



*Perturbatively Confined Phase of QCD
under Imaginary Rotation*



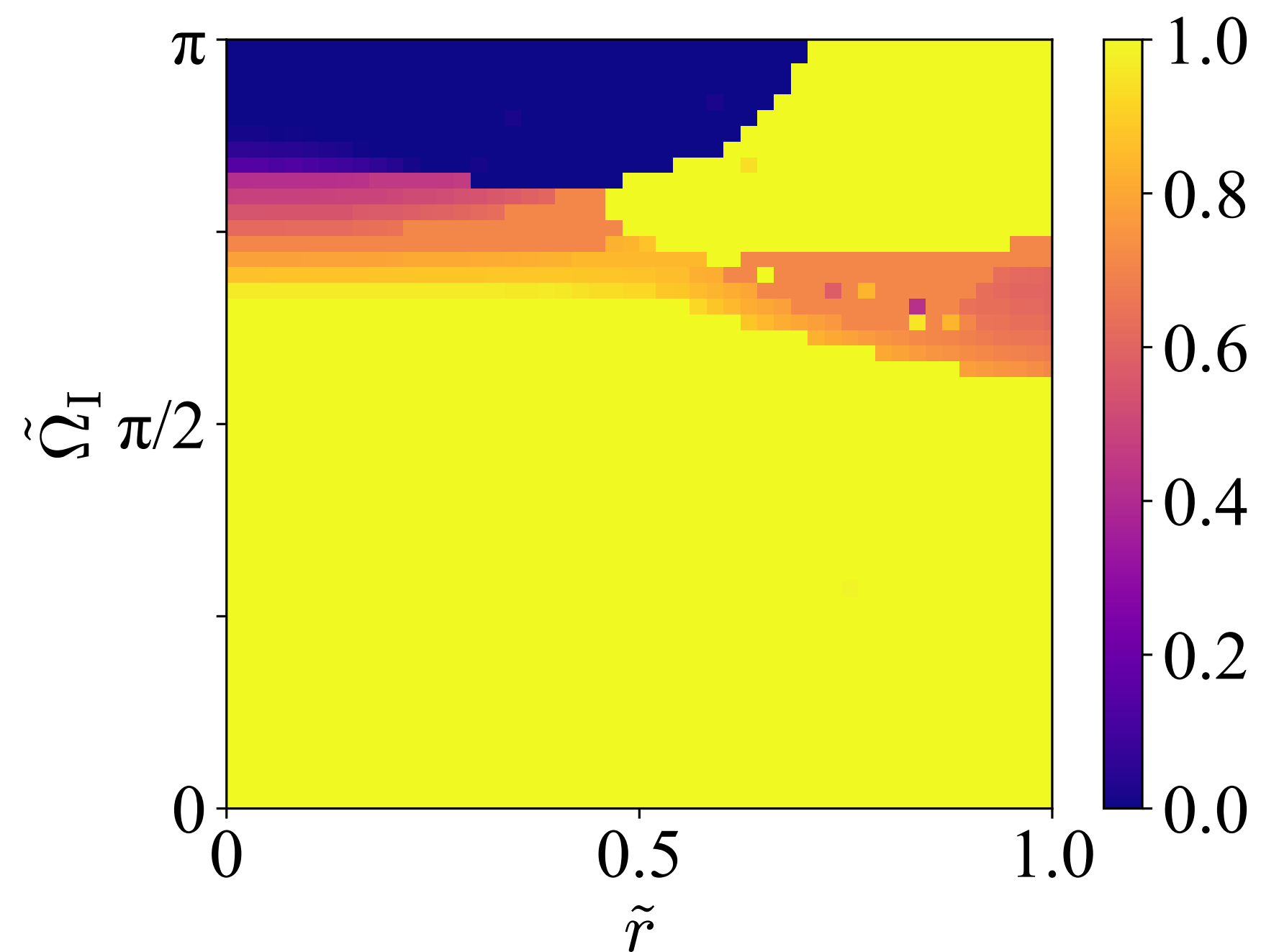
Kenji Fukushima

The University of Tokyo

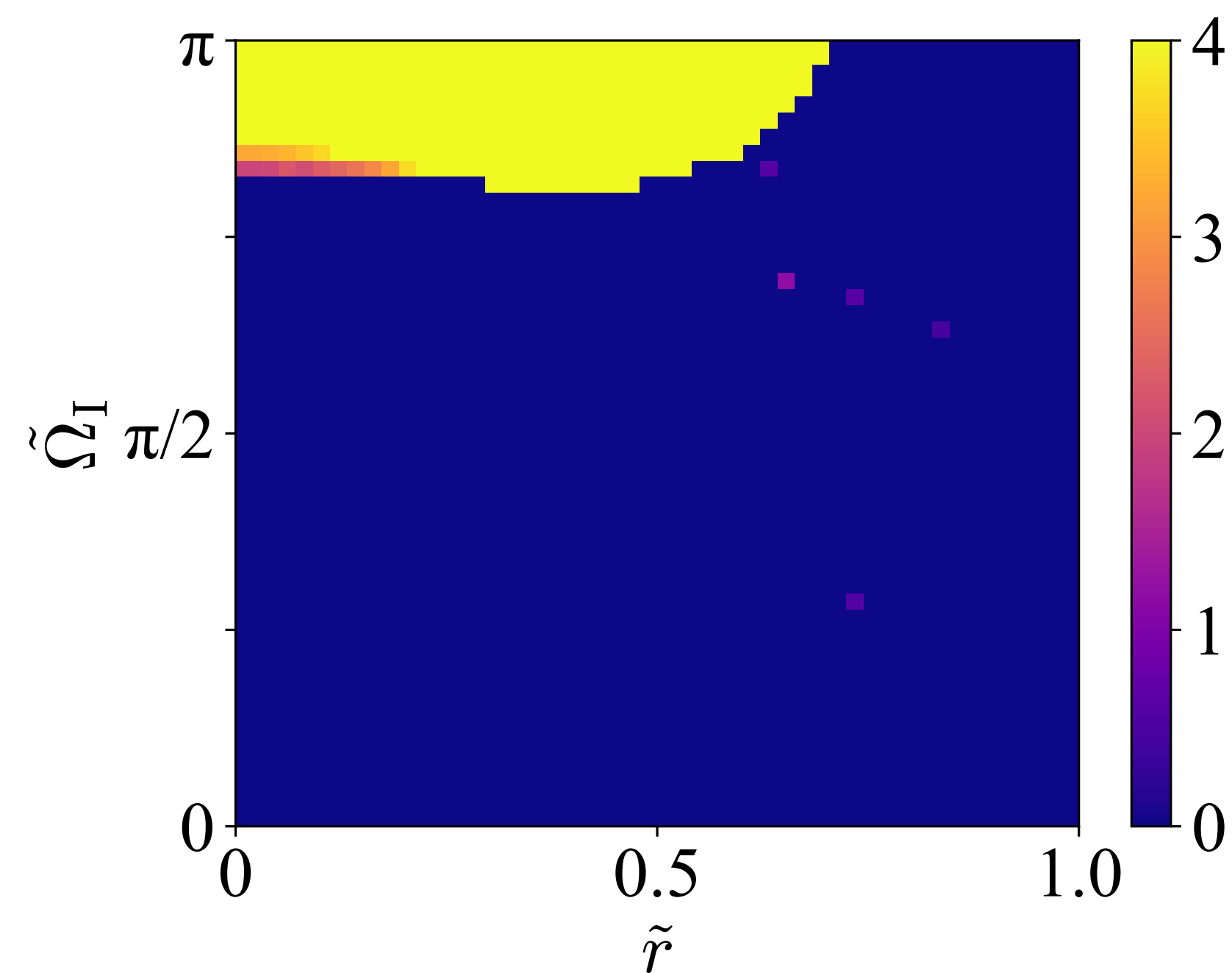
— The 20th International Conference on
QCD in Extreme Conditions (XQCD2024) —

