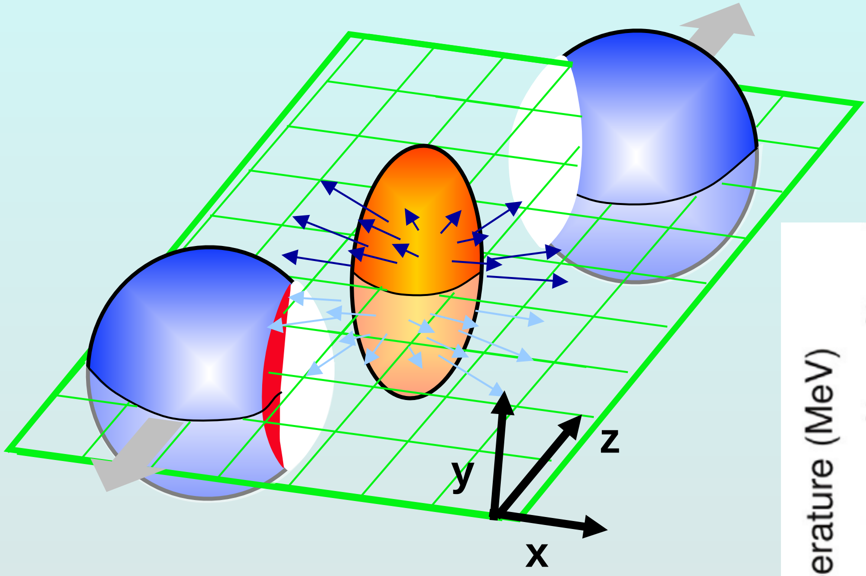
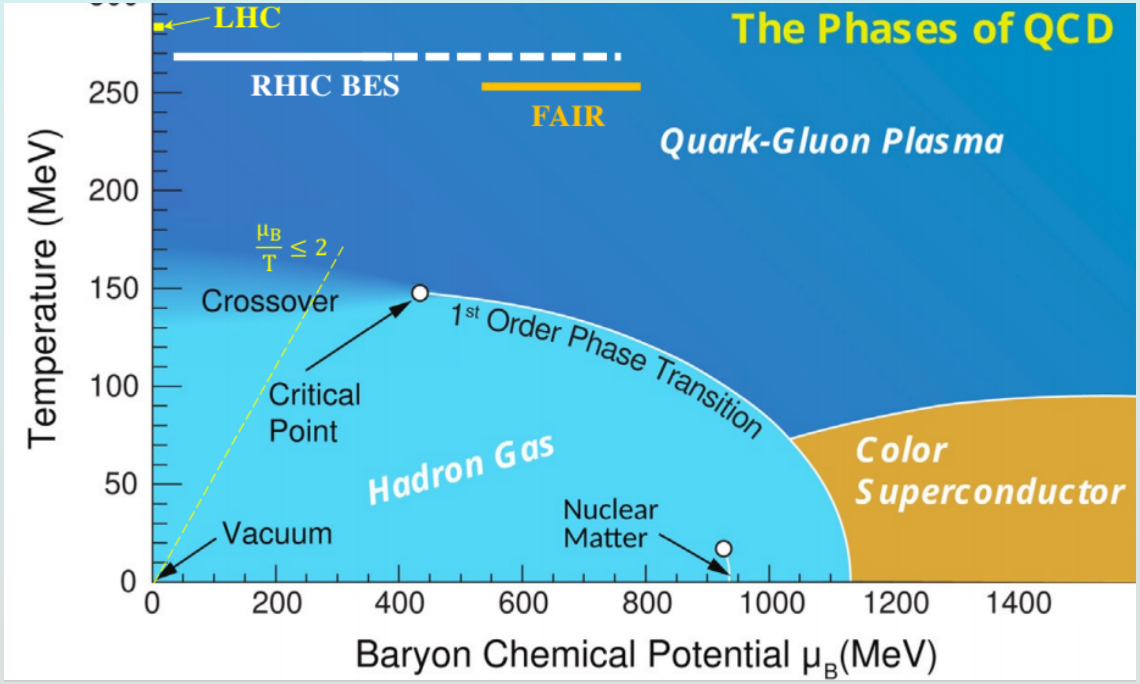
QCD Matter in Collisions of Heavy Ions
Lecture 1: Quark Gluon Plasma = many-body QCD





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UC Berkeley & LBNL
June 10, 2023

Outline(s)

update

Lectures on QCD Matter in ion collisions

1. Intro, radiation, hydrodynamic flow. T, ε, η/s
2. Energy loss and opacity in the quark gluon plasma
3. Properties of strongly coupled plasmas and what the string theorists tell us
4. Electromagnetic probes, screening, and QGP outlook

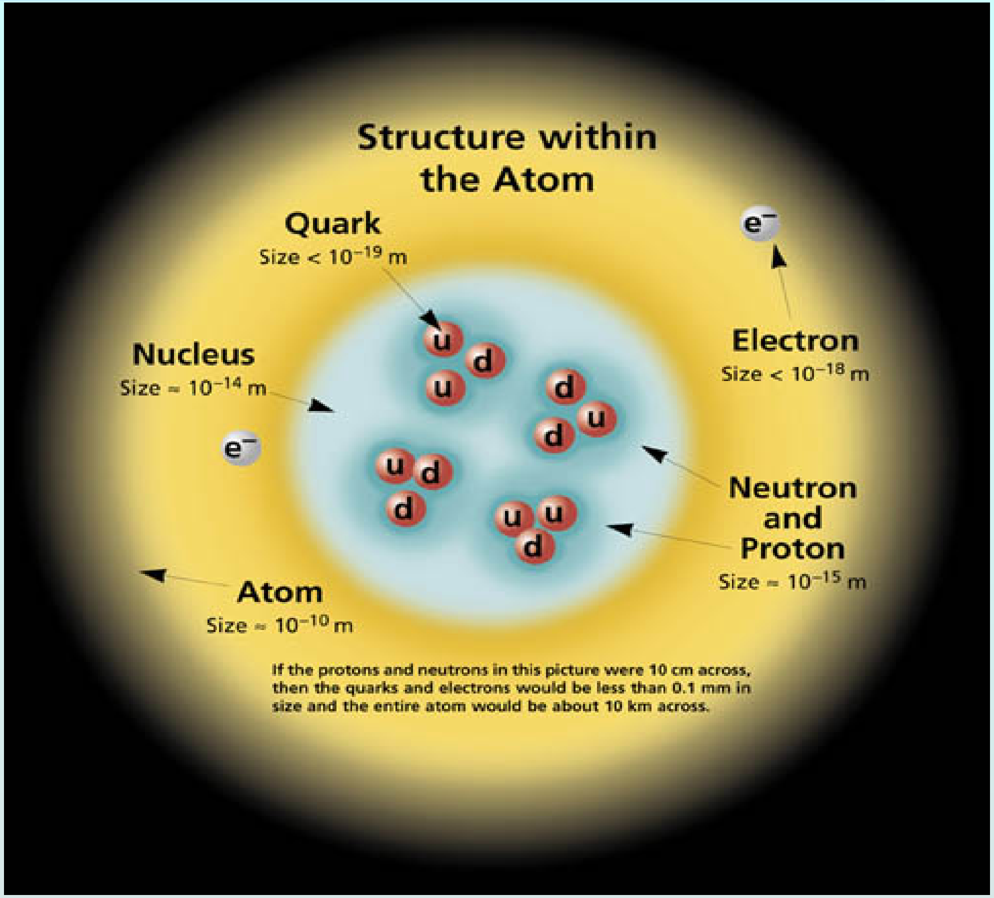
TODAY

- Introduction and motivation to study the QCD plasma
- Stages and timescales in heavy ion collisions
- Geometry of the collisions
- Collective flow, hydrodynamics, and “the perfect liquid”
- Effects of fluctuations

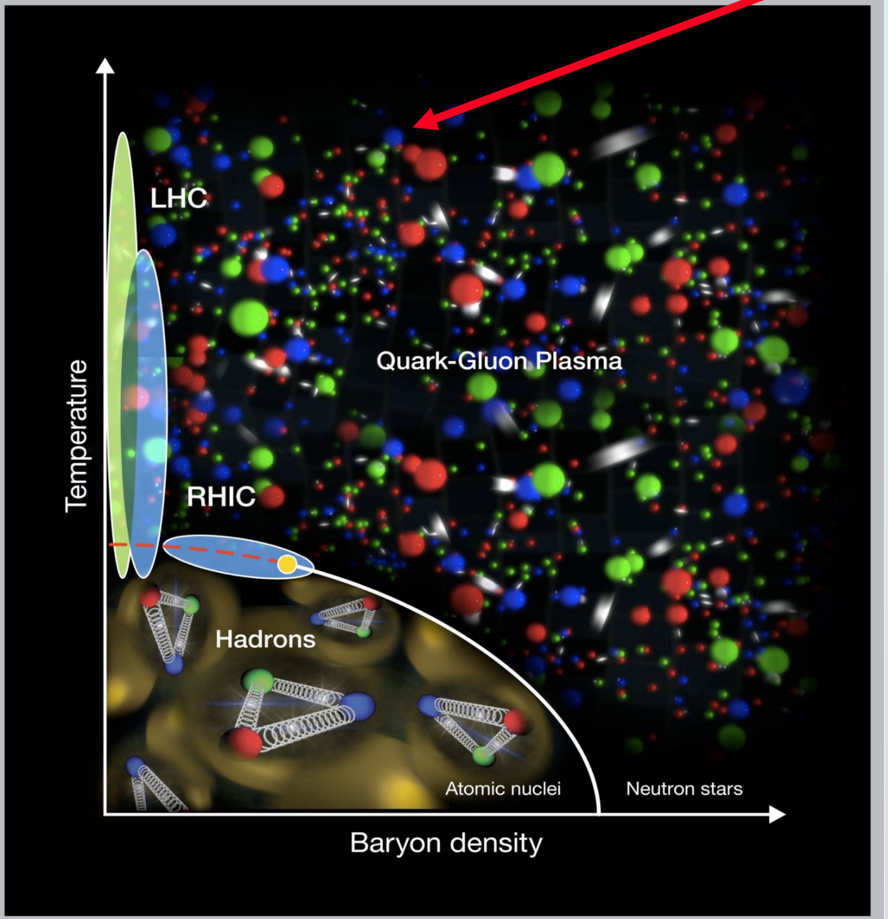
Create the hot, dense QCD matter in the lab

Heat to $T > 10^{12}$ K

last seen: ~ 1 μ second after the Big Bang!



If the protons and neutrons in this picture were 10 cm across, then the quarks and electrons would be less than 0.1 mm in size and the entire atom would be about 10 km across.



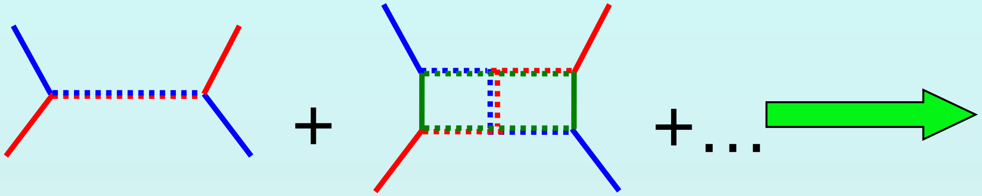
How does it work?

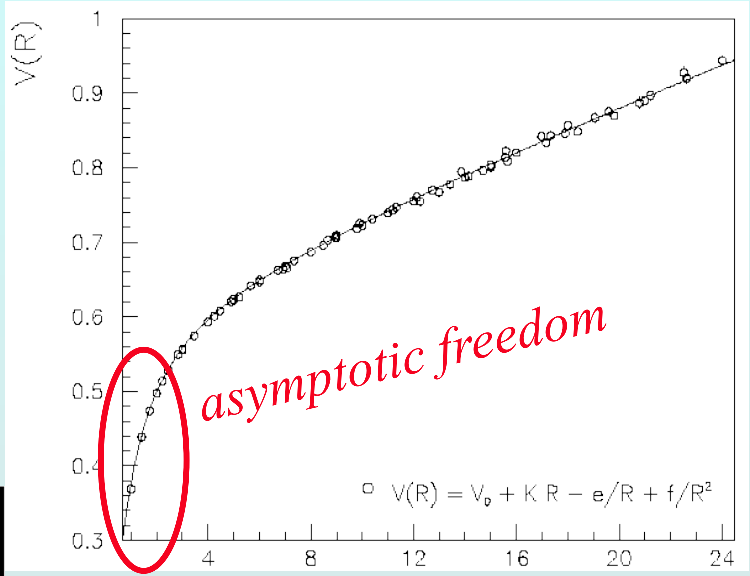
What are its properties?

Phase transitions? ***(KR)***

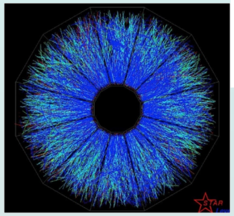
What to expect in hot, dense QCD matter?

- **Gluons carry color → interact among themselves**
  theory is non-abelian

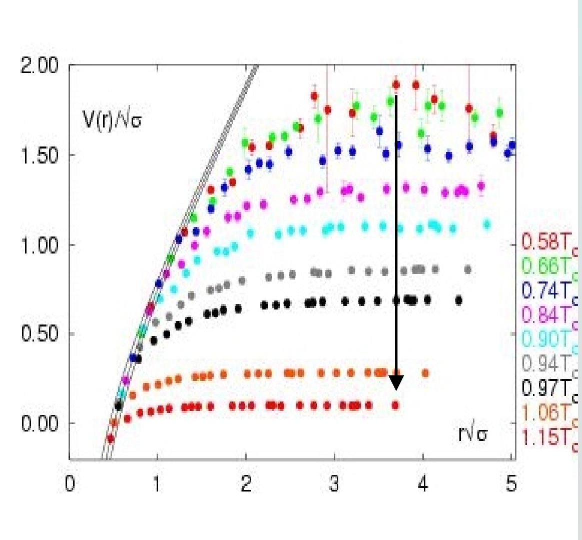




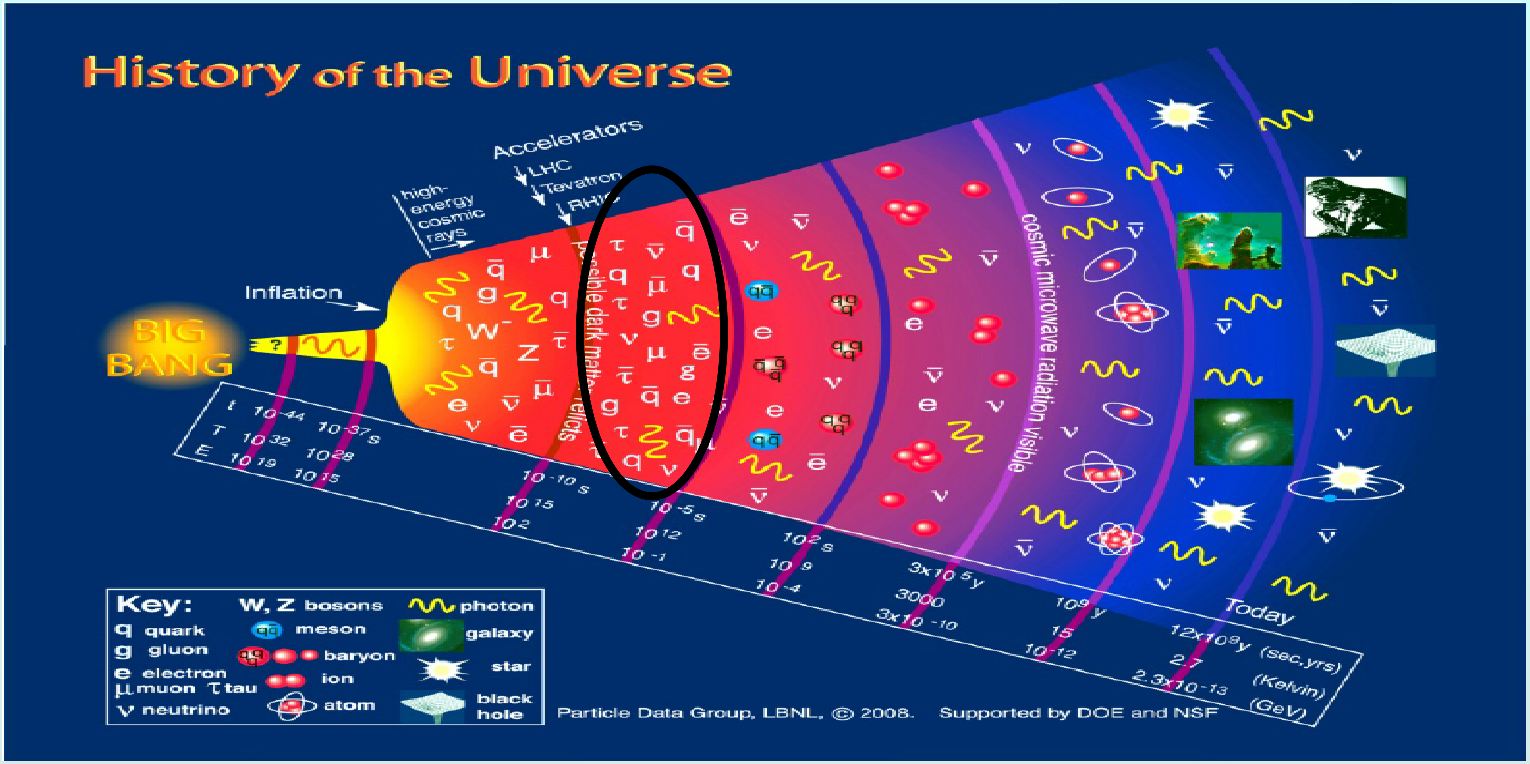
- **Curious property at large distance:**
  confinement of quarks in hadrons



At high temperature/density
screening by produced colored particles
Expect phase transition to
deconfined quark gluon plasma
Lattice QCD → T_c ~ 150 MeV



Quark gluon plasma in early universe

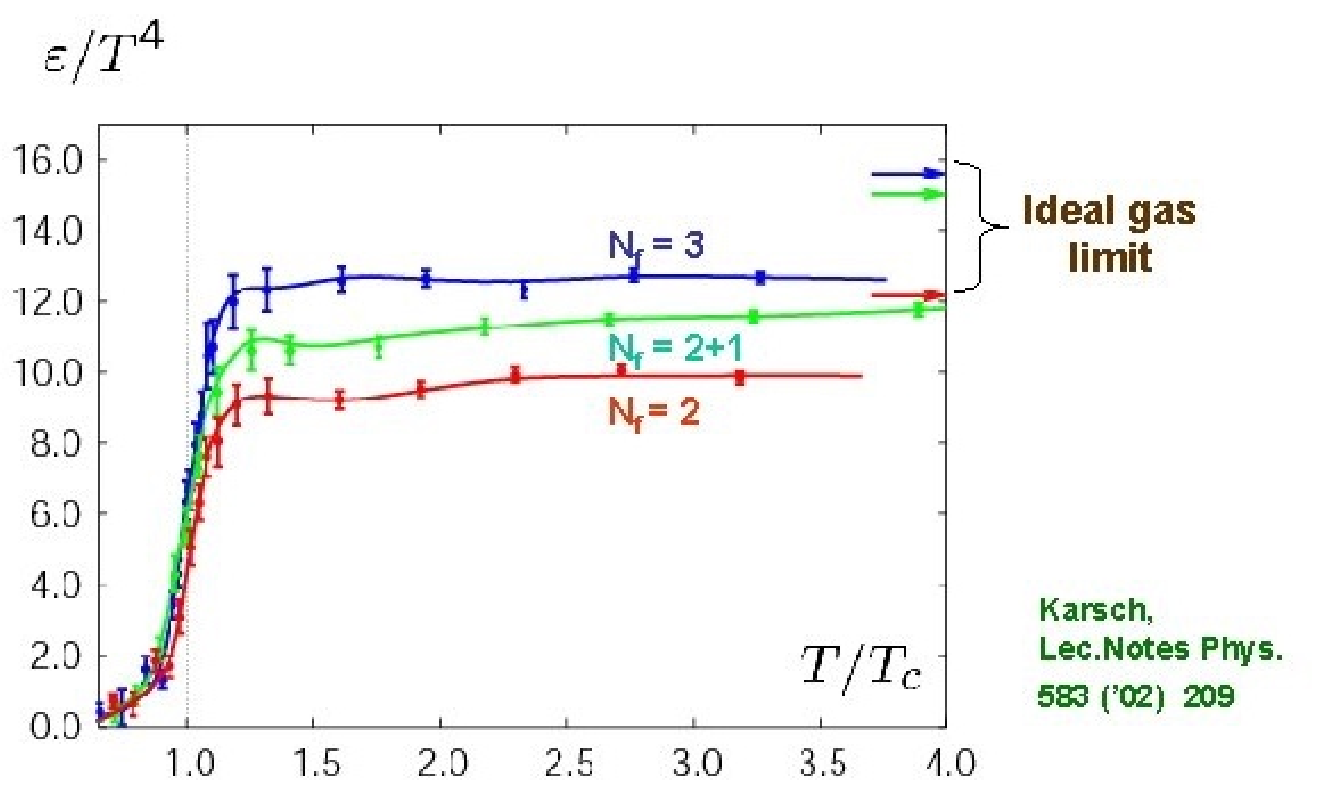


QGP likely also in core of massive neutron stars

- **Electromagnetic interactions: photons are exchanged photons are electrically uncharged**
- **Interaction between quarks = strong interaction**
  Force is carried by exchanged gluons
  Both quarks and gluons have a "color charge"

Why many-body interactions?

