F. Becattini (University and INFN Firenze)

Introduction to the physics of Quark Gluon Plasma and the relativistic heavy ion collisions

OUTLINE

- Introduction
- Quark Gluon Plasma and relativistic heavy ion collisions
- Signatures of the Quark Gluon Plasma
- The QGP as a nearly perfect fluid

Recent review book: *Relativistic heavy ion physics*, Landolt-Bornstein 1-23, ed. R. Stock, list and contributions in http://aliceinfo.cern.ch/static/HIF/RStockList.html

QCD is a SU(3) gauge theory

$$\begin{aligned}\mathcal{L}_{\rm QCD} &= \bar{\psi}_i \left(i\gamma^\mu (D_\mu)_{ij} - m\,\delta_{ij}\right)\psi_j - \frac{1}{4}G^a_{\mu\nu}G^{\mu\nu}_a \\ &= \bar{\psi}_i(i\gamma^\mu\partial_\mu - m)\psi_i - gG^a_\mu\bar{\psi}_i\gamma^\mu T^a_{ij}\psi_j - \frac{1}{4}G^a_{\mu\nu}G^{\mu\nu}_a\,,\end{aligned}$$

$$G^a_{\mu\nu} = \partial_\mu G^a_\nu - \partial_\nu G^a_\mu - g f^{abc} G^b_\mu G^c_\nu\,,$$

QCD as a gauge theory has two key features:

• Asymptotic freedom: at high energy or very short distance, quarks and gluons interact weakly

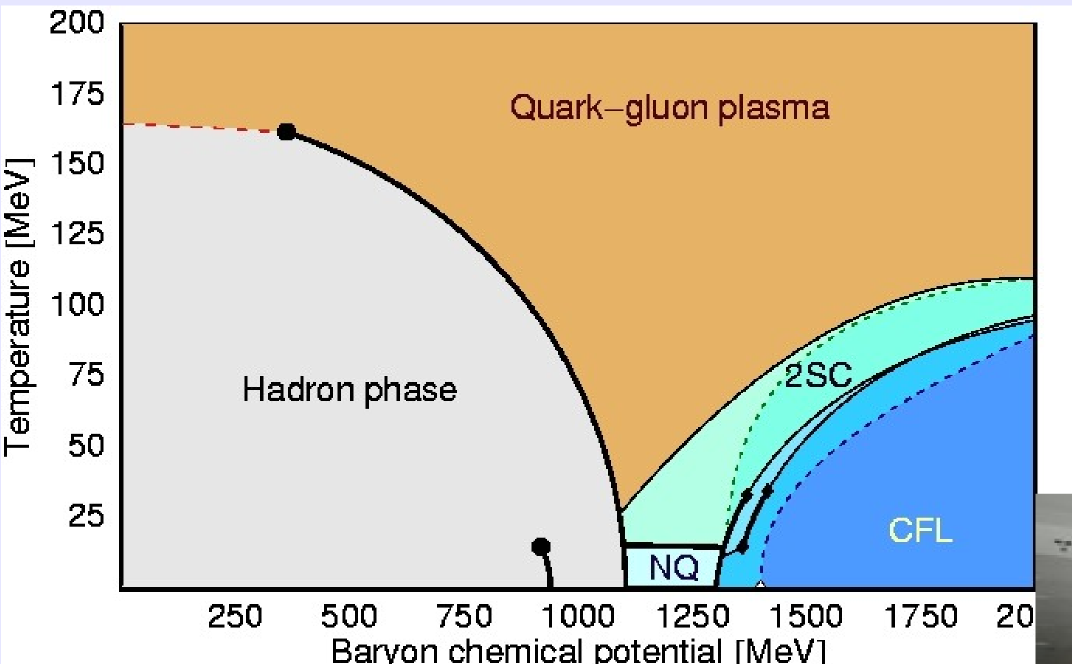
$$\alpha_S(q^2) \simeq \frac{12\pi}{(33-2n_f)\log\frac{q^2}{\Lambda^2}} \qquad \Lambda \approx 200\ \text{MeV}$$

• Confinement: the interaction of quarks and gluons gets stronger at large distance or low energy which means that they cannot be separated (typical scale: 1fm or 200 MeV)

Confinement on QCD has not been proved analytically, but there are numerical evidences

The Quark Gluon Plasma

The phase of strongly interacting matter which should exist at large temperature and/or density. It is a specific prediction of QCD



$T_c = 170$ MeV

$\sim 2 \times 10^{12}$ ^{o}K

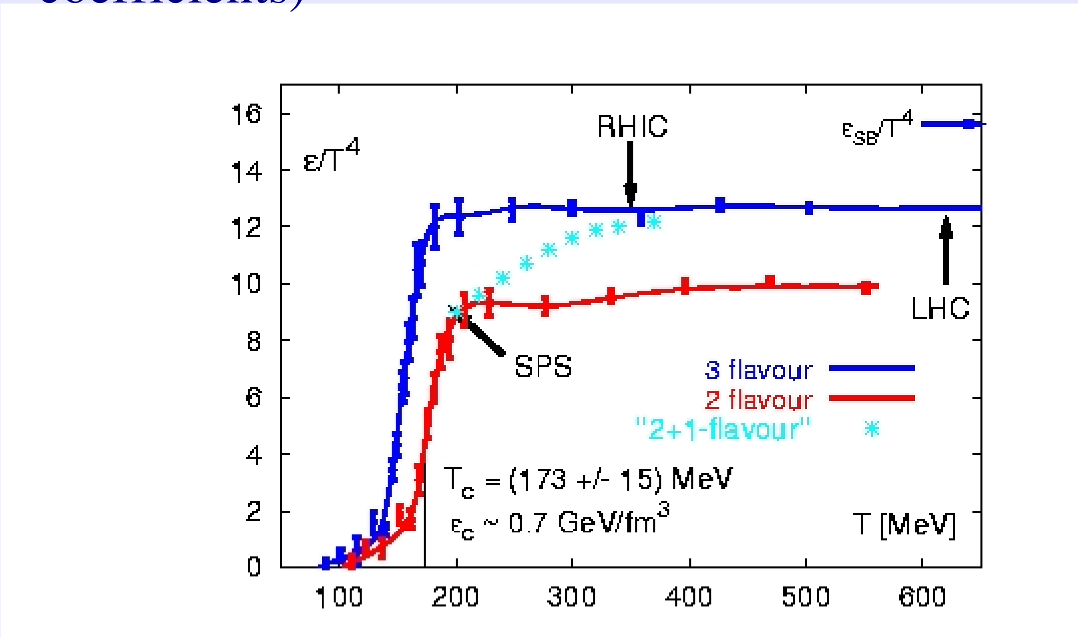
Our knowledge of QCD thermodynamics and phase diagram at low baryonic density mainly comes from numerical calculations because no analytical approach is possible.

Perturbation theory cannot work "near" the transition from confined to deconfined phase

IBM Blue Gene – 360 Tflop/sec

What do we know about QGP from theory?

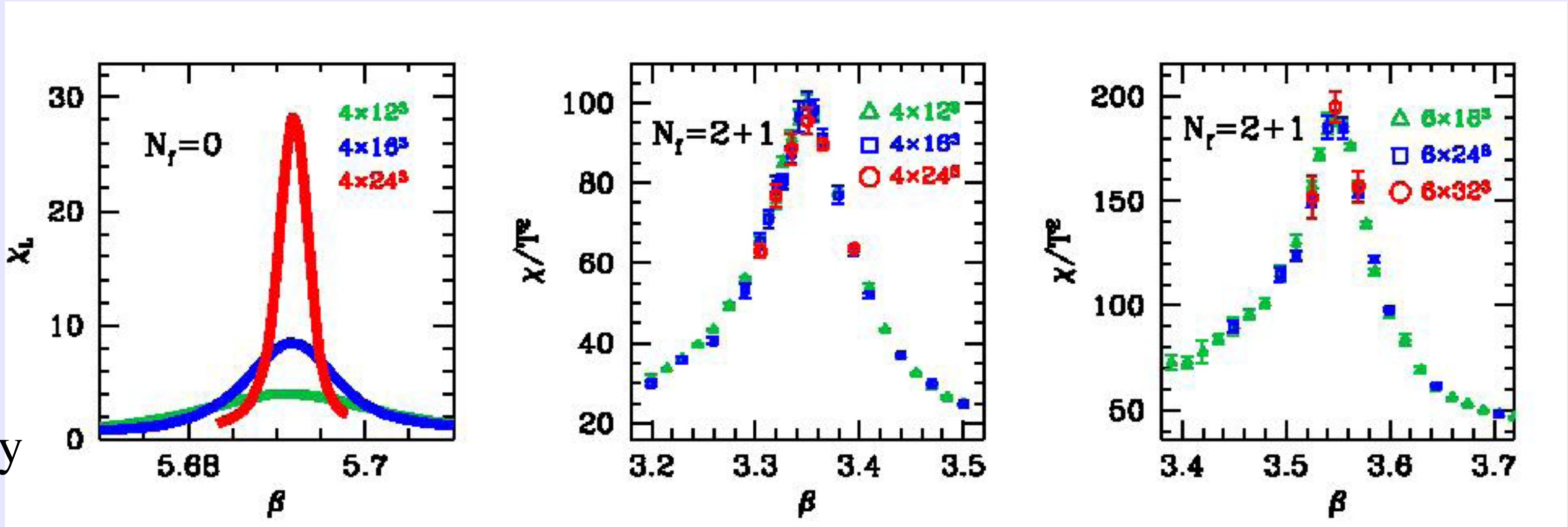
Lattice QCD: much about thermodynamics (at zero μ_B) and little about kinetics (transport coefficients)



2+1 flavours:
2 $m_q/T = 0.4$
1 $m_q/T = 1.0$

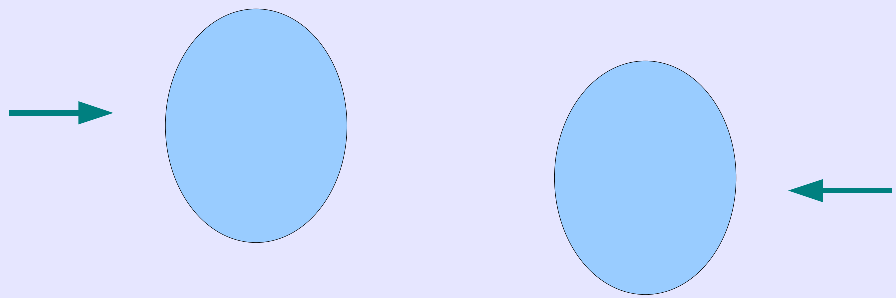
F. Karsch, E. Laermann
in "Quark Gluon Plasma 3"
World Sc. P. 1

Phase transition at μ_B=0 is indeed a crossover (Z. Fodor et al. Nature 443 (2006) 675)



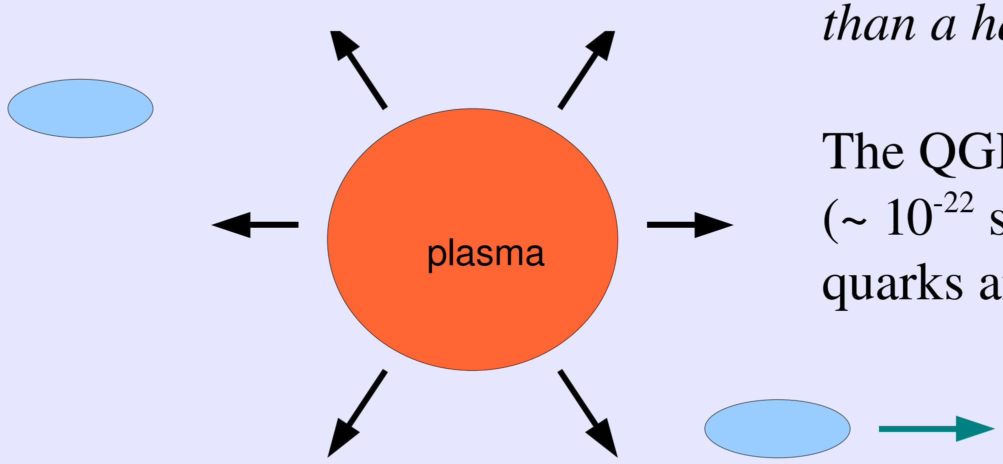
Chiral susceptibility

Can we produce a QGP in the lab?



The best method is to collide two atomic nuclei at high energy so that protons and neutrons, hence quarks and gluons, are compressed and heated beyond the critical temperature

The QGP is "macroscopic" as if nuclei are heavy they are large enough to effectively free the coloured constitutents over a region which is much larger than a hadron.



The QGP is a transient. Within a short time (~ 10^{-22} sec) expands, cools and hadronizes: quarks and gluons go back to their hadronic jails.

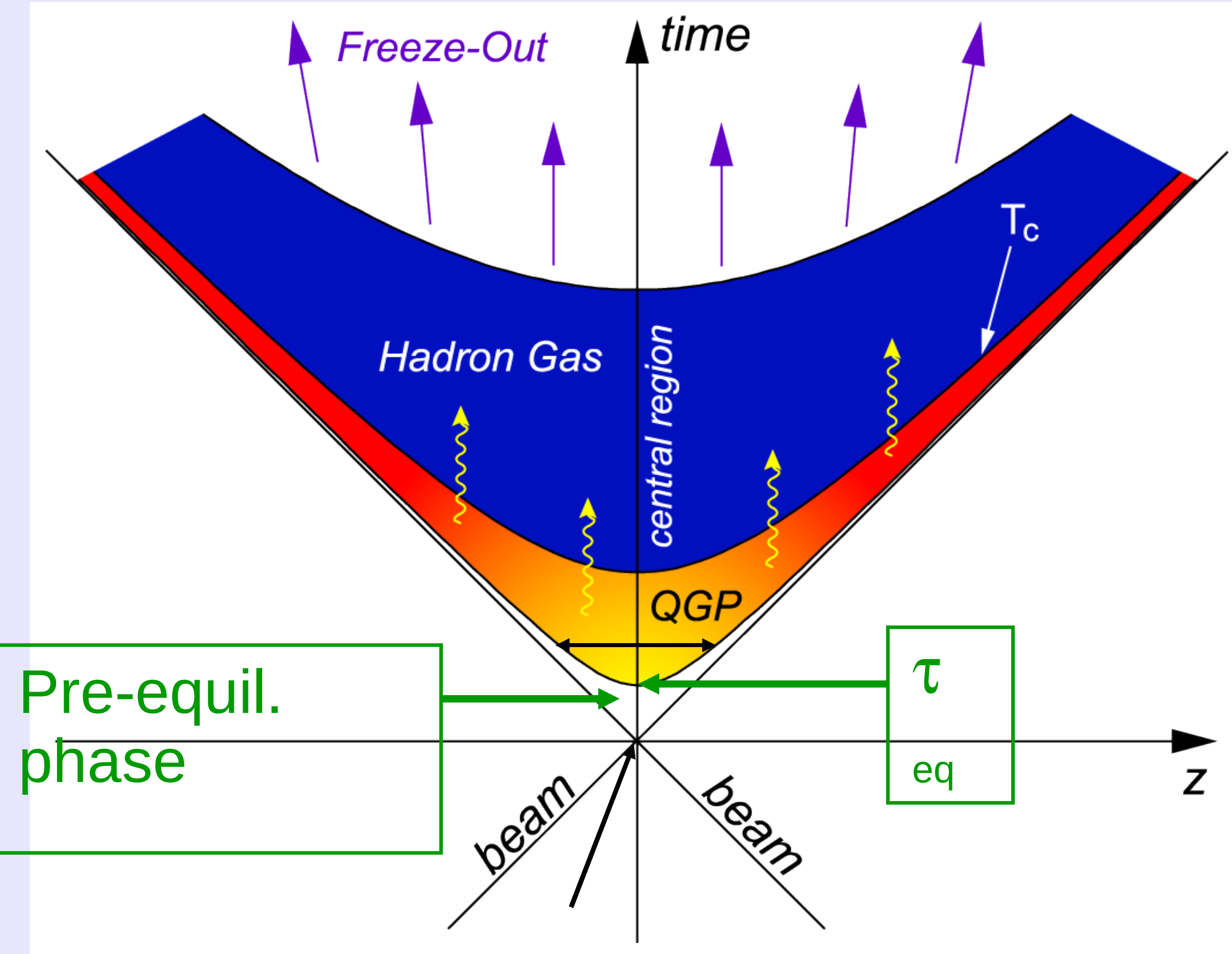
Experimental programme

	Energy (NN c.o.m.)	(estimated) Tmax
AGS – Brookhaven (USA)	1-5 GeV	?
SPS – CERN	6-18 GeV	250 MeV
RHIC – Brookhaven (USA)	62-200 GeV	350 MeV
LHC – CERN	5500 GeV	750 MeV

Ion beams

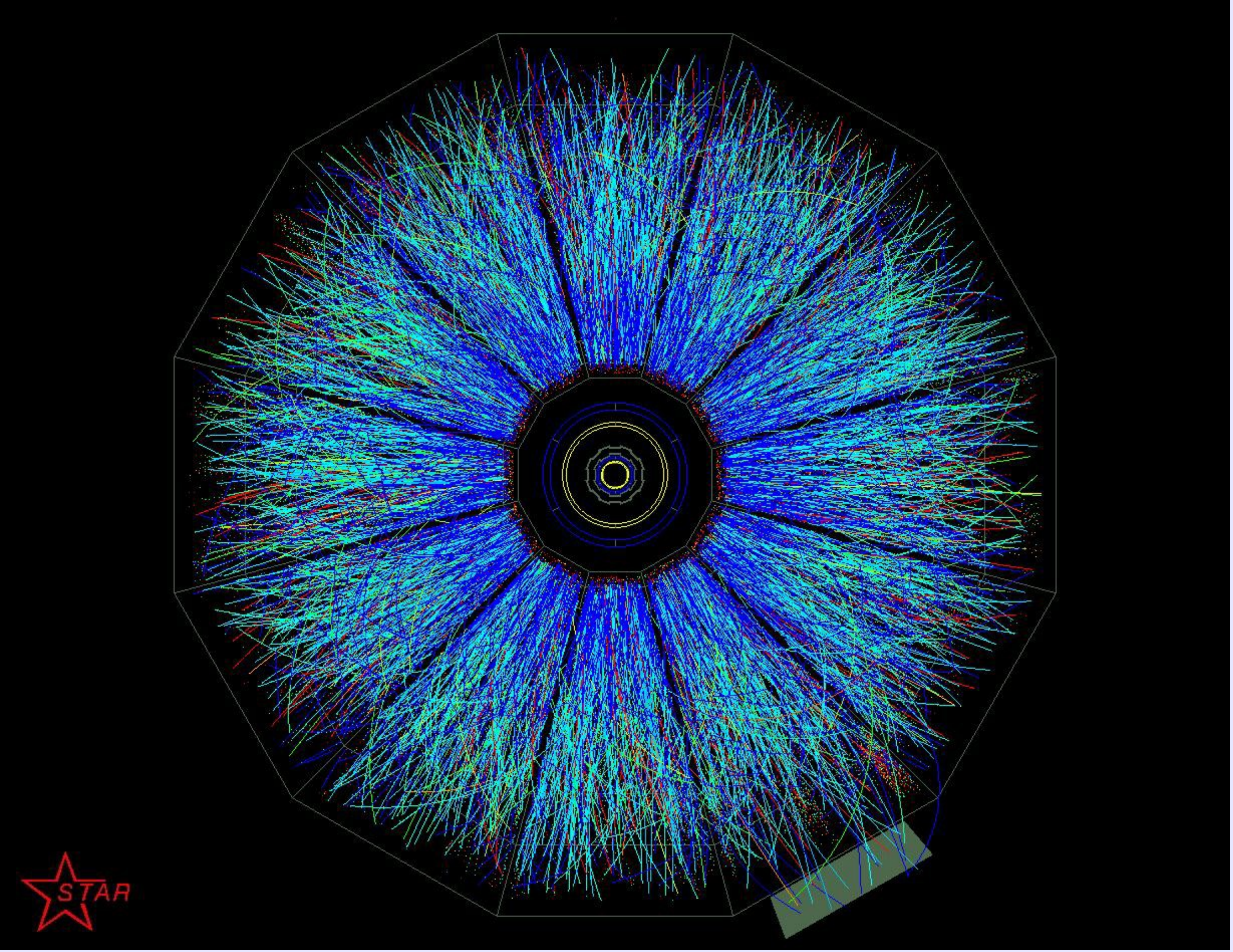
USA: Au
Europe: Pb

QGP evolution



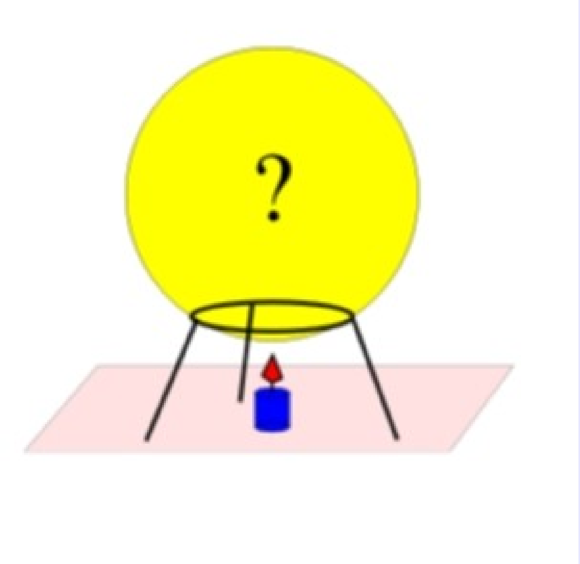
Succesful description
of Quark Gluon Plasma
expansion with
nearly ideal fluid dynamics

System	$\sqrt{s_{NN}}$ (GeV)	τ_0 (fm)	$\tau_{\rm tot}$ (fm)	T_0 (MeV)	ϵ_0 (GeV/fm^3)
SPS (Pb+Pb)	17	0.8	$1.4 - 2$	$210 - 240$	$1.5 - 2.5$
RHIC (Au+Au)	200	0.6	$6 - 7$	$380 - 400$	$14 - 20$
LHC (Pb+Pb)	5500	0.2	$18 - 23$	$710 - 850$	$190 - 400$



Au-Au collision at 200 GeV as seen in the transverse plane

Probing the Quark Gluon Plasma formation



Several possible probes at our disposal, that can be clustered in three groups

- Hadron radiation

- Electromagnetic radiation

- Hard probes: heavy quarks and quarkonia, jets, hard photons etc.

