



Rotating QCD matter in strong coupling limit

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Outline

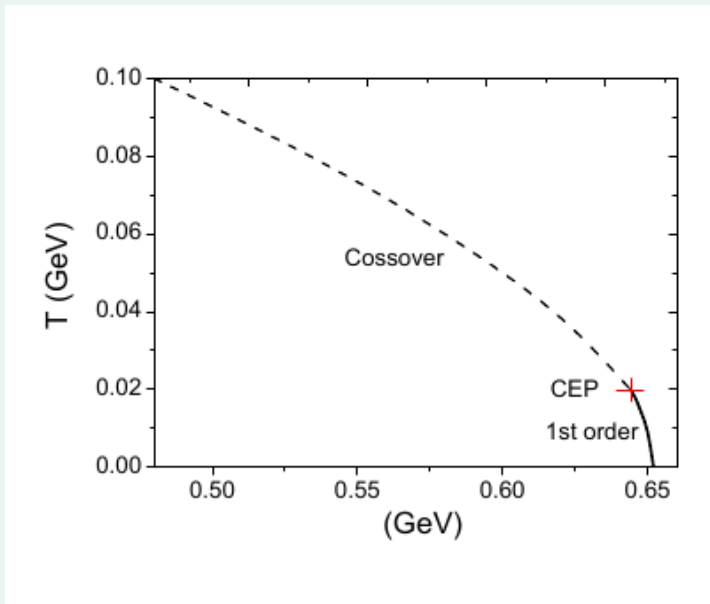
- The conflict between lattice results and theoretical results
- Why strong coupling, and the results
- In the strong-coupling regime, the lattice and theoretical results begin to converge!

Theoretical phase diagrams

- T_c decrease with **real** rotation

Chiral transition

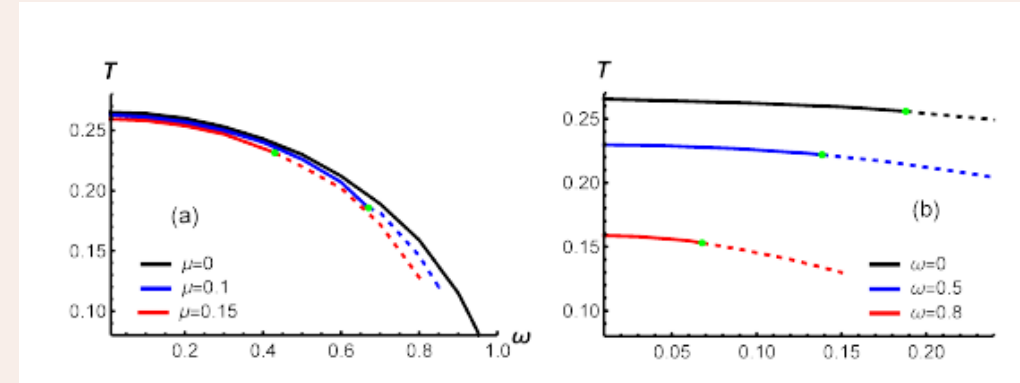
Jiang–Liao (2016)



[Y. Jiang & J. Liao, Phys. Rev. Lett. 117, 192302 (2016)
| arXiv:1606.03808]

Confinement / deconfinement

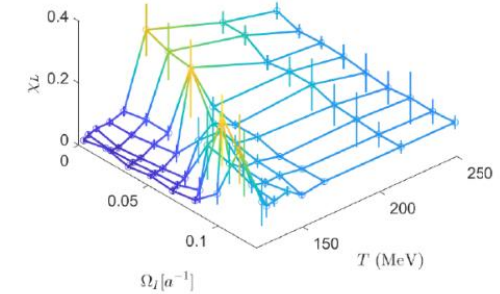
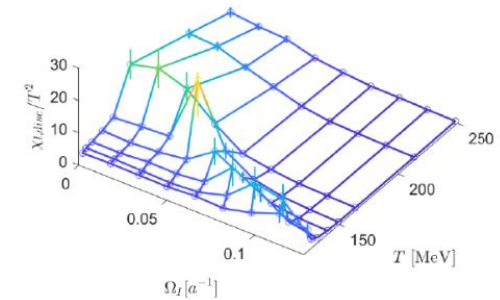
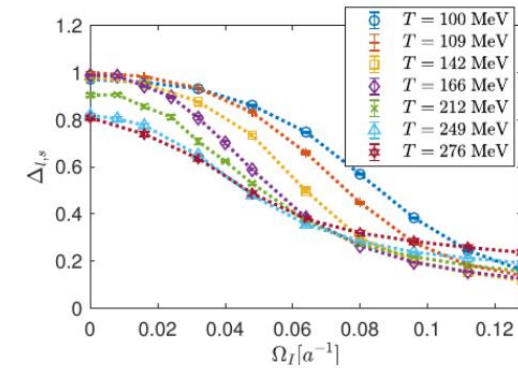
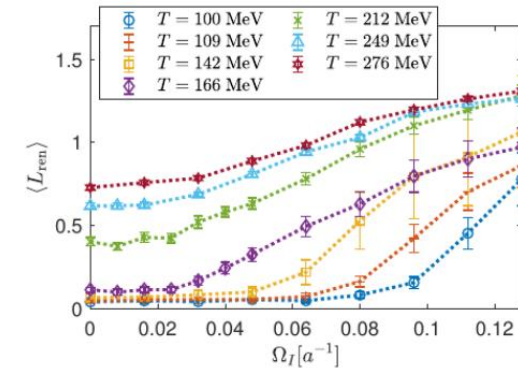
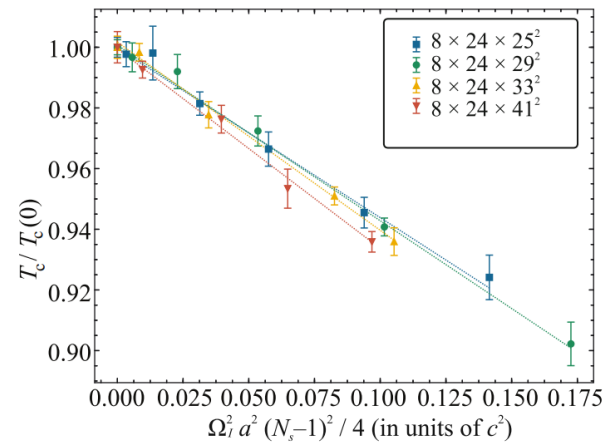
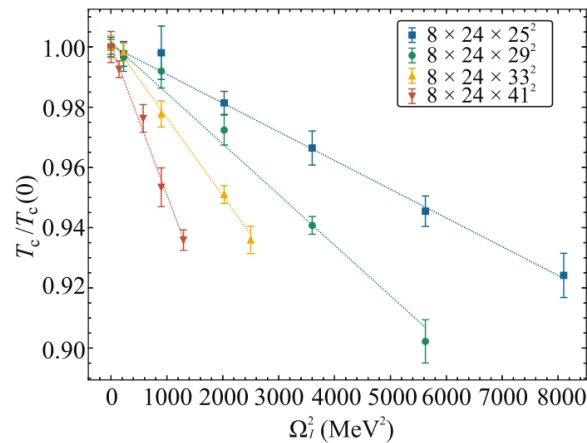
Chen–Zhang–Li–Hou–Huang (2020/2021)



[X. Chen et al., JHEP 07 (2021) 132 |
arXiv:2010.14478]

Phase transition driven by the imaginary rotation

- Action from [Yamamoto et al.
- Phys.Rev.Lett. 111 (2013) 081601 • e-Print: 1303.6292]
- T_c decrease with **imaginary** rotation



- [Braguta et al. JETP Letters, 2020, Vol. 112, No. 1, pp. 6–12, Phys. Rev. D 103, 094515 (2021), arXiv:2102.05084]

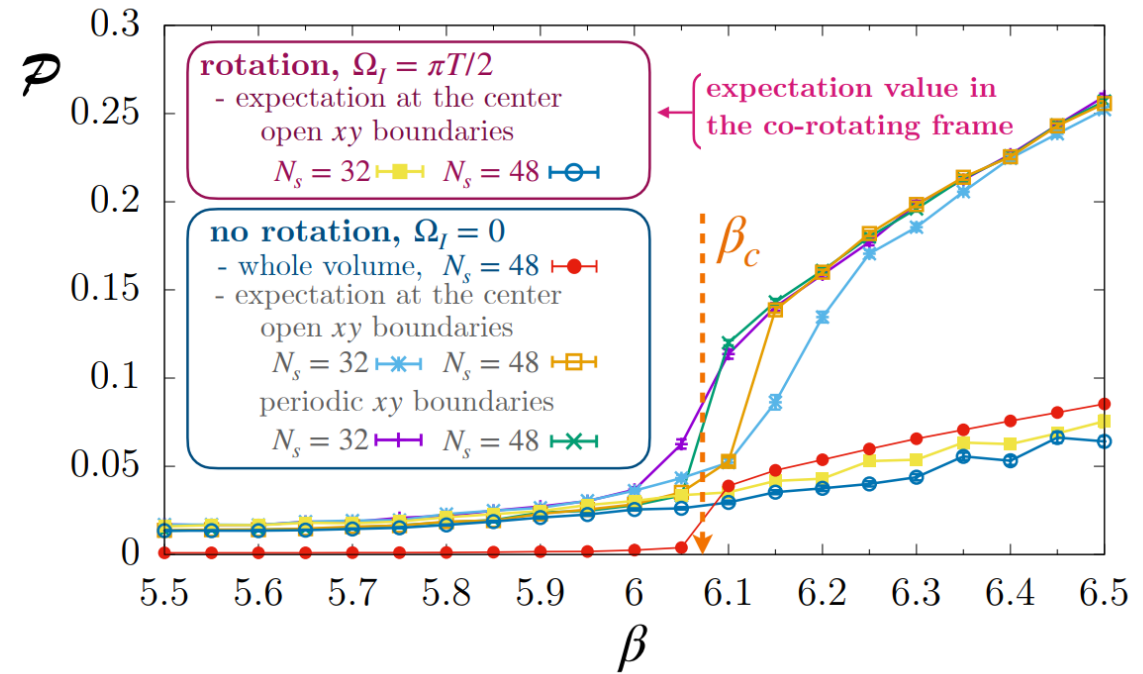
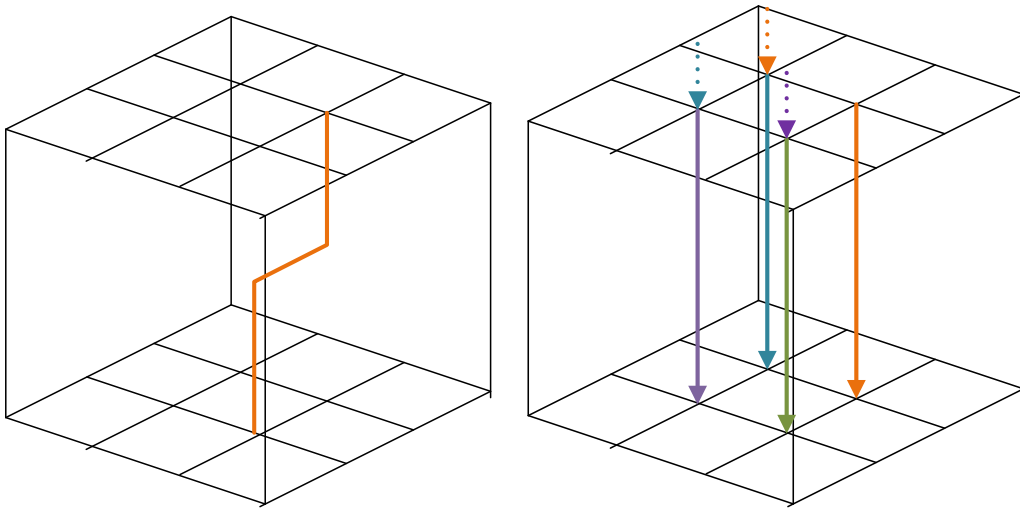
- [JCY, Xu-Guang Huang, 2307.05755]

Rotwist boundary condition

• [M. N. Chernodub et al. Phys.Rev.D 107 (2023) 11, 114502 • e-Print: 2209.15534]

- Quenched
- Open boundary
- Polyakov loop

$$\Omega_I = \frac{\pi T}{2}$$



Strong coupling results

- Models reproduce the lattice trend: T_c rises with **real** rotation.

