

# Partial Deconfinement and the Quark-Gluon Plasma

**Based on:**

**2112.11398 - M Hanada, JH, M Knaggs, A O'Bannon**

**2208.14402 - V Gautam, M Hanada, JH, E Rinaldi**

Holography for Astrophysics and Cosmology  
Nordita

**Jack Holden**

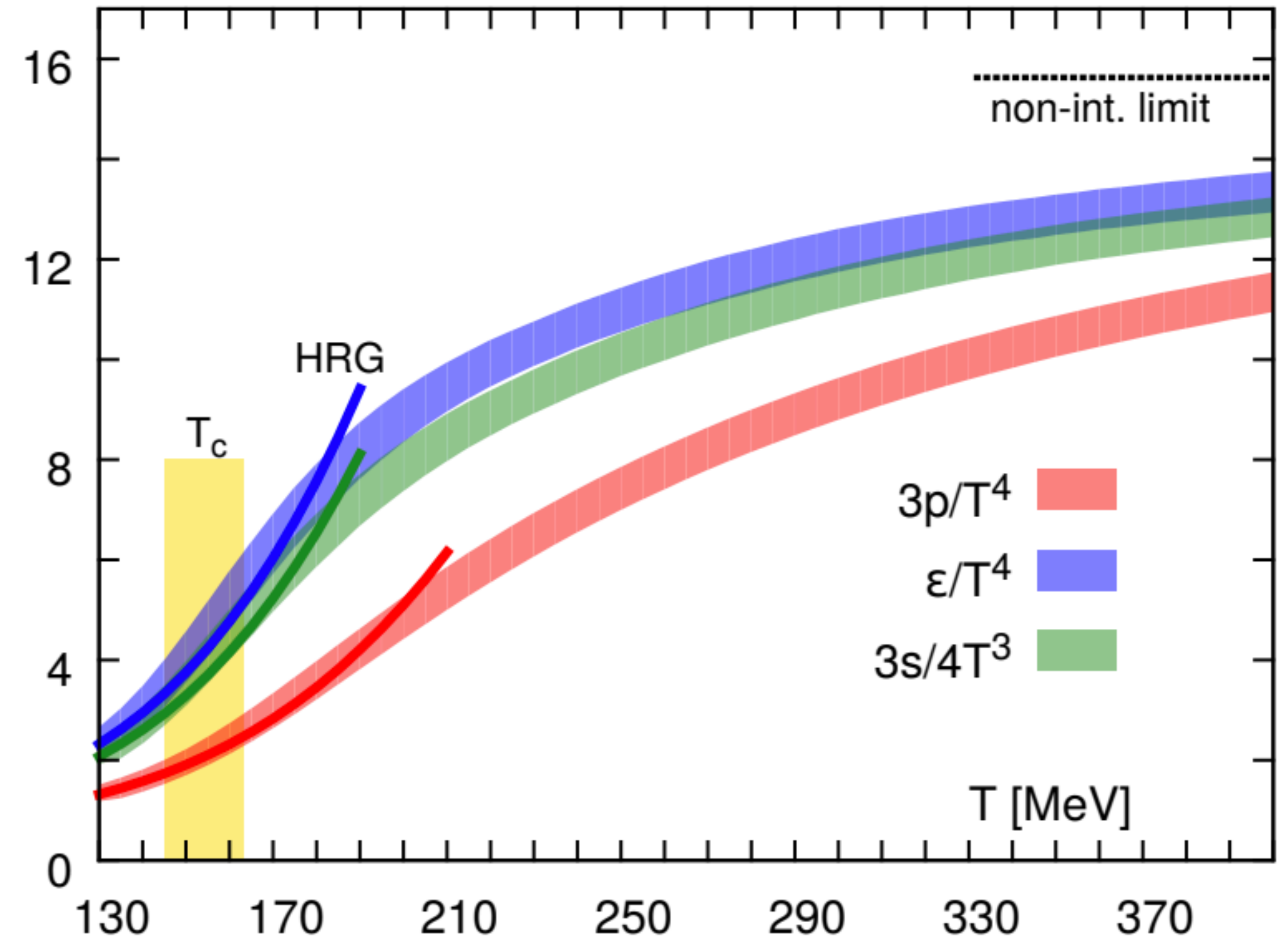
**19th October 2022**

# Outline

- 1. Introduction**
2. Partial confinement and holography
3. Global symmetries
4. Applied to QCD
5. Holography questions
6. Flux tubes

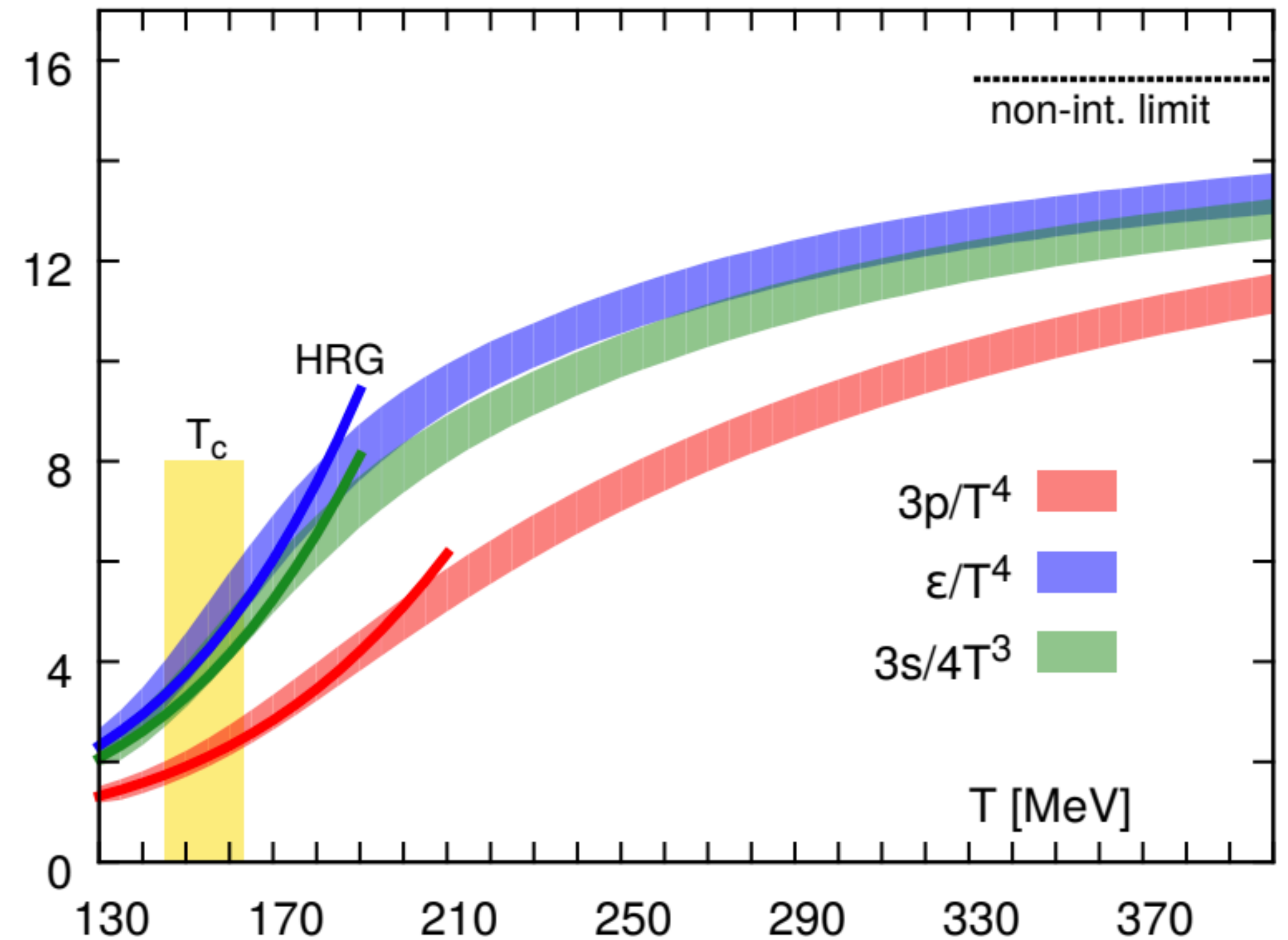
# Motivation

- Quark-gluon plasma



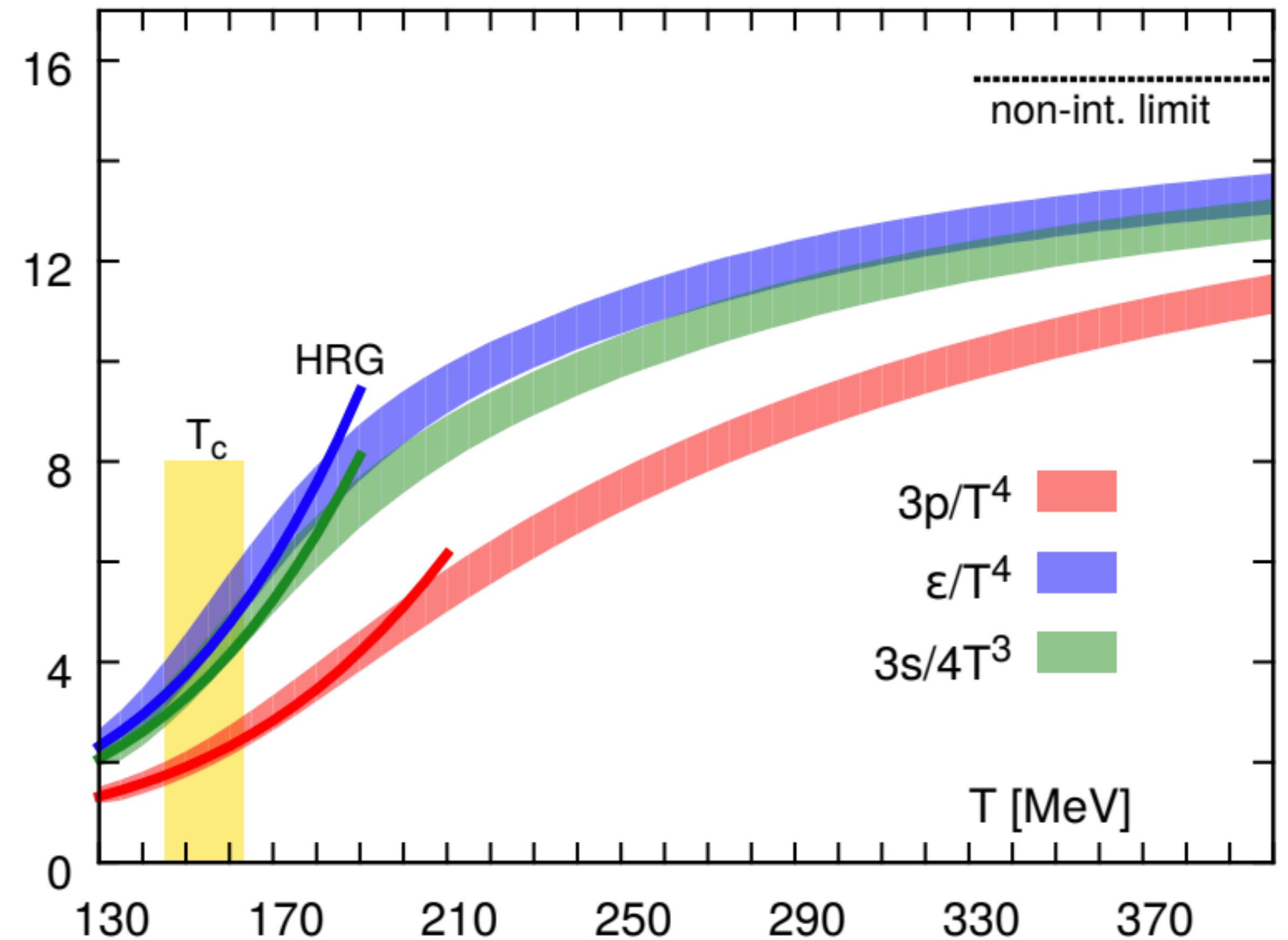
# Motivation

- Quark-gluon plasma
  - Dominated universe  $\sim \mu\text{s}$  after big bang
  - ‘Crossover’ may be a true transition  $\rightarrow$  cosmological consequences?

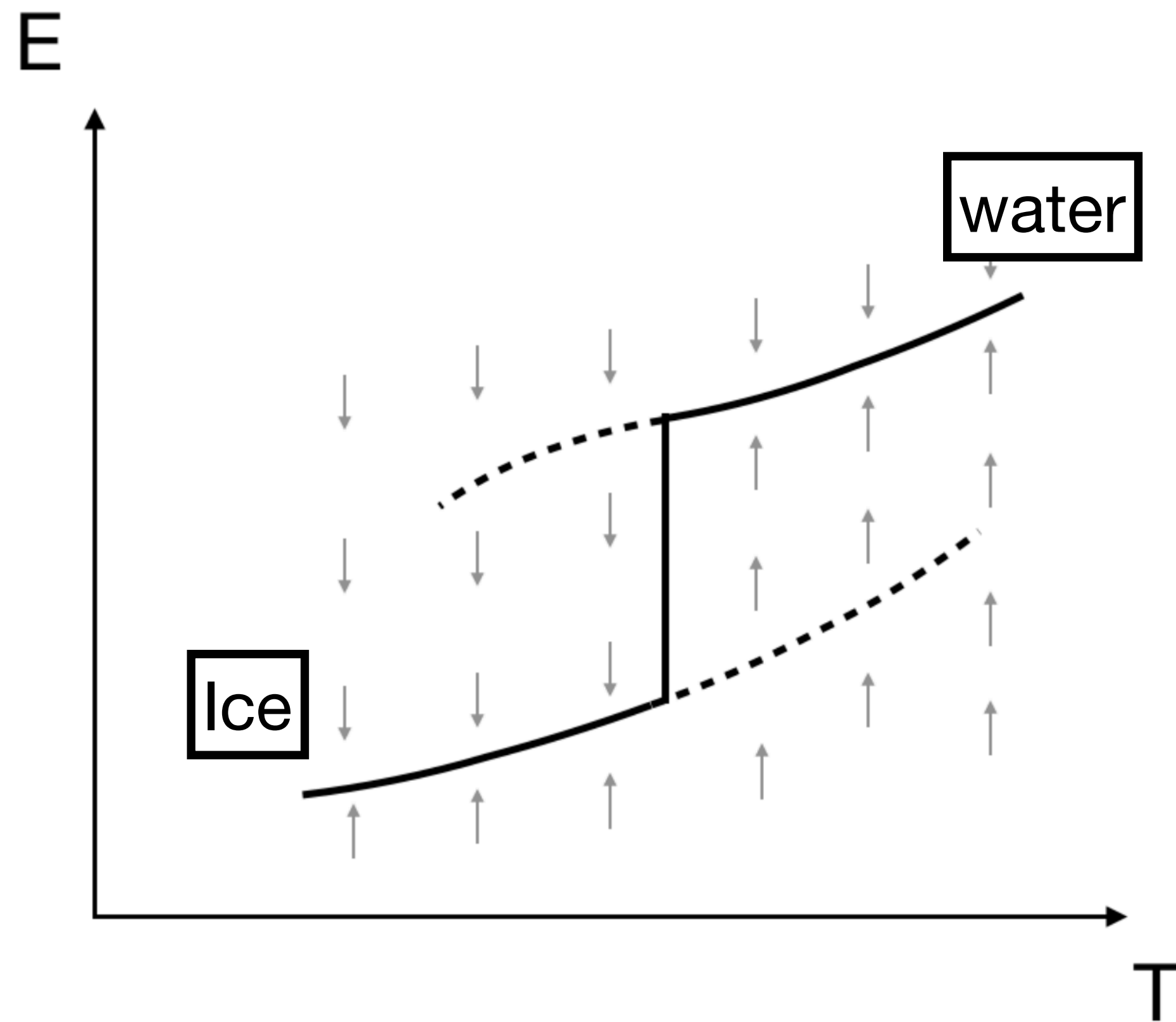


# Motivation

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  - Dominated universe  $\sim \mu\text{s}$  after big bang
  - ‘Crossover’ may be a true transition  $\rightarrow$  cosmological consequences?
- Strongly-coupled gauge fields
  - ‘Colour space’ (thermo)dynamics

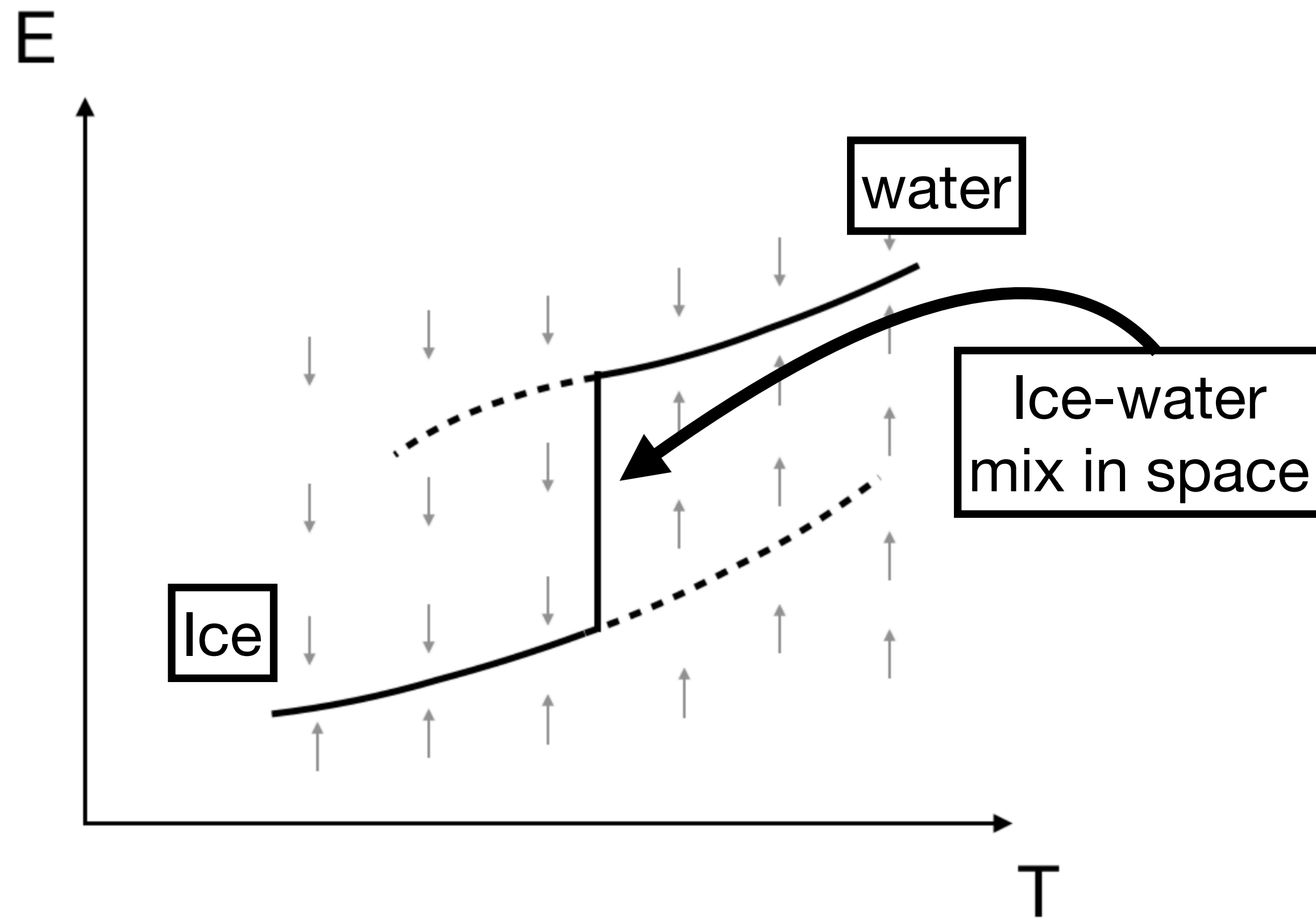


# Partial deconfinement

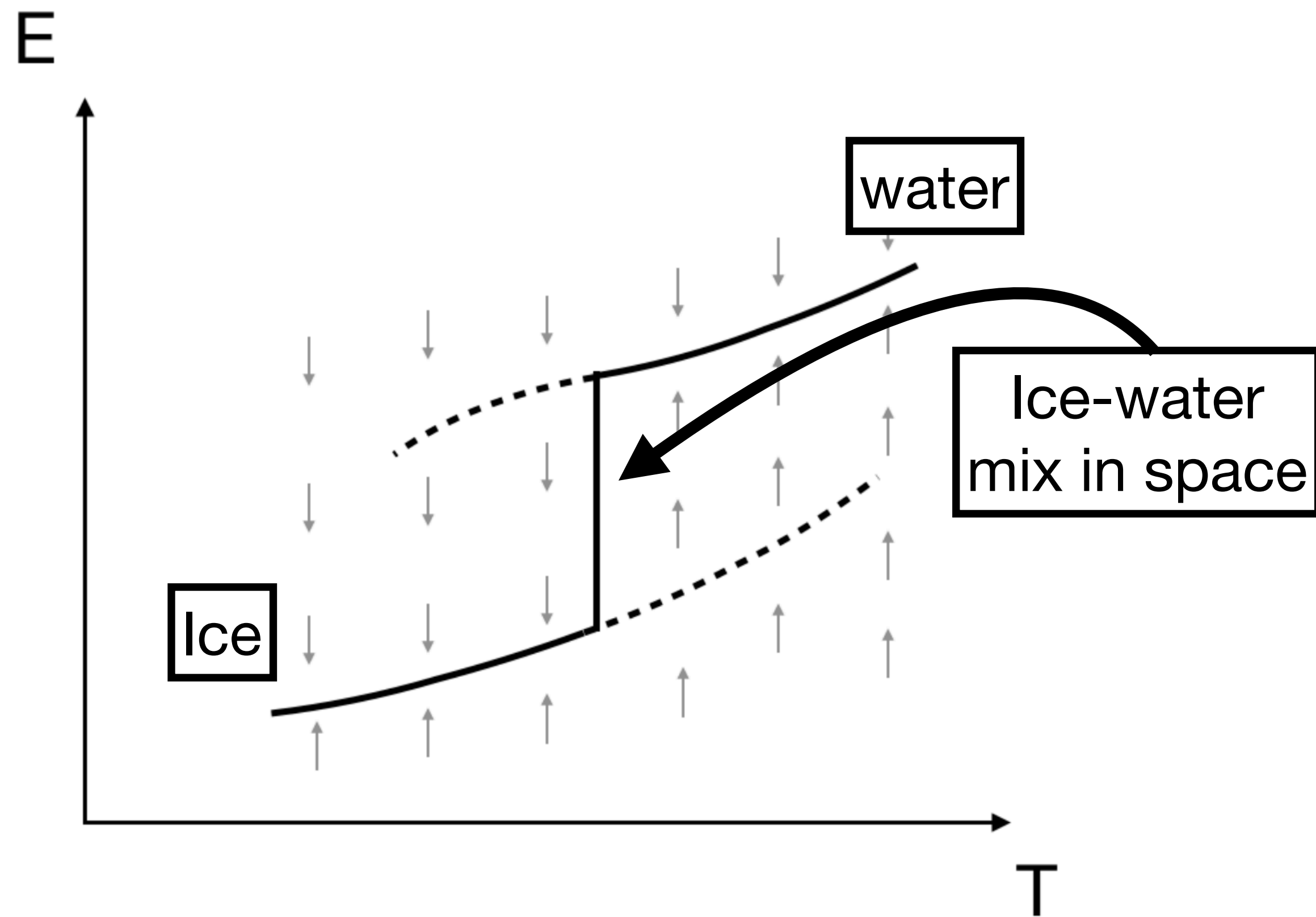


*Hanada, Ishiki, Watanabe, arXiv: 1812.05494*

# Partial deconfinement



# Partial deconfinement

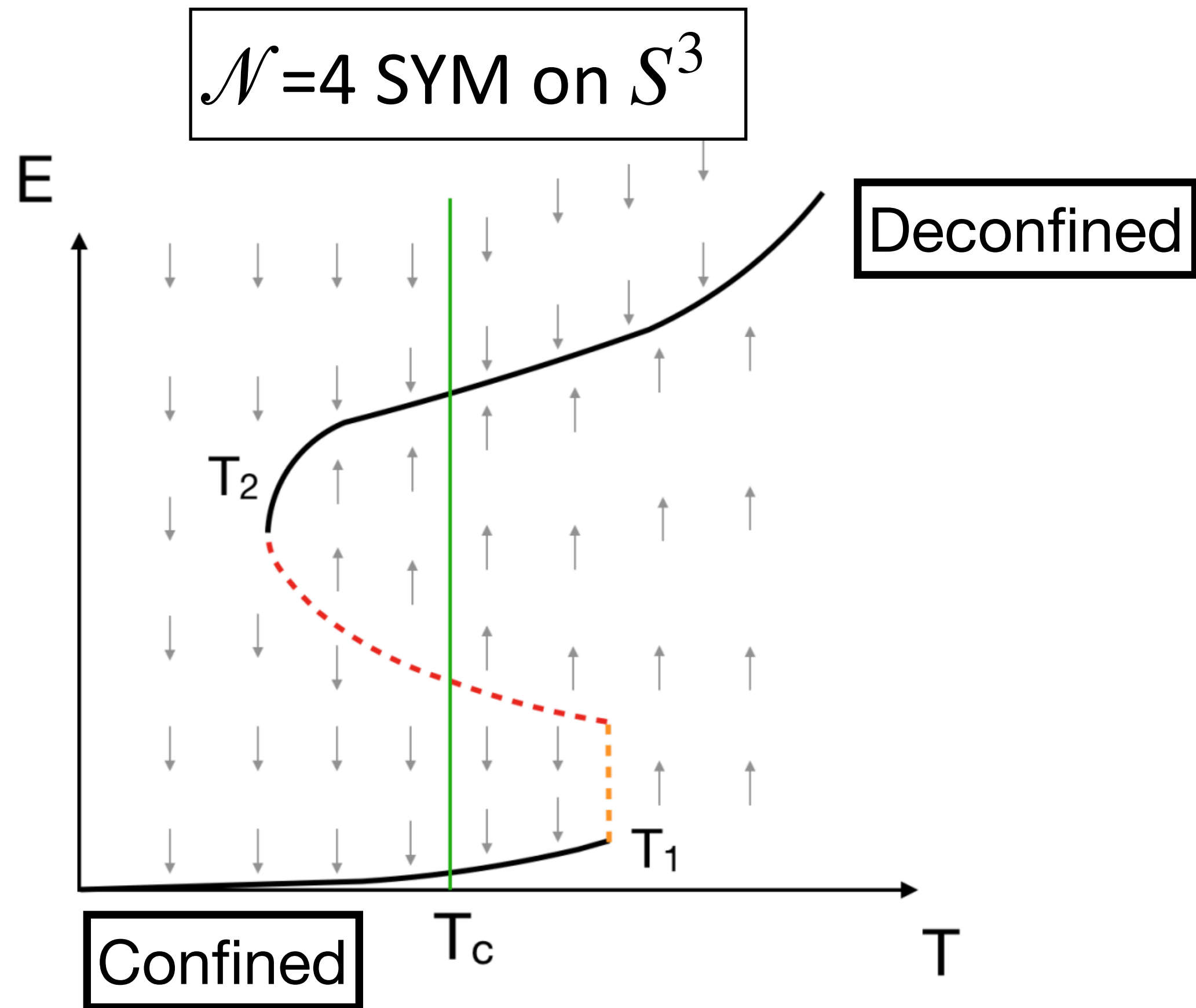


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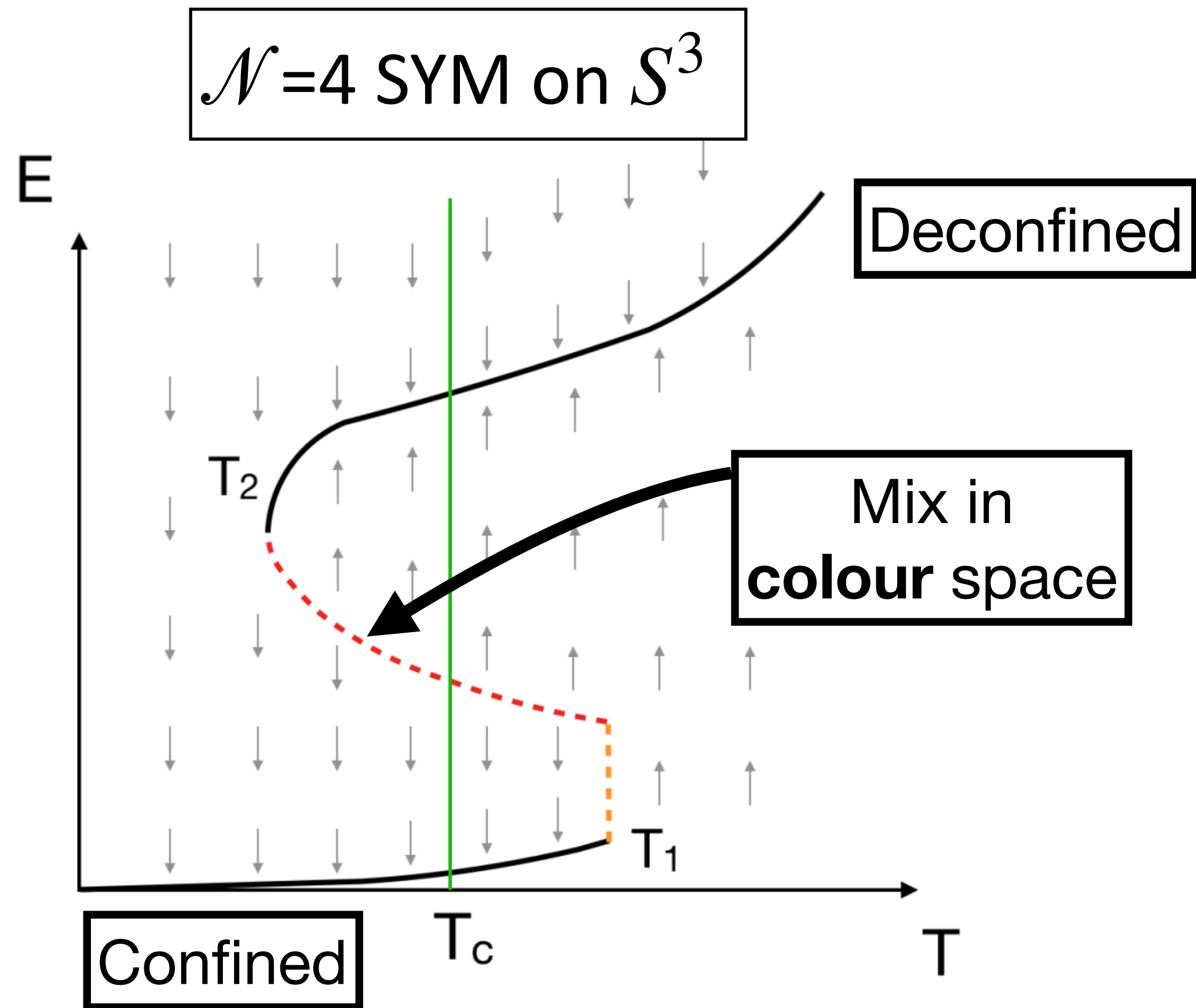




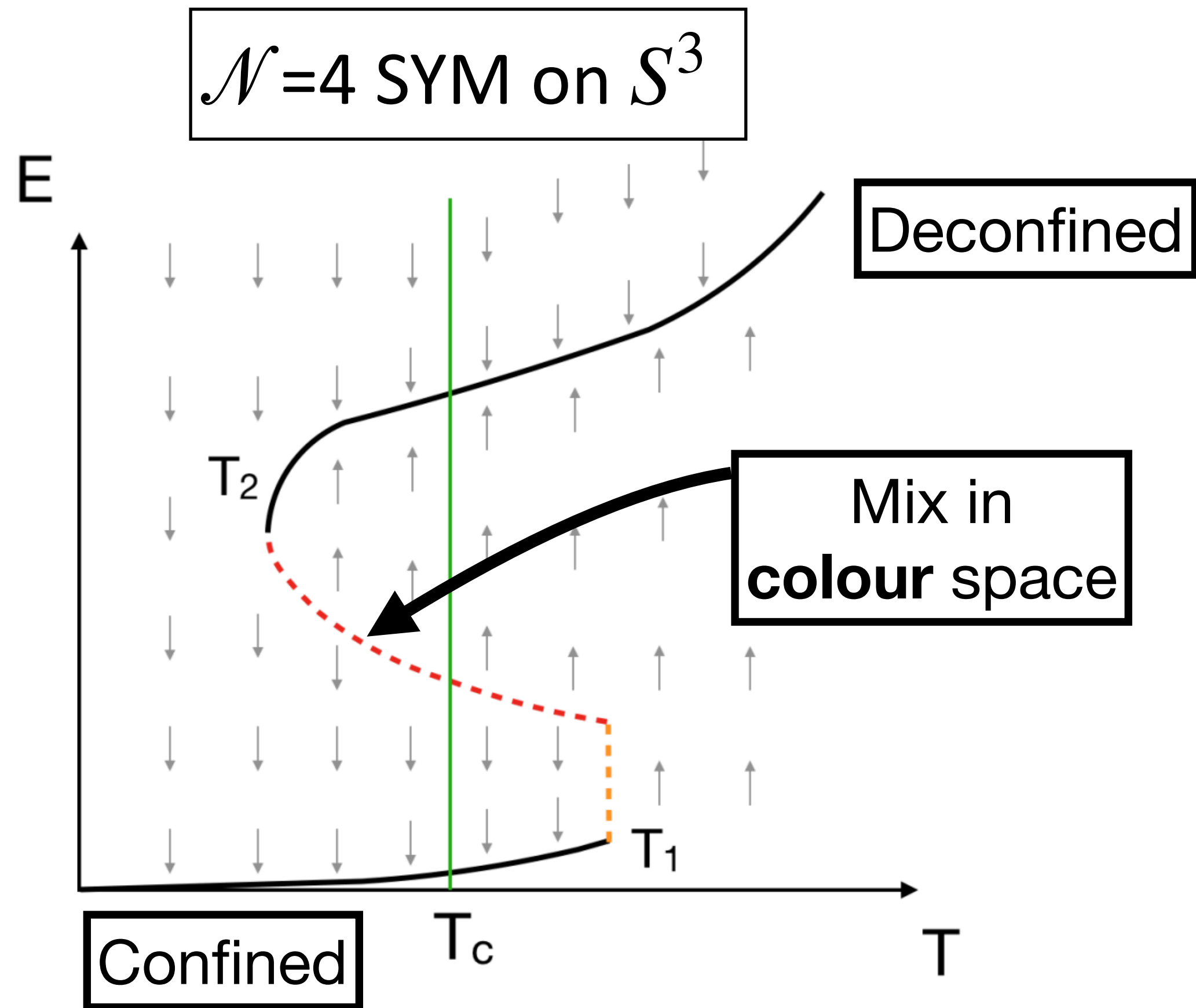
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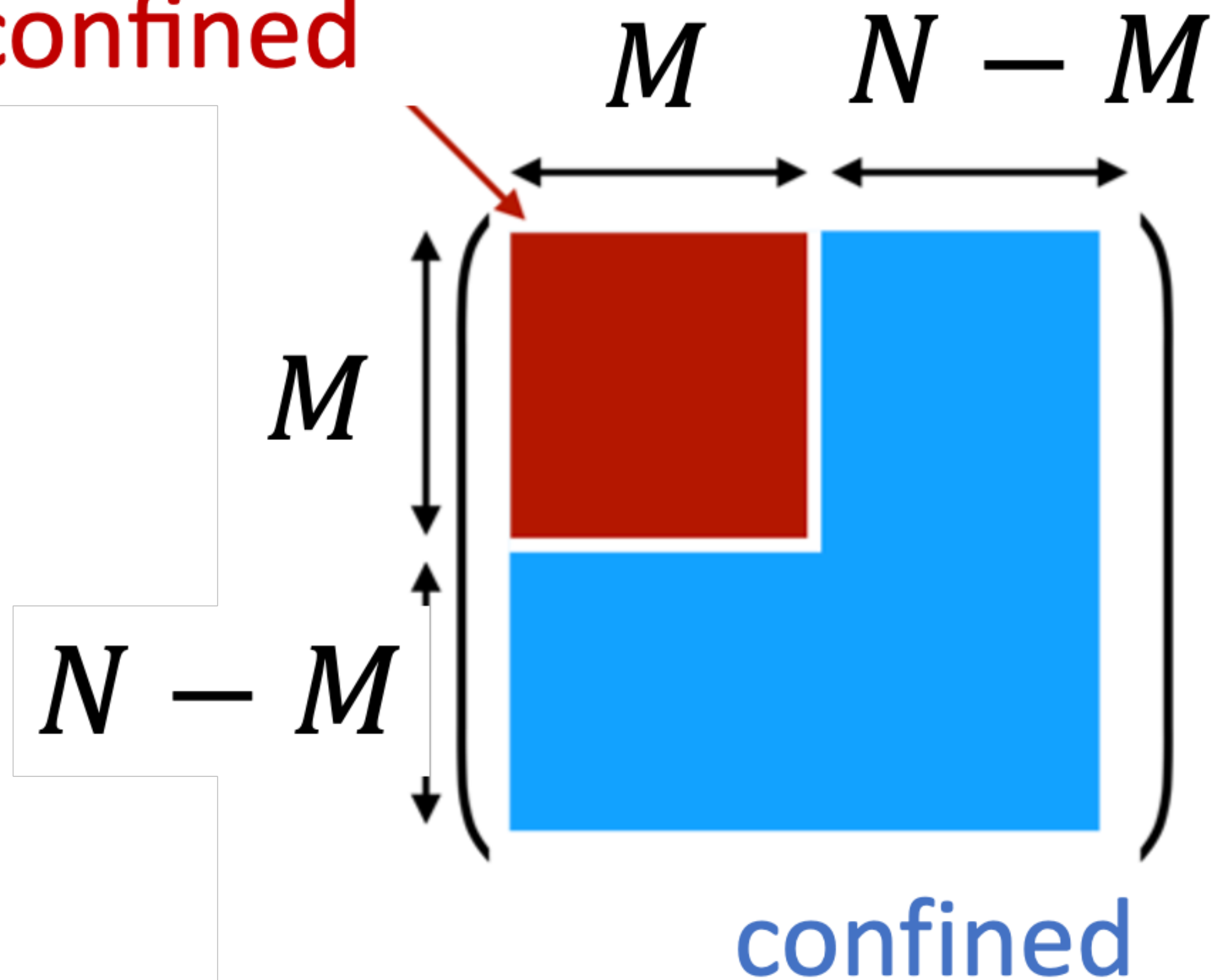


# Partial deconfinement



Hanada, Ishiki, Watanabe, arXiv: 1812.05494

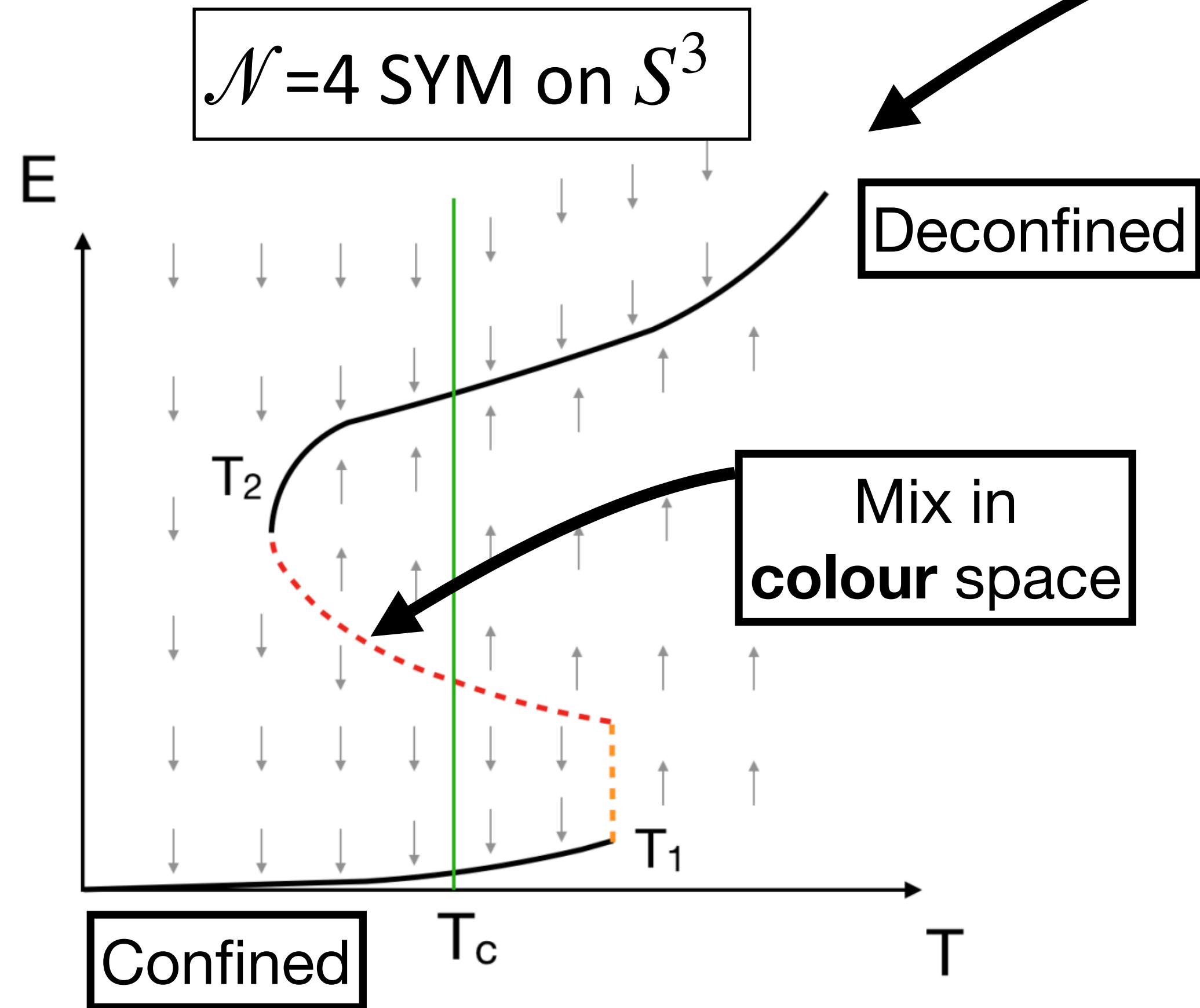
deconfined



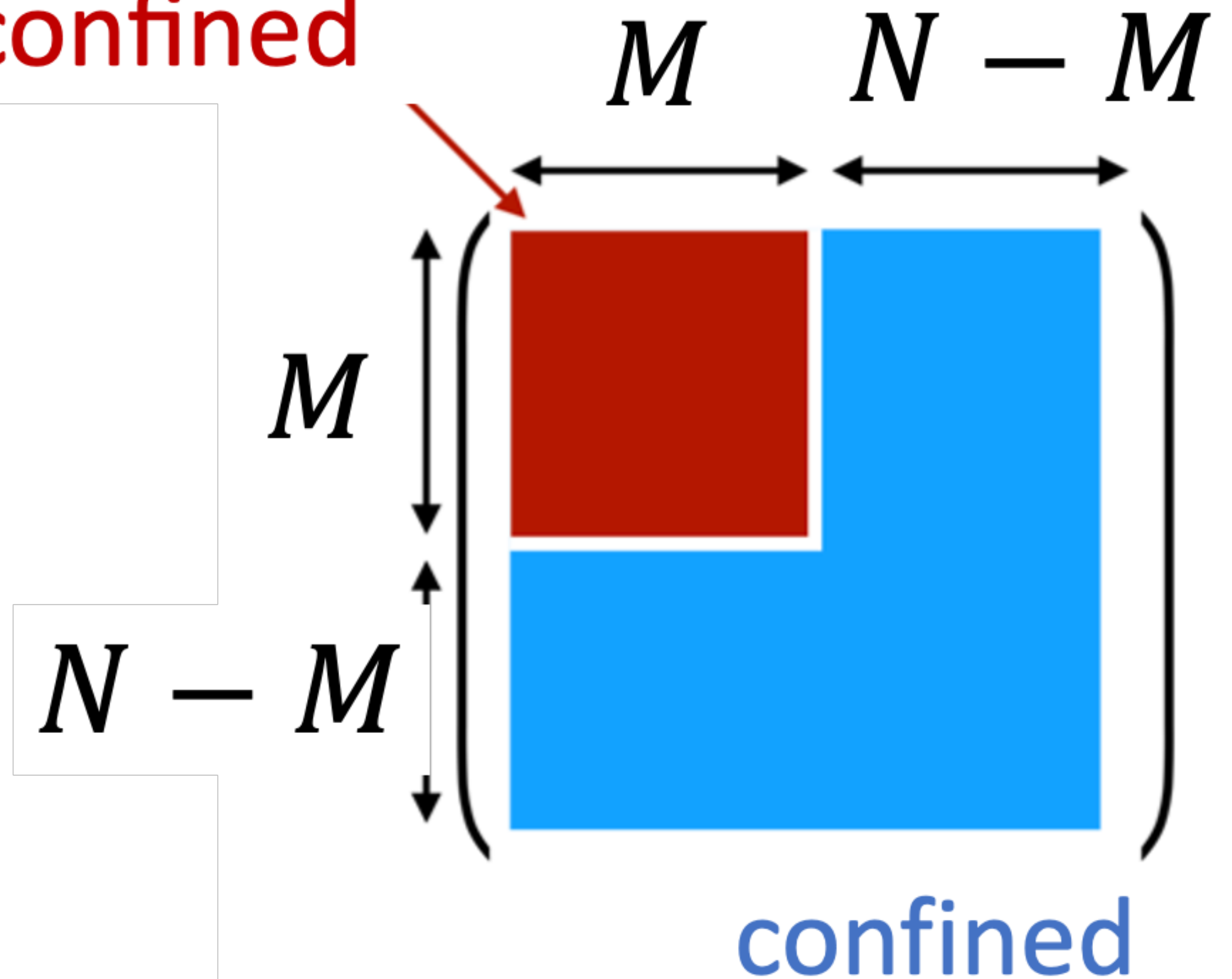
Hanada, Shimada, Wintergest, arXiv: 2001.10459

# Partial deconfinement

Also seen in matrix models (BFSS)



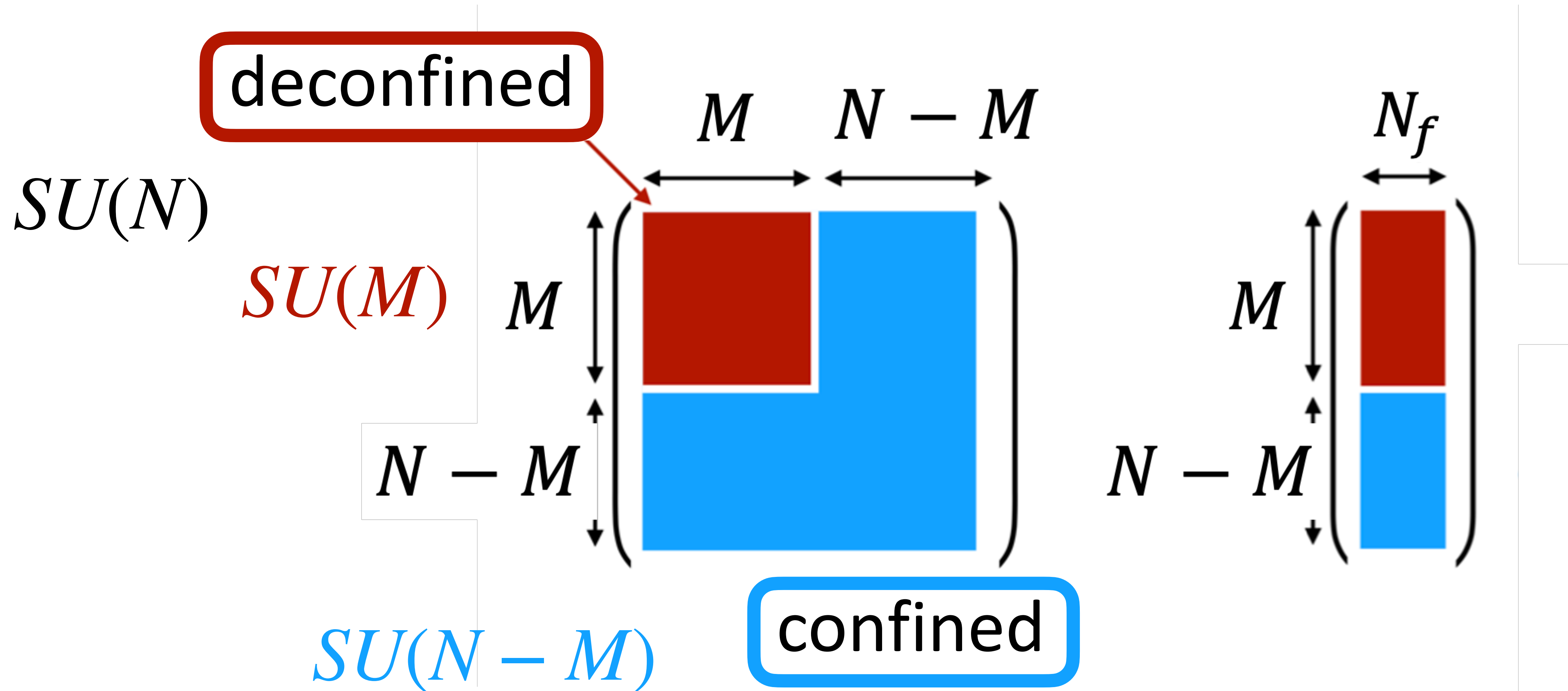
deconfined



Hanada, Ishiki, Watanabe, arXiv: 1812.05494

Hanada, Shimada, Wintergest, arXiv: 2001.10459

# Partial deconfinement: cartoon



source: Hanada, Shimada, Wintergerst 2001.10459

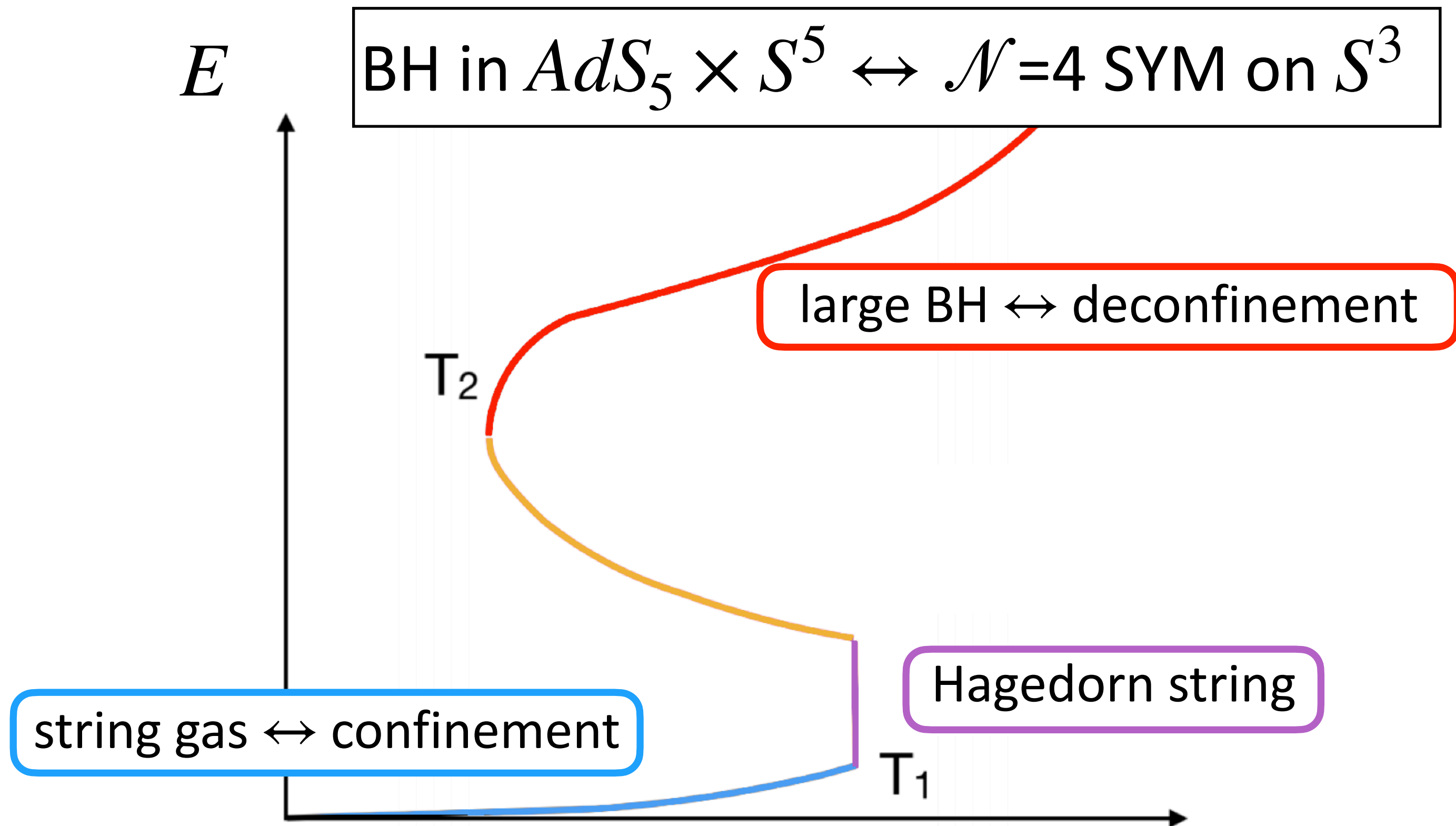
Hanada, Maltz 1608.03276

Berenstein 1806.05729

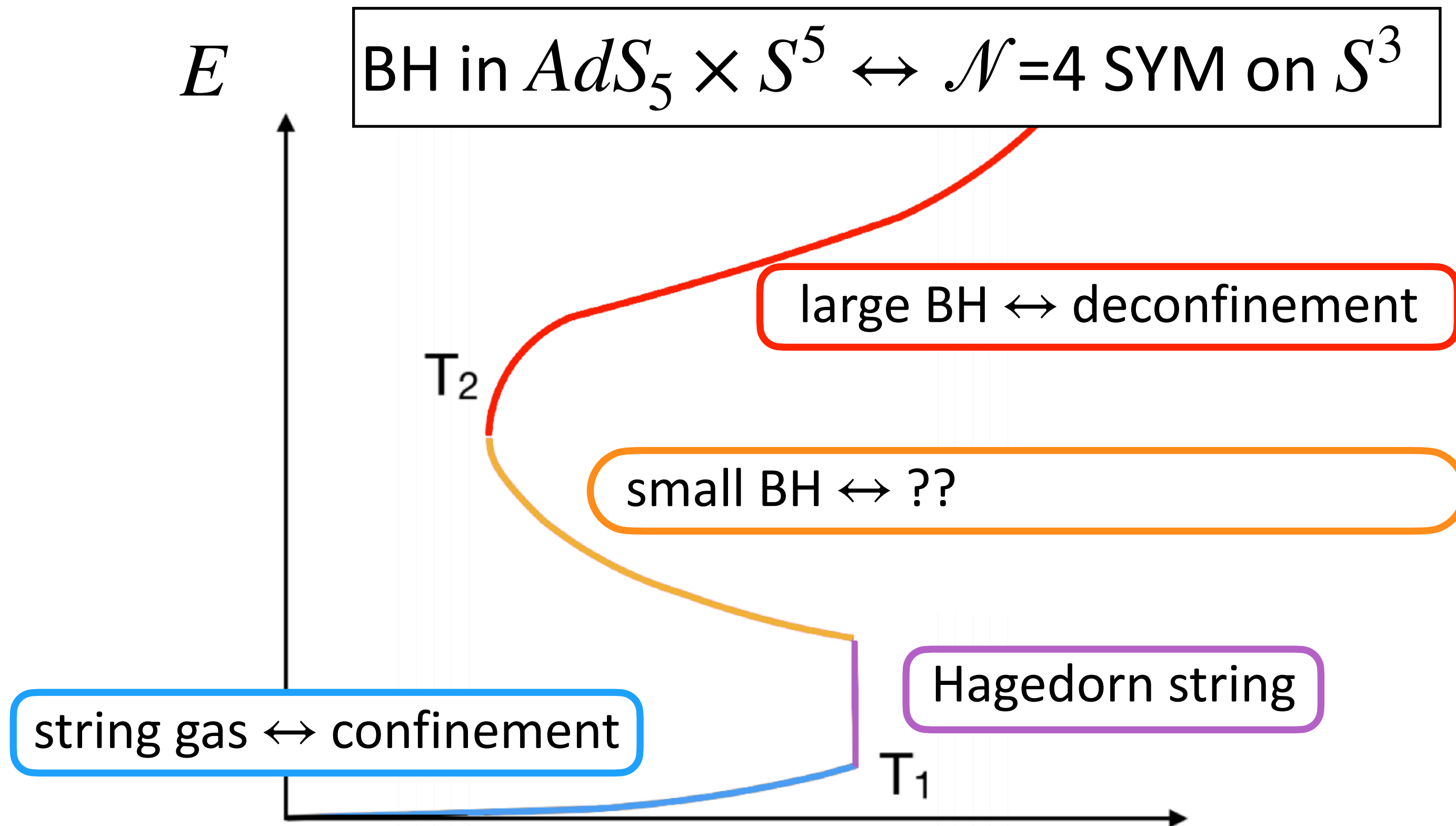
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# Holography