- Initial idea: nearly an ideal gas



Karsch, Lec.Notes Phys. 583 ('02) 209

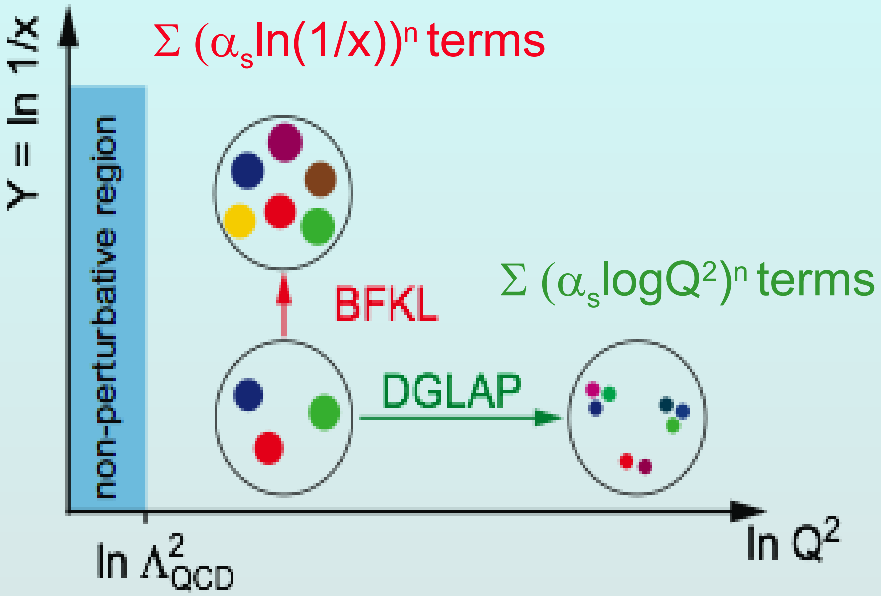
- *Range of strong interaction: ~ 1 fm*
- *Number of gluons inside 1fm radius sphere: lots!*

  So, why an ideal gas? Should have many-body interactions

Starting point: inside a nucleon

x: momentum fraction carried by parton

Theorists' view



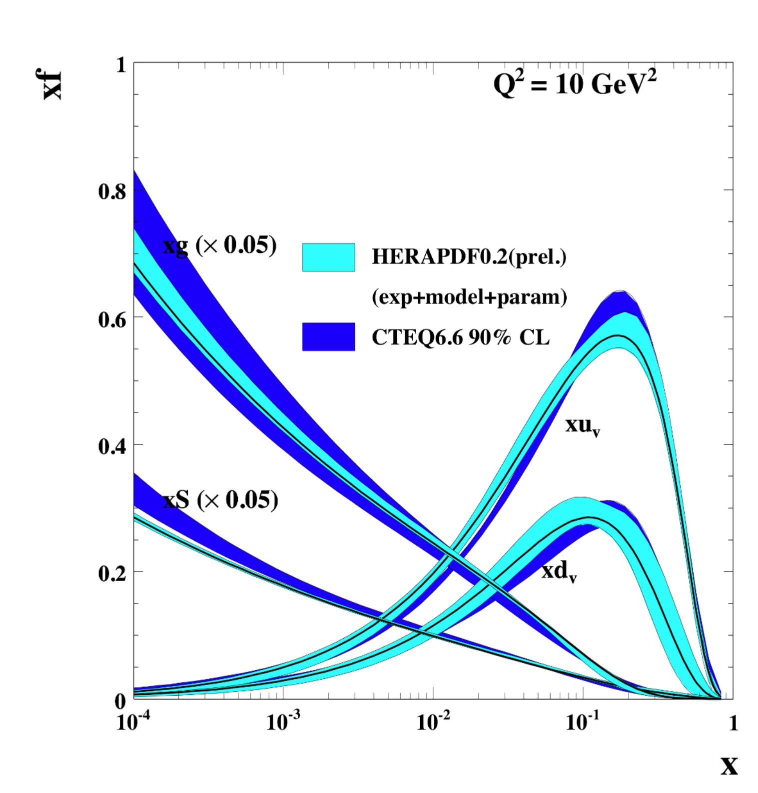
Q^2: momentum transfer in a collision

Gluon number is not fixed

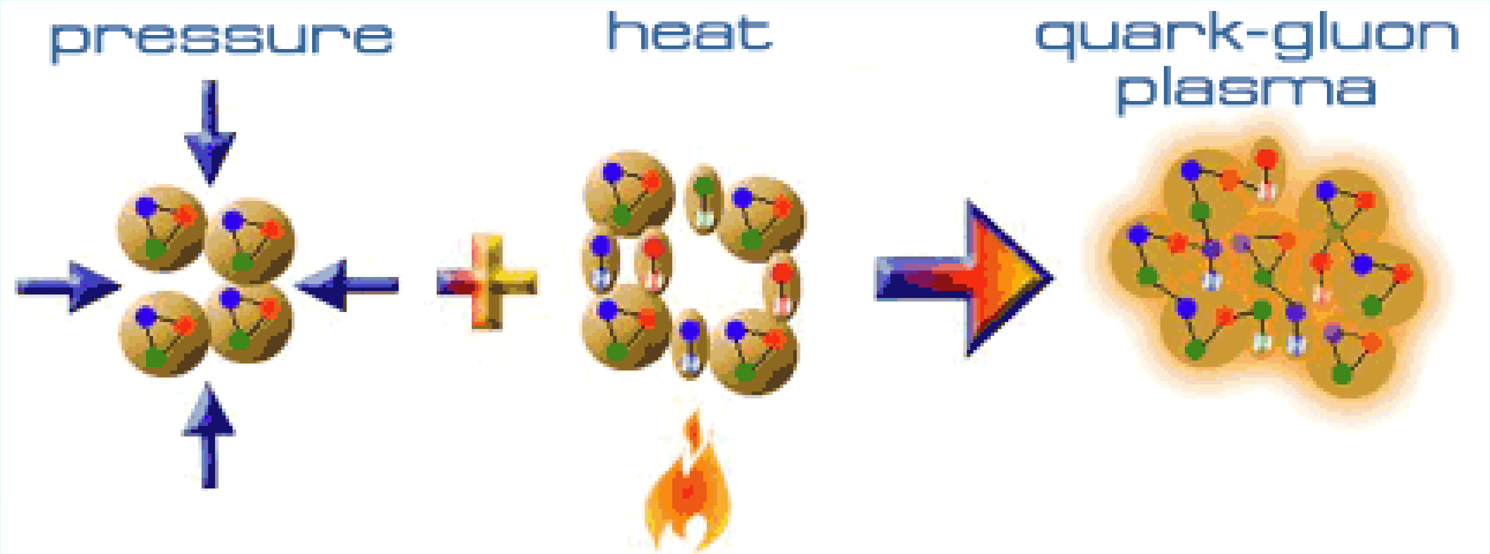
Virtual q-$\bar{q}$ pairs abundant

Experimenter's view

Scatter electrons off a p

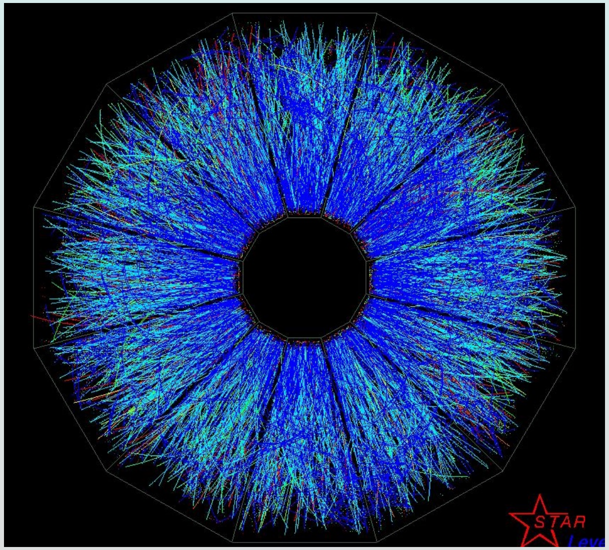


From the practical point of view



What we see in the lab:

All the particles which come out at the end of the collision



The heaters

Large Hadron Collider

CERN in Geneva

Pb+Pb @ 2.76 TeV/A

Relativistic Heavy Ion Collider

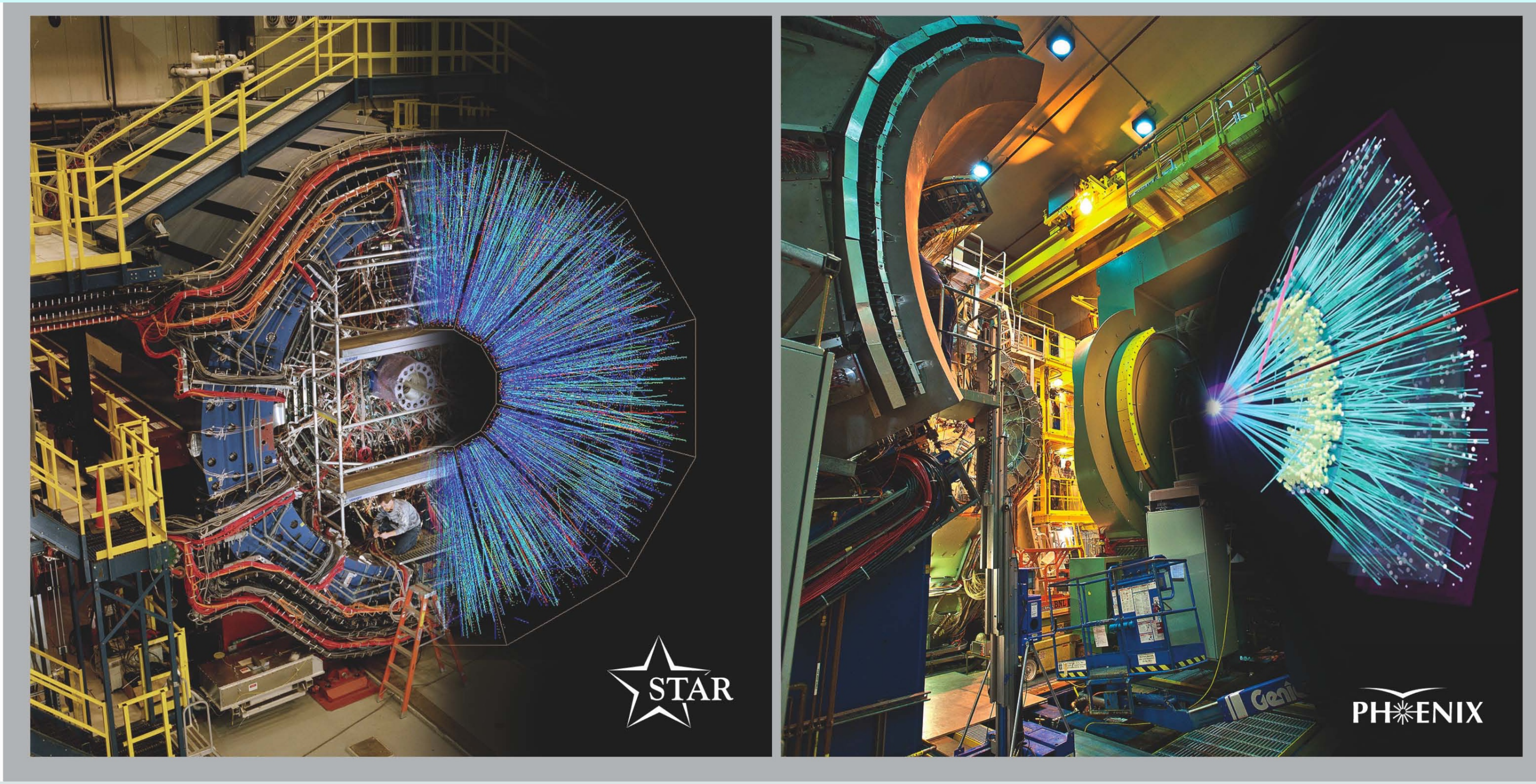
Brookhaven in New York

Au+Au @ 200 MeV/A

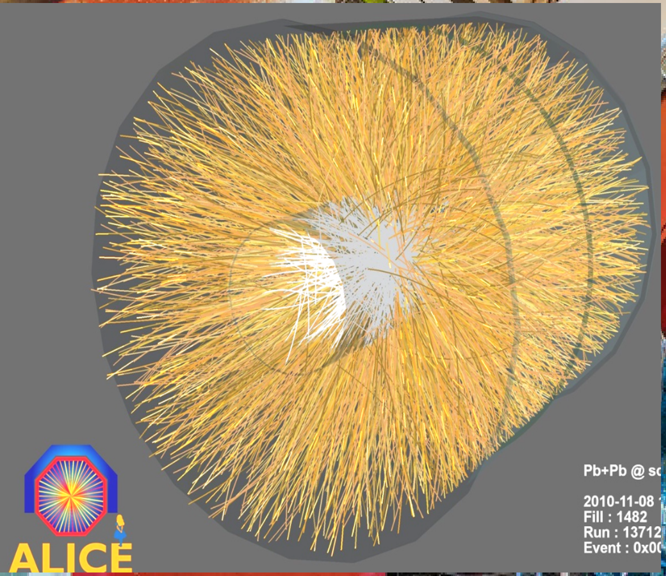
Collide heavy nuclei for max temperature & volume

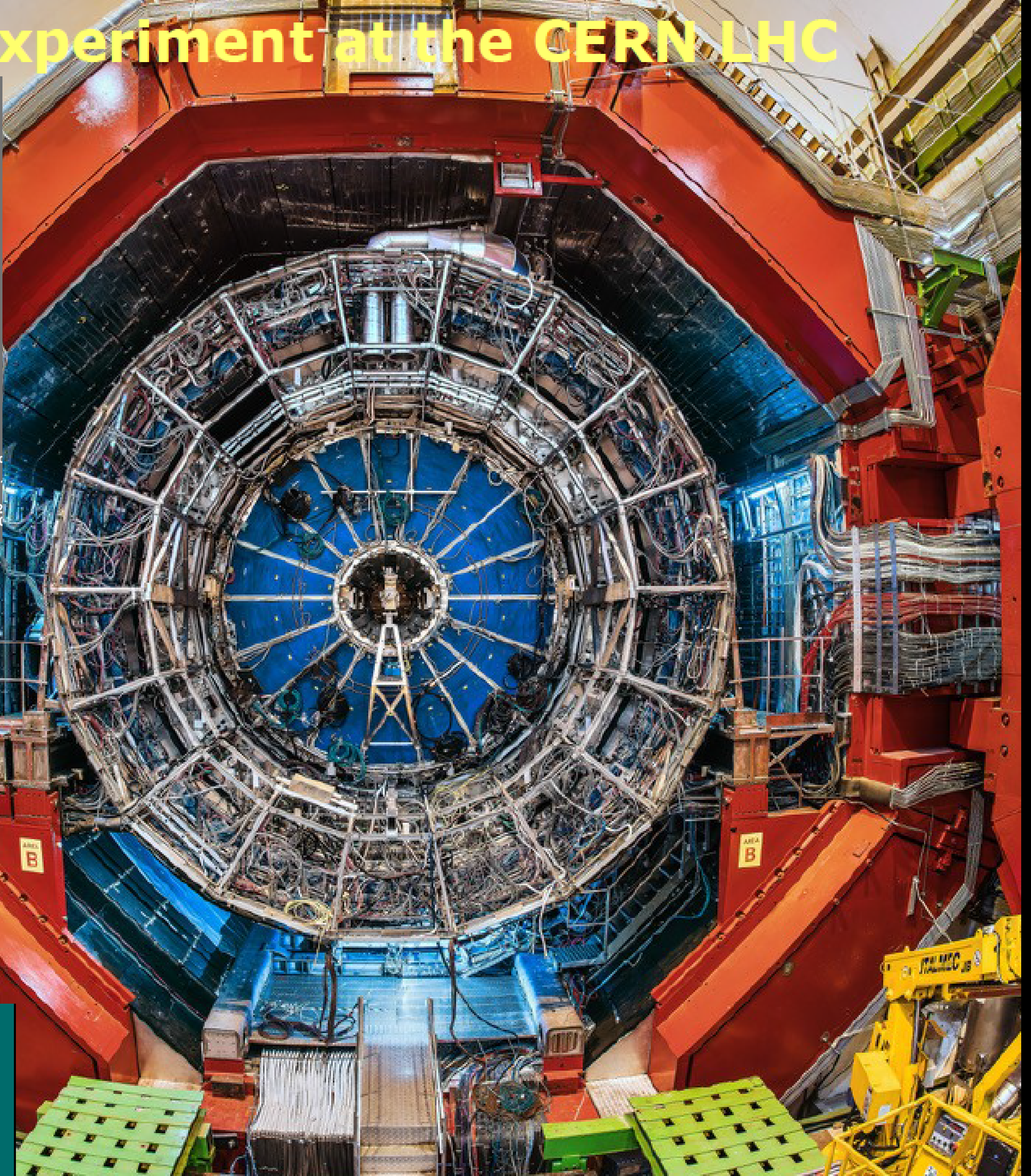
p+p and p+A for comparison

Experiments at RHIC



The ALICE experiment at the CERN LHC

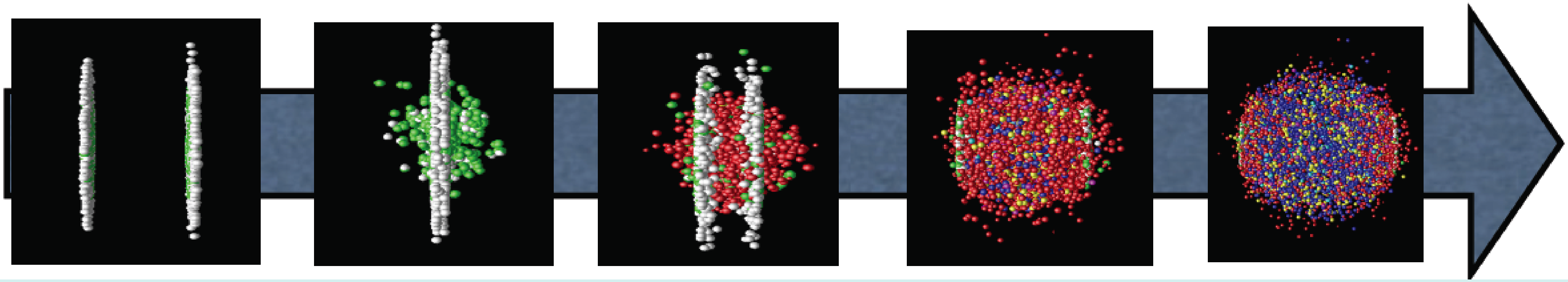




1000 scientists
in 172 institutes
from 40 countries

Nuclear collision timeline

plasma lives ~3x10^{-23} seconds, ~10^{-12} cm across



Lorentz contracted nuclei on their way in.

