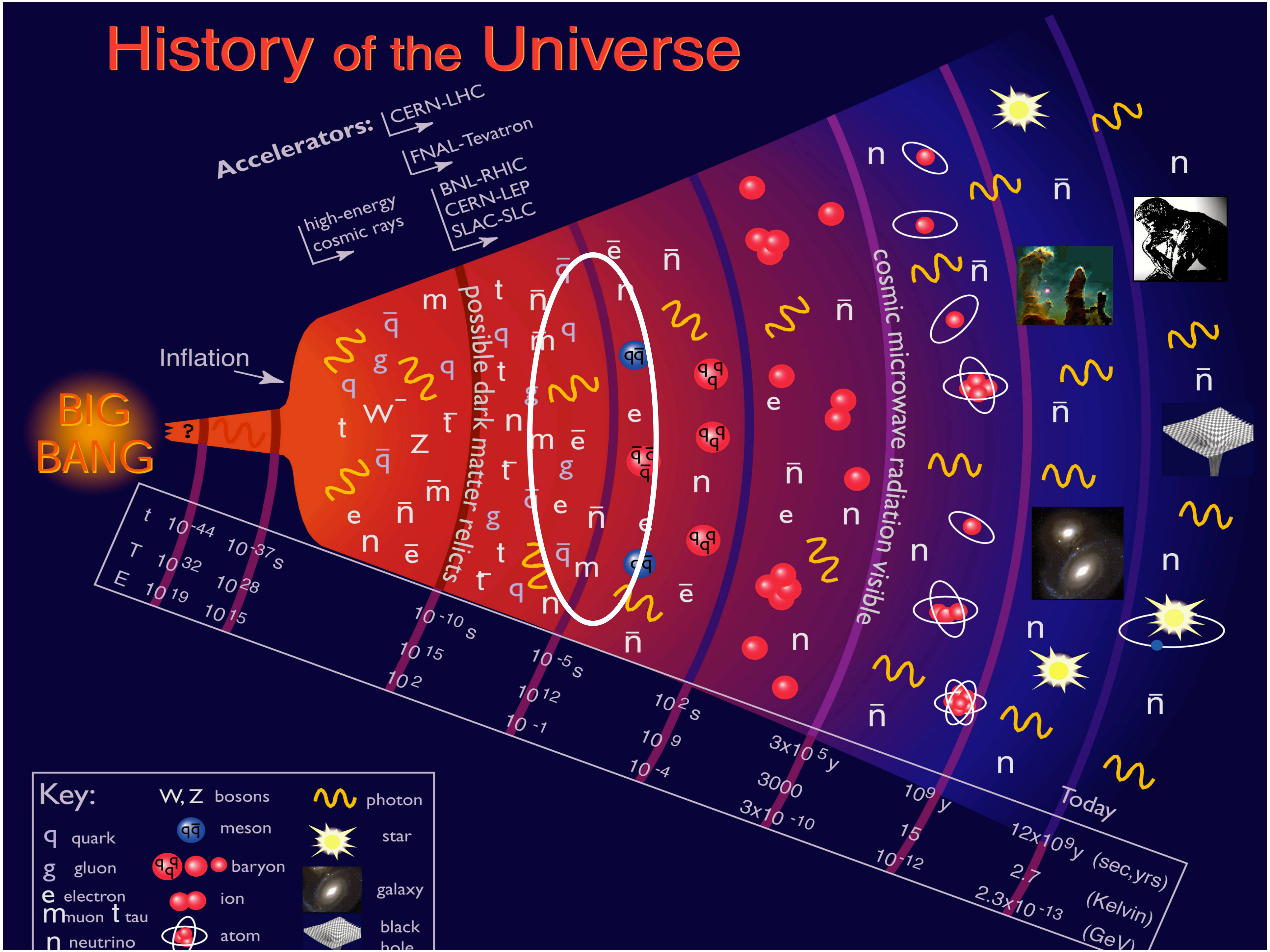
How hot glue becomes a perfect fluid: the problem of thermalization in heavy-ion collisions

Raju Venugopalan

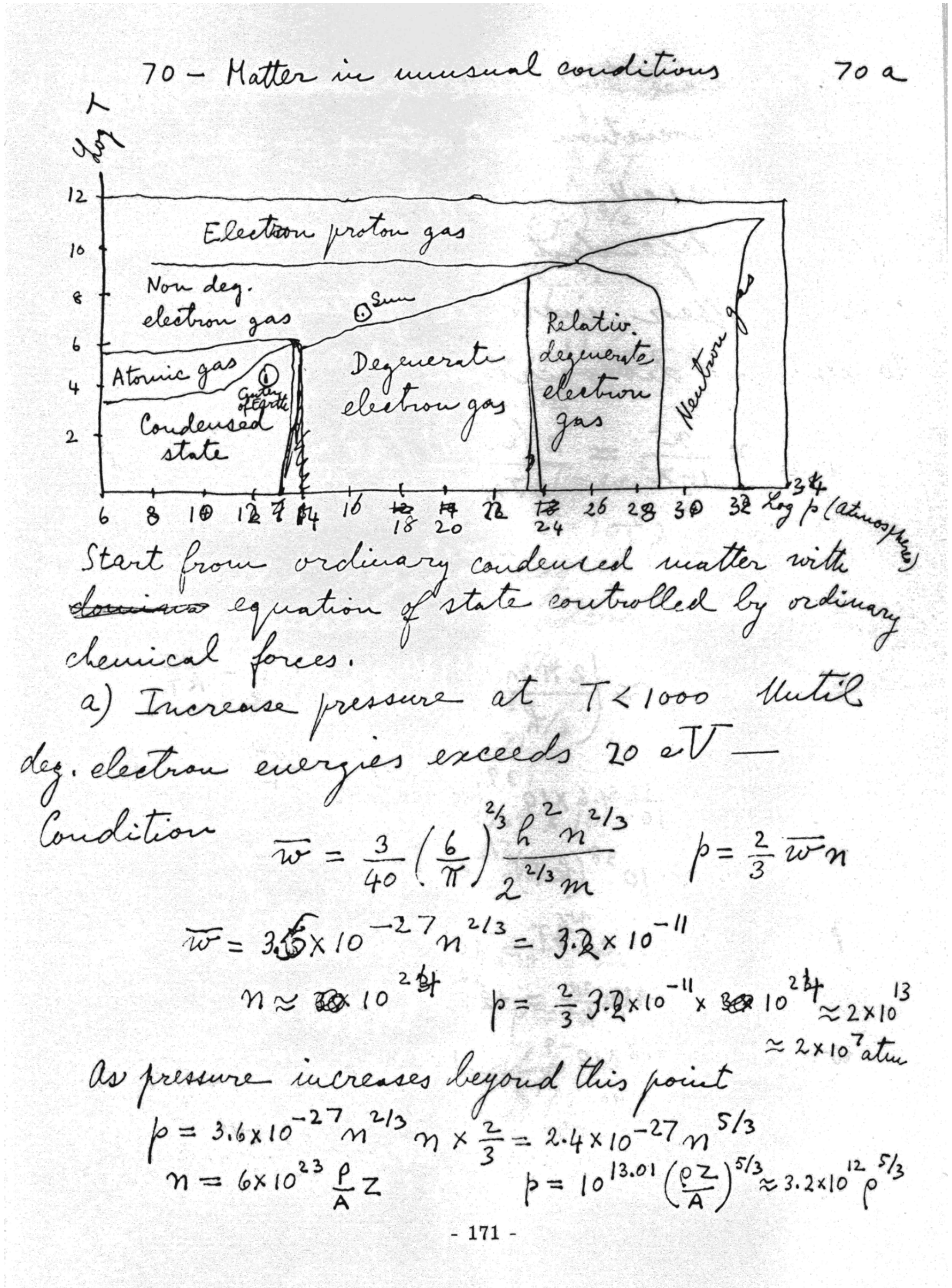
BNL / Heidelberg Univ.

DESY Seminar, April 2016


History of the Universe
Accelerators:
CERN-LHC
FNAL-Tevatron
BNL-RHIC
CERN-LEP
SLAC-SLC
high-energy cosmic rays
Inflation
BIG BANG
?
possible dark matter relicts
cosmic microwave radiation visible
t 10-44 10-37 s
T 10 32 10 28
E 10 19 10 15
10 -10 s
10 15
10 2
10 -5 s
10 12
10 -1
10 2 s
10 9
10 -4
3x10 5 y
3000
3x10 -10
10 9 y
15
10 -12
Today
12x10 9 y (sec,yrs)
2.7 (Kelvin)
2.3x10 -13 (GeV)
Key:
q quark
g gluon
e electron
m muon t tau
n neutrino
W, Z bosons
meson
baryon
ion
atom
photon
star
galaxy
black hole

Matter in unusual conditions

E. Fermi: " Notes on Thermodynamics and Statistics " (1953)



Start from ordinary condensed matter with ~~[illegible]~~ equation of state controlled by ordinary chemical forces.

a) Increase pressure at $T < 1000$ until deg. electron energies exceeds 20 eV —

Condition $\bar{w} = \frac{3}{40}\left(\frac{6}{\pi}\right)^{2/3}\frac{h^2 n^{2/3}}{2^{2/3} m}$ $\quad p = \frac{2}{3}\bar{w} n$

$\bar{w} = 3.6 \times 10^{-27} n^{2/3} = 3.2 \times 10^{-11}$

$n \approx$ [illegible] $\times 10^{24}$ $\quad p = \frac{2}{3} 3.2 \times 10^{-11} \times$ [illegible] $10^{24} \approx 2 \times 10^{13}$

$\approx 2 \times 10^{7}$ atm

As pressure increases beyond this point

$p = 3.6 \times 10^{-27} n^{2/3} n \times \frac{2}{3} = 2.4 \times 10^{-27} n^{5/3}$

$n = 6 \times 10^{23} \frac{\rho}{A} Z$ $\quad p = 10^{13.01}\left(\frac{\rho Z}{A}\right)^{5/3} \approx 3.2 \times 10^{12} \rho^{5/3}$

On heating strongly interacting matter

A limiting temperature for hadron matter?

The apparent exponential increase in the density of hadron states suggested that the pressure of strongly interacting matter diverged at a limiting "Hagedorn" temperature

Thus, our ignorance of microscopic physics stands as a veil, obscuring our view of the very beginning.

Steven Weinberg, The First Three Minutes (1973)

QCD : brief pre/post-history

From E. Fermi: " Notes on Thermodynamics and Statistics " (1953)

↓

Hagedorn (1965)

↓

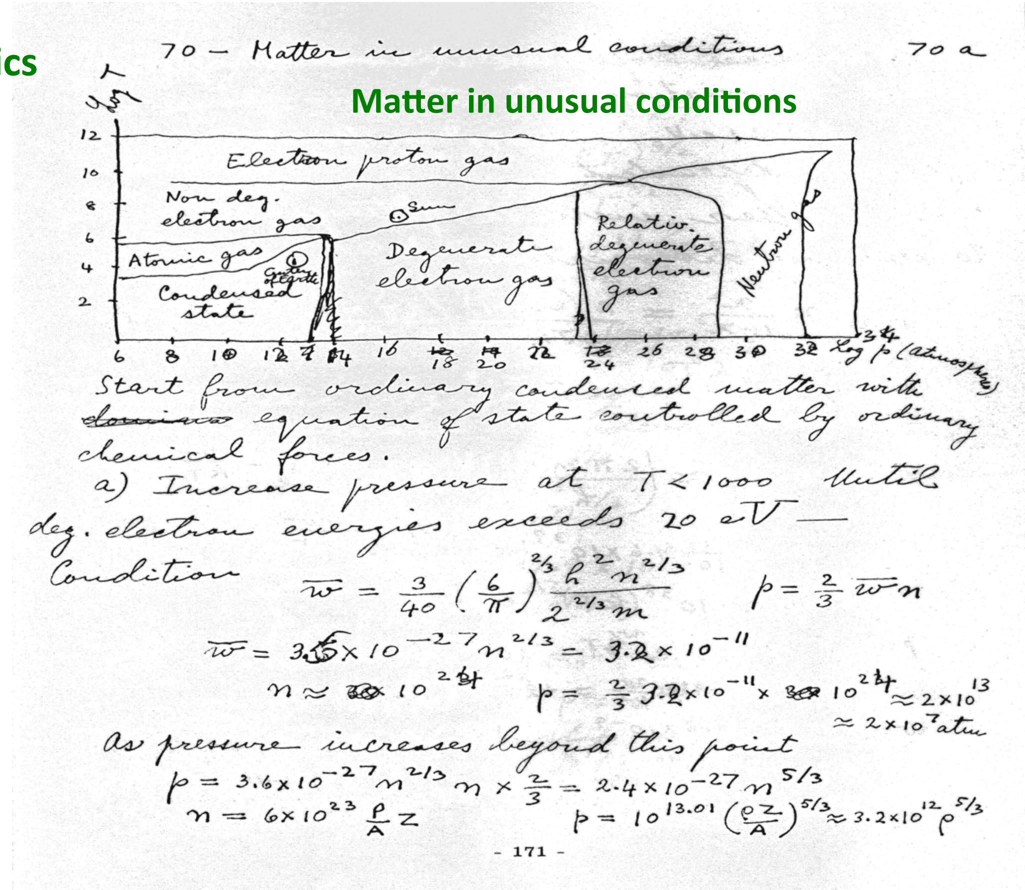
Lee-Wick matter (1974)

↓

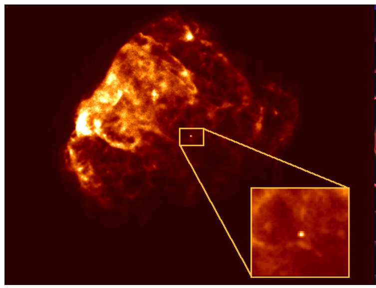
Collins-Perry/Cabibbo-Parisi (1975)

↓

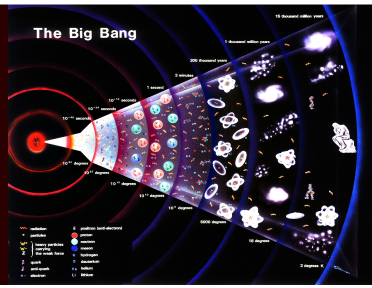
Quark-Gluon Plasma (QGP)
Shuryak (1978)



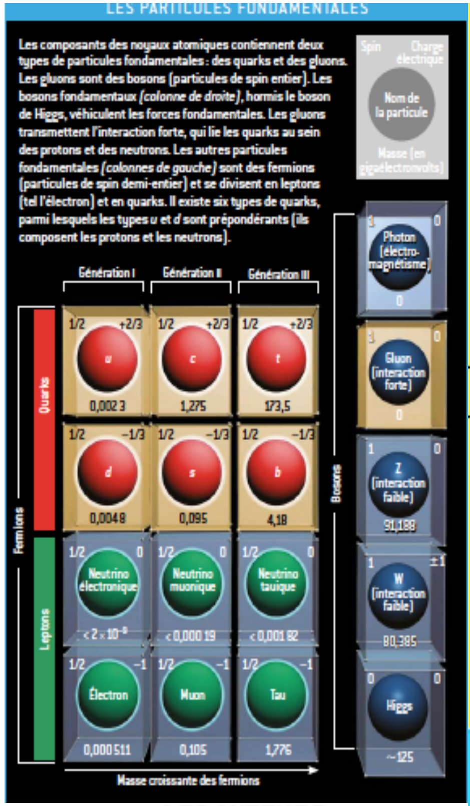
Neutron Stars



Big Bang



RHIC



■ LES AUTEURS

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Thomas ULLRICH est chercheur au Laboratoire américain de Brookhaven et à l'université Yale.

Raju VENUGOPALAN dirige le groupe de théorie nucléaire au Laboratoire américain de Brookhaven.

Also,Spektrum der Wissenshaft, December 2015

QCD: structure & consequences

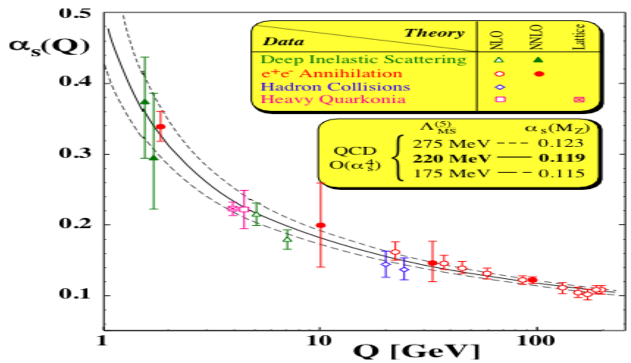
Asymptotic freedom:

S: Coupling strength of quarks and gluons weaker at short separation

C: Super-dense & super-hot QCD matter is weakly coupled gas of quarks & gluons

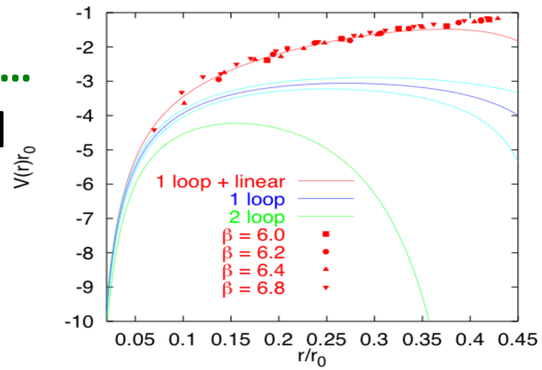
Collins-Perry (1975); Cabibo-Parisi (1975)

Gross, Wilczek, Politzer (1973)



Infrared slavery: Wilson (1974), Polyakov, …

S: Linear growth of static quark-anti-quark potential at large separation-intuitive picture of confinement

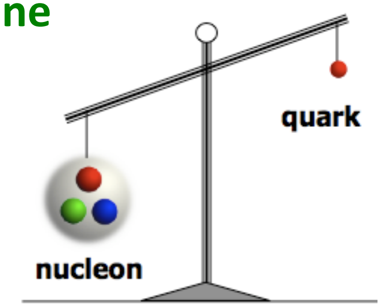


C: QCD matter is strongly interacting at lower temp. & density- Rich QCD Phase Diagram

(Broken) Chiral symmetry

Nambu-Goldstone

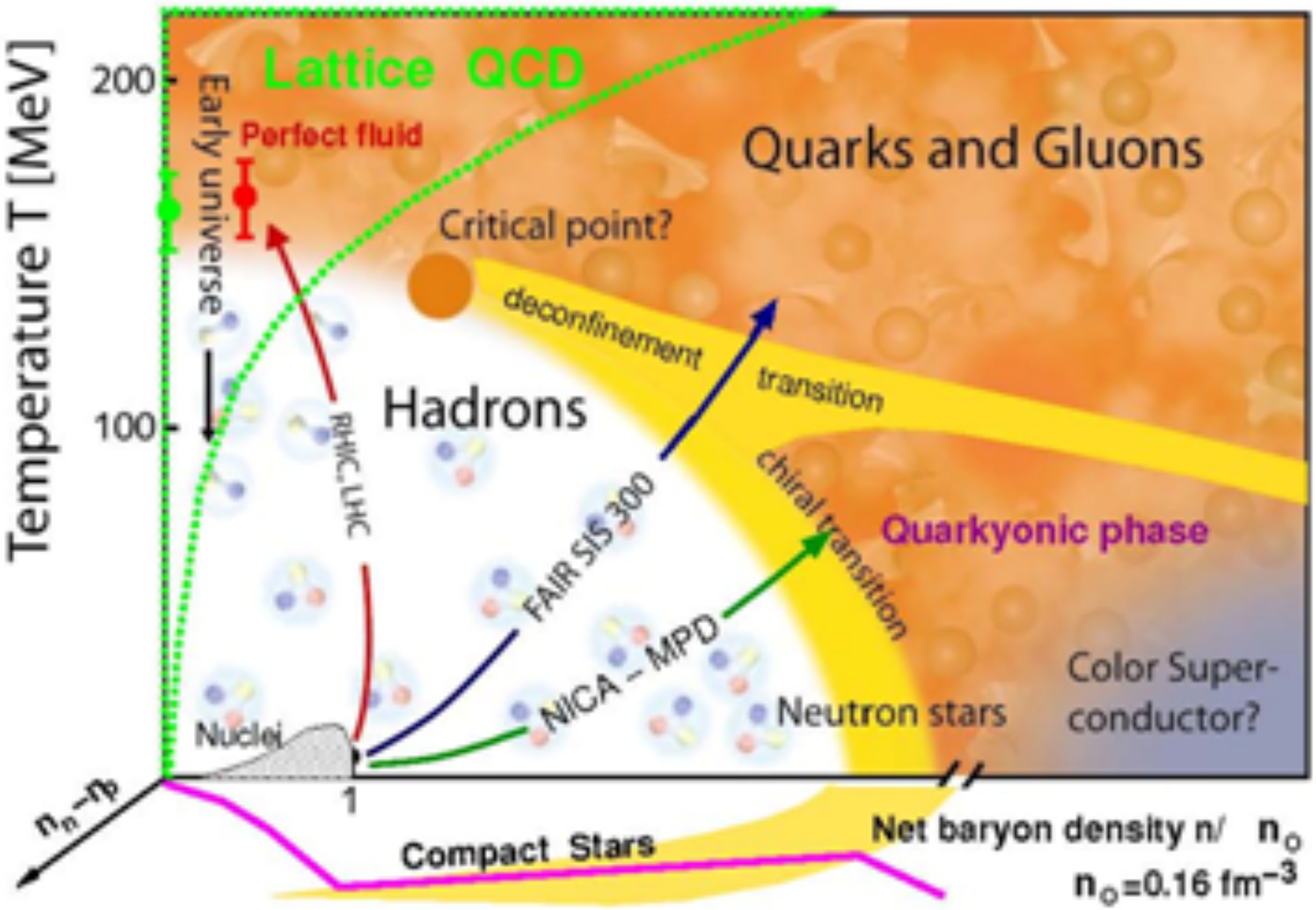
$$\langle \bar{q}_R q_L \rangle \neq 0$$



S: spontaneously generated Chiral condensate

C: Chiral symmetry restored at finite T

QCD phase diagram



Heavy Ion Experiments

Facility	Location	System	Energy (CMS)
AGS	BNL, New York	Au+Au	2.6-4.3 GeV
SPS	CERN, Geneva	Pb+Pb	8.6-17.2 GeV
RHIC	**BNL, New York**	**Au+Au**	**200 GeV**
LHC	CERN, Geneva	Pb+Pb	5.5 TeV

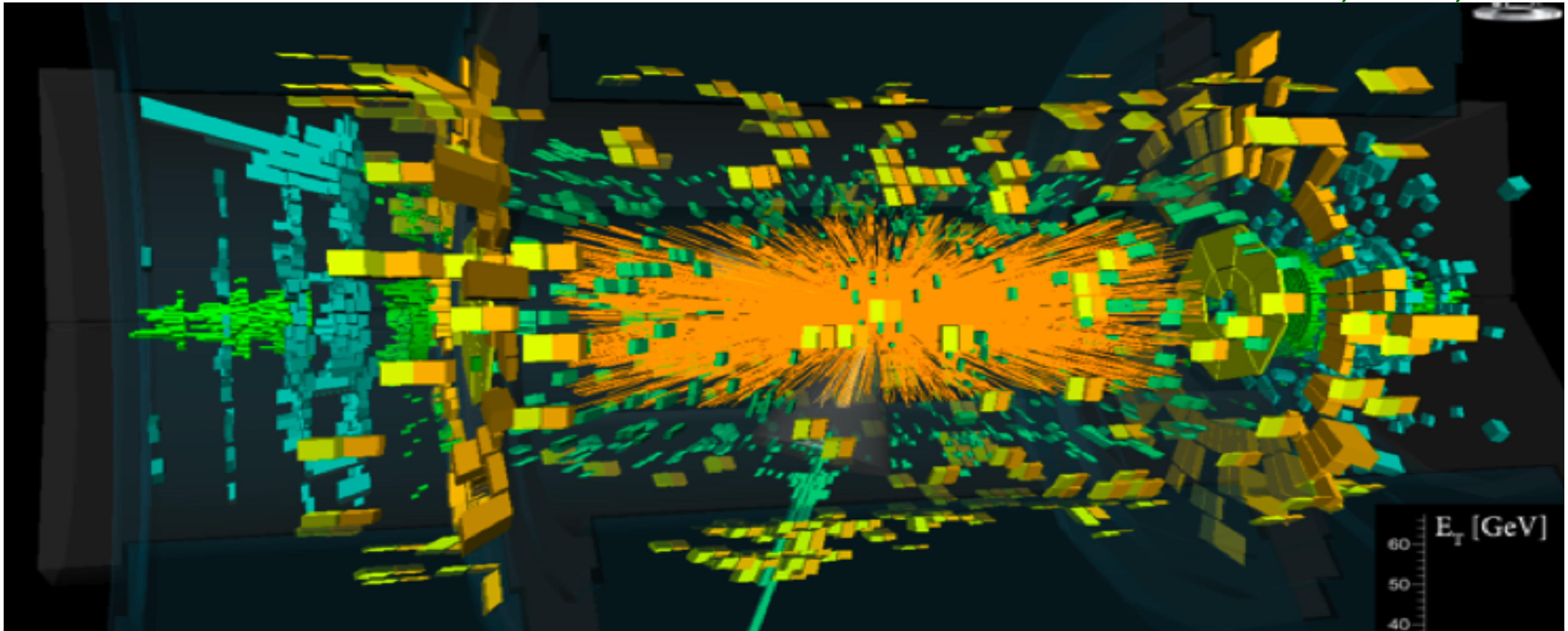
Traditional picture of heavy ion collisions

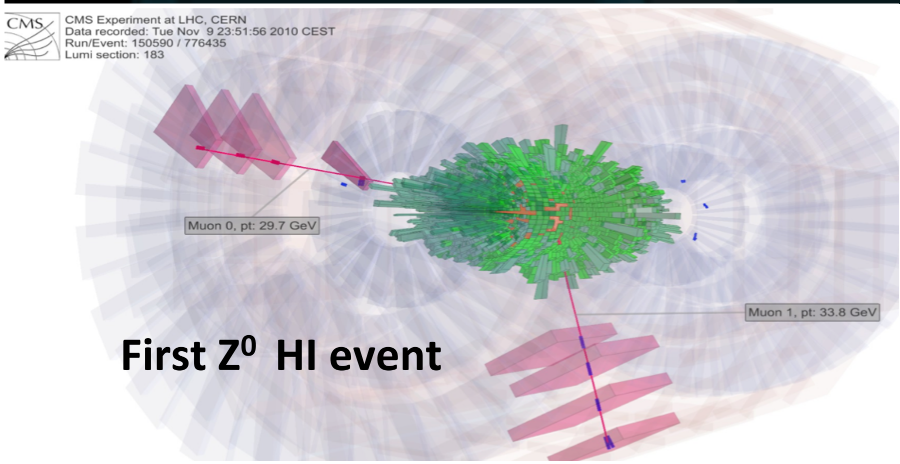
***@$#! on *@$#!**

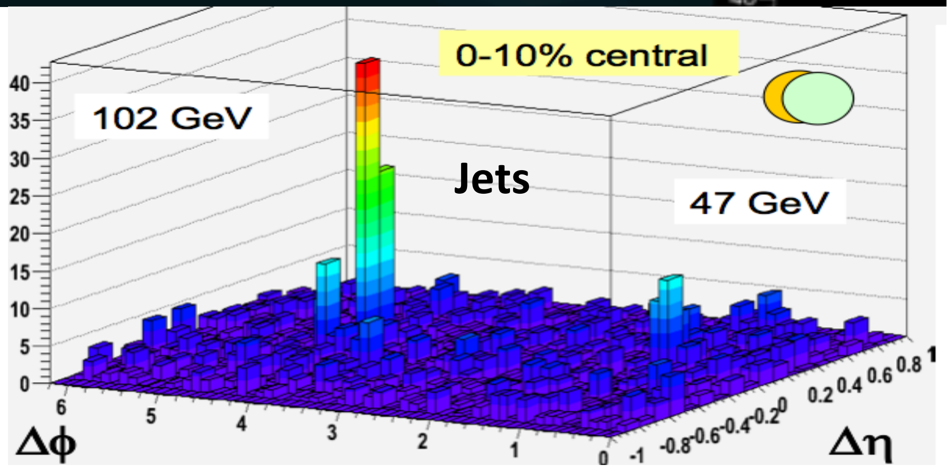
Well known particle physicist (circa early 1990s)

A contemporary view

CERN seminar, Dec. 2nd, 2010

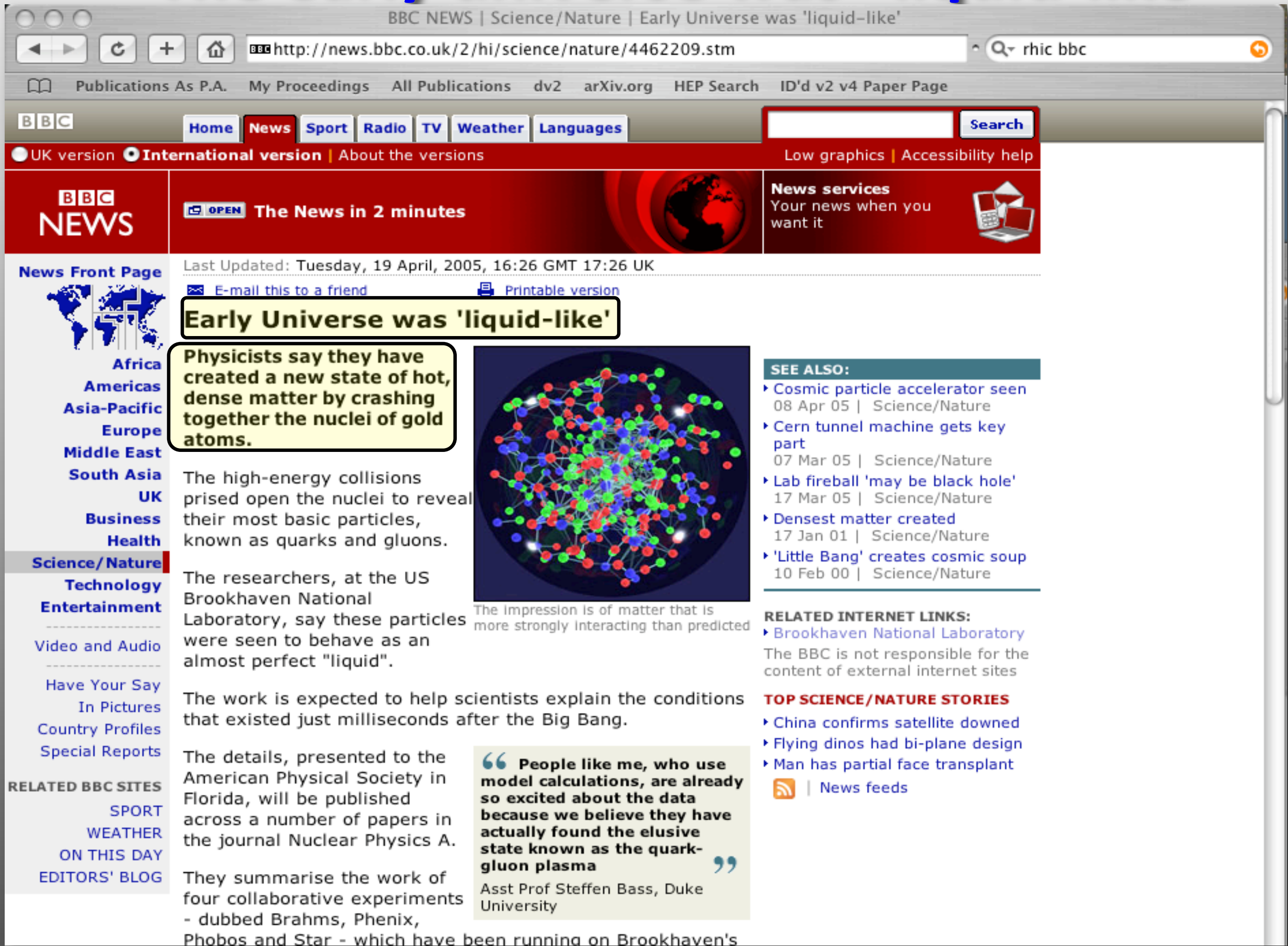






the universe a micro-second after the Big Bang was similar stuff and had the same temperature

"The early universe was "liquid-like"



BBC NEWS | Science/Nature | Early Universe was 'liquid-like'

http://news.bbc.co.uk/2/hi/science/nature/4462209.stm

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Last Updated: Tuesday, 19 April, 2005, 16:26 GMT 17:26 UK

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Early Universe was 'liquid-like'

Physicists say they have created a new state of hot, dense matter by crashing together the nuclei of gold atoms.

