Lattice QCD at Finite Temperature and Density

Zimányi 2009 Winter School
on Heavy Ion Physics
and
Eötvös Loránd Physical Society

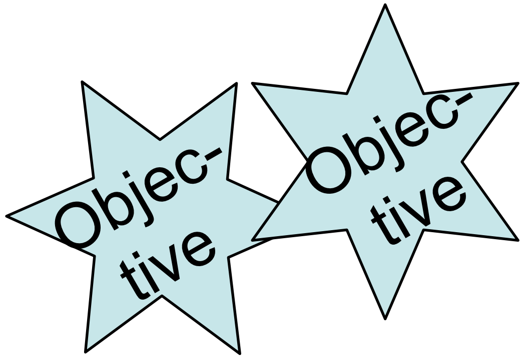
Nov.2, 2009

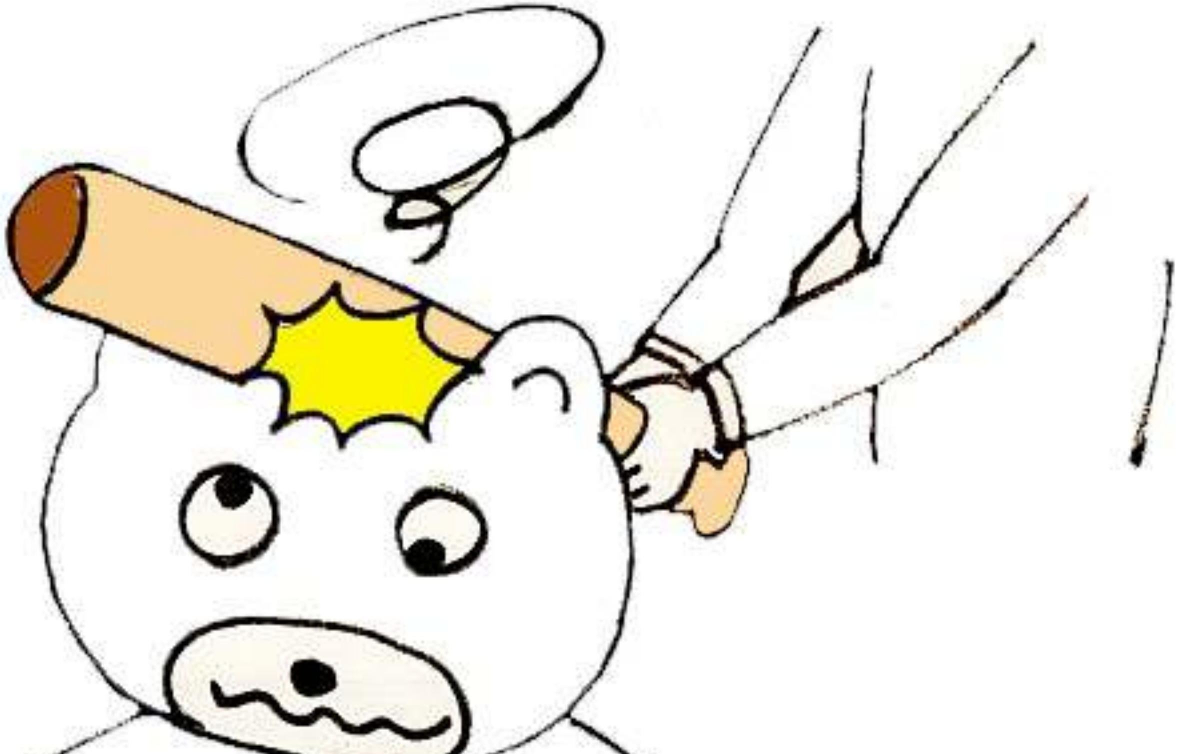
Atsushi Nakamura
Hiroshima University

Objective of the Talk today

- Why is QCD at finite Temperature and Density interesting for a Lattice person ?
- Brief Overview
- Points which I want to understand
  - Approaches to Finite Density
  - Transport Coefficients
  - Confinement/Deconfinement Transition and Topological Objects

Why do Audiences the same Interest as You !





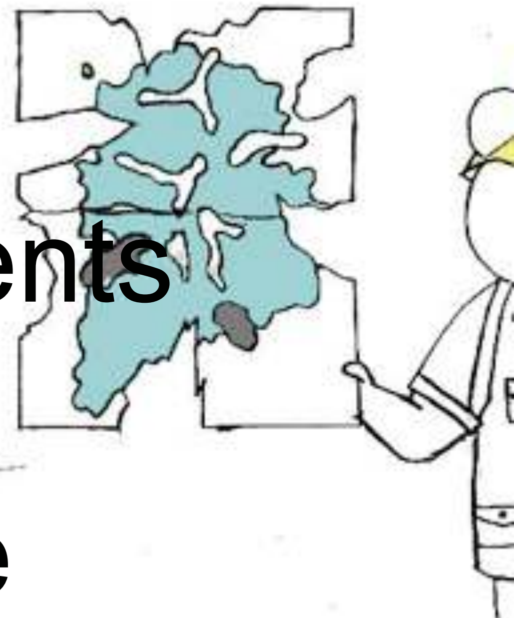
1979 Ph.D Thesis “High Energy Hadron-Nucleus Collisions”

1979 Visiting (and disturbing) Nagamiya at Berkley

1984 Lattice QCD Calculation at Finite Temperature and Density

1989 Meson Masses at Finite Temperature

1995 Starting Transport Coefficients Calculation



1999 Screening Masses at Finite

Cernodub and Zakharov

Sakai

Saito

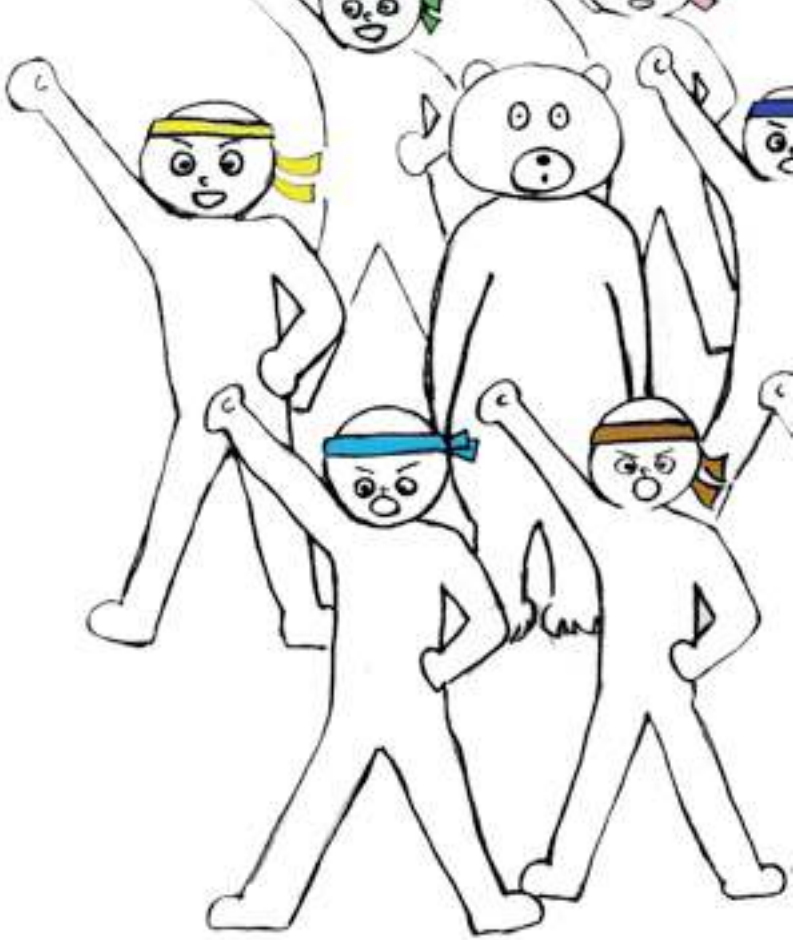
Nakagawa

Nagata

Yahiro and Kouno

Fukushima, Iida, Nonaka, Muroya

QCD-TARO (deForcrand,Stamatescu, Garcia-Perez,Pushkina, Miyamura, Hioki, Matsufuru, Takaishi, Umeda)



$$Z = \mathrm{Tr}\, e^{-\beta(\hat{H}-\mu\hat{N})} \qquad \beta \equiv 1/kT$$

$$\mathcal{L} = \bar{\psi}\,(i\gamma^{\mu} D_{\mu} - m)\,\psi$$

$$-\frac{1}{4}\mathrm{Tr}\,F_{\mu\nu}F^{\mu\nu}$$

$$Z = \int \prod d\bar{\psi}(x)\,d\psi(x)\,dA_{\mu}(x)$$

$$- \int^{\beta} (\mathcal{L} \ldots + \bar{\psi}\Delta\psi)$$

$$Z = \int \prod dA_\mu(x) \det \Delta\, e$$

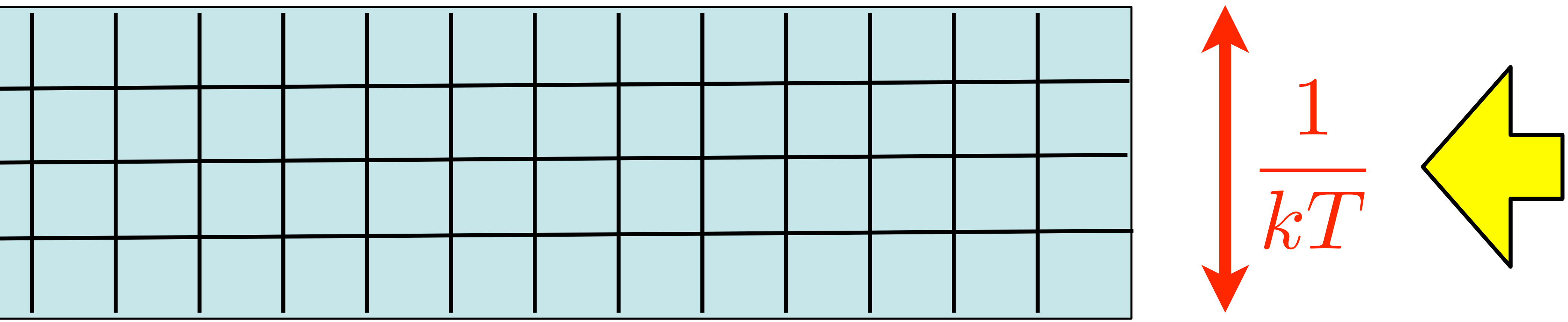
Quark Matrix $\Delta = i\gamma^\mu D_\mu - m - \mu$

ace-Time → Lattice

$$Z = \int \prod dA_\mu(x) \det \Delta \, e$$

Quark Matrix $\Delta = i\gamma^\mu D_\mu - m - \mu$

ace-Time → Lattice

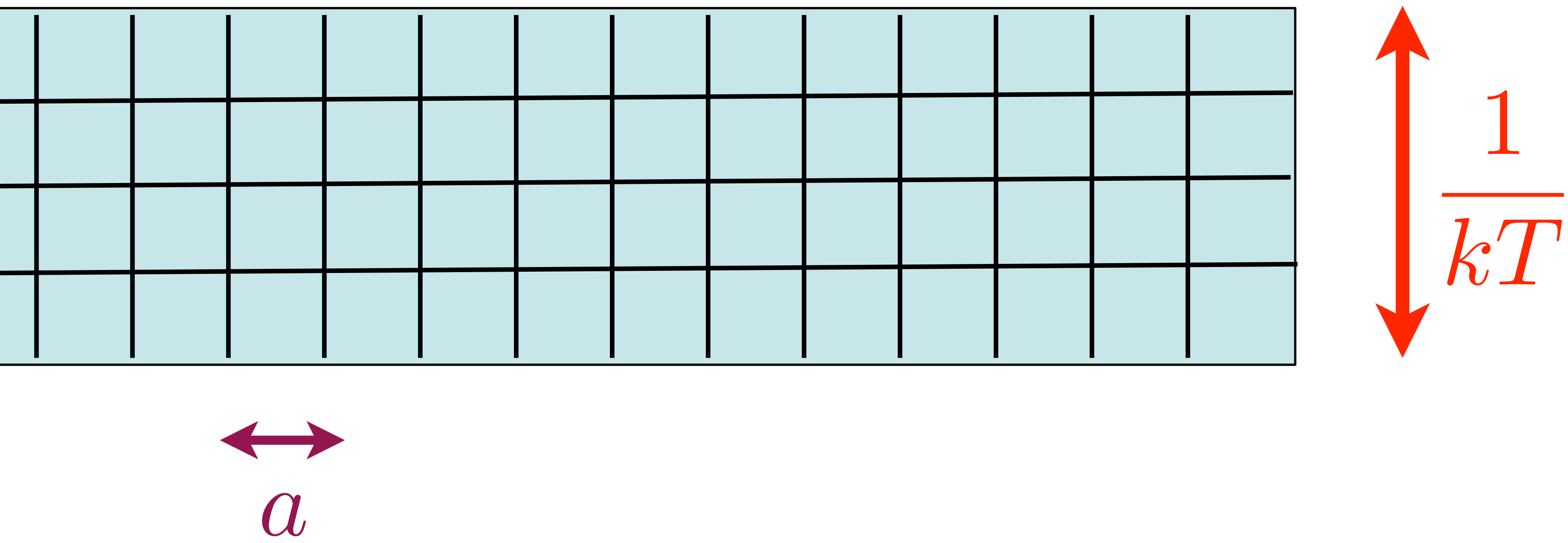


Lin
Le

$$Z = \int \prod dA_\mu(x) \det \Delta \, e$$

Quark Matrix $\Delta = i\gamma^\mu D_\mu - m - \mu\gamma$

ace-Time → Lattice



Lin
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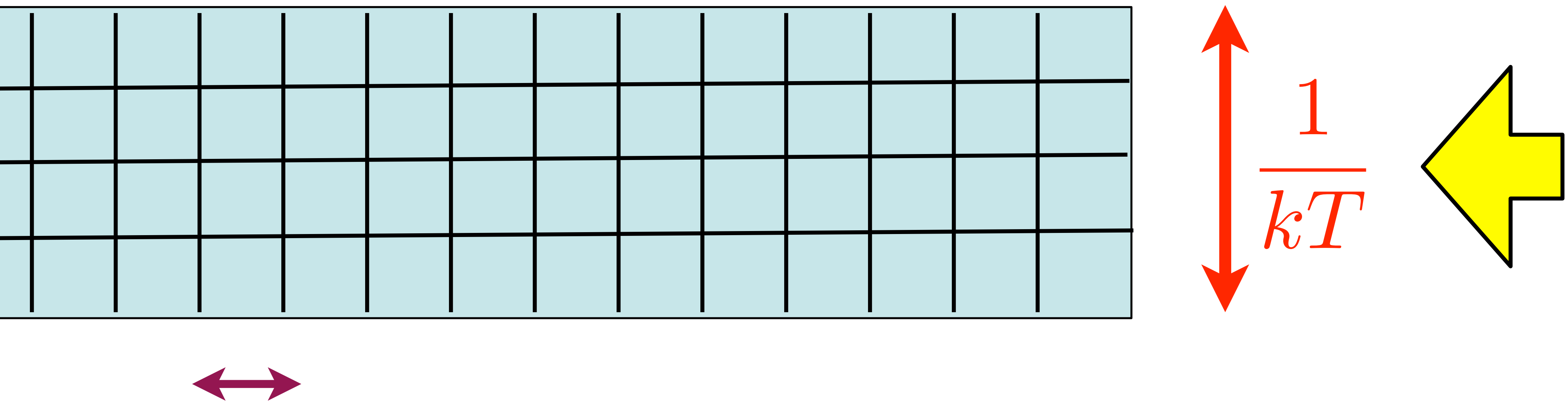
Lattice Spacing

$$Z = \int \prod dA_\mu(x) \det \Delta \, e$$

Quark Matrix $\Delta = i\gamma^\mu D_\mu - m - \mu\gamma$

ace-Time → Lattice



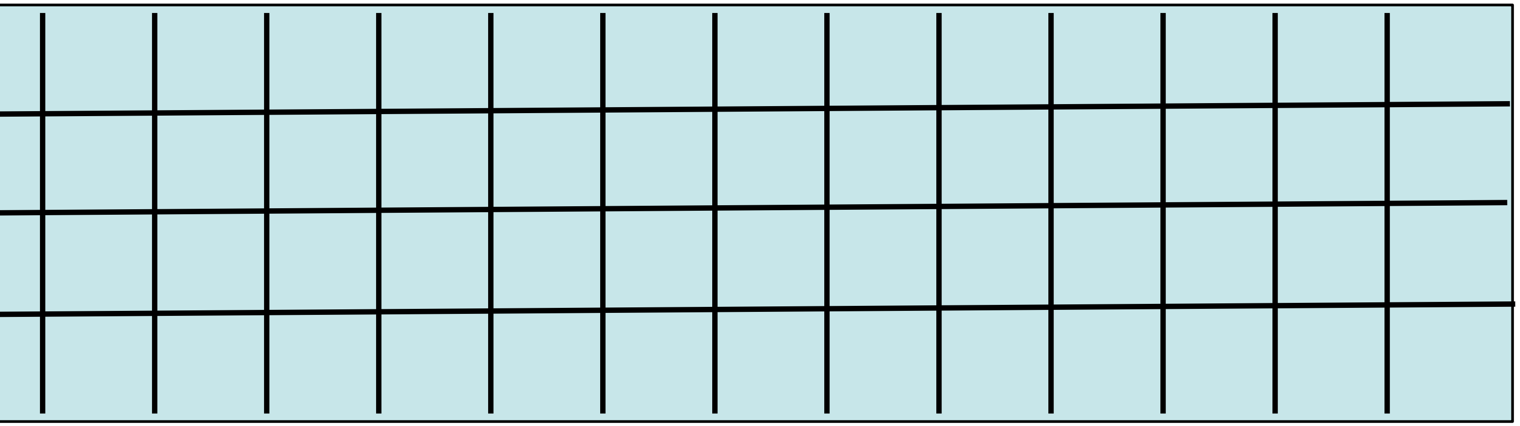
π

Lattice Spacing

$$Z = \int \prod dA_\mu(x) \det \Delta \, e$$

Quark Matrix $\Delta = i\gamma^\mu D_\mu - m - \mu$

ace-Time ➡ Lattice



$\frac{1}{kT}$

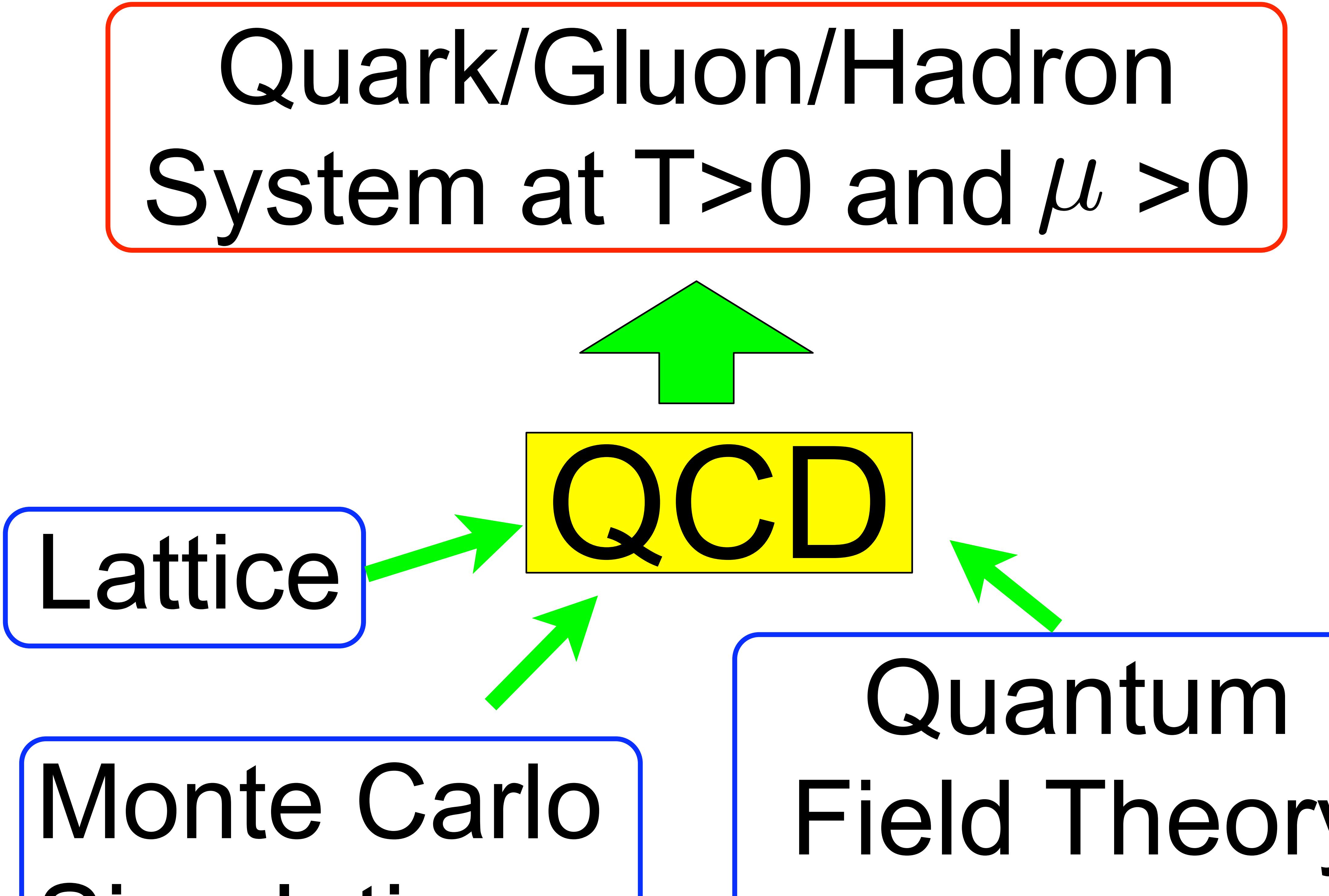
Lin
Le

a

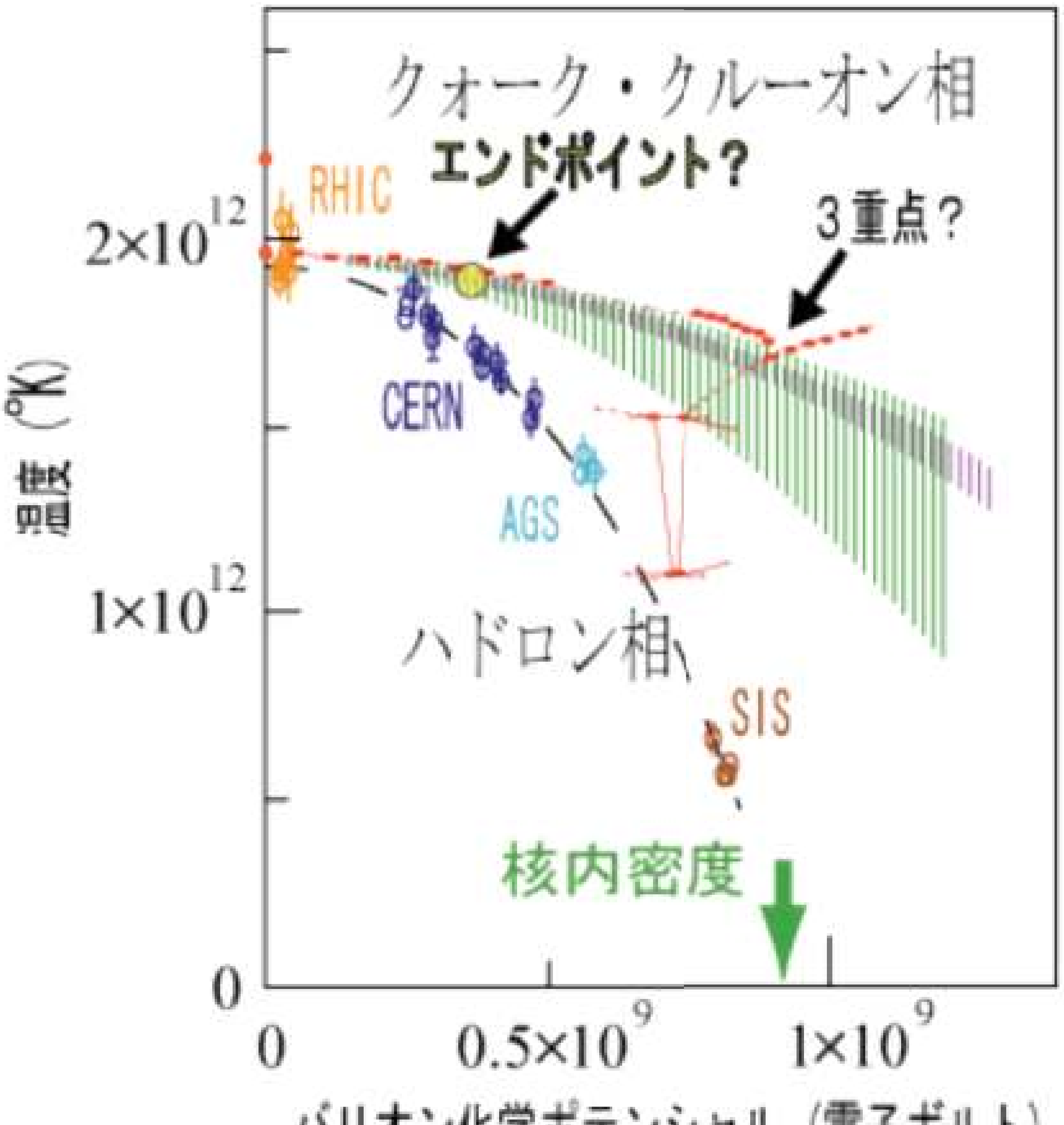
π

Lattice Spacing

Momentum Cut Off



Quark/Gluon/Hadron
System at T>0 and μ >0
QCD
Lattice
Monte Carlo
Quantum
Field Theor



