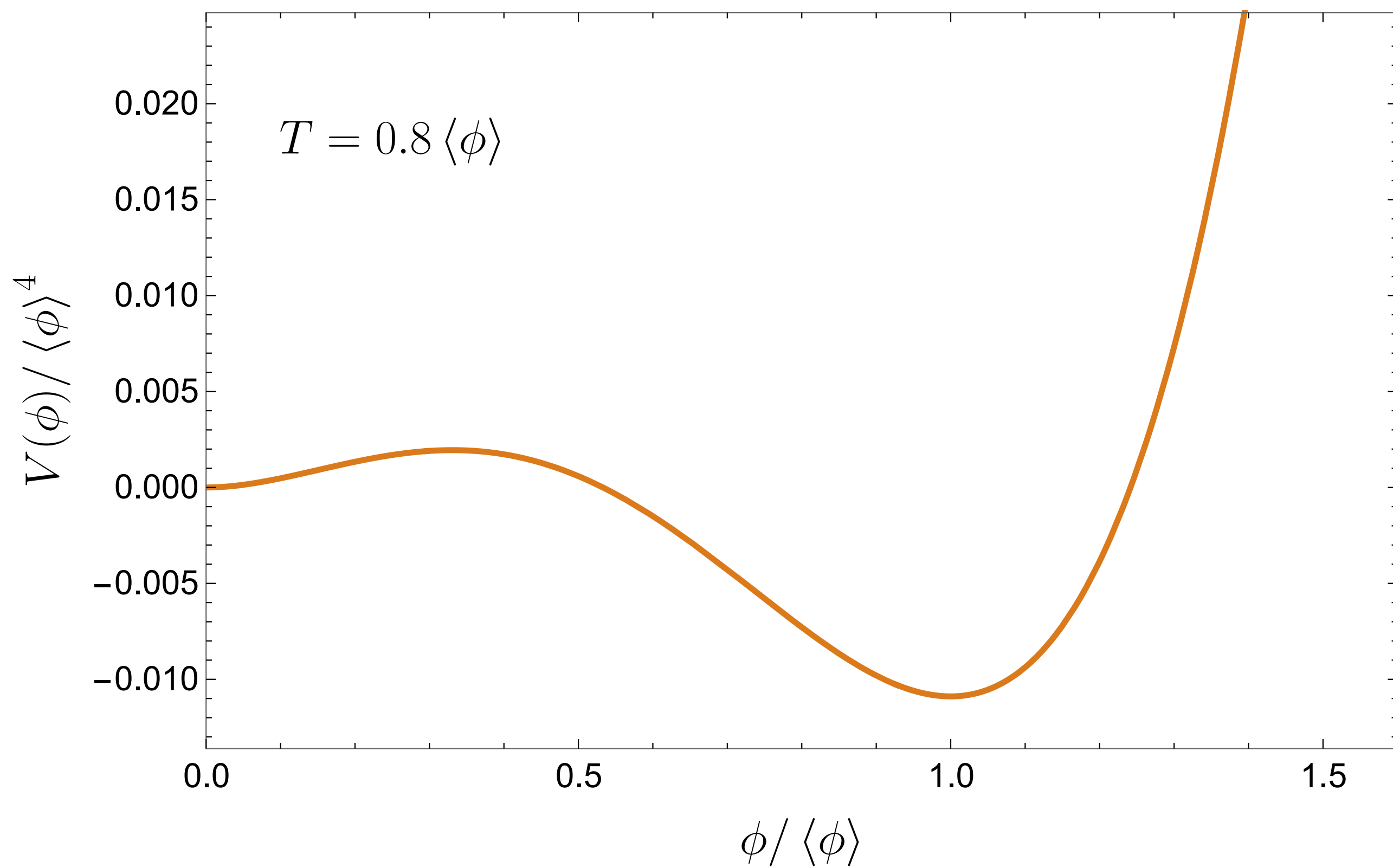
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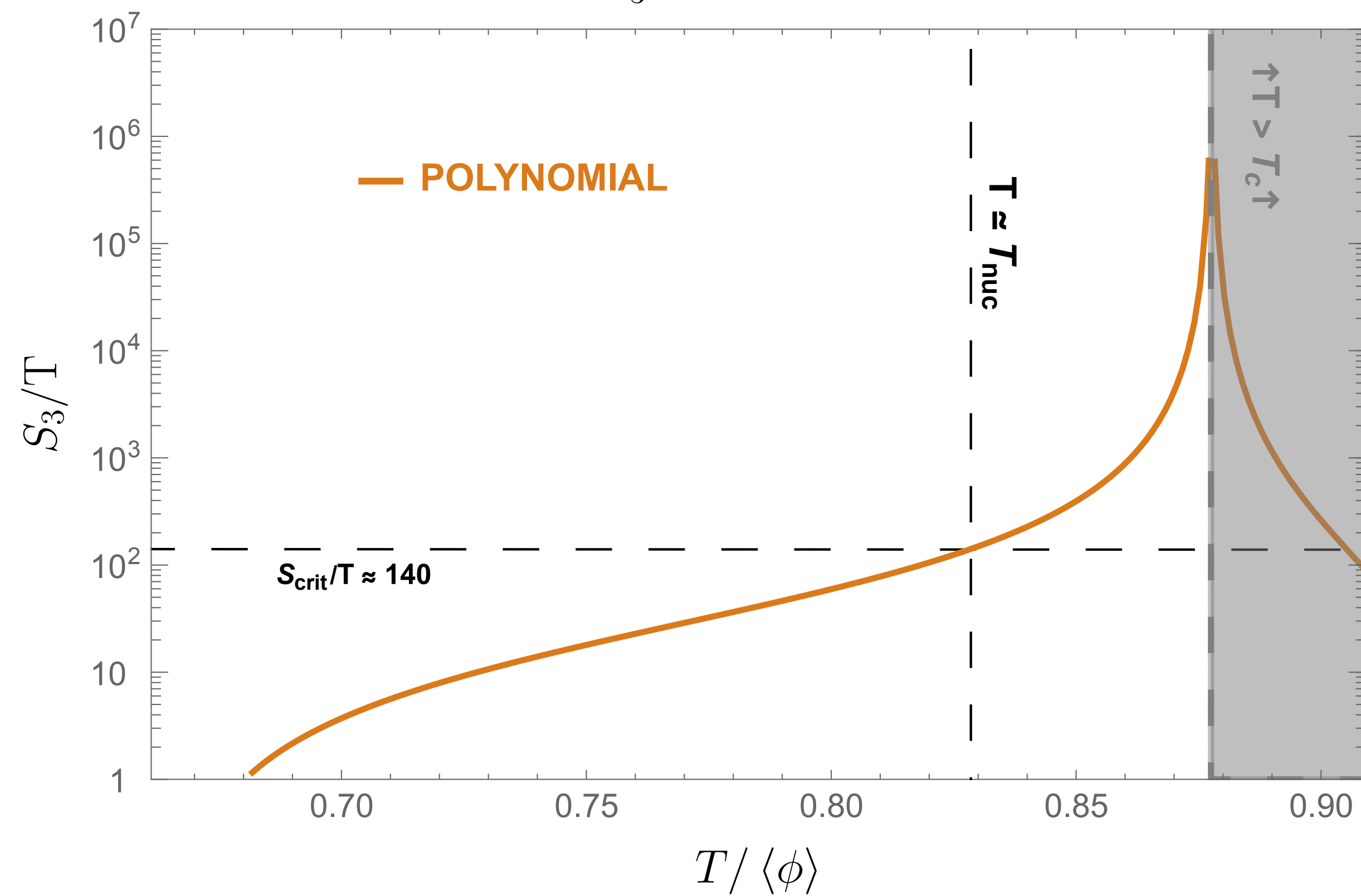
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Potential



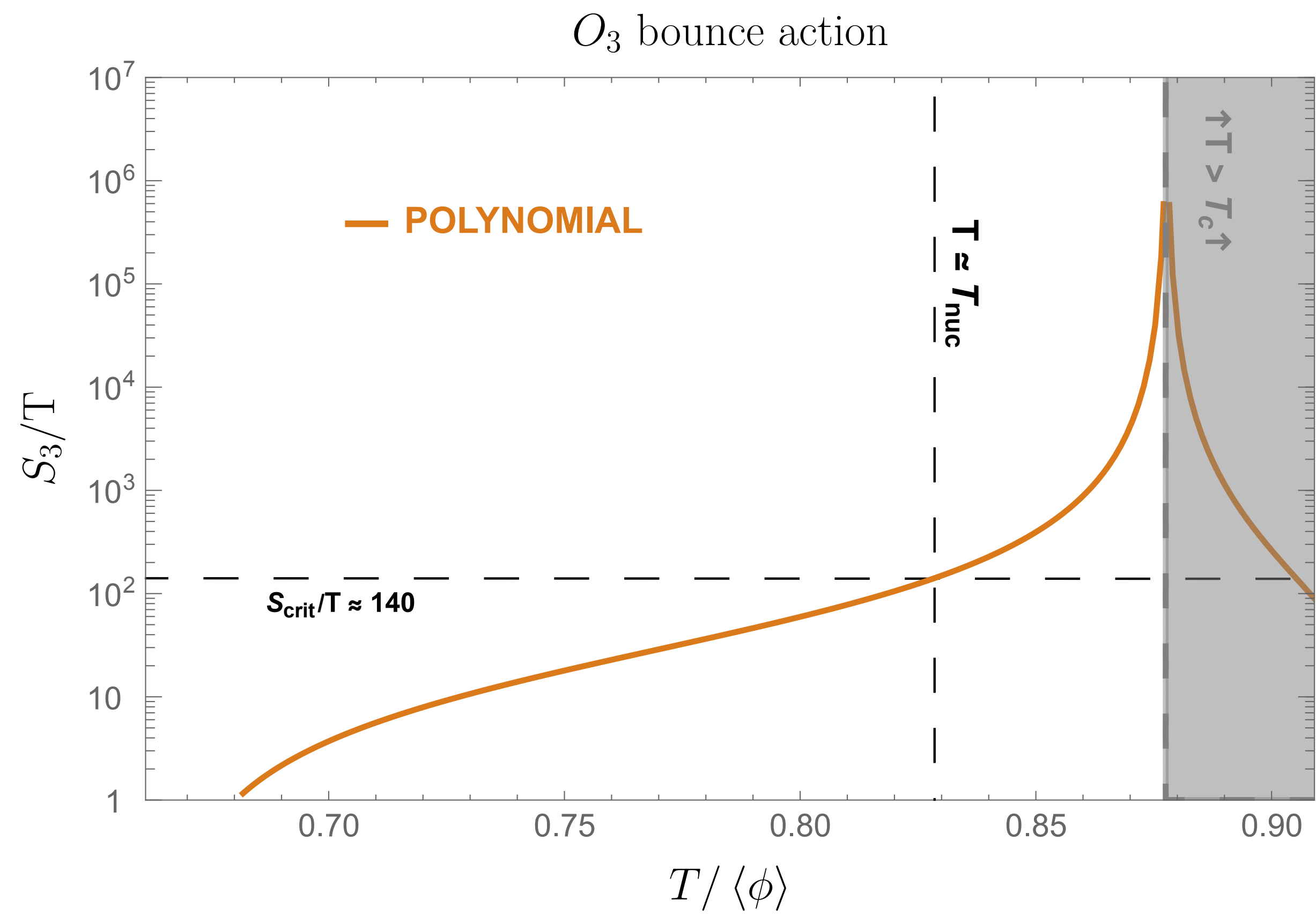
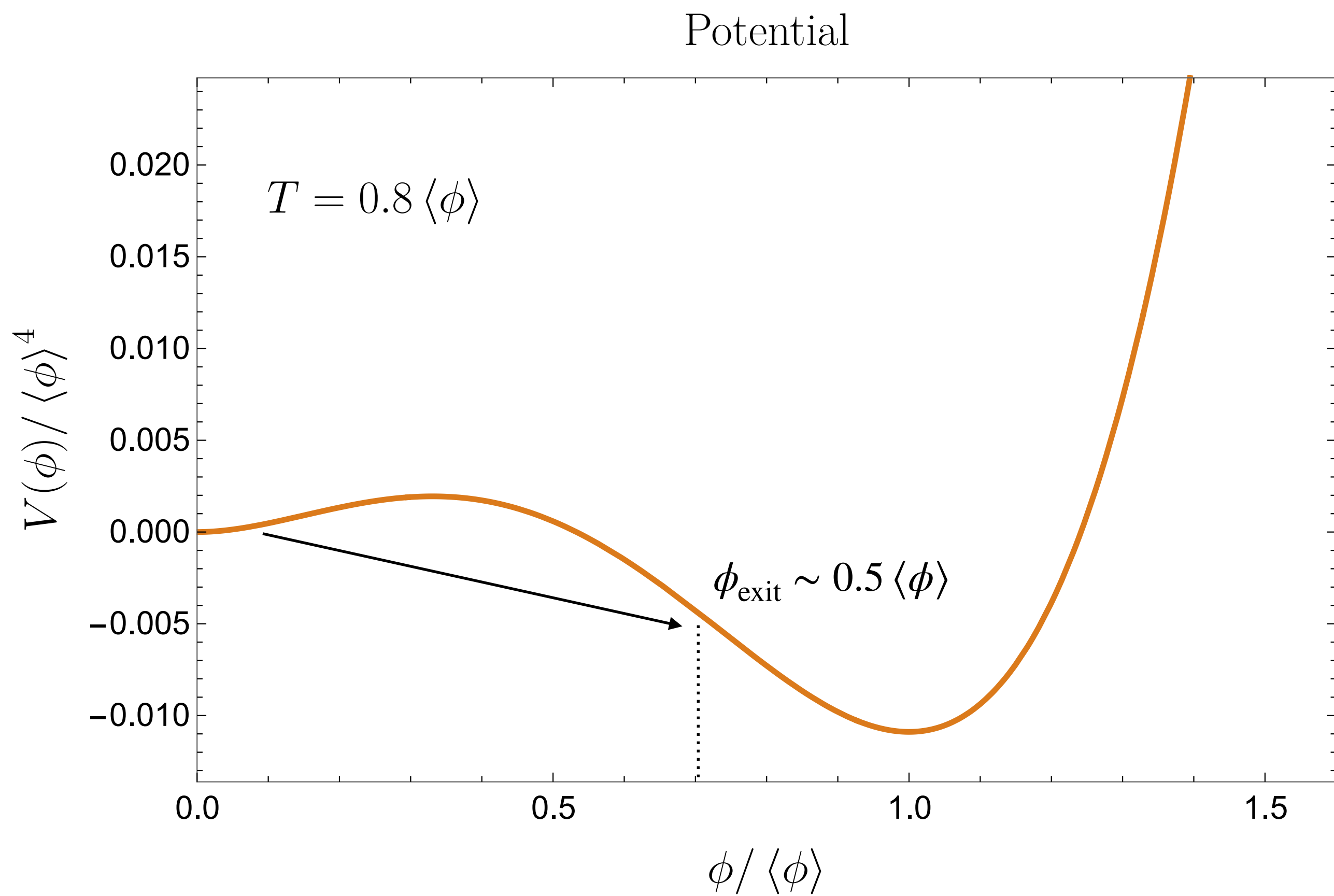
$O_3$  bounce action





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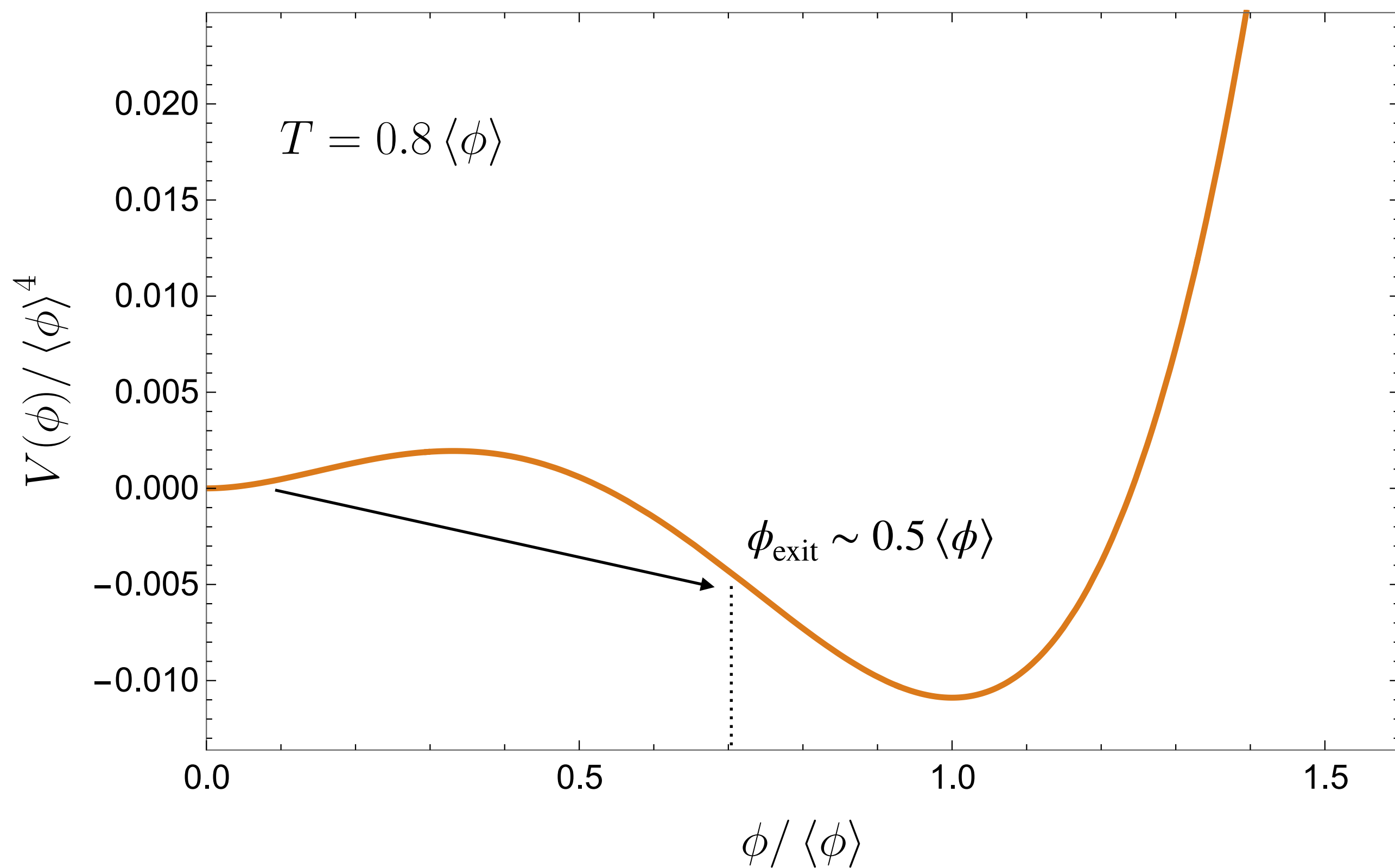
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VS

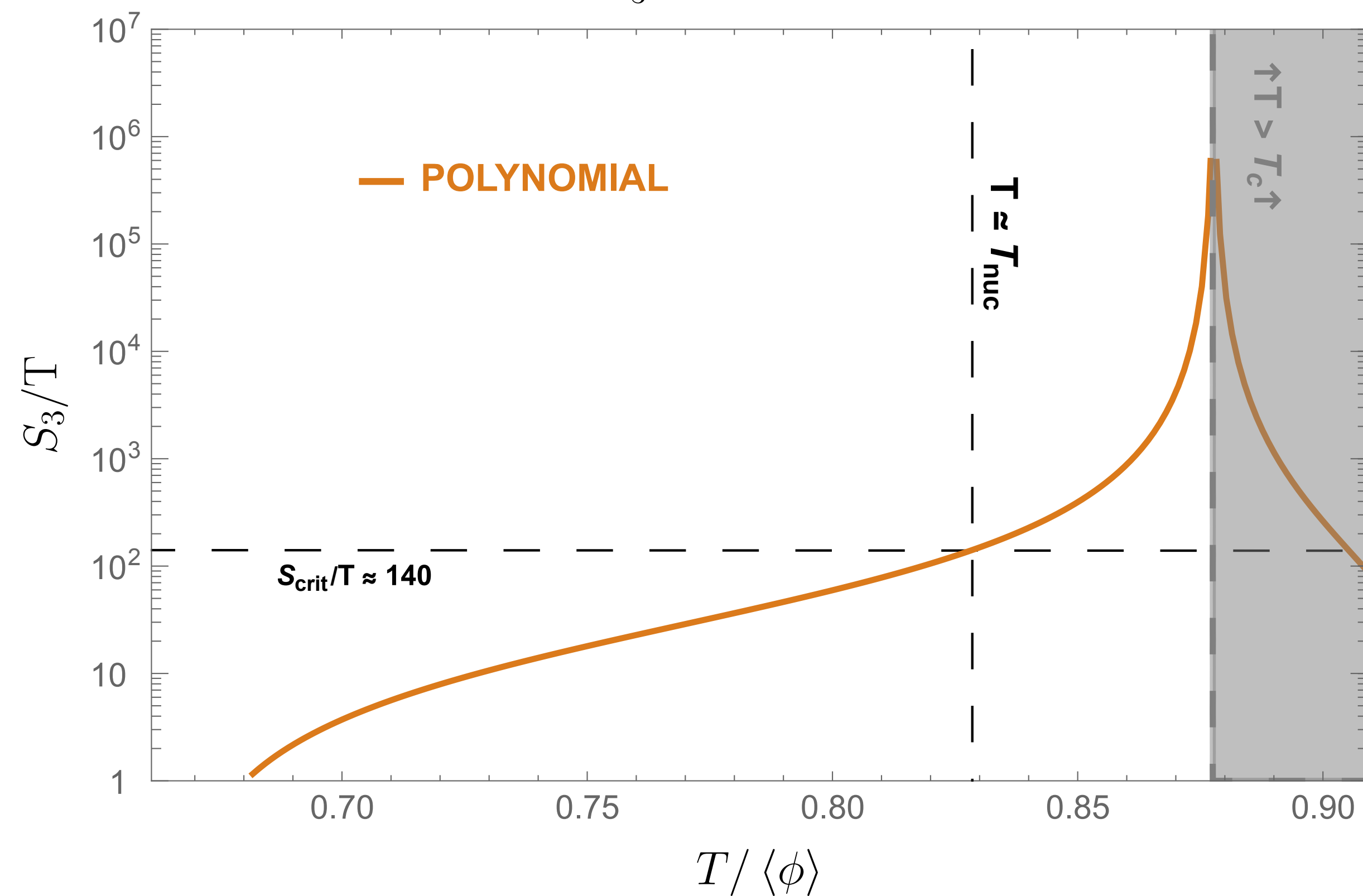
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Potential



$O_3$  bounce action



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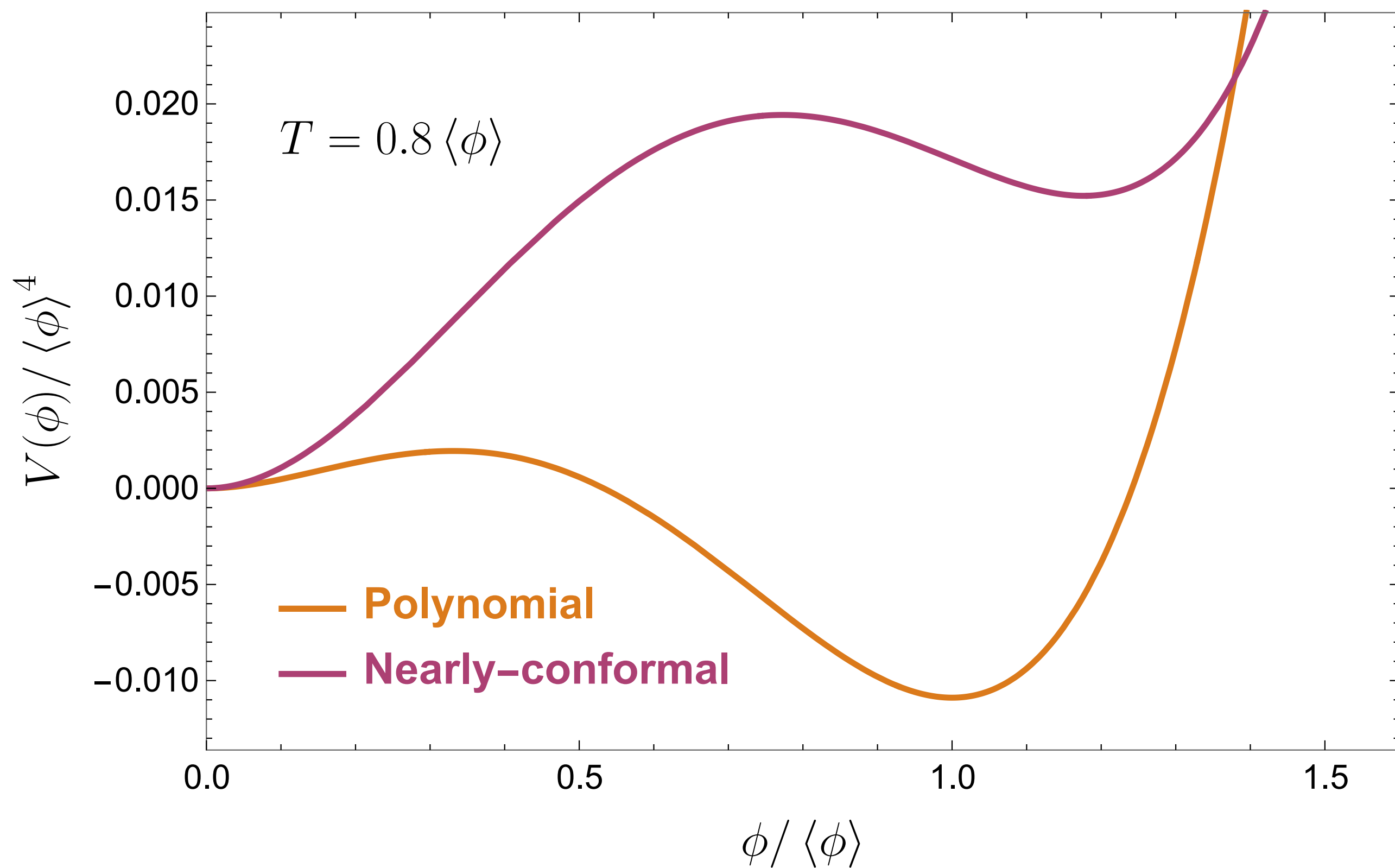
VS

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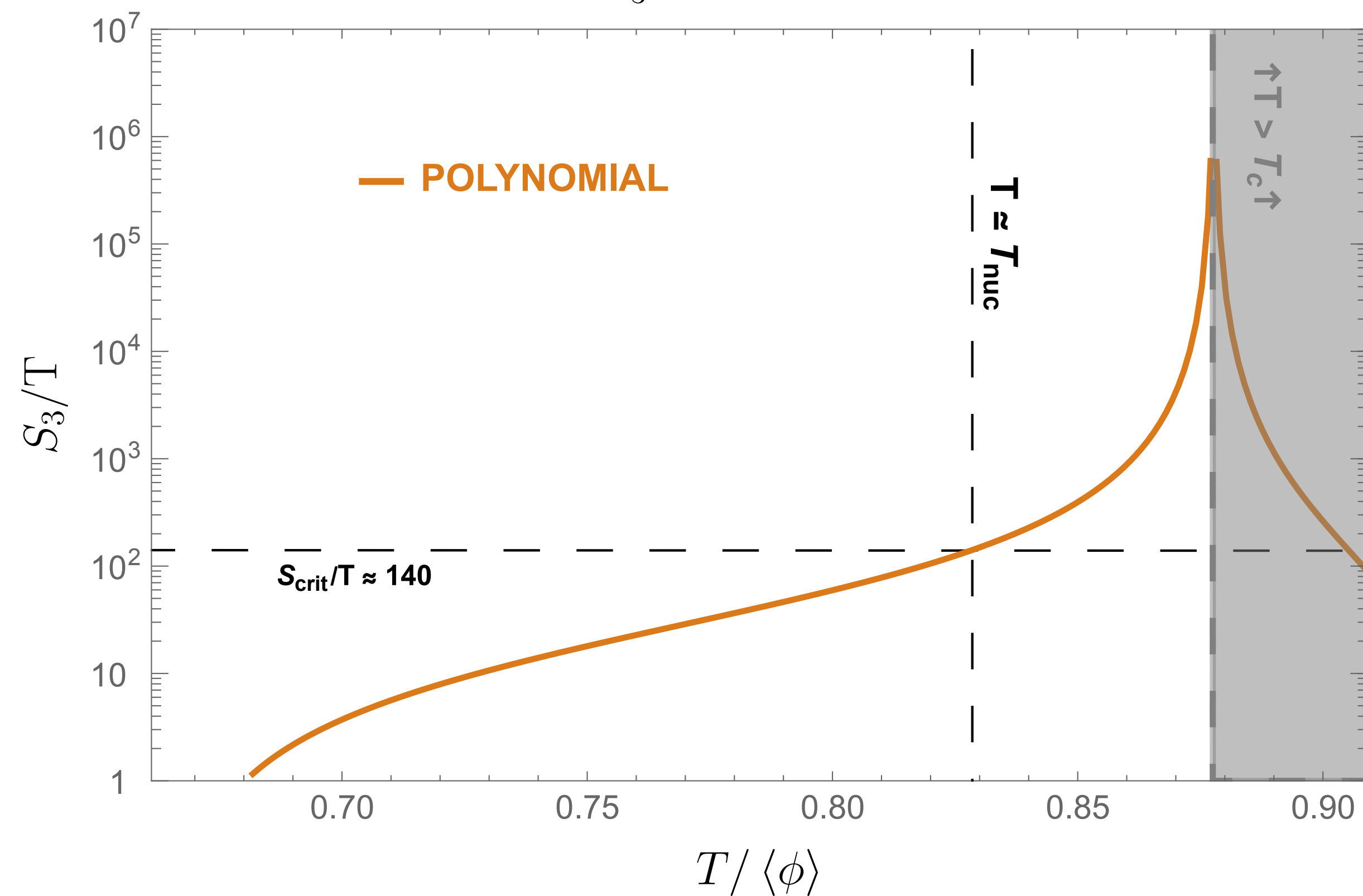
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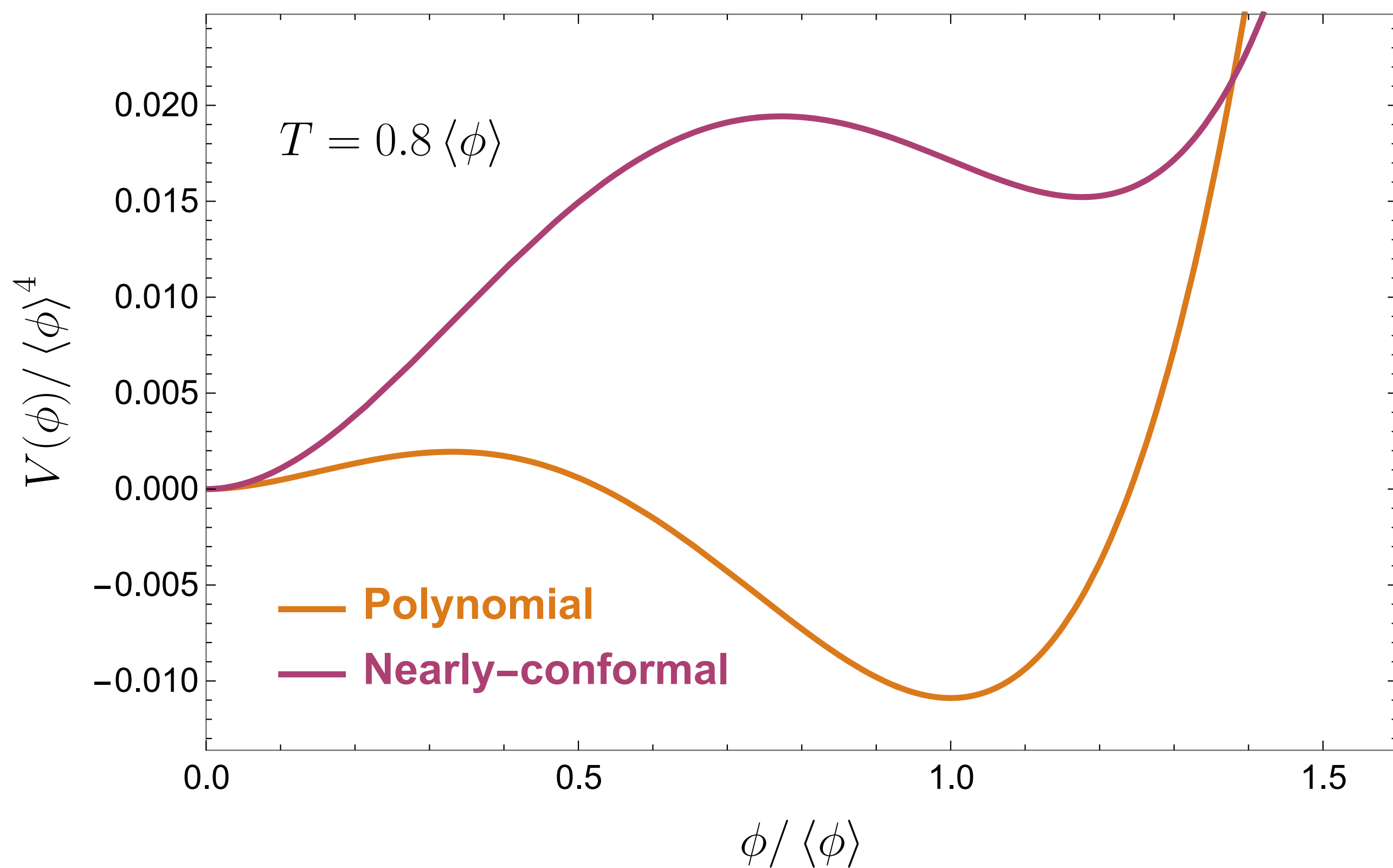
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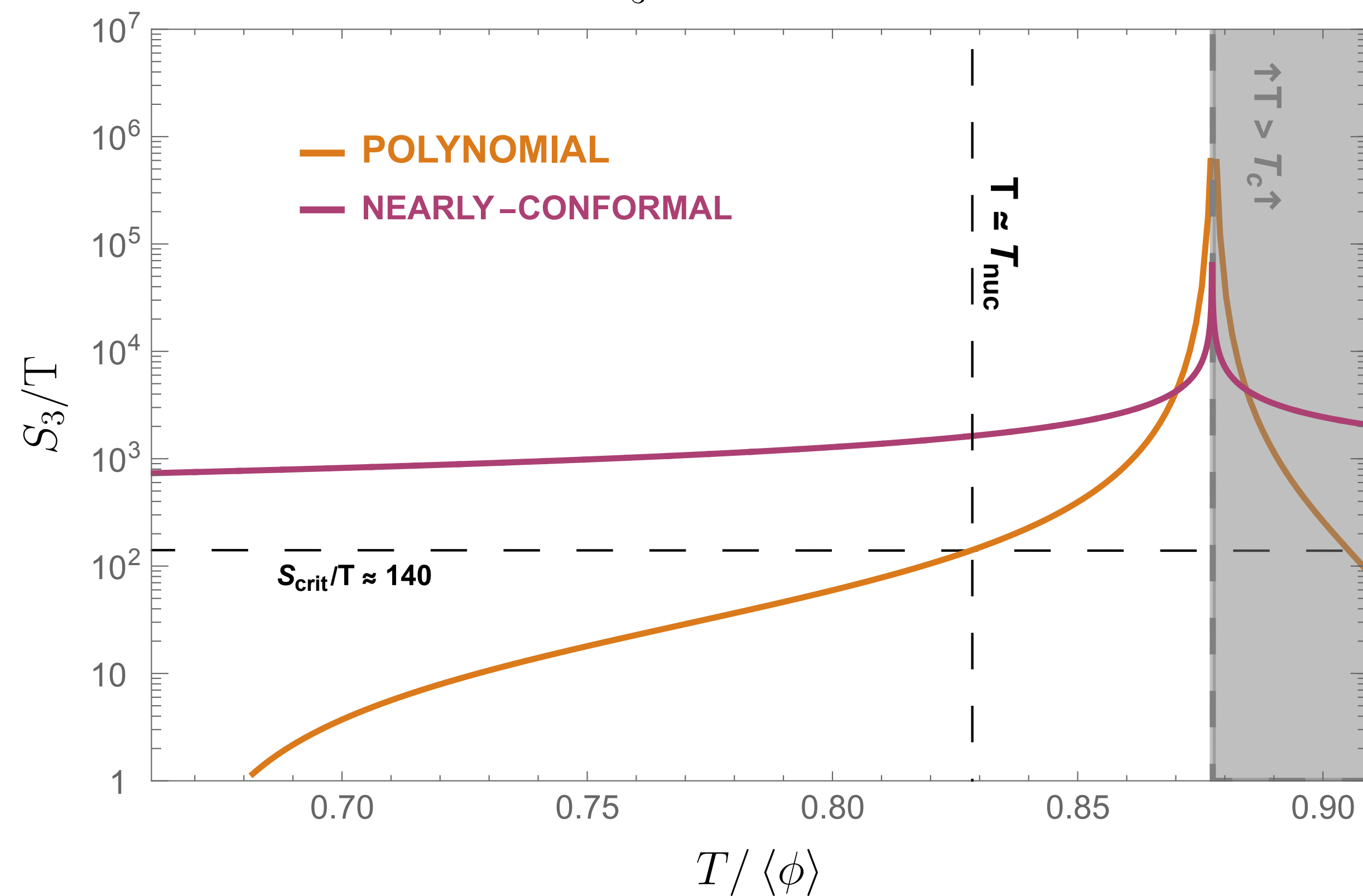
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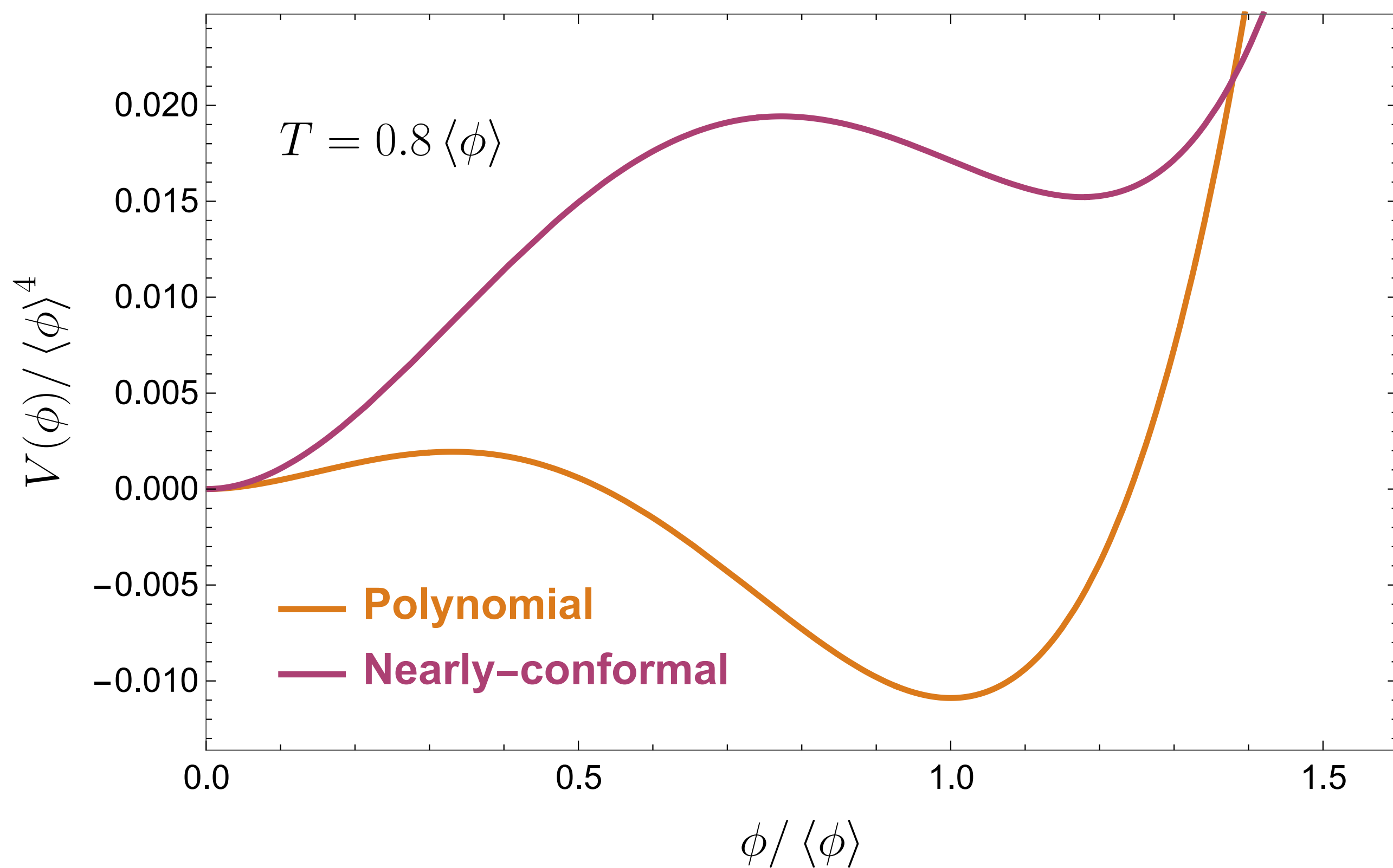
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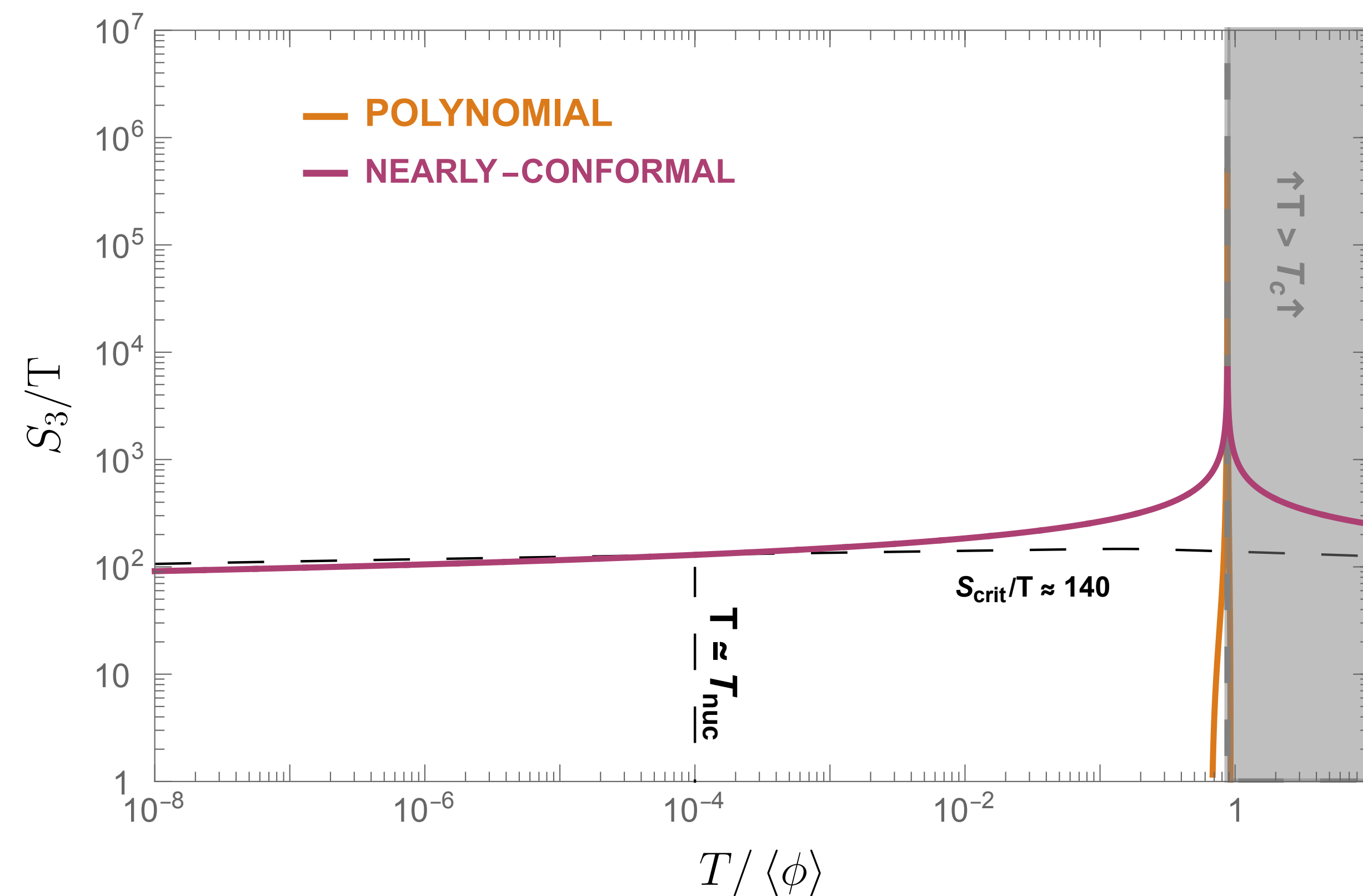
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VS

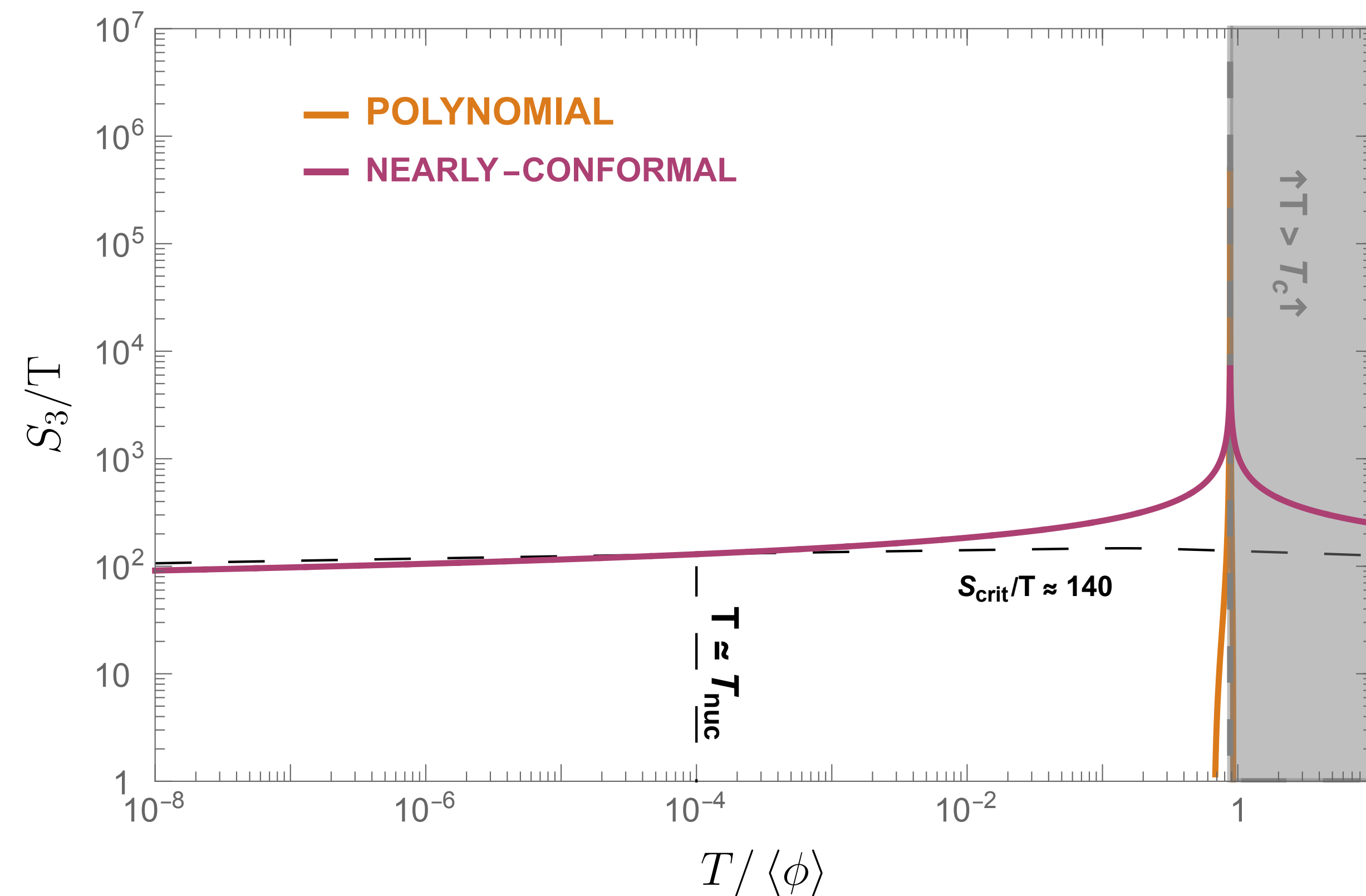
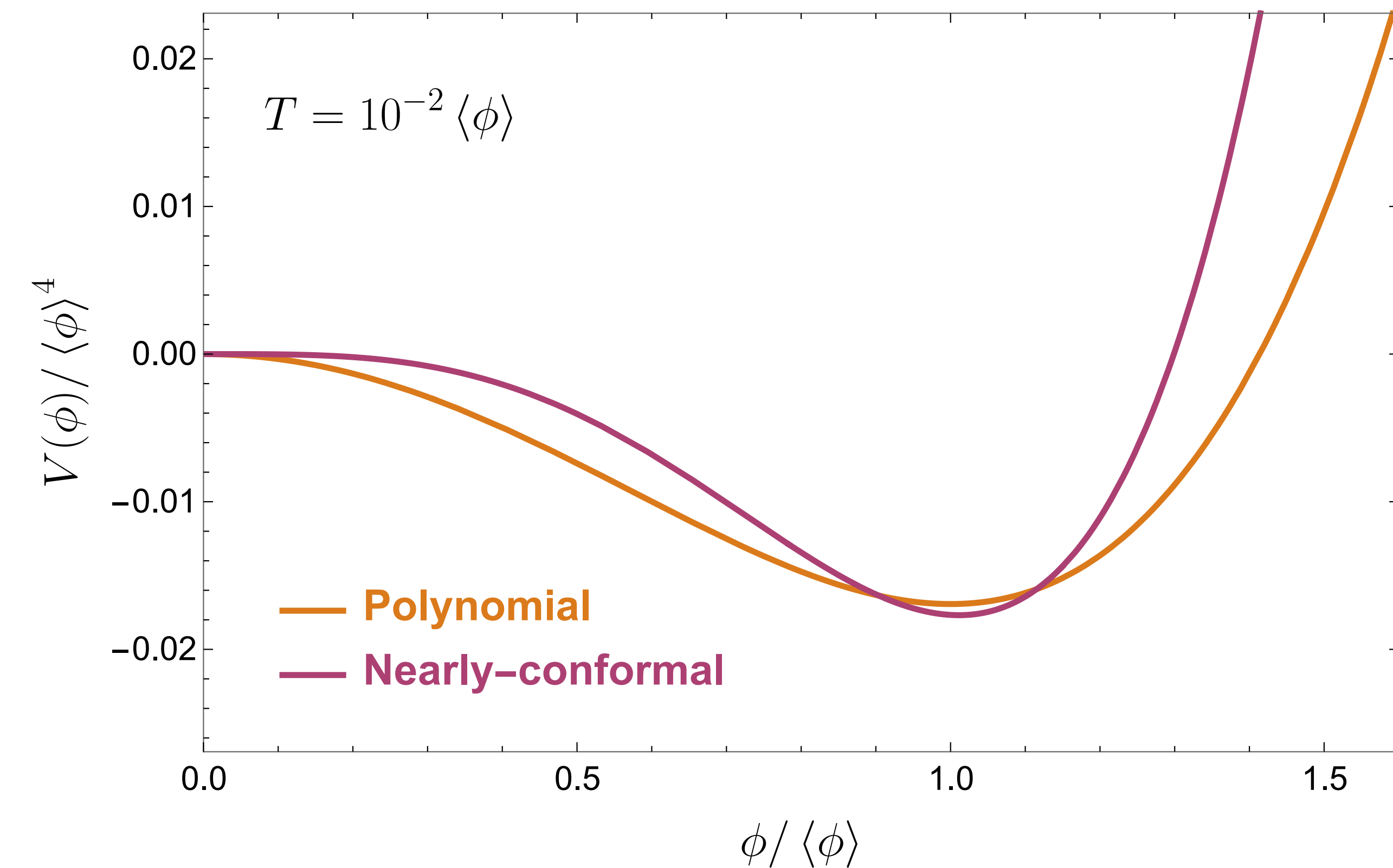
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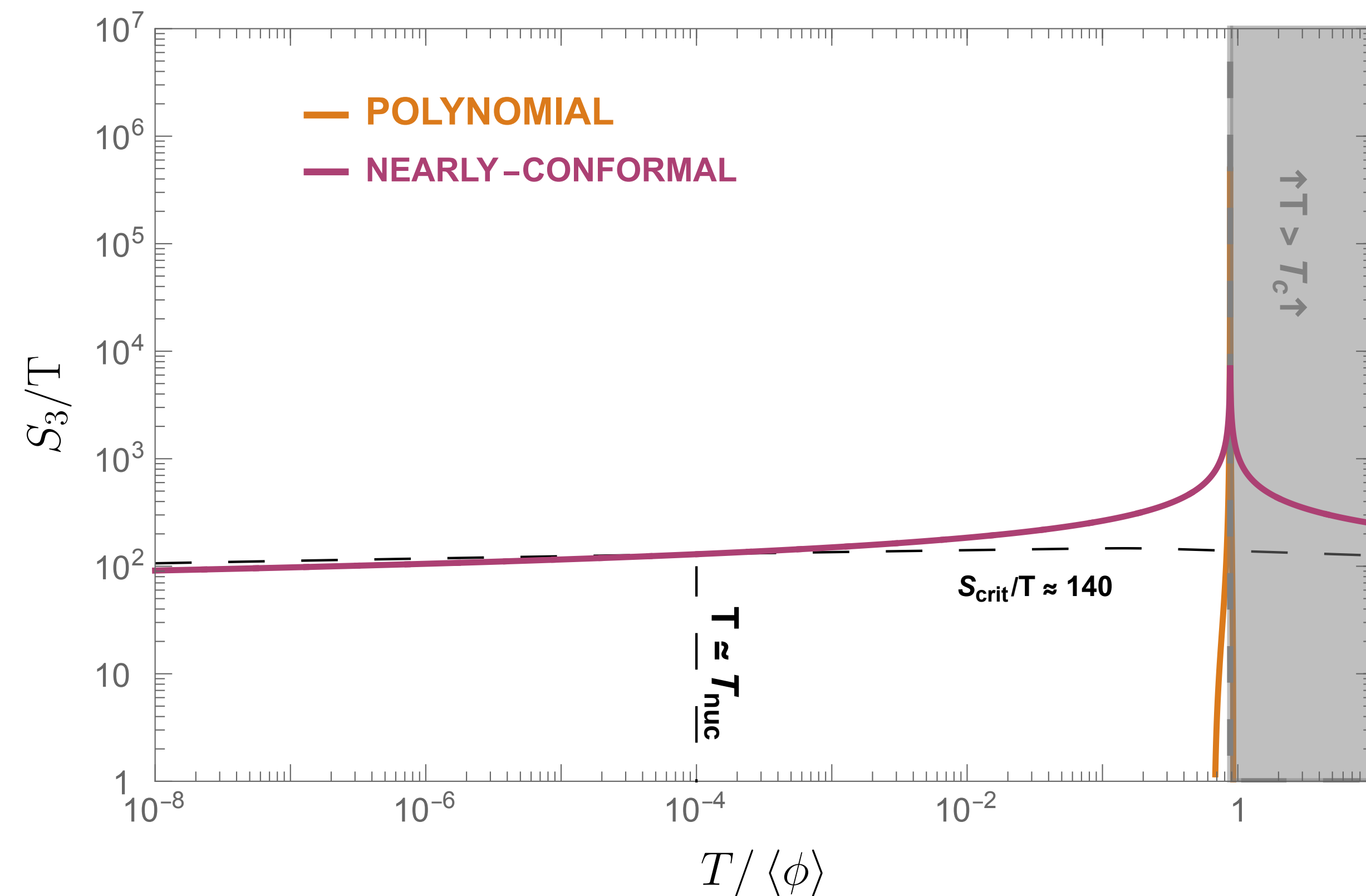
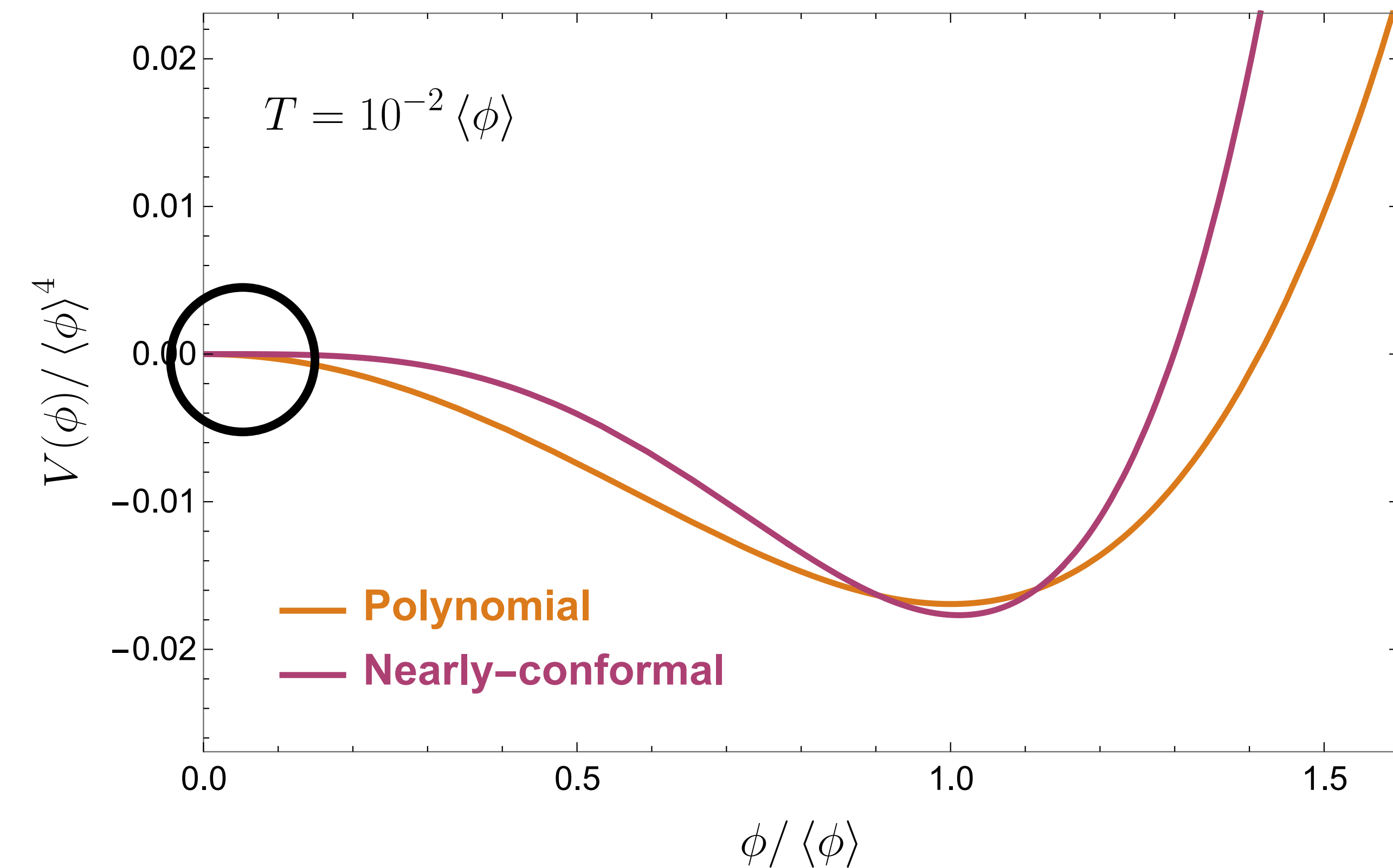
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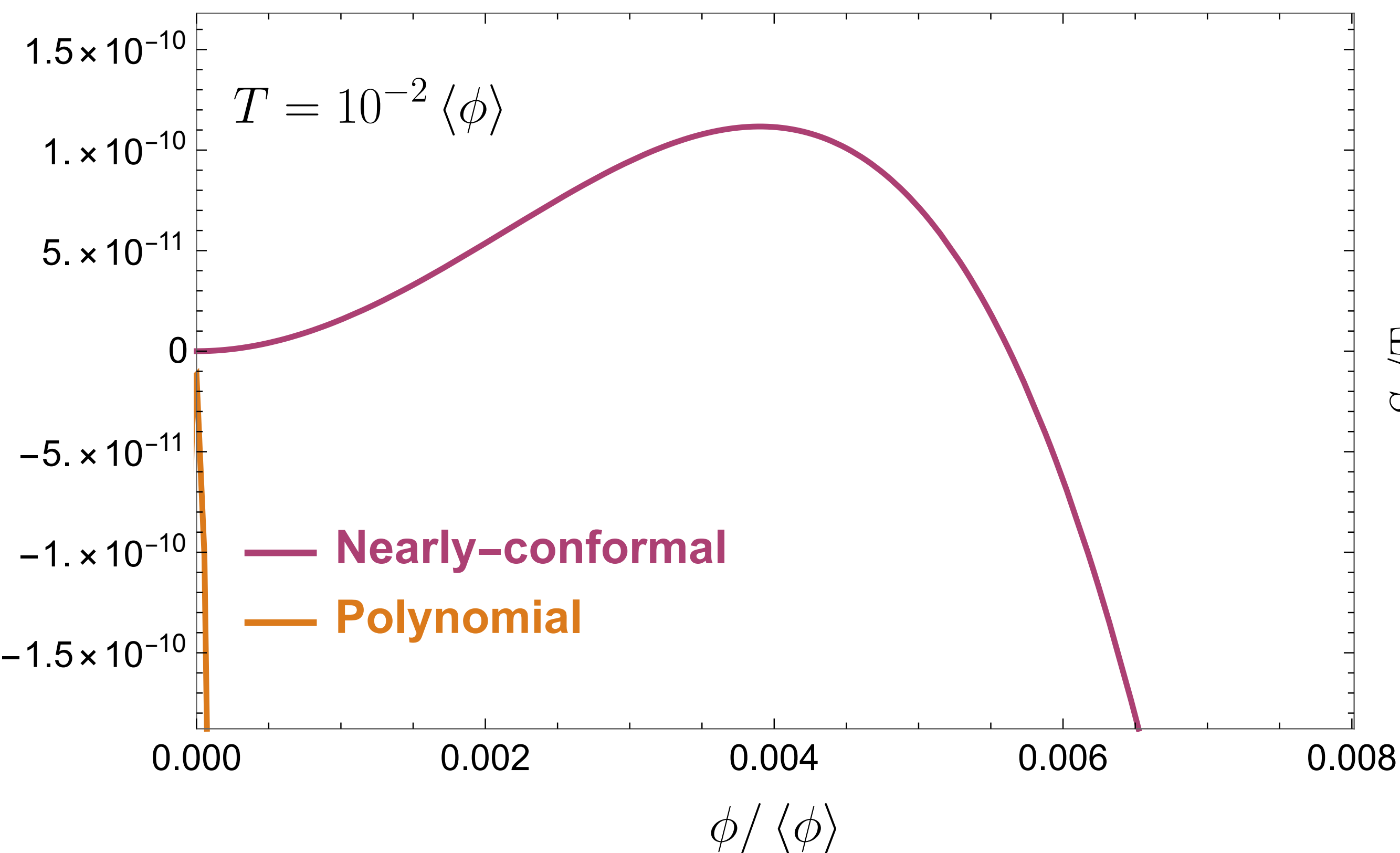
VS

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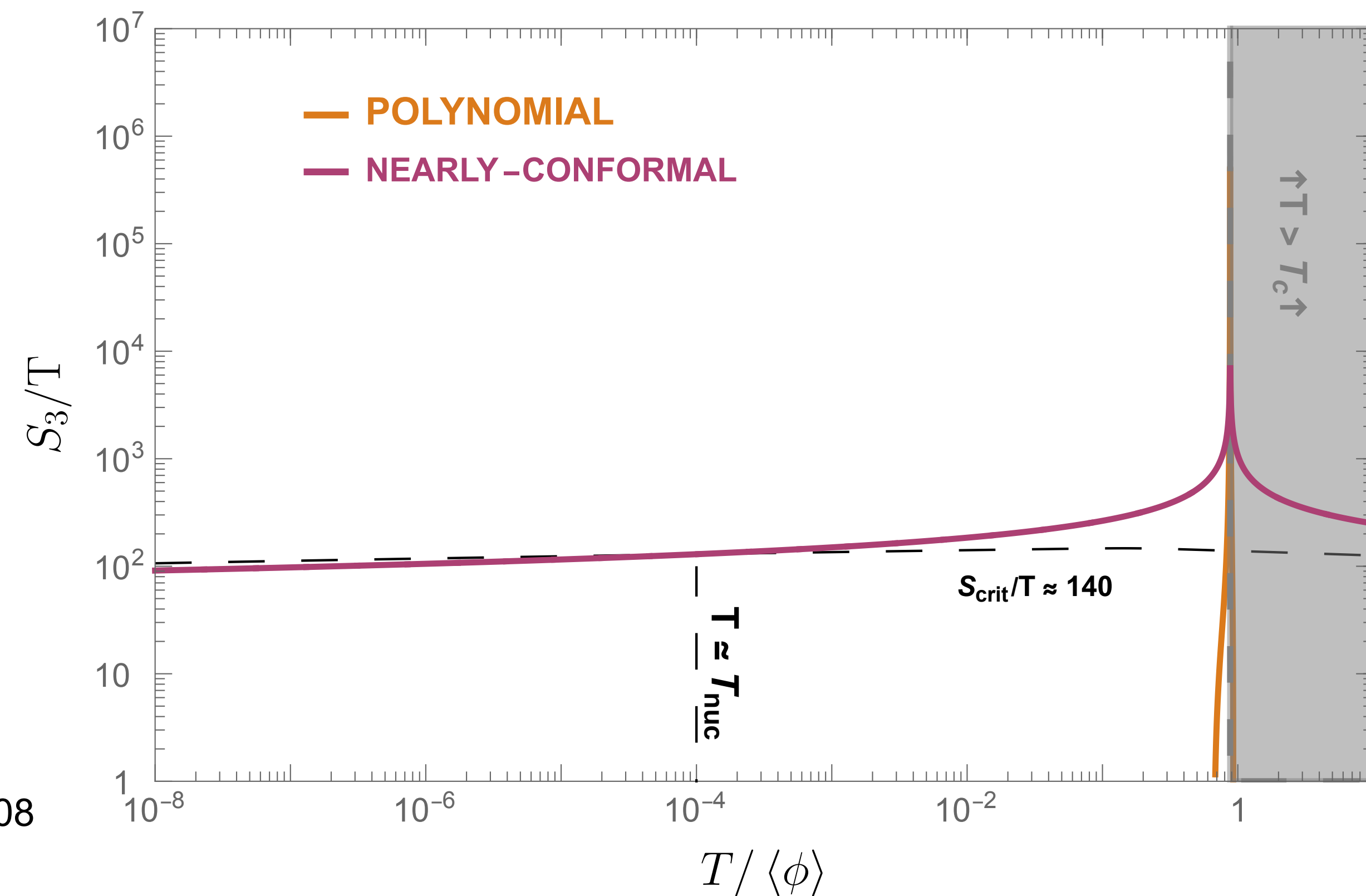
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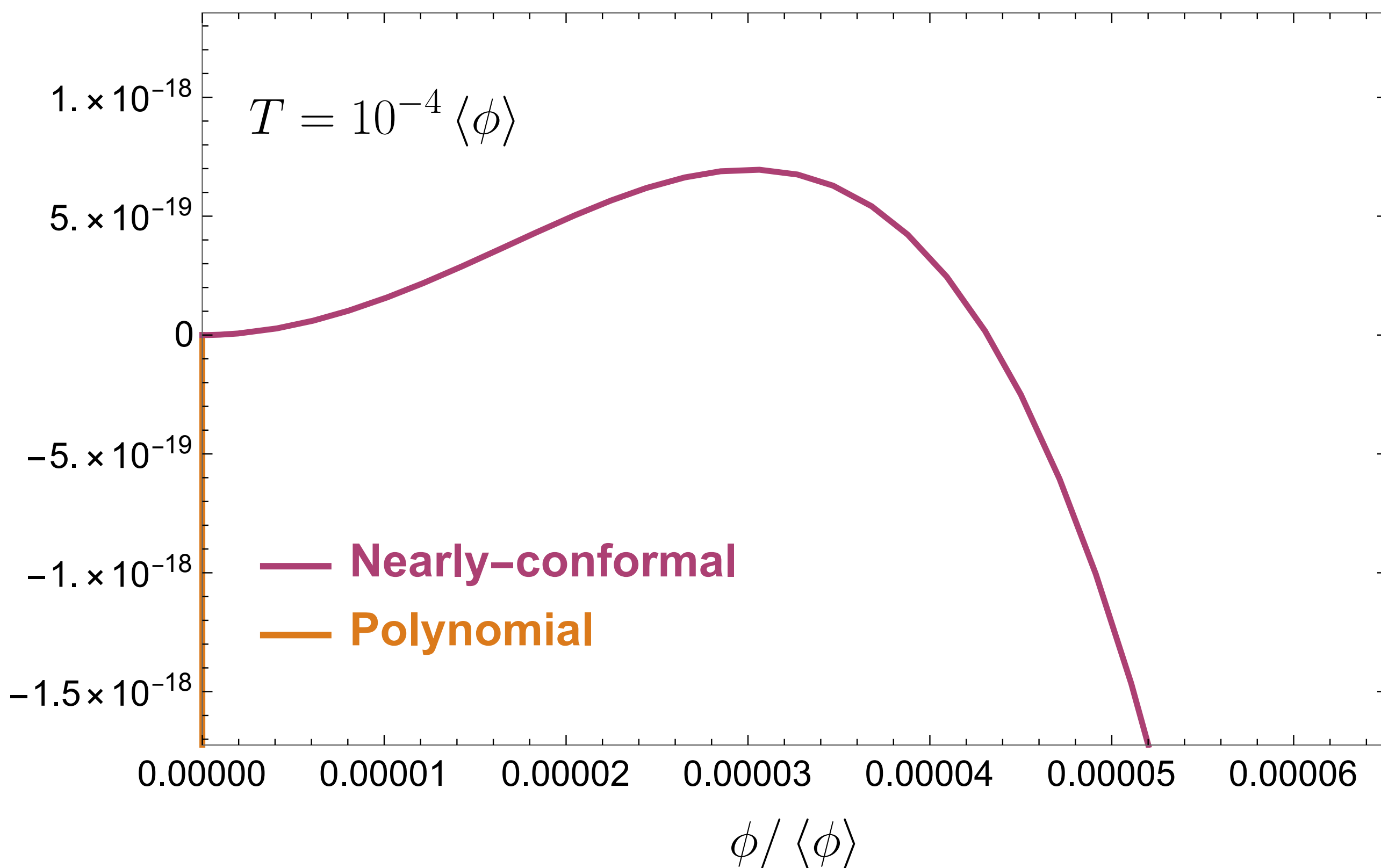
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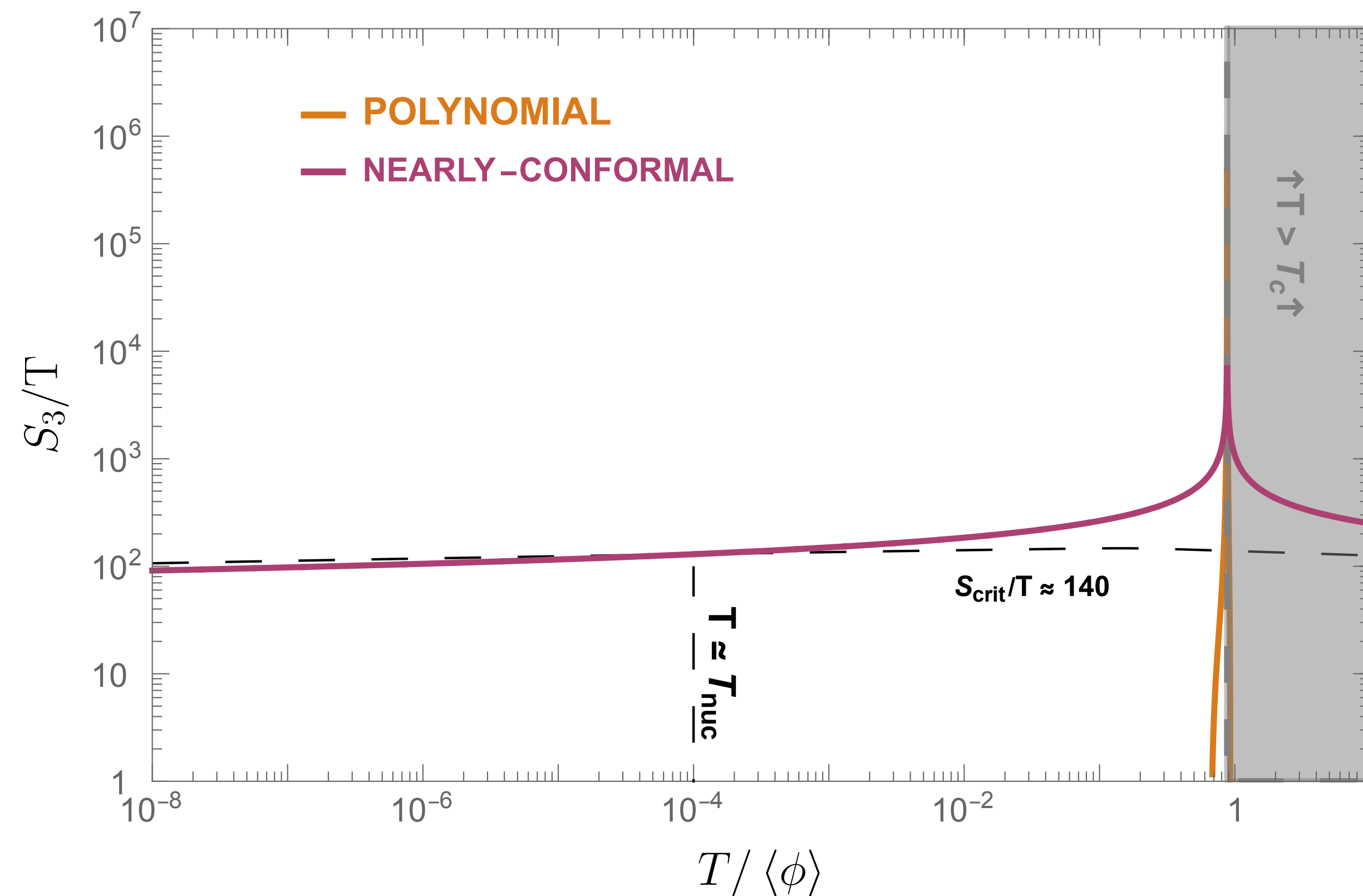
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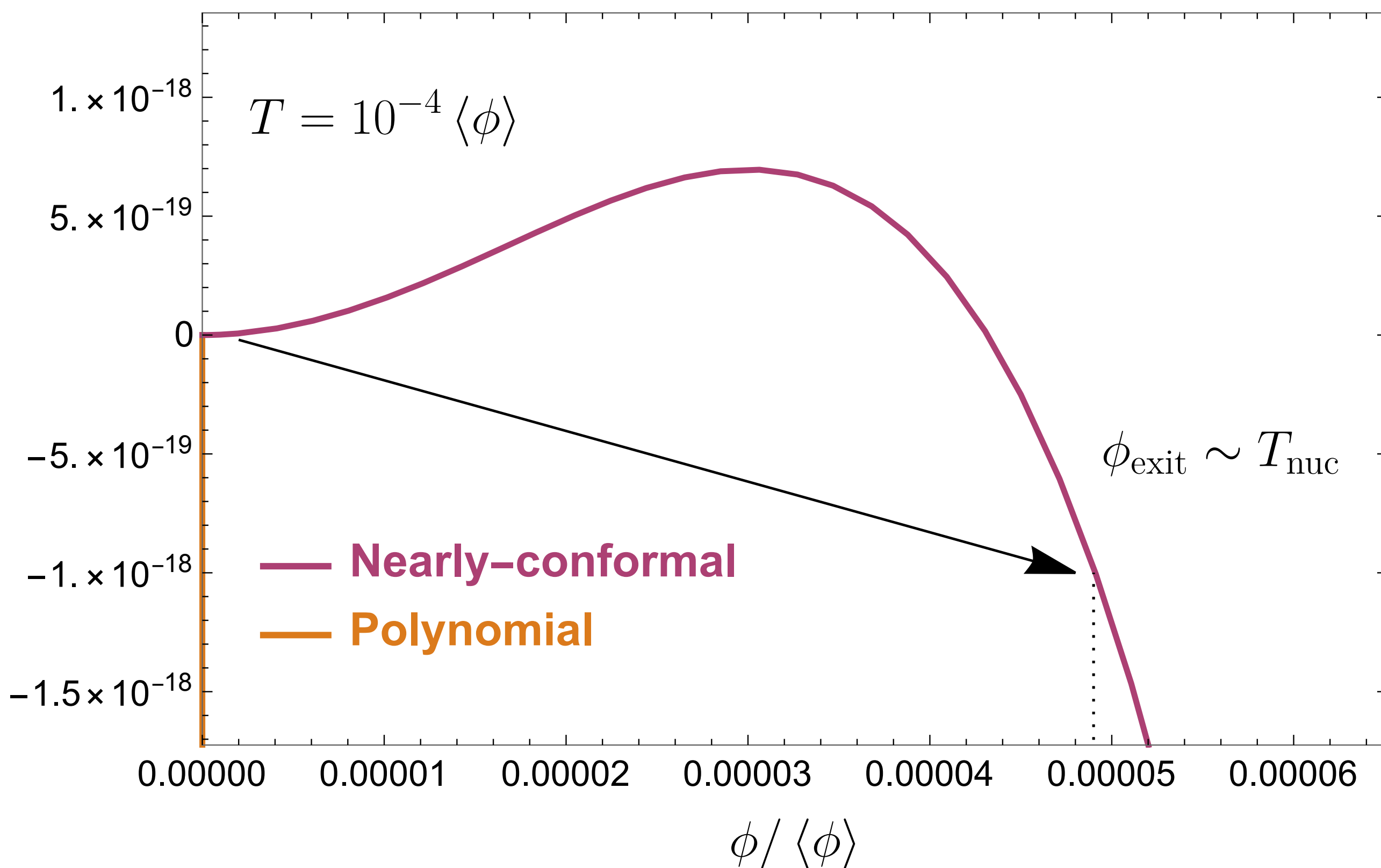
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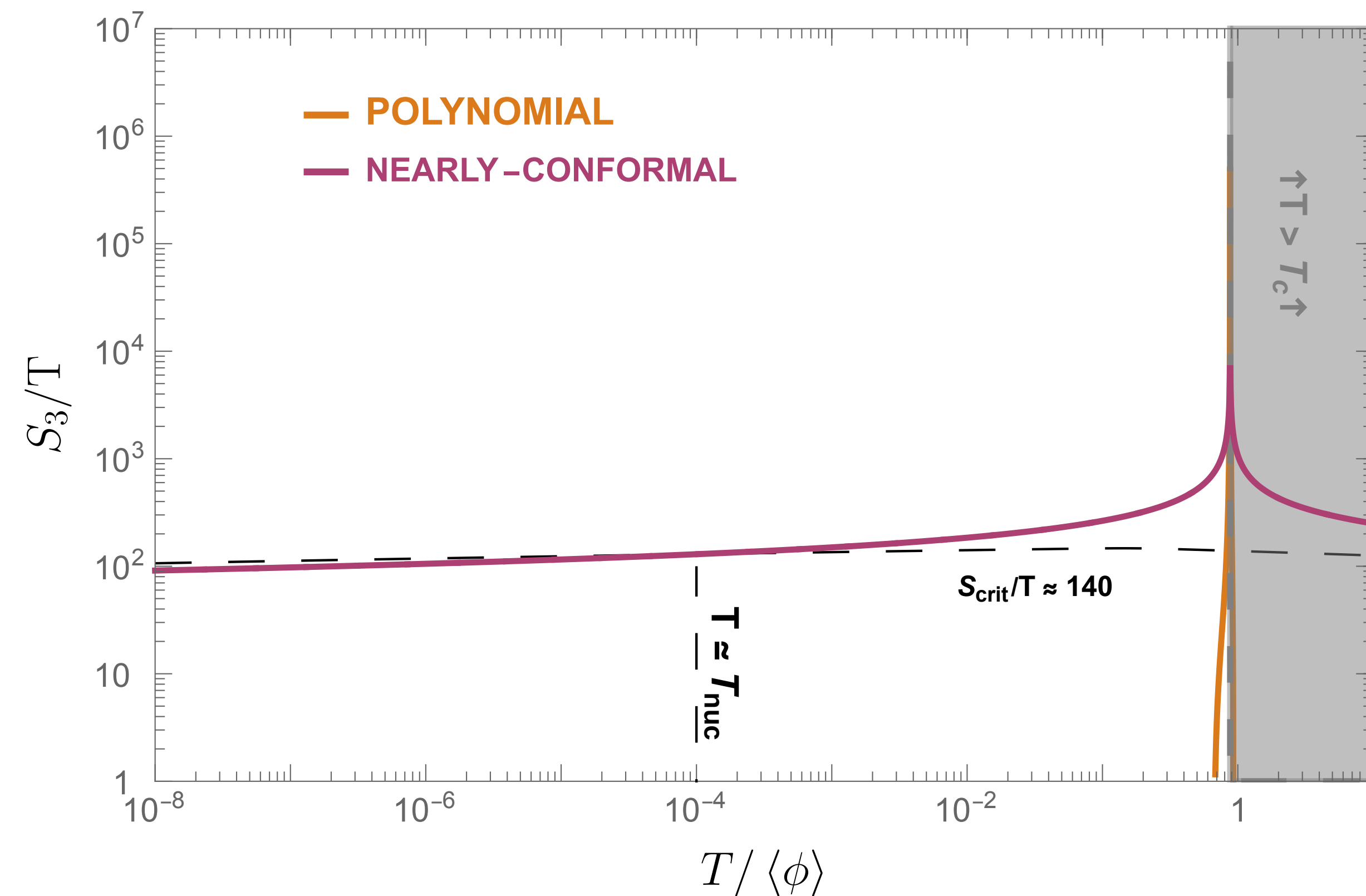
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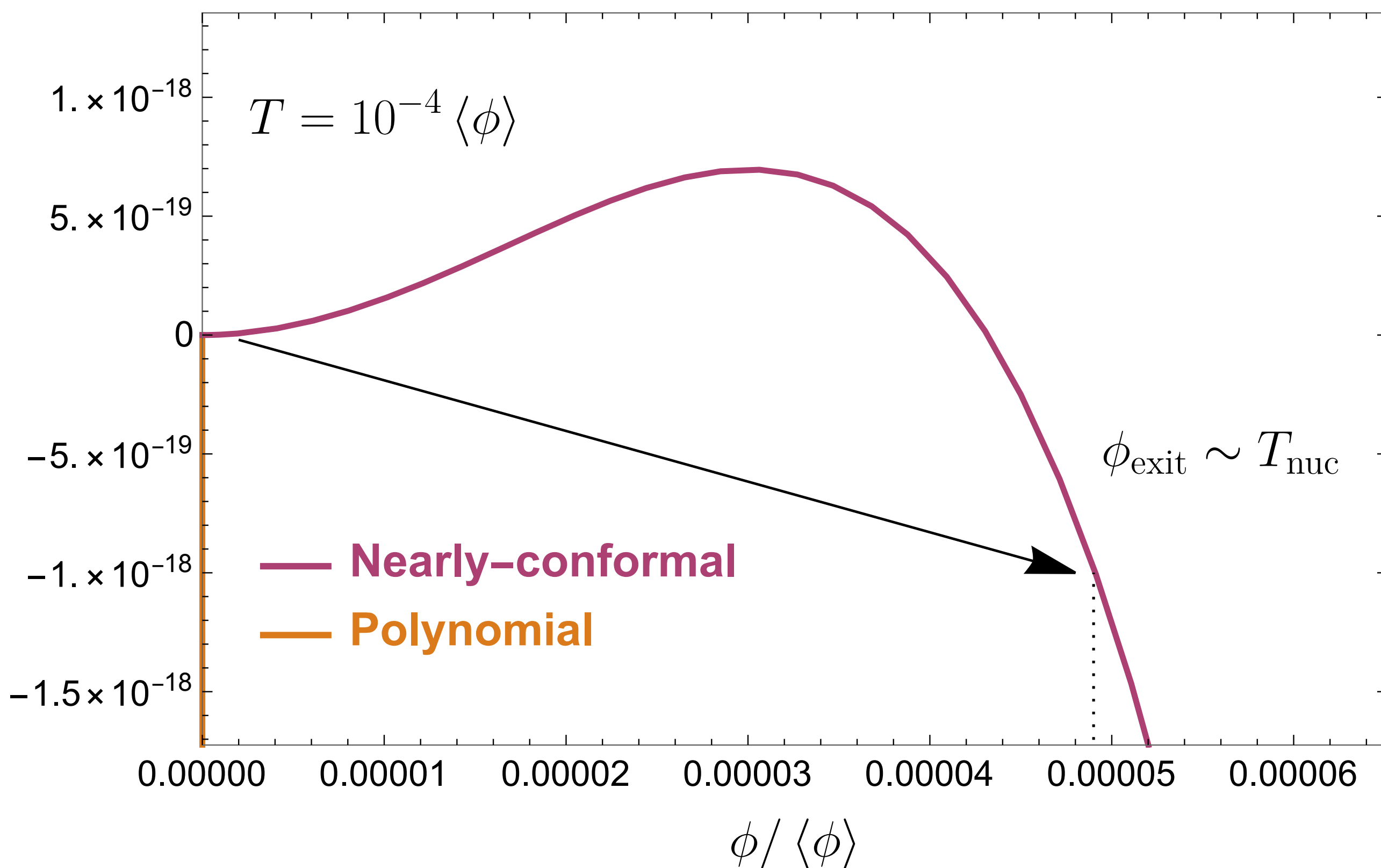
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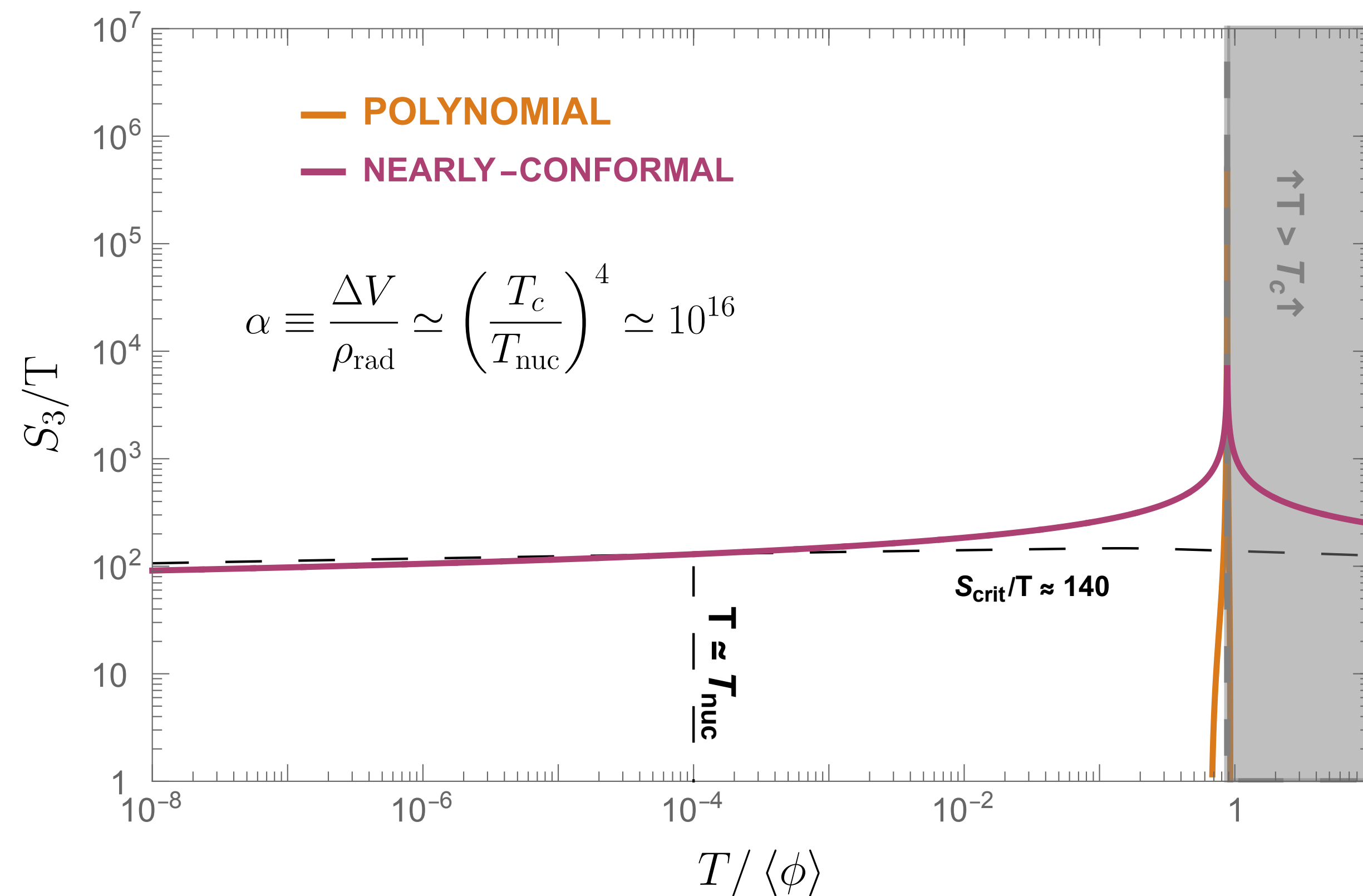
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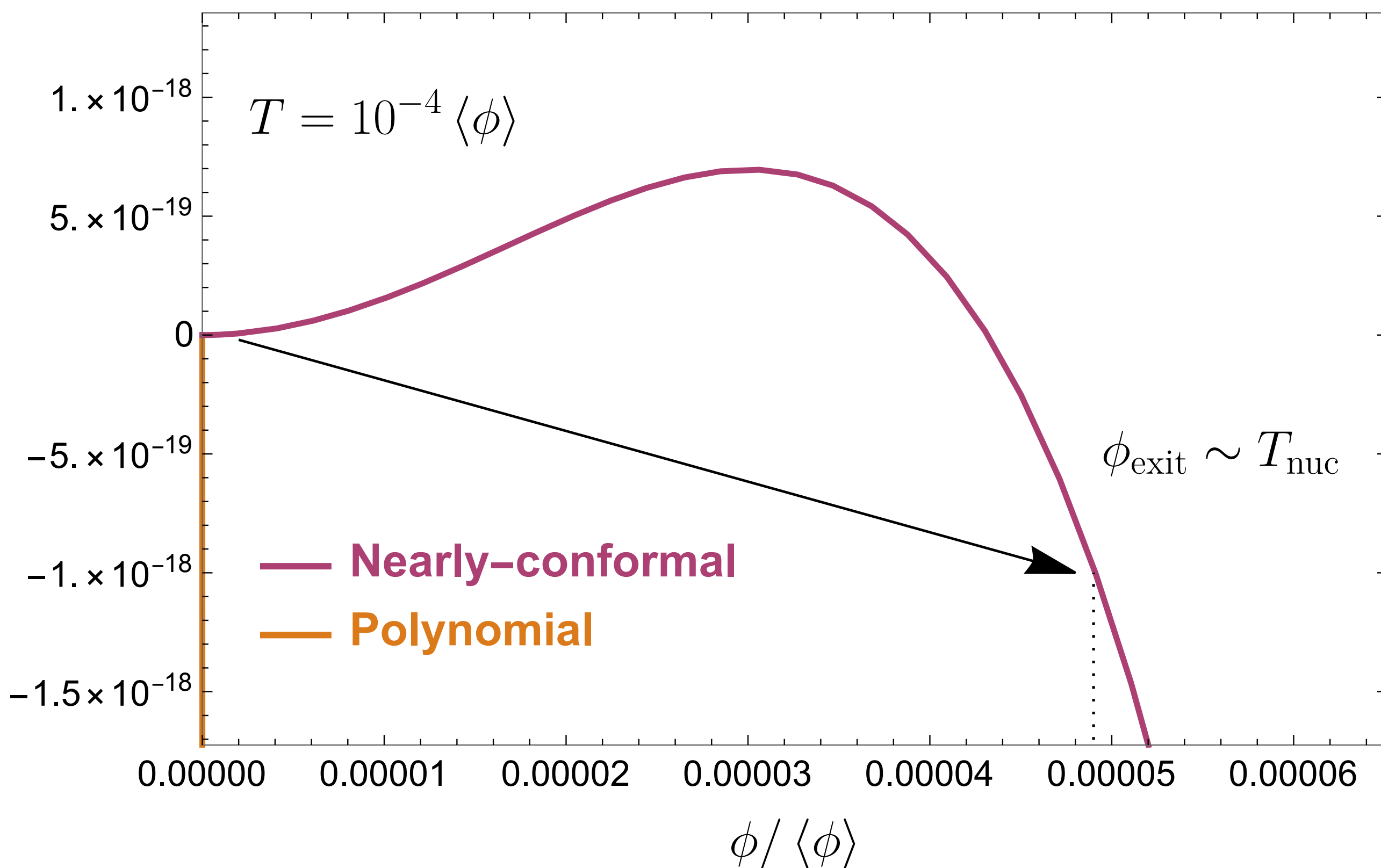
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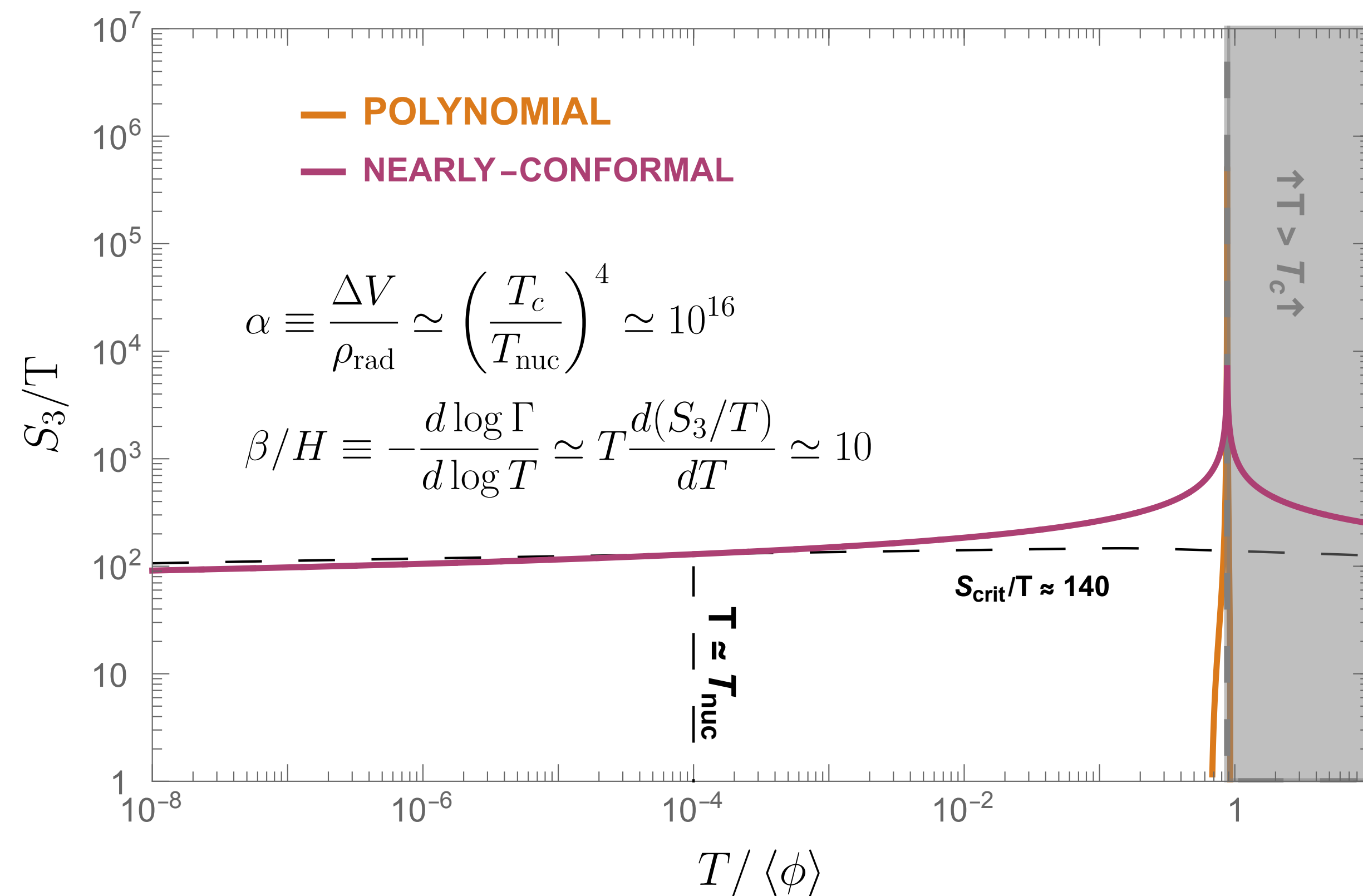
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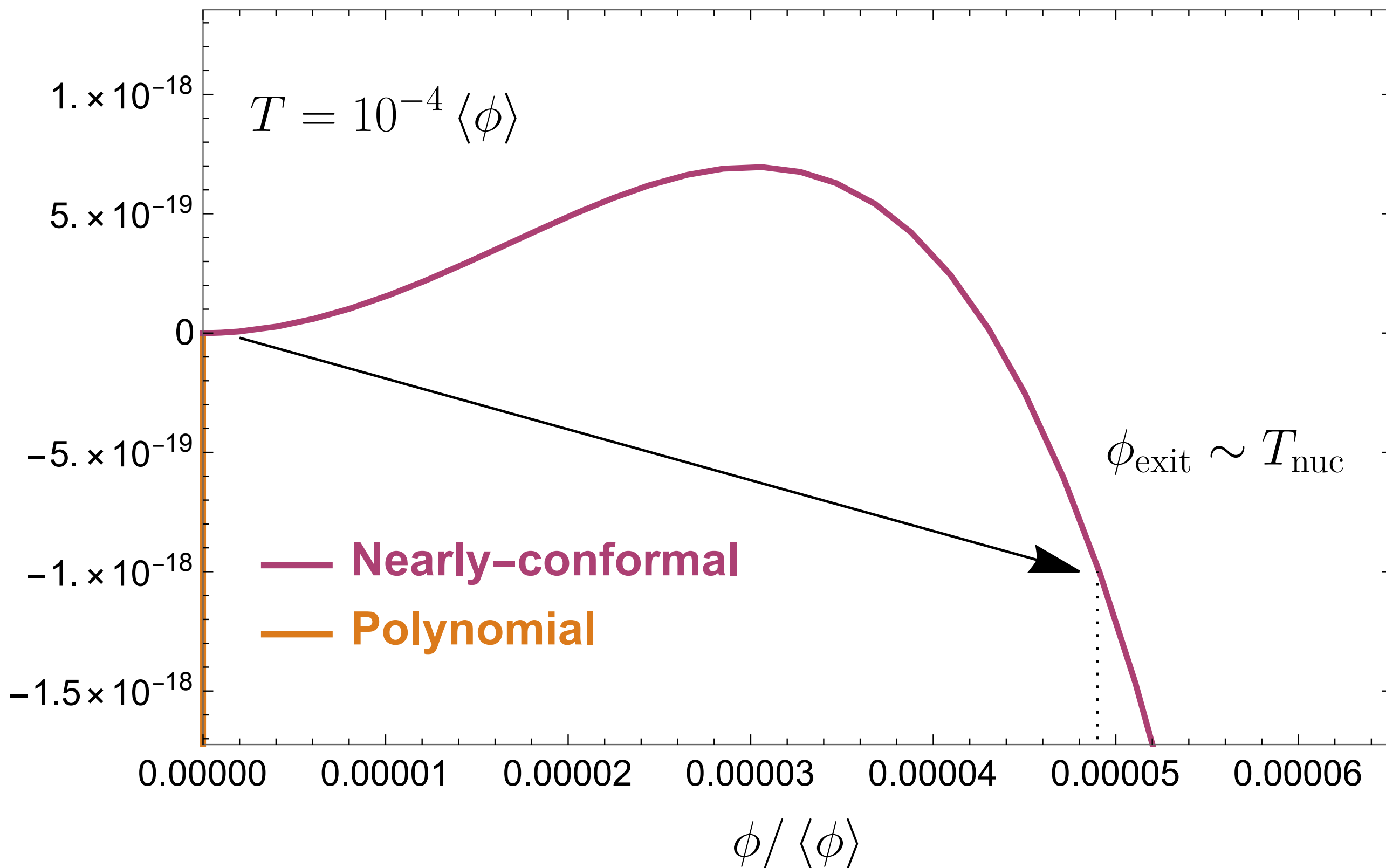


# TAKE HOME : Supercooled phase transitions arises in presence of FLAT direction, are STRONG and SLOW

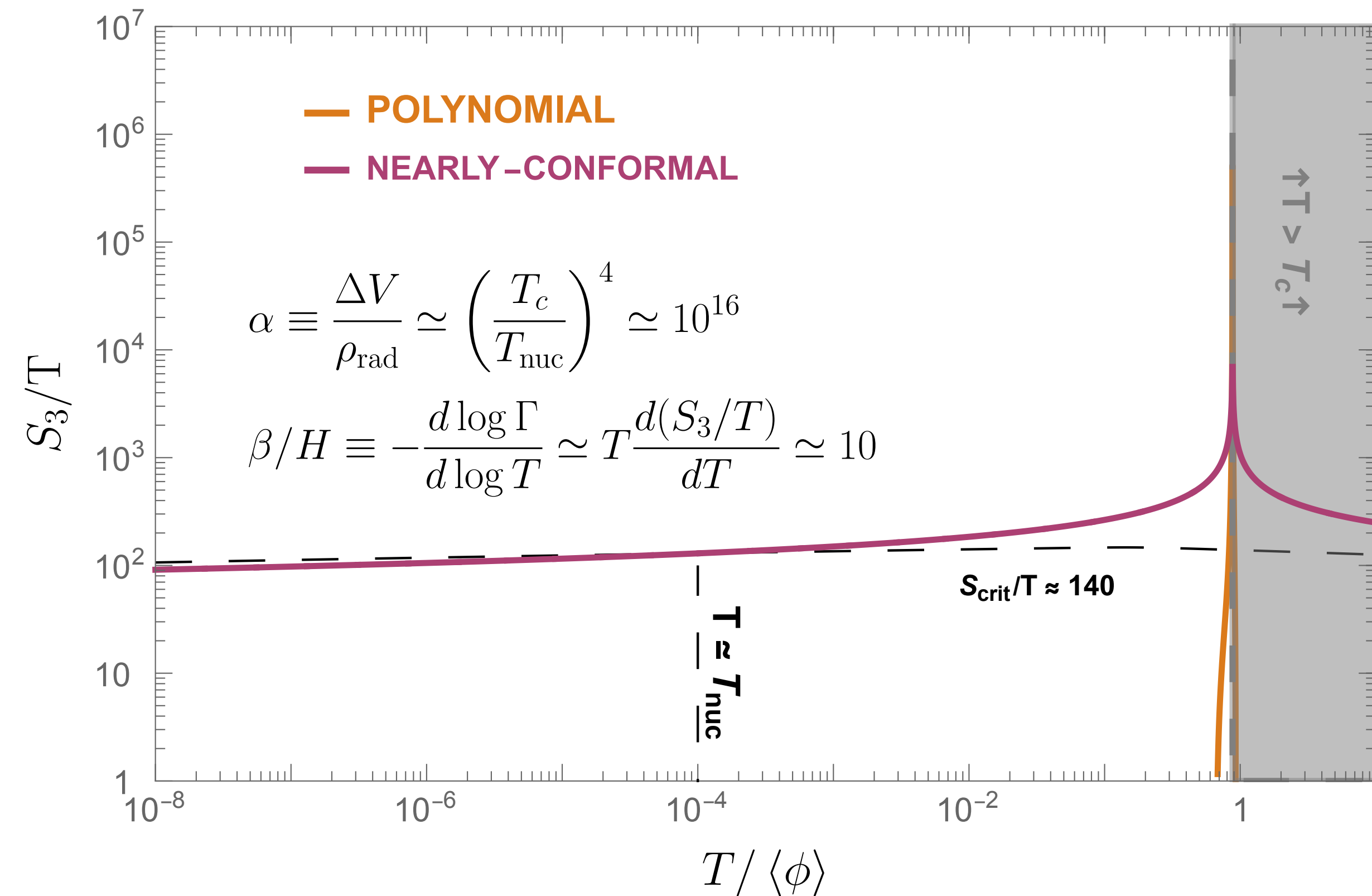
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$O_3$  bounce action



# Classes of nearly-conformal models

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

# Classes of nearly-conformal models

Space-time dimension \ Strength coupling	Weakly-coupled	Strongly-coupled
D = 4	<b>Coleman-Weinberg</b> $V(\phi) = \beta_\lambda \frac{\phi^4}{4} \left[ \log \left( \frac{\phi}{f} \right) - \frac{1}{4} \right]$	
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$$\left[ \beta_\lambda \frac{\phi^4}{4} \left[ \log \left( \frac{\phi}{f} \right) - \frac{1}{4} \right] \right] \xleftarrow{\epsilon \rightarrow 0} \left[ g_\chi^2 \frac{\sigma^4}{4} \left[ 1 - \frac{1}{1+\epsilon} \left( \frac{\sigma}{f} \right)^\epsilon \right] \right]$$