Goals

Polyakov loop



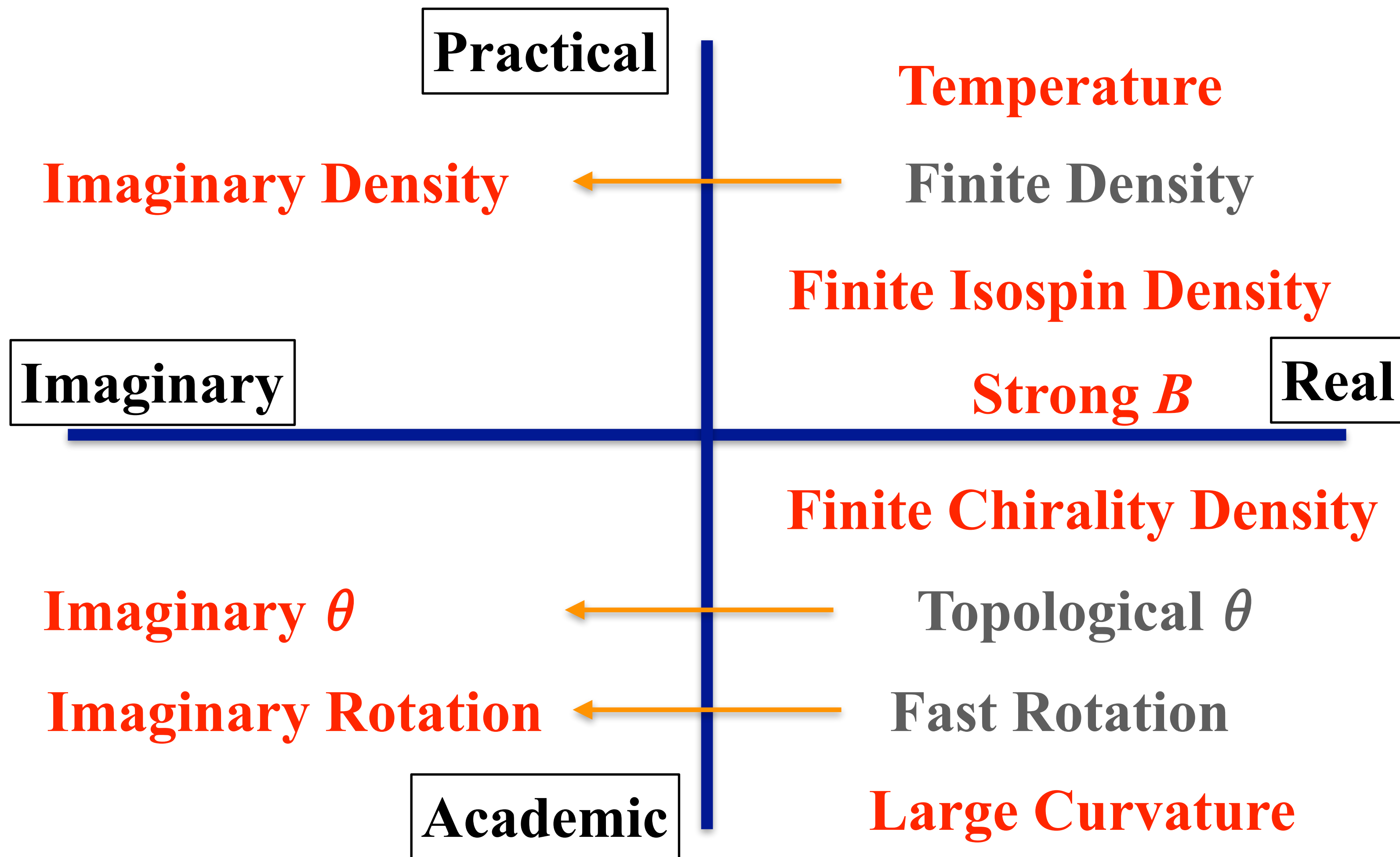
Chiral condensate



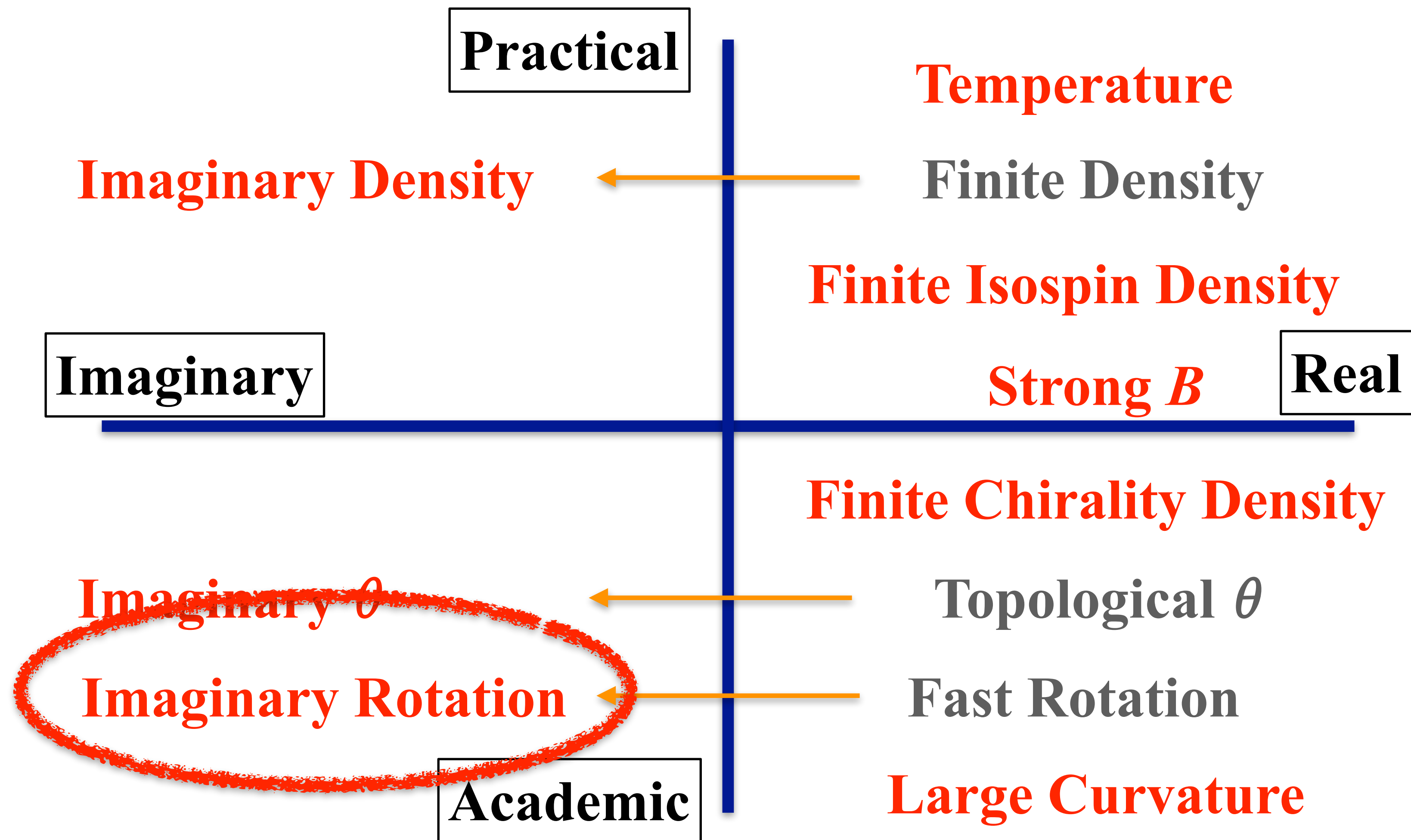
Radial direction from the rotational center \longrightarrow

Chen-Fukushima-Shimada (2024)

Real / Imag. / Academic / Practical



Real / Imag. / Academic / Practical



Motivation (excuse)

What if rotation is as fast as the QCD scale?



Newsroom Media & Communications Office

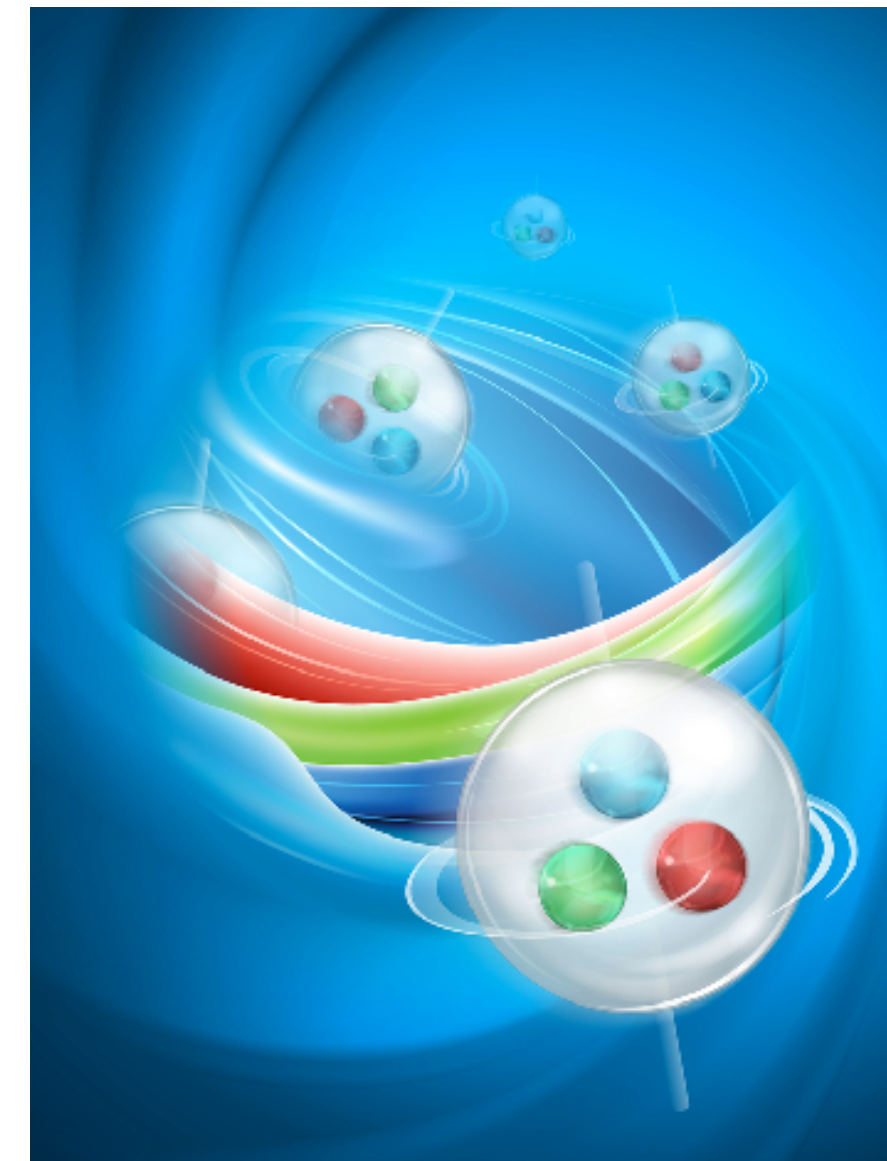
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'Perfect Liquid' Quark-Gluon Plasma is the Most Vortical Fluid

Swirling soup of matter's fundamental building blocks spins ten billion trillion times faster than the most powerful tornado, setting new record for "vorticity"



Can rotation affects confinement?

