Finite Temperature Transition in Hyper Stealth Dark Matter Using Mobius Domain Wall fermions

Sungwoo Park
Lawrence Livermore National Laboratory

Nobuyuki Matsumoto, Venkitesh Ayyar and [LSD Collaboration],
08/02/2024, Lattice 2024

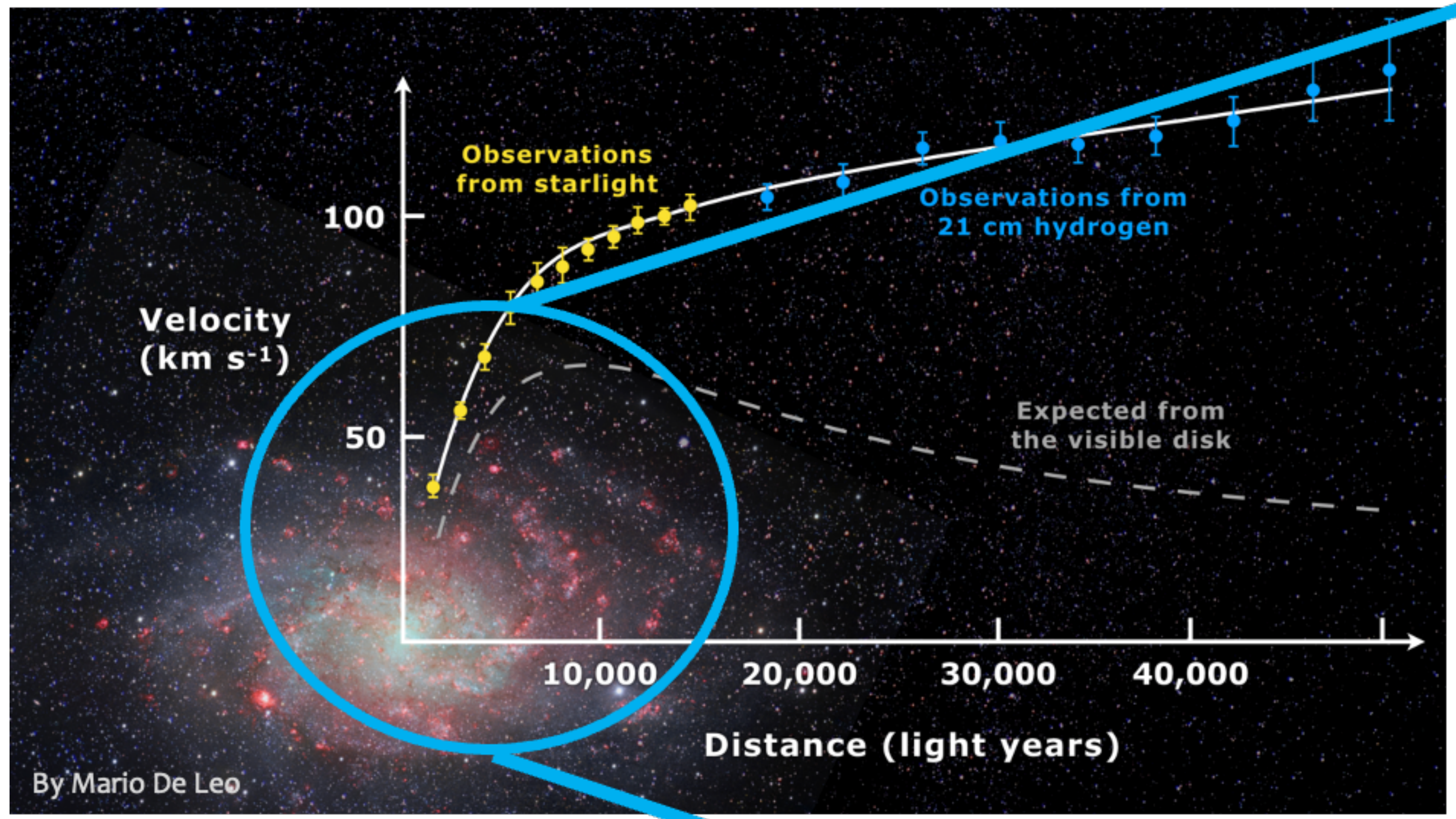
This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344.

