Center Domains and Their Phenomenological Consequences in Ultrarelativistic Heavy Ion Collisions

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Based on work S. A. Bass, B. Müller, M.A., PRL 110 (2013) 202301

Some major achievements @RHIC/LHC

i) measurement of strong elliptic flow

success of relativistic viscous hydrodynamics with a very small value of η/s

ii) measurement of very strong suppression of high energy particles

rapid redistribution of the jet energy into the whole solid angle

iii) observation of constituent quark number scaling law for the elliptic flow of identified hadrons

i) – iii) : often attributed to the formation of QGP

iii) is the most direct evidence to date for quark deconfinement, but little information on dynamical properties of (s)QGP

Neither i) nor ii): direct evidence of (s)QGP   why?

Transport properties of QGP

i) measurement of strong elliptic flow

success of relativistic viscous hydrodynamics with a very small value of η/s

ii) measurement of very strong suppression of high energy particles

rapid redistribution of the jet energy into the whole solid angle

For i): No first principle nonperturbative calculation of η/s

2 lattice calculations, but not completely first principle calculation

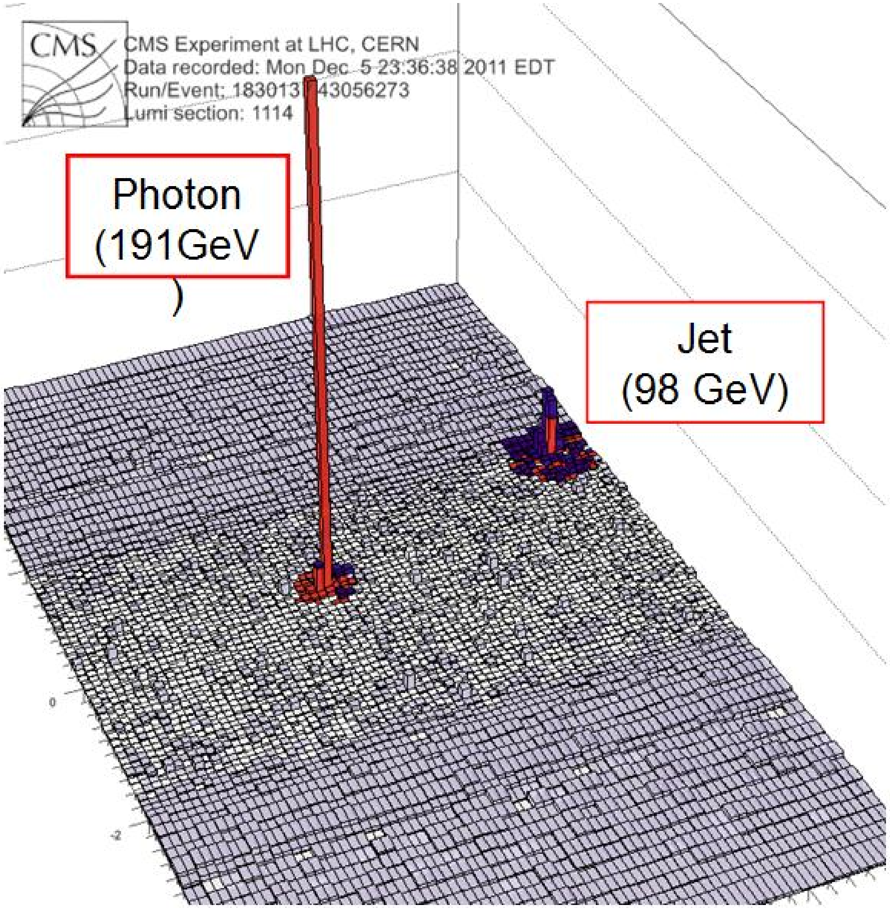
AdS/CFT: applicability of AdS/CFT correspondence conjecture to QCD?

For ii): Most calculations of jet energy-loss: based on pQCD

Sensitive to the gluon content of the matter, do not distinguish phases

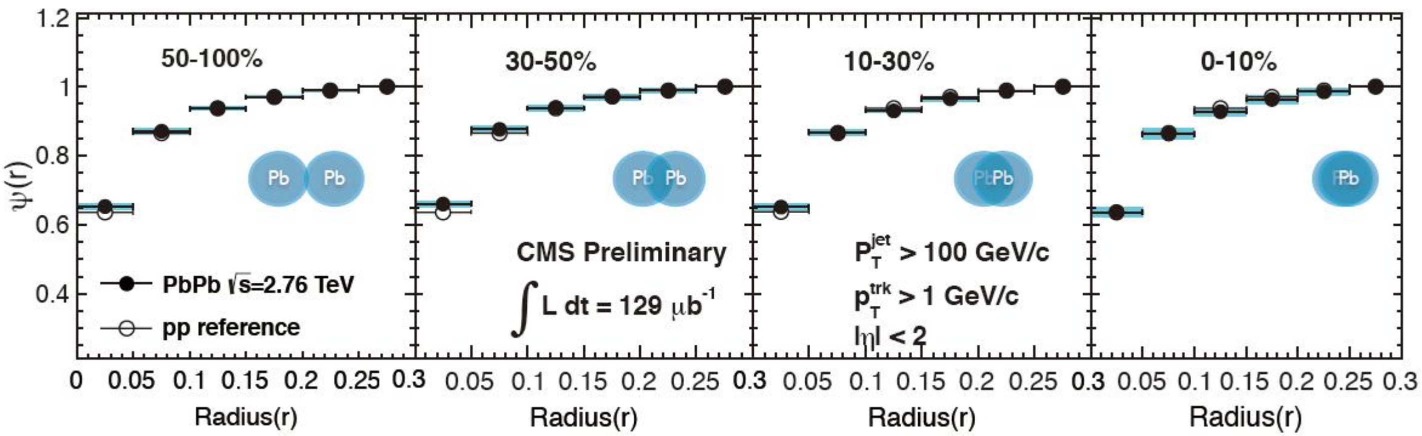
No explanation so far *for the rapid redistribution of the jet energy*

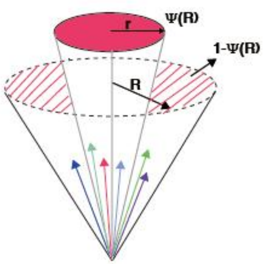
Remarkable features observed @CMS



Remarkable features observed @CMS

Integrated Jet Shapes





Radius(r)	Energy Fraction in 0-10% (pp)	Energy Fraction in 0-10%(PbPb)
0.05	65%	65%
0.1	86%	86%
0.15	94%	93%

More than 95% of the jet energy deposited in r < 0.2

Jet Core is unmodified!