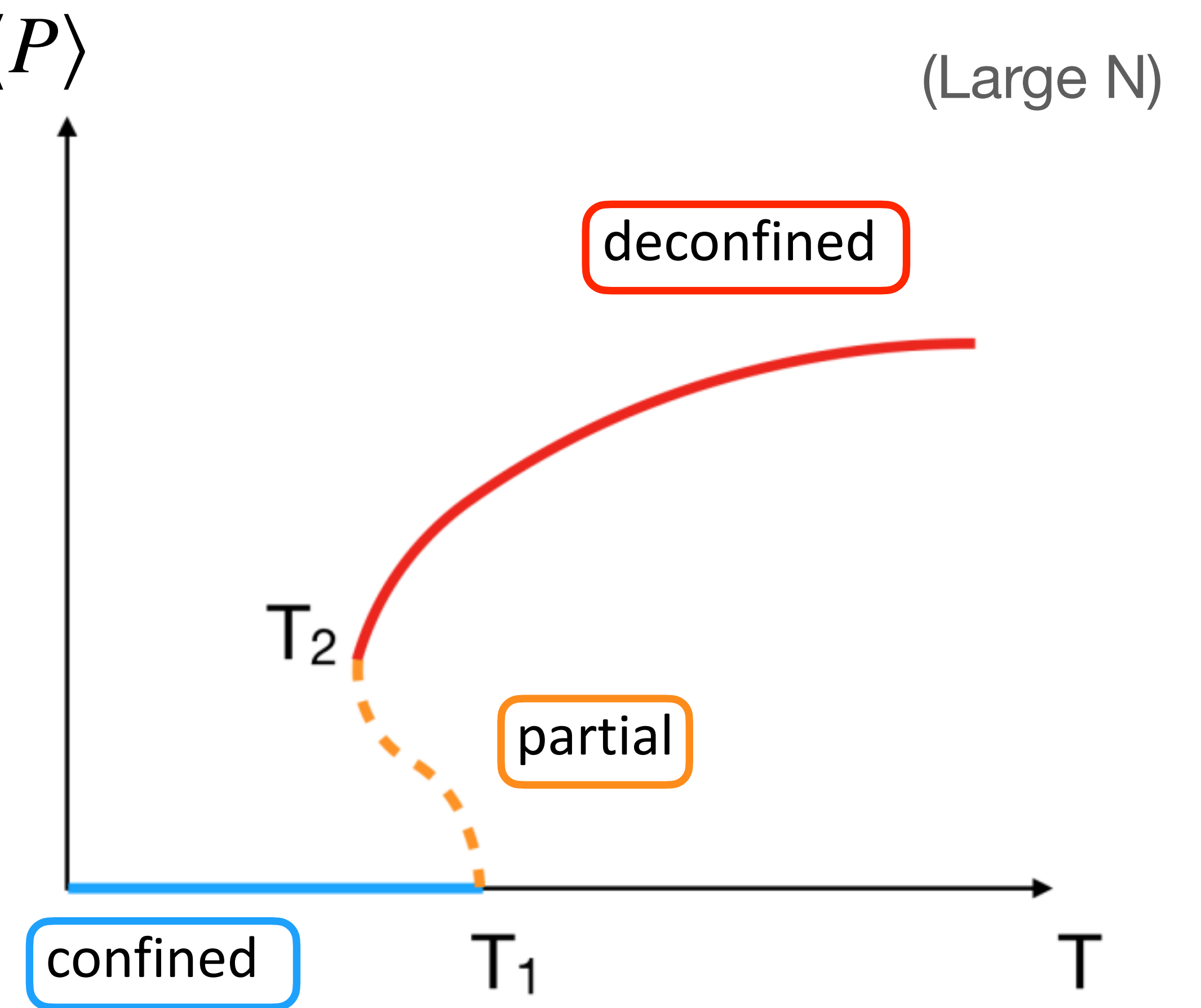
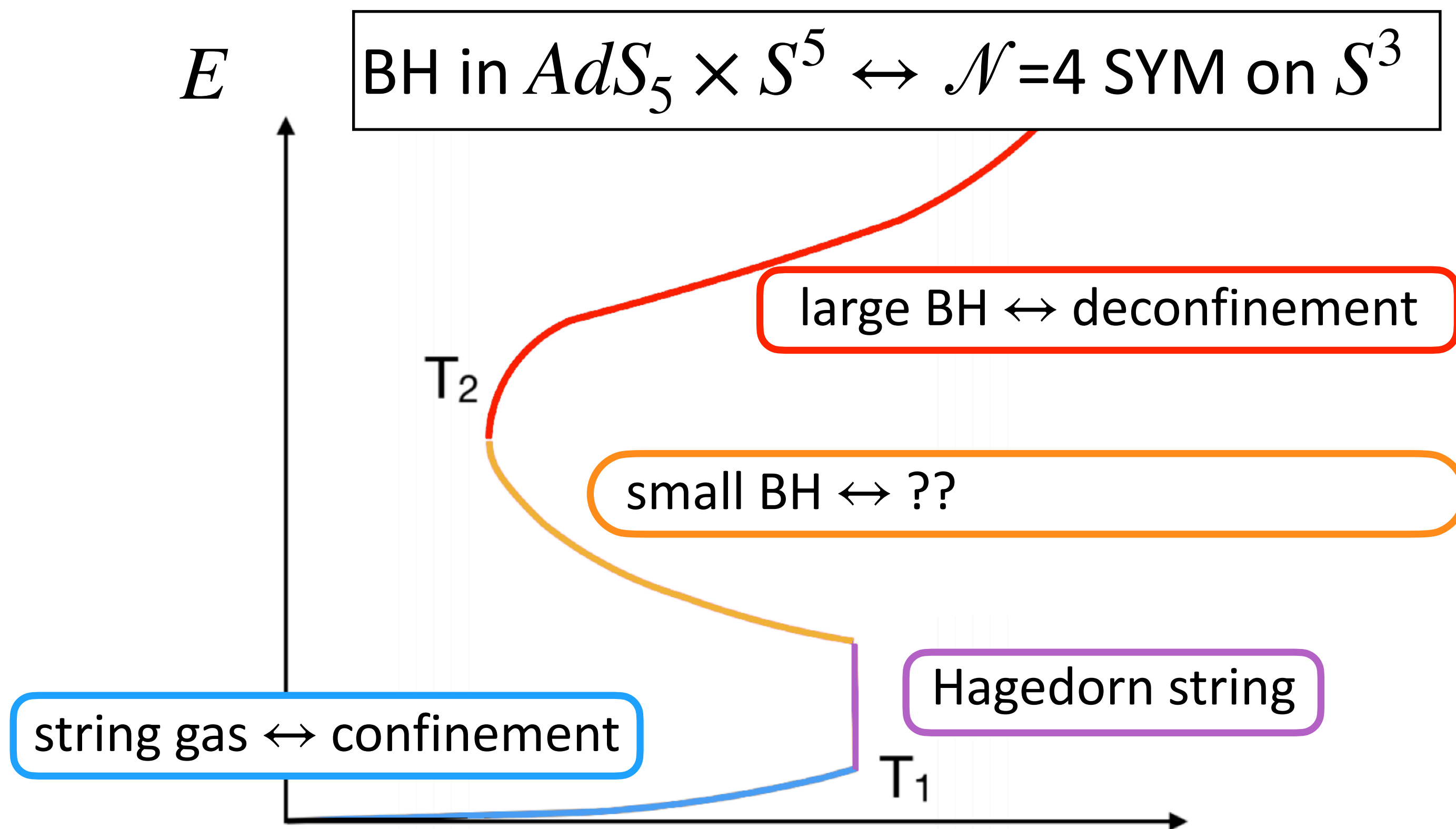


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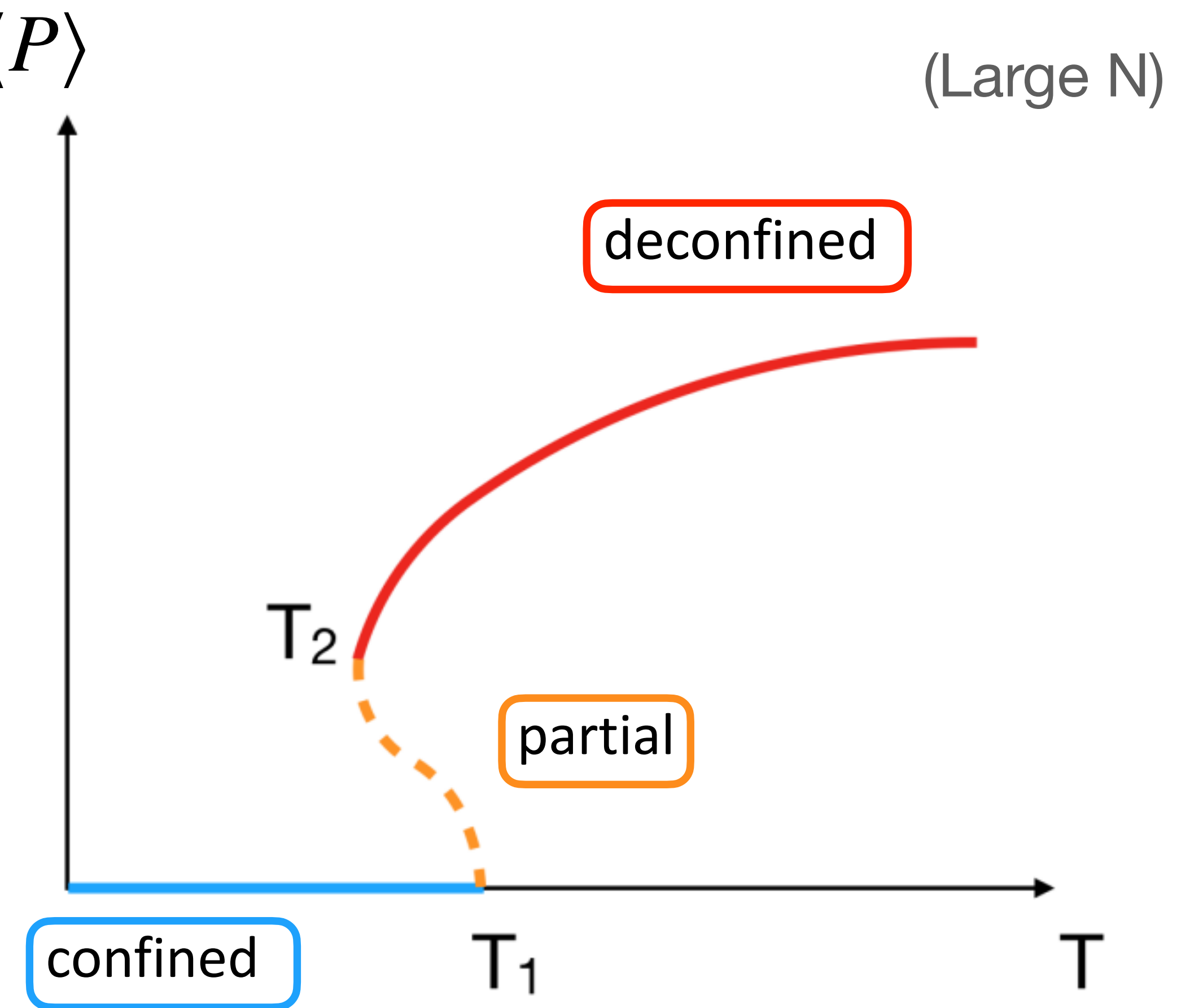
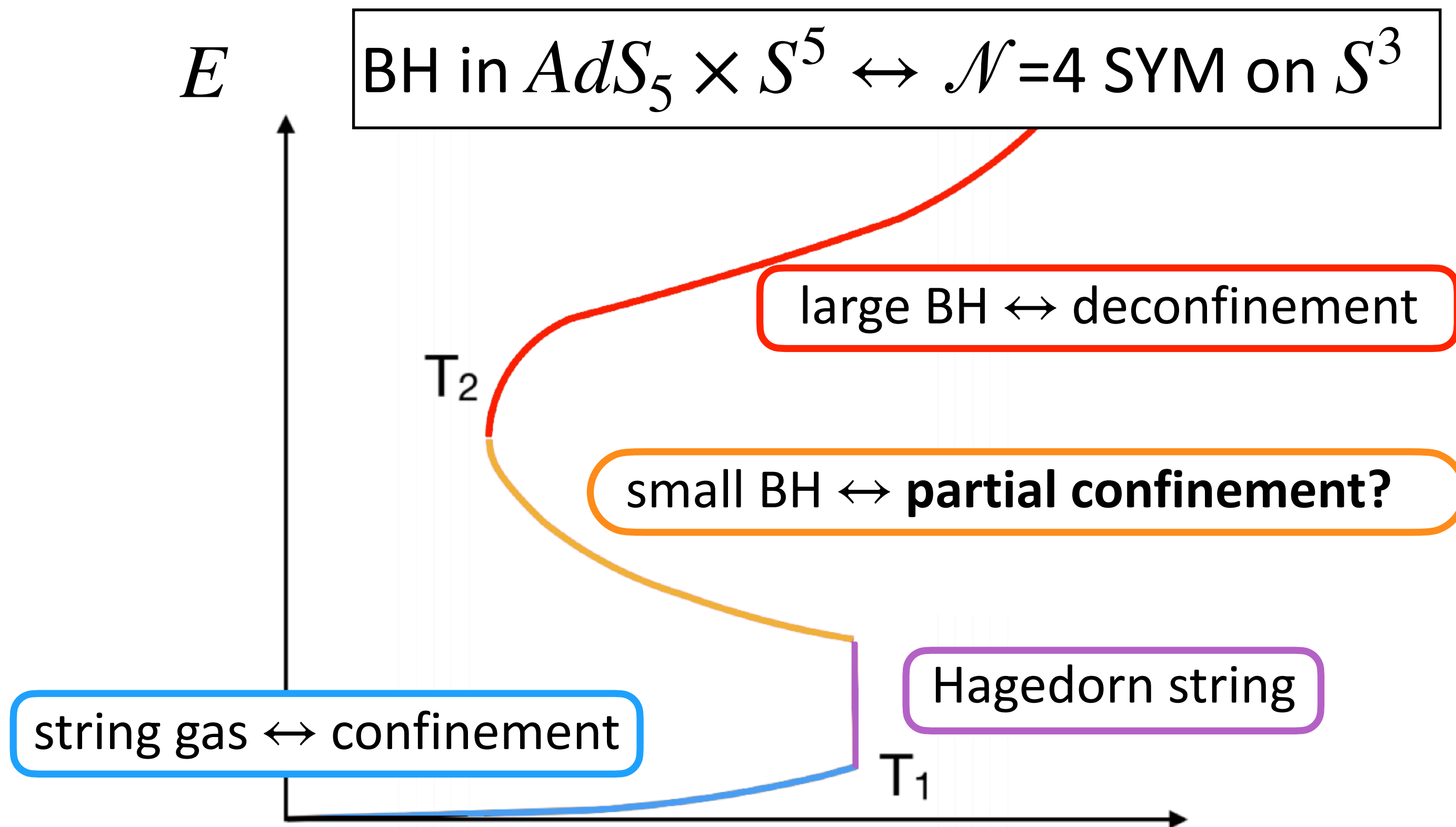




# Holography



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# Holography

Small black hole could be new partial deconfinement playground

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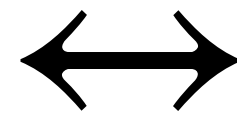
Examples:

- Jokela, Pönni, Vuorinen [1508.00859]
- Dias, Santos, Way [1605.04911, 1702.07718]

# Holography

Also:

11D Schwarzschild black hole in M-theory



partial deconfinement in D0 matrix model  
(Bergner et al. [2110.01312])

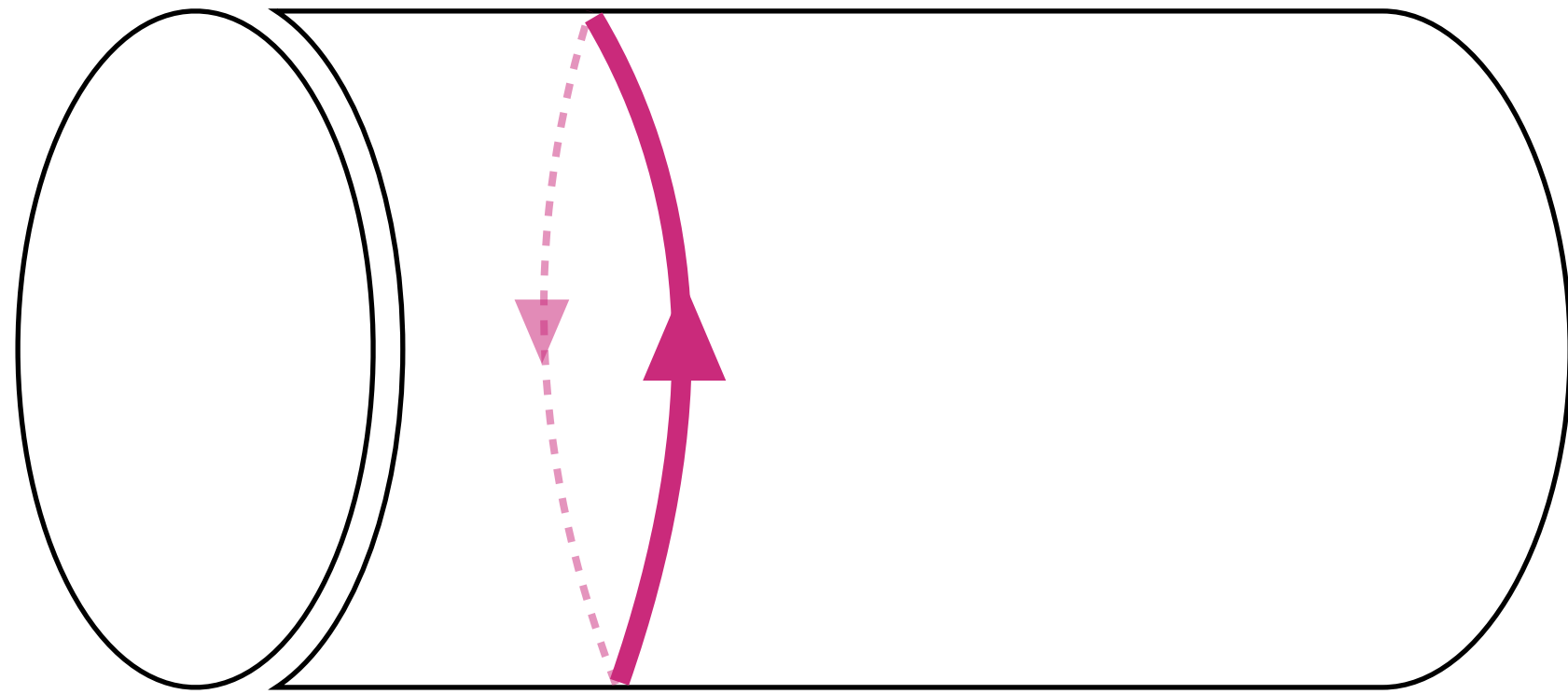
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# Polyakov loop and GWW

Centre symmetry is signature  
of confinement

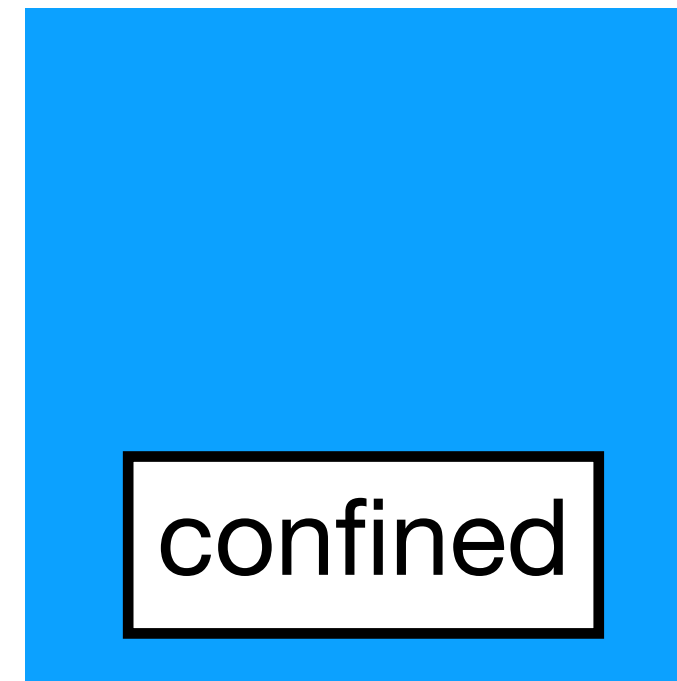
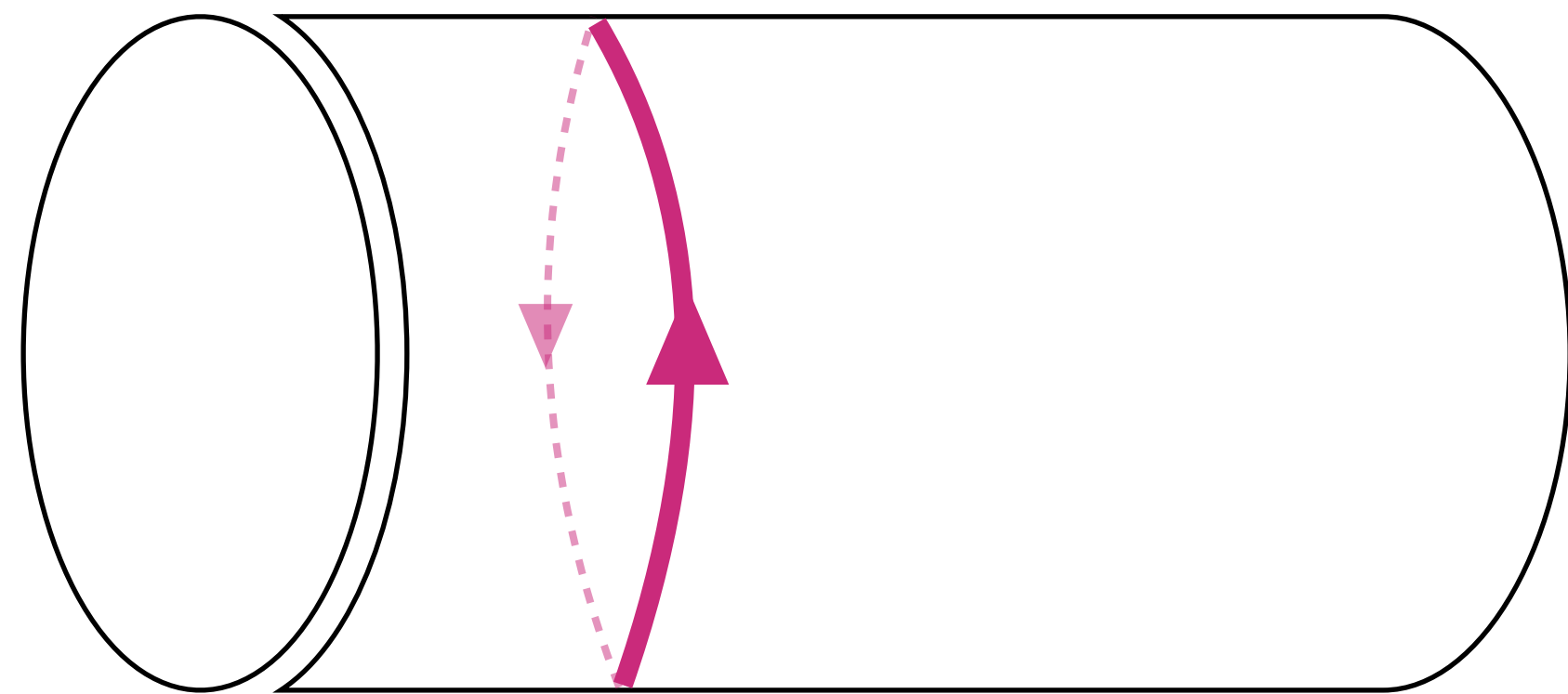
Can be seen by the eigenvalues  
of the Polyakov loop



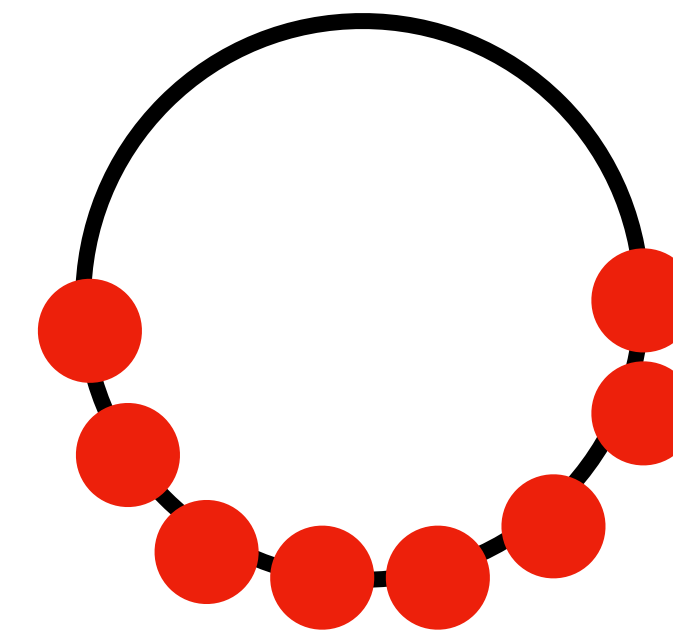
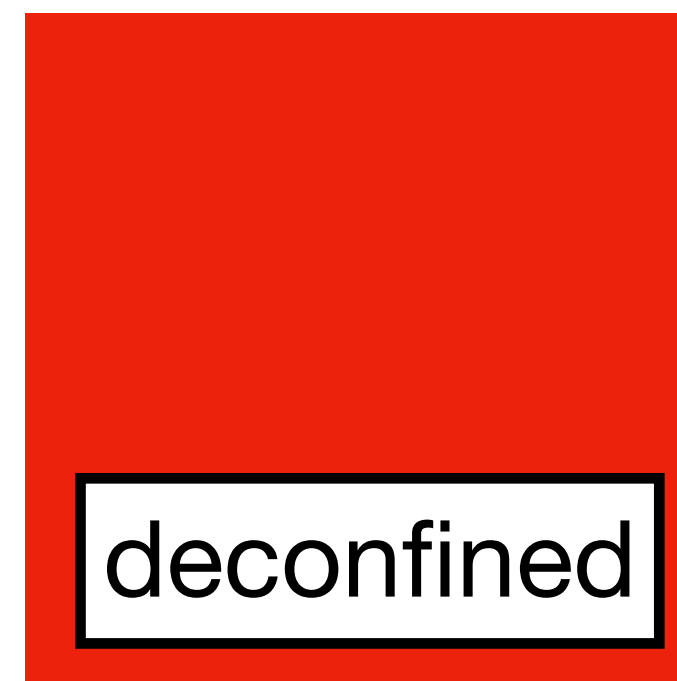
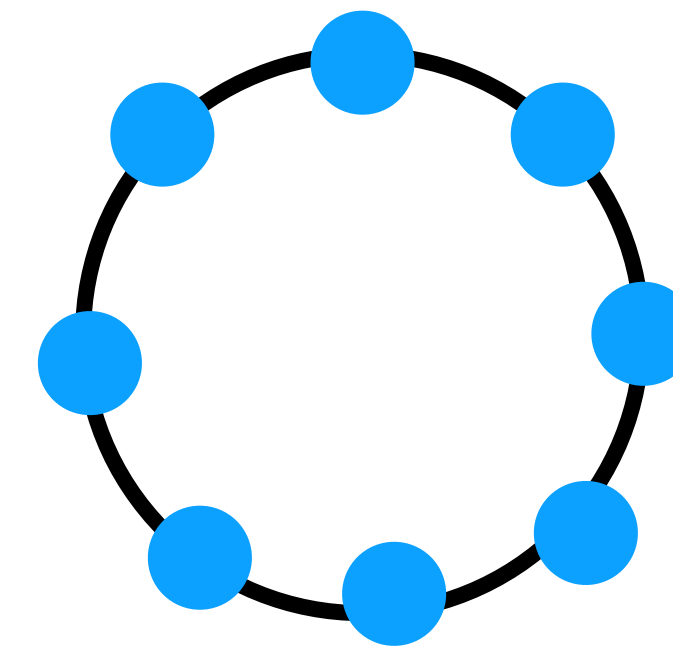
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Can be seen by the eigenvalues of the Polyakov loop



Eigenvalues  
 $e^{i\psi_k}$

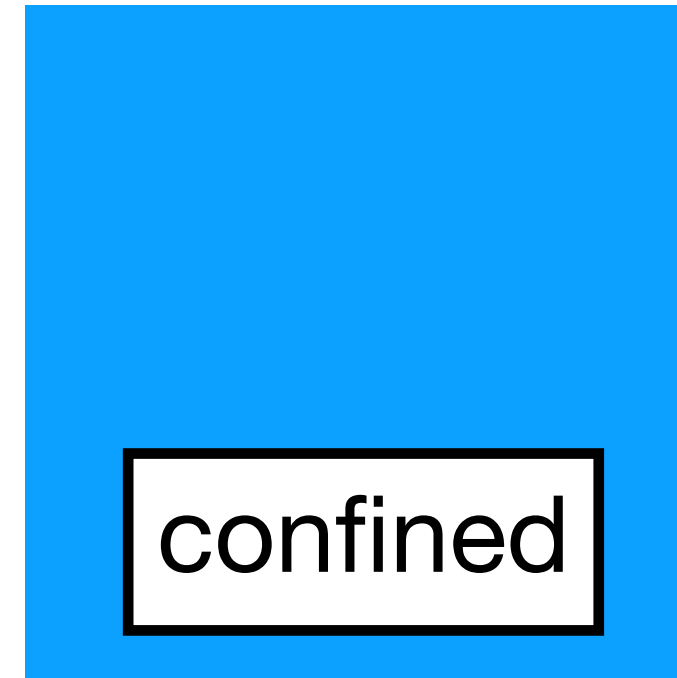
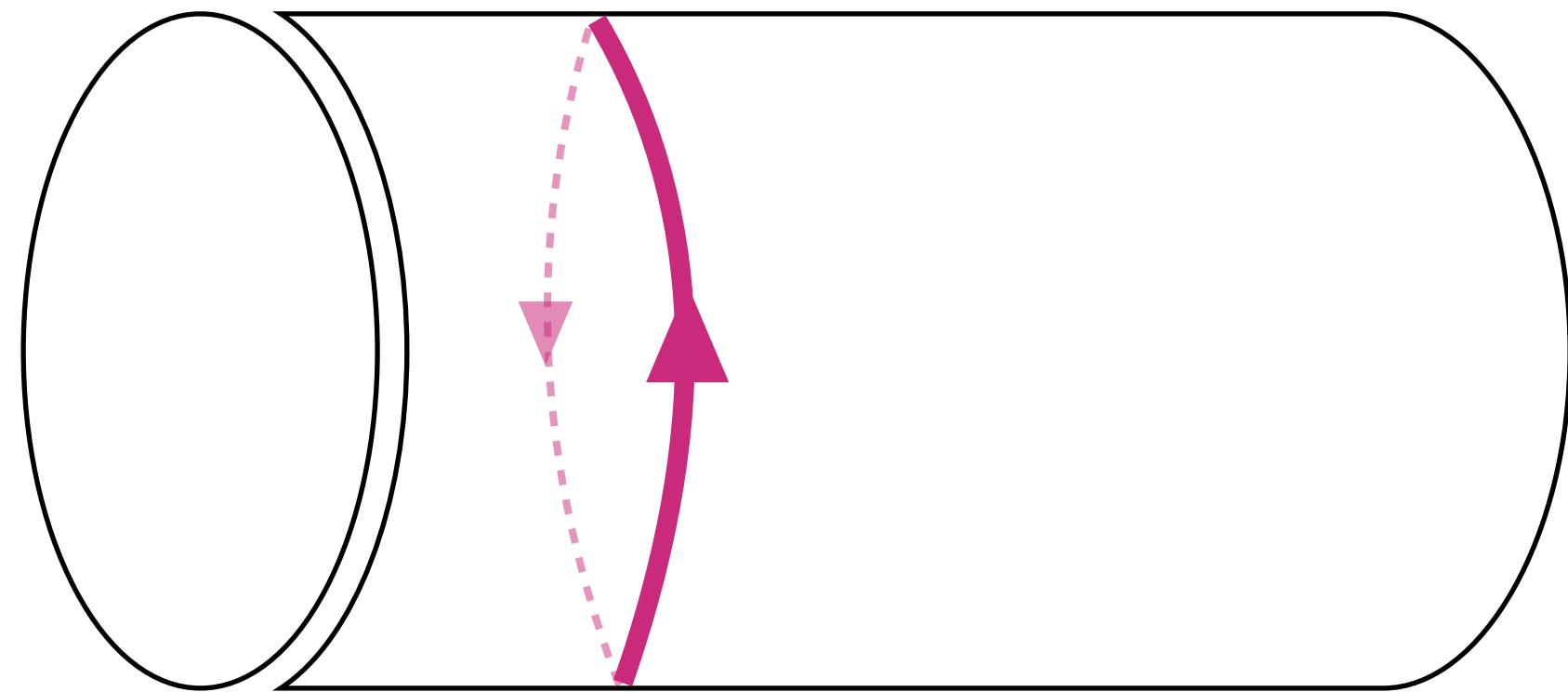




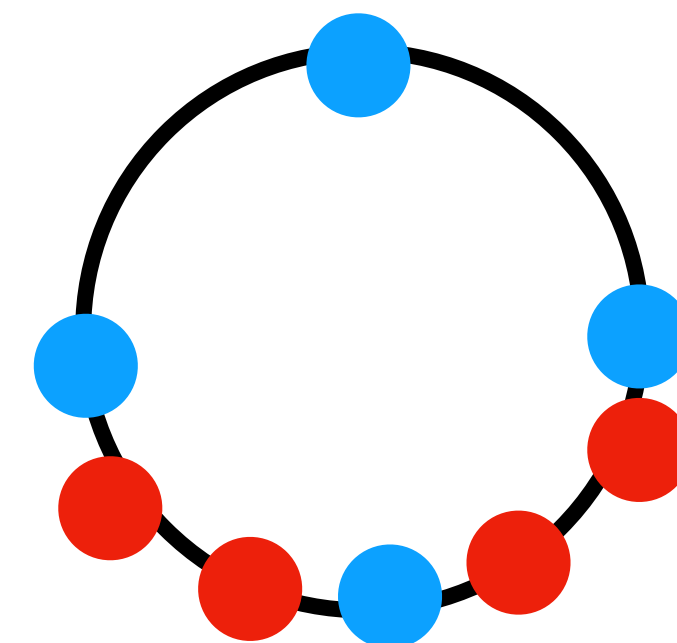
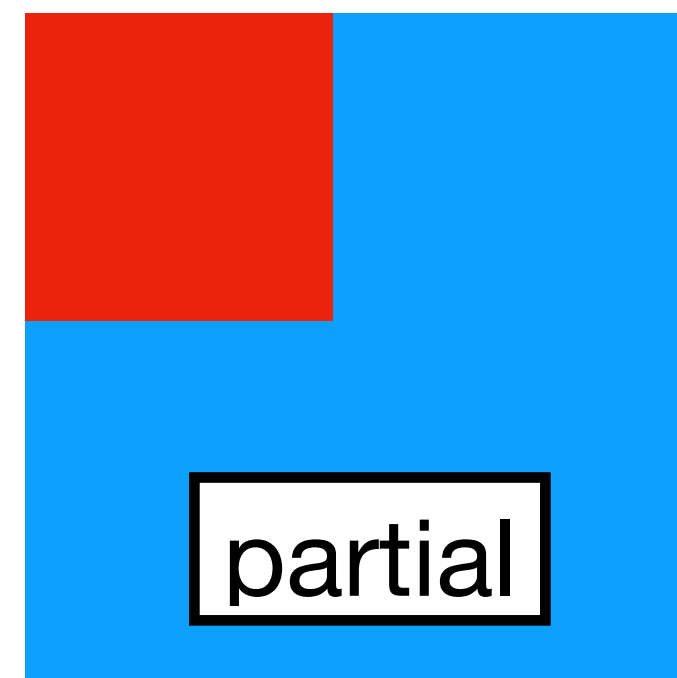
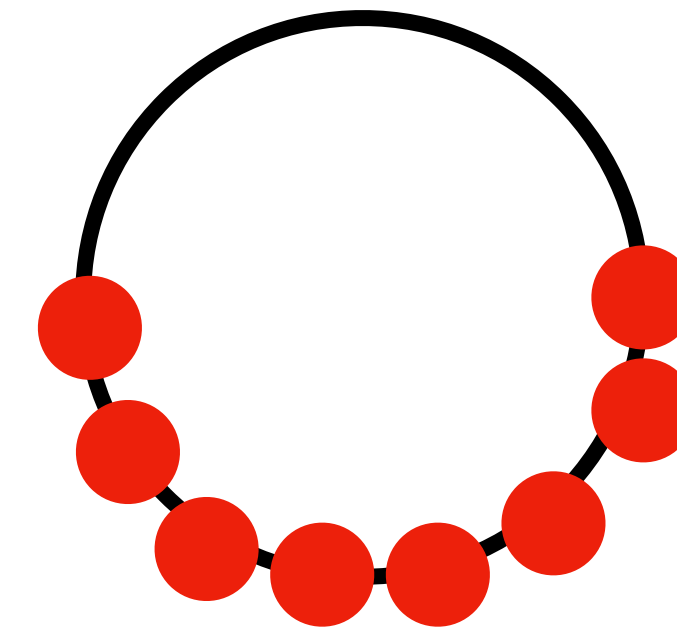
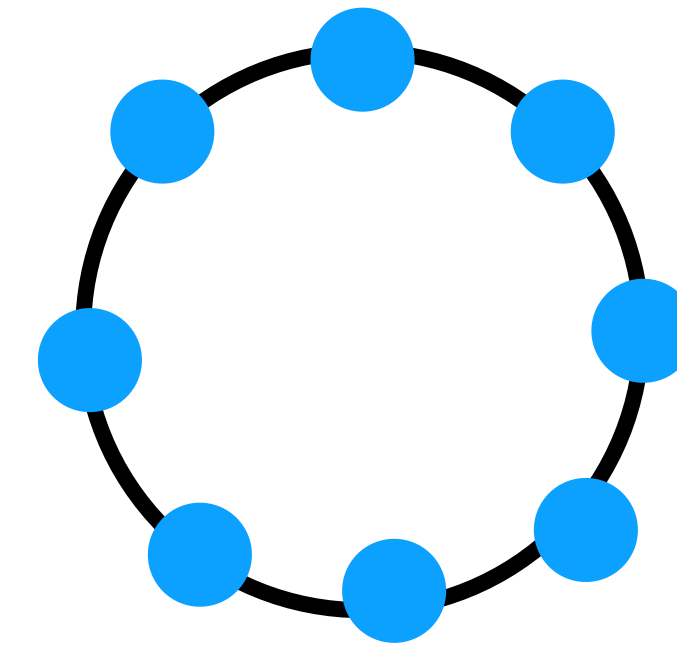
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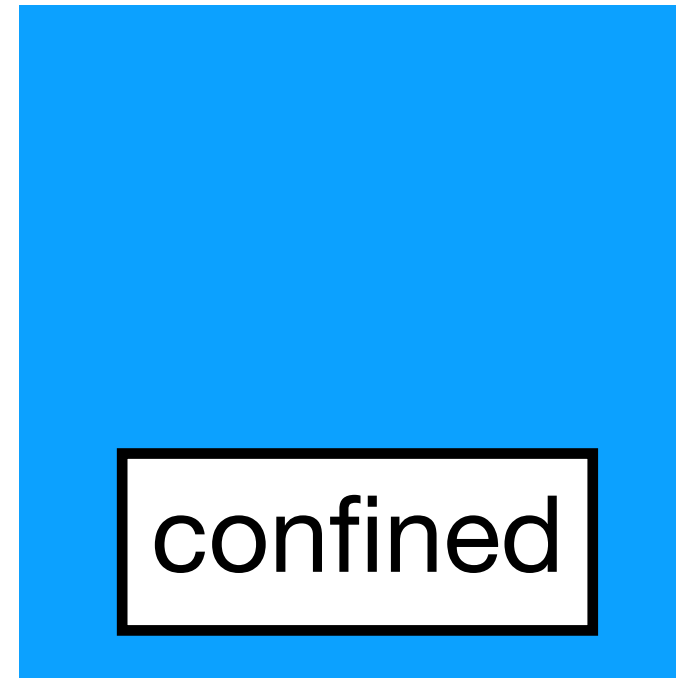
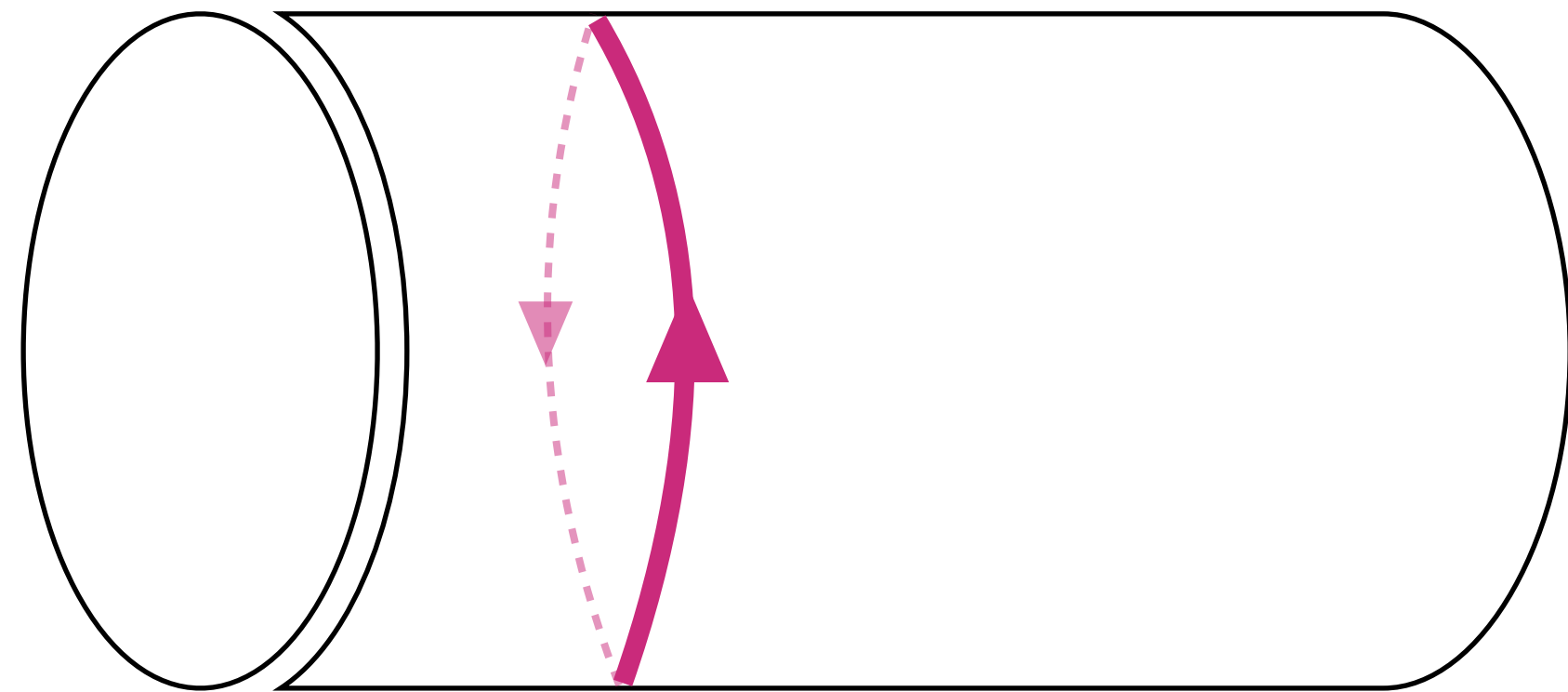
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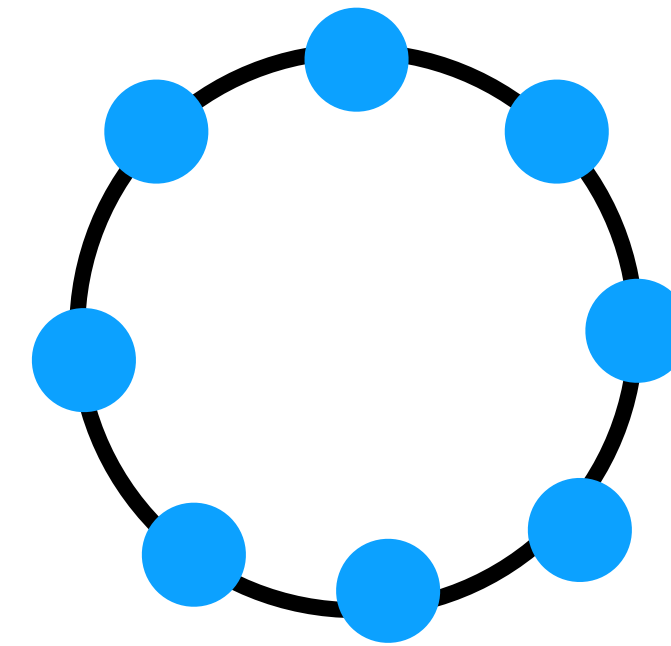
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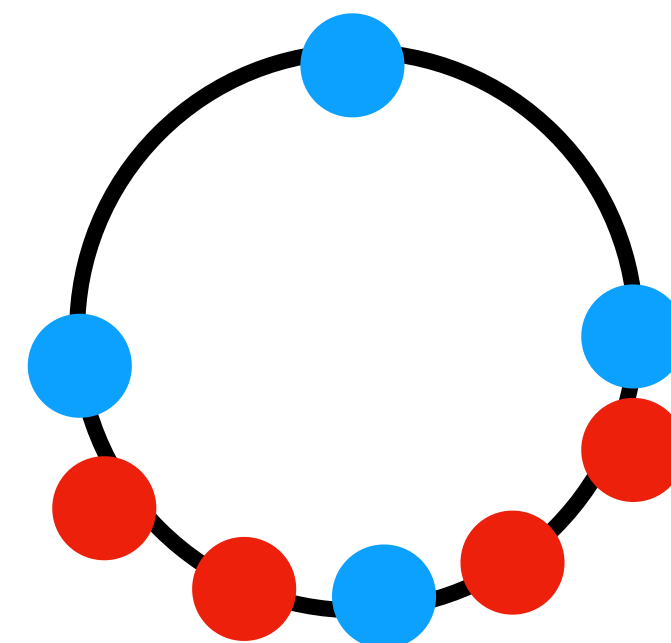
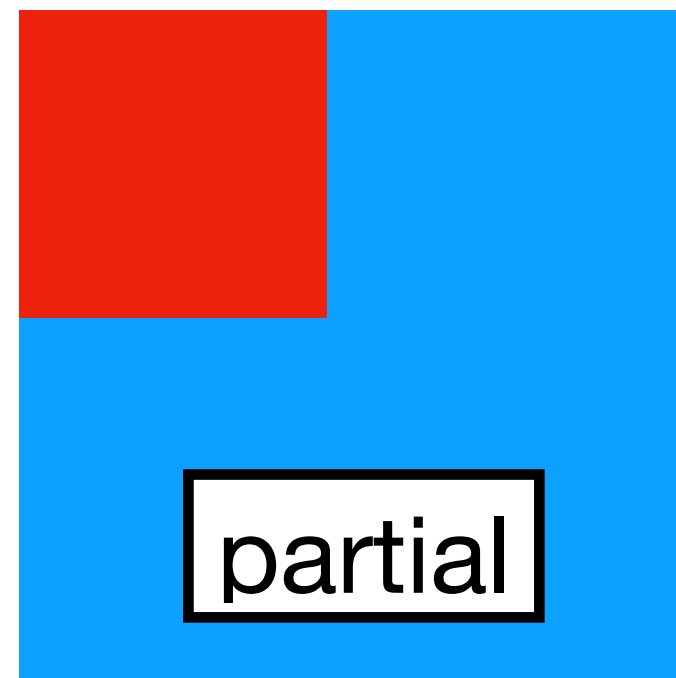
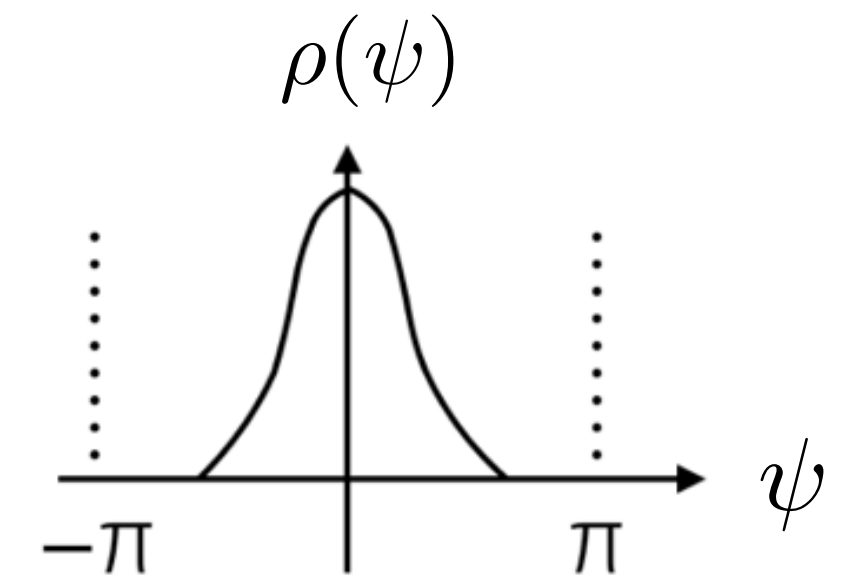
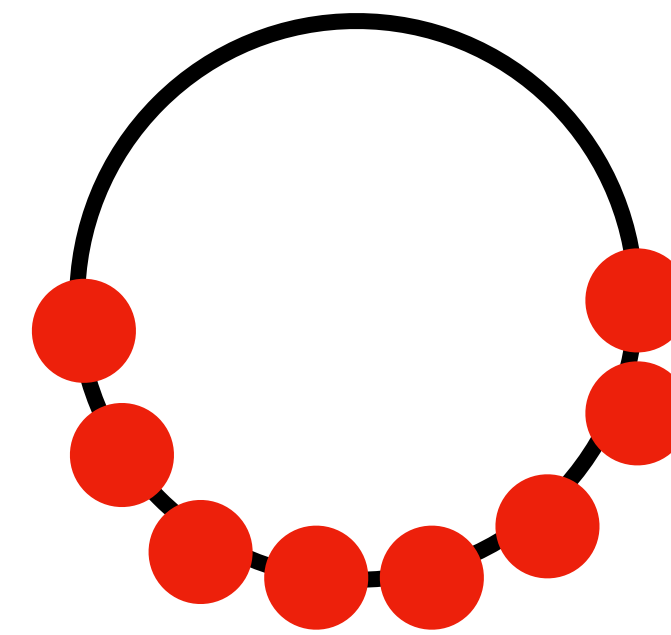
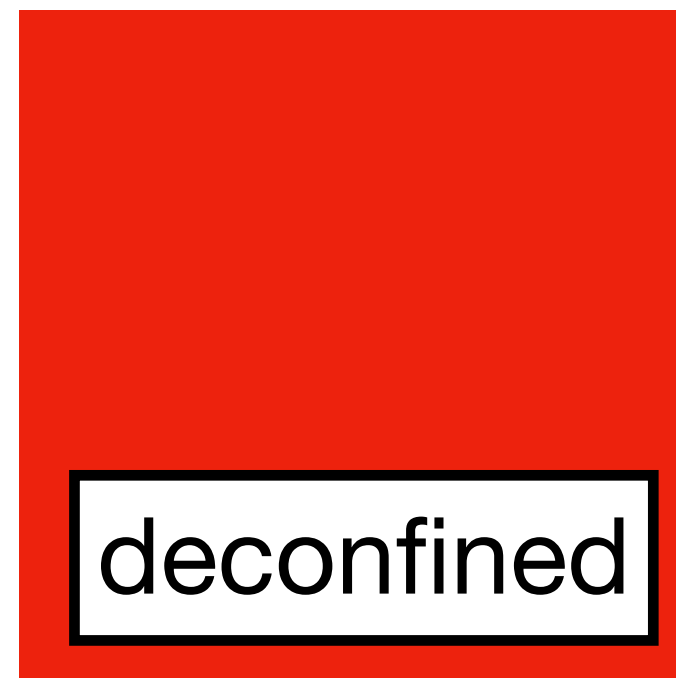
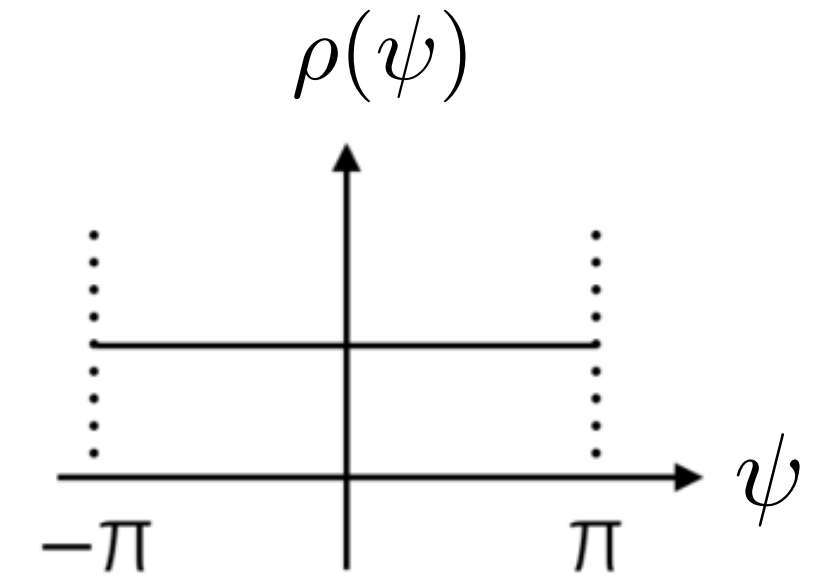
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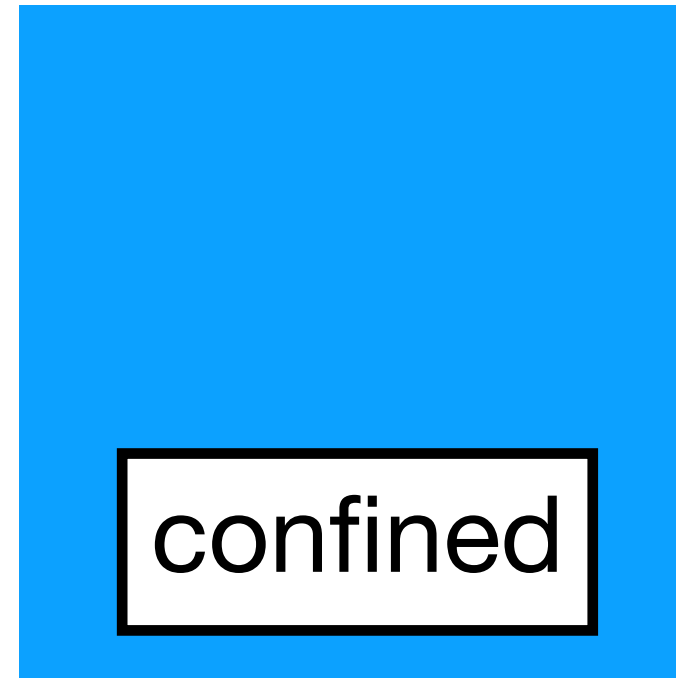
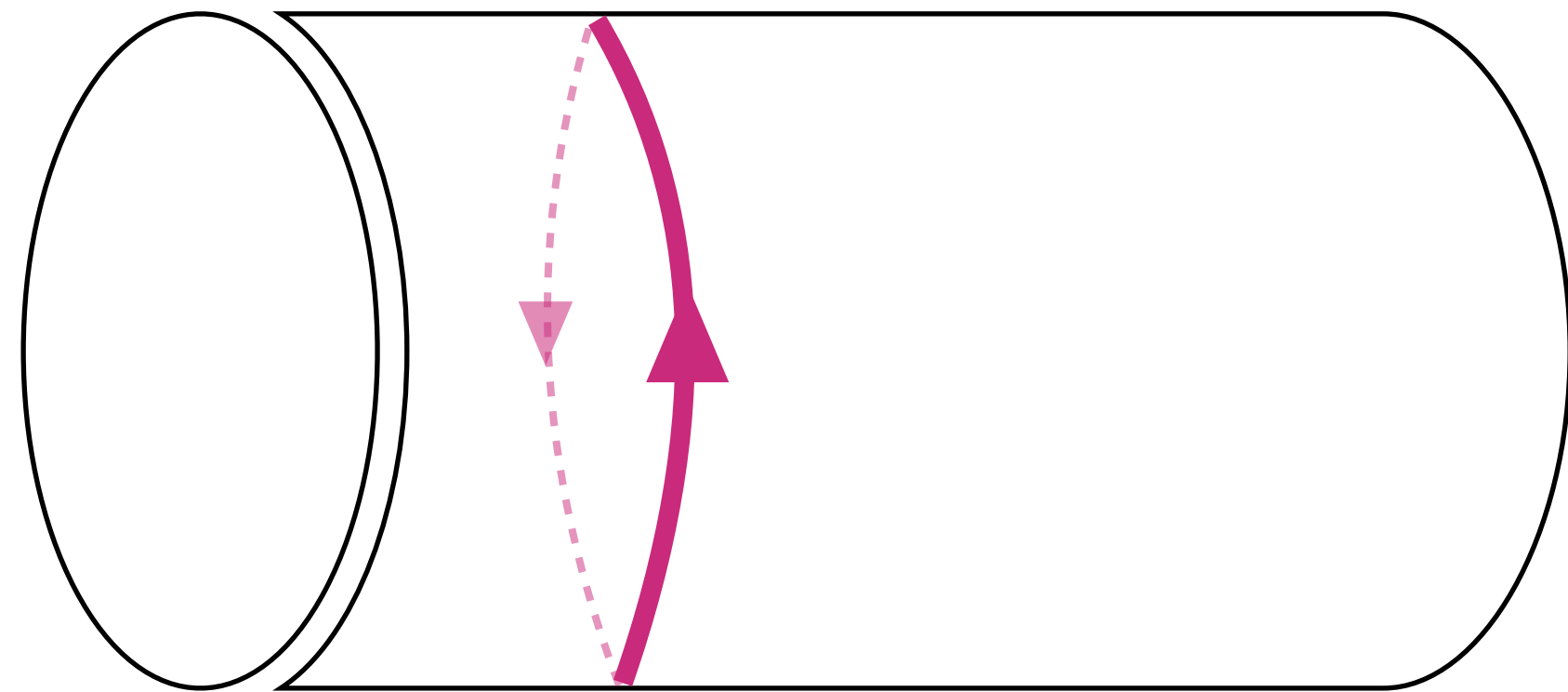
Eigenvalue density



