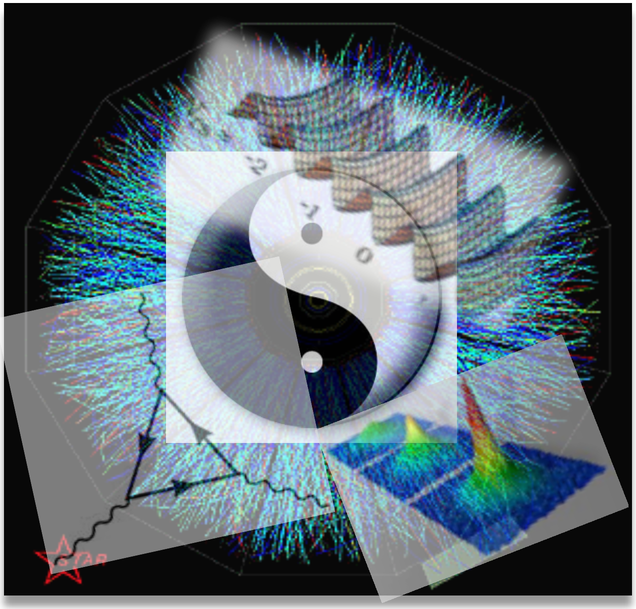
New Frontiers in QCD 2013 @ YITP, Kyoto Japan, DEC.4th, 2013

Strongly Interacting Matter In & Out of Equilibrium



Jinfeng Liao

Indiana University, Physics Dept. & CEEM

RIKEN BNL Research Center

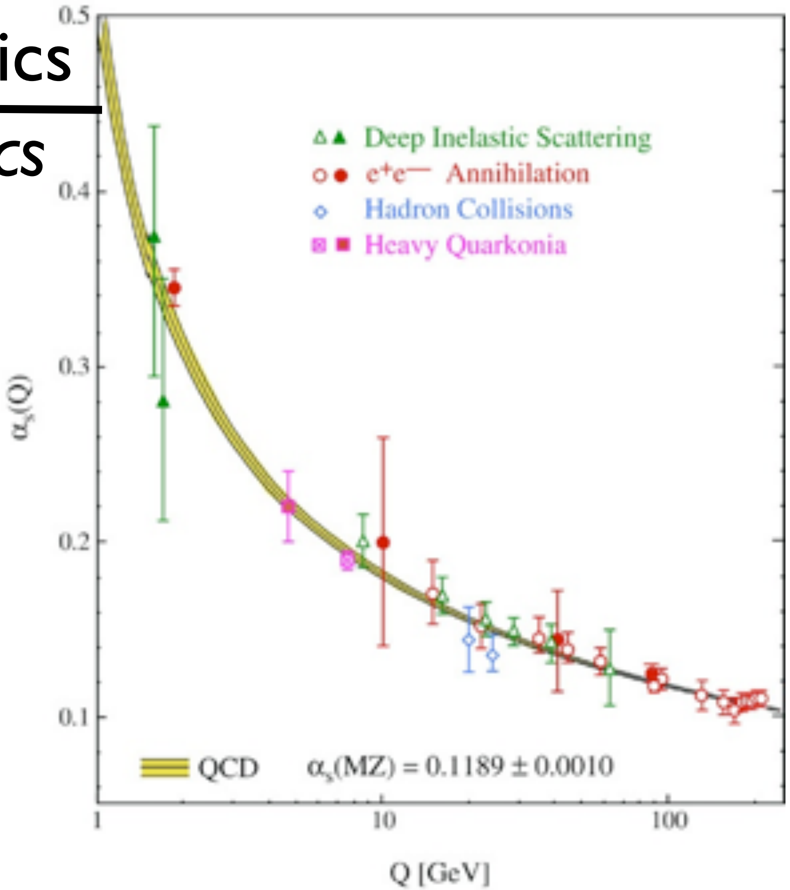
Outline

- Introduction: Strongly Interacting Matter
- Thermal QGP as A Topological Matter
- Thermal QGP as A Chiral Matter
- The Overpopulated Pre-Equilibrium Matter
- Summary & Outlook

40 Years of Asymptotic Freedom

Nuclear Physics

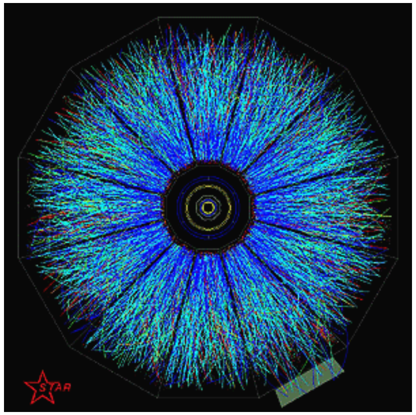
Unclear Physics

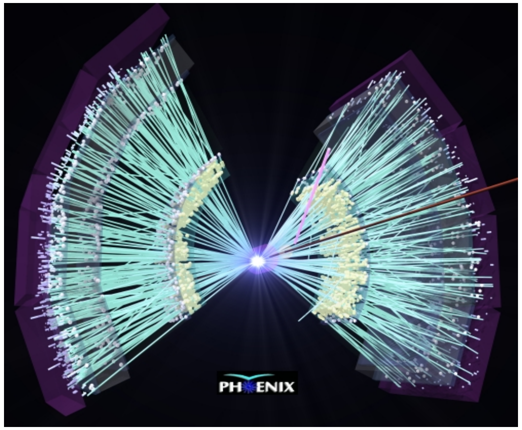


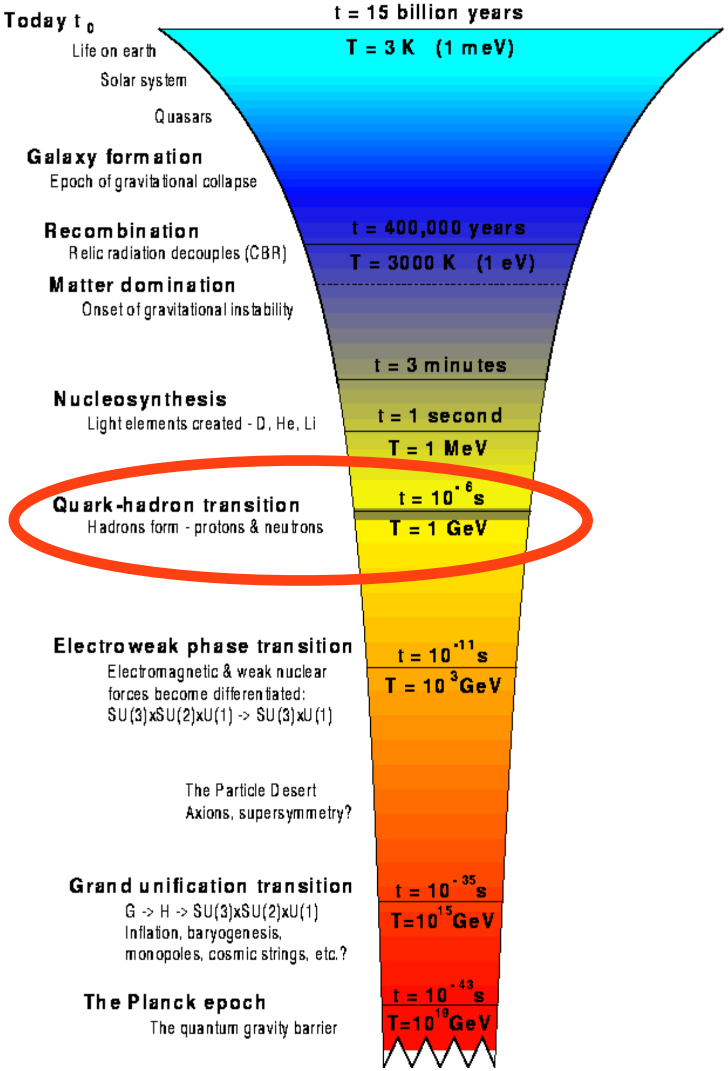
Early ideas for QGP/HIC developed from the notion of asymptotically free matter:

color confined world --> color (fully) liberated world

Beautiful “Little Bangs” Delivered







Today t_0
Life on earth
Solar system
Quasars

Galaxy formation
Epoch of gravitational collapse

Recombination
Relic radiation decouples (CBR)

Matter domination
Onset of gravitational instability

Nucleosynthesis
Light elements created - D, He, Li

Quark-hadron transition
Hadrons form - protons & neutrons

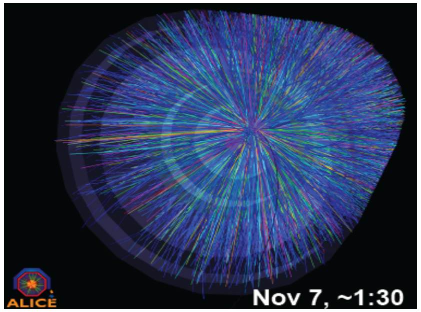
Electroweak phase transition
Electromagnetic & weak nuclear forces become differentiated: SU(3)xSU(2)xU(1) -> SU(3)xU(1)

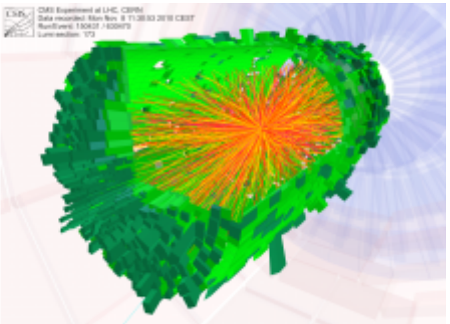
The Particle Desert
Axions, supersymmetry?

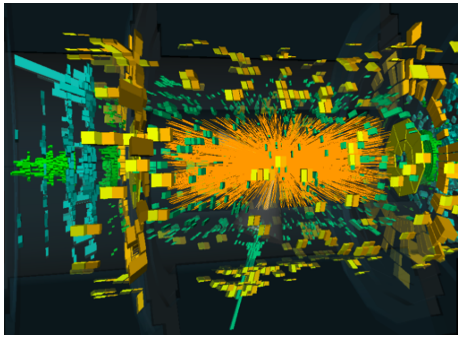
Grand unification transition
G -> H -> SU(3)xSU(2)xU(1)
Inflation, baryogenesis, monopoles, cosmic strings, etc.?

The Planck epoch
The quantum gravity barrier

t = 15 billion years
T = 3 K (1 meV)
t = 400,000 years
T = 3000 K (1 eV)
t = 3 minutes
t = 1 second
T = 1 MeV
$t = 10^{-6}$ s
T = 1 GeV
$t = 10^{-11}$ s
$T = 10^{3}$ GeV
$t = 10^{-35}$ s
$T = 10^{15}$ GeV
$t = 10^{-43}$ s
$T = 10^{19}$ GeV

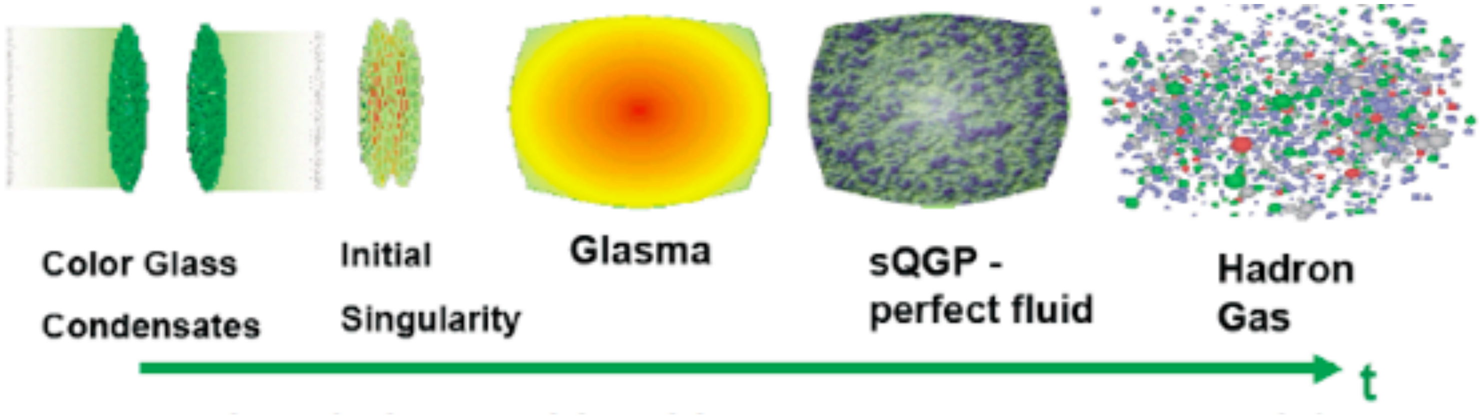


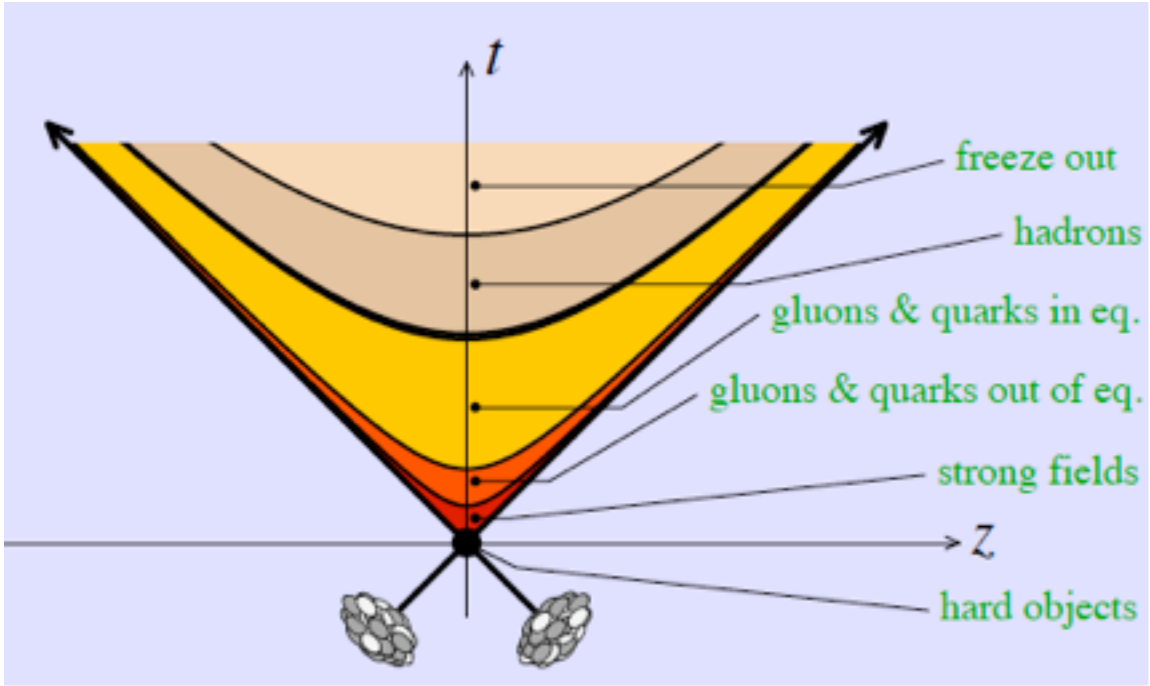




Heavy Ion Collision: the only “Time Machine”
to trace back the matter in early cosmos environment

Different Stages of Heavy Ion Collisions

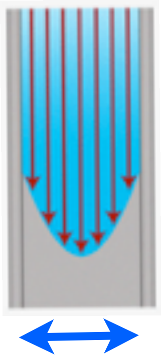




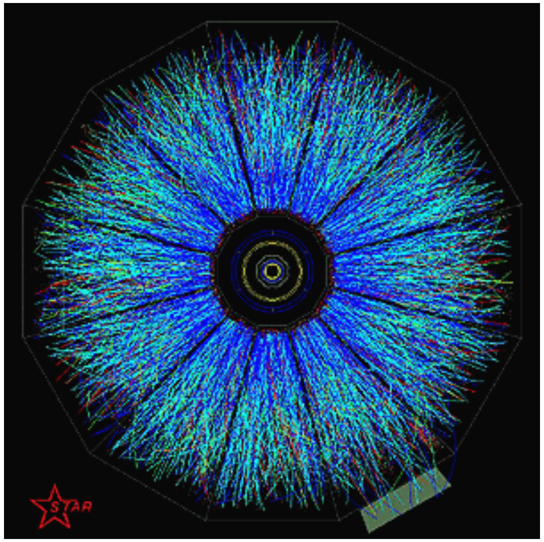
Probing
matter properties:
thermal
&
near thermal
(transport)
&
far-from thermal

The Strongly Interacting Matter

A nearly perfect fluid
able to flow through
fermi-scale “pipe”



~ *fermi*



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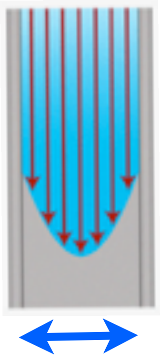

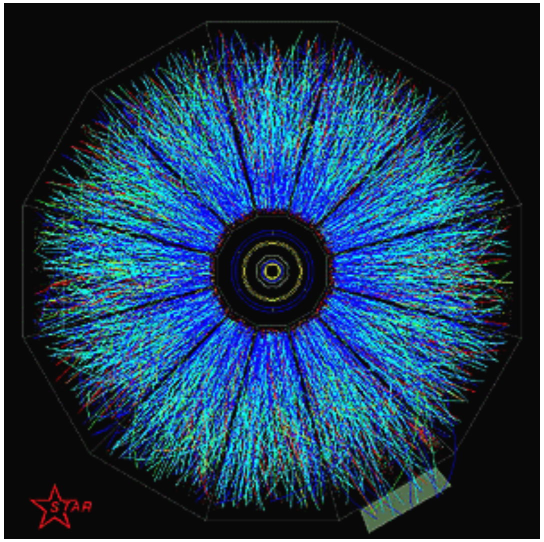

A dense partonic matter opaque to high energy color probe

The Strongly Interacting Matter

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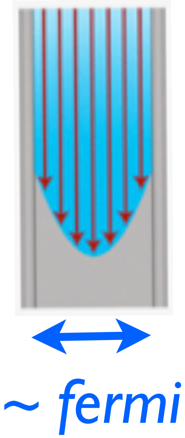

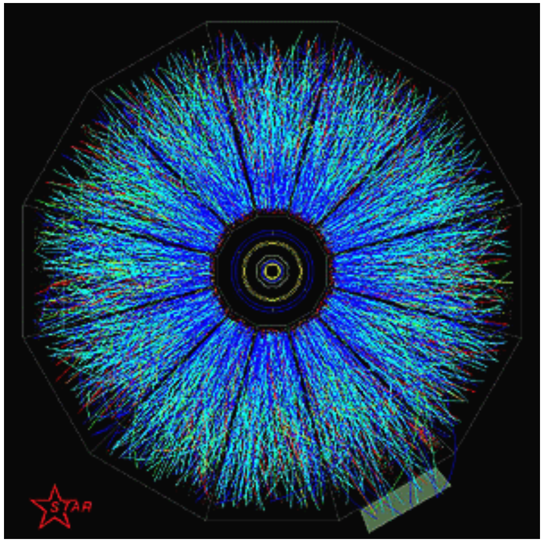

A dense partonic matter opaque to high energy color probe

A pre-equilibrium matter that quickly relaxes toward equilibrium like a very stiff spring

The Strongly Interacting Matter

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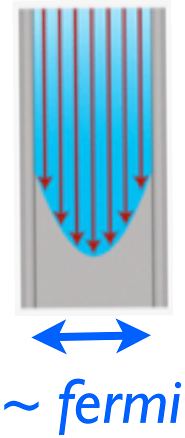
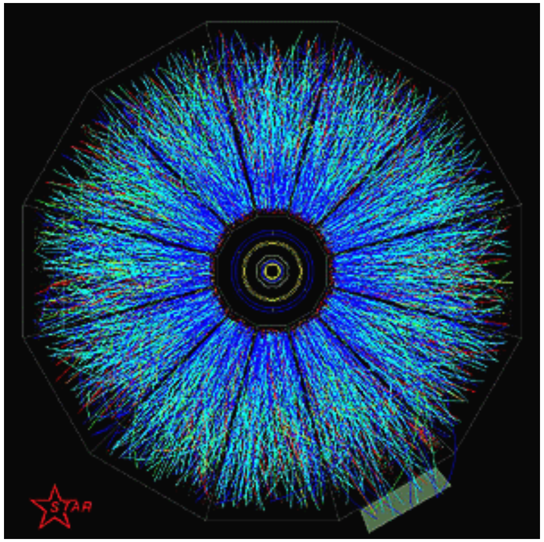


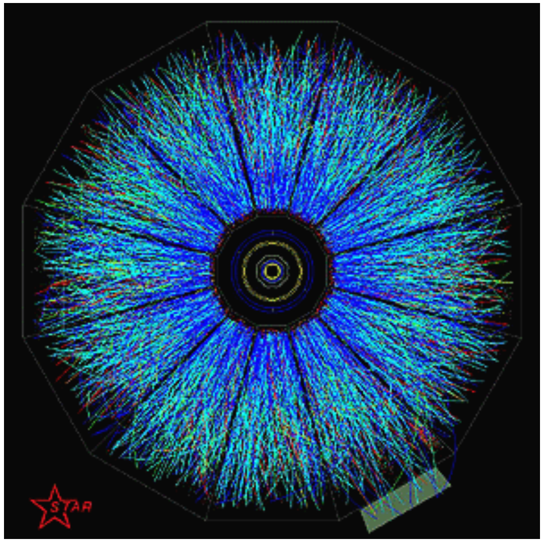


A dense partonic matter opaque to high energy color probe

A pre-equilibrium matter that quickly relaxes toward equilibrium like a very stiff spring

Strongly interacting matter created & measured in heavy ion collisions: a unique laboratory for understanding how QCD operates in Nature.

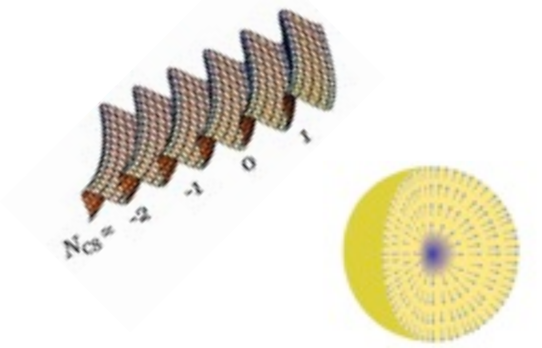
The Strongly Interacting Matter

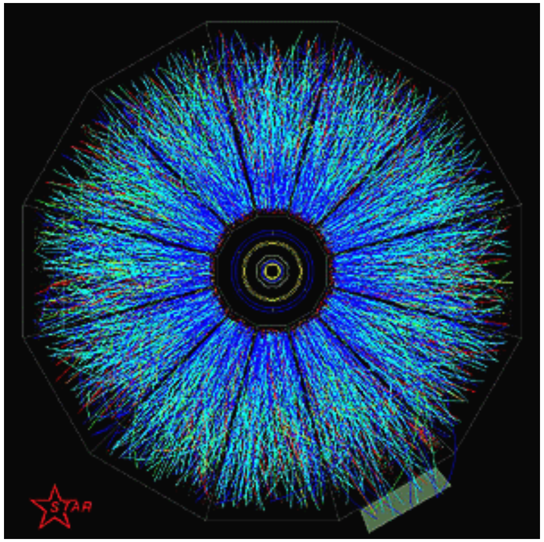


This talk will discuss some of our recent progress in understanding the structure & dynamics of this strongly interacting matter in light of its measured properties.