Kurt (CMS), QM2012

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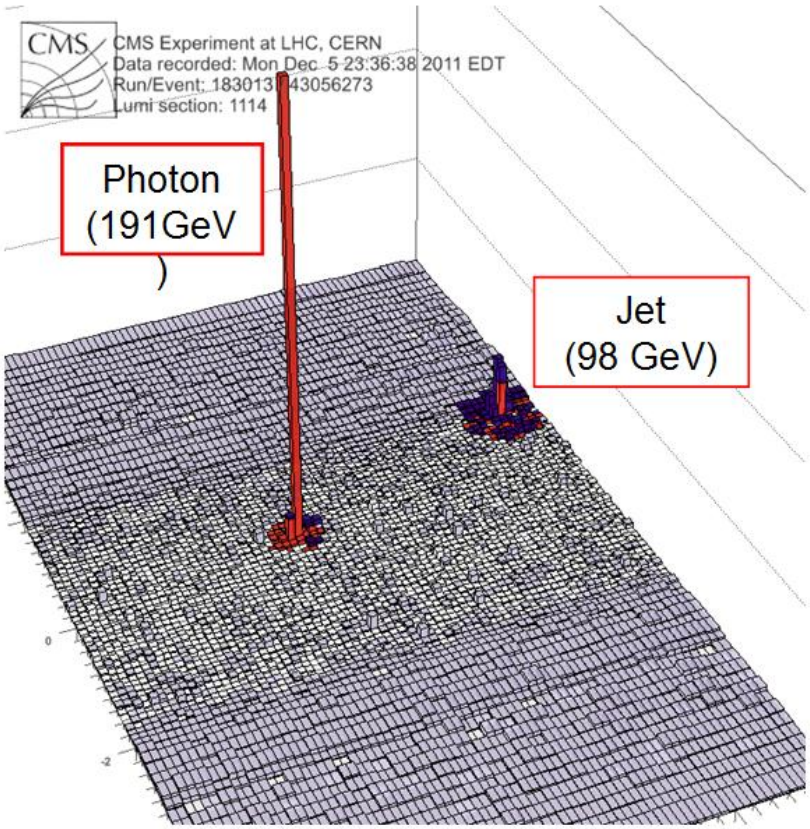
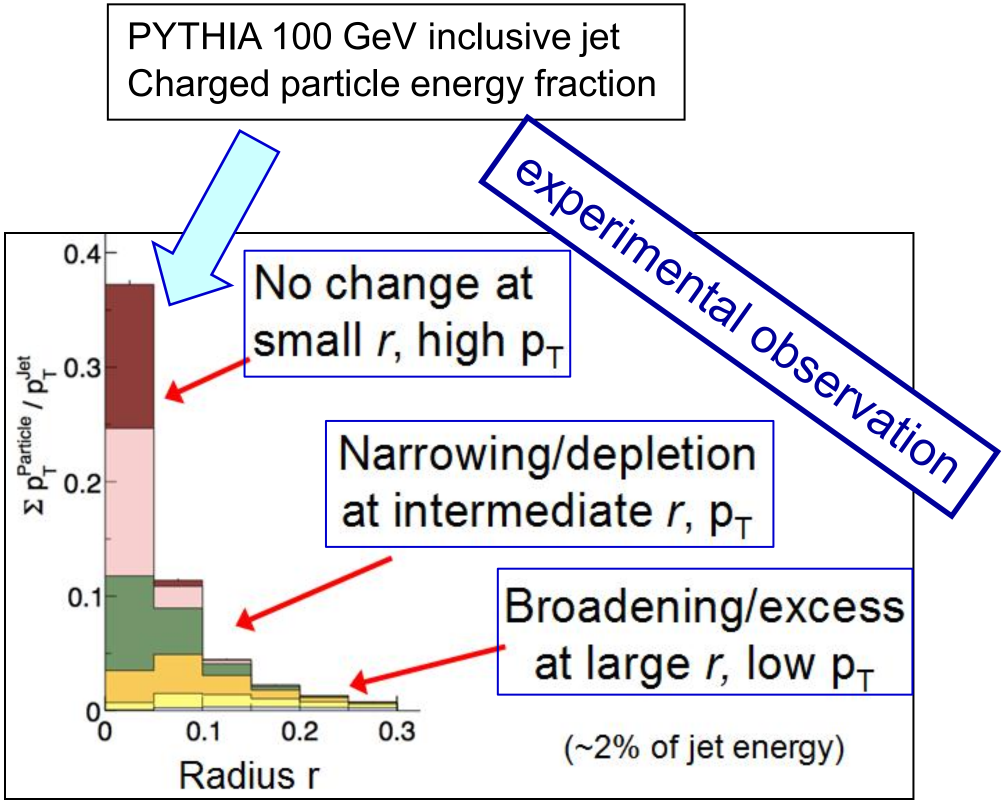
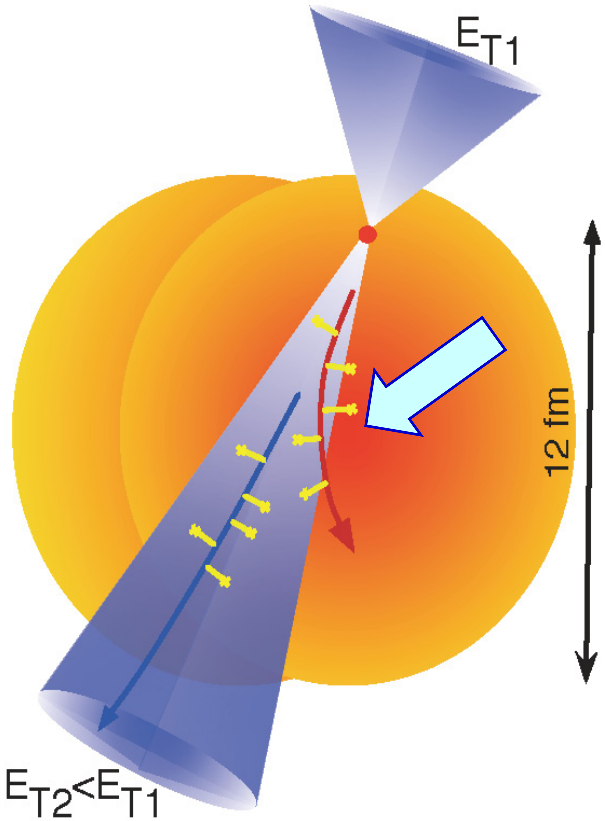




Roland (CMS), QM2012

Idea of Frequency Collimation

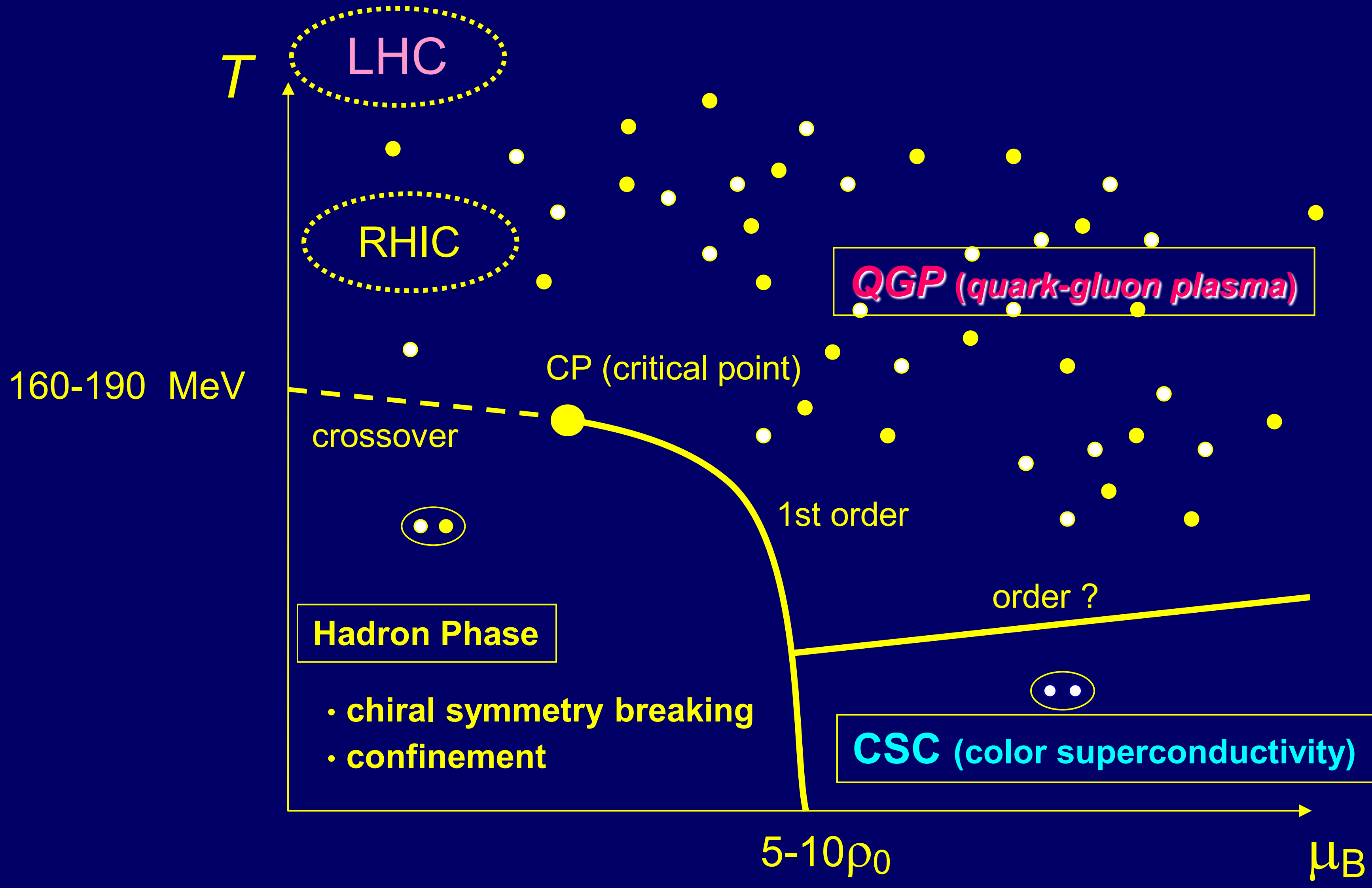


An attractive working conjecture:

Medium acts as a *frequency collimator*
trims away the soft components of the jet

Casalderry-Solana, Milhano, and Wiedemann, J. Phys. G (2011)

QCD Phase Diagram



Order Parameters

- What characterizes QCD phase transition?
  - Chiral Symmetry : $SU(N_f)_L \times SU(N_f)_R$ in the massless limit

    Quark condensate $\langle \bar{\psi}\psi \rangle$: finite value $\rightarrow 0$

  - Confinement : Z_3 in the pure gauge theory

    Polyakov loop $\langle L(\vec{x}) \rangle : 0 \rightarrow 1,\ \exp\left(\frac{2}{3}\pi i\right),\ \exp\left(\frac{4}{3}\pi i\right) \in Z_3$

$$L(\vec{x}) = \frac{1}{3} \mathrm{tr}\, \mathrm{P} \exp\left(ig \int_0^{1/T} A_4(\tau, \vec{x}) d\tau \right)$$

Z_3 symmetry is *spontaneously broken* in QGP

⇒ Center symmetry is *spontaneously broken* in QGP

Center Symmetry in Equilibrium

- Center symmetry has been discussed many times in many contexts

  - Decay of Polyakov Loop condensate for event-by-event fluctuation

    Dumitru and Pisarski, 2001

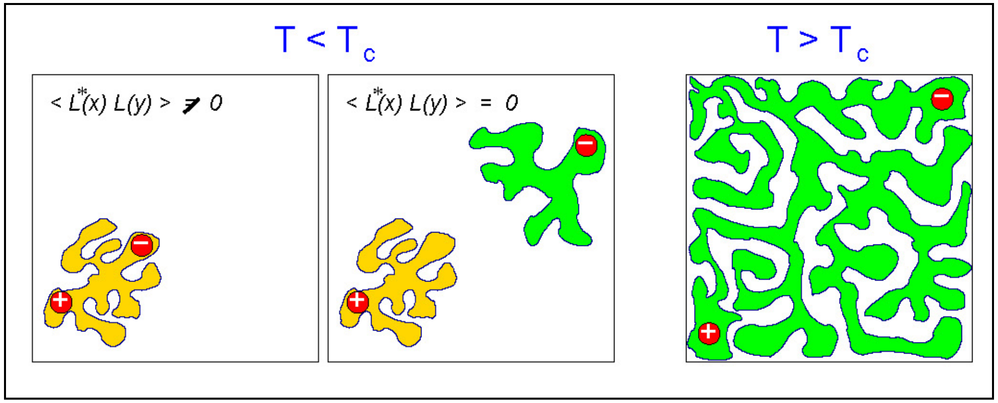
  - Possibility of Center Domains (where L takes one of the three values) in equilibrium

    On Lattice

    Gattringer et al., ca. 2010 ~

    Itou, Kashiwa, and Nakamoto for 5dim gauge theory, 2014

ex.) Fractal nature of domains (Pure SU(N)) Gattringer et al.

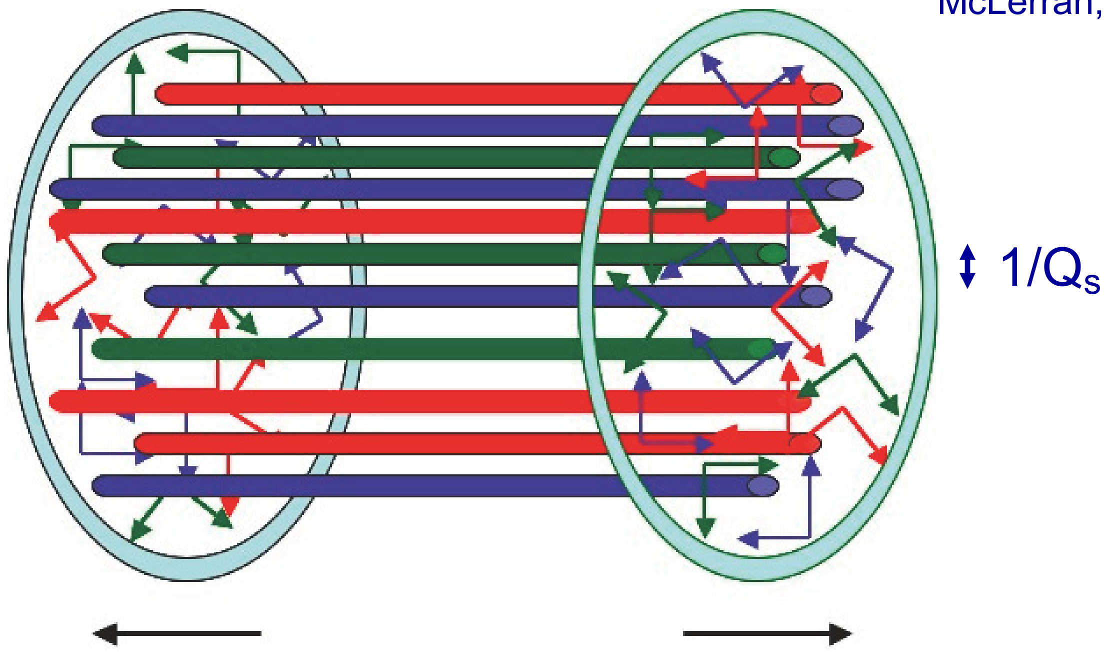


schematic picture for SU(2)

How is QGP created in HI collisions ?

Glasma [glǽzmə]: longitudinally slowly varying coherent color field

McLerran, Venugopalan, et al.



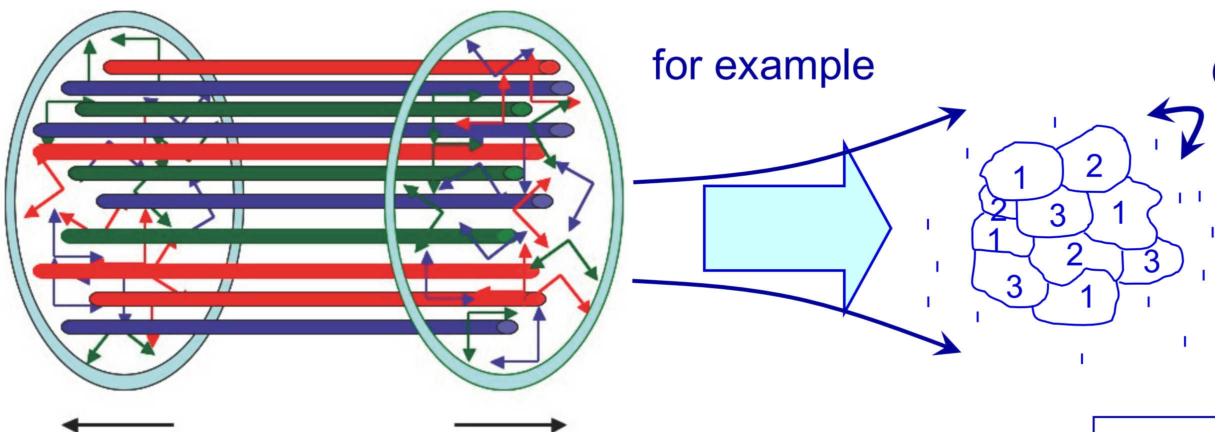
Standard scenario

Glasma decays into QGP

Typical transverse correlation scale: $1/Q_s$ @LHC $Q_s \sim 2$ GeV

Z_3 valued QGP

Since the typical transverse scale of the gauge field ~ $1/Q_s$,
in the transverse direction in the QGP created in HI collisions,
$L(\vec{x})$ changes from one of the three Z_3 elements to another with scale $1/Q_s$



