Phase diagram of rotating gluodynamics and QCD matter

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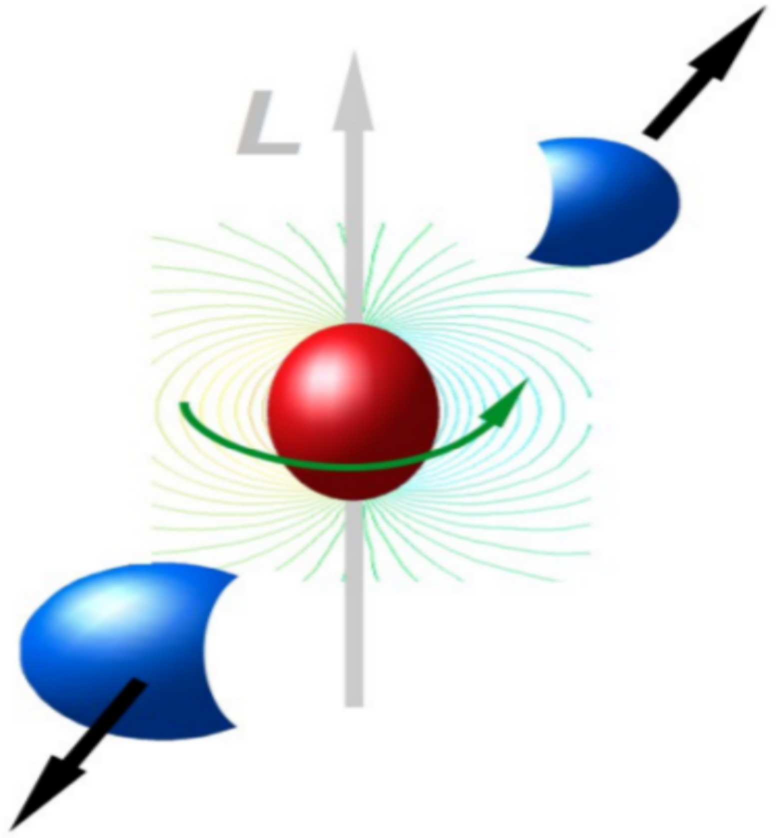
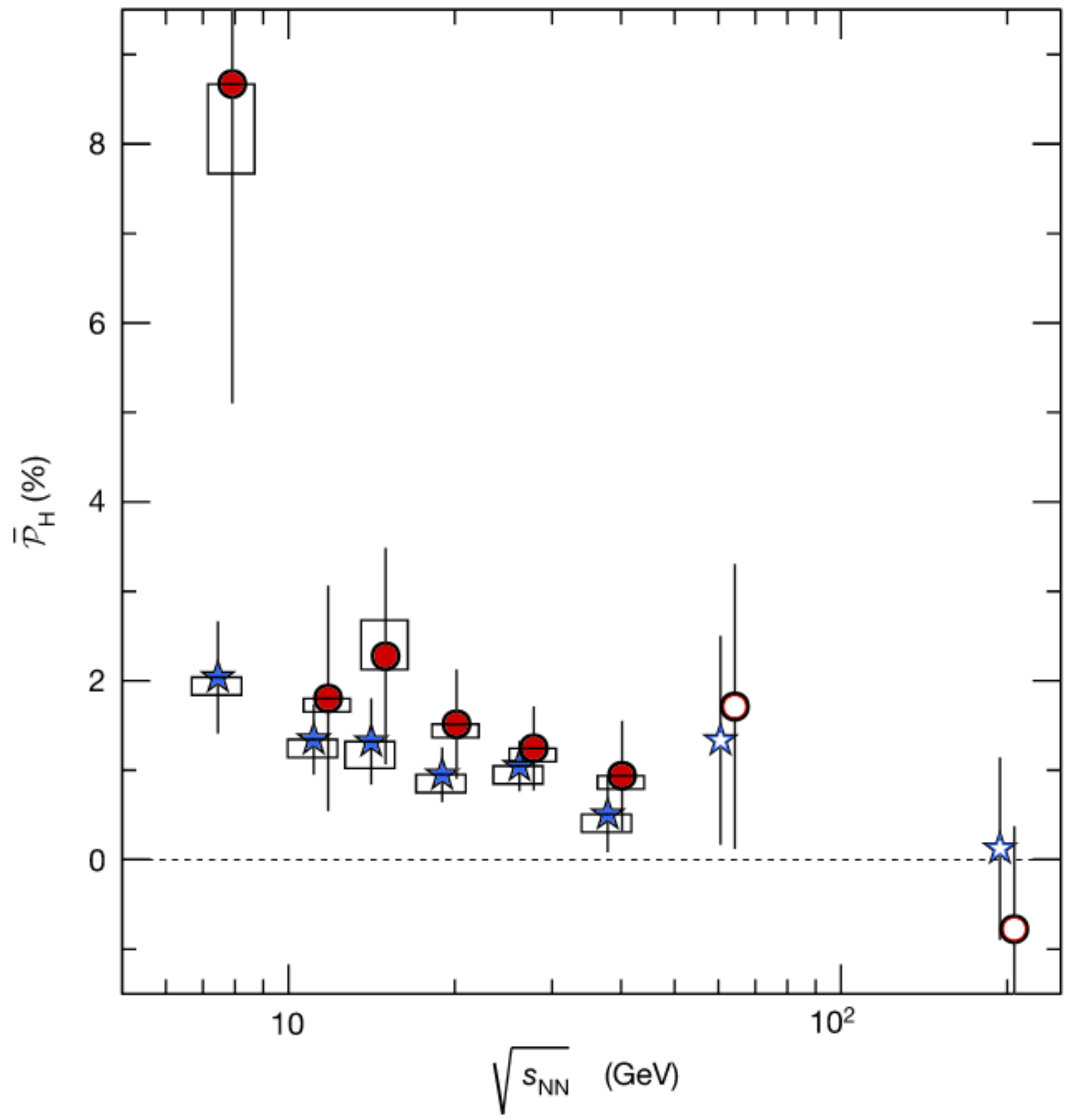
Talk by A. Roenko @ Lattice 2021 conference, arXiv:2110.12302

Rotation and heavy ion collisions

- Non-central heavy ion collisions

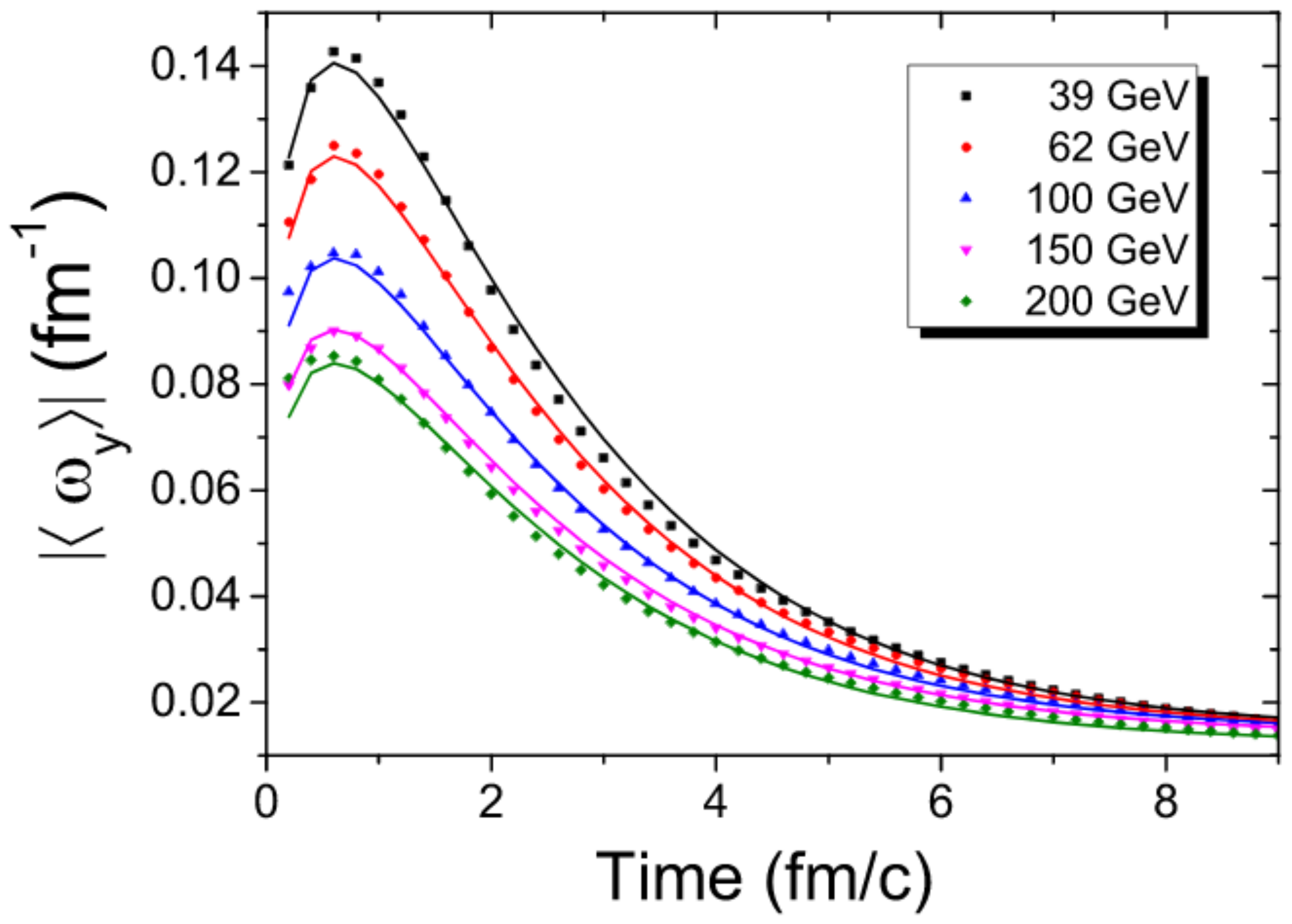


- Polarisation of Λ hyperons: $\Omega \sim 6$ MeV [STAR, 2017]