The Strongly Interacting Matter

A Topological Matter





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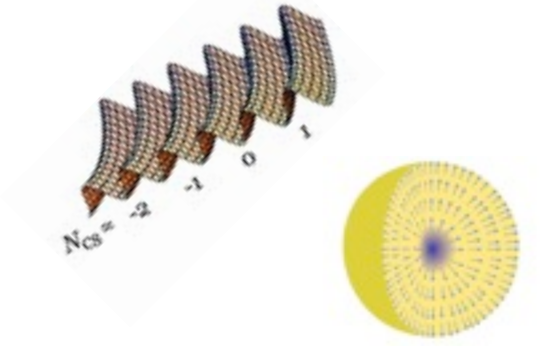
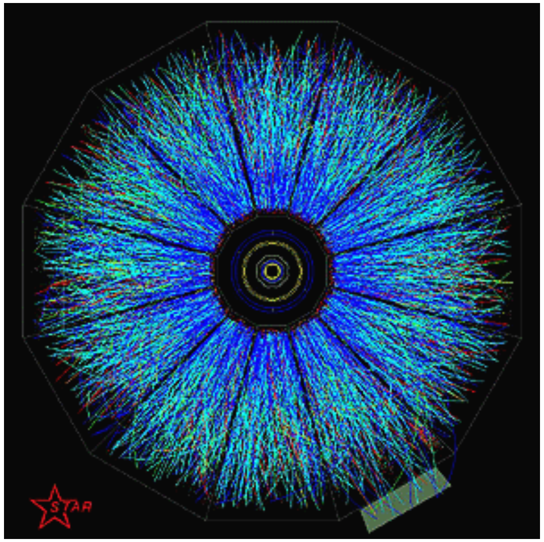
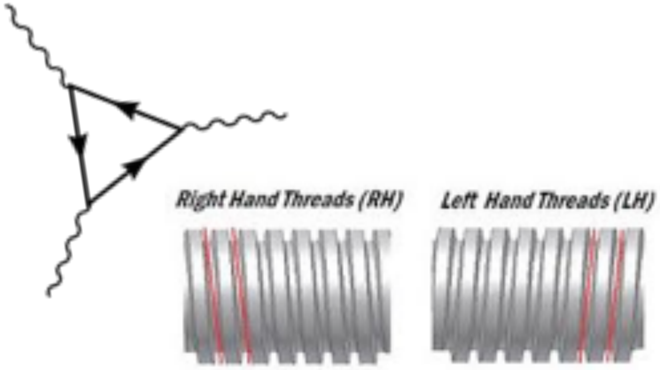




A Chiral Matter



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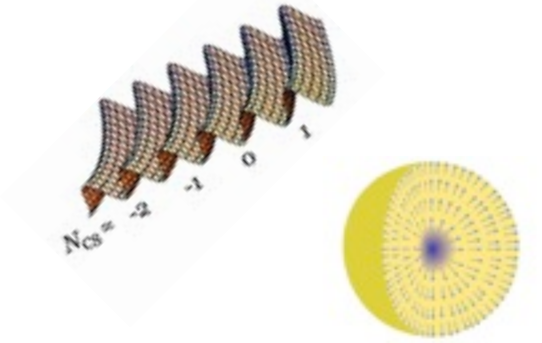
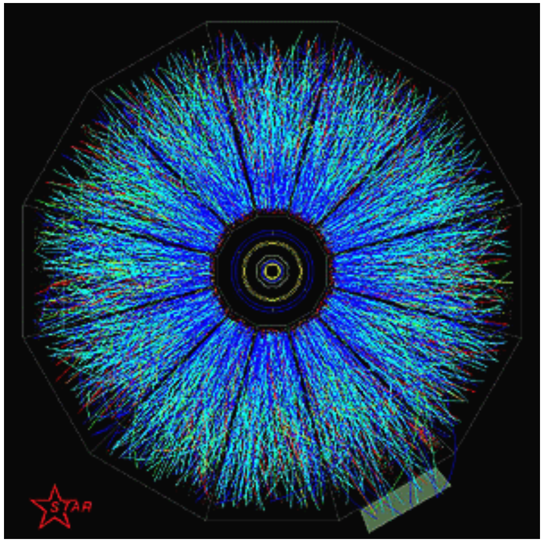
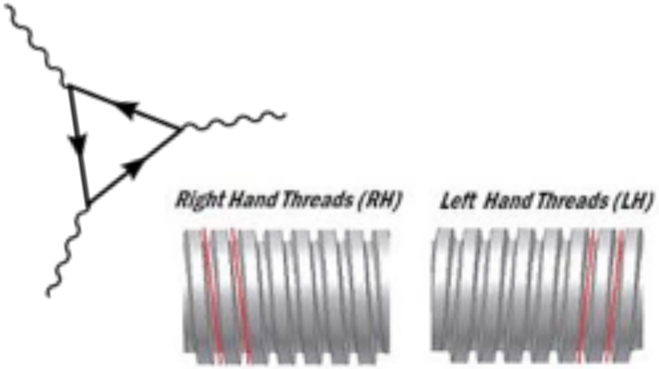
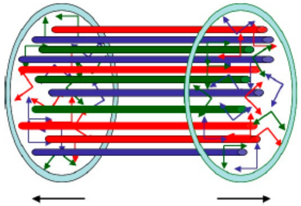


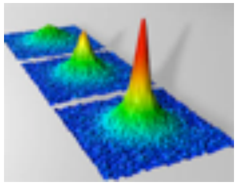


A Chiral Matter



An Overpopulated Pre-Equilibrium Matter





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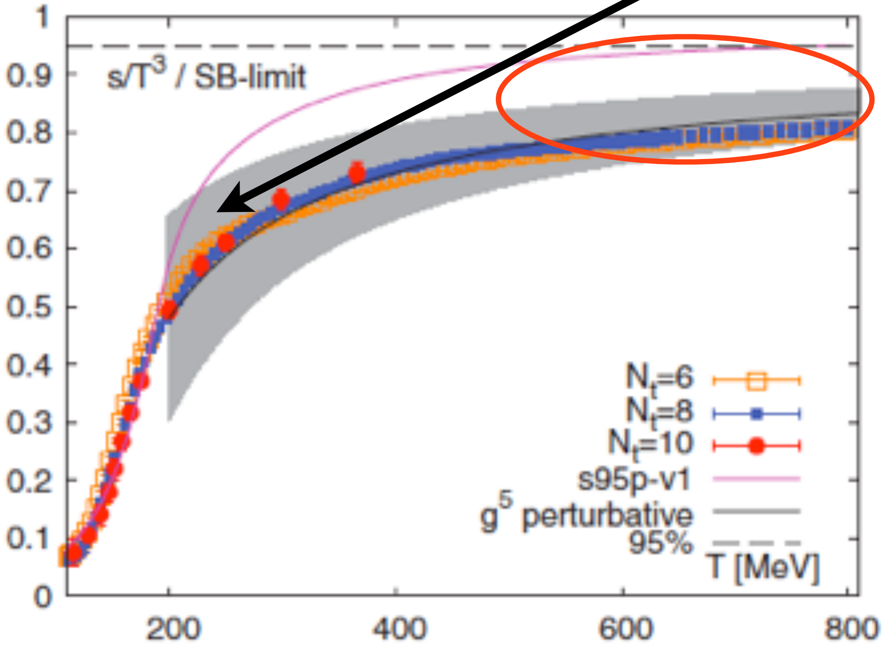
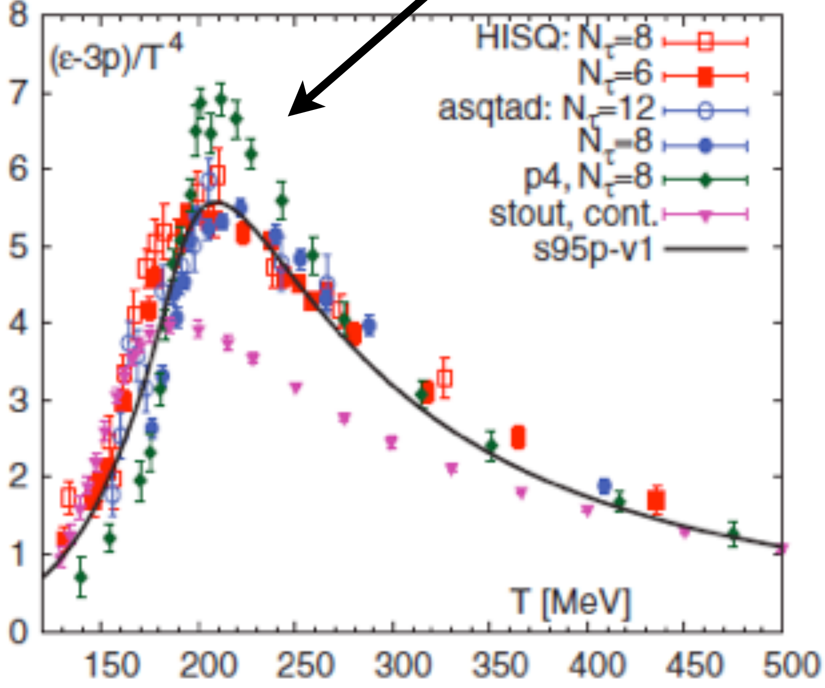
THERMAL QGP AS A TOPOLOGICAL MATTER

Hot off the Lattice: **Crossover**, but **Rapid**



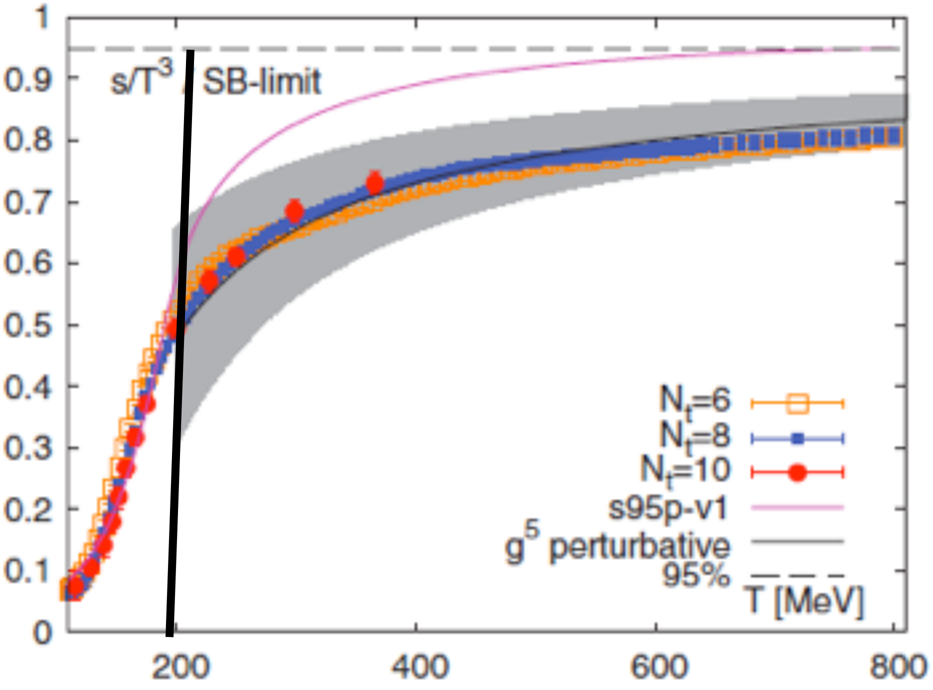


"Rapid Up" or "Rapid Down":
pressure/energy density/entropy density/
2-nd q-susceptibilities/
chiral condensate/Q-bar-Q free energy/...

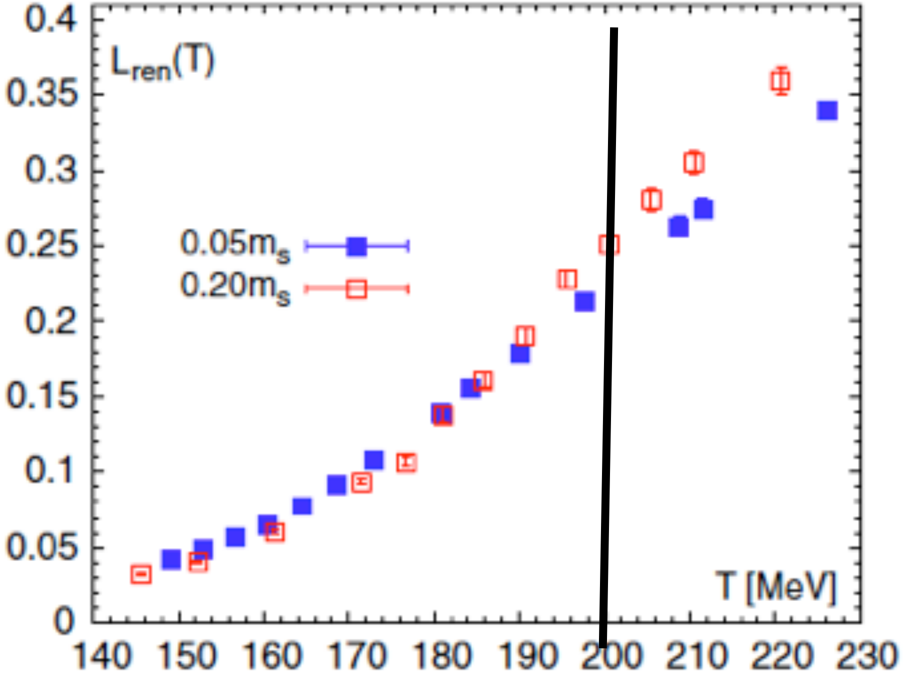
"Peak" or "Dip":
trace anomaly/chiral susceptibility/
4-th q-susceptibilities/
Q-bar-Q internal energy/
speed of sound//...

Liberation of Color?

Degrees of freedom



Degree of color liberation



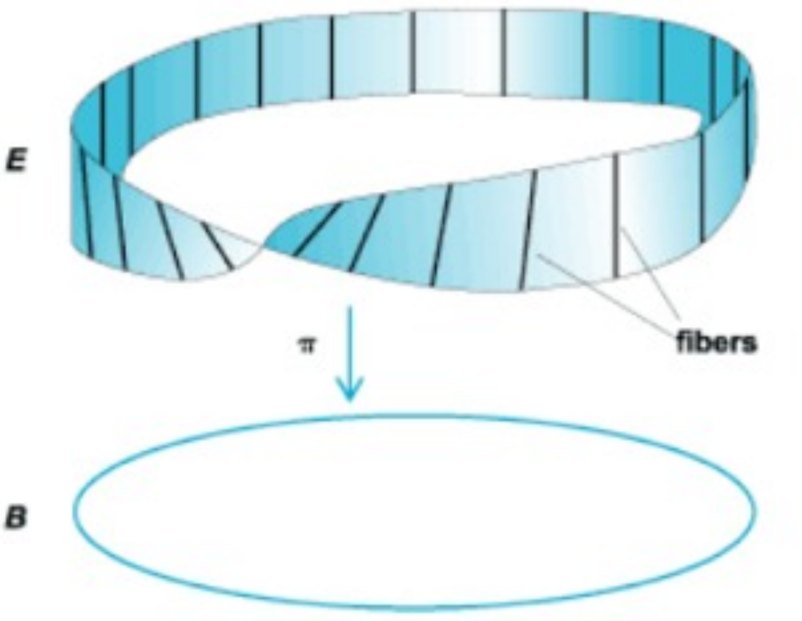
A region around Tc with liberated degrees of freedom but only partially liberated color-electric objects.

(Pisarski & collaborators: semi-QGP --- **glue~L^2, quark~L**)

Then what are the "extra" dominant DoF here???

To answer this, we need the topological objects.

GAUGE THEORY & TOPOLOGY



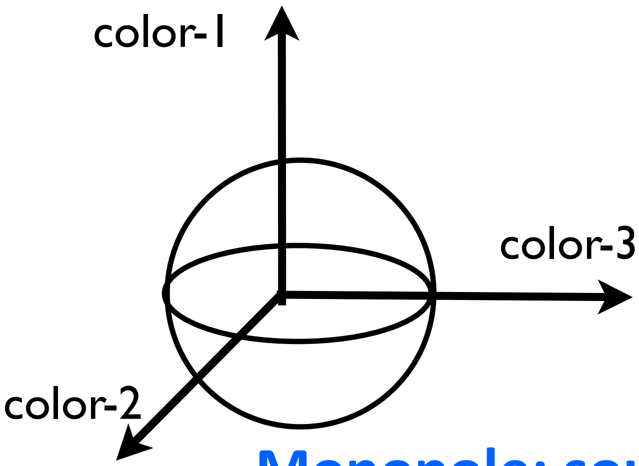
Möbius strip, the simplest nontrivial example of a fiber bundle

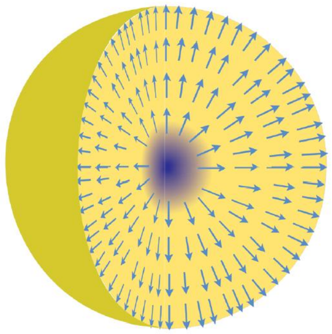
Embedding gauge group (color-)space across space-time

→ nontrivial topological structure

(instantons, sphelarons, monopoles,…)

EMERGENT D.O.F. AT STRONG COUPLING





$$q_{mag} = 1/g$$

$$M_{mag} \sim \frac{v}{g}$$

Monopole: source of long range color-magnetic field;
They become light and weakly coupled at strong gauge coupling!

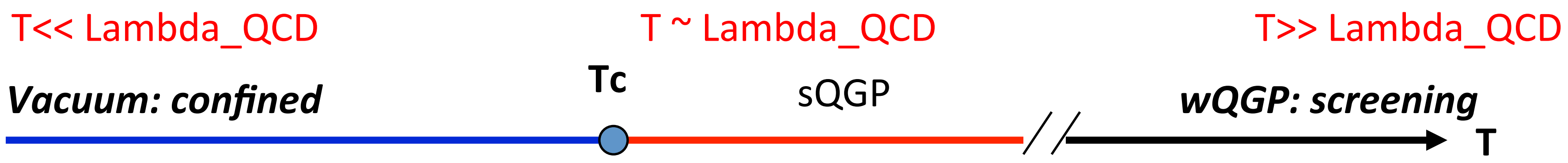
Dirac (1931): gauge invariance & quantum mechanics
--> Dirac quantization condition

$$\boxed{\alpha_E * \alpha_M = 1.}$$

Motonen & Olive (1977); Seiberg-Witten (1994):
Electric-Magnetic Duality

E weakly coupled: theory in terms of E language;
E strongly coupled: theory better described by emergent M-D.o.F.

Emergent Magnetic Plasma Near Tc



T<< Lambda_QCD

T ~ Lambda_QCD

T>> Lambda_QCD

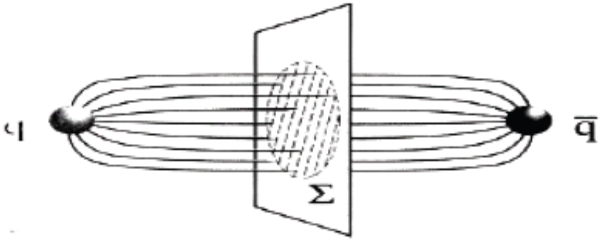
Vacuum: confined

Tc

sQGP

wQGP: screening

T



Emergent plasma with <u>E & M</u> charges:

chromo-magnetic monopoles are the “missing DoF”

Plasma of E-charges

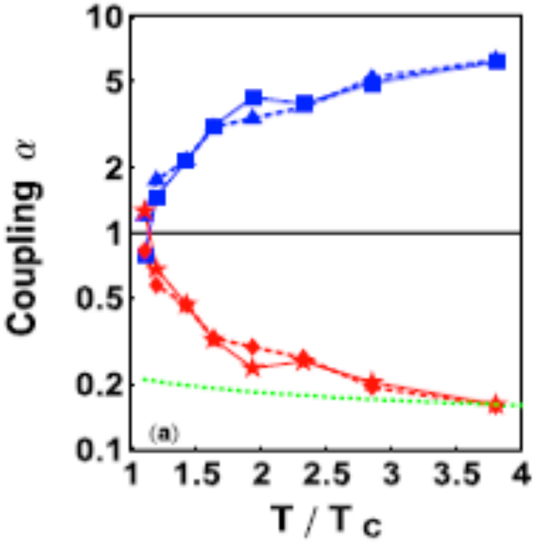
E-screening: g T

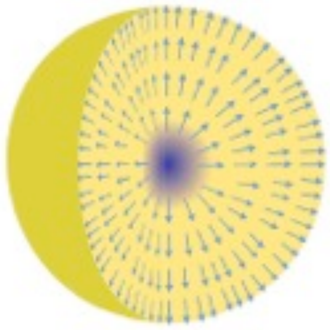
M-screening: g^2 T

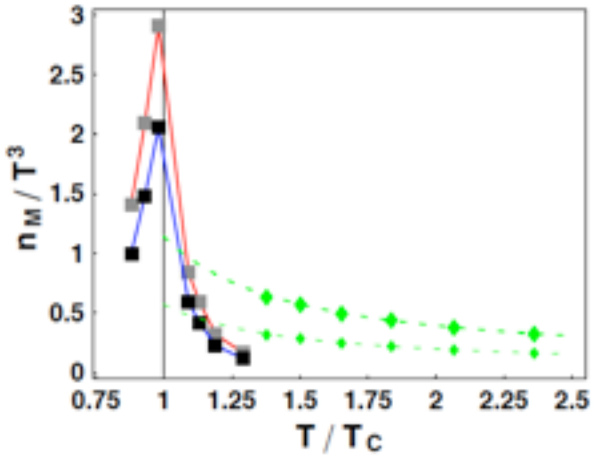
Electric Flux Tube:

Magnetic Condensate

$$\alpha_E * \alpha_M = 1.$$



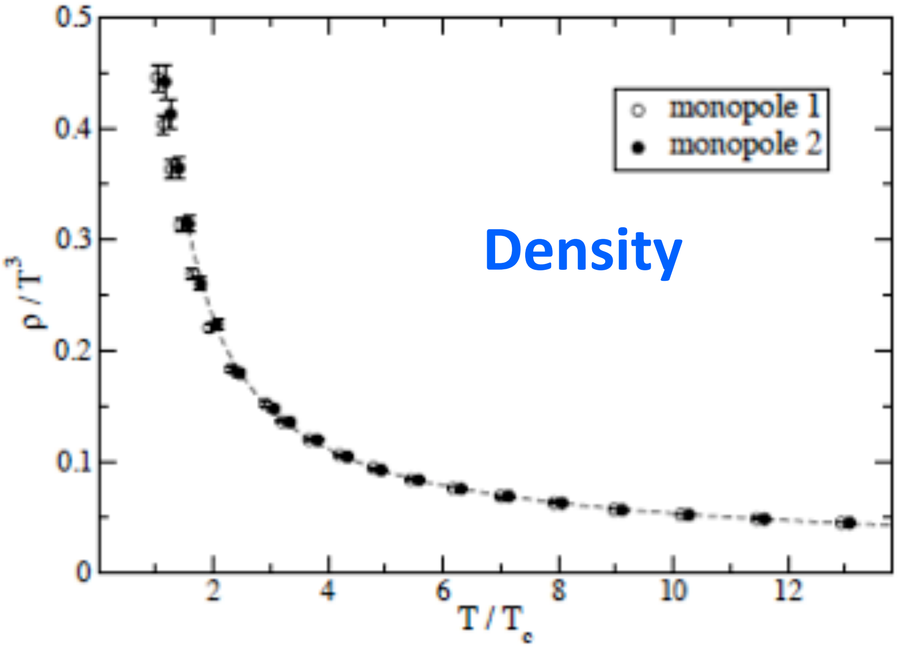




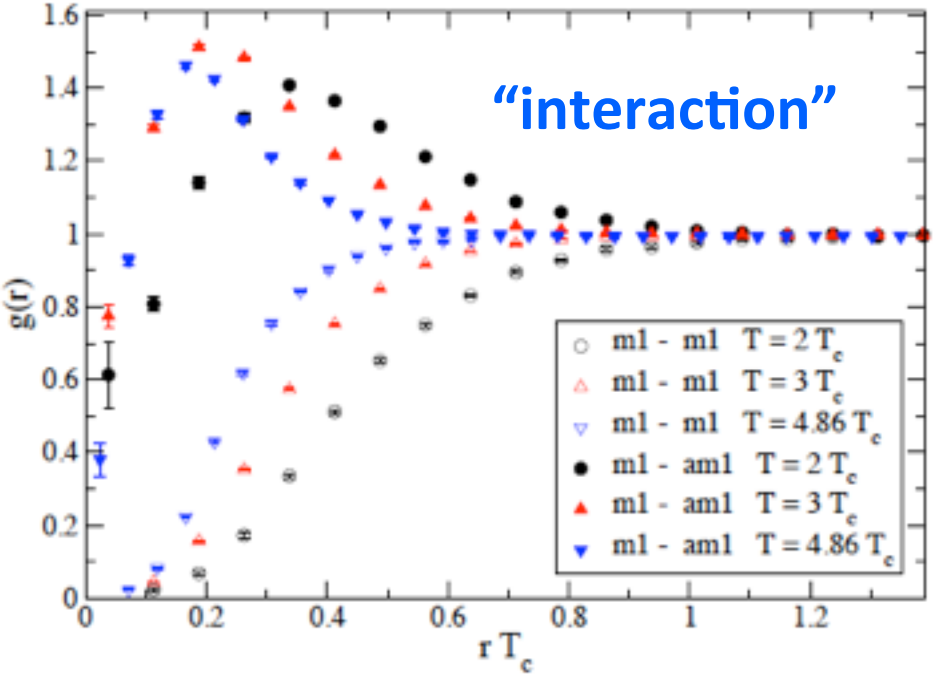
JL & Shuryak:

Phys.Rev.C75:054907,2007; Phys.Rev.Lett.101:162302,2008; Phys.Rev.C77:064905,2008; Phys.Rev.D82:094007,2010; Phys.Rev.Lett.109:152001,2012.

Most Recent Lattice Evidence



Density



"interaction"

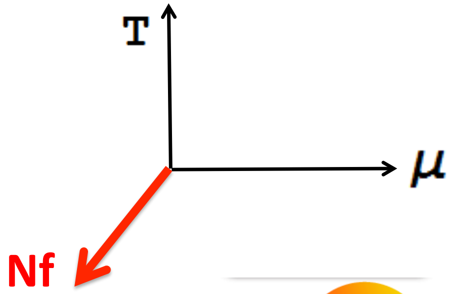
for SU(3) pure gauge theory

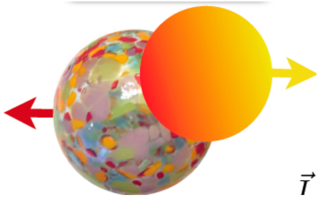
Bonati & D'Elia, arXiv:1308.0302[hep-lat]

CONFINEMENT AS BEC OF MONOPOLES

The magnetic scenario helps explain many aspects of near-Tc plasma. Let us here focus on very important issue: confinement transition.

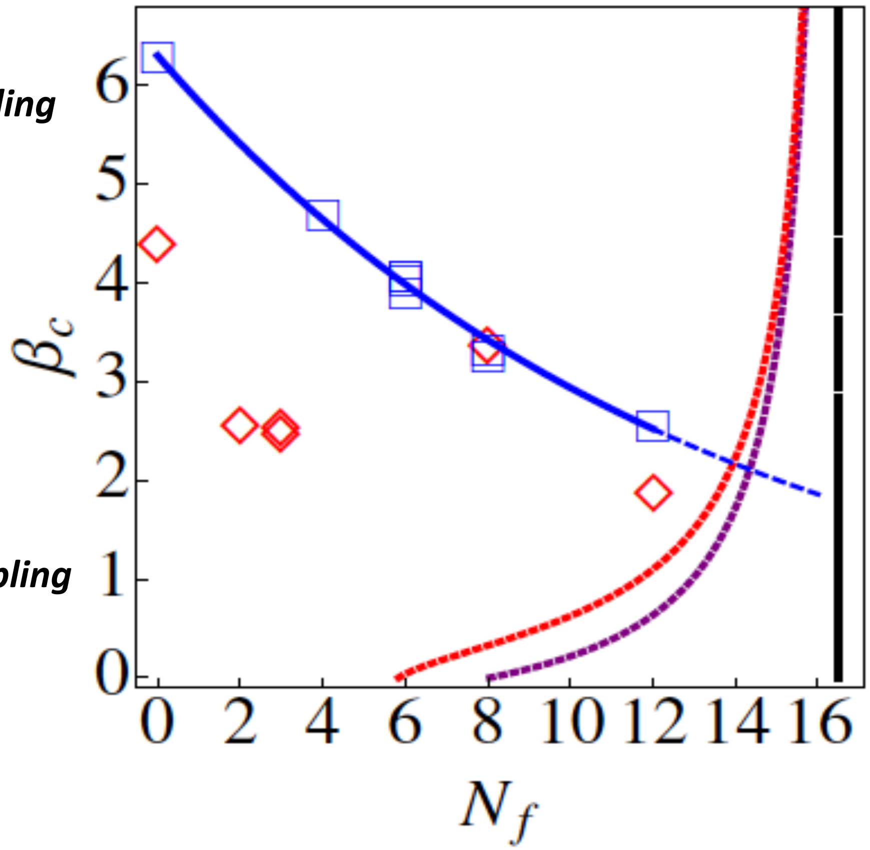
How the confinement transition changes with light flavor number?





