Thermodynamics in (2+1)-flavor QCD by the gradient flow method

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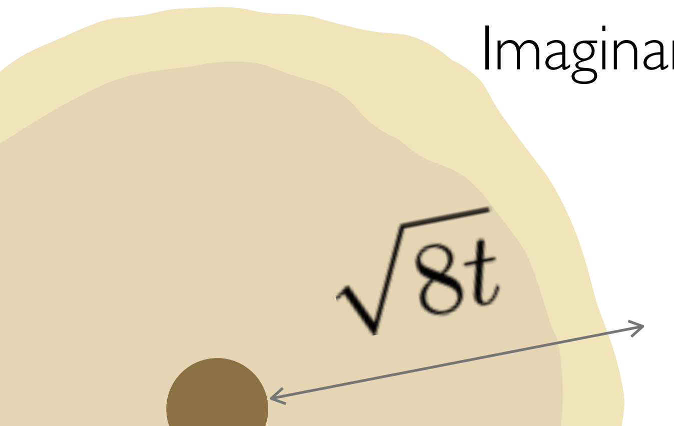
QCD Thermodynamics with Gradient Flow

Gradient flow

Lüscher(2009–), Narayanan-Neuberger(2006)



Imaginary evolution of the system into a fictitious "time" t preserving gauge sym. etc.:

(ex) pure gauge theory $\dot{B}_\mu = D_\nu G_{\nu\mu}$, $\quad B_\mu|_{t=0} = A_\mu$ ← original gauge field

We may view the flowed field $B\mu$ as a smeared $A\mu$ over a physical range of $\sqrt{(8t)}$.

It was shown that operators of flowed fields have no UV divergences nor short-dist. singularities at $t > 0$. Lüscher-Weisz(2011)

GF provides us with a new physical (i.e. non-perturbative) renormalization scheme, which is directly calculable on the lattice in the $a \to 0$ limit.

This opened many possibilities to drastically simplify lattice evaluation of physical observables.

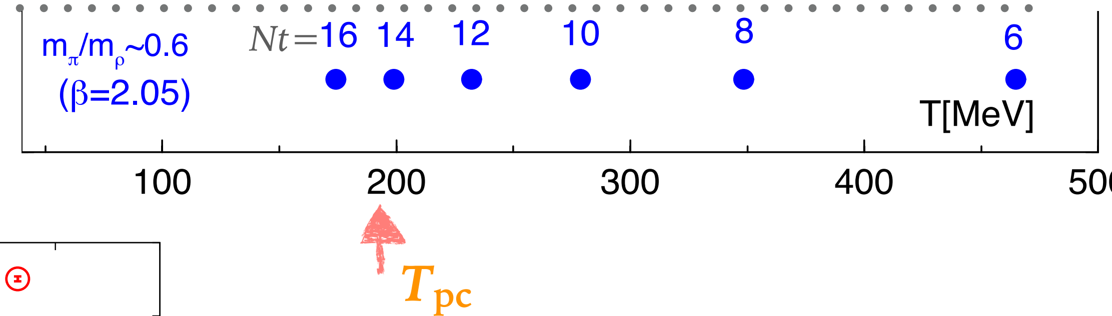
Our project: Application of GF to thermodyn. of (2+1)-flavor QCD

- EMT / EOS — H. Suzuki (2013), Makino-Suzuki (2014)
- Chiral condensate — Hieda-Suzuki (2016)
- Topological charge / susceptibility, ...