The high-energy collisions prised open the nuclei to reveal their most basic particles, known as quarks and gluons.

The researchers, at the US Brookhaven National Laboratory, say these particles were seen to behave as an almost perfect "liquid".

The impression is of matter that is more strongly interacting than predicted

The work is expected to help scientists explain the conditions that existed just milliseconds after the Big Bang.

The details, presented to the American Physical Society in Florida, will be published across a number of papers in the journal Nuclear Physics A.

"People like me, who use model calculations, are already so excited about the data because we believe they have actually found the elusive state known as the quark-gluon plasma"

Asst Prof Steffen Bass, Duke University

They summarise the work of four collaborative experiments - dubbed Brahms, Phenix, Phobos and Star - which have been running on Brookhaven's

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A perfect fluid at RHIC

"Bjorken Hydrodynamics"

$$\frac{d\varepsilon}{d\tau} = -\frac{\left(\varepsilon + P - \frac{4}{3}\frac{\eta}{\tau}\right)}{\tau}$$

Viscous term smaller than ideal term for

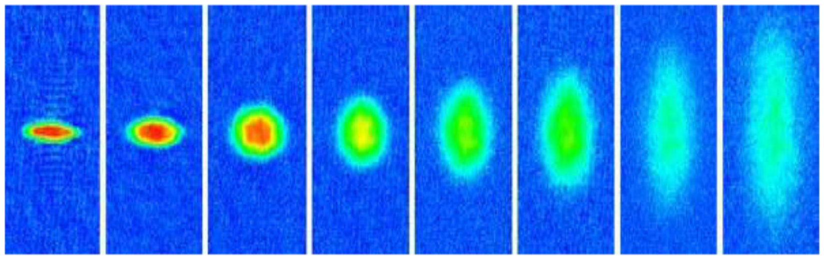
$$\frac{\eta}{\varepsilon + P}\frac{1}{\tau} \equiv \frac{\eta}{s}\frac{1}{\tau T} << 1$$

From kinetic theory

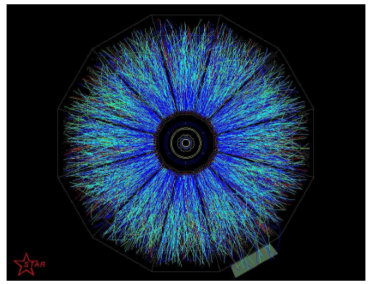
$$\frac{\eta}{s} \sim \frac{\hbar}{k_B}\frac{\tau_{\text{relax.}}}{\tau_{\text{quant.}}}$$

H_2O

^4He



^6Li



sQGP

A perfect fluid at RHIC (and LHC)

"Bjorken Hydrodynamics"

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From kinetic theory

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Fluid	T [K]	η [$Pa \cdot s$]	η/n [$\hbar$]	η/s [$\hbar/k_B$]
H_20	370	2.9×10^{-4}	85	8.2
^4He	2	1.2×10^{-6}	0.5	1.9
^6Li ($\lvert a_s \rvert \simeq \infty$)	23×10^{-6}	$\leq 1.7 \times 10^{-15}$	≤ 1	≤ 0.5
QGP	2×10^{12}	$\leq 5 \times 10^{11}$	-	≤ 0.4

A perfect fluid at RHIC (and LHC)

"Bjorken Hydrodynamics"

$$\frac{d\varepsilon}{d\tau} = -\frac{\left(\varepsilon + P - \frac{4}{3}\frac{\eta}{\tau}\right)}{\tau}$$

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$$\frac{\eta}{\varepsilon + P}\frac{1}{\tau} \equiv \frac{\eta}{s}\frac{1}{\tau T} << 1$$

From kinetic theory

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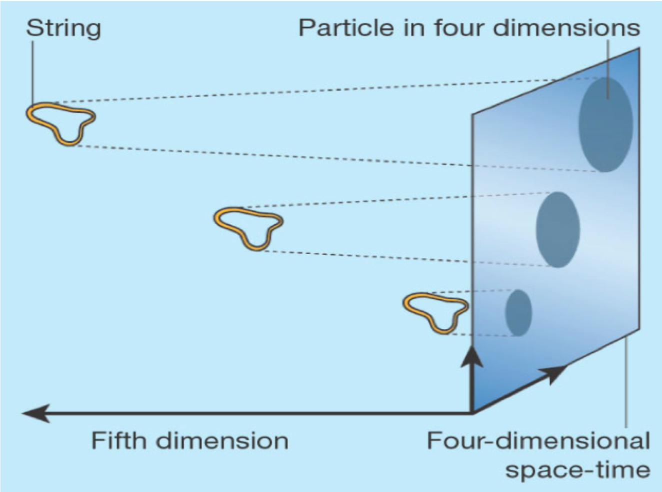
QGP is ~ 10^4 times more viscous than pitch tar…

Viscosity of strongly coupled relativistic fluids

AdS/CFT conjecture:

Duality between strongly coupled N=4 supersymmetric Yang-Mills theory at large coupling and Nc & classical 10 dimensional gravity in the background of D3 branes



J.Maldacena, Nature 2003

KSS bound:
Conjectured lower bound for a ``perfect fluid"

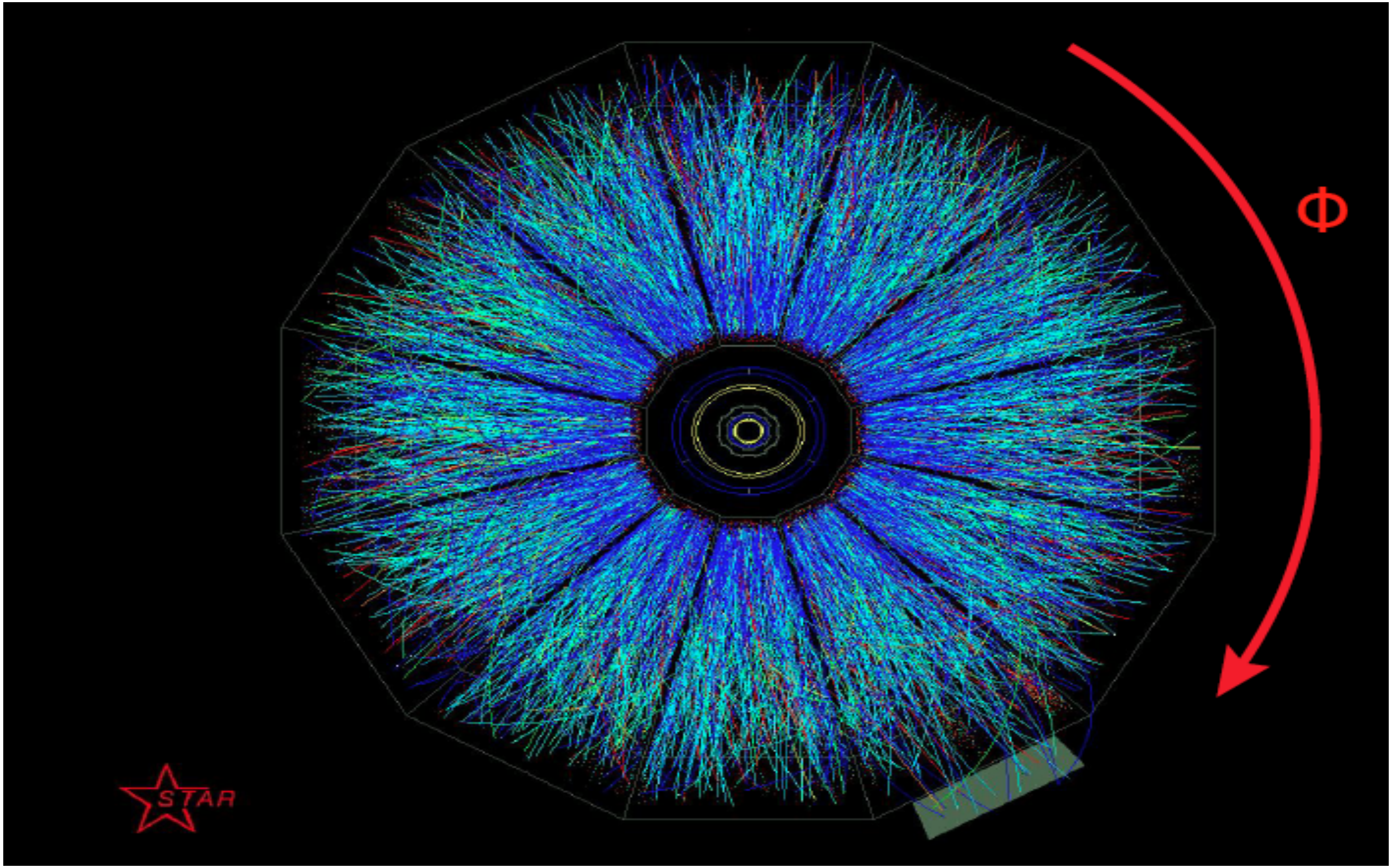
Kovtun,Son,Starinets (2006)

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

Derived using classical absorption cross-section of a graviton with energy ω on a black brane and Bekenstein's formula relating its Entropy to its area

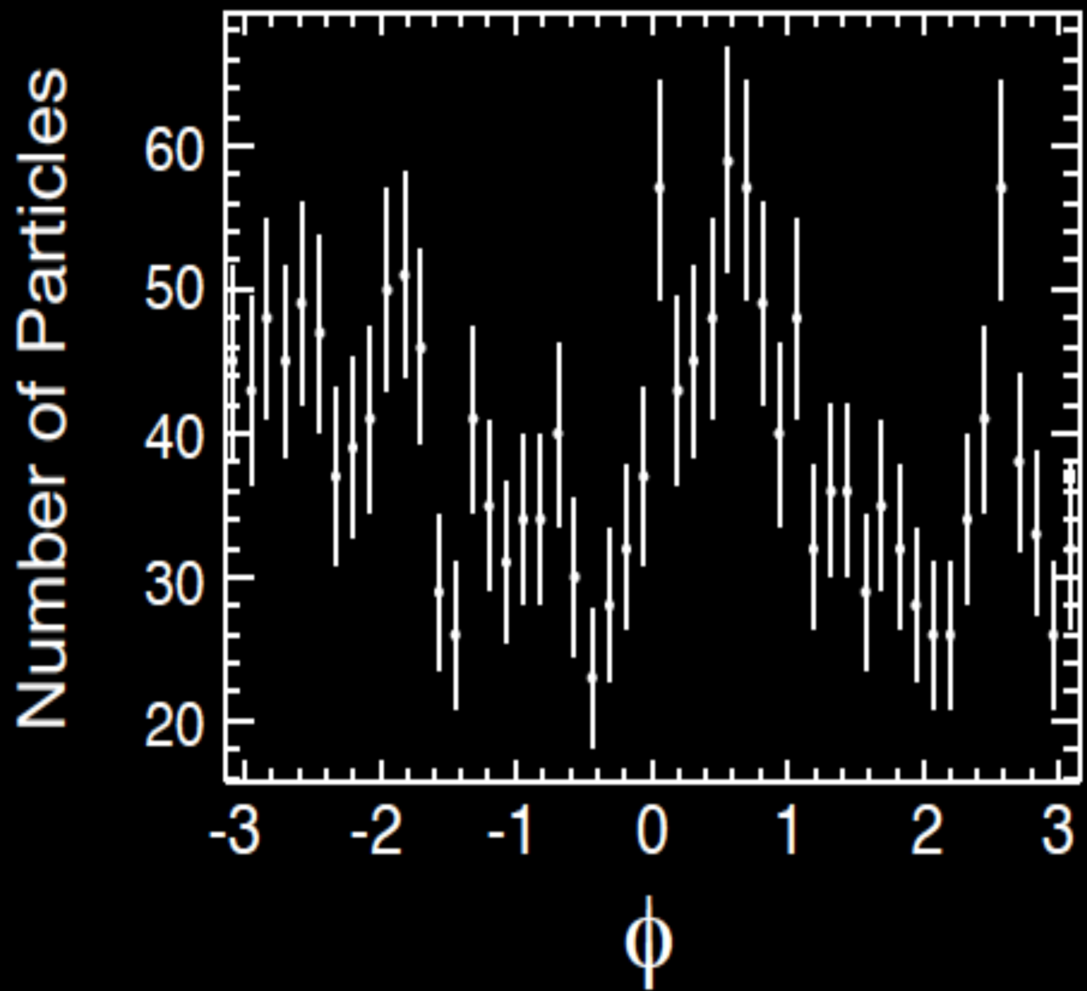
$$\sigma(\omega) = \frac{8\pi G}{\omega}\int dt d\mathbf{x}\, e^{i\omega t}\langle[T_{xy}(t,\mathbf{x}), T_{xy}(0,0)]\rangle$$

Deconstructing lumpiness



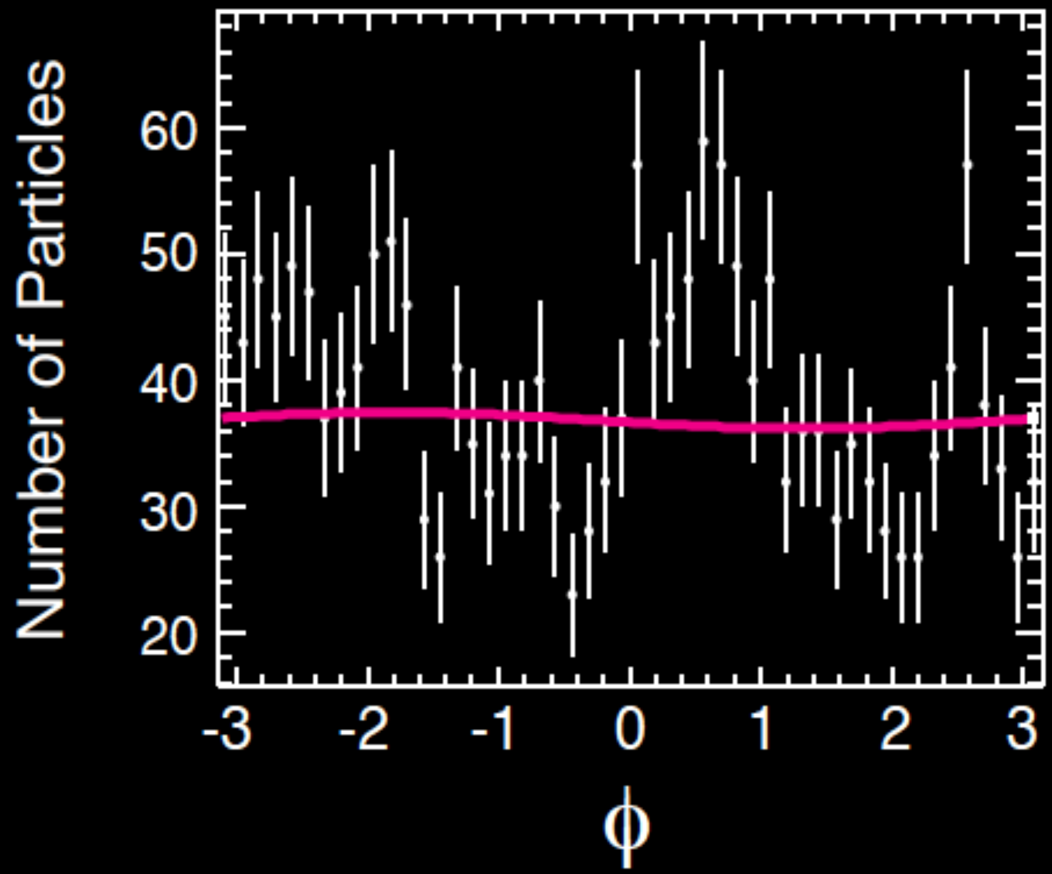
ANGULAR PARTICLE DISTRIBUTION

EXPERIMENTAL DATA: ATLAS COLLABORATION



ANGULAR PARTICLE DISTRIBUTION

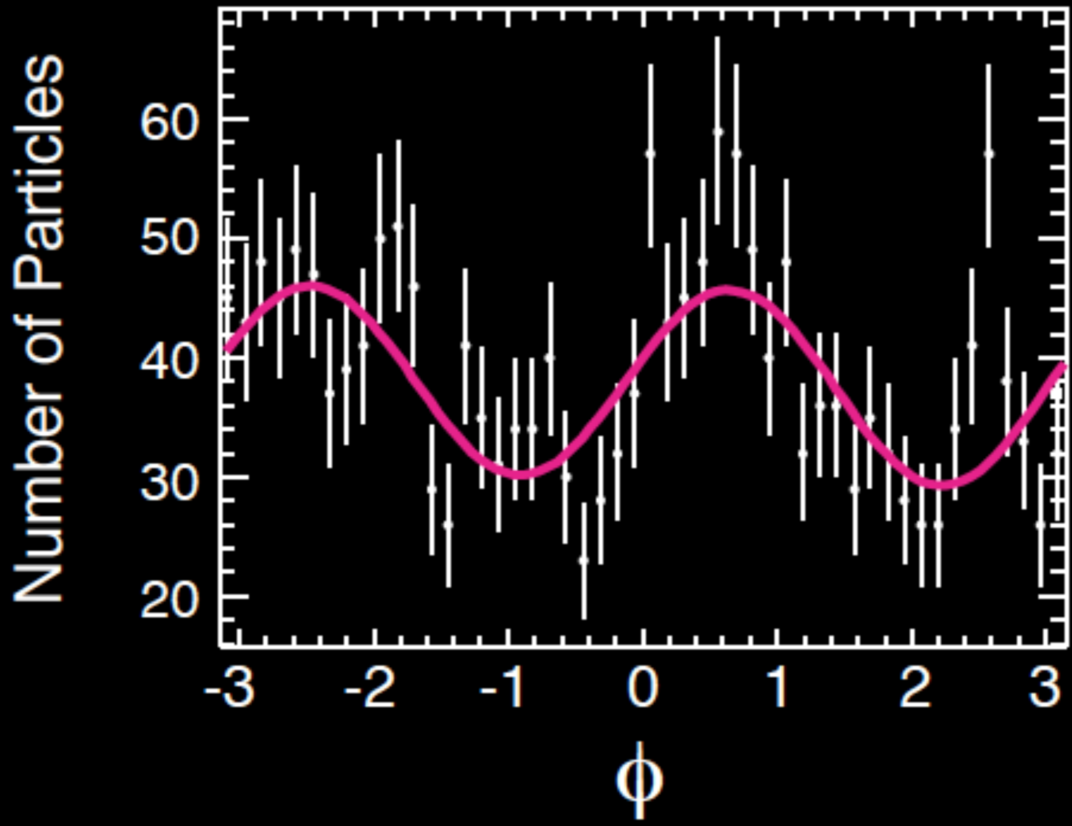
EXPERIMENTAL DATA: ATLAS COLLABORATION



$$\frac{dN}{d\phi} = \frac{N}{2\pi}\left(1 + 2\left(v_1 \cos(\phi)\right)\right)$$

ANGULAR PARTICLE DISTRIBUTION

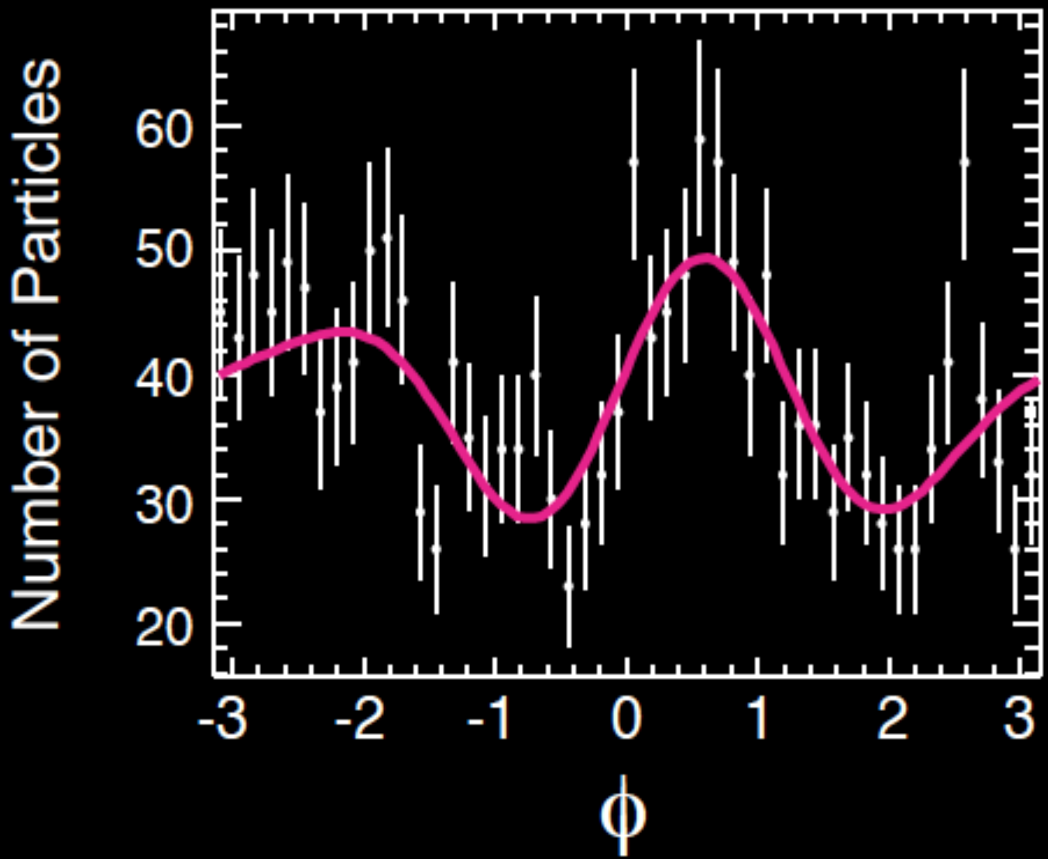
EXPERIMENTAL DATA: ATLAS COLLABORATION



$$\frac{dN}{d\phi} = \frac{N}{2\pi}\left(1 + 2(v_1 \cos(\phi) + v_2 \cos(2\phi))\right)$$

ANGULAR PARTICLE DISTRIBUTION

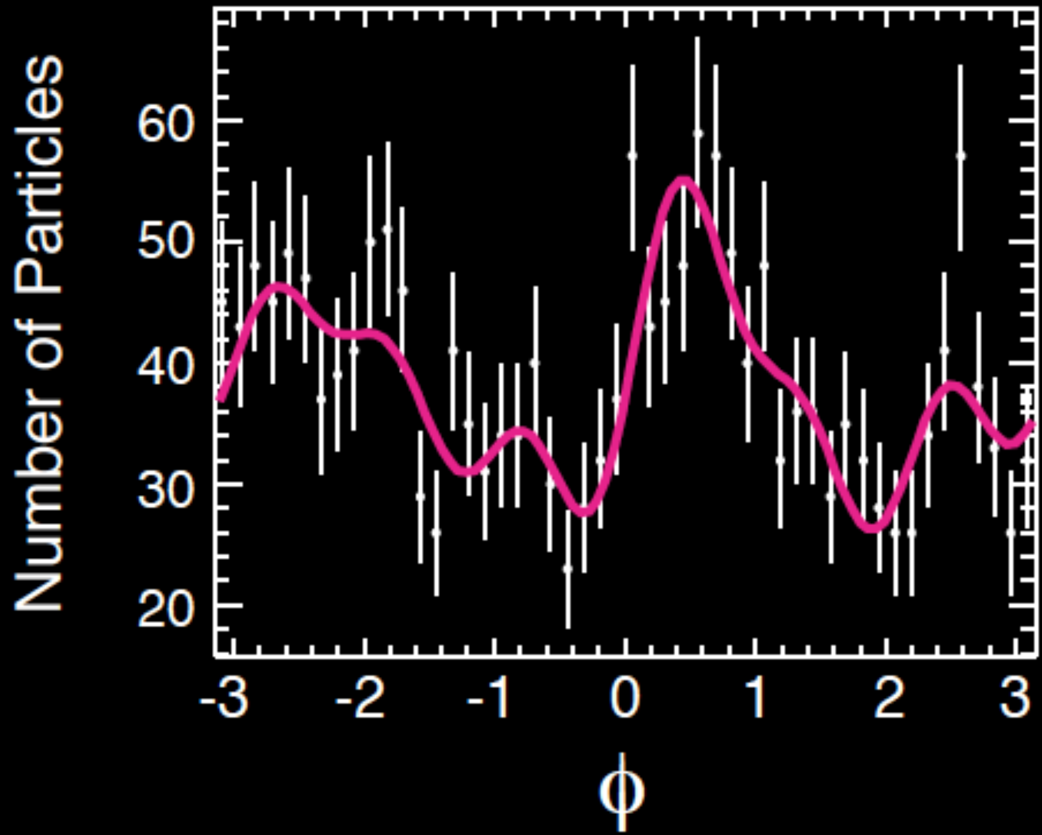
EXPERIMENTAL DATA: ATLAS COLLABORATION



$$\frac{dN}{d\phi} = \frac{N}{2\pi}\left(1 + 2\left(v_1 \cos(\phi) + v_2 \cos(2\phi) + v_3 \cos(3\phi)\right)\right)$$