Weaker coupling

Stronger coupling



$$\beta_c(N_f) = \beta_0(1+f)^{-8N_fN_M/15}$$

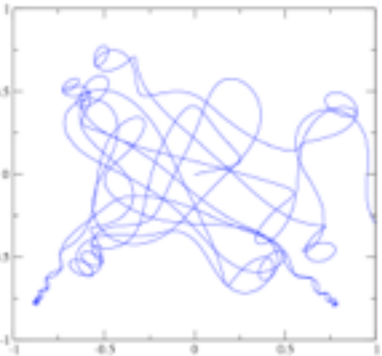
$$f \approx 0.154$$

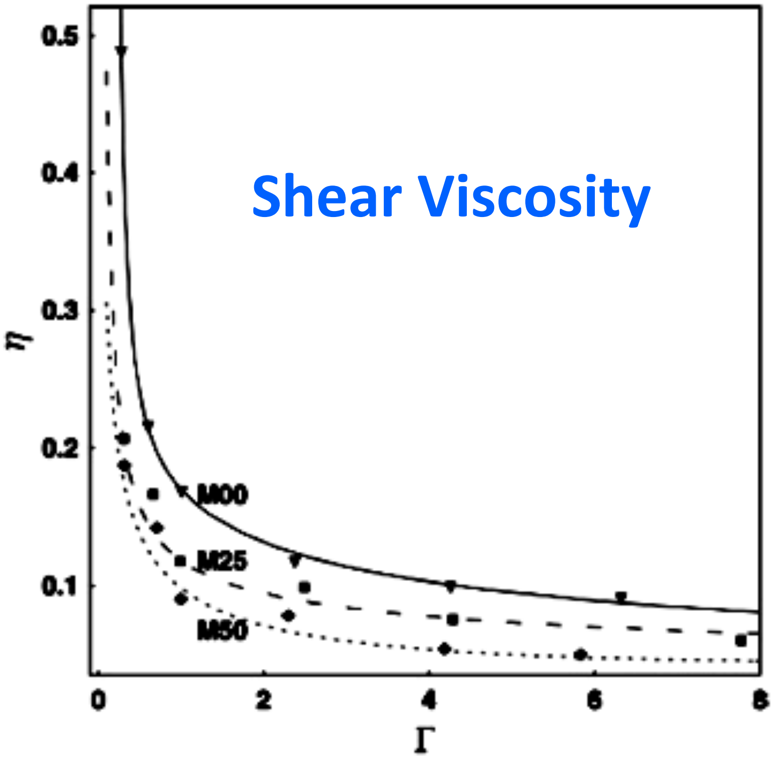
JL & Shuryak, PRL2012

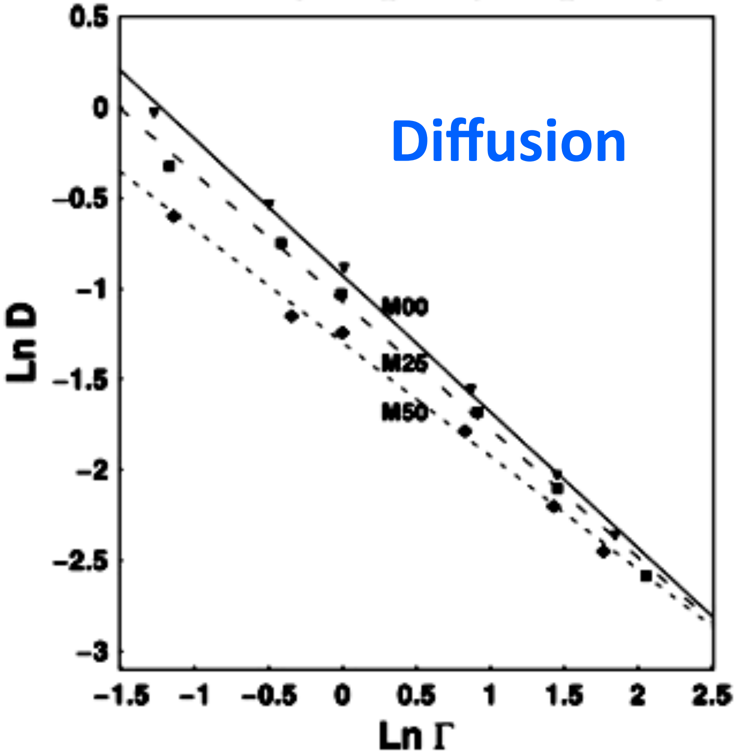
Low Shear Viscosity of E-M Plasma

We first studied the plasma of a completely new kind:
Coulomb-Lorentz Plasma!

Molecular Dynamics for 1000 particles with long range forces for varying E/M ratio:
pure electric ; 25% magnetic charges ; 50% magnetic charges

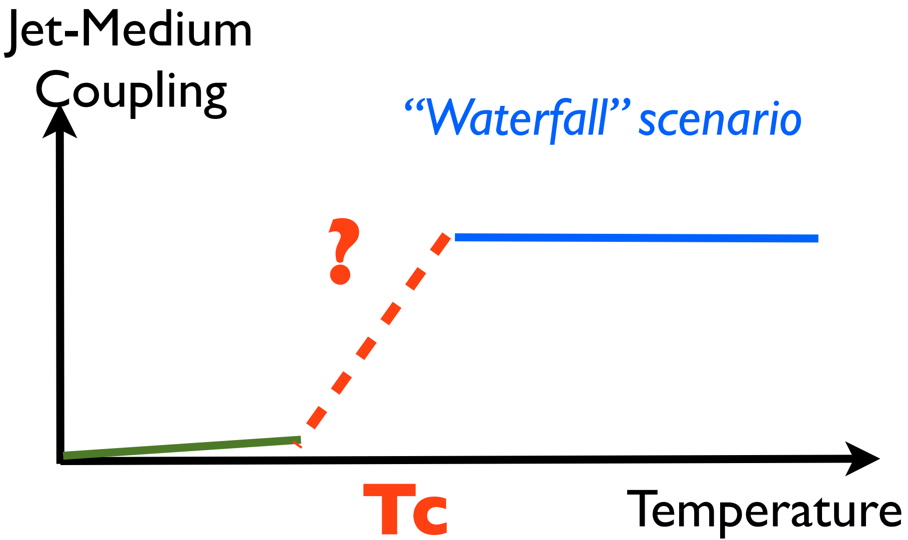


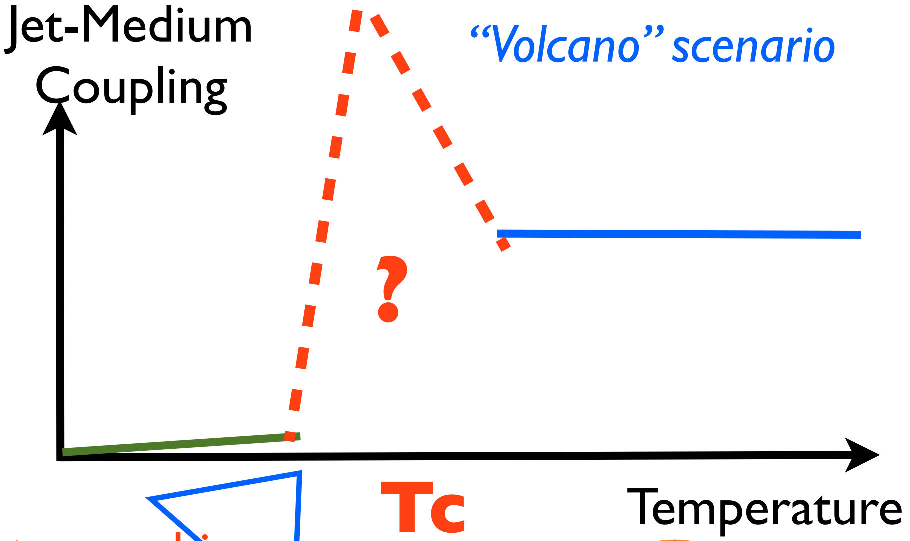




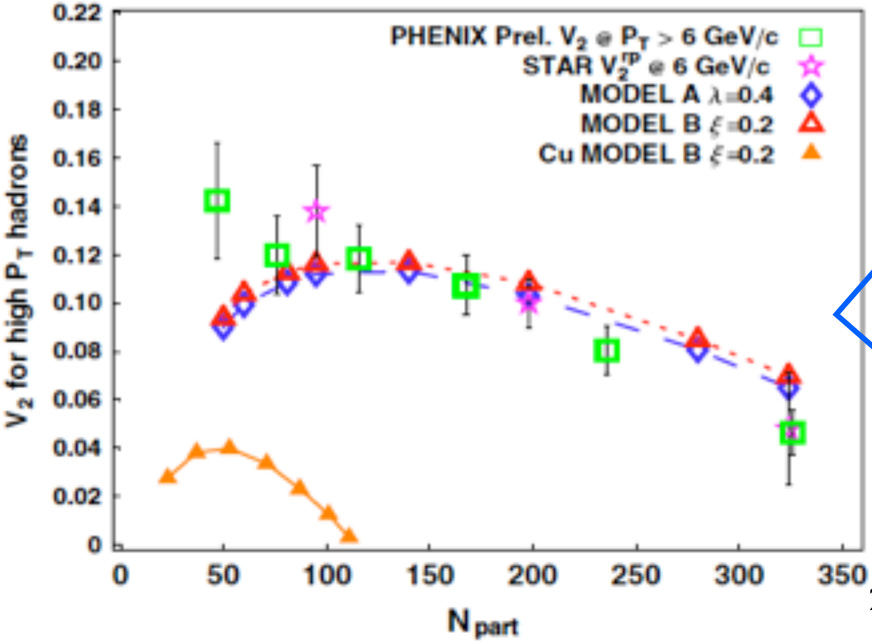
A mixture of E&M charges help explain the observed transport properties.

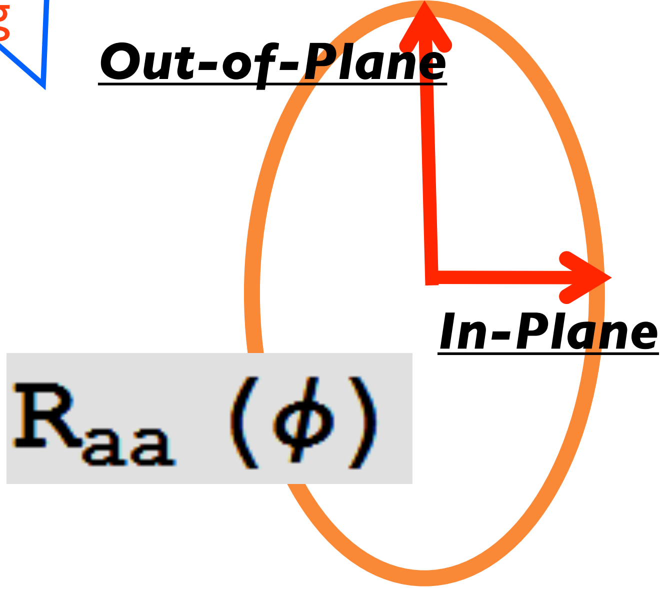
Strong Near-Tc Jet Quenching





a fundamental question for understanding of jet-quenching





$R_{aa}\ (\phi)$

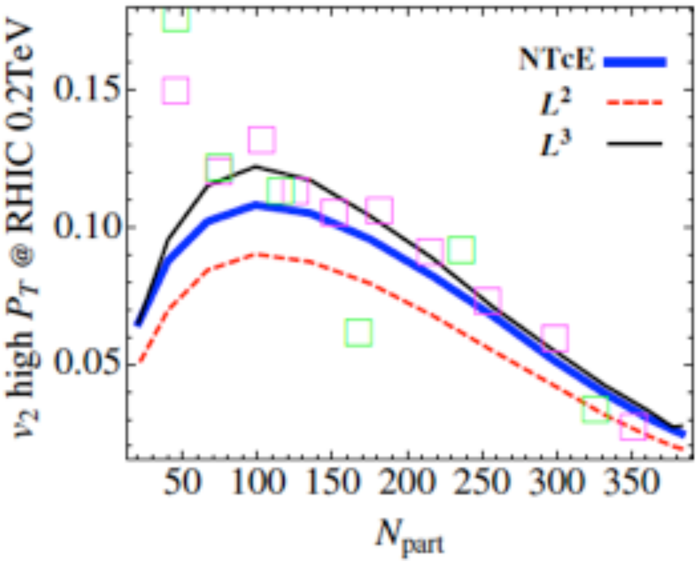
JL & Shuryak, PRL(2009); JL, arXiv:1109.0271

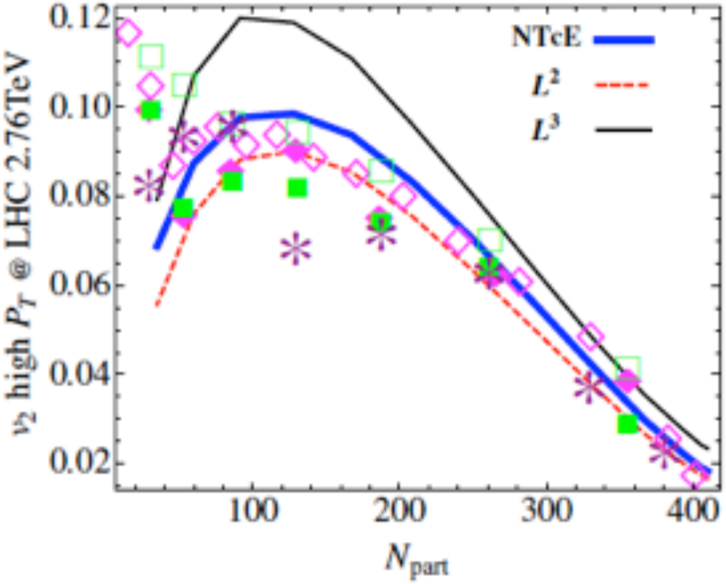
Hard Probe from RHIC to LHC

Opaqueness evolution from RHIC to LHC

$$\boxed{< \kappa >_{\mathrm{RHIC}} : < \kappa >_{\mathrm{LHC}} \approx 1 : 0.72}$$

Hard probe of geometry & fluctuations with RHIC + LHC data





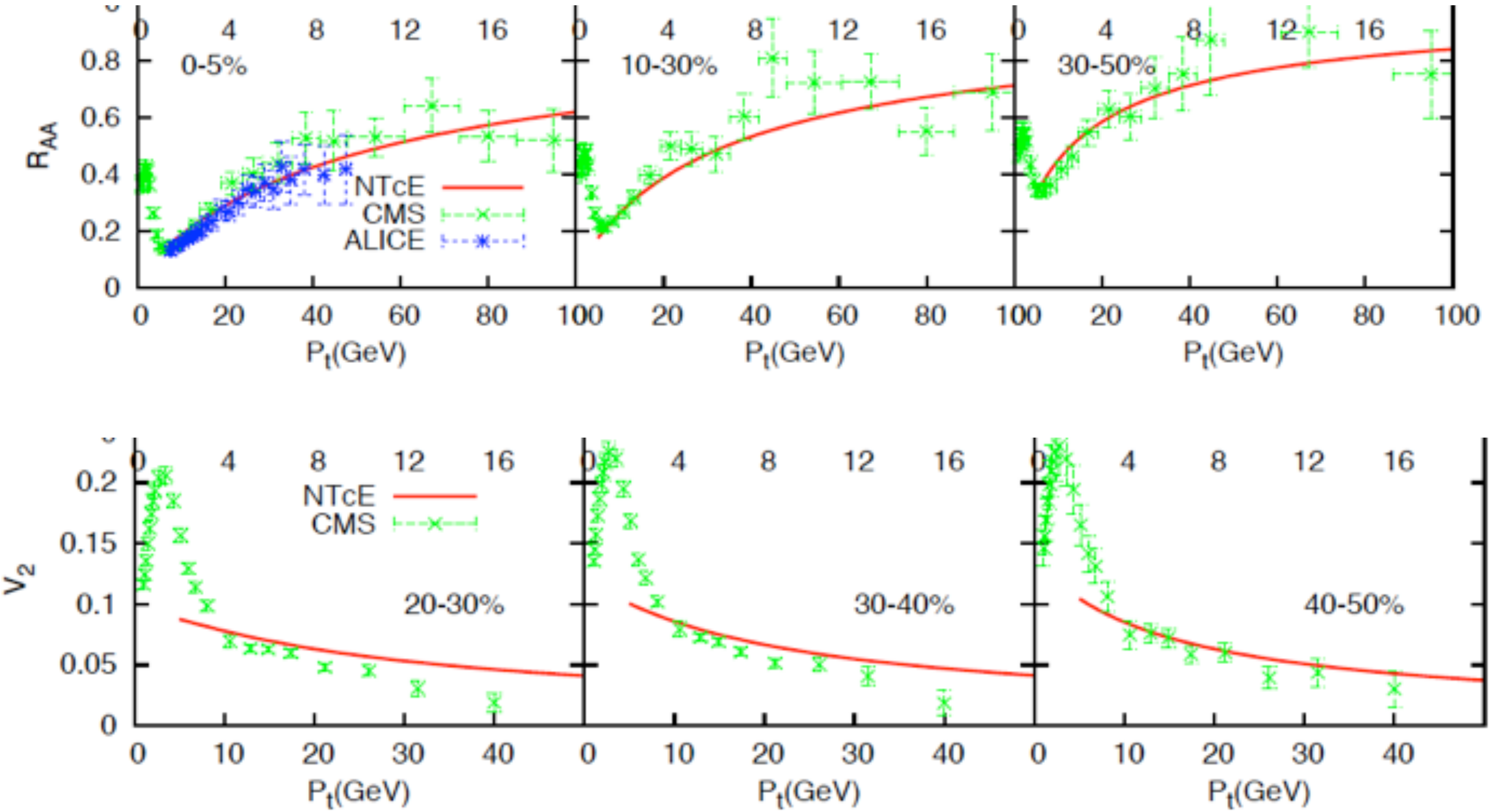
Opaqueness + Responses to Geo. & Fluc. with RHIC+LHC: in favor of strongly enhanced near-Tc jet quenching

X.Zhang & JL, PLB(2012), arXiv:1208.6361,1210.1245(PRC2013)

The P_t Dependence

RHIC: rather flat in both data and calculations (see reference below for details)

LHC: strong p_t dependence, so it is important to implement it in modelings



X.Zhang & JL, arXiv:13 11.5463

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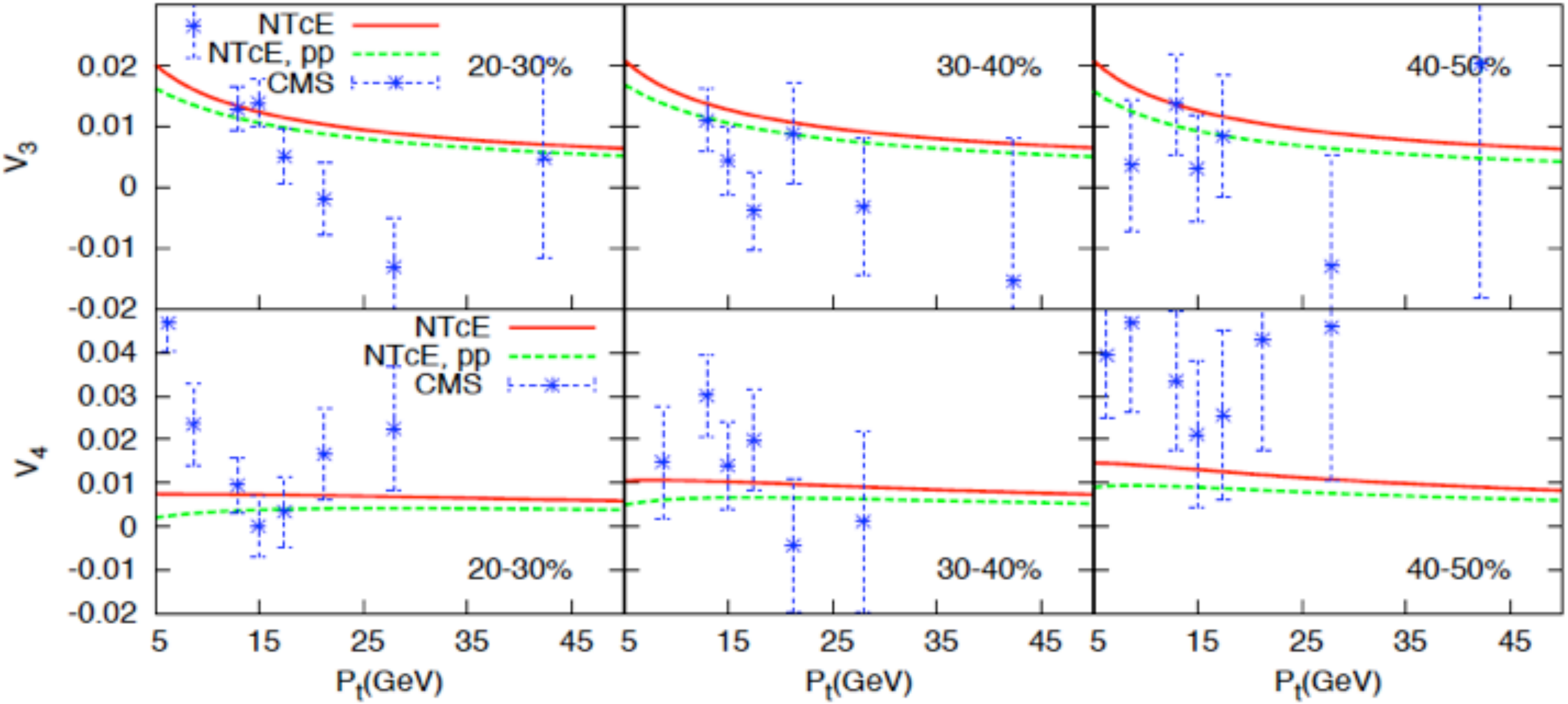
RHIC: rather flat in both data and calculations (see reference below for details)

LHC: strong p_t dependence, so it is important to implement it in modelings



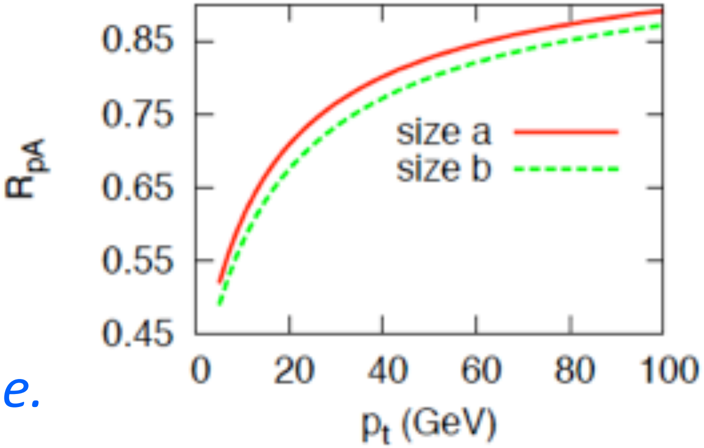
X.Zhang & JL, arXiv:13 11.5463

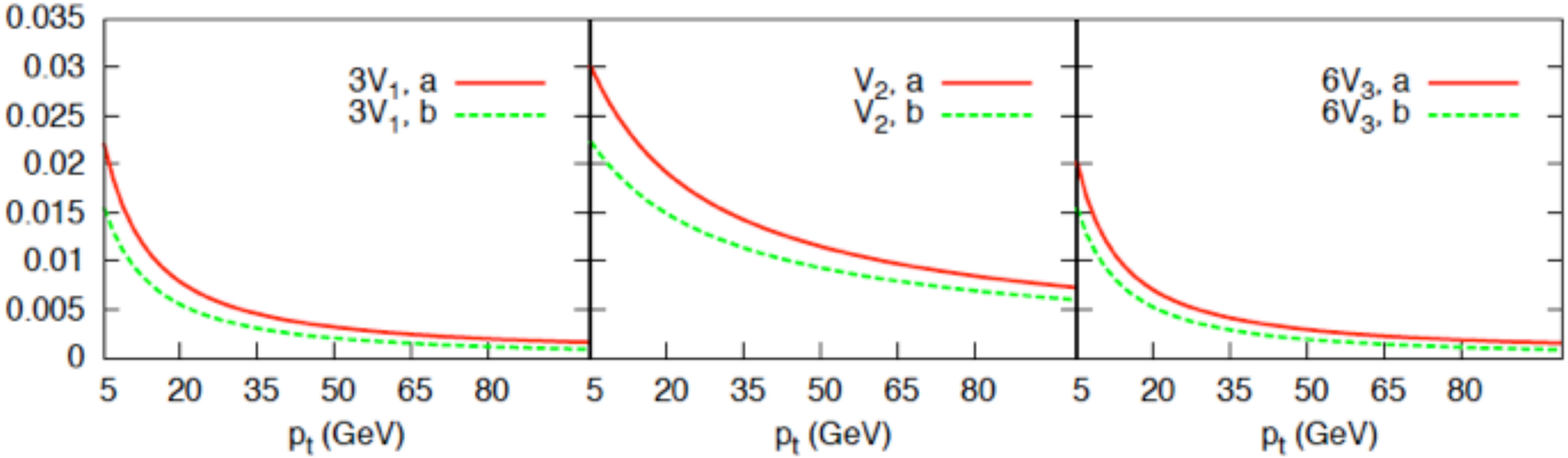
Final State Attenuation in the Mini-Bang?

High multiplicity pPb collisions at LHC (and dAu at RHIC) have generated significant interests recently:

Are they "Mini-Bangs" creating matter with significant final state interactions?

Possible jet attenuation is an independent probe.





R_pA itself could be rather tricky!

High p_t anisotropy, particularly v_2 could be a golden signal!