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# Classes of nearly-conformal models

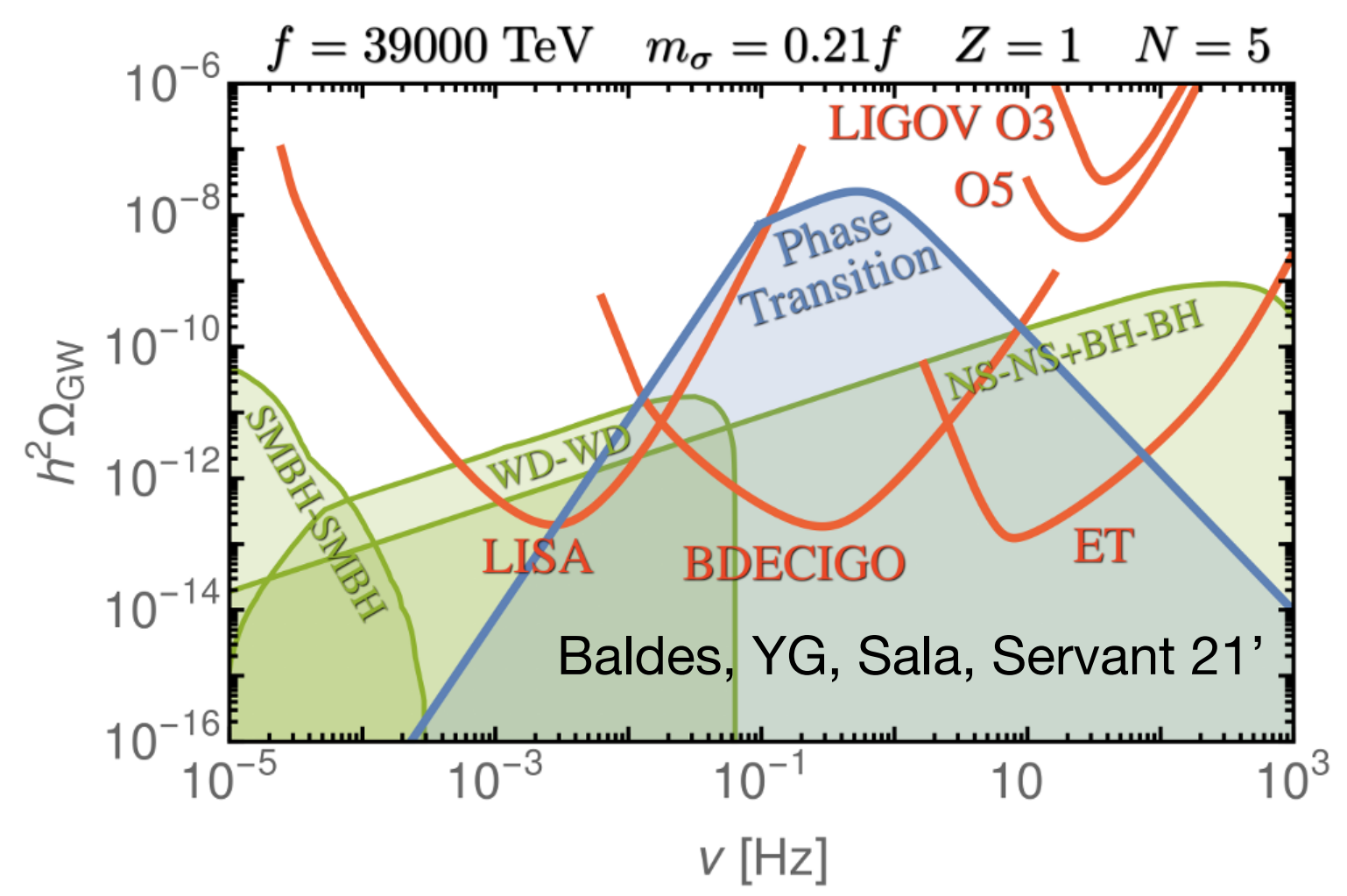
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$\epsilon \rightarrow 0$   
 ←  
 holography  
 ↗

# Cosmological consequences of supercooling

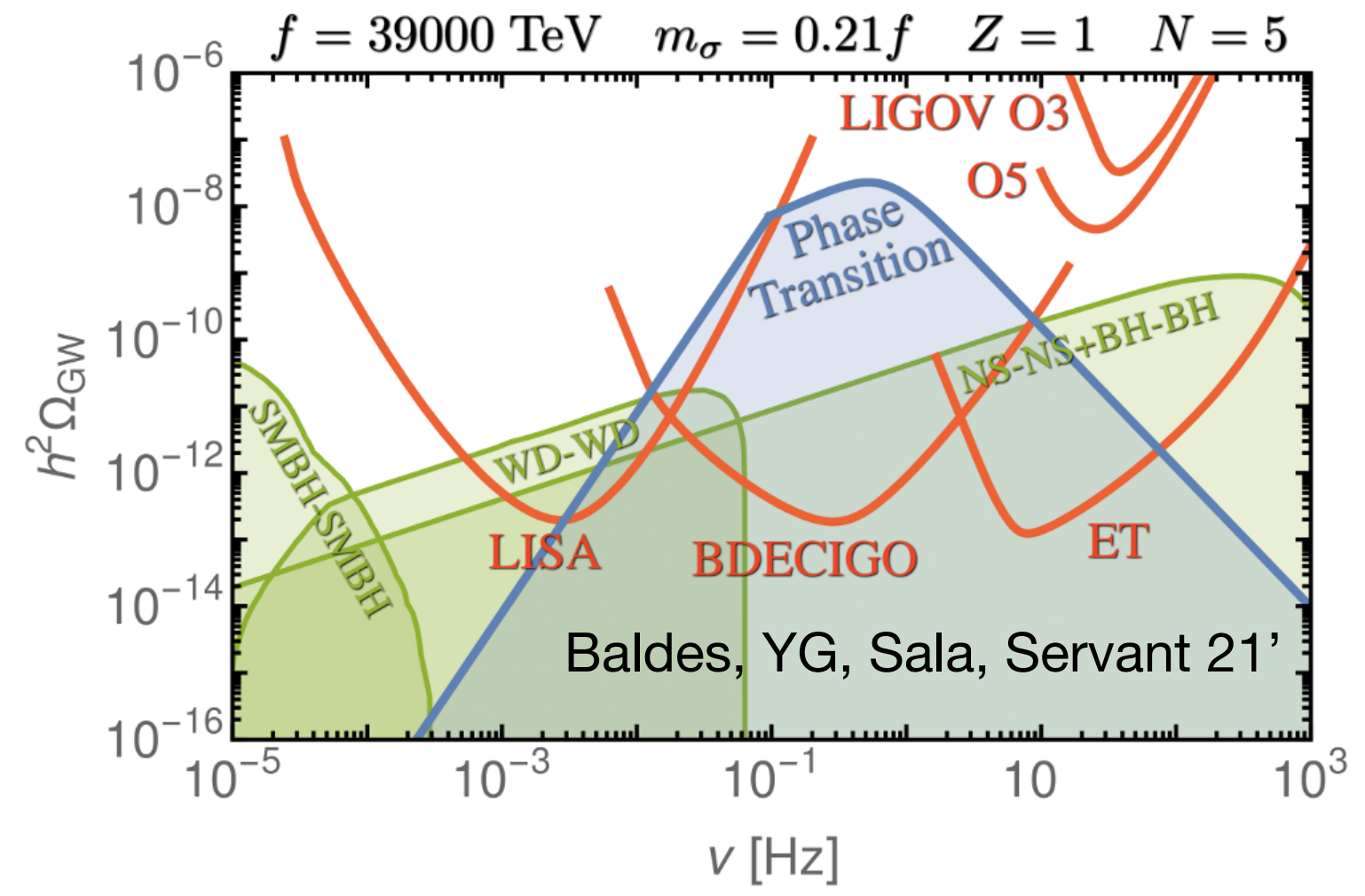
# 1) Large GW spectrum

Randall, Servant 06'



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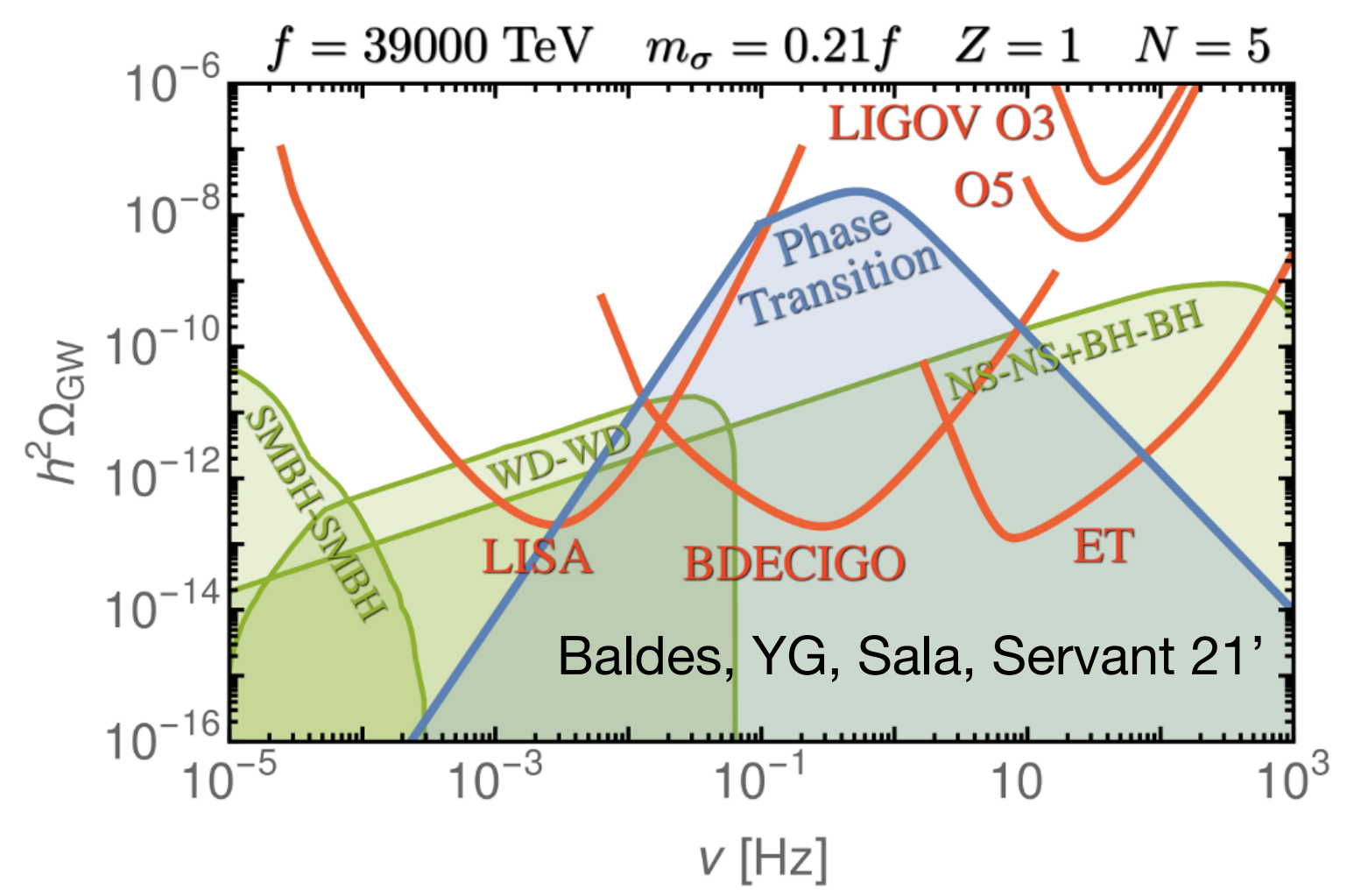
Randall, Servant 06'



# 2) Relativistic bubble walls

# 1) Large GW spectrum

Randall, Servant 06'

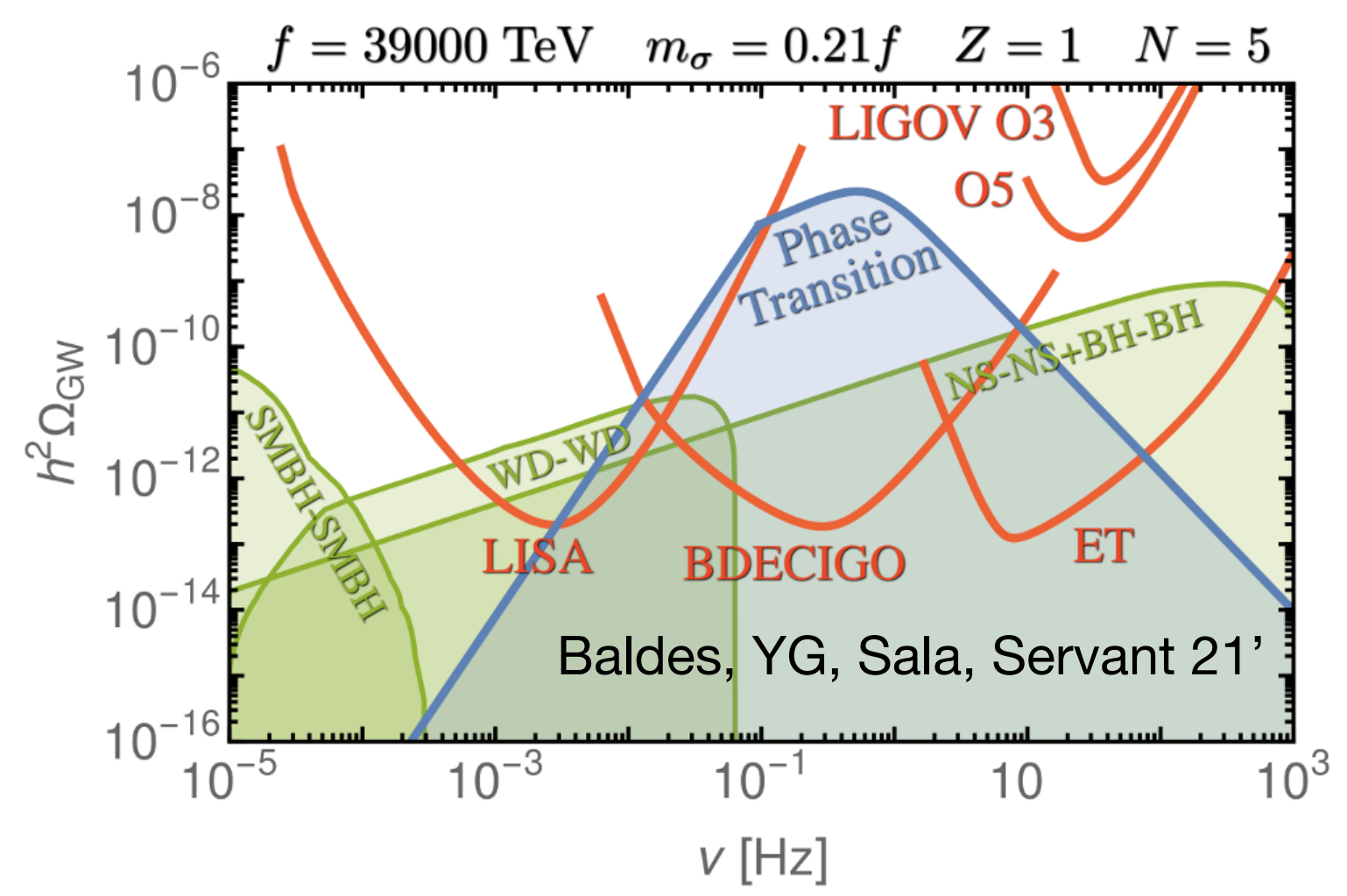


# 2) Relativistic bubble walls

Bodeker, Moore 17' (Perturbative level)

# 1) Large GW spectrum

Randall, Servant 06'



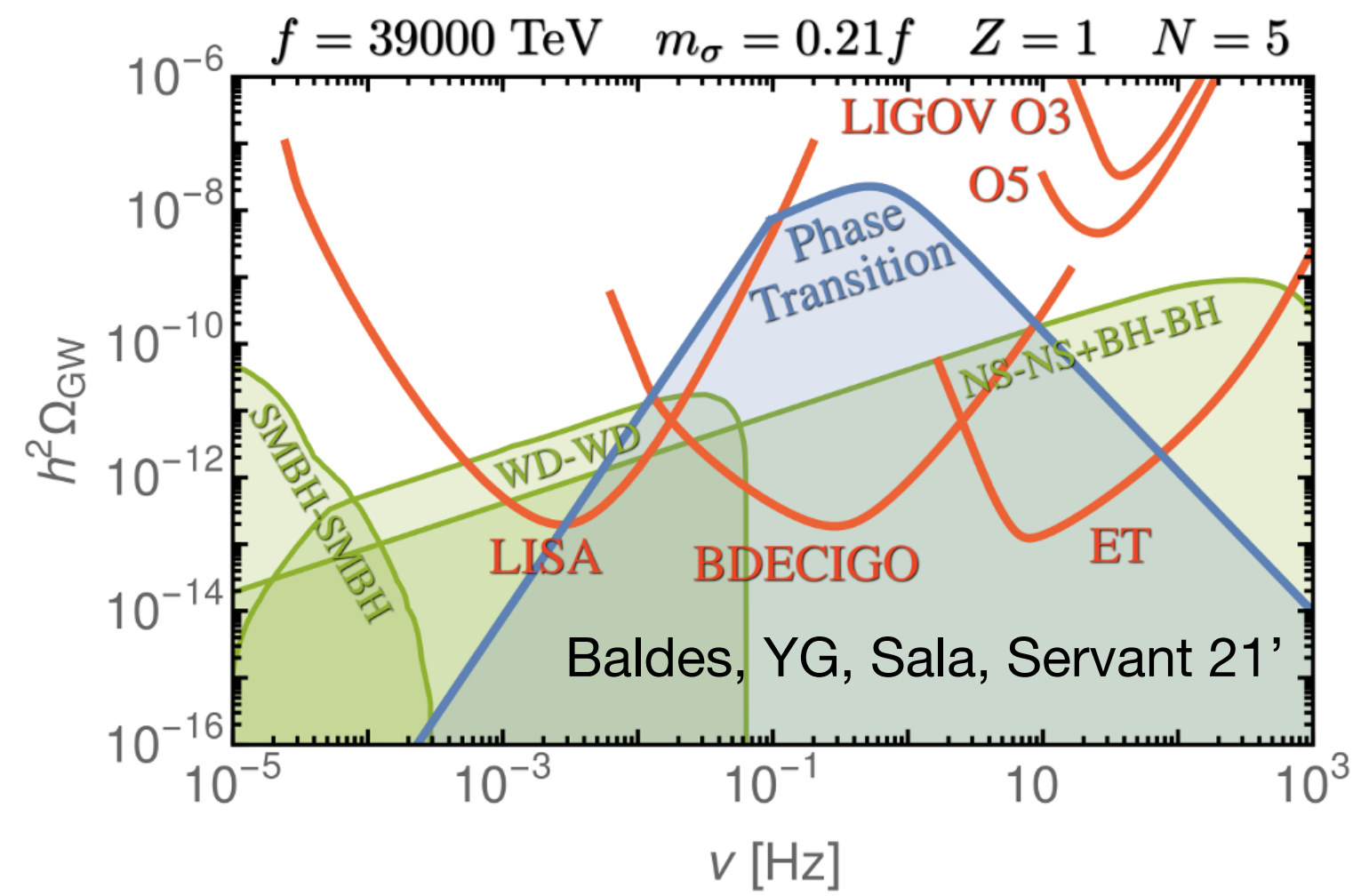
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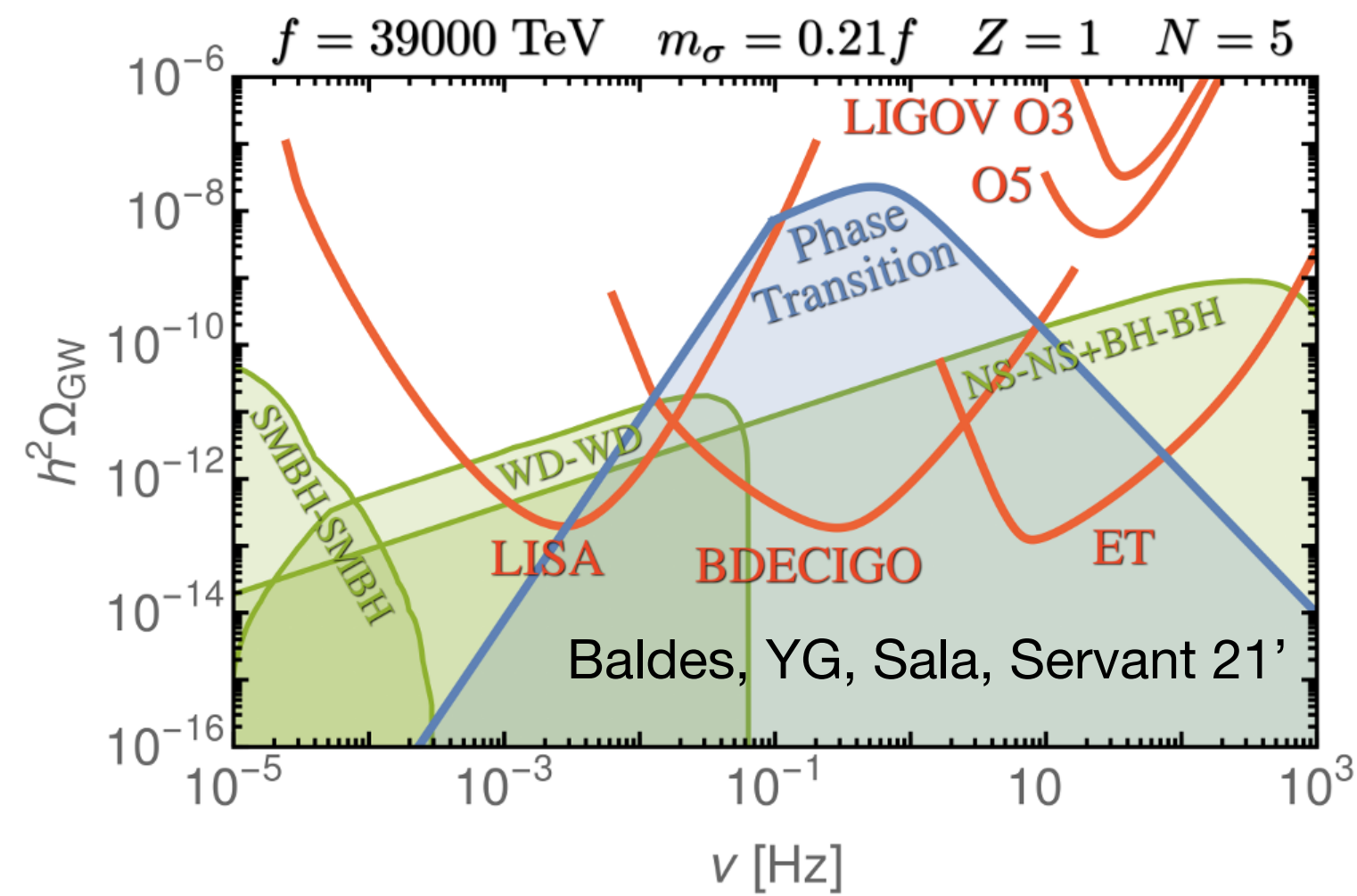


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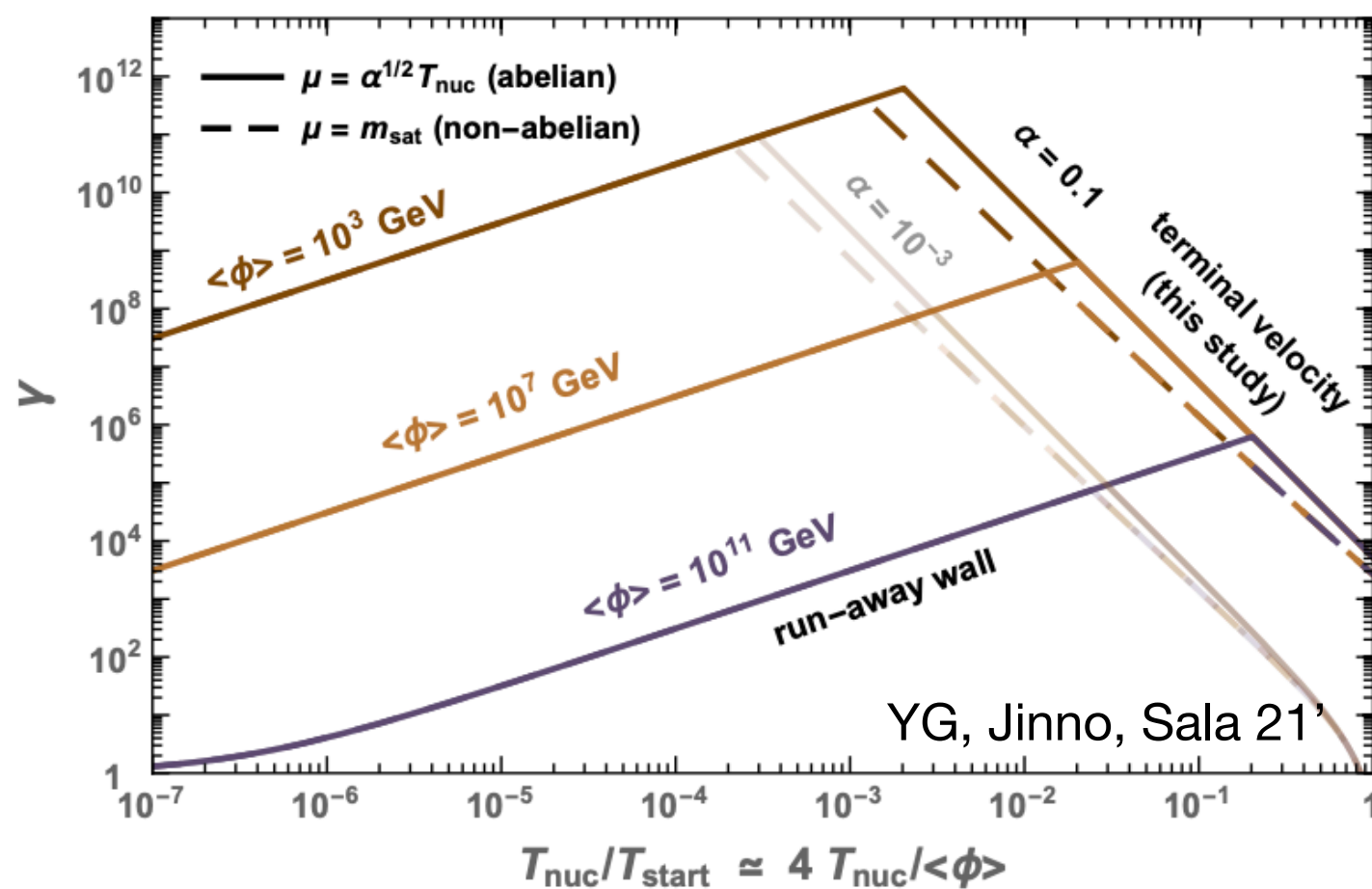
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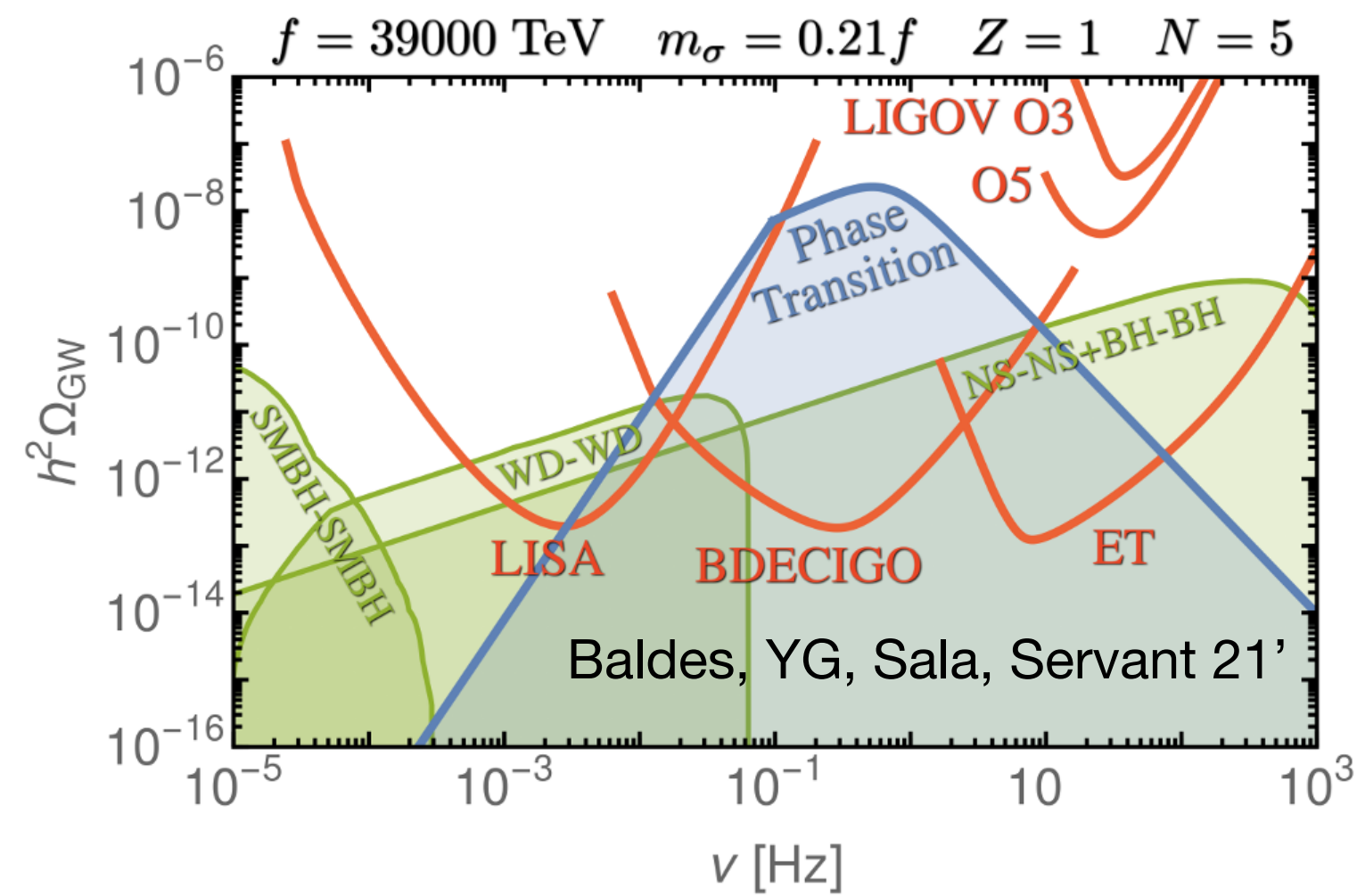
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Bubble wall Lorentz factor



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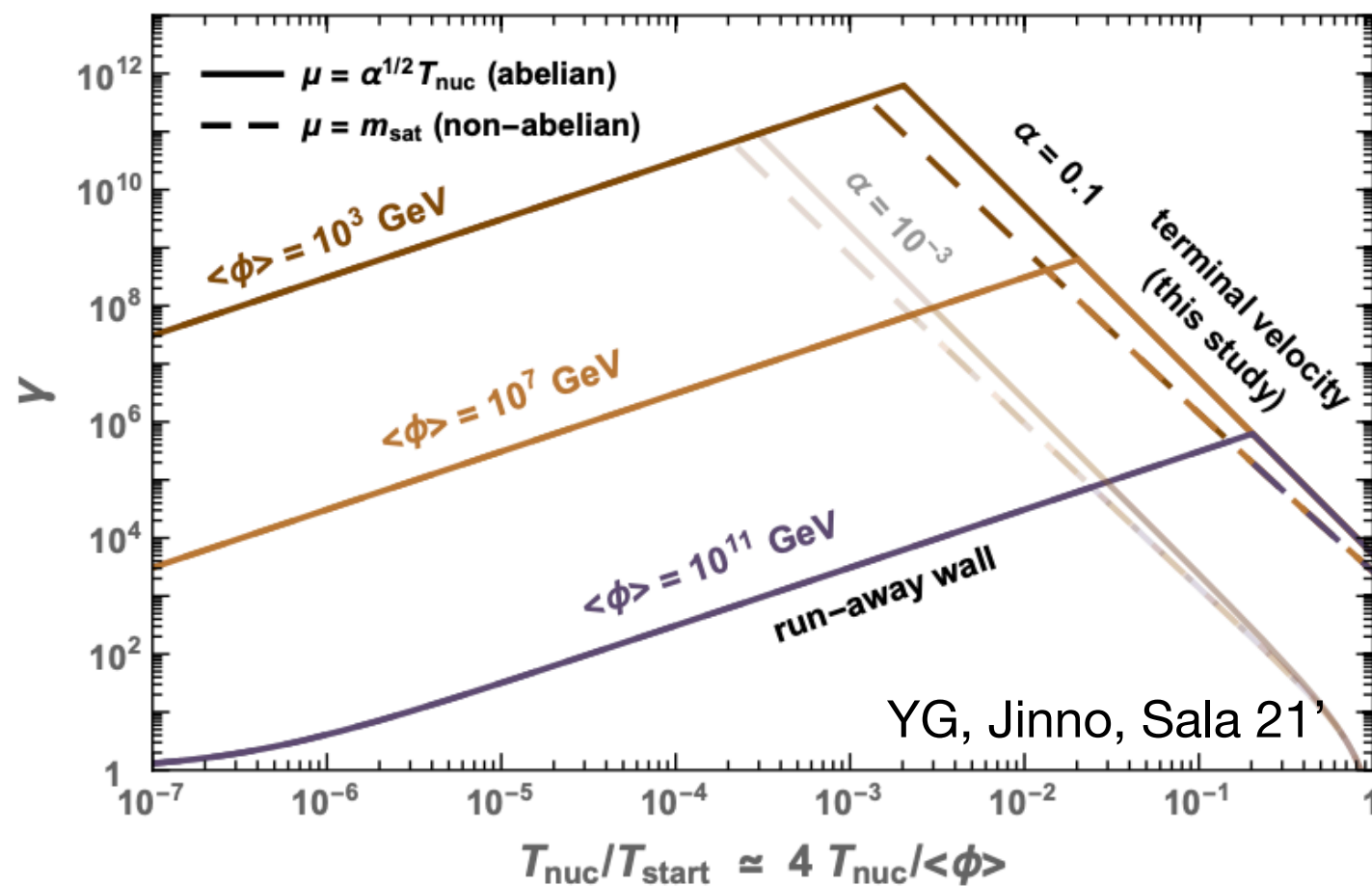
Randall, Servant 06'



# 2) Relativistic bubble walls

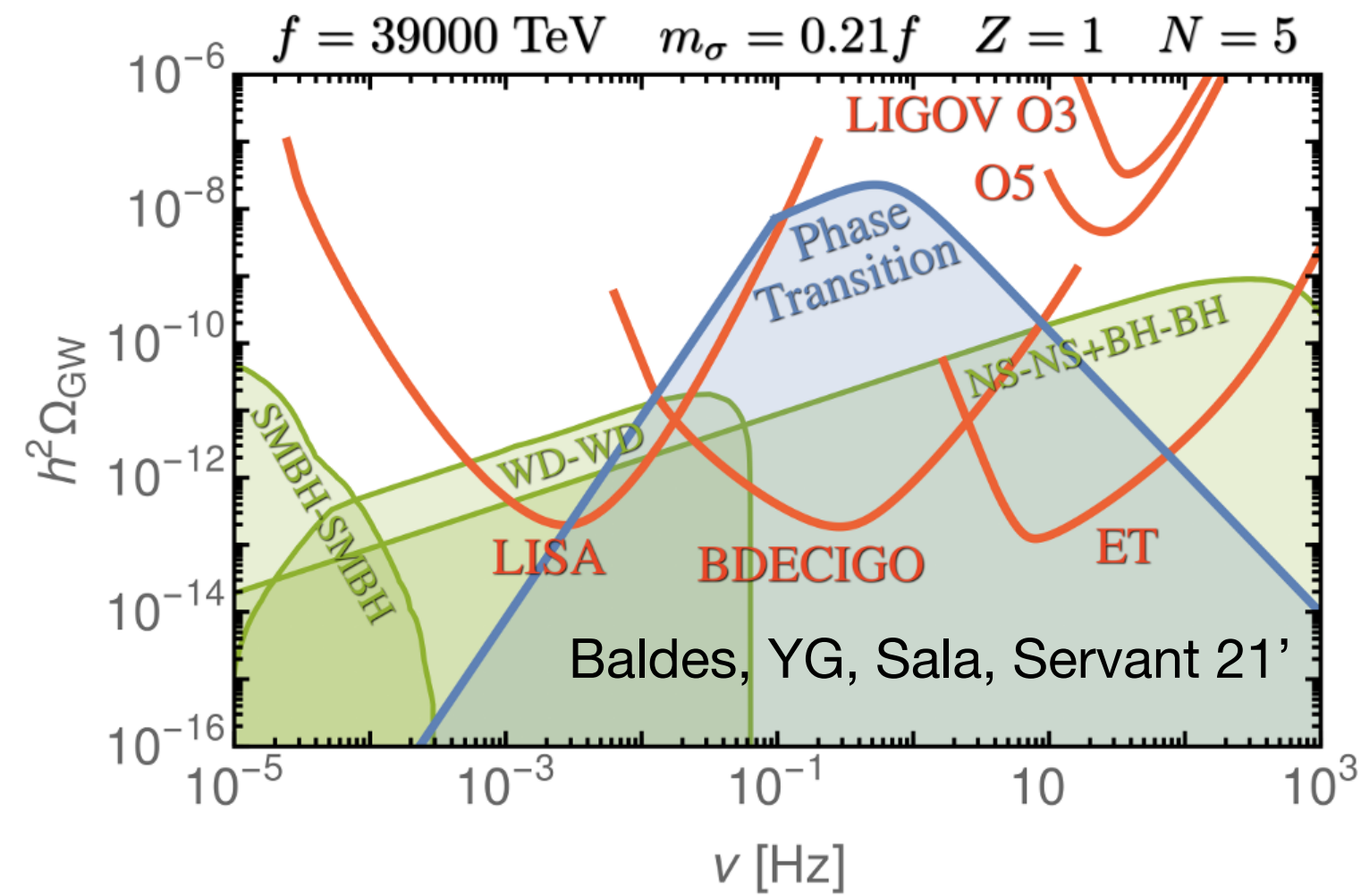
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Bubble wall Lorentz factor



# 1) Large GW spectrum

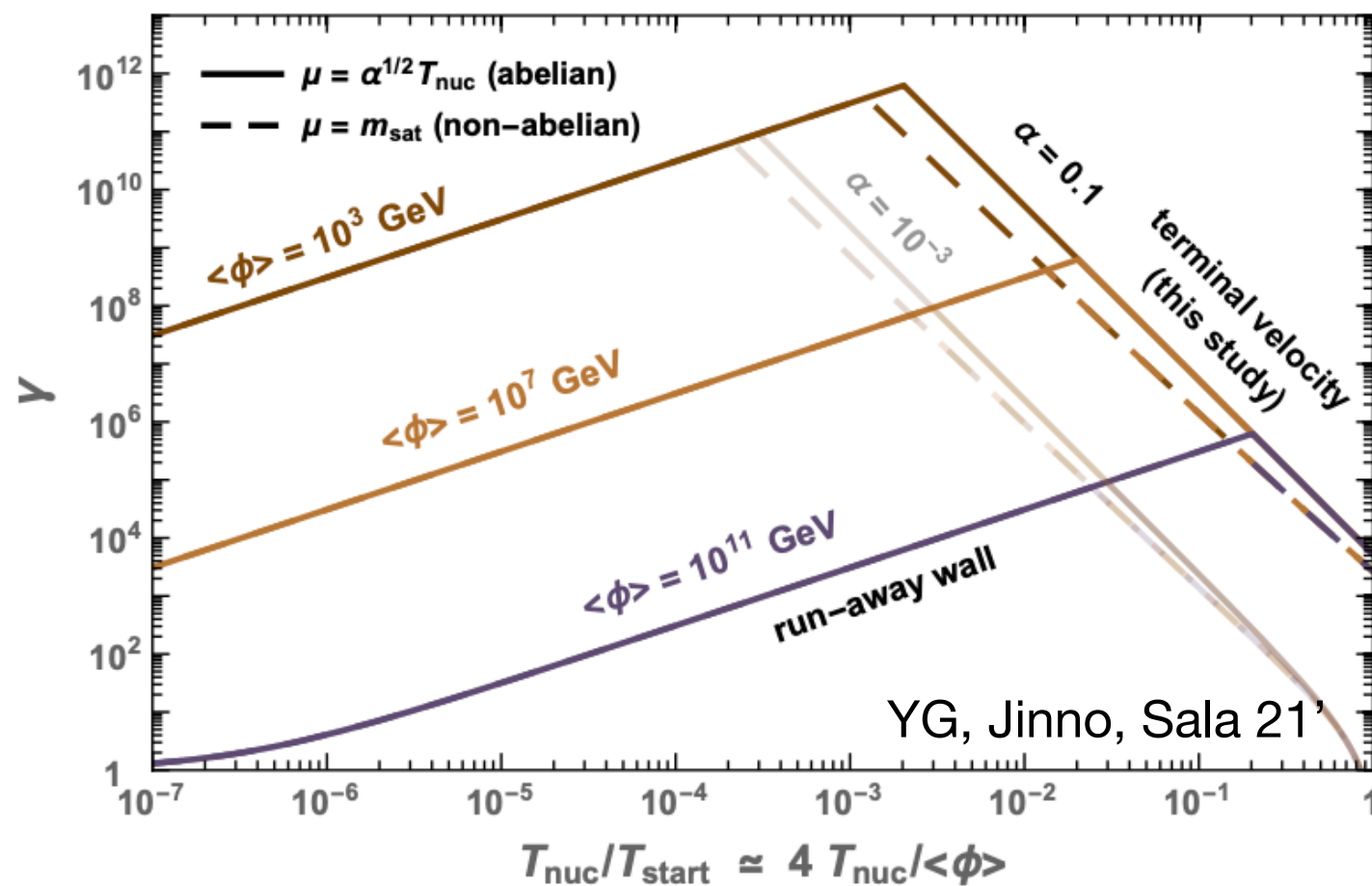
Randall, Servant 06'



# 2) Relativistic bubble walls

- Bodeker, Moore 17' (Perturbative level)
- YG, Jinno, Sala 21' (Sudakov resummation)
- Baldes, YG, Sala 20' (Gluon string description)

Bubble wall Lorentz factor



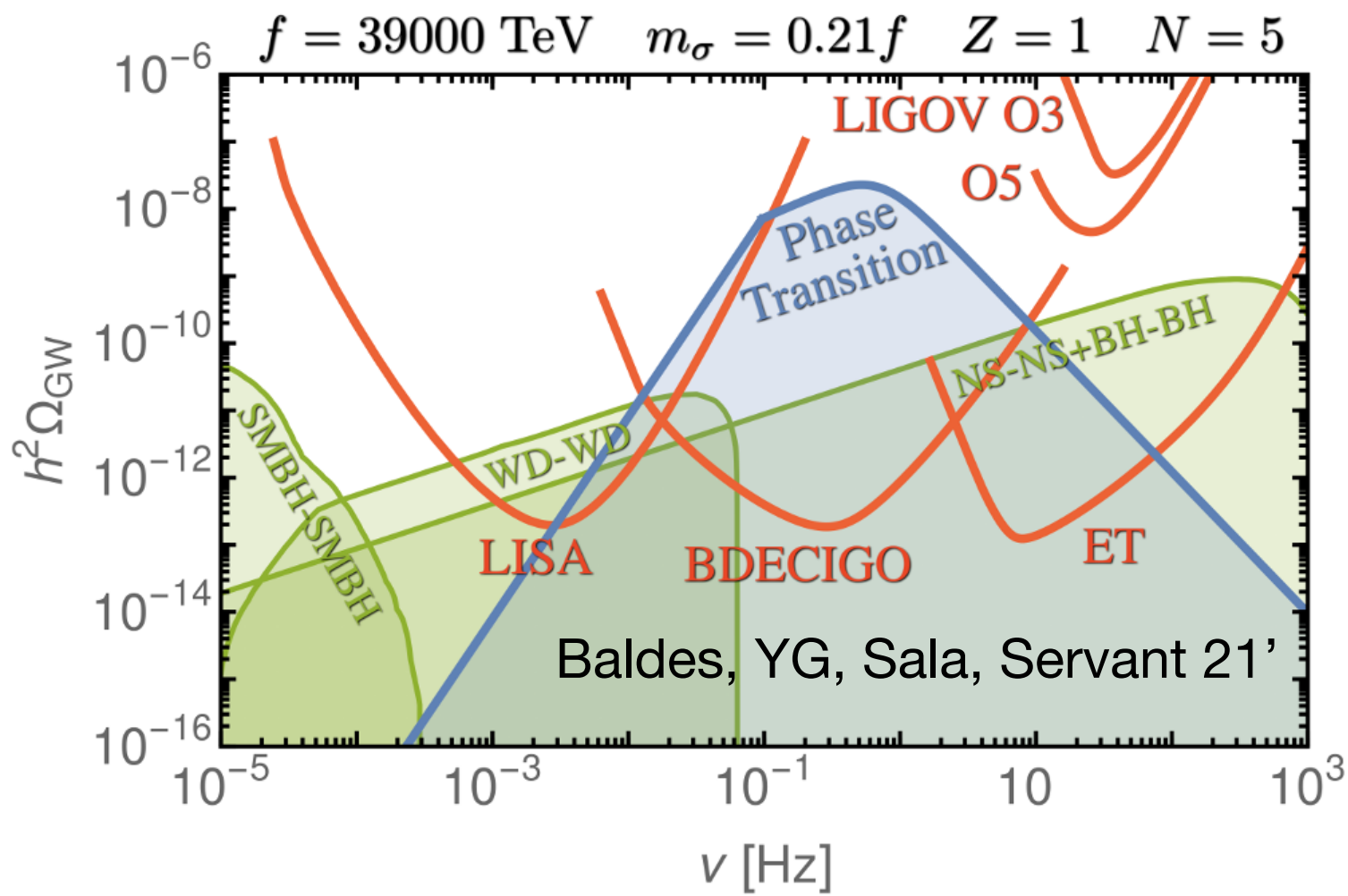
See Isabel Garcia Garcia's talk

Hoche, Kozaczuk, Long, Turner, Wang 20' (Gauge-invariant pressure ?)

# 1) Large GW spectrum

Randall, Servant 06'

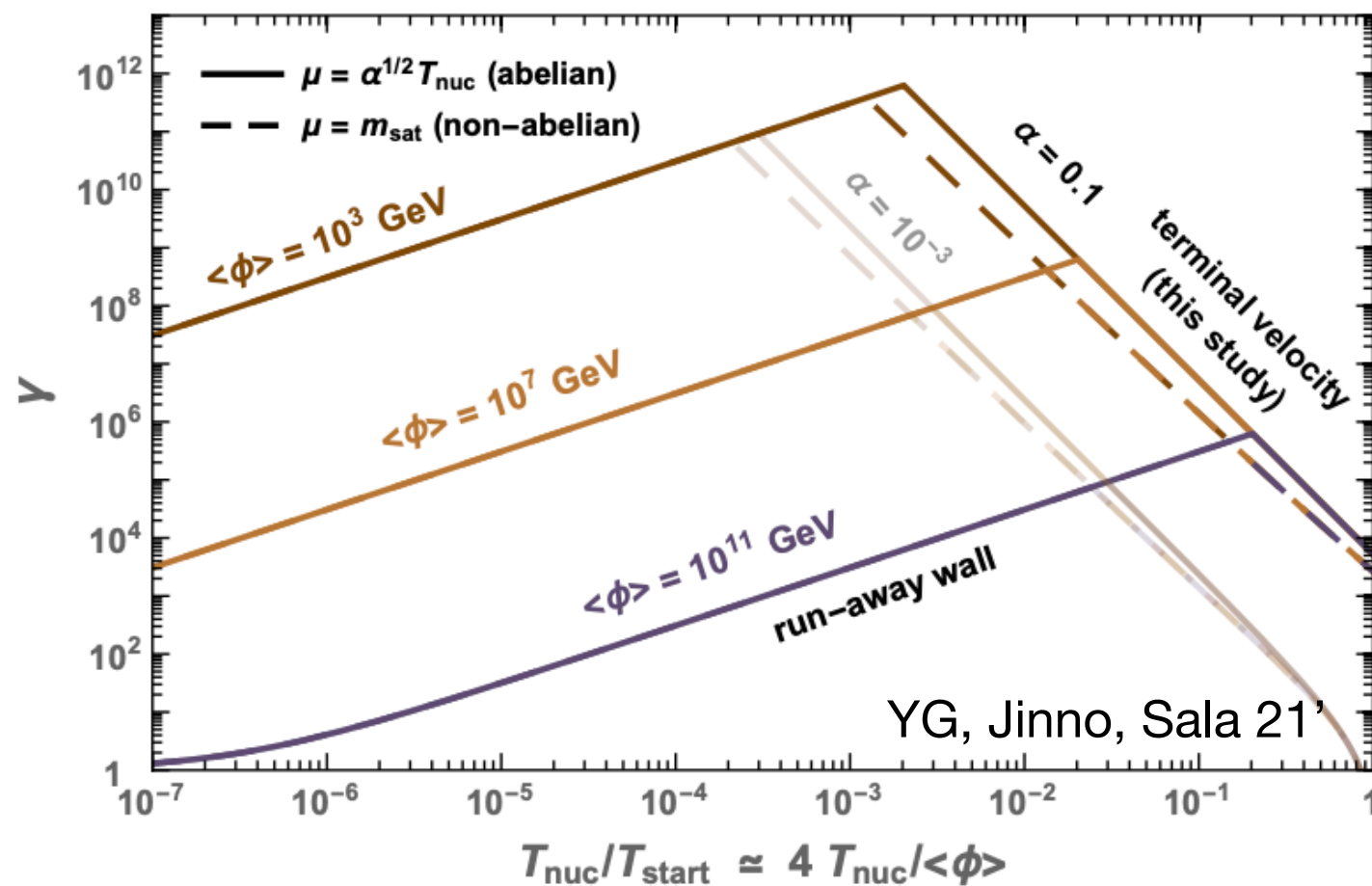
# 3) Dilution of relics



# 2) Relativistic bubble walls

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See Isabel Garcia Garcia's talk

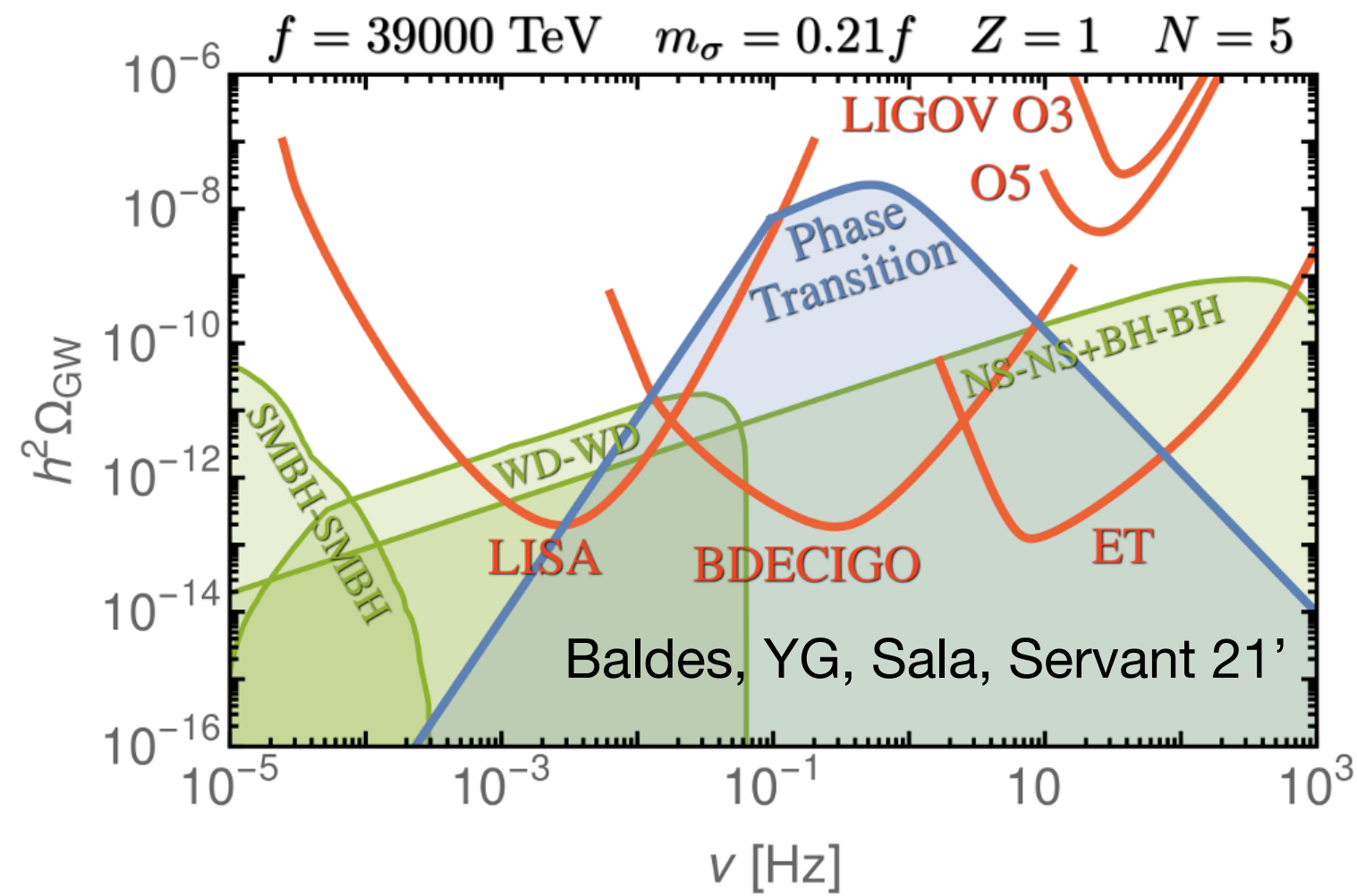
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# 1) Large GW spectrum

Randall, Servant 06'

# Cosmological consequences of supercooling

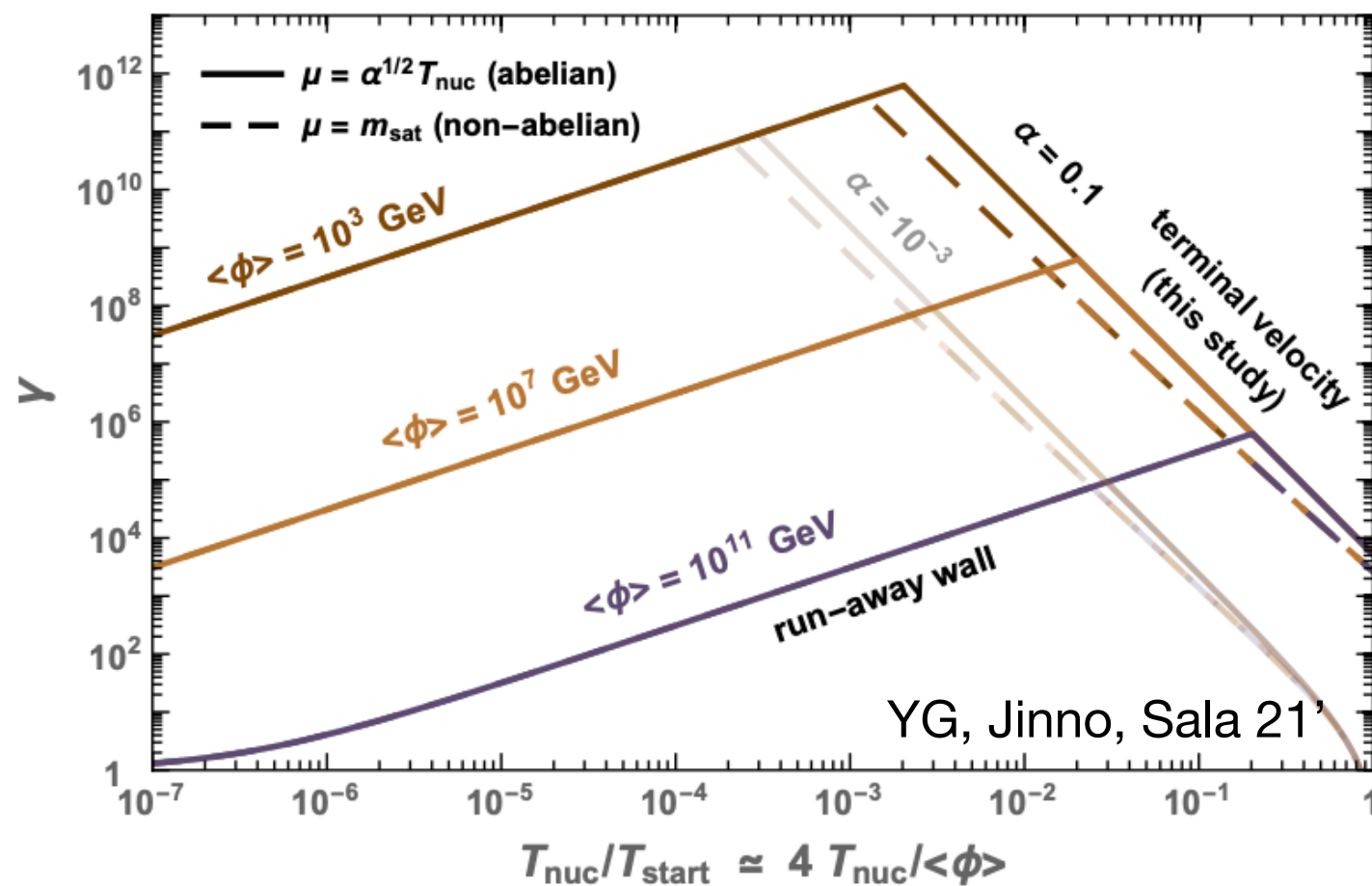
## 3) Heavy thermal dark matter



## 2) Relativistic bubble walls

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Bubble wall Lorentz factor



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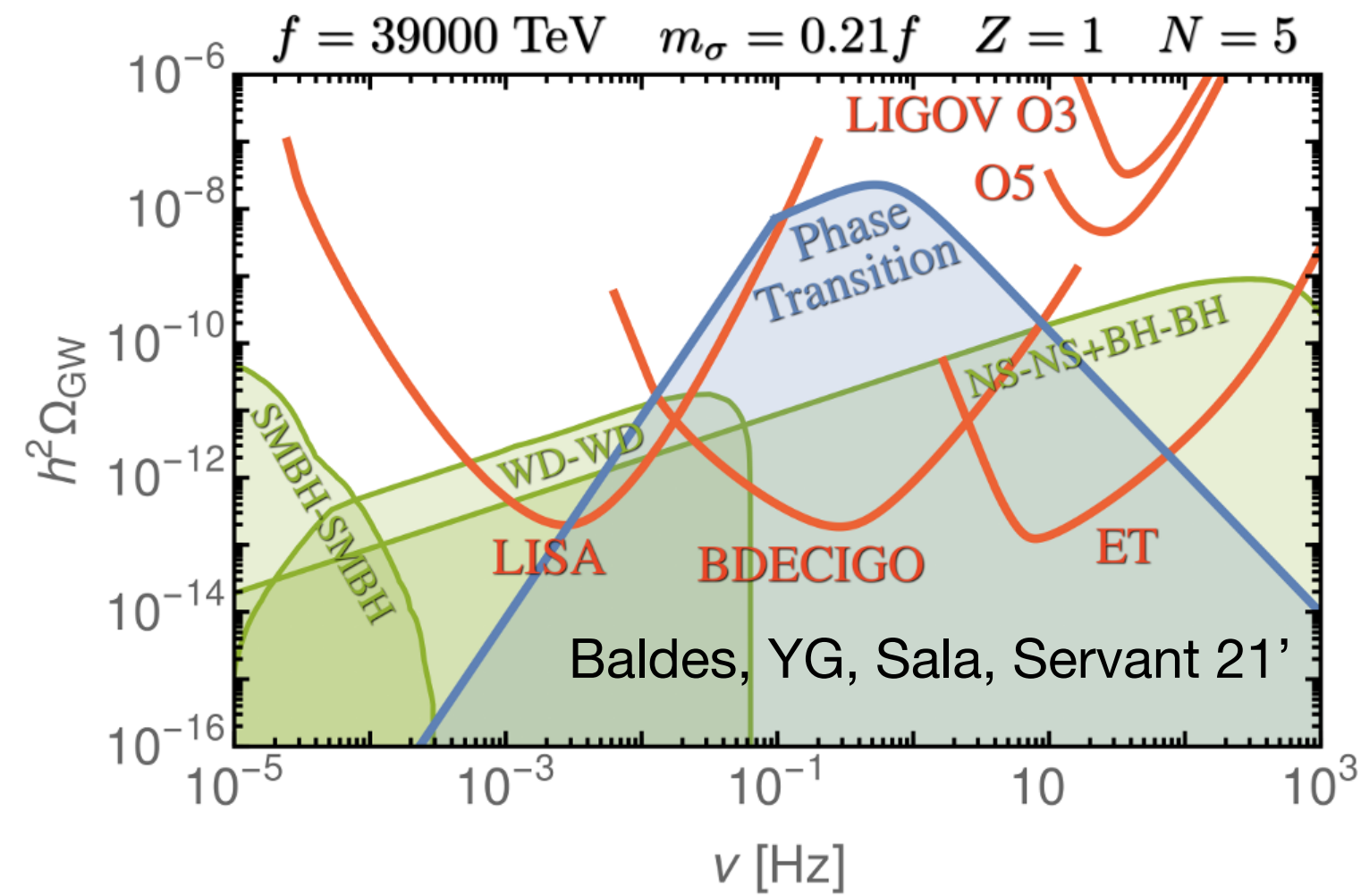
# 1) Large GW spectrum

Randall, Servant 06'

# Cosmological consequences of supercooling

## 3) Heavy thermal dark matter

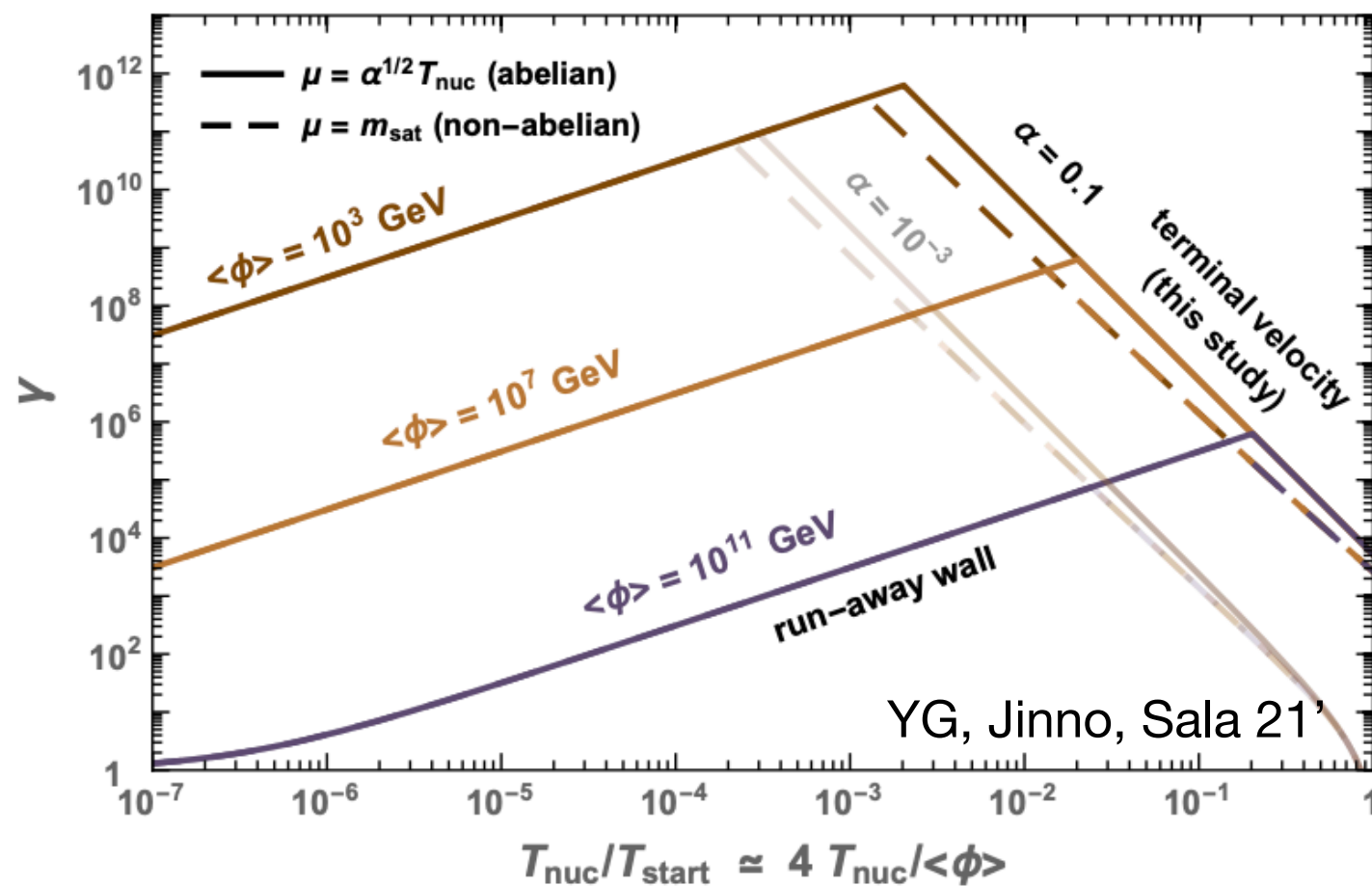
$$\frac{\Omega_{\text{DM}} h^2}{0.12} = \frac{(16 \text{ TeV})^2}{\langle \sigma v \rangle_{\text{FO}}}$$



## 2) Relativistic bubble walls

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Bubble wall Lorentz factor

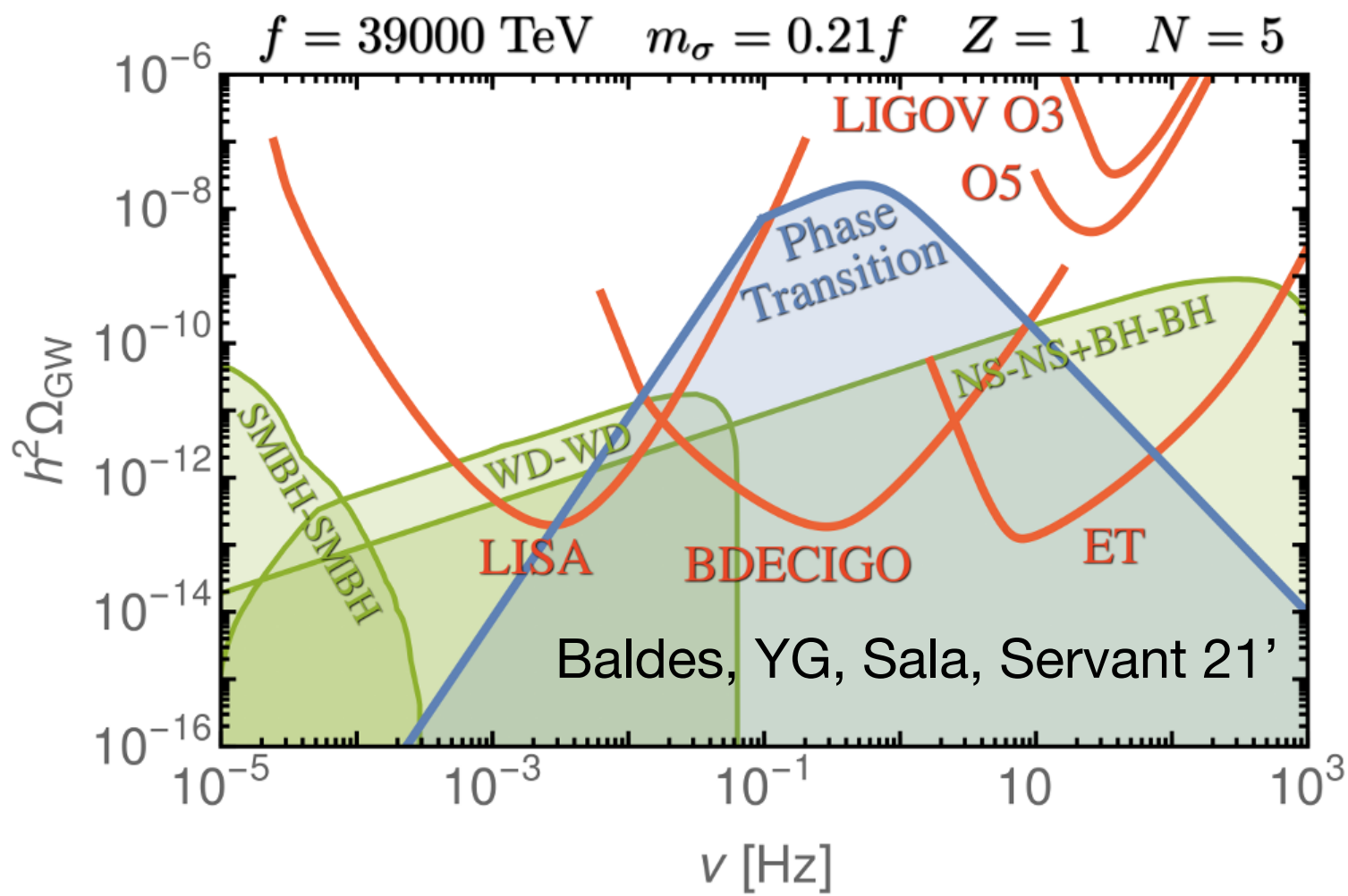


See Isabel Garcia Garcia's talk

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# 1) Large GW spectrum

Randall, Servant 06'



# Cosmological consequences of supercooling

## 3) Heavy thermal dark matter

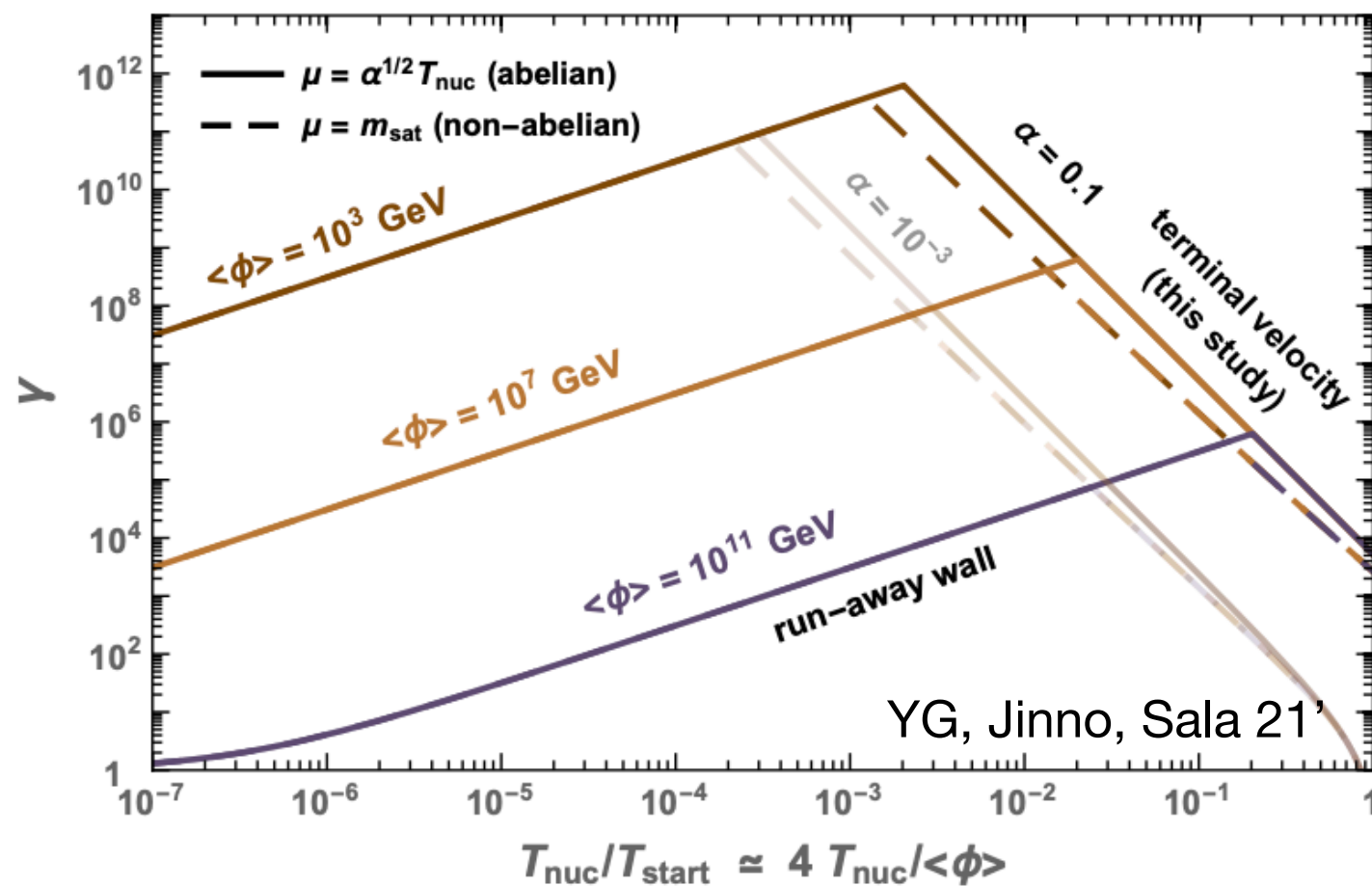
$$\frac{\Omega_{\text{DM}} h^2}{0.12} = \frac{(16 \text{ TeV})^2}{\langle \sigma v \rangle_{\text{FO}}}$$

$$\sigma < \frac{4\pi}{M_{\text{DM}}^2 v^2} \sim \pi^2 \lambda_{\text{dB}}^2$$

# 2) Relativistic bubble walls

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Bubble wall Lorentz factor



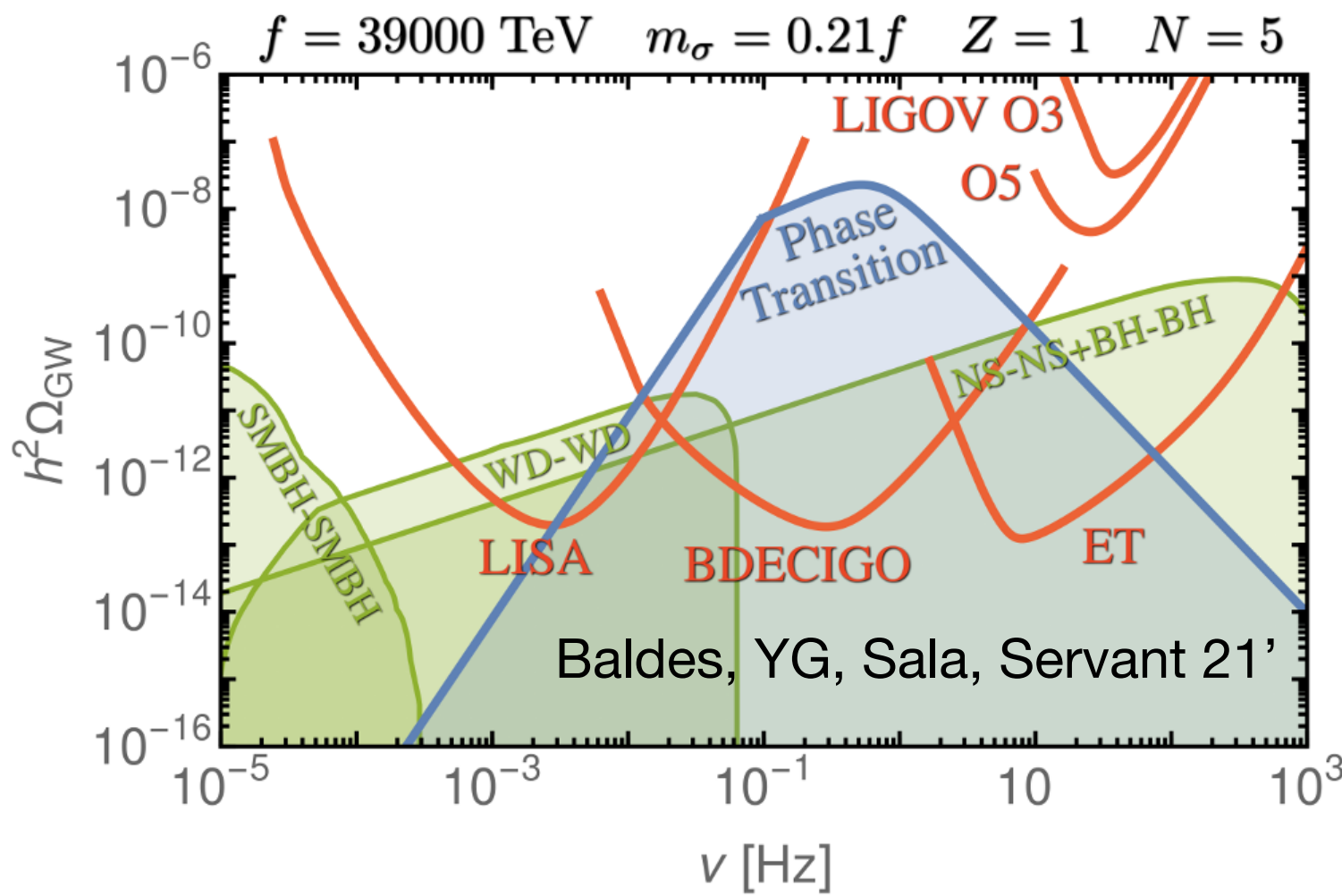
See Isabel Garcia Garcia's talk

Hoche, Kozaczuk, Long, Turner, Wang 20' (Gauge-invariant pressure ?)



# 1) Large GW spectrum

Randall, Servant 06'



# Cosmological consequences of supercooling

## 3) Heavy thermal dark matter

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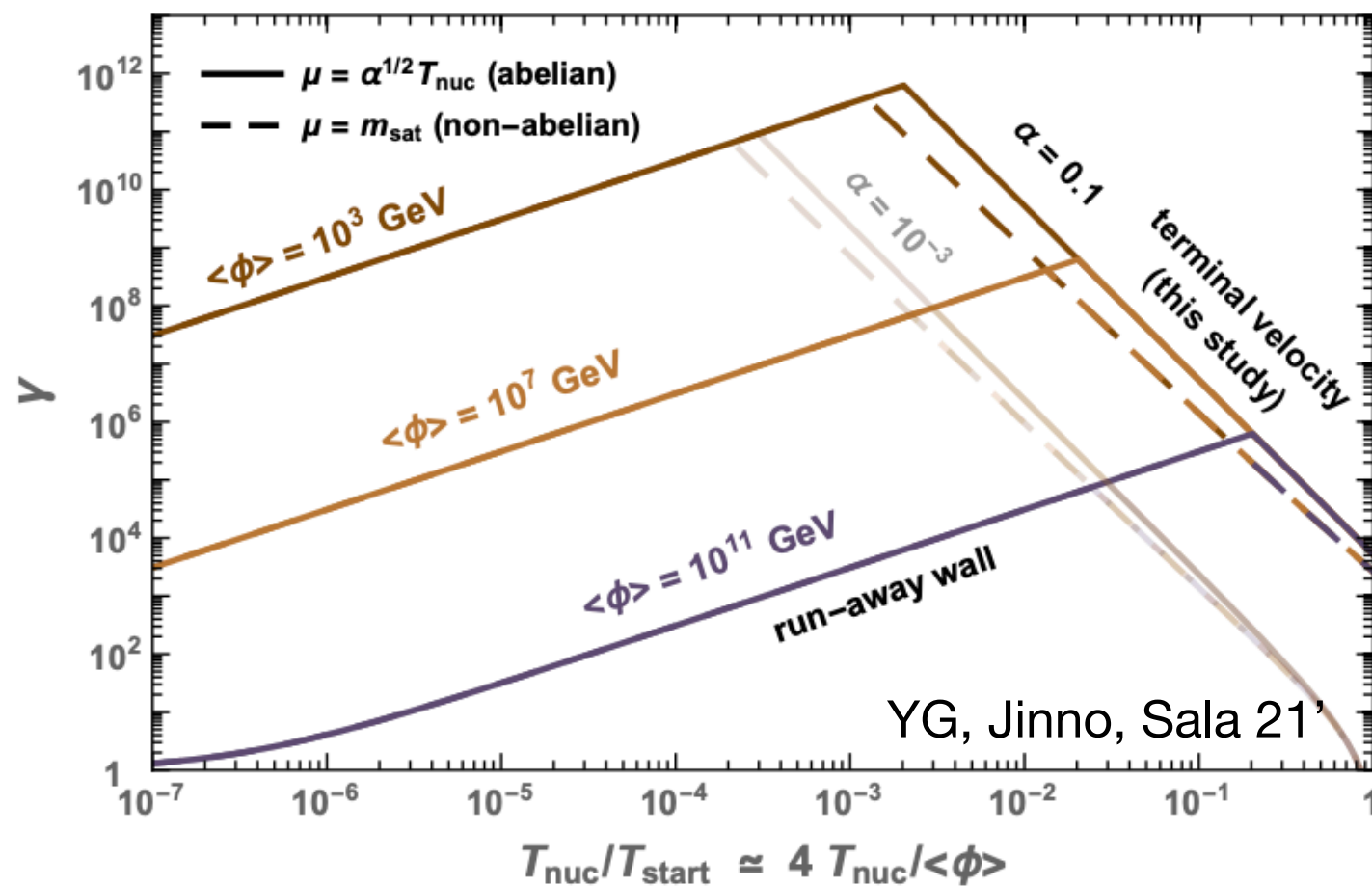
→  $M_{\text{DM}} < 100 \text{ TeV}$

Griest & Kamionkowski 91'

## 2) Relativistic bubble walls

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Bubble wall Lorentz factor

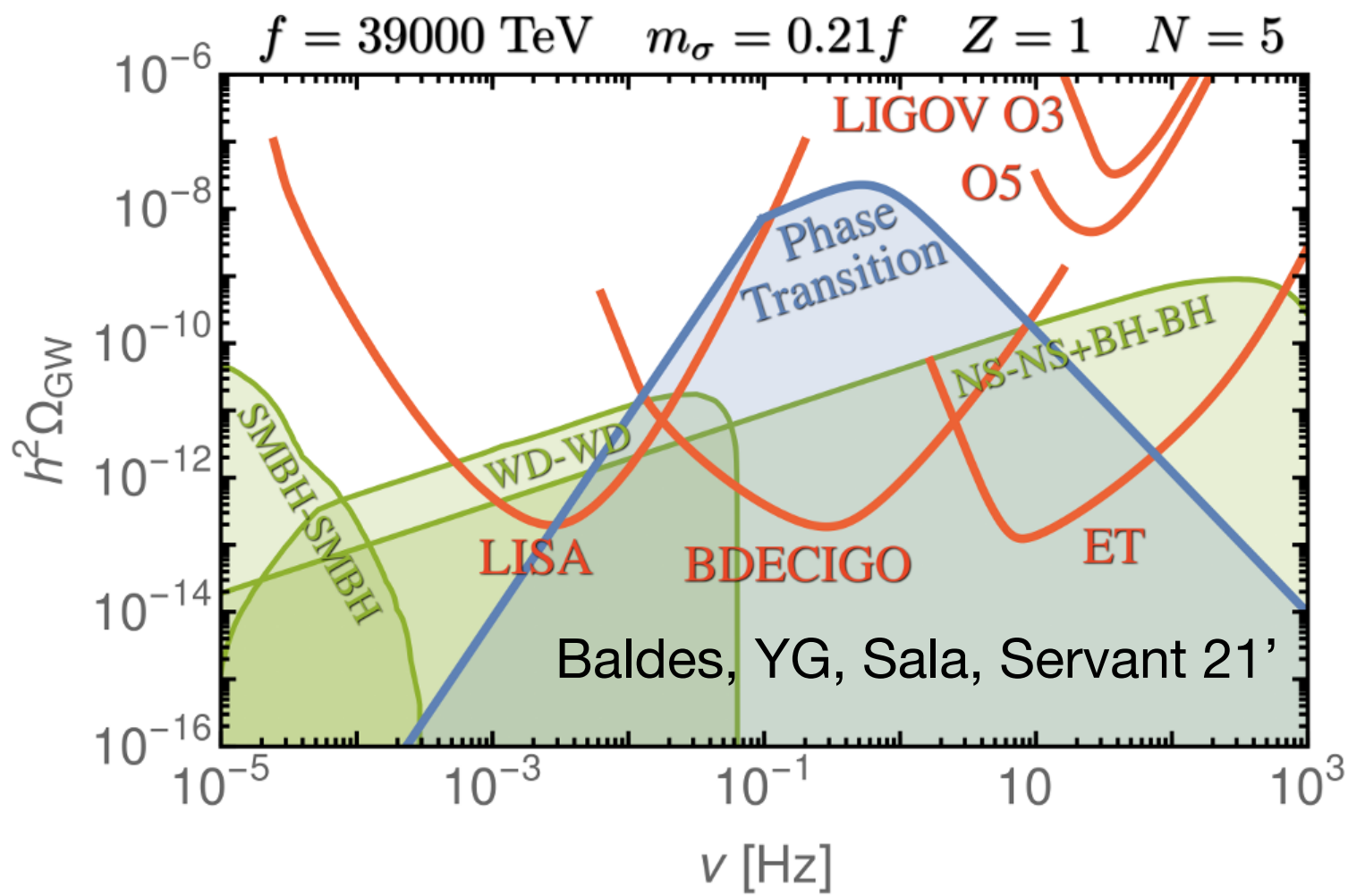


See Isabel Garcia Garcia's talk

Hoche, Kozaczuk, Long, Turner, Wang 20' (Gauge-invariant pressure ?)

# 1) Large GW spectrum

Randall, Servant 06'



# Cosmological consequences of supercooling

## 3) Heavy thermal dark matter

$$\frac{\Omega_{\text{DM}} h^2}{0.12} = \frac{(16 \text{ TeV})^2}{\langle \sigma v \rangle_{\text{FO}}} \frac{1}{D}$$

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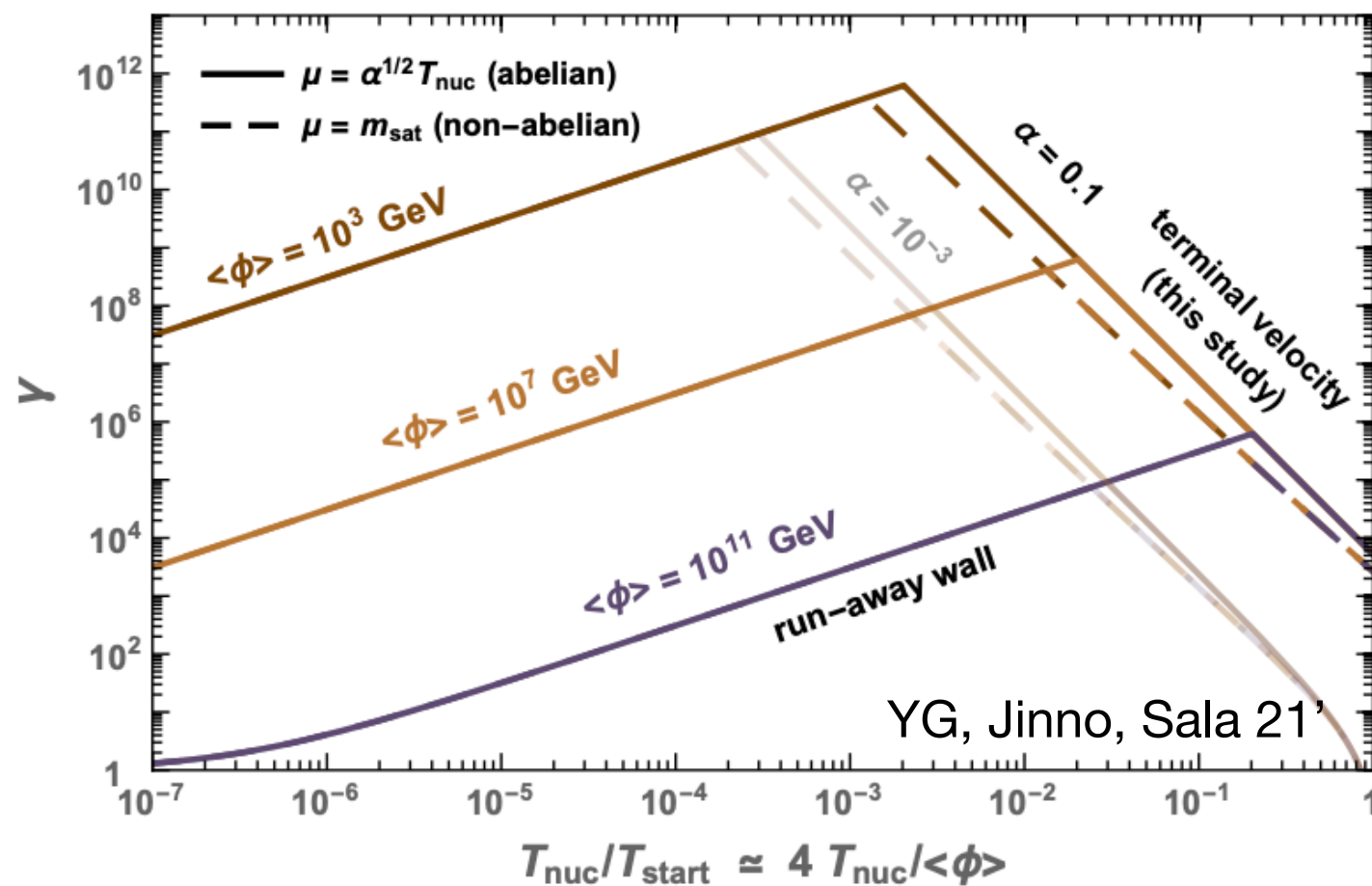
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Griest & Kamionkowski 91'

## 2) Relativistic bubble walls

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Bubble wall Lorentz factor

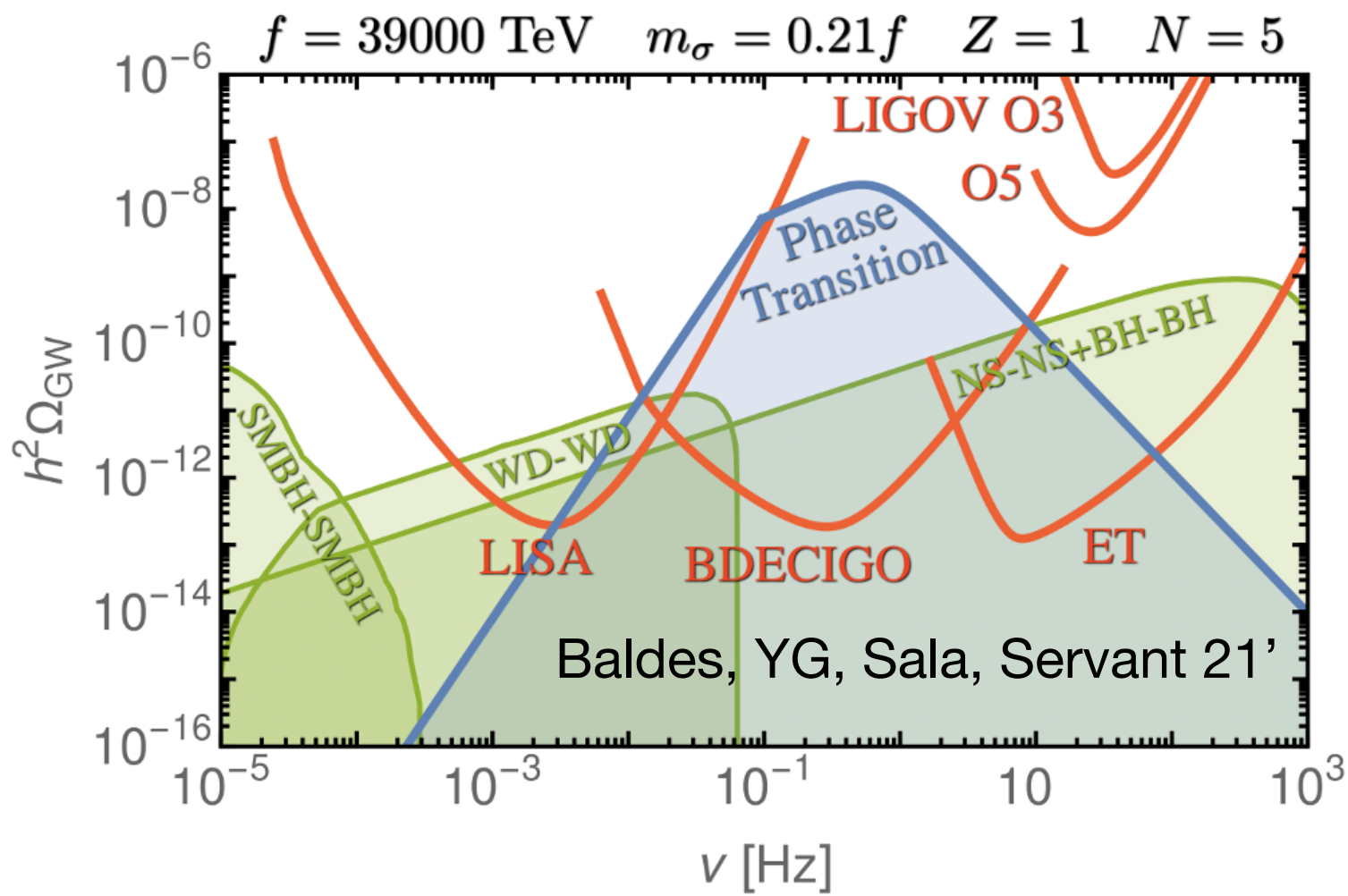


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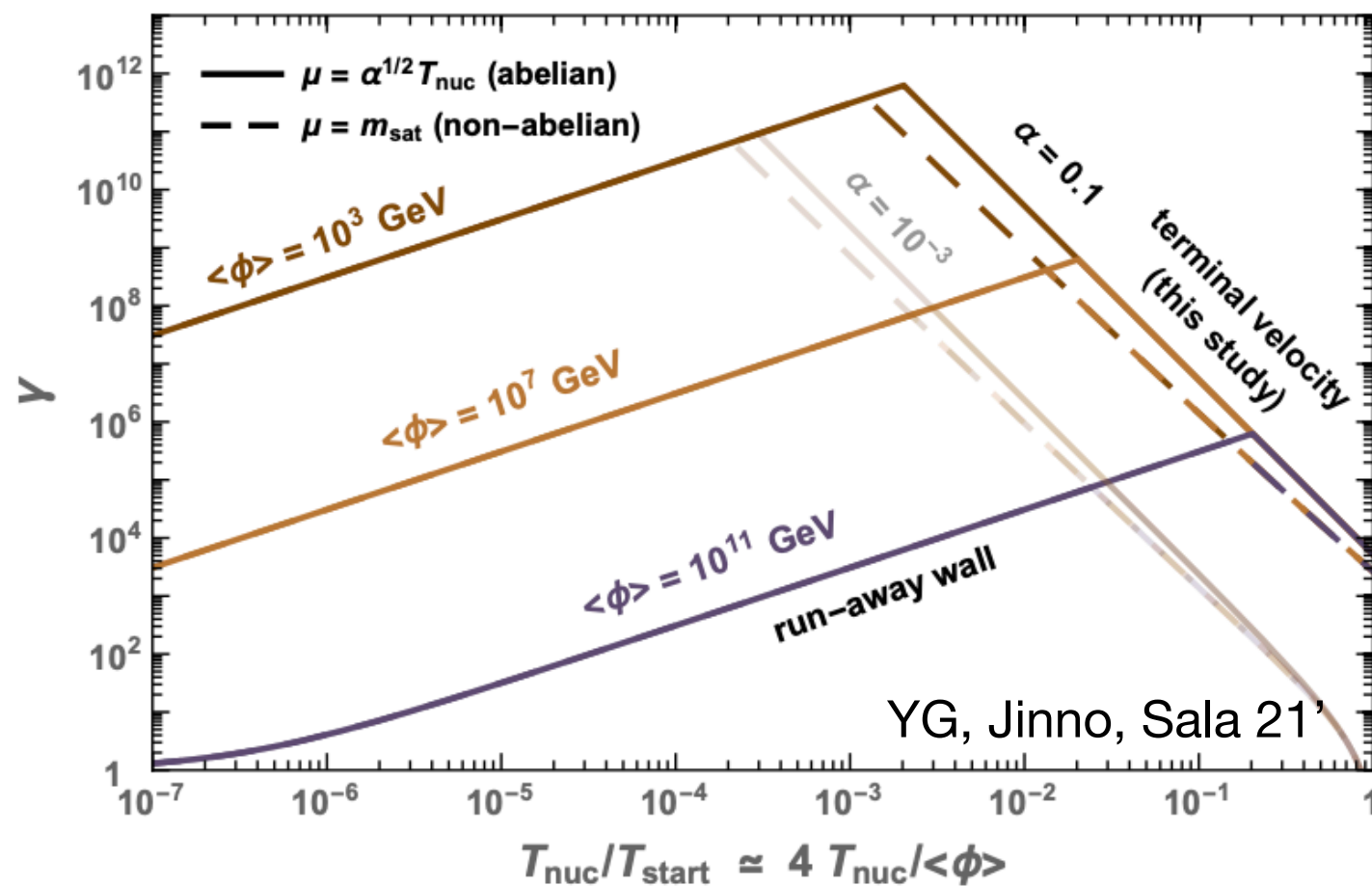
Randall, Servant 06'



# 2) Relativistic bubble walls

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Griest & Kamionkowski 91'

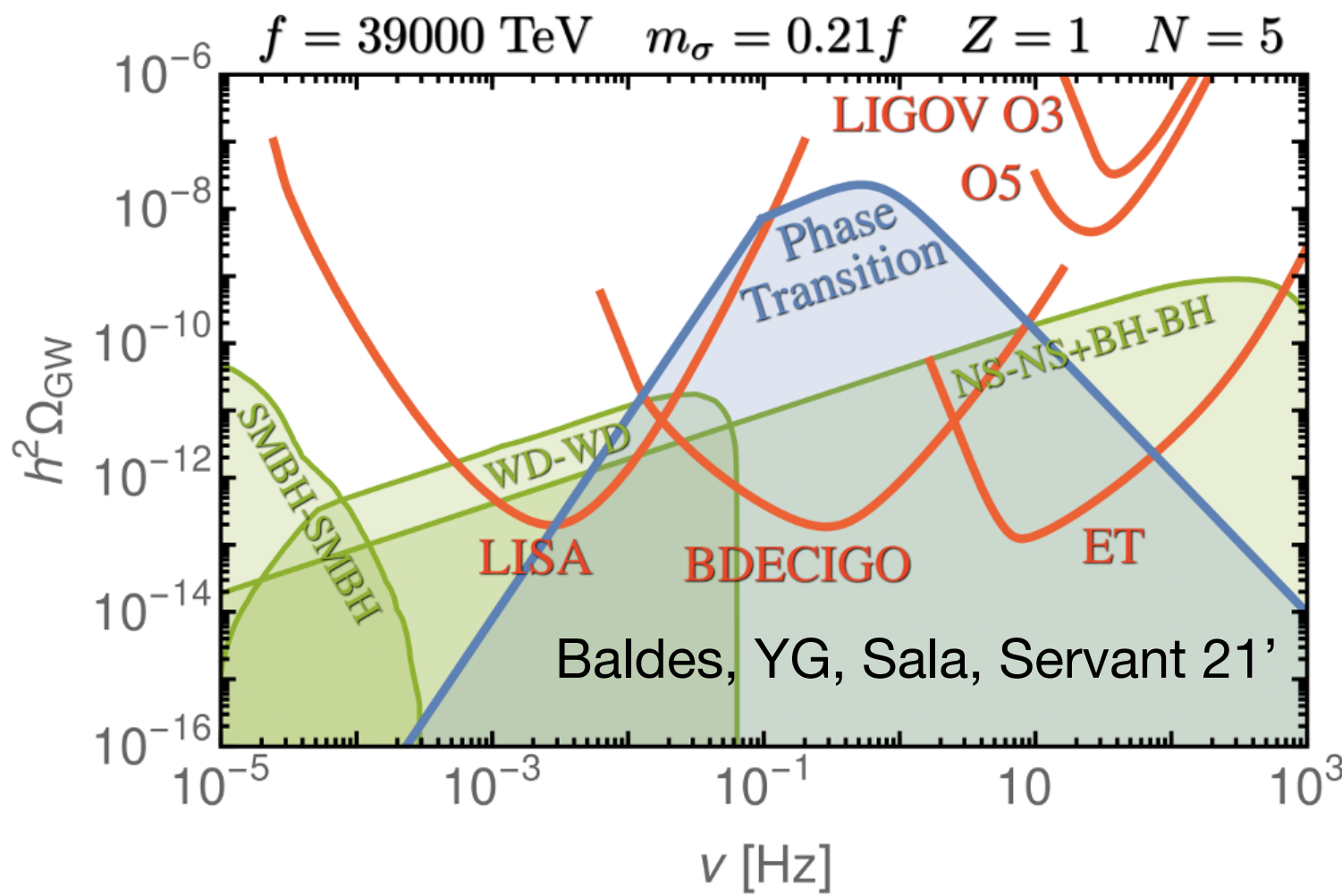
How do you get D ?

See Isabel Garcia Garcia's talk

Hoche, Kozaczuk, Long, Turner, Wang 20' (Gauge-invariant pressure ?)

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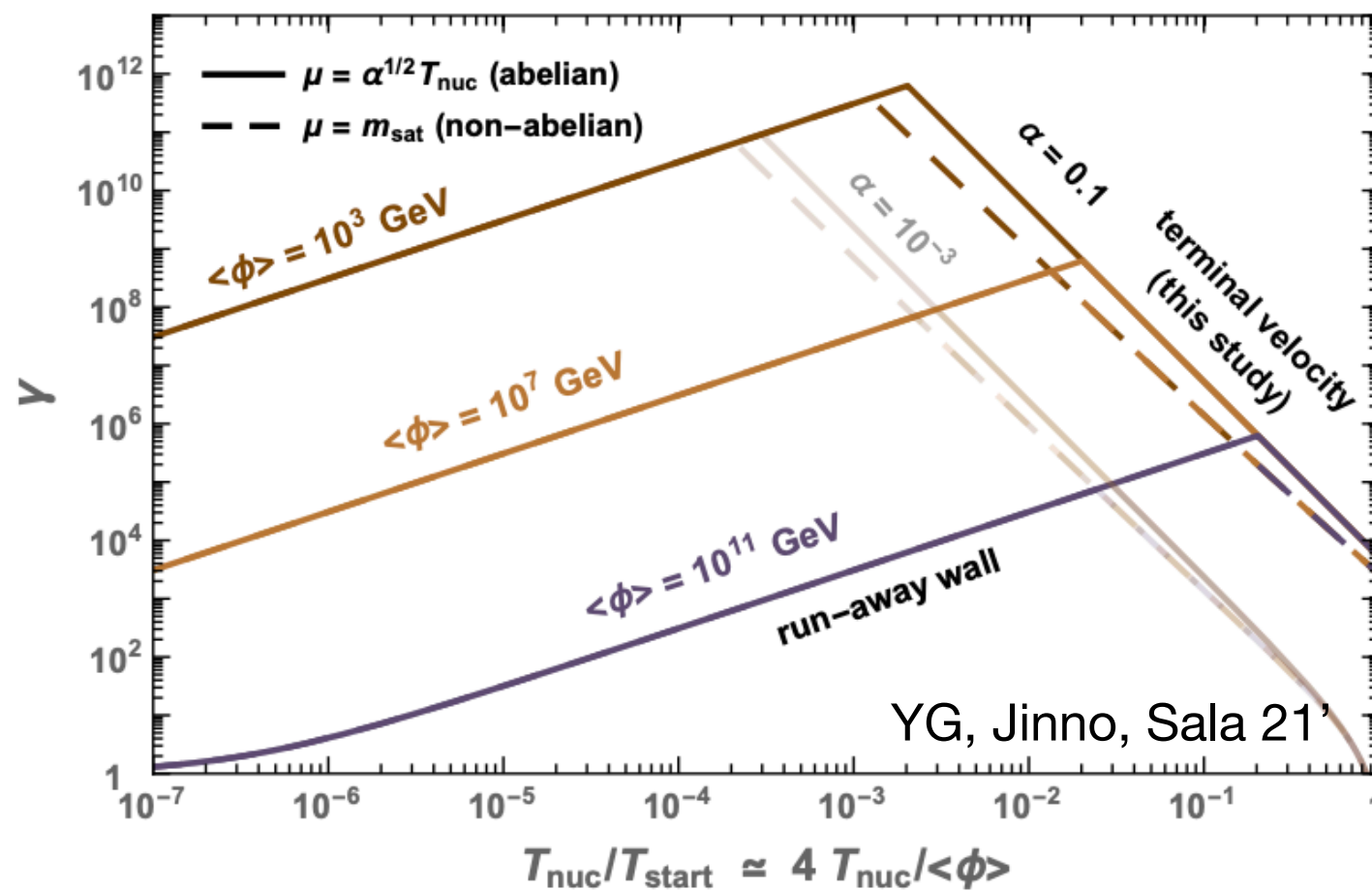
Randall, Servant 06'



# 2) Relativistic bubble walls

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# Cosmological consequences of supercooling

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Griest & Kamionkowski 91'

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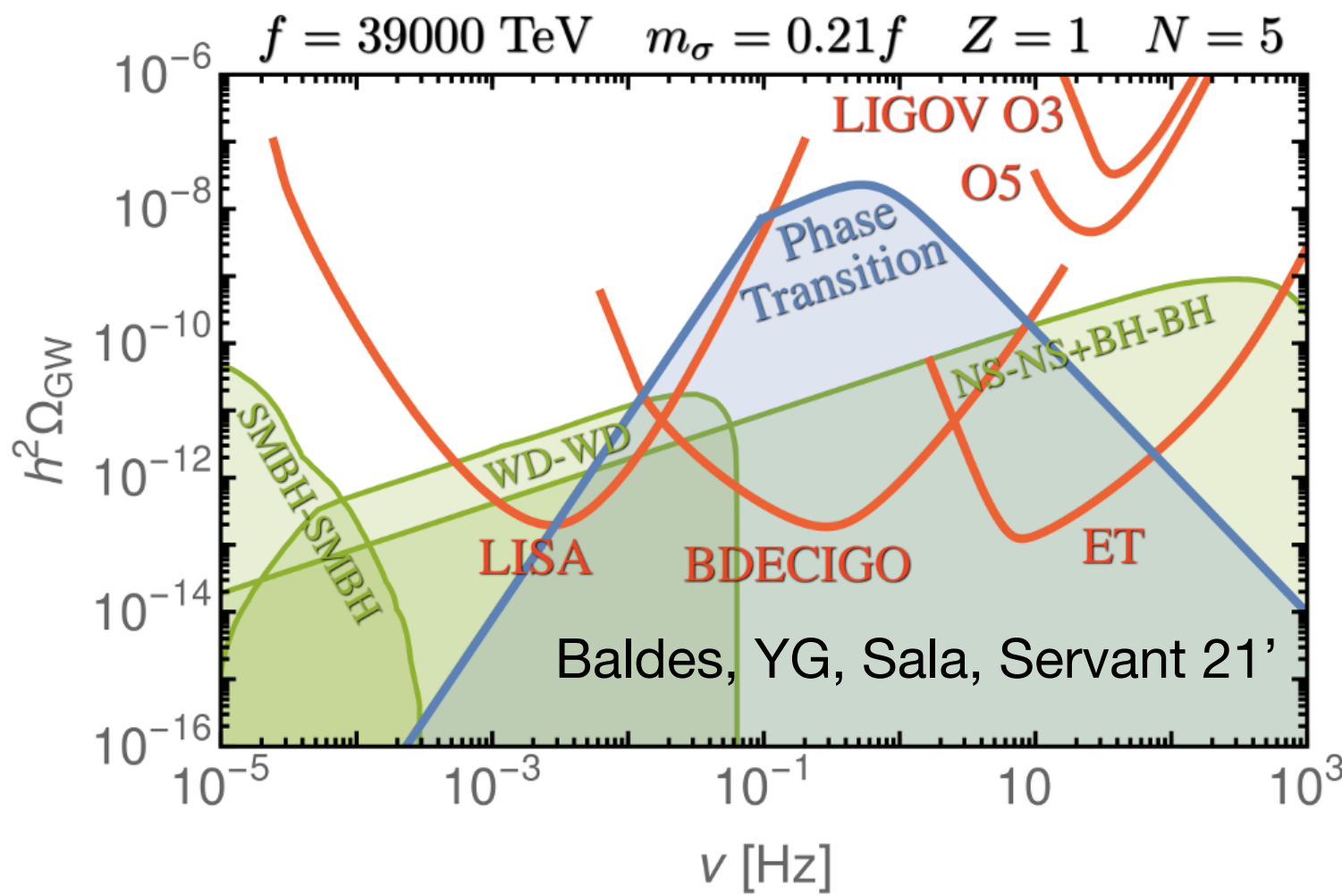
Dilution by a matter era (McDonald 91', Cirelli, YG, Petraki, Sala 18')

See Isabel Garcia Garcia's talk

Hoche, Kozaczuk, Long, Turner, Wang 20' (Gauge-invariant pressure ?)