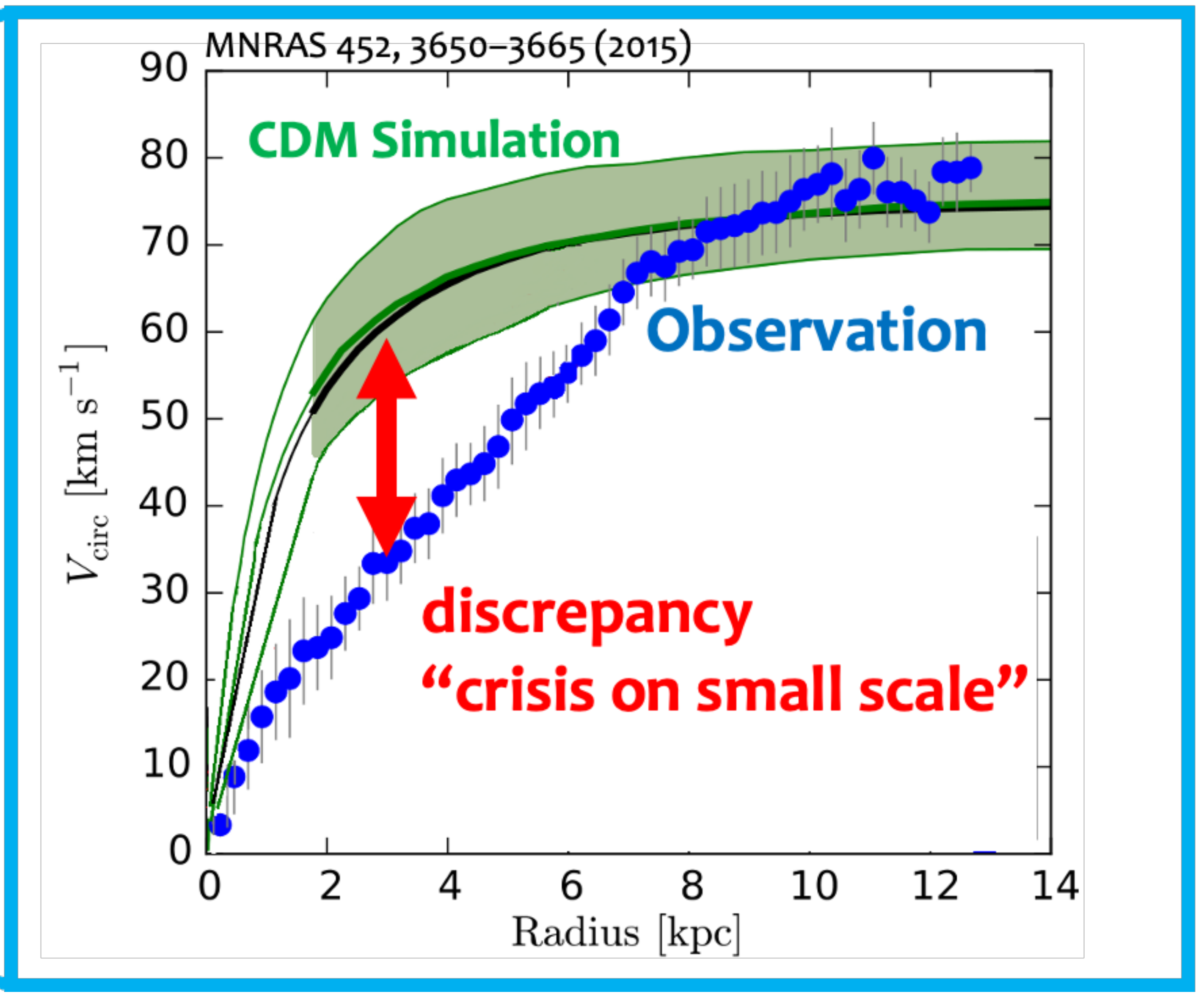
LLNL-PRES-867632

Motivation

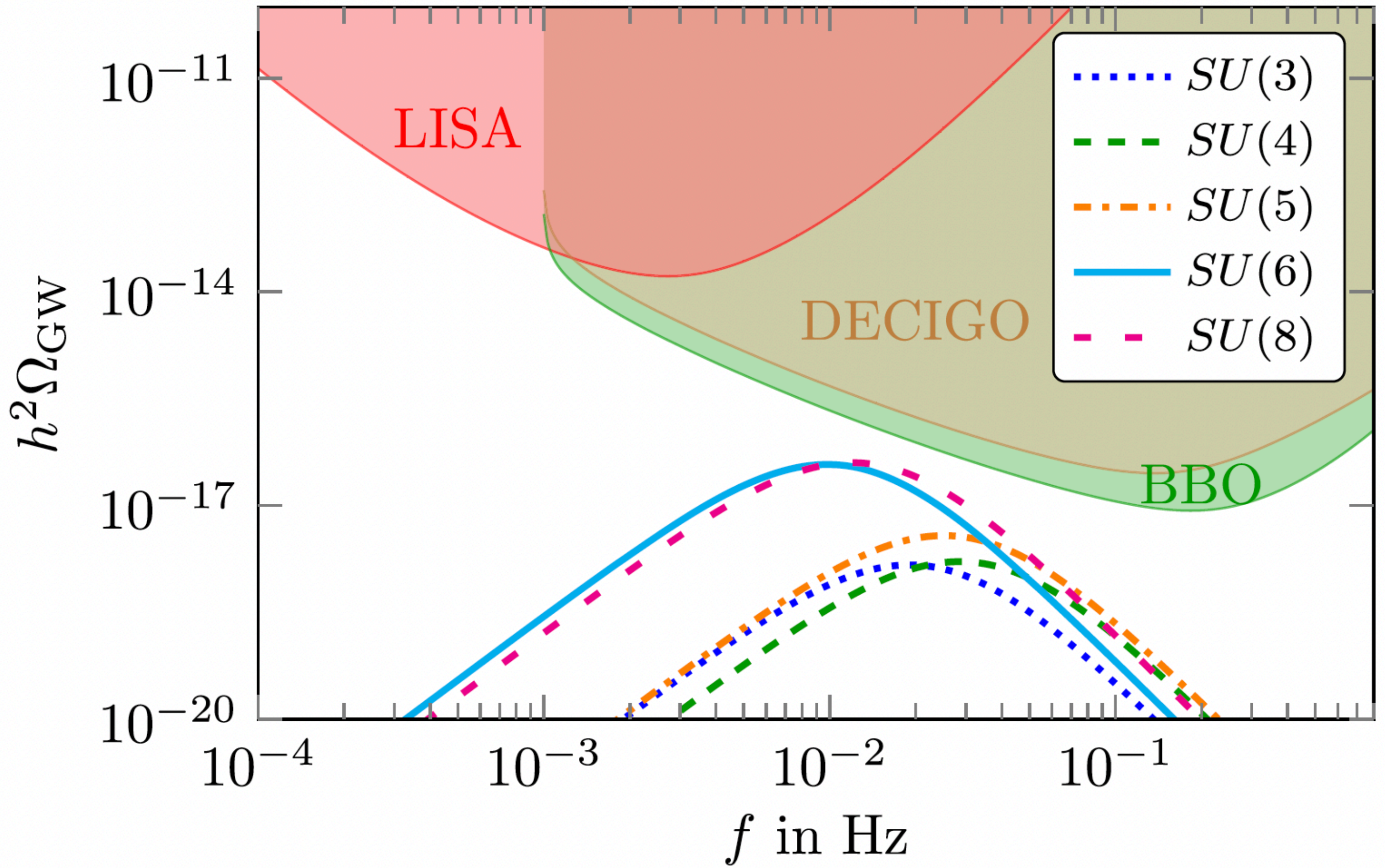
strongly interacting dark matter and gravitational wave

- Dark matter existence is shown from many evidences (Galaxy rotational curve, bullet clusters)
  - Strongly coupled dark gauge theory can provide solutions to the small-scale structure issue





- 1st order phase transition of the strongly interacting dark matter in the early universe can be the source of the gravitational wave that we are observing



Huang, Reichert, Sannino, Wang, PhysRevD.104.035005 (2021)

Hyper Stealth Dark Matter (HSDM)

SU(4) gauge theory with $N_f = 1$

- Stealth Dark Matter: LSD, PhysRevD.92.075030(2015)
  SU(4) 4-dark quark bosonic baryon as a composite DM candidate, coupled via EW to SM particles

LSD, PhysRevD.103.014505(2021)

- Previous finite T study with SU(4) 4-flavor found 1st order phase transition at $am_f \geq 0.4$.

- Here we are going to study 1-flavor theory (HSDM)
  Fleming, Kribs, Neil, Schaich, Vranas, in preparation

  - No spontaneous chiral symmetry breaking as $U_A(1)$ broken explicitly by the anomaly, the lightest meson η' mass is not small, no chiral transition

