Extreme QCD in Heavy Ion Collisions

Raju Venugopalan

BNL

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Quantum Chromodynamics (QCD)

- QCD - "nearly perfect" fundamental quantum theory of quark and gluon fields (F.Wilczek, hep-ph/9907340)
- **Theory is rich in symmetries:**

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ii) Global “chiral” symmetry: exact for massless quarks
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v) Discrete C,P & T symmetries

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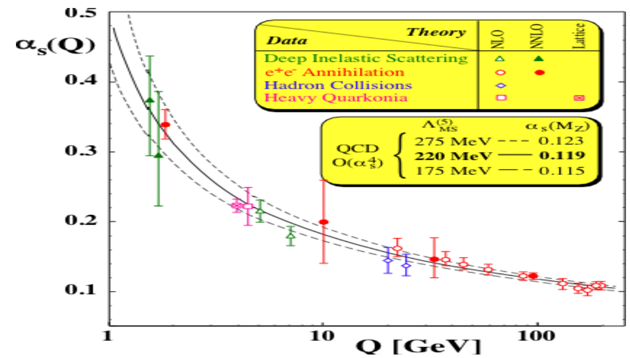
- Chiral, Axial, Scale and (in principle) P &T broken by vacuum/quantum effects - "emergent" phenomena
- What happens at finite temperature & density ?

QCD: structure & consequences

Asymptotic freedom:

Gross, Wilczek, Politzer (1973)



S: Coupling strength of gluons weaker at short separation

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

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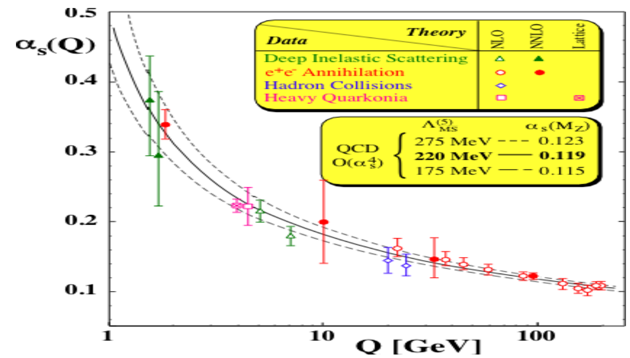
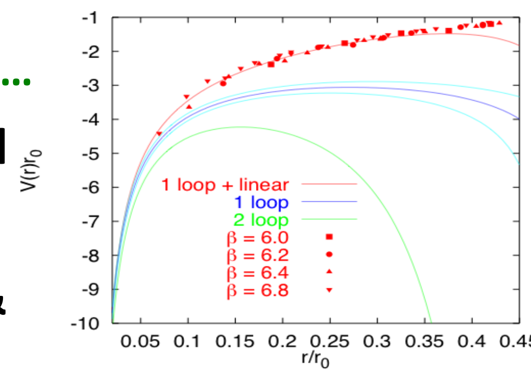


Infrared slavery:

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 low temp. & density- Rich QCD Phase Diagram (O. Philipsen's talk)



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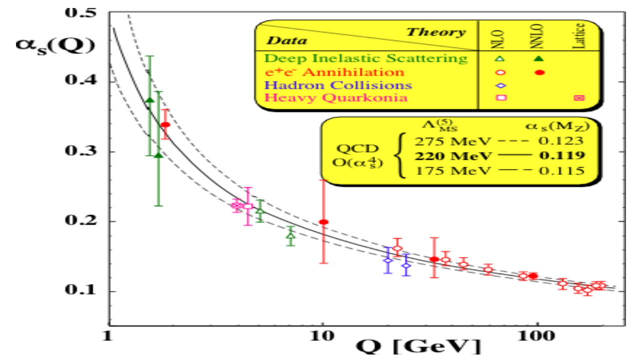

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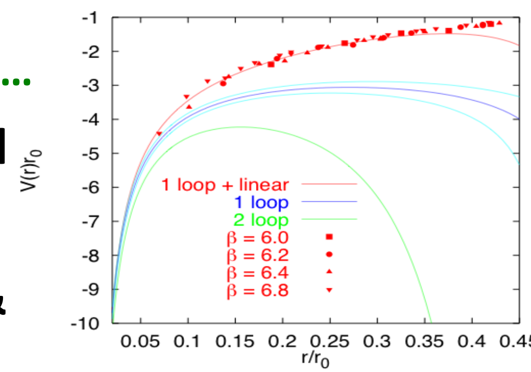
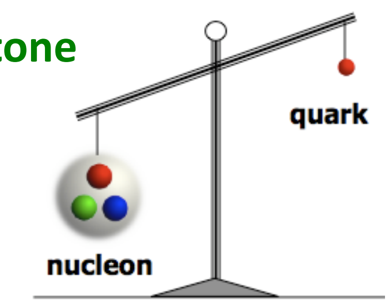


(Broken) Chiral symmetry

Nambu-Goldstone

S: spontaneously generated Chiral condensate $\langle \bar{q}_R q_L \rangle \neq 0$

C: Chiral symmetry restored at finite T



QCD : brief pre-history

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

↓

Hagedorn (1965)

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Lee-Wick matter (1974)

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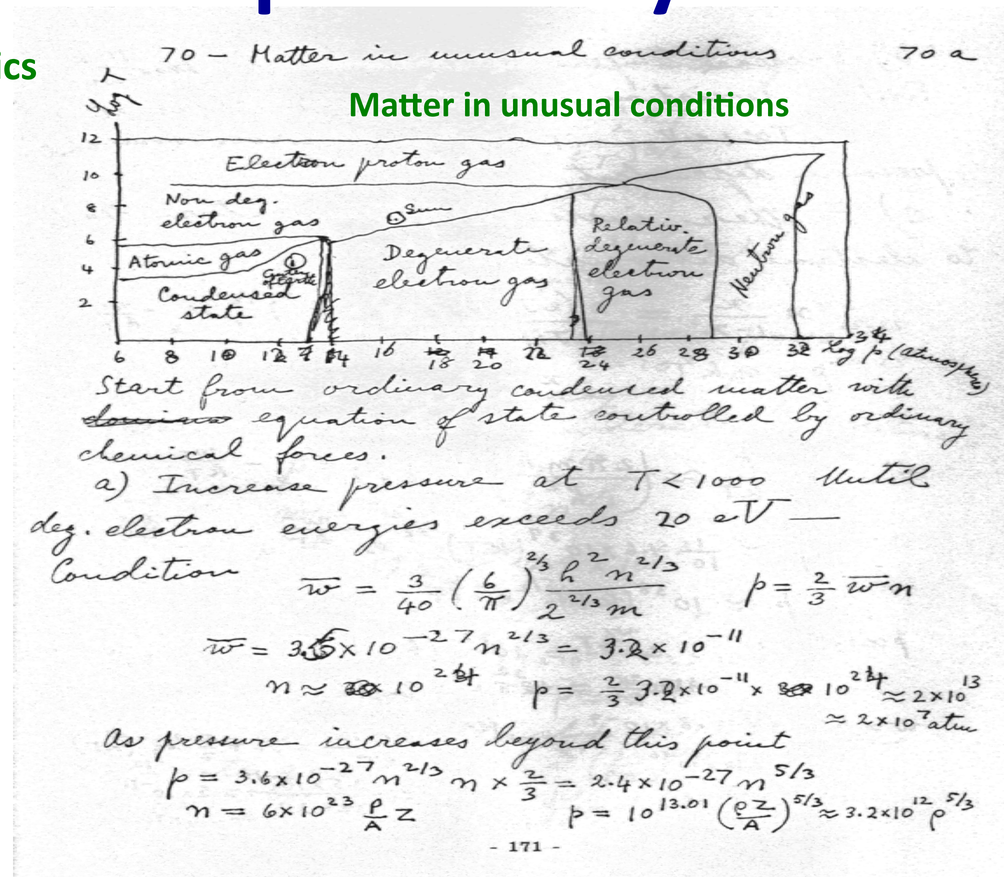
Quark-Gluon Plasma (QGP)
Shuryak (1978)



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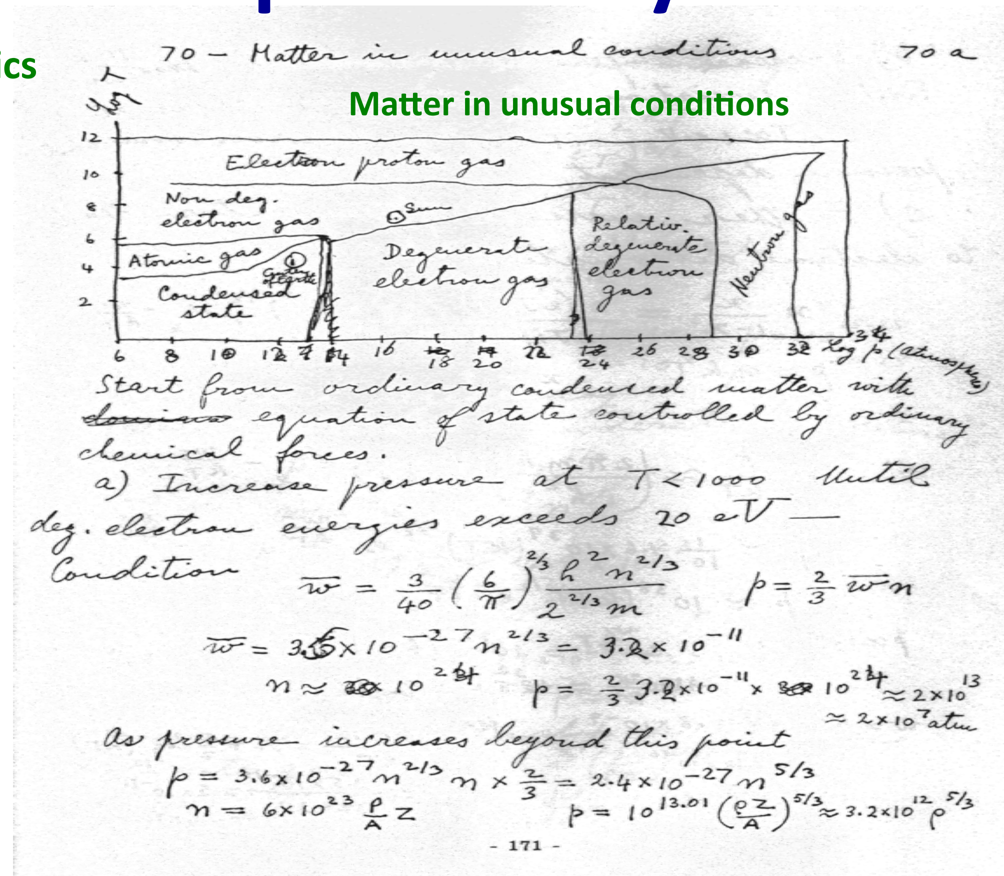

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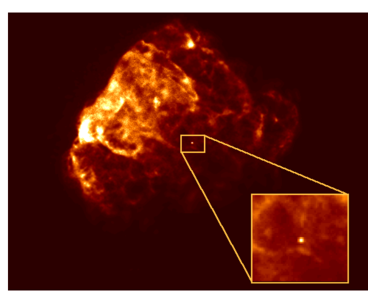
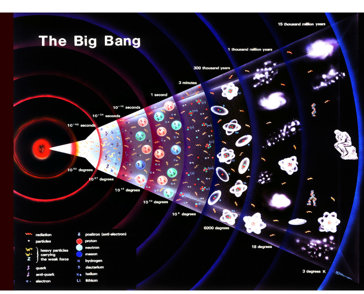
Neutron Stars

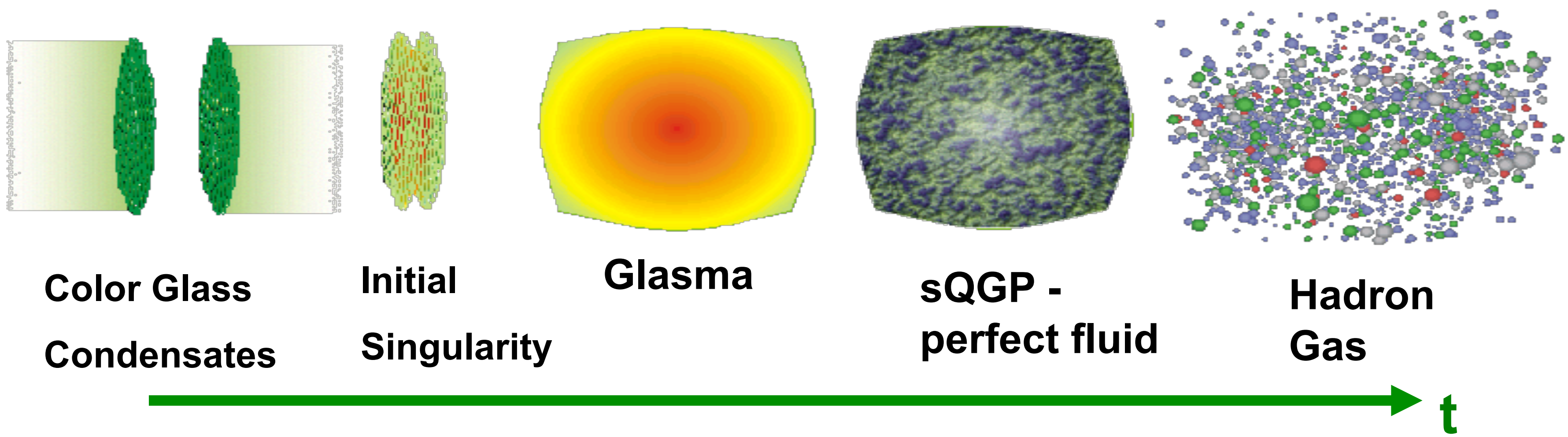


Big Bang



RHIC

Standard model of HI Collisions



- Though broad outlines could be guessed, current understanding far beyond anything anticipated when RHIC was proposed
- Solidify, Improve, Falsify ?