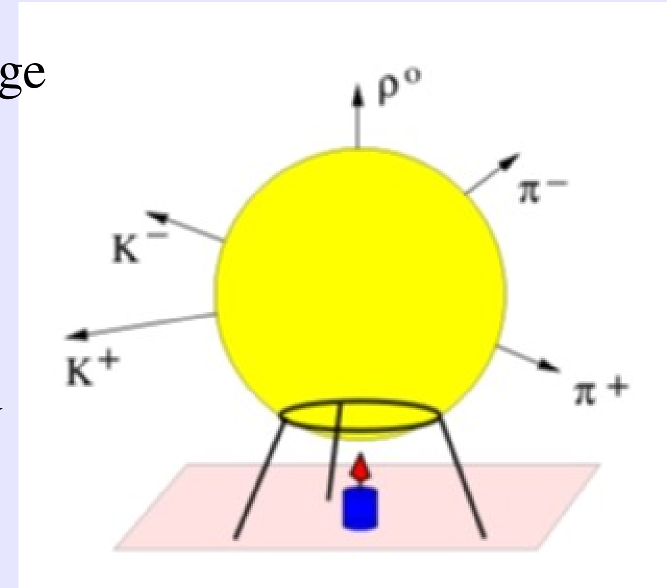
Common feature: early production, “calculable” in perturbative QCD, easily comparable to pp and pA

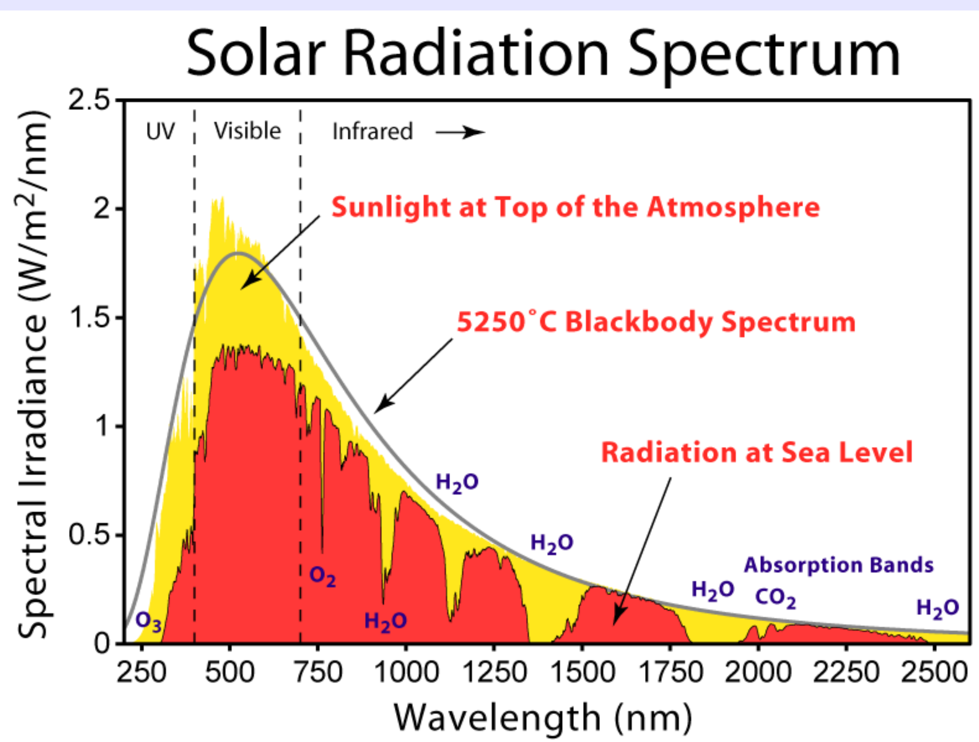
The plasma is a transient and rapidly decays. This situation is dramatically different from the idealized situation of lattice QCD calculations.

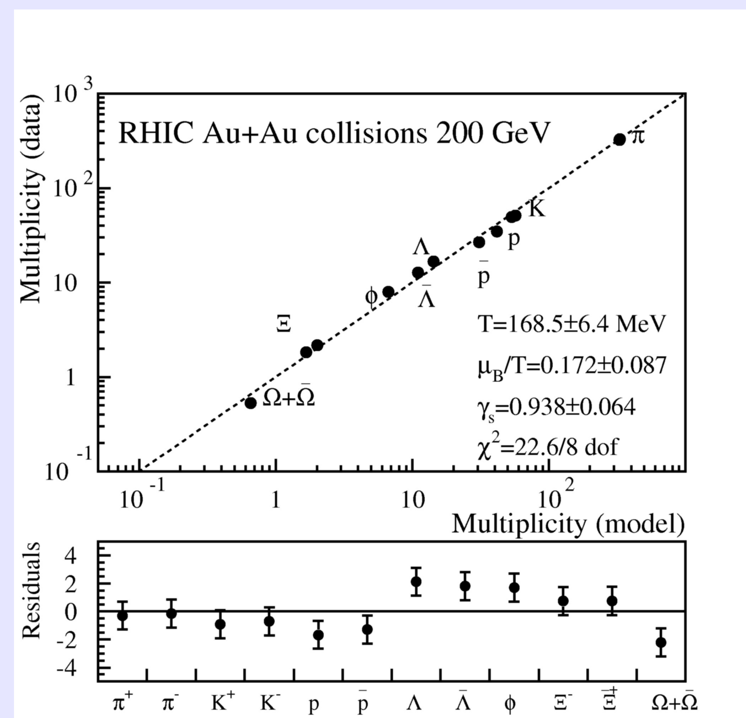
Hadron radiation

Provides direct information about the hadronization stage of the plasma.
Allows to determine the thermodynamical state at the stage when hadrons cease interactions and decouple

Enhanced production of strange particles was predicted to be a signature of QGP formation
(see tomorrow's lecture)

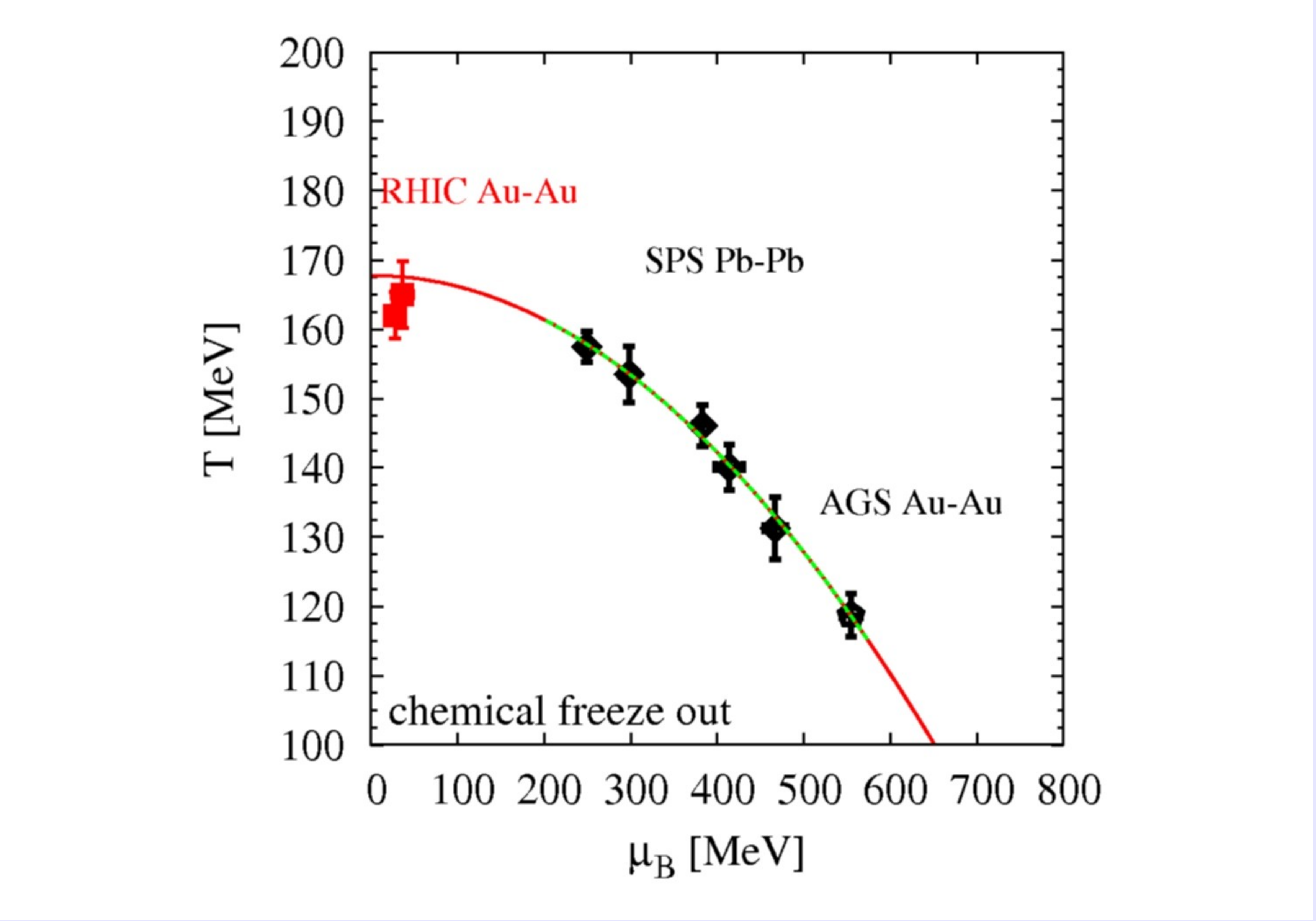






F. B., J. Manninen, Phys. Rev. C 78 (2008) 054901

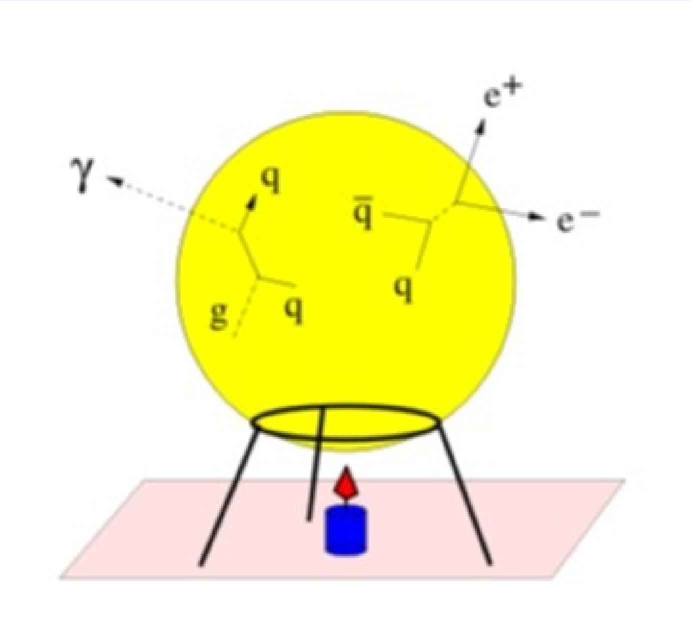
F. B., J. Manninen, Phys. Rev. C 78 (2008) 054901



The temperature at the chemical freeze-out at RHIC is that of a hadronic black-body and it is the largest ever measured on Earth (~ 2 10^{12} K)

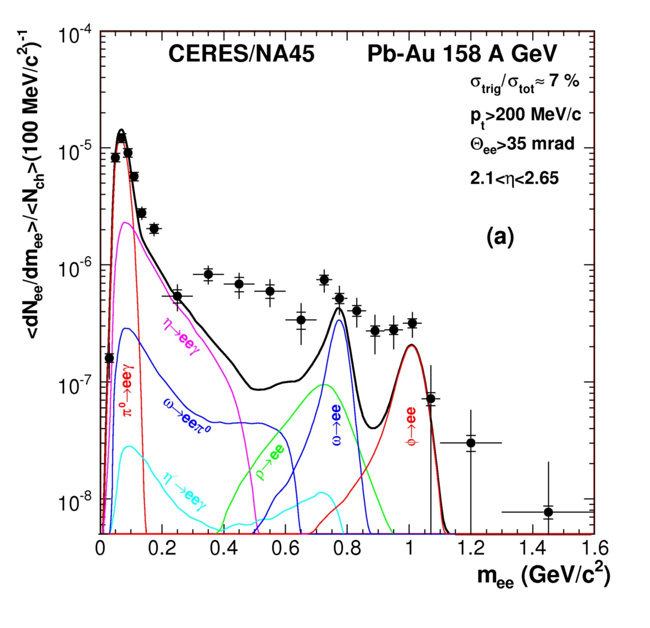
Thermal electromagnetic radiation

Even in a transient plasma, there should be electromagnetic processes involving quarks and gluons at thermal equilibrium leading to emission of photons and lepton pairs, which leave the plasma unaffected



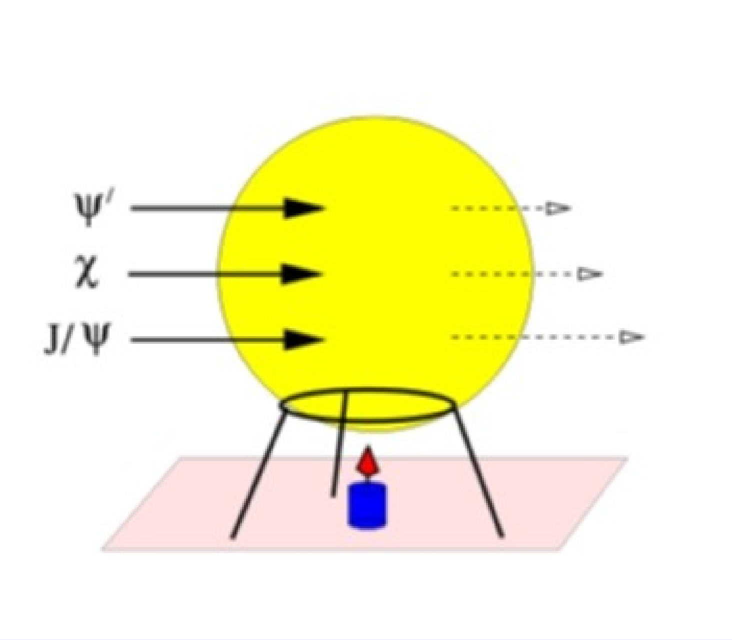
PROBLEM

To subtract the background of photons and leptons from post-hadronization decays



Charmonium suppression

Matsui and Satz 1984

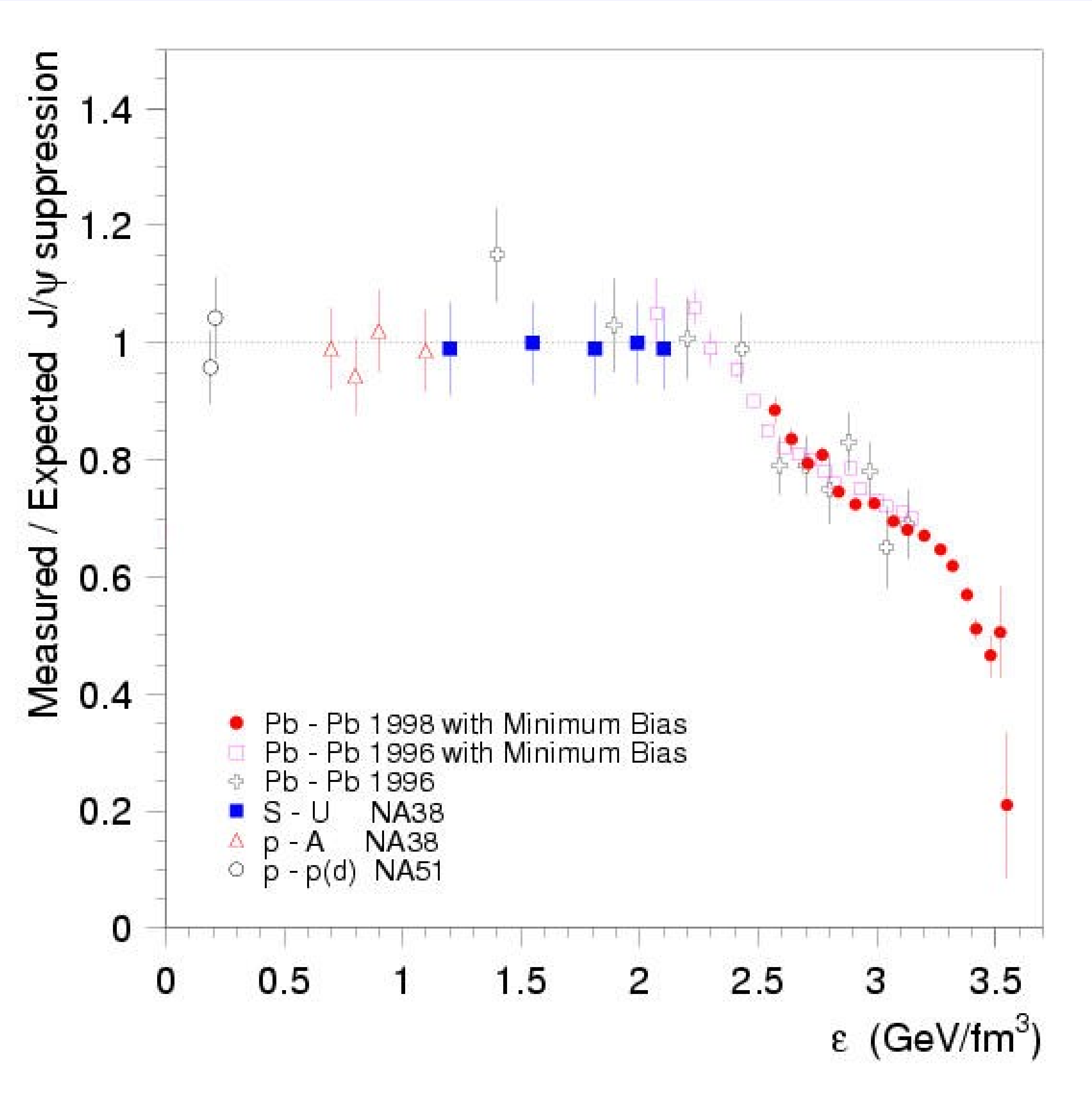


Bound states of c and $\bar{c}$ quarks: J/ψ, ψ', χ_c ...

Produced at the early stage of the collision, before the plasma is formed. Thereafter, they interact with the medium and may be dissociated

J/ψ	r ~ 0.2 fm
χ_c	r ~ 0.3 fm
ψ'	r ~ 0.4 fm

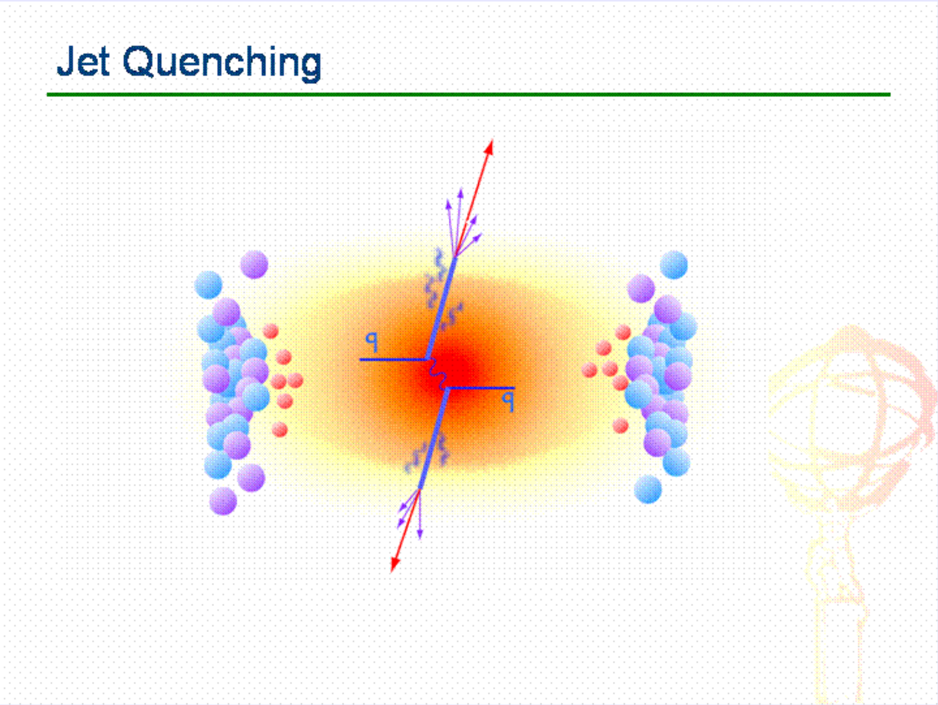
According to physical considerations and confirmed by lattice QCD, they dissolve sequentially in the plasma, at different temperatures: the more loosely bound the state, the lower the dissociation temperature.



