Axial U(1) symmetry at high temperature in 2-flavor lattice QCD

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from JLQCD Collaboration:
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Outline of this talk

1. Motivation
2. Axial U(1) symmetry and Dirac spectrum
3. Results

    3-1: $U(1)_A$ susceptibility at finite T

    (3-2: Topological susceptibility) ⇒ Next talk by Y. Aoki
4. Summary

Related talks from JLQCD:

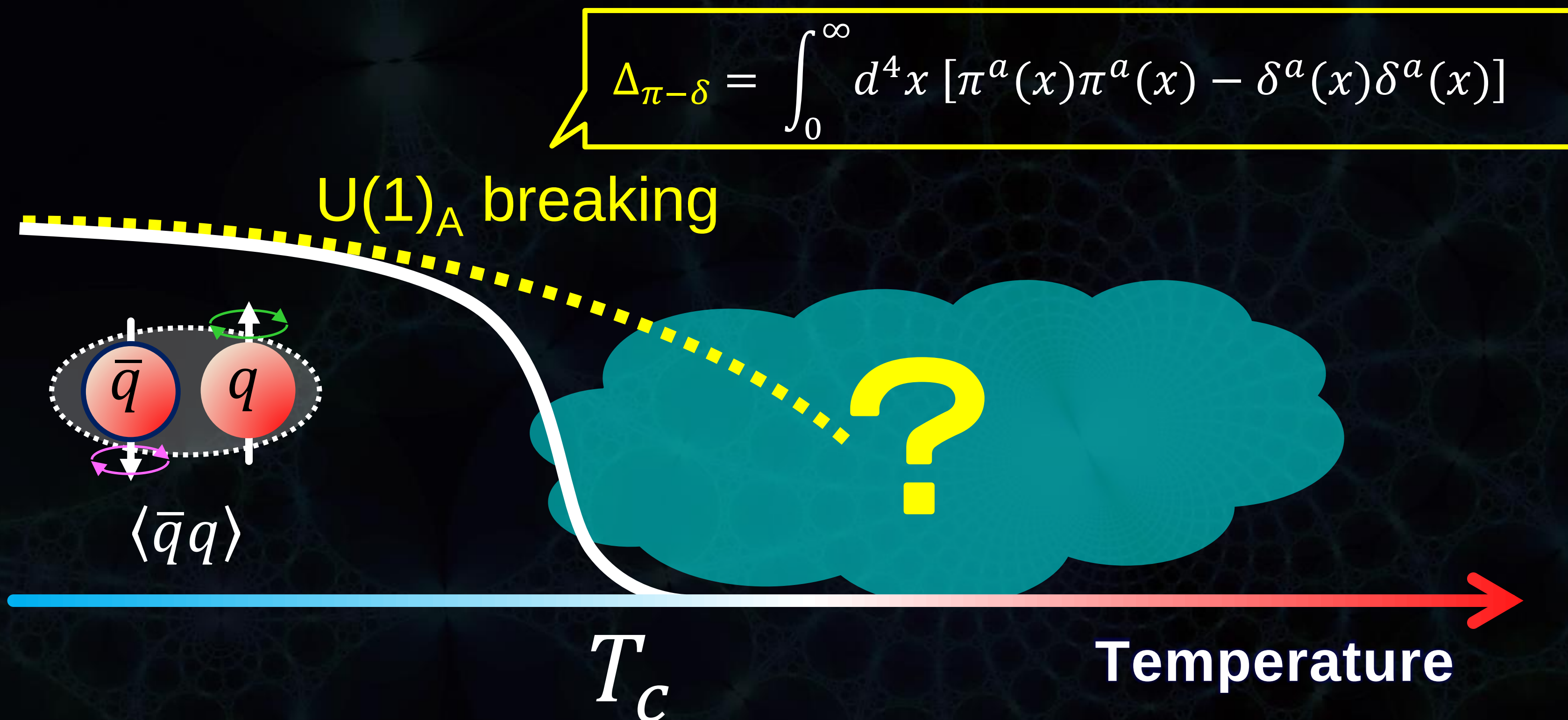
H. Fukaya (Thu. plenary) – Summary of finite T

H. Fukaya (Thu.) – Topological susceptibility at zero T

C. Rohrhofer (Wed.) – Mesonic collelator at finite T

Motivation: Is $U(1)_A$ symmetry restored above T_c?

- For $T > T_c$, chiral symmetry breaking by $\langle \bar{q}q \rangle$ is restored
  ⇒How about $U(1)_A$ symmetry?