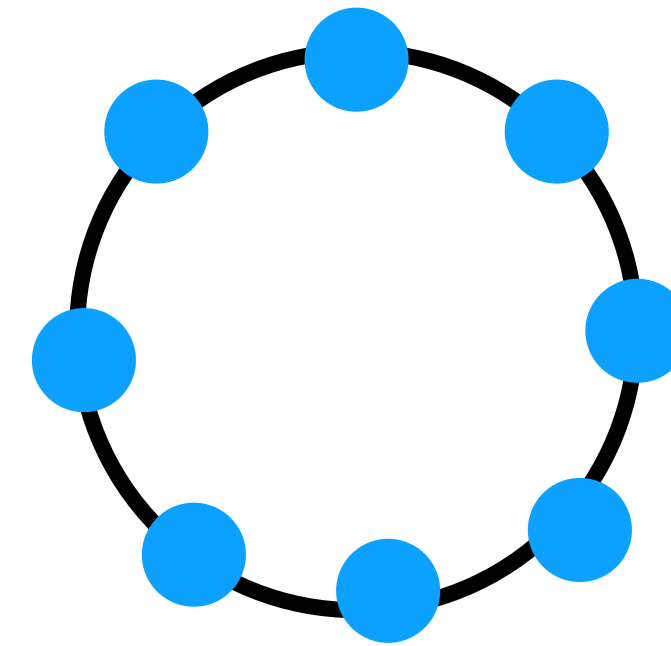
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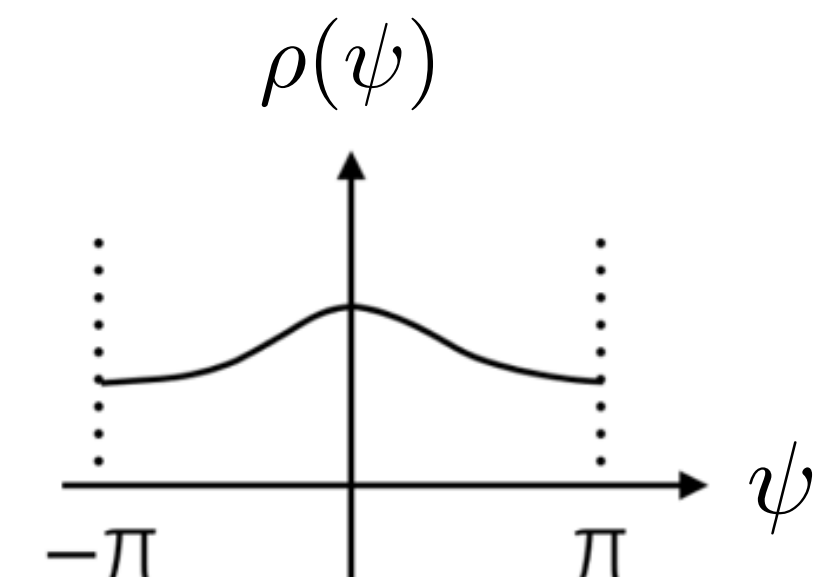
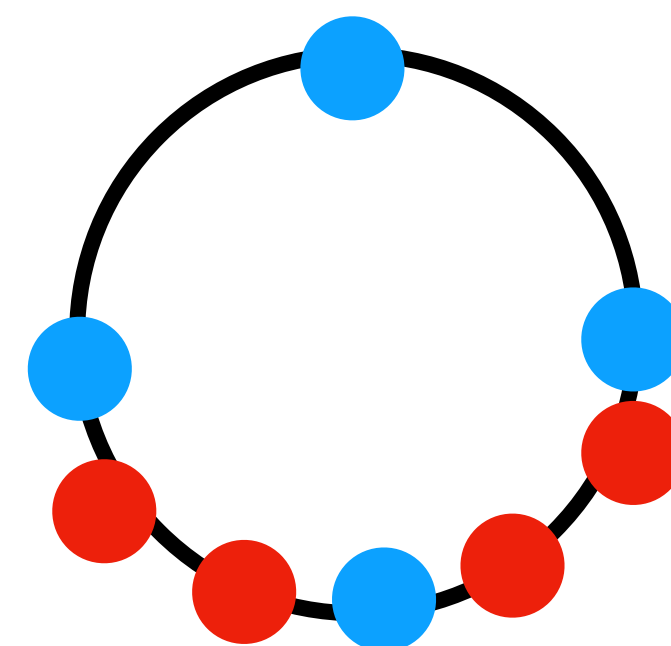
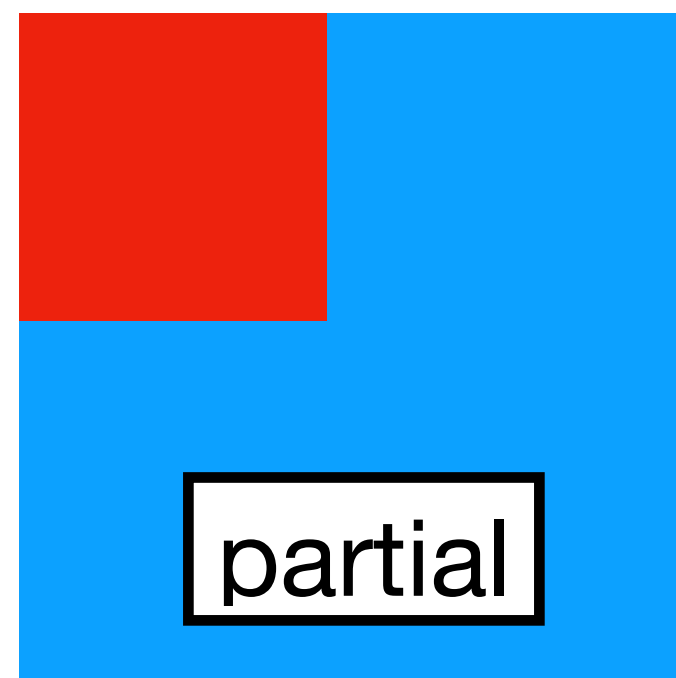
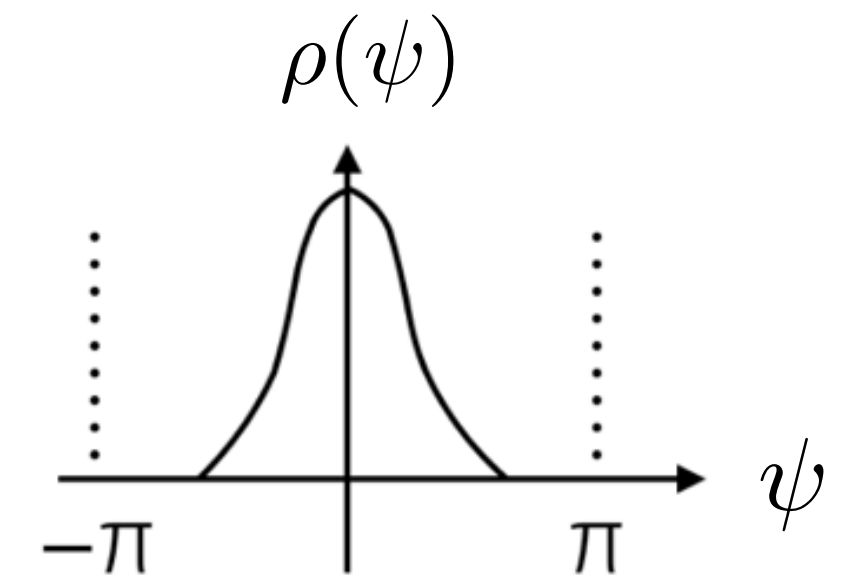
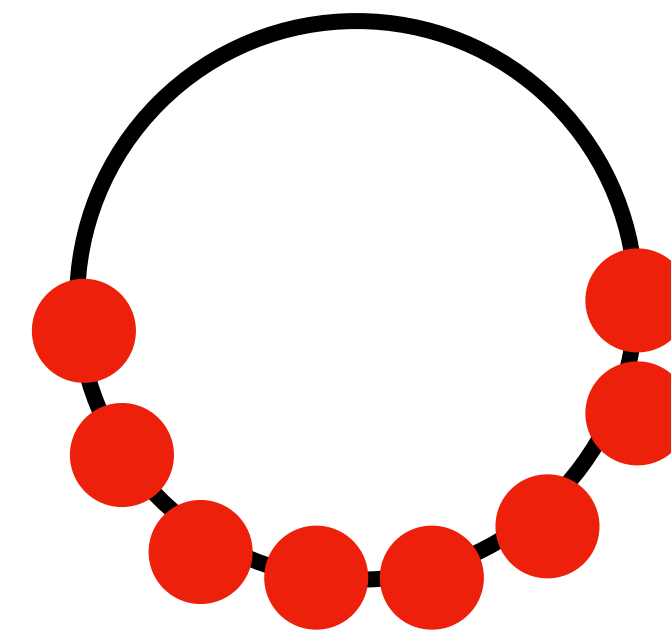
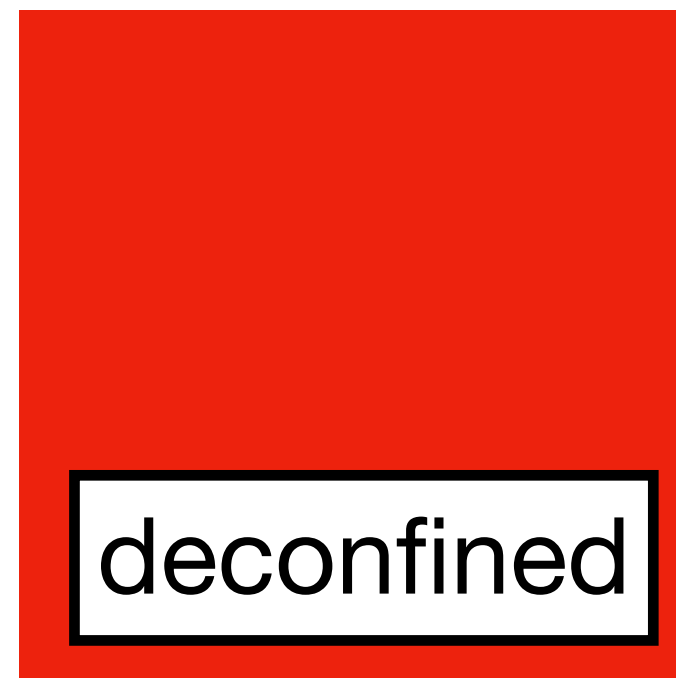
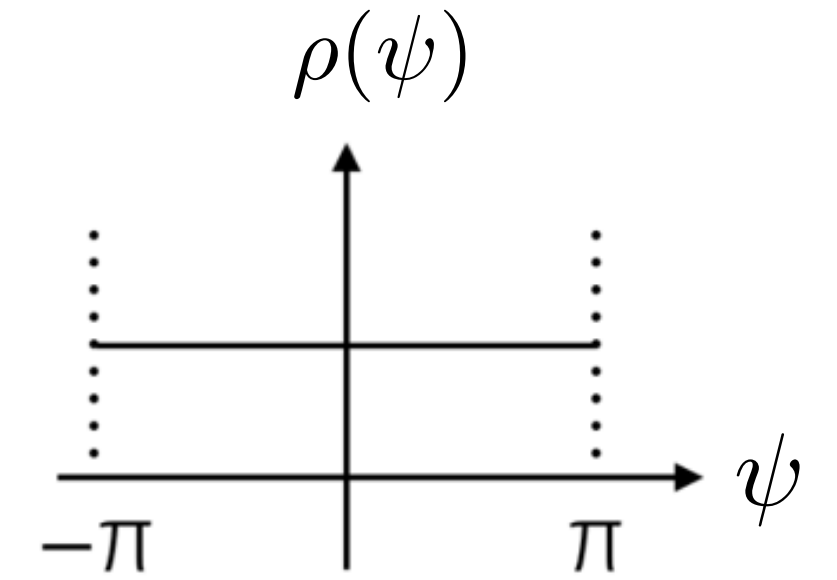
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Eigenvalues  $e^{i\psi_k}$

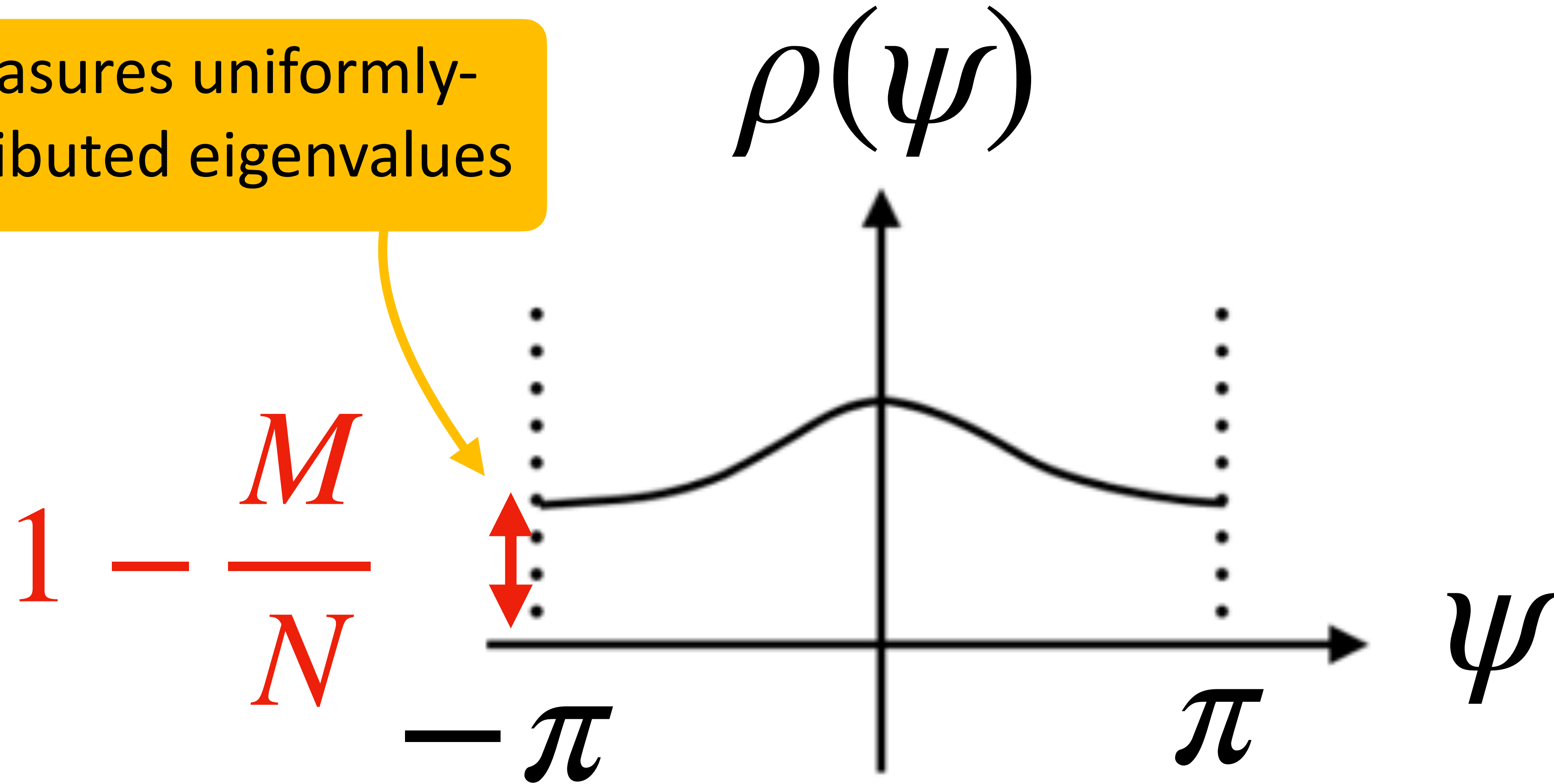


Eigenvalue density

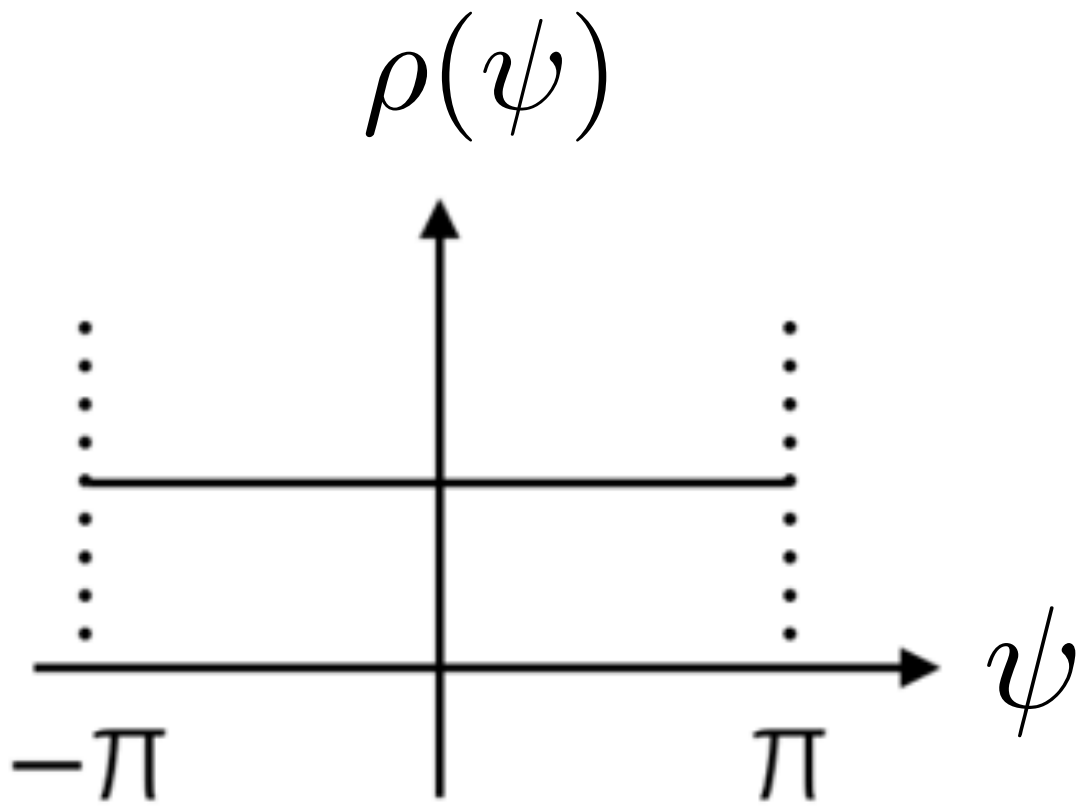


# Finding $M$ ( $SU(M) \subset SU(N)$ )

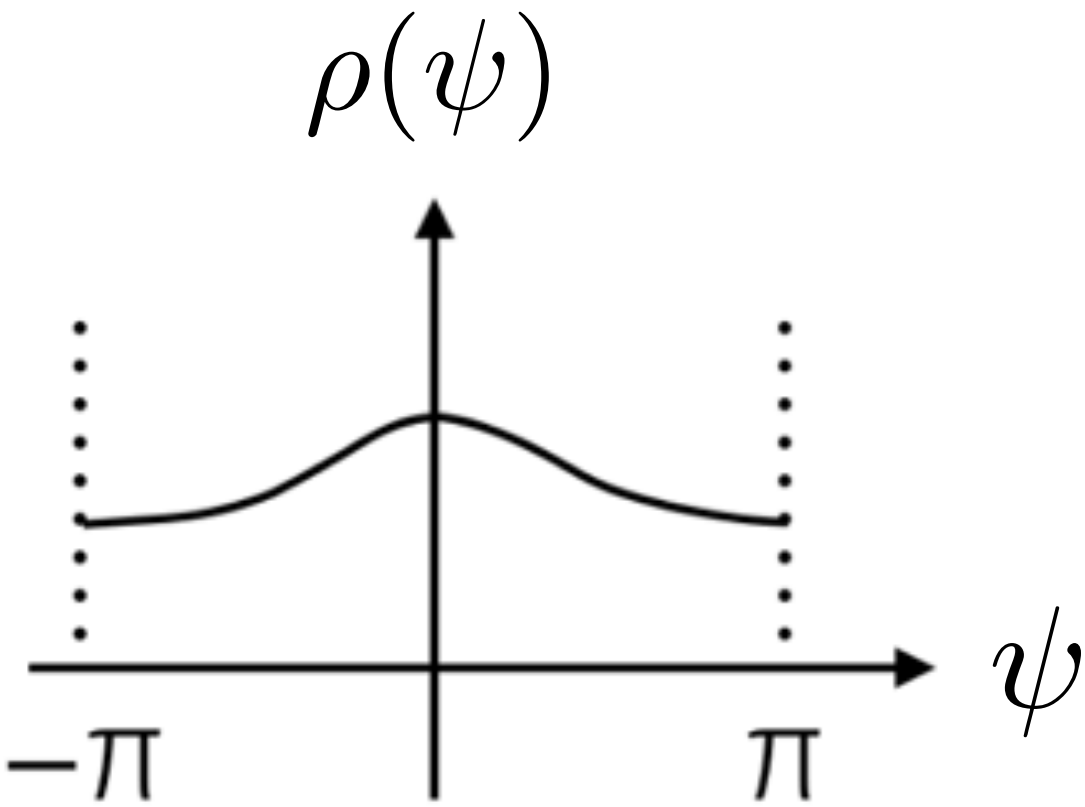
Measures uniformly-distributed eigenvalues



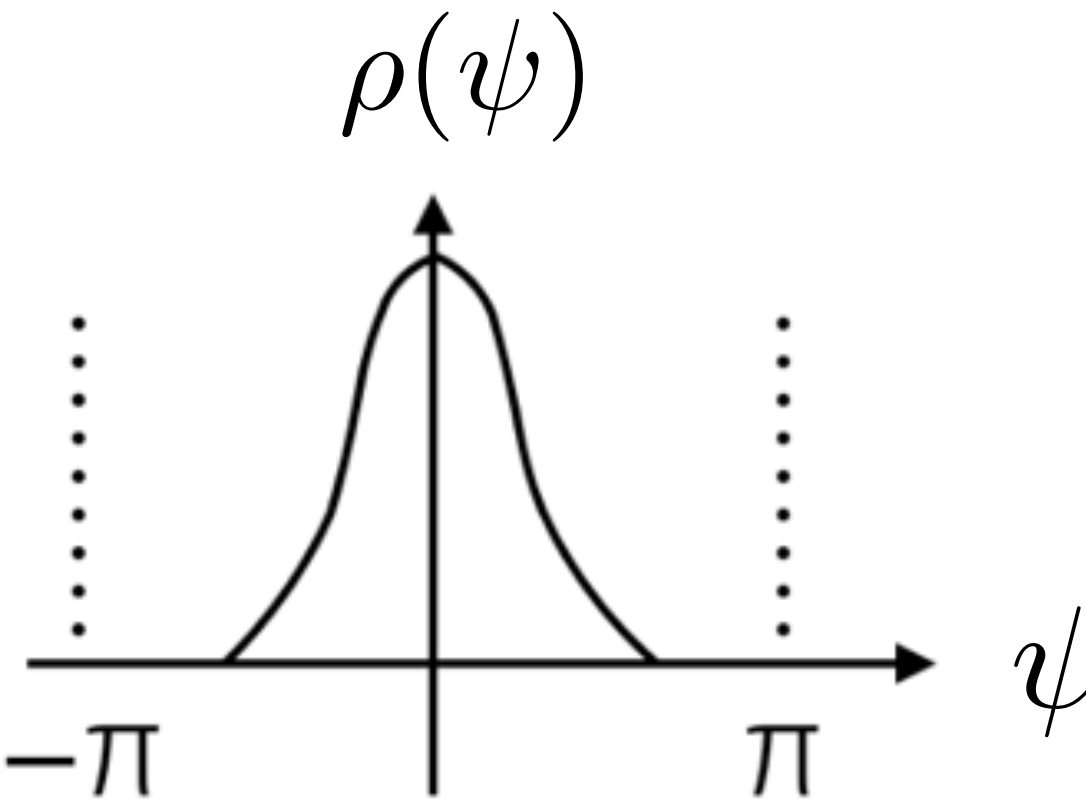
# Gross-Witten-Wadia



confined



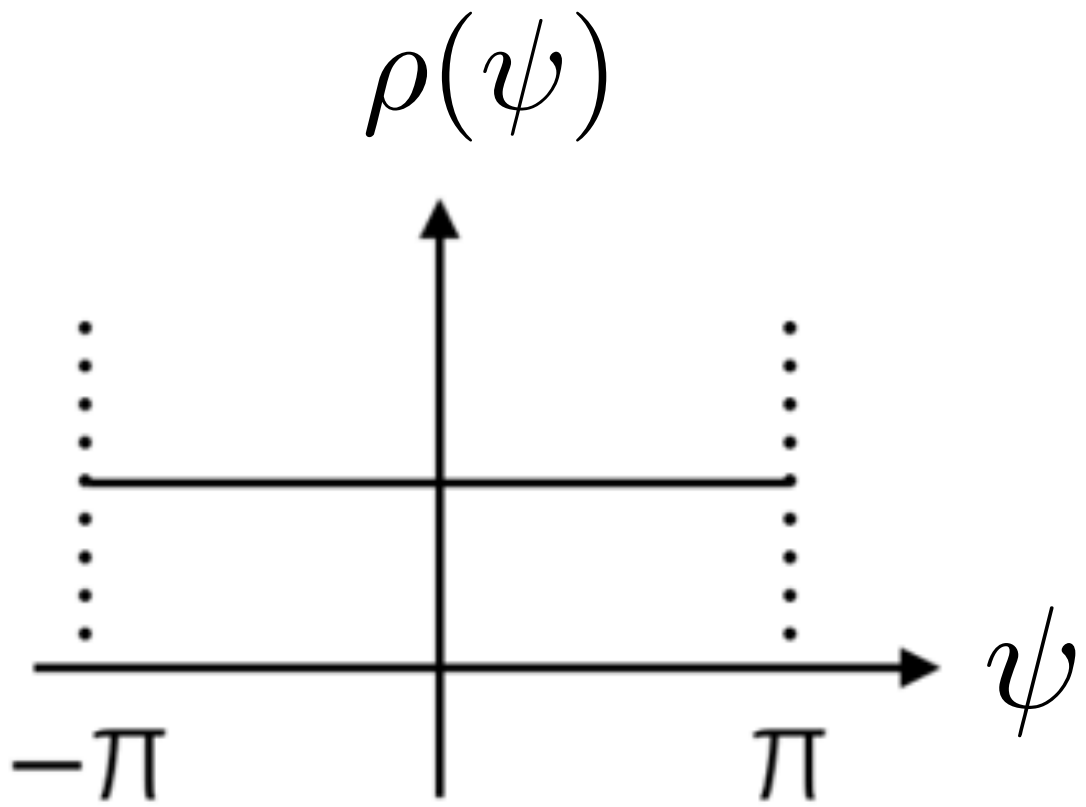
partially  
confined



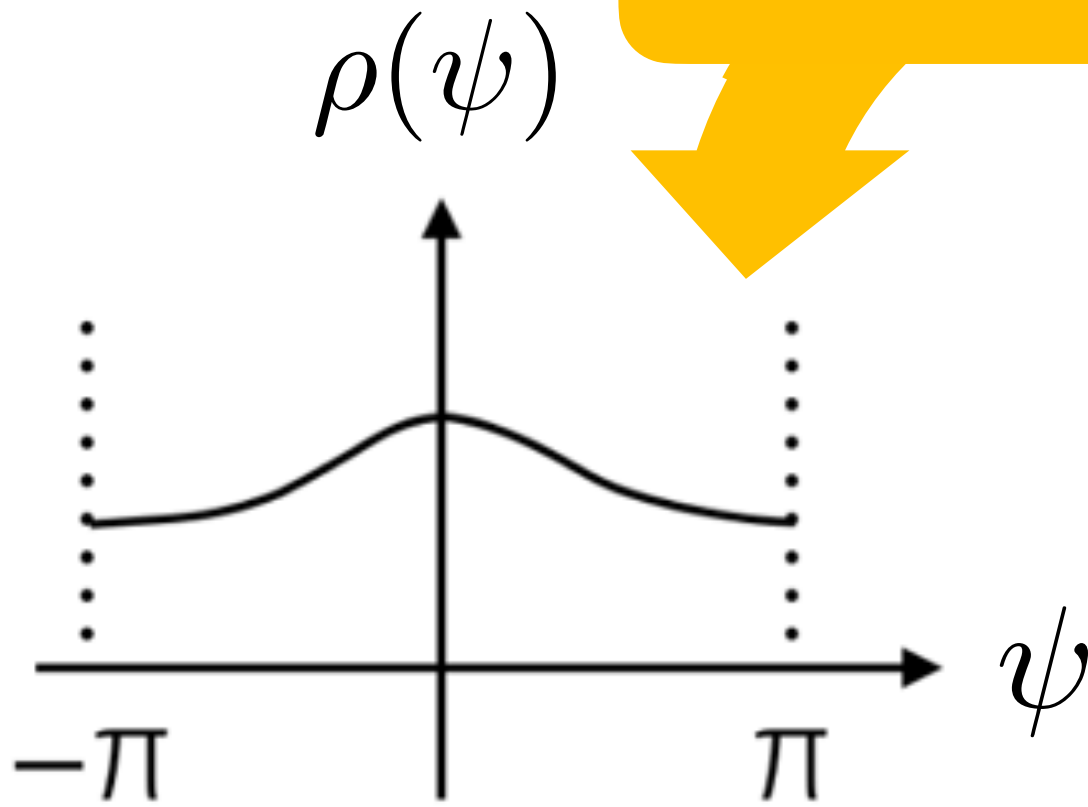
deconfined

# Gross-Witten-Wadia

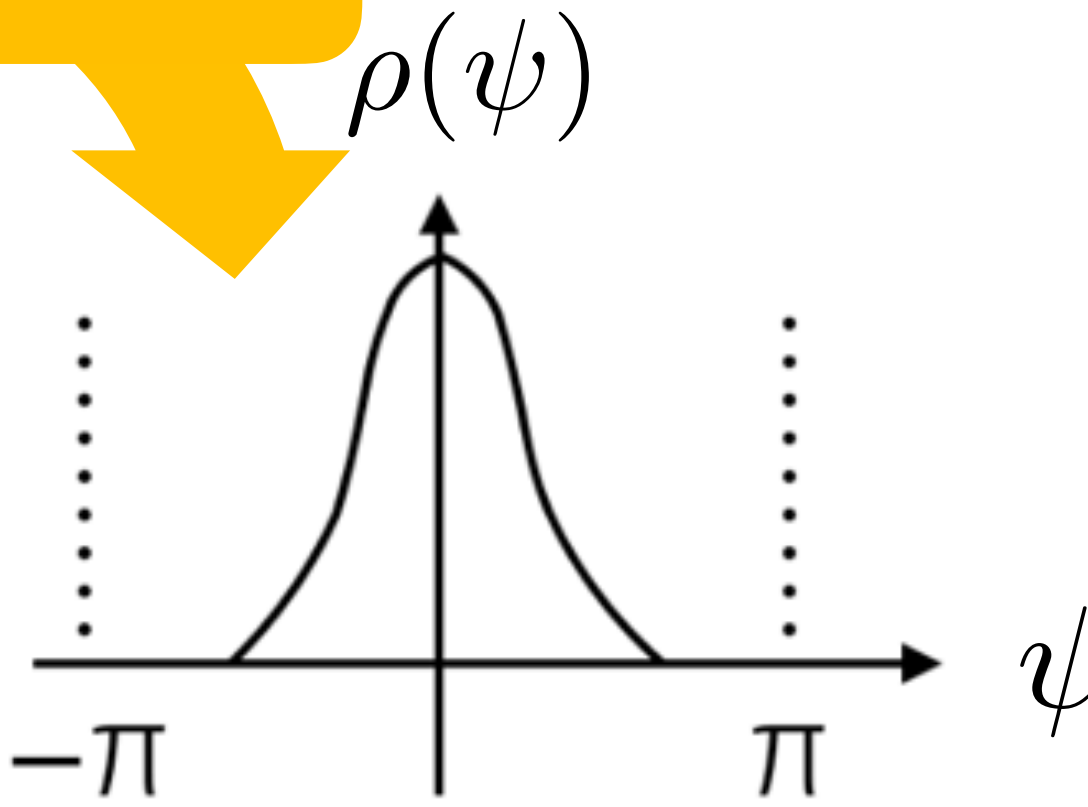
**GW  
transition**



confined



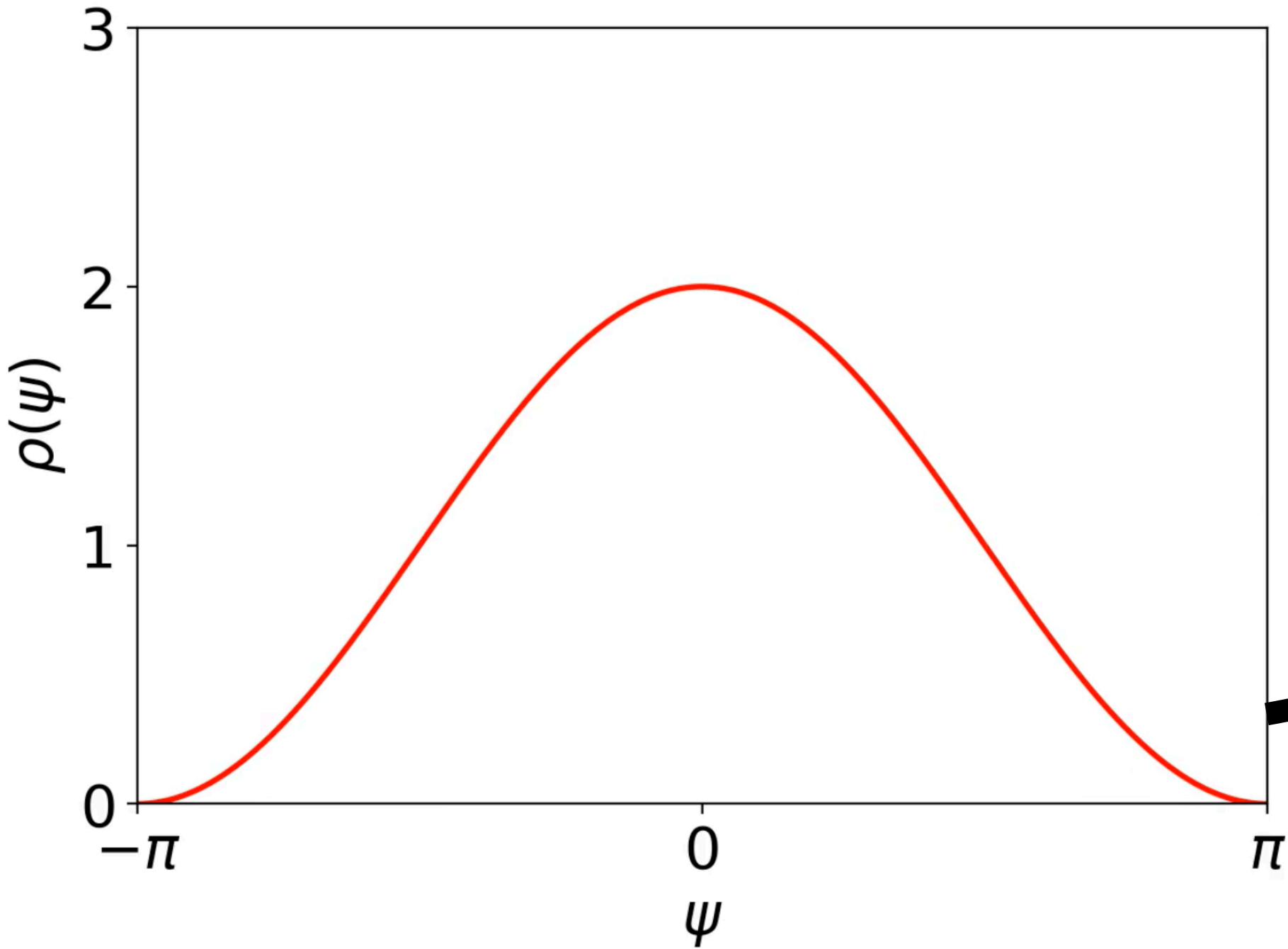
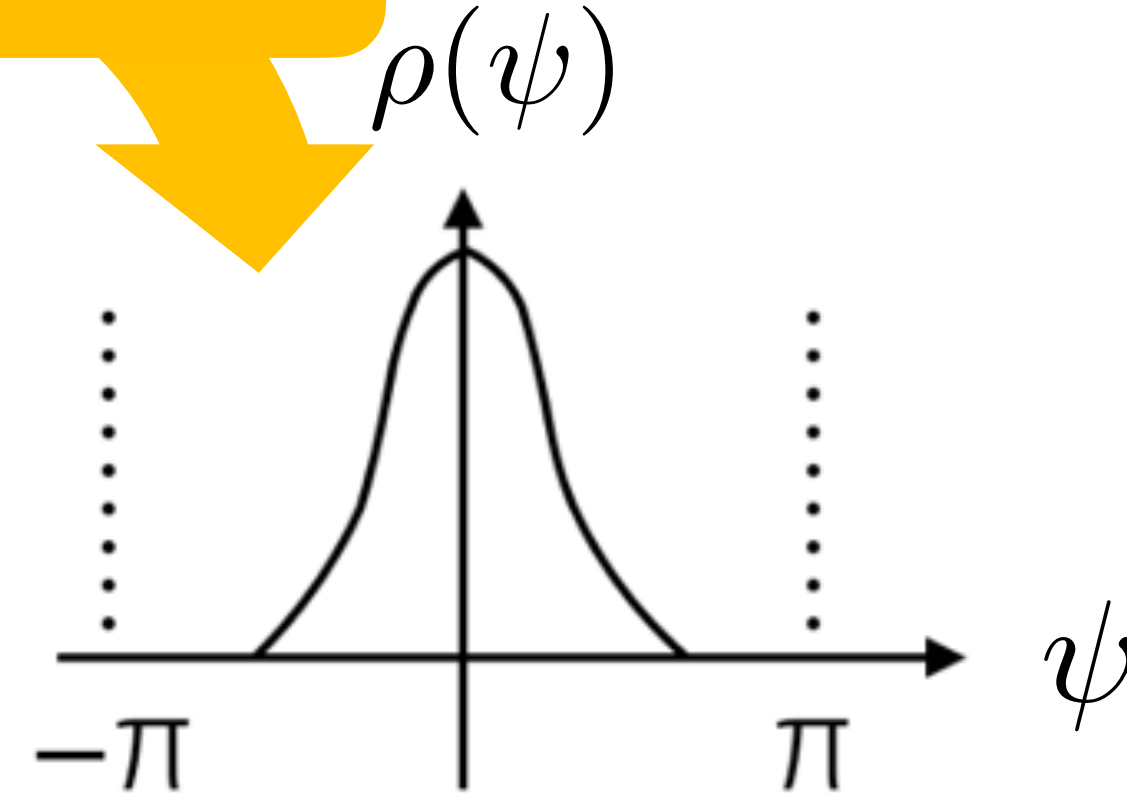
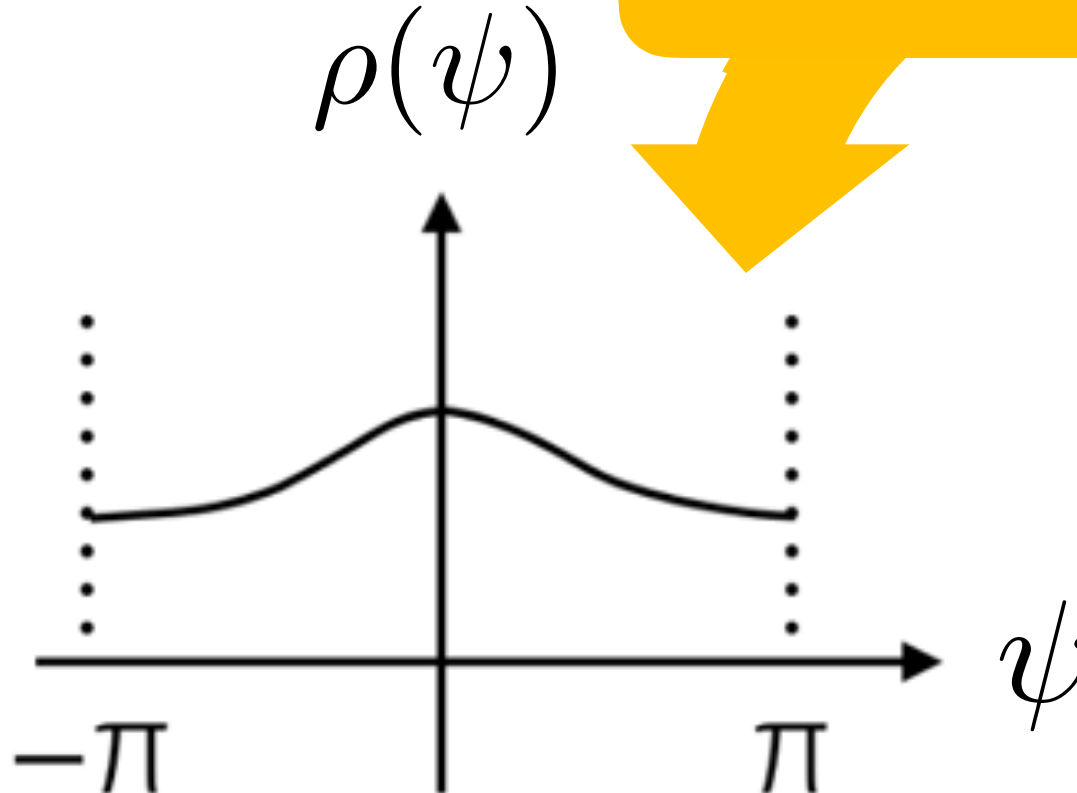
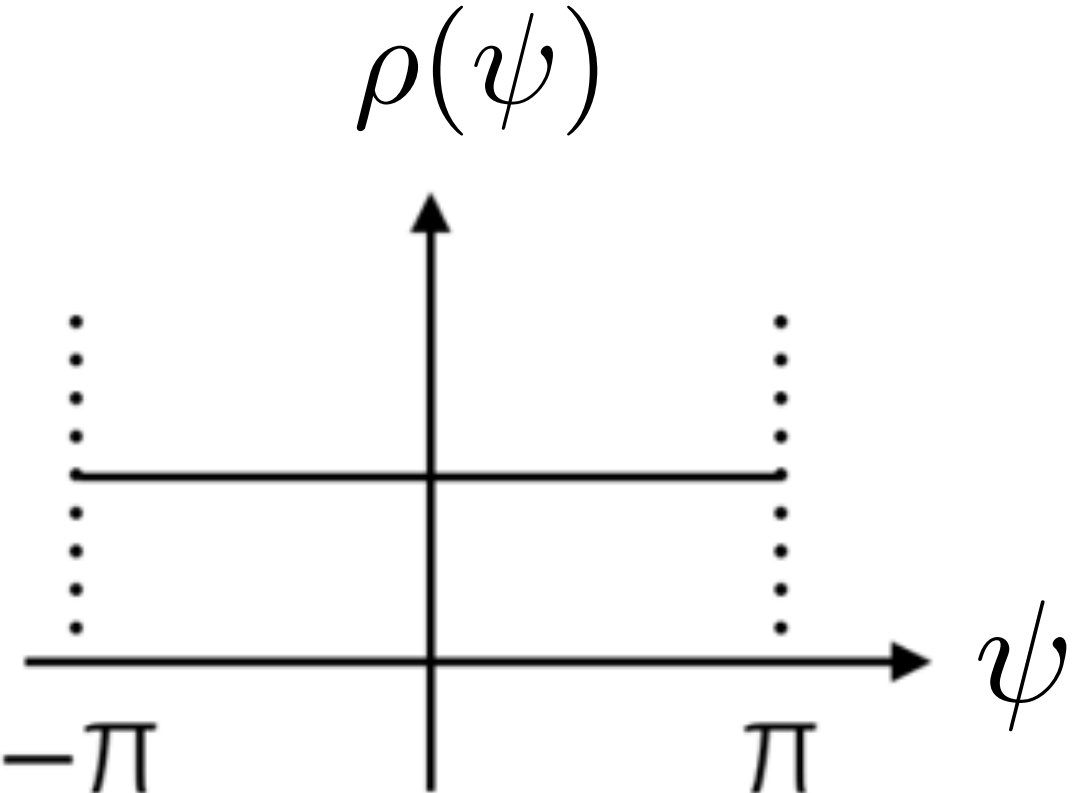
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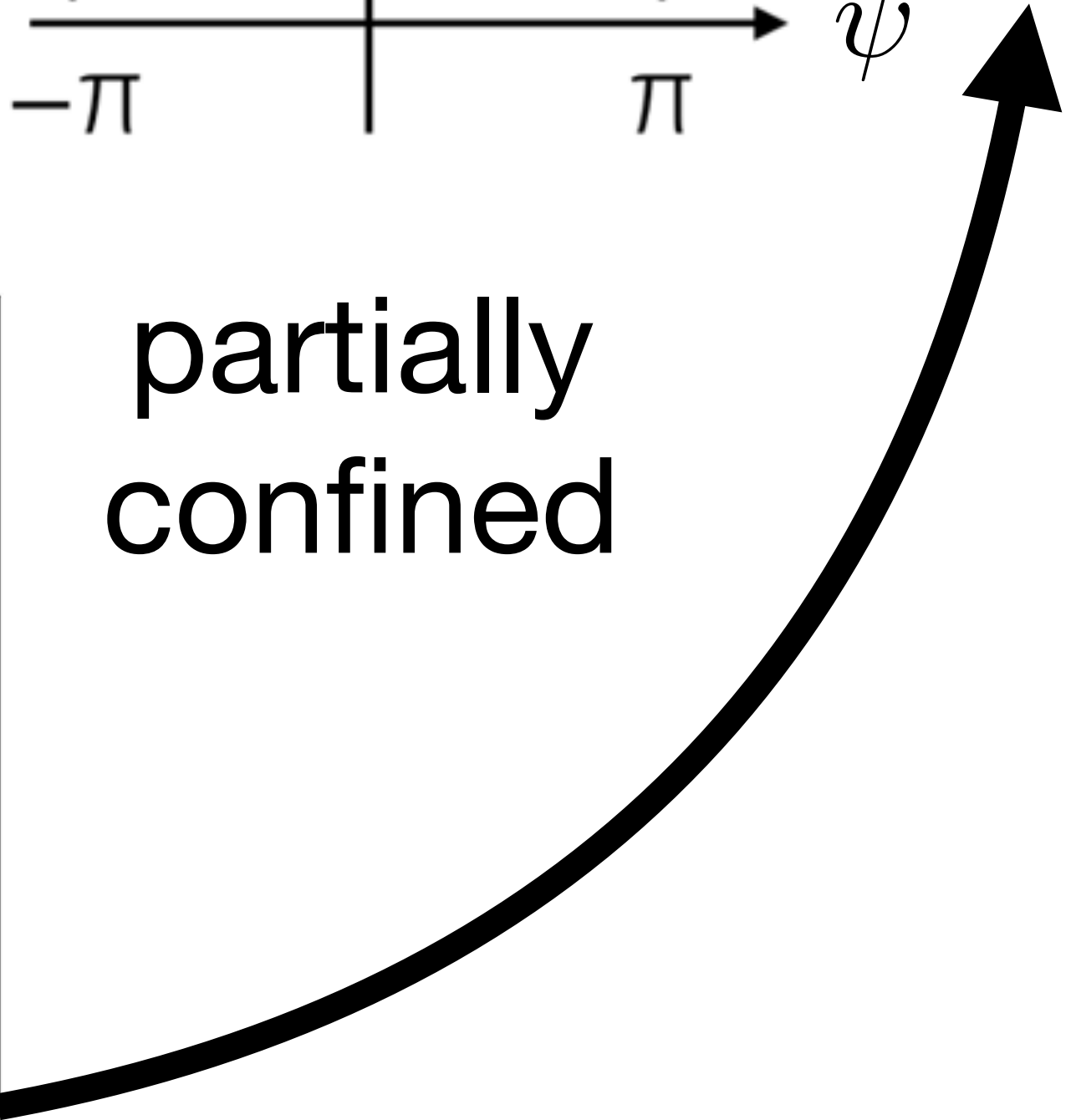
# Gross-Witten-Wadia