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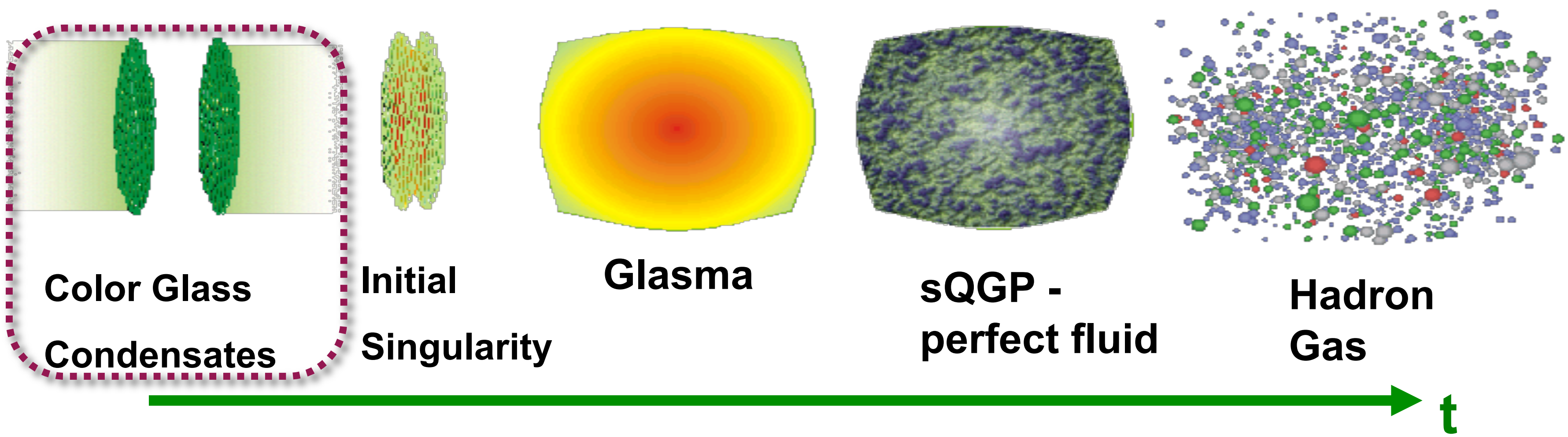

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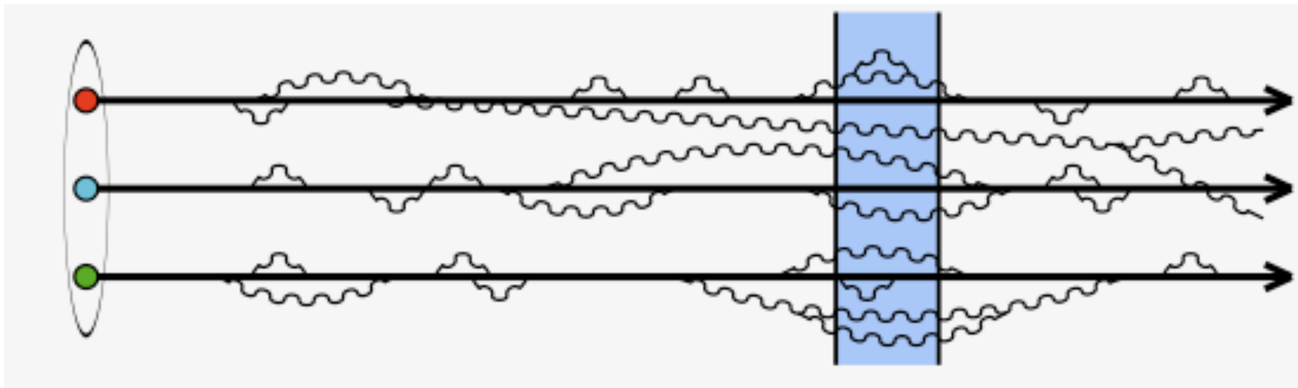
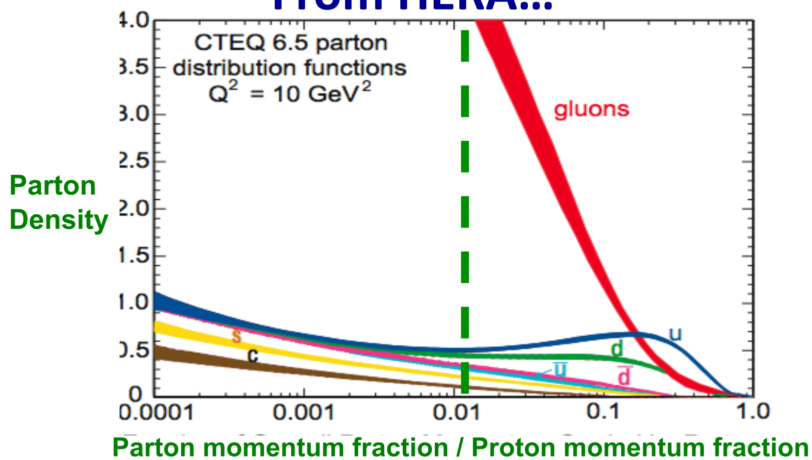
Gluon Saturation in a nucleus: classical coherence from quantum fluctuations



Wee parton fluctuations time dilated on strong interaction time scales

From HERA…



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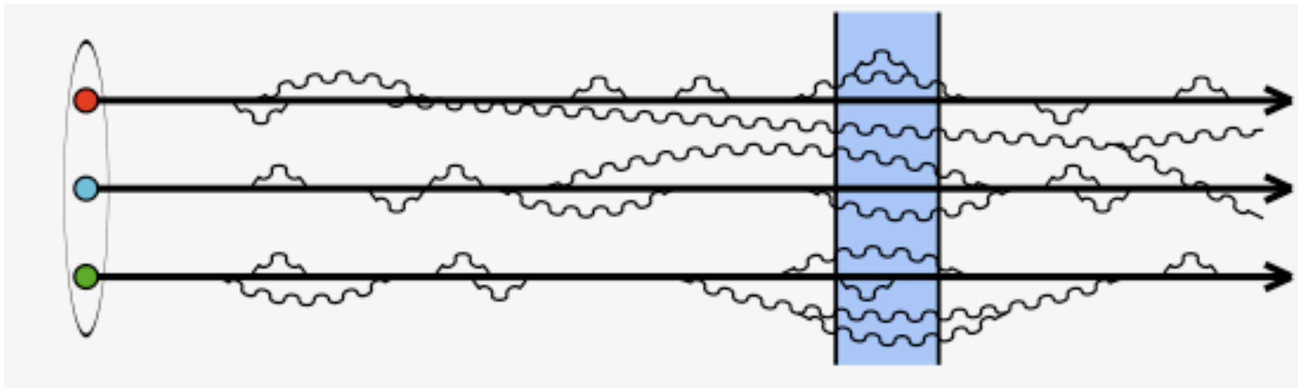

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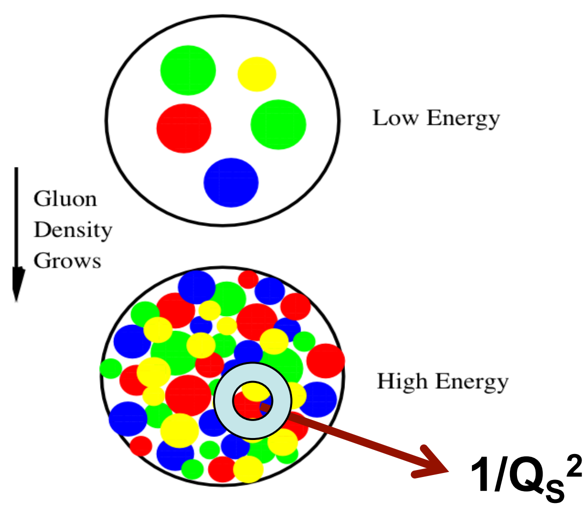

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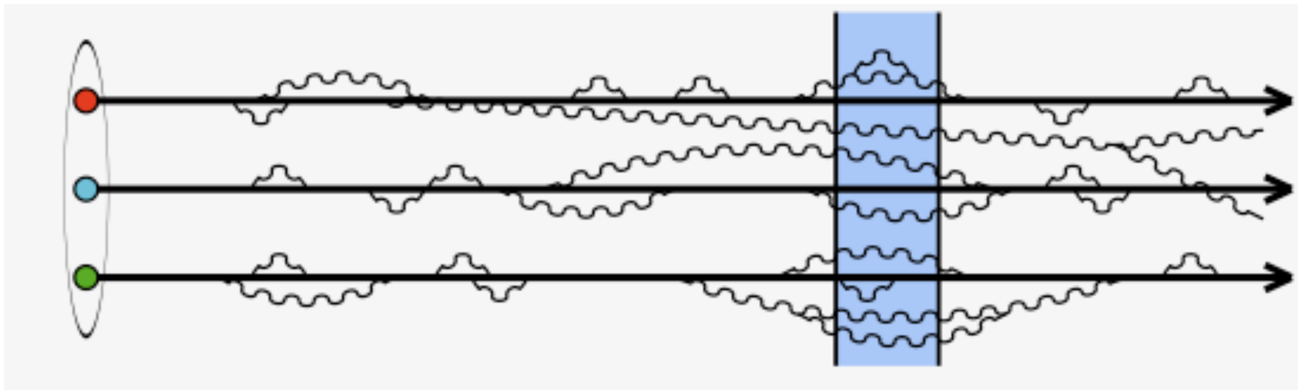

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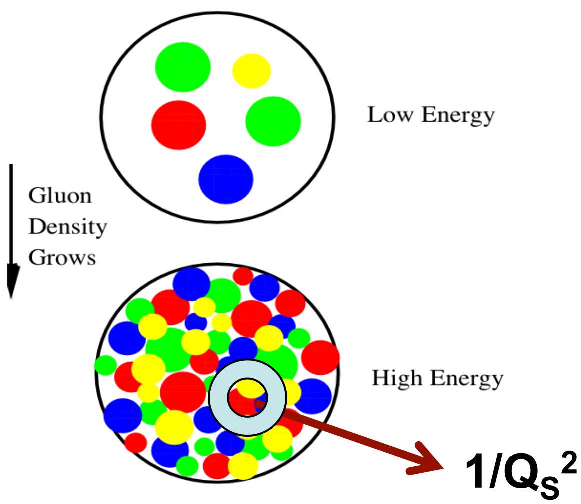

The gluon density saturates at a maximal value of ~ $1/\alpha_S$

➔ **gluon saturation**

Gribov,Levin,Ryskin; Mueller,Qiu

Large occupation # => classical color fields

McLerran,RV

Many-body high energy QCD: The Color Glass Condensate

- QCD EFT framework to understand strongly correlated wee gluons in nuclei and their evolution with energy

- Dynamics characterized primarily by one universal semi-hard scale -- the saturation scale Q^A_S (geometrical scaling-Peschanski talk)

- Physics highly non-perturbative, but can be described in weak coupling -- novel regime of many body QCD

- Strong hints from HERA (esp. diffractive/exclusive data-M. Machado talk) AND RHIC data

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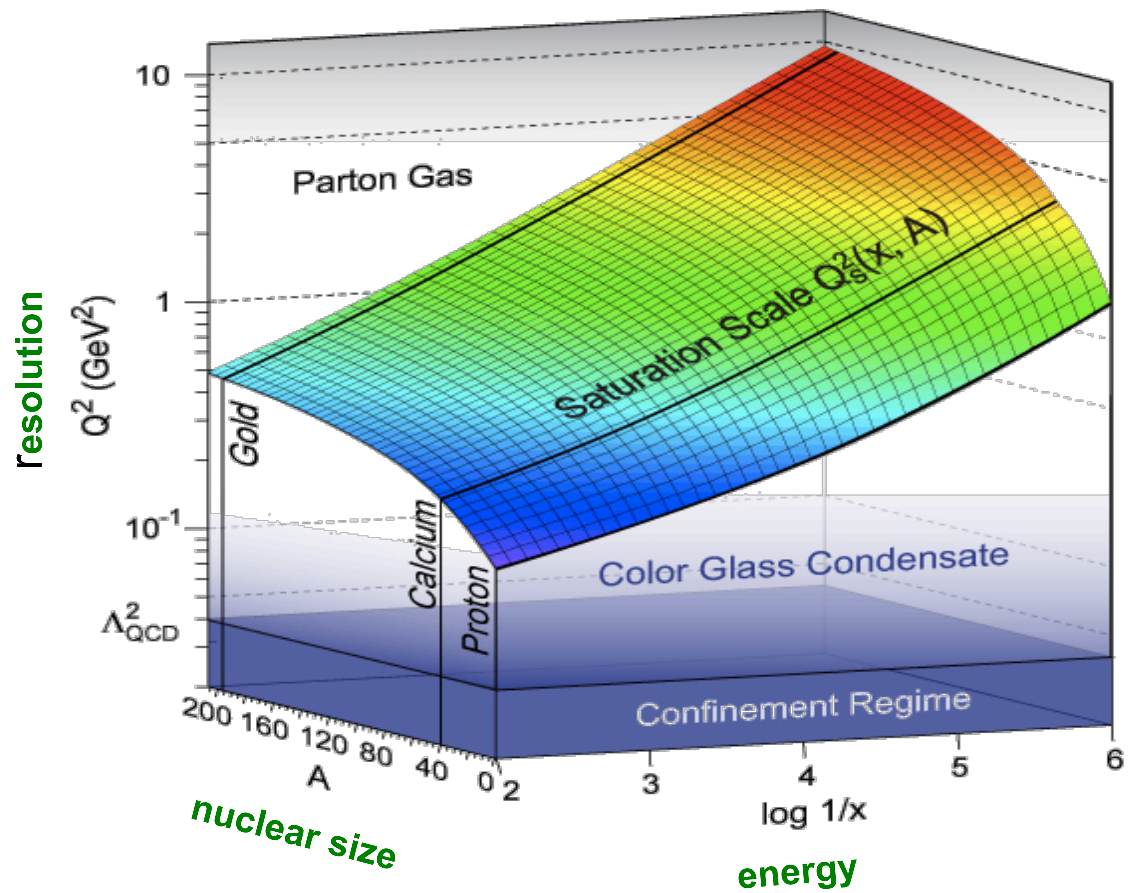
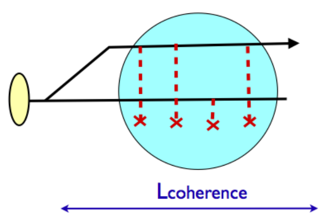


Evidence for Saturation @ RHIC ?

- Rich Deuteron+Gold physics program



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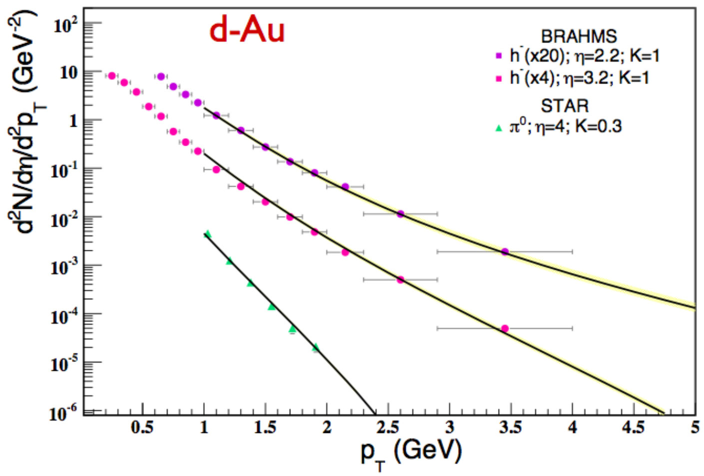
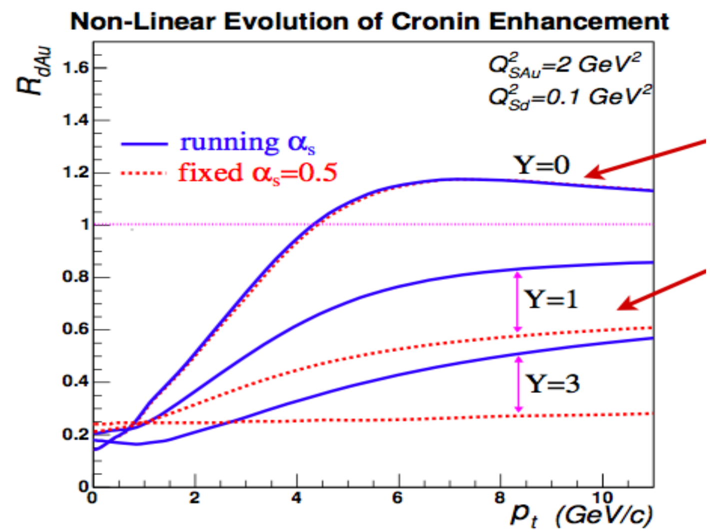
Caveats: M. Sumbara





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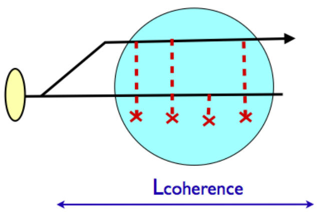

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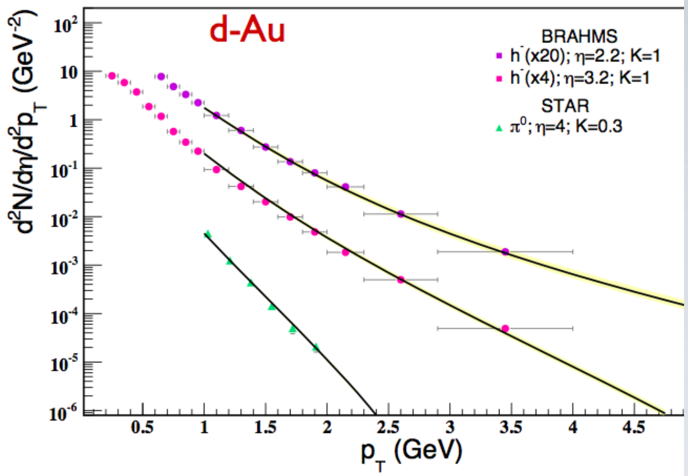