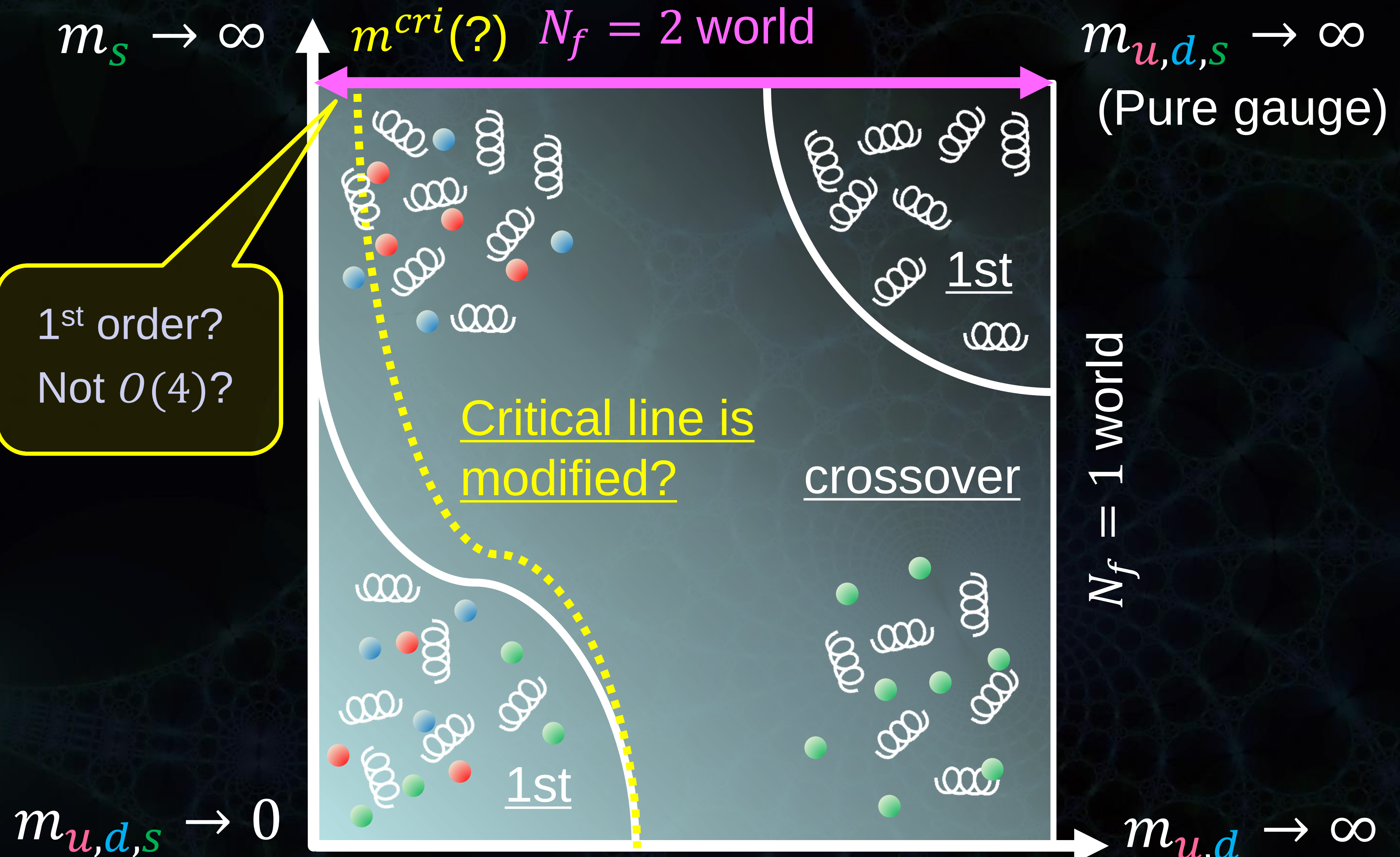
Motivation: Is $U(1)_A$ symmetry restored above T_c?

- For $T \gg T_c$, $U(1)_A$ symmetry will be restored because of dilute instanton gas picture (Gross-Pisarski-Yaffe, 1981)
- HotQCD (DW, 2012) broken
- JLQCD (topology fixed overlap, 2013) restored
- TWQCD (optimal DW, 2013) restored
- LLNL/RBC (DW, 2014) broken
- Dick et al. (overlap on HISQ, 2015) broken
- JLQCD (reweighted overlap from DW, 2016) restored

⇒ It is still an unsettled problem

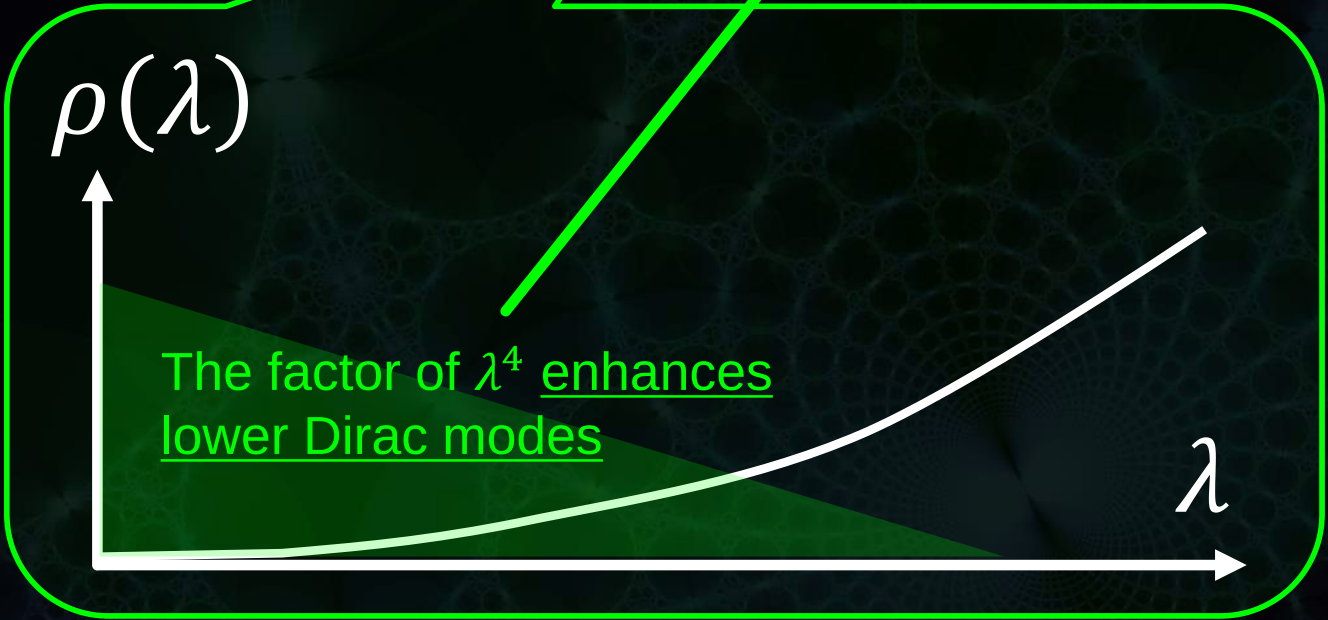
If $U(1)_A$ is restored…

the Colombia plot is modified?