**GWW transition**



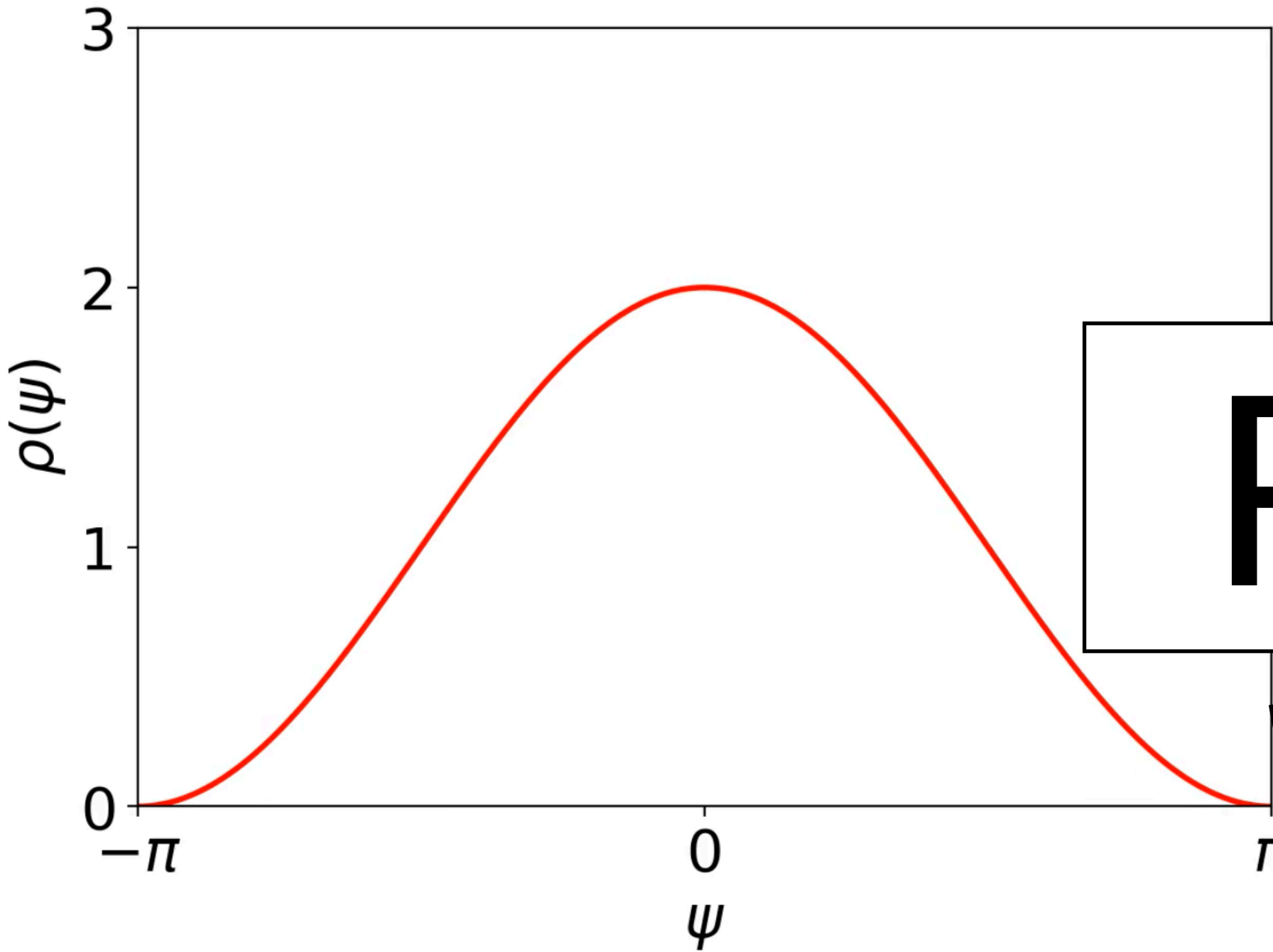
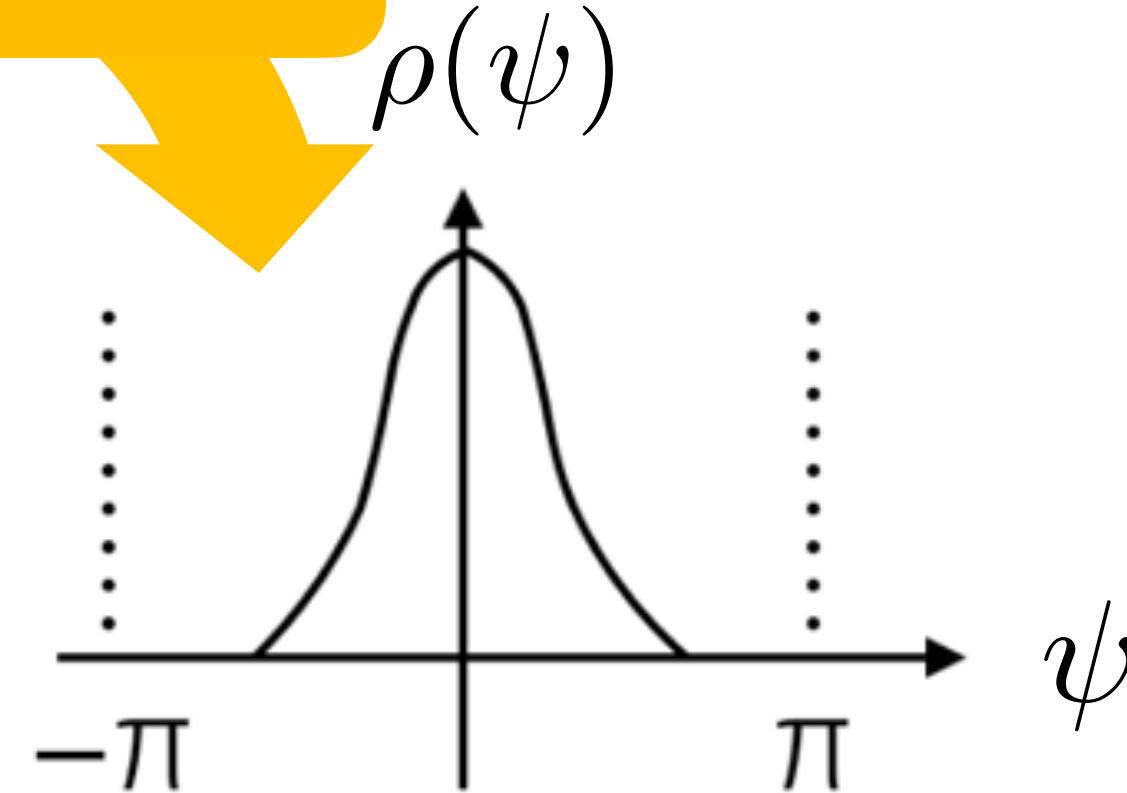
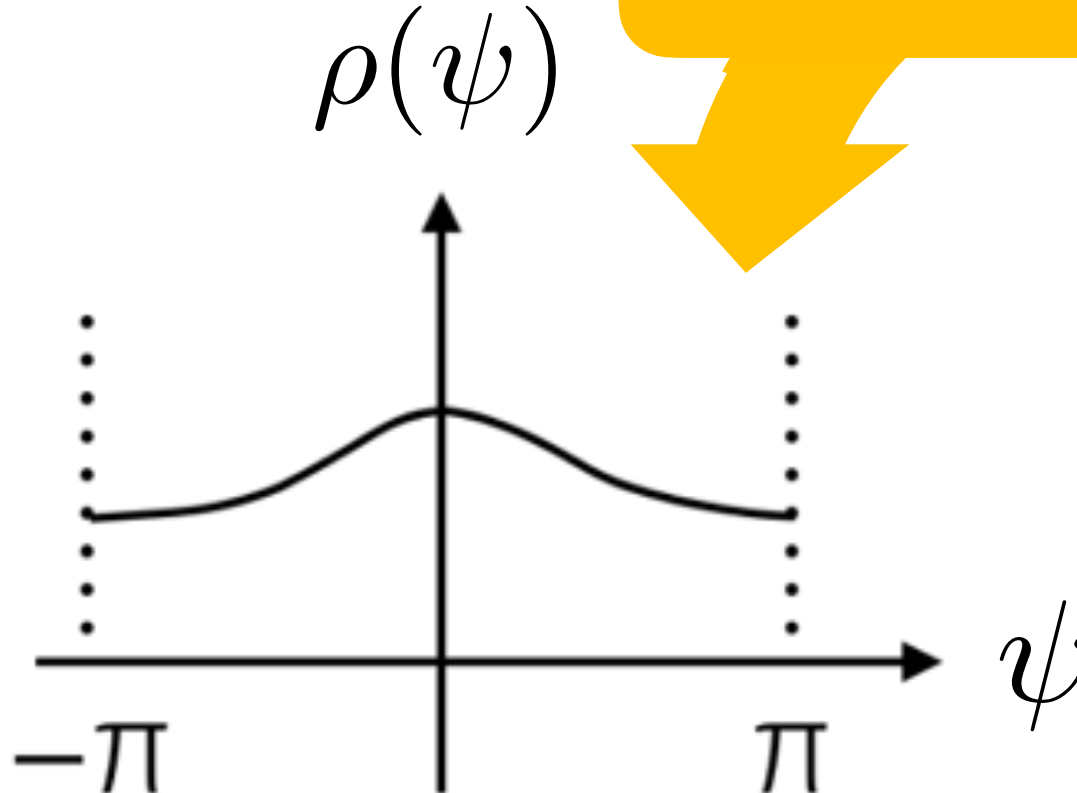
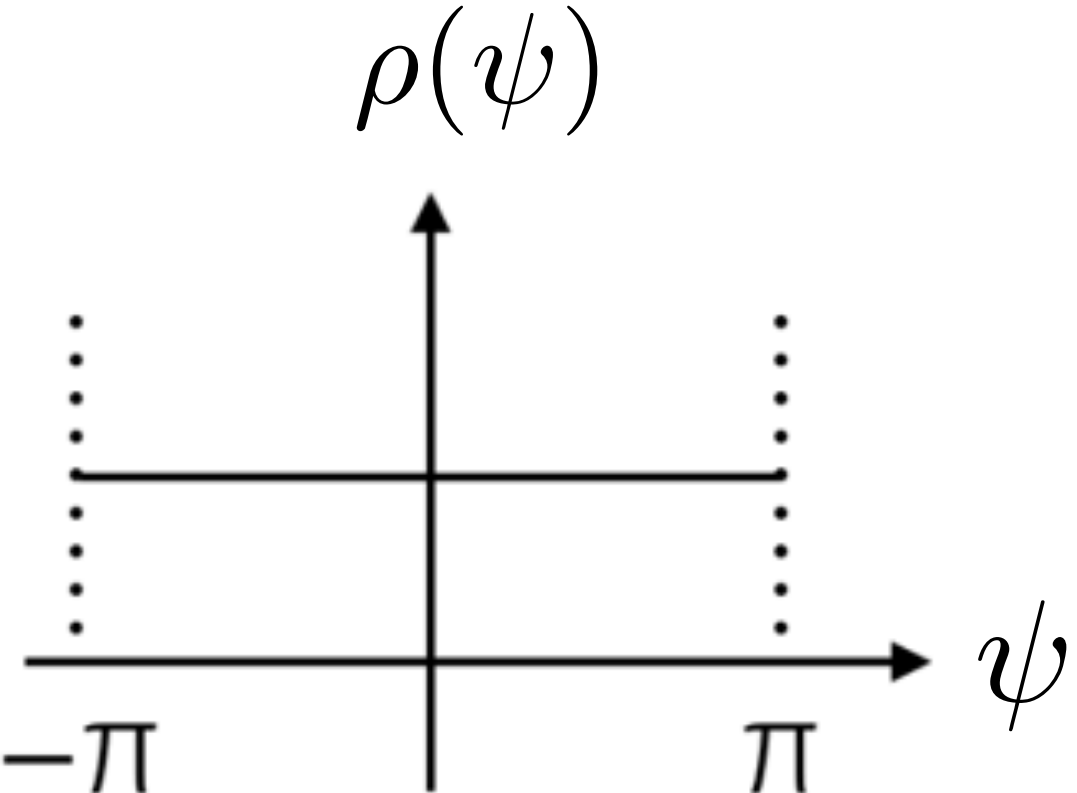
partially  
confined

deconfined



# Gross-Witten-Wadia

**GWW transition**



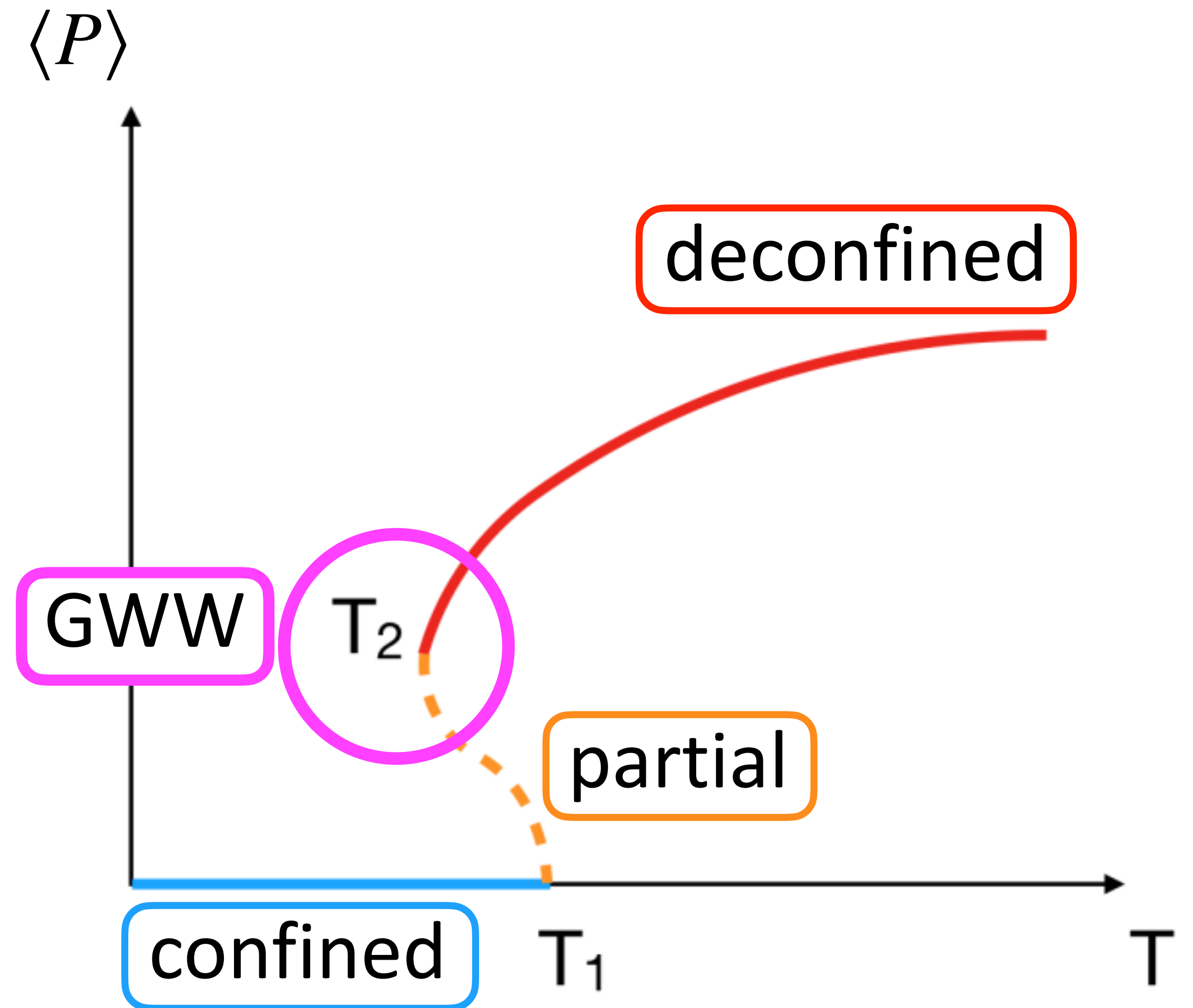
partially  
confined

deconfined

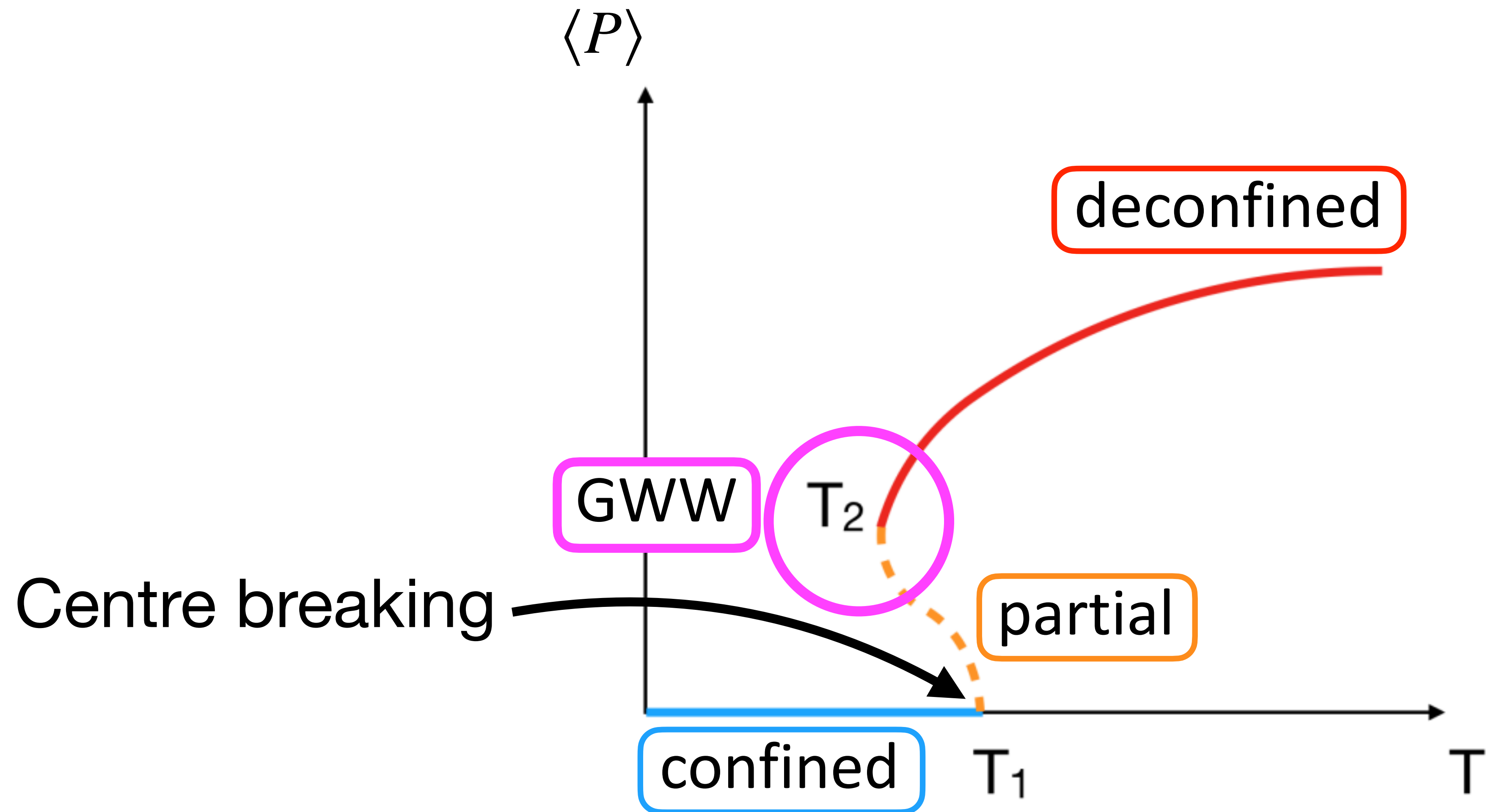
**Precise at large N**



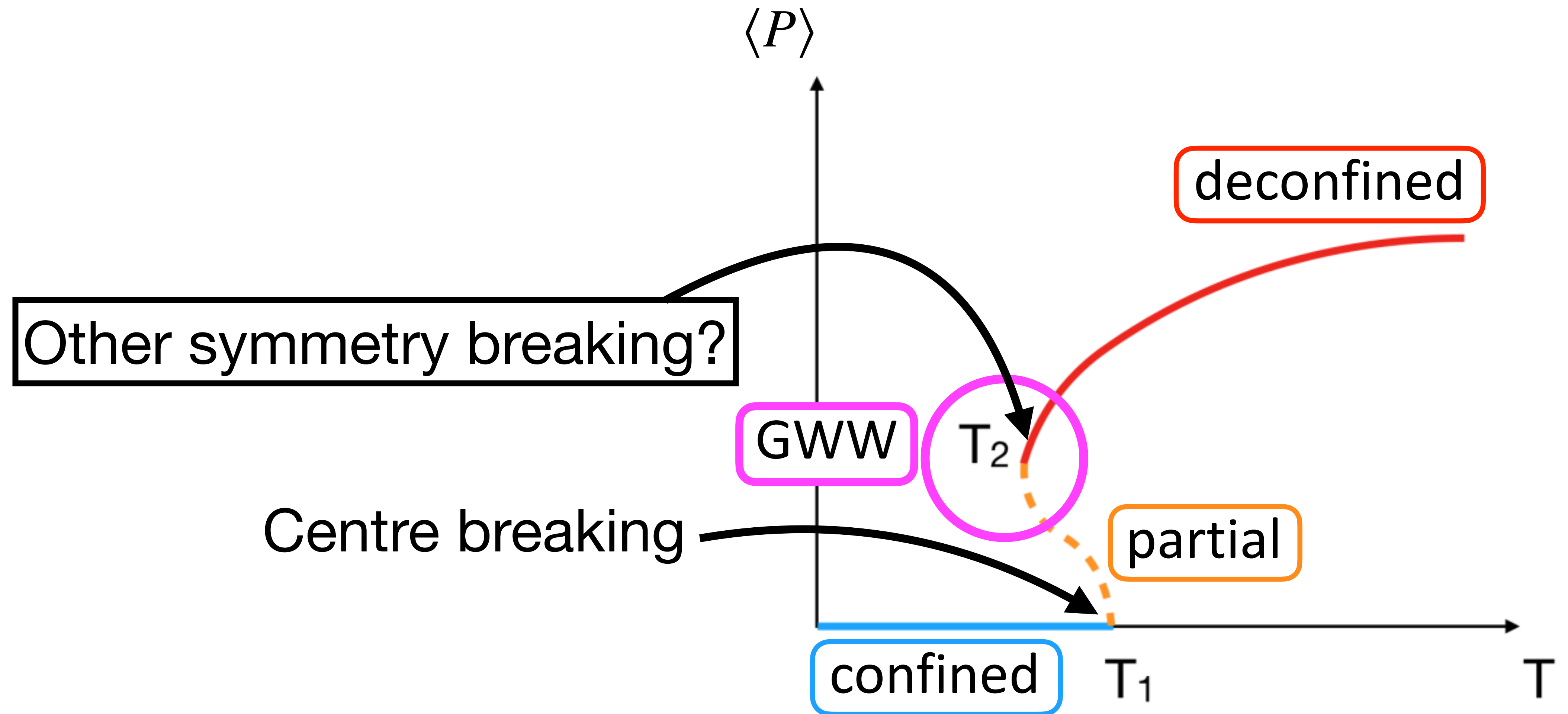
# Global symmetries



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# Large N U(N) YM + probe fermions, lattice

$\langle P \rangle$	$\langle \bar{\psi} \psi \rangle$	
Centre	Chiral	
✓	✗	Confined
✗	✓	Deconfined

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$\langle P \rangle$	$\langle \bar{\psi} \psi \rangle$	
Centre	Chiral	
✓	✗	Confined
✗	✓	Deconfined
✗ ✗ ✗	✗ ✗ ✗	Partial

Large N U(N) YM + probe fermions, lattice

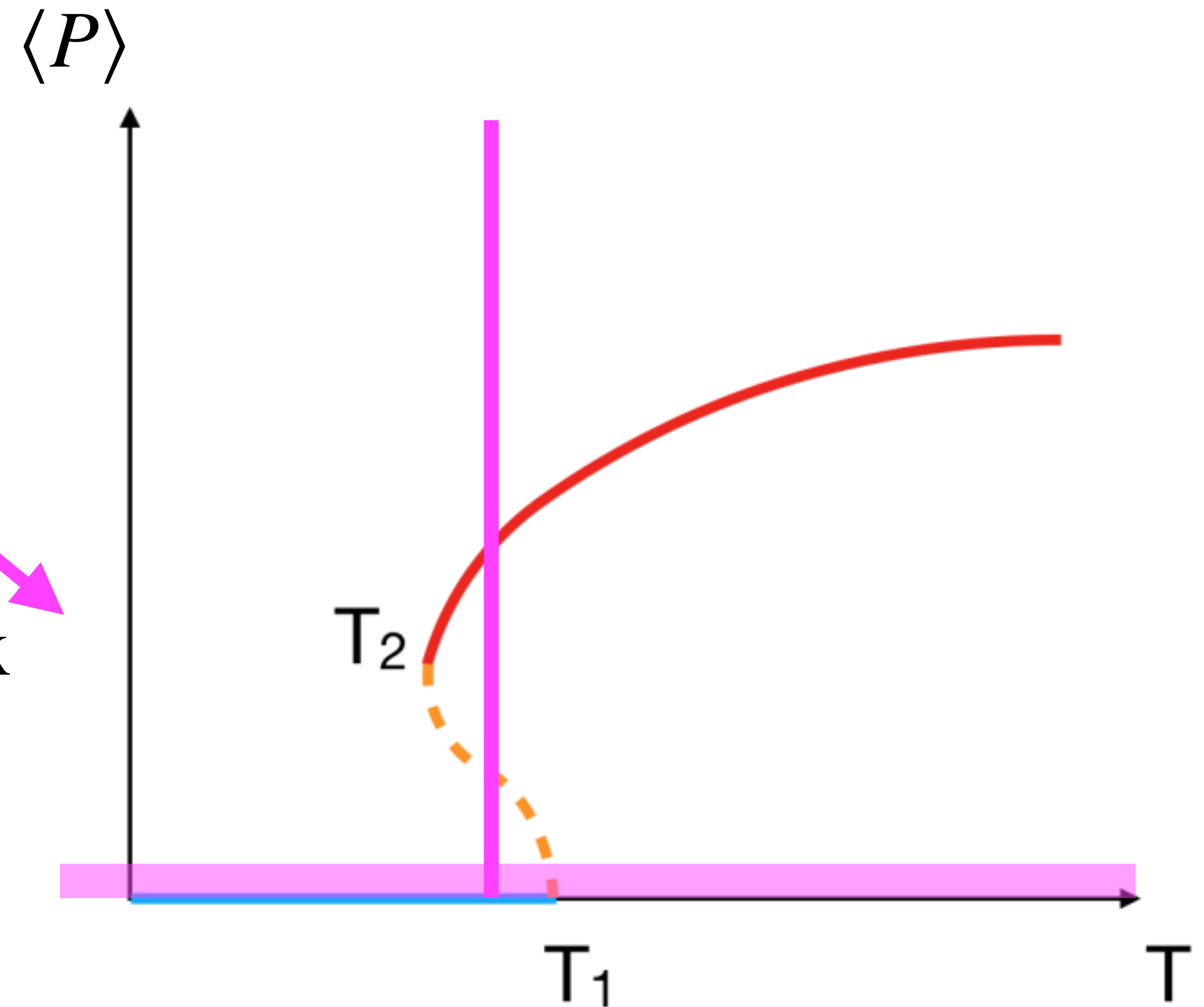
Check symmetries at transition

Transition  $\langle P \rangle \sim 0.35$

$P_{\text{fix}}$

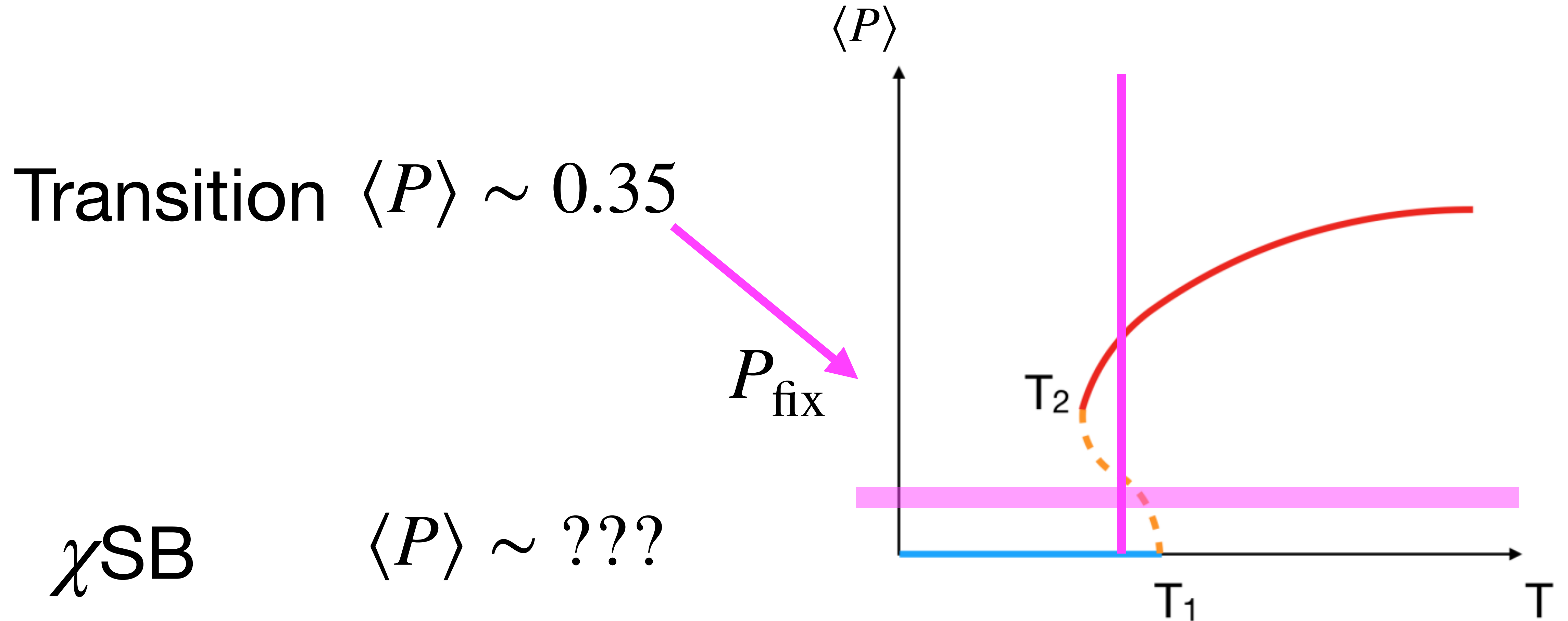
$\chi^{\text{SB}}$

$\langle P \rangle \sim ???$



Large N U(N) YM + probe fermions, lattice

Check symmetries at transition



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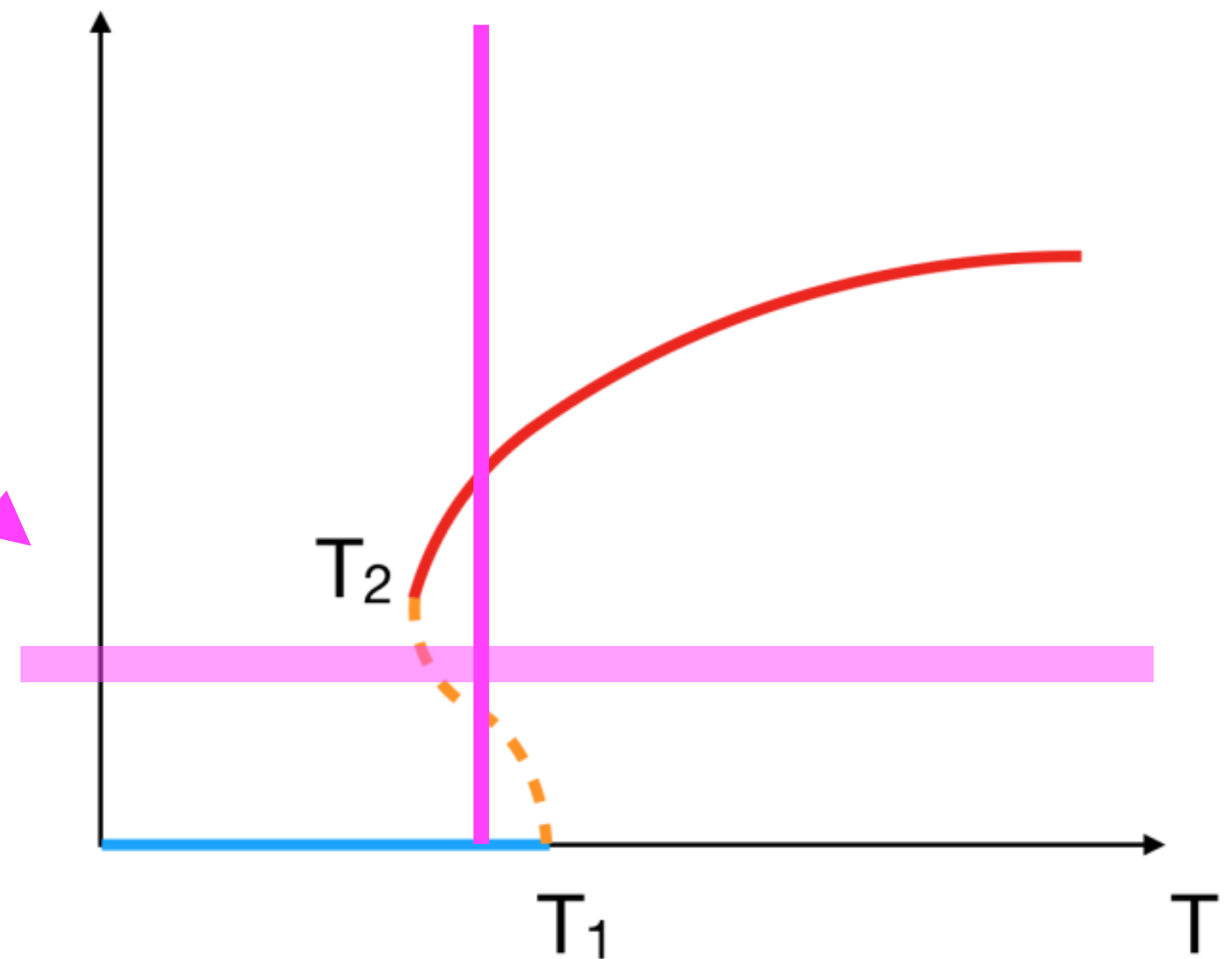
$\langle P \rangle$

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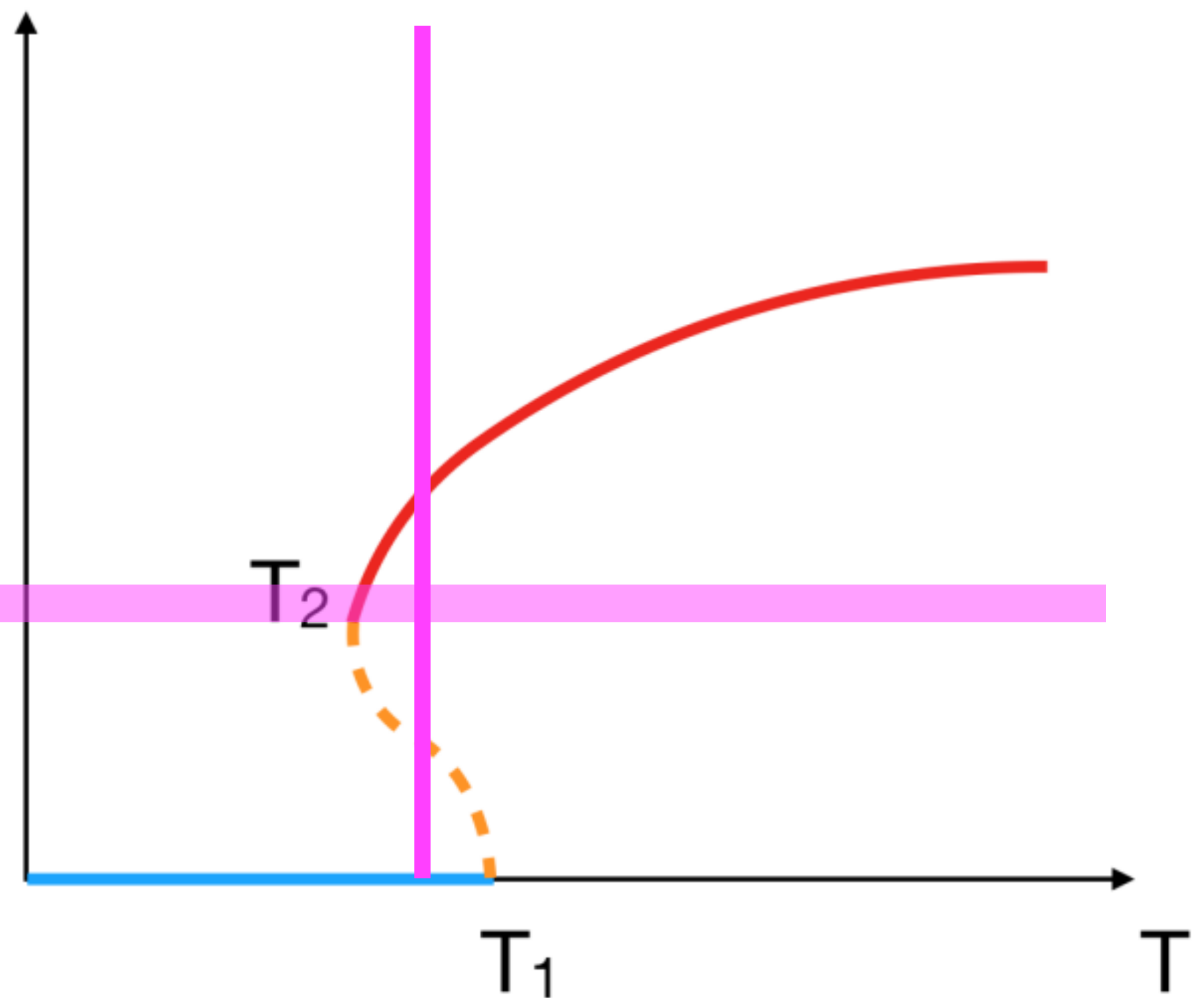
$\langle P \rangle$

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$P_{\text{fix}}$

$\chi^{\text{SB}}$

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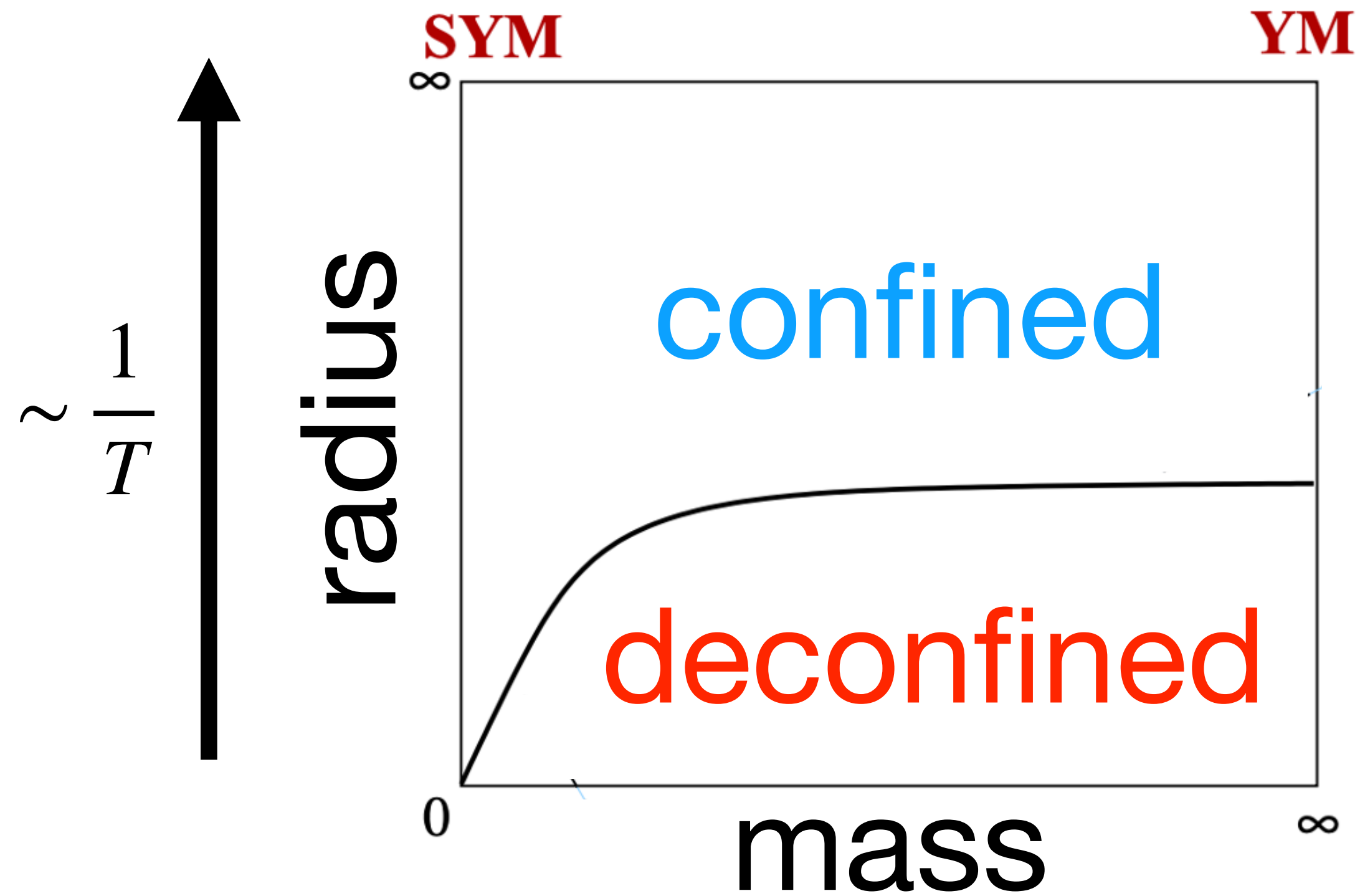
$\langle P \rangle$ Centre	$\langle \bar{\psi} \psi \rangle$ Chiral	
✓	✗	Confined
✗	✓	Deconfined
✗	✗	Partial

$\mathcal{N} = 1$  SU(N) dSYM on  $\mathbb{R}^3 \times S^1$ ,  $\theta = \pi$

dSYM : small fermion mass breaks SUSY

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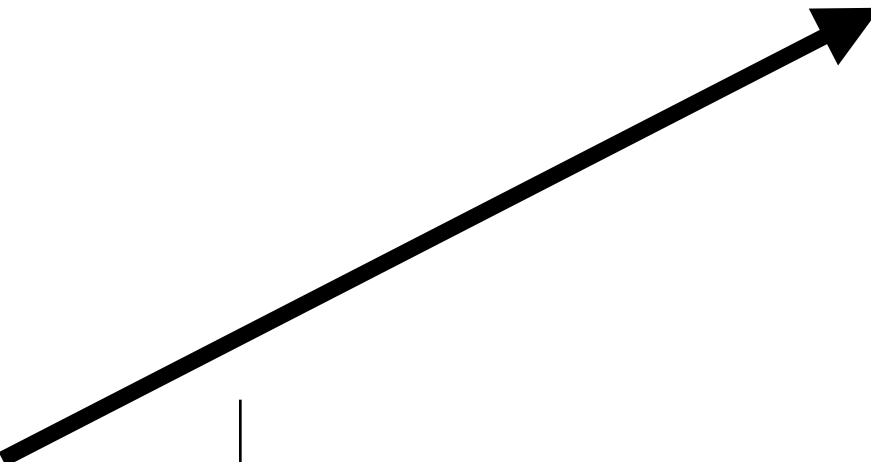
dSYM : small fermion mass breaks SUSY



source: Poppitz, Schäfer, Ünsal 1205.0290 (modified)

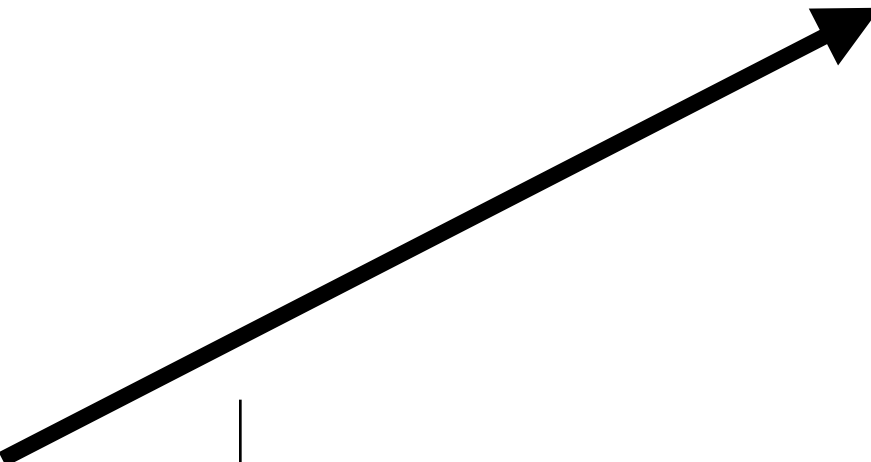
$\mathcal{N} = 1$  SU(N) dSYM on  $\mathbb{R}^3 \times S^1$ ,  $\theta = \pi$

$\langle P \rangle$ Centre	$\langle \tilde{F}F \rangle$ CP	
✓	✗	Confined
✗	✓	Deconfined



$\mathcal{N} = 1$  SU(N) dSYM on  $\mathbb{R}^3 \times S^1$ ,  $\theta = \pi$

$\langle P \rangle$ Centre	$\langle \tilde{F}F \rangle$ CP	
✓	✗	Confined
✗	✓	Deconfined
✗	✗	Partial



$\mathcal{N} = 1$  SU(N) dSYM on  $\mathbb{R}^3 \times S^1$ ,  $\theta = \pi$

$\langle P \rangle$	$\langle \tilde{F}F \rangle$	
Centre	CP	
✓	✗	Confined
✗	✓	Deconfined
✗	✗	Partial

Checked at:

Large  $N$

$N = 70$

$N = 50$

$N = 30$

$\mathcal{N} = 1$  SU(N) dSYM on  $\mathbb{R}^3 \times S^1$ ,  $\theta = \pi$

$\langle P \rangle$	$\langle \tilde{F}F \rangle$	
Centre	CP	
✓	✗	Confined
✗	✓	Deconfined
✗	✗	Partial

Checked at:  
 Large  $N$   
 $N = 70$   
 $N = 50$   
 $N = 30$

Proposal:

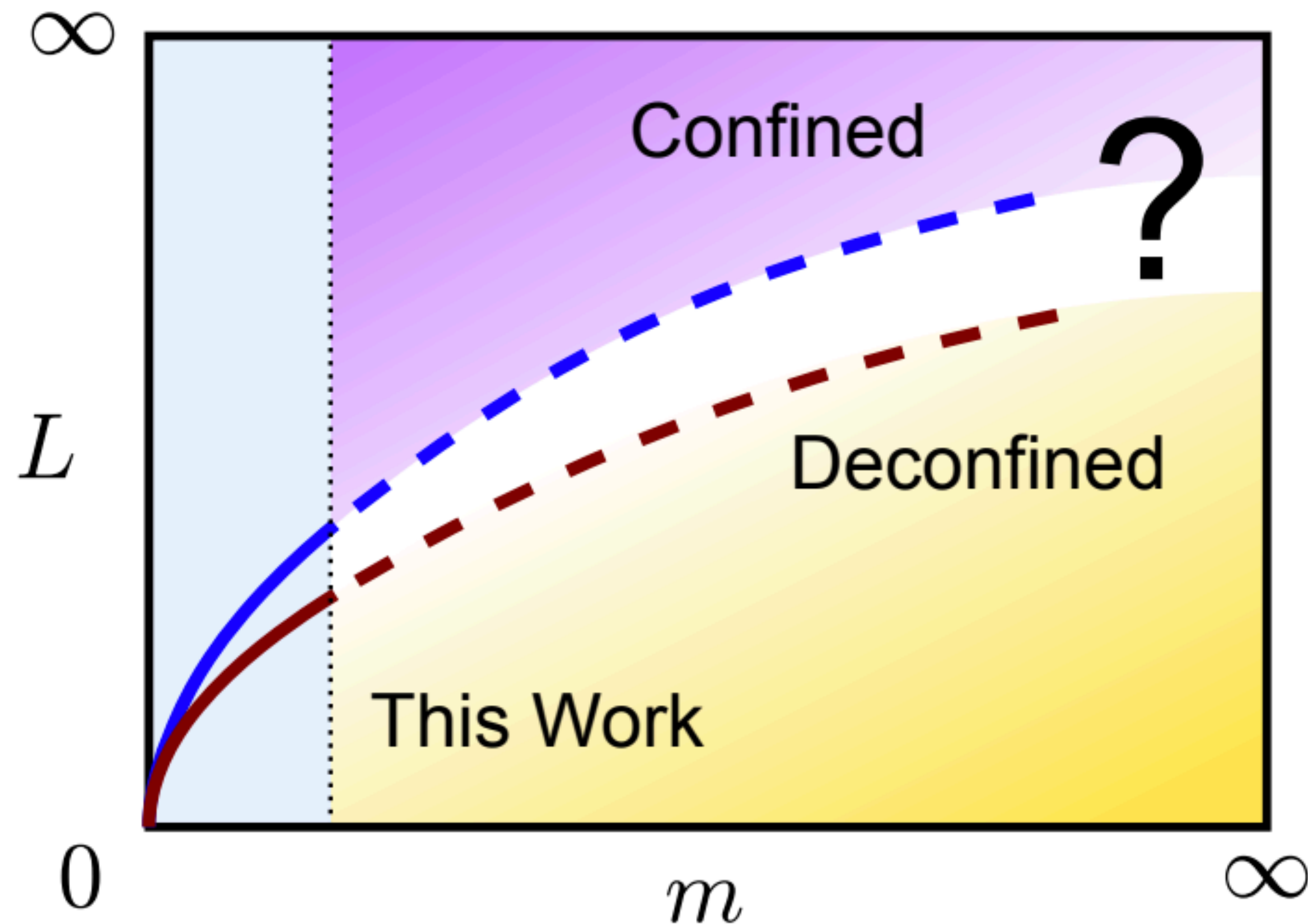
Global symmetries can characterise partial confinement at finite  $N$



$\mathcal{N} = 1$  **SU(2)** dSYM on  $\mathbb{R}^3 \times S^1$ ,  $\theta = \pi$

$\mathcal{N} = 1$  **SU(2)** dSYM on  $\mathbb{R}^3 \times S^1$ ,  $\theta = \pi$

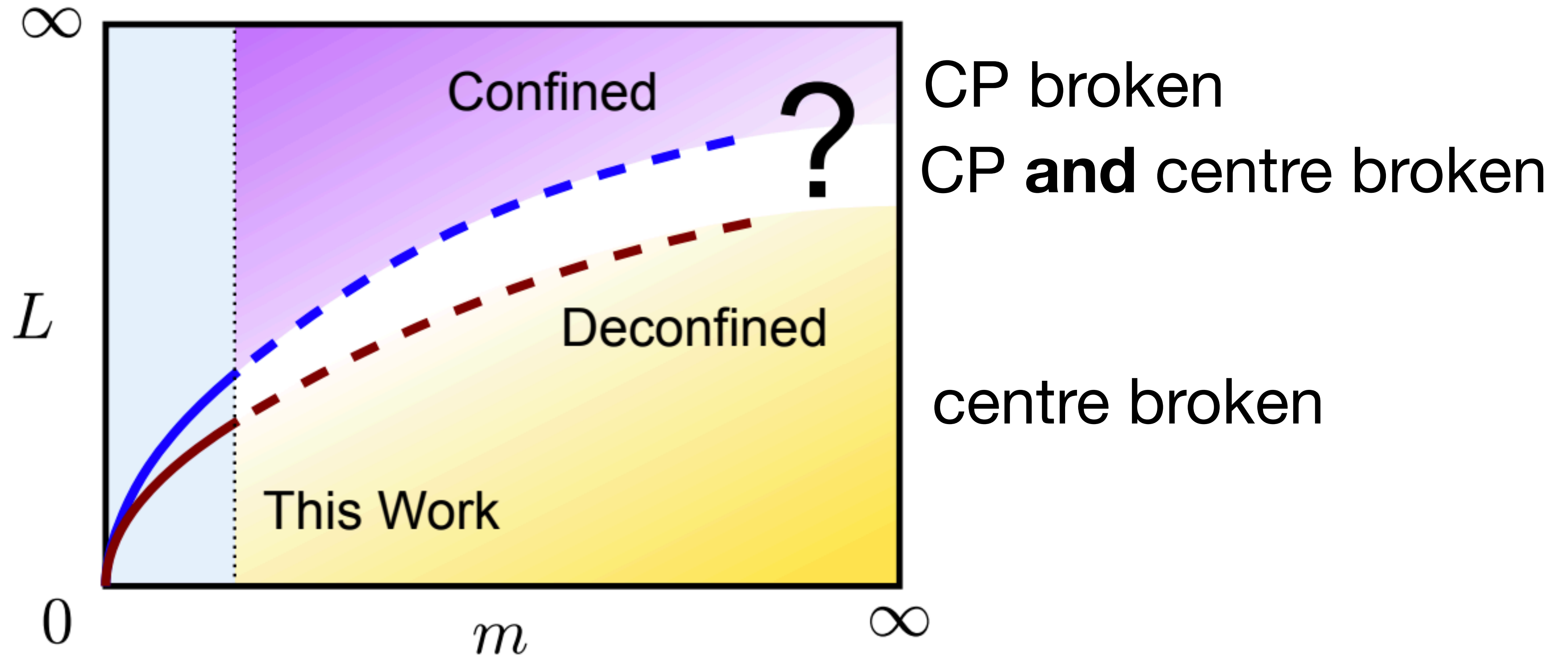
Chen, Fukishima, Nishimura, Tanizaki: 2006.01487



source: Chen et al. 2006.01487

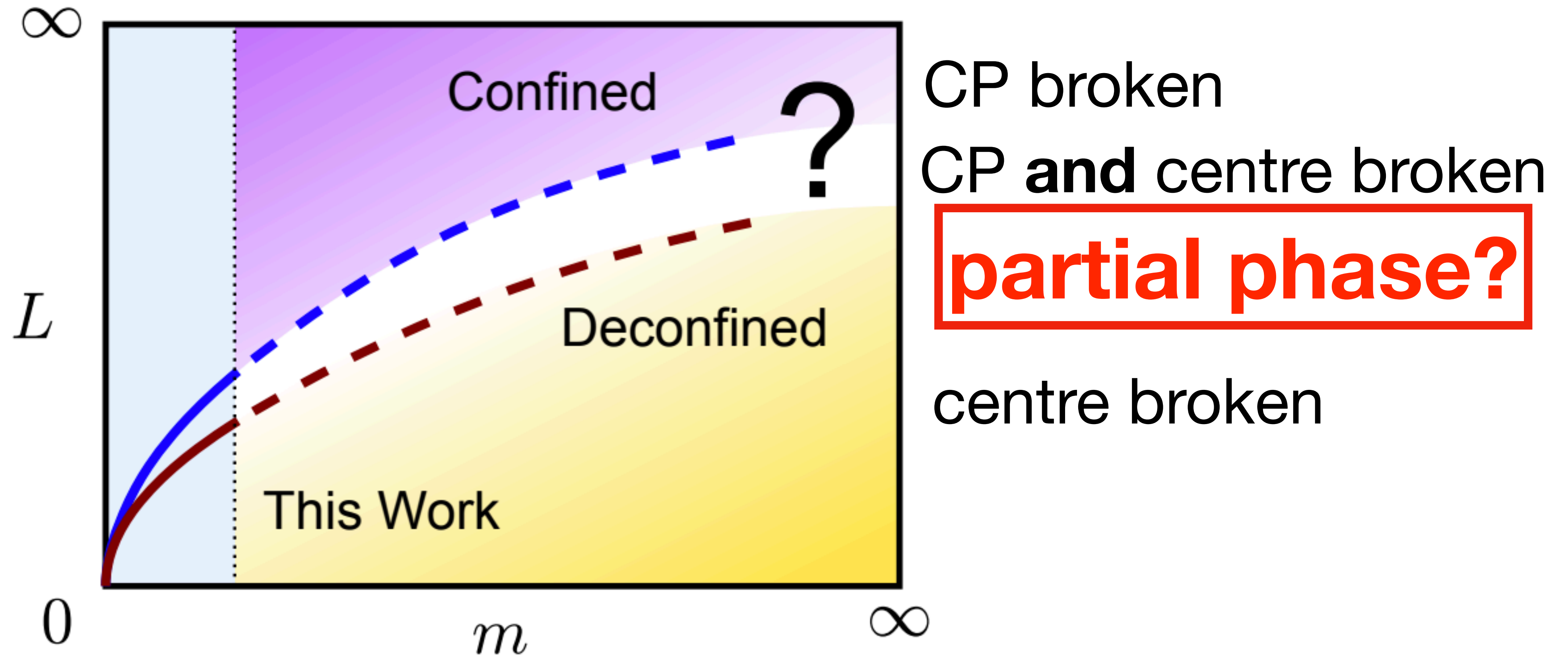
$\mathcal{N} = 1$  **SU(2)** dSYM on  $\mathbb{R}^3 \times S^1$ ,  $\theta = \pi$