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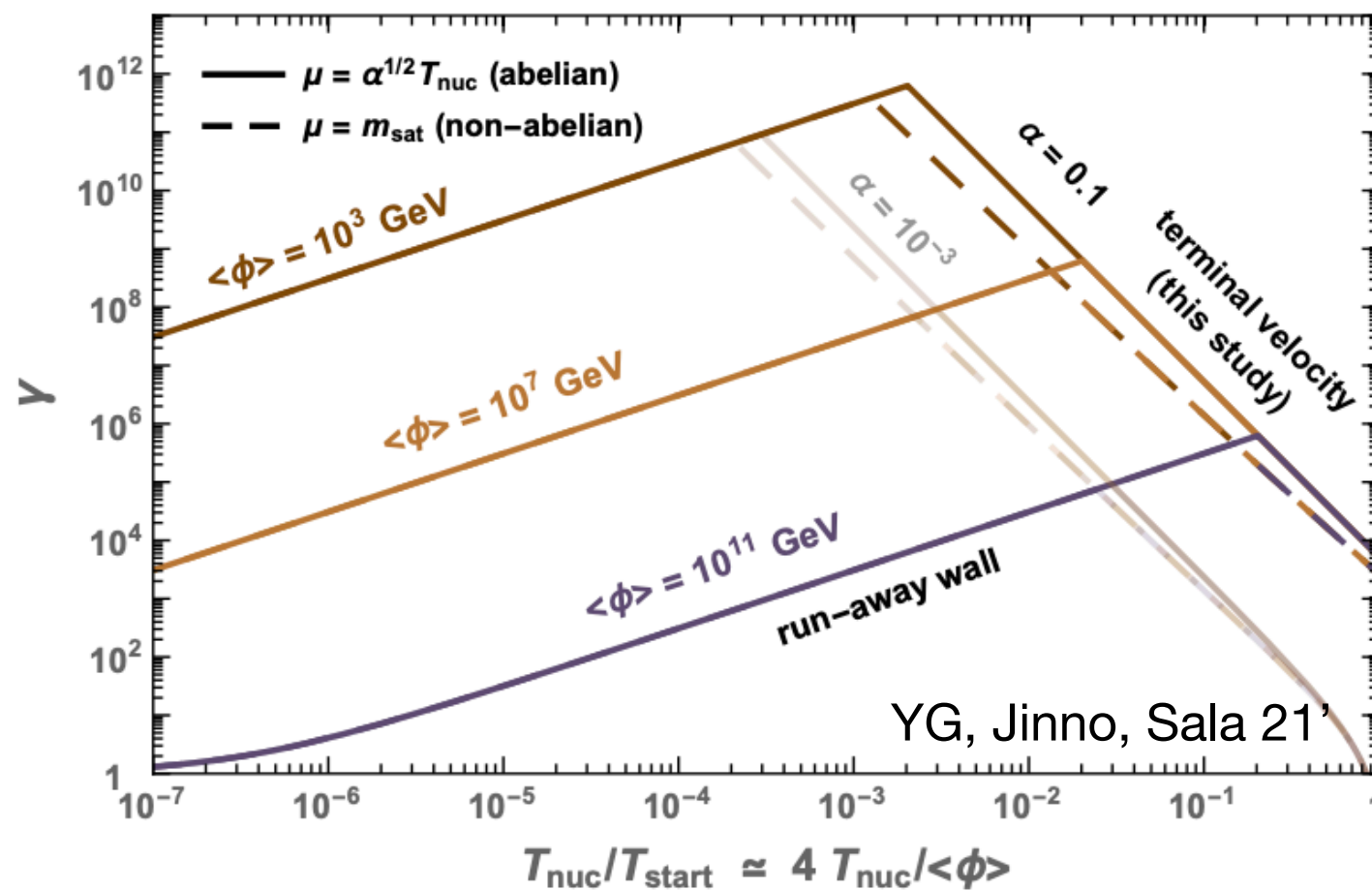
Randall, Servant 06'



# 2) Relativistic bubble walls

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Griest & Kamionkowski 91'

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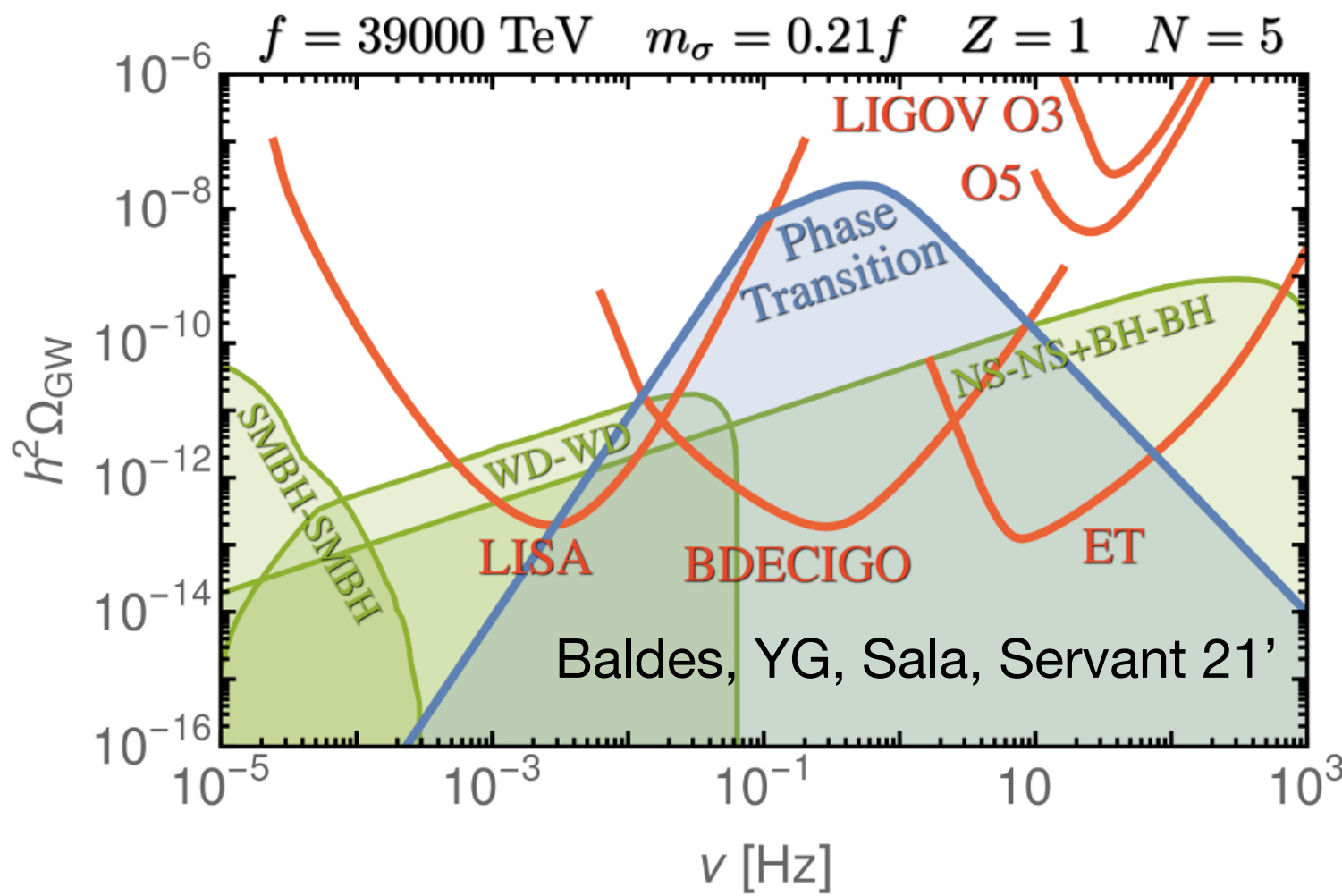
Second annihilation stage via bubble squeezing (Asadi, Kramer, Kuflik, Ridgway, Slatyer, Smirnov 21')

See Isabel Garcia Garcia's talk

Hoche, Kozaczuk, Long, Turner, Wang 20' (Gauge-invariant pressure ?)

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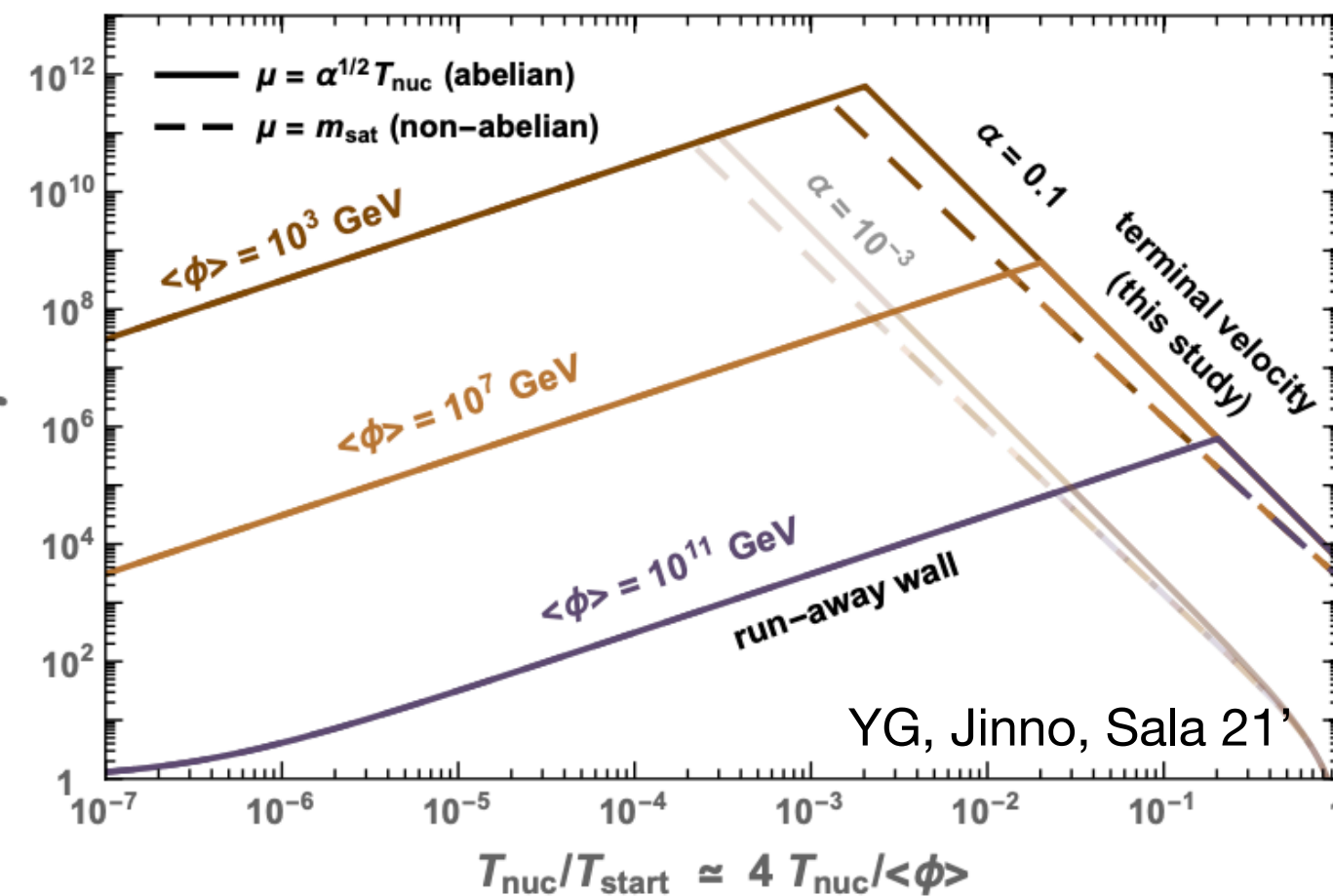
Randall, Servant 06'



# 2) Relativistic bubble walls

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Griest & Kamionkowski 91'

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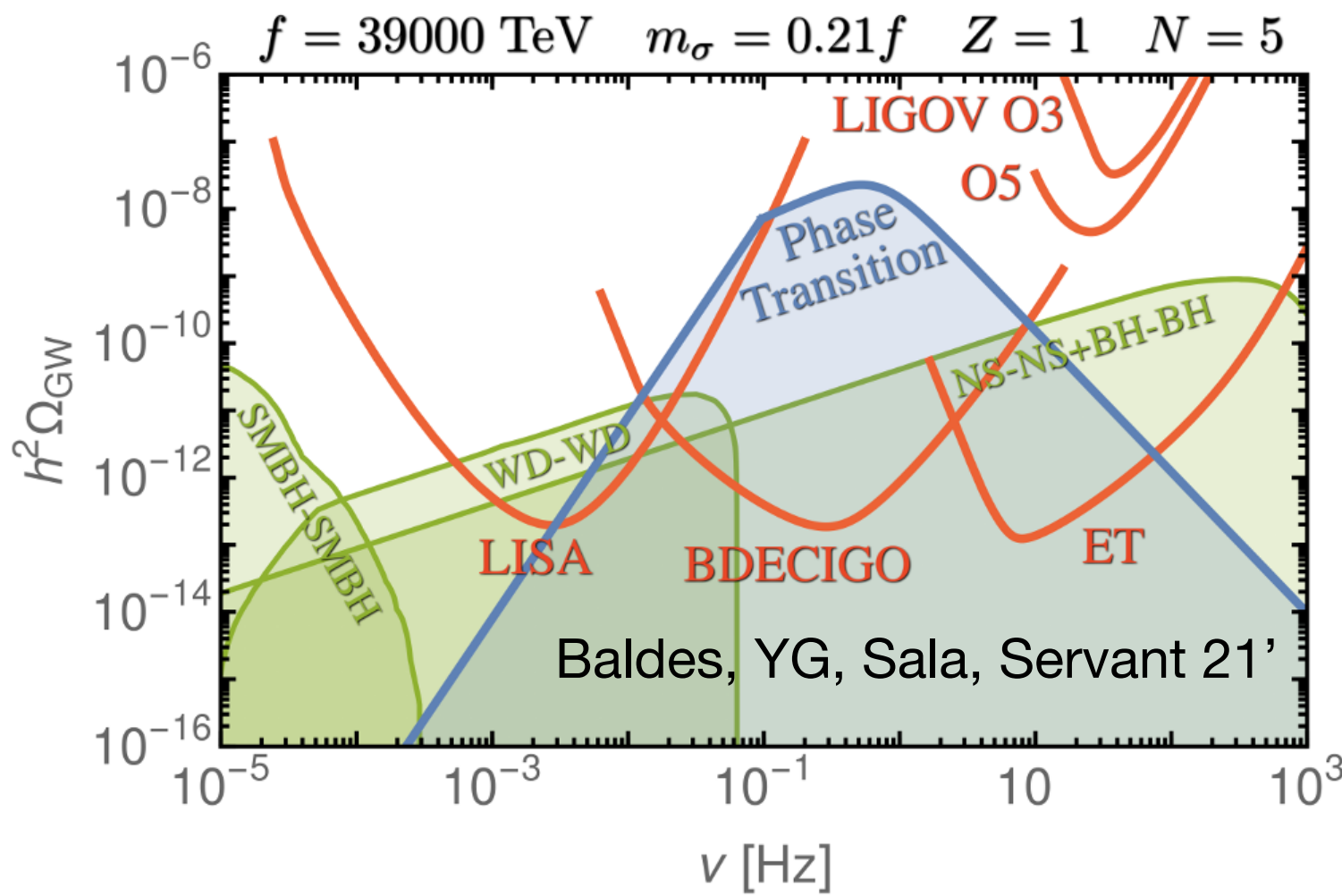
with many spectator fields (Kim, Kuflik 21')

See Isabel Garcia Garcia's talk

Hoche, Kozaczuk, Long, Turner, Wang 20' (Gauge-invariant pressure ?)

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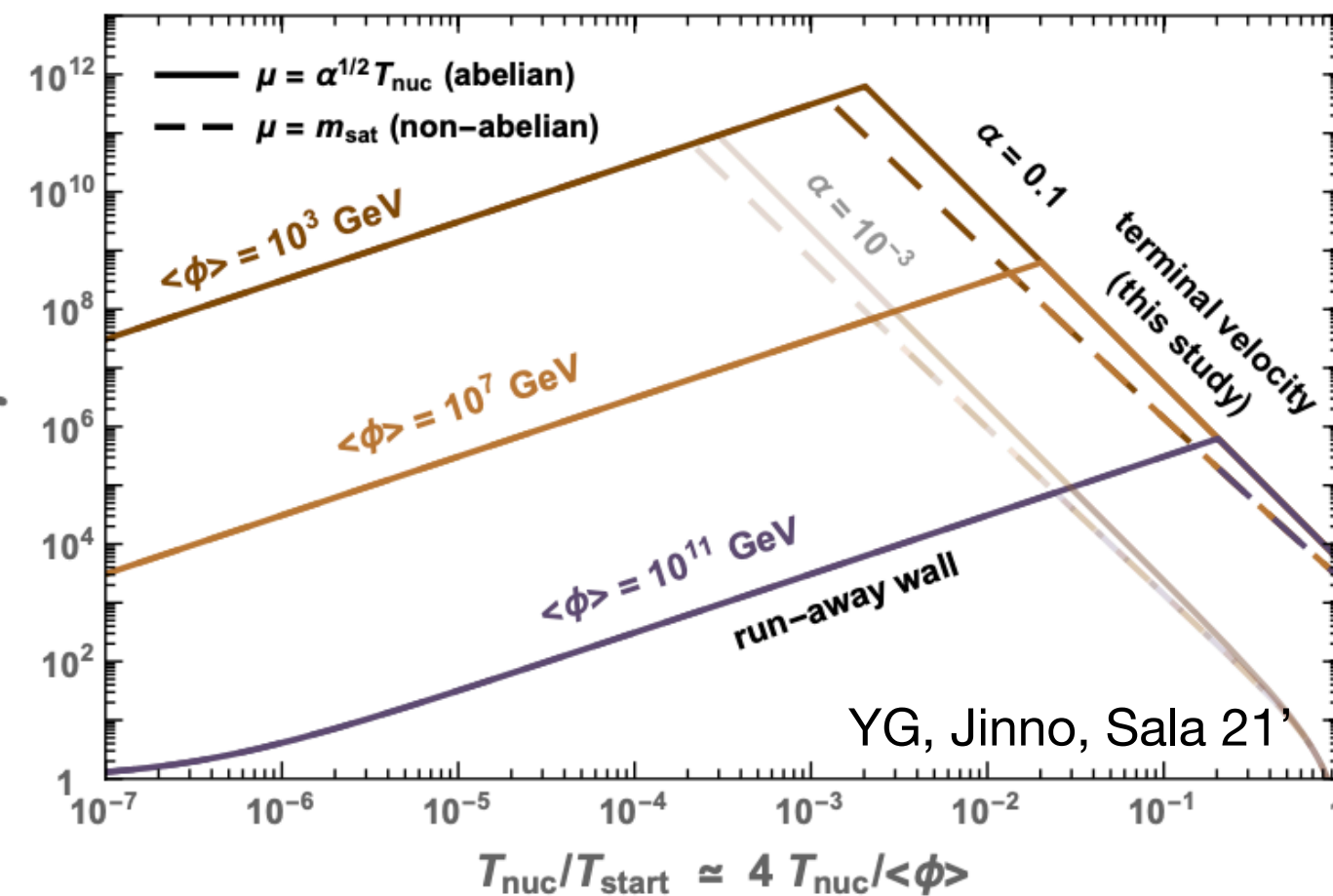
Randall, Servant 06'



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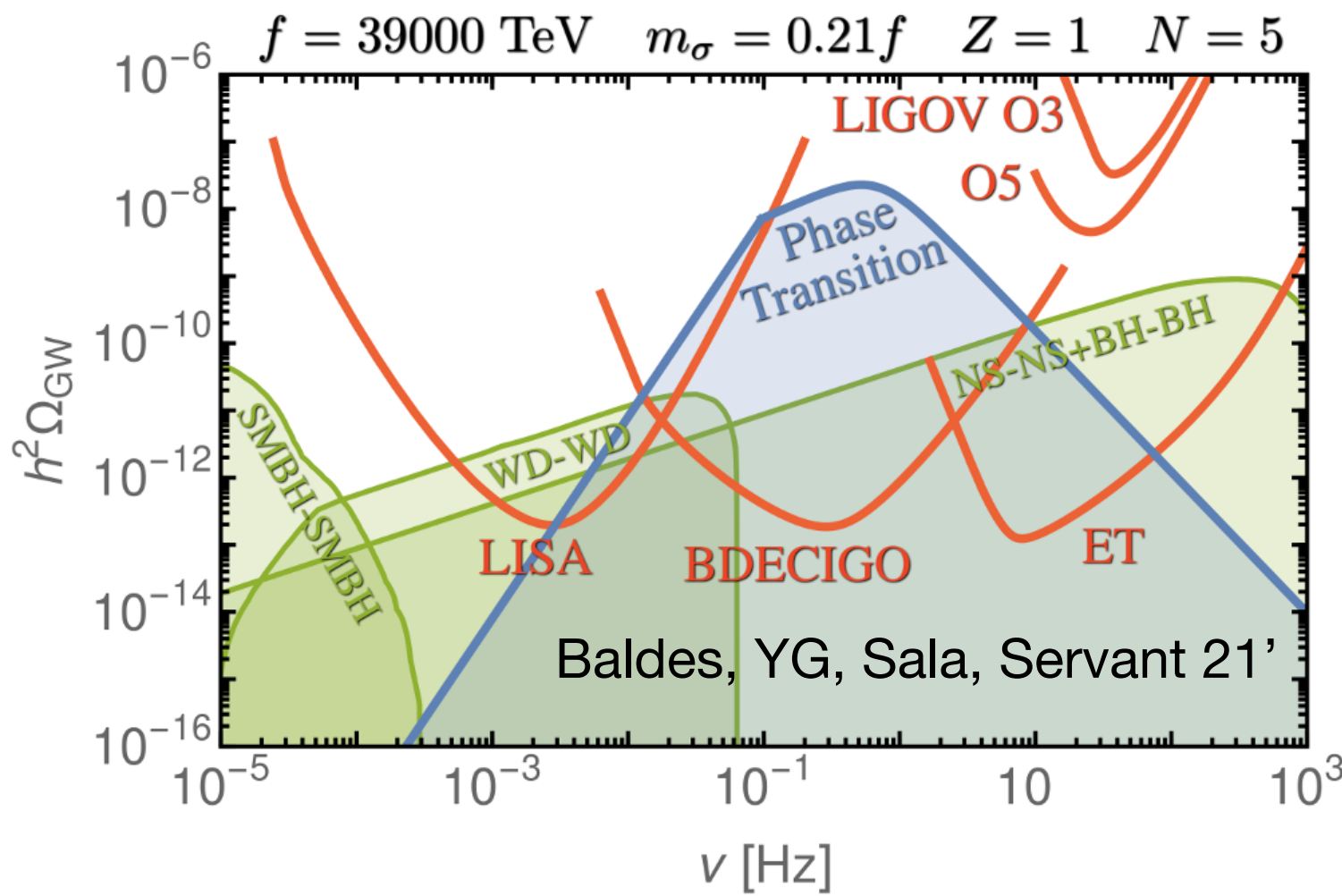
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See Isabel Garcia Garcia's talk

Hoche, Kozaczuk, Long, Turner, Wang 20' (Gauge-invariant pressure ?)

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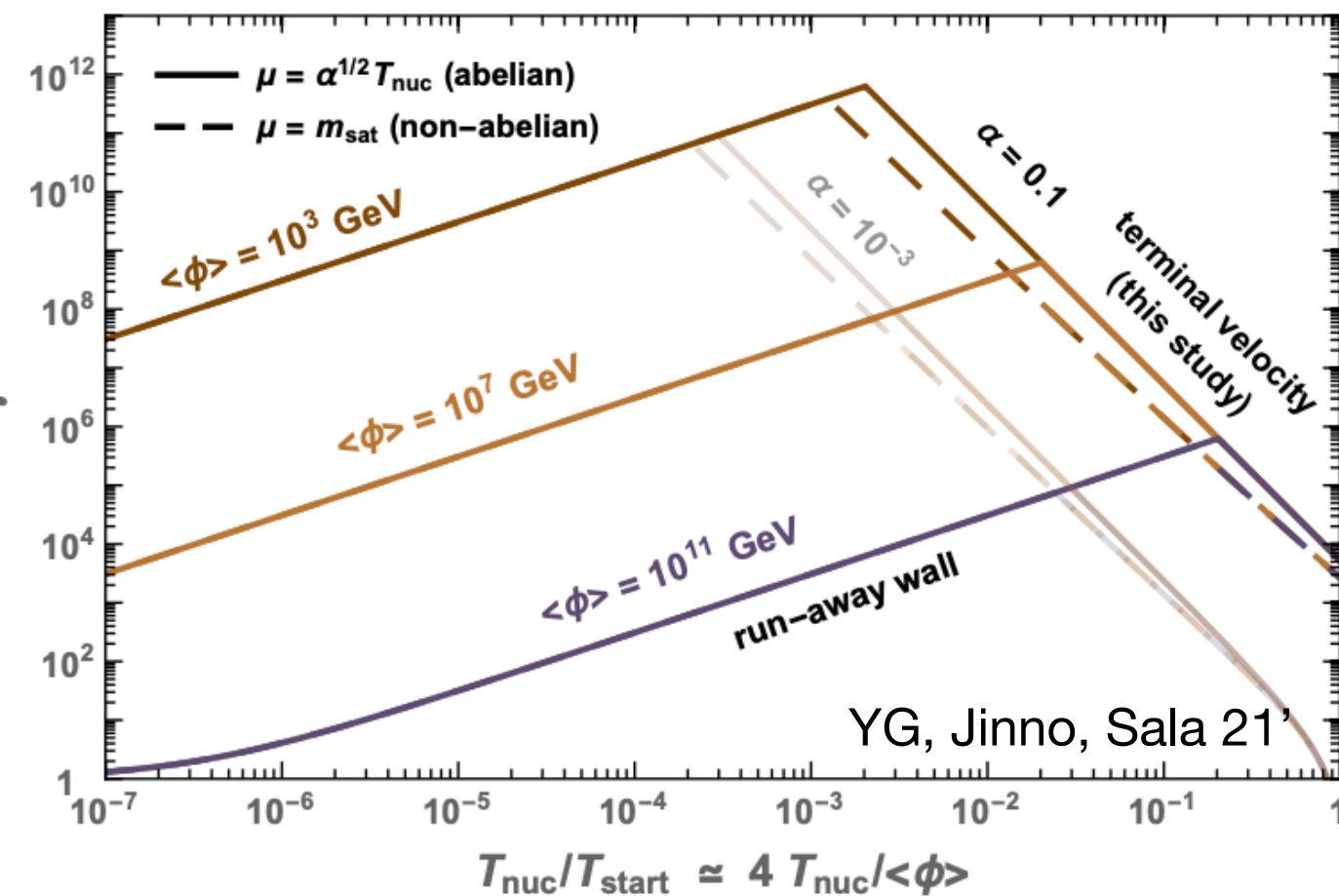
Randall, Servant 06'



# 2) Relativistic bubble walls

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Griest & Kamionkowski 91'

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Warped fifth dimension

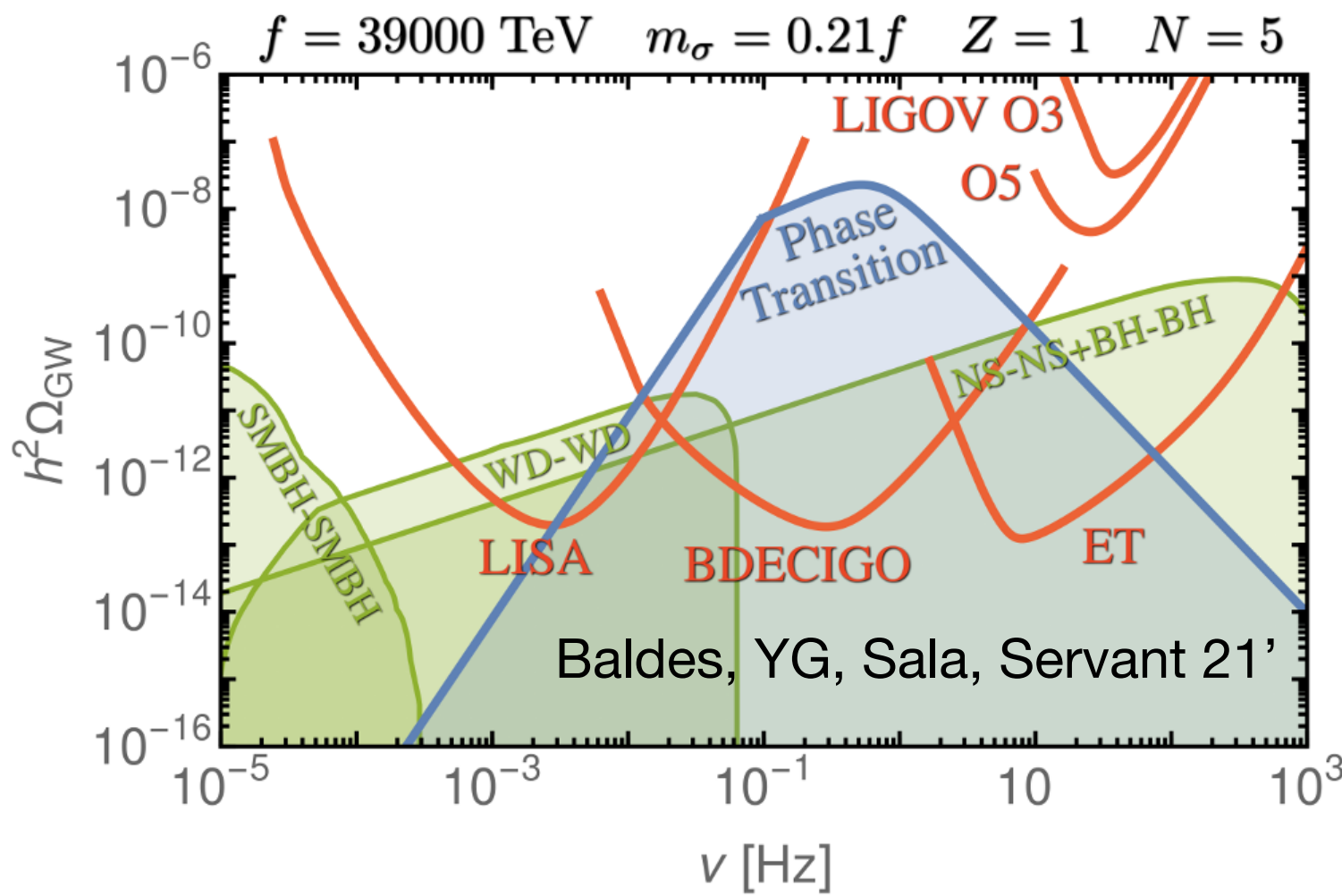
See Isabel Garcia Garcia's talk

Hoche, Kozaczuk, Long, Turner, Wang 20' (Gauge-invariant pressure ?)



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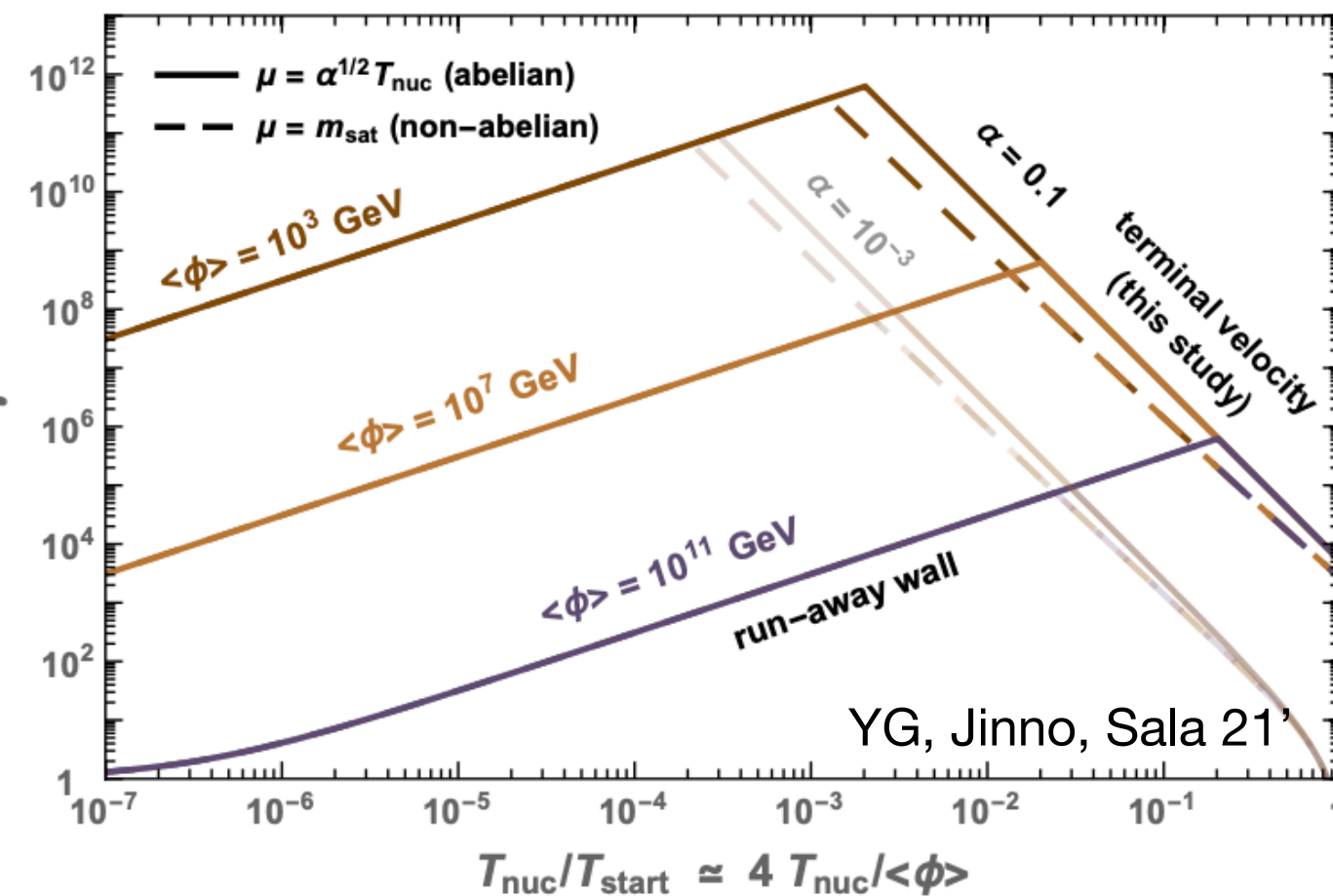
Randall, Servant 06'



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Griest & Kamionkowski 91'

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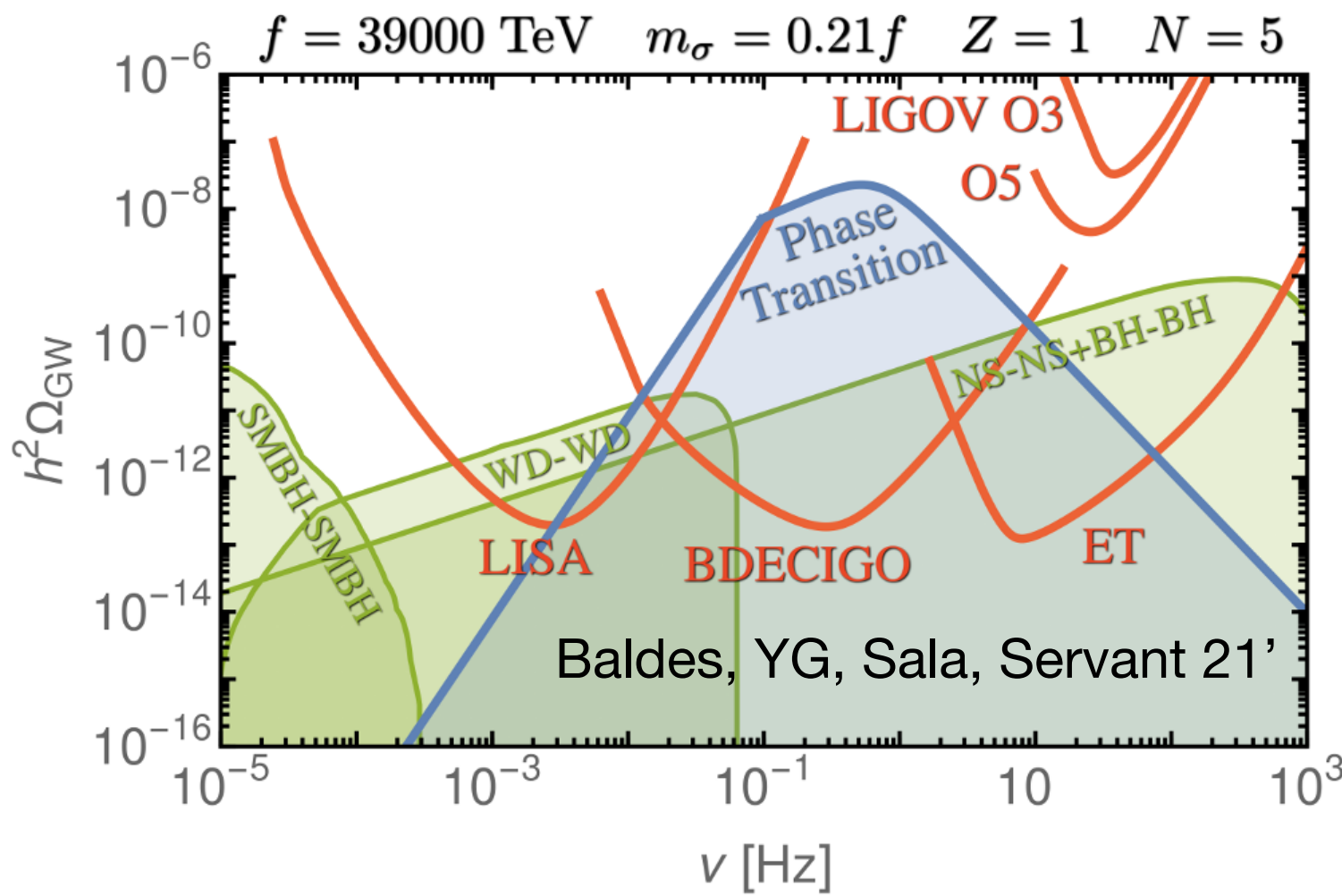
Warped fifth dimension  
Weakly-coupled

See Isabel Garcia Garcia's talk

Hoche, Kozaczuk, Long, Turner, Wang 20' (Gauge-invariant pressure ?)

# 1) Large GW spectrum

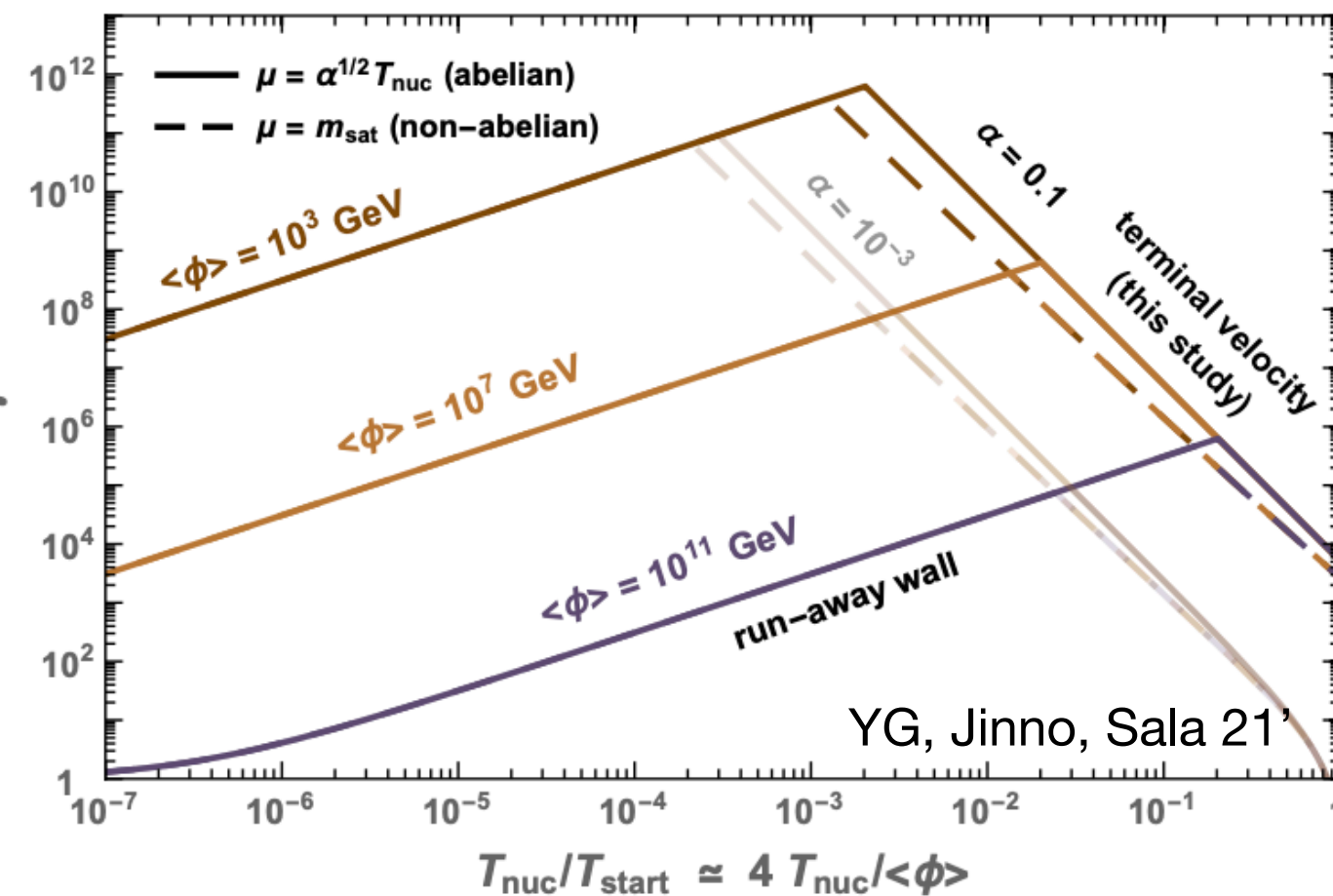
Randall, Servant 06'



# 2) Relativistic bubble walls

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Bubble wall Lorentz factor



# Cosmological consequences of supercooling

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Griest & Kamionkowski 91'

### How do you get D ?

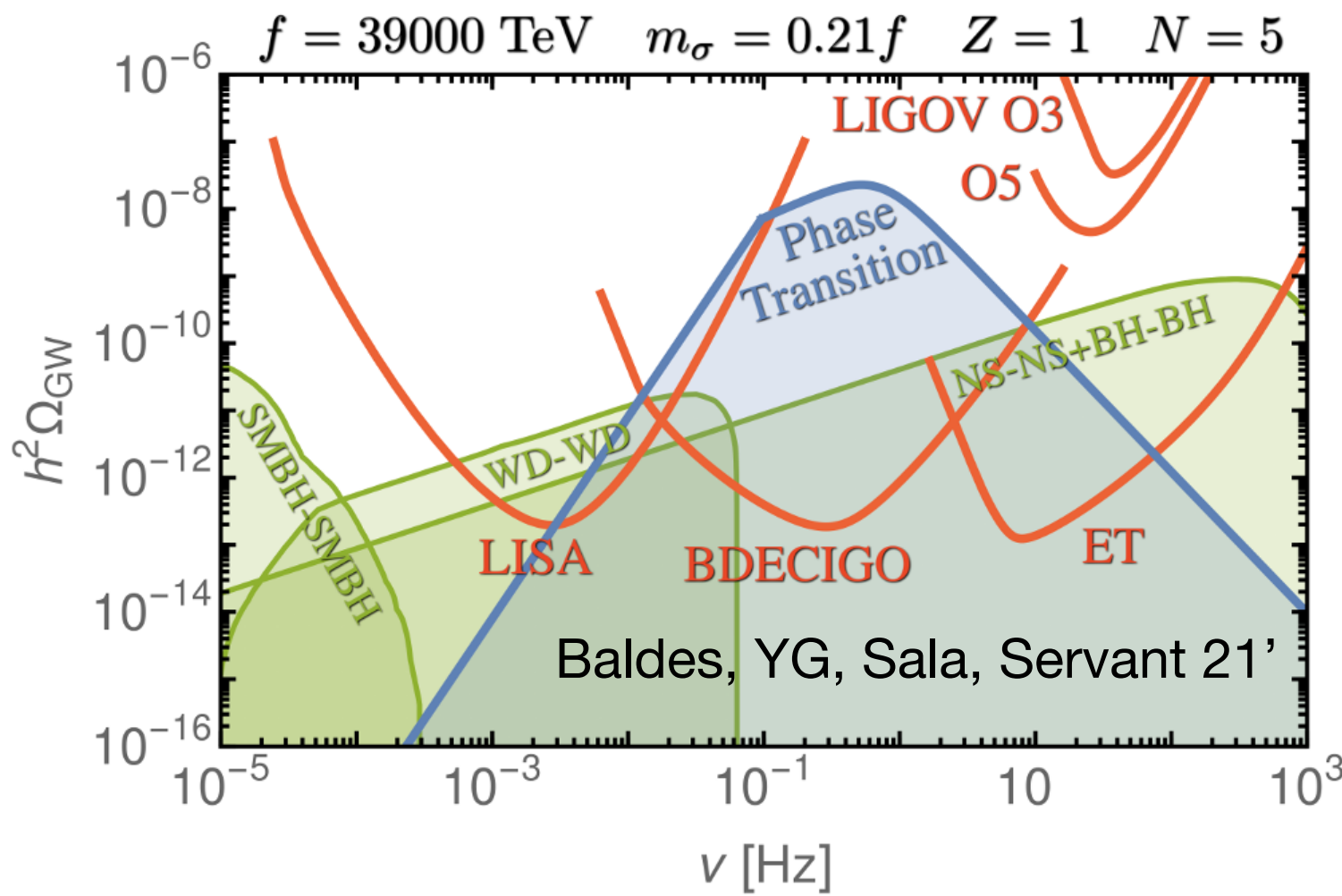
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  - (Baratella, Pomarol, Rompeneve 18')

Warped fifth dimension  
Weakly-coupled  
Strongly-coupled

See Isabel Garcia Garcia's talk  
Hoche, Kozaczuk, Long, Turner, Wang 20' (Gauge-invariant pressure ?)

# 1) Large GW spectrum

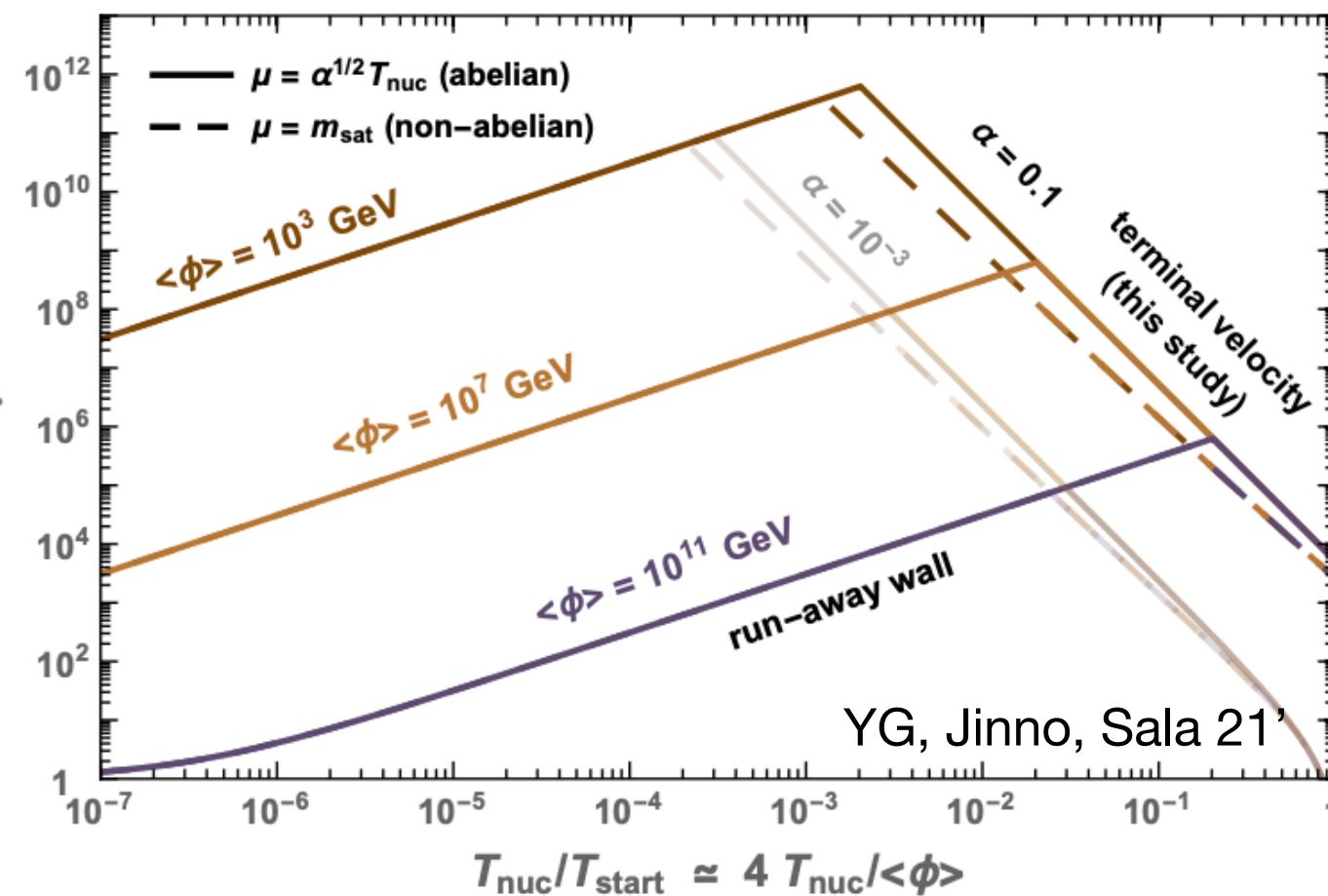
Randall, Servant 06'



# 2) Relativistic bubble walls

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Bubble wall Lorentz factor



# Cosmological consequences of supercooling

## 3) Heavy thermal dark matter

$$\frac{\Omega_{\text{DM}} h^2}{0.12} = \frac{(16 \text{ TeV})^2}{\langle \sigma v \rangle_{\text{FO}}} \frac{1}{D}$$

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Griest & Kamionkowski 91'

## How do you get D ?

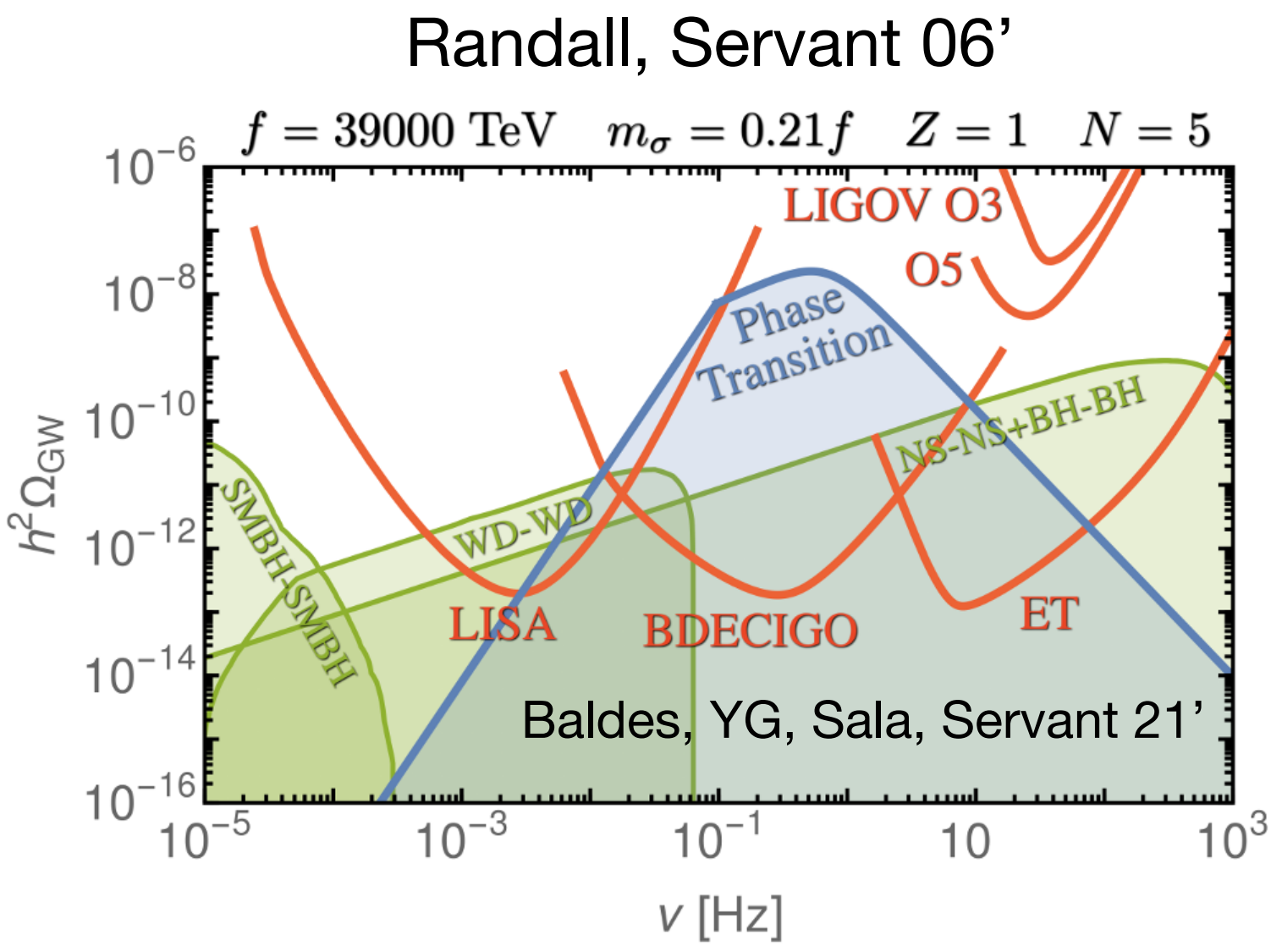
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(Hambye, Strumia, Teresi 18')	Warped fifth dimension
(Baratella, Pomarol, Rompeneve 18')	Weakly-coupled
Baldes, YG, Sala 20'	Strongly-coupled
Baldes, YG, Sala, Servant 21'	DM production at the wall due to flux tube formation

See Isabel Garcia Garcia's talk

Hoche, Kozaczuk, Long, Turner, Wang 20' (Gauge-invariant pressure ?)

# 1) Large GW spectrum



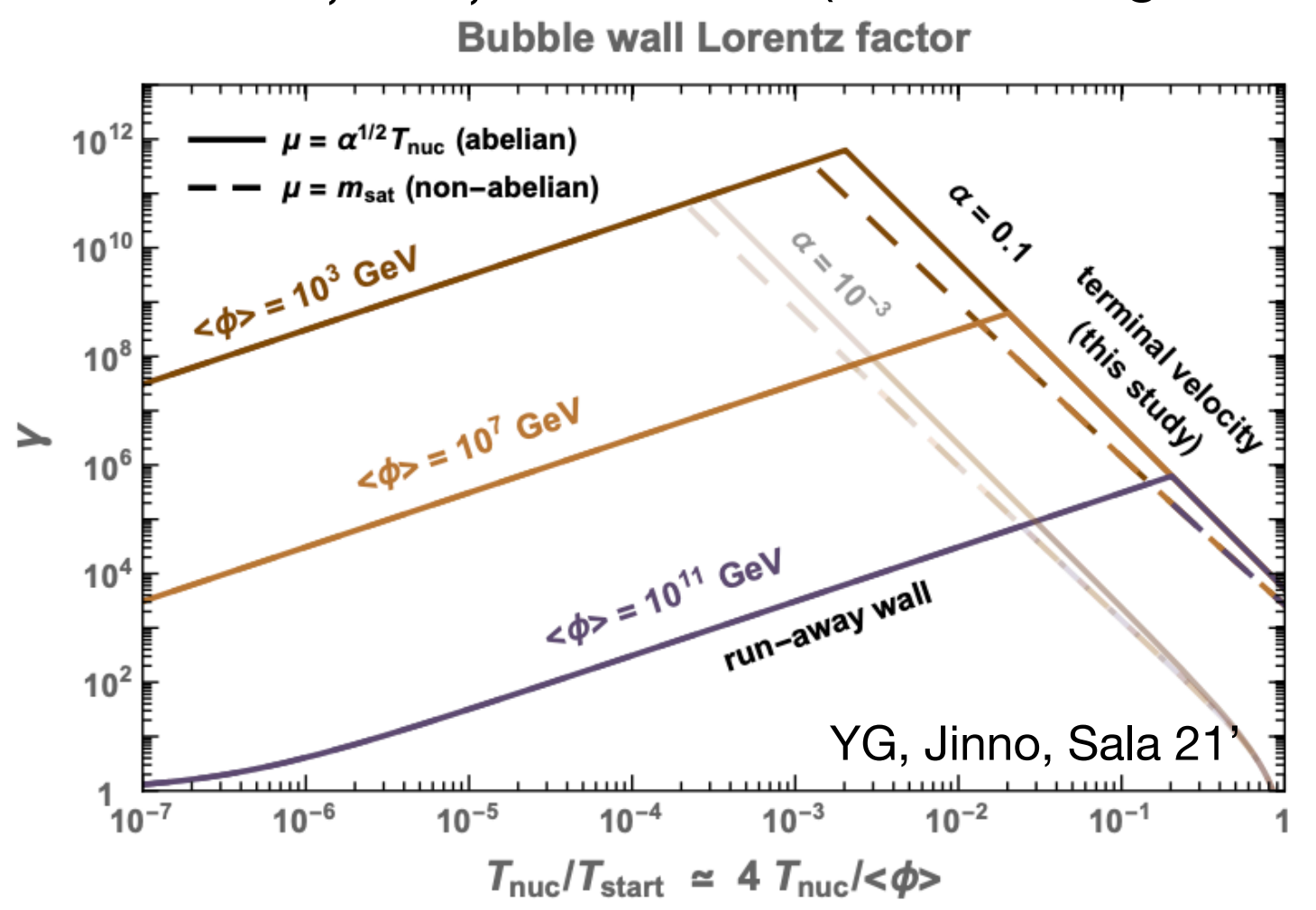
# 3) Heavy thermal dark matter

- (Konstandin, Servant 11') Warped fifth dimension
- (Hambye, Strumia, Teresi 18') Weakly-coupled
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- Baldes, YG, Sala 20' DM production at the wall due to flux tube formation
- Baldes, YG, Sala, Servant 21' DM production at the wall due to flux tube formation

More details soon

# 2) Relativistic bubble walls

- Bodeker, Moore 17' (Perturbative level)
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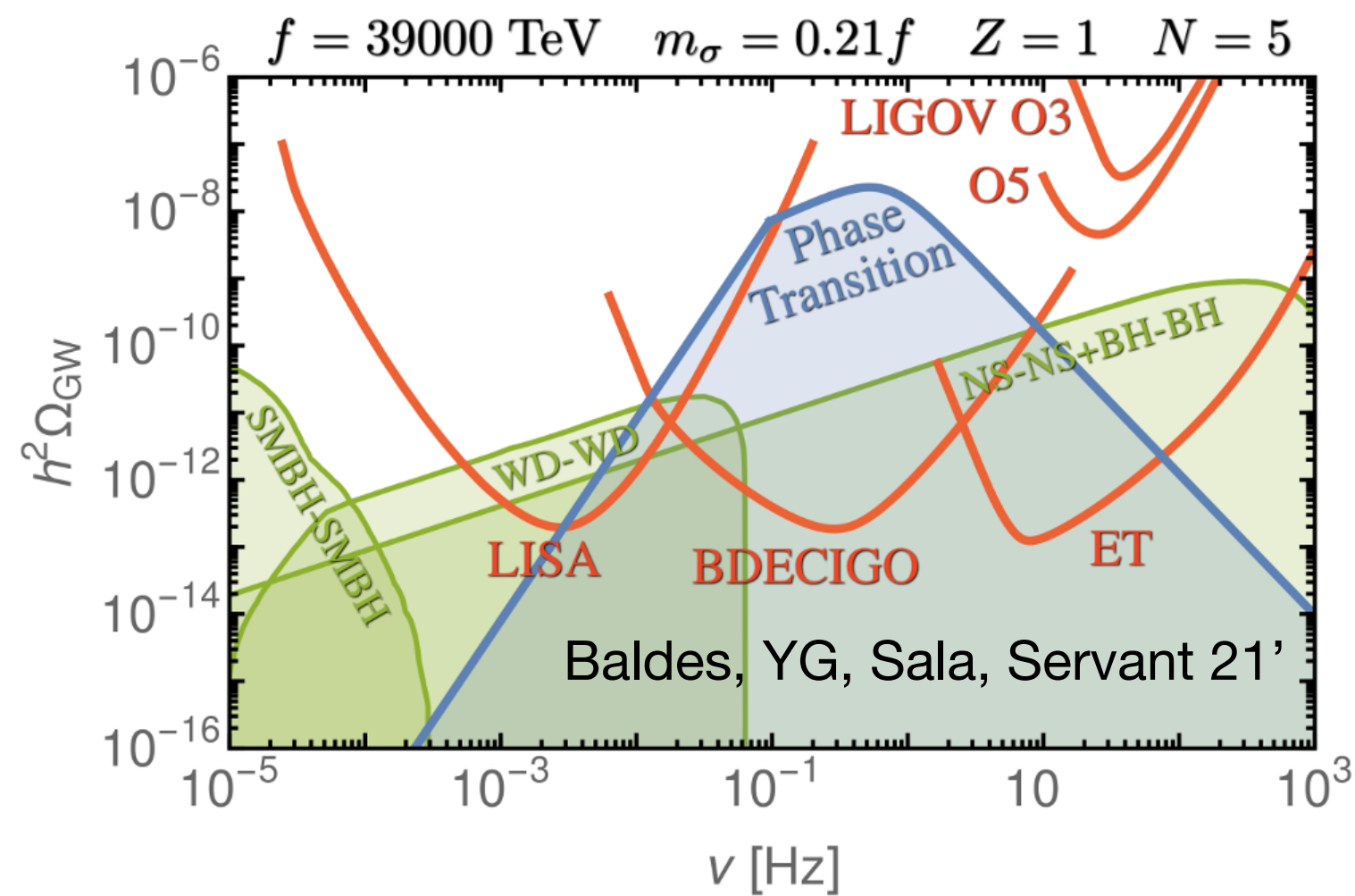


See Isabel Garcia Garcia's talk  
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# Cosmological consequences of supercooling

## 1) Large GW spectrum

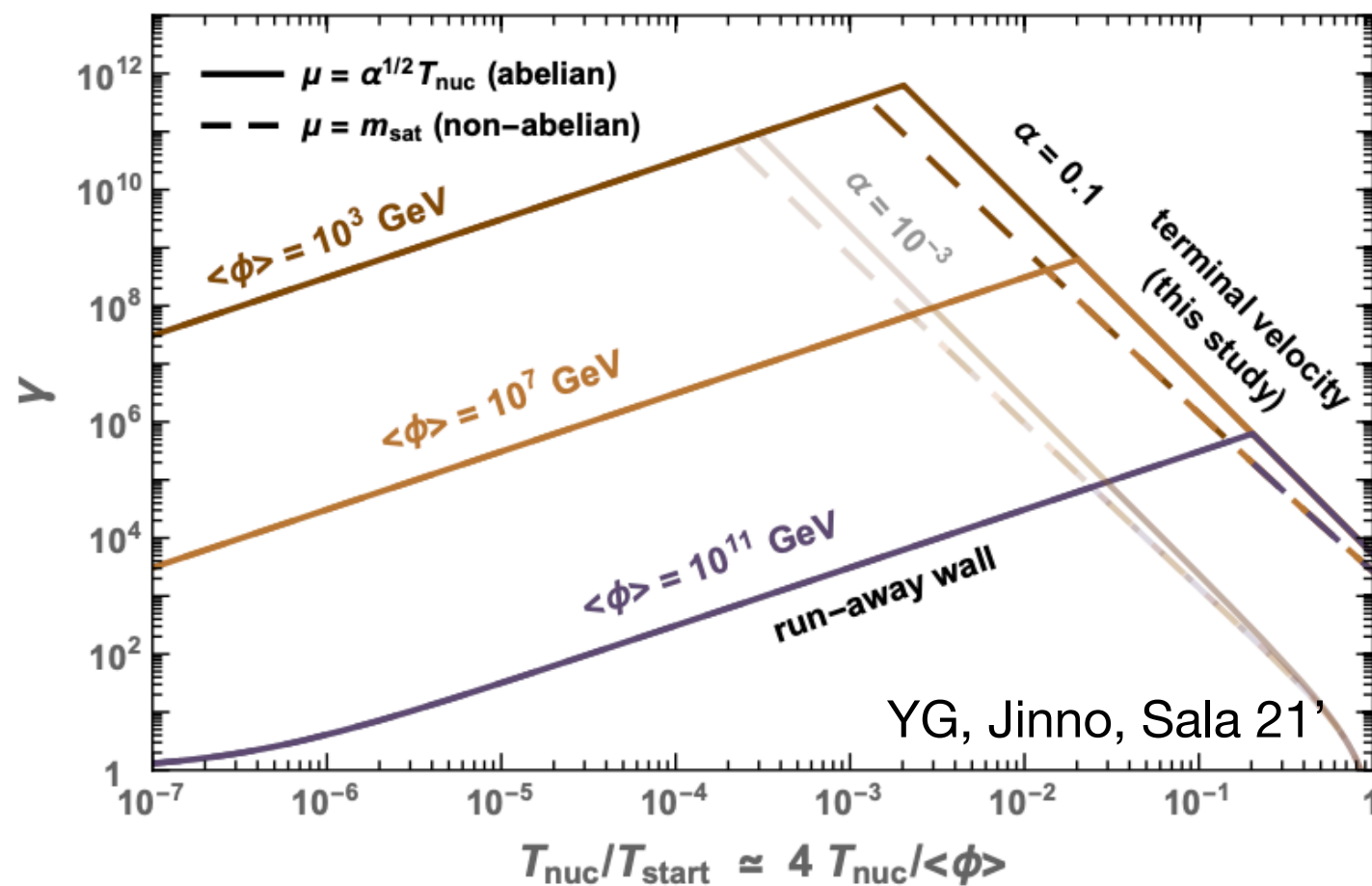
Randall, Servant 06'



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- Bodeker, Moore 17' (Perturbative level)
- YG, Jinno, Sala 21' (Sudakov resummation)
- Baldes, YG, Sala 20' (Gluon string description)

Bubble wall Lorentz factor



## 3) Heavy thermal dark matter

- (Konstandin, Servant 11') Warped fifth dimension
- (Hambye, Strumia, Teresi 18') Weakly-coupled
- (Baratella, Pomarol, Rompeneve 18') Strongly-coupled
- Baldes, YG, Sala 20' DM production at the wall due to flux tube formation
- Baldes, YG, Sala, Servant 21'

More details soon

## 4) Particle production

### a) Strongly-coupled case

More details soon

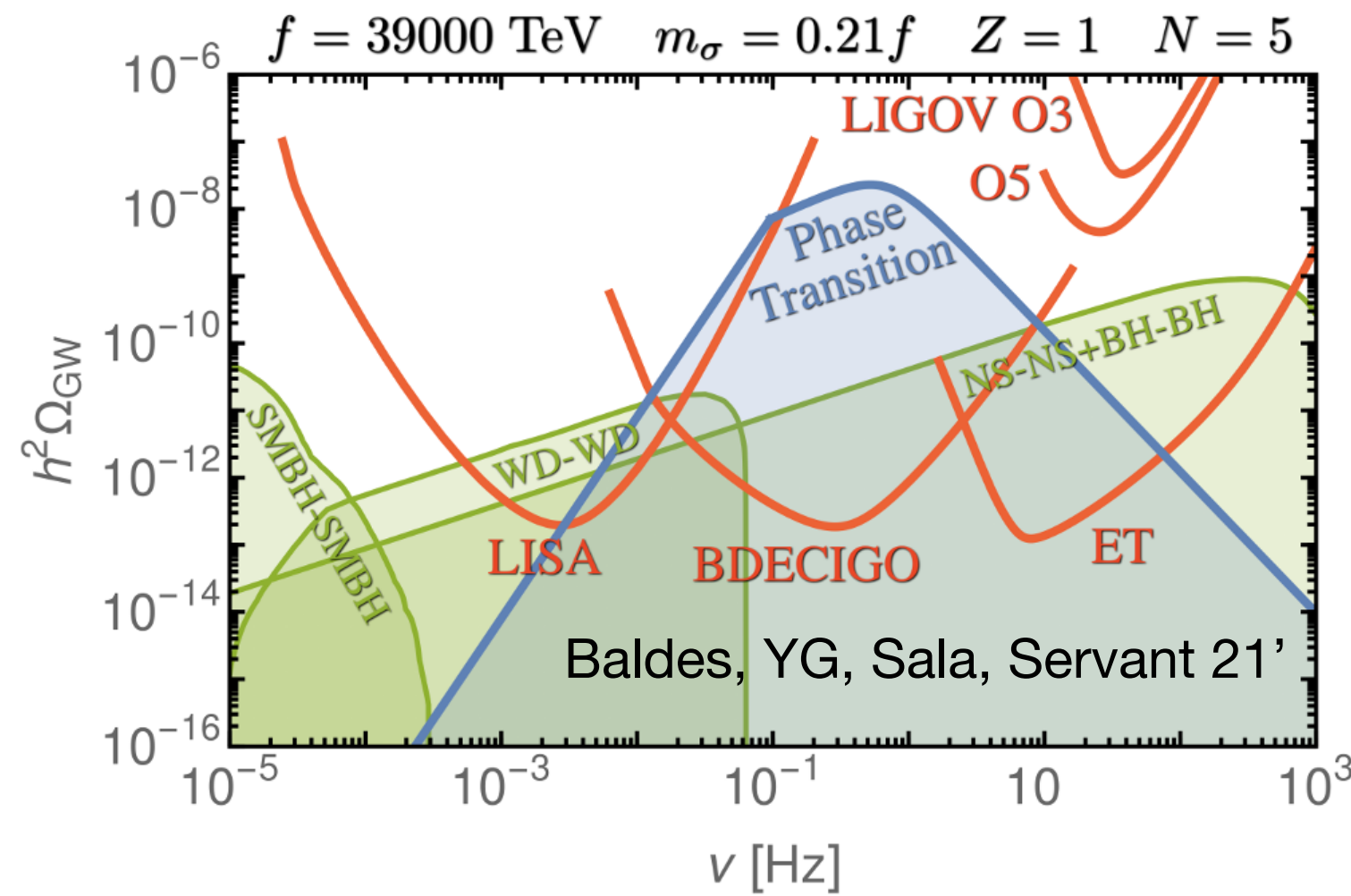


See Isabel Garcia Garcia's talk

Hoche, Kozaczuk, Long, Turner, Wang 20' (Gauge-invariant pressure ?)

# 1) Large GW spectrum

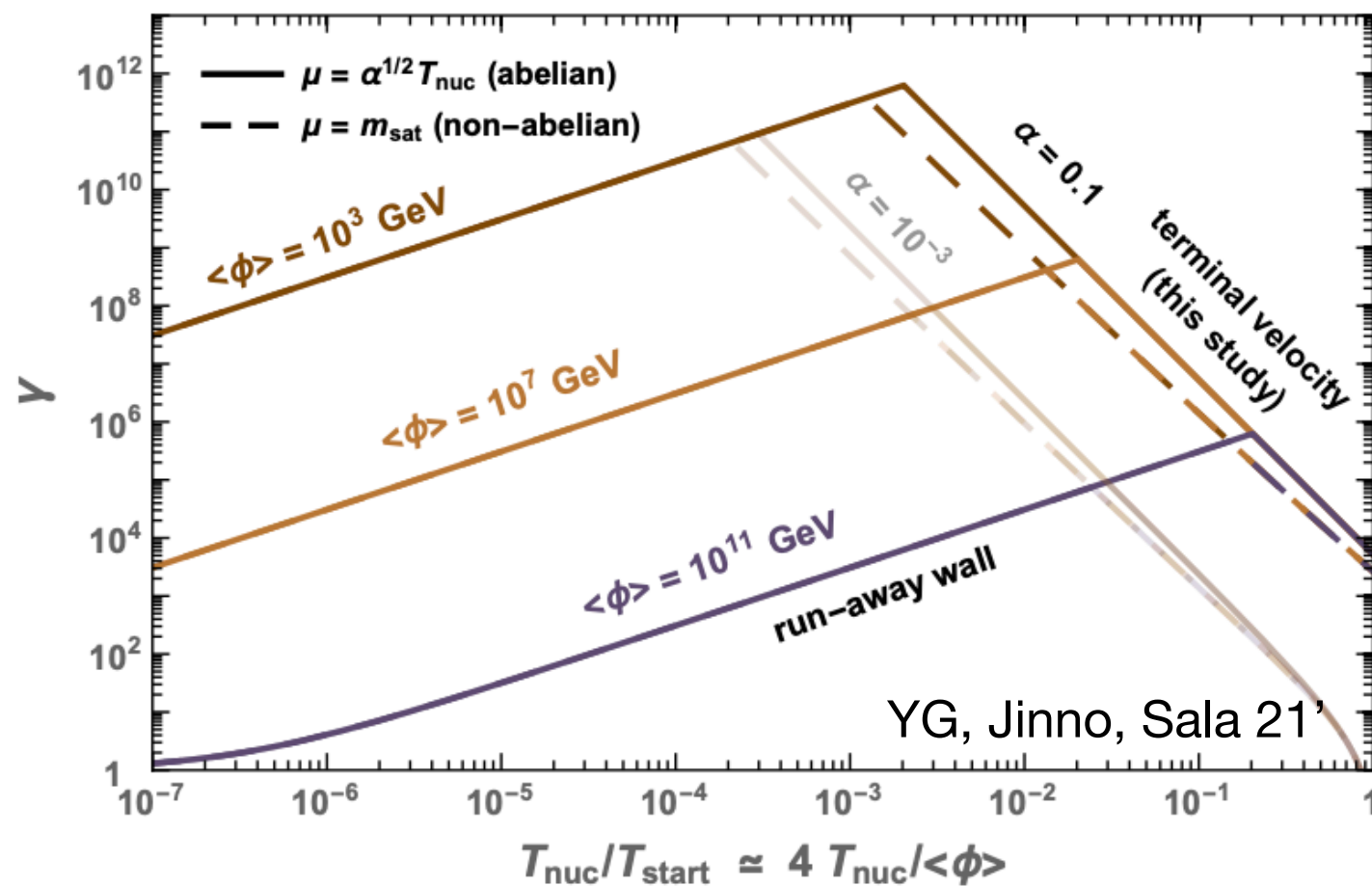
Randall, Servant 06'



# 2) Relativistic bubble walls

Bodeker, Moore 17' (Perturbative level)  
 YG, Jinno, Sala 21' (Sudakov resummation)  
 Baldes, YG, Sala 20' (Gluon string description)

Bubble wall Lorentz factor



# Cosmological consequences of supercooling

## 3) Heavy thermal dark matter

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- (Hambye, Strumia, Teresi 18') Weakly-coupled
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More details soon

## 4) Particle production

- a) Strongly-coupled case
- b) Weakly-coupled case

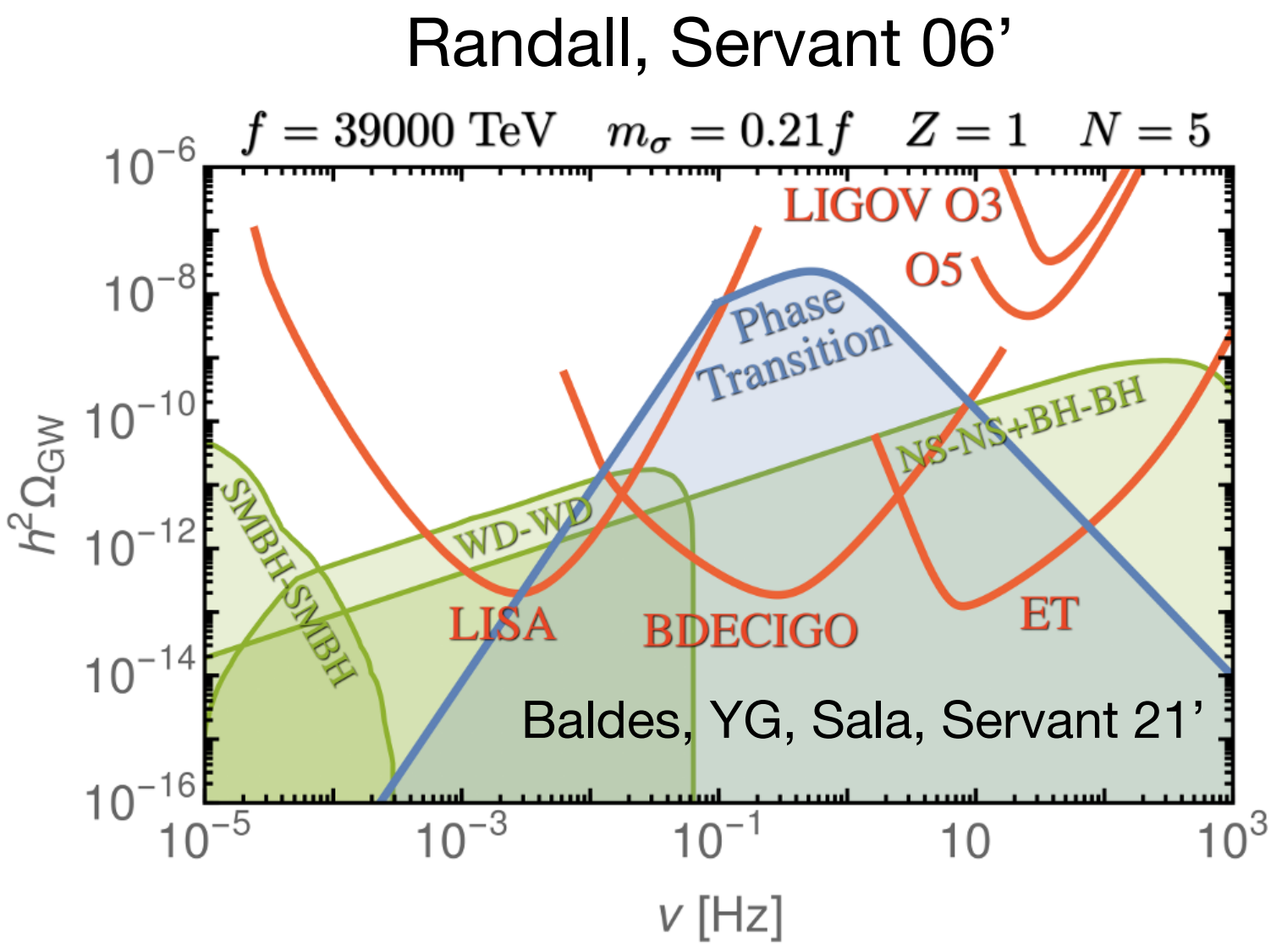
More details soon

See Isabel Garcia Garcia's talk

Hoche, Kozaczuk, Long, Turner, Wang 20' (Gauge-invariant pressure ?)

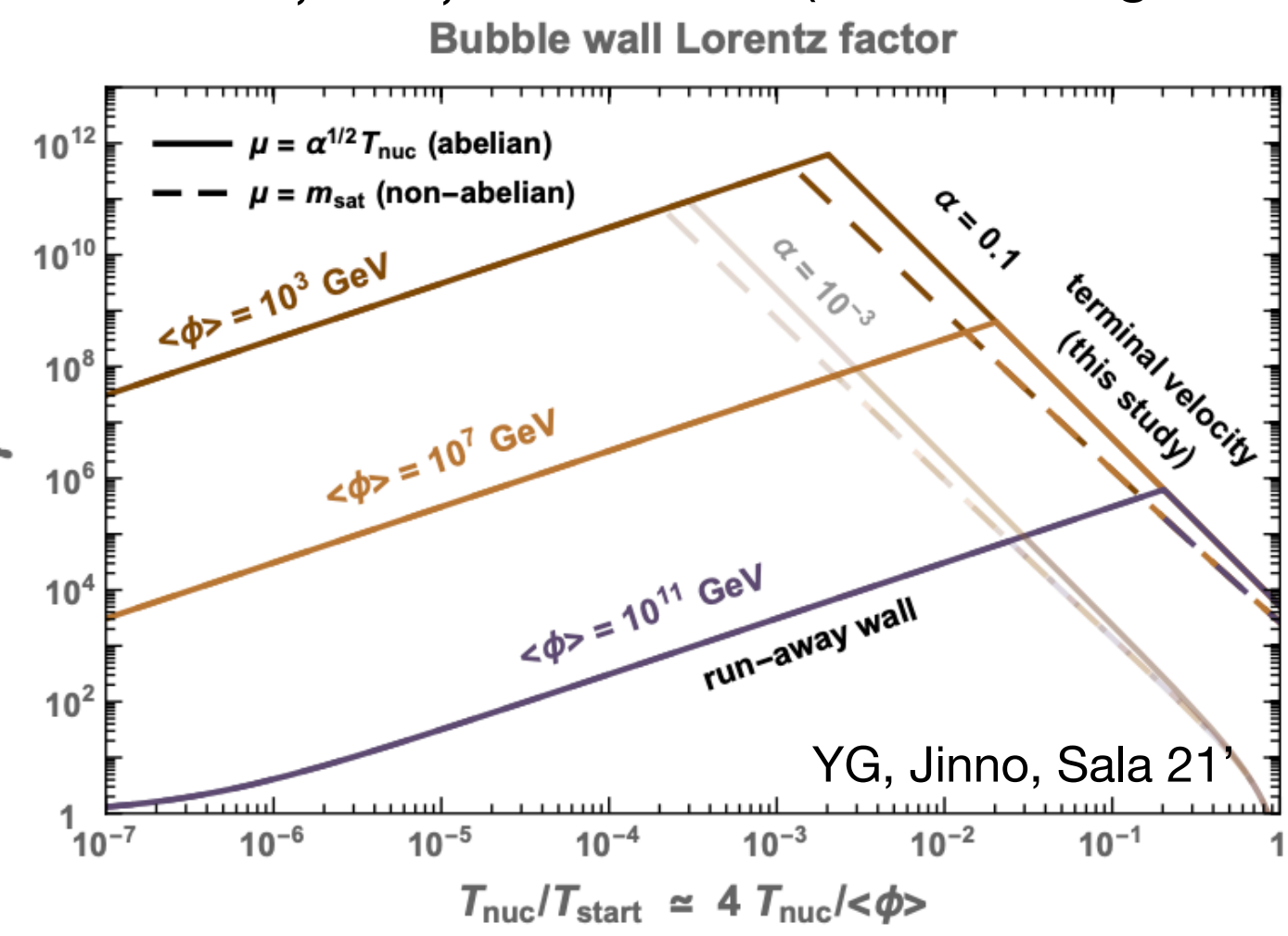
# Cosmological consequences of supercooling

## 1) Large GW spectrum



## 2) Relativistic bubble walls

Bodeker, Moore 17' (Perturbative level)  
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More details soon

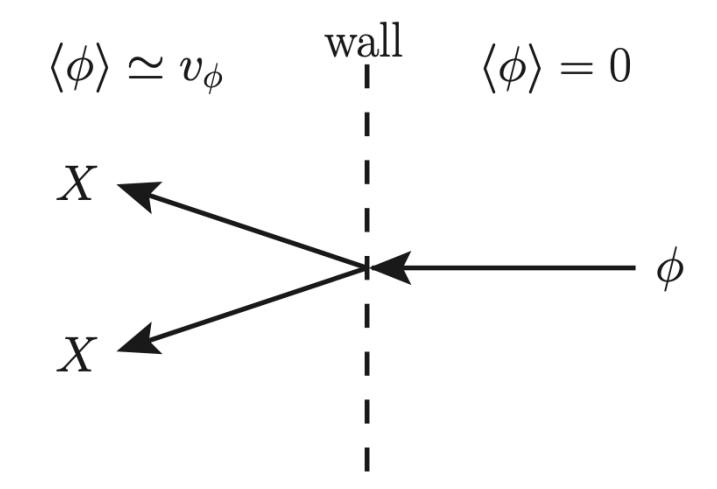
## 4) Particle production

### a) Strongly-coupled case

More details soon

### b) Weakly-coupled case

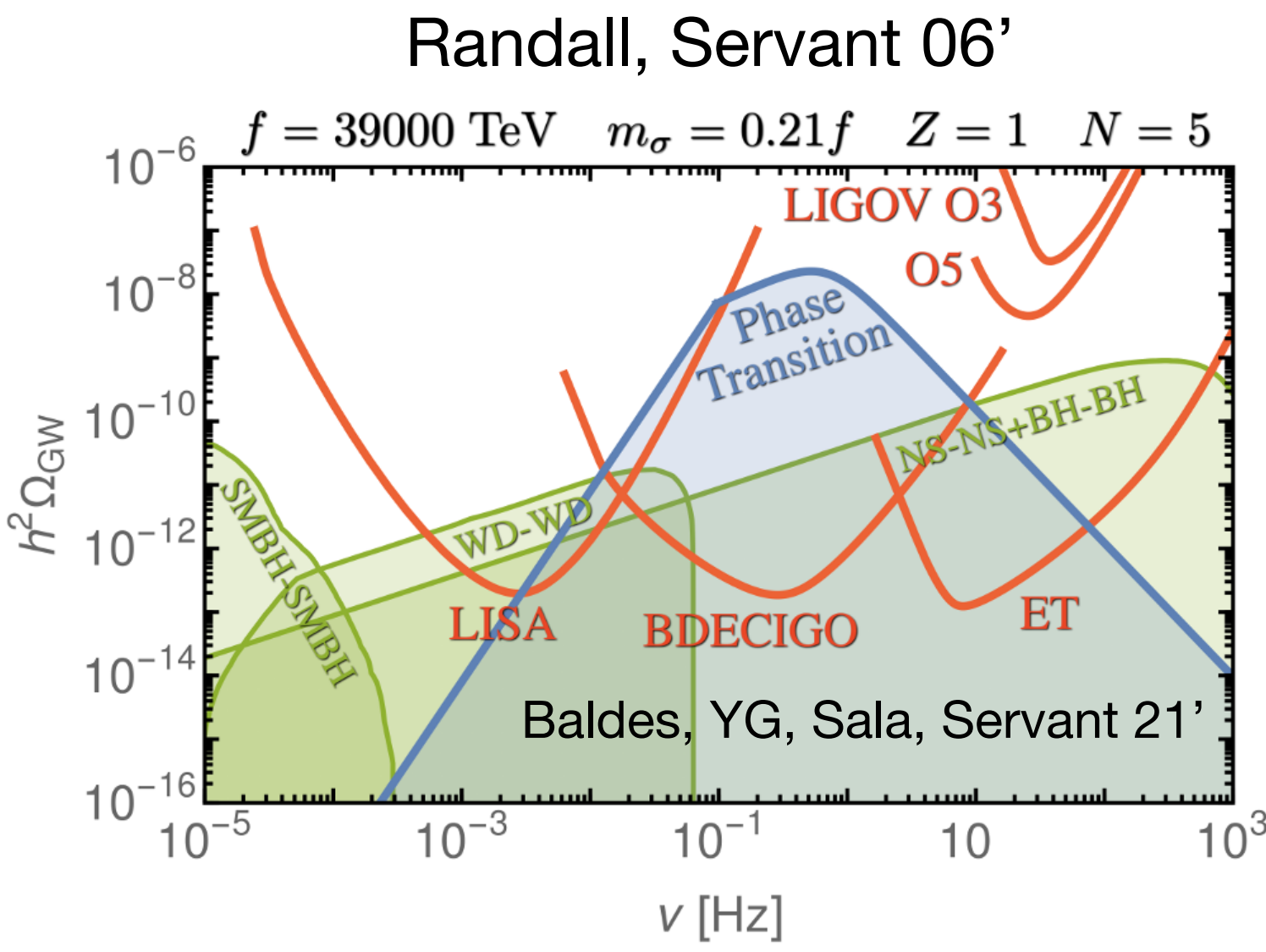
Azatov, Vanvlasselaer, Yin 21'



See Isabel Garcia Garcia's talk  
 Hoche, Kozaczuk, Long, Turner, Wang 20' (Gauge-invariant pressure ?)

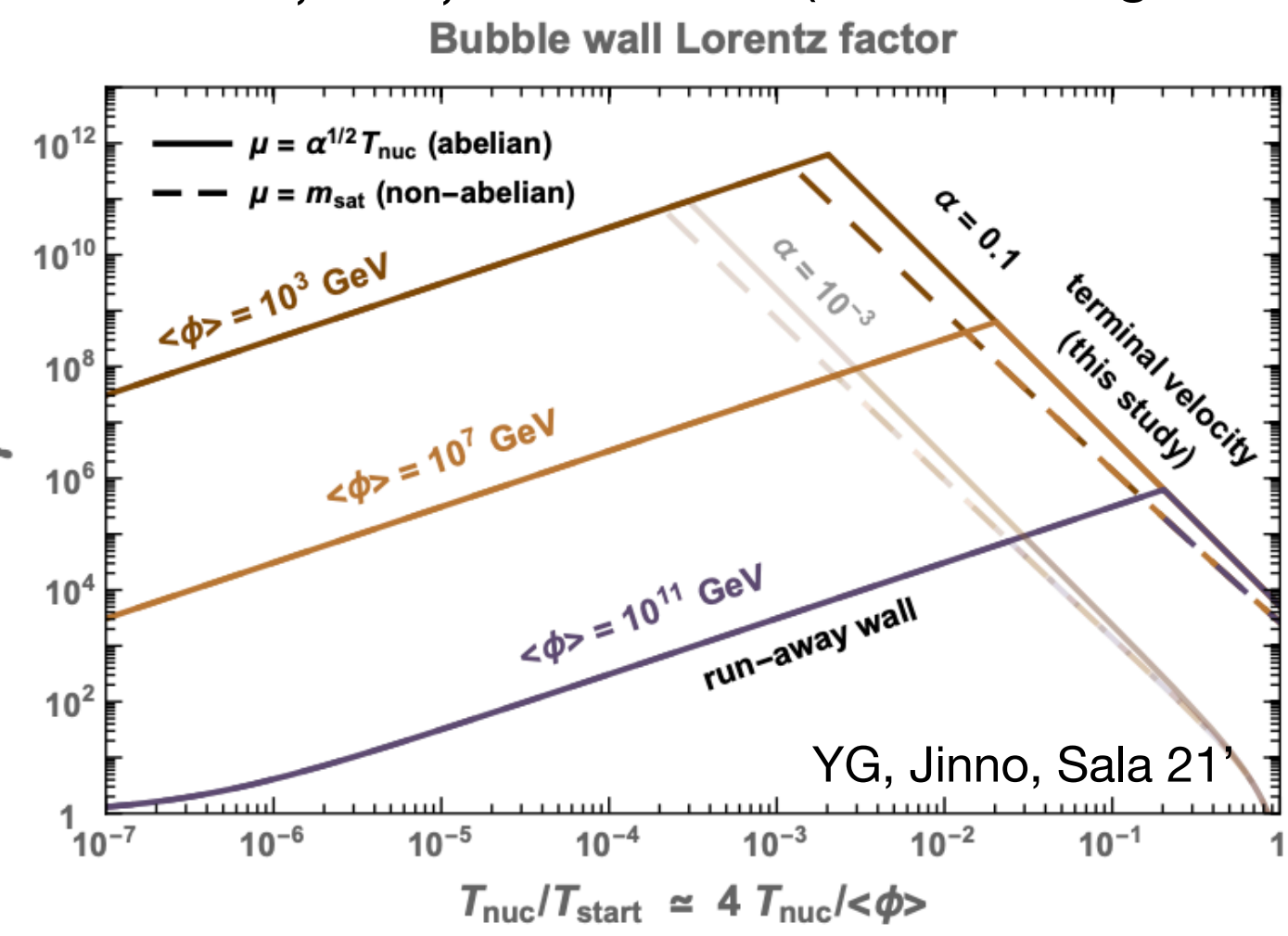
# Cosmological consequences of supercooling

## 1) Large GW spectrum



## 2) Relativistic bubble walls

Bodeker, Moore 17' (Perturbative level)  
 YG, Jinno, Sala 21' (Sudakov resummation)  
 Bales, YG, Sala 20' (Gluon string description)



## 3) Heavy thermal dark matter

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More details soon

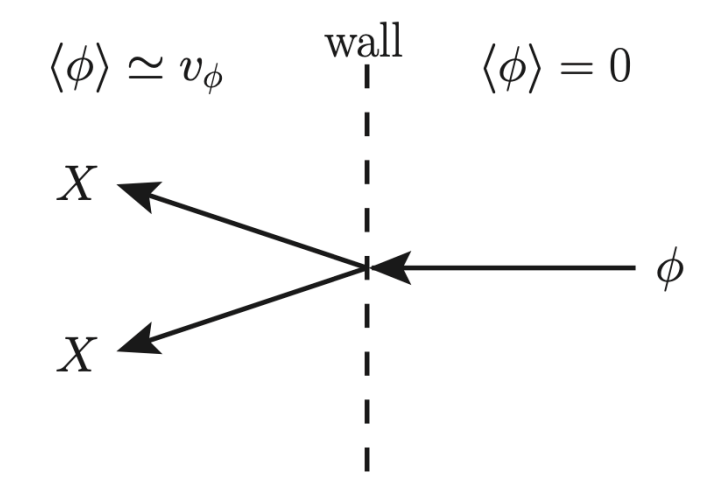
## 4) Particle production

### a) Strongly-coupled case

More details soon

### b) Weakly-coupled case

Azatov, Vanvlasselaer, Yin 21'



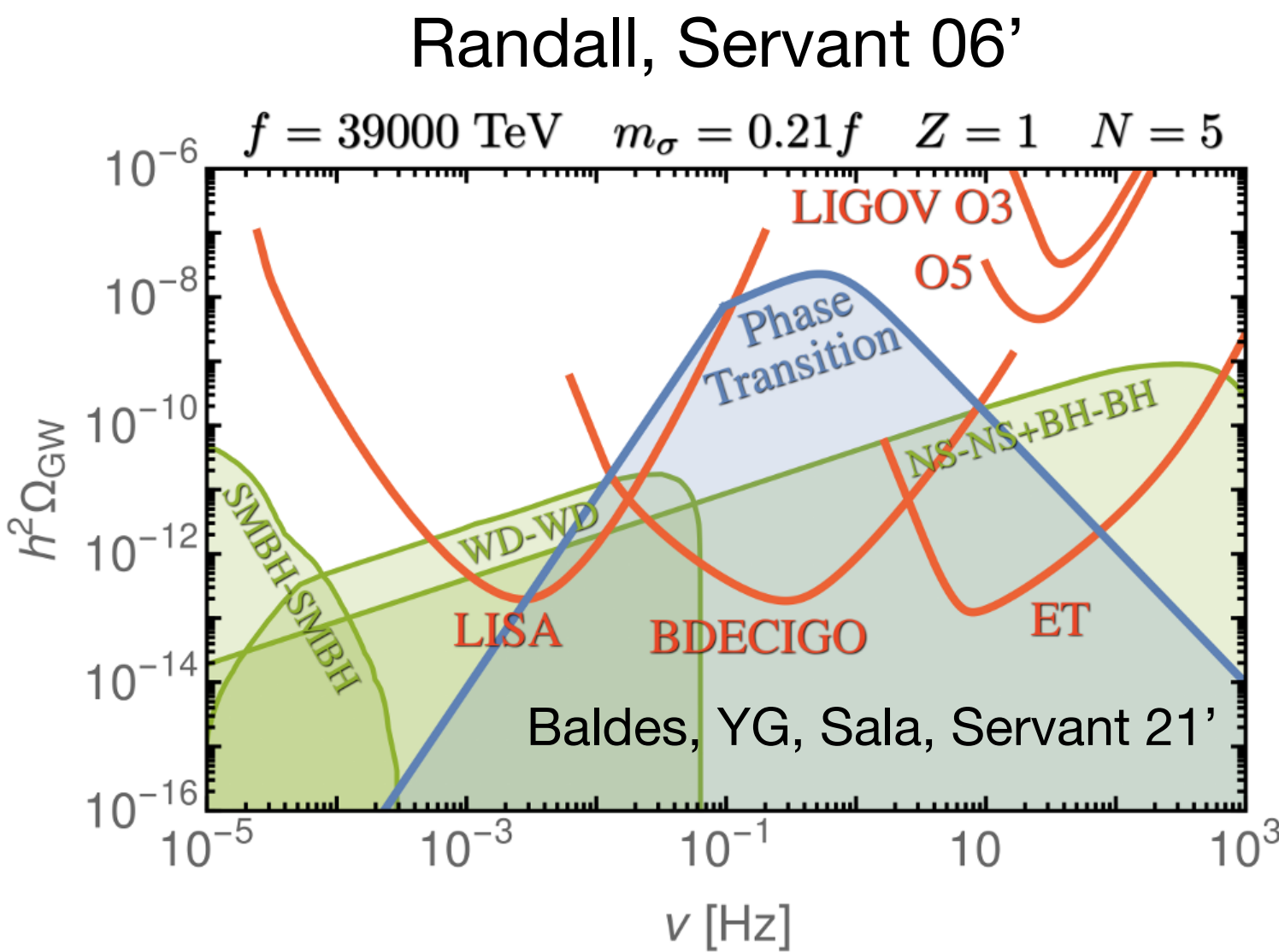
Bales, YG, Sala 22'

$M_{\text{DM}} \sim 10^8 \text{ GeV}$   
 $v(t_{\text{eq}}) \sim 10^{-4}$  with PT at the weak scale

See Isabel Garcia Garcia's talk  
 Hoche, Kozaczuk, Long, Turner, Wang 20' (Gauge-invariant pressure ?)