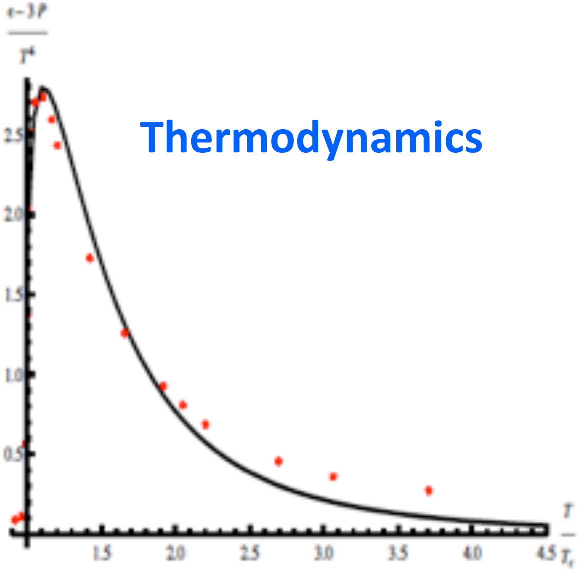
X.Zhang & JL, arXiv:13 11.5463

Non-Conformal Dynamics in Jet Quenching

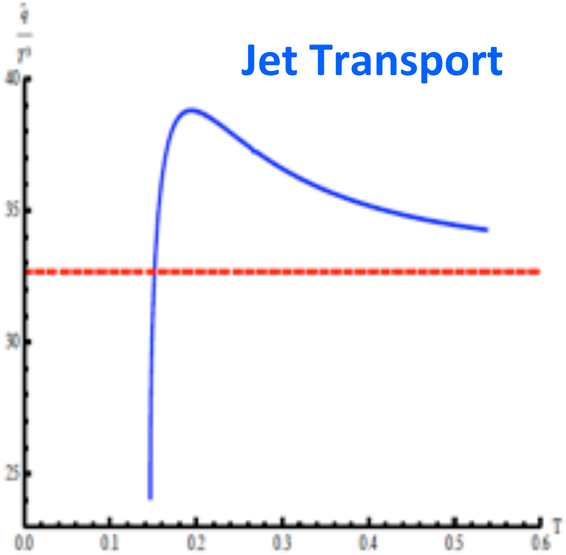
Use holographic model to reveal the non-formal dynamics in thermo & transport properties of sQGP

$$S = \frac{1}{16\pi G_5}\int d^5x\sqrt{-g}e^{-2\Phi}(R + 4\partial_M\Phi\partial^M\Phi - V(\Phi))$$

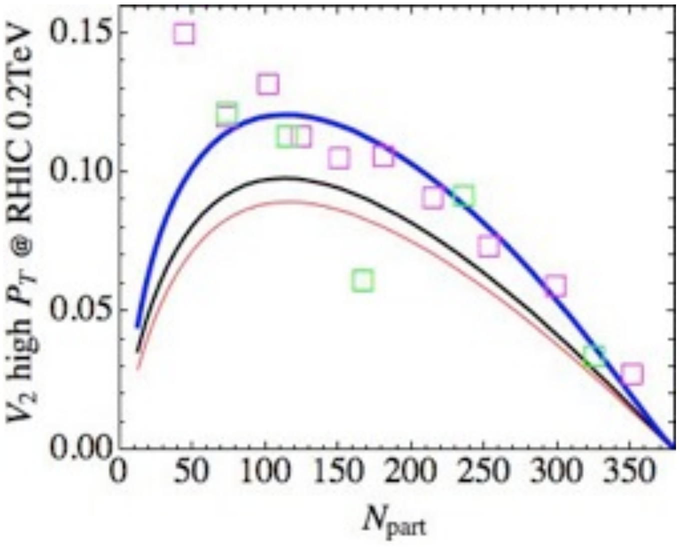
a specific extension of soft-wall Ads/QCD model (Mei Huang & Danning Li)



Thermodynamics



Jet Transport

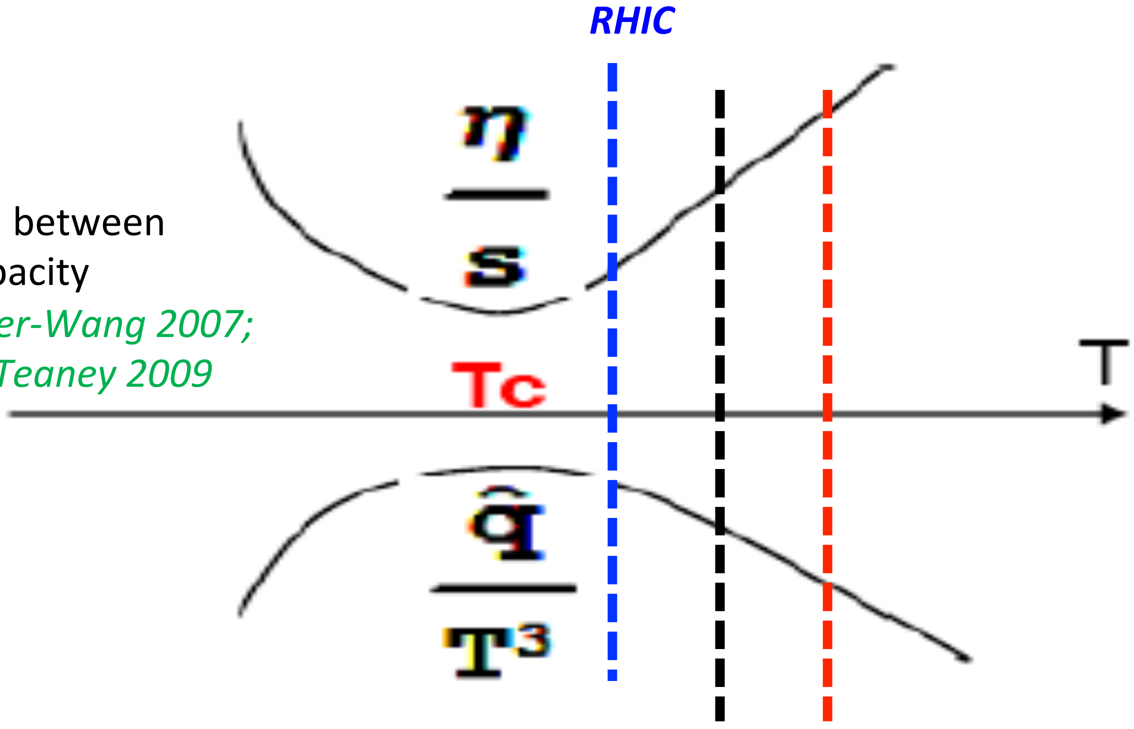


Same non-conformal, non-monotonic, non-perturbative dynamics
--- shows up in trace anomaly and in jet transport parameter
---- increases jet anisotropy in response to geometry

Mei Huang, Danning Li, JL, in preparation.

FROM TALK @ DNP2011

QUENCHING & VISCOSITY LINKED-UP: FROM NEAR TC TO HIGHER T



Inverse relation between viscosity and opacity
Majumder-Muller-Wang 2007;
Dusling-Moore-Teaney 2009

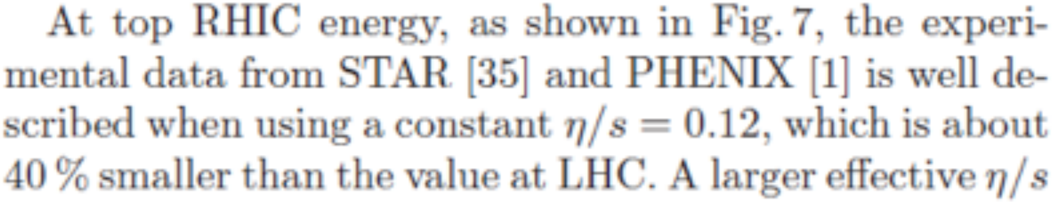
LHC: 2.76 → top energy?!

Will we see a systematic deviation from RHIC to LHC?

The "see-saw"-QGP expects such a picture to occur in a narrow regime 1-4Tc.

At Work From RHIC to LHC

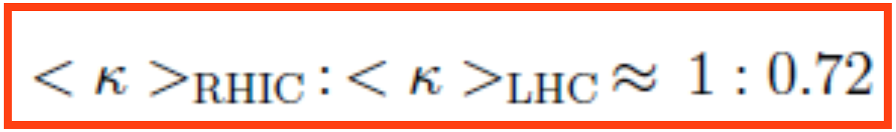
* Harmonic flows from RHIC to LHC:
hydro simulations suggest a clear increase of ~40% in eta/s


At top RHIC energy, as shown in Fig. 7, the experimental data from STAR [35] and PHENIX [1] is well described when using a constant $\eta/s = 0.12$, which is about 40 % smaller than the value at LHC. A larger effective η/s

Gale,Jeon,Schenke,Tribedy,Venugopalan
arXiv:1209.6330

Also earlier analysis by Frankfurt group and OSU group

* Raa + Geometry + Evolution from RHIC to LHC:
strong evidences for Near-Nc Enhancement
--> predicts a less opaque medium at LHC!


$$< \kappa >_{\mathrm{RHIC}} : < \kappa >_{\mathrm{LHC}} \approx 1 : 0.72$$

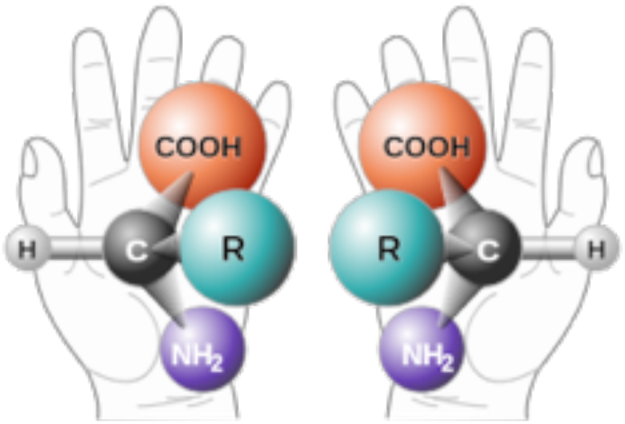
X.Zhang & JL, PLB(2012), arXiv:1208.6361,1210.1245(PRC2013)

Consistent messages from independent analysis by
Horowitz&Gyulassy; Betz & Gyulassy; Lacey, et al; B. Zakharov

RHIC+LHC: E-M "See-Saw" Scenario at work
---> anticipating critical test at LHC top energy!

THERMAL QGP AS A CHIRAL MATTER

ENVIRONMENTALLY "BROKEN" SYMMETRY



Our life system is a perfect example of environmental symmetry breaking.

Could a local domain with nonzero macroscopic chirality,
that is, a <u>CHIRAL MATTER</u>,
be created in heavy ion collisions?
YES!

In the local P-Odd QGP domain, there can be anomalous effects that normally could not occur: e.g. the Chiral Magnetic Effect (CME) ,generation of a vector current through an external Maxwell B field (Kharzeev, et al)

Vector current: P-odd
B field: P-even
It happens only because of the nonzero \mu_A

$$\boxed{\boldsymbol{j}_V = \frac{N_c e}{2\pi^2}\mu_A \boldsymbol{B}}$$

Macroscopic chirality
in chiral medium

Current Generation in External Fields

Extremely strong EM fields
at early moments in HIC

$$E, B \sim \gamma \frac{Z\alpha_{EM}}{R_A^2} \sim 3m_\pi^2$$

New interest in century-old quest of fundamental transport properties of matter: response to external fields in chiral matter

Ohm's Law

$$j_V = \sigma E,$$

Chiral Magnetic Effect (CME)

$$j_V = \sigma_5 \mu_A B;$$

Chiral Separation Effect (CSE)

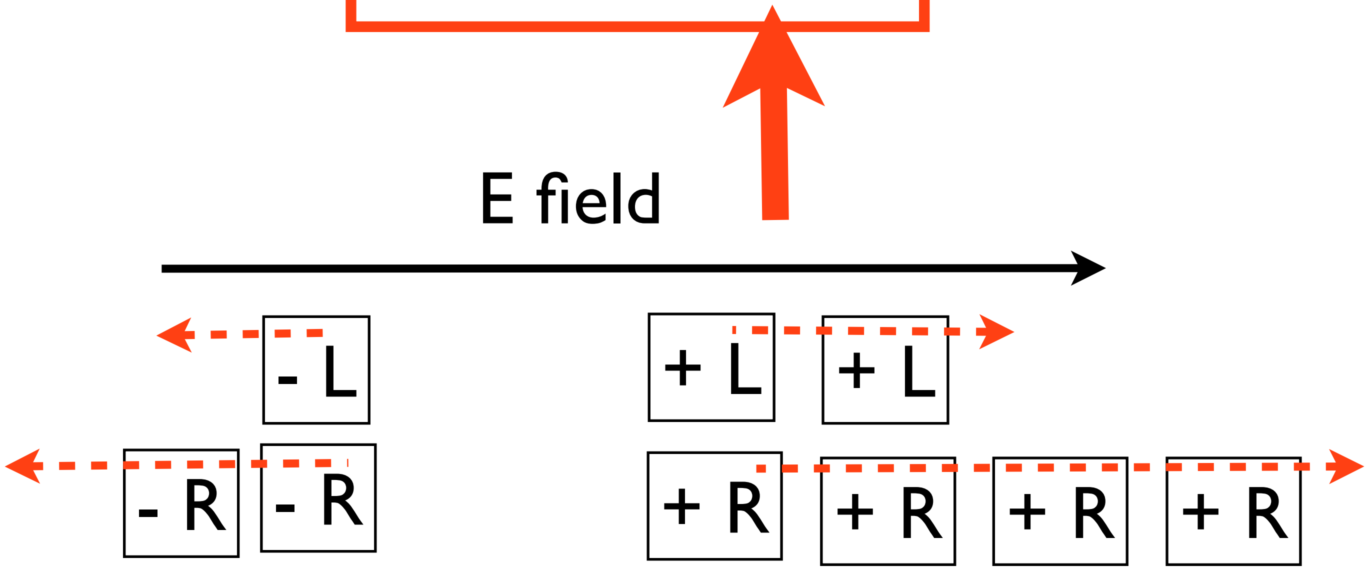
$$j_A = \sigma_5 \mu_V B.$$

	E	B
J_v	YES	YES Mu_A
J_A	???	YES Mu_A

CESE

Chiral Electric Separation Effect (CESE)

$$\boxed{j_A = \chi_e \mu_V \mu_A E,}$$



E field

- L

- R - R

+ L + L

+ R + R + R + R

Imbalance between +/- (nonzero Mu_V)

&

Imbalance between L/R (nonzero Mu_A)

--> Axial current

[X.Huang & JL, arXiv:1303.7192, PRL(2013)]

Summarizing the Effects together

Ohm, CME, CSE, CESE:

$$\begin{pmatrix} j_V \\ j_A \end{pmatrix} = \begin{pmatrix} \sigma & \sigma_5 \mu_A \\ \chi_e \mu_V \mu_A & \sigma_5 \mu_V \end{pmatrix} \begin{pmatrix} \boldsymbol{E} \\ \boldsymbol{B} \end{pmatrix}$$

Linearizing the fluctuations: we can find several collective excitation modes:

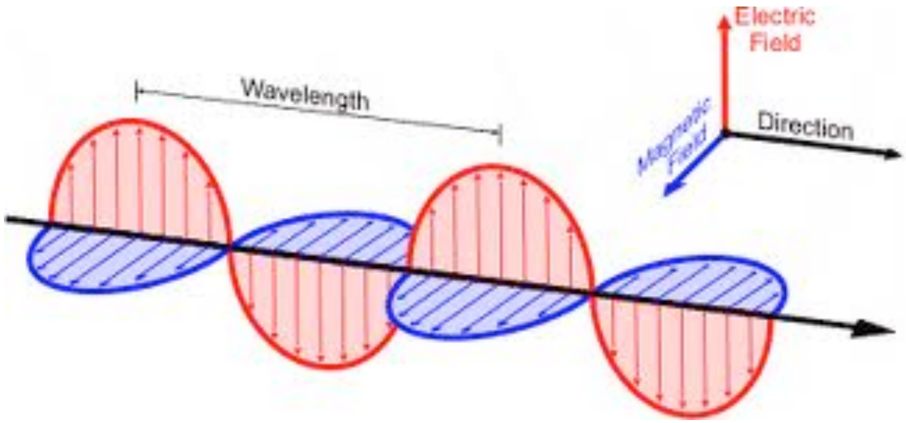
Chiral Electric/Magnetic Waves, Vector/Axial Density Waves

[X.Huang & JL, arXiv:1303.7192, PRL(2013)]

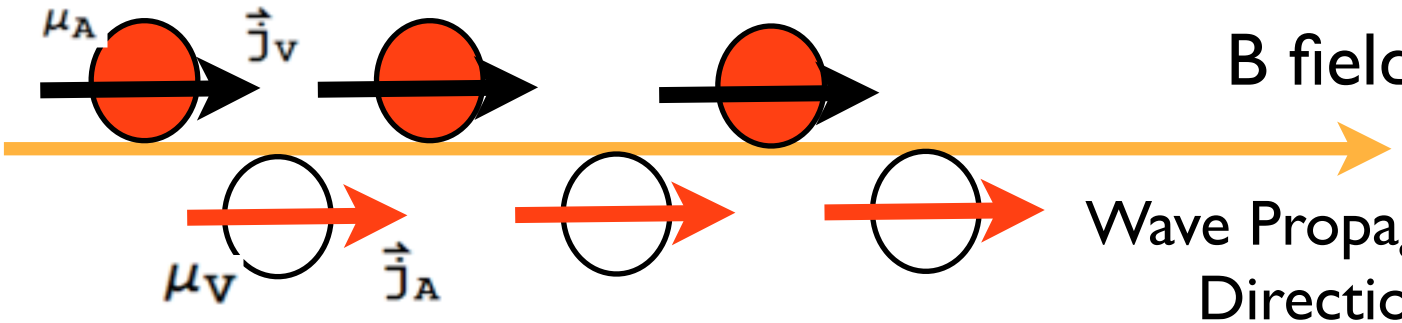
All very nice, but:
can we experimentally observe
one or more of these effects?
--- We discuss one example here, the Chiral Magnetic Wave

The Chiral Magnetic Wave

Wave: propagating "oscillations" of two coupled quantities
e.g. sound wave (pressure & density); EM wave (E & B fields)



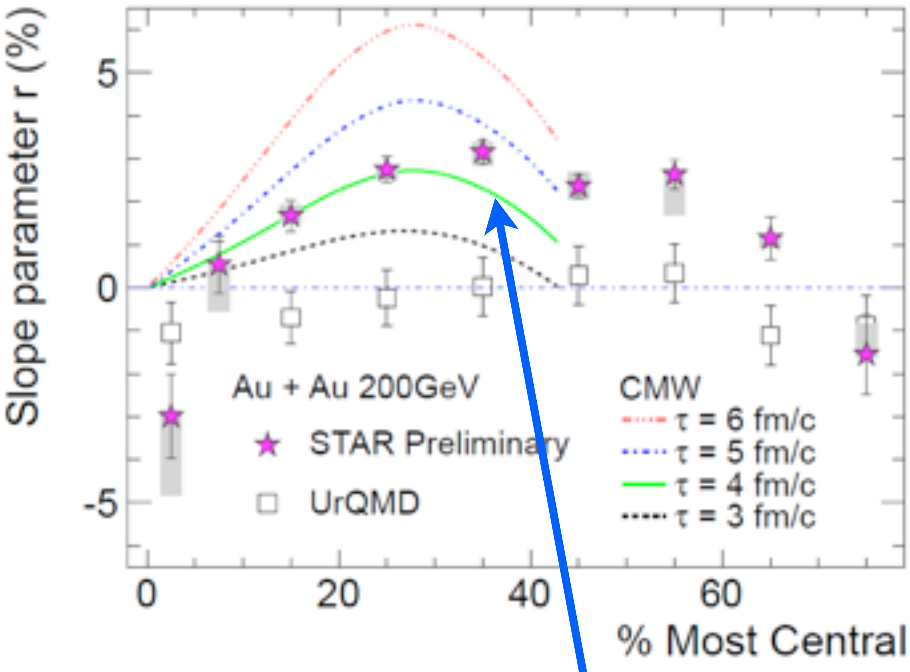
Chiral Magnetic Wave (CMW):
coupled evolution of Vector & Axial Charge Densities



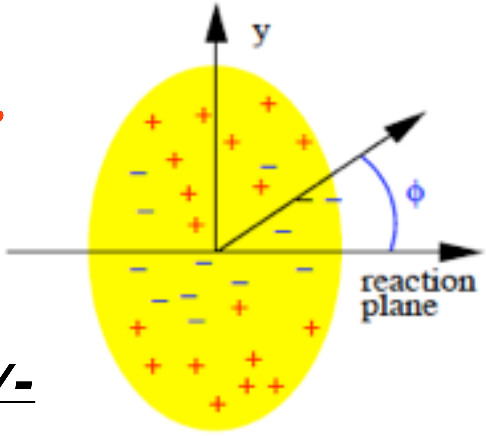
B field

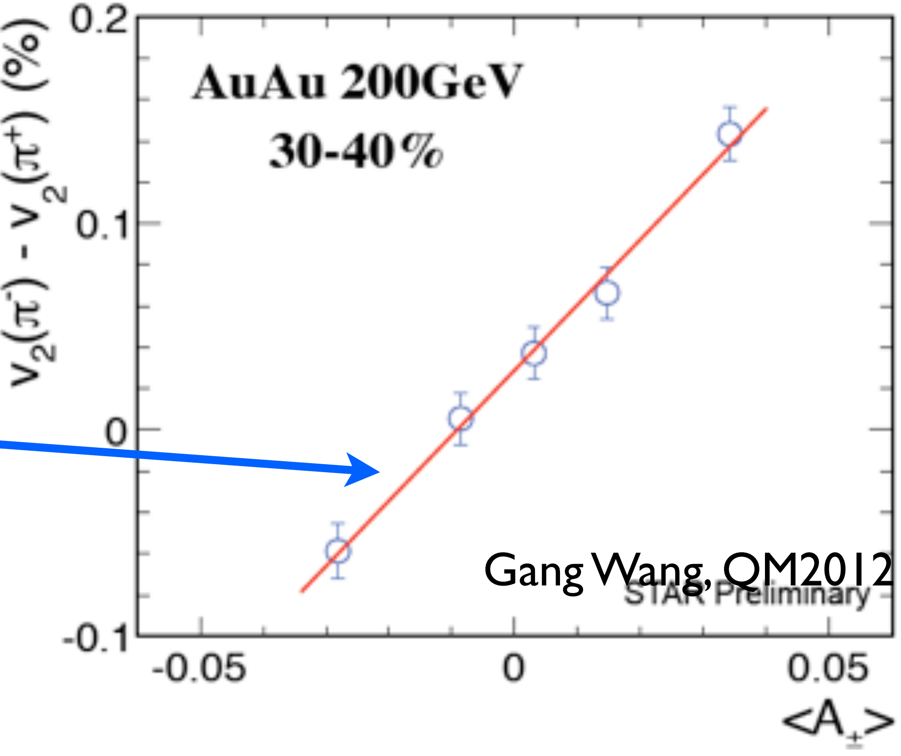
Wave Propagation Direction

CMW PREDICTIONS



CMW Predictions:
[Burnier, Kharzeev, JL, Yee, **PRL2011**; arXiv: 1208.2537]
A Quadrupole of Charge Distribution
leads to ***splitting of +/- charge elliptic flow!***





Gang Wang, QM2012

$$v_2^- - v_2^+ = r_e A$$

$$A = \frac{\bar{N}_+ - \bar{N}_-}{\bar{N}_+ + \bar{N}_-}$$

SOME MORE RECENT PROGRESS

* Better understanding of the strong EM fields

--- fluctuating initial conditions: both matter geometry & EM fields are fluctuating and their azimuthal correlations affect ALL EM field induced effects [Bloczynski,Huang,Zhang,JL, arXiv:1209.6594 (PLB)]

--- Time dependence: Skokov & McLerran; Tuchin; etc

* Chiral Magnetic Wave with hydrodynamic approach

--- CMW from Anomalous hydro:
Hongo & Hirono & Hirano; Taghavi & Wiedemann

--- Realistic simulations & proper freezeout: Yee & Yin

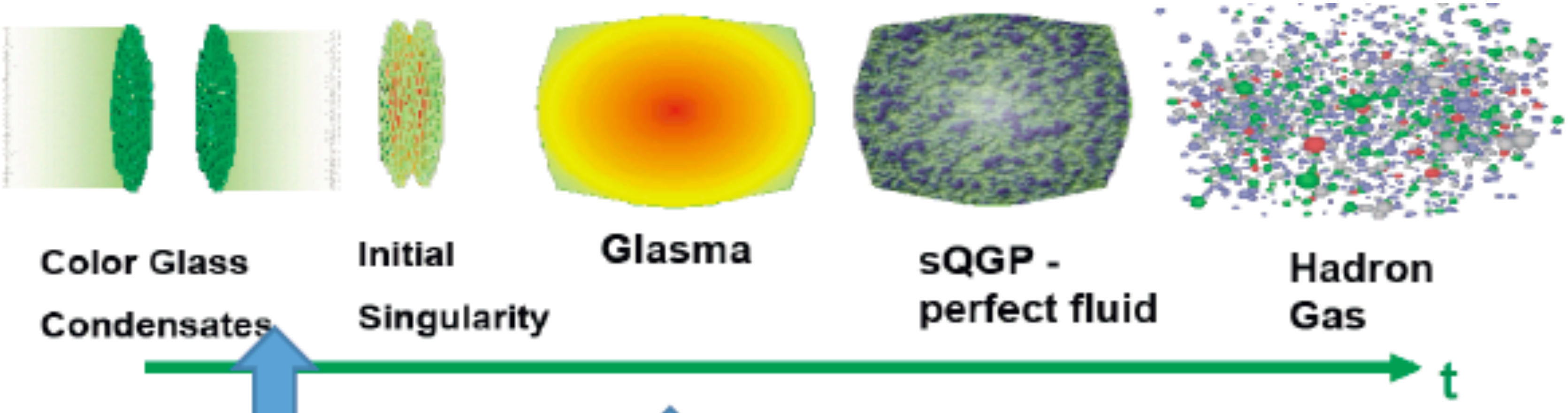
--- alternative contributions:
Ko, et al; Koch, et al; Bzdak, et al; Lisa, et al...

* CME & Charge-dependent azimuthal correlations

--- coherent understanding of AuAu versus UU data:
two components (flow-driven + CME like) viable,
but not perfect [Bloczynski,Huang,Zhang,JL, arXiv:1311.5451]

The Over-Populated Pre-Equilibrium Matter

Thermalization: An Outstanding Puzzle



Color Glass Condensates

Initial Singularity

Glasma

sQGP - perfect fluid

Hadron Gas

t

Strong constraint from the initial condition:
saturation

$$\boxed{\frac{xG(x,Q^2)}{\pi R^2 Q_s^2} \sim \frac{1}{\alpha_s}}$$

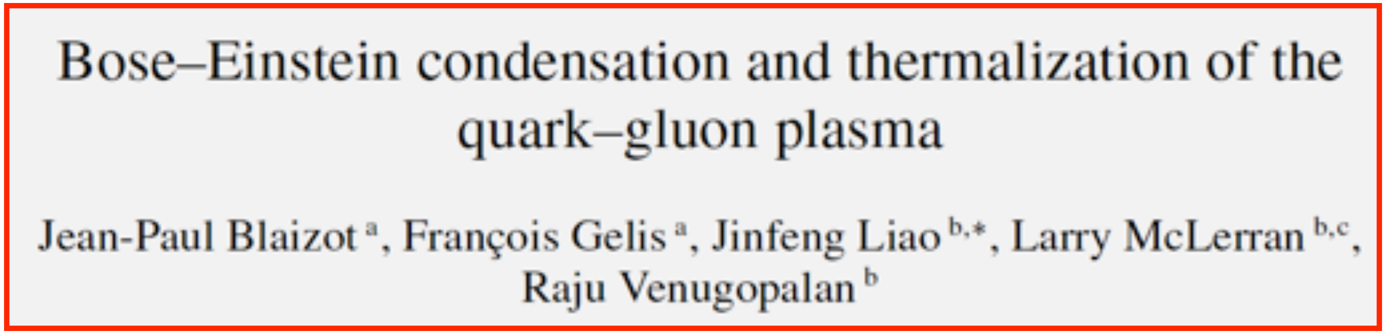
from classical fields
to quantum particles

Pre-Equilibrium Matter
(We focus on this!)