- Hydrodynamics, transport models: $\Omega \sim 20 - 40$ MeV

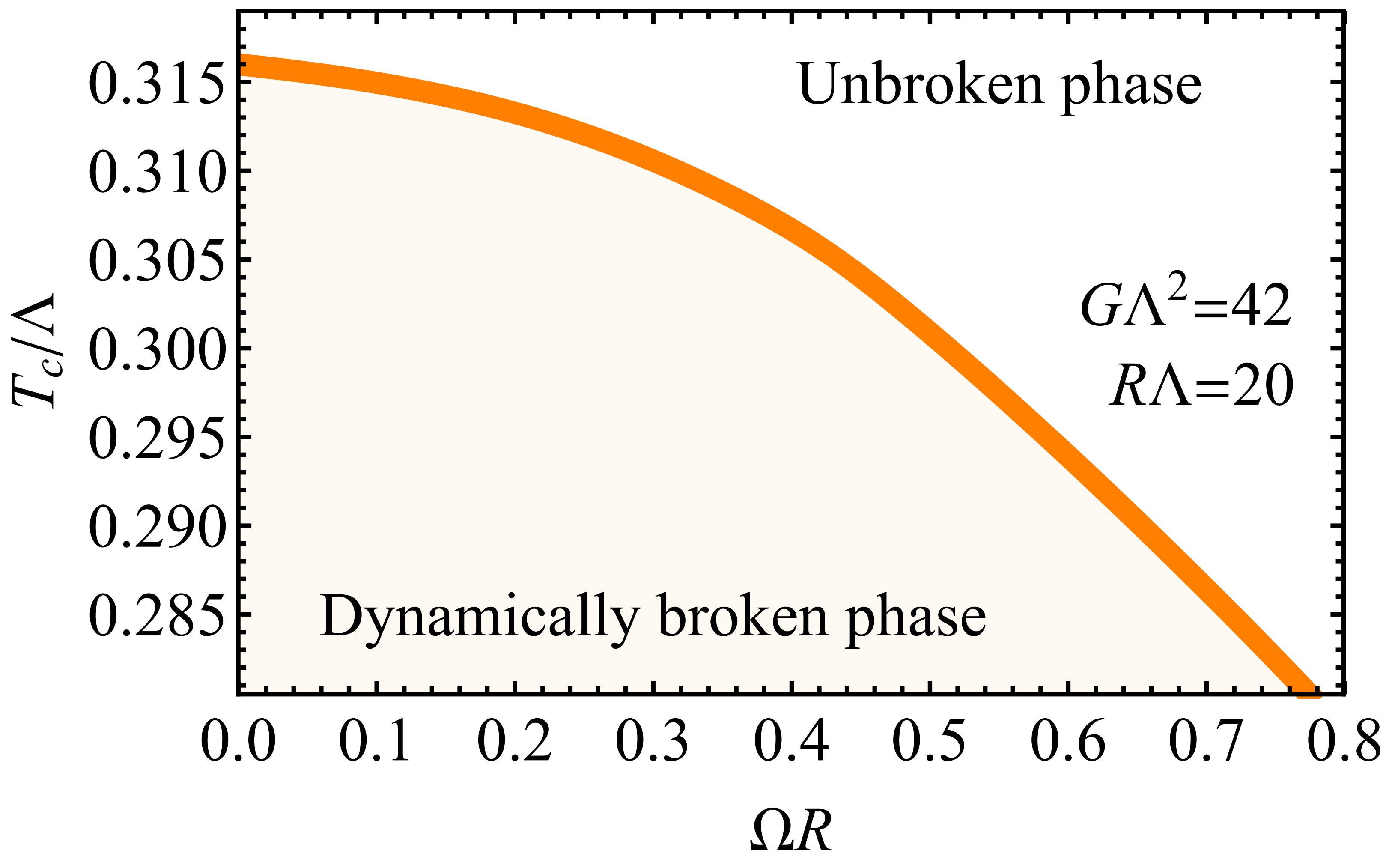
[F. Becattini et al., 2015] [Y.Jiang, Z.-W. Lin, J.Liao, 2016]



Rotation and QCD phase diagram

Rotation decreases the critical temperature of QCD phase transition

- Holography: [X. Chen et al., 2020]
- NJL [M. Chernodub and S. Gongyo, 2017][Y. Jiang and J. Liao, 2016] [H. Zhang, D. Hou, and J. Liao][X. Wang et al., 2019][S.Ebihara et al. 2019]…
- HRG model [Y. Fujimoto, K. Fukushima, and Y. Hidaka, 2021]



[M. Chernodub and S. Gongyo, 2017]

Possible mechanism: suppression of chiral condensate (spin-0 object)

[Y. Jiang and J. Liao, 2016]

Often: ignored the effect of rotating gluons

Can be checked on the lattice!

Rotation and lattice simulations

- Reference frame which rotates with the system with angular velocity Ω
- External gravitation field: [A.Yamamoto and Y. Hirono, 2013]

$$g_{\mu\nu} = \begin{pmatrix} 1 - r^2\Omega^2 & \Omega y & \Omega x & 0 \\ \Omega y & -1 & 0 & 0 \\ -\Omega x & 0 & -1 & 0 \\ 0 & 0 & 0 & -1 \end{pmatrix}$$

Gravitational field in rotating reference frame

$$g_{\mu\nu} = \begin{pmatrix} 1 - r^2\Omega^2 & \Omega y & \Omega x & 0 \\ \Omega y & -1 & 0 & 0 \\ -\Omega x & 0 & -1 & 0 \\ 0 & 0 & 0 & -1 \end{pmatrix}$$

Partition function:

$$Z = Tr \exp[-\beta \hat{H}] = \int DA \exp[-S_E]$$

Conserved Hamiltonian:

$$H = \int dV \sqrt{g_{00}} \epsilon(r)$$

Euclidean action:

$$S_E = \frac{1}{2g^2} \int d^4x \sqrt{g_E} g_E^{\mu\nu} g_E^{\alpha\beta} F^a_{\mu\alpha} F^a_{\nu\beta}$$

Euclidean action:

$$S_G = \frac{1}{2g^2} \int d^4x \Big[(1 - r^2\Omega^2) F^a_{xy} F^a_{xy} + (1 - y^2\Omega^2) F^a_{xz} F^a_{xz} + (1 - x^2\Omega^2) F^a_{yz} F^a_{yz} + F^a_{x\tau} F^a_{x\tau} + F^a_{y\tau} F^a_{y\tau} + F^a_{z\tau} F^a_{z\tau} -$$
$$- 2iy\Omega (F^a_{xy} F^a_{y\tau} + F^a_{xz} F^a_{z\tau}) + 2ix\Omega (F^a_{yx} F^a_{x\tau} + F^a_{yz} F^a_{z\tau}) - 2xy\Omega^2 F^a_{xz} F^a_{zy} \Big]$$

Gravitational field in rotating reference frame

Euclidean action:

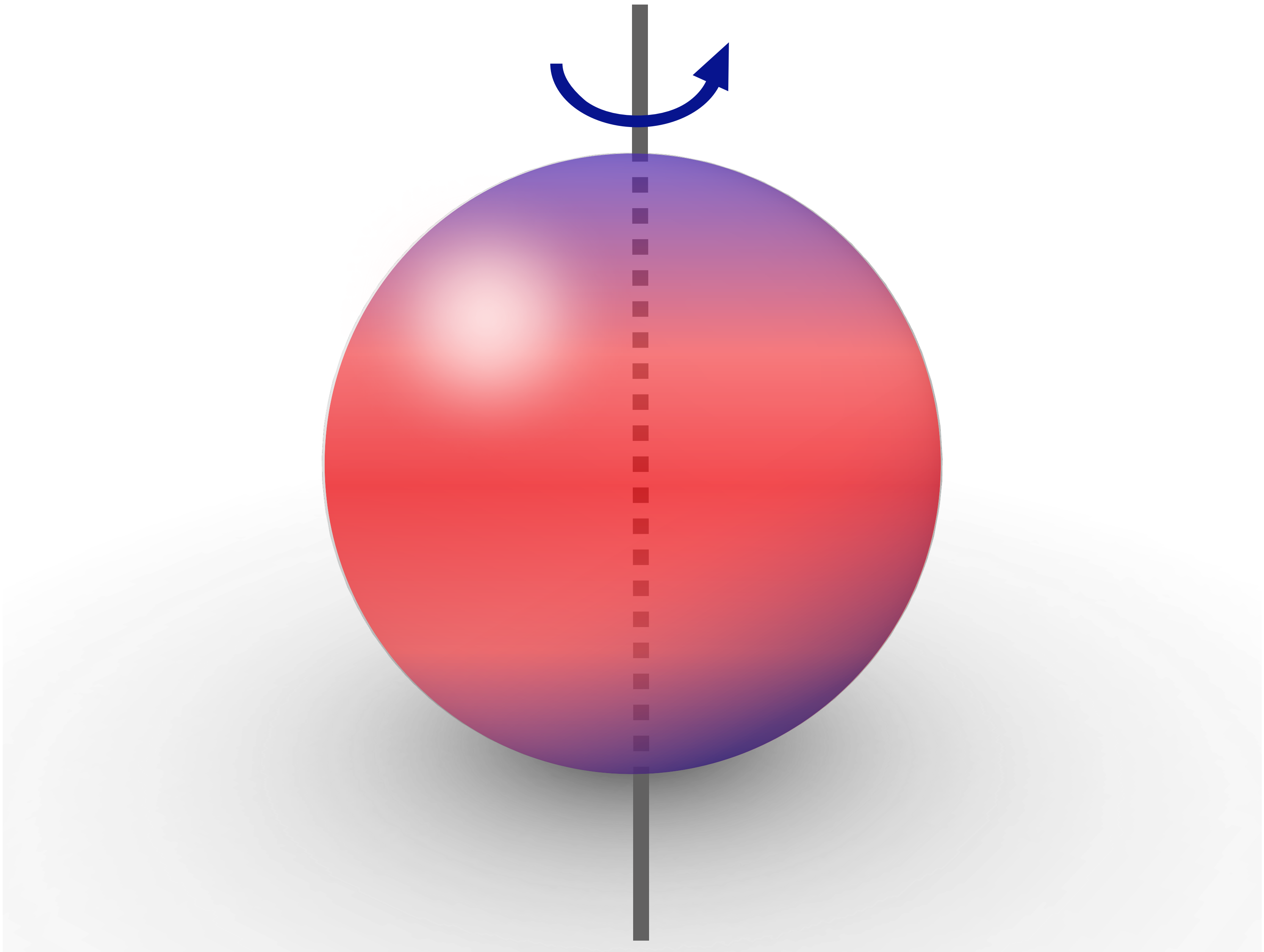
$$S_G = \frac{1}{2g^2}\int d^4x\Big[(1-r^2\Omega^2)F^a_{xy}F^a_{xy} + (1-y^2\Omega^2)F^a_{xz}F^a_{xz} + (1-x^2\Omega^2)F^a_{yz}F^a_{yz} + F^a_{x\tau}F^a_{x\tau} + F^a_{y\tau}F^a_{y\tau} + F^a_{z\tau}F^a_{z\tau} -$$

$$-2iy\Omega(F^a_{xy}F^a_{y\tau} + F^a_{xz}F^a_{z\tau}) + 2ix\Omega(F^a_{yx}F^a_{x\tau} + F^a_{yz}F^a_{z\tau}) - 2xy\Omega^2F^a_{xz}F^a_{zy}\Big]$$

- Sign problem
- Imaginary angular velocity $\Omega \to \Omega_I = -i\Omega$
- Analytical continuation

Ehrenfest-Tolman effect

- $T(r) \neq$ const, but $T(r)\sqrt{g_{00}} =$ const
- Rotation: $T(r)\sqrt{1 - r^2\Omega^2} =$ const $= T(r = 0)$
- $T(r) > T(0)$: rotation warms up the periphery



Lattice setup

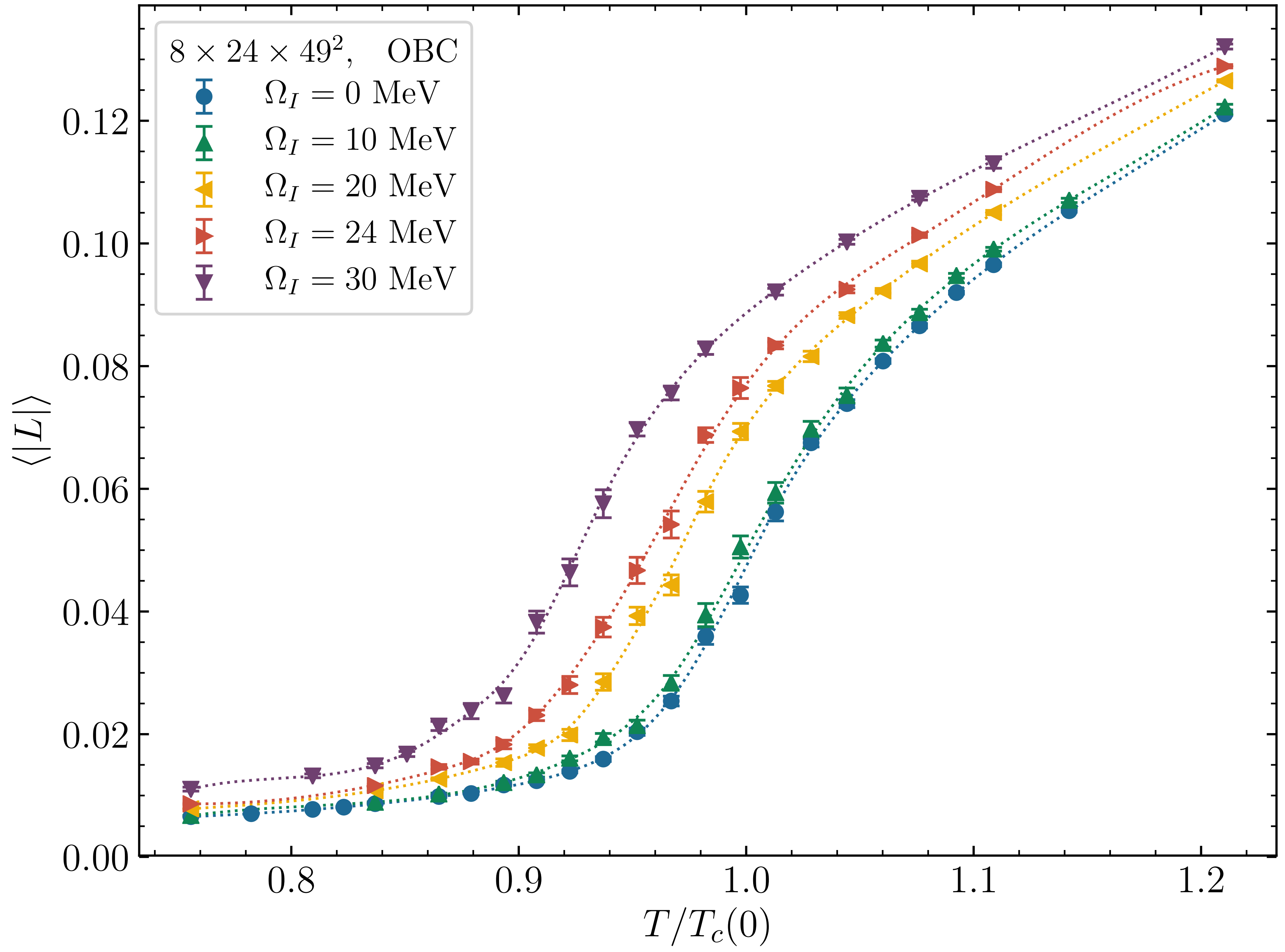
- Lattice size: $N_t \times N_z \times N_s^2$, rotation around z-axis
- $\Omega r < 1 \Rightarrow$ Importance of boundary conditions
- In any approach results depend on BC!
- In z, t directions: periodic BC