ANGULAR PARTICLE DISTRIBUTION

EXPERIMENTAL DATA: ATLAS COLLABORATION

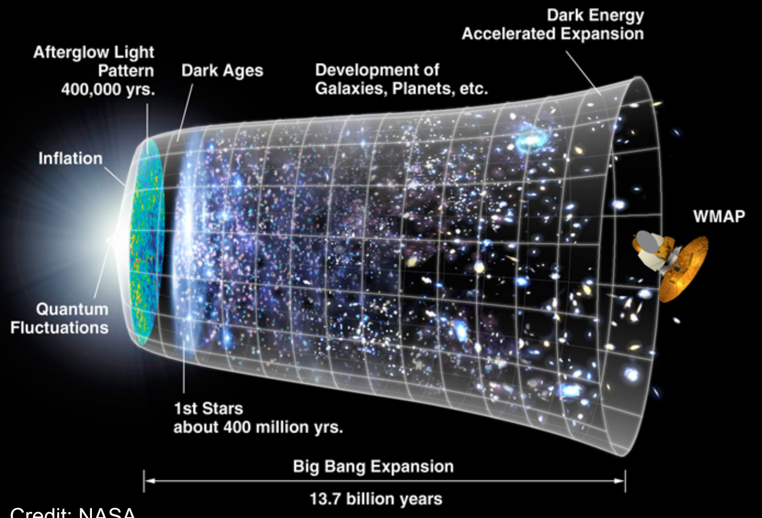


$$\frac{dN}{d\phi} = \frac{N}{2\pi}\left(1 + 2\left(v_1 \cos(\phi) + v_2 \cos(2\phi) + v_3 \cos(3\phi) + v_4 \cos(4\phi) + \ldots\right)\right)$$

Flow moments: analogy with the Early Universe

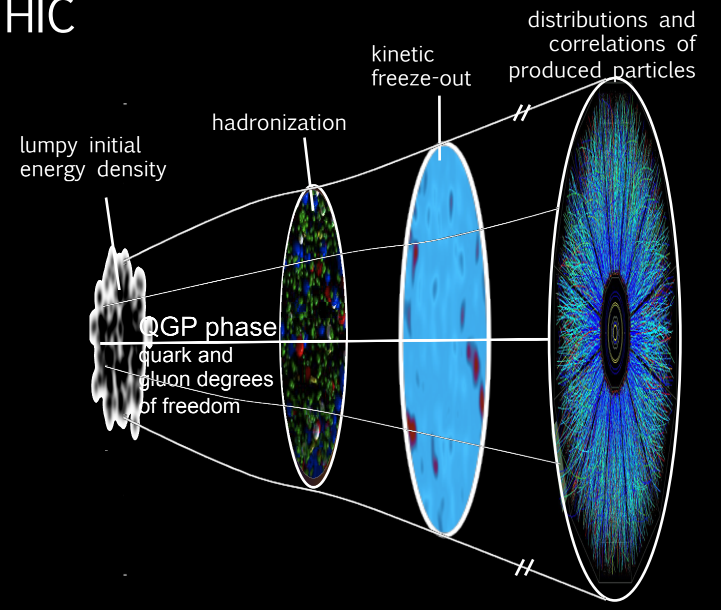
Mishra et al; Mocsy- Sorensen; Floerchinger, Wiedemann

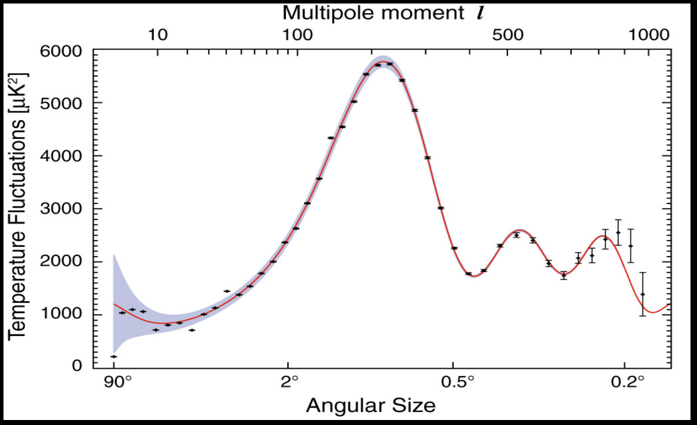
The Universe



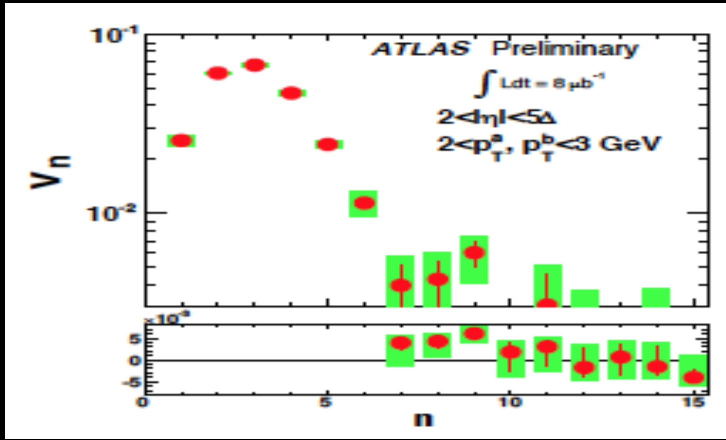
Credit: NASA

HIC

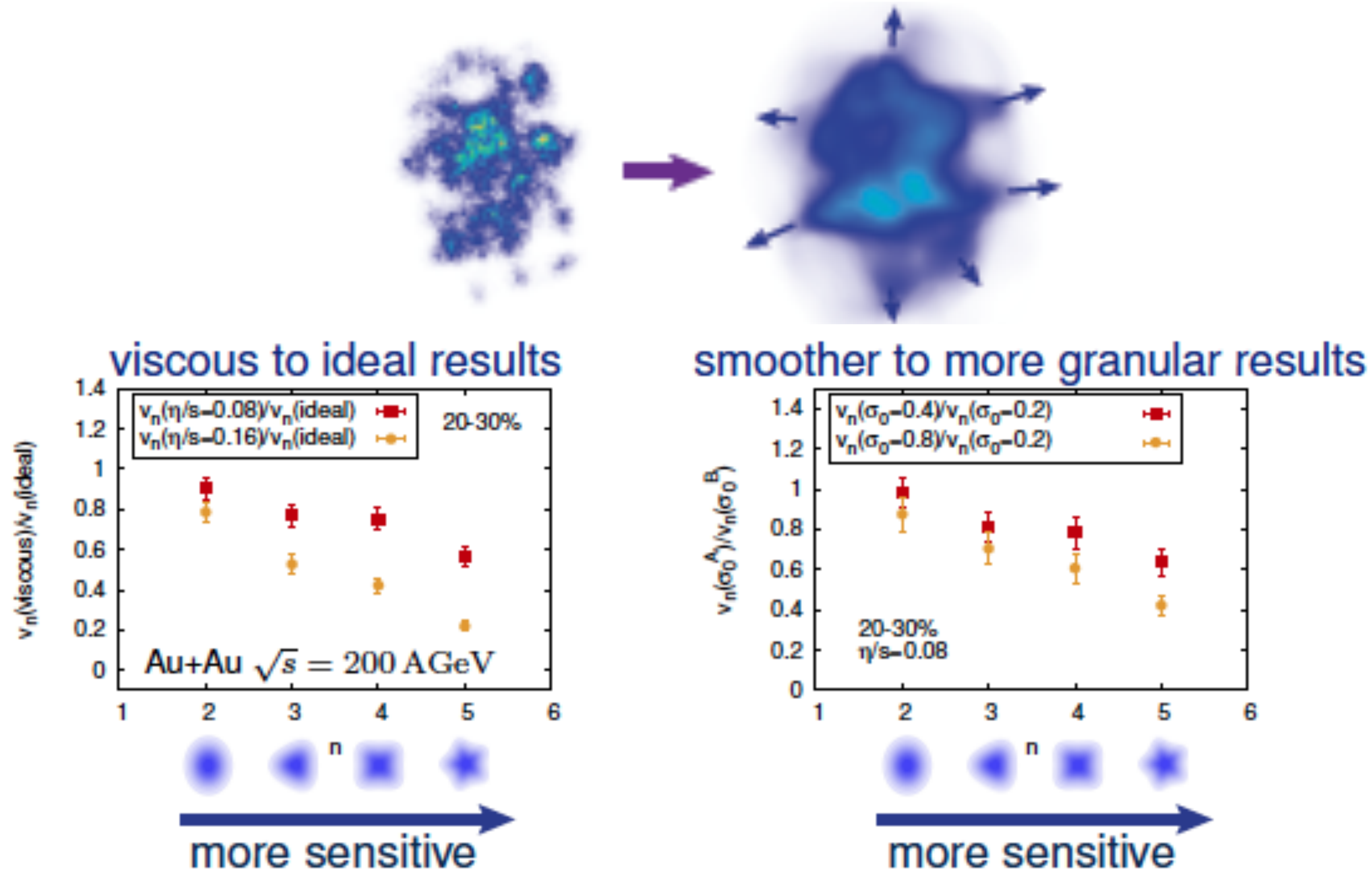




WMAP



Flow driven by initial geometry: relativistic viscous hydrodynamics



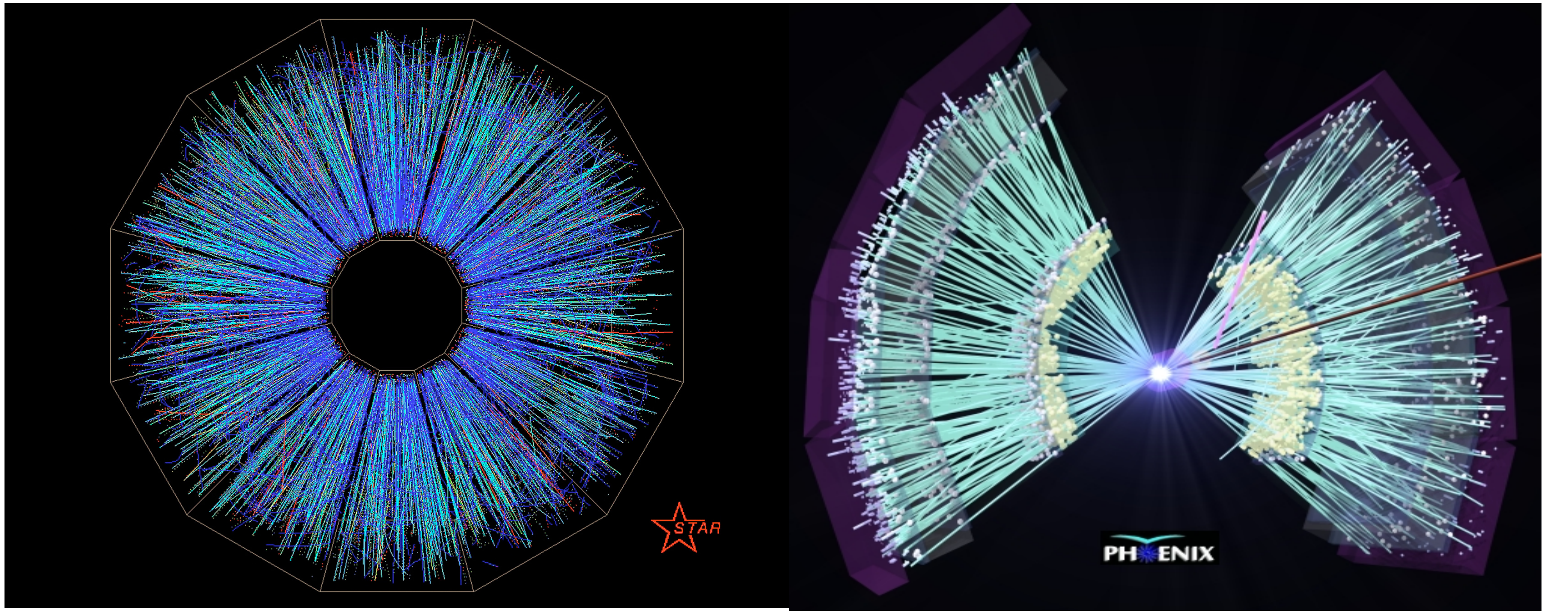
B. Schenke, S. Jeon, C. Gale, Phys.Rev.C85, 024901 (2012)

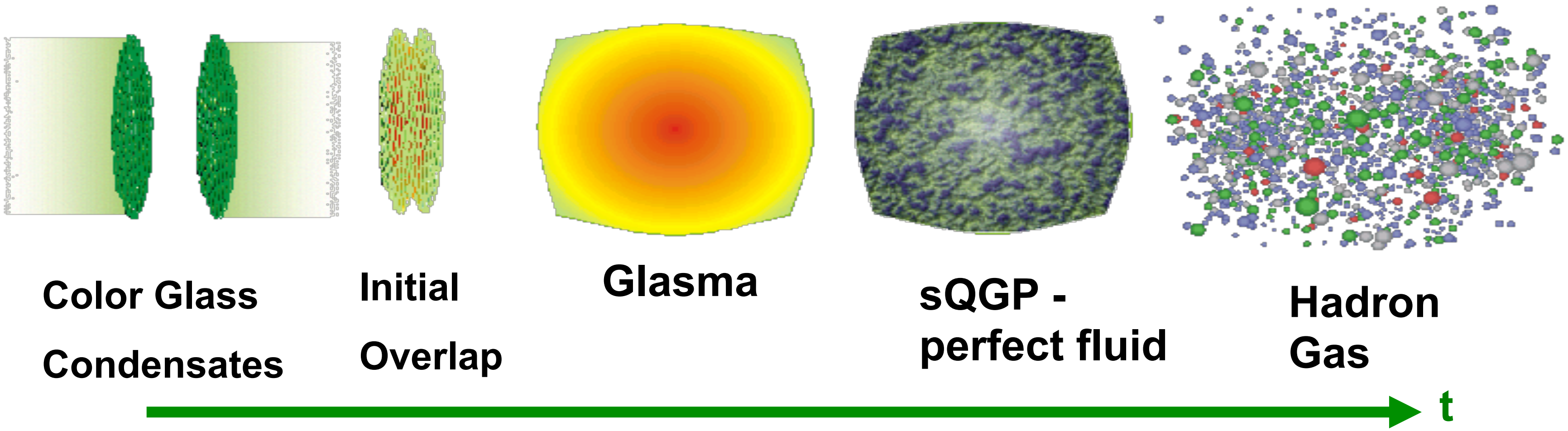
High harmonics of angular distribution very sensitive to viscosity

… and to details of the initial state

“Standard model” of heavy ion collisions

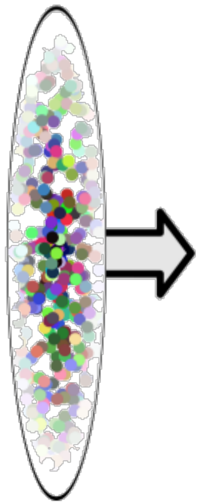
RV, ICHEP plenary, arXiv:1012.4699





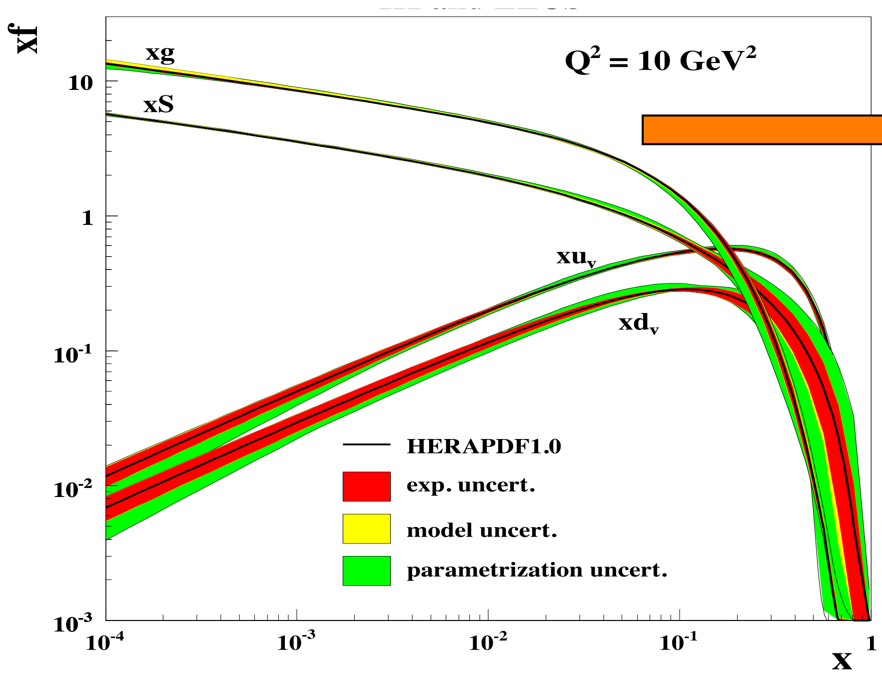
Unifying paradigm: relativistic viscous hydrodynamics

The nuclear wavefunction at high energies



|A> = |qqq…q> + … + |qqq…qgg…gg>

For Lorentz factors Y➔∞ dominant configurations are valence quarks of longitudinal size 2 R/Y, surrounded by a fuzz of "wee" gluons and sea quarks

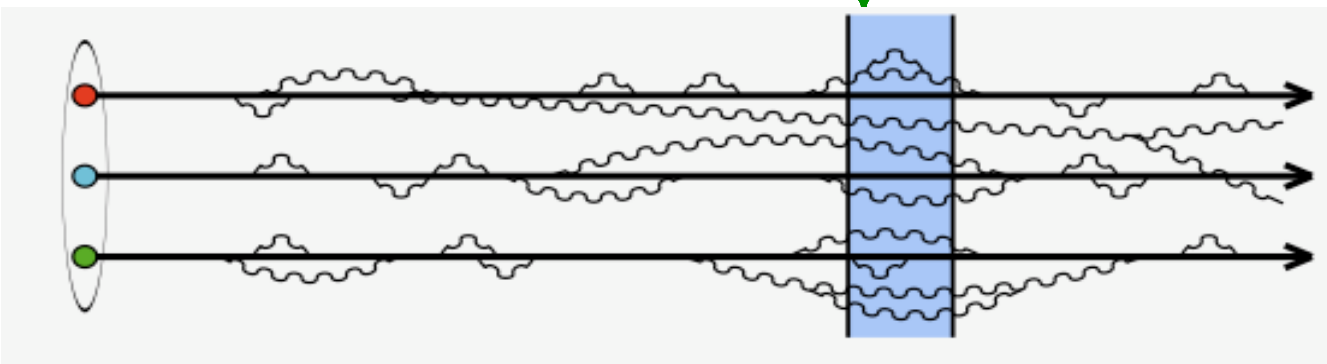


Lesson from HERA:

The proton at high energies (small x) is dominated by glue!

The nuclear wavefunction at high energies

|A> = |qqq…q> + … + |qqq…q**gg…g**>



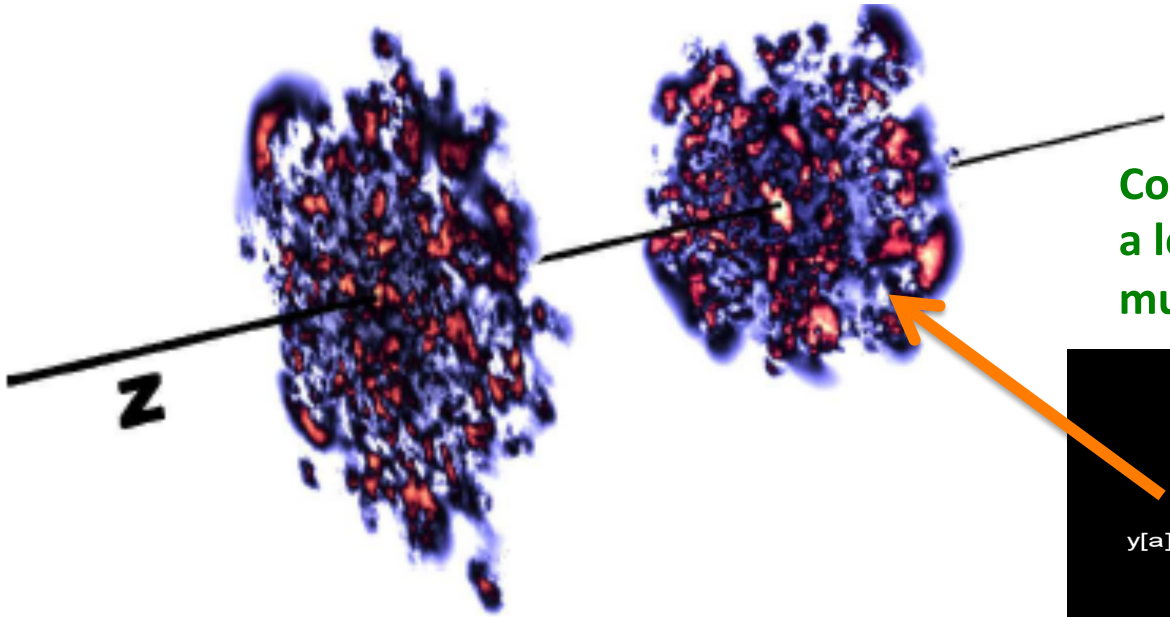
- At high energies, interaction time scales of fluctuations are dilated well beyond typical hadronic time scales

- Lots of short lived (gluon) fluctuations now seen by probe -- proton/nucleus -- dense many body system of (primarily) gluons

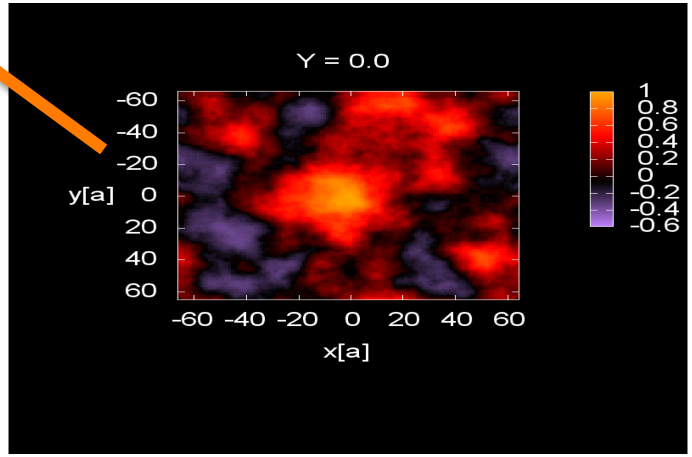
- Fluctuations with lifetimes much longer than interaction time for the probe function as static color sources for more short lived fluctuations

Nuclear wave function at high energies is a Color Glass Condensate

Multi-particle production: saturated wave-functions



Color charge fluctuations on a length scale $1/Q_S$ much smaller than proton size



Incoming nuclei are Color Glass Condensates: Highly occupied gluon states with maximal occupancy in QCD.

Idea ! high occupancy of gluons at small x (high energy) admits a classical EFT description

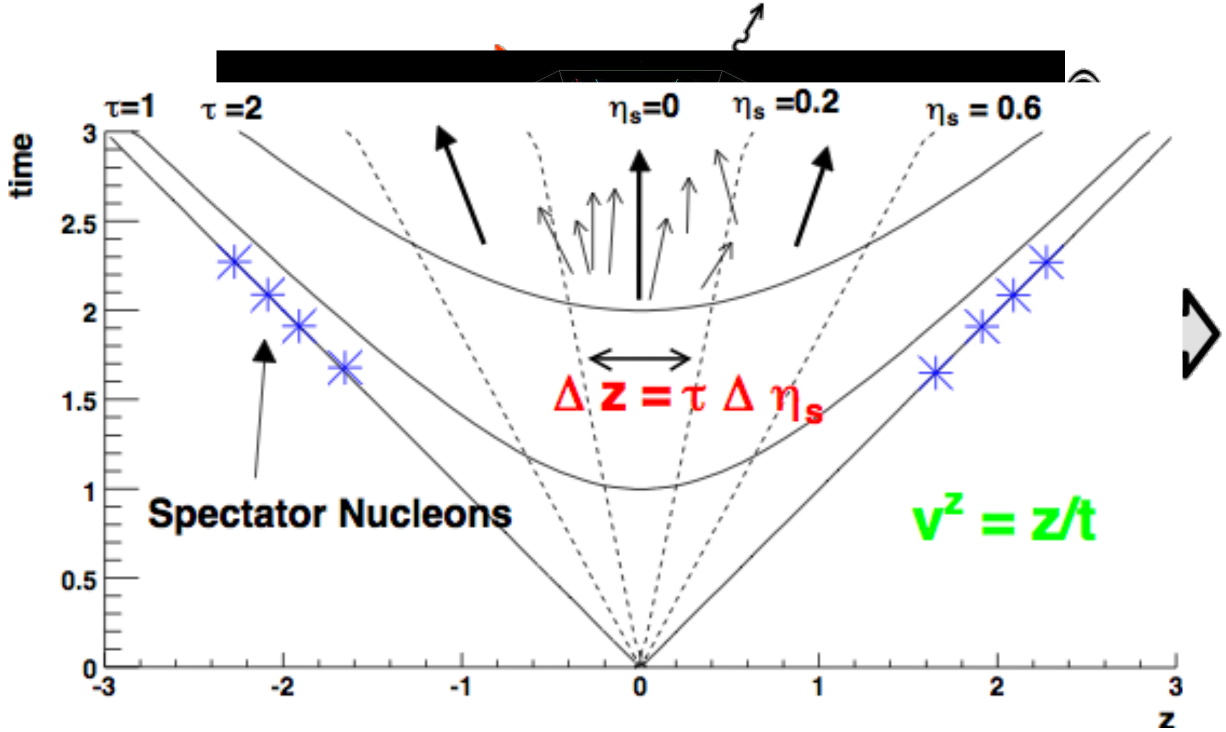
McLerran, Venugopalan (1994)

Computations in this framework becoming available at next-leading-log accuracy

Forming a Glasma in the little Bang

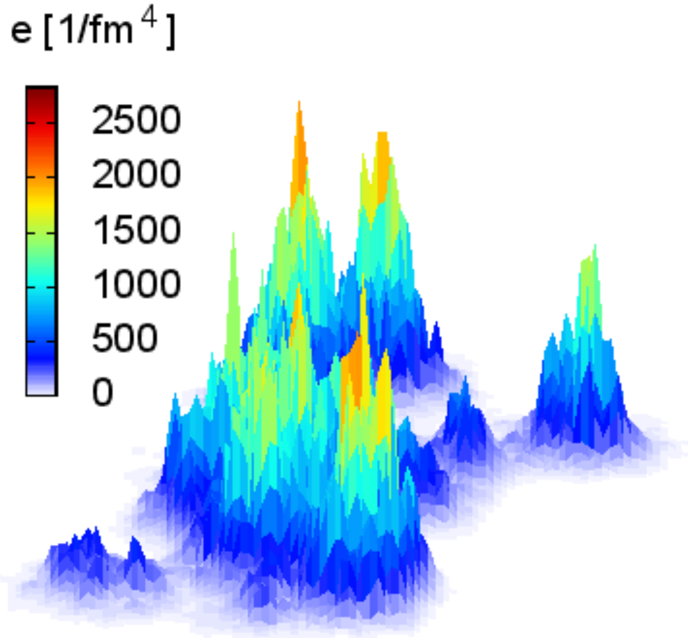
Glasma (\Glahs-maa\): ***Noun:*** non-equilibrium matter between Color Glass Condensate (CGC)& Quark Gluon Plasma (QGP)

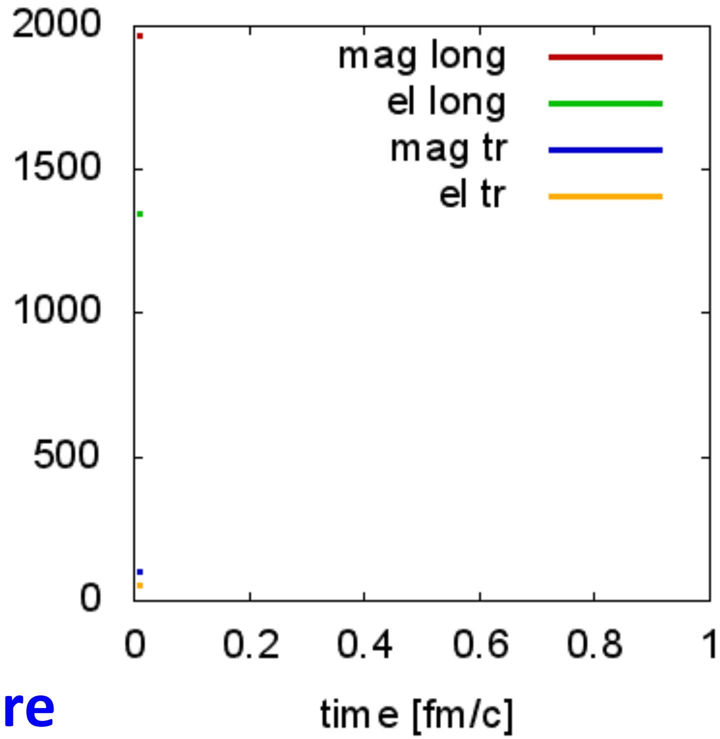
Lappi,McLerran (2006)



Matching boost invariant Yang-Mills to hydrodynamics

Krasnitz,Venugopalan (1998)