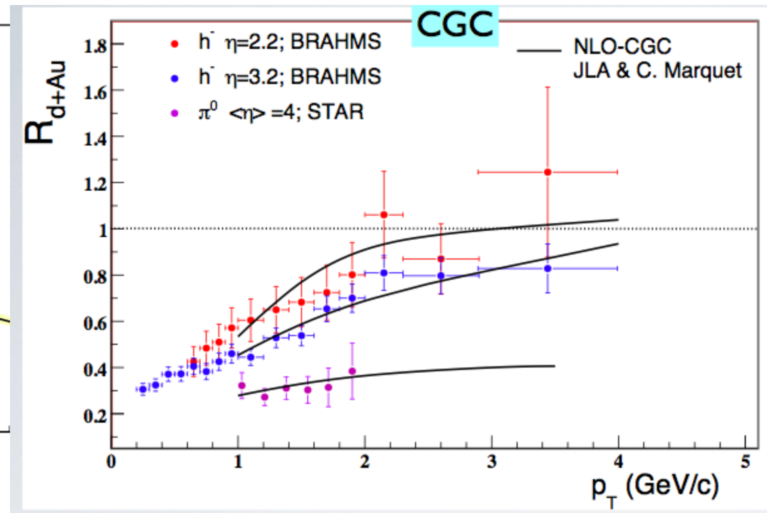

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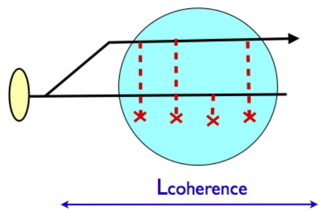

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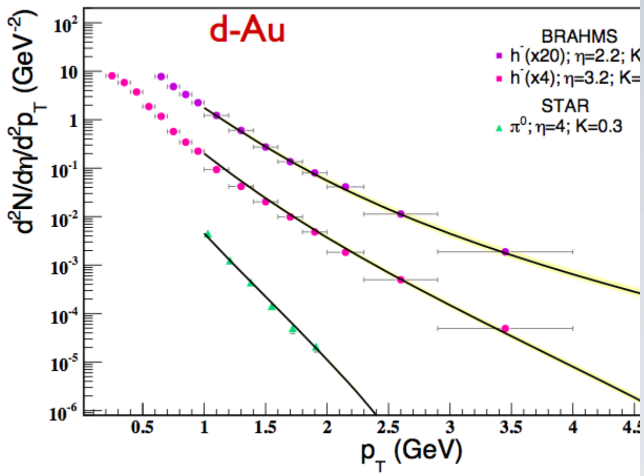

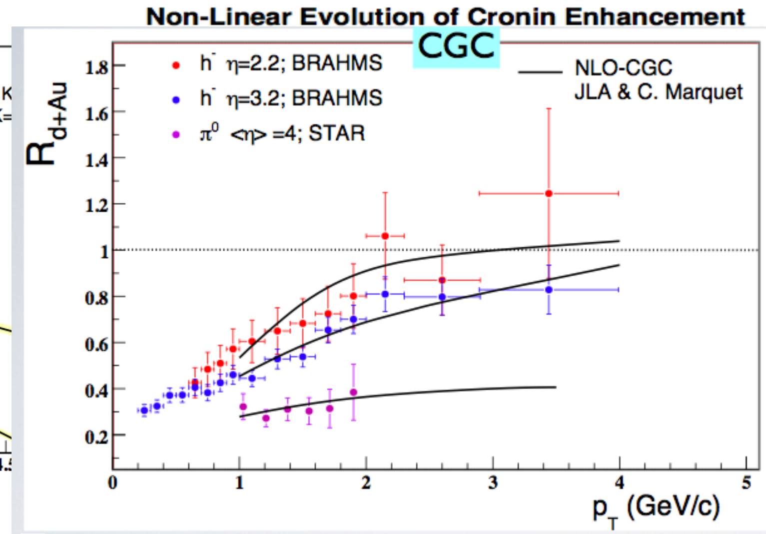

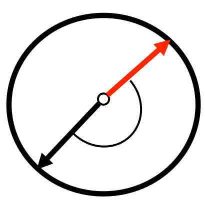

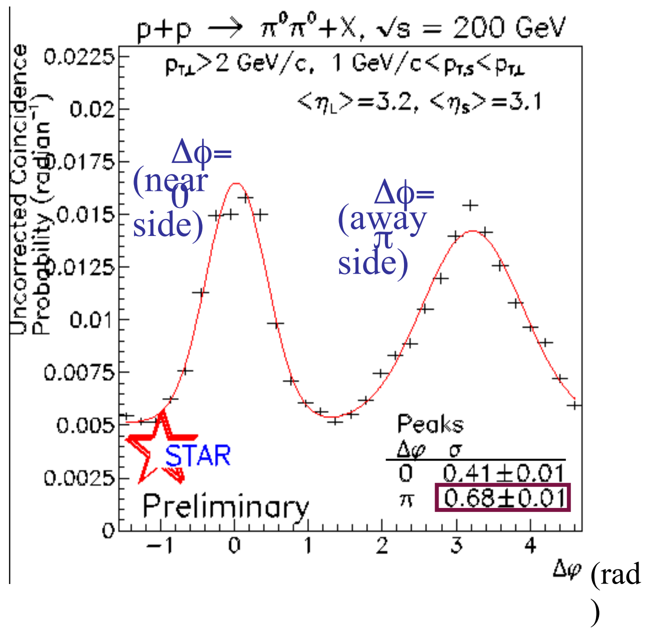

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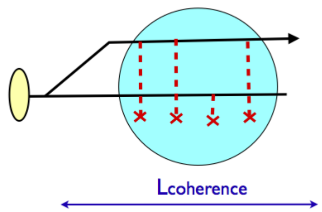

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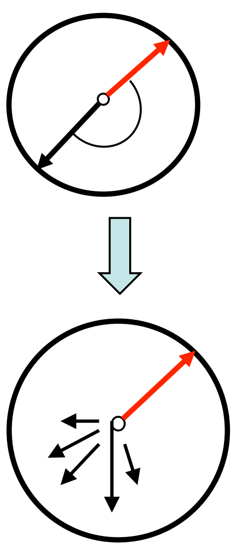
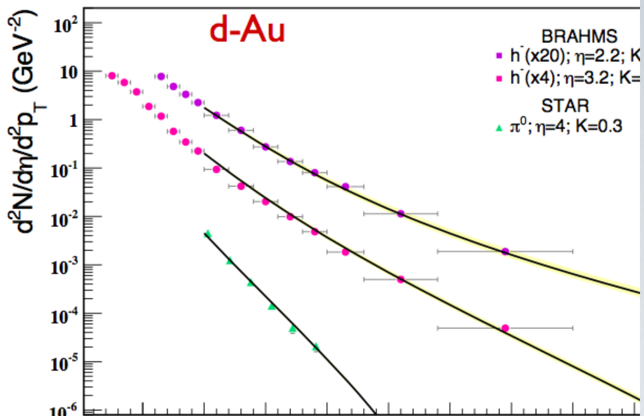
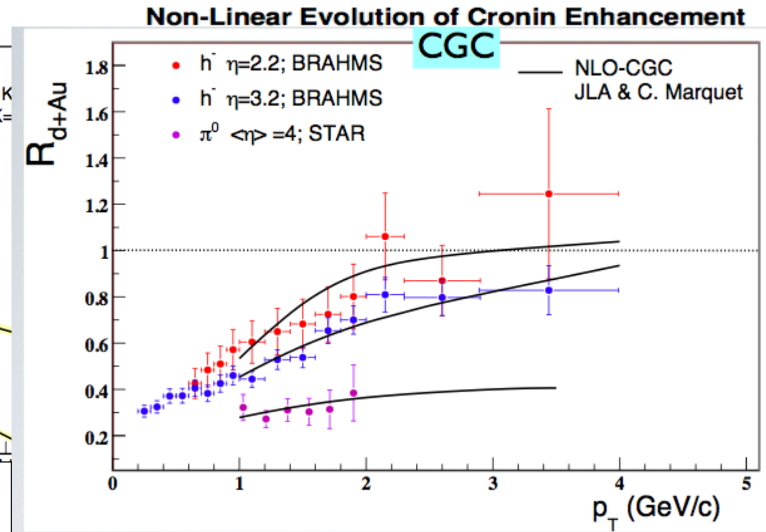
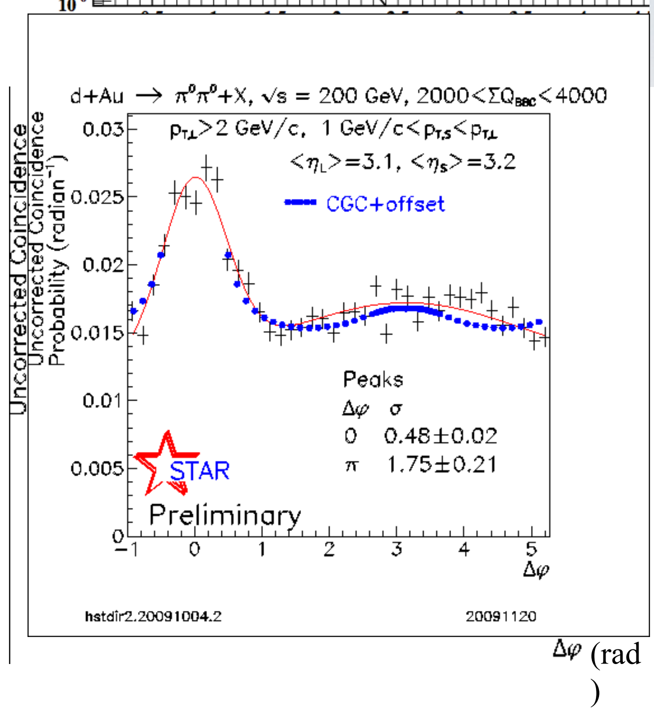






Away side parton
randomized
by strong color field



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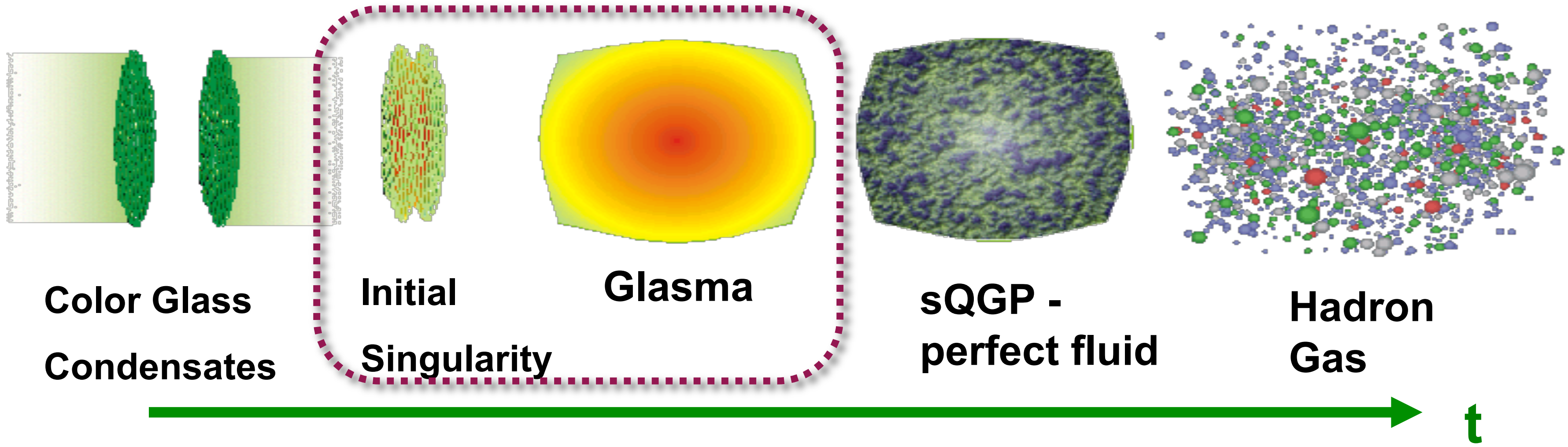

Glasma (\Glahs-maa\): ***Noun:*** non-equilibrium matter between Color Glass Condensate (CGC)& Quark Gluon Plasma (QGP)

The big role of wee glue

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D. Nucleus-Nucleus Collisions at Fantastic Energies

(Nucleus-Nucleus Collisions at Fantastic Energies)

Before leaving this subject it is fun to consider the collision of two nuclei at energies sufficiently high so that in addition to the fragmentation regions, a central plateau region can develop. Let us consider a central collision of a relatively small nucleus, say carbon, with a big one, say lead. Let us look at this collision in a center-of-mass frame for which the rapidities of both of the nucleus projectiles exceeds the critical rapidity. In such a frame they both possess the fur coat of wee-parton vacuum fluctuations. In such a central collision we see that the collision initially occurs between the fur of wee partons in each of the projectiles. Therefore the number of independent collisions will be of order of the area of overlap of the two projectiles; namely the cross-sectional area of the smaller nucleus.

At LHC, ~14 units in rapidity!

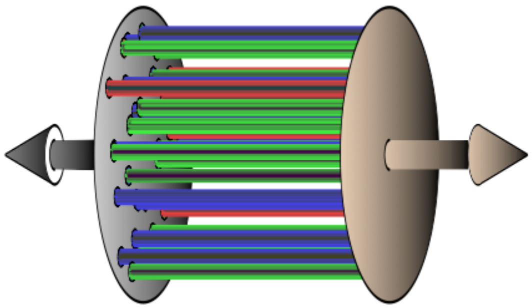
Bj, DESY lectures (1975)

The big role of wee glue

- These humble wee gluons are responsible for producing the hottest matter on earth

- We now understand that they can be described as classical fields (MV) with (quantum) energy evolution given by “Wilsonian” renorm. group (JIMWLK/BK)

Classical features of the Glasma



Solutions of Yang-Mills equations produce (nearly) boost invariant gluon field configurations: "Glasma flux tubes"

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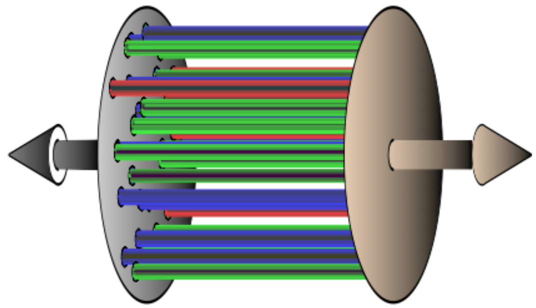

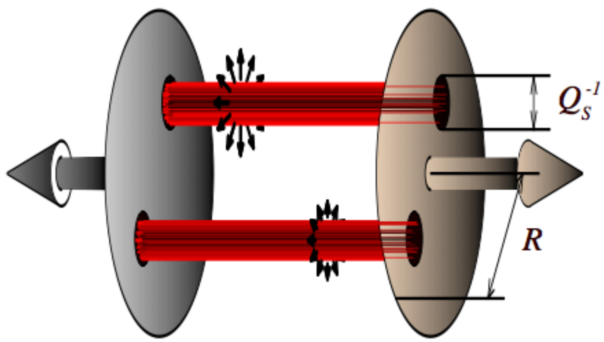

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Lumpy gluon fields are color screened in transverse plane over distances ~ $1/Q_S$
- Negative Binomial multiplicity distribution.