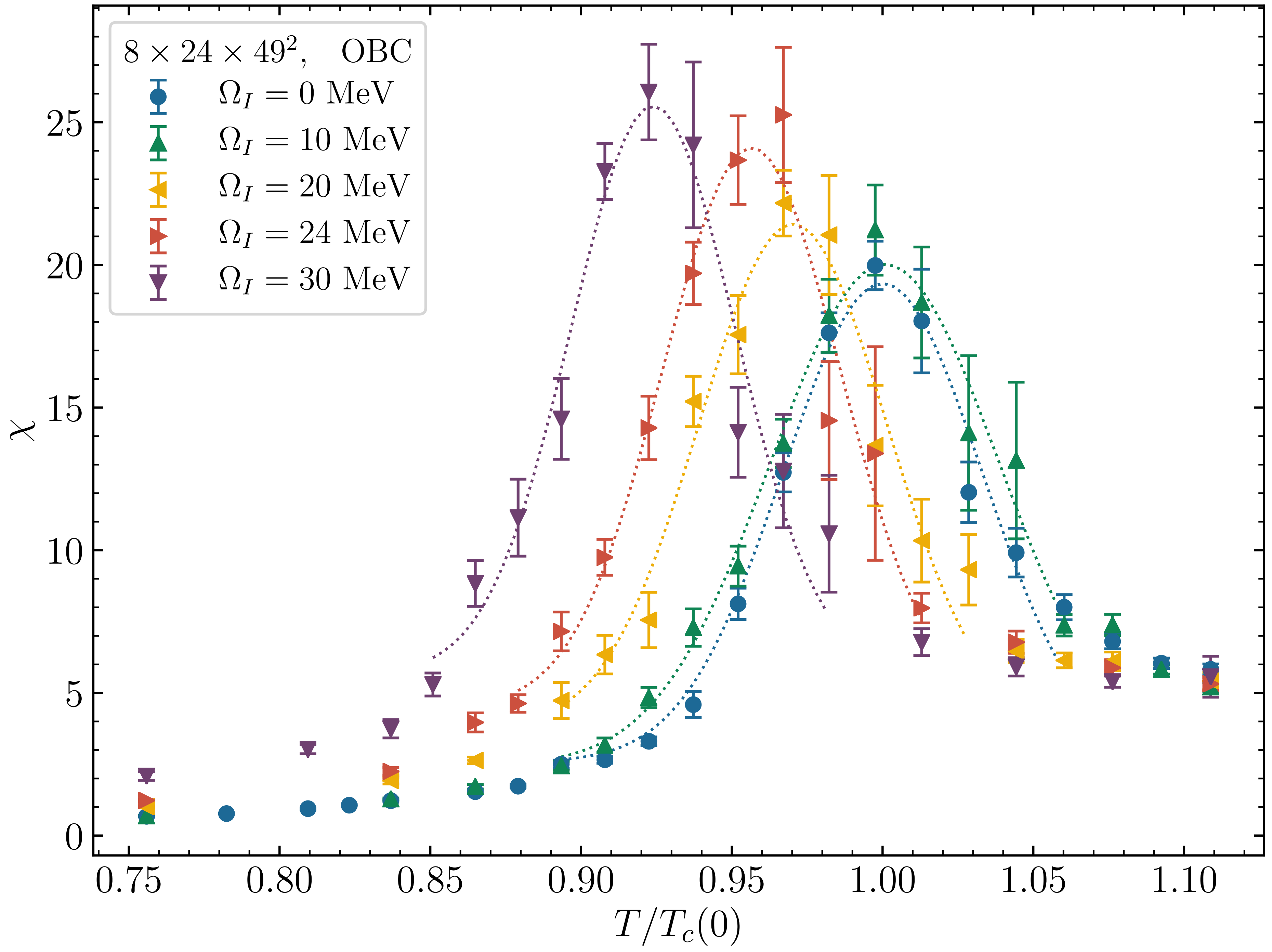
Boundary conditions

- Open:
  - Links outside of the lattice excluded
  - does not break any symmetries
  - «low» temperature on the boundary
- Dirichlet:
  - $U_\mu = 1$ at the boundary
  - Polyakov loop $L = 3$ at the boundary, «high» temperature on the boundary
  - violate center Z_3 symmetry
- Periodic:
  - not consistent with velocity distribution

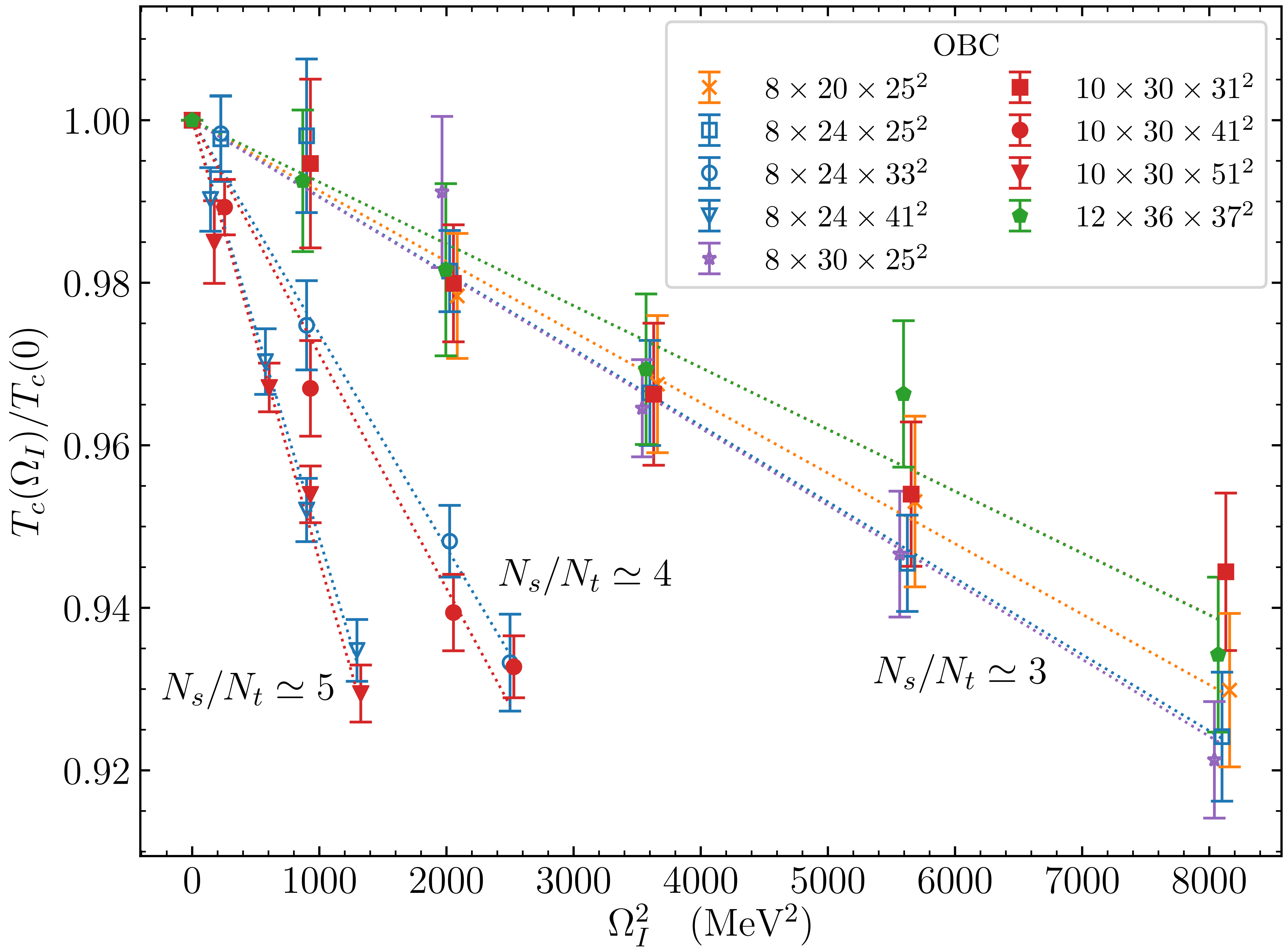
Polyakov loop and its susceptibility

Open boundary conditions





Critical temperature (OBC) vs angular velocity



$$\frac{T_c(\Omega_I)}{T_c(0)} = 1 - C_2\Omega_I^2$$

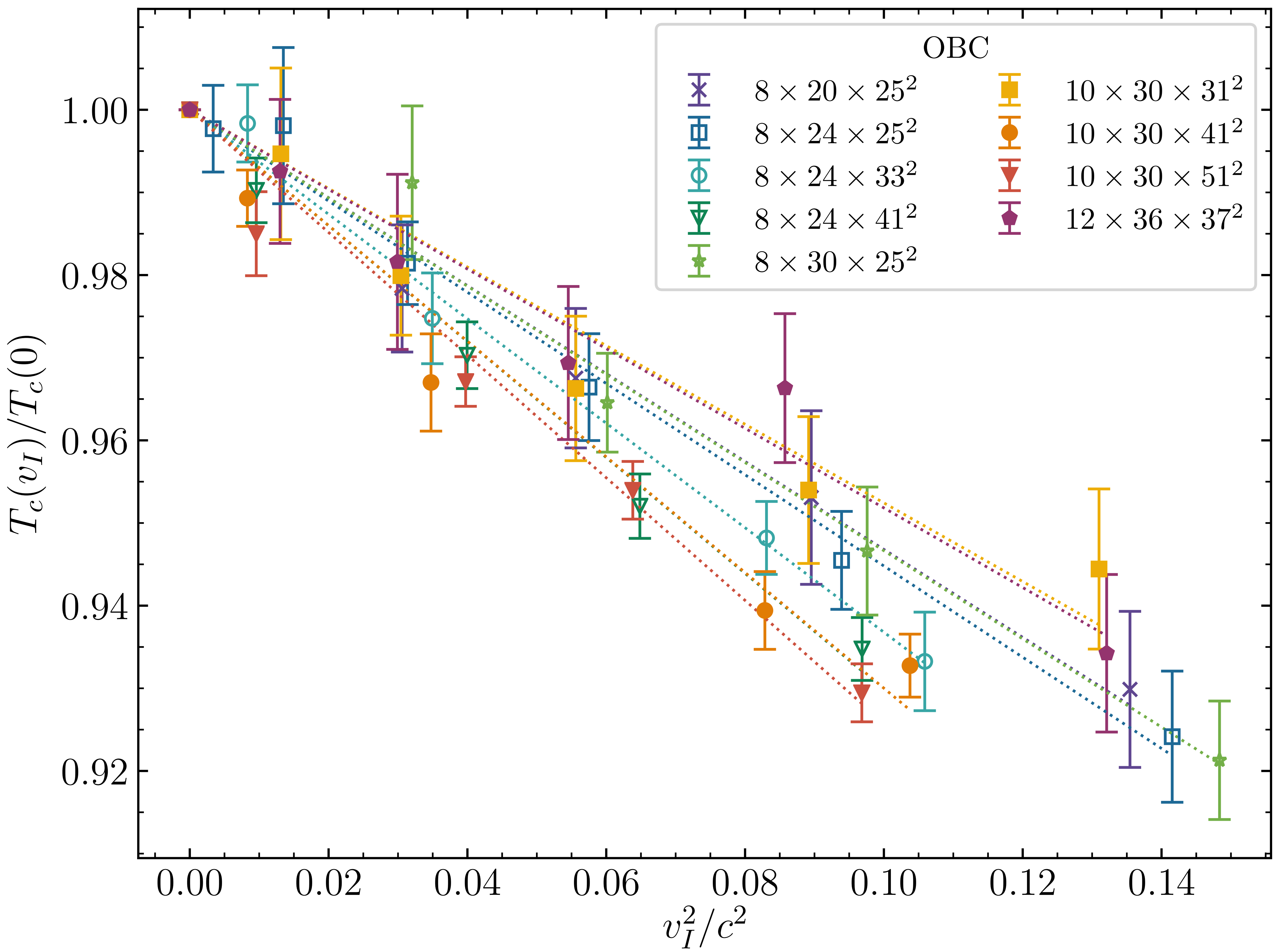
$C_2 > 0$ depends on aspect ratio (or N_s)