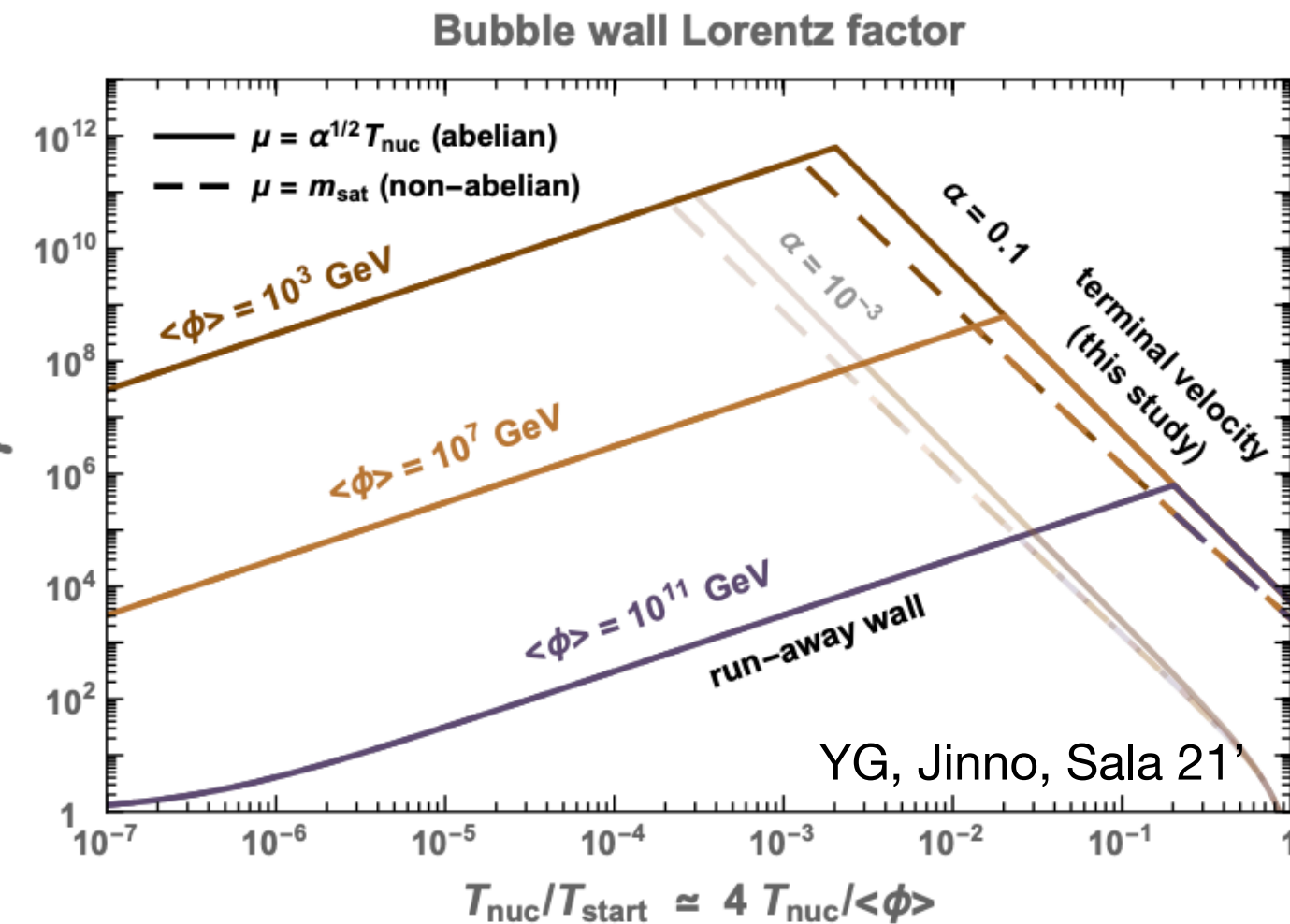


# 1) Large GW spectrum



# 2) Relativistic bubble walls

Bodeker, Moore 17' (Perturbative level)  
 YG, Jinno, Sala 21' (Sudakov resummation)  
 Baldes, YG, Sala 20' (Gluon string description)



# Cosmological consequences of supercooling

## 3) Heavy thermal dark matter

(Konstandin, Servant 11') Warped fifth dimension  
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 Baldes, YG, Sala 20' DM production at the wall due to flux tube formation  
 Baldes, YG, Sala, Servant 21'

More details soon

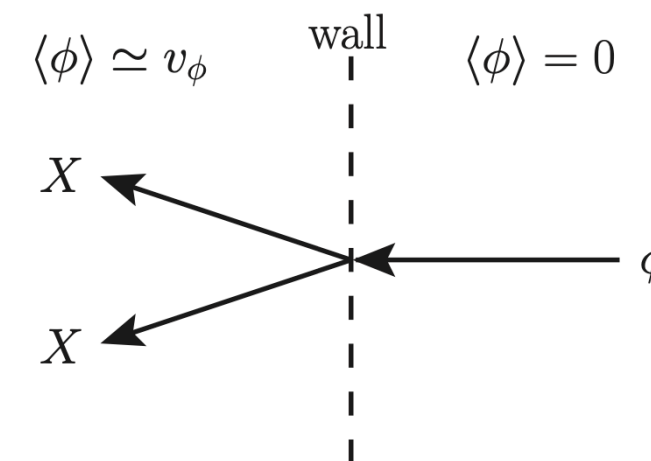
## 4) Particle production

### a) Strongly-coupled case

More details soon

### b) Weakly-coupled case

Azatov, Vanvlasselaer, Yin 21'



Baldes, YG, Sala 22'

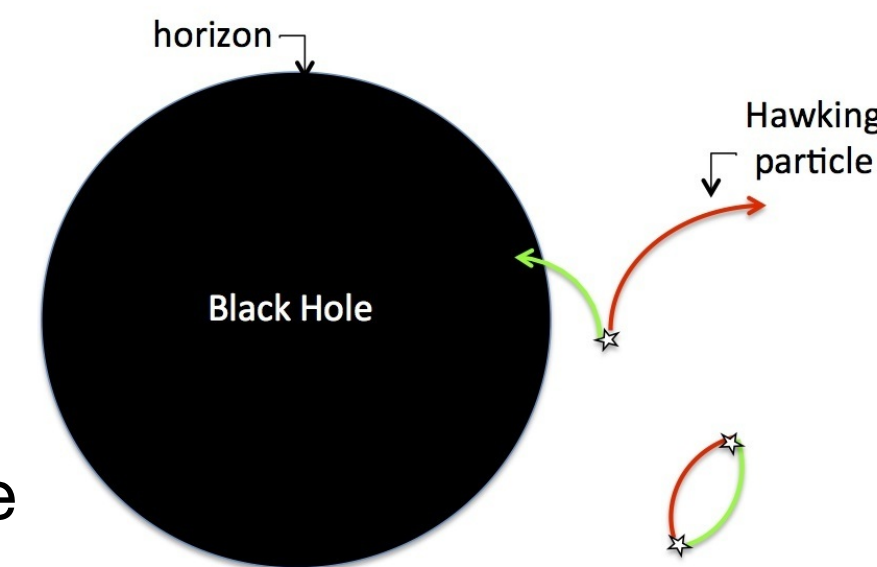
$M_{\text{DM}} \sim 10^8 \text{ GeV}$

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

with PT at the weak scale

### c) Unruh radiation

YG (to appear)

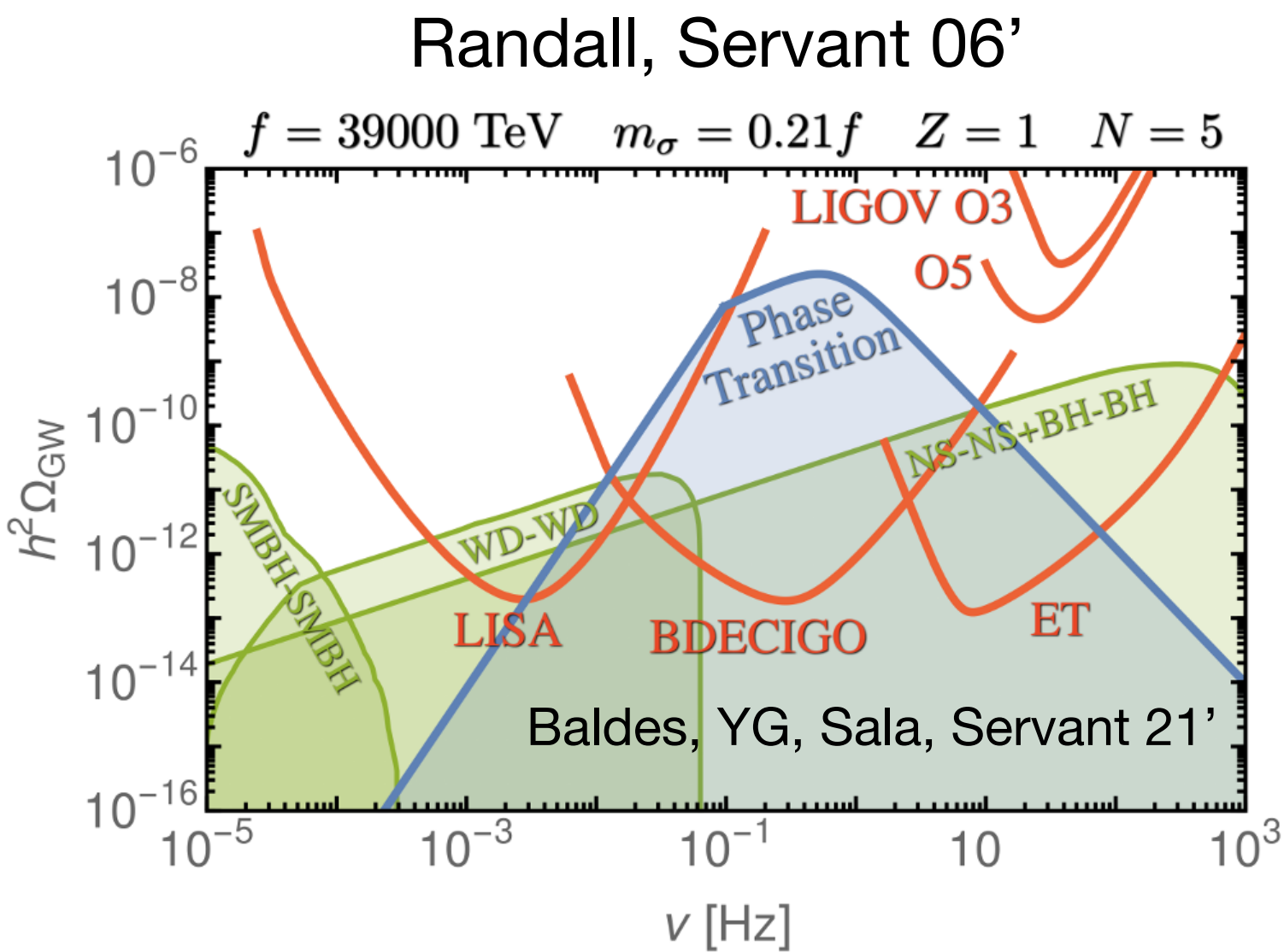


See Isabel Garcia Garcia's talk

Hoche, Kozaczuk, Long, Turner, Wang 20'

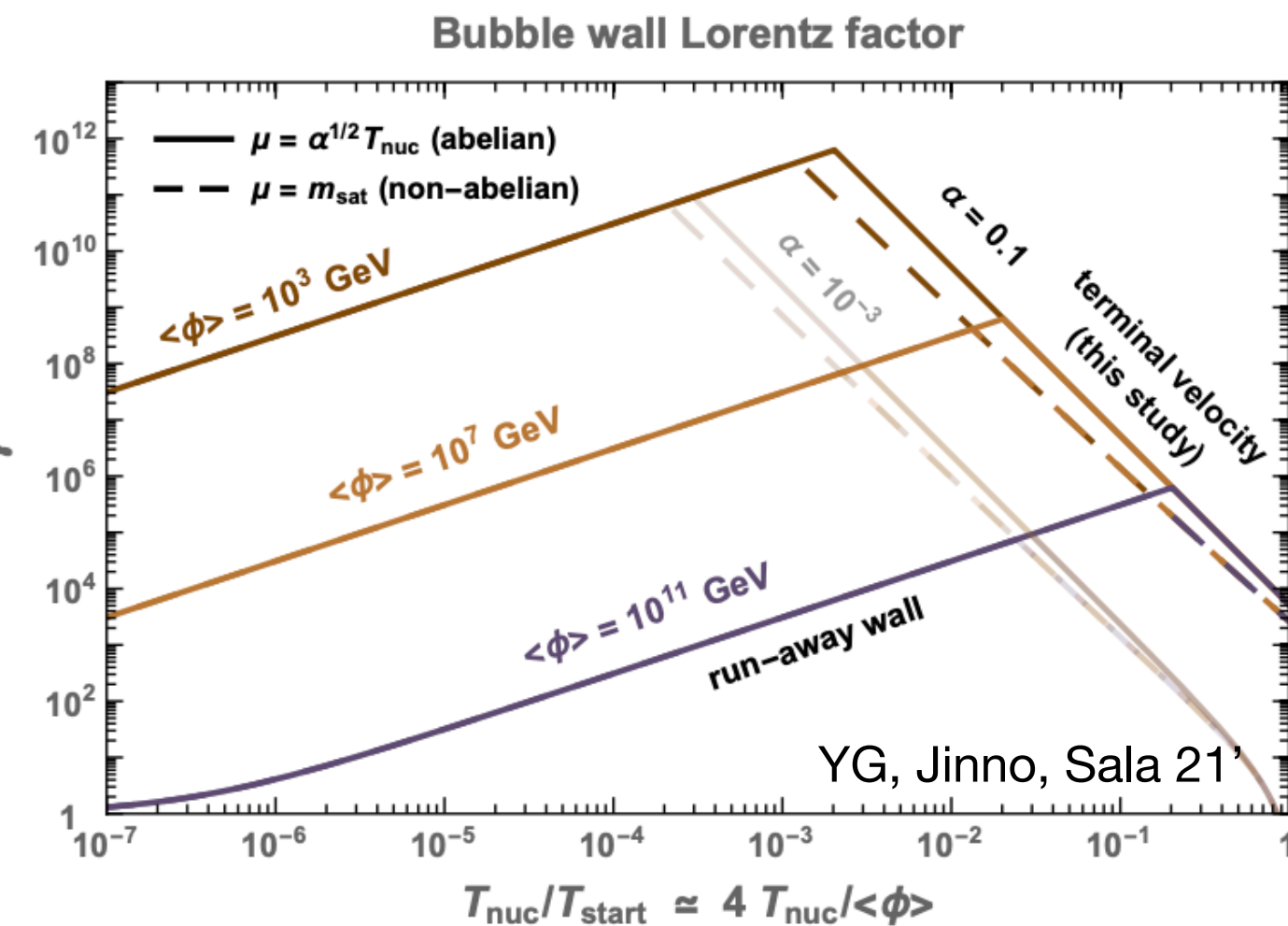
(Gauge-invariant pressure ?)

# 1) Large GW spectrum



# 2) Relativistic bubble walls

Bodeker, Moore 17' (Perturbative level)  
 YG, Jinno, Sala 21' (Sudakov resummation)  
 Baldes, YG, Sala 20' (Gluon string description)



# Cosmological consequences of supercooling

## 3) Heavy thermal dark matter

(Konstandin, Servant 11')  
 (Hambye, Strumia, Teresi 18')  
 (Baratella, Pomarol, Rompeneve 18')

Warp ed fifth dimension  
 Weakly-coupled  
 Strongly-coupled

Baldes, YG, Sala 20'  
 Baldes, YG, Sala, Servant 21'

DM production at the wall due to flux tube formation

More details soon

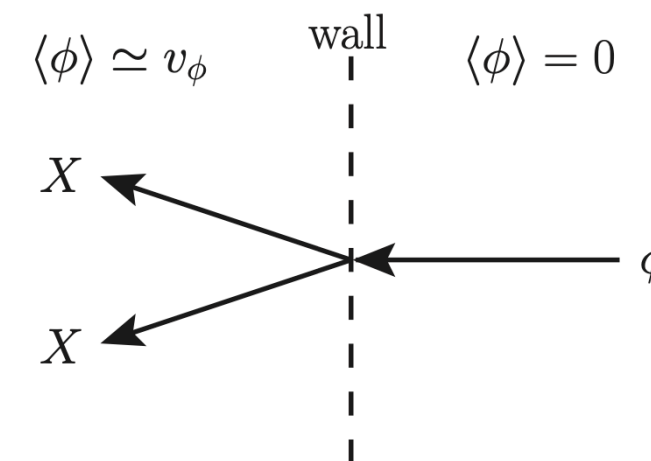
## 4) Particle production

### a) Strongly-coupled case

More details soon

### b) Weakly-coupled case

Azatov, Vanvlasselaer, Yin 21'



Baldes, YG, Sala 22'

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

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

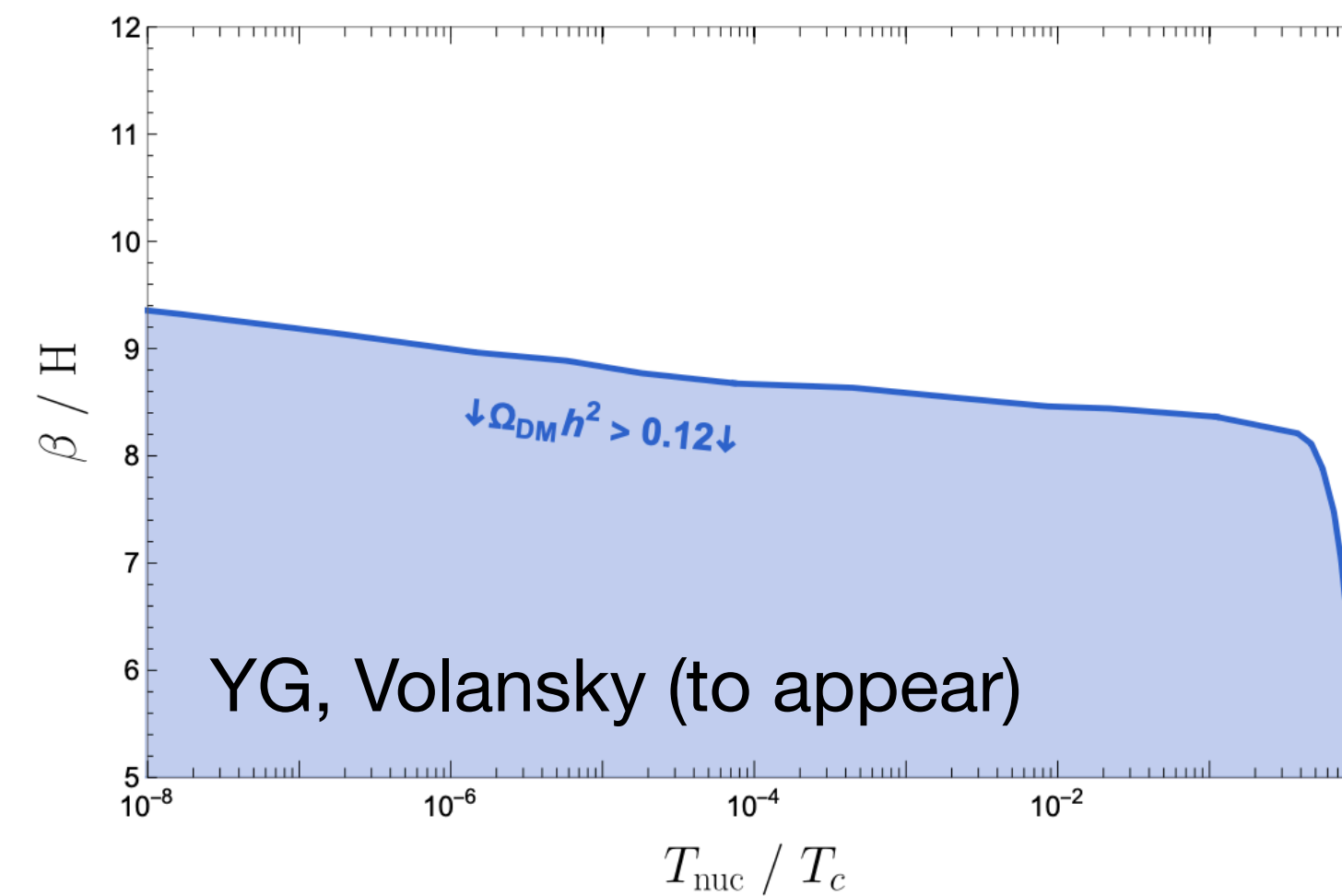
with PT at the weak scale

## 5) Black hole production

Liu, Bian, Cai, Guo, Wang 21'

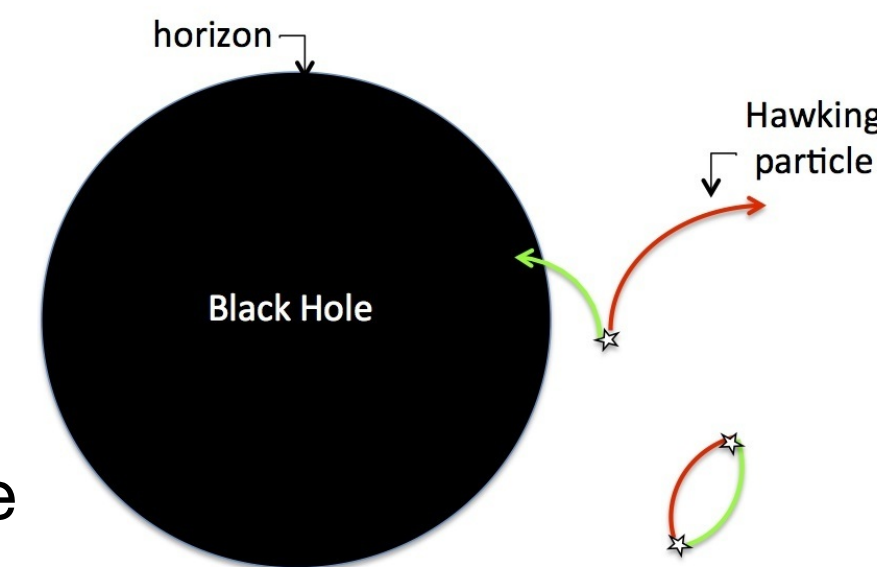
YG, Volansky (to appear)

PBH dark matter from supercooled 1stOPT



### c) Unruh radiation

YG (to appear)



See Isabel Garcia Garcia's talk

Hoche, Kozaczuk, Long, Turner, Wang 20'

(Gauge-invariant pressure ?)

# Heavy Dark Matter from supercool confinement

Baldes, YG, Sala 20'

Baldes, YG, Sala, Servant 21'

# Supercool confinement ?

# Super-uncool confinement



# Super-uncool confinement

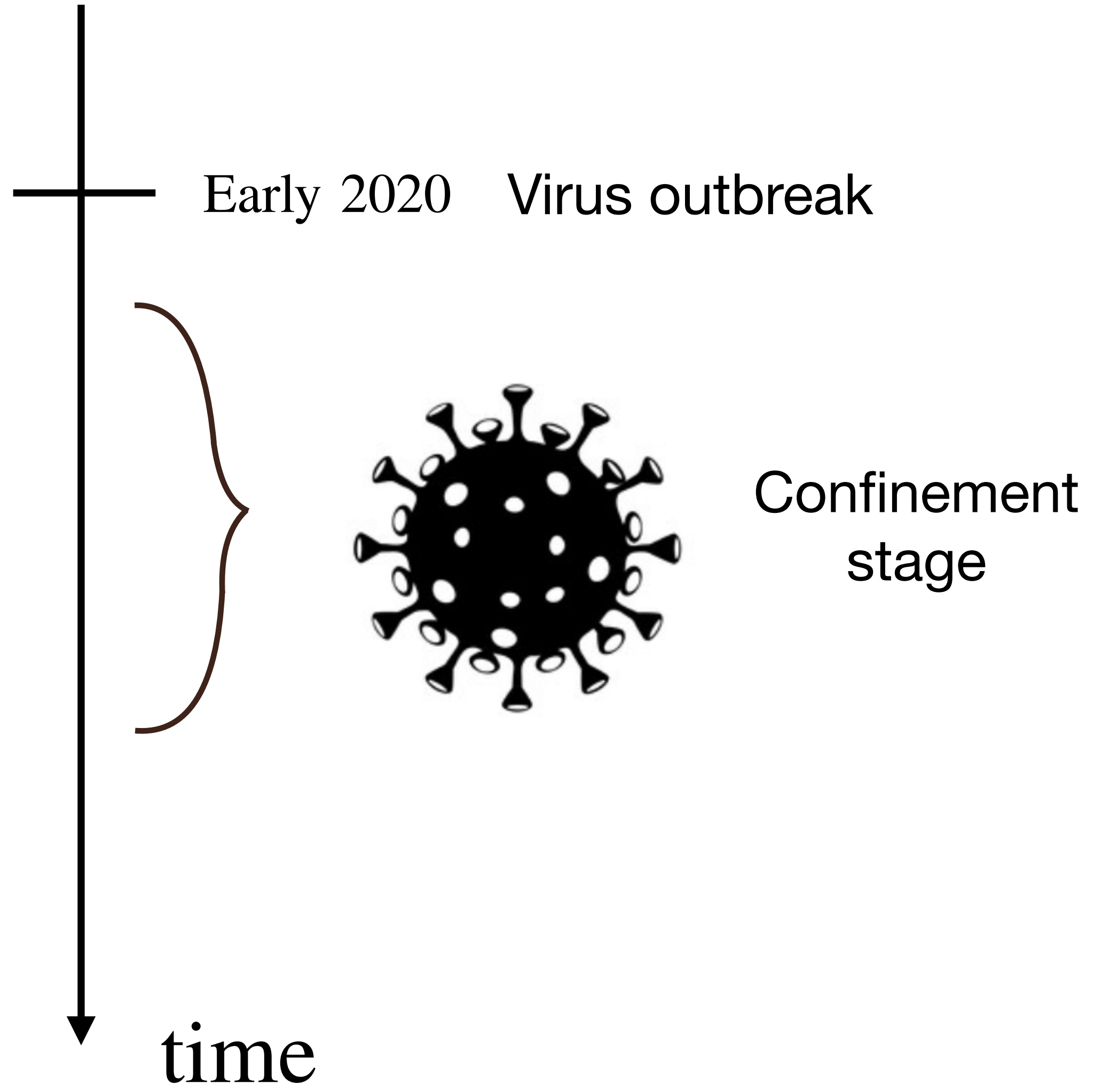
Early 2020 Virus outbreak



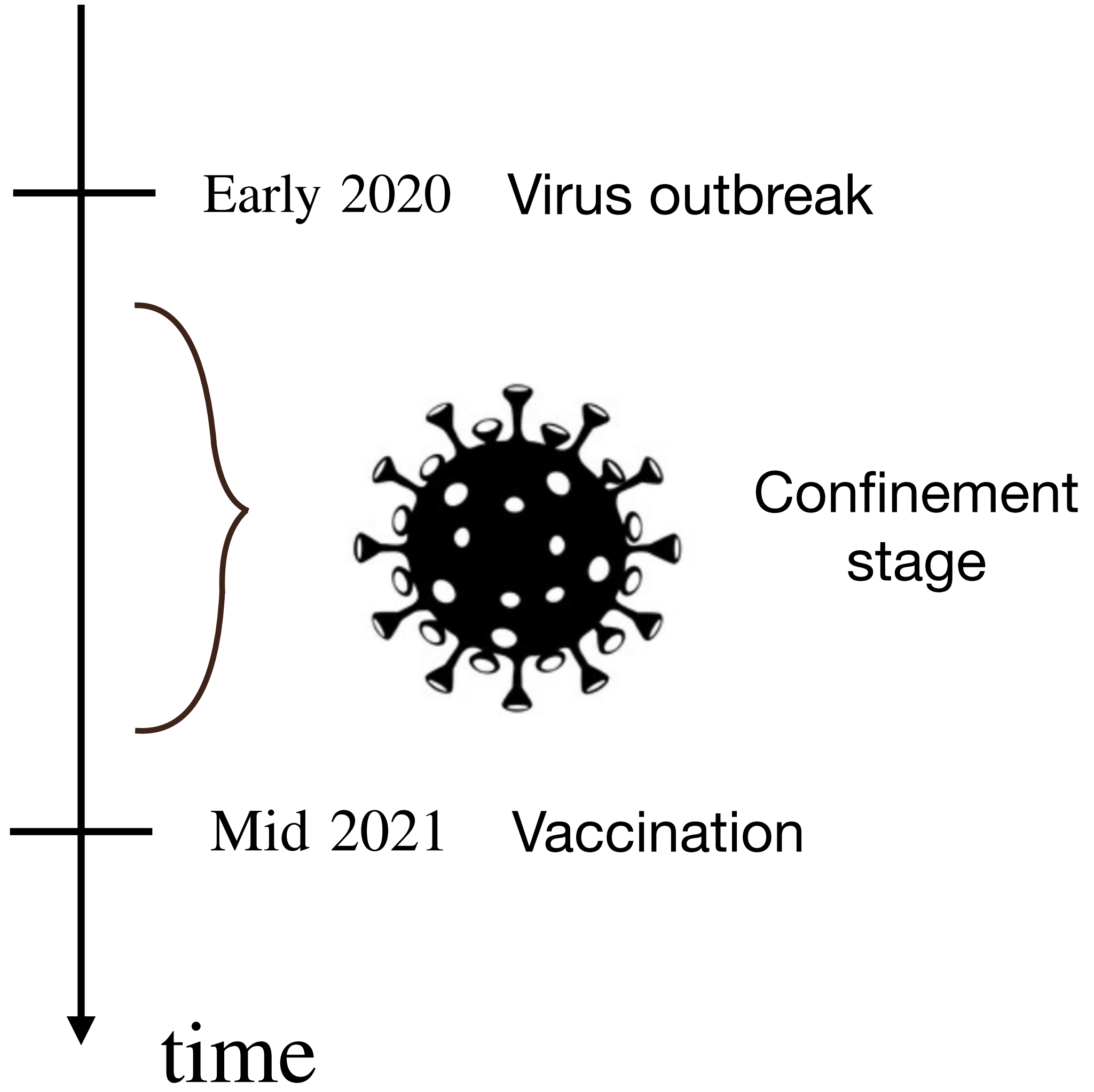
time



# Super-uncool confinement



# Super-uncool confinement

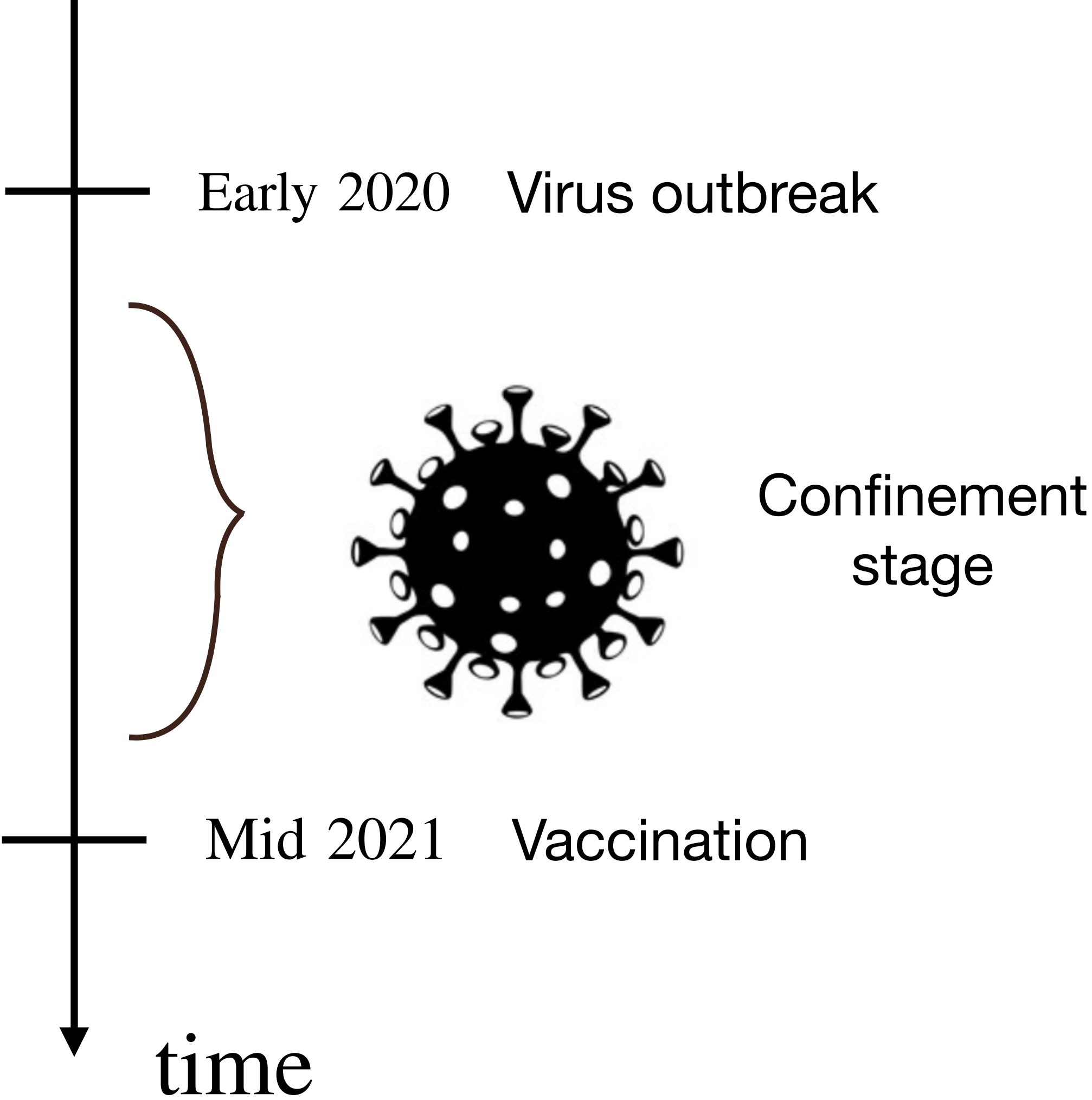




~~Super-uncool confinement~~

**Super-cool**

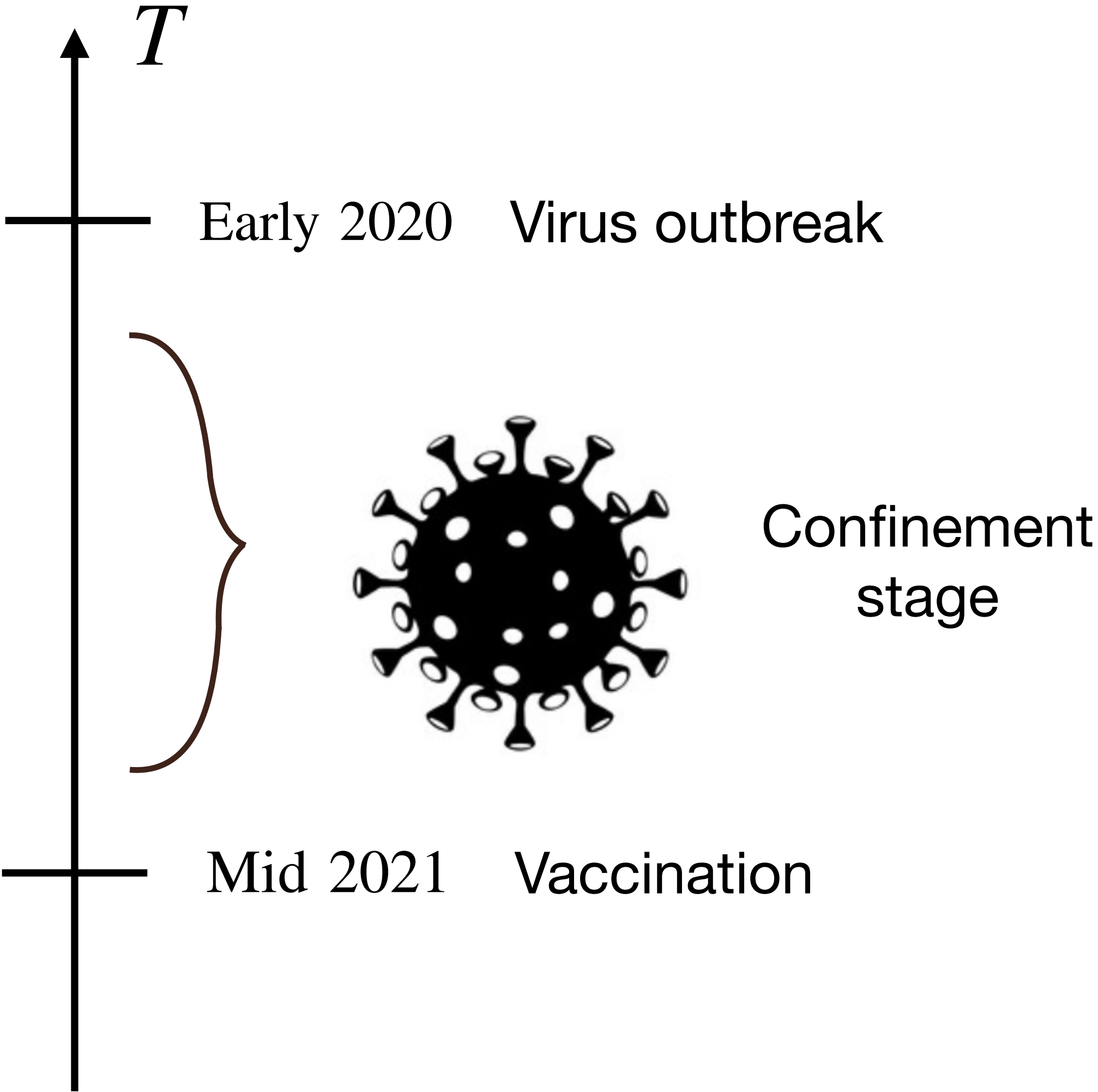
Baldes, YG, Sala 20'  
Baldes, YG, Sala, Servant 21'



~~Super-uncool confinement~~

**Super-cool**

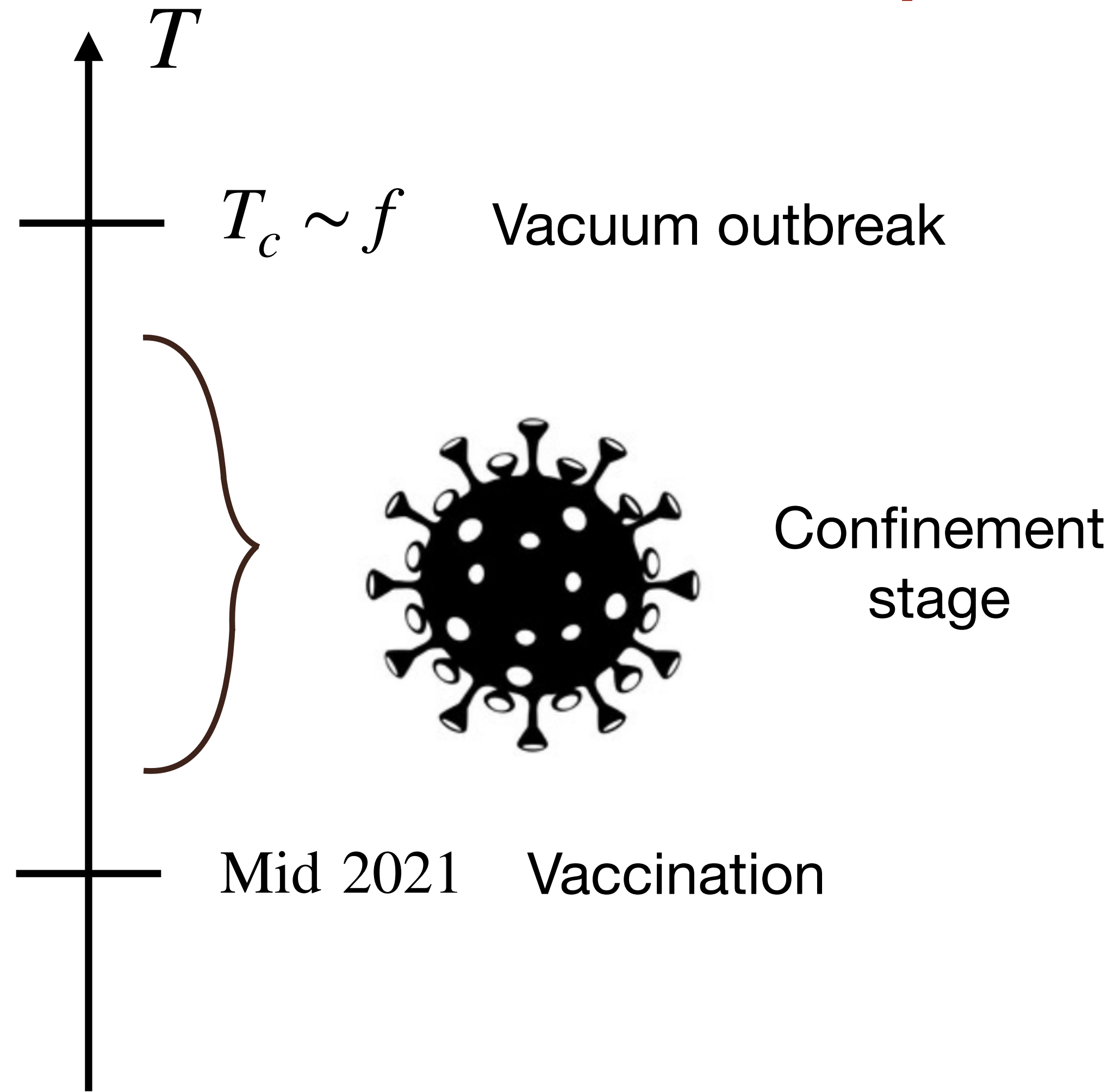
Baldes, YG, Sala 20'  
Baldes, YG, Sala, Servant 21'



~~Super-uncool confinement~~

Baldes, YG, Sala 20'  
Baldes, YG, Sala, Servant 21'

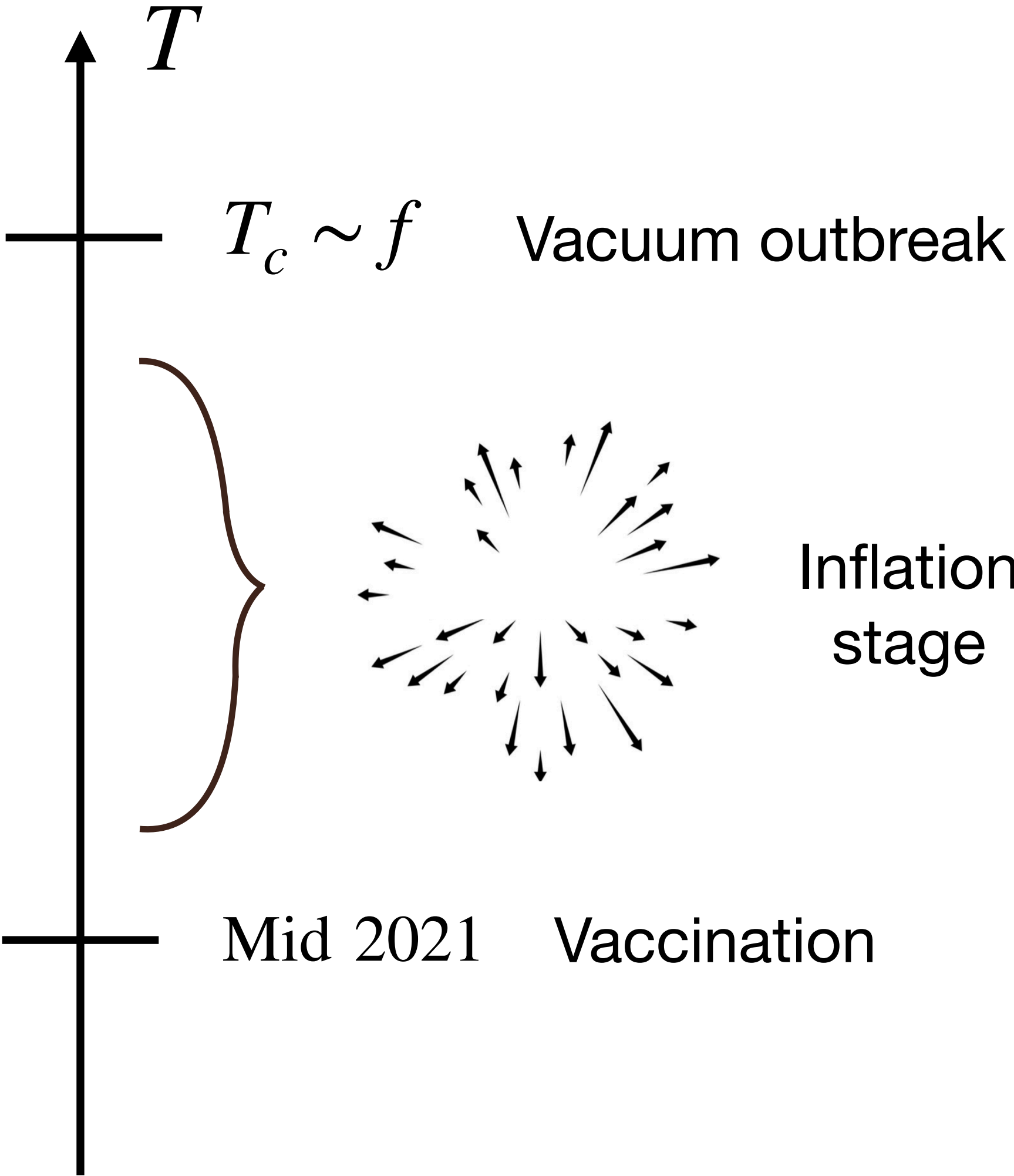
**Super-cool**



~~Super-uncool confinement~~

**Super-cool**

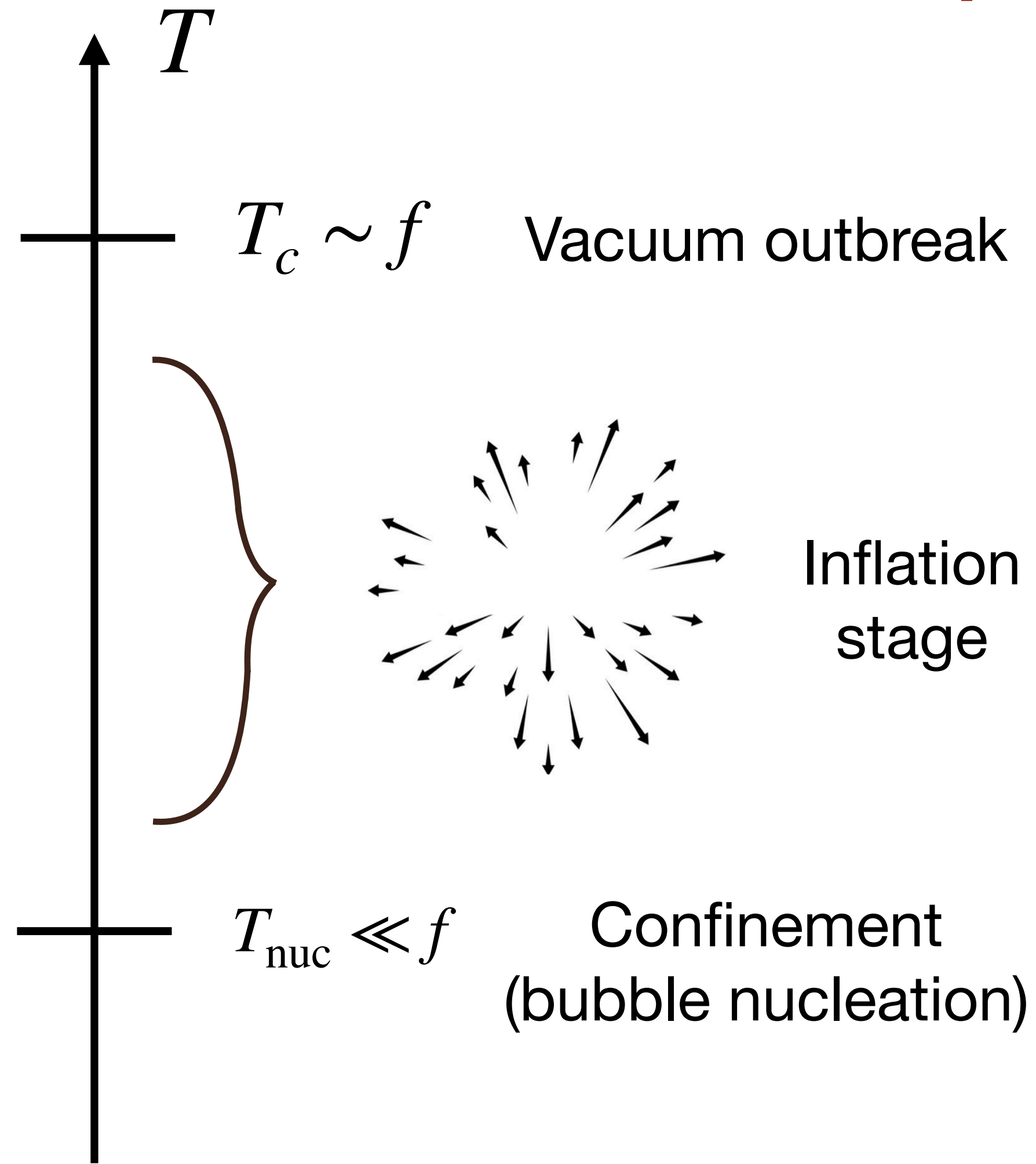
Baldes, YG, Sala 20'  
Baldes, YG, Sala, Servant 21'



~~Super-uncool confinement~~

Baldes, YG, Sala 20'  
Baldes, YG, Sala, Servant 21'

**Super-cool**

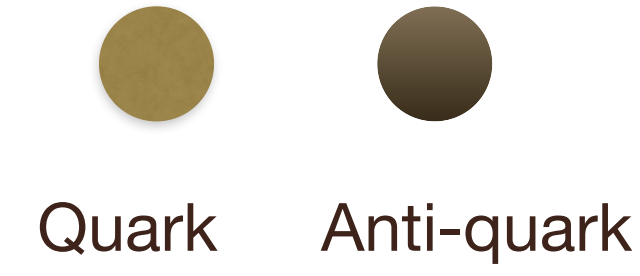
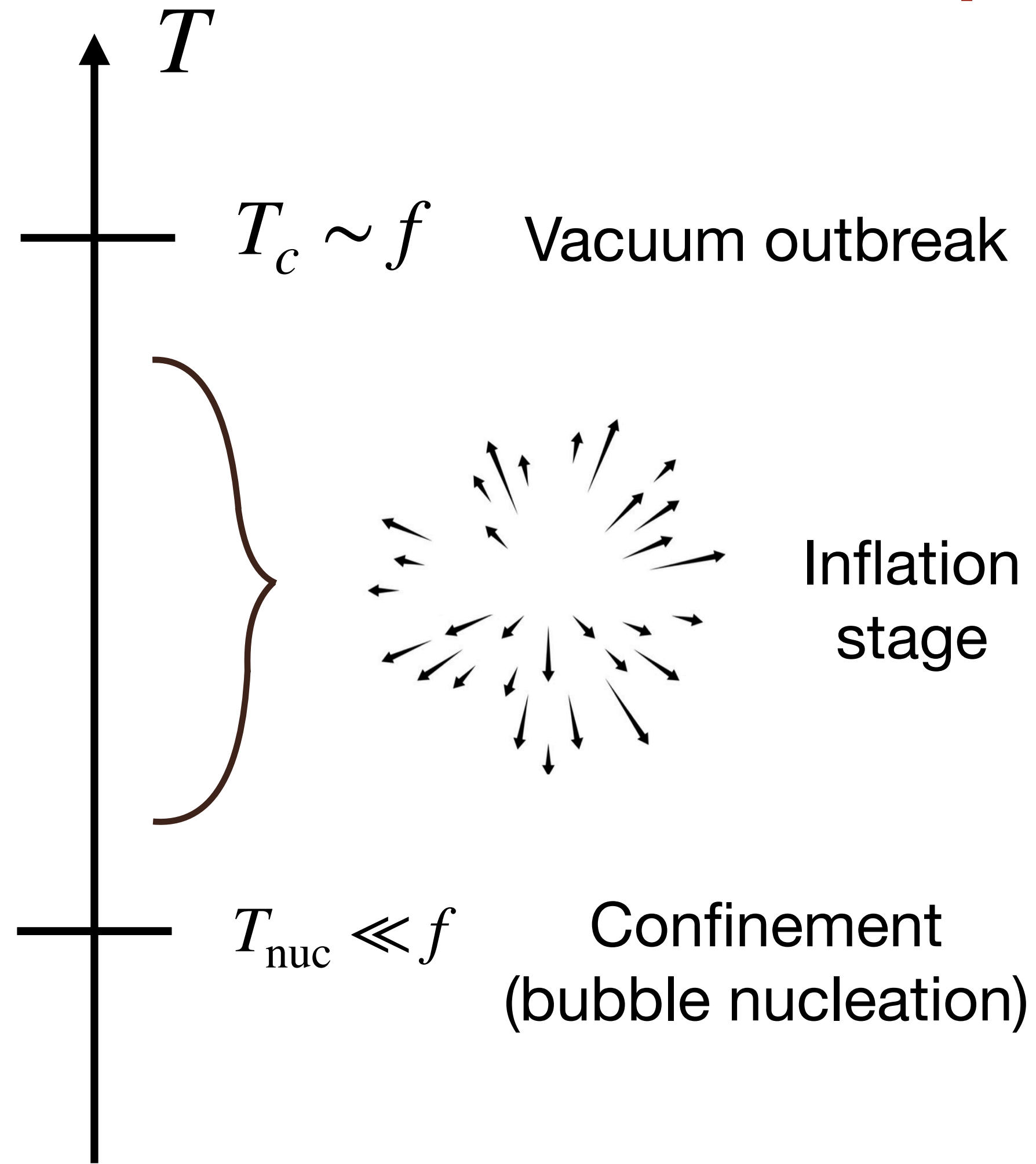


~~Super-uncool confinement~~

Baldes, YG, Sala 20'  
Baldes, YG, Sala, Servant 21'

Super-cool

Naive picture

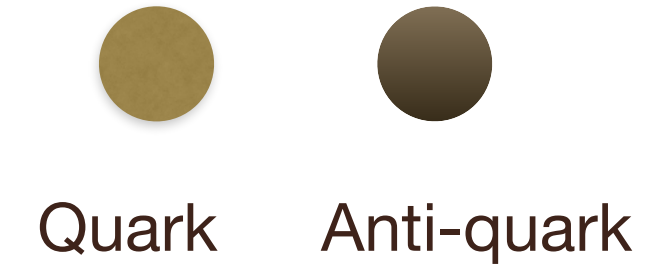
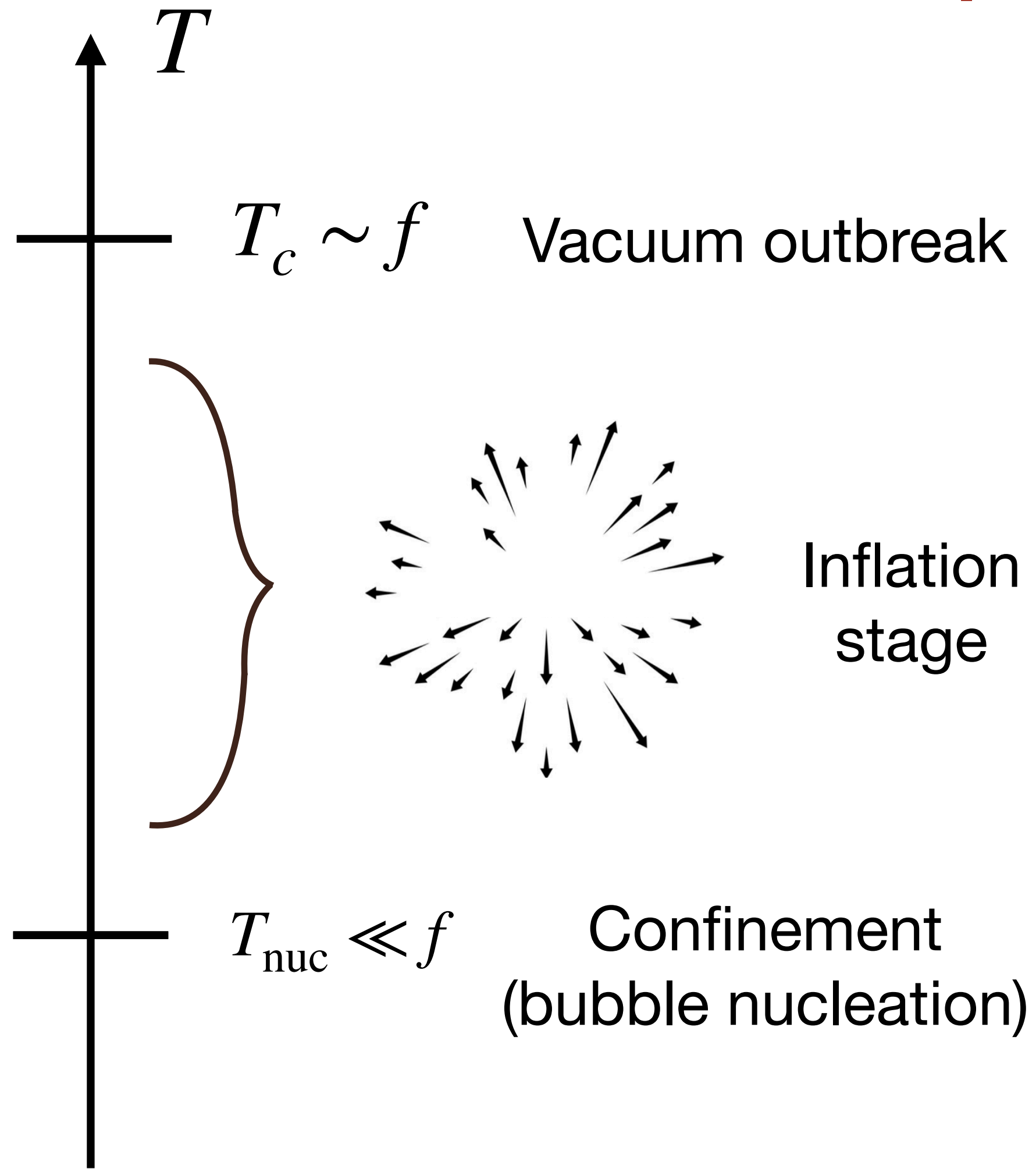


# ~~Super-uncool confinement~~

Baldes, YG, Sala 20'  
Baldes, YG, Sala, Servant 21'

## Super-cool

### Naive picture



↓ Dilution

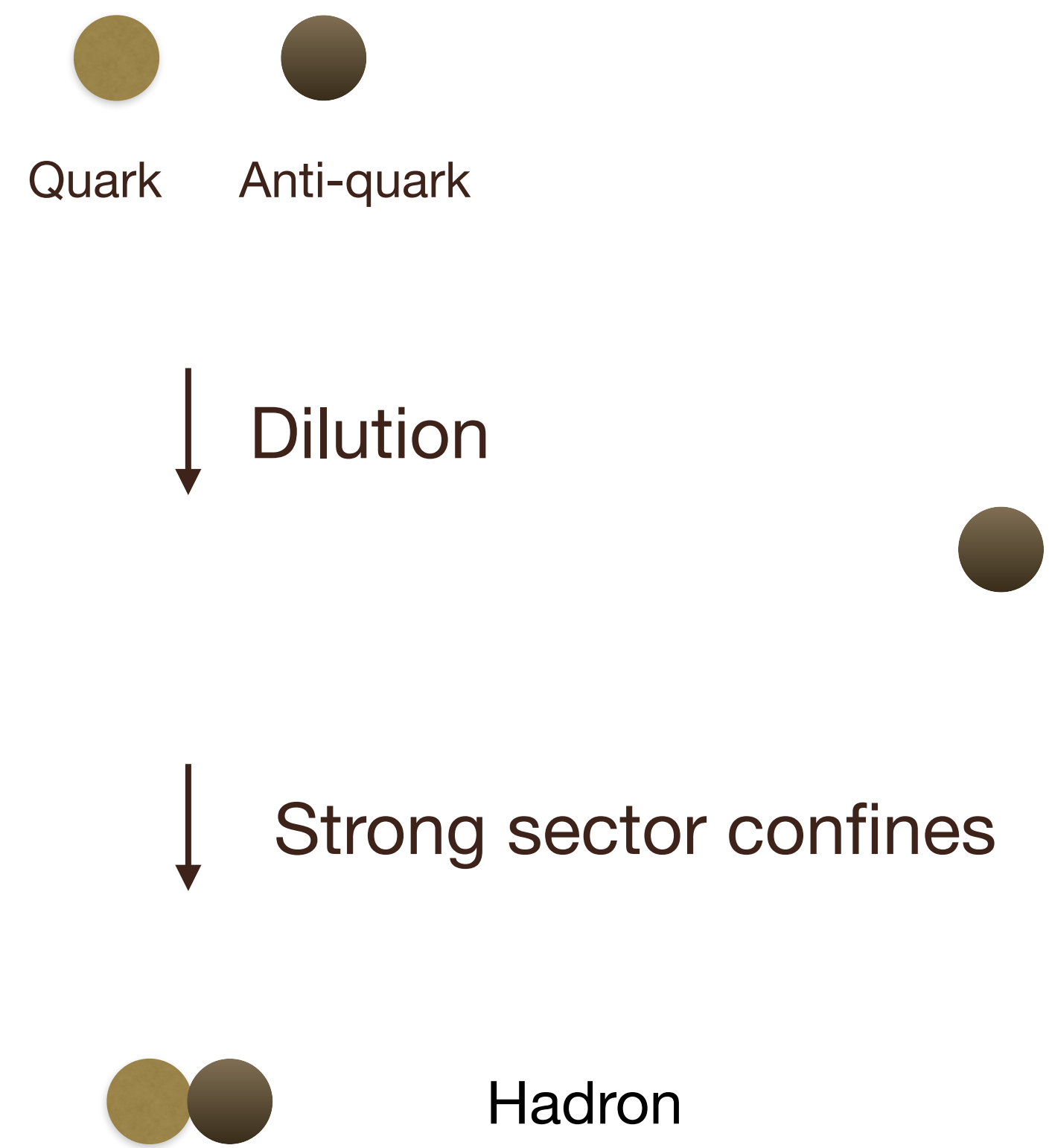
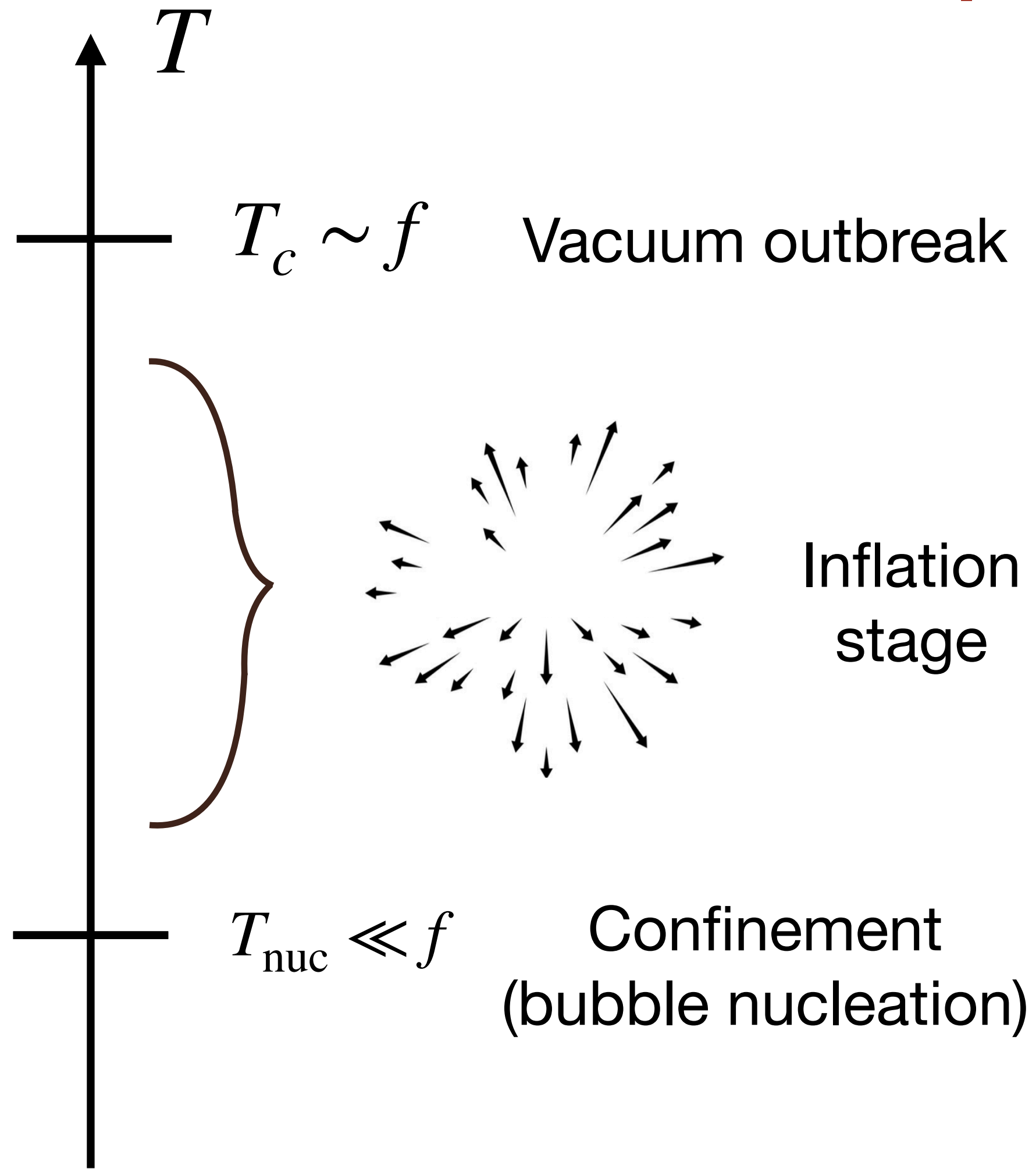


# ~~Super-uncool~~ confinement

Baldes, YG, Sala 20'  
Baldes, YG, Sala, Servant 21'

## Super-cool

### Naive picture



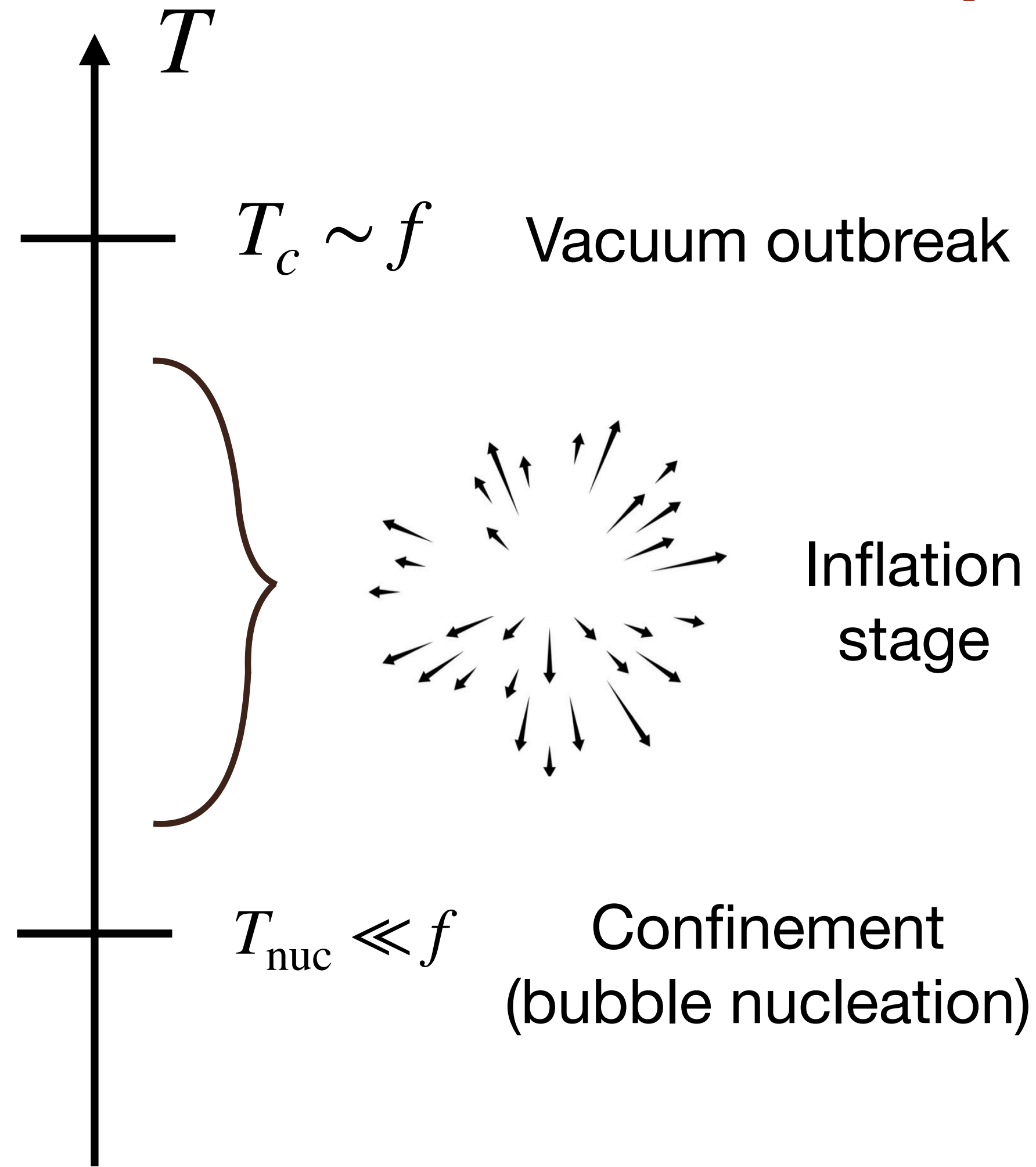


# ~~Super-uncool~~ confinement

Baldes, YG, Sala 20'  
Baldes, YG, Sala, Servant 21'

## Super-cool

### Naive picture



Quark    Anti-quark

Dilution

Strong sector confines

Hadron

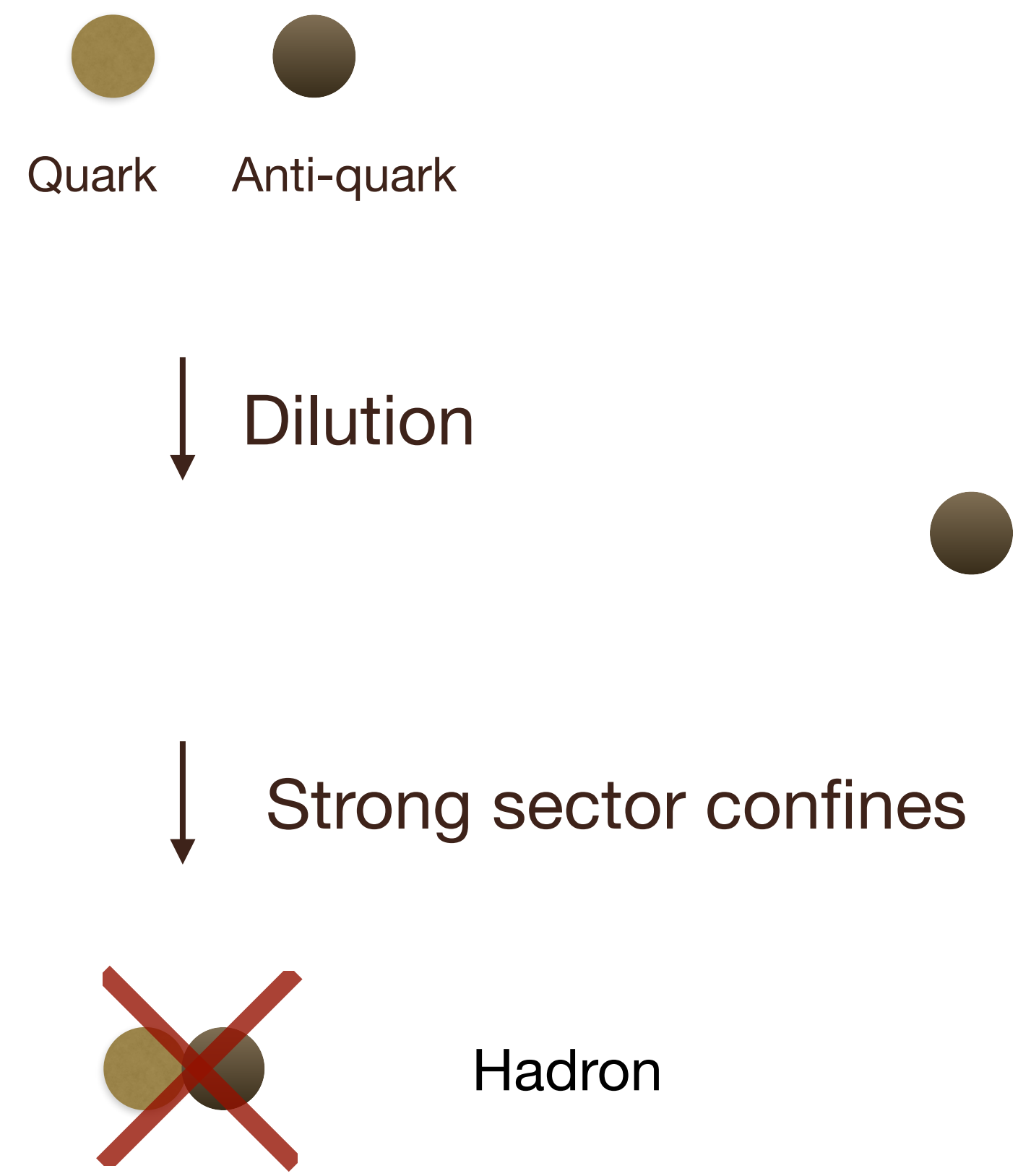
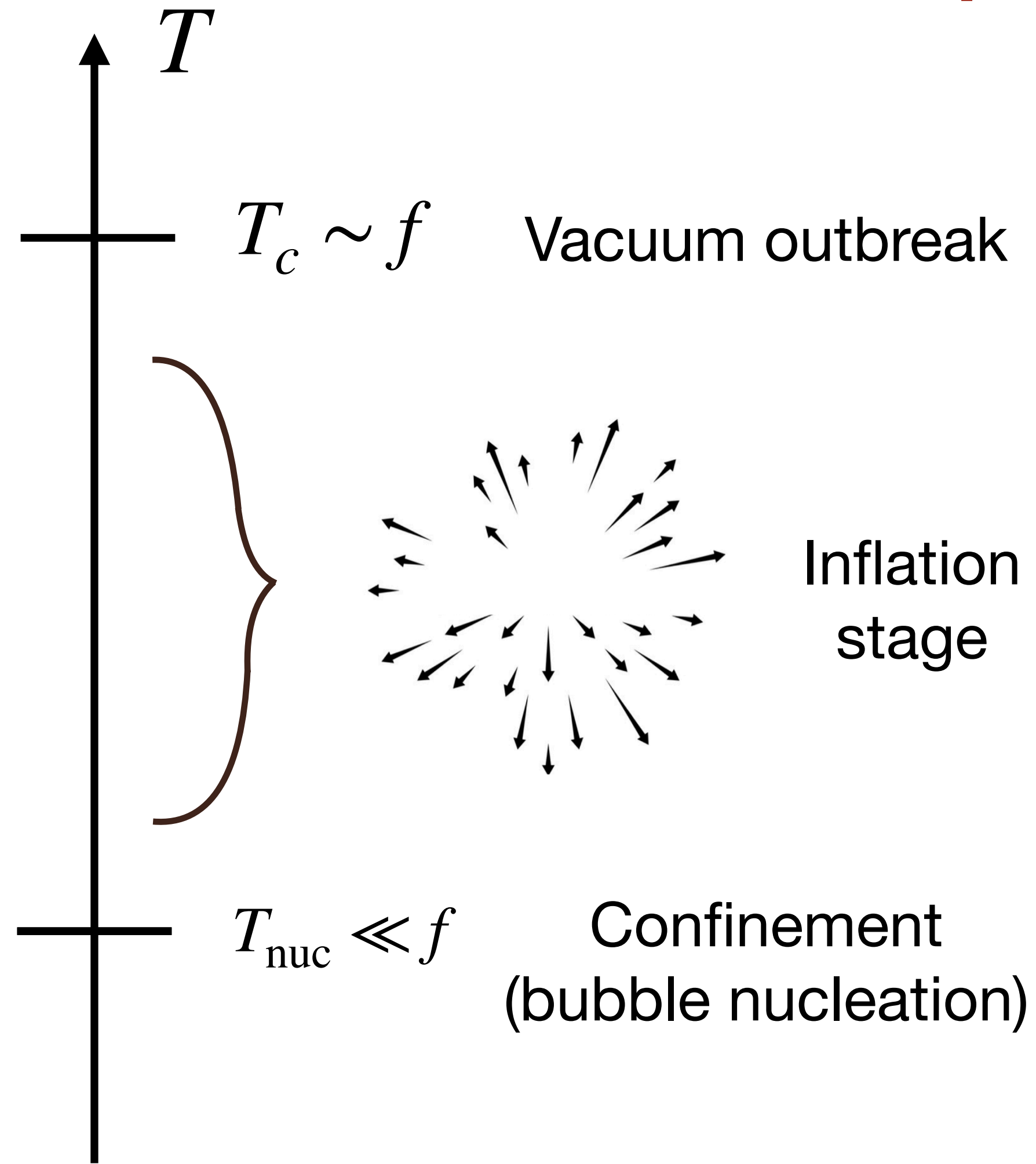
$$Y_{\text{DM}} \propto \left( \frac{T_{\text{nuc}}}{T_c} \right)^3$$

# ~~Super-uncool confinement~~

Baldes, YG, Sala 20'  
Baldes, YG, Sala, Servant 21'

## Super-cool

### Naive picture



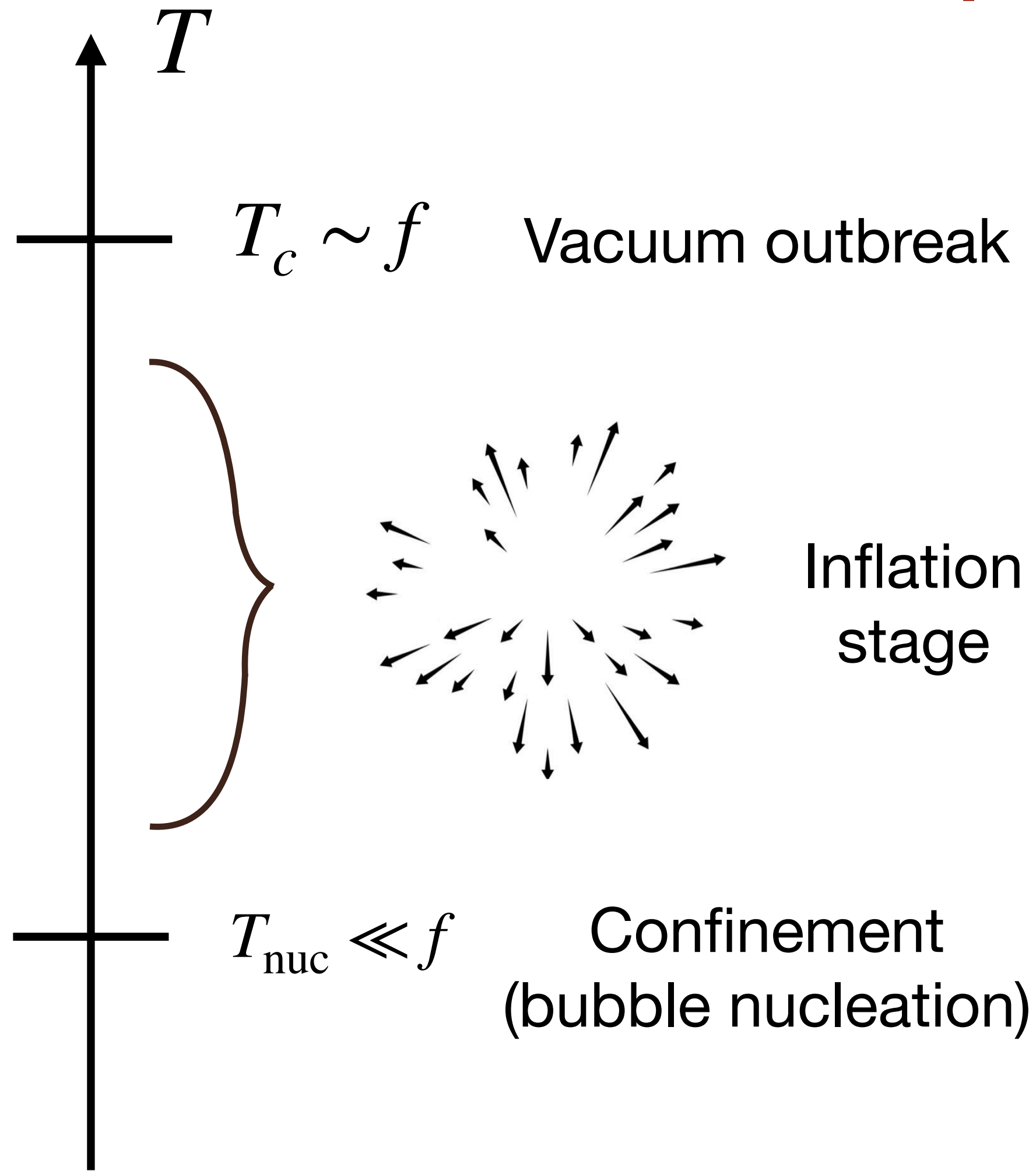
$\rightarrow Y_{\text{DM}} \propto \left( \frac{\cancel{T_{\text{nuc}}}}{\cancel{T_c}} \right)^3$

# ~~Super-uncool confinement~~

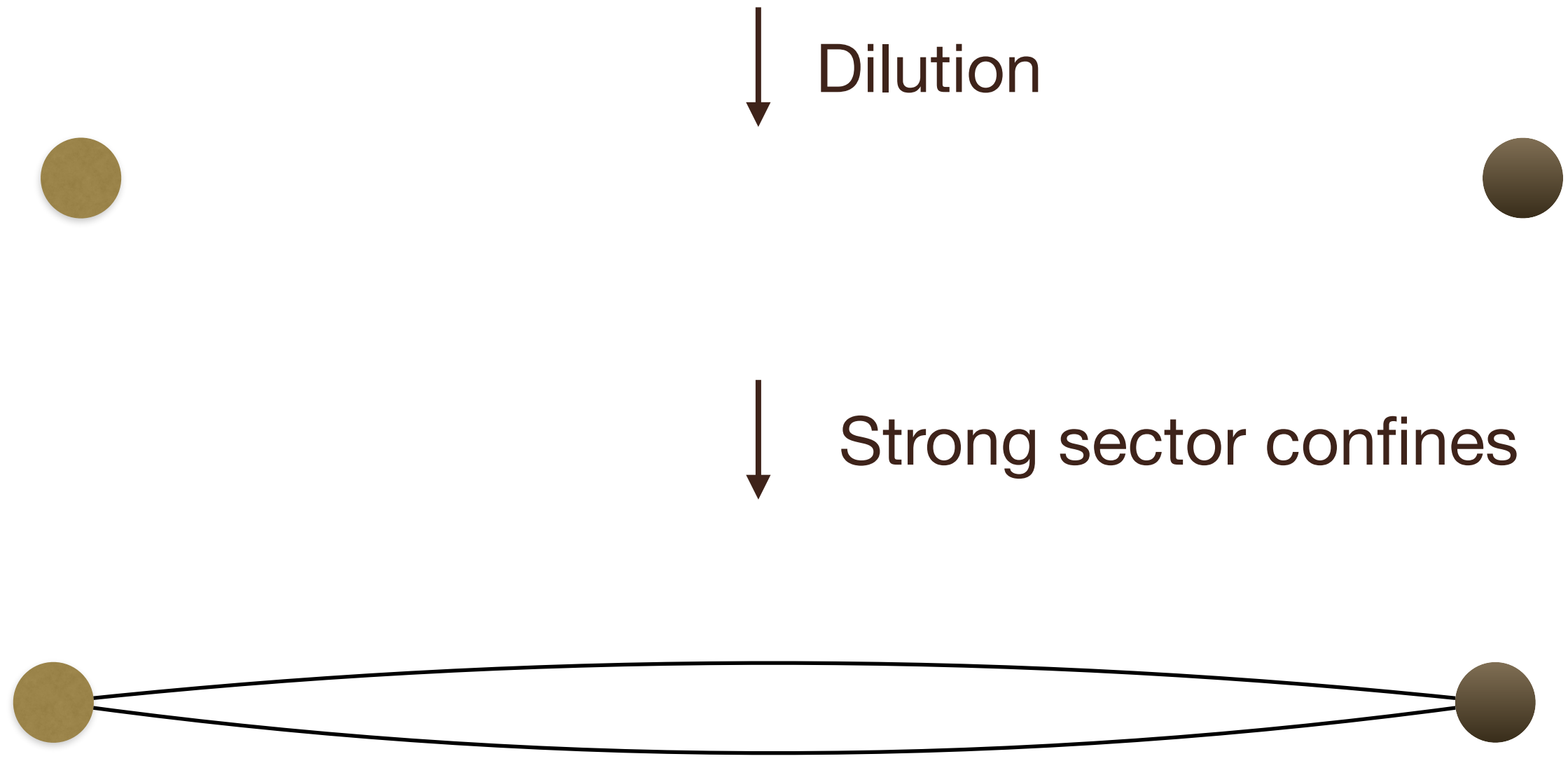
Baldes, YG, Sala 20'  
Baldes, YG, Sala, Servant 21'

