The Abdus Salam International Centre for Theoretical Physics

United Nations Educational, Scientific and Cultural Organization

IAEA International Atomic Energy Agency

2134-12

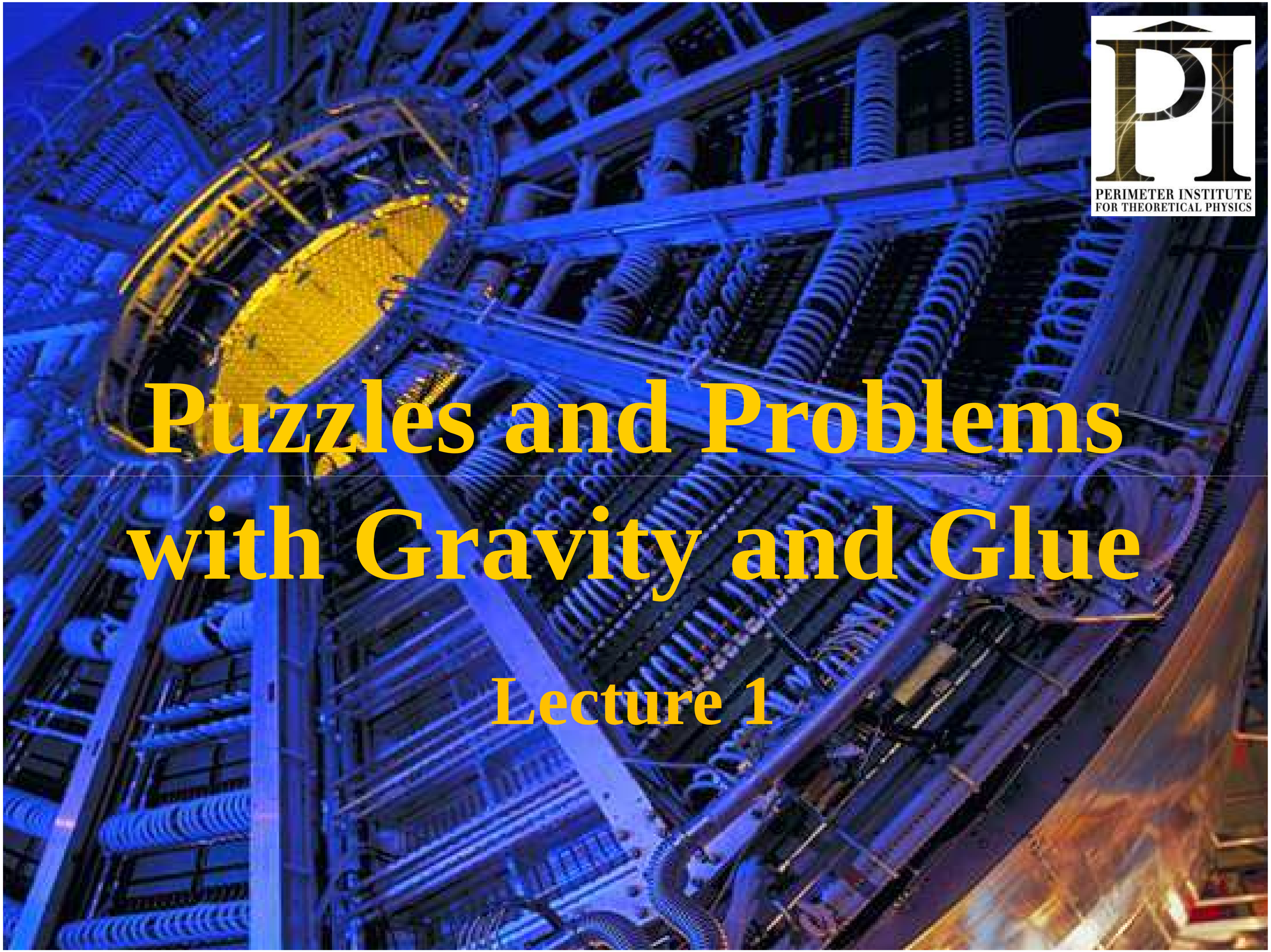
Spring School on Superstring Theory and Related Topics

22 - 30 March 2010

Puzzles and Problems for Gravity and Glue
Lecture I

R.C. Myers

Perimeter Institute for Theoretical Physics
Waterloo
Canada



Puzzles and Problems with Gravity and Glue

Lecture 1

PERIMETER INSTITUTE FOR THEORETICAL PHYSICS

PERIMETER INSTITUTE FOR THEORETICAL PHYSICS

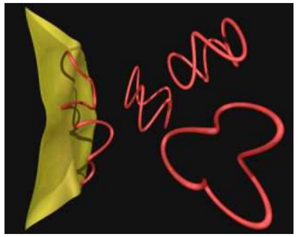
Topics in AdS/sQGP

Lecture 1

Themes:

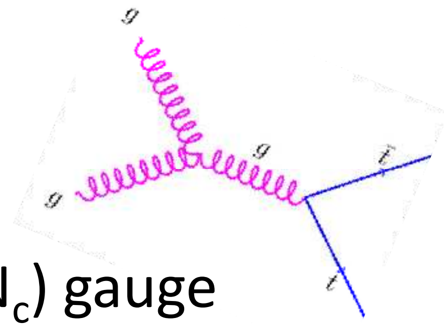
- AdS/CFT correspondence may be a powerful tool to study (certain phases of) QCD
- touch on holographic hydrodynamics
- examine role/effects of higher curvature gravity interactions in AdS/CFT calculations

AdS/CFT primer: an order of limits



N_c D3-branes:
open & closed strings

Low energy limit

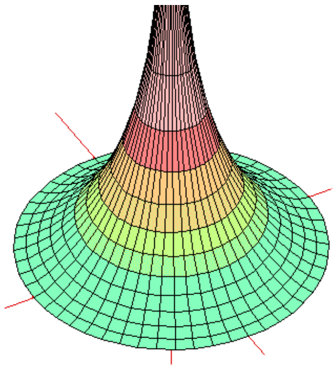


$SU(N_c)$ gauge
field theory

Strong coupling limit:
D3-branes develop
strong gravitational
fields

Strong coupling
limit

Curved space gravity
solution for N_c D3-branes:
closed strings



Low energy limit

~~Strongly coupled
gauge theory~~

Closed strings
in D3-brane throat

It's still the same physics!
Maldacena, 1997

(Maldacena; Witten; Gubser, Klebanov & Polyakov, . .

AdS/CFT correspondence:

Type IIb superstrings
on $AdS_5 \times S^5$
with RR flux N_c

$\Longleftrightarrow$

(3+1)-dimensional
$\mathcal{N}$=4 SU(N_c)
super-Yang-Mills

Holographic dictionary begins:

$$\lambda \;=\; g^2_{YM}\, N_c \;=\; L^4/\ell_s^4$$

$$g^2_{YM} \;=\; 4\pi\, g_s$$

- much of subsequent work is extending/better understanding the entries in this dictionary

(Maldacena; Witten; Gubser, Klebanov & Polyakov, . .

AdS/CFT correspondence:

gravity

~~Type IIb superstrings~~
on AdS_5 X S^5
with RR flux N_c

$\Longleftrightarrow$

(3+1)-dimensional
$\mathcal{N}$=4 SU(N_c)
super-Yang-Mills

Problem: we don't know how to do string theory in RR backgrounds very well!!

Solution: take limit to classical (super)gravity

$g_s \ll 1$ ← control loop/quantum string effects

$L^4/\ell_s^4 \gg 1$ ← control contribution of higher curvature or higher derivative interactions

(Maldacena; Witten; Gubser, Klebanov & Polyakov, . .

AdS/CFT correspondence:

gravity

~~Type IIb superstrings~~
on $AdS_5 \times S^5$
with RR flux N_c

⟺

(3+1)-dimensional
$\mathcal{N}$=4 SU(N_c)
super-Yang-Mills

$$g_s \ll 1 \qquad\qquad L^4/\ell_s^4 \gg 1$$

work with classical two-derivative (super)gravity action

[as well as occasional string/D-brane probes]

in dual gauge theory: $N_c \gg \lambda \gg 1$

't Hooft limit – physics dominated by planar diagrams
[still lots of SYM loops]

with AdS/CFT correspondence, we have a great tool to study strongly coupled gauge theories – only problem is that its the "wrong" gauge theory!

QCD	**$\mathcal{N}$=4 SYM**
$N_c = 3 = N_f$	N_c large
Matter: fermions in fundamental rep.	Matter: fermions & scalars in adjoint rep.
confinement, discrete spectrum, chiral symmetry breaking, ...	deconfined, conformal, supersymmetric, ...

very different !!

with AdS/CFT correspondence, we have a great tool to study strongly coupled gauge theories – only problem is that its the “wrong” gauge theory!

so work harder! – break SUSY and conformal symmetries, e.g.,

top-down
- Witten, hep-th/9803131
- Sakai & Sugimoto, hep-th/0412141 (2009 Trieste summer school)

bottom-up
- Gursoy, Kiritsis & Nitti, 0707.1324, 0707.1349

Not the topic of these lectures

- we will look at possible connection between AdS/CFT and QCD from different angle

$\longrightarrow$ finite temperature

(breaks both SUSY and conformal symmetries)

- recent years have seen a great deal of activity which is primarily driven by two suprises:

Surprise 1: experiments at RHIC have discovered a new phase of nuclear matter, known as the strongly coupled quark-gluon plasma, which behaves like a **near ideal fluid** with:

$$\eta/s \simeq .08 \; - \; .16$$

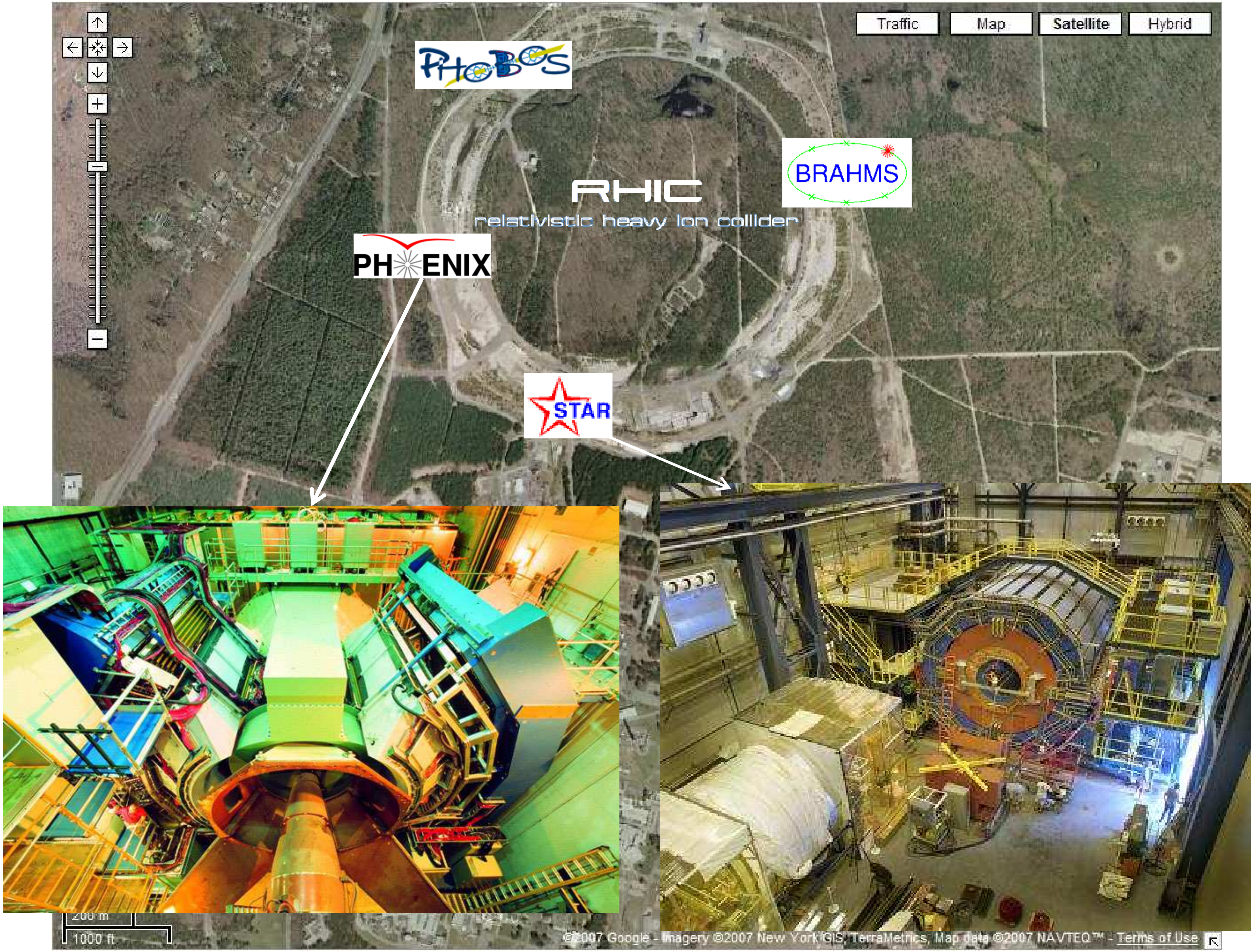
Theoretical challenge: strong-coupling dynamics!!

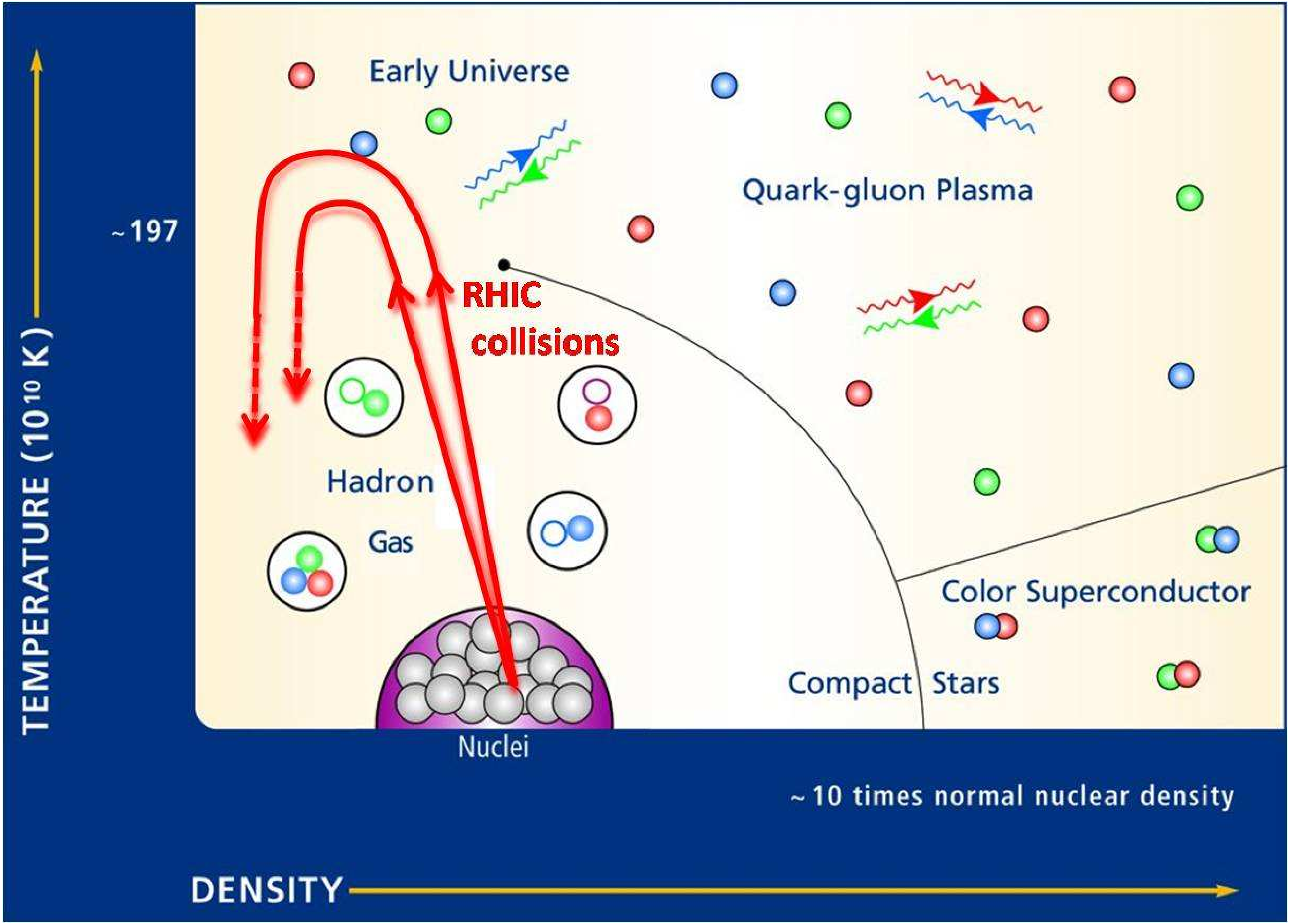
Surprise 2: examining hydrodynamic properties of N=4 SYM plasma with AdS/CFT, Kovtun, Son & Starinets found:

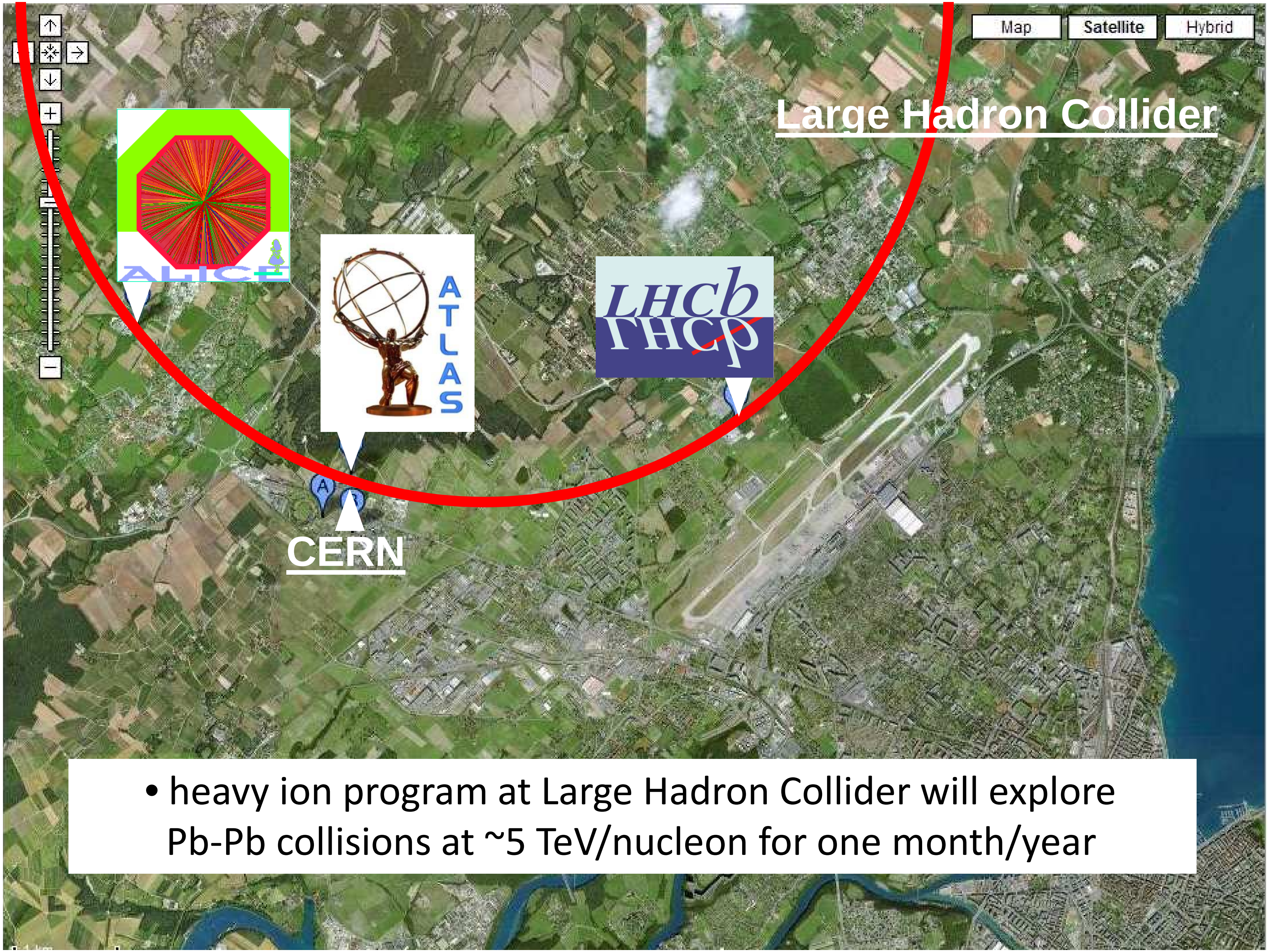
$$\frac{\eta}{s} = \frac{1}{4\pi} \sim 0.08$$

"universal result for all theories with Einstein gravity dual"

(Kovtun, Son & Starinets; Buchel & Liu; Benincasa, Buchel &Naryshkin; Iqbal & Liu; . . .)