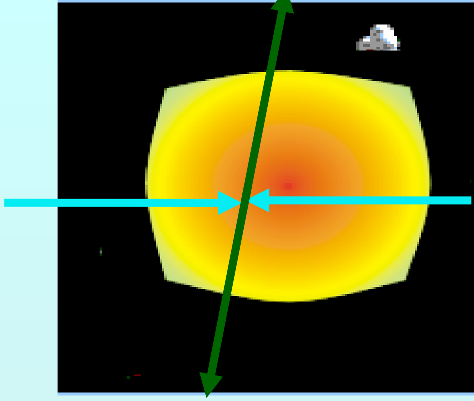
First scattering of q & g inside the nucleons. Some high momentum transfers.

Secondary collisions, creating high density and temperature

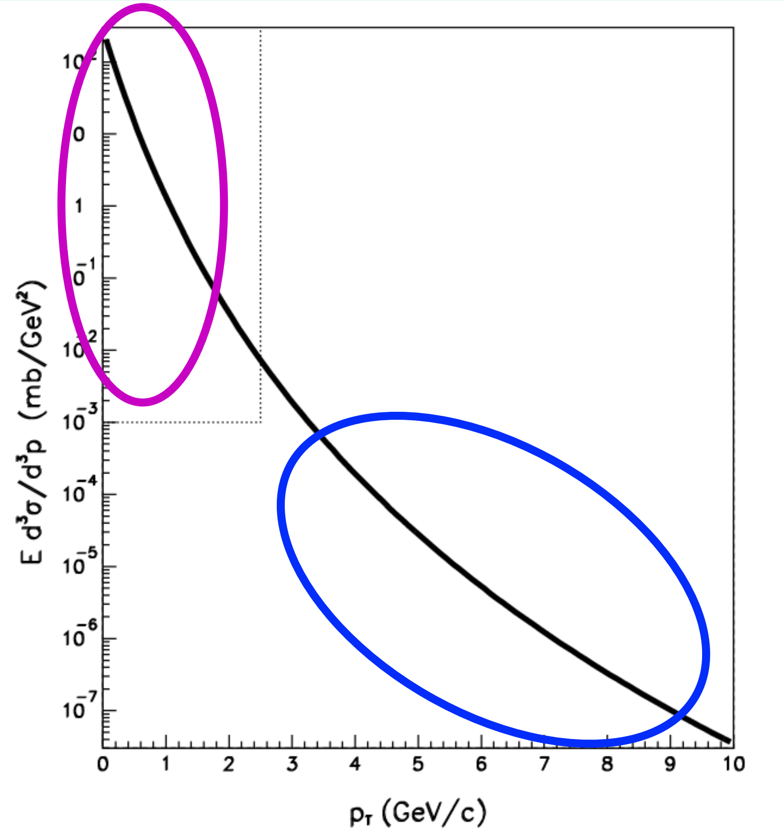
Quark gluon plasma expands and cools, eventually condensing into hadrons.

Hadron gas interacts, expands and cools further. Eventually collisions stop & hadrons stream freely.

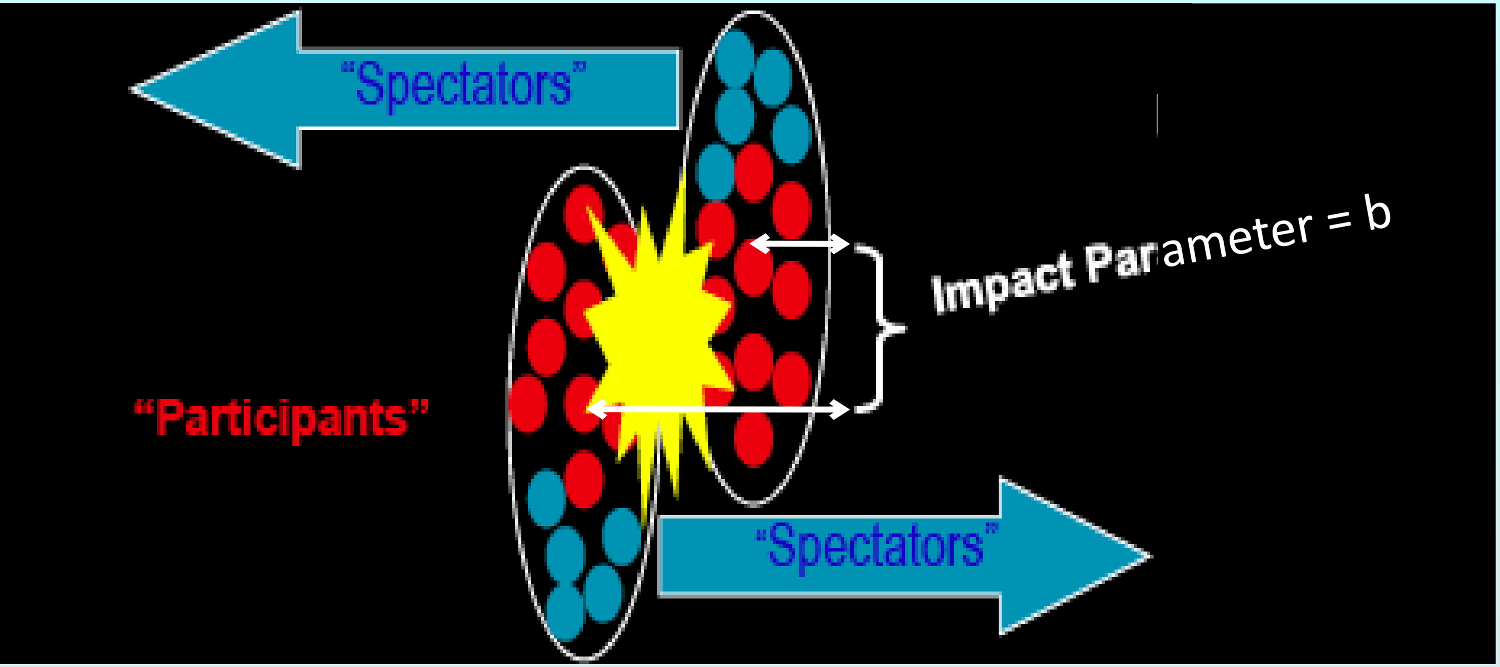
study plasma with radiated & “probe” particles



- as a function of transverse momentum
  90° is where the action is (max T, ρ)
  p_L between the two beams: midrapidity
- p_T < 1.5 GeV/c
  “thermal” particles
  radiated from bulk medium
  “internal” plasma probes
- p_T > 3 GeV/c
  large E_{tot} (high p_T or M)
  set scale other than T(plasma)
  autogenerated “external” probe
  describe by perturbative QCD
- control probe: photons
  EM, not strong interaction
  produced in Au+Au by QCD
  Compton scattering



Geometry matters



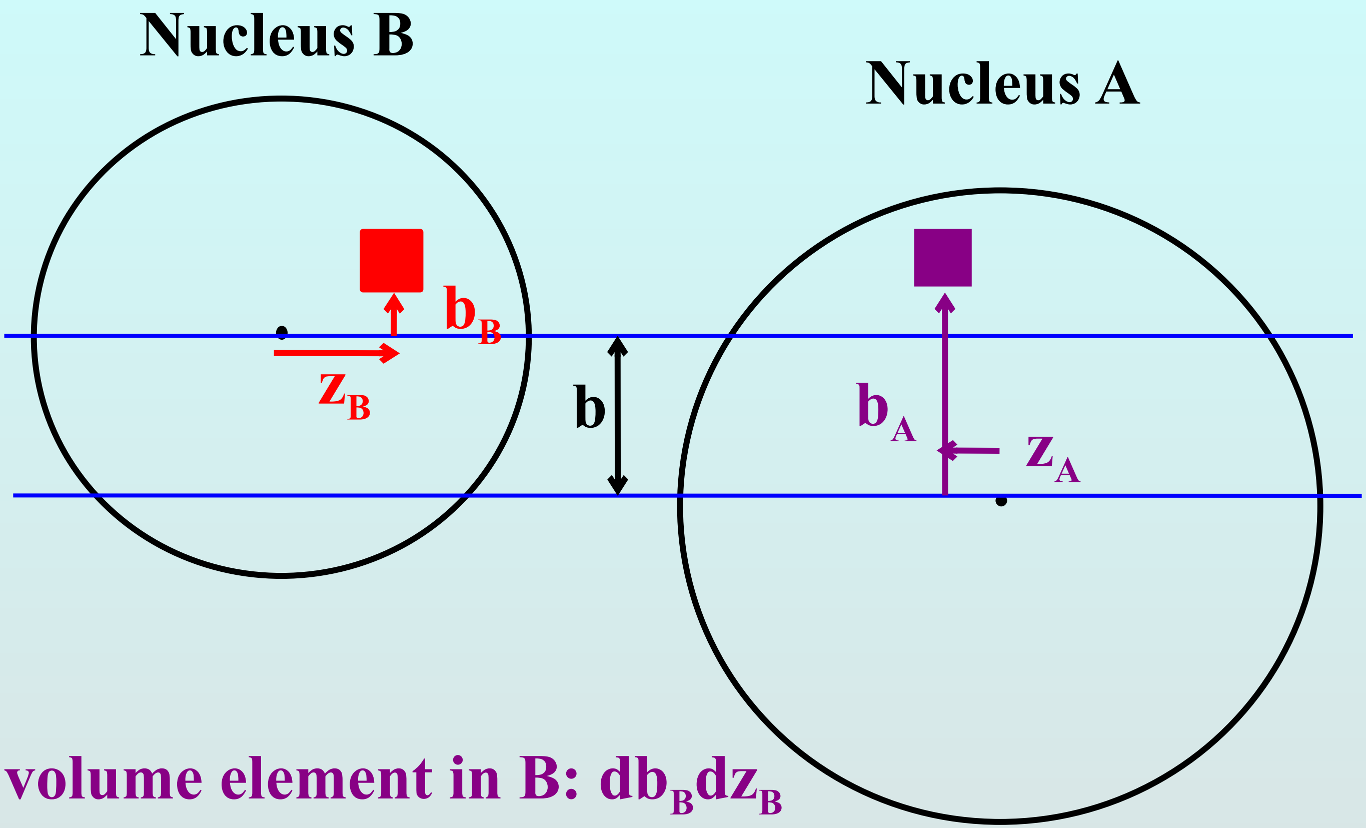
Use Glauber model of nucleons in the nucleus

calculate # of participant nucleons N_{part}

# of binary NN collisions N_{coll}

Central collisions (b ~ 0) produce maximum volume of plasma

Glauber model: calculate probabilities



volume element in B: $db_B dz_B$

volume element in A: $db_A dz_A$

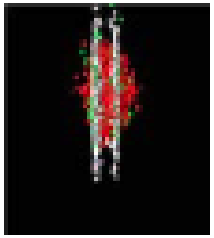
Probability of finding a nucleon in volume element B =

$\rho_B(b_B, z_B)\, db_B dz_B$ (ρ_B is nuclear density * nucleons in B)

OK, so what happens when two nuclei collide?

NB: $b \neq 0$!

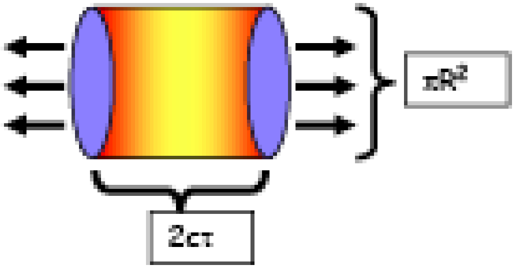
Energy Density

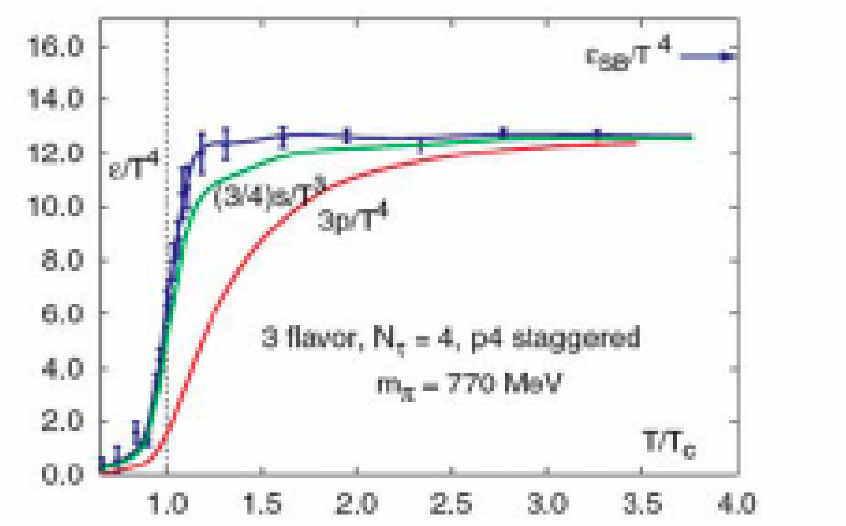


Energy density far above transition value predicted by lattice.

$$\varepsilon_{Bj} = \frac{1}{\pi R^2}\,\frac{1}{2c\tau}\left(2\,\frac{dE_T}{dy}\right)$$

R~7fm





Lattice: T_C~190 MeV (ε_C ~ 1 GeV/fm³)

PHENIX: Central Au-Au yields

$$\boxed{\left\langle \frac{dE_T}{d\eta} \right\rangle_{\eta=0} = 503 \pm 2\,GeV}$$

$$\varepsilon \sim 15\,\frac{GeV}{fm^3}\ @\,\tau = 0.6\,fm/c\ (thermalization)$$

Quark Gluon Plasma properties

- **thermodynamic properties (equilibrium)**

  T, P, ρ

  Equation Of State (relation btwn T, P, V, energy density)

  v_{sound}, static screening length

- **transport properties (non-equilibrium)***

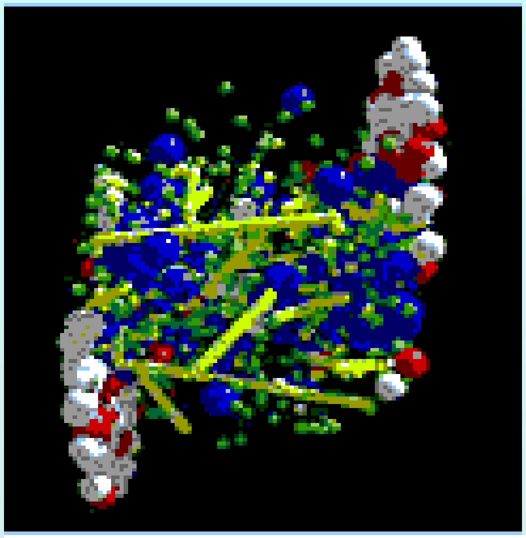
  particle number, energy, momentum, charge

  diffusion *sound* *viscosity* *conductivity*

***measuring these is new for nuclear/particle physics!**

How hot is our QCD matter?

Hottest Science Experiment on the Planet*

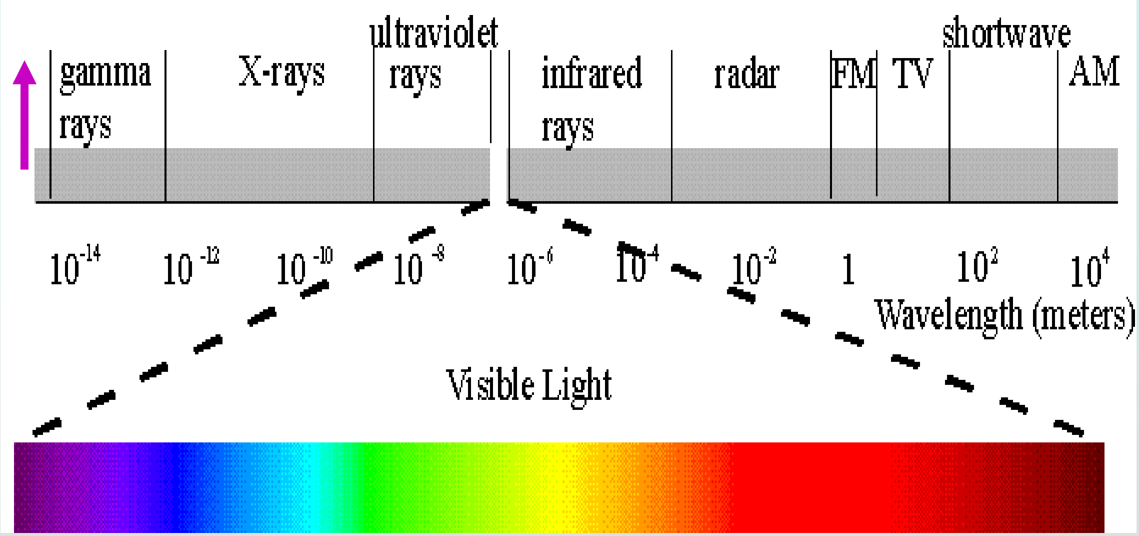


plasma lives for 3×10^{-23} s

droplet is 10^{-12} cm across

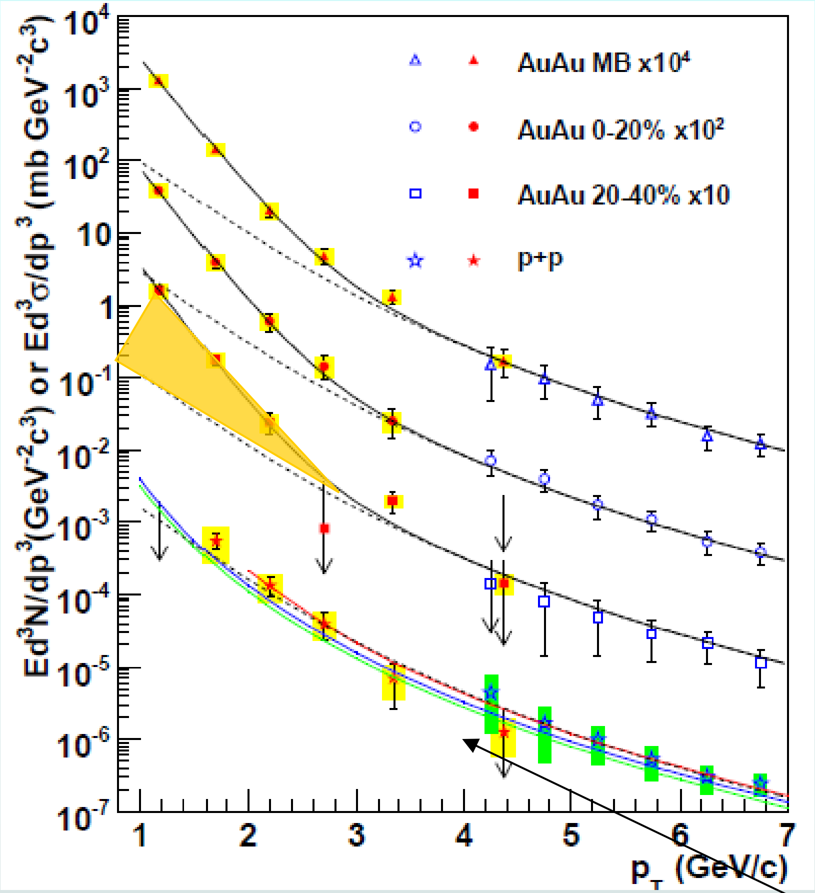
can't use a thermometer!