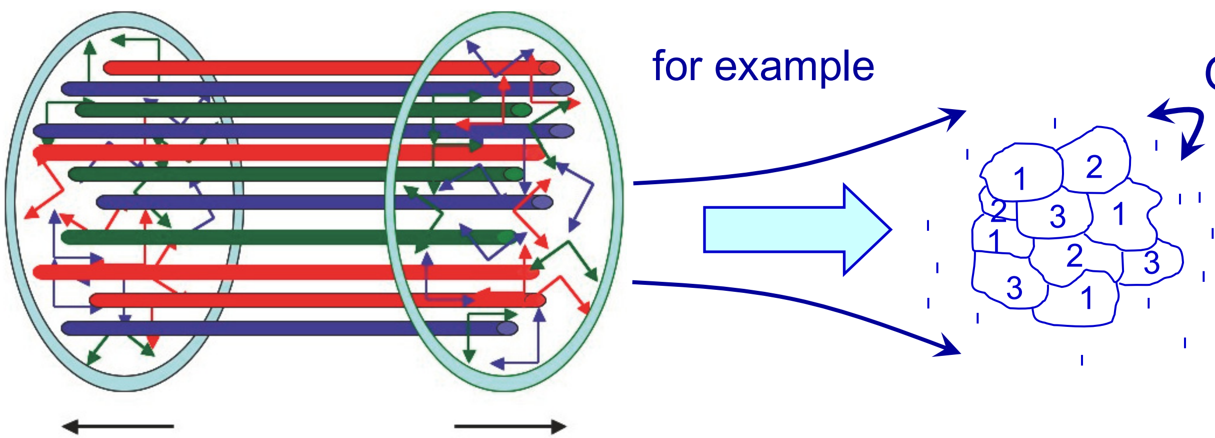
$$i = \omega^i \quad \left(\omega = \exp\left(\frac{2}{3}\pi i\right) \right)$$

on the transverse plane

Note: Z_3 is a discrete group

Effective potential for L has three distinct minima above T_c

L between Center Domains



O(1/Q_s), at most τ_{th}

$$i = \omega^i \quad \left(\omega = \exp\left(\frac{2}{3}\pi i\right)\right)$$

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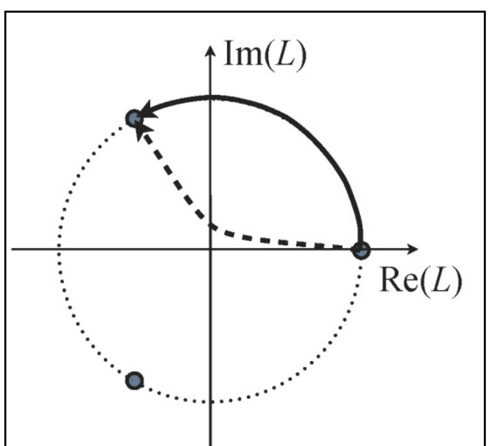
How does L change between domains ?



- two of possibilities
  - modulus ~ const. (solid)
  - modulus changes (dashed)

Empirical form of Polyakov Loop potential

Commonly used form in PNJL model

$$U(\langle L\rangle) = -bT\left[54e^{-a/T}\left|\langle L\rangle\right|^2 + \log P\left(\langle L\rangle, \langle L^\dagger\rangle\right)\right]$$

$$P(z,\bar{z}) = 1 - 6|z|^2 + 3|z|^4 + 4(z^3 + \bar{z}^3)$$

$a = 0.664$ GeV, $b = 0.0075$ GeV^3

Form of P : from SU(3) Haar measure

- From lattice data
  - dominated by information around the potential minima
  - a lot of ambiguity

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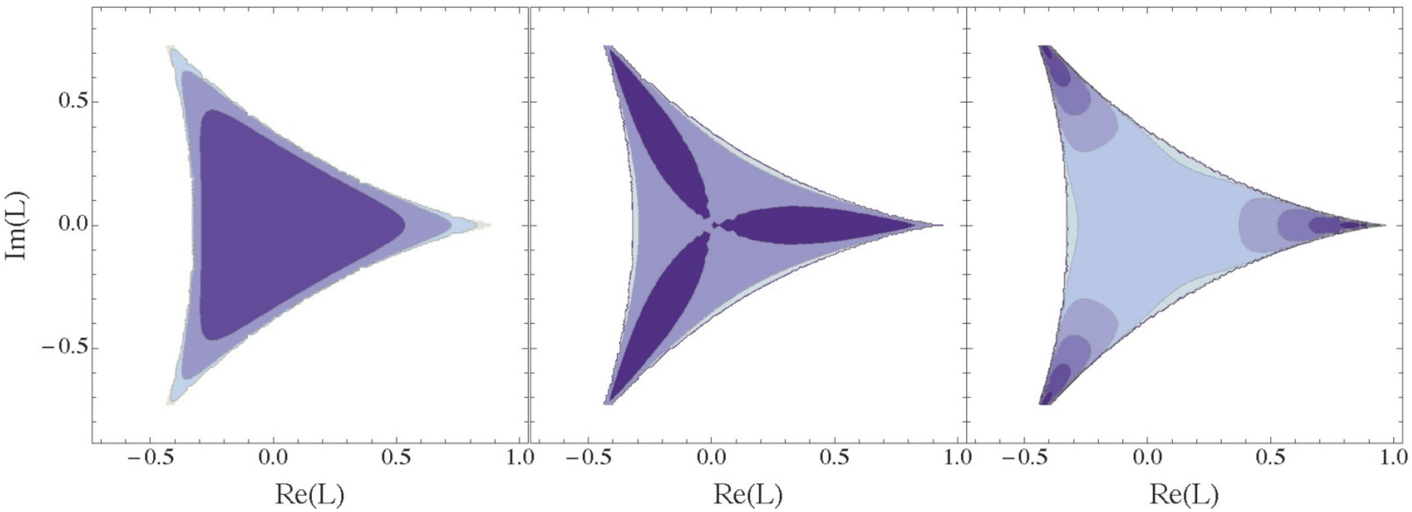

T = 100 MeV 300 MeV 500 MeV

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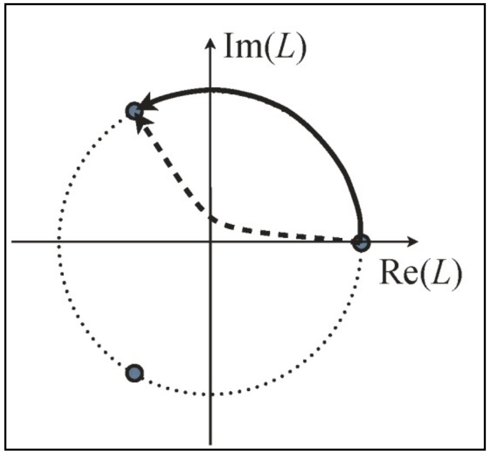