[Y. Chen et al. Phys.Rev.D 111 (2025) 046006 • e-Print: 2405.06386]

[J.-X. Chen et al. Phys.Rev.D 111 (2025) 026020 • e-Print: 2410.04763]

- Analytic continuation is debated: test **imaginary** rotation directly.

[G. Cao, Phys.Rev.D 109 (2024) 014001 • e-Print: 2310.03310]

- High- T perturbation: **imaginary** rotation can induce confinement.

[S. Chen, K. Fukushima, Y. Shimada, Phys.Rev.Lett. 129 (2022) 242002 • e-Print: 2207.12665]

- Strong-coupling expansion of pure-gauge lattice theory:

$T_c \uparrow$ (**imaginary** rotation); $T_c \downarrow$ (**real** rotation, to $O(\Omega^2)$).

[K. Fukushima, Y. Shimada, Phys.Lett.B 868 (2025) 139716 • e-Print: 2506.03560]

[S. Wang et al. e-Print: 2505.15487]

$$\beta = 2N_c/g_{\text{YM}}^2$$

Opposite to the early rotating-frame lattice results.

Imaginary rotation and anisotropic lattice spacing

$$\Omega = i\omega, \quad \omega \in R$$

$$a_\tau = \xi a_s$$

$$T = 1/(N_t a_\tau) = 1/(\xi N_t a_s)$$

- Action:

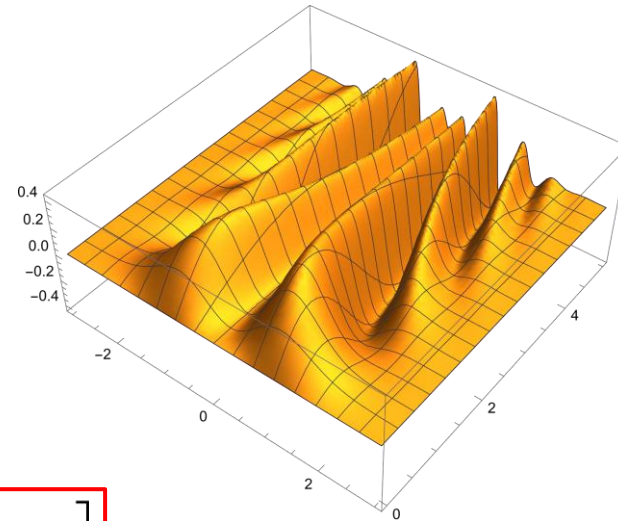
$$\begin{aligned} S_G^E = \frac{\beta}{N_c} \sum_n \bigg\{ & \xi \sum_{i < j} \text{ReTr} [1 - \bar{U}_{ij}(n)] + \frac{1}{\xi} \sum_i \text{ReTr} [1 - \bar{U}_{i4}(n)] \\ & - \omega \left[x \left(\text{ReTr} V_{412}(n) + \text{ReTr} V_{432}(n) \right) - y \left(\text{ReTr} V_{421}(n) + \text{ReTr} V_{431}(n) \right) \right] \\ & + \xi \omega^2 \left[r^2 \text{ReTr} (1 - \bar{U}_{12}(n)) + x^2 \text{ReTr} (1 - \bar{U}_{23}(n)) \right. \\ & \left. + y^2 \text{ReTr} (1 - \bar{U}_{13}(n)) - xy \text{ReTr} V_{231}(n) \right] \bigg\}. \end{aligned}$$

- Strong coupling $\rightarrow$ small beta $\rightarrow$ hard to see the deconfined phase

Imaginary rotation: analytical continuation

- A simple example:

$$\begin{aligned}
 & \int_0^\infty dx \int_0^\infty dy x \exp(-x^2) \sin(2xy) \\
 &= \frac{1}{2} \int_{-\infty}^\infty dx \int_0^\infty dy x \exp(-x^2) \sin(2xy) \\
 &= -\frac{1}{2} \operatorname{Im} \left[\int_{-\infty}^\infty dx \int_0^\infty dy x \exp(-x^2 - 2ixy) \right] \\
 &= \frac{\sqrt{\pi}}{4}
 \end{aligned}$$



$$result = -\operatorname{Im} [f(i)]$$

$$\begin{aligned}
 f(a) &= \int_0^\infty dx \int_0^\infty dy x \exp(-x^2 - 2axy) \\
 &\approx \int_0^{100} dx \int_0^{100} dy x \exp(-x^2 - 2axy)
 \end{aligned}$$

$$\begin{aligned}
 & \int_{-\infty}^\infty dx \int_0^\infty dy x \exp(-x^2 - 2ixy) \\
 &= \int_{-\infty}^\infty dx \int_0^\infty dy x \exp(-(x + iy)^2 - y^2) \\
 &= \int_{-\infty}^\infty dx' \int_0^\infty dy x' \exp(-x'^2 - y^2) - iy \int_{-\infty}^\infty dx \int_0^\infty dy \exp(-x'^2 - y^2) \\
 &= -i\sqrt{\pi} \int_0^\infty dy y e^{-y^2} \\
 &= -\frac{i}{2} \sqrt{\pi}
 \end{aligned}$$

analytical continuation (ansatz is important)

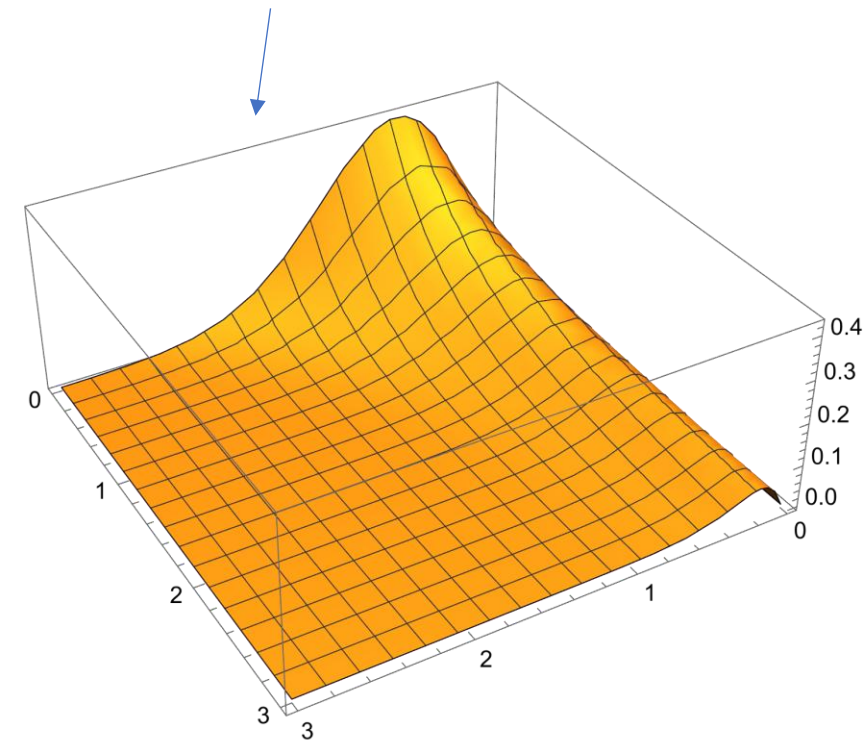
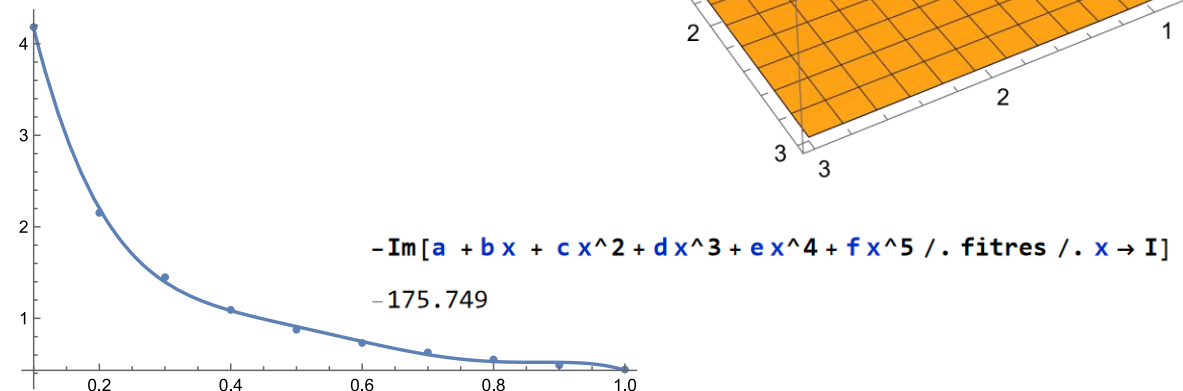
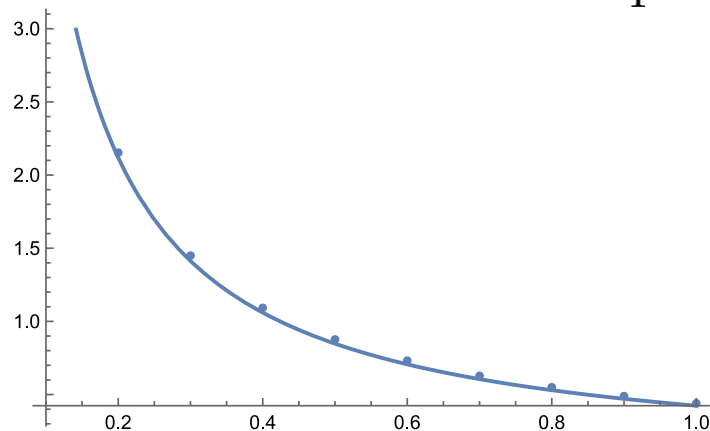
- This numerical integration has no sign-problem