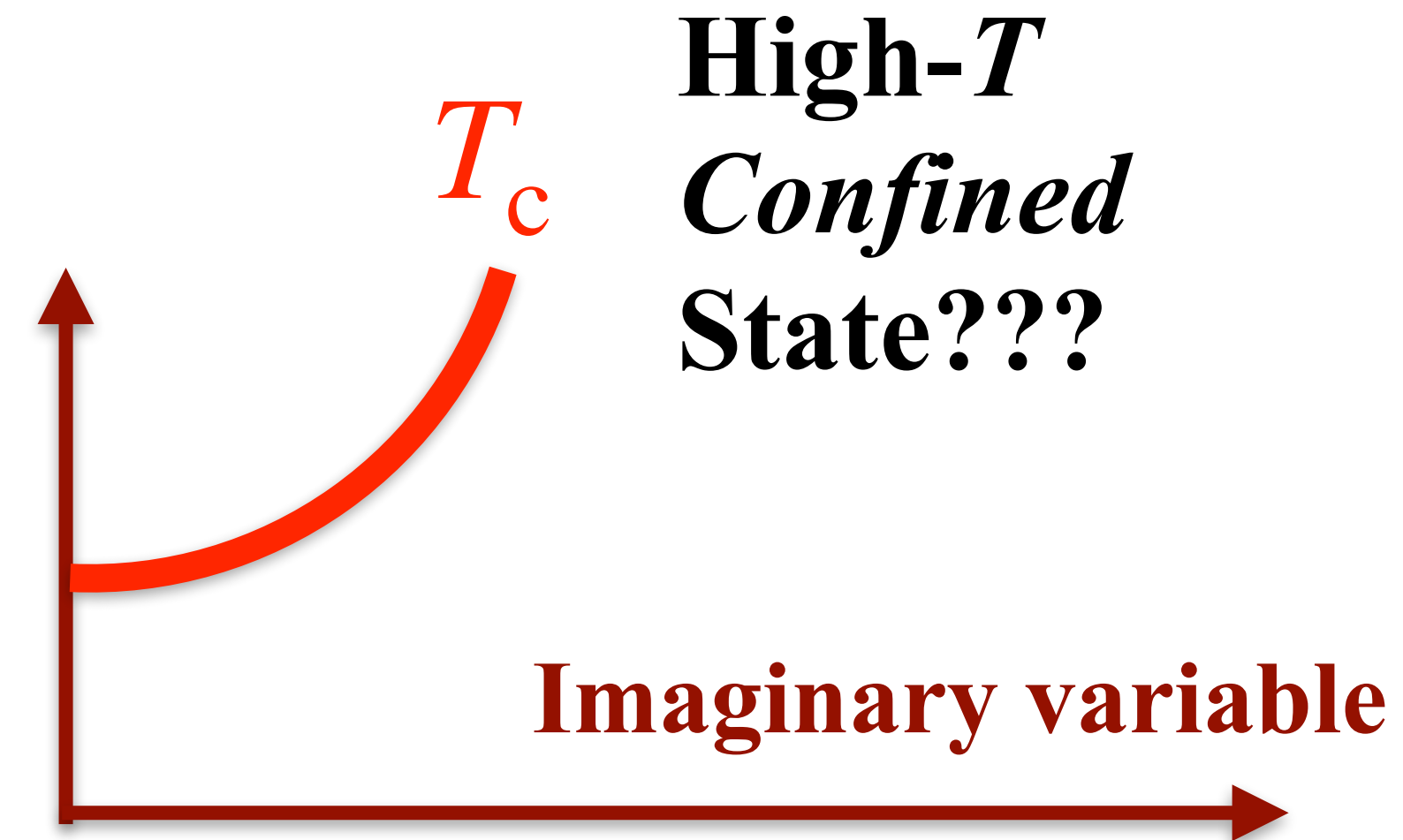
Imaginary Chemical Potential

Finite Imaginary Density

$$T(\mu_I^2) \rightarrow T(-\mu^2)$$

Increasing
Function

Decreasing
Function



This is a common technique to evade the sign problem.

Is it possible to realize “perturbative confinement”?

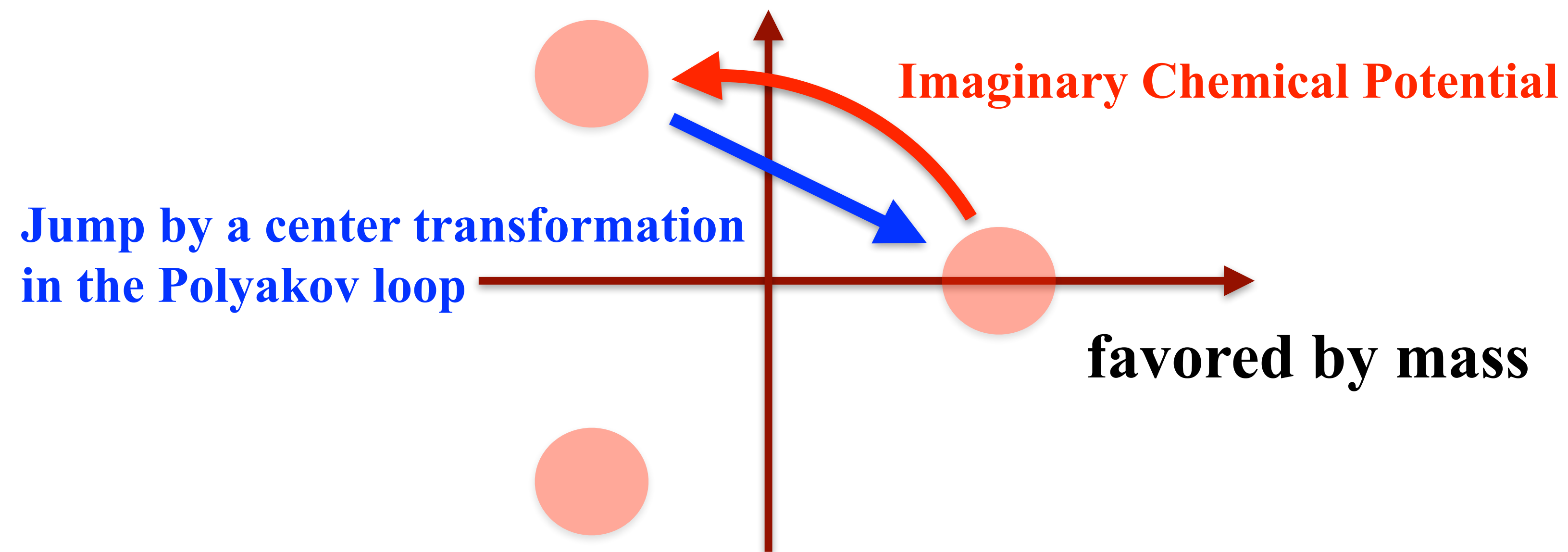
The answer is... no...

Imaginary Chemical Potential

Finite Imaginary Density

Chemical potential dependence in fermions through

$$L e^{i\beta\mu_I} \quad L = \mathcal{P} e^{ig \int^\beta dx_4 A_4}$$



Imaginary Rotation

Angular Velocity ~ Finite Density

Chen-Fukushima-Huang-Mameda (2015)

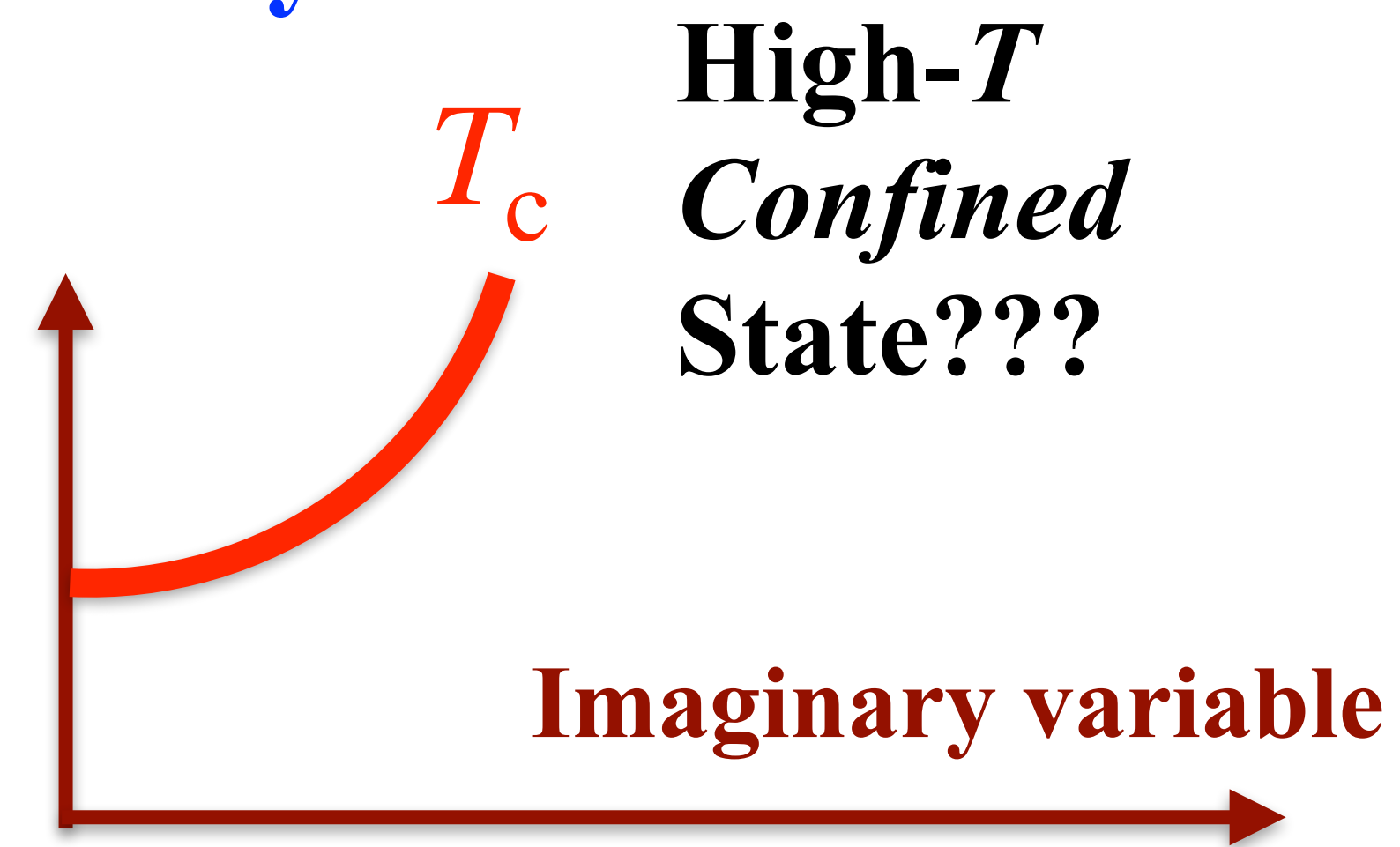
$$H \rightarrow H - \mathbf{J} \cdot \boldsymbol{\Omega} \Leftrightarrow H - N\mu$$

Finite Imaginary Angular Velocity

$$T(\Omega_I^2) \rightarrow T(-\Omega^2)$$

Increasing
Function

Decreasing
Function



Imaginary Rotation

Rotating matter of gluons/quarks

Pure rotation does not change the vacuum.

e.g., $\Omega + T$, $\Omega + \mu$, $\Omega + B$, etc.