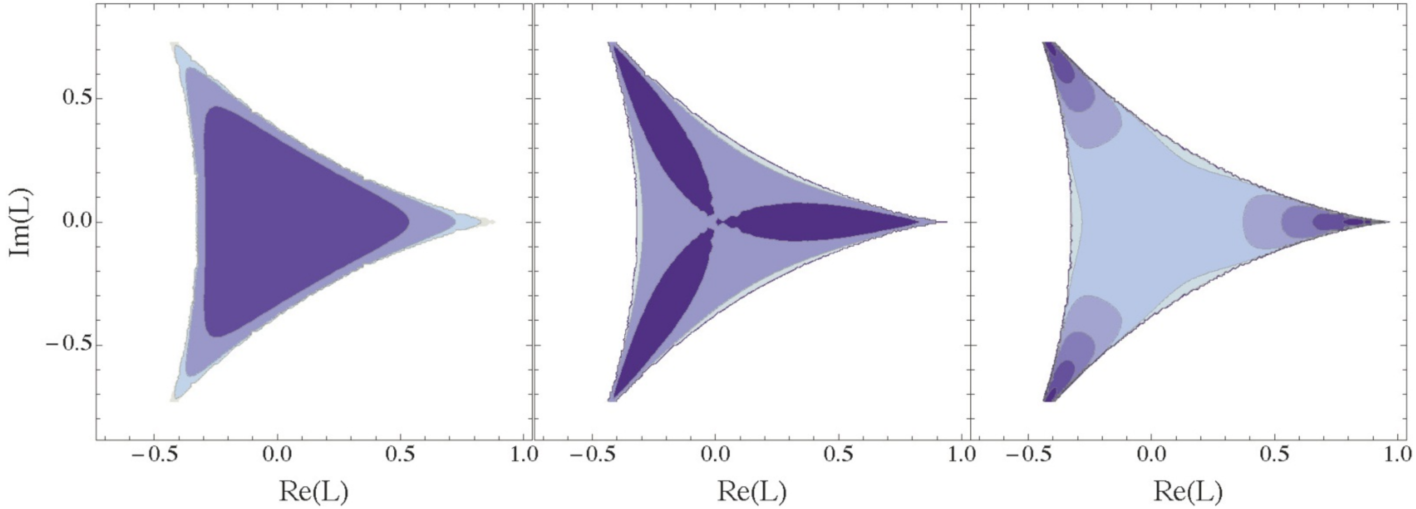

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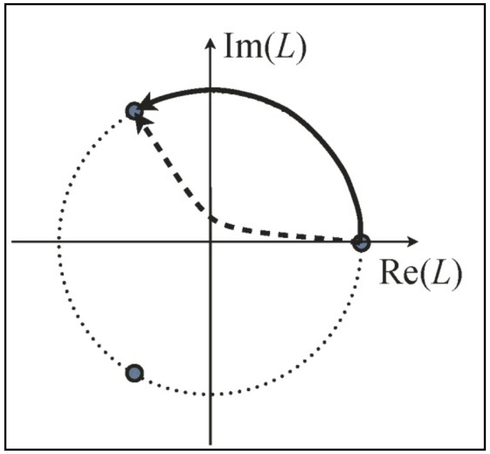
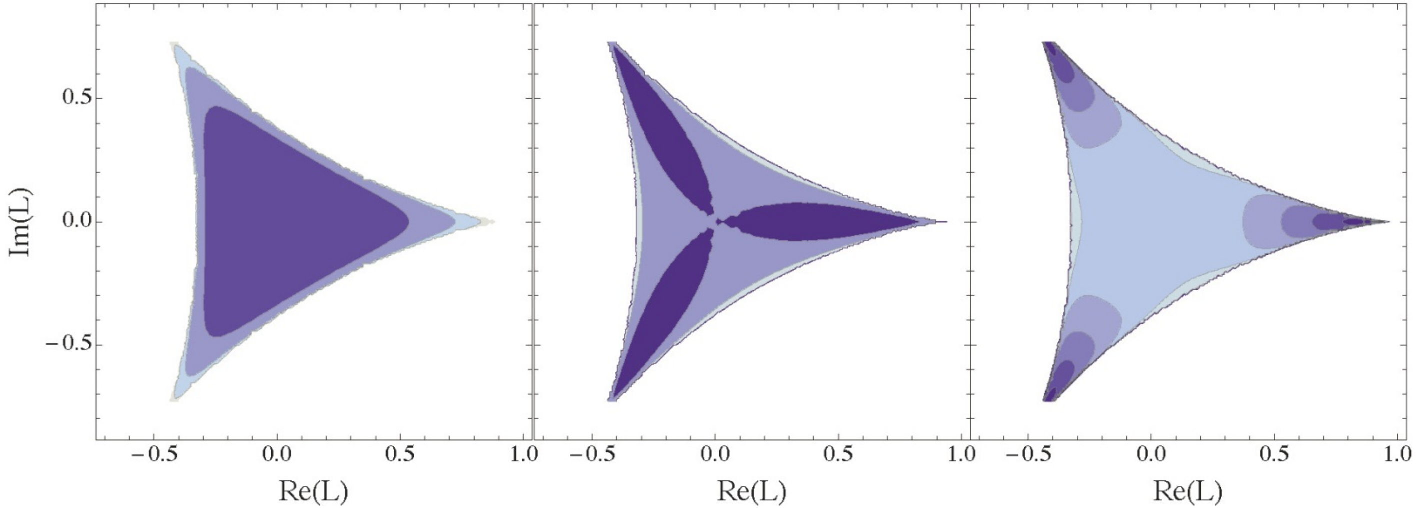
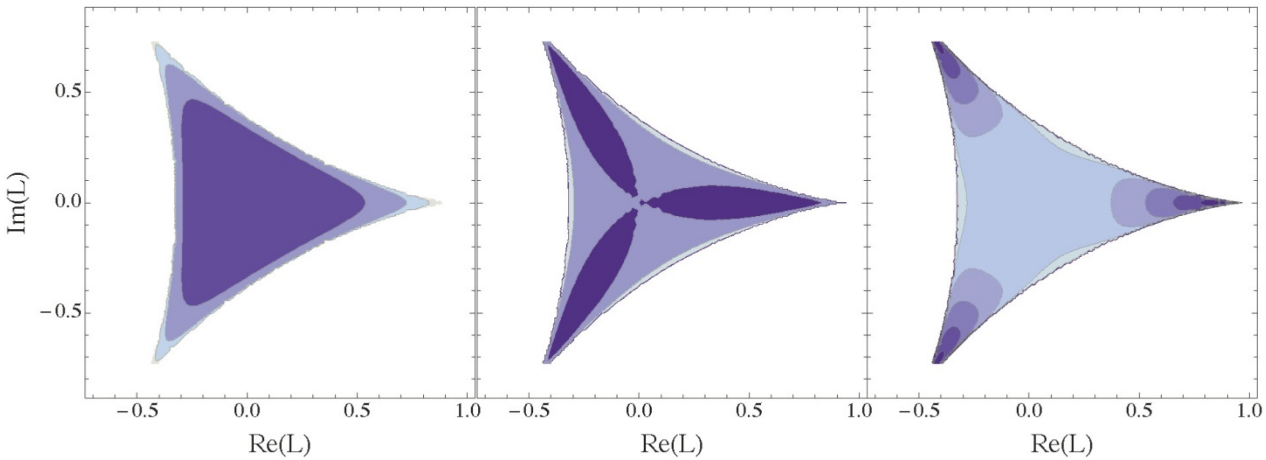


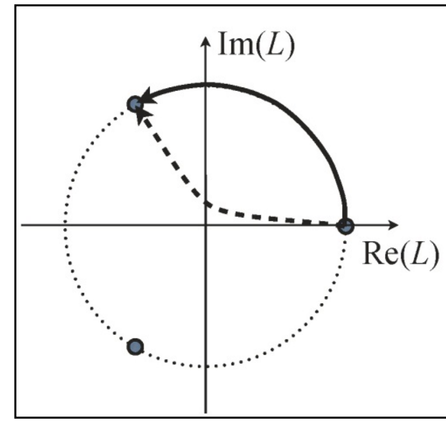


T = 100 MeV　　300 MeV　　500 MeV

Consistent with Lattice data for L fluctuation

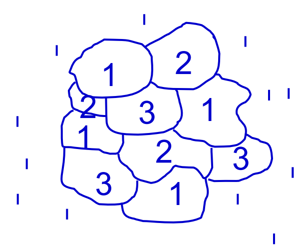
Gauge configuration on domain boundaries





- Relation between heavy static quark free energy and L
  in the pure gauge theory

$$F_Q(\vec{x},T) = -T \log \left| \langle L(\vec{x},T) \rangle \right|$$



In between center domains,
gauge field configuration : similar to those in the confined phase