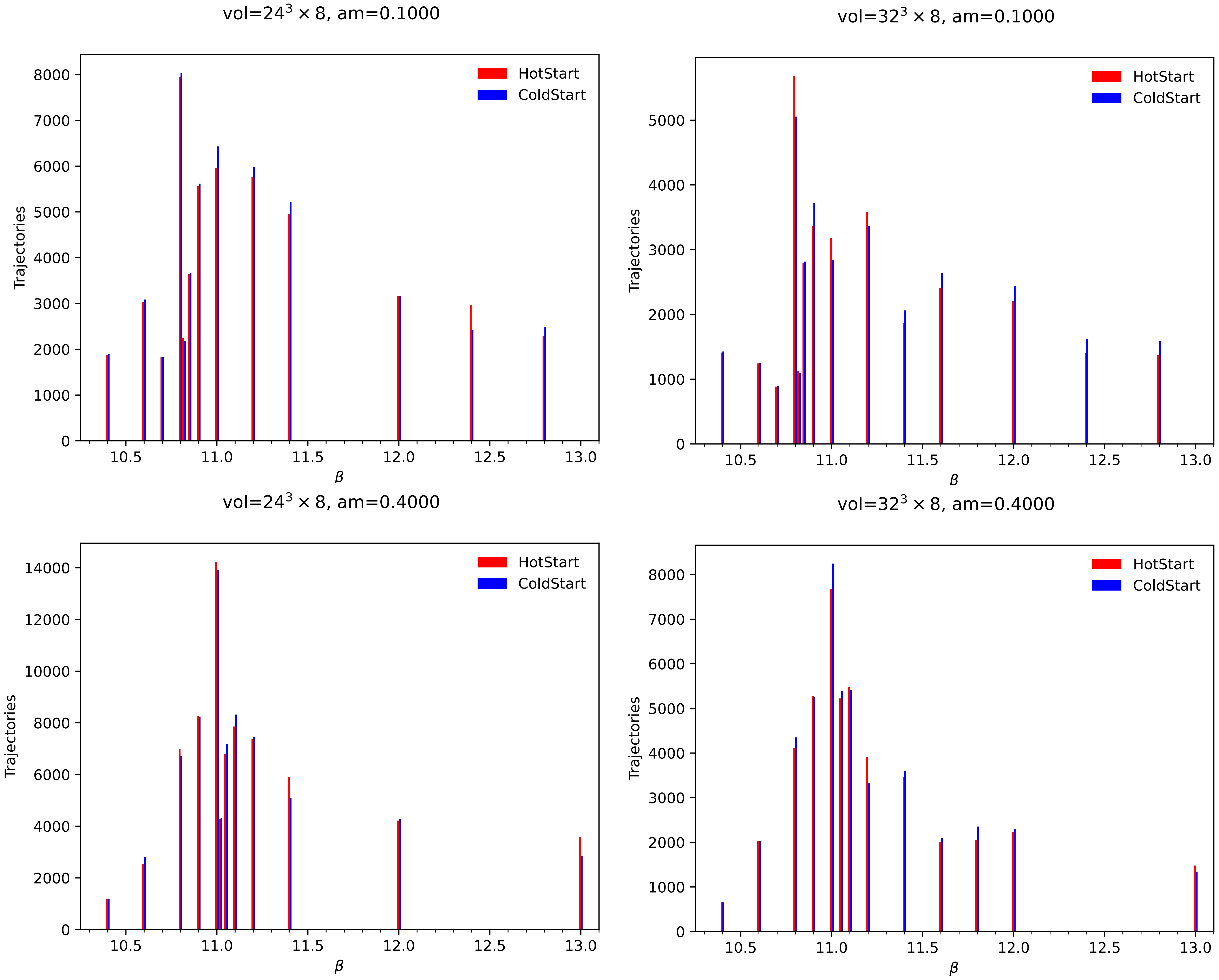
  - Stable baryon protected from decay by $U_V(1)$, Expected baryon mass is ~few GeV

Simulation details

- Mobius Domain wall fermion (MDWF, Ls=16, b=1.5, c=0.5), 1flavor (EOFA) HMC algorithm with Wilson gauge action
- Grid (`github.com/paboyle/Grid`), Hadron (`github.com/aportelli/Hadrons`)
- LLNL GPU clusters: Tioga (AMD MI250x), Lassen (NVIDIA V100)
- Update on the finite T study from last year Venkitesh Ayyar [LSD], Lattice 2023
    - Fermionic boundary condition, more statistics, chiral condensate
    - Wilson-flow (PL, Q) to reduce UV fluctuations with flow time $\sqrt{8t_W}/N_t \leq 0.5$

Statistics

- $am \in \{0.1, 0.4\}$, $L^3 \in \{24^3, 32^3\}$, $N_t = 8$ fixed
- Cold ($U_\mu = 1$, $\langle PL \rangle = 1$) and Hot ($U_\mu =$ random, $\langle PL \rangle = 0$) initial gauge field streams
  - compare them to ensure thermalization
  - ≥ 3000 trajectories required for thermalization near β_{crit}



Chiral property of DWF

Small eigenvalues in 5th dim $H_4(M_5) = \gamma_5 D\!\!\!/_W(-M_5)$

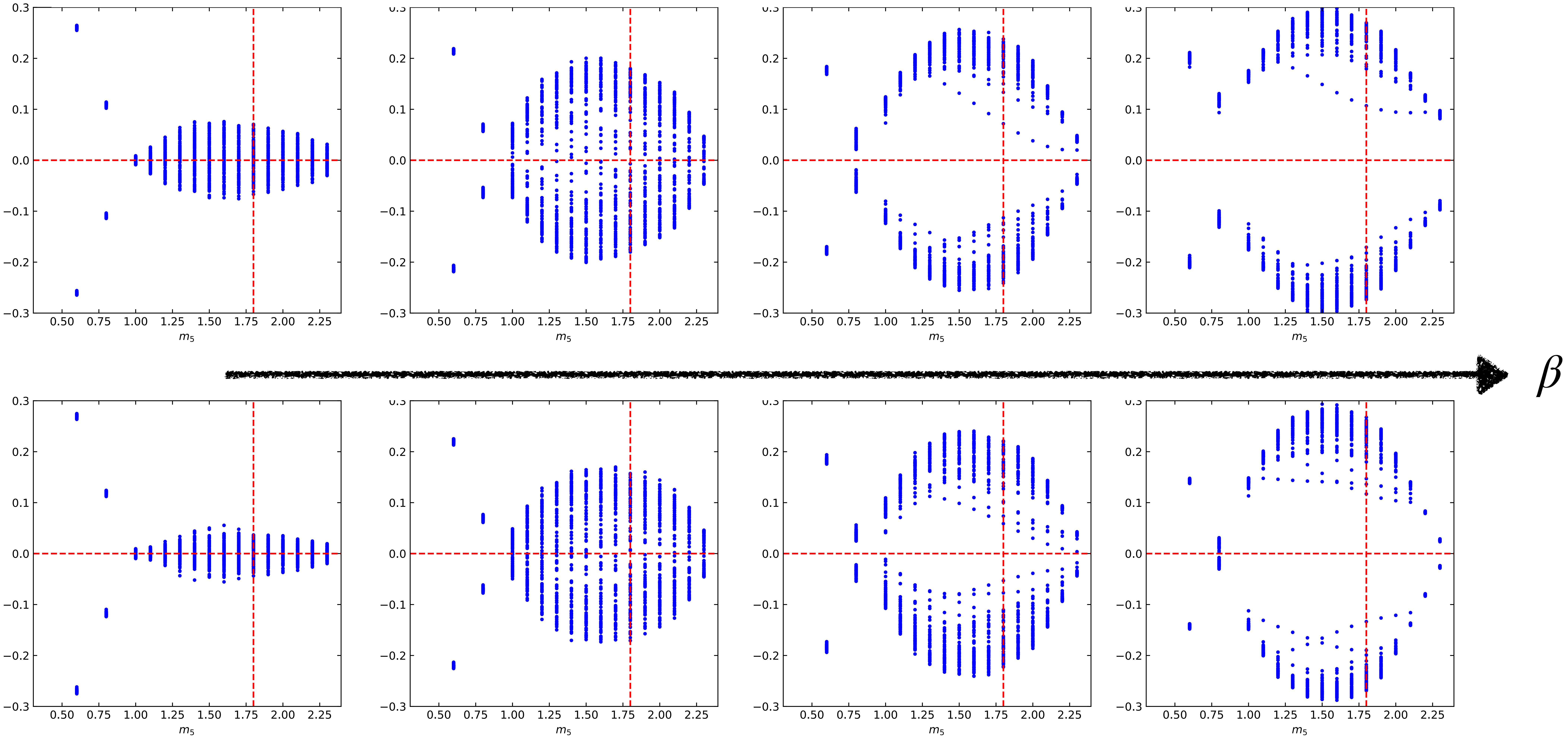
- M_5: 5th-dimensional mass representing the height of the domain wall
- L_s: 5th dimension length
  - $L_s \to \infty$, overlap, 4d chiral symmetric theory
  - finite L_s: chiral symmetry breaking remains, m_{res} (Residual mass, additive shift to the bare mass due to the chiral symmetry breaking)
- if $H_4(M_5) = \gamma_5 D\!\!\!/_W(-M_5)$ has very small eigenvalues, the exponential decay will be overshadowed by slow power law decay even for very large
- small $|\lambda|$ -> large m_{res}