Chen, Fukishima, Nishimura, Tanizaki: 2006.01487

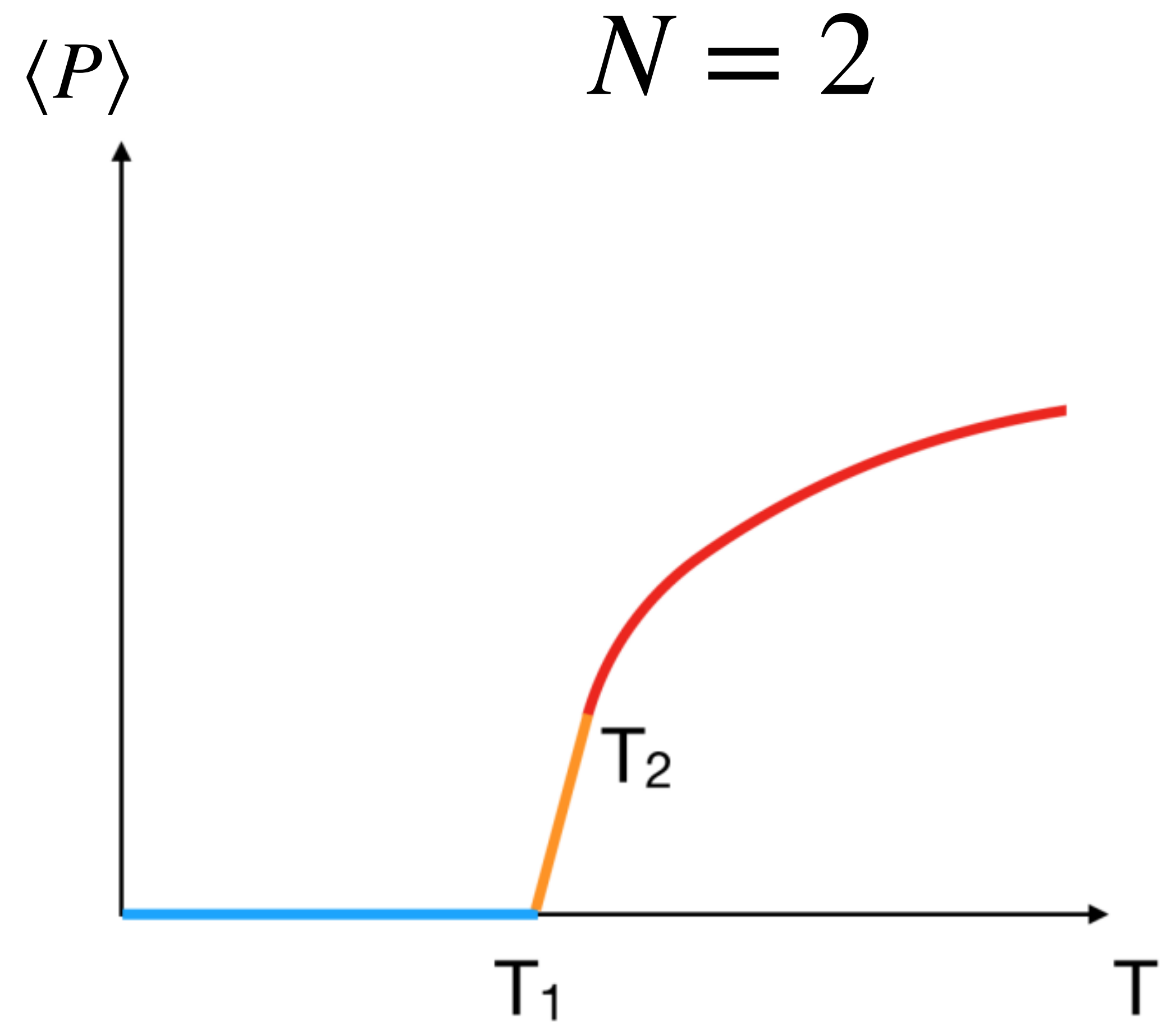
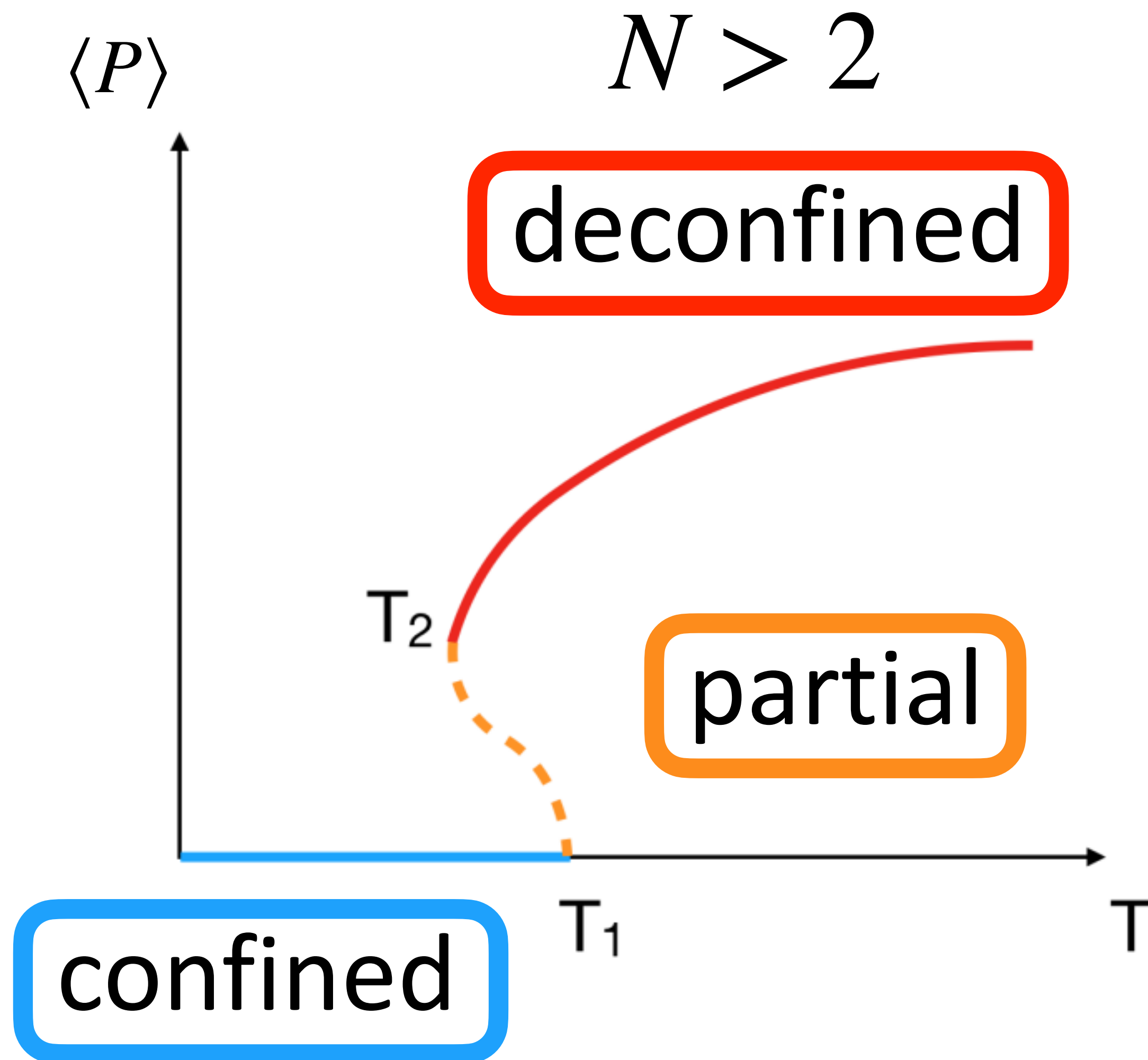


$\mathcal{N} = 1$  **SU(2)** dSYM on  $\mathbb{R}^3 \times S^1$ ,  $\theta = \pi$

Chen, Fukishima, Nishimura, Tanizaki: 2006.01487



$\mathcal{N} = 1$  **SU(2)** dSYM on  $\mathbb{R}^3 \times S^1$ ,  $\theta = \pi$



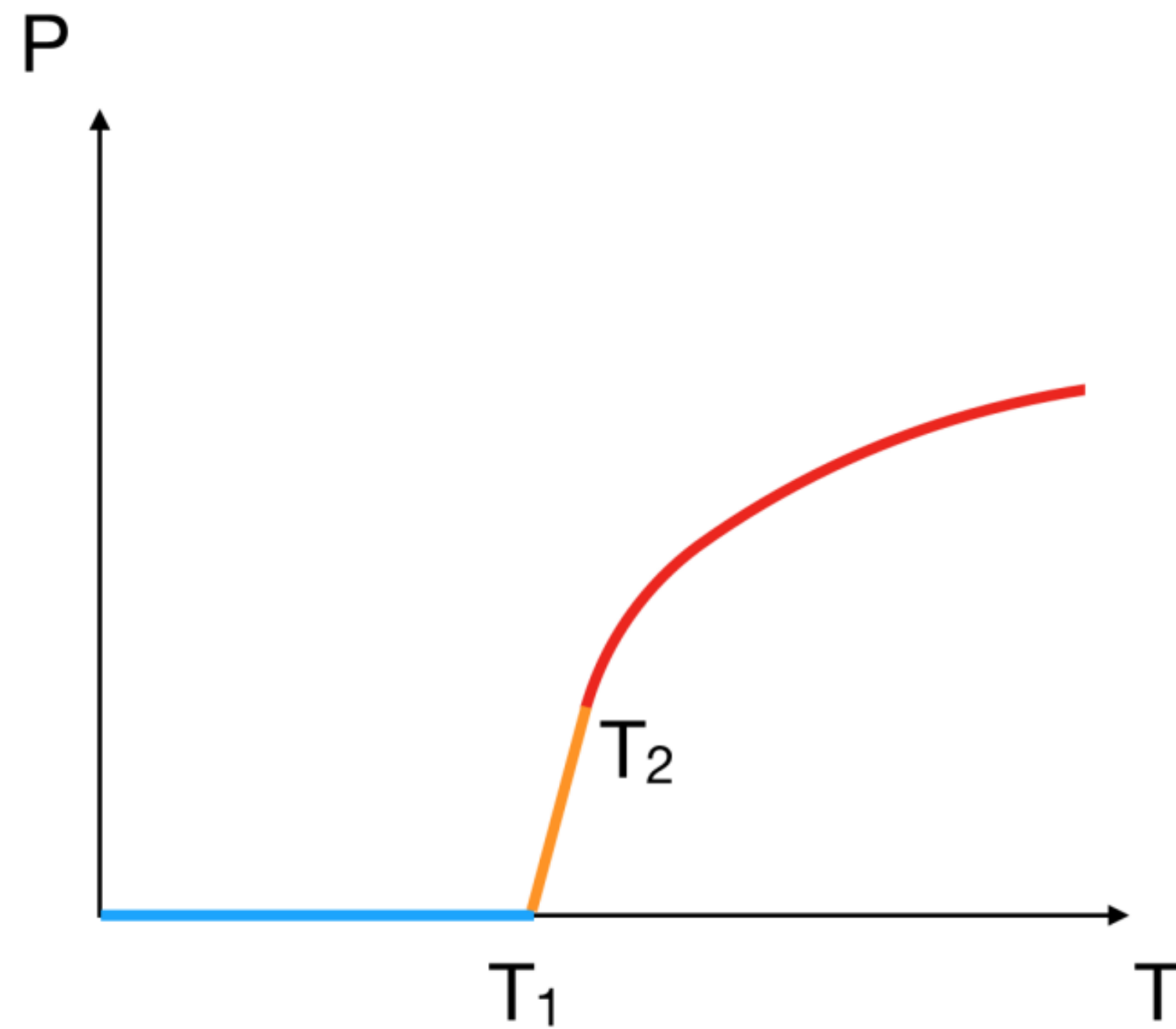
# Outline

1. Introduction
2. Partial confinement and holography
3. Global symmetries
- 4. Applied to QCD**
5. Holography questions
6. Flux tubes

**QCD: is the crossover a transition?**

# QCD: is the crossover a transition?

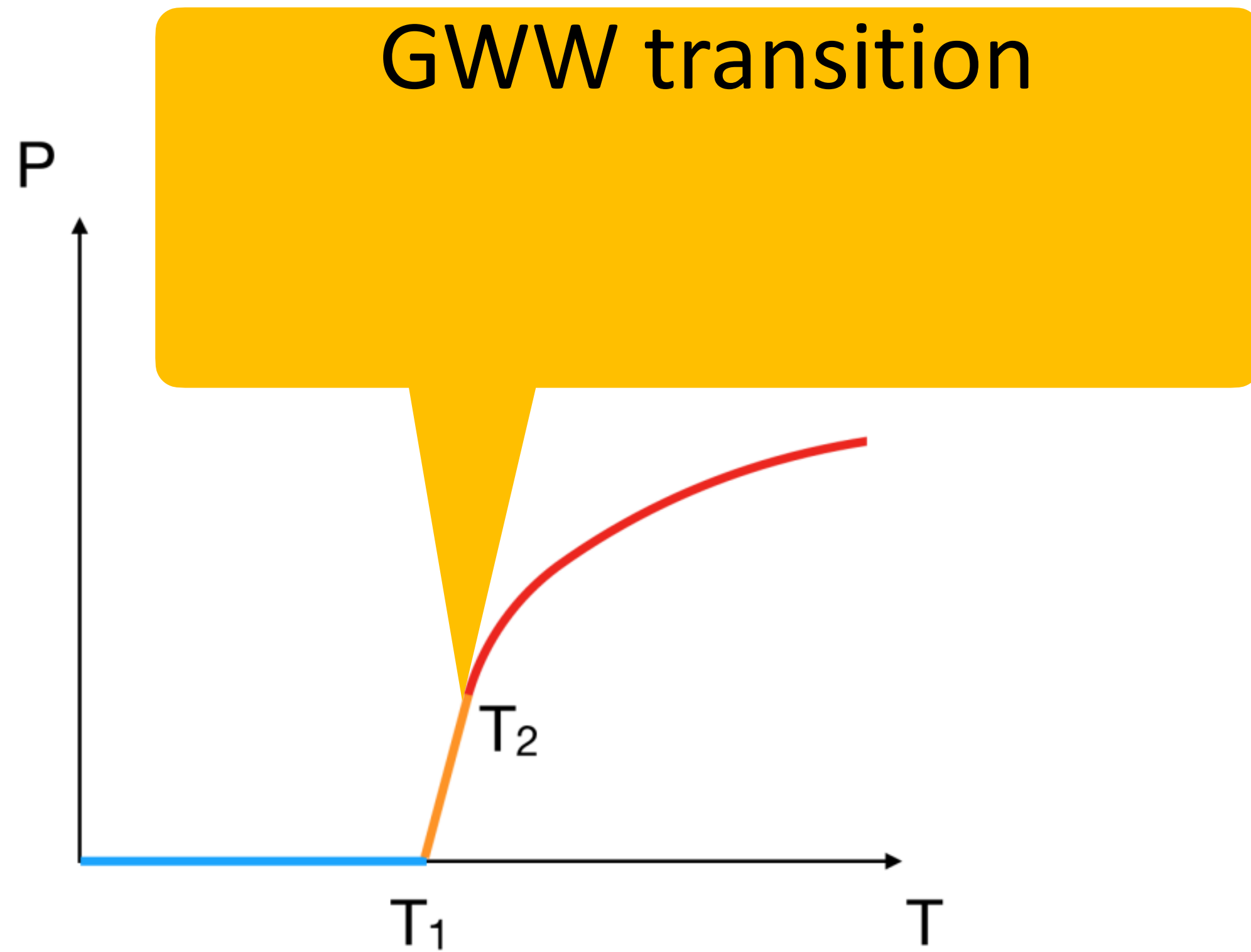
Large N QCD





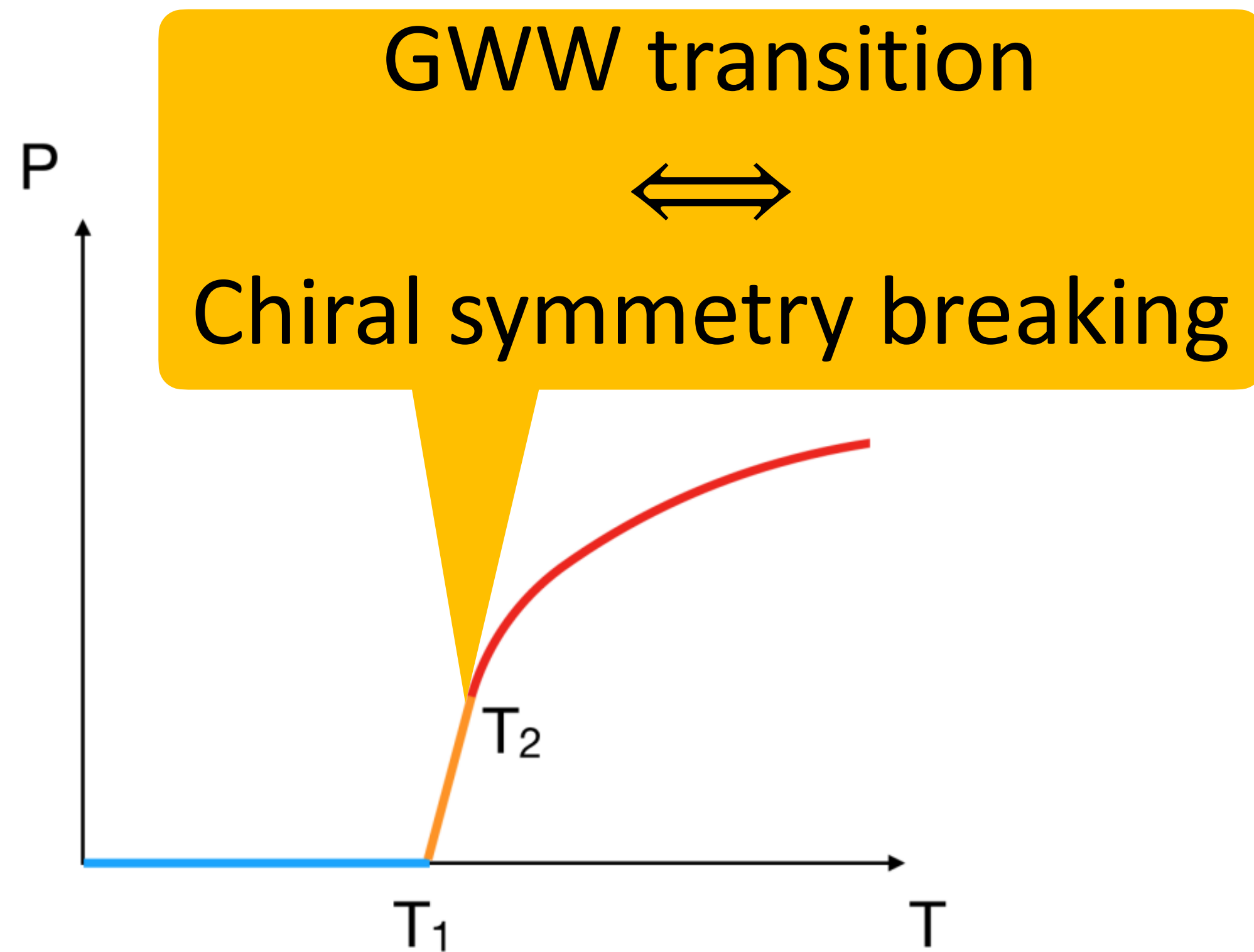
# QCD: is the crossover a transition?

## Large N QCD



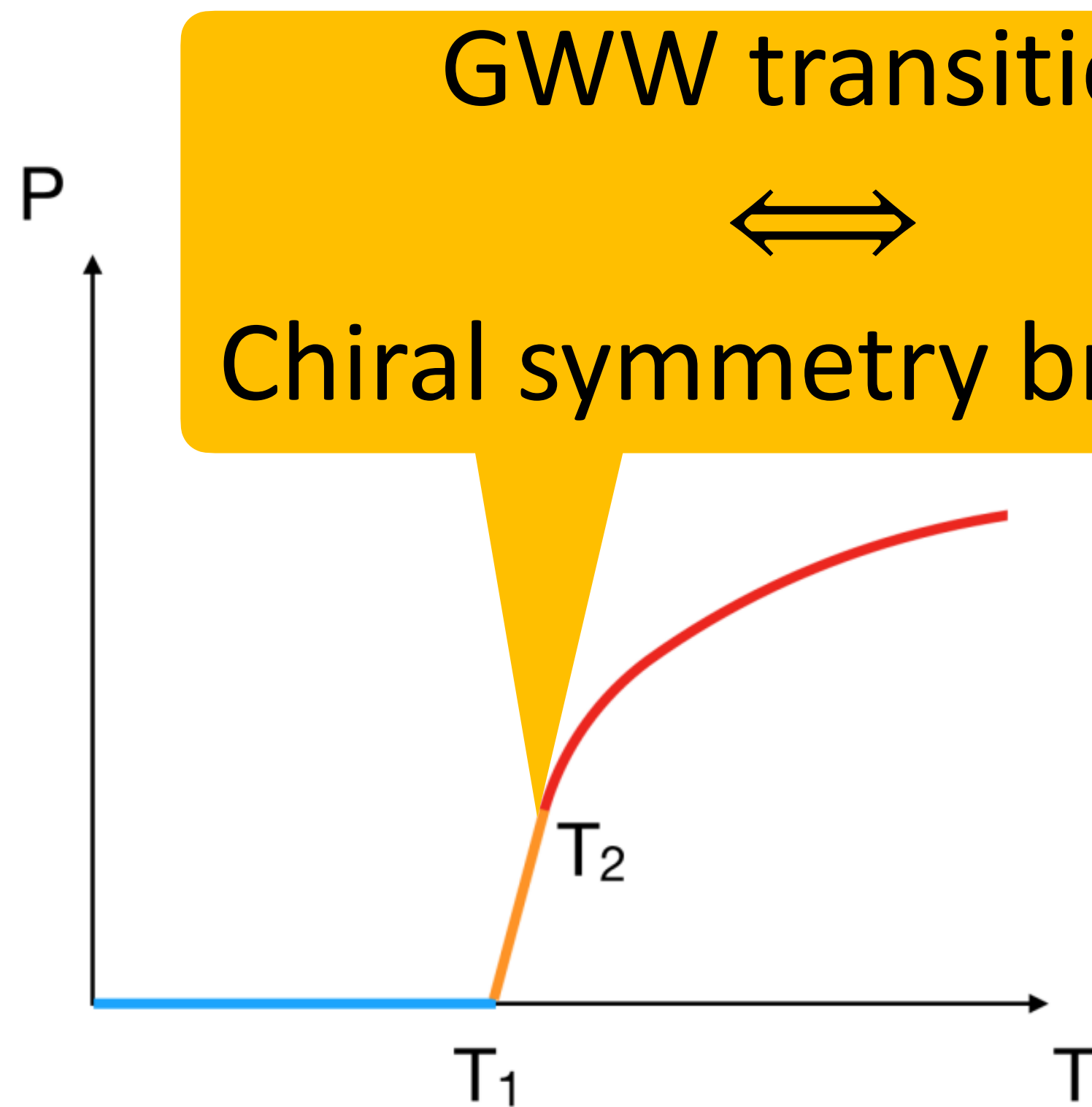
# QCD: is the crossover a transition?

## Large N QCD



# QCD: is the crossover a transition?

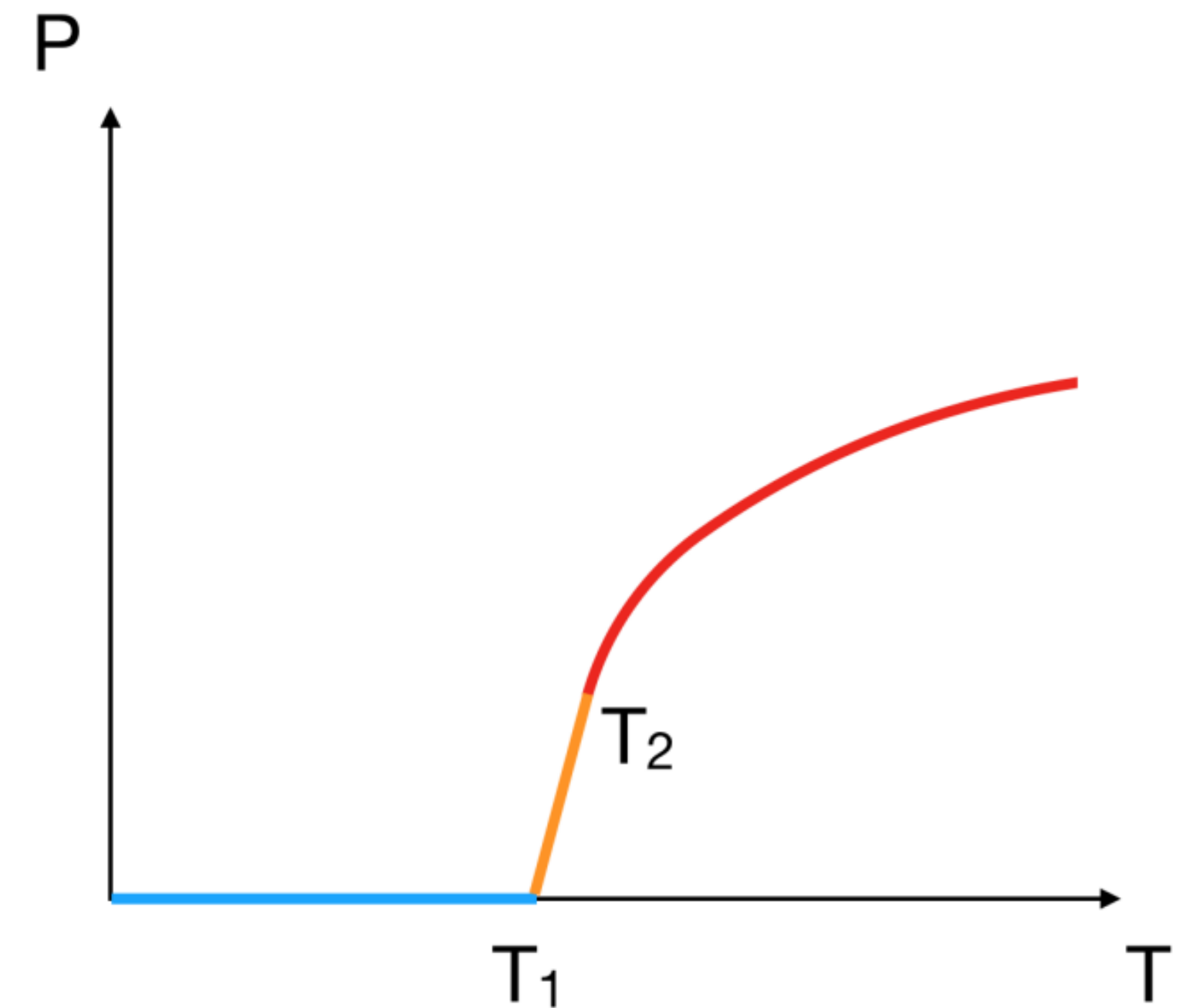
## Large N QCD



Finite N

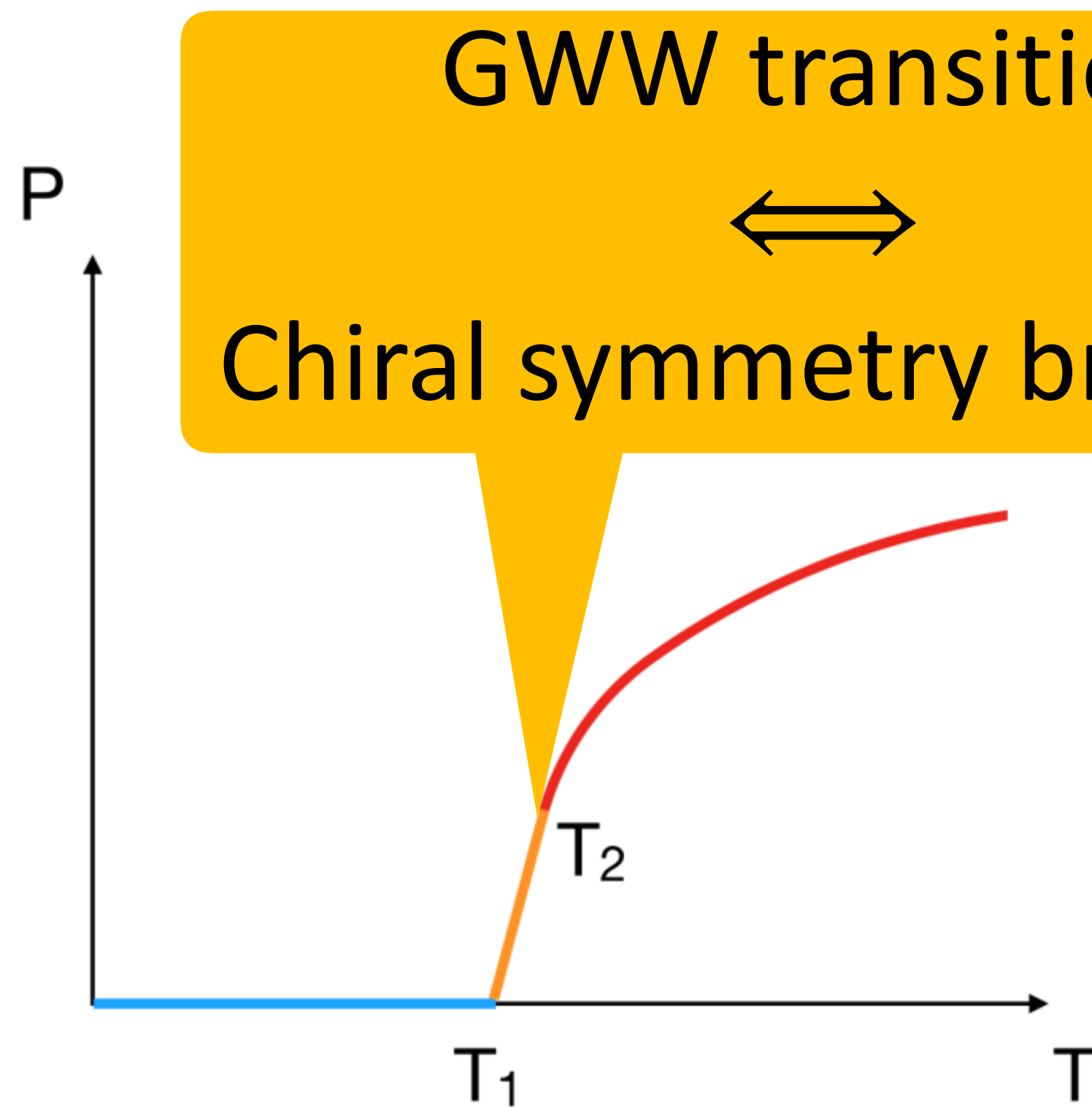


## SU(3) QCD



# QCD: is the crossover a transition?

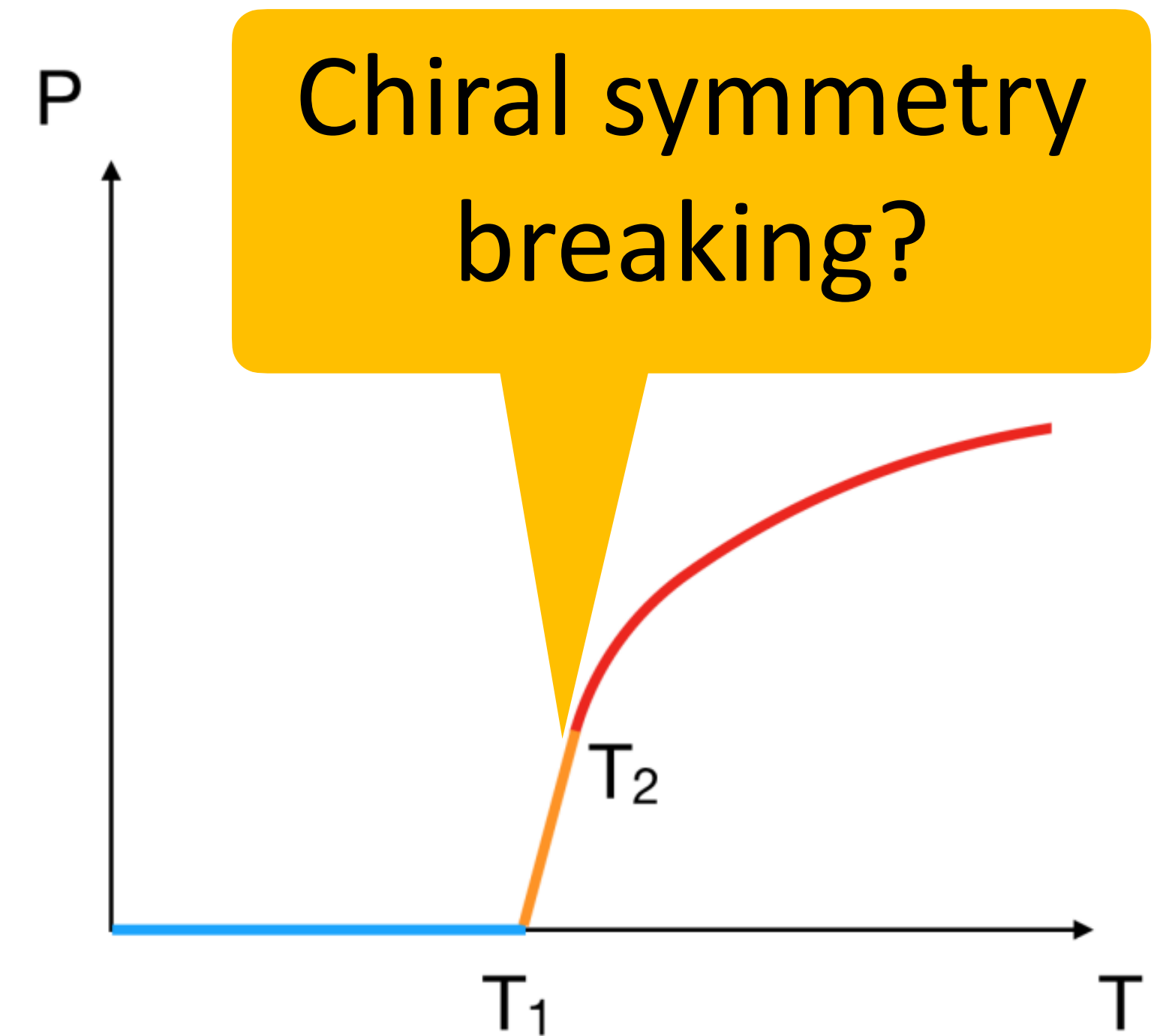
## Large N QCD



Finite N

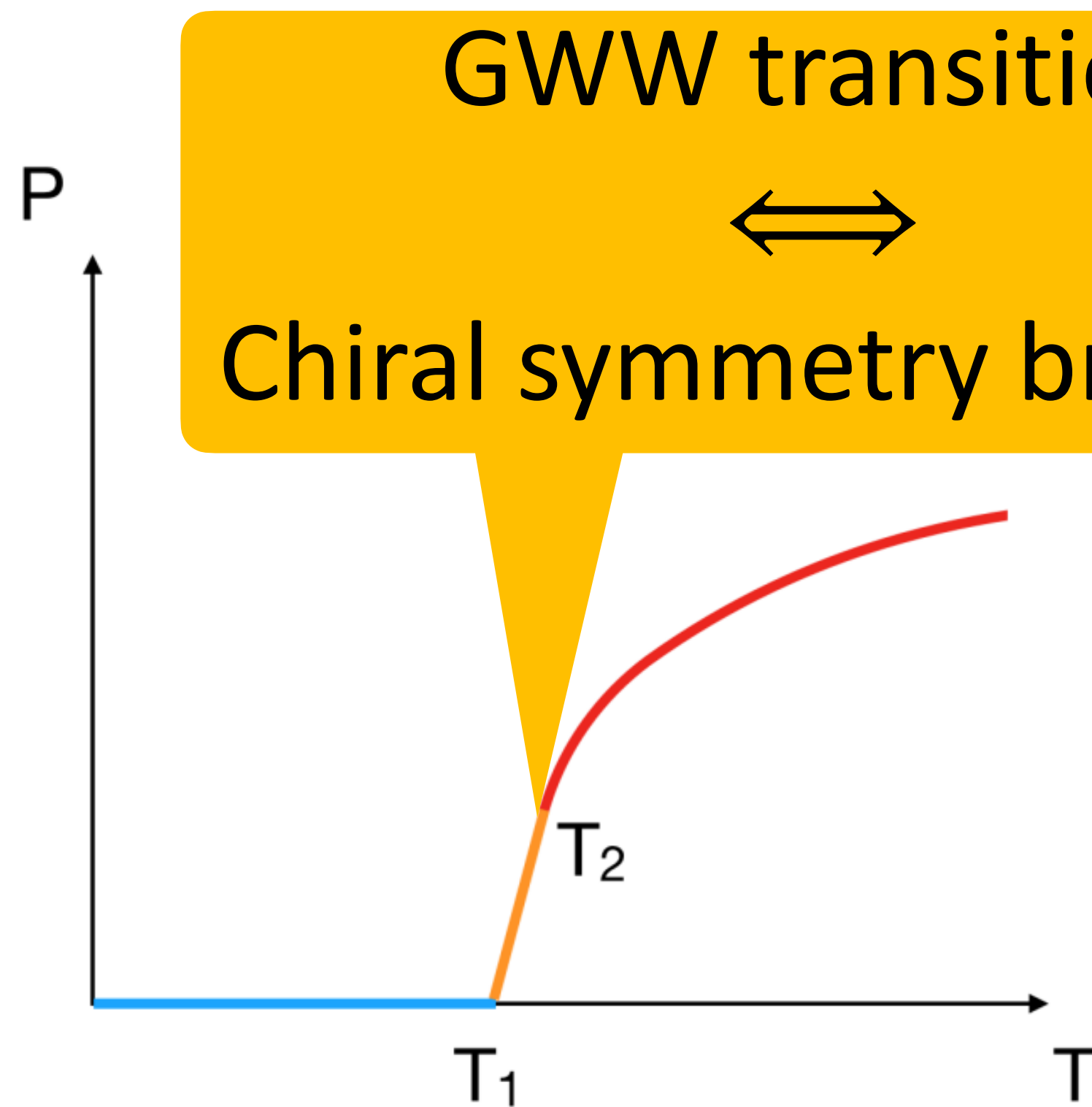


## SU(3) QCD



# QCD: is the crossover a transition?

## Large N QCD

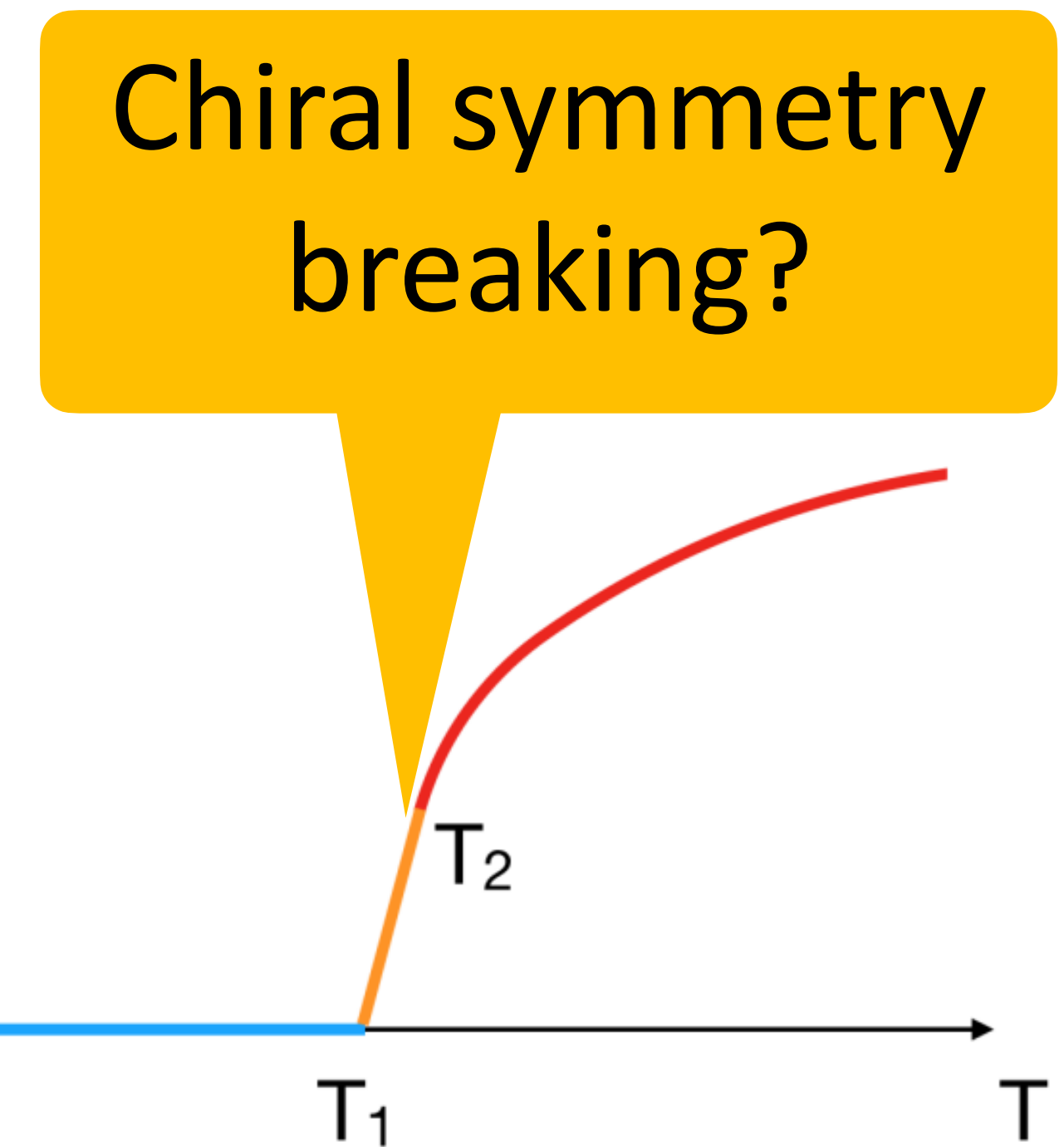


Finite N

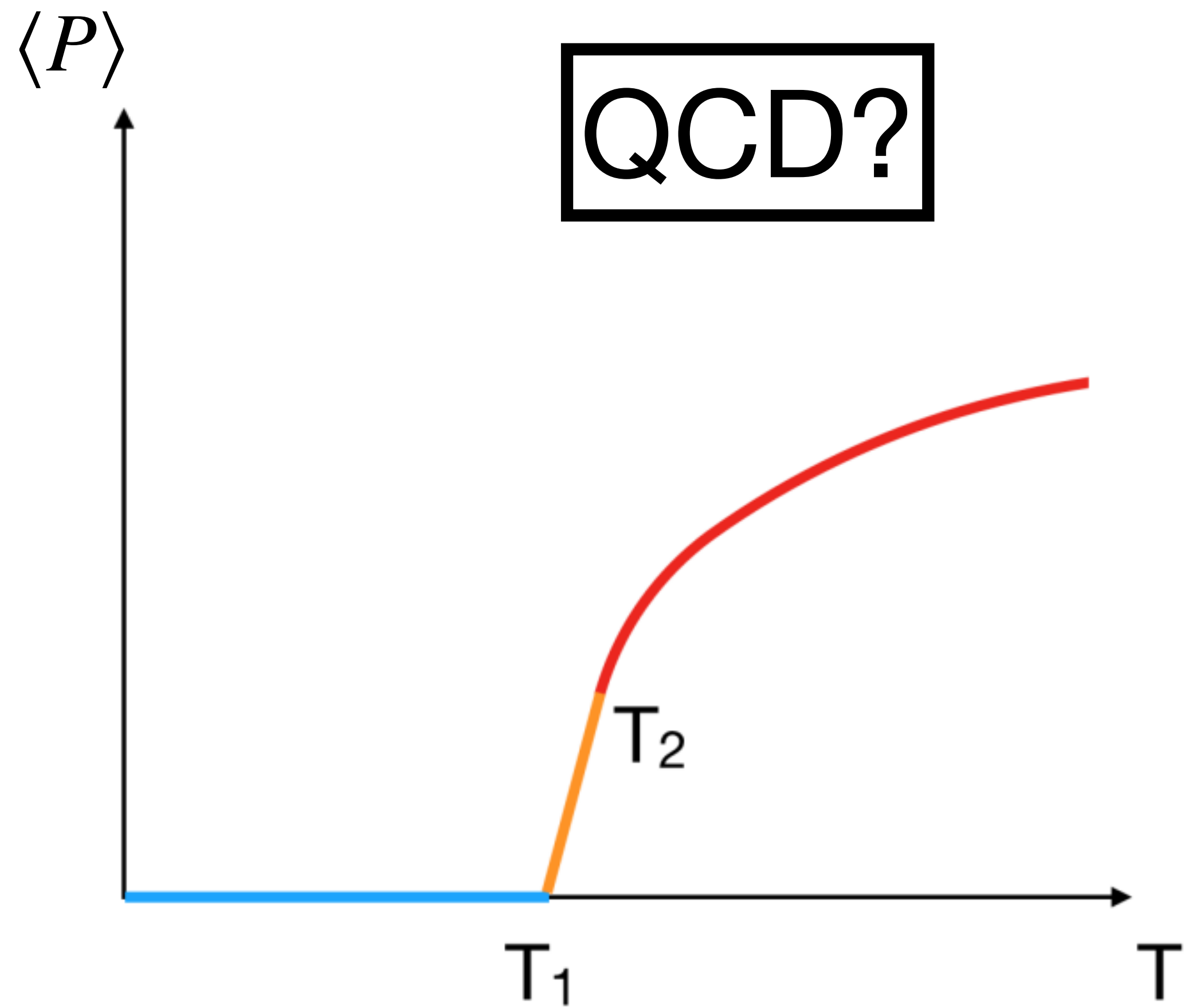
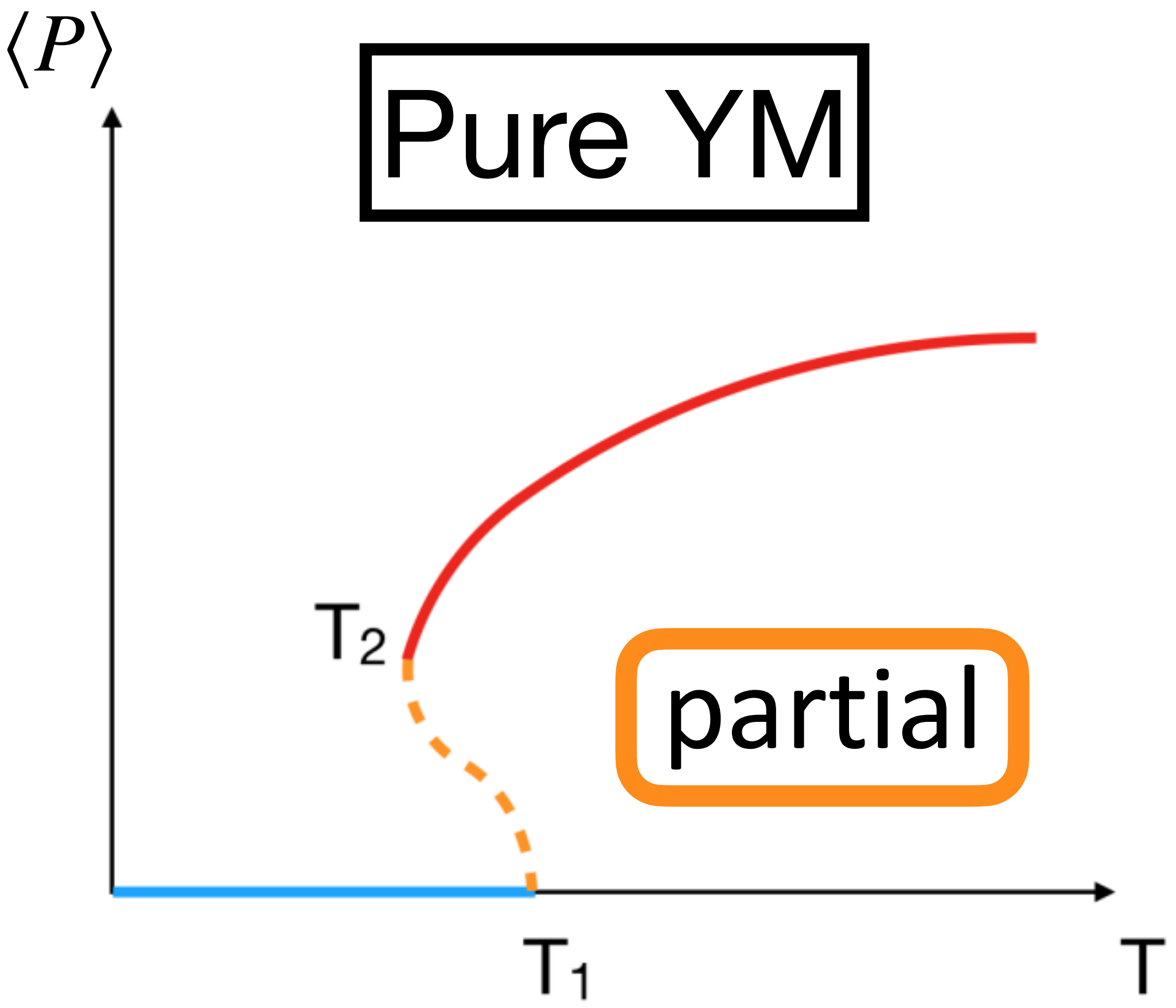


Aside: finite N GWW generalisation **does** seem to exist

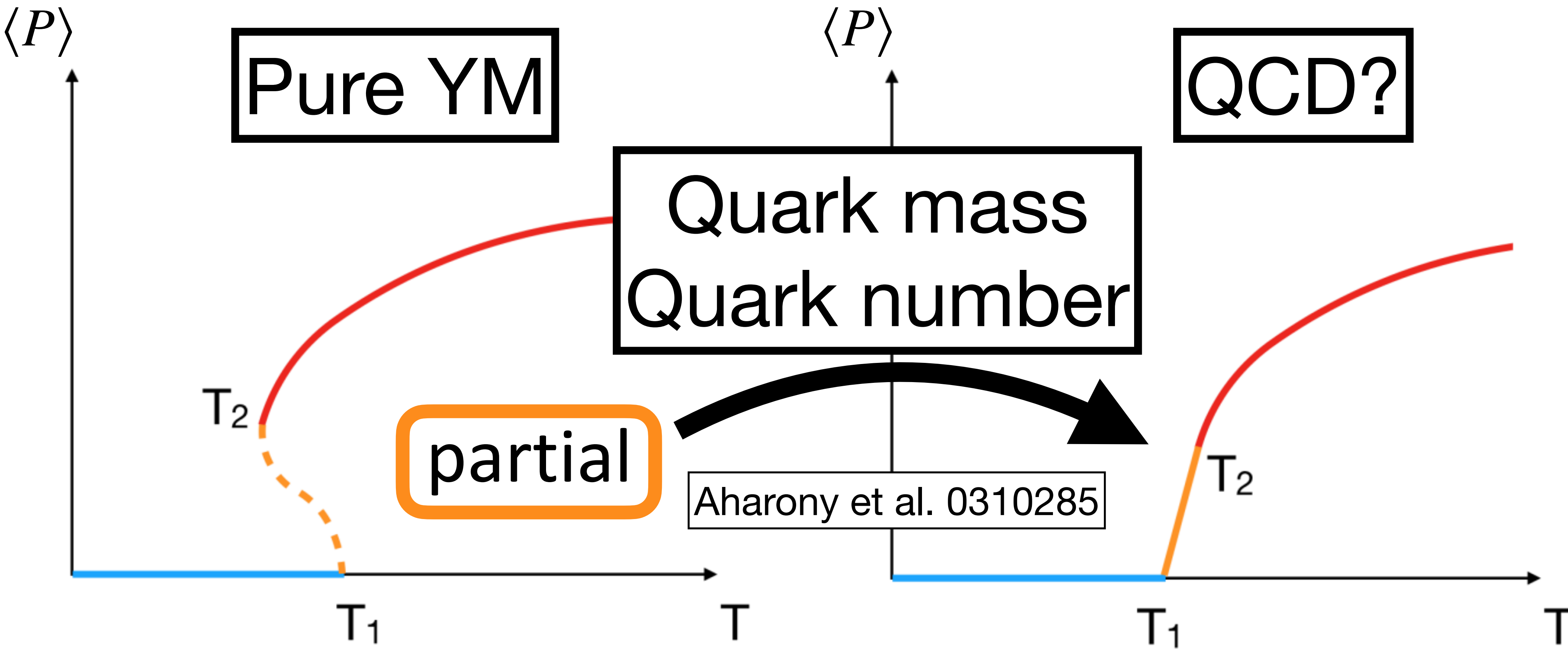
## SU(3) QCD



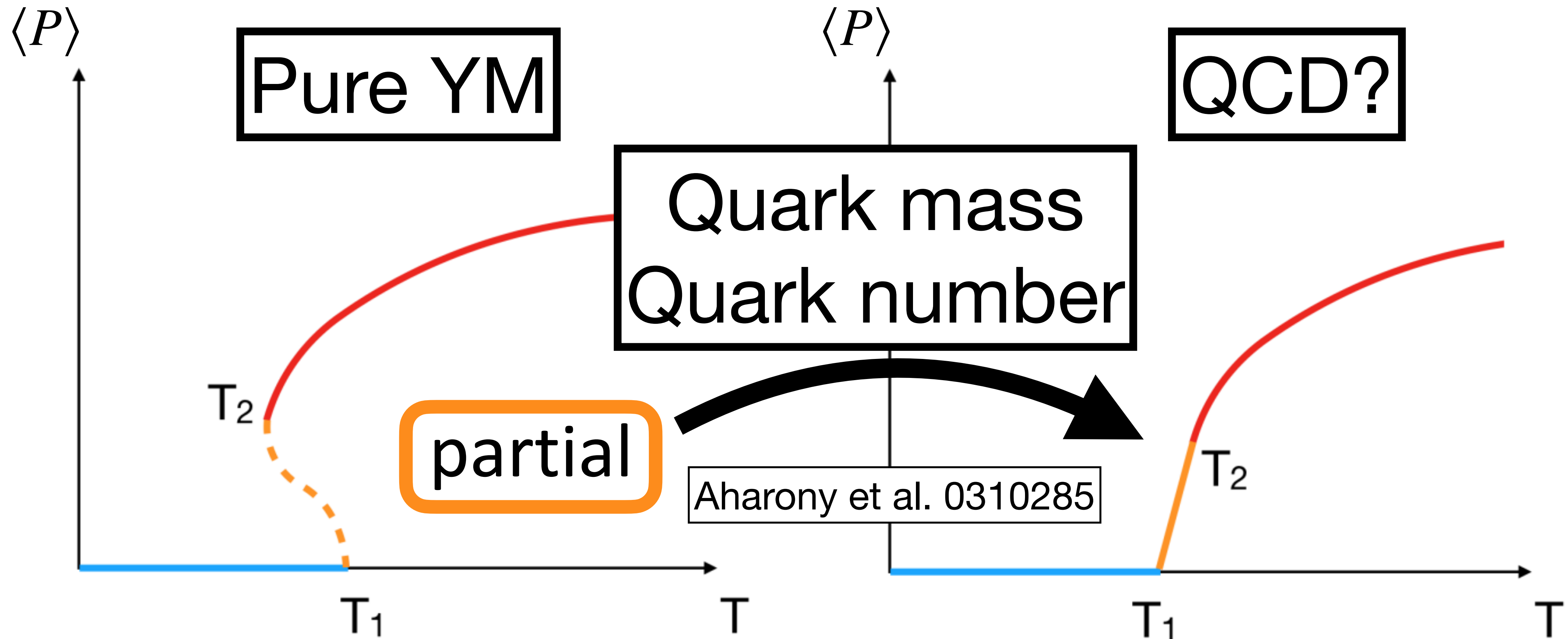
# QCD: partial confinement stable?