$$\int_0^{100} dx \int_0^{100} dy x \exp(-x^2 - 2axy)$$

An example with $a=1$

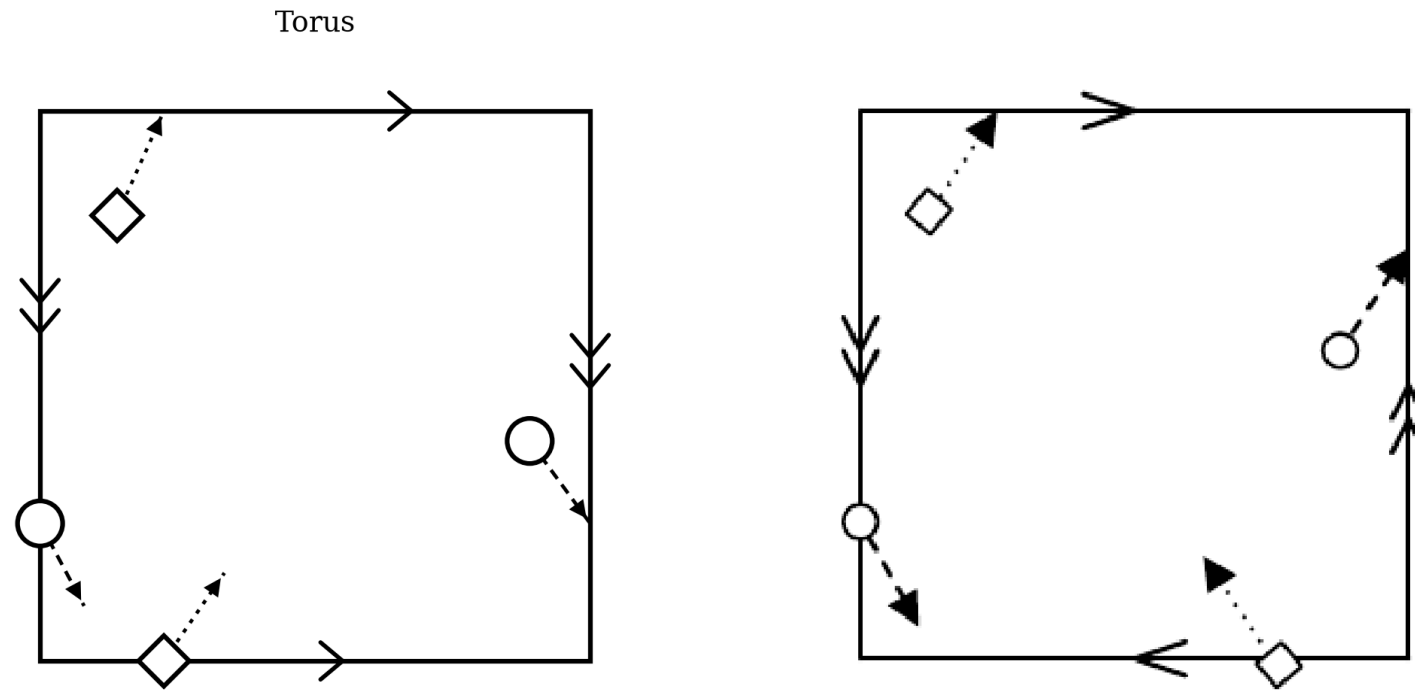
$$f(a) \approx \frac{0.423878}{a} \quad \longrightarrow \quad \frac{\sqrt{\pi}}{4} = 0.443113$$

$-\text{Im}[f(i)] \approx 0.423878$



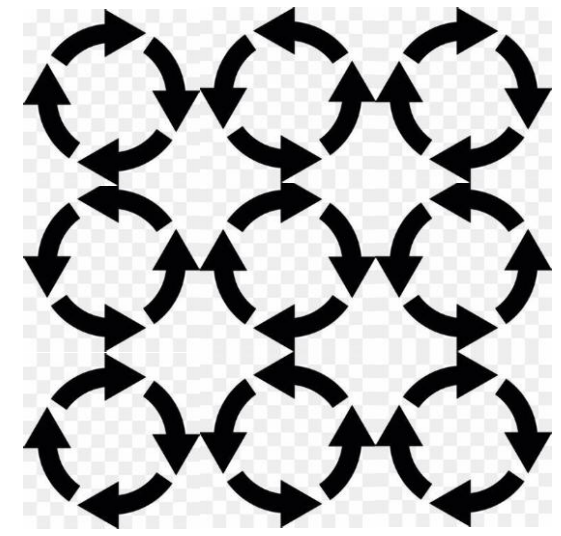
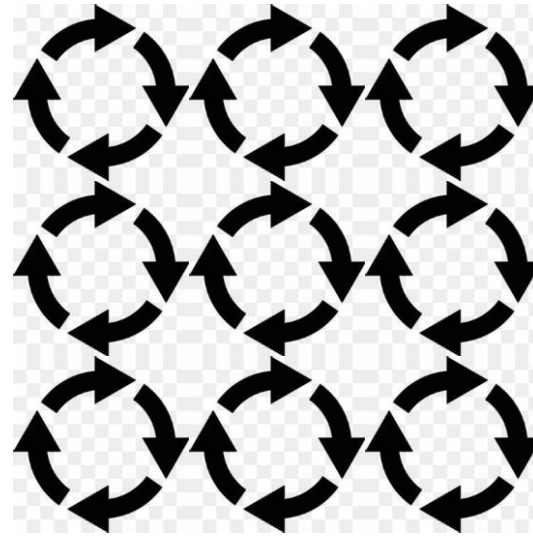
Projective plane boundary condition

- (torus) periodic boundary vs projective plane periodic boundary



Projective plane boundary condition

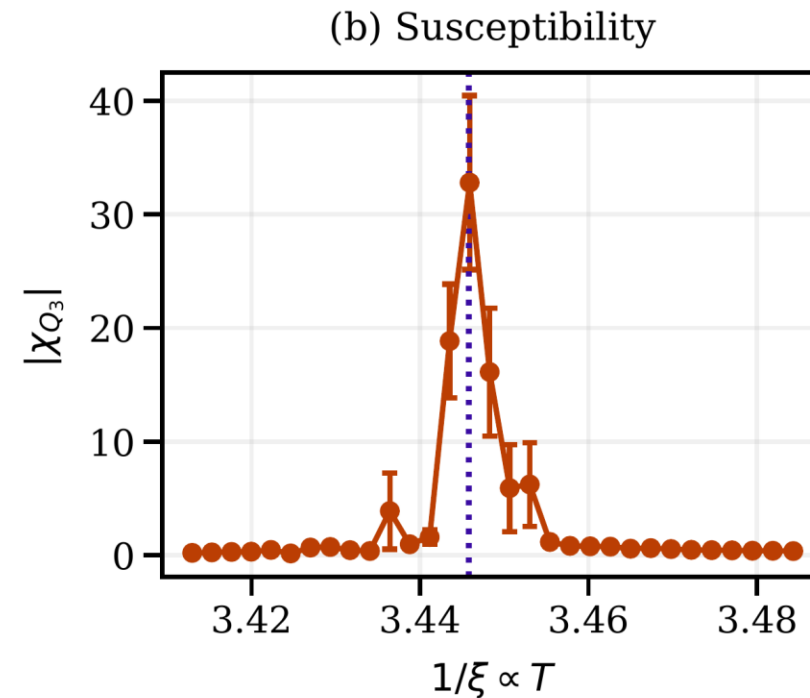
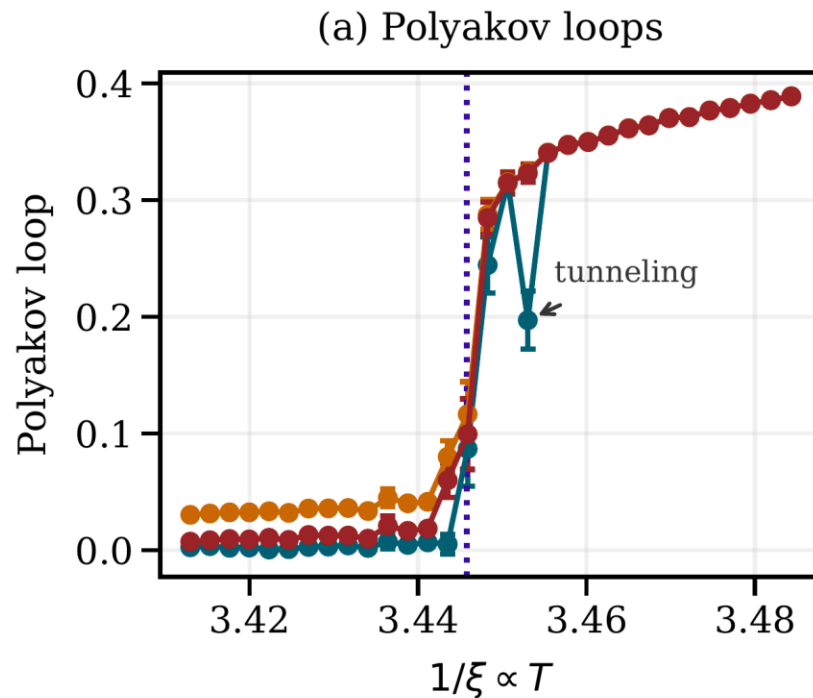
- Suitable for rotation:



The Polyakov loop, and result without rotation

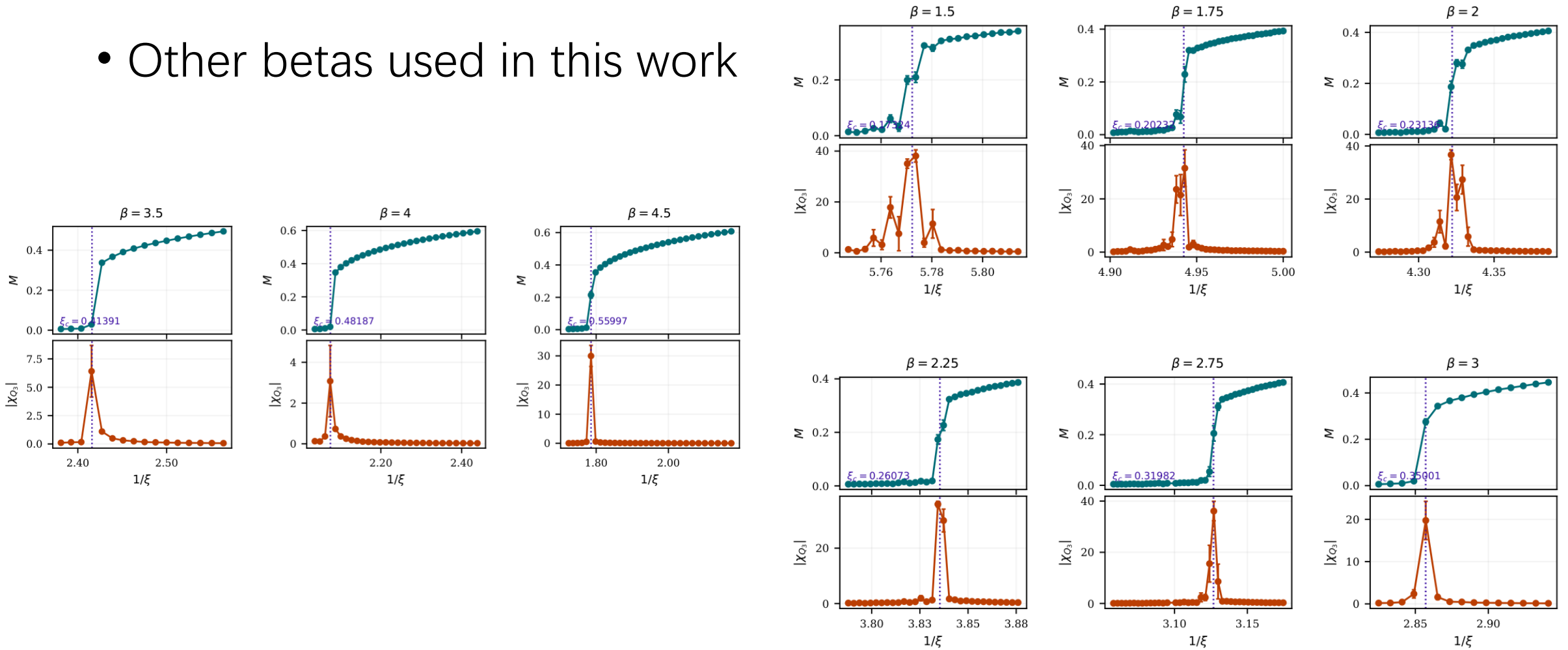
- Polyakov loop $Q_3 \equiv |P|e^{3i \arg P}$, $M \equiv |\langle Q_3 \rangle|$.