$U(1)_A$ susceptibility from Dirac spectra

$$\Delta_{\pi-\delta} = \int_0^\infty d\lambda\, \rho(\lambda)\, \frac{2m^2}{(\lambda^2+m^2)^2}$$

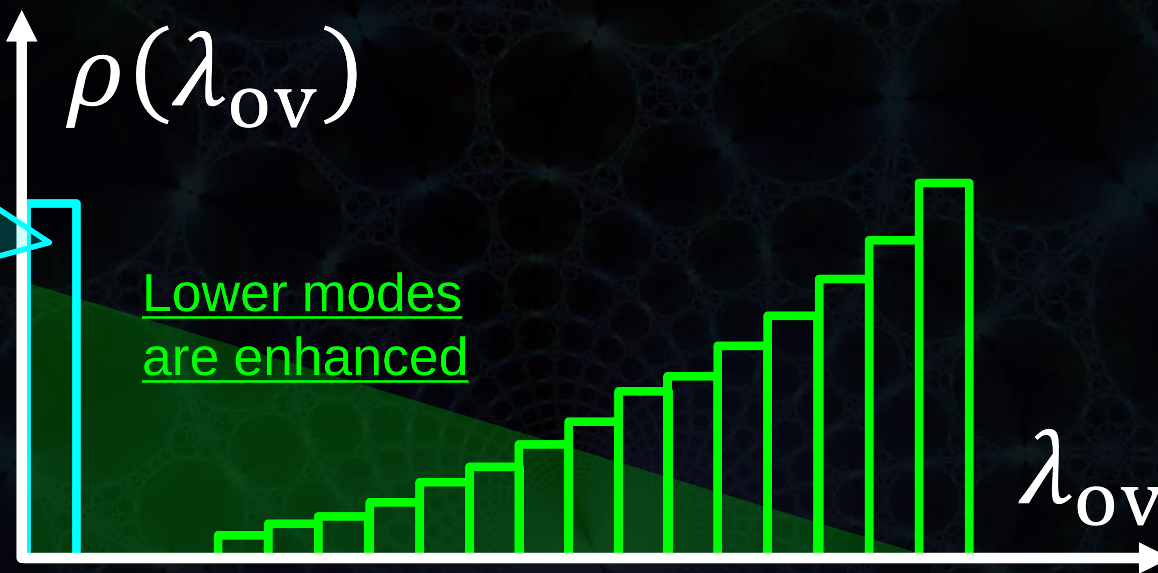


Cf.) Banks-Casher relation: $\langle \bar{q}q \rangle = \lim_{m\to 0} \int_0^\infty d\lambda\, \rho(\lambda)\, \frac{2m}{\lambda^2+m^2}$

Observables: Dirac spectra on the lattice

$$\Delta_{\pi-\delta} = \int_0^\infty d\lambda\, \rho(\lambda) \frac{2m^2}{(\lambda^2 + m^2)^2} \Rightarrow \Delta^{\text{ov}}_{\pi-\delta} \equiv \frac{1}{V(1-m^2)^2} \sum_i \frac{2m^2 (1 - \lambda^{(i)4}_{\text{ov}})^2}{\lambda^{(i)4}_{\text{ov}}}$$

Practically, (physical) zero-modes will be dominant
⇒ instanton contributions in finite box



Practical observable: $\bar{\Delta}^{\text{ov}}_{\pi-\delta} \equiv \frac{1}{V(1-m^2)^2} \sum_{i>0-mode} \frac{2m^2 (1 - \lambda^{(i)4}_{\text{ov}})^2}{\lambda^{(i)4}_{\text{ov}}}$

Subtracted zero-modes

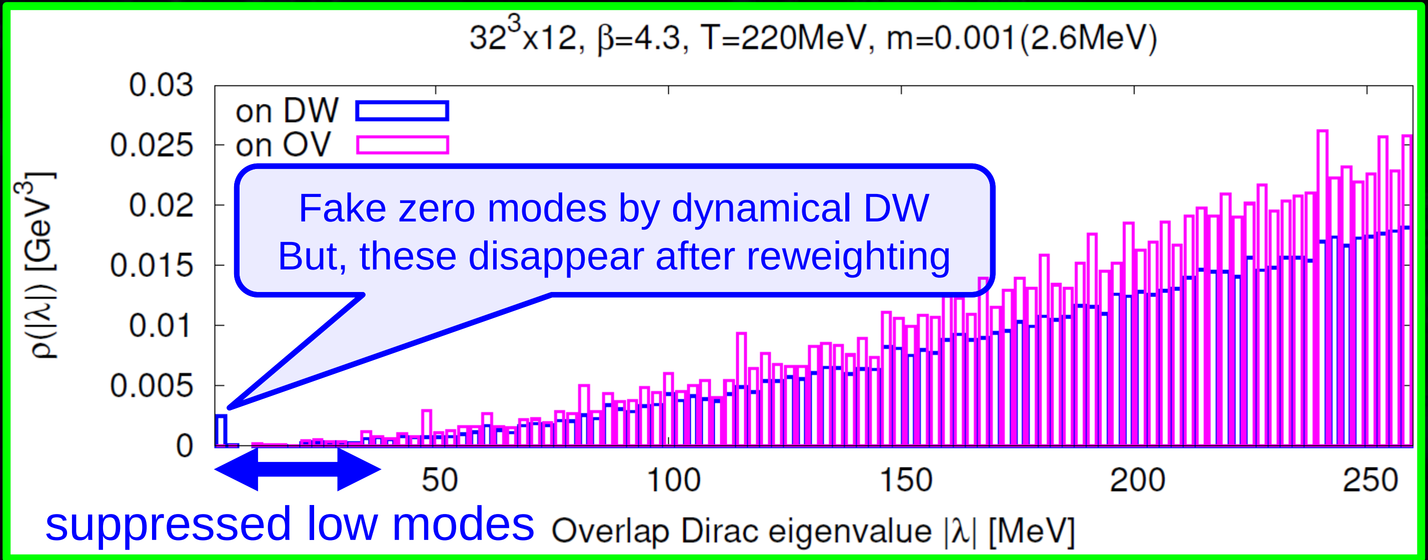
(Instanton contribution becomes zero at $V \to \infty$: $\bar{\Delta}^{\text{ov}}_{0-mode} = \frac{2N_0}{Vm^2} (\propto 1/\sqrt{V})$)