Scale in PEM high! Qs~GeV Asyp. Free.
Is weak coupling description
viable with "fast thermalization"?
YES → More is different!

Strong constraint from
Hydro modeling and empirical data:
fast "thermalization" ~ fm/c
(to the extent of justifying hydro)

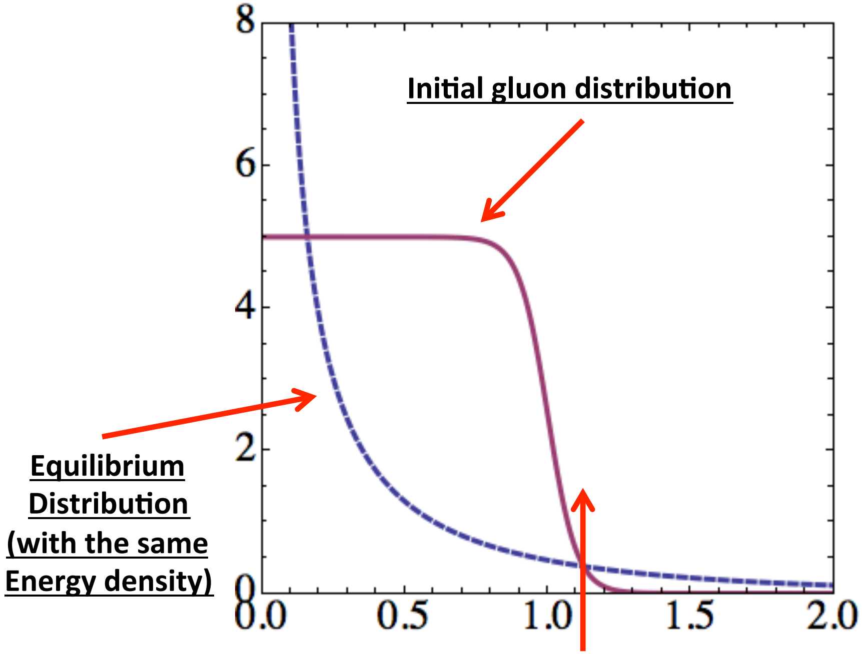
High Overpopulation as a Key



Bose–Einstein condensation and thermalization of the quark–gluon plasma

Jean-Paul Blaizot[a], François Gelis[a], Jinfeng Liao[b,*], Larry McLerran[b,c], Raju Venugopalan[b]

The precursor of a thermal quark-gluon plasma, known as glasma, is born as a gluon matter with **HIGH OVERPOPULATION**:



Saturation Scale Qs ~ 1 GeV or larger, weakly coupled

Very large occupation number

$$f \sim \frac{1}{\alpha_s}$$

Saturation fixes initial scale

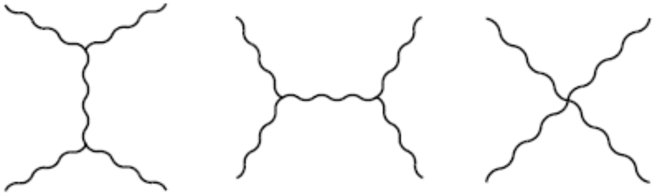
$$\epsilon_0 \sim \frac{Q_s^4}{\alpha_s}$$

$$n_0 \sim \frac{Q_s^3}{\alpha_s}$$

$$\epsilon_0 / n_0 \sim Q_s$$

Elastic Collisions at High Occupation

$$\mathcal{D}_t f_1 = \frac{1}{2}\int \frac{d^3p_2}{(2\pi)^3 2E_2}\frac{d^3p_3}{(2\pi)^3 2E_3}\frac{d^3p_4}{(2\pi)^3 2E_4}\frac{1}{2E_1} \mid M_{12\to34} \mid^2$$
$$\times(2\pi)^4\delta(p_1+p_2-p_3-p_4)\{f_3f_4(1+f_1)(1+f_2)-f_1f_2(1+f_3)(1+f_4)\}$$



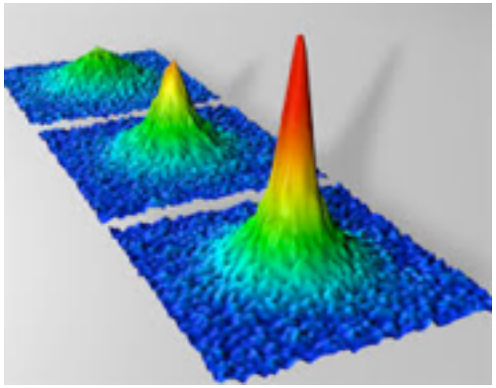
$$f * f * \alpha_s{}^2 \sim O\ (1)$$

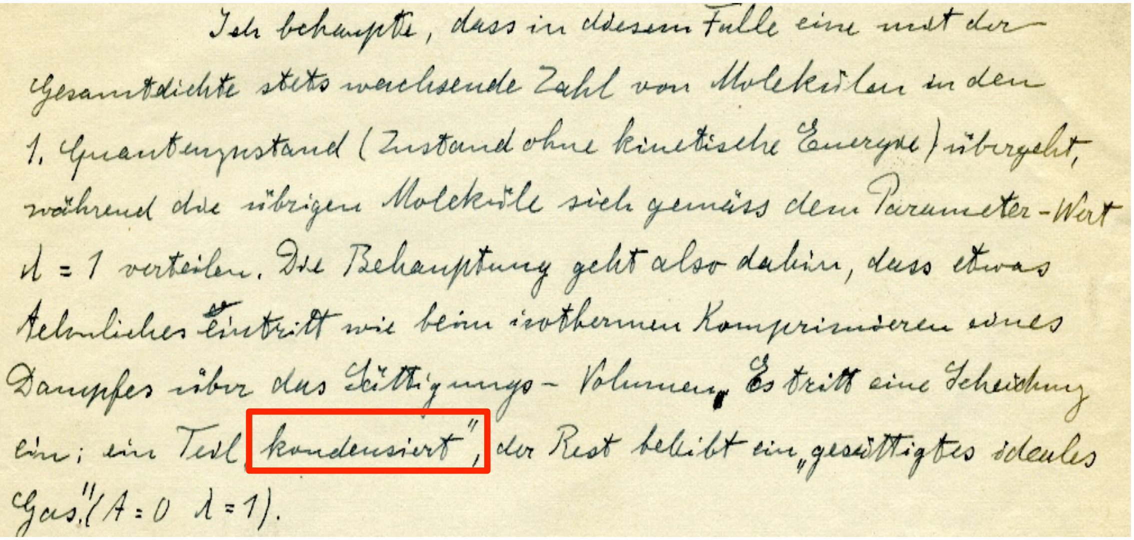
$$\mid M_{12\to34} \mid^2 = 72g^4\left[3-\frac{t\,u}{s^2}-\frac{s\,u}{t^2}-\frac{t\,s}{u^2}\right]$$

When f~1/alpha_s, dependence on the coupling drops out!
The quantum nature is important at high occupation.

BEC in The Very Cold

$$f_{\mathrm{eq}}(\boldsymbol{k}) = n_{\mathrm{c}}\delta(\boldsymbol{k}) + \frac{1}{e^{\beta(\omega_{\boldsymbol{k}} - m_0)} - 1}$$





Ich behauptete, dass in diesem Falle eine mit der
Gesamtdichte stets wachsende Zahl von Molekülen in den
1. Quantenzustand (Zustand ohne kinetische Energie) übergeht,
während die übrigen Moleküle sich gemäss dem Parameter-Wert
$\lambda = 1$ verteilen. Die Behauptung geht also dahin, dass etwas
Aehnliches eintritt wie beim isothermen Komprimieren eines
Dampfes über das Sättigungs-Volumen. Es tritt eine Scheidung
ein; ein Teil „kondensiert", der Rest bleibt ein „gesättigtes ideales
Gas" ($A = 0$ $\lambda = 1$).

It took ~70 years to achieve BEC in ultra-cold bose gases.
The key is to achieve **OVERPOPULATION**:

$$n \cdot \epsilon^{-3/4} > \hat{O}(1)\ threshold$$

OVERPOPULATION implies *quantum coherence*:

$$n \cdot \epsilon^{-3/4} \sim (d/\lambda_{dB})^{\alpha} \sim \hat{O}(1)$$

BEC in The Very Hot?!

Our initial gluon system is highly OVERPOPULATED:

$$f(p) = f_0\,\theta(1 - p/Q_s),$$

$$\epsilon_0 = f_0 \frac{Q_s^4}{8\pi^2}, \qquad n_0 = f_0 \frac{Q_s^3}{6\pi^2}, \qquad n_0\,\epsilon_0^{-3/4} = f_0^{1/4} \frac{2^{5/4}}{3\,\pi^{1/2}},$$

This is to be compared with the thermal BE case:

$$\epsilon_{SB} = (\pi^2/30)\,T^4 \qquad n_{SB} = (\zeta(3)/\pi^2)\,T^3$$

$$n\,\epsilon^{-3/4}|_{SB} = \frac{30^{3/4}\,\zeta(3)}{\pi^{7/2}} \approx 0.28$$

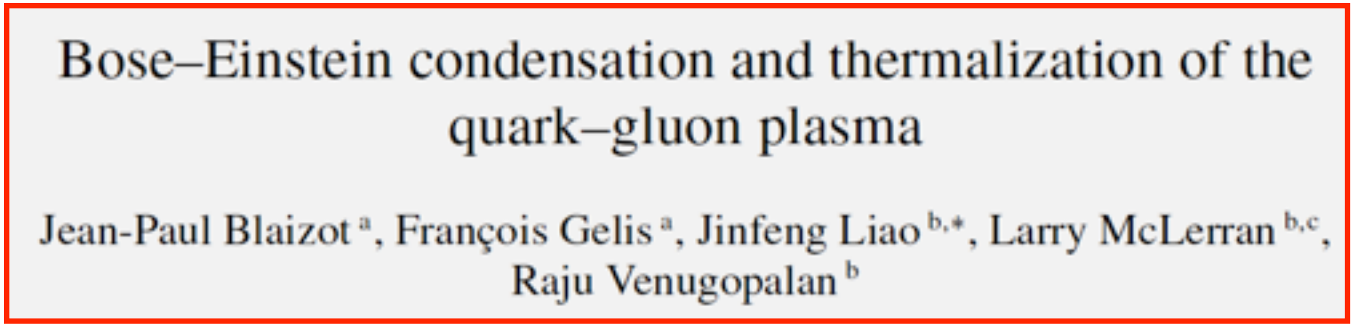
Overpopulation occurs when: $f_0 > f_0^c \approx 0.154$

Identifying f_0 -> 1/alpha_s, even for alpha_s =0.3, the system is highly overpopulated!!

The smaller the alpha_s, the larger overpopulation

Will the system accommodate the excessive particles by forming a Bose-Einstein Condensate (BEC) ?

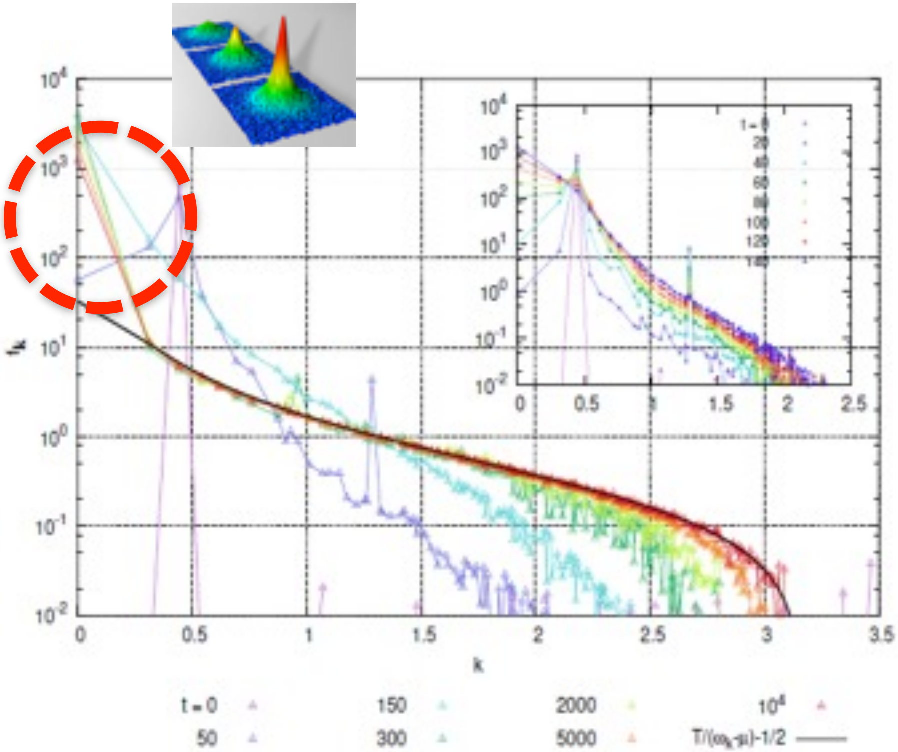
Strong Evidence of BEC from Scalar Field Theory Simulations



Bose–Einstein condensation and thermalization of the quark–gluon plasma

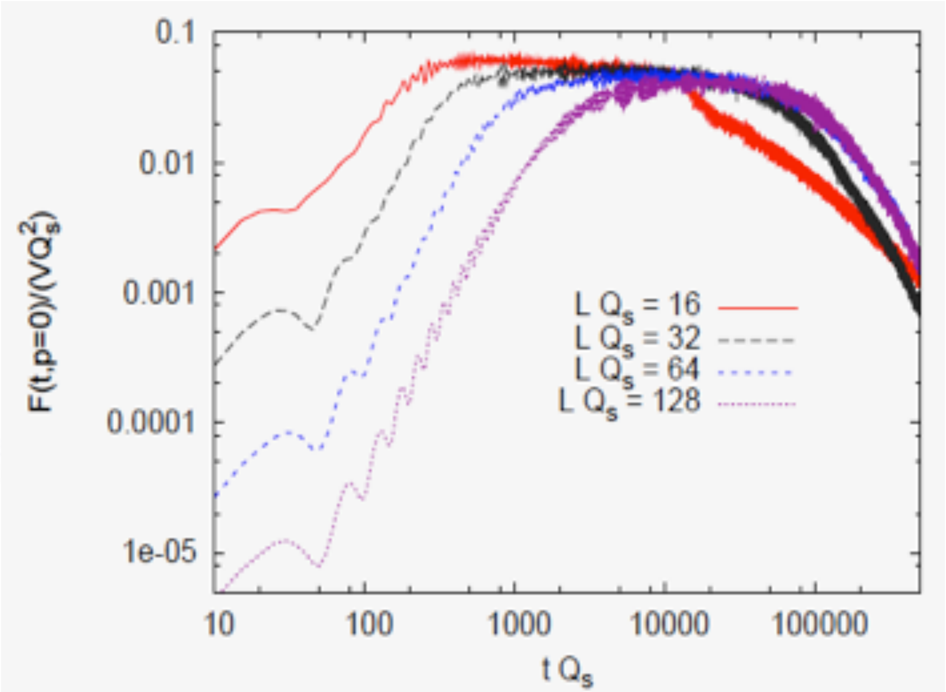
Jean-Paul Blaizot [a], François Gelis [a], Jinfeng Liao [b,*], Larry McLerran [b,c], Raju Venugopalan [b]

Absolutely true for pure elastic scatterings;
True, in transient sense, for systems with inelastic processes



From: Epelbaum & Gelis 1107.0668

From: Berges & Sexty 1201.0687



Small Angle Approximation

Kinetic equation under small angle approximation (Blaizot-Liao-McLerran)

$$\boxed{\mathcal{D}_t f(\vec{p}) = \xi\left(\Lambda_s^2\Lambda\right)\vec{\nabla}\cdot\left[\vec{\nabla} f(\vec{p}) + \frac{\vec{p}}{p}\left(\frac{\alpha_S}{\Lambda_s}\right) f(\vec{p})[1+f(\vec{p})]\right]}$$

$$\Lambda\left(\frac{\Lambda_s}{\alpha_S}\right)^2 \equiv (2\pi^2)\int\frac{d^3p}{(2\pi)^3} f(\vec{p})\,[1+f(\vec{p})]$$

$$\Lambda\frac{\Lambda_s}{\alpha_S} \equiv (2\pi^2)\,2\int\frac{d^3p}{(2\pi)^3}\frac{f(\vec{p})}{p}$$

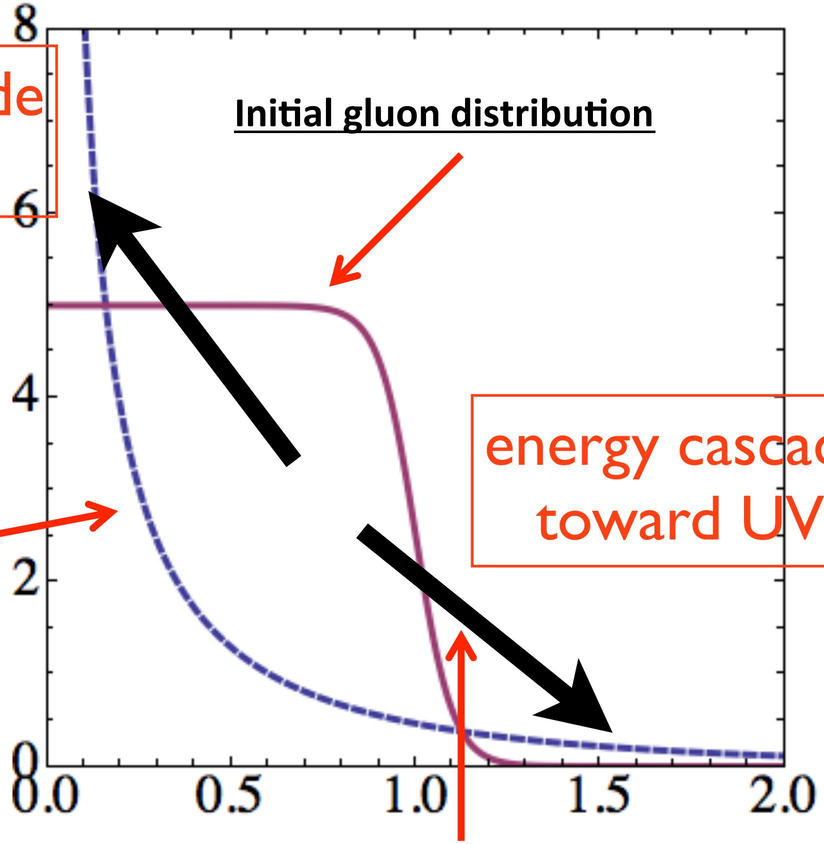
Two important scales:
hard scale Lambda
soft scale Lambda_s

Elastic scattering
time scale

$$t_{scat} \sim \frac{\Lambda}{\Lambda_s^2}$$

When f~1/alpha_s: the coupling drops out from the problem
emergent strongly interacting properties despite small coupling

How Thermalization Proceeds



particle cascade toward IR

Initial gluon distribution

energy cascade toward UV

Equilibrium Distribution (with the same Energy density)

Saturation Scale Qs ~ 1 GeV or larger, weakly coupled

Initial glasma:

$$\Lambda \sim \Lambda_s \sim Q_s$$

Thermalized weakly-coupled QGP:

$$\Lambda \sim T$$

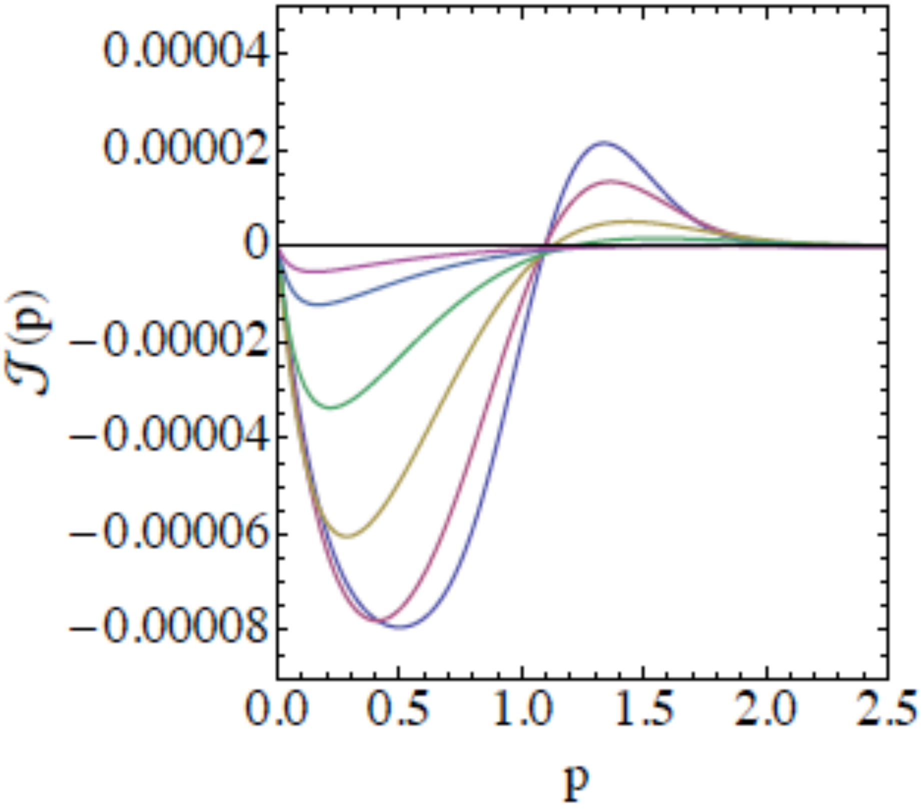
$$\Lambda_s \sim \alpha_s * T$$

$$\Lambda_s \sim Q_s\left(\frac{t_0}{t}\right)^{\frac{3}{7}} \qquad \Lambda \sim Q_s\left(\frac{t}{t_0}\right)^{\frac{1}{7}}$$

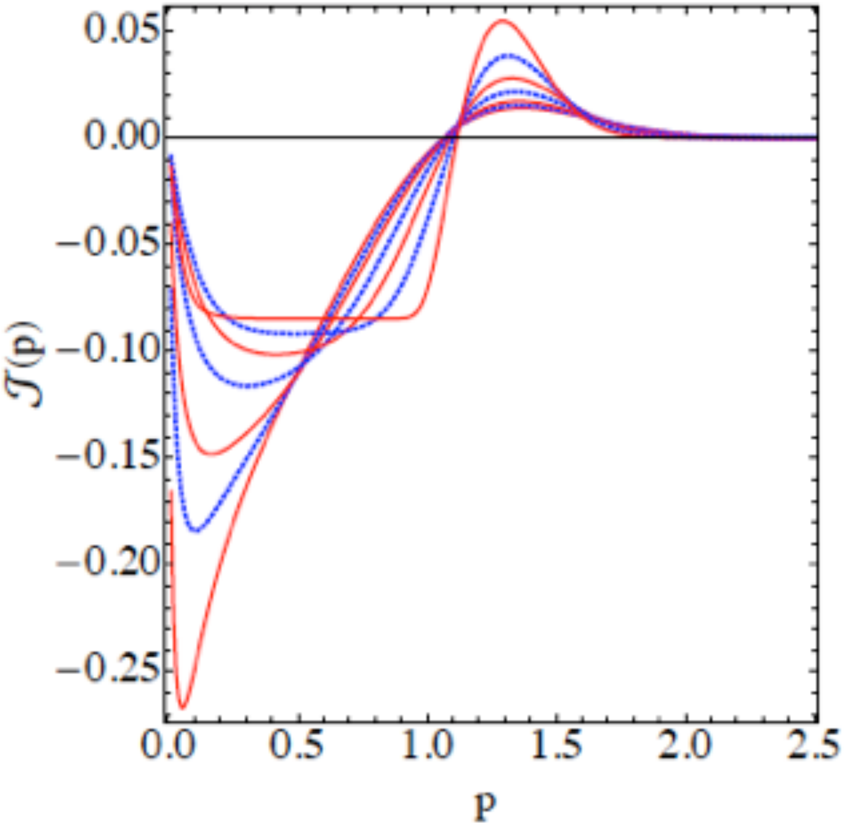
separation of two scales toward thermalization $\boxed{\frac{\Lambda_s}{\Lambda} \sim \alpha_s}$

static box $\boxed{t_{\mathrm{th}} \sim \frac{1}{Q_s}\left(\frac{1}{\alpha_s}\right)^{7/4}}$

IR and UV Cascade



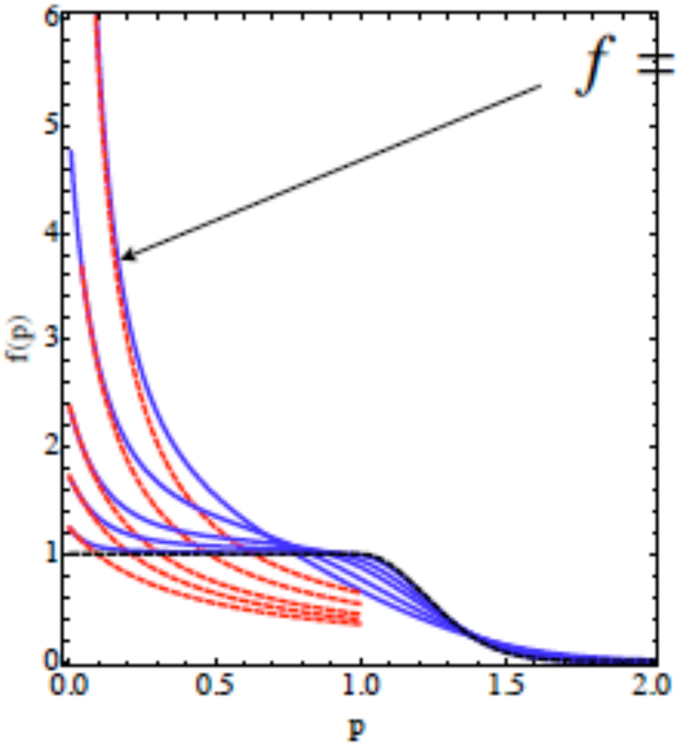
f_0=0.1
(underpopulated)



f_0=1
(overpopulated)

Blaizot, JL, McLerran, 1305.2119, NPA2013

Rapid IR “Local Thermalization”