Traffic
Map
Satellite
Hybrid
PHOBOS
BRAHMS
RHIC
relativistic heavy ion collider
PHENIX
STAR
200 m
1000 ft
©2007 Google - Imagery ©2007 New York GIS, TerraMetrics, Map data ©2007 NAVTEQ™ - Terms of Use

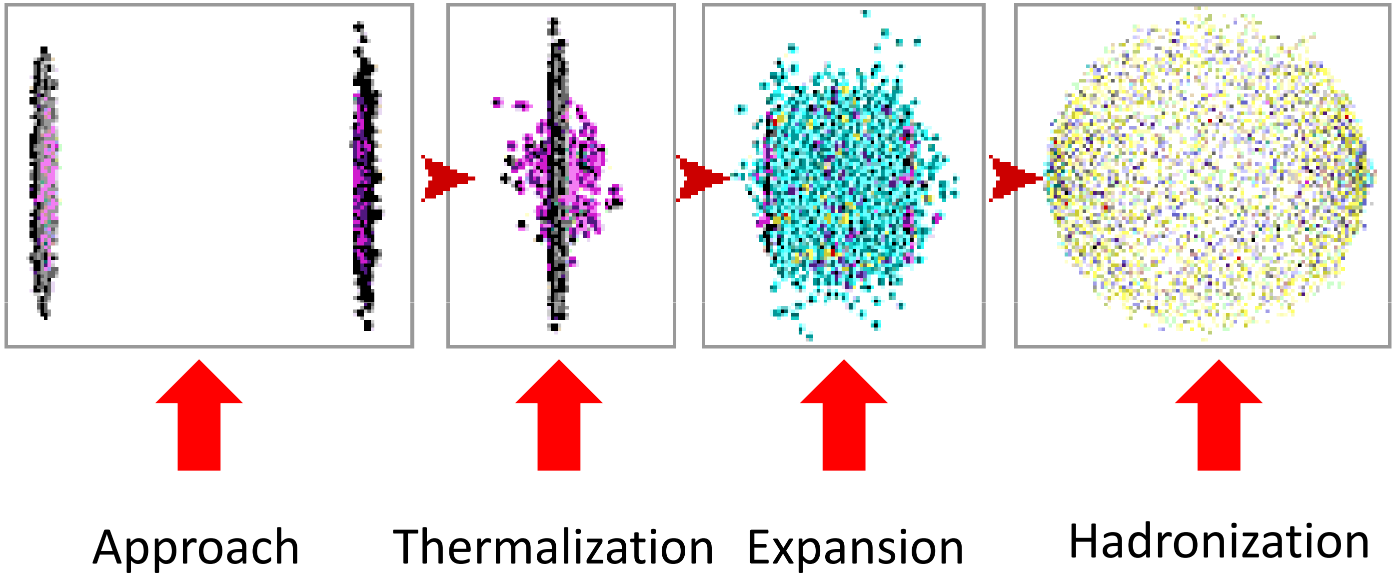

Early Universe
Quark-gluon Plasma
~197
TEMPERATURE (10^{10} K)
RHIC
collisions
Hadron
Gas
Color Superconductor
Compact Stars
Nuclei
~10 times normal nuclear density
DENSITY



- heavy ion program at Large Hadron Collider will explore Pb-Pb collisions at ~5 TeV/nucleon for one month/year

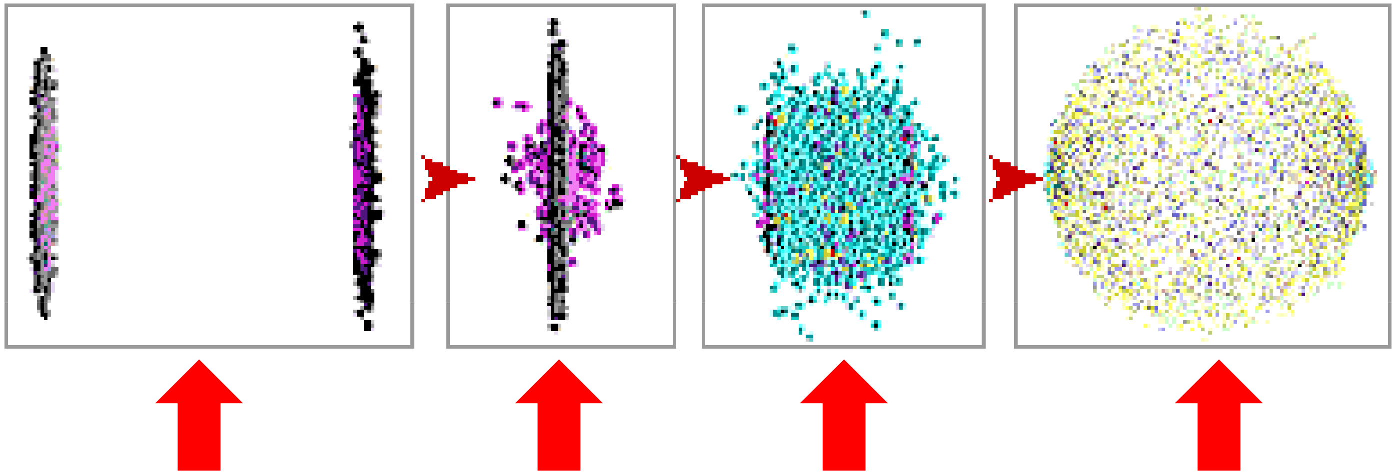
RHIC data indicates collisions produce thermally equilibriated matter which subsequently expands like a **near ideal fluid** (not a gas!)

Anatomy of collision:



RHIC data indicates collisions produce thermally equilibriated matter which subsequently expands like a **near ideal fluid** (not a gas!)

Anatomy of collision:

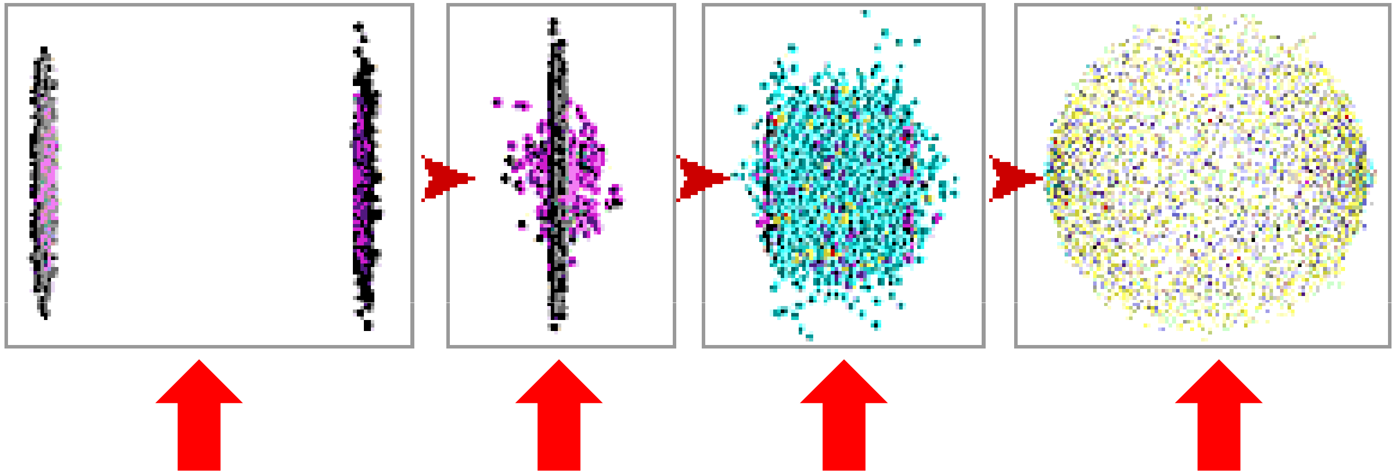


Approach Thermalization Expansion Hadronization

Gold nuclei flattened by relativistic effects; energy ~ 100 GeV/nucleon

RHIC data indicates collisions produce thermally equilibriated matter which subsequently expands like a **near ideal fluid** (not a gas!)

Anatomy of collision:

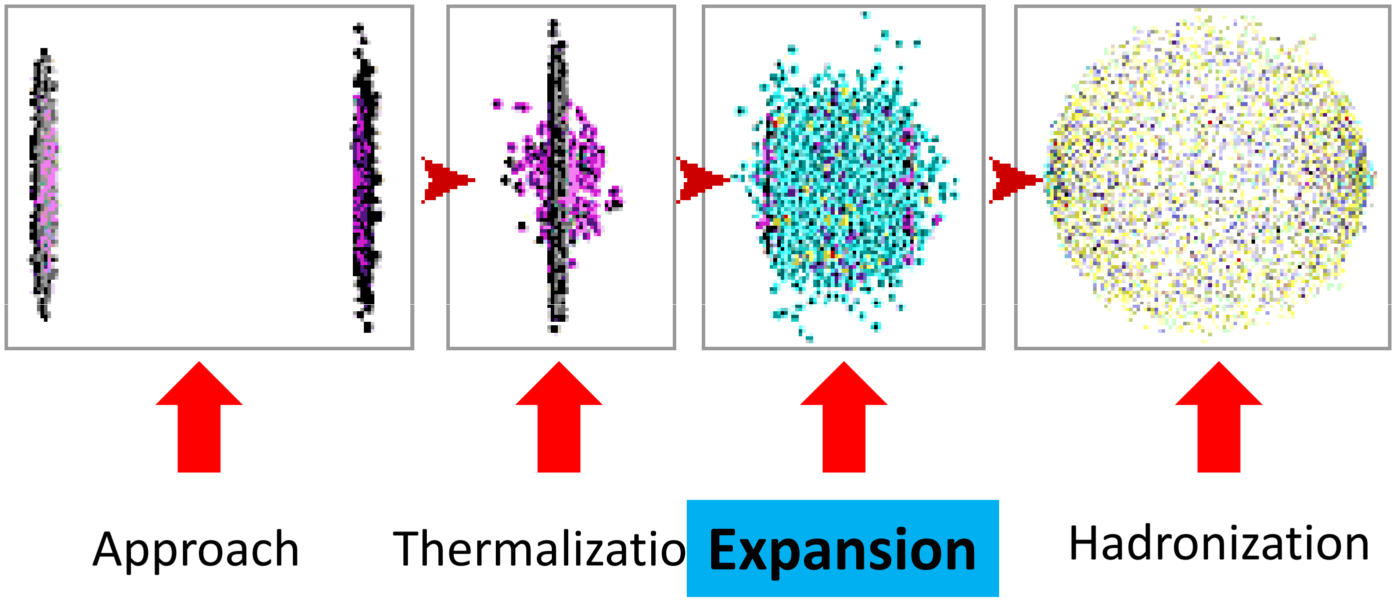


Approach **Thermalization** xpansion Hadronization

some of the energy
converted to intense heat
liberating quarks and gluons;
timescale ~ 2-3 X 10^{-22} sec

RHIC data indicates collisions produce thermally equilibriated matter which subsequently expands like a **near ideal fluid** (not a gas!)