Consequence I: shear viscosity

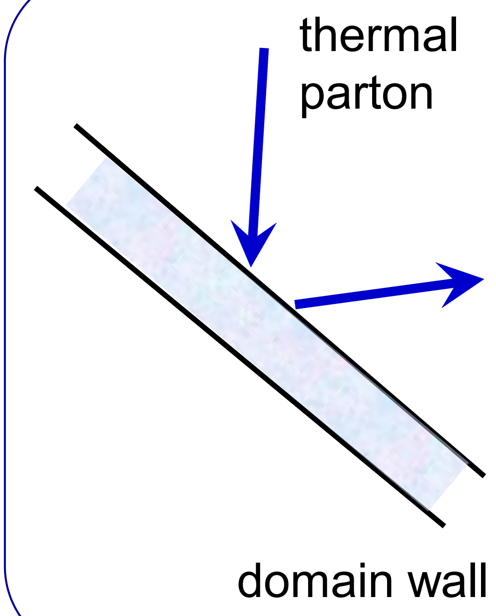
- Partons with thermal momenta cannot penetrate the walls but are reflected on them

Domain size R_d, and mean free path λ_f

$$\lambda_f \approx \frac{R_d}{2}$$

and $\eta \approx \frac{1}{3} n \bar{p} \lambda_f$

$$\frac{\eta}{s} \approx \frac{1}{8} T R_d \quad \text{for} \quad p \approx 3T, \ \frac{s}{n} \approx 4$$



in the right ball park!

Consequence II: Frequency Collimation

- For partons with momenta higher than the thermal scale:

domain walls act like the combination of
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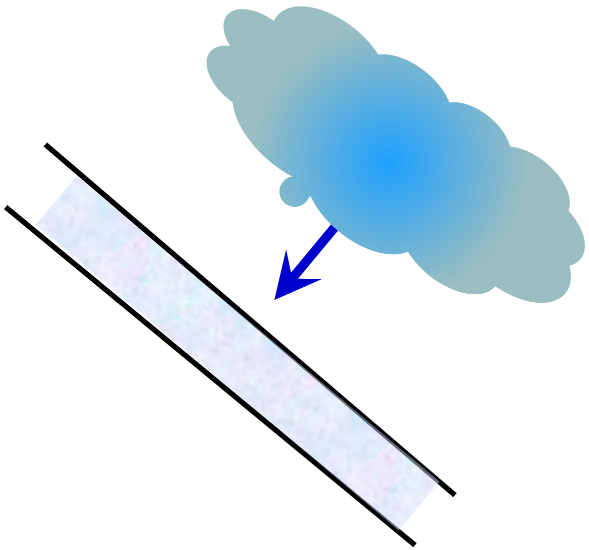

domain wall

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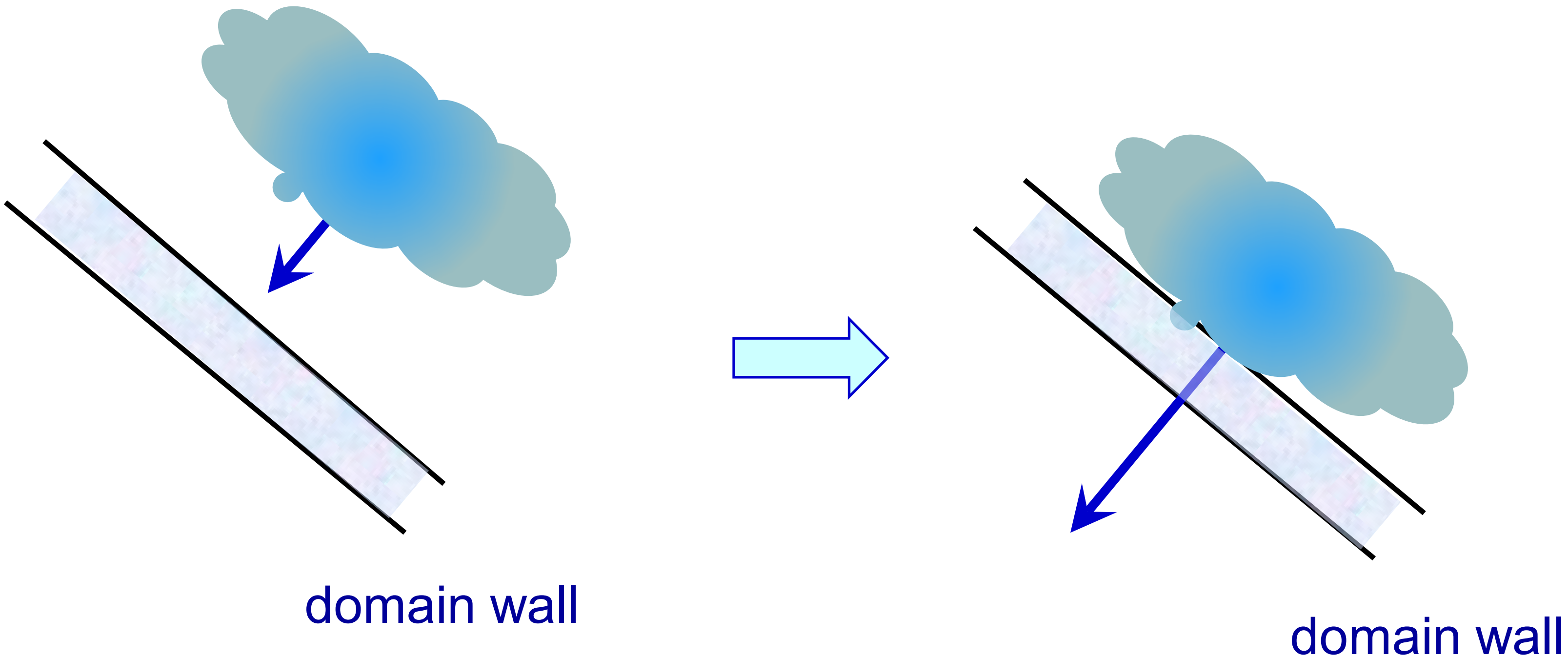

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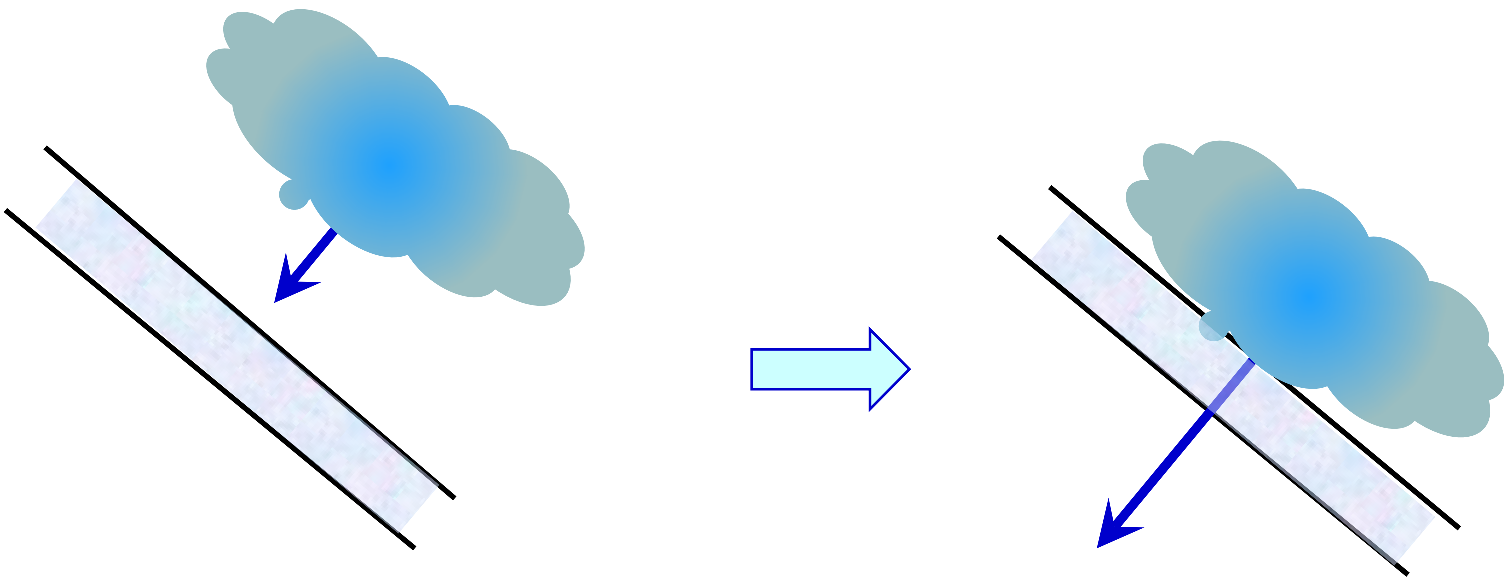


domain wall

domain wall

frequency collimation !