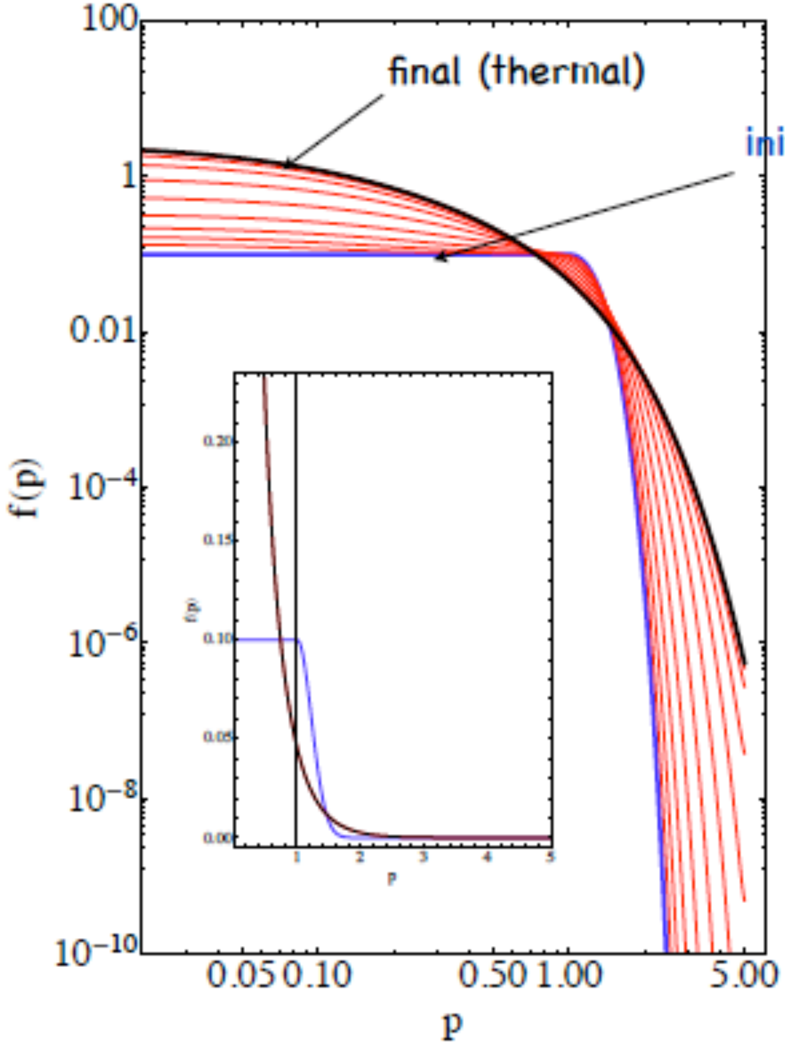
$$f = \frac{T^*}{p - \mu^*} \qquad (\mu^* < 0)$$

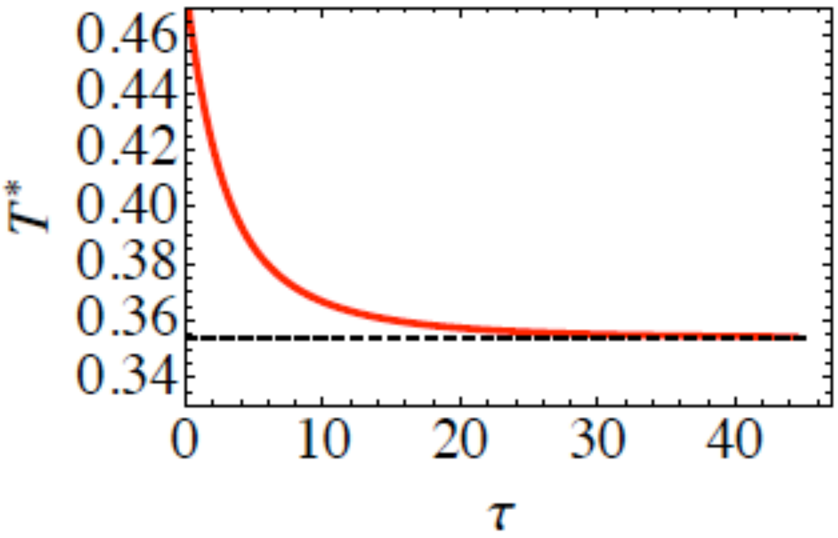
Very strong particle flux toward IR, leading to rapid growth and almost instantaneous local thermal distribution of very soft modes

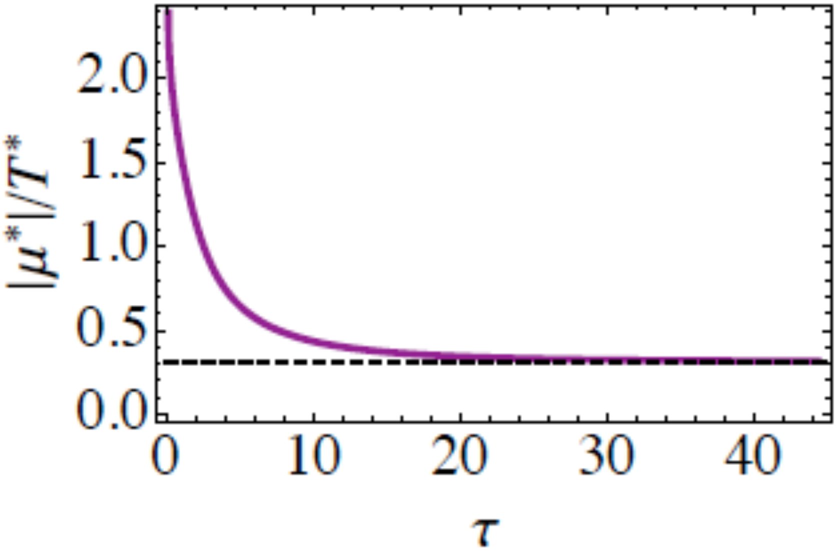
Blaizot, JL, McLerran, 1305.2119, NPA2013

Underpopulated Case:
Evolve toward Thermal Fixed Point

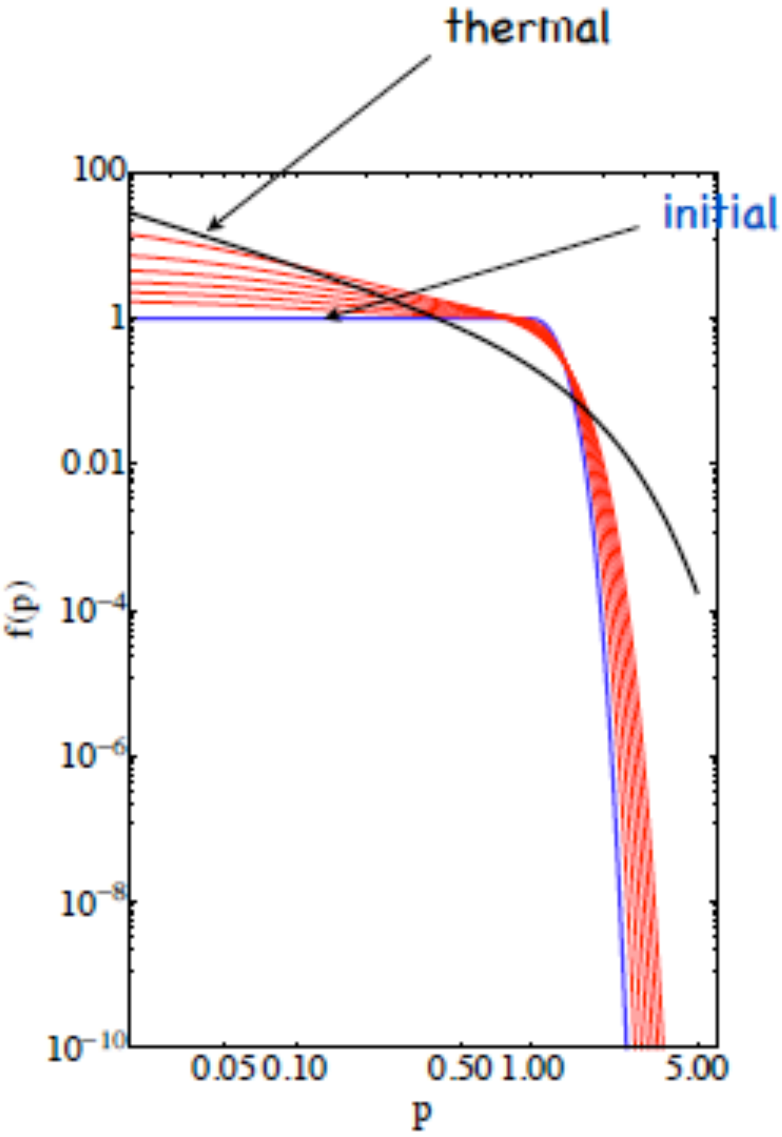
f_0=0.1



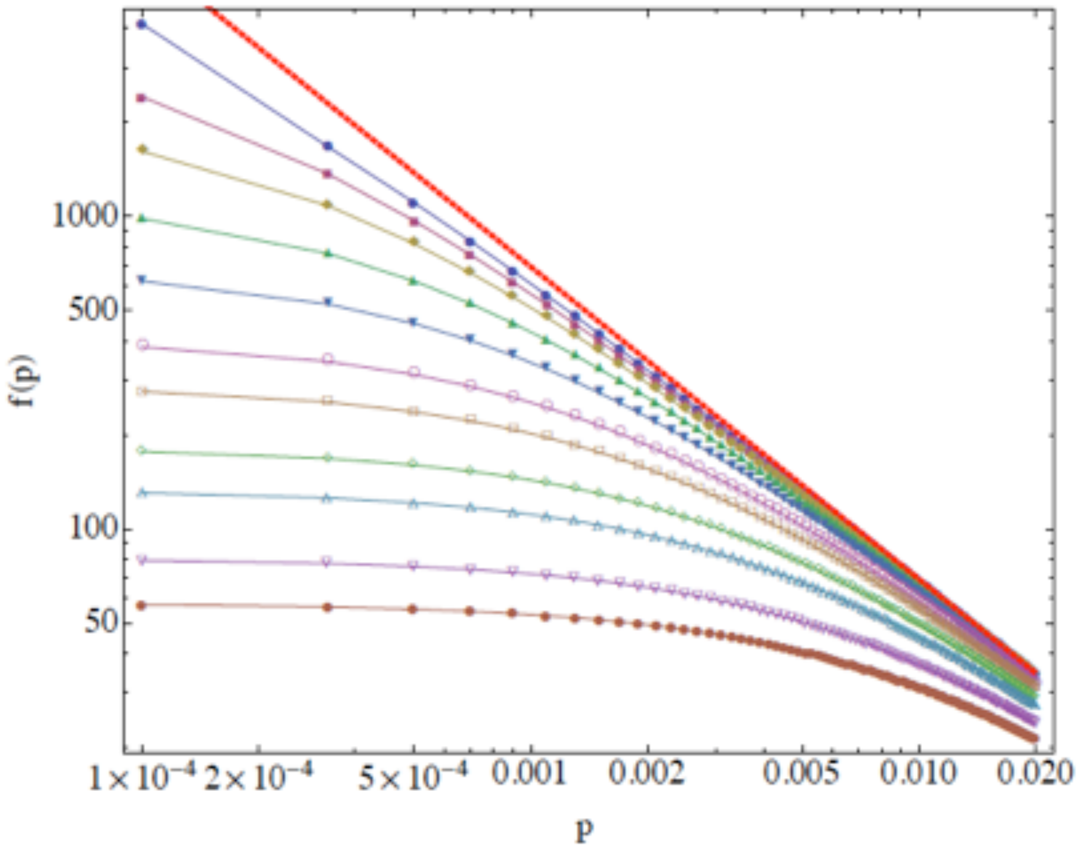




Overpopulated Case:
How Onset of BEC Develops?



f_0=1



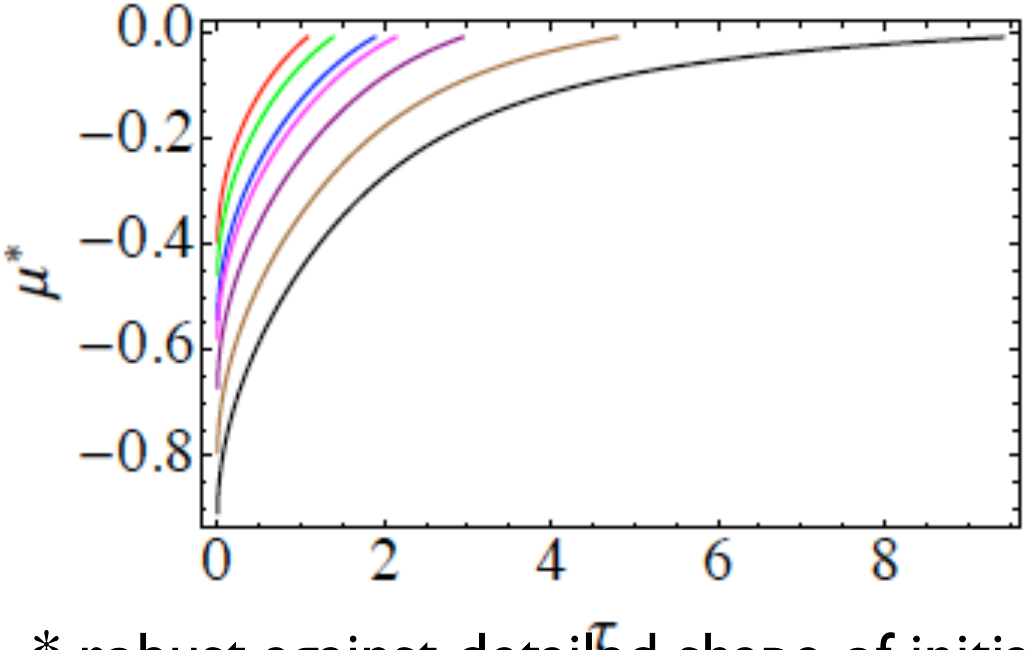
Onset of Dynamical BEC

Onset of dynamical (out-of-equilibrium) BEC in a plasma with long range gauge interactions:

* occurring in a finite time

* local Mu* vanishes with a scaling behavior

* persistence of particle flux toward zero momentum



$$\boxed{|\mu^*| = C(\tau_c - \tau)^\eta.}$$

$$\eta \simeq 1$$

For different
f_0 = 0.2, 0.3, 0.5, 0.8, 1, 2, 5

* robust against detailed shape of initial condition: same found for Guassian shape initial distribution with overpopulation

* robust against longitudinal expansion & finite initial anisotropy

How Robust is the BEC Onset Dynamics?

There are a number of important aspects to
further understand about this
dynamical process from initial overpopulation to the onset of BEC:

✦ How does that depend on the initial distribution shape?

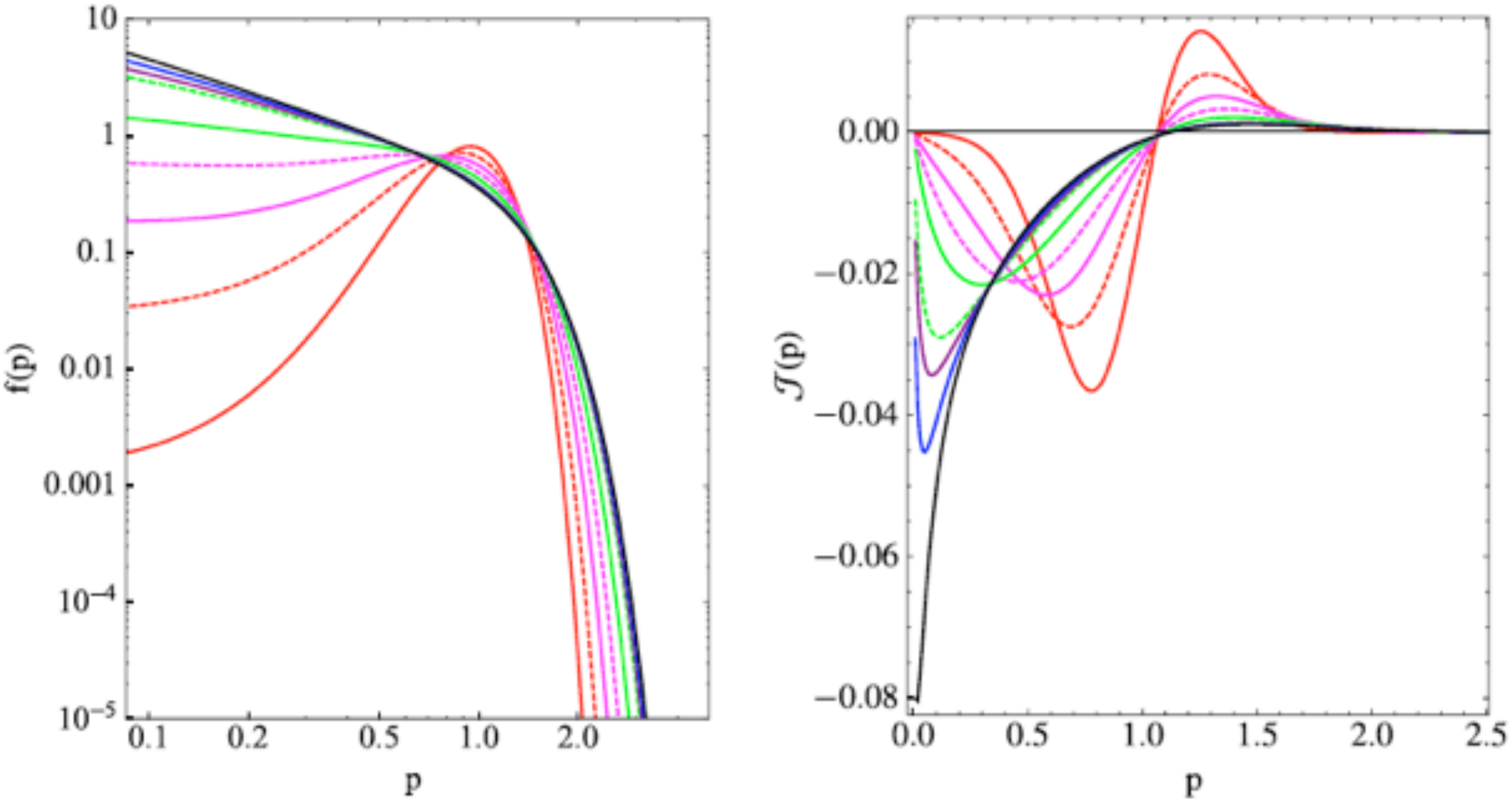
✦ How does that depend on a finite mass (e.g. from medium effect)

✦ How is that influenced by the inelastic processes?

✦ How is that influenced by the longitudinal expansion?

Gaussian Initial Condition

$$f(p) = f_0\, g(p/Q_s), \quad g(p/Q_s) = a\, e^{-[b*(p/Q_s-1)]^2}$$

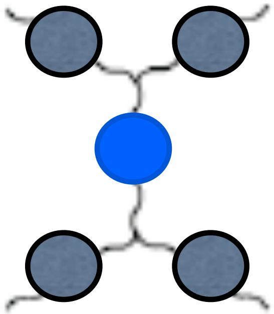


Same IR dynamics quickly develops and reaches onset in scaling way

Blaizot, JL, McLerran, 1305.2119, NPA2013

The Onset with Massive Particles

Medium effect could "dress up" both the external line gluons and internal exchange gluons.



$$C[f_{\vec{p}_1}] = -\vec{\nabla}_{\vec{p}_1} \cdot \vec{S}(\vec{p}_1)$$

$$\vec{S} = \vec{e}_{\vec{p}_1} \frac{36\alpha^2}{\pi} \int \frac{dq}{q} \int dp_2 p_2^2 \frac{Z}{v_1} (h_1 \dot{f}_2 - h_2 \dot{f}_1)$$

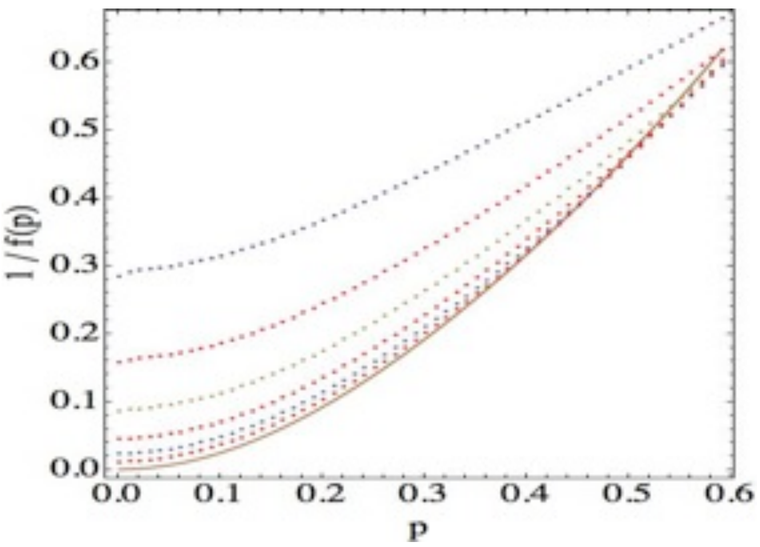
$$c(q) = 1 + \frac{M^2}{q^2}$$

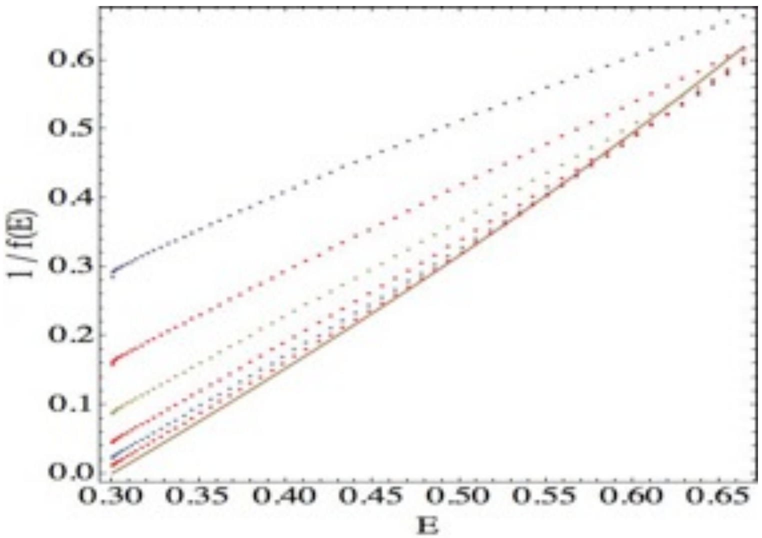
$$v_1 v_2 Z(c_q) = \frac{E_1}{c - v^2} + E_2(c - v^2) + E_3 + \sqrt{c_q} ArcTanh(\frac{v}{\sqrt{c_q}}) \times [E_4(1 - c_q) + E_5 \frac{c_q - 1}{c_q} + E_6]$$

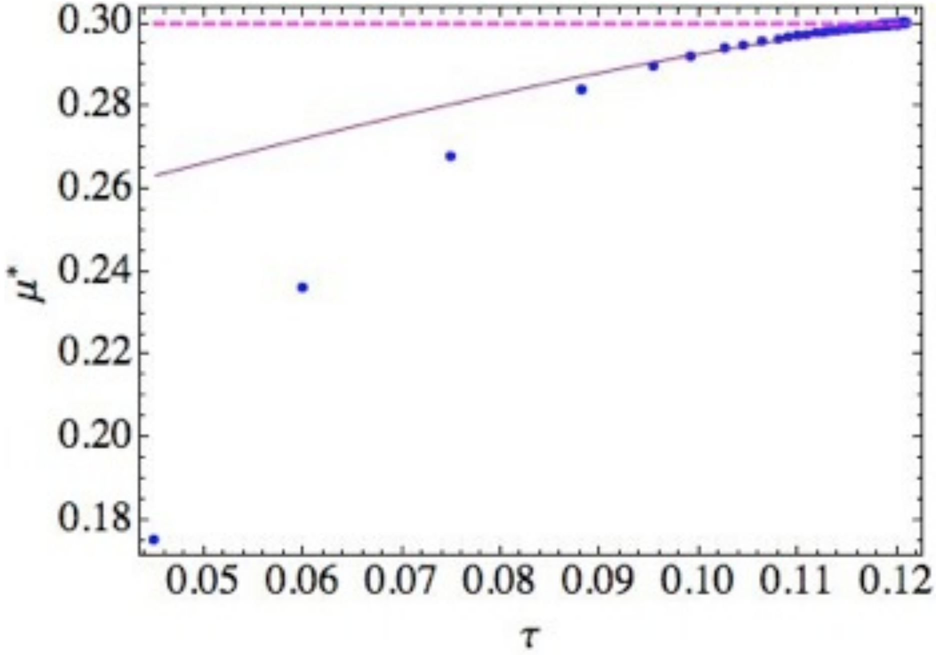
Most interesting issues in massive case:
* Onset changes, Mu* --> Mass
* Deep IR dispersion changes, ~ p^2 (NR) instead of ~ p (UR)
* BEC is deep-IR physics, how scaling would change?