Anatomy of collision:

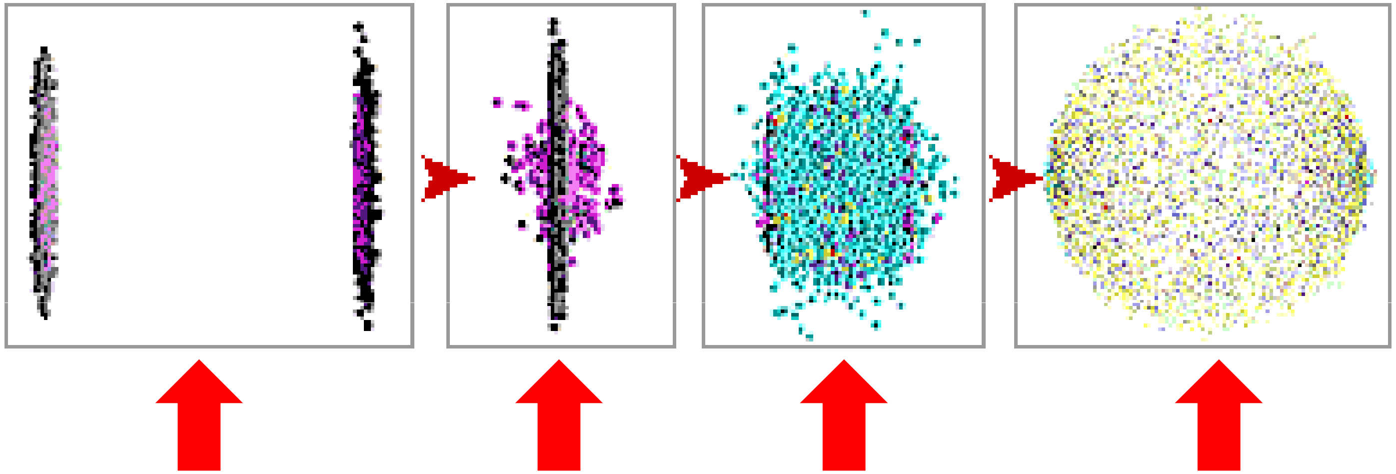


quark-gluon plasma exhibits
collective flow described
by hydrodynamics

→ "Elliptic flow"

RHIC data indicates collisions produce thermally equilibriated matter which subsequently expands like a **near ideal fluid** (not a gas!)

Anatomy of collision:

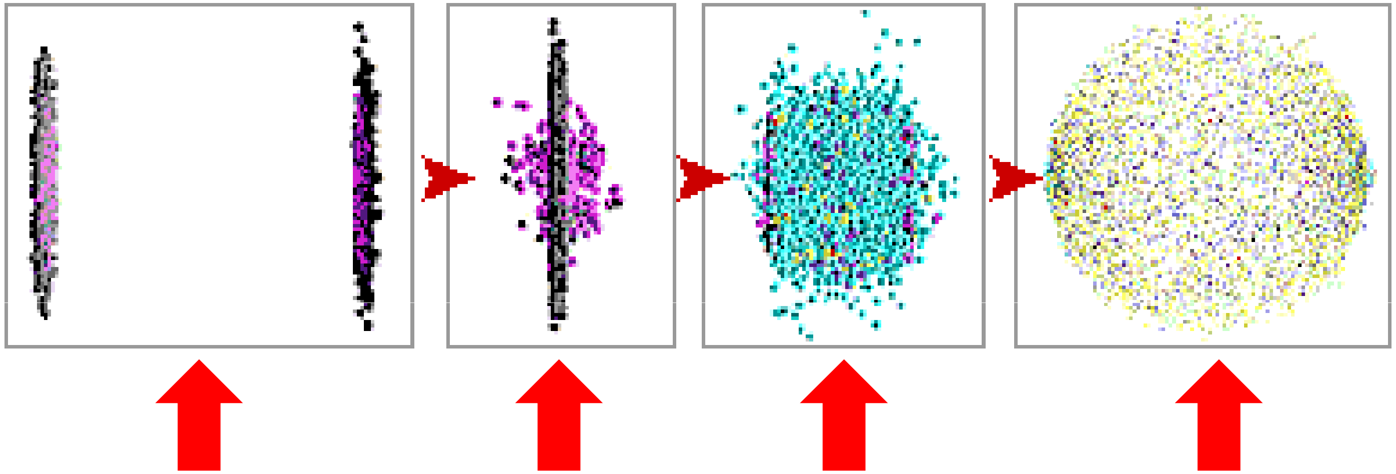


Approach Thermalization Expansion **Hadronization**

with expansion and cooling,
matter converted
back to hadrons

- AdS/CFT may have interesting things to say about any of the last three phases but primary focus has been on Expansion

Anatomy of collision:

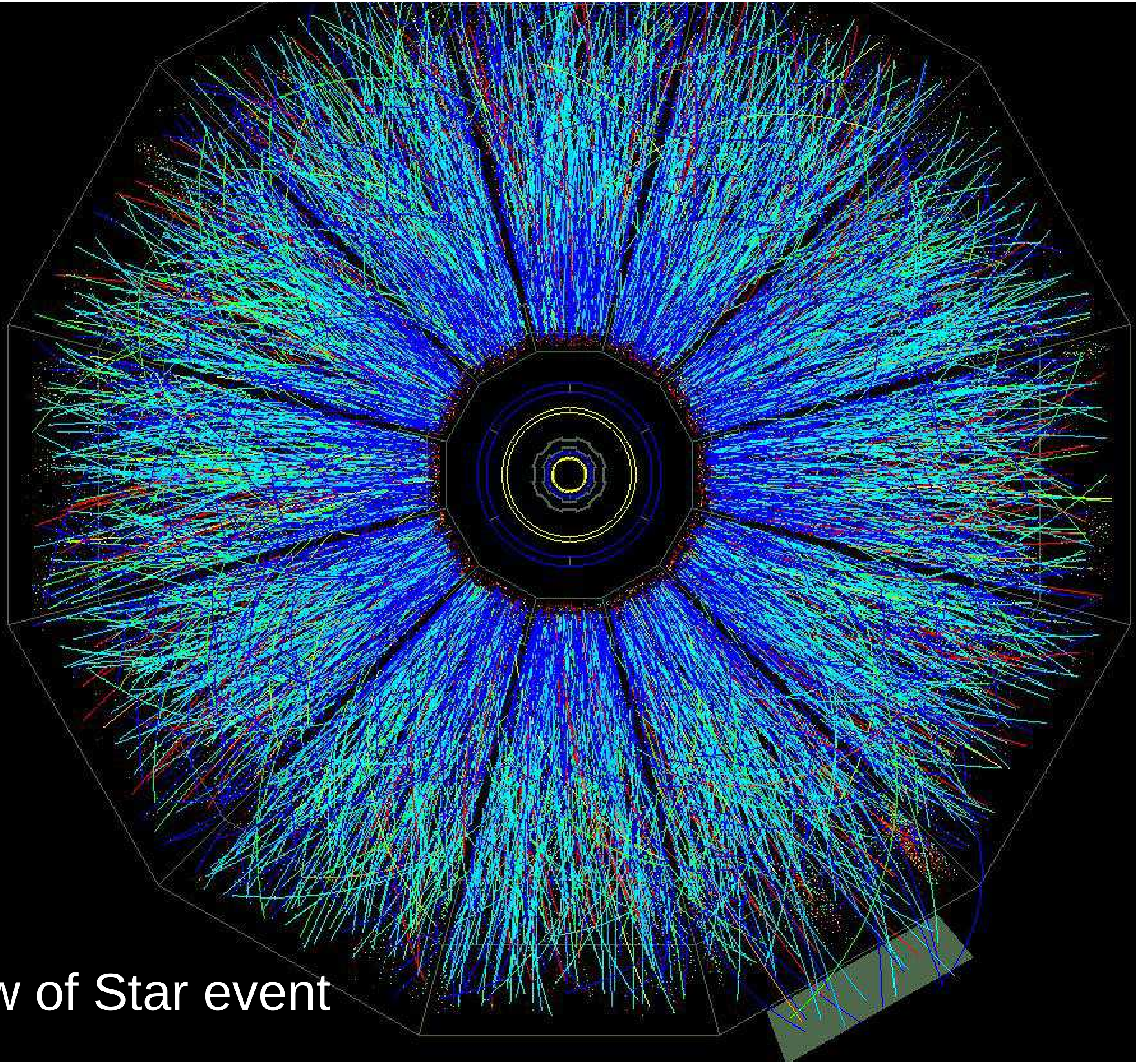


Approach   Thermalizatio   **Expansion**   Hadronization

quark-gluon plasma exhibits
collective flow described
by hydrodynamics

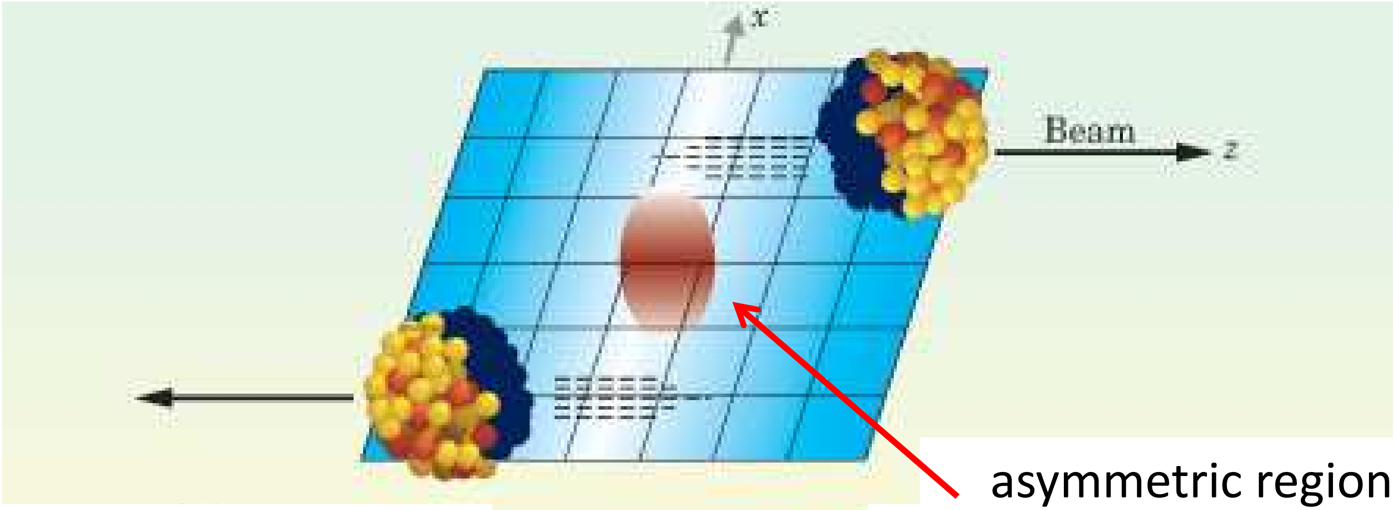
→ "Elliptic flow"

How do we learn anything from explosion of fireball?