## Super-cool

### Naive picture

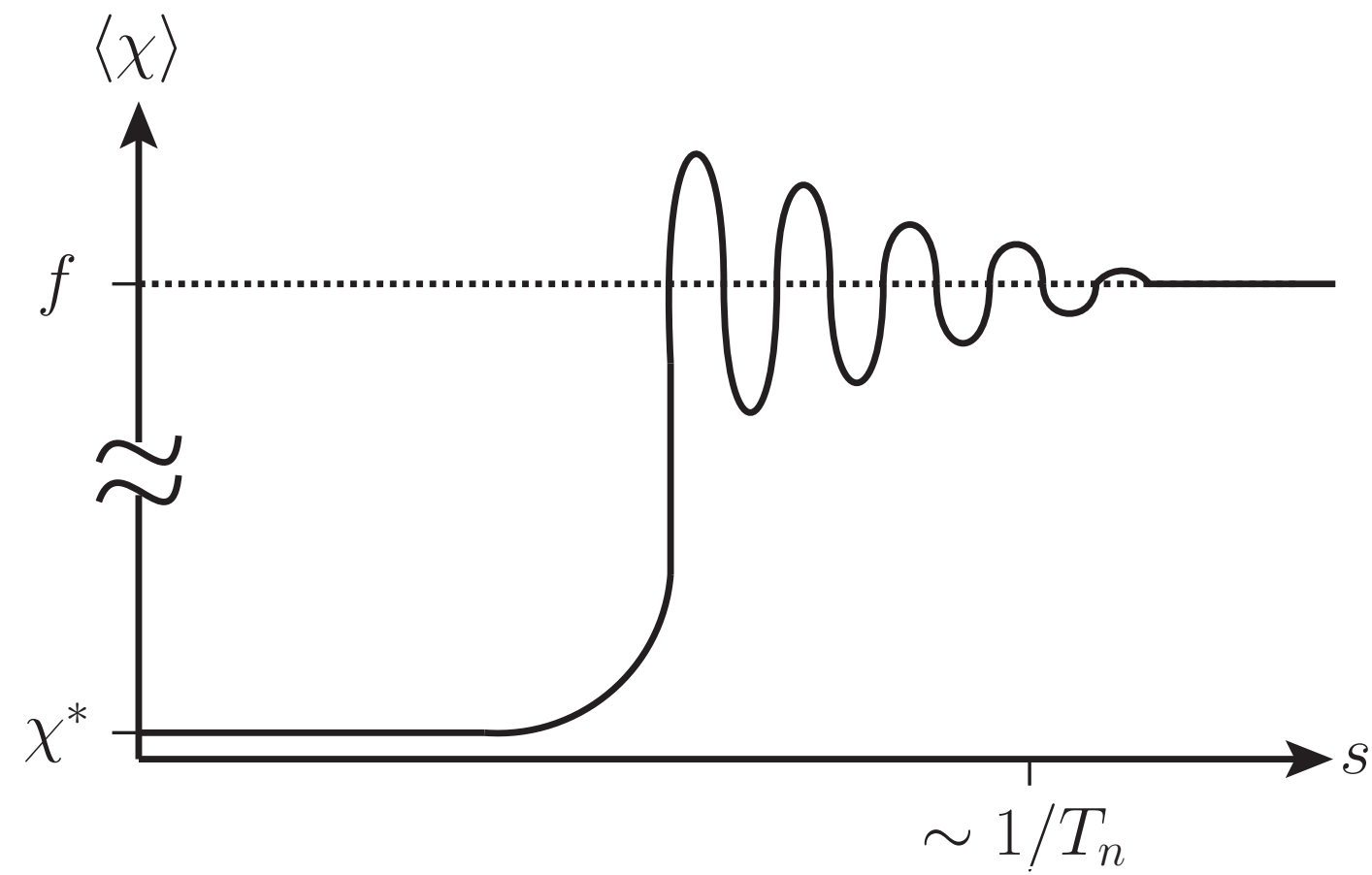


Quark    Anti-quark



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

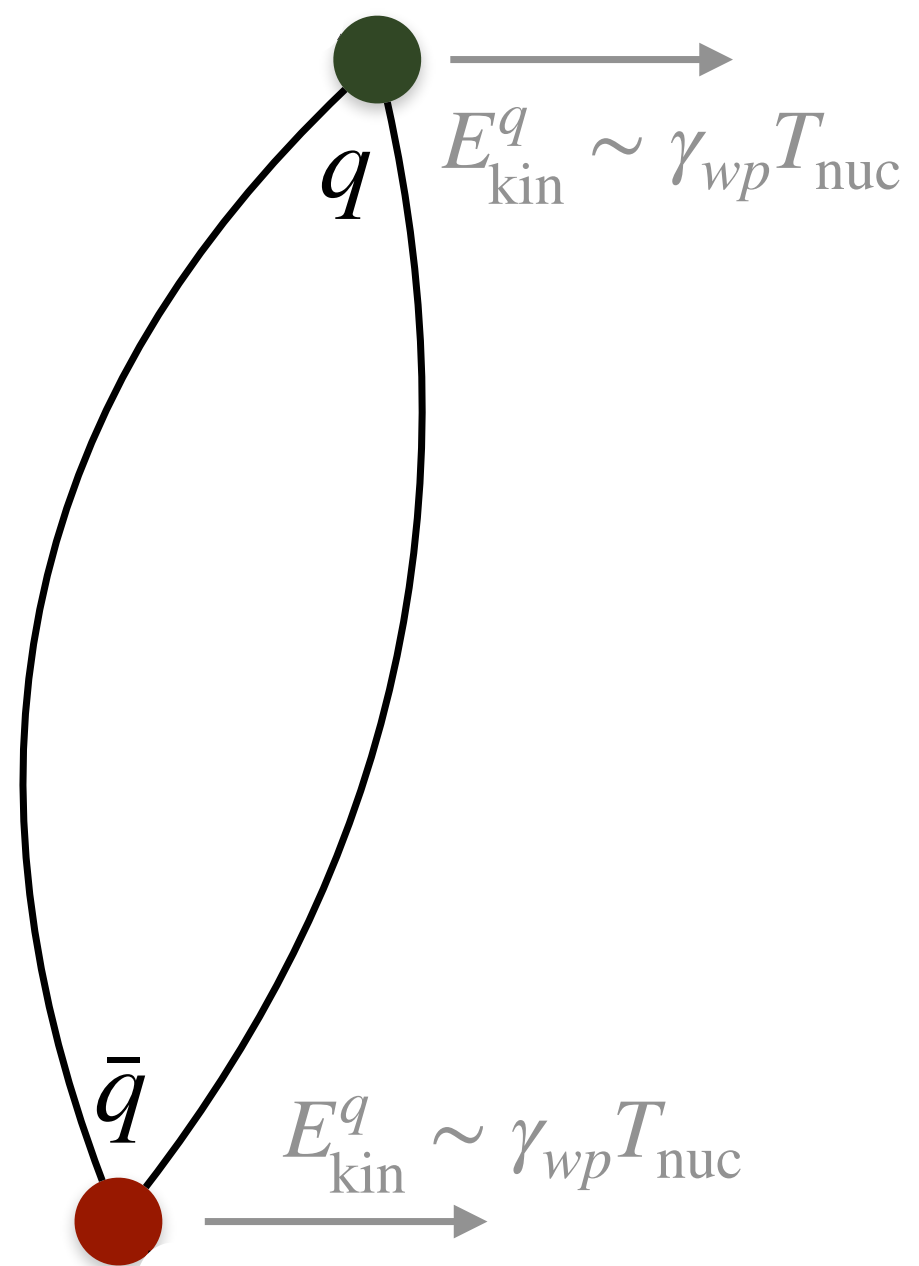
# Confinement



Bubble wall profile

## Deconfined phase

$$\chi = 0$$



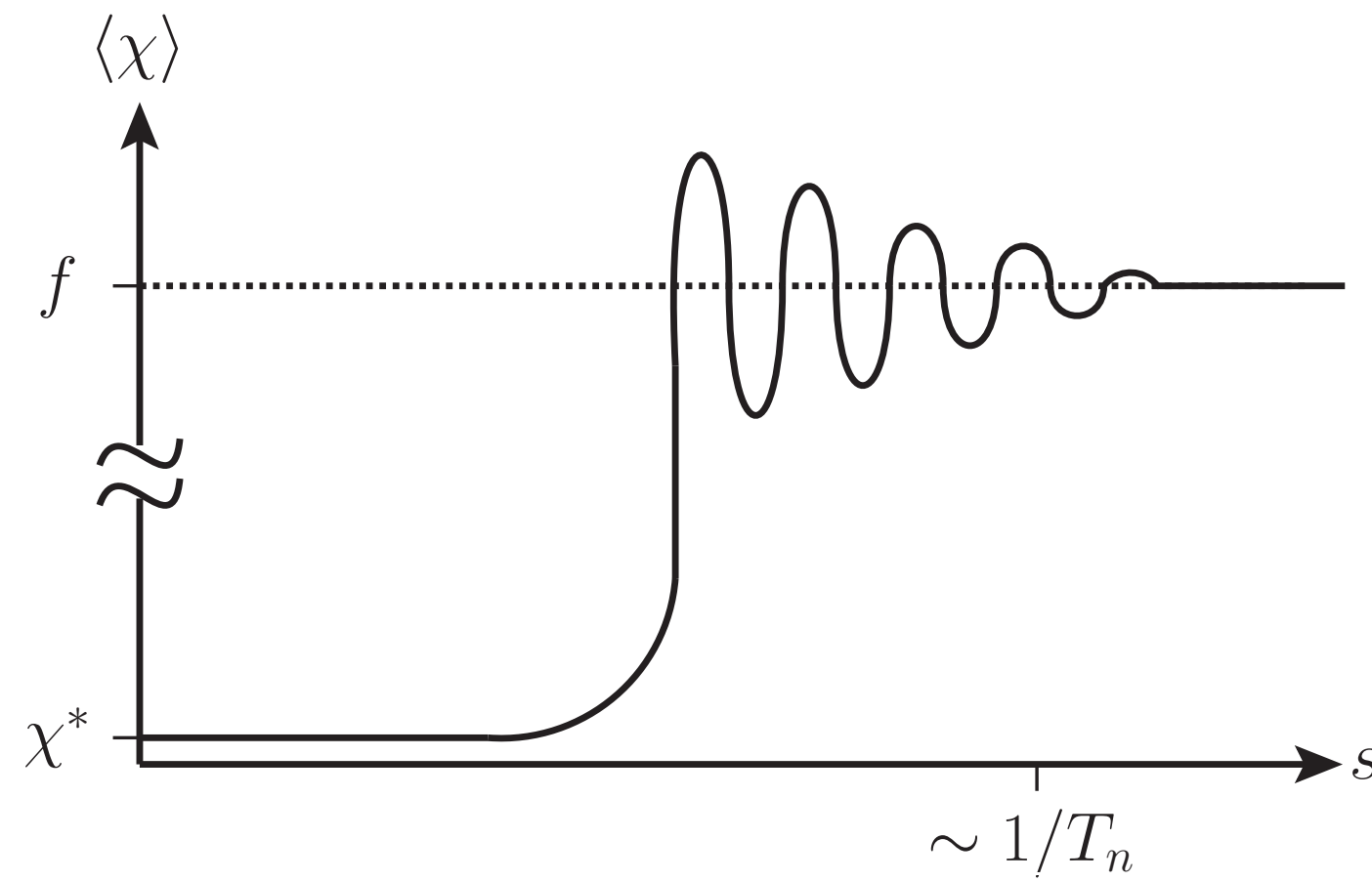
## Confined phase

$$\chi = f$$

## Bubble wall frame



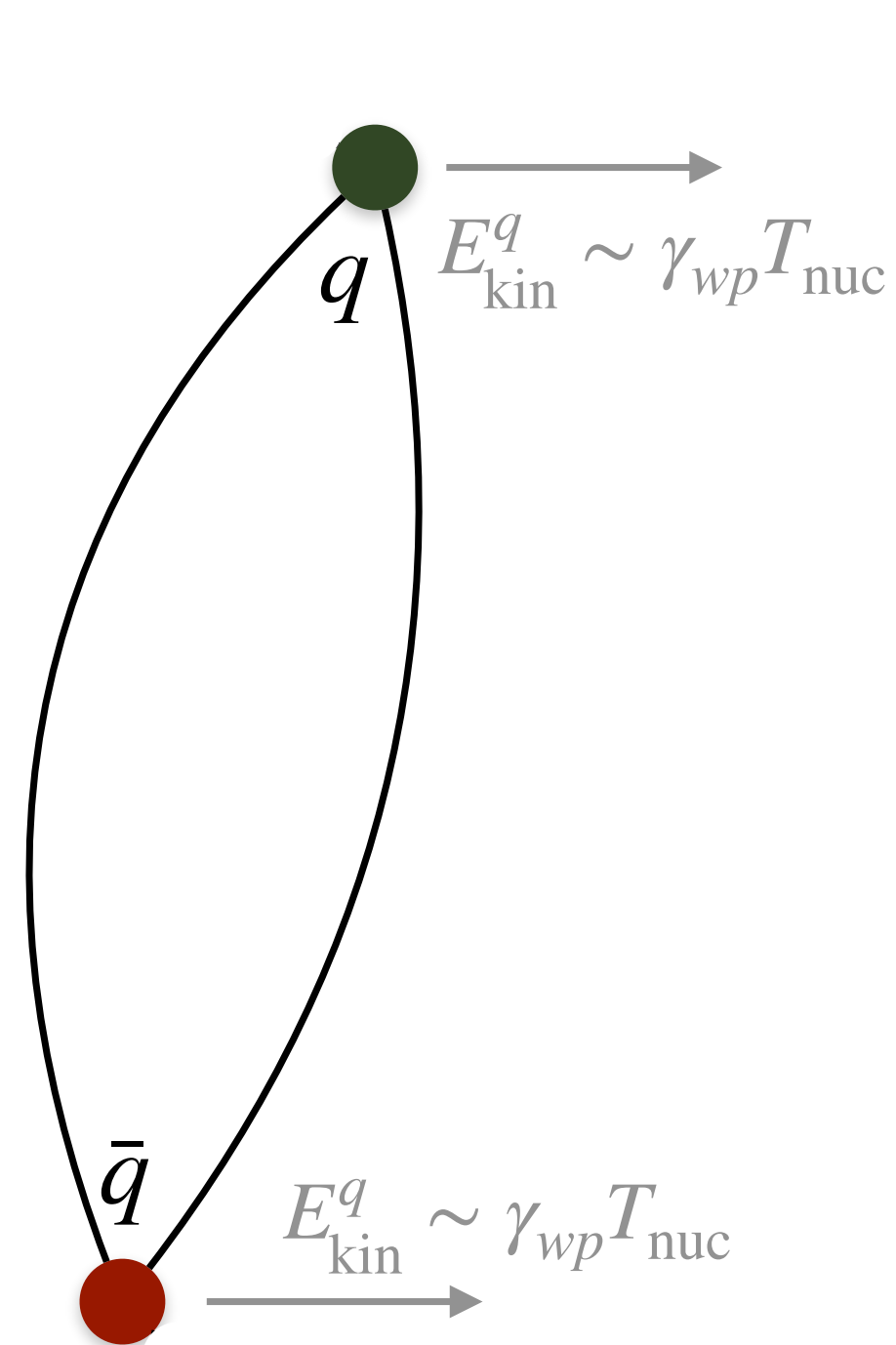
# Confinement



Bubble wall profile

Deconfined phase

$$\chi = 0$$

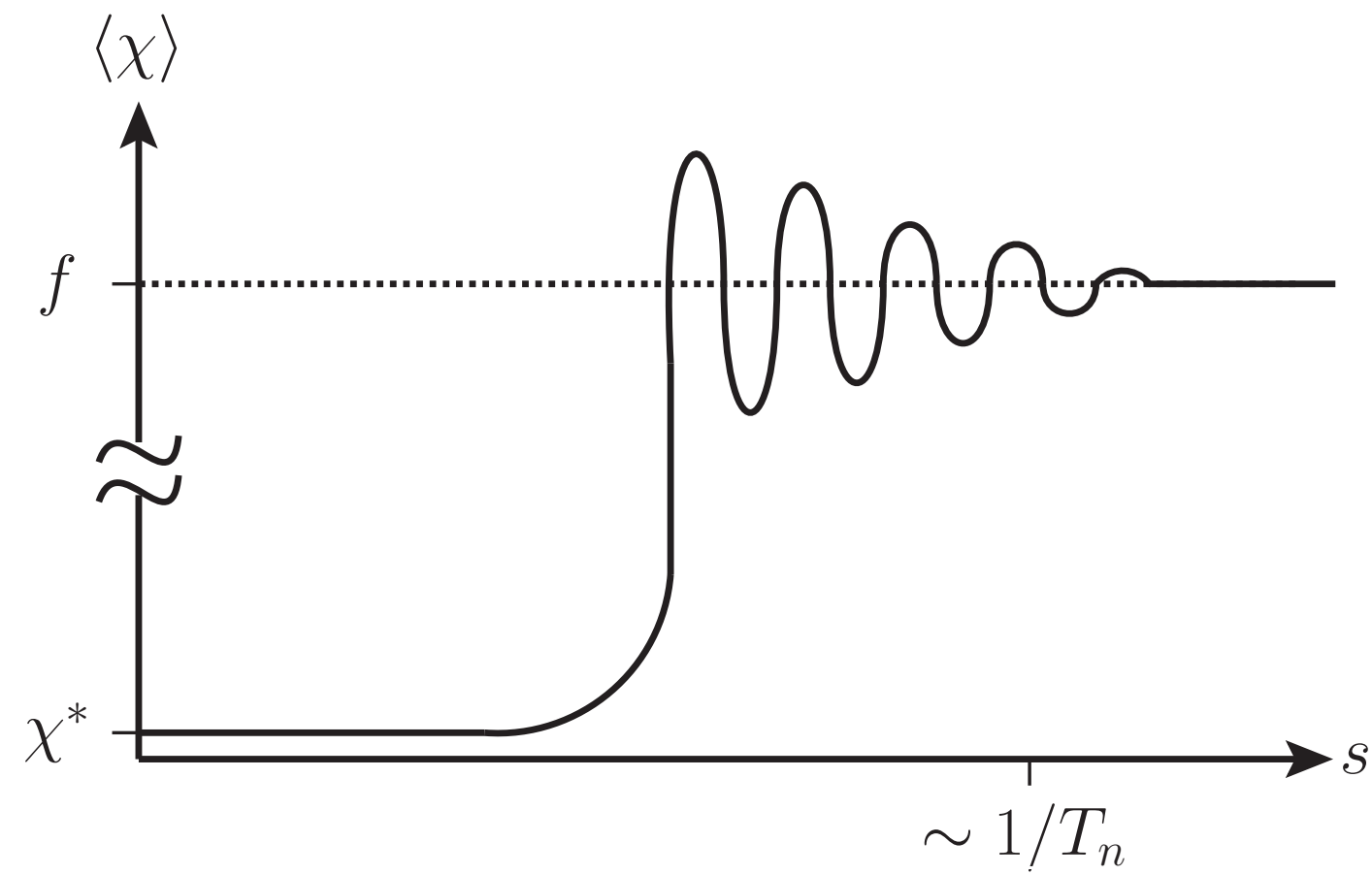


Bubble wall frame

Confined phase

$$\chi = f$$

# Confinement



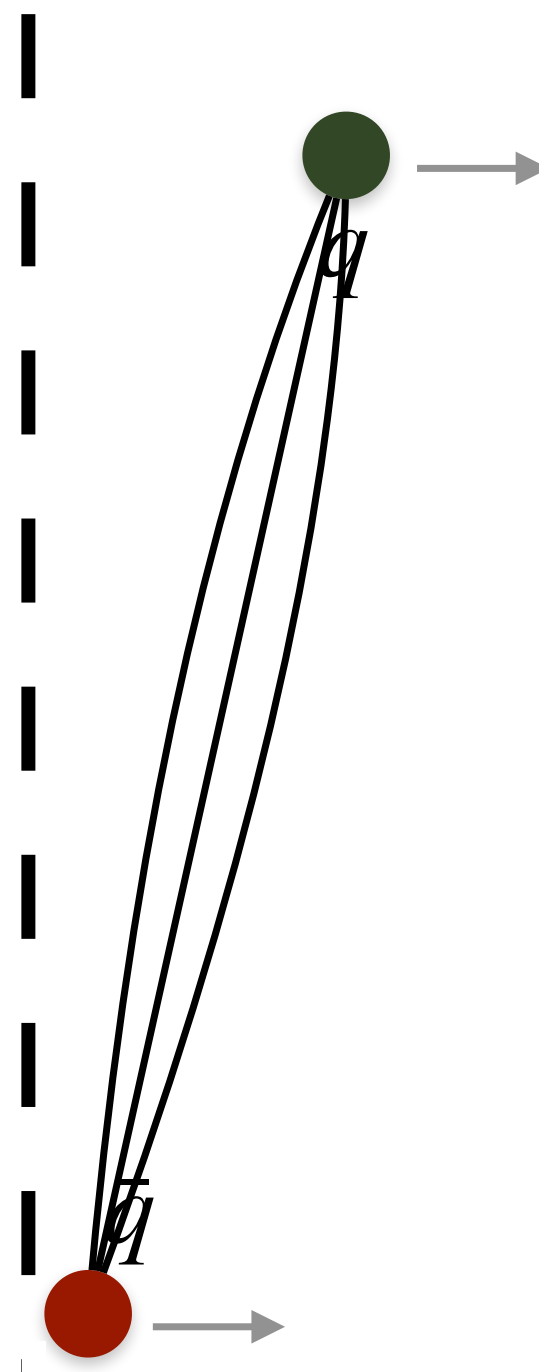
Bubble wall profile

Deconfined phase

$$\chi = 0$$

Confined phase

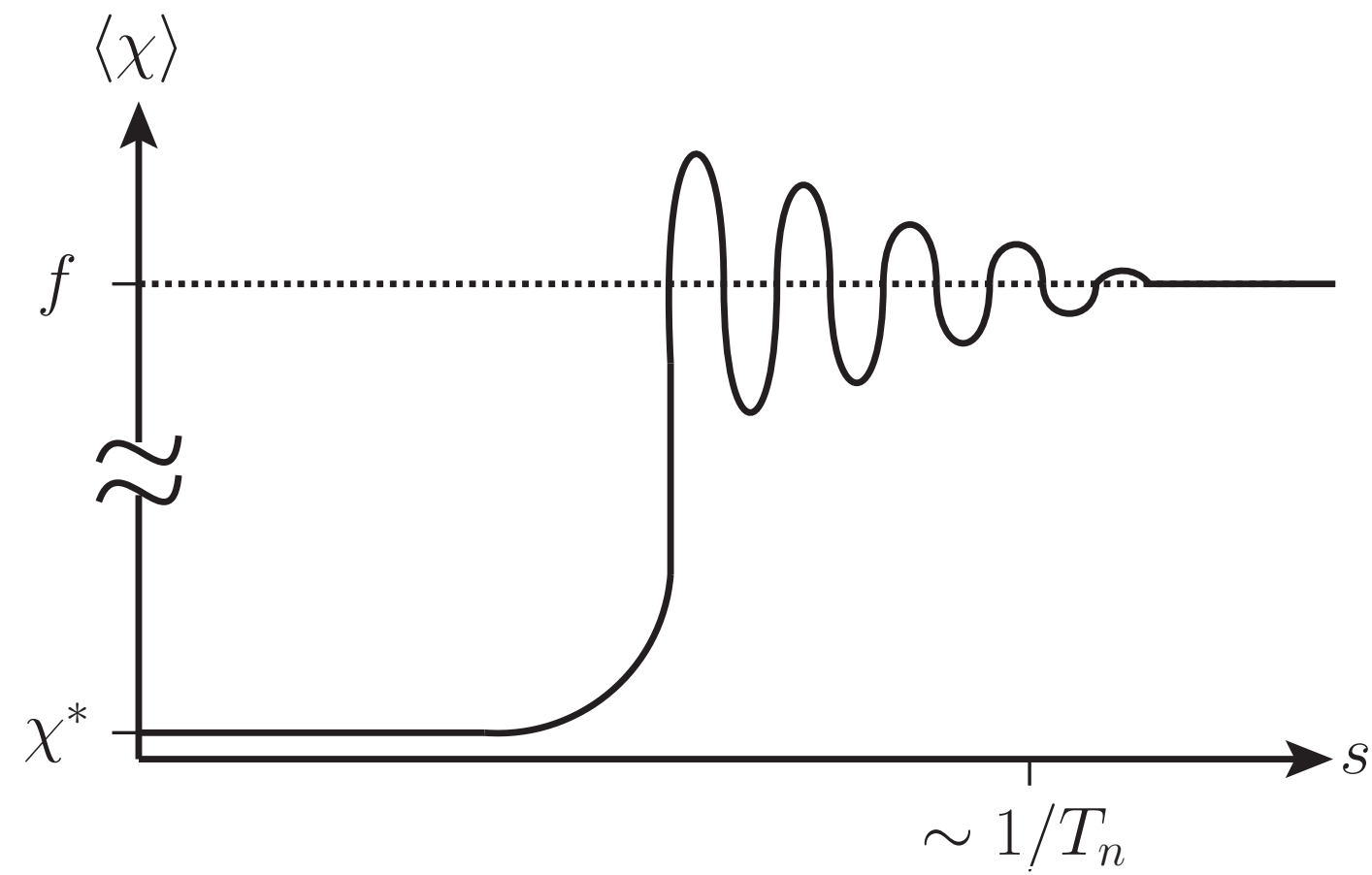
$$\chi = f$$



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

Bubble wall frame

# Confinement



Bubble wall profile

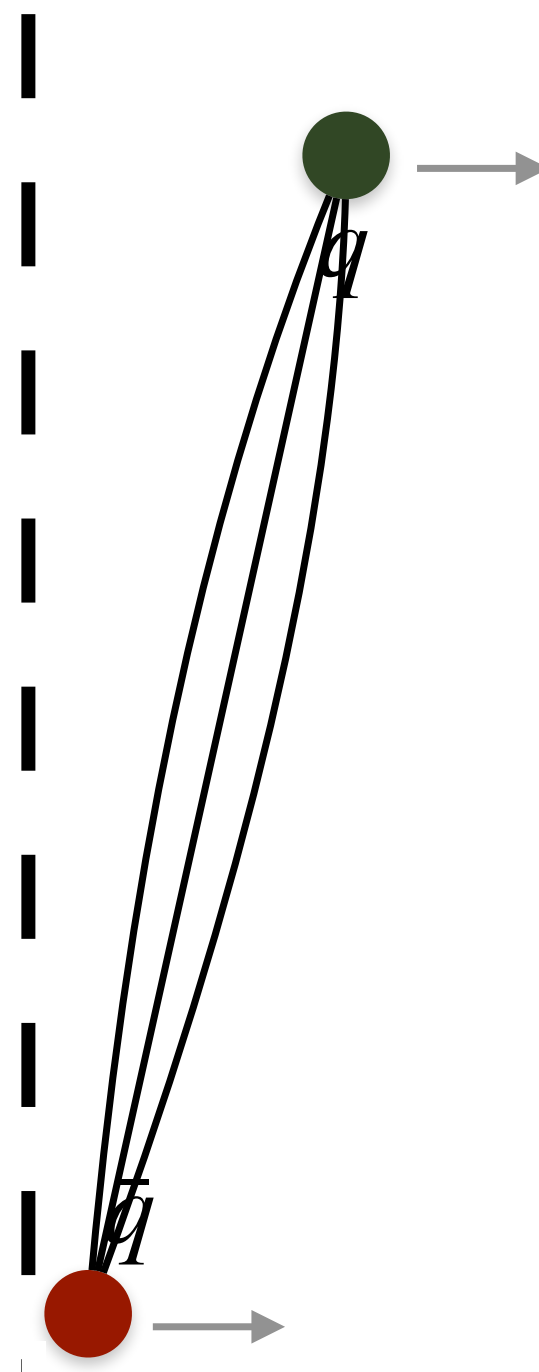
Deconfined phase

$$\chi = 0$$

Confined phase

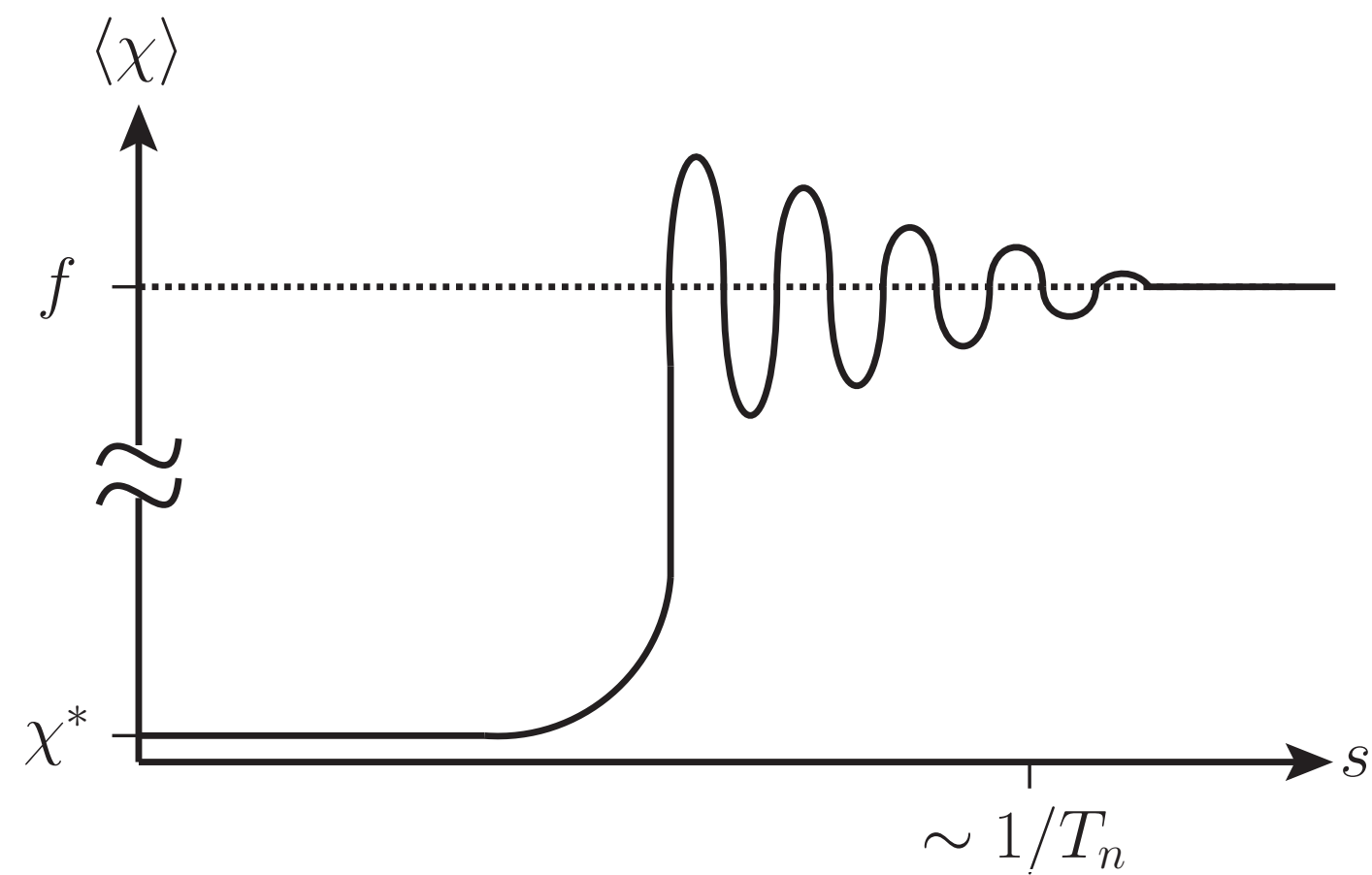
$$\chi = f$$

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



Bubble wall frame

# Confinement



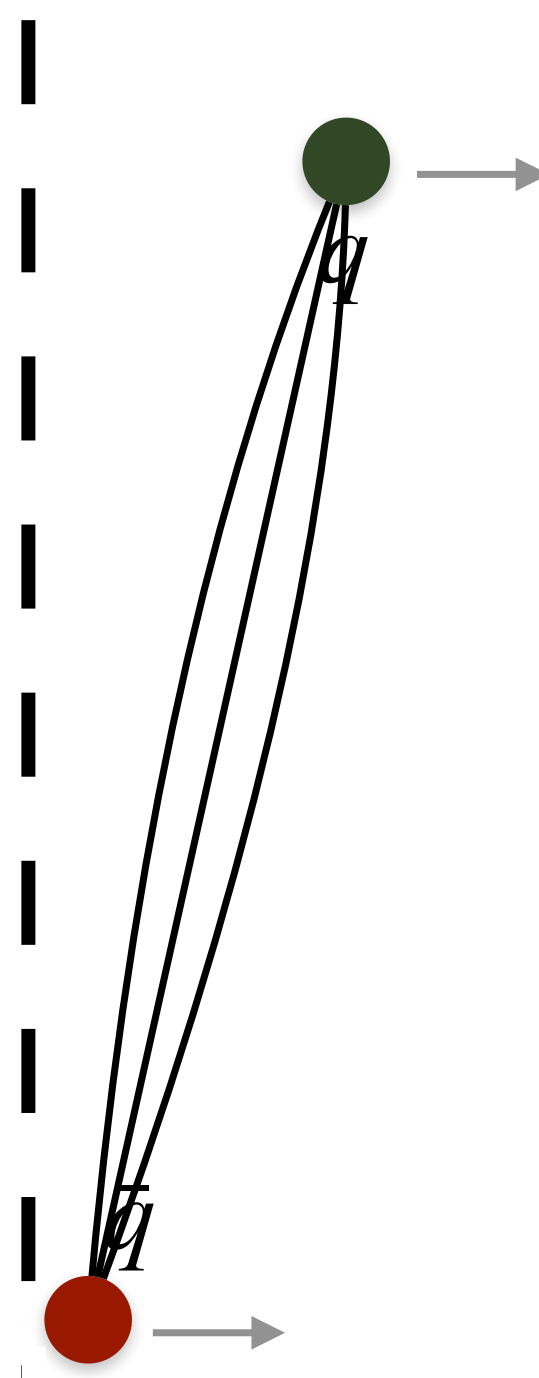
Bubble wall profile

Deconfined phase

$$\chi = 0$$

Confined phase

$$\chi = f$$

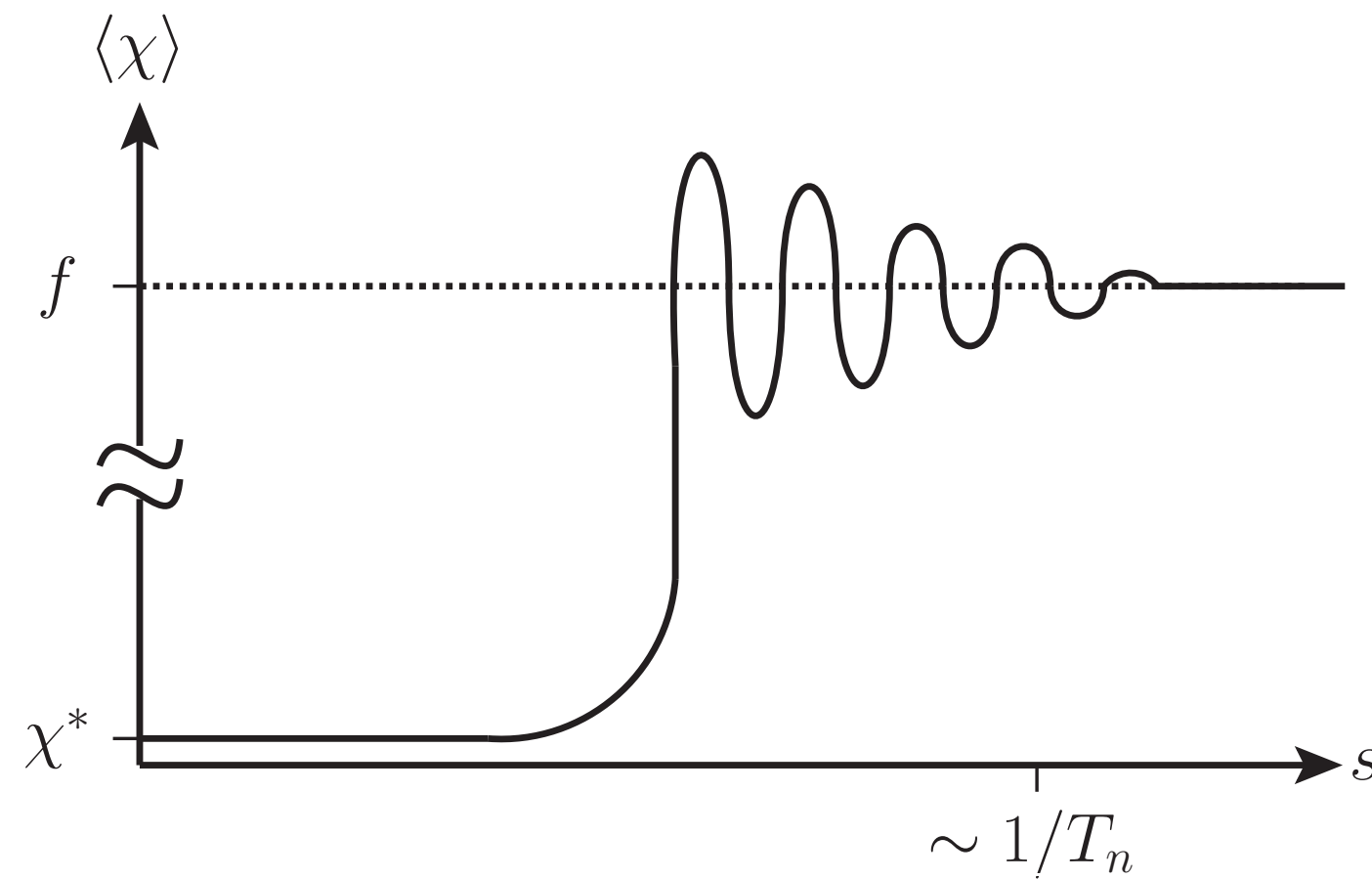


$$V_{\text{string}} \simeq f^2 r \simeq \frac{f^2}{T_{\text{nuc}}} \gg f$$

Bubble wall frame



# Confinement



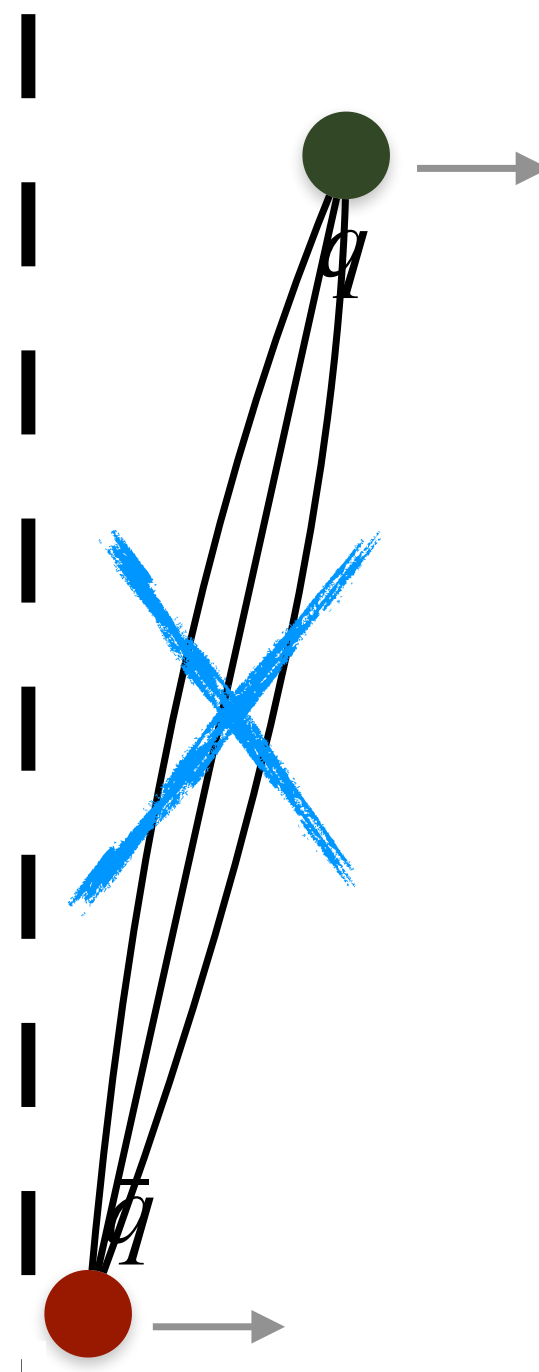
Bubble wall profile

Deconfined phase

$$\chi = 0$$

Confined phase

$$\chi = f$$

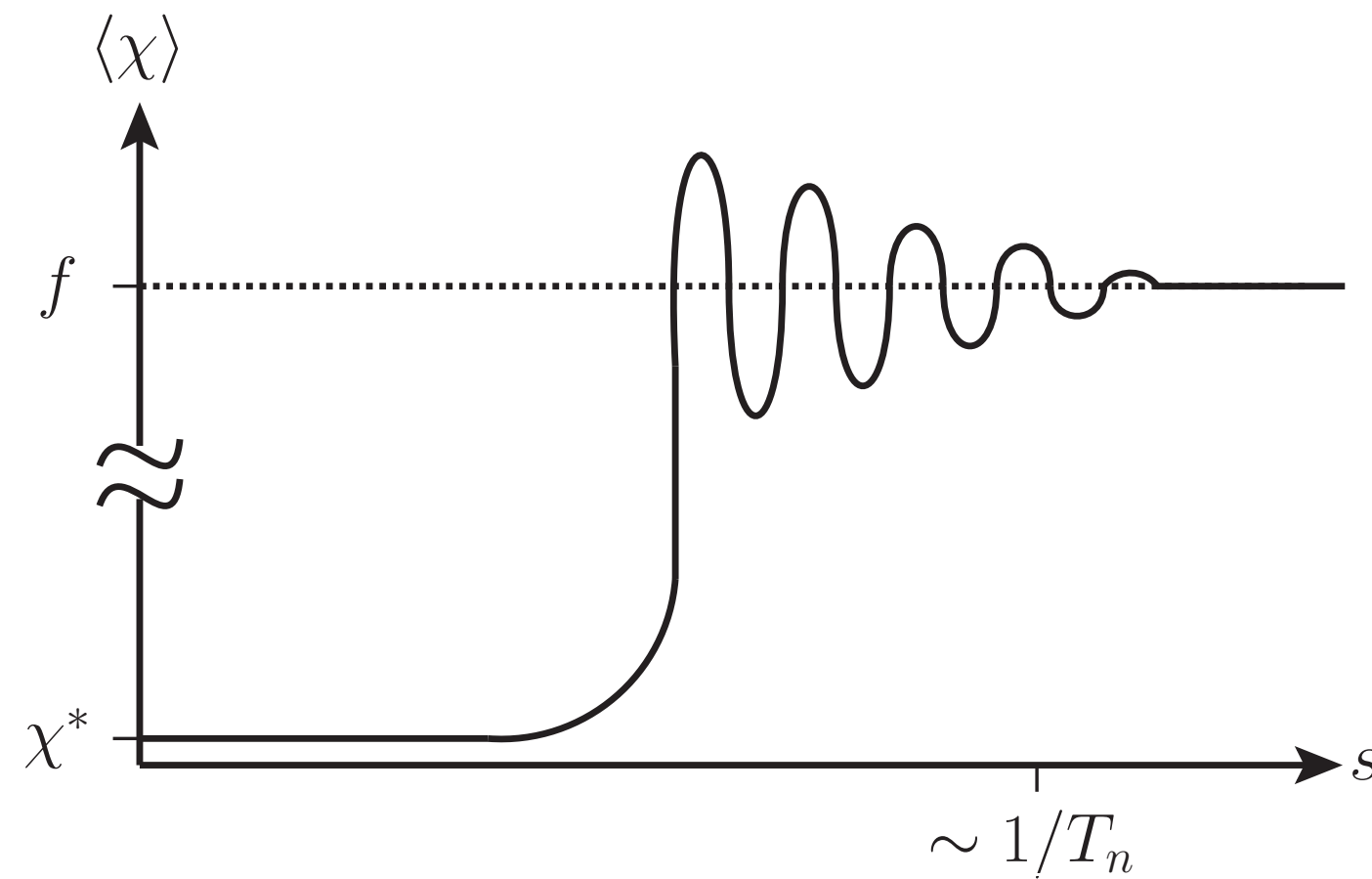


$$V_{\text{string}} \simeq f^2 r \simeq \frac{f^2}{T_{\text{nuc}}} \gg f$$

Cost too much energy!

Bubble wall frame

# Confinement



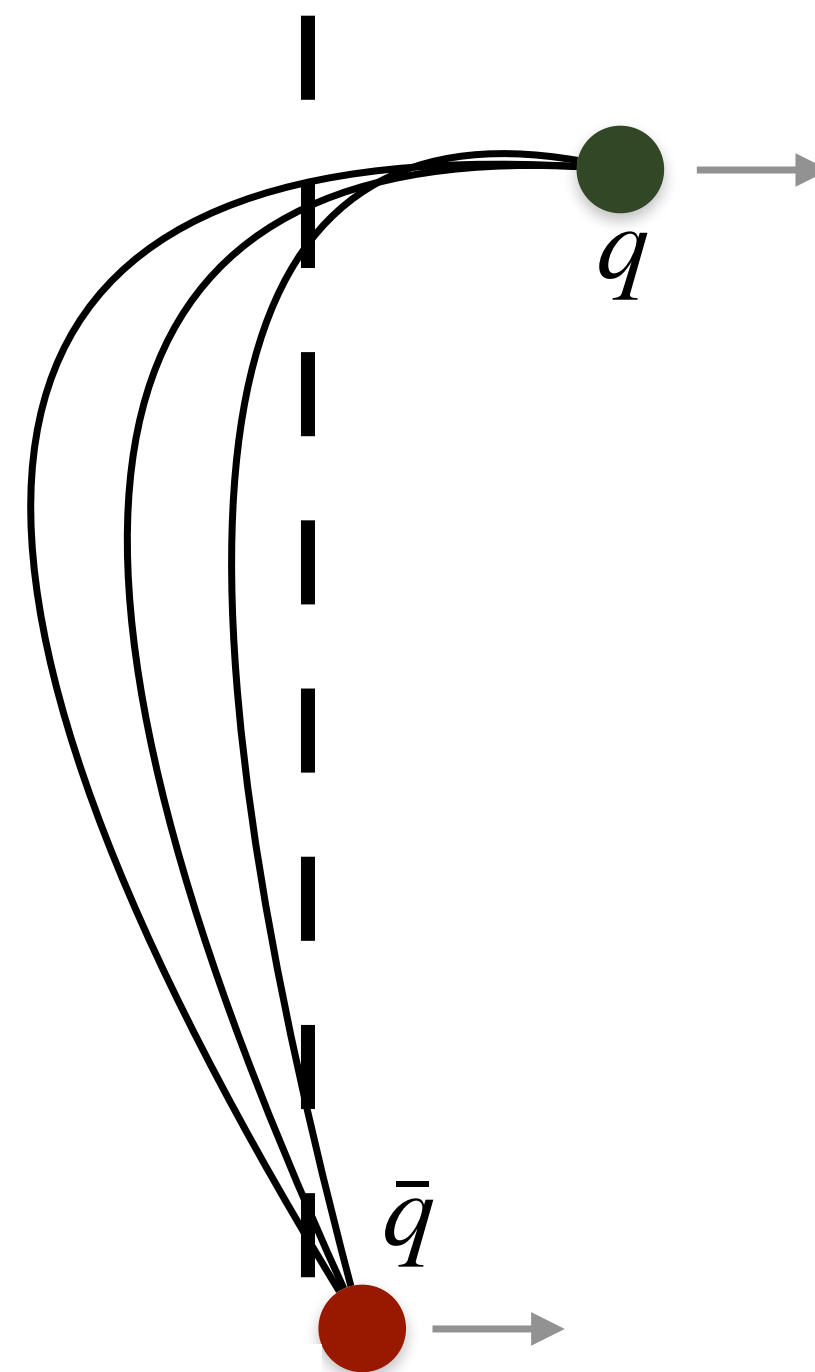
Bubble wall profile

Deconfined phase

$$\chi = 0$$

Confined phase

$$\chi = f$$

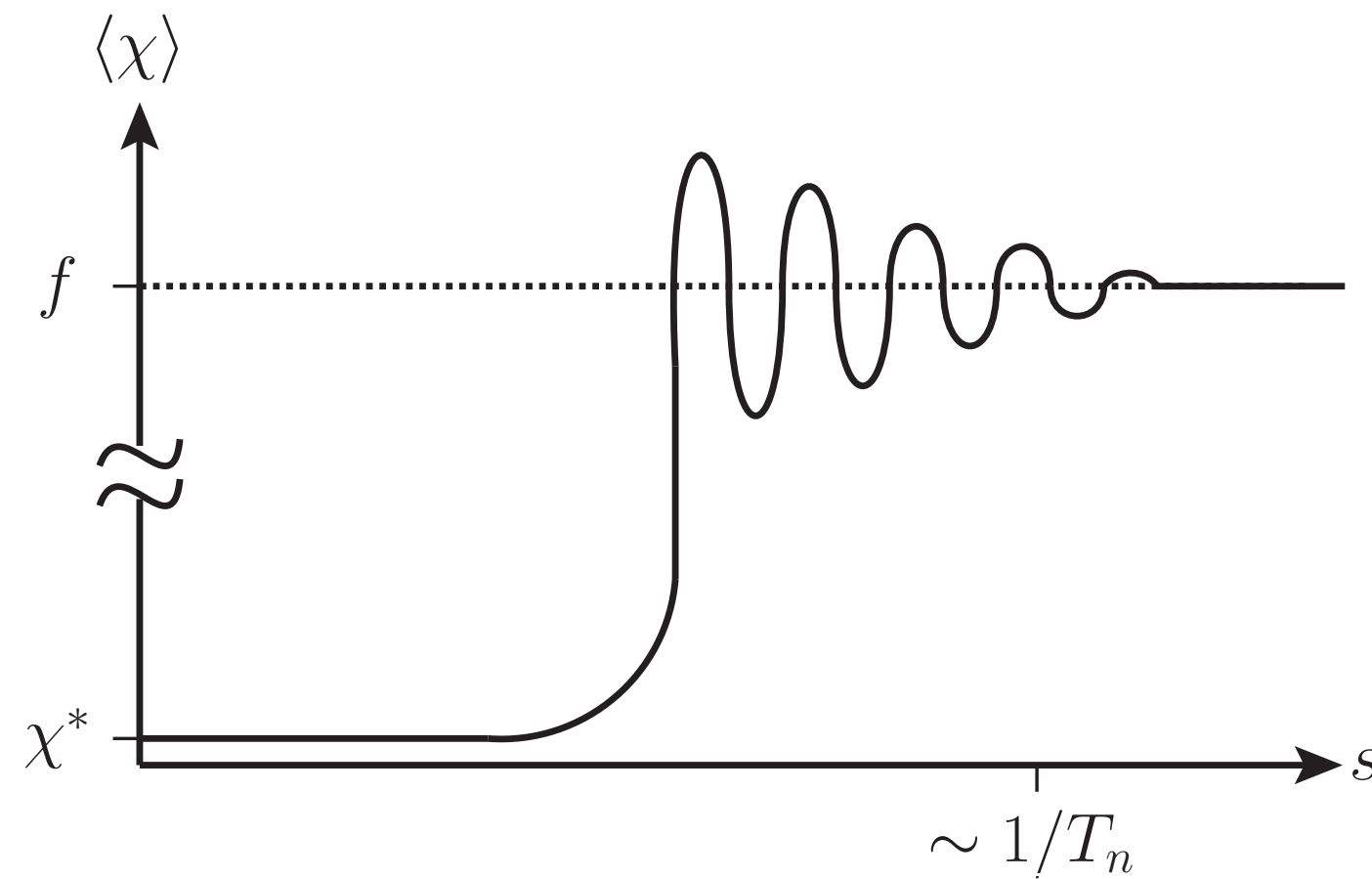


$$V_{\text{string}} \simeq f^2 r \sim f$$

Flux tube minimises its energy !

Bubble wall frame

# Confinement



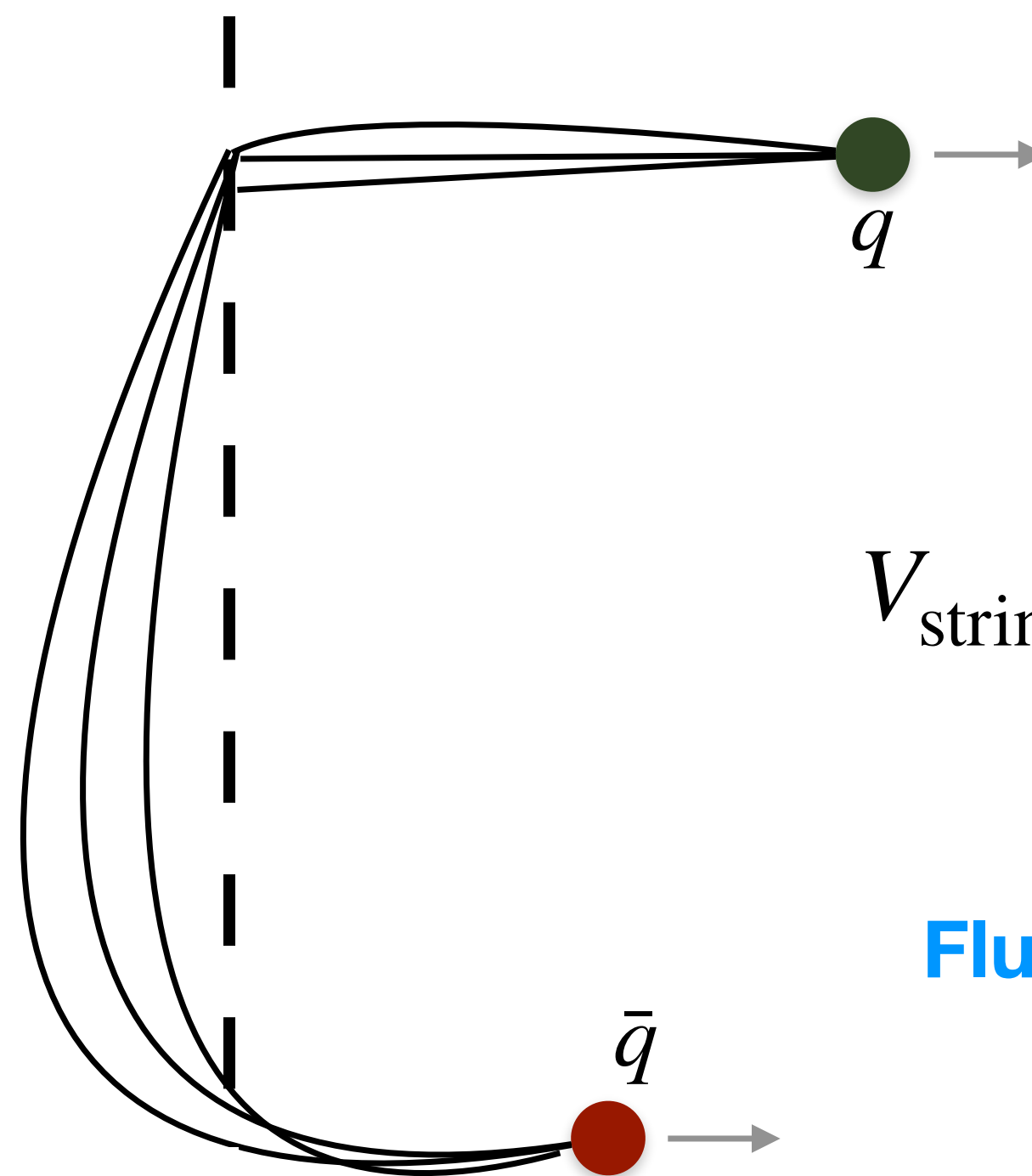
Bubble wall profile

Deconfined phase

$$\chi = 0$$

Confined phase

$$\chi = f$$

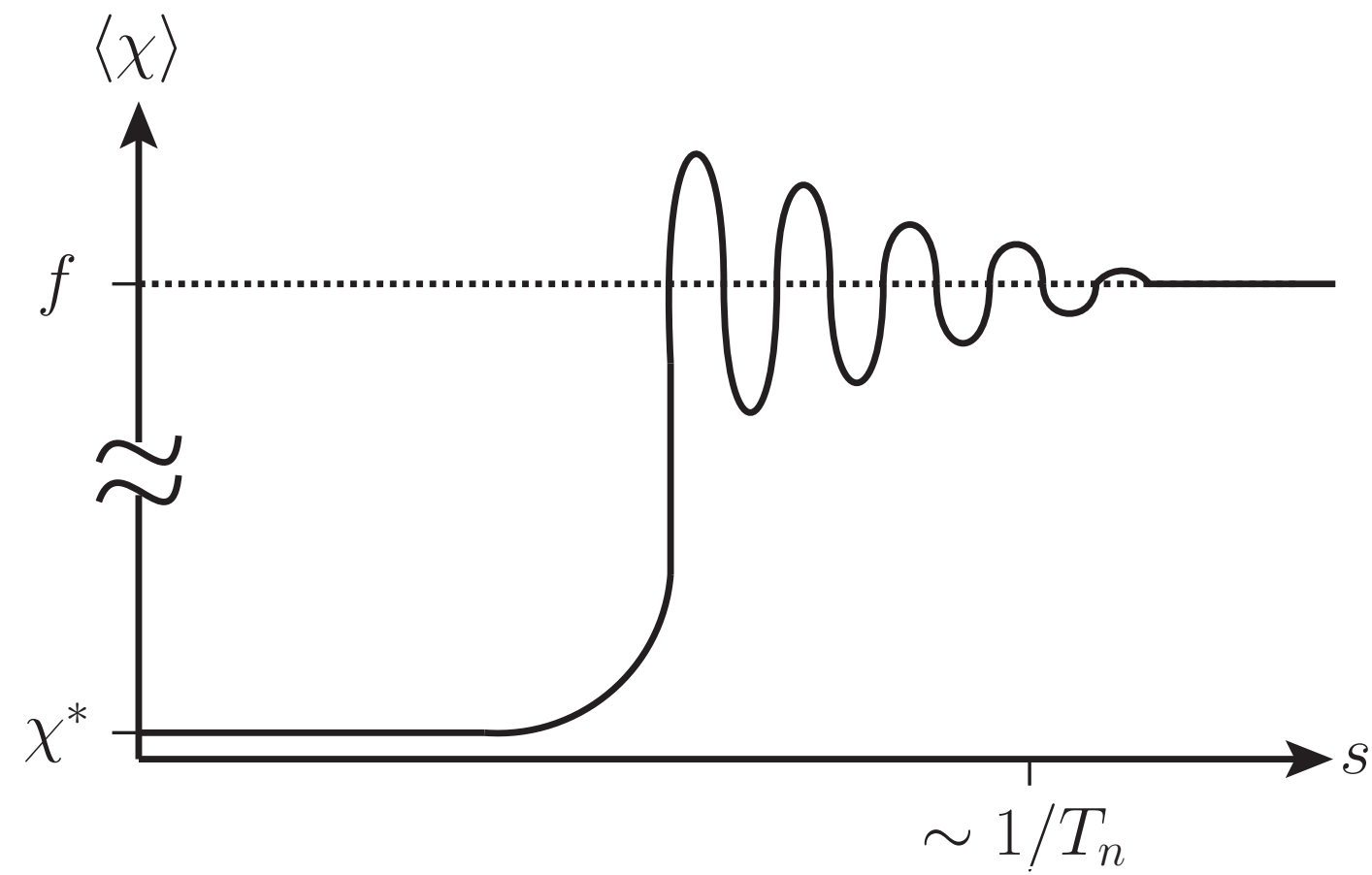


$$V_{\text{string}} \simeq f^2 r \sim f$$

Flux tube minimises its energy !

Bubble wall frame

# Confinement



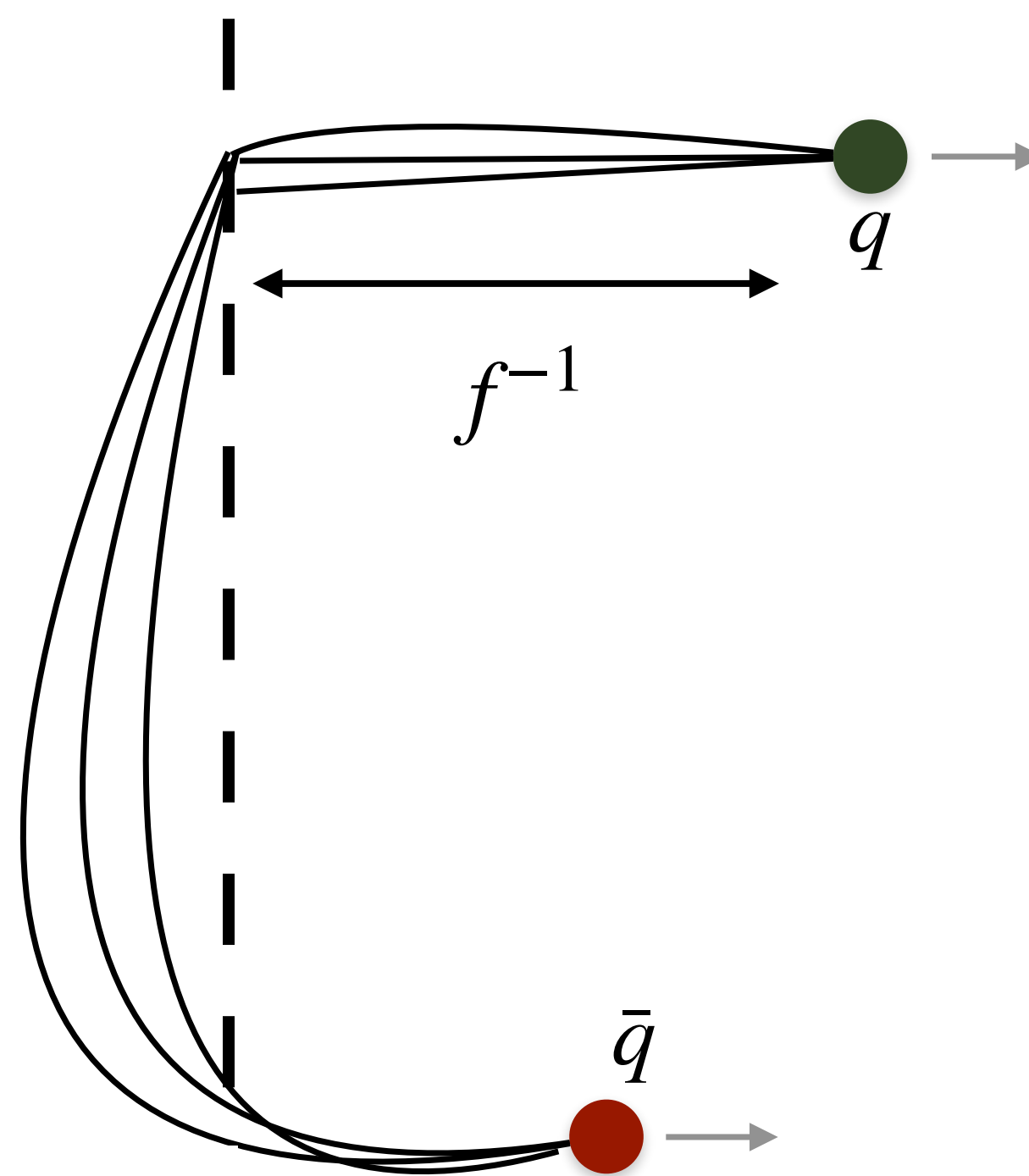
Bubble wall profile

Deconfined phase

$$\chi = 0$$

Confined phase

$$\chi = f$$



Bubble wall frame

# Confinement

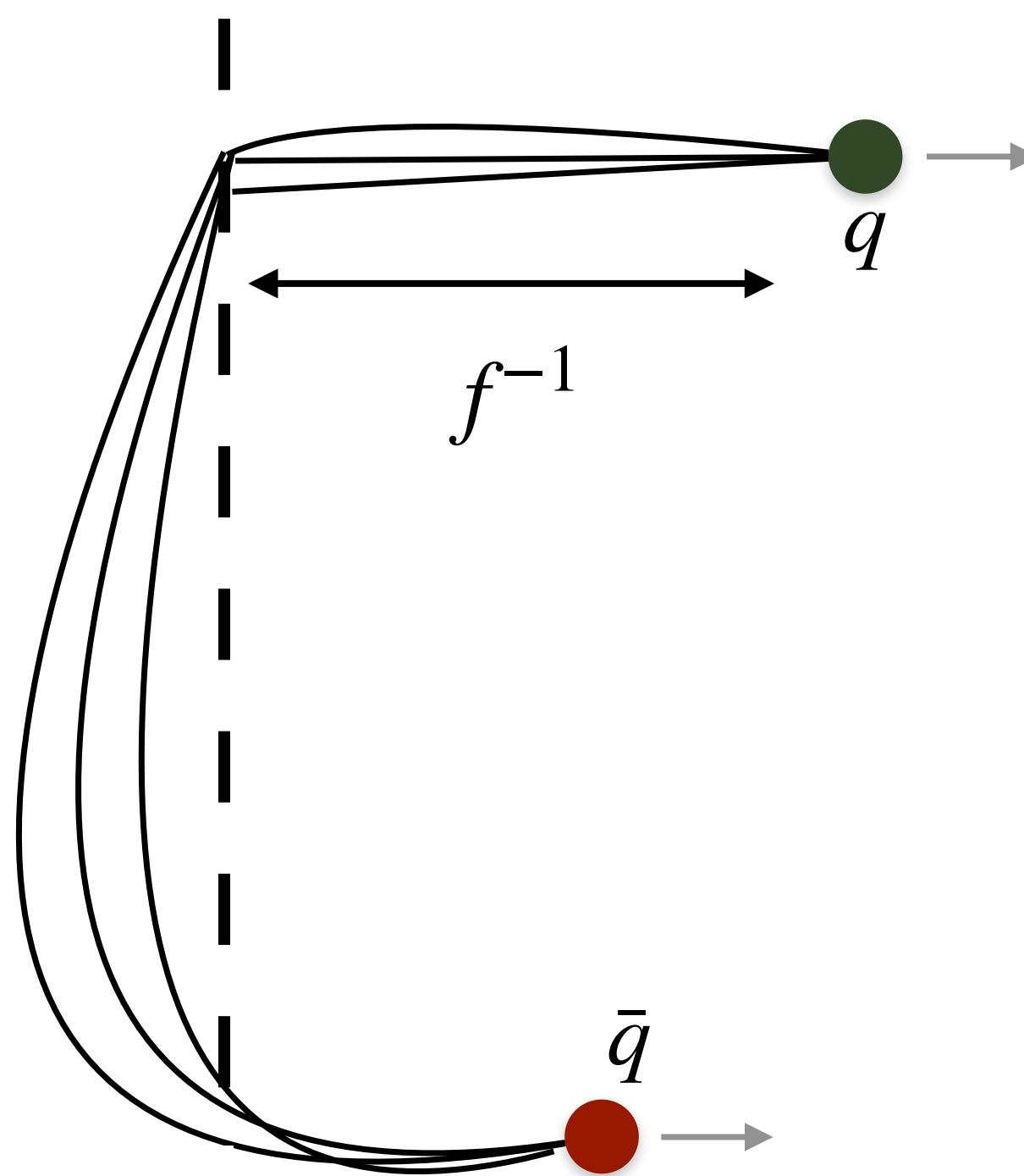


Deconfined phase

$$\chi = 0$$

Confined phase

$$\chi = f$$



Bubble wall frame

# Confinement

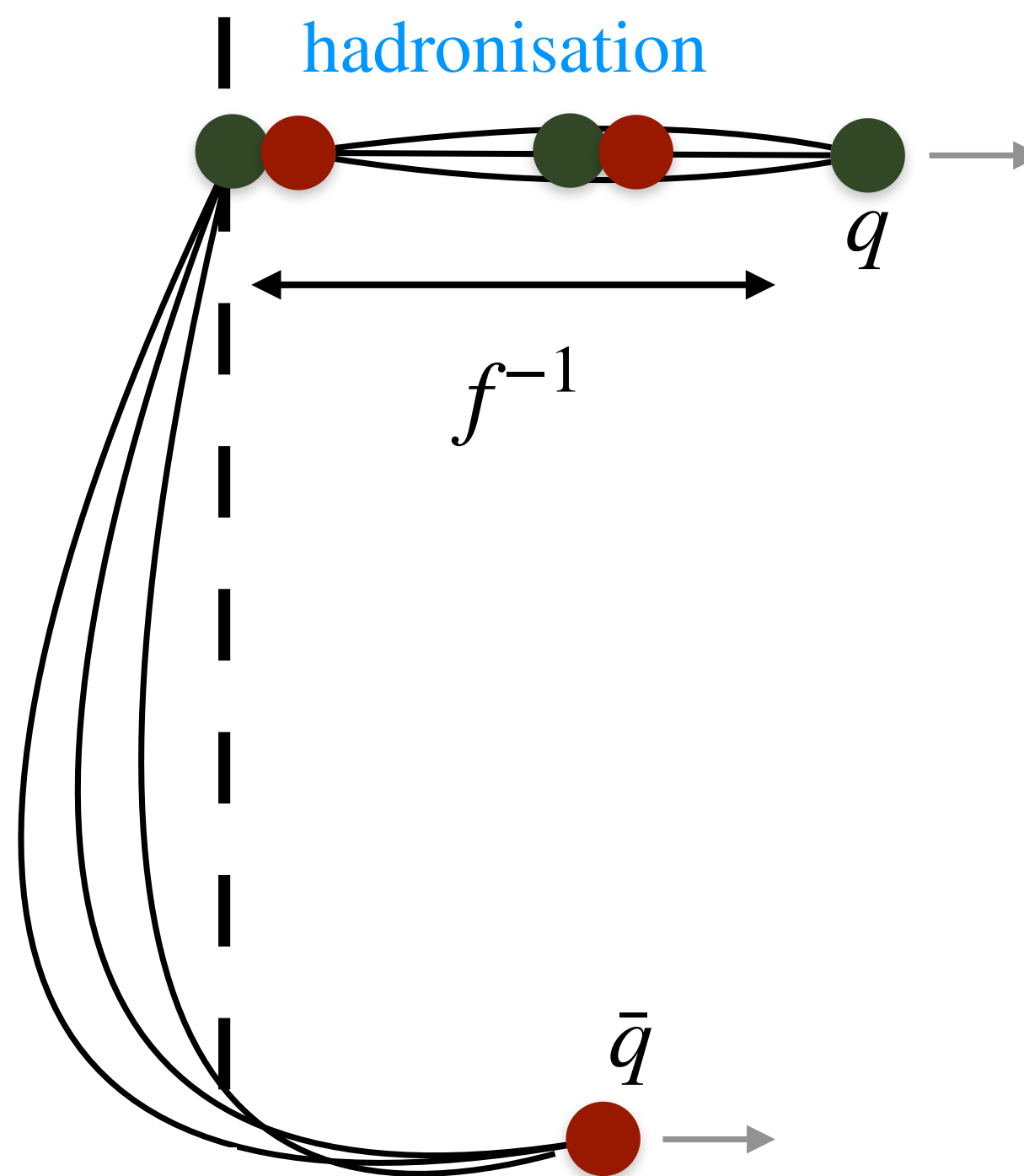


Deconfined phase

$$\chi = 0$$

Confined phase

$$\chi = f$$



Bubble wall frame

# Confinement

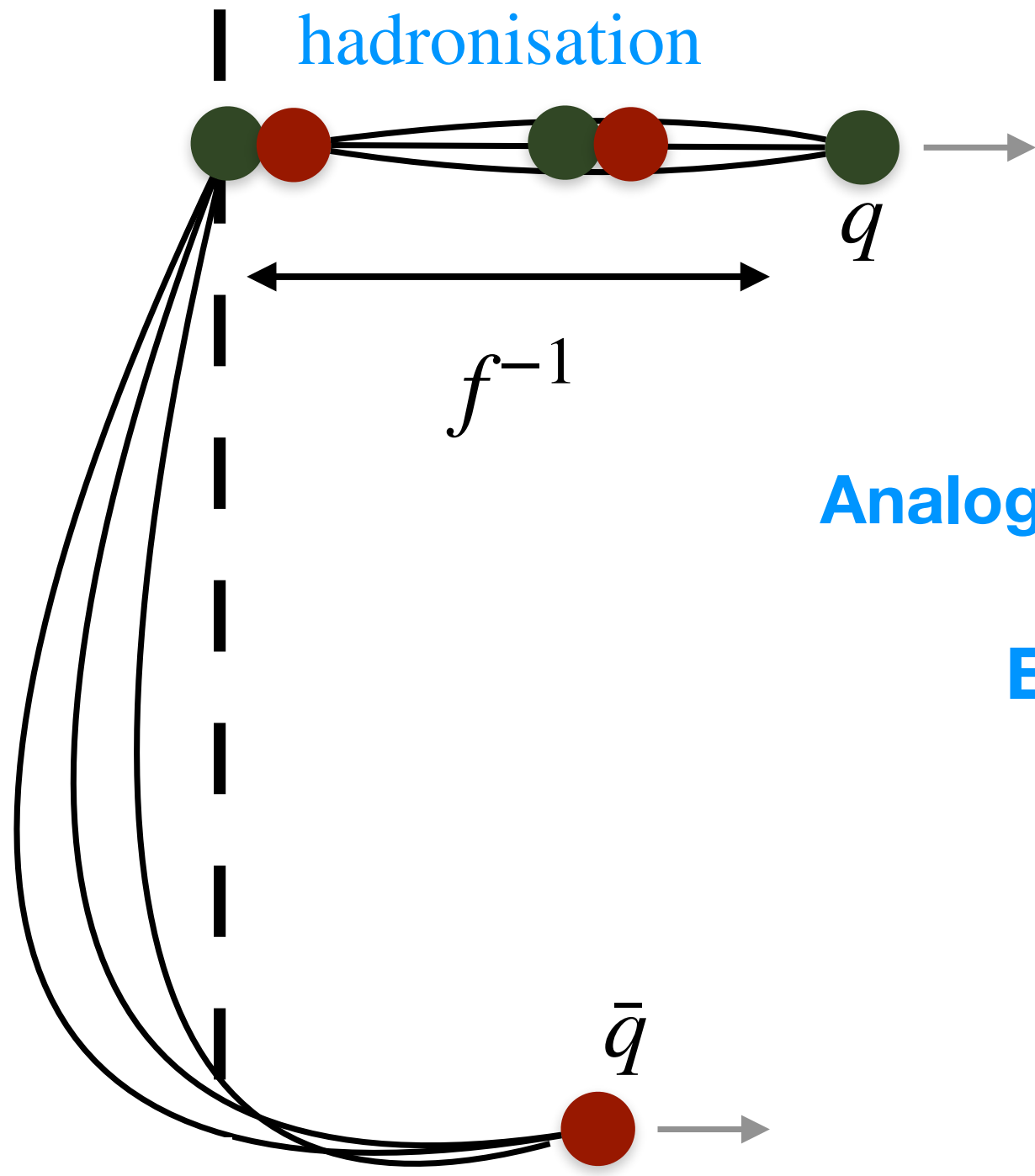


Deconfined phase

$$\chi = 0$$

Confined phase

$$\chi = f$$



Analog to string fragmentation in QCD !

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

Bubble wall frame

# Confinement



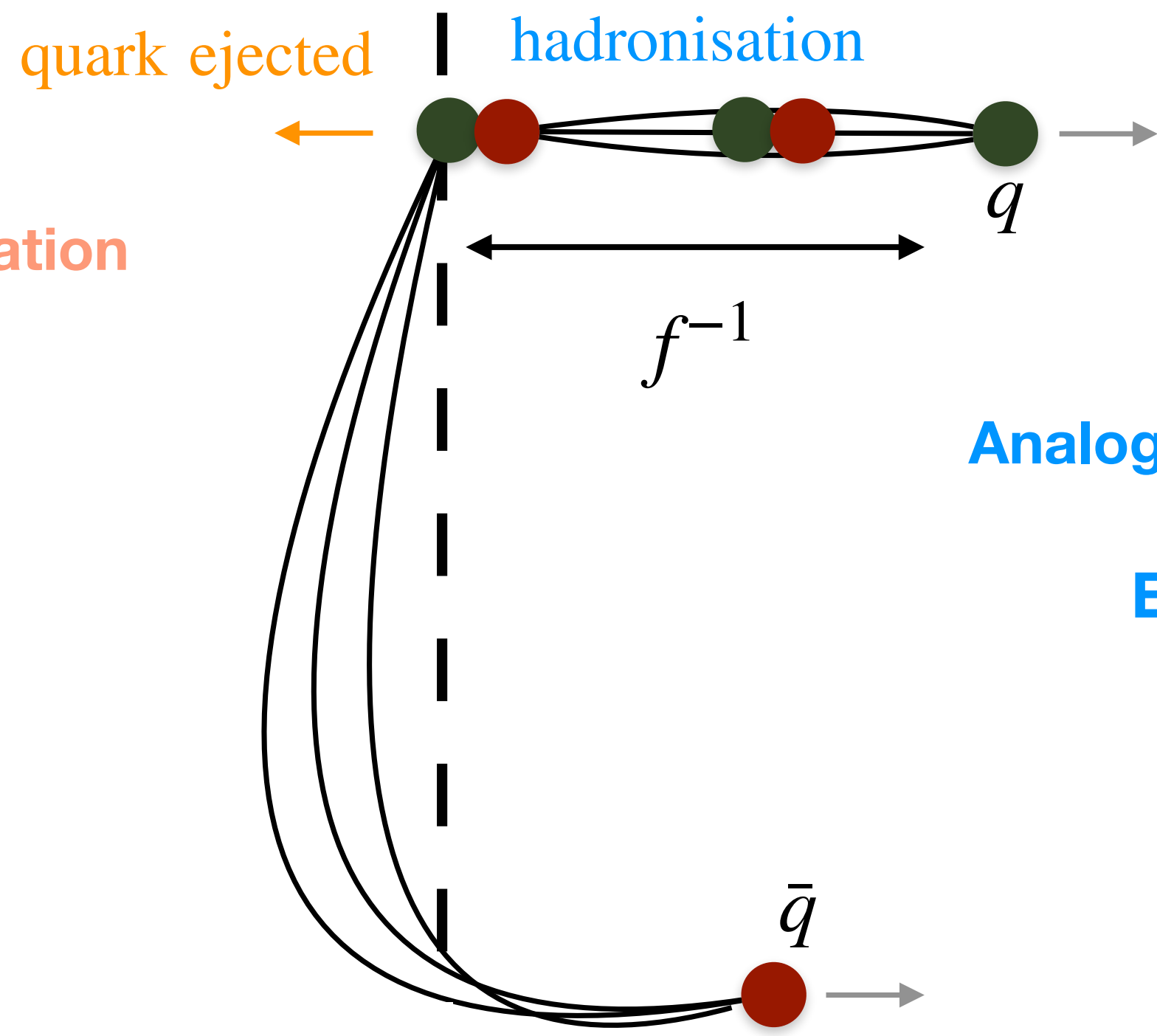
Deconfined phase

$$\chi = 0$$

Confined phase

$$\chi = f$$

Due to color conservation



Analog to string fragmentation in QCD !

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

Bubble wall frame



# Confinement



Deconfined phase

$$\chi = 0$$

Due to color conservation

Analog to Hawking evaporation !

"Color radiation"

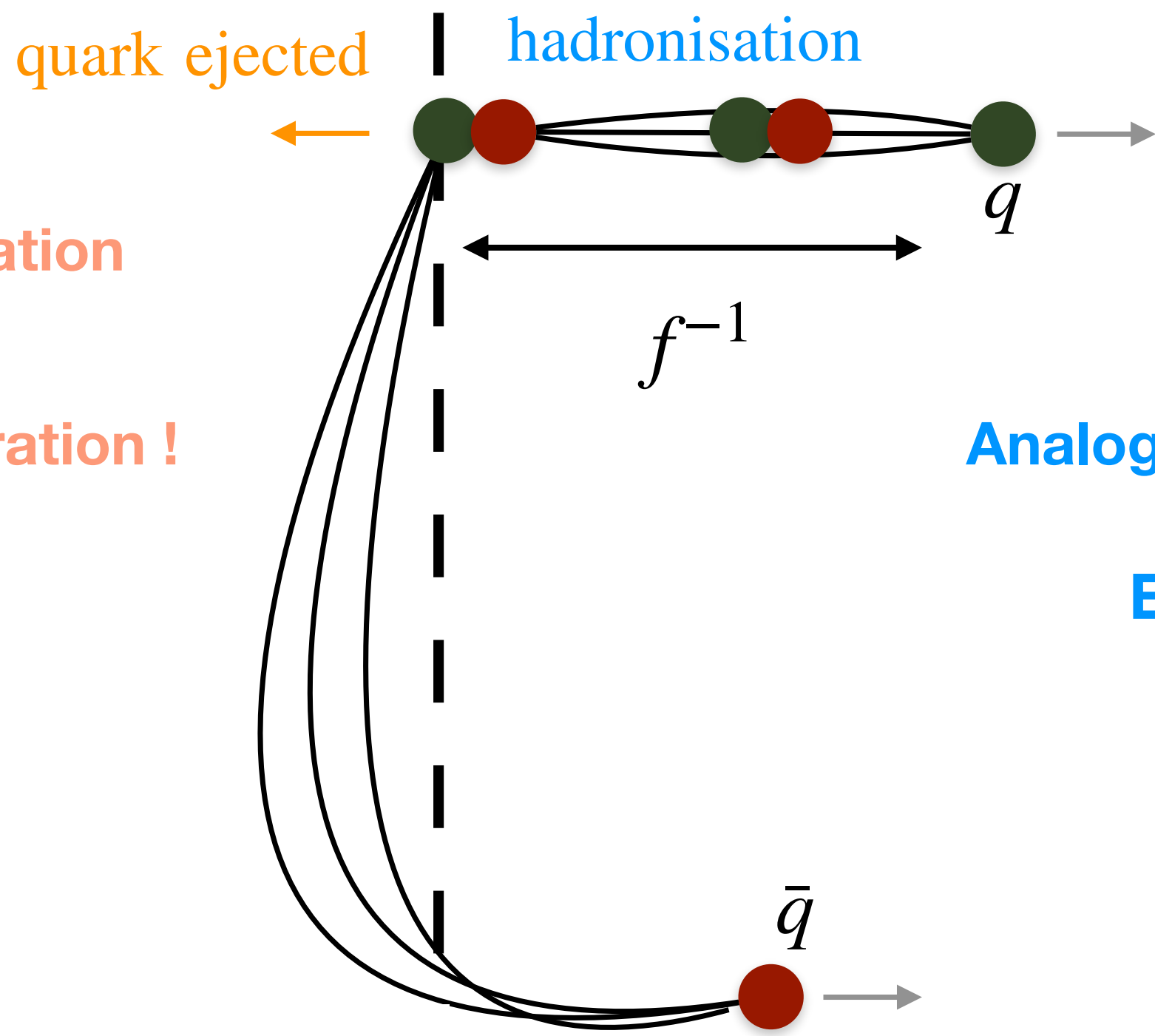


Confined phase

$$\chi = f$$

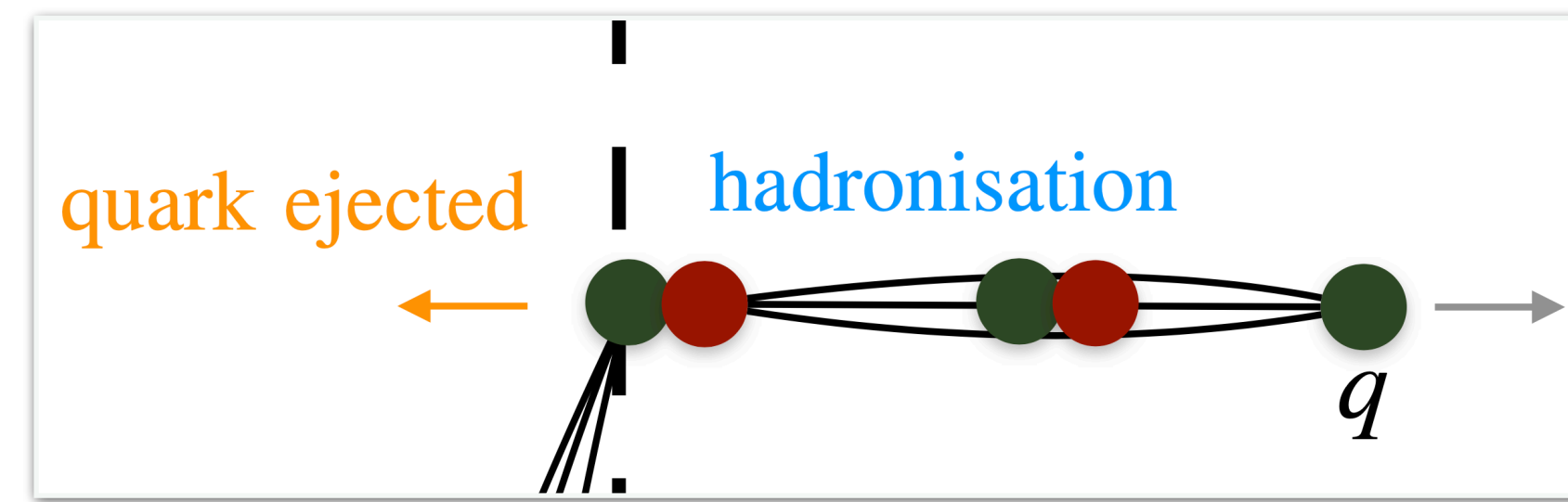
Analog to string fragmentation in QCD !

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



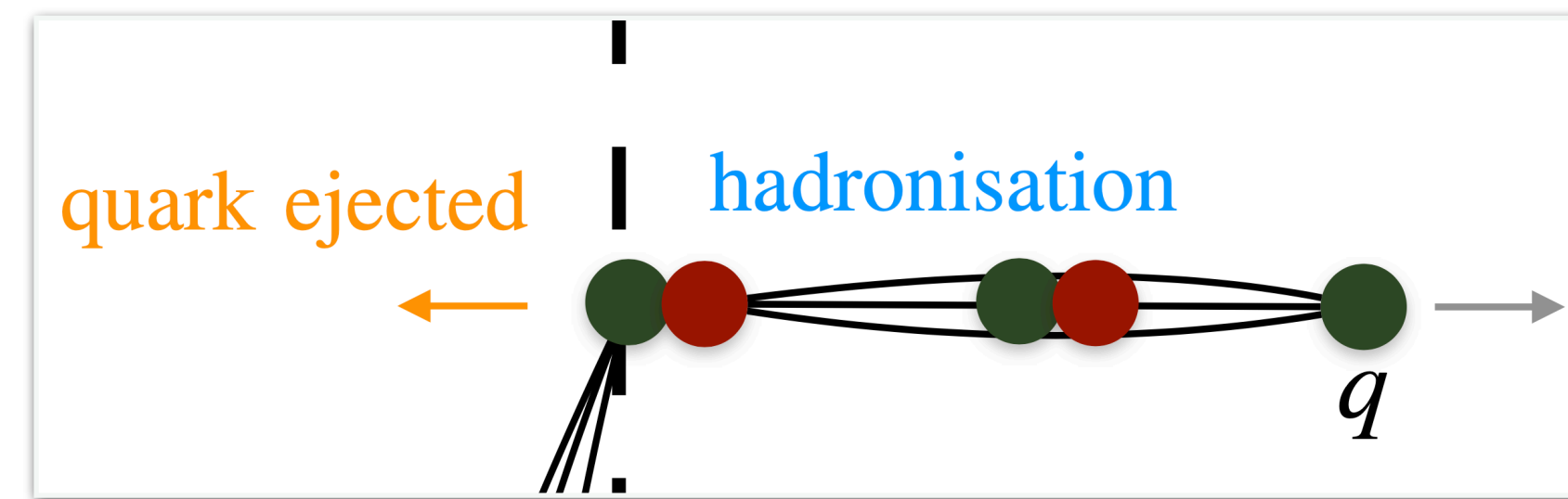
Bubble wall frame

# Impact on DM



1. More hadrons per initial quark pair

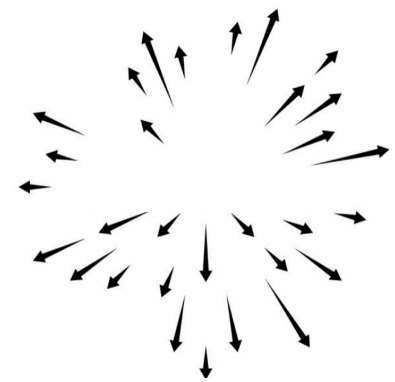
# Impact on DM



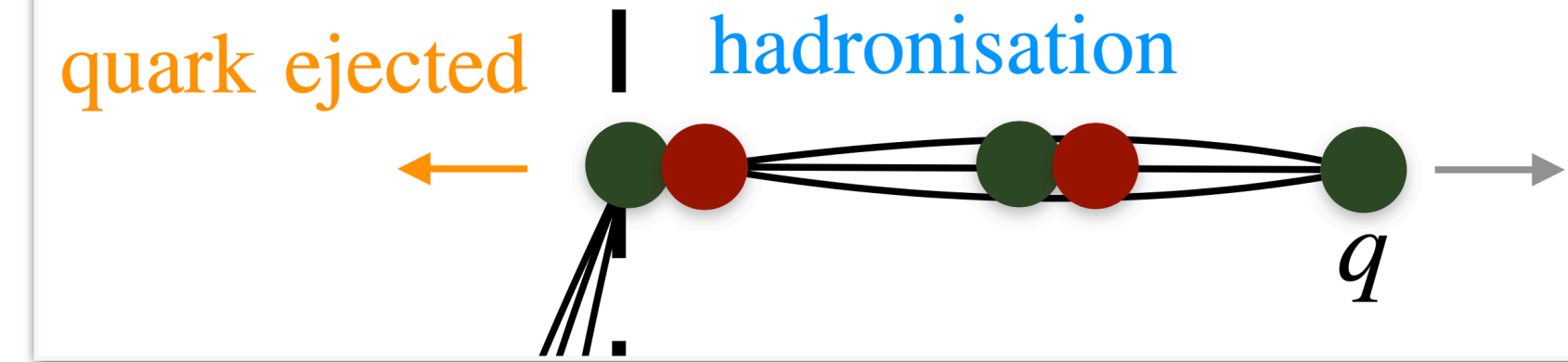
## 1. More hadrons per initial quark pair

DM abundance dilution

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



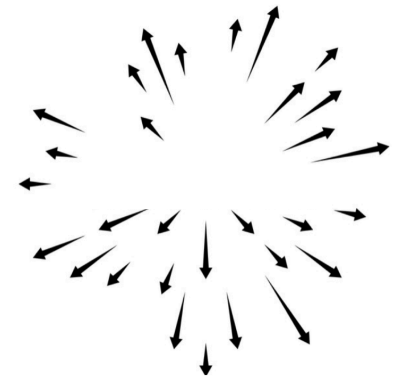
# Impact on DM



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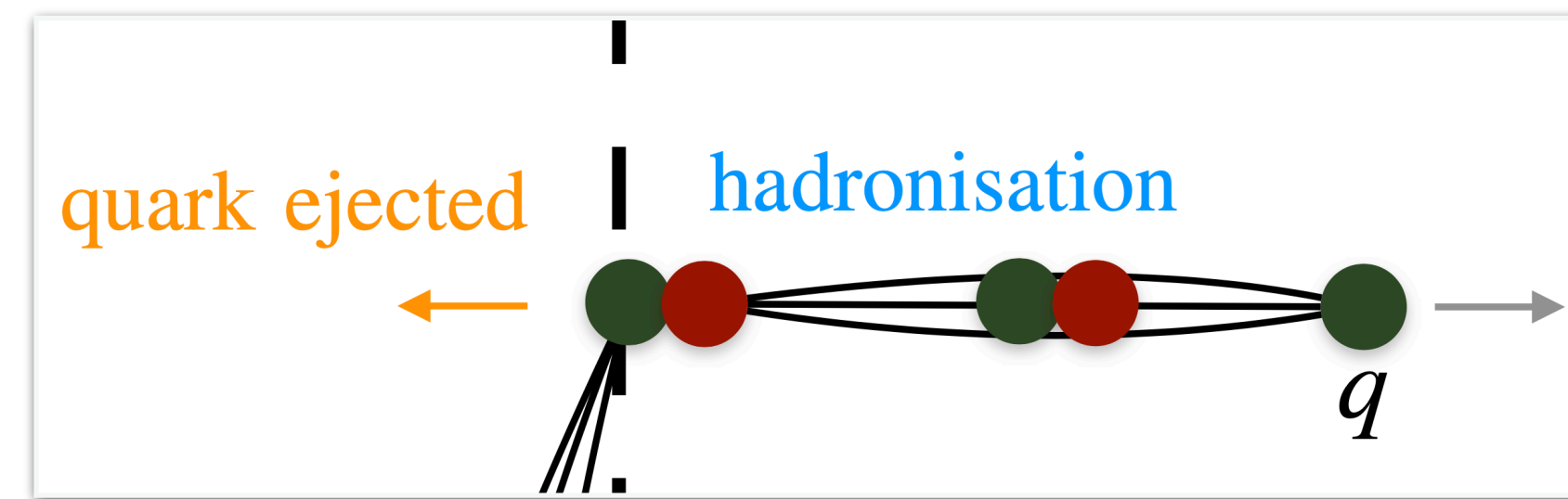


DM abundance enhancement

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



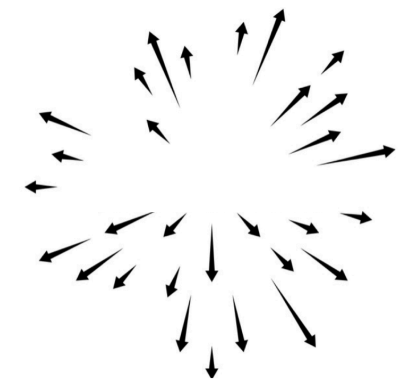
# Impact on DM



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

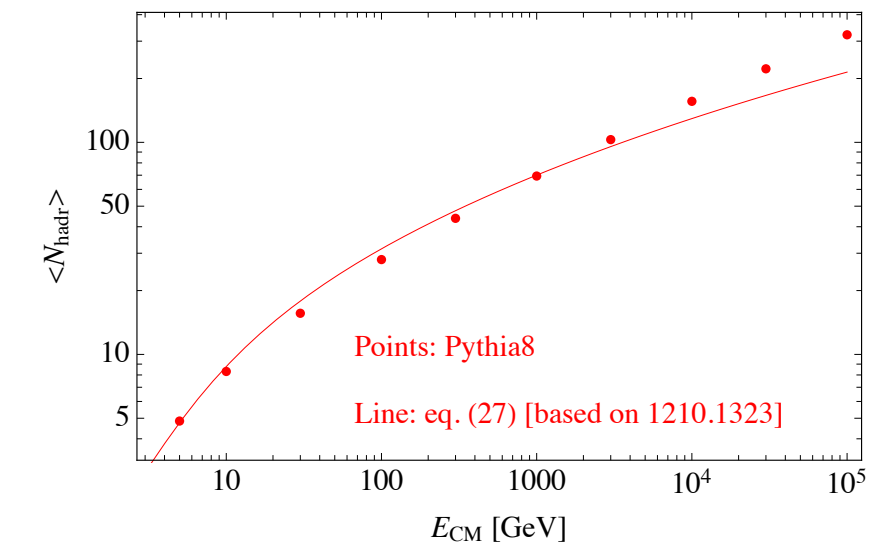


DM abundance enhancement

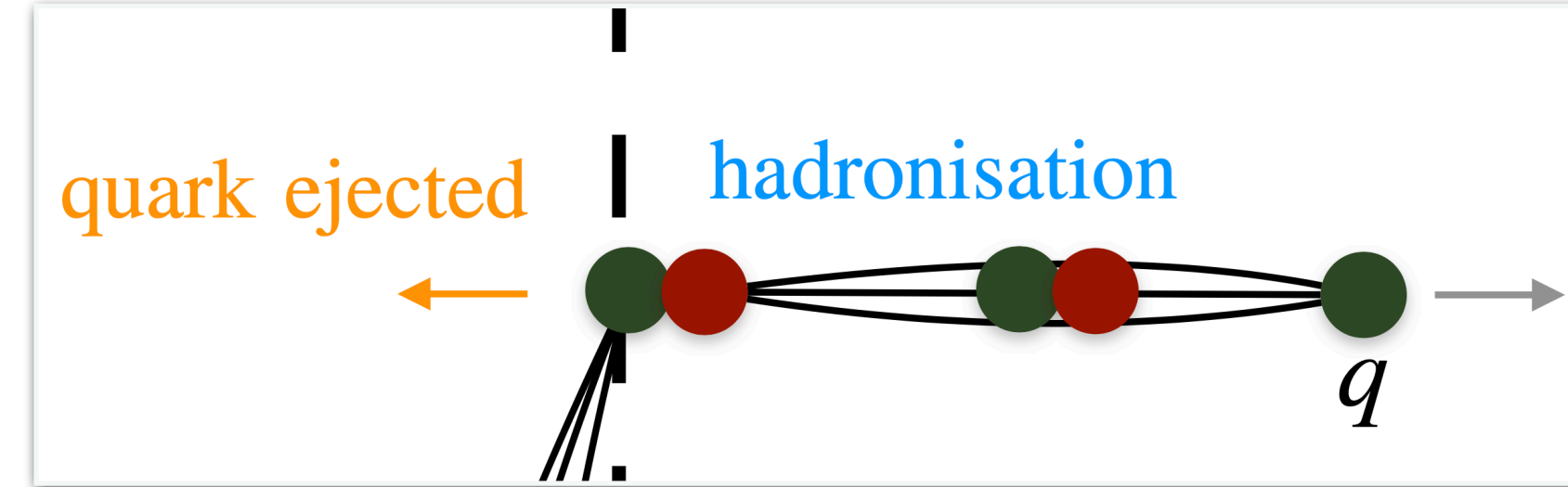
$$Y_{\text{DM}} / Y_{\text{DM}}^{\text{naive}} \propto \log^n \left( \gamma T_{\text{nuc}} / f \right)$$



Pythia



# Impact on DM



## 1. More hadrons per initial quark pair

DM abundance dilution

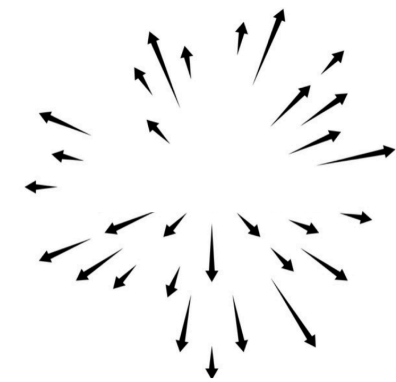
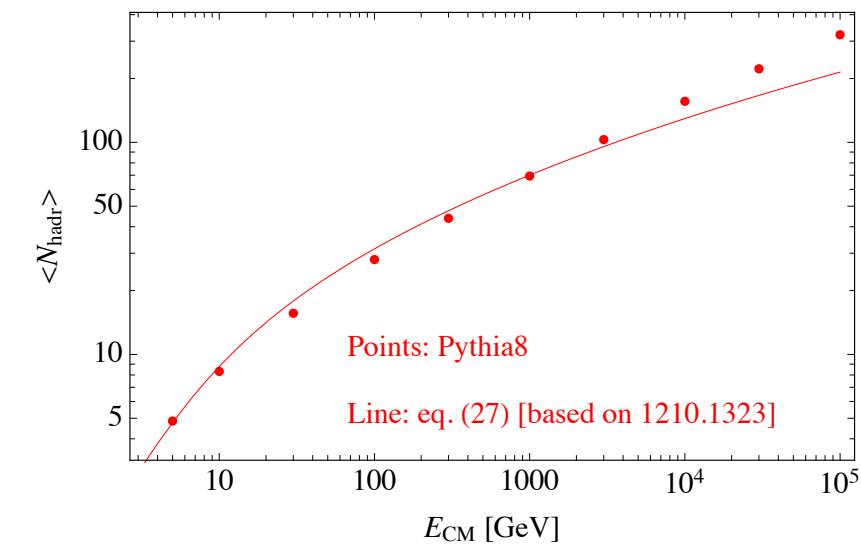
$$Y_{\text{DM}}^{\text{naive}} \propto \left( \frac{T_{\text{nuc}}}{f} \right)^3$$



DM abundance enhancement

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

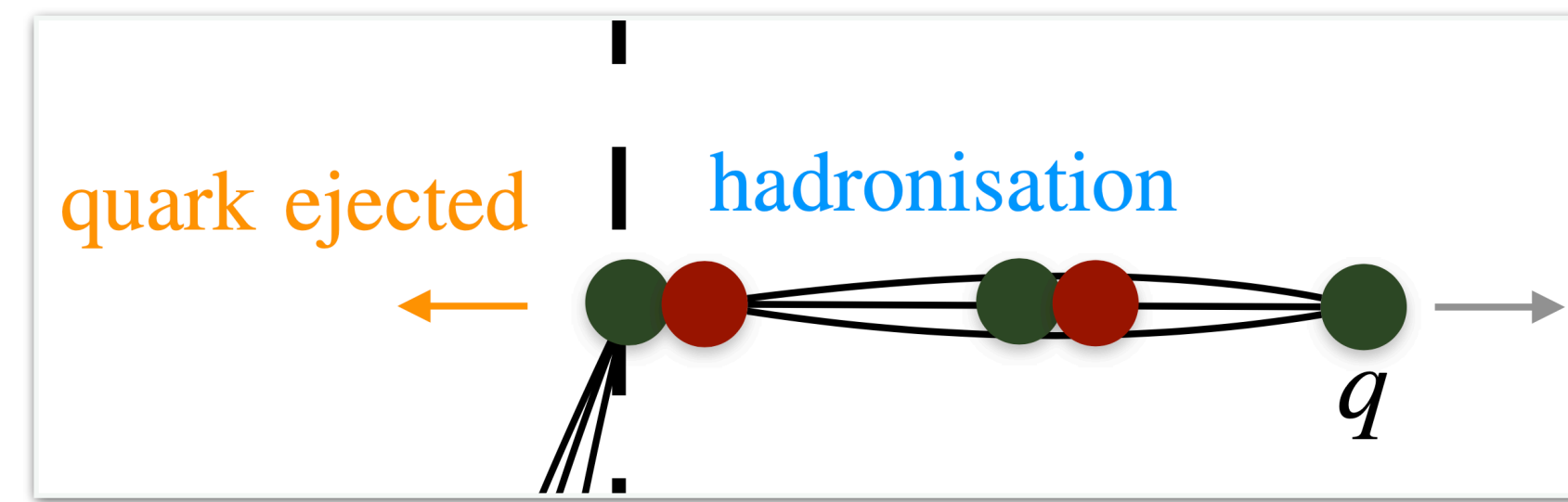
Pythia



## 2. Cosmological catapult



# Impact on DM



## 1. More hadrons per initial quark pair

DM abundance dilution

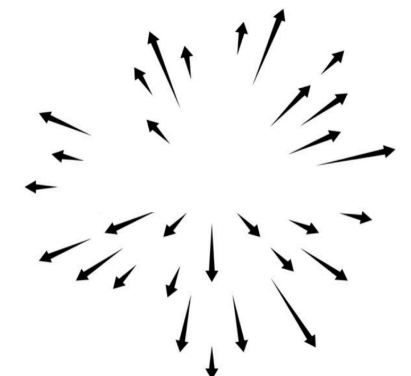
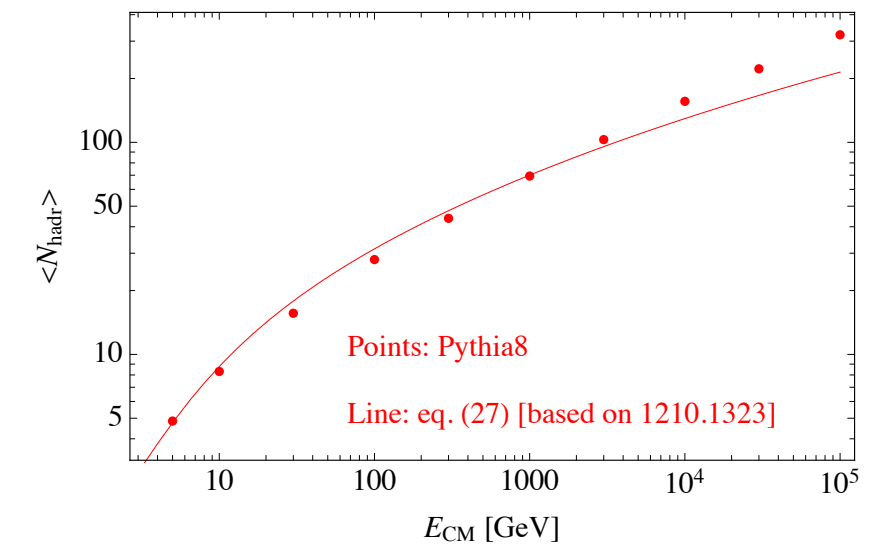
$$Y_{\text{DM}}^{\text{naive}} \propto \left( \frac{T_{\text{nuc}}}{f} \right)^3$$



DM abundance enhancement

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Pythia



## 2. Cosmological catapult

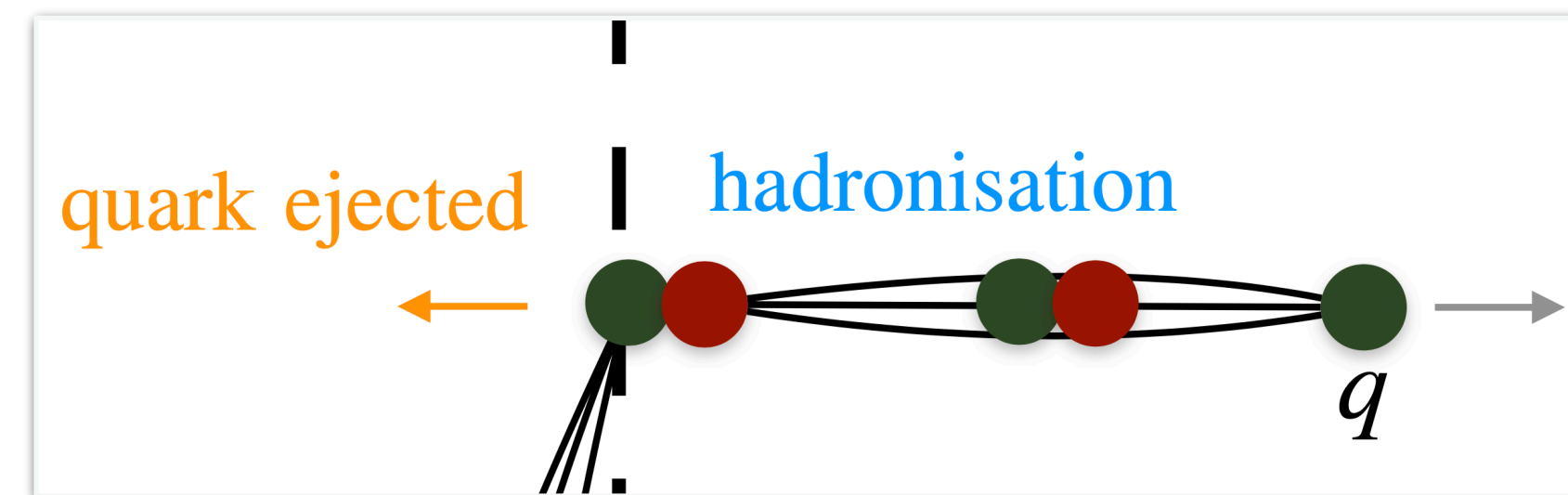


★ →

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



# Impact on DM



## 1. More hadrons per initial quark pair

DM abundance dilution

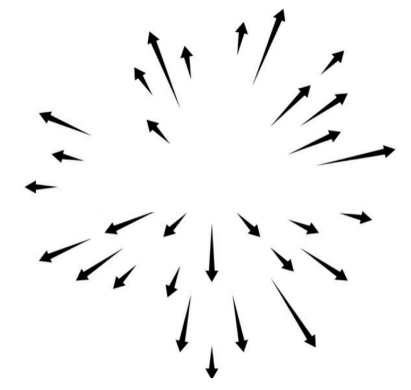
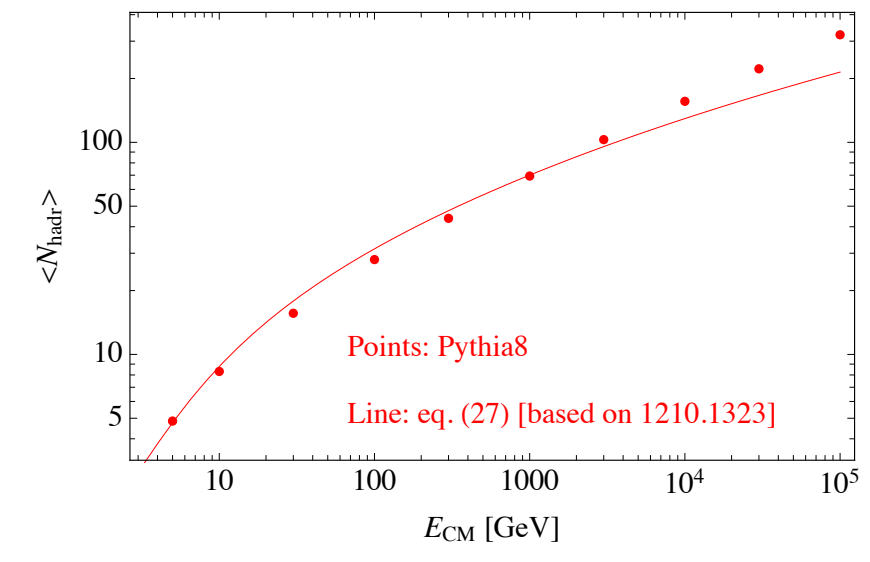
$$Y_{\text{DM}}^{\text{naive}} \propto \left( \frac{T_{\text{nuc}}}{f} \right)^3$$



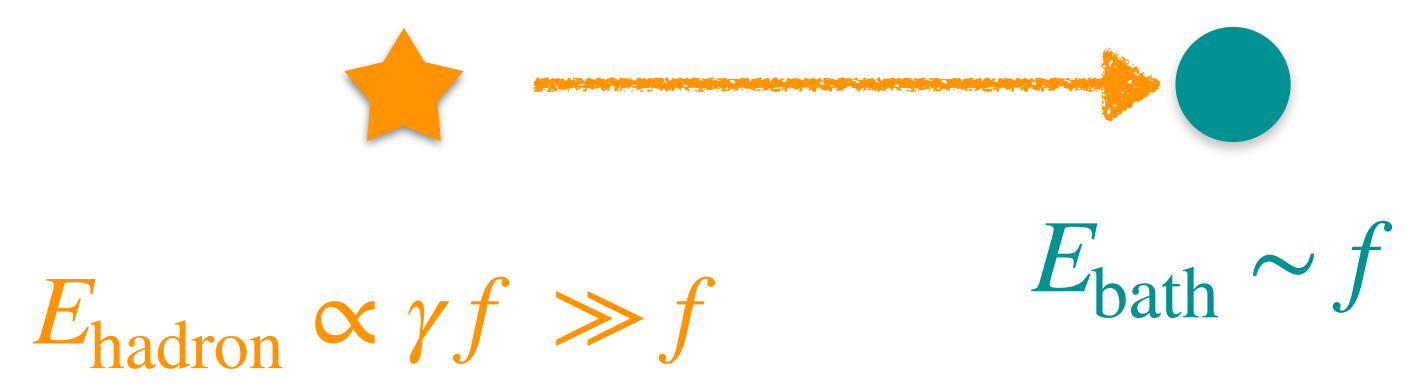
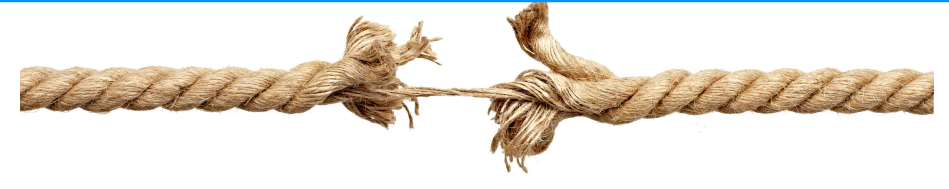
DM abundance enhancement

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

Pythia

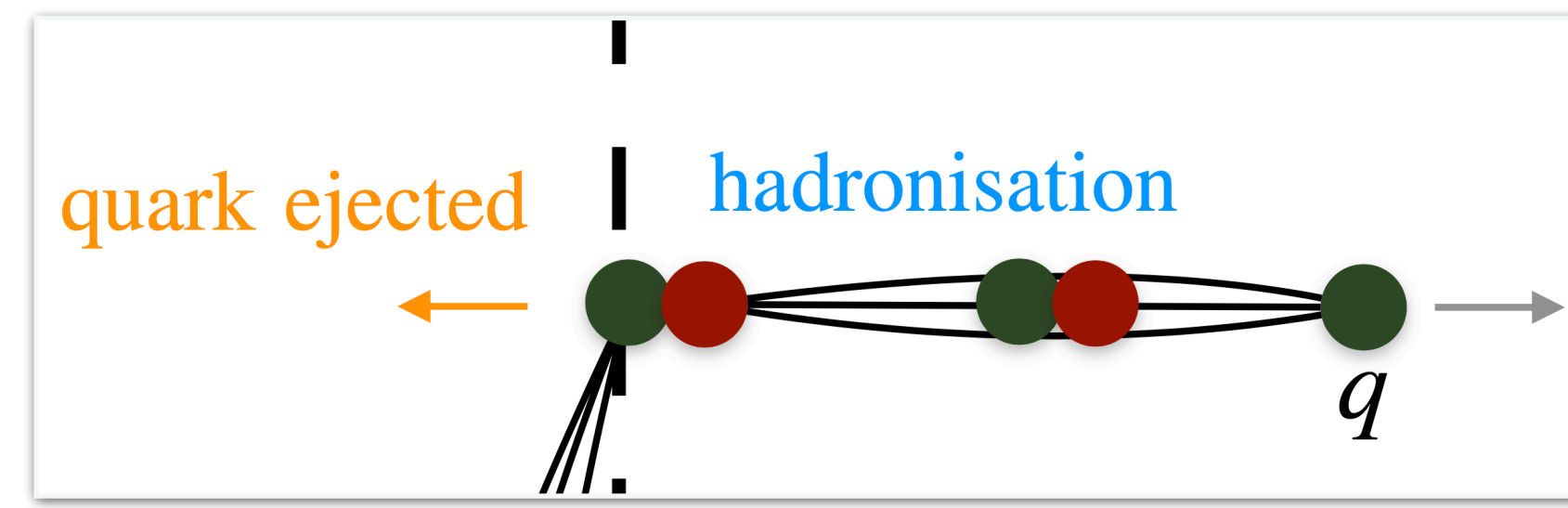


## 2. Cosmological catapult





# Impact on DM



## 1. More hadrons per initial quark pair

DM abundance dilution

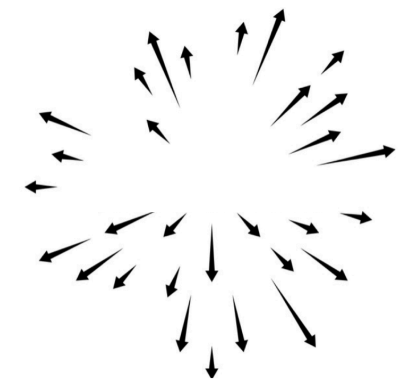
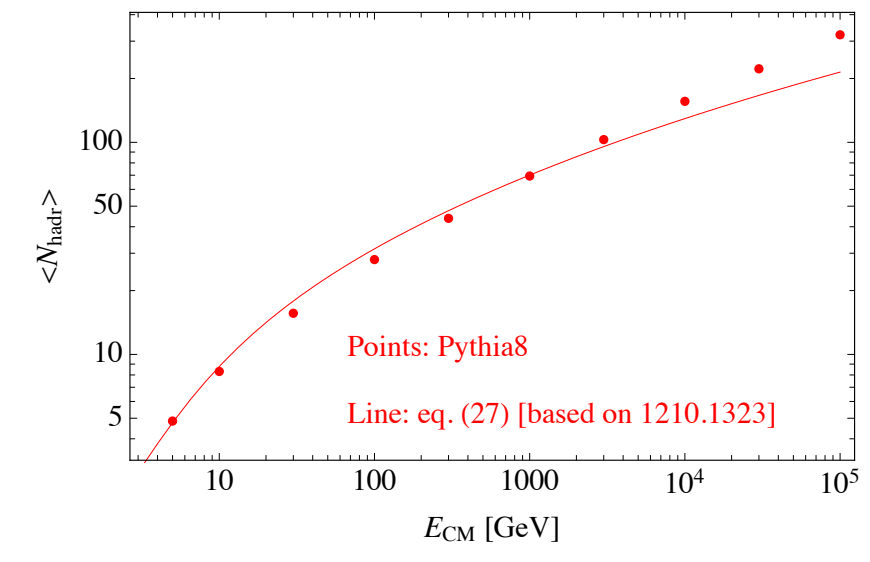
$$Y_{\text{DM}}^{\text{naive}} \propto \left( \frac{T_{\text{nuc}}}{f} \right)^3$$



DM abundance enhancement

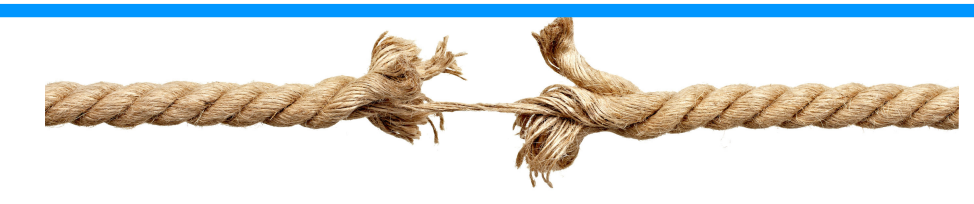
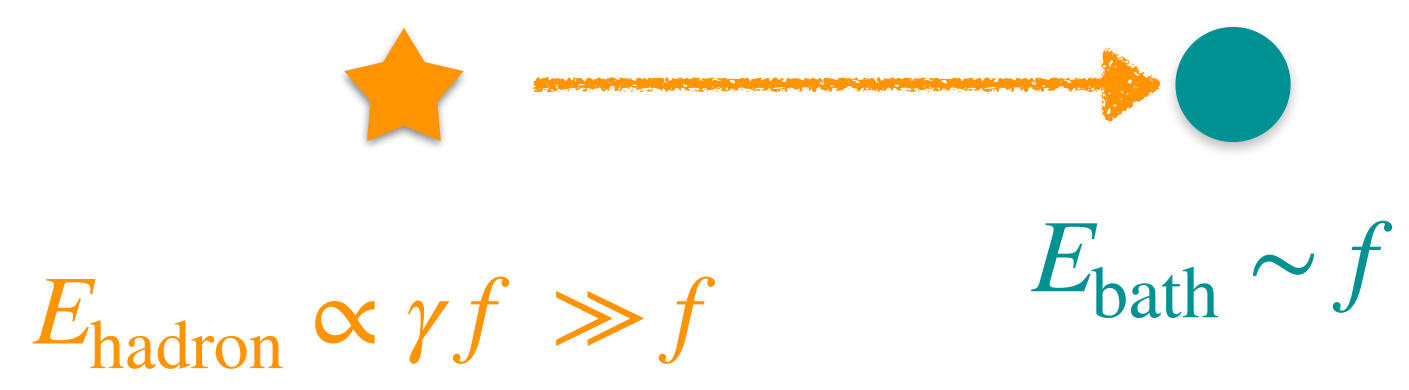
$$Y_{\text{DM}} / Y_{\text{DM}}^{\text{naive}} \propto \log^n \left( \gamma T_{\text{nuc}} / f \right)$$

Pythia

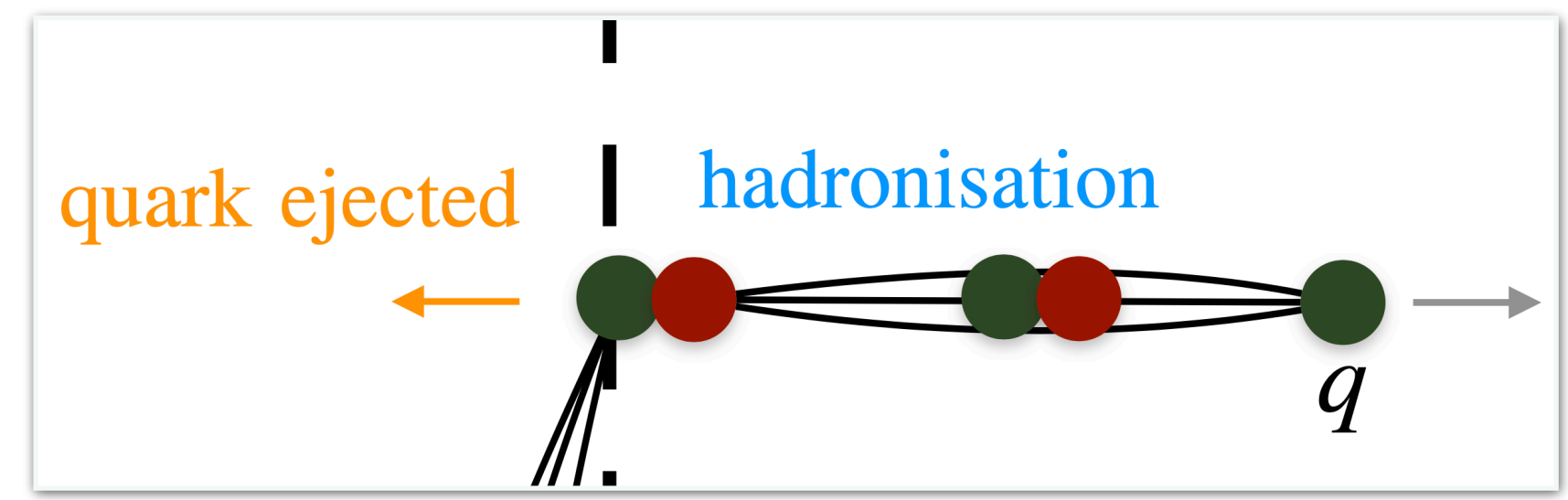


## 2. Cosmological catapult

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



# Impact on DM



## 1. More hadrons per initial quark pair

DM abundance dilution

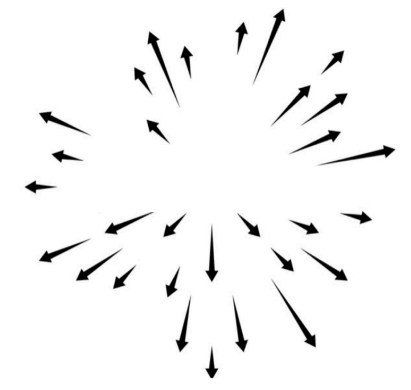
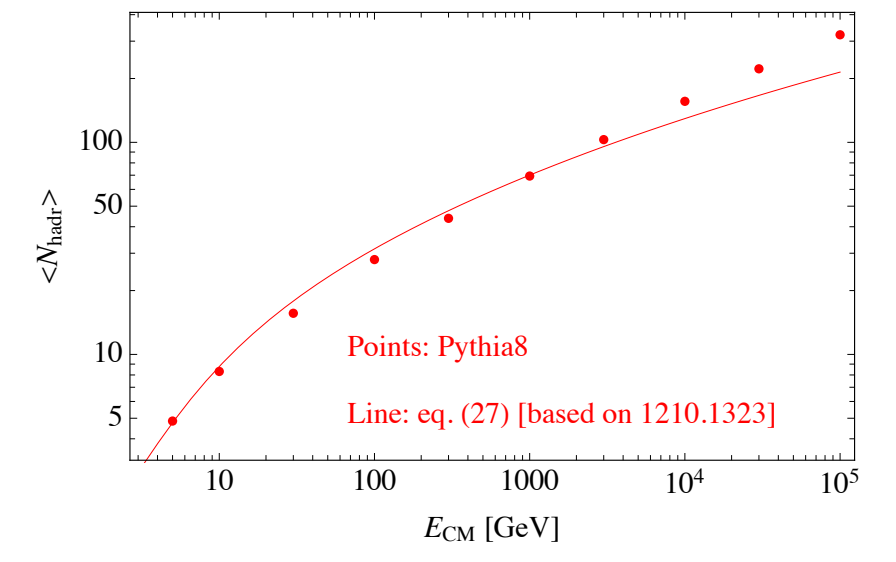
$$Y_{\text{DM}}^{\text{naive}} \propto \left( \frac{T_{\text{nuc}}}{f} \right)^3$$



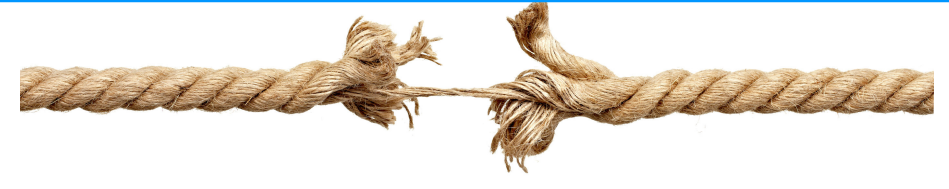
DM abundance enhancement

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

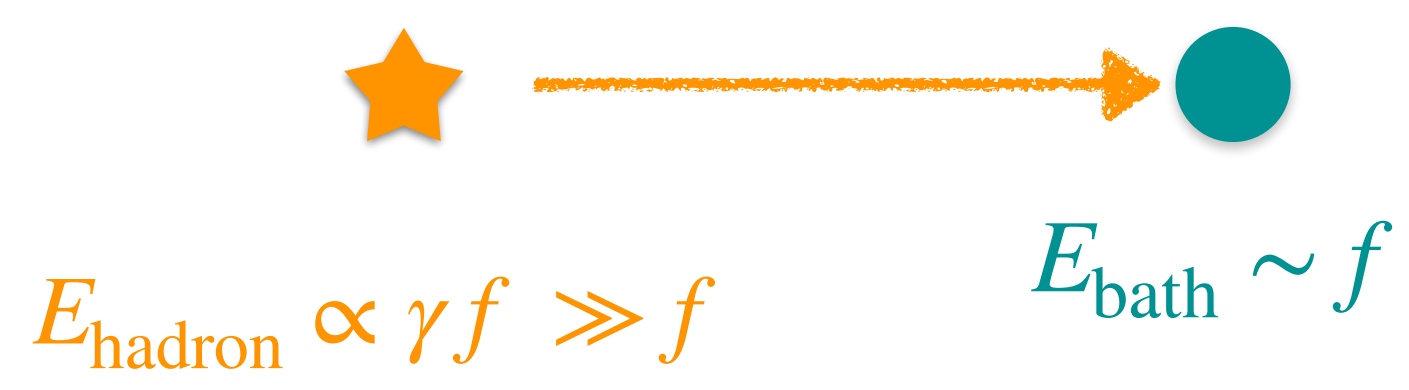
Pythia



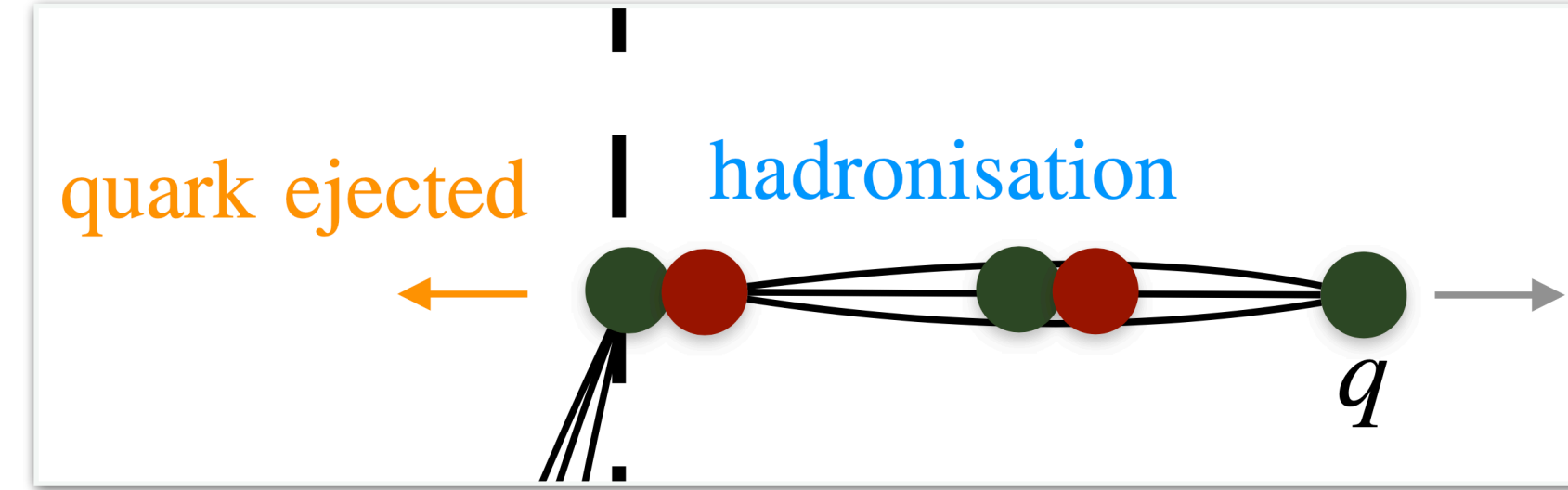
## 2. Cosmological catapult



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



# Impact on DM



## 1. More hadrons per initial quark pair

DM abundance dilution

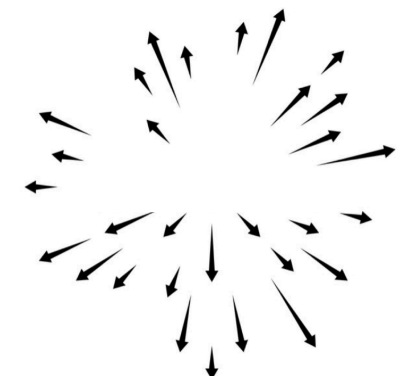
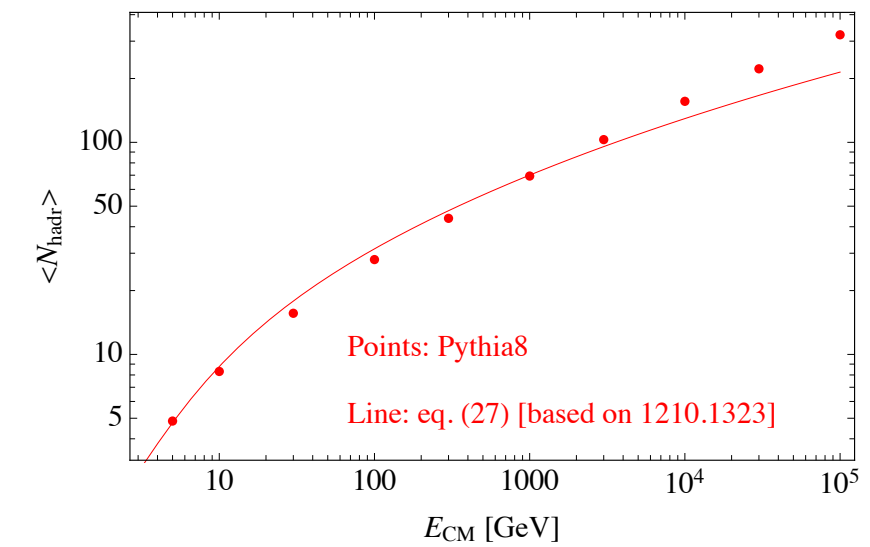
$$Y_{\text{DM}}^{\text{naive}} \propto \left( \frac{T_{\text{nuc}}}{f} \right)^3$$