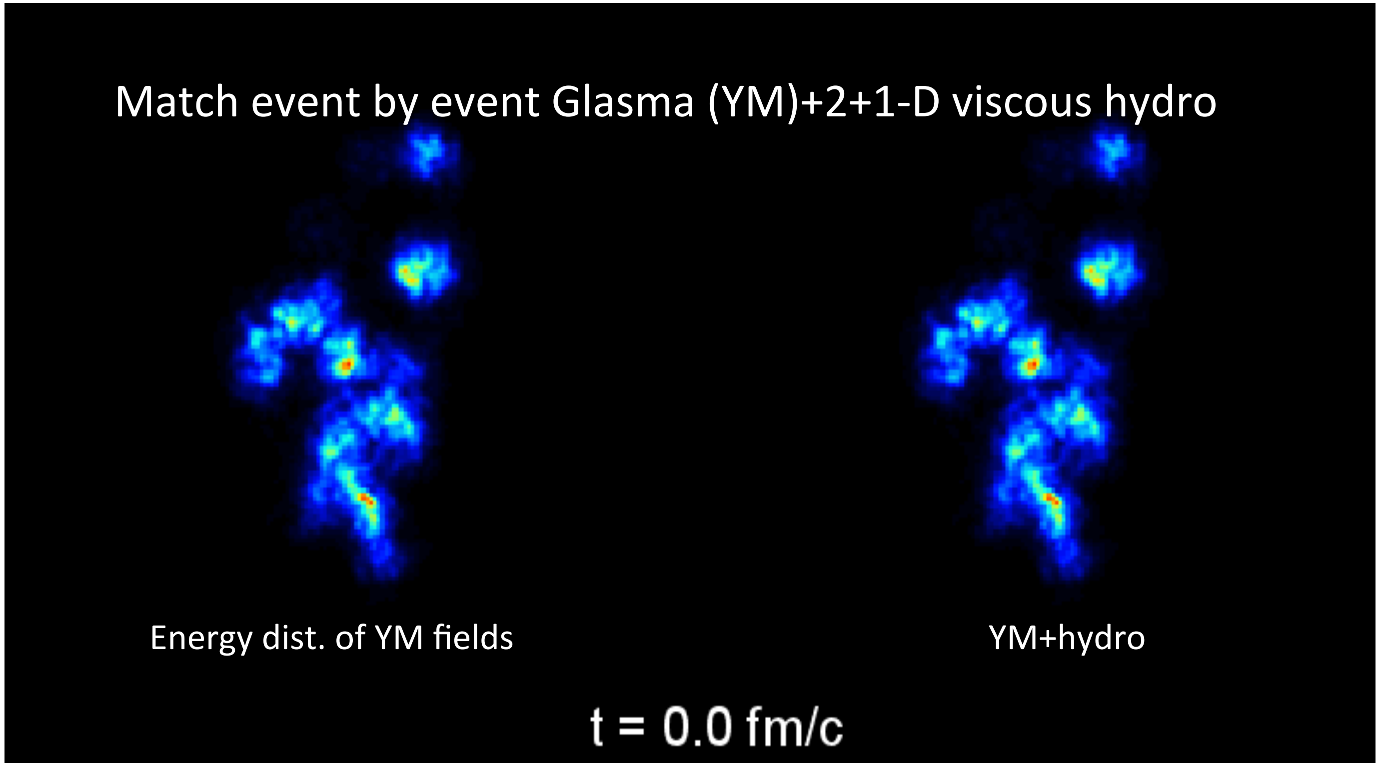
Glasma energy density and pressure

$$T_{\mu\nu}(\tau = 0) = \frac{1}{2}(B_z^2 + E_z^2) \times \text{diag}(1, 1, 1, -1)$$

Initial longitudinal pressure is negative:
Goes to P_L =0 from below with time evolution

Matching Yang-Mills glue to viscous hydro

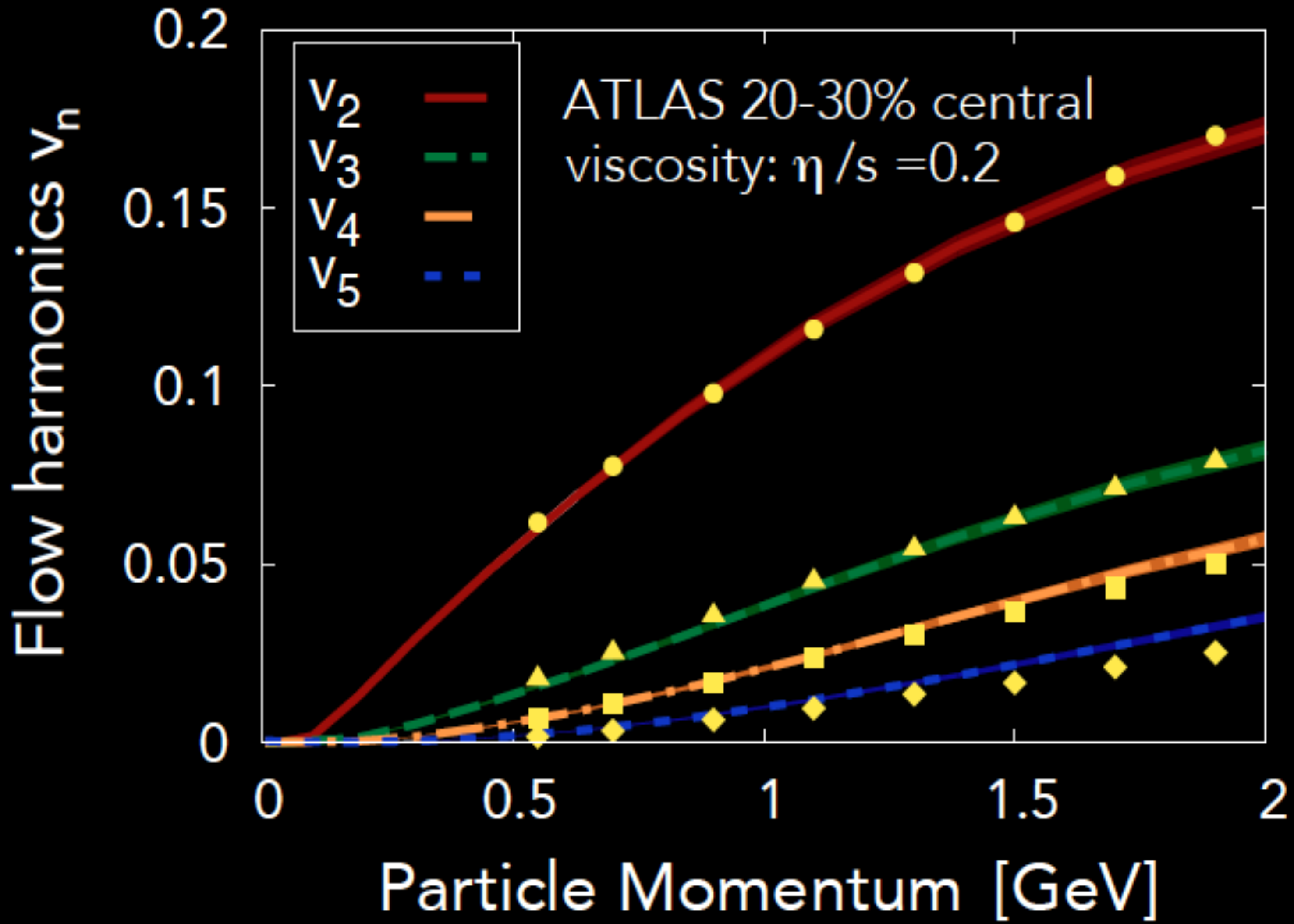
State of the art phenomenology: Solve relativistic viscous hydrodynamic equations with Glasma (Yang-Mills) initial conditions



Schenke,Tribedy,RV, PRL 108 (2012) 252301, PRC 86 (2012) 034908
Gale, Jeon, Schenke, Tribedy, RV, PRL 110 (2013) 1, 012302

VISCOUS FLOW AT LHC

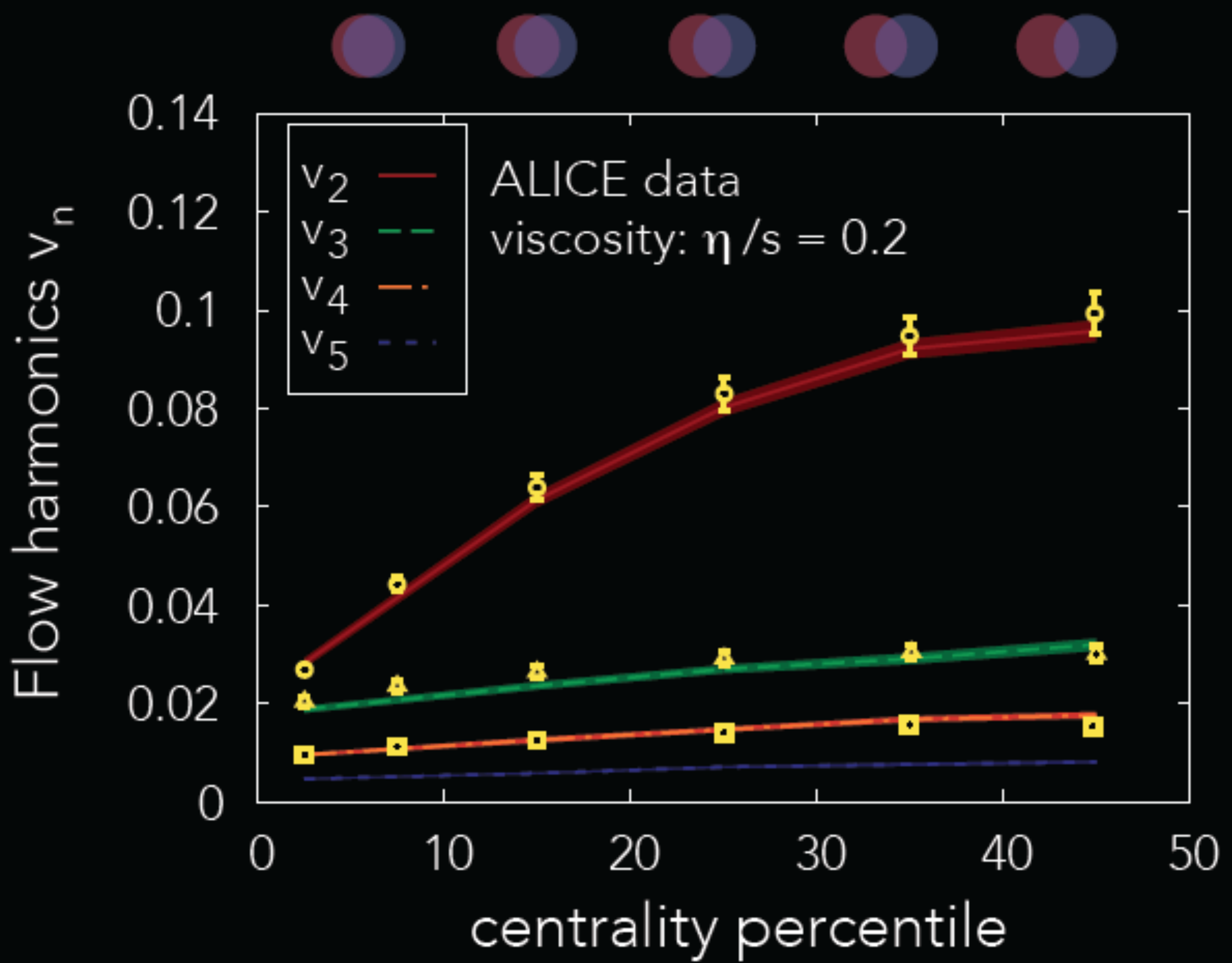
C.GALE, S.JEON, B.SCHENKE, P.TRIBEDY, R.VENUGOPALAN, PHYS.REV.LETT.110, 012302 (2013)



EXPERIMENTAL DATA: ATLAS COLLABORATION, PHYS. REV. C86, 014907 (2012)

GEOMETRY AND FLUCTUATIONS DRIVE FLOW

C.GALE, S.JEON, B.SCHENKE, P.TRIBEDY, R.VENUGOPALAN, PHYS.REV.LETT.110, 012302 (2013)



EXPERIMENTAL DATA: ALICE COLLABORATION, PHYS. REV. LETT. 107, 032301 (2011)

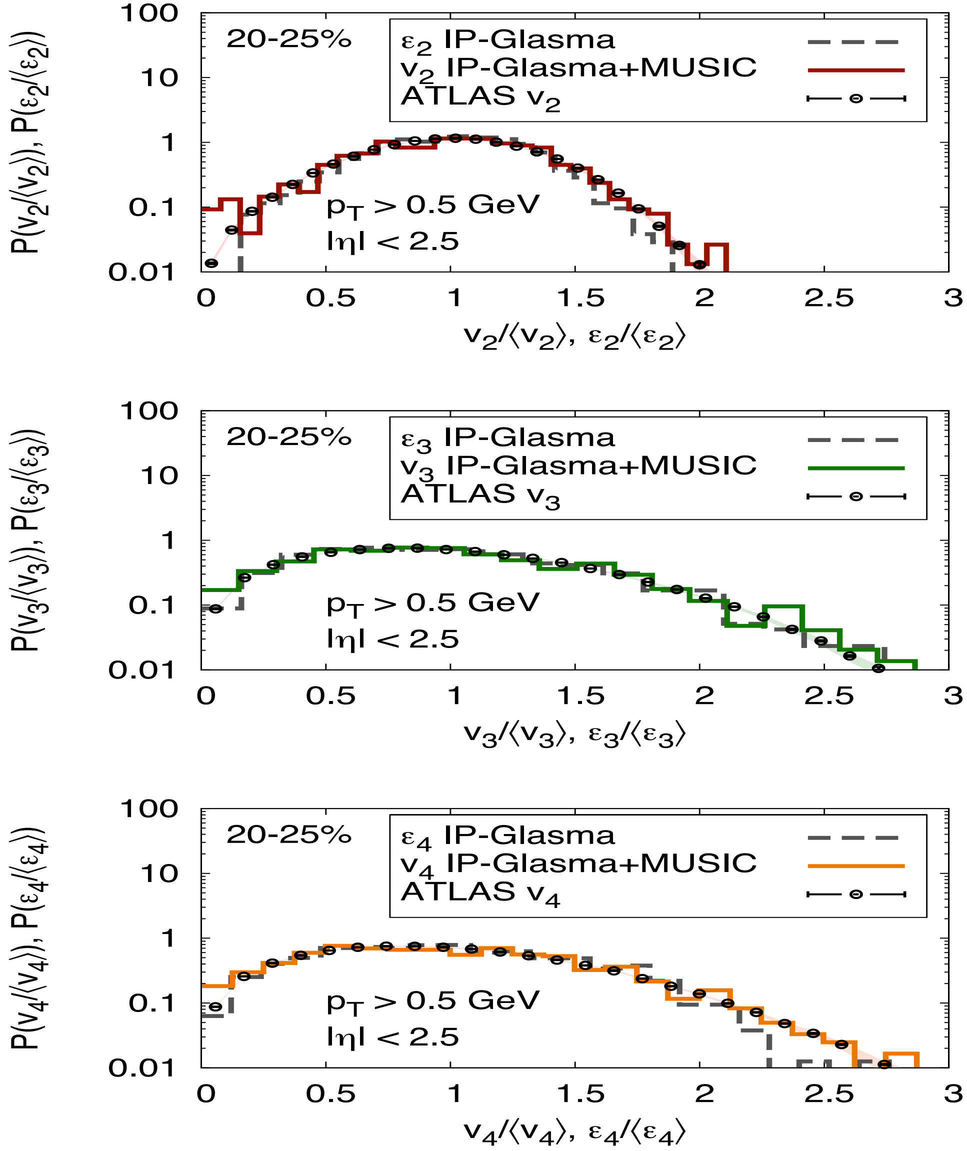
Event-by-Event Flow Distributions

v_n distributions track eccentricities ε_n

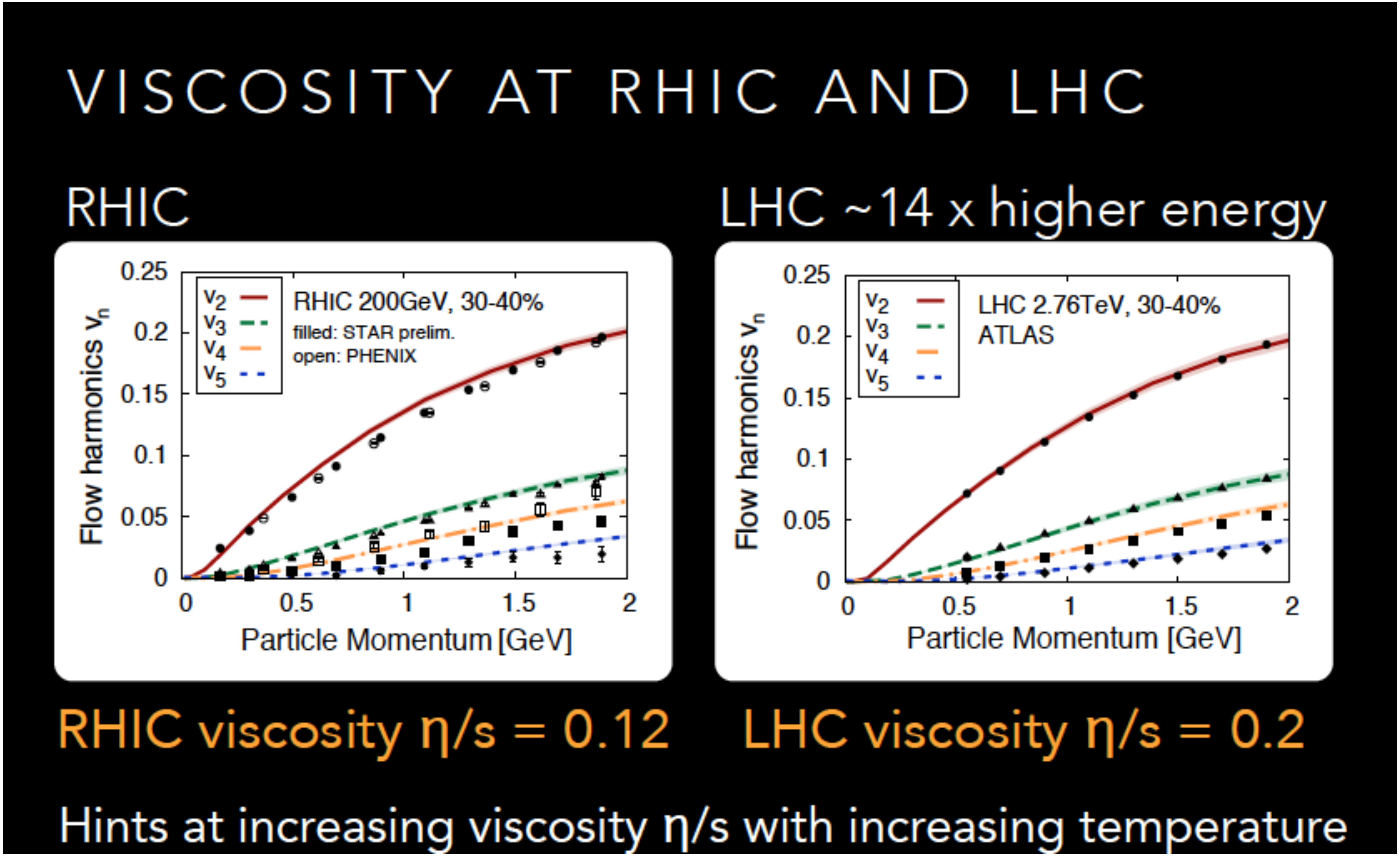
spatial fluctuations

efficiency => perfect fluidity

momentum anisotropies

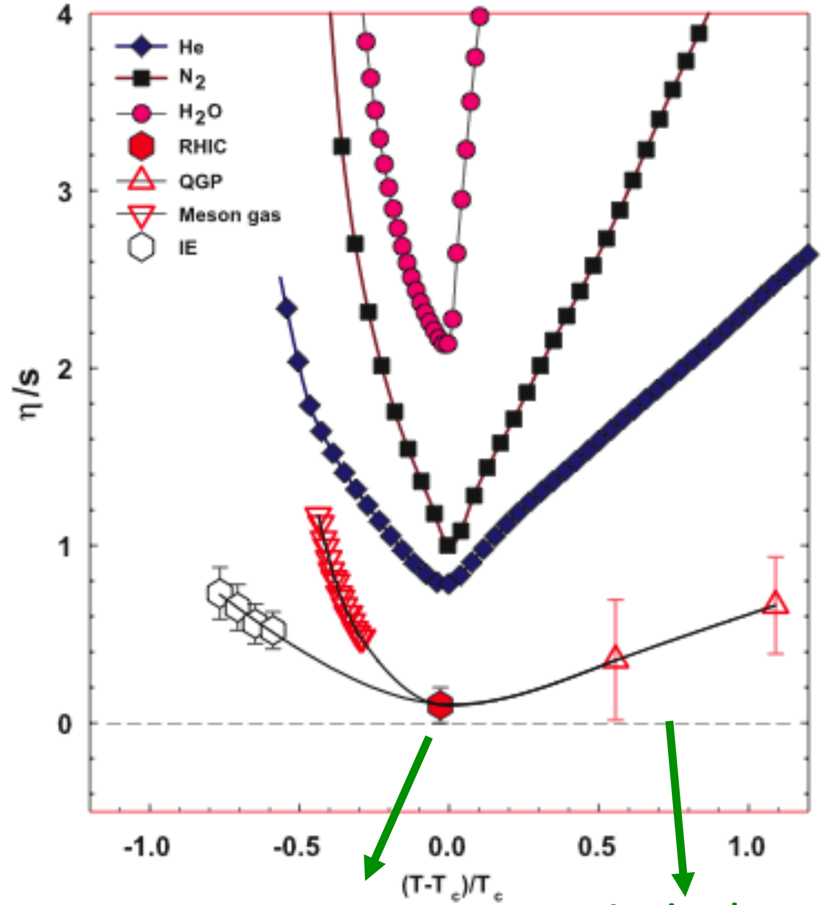


Gale, Jeon, Schenke, Tribedy, Venugopalan, PRL 110, 012302 (2013)



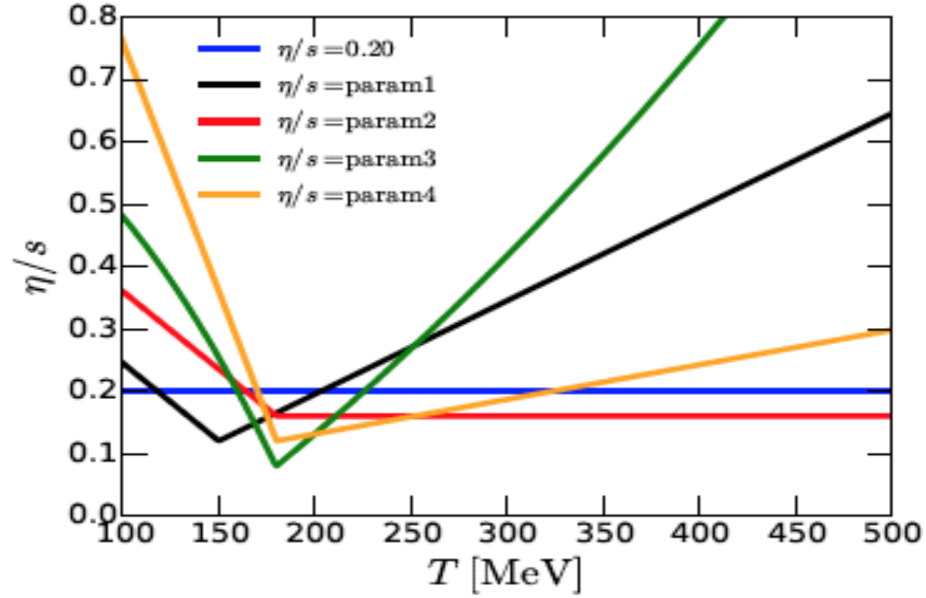
Viscosity/entropy density very close to conjectured lower bound. The hottest fluids on earth are nearly perfect !

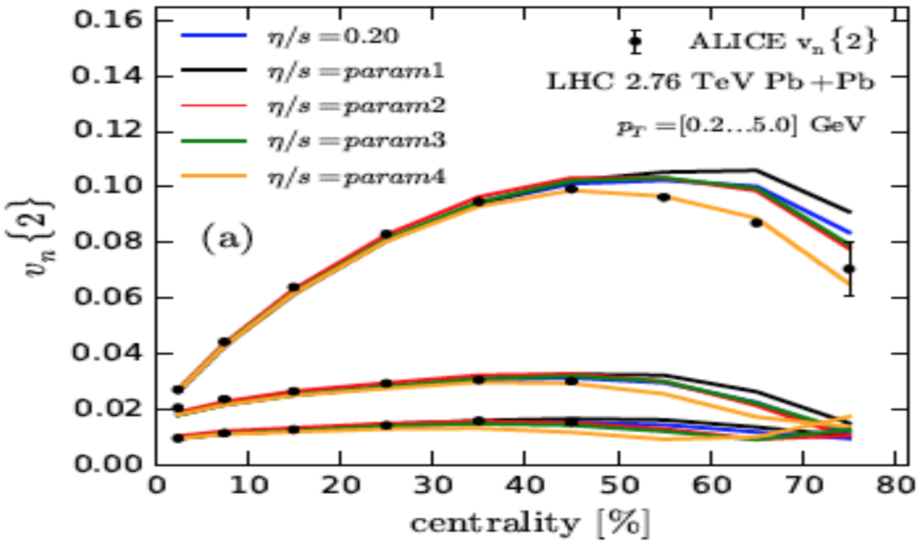
Narrowing down dissipation in the QGP



Lacey, nucl-ex/0608046

Lattice data: Nakamura, Sakai, PRL94 (2005)





Eskola,Niemi,Paatelainen,arXiv:1509.02767

From the violence of a nuclear collision
…to the calm of a quark-gluon fluid

Initial state:
Far from equilibrium

Non-equilibrium dynamics

Final state:
Thermal equilibrium

→

How is thermal equilibrium achieved?