So we look at radiation

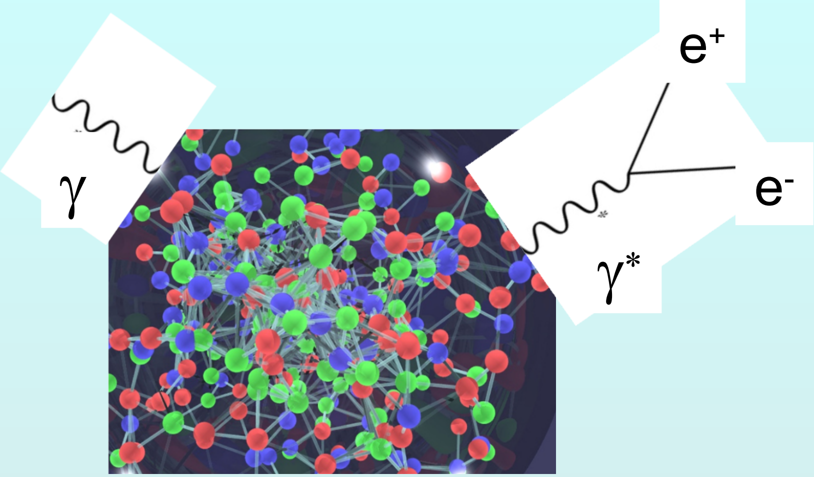


*** According to Discover Magazine (2010)**

Thermal radiation



PRL 104, 132301 (2010)



Low mass, high p_T e^+e^- →

nearly real photons

Large enhancement above

p+p in the thermal region

pQCD γ spectrum

(Compton scattering @ NLO)

agrees with p+p data

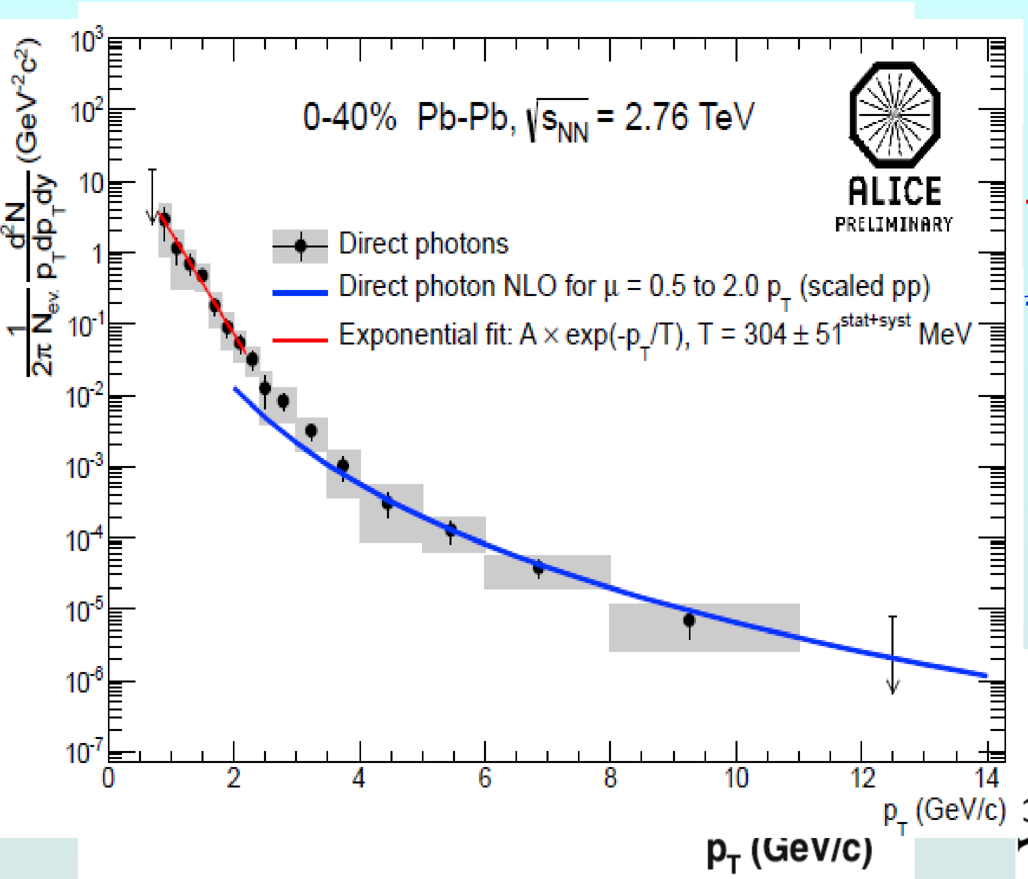
Analogy to the bronze is not quite right

- Similar to black body radiation, but…
- The photons are not bouncing around in equilibrium with QGP
  - Produced by interactions among partons in equilbrium
  - Exit the plasma with no further (strong) interactions

- The plasma is not static
  - It is expanding at v=c longitudinally and v~0.5c radially
  - Photons arise from velocity boosted partons

- What to do about this?
- Try hydrodynamics to play the movie backwards!

direct photons: $T_{init} > T_c$!



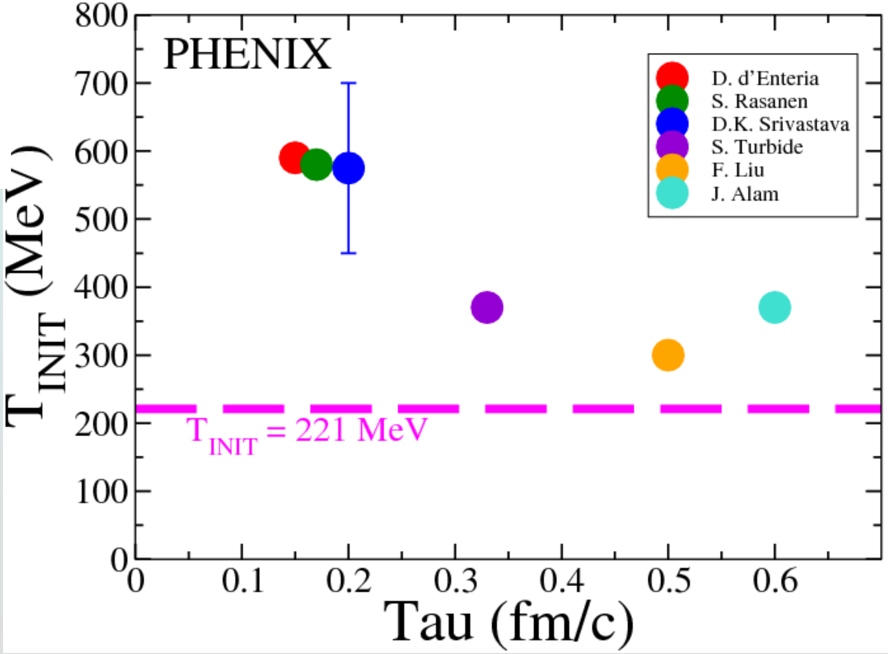
- **Exponential fit in p_T:**

***$\underline{T_{avg}}$* = 221 ±23 ±18 MeV**

But, a hot system expands!

- **Use hydrodynamics models to reproduce data**

T > 300 MeV

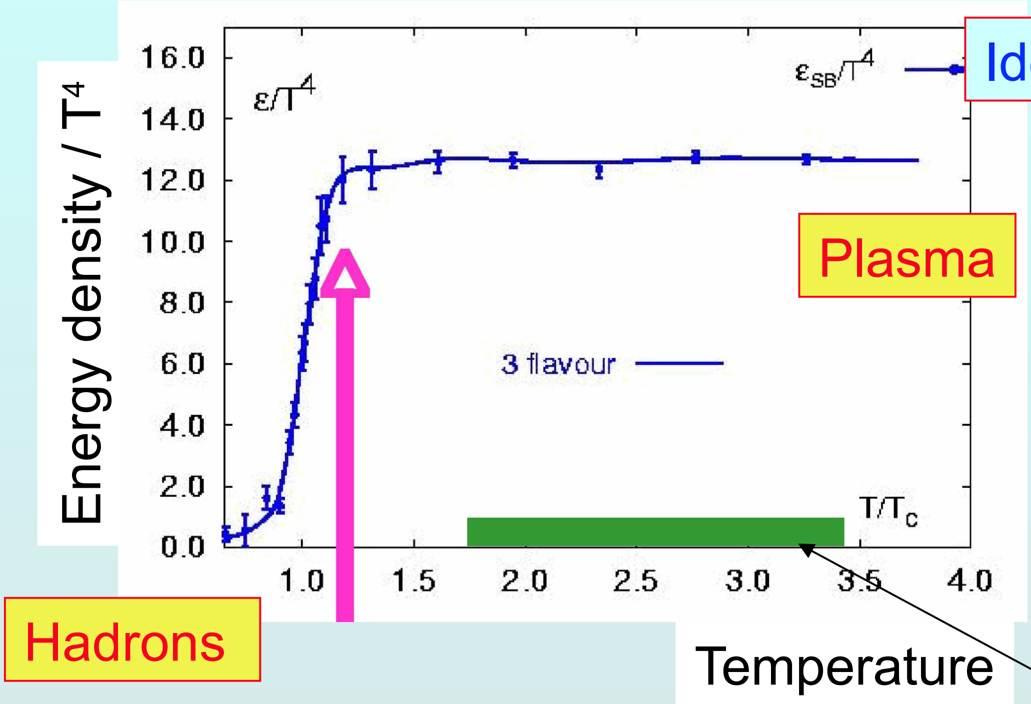


NB: T_c ~ 150 MeV

@ LHC T_{avg} = 304±51 MeV

T ~ 30% higher than at RHIC

Now we are on the map



$$\varepsilon = g\frac{\pi^2}{30}T^4$$

Energy density $\propto T^4$

more degrees of freedom in the plasma phase

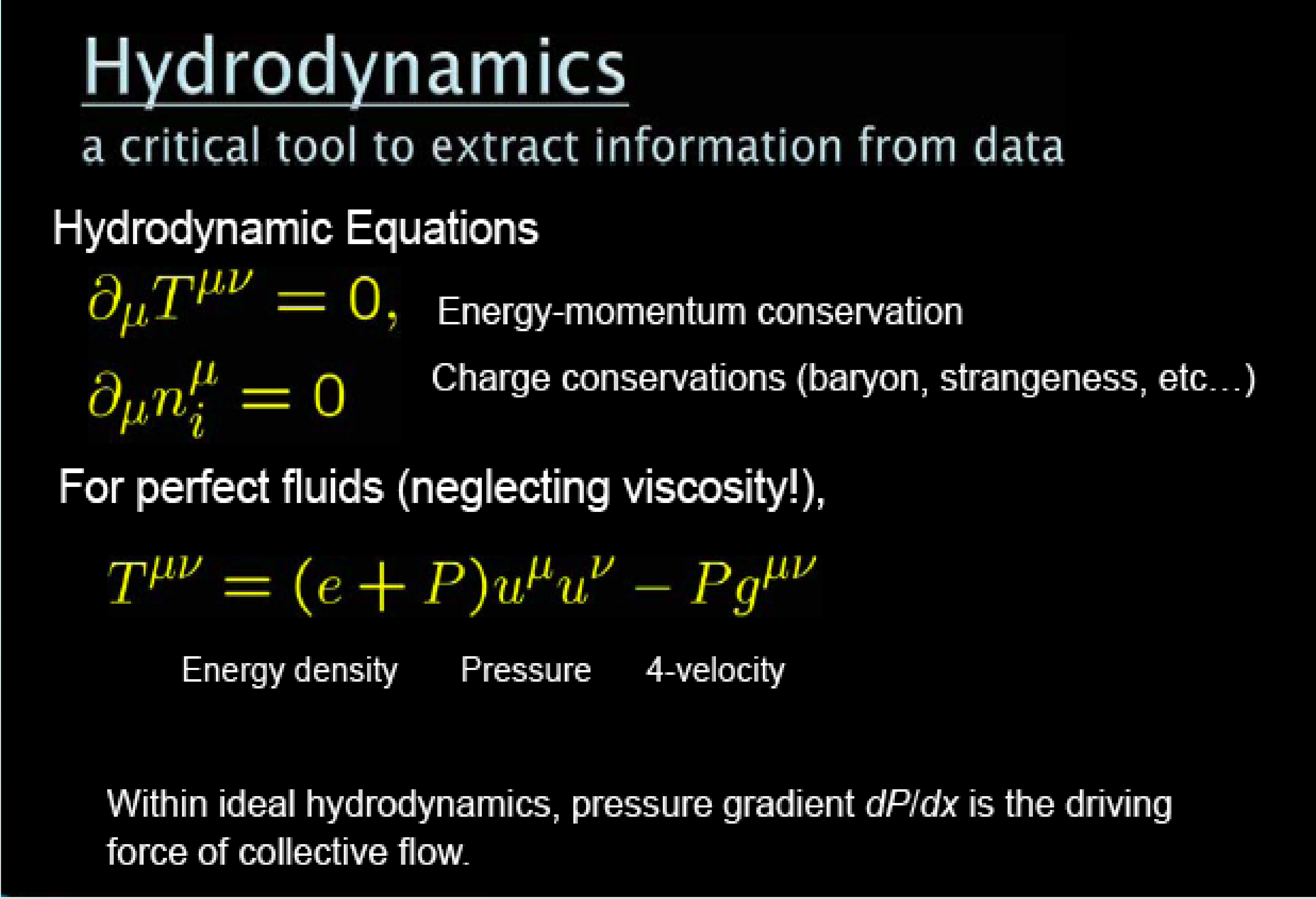
We are here

$T \sim 250\text{–}500$ MeV

$T_c \sim 150 \pm 10$ MeV

$\varepsilon \sim 3$ GeV/fm^3

Is QCD matter evolution well described by hydrodynamics??



Hydrodynamics

a critical tool to extract information from data

Hydrodynamic Equations

$$\partial_\mu T^{\mu\nu} = 0,$$ Energy-momentum conservation

$$\partial_\mu n_i^\mu = 0$$ Charge conservations (baryon, strangeness, etc…)

For perfect fluids (neglecting viscosity!),

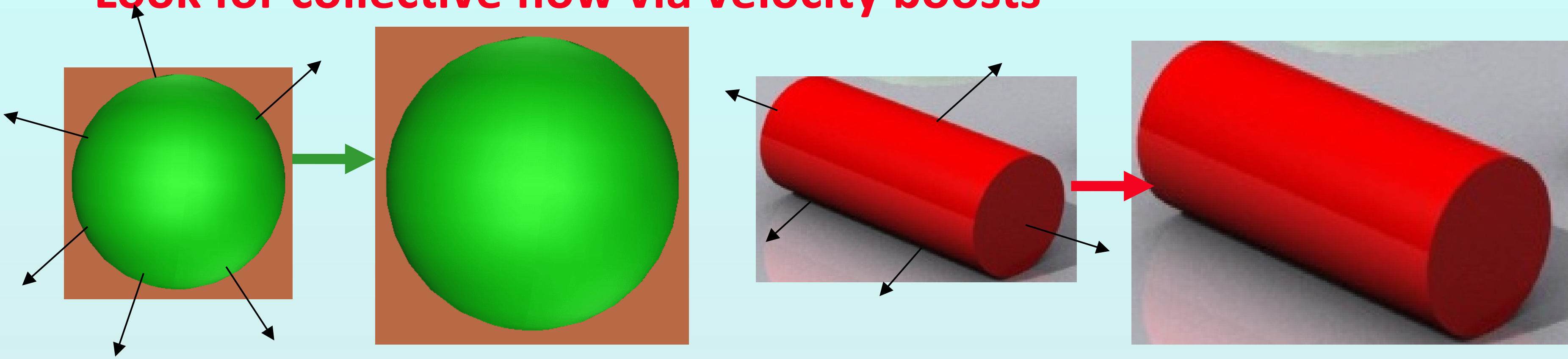
$$T^{\mu\nu} = (e + P)u^\mu u^\nu - P g^{\mu\nu}$$

Energy density Pressure 4-velocity

Within ideal hydrodynamics, pressure gradient *dP/dx* is the driving force of collective flow.

Does the matter exhibit collectivity?

- Look for collective flow via velocity boosts



- Is the expansion hydrodynamical?

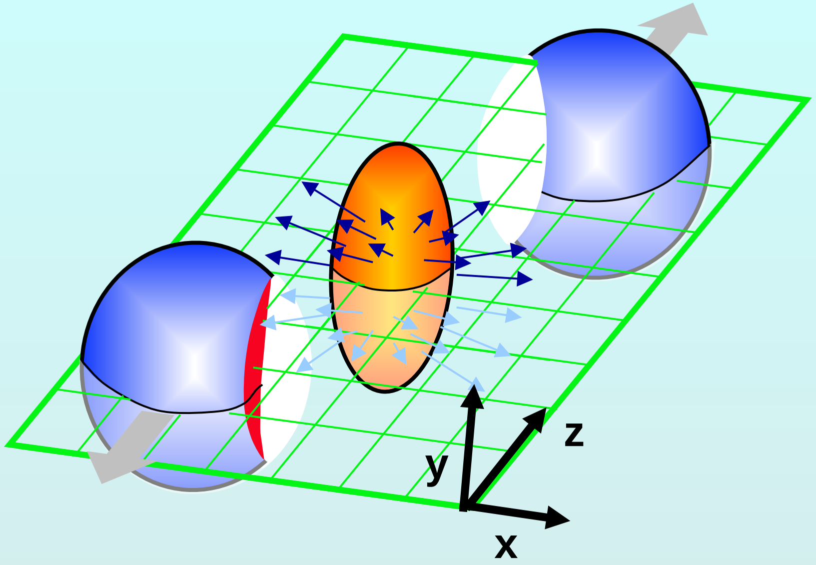
  Model expansion of the system with fluid dynamics

$$\partial_t \begin{pmatrix} \rho \\ \rho u \\ \rho v \\ e \end{pmatrix} + \partial_x \begin{pmatrix} \rho u \\ \rho u^2 + p \\ \rho u v \\ u(e+p) \end{pmatrix} + \partial_y \begin{pmatrix} \rho v \\ \rho u v \\ \rho v^2 + p \\ v(e+p) \end{pmatrix} -$$

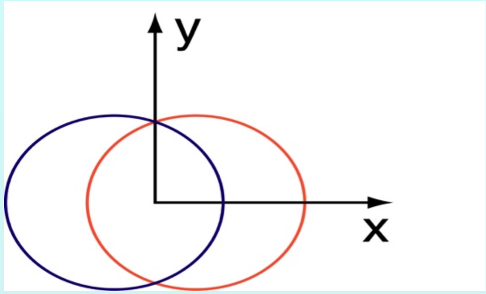
$$\partial_x \begin{pmatrix} 0 \\ \tau_{11} \\ \tau_{12} \\ \tau_{11} u + \tau_{12} v + k \partial_x \Theta \end{pmatrix} - \partial_x \begin{pmatrix} 0 \\ \tau_{21} \\ \tau_{22} \\ \tau_{21} u + \tau_{22} v + k \partial_y \Theta \end{pmatrix} = 0 \,,$$

where u and v are the components of the velocity, ρ the density, p the pressure, e total energy density, τ_{ij} the components of the viscous part of the stress tensor, Θ the absolute temperature and k is the heat conductivity.