Project of $U(1)_A$ at finite T by JLQCD collaboration

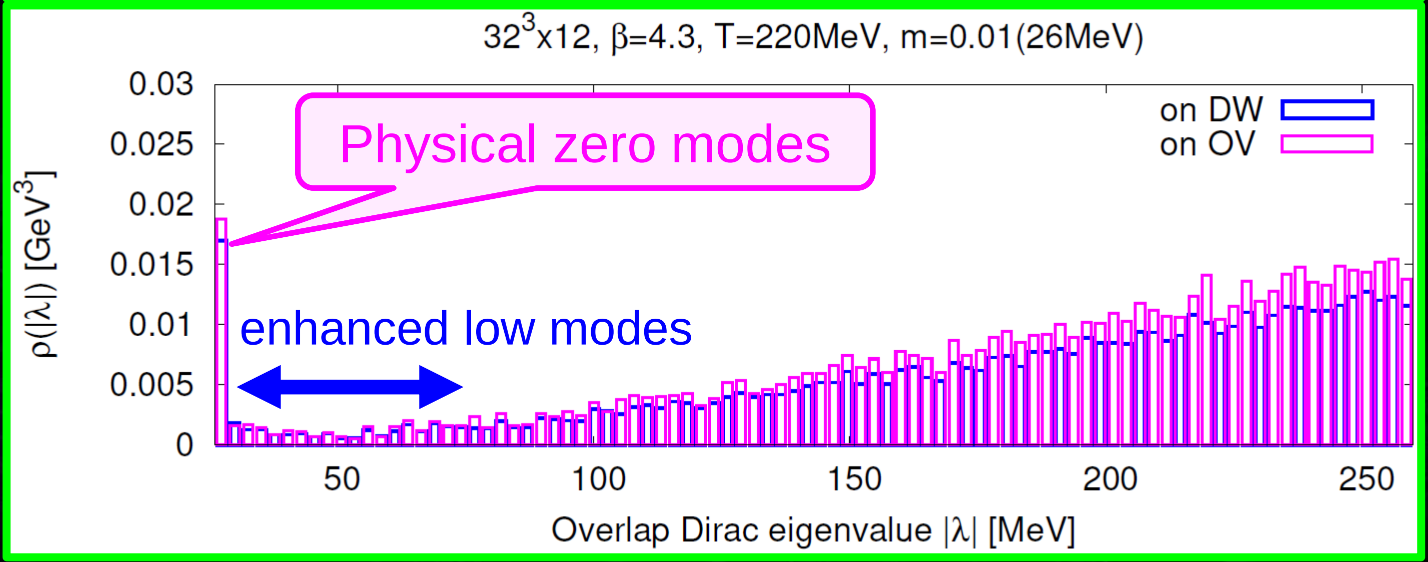
	Valence/Sea quarks	Setup
G. Cossu et al. PRD87 (2013)	OV on OV (Topology fixed sector)	
A. Tomiya et al. [arXiv:1612.01908]	DW on DW OV on DW OV on (reweighted) OV	1/a=1.7GeV
This work	OV on DW OV on (reweighted) OV	1/a=2.6GeV (More fine)

Results (overlap Dirac spectra)