DM abundance enhancement

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

Pythia



## 2. Cosmological catapult

Iterate

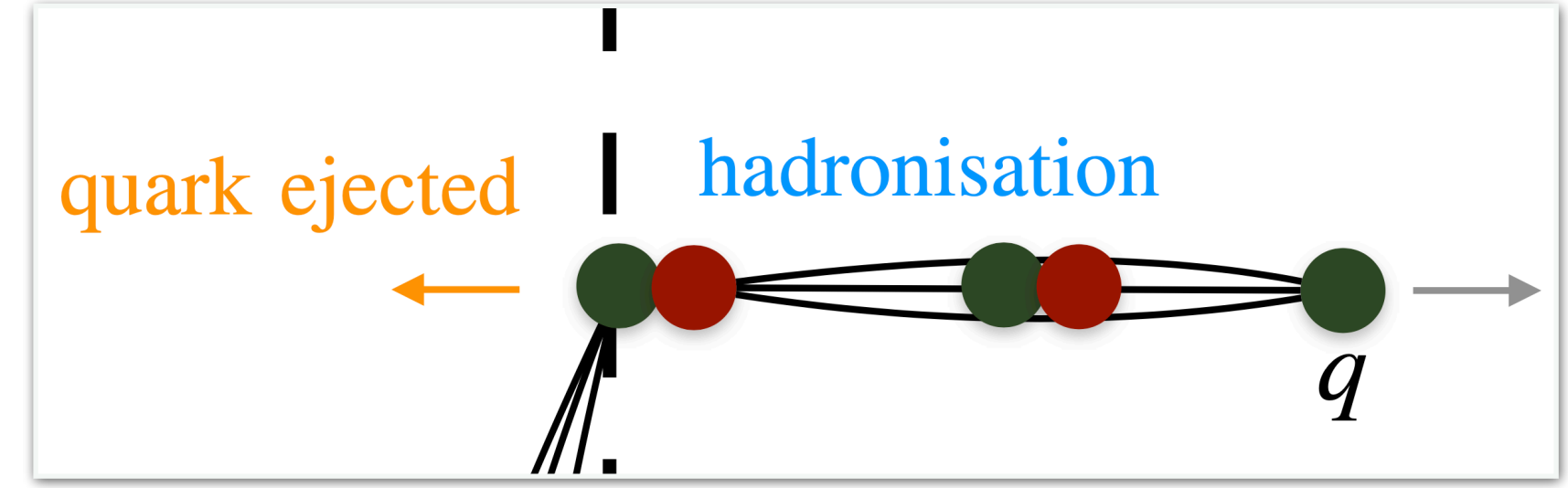
$$s \sim E_{\text{hadron}} E_{\text{bath}}$$

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

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



# Impact on DM



## 1. More hadrons per initial quark pair

DM abundance dilution

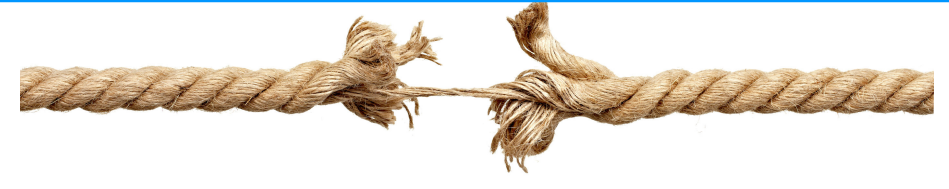
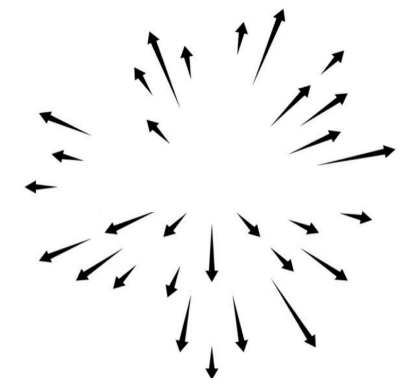
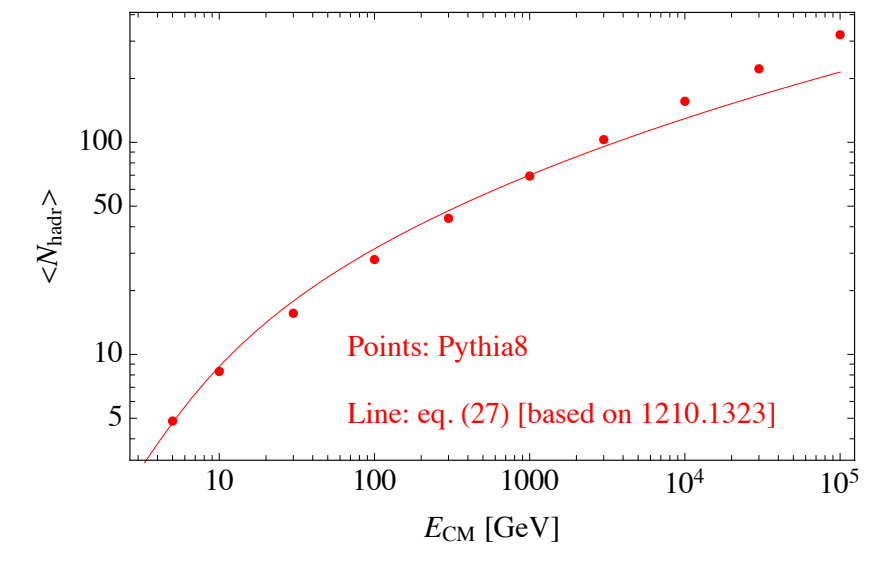
$$Y_{\text{DM}}^{\text{naive}} \propto \left( \frac{T_{\text{nuc}}}{f} \right)^3$$



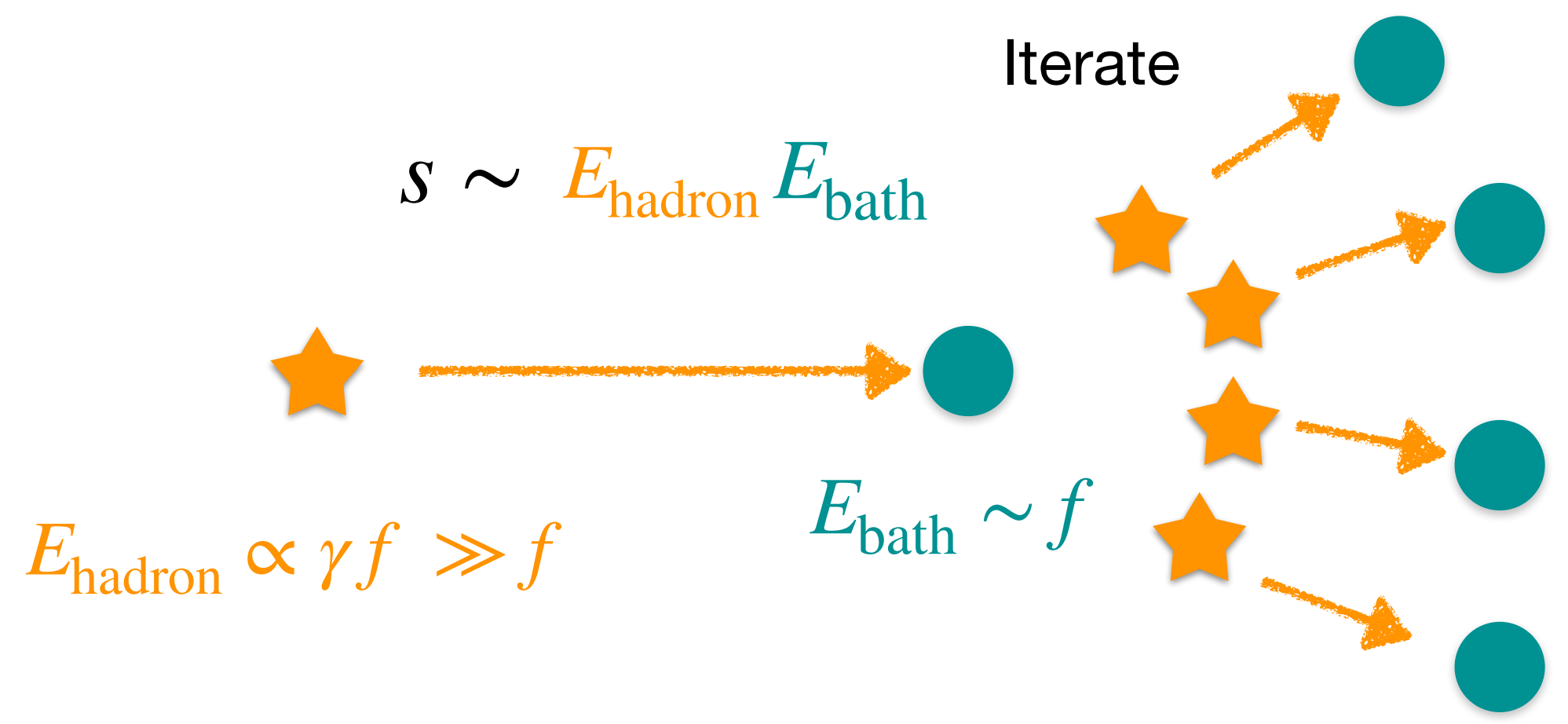
DM abundance enhancement

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

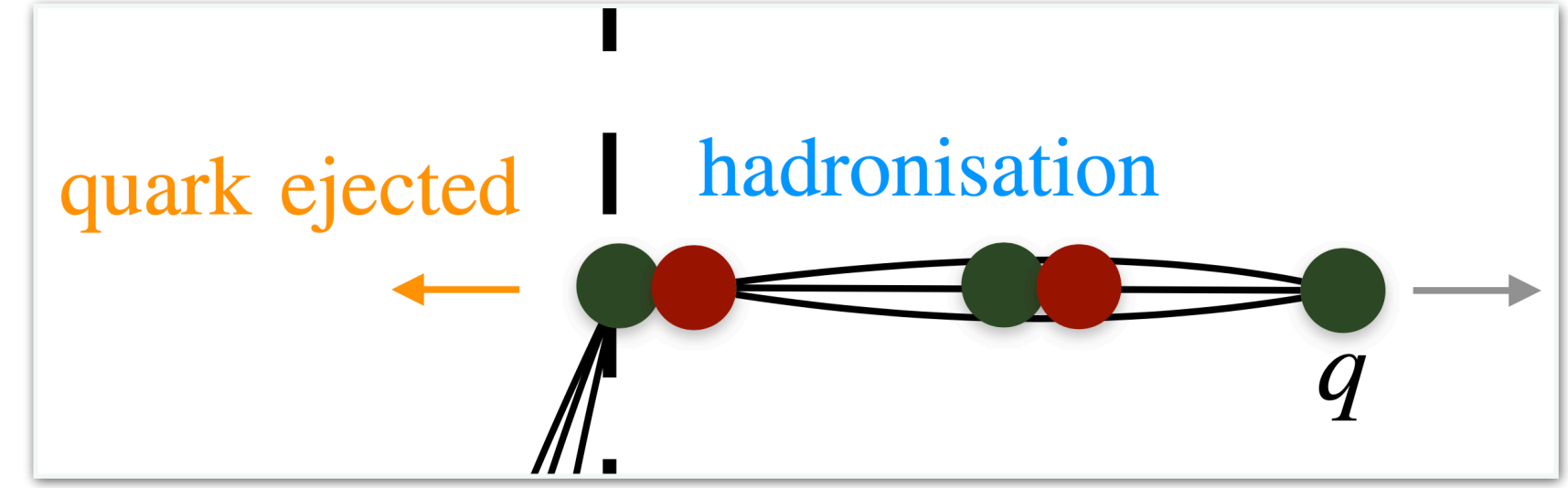
Pythia



## 2. Cosmological catapult



# Impact on DM



## 1. More hadrons per initial quark pair

DM abundance dilution

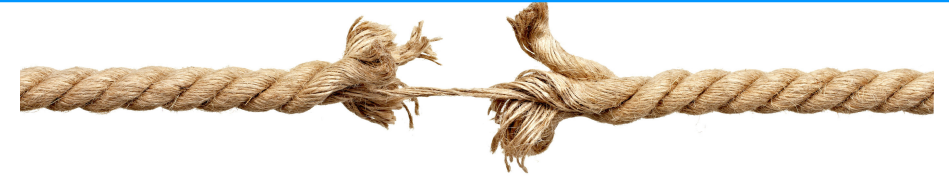
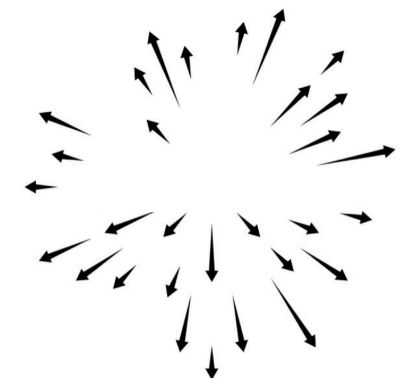
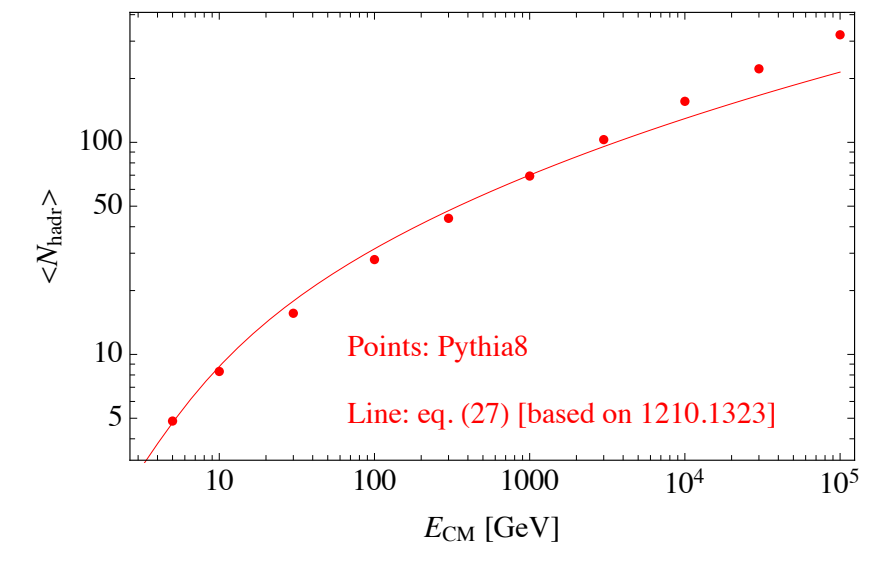
$$Y_{\text{DM}}^{\text{naive}} \propto \left( \frac{T_{\text{nuc}}}{f} \right)^3$$



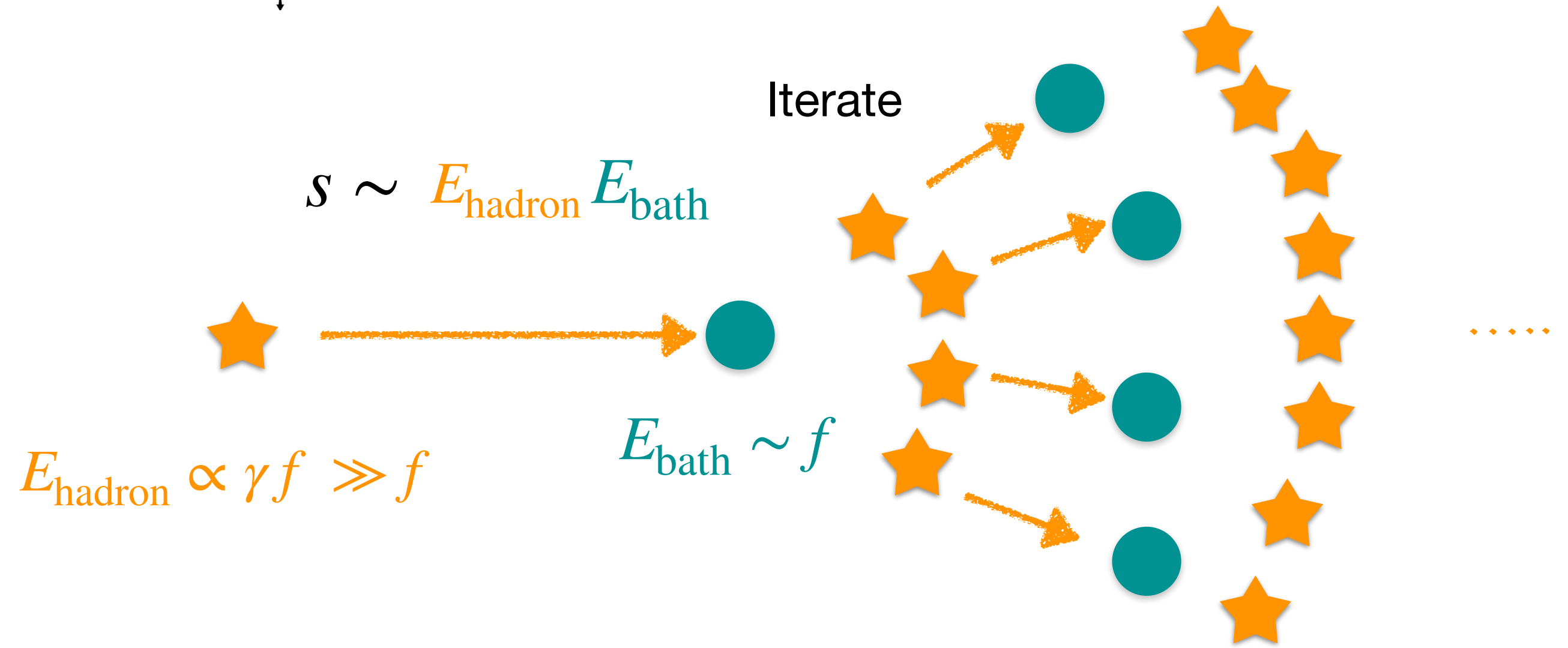
DM abundance enhancement

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

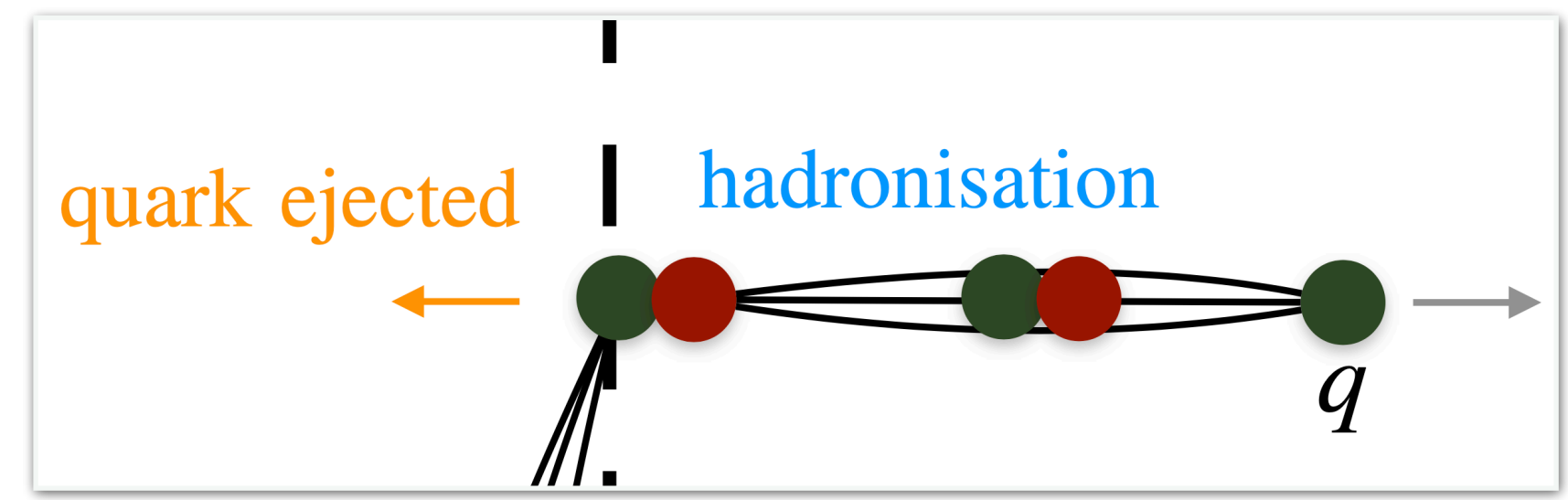
Pythia



## 2. Cosmological catapult



# Impact on DM



## 1. More hadrons per initial quark pair

DM abundance dilution

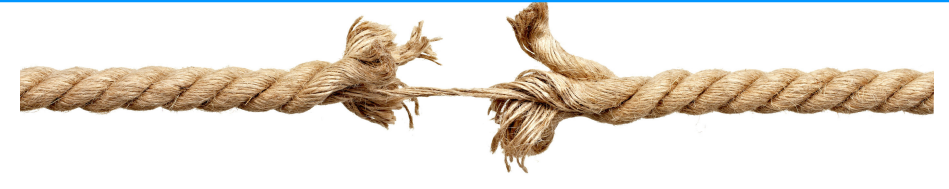
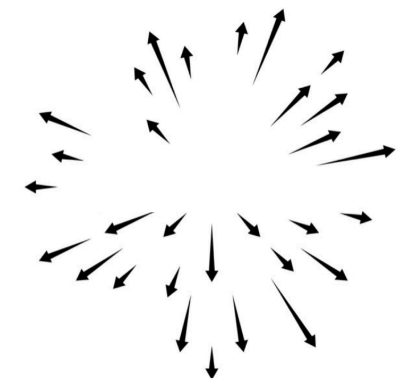
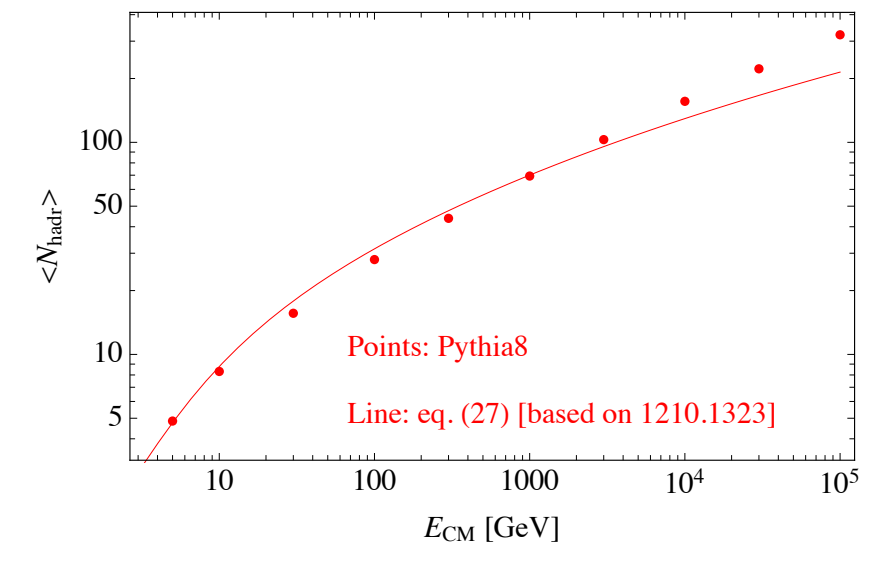
$$Y_{\text{DM}}^{\text{naive}} \propto \left( \frac{T_{\text{nuc}}}{f} \right)^3$$



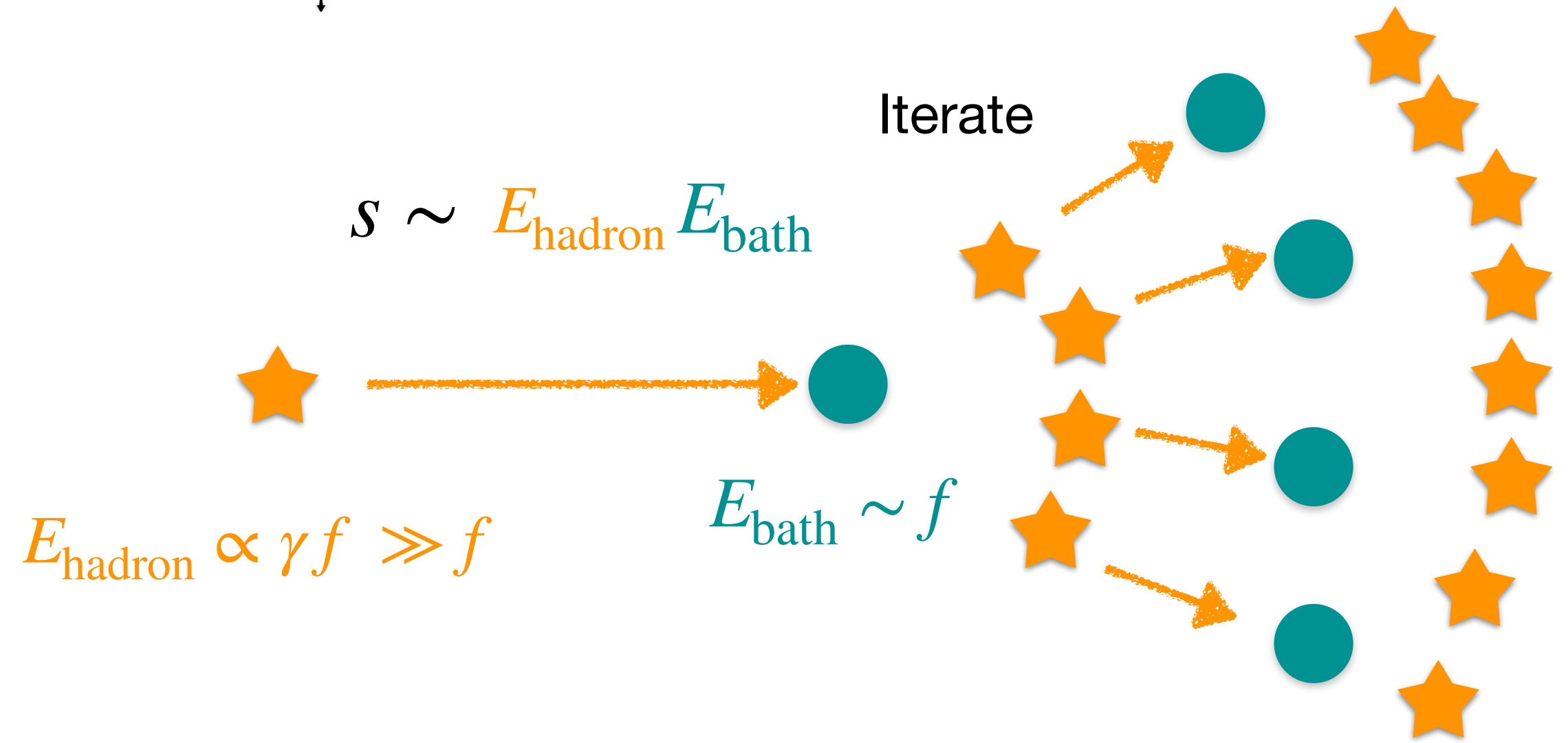
DM abundance enhancement

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

Pythia



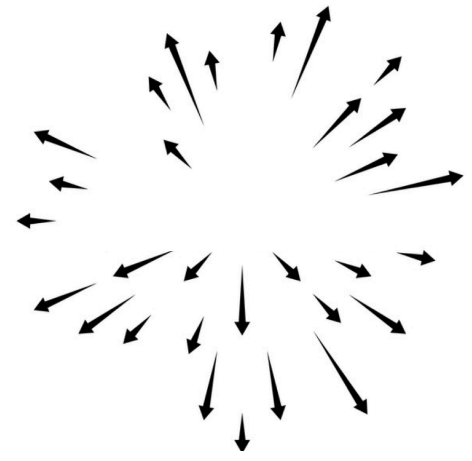
## 2. Cosmological catapult



DM abundance enhancement

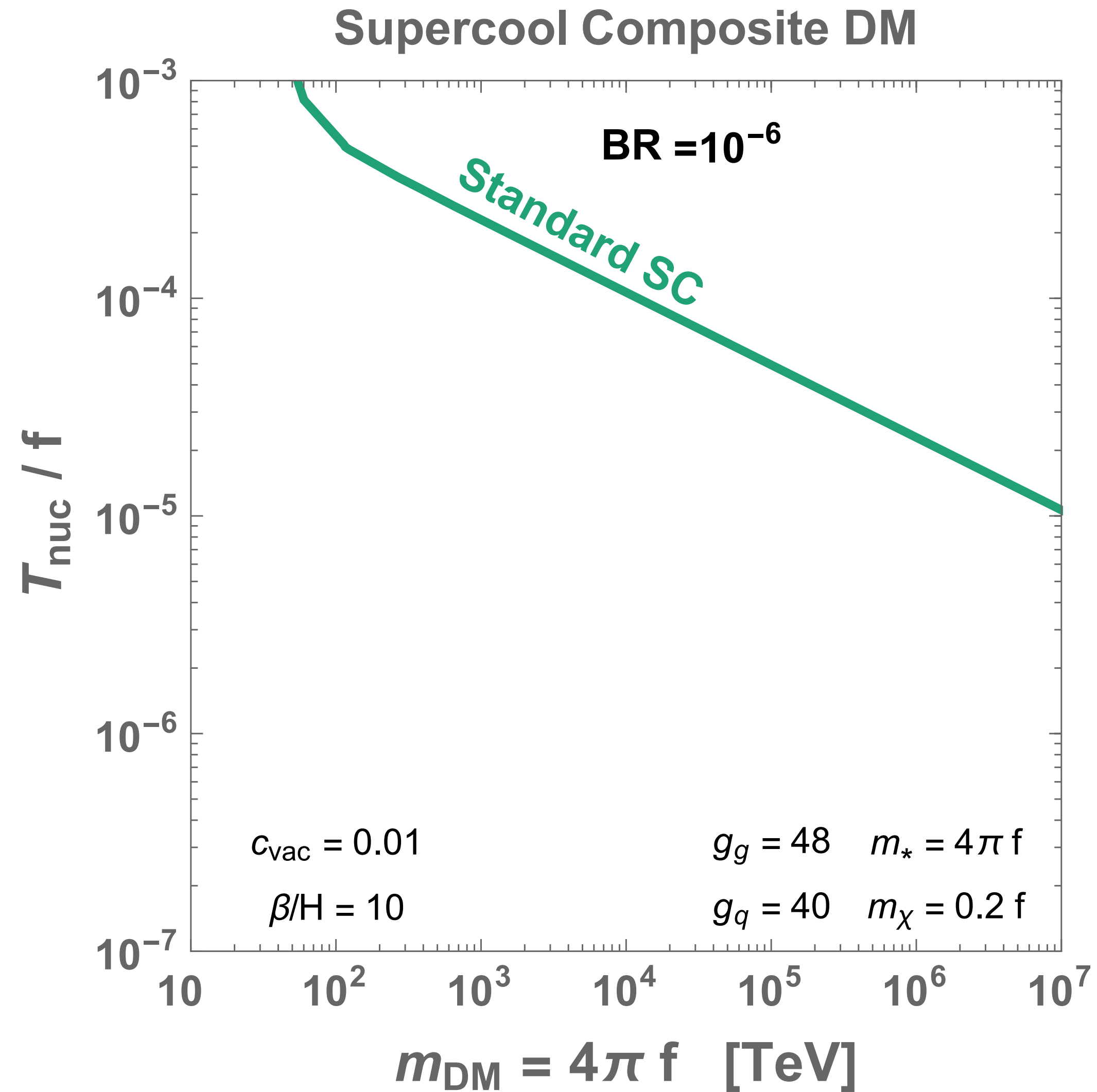
$$Y_{\text{DM}} / Y_{\text{DM}}^{\text{naive}} \propto \gamma \propto \frac{T_{\text{nuc}}}{f} \frac{M_{\text{Pl}}}{f}$$

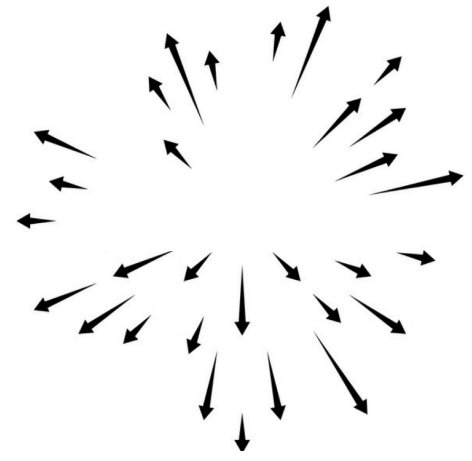
runaway regime



## Consequences on DM abundance

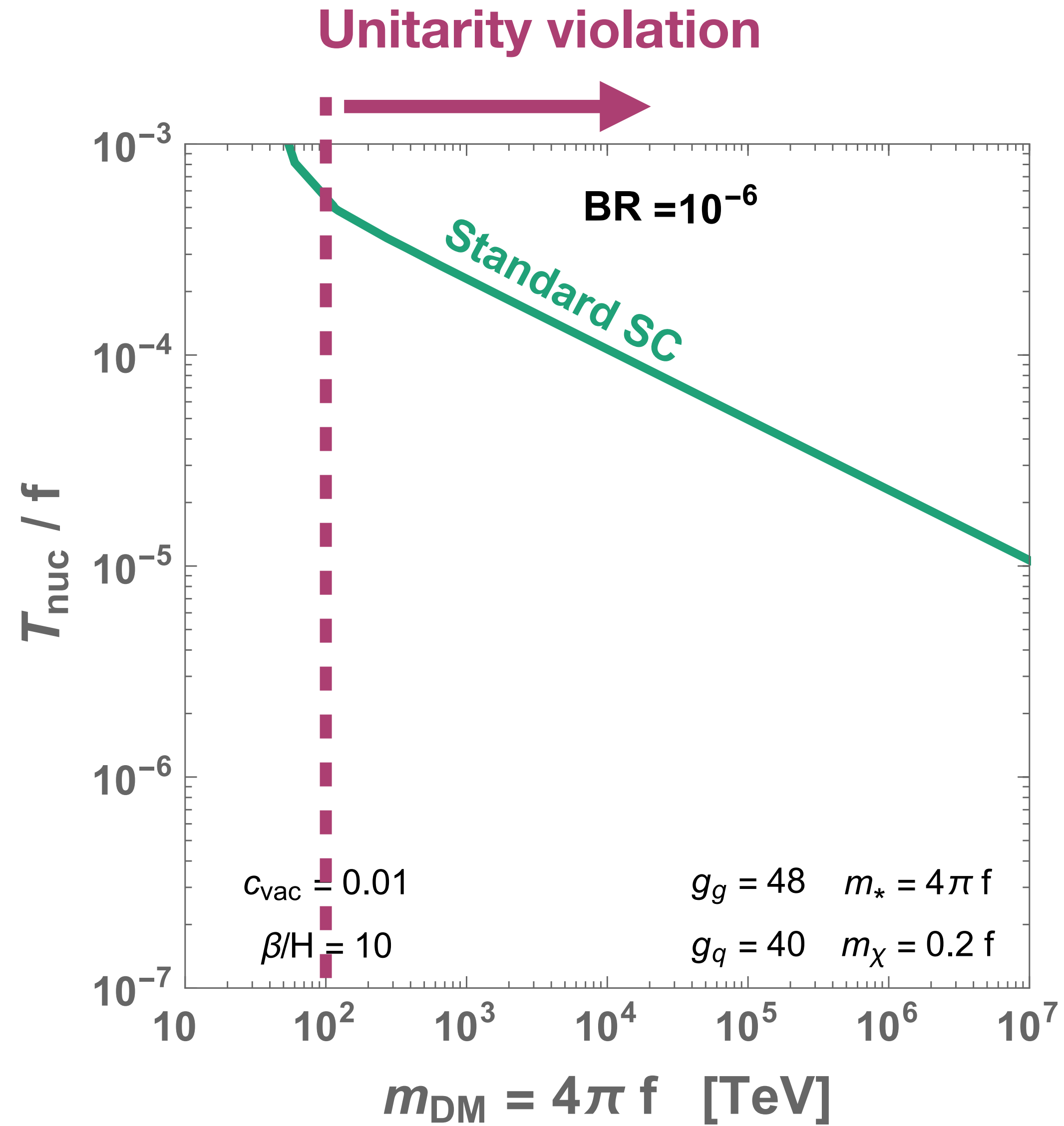
$$Y_{\text{DM}}^{\text{naive}} \propto \left( \frac{T_{\text{nuc}}}{f} \right)^3$$





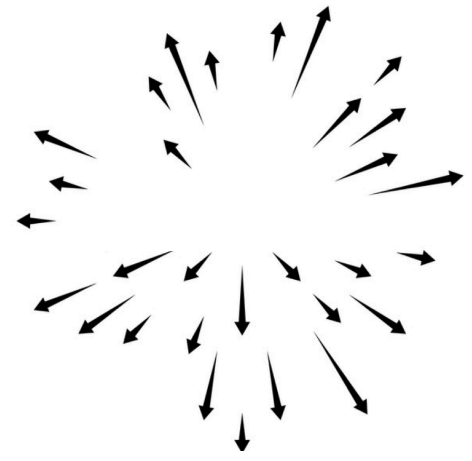
# Consequences on DM abundance

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





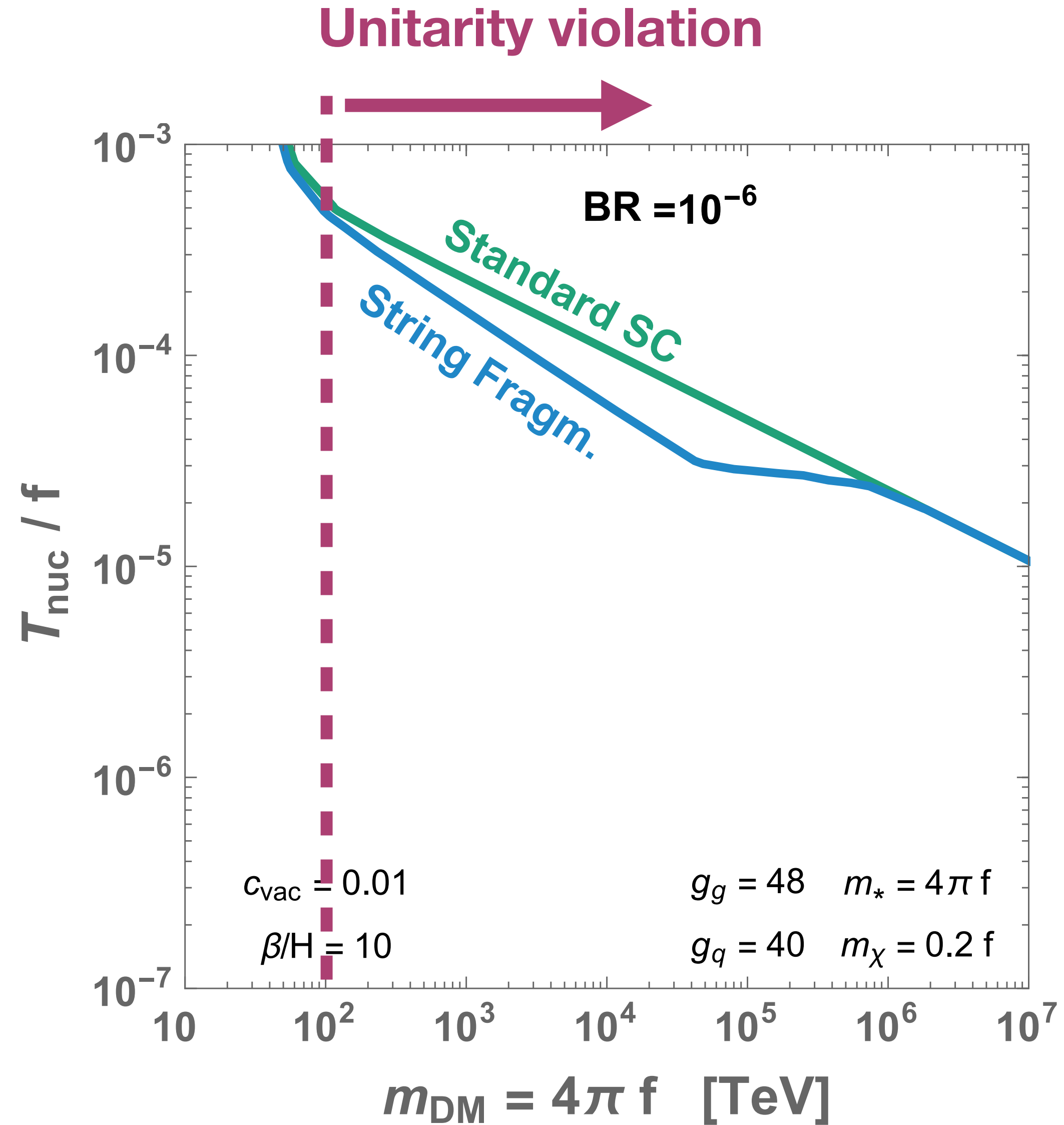
# Consequences on DM abundance



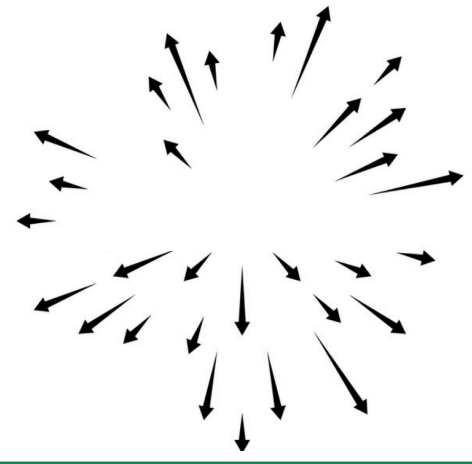
$$Y_{\text{DM}}^{\text{naive}} \propto \left( \frac{T_{\text{nuc}}}{f} \right)^3$$



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



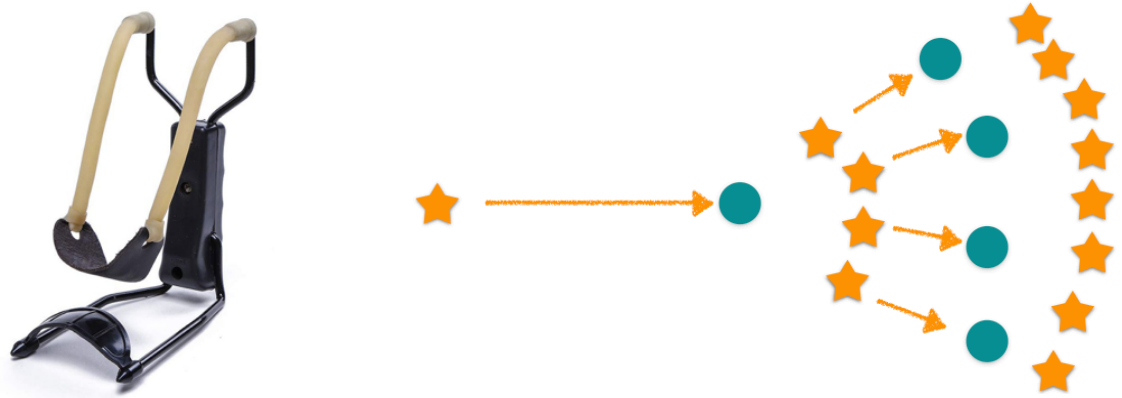
# Consequences on DM abundance



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

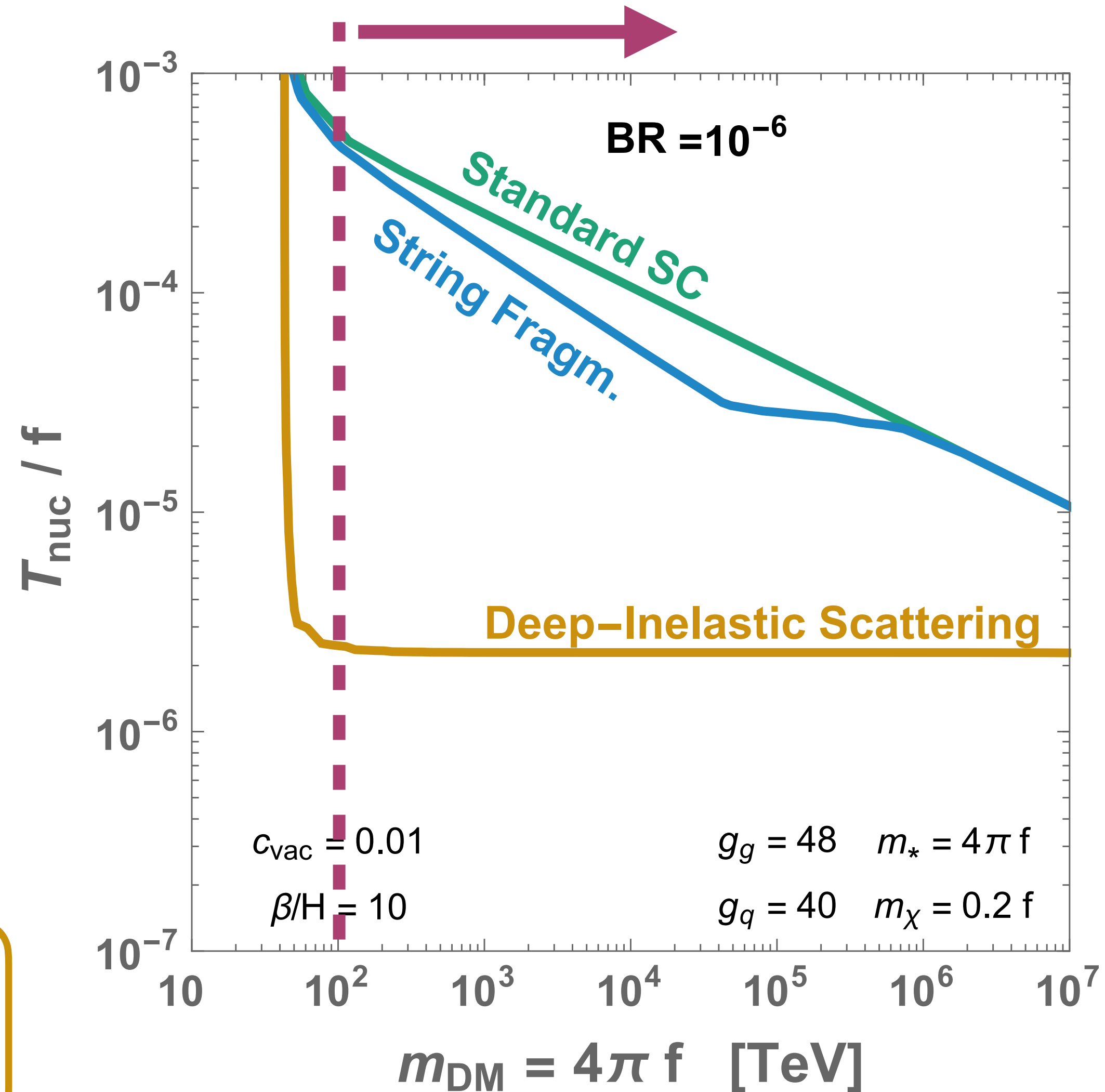


$$Y_{\text{DM}} / Y_{\text{DM}}^{\text{naive}} \propto \log^n(\gamma T_{\text{nuc}} / f)$$

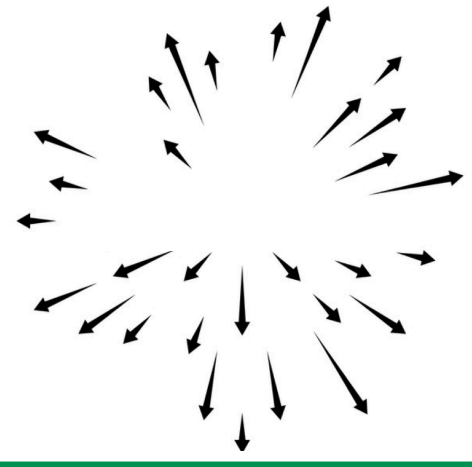


$$Y_{\text{DM}} / Y_{\text{DM}}^{\text{naive}} \propto \gamma \propto \frac{T_{\text{nuc}} M_{\text{Pl}}}{f^2}$$

Unitarity violation



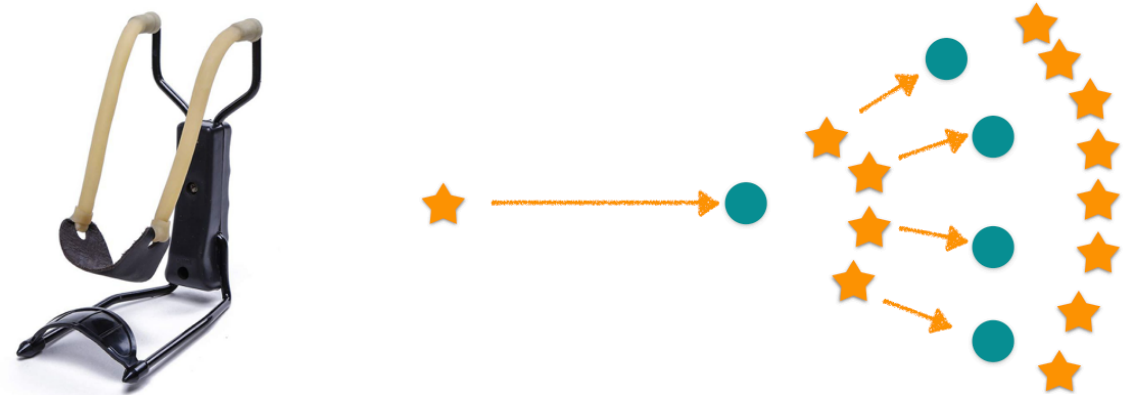
# Consequences on DM abundance



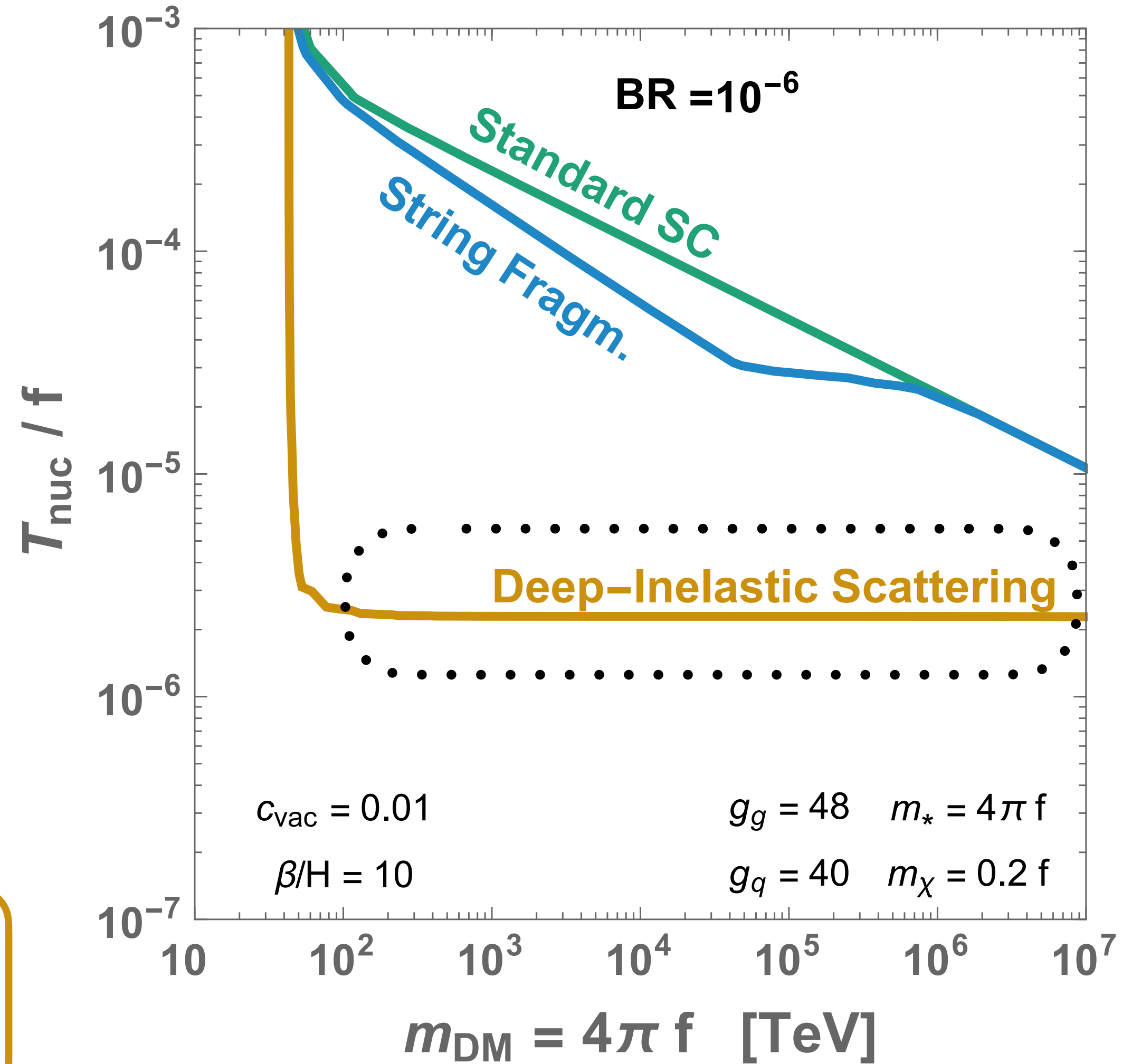
$$Y_{\text{DM}}^{\text{naive}} \propto \left( \frac{T_{\text{nuc}}}{f} \right)^3$$



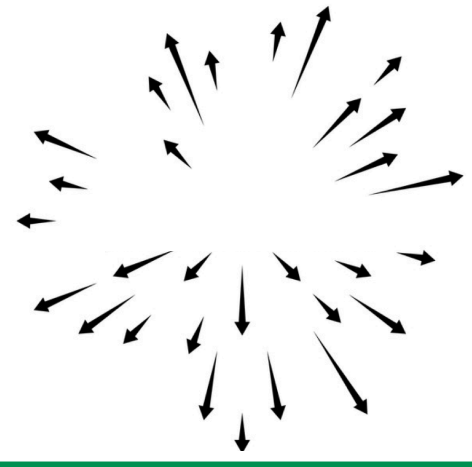
$$Y_{\text{DM}} / Y_{\text{DM}}^{\text{naive}} \propto \log^n(\gamma T_{\text{nuc}} / f)$$



$$Y_{\text{DM}} / Y_{\text{DM}}^{\text{naive}} \propto \gamma \propto \frac{T_{\text{nuc}} M_{\text{Pl}}}{f^2}$$



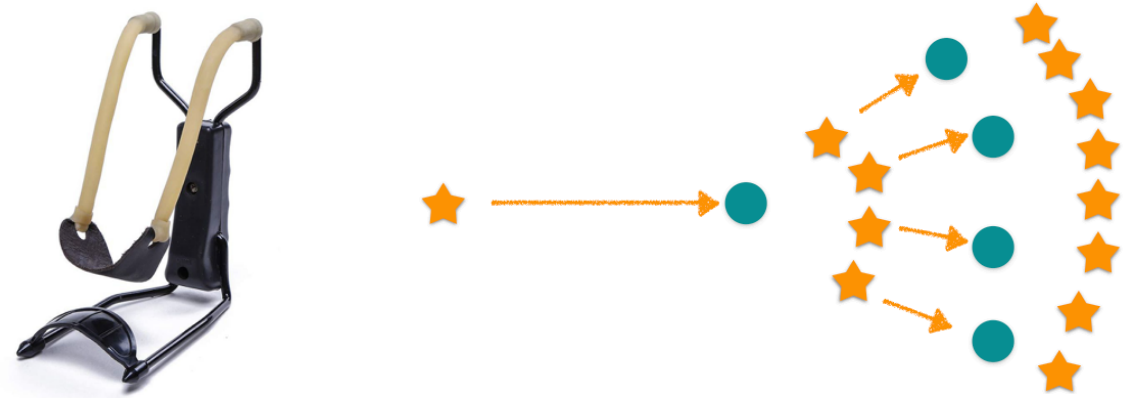
# Consequences on DM abundance



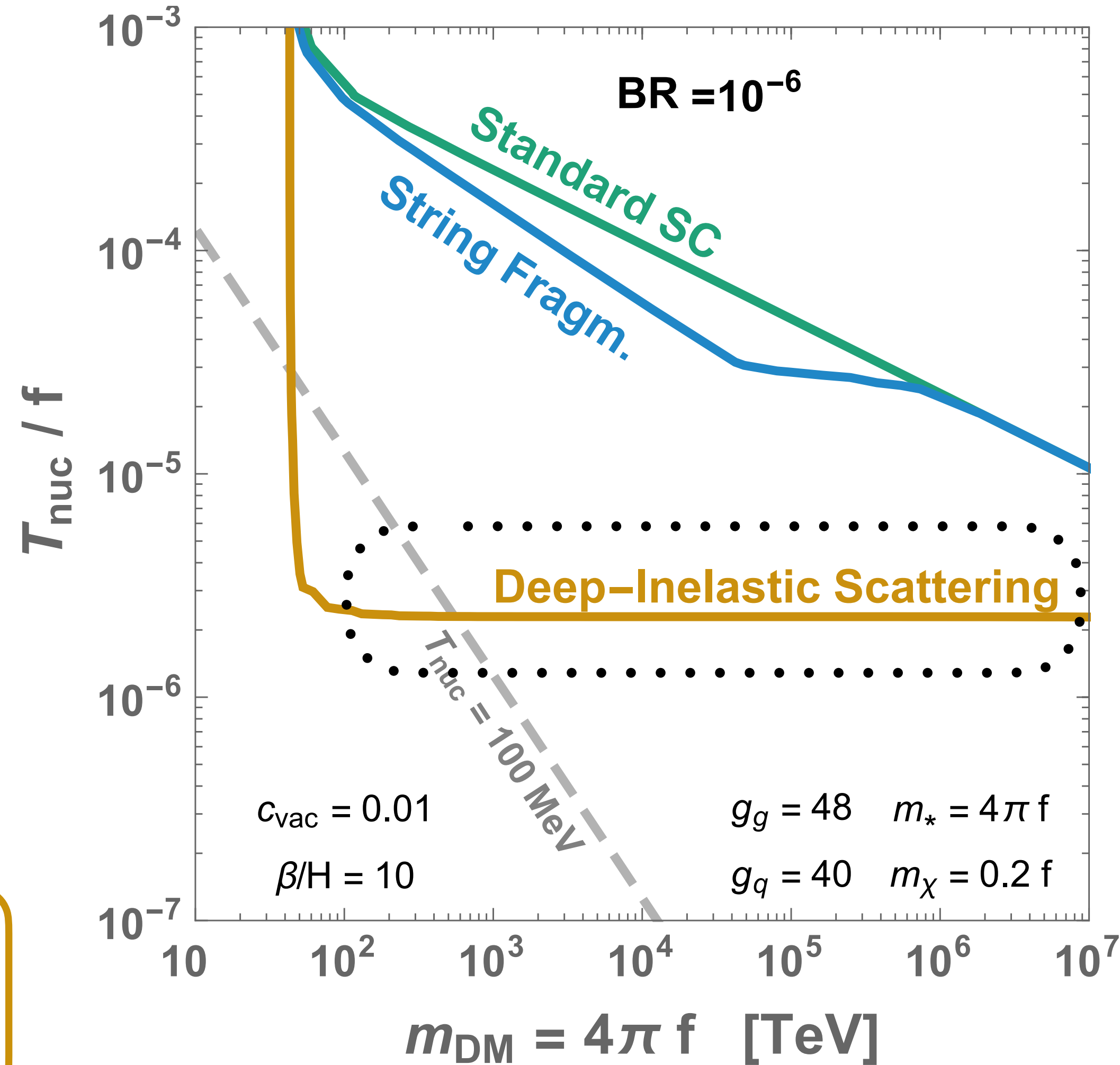
$$Y_{\text{DM}}^{\text{naive}} \propto \left( \frac{T_{\text{nuc}}}{f} \right)^3$$



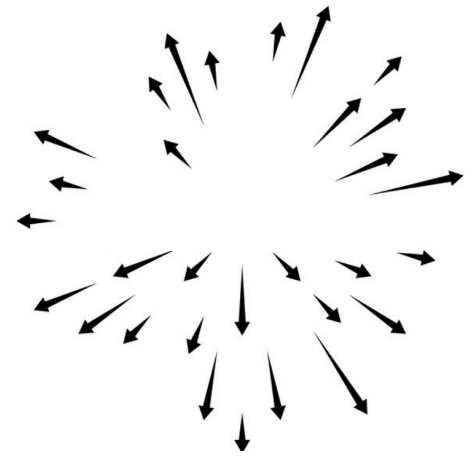
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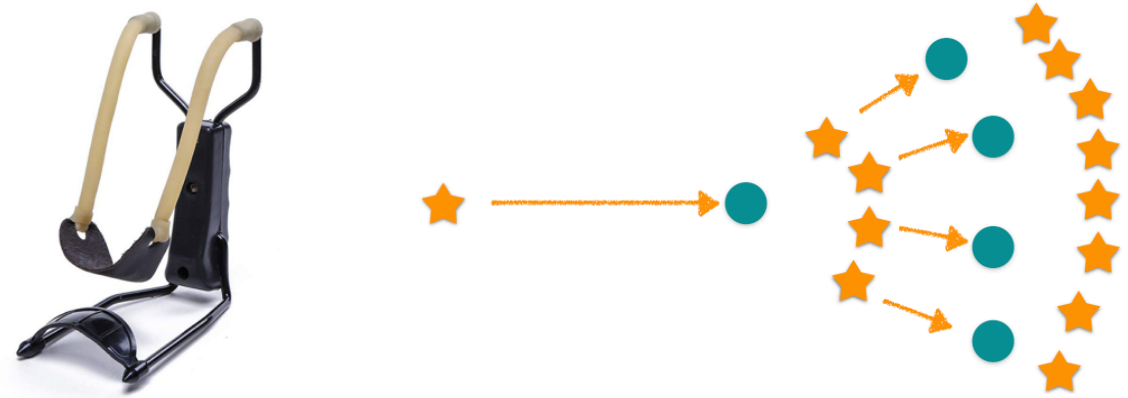
# Consequences on DM abundance



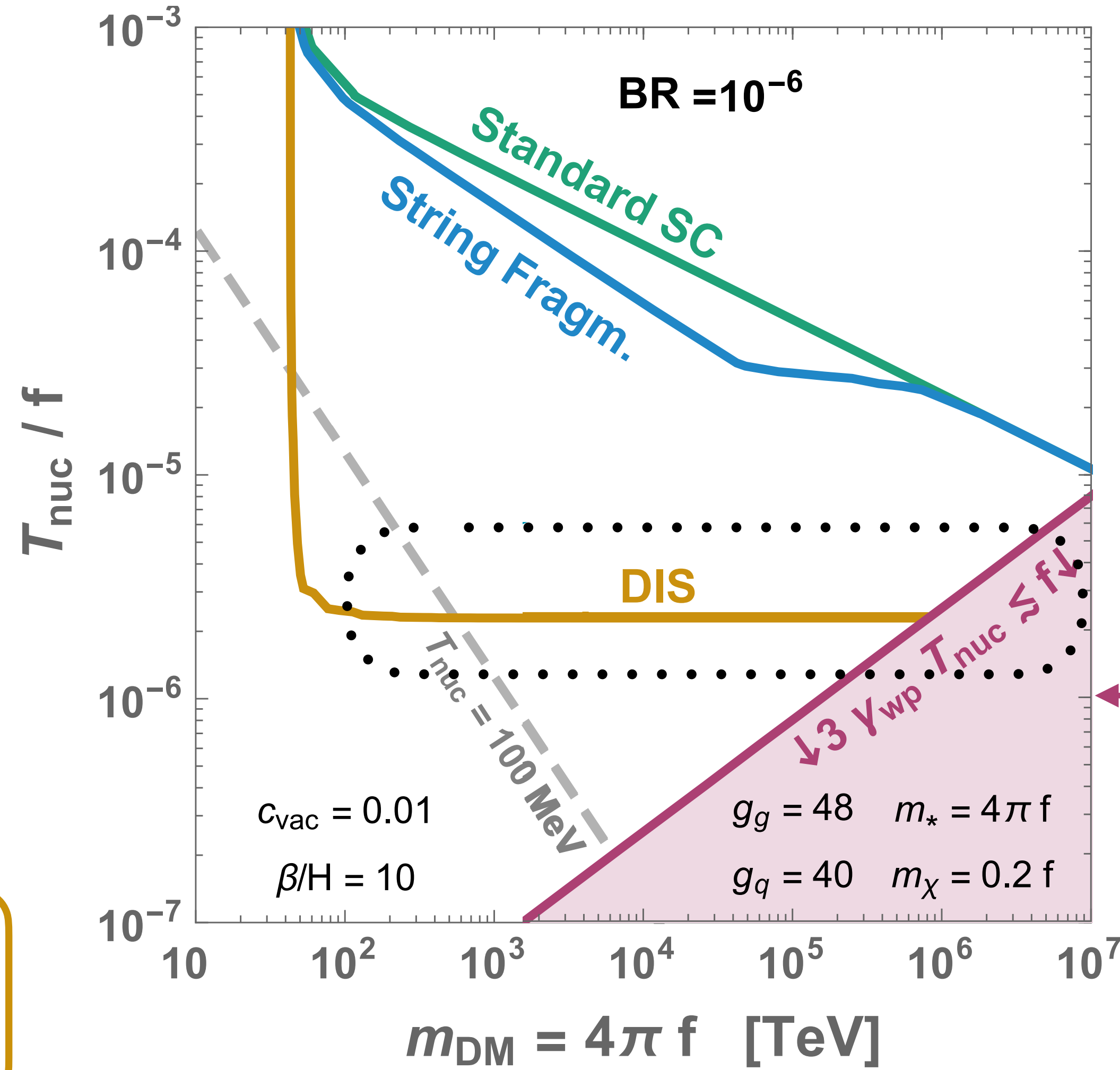
$$Y_{\text{DM}}^{\text{naive}} \propto \left( \frac{T_{\text{nuc}}}{f} \right)^3$$



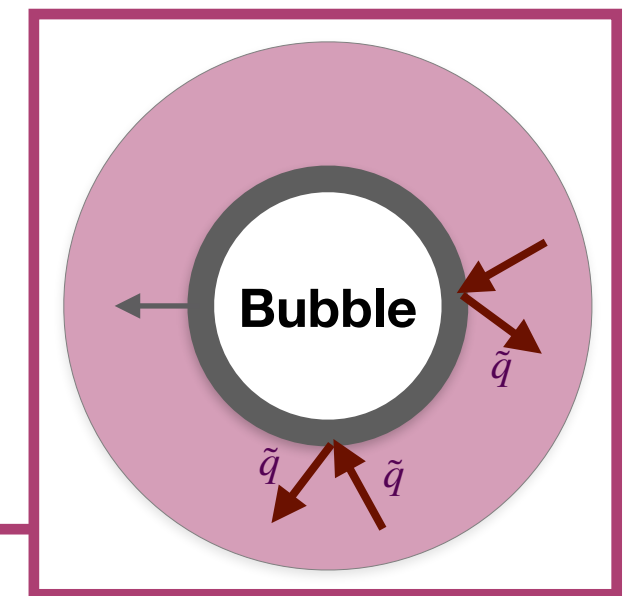
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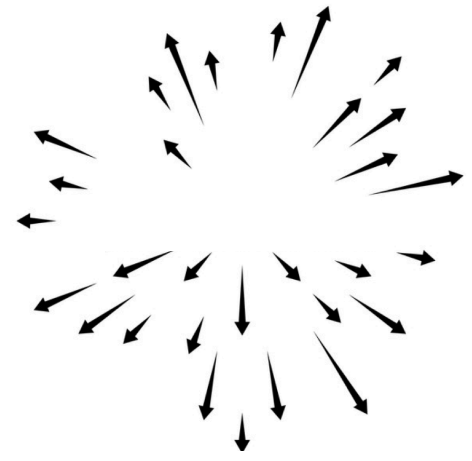
$$Y_{\text{DM}} / Y_{\text{DM}}^{\text{naive}} \propto \gamma \propto \frac{T_{\text{nuc}} M_{\text{Pl}}}{f}$$



Quarks can not enter



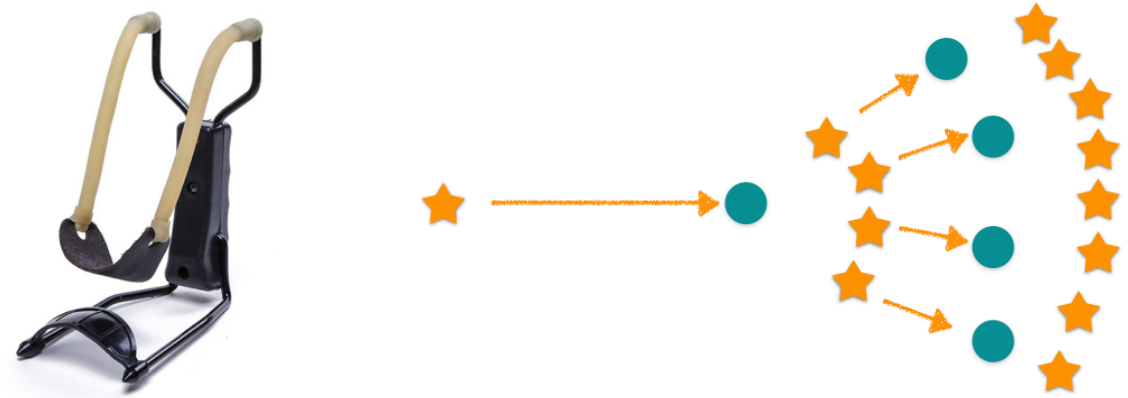
# Consequences on DM abundance



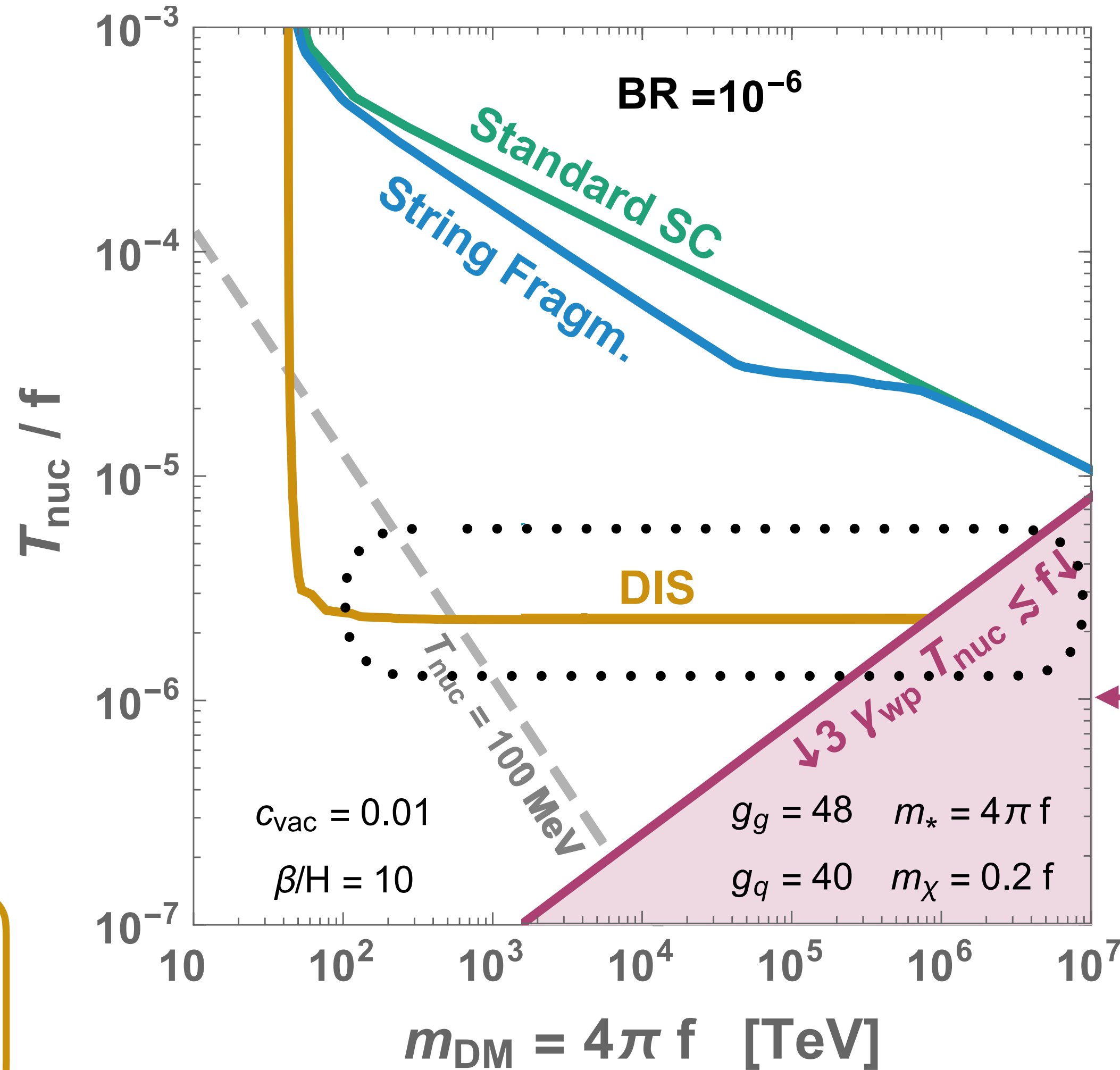
$$Y_{\text{DM}}^{\text{naive}} \propto \left( \frac{T_{\text{nuc}}}{f} \right)^3$$



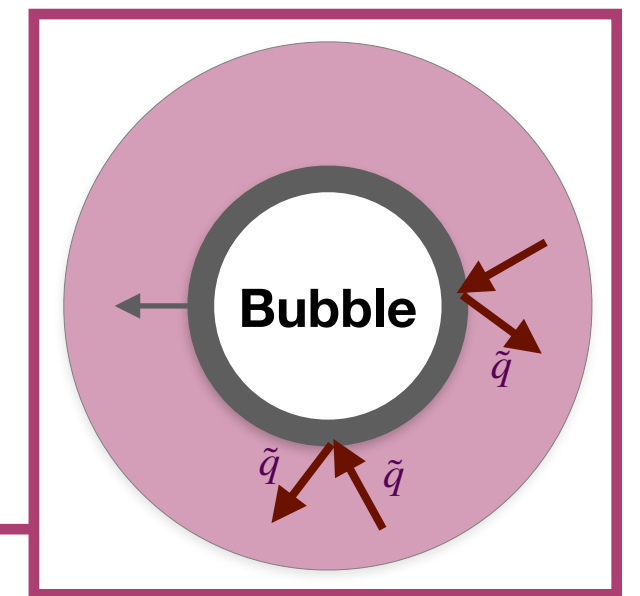
$$Y_{\text{DM}} / Y_{\text{DM}}^{\text{naive}} \propto \log^n(\gamma T_{\text{nuc}} / f)$$



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

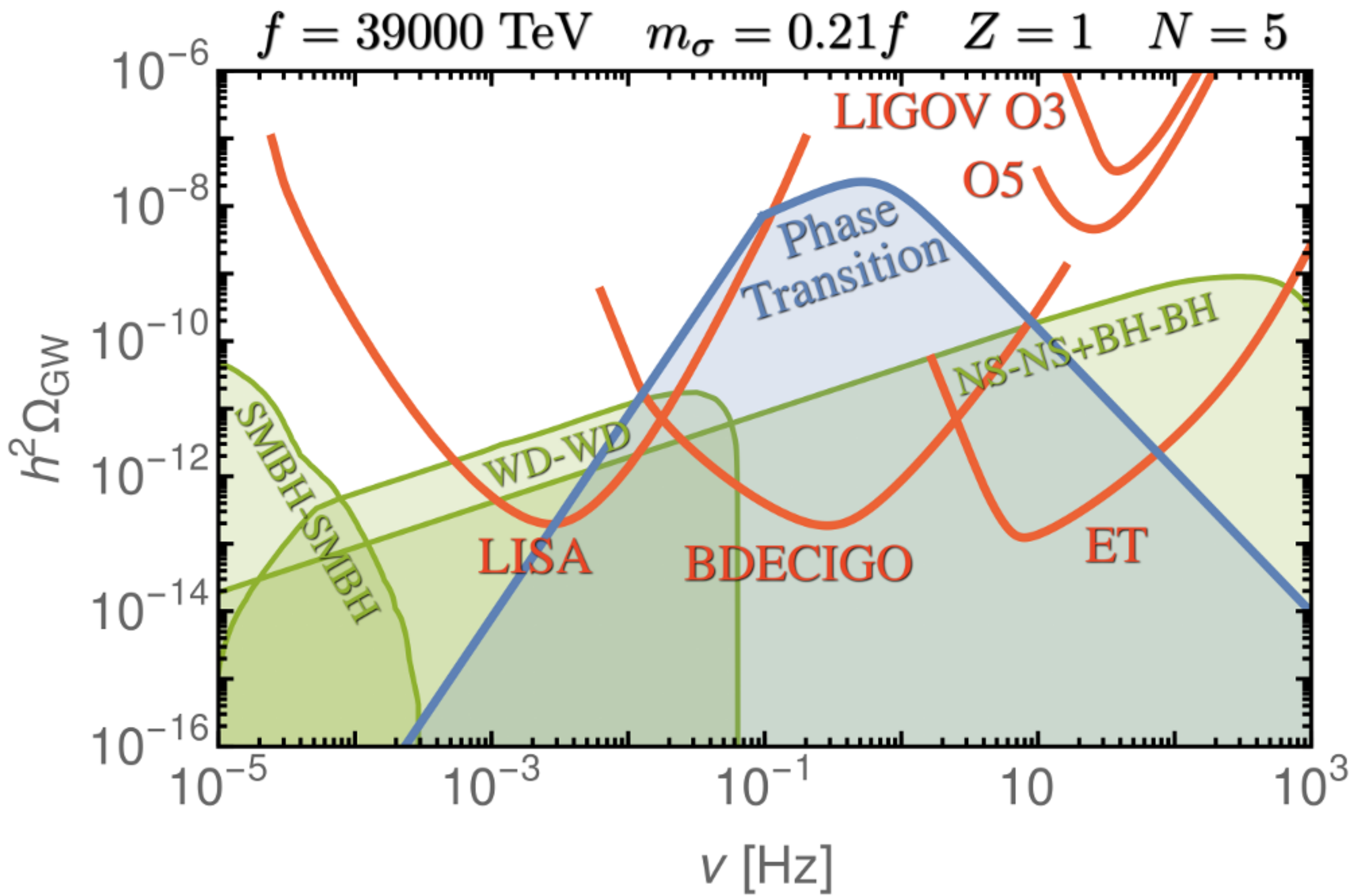


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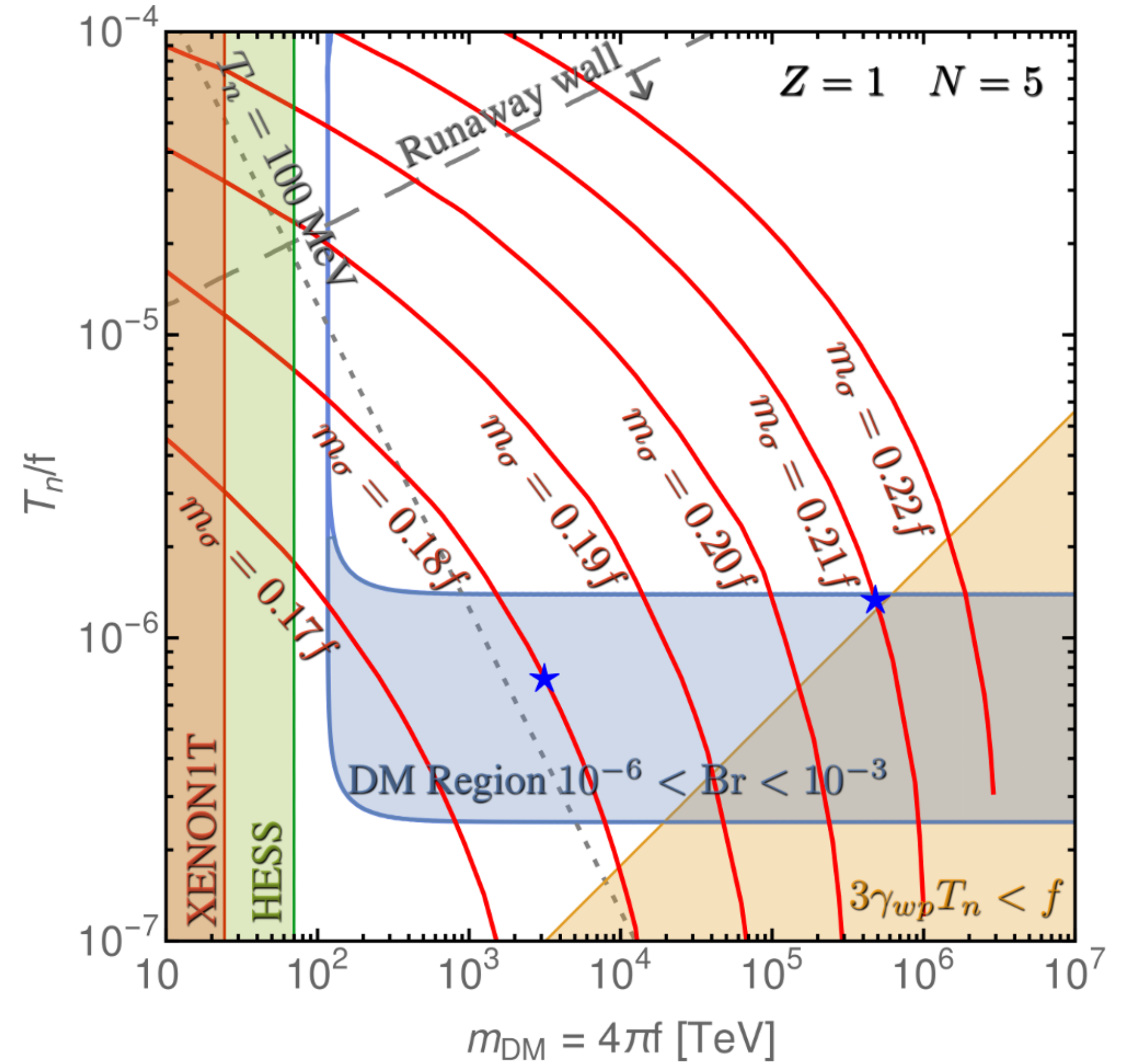
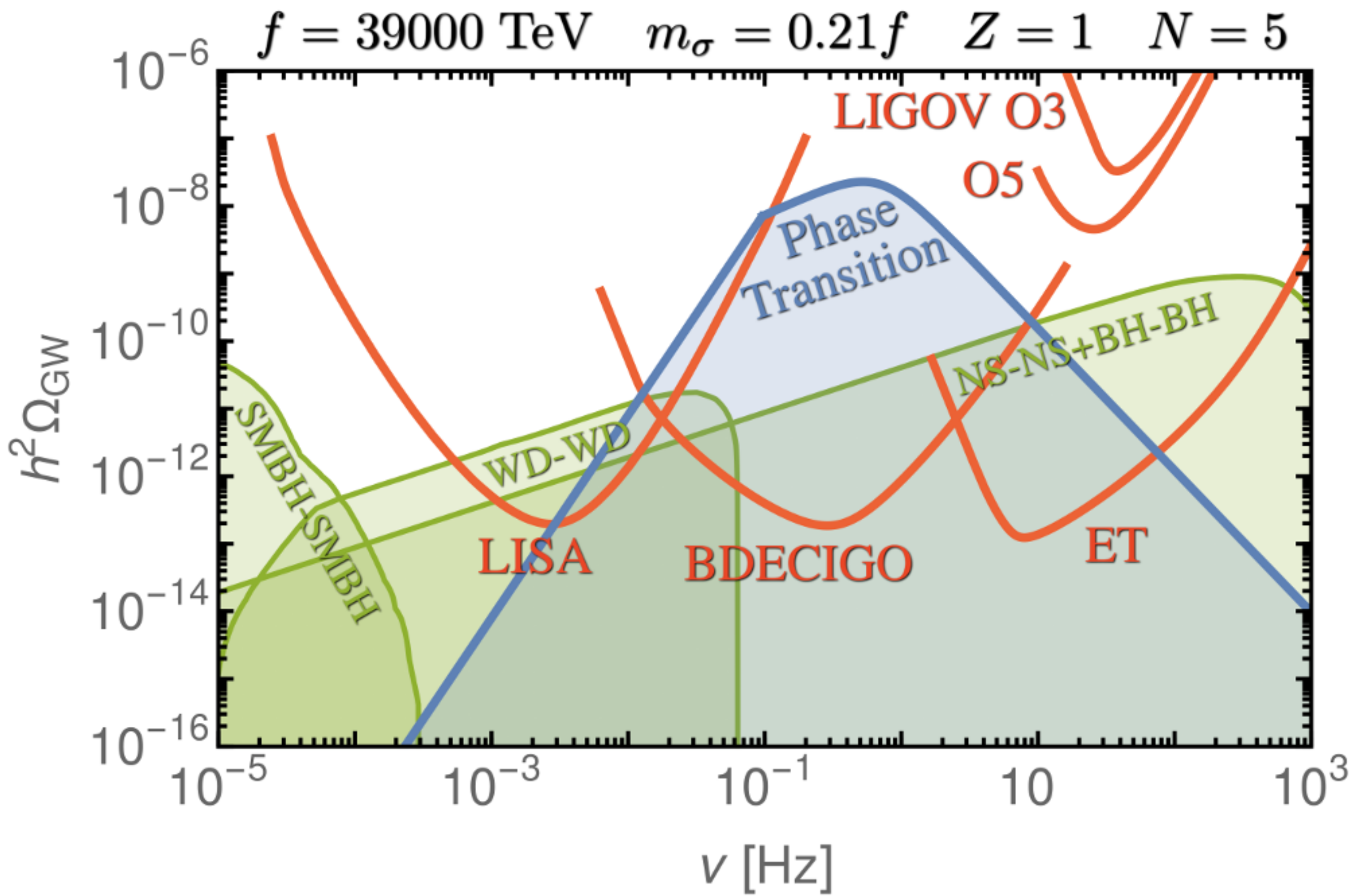


Supercool version of  
Asadi, Kramer, Kuflik, Ridgway, Slatyer, Smirnov 21  
Squeeze-out DM

# Gravitational waves signature

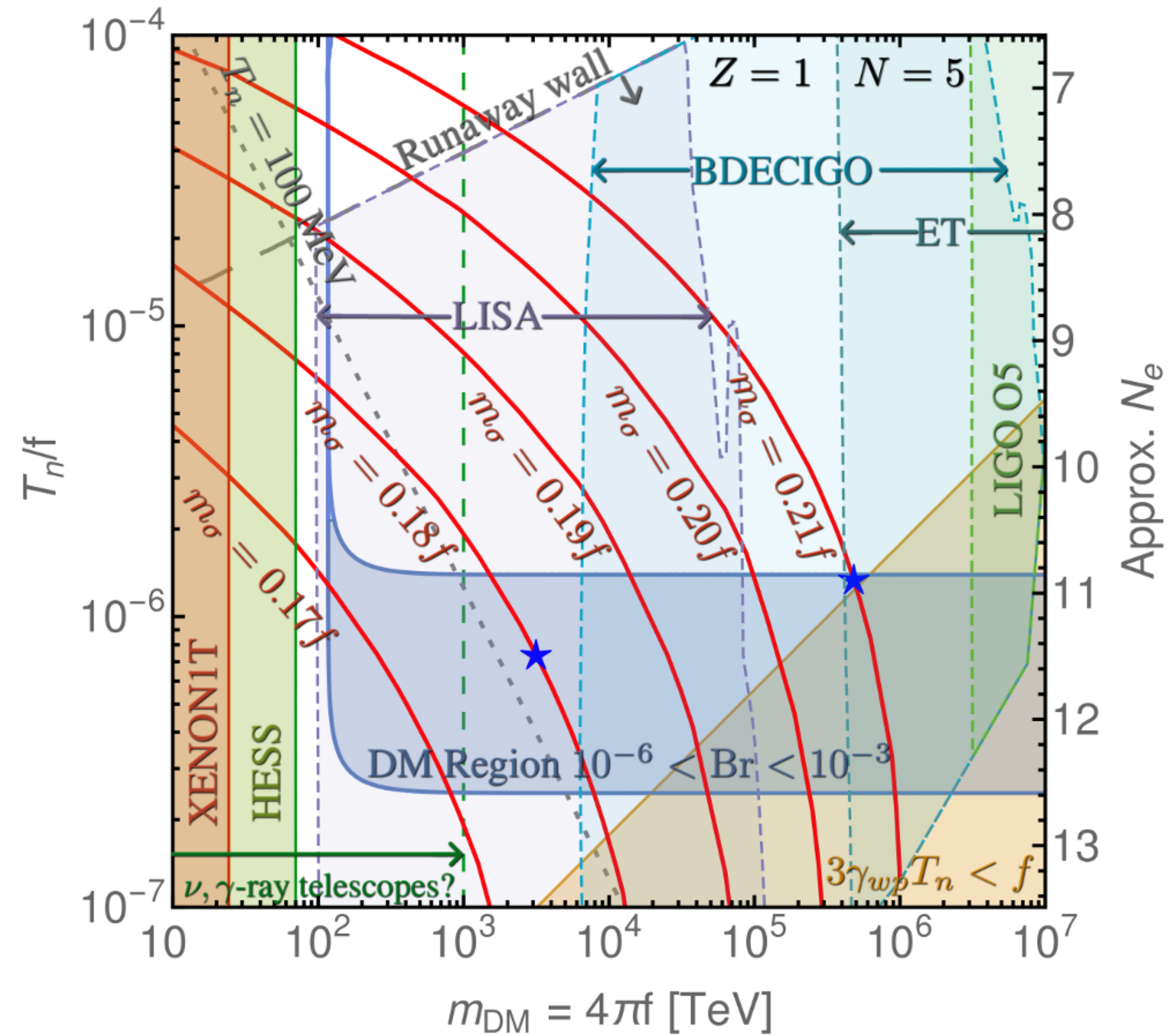
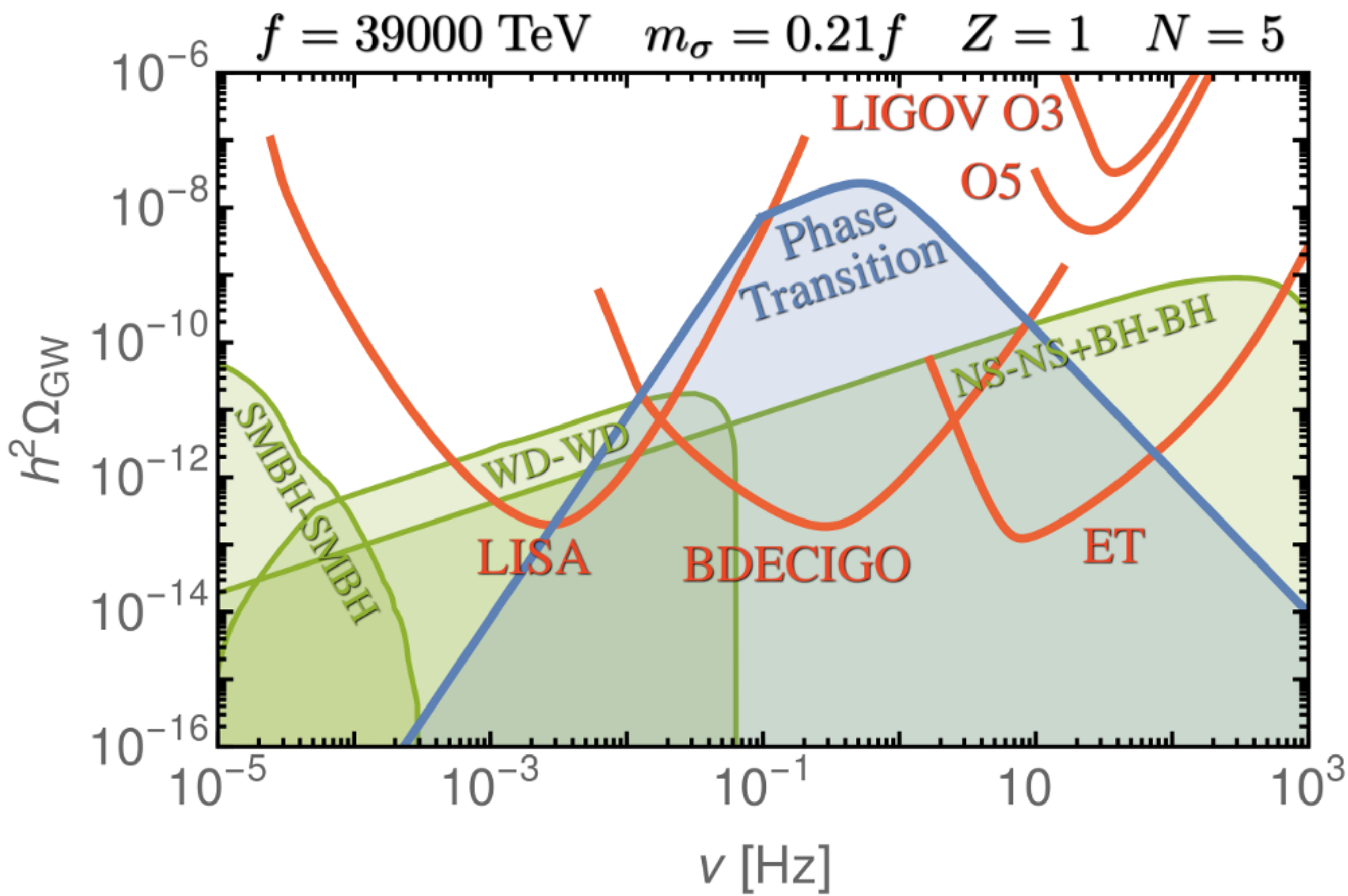


# Gravitational waves signature





# Gravitational waves signature



# 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**

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

## Other consequences of supercooling:

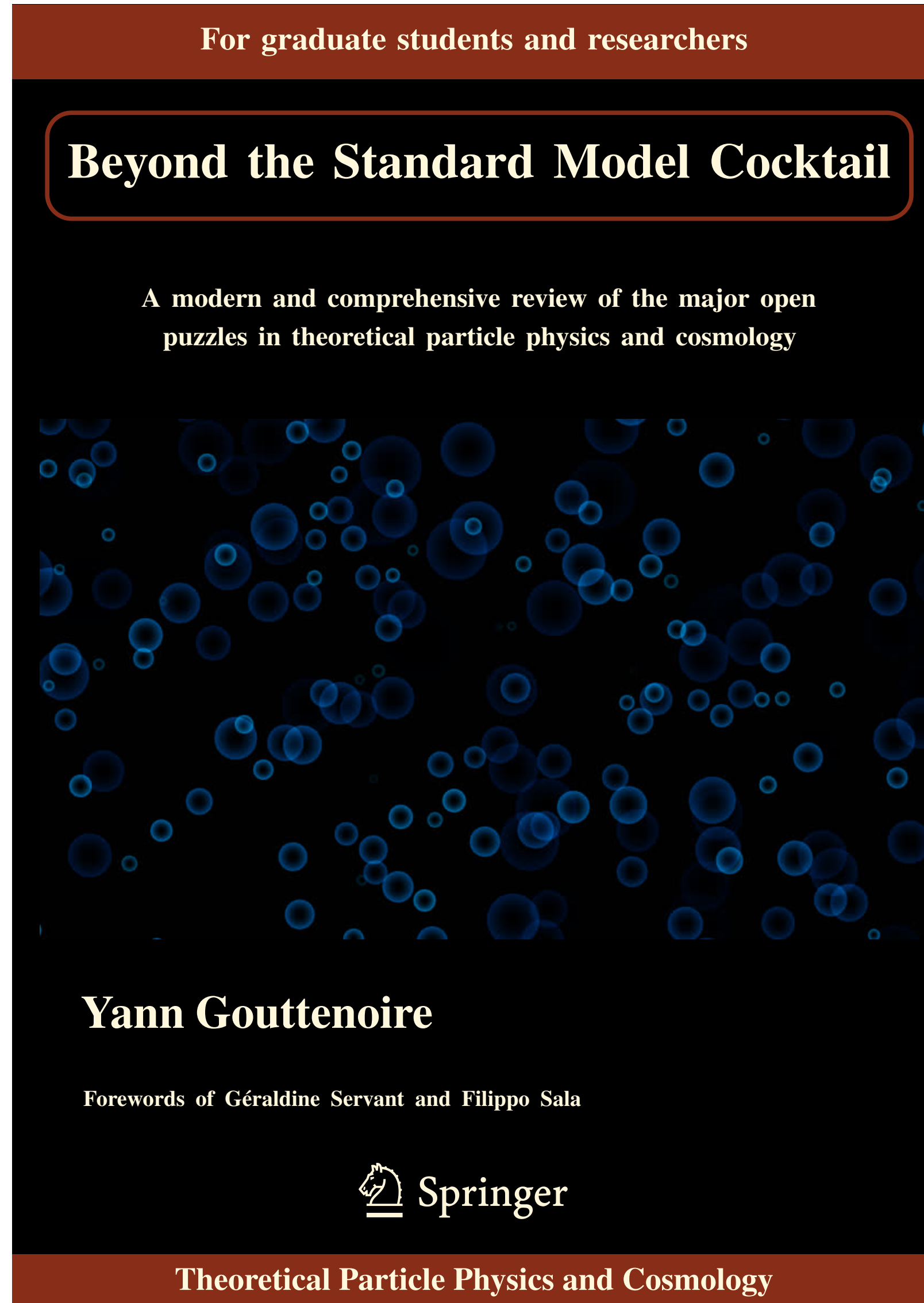
1. Other particle production:
  - i) Off-shell decay
  - ii) Unruh radiation
2. Black hole formation

**For more details on supercooled phase transitions**

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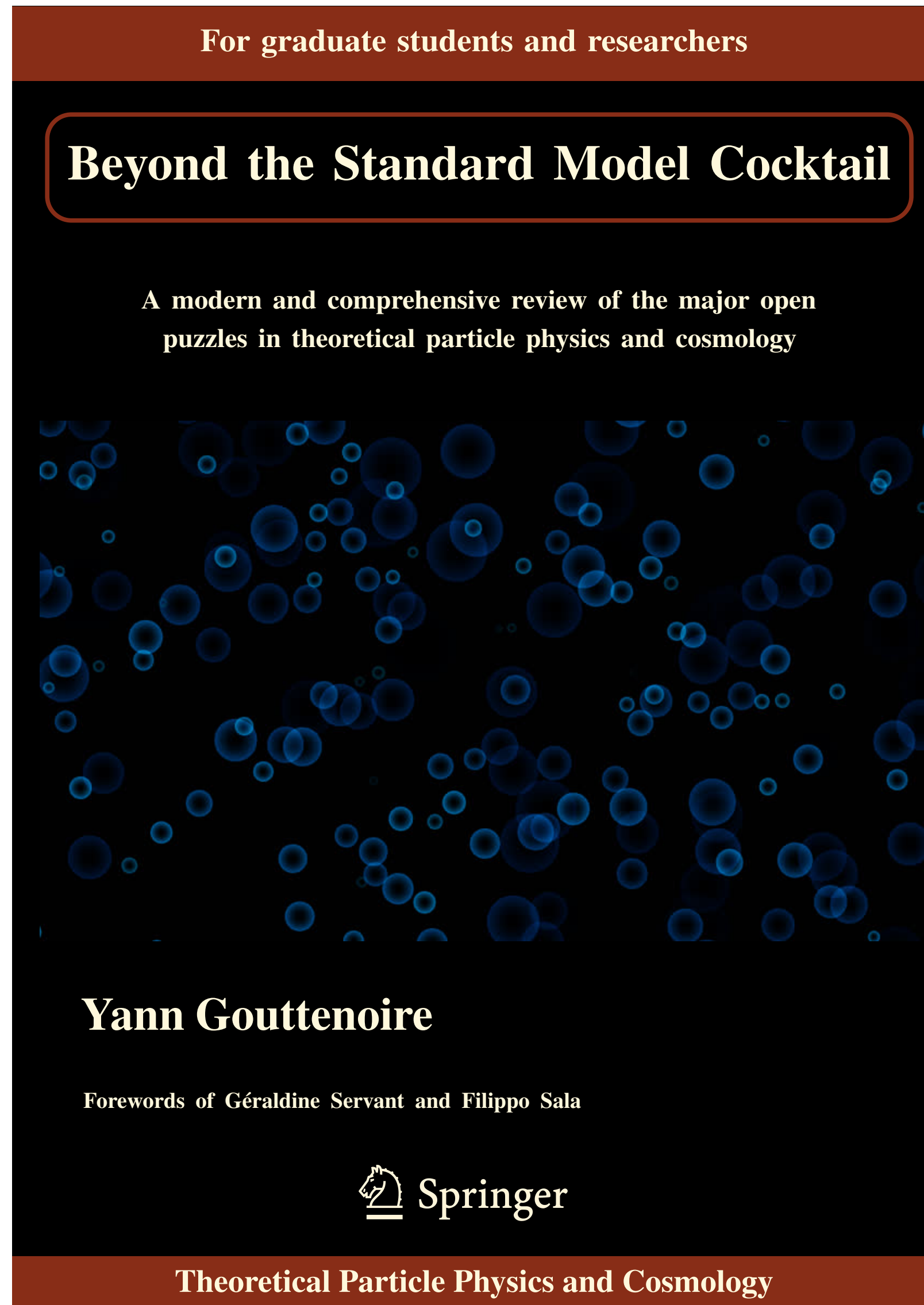
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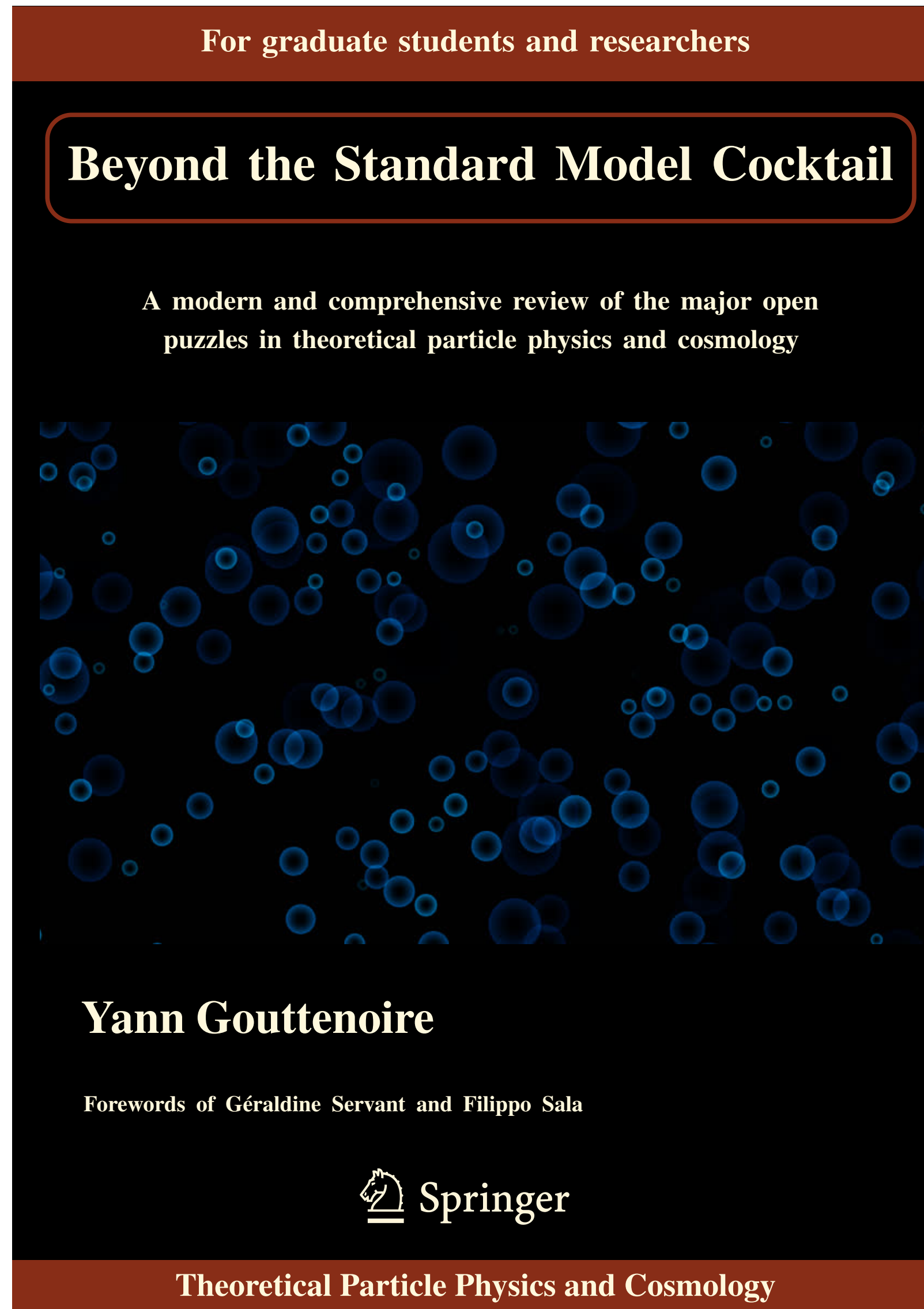