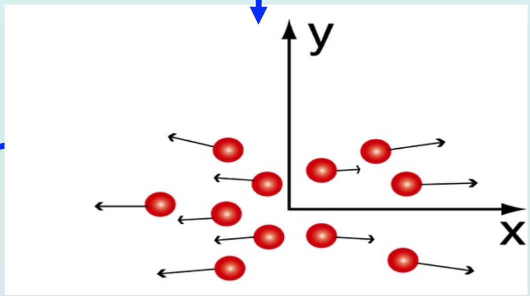
Measuring collective flow

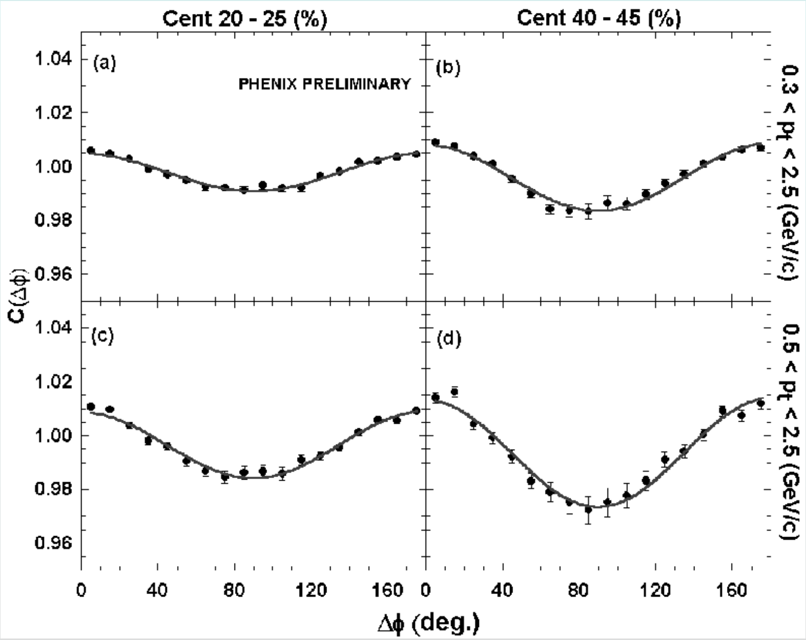


Almond shape overlap region in coordinate space



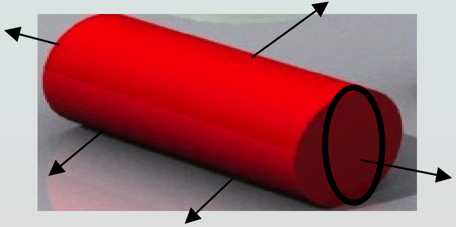
momentum space



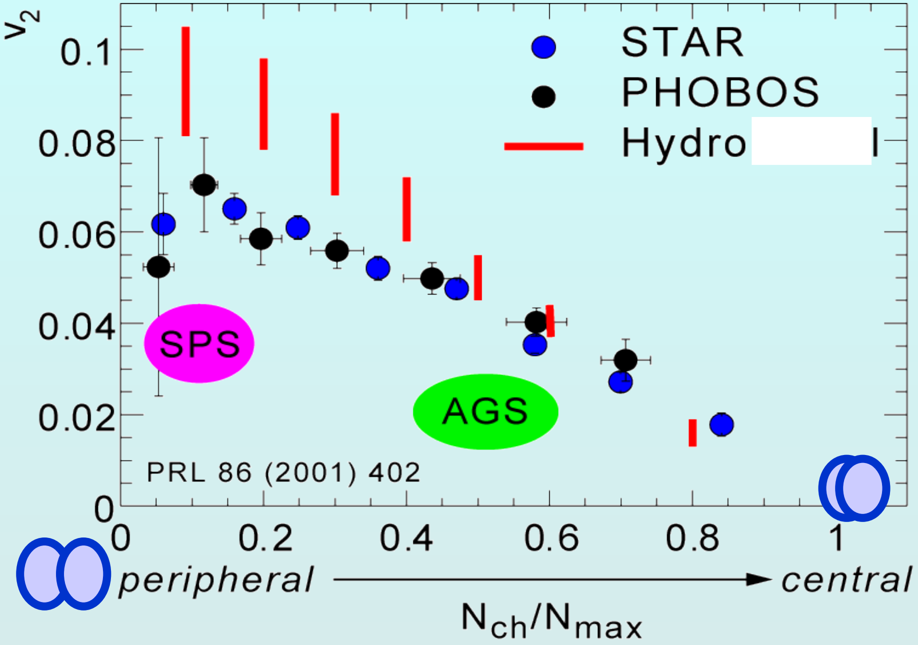


$dN/d\phi \sim 1 + 2\, v_2(p_T) \cos(2\phi) + \ldots$

“elliptic flow”

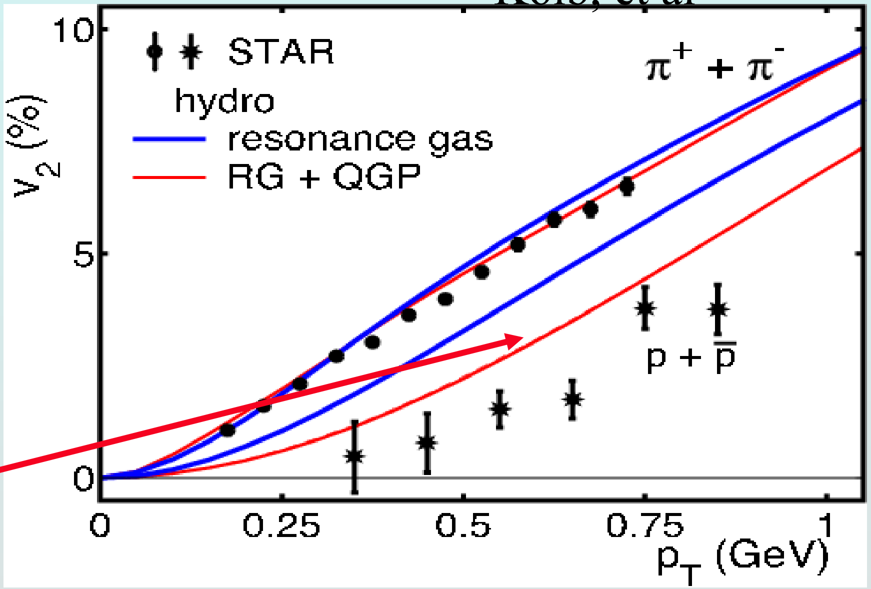


QGP flows hydronamically



- large anisotropy!
- huge pressure buildup
- build up quickly, else hydro misses data

Kolb, et al



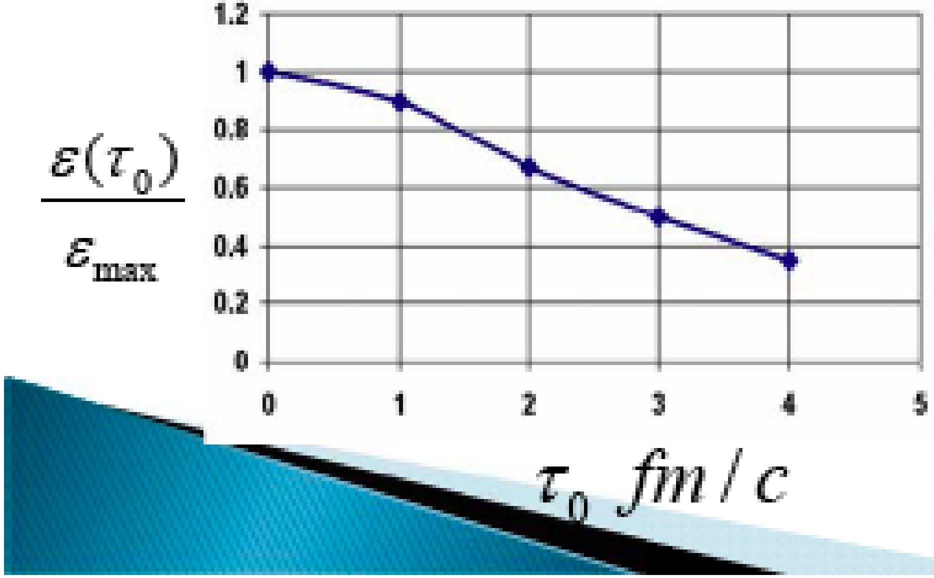
Hydrodynamics reproduces elliptic flow of q-$\bar{q}$ and 3q states
Mass dependence was first signal
QGP - NOT gas of hadrons

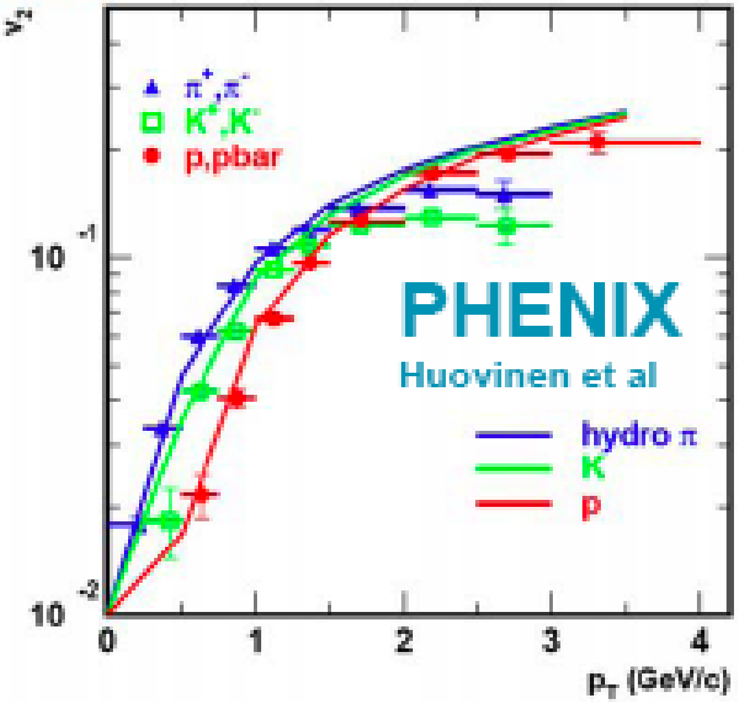
only works with very low viscosity/entropy
“perfect” liquid (D. Teaney, PRC68, 2003)
Many advances in relativistic viscous hydrodynamics in 20 years!

Strong flow Implies early thermalization

- If system free streams
  - spatial anisotropy is lost
  - v_2 is not developed

Eccentricity: $\varepsilon = \dfrac{\langle y^2\rangle - \langle x^2\rangle}{\langle y^2\rangle + \langle x^2\rangle}$

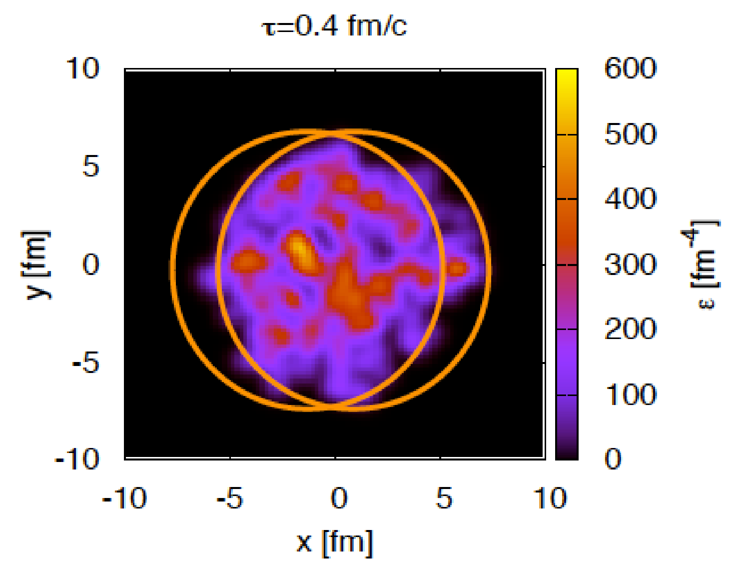




detailed hydro calculations (QGP+mixed+RG, zero viscosity

- τ_0 ~ 0.6 –1.0 fm/c
- ε~15–25GeV/fm³
- (ref: cold matter 0.16 GeV/fm³)

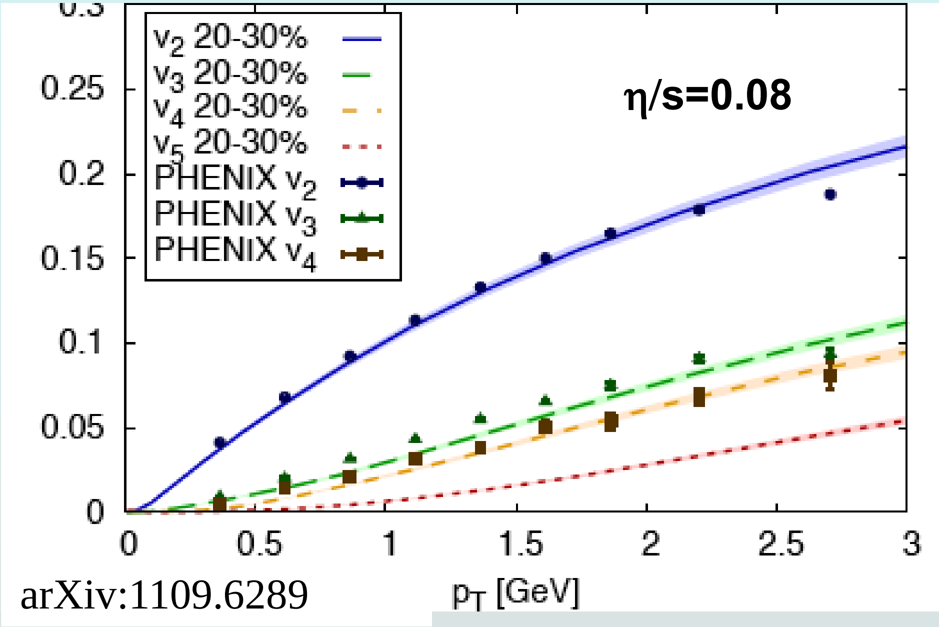
Fluctuations matter!



- Nucleons move around inside the nucleus

-> locations of NN scattering fluctuate

-> apparent symmetry effects yielding only even harmonics not realistic



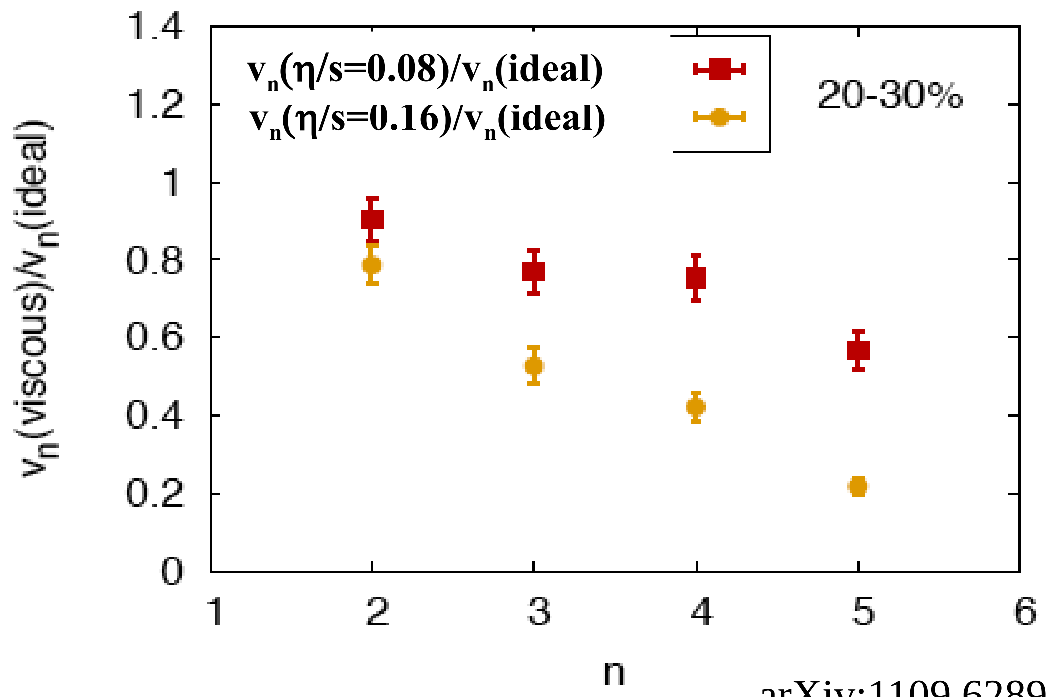
arXiv:1109.6289

- Reproduce with hydro
- IF include fluctuating initial conditions
- Provides a tool to better pin down the viscosity/entropy ratio

$dN/d\phi \sim 1 + 2\, v_2(p_T) \cos(2\phi) + \ldots$

"elliptic flow"

Higher moments more sensitive to viscosity



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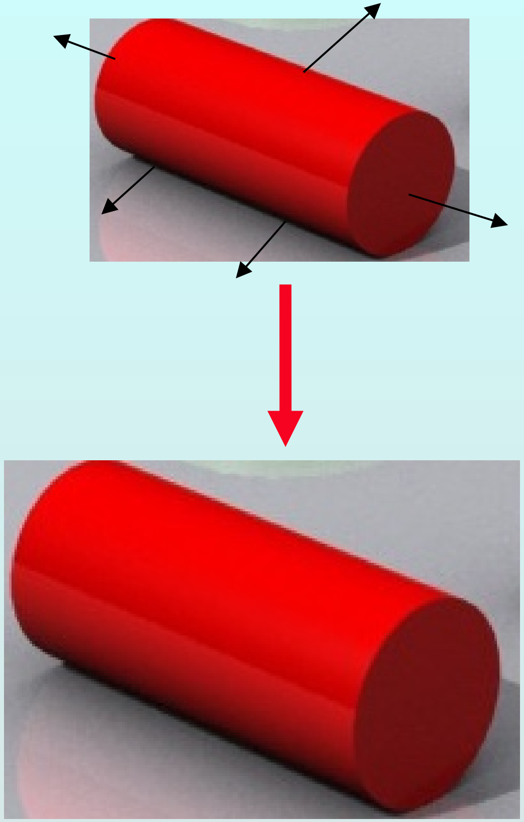
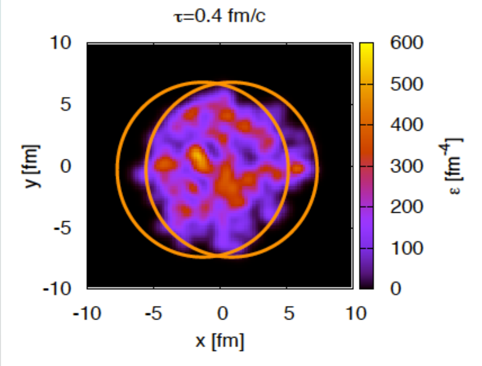


- Longitudinal expansion at v ~ c
- “freezes in” small shape perturbations
  e.g. triangular fluctuations (v_3)
- Viscosity opposes dissipation!



Small viscosity/entropy

Viscosity: *inability* to transport momentum & sustain a wave

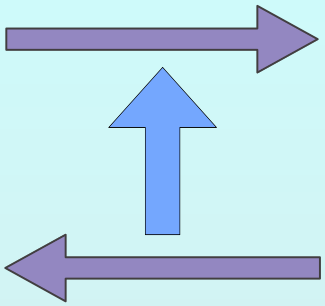
internal friction damps waves

low η → large σ, transports momentum across fluid

normal QCD: σ not so large

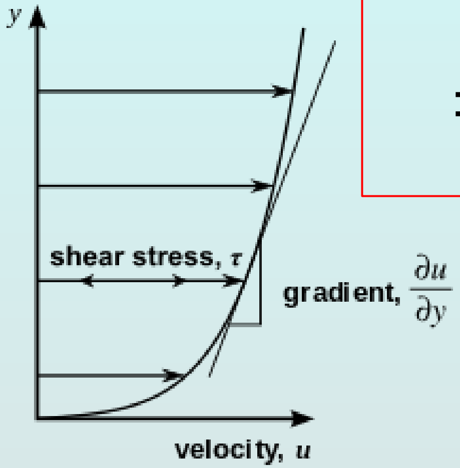
large σ in QGP→ strongly coupled!

large σ → many-body interactions when the density is high



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

$$\bar{p} \sim T$$



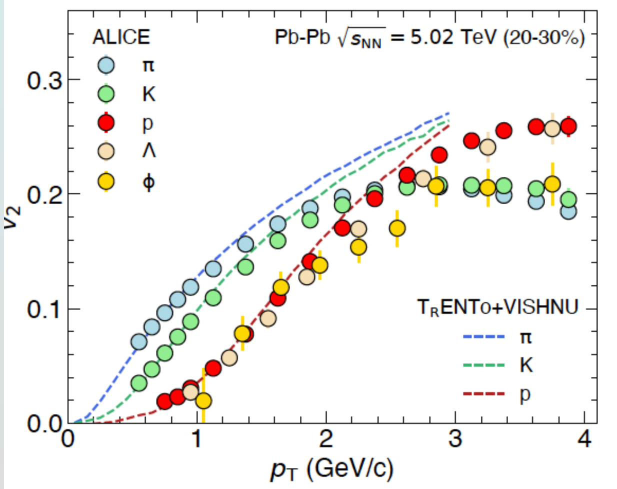
= ——

So dense QCD matter should also strongly affect quarks & gluons transiting it

Example: milk. Liquids with higher viscosities will not splash as high when poured at the same velocity.

Perfect liquid? Quantify viscosity of QGP!