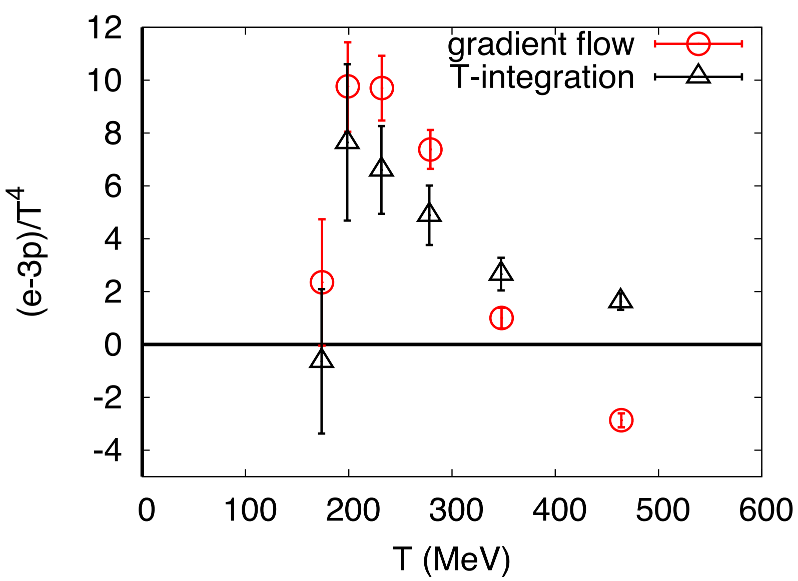
Main Results

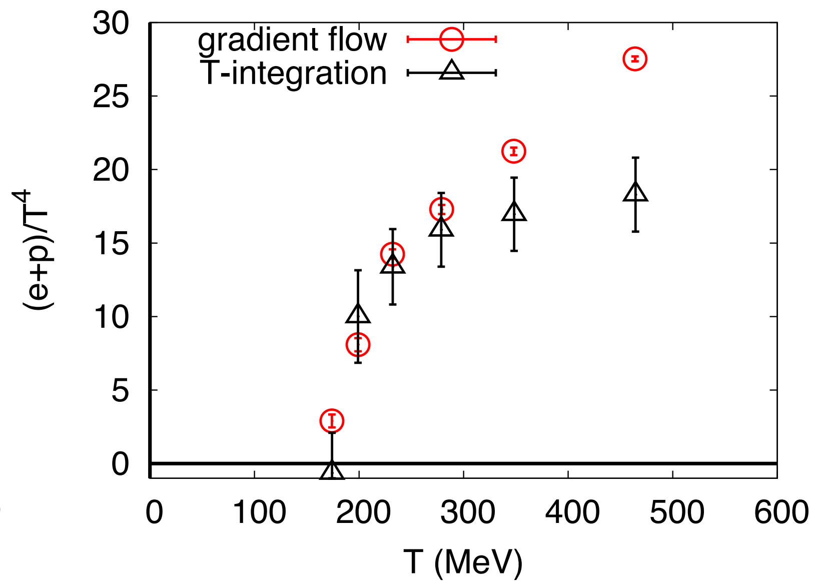
Iwasaki gauge + NP clover at $a \approx 0.07$fm, $m_{PS}/m_V \approx 0.63$

$T/T_{pc} \approx 0.92$ -- 2.44 with the fixed-scale approach.