Anomalous J/ψ suppression measured by NA50 at SPS

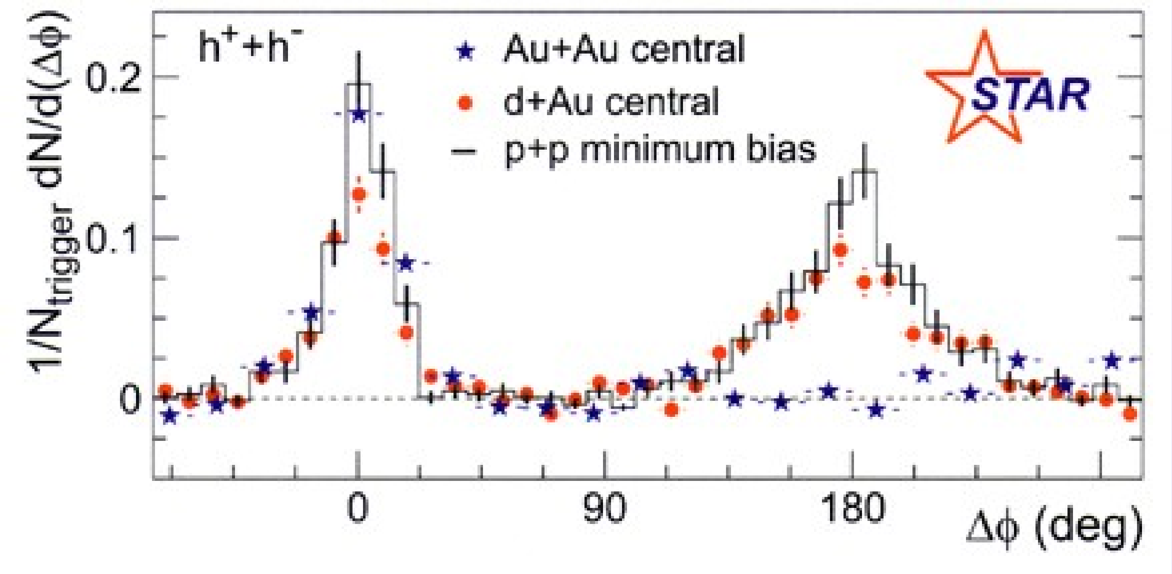
At LHC, the number of cc pairs per event will be so large that J/ψ will be regenerated by the statistical coalescence of charm quarks at hadronization (Thews, Braun-Munzinger et al.)

Jet suppression (or quenching)



Unlike in pp, high pT jets can be produced which thereafter interact with a medium.

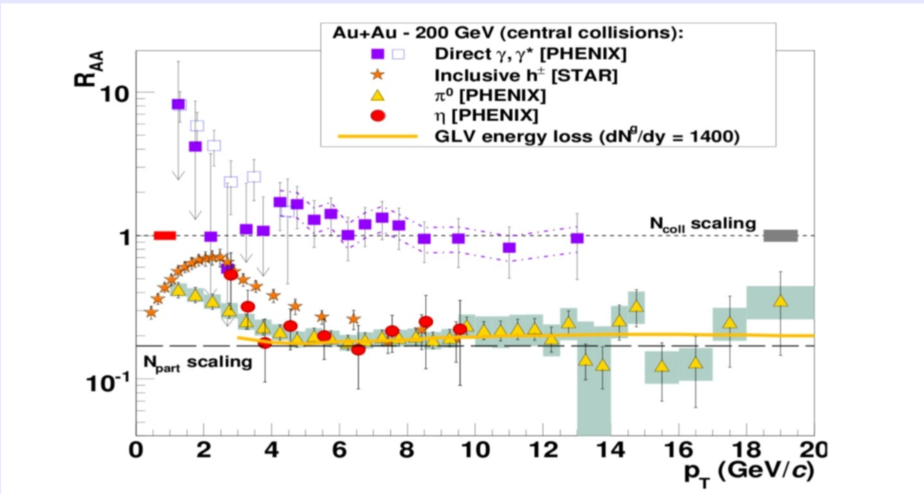
Energy loss is determined by the density of the medium, increases with the temperature.
Several calculations available, yet to converge to an accepted theoretical value.



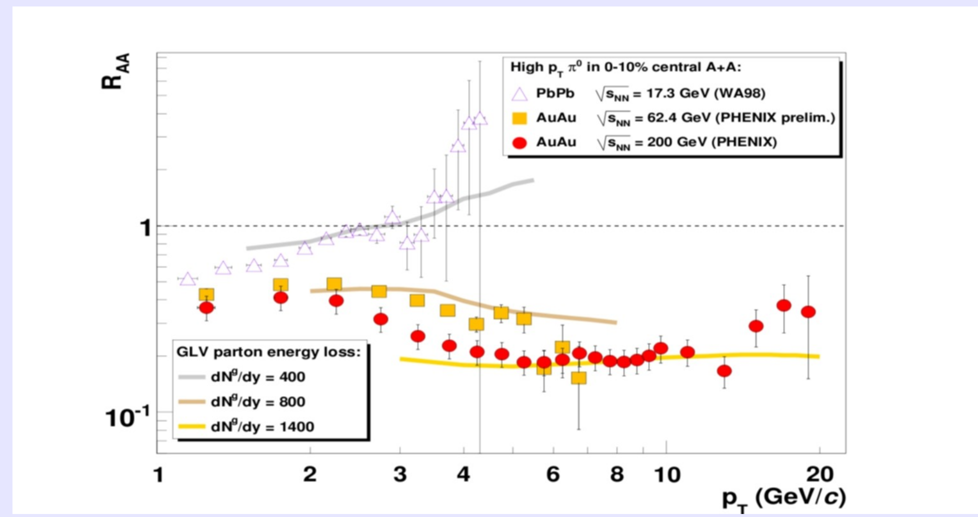
First evidence from RHIC experiments

Nuclear modification factor: a gauge for jet quenching

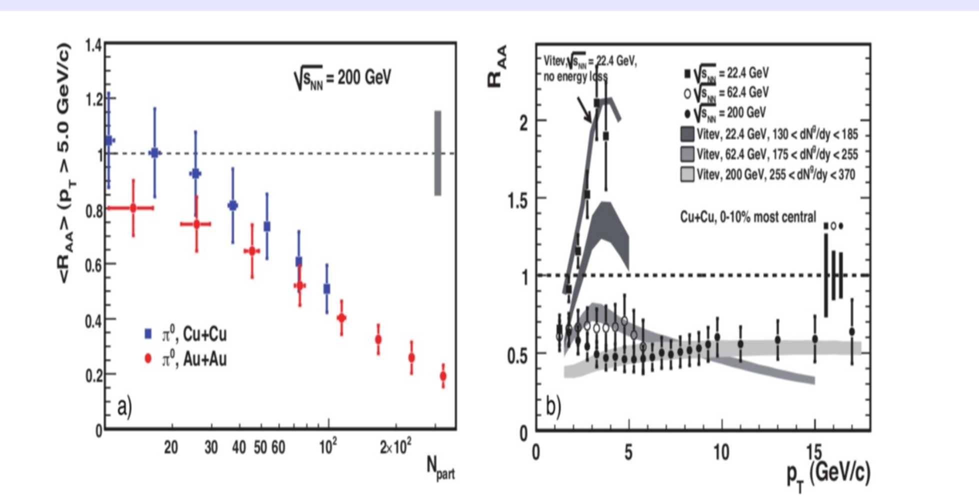
$$R^h_{AB}(p_T, y, \text{centrality}) = \frac{\dfrac{\mathrm{d}N^{AB\to h}_{\text{medium}}}{\mathrm{d}p_T\,\mathrm{d}y}}{\langle N^{AB}_{\text{coll}}\rangle \dfrac{\mathrm{d}N^{pp\to h}_{\text{vacuum}}}{\mathrm{d}p_T\,\mathrm{d}y}}.$$



From: D. D'Enterria, in Relativistic Heavy ion physics, arXiv: 0902.2011



As a function of collision energy



As a function of centrality and system size

This will be a major topic at LHC

The QGP as a nearly perfect fluid

Brookhaven National Laboratory News

BROOKHAVEN NATIONAL LABORATORY Home

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*.

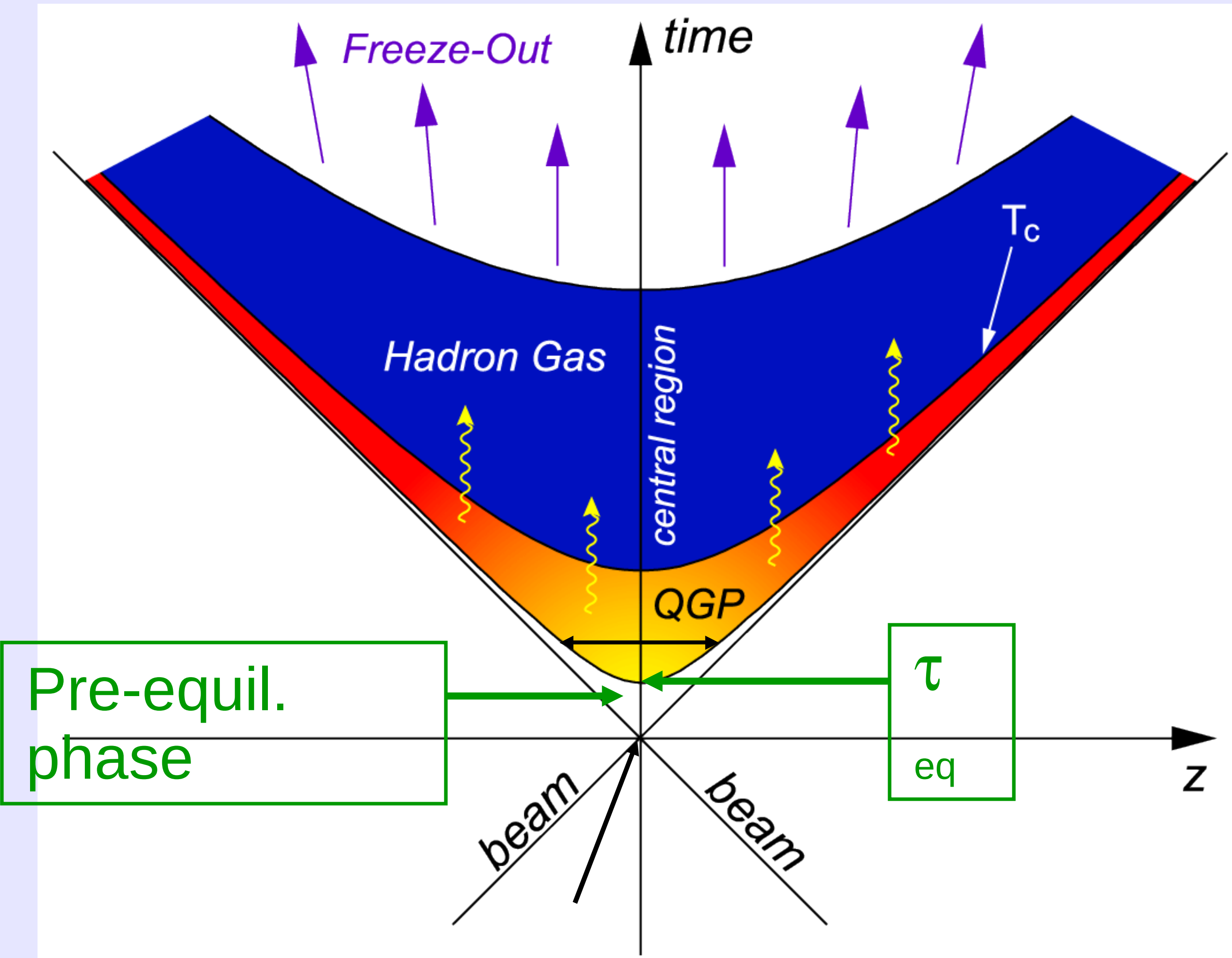
"Once again, the physics research sponsored by the Department of Energy is producing historic results," said Secretary of Energy Samuel Bodman, a trained chemical engineer. "The DOE is the principal federal funder of basic research in the physical sciences, including nuclear and high-energy physics.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

"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.

Secretary of Energy Samuel Bodman

Hydrodynamical description



Usual assumptions

☆Local thermodynamical equilibrium

☆Ideal fluid

☆<u>Bjorken solution v_z=z/t</u> either initially (3+1) or always (2+1)

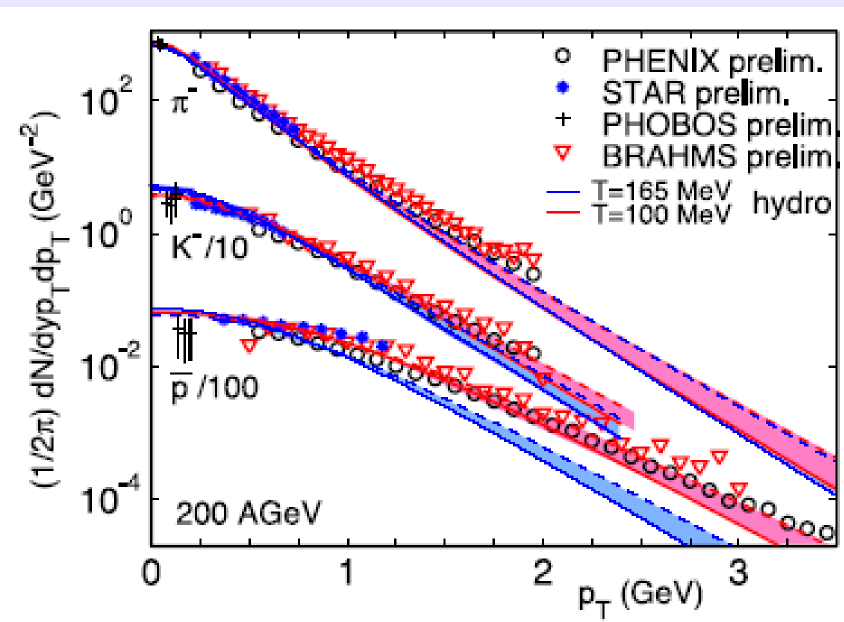
☆ Initial conditions determined from a fit to the data

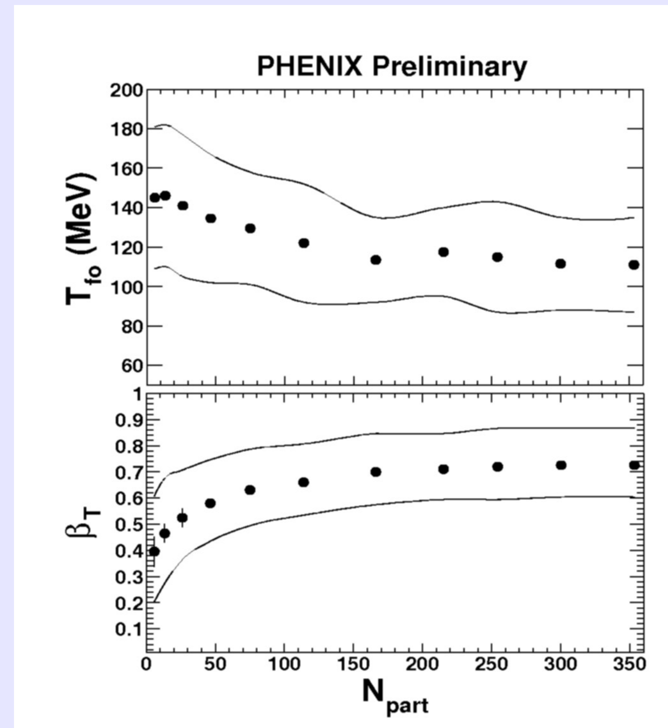
T_i (ε_i), n_i, T_{kin}

Numerical (ideal) relativistic hydrodynamics

(Huovinen, Kolb, Heinz, Hirano, Teaney, Shuryak, Romatschke etc.)

Longitudinal motion: Bjorken scaling model
always (2+1) or just initially (3+1)





	SPS	RHIC 1	RHIC 2
$\sqrt{s_{NN}}$ (GeV)	17	130	200
s_{eq} (fm^{-3})	43	95	110
T_{eq} (MeV)	257	340	360
τ_{eq} (fm/c)	0.8	0.6	0.6

Fitted parameters by using pT spectra (Heinz).
Initial temperature largely exceeds the estimated critical temperature Tc

Non trivial result

If flow is present, there must have been partonic thermalization

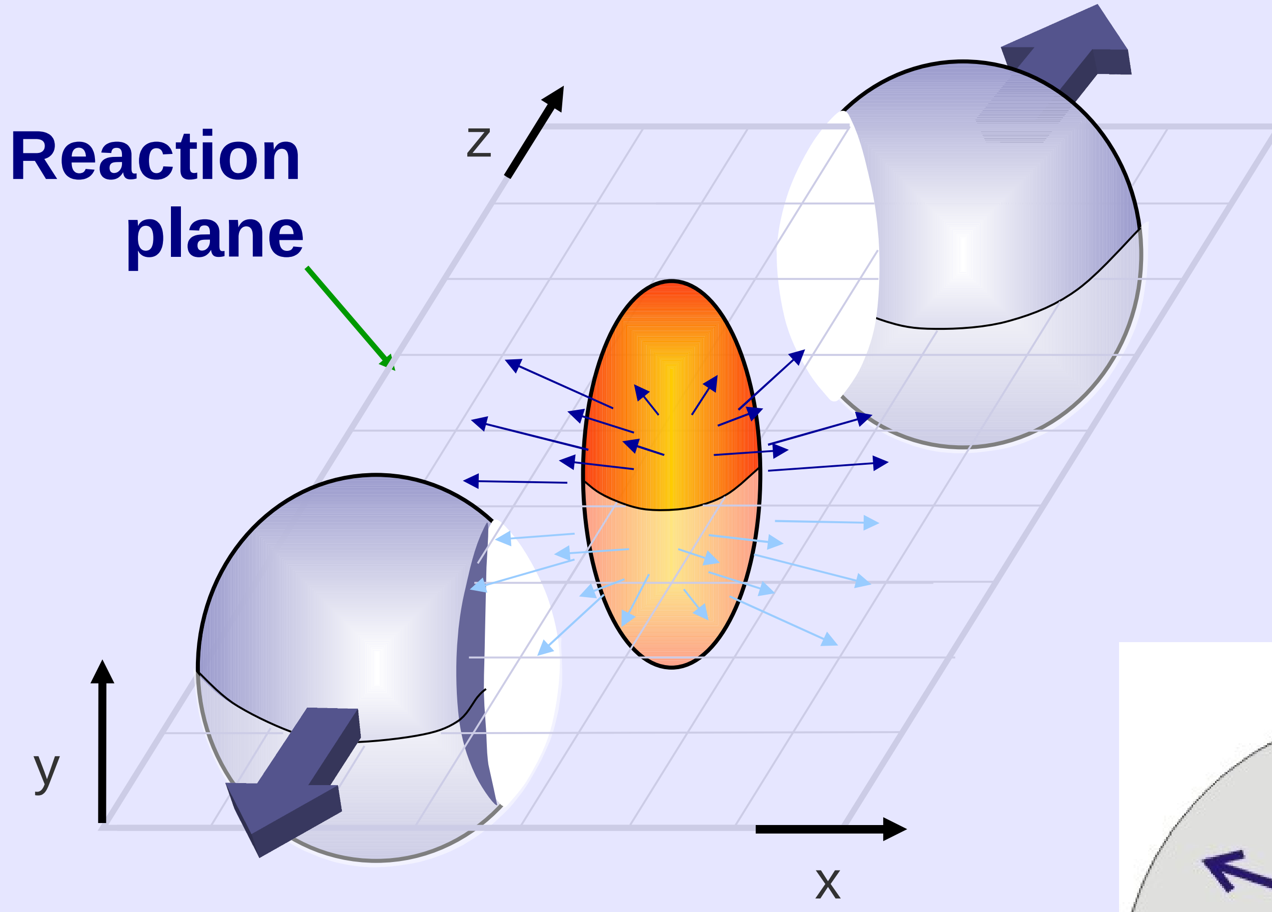
Thermalization sets in very early, more quickly at RHIC (200 GeV) than SPS (17 GeV)

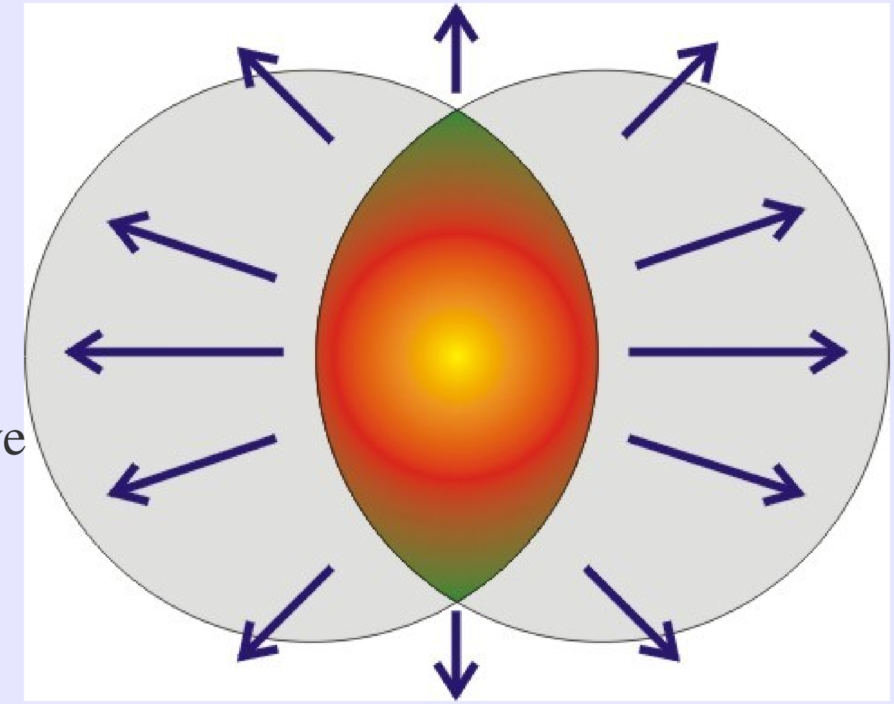
If collision energy increases, early interaction among partons gets weaker, but their initial density increases: the latter effect prevails.