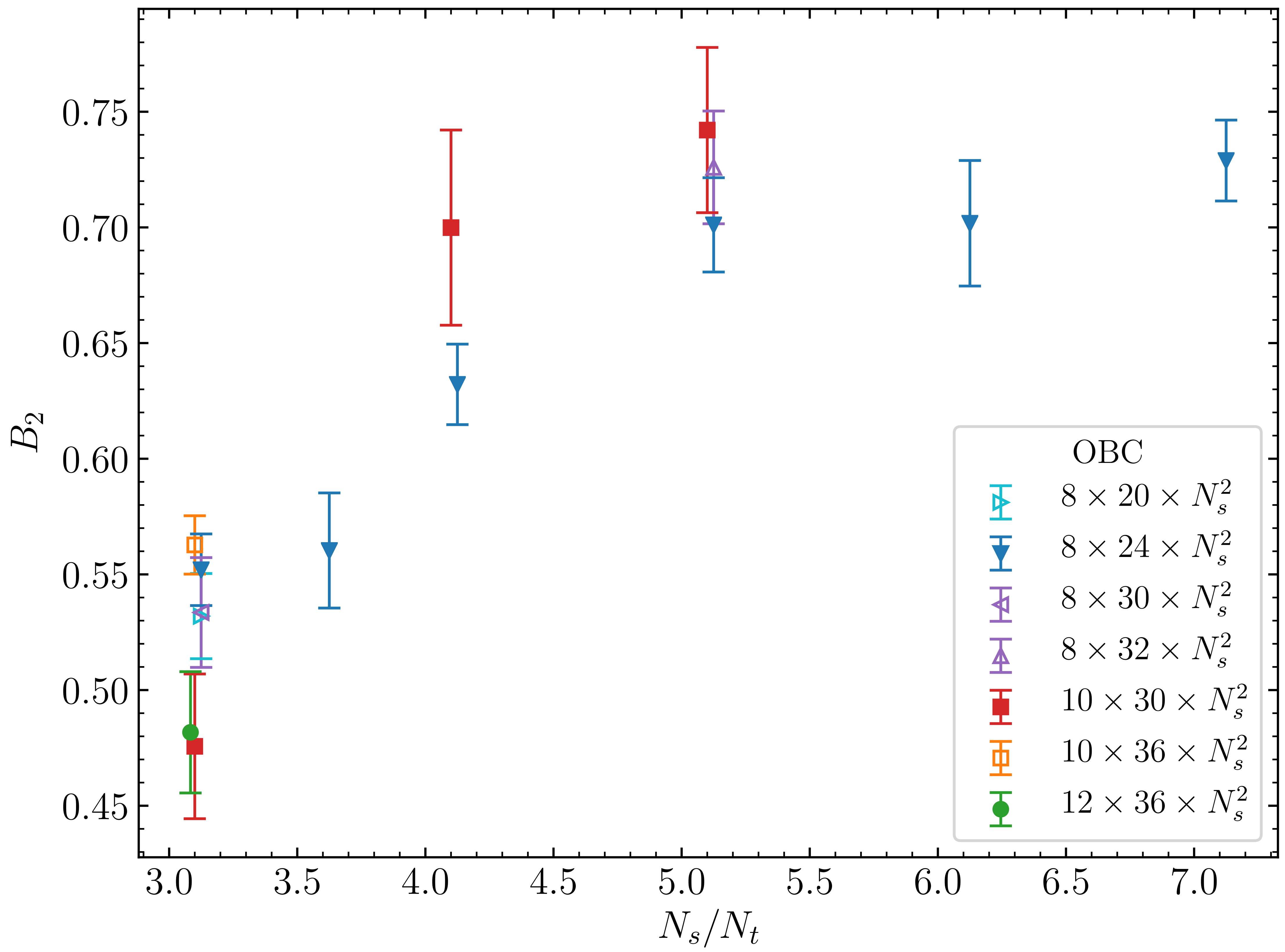
Analytic continuation:

$$\frac{T_c(\Omega)}{T_c(0)} = 1 + C_2\Omega^2$$

Critical temperature T_c of the confinement-deconfinement phase transition grows with (real) angular velocity - in contradiction with theoretical studies