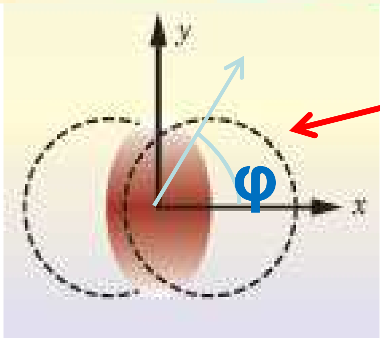


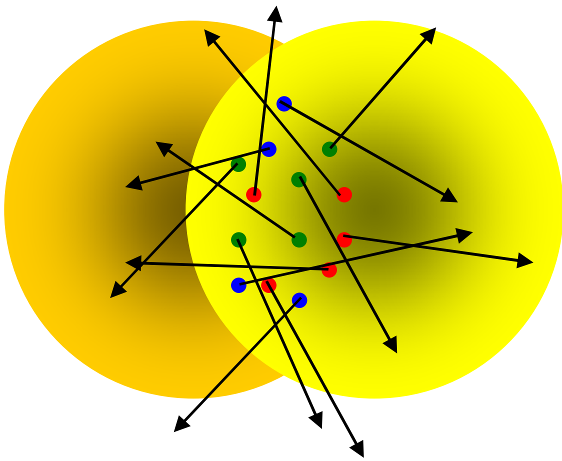
End-view of Star event

Consider collisions which are not head-on:



asymmetric region participates in collision; almond shape

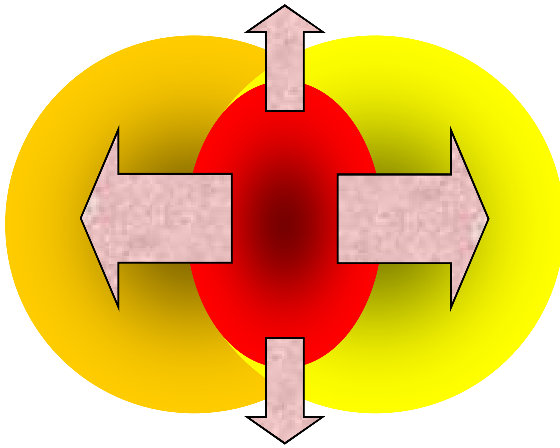




free-streaming particles emerge uniformly in φ

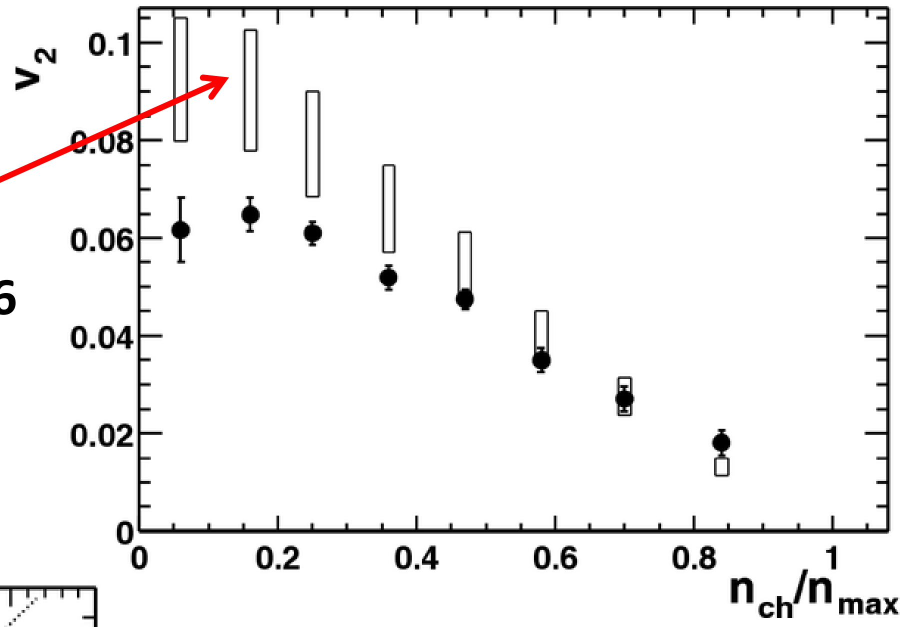
Collective flow: pressure gradients generate nonuniform distribution

$$v_2 \sim \langle \cos 2\phi \rangle \neq 0$$

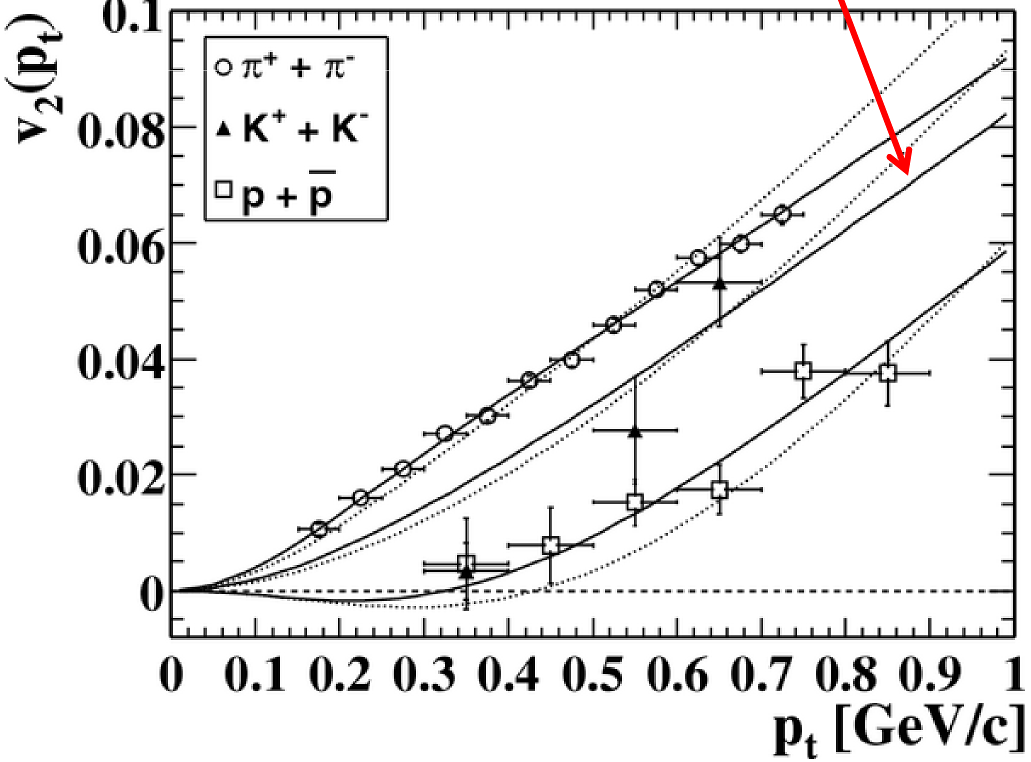


Data:

STAR (nucl-ex/0009011)

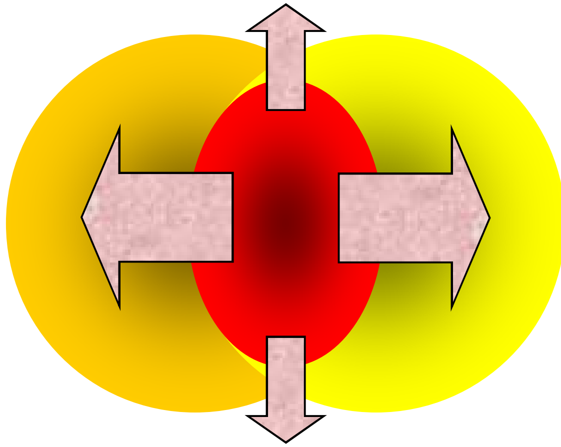


Theoretical predictions from hydrodynamic model: **hep-ph/0101136**



STAR (nucl-ex/0107003)

Elliptic flow:

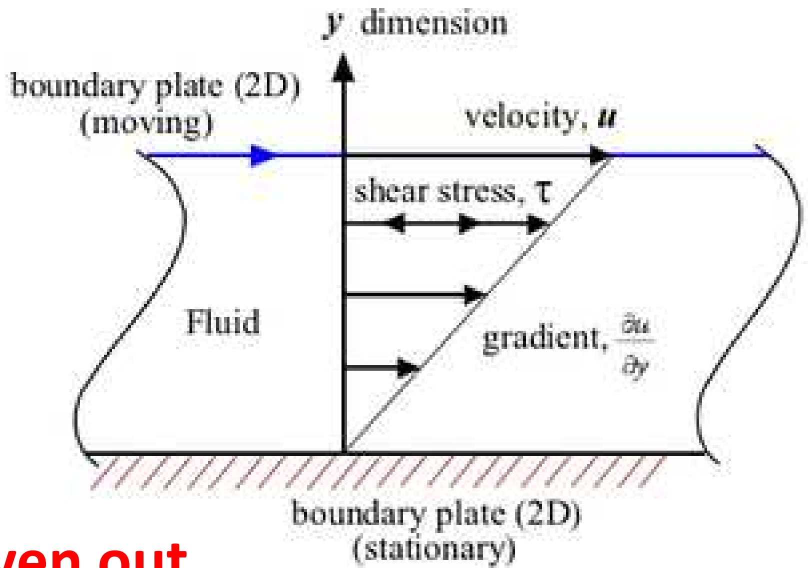


Collective flow:
pressure gradients generate
nonuniform distribution

$$v_2 \sim \langle \cos 2\phi \rangle \neq 0$$

theoretical models assume
Shear Viscosity η is small!