System	$\sqrt{s_{NN}}$ (GeV)	τ_0 (fm)	$\tau_{\rm tot}$ (fm)	T_0 (MeV)	ϵ_0 (GeV/fm^3)
SPS (Pb+Pb)	17	0.8	$1.4-2$	$210-240$	$1.5-2.5$
RHIC (Au+Au)	200	0.6	$6-7$	$380-400$	$14-20$
LHC (Pb+Pb)	5500	0.2	$18-23$	$710-850$	$190-400$

I. Vitev, J. Phys. G 30 (2004) S791

Elliptic flow

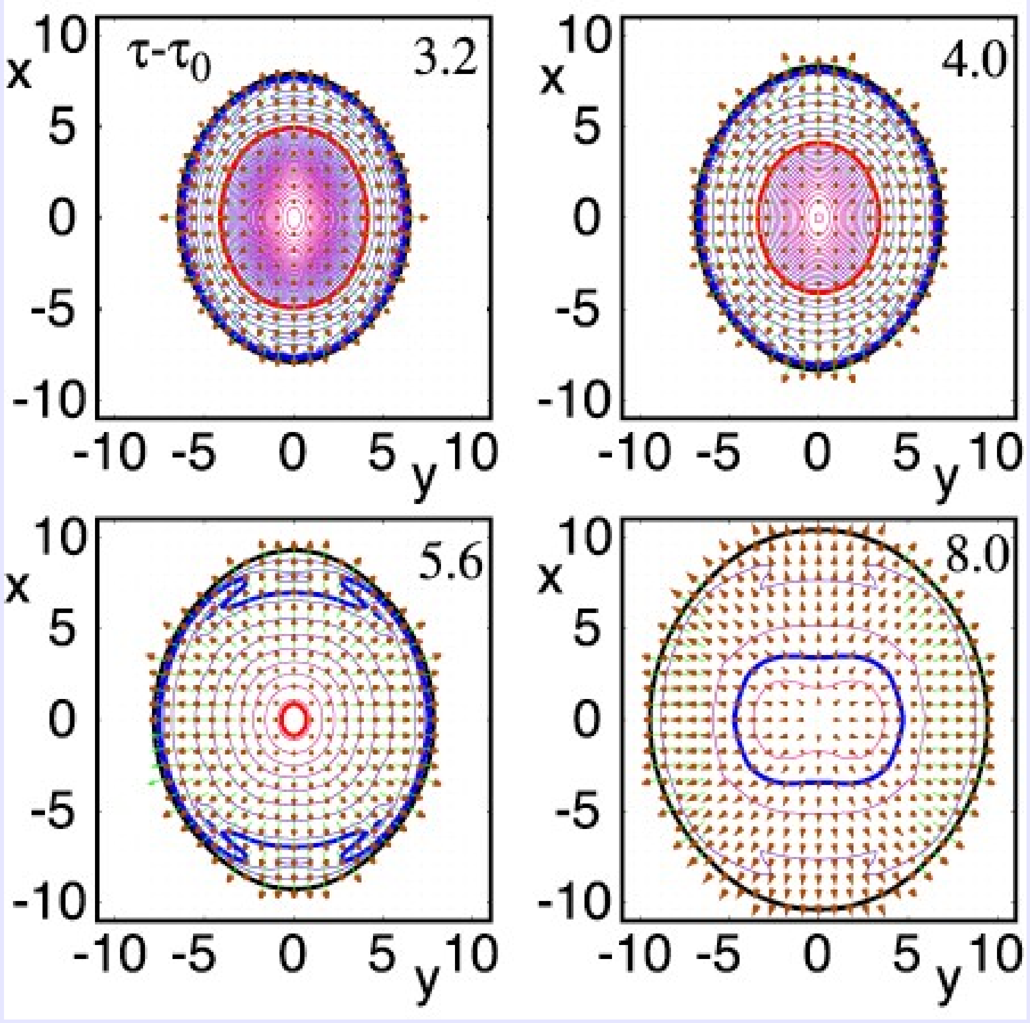


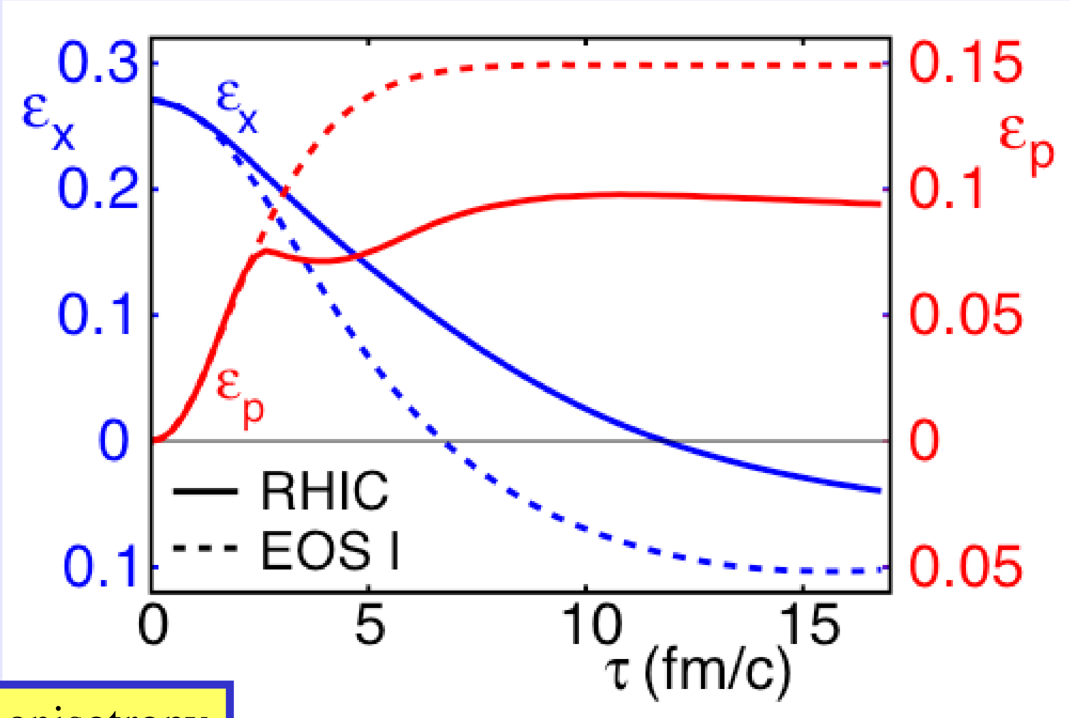


Anisotropic pressure gradient: if there is collective flow, particles get, on average, larger momentum in the reaction plane.

Momentum anisotropy

$$\epsilon_p = \frac{\langle T^{xx} - T^{yy} \rangle}{\langle T^{xx} + T^{yy} \rangle}$$

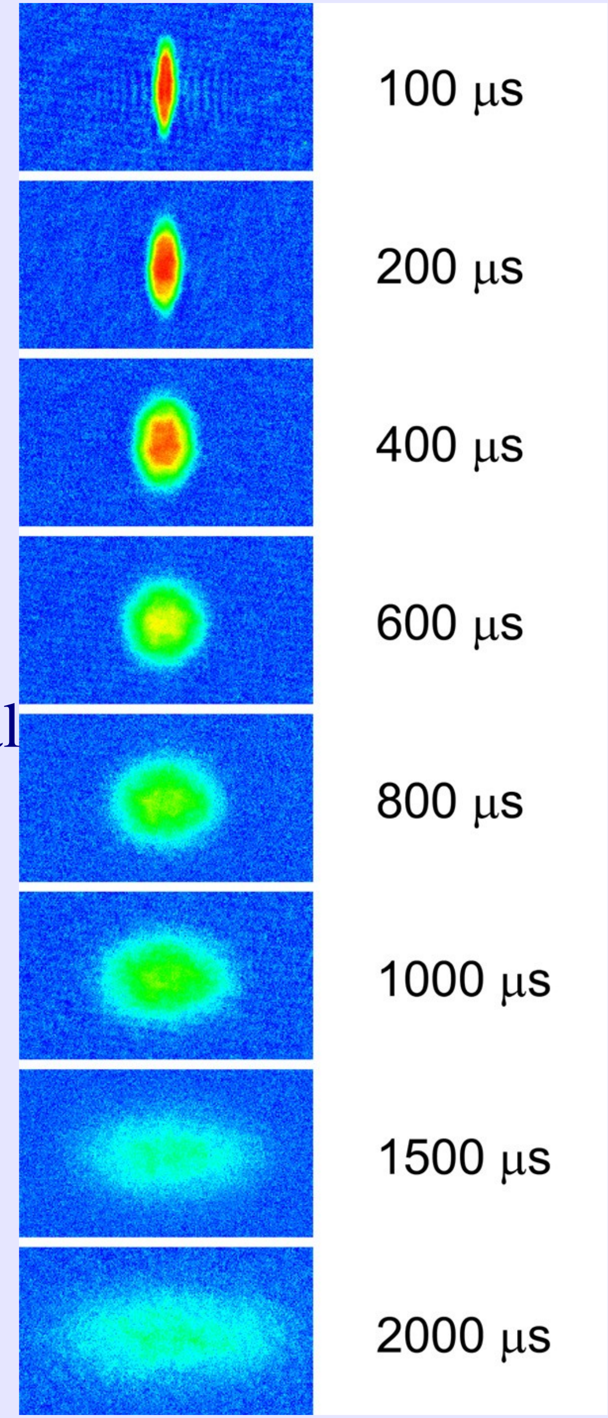




Conversion of space eccentricity into momentum anisotropy

- Short times, when the system is in the plasma phase (< 5 fm/c)
- Quick thermalization (<1 fm/c), when eccentricity is still significant

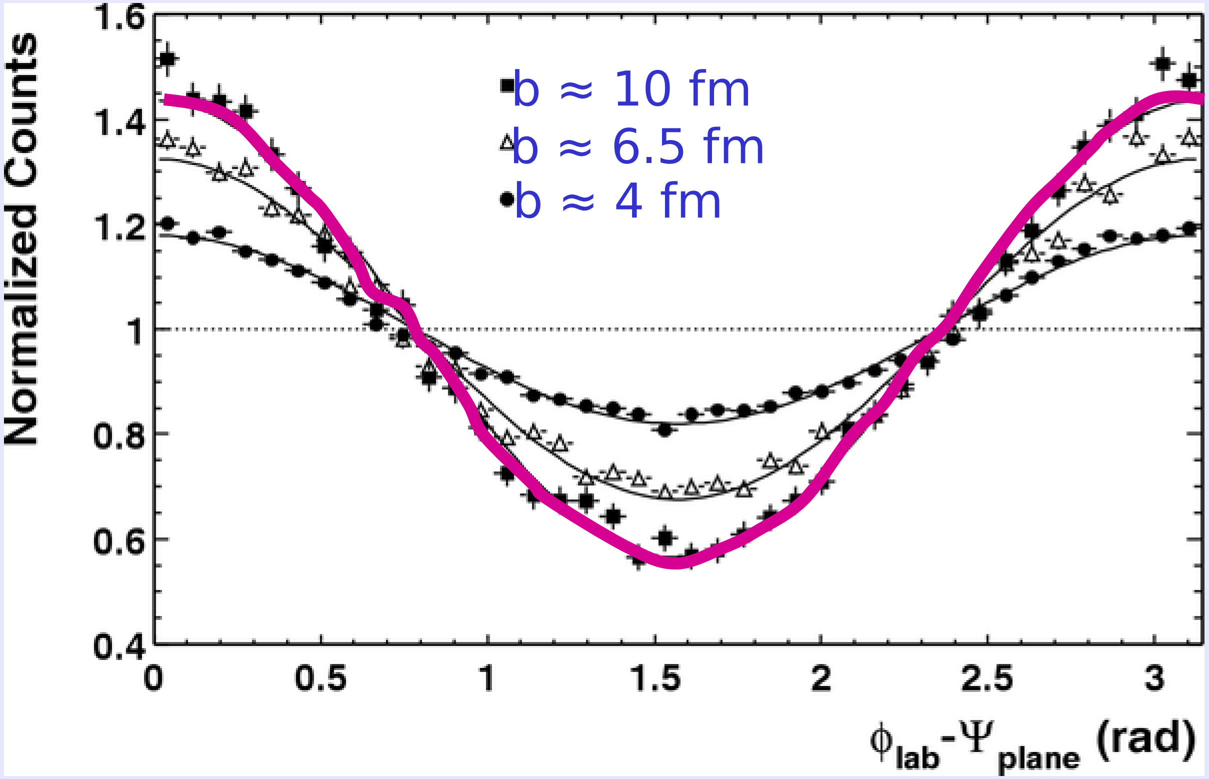
Similar phenomenon observed in atomic physics: cold atoms (Li) strongly coupled in a magneto-optical trap, then released.



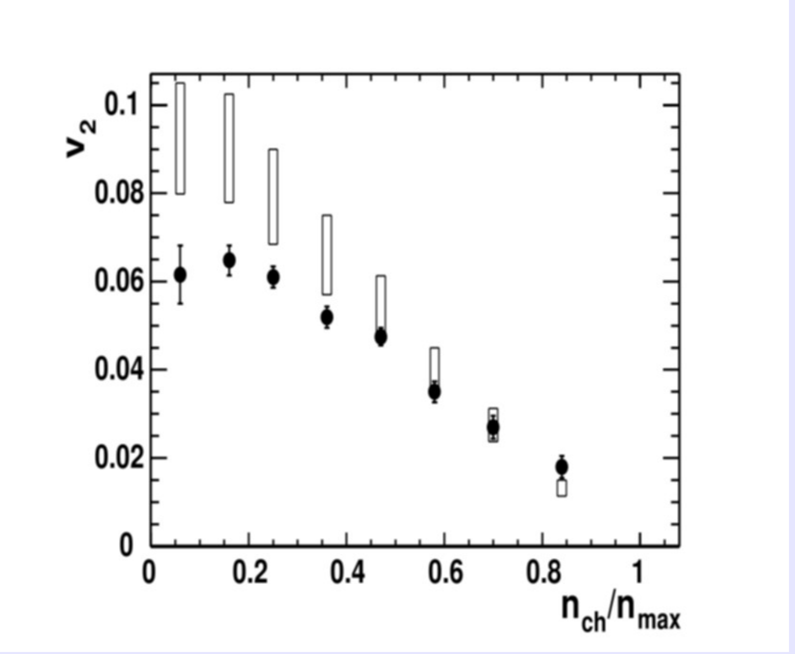
Fourier azimuthal expansion: v_2

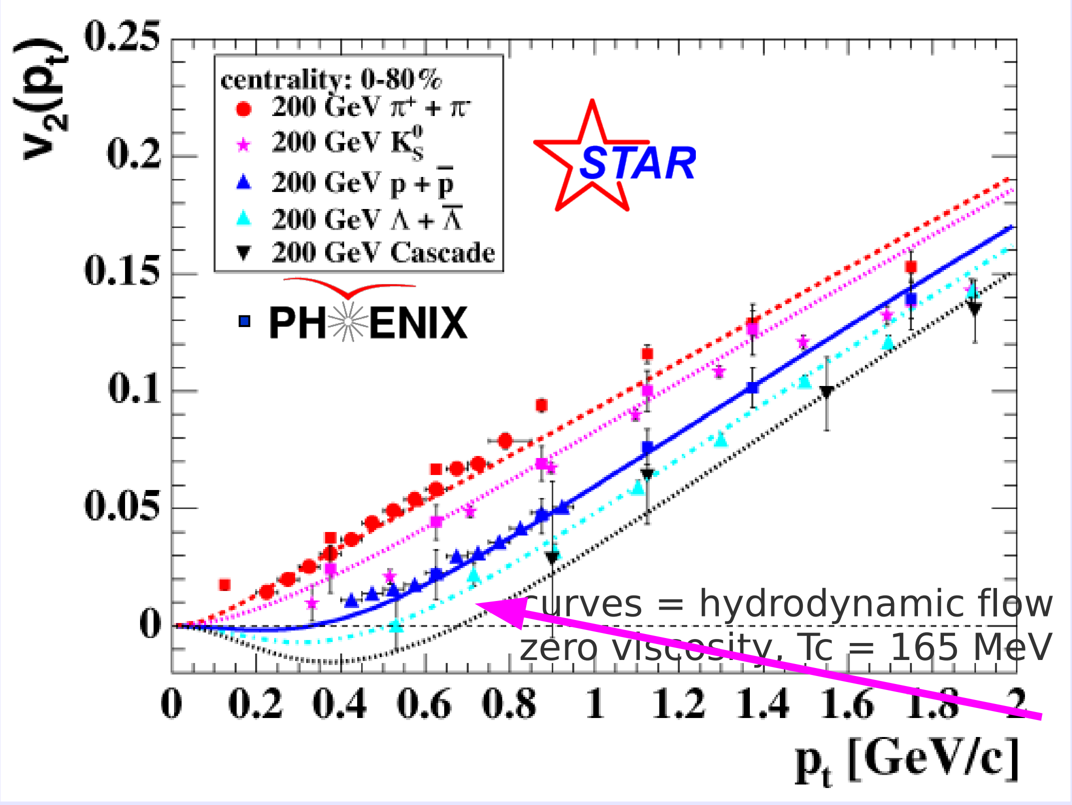
$$\frac{dN_i}{dy\,p_\perp dp_\perp\,d\varphi_p}(b) = \frac{1}{2\pi}\frac{dN_i}{dy\,p_\perp dp_\perp}(b)\left(1 + 2\,v_2^i(p_\perp, b)\cos(2\varphi_p) + \ldots\right).$$

STAR, PRL**90** 032301 (2003)



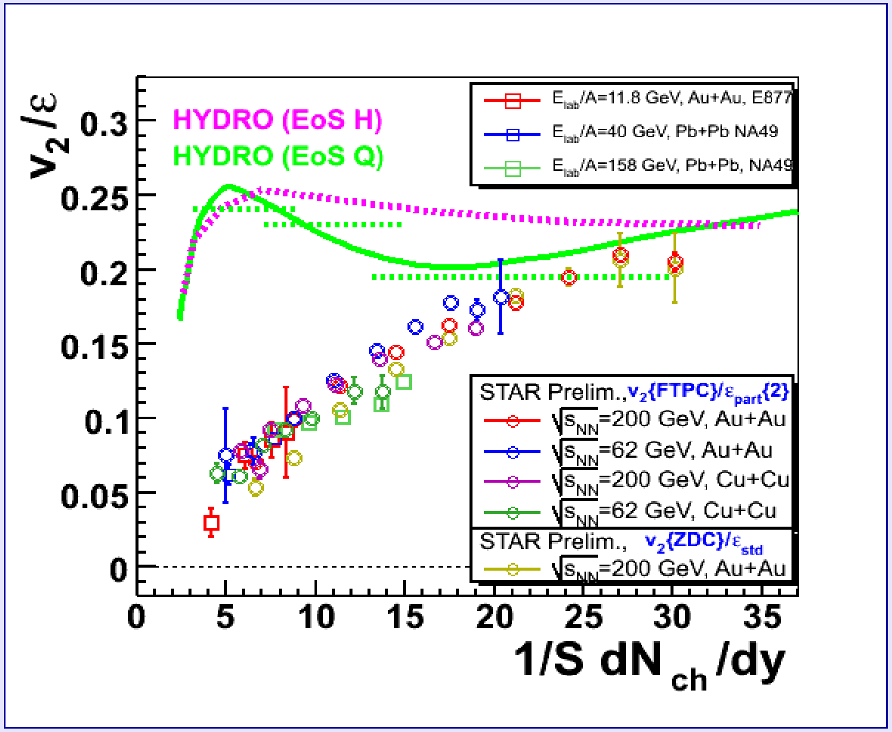
v_2 is in good agreement with (ideal) hydrodynamical model predictions especially for quasi-central collisions





Mass ordering at low pT in striking agreement with hydrodyanmics (more fairly: thermodynamics)

v_2 as a function of centrality: deviations from ideal hydrodynamics



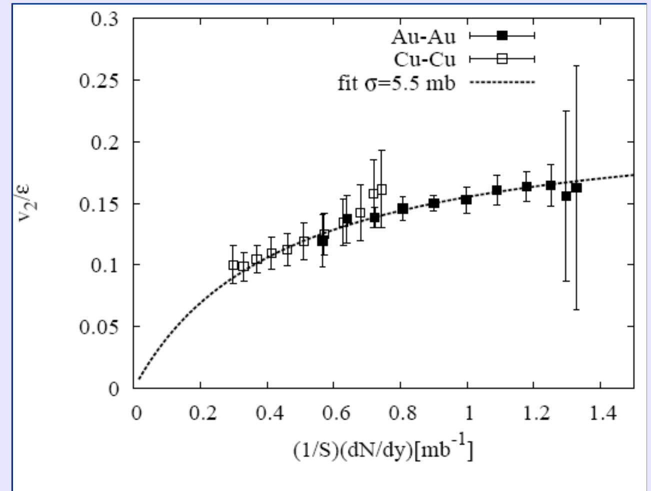


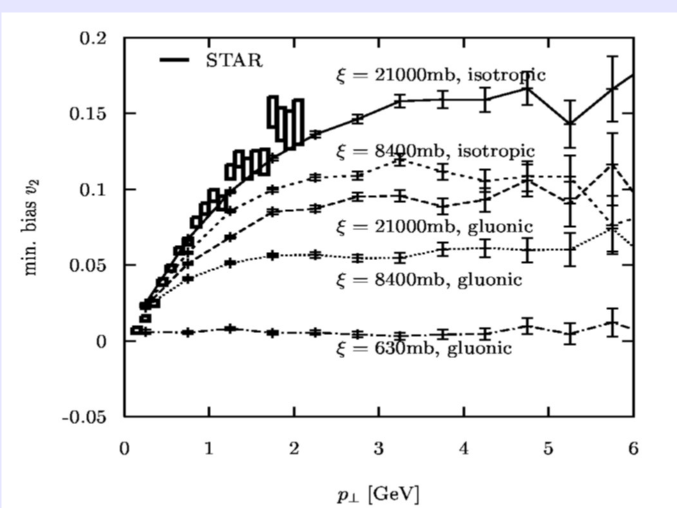
FIG. 2: Same as Fig. 1, using CGC initial conditions.