A.Nakamura
Parity (Japanese Popular
Science Journal), 2007
"Tri-Critical Point of
Experimental Physics,
Theoretical Physics and

Recent Reviews

- Lombardo, Quark Matter 2008
  - “QCD at Non-Zero Density : Lattice Results”
    - The Critical line and the Critical Point
    - Equation of State and Critical Behaviour
    - Towards Fair
    - Cold and dense matter: QCD-like models
- Lain, Lattice 2009
  - “Finite Temperature QCD”
- deForcrand, Lattice 2009
  - “Simulatin QCD at finite density”

Sign Problem in Finite Density QCD

Finite Density QCD

$$Z = \mathrm{Tr}\, e^{-\beta(H-\mu N)} = \int \mathcal{D}U \mathcal{D}\bar{\psi} \mathcal{D}\psi\, e^{-\beta S_G - \bar{\psi}\Delta}$$

$$= \int \mathcal{D}U \prod_f \det \Delta(m_f)\, e^{-\beta S_G}$$

$$\Delta(\mu) = D_\nu \gamma_\nu + m + \mu\gamma_0$$

$$\Delta(\mu)^\dagger = -D_\nu \gamma_\nu + m + \mu^* \gamma_0 = \gamma_5 \Delta(-\mu^*)\gamma_5$$

$$(\det \Delta(\mu))^* = \det \Delta(\mu)^\dagger = \det \Delta(-$$

$$(\det \Delta(0))^* = \det \Delta(0)$$

$\det \Delta$ ⇒ *Real*

For $\mu \neq 0$ (in general)

$\det \Delta$ ⇒ *Complex*

$$Z = \int \mathcal{D}U \prod_f \det \Delta(m_f, \mu_f) e^{-\beta S_G}$$

In Monte Carlo simulation, configurations are generated according to the Probability:

$$\det \Delta \, e^{-\beta S_G} / Z$$

$\det \Delta$: *Complex*

Monte Carlo Simulations very difficult !

OK ?

$$\mathrm{Tr}AB^\dagger \leq \sqrt{\mathrm{Tr}AA^\dagger}\sqrt{\mathrm{Tr}BB^\dagger}$$

(Cauchy-Schwarz)

son $\bar{\psi}\Gamma\psi$
pagators

$$\mathrm{Tr}\Delta^{-1}(x,0)\Gamma\Delta^{-1}(0,x)\Gamma$$

$$= \mathrm{Tr}\Delta^{-1}(x,0)\Gamma\gamma_5\Delta^{-1}(x,0)^\dagger\gamma_5$$

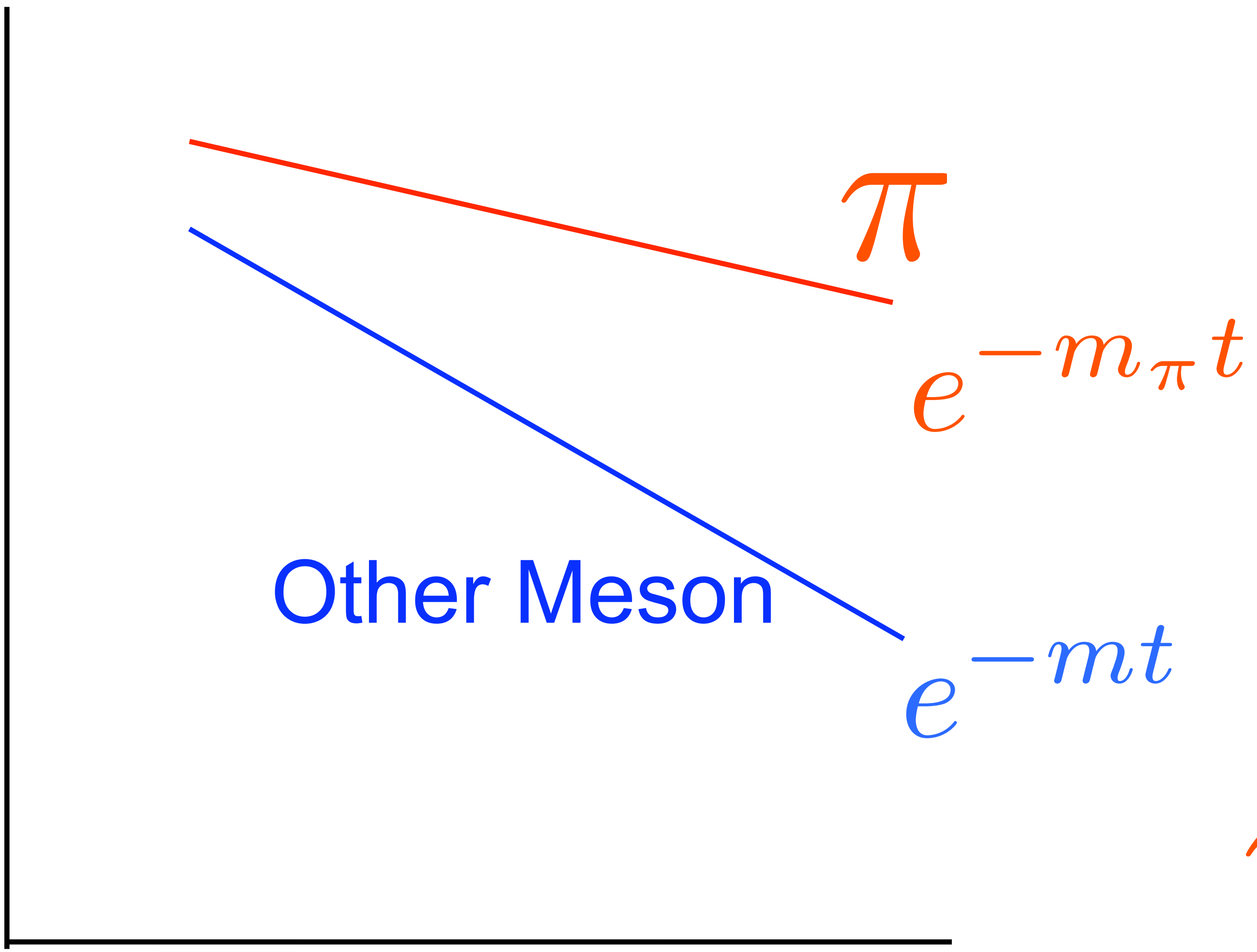
$$\leq \sqrt{\Delta^{-1}(x,0)\Delta^{-1}(x,0)^\dagger}$$

$$\sqrt{\Gamma\gamma_5\Delta^{-1}(x,0)^\dagger\gamma_5\Gamma\left(\Gamma\gamma_5\Delta^{-1}(x,0)^\dagger\gamma_5\right.}$$

$$= \mathrm{Tr}\Delta^{-1}(x,0)\Delta^{-1}(x,0)^\dagger$$

π Propagato

(Any Meson Propagators) $\leq$ (pi Meson Propagators)



$m_\pi \leq$

π is light

Does not hold for $\mu \neq 0$

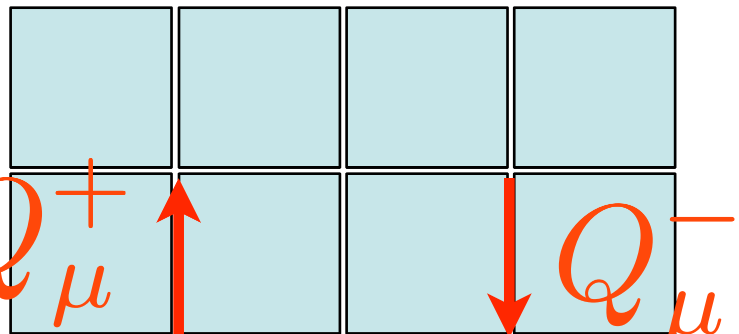
Physical Origin of Sign Problem

ilson Fermions $\Delta = I - \kappa Q$

S(Staggered) Fermions $\Delta = m - Q'$

$$= m(I - \frac{1}{m} \dots$$

$$Q = \sum_{i=1}^{3} (Q_i^+ + Q_i^-) + (e^{+\mu} Q_4^+ + e^{-\mu} Q \dots$$



$$Q_\mu^+ = * * U_\mu(x) \delta_{x', x- \dots}$$

$$Q_\mu^- = * * U^\dagger(x') \delta \dots$$

$$= e^{-\sum_n \frac{1}{n}\kappa^n \mathrm{Tr} Q^n}$$

Large Mass Expansion

n-vanishing are
osed Loops
L -dependent lowest

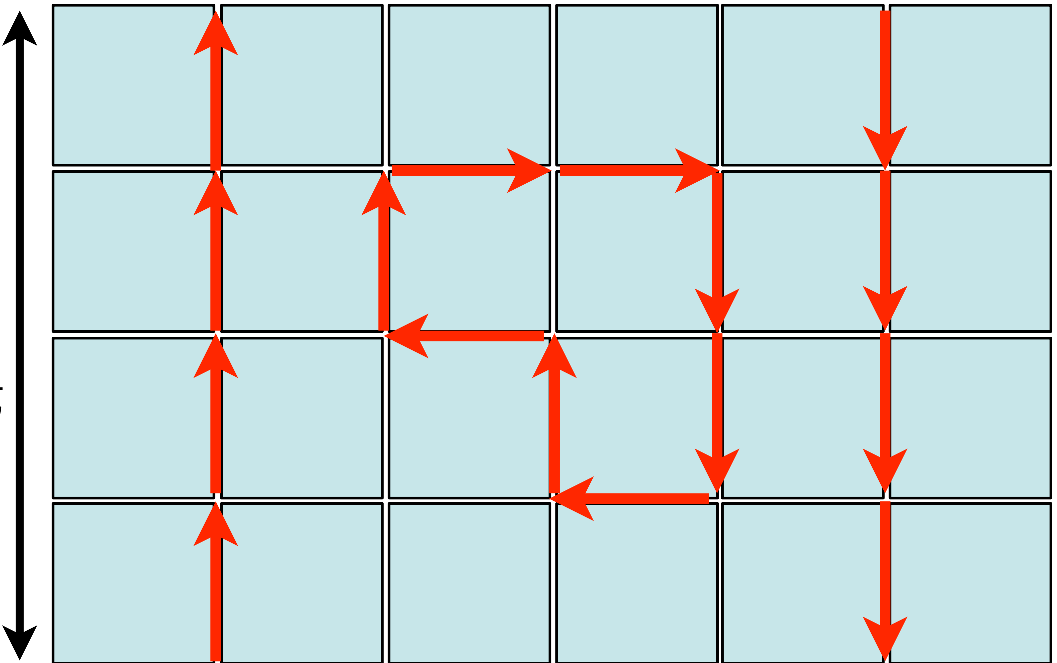
$$\kappa^{N_t} e^{\mu N_t} \mathrm{Tr}(Q^+ \cdots Q^+)$$

$$= ** \kappa^{N_t} e^{\mu/T} \mathrm{Tr} L$$

$$\kappa^{N_t} e^{-\mu N_t} \mathrm{Tr}(Q^- \cdots Q^-)$$

$$= ** \kappa^{N_t} e^{-\mu/T} \mathrm{Tr} L^\dagger$$

$\mathrm{Tr} L$: Polyakov Loop



Add Both Contributions

$$** \kappa^{N_t} \left(\cosh \frac{\mu}{T} \Re \mathrm{Tr} L + i \sinh \frac{\mu}{T} \right.$$

where No Sign Problem

Think and then You can easily find them.

Really ?

They are not our final Solution,

1. Imaginary Chemical Potential

$$(\det \Delta(\mu))^* = \det \Delta(-\mu^*)$$

$$\mu = i\mu_I \qquad (\det \Delta(\mu_I))^* = \det \Delta(\mu$$

2. Color SU(2) $\quad U_\mu^* = \sigma_2 U_\mu \sigma_2$

$$\det \Delta(U, \gamma_\mu)^* = \det \Delta(U^*, \gamma_\mu^*) = \det \sigma_2 \Delta(U, \gamma_\mu^*) \sigma_2$$

$$= \det \Delta(U, \gamma_\mu)$$

3. Iso-Vector Type（finite iso-spin)

$$\mu_d = -\mu_u$$

$$\det \Delta(\mu_u) \det \Delta(\mu_d) = \det \Delta(\mu_u) \det \Delta(-\mu_u)$$

$$= \det \Delta(\mu_u) \det \Delta(\mu_u)^* = |\det \Delta(\mu_u)|^2$$

(Phase Q

imple Idea

- We cannot calculate at finite μ , then expand at $\mu = 0$

$$f(\mu) = f(0) + \mu f'(0) + \frac{1}{2}\mu^2 f''(0) + \cdots$$

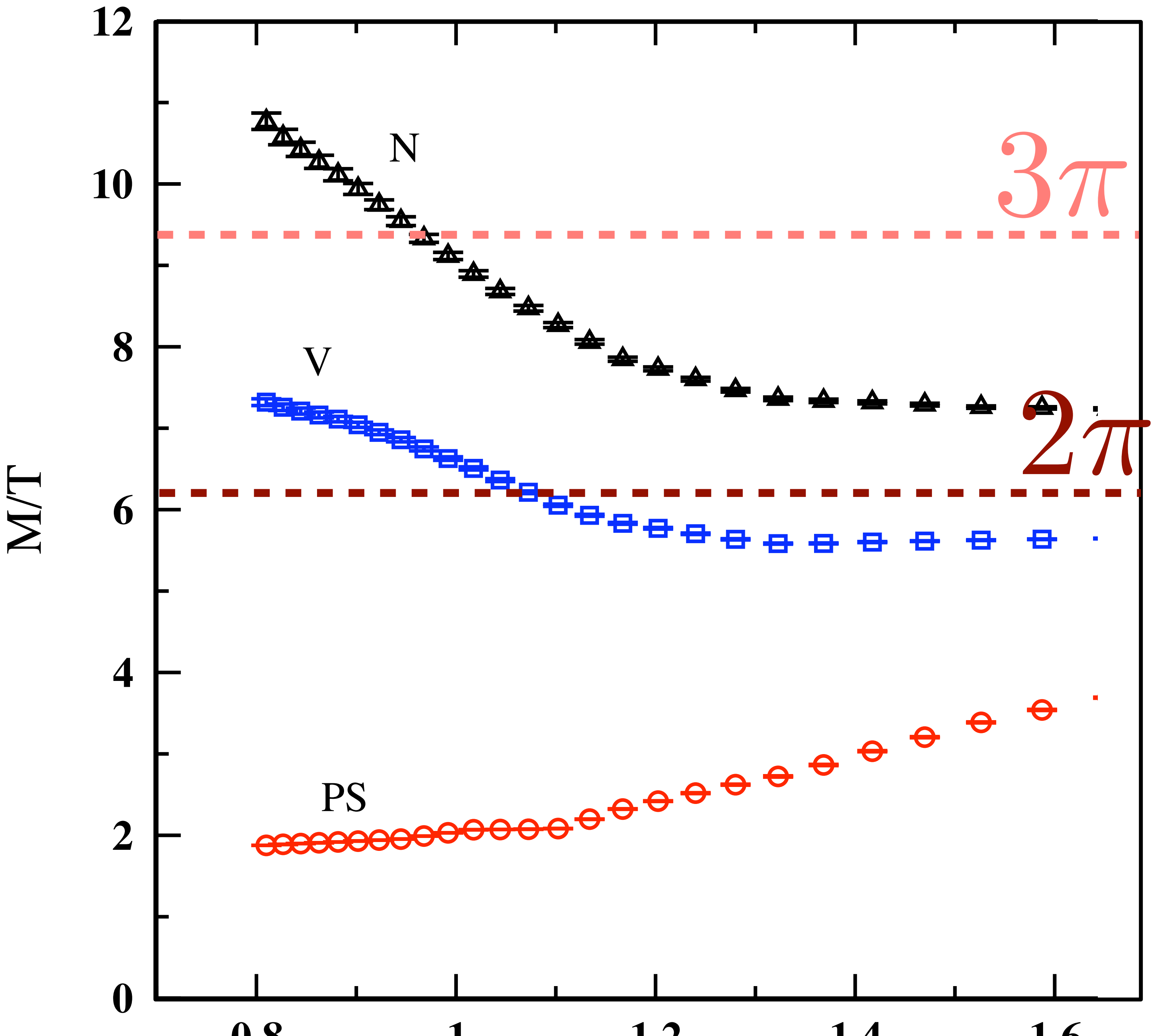
- Gottlieb et al. Phys. Rev. D55 (1997) 6852

$$\chi_S = \left(\frac{\partial}{\partial \mu_u} + \frac{\partial}{\partial \mu_d}\right)\left(\langle n_u \rangle + \langle n_d \rangle\right)$$

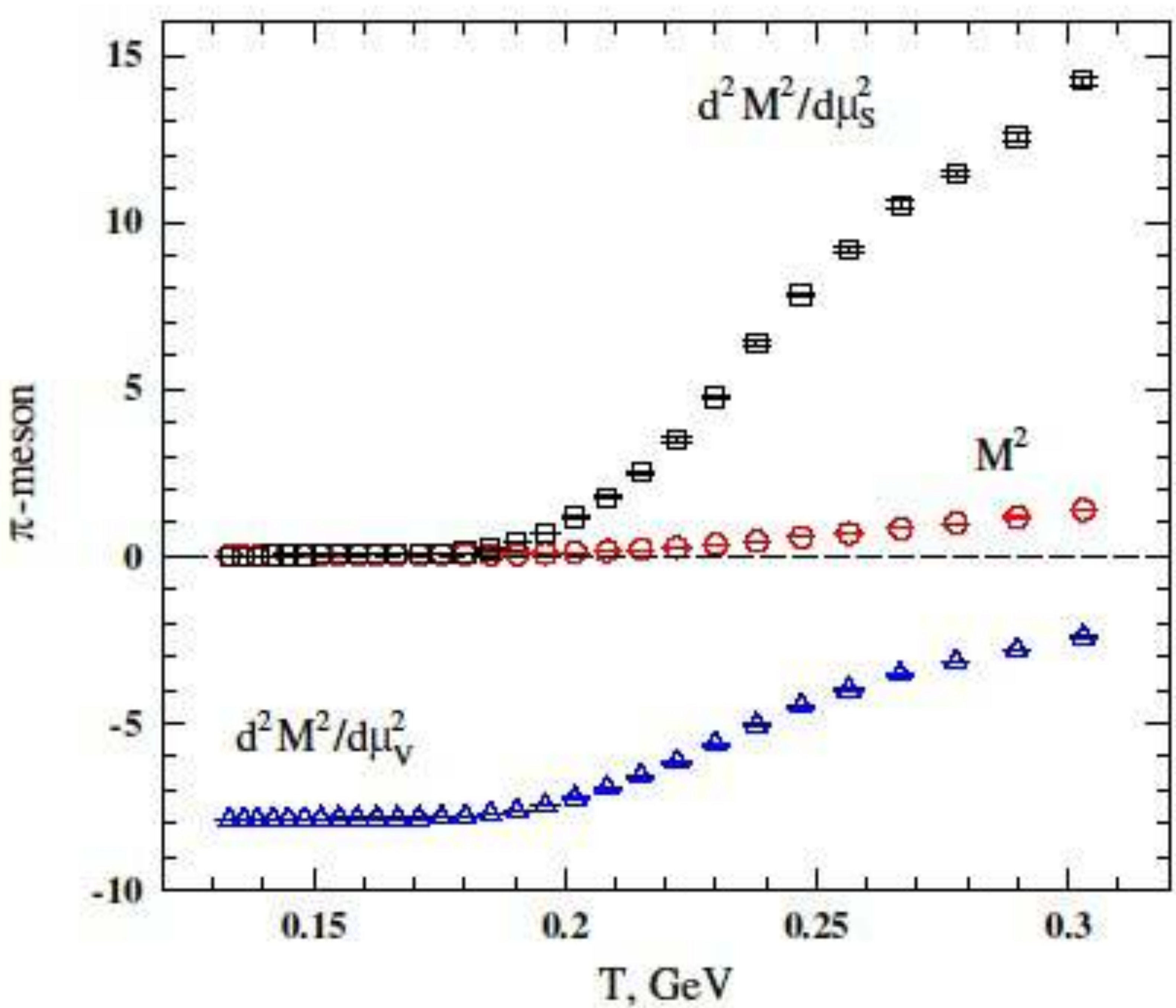
$$\chi_{NS} = \left(\frac{\partial}{\partial \mu_u} - \frac{\partial}{\partial \mu_d}\right)\left(\langle n_u \rangle - \langle n_d \rangle\right)$$

- QCD-TARO: Phys. Rev. D65 (2002) 054501 → Screening Mass
- Swansea-Bielefeld: Phys. Rev. D66, 074507 (2002) → EoS

Screening Masses



w.r.t. Chemical Potentials



o Sign Problem → MC is possible

has Confinement and De-Confinement Pha

o Difference between Meson and Baryo

ood place to study finite density field theory

on-perturbatively.