Approaches to thermalization

Two ``clean" theoretical limits:

- **Holographic thermalization (based on duality of strongly coupled ($g^2 N_c \rightarrow \infty$; $N_c \rightarrow \infty$) N=4 SUSY YM to classical gravity in $AdS_5 \times S_5$)**

- **Highly occupied QCD at weak coupling ($g^2 \rightarrow 0$; $g^2 f \sim 1$)**

Our focus: non-equilibrium strongly correlated gluodynamics at weak coupling

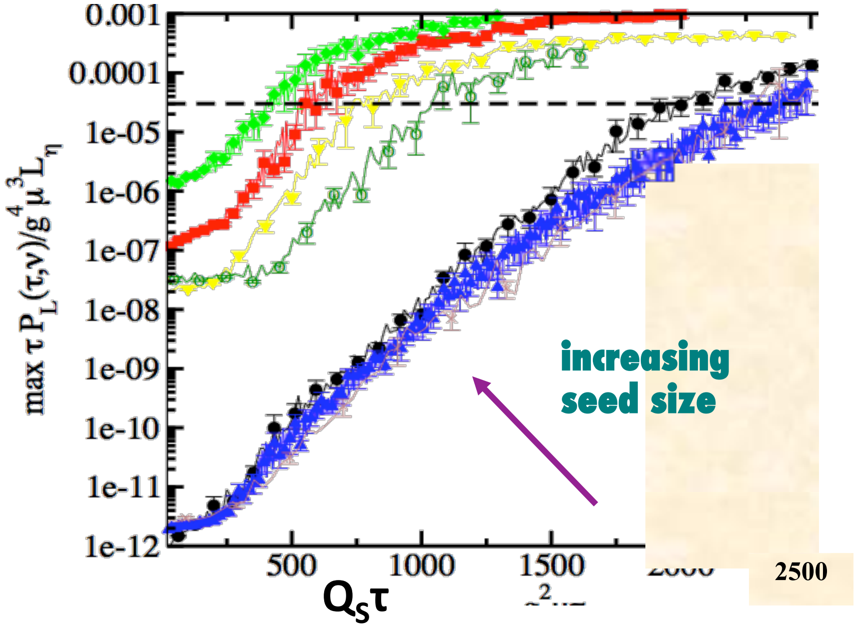
The Glasma at NLO: plasma instabilities

Romatschke,Venugopalan
Dusling,Gelis,Venugopalan
Gelis, Epelbaum

At LO: boost invariant gauge fields $A_{cl}^{\mu,a}(x_T,\tau) \sim 1/g$

NLO: $A^{\mu,a}(xT,\tau,\eta) = A_{cl}^{\mu,a}(x_T,\tau) + a^{\mu,a}(\eta)$

$a^{\mu,a}(\eta) = O(1)$

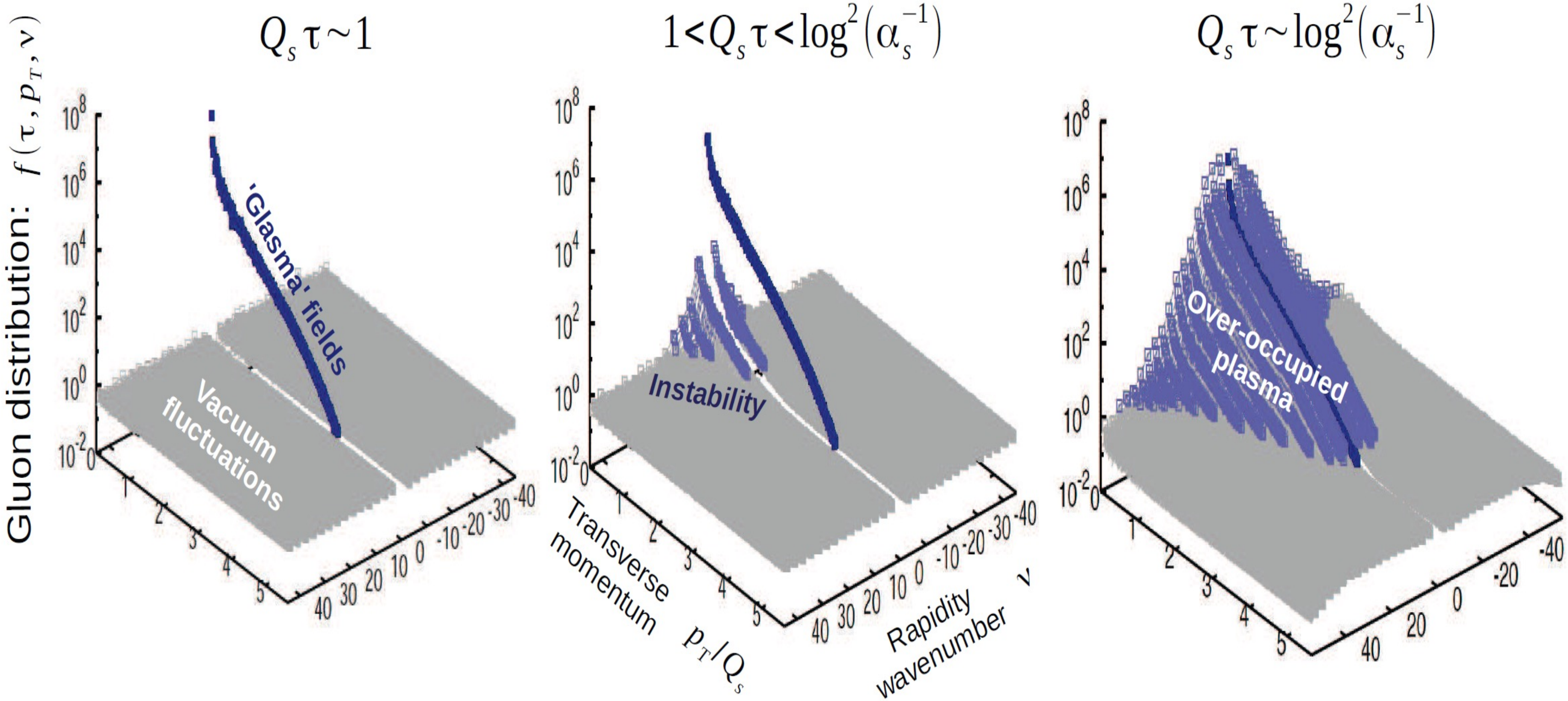


- Small fluctuations grow exponentially as ~ $e^{\sqrt{Q_S\tau}}$
- Same order of classical field at $\tau = \frac{1}{Q_S}\ln^2\frac{1}{\alpha_S}$
- Resum such contributions to all orders $(g\, e^{\sqrt{Q_S\tau}})^n$

◆ Leading quantum corrections can be expressed as average over a classical-statistical ensemble of initial conditions

Initial conditions in the overpopulated QGP

Overpopulation occurs…*even starting from the "first principles CGC"* initial conditions



Classical-statistical real time numerical lattice simulations of an expanding gauge theory

Berges,Schenke,Schlichting,RV, NPA 931 (2014) 348

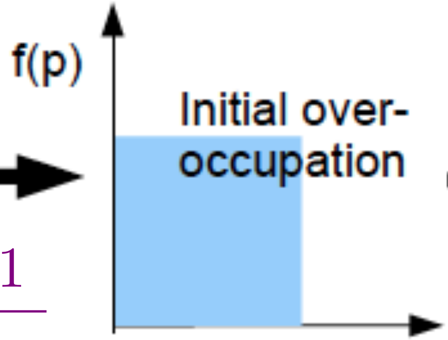
Initial conditions in the Glasma

Glasma + vacuum fluctuations

$$\tau = \frac{1}{Q_S}$$

Plasma Instabilities

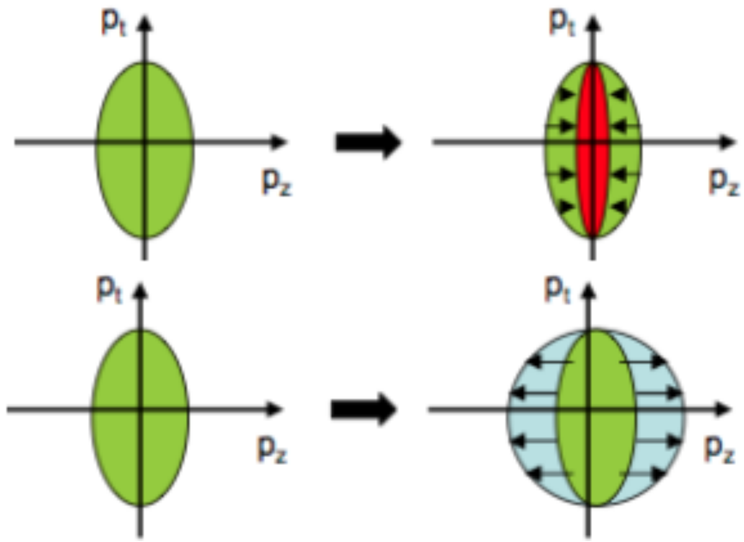
$$\tau = \frac{1}{Q_S} \ln^2 \frac{1}{\alpha_S}$$



???

$$\tau >> \frac{1}{Q_S} \ln^2 \frac{1}{\alpha_S}$$

- There is a natural ***competition*** between ***interactions*** and the ***longitudinal expansion*** which renders the system ***anisotropic*** on large time scales



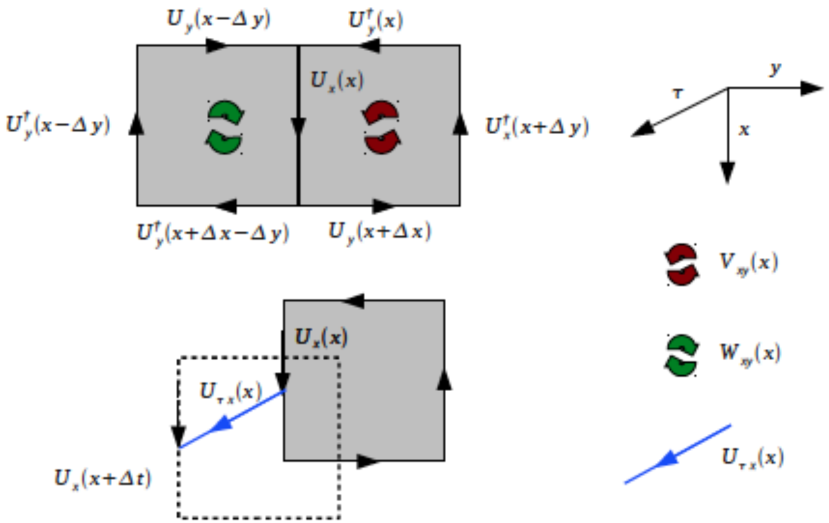
Longitudinal Expansion:
- Red-shift of longitudinal momenta p_z $\rightarrow$ increase of anisotropy
- Dilution of the system

Interactions:
- Isotropize the system

Temporal evolution in the overpopulated QGP

Berges,Boguslavski,Schlichting,Venugopalan
arXiv: 1303.5650, 1311.3005

Solve Hamilton's equation for 3+1-D SU(2) gauge theory in Fock-Schwinger gauge



Fix residual gauge freedom imposing Coloumb gauge at each readout time

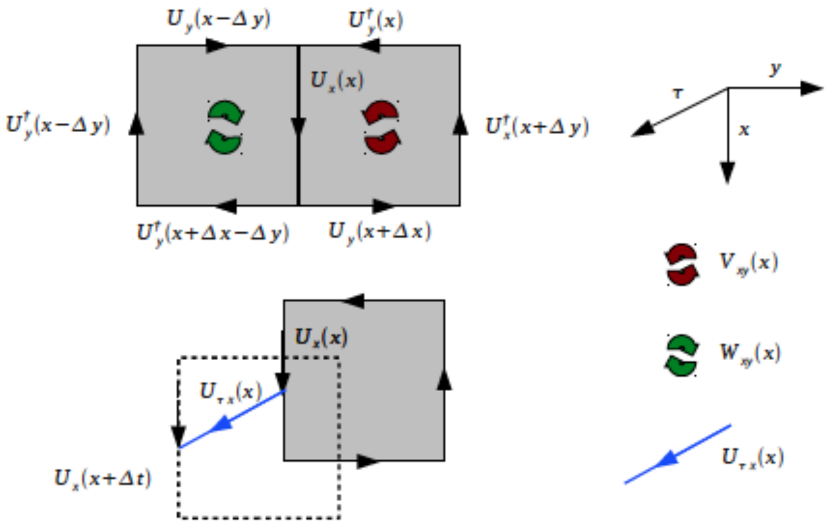
$$\partial_i A_i + t^{-2}\partial_\eta A_\eta = 0$$

◆ **Largest classical-statistical numerical simulations of expanding Yang-Mills to date: $256^2 \times 4096$ lattices**

Temporal evolution in the overpopulated QGP

Berges,Boguslavski,Schlichting,Venugopalan
arXiv: 1303.5650, 1311.3005

Solve Hamilton's equation for 3+1-D SU(2) gauge theory in Fock-Schwinger gauge

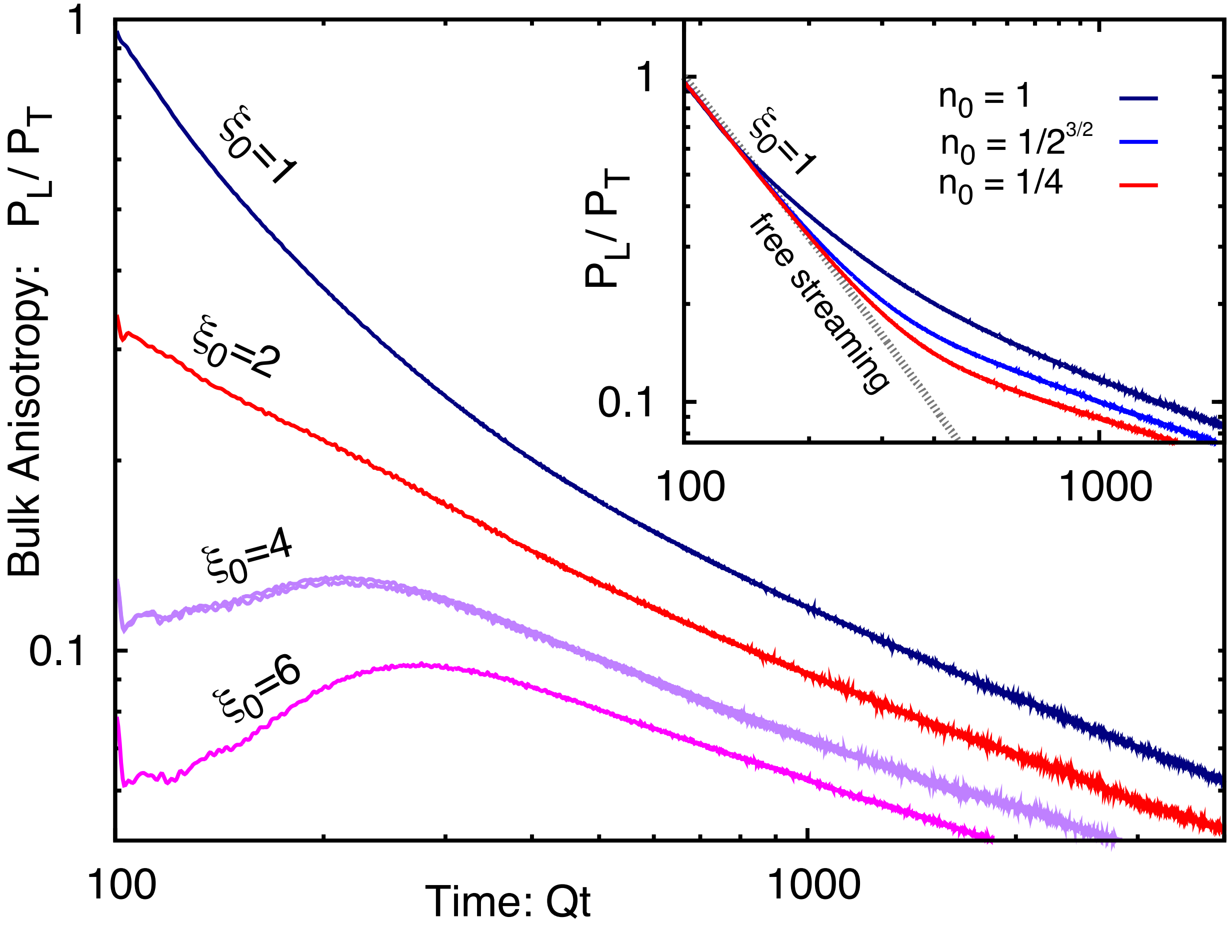


Fix residual gauge freedom imposing Coloumb gauge at each readout time

$$\partial_i A_i + t^{-2}\partial_\eta A_\eta = 0$$

◆ **Classical-statistical computations performed at weak coupling…**
$\alpha_S=10^{-5}$ for "classical dominance" at all times in simulation:
-- corresponds to $Q\tau_0 \approx \mathrm{Ln}^2(1/\alpha_S) \approx 100$

Result: Pressure becomes increasingly anisotropic

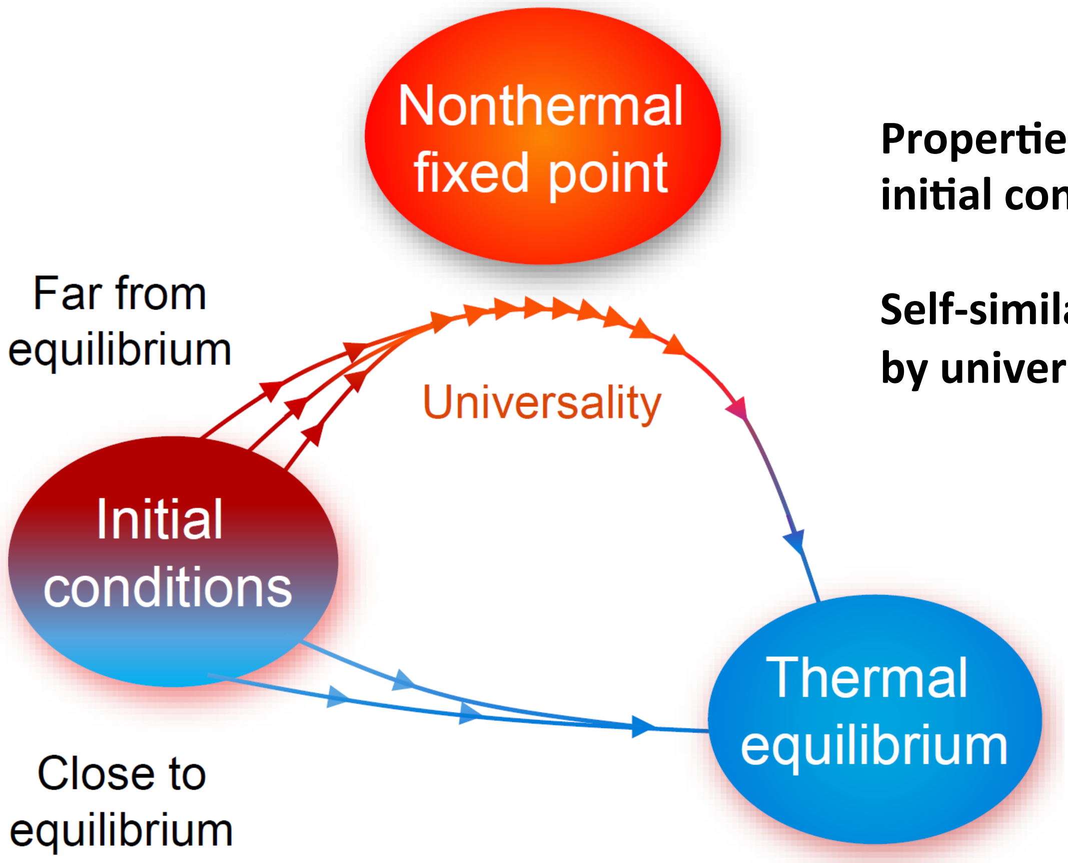


P_L/P_T approaches universal $\tau^{-2/3}$ behavior

Kinetic theory in the overoccupied regime

For $1 < f < 1/\alpha_S$ a dual description is feasible either in terms of kinetic theory or classical-statistical dynamics …

Mueller,Son (2002)
Jeon (2005)

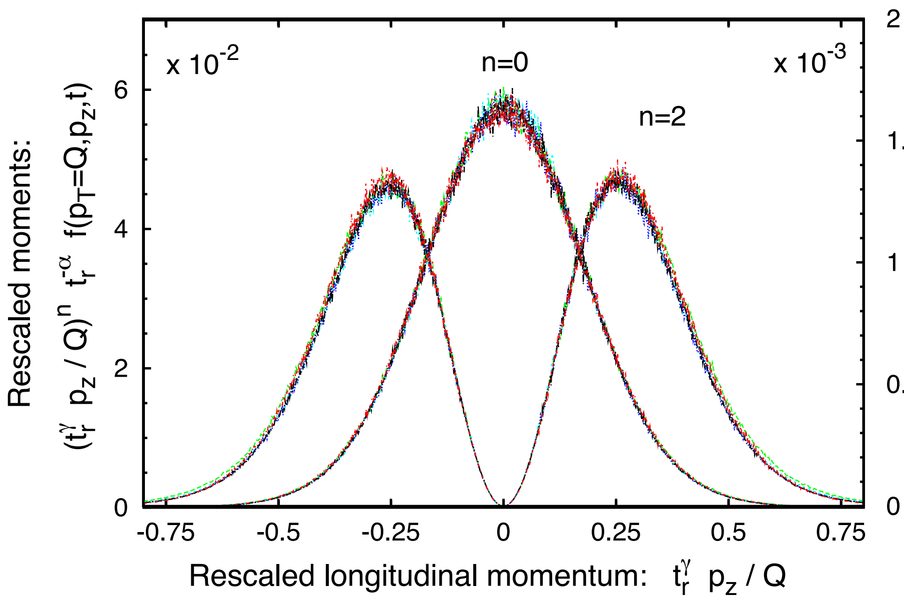


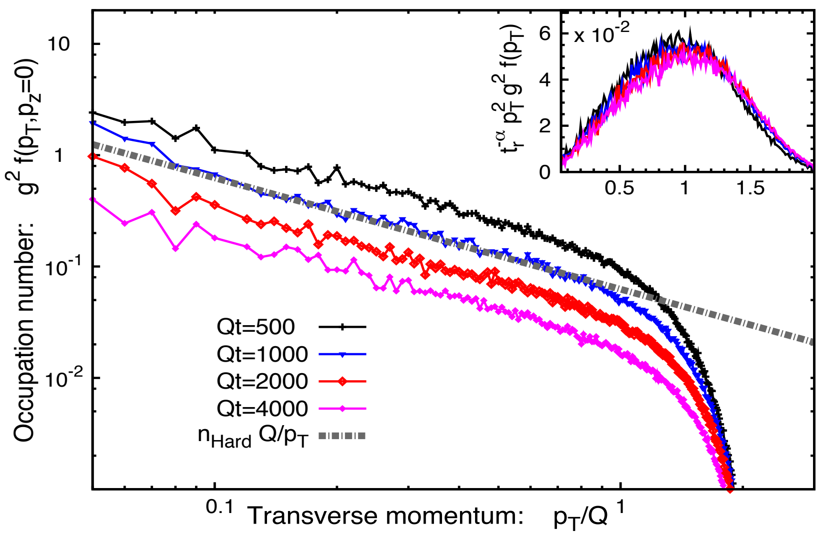
Properties independent of initial conditions

Self-similar evolution characterized by universal scaling exponents

Result: universal non-thermal fixed point

Conjecture: $f(p_\perp, p_z, t) = t^\alpha \; f_S(t^\beta p_T, t^\gamma p_z)$



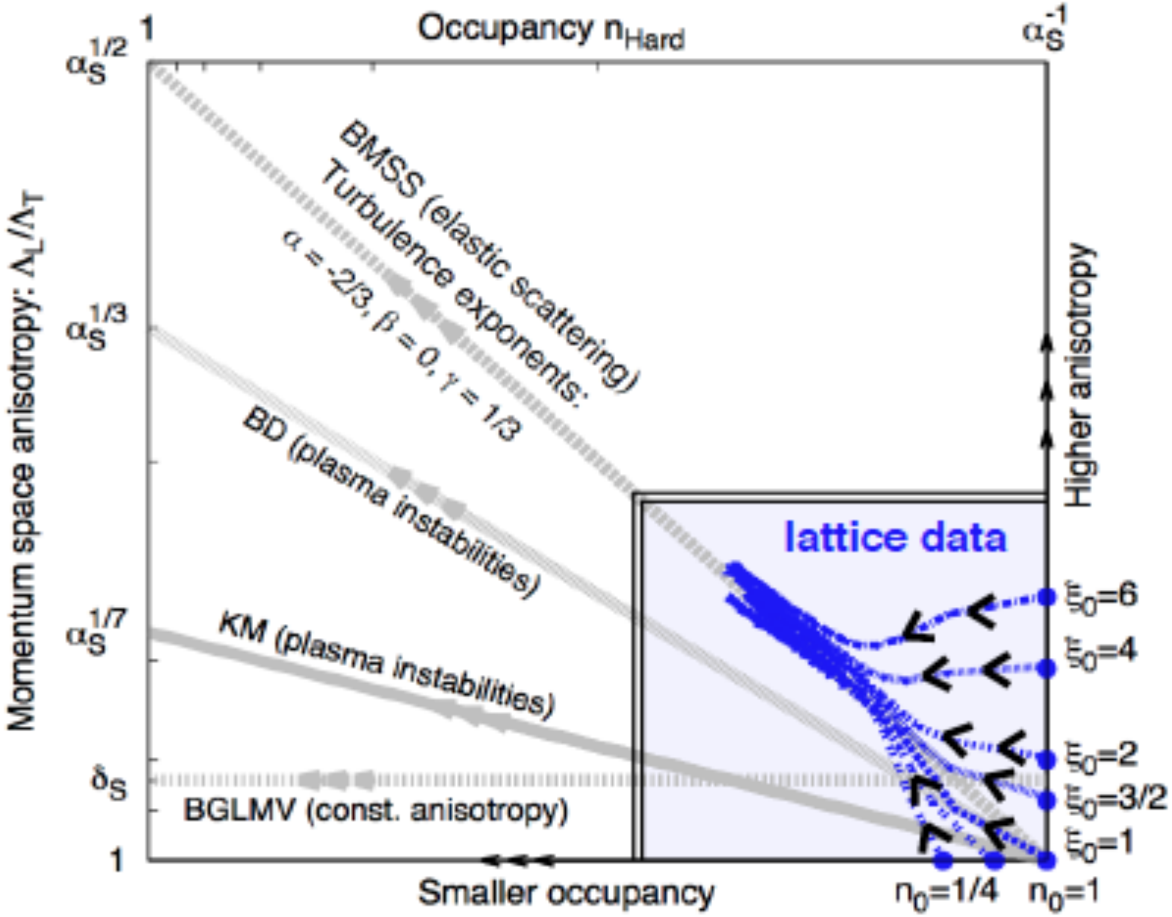


Moments of distribution extracted over range of time slices lie on universal curves

Distribution as function of p_T displays 2-D thermal behavior

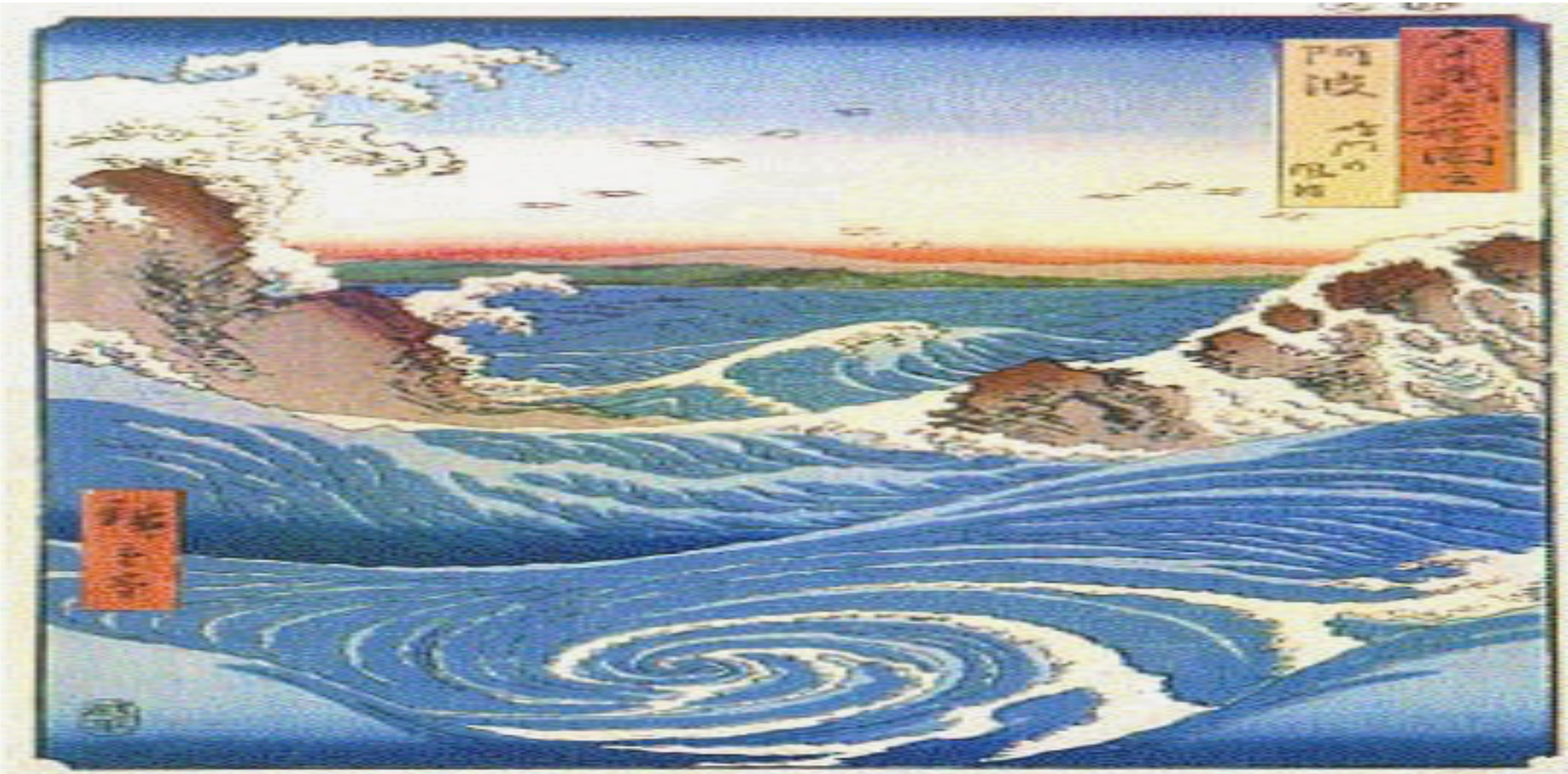
Non-thermal fixed point in overpopulated QGP

Berges,Boguslavski,Schlichting,Venugopalan. PRD89 (2014) 114007



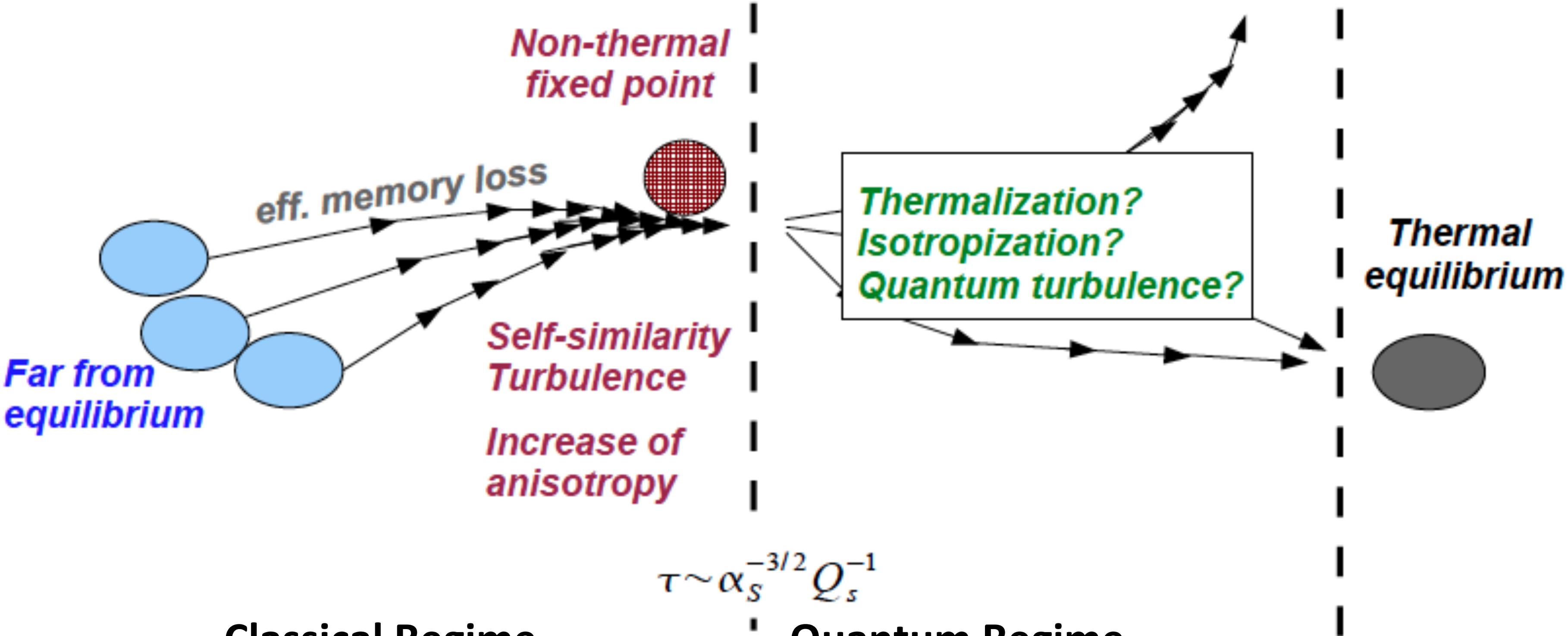
BMSS: Baier,Mueller,Schiff,Son
BD: Bodeker
KM: Kurkela, Moore
BGLMV: Blaizot,Gelis,Liao,McLerran,Venugopalan

Universal non-thermal attractor in QCD



"Big whorls have little whorls, which feed on their velocity,
And little whorls have lesser whorls, and so on to viscosity."