R. S. Bhalerao, J. P. Blaizot, N. Borghini and J. Y. Ollitrault, Phys. Lett. B **627**, 49 (2005).

$$\frac{v_2}{\varepsilon} = \frac{v_2^{\mathrm{hydro}}}{\varepsilon} \frac{1}{1 + K/K_0}$$

$$\frac{1}{K} = \frac{\sigma}{S}\frac{dN}{dy} c_s$$

$K_0 \simeq 0.7$



Partonic cross sections needed to have such a quick thermalization are higher than those estimated by using p-QCD

Viscosity in strongly coupled field theories from "black hole" physics

Kovtun, Son, Starinets PRL 94, 111601 (2005)

Amazing result from string "theory"

Maldacena conjecture (1998):
supersymmetric gauge Yang-Mills N=4 theory on the boundary is equivalent (dual) to some special string theory on a background Anti de Sitter $\times$ S_5

AdS/CFT correspondance

Duality: when the coupling of the gauge theory is large, then the corresponding string theory becomes a "simple" classical supergravity and calculations can be done analytically
CAVEAT: in conformal theory there is no running of the coupling constant, hence this duality cannot be applied exactly to QCD

More instances of duality based on this holographic principle have been found, yet in all these theories in the large coupling limit it has been found that:

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

KSS conjecture: it is a universal quantum limit.
Nobody has been able to prove it with simpler method.

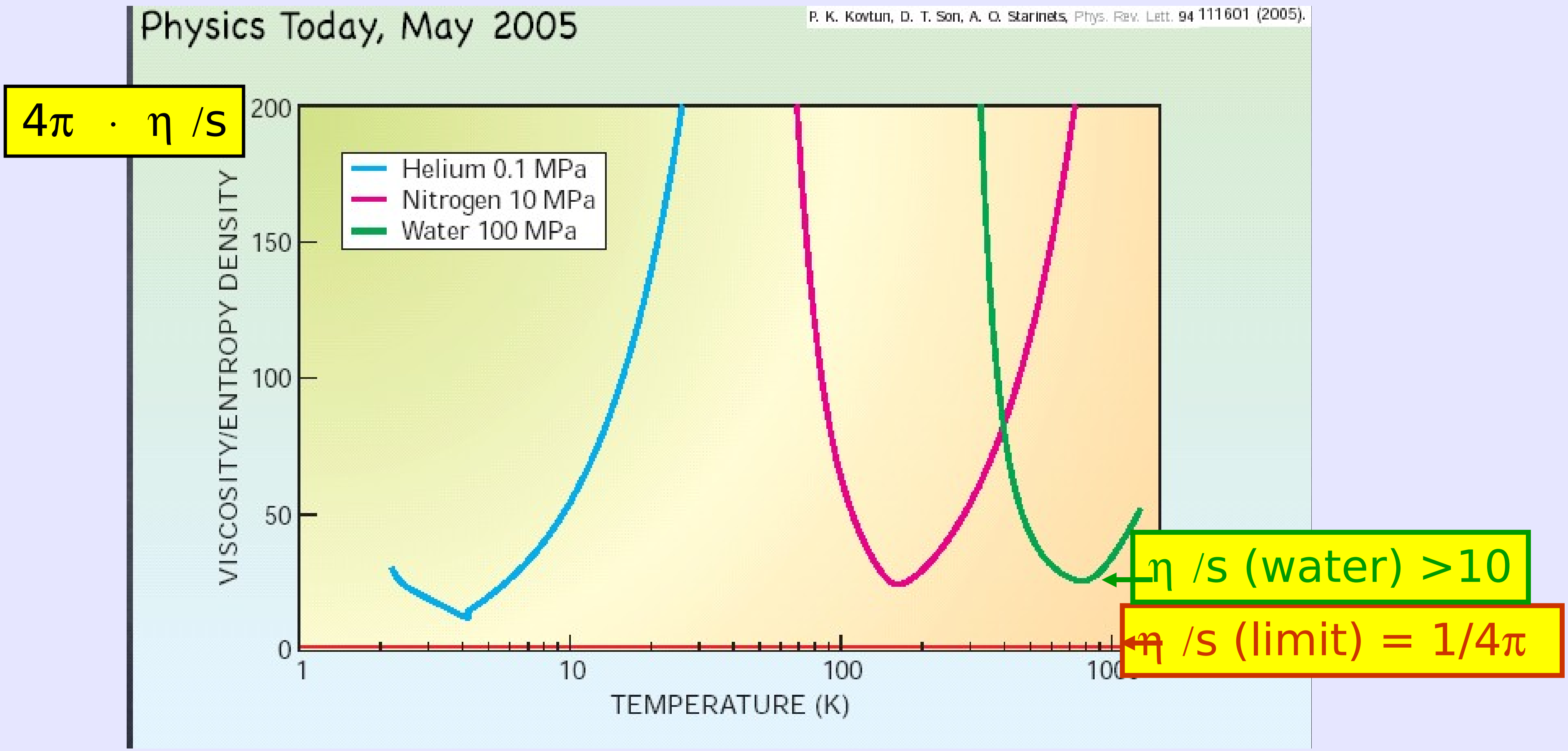
$$\eta \sim \rho v \ell, \qquad s \sim n = \frac{\rho}{m}$$

$$\frac{\eta}{s} \sim m v \ell \sim \hbar \frac{\text{mean free path}}{\text{de Broglie wavelength}}$$

Quasiparticles: de Broglie wavelength $\lesssim$ mean free path

Therefore $\eta/s \gtrsim \hbar$

Universal bound seems to apply to all known substances



What about actual QCD ?

- Chiral perturbation theory at low T (Prakash *et al.*):

grows with decreasing T

$$\frac{\eta}{s} = \frac{15}{16\pi} \frac{f_\pi^4}{T^4}$$

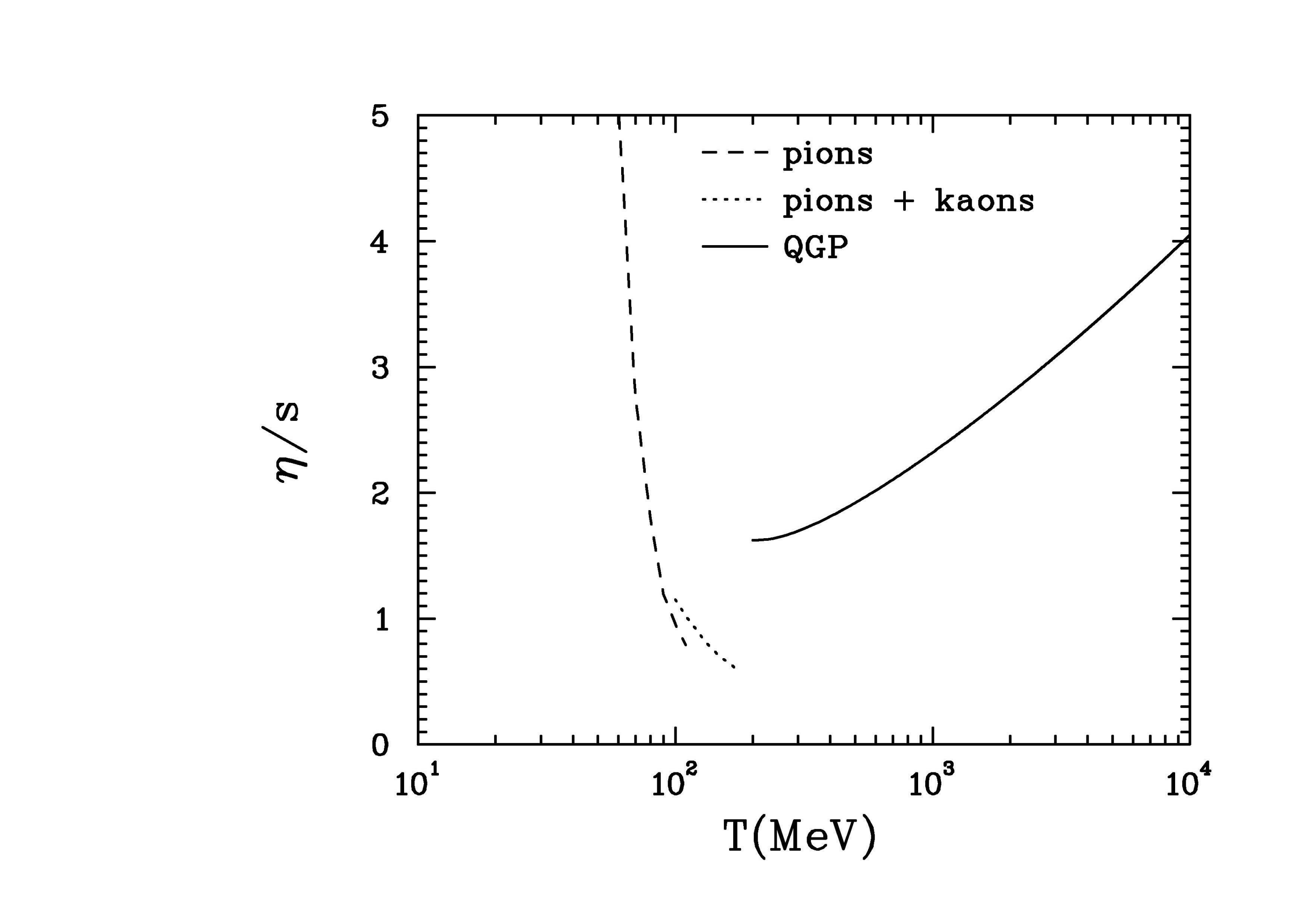
- Quark-gluon plasma at high T (Arnold, Moore, Yaffe):

grows with increasing T

$$\frac{\eta}{s} = \frac{5.12}{g^4 \ln(2.42/g)}$$

$$\frac{1}{g^2(T)} = \frac{9}{8\pi^2} \ln\left(\frac{T}{\Lambda_T}\right) + \frac{4}{9\pi^2} \ln\left(2\ln\left(\frac{T}{\Lambda_T}\right)\right) \qquad \Lambda_T = 30\,MeV$$

QCD



η/s ~1/2 just above T_c from lattice (Nakamura, Sakai pure gauge SU(3)) and a quasi-particle model (Gelman, Shuryak, Zahed)

Viscous relativistic hydrodynamics (Israel & Stewart 1979)

Include shear viscosity η, neglect bulk viscosity (massless partons) and heat conduction ($\mu_B \approx 0$); solve

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

with modified energy momentum tensor

$$T^{\mu\nu}(x) = T_0^{\mu\nu}(x) + \pi^{\mu\nu} = \big(e(x)+p(x)\big)u^\mu(x)u^\nu(x) - g^{\mu\nu}p(x) + \pi^{\mu\nu}.$$

$\pi^{\mu\nu}$ = traceless viscous pressure tensor which relaxes locally to 2η times the shear tensor $\sigma^{\mu\nu} \equiv \nabla^{\langle\mu}u^{\nu\rangle}$ on a microscopic kinetic time scale τ_π:

$$D\pi^{\mu\nu} = -\frac{1}{\tau_\pi}\left(\pi^{\mu\nu} - 2\eta\nabla^{\langle\mu}u^{\nu\rangle}\right) - \left(u^\mu\pi^{\nu\lambda}+u^\nu\pi^{\mu\lambda}\right)Du_\lambda$$

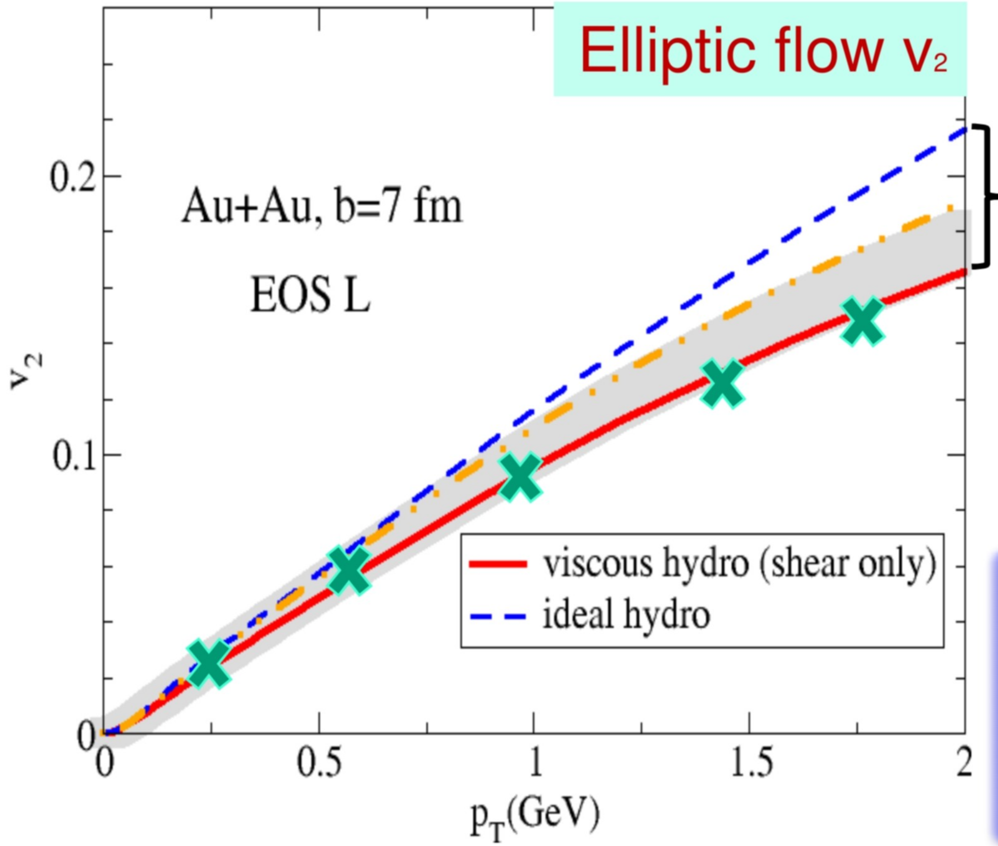
where $D \equiv u^\mu\partial_\mu$ is the time derivative in the local rest frame.

Kinetic theory relates η and τ_π, but for a strongly coupled QGP neither η nor this relation are known $\Longrightarrow$ treat η and τ_π as independent phenomenological parameters. For consistency: $\boxed{\tau_\pi\theta \ll 1}$ ($\theta = \partial^\mu u_\mu$ = local expansion rate).

U. Heinz, QM2008

U. Heinz, talk given at DM2010 (CapeTown)

Shear viscosity η & elliptic flow v_2



20-25% v_2 suppression $\frac{\eta}{s} = \frac{1}{4\pi}$

Example: If v_2 is increased by 10%, one needs to increase η / s by $\mathbf{0.5/(4\pi)}$ in order to describe the same exp. data

for $\eta / s \sim O(1/4\pi)$
-**10%** uncertainties in v_2 translate into **50%** uncertainties for the extracted value of η / s

- v_2 can be used to extract the QGP shear viscosity
- for an accurate extraction of QGP viscosity, one needs very precise v_2 (experimental data & theoretical results)

There are still many uncertainties in extracting viscosity from the data

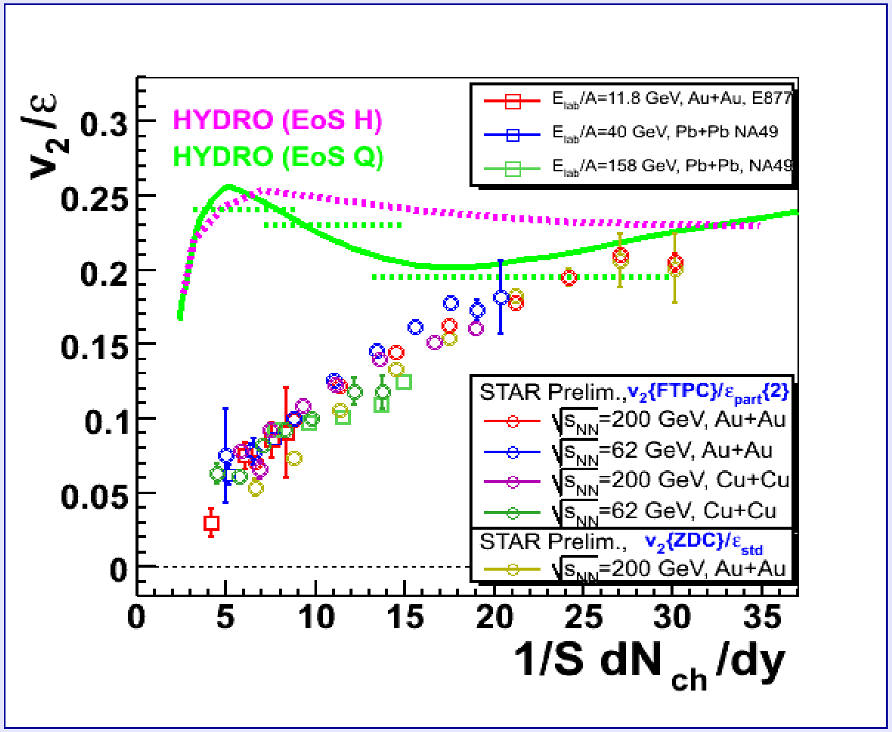
LHC forecast

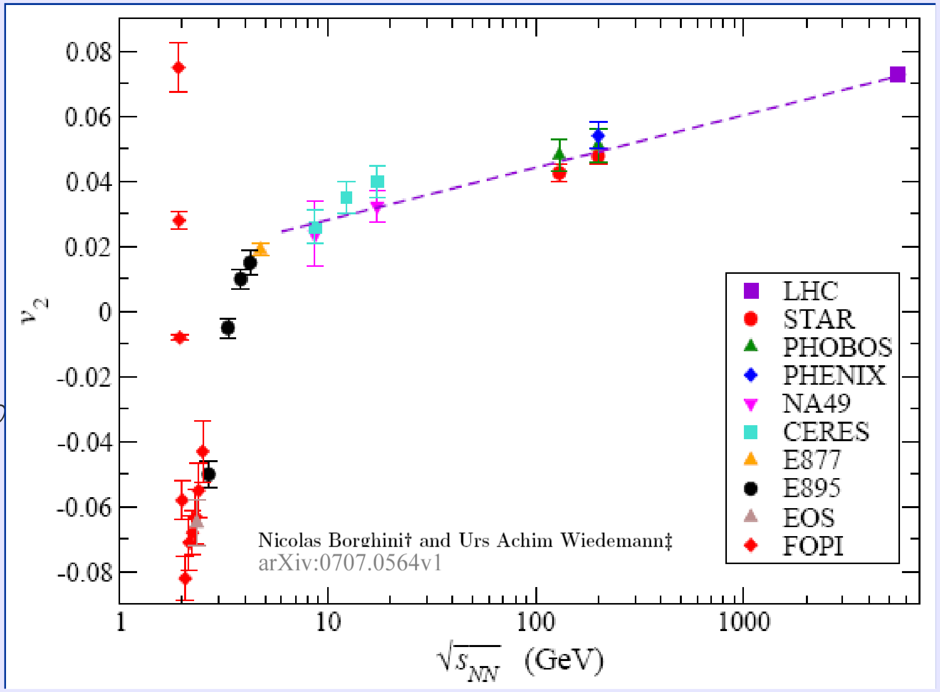
Several unknowns in the problem

- What is the behaviour of viscosity with T?
- Have we interpreted correctly the data from RHIC?
- Why don't we see the “ideal hydrodynamic limit”?

