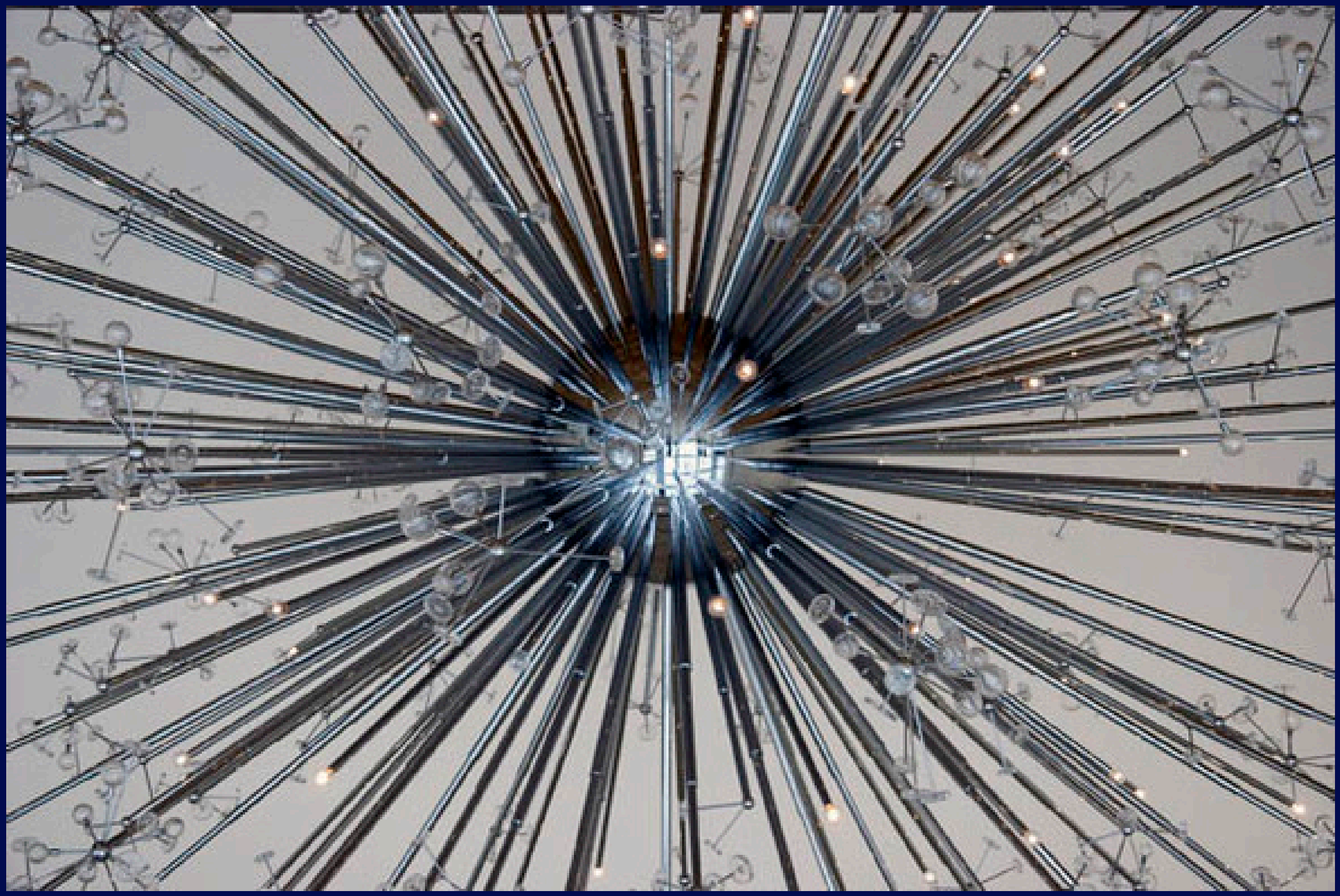


Scientific Status of the RHIC Heavy Ion Program

Peter Steinberg
Brookhaven National Laboratory
Phases of QCD Matter, Rutgers, Jan 12-14, 2007

Contacts: Karen McNulty Walsh, (631) 344-8350 or Mona S. Rowe, (631) 344-5056

RHIC Scientists Serve Up "Perfect" Liquid

New state of matter more remarkable than predicted -- raising many new questions

April 18, 2005

TAMPA, FL -- The four detector groups conducting research at the Relativistic Heavy Ion Collider (RHIC) -- a giant atom "smasher" located at the U.S. Department of Energy's Brookhaven National Laboratory -- say they've created a new state of hot, dense matter out of the quarks and gluons that are the basic particles of atomic nuclei, but it is a state quite different and even more remarkable than had been predicted. In peer-reviewed papers summarizing the first three years of RHIC findings, the scientists say that instead of behaving like a gas of free quarks and gluons, as was expected, the matter created in RHIC's heavy ion collisions appears to be more like a *liquid*.

"Once again, the physics research sponsored by the Department of Energy is producing historic results," said Secretary of Energy Samuel Bodman, a trained chemical engineer. "The DOE is the principal federal funder of basic research in the physical sciences, including nuclear and high-energy physics. With today's announcement we see that investment paying off."

Secretary of Energy Samuel Bodman

"The truly stunning finding at RHIC that the new state of matter created in the collisions of gold ions is more like a liquid than a gas gives us a profound insight into the earliest moments of the universe," said Dr. Raymond L. Orbach, Director of the DOE Office of Science.

Also of great interest to many following progress at RHIC is the emerging connection between the collider's results and calculations using the methods of string theory, an approach that attempts to explain fundamental properties of the universe using 10 dimensions instead of the usual three spatial dimensions plus time.

ANTICANCER BLOCKBUSTER? • RISE AND FALL OF THE SLIDE RULE

SCIENTIFIC AMERICAN

Bringing
DNA Computers
to Life

MAY 2006
WWW.SCIAM.COM

Quark Soup

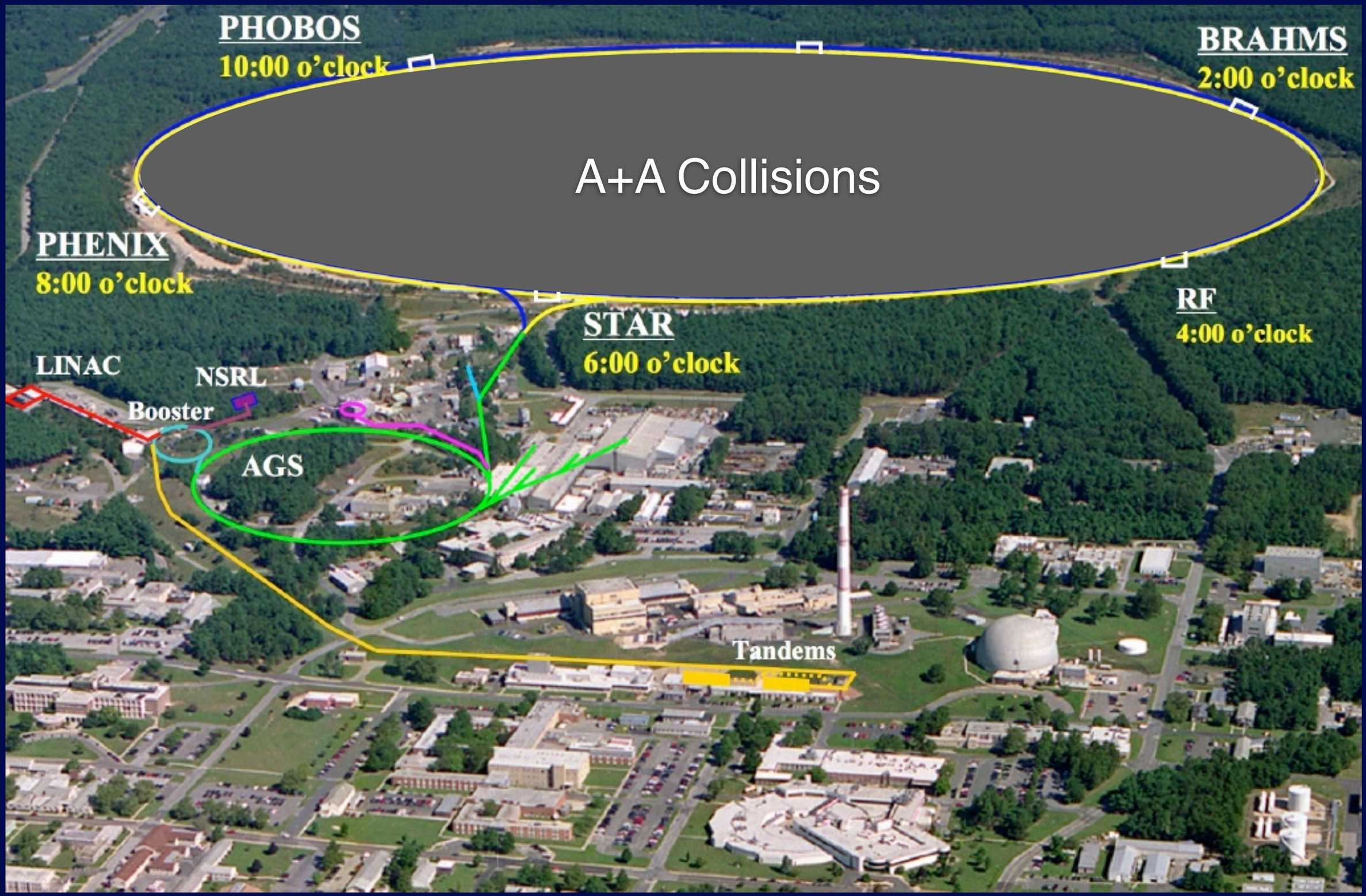
PHYSICISTS RE-CREATE THE LIQUID STUFF OF **THE EARLIEST UNIVERSE**

Stopping
Alzheimer's

Birth of
the Amazon

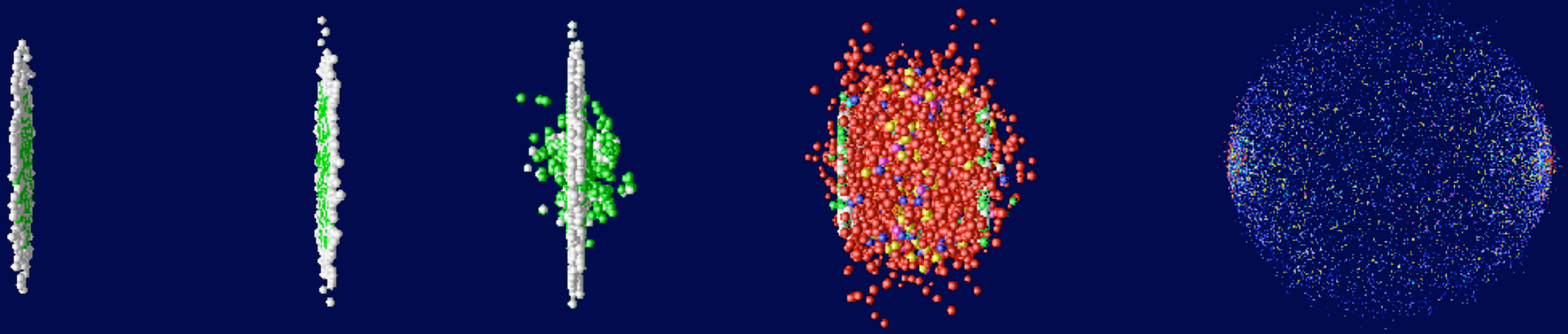
Future
Giant Telescopes

Needs No Introduction



Heavy Ion Collisions

A+A Collisions



QCD

The Science of RHIC

Measurements

A+A Collisions

Global Variables

High p_T Probes

Particle Yields

"Phenomenology"

Hydrodynamics

Hadronization

Energy loss

Theory

strong-field QCD

perturbative QCD

lattice QCD

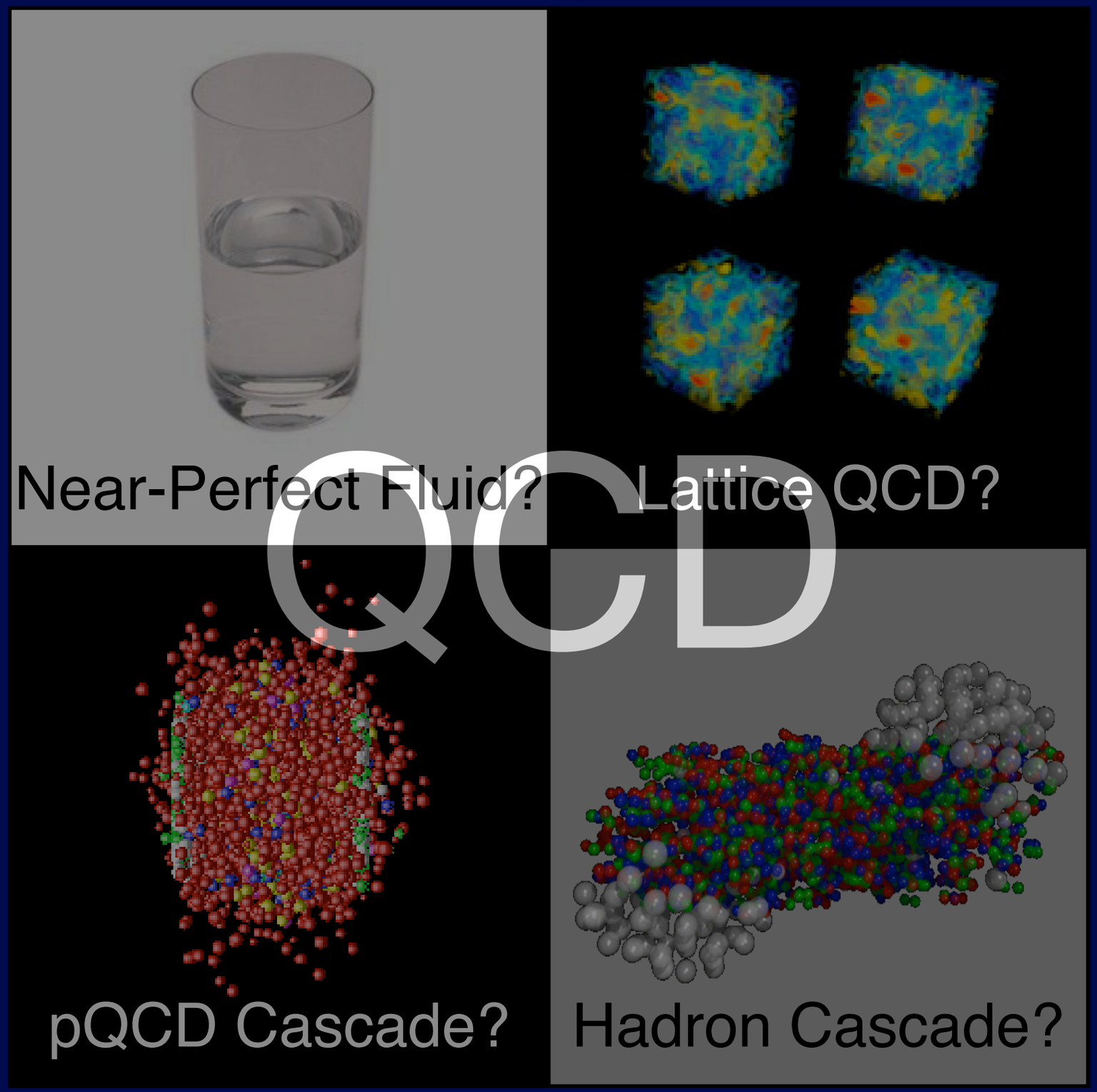
AdS/QCD
(strong coupling)