Ve can get information of the real world if we

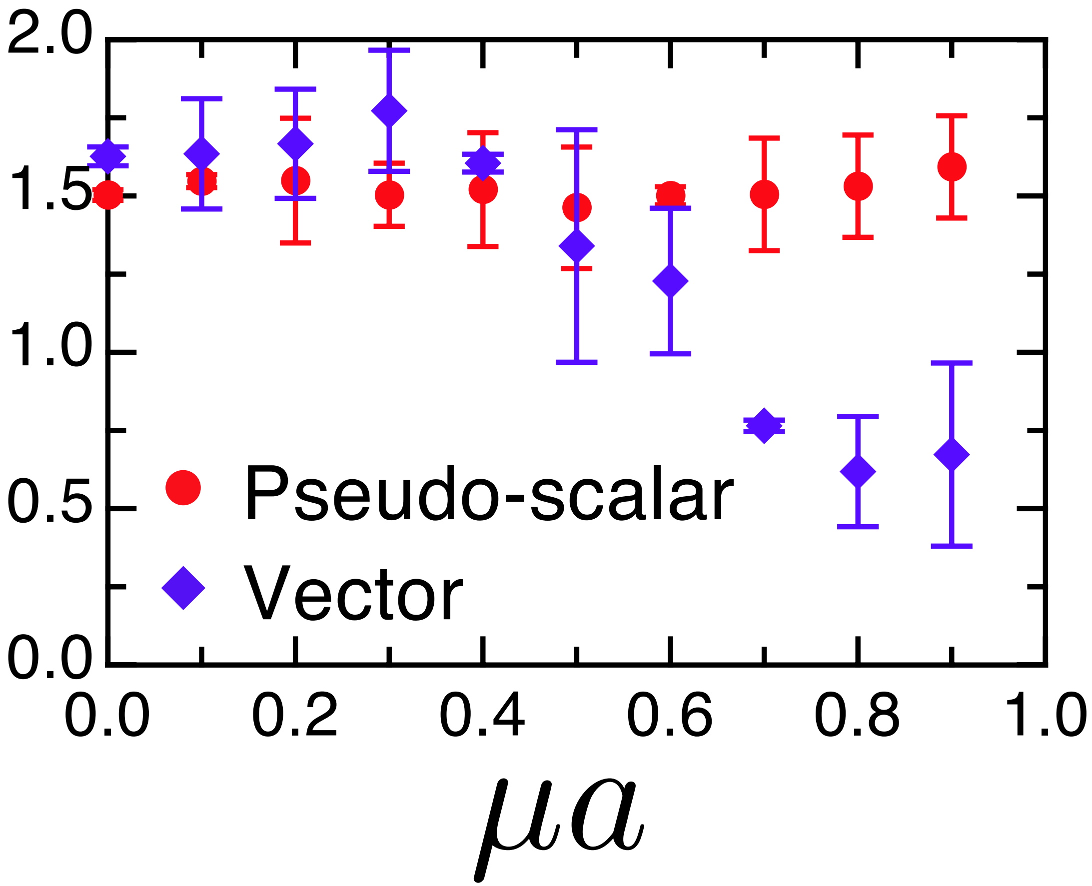
mbine it with theoretical analysis/model (Str

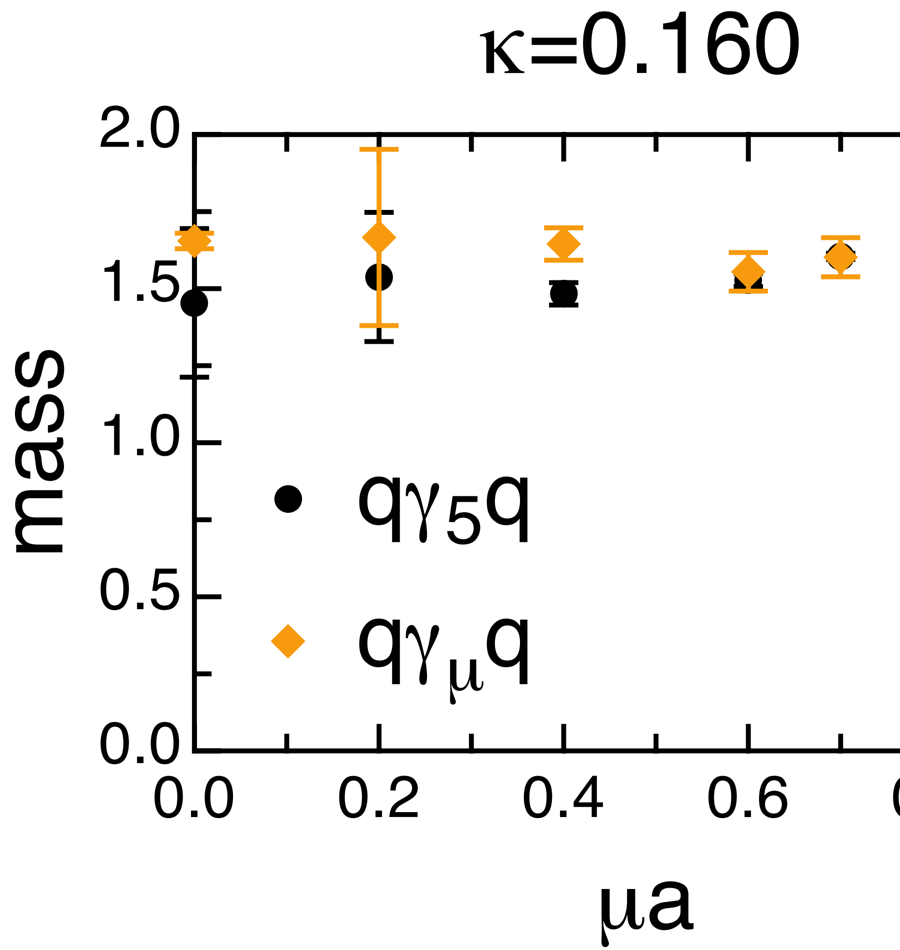
oupling, Random Matrix, PNJL etc) 報

Which outcome is general, and which is special for

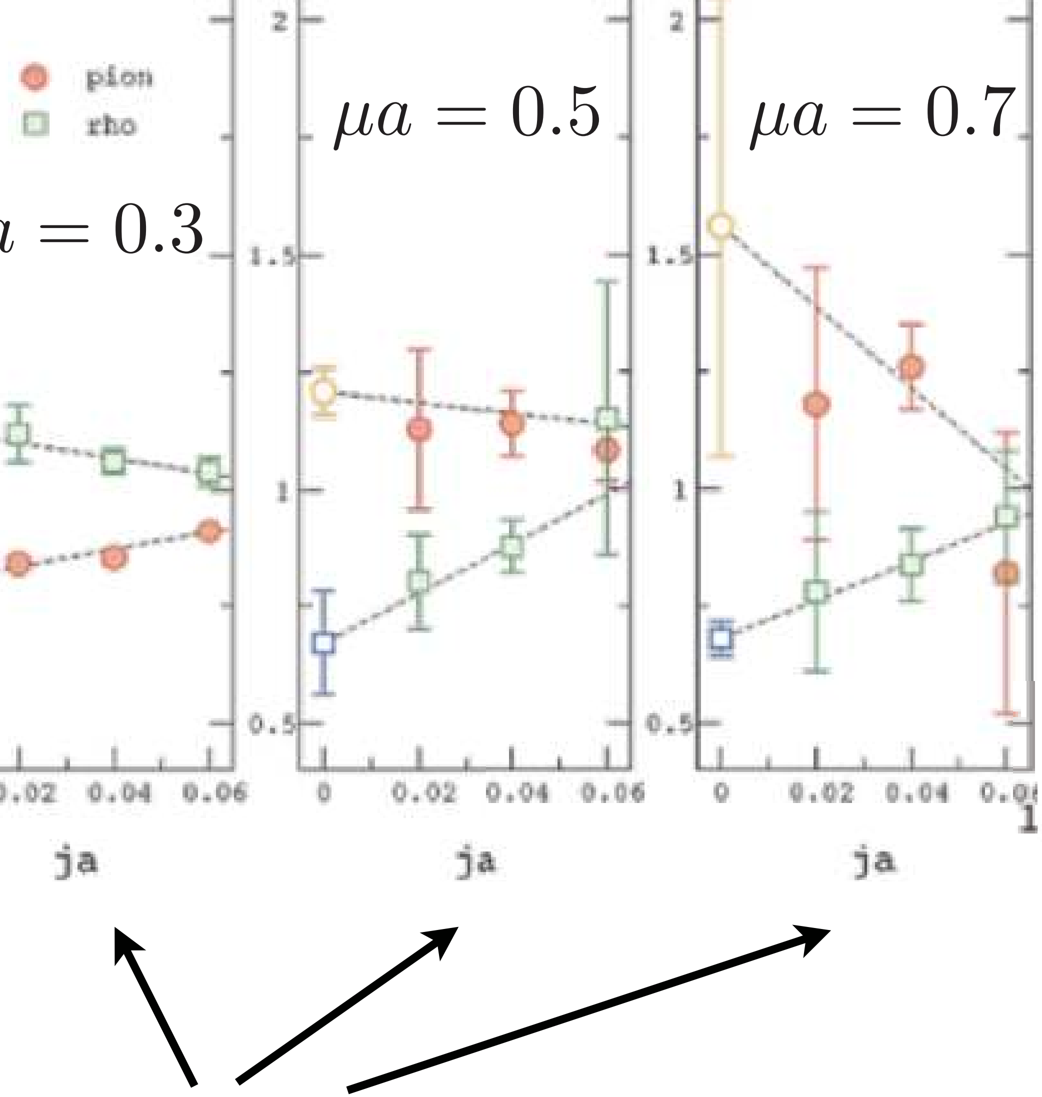
SU(2)

$$\kappa = 0.160$$

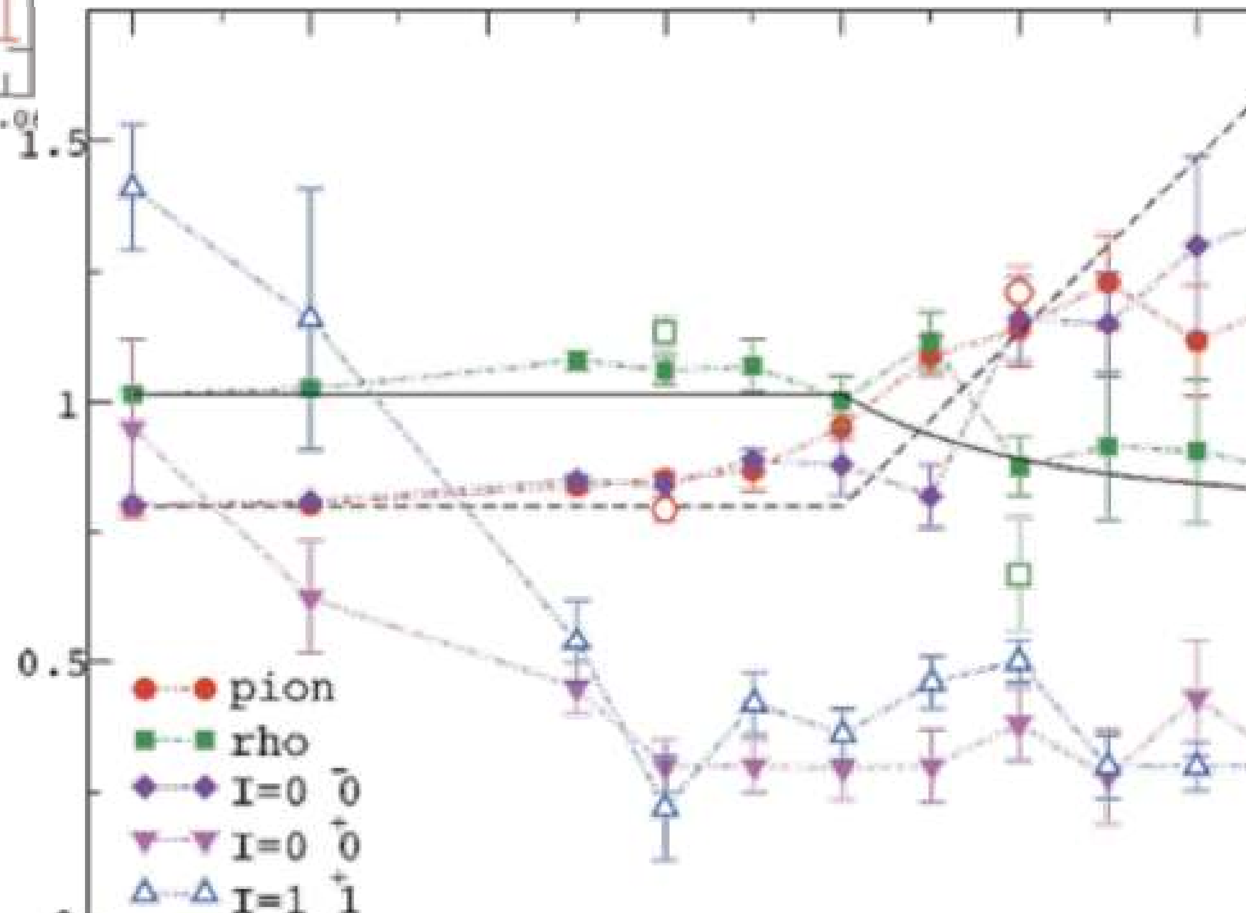




Muroya, A.N. and Nonaka
Phys.Lett. B551 (2003) 305
(hep-lat/0211010)

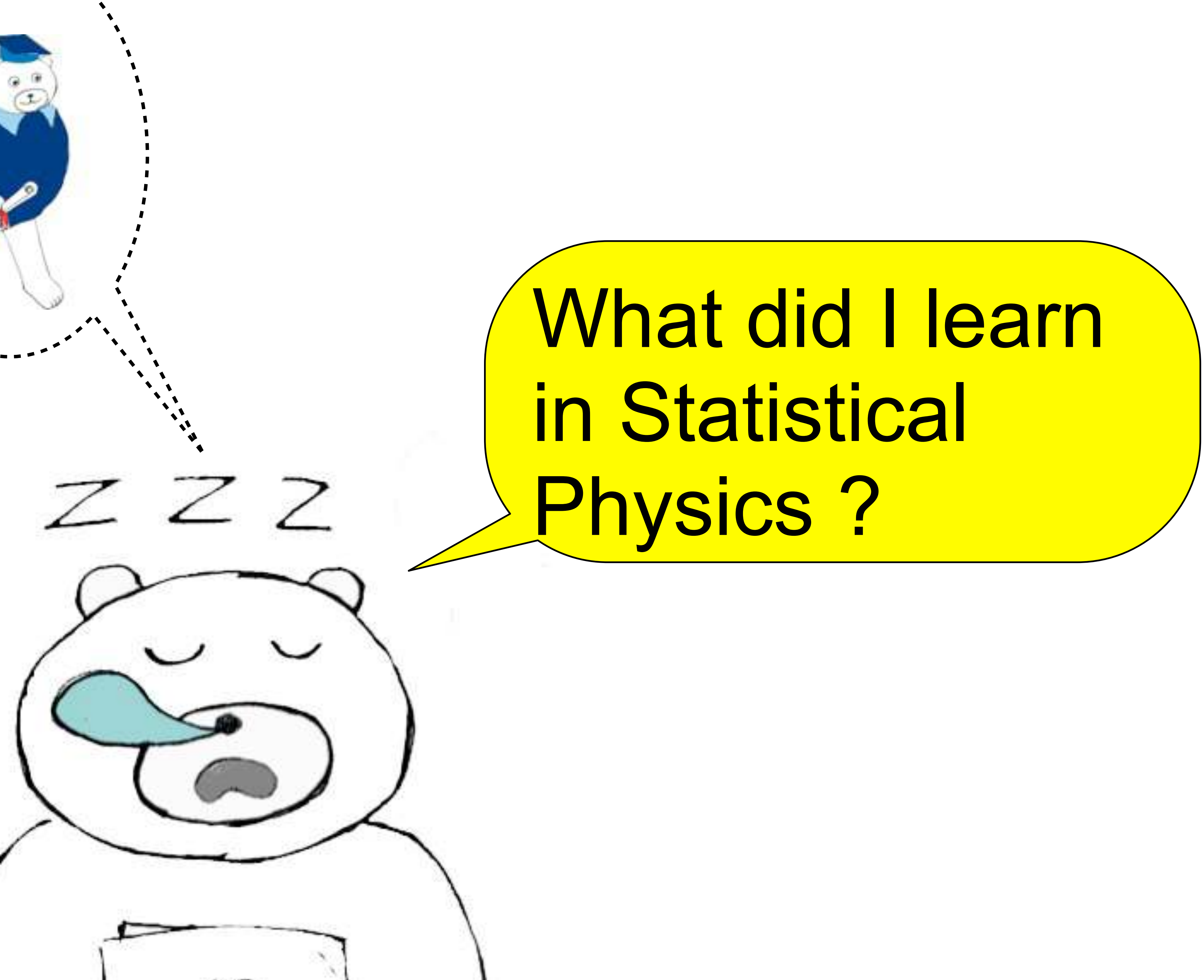


di-quark source



ds, Sitch and Skullerud
s.Lett. B662, (2008)405
(iv:0710.1966)

Other Methods ?



Miller and Redlich

-Phys. Rev. D35 (1987) 2524

.Hasenfratz and Toussaint

- Nucl.Phys.B371 (1992) 539

ngels, Kaczmarek, Karsch and Laermann

- Nucl.Phys. B558 (1999) 307 (hep-lat/9903030)

- hep-lat/9905022

orcrand and Kratochvila

- Nucl. Phys. B (P.S.) 153 (2006) 62 (hep-lat/0602O

.Li, Meng, Alexandru, K-F. Liu

-PoS LAT2008:032 and 178 (arXiv:0810.2349, arX

Z_{GC} Z_C

$$\int \mathcal{D}U\mathcal{D}\bar{\psi}\mathcal{D}\psi e^{-\beta S_G - \bar{\psi}\Delta\psi}$$

$$\hat{N} \equiv \int d^3x \bar{\psi}(x)\gamma_0\psi(x)$$

$$\delta(\hat{N} - Q) = \int d\phi\, e^{i\phi(\hat{N}-Q)}$$

$$\phi = \frac{\mu_I}{T}$$

$$\frac{3}{2\pi}\int_{-\frac{\pi}{3}}^{+\frac{\pi}{3}} d\frac{\mu_I}{T}\, e^{-iQ\frac{\mu_I}{T}}\, Z_{GC}(i\mu_I)$$

μ_I has Periodicity $\frac{2\pi T}{}$

Z_{GC} Z_C

$$\int \mathcal{D}U\mathcal{D}\bar{\psi}\mathcal{D}\psi e^{-\beta S_G-\bar{\psi}\Delta\psi}\,\delta(\hat{N}-Q)$$

$$\hat{N} \equiv \int d^3x\bar{\psi}(x)\gamma_0\psi(x)$$

$$\delta(\hat{N}-Q) = \int d\phi\, e^{i\phi(\hat{N}-Q)}$$

$$\phi = \frac{\mu_I}{T}$$

$$\frac{3}{2\pi}\int_{-\frac{\pi}{3}}^{+\frac{\pi}{3}} d\frac{\mu_I}{T}\, e^{-iQ\frac{\mu_I}{T}}\; Z_{GC}(i\mu_I)$$

μ_I has Periodicity $\frac{2\pi T}{}$

Z_{GC} Z_C

$$_C = \int \mathcal{D}U\mathcal{D}\bar{\psi}\mathcal{D}\psi e^{-\beta S_G - \bar{\psi}\Delta\psi} \delta(\hat{N} - Q)$$

$$\hat{N} \equiv \int d^3x \bar{\psi}(x)\gamma_0\psi(x)$$

$$\delta(\hat{N} - Q) = \int d\phi\, e^{i\phi(\hat{N} - Q)}$$

$$\phi = \frac{\mu_I}{T}$$

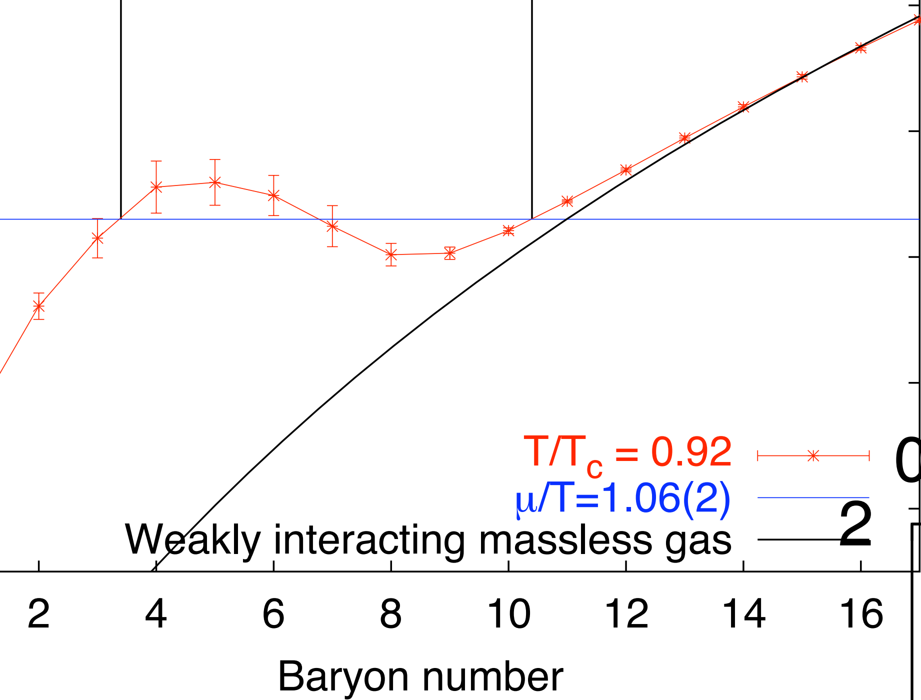
$$\frac{3}{2\pi} \int_{-\frac{\pi}{3}}^{+\frac{\pi}{3}} d\frac{\mu_I}{T}\, e^{-iQ\frac{\mu_I}{T}}\, Z_{GC}(i\mu_I)$$