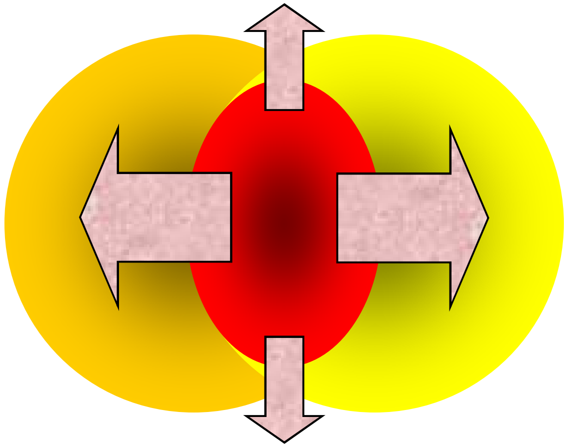
$$\tau = \eta \, \frac{\partial u}{\partial y}$$



[much more later]

large shear viscosity would even out flow and produce uniform distribution

Elliptic flow:



Collective flow:
pressure gradients generate
nonuniform distribution

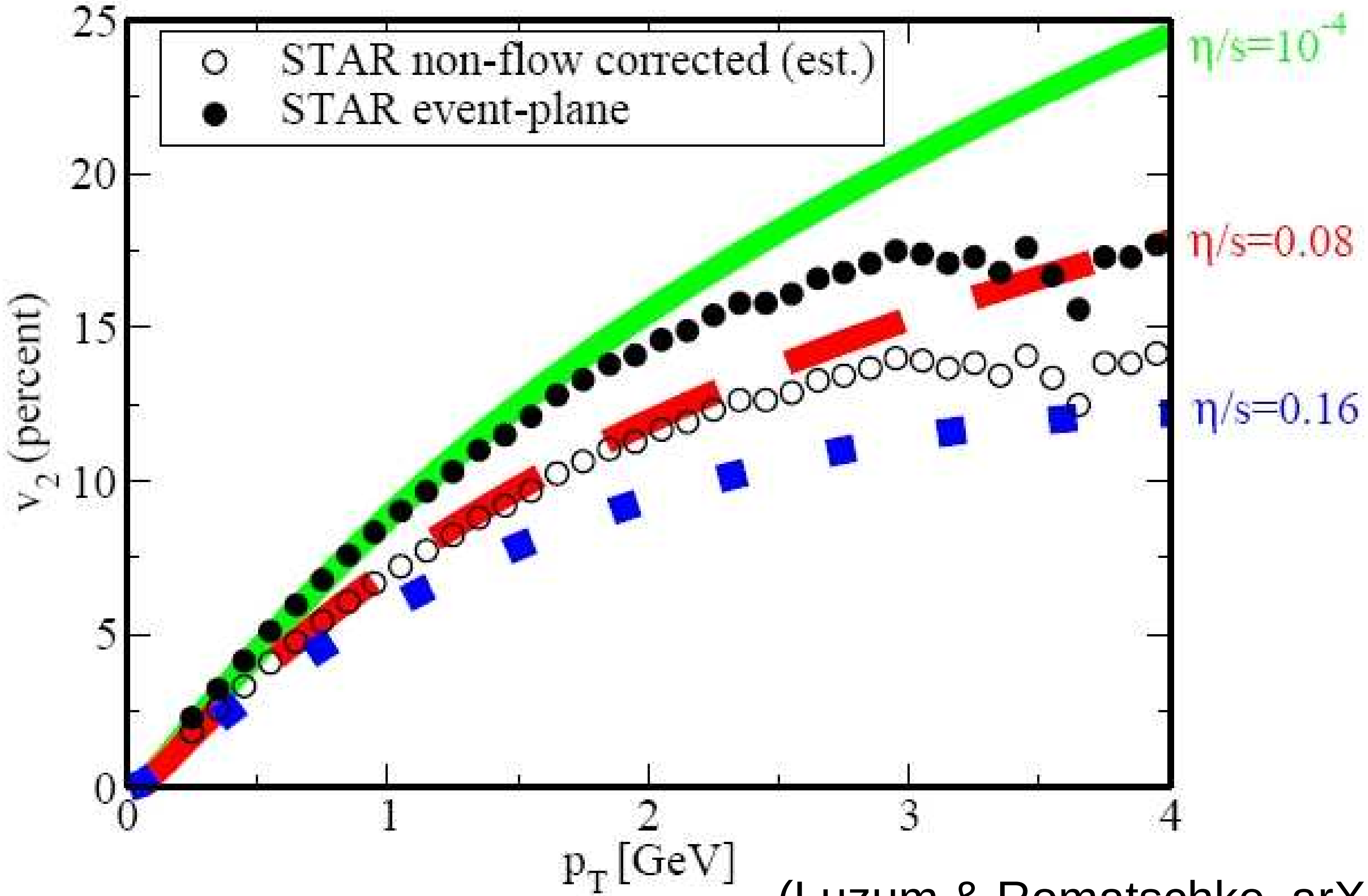
$$v_2 \sim \langle \cos 2\phi \rangle \neq 0$$

theoretical models assume
Shear Viscosity η is small!

How small?

Elliptic flow: **shear viscosity η is small!**

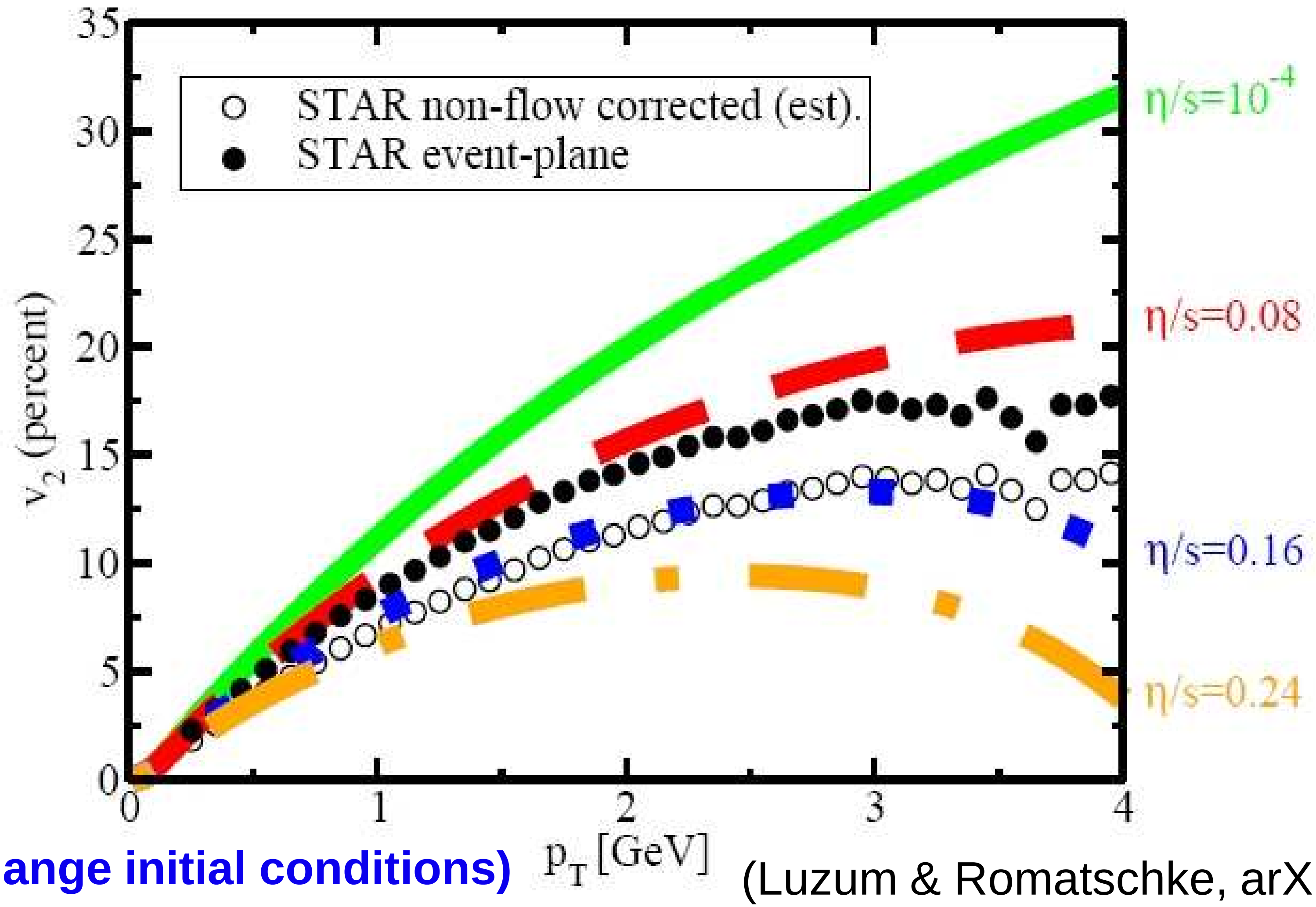
• simulations characterized in terms of ratio of shear viscosity to entropy density: η/s (dimensionless in units where $\hbar = 1 = k_B$)



(Luzum & Romatschke, arXiv:0804.4015)

Elliptic flow: shear viscosity η is small!

- simulations characterized in terms of ratio of shear viscosity to entropy density: η/s (dimensionless in units where $\hbar = 1 = k_B$)



(change initial conditions) (Luzum & Romatschke, arXiv:0804.4015)

Elliptic flow: $\boxed{\text{shear viscosity } \eta \text{ is small!}}$

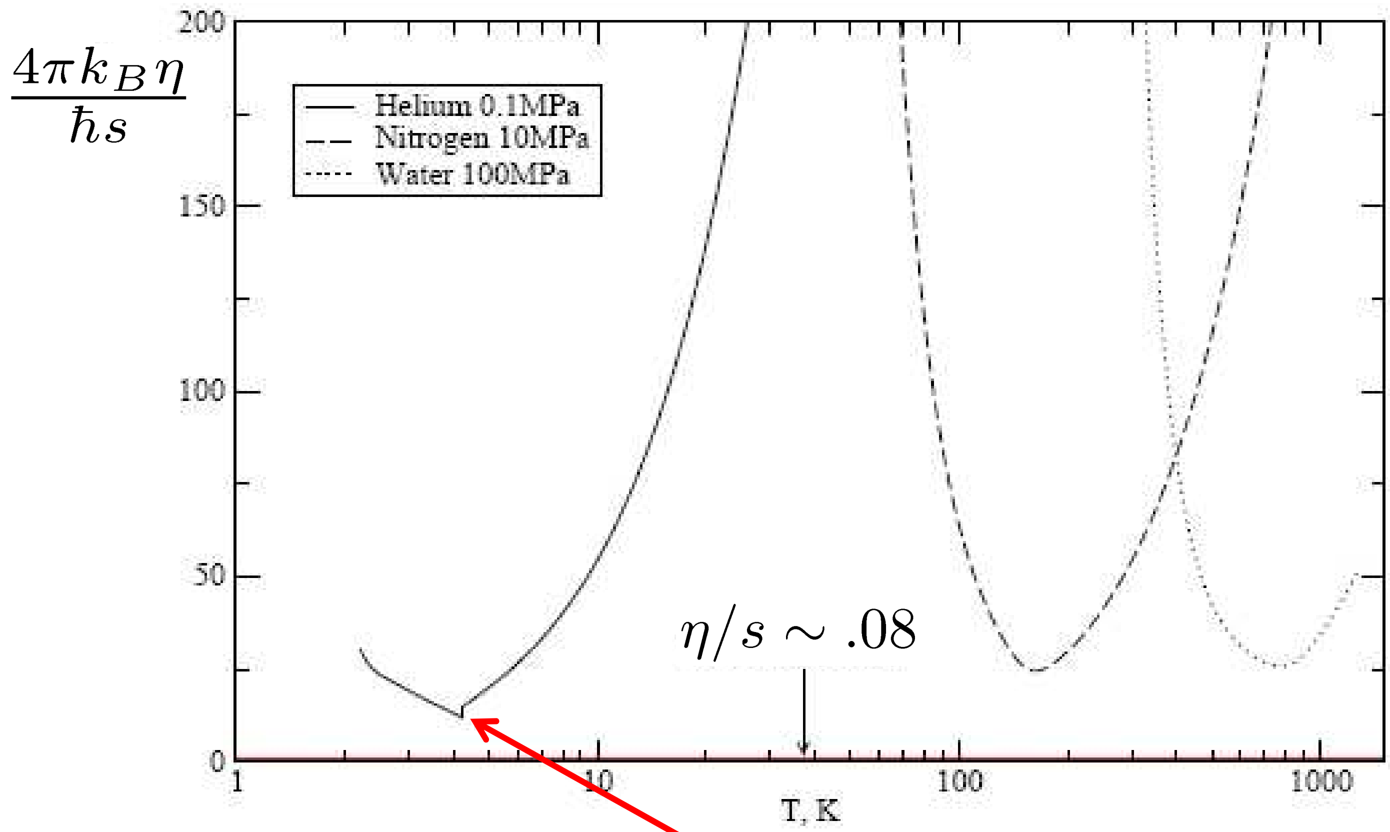
- simulations characterized in terms of ratio of shear viscosity to entropy density: η/s (dimensionless in units where $\hbar = 1 = k_B$)