Energy loss by frequency collimation

- Energy loss in a single wall crossing

$$\Delta E = \int_0^{\omega_c} \omega \frac{dN_g}{d\omega} d\omega$$

ω_c: critical frequency

- Weizsäcker-Williams approximation for gluon spectrum

$$\frac{dN_g}{d\omega} \approx \frac{C_2 \alpha_s}{\pi \omega} \log\left(\frac{\omega}{\omega_0}\right) \theta(\omega - \omega_0)$$

ω_0: infrared cutoff

- Energy loss per unit length

$$\frac{dE}{dx} \approx \frac{C_2 \alpha_s}{\pi R_d} \left\{ \omega_c \log\left(\frac{\omega_c}{\omega_0}\right) - (\omega_c - \omega_0) \right\}$$

For $\omega_c \approx 1-2\,\mathrm{GeV}$, $\omega_0 \approx 0.4\,\mathrm{GeV}$, and $R_d \approx 0.5\,\mathrm{GeV}$,

$$\frac{dE}{dx} \approx (0.2-1) C_2 \alpha_s \ \mathrm{GeV/\,fm}$$

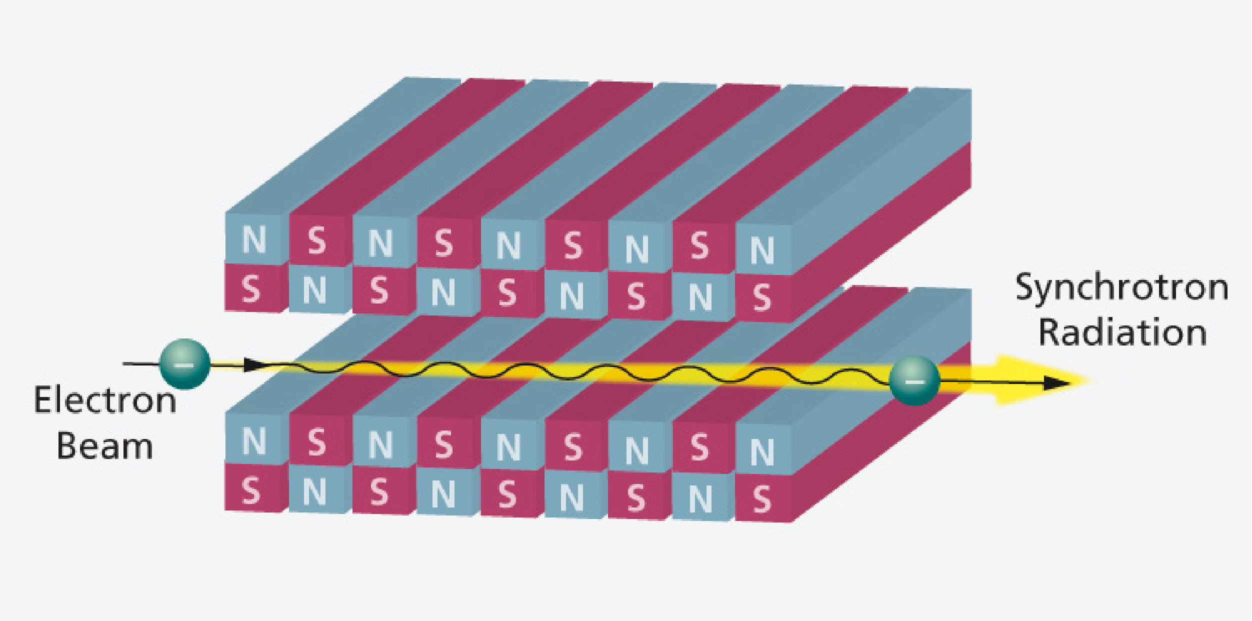
in the right ball park!

Consequence III: Irregular Undulation

Undulator @ photon factories

SPring-8 (Japan)

coherent undulator



from SLS homepage

Consequence III: Irregular Undulation

$$\langle L(\vec{x})\rangle = \frac{1}{3}\left\langle \mathrm{tr}\,\mathrm{P}\exp\left[ig\int_0^{1/T} A_0(\tau,\vec{x})d\tau\right]\right\rangle$$

$$\approx \exp\left[-\frac{g^2}{2T^2}\mathrm{tr}\left\langle A^0(\vec{x})^2\right\rangle\right]$$

✓ Inside domain walls (L=0), A^0 fluctuates with large amplitude

⇒

- Strong and uncorrelated radiation of gluons
- Prompt restoration of Weizsäcker-Williams field

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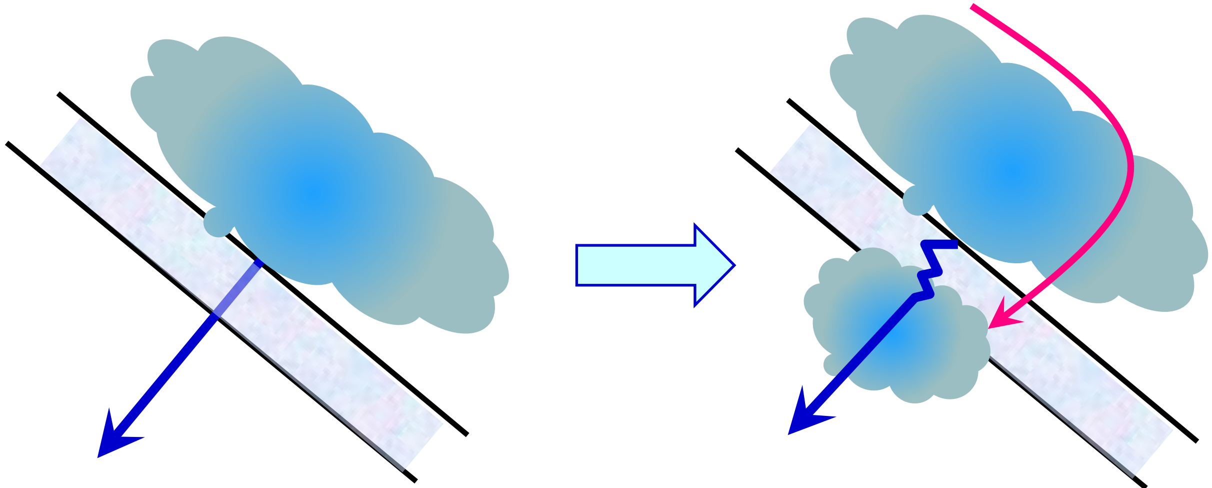