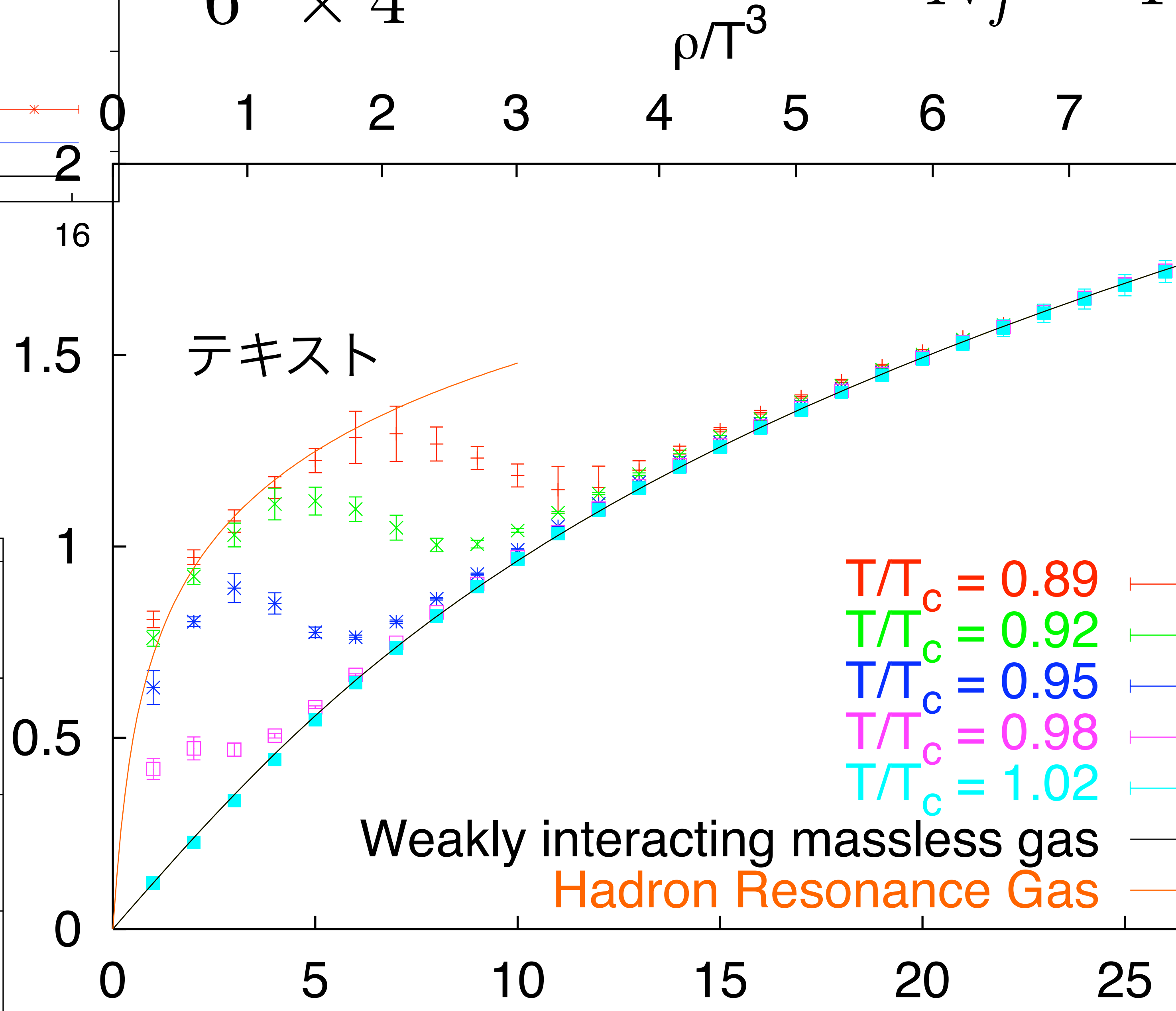
μ_I has Periodicity $\frac{2\pi T}{}$

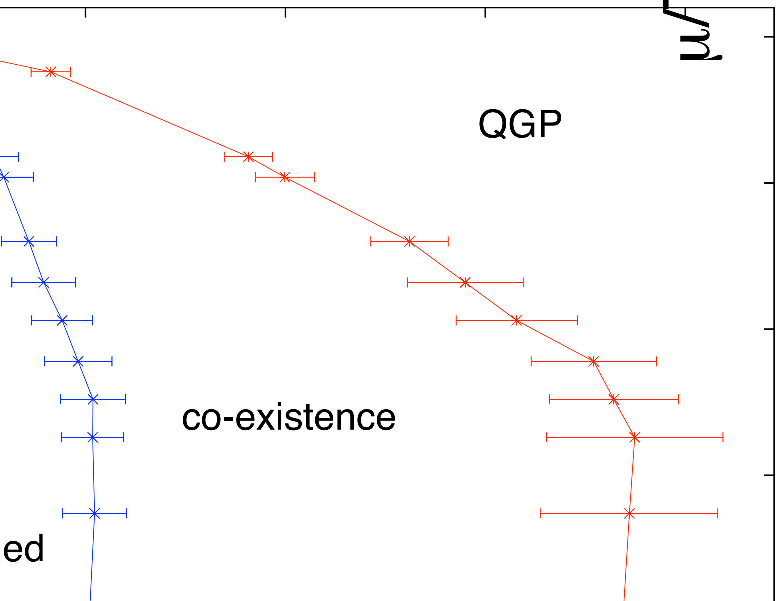
hep-lat/0602024

$m_\pi = 300\mathrm{MeV}$ KS Fermions

$6^3 \times 4$ $N_f = 4$

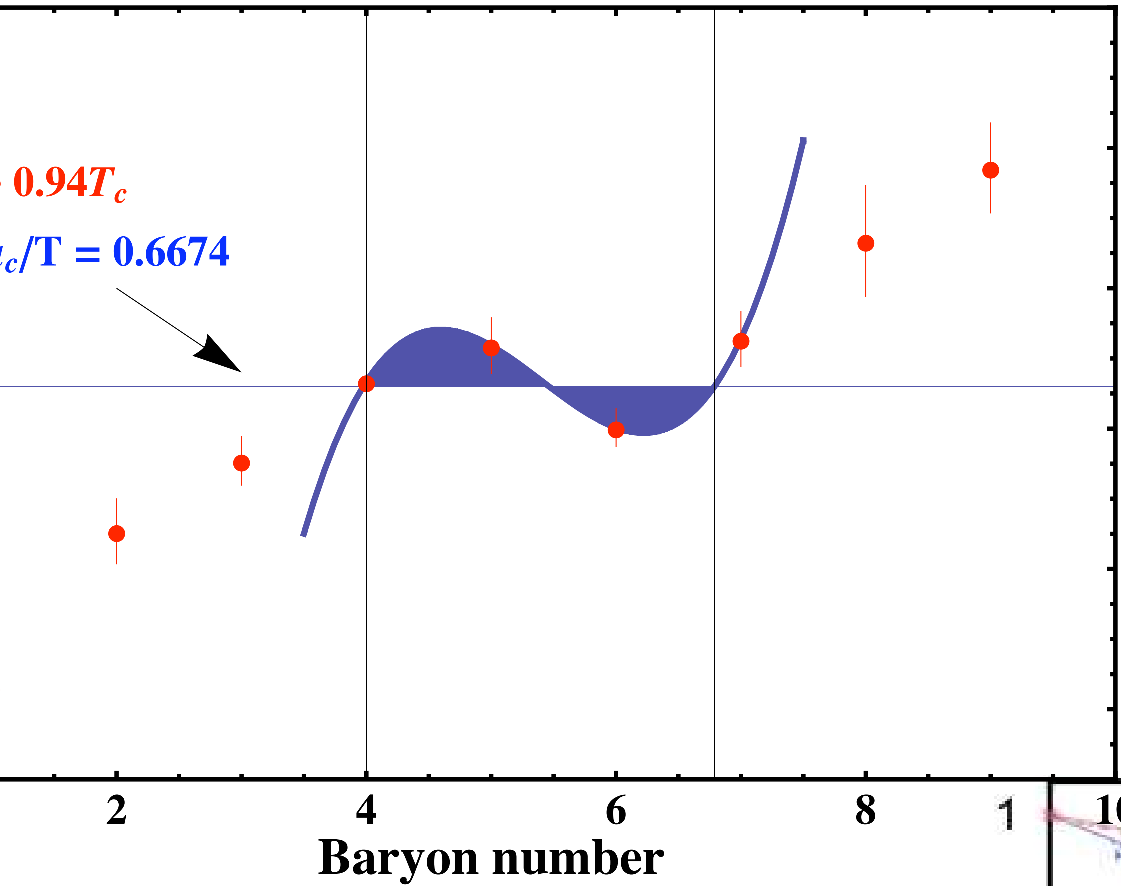






Winding Number Expan

Maxwell Construction

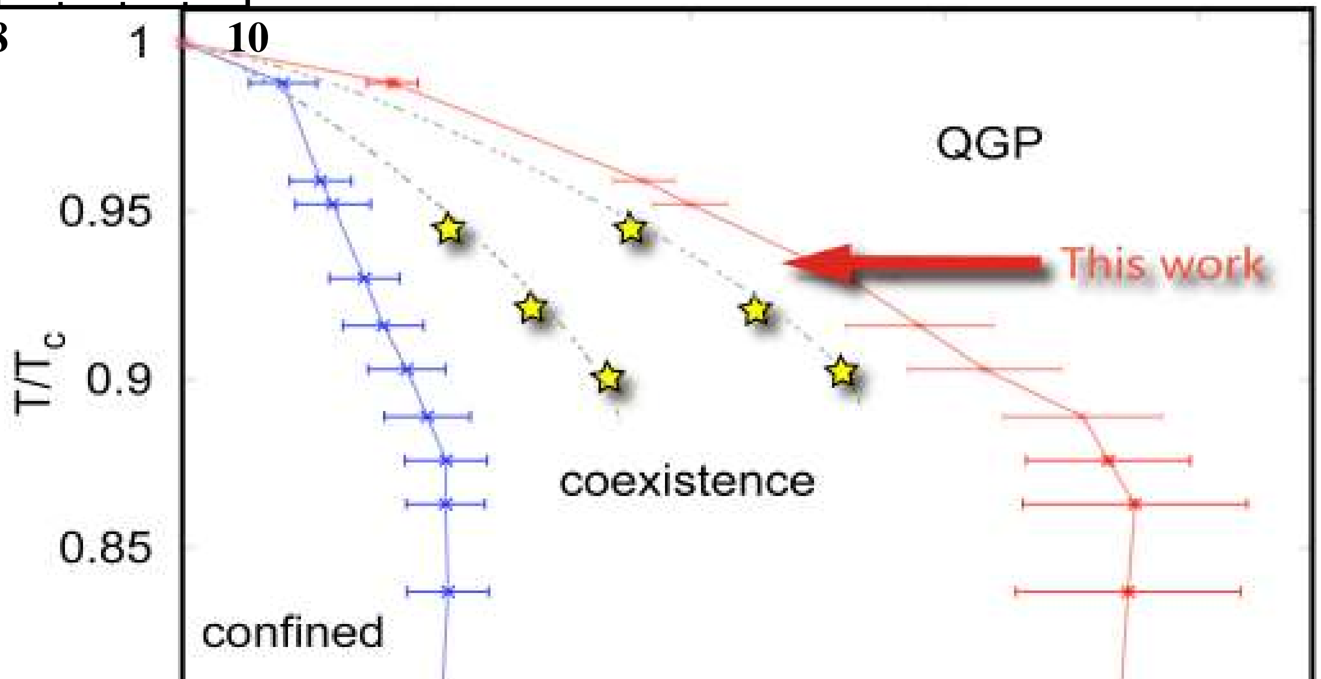


$$N_f = 4$$

$$6^3 \times 4$$

$$m_\pi = 1\mathrm{GeV}$$

Wilson Fermions



Apology

The next 4 slides are technical, and have no Physical Results yet !

Wilson Fermions without Approximation

Nagata and A.N.

arXiv:0911.416

$$\det \Delta = z^{-N} \det(T - zS)$$

$z \equiv e^{-}$

$$TX = zSX$$

Generalized Eigen Value Problem

Generalized Schur Decomposition

There exist unitary Q and Z such that $Q^\dagger T Z$ and $Q^\dagger S Z$ are upper triangular.

$T - zS)$

$\text{t}\, QZ^\dagger$

$$\begin{pmatrix} \alpha_1 & * & * & \cdots & & * \\ 0 & \alpha_2 & * & \cdots & & * \\ 0 & 0 & & \cdots & & \\ \cdots & \cdots & \cdots & \cdots & * & * \\ 0 & 0 & & \cdots & \alpha_{N-1} & * \end{pmatrix} - z \begin{pmatrix} \beta_1 & * & * & \cdots & \\ 0 & \beta_2 & * & \cdots & \\ 0 & 0 & & \cdots & \\ \cdots & \cdots & \cdots & \cdots & * \\ 0 & 0 & & \cdots & \beta_{N-1} \end{pmatrix}$$

$$= z^{-N} \det QZ^{\dagger} \prod (\alpha_i - z\beta$$

$$z \equiv e^{-\mu}$$

$$, S : (4N_c N_x N_y N_z) \times (4N_c N_x N_y N$$

$$: \mathrm{Singular}$$

Someone knows a Good Algorithm to solve Generalized Eigenvalue Problem ?

$$T\vec{X} = zS\vec{X}$$

a good Algorithm
r Matrix Reduction

$$T\vec{X} = zS\vec{X}$$

rst reduce
our weight

QCD's Phase

How the World
at finite T and μ
looks like ?

HotQCD+RBC-Bielefeld: All US, Improved KS

Budapest+Wuppertal:

WHOT: Wilson+Clover, Improved Gauge Action

deForcrand+Philipsen: Imaginary chemical pot.

Lombardo, D'Elia: Imaginary chemical pot.

Kentucky: Canonical

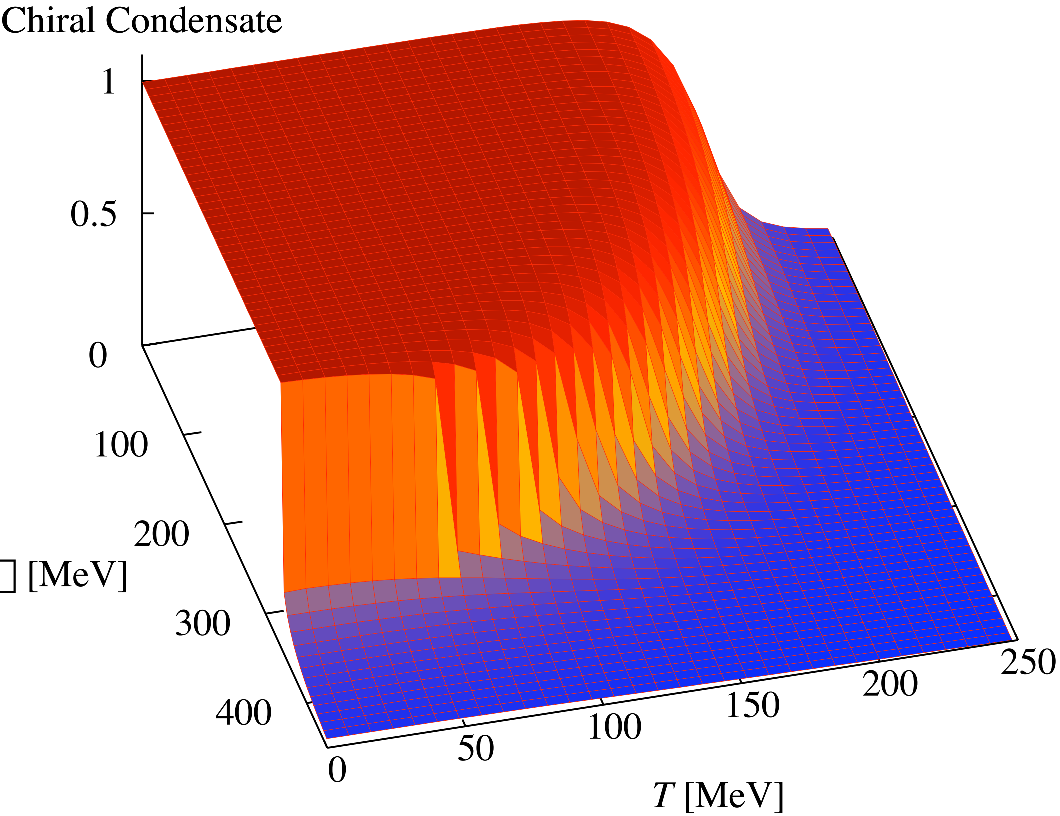
Swansea: SU(2), Complex Langevin

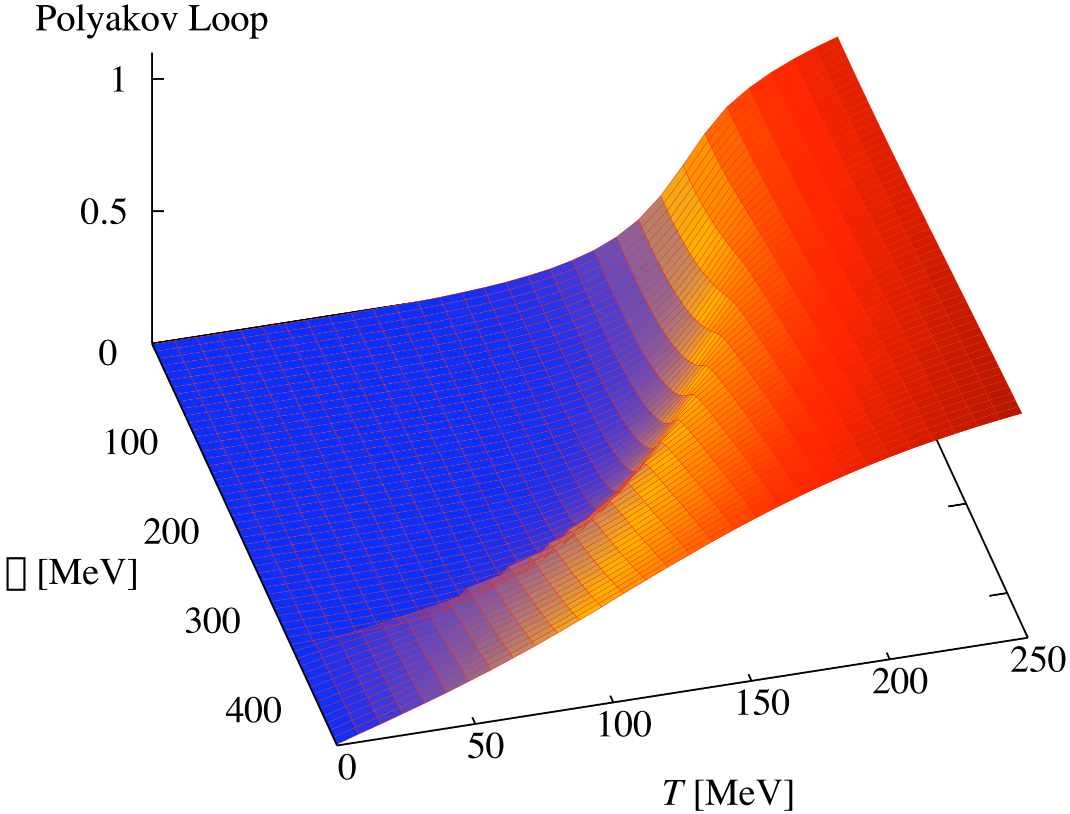
Stamatescu: Complex Langevin etc.