Critical temperature (OBC) vs velocity at the boundary

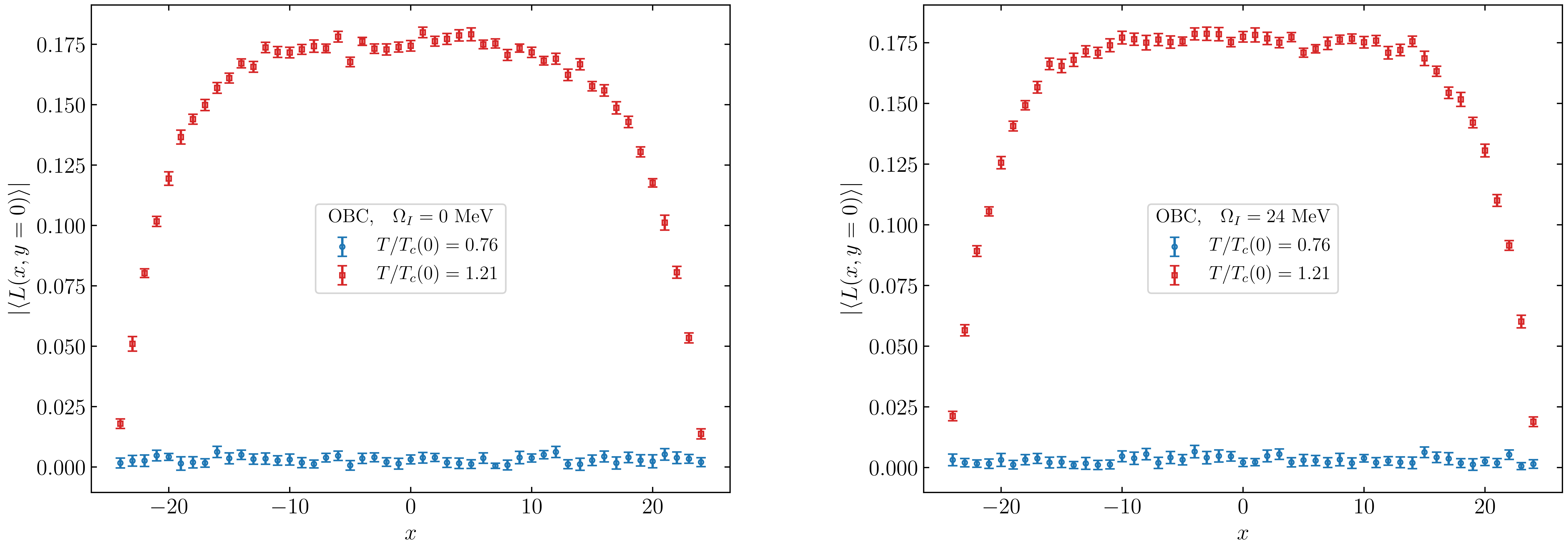




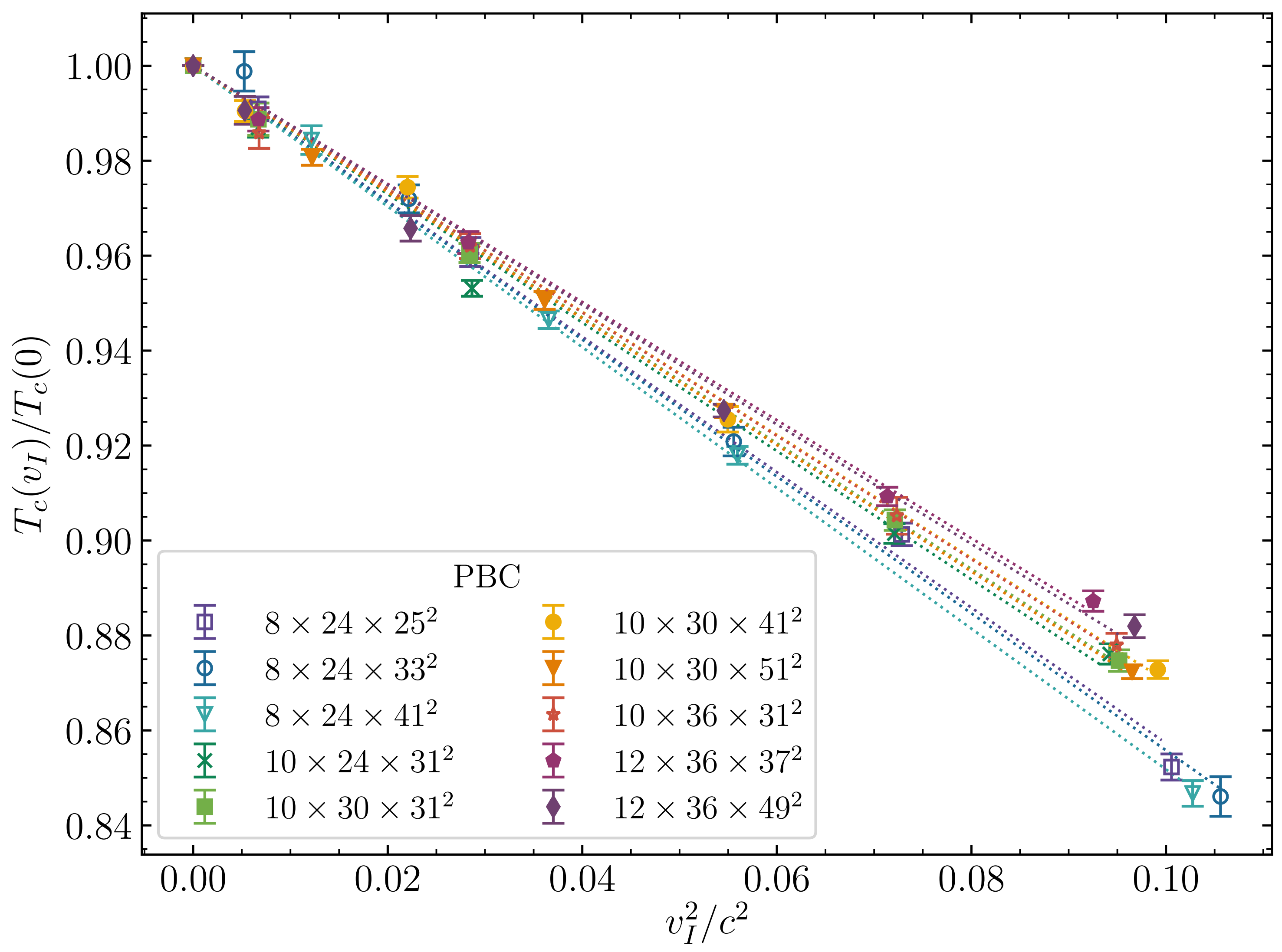
Velocity at the boundary $v_I = \Omega_I(N_s - 1)a/2$:

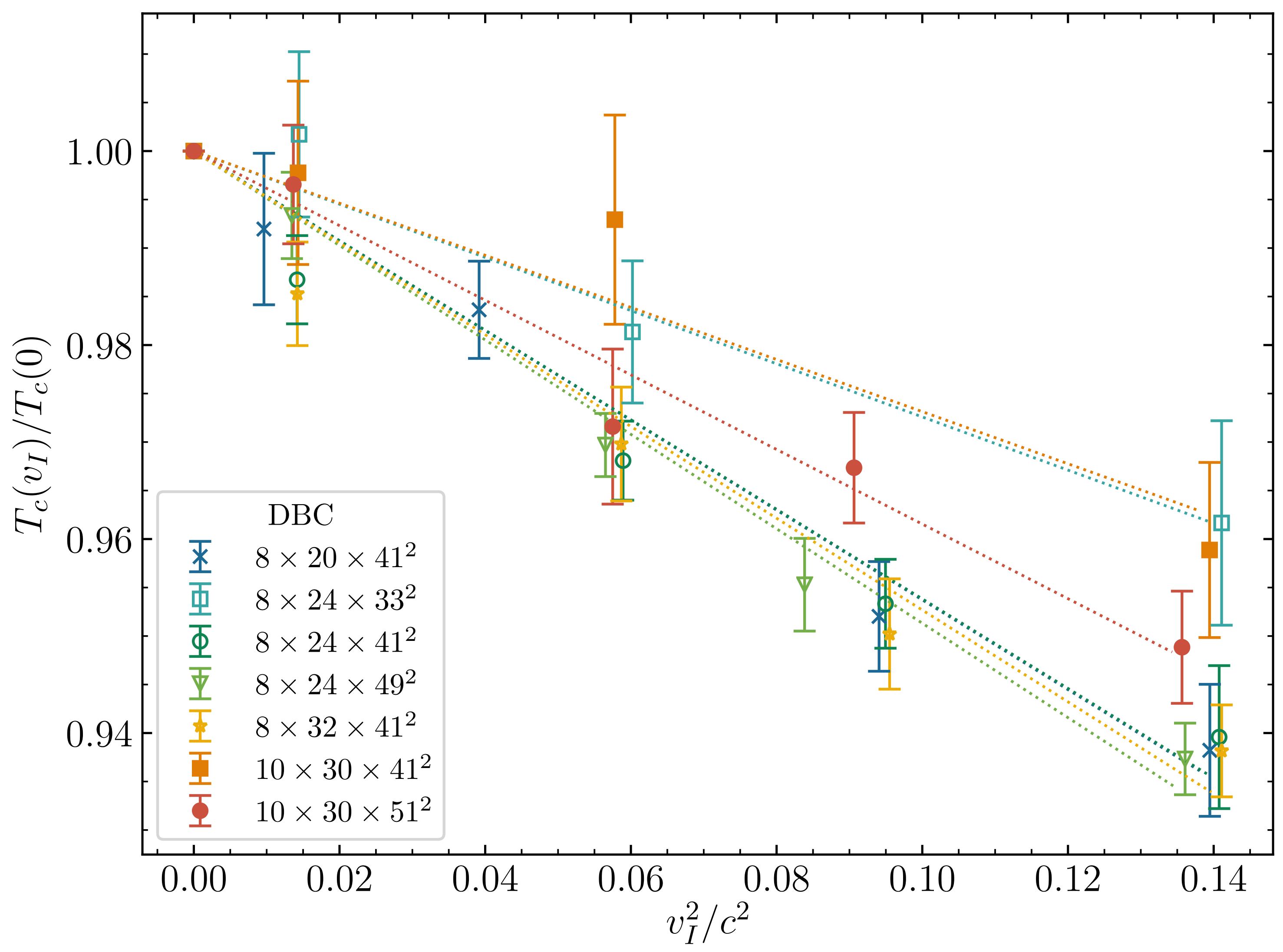
$$\frac{T_c(v_I)}{T_c(0)} = 1 - B_2 v_I^2 \Longrightarrow \frac{T_c(v)}{T_c(0)} = 1 + B_2 v^2;$$ at large size $B_2 \sim 0.7$