$\text{---} \text{---} \text{---} |\langle P \rangle|$ $\text{---} \text{---} \text{---} \langle |P| \rangle$ $\text{---} \text{---} \text{---} M$



Results without rotation

- Other betas used in this work



Deconfine-Confine-Deconfine structure

[K. Fukushima, Y. Shimada, Phys.Lett.B 868 (2025) 139716 • e-Print: 2506.03560]

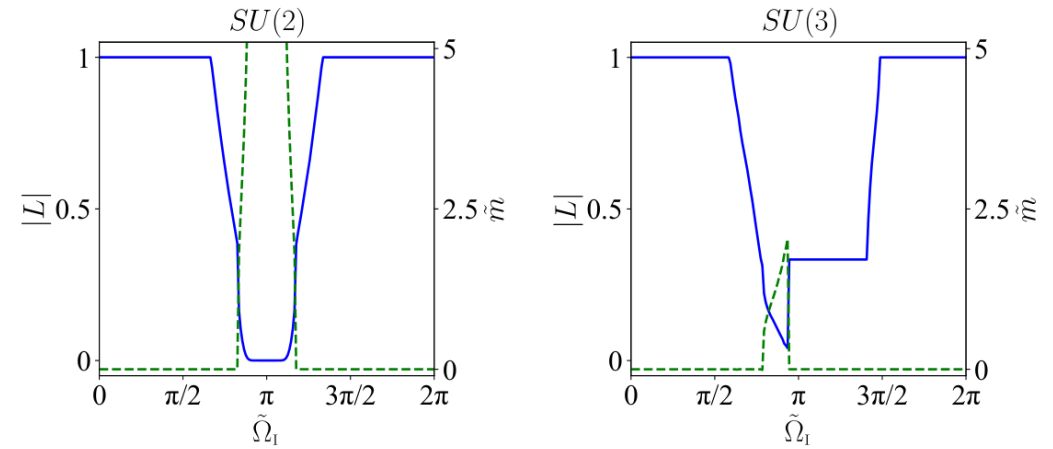
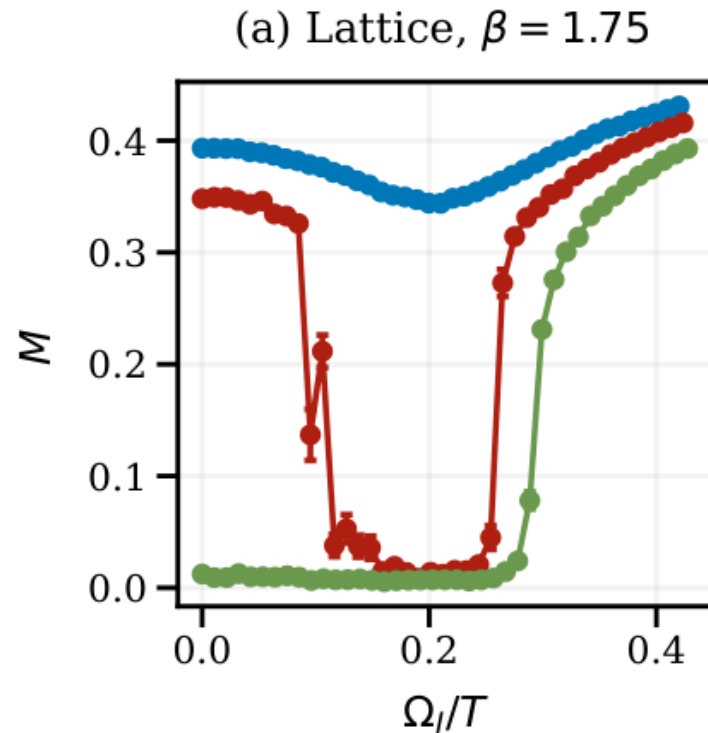
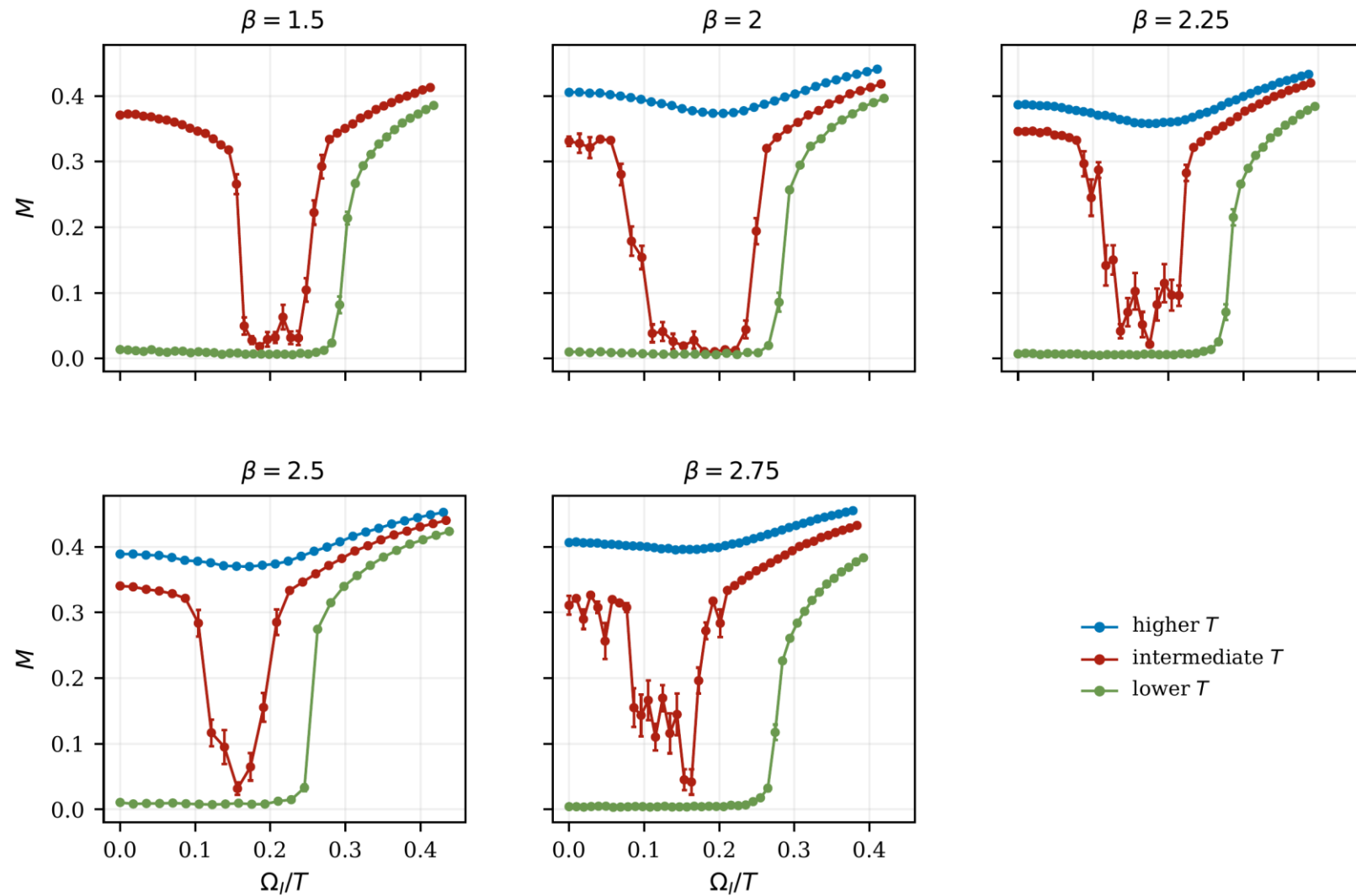


Figure 5: Order parameters, $|L|$ and $\tilde{m}$, as functions of $\tilde{\Omega}_I$ for $N_f = 2$, $N_c = 2$ (left) and $N_c = 3$ (right). The blue solid line represents the Polyakov loop $|L|$, and the green dashed line represents the dynamical mass $\tilde{m}$. The horizontal axis is discretized by 200 points with equal spacing to capture spiky structures.

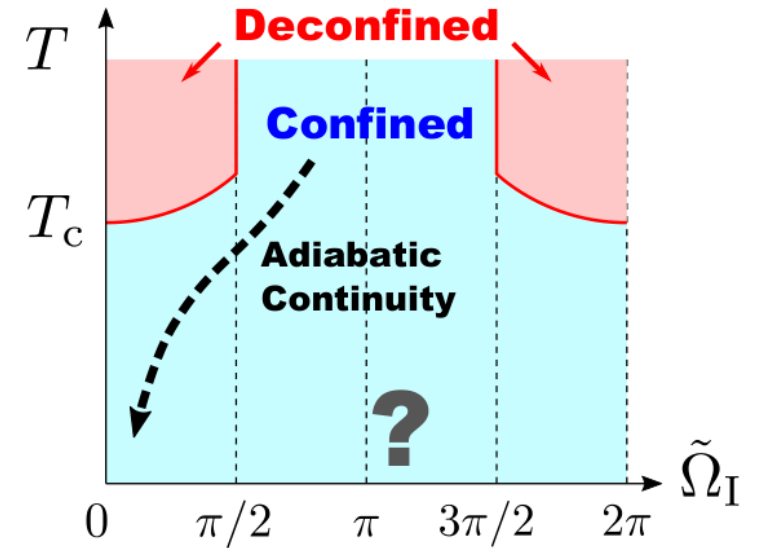
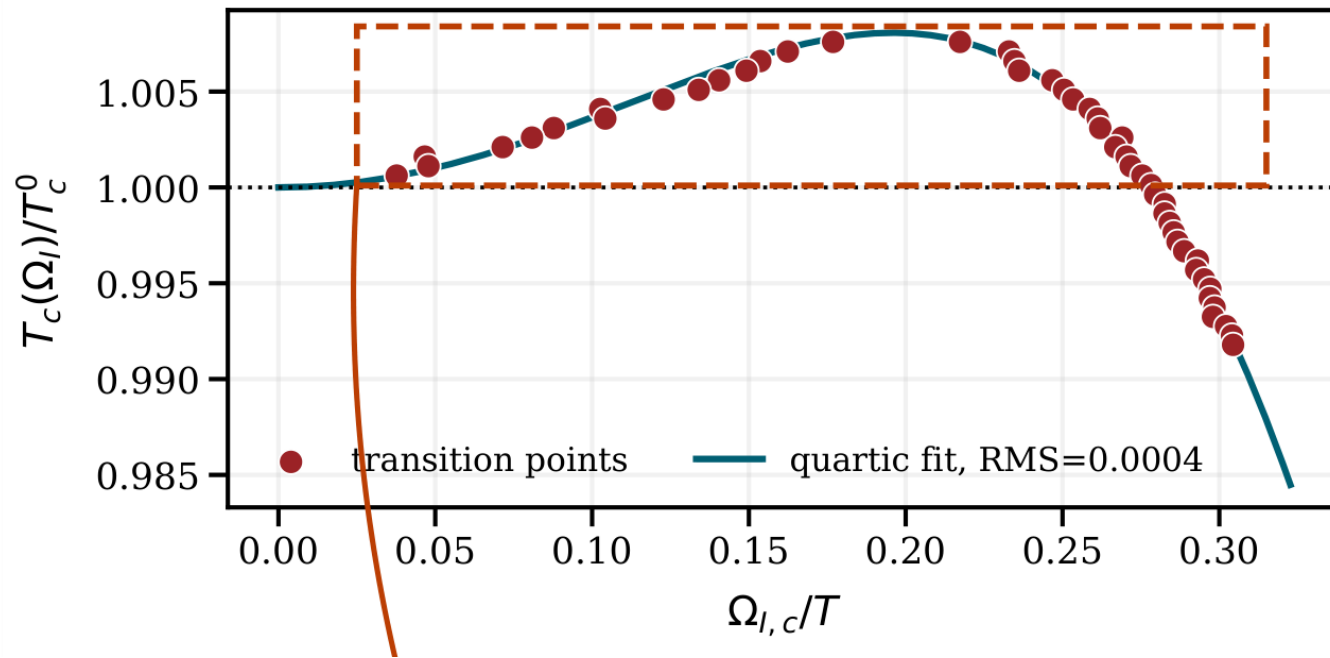
D-C-D phase structure at other beta