M_5 tuning for small eigenvalues of $\gamma_5 \not{D}_W(-M_5)$

eye diagram: 10 smallest magnitude λ, at $24^3 \times 8$

$am = 0.1$

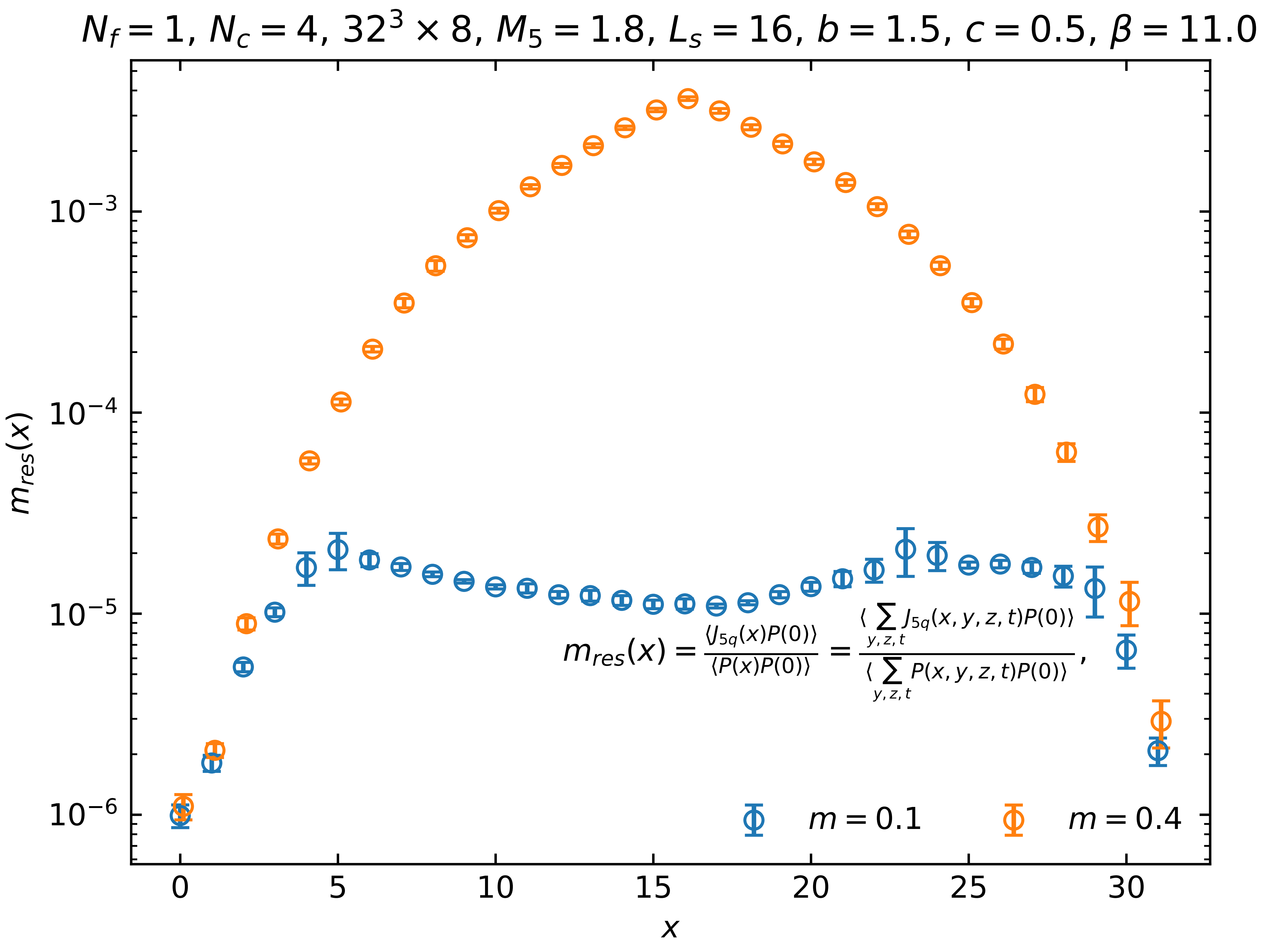
$am = 0.4$



$\beta = 10.6$ $\beta = 10.8$ $\beta = 11.0$ $\beta = 11.2$

Residual mass $m_{\rm res}$: additive shift to the bare mass

chiral symmetry breaking in DWF at $M_5 = 1.8$

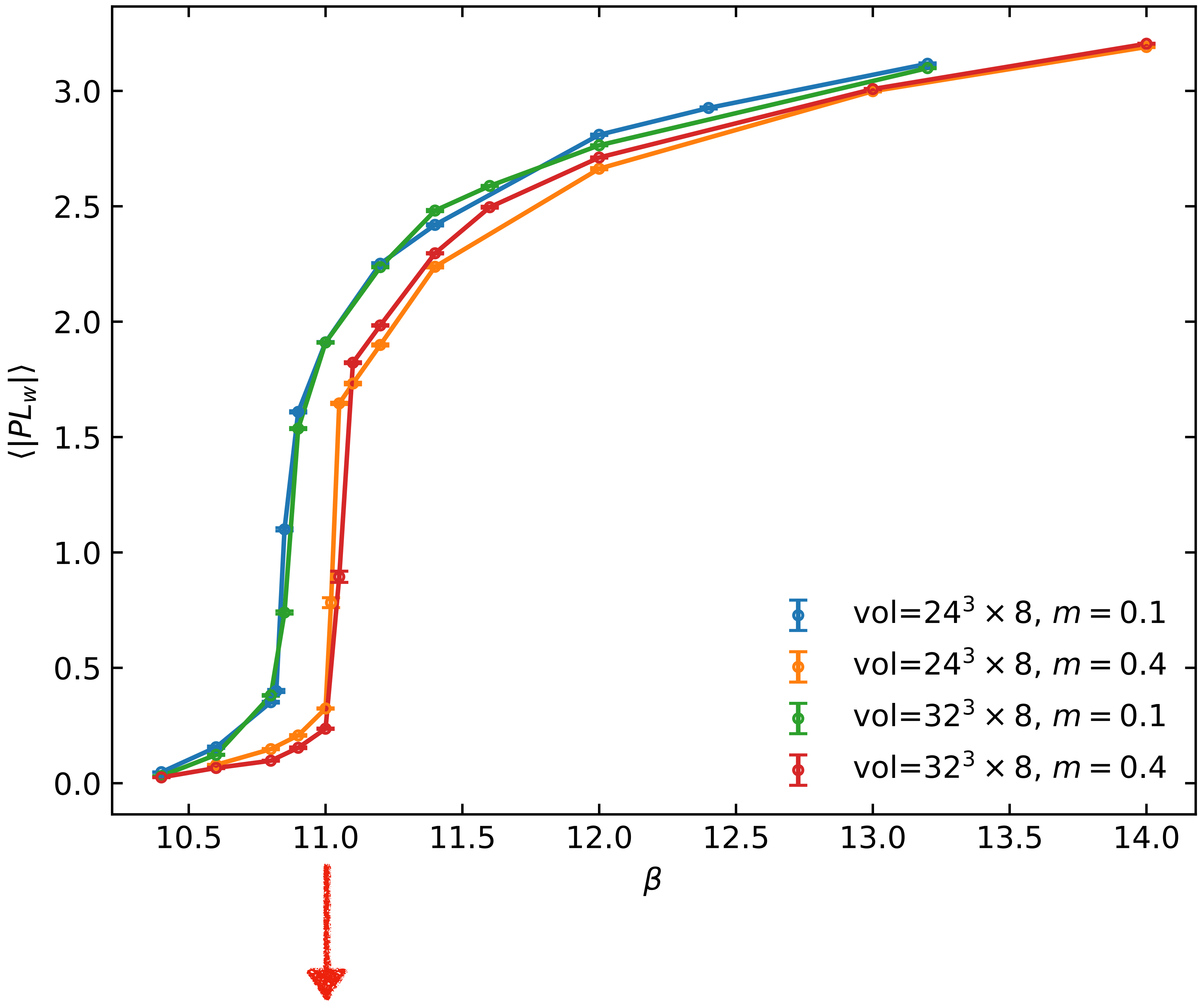


- Effective $m_{\rm res}$ calculated from 2pt functions with source-sink separation in a spatial (x) direction
- $am = 0.1$ have a plateau at small 10^{-5} value,
- Effective $m_{\rm res}$ ($am = 0.4$) diverges with no plateau. We will need smaller am for safety, and the chiral symmetry restoration

SU(3) study, JHEP04(2016)037, RBC

Polyakov Loop (PL)

Deconfinement phase transition order parameter



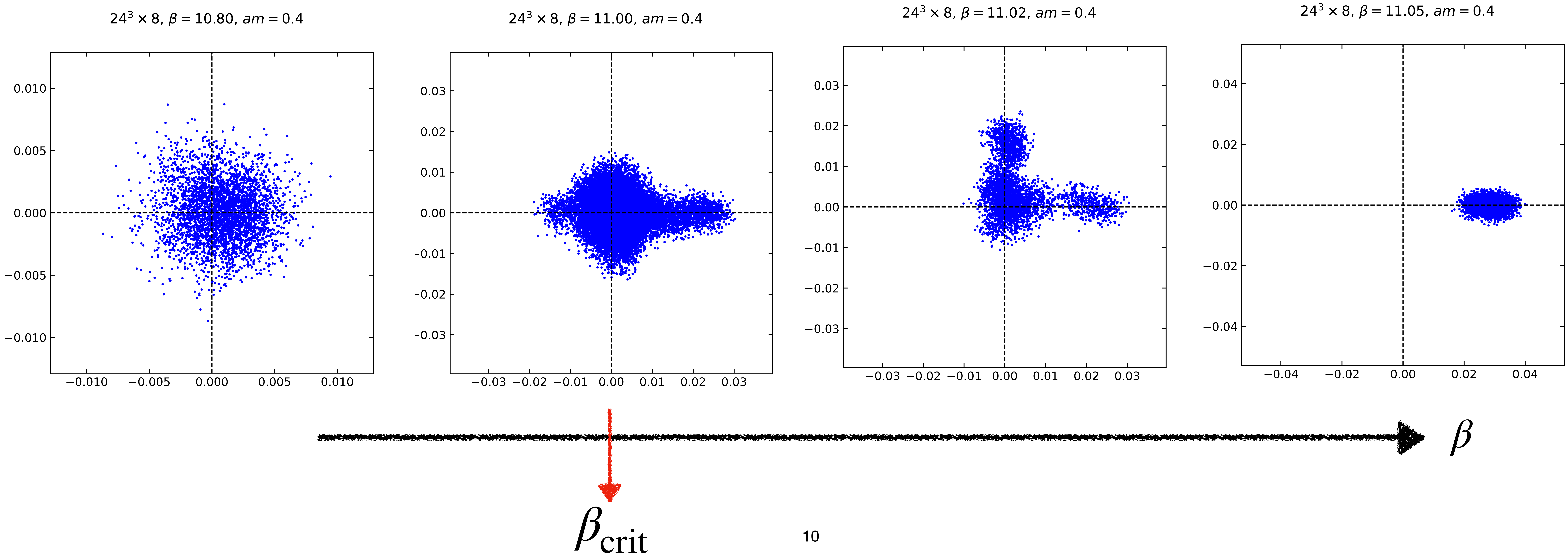
β_{crit} in $am = \infty$ (pure gauge)

- Volume averaged, Wilson-flowed PL (maximum=$N_c = 4$)
- β_{crit} from Wilson-flowed PL
  - Volume dependence negligible
  - $\beta_{\text{crit}} \sim 10.8$ for $am = 0.1$
  - $\beta_{\text{crit}} \sim 11.0$ for $am = 0.4$ and $am = \infty$ (pure gauge)