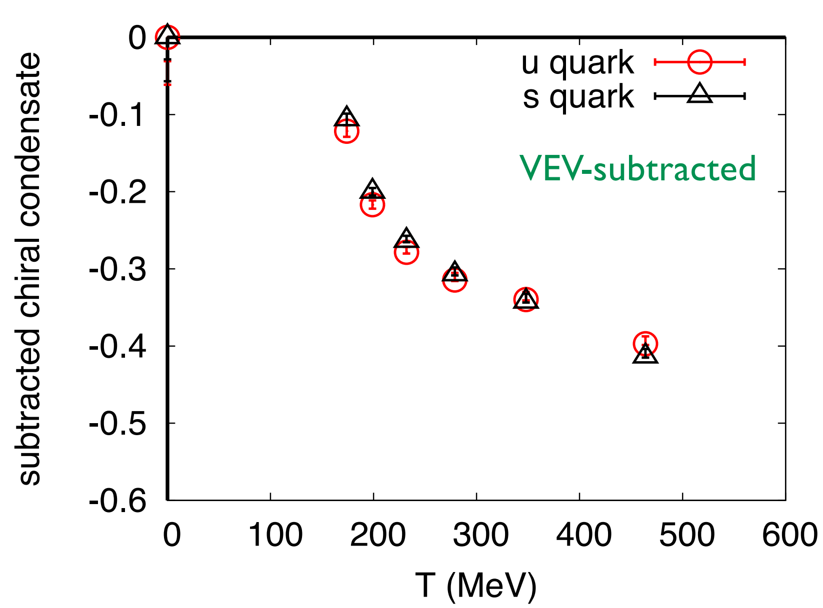
Energy-momentum tensor and EOS

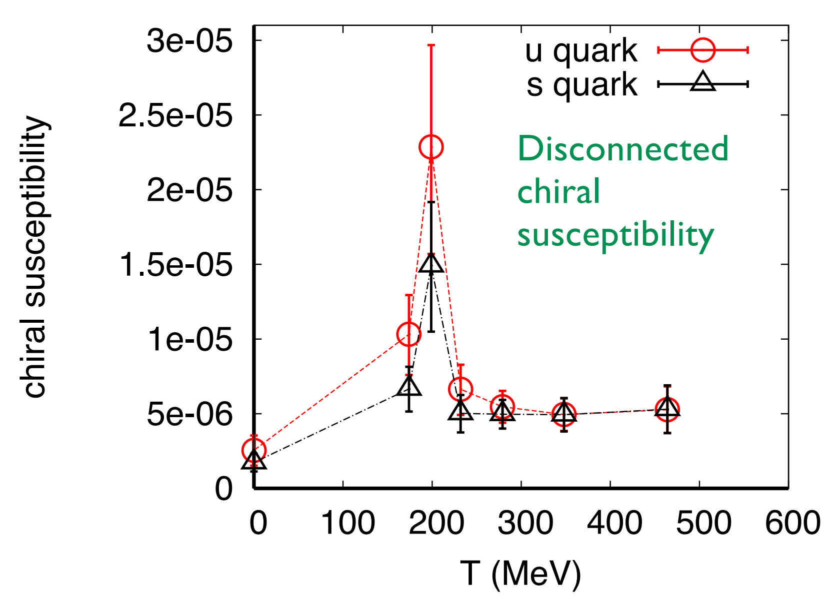




- Good agreement with the conventional method at $T \leq$ 300 MeV ($Nt \geq 10$), suggesting small-Nt artifacts at $Nt < 10$.

Chiral condensate / disconnected susceptibility





- Clear signal of T_{pc} at ≈190 MeV, with Wilson-type quarks! Peak higher with lighter quark.

Main Results

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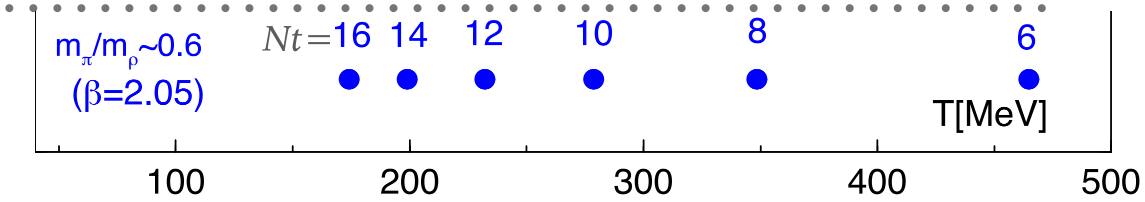


Topological susceptibility

We test two alternative definitions:

(a) gauge definition

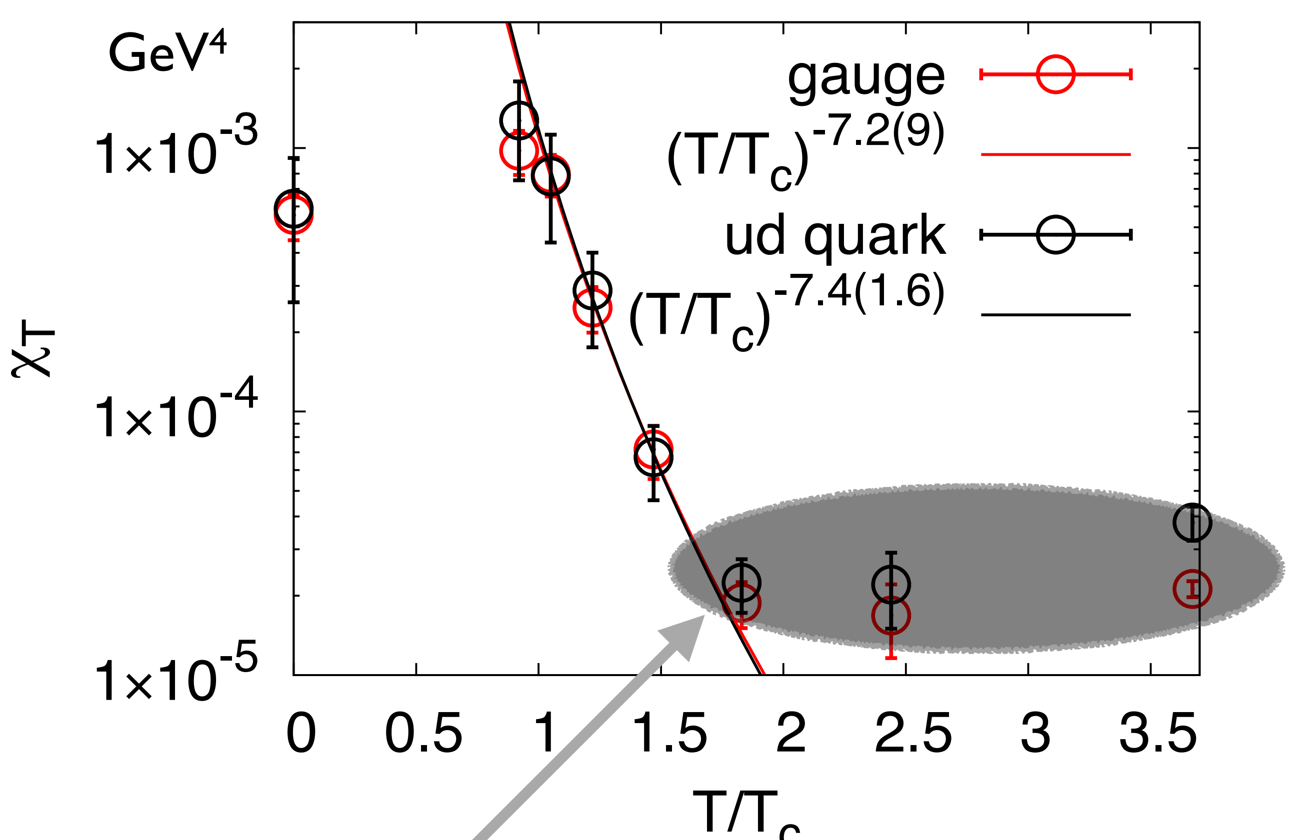
Lüscher('10), Consonni-Engel-Giusti('15)