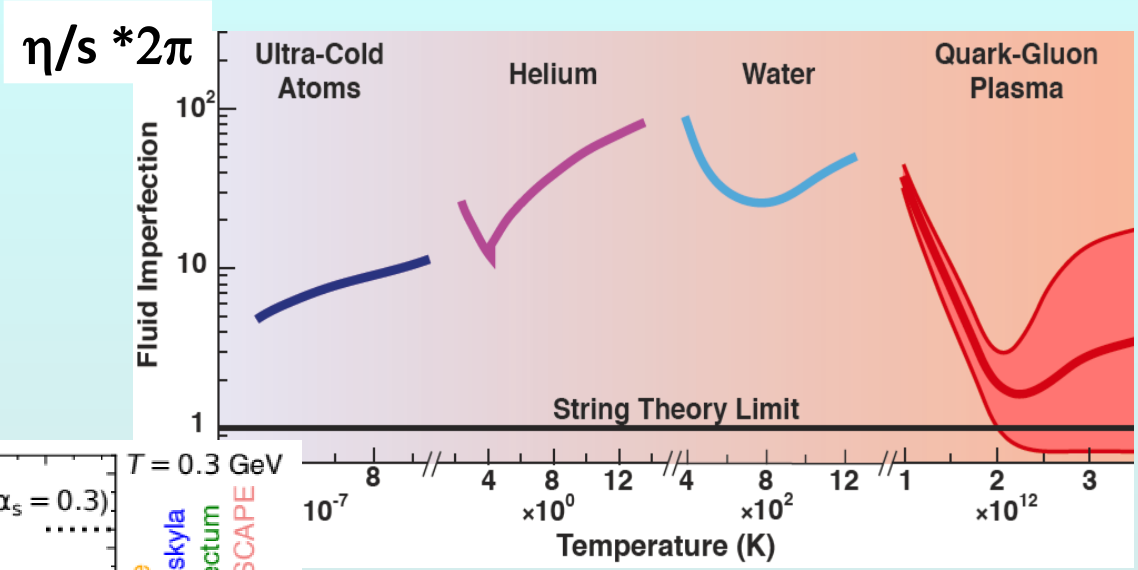
- Use hydro with lattice QCD-based EOS
- Set initial energy density to reproduce observed particle multiplicity
- Use various values of η/s
  - Quantum mechanical lower bound is $1/4\pi$ determined with help from AdS/CFT
- Constrain with data
  - Account for hadronic state viscous effects with a hadron cascade afterburner
  - Precision data required!
    - and provided…

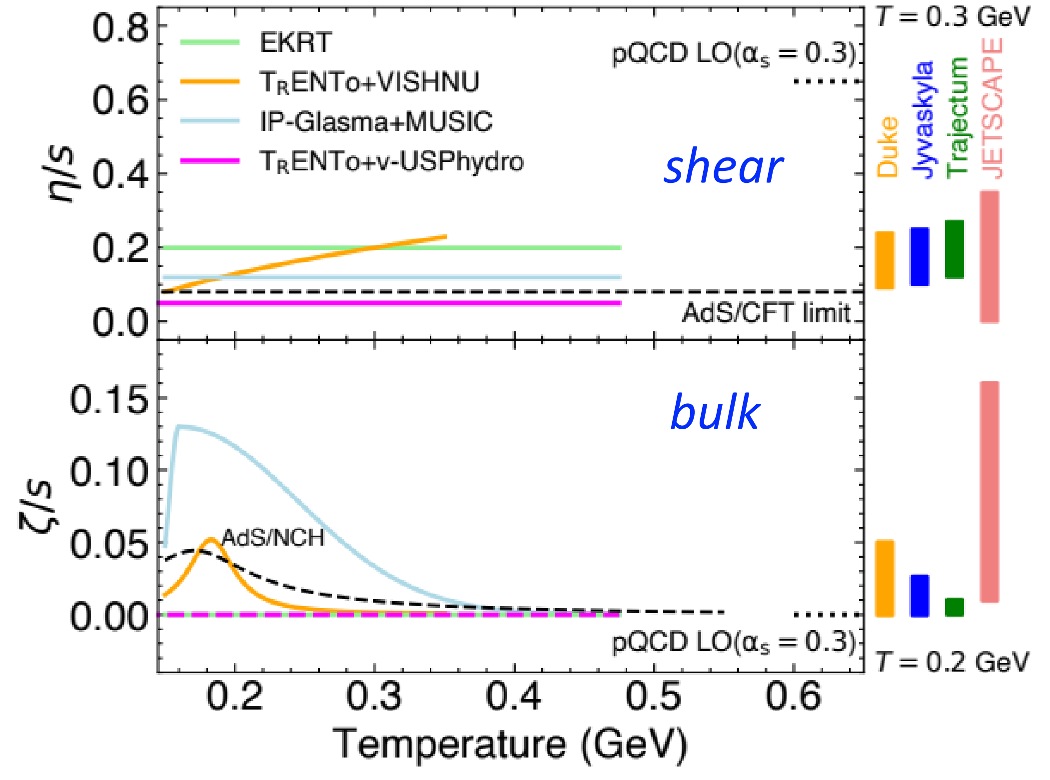


QGP property: viscosity per particle

hydrodynamic flow -> Nearly perfect liquid

Strongly coupled QCD system!

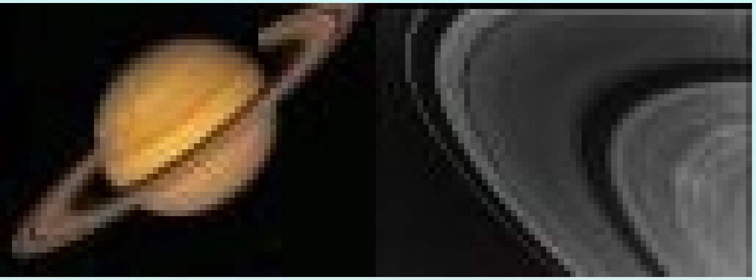




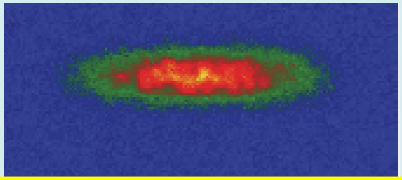
Bulk viscosity = resistance to volume growth

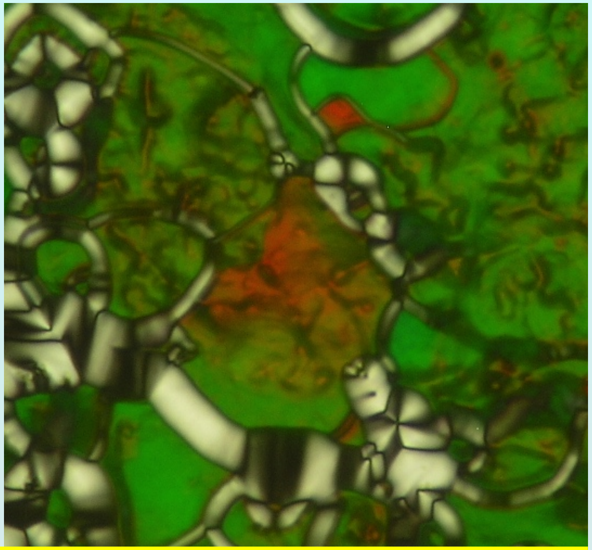
Many types of strongly coupled matter

*Quark gluon plasma is like other systems with strong coupling -
all flow and exhibit phase transitions*



Cold atoms: coldest & hottest matter on earth are alike!





Dusty plasmas &

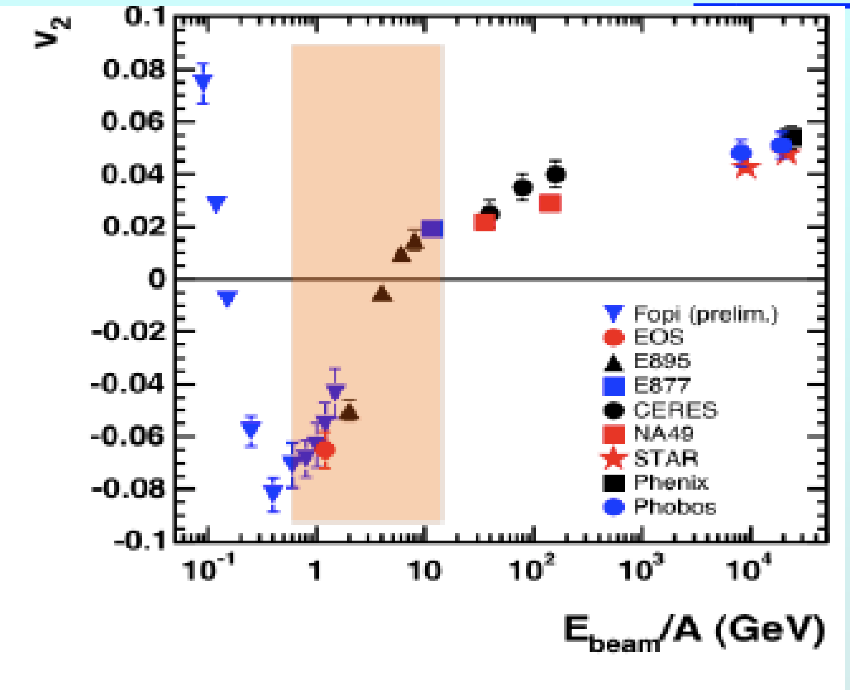
In all these cases have a competition:

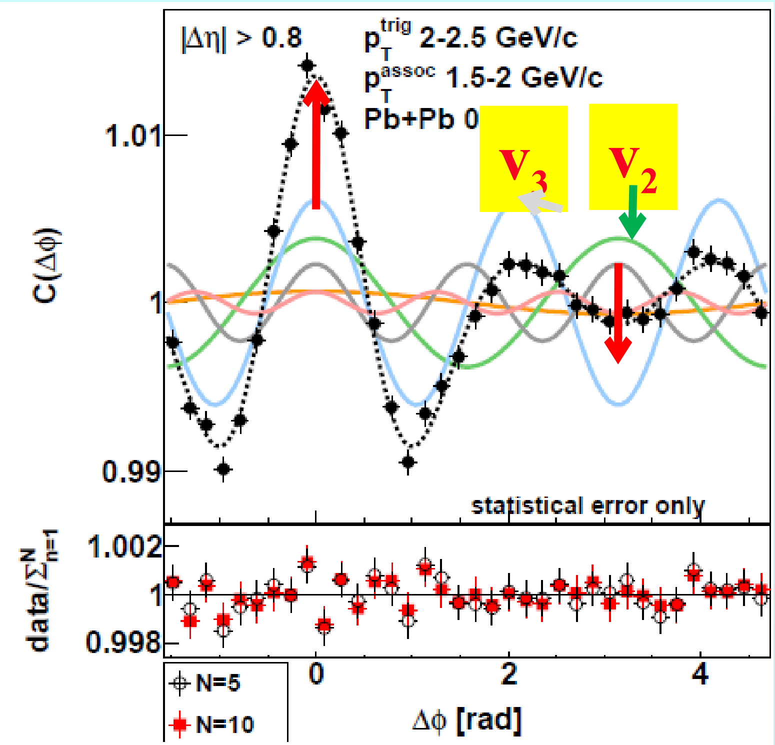
Attractive forces ⇔ repulsive force or kinetic energy

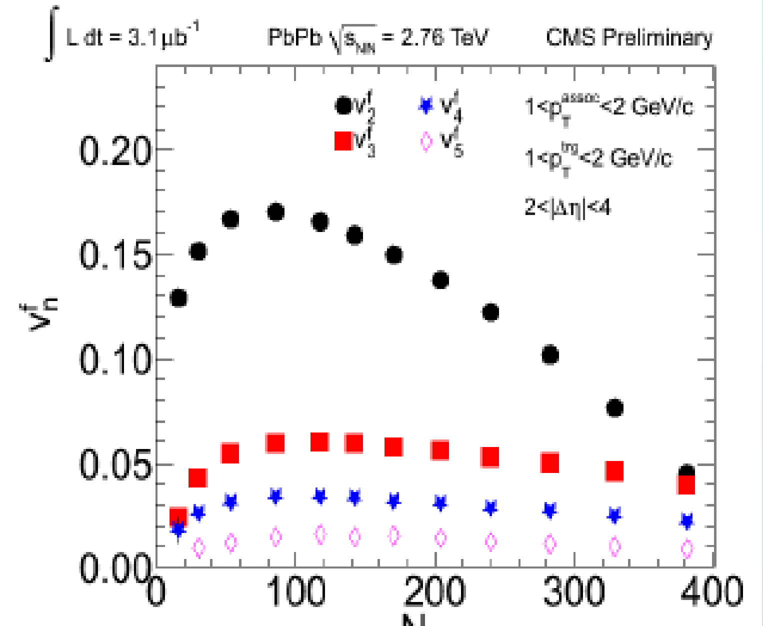
High T_c superconductors: magnetic vs. potential energy

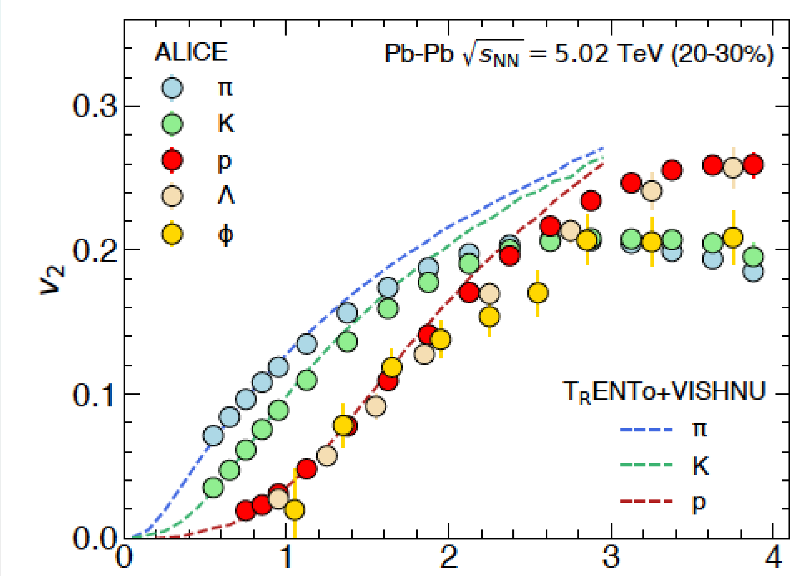
Result: many-body interactions, not pairwise!

√s dependence





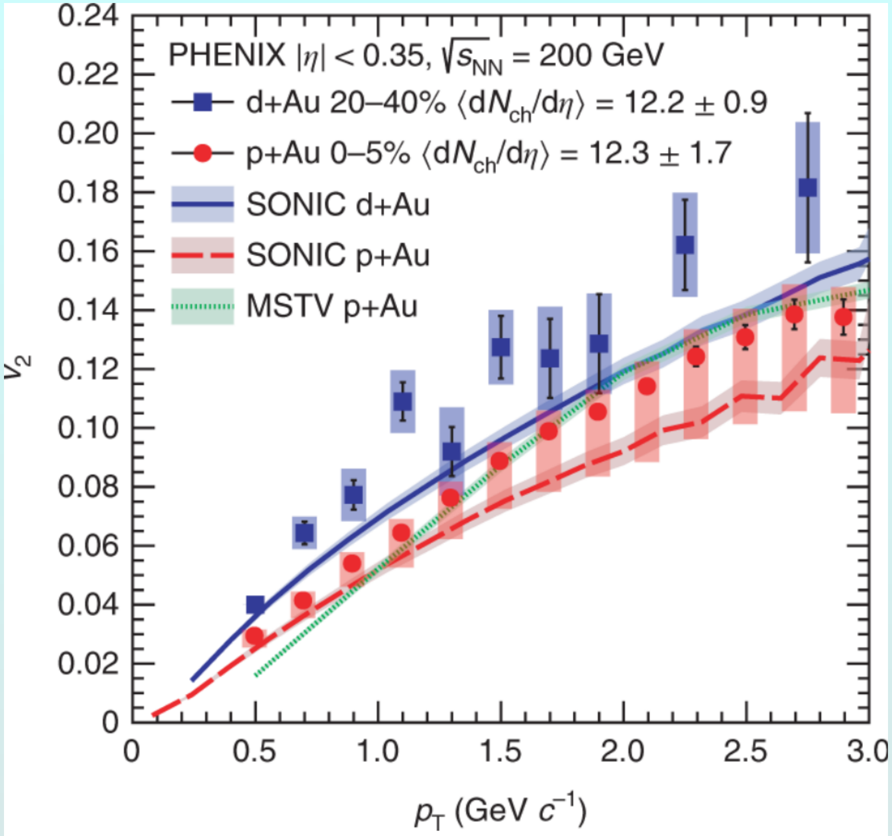


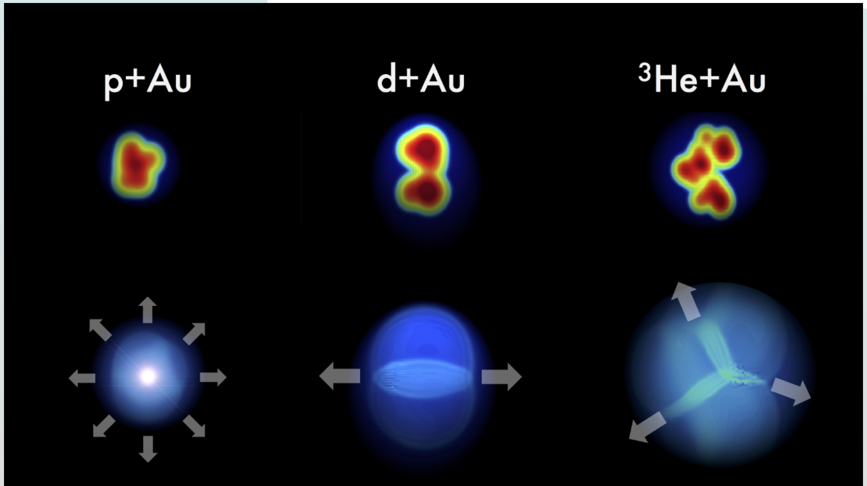


Eeek! Hydrodynamics in small systems!

PHENIX Collaboration

Nature Physics (2018)





Not big & dense

But, we see collective flow!

Seeded by the initial geometry

A small droplet of QGP?!

Mechanism for fast thermalization?

- Must be thermalized in < 1 fm/c!

  Otherwise (viscous) hydro v_2 smaller than in data

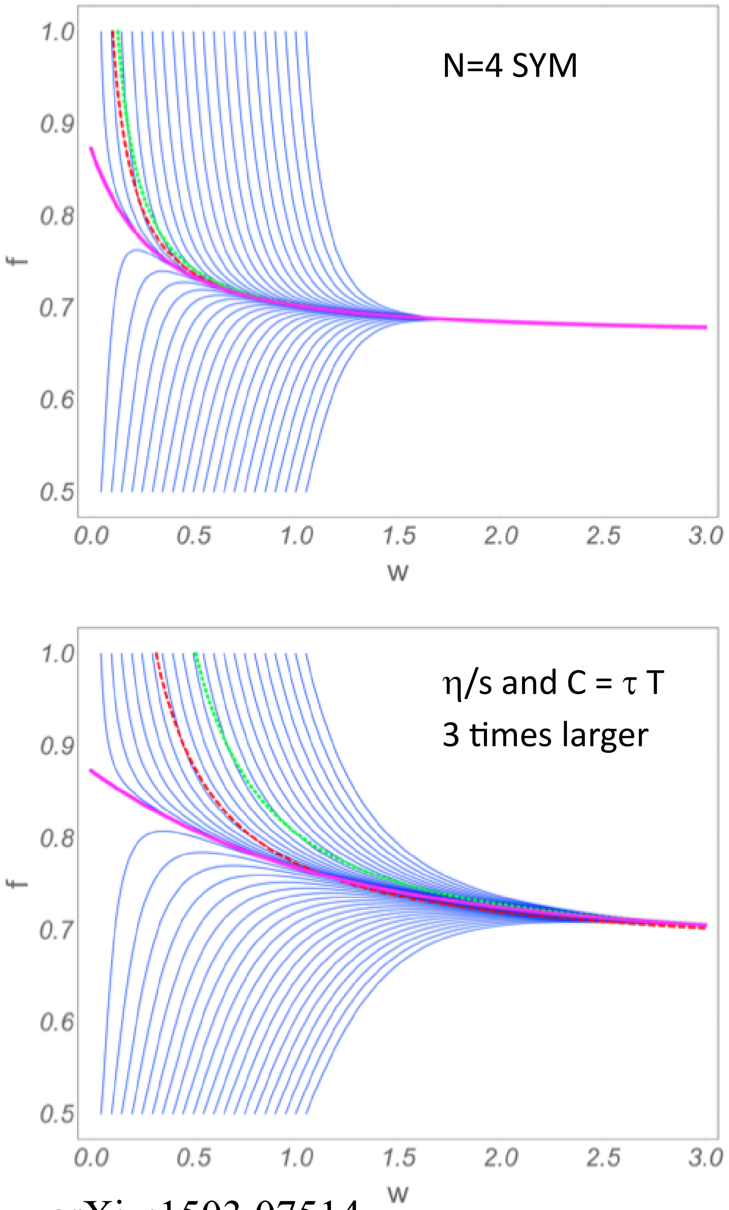
- Can this be achieved with gg, qg, and qq binary scatterings?