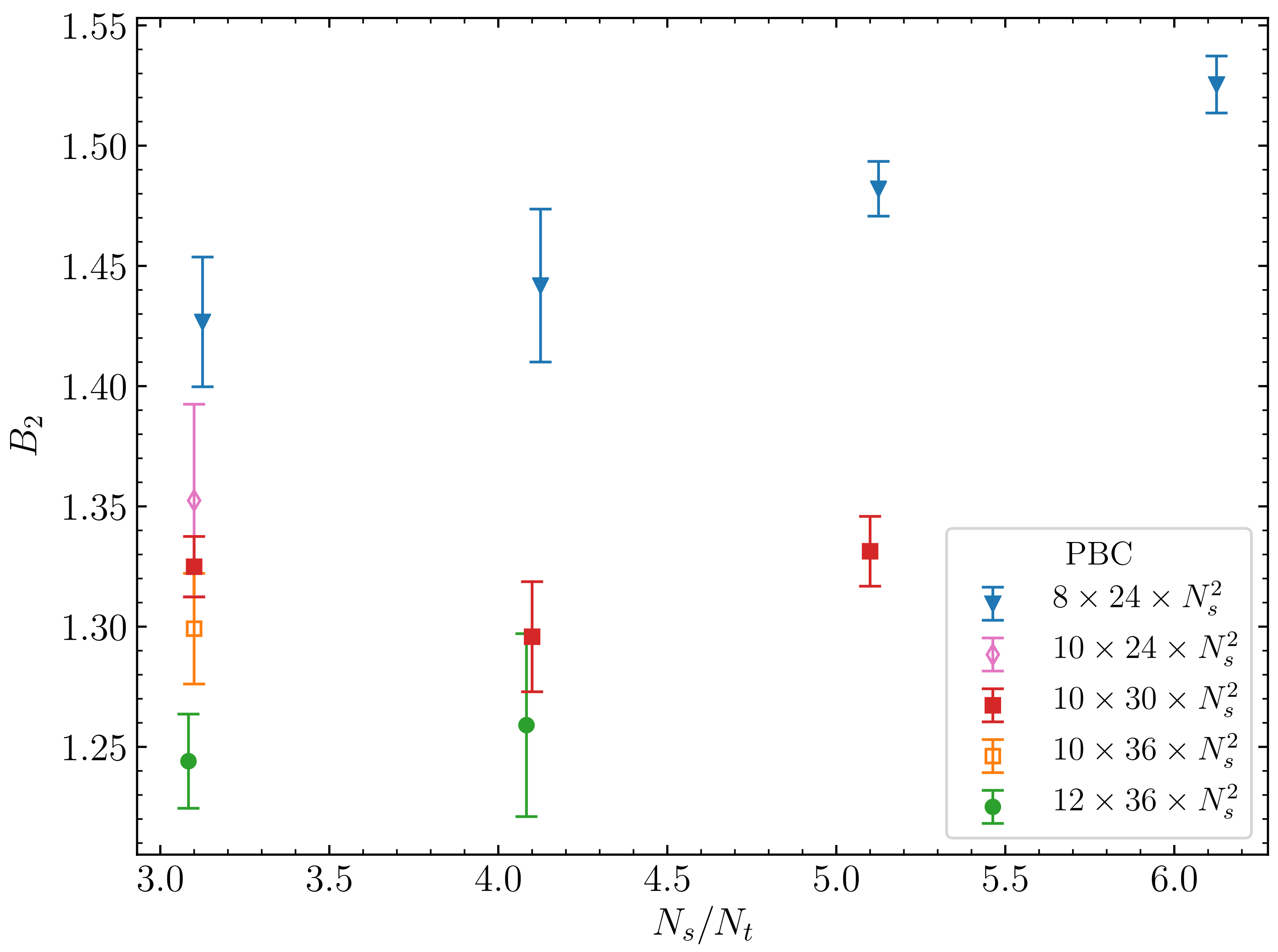
Polyakov loop distribution

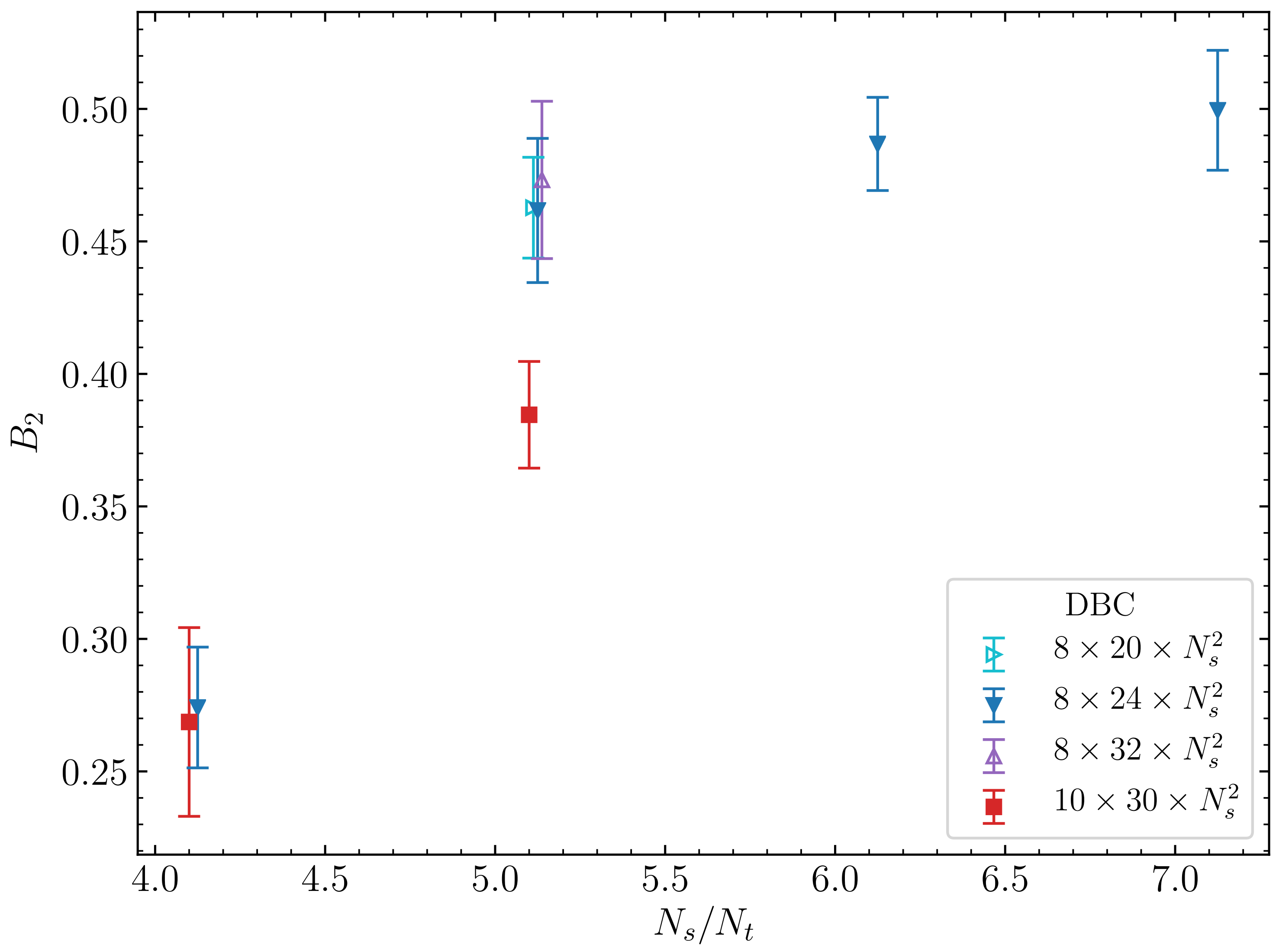


Other BC


PBC
$T_c(v_I)/T_c(0)$
v_I^2/c^2
$8 \times 24 \times 25^2$
$8 \times 24 \times 33^2$
$8 \times 24 \times 41^2$
$10 \times 24 \times 31^2$
$10 \times 30 \times 31^2$
$10 \times 30 \times 41^2$
$10 \times 30 \times 51^2$
$10 \times 36 \times 31^2$
$12 \times 36 \times 37^2$
$12 \times 36 \times 49^2$


DBC
$T_c(v_I)/T_c(0)$
v_I^2/c^2
$8 \times 20 \times 41^2$
$8 \times 24 \times 33^2$
$8 \times 24 \times 41^2$
$8 \times 24 \times 49^2$
$8 \times 32 \times 41^2$
$10 \times 30 \times 41^2$
$10 \times 30 \times 51^2$

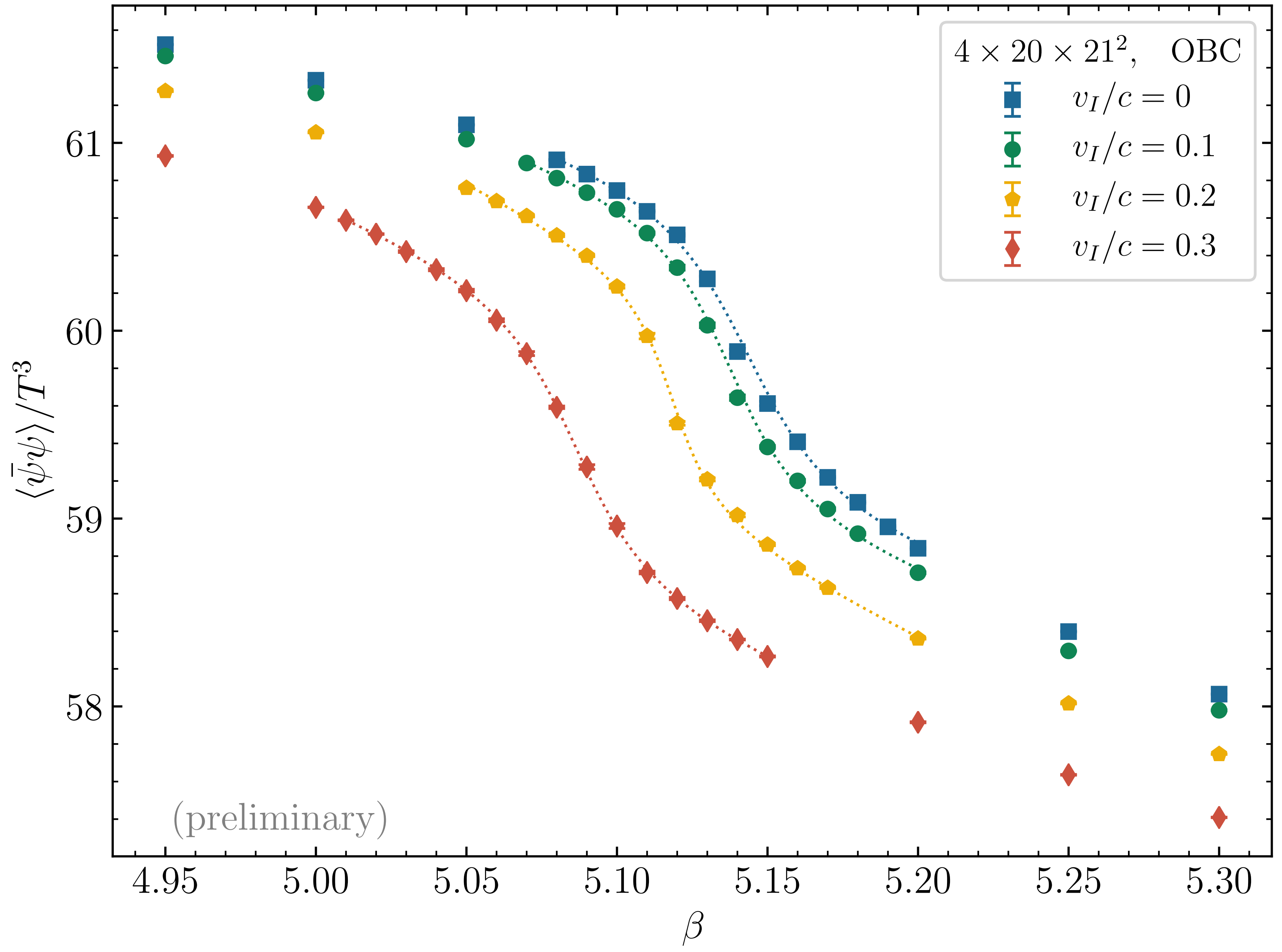

PBC
B_2
N_s/N_t
$8 \times 24 \times N_s^2$
$10 \times 24 \times N_s^2$
$10 \times 30 \times N_s^2$
$10 \times 36 \times N_s^2$
$12 \times 36 \times N_s^2$