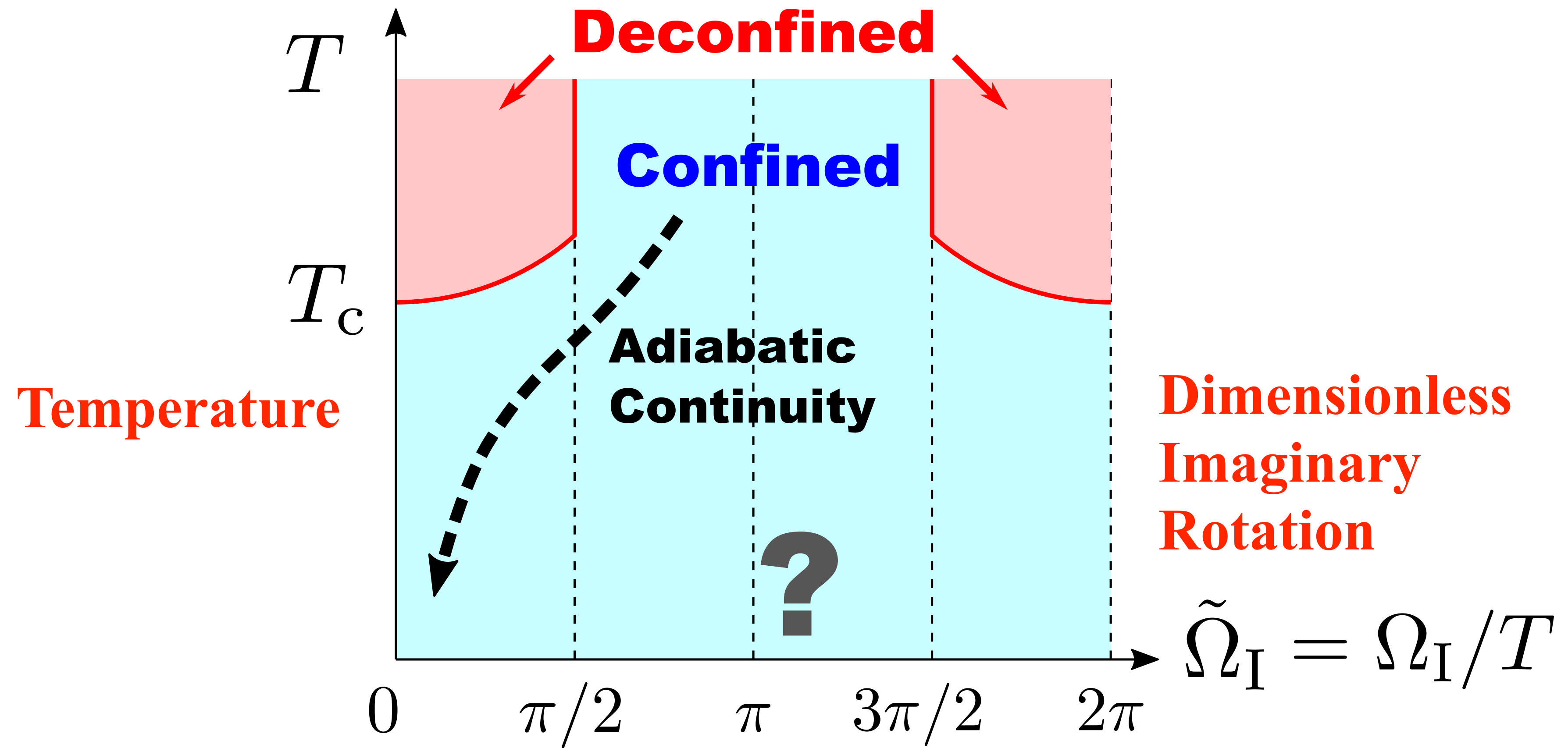
Unlike finite density, pure Yang-Mills theory can be rotated.

Period is not given by $2\pi/N_c$ but 2π .

New probe to investigate confinement physics.

Confinement \sim chiral symmetry ?

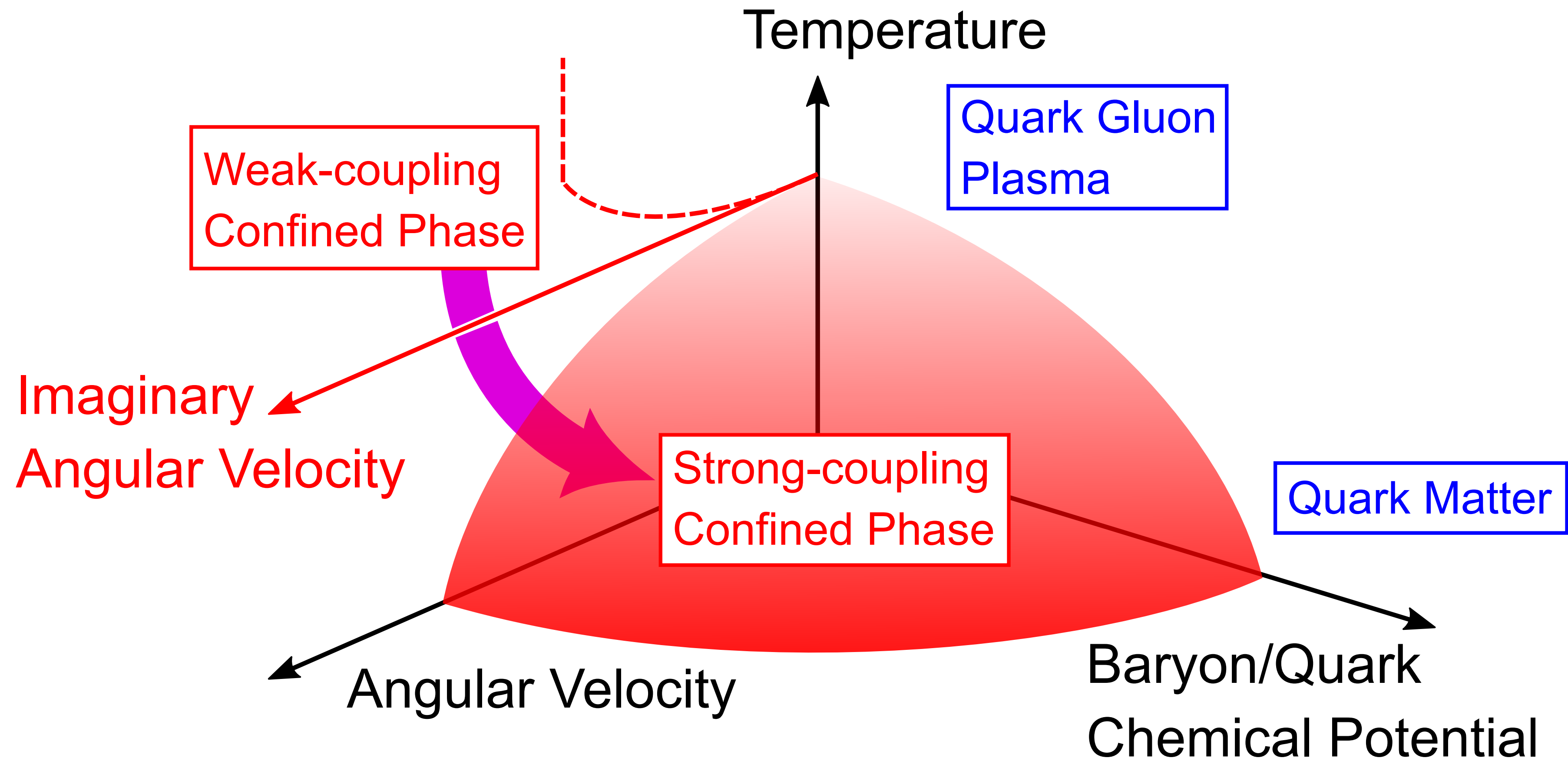
Imaginary Rotation



Chen-Fukushima-Shimada (2022)

Imaginary Rotation

New approach to confinement physics



Polyakov Loop Potential

Rotating GPY-Weiss potential

Chen-Fukushima-Shimada (2022)

$$V_g(\boldsymbol{\phi}; \tilde{\Omega}_I) = -\frac{2T^4}{\pi^2} \sum_{\alpha \in \Phi} \sum_{n=1}^{\infty} \frac{\cos(n\boldsymbol{\phi} \cdot \alpha) \cos(n\tilde{\Omega}_I)}{\left\{n^2 + 2\tilde{r}^2[1 - \cos(n\tilde{\Omega}_I)]\right\}^2}$$