# QCD: partial confinement stable?



# QCD: partial confinement stable?



Claim: We can learn about the stable case from the unstable saddle

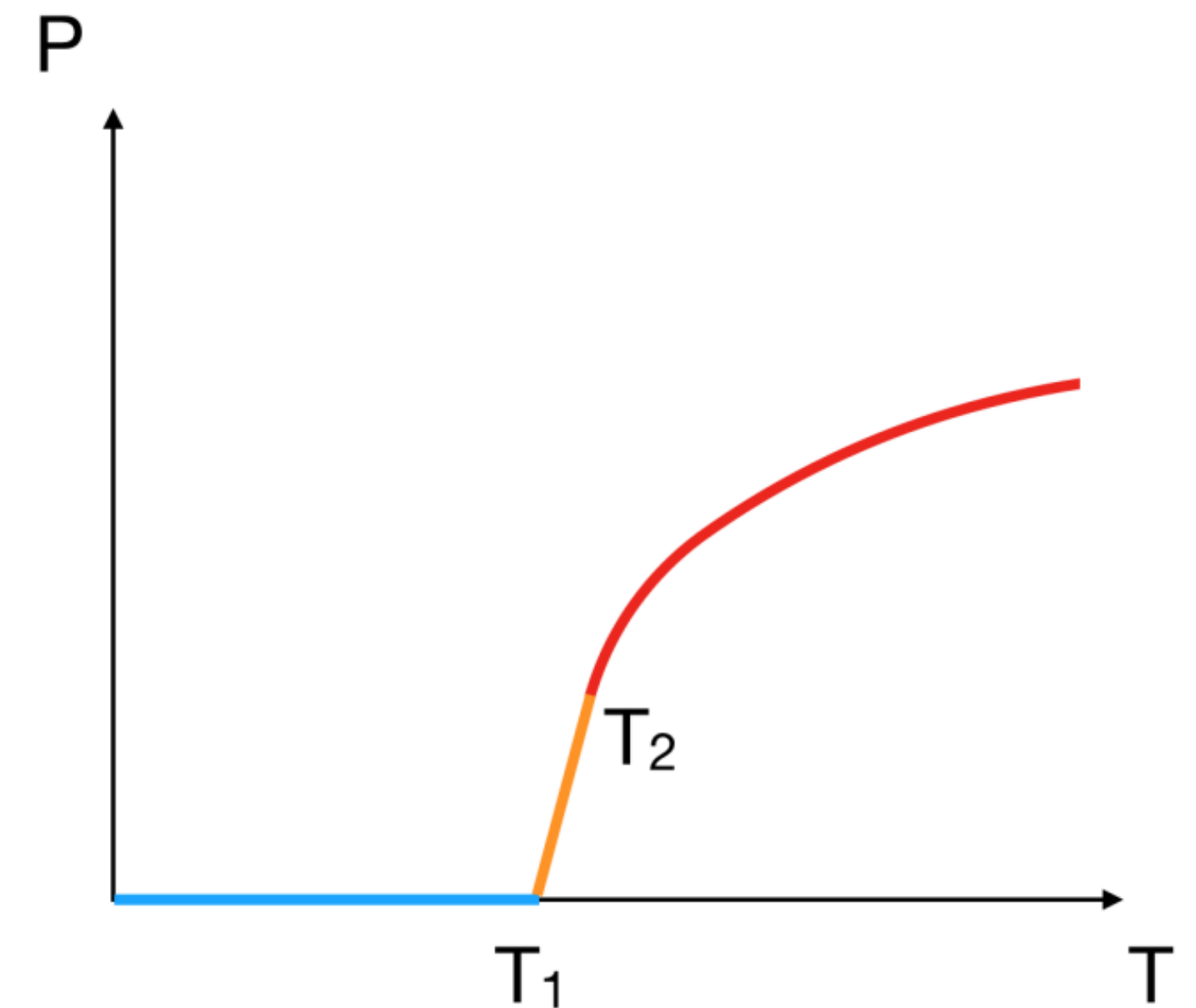
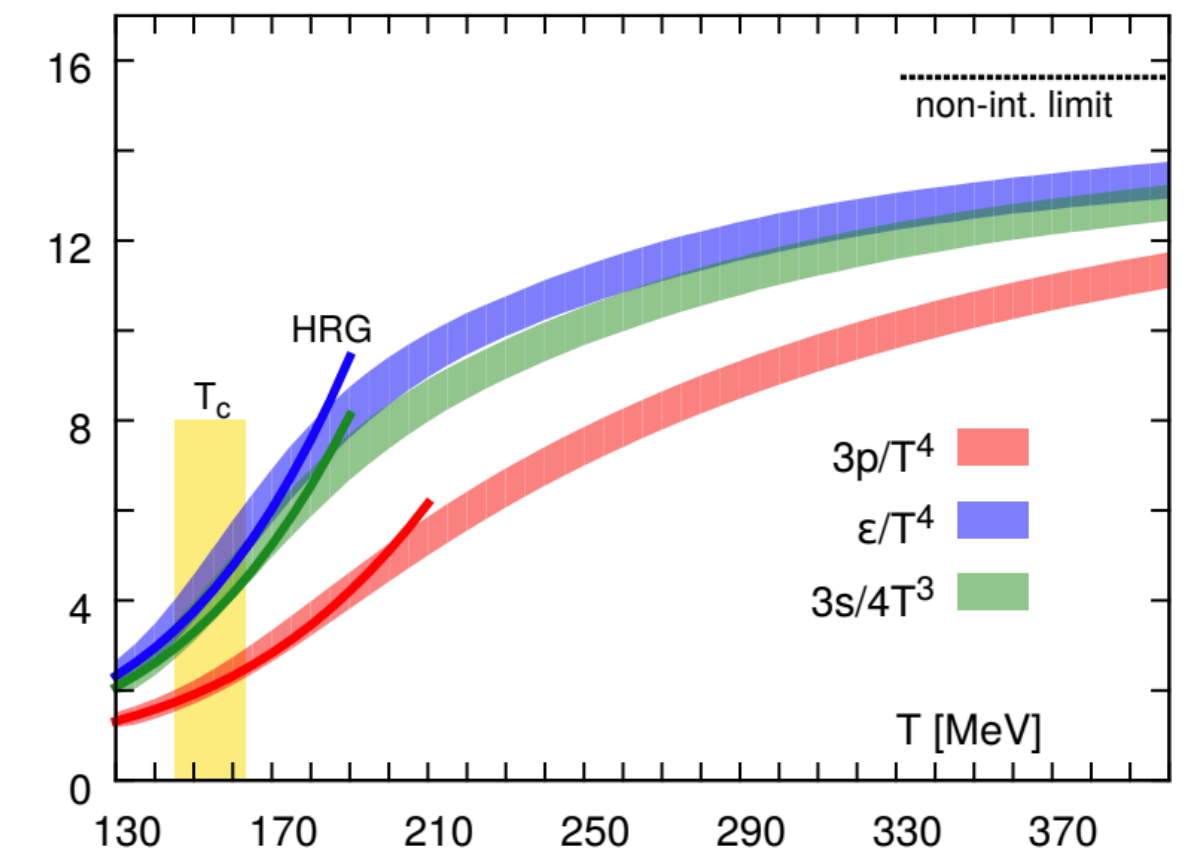


# QCD and the quark-gluon plasma

Source: A Bazavov et al. 1407.6387

## Questions:

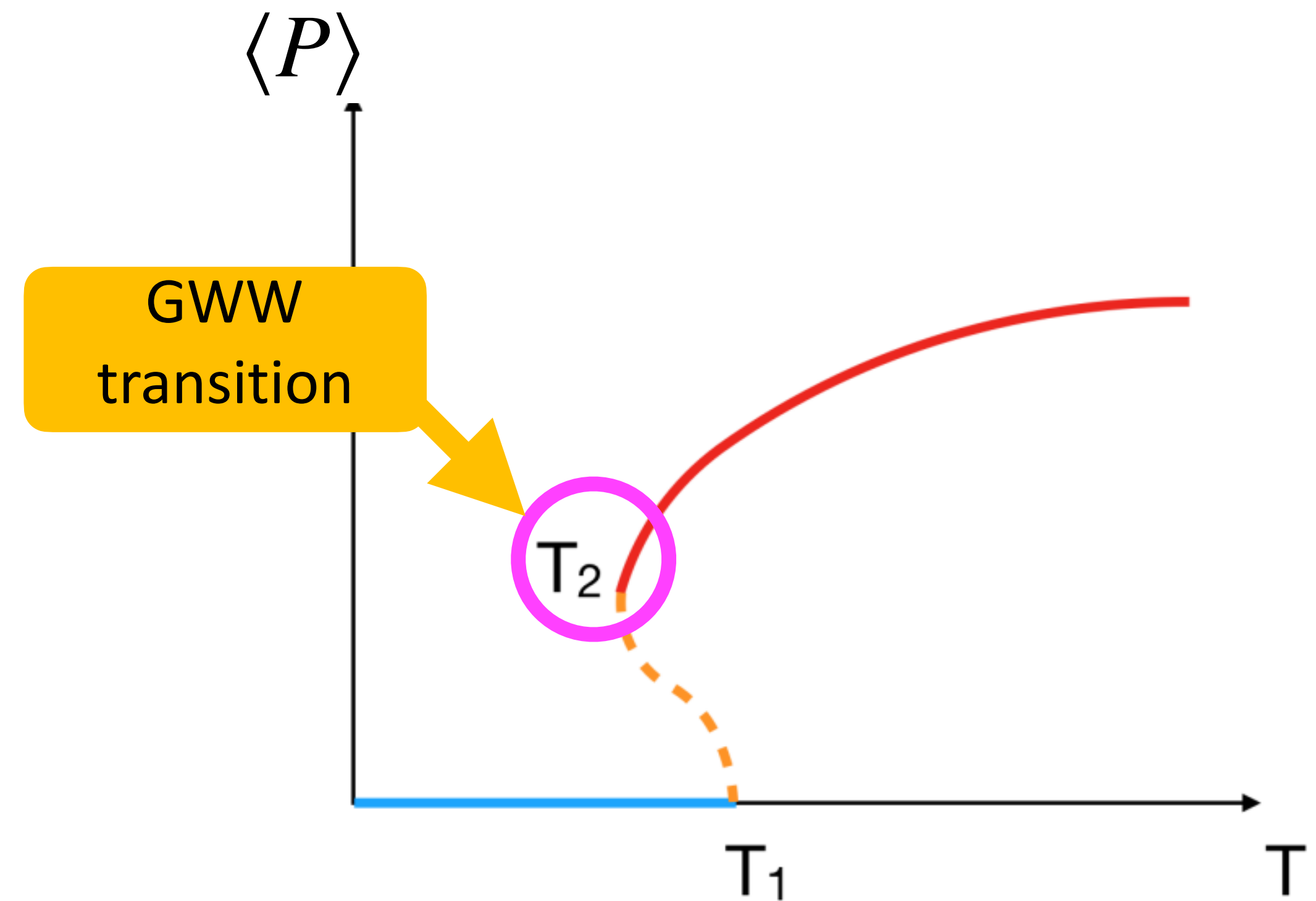
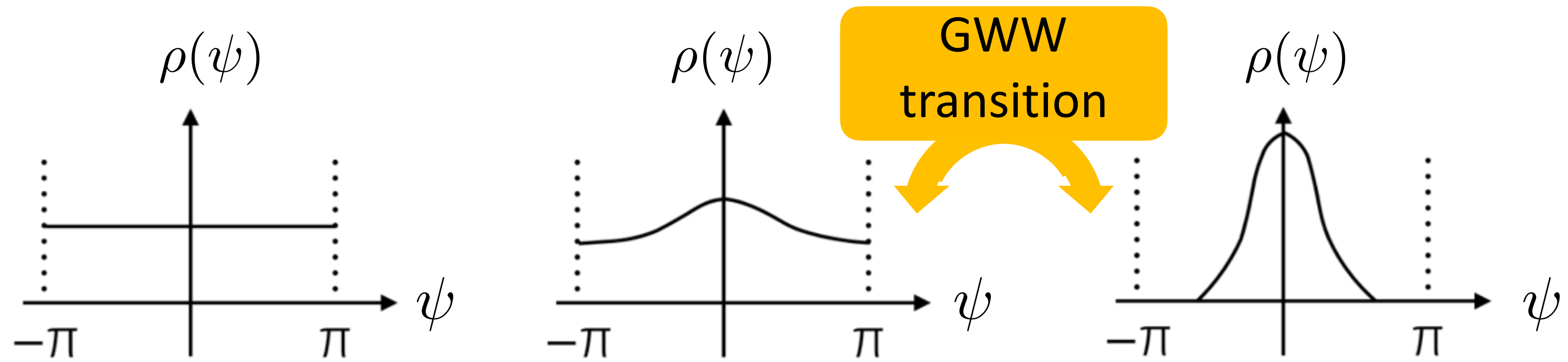
- Is the partial phase stable?
- Is the 'crossover' a true transition?
- Does  $\chi$ SB coincide with GWW?



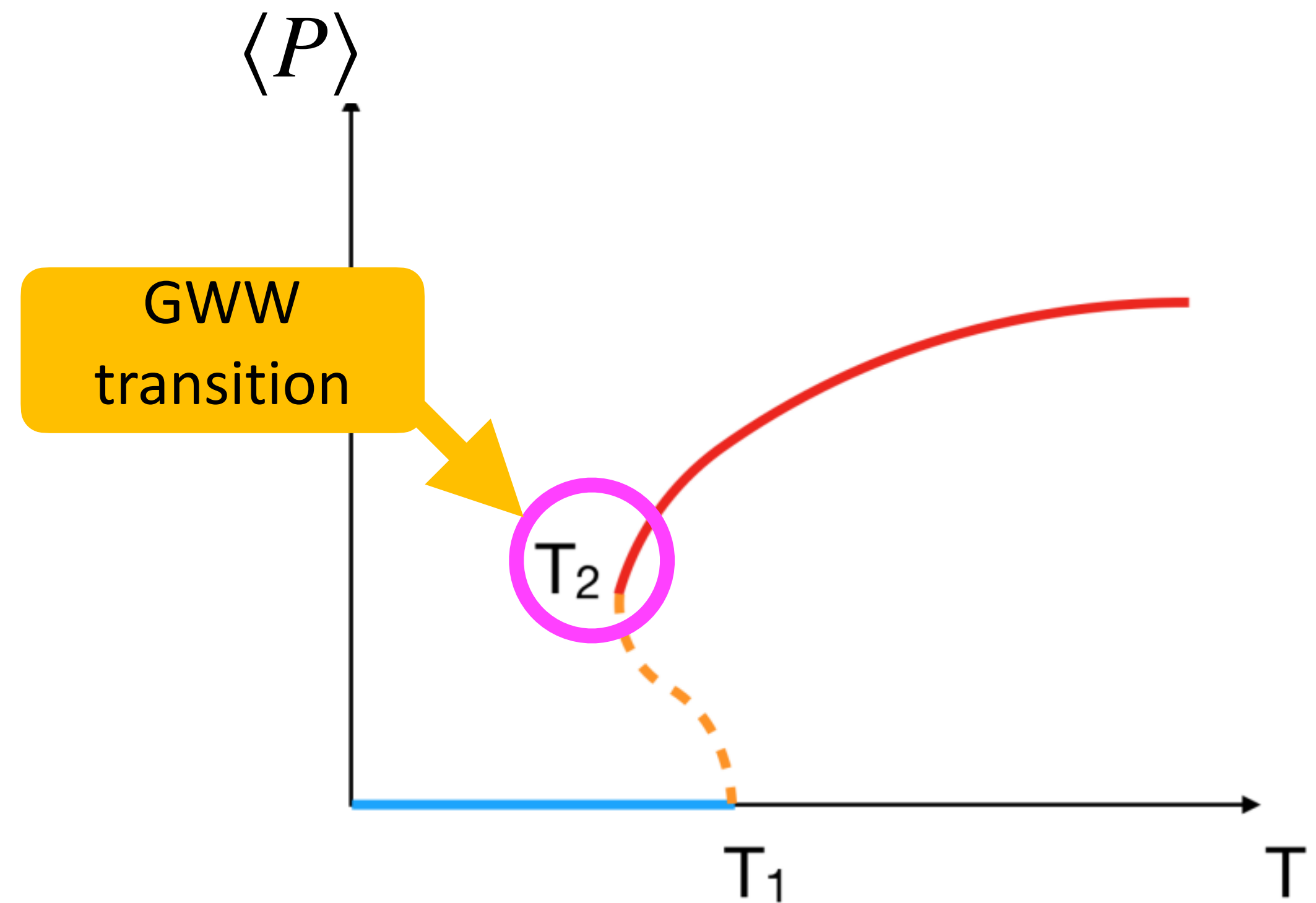
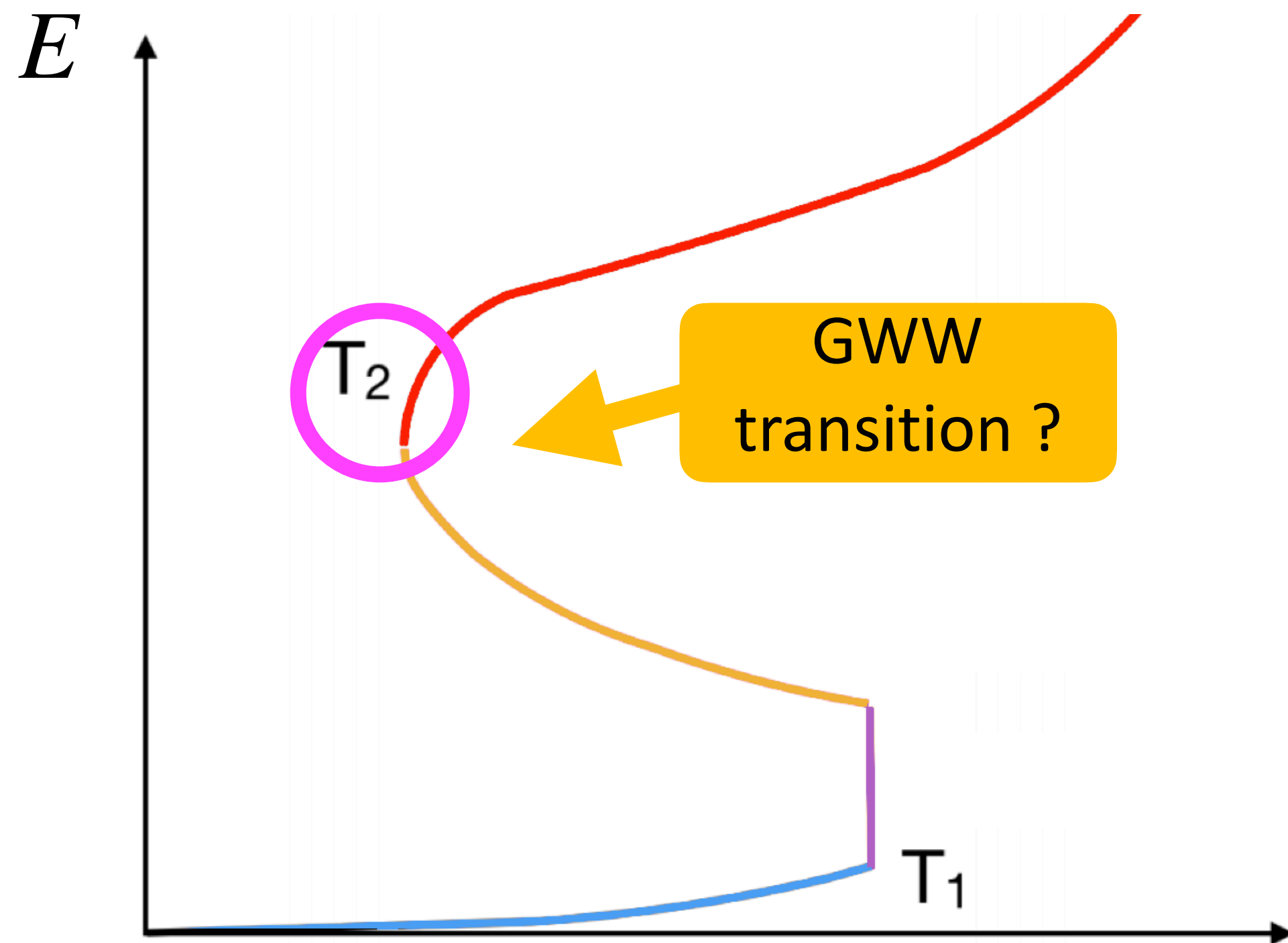
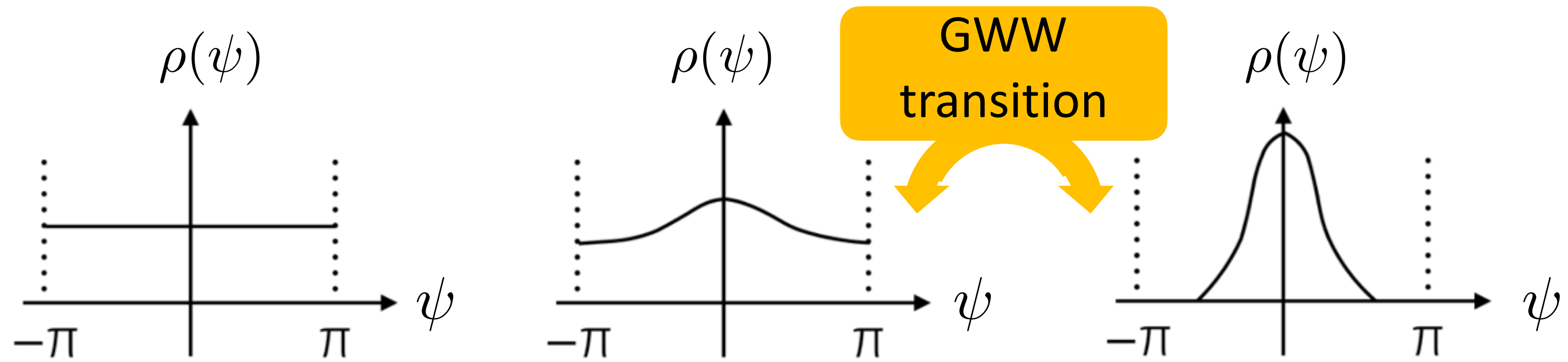
# Outline

1. Introduction
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4. Applied to QCD
- 5. Holography questions**
6. Flux tubes

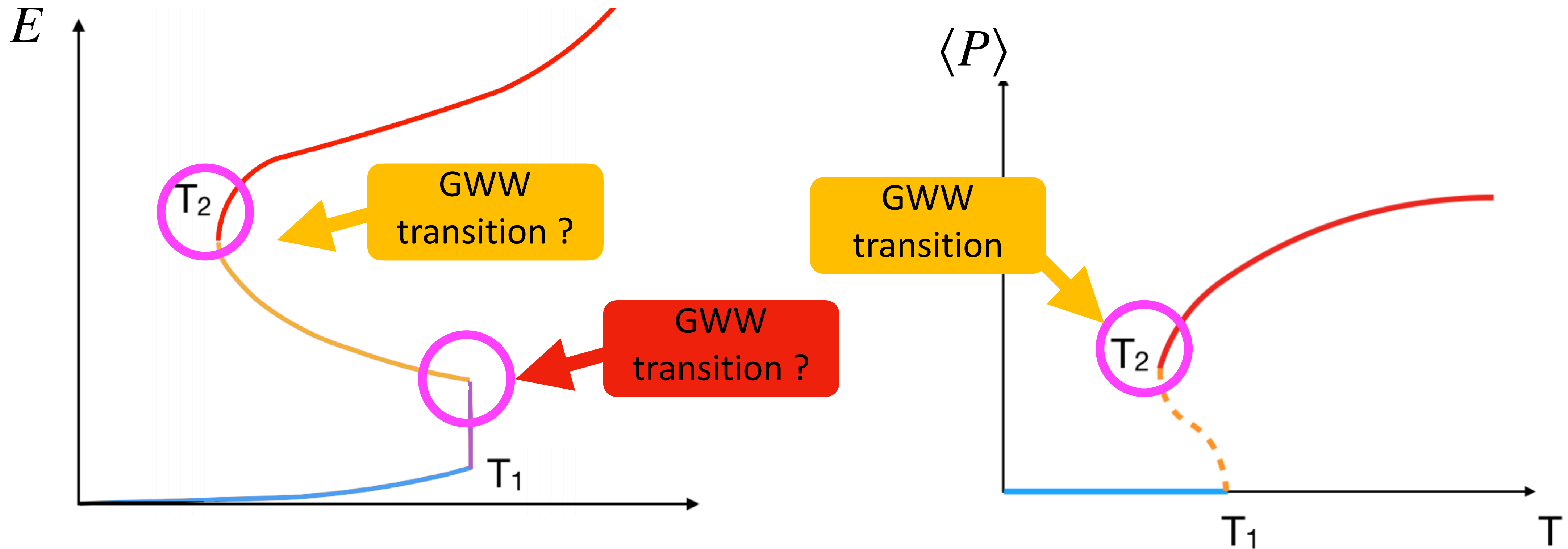
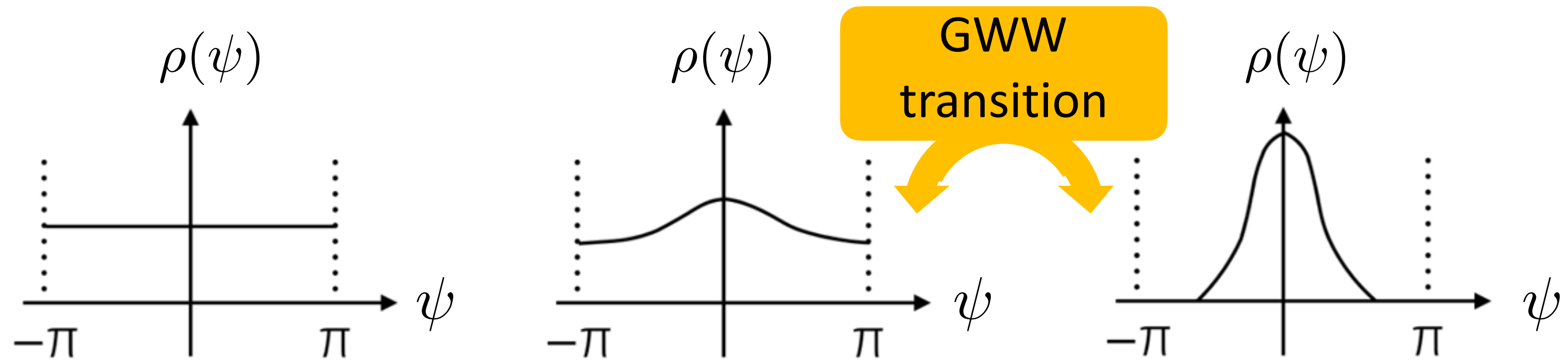
# Holography



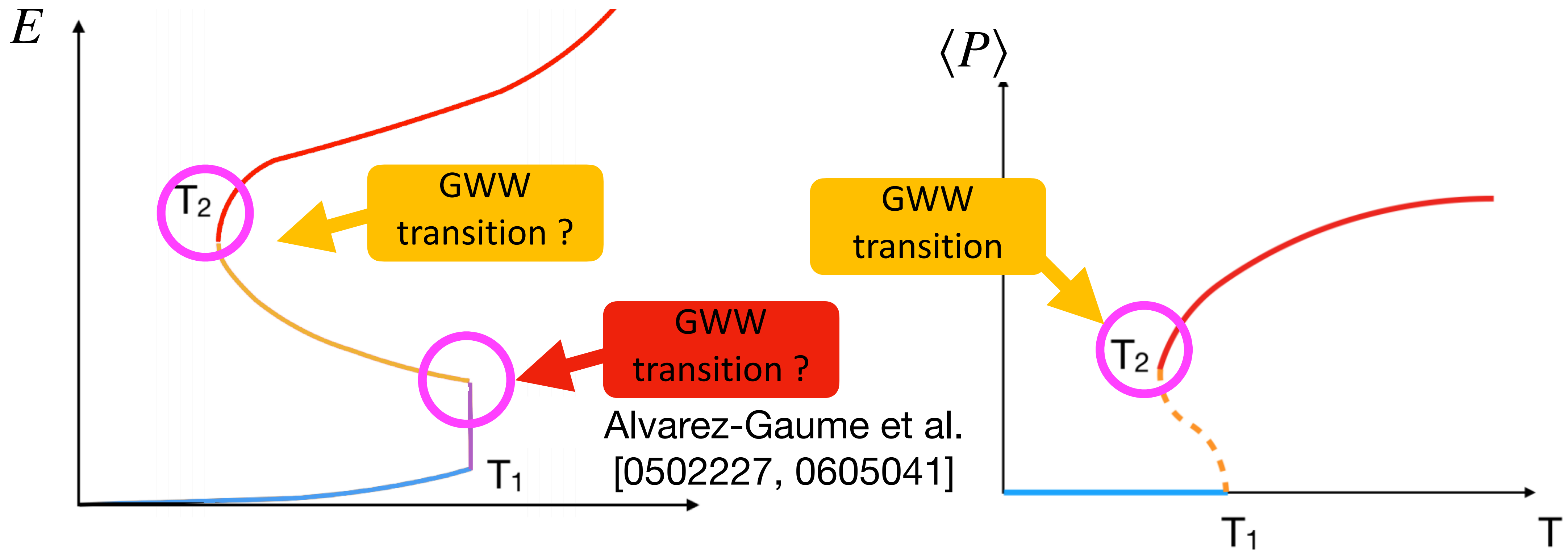
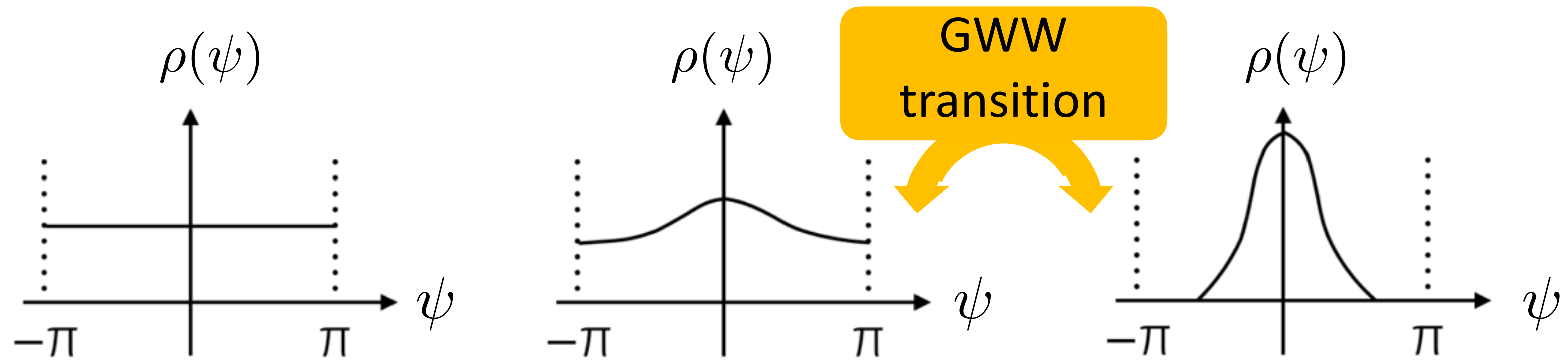
# Holography



# Holography



# Holography



# Holography

## Questions:

- a. Where is GWW point?
- b. What are the details of the partial confinement dual?
- c. Coincides with symmetry breaking?

# Outline

1. Introduction
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- 6. Flux tubes**

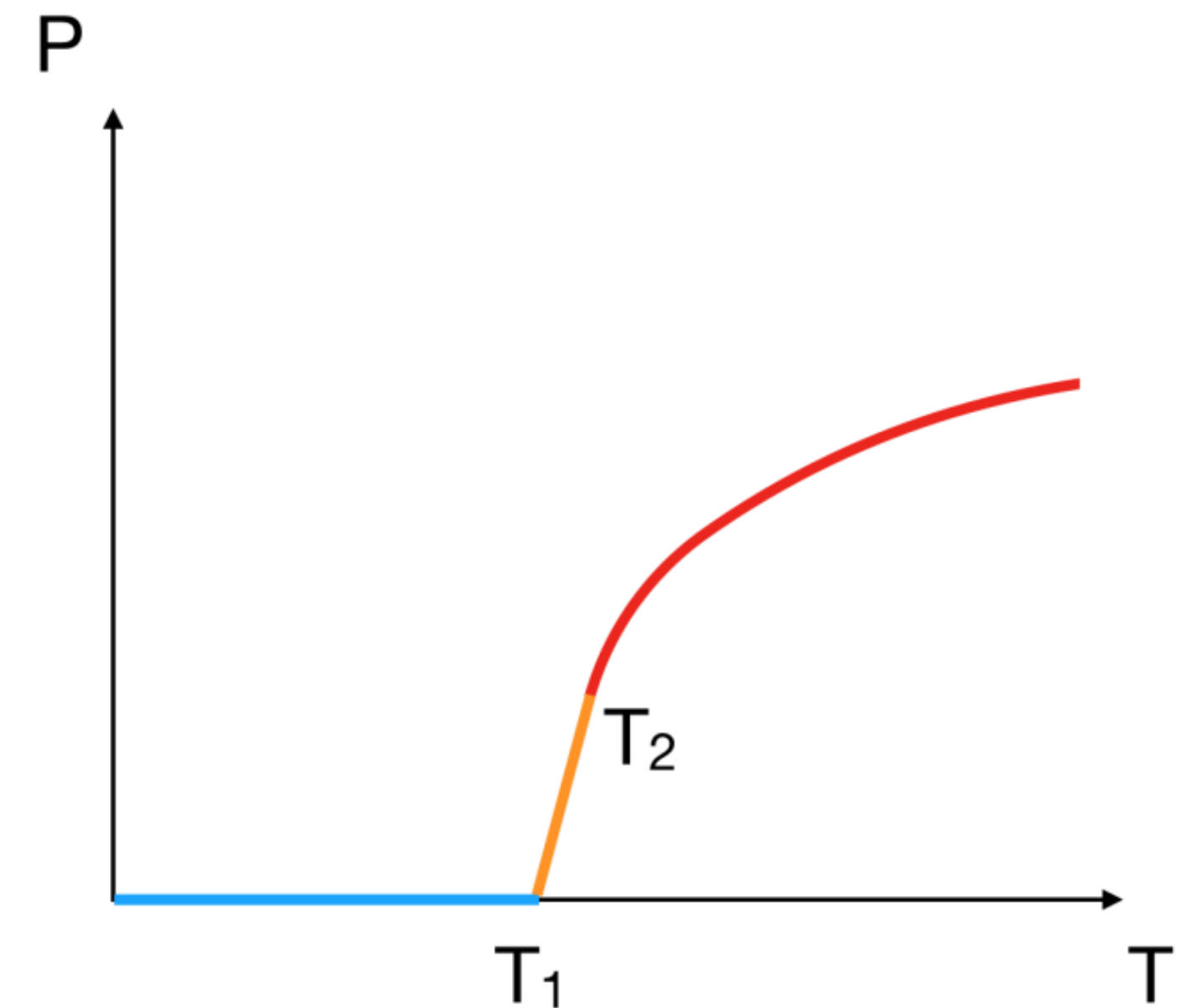
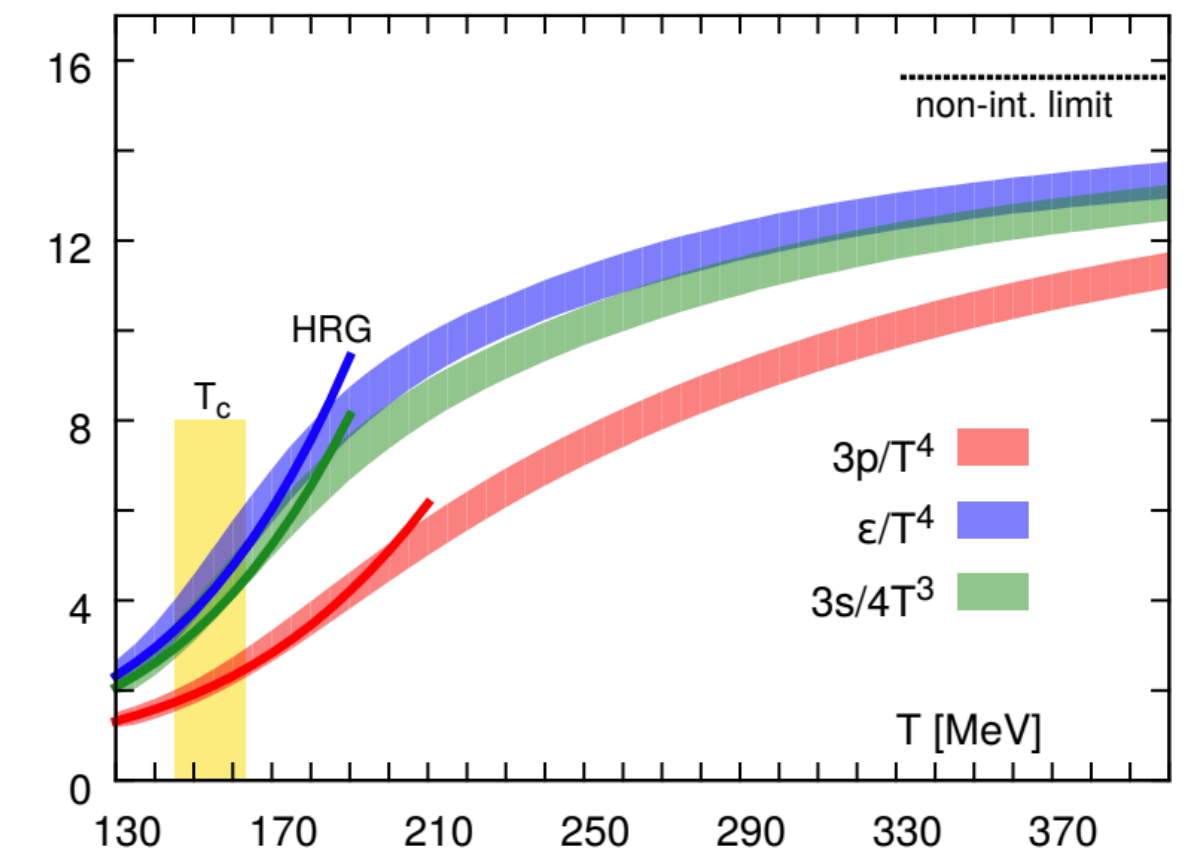


# QCD and the quark-gluon plasma

Source: A Bazavov et al. 1407.6387

## Questions:

- Is the partial phase stable?
- Is the 'crossover' a true transition?
- Does  $\chi$ SB coincide with GWW?

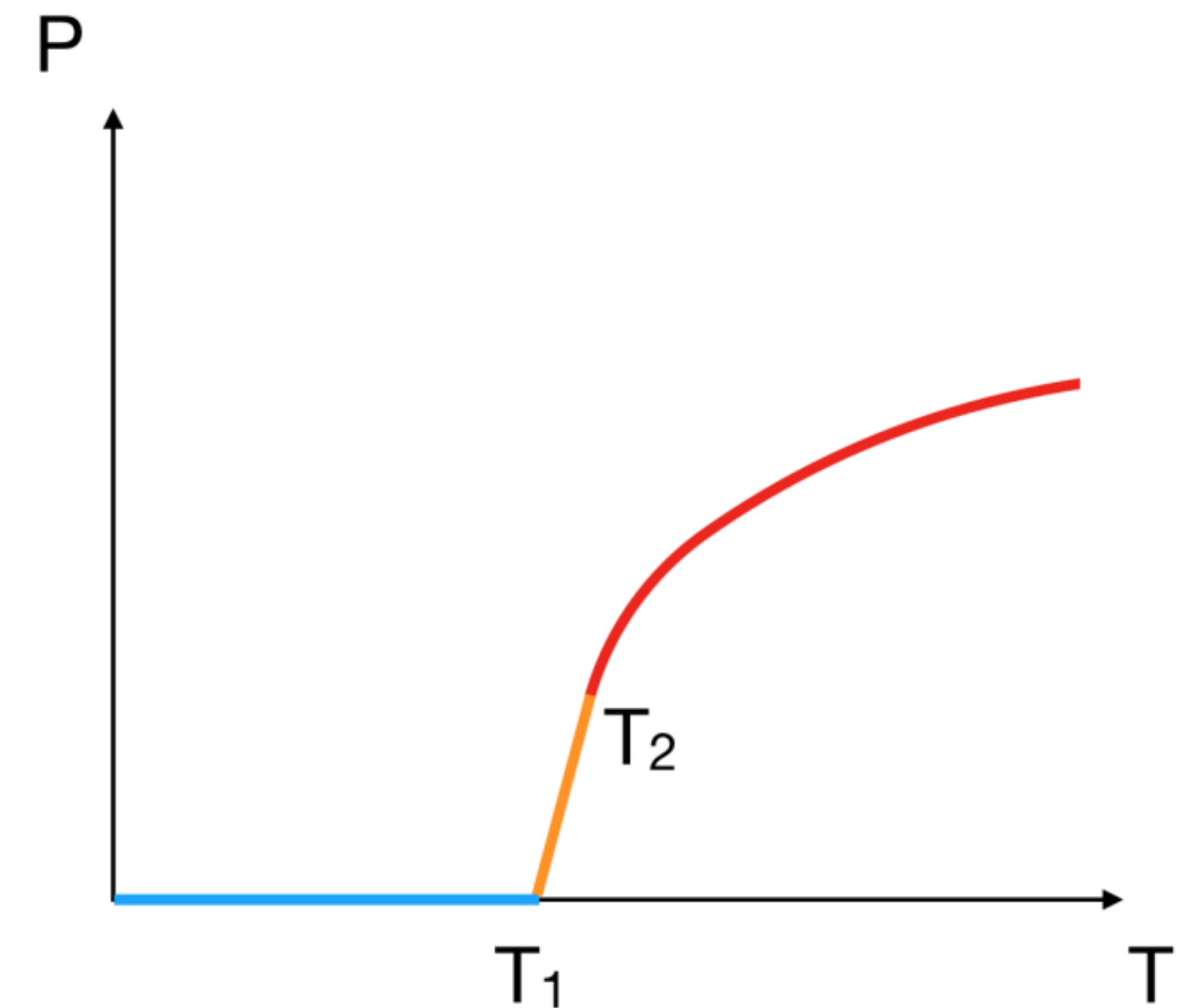
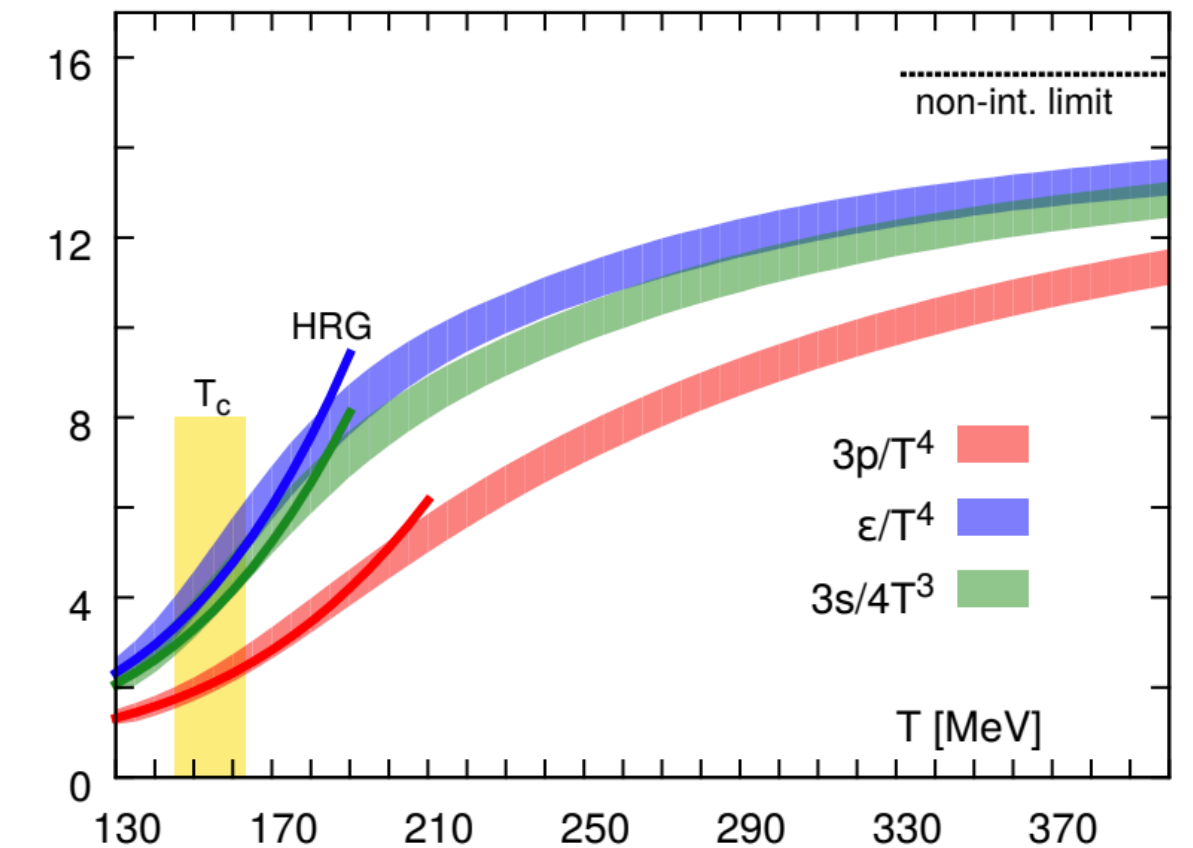


# QCD and the quark-gluon plasma

Source: A Bazavov et al. 1407.6387

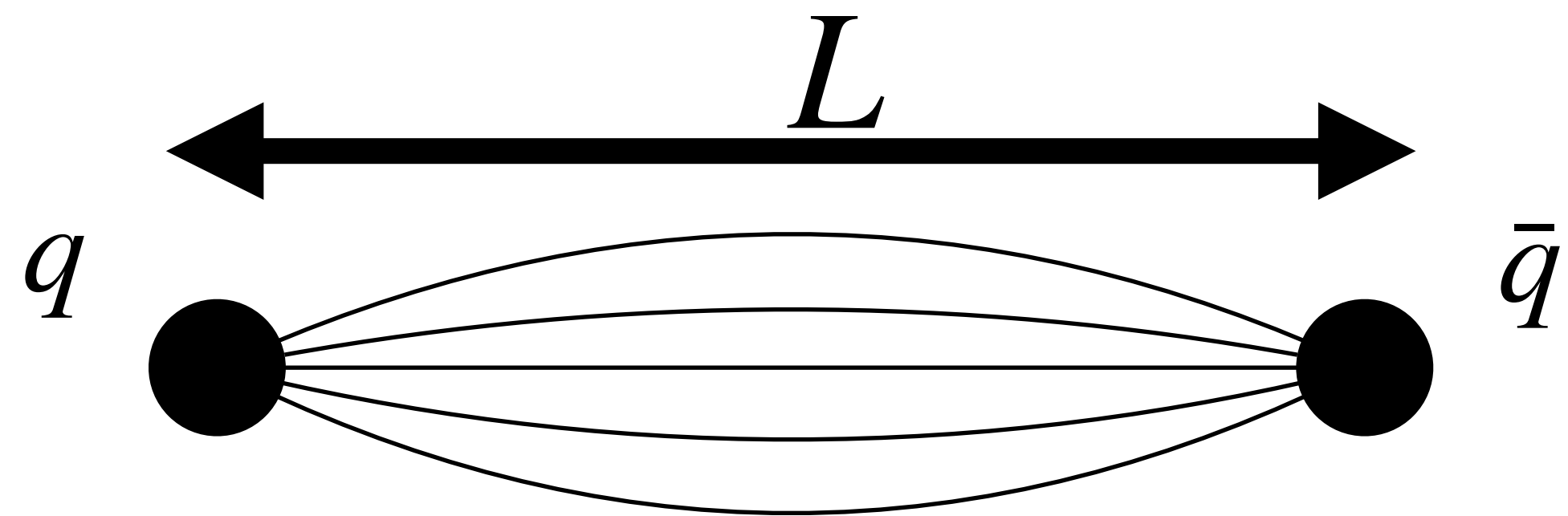
## Questions:

- Is the partial phase stable?
- Is the 'crossover' a true transition?
- Does  $\chi$ SB coincide with GWW?
- Bound states and dynamics?
- Collider signature?