$$q(t,x) = \frac{1}{64\pi^2}\epsilon_{\mu\nu\rho\sigma}G^a_{\mu\nu}(t,x)G^a_{\rho\sigma}(t,x) \qquad Q(t) = \int d^4x\, q(t,x)$$

(b) fermion definition

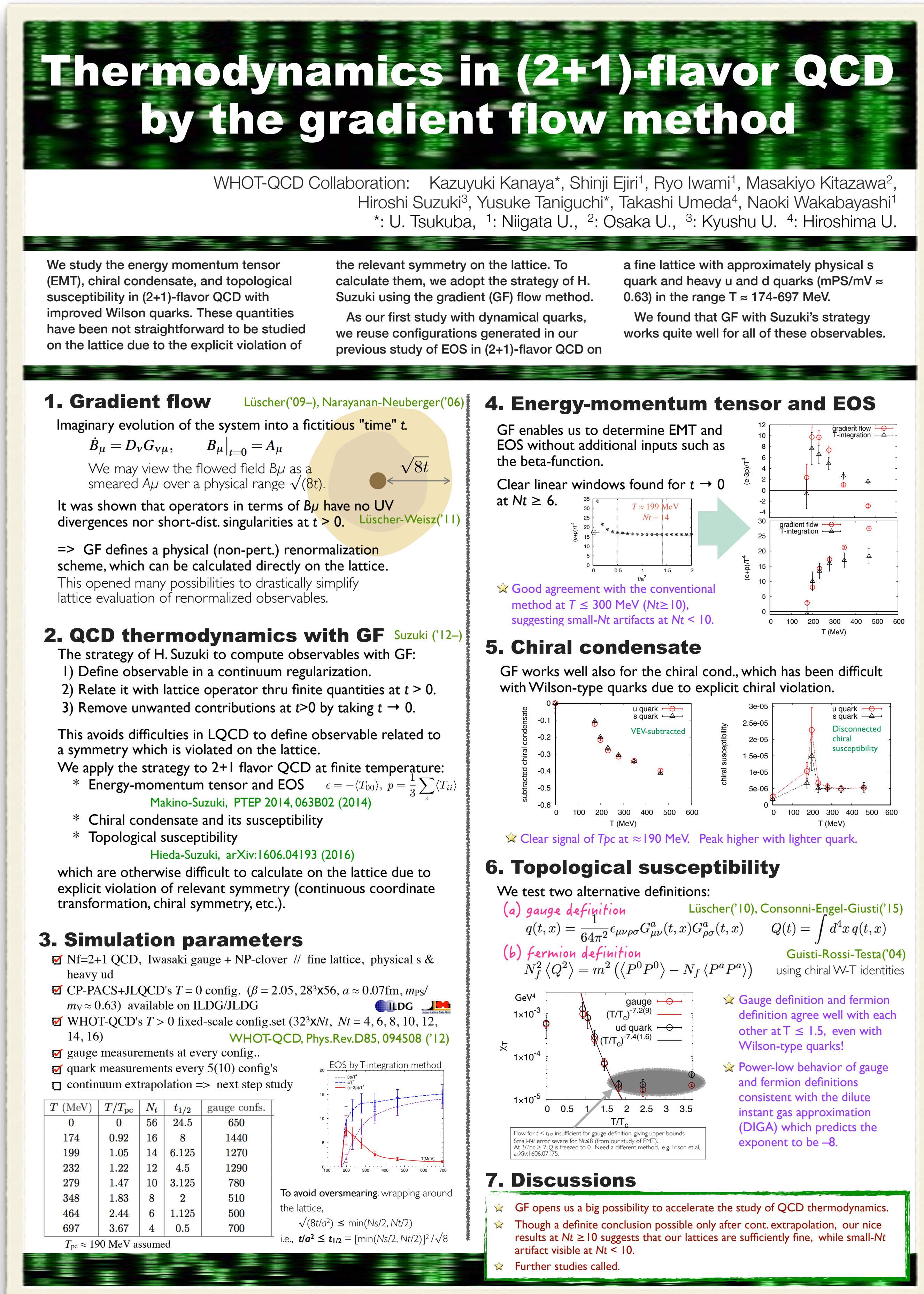
$$N_f^2 \langle Q^2 \rangle = m^2 \left(\langle P^0 P^0 \rangle - N_f \langle P^a P^a \rangle \right)$$