  NO!

  Making this picture yield sufficient v_2, requires boosting the pQCD parton-parton cross sections by a factor of ~50!

- Many-body interactions can do just that!
- But, how can hydro set in before equilibrium?

Hydrodynamic attractor



arXiv:1503.07514

Numerical solutions of viscous hydro

For conformal fluid

Lines = various initial conditions

Red & green = 1st and 2nd order hydrodynamics

Can consider hydro as a systematic gradient expansion in powers of w

τ = relaxation time

T = temperature

w = T x time

Since non-hydro modes decay exponentially, system relaxes to an attractor

Driven by fast longitudinal expansion & competition of free streaming vs. dissipation

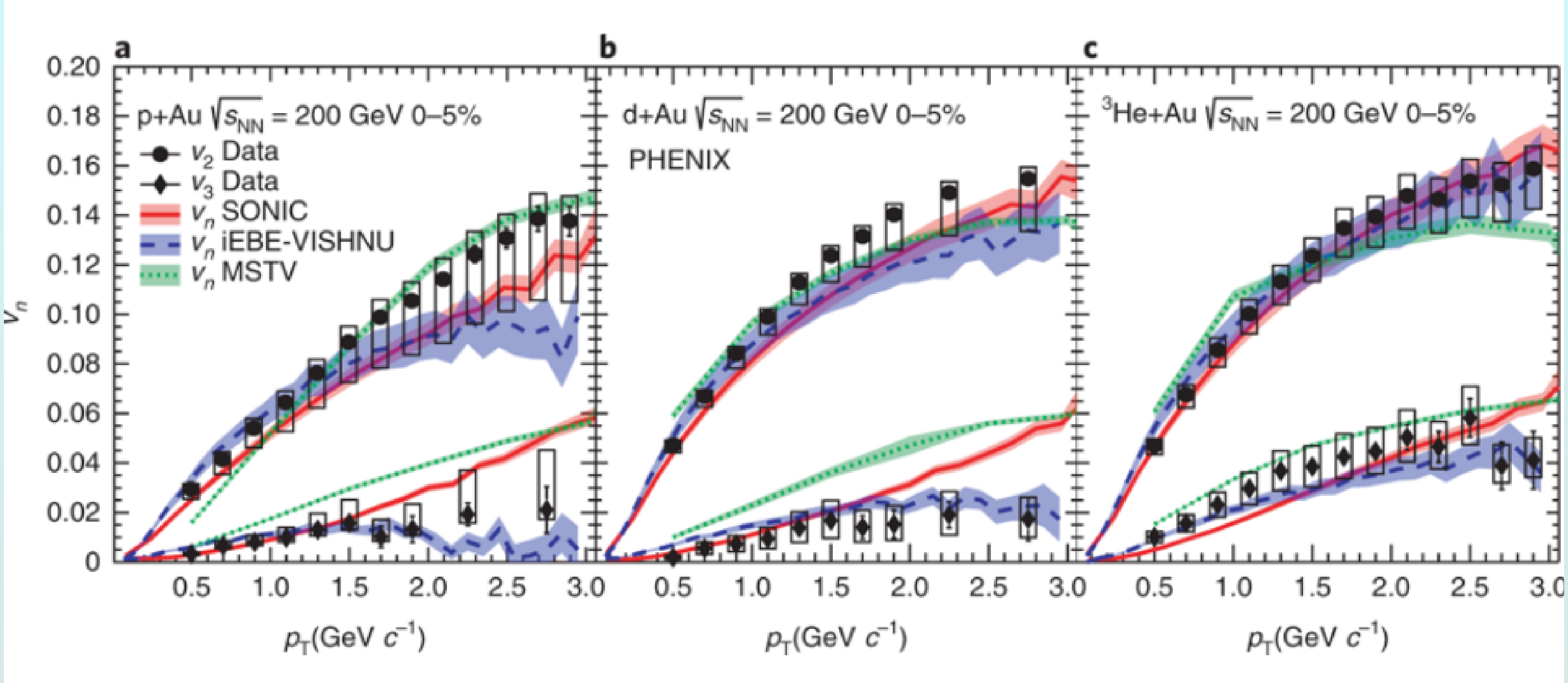
Attractor is present for larger η/s, but it takes longer for system to reach it

Take aways

- Make hot QCD matter (quark gluon plasma) in heavy ion collisions
- Measure properties via radiated particles and photons
  - T_{max} = 250 – 500 MeV, depending on collision energy
    - Then system expands and cools
- Dynamics is well described by relativistic viscous hydrodynamics
  - We measure particle correlations to constrain hydro
  - Shear viscosity $\eta/s < 0.25$. Most “perfect” liquid
  - Bulk viscosity non-zero only near plasma phase transition
- Even small systems show collective flows
  - Likely due to fast longitudinal expansion driving relaxation to hydrodynamic attractor
  - non-hydro modes decay exponentially so pre-equilibrium dynamics relax very quickly

- **backup slides**

Hydro for p, d, ^{3}He + Au



PHENIX Collaboration

Nature Physics (2018)

Lepton pair emission ↔ EM correlator

e.g. Rapp, Wambach Adv.Nucl.Phys 25 (2000)

Emission rate of dileptons per volume

$$\frac{dR_{ll}}{d^4q} = -\frac{\alpha^2}{3\pi^3}\frac{L(M)}{M^2}\mathrm{Im}\Pi^{\mu}_{em,\mu}(M,q;T)f^B(q_0,T)$$

$$f^B(q_0,T) = 1/(e^{q_0/T}-1)$$

$$L(M) = \sqrt{1-\frac{4m_l^2}{M^2}}(1+\frac{2m_l^2}{M^2})$$

γ*→ee
decay

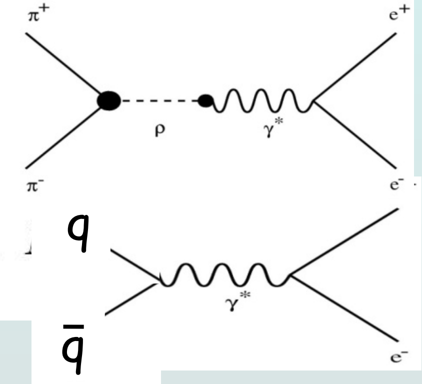
EM correlator
Medium property

Boltzmann factor
temperature

Hadronic contribution
Vector Meson Dominance

Medium modification of meson
Chiral restoration

$$\mathrm{Im}\Pi^{\mathrm{vac}}_{\mathrm{em}}(M) = \begin{cases} \sum_{V=\rho,\omega,\phi}\left(\frac{m_V^2}{g_V}\right)^2 \mathrm{Im}D_V(M) & , \\ -\frac{M^2}{12\pi}\left(1+\frac{\alpha_s(M)}{\pi}+\ldots\right)N_c\sum_{q=u,d,s}(e_q)^2 & , \end{cases}$$

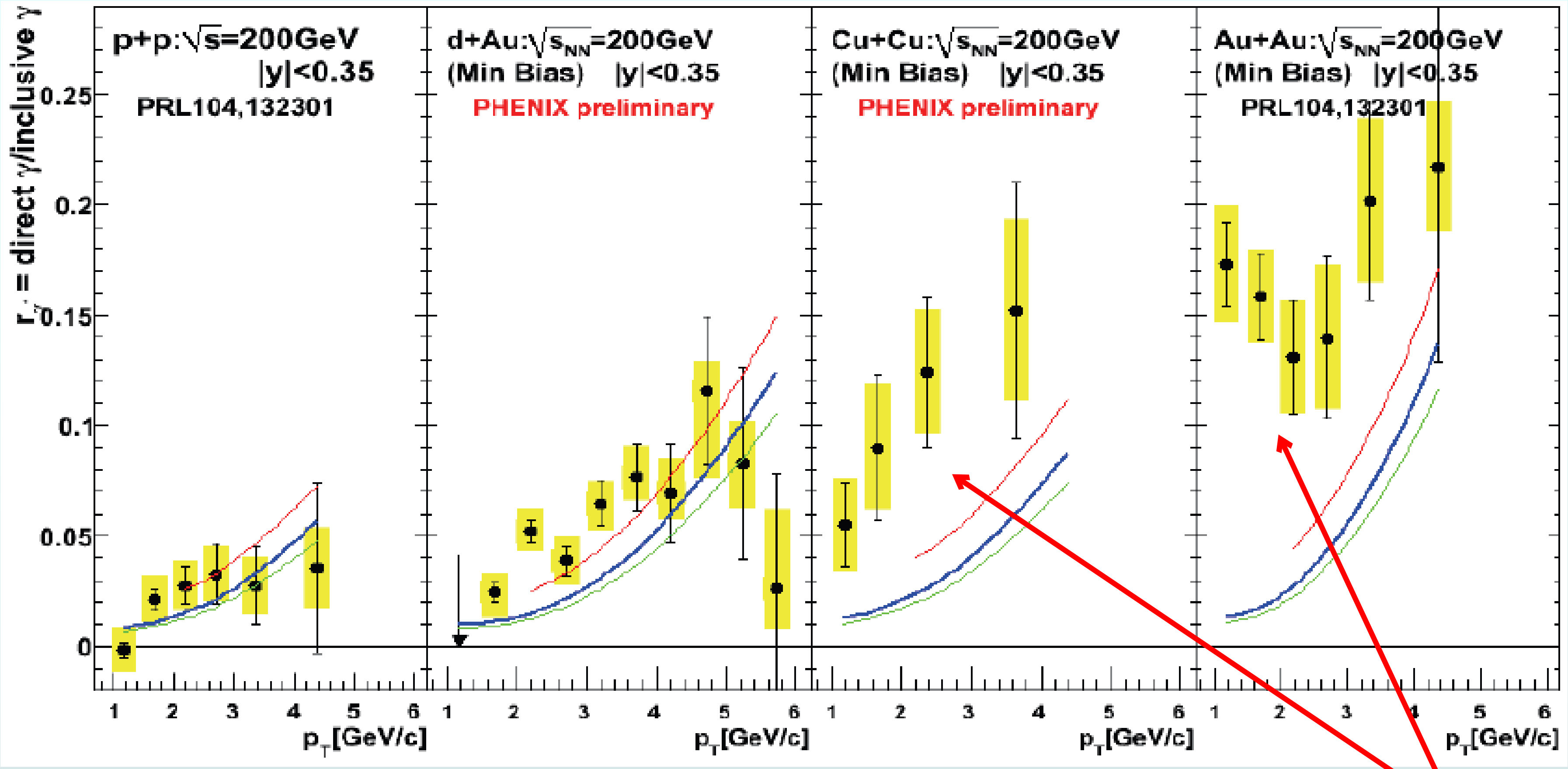


$\overline{q}$q annihilation

Thermal radiation from
partonic phase (QGP)

From emission rate of dileptons, the medium effect on the EM correlator as well as temperature of the medium can be decoded.

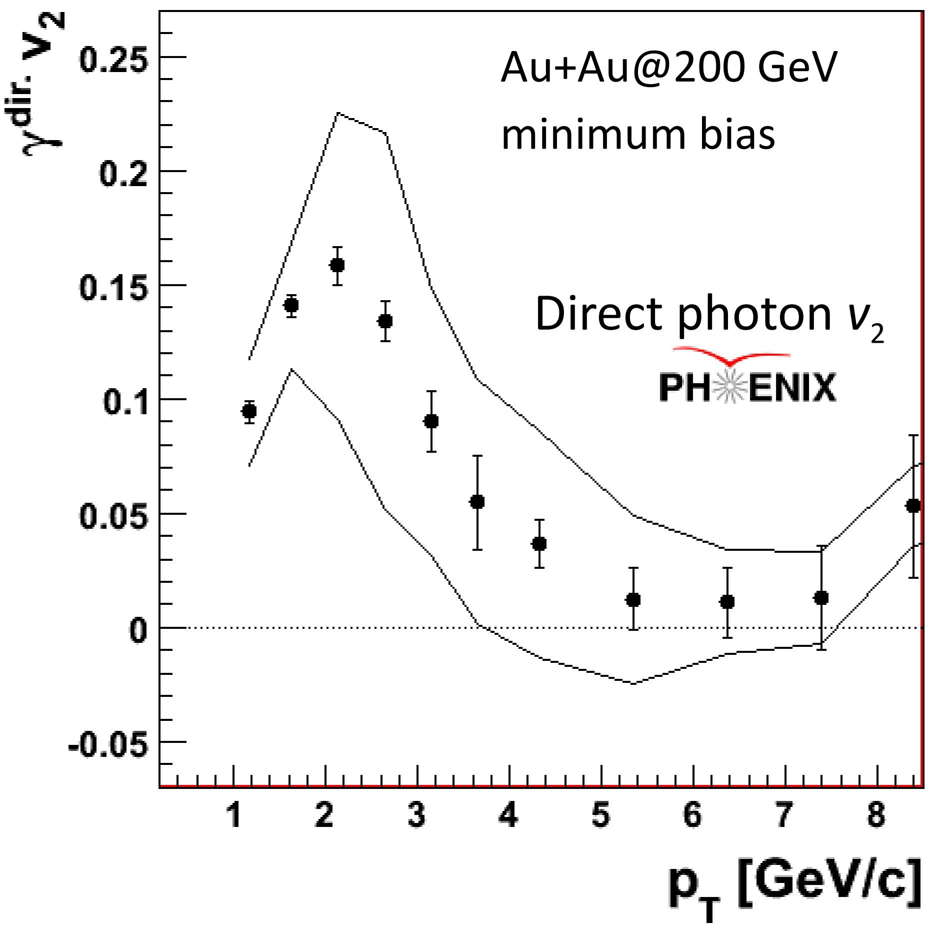
Thermal photons (virtual)

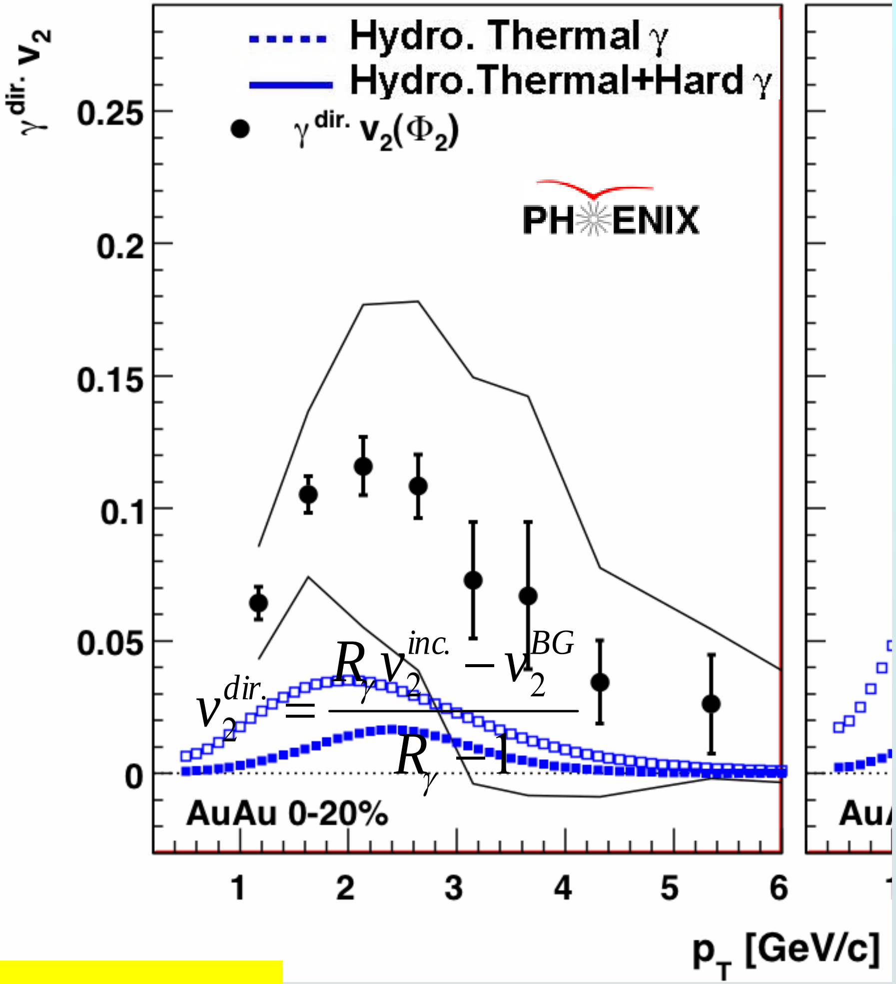


Observe excess photons beyond pQCD in AA collisions. In thermal p_T region

Thermal photons also flow!

arXiv:1105.4126

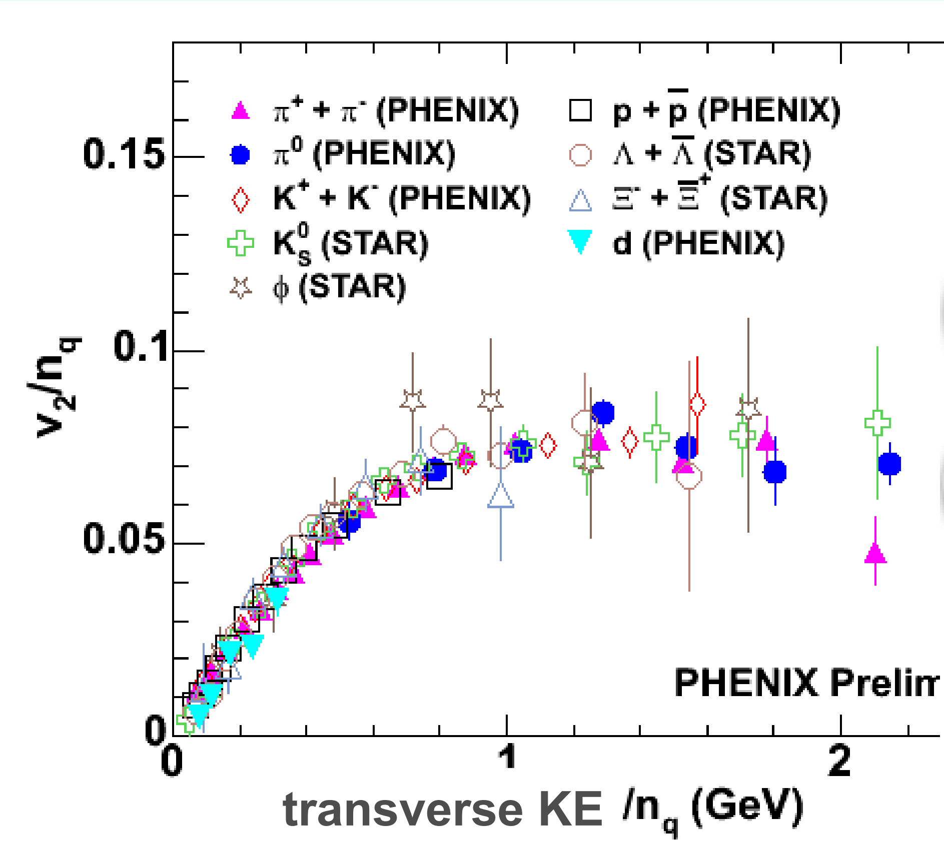




$$v_2^{dir.} = \frac{R_\gamma v_2^{inc.} - v_2^{BG}}{R_\gamma - 1}$$

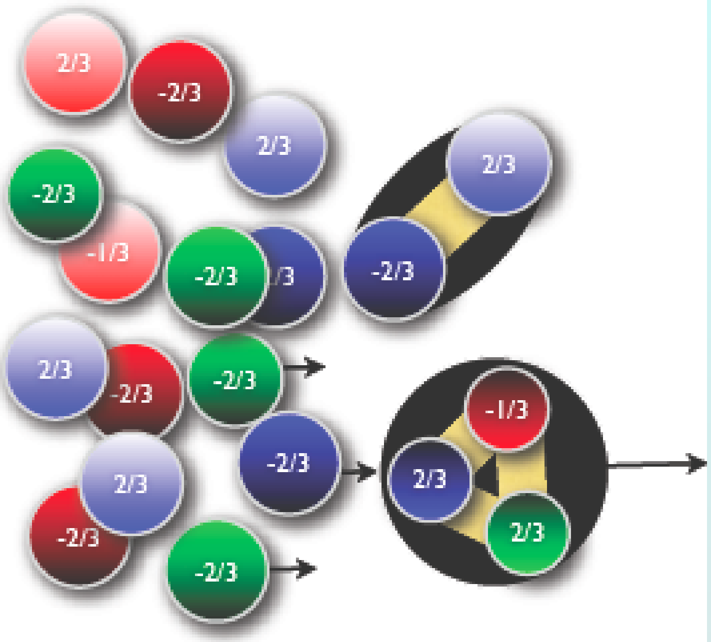
Large flow magnitude is very surprising!