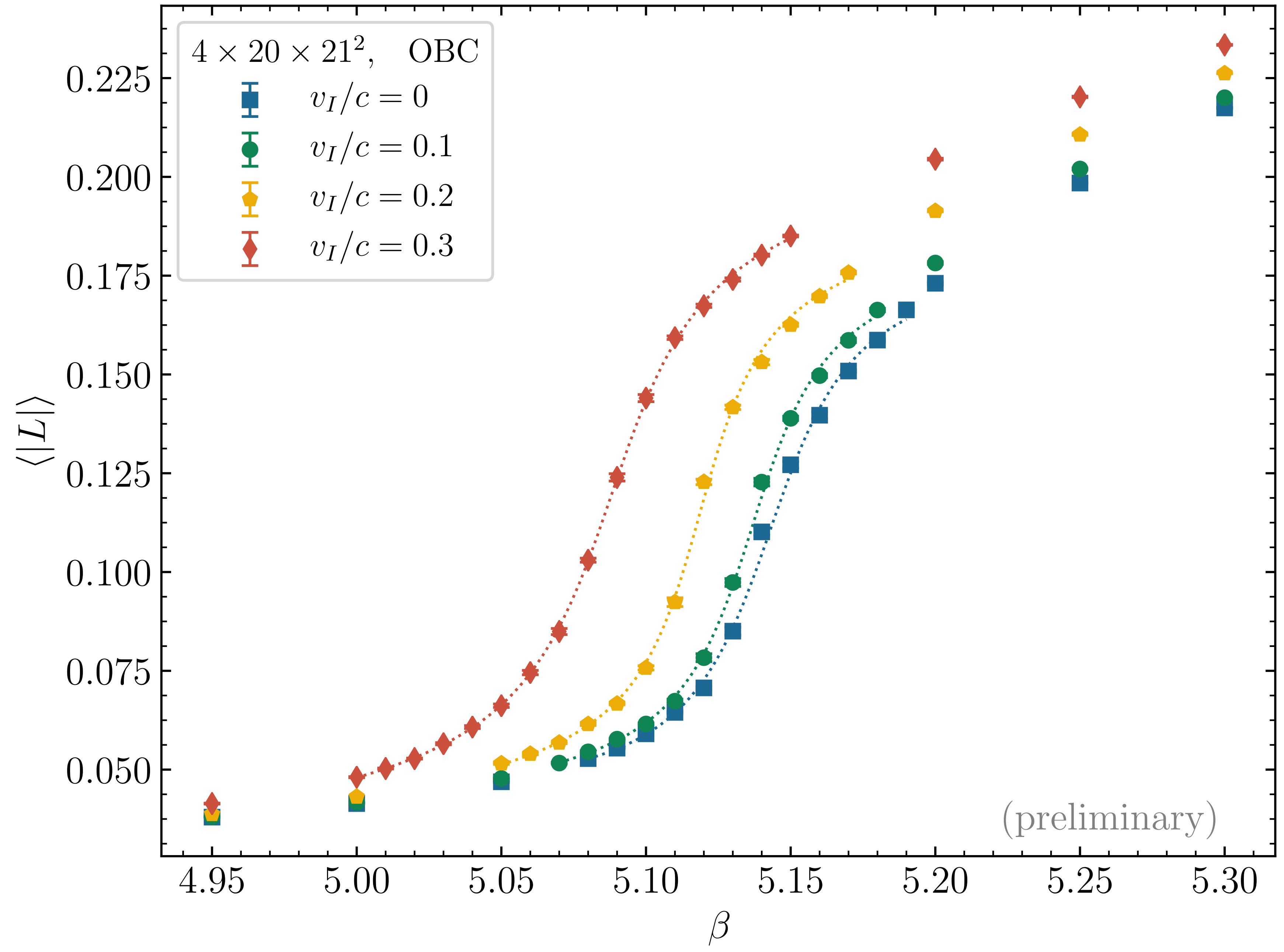

DBC
B_2
N_s/N_t
$8 \times 20 \times N_s^2$
$8 \times 24 \times N_s^2$
$8 \times 32 \times N_s^2$
$10 \times 30 \times N_s^2$

Critical temperature of rotating gluodynamics

- $\frac{T_c(\Omega_I)}{T_c(0)} = 1 - C_2\Omega_I^2 \Longrightarrow \frac{T_c(\Omega)}{T_c(0)} = 1 + C_2\Omega^2$ grows with Ω
- Contradicts model studies
- Cannot be described by Ehrenfest-Tolman effect
- Fermions?

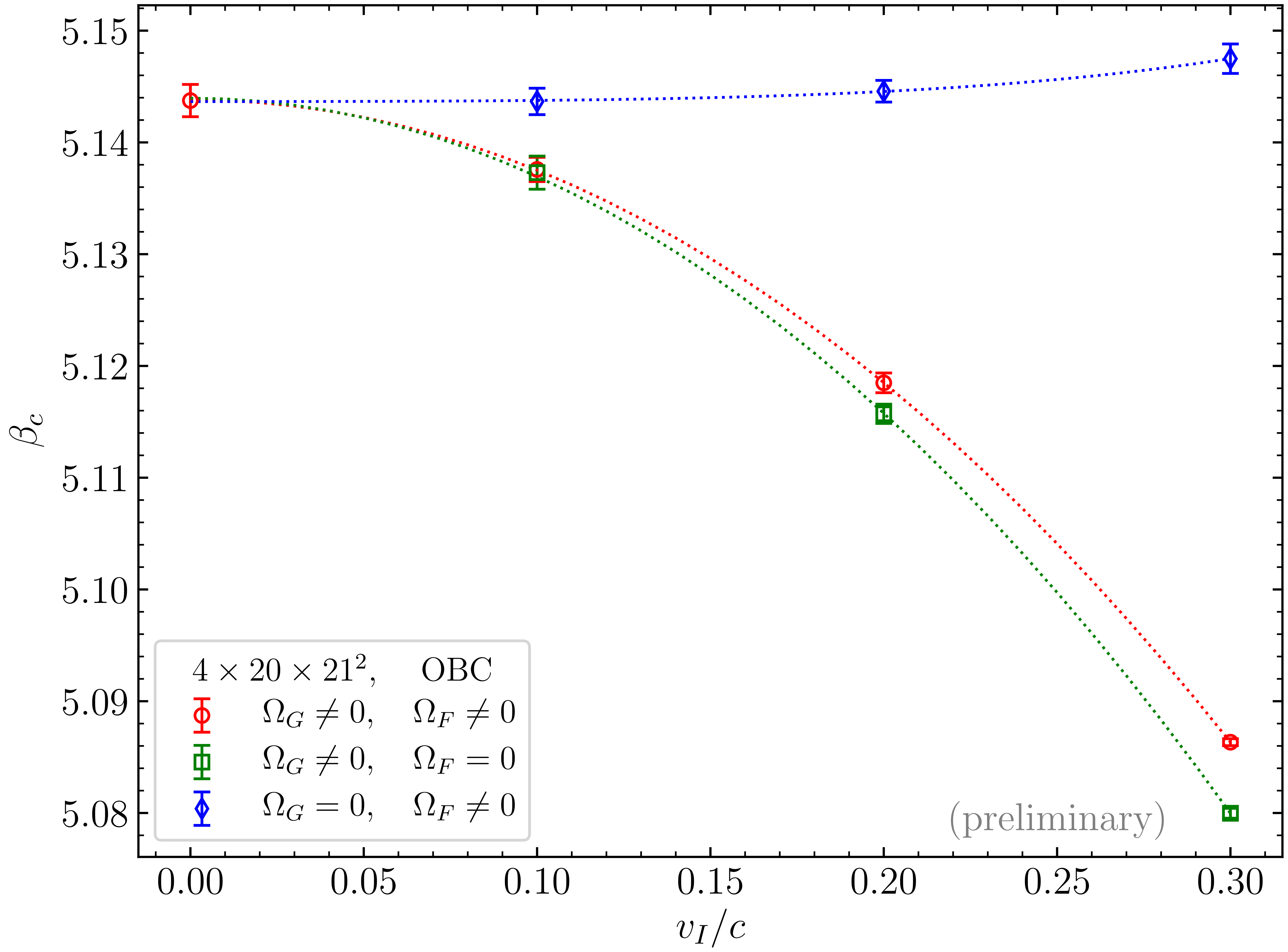
Simulations with fermions





- $N_f = 2$ Wilson fermions; $m_\pi \sim 700$ MeV
- Critical couplings for chiral and deconfinement phase transition coincide

Simulations with fermions



- $N_f = 2$ Wilson fermions; $m_\pi \sim 700$ MeV
- Introduce separate angular velocity $\Omega_G \neq \Omega_F$
- Gluonic and fermonic effects are opposite

Conclusions

- Phase diagram of rotating gluodynamics and QCD (heavy pion, preliminary)
- Three boundary conditions: open, periodic, Dirichlet
- Gluodynamics: $\frac{T_c(\Omega)}{T_c(0)} = 1 + C_2\Omega^2$, $C_2 > 0$
- In gluodynamics rotation increases critical temperature of the deconfinement phase transition
- $\frac{T_c(\Omega)}{T_c(0)} = 1 + B_2\frac{v^2}{c^2}$, v - velocity on the boundary, B_2 mildly depends on size
- QCD with heavy pions: competition between fermions and gluons ($m_\pi \sim 700$ MeV gluons win): possible reconciliation with theoretical studies