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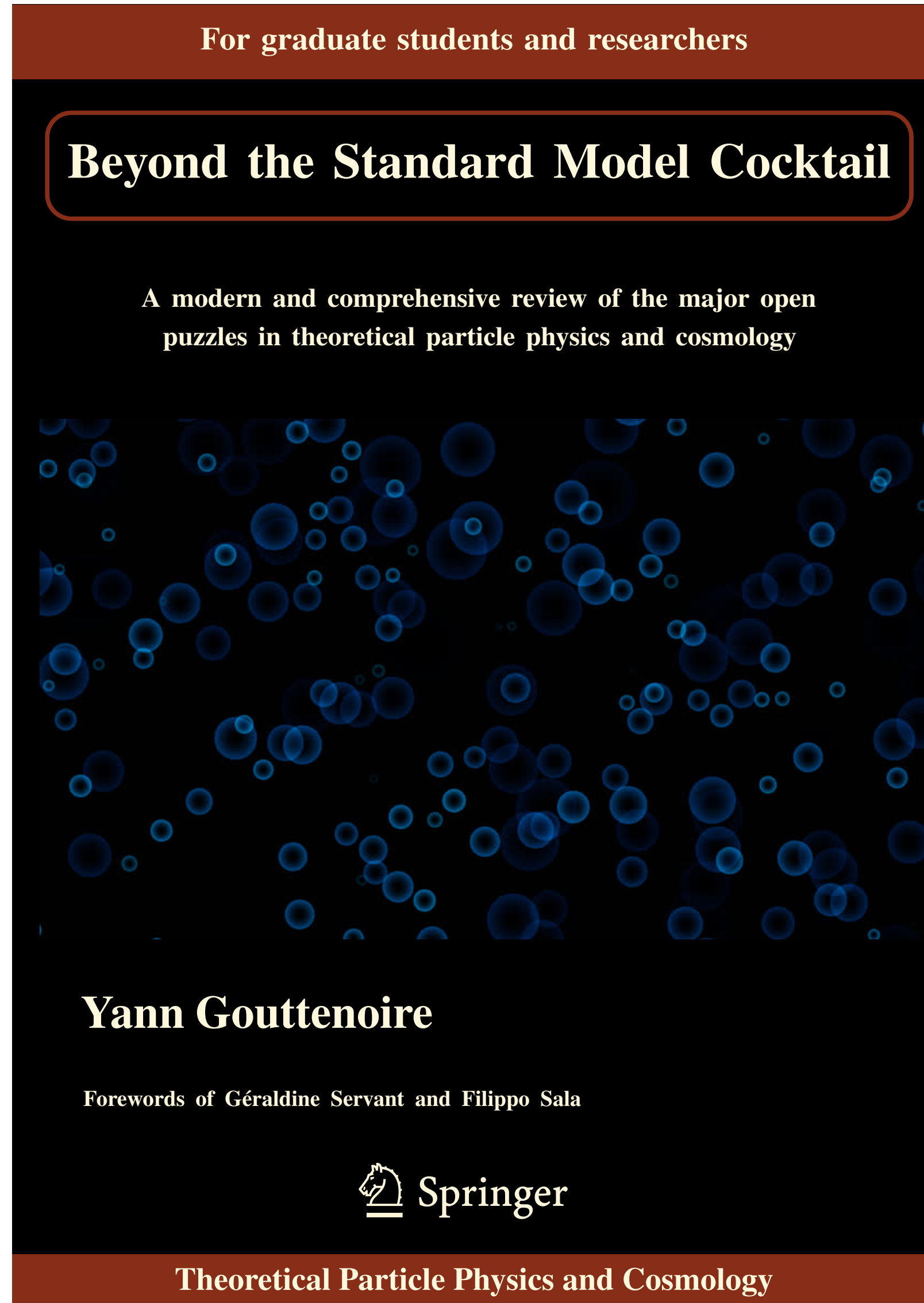


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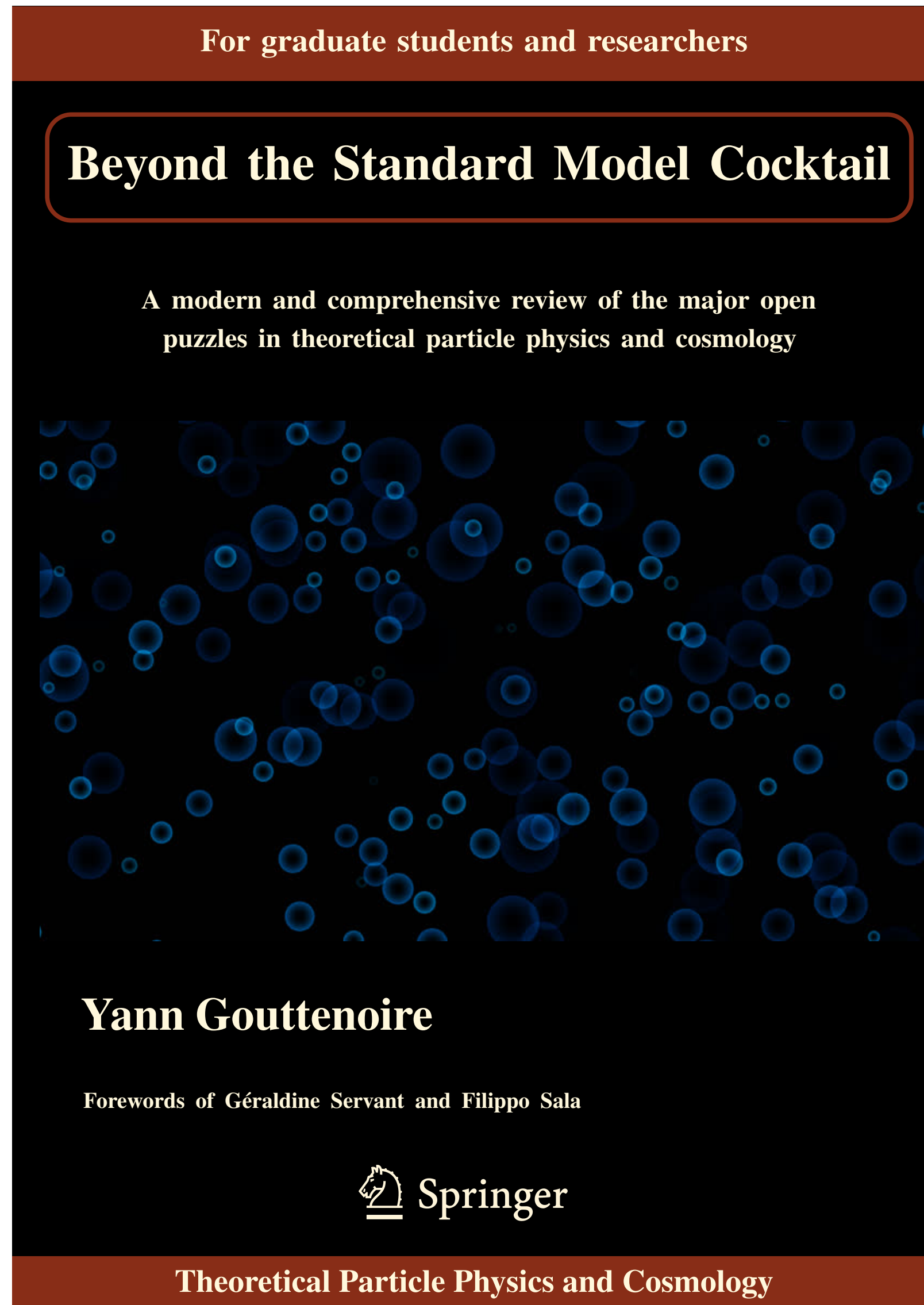
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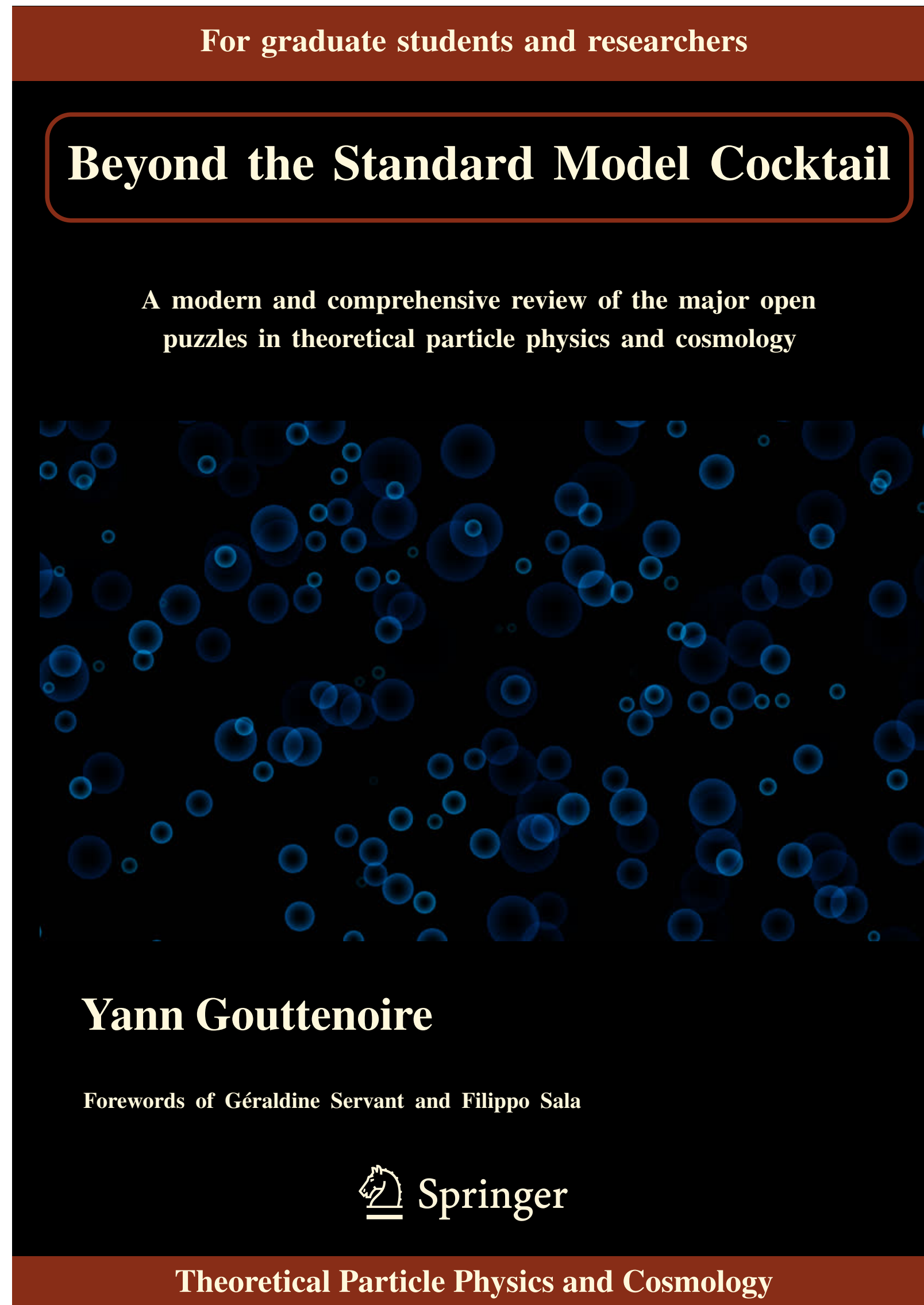
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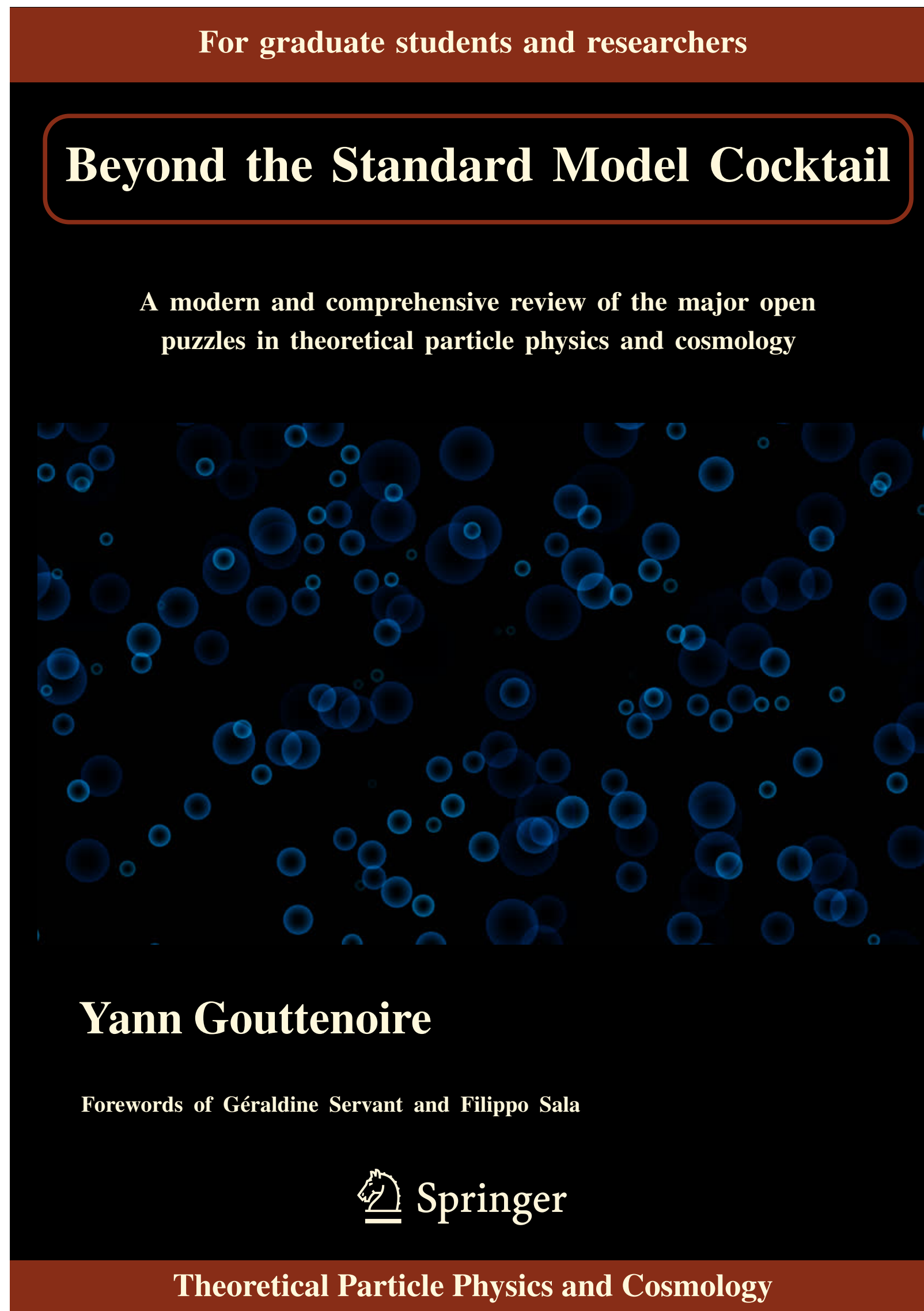
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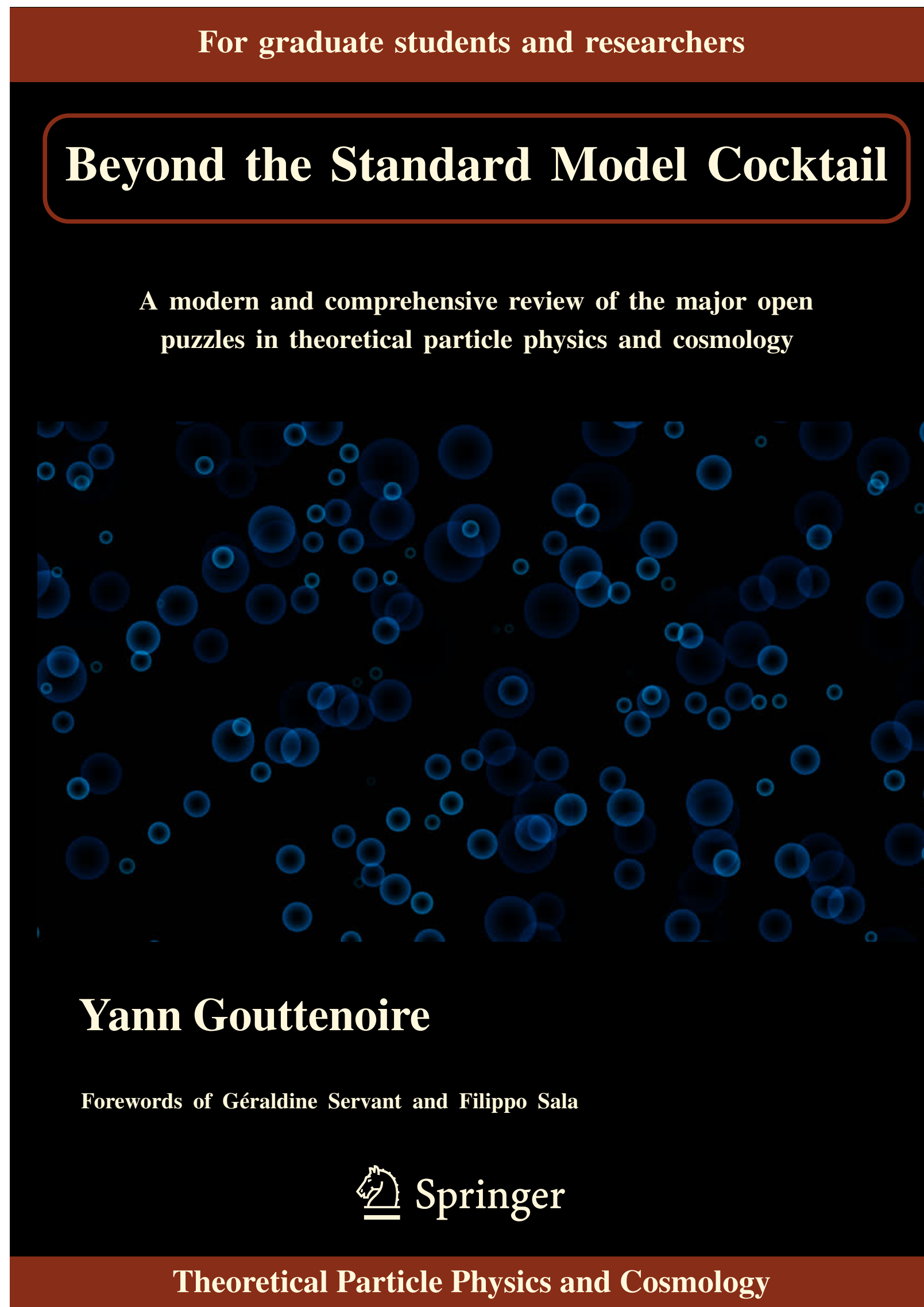
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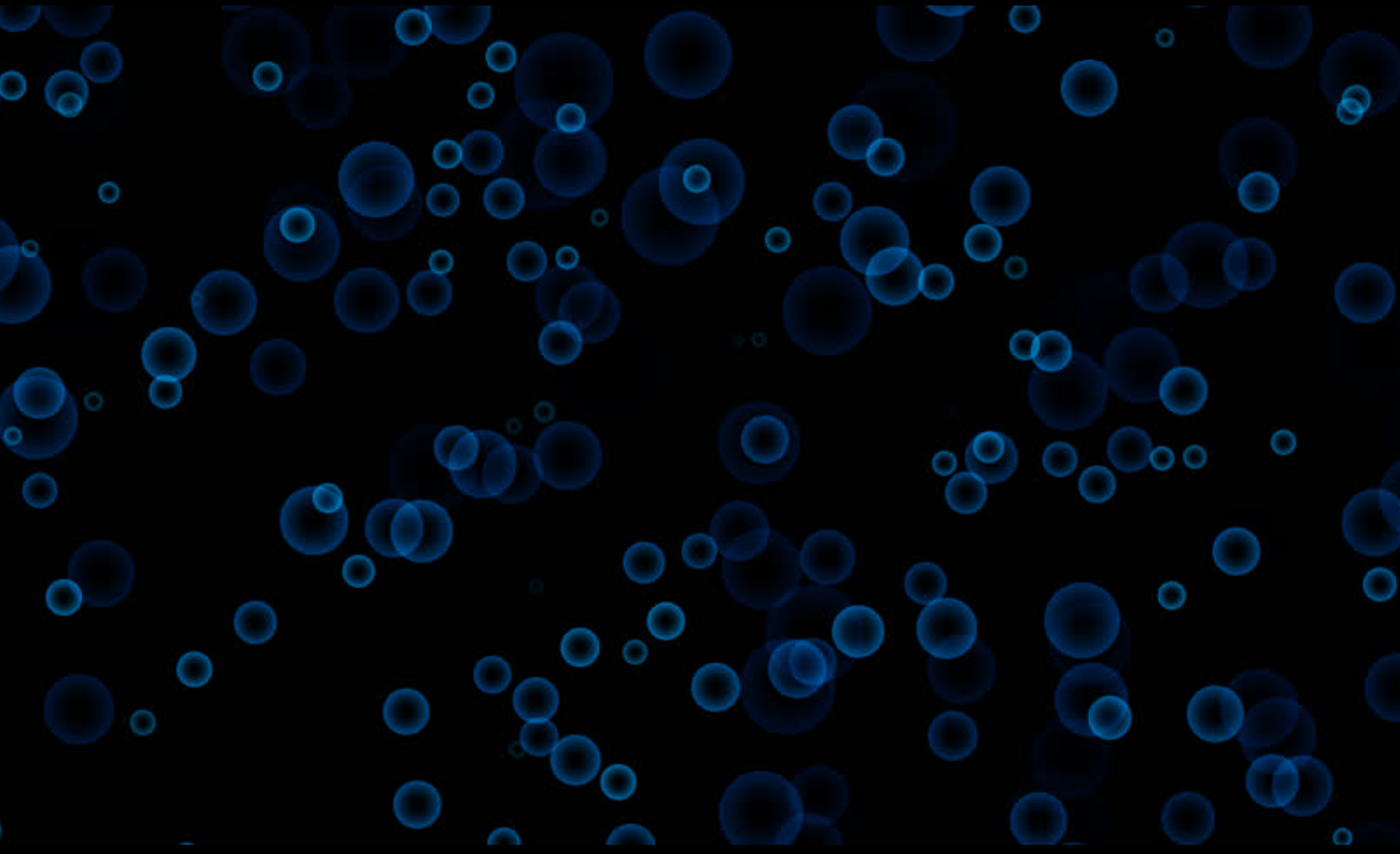
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A modern and comprehensive review of the major open puzzles in theoretical particle physics and cosmology



**Yann Gouttenoire**

Forewords of Géraldine Servant and Filippo Sala



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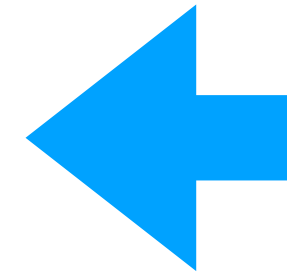
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**Additional slides**



# Consequences on bubble wall velocity

Bubble wall

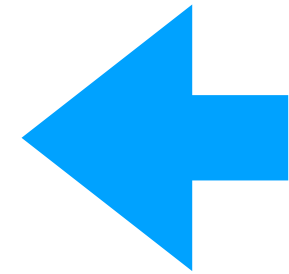
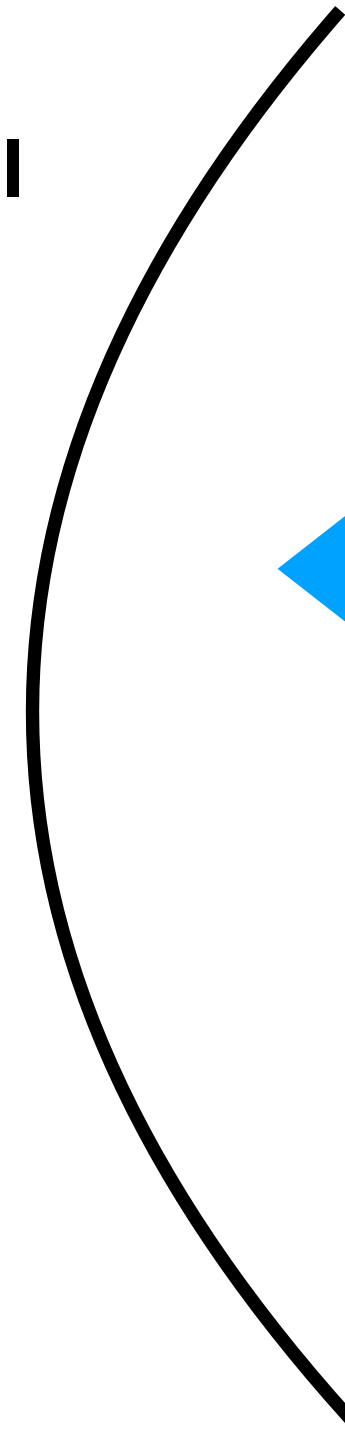
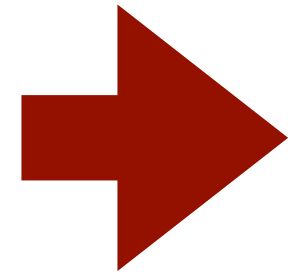


$$\Delta V_{\text{vac}} = c_{\text{vac}} f^4$$

## Consequences on bubble wall velocity

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

Bubble wall



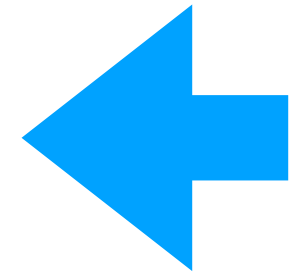
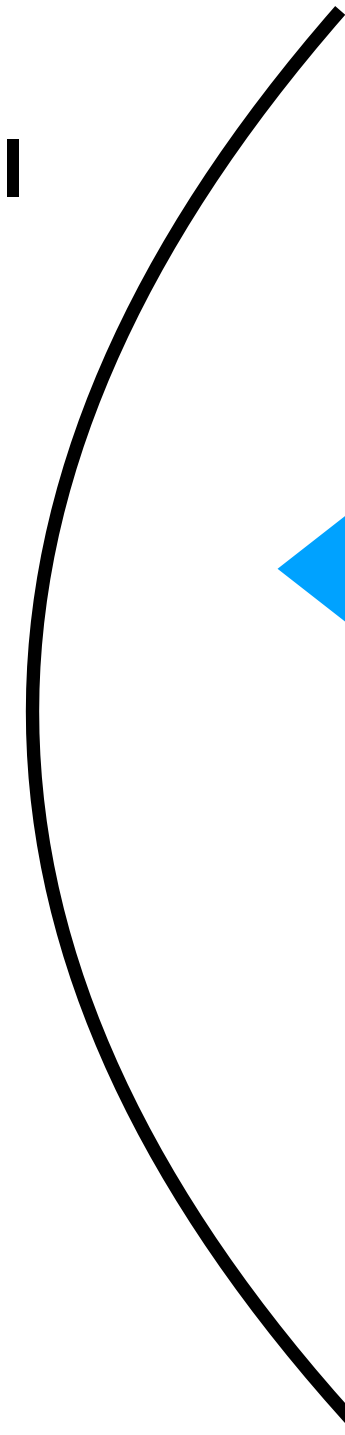
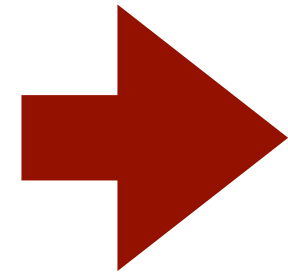
$$\Delta V_{\text{vac}} = c_{\text{vac}} f^4$$

## Consequences on bubble wall velocity

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

$$\Delta p = ?$$

Bubble wall



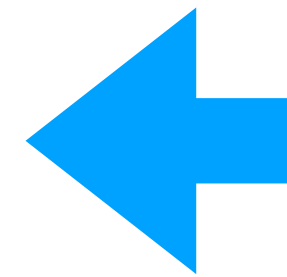
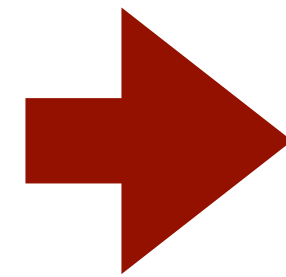
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## Consequences on bubble wall velocity

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

$$\Delta p = ?$$

Bubble wall



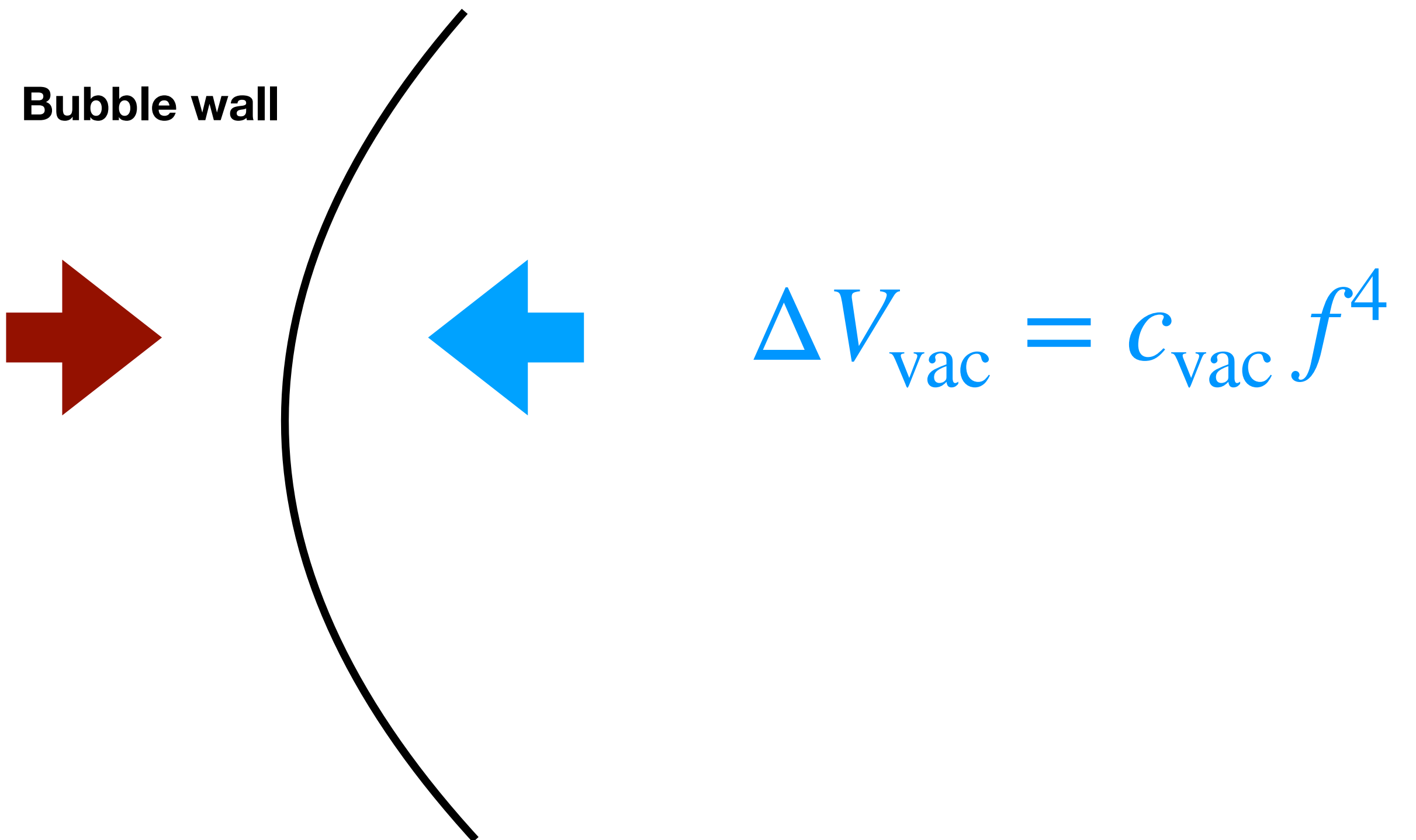
$$\Delta V_{\text{vac}} = c_{\text{vac}} f^4$$

**Weakly-coupled PT**

## Consequences on bubble wall velocity

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

$$\Delta p = ?$$



**Weakly-coupled PT**

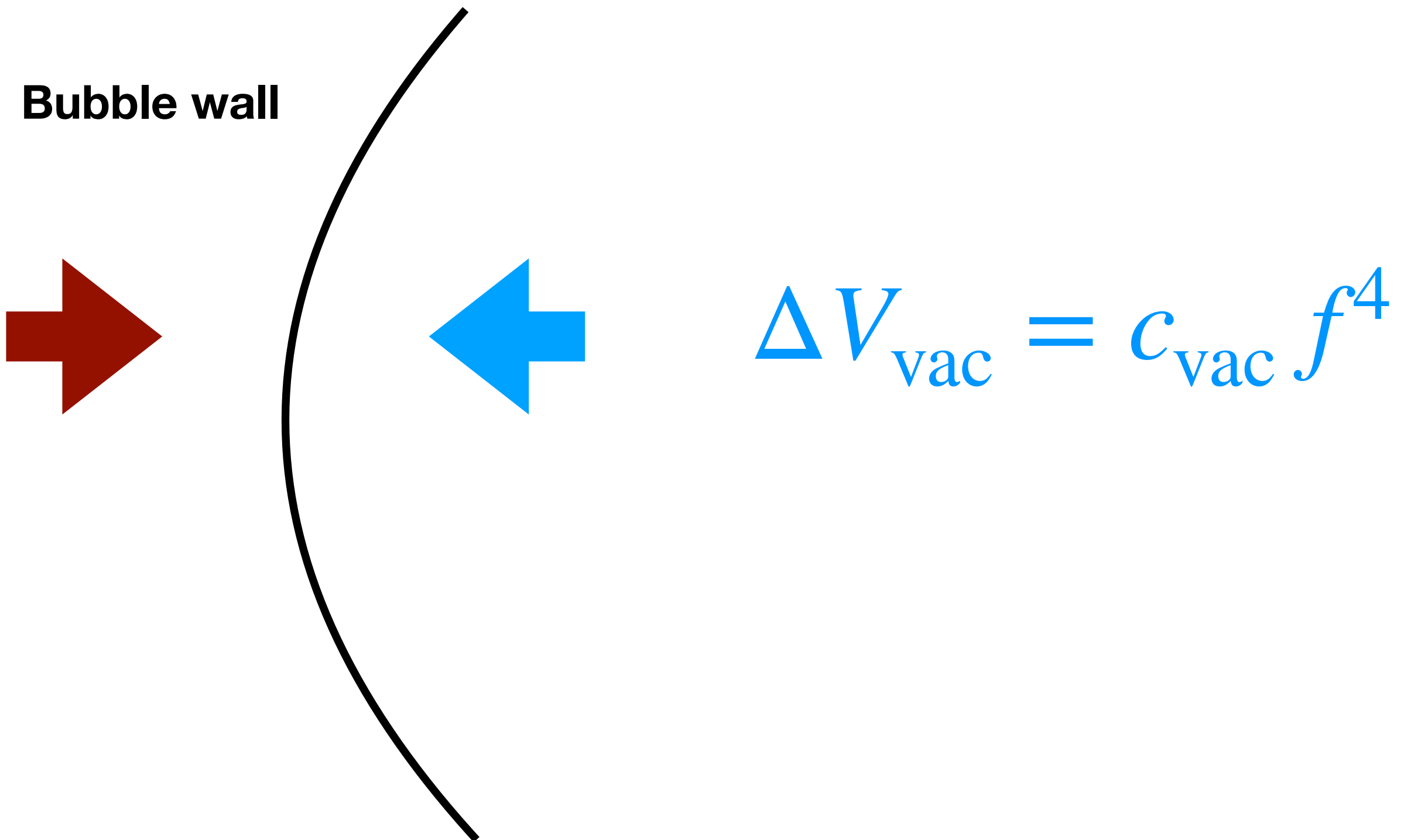
**Bodeker&Moore (09' and 17')**

**Azatov+ 20'**

## Consequences on bubble wall velocity

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

$$\Delta p = ?$$



### Weakly-coupled PT

Bodeker&Moore (09' and 17')

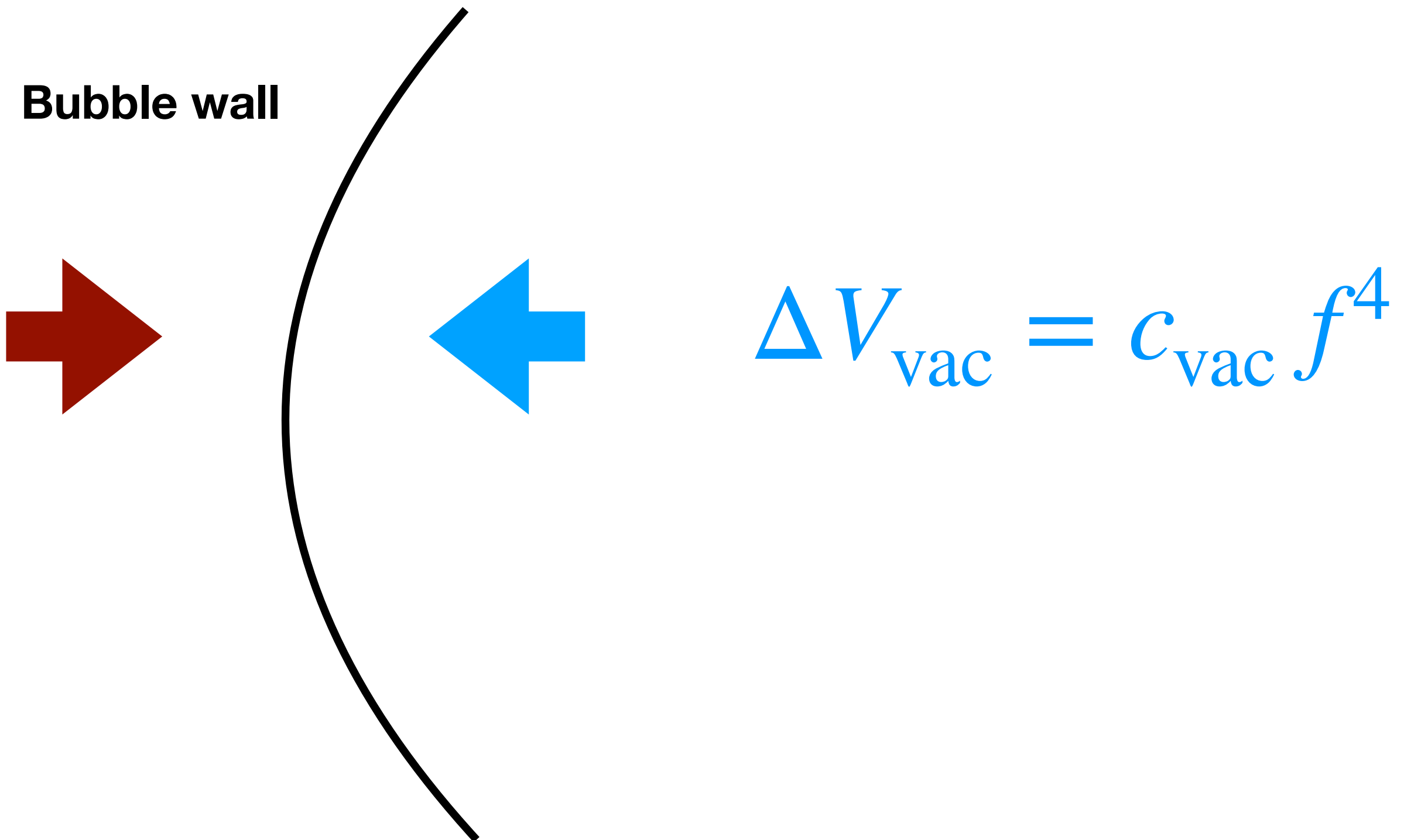
Azatov+ 20'

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

# Consequences on bubble wall velocity

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

$$\Delta p = ?$$



## Weakly-coupled PT

Bodeker&Moore (09' and 17')

Azatov+ 20'

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

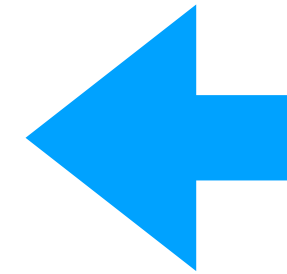
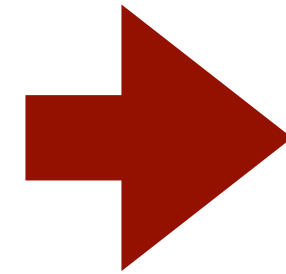
⋮

# Consequences on bubble wall velocity

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

$$\Delta p = ?$$

Bubble wall



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

**Weakly-coupled PT**

**Strongly-coupled PT**

**Bodeker&Moore (09' and 17')**

**Azatov+ 20'**

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

⋮

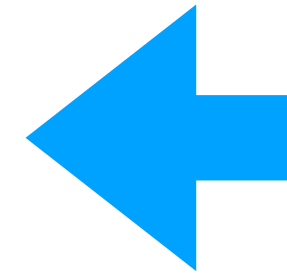
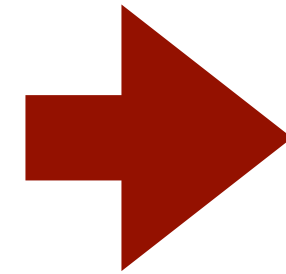


# Consequences on bubble wall velocity

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

$$\Delta p = ?$$

Bubble wall



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

## Weakly-coupled PT

Bodeker&Moore (09' and 17')

Azatov+ 20'

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

## Strongly-coupled PT

Hoeche, Kozaczuk, Long, Turner, Wang 20'

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

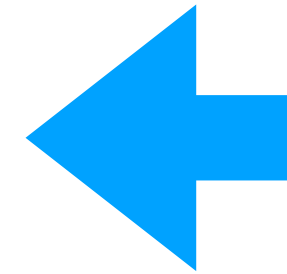
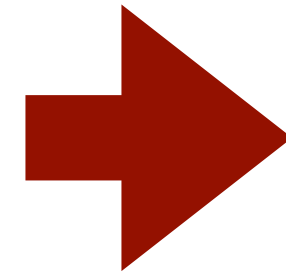
⋮

# Consequences on bubble wall velocity

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

$$\Delta p = ?$$

Bubble wall



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

## Weakly-coupled PT

Bodeker&Moore (09' and 17')

Azatov+ 20'

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

## Strongly-coupled PT

Hoeche, Kozaczuk, Long, Turner, Wang 20'

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

Baldes, YG, Sala 20'

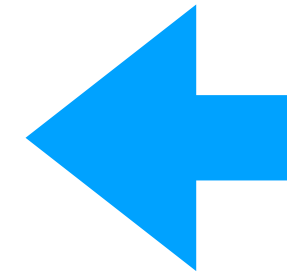
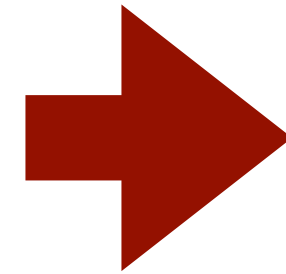
$$\mathcal{P}_{\text{flux-tube}} \simeq \gamma f T_{\text{nuc}}^3$$

# Consequences on bubble wall velocity

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

$$\Delta p = ?$$

Bubble wall



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

## Weakly-coupled PT

Bodeker&Moore (09' and 17')

Azatov+ 20'

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

## Strongly-coupled PT

Hoeche, Kozaczuk, Long, Turner, Wang 20'

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

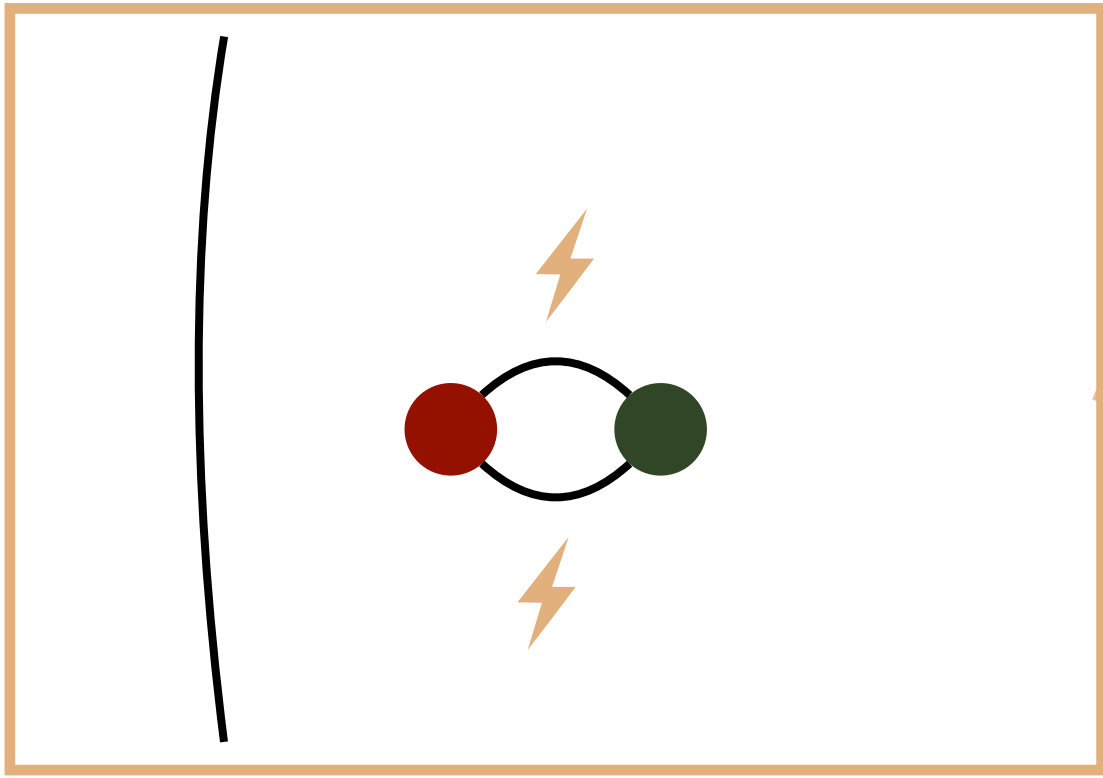
Baldes, YG, Sala 20'

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

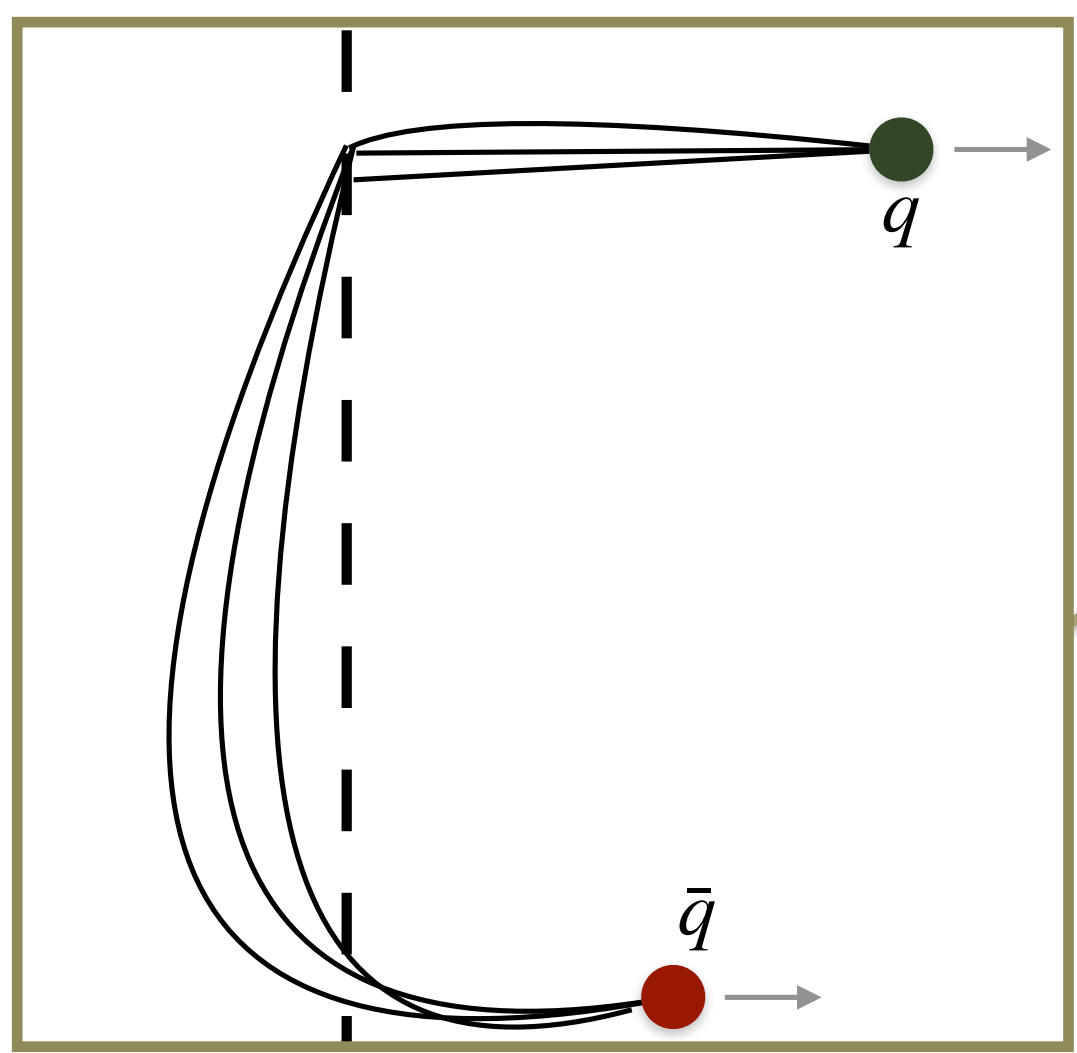
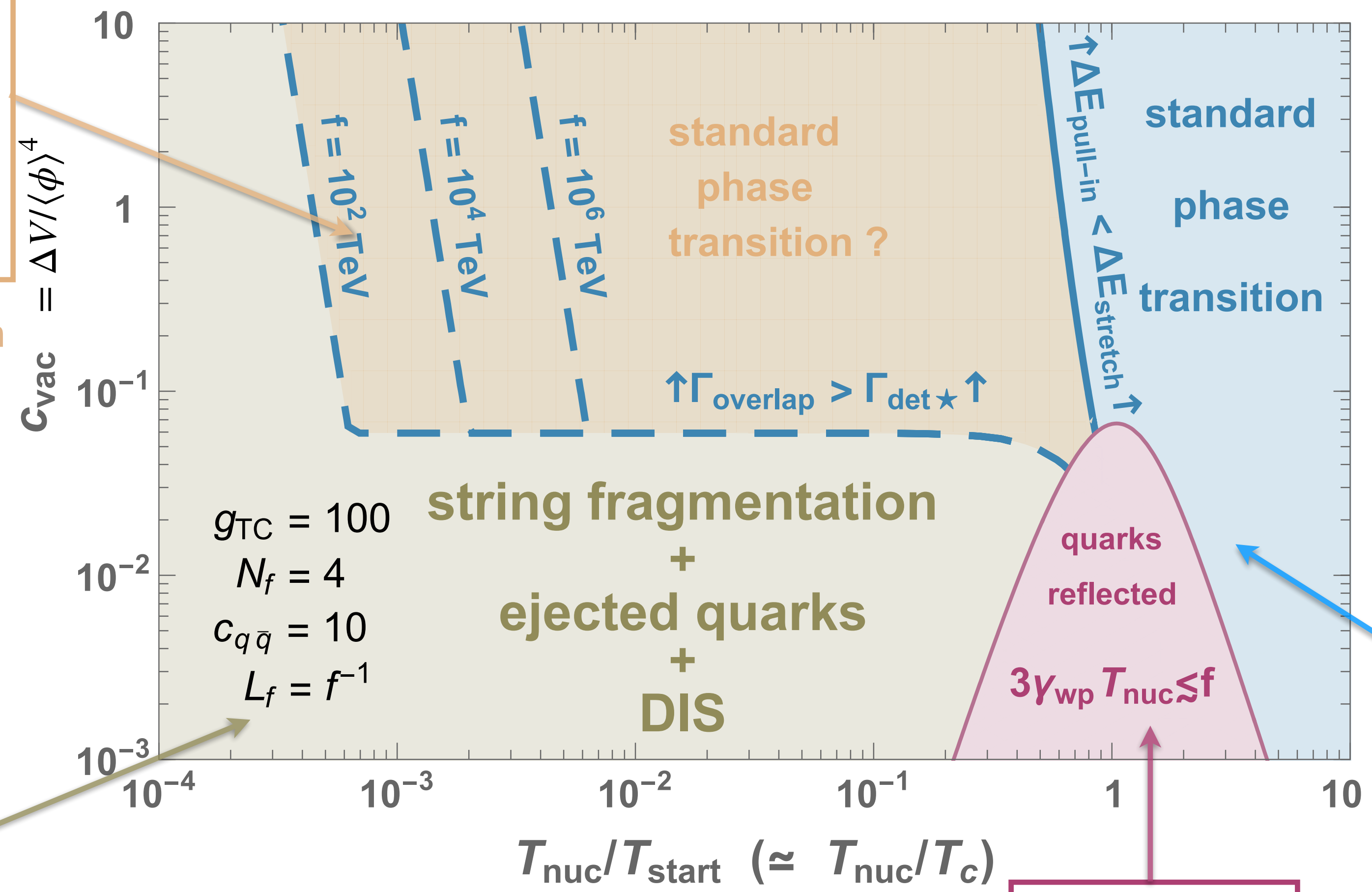
YG, Jinno, Sala 21'

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

# How much supercooling is needed ?

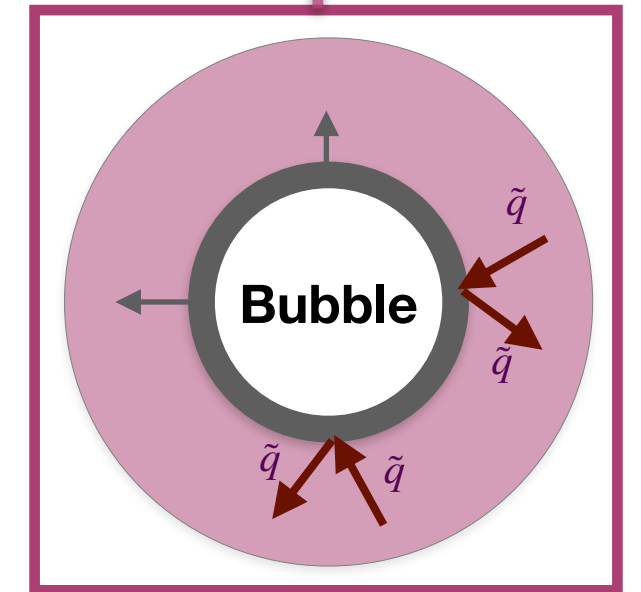


quark-string interaction win

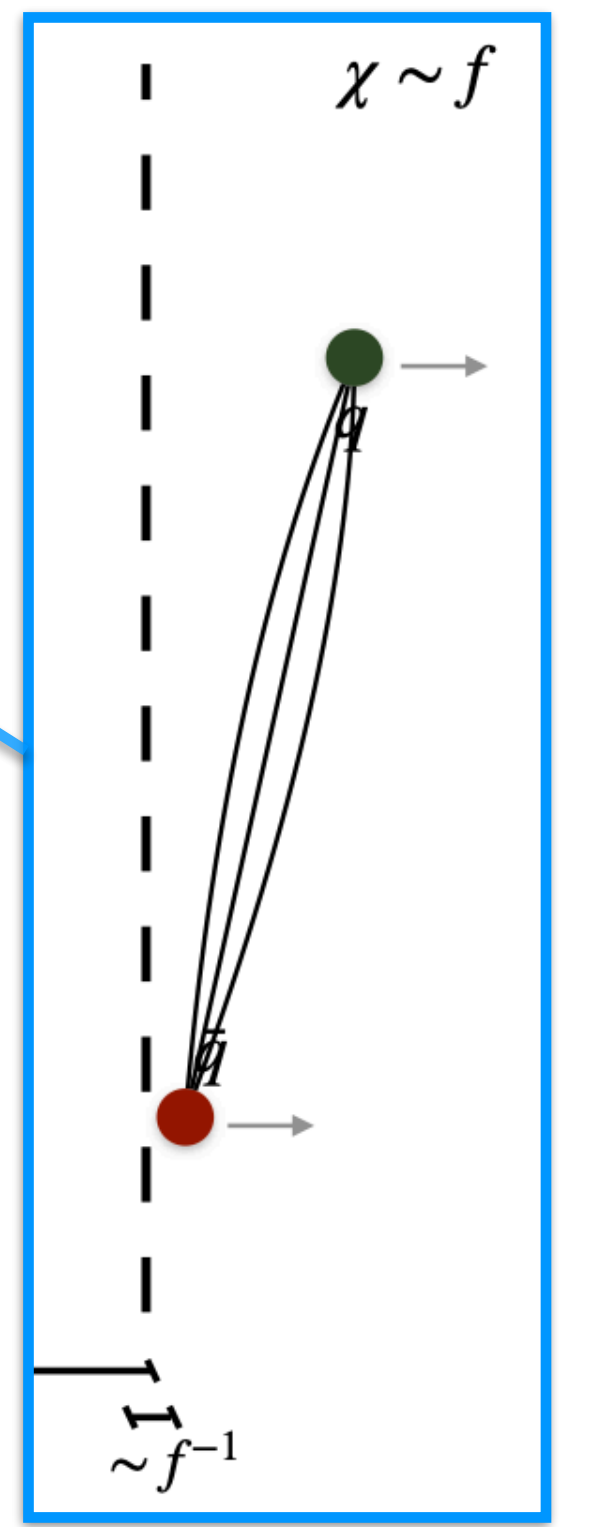


Quark nuggets Witten 1984  
Filtered DM. 1912.02830  
Thermal Squeezeout of DM. 2103.09827

Snow ball effect  
Ping-pong effect



No line distortion



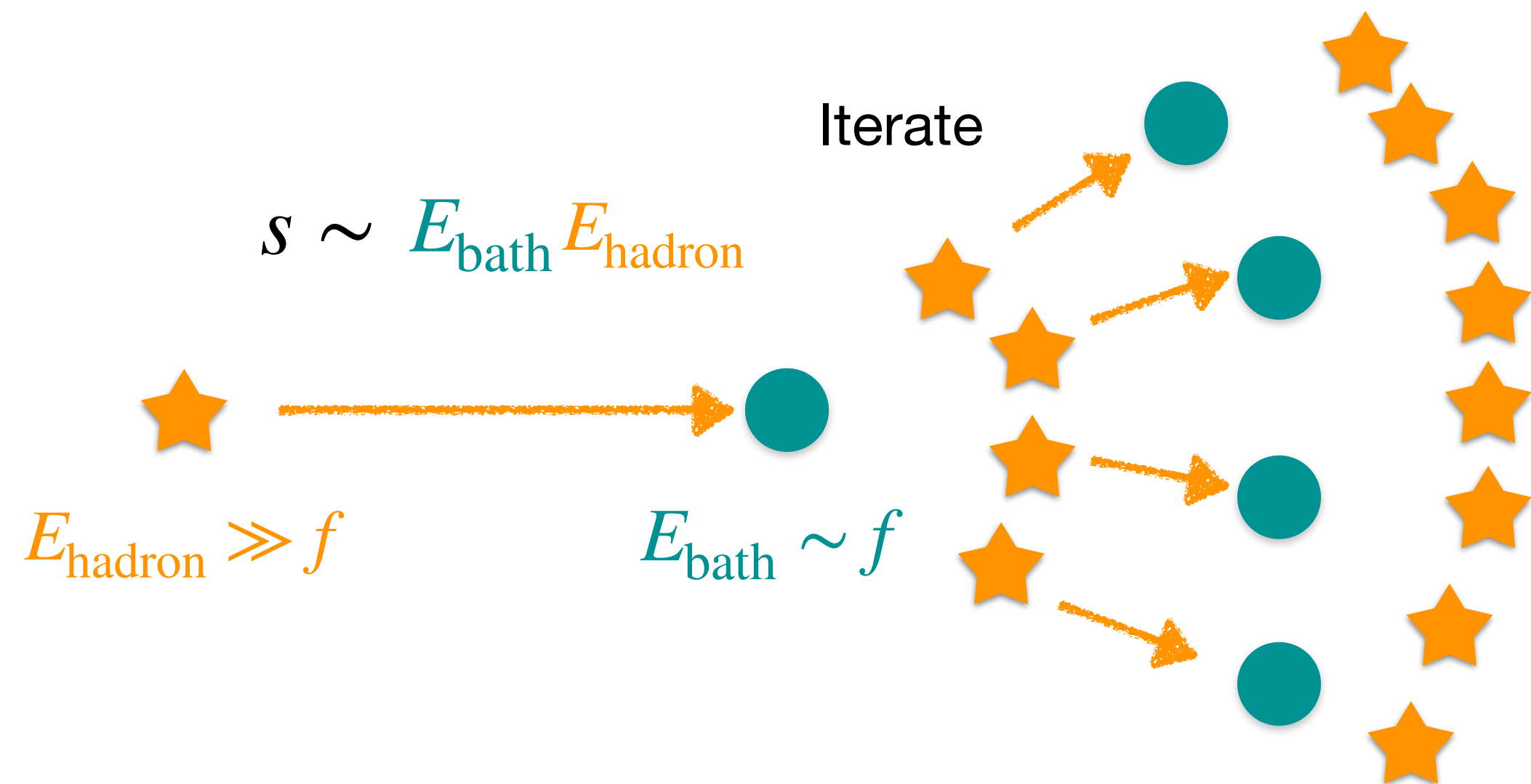
# Deep Inelastic Scattering in the Early Universe

Hadron energy in plasma (= CMB) frame

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

We find dominant scatterers in (p)reheated bath at

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



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

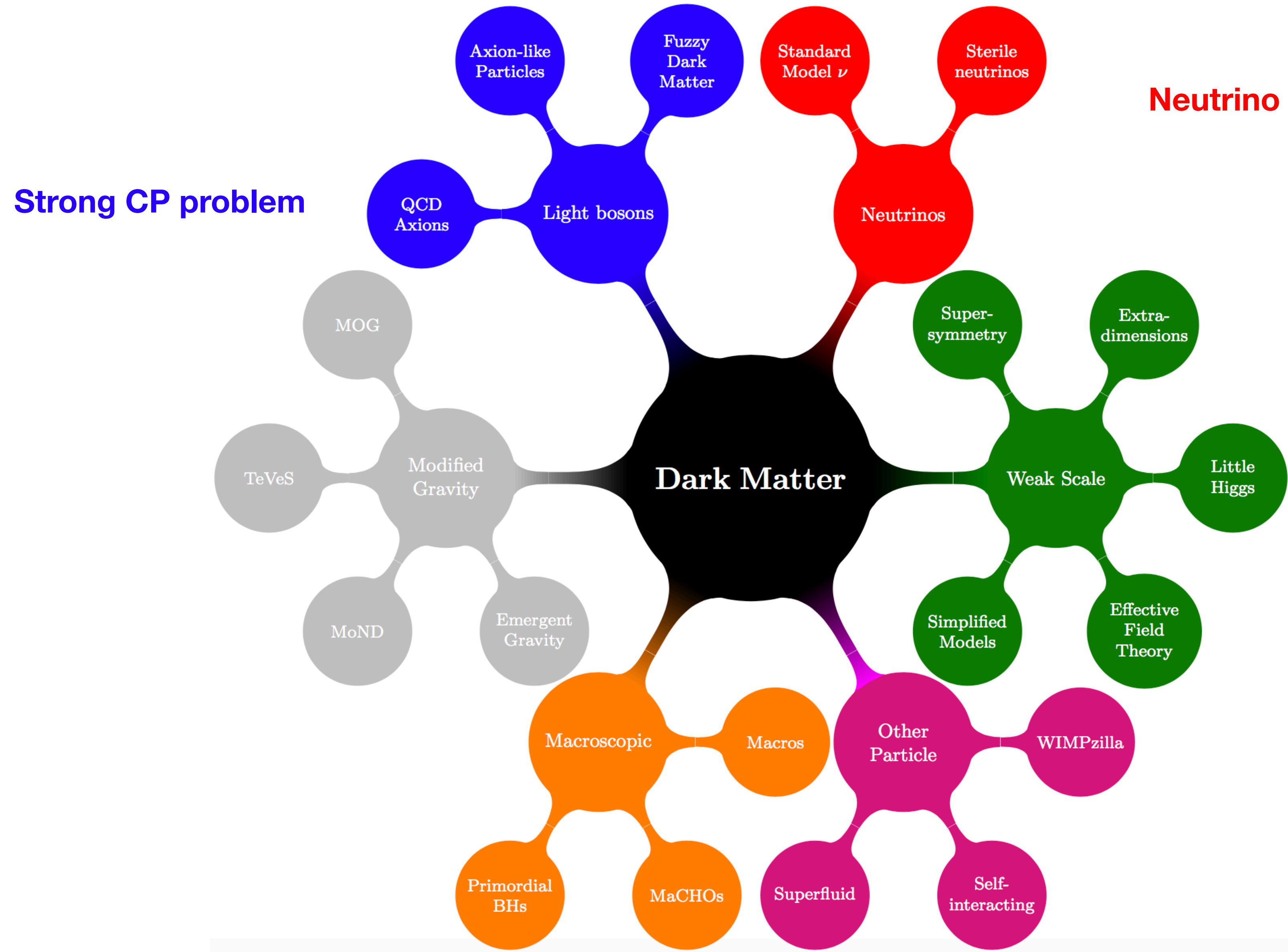
$$\gamma_{\text{cp}} \simeq \frac{\gamma_{\text{wp}}}{\gamma_{\text{wc}}} \quad \gamma_{\text{wc}} \simeq \frac{E_{\text{cm}}^{q\bar{q}}}{f} \simeq \sqrt{\gamma_{\text{wp}} \frac{T_{\text{nuc}}}{f}}$$

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

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

# Dark Matter candidates

(WIMPs=Weakly-Interacting Massive Particles)



Neutrino oscillations puzzle

Hierarchy problem

Two motivations for the WIMPs:

1) Connection with Hierarchy problem

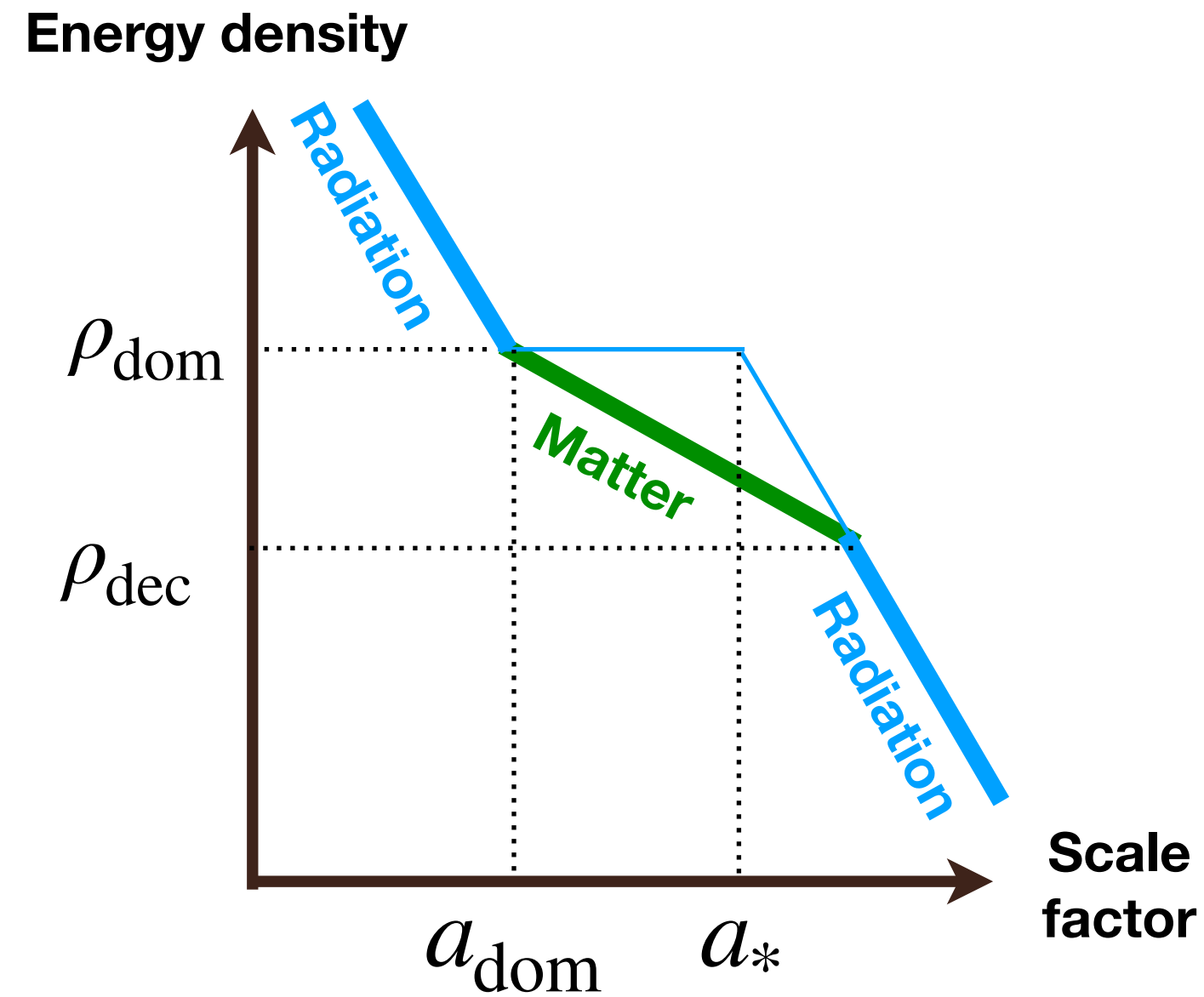
$$M_{DM} \sim 1 \text{ TeV}, \quad \alpha \sim \alpha_{\text{weak}}$$

2) Thermal Dark Matter

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

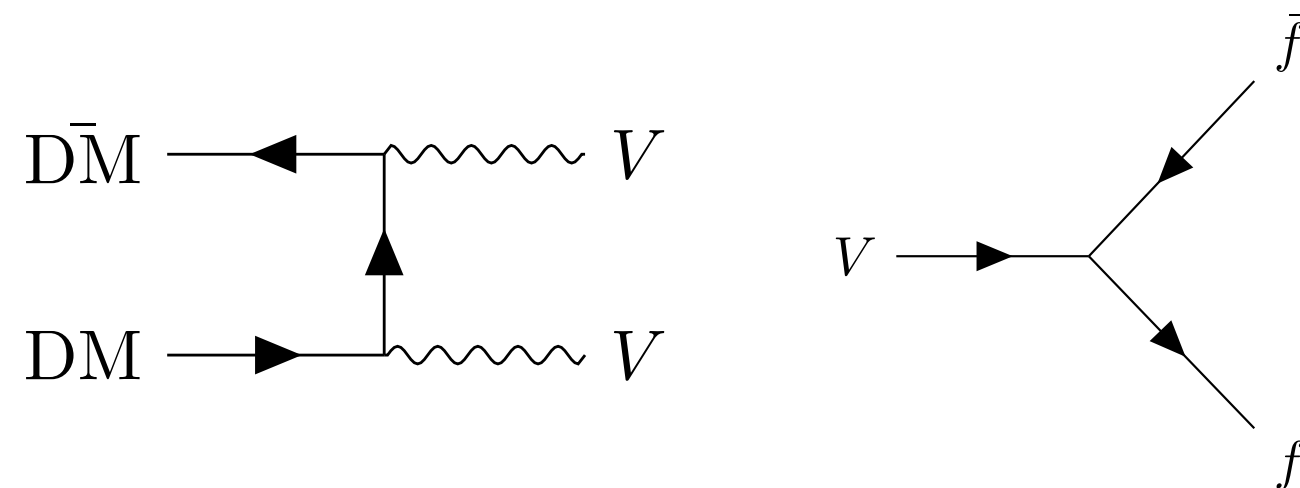
# Entropy injection

## 1) After a matter era



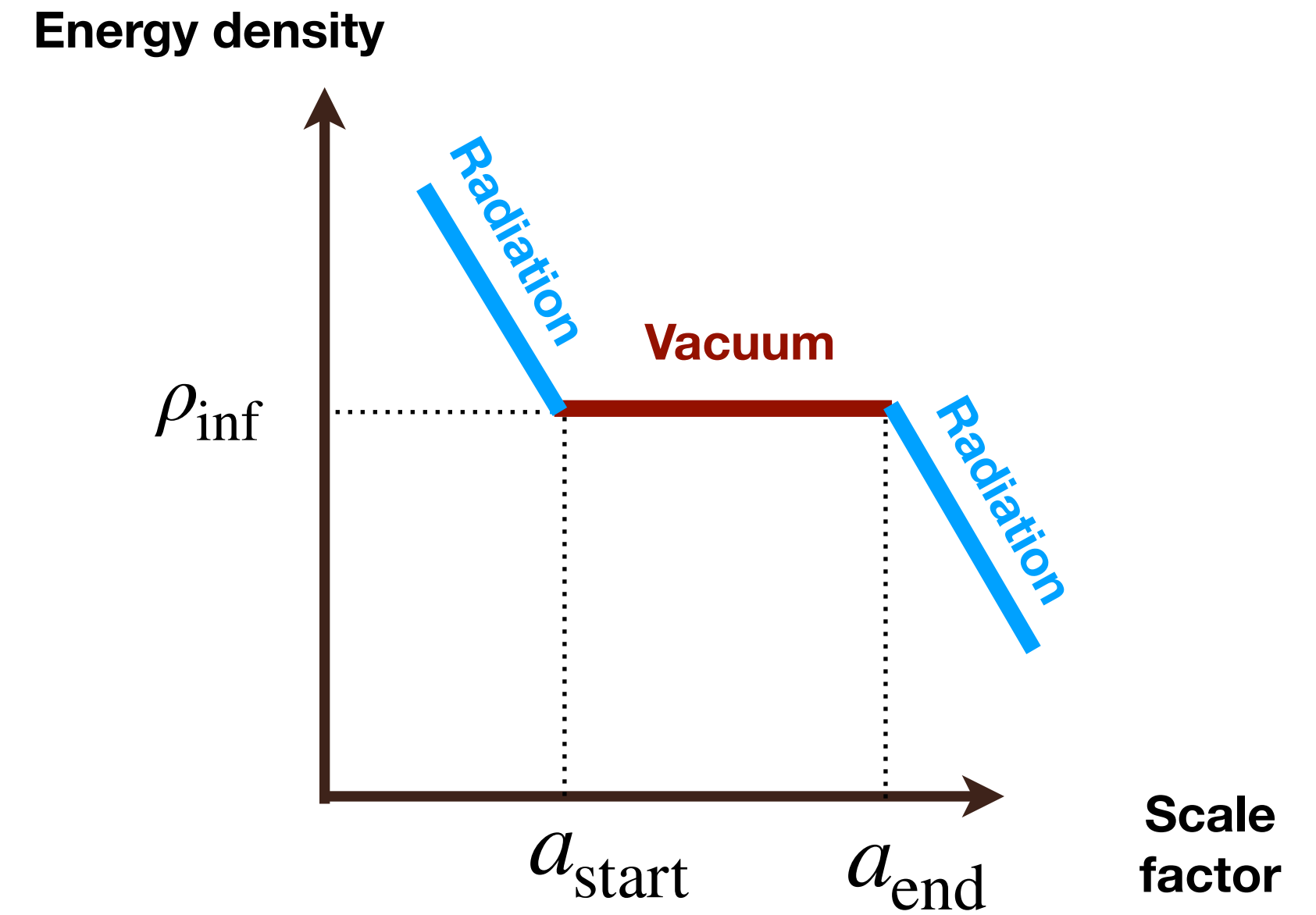
$$D = \left( \frac{a_{\text{dom}}}{a_*} \right)^3 = \frac{T_{\text{dom}}}{T_{\text{dec}}} \simeq \frac{m_V}{\sqrt{M_{\text{pl}} \Gamma_V}}$$

Homeopathic DM



Cirelli, Gouttenoire, Petraki, Sala, 2018

## 2) After an inflationary era



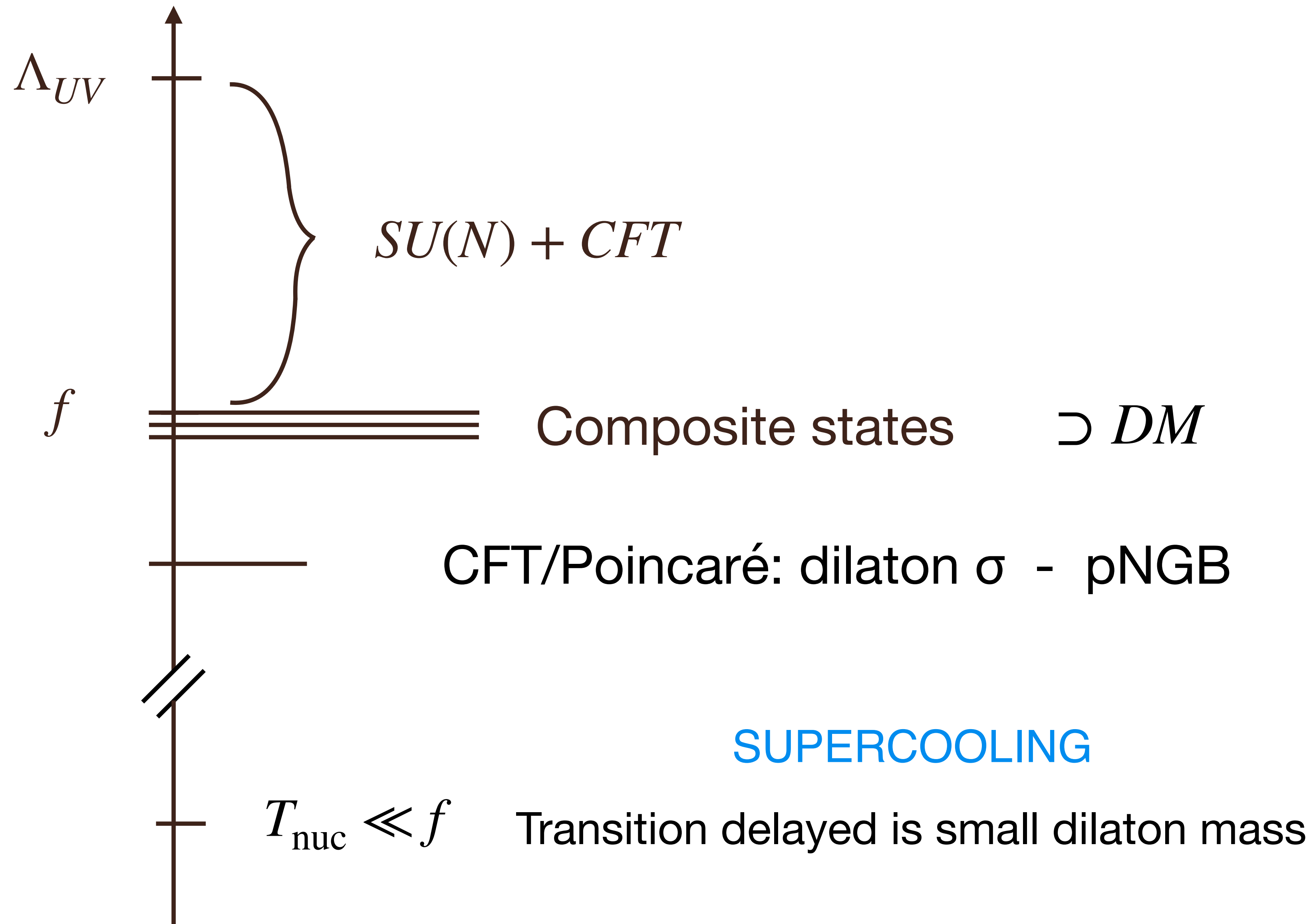
$$D = \left( \frac{a_{\text{end}}}{a_{\text{start}}} \right)^3 = e^{3 N_e} = \left( \frac{f}{T_{\text{nuc}}} \right)^3$$

Supercooled confinement

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

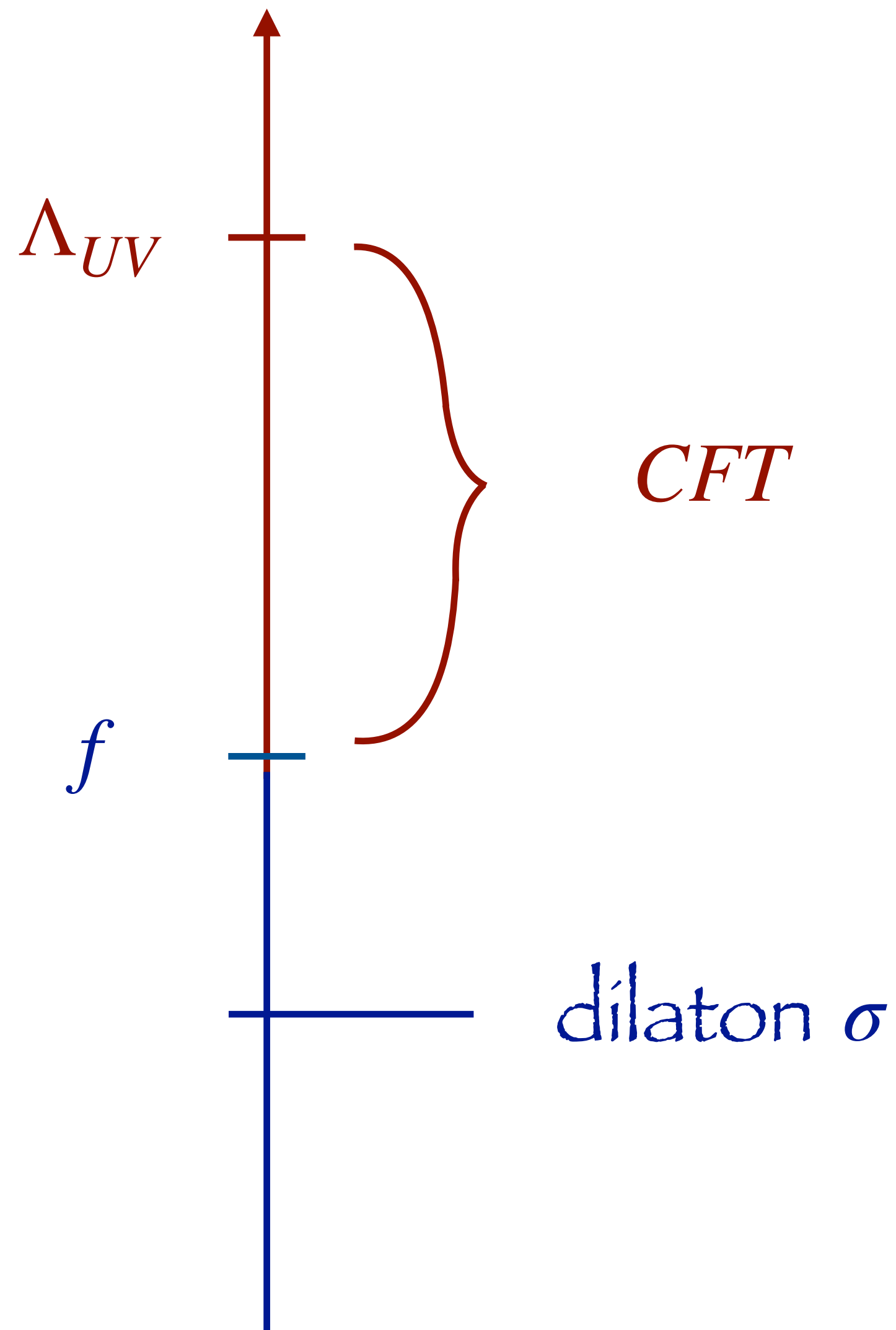
Baldes, Gouttenoire, Sala, 2020

# Nearly-conformal strong sector





# Nearly-conformal strong sector



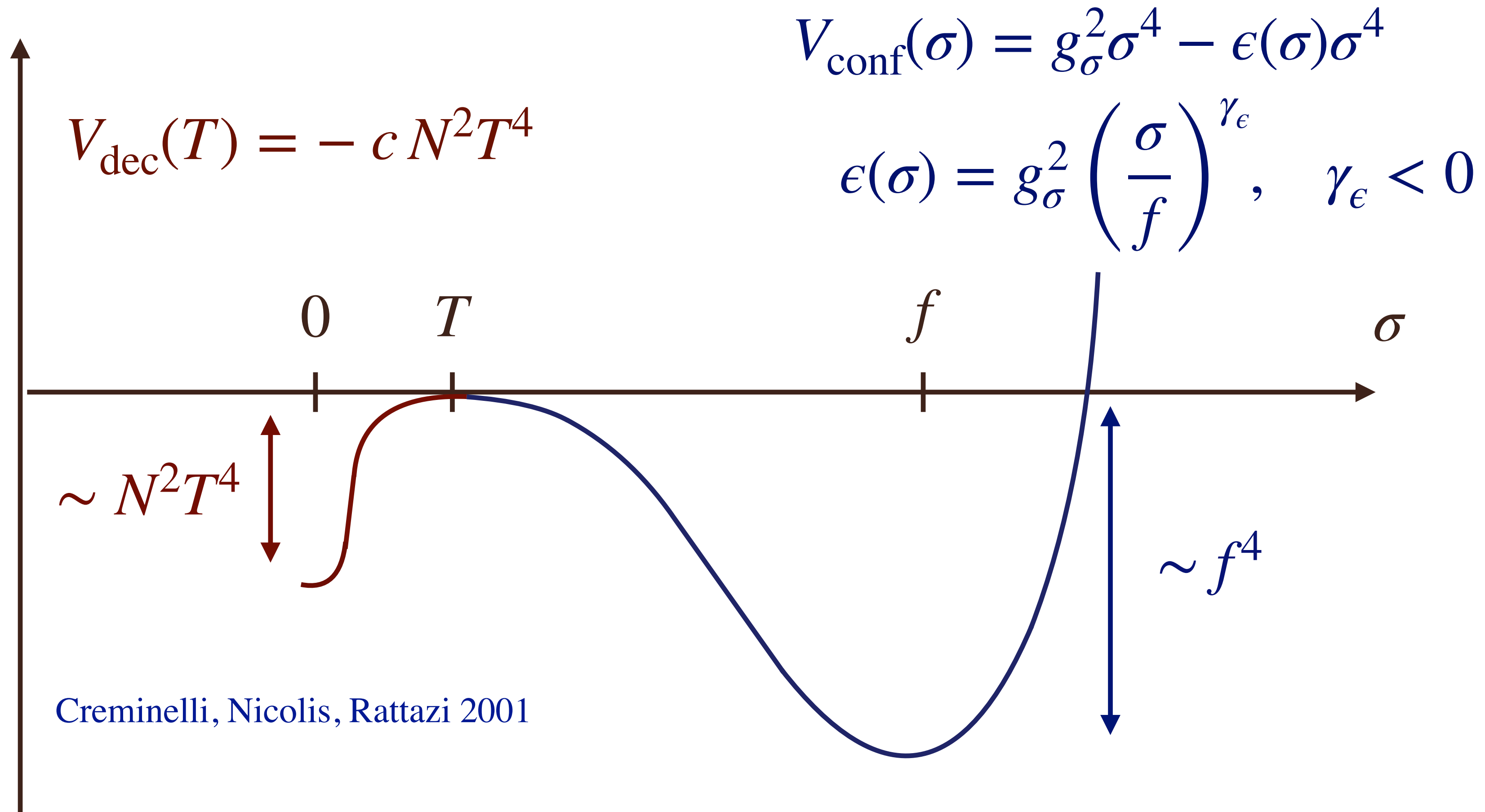
Deconfined phase

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

Confined phase

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

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



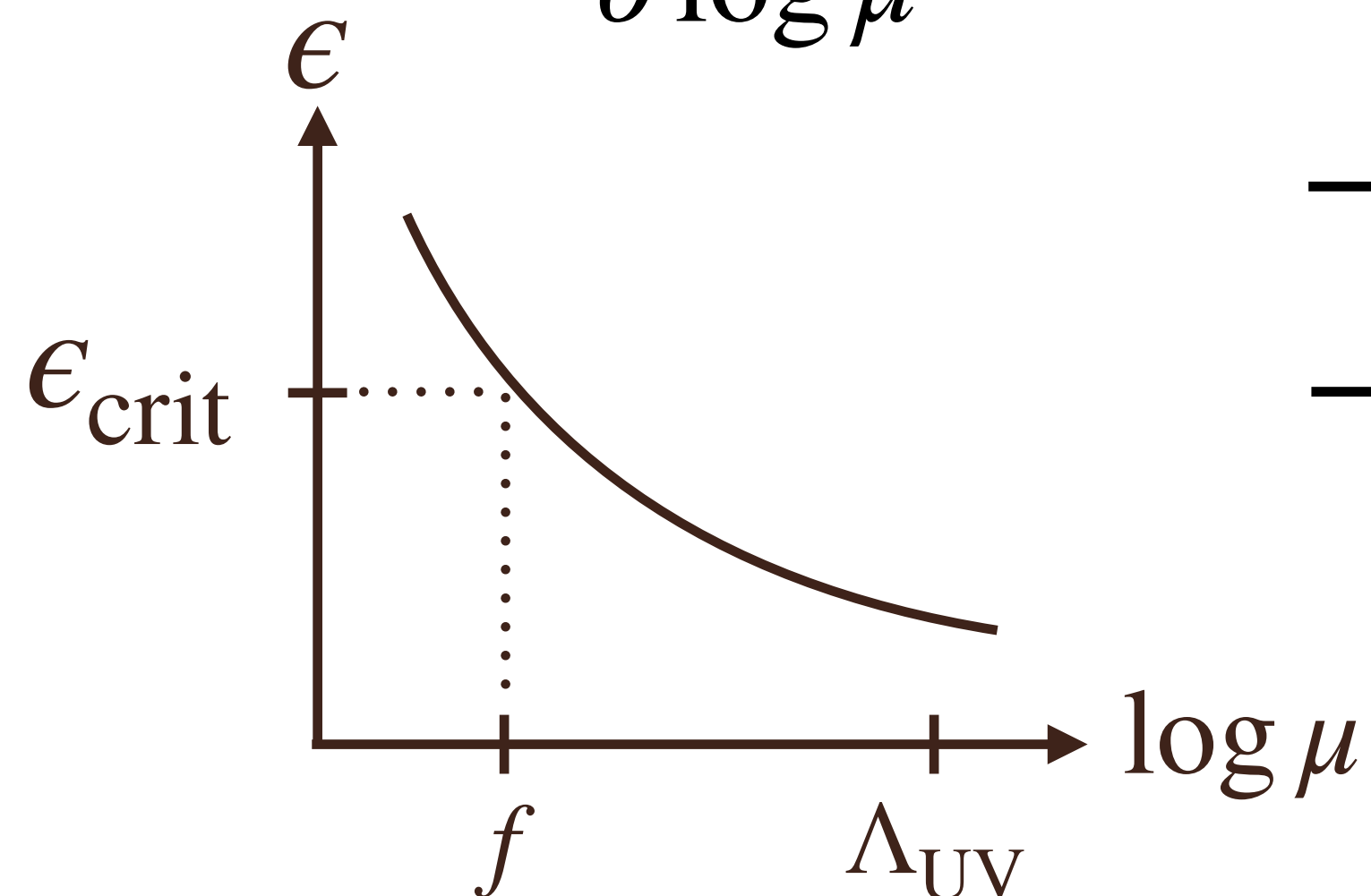
**Super-cooling starts for:**  $T_{\text{start}} \sim f$

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

# Nearly-conformal strong sector

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

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



→ Scale inv. spontaneously broken

→ pNGB: the dilation  $\sigma$

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

# Gravitational Waves from Supercool Phase Transition

Randall Servant hep-ph/0607158,...

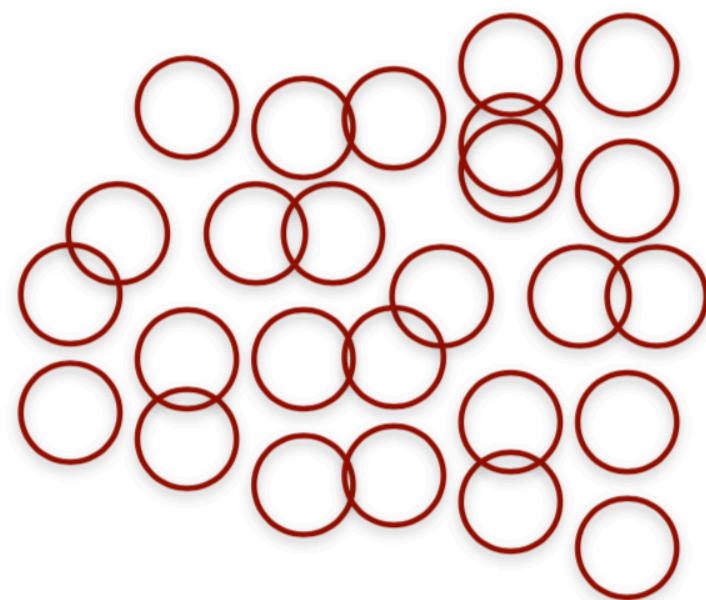
$$\Omega_{\text{GW}} \propto (H/\beta) \times (H/\beta)$$

Bubble size  $\times$  Collision time

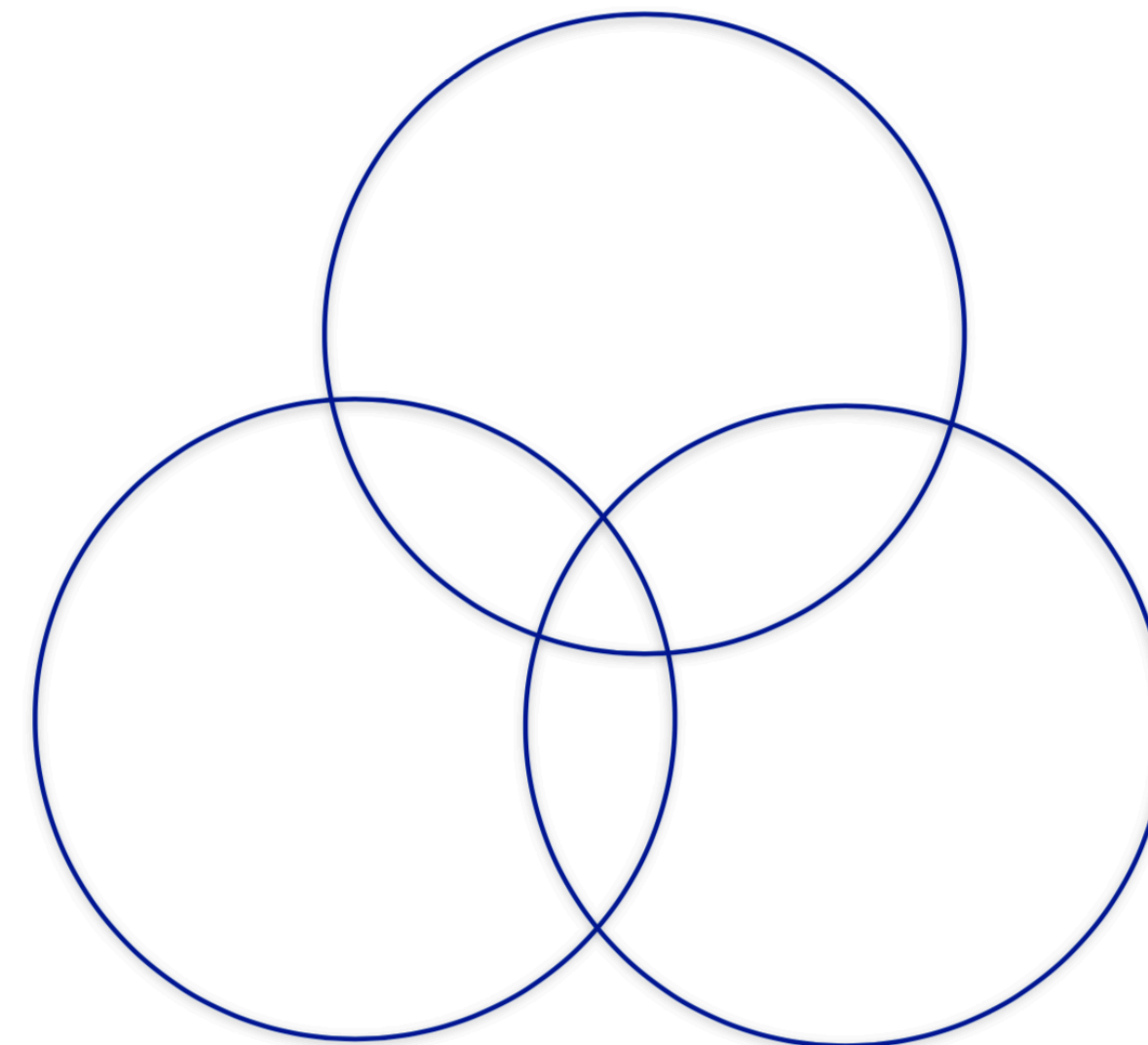
$$\frac{\beta}{H} \simeq T \left. \frac{dS_4}{dT} \right|_{T_{\text{nuc}}} \simeq 15 \left( \frac{10}{N_{\text{e-fold}}} \right)^2$$

Standard 1st order PT

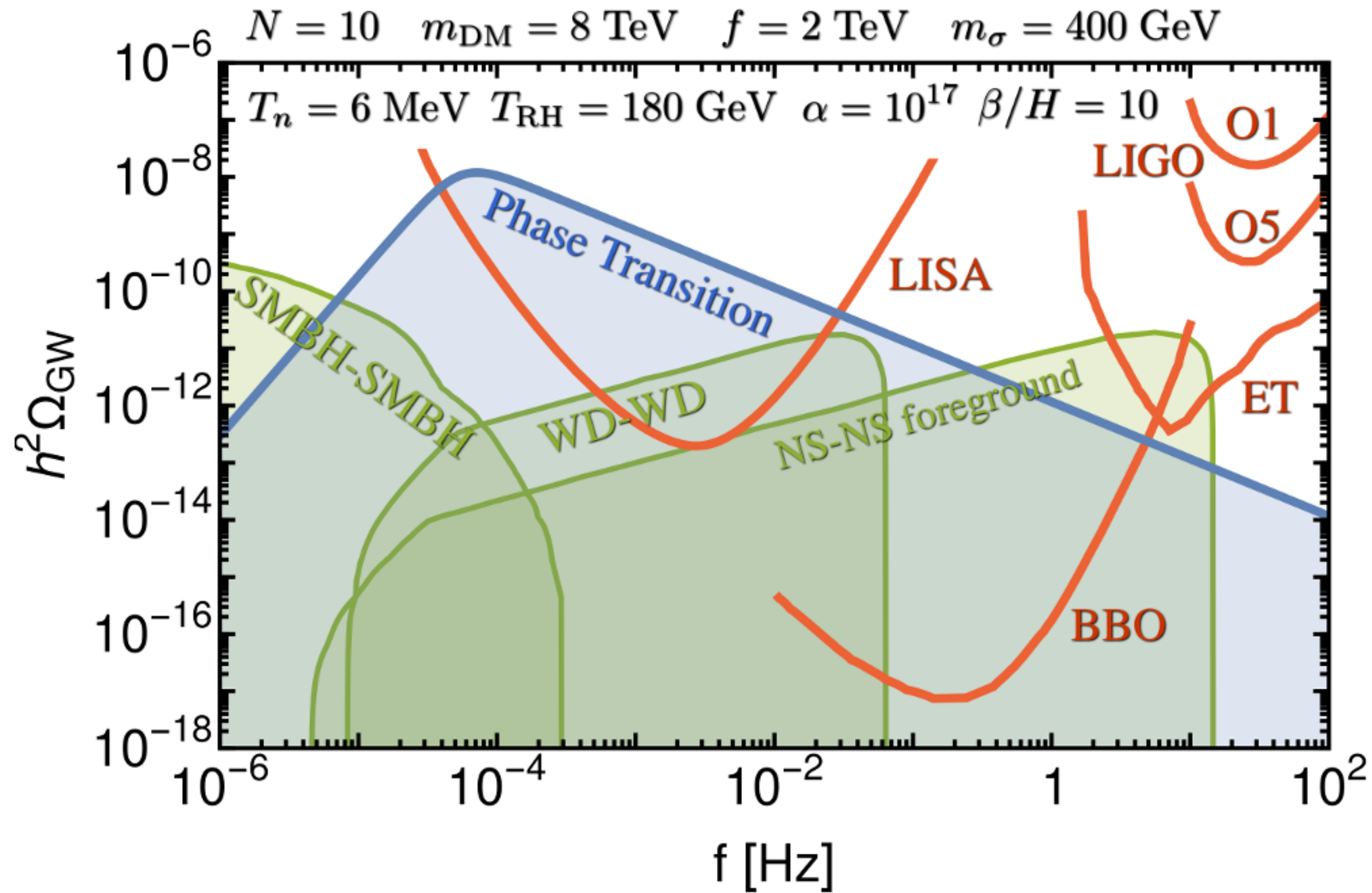
$\beta/H \sim 100$



Supercooled PT  
 $\beta/H \sim 10$



# Gravitational Waves from Phase Transition



# Nucleation Temperature

Supercooling begins at

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

Bubble nucleation ends SC at

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

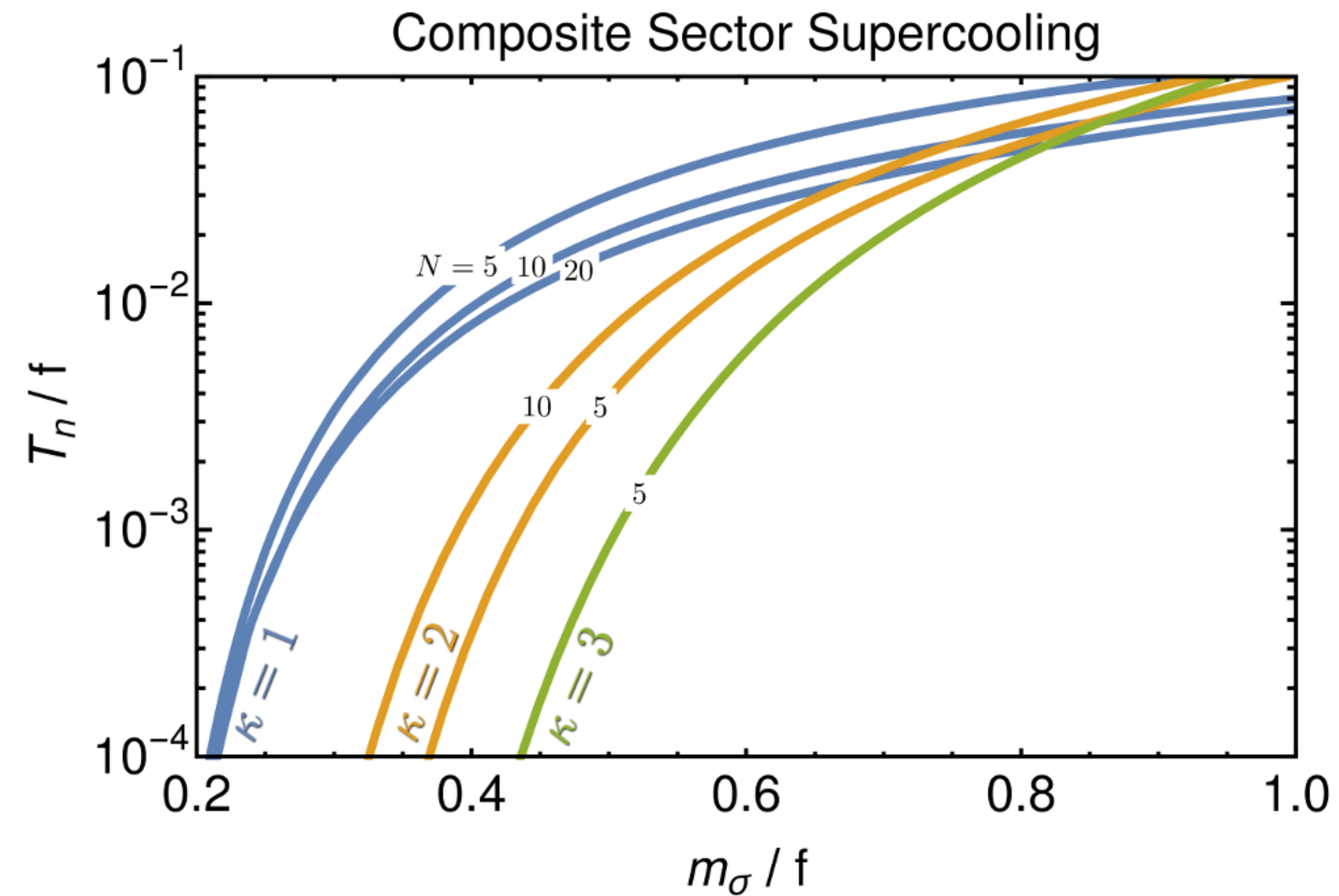
Nucleation happens when tunnelling rate  $\sim$  Hubble

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

Bounce action  $S_4 \approx 100$

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

# Nucleation Temperature



For small  $m_\sigma$  PT seem to never complete!