Kogut+Sinclair: Finite Isospin

Maple: Color SU(2)

Hiroshima: Wilson+Clover, Improved Gauge Action





PNJL by Fukushima (QM08)

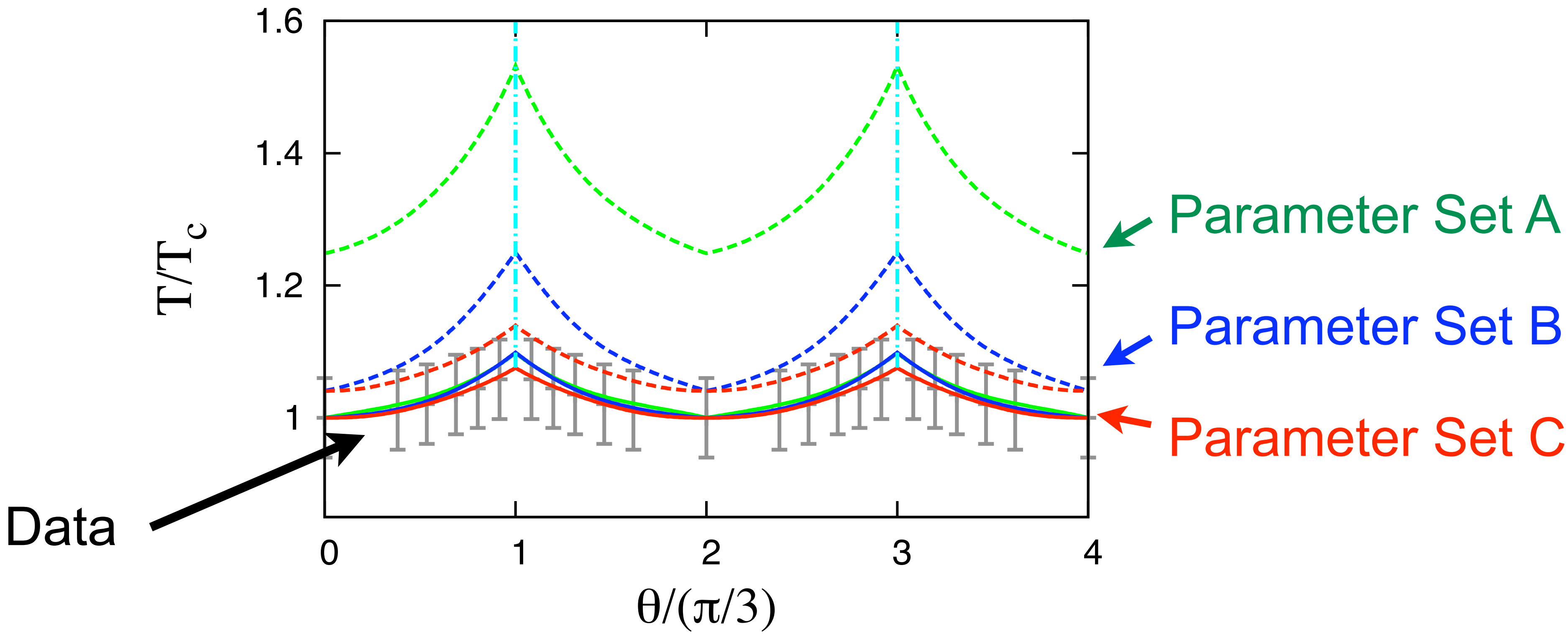
EoS by Lattice

Katz's tai

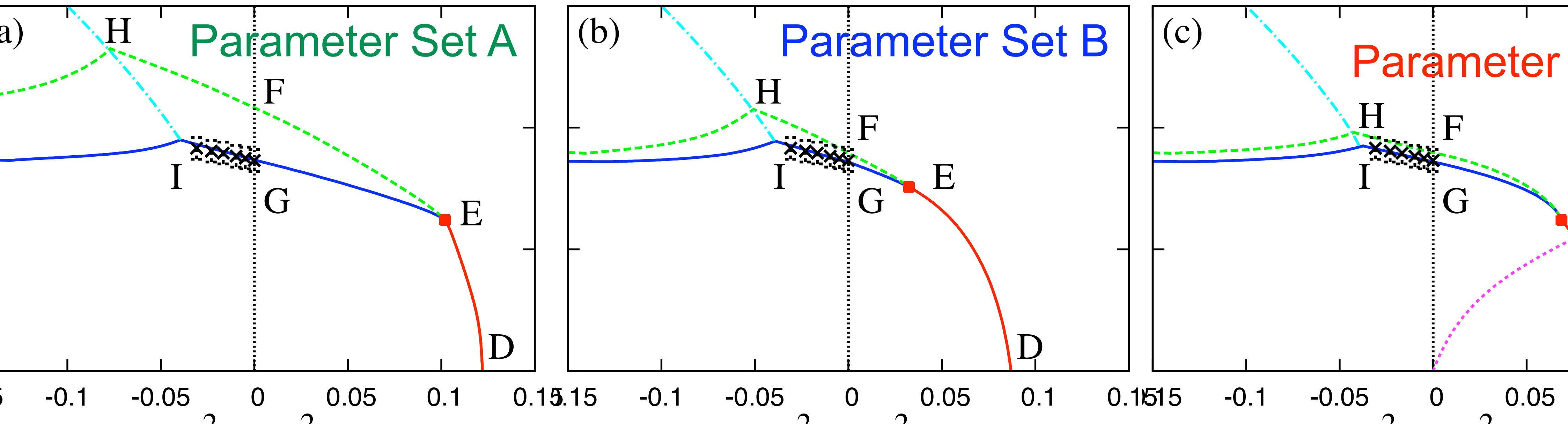
Hungary-Wupp

Oh, Gr
Fightin

S-Bielefeld



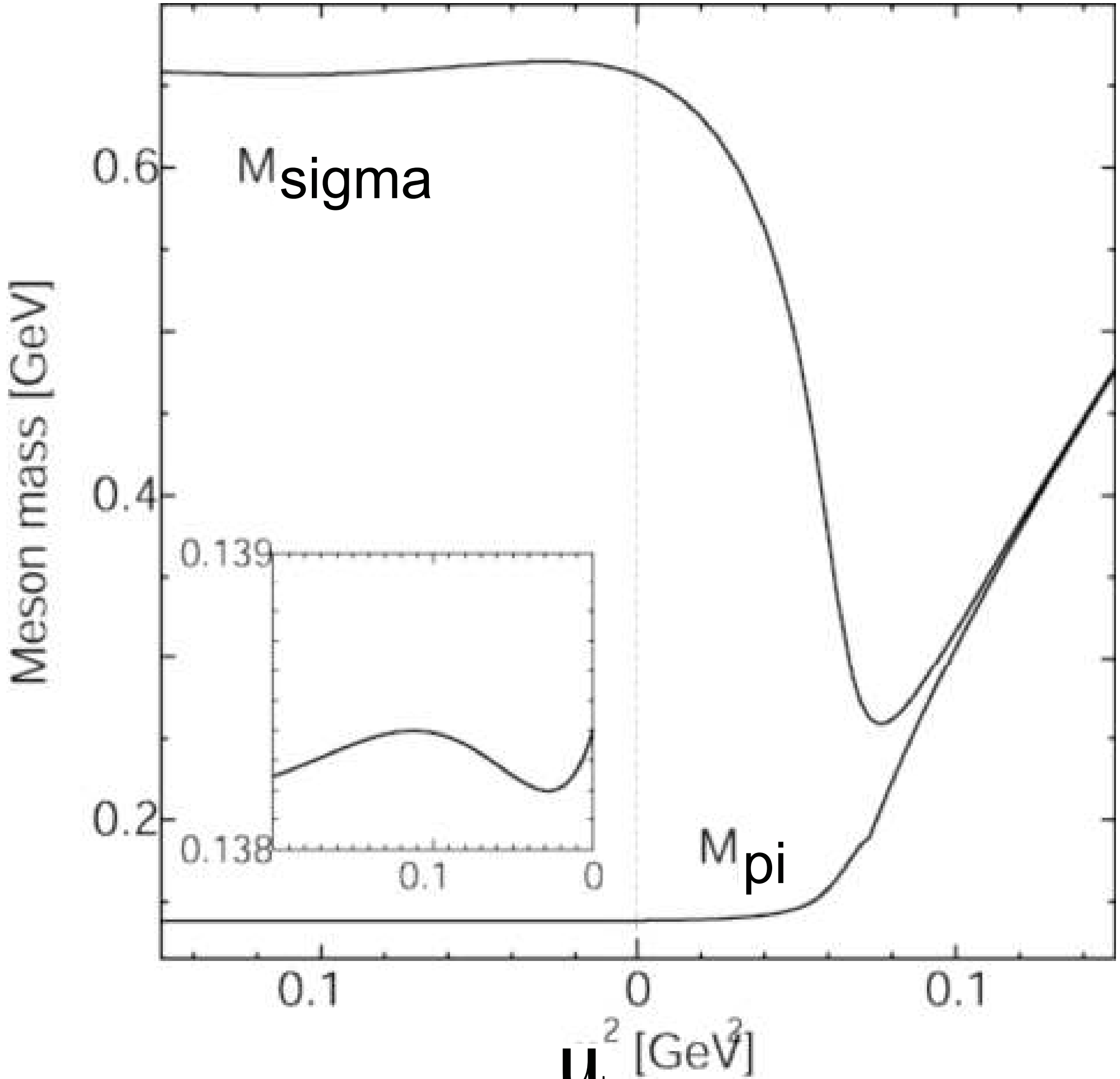
1.6
1.4
1.2
1
T/T_c
0
1
2
3
4
θ/(π/3)
Parameter Set A
Parameter Set B
Parameter Set C
Data



a)
Parameter Set A
H
F
I
G
E
D
-0.1
-0.05
0
0.05
0.1
(b)
Parameter Set B
H
F
E
I
G
D
-0.1
-0.05
0
0.05
0.1
(c)
Parameter
H
F
I
G
-0.1
-0.05
0
0.05

(Phys.Rev

_ +Potential V(Polyakov Loop)



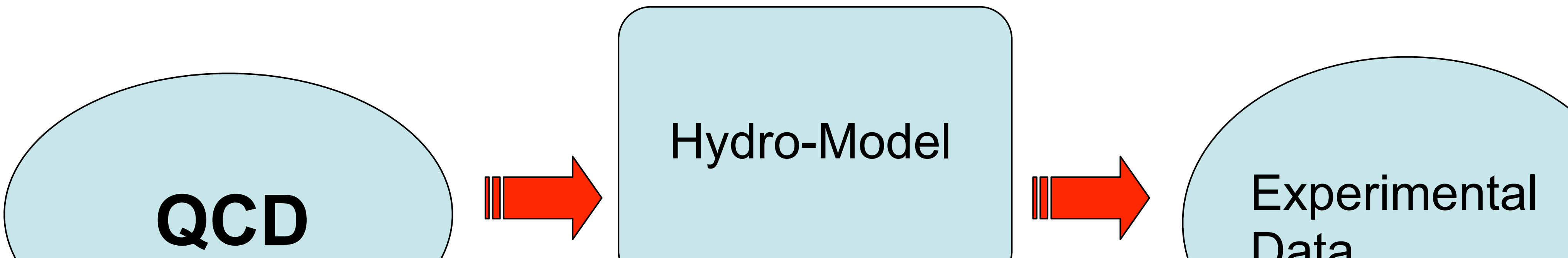
Lattice calculation als
show that M_pi is als
almost constant in μ^2

Story of Transport Coefficients

A Step towards Gluon Dynamical Behavior.

They can be (in principle) calculated by a we
established formula (Linear Response Theo

They are important to understand QGP whic
realized in RHIC (and CERN-SPS)
and LHC.



Another (Personal) Motivation

- When I was a graduate student in Prof. Namiki's Lab, it was the only place in Japan where Hydro-Dynamical Model was discussing every day.
  - Muroya, Hirano, Nonaka, Morita ... graduated this Lab.
- Since I started Lattice, Transport Coeff. are a target to study.

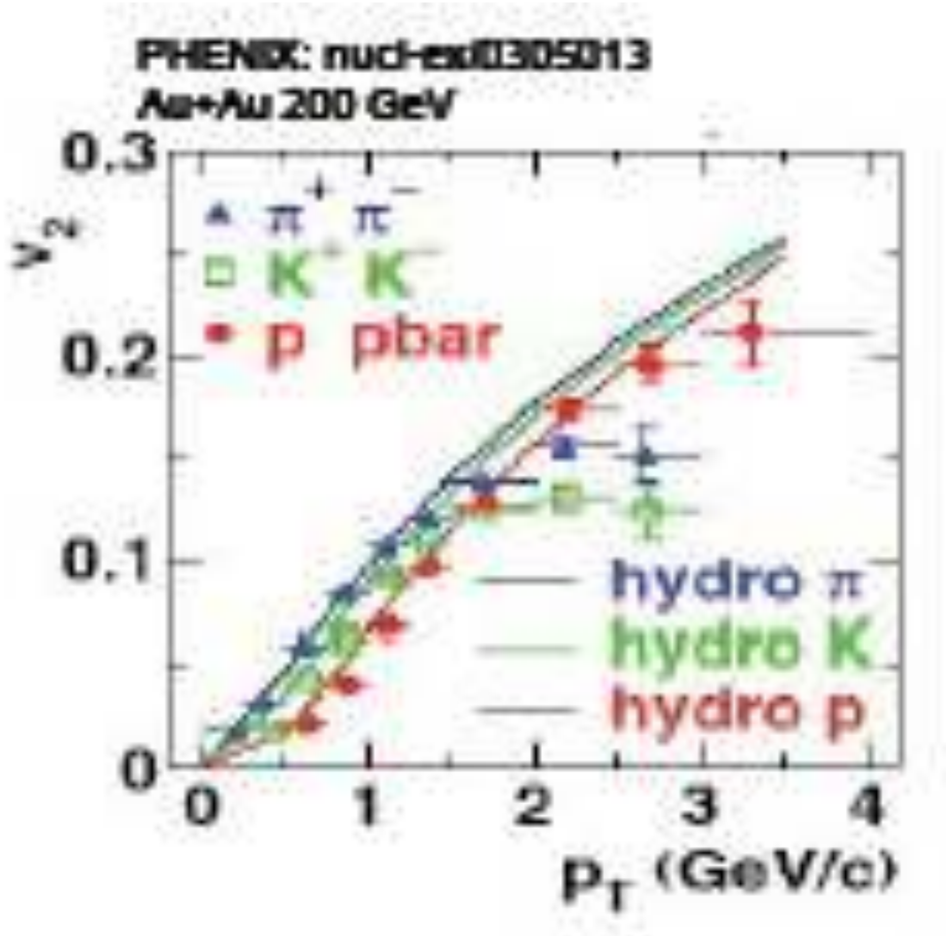
RHIC-data ⇒ Big Surprise !

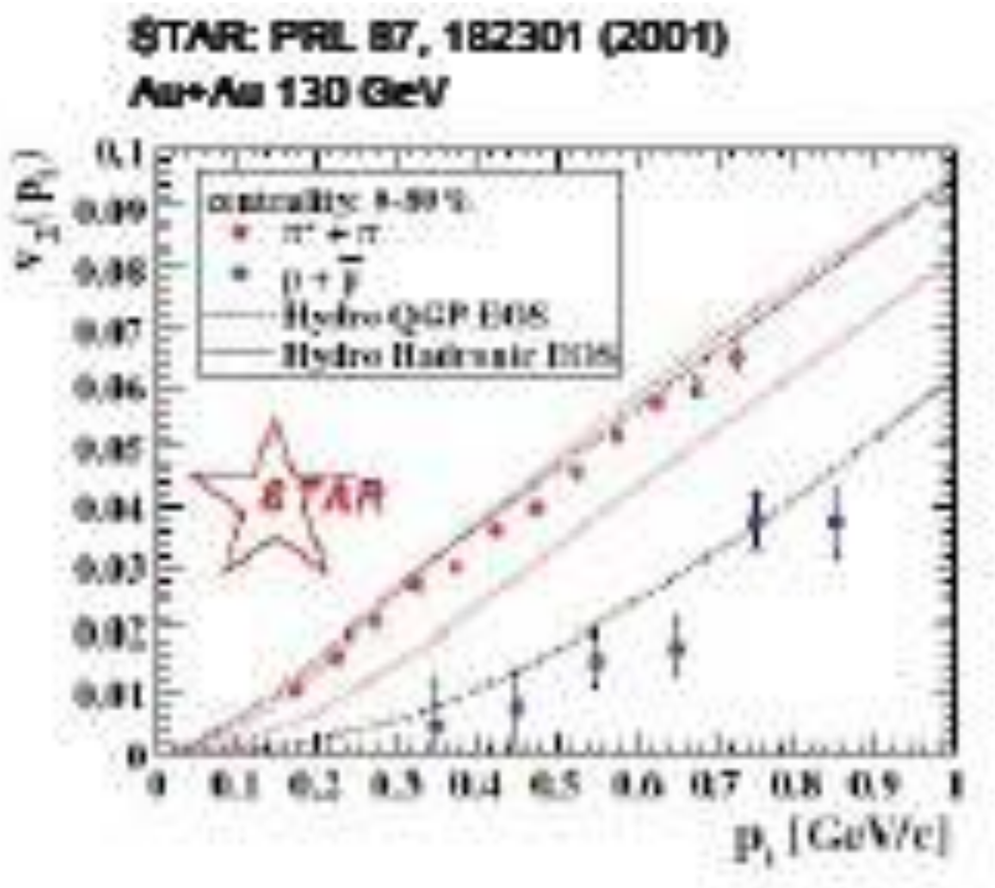
Hydro-dynamical Model describes RHIC data well !

At SPS, the Hydro describes well one-particle distributions,

HBT etc., but fails for the elliptic flow.

Hydro describes well v2





Hydrodynamical calculations are based on Ideal Fluid, i.e., zero shear viscosity

Or not so surprise …

E. Fermi, Prog. Theor. Phys. 5 (1950) 570

–Statistical Model

S.Z.Belen'skji and L.D.Landau, Nuovo.Cimento Suppl. 3 (1956) 15

–Criticism of Fermi Model

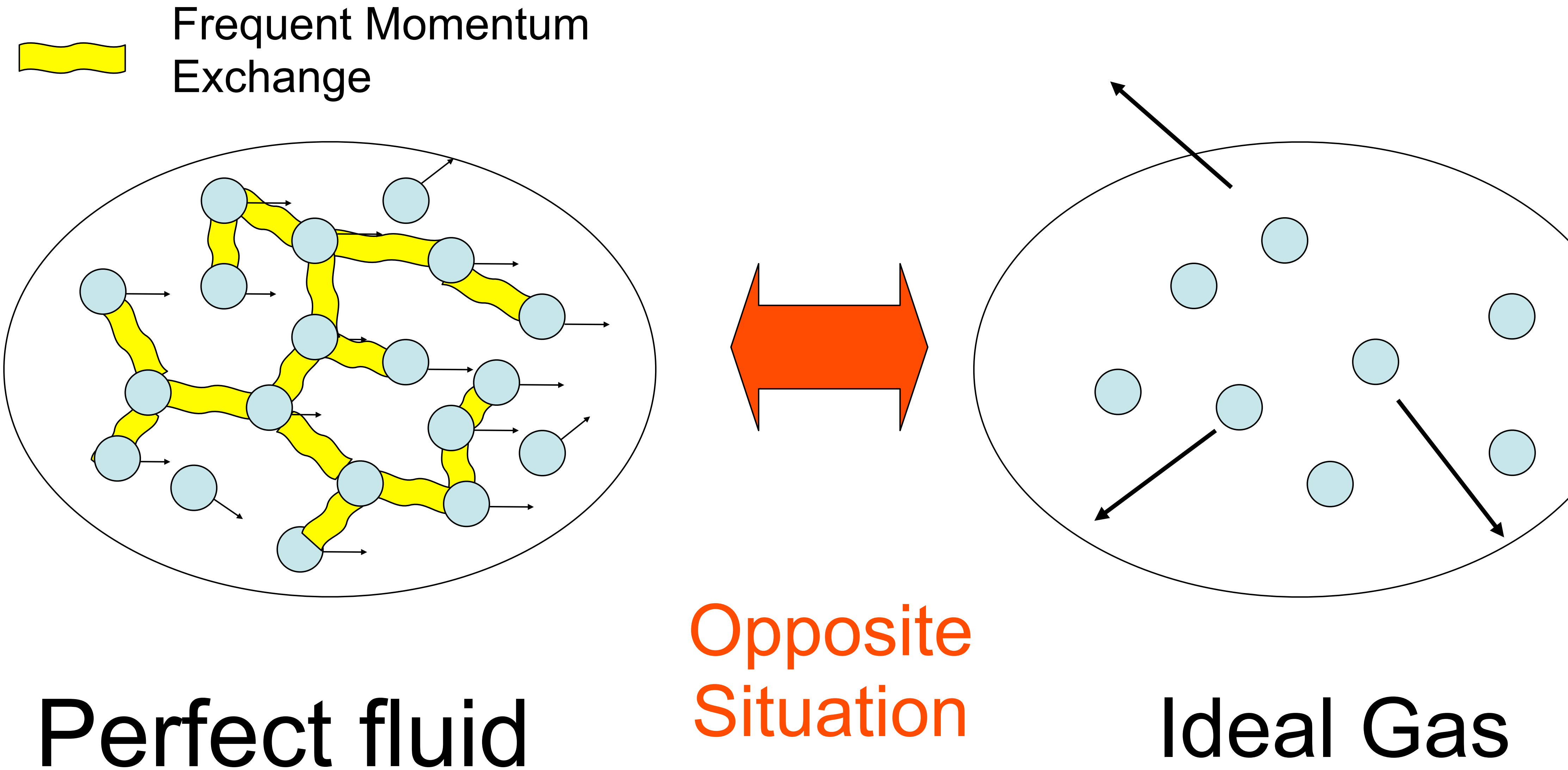
"Owing to high density of the particles and to strong interaction between them, one cannot really speak of their number."

Hagedorn, Suppl. Nuovo Cim. 3 (19

Another Big Surprise !

- The Hydrodynamical model assumes zero viscosity,
  i.e., Perfect Fluid.
- Phenomenological Analyses suggest also small viscosity.

Liquid or Gas ?



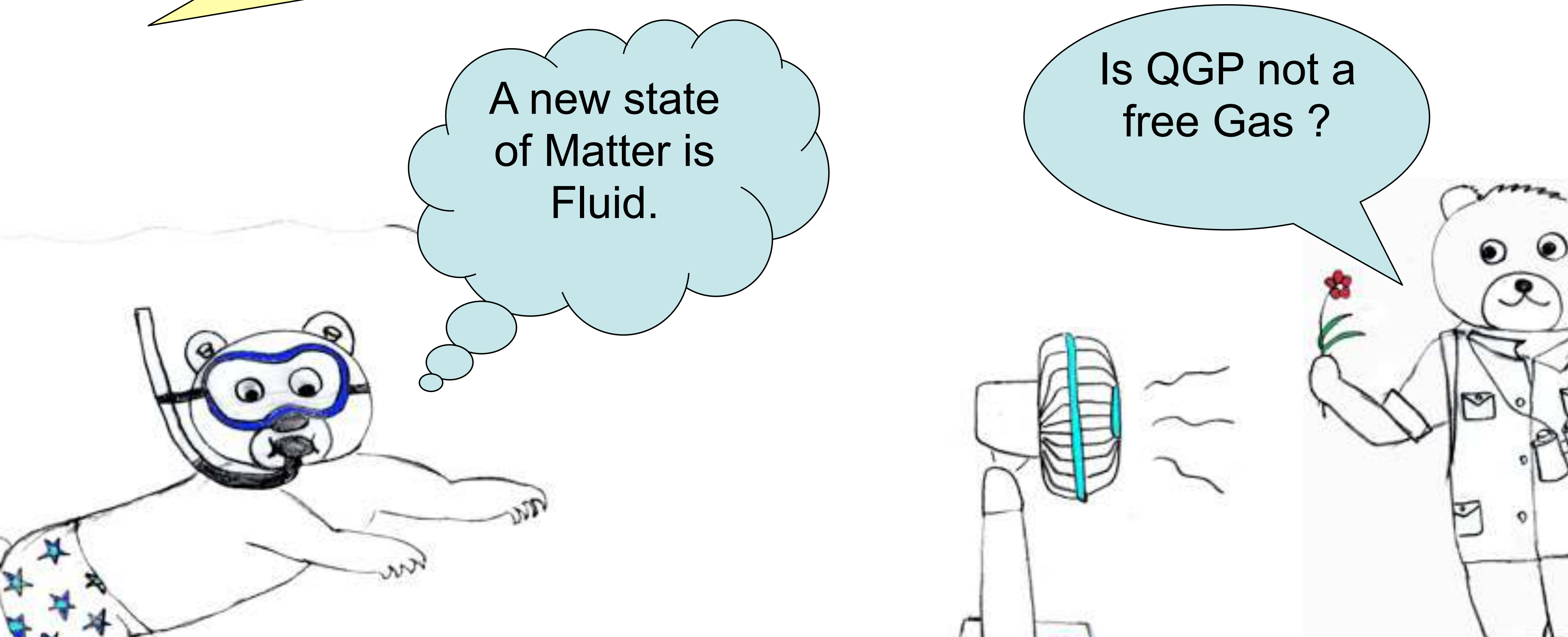
Literature (I)

Iso, Mori and Namiki, Prog. Theor. Phys. 22 (1959) pp.403-429

- The first paper to analyze the Hydrodyanamical Model from Field Theory.
- Applicability Conditions were derived:
  - Correlation Length << System Size
  - Relaxation time << Macroscopic Characteristic Time
  - Transport Coefficients must be small

If produced matter at RHIC is (perfect) Fluid, not Free Gas what does it matter ?