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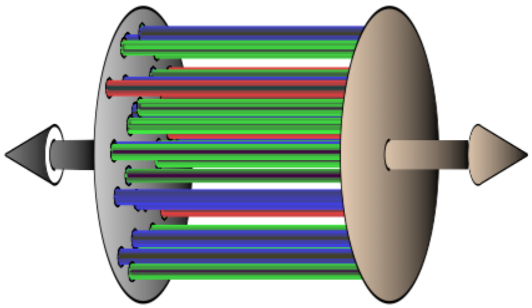

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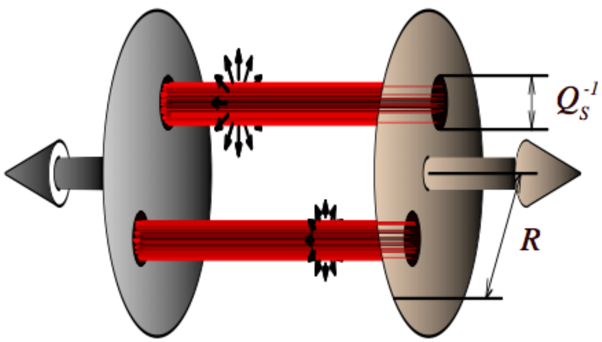

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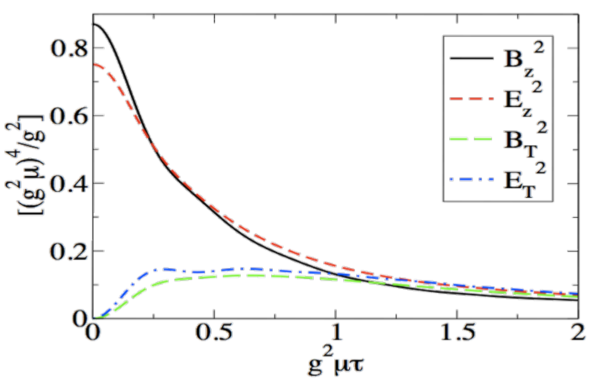
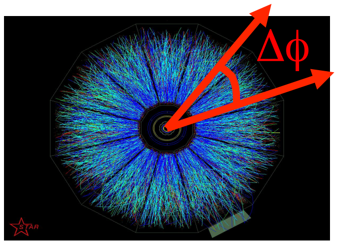
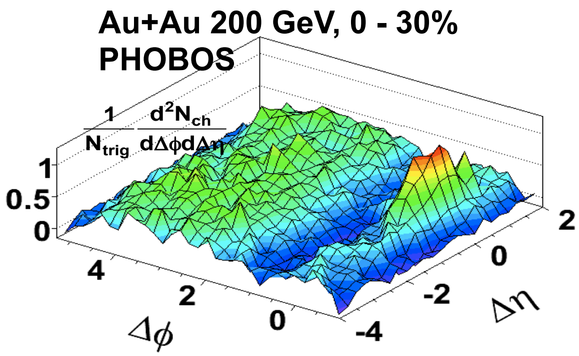
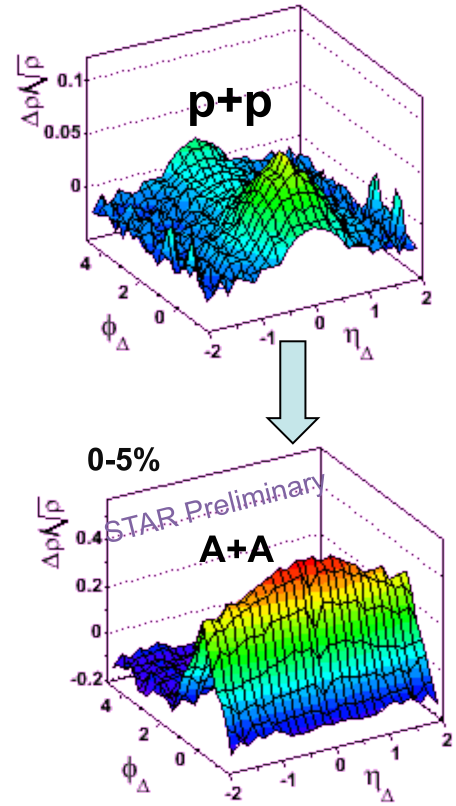


"Glasma flux tubes" have non-trivial longitudinal color E & B fields at early times
--generate Chern-Simons topological charge

The Ridge: Glasma flux tubes+ Radial flow







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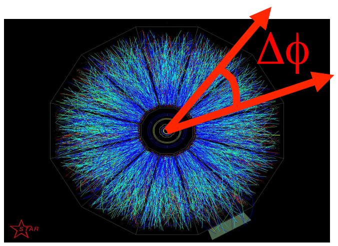
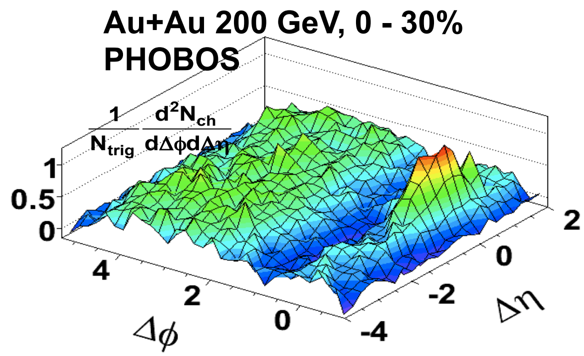
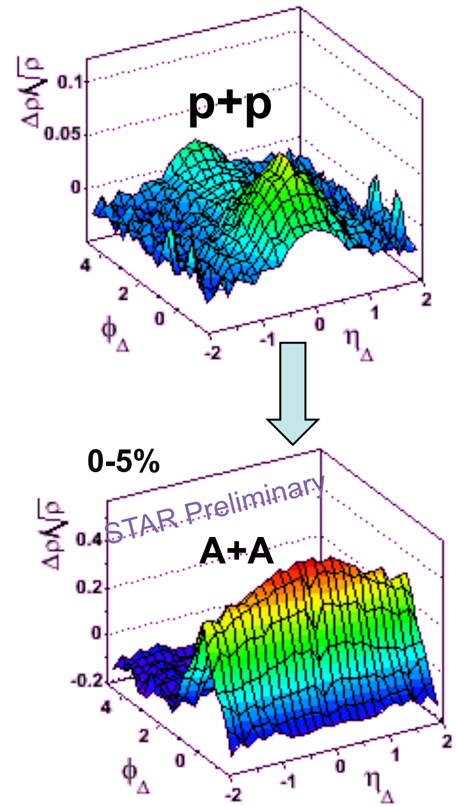
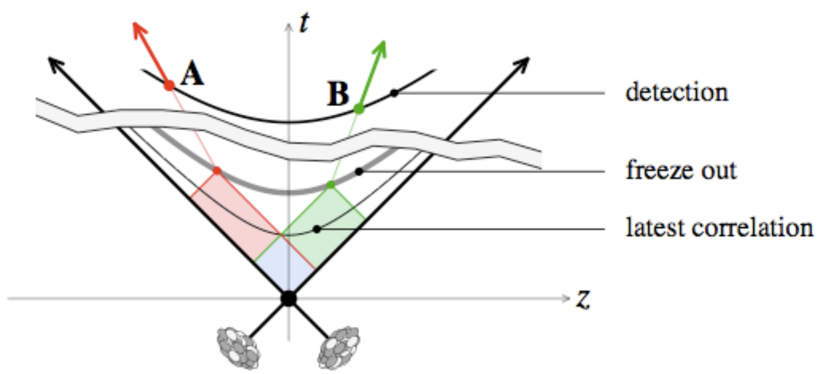




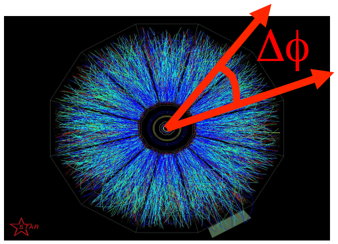


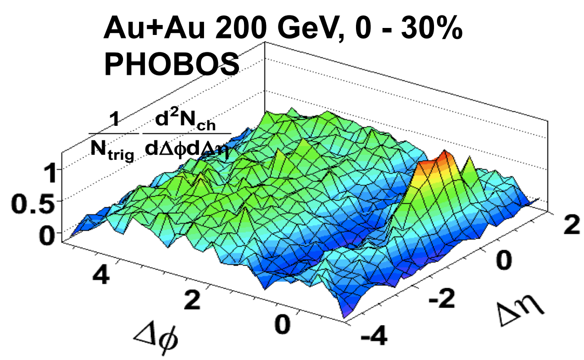


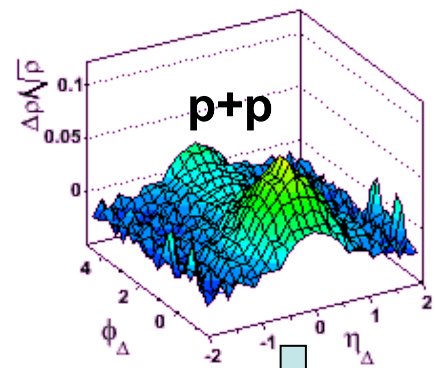
Long range rapidity correlations are sensitive to Glasma dynamics at early times

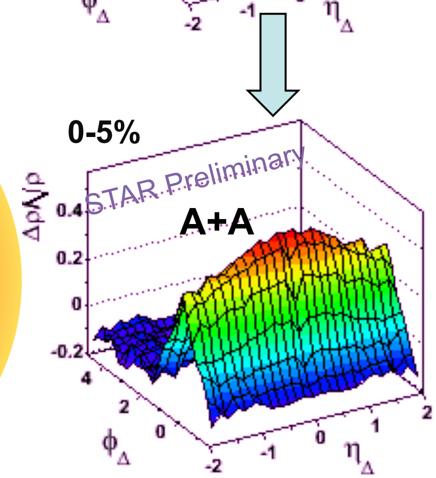
$$\tau \leq \tau_{\mathrm{freeze-out}} \exp\left(-\frac{1}{2}|y_A - y_B|\right)$$

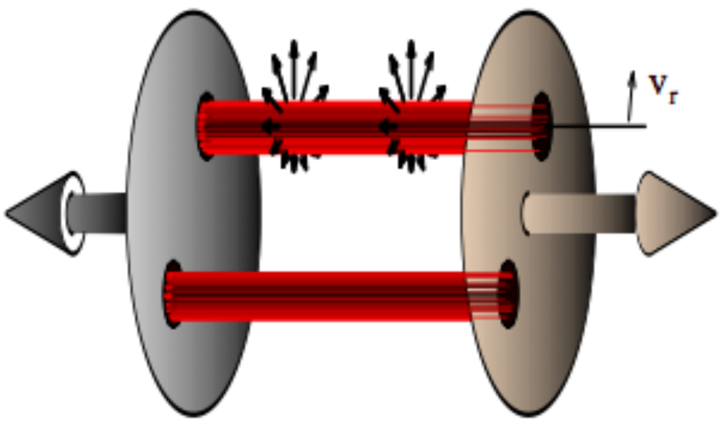
The Ridge: Glasma flux tubes+ Radial flow

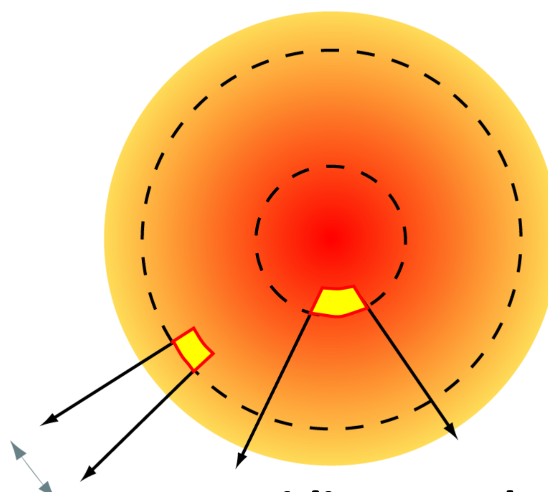












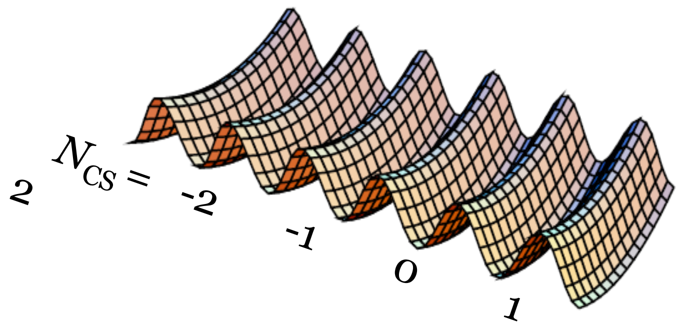
Glasma flux tubes provide the long range rapidity correlation

Dumitru, Gelis, McLerran, RV; Gavin, McLerran, Moschelli

Radial (“Hubble”) flow of the tubes provides the azimuthal collimation

Voloshin; Shuryak

Chiral Magnetic Effect: Local strong parity violation



Topological fluctuations
-sphaleron transitions in Glasma
-as in EW baryogenesis

Kharzeev,McLerran,Warringa
Kharzeev,Fukushima,Warringa
(Talk by Fraga; Poster: Chernodub)

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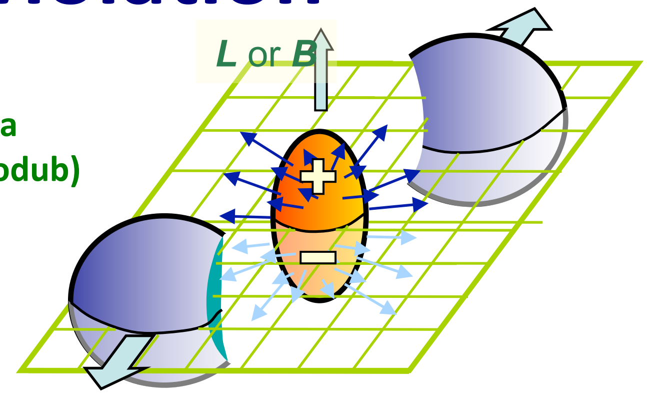
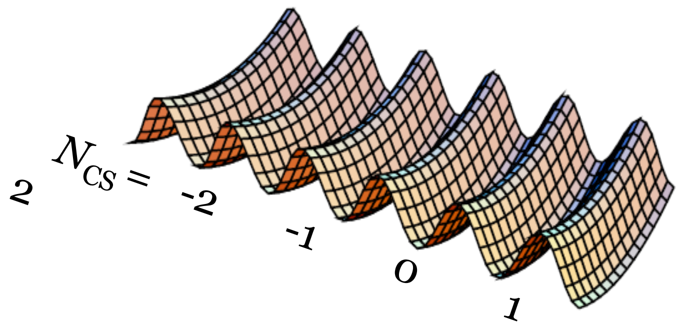


External (QED) magnetic field

Chiral Magnetic Effect: Local strong parity violation



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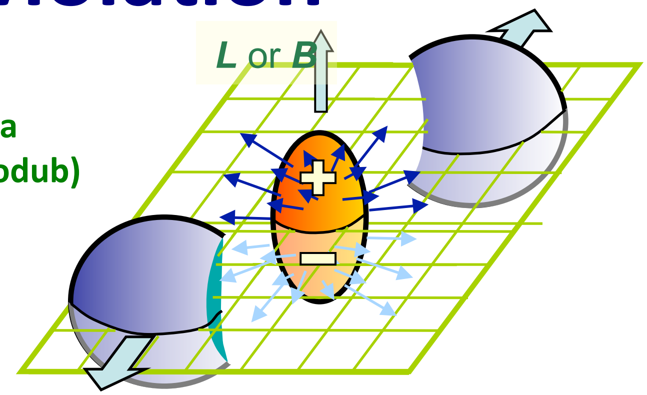