Blaizot, Jiang, JL, McLerran, in progress

IR Local Thermal Form & Scaling toward Onset







IR Local Thermal Form

$$\frac{1}{f} \to \frac{E-\mu^*}{T^*} \sim \frac{\boxed{p^2}/(2M)+M-\mu^*}{T^*}$$

Scaling toward Onset

$$\mu^* = \boxed{M} + C(\tau_c - \tau)^\eta$$

$$\boxed{\eta \approx 1.29}$$

Blaizot, Jiang, JL, McLerran, in progress

Including the Inelastic

An inelastic kernel including 2<-->3 processes
(Gunion-Bertsch, under collinear and small angle approxation)

$$\mathcal{D}_t f_p = \mathcal{C}^{\rm eff}_{2\leftrightarrow 2}[f_p] + \mathcal{C}^{\rm eff}_{1\leftrightarrow 2}[f_p],$$

Huang & JL, arXiv:1303.7214

$$\begin{aligned}\mathcal{C}^{\rm eff}_{1\leftrightarrow 2} \;=\; & \xi\,\alpha_s^2\,R\,\frac{I_a}{I_b}\Big\{\int_0^{z_c}\frac{dz}{z}\left[g_p f_{(1-z)p} f_{zp} - f_p g_{(1-z)p} g_{zp}\right] \\ & + \int_0^{z_c}\frac{dz}{(1-z)^4 z}\left[g_p g_{zp/(1-z)} f_{p/(1-z)} - f_p f_{zp/(1-z)} g_{p/(1-z)})\right]\Big\}\end{aligned}$$

A number of features:

* fixed point: BE distribution with zero chemical potential

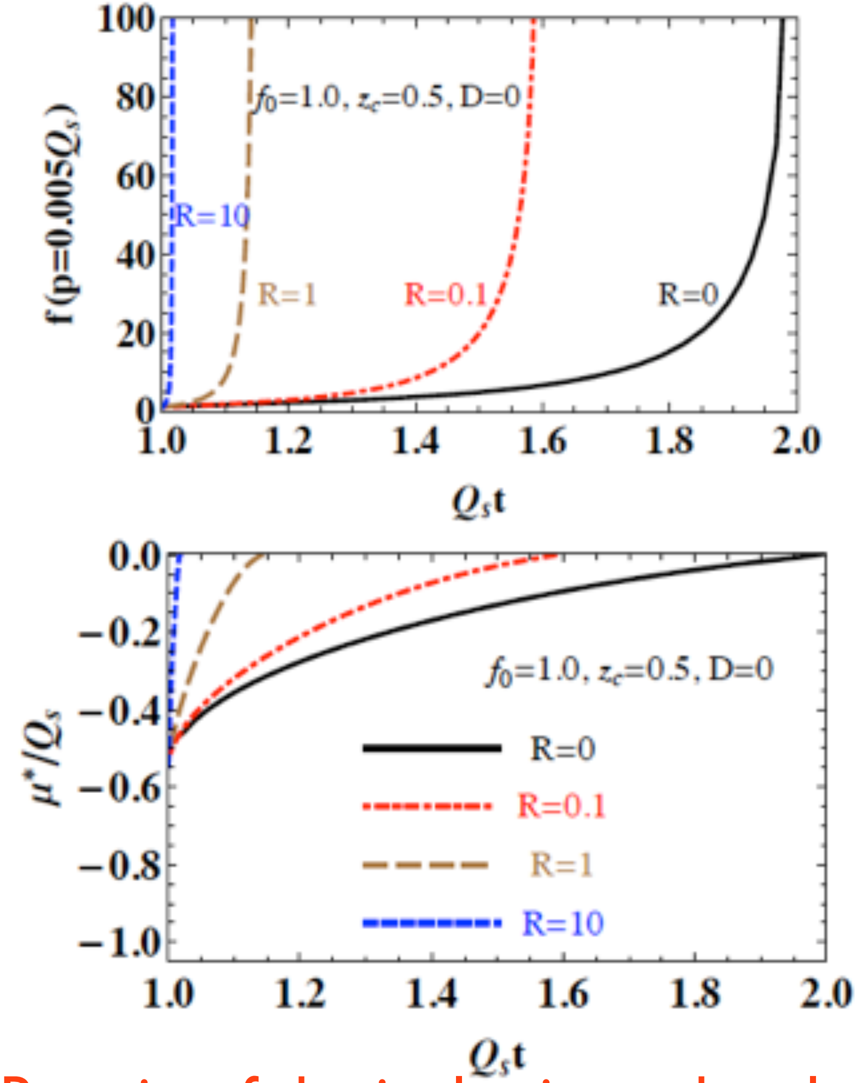
* always positive at very small momentum

* purely inelastic case --- correctly thermalize to BE

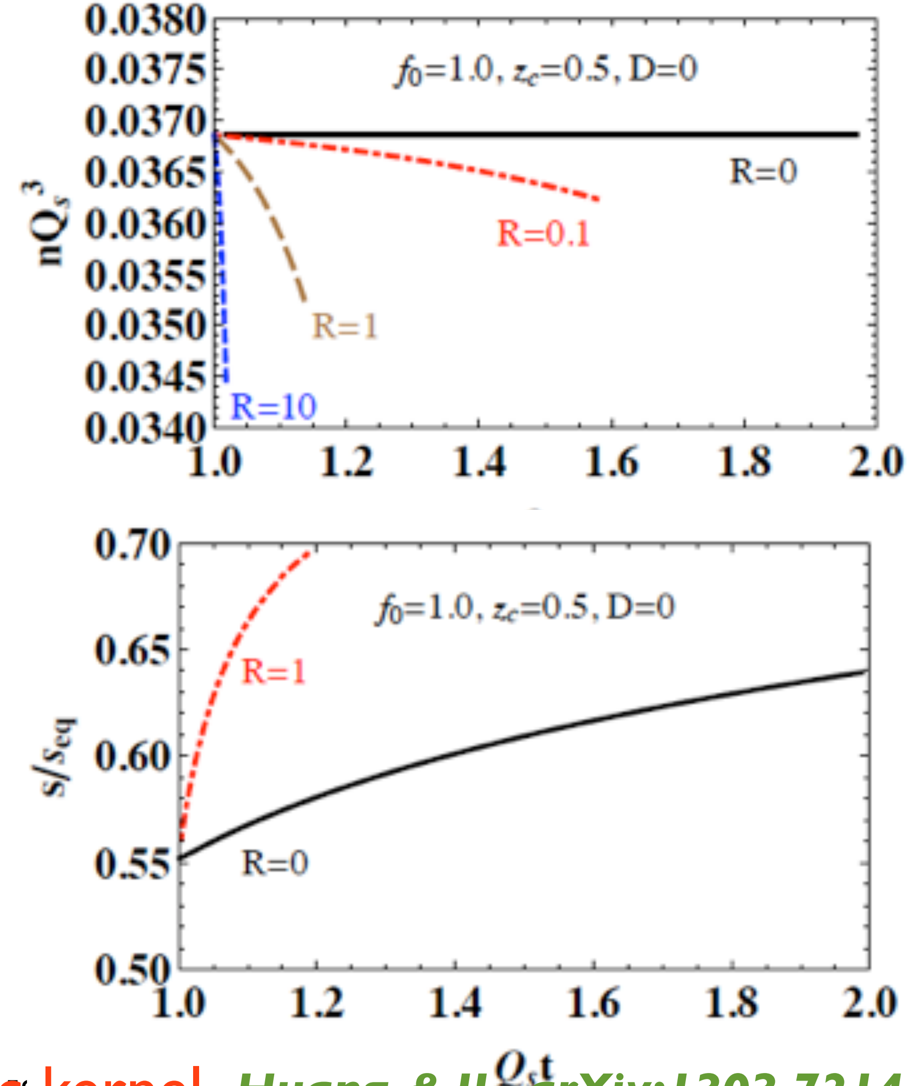
The question changes now:
no condensate in thermal states,
but dynamical BEC while still far from being thermal.

Effects from the Inelastic

Local effect: enhance IR growth, accelerate the onset



Global effect: reduce number density, enhance entropy growth

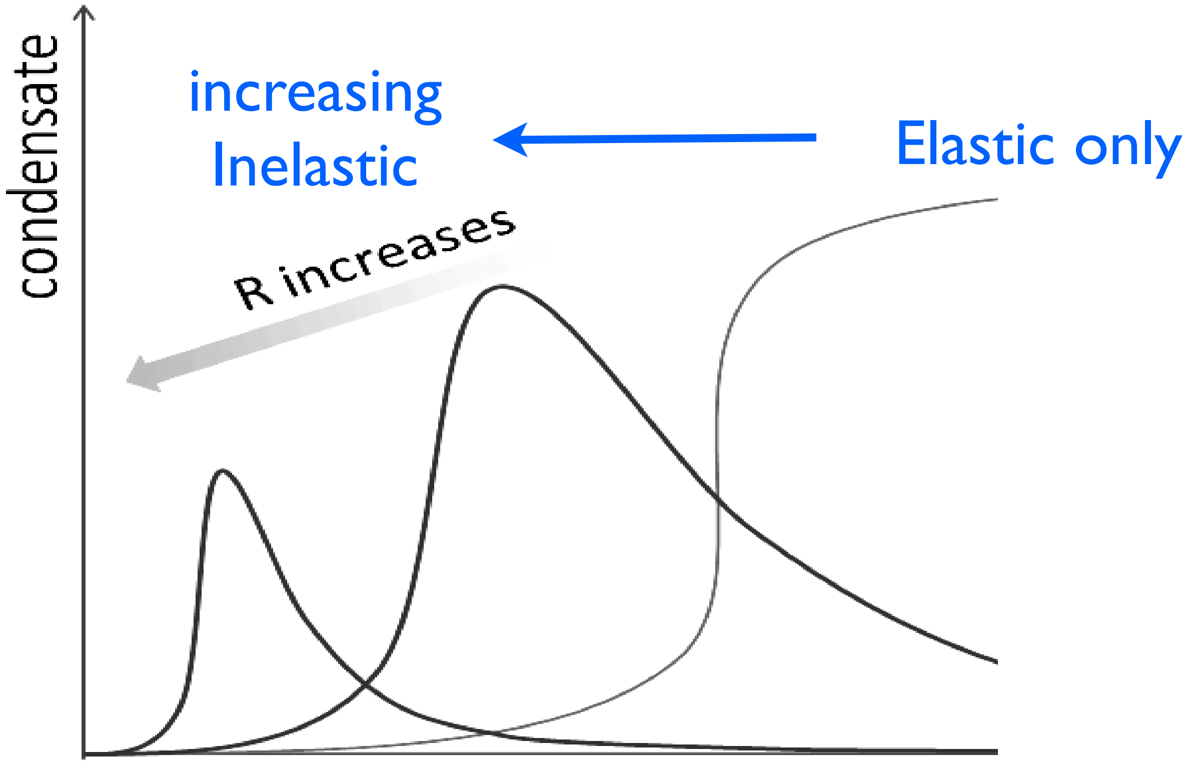


R: ratio of the inelastic to the elastic kernel

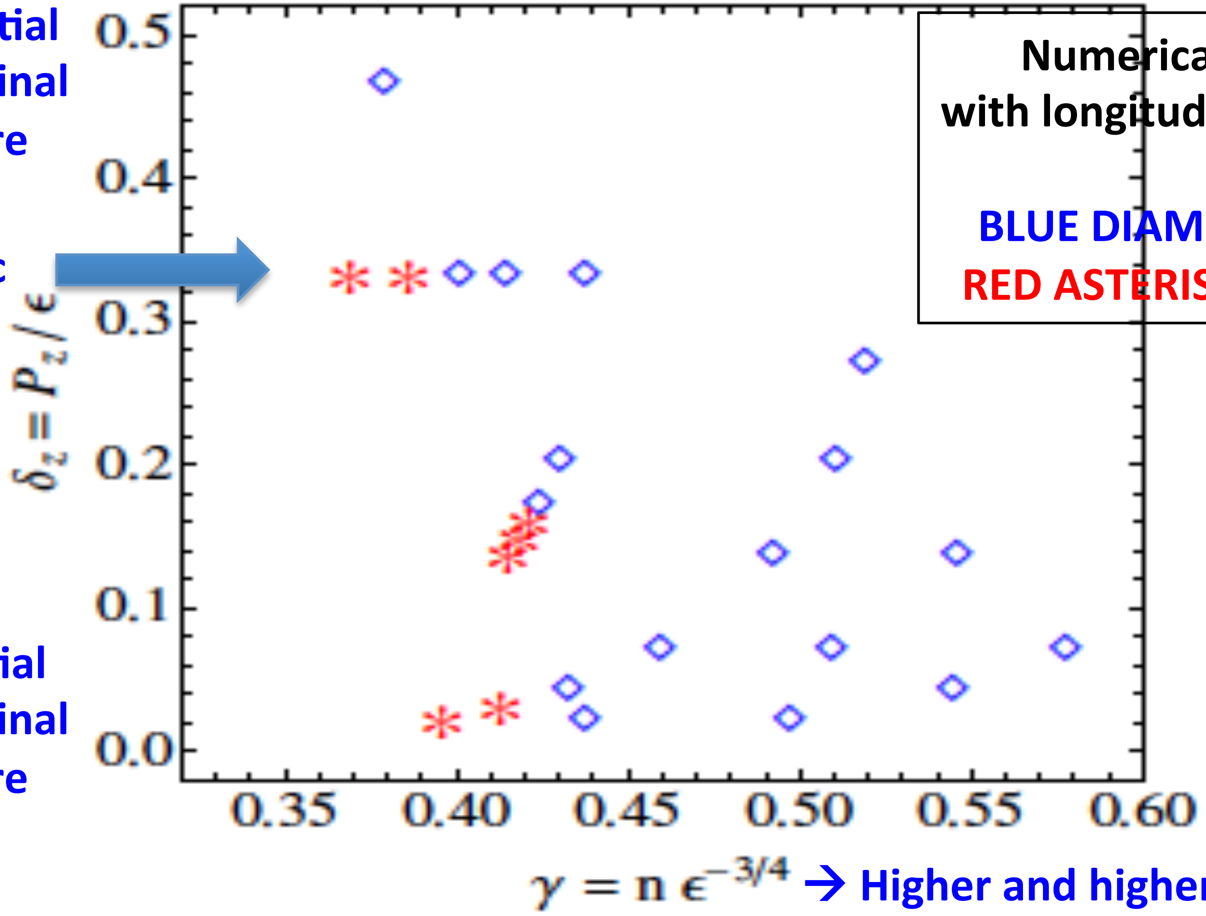
Huang & JL, arXiv:1303.7214

The “Fuller” Picture

What we find: the inelastic process catalyzes
the onset of dynamical (out-of-equilibrium) BEC.
It might sound contradicting with common wisdom ...
but it is NOT.



Longitudinal Expanding System



More initial Longitudinal pressure

Initially isotropic

Less initial Longitudinal pressure

→ **Higher and higher overpopulation**

Numerical solutions with longitudinal expansion

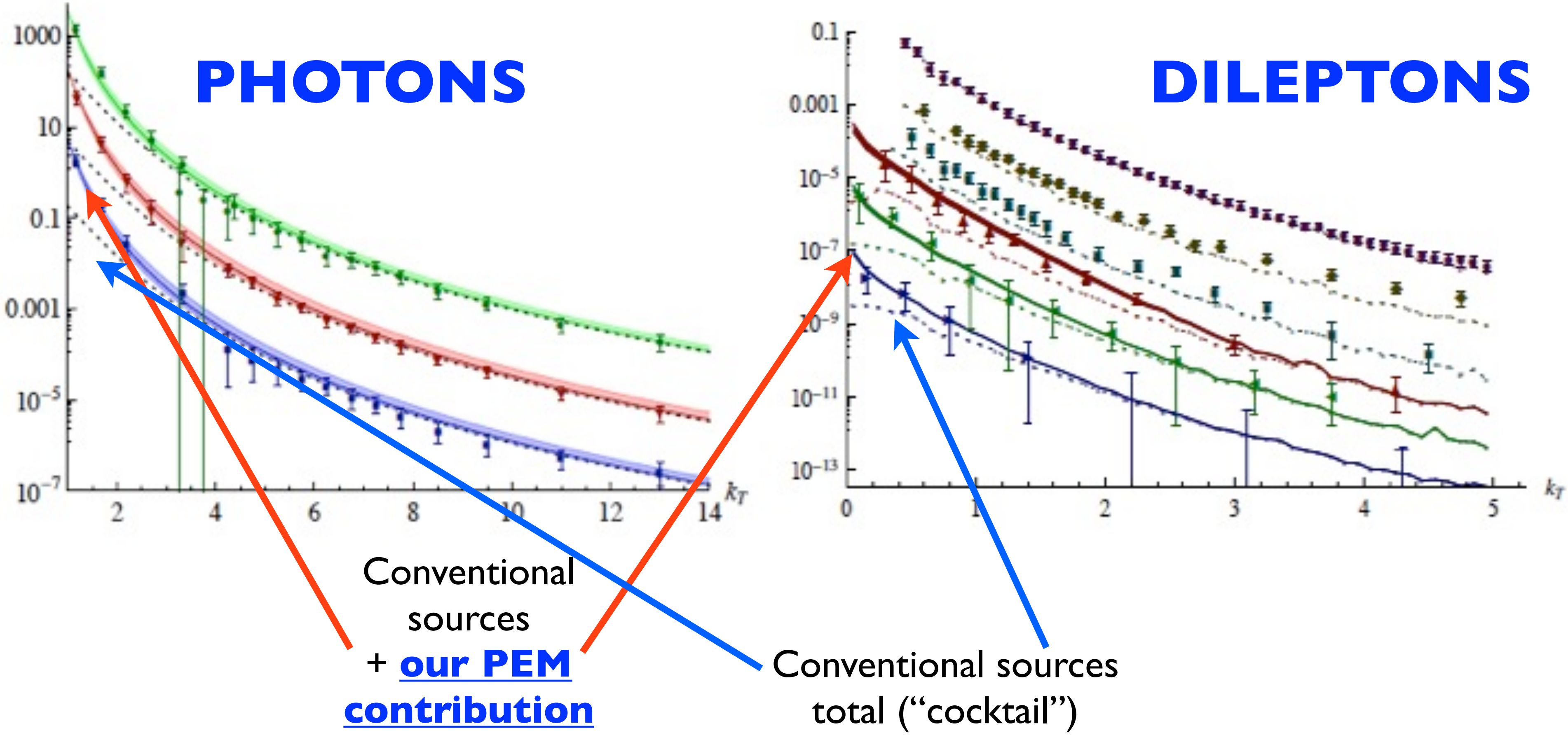
BLUE DIAMOND: ONSET

RED ASTERISK: NO ONSET

High enough initial occupation f_0~1 is able to compete with anisotropy and expansion to reach BEC onset!

Glow of the Pre-Equilibrium Matter

There should be additional EM emission from the pre-equilibrium stage.
We derived formula based on our thermalization scenario and describe interesting aspects of data.



Conventional sources + **our PEM contribution**

Conventional sources total (“cocktail”)

Important contributions to EM production from the pre-equilibrium matter !

Chiu, Hemmick, Khachatryan, Leonidov, JL, McLerran, arXiv:1202.3679, NPA

Summary

* Thermal QGP near Tc as a **topological matter,** dominated by emergent magnetic monopoles:

---- confinement as monopole BEC;

---- from RHIC to LHC, getting more viscous and less opaque.

* Chiral-restored QGP as a **chiral matter,** with macroscopic chirality created in local domains on E-by-E basis:

---- new anomalous effect Chiral Electric Separation Effect;

---- Chiral Magnetic Wave, manifested via pi+/- flow splitting.

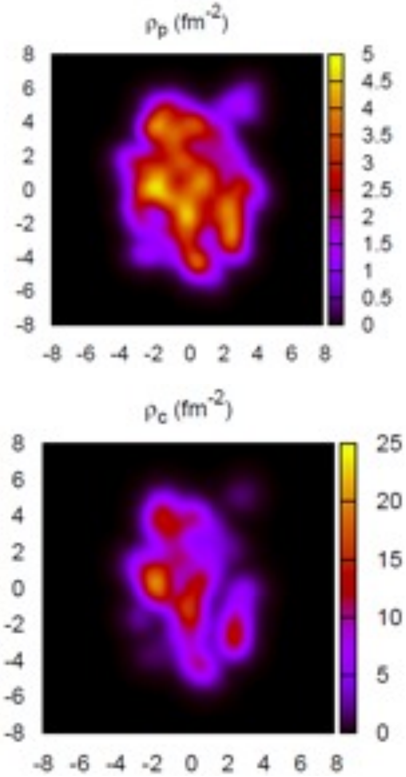
* The early time evolution in the **pre-equilibrium matter,** with **overpopulation** playing a key role:

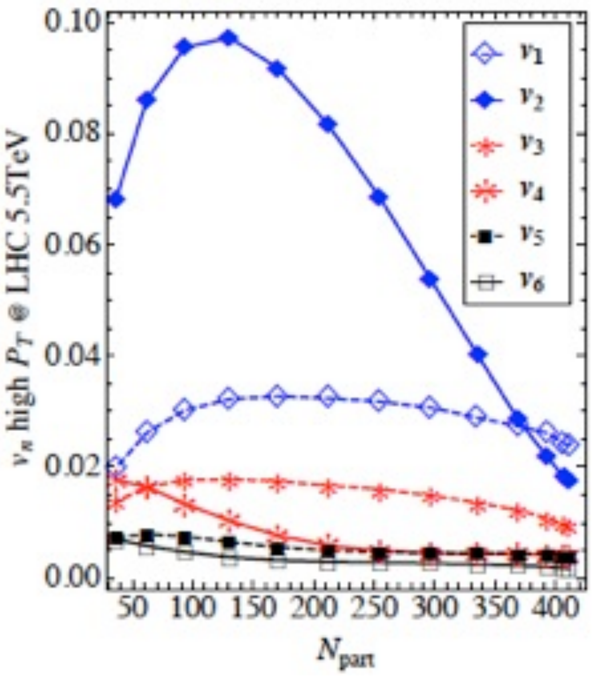
---- kinetic evolution & thermalization in overpopulated matter;

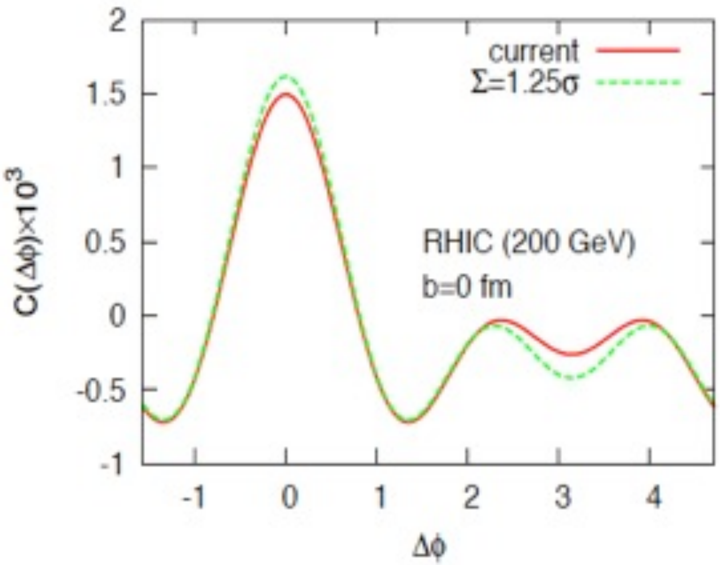
---- a possible transient Bose-Einstein Condensation.

Backup Slides

Harmonic Tomography







*** Jet also probes initial fluctuations -->**
harmonic tomography at high p_t;
*** Sensitive to initial states & energy loss models;**
*** Hard response & soft response to common initial geometry**
--> nontrival azimuthal correlations like hard ridge

X.Zhang & JL, PLB(2012), arXiv:1208.6361,1210.1245(PRC2013); arXiv:13 11.5463

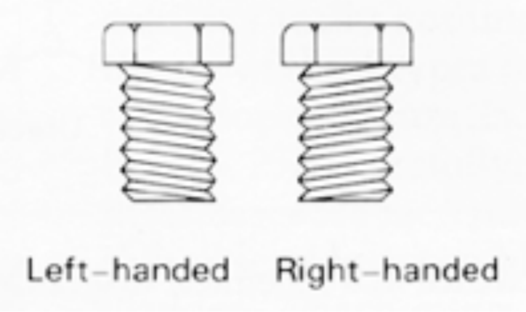
QGP WITH CHIRAL RESTORATION

In the QGP with chiral restoration, we have approximately chiral fermions (u,d quarks), with vector and axial currents

$$J_V^\mu = \bar{\Psi}\gamma^\mu\Psi \qquad J_A^\mu = \bar{\Psi}\gamma^\mu\gamma^5\Psi$$

$$J_V = J_R + J_L \ , \ J_A = J_R - J_L$$

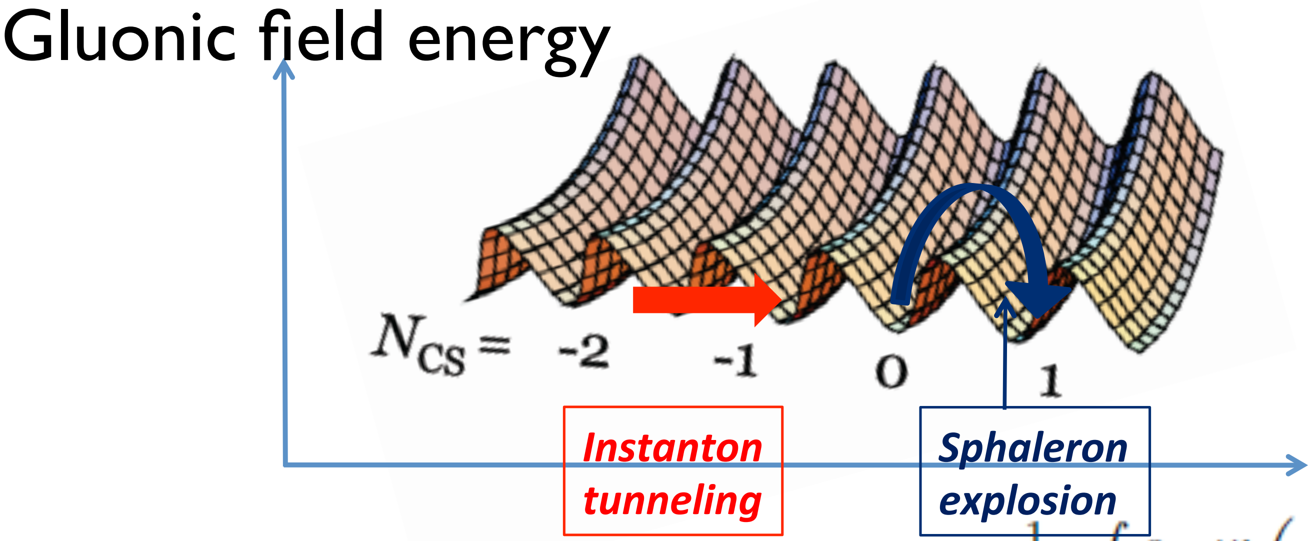
$$P : L \leftrightarrow R$$



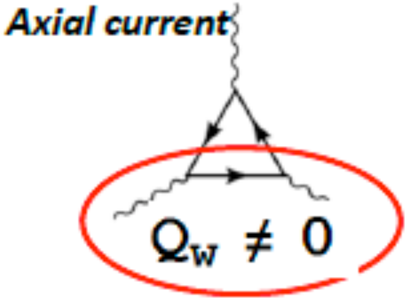
Normally the matter has zero macroscopic chirality: that is, the total numbers of L and R fermions are balanced.

Could a local domain with nonzero macroscopic chirality, that is, a *CHIRAL MATTER*, be created in heavy ion collisions?