QCD

Dynamical Regimes of QCD

Large opacity

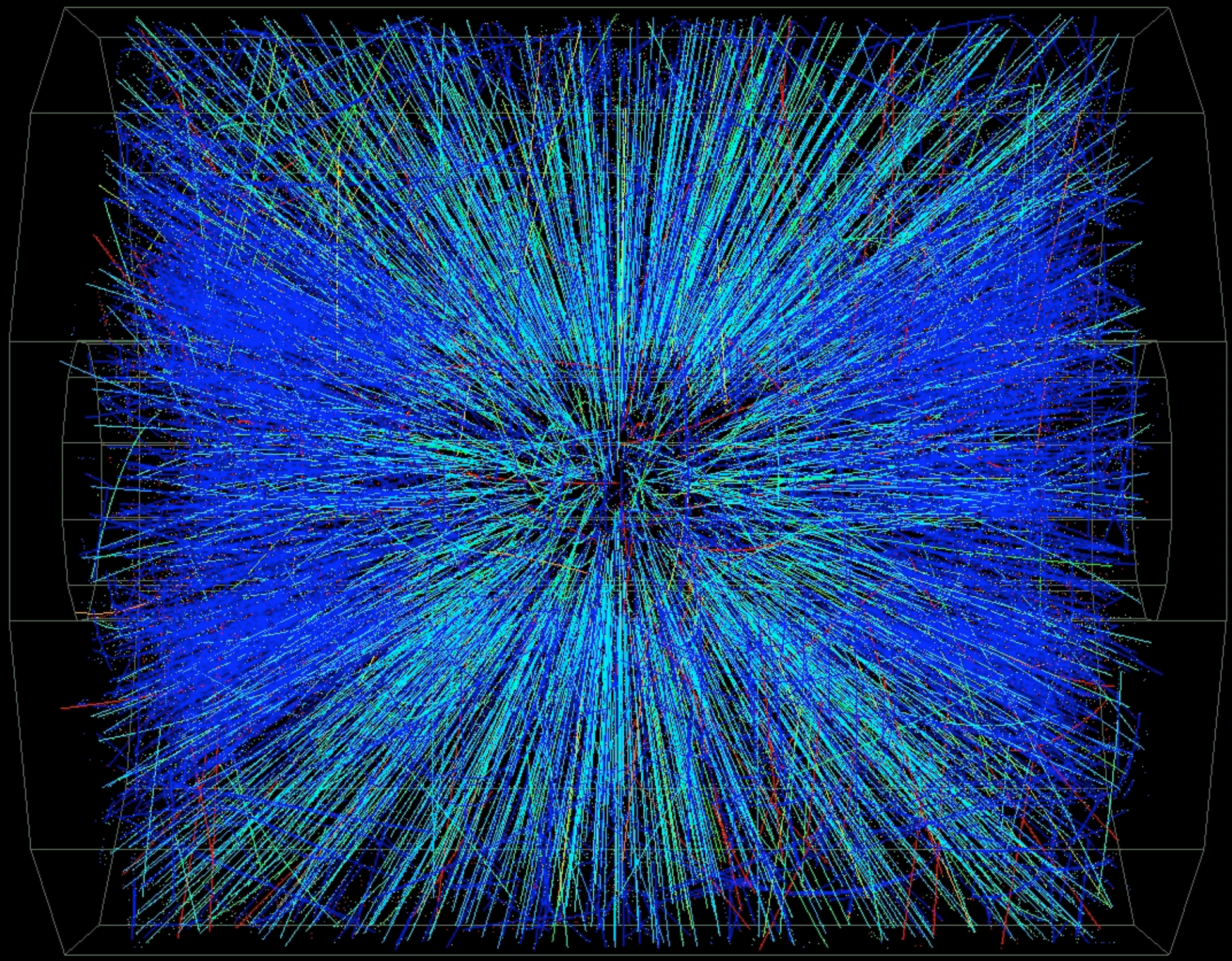
Small opacity



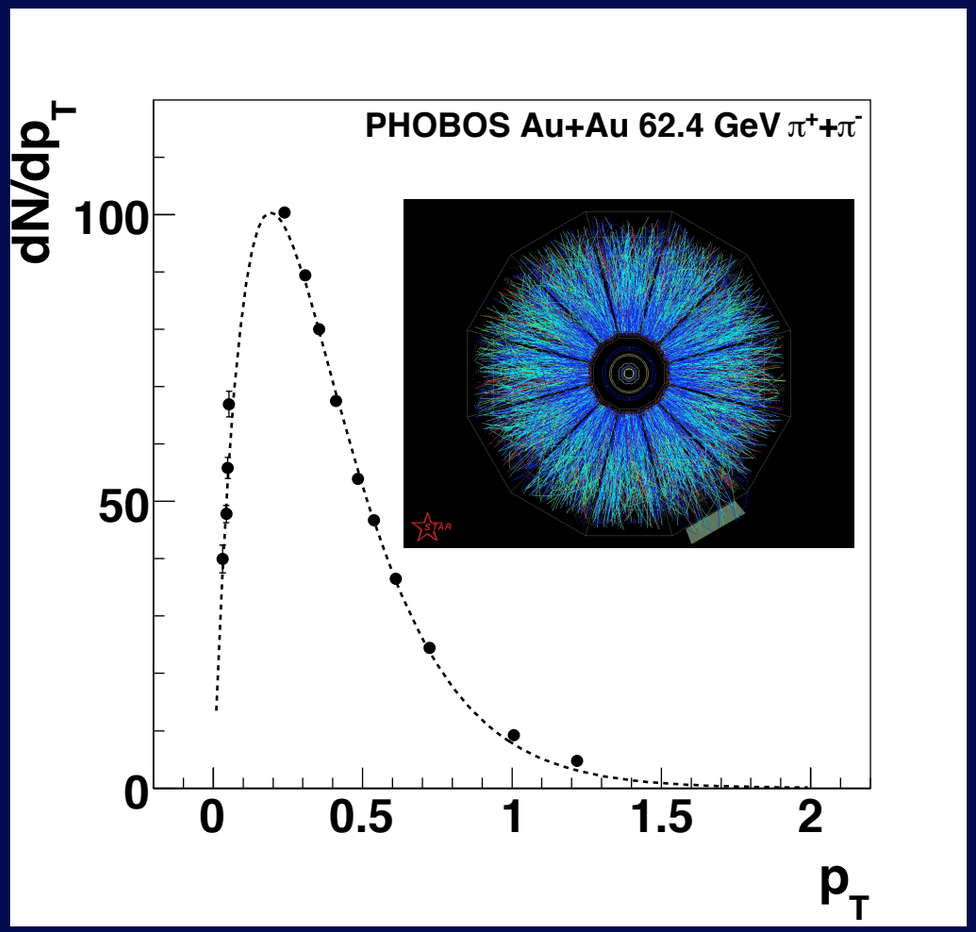
Short times

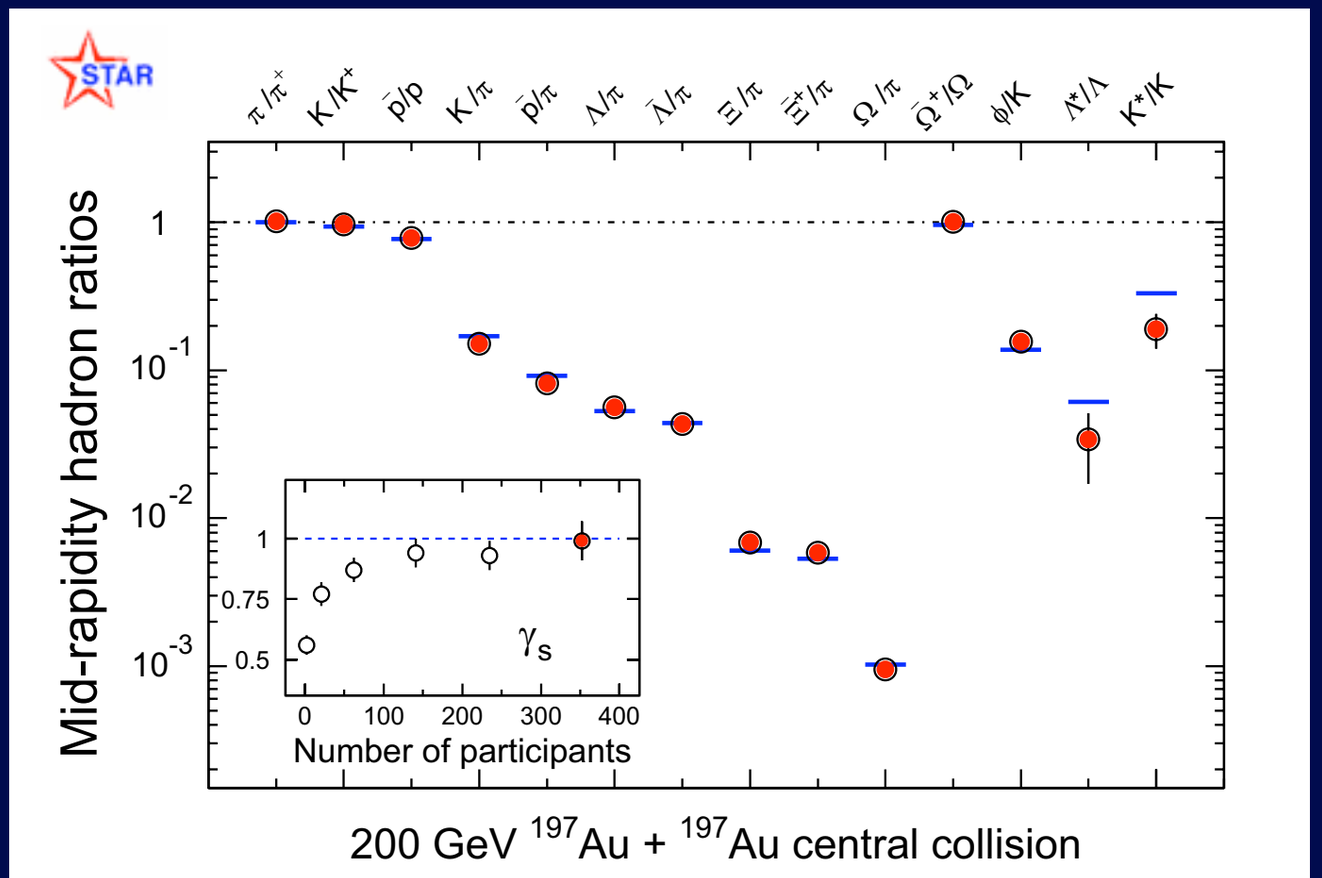
Long times

Phenomena @ RHIC



Strong Blackbody





T	Chemical freezeout temperature
μ_B	Baryochemical potential (more matter than antimatter)

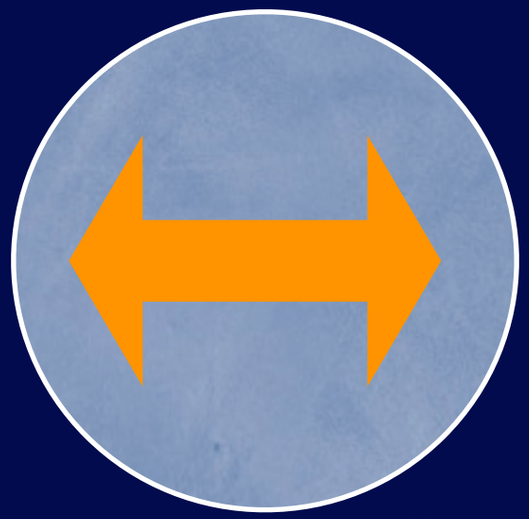
$$N_i \propto V \int \frac{d^3p}{(2\pi)^3} \frac{1}{e^{(\sqrt{p^2+m^2}-\mu_B)/T} \pm 1}$$

k_BT=177 MeV~2x10^{12} ºK

All hadrons are available with thermal abundances @ freezeout

Hydrodynamics

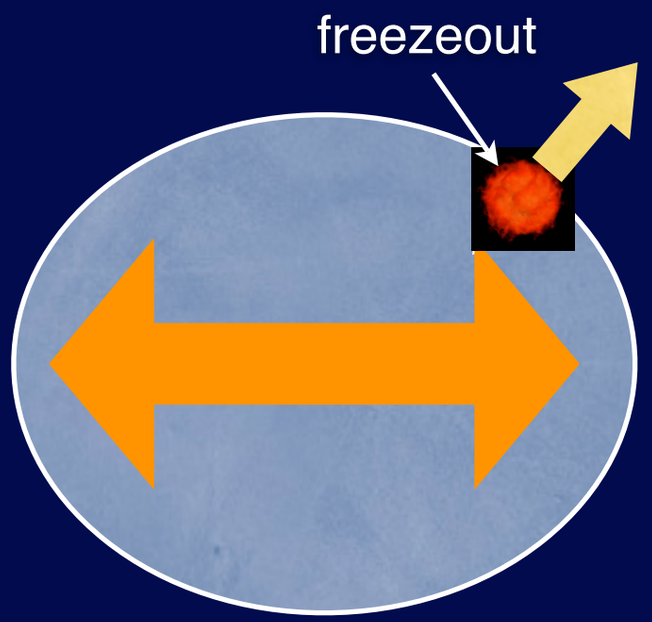
Energy **locally** equilibrated in a volume, adjacent cells are in causal contact



Pressure gradients develop via **ideal** (inviscid) **scale-invariant** expansion into vacuum

$$\partial_\mu T^{\mu\nu} = 0$$

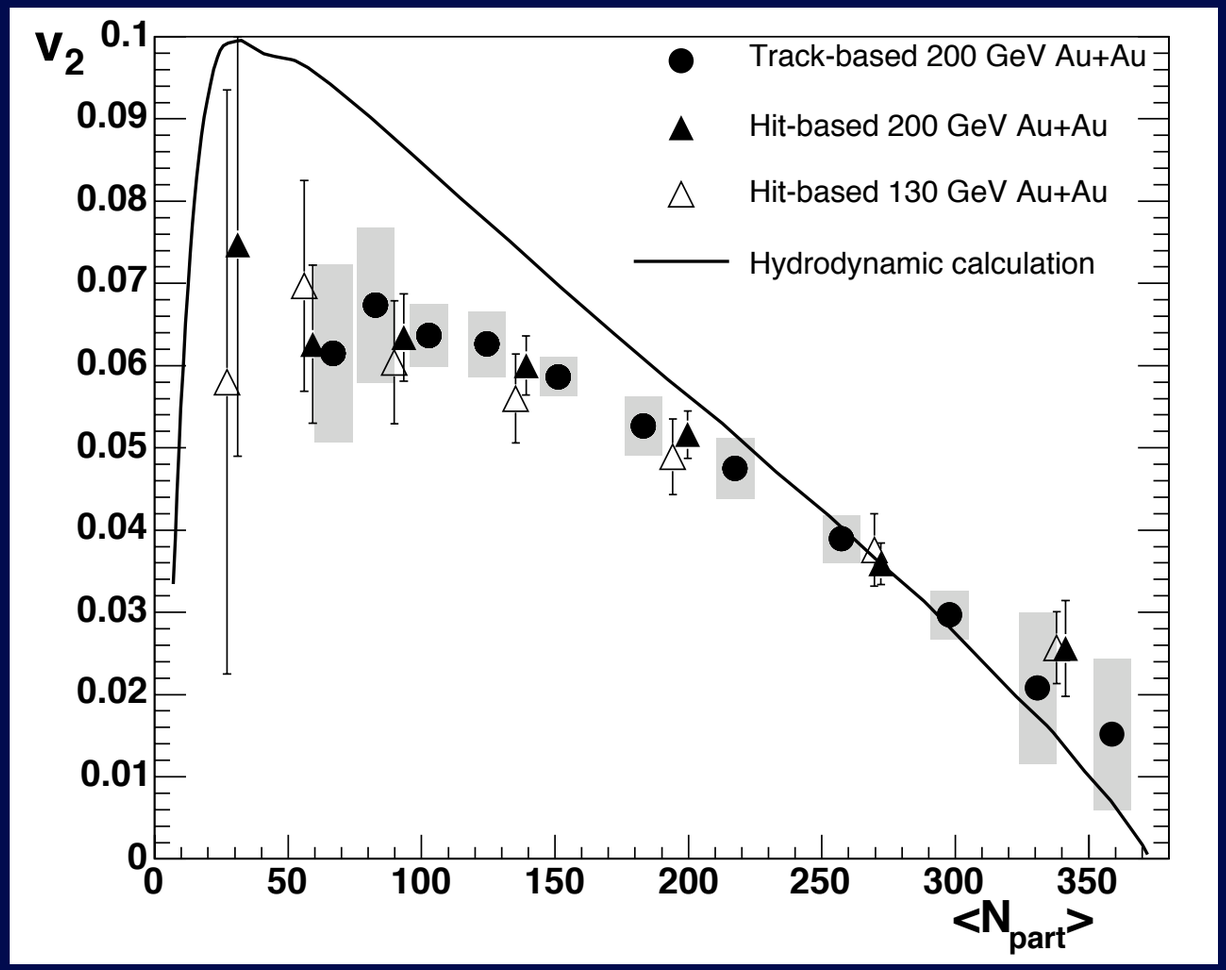
$$c_s^2 = dp/d\epsilon$$

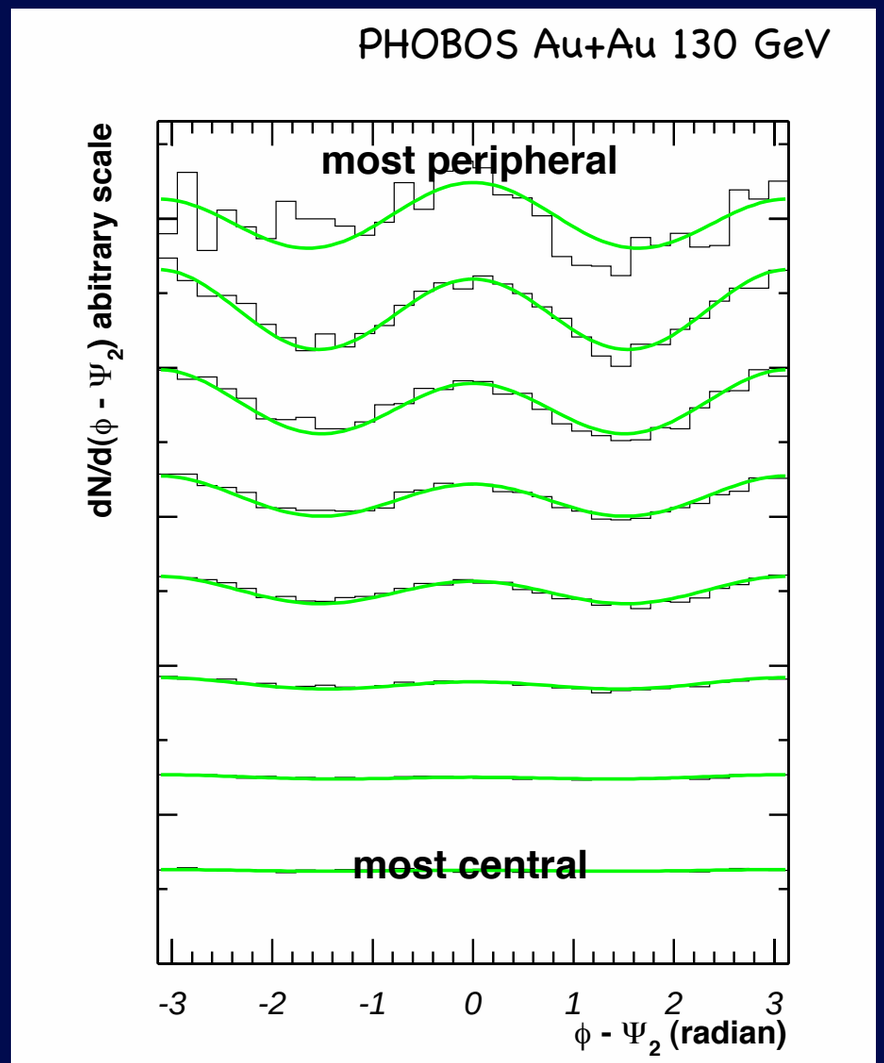


Fluid elements freezeout isotropically in local rest frame into hadron states when