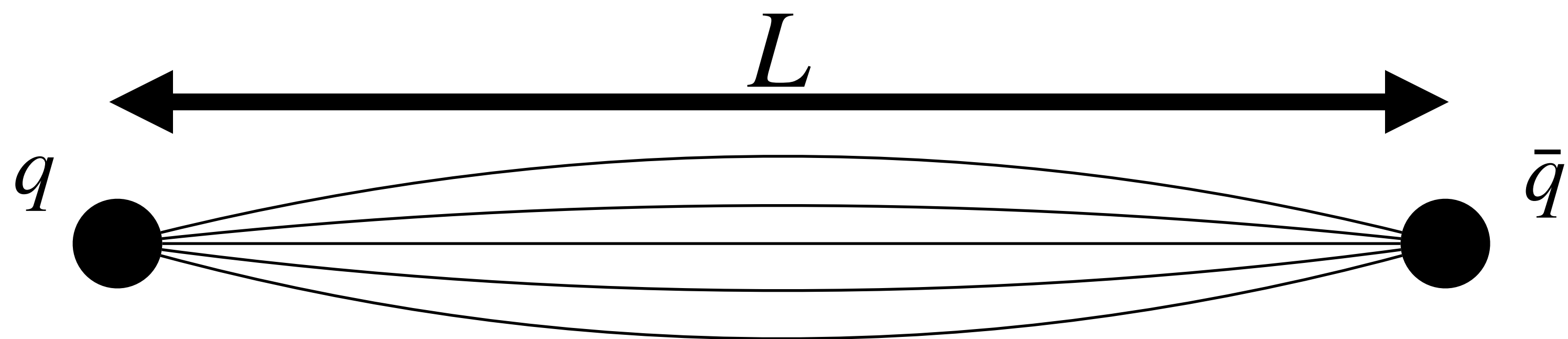


# Flux tubes

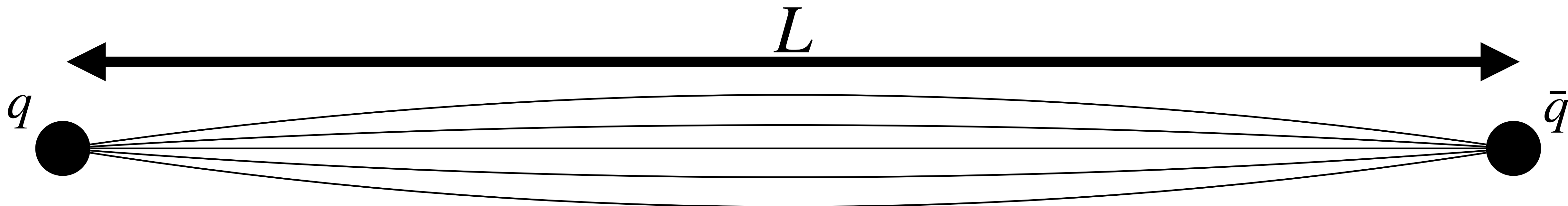
# Flux tubes



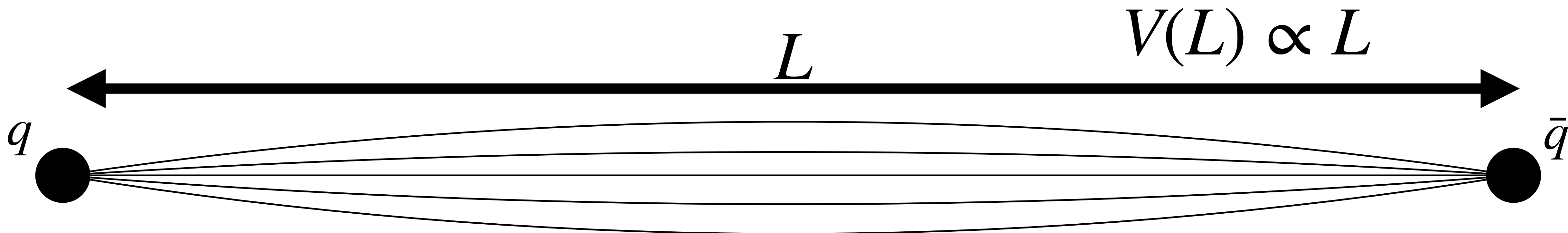
# Flux tubes



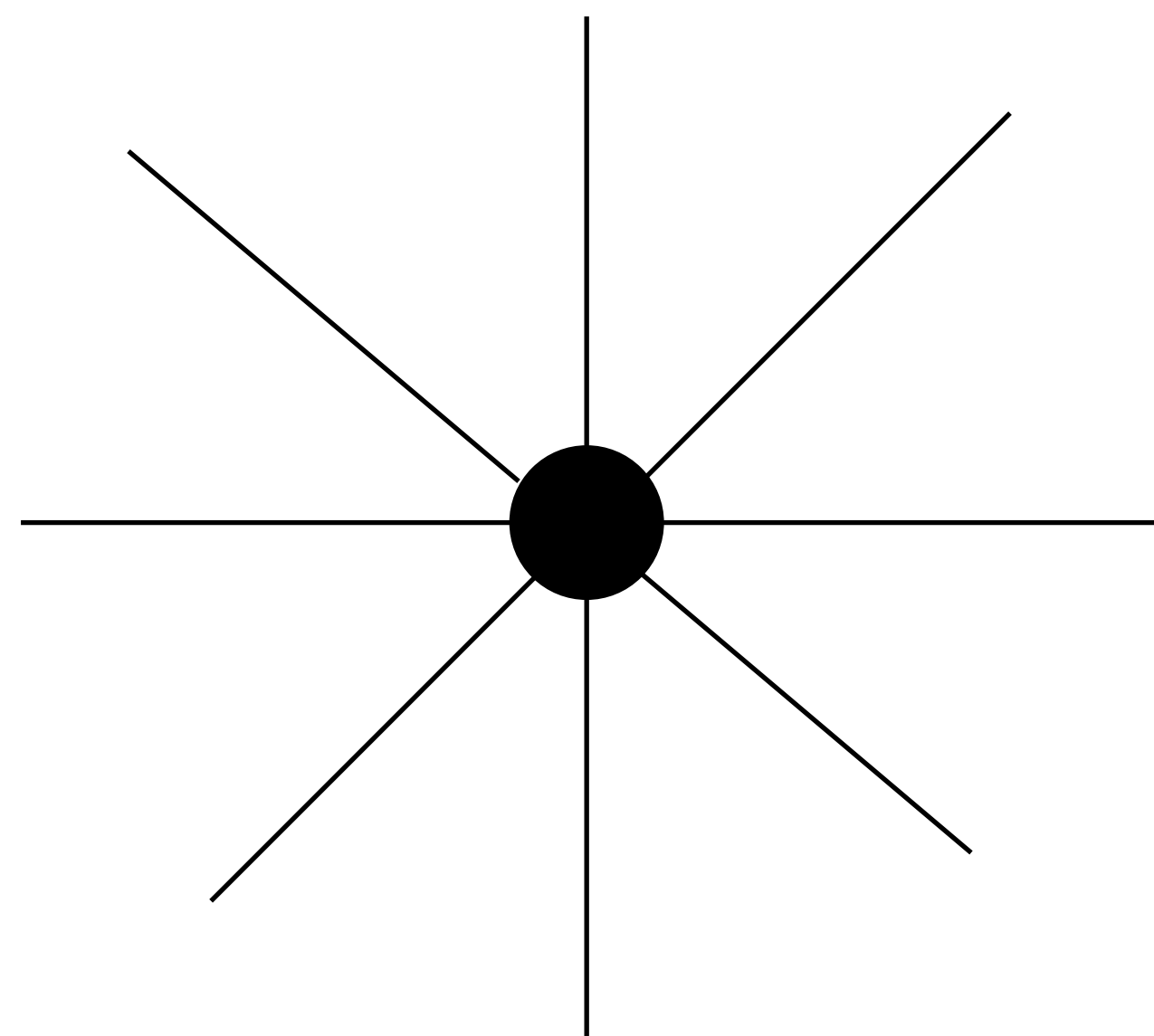
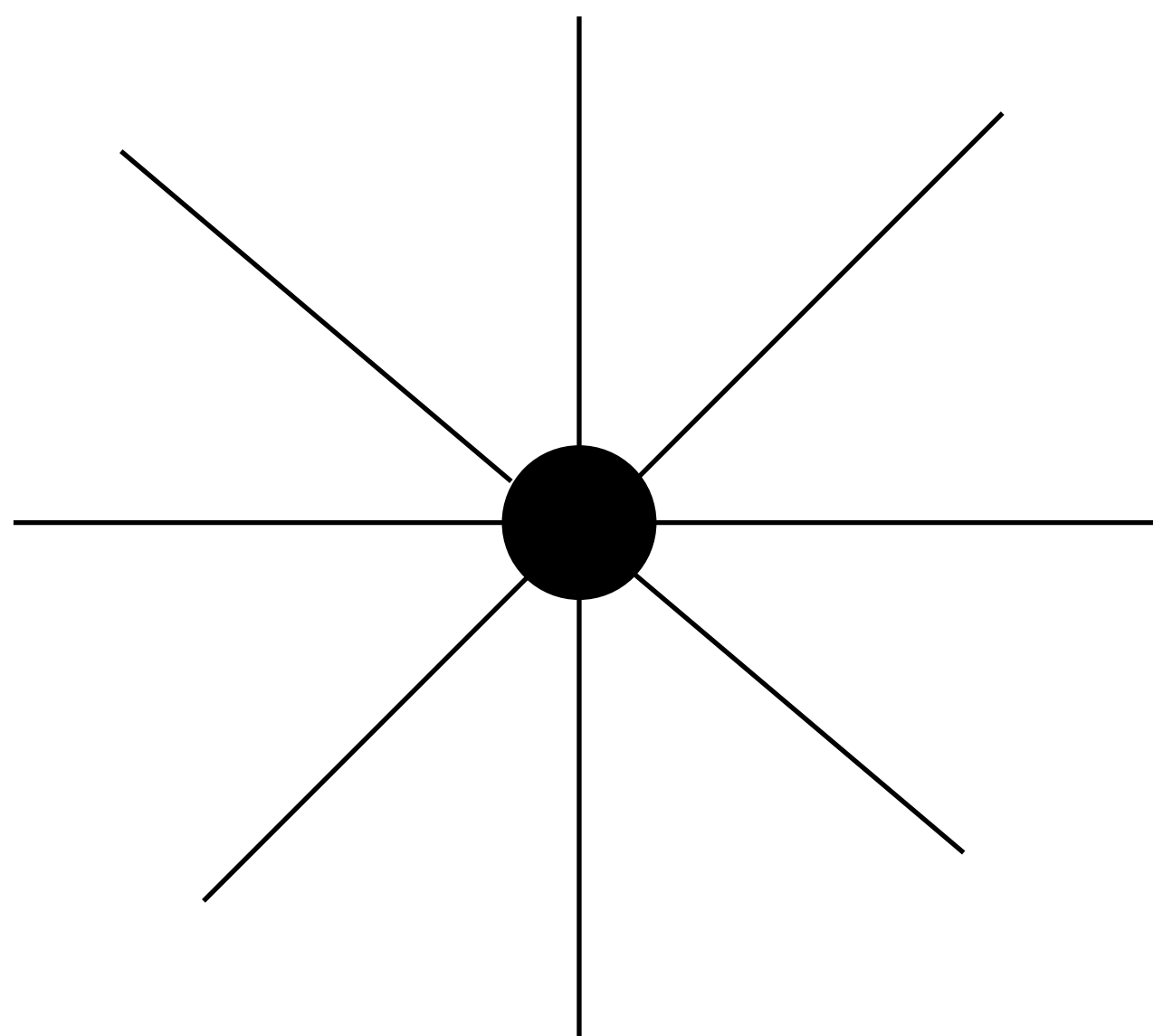
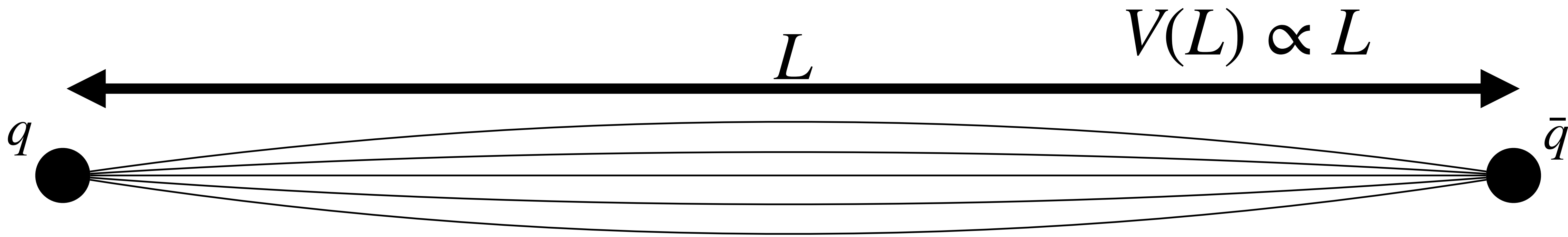
# Flux tubes



# Flux tubes

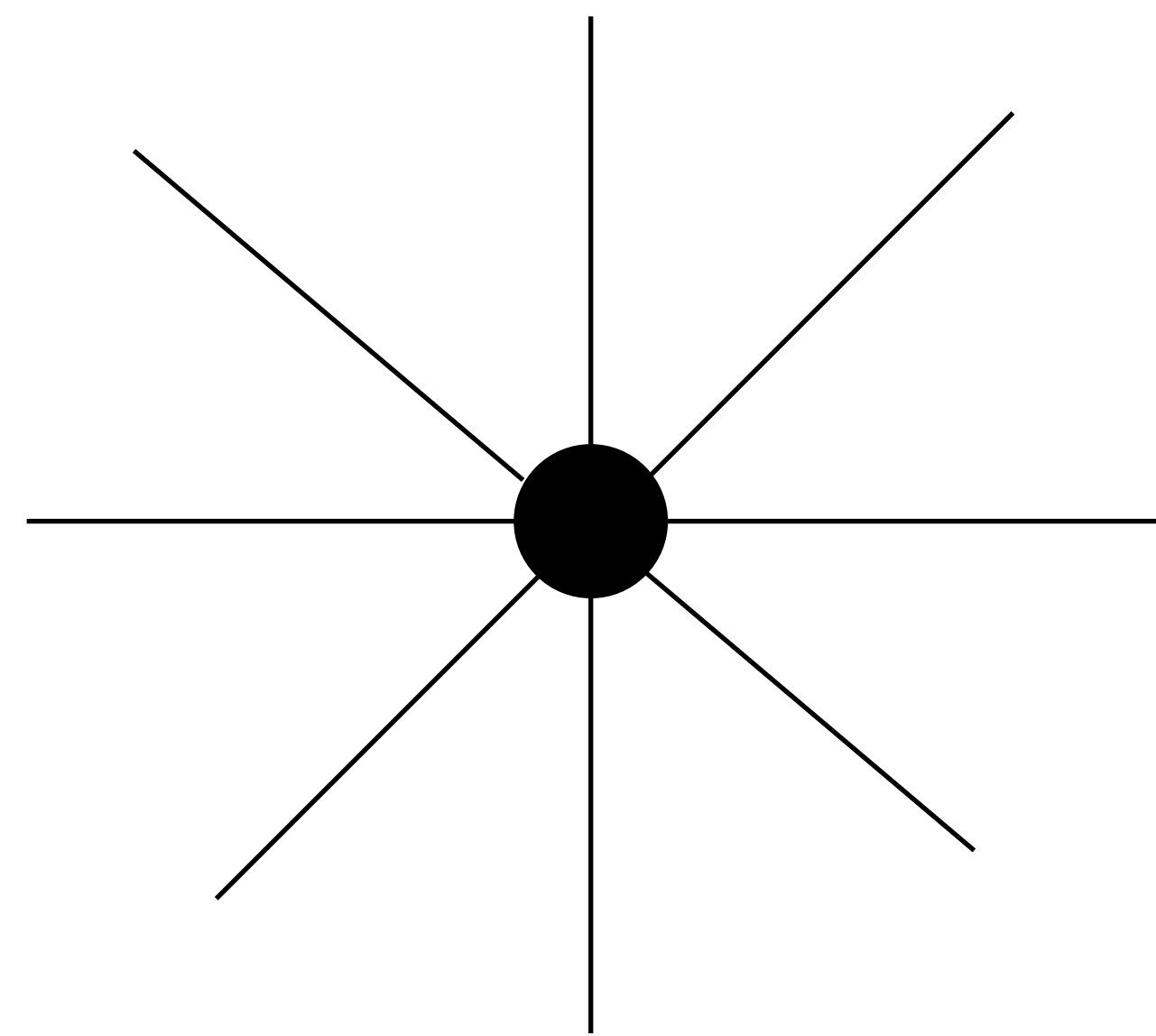
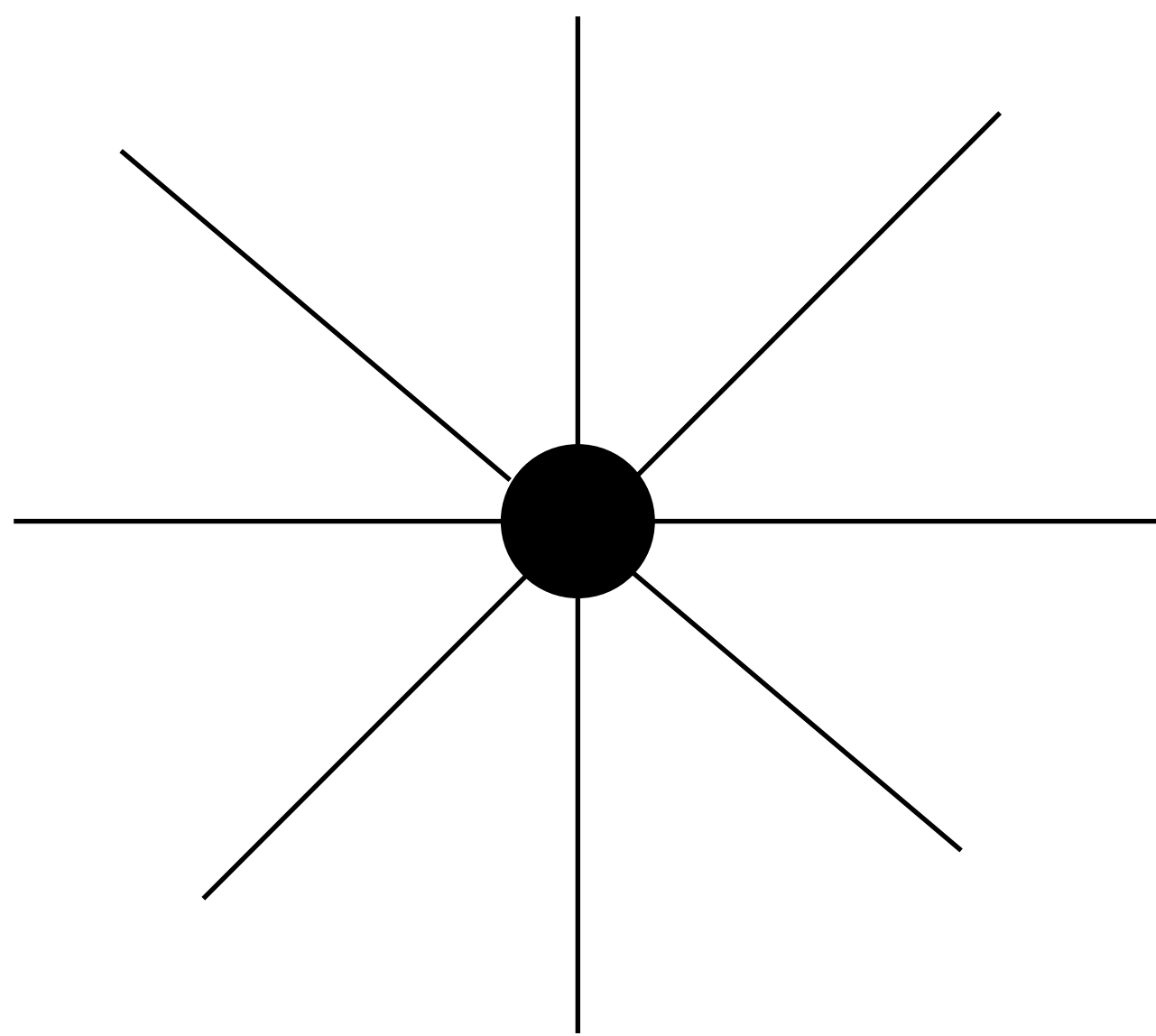
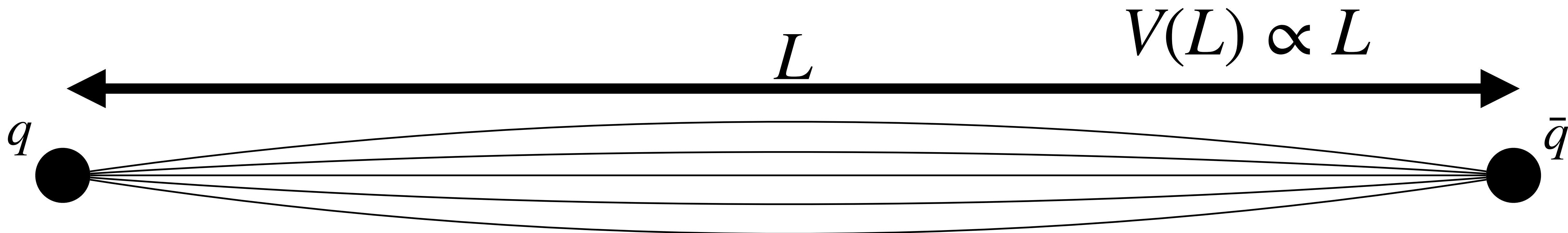


# Flux tubes

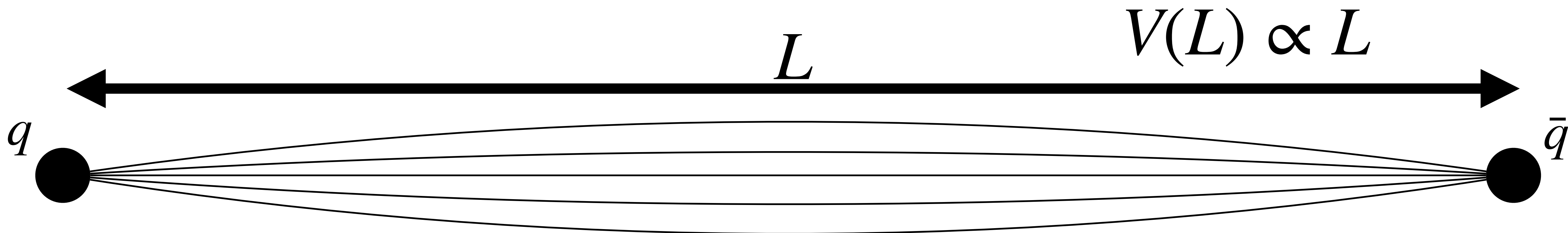




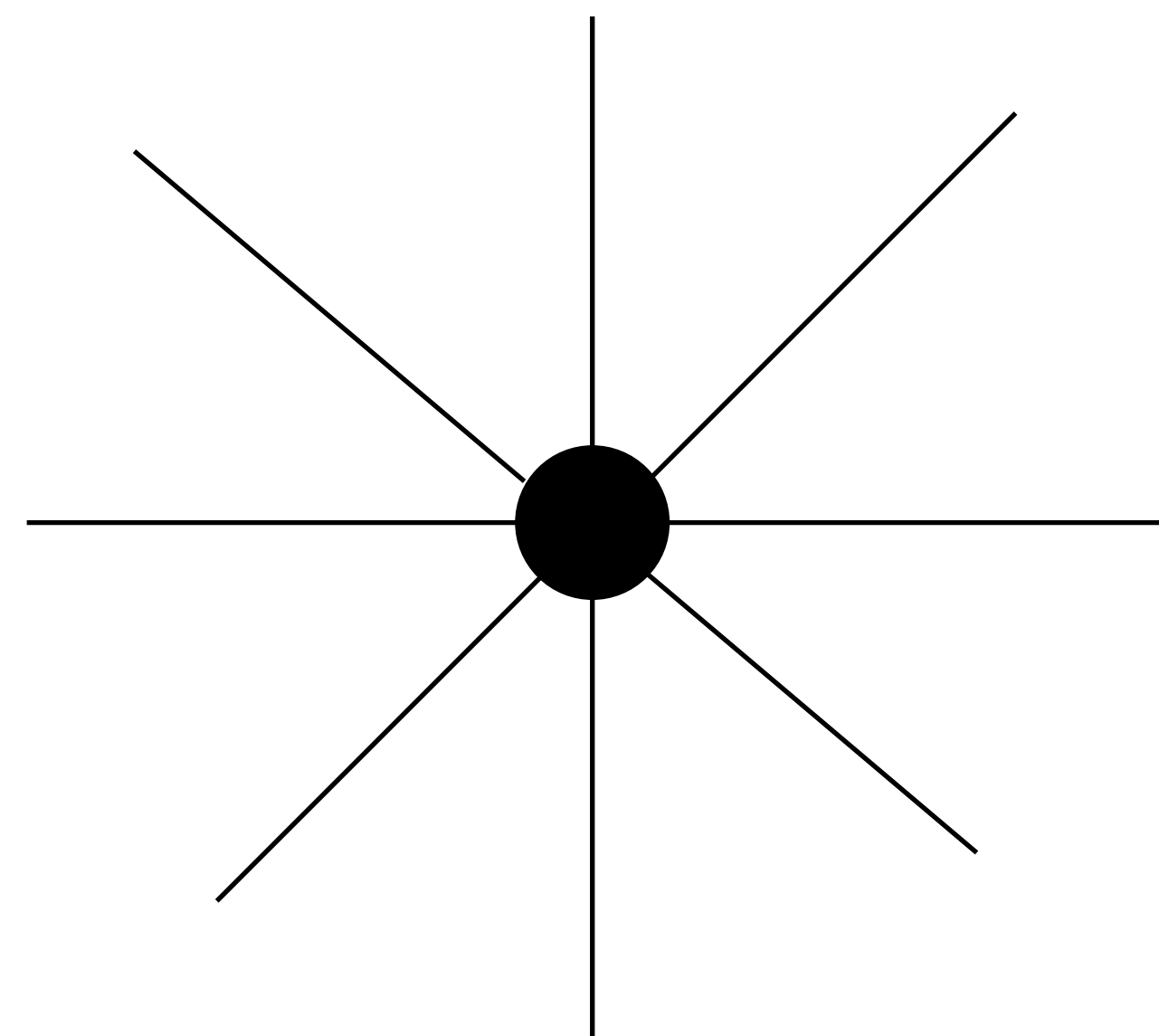
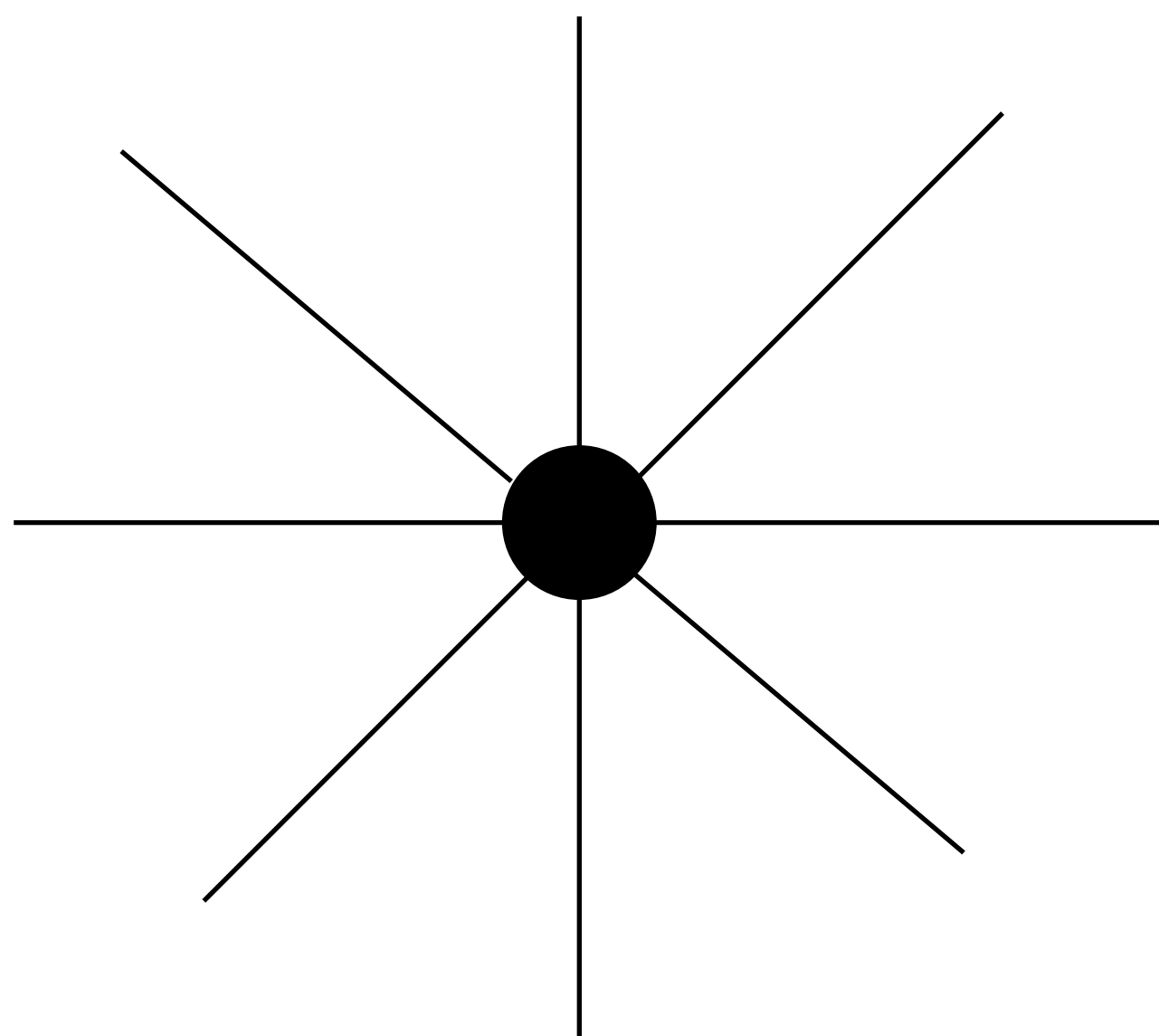
# Flux tubes



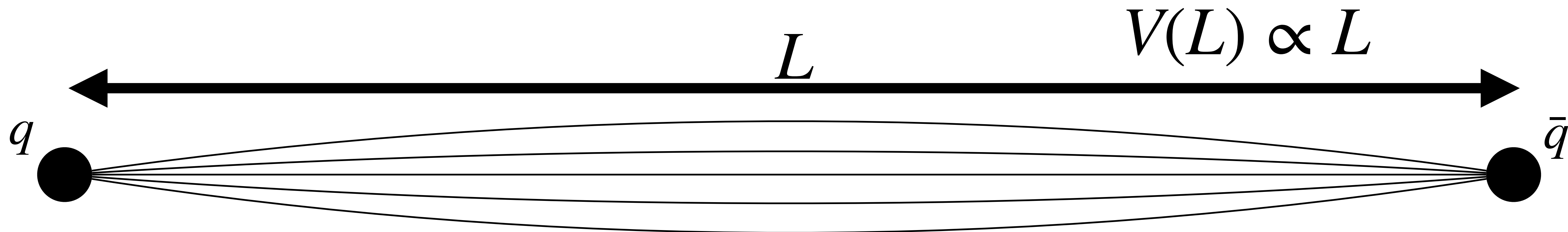
# Flux tubes



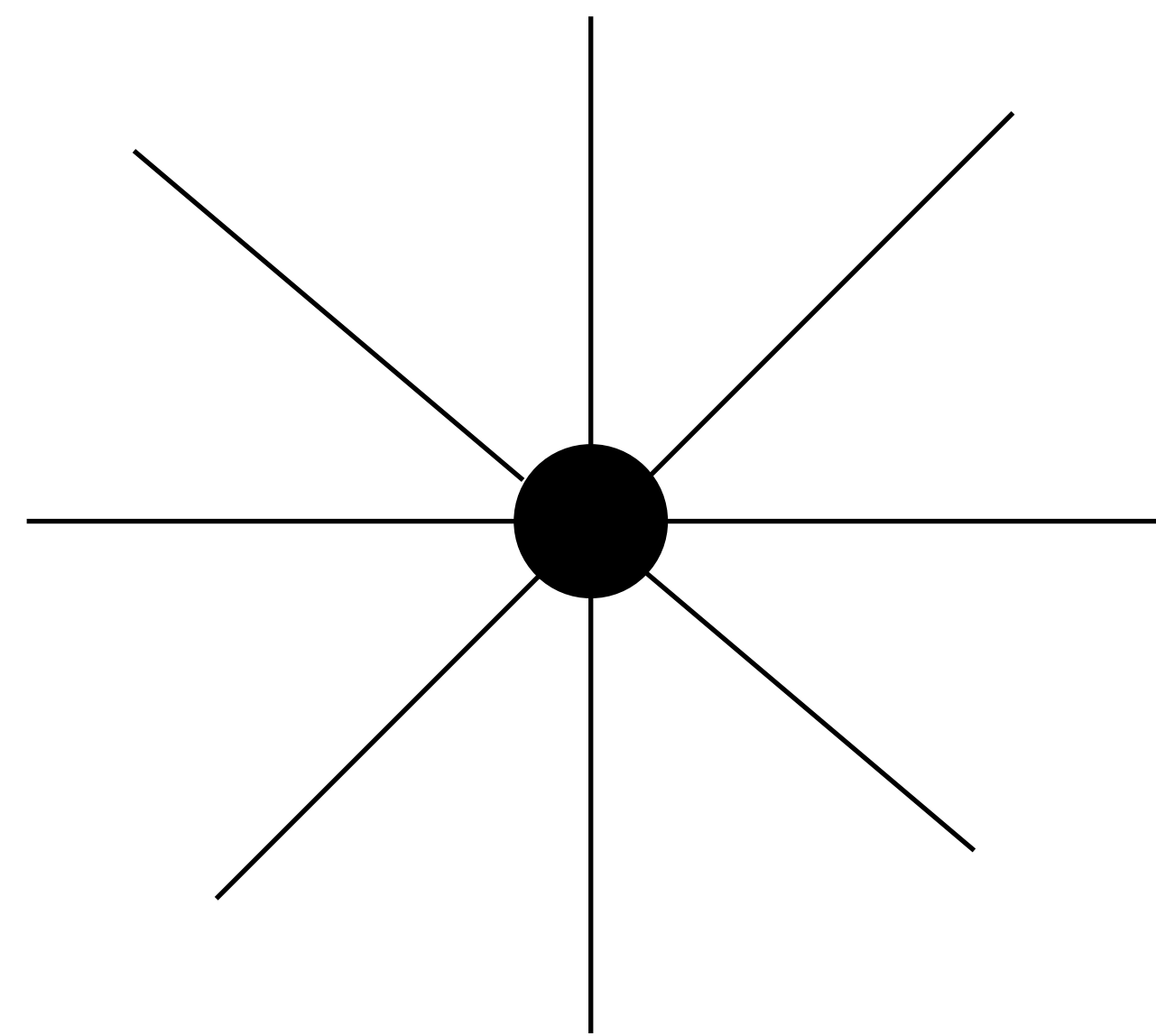
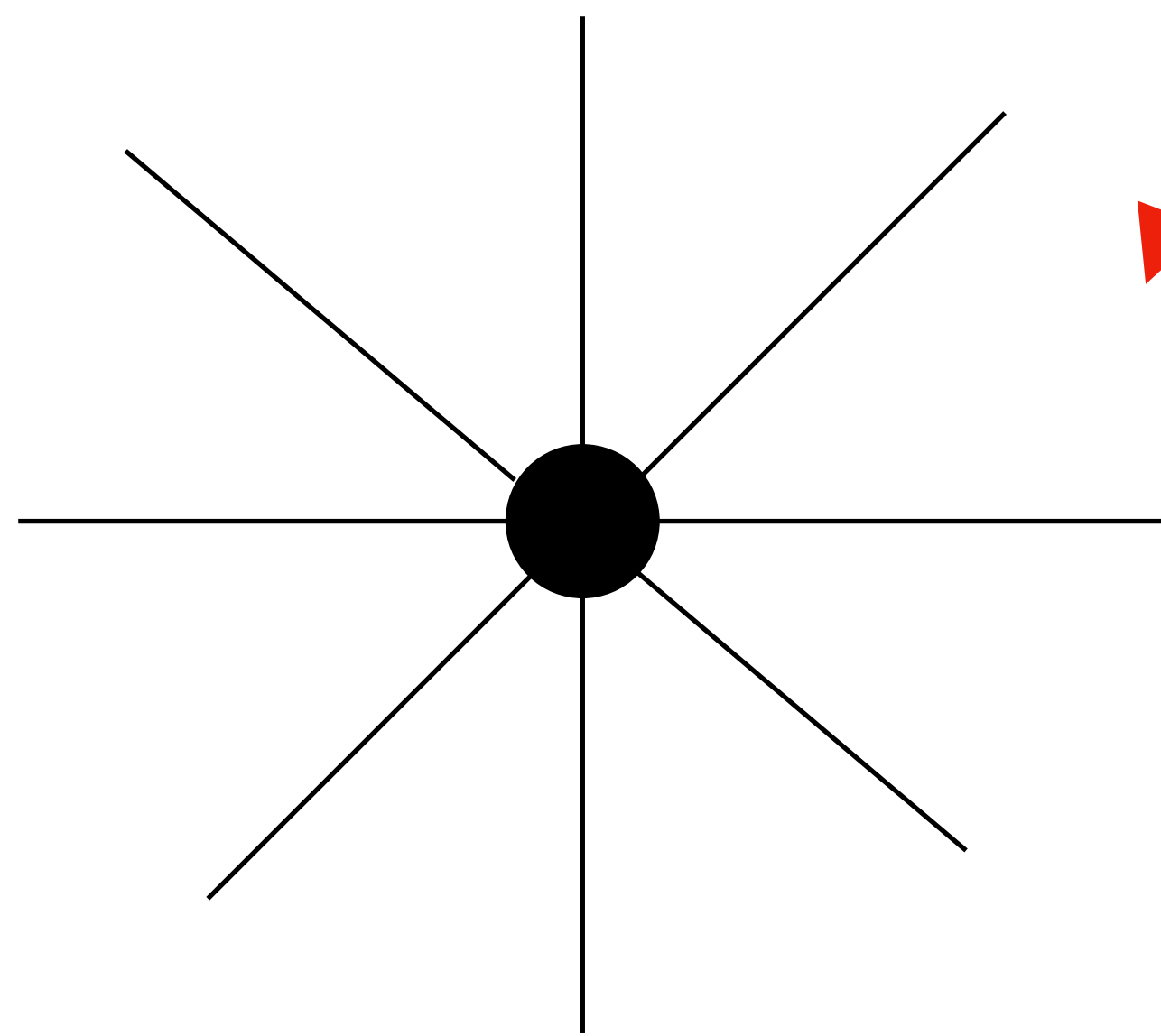
$V(L)$  deconfining



# Flux tubes: conjecture



$V(L)$  deconfining

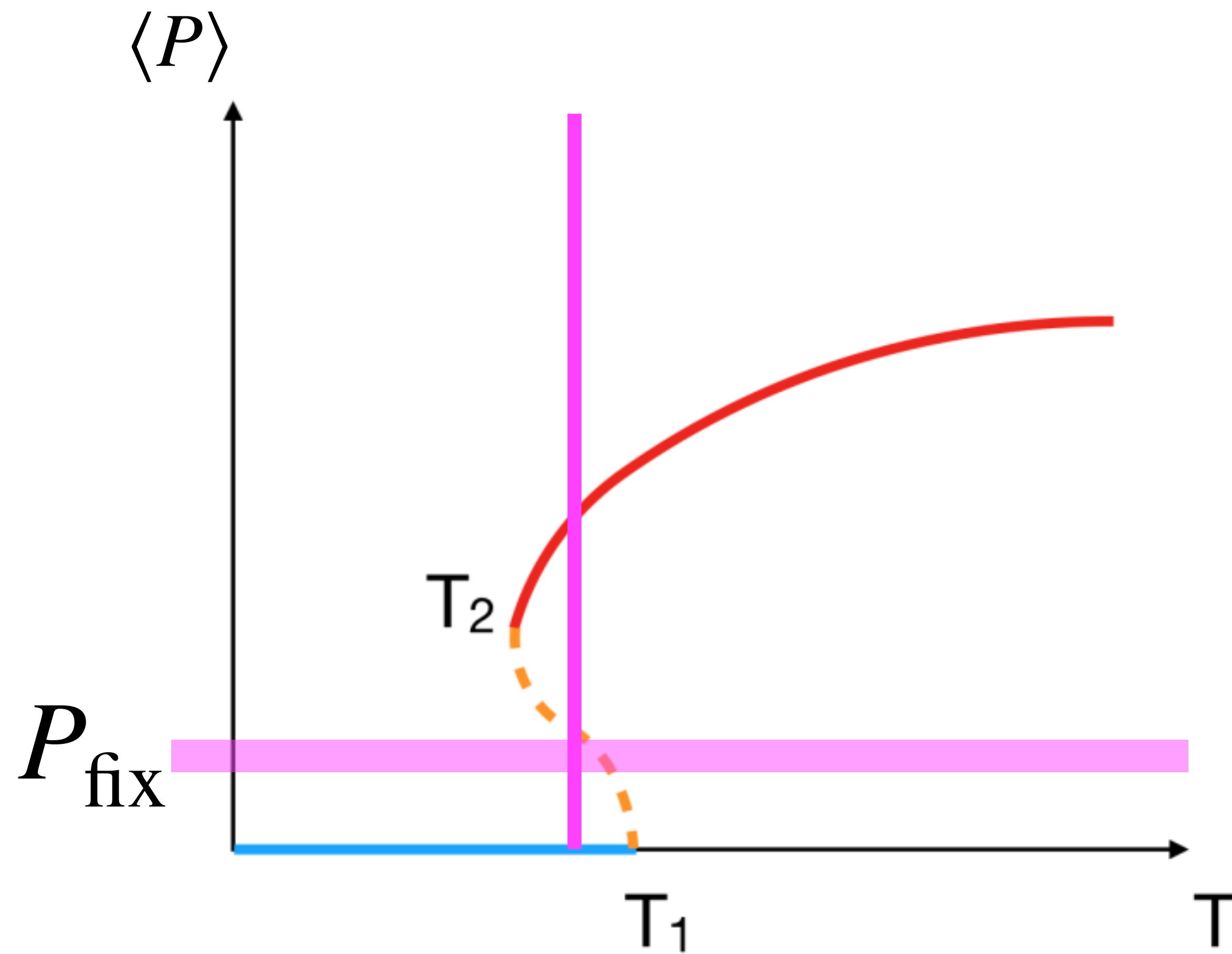


**U(N) pure YM**

**large N**

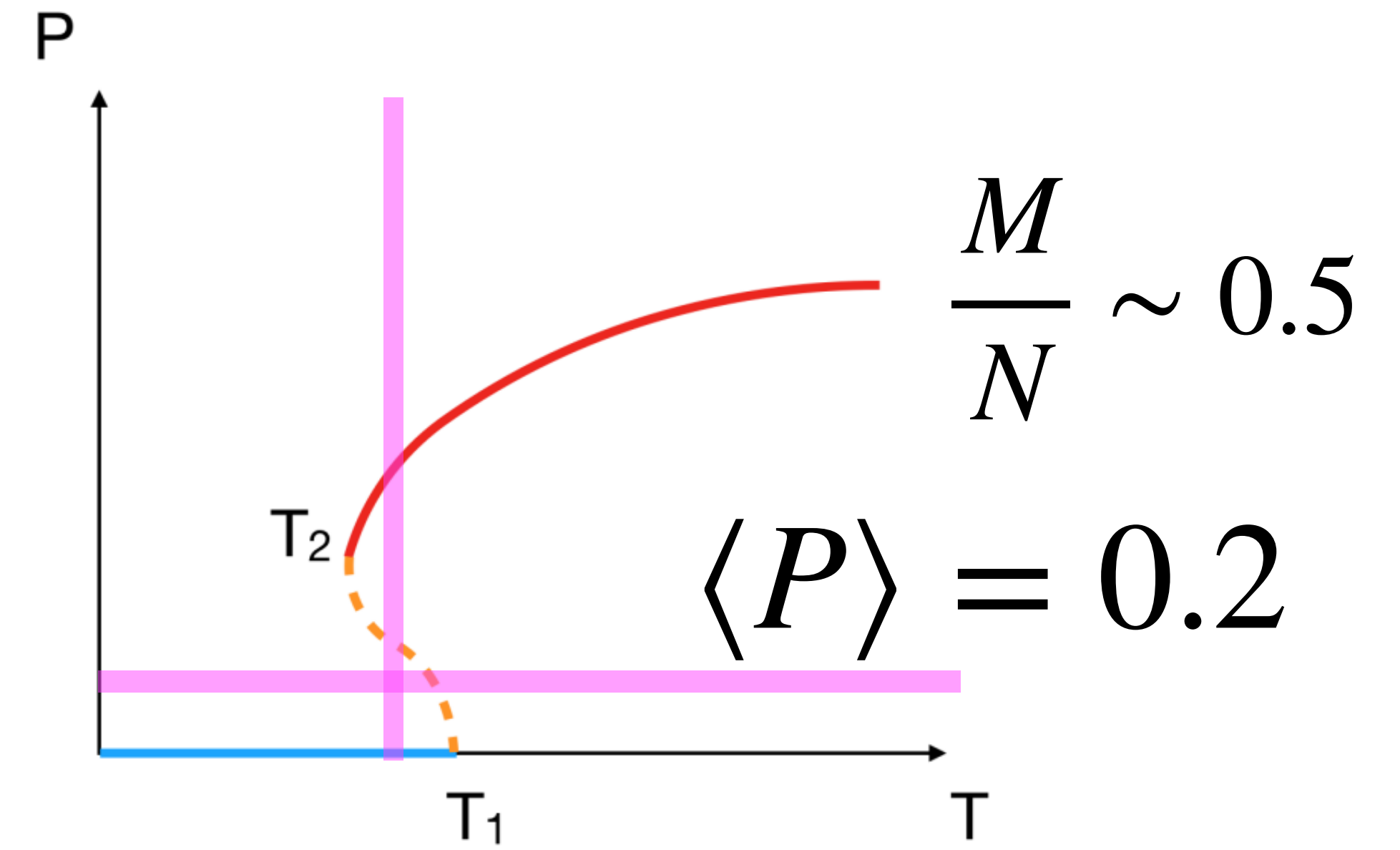
**strong coupling**

# Large N U(N) YM



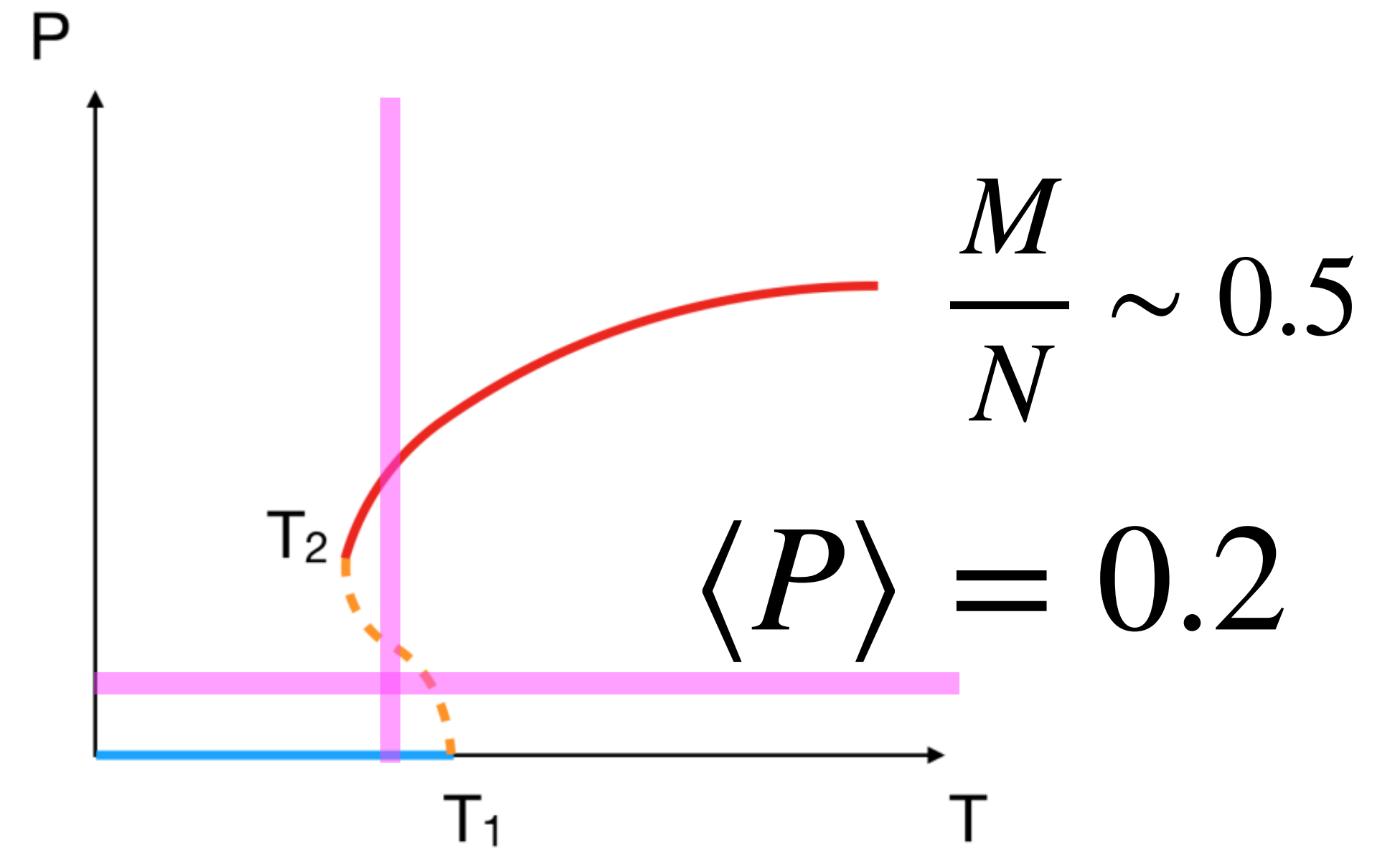
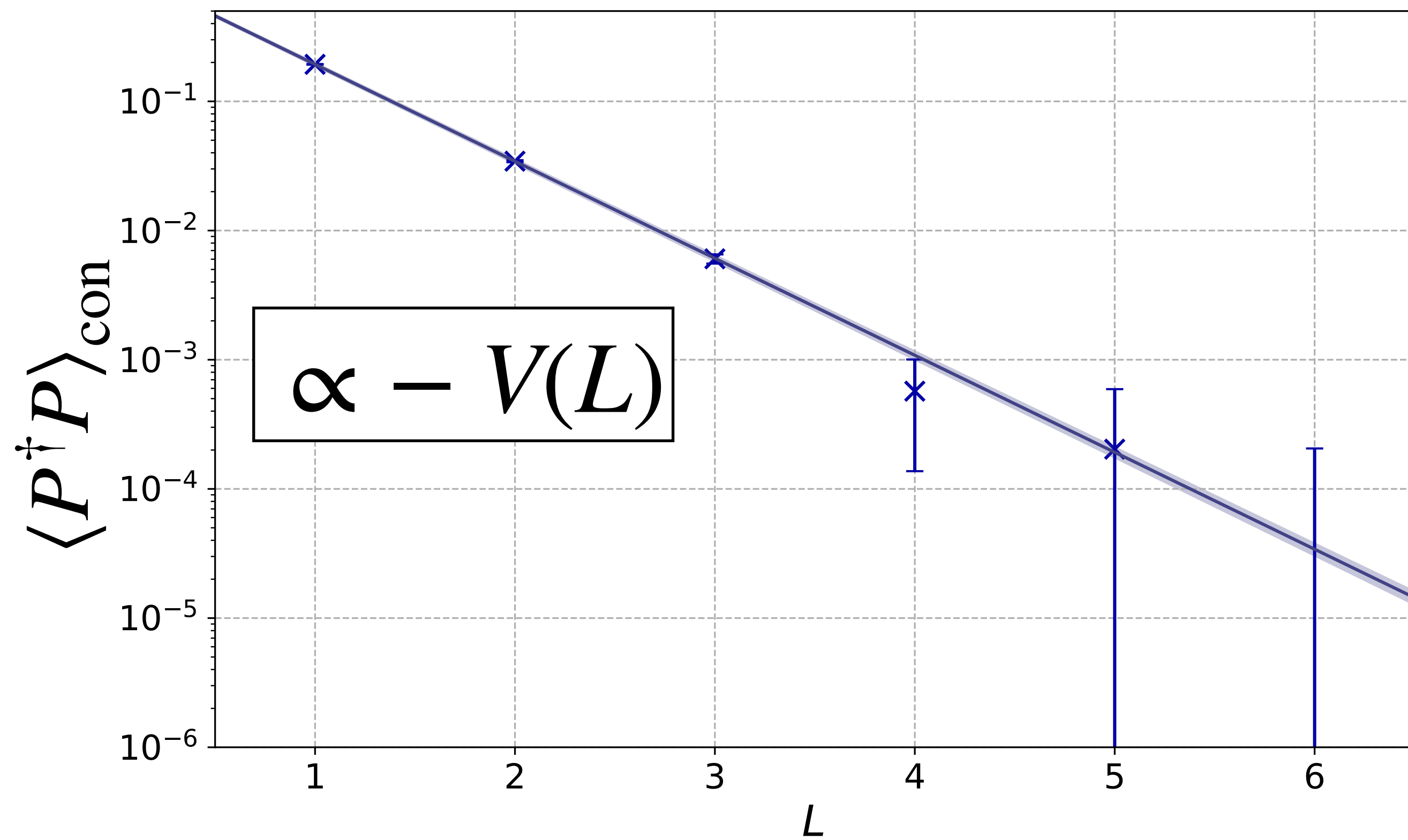
# Partially deconfined

Confined subsector:



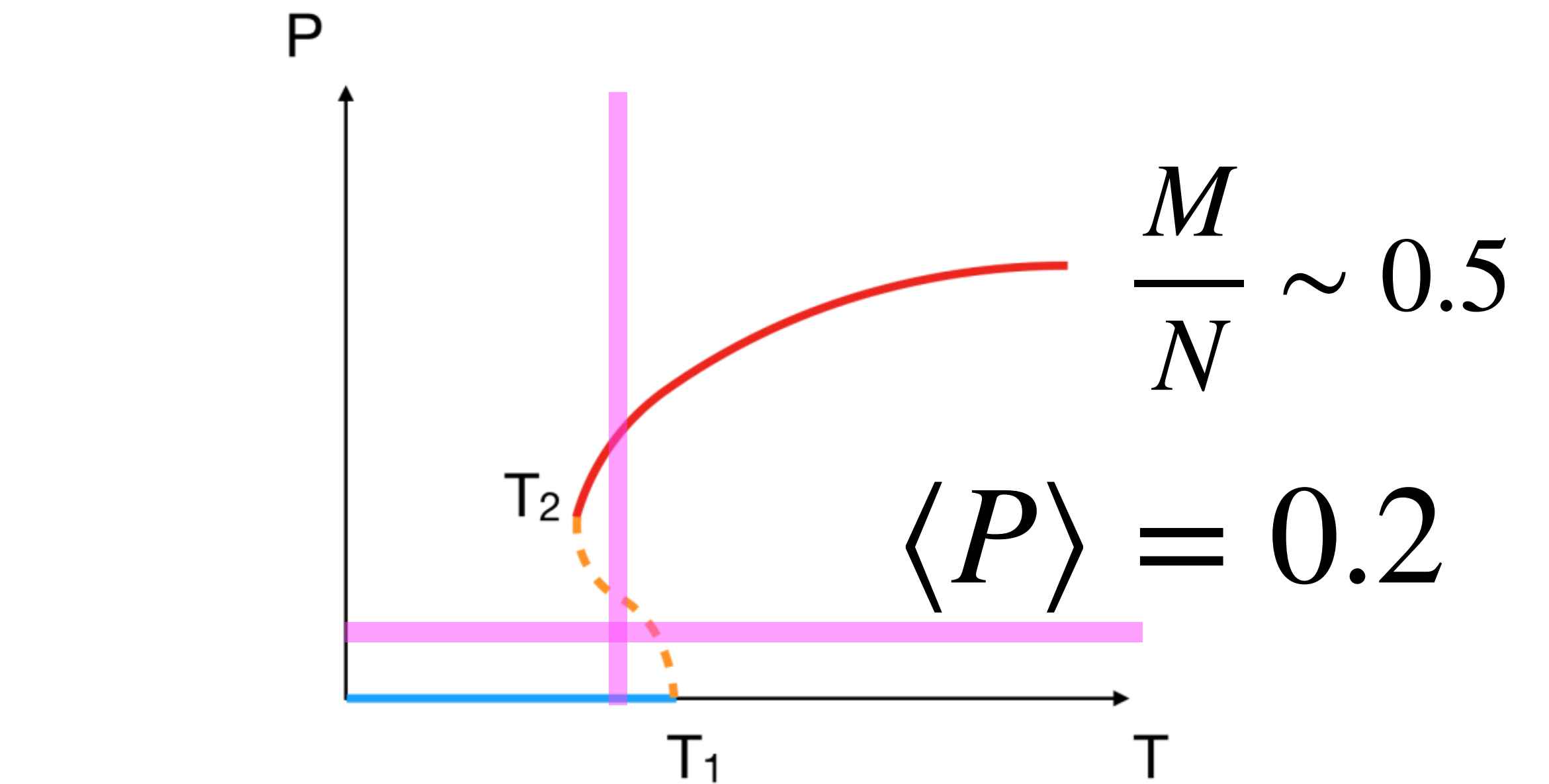
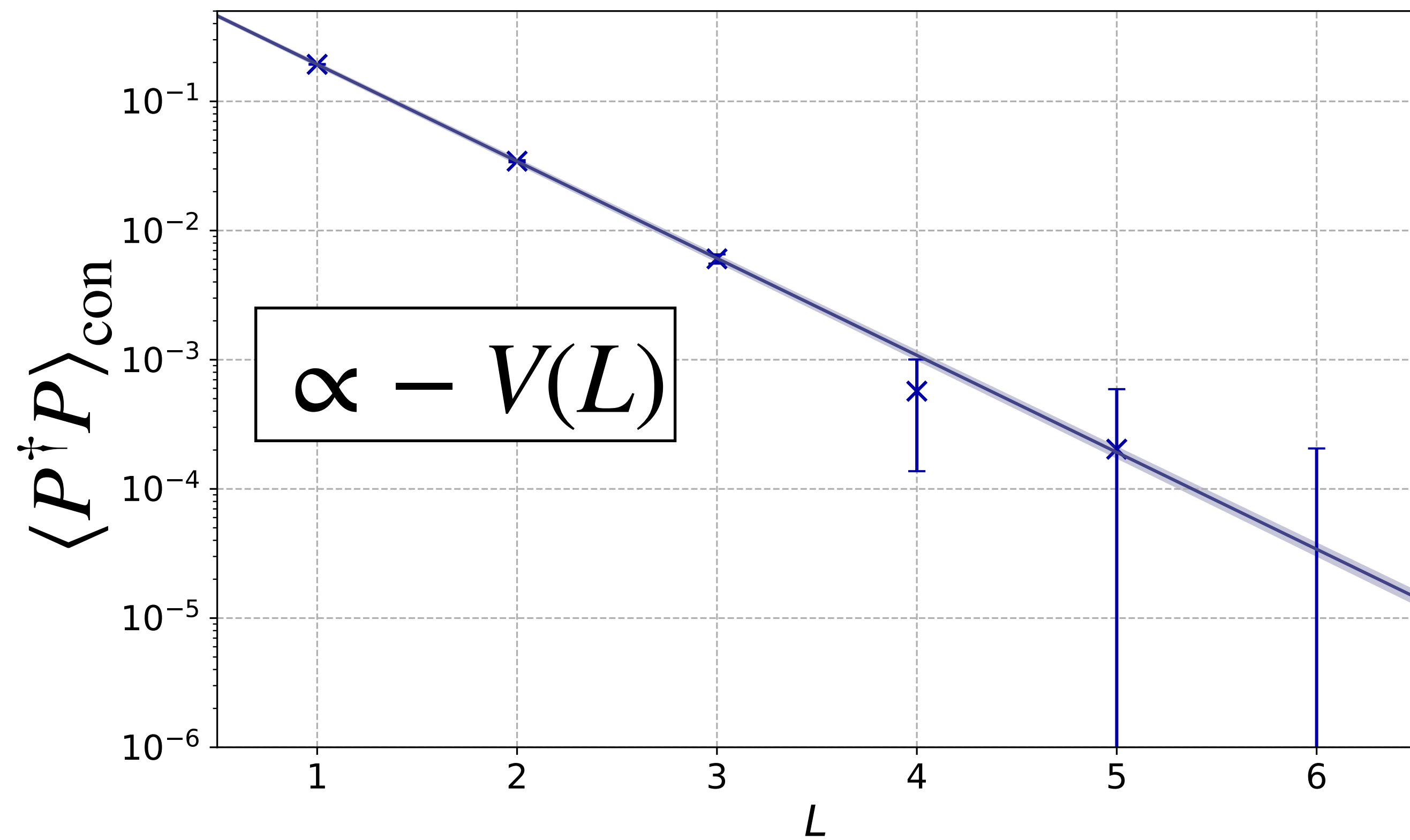
# Partially deconfined