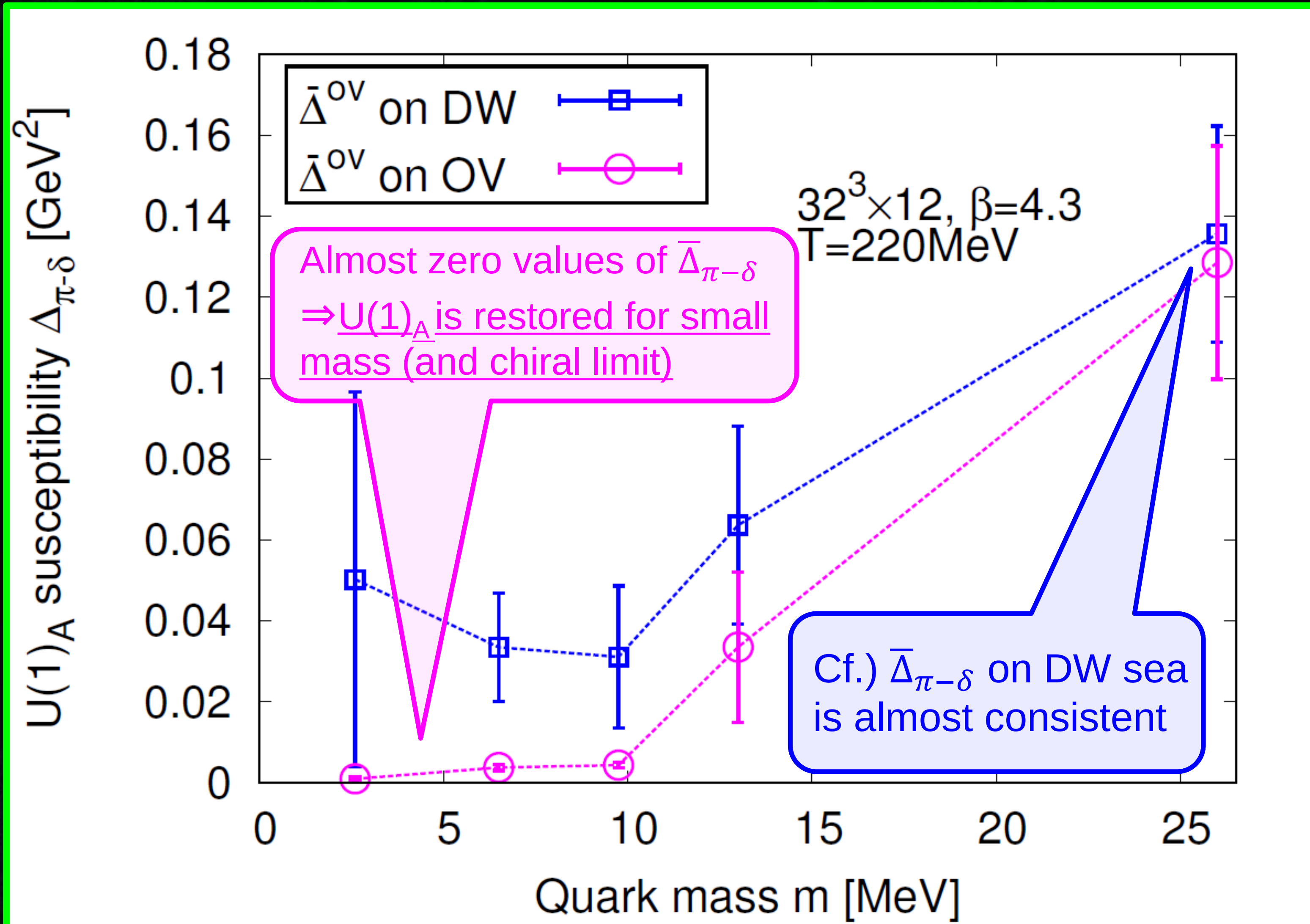
m=2.6MeV

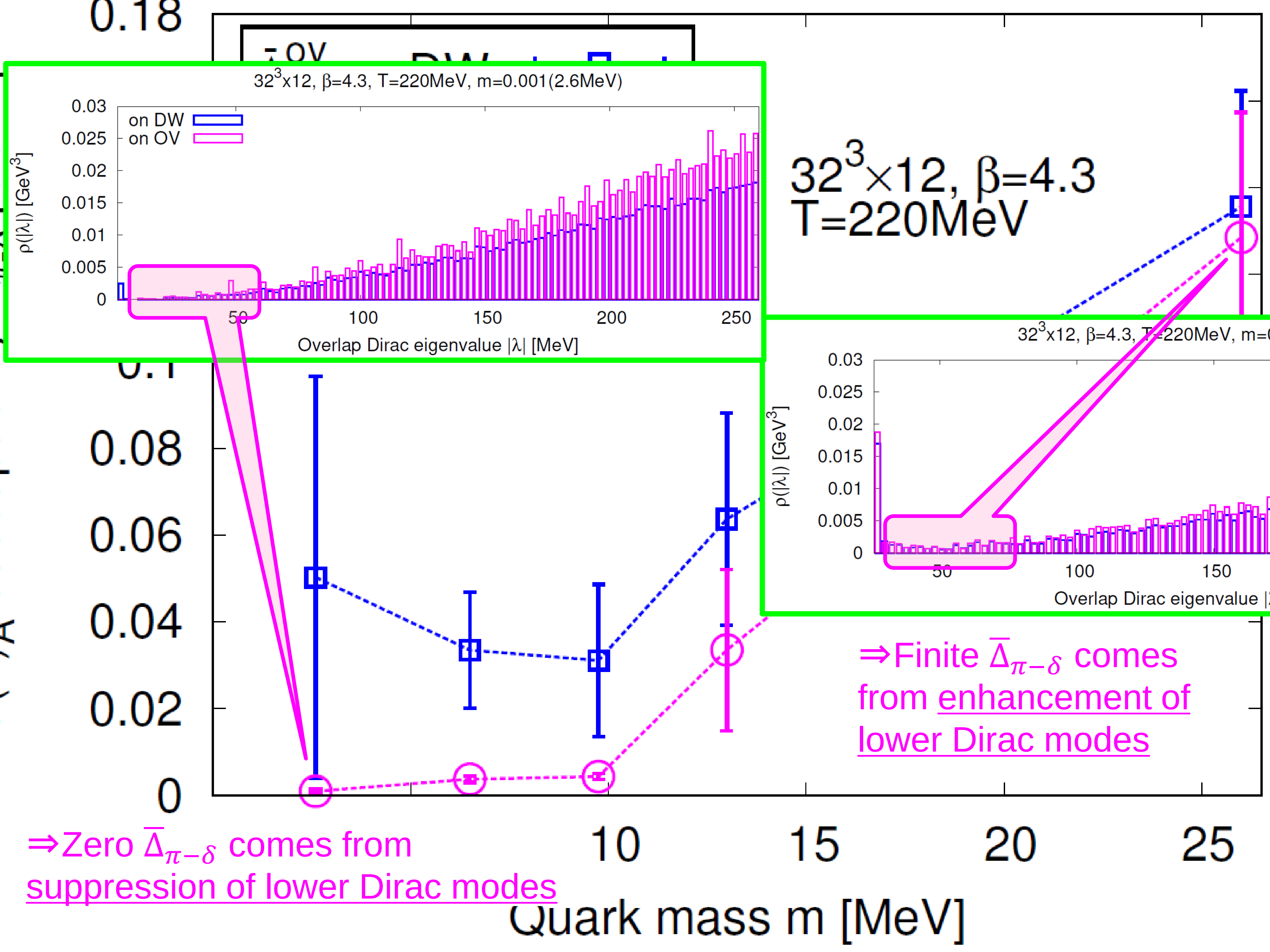


m=26MeV



$U(1)_A$ symmetry at T = 220MeV

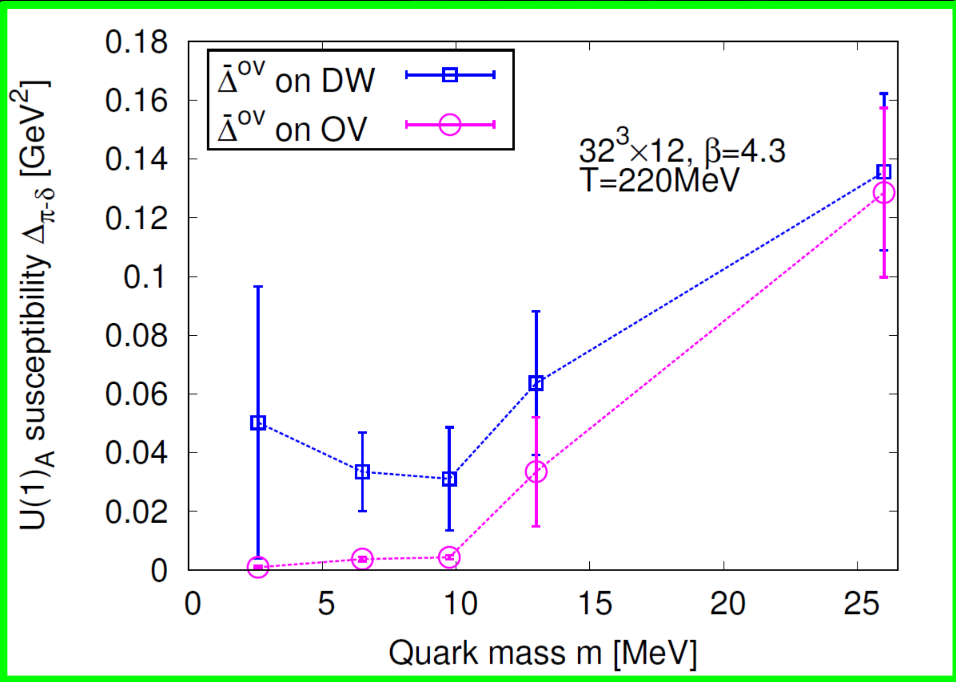




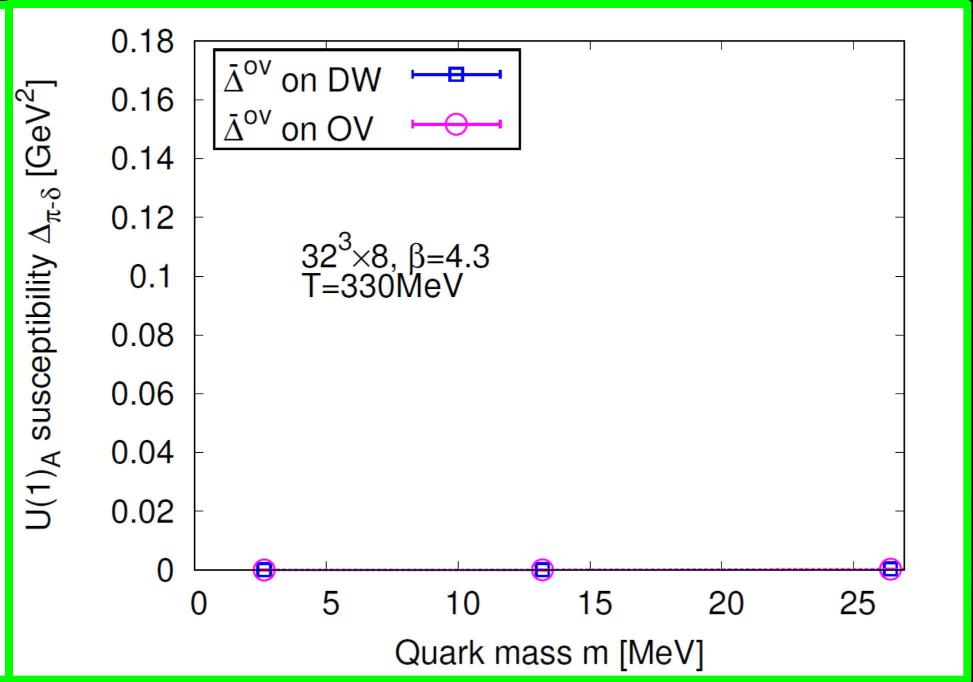
$32^3 \times 12$, β=4.3
T=220MeV
32^3x12, β=4.3, T=220MeV, m=0.001(2.6MeV)
on DW
on OV
ρ(|λ|) [GeV^3]
Overlap Dirac eigenvalue |λ| [MeV]
0.03
0.025
0.02
0.015
0.01
0.005
0
50
100
150
200
250
0.18
0.1
0.08
0.06
0.04
0.02
0
10
15
20
25
Quark mass m [MeV]
⇒Finite $\bar{\Delta}_{\pi-\delta}$ comes from enhancement of lower Dirac modes
⇒Zero $\bar{\Delta}_{\pi-\delta}$ comes from suppression of lower Dirac modes