$T < T_{ch}$

Hydro @ RHIC

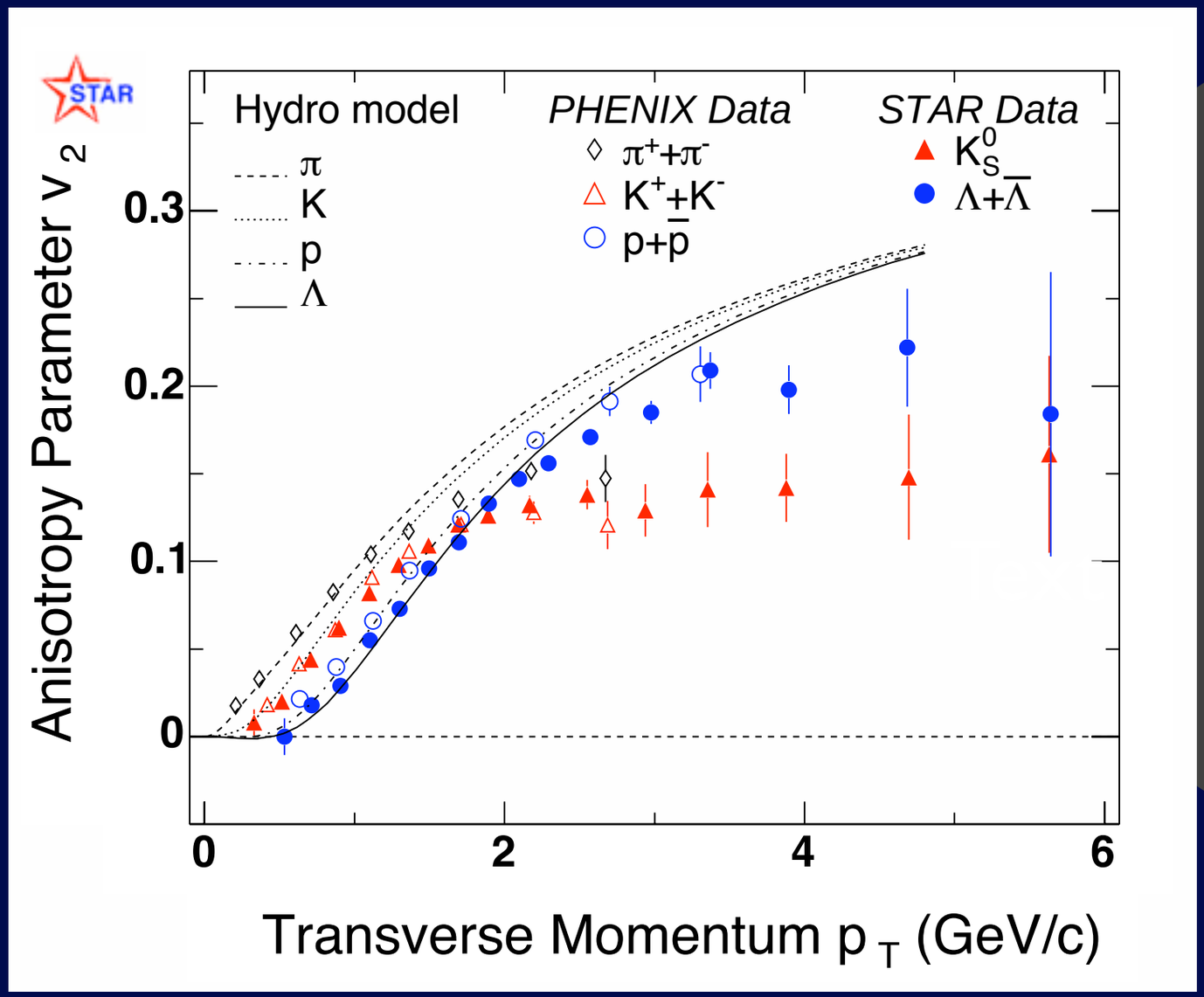


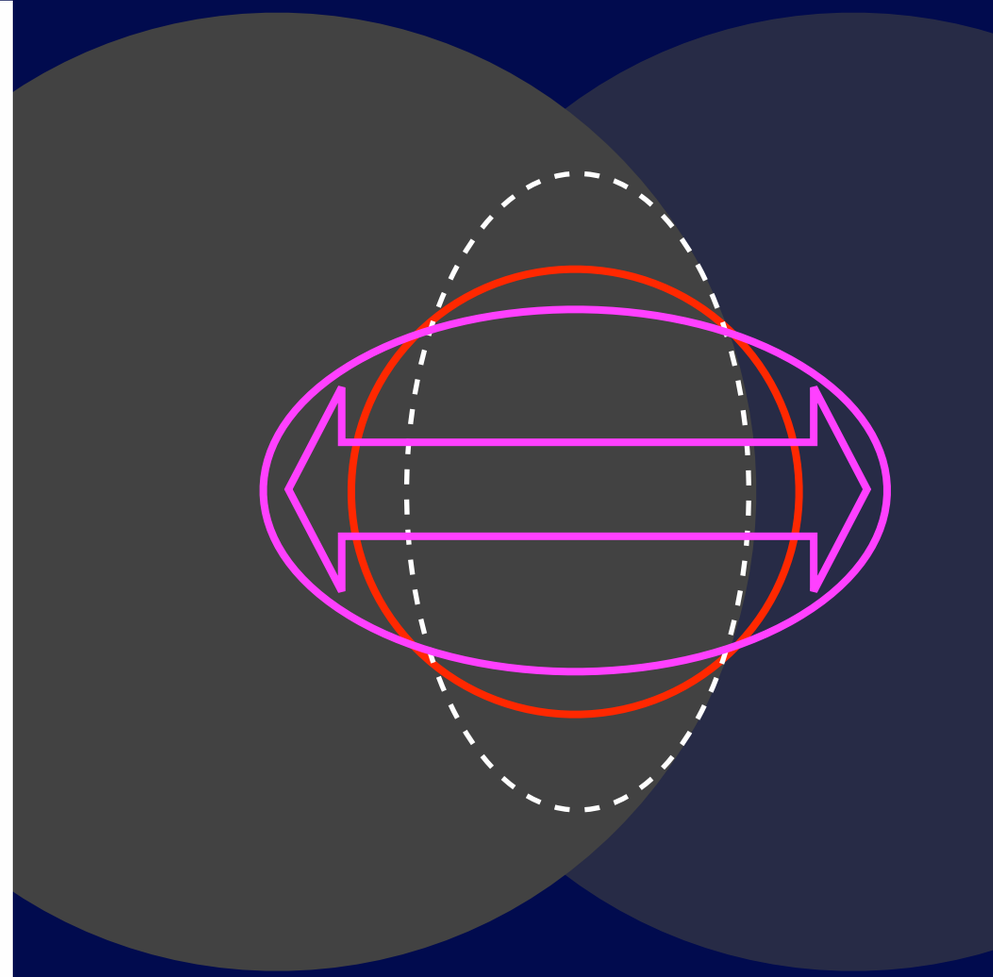


$$\frac{1}{N}\frac{dN}{d\phi} = 1 + 2v_1\cos(\phi - \Phi_R) + 2v_2\cos(2[\phi - \Phi_R]) + \ldots$$

hydro scales $\tau_0 \sim 0.6 fm/c$, $\epsilon \sim 30\ GeV/fm^3$ $\Longleftrightarrow$ $\tau_0 \sim 1\ fm/c$, $\epsilon \sim 500\ MeV/fm^3$ **hadronic scales**

“Fine Structure”

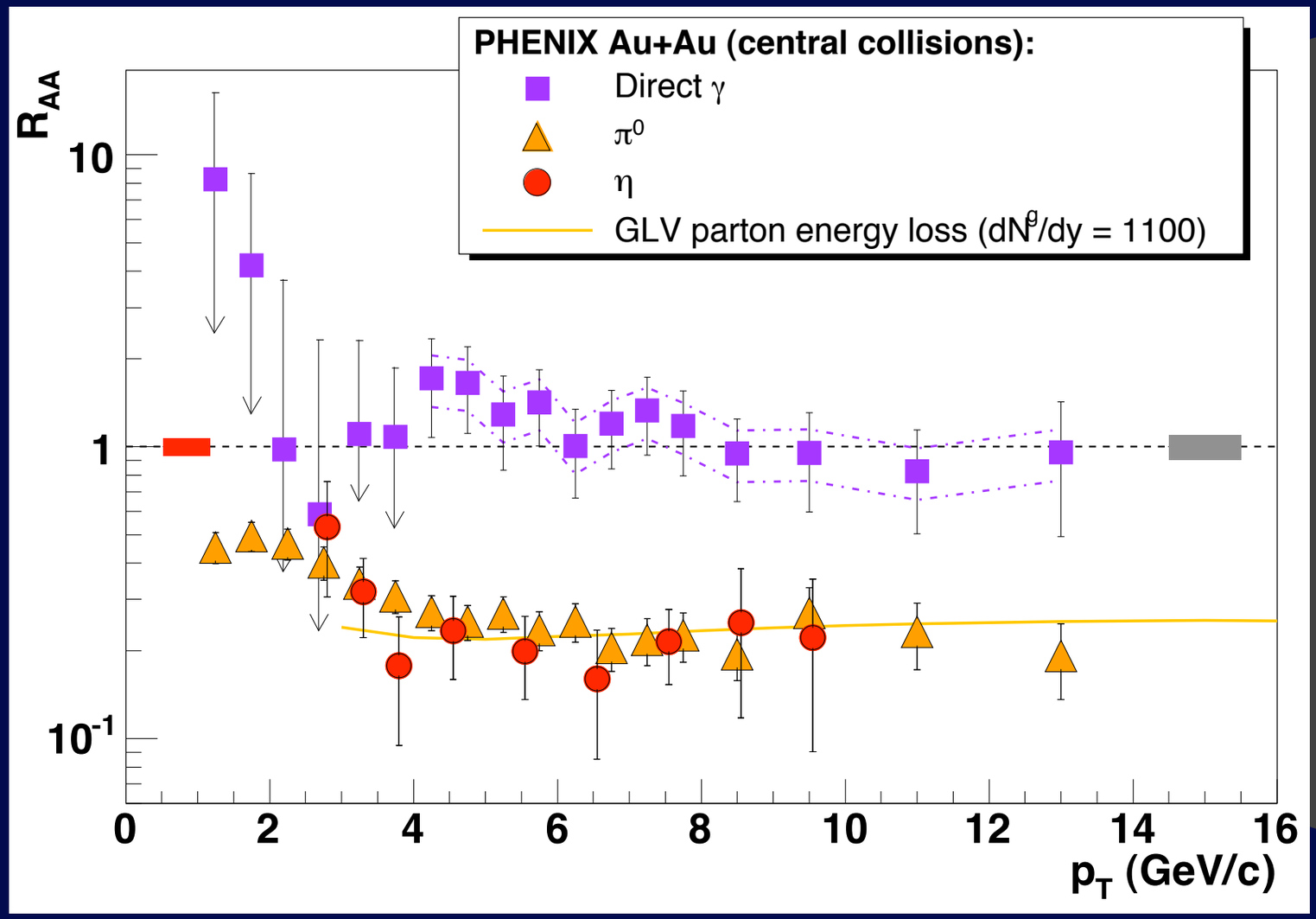


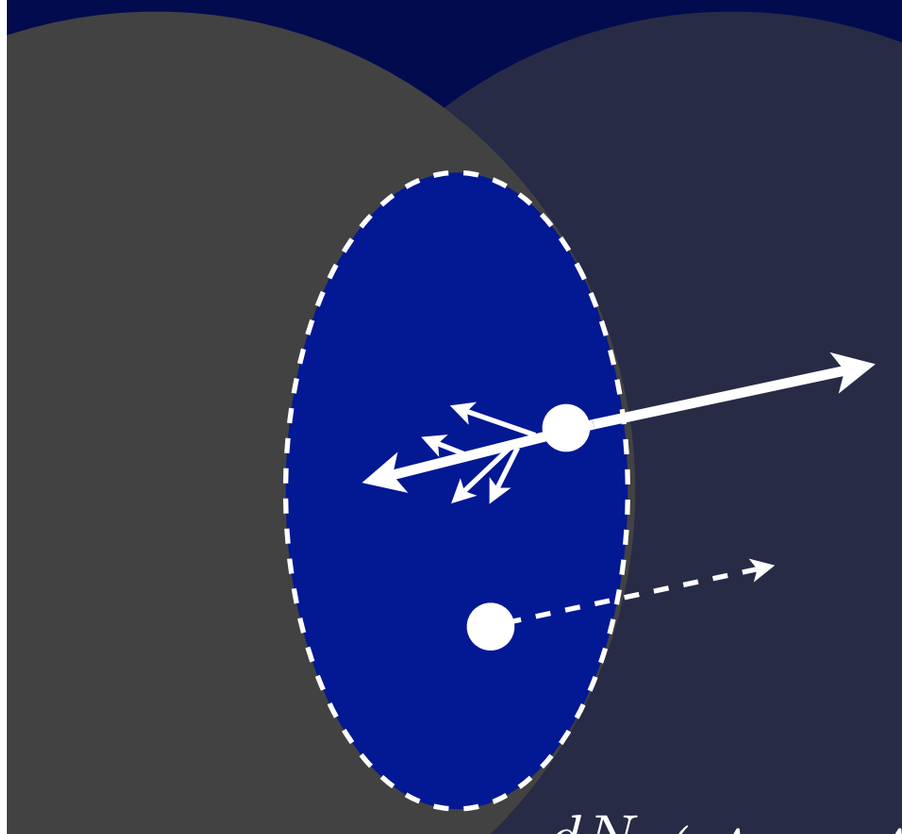


Low energy particles are ~isotropically emitted

Higher energy particles “feel” the geometry

Jet Quenching



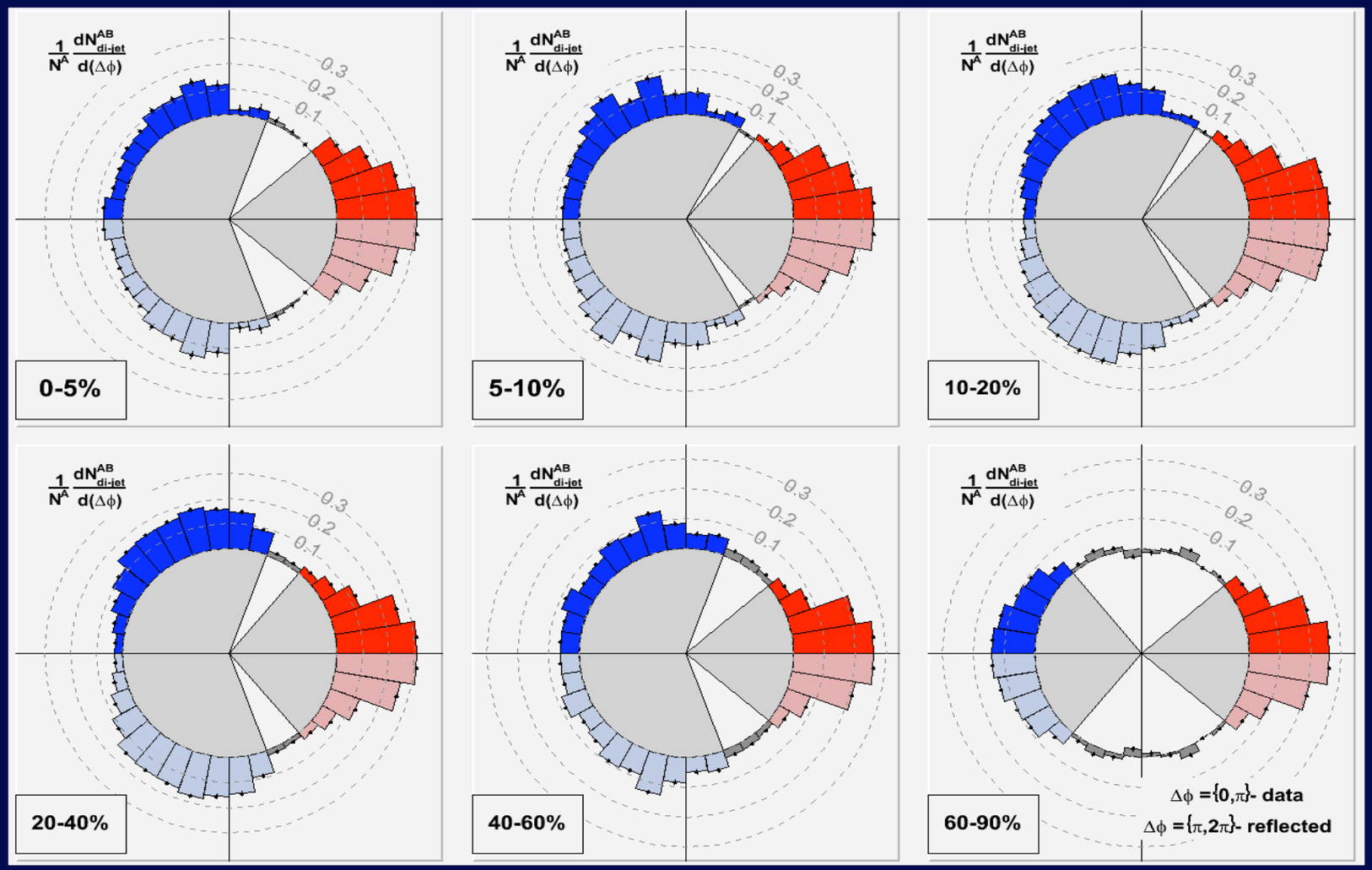


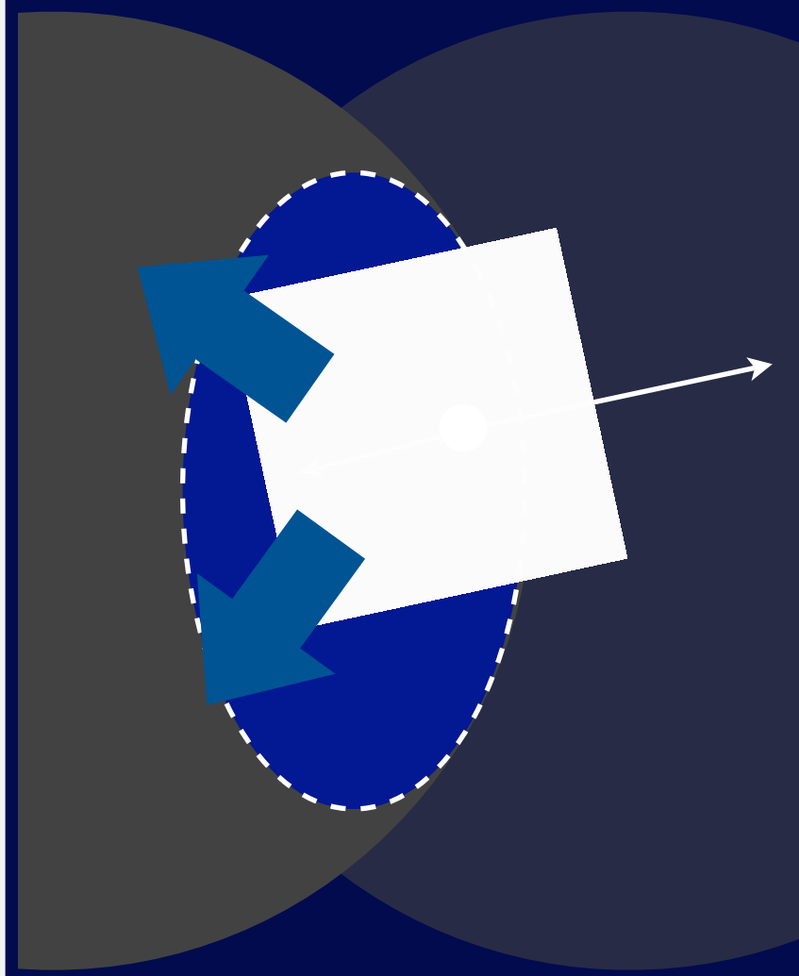
$$R_{AA} = \frac{1}{N_{coll}} \frac{\frac{dN}{dp_T}(A+A)}{\frac{dN}{dp_T}(p+p)}$$

High p_T particles are strongly suppressed relative to p+p spectrum × binary collisions (N_{coll}). Photons not.

pQCD energy loss calculations sufficient to describe light hadrons

Medium Effects on Jets





In central events, 2-particle correlations not back-to-back!

Suppression is a “redistribution” of energy/momentum. Mach cones?
Excitations couple strongly to medium, rapidly thermalize

What have we seen?

thermalized, collective matter that is...

Hotter (>10^{12} ^{o}K)
Denser (>30 GeV/fm^3)
Smaller (~6 fm)
Faster (τ_0<1 fm/c)

than other known liquids

and perfect?

Do we know that it has zero viscosity?

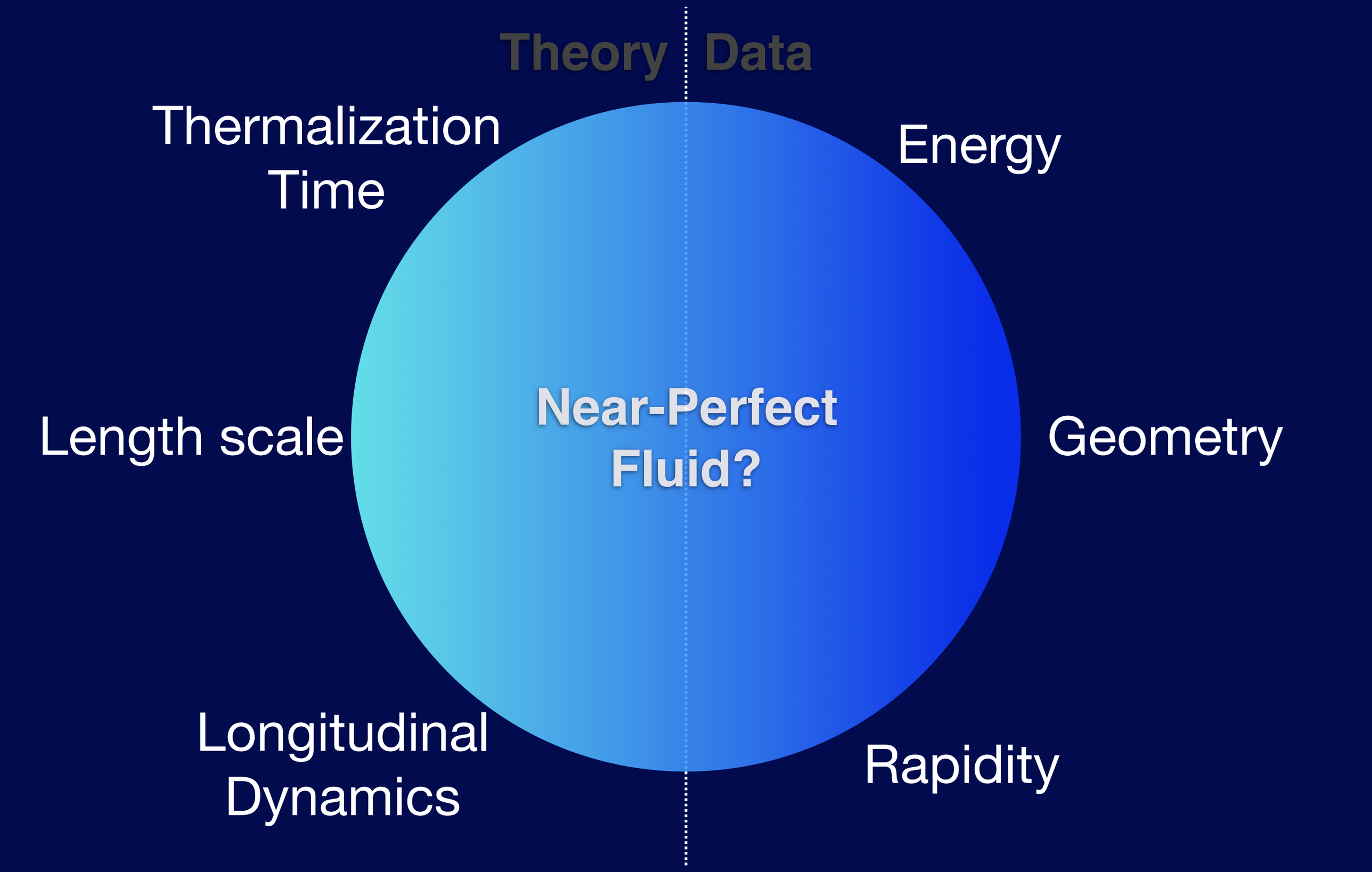
Does it have attractive interactions characteristic of liquids?