Phase diagram

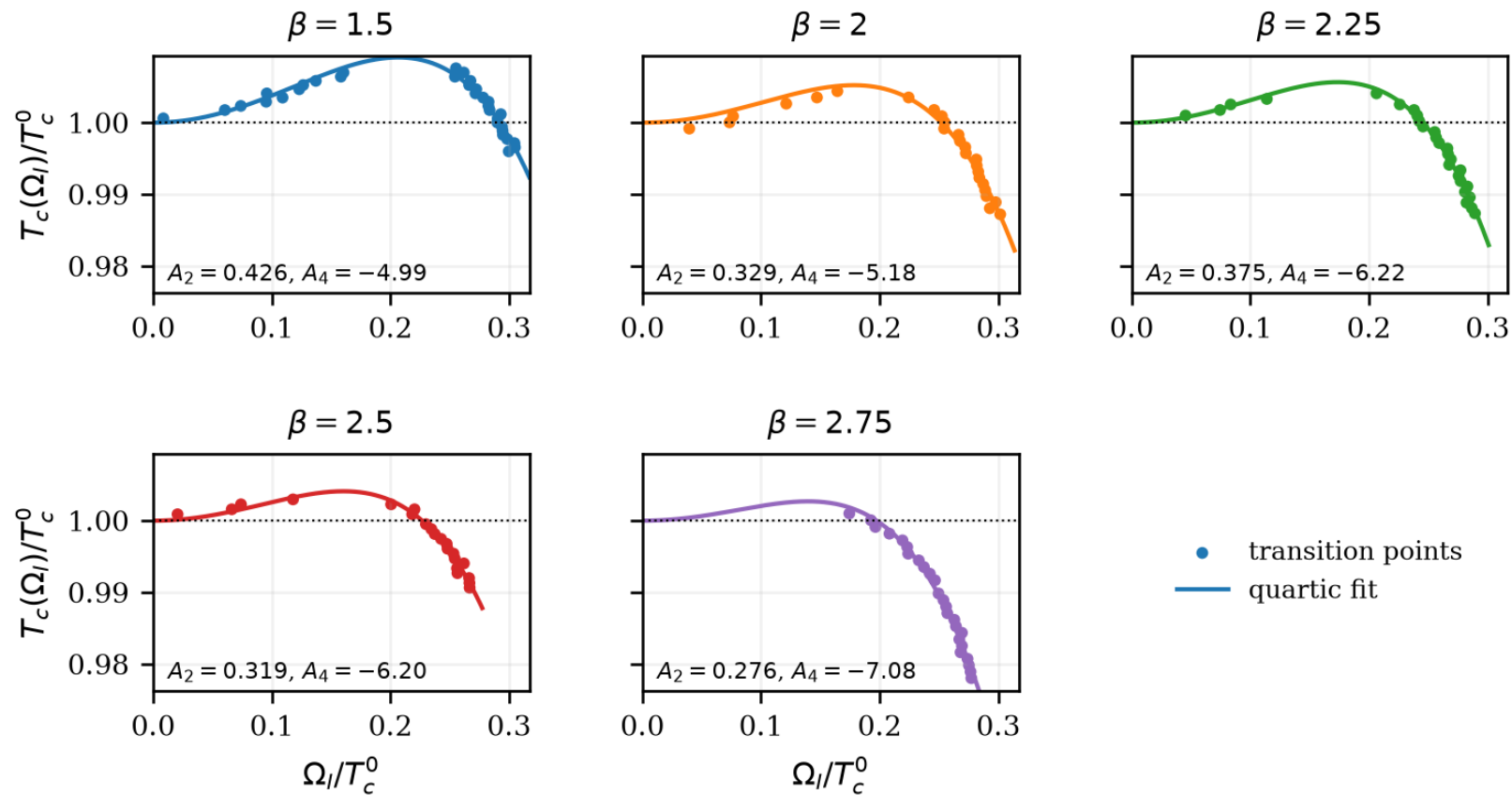
- An example at beta = 1.75

(a) Simulation, $\beta = 1.75$



Phase diagram at other beta

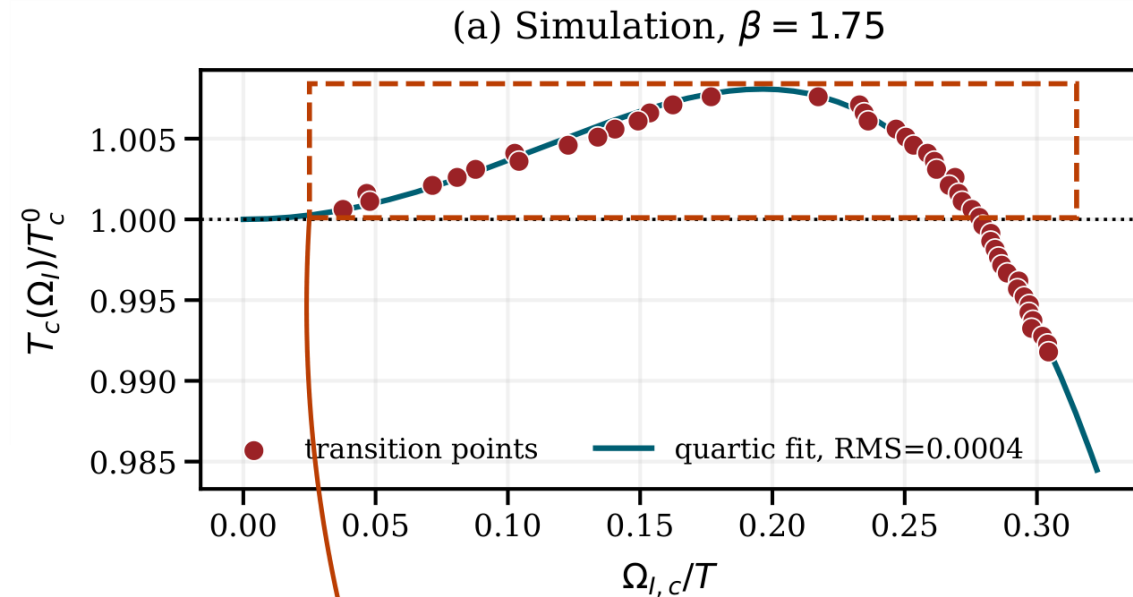
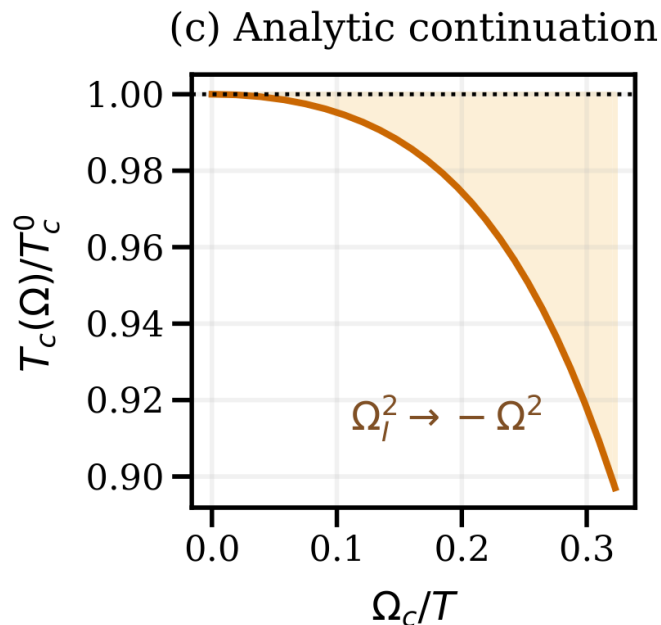
Phase boundaries at other strong couplings, $M = |\langle P \rangle|$



Fitting of the phase diagram

- Quartic is not enough

$$\frac{T_c}{T_c^0} = 1 + A_2 \left(\frac{\Omega_{I,c}}{T} \right)^2 + A_4 \left(\frac{\Omega_{I,c}}{T} \right)^4$$

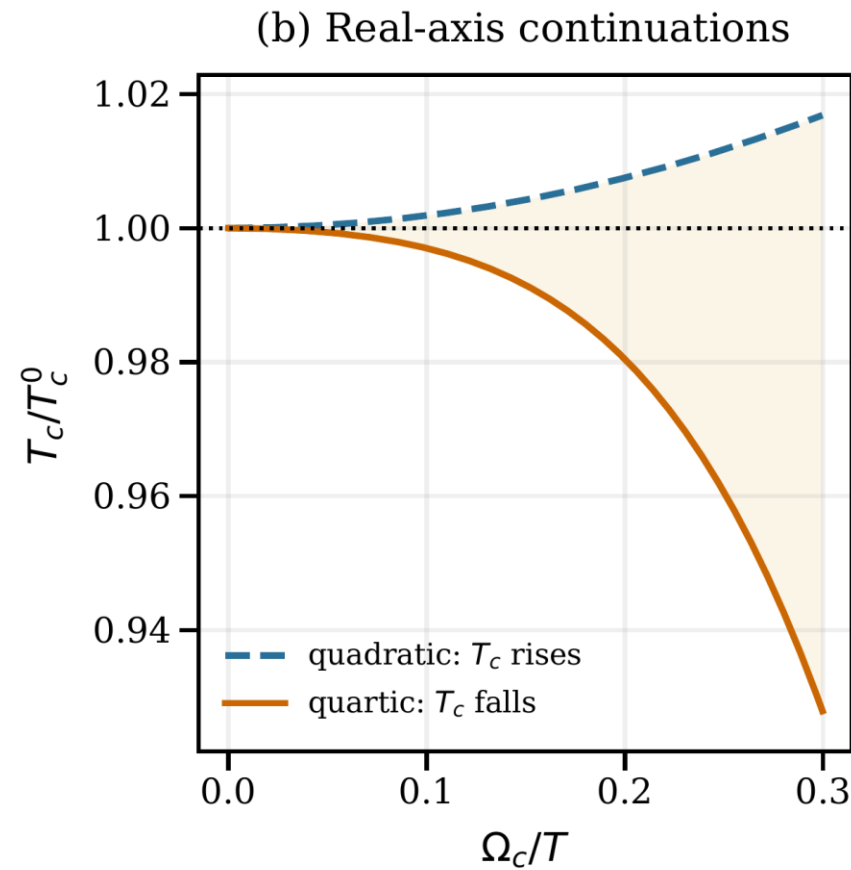
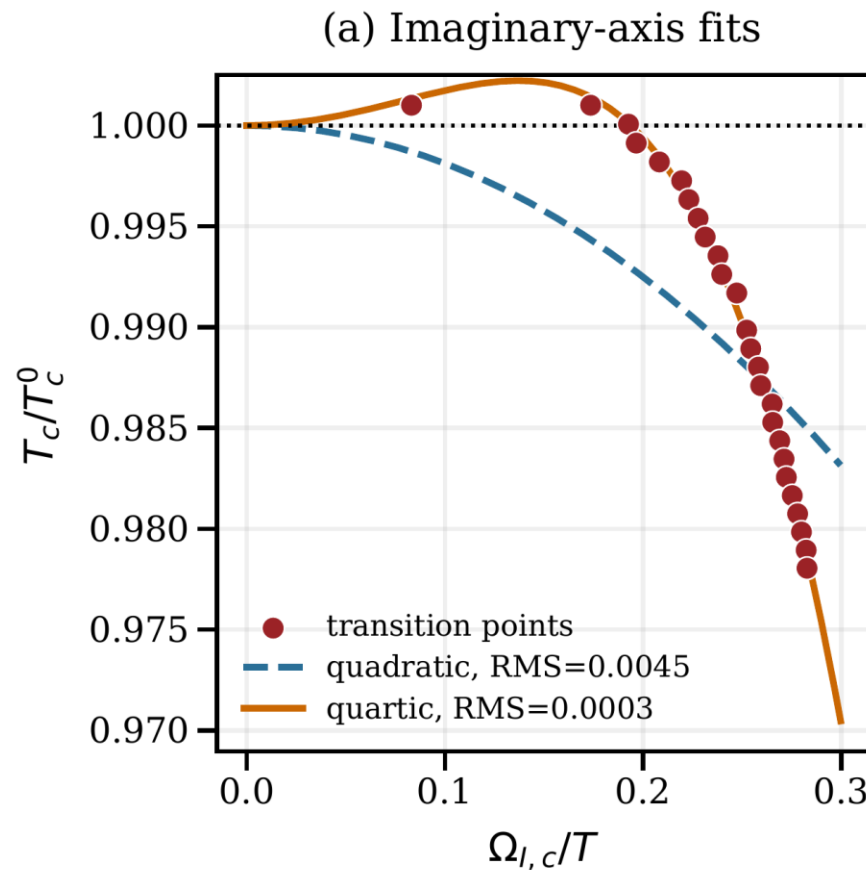


With quadratic term, the T_c decrease with **imaginary** rotation and **real** rotation can be at the same time true.