Quo vadis, thermal QGP?



Classical Regime

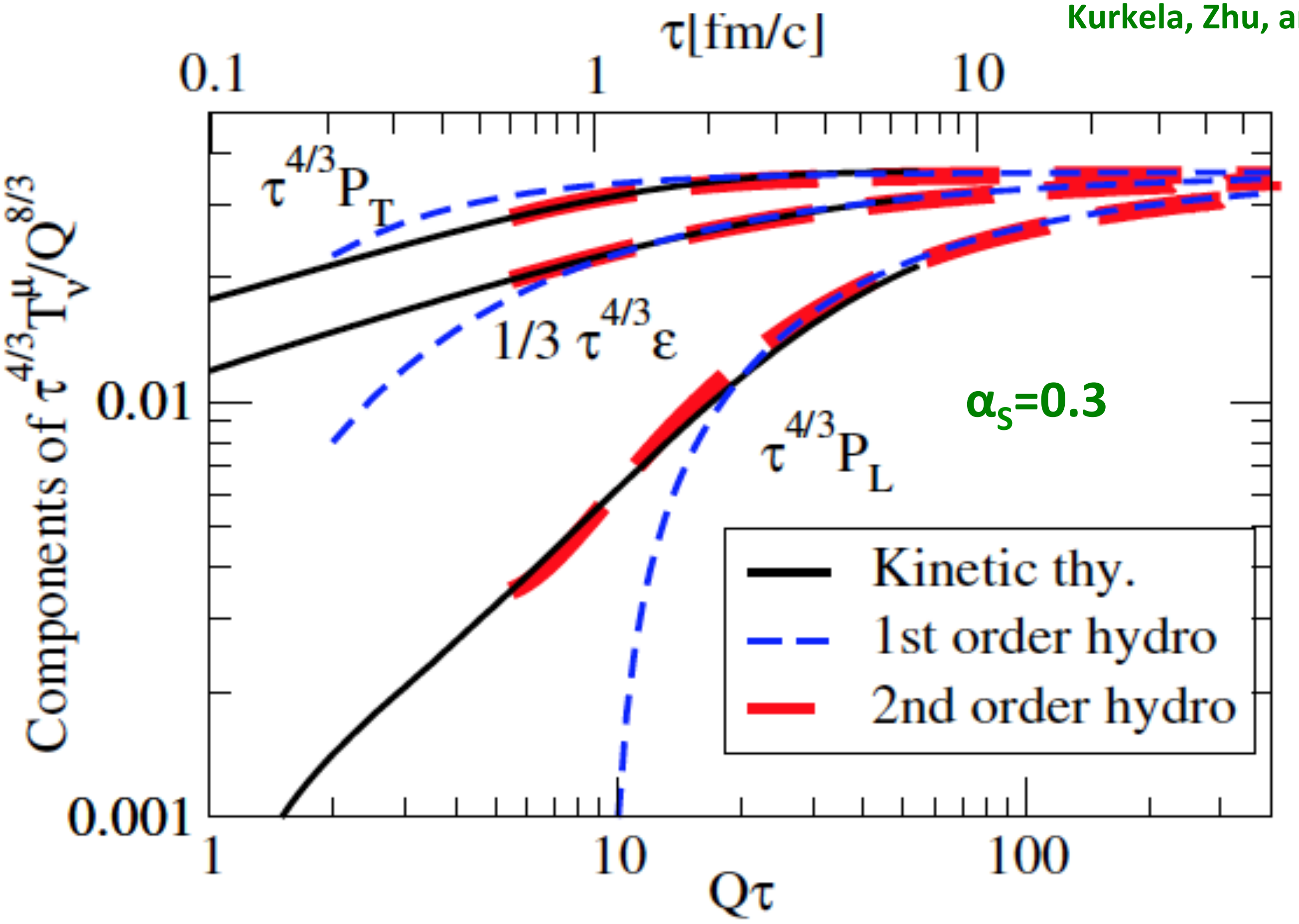
Quantum Regime
-described by kinetic theory

Thermalized soft bath of gluons for $\tau > \frac{1}{\alpha_S^{5/2}} \frac{1}{Q_S}$

Thermalization temperature of $T_i = \alpha_S^{2/5} Q_S$

Matching to hydrodynamics

Kurkela, Zhu, arXiv: 1506.06647

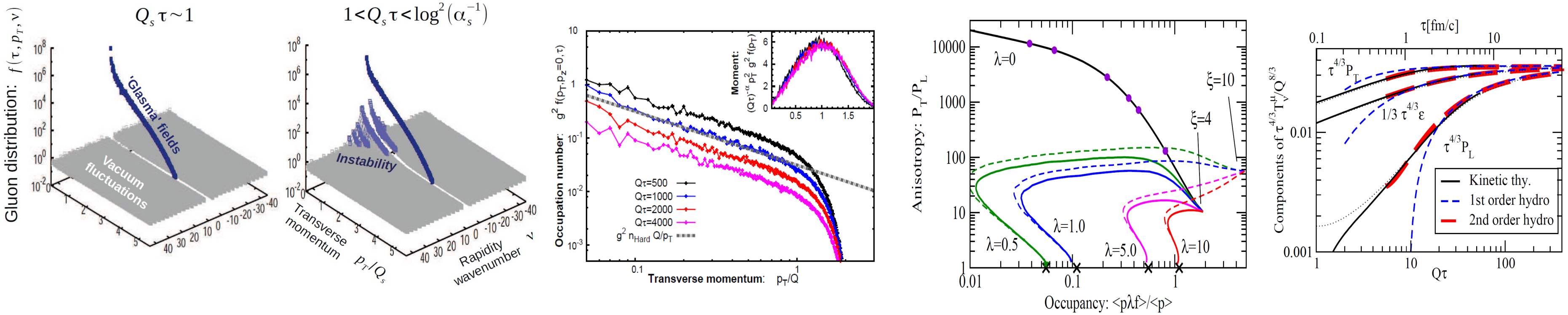


Good matching of quantitative implementation of kinetic theory to hydrodynamics at times ~ 1 fm
… when extrapolated to realistic couplings

Glasma to Plasma: from nuts to soup

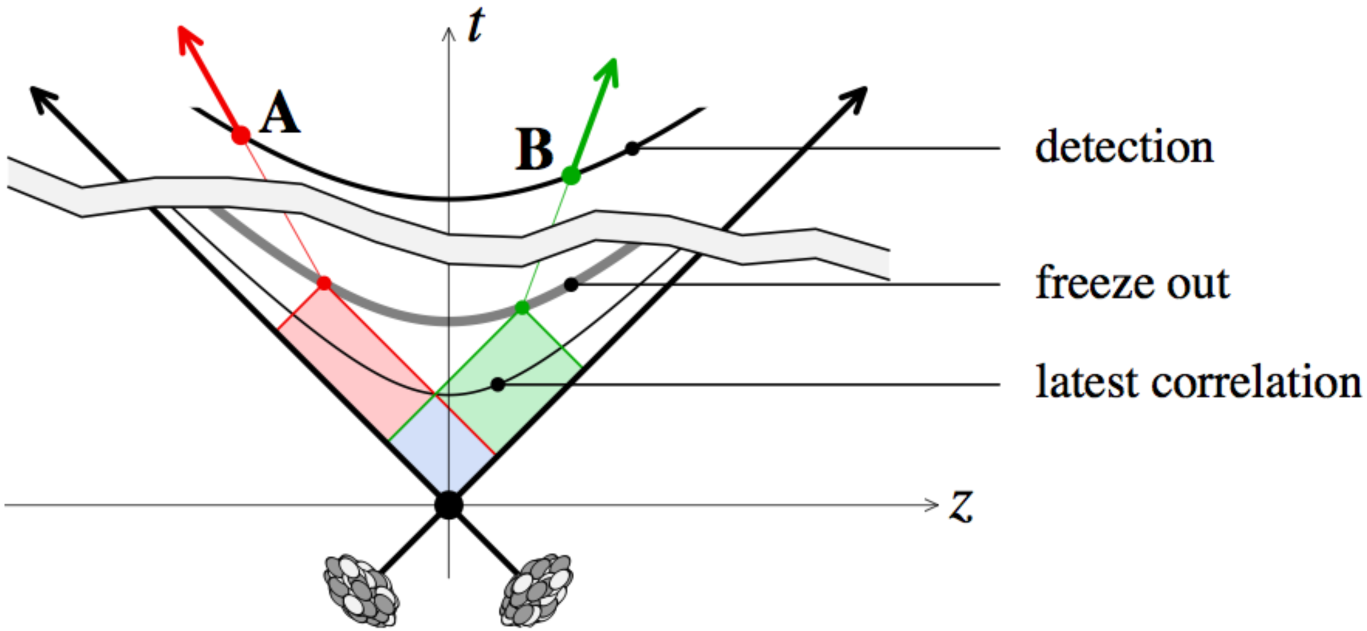
Boguslavski

$Q_s\tau = 0^+$ $\quad$ $Q_s\tau = \ln^2(\alpha_s^{-1})$ $\quad$ $Q_s\tau = \alpha_s^{-3/2}$ $\quad$ $Q_s\tau = \alpha_s^{-13/5}$



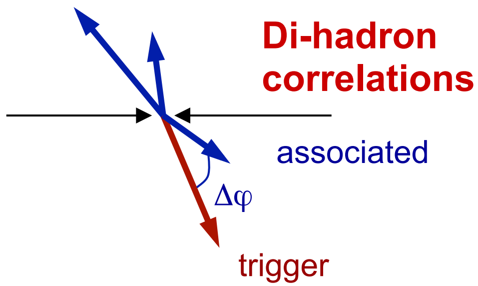
Glasma; **Instabilities;** **Classical NTFP;** **Constant anisotropy, Radiational breakup;** **Hydrodynamics, Thermalization**

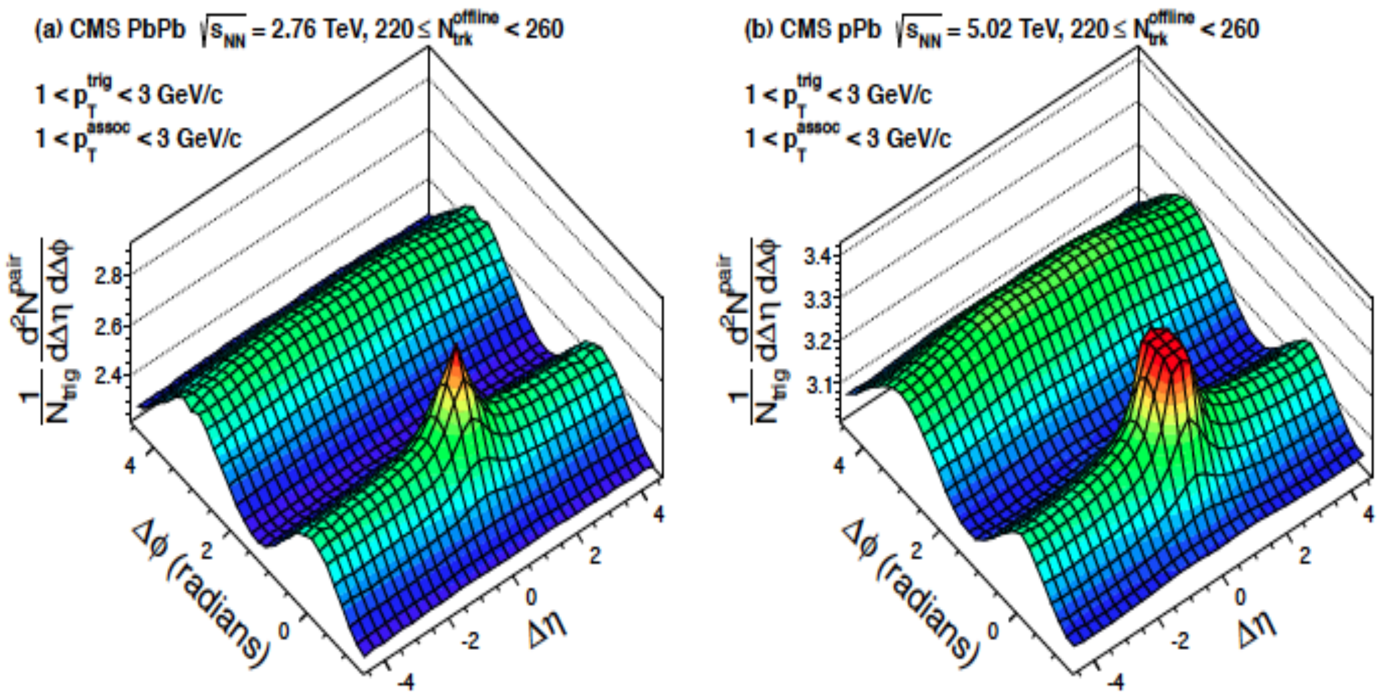
Engineering the world's smallest fluid?

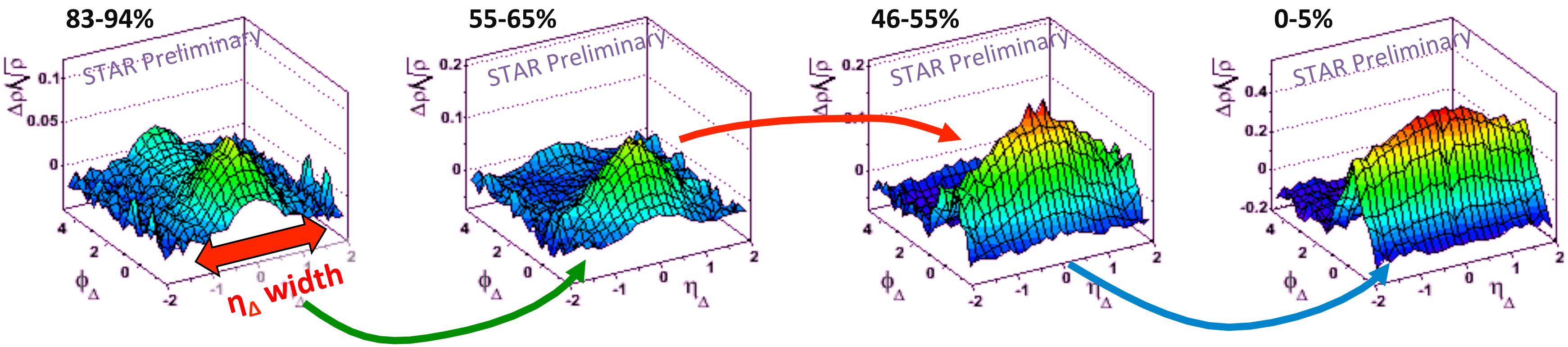


$$\tau \leq \tau_{\text{frz-out}} \exp\left(-\frac{1}{2}|y_A - y_B|\right)$$

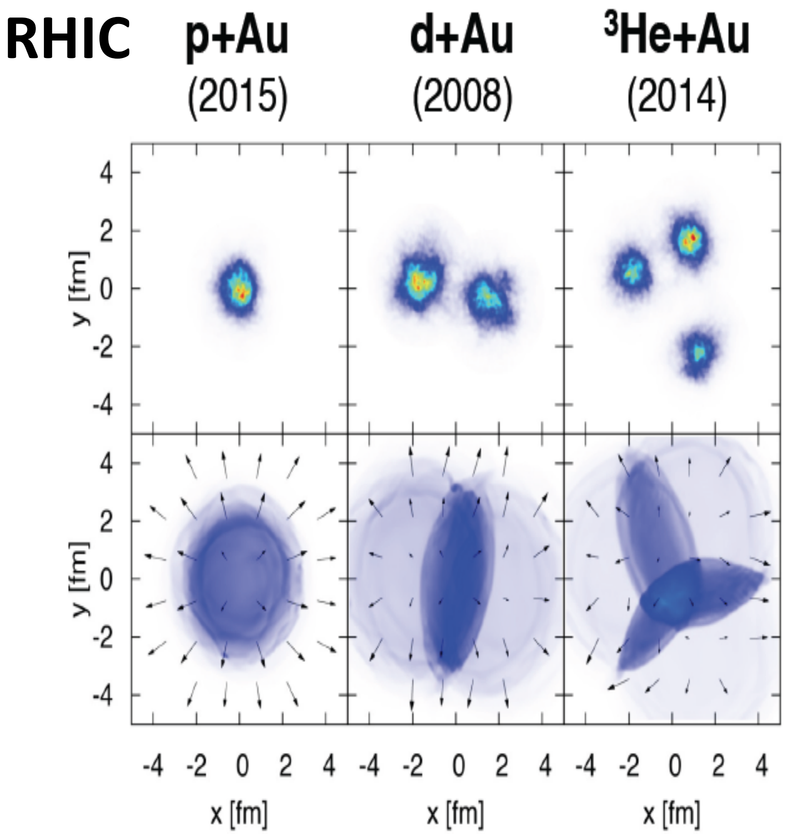
Long-range rapidity correlations in p+p, p+A and A+A collisions

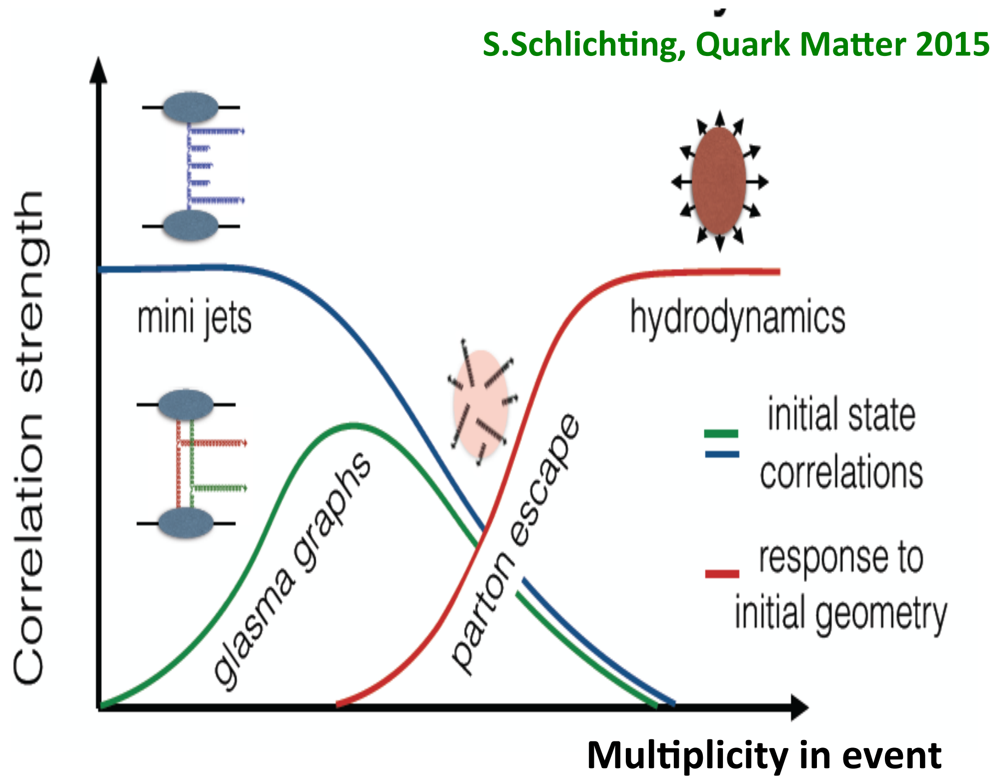






Long-range rapidity correlations in p+p, p+A and A+A collisions

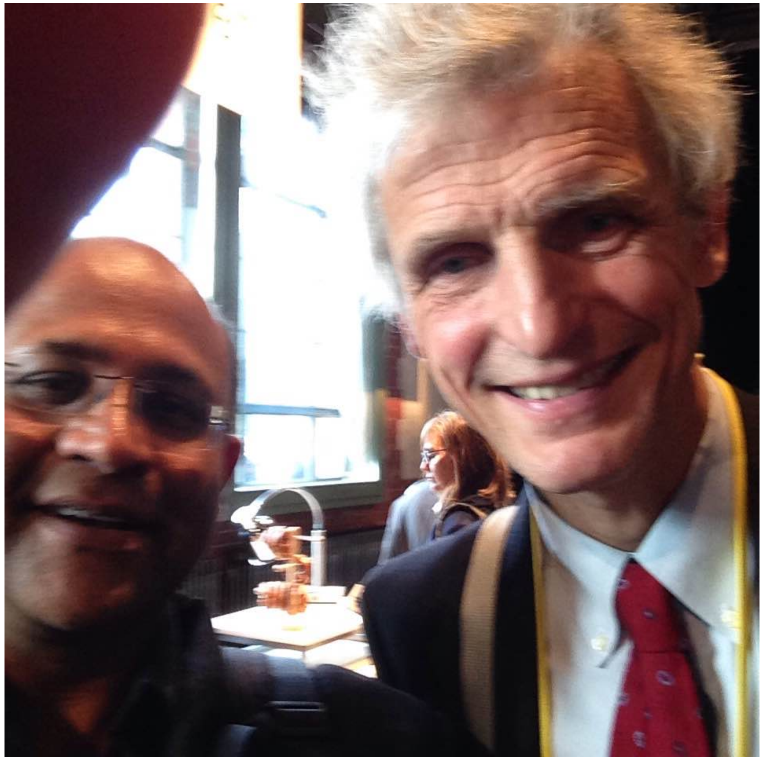




Non-equilibrium → Equilibrium

Highly precise data on multiplicity triggered 2 & 4 particle correlations from RHIC and LHC will test onset of hydrodynamic behavior within a system and across systems

Universality: hotness is also cool



Wolfgang Ketterle, Nobel Prize (2001)

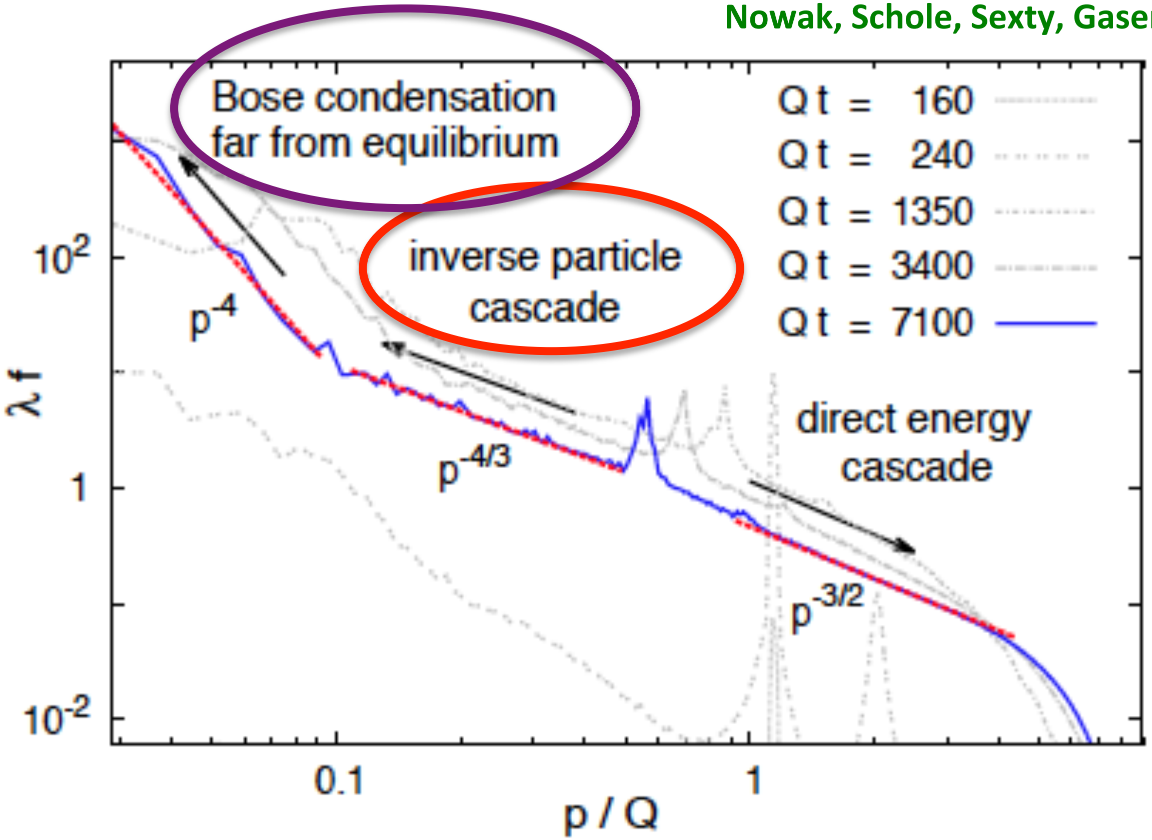
For the achievement of Bose-Einstein condensation in dilute gases of alkali atoms, and for early fundamental studies of the properties of the condensates

Over-occupied self-interacting scalars

$$S = \int d\tau d^2 x_T d\eta \; \tau \left(\frac{g^{\mu\nu}}{2} (\partial_\mu \varphi_a)(\partial_\nu \varphi_a) - \frac{\lambda}{4! N} (\varphi_a \varphi_a)^2 \right)$$

In a non-relativistic limit, can be used to model cold atomic gases

Scheppach,Berges,Gasenzer, PRA 81 (2010) 033611
Nowak, Schole, Sexty, Gasenzer, PRA85 (2012) 043627



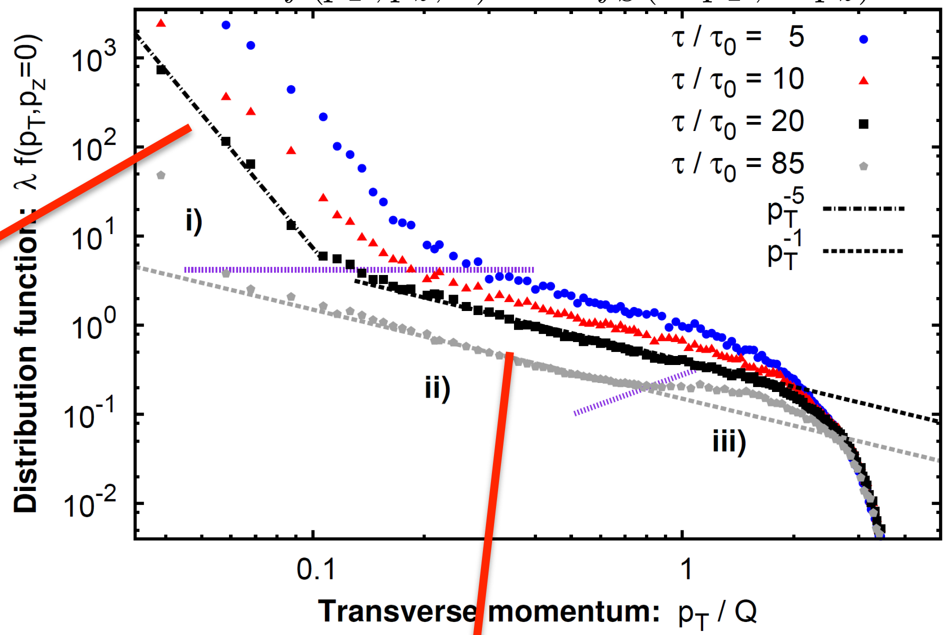
Berges, Sexty PRL 108 (2012) 161601
Berges,Boguslavski,Orioli, PRD 92, 025041 (2015)
Berges,Boguslavskii,Schlichting,Venugopalan, JHEP 1405 (2014) 054

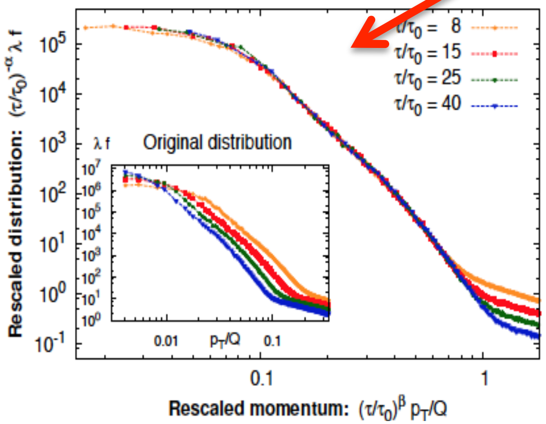
What about longitudinally expanding scalars?