Perfect Liquid?

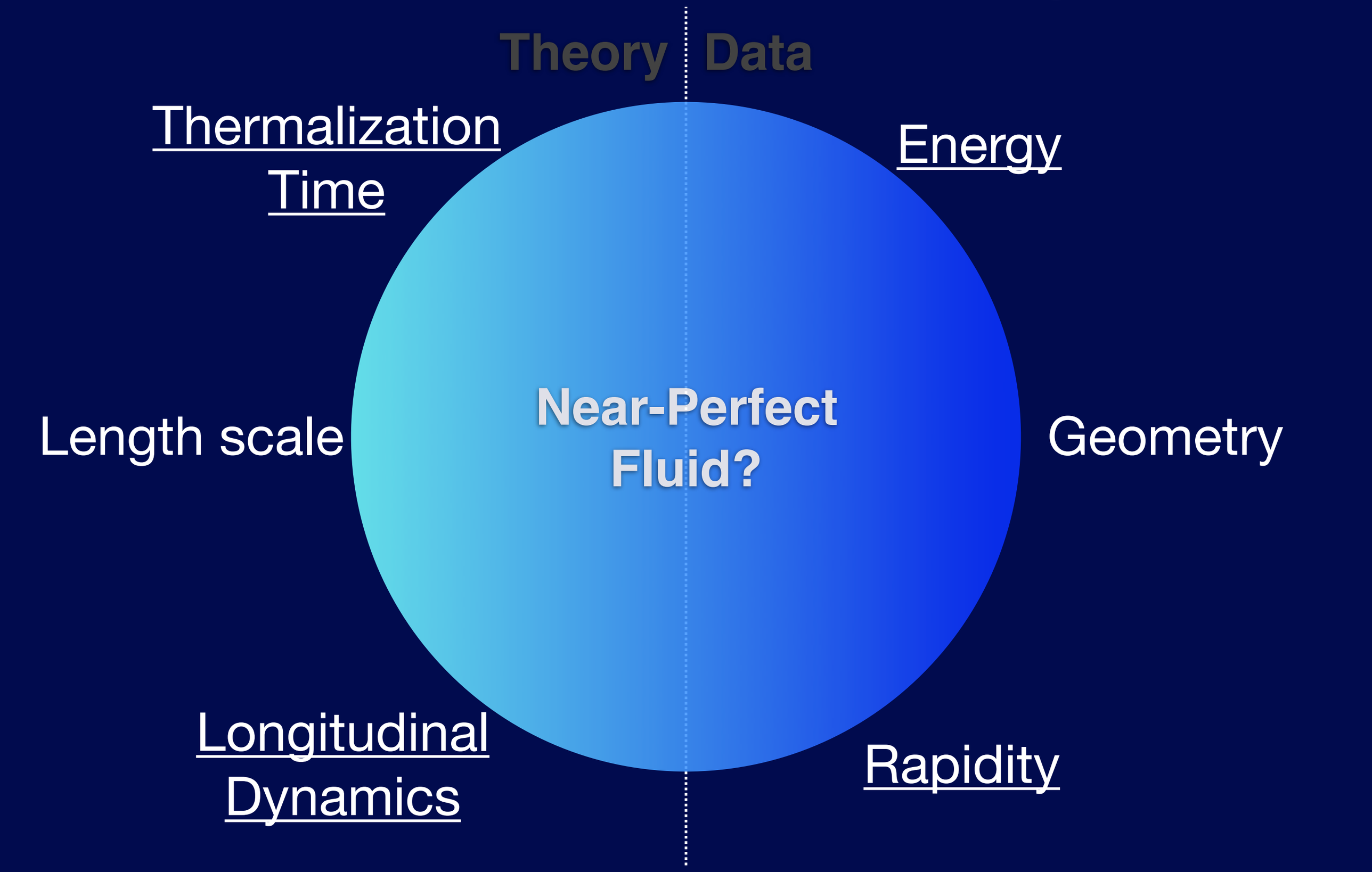
Near-Perfect Fluid?

How does this all relate to QCD?

Frontiers of RHIC Physics

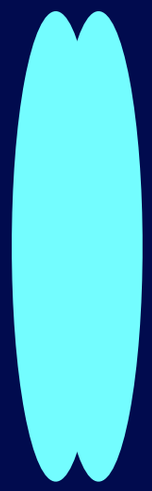


Frontiers of RHIC Physics



Initial Conditions: τ_0

Landau



Total stopping, immediate thermalization & longitudinal **3D** re-expansion

$$\tau_0 \sim \frac{1}{\sqrt{s}} fm/c$$

Bjorken

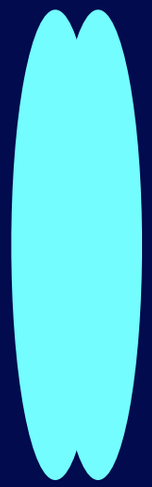
Partial stopping, “boost-invariant” **2D** expansion

$$\tau_0 \sim 1 fm/c$$

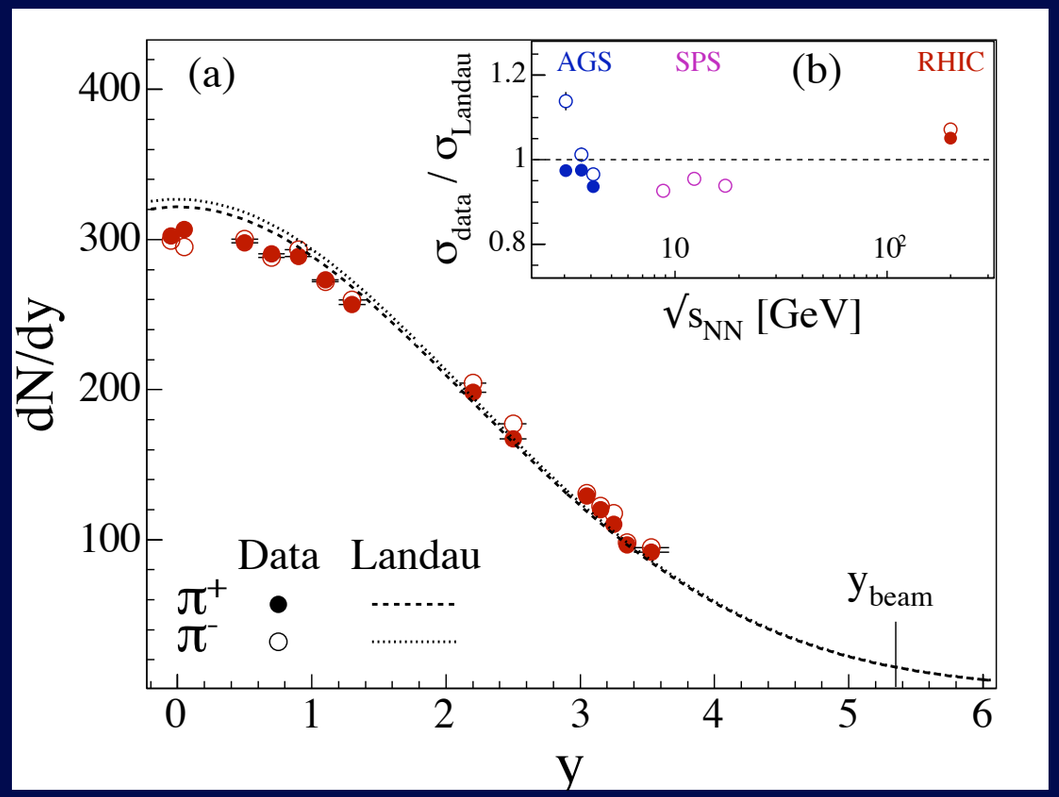
<u>Same</u> hydro, different initial conditions!

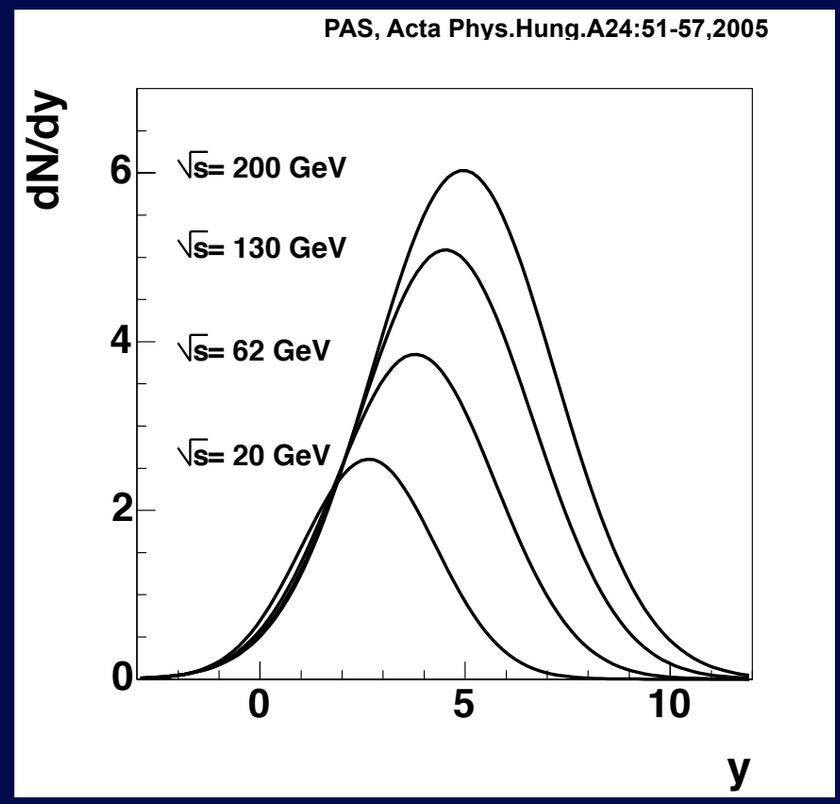
Rapid Thermalization

Landau



$$\tau_0 \sim \frac{1}{\sqrt{s}} fm/c$$

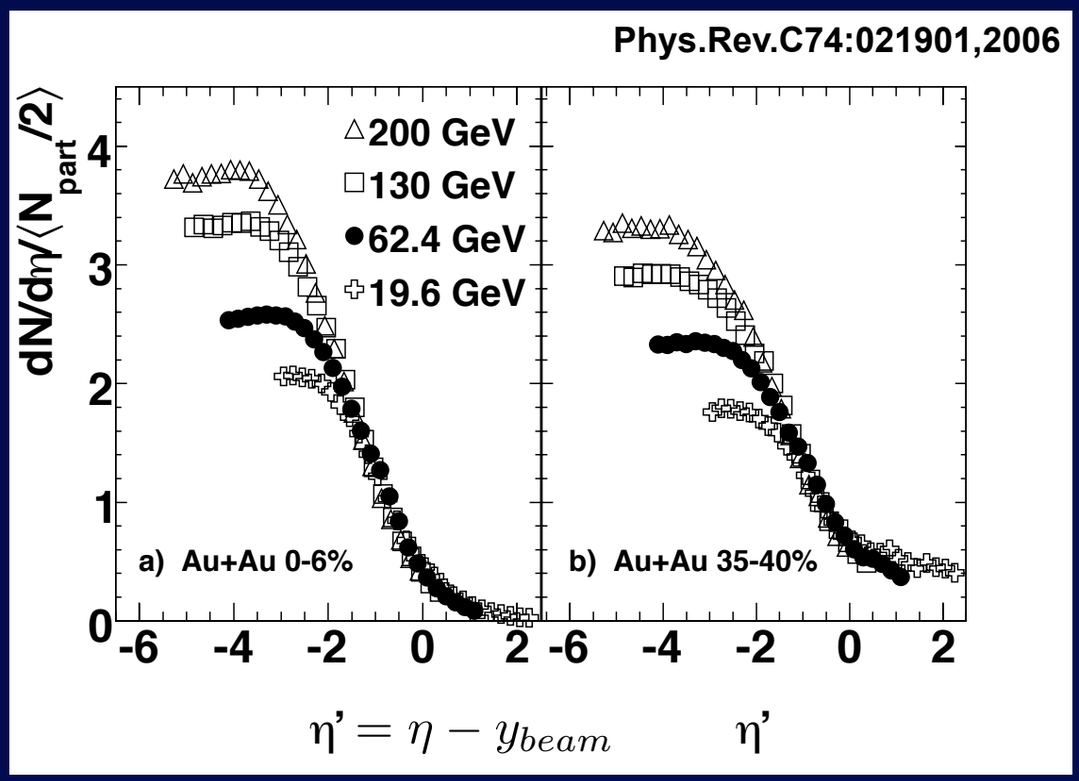


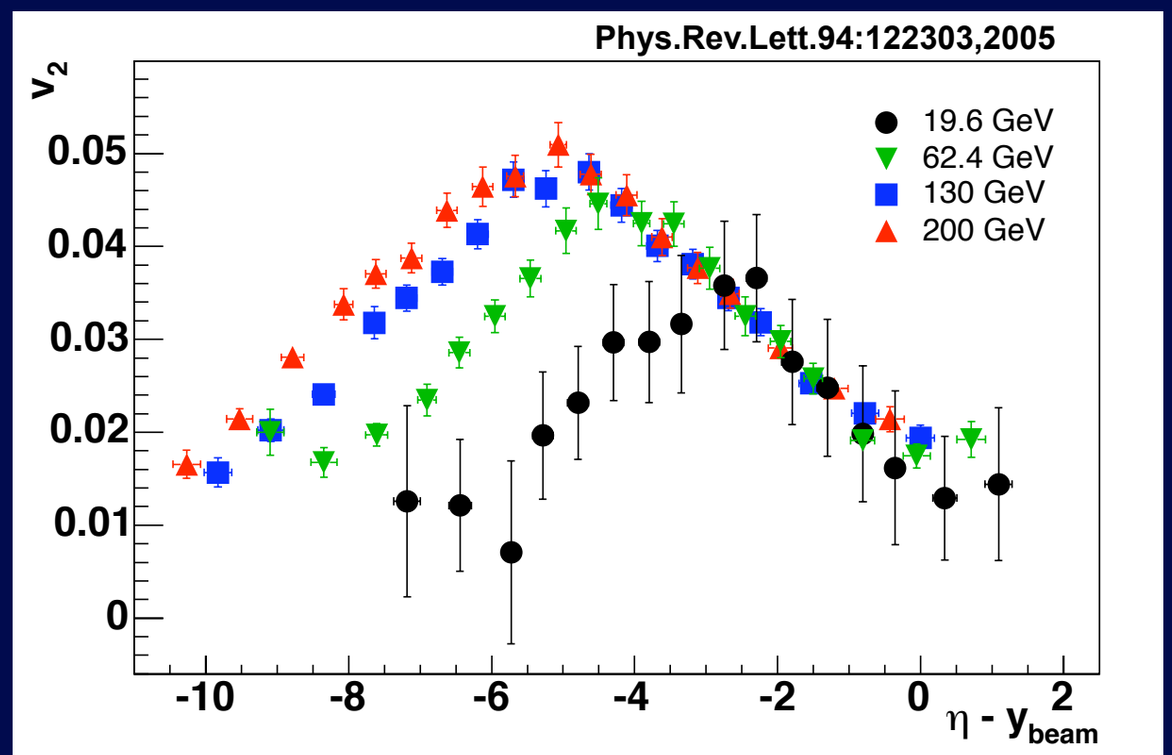


Rapid thermalization → Longitudinal explosion → Forward physics!

e.g. “**extended longitudinal scaling**”
energy invariance of yields in projectile rest frame

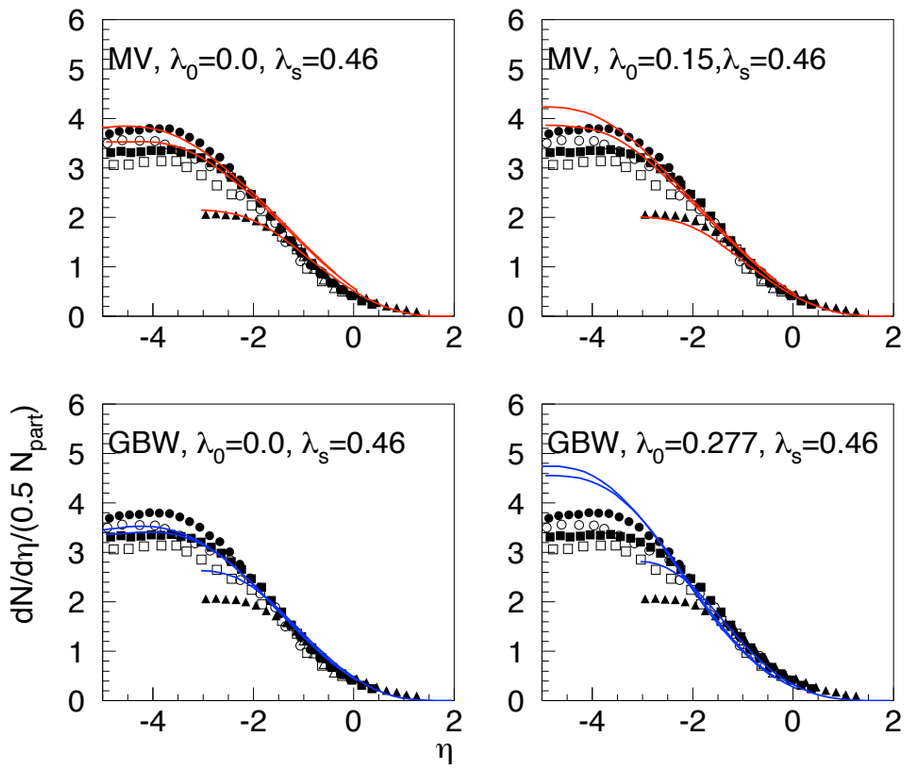
Longitudinal Scaling



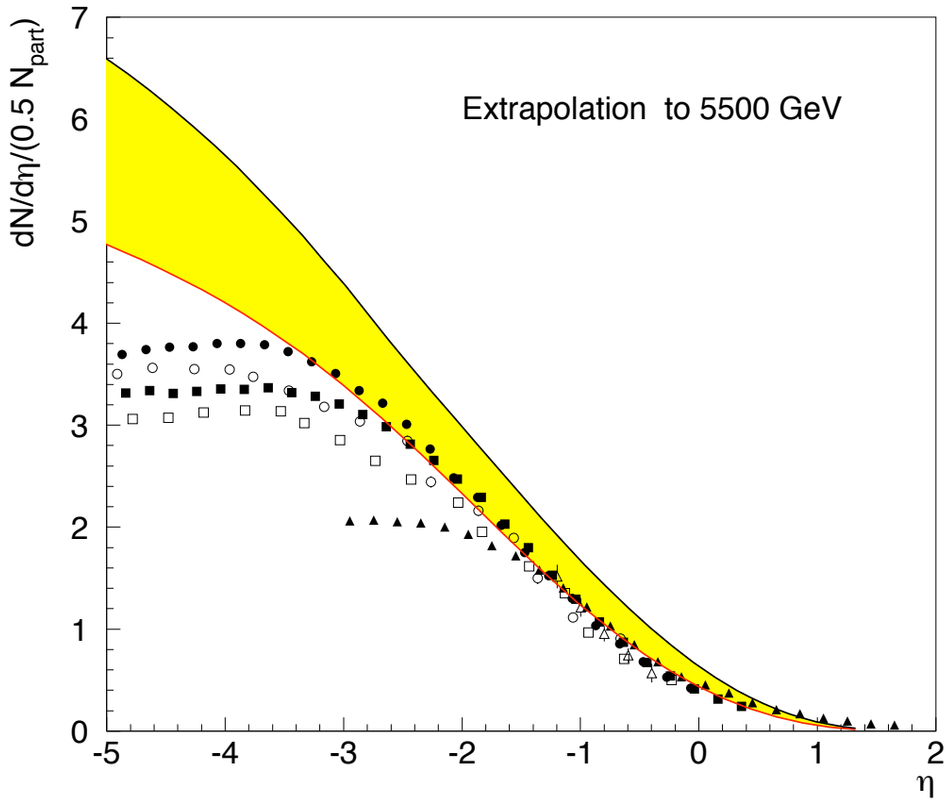


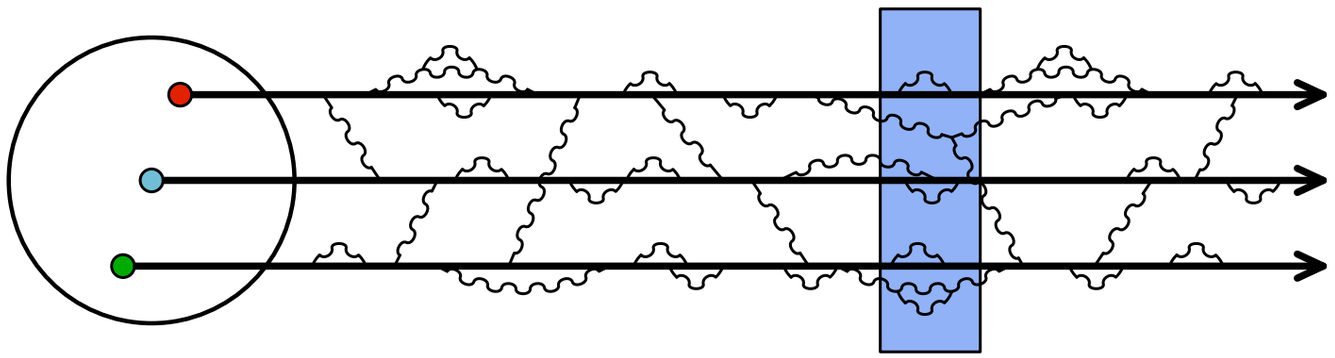
Longitudinal scaling is a major feature of A+A data at RHIC, both in yields and elliptic flow:
Must emerge naturally from theoretical description