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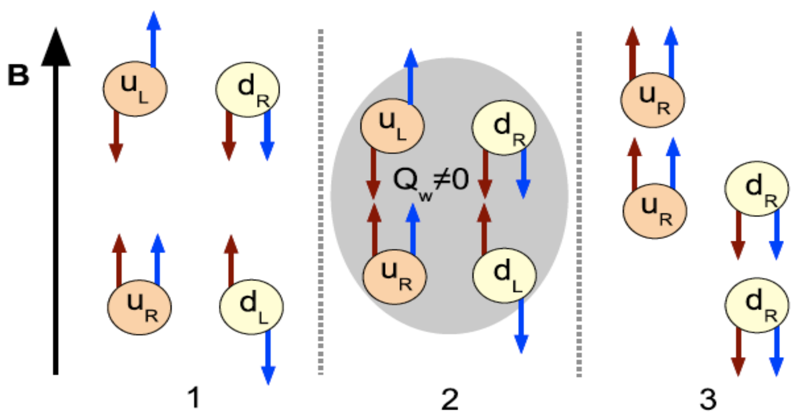
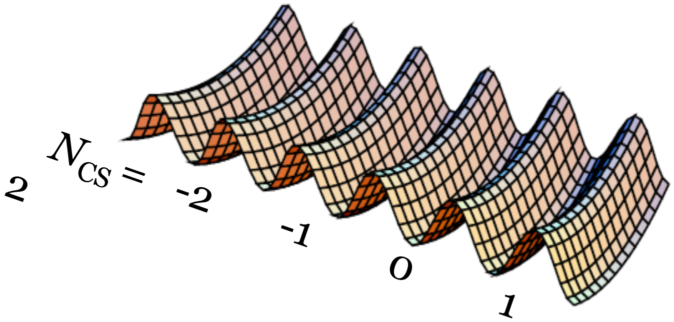


Chiral magnetic effect

Chiral Magnetic Effect: Local strong parity violation



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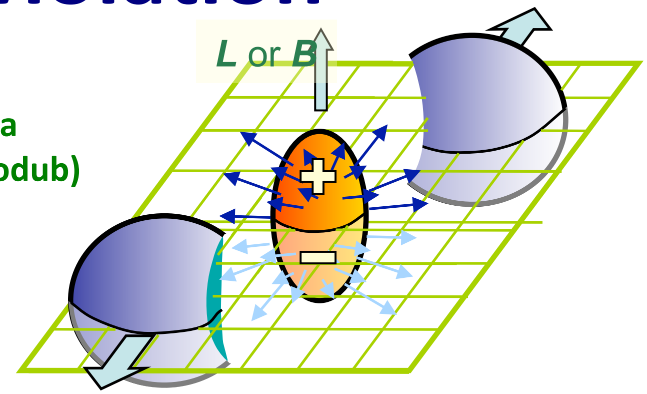

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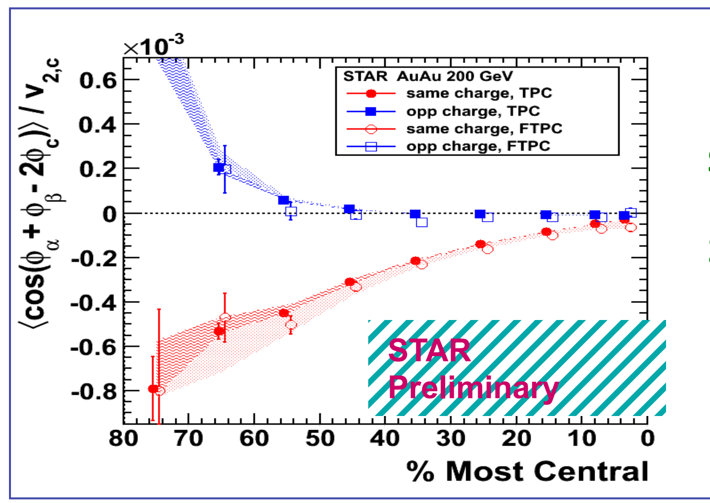
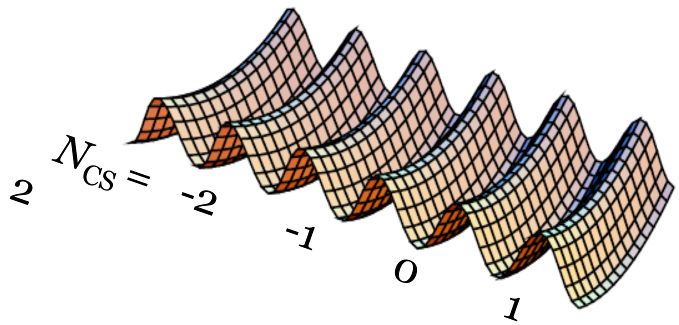


STAR,
PRL 103,
251601 (2010)

Possible experimental signal of charge separation
Important caveats (Wang:Bzdak,Koch,Liao; Pratt)

Chiral Magnetic Effect:
Local strong parity violation



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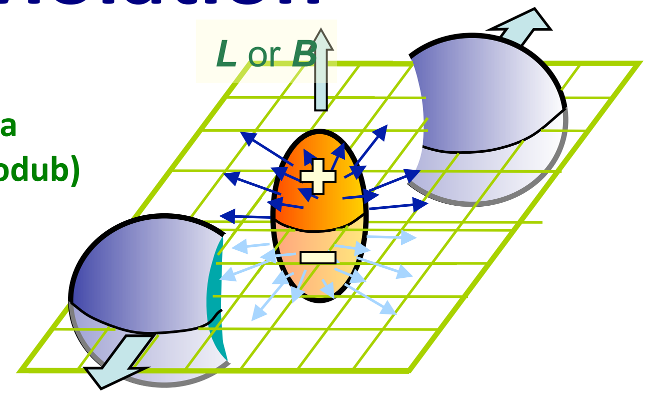

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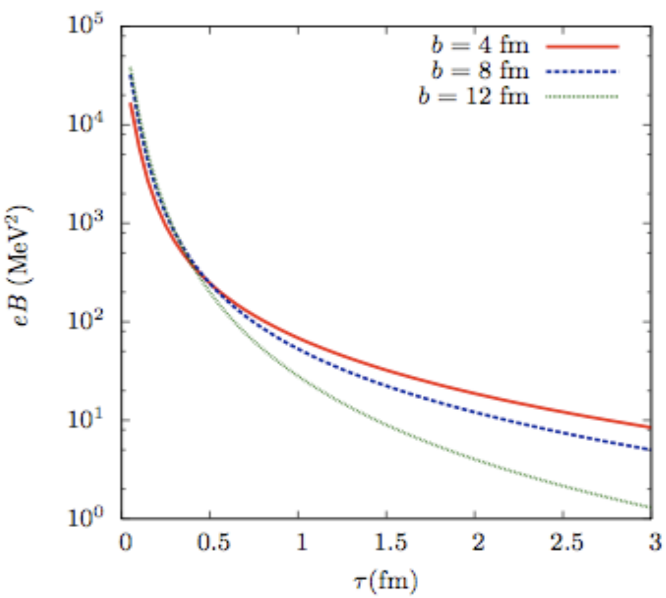
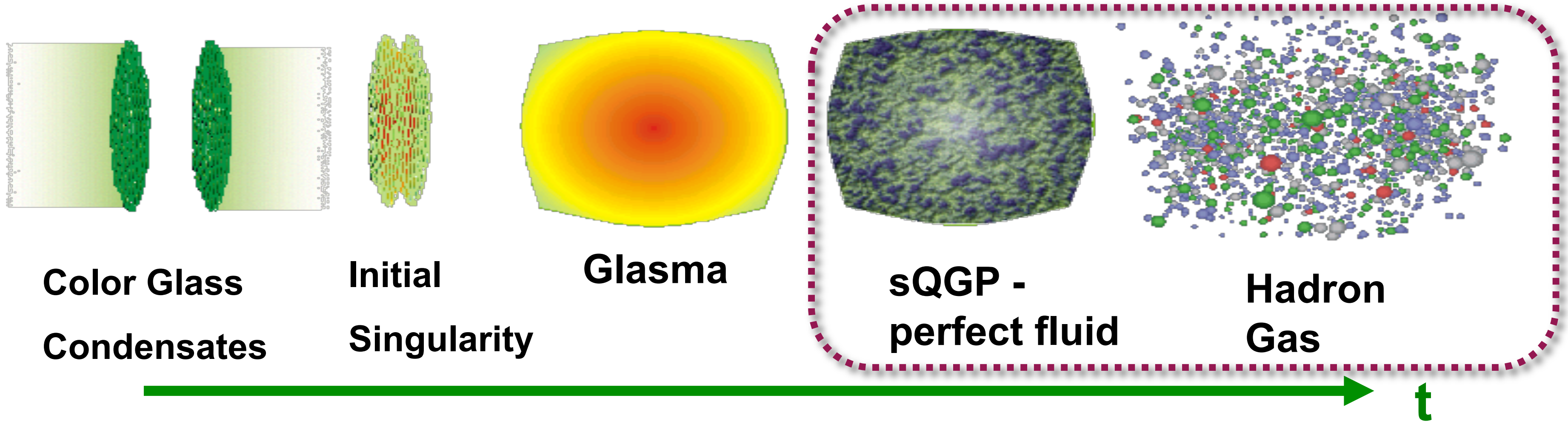


Effect most significant,
for transitions at early times

Standard model of HI Collisions



- **Thermalization of Glasma still not understood**

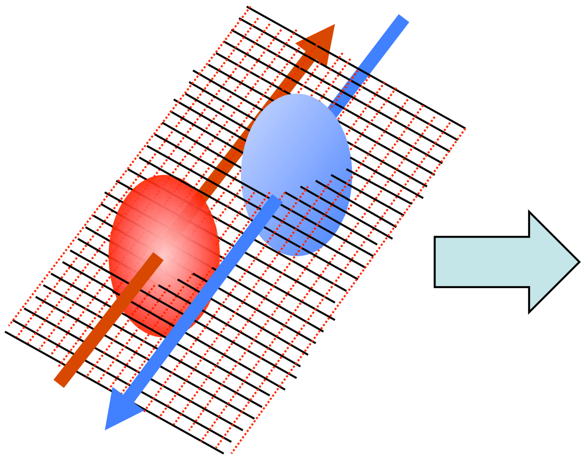
- **Fast isotropization may occur due to instability induced field amplification**
  - very analogous to "preheating" phenomenon in inflationary cosmology

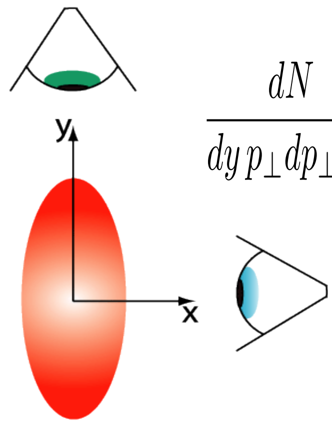
Dusling,Gelis,Epelbaum,RV

- **Glasma provides initial conditions for hydrodynamic flow**

Hirano et al.; Lappi, RV;
Dumitru,Drescher, Nara

Strong flow = (nearly) ideal hydrodynamics





$$\frac{dN}{dy\, p_\perp dp_\perp d\phi} = \frac{1}{2\pi}\frac{dN}{dy\, p_\perp dp_\perp}\left(1 + 2\, v_2(p_\perp) \cos 2(\phi - \Psi_{\rm RP}) + \cdots\right)$$

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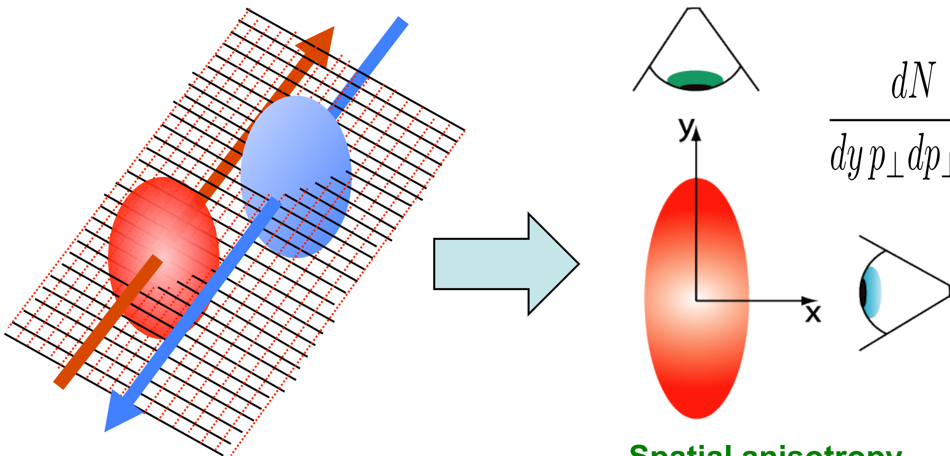

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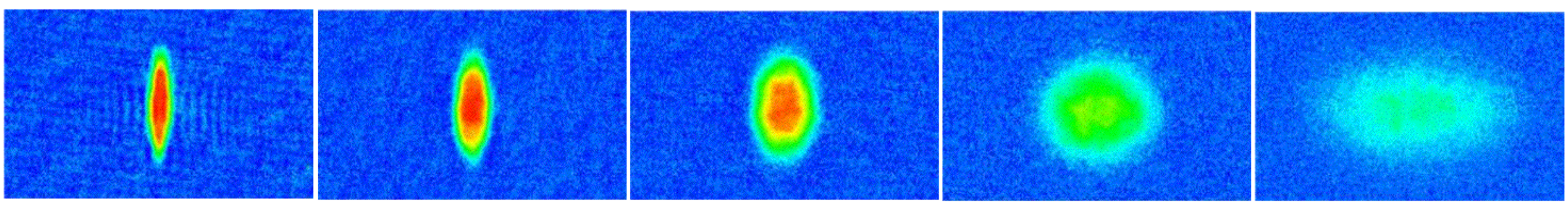
Spatial anisotropy



v_2 measures how efficiently hot matter converts spatial anisotropies to momentum anisotropy – most efficient way is hydrodynamics

v_2 at RHIC is large (B.Cole talk)
– hydro flow must set in early

A perfect fluid at RHIC

"Bjorken Hydrodynamics"

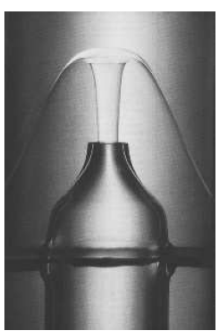
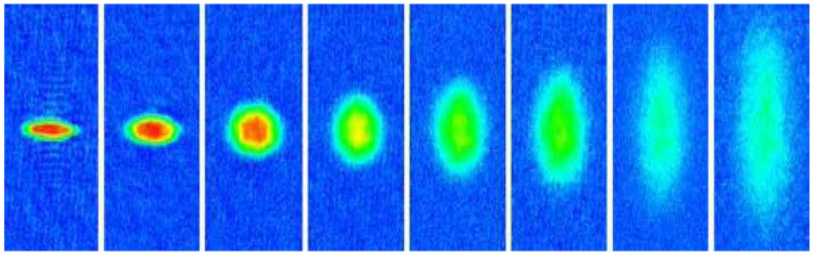
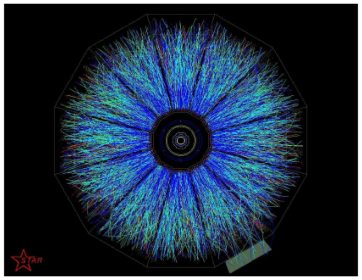
$$\frac{d\varepsilon}{d\tau} = -\frac{\left(\varepsilon + P - \frac{4}{3}\frac{\eta}{\tau}\right)}{\tau}$$