(Luzum & Romatschke, arXiv:0804.4015)

- find: $\eta/s \simeq .08 \; - \; .16$
- greatest uncertainty is in initial energy distribution within almond shaped region
- simulations will continue to improve

  upper bound: $\eta/s < .2$ (D. Teaney: $\eta/s < .5$)
- note η/s is really small here – typical materials (liquid Helium, water) exhibit $\eta/s \gg 1$

- $\eta/s \simeq .08 - .16$ **is really small!**



$\eta/s|_{LiquidHelium} \simeq .8$

(hep-th/0405231)

Elliptic flow: shear viscosity η is small!

- simulations characterized in terms of ratio of shear viscosity to entropy density: η/s (dimensionless in units where $\hbar = 1 = k_B$)

(Luzum & Romatschke, arXiv:0804.4015)

- find: $\eta/s \simeq .08 \; - \; .16$
- greatest uncertainty is in initial energy distribution within almond shaped region
- simulations will continue to improve

  upper bound: $\eta/s < .2$ (D. Teaney: $\eta/s < .5$)
- note η/s is really small here – typical materials (liquid Helium, water) exhibit $\eta/s \gg 1$
- challenge for theorists – we need to describe strong coupling (real-time) dynamics
- standard tools (e.g., lattice gauge theory) are not effective

Elliptic flow: $\boxed{\text{shear viscosity } \eta \text{ is small!}}$

- simulations characterized in terms of ratio of shear viscosity to entropy density: η/s (dimensionless in units where $\hbar = 1 = k_B$)

(Luzum & Romatschke, arXiv:0804.4015)

- find: $\eta/s \simeq .08 \; - \; .16$

- recall:

Surprise 2: examining hydrodynamic properties of N=4 SYM plasma with AdS/CFT, Kovtun, Son & Starinets found:

$$\frac{\eta}{s} = \frac{1}{4\pi} \sim 0.08$$

- numbers look similar . . . . but so what??

	QCD	$\mathcal{N}$=4 SYM
T=0	N_c=3=N_f , fundamental fermions, confinement, discrete spectrum, ...	N_c large, adjoint fermions & scalars, deconfined, conformal, susy, ...

very different !!

Universal behaviour??

T>T$_C$	strongly-coupled plasma of gluons & fundamental matter deconfined, screening, finite corr. lengths, . . .	strongly-coupled plasma of gluons & adjoint (and fundamental) matter deconfined, screening, finite corr. lengths, . . .

very similar !!

T>>T$_C$	runs to weak coupling; free gas of quarks & gluons	coupling remains strong; strongly-coupled plasma

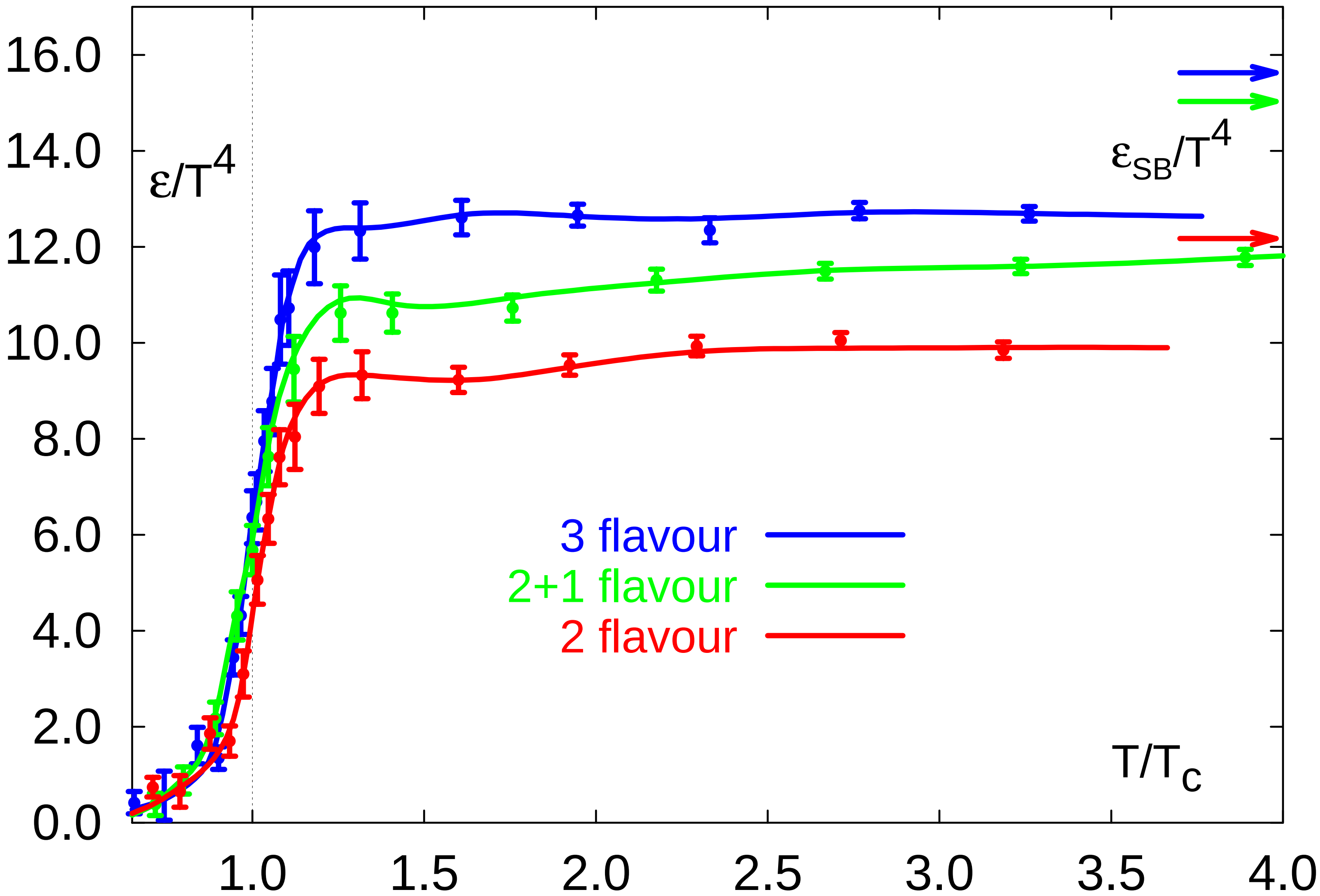
very different !!

- may find universal behaviour in intermediate regime (just above T_c) where we can import (qualitative and quantitative?) insights from N=4 SYM to understand QCD plasma

- sounds good but . . . .

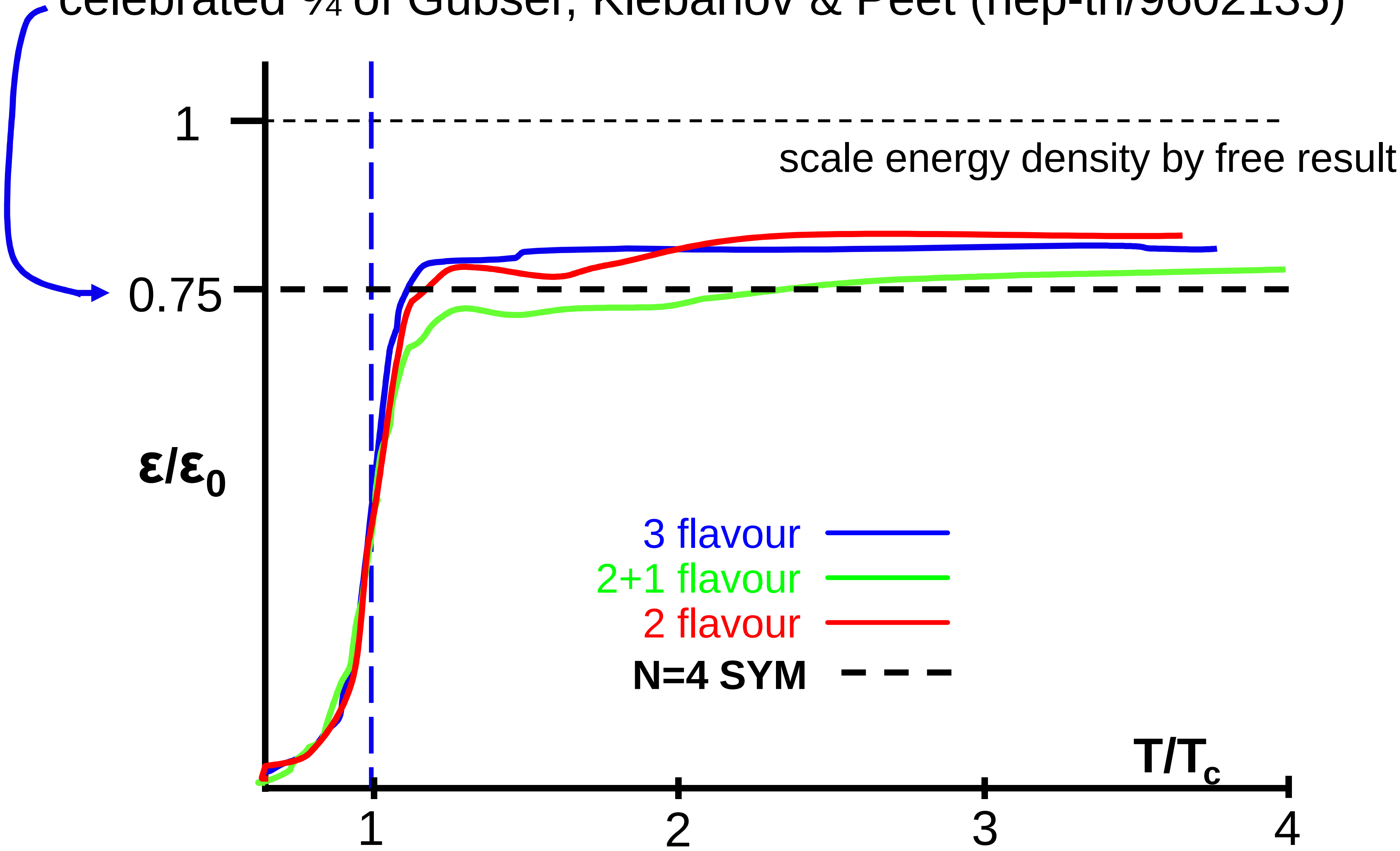
Lattice studies suggest that QCD makes a cross-over to quark-gluon plasma at T ~ 175 ± 15 MeV (~ 10^{12} K)