Color Glass Condensate



Gelis, Stasto, Venugopalan (2006)



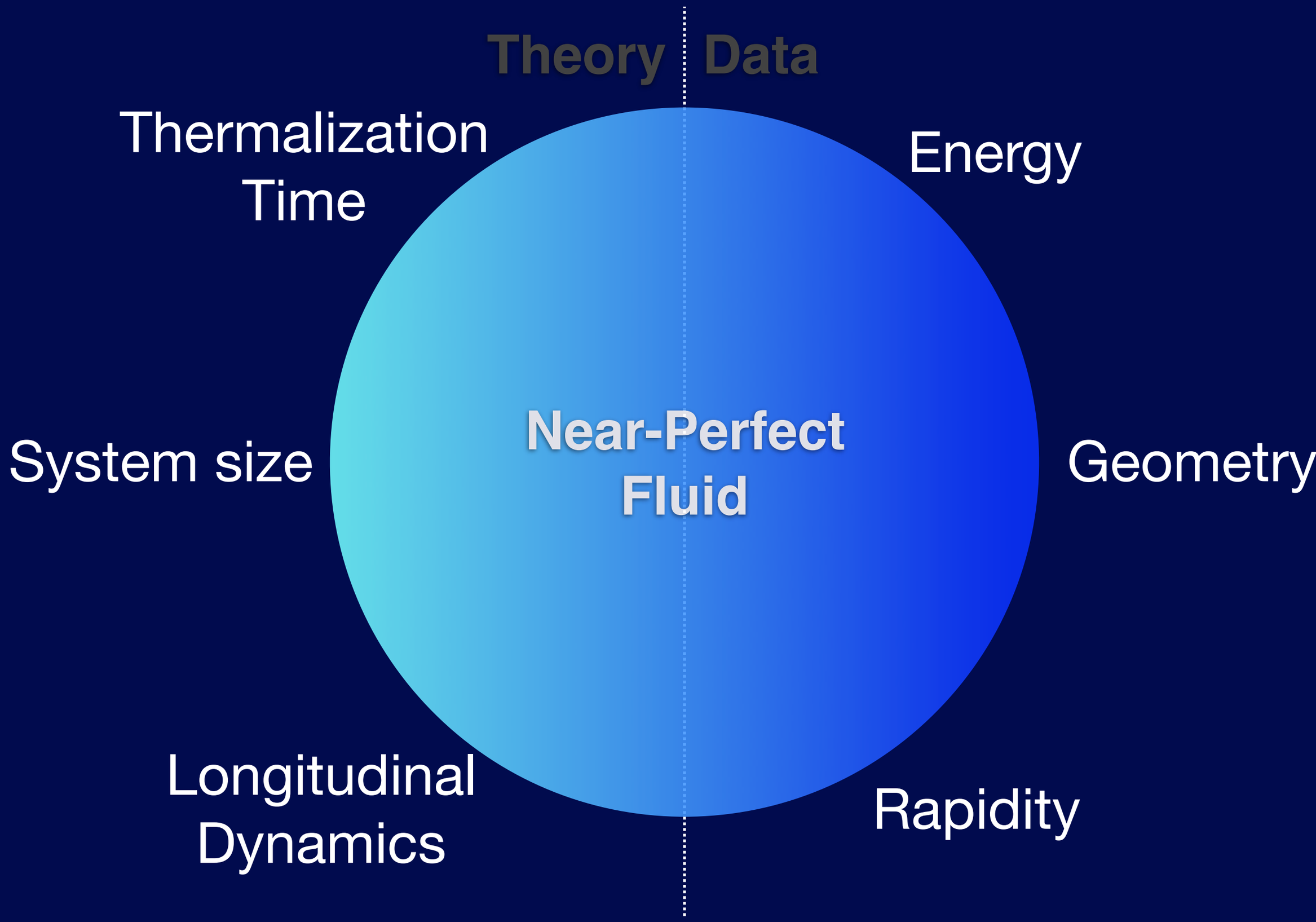


Gelis QM2006

Nucleon and nuclear wave function in an essential feature of initial state → physics @ RHIC II (y), EIC, LHC

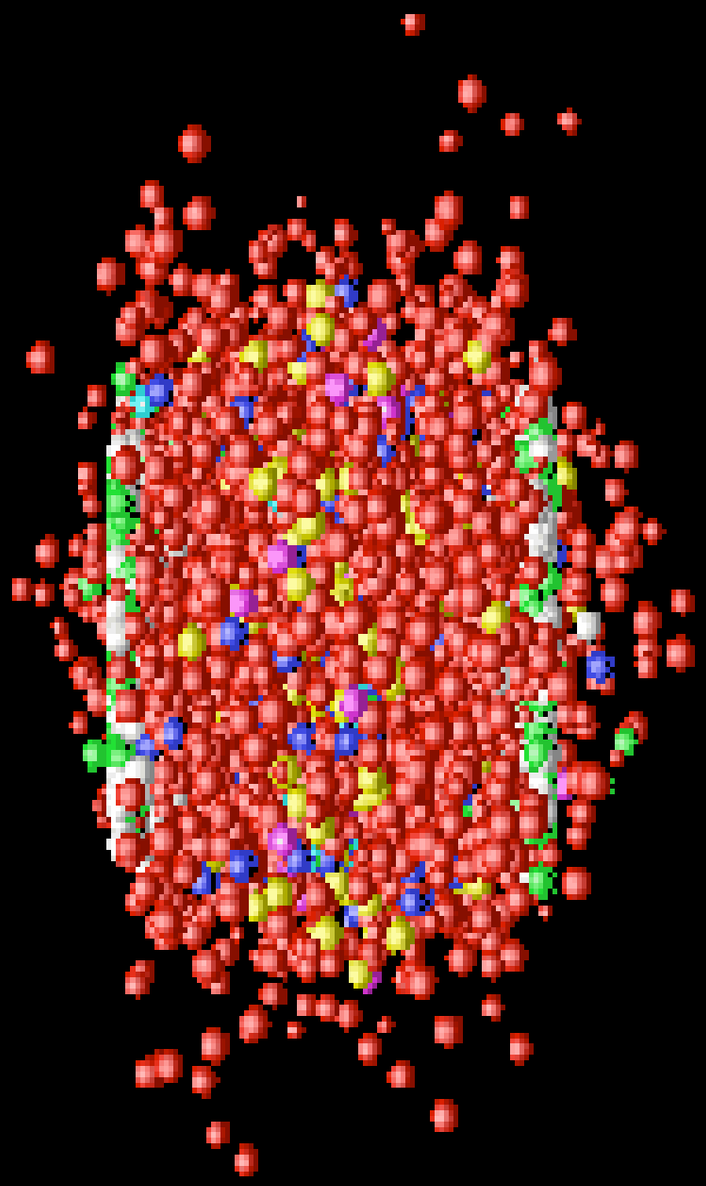
Is there a deep connection w/ hydro?

Near-perfect fluid paradigm may well have relevance even as we push to various frontiers...



But even if the near-perfect fluid is ubiquitous:
what is it? how did it come into being?

What is the fluid made of?



<u>Rapidly</u> thermalized matter

$$\tau_0 \ll 1 fm/c$$

But of what? and how so fast?

Quarks & gluons?
Is it a real “quark-gluon plasma” (QGP)?

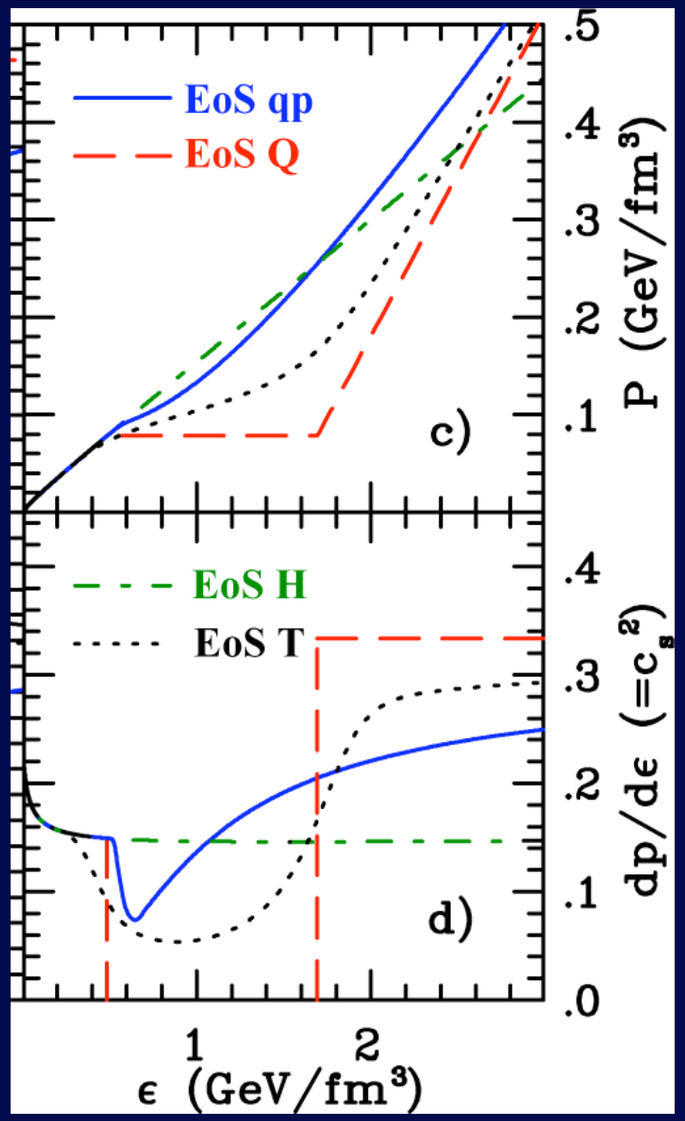
Equation of State

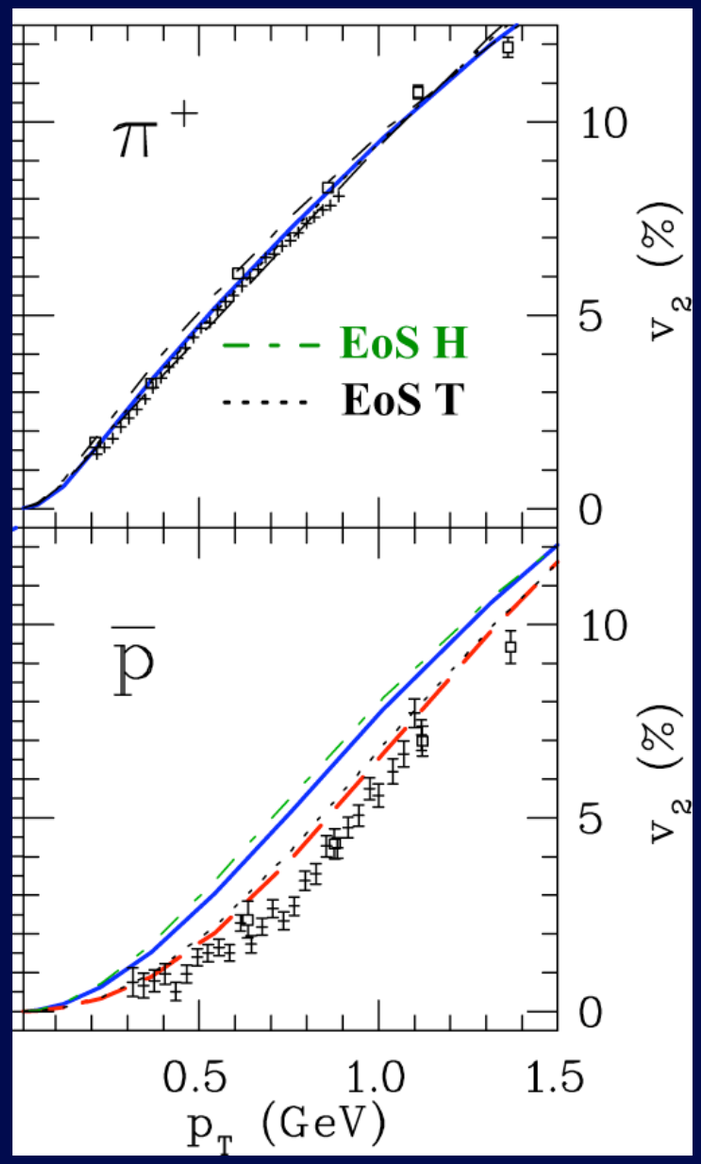
Lattice

1st order PT

Crossover

Hadronic





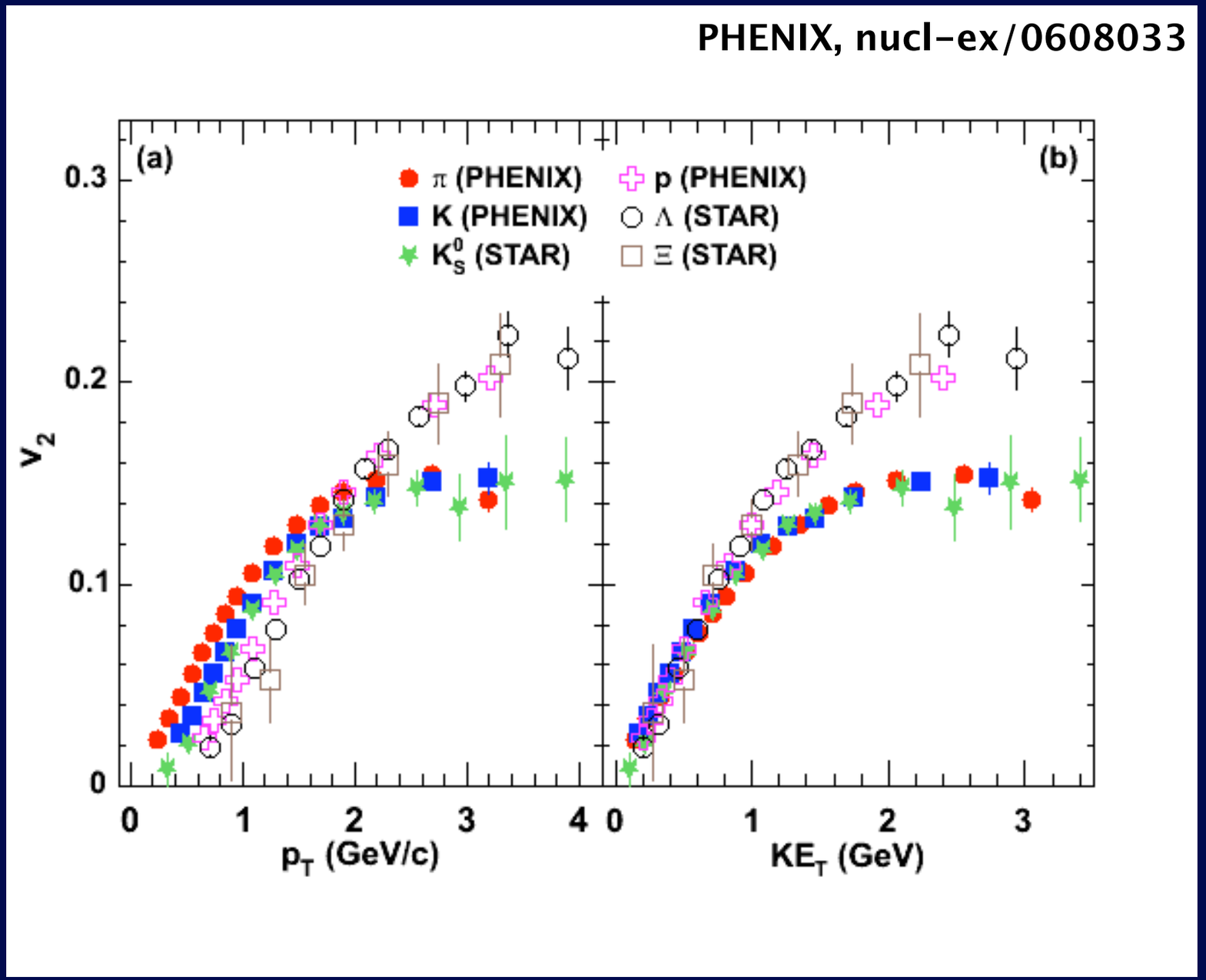
Nucl.Phys.A761:296-312,2005

EOS encodes degrees of freedom, phase transitions

Lattice EOS *disagrees* w/ data: need to put in 1st-order PT by hand...maybe 2+1D insufficient?