The predicted T_c decrease with real rotation can be seen in strong coupling limit

Ansatz is important when doing analytical continuation

- An example with $\beta=2.75$



The middle of the D-C-D phase structure

- The difference

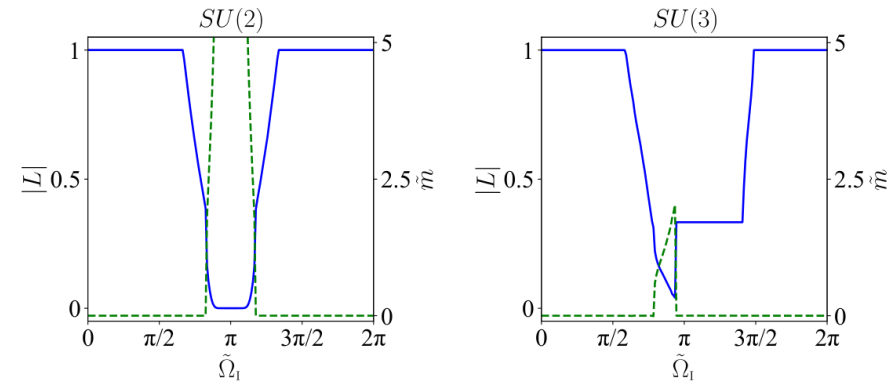
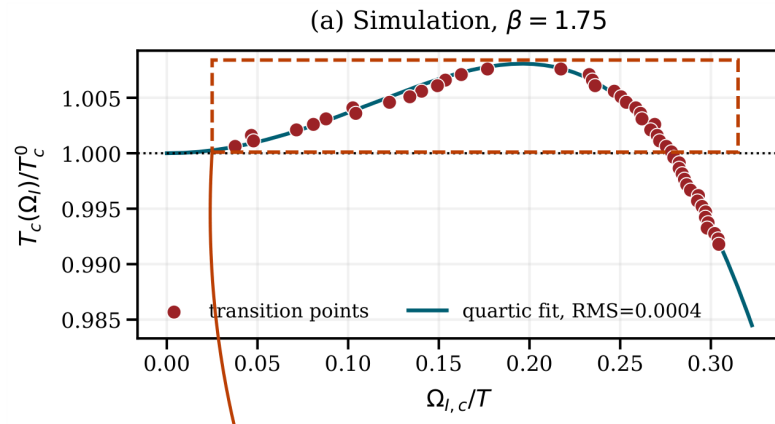
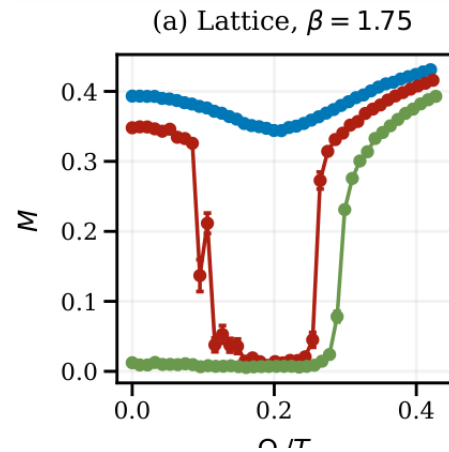
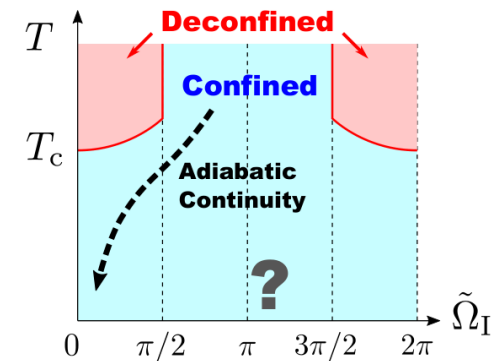
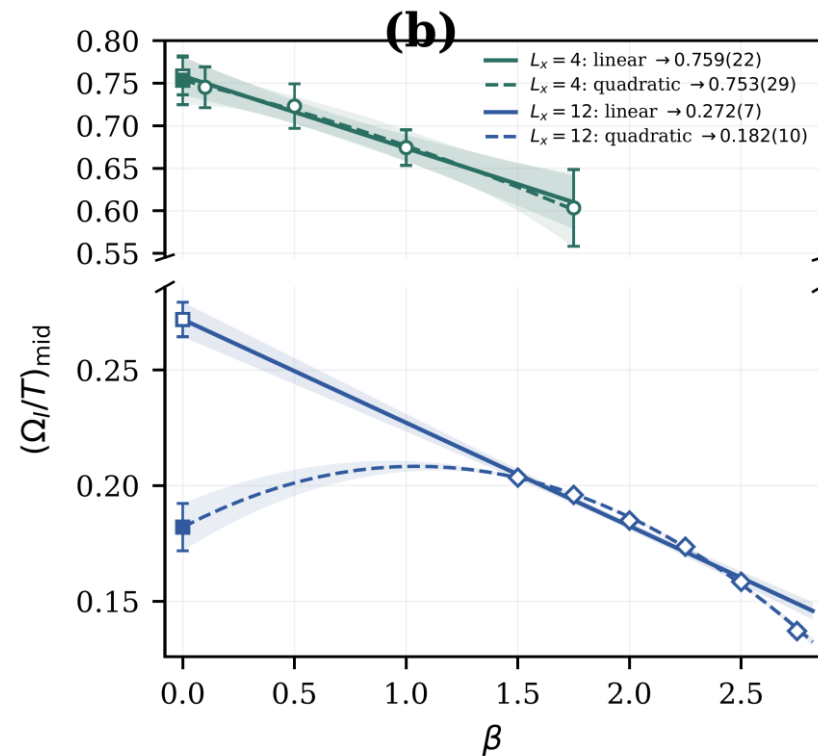
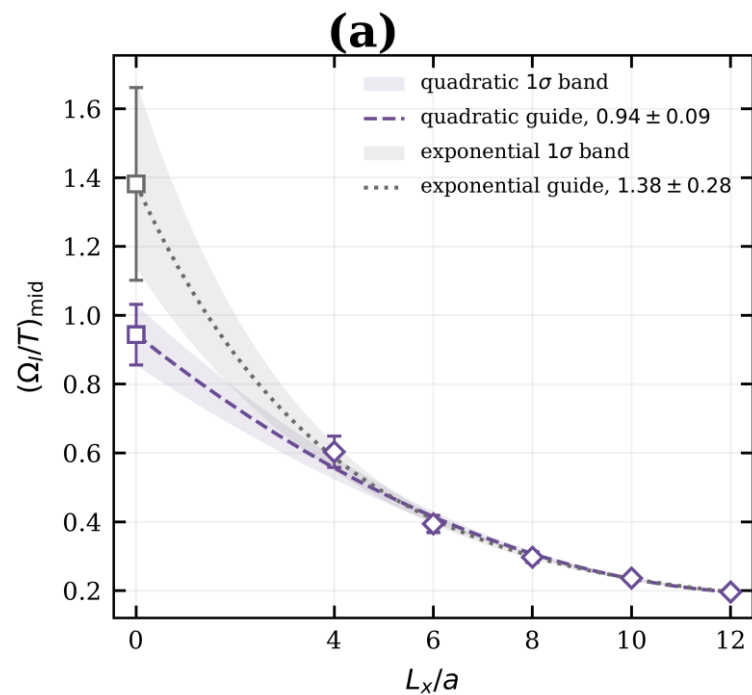


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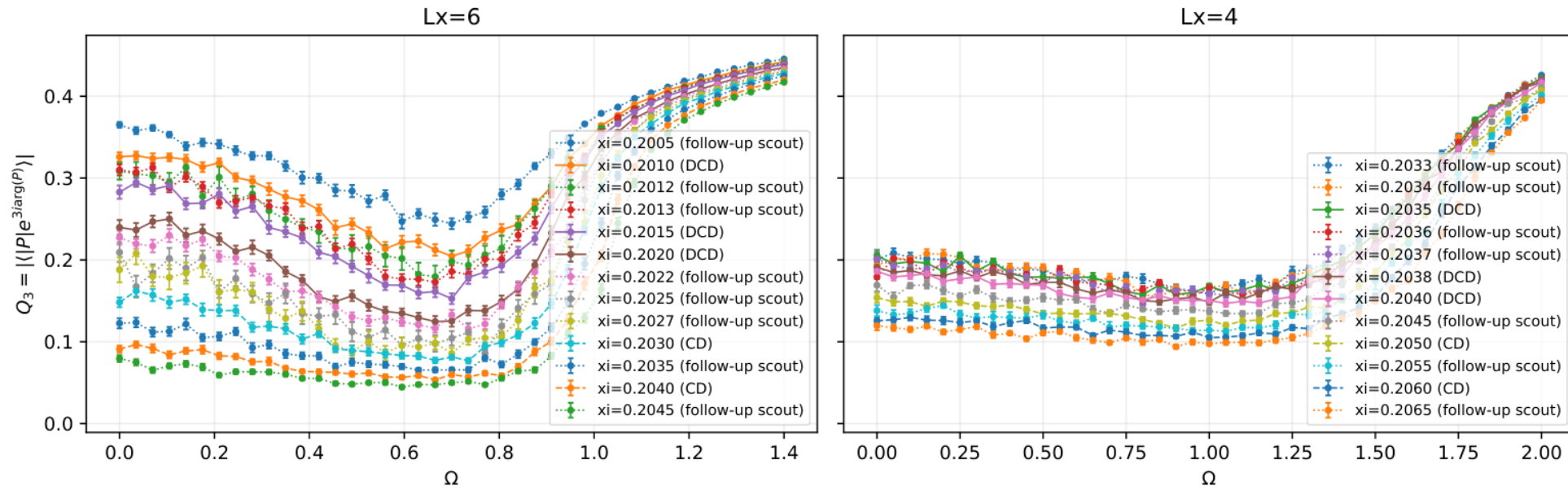
$L_x \rightarrow 0, \beta \rightarrow 0$



$$\begin{aligned}
 (\Omega_I/T)_{\text{mid}}(\ell, \beta) &\simeq 1.287 - 0.168\beta - 0.149\ell \\
 &\quad + 0.00477\ell^2 + 0.0183\beta\ell - 0.00202\beta^2\ell. \\
 (\Omega_I/T)_{\text{mid}}(\ell \rightarrow 0, \beta \rightarrow 0) &= 1.287(38).
 \end{aligned}$$