If produced matter at RHIC is (perfect) Fluid, not Free Gas what does it matter ?



(Illustration purpose only)

essure

$$P = \frac{\pi^2}{90} T^4 \left(1 - \frac{15}{8} \left(\frac{g}{\pi} \right)^2 + \cdots \right)$$

Ideal Free Gas

scosity

(Illustration purpose only)

essure

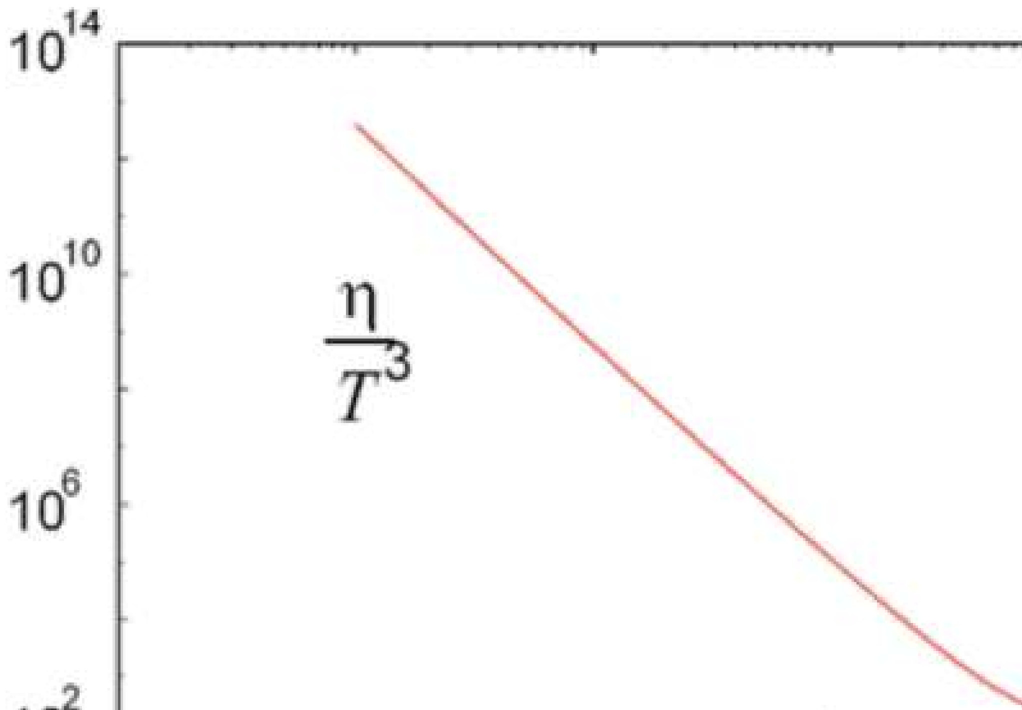
$$P = \frac{\pi^2}{90} T^4 \left(1 - \frac{15}{8} \left(\frac{g}{\pi}\right)^2 + \cdots \right)$$

Ideal Free Gas

scosity

$$\eta = \kappa \frac{T^3}{g^4 \ln g^{-1}}$$

$$\kappa = 27.126 (N_f = 0),$$
$$86.473 (N_f = 2)$$



At weak coupling,

(Illustration purpose only)

essure

$$P = \frac{\pi^2}{90} T^4 \left(1 - \frac{15}{8} \left(\frac{g}{\pi}\right)^2 + \cdots \right)$$

Ideal Free Gas

scosity

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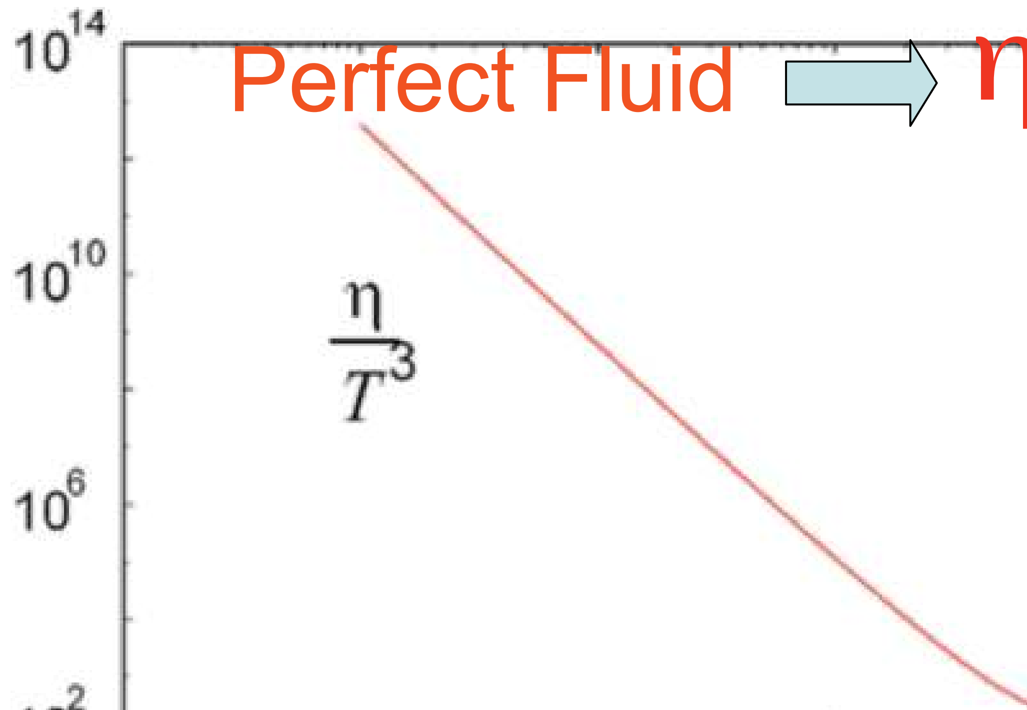


Literature (2)

- G. Baym, H. Monien, C. J. Pethick and D. G. Ravenhall,
  - –Phys. Rev. Lett. 16 (1990) 1867.
- P. Arnold, G. D. Moore and L. G. Yaffe
  - –JHEP 0011 (2000) 001, (hep-ph/0010177).
  - –Leading-log results"
- P. Arnold, G. D. Moore and L. G. Yaffe
  - –JHEP 0305 (2003) 051, (hep-ph/0302165).
  - –Beyond leading log"

Hosoya, Sakagami and Takao, Ann. Phys. 154 (1984) 228.

– Transport Coefficients Formulation

Hosoya and Kayantie, Nucl. Phys. B250 (1985) 66

Horsley and Shoenmaker, Phys. Rev. Lett. 57 (1986) 2894; Nucl. Phys. B280 (1987) 716.

Karsch and Wyld, Phys. Rev. D35 (1987) 2518.

– The first Lattice QCD Calculation

Aarts and Martinez-Resco, JHEP0204 (2002)053

– Criticism against the Spectrum Function Ansatz.

Literature (4)

- Masuda, A.N.,Sakai and Shoji
  - Nucl.Phys. B(Proc.Suppl.)42, (1995),526
- A.N., Sakai and Amemiya
  - Nucl.Phys. B(Proc.Suppl.)53, (1997), 432
- A.N, Saito and Sakai
  - Nucl.Phys. B(Proc.Suppl.)63, (1998), 424
- Sakai, A.N. and Saito
  - Nucl.Phys. A638, (1998), 535c
- A.N, Sakai
  - Phys.Rev.Lett. 94 (2005) 072305
    - hep-lat/0406009
- Harvey B. Meyer
  - Phys.Rev.Lett.100:162001,2008

uda, Nakamura and Sakai (Lattice 95)

i, Nakamura, Saito(QM97,Lattice 98)
roved Action)

s and Martinez-Resco (2002)

i, Nakamura (2004) Anisotropic Lattice
uration for improved gauge actions

amura and Sakai (2005) η/s

s, Allton, Foley, Hands, Kim (2007)

er (2007) Luescher-Weiz 2-level

20th Ce

21th Century

Linear Response Theory

- Zubarev
  “Non-Equilibrium Statistical Thermo-dynamics”
- Kubo, Toda and Saito
  “Statistical Mechanics”

Deviation from Equilibriu

$$\langle T_{\mu\nu} \rangle = \langle T_{\mu\nu} \rangle_{eq} +$$

$$\int d^3x' \int_{-\infty}^{t} dt' e^{\varepsilon (t'-t)} (T_{\mu\nu}(x,t), T_{\rho\sigma}(x',t'))_{eq} \partial^{\rho} (($$

where $(T_{\mu\nu}(x,t), T_{\rho\sigma}(x',t'))_{eq}$

$$\equiv \int_0^1 d\tau \left\langle T_{\mu\nu}(x,t) \left(e^{-A\tau} T_{\rho\sigma}(x',t') e^{A\tau} - \langle T_{\rho\sigma}(x',t') \right. \right.$$

$$\langle T^{ij} \rangle = \eta (\partial^i u^j + \partial^j u^i)/2$$

$$\langle T^{0i} \rangle = -\chi (\beta^{-1}(x,t) \partial^i \beta + \partial_\alpha u^\alpha)$$

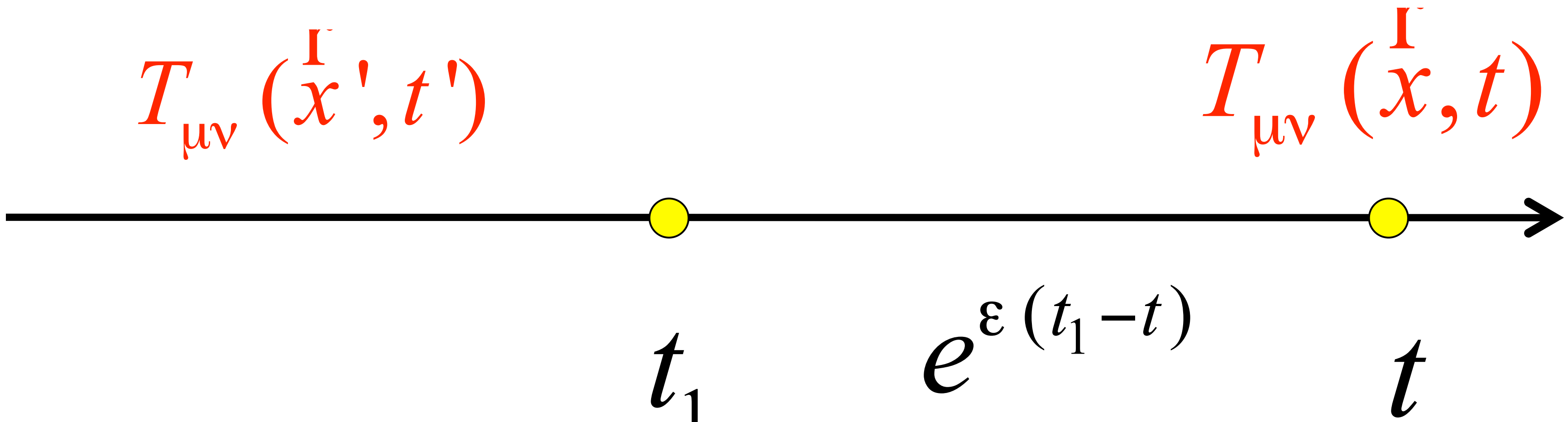
$$\langle p \rangle - \langle p \rangle_{eq} = -\varsigma \partial_\alpha u^\alpha \qquad \frac{1}{\ } T^i$$

$$\frac{4}{3}\eta + \varsigma = -\int d^3x' \int_{-\infty}^{t} dt_1 e^{\varepsilon(t_1 - t)} \int_{-\infty}^{t_1} dt' < T_{11}(\vec{x}, t) T_{11}(\vec{x}$$

$$\chi = -\frac{1}{T} \int d^3x' \int_{-\infty}^{t} dt_1 e^{\varepsilon(t_1 - t)} \int_{-\infty}^{t_1} dt' < T_{01}(\vec{x}, t) T_{01}(\vec{x}', t$$

η : Shear Viscosity **ς : Bulk Viscosity**

χ : Heat Conductivity ⇒ we do not consider
Quench simulations



the Spectral Functions

e measure Matsubara Green Function on Lattice (in ordinate space).

$$< T_{\mu\upsilon}(t,\vec{x})T_{\mu\upsilon}(0) >= G_{\beta}(t,\vec{x}) = F.T.G_{\beta}(\omega_n,\vec{p})$$

$$G_{\beta}(\vec{p},i\omega_n) = \int d\omega \frac{\rho(\vec{p},\omega)}{i\omega_n - \omega}$$

We assume (Karsch-Wyld)

$$\rho = \frac{A}{\pi}\left(\frac{\gamma}{(m-\omega)^2+\gamma^2} + \frac{\gamma}{(m+\omega)^2+\gamma^2}\right)$$

and determine three parameters,

A, m, γ

Lattice and Statistics

Iwasaki Improved Action

$$16^3 \times 8$$

β=3.05 : 1.3M sweeps → β=3.05 : 3.0M sweeps

β=3.20 : 1.2M sweeps → β=3.20 : 2.5M sweeps

β=3.30 : 1.3M sweeps → β=3.30 : 2.0M sweeps

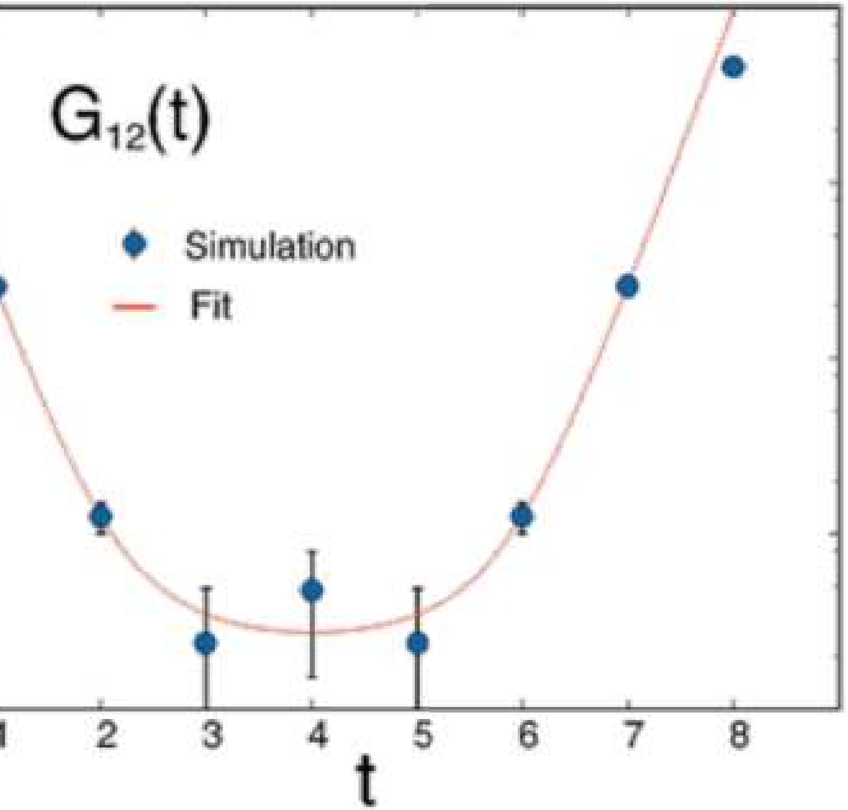
$$24^3 \times 8$$

β=3.05 : 0.6M sweeps → β=3.05 : 6.0M sweeps

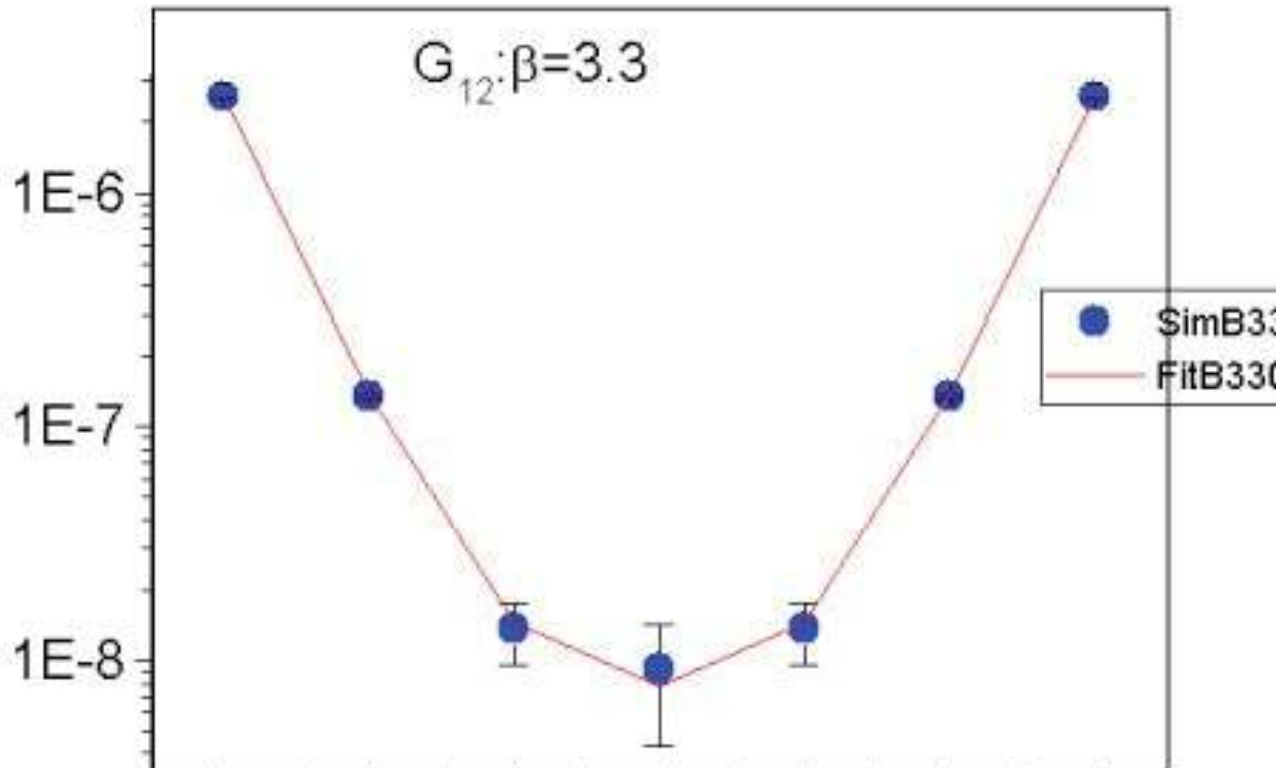
β=3.30 : 0.8M sweeps → β=3.30 : 6.0M sweeps