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

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Schafer,Teaney

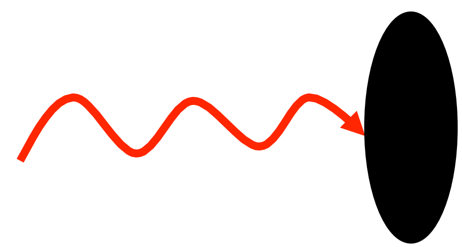
Fluid	$T\ [K]$	$\eta\ [Pa \cdot s]$	$\eta/n\ [\hbar]$	$\eta/s\ [\hbar/k_B]$
H_20	370	2.9×10^{-4}	85	8.2
^{4}He	2	1.2×10^{-6}	0.5	1.9
^{6}Li ($\lvert a_s \rvert \simeq \infty$)	23×10^{-6}	$\leq 1.7 \times 10^{-15}$	≤ 1	≤ 0.5
QGP	2×10^{12}	$\leq 5 \times 10^{11}$	-	≤ 0.4

AdS/CFT and the KSS bound

AdS/CFT conjecture: Maldacena

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

KSS bound: Kovtun,Son,Starinets



Classical absorption cross-section of a graviton with energy ω on a black brane

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

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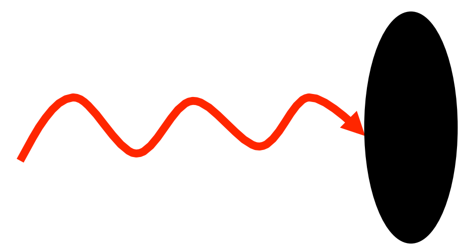


$$\sigma(\omega) = \frac{8\pi G}{\omega} \int dt d\mathbf{x}\, e^{i\omega t} \langle [T_{xy}(t,\mathbf{x}), T_{xy}(0,0)] \rangle$$

From Kubo: $\eta = \frac{\sigma(0)}{16\pi G}$

From Beckenstein: $s = \frac{a}{4G}$

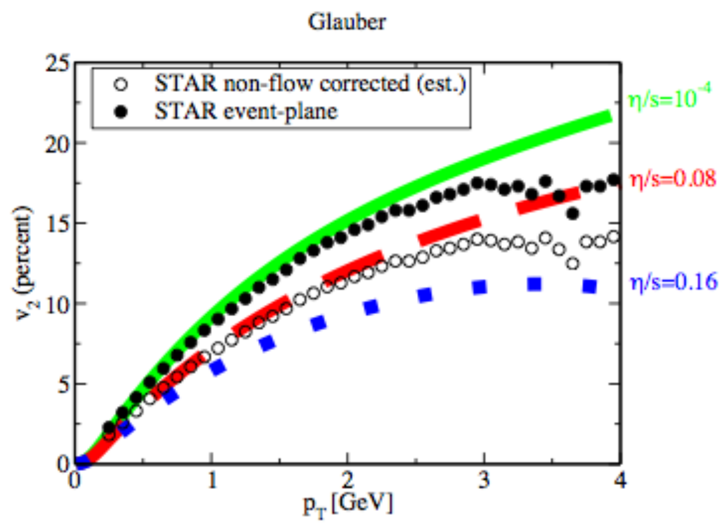
where a= area of black brane

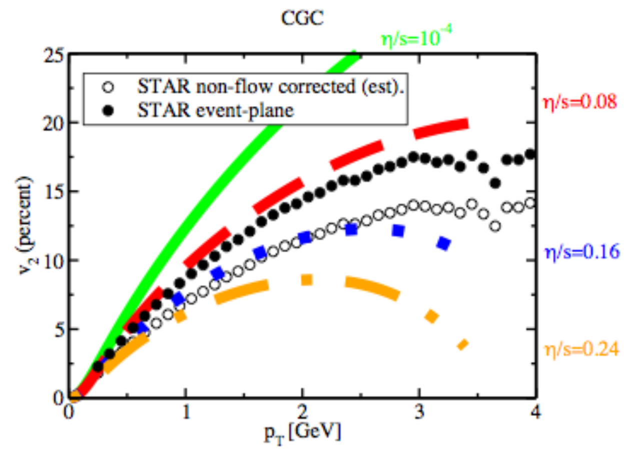
Theorem: $\sigma(0) = a$

Putting it all together: $\frac{\eta}{s} \geq \frac{\hbar}{k_B} \frac{1}{4\pi}$

η/s and viscous hydro @ RHIC

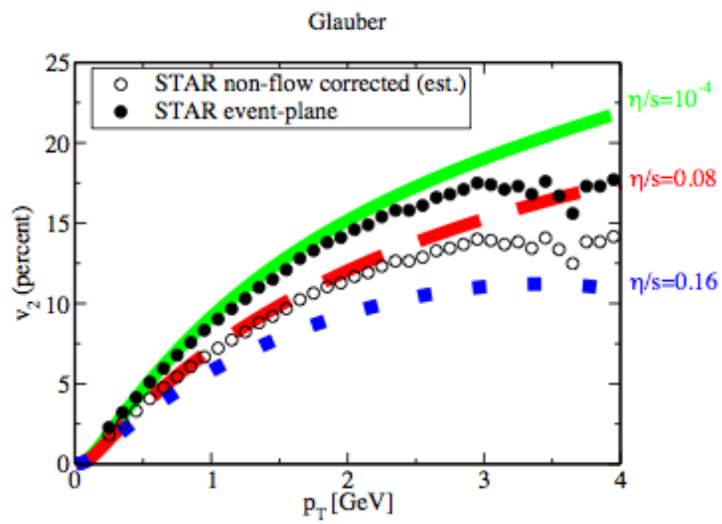
Luzum,Romatschke





- η/s from comparisons of viscous hydro codes to RHIC data suggest it nearly saturates the KSS bound – perfect fluid
- Quantitative value quite sensitive to initial conditions – Glasma!
- Probably safe to say its lower than any fluid with possible exception of cold ^{6}Li atoms in the unitarity limit (Feshbach resonance)

η/s and viscous hydro @ RHIC



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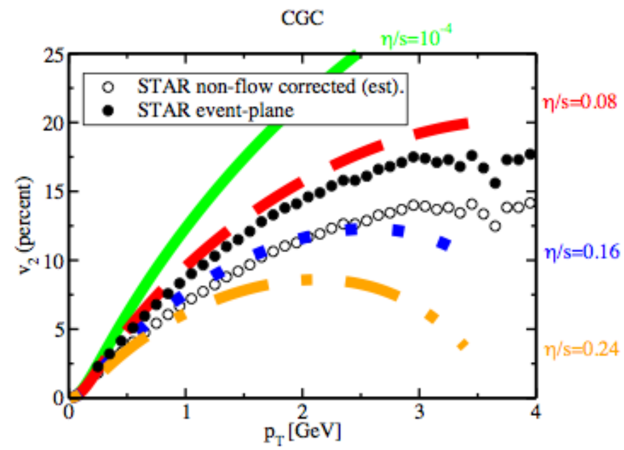
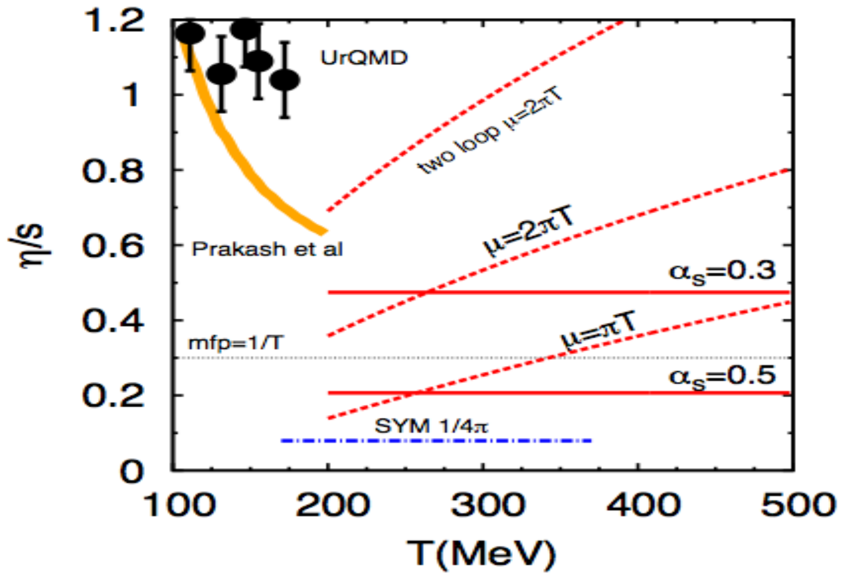
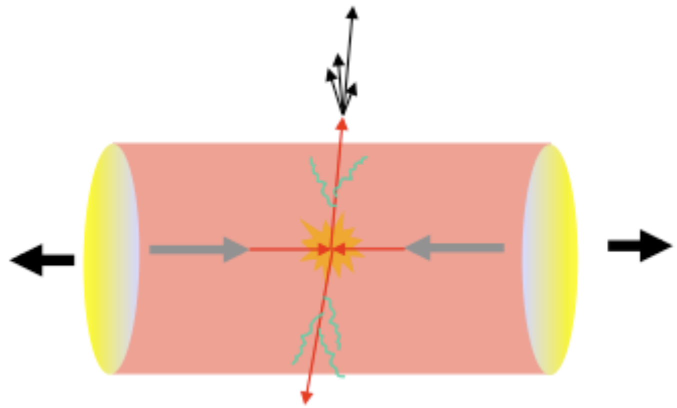
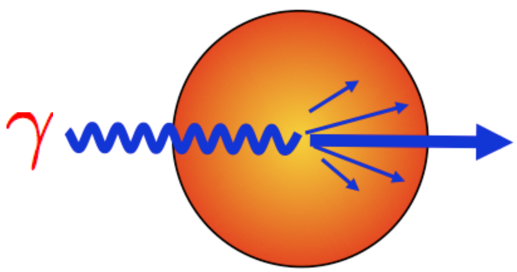


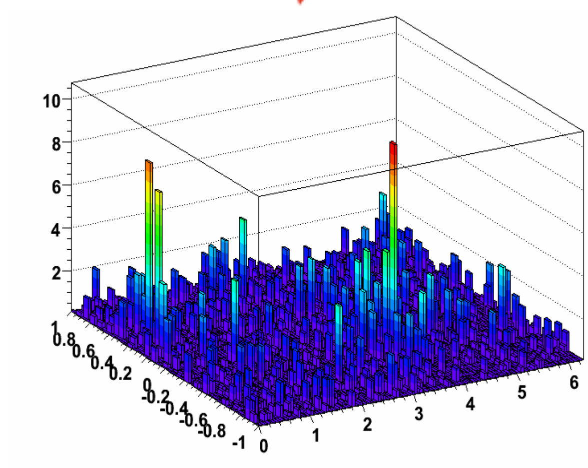


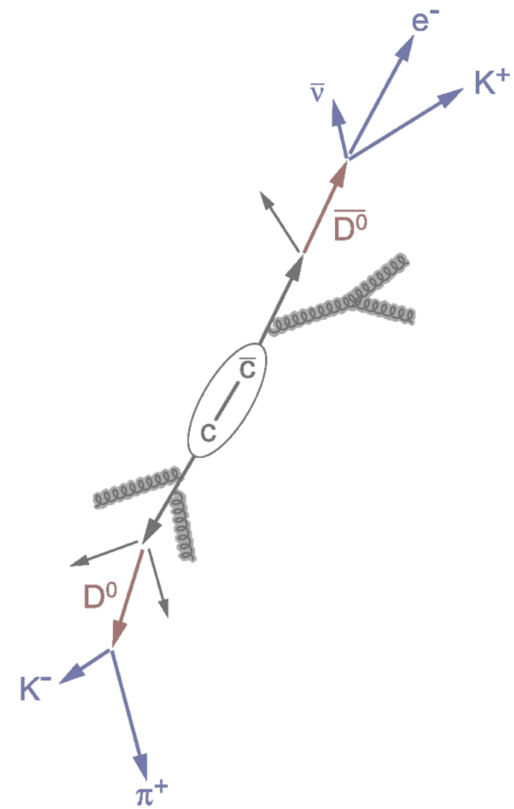
Viscosity from perturbative estimates is significantly larger

Hard Probes of the sQGP





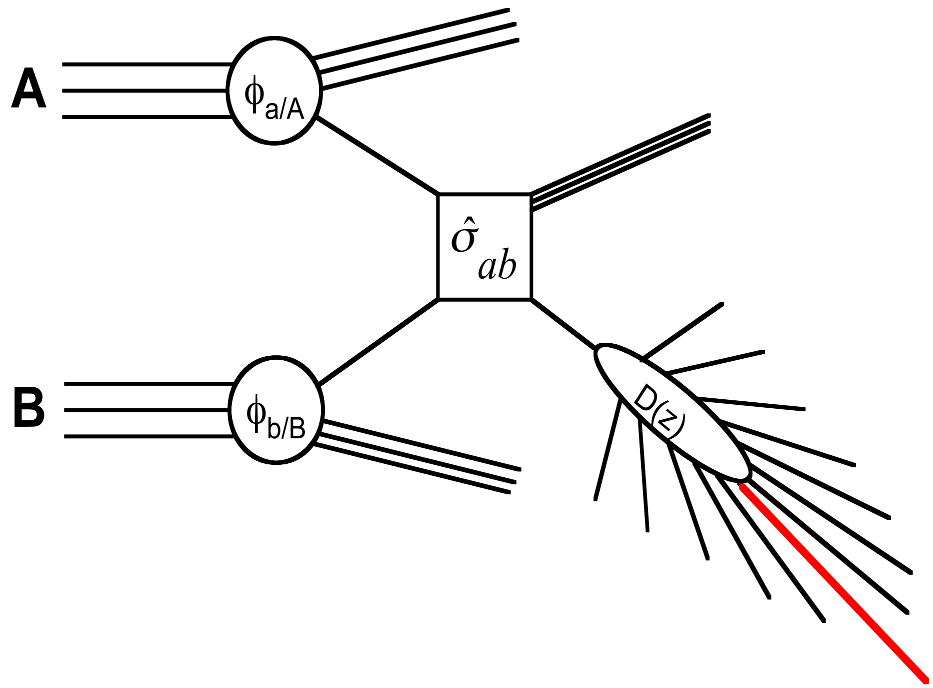




High p_T (>> T) hadrons, heavy mesons (charm and beauty), J/ψ and Upsilon, hard photons and JETS…

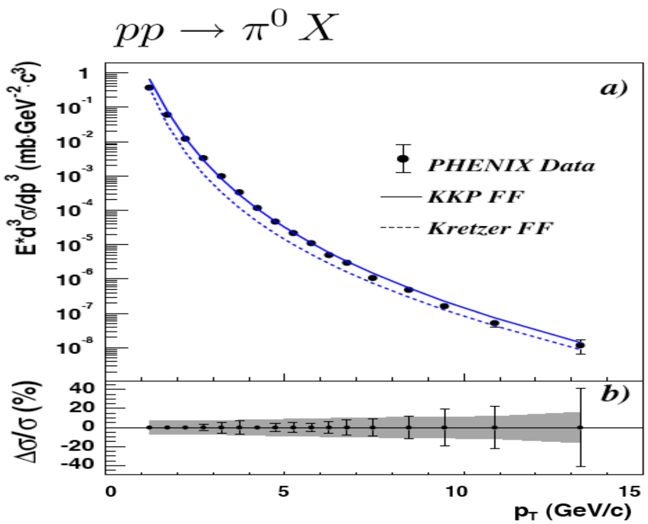
(**Jet reconstruction techniques in HI collisions – M. Cacciari talk**
MCs for soft background- F. Krauss talk)