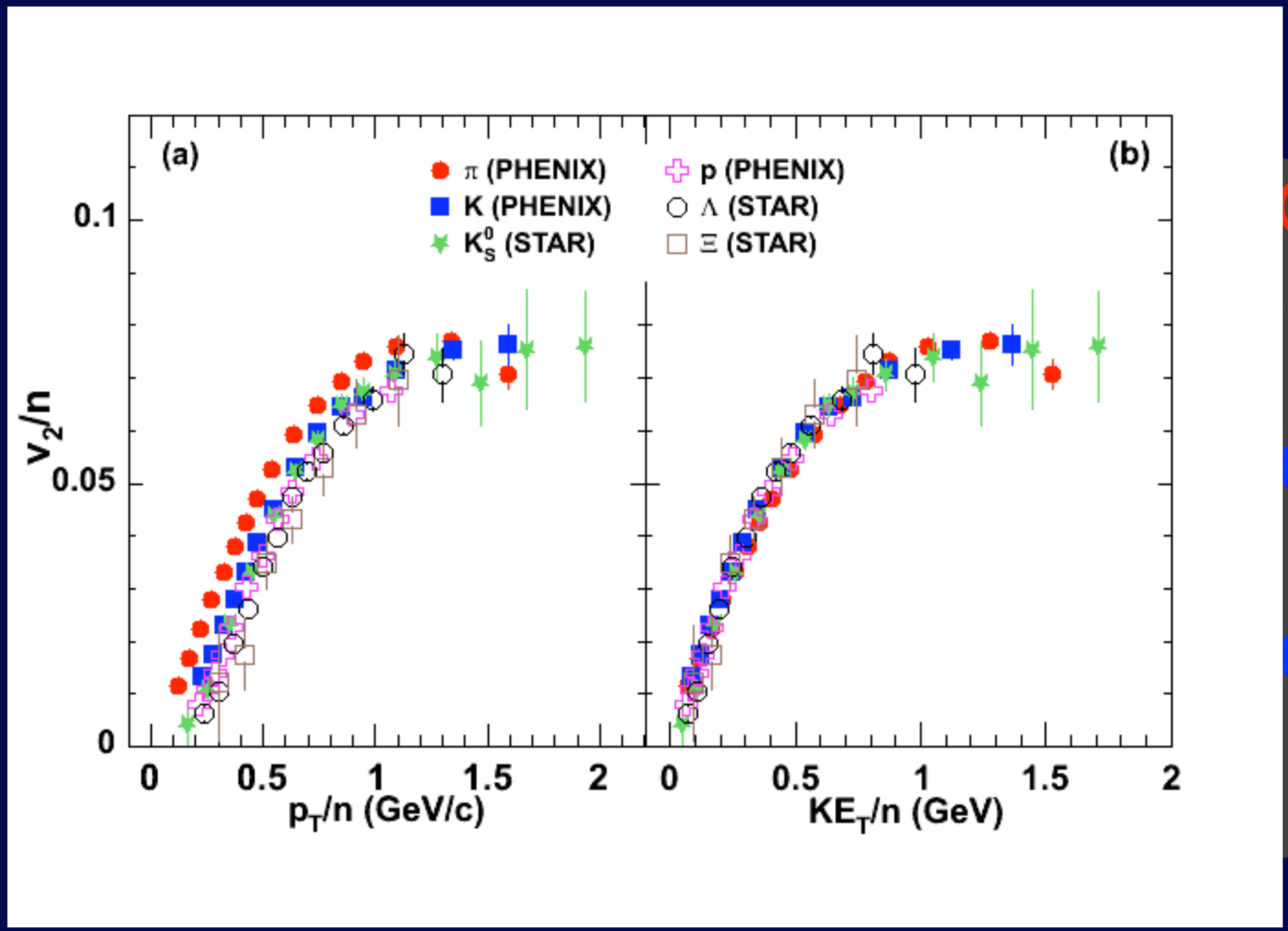
Identified Particle Flow

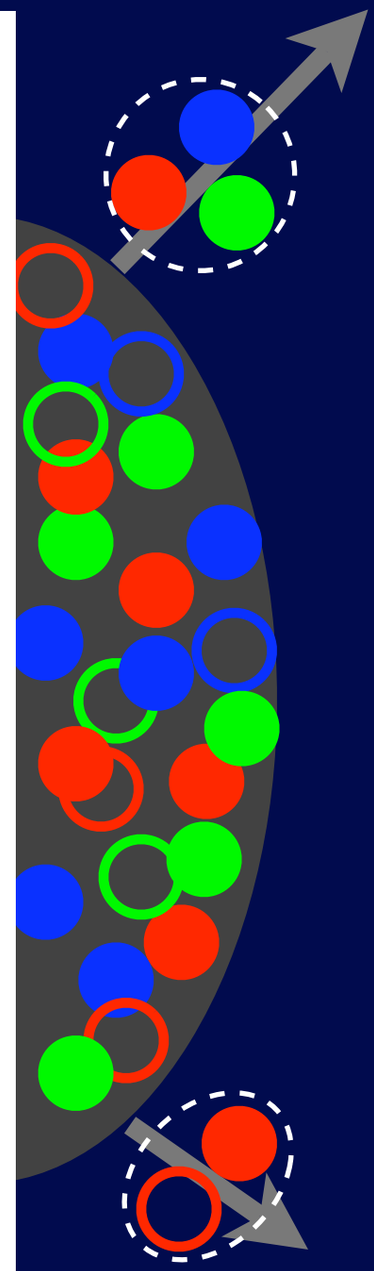
PHENIX, nucl-ex/0608033



Complicated particle dependence of v_2 vs. p_T is simpler when plotted vs. kinetic energy: $KE_T = m_T - m$

Constituent Quark QGP?

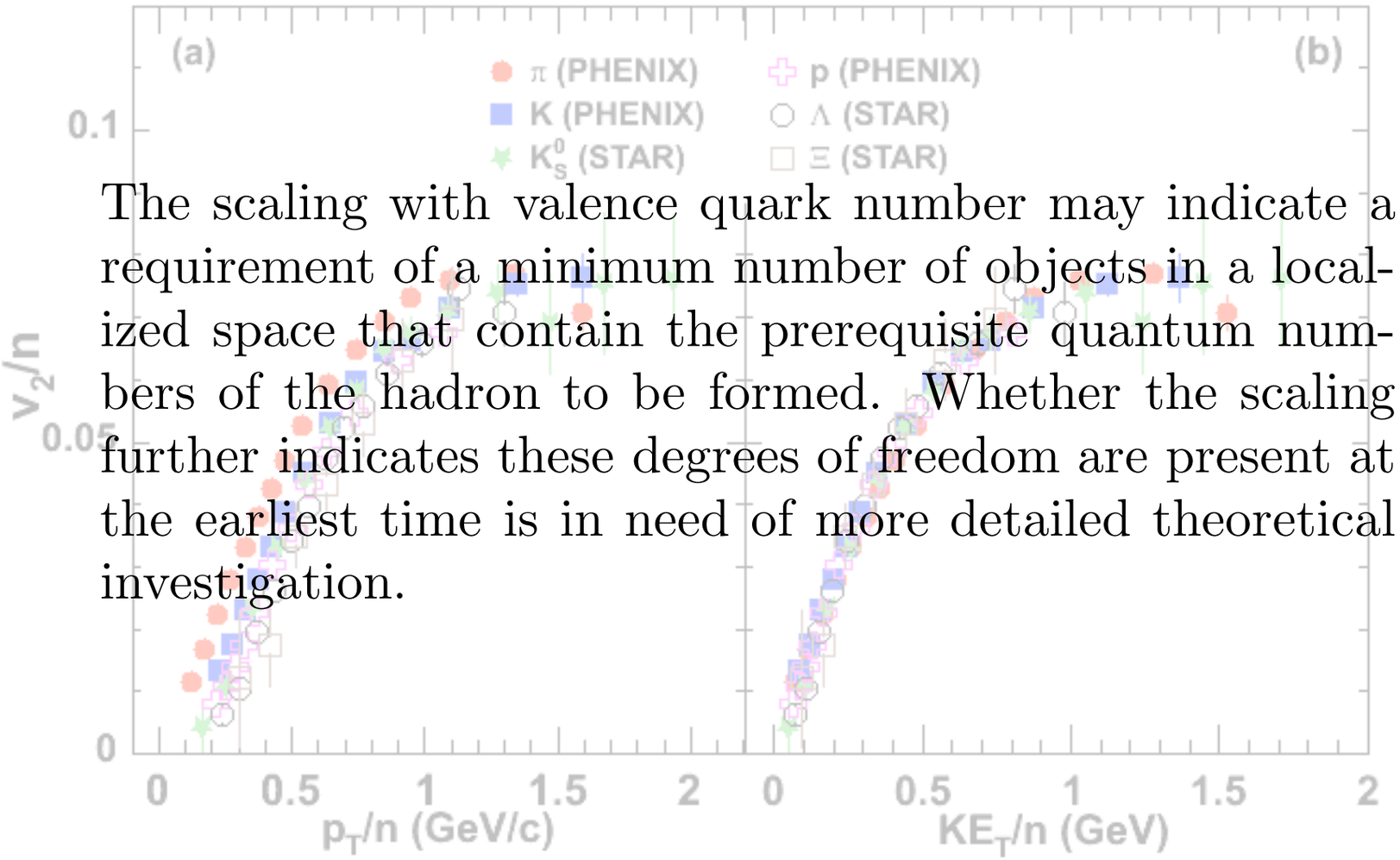




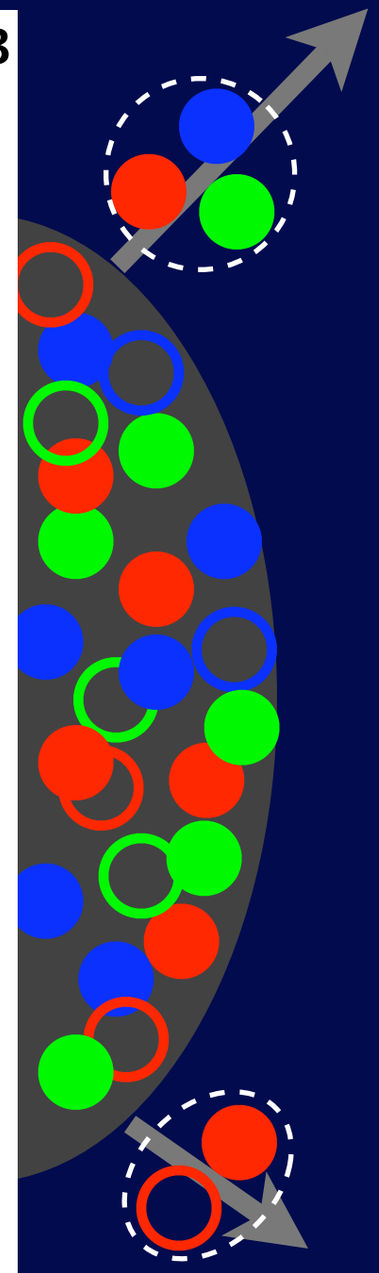
Even simpler when dividing by the number of constituent quarks (CQ): is the QGP a fluid of quarks?

Constituent Quark Scaling?

PHENIX, nucl-ex/0608033



The scaling with valence quark number may indicate a requirement of a minimum number of objects in a localized space that contain the prerequisite quantum numbers of the hadron to be formed. Whether the scaling further indicates these degrees of freedom are present at the earliest time is in need of more detailed theoretical investigation.



Degrees of Freedom

Parton distributions,
Nuclear Geometry,
Nuclear shadowing

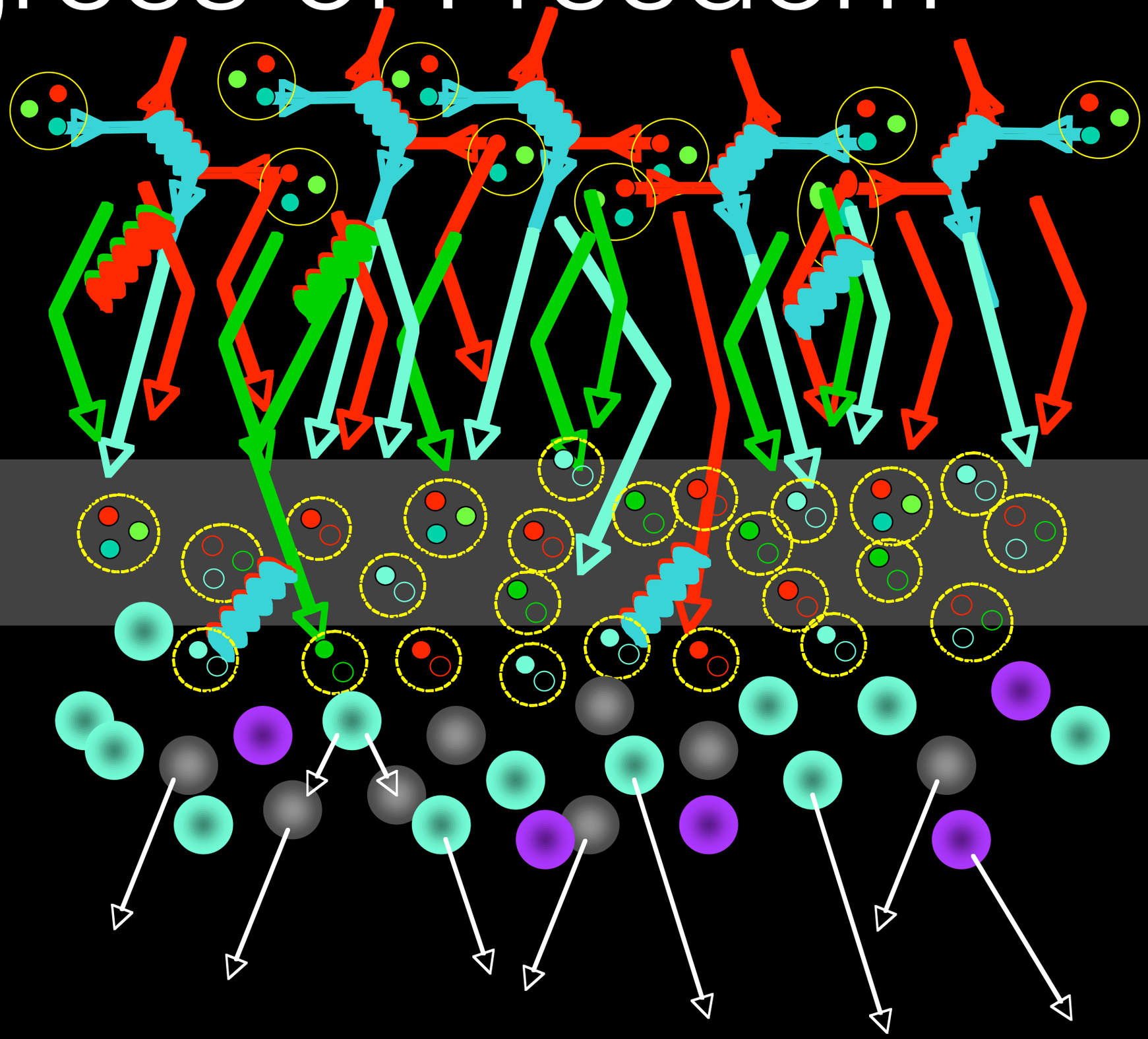
Parton production &
reinteraction
(or, sQGP!)

Chemical freezeout
(Quark recombination)

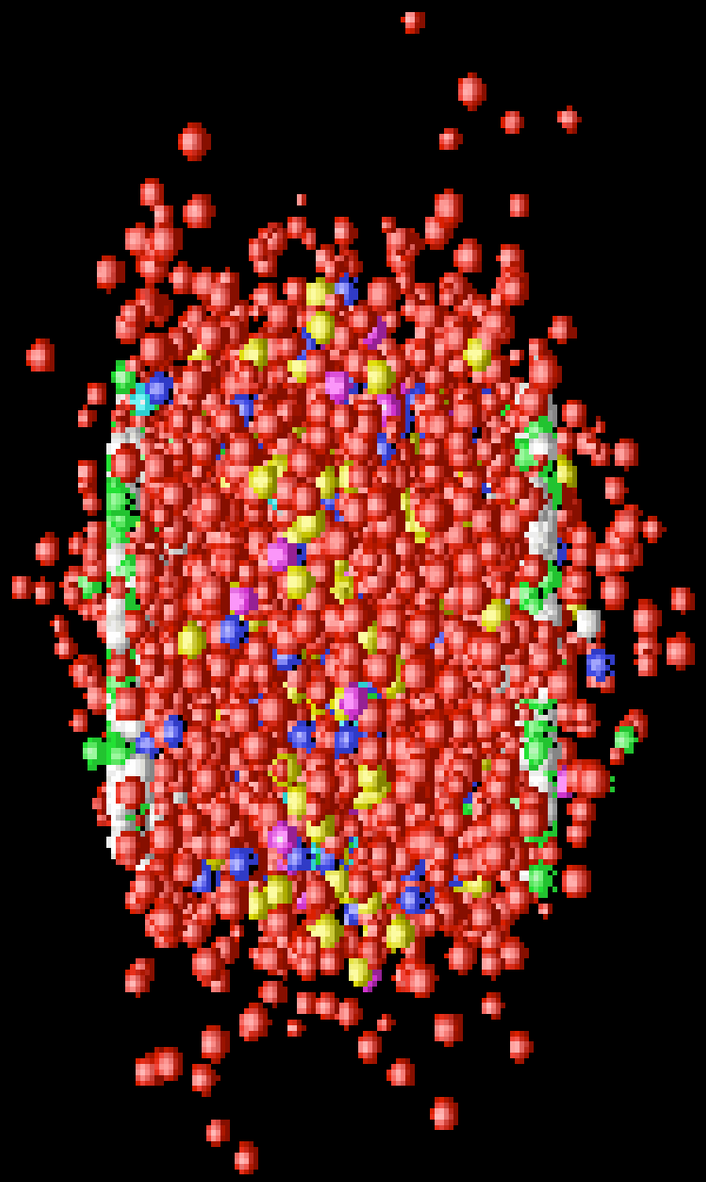
Jet fragmentation functions

Hadron rescattering

Thermal freezeout &
Hadron decays

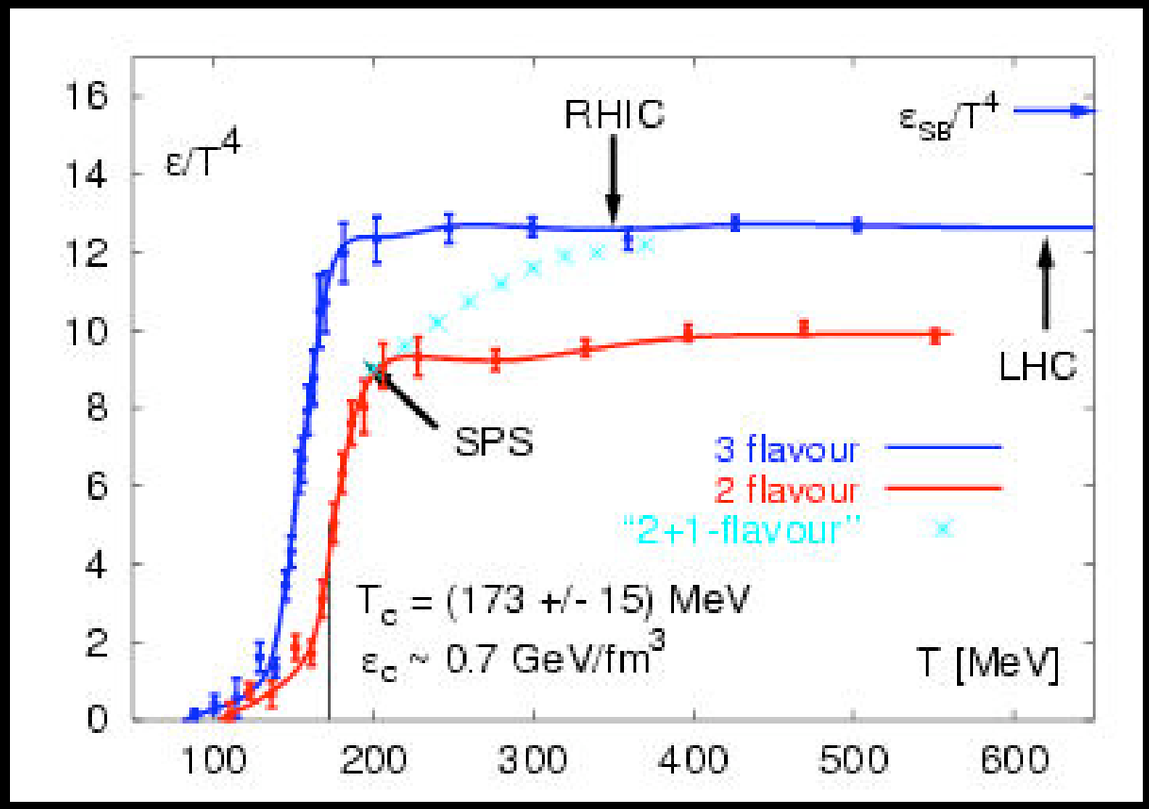


What is the fluid made of?