Guisti-Rossi-Testa('04)
using chiral W-T identities



Flow for $t < t_{1/2}$ insufficient for gauge definition, giving upper bounds.
Small-Nt error severe for $Nt \leq 8$ (from our study of EMT).
At $T/T_{pc} > 2$, Q is freezed to 0. Need a different method, e.g. Frison et al, arXiv:1606.07175.

- ⭐ Gauge definition and fermion definition agree well with each other at $T \leq 1.5$, even with Wilson-type quarks!
- ⭐ Power-low behavior of gauge and fermion definitions consistent with the dilute instant gas approximation (DIGA) which predicts the exponent to be –8.



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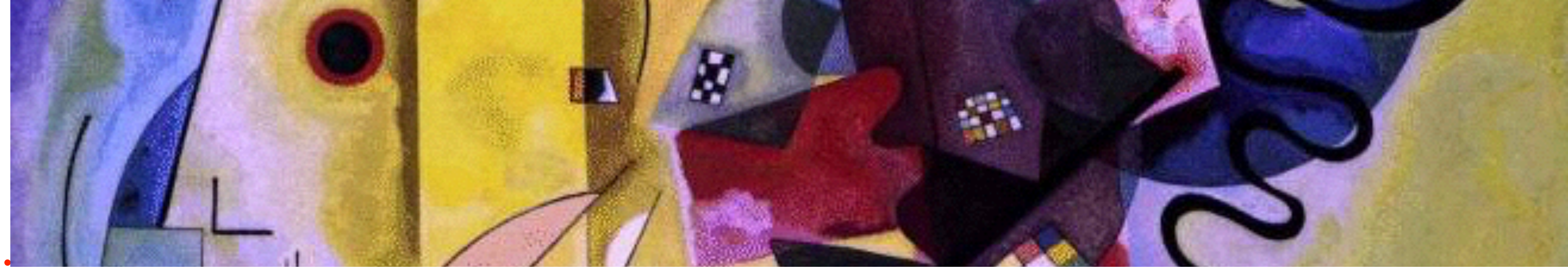
SUMMARY



- We apply gradient flow ideas to investigate thermodynamics of (2+1)-flavor QCD. As the first test, we choose heavy ud quarks with physical s quark, on a fine lattice ($a \approx 0.07$fm, $m_{PS}/m_V \approx 0.63$), and adopt the fixed-scale approach.
- EOS agrees with conventional T-integration method at $T \leq 300$ MeV ($Nt \geq 10$).
- Chiral condensate and its disconnected susceptibility also calculated. Even with the explicit chiral violation of Wilson-type quarks, we obtain reasonable results,
- Topological susceptibility by gauge definition and by fermion definition beautifully agree with each other, and reproduce the T-dep. of DIGA.
- But, note that our $m_\pi \sim 400$ MeV and finite a. A definite conclusion possible only after cont. extrapolation.
- Our good results at $Nt \geq 10$, however, suggests that our lattices are sufficiently fine, while small-Nt artifacts visible at $Nt < 10$.
- Further study needed to complete the cont. extrapolation, and at lighter m_{ud}.