Quench

Nt=8

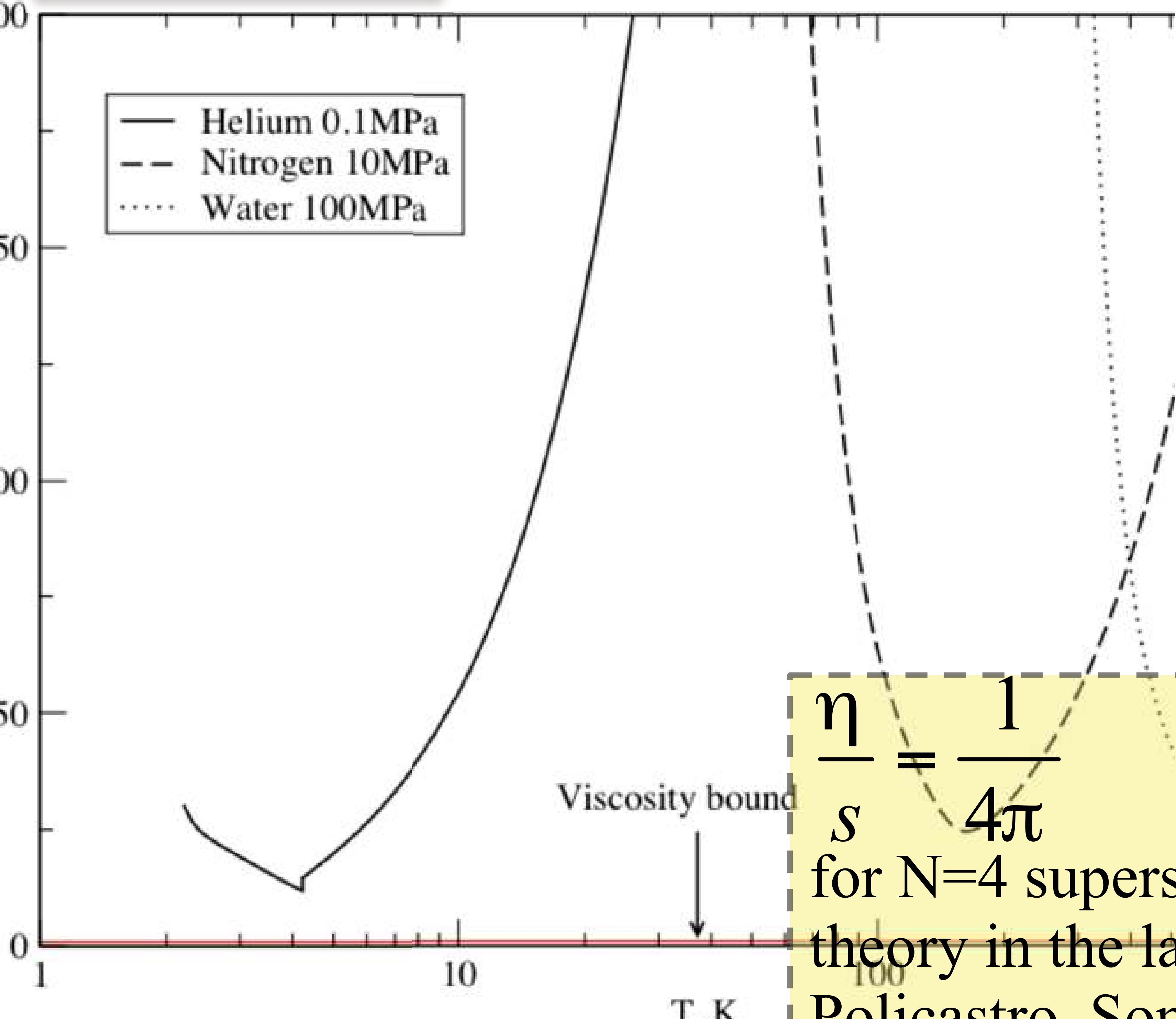


G12(t)
Simulation
Fit
1
2
3
4
5
6
7
8
t



G12:β=3.3
1E-6
1E-7
1E-8
SimB33
FitB330

$$\frac{\eta}{s} = \frac{1}{4\pi}$$



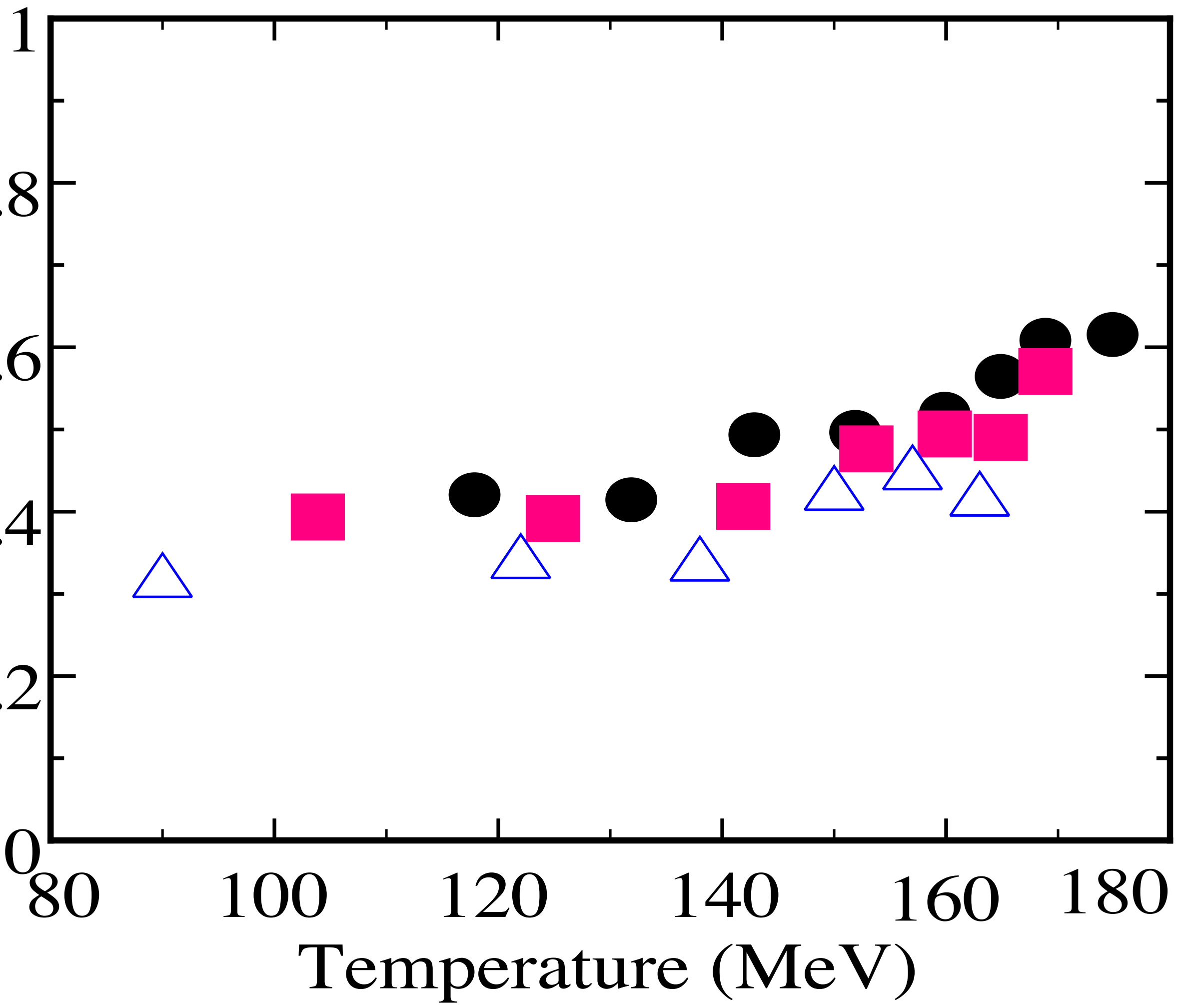
$$\frac{\eta}{s} = \frac{1}{4\pi}$$

for N=4 supersymmetric Yang
theory in the large N.
Policastro, Son and Starinets

Calculation by URaSiMA(*)

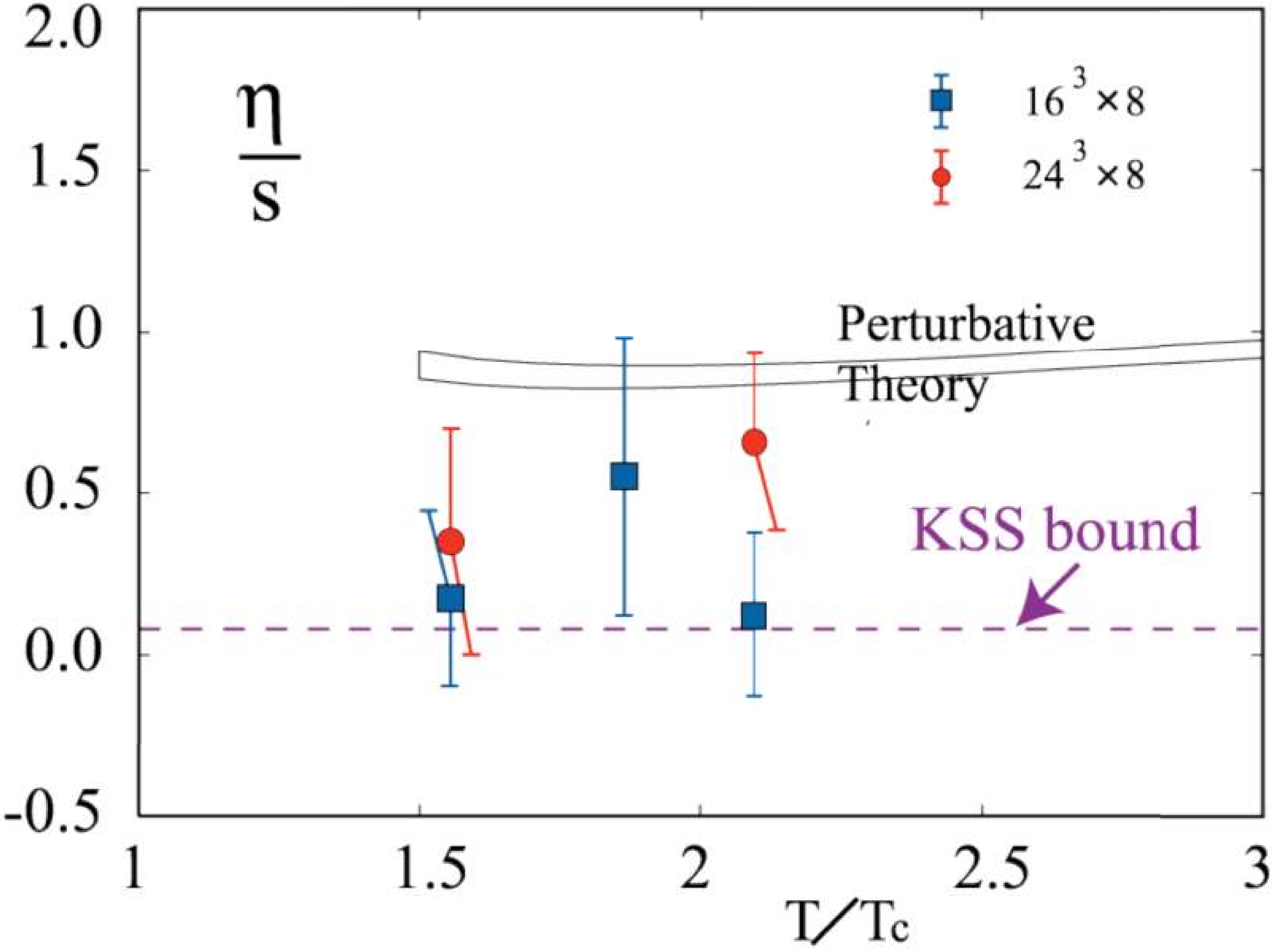
Muroya and Sasaki

arXiv:nucl-th/040805
Prog.Theor.Phys. 1
(2005) 457-462



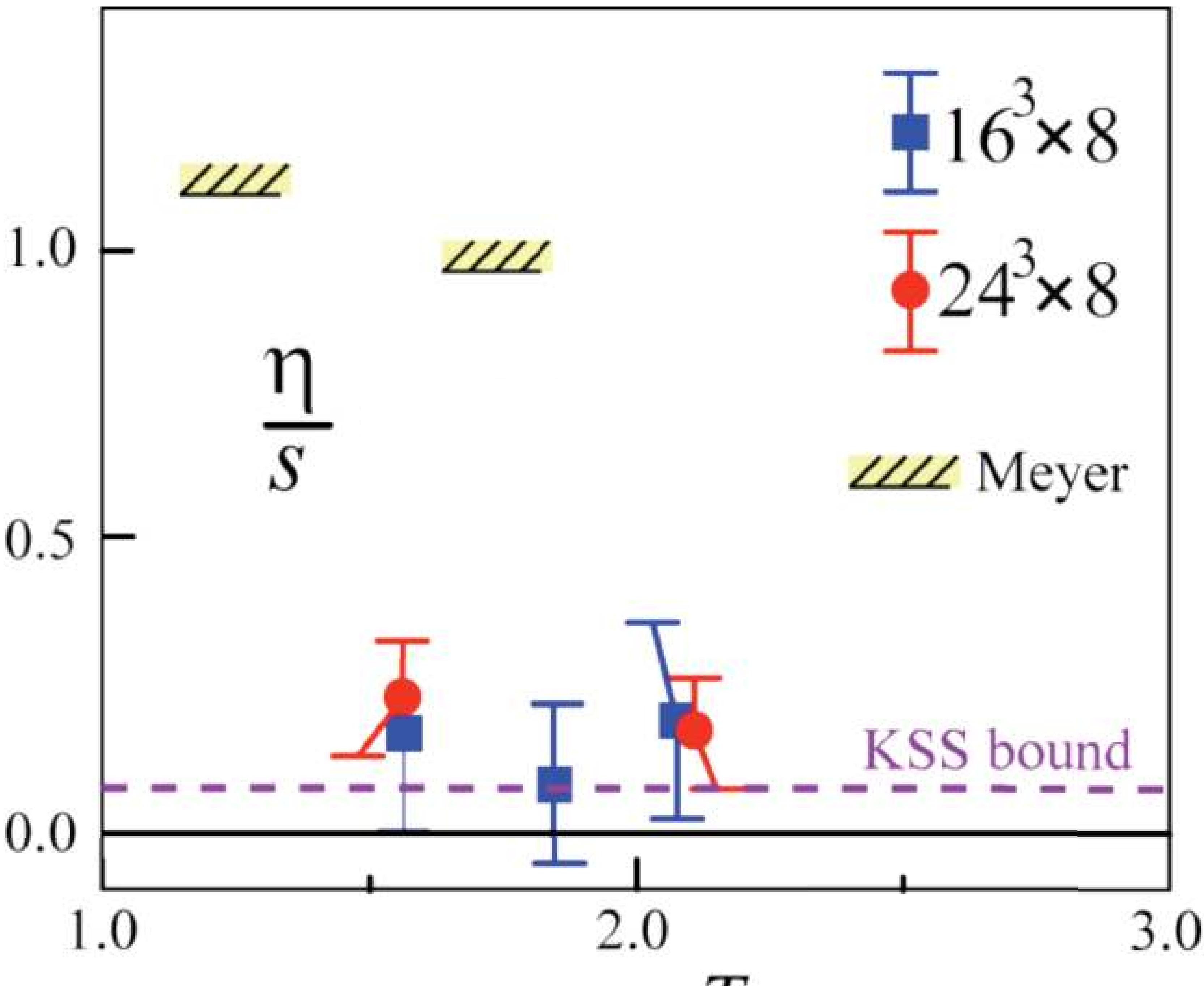
(*) Event generator ma
by Date, Miyamura
Muroya and Sasak

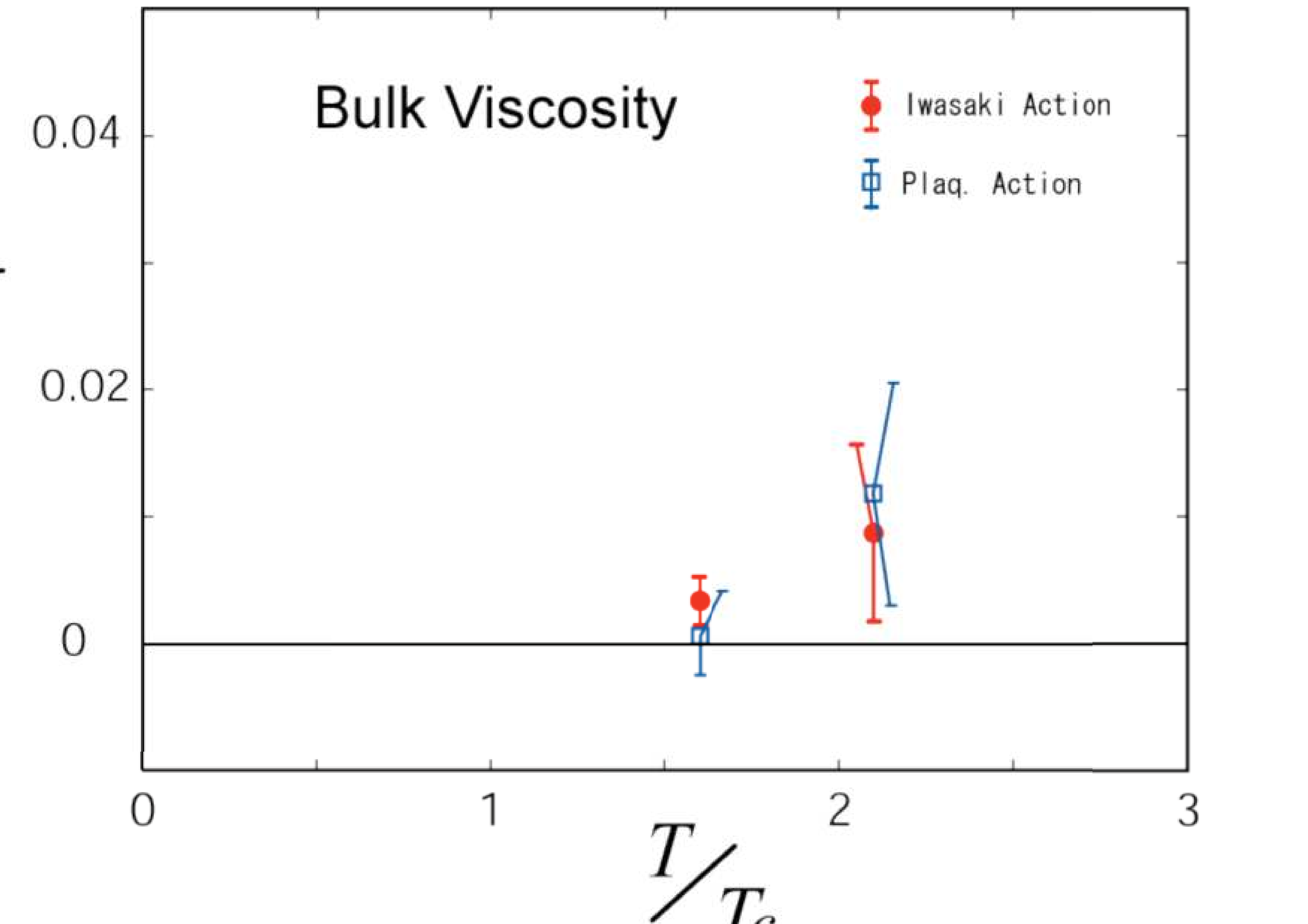
Hadrons in a Box



η/s
16³×8
24³×8
Perturbative Theory
KSS bound
2.0
1.5
1.0
0.5
0.0
-0.5
1
1.5
2
2.5
3
T/Tc

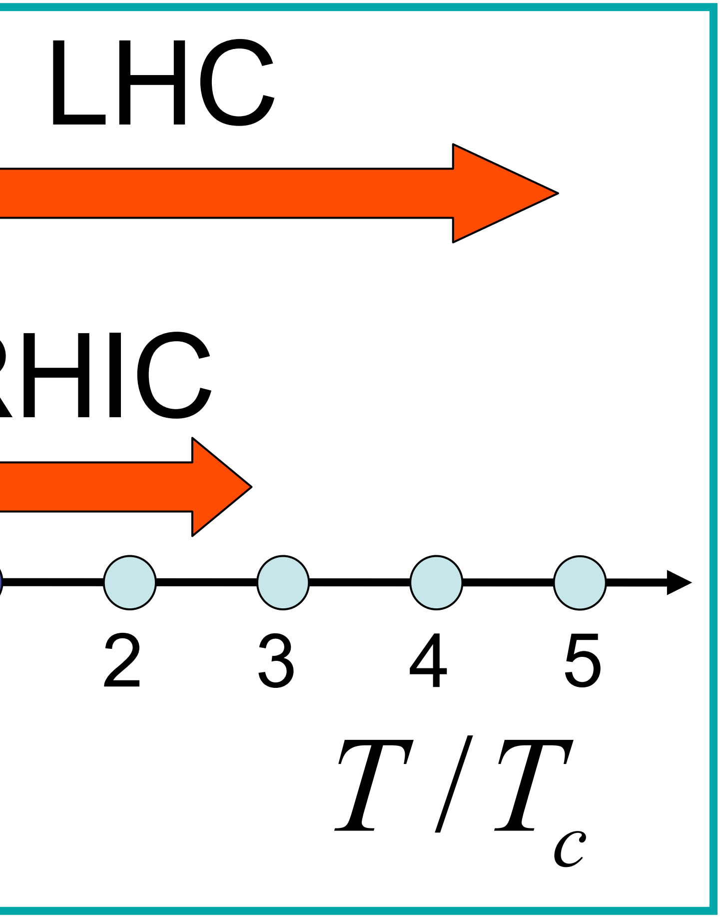
Shear Viscosity





Bulk Viscosity
Iwasaki Action
Plaq. Action
0.04
0.02
0
0
1
2
3
T/Tc

asked me



“What is most important for Lattice
now ?”

AN: “Reliable Calculation of
Viscosity, and to check if the
behavior is the same or different i
LHC temperature regions.”

He (Nakagawa) shouted “Then w
don’t we do that !”, and is calculati
every day and night.

- M. Chernodub and V. Zakharov
  - hep-lat/0611228
- J. Liao and E. Shuryak
  - hep-ph/0611131

What is Confinement (Deconfinement Mechanism ?

- M. Chernodub and V. Zakharov
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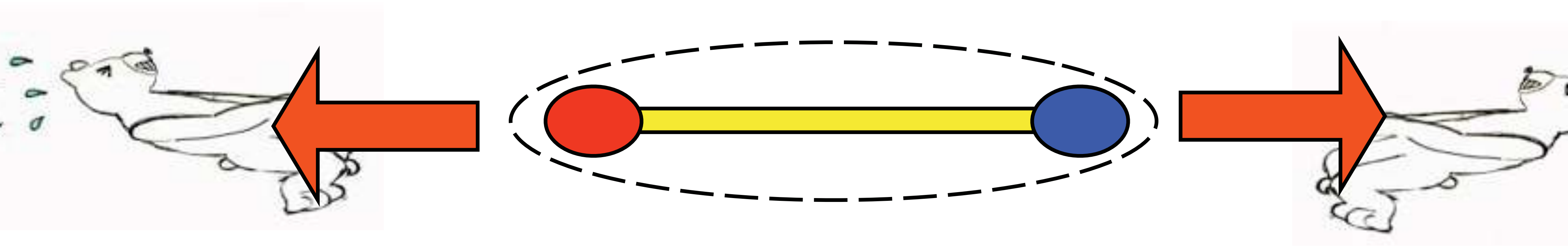
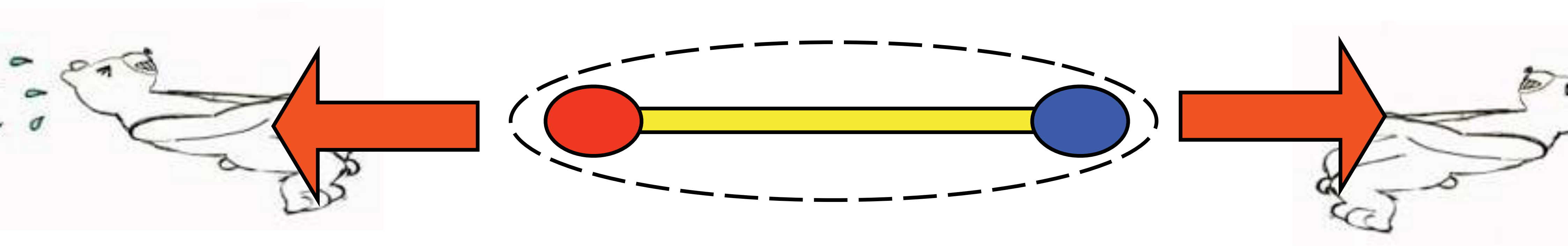
What is Confinement (Deconfinement Mechanism ?



More Energy

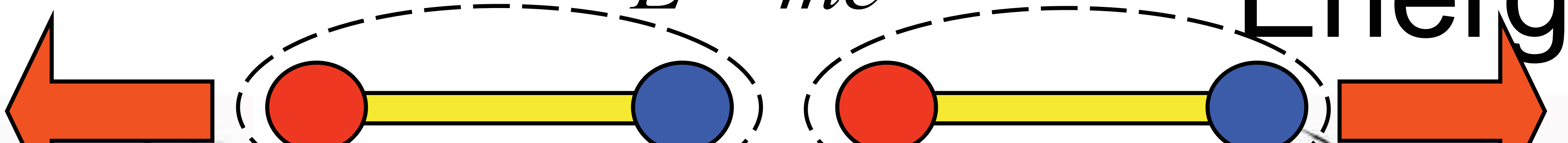
- M. Chernodub and V. Zakharov
  - hep-lat/0611228
- J. Liao and E. Shuryak
  - hep-ph/0611131

What is Confinement (Deconfinement) Mechanism ?