Karsch (hep-lat/0106019)

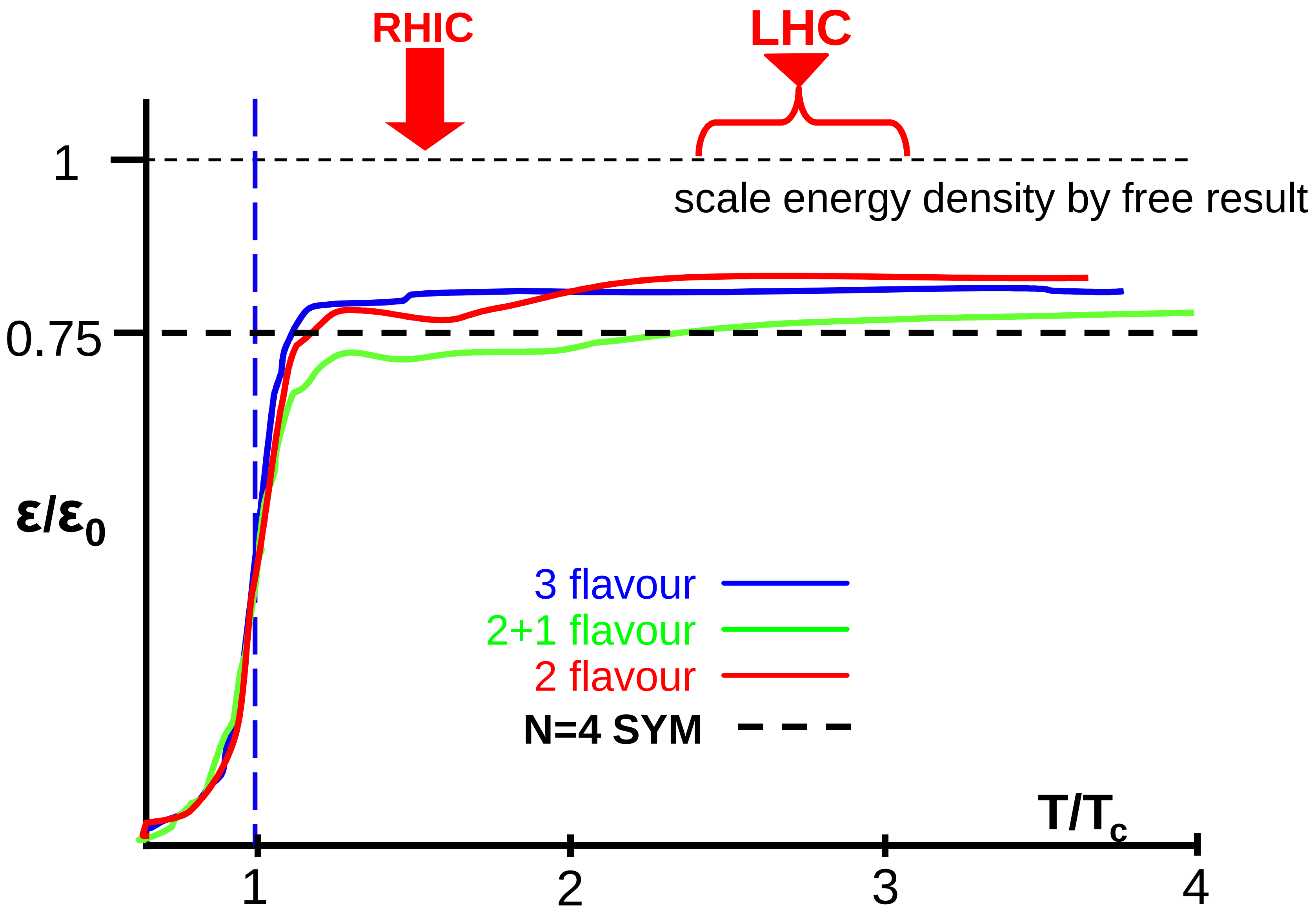


- scale energy density by free result: $\frac{\varepsilon_0}{T^4} = \frac{\pi^2}{30} N_{m=0}$

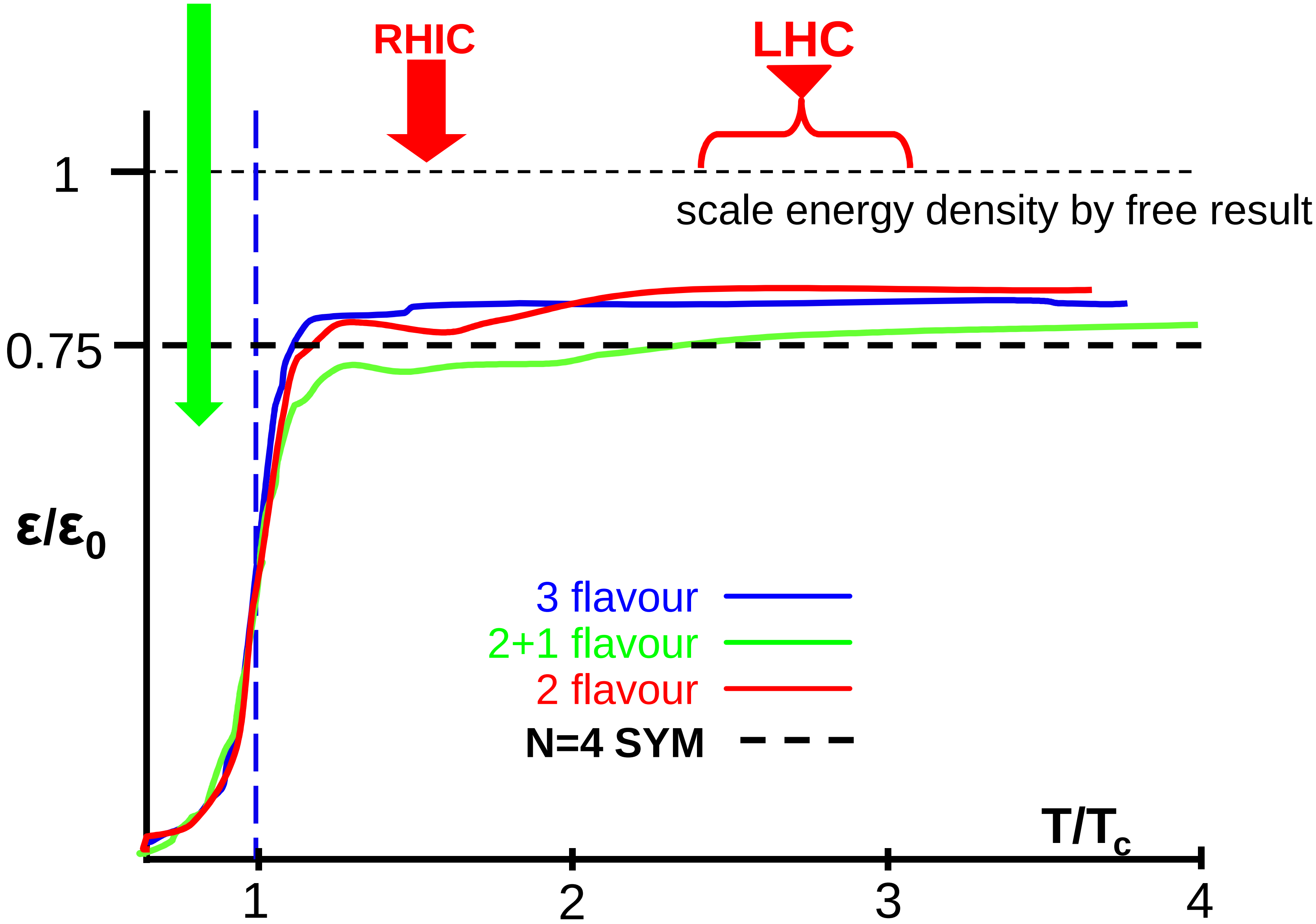
celebrated ¾ of Gubser, Klebanov & Peet (hep-th/9602135)



Strongly coupled QGP seems to be "conformal", just above T_c



AdS/CFT does not give identical physics to QCD, but may still give insight into sQGP



Hints from the lattice about sQGP:

- plotting $\varepsilon/\varepsilon_0$ vs T/T_c, various QCD-like theories show a plateau near $\varepsilon/\varepsilon_0 \sim .8$ (universal behaviour??)
- plateau is significantly less than 1 (strongly coupled)
- plateau shows T is only relevant scale (conformal phase)
- N=4 plasma quite close to plateau in lattice studies (universal behaviour??)

Note 1: N=4 SYM shows no transition (of course) – not capture full physics of QCD but perhaps still a good model of sQGP

Note 2: more recent lattice results still show same dramatic plateau but $\varepsilon/\varepsilon_0 \sim .85 – .9$ (Cheng et al, 0710.0354)

Next day, more on shear viscosity and hydrodynamics

Exercise:

Express the critical temperature for deconfinement
In QCD in degrees Kelvin.

(Ans.: $T_c \ \sim \ 2 \times 10^{12} K$)

Exercise:

Express the density of nuclear matter in gram/centimeter^3.

(Ans.: $\rho \ \sim \ 2 \times 10^{14} g/cm^3$)