But then it can be triggered by QCD

Iso Serpico Shimada 1704.04955

von Harling Servant 1711.11554

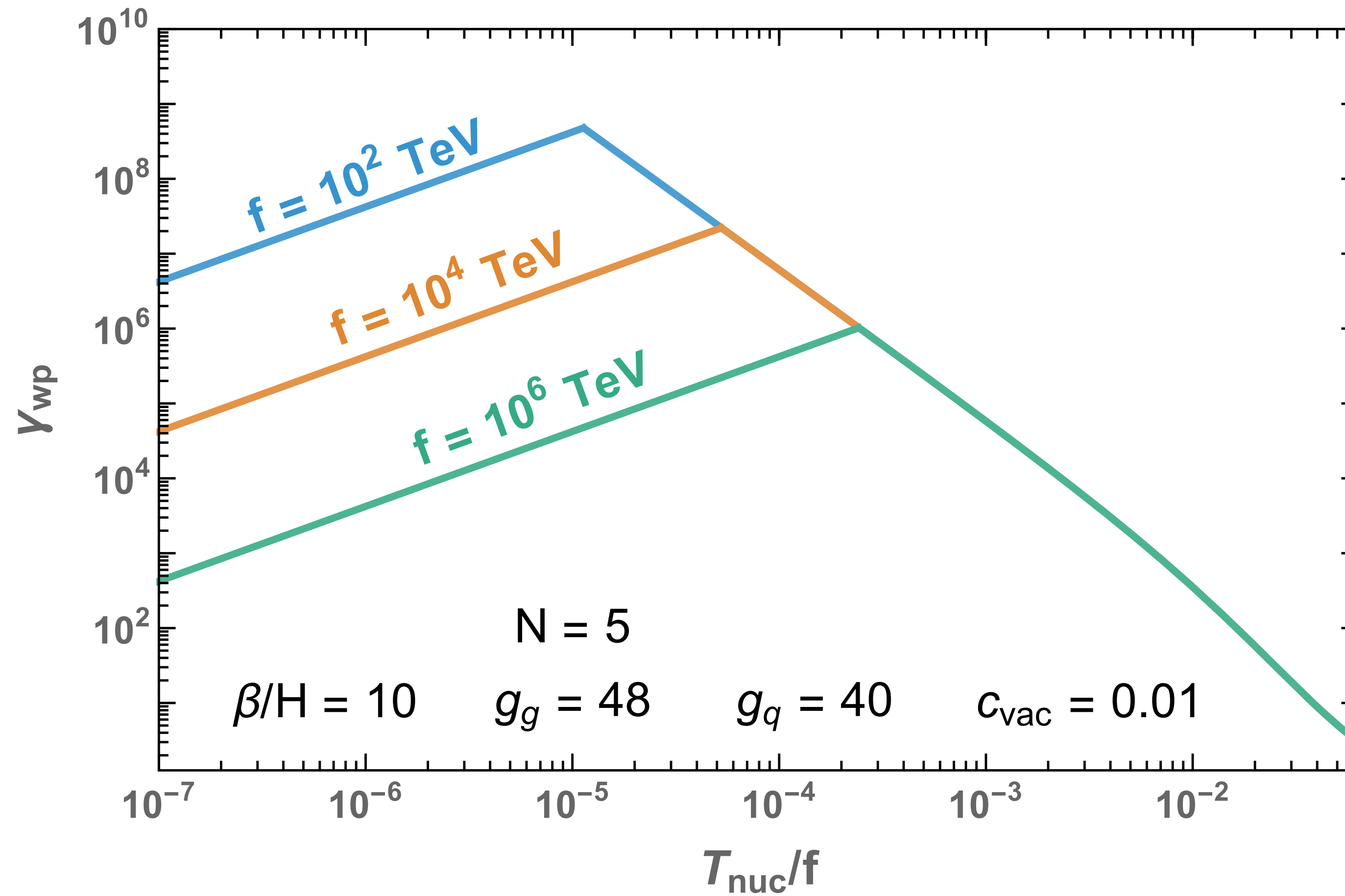


Catalysed by black holes ?

Gregory, Moss, Withers 15

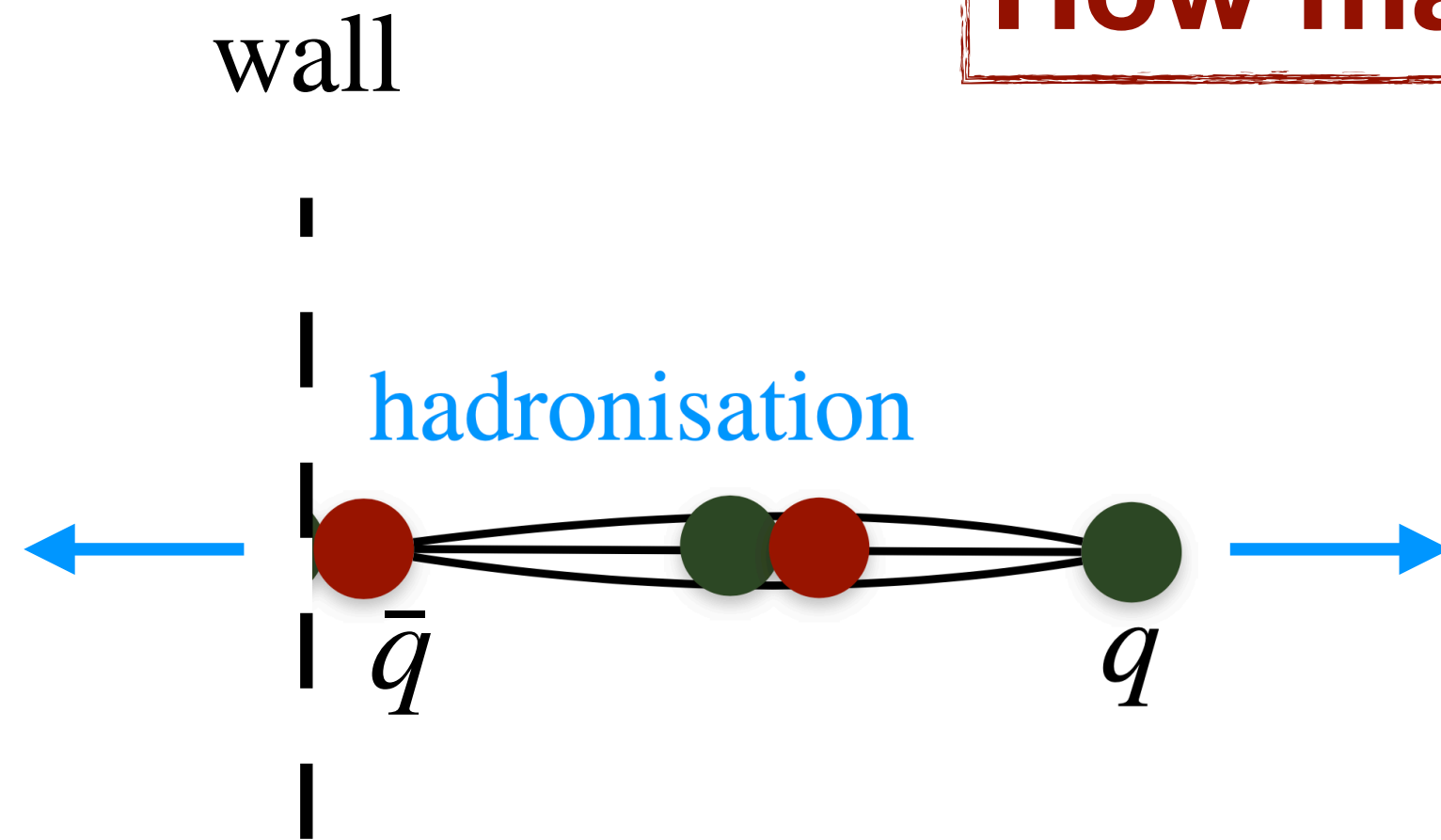
Mukaïda, Yamada 17

# Bubble wall Lorentz factor





# How many hadrons ?



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

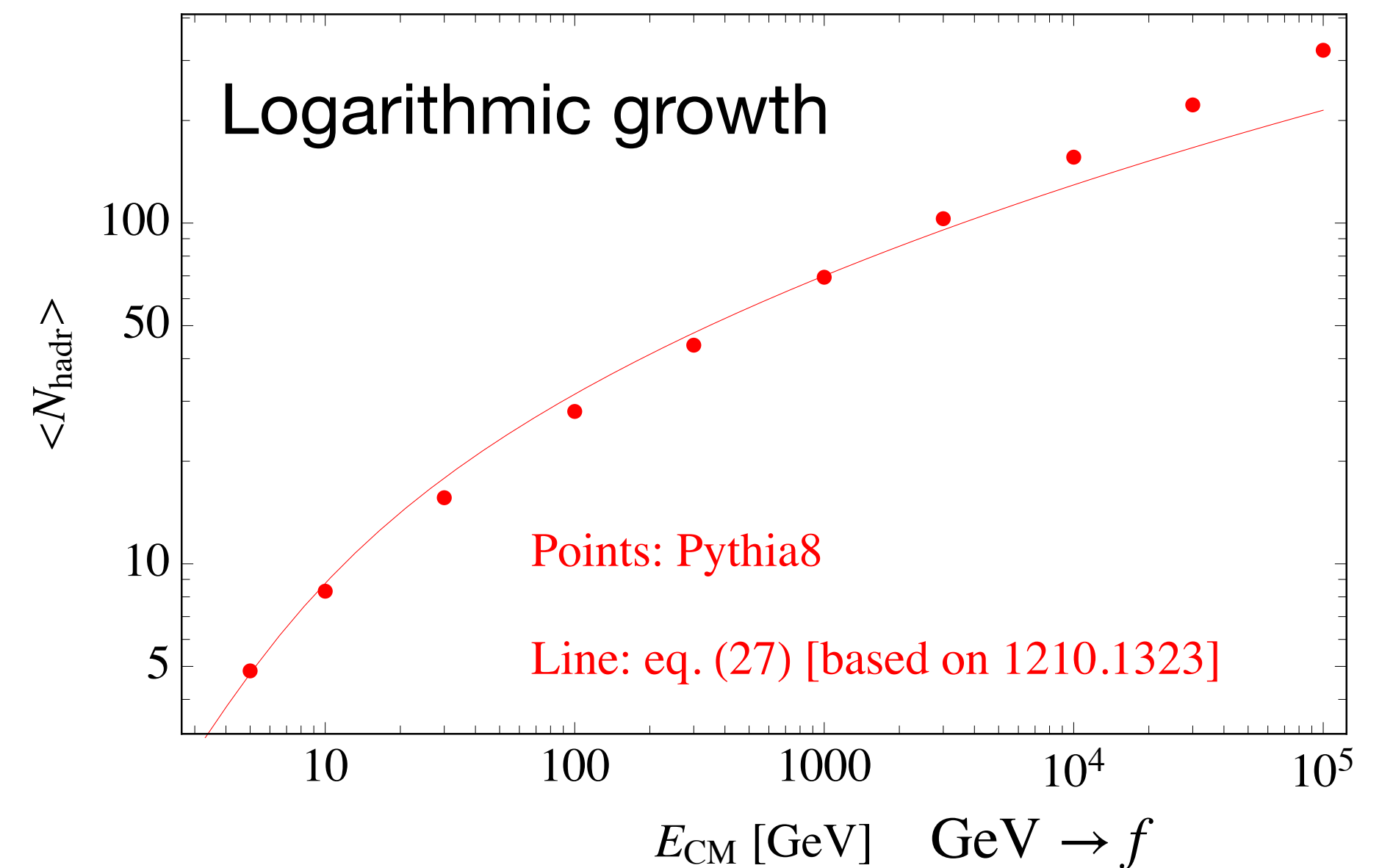
Analogous to  $e^+e^- \rightarrow q\bar{q}$  in QCD

Use Pythia with

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

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

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



# DM abundance after supercooling

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

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

Standard Supercooling Branching ratio quark  $\rightarrow$  DM String fragmentation

2 possibilities:

Combinatoric

Thermal distrib.

DM: light meson

DM: heavy baryon

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

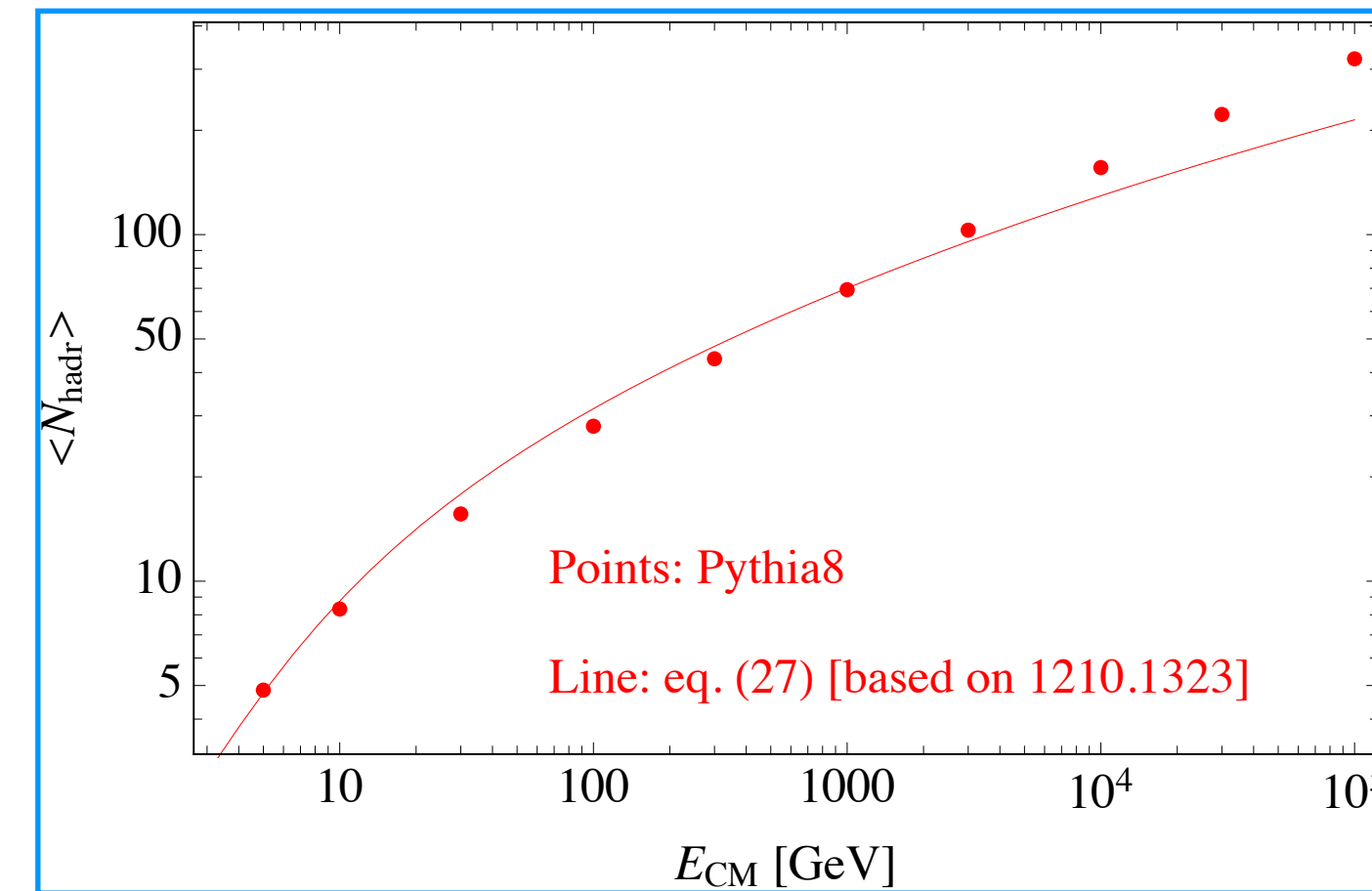
$$BR \propto \exp - m_{\text{DM}}/f$$

# DIS in the Sky: result



Brute force: iterate this  $\longrightarrow$

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



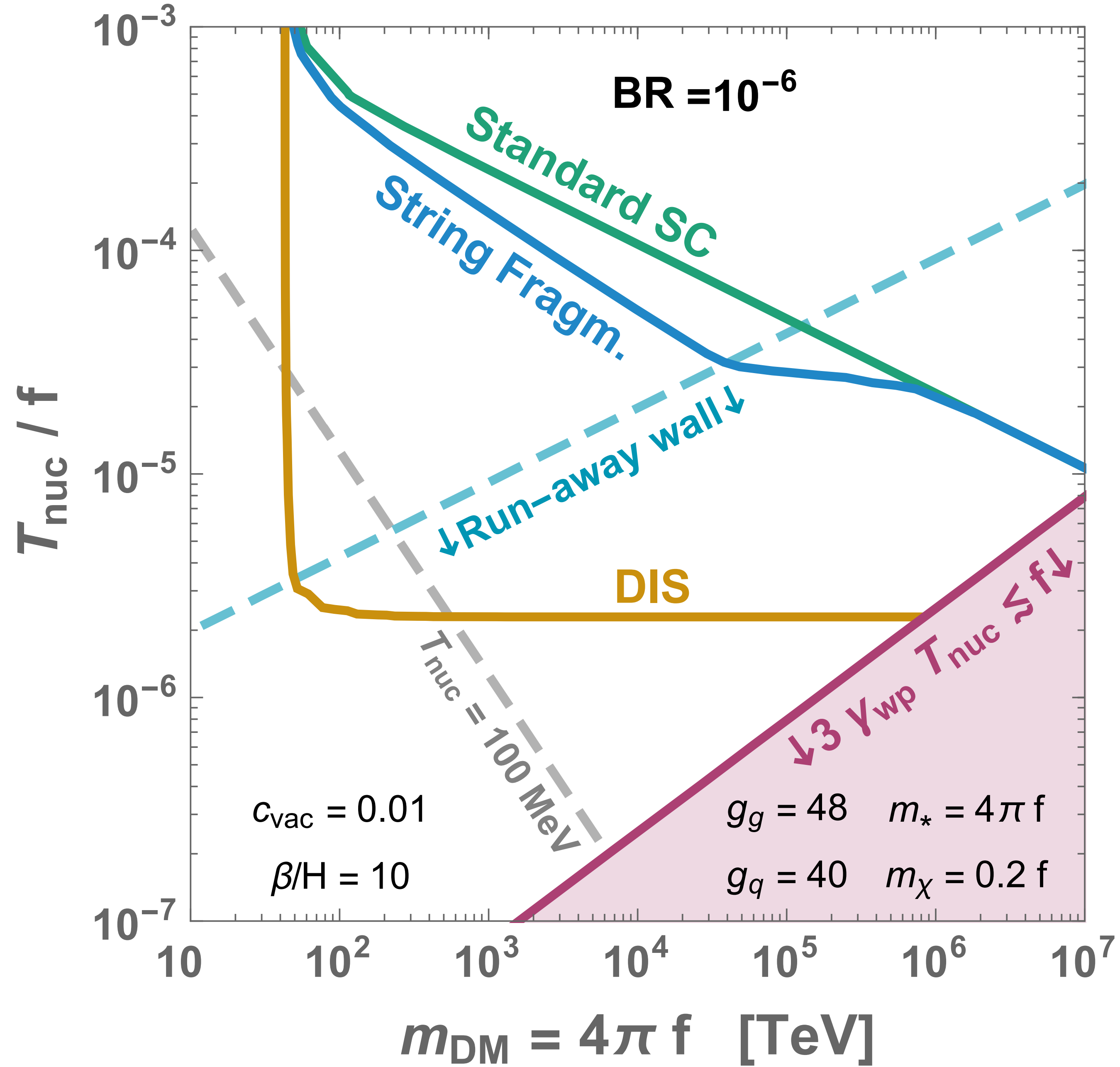
O(1) fraction of initial hadron energy converted into hadron masses

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

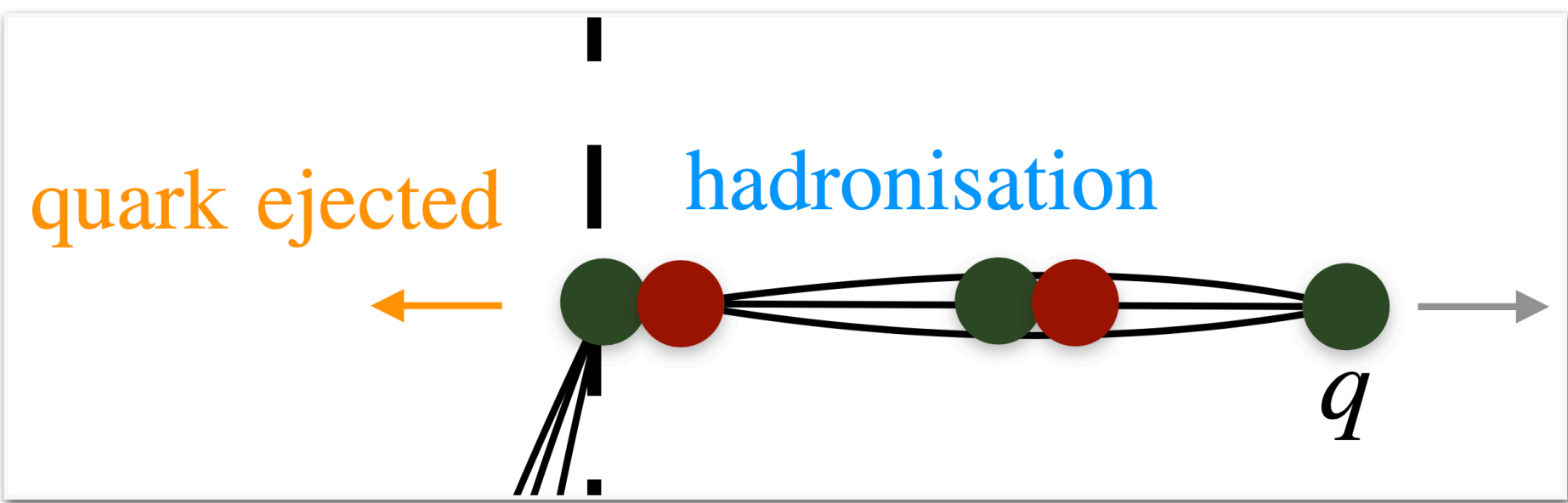
$$\frac{\gamma_{cp} E_{q\bar{q}}^{\text{CM}}}{\langle N_{\text{hadr}} \rangle} \quad \langle N_{\text{hadr}} \rangle Y_{\text{SC}} \quad \longrightarrow \quad \langle N_{\text{hadr}} \rangle \text{ simplifies!}$$

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

# Supercool Composite DM



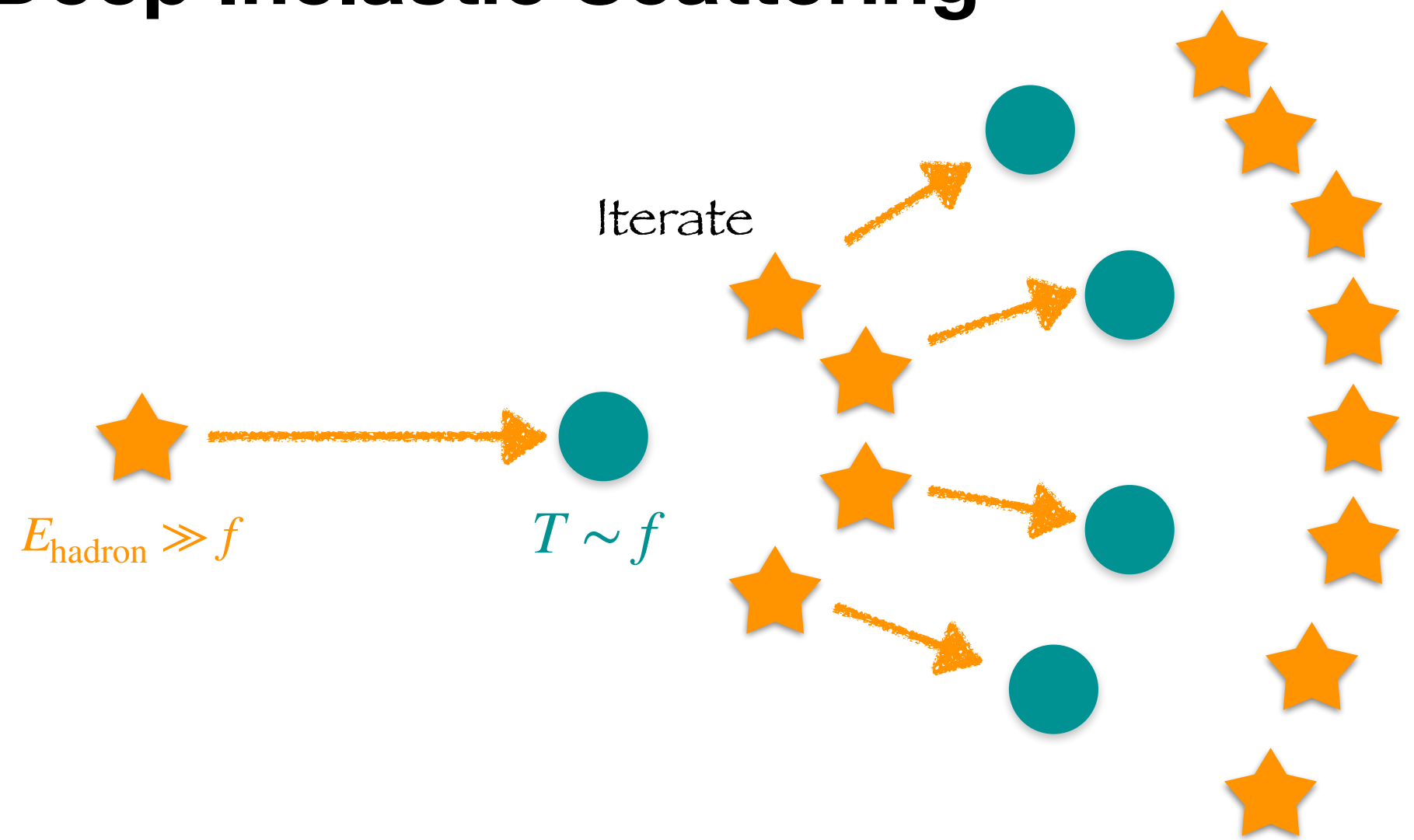
# Consequences on DM abundance



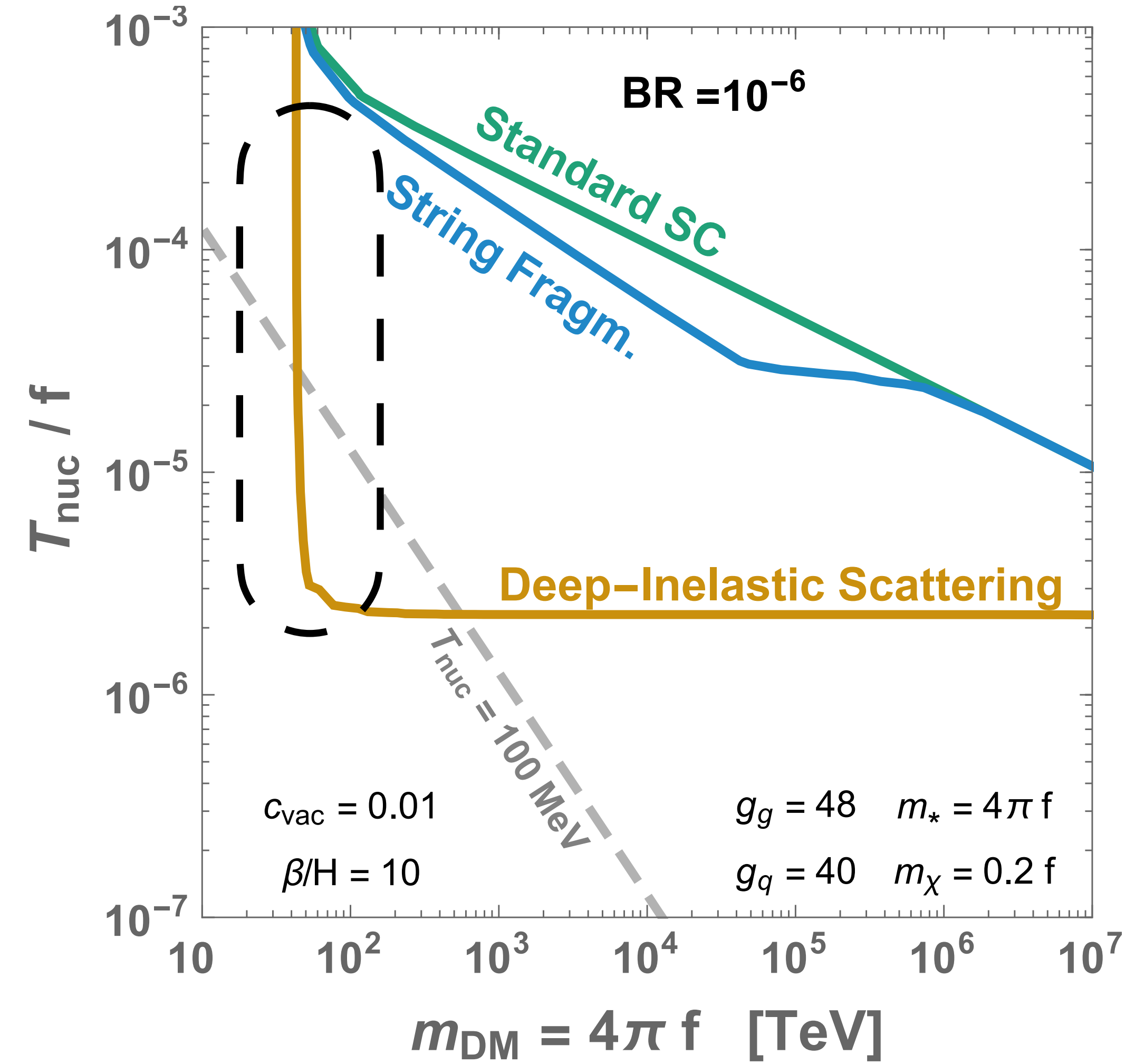
## 1. String fragmentation + quark ejection

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

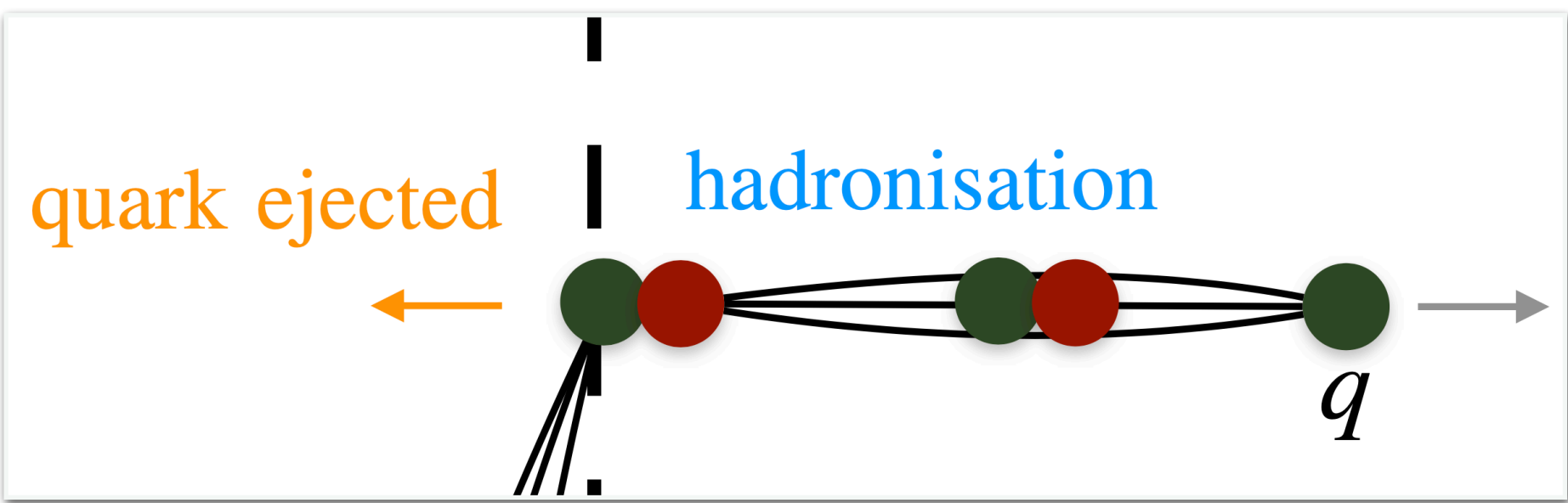
## 2. Deep Inelastic Scattering



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



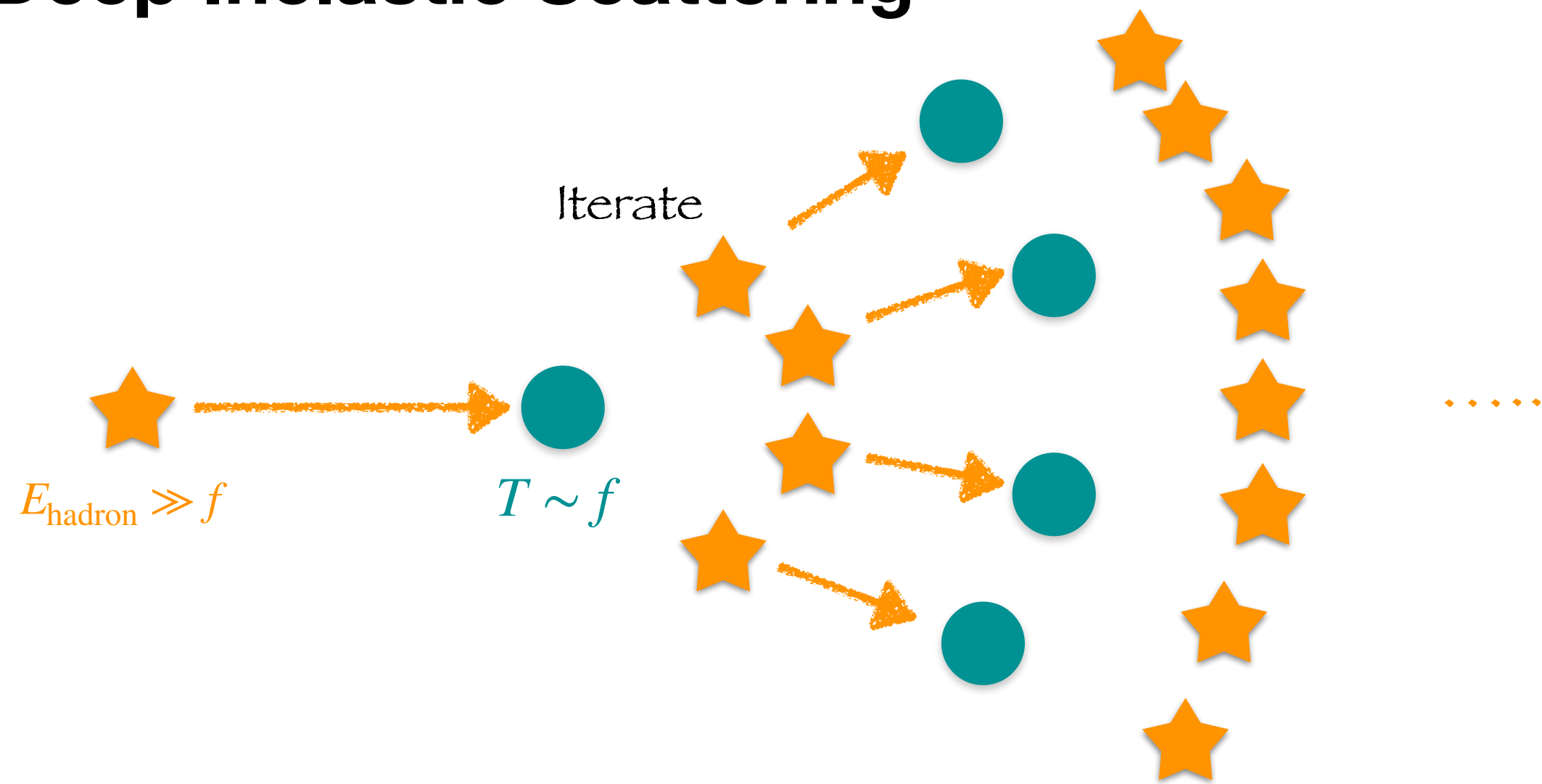
# Consequences on DM abundance



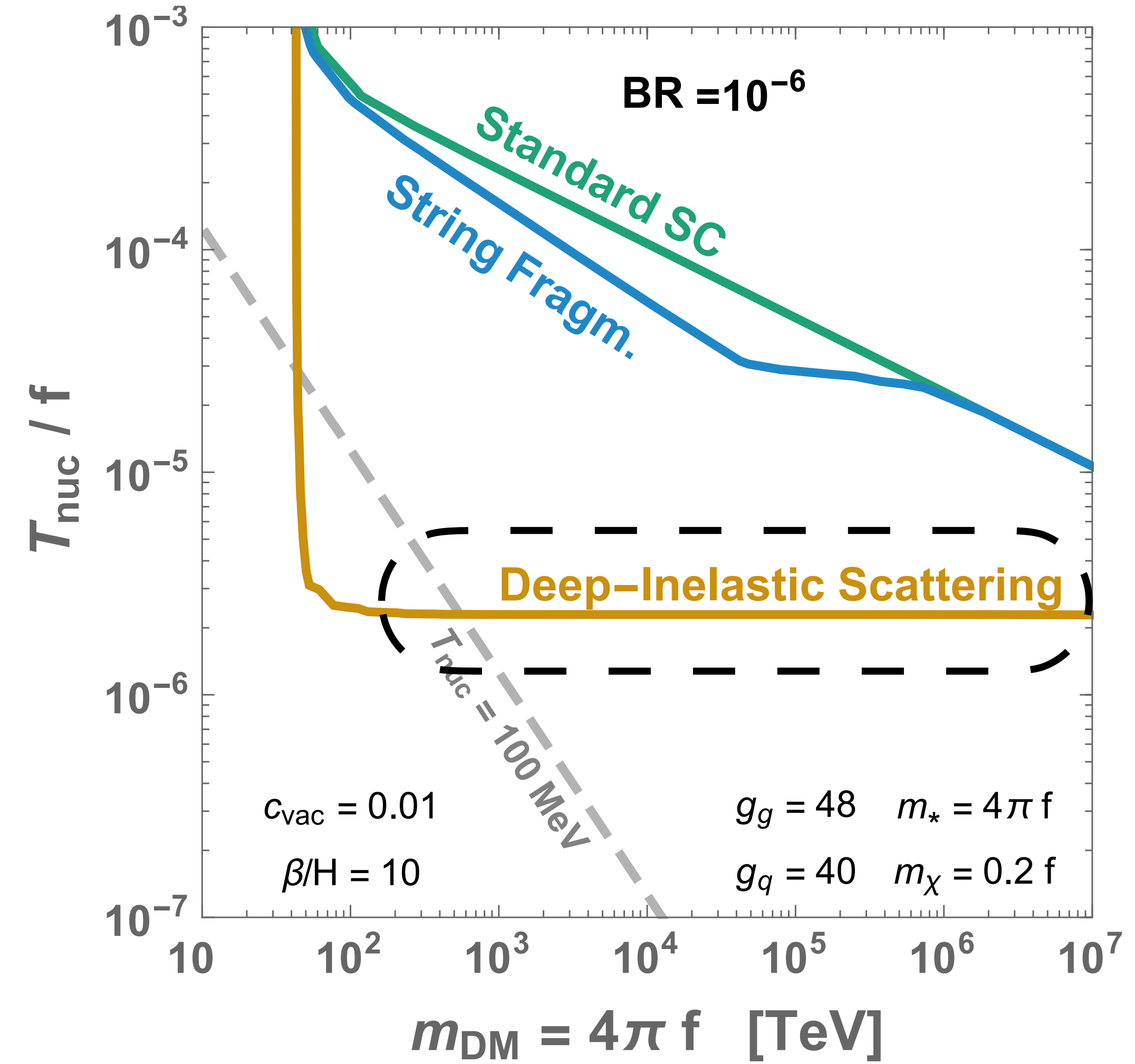
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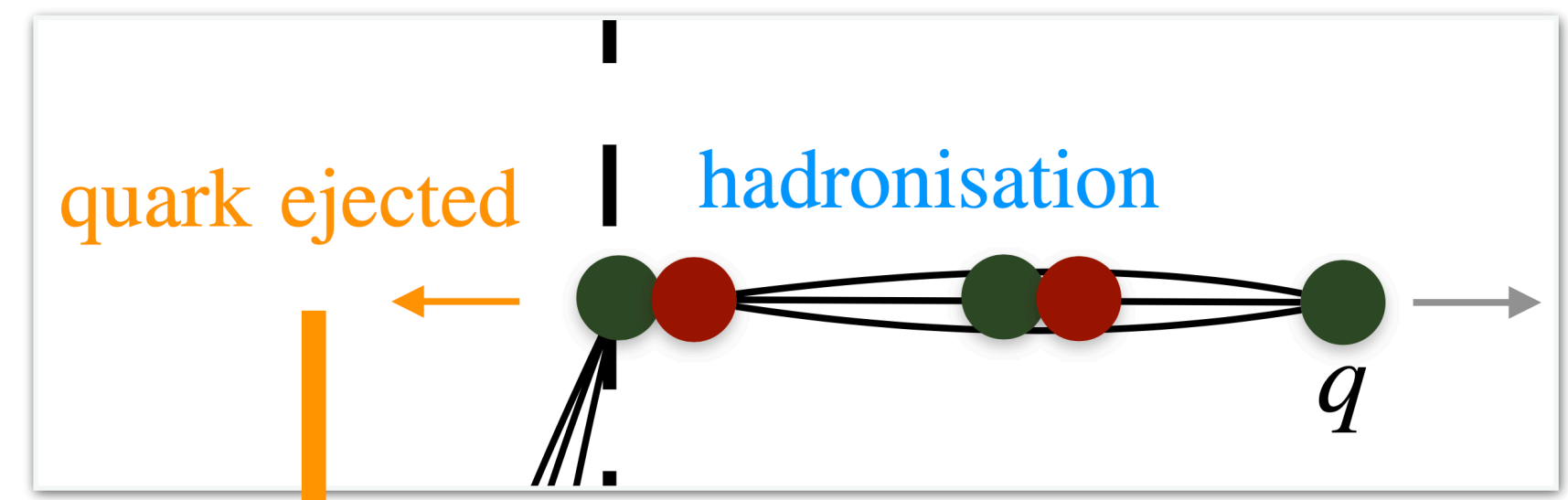
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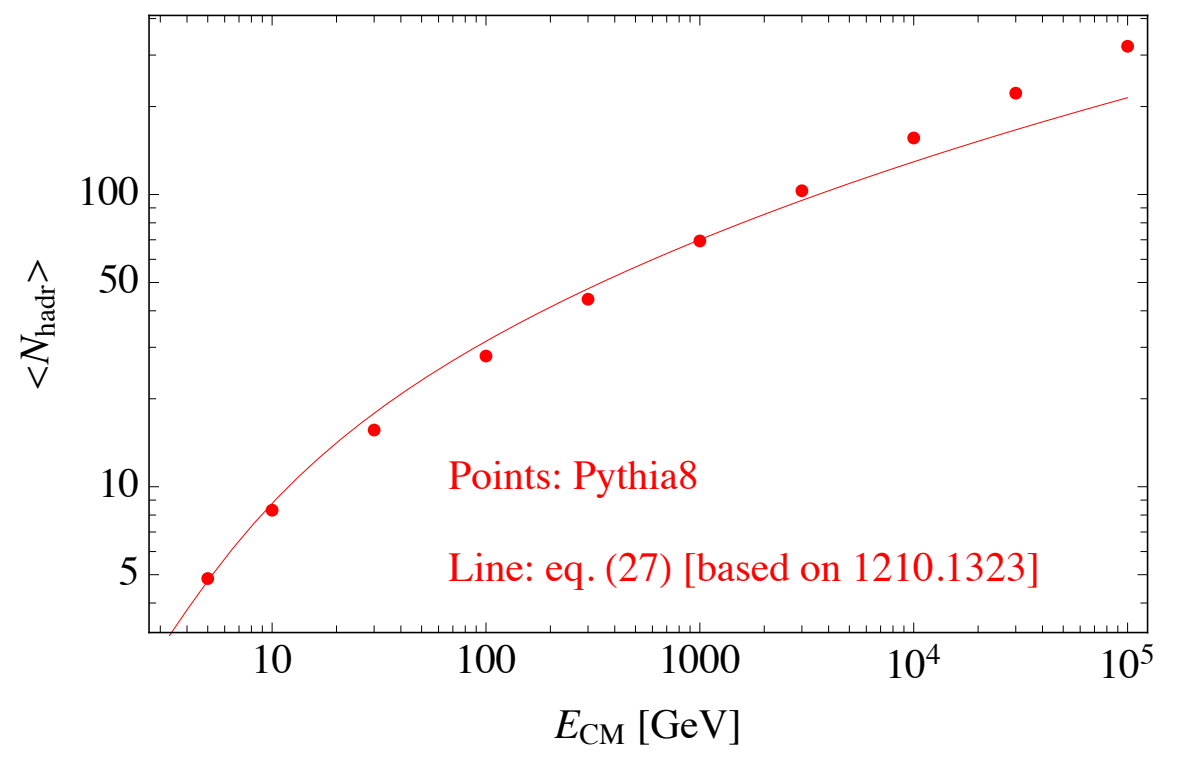
$$Y_{\text{DM}} / Y_{\text{DM}}^{\text{naive}} \propto \gamma_{\text{wp}} \propto \frac{T_{\text{nuc}}}{f} \frac{M_{\text{Pl}}}{f}$$



# Cosmological consequences



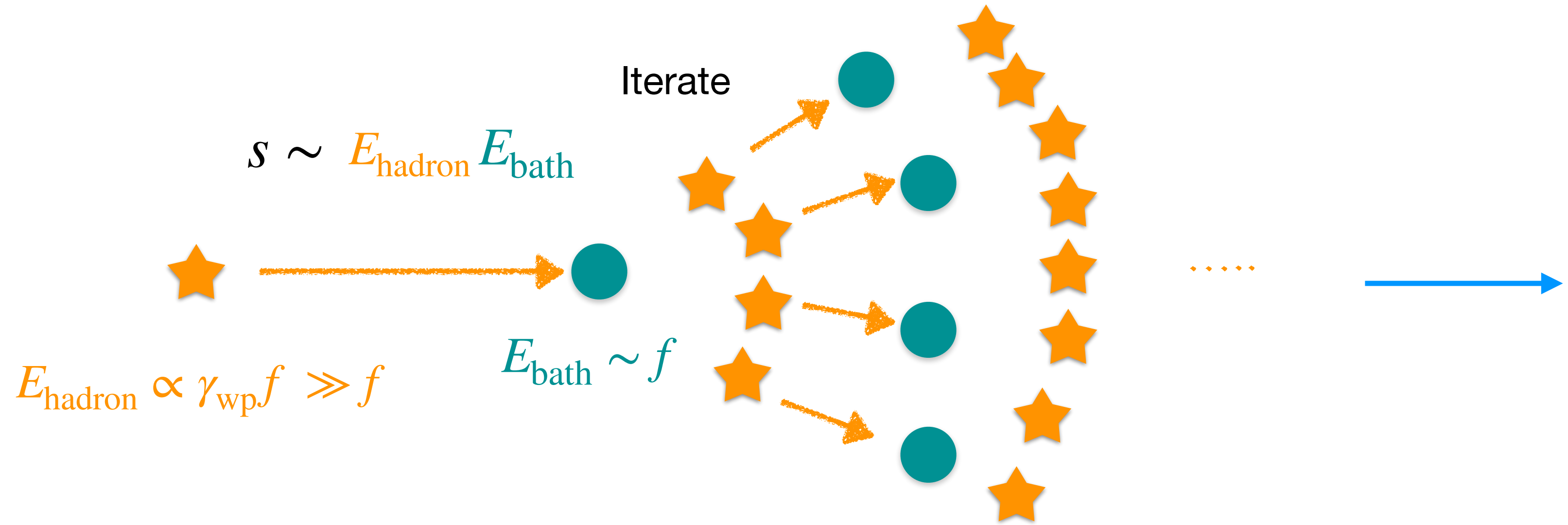
## 1. More hadrons per initial quark pair



$Y_{\text{D}}$

Ejected quarks give contribution of same order of magnitude

## 2. Cosmological catapuit

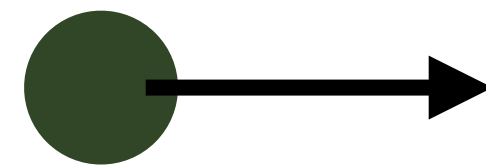


runaway regime

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

# Interaction with other quarks ?

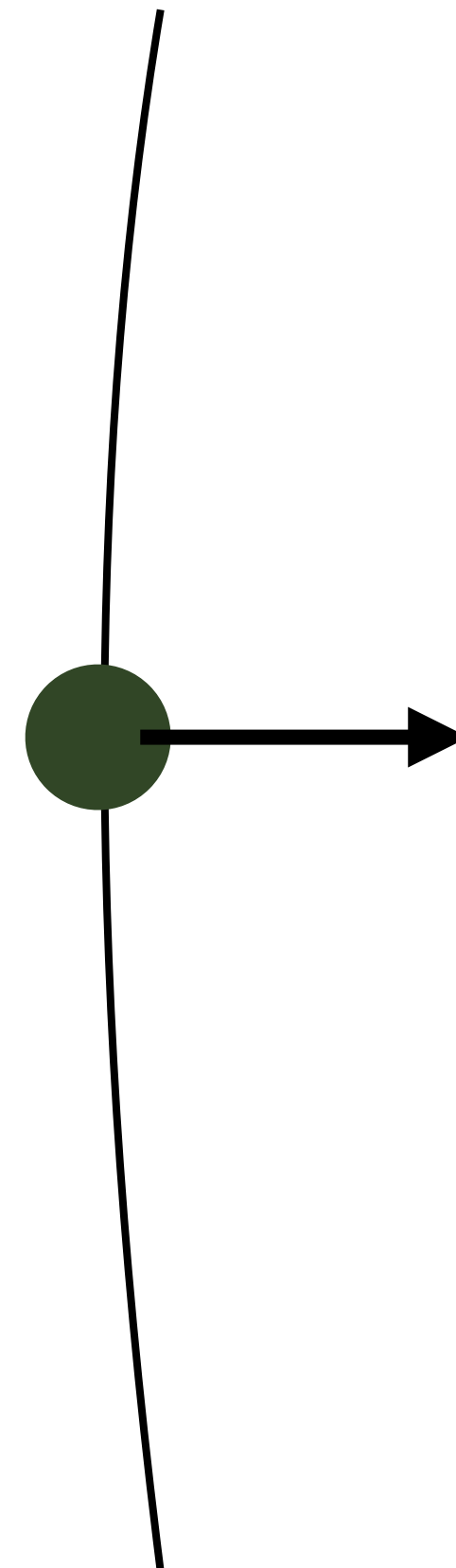
Bubble wall





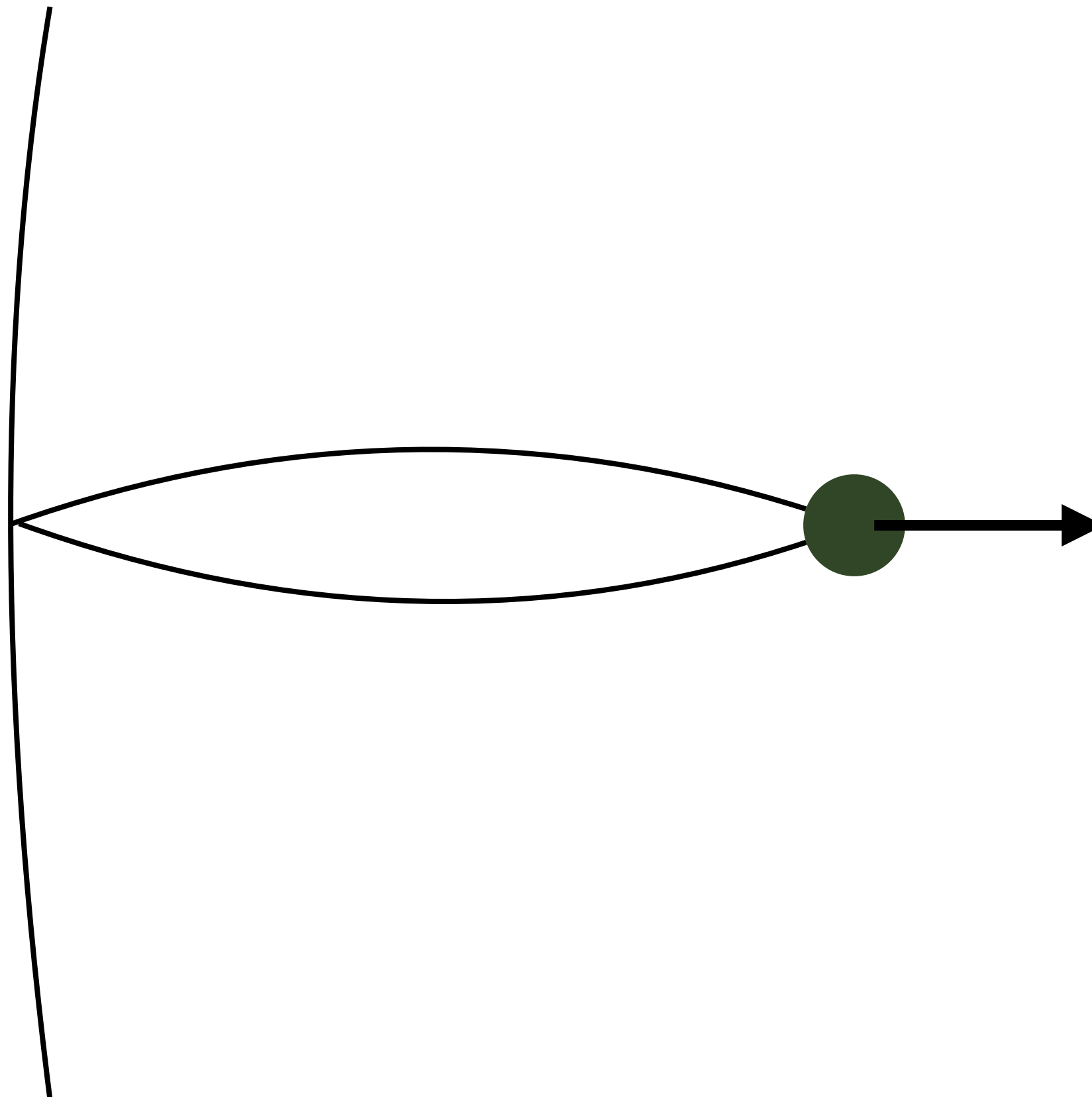
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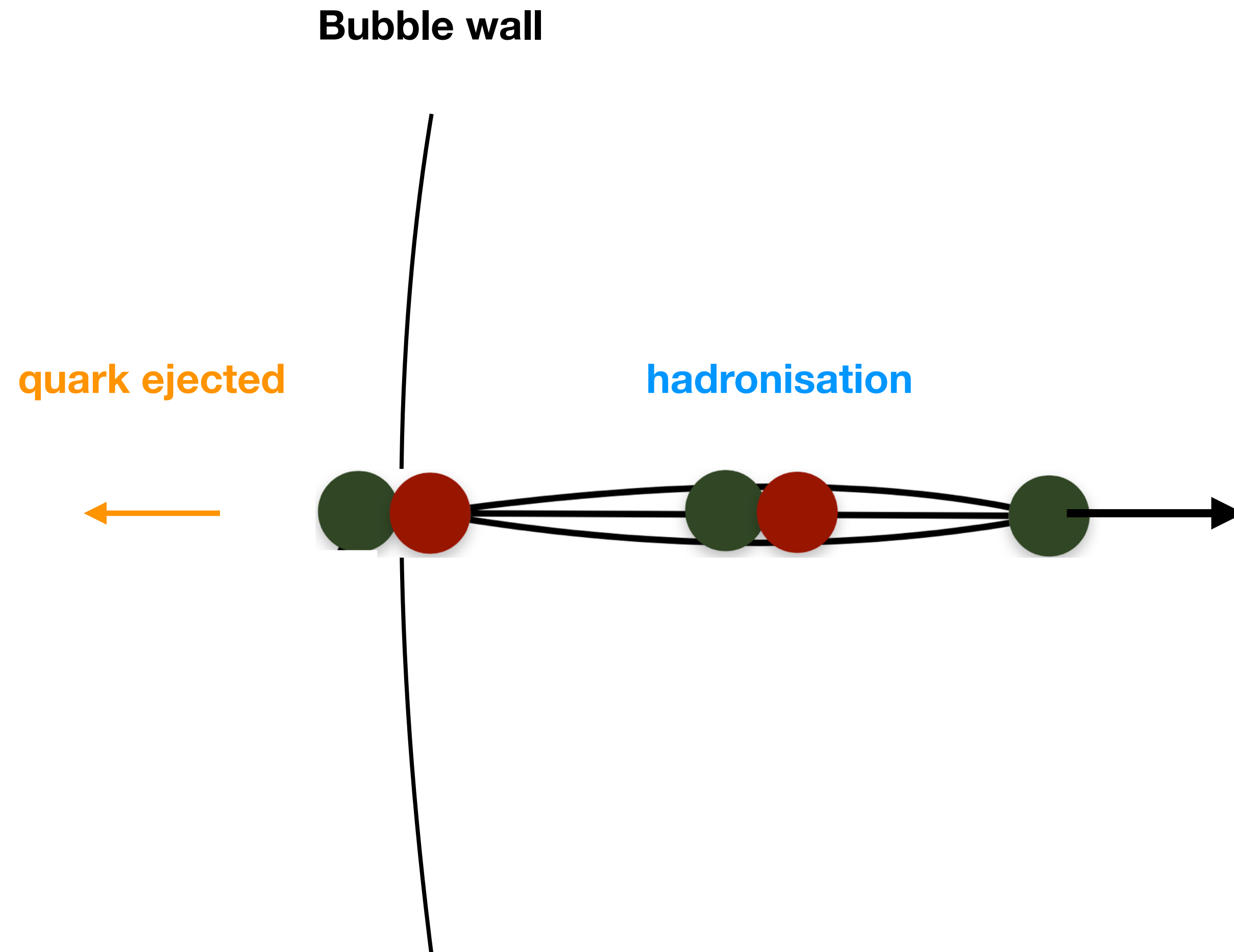
# Interaction with other quarks ?

Bubble wall



# Interaction with other quarks ?

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

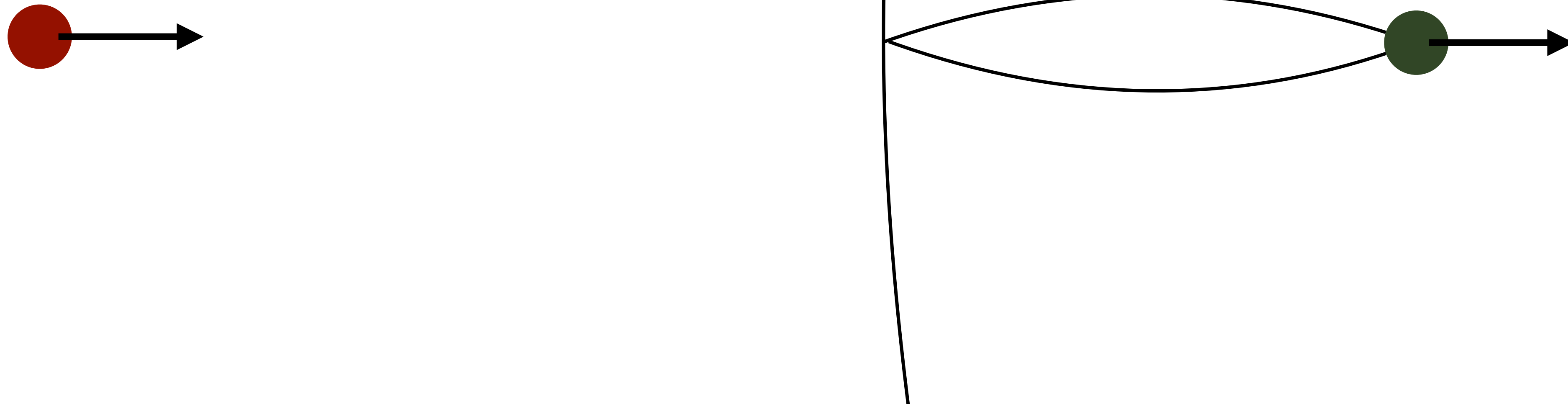


# Interaction with other quarks ?

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

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

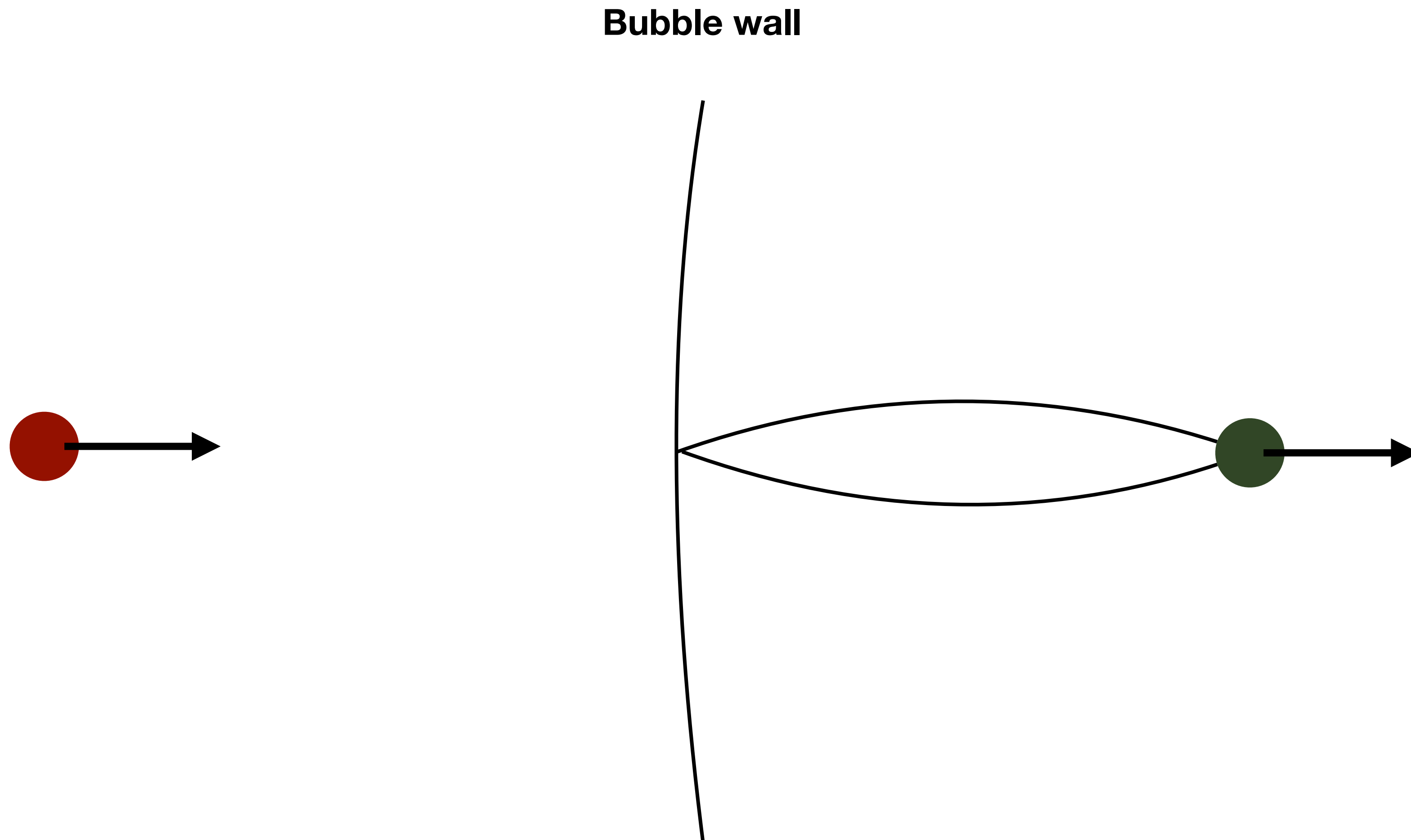
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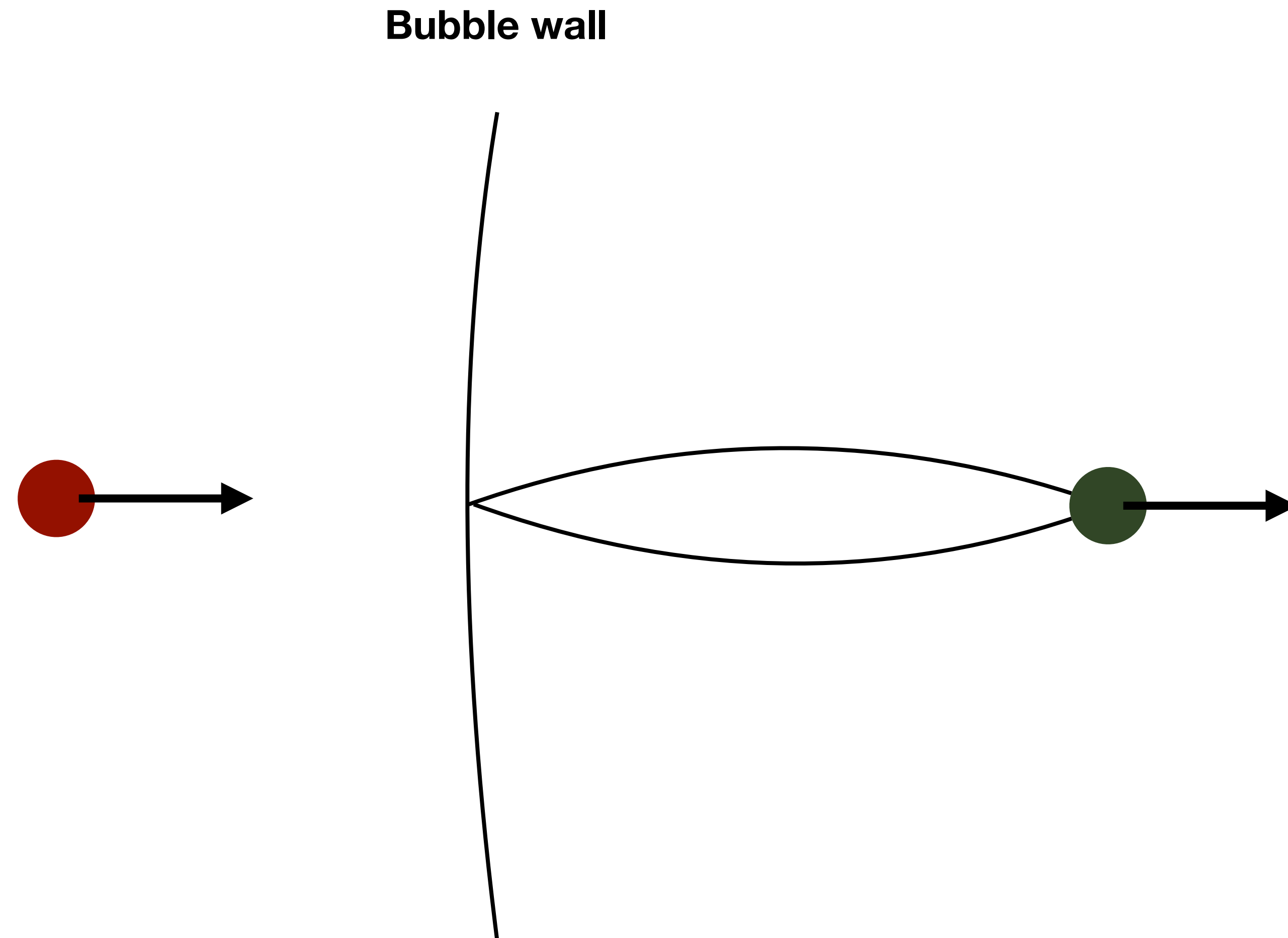
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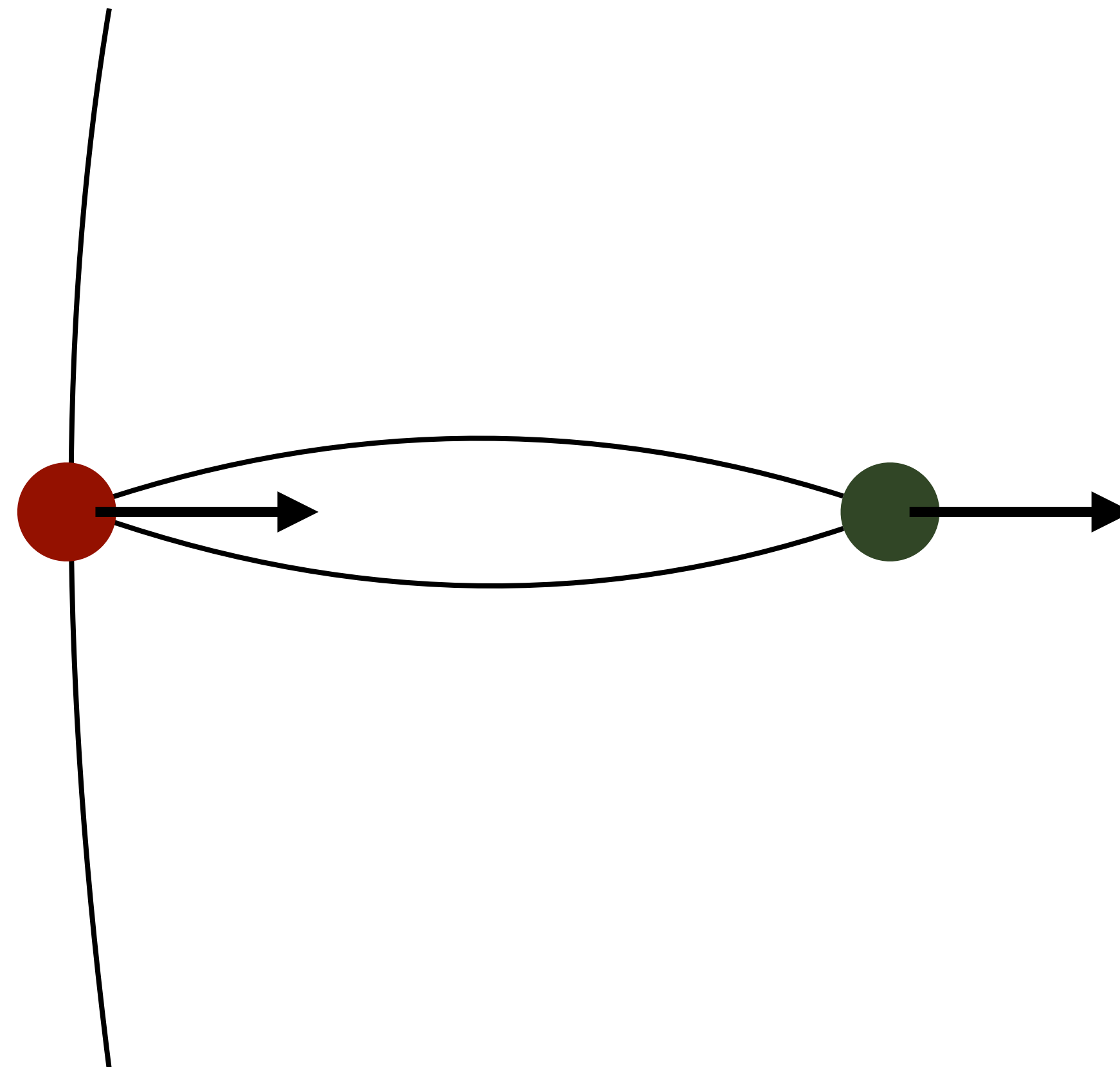


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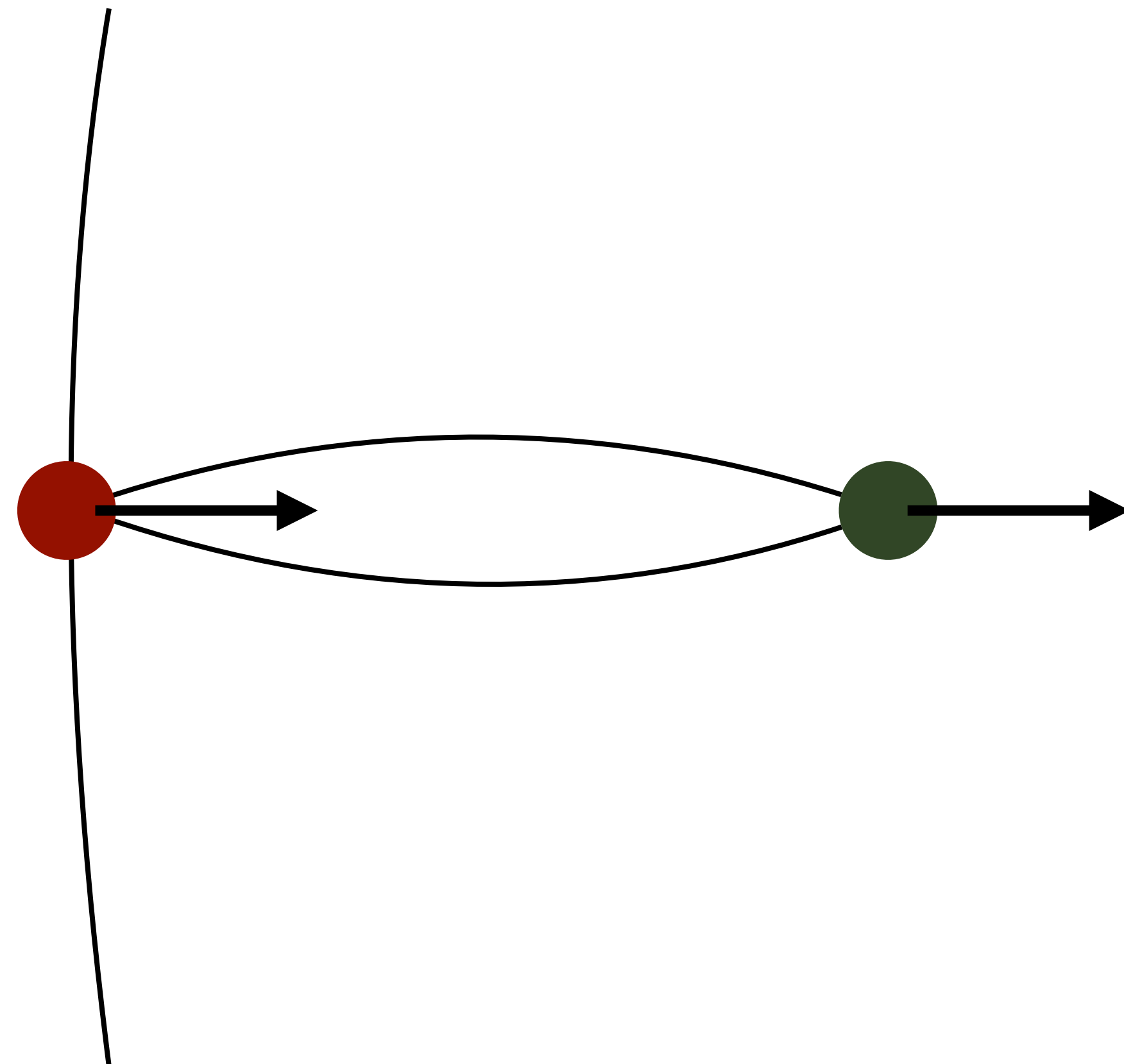
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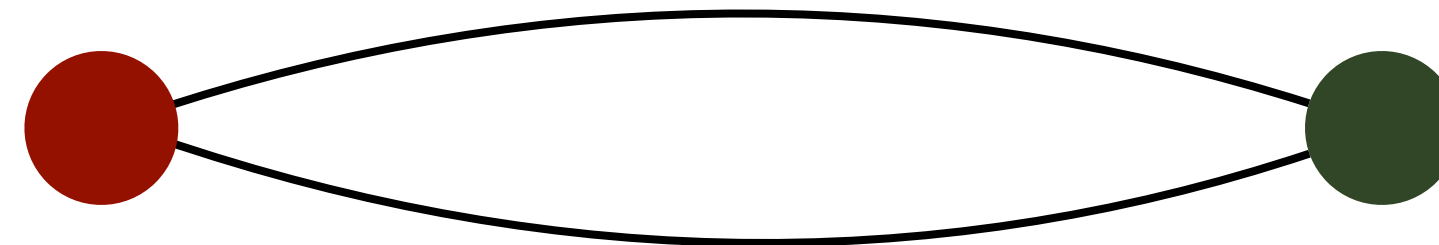
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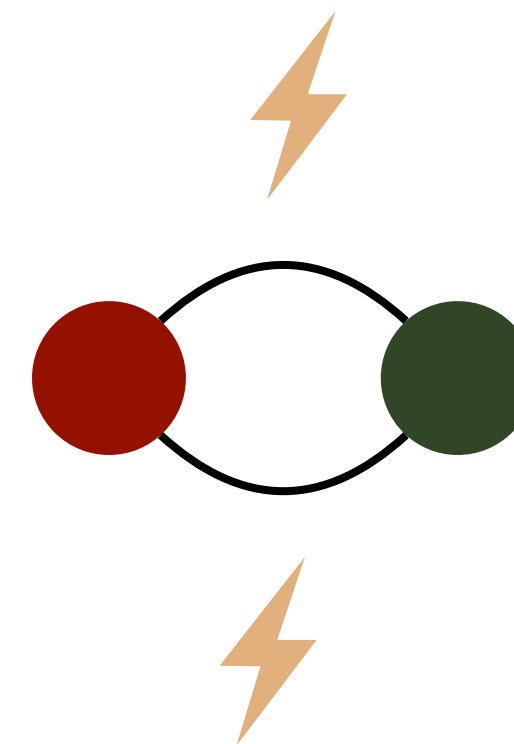
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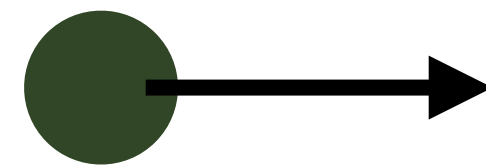
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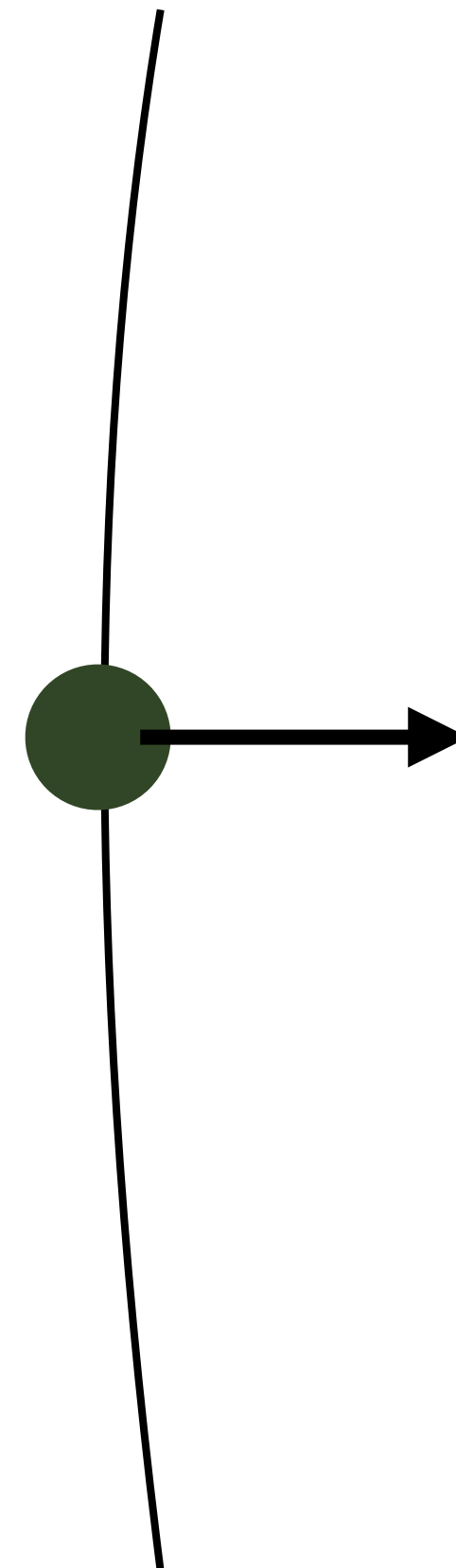
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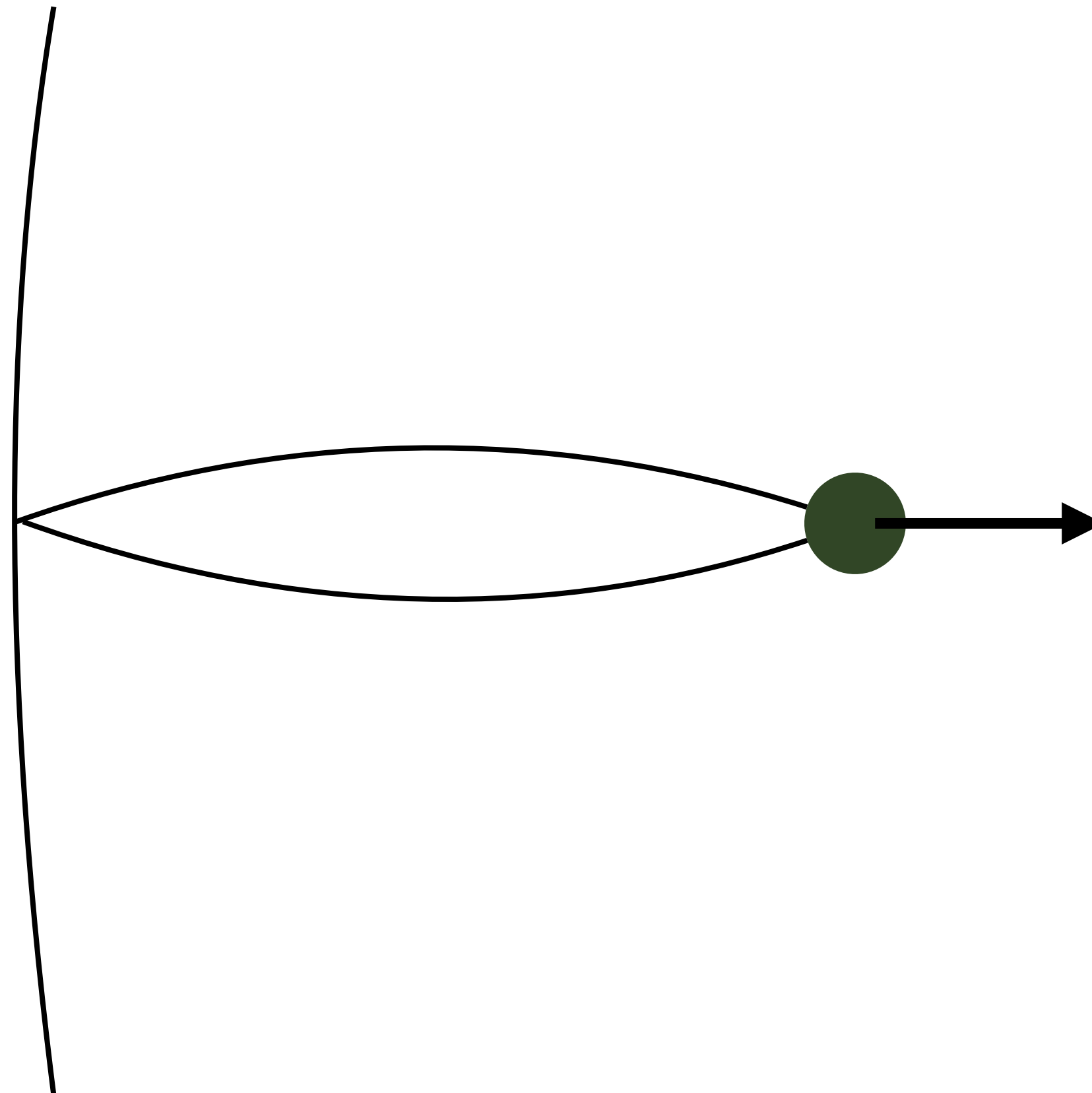
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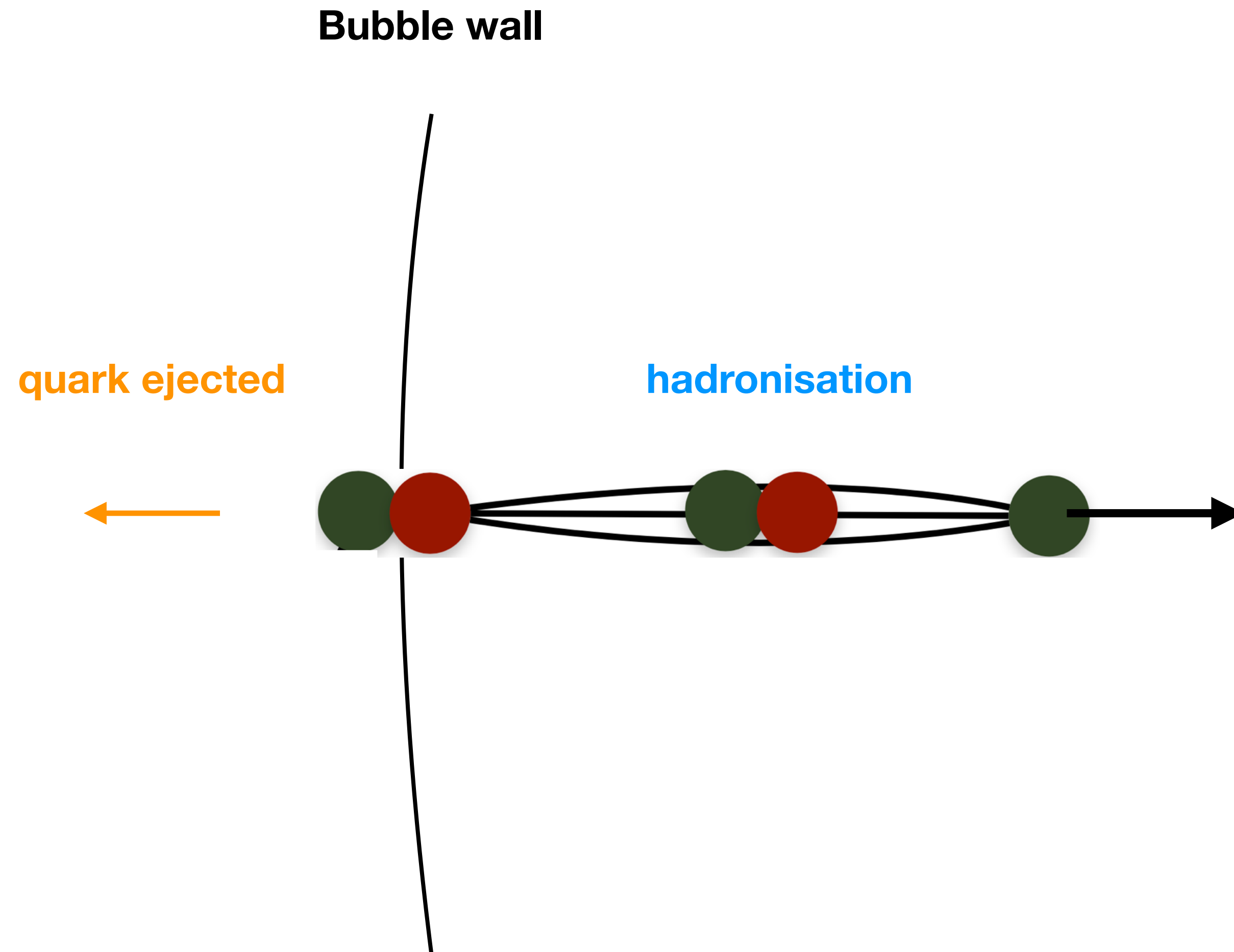
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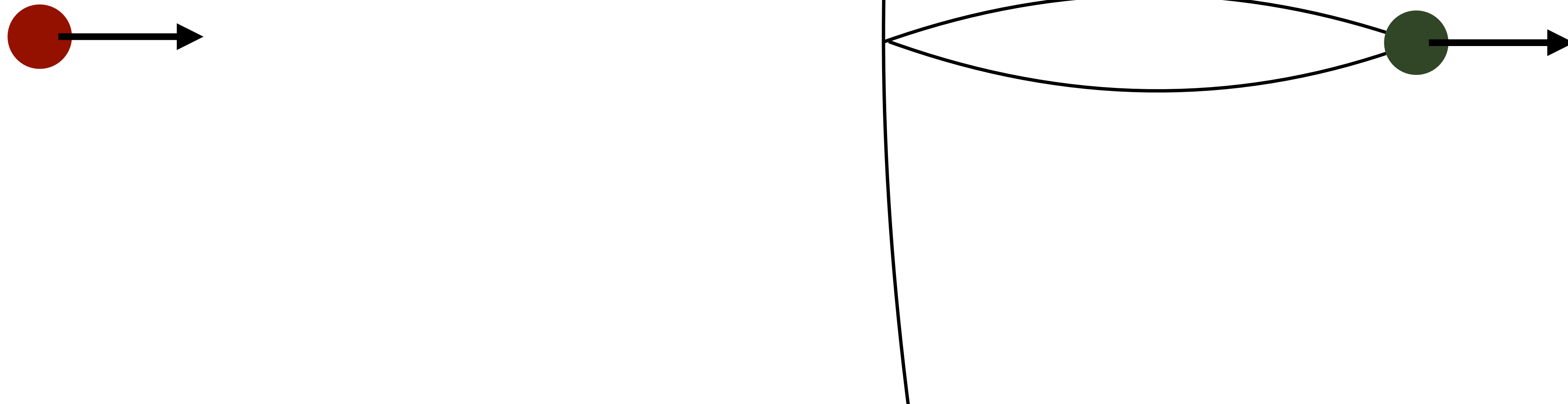


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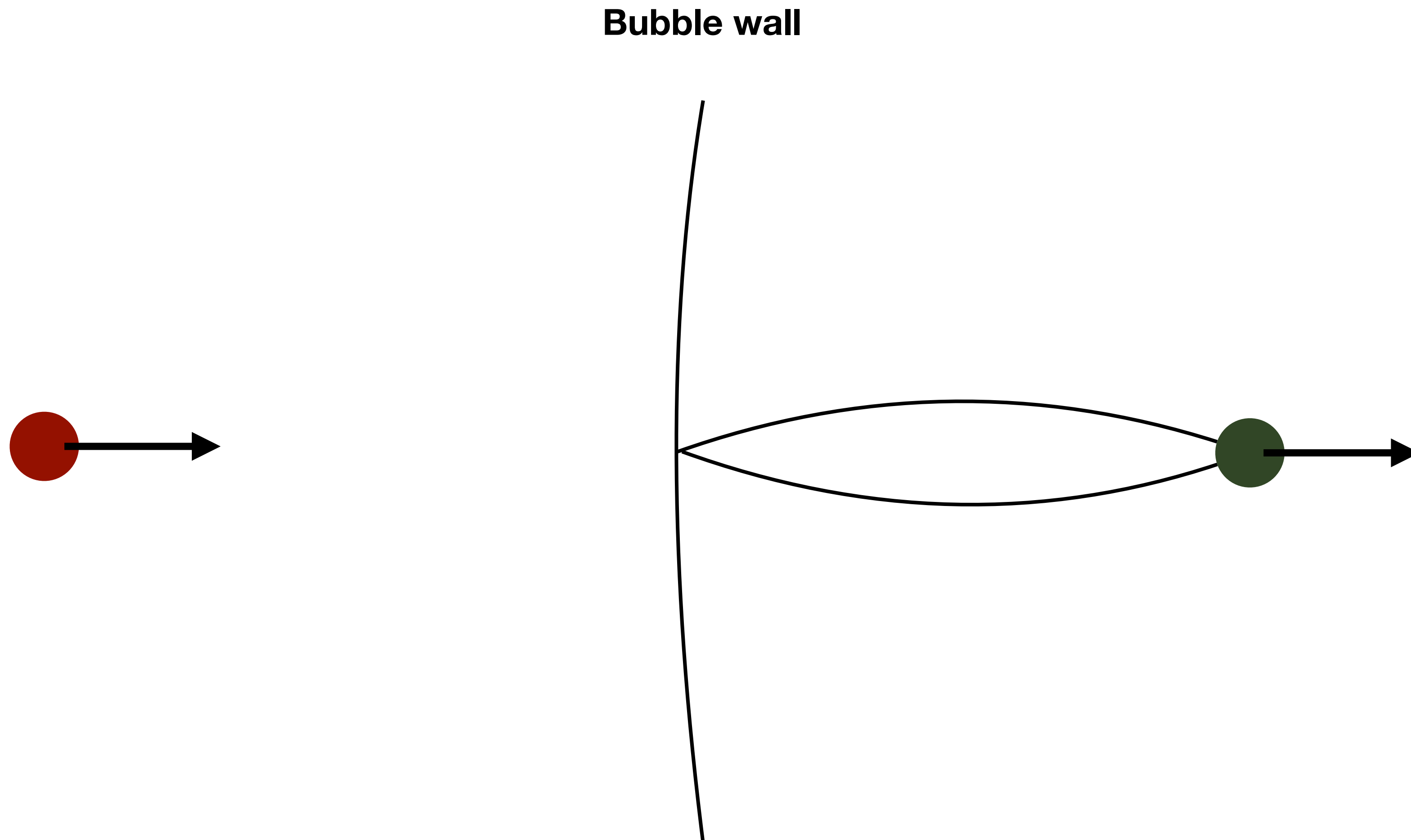
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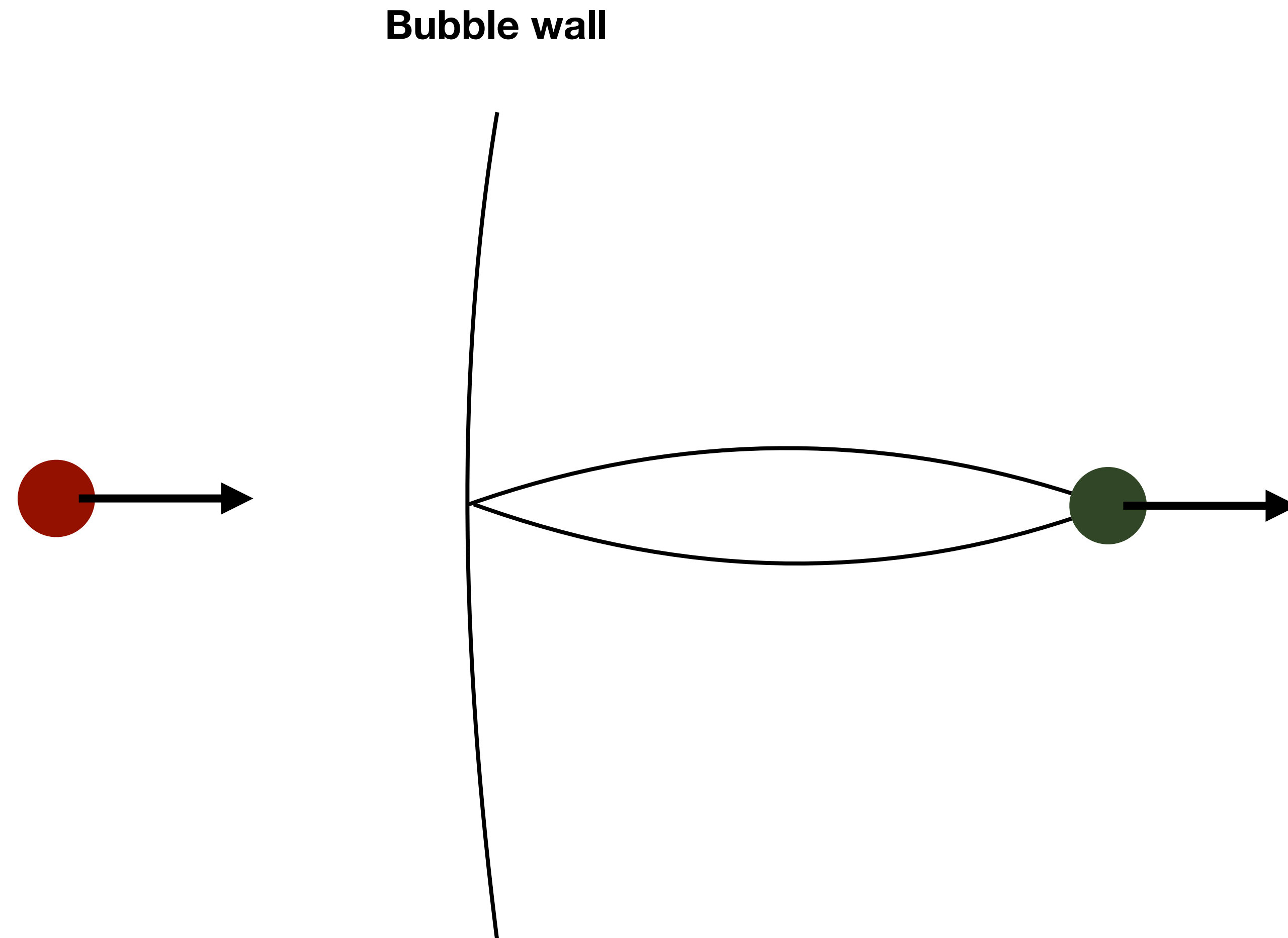




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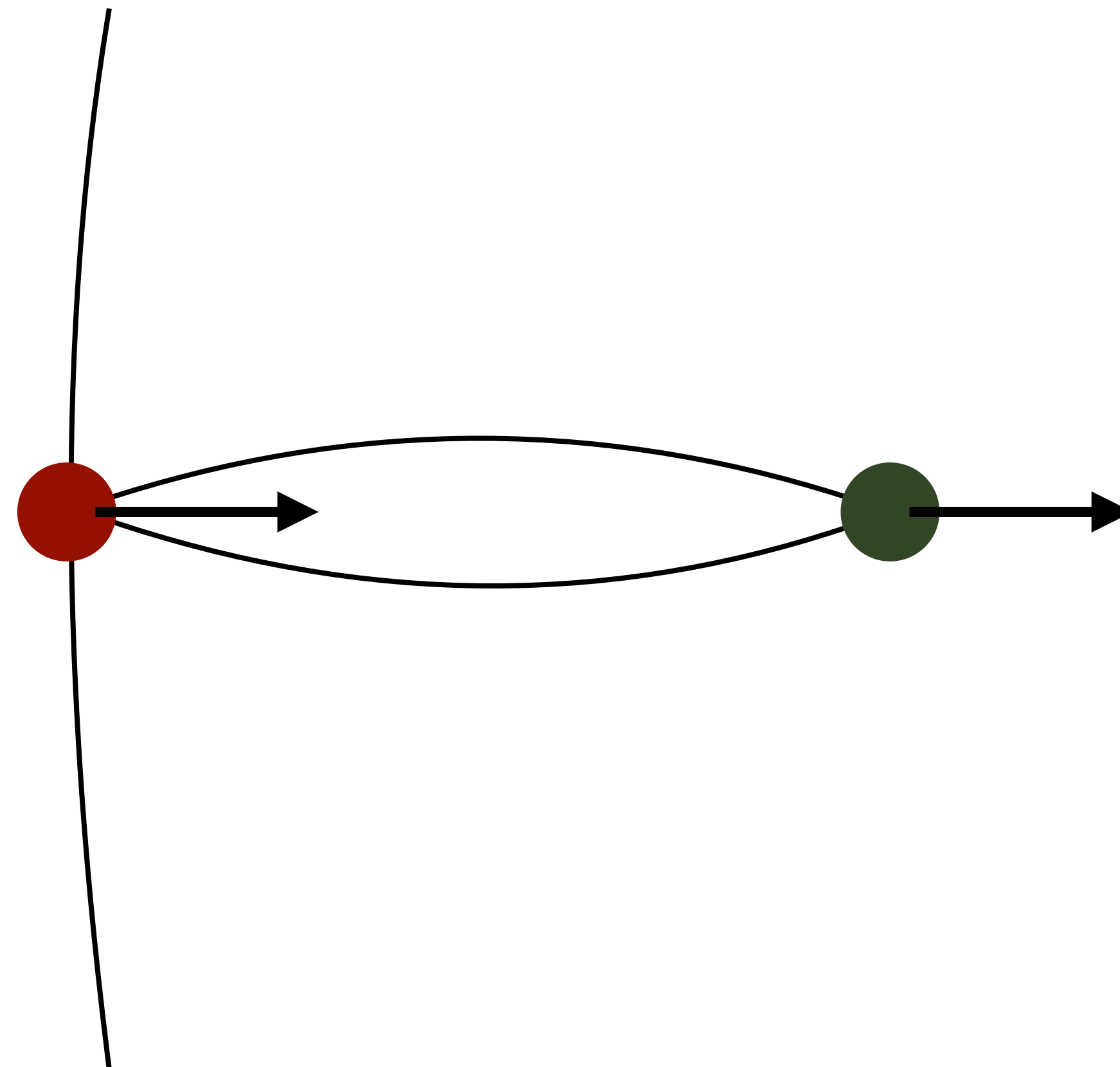


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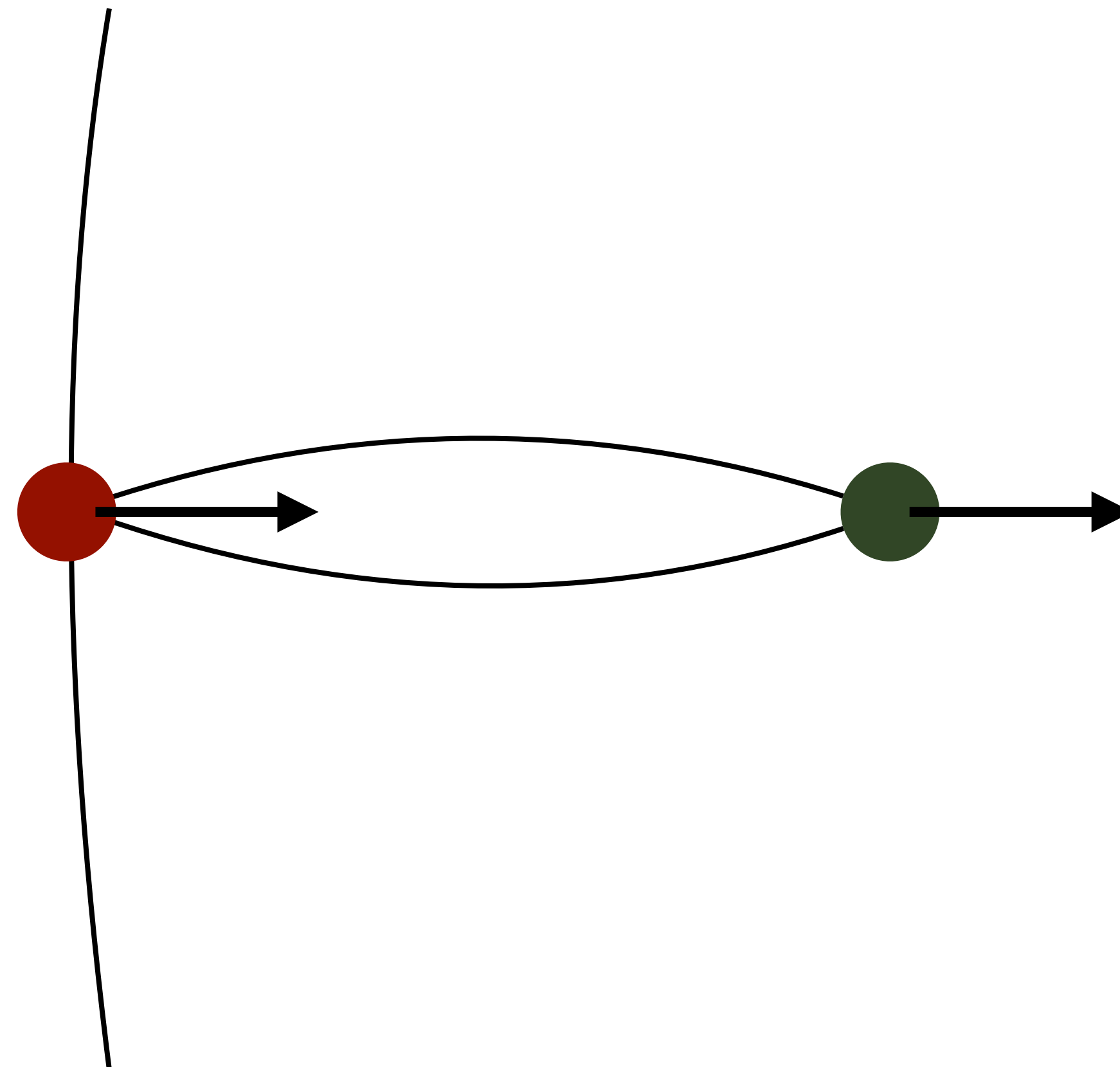
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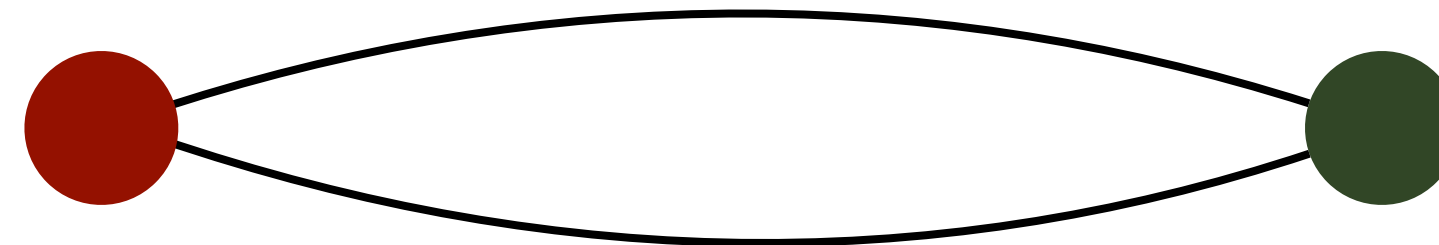
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