Comments

- ✓ This energy loss mechanism works only in Z_3 (or Z_N) valued QGP
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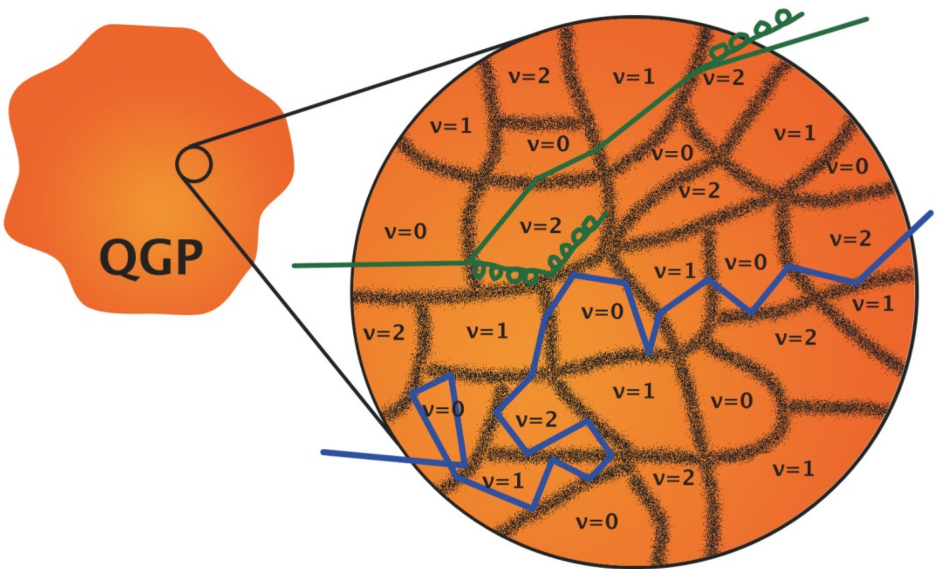

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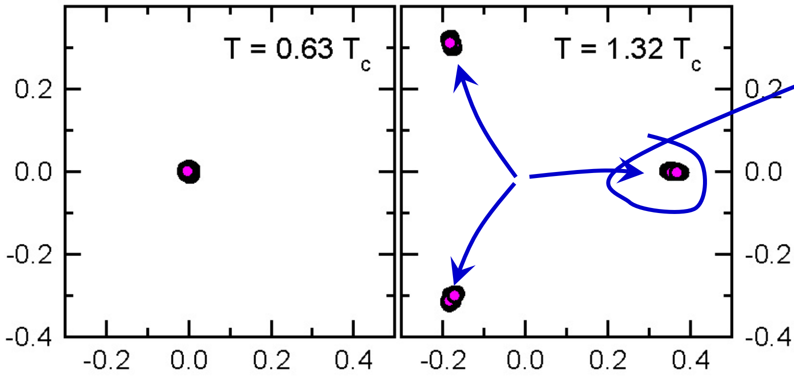
- ✓ This mechanism is nonperturbative
- ✓ This picture naturally leads to the immediate randomization of soft gluons
- ✓ Full QCD Lattice calculation observes domain structure
  Early stage of QGP is dominated by gluons: close to pure gauge
- ✓ This mechanism is not exclusive
  Other ordinary mechanisms can work together

Back Ups

Lattice Example

Effective potential for L has three minima above T_c

with volume average



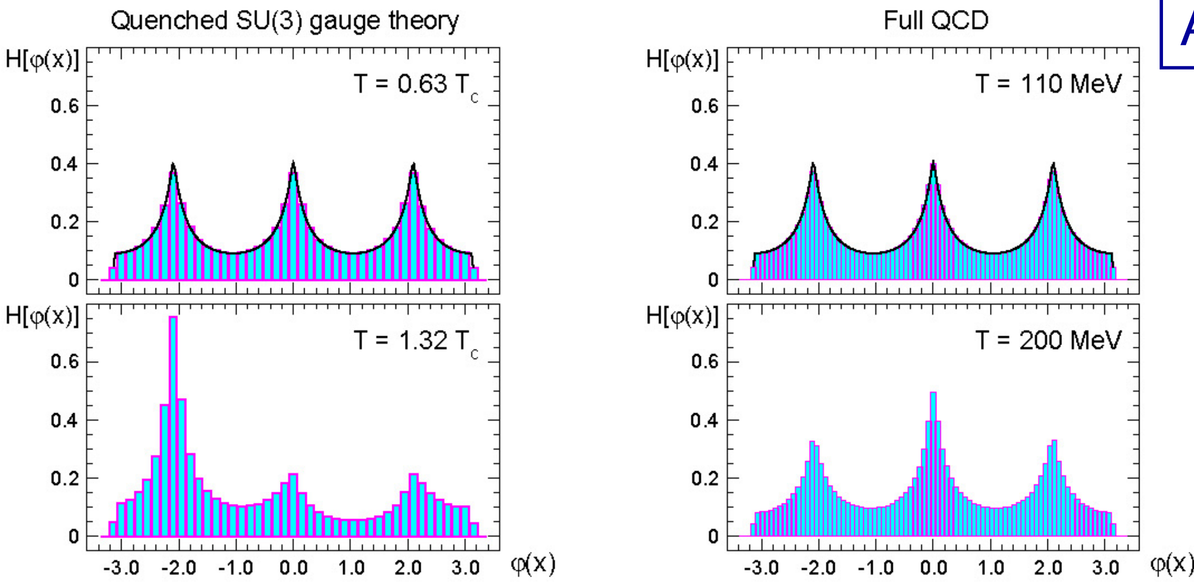
in most lattice calculations, only this L is measured

This depends on the choice of the initial condition

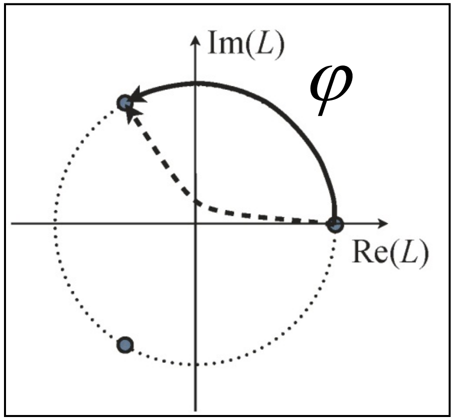
Figure 1: Scatter plots of the spatially averaged Polyakov loop P in the complex plane for configurations below (lhs. panel) and above T_c (rhs.). We show the results for our $40^3 \times 6$ ensembles.

Pure SU(3), Gattringer et al., 2011

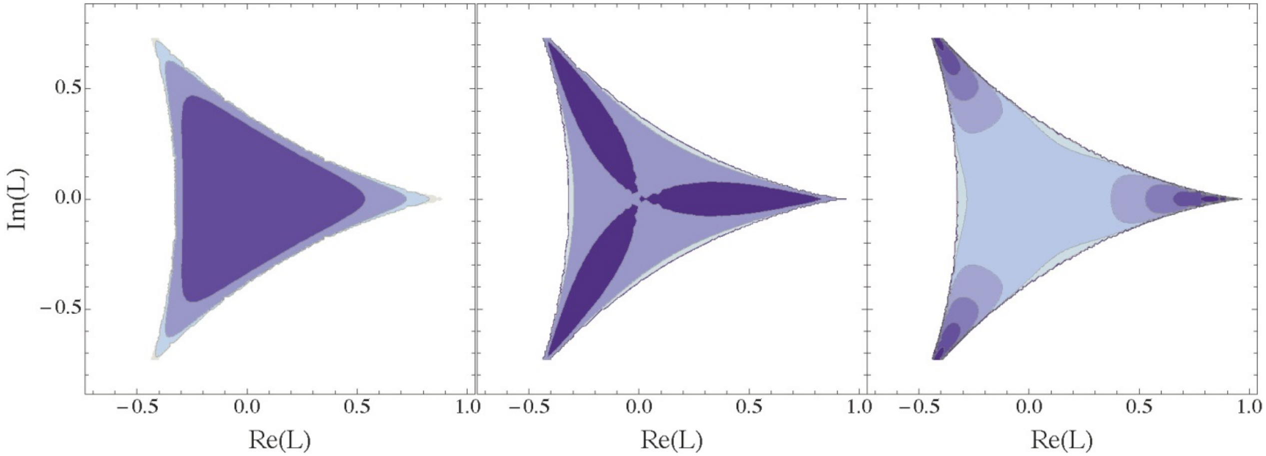
Fluctuation of L in Full QCD



Angle of L on complex plane



Danzer et al, 2010



effective potential used in PNJL

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  Early stage of QGP is dominated by gluons: close to pure gauge

  So, at least in this context,

  not much sense to fuss over, e.g., perturbative correction to
  the pure gauge Polyakov loop potential due to finite quark mass