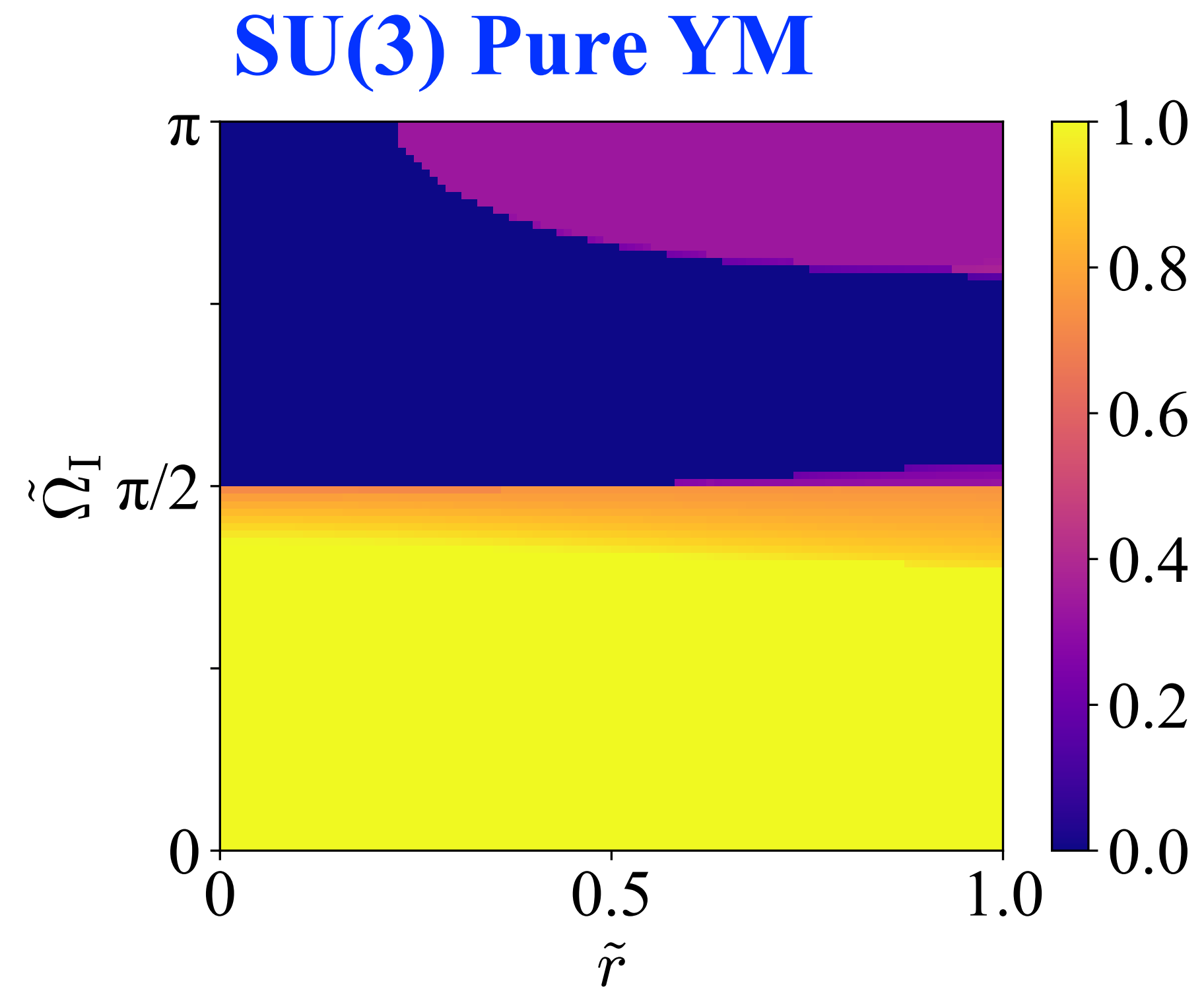
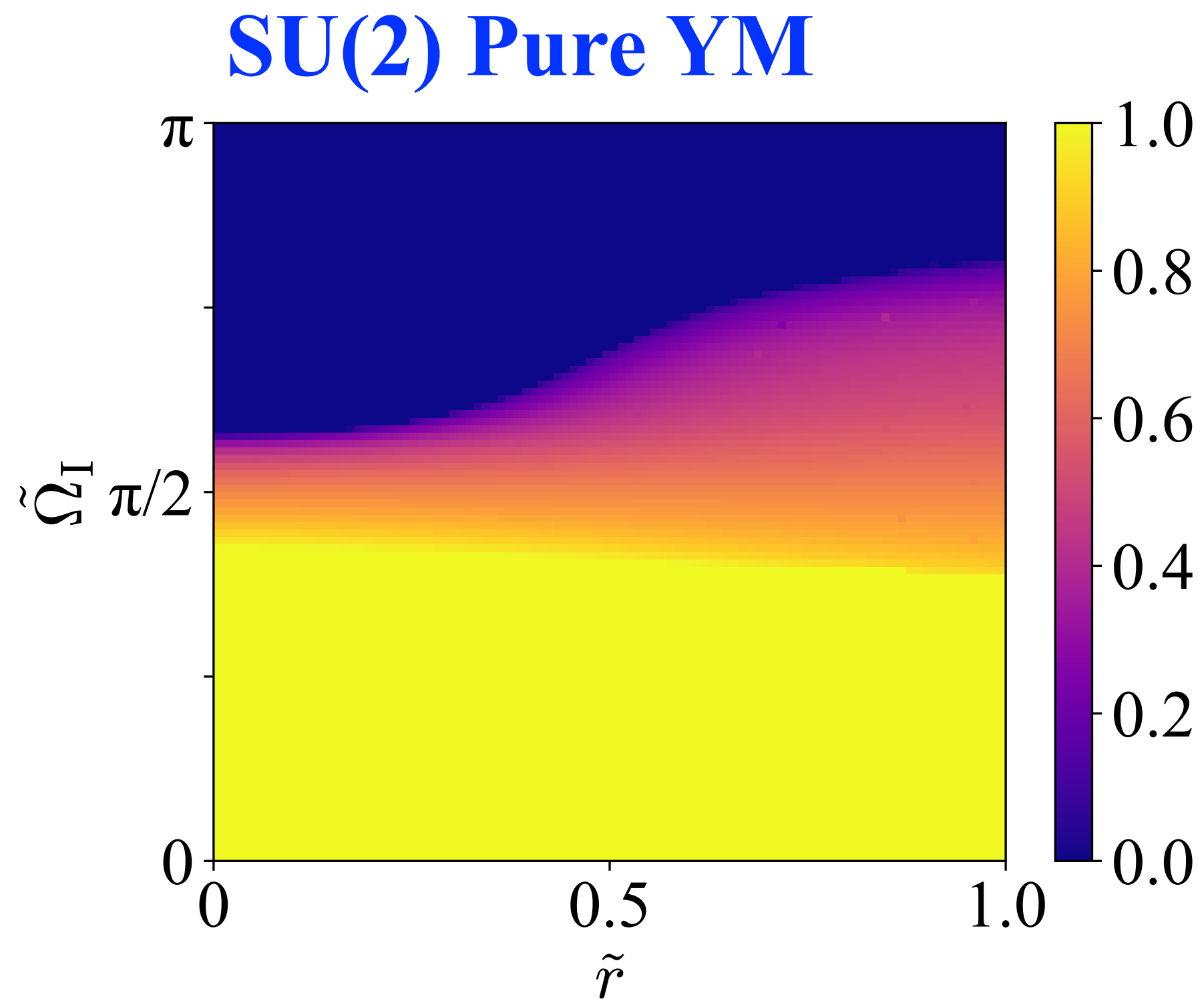
**Singular for
analytical cont.**

**The singularity physically represents
the violation of causality if the boundary is not imposed.**

**The analytical continuation is possible with the
boundary, but the results are contaminated...**

Polyakov Loop Potential

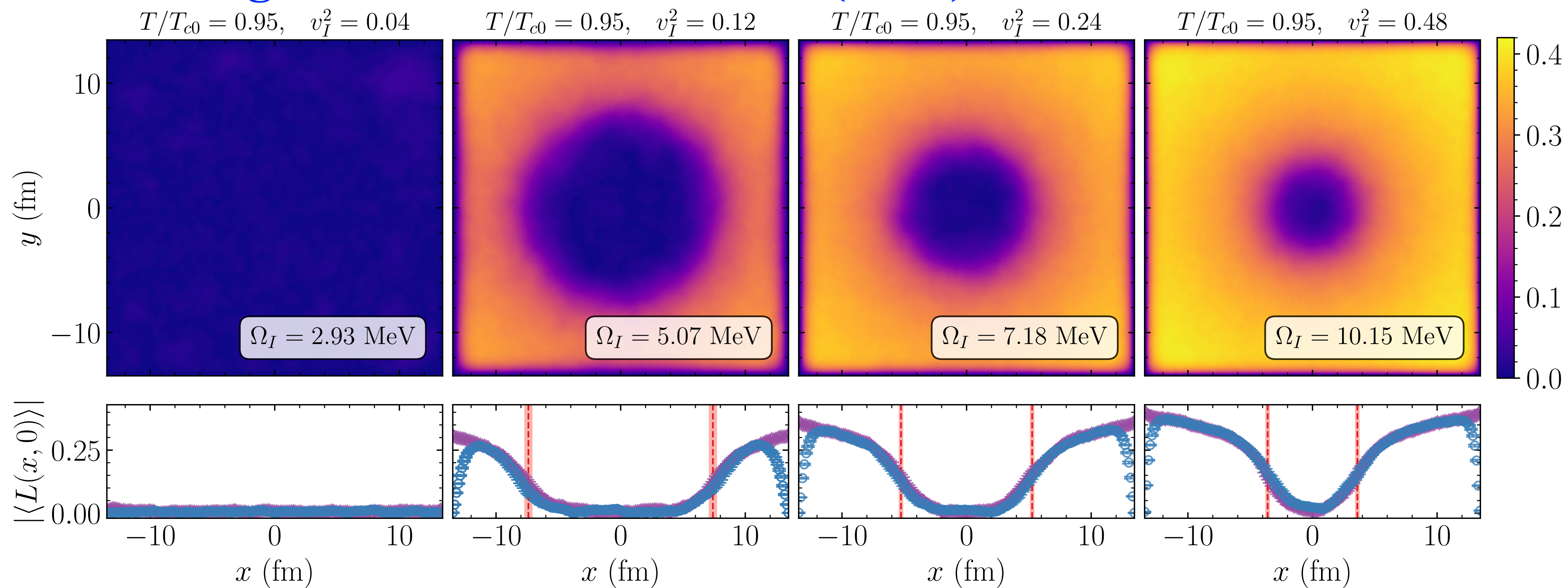
Chen-Fukushima-Shimada (2024)



**More “deconfined” for farer from the center
→ Real rotation would favor “confinement” ?**

vs. Lattice

Braguta-Chernodub-Roenko (2023)