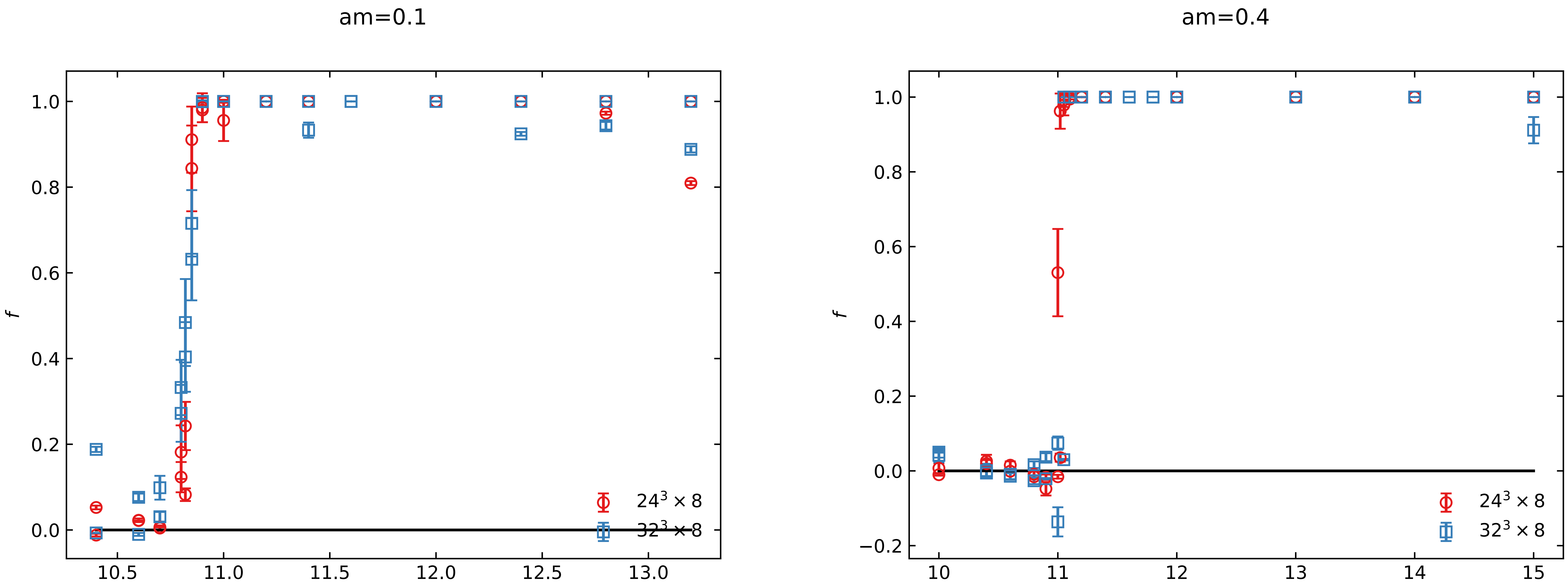
Polyakov Loop in Complex Plane

spontaneous Z(4) sym breaking as deconfinement transition crossed

- pure gauge limit (am=0.4)