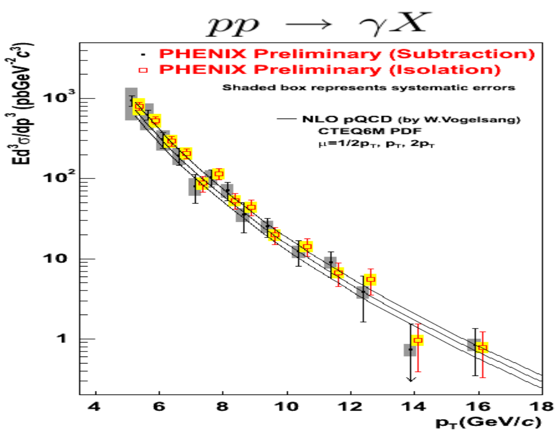
The pp Benchmark

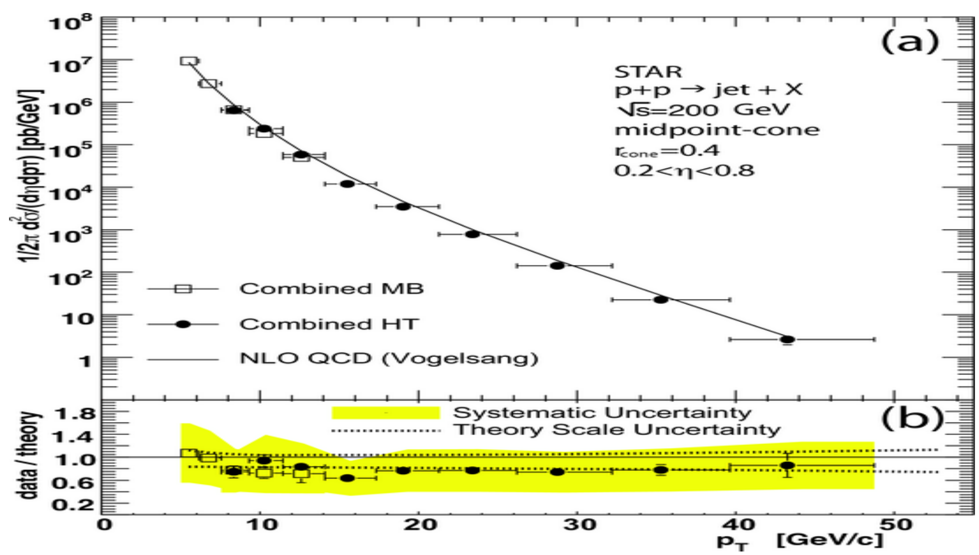


$$E\frac{d^3\sigma}{dp^3} = \sum_{abc}\int dx_a dx_b\, \phi_{a/A}(x_a, Q^2, \mu)\phi_{b/B}(x_a, Q^2, \mu)\, \frac{D_{\pi^0/c}(z, Q^2, \mu)}{z\pi}\frac{d\hat{\sigma}}{dt}$$

The pp Benchmark

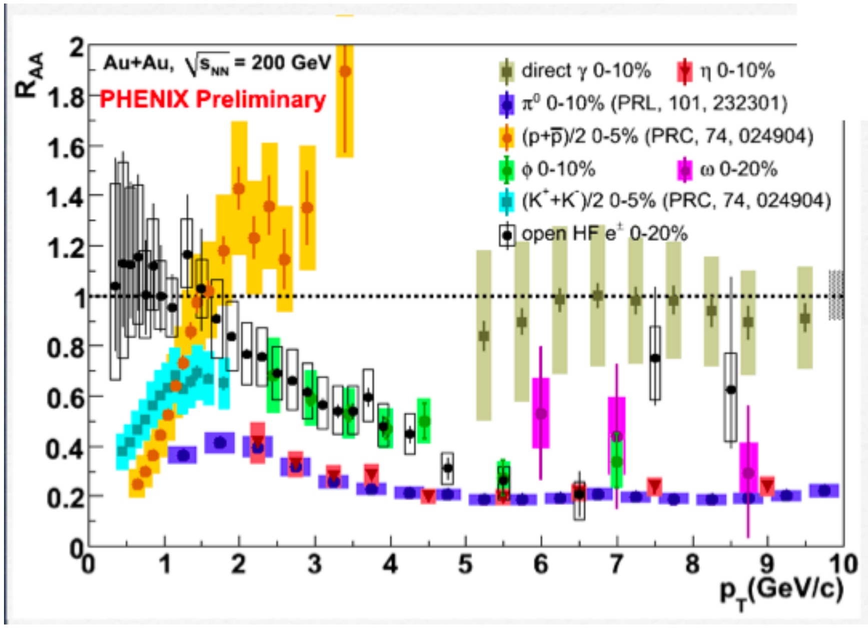


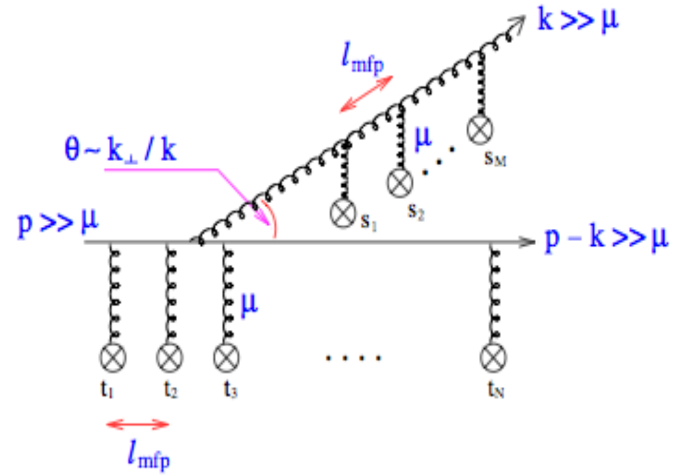




pQCD works exceptionally well @ RHIC to fairly low p_T

Parton energy loss





$$\frac{dE}{dz} = -\frac{\alpha_S N_c}{4} p_\perp^2$$

$$p_\perp^2 = \hat{q}\, L$$

Characterizes properties of hot medium

Bjorken; Gyulassy, Wang;
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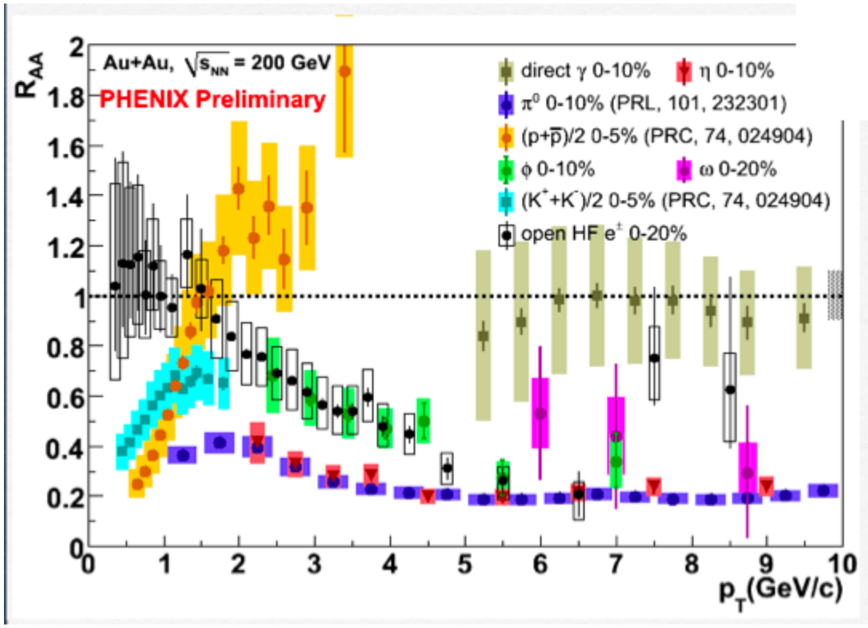

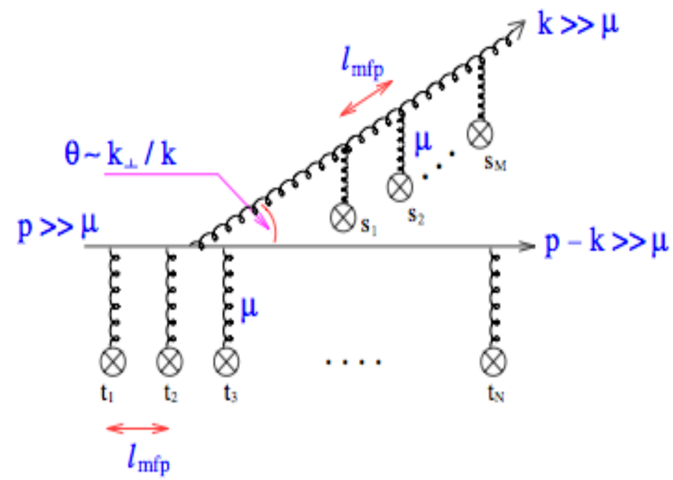

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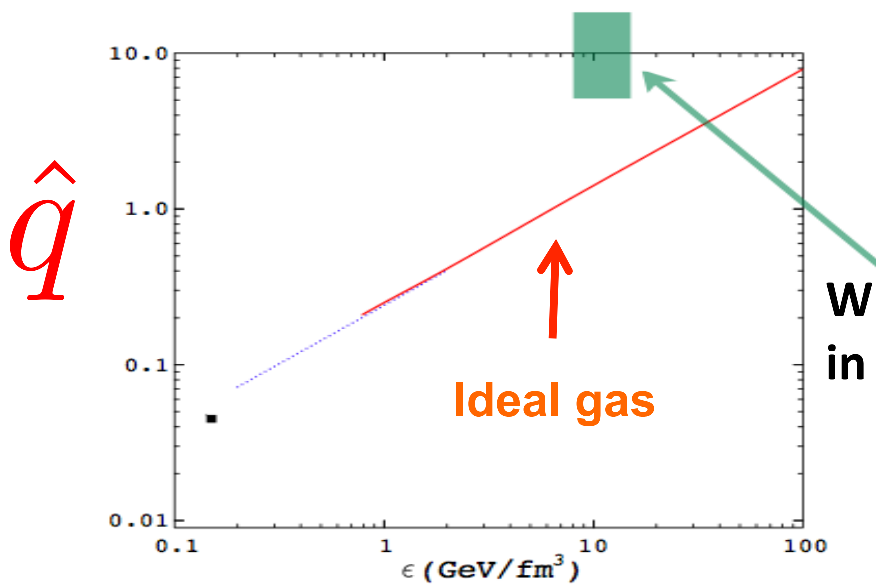

Wide dispersion in theory estimates

Characterizes properties of hot medium

Bjorken; Gyulassy, Wang;
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Weak versus Strong coupling in the sQGP

Weak coupling approaches fit the jet quenching data
-- however, computations are not under control
& large heavy quark energy loss is difficult to reconcile

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Liu et al; Gubser et al;
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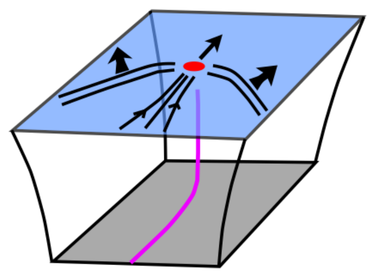
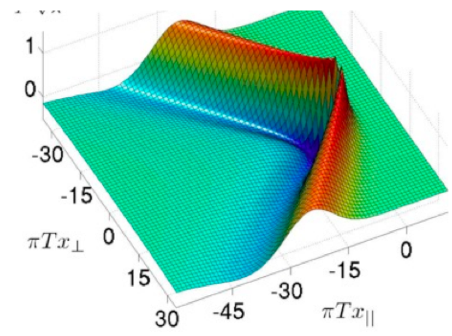
Large energy loss for light and heavy quarks "natural" in AdS/CFT approach

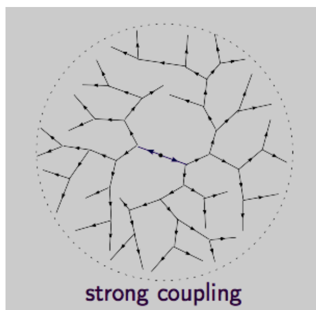




Energy density

But no jets in AdS !

Hatta,Iancu,Mueller
Hofman,Maldacena



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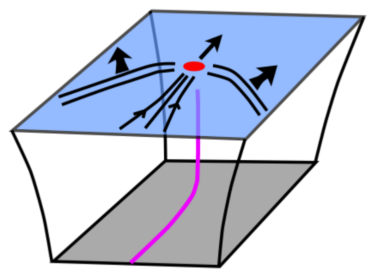

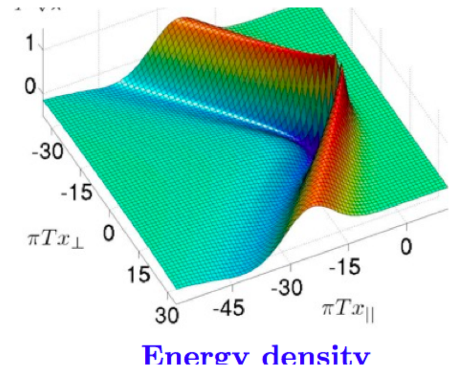

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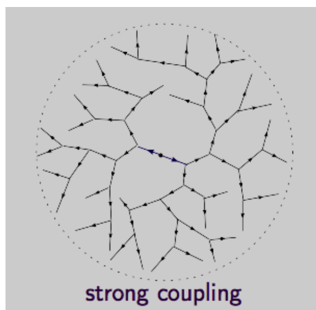
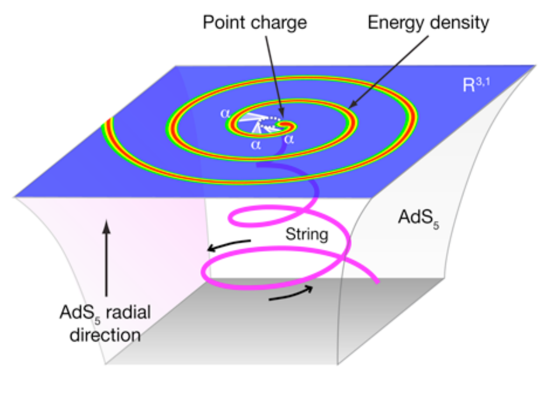




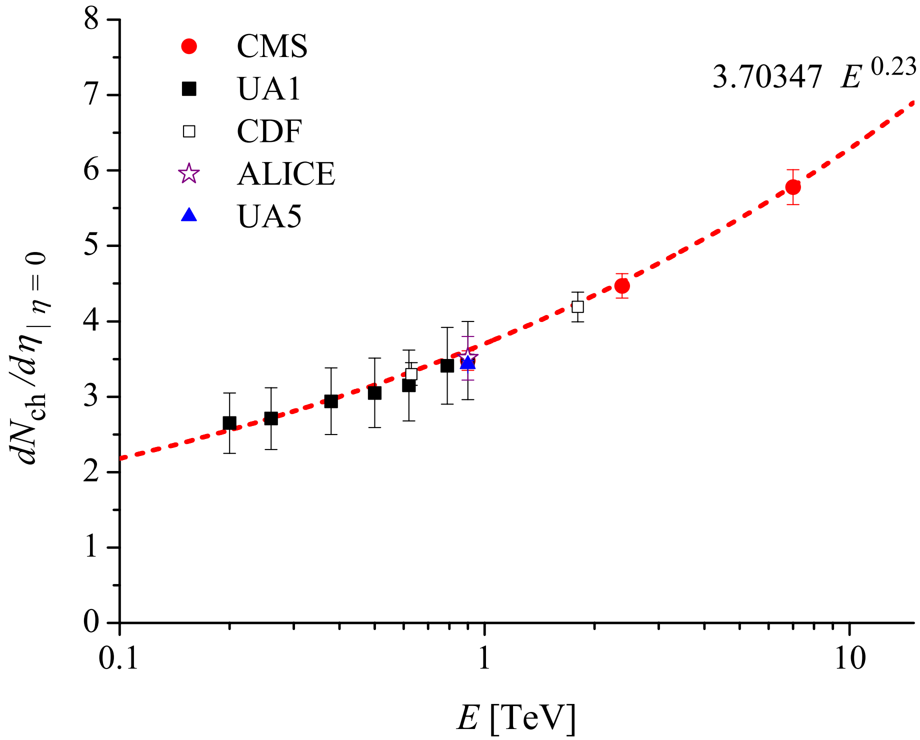
Synchrotron radiation in AdS
may be more like in QCD-collimated jets

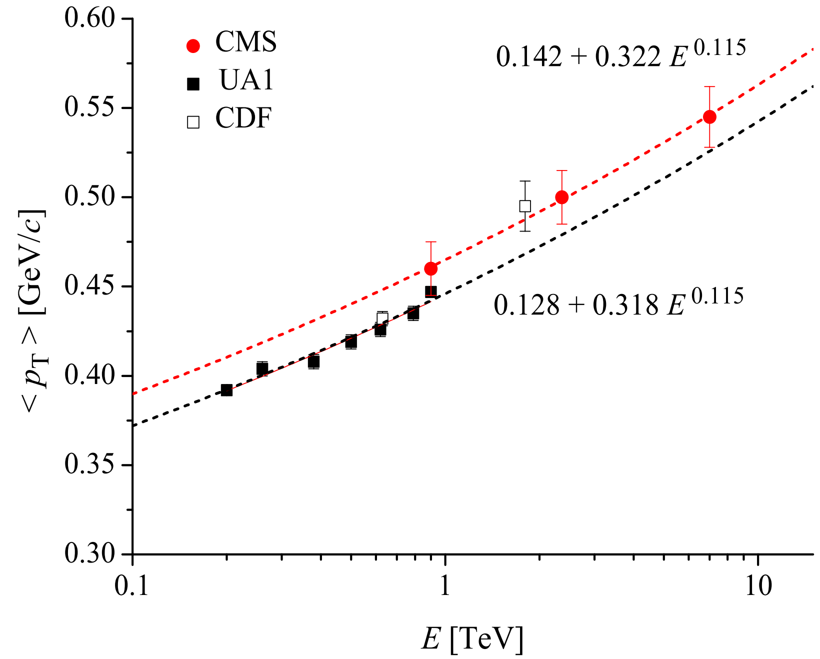
Chesler et al.