$$\epsilon = \frac{E}{V} \propto n_{d.o.f.} T^4$$

energy density



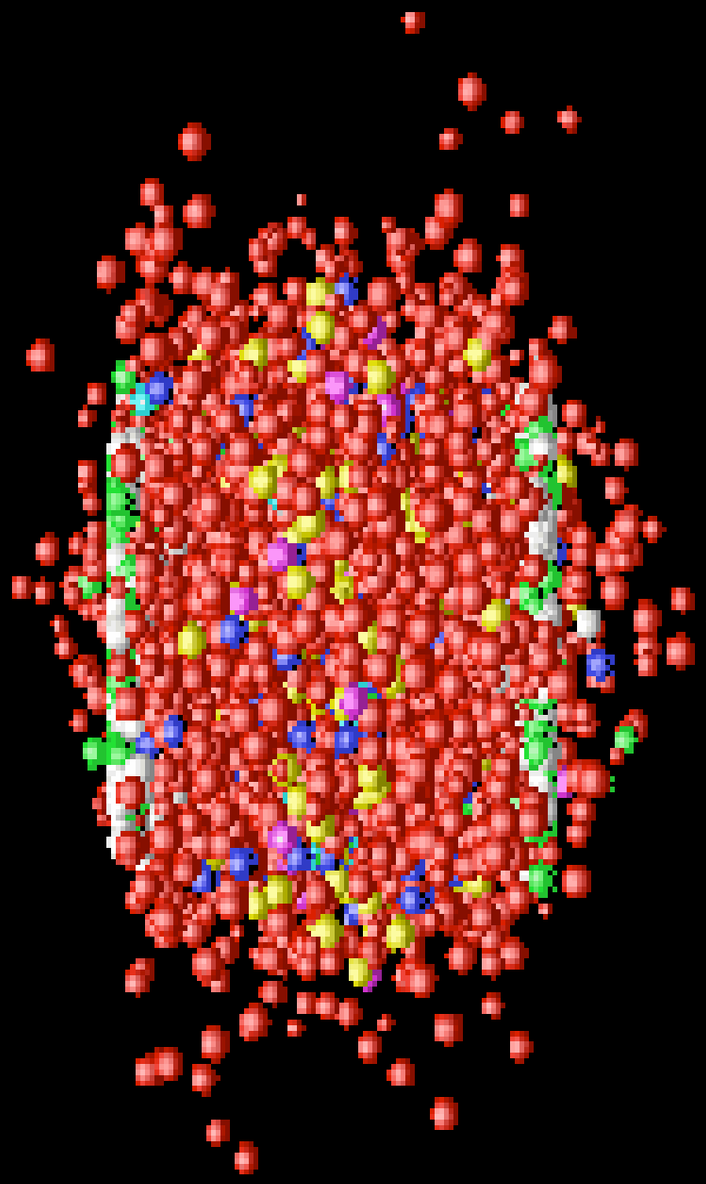
← ?

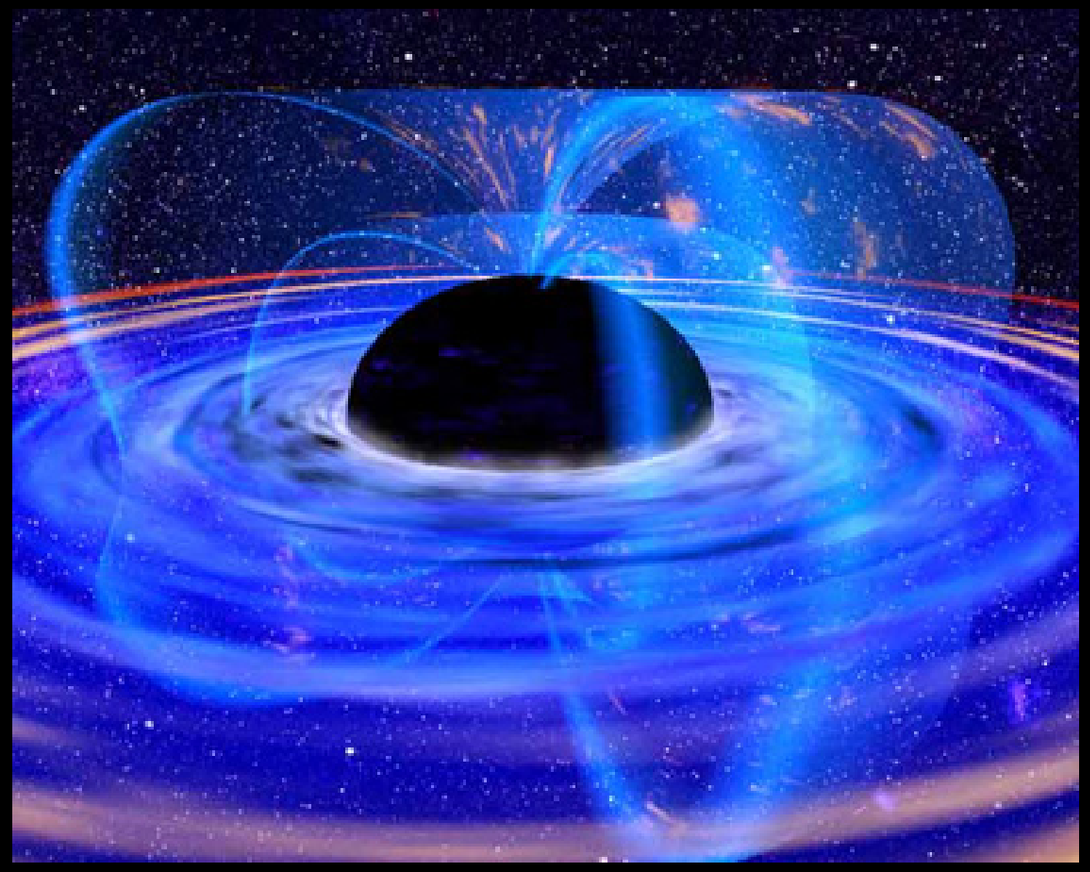
Karsch et al, 2001

↑

“deconfinement” @ T_c

What is the fluid made of?

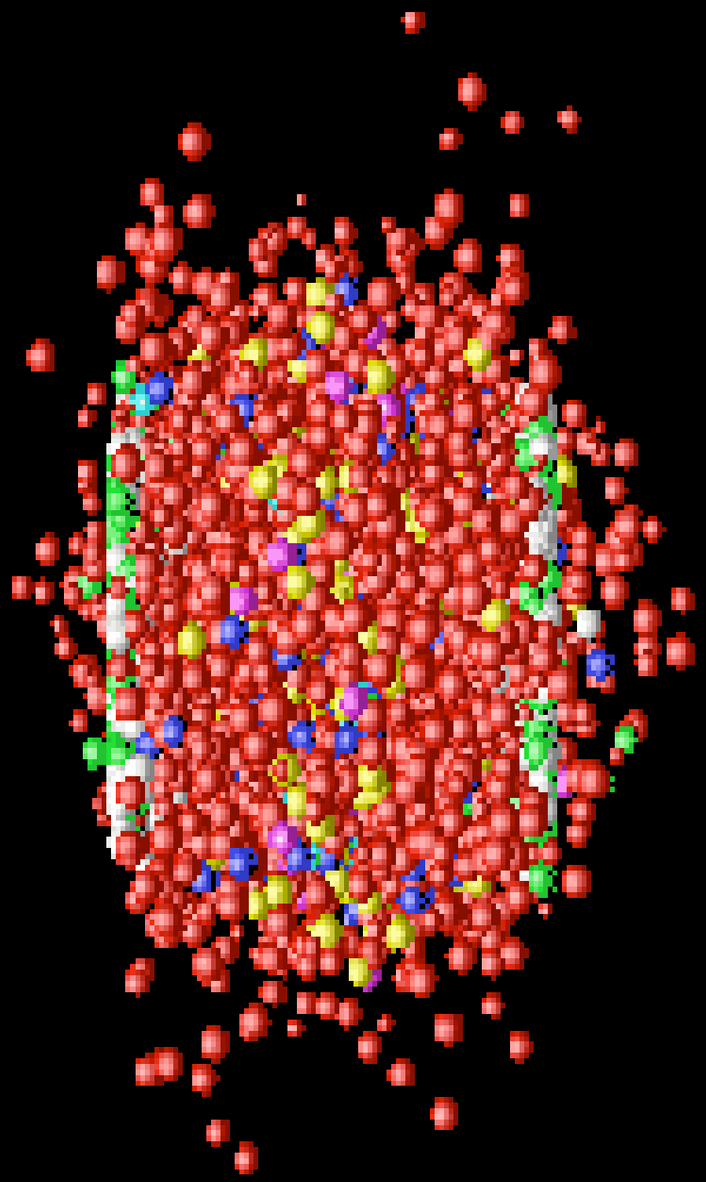




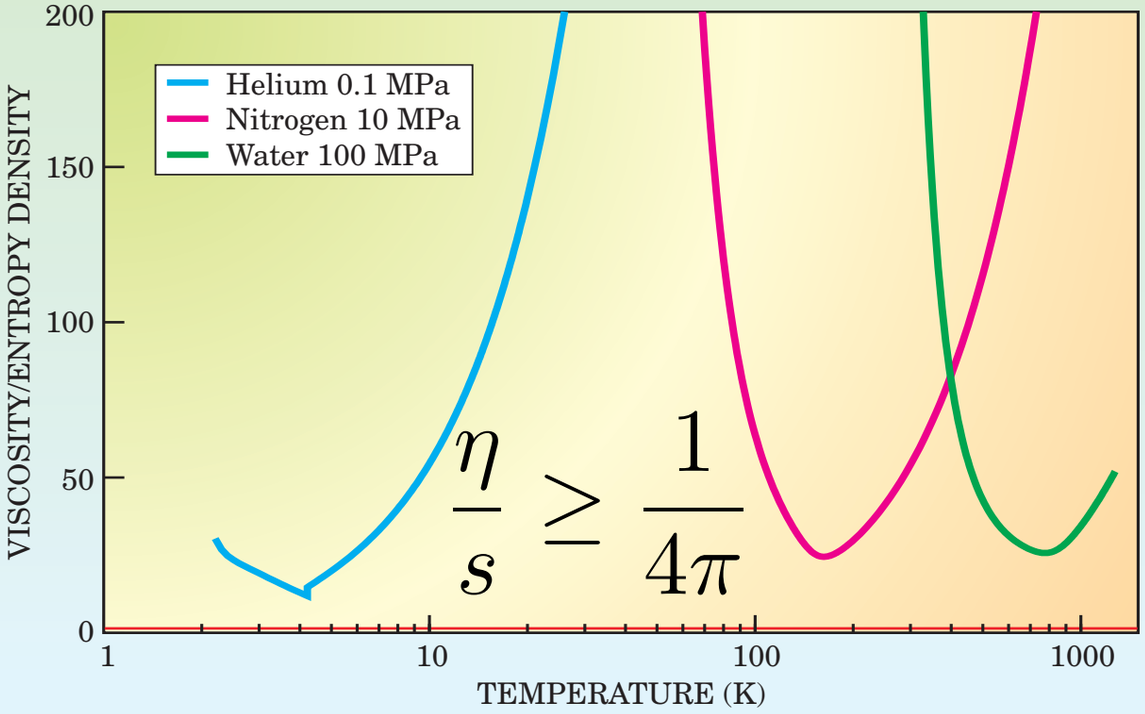
AdS/CFT arguments suggest that a QGP should be “strongly coupled”

$$n_{d.o.f.}^{sQGP} = \frac{3}{4} n_{d.o.f.}^{SB}$$

What is the fluid made of?



P. Kovtun, D.T. Son, A.O. Starinets Phys.Rev.Lett.94:111601,2005



Data suggests that A+A produces a strongly-coupled system with subhadronic degrees of freedom (“sQGP”) → perhaps saturating “viscosity bound” from AdS/CFT

hep-th/0605182
PUPT-2198

Drag force in AdS/CFT

Jay 2006

Mach cones from AdS/CFT, Gubser et al hep-th/0607022

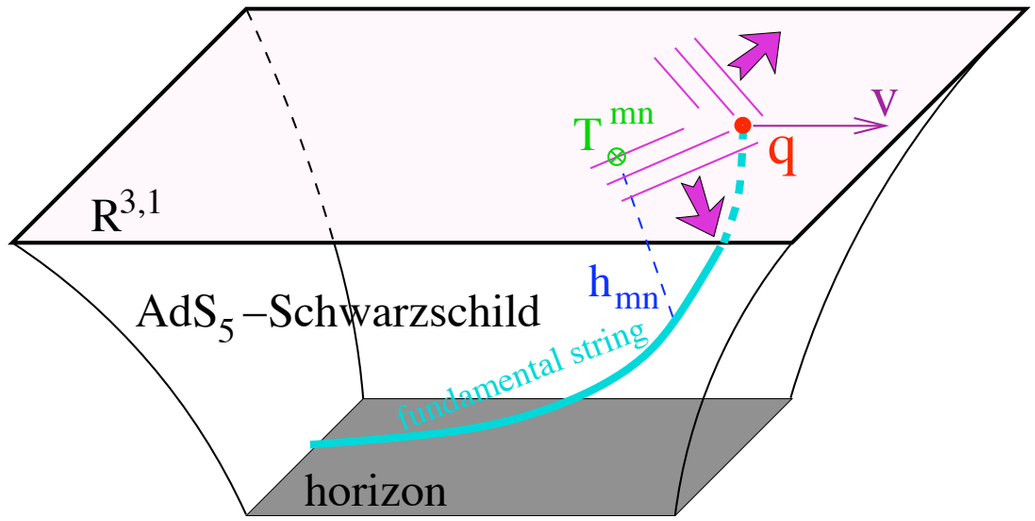


Figure 1: The AdS_5-Schwarzschild background is part of the near-extremal D3-brane, which encodes a thermal state of $\mathcal{N} = 4$ supersymmetric gauge theory [24]. The external quark trails a string into the five-dimensional bulk, representing color fields sourced by its fundamental charge and interacting with the thermal medium.

May 2006

QCD review
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Energy Loss of Gluons, Baryons and k-Quarks in an N=4 SYM Plasma
Sunday, 07:00 PM
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Dec 14, '06, 07:00 PM

YEAR IN SCIENCE 2006

EMAIL PRINT

THE VANGUARD OF SCIENCE

We picked a few of the most exciting research areas and asked leading scientists: Where is your field heading in 2007?

by EDIT STAFF • Posted January 3, 2007 06:20 PM

High Energy Physics

The coming year will see a number of interesting developments as the Large Hadron Collider (LHC) goes online. The enormous amount of data generated by the LHC will force us to refine our methods—and explore new ones—for extracting and interpreting information from high energy collisions. This work should lead to new insights into the masses of elementary particles and the consequences of various models for particle physics and cosmology.

Also of interest is the recent application of string theory to the physics being done at the Relativistic Heavy Ion Collider (RHIC), where string theory permits some calculations that would otherwise be intractable. The idea at RHIC is to better understand the strong force that binds together the elements of a nucleon, and 2007 may see the theoretical advances of string theory inform the experimental results from RHIC.

—Lisa Randall, Harvard University

Astrobiology

On February 28, 2007, for the first time, human technology will be operating on five

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—Lisa Randall, Harvard University

Of course, some may disagree...

...but in the end the "right" approach will be validated by both qualitative concepts, and quantitative predictions

New Yorker, Jan. 8, 2007

Qualitative Assessment

Hotter (>10^{12} ^{o}K)
Denser (>30 GeV/fm^3)
Smaller (~6 fm)
Faster (τ_0<1 fm/c)

and “nearly” perfect

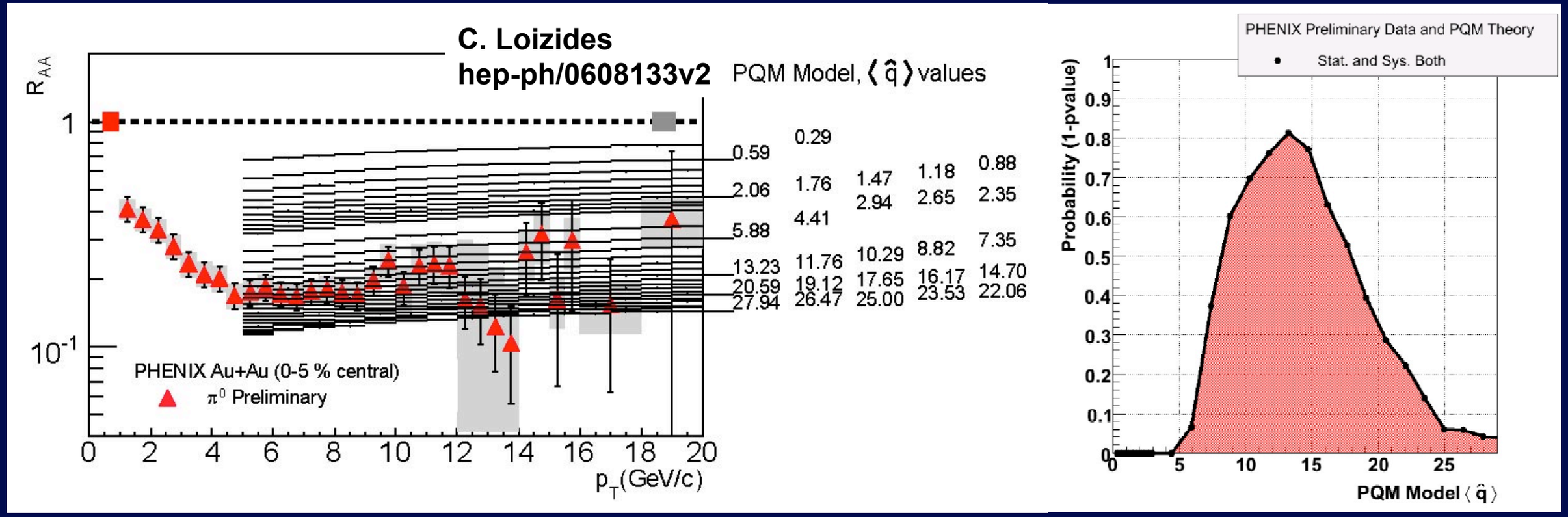
Quantitative Assessment

What is the

Thermalization time
Energy density
Stopping power
Viscosity

and with what
precision?