A note for $Lx=4, 6$

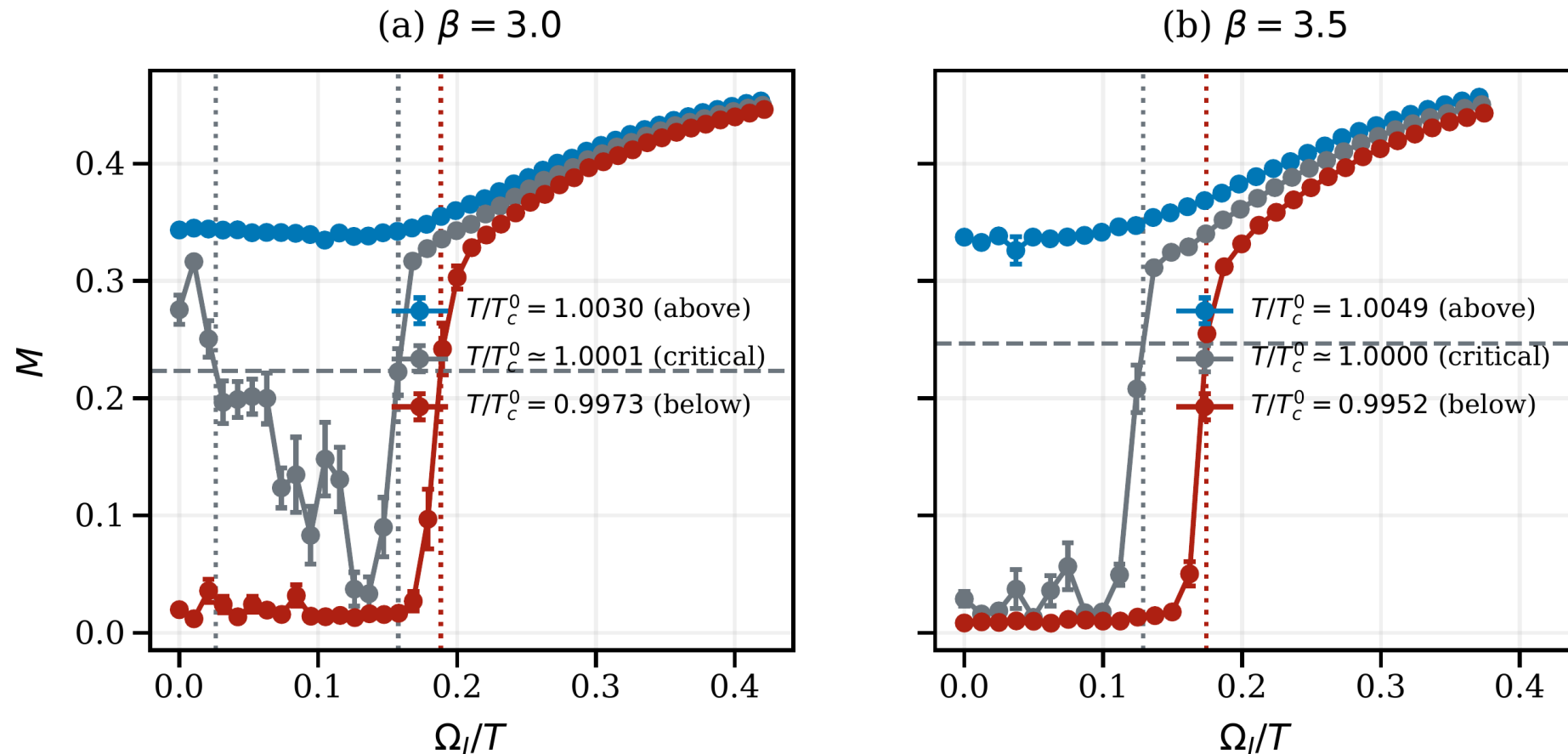
- D-C-D phase structure already gone



Can we go back to the old lattice results?

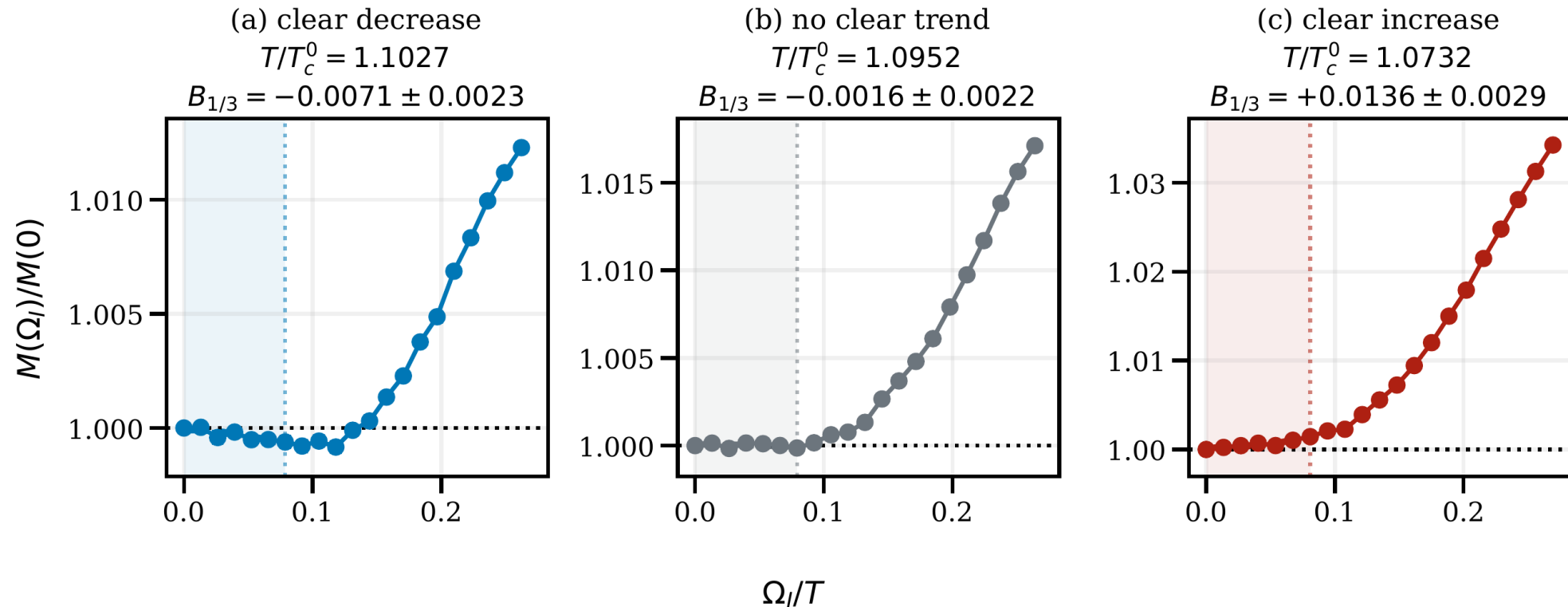
- Imaginary angular velocity decrease T_c
- The Polyakov loop increase with imaginary angular velocity

Evidence that D-C-D will disappear



Evidence that the Polyakov loop will not decrease

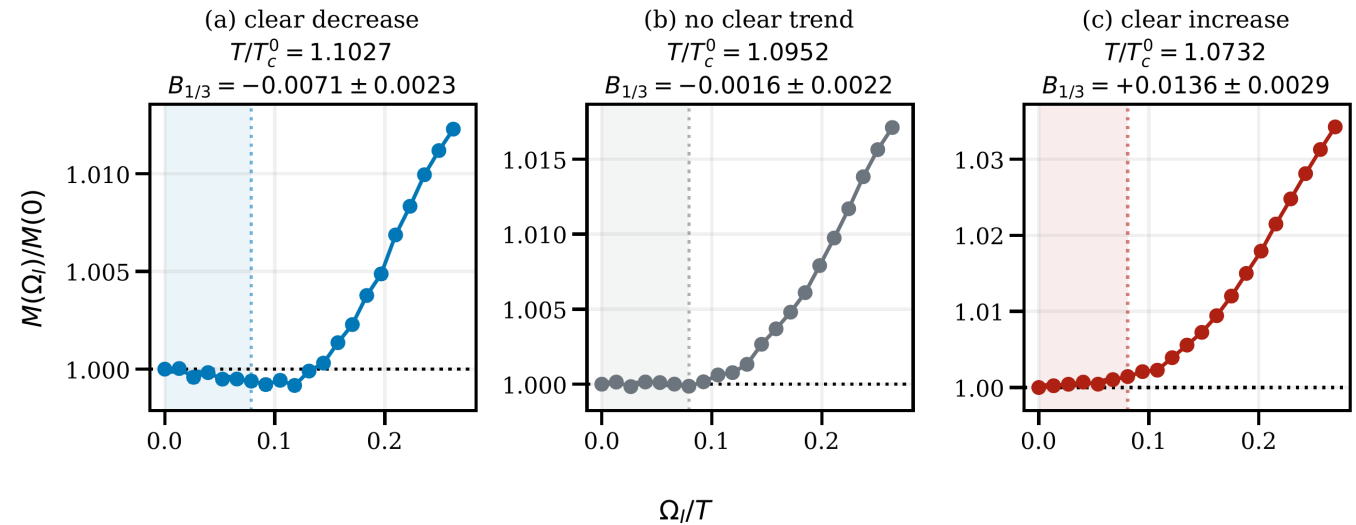
$\beta = 4.0$: full response curves



A criterion on the trend of Polyakov loop

$$\frac{M}{M(0)} - 1 = A + B_{1/3} \left(\frac{\Omega_I}{\Omega_I^{\max}} \right)^2, \\ 0 \leq \Omega_I / \Omega_I^{\max} \leq \frac{1}{3}.$$