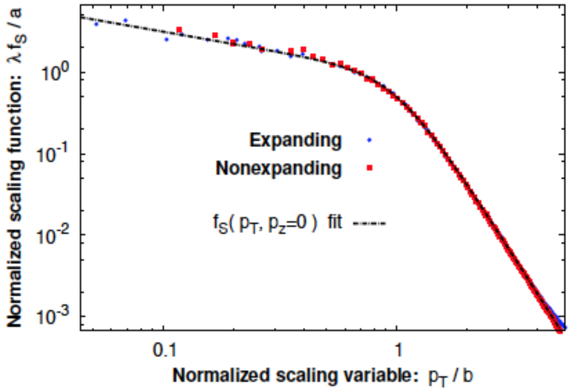
Berges, Boguslavski, Schlichting, Venugopalan, PRD92 (2015) 096 006

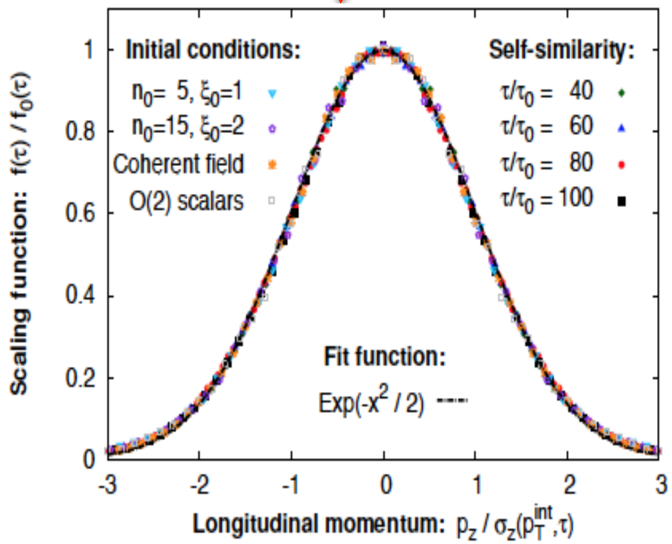
Three distinct inertial regimes with self-similar behavior

$$f(p_T, p_z, \tau) = \tau^{\alpha} f_S(\tau^{\beta} p_T, \tau^{\gamma} p_z)$$





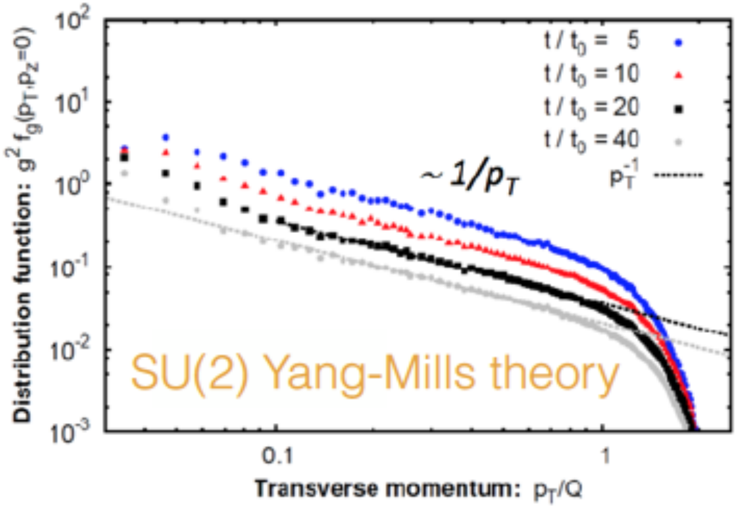


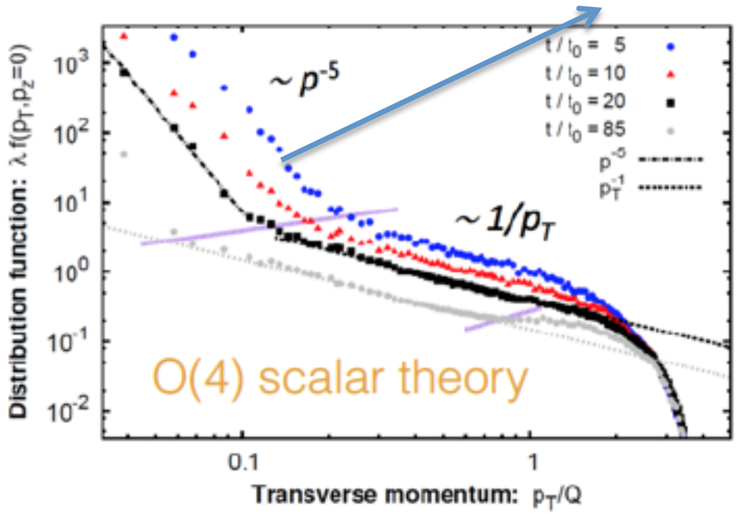


A remarkable universality

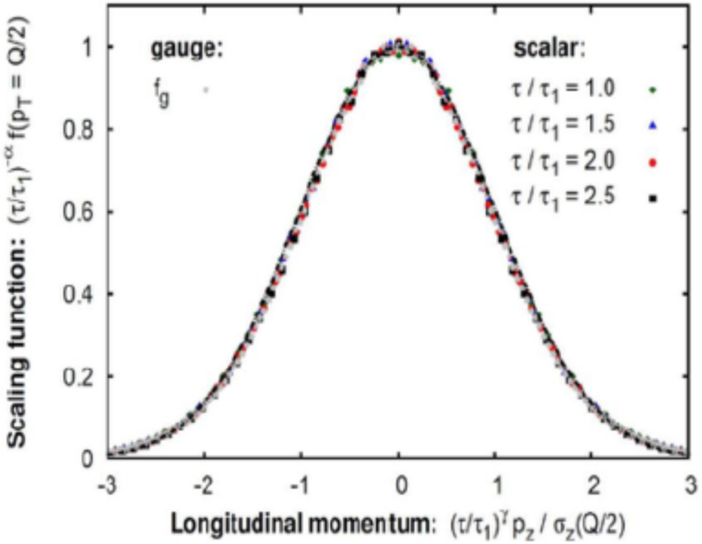
Evolution of the single particle spectrum

Leads to Bose-Einstein condensation





Normalized fixed-point distribution



Berges, Boguslavski, Schenke, Venugopalan, PRL 114 (2015) 061601, Editor's suggestion

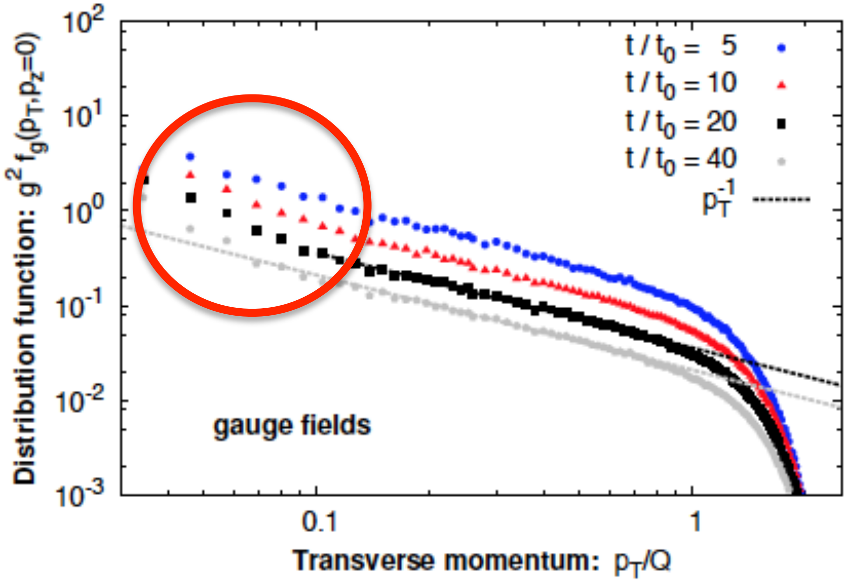
In a wide inertial range, scalars and gauge fields have identical scaling exponents and scaling functions

Very surprising from a kinetic theory perspective

A remarkable universality

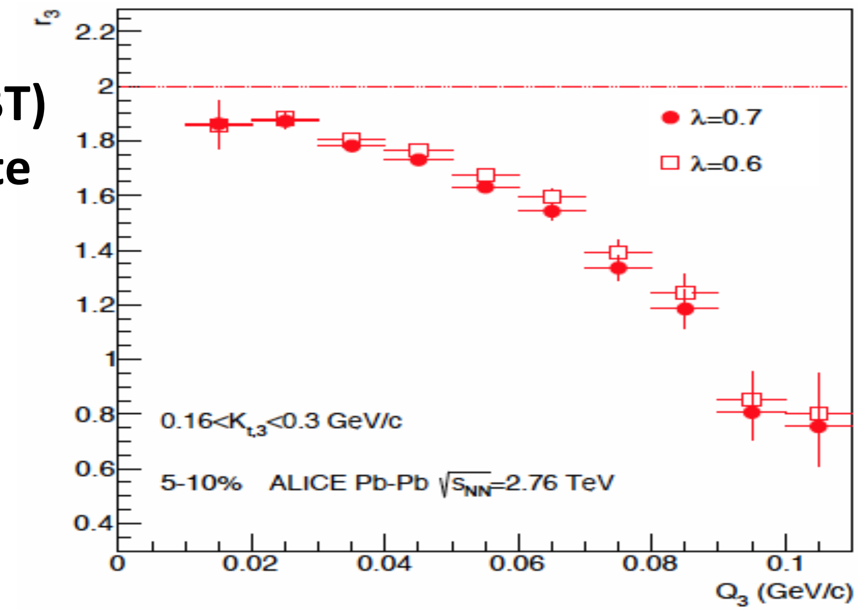
Can this provide insight into possible transient BEC in heavy-ion collisions ?

Blaizot,Gelis,Liao,McLerran,RV NPA (2012)
Floerchinger,Wetterich, JHEP 1403 (2014) 121

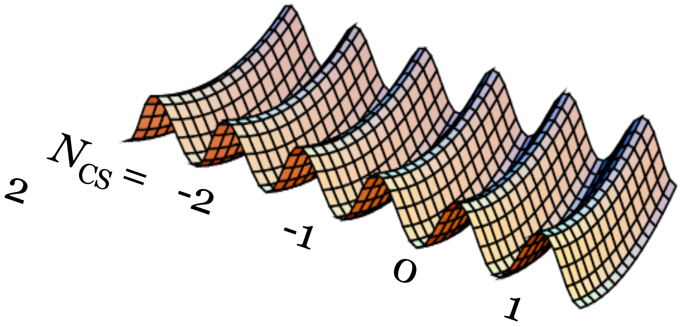


Intriguing data from ALICE on three pion Hanbury-Brown—Twiss (HBT) correlations hint at possible condensate fraction of 22 ± 12 %

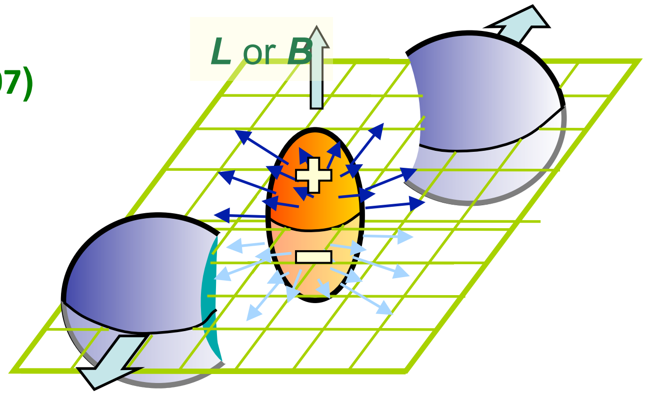
ALICE, arXiv:1310.7808
arXiv:1512.08908



Topological in heavy-ion collisions:
The Chiral Magnetic Effect



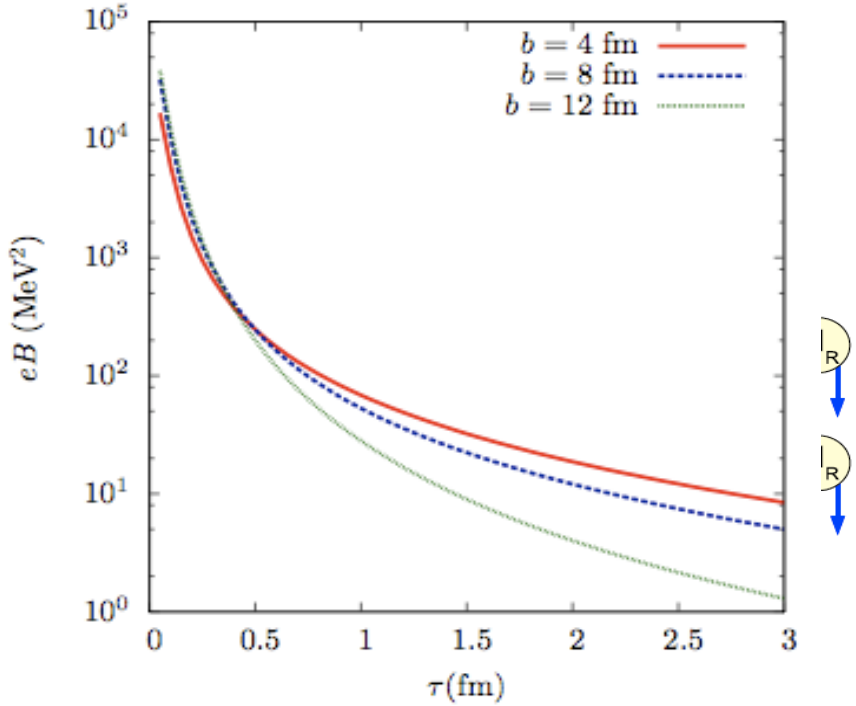
Kharzeev,McLerran,Warringa (2007)

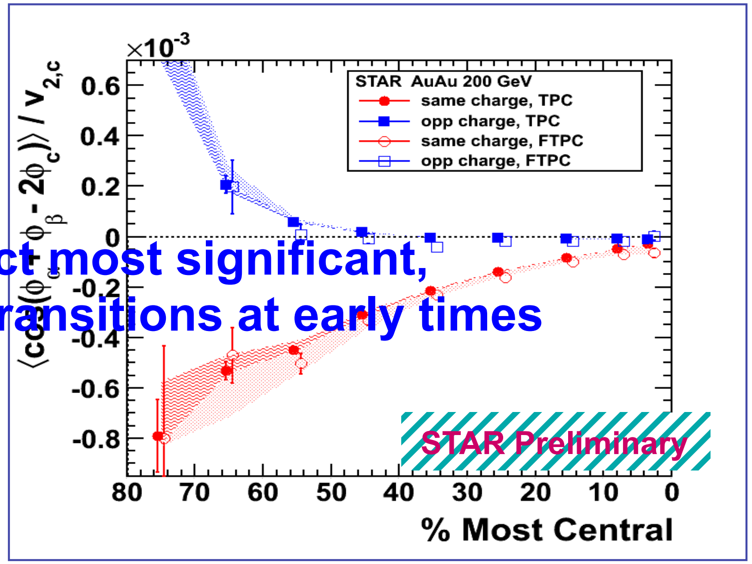


+

Topological fluctuations-over barrier -sphaleron transitions in Glasma

External (QED) magnetic field





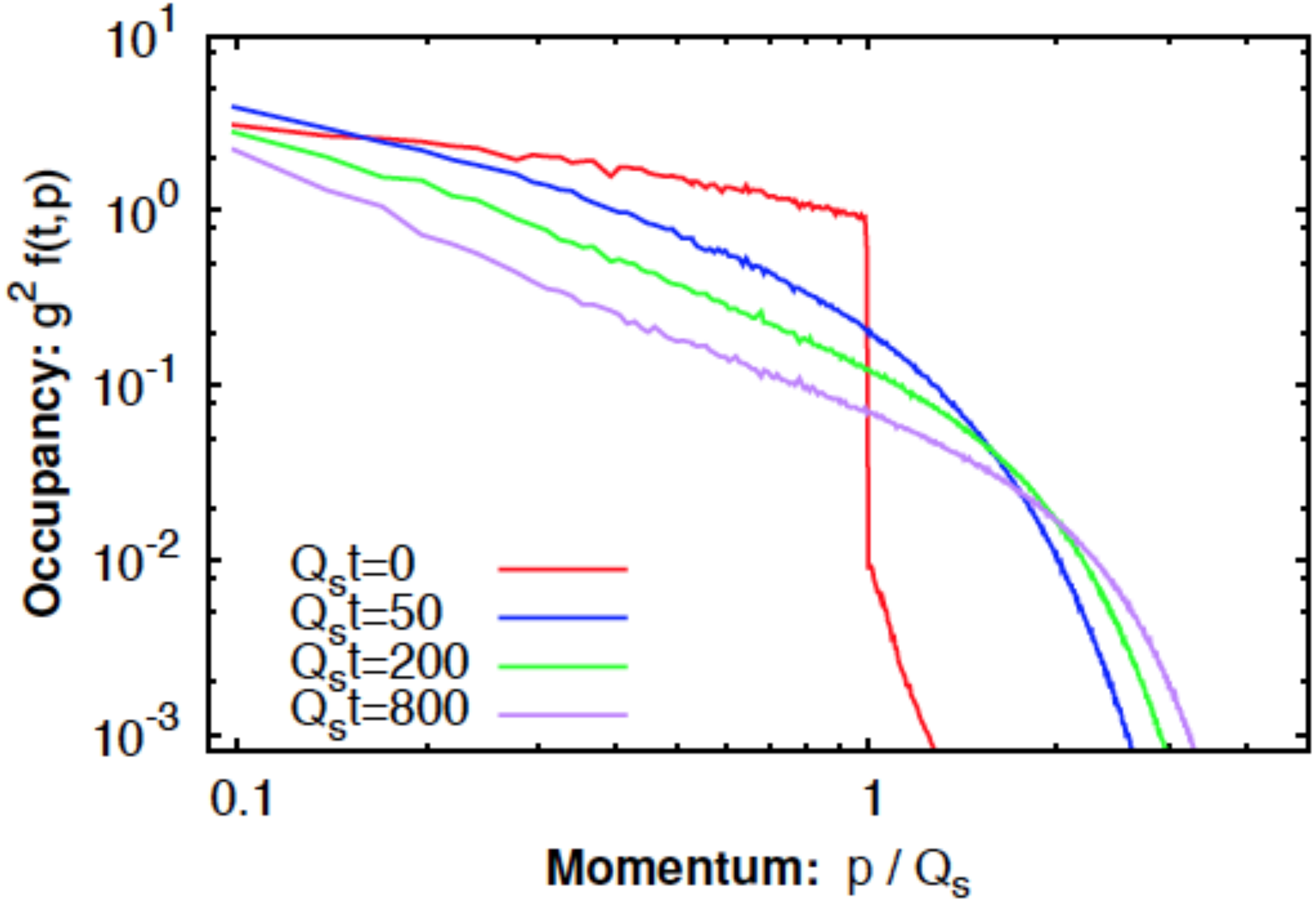
Effect most significant, for transitions at early times

Possible experimental signal of charge separation

Topological transitions in the Glasma

Mace,Schlichting,Venugopalan, arXiv:1601.07342

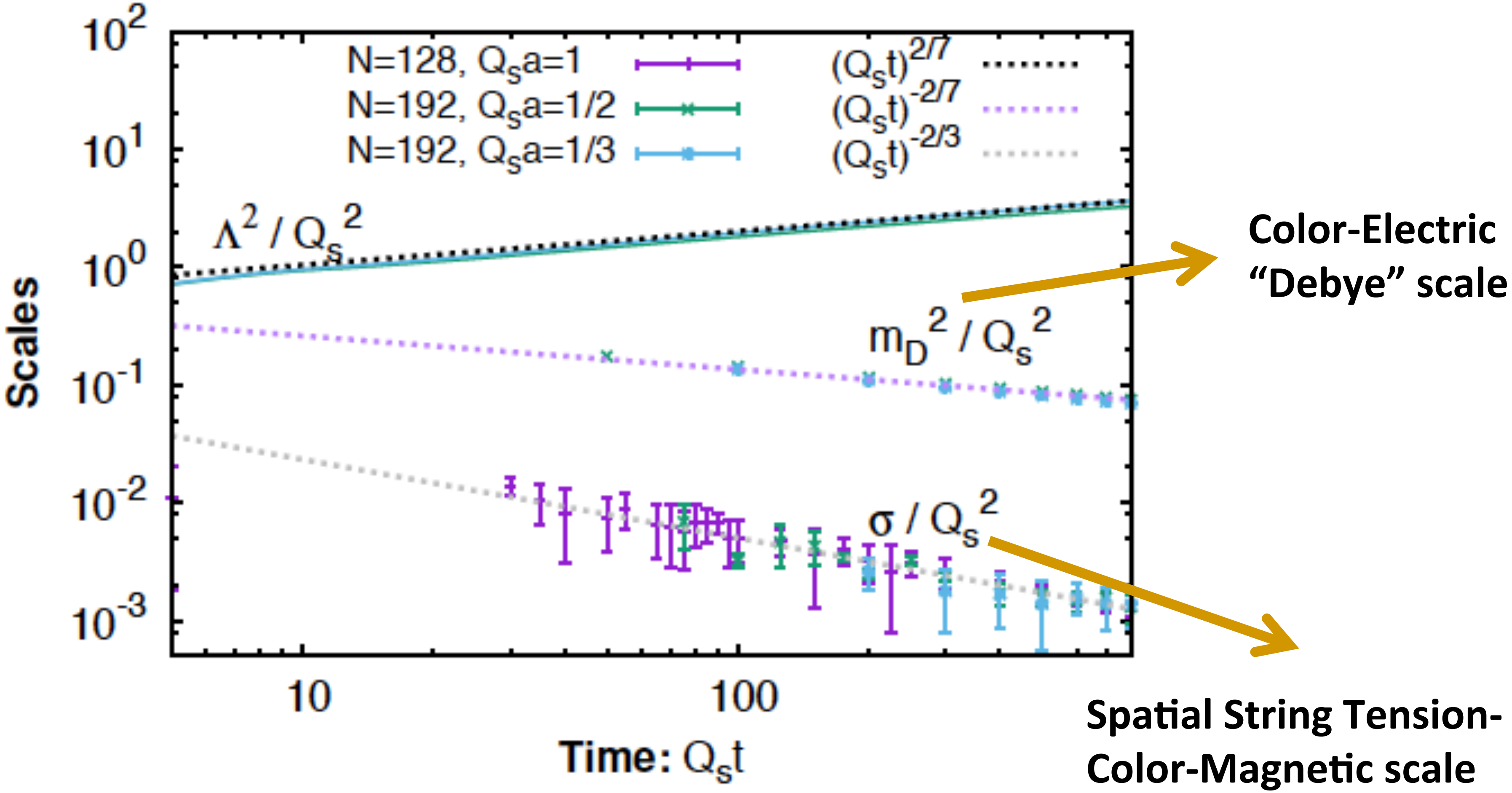
Overoccupied initial conditions:



Topological transitions in the Glasma

Mace, Schlichting, Venugopalan, arXiv:1601.07342

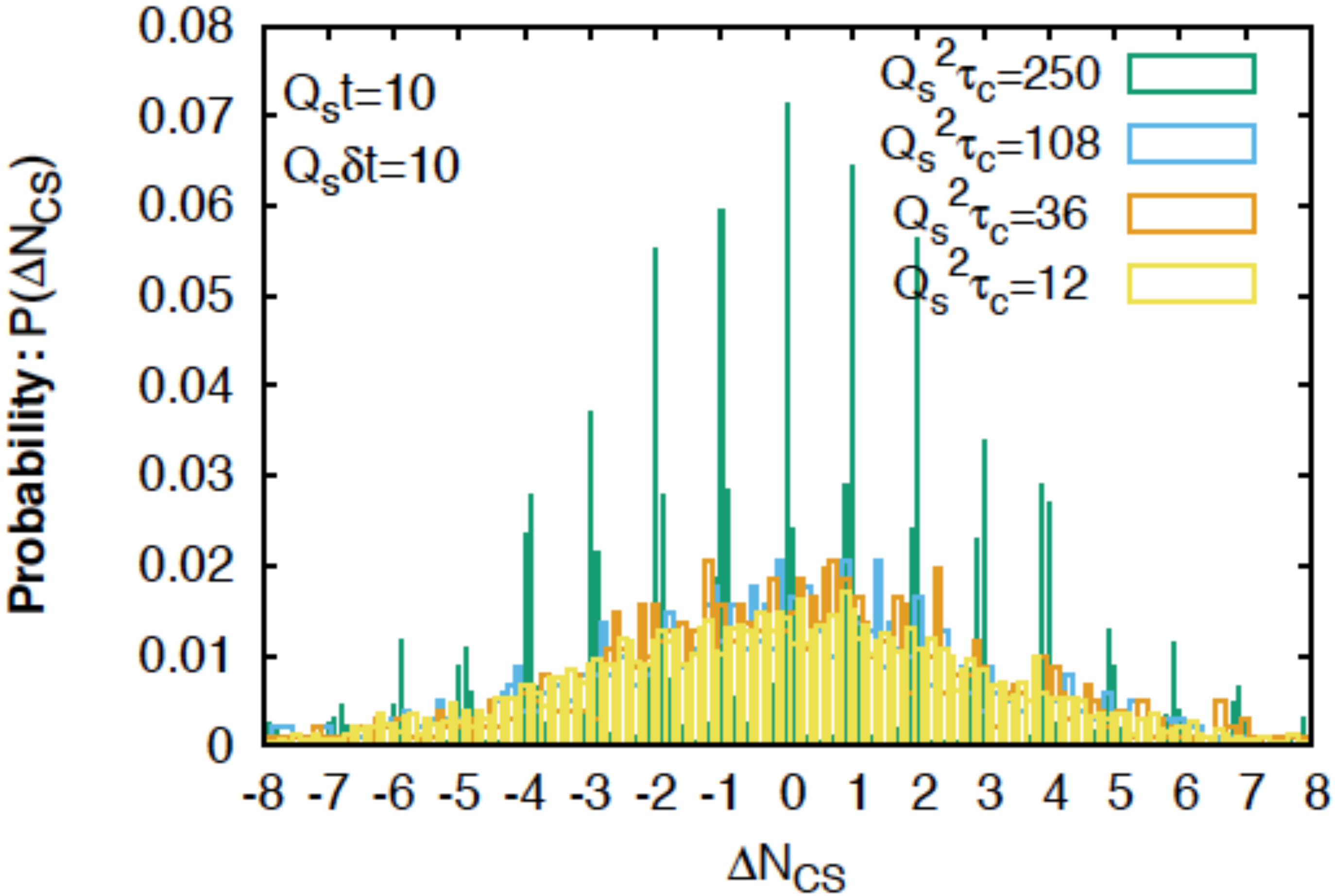
Soft electric and magnetic scales develop:



Topological transitions in the Glasma

Mace,Schlichting,Venugopalan, arXiv:1601.07342

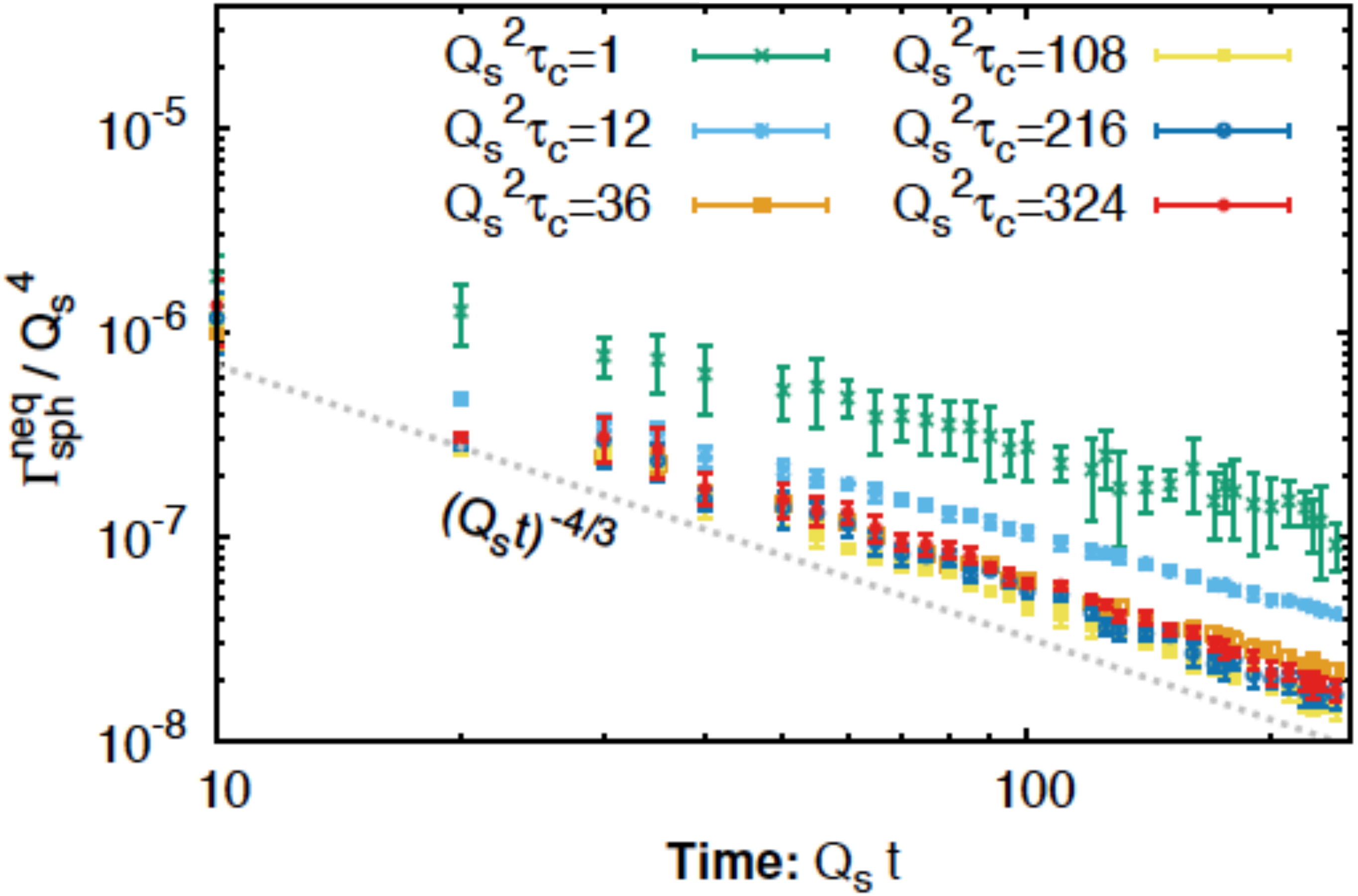
“Cooled” soft Glue configurations are topological—peak around integer valued transitions in Chern-Simons number



Topological transitions in the Glasma

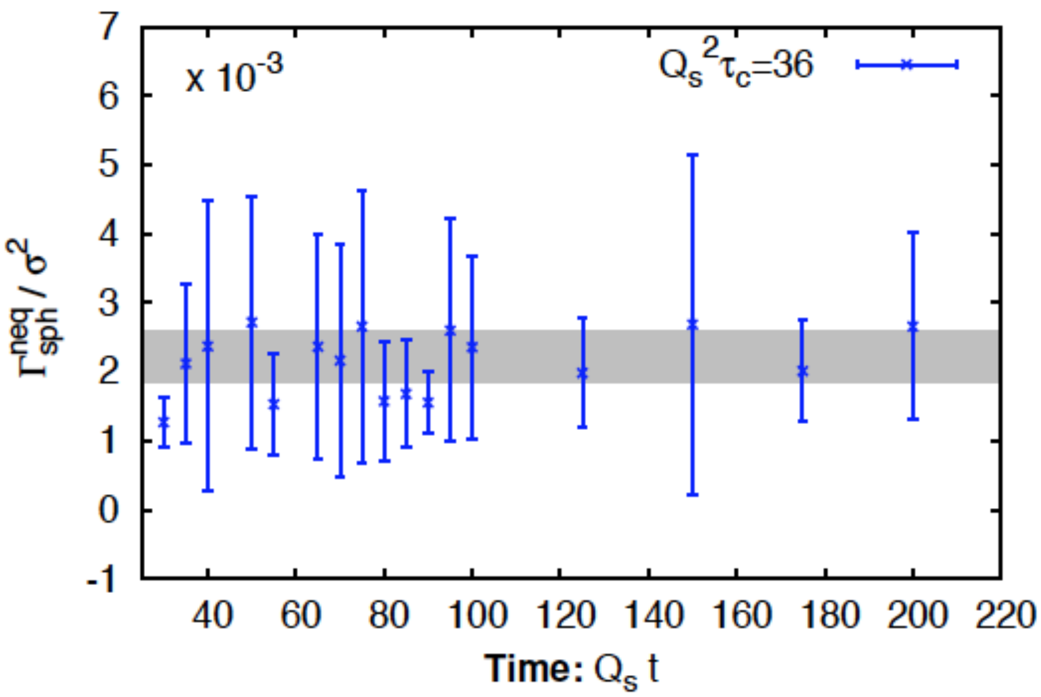
Mace,Schlichting,Venugopalan, arXiv:1601.07342

Non-equilibrium sphaleron transition rate: $\Gamma^{neq}_{sph}(t) = \left\langle \frac{(N_{CS}(t+\delta t) - N_{CS}(t))^2}{V\ \delta t} \right\rangle_{Q_s \delta t < 10}$



Topological transitions in the Glasma

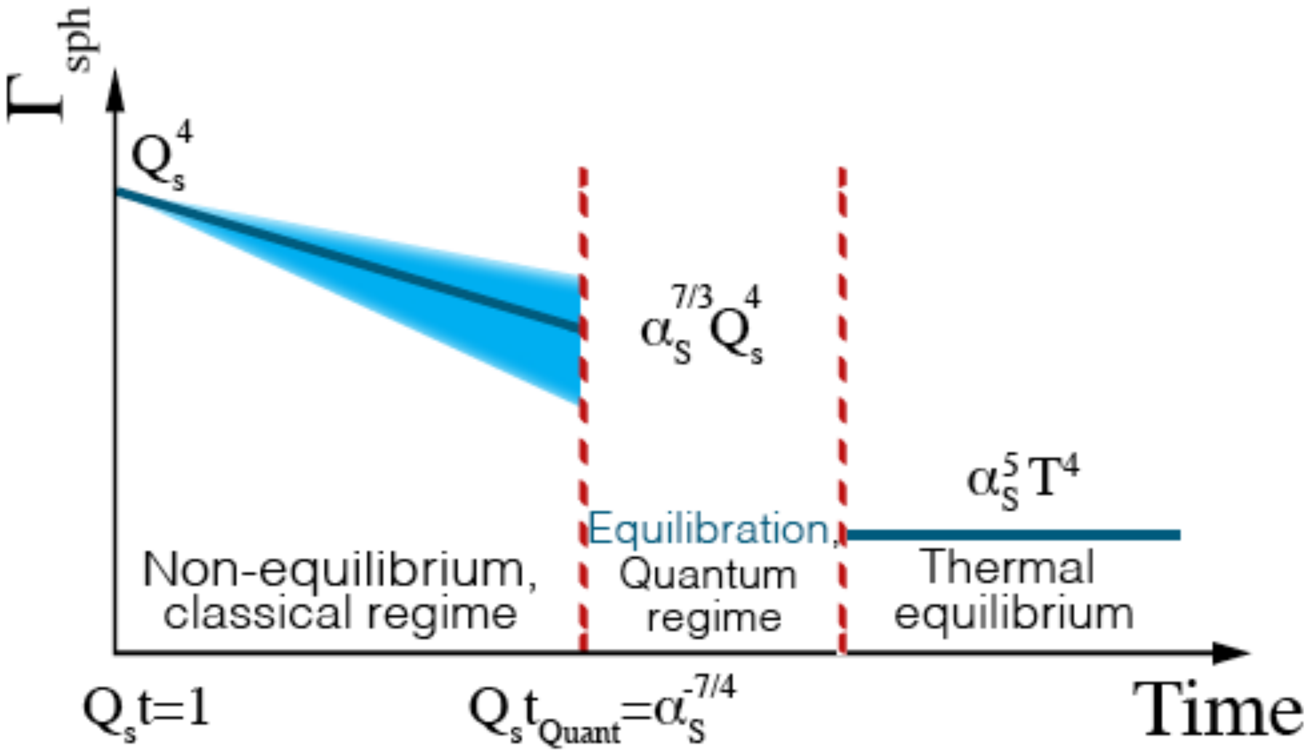
Mace,Schlichting,Venugopalan, arXiv:1601.07342



Scaling with string tension precisely as if topological transitions are controlled entirely by the color-magnetic screening scale

Topological transitions in the Glasma

Mace,Schlichting,Venugopalan, arXiv:1601.07342



Sphaleron transitions are large in the Glasma-can couple
with fermions and external E&M fields to simulate the Chiral Magnetic Effect

Gelfand,Hebenstriet,Berges,arXiv:1601.03576

Outlook

- We are beginning to explore the non-equilibrium dynamics of strongly correlated gluon matter in QCD

- Early studies reveal striking features such as non-thermal fixed points, possible transient BEC formation, sphaleron transitions…

- Can we uncover these in experiment…promising experimental signatures exist. Significant challenges for theory and phenomenology


QGP

Quantum Chromodynamics (QCD)

- QCD - “nearly perfect” fundamental quantum theory of quark and gluon fields (F.Wilczek, hep-ph/9907340)

- Theory is rich in symmetries:

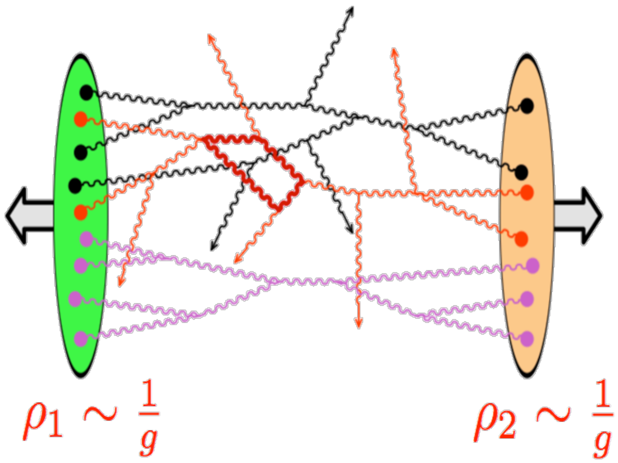
$$\underbrace{SU(3)_c}_{\text{i}} \times \underbrace{SU(3)_L \times SU(3)_R}_{\text{ii}} \times \underbrace{U(1)_A \times U(1)_B}_{\text{iii}}$$

i) Gauge “color” symmetry: unbroken but confined
ii) Global “chiral” symmetry: exact for massless quarks
iii) Baryon number and axial charge (m=0) are conserved
iv) Scale invariance of quark (m=0) and gluon fields
v) Discrete C,P & T symmetries

- Chiral, Axial, Scale and (in principle) P &T broken by vacuum/quantum effects - ”emergent” phenomena

- What happens at finite temperature & density ?

Factorization of quantum fluctuations



CGC Classical EFT:
Separation of long-lived (large x sources) and short-lived (small x dynamical fields):

LO ~ $1/\alpha_S$ (all orders: $(g\,\rho)^n$)

NLO: O(1) (all orders: $(g\,\rho)^n$) but of same size of LO for large Ln(1/x) – resummation

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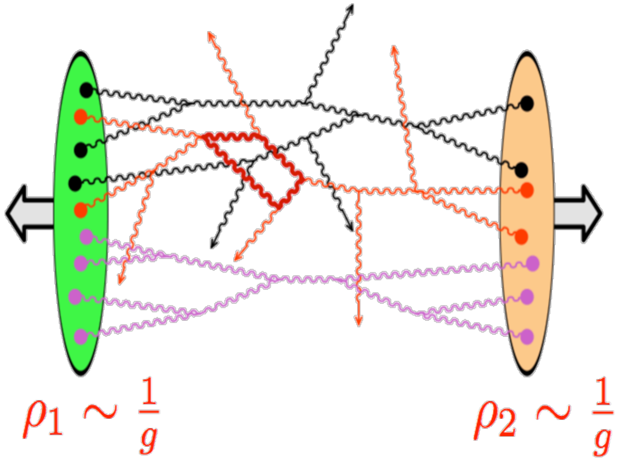

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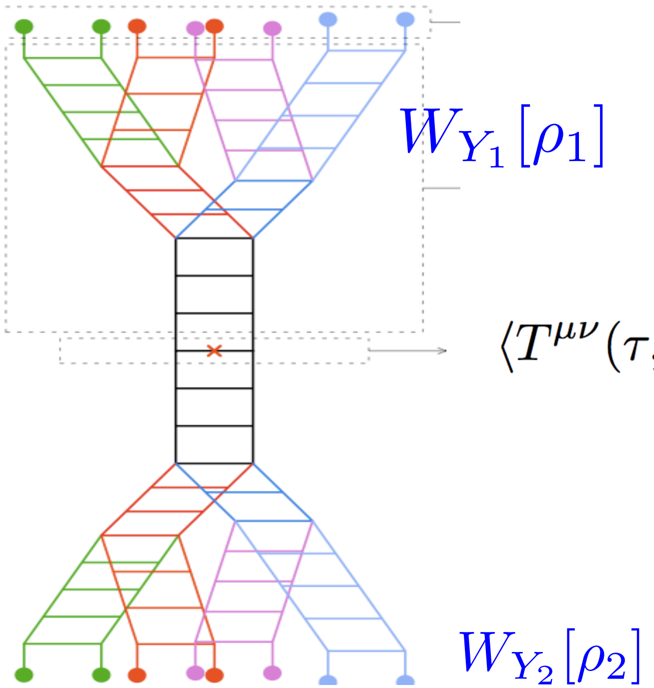


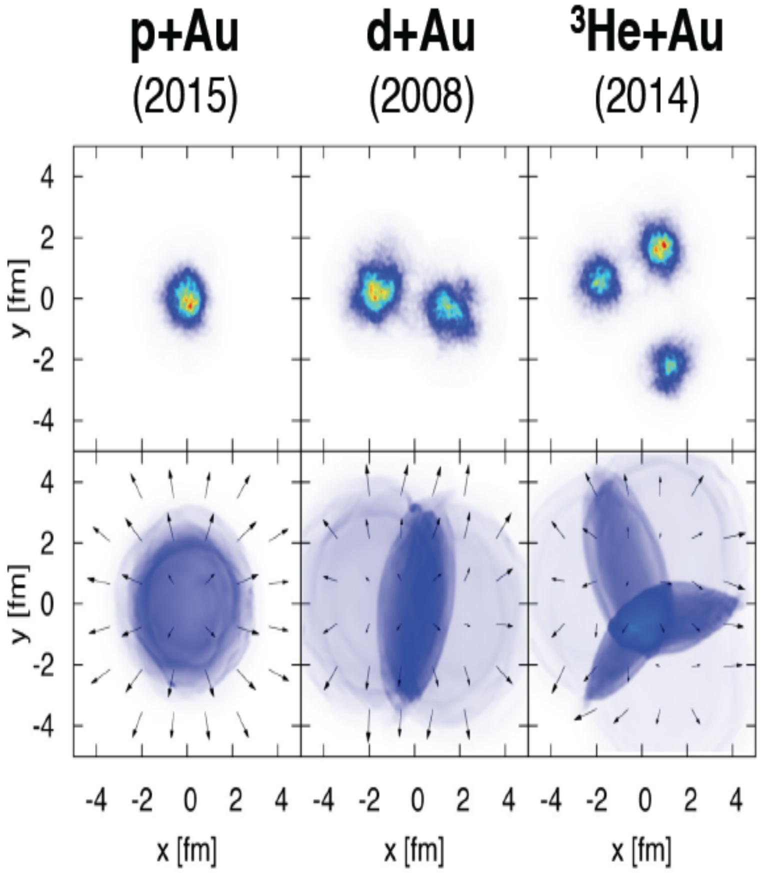
Large quantum corrections/strong field insertions absorbed in RG evolution of W's (JIMWLK eqns.)

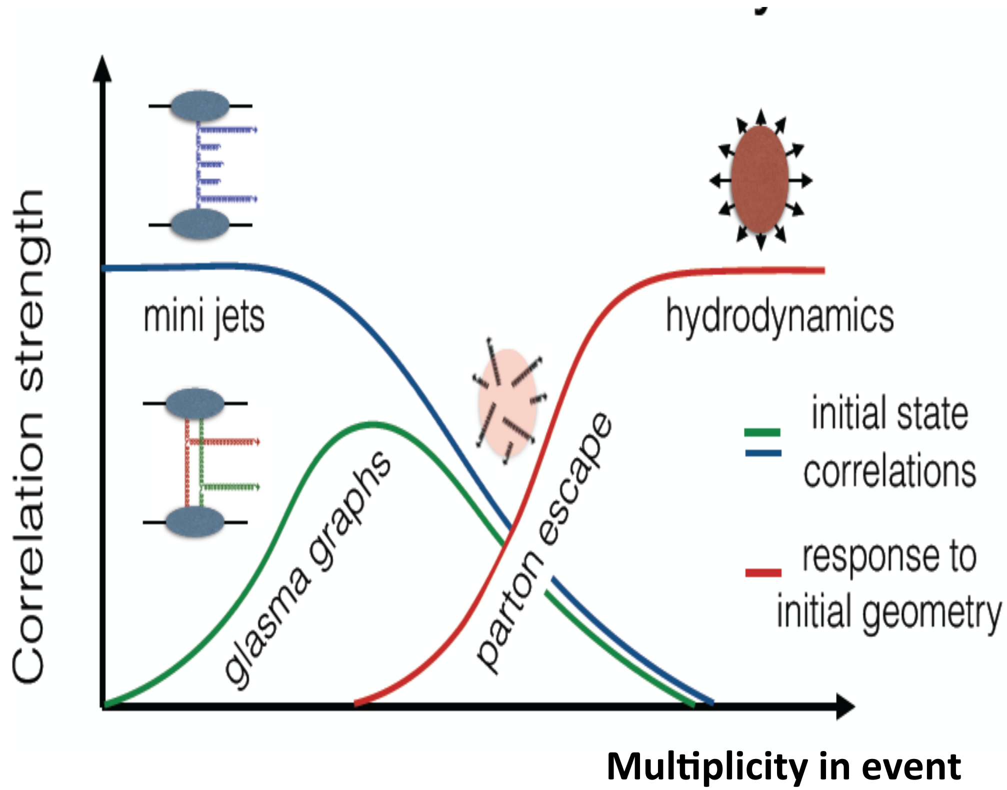
$$\langle T^{\mu\nu}(\tau,\eta,x_\perp)\rangle_{\rm LLog} = \int [D\rho_1 d\rho_2]\, W_{Y_1}[\rho_1]\, W_{Y_2}[\rho_2]\, T^{\mu\nu}_{\rm LO}(\tau,x_\perp)$$

$$T^{\mu\nu}_{LO} = \frac{1}{4} g^{\mu\nu} F^{\lambda\delta} F_{\lambda\delta} - F^{\mu\lambda} F^{\nu}_{\lambda}$$
$$Y_1 = Y_{\rm beam} - \eta\,;\; Y_2 = Y_{\rm beam} + \eta$$

Event-engineering of correlations in p+p, p+A and A+A collisions

S.Schlichting, Quark Matter 2015





Non-equilibrium → Equilibrium

Multiplicity triggered 2 & 4 particle correlations from RHIC and LHC will test onset of hydrodynamic behavior within a system and across systems

Initial conditions in the overpopulated QGP

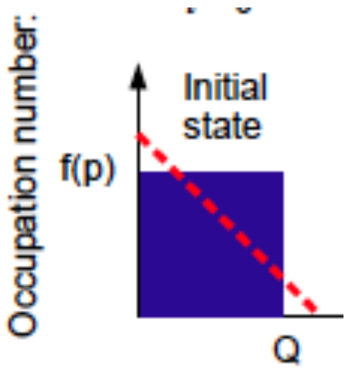
Choose for the initial classical-statistic ensemble of gauge fields

$$A_\mu^a(\tau_0, \mathbf{x}_\perp, \eta) = \sum_{\lambda=1,2} \int \frac{d^2\mathbf{k}_\perp}{(2\pi)^2} \frac{d\nu}{2\pi} \sqrt{f(\mathbf{k}_\perp, \nu, \tau_0)} \times \left[c_{\lambda,a}^{\mathbf{k}_\perp \nu} \, \xi_\mu^{(\lambda)\mathbf{k}_\perp \nu +}(\tau_0) \, e^{i\mathbf{k}_\perp \mathbf{x}_\perp} \, e^{i\nu\eta} + c.c. \right]$$

Stochastic random variables

$$\begin{aligned}
\langle c^{(\lambda)\boldsymbol{k}_\perp \nu} c^{(\lambda')\boldsymbol{k}'_\perp \nu'} \rangle &= 0 \,, \\
\langle c^{(\lambda)\boldsymbol{k}_\perp \nu} c^{*(\lambda')\boldsymbol{k}'_\perp \nu'} \rangle &= (2\pi)^3 \delta^{\lambda\lambda'} \delta(\boldsymbol{k} - \boldsymbol{k}') \delta(\nu - \nu') \\
\langle c^{*(\lambda)\boldsymbol{k}_\perp \nu} c^{*(\lambda')\boldsymbol{k}'_\perp \nu'} \rangle &= 0.
\end{aligned}$$

Polarization vectors ξ expressed in terms of Hankel functions in Fock-Schwinger gauge $A^\tau = 0$



$$f(p_\perp, p_z, t_0) = \frac{n_0}{\alpha_S} \Theta\left(Q - \sqrt{p_\perp^2 + (\xi_0 p_z)^2} \right)$$

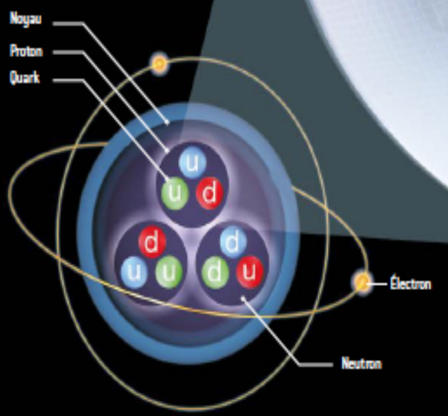
Controls "prolateness" or "oblateness" of initial momentum distribution

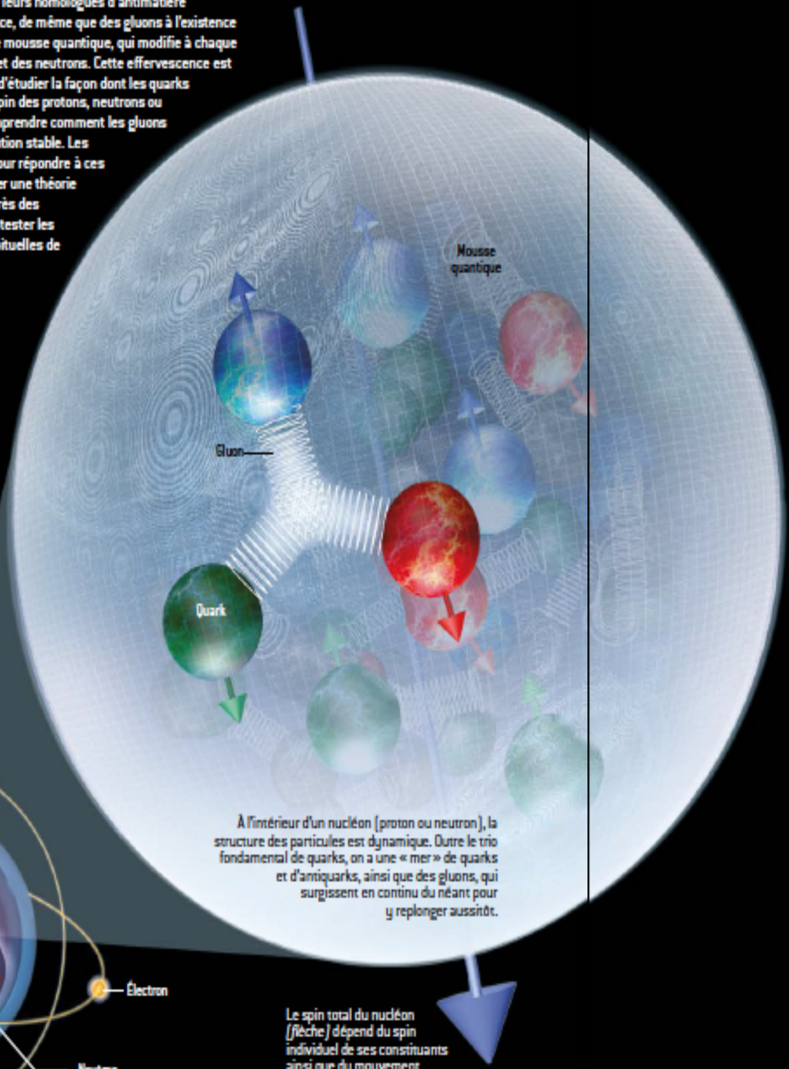
QUARKS ET GLUONS : LA STRUCTURE DE LA MATIÈRE EN QUESTION

Chacun des protons et des neutrons qui constituent les noyaux des atomes contient trois quarks primaires liés par des gluons. Outre ces trois quarks principaux, des paires supplémentaires de quarks et de leurs homologues d'antimatière apparaissent et disparaissent en permanence, de même que des gluons à l'existence éphémère. Il en résulte ce qu'on nomme une mousse quantique, qui modifie à chaque instant le paysage à l'intérieur des protons et des neutrons. Cette effervescence est difficile à prendre en compte lorsqu'il s'agit d'étudier la façon dont les quarks et les gluons contribuent à la masse et au spin des protons, neutrons ou autres hadrons. De même, on cherche à comprendre comment les gluons maintiennent les quarks dans une configuration stable. Les physiciens explorent plusieurs approches pour répondre à ces questions. L'une d'elles consiste à développer une théorie précise de ces interactions, de la tester auprès des accélérateurs de particules mais aussi d'en tester les limites en étudiant des configurations inhabituelles de gluons et de quarks.

STRUCTURE ATOMIQUE : DEUX VISIONS

Le schéma classique d'un atome présenté ci-dessous comprend des électrons en orbite autour d'un noyau de protons et de neutrons constitués de trois quarks chacun *(les dimensions ne sont pas respectées)*. Plus proche de la réalité, l'image ci-contre représente la mousse quantique du proton ou du neutron, avec d'éphémères paires quark-antiquark et gluons.





À l'intérieur d'un nucléon (proton ou neutron), la structure des particules est dynamique. Outre le trio fondamental de quarks, on a une « mer » de quarks et d'antiquarks, ainsi que des gluons, qui surgissent en continu du néant pour y replonger aussitôt.

Le spin total du nucléon *(flèche)* dépend du spin individuel de ses constituants ainsi que du mouvement orbital de ces derniers.

ÉTATS EXOTIQUES DE LA MATIÈRE

Les physiciens ont imaginé, et dans certains cas créé, des combinaisons inhabituelles de quarks et de gluons se démarquant des protons et des neutrons familiers. Ces états exotiques offrent de nouvelles possibilités pour étudier les interactions susceptibles de se produire entre quarks et gluons.

Boules de gluons et autres édifices

Des simulations théoriques suggèrent que les quarks et les gluons peuvent se combiner pour créer, par exemple, des « boules de gluons » *(a)* constituées exclusivement de gluons, ou des particules « hybrides » formant un assemblage quark-antiquark-gluon *(b)*, ou encore des « tétraquarks », états liés de deux antiquarks et de deux quarks *(c)*. Plusieurs indices expérimentaux suggèrent que des tétraquarks ont été observés. Les boules de gluons et les états hybrides restent à découvrir.

État saturé

Quand le proton (ou le neutron) est accéléré à des vitesses extrêmes, la théorie prévoit que ses gluons se multiplient. À mesure que son énergie augmente, le proton atteint un état d'occupation maximale qui ne peut plus loger davantage de gluons, un état théorique nommé « condensat de verre de couleur ». Des indices obtenus auprès des accélérateurs de particules suggèrent que ces condensats existent, mais une preuve décisive manque.

Reproduire l'Univers des débuts

Quand le cosmos était jeune, il était trop chaud pour que des protons et des neutrons stables se forment. Les quarks et les gluons s'agitaient librement, en tous sens, dans ce qu'on nomme un plasma de quarks et de gluons *(vue d'artiste ci-dessous à gauche)*. Sur Terre, des accélérateurs reproduisent cet état en fracassant des noyaux atomiques les uns contre les autres à des vitesses proches de celle de la lumière. En étudiant le plasma qui se refroidit, les physiciens glanent des informations sur le comportement des quarks et des gluons, mais aussi sur l'évolution de l'Univers juste après sa formation.

Where to study QCD matter ?

Peter Steinberg