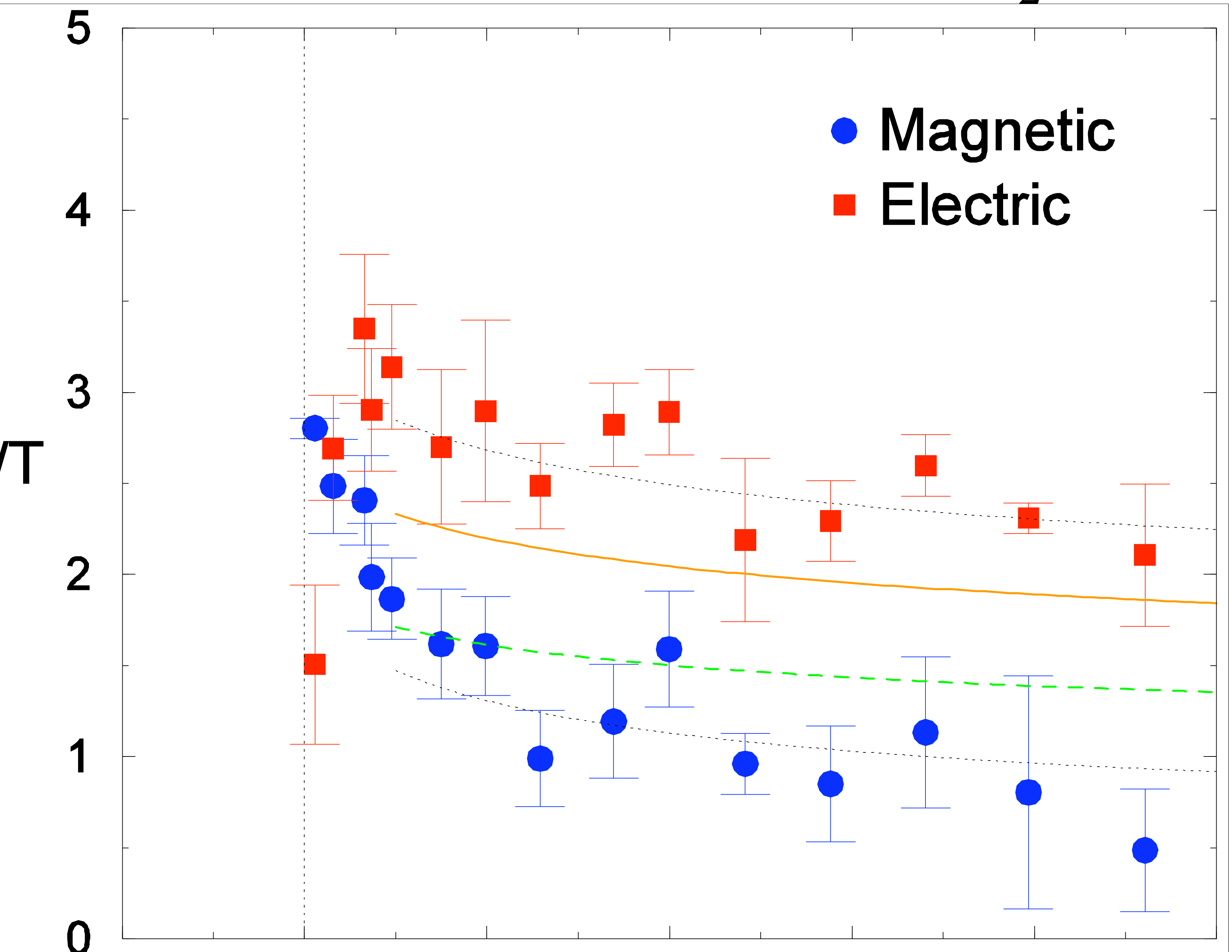
More Energy

$$E = mc^2$$



Fitting to extrapolate mass

$$G(z) = C \cdot \cosh(m(z - N_z/2)) \quad \text{at } z > 1/$$

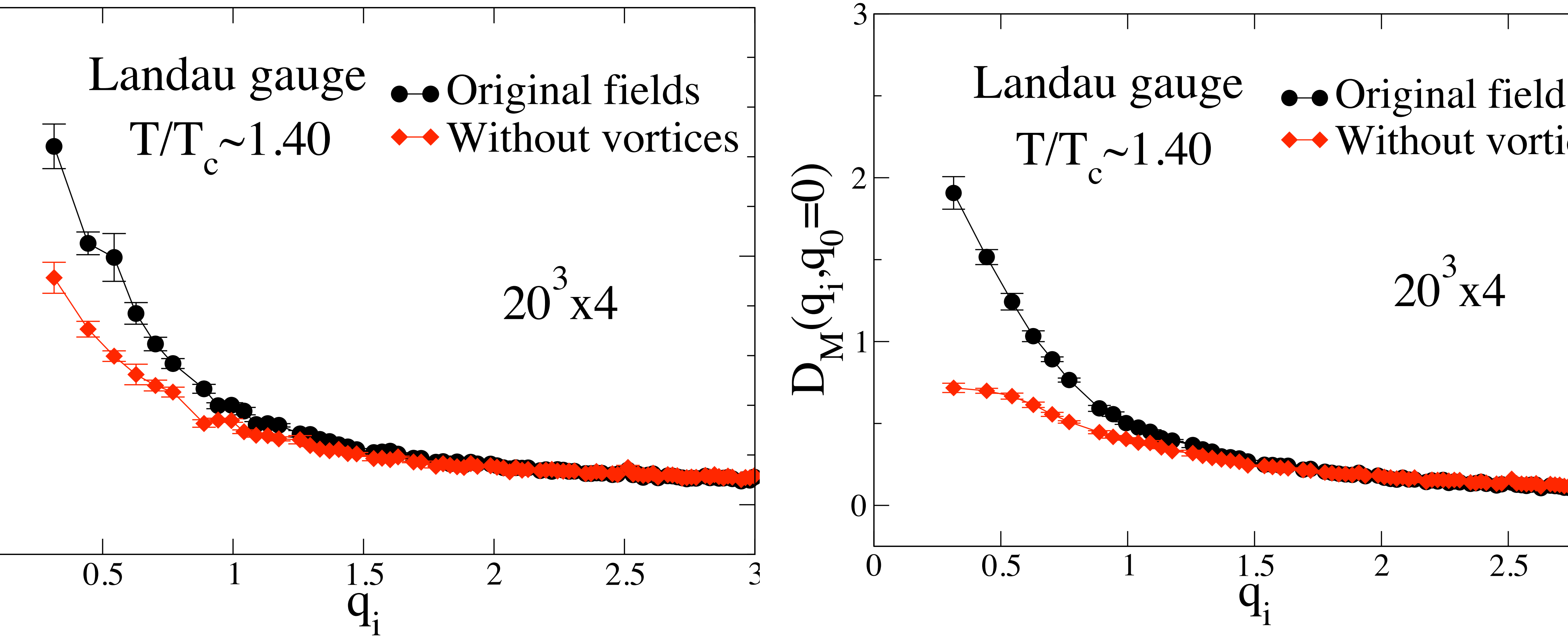


Nakamura, Sa
Saito,

Phys. Rev. D6
(2004) 014506

hep-lat/031102

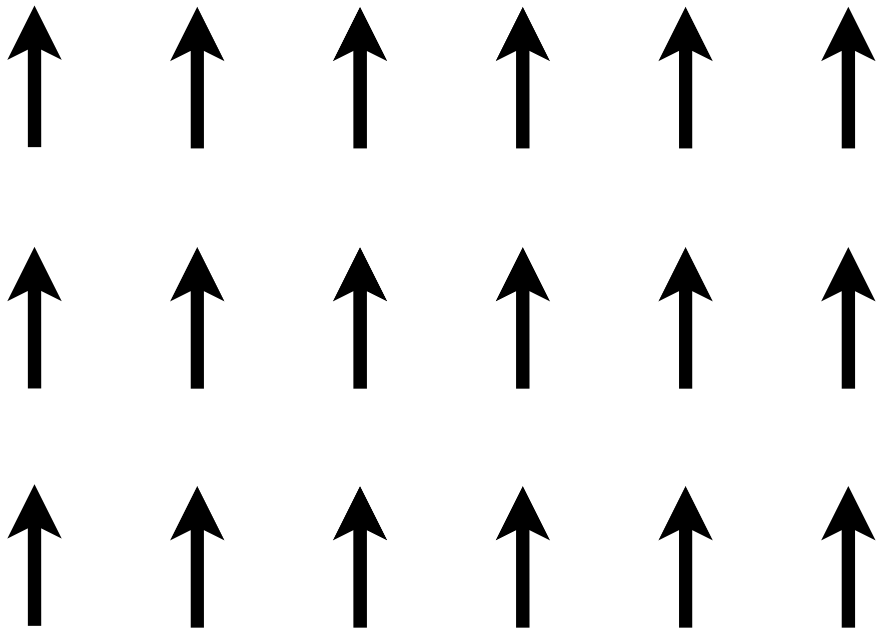
Effects of Vortex (SU(2))



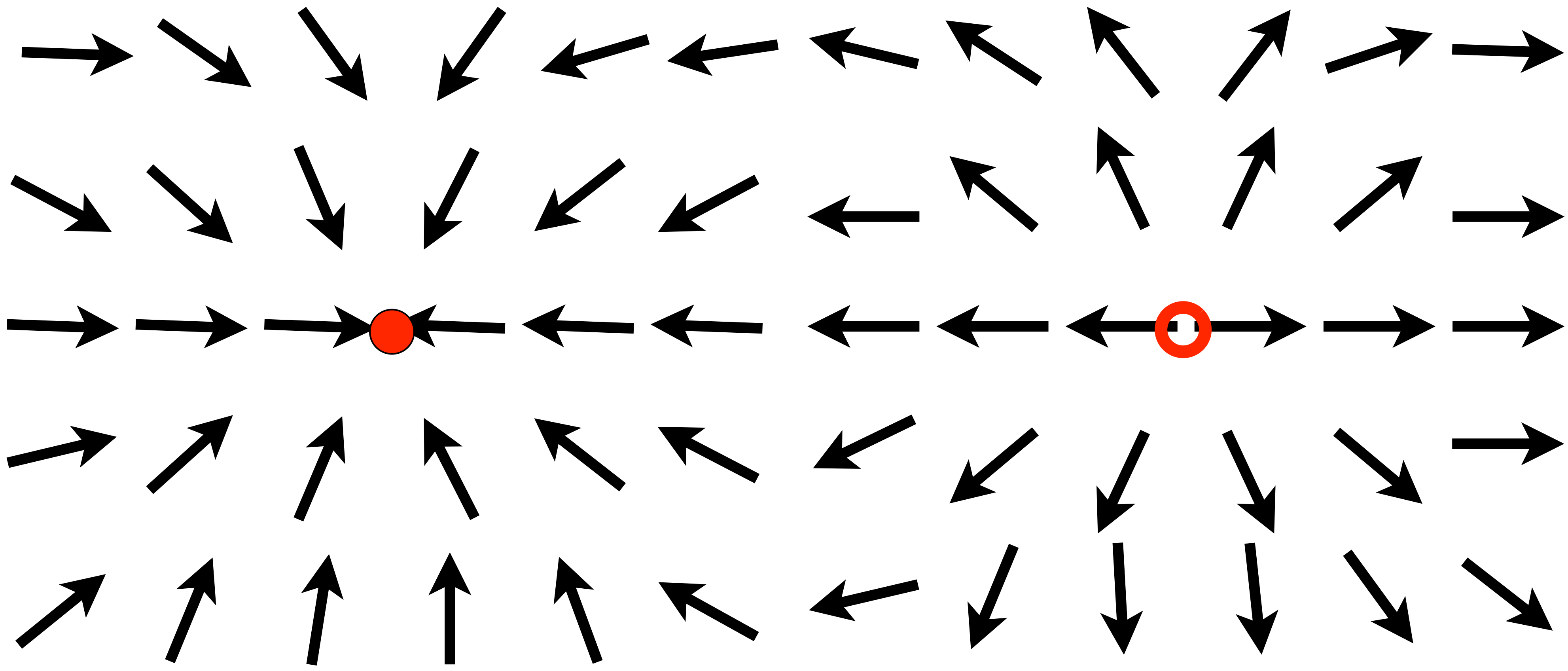
ra-Red Regions of Magnetic Propagato
upressed after Vortex Removal

Monopole ?

Simple Example: 2-d Spir

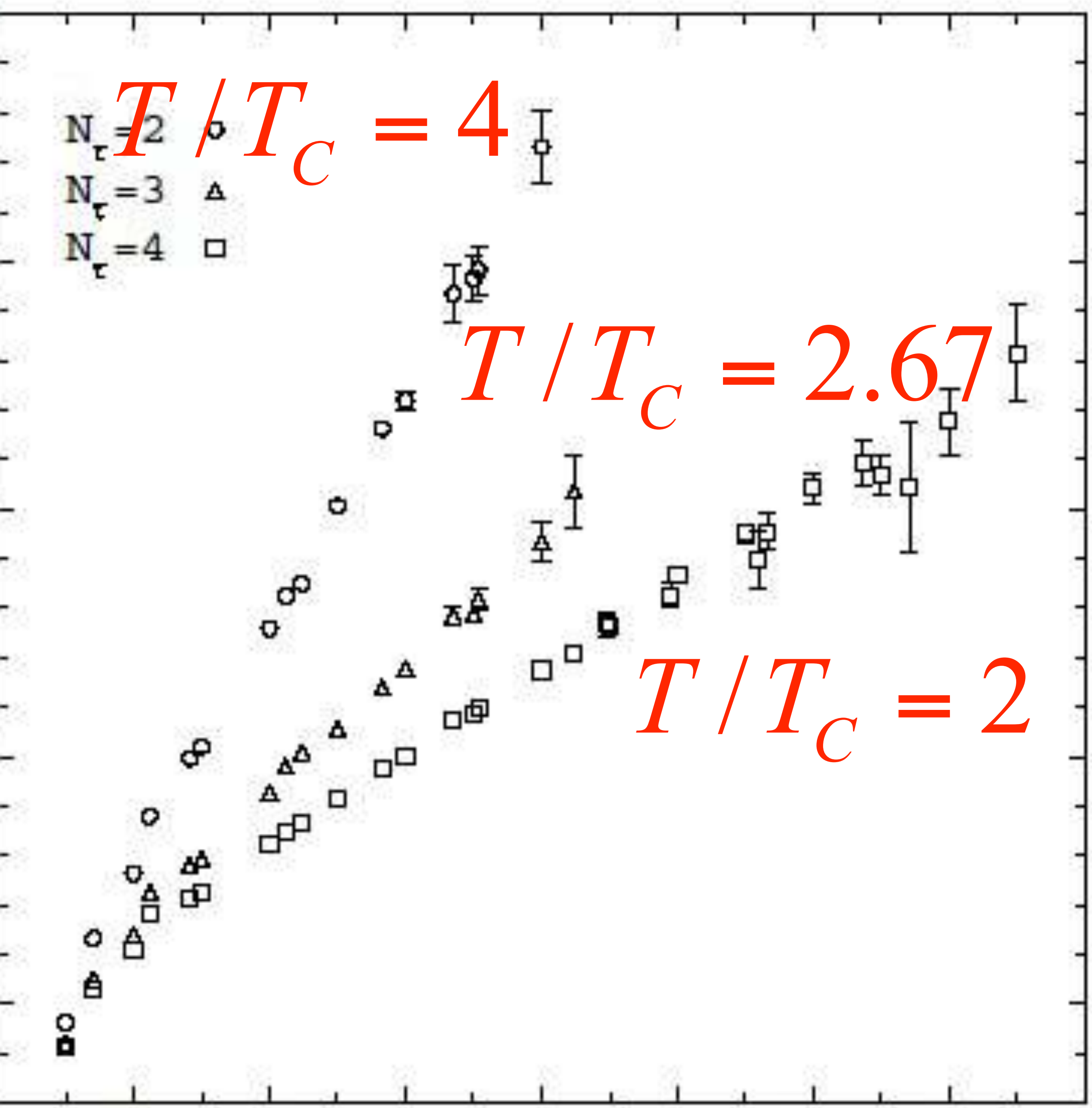


Monopole ?



Monopole/Anti-Monopole ?

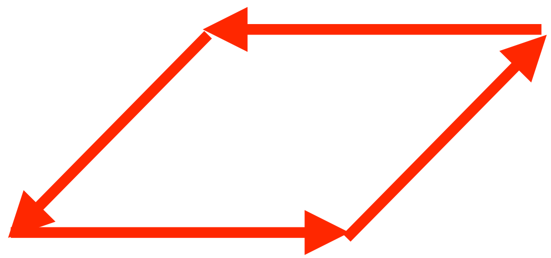
Spatial Wilson Loops



Karsch, Laermann, and Luetgemeier,

Phys.Lett. B346 (1995) 94

It is well known that Spatial Wi
Loops give a Confinement
Potential. even above Tc.



$$F_{ij} = $$

Confinement is due to monopole condensation

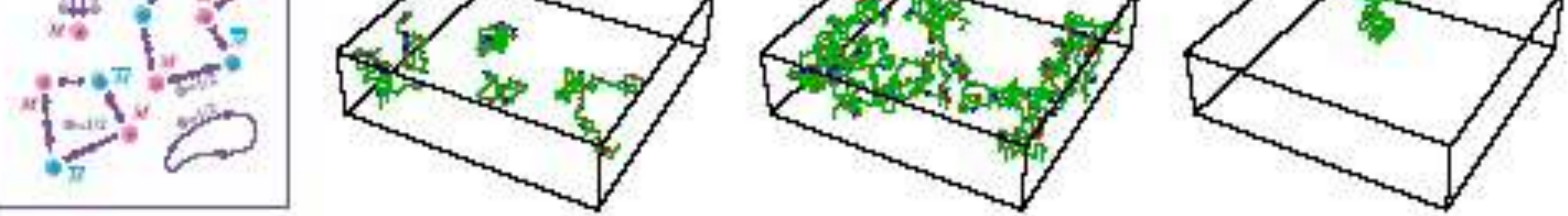
Center vortex mechanism

– Del Debbio, Faber, Greensite, Olejnik, ’97

a realization of spaghetti (Copenhagen) vacuum

Center strings are classified with respect to the center
Z_N of the $SU(N)$ gauge group

Confinement is due to vortex percolation



esults of numerical simulations are taken from Feldmann, Ilgenfritz, Schiller & M.Ch. '05]

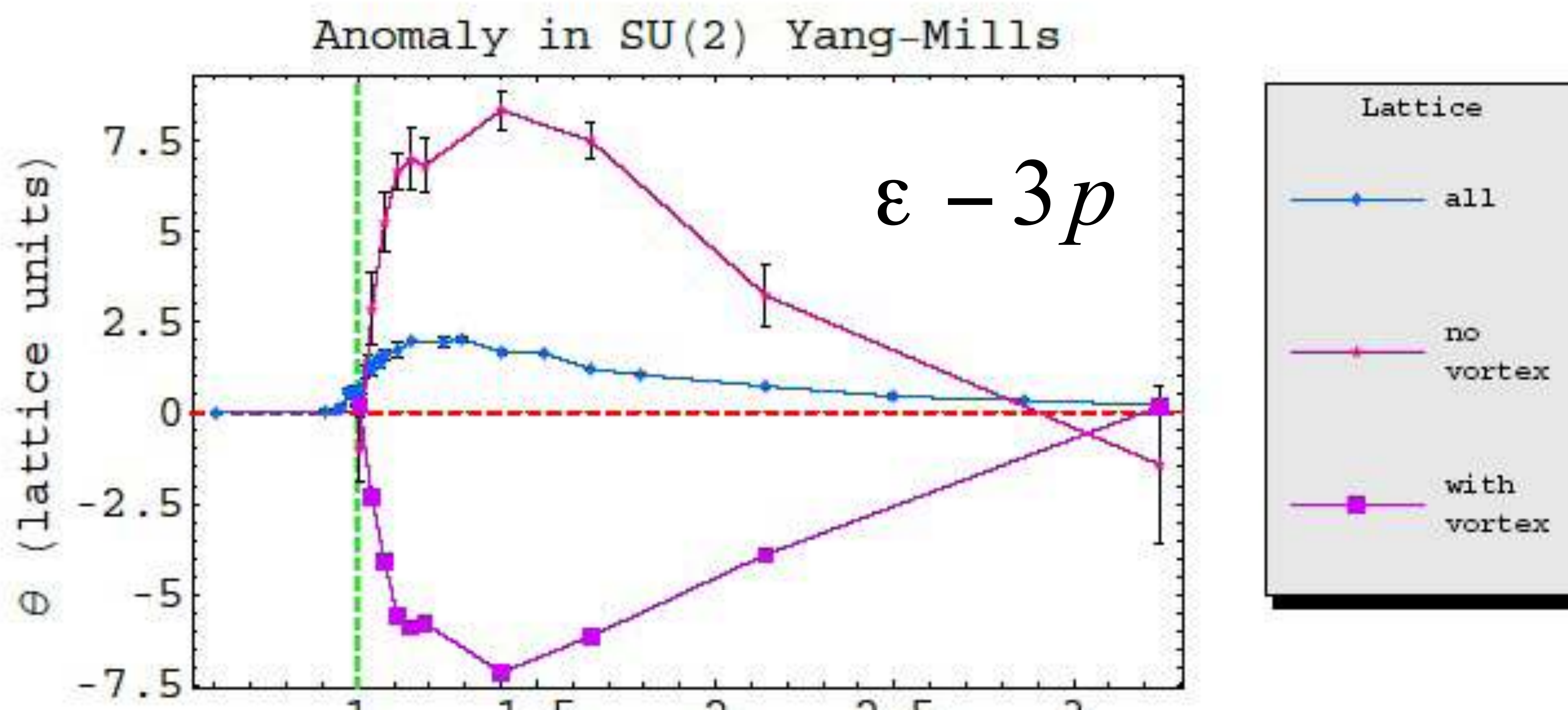
Observation of monopoles in the vortex chains:

monopole is a defect, at which the flux of the vortex alternates.

$SU(2)\ 12^3 \times 4$

T_C

(Very)^k Preliminary ($k > 2$)



Viscosity and Magnetic Vortex

Nakagawa and Saito (and
Chernodub, Zakharov and AN
are calculating Viscosity with
and without Vortex.

We are not a big group.
We do not have a big Machine.
But we do Lattice Calculations for Interesting Hadron/Quark/Gluon Physics.