**More “deconfined” for farer from the center
→ Real rotation would favor “confinement” ?**

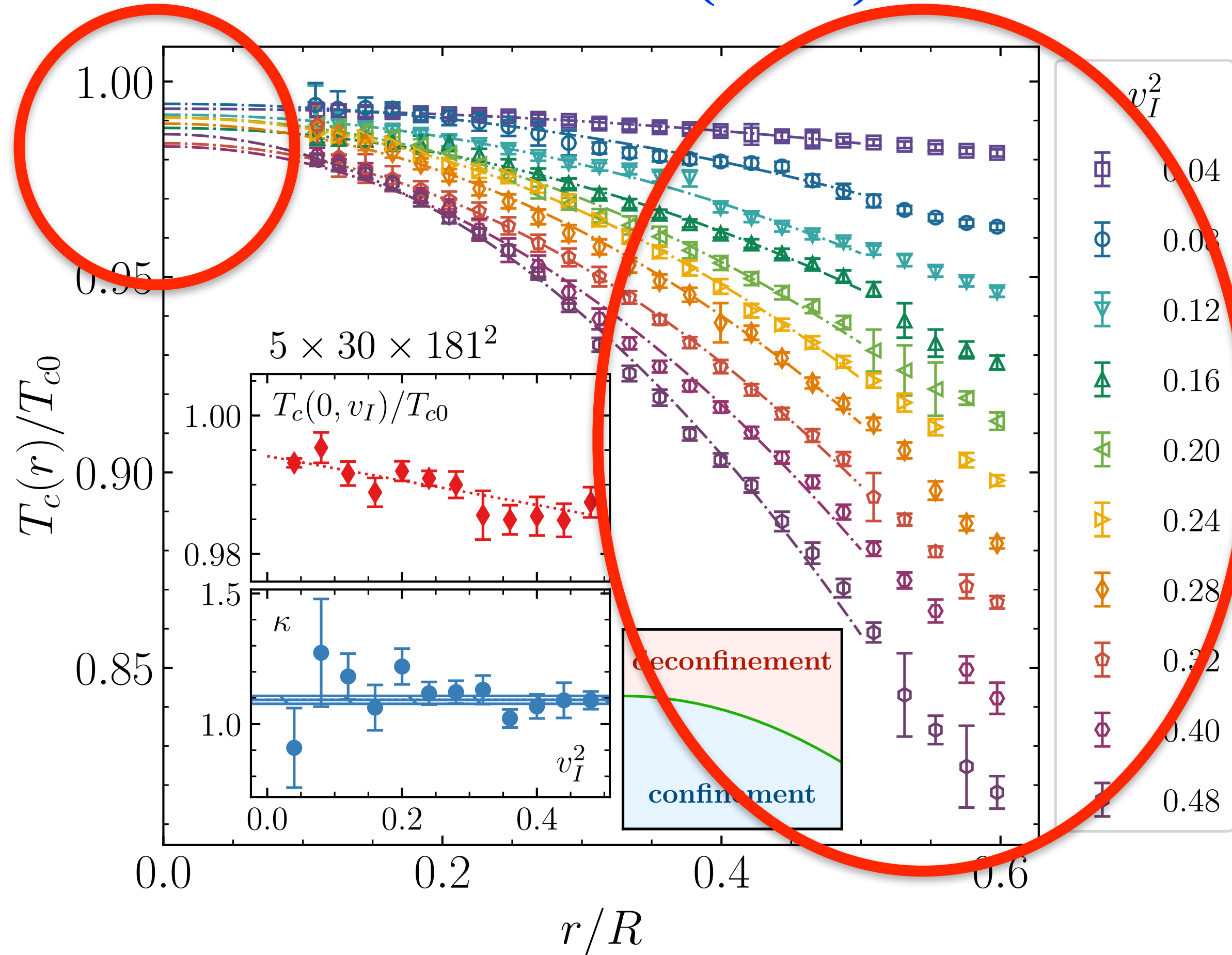
vs. Lattice

Braguta-Chernodub-Roenko (2023)



Qualitatively inconsistent!

Spin missing?

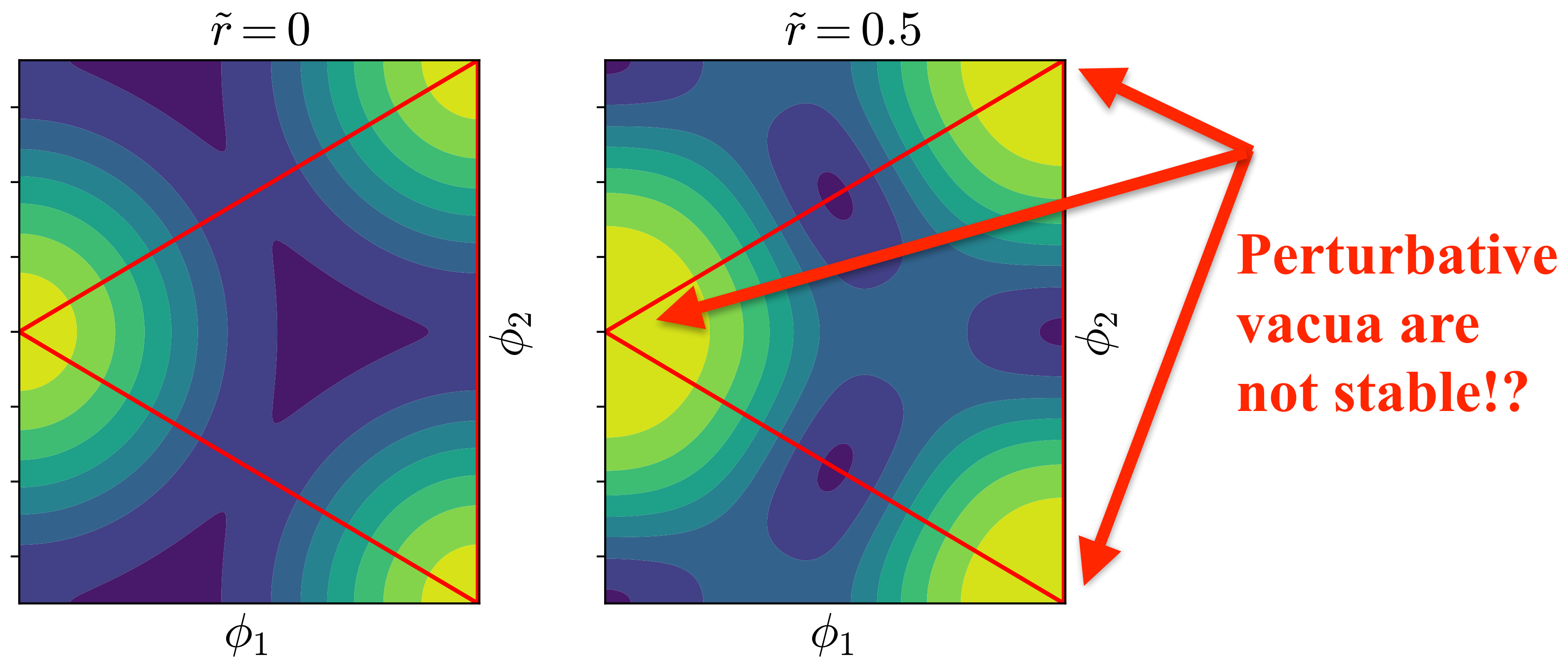


Consistent with pQCD

Polyakov Loop Potential

Chen-Fukushima-Shimada (2024)

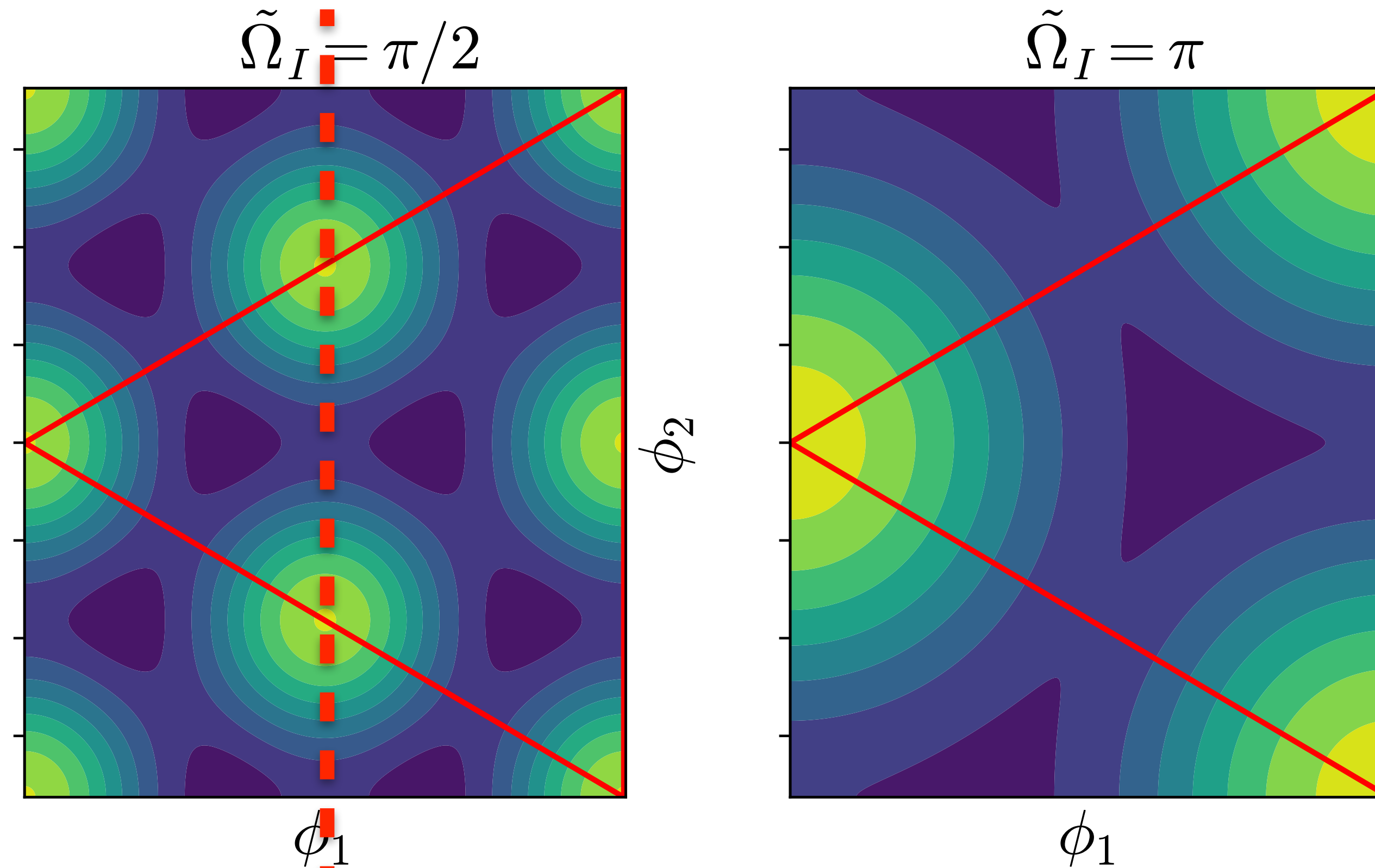
Not a standard “deconfined” phase



This is a testable prediction for lattice!

Polyakov Loop Potential

Accidental “emergent symmetry” ???