Lots of exciting ideas but no clear picture of transport in sQGP

Looking forward: Heavy Ions at the LHC

Initial CGC based comparisons to LHC pp data are promising



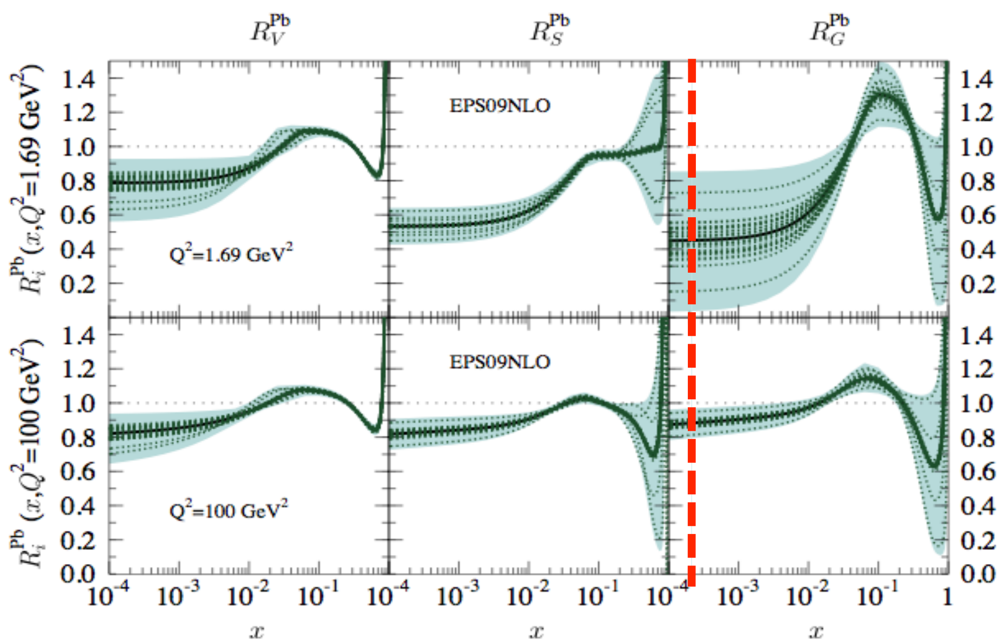


p_T α $Q_S(\sqrt{s})$
$dN/d\eta$ α $Q_S^2(\sqrt{s})$

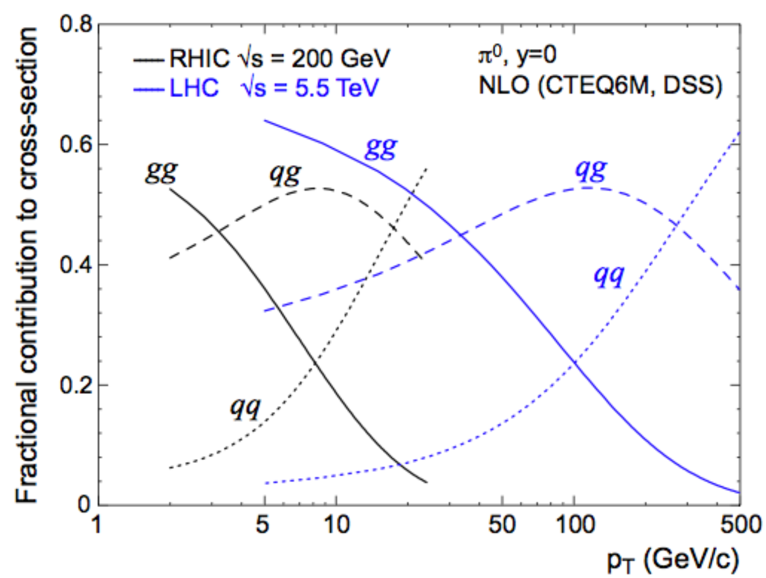
L. McLerran, M. Praszalowicz, arXiv:1006.4293
E. Levin, A. Rezaian, arXiv:1005.0631

Looking forward: Heavy Ions at the LHC

x ~ 5*10^{-4} for semi-hard physics at LHC – large gluon shadowing



H.Paukkunen's talk

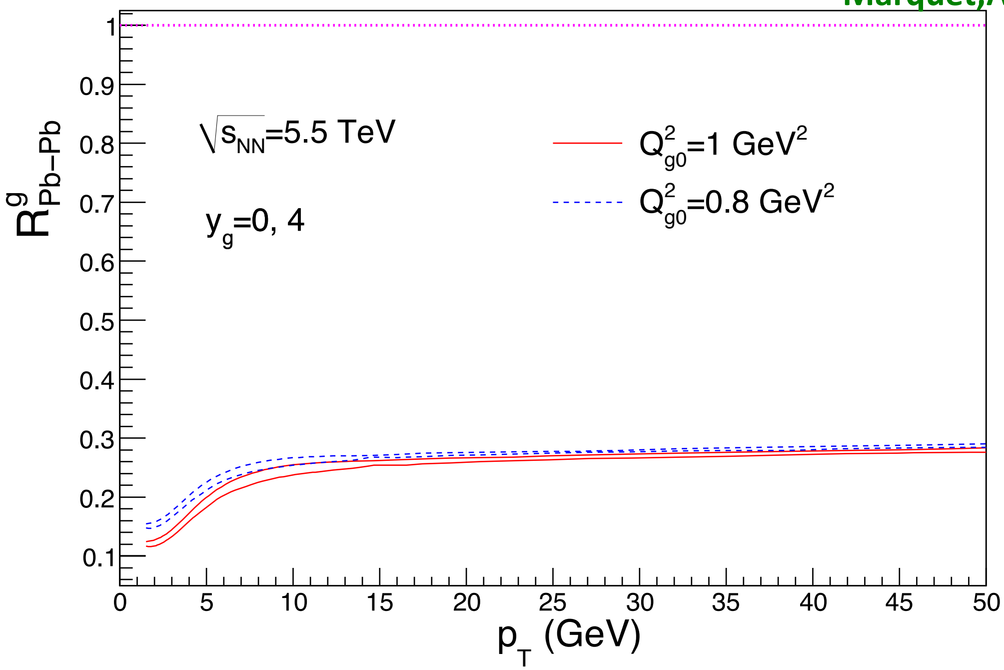


d+A RHIC data and (possibly future) p+A LHC will help quantify results

Looking forward: Heavy Ions at the LHC

Quenching of hadron spectrum (rel. to pp) from initial state effects alone is large

Marquet,Albacete,PLB687 (2010)174

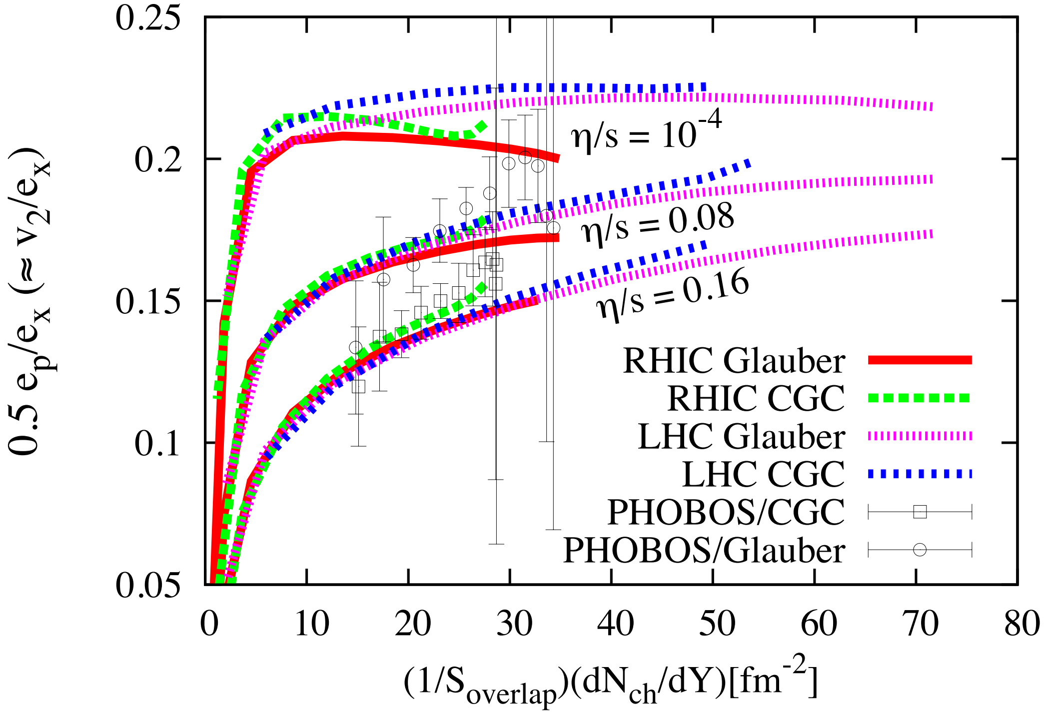


Challenging to extract sQGP properties –will need full array of impressive final states feasible

Looking forward: Heavy Ions at the LHC

Early flow analyses – confirm if RHIC has saturated the "hydro bound"

Luzum,Romatschke, 0901.4588



Outlook

- We now have a standard model of HI collisions with unanticipated features like the CGC, the Glasma & sQGP

- The sQGP produced at RHIC may be the most perfect fluid in nature

- Many approaches to understand and quantify further the properties of the sQGP – but no consensus yet

- LHC Pb+Pb data and future RHIC upgrades will significantly enrich (alter?) the picture outlined here

THANK YOU FOR YOUR ATTENTION!

Strong flow = (nearly) ideal hydrodynamics

- QCD Hydrodynamics = low energy effective theory of QCD
  valid at large distances (L >> λ_{mfp})

- Relativistic hydrodynamics:
  Conservation laws $\partial_\mu T^{\mu\nu} = 0 \qquad \partial_\mu j^\mu = 0$

- Constitutive equations:

$$T^{\mu\nu} = (\varepsilon + P) U^\mu U^\nu + P g^{\mu\nu} + \tau^{\mu\nu}$$

$$j^\mu = n\, U^\mu + \nu^\mu$$

- Dissipative terms:

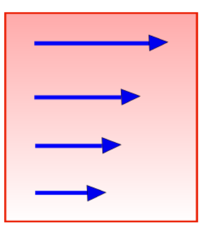
$$\tau^{ij} = -\eta \left(\partial^i U^j + \partial^j U^i - \frac{2}{3} \delta^{ij} \vec{\nabla} \cdot \vec{U} \right) - \zeta\, \delta^{ij} \vec{\nabla} \cdot \vec{U}$$

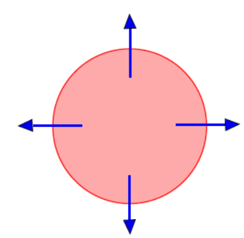
Shear viscosity

Bulk viscosity

$$\nu^i = -\sigma T \partial^i \left(\frac{\mu}{T} \right)$$

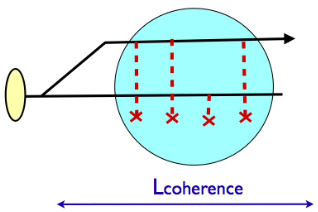
Conductivity (diffusion)



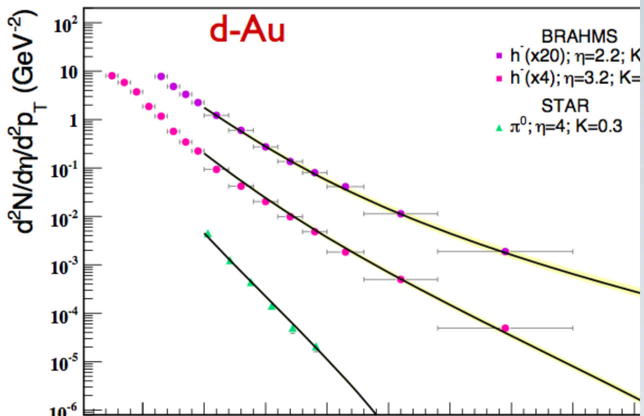


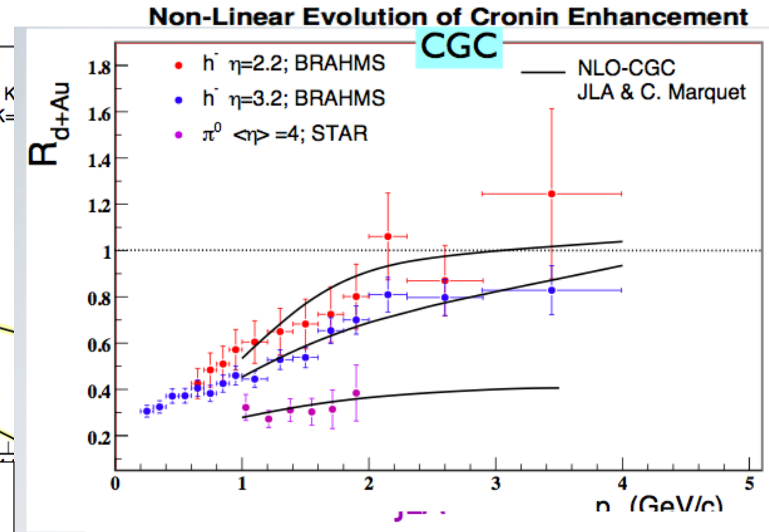
Evidence for Saturation @ RHIC ?

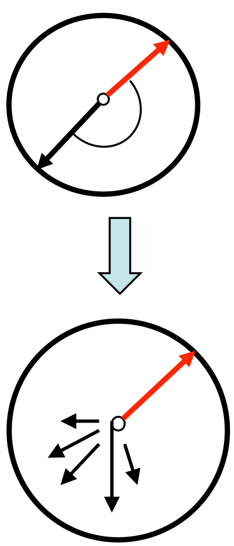
- Rich Deuteron+Gold physics program



Talks by J. Albacete
& C. Marquet
Caveats: M. Sumbara







Away side parton
randomized
by strong color field