Confined subsector:

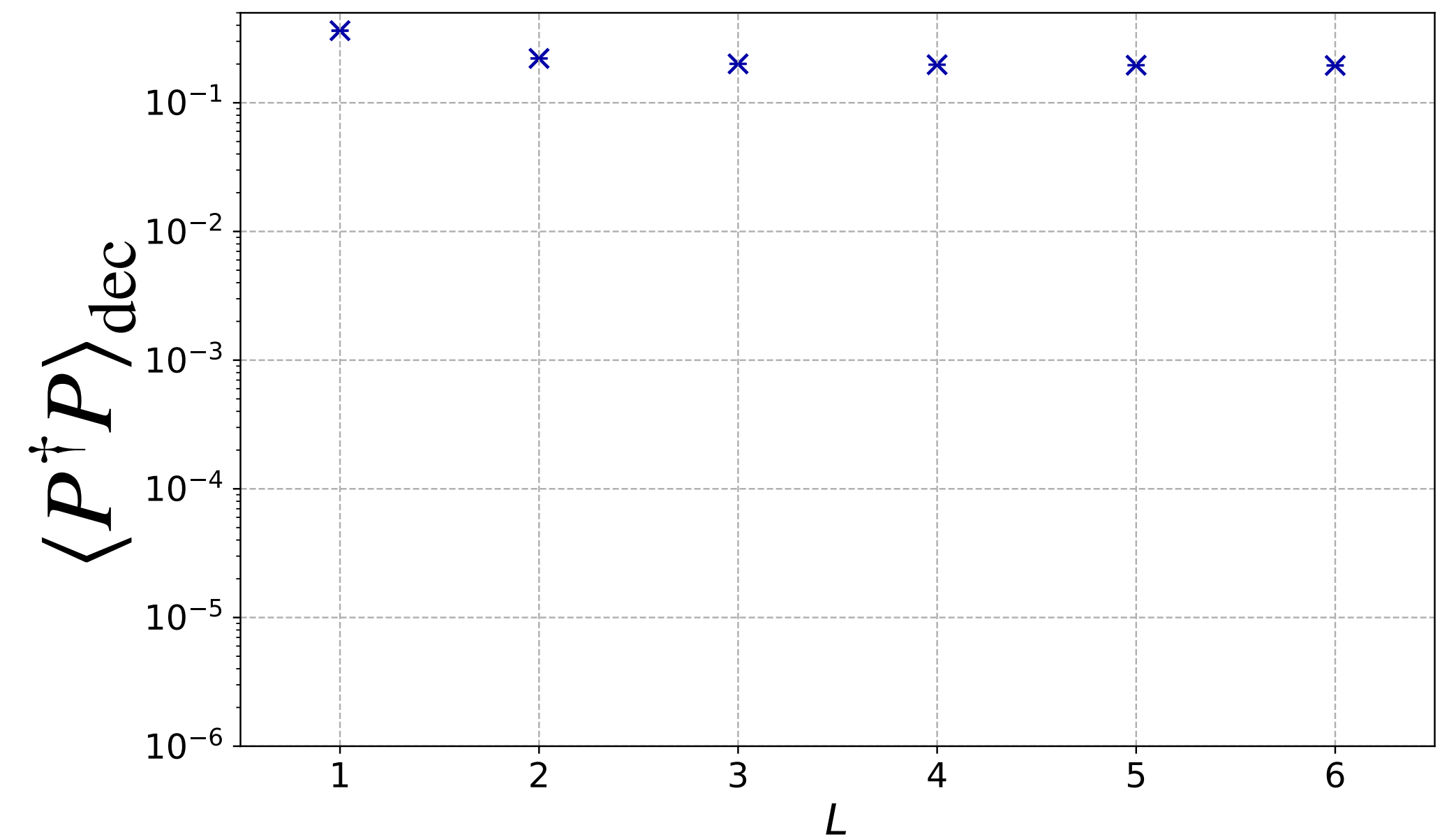


# Partially deconfined

Confined subsector:



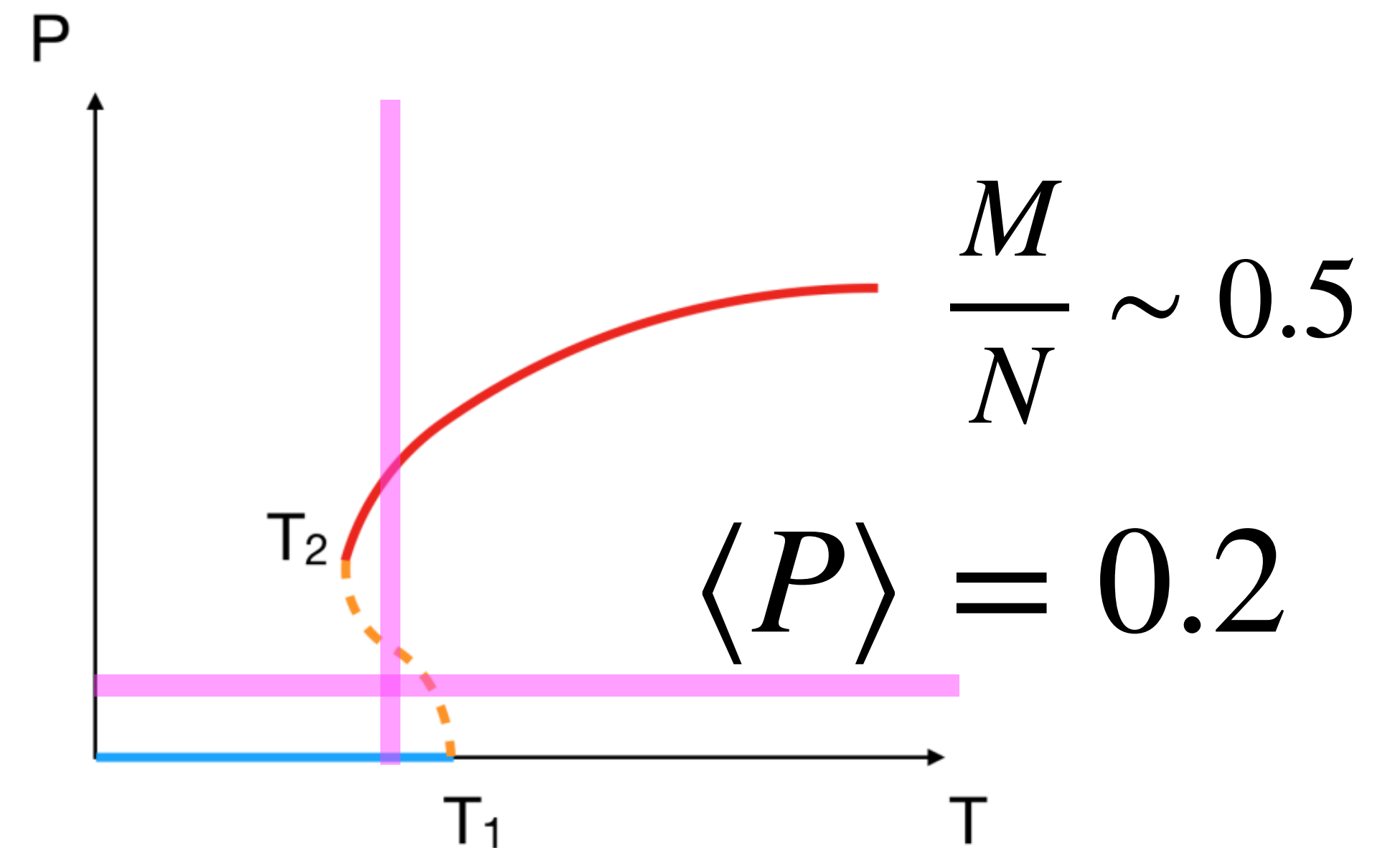
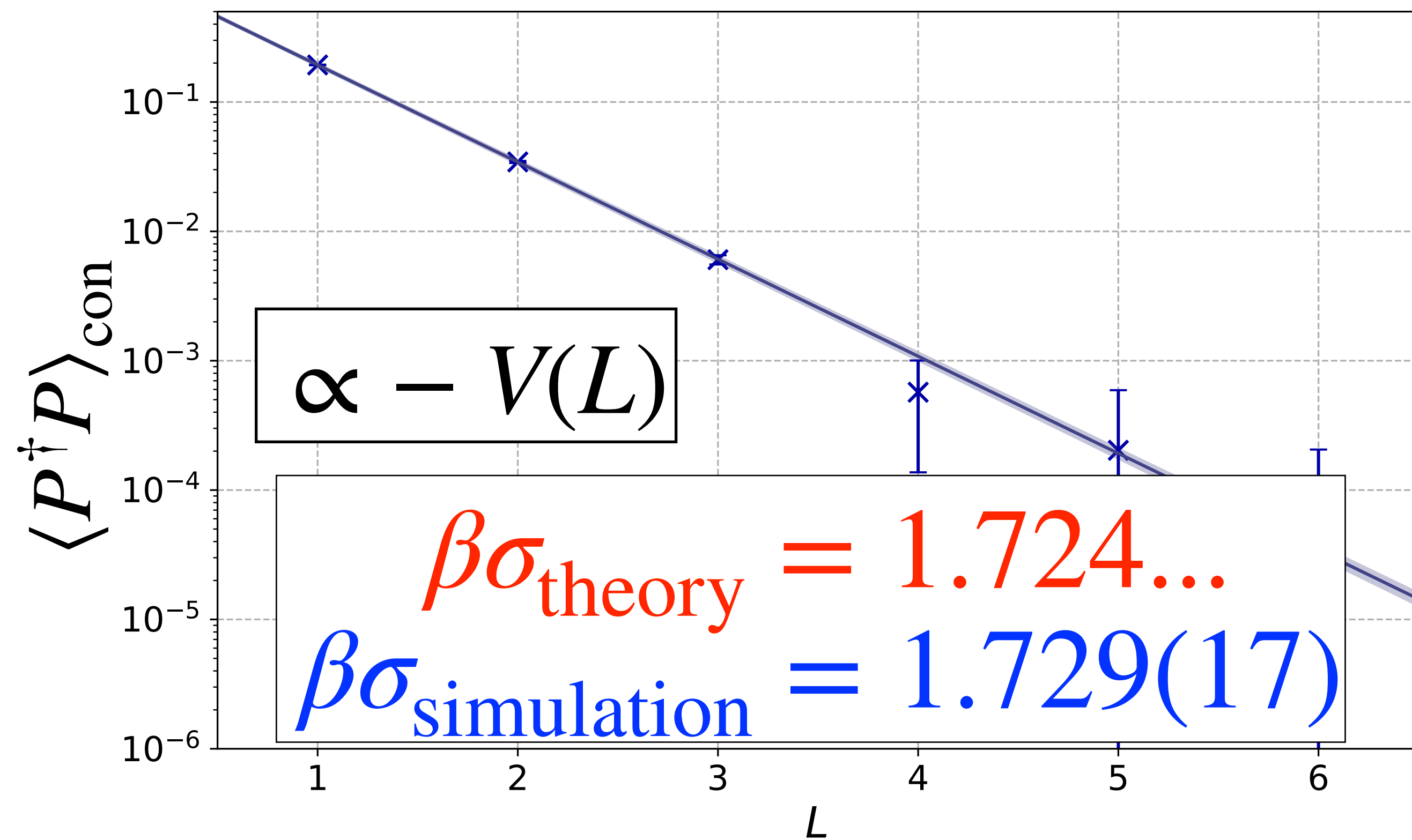
Deconfined subsector:



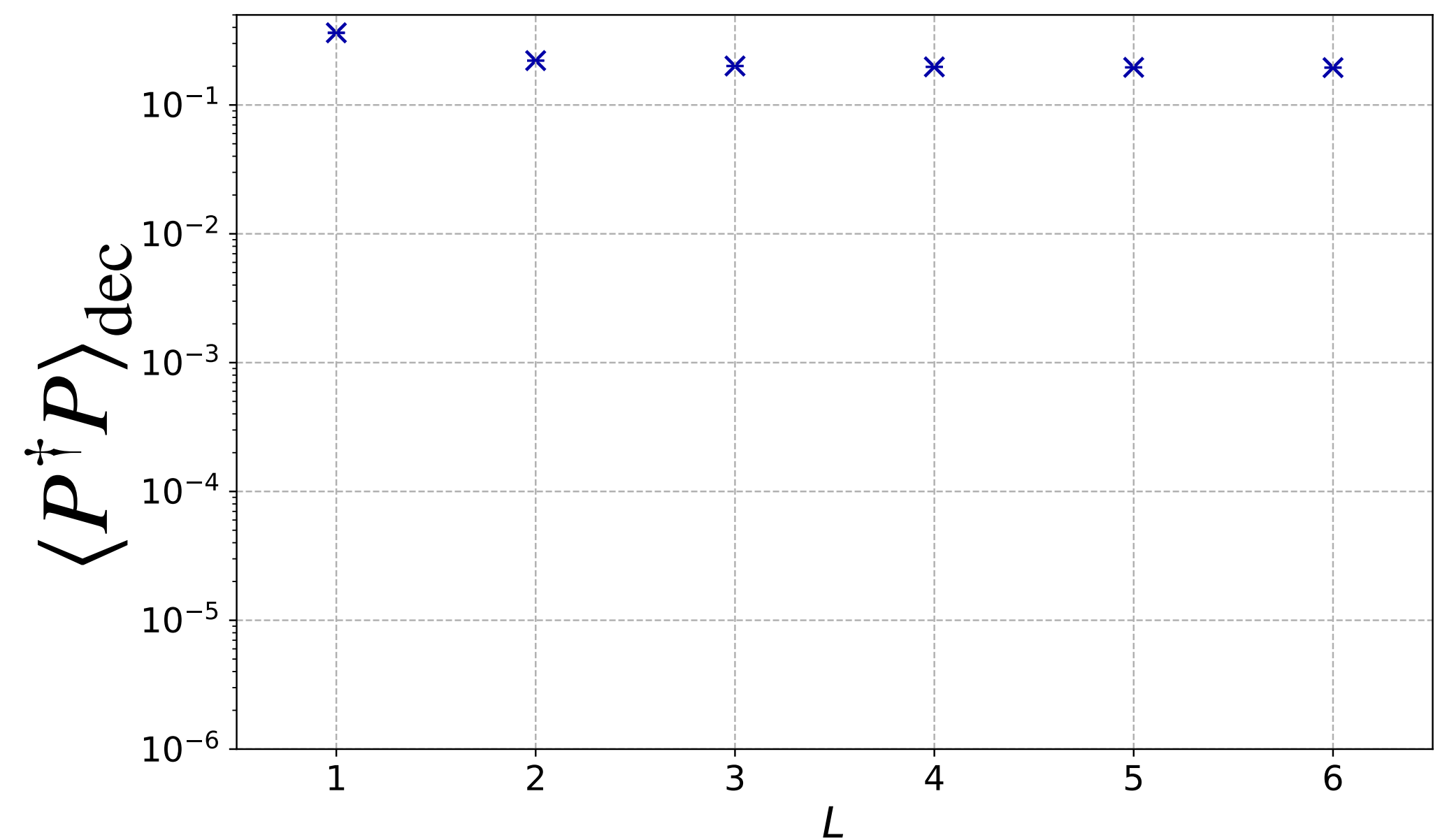


# Partially deconfined

Confined subsector:

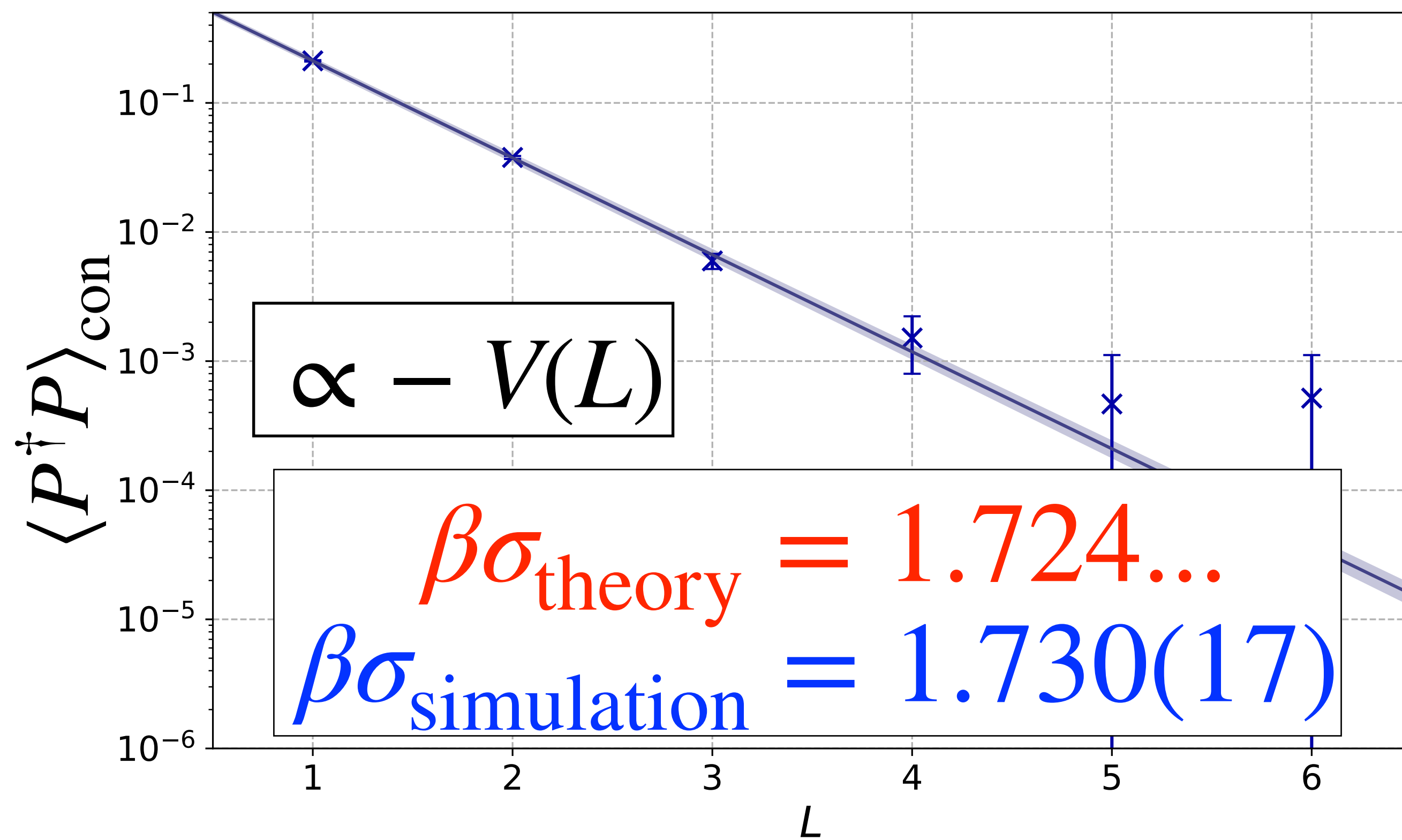


Deconfined subsector:

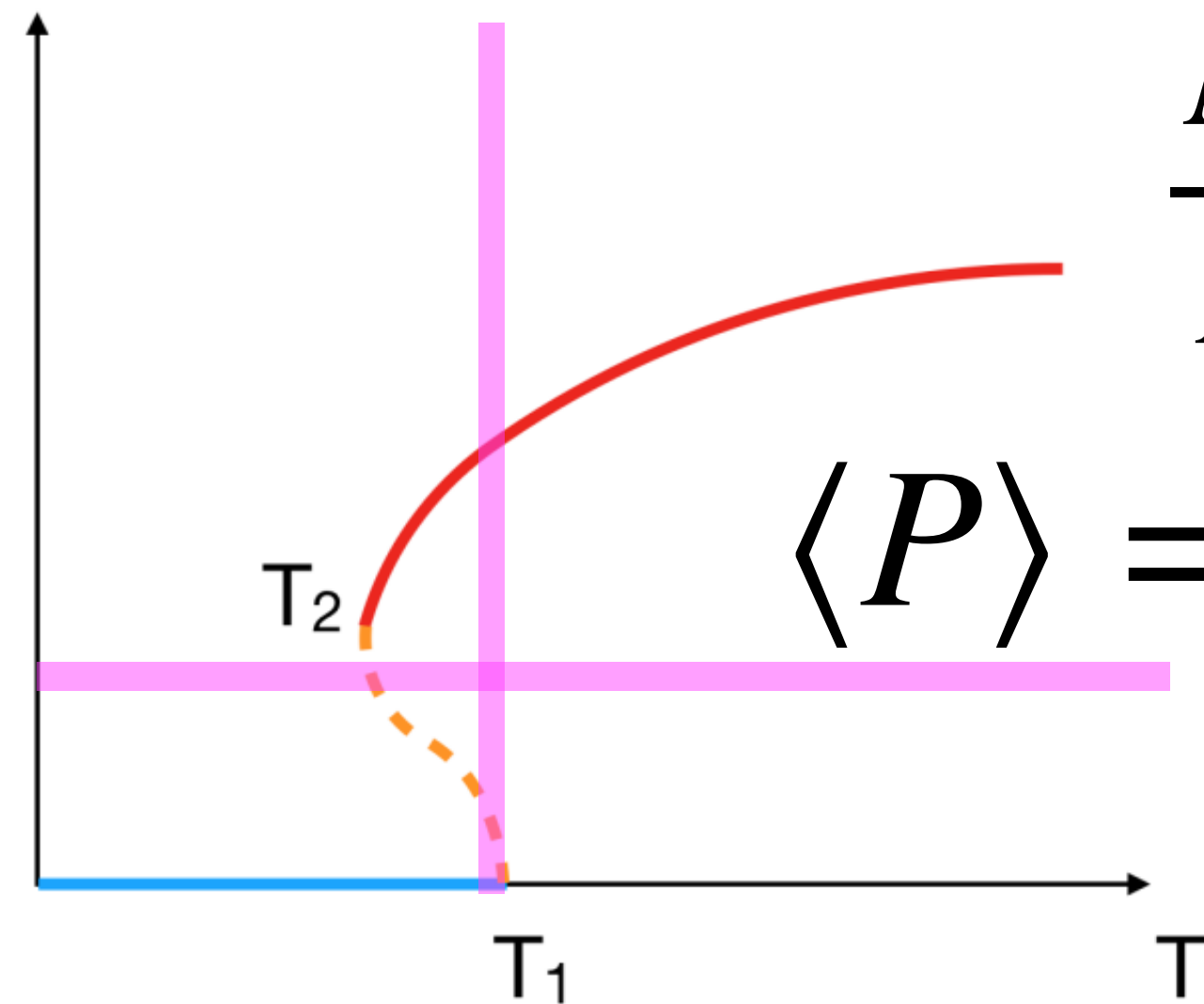


# Partially deconfined

Confined subsector:



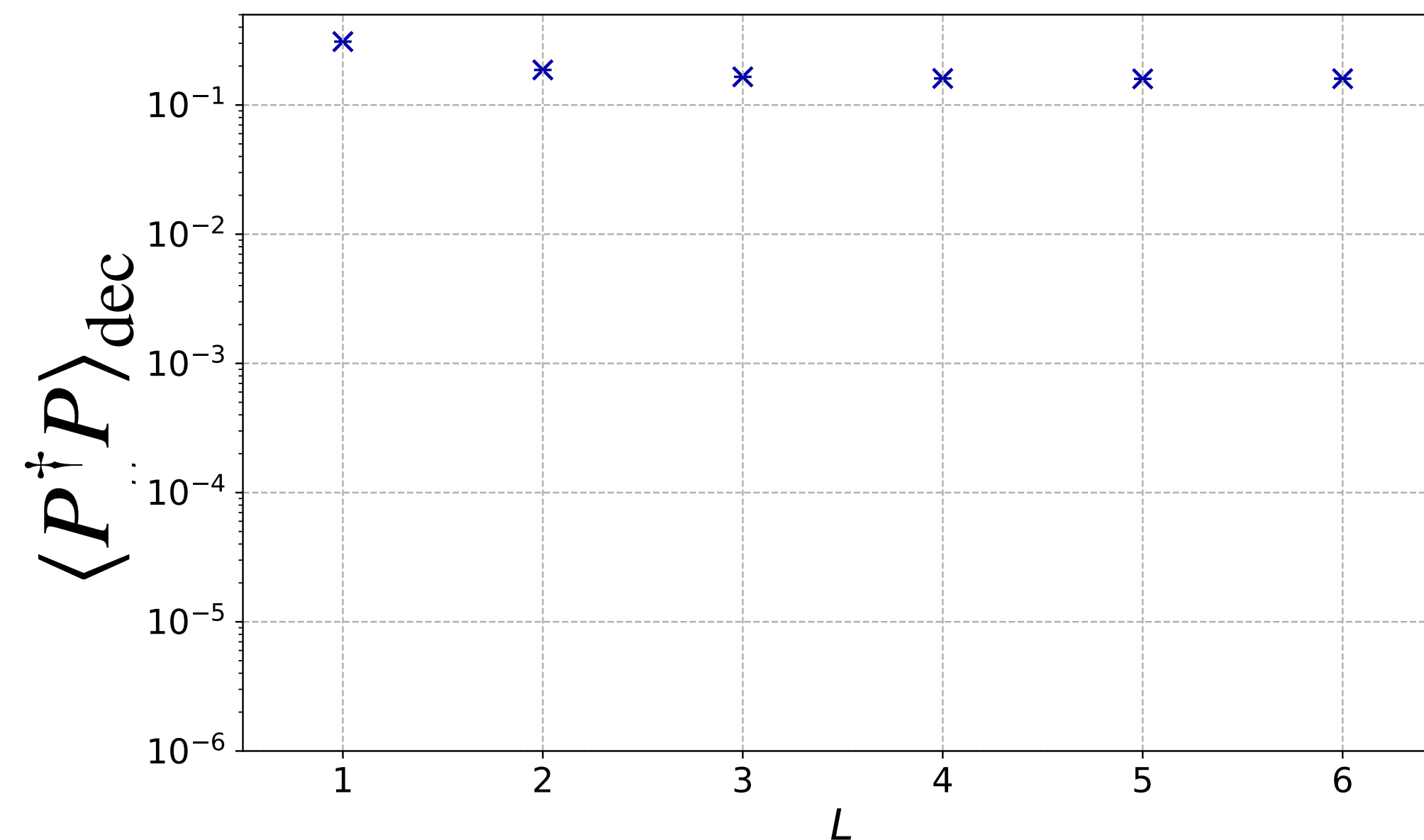
P



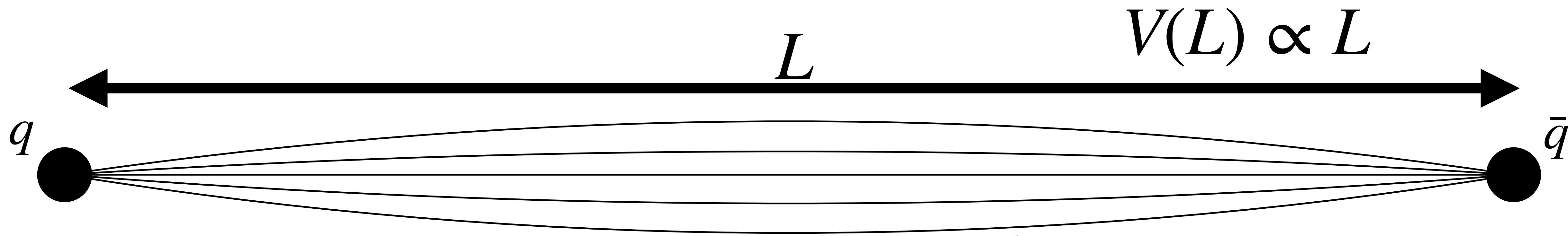
$$\frac{M}{N} \sim 0.62$$

$$\langle P \rangle = 0.25$$

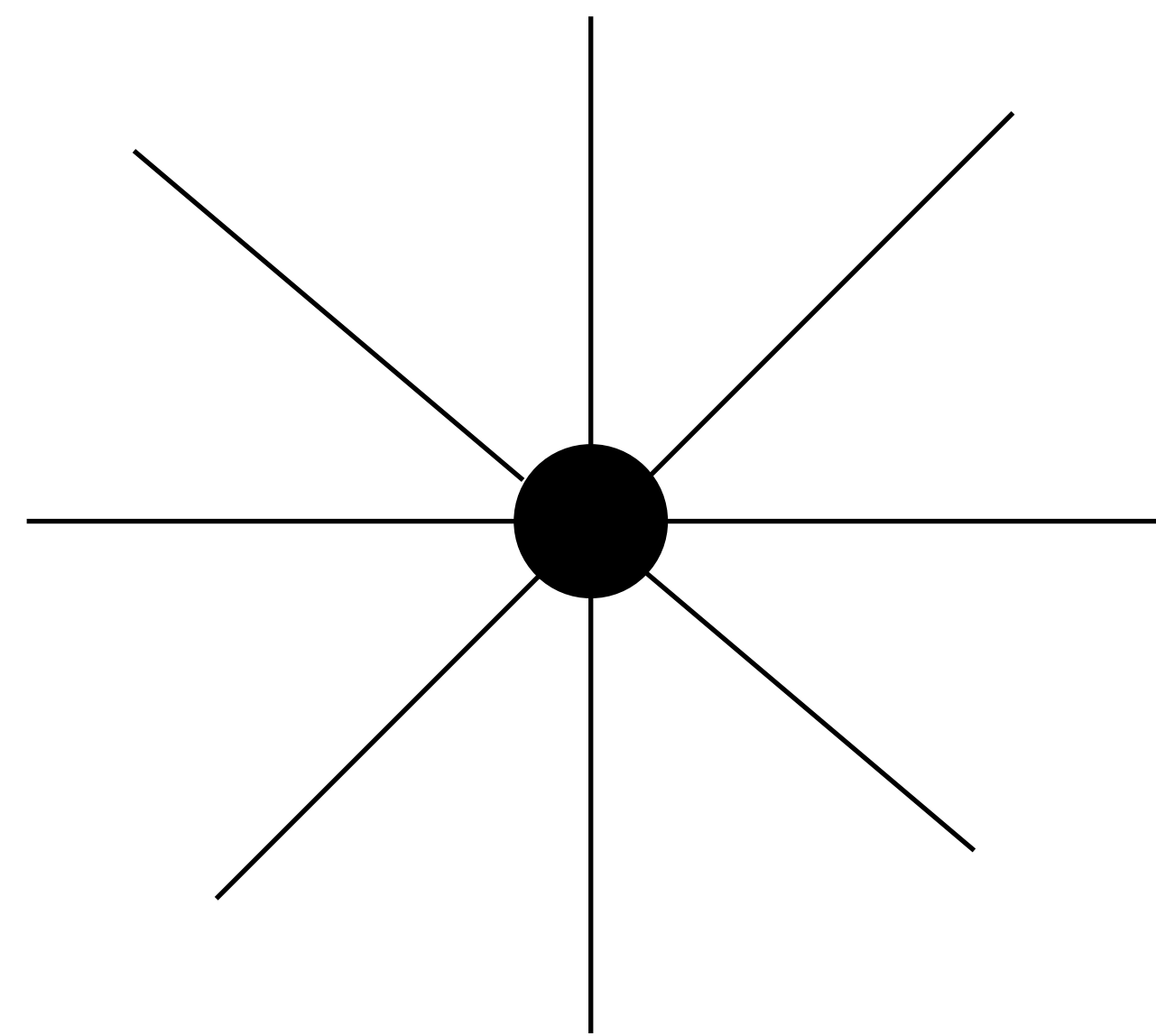
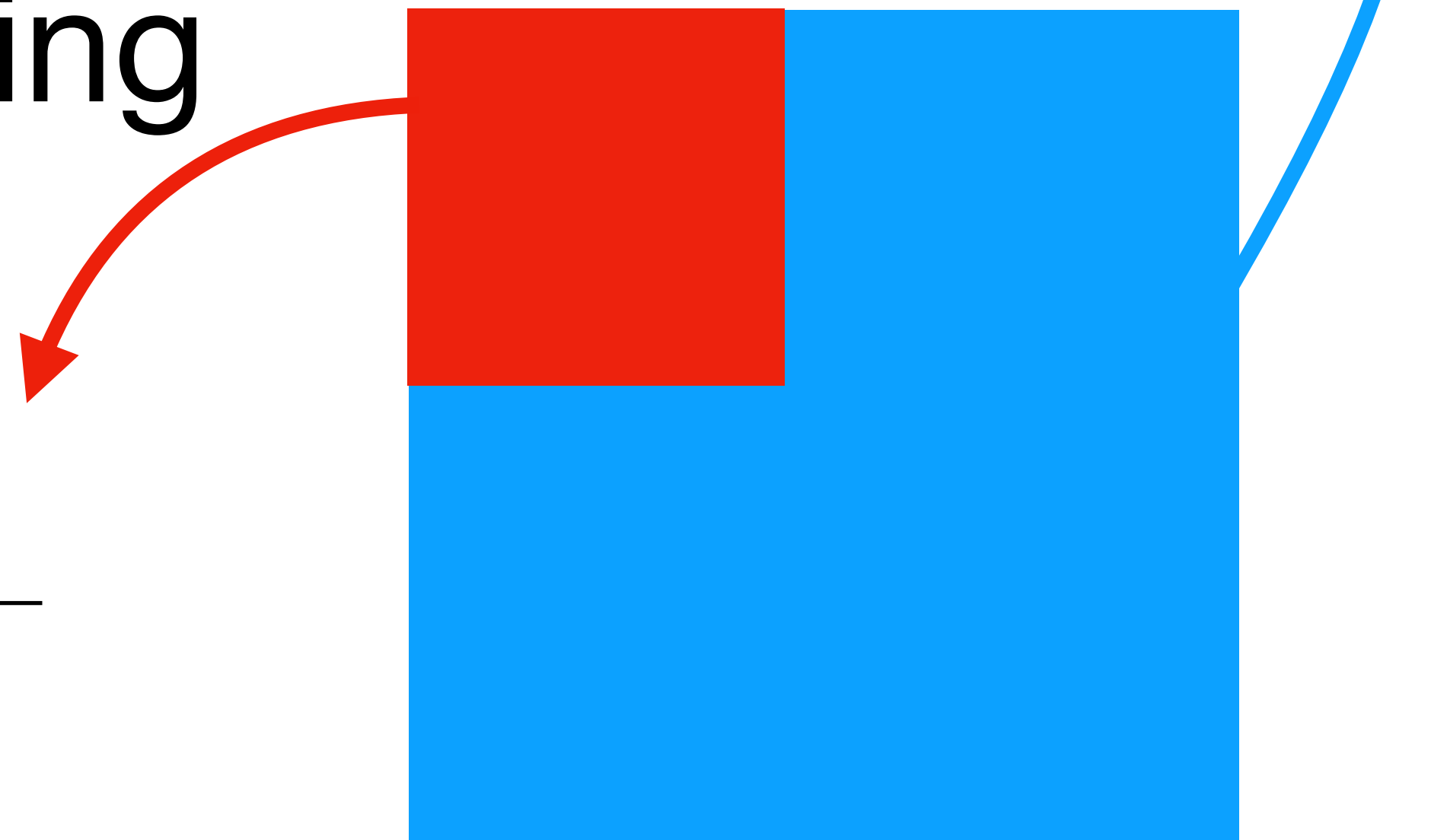
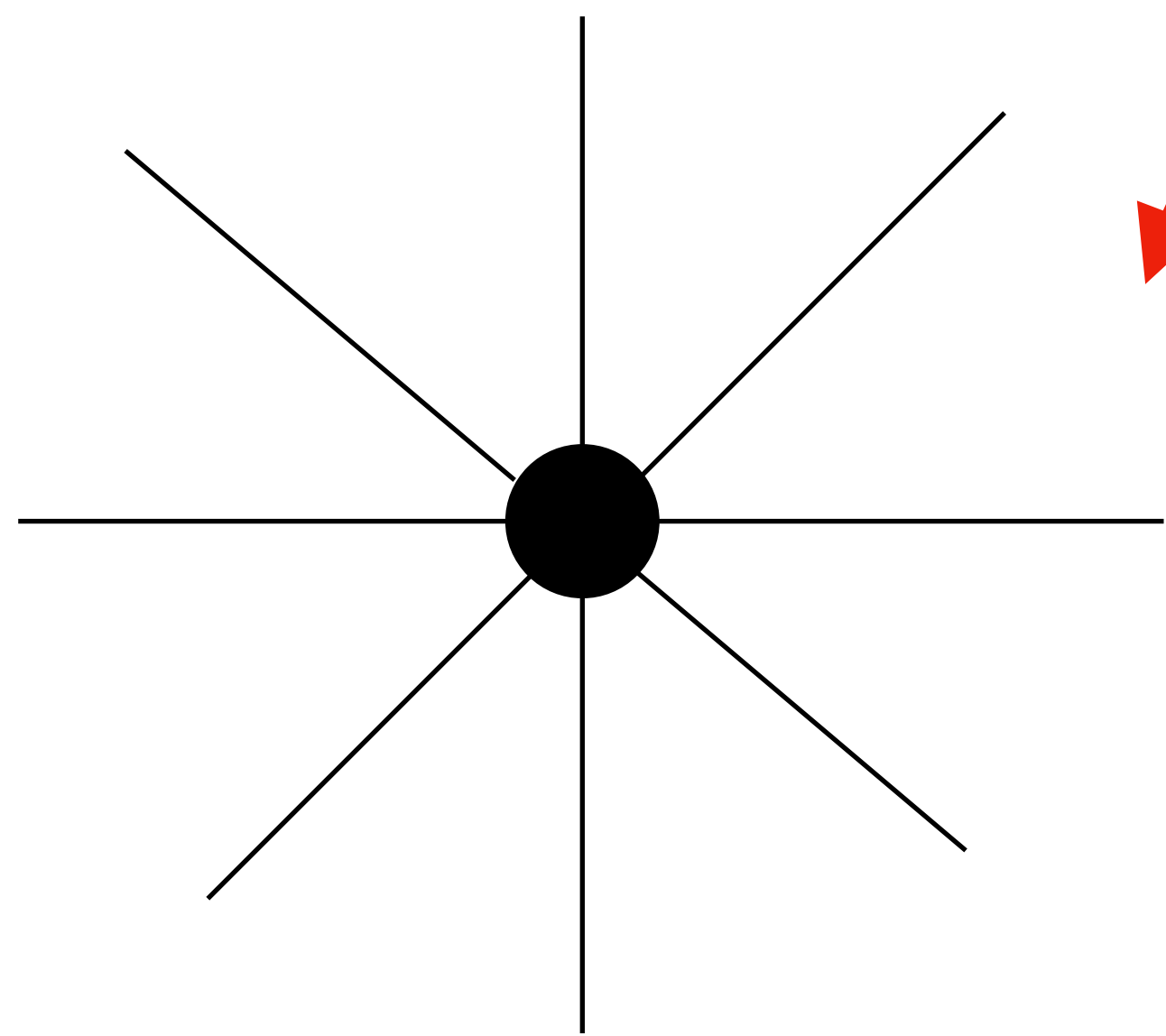
Deconfined subsector:



# Flux tubes: conclusion

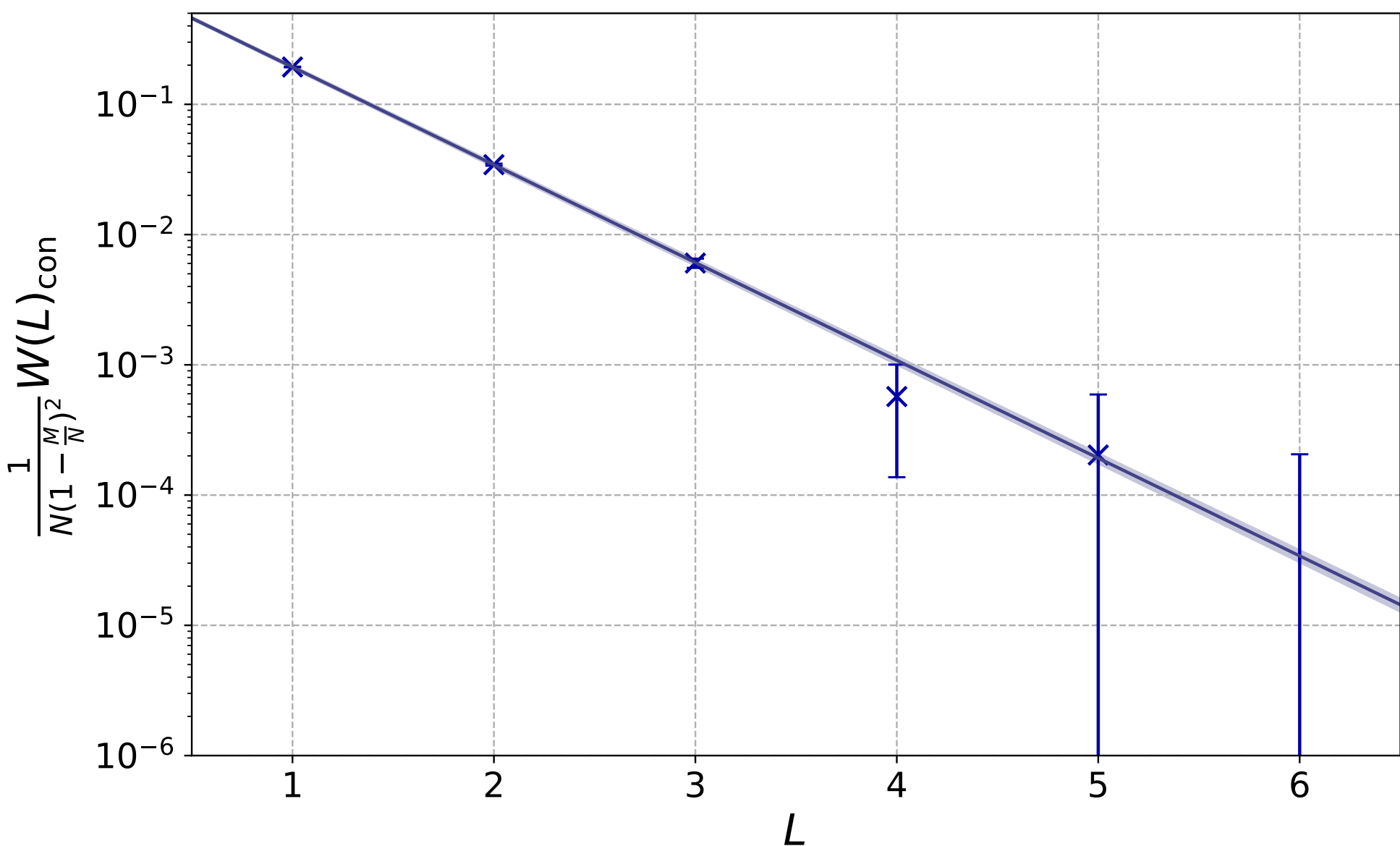


$V(L)$  deconfining



# Summary

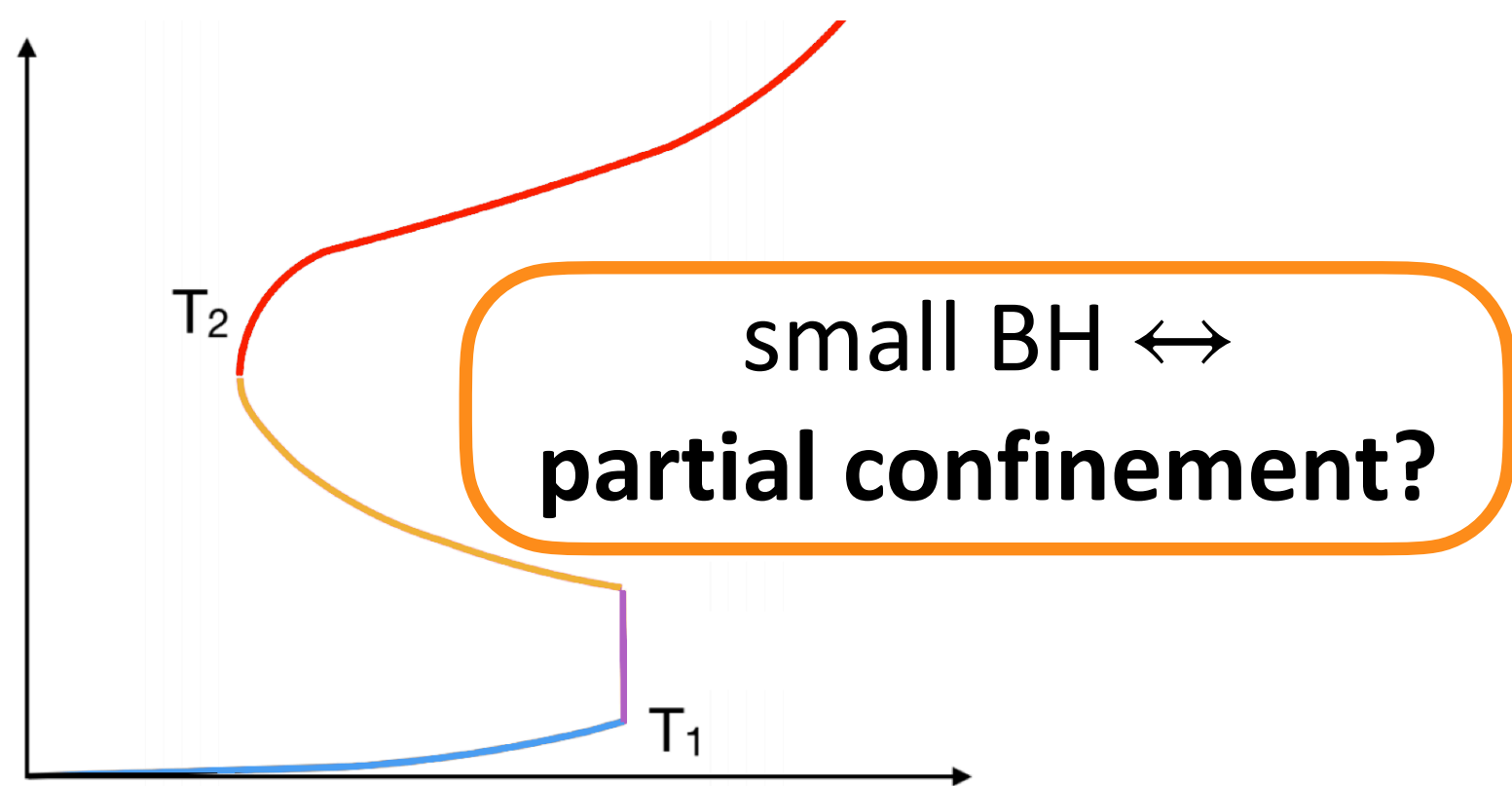
## Linear potential



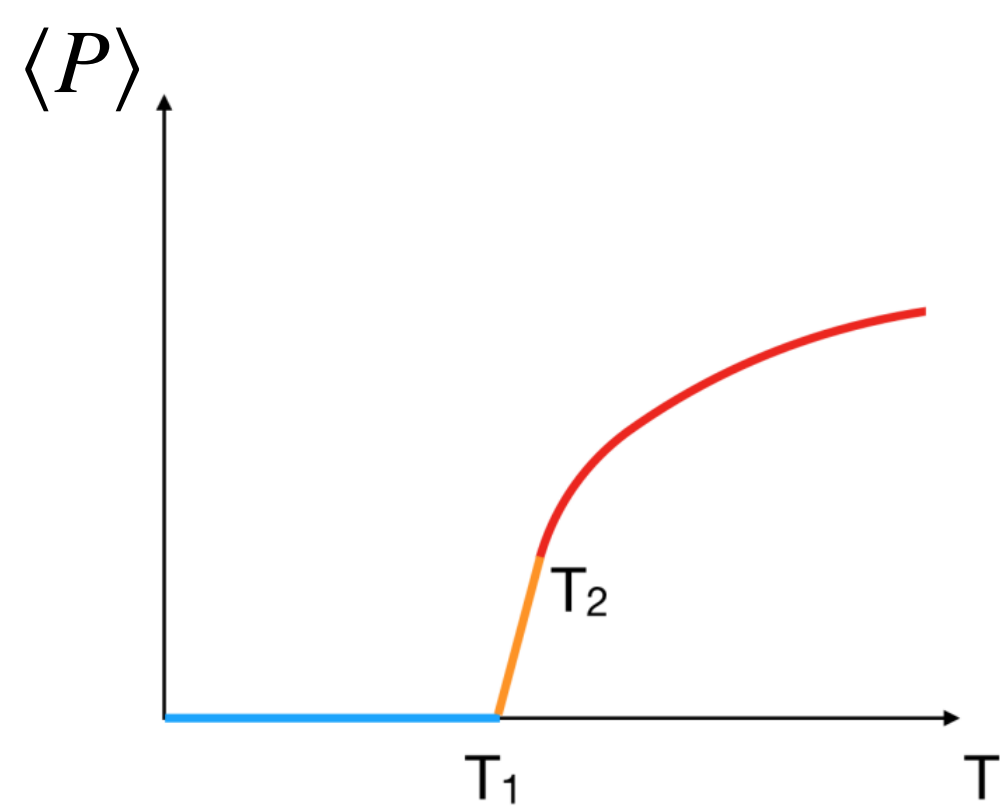
## Global symmetries

Centre	Chiral	
✓	✗	Confined
✗	✓	Deconfined
✗	✗	Partial

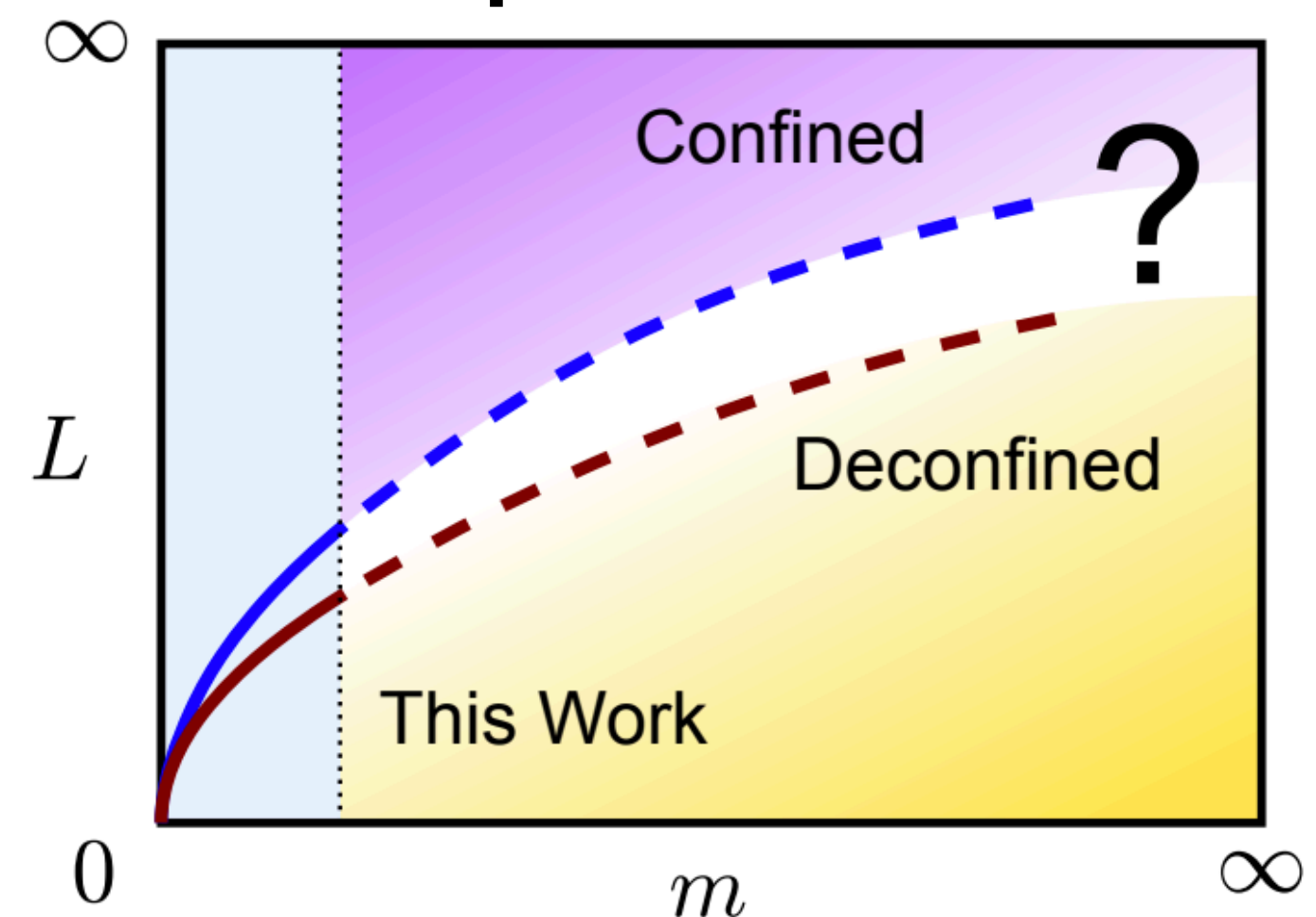
## Holography



## Quark-gluon plasma



## Mysterious phase explanation



# Open questions

1. Stable phase in quark-gluon plasma?
  - a. Is the partial phase stable?
  - b. Is the 'crossover' a true transition?
  - c. Does  $\chi$ SB coincide with GWW?
  - d. Bound states and dynamics?
  - e. Collider signature?
2. Holographic mapping
  - a. Where is GWW point?
  - b. Details of partial confinement dual?
  - c. Coincides with symmetry breaking?