Z(2) symmetry that didn't exist...?

Including Fermions

Chen-Fukushima-Shimada (2024)

Adding “free” fermions with dynamical mass

$$\mathcal{Z}_{fT,\omega} = \text{Det}(\gamma^\mu G_{B\mu} + m)$$

Search for the potential minimum of the Polyakov loop and the dynamical mass.

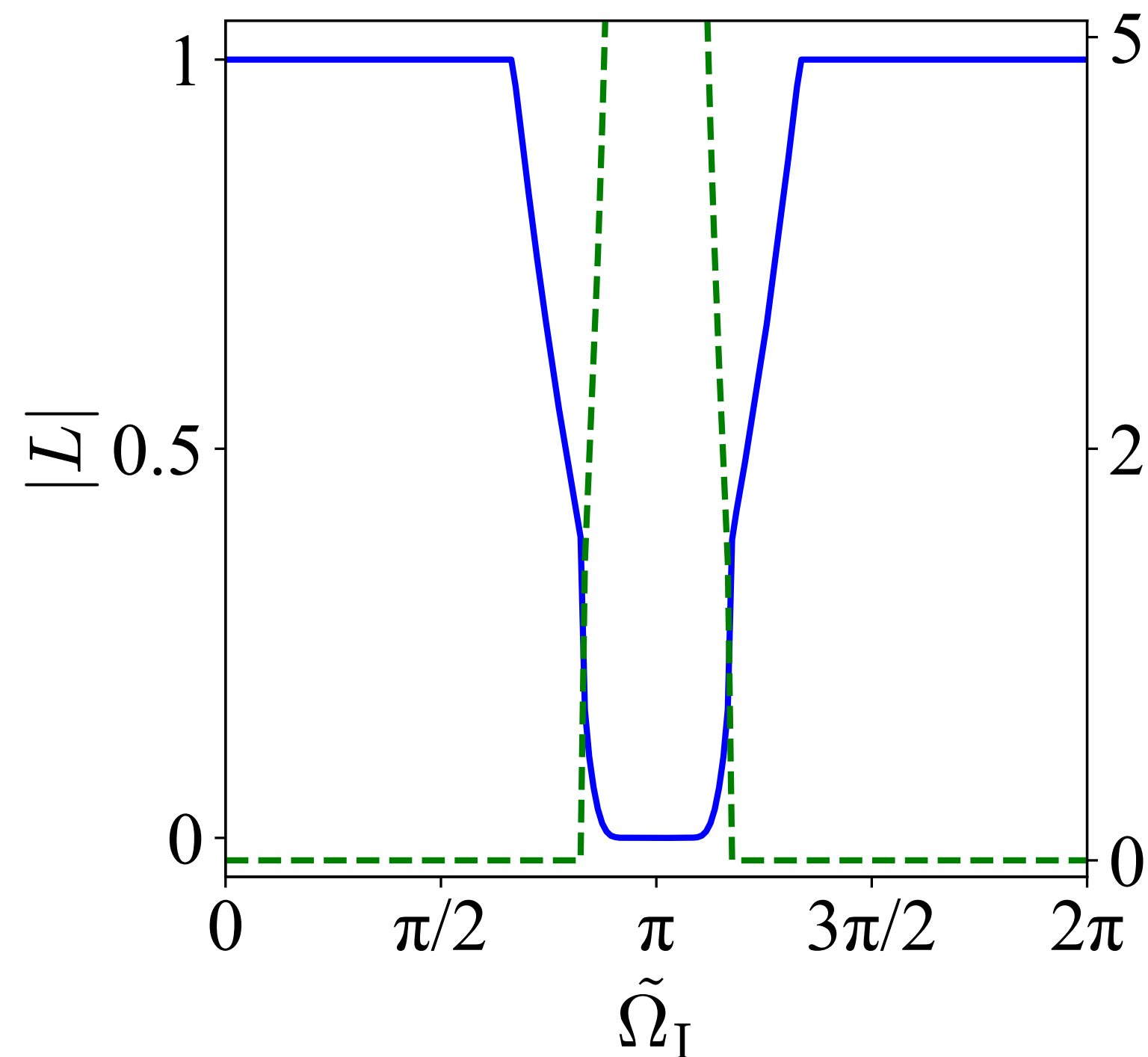
Once symmetry breaking is turned on, the mass blows up.

We may introduce a model such as NJL, but this is the model-independent analysis based on QCD!

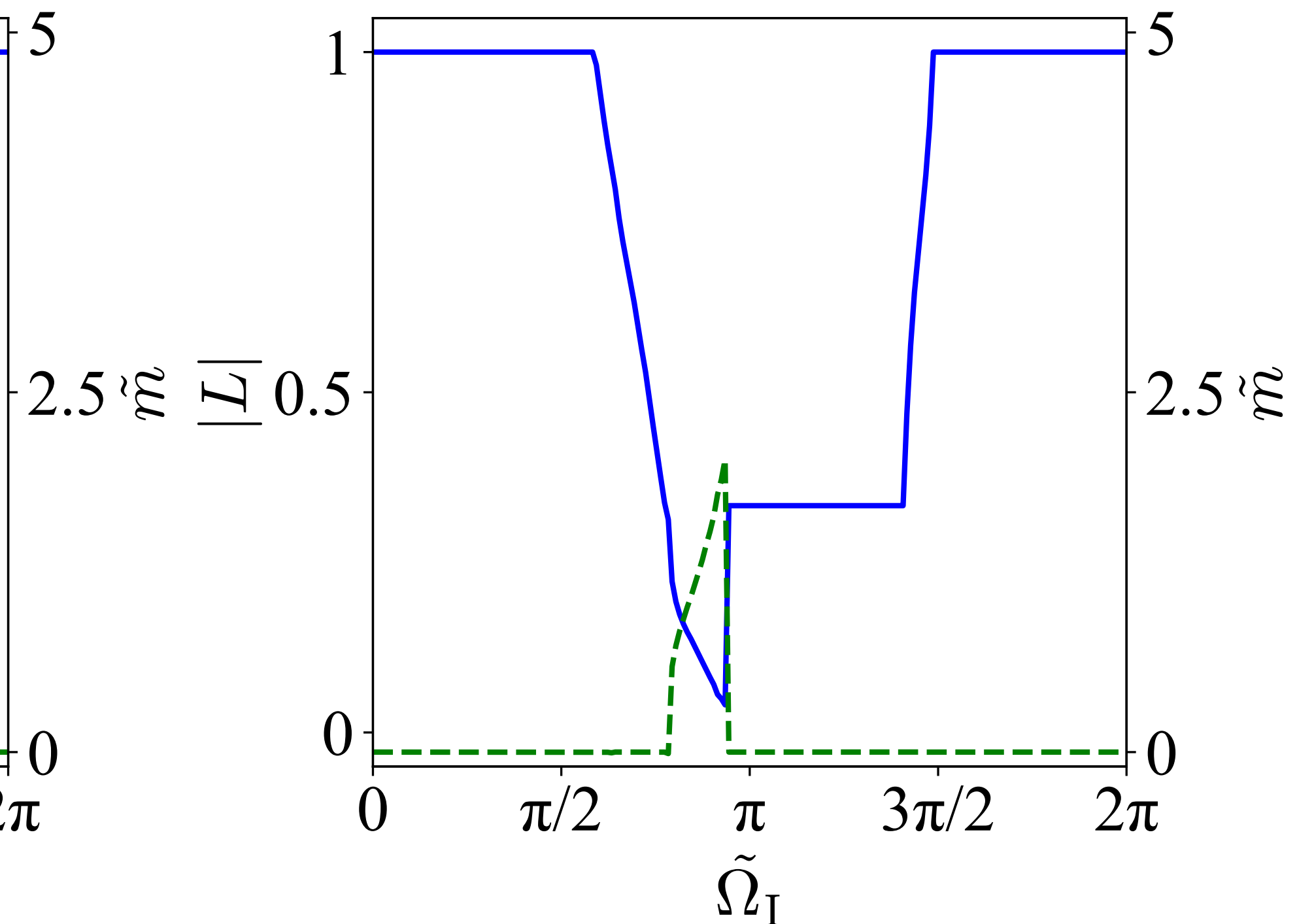
Including Fermions

Chen-Fukushima-Shimada (2024)

SU(2) full (2 flavor)



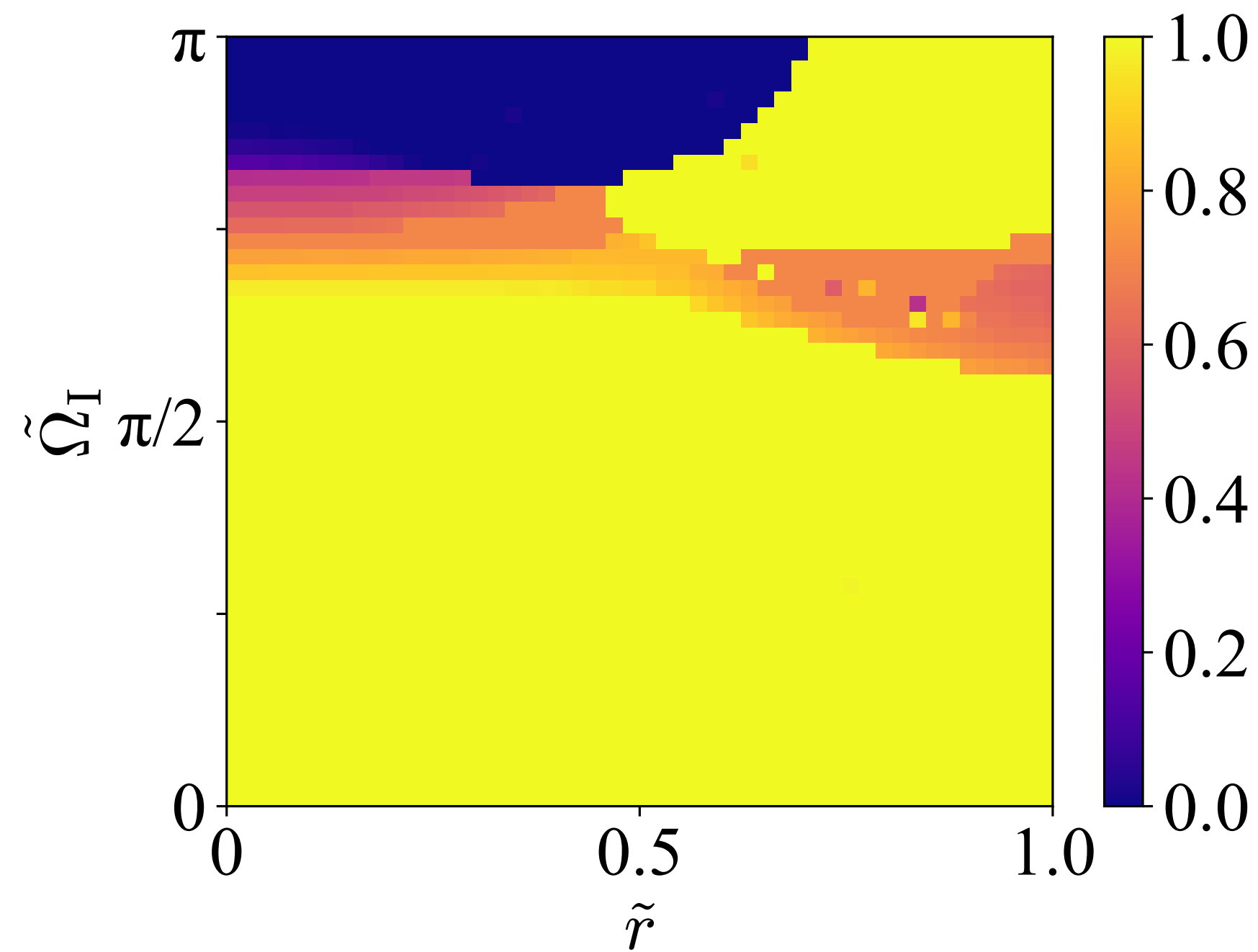
SU(3) full (2 flavor)