Elliptic flow scales with number of quarks



implication: valence quarks, not hadron

pressure builds early, dressed quarks ar



All particles flow
as if frozen out from
a flowing soup of
constituent quarks

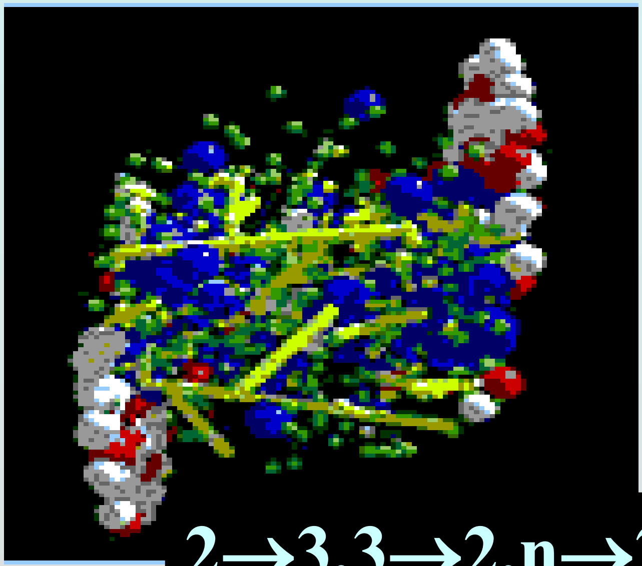
Calculating transport in QGP

weak coupling limit

perturbative QCD

kinetic theory, cascades

interaction of particles



$2\rightarrow3, 3\rightarrow2, n\rightarrow2\ldots$

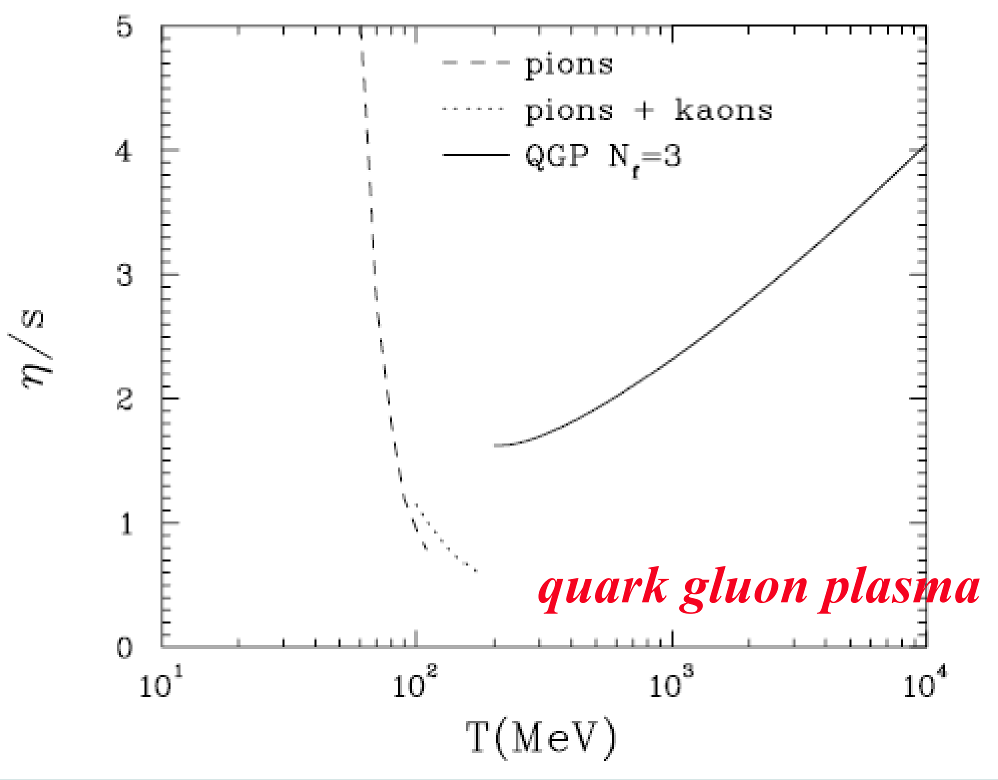
∞ strong coupling limit

not easy! Try a pure field…

gravity ↔ supersym 4-d

(AdS/CFT)

minimum η at phase boundary?

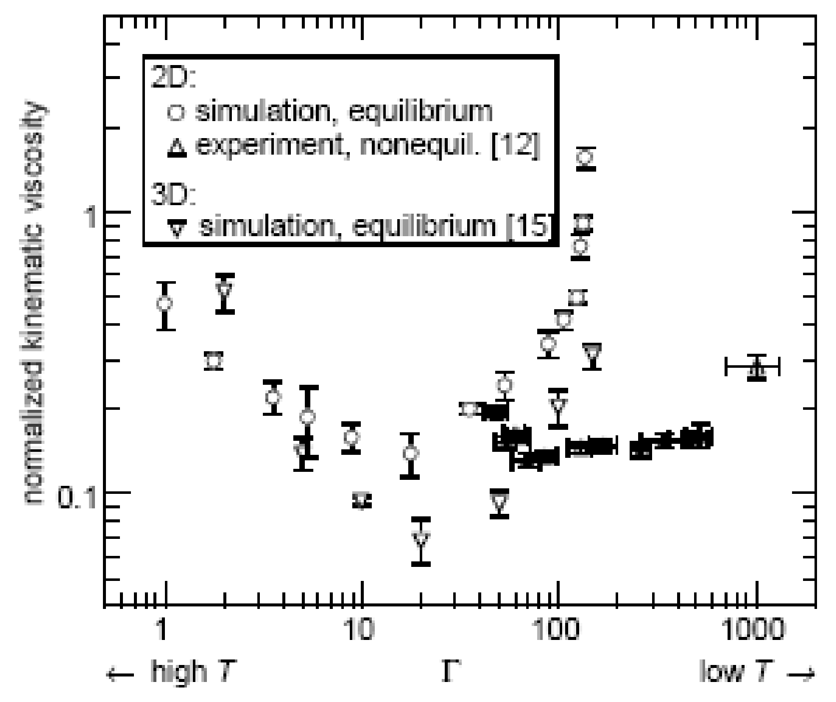


quark gluon plasma

Csernai, Kapusta & McLerran
PRL97, 152303 (2006)

strongly coupled dusty plasma

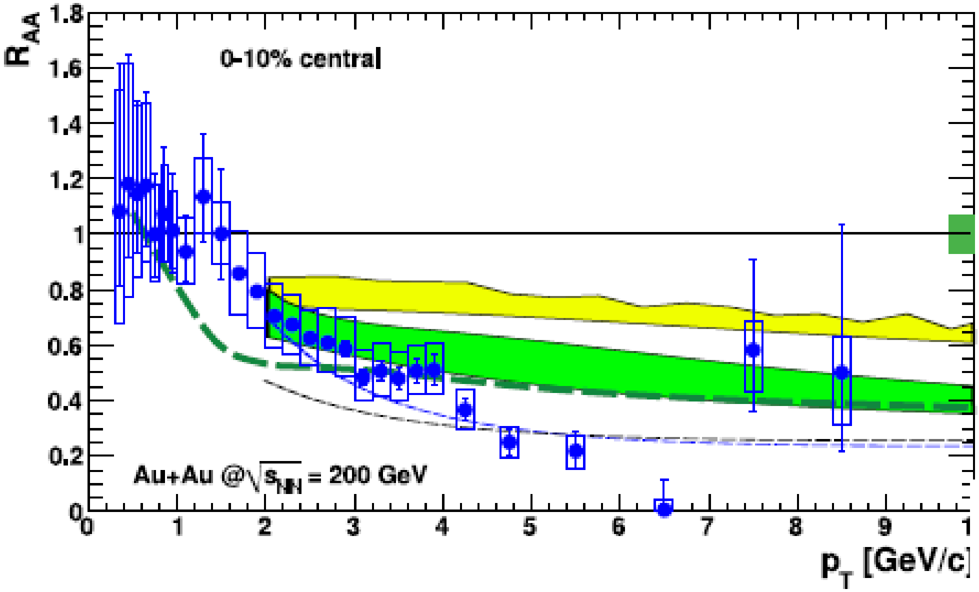
B. Liu and J. Goree,



minimum observed in other strongly coupled systems –
kinetic part of η decreases with Γ while potential part increases

heavy quark suppression & flow?

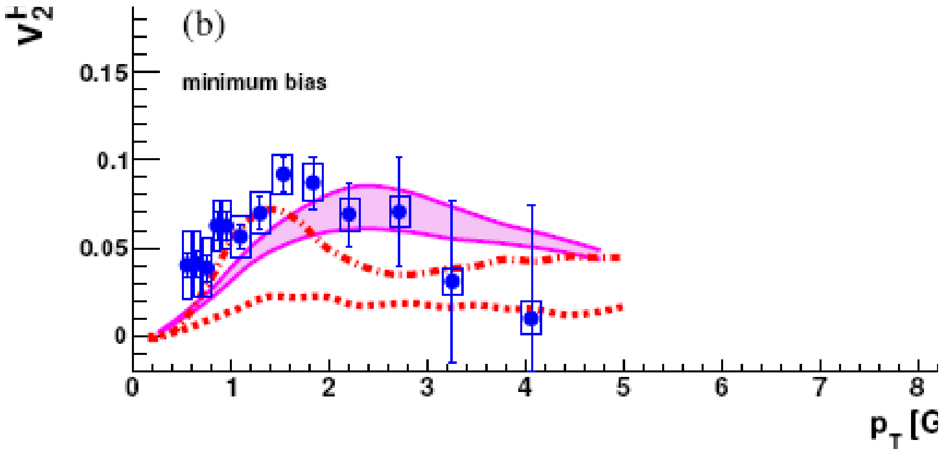
PRL.98: 172301,2007
arXiV: 1005.1627

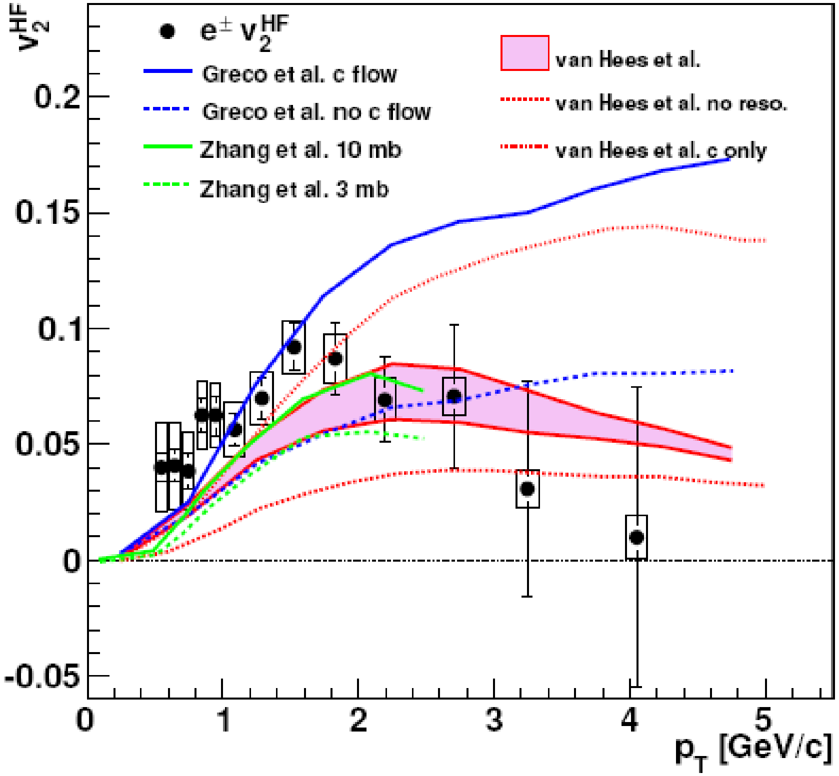


Collisional energy loss?

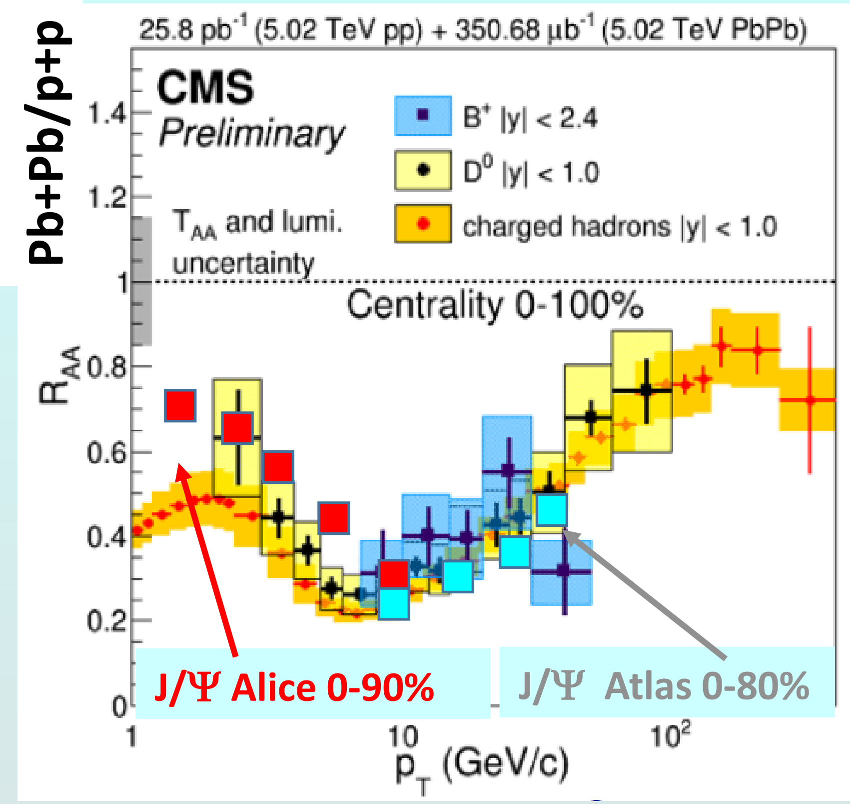
v_2 decrease with p_T?

role of b quarks?





Heavy flavor R_{AA}



Pb+Pb/p+p

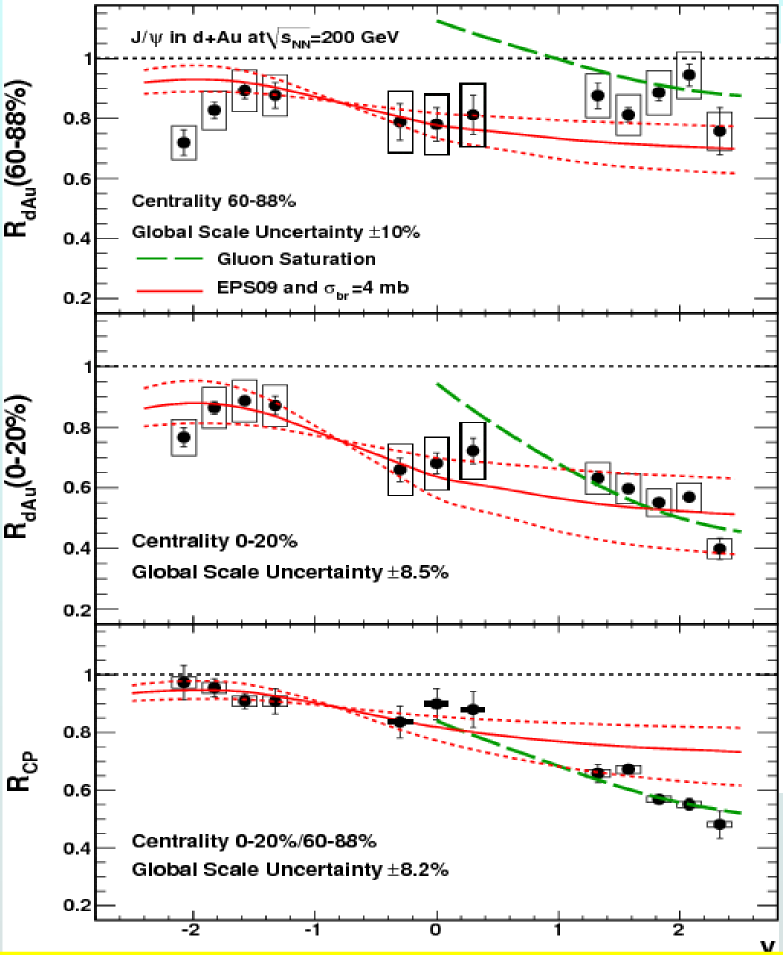
J/Ψ Alice 0-90%

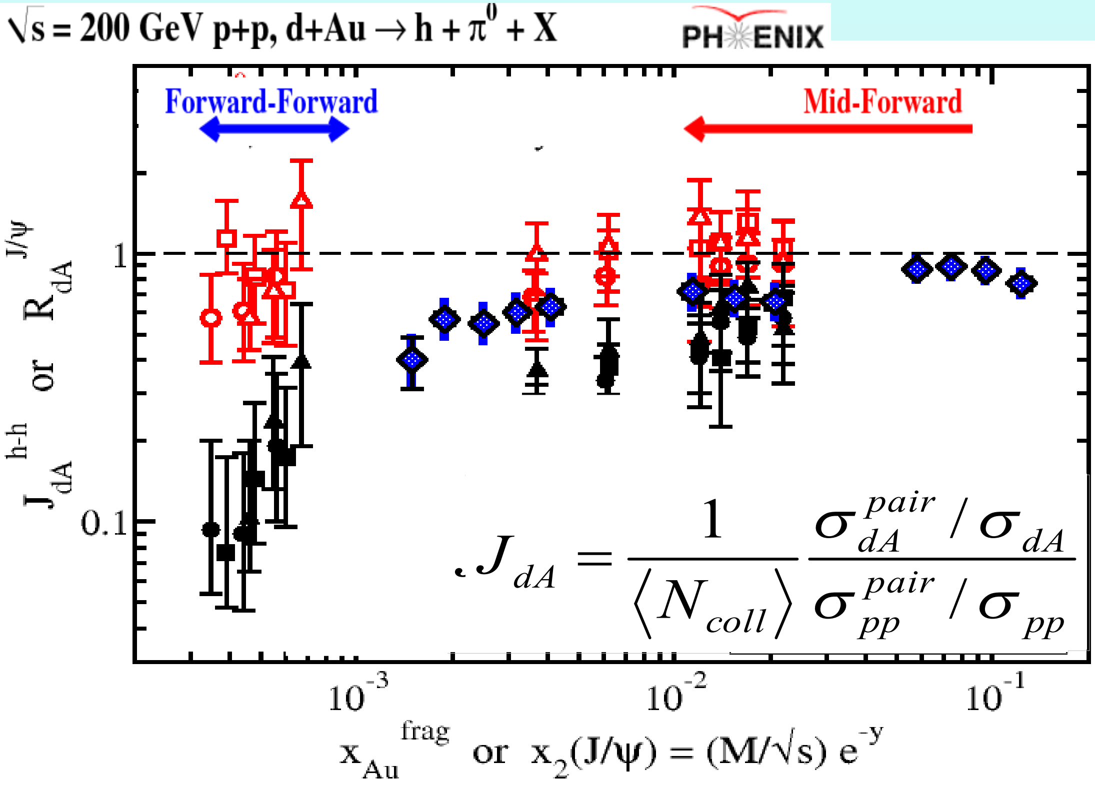
J/Ψ Atlas 0-80%

Dense gluonic matter (d+Au, forward y): large effects observed

arXiv:1010.1246

arXiv:1105.5112





Di-hadron suppression at low x

pocket formula (for 2➔2):

$$x_{Au}^{frag} = \frac{<p_{T1}> e^{-<\eta_1>} + <p_{T2}> e^{-<\eta_2>}}{\sqrt{s}}$$

trend as, e.g. in CGC …

Shadowing/absorption stronger than linear w/nuclear thickness

Viscosity/Entropy (natural units)

Duke Physics
Atom Cooling and Trapping