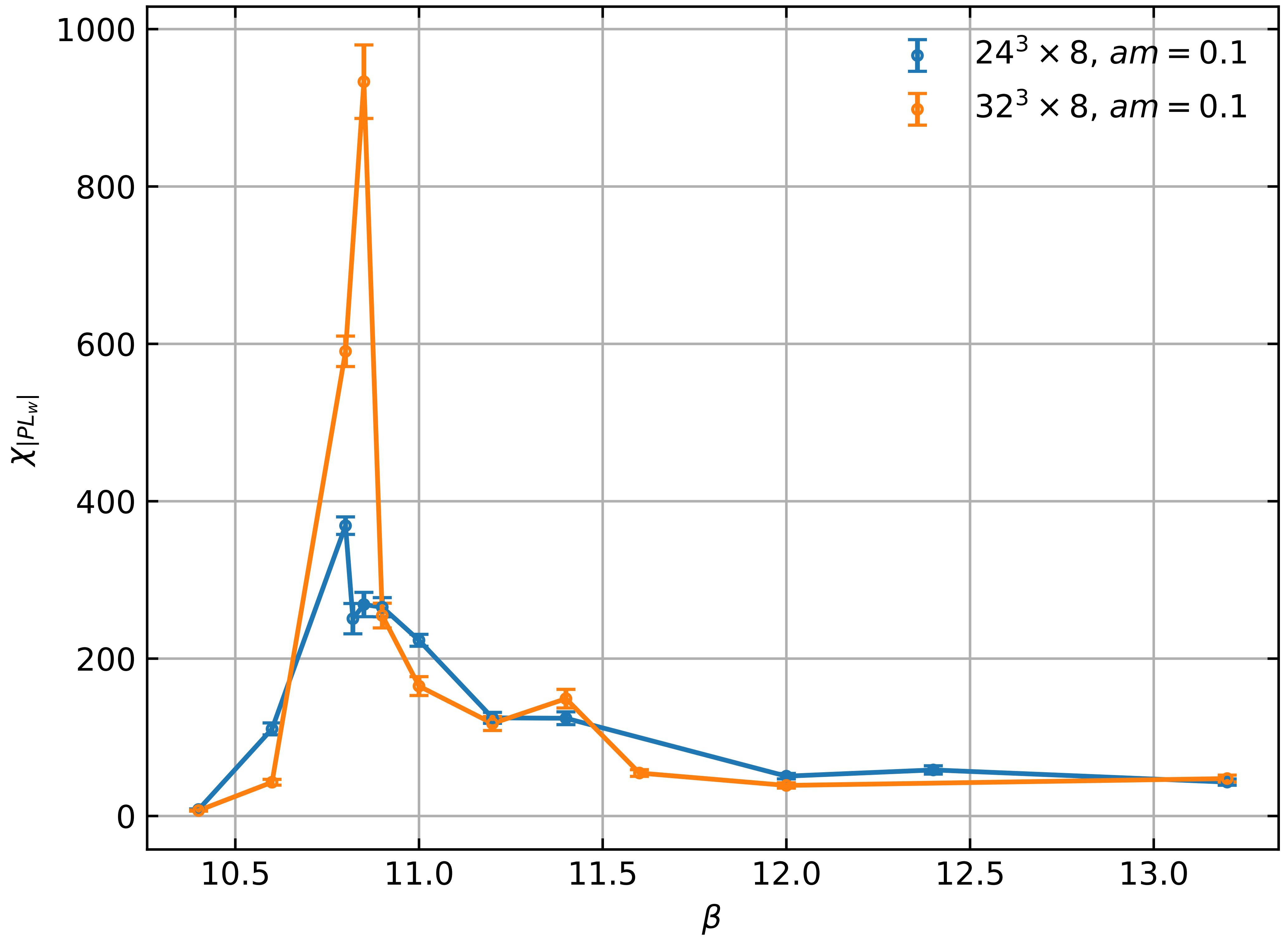


Deconfinement Fraction

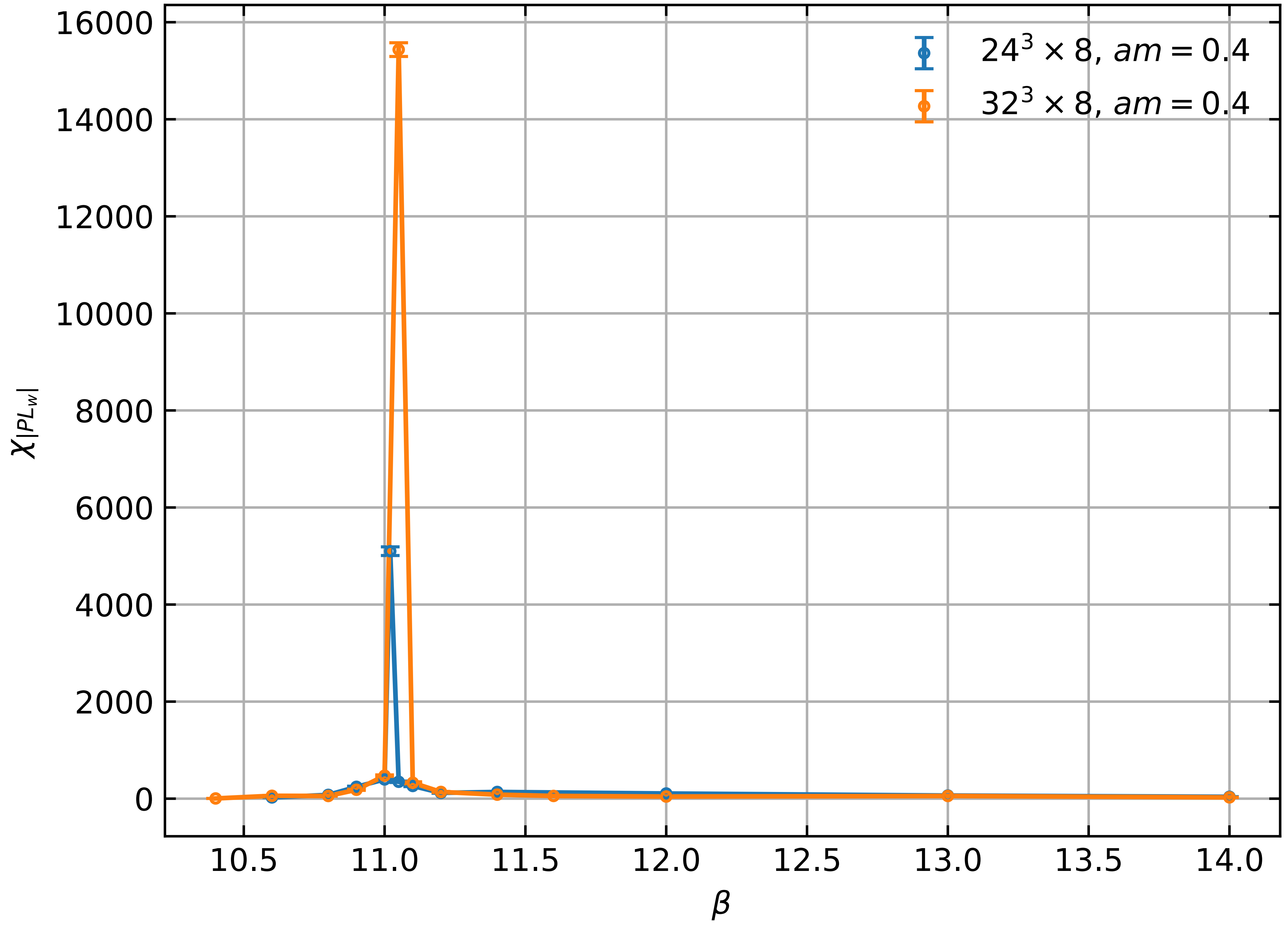


PL Susceptibility $\chi_{\max} \propto L^3$: Volume Scaling

signature of 1st order phase transition



$$am = 0.1, \chi_{\max} \propto L^{3.2}$$

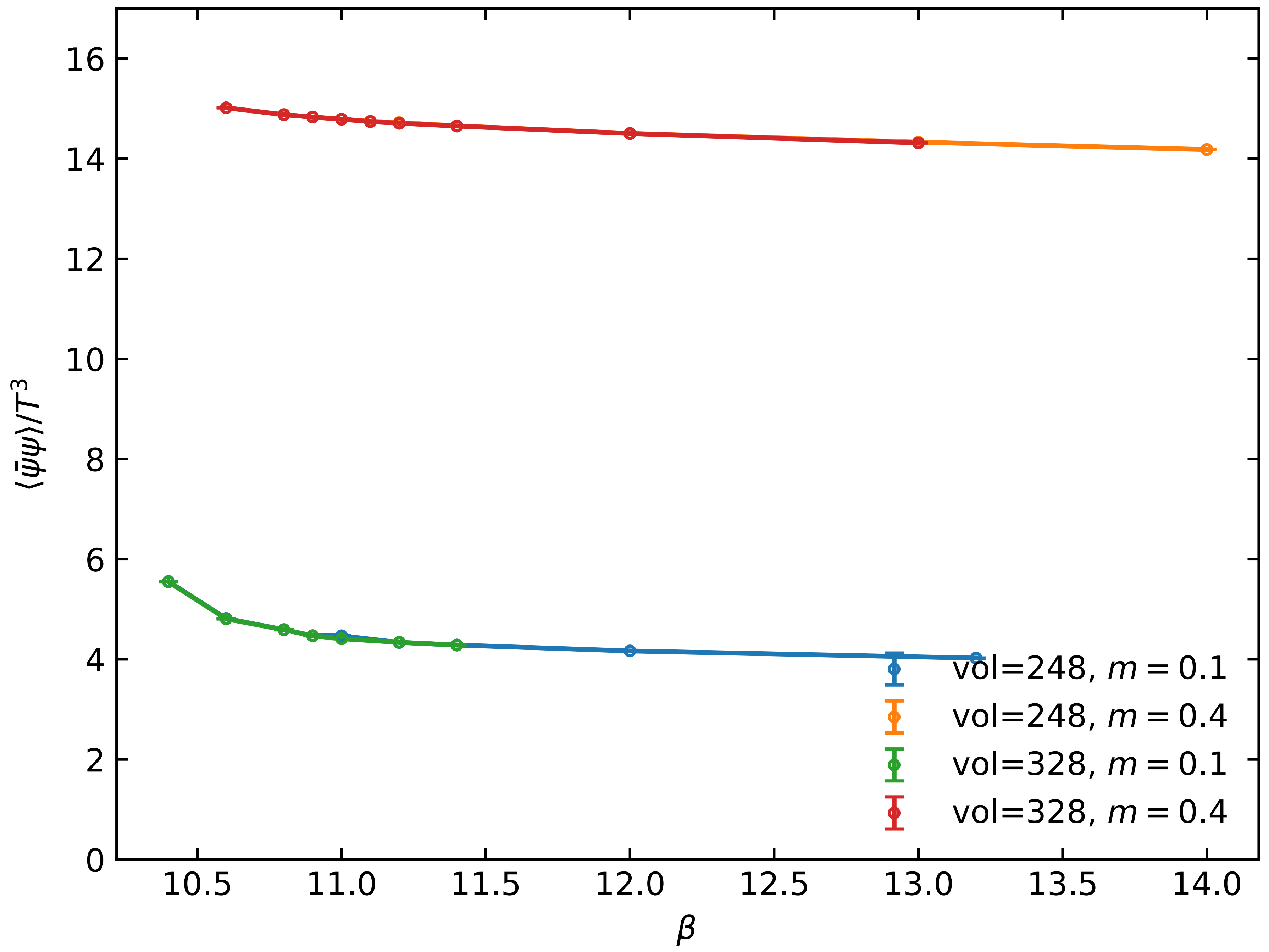


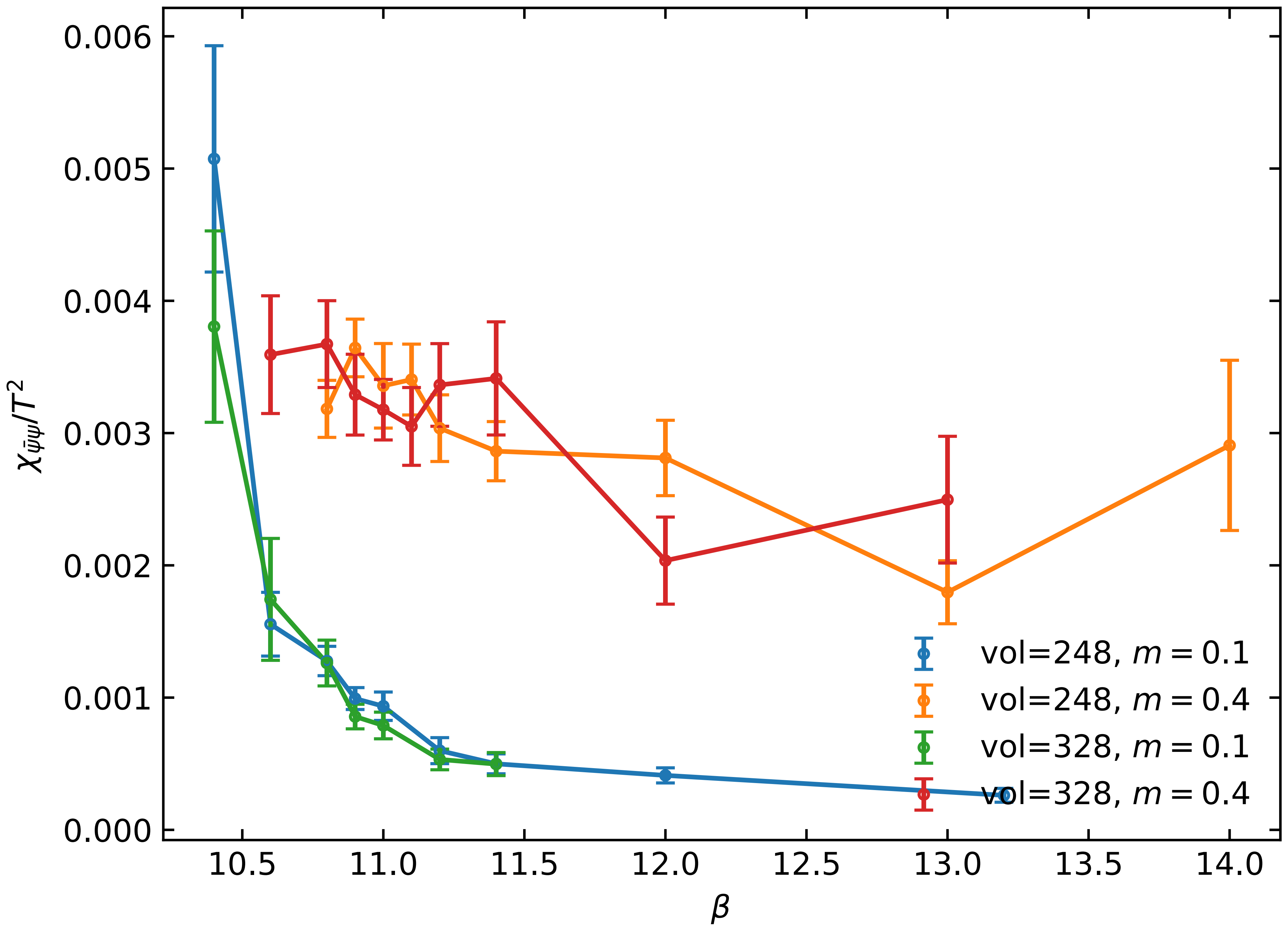
$$am = 0.4, \chi_{\max} \propto L^{3.8}$$

(pure gauge limit)

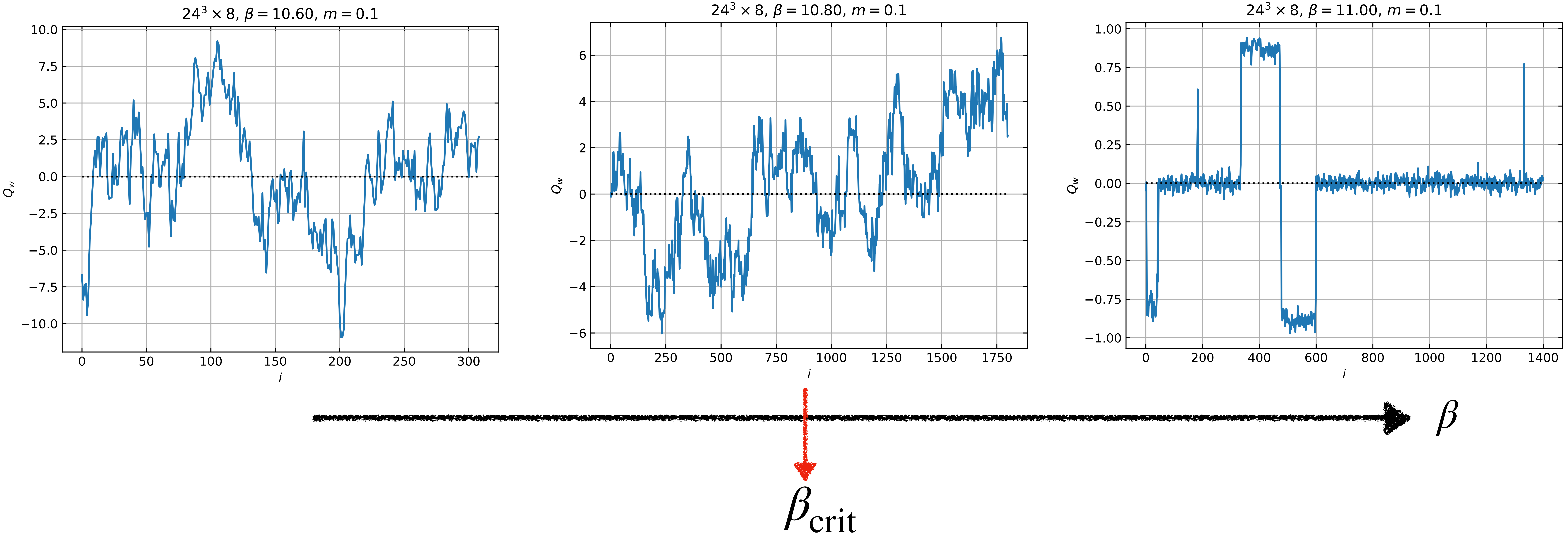
Chiral condensate

- no chiral transition for $N_f = 1$





Topological Charge



Conclusion and Future Plan

- We studied chiral property of MDWF with a large fermion mass for SU(4) gauge theory from the eigenvalues of 5th dim hamiltonian $H_4(M_5)$ and m_{res}.
- We studied the finite temperature transition in HSDM, strongly interacting composite DM with 1-flavor SU(4) gauge theory. For this, we monitored various observables (PL, χ_{PL}, Q, $\langle\bar{\psi}\psi\rangle$)
- We found signatures of 1st order phase deconfinement phase transition that can be a source of the gravitational wave.
- Future plan
  - Latent heat, bubble wall velocity
  - Find the lowest limit of fermion mass that have 1st order phase transition
  - Zero temperature calculation for the hadronic mass calculation and scale setting
  - More statistics needed, checking autocorrelation