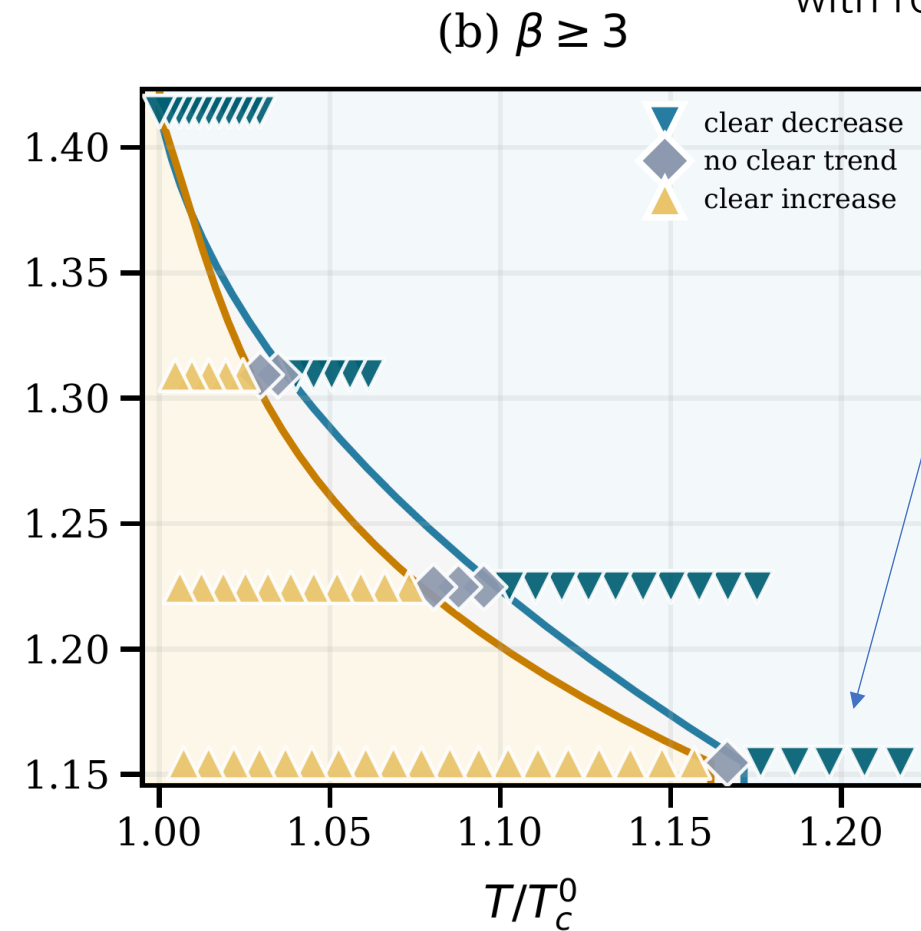
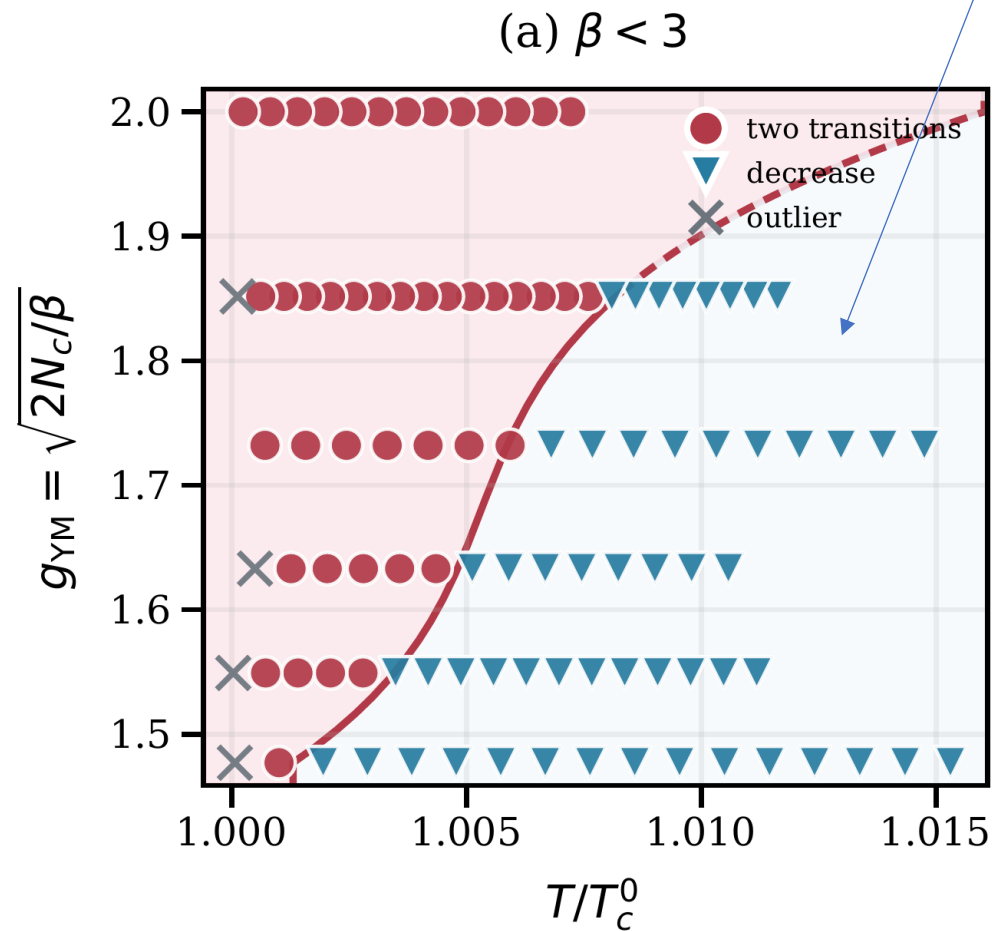
$\beta = 4.0$: full response curves



Different regions

Rotation cannot push down
Polyakov loop to deconfined phase

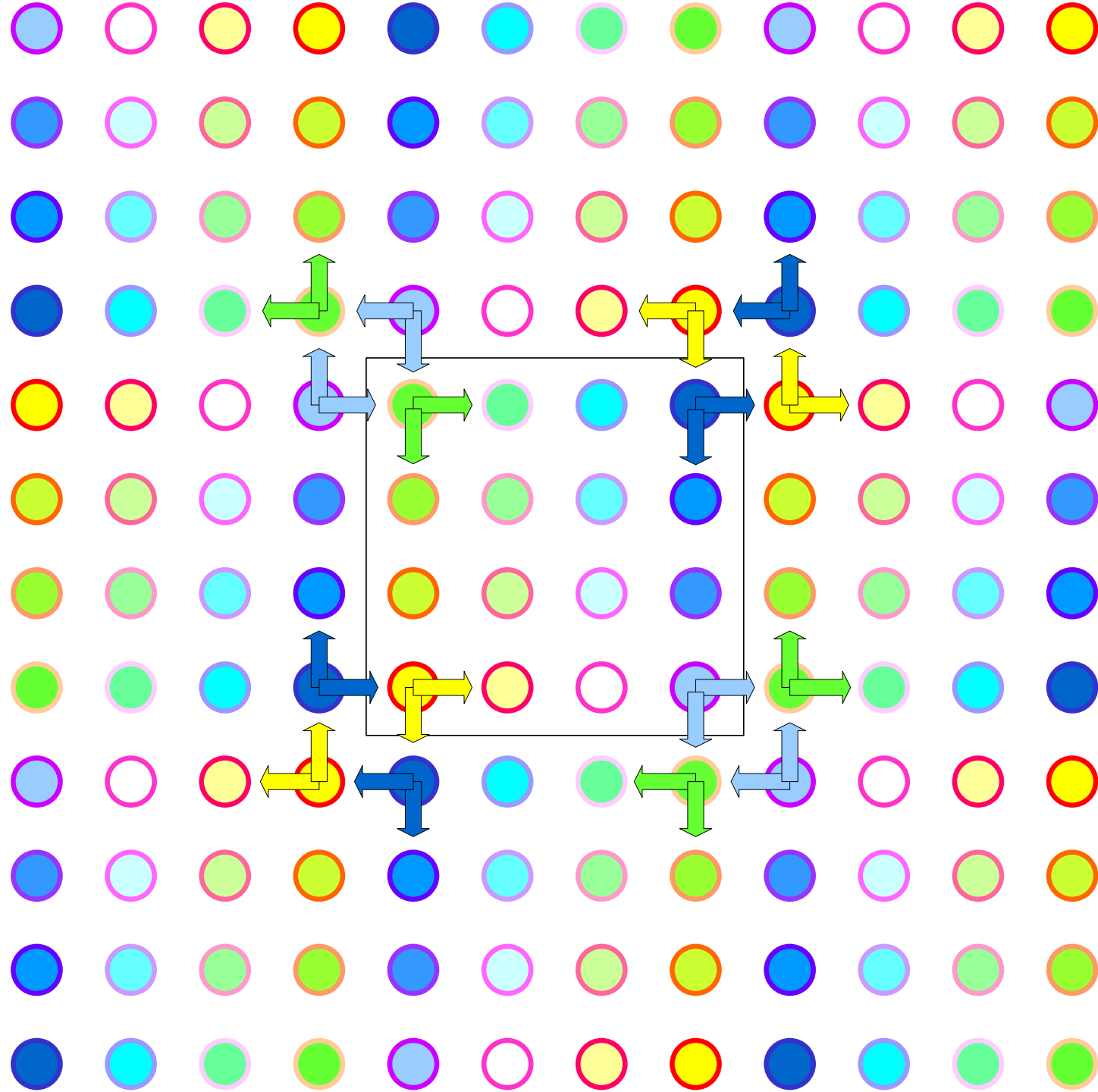
When beta > 4.5, one
need a very high
temperature to see
the Polyakov decrease
with rotation



Summary

- D-C-D phase structure confirmed in strong coupling limit.
- In strong coupling limit, T_c decrease with **real** angular velocity.
- Strong coupling is **not** QCD.
- (I guess) UV is important.

Thank you very much!



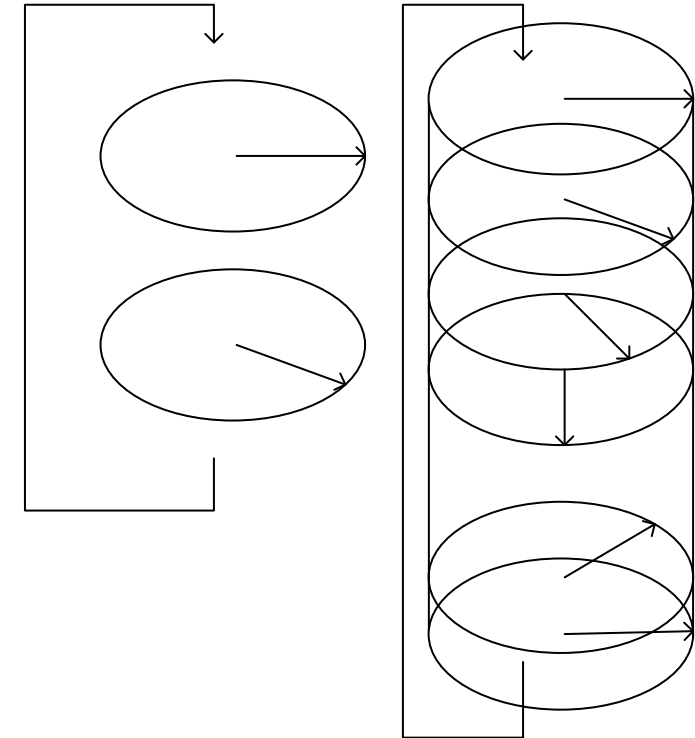
Rotwisted boundary condition

- [M. N. Chernodub et al. Phys.Rev.D 107 (2023) 11, 114502 • e-Print: 2209.15534]
- Change the periodic boundary condition in tau direction
- Redefine: $\phi = e^{-i\Omega_I \tau J_z} \psi$

$$\phi(\rho, \phi, z, \tau) = \Lambda \phi(\rho, \phi - \beta \Omega_I, z, \tau + \beta)$$

- In the case of square lattice

$$\Omega_I = n \frac{\pi T}{2}$$



Trajectories

beta	Lx	N_xi	Omega/xi	chains	trajectories
1.50	12	21	41	861	29.4 M
1.75	12	41	41	1681	55.5 M
2.00	12	31	31	961	31.9 M
2.25	12	31	41	1271	40.6 M
2.50	12	31	26	806	27.1 M
2.75	12	40	41	1640	51.4 M
3.00	12	15	41	615	20.2 M
3.25	12	26	23	598	19.0 M
3.50	12	16	31	496	15.9 M
4.00	12	28	21	588	18.6 M
4.50	12	31	19	589	18.9 M
total	12			10,106	328.6 M
0.1, 0.5, 1.0	4			1,700	79.4 M

Retained trajectories exclude the common 2000-trajectory thermalization cut; the 30 000-trajectory continuation stages are included. The beta = 1.75 finite-volume scans add Lx = 6, 8 and 10.

Dirichlet boundary

- Anisotropic lattice: $\beta=0.2$ and $\beta=3.0$