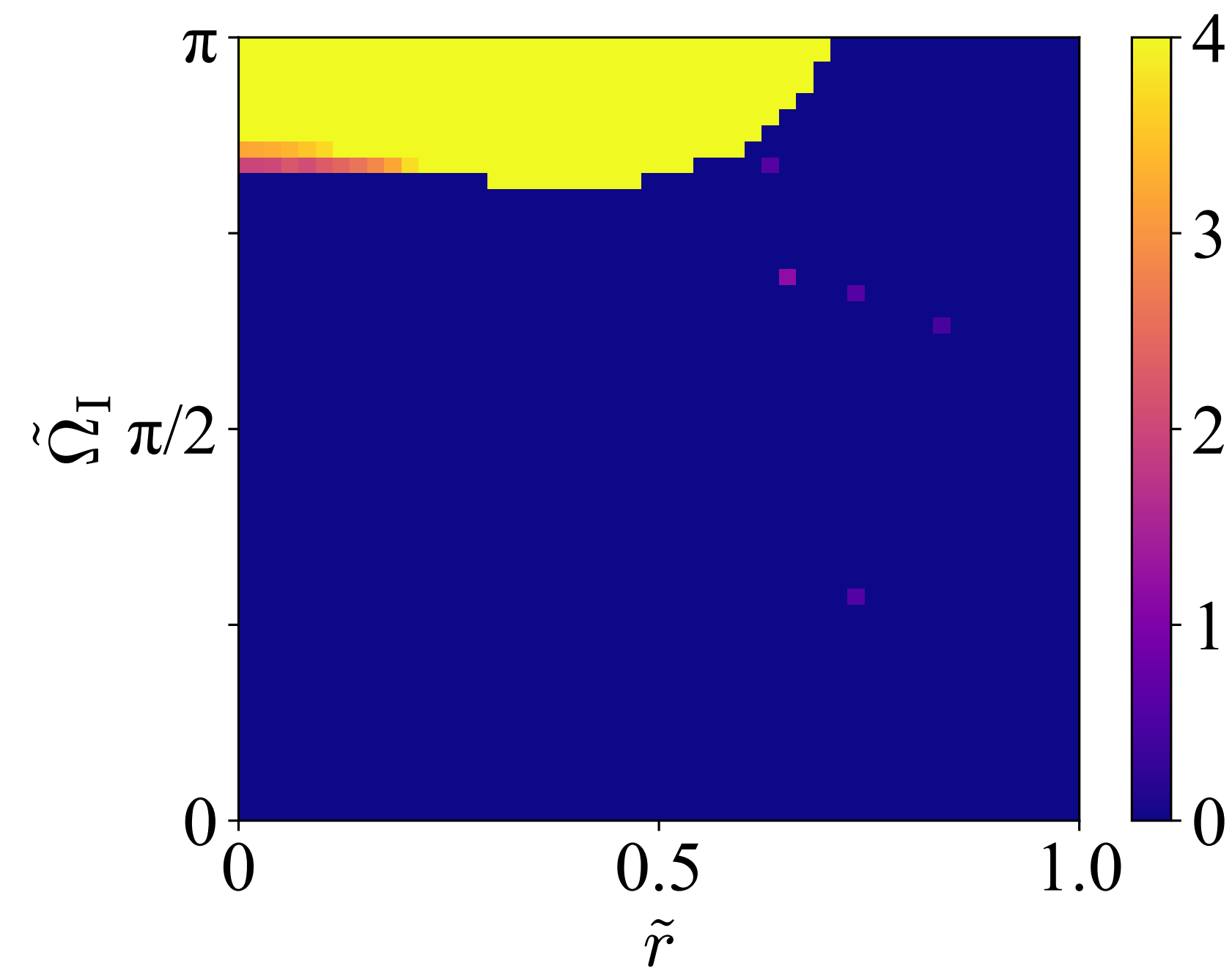
Almost correlated... but SU(3) is terribly complicated!

Including Fermions

Polyakov loop



Chiral condensate



Chen-Fukushima-Shimada (2024)

It seems that fermion mass dictates the Polyakov loop.

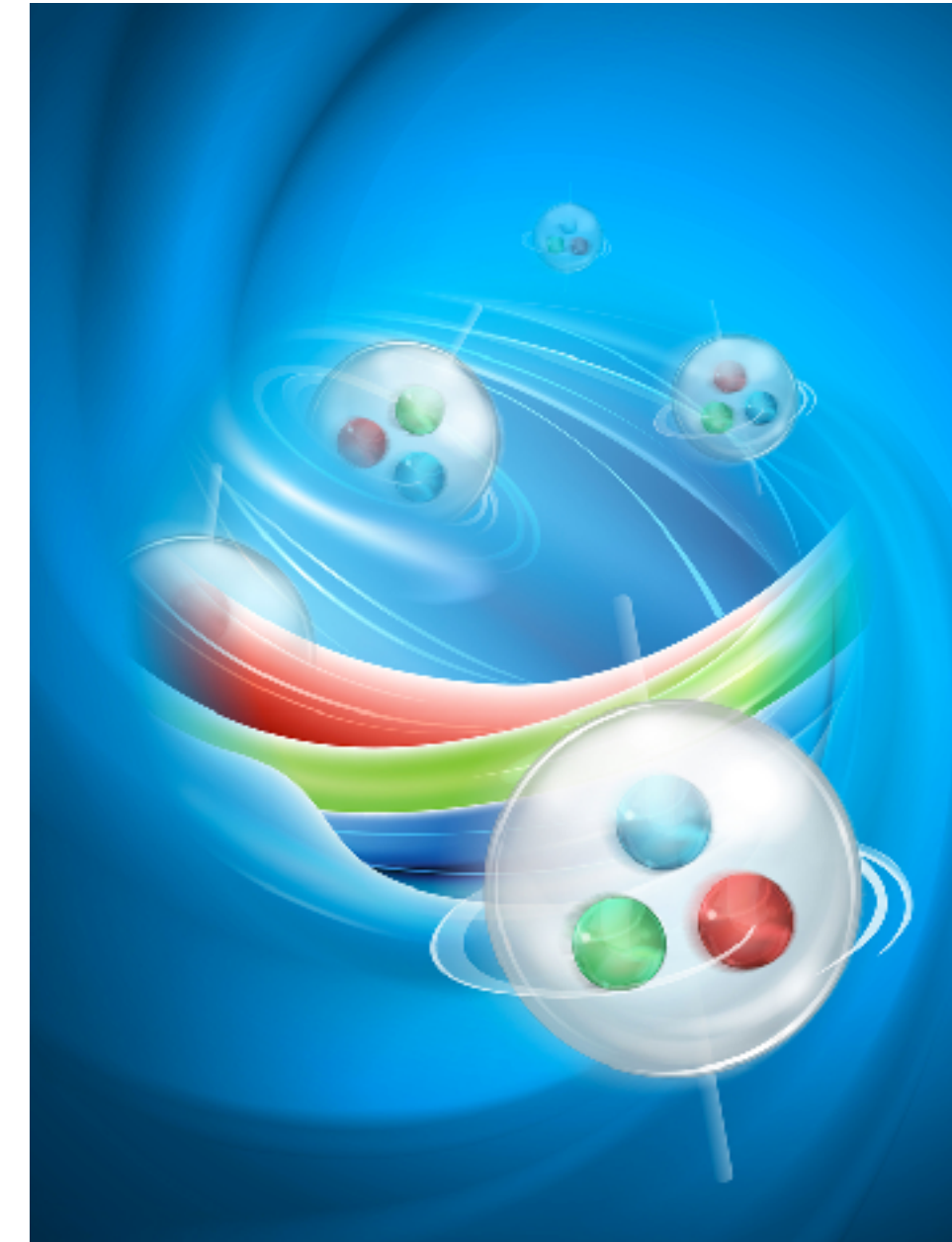
Implication

If analytically continuable... then...

**Even if Ω is smaller than Λ_{QCD}
it has a huge impact to the
rotation edges, where the velocity
is not small!**

**There, more “confined” and
“chiral broken” matter is
favored.**

**However, the mathematical structure of the analytical
continuation must be more carefully studied...**



Summary



■ So many interesting stuffs in the imaginary world.

- Perturbative confinement
- Perturbative chiral symmetry breaking

■ Partial agreement between pQCD and LQCD

- Radial dependence is qualitatively consistent.
- The remaining puzzle is the behavior at the center.
- At the center, only the spin makes the contribution...?

■ Extremely rich inhomogeneous structures...

- Even the pure YM is not fully understood yet...