Temperature dependence (220 or 330MeV)

T=220MeV



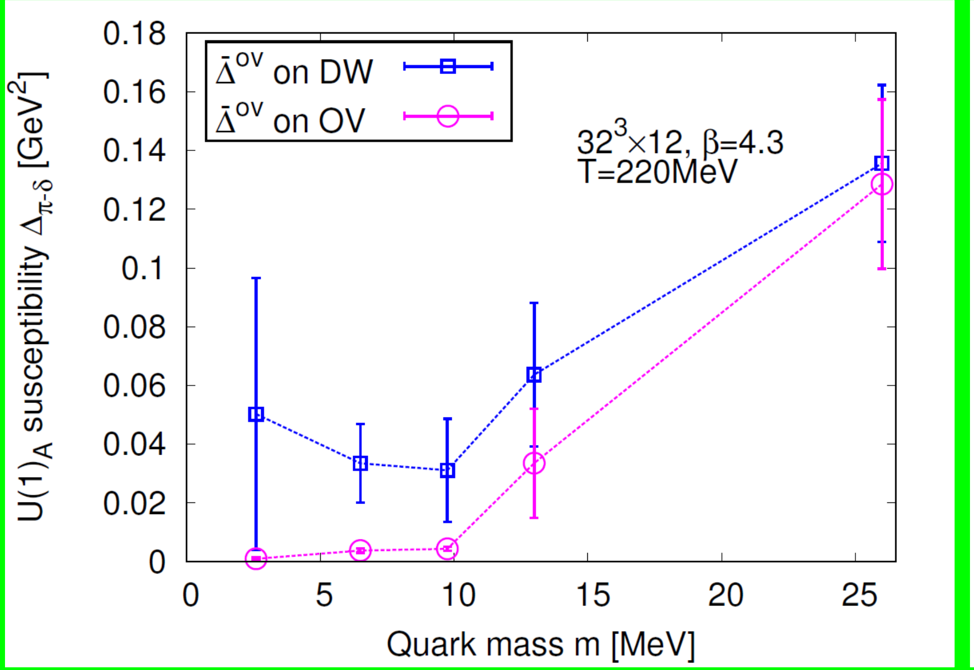
T=330MeV



⇒ With increasing T, U(1)$_A$ symmetric region becomes wider

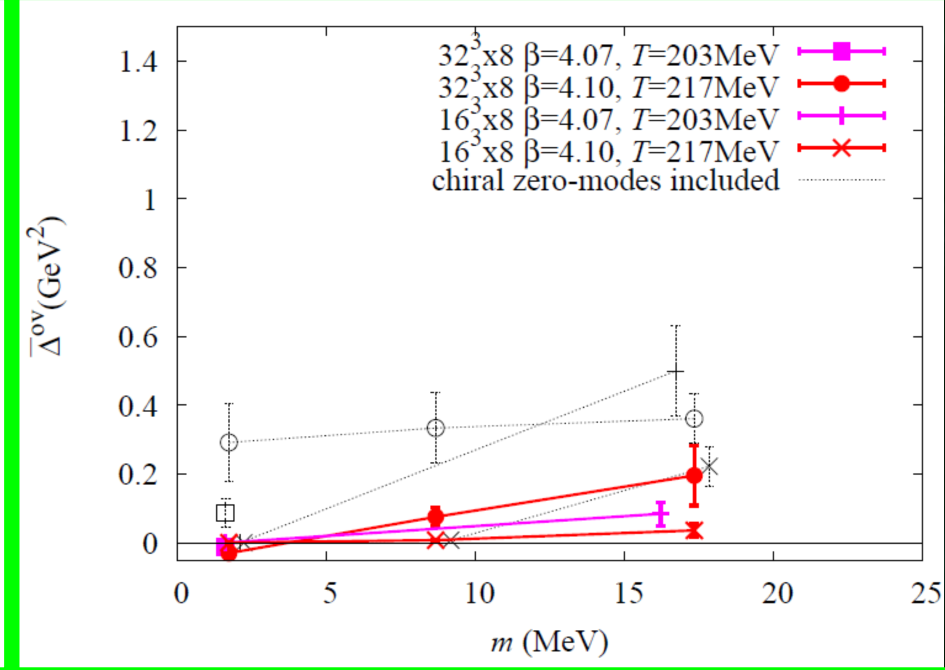
Comparison with Coarse lattice

JLQCD, preliminary (2017)