Interplay of Topology & Anomaly



$$N_{CS} = \frac{1}{16\pi^2}\int d^3x\,\epsilon^{ijk}\left(A_i^a\partial_j A_k^a + \frac{1}{3}\epsilon^{abc}A_i^a A_j^b A_k^c\right)$$



$$\partial^\mu j^5_\mu = 2\sum_f m_f \langle \bar{\psi}_f i\gamma_5 \psi_f \rangle_A - \frac{N_f g^2}{16\pi^2} F^a_{\mu\nu}\tilde{F}^{\mu\nu}_a \sim \vec{E}^a \cdot \vec{B}^a$$

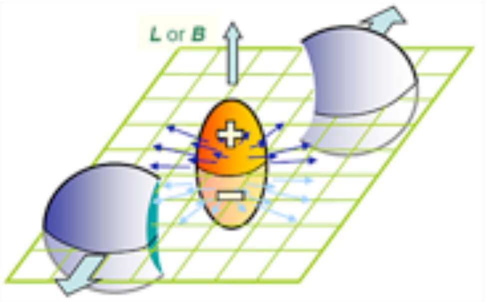
$$\boxed{(N_L^f - N_R^f) = 2Q_w}$$

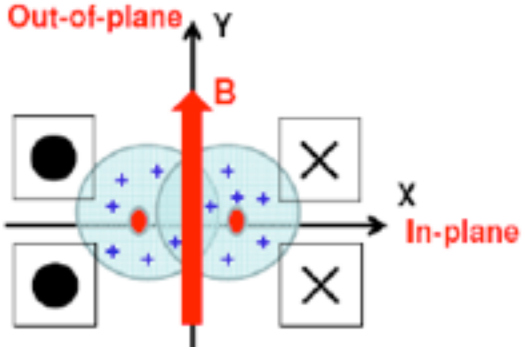
P & CP ODD

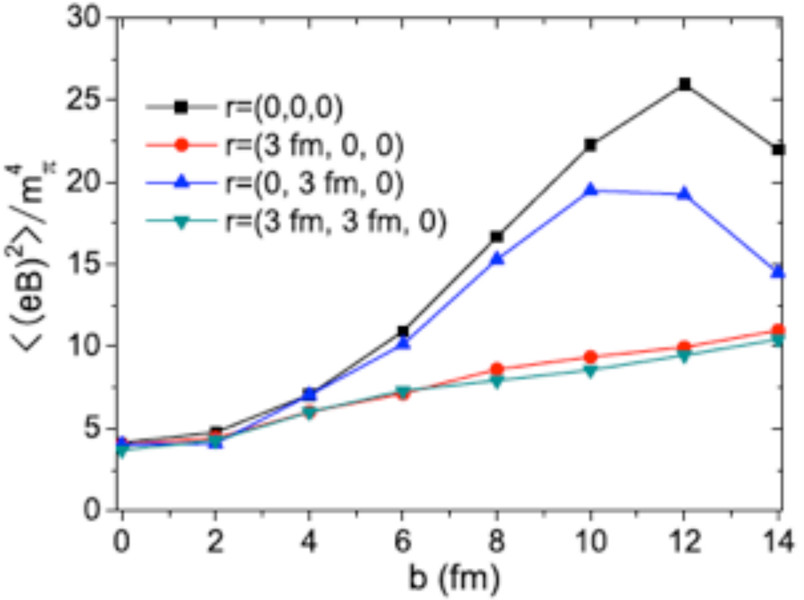
Nonzero topological charge generates chirality change

E-by-E creation of locally P- and CP-Odd environment: chiral medium.

Strong EM Fields in Heavy Ion Collisions







$$E, B \sim \gamma \frac{Z\alpha_{EM}}{R_A^2} \sim 3m_\pi^2$$

Earth	Common Magnet	Strongest Steady B-field	Compact Astro-objects	B field at RHIC	B-ometer (Gauss)
0.6	100	10^5	10^13-15	10^17	

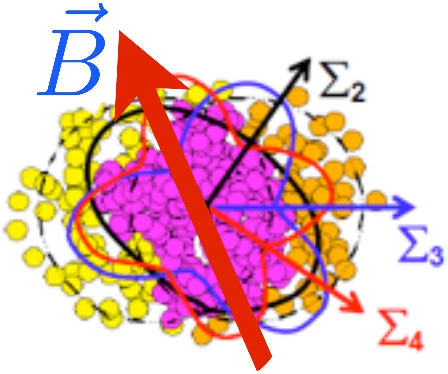
- Strongest B field (and strong E field as well) naturally arises!

[Kharzeev,McLerran,Warringa;Skokov,et al; Bzdak-Skokov; Deng-Huang; Bloczynski-Huang-Zhang-Liao;Tuchin; ...]

- “Out-of-plane” orientation (approximately)

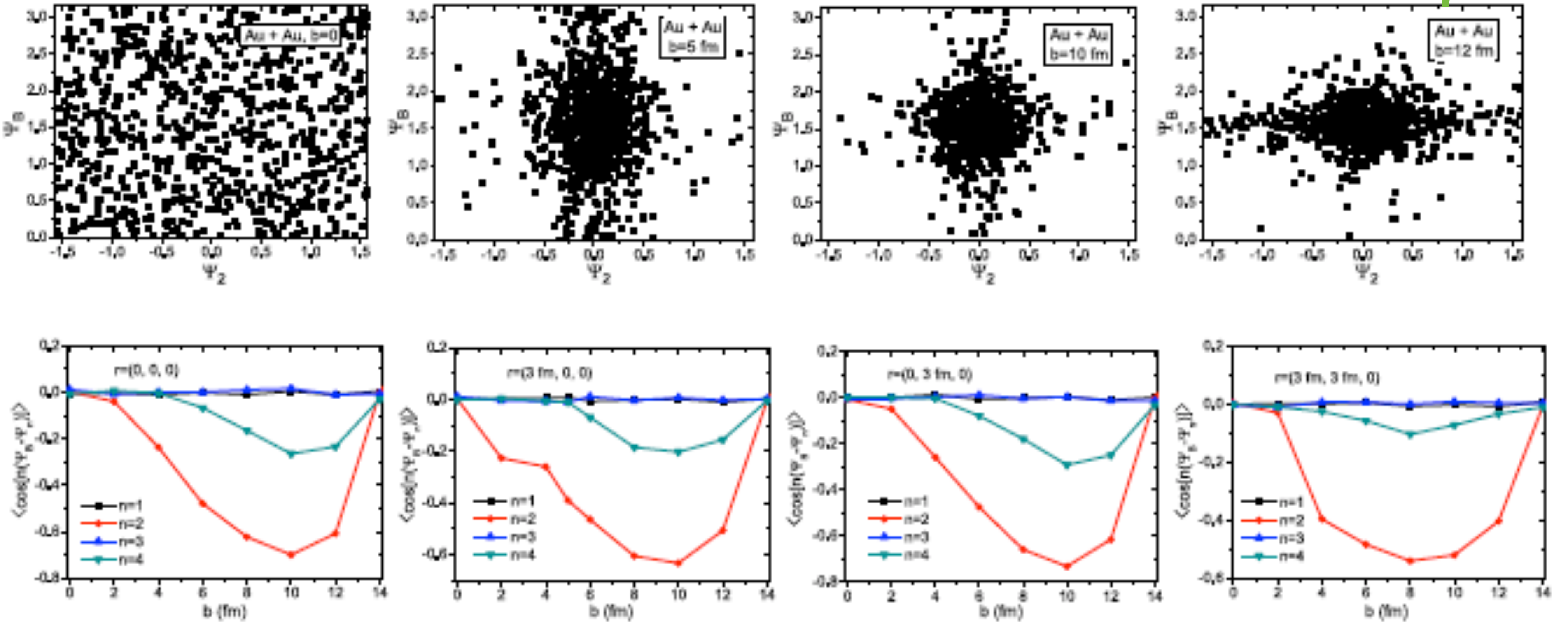
Azimuthal Fluctuations of B field

Both B field orientation and matter geometry fluctuates from event to event --- we need to know their correlations.



Central

Peripheral



Bloczynski, Huang, Zhang, JL, arXiv: 1209.6594, Phys. Lett. B

THE CMW WAVE EQUATIONS

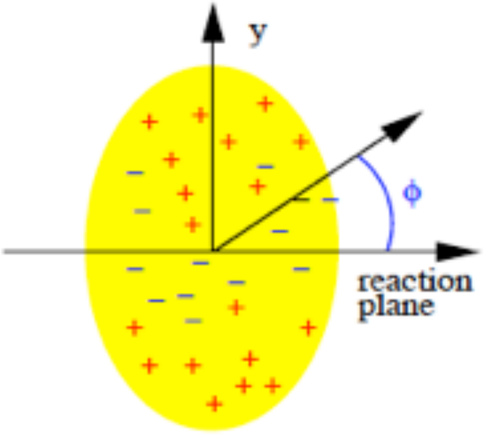
Coupling together the CME + CSE:
(using susceptibilities to relate chemical potential with charge density)

Combined with continuity equations we can get the CMW wave equation:
[Kharzeev & Yee, PRD83(2011)085007.]

$$\left(\partial_0 \mp v\partial_1\right) j^0_{L,R} = 0 \qquad v = \frac{N_c e B \alpha}{2\pi^2}$$

CMW Predictions:

[Burnier,Kharzeev,JL,Yee,PRL2011]



- * A Dipole of Axial Charge Distribution
- * A Quadrupole of Vector Charge Distribution

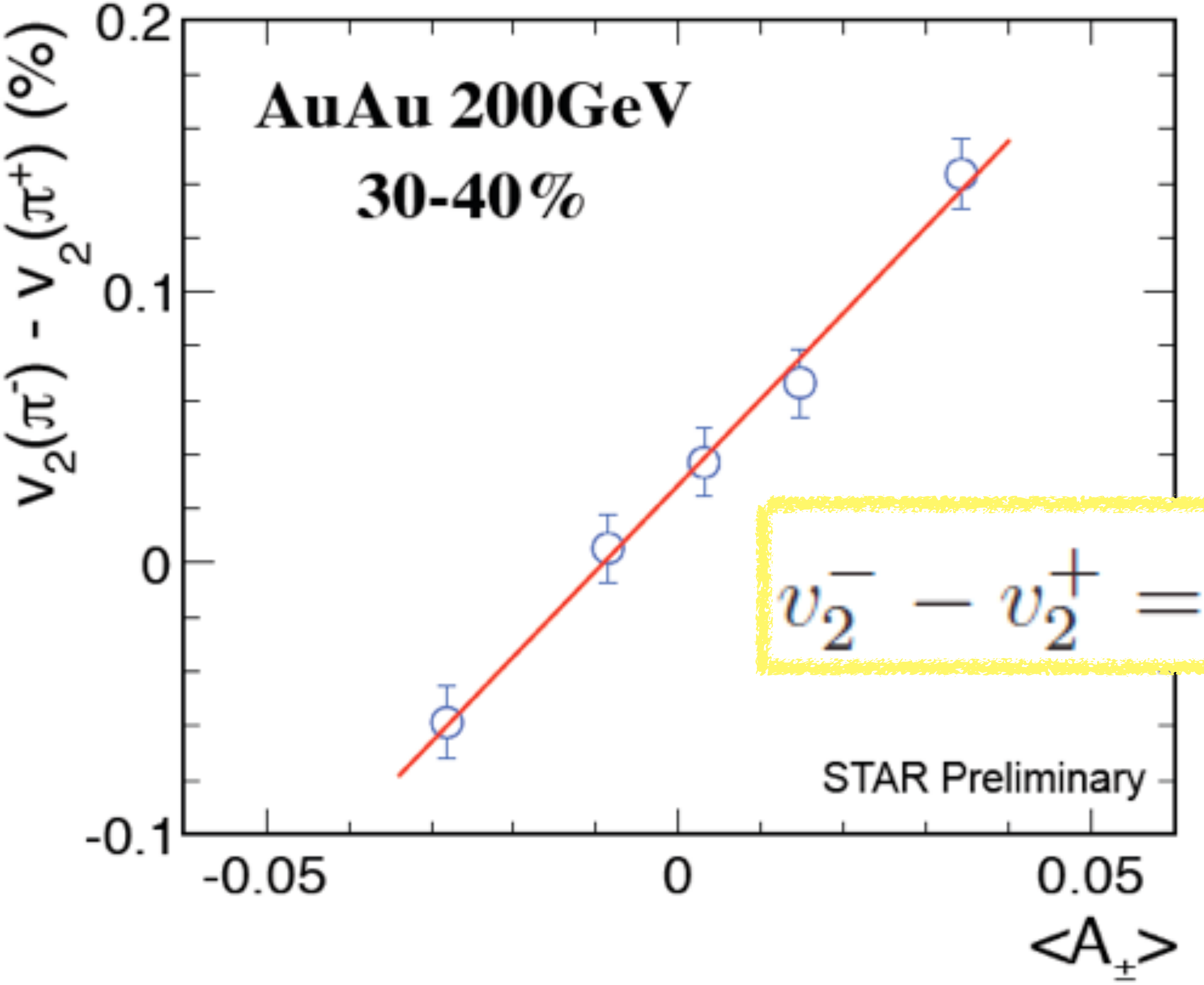
leads to ***splitting of +/- charge elliptic flow!***

The Minus v2 is bigger, and the splitting is proportional to net charge asymmetry

$$\boxed{v_2^- - v_2^+ = r_e A}$$

$$A = \frac{\bar{N}_+ - \bar{N}_-}{\bar{N}_+ + \bar{N}_-}$$

STAR MEASUREMENTS: BINNING THE CHARGE ASYM.

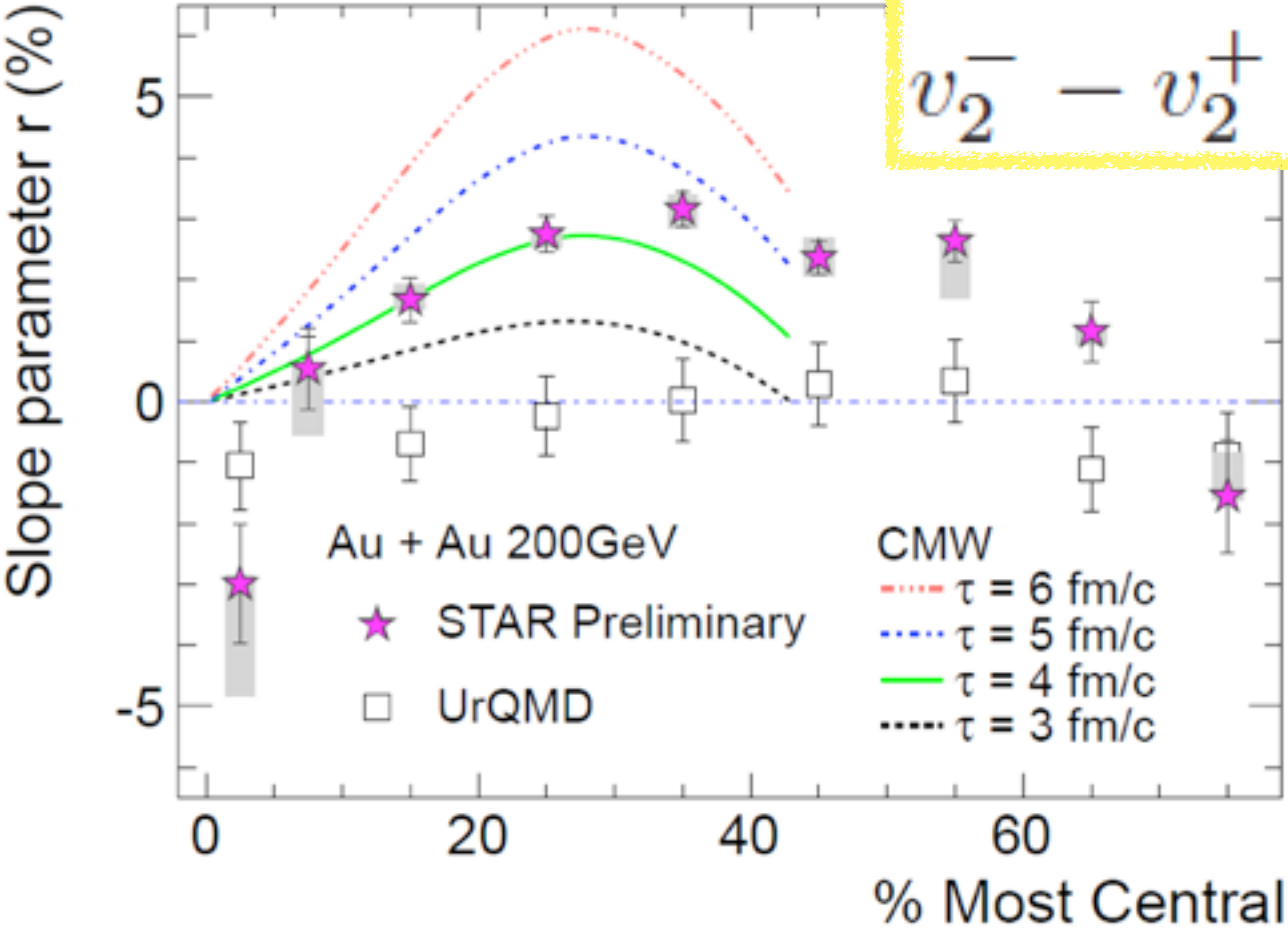


$$v_2^- - v_2^+ = r_e\, A$$

Gang Wang, QM2012

CENTRALITY DEPENDENCE OF CHARGE QUADRUPOLE

CMW Predictions [Burnier,Kharzeev,JL,Yee,PRL2011; arXiv:1208.2537]
In Agreement with STAR Data [Gang Wang, QM2012]



$$v_2^- - v_2^+ = \boxed{r_e} A$$

Gang Wang, QM2012

Thermalization: An Outstanding Puzzle

Ample Evidences of a thermal QGP:

chemical equilibrium freezeout; thermal photons;
hydrodynamical flow from very early time
(elliptic flow; sensitively preserve initial fluctuations)...

Strongly Interacting even before equilibrium:

short equilibration time;
longitudinal expansion makes system fall out of isotropy

"Tension" for understanding thermalization:

early time scale ~Qs is high, coupling NOT large;
weak-coupling-based understanding of initial states;

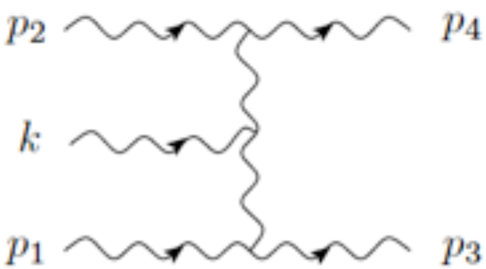
The thermalization problem presents:

* A significant gap in phenomenological description of heavy ion collision experiments;

* A great theoretical challenge to understand the far-from-equilibrium evolution in a non-Abelian gauge theory.

Elastic v.s. Inelastic Processes

The two rates are parametrically at the same order



$$\frac{1}{t_{scat}} \sim \alpha_s^{n+m-2} \left(\frac{\Lambda_s}{\alpha_s}\right)^{n+m-2} \left(\frac{1}{m^2}\right)^{n+m-4} \Lambda^{n+m-5}$$

$$m^2 \sim \Lambda_s \Lambda$$

$$\boxed{t_{\rm scat} = \frac{\Lambda}{\Lambda_{\rm s}^2},}$$

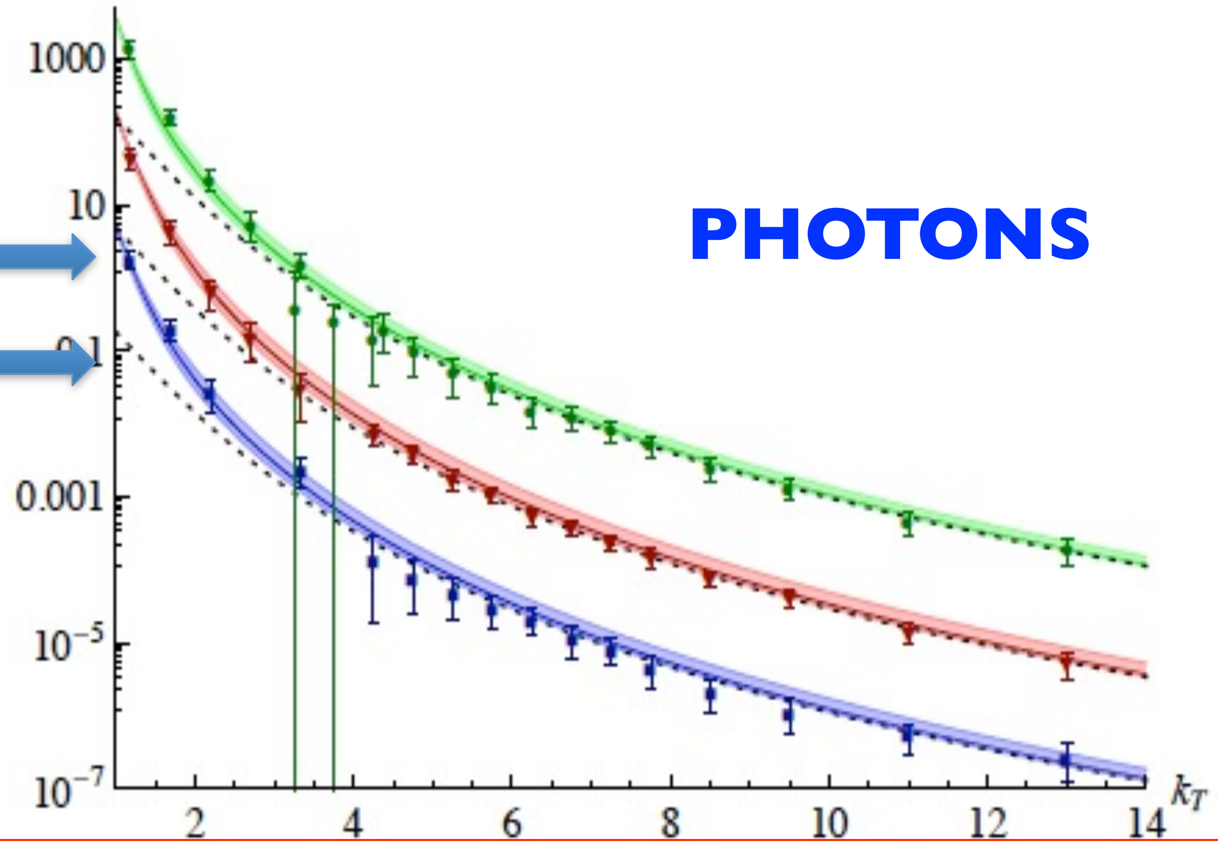
*With inelastic process, NO condensate will survive in the final thermal equilibrium.
* However a transient (out-of-equilibrium) condensate can occur. The issue at hand would rather be: if transient BEC occurs, and if the transient condensate persists for long.
* If the elastic is parametrically large than the inelastic, YES (e.g. the scalar field case).
*The case of gluons is a more complicated, and tough problem.

PHENOMENOLOGY: EM PRODUCTION IN THE PRE-EQUILIBRIUM MATTER

There should be additional EM emission from the pre-equilibrium stage
We derived fitting formula motivated by our thermalization scenario.

Conventional sources
+ **our PEM contribution**

Conventional
sources
total ("cocktail")



PHOTONS

Important contributions to EM production from the pre-equilibrium matter !

Chiu, Hemmick, Khachatryan, Leonidov, JL, McLerran, arXiv:1202.3679, NPA

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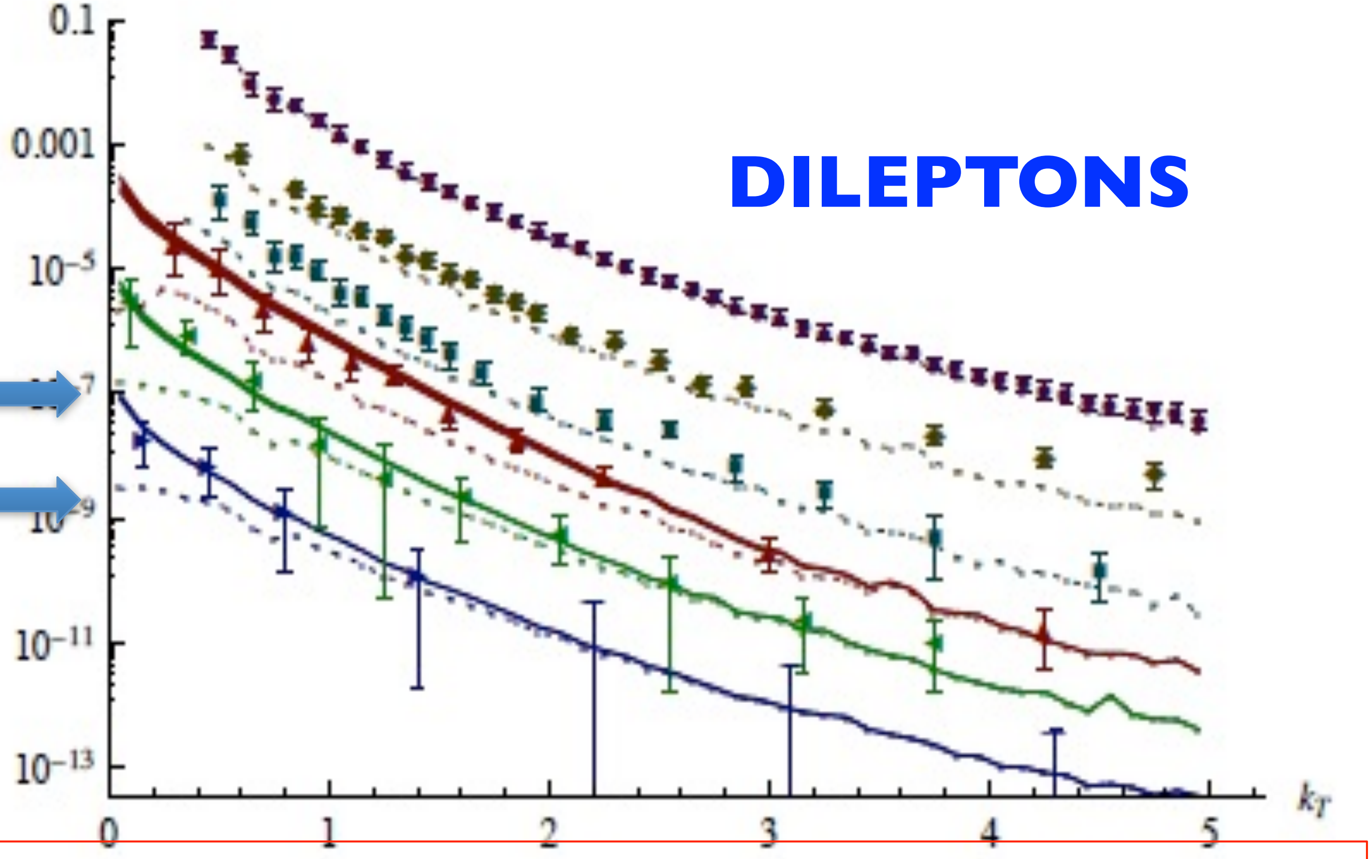

DILEPTONS

Conventional sources
+ **our PEM contribution**

Conventional sources total (“cocktail”)

Important contributions to EM production from the pre-equilibrium matter !

Chiu, Hemmick, Khachatryan, Leonidov, JL, McLerran, arXiv:1202.3679, NPA