Estimating Stopping Power

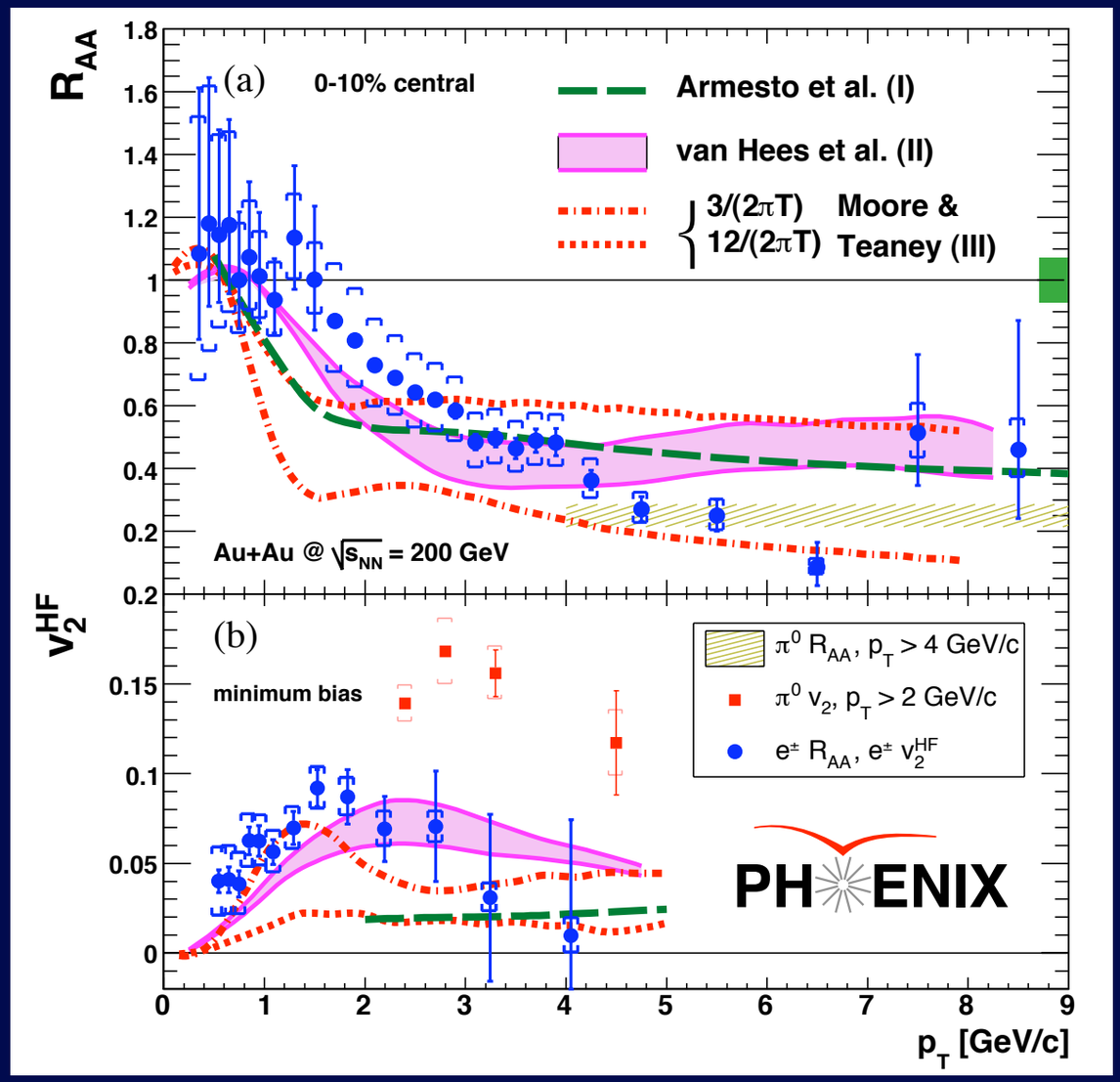


$$\Delta E \propto \hat{q} \propto \langle p_T^2 \rangle / \lambda$$

PHENIX χ^2 fits to PQM indicate $6 < \hat{q} < 24\ \mathrm{GeV}^2/\mathrm{fm}$.
(model dependent: transverse flow, 2+1D, 3+1D)

Comparisons with theory will require advances in experimental precision at high p_T: RHIC II luminosities

Estimating η w/ Heavy Quarks

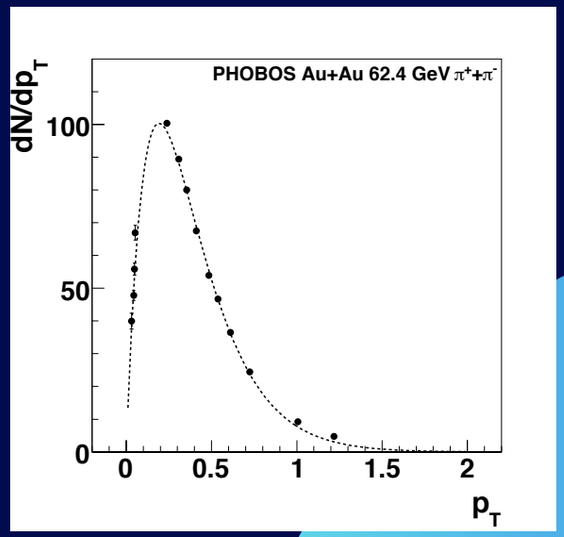


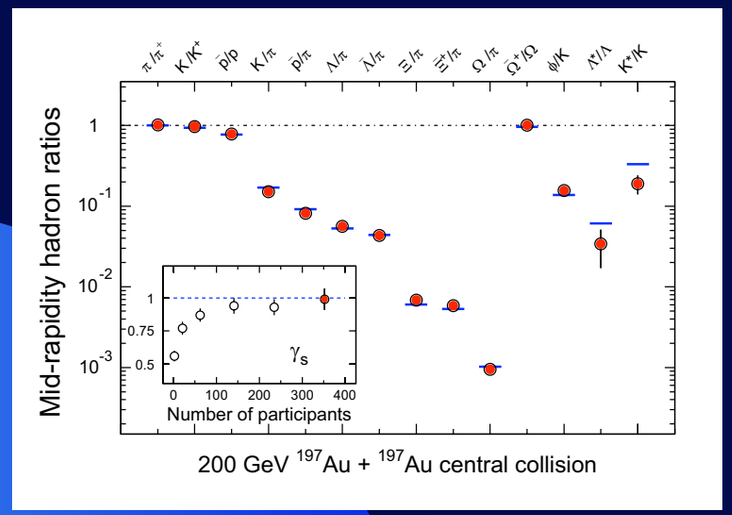
Charm R_{AA} is correlated with v_2:
comparisons with heavy quark rescattering models→ η/s

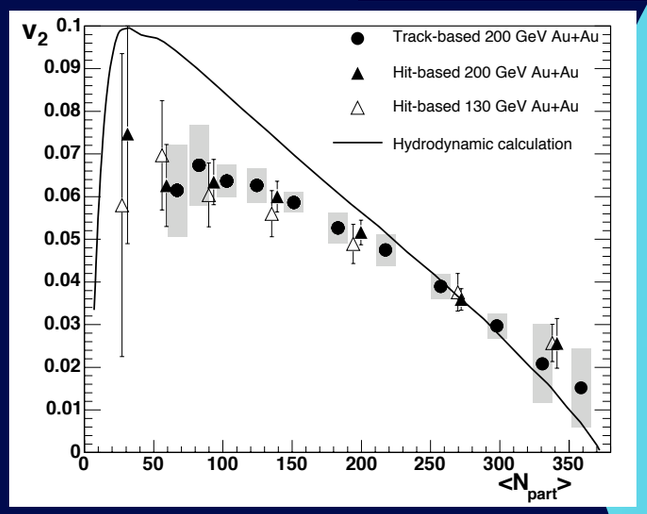
Comes close to quantum limit suggested by AdS/CFT

RHIC II detector upgrades will allow direct charm ID

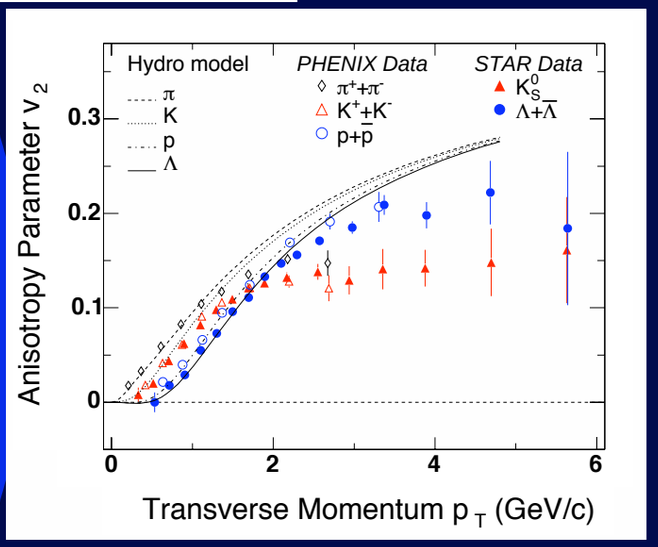
Status of RHIC Science

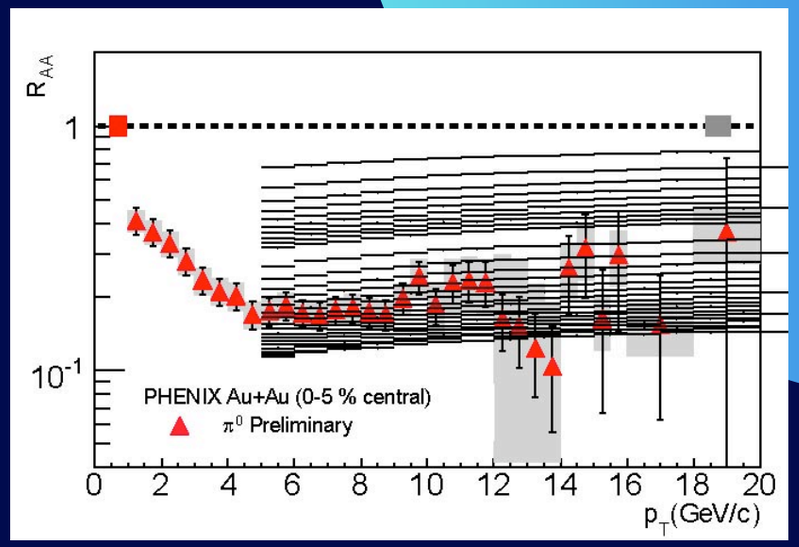


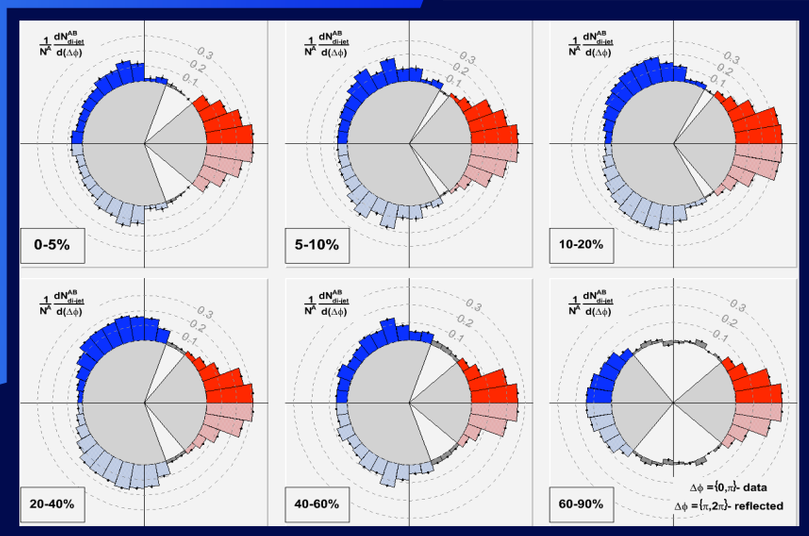




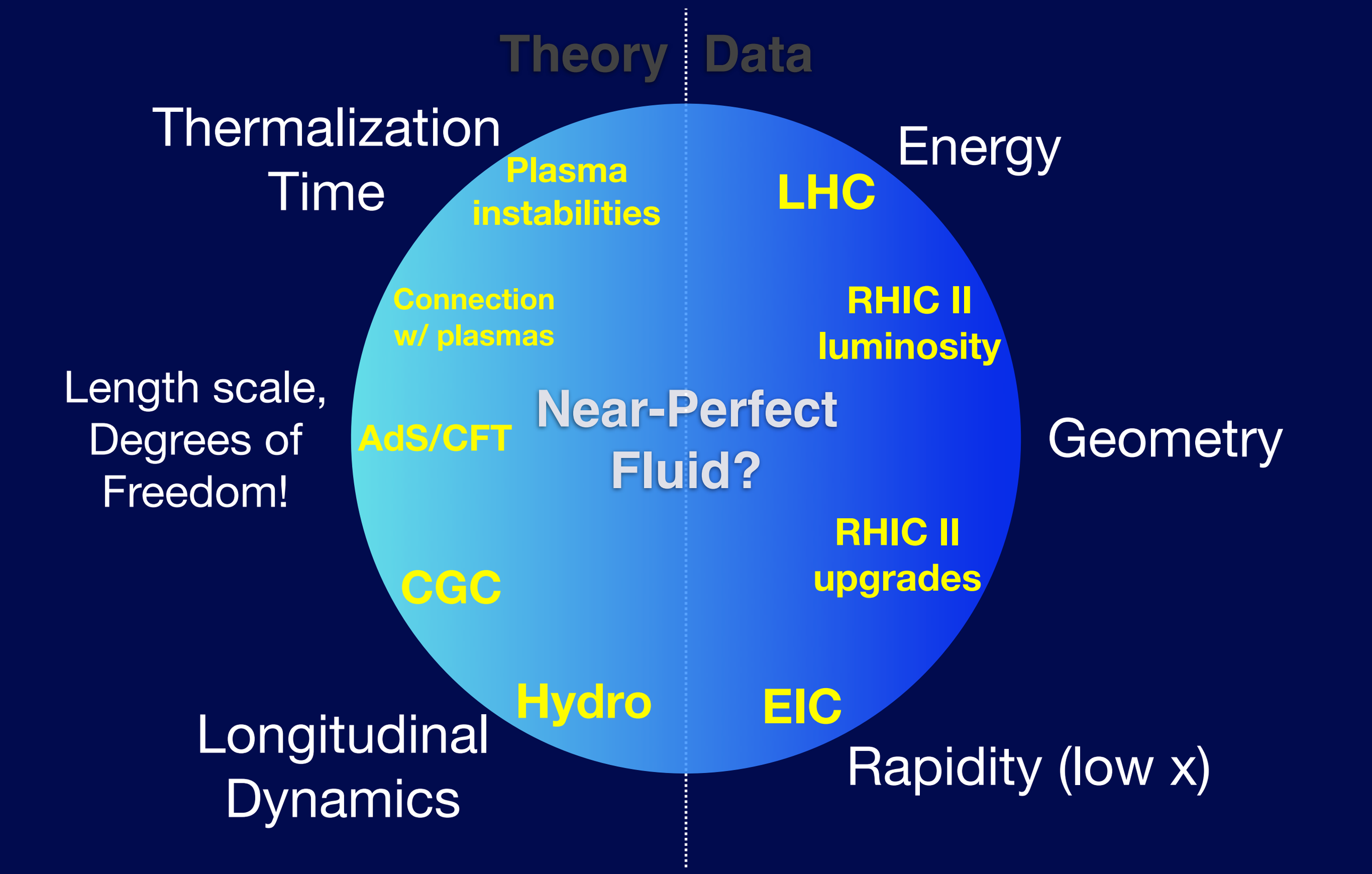
Near-Perfect Fluid?







Westward, Ho!


Theory
Data
Thermalization Time
Energy
Plasma instabilities
LHC
Connection w/ plasmas
RHIC II luminosity
Length scale, Degrees of Freedom!
Near-Perfect Fluid?
AdS/CFT
Geometry
RHIC II upgrades
CGC
Hydro
EIC
Longitudinal Dynamics
Rapidity (low x)

Closing Thoughts

Measurements

A+A Collisions

Phenomenology

Global Variables

High p_T Probes

Particle Yields

Theory

Hydrodynamics

Hadronization

Energy loss

strong-field QCD

perturbative QCD

lattice QCD

AdS/QCD
(strong coupling)

QCD

Closing Thoughts

Measurements

RHIC data has reached new heights of scope and precision: RHIC II, EIC and LHC will consolidate these advances

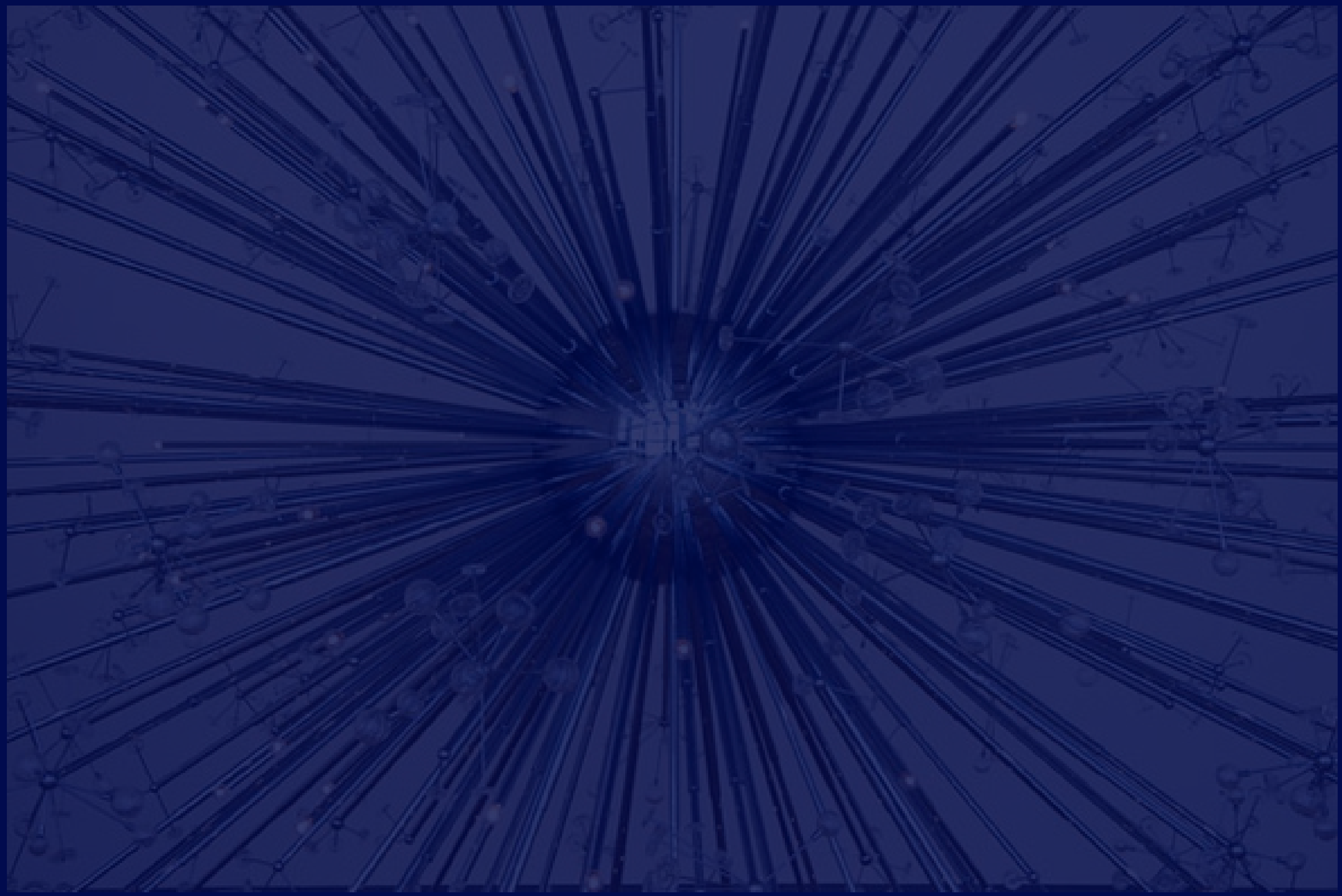
Phenomenology

There remain great opportunities in RHIC phenomenology to quantitatively link data & theory with systematic studies

Theory

RHIC theory is pushing the frontiers of QCD in a wide variety of dynamical regimes

QCD



Josiah McElheny. *The End of Modernity: Extended model for Total Reflected Abstraction*. 2004