1/a=2.6GeV

A. Tomiya et al. (JLQCD) [arXiv:1612.01908]



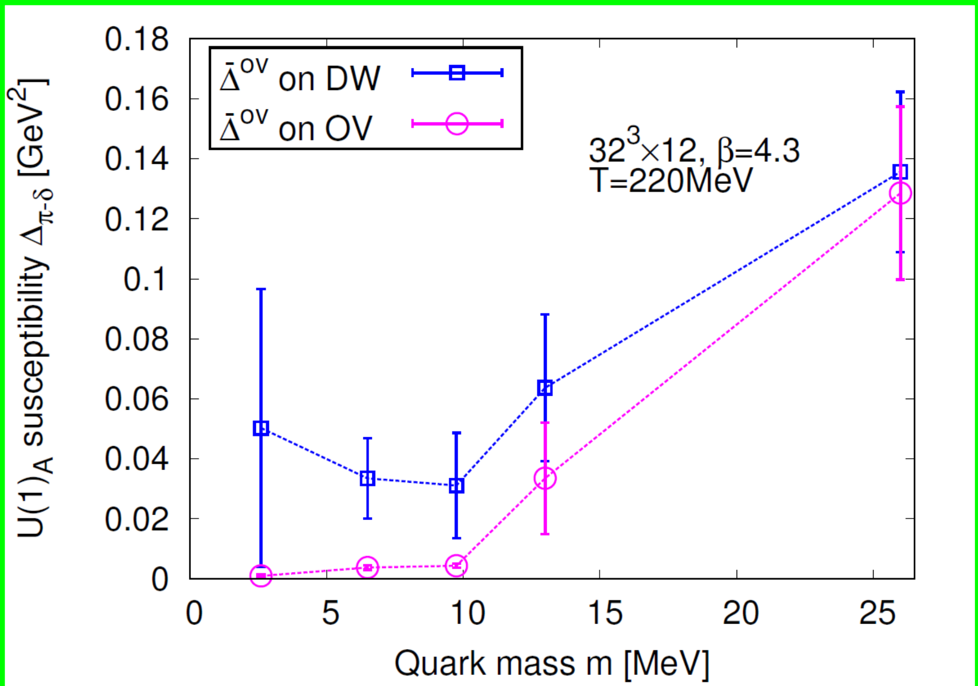
1/a=1.7GeV

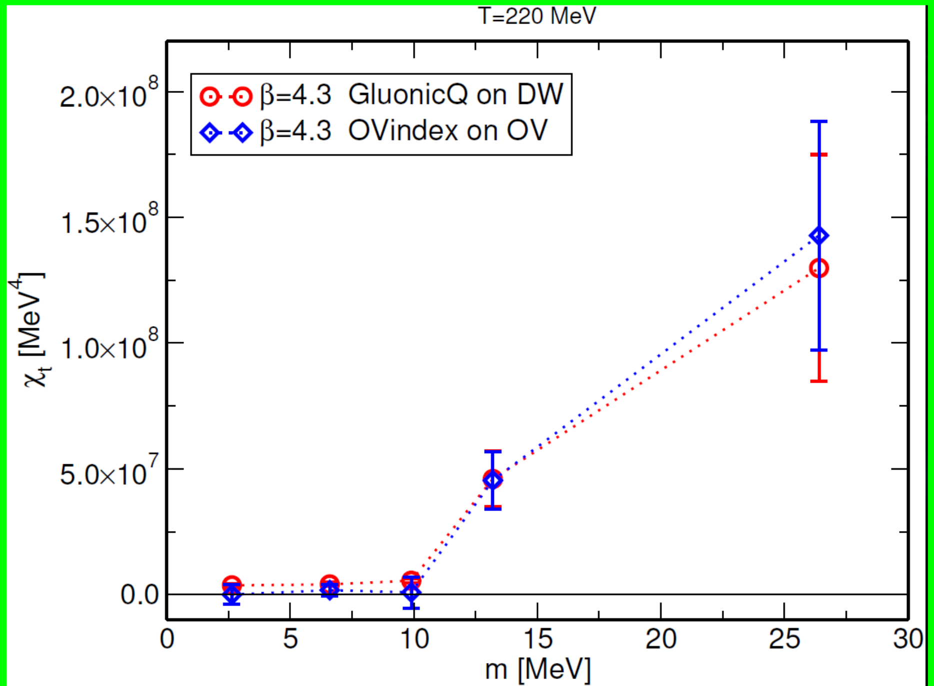
⇒Results from two lattice are consistent

Comparison with Topological susceptibility

- Q_t is related to Dirac operator by the index theorem:

$$Q_t = n_+ - n_- = index(D)$$



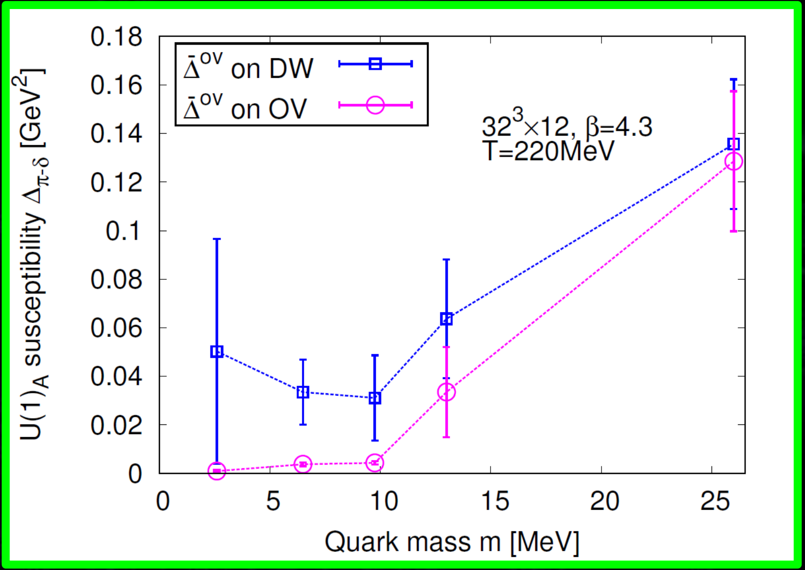


The behavior seems to be similar? ⇒Next talk by Y. Aoki

Summary and Outlook

- U(1)$_A$ susceptibility at high T for $N_f = 2$ was simulated from OV Dirac spectra on the chiral sea quarks

⇒ It seems to be restored in the chiral limit for T=220-330MeV



- Relation to topological susceptibility ⇒ Next talk
- Functional form of $\Delta(m)$ (powers of m …?)
- Going to near T_c (critical exponent for chiral transition?)
- Going to $N_f = 2 + 1$ sector

Backup