Predictions (*LHC last call for predictions*, CERN workshop june 2007)

- Based on quasi-ideal hydro: v_2 will almost be the same as at RHIC (Heinz)
- Based on simple arguments of minimal viscosity and scaling: v_2 will consistently decrease (Molnar)
- *Naive extrapolation*: it will increase by almost 50%





CONCLUSIONS

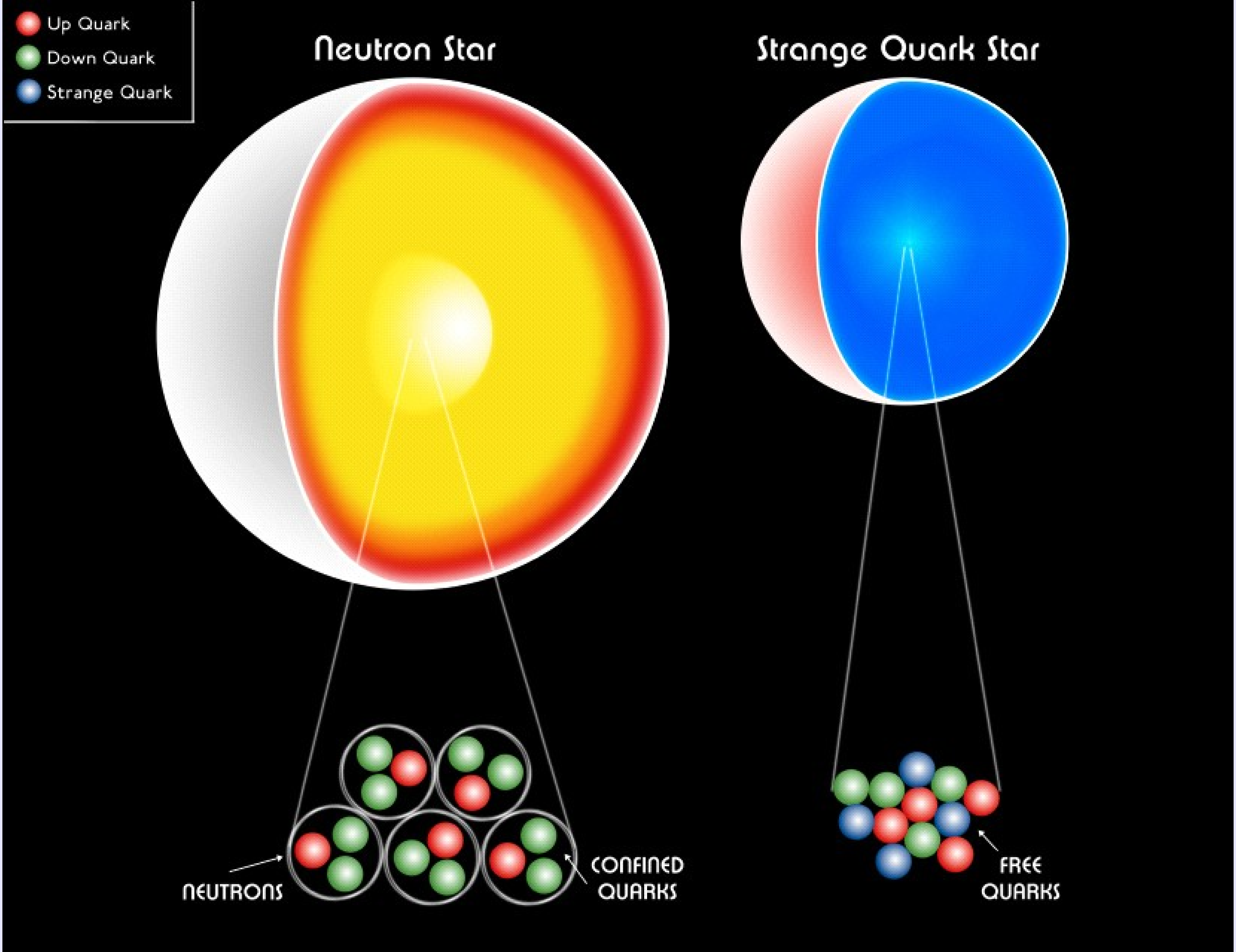
- Successo della descrizione fluidodinamica con equilibrio termodinamico locale nella descrizione delle collisioni di ioni pesanti ad energie ultrarelativistiche

- Densita' di energia stimata e' ben oltre il punto di crossover come indicato da lattice QCD

- Flusso ellittico: termalizzazione rapida e comportamento da fluido quasi ideale.

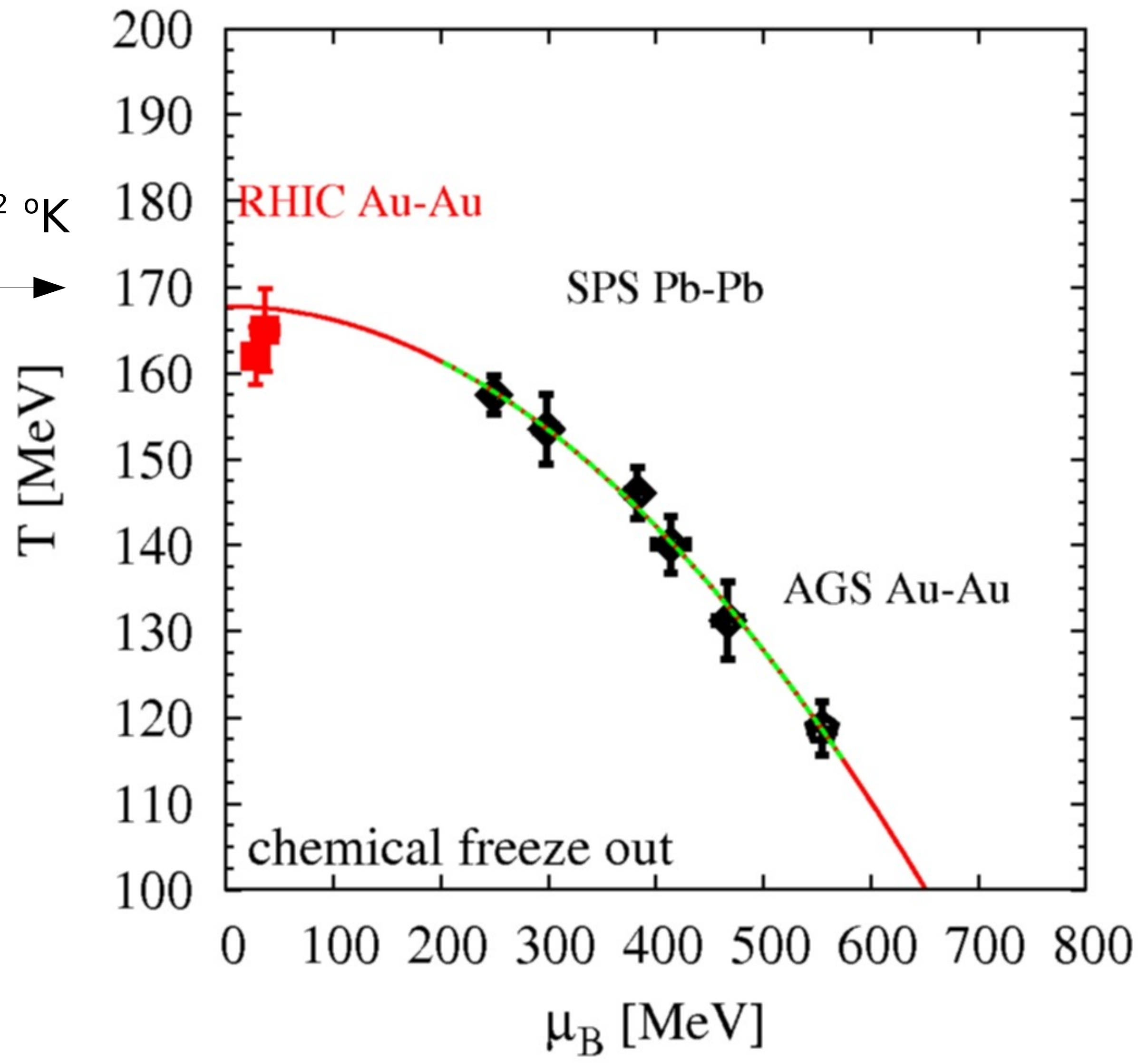
- Calcoli di fluidodinamica relativistica viscosa *in progress*

- LHC permettera' di studiare molto piu' accuratamente le proprieta' della materia fortemente interagente nello stato di plasma



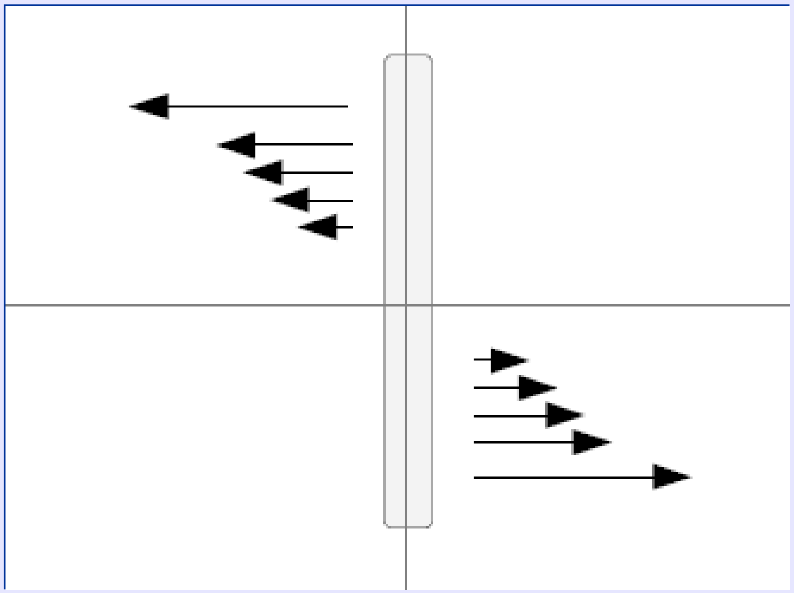
Up Quark
Down Quark
Strange Quark
Neutron Star
Strange Quark Star
NEUTRONS
CONFINED
QUARKS
FREE
QUARKS

2 x 10^{12} °K


200
190
180
170
160
150
140
130
120
110
100
T [MeV]
RHIC Au-Au
SPS Pb-Pb
AGS Au-Au
chemical freeze out
0
100
200
300
400
500
600
700
800
μ_B [MeV]

Possibile ingrediente trascurato: vorticita' iniziale non nulla (rotazione)

F. B., F. Piccinini, J. Rizzo, Phys. Rev. C 77 (2008) 024906



Caso limite di termalizzazione istantanea per energia di collisione infinita: la conservazione del momento angolare comporta:

$$\frac{\partial v_z}{\partial x} \neq 0$$

contrariamente all'assunzione *Bjorken scaling*

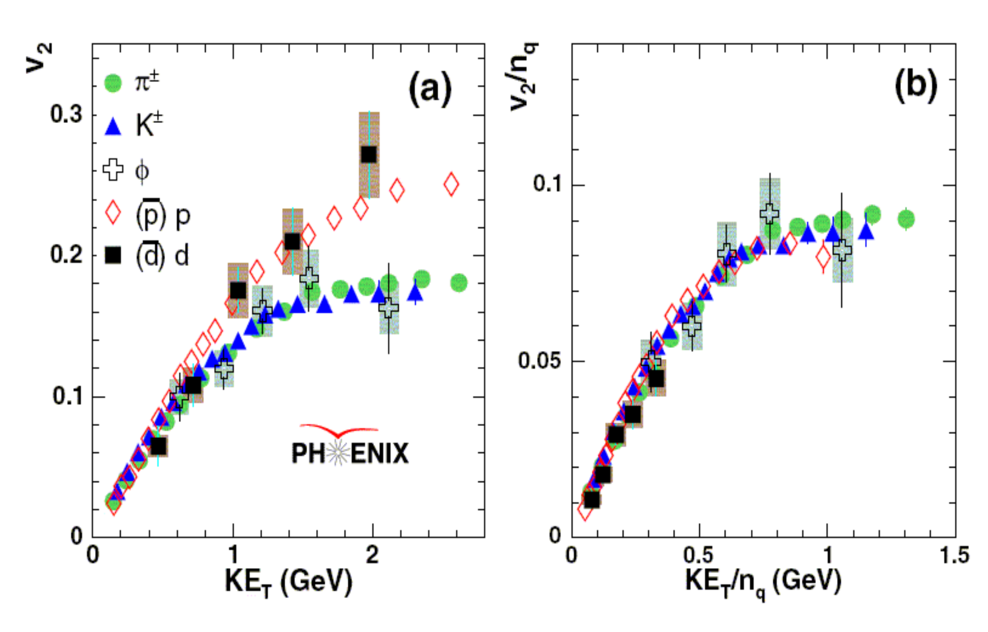
Termine aggiuntivo nell'equazione di evoluzione che AUMENTA il flusso ellittico

$$\rho_0 \gamma_0^3 \frac{\partial u_i}{\partial t}\Big|_{t=0} = -\frac{1}{4}\frac{\partial \rho \gamma^2}{\partial x_i}\Big|_{t=0} + \frac{1}{4} 2 \rho_0 \gamma_0^4 v_{z0} \frac{\partial v_{z0}}{\partial x_i}\Big|_{t=0}$$

Sotto studio con codice numerico di fluidodinamica relativistica 3+1 in collaborazione con il gruppo di plasmi astrofisici di Arcetri (L. Del Zanna)

Argomento qualitativo: v_2 aumentera' a LHC se la termalizzazione sara' ancora piu' rapida

v_2 in funzione dell' impulso: constituent quark scaling



Osservazione che ha portato alla formulazione del modello di adronizzazione per ricombinazione

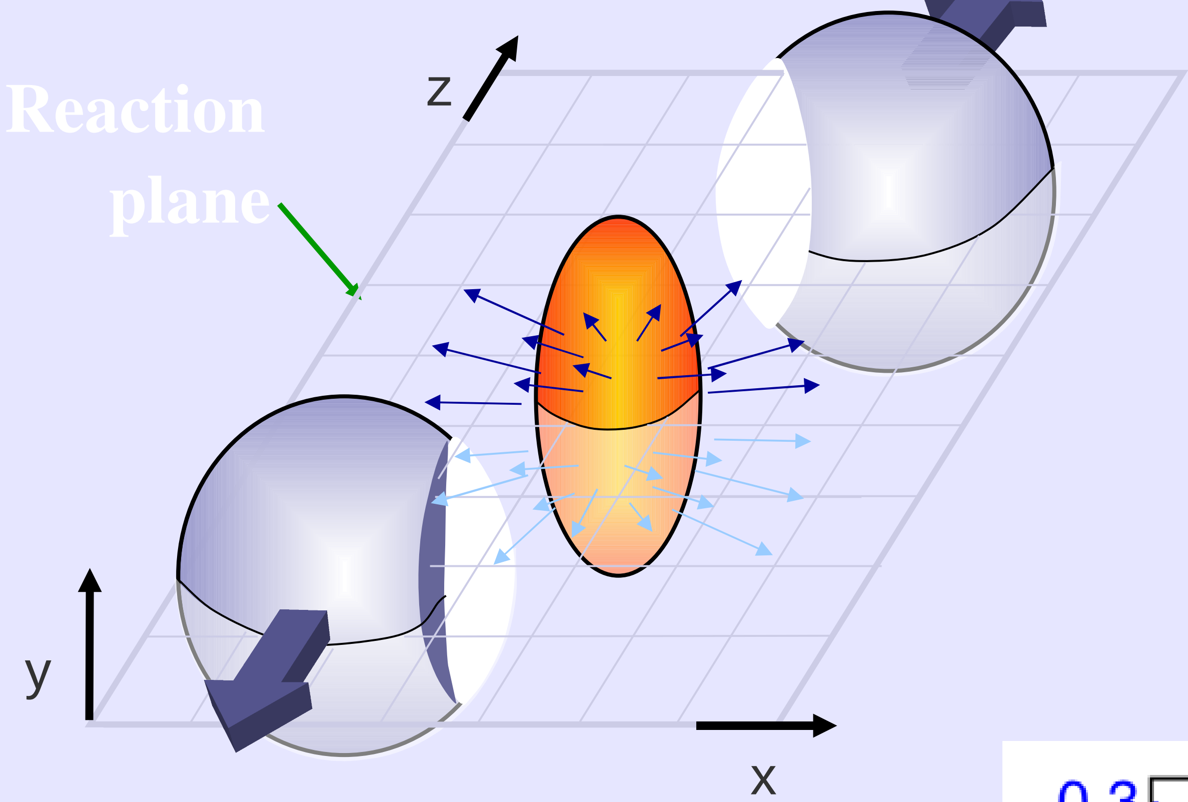
Ingrediente fondamentale: numero di quarks costituenti

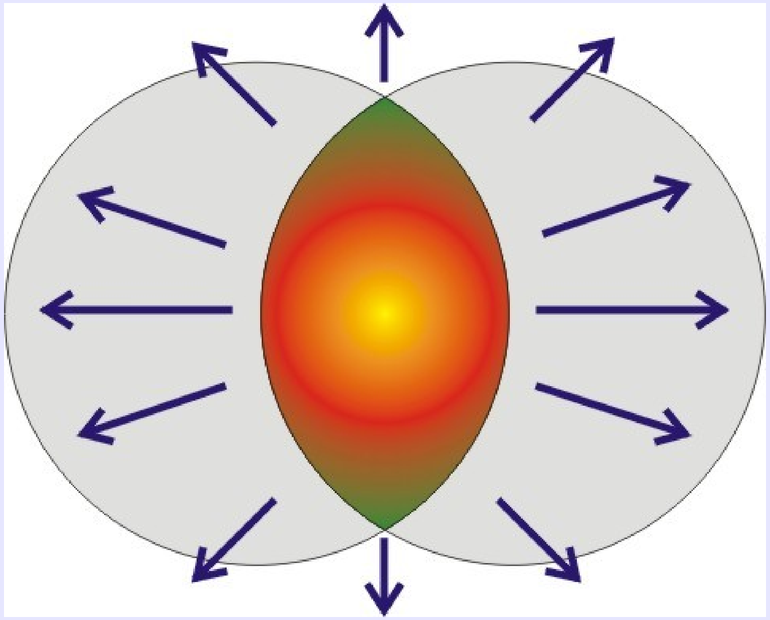
Attivita' teorica in Italia: V. Greco (Catania)

Scaling utilizzato per determinare il numero di quarks costituenti dei mesoni scalari:

L. Maiani, A. Polosa, V. Riquer, C. Salgado, Phys. Lett. B 645 (2007) 138;
arXiv 0707.4578

Hadron radiation: elliptic flow

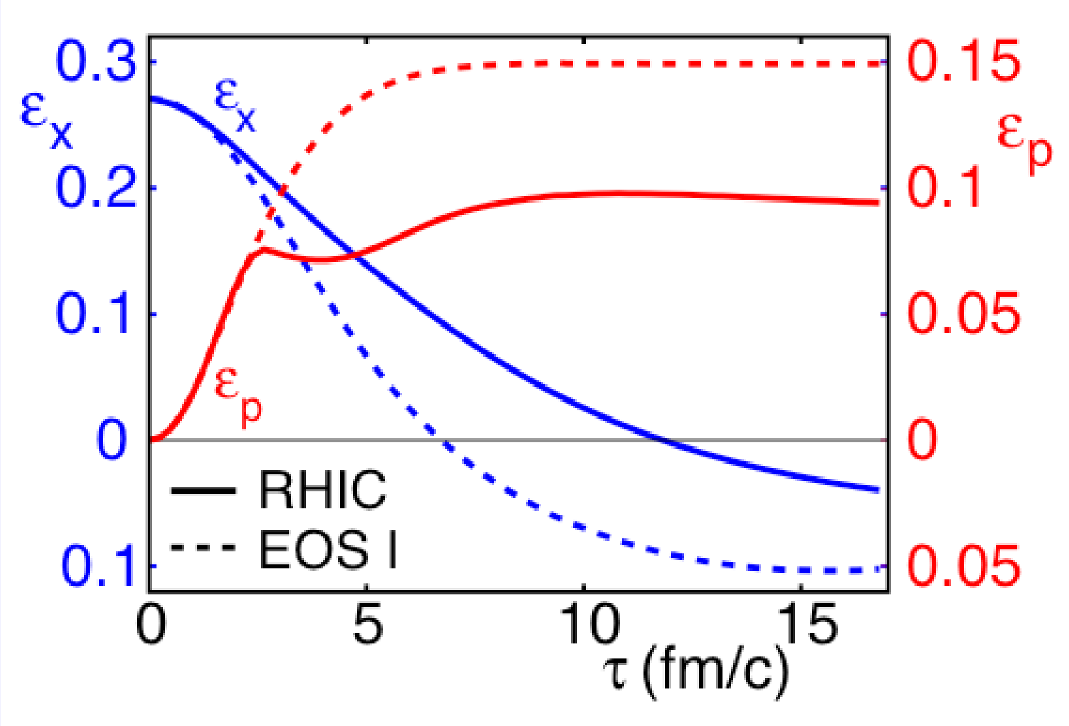




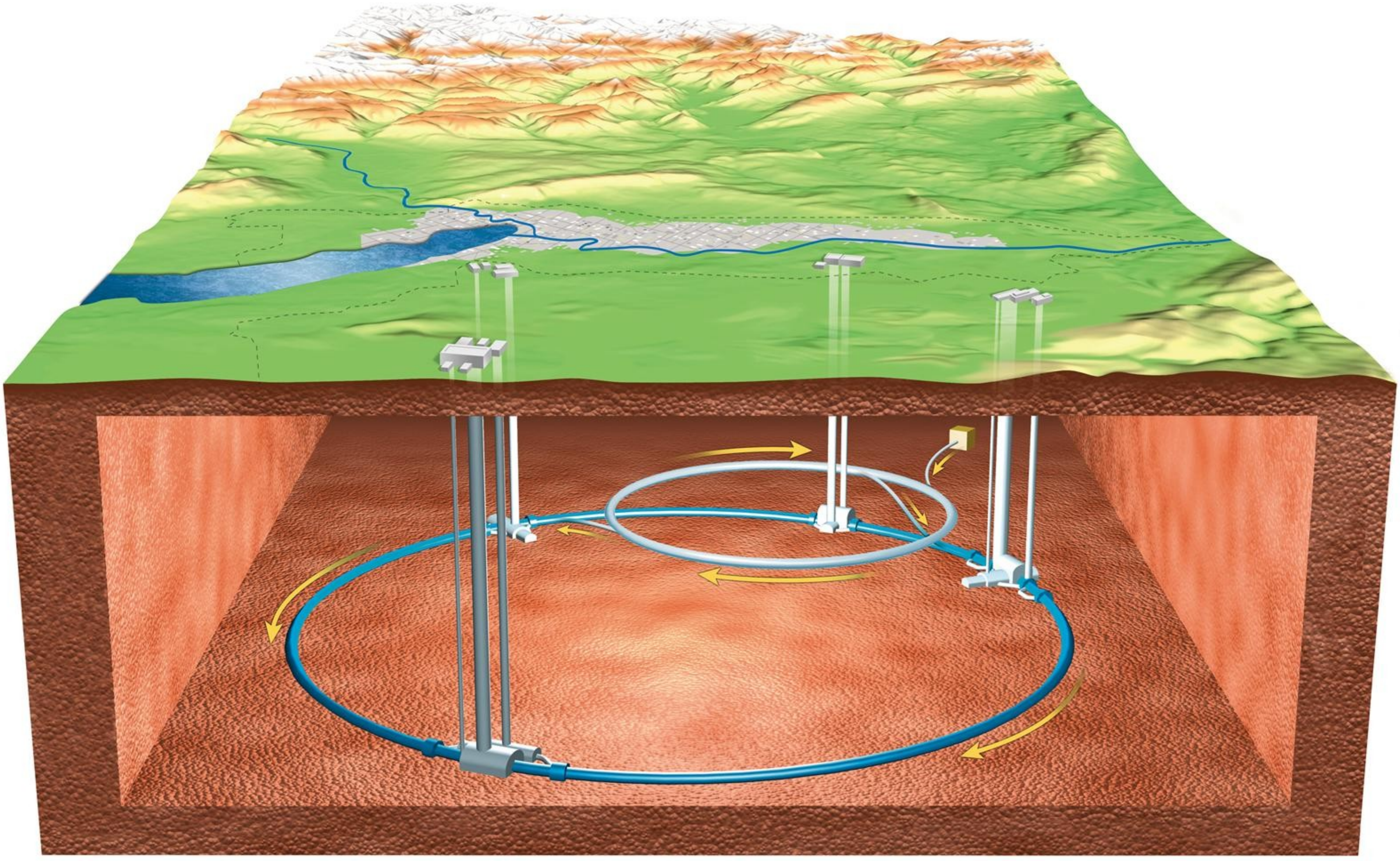
Anisotropia di impulso

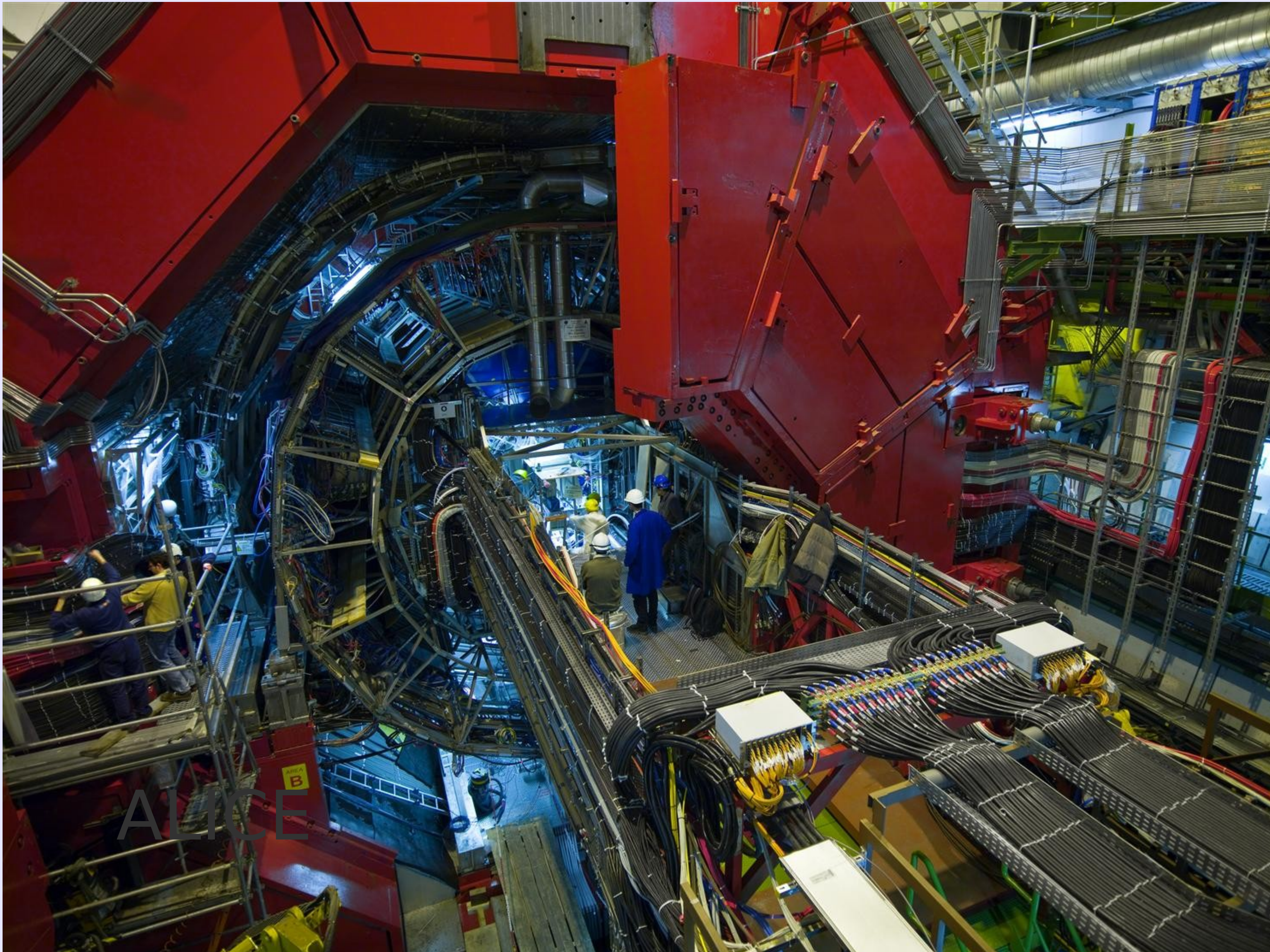
$$\epsilon_p = \frac{\langle T^{xx} - T^{yy} \rangle}{\langle T^{xx} + T^{yy} \rangle}$$

Elliptic flow

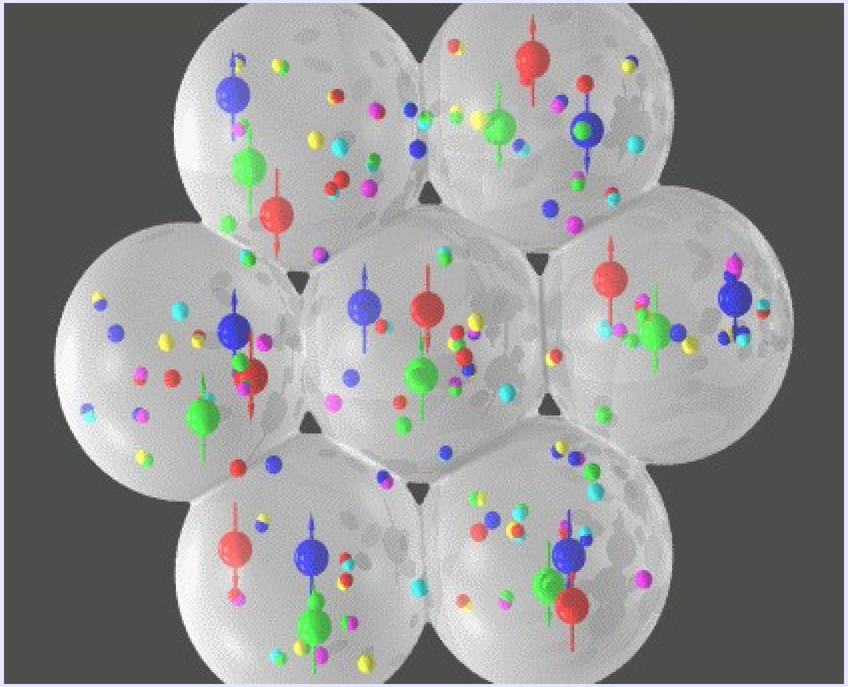


What next?




ALICE

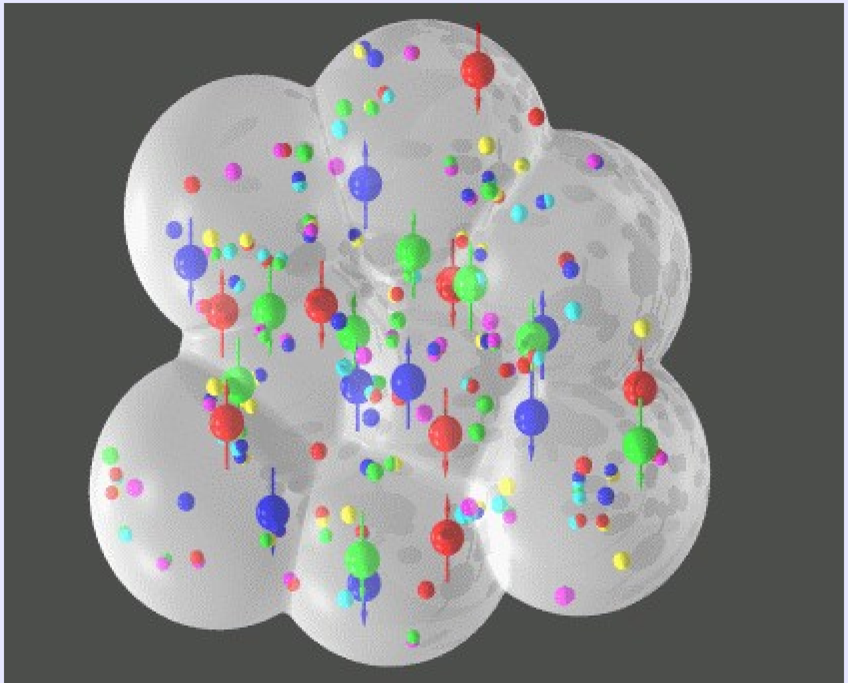
How can we observe the behaviour of free quarks and gluons ?



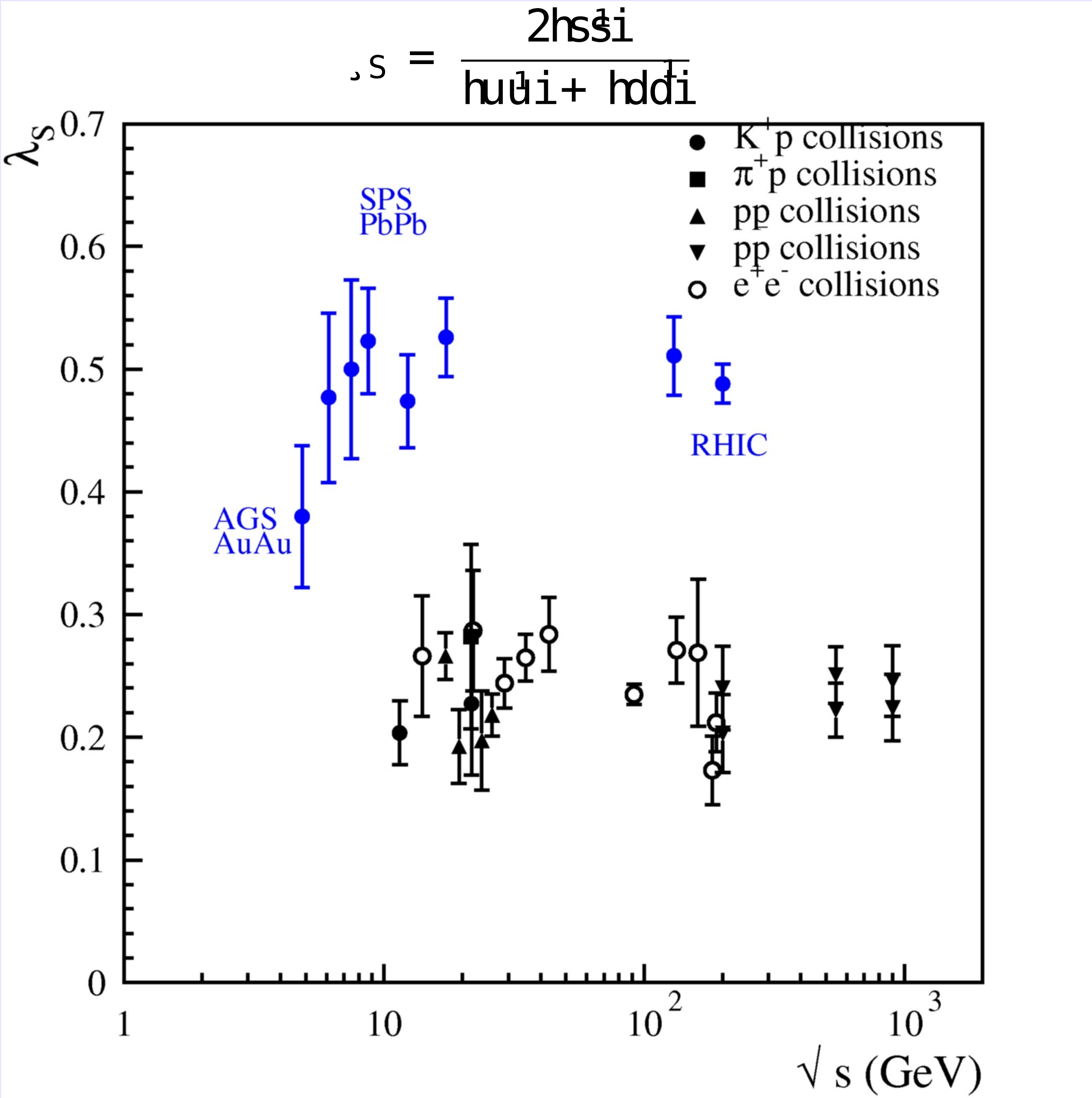
To free the fundamental constituents from their hadronic bounds we have to get them closer to each other in order to reduce the interaction strenght

i.e. to compress nucleons

If many nucleons are compressed, the coloured constituents can freely move from one nucleon to another



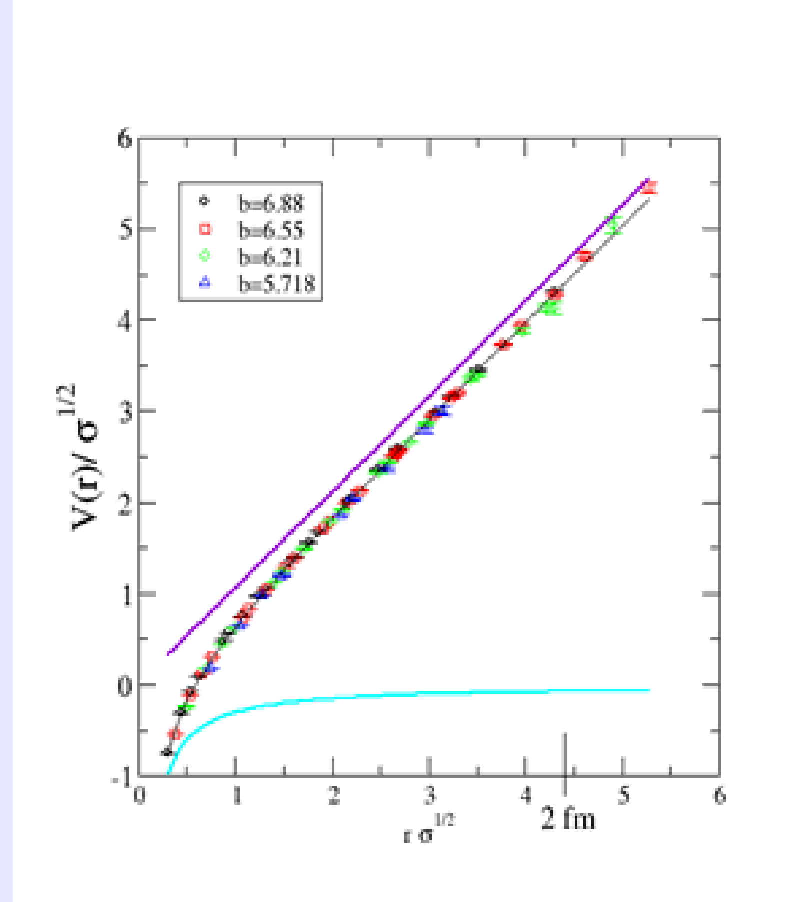
Wroblewski ratio: current status

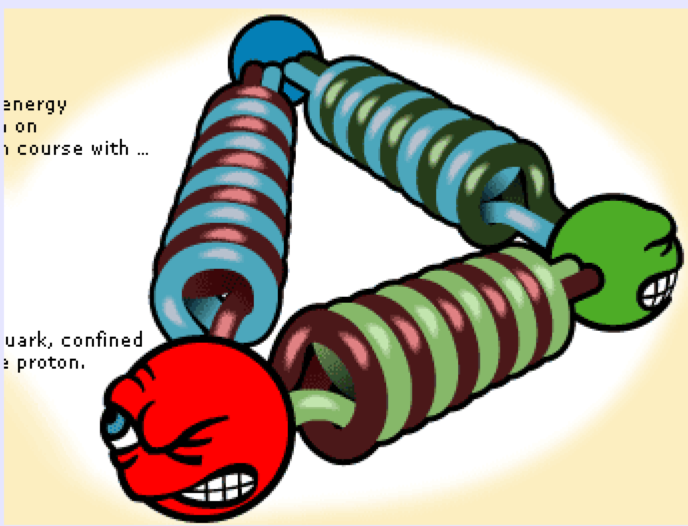


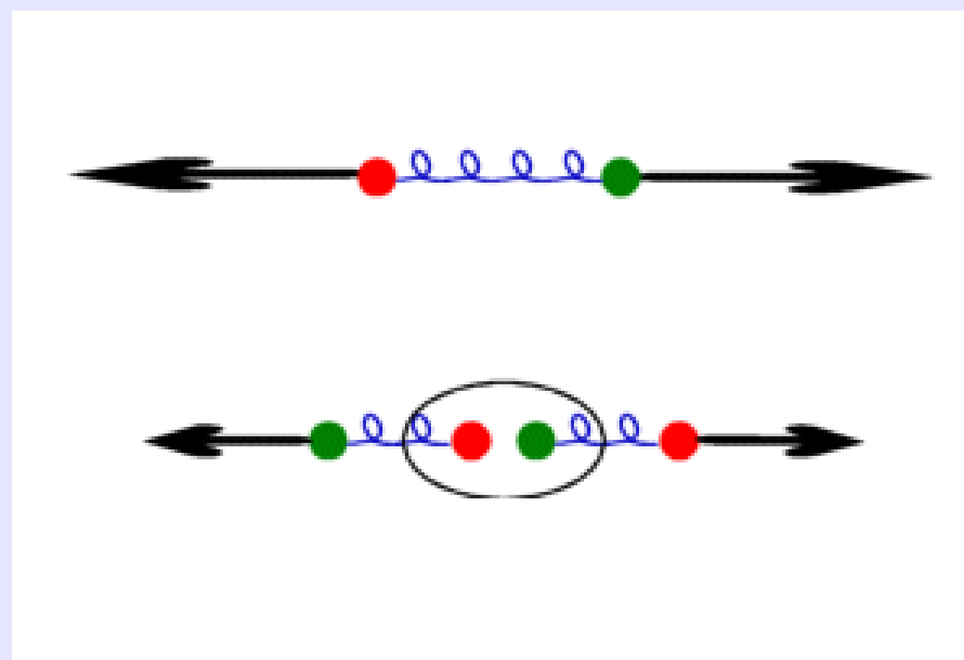
For a calculation on the lattice:

R. Gavai, S. Gupta,
Eur. Phys. J. C 43, 31 (2005)
and refs. therein

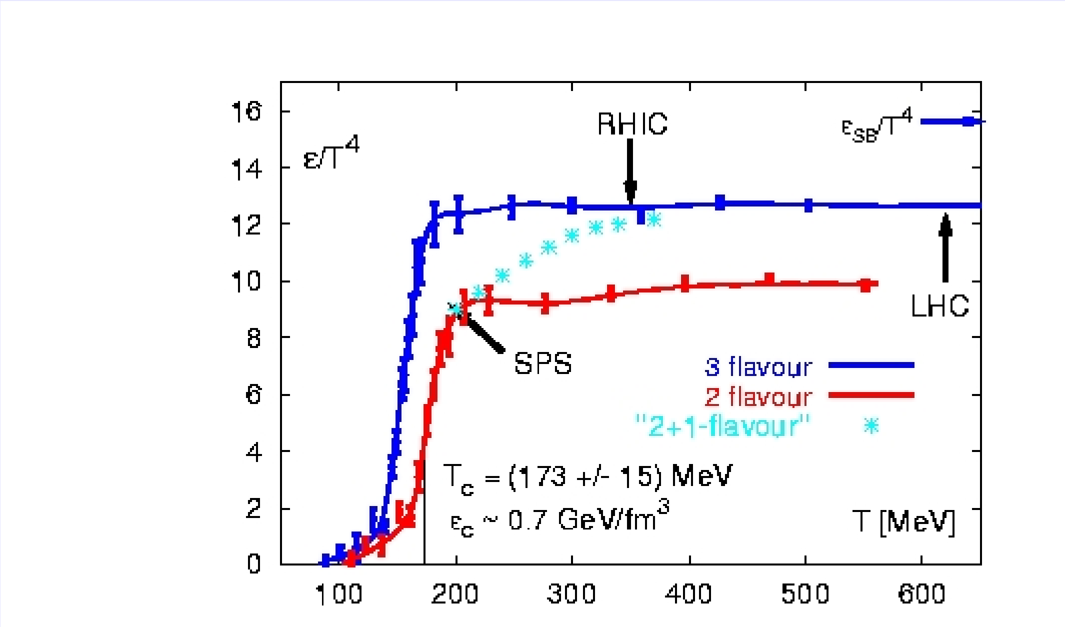
Linear rise of the potential energy between two static quarks







If we try, with e.g. an external probe, to pull a a quark out, the potential energy gets converted in a new quark-antiquark pair and new hadrons are formed



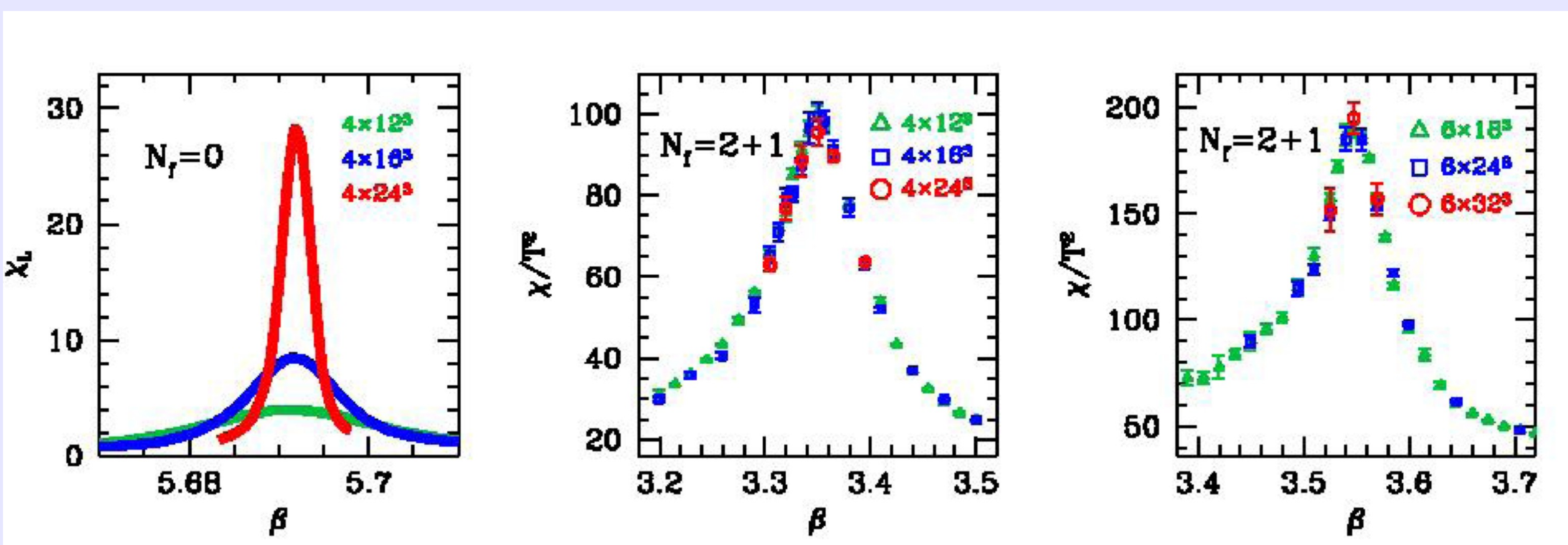
2+1 flavours:
2 $m_q/T = 0.4$
1 $m_q/T = 1.0$

F. Karsch, E. Laermann
in "Quark Gluon Plasma 3"
World Sc. P. 1

The phase transition at μ_B=0 is indeed a crossover **(Z. Fodor et al. Nature 443 (2006) 675)**

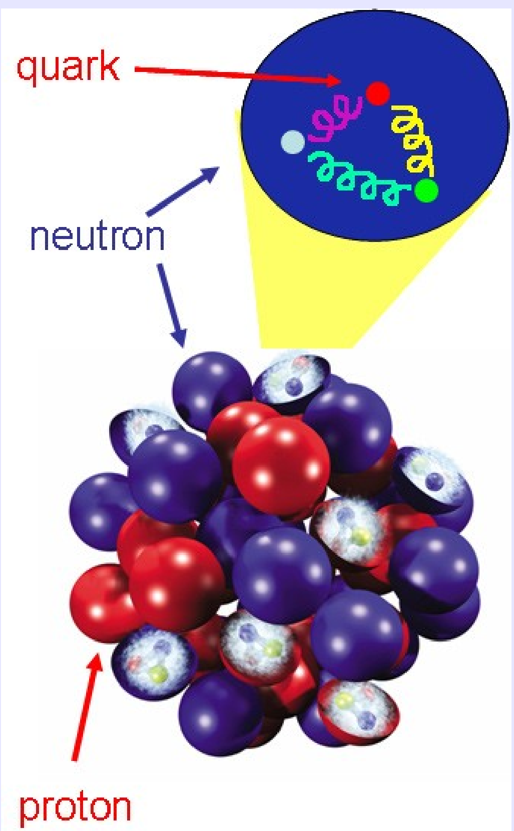
Two concurring transitions at the same or nearby temperature value:
deconfinement and chiral symmetry restoration

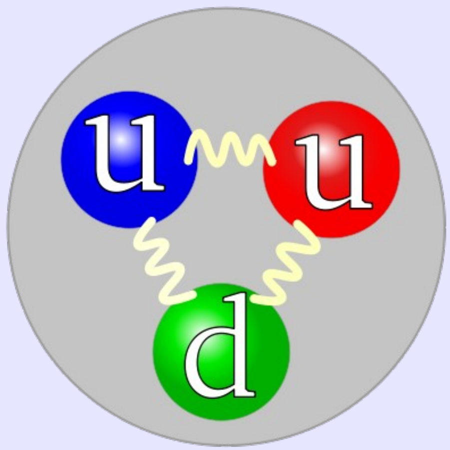
Chiral
susceptibility



What is Quantum Chromo Dynamics (QCD) ?

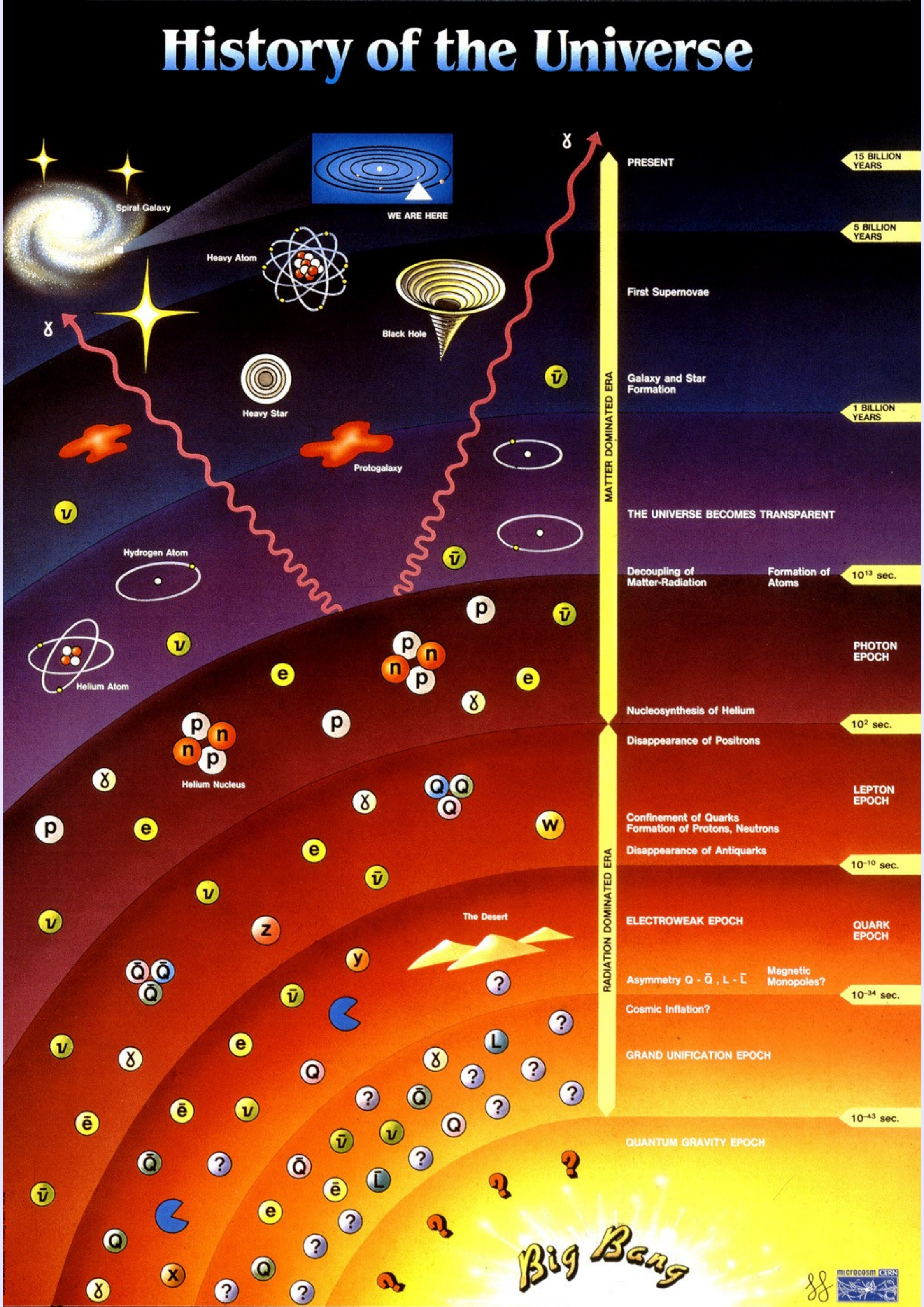
QCD is the theory of strong interaction. Its fundamental objects are quarks and gluons, elementary particles constituents of hadrons (by definition, strongly interacting particles).





The "charge" responsible for the strong interaction is called *colour*. Unlike QED, both quarks and gluons carry colour charge.

Unlike in QED, macroscopic effects of colour cannot be observed. In fact, observable particles made of quarks and gluons, hadrons, are colour singlets.



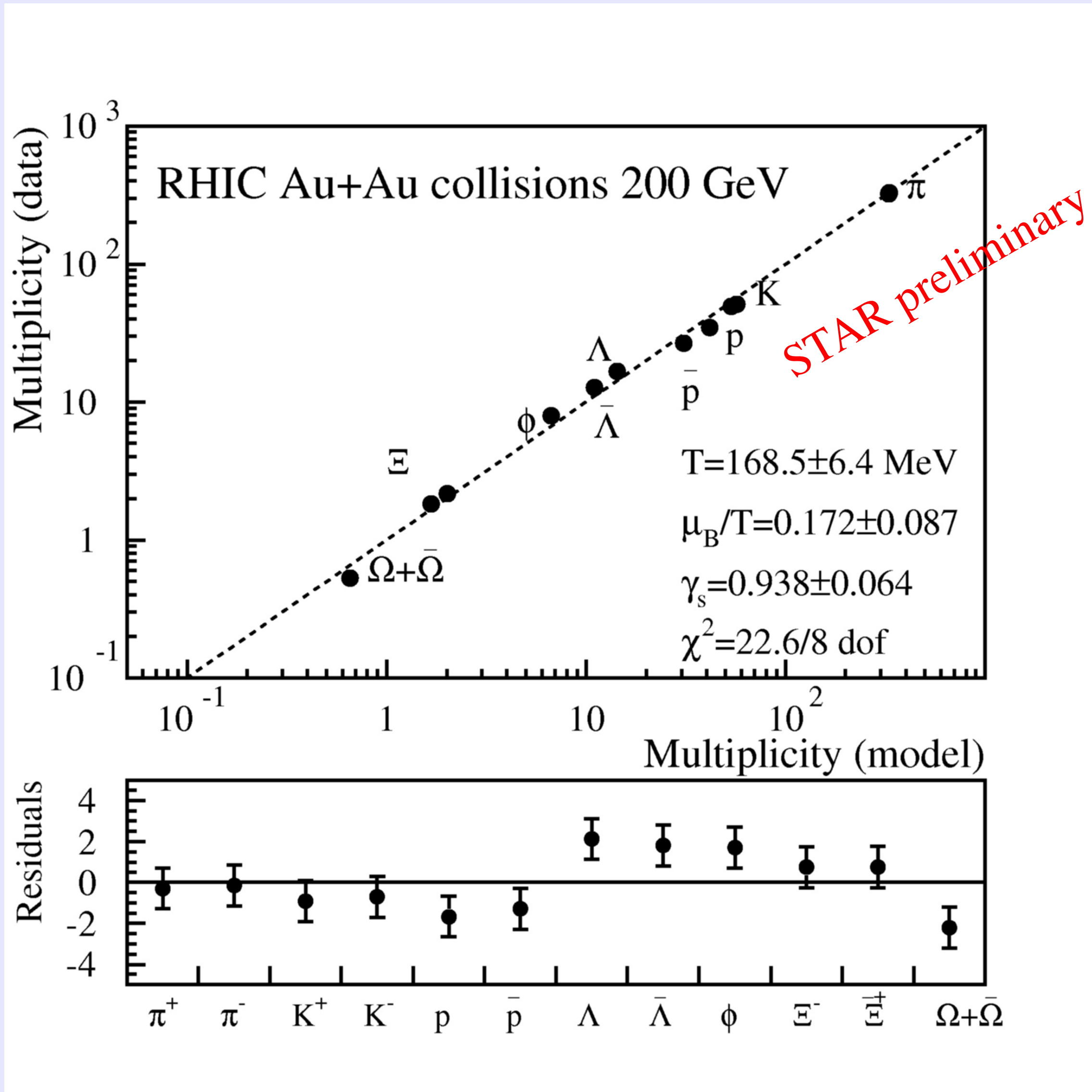
The phase transition
occurred in the
first moments of
Universe's life

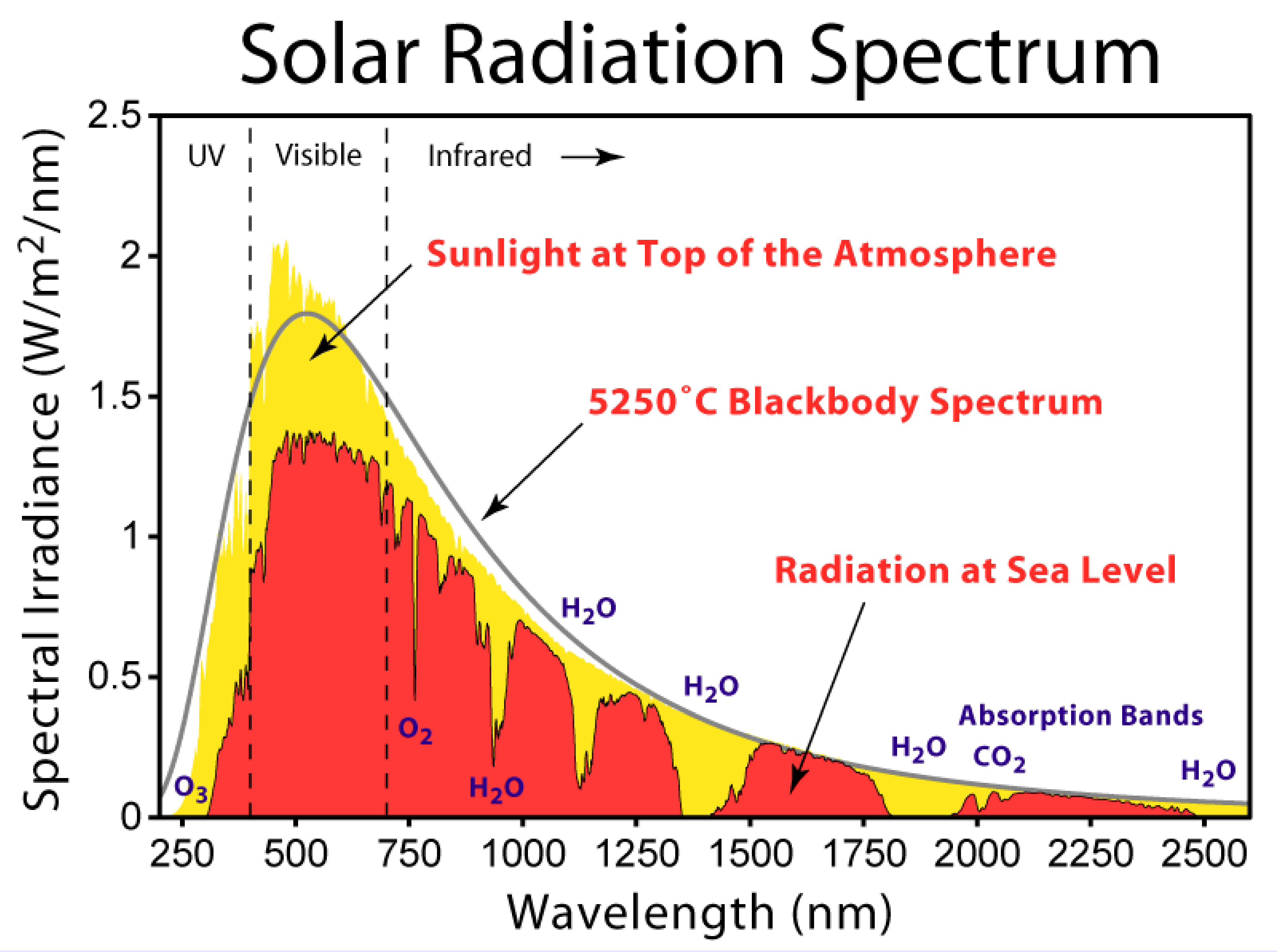
Cosa abbiamo imparato sul QGP dagli esperimenti di RHIC?

- Equilibrio chimico completo delle specie adroniche in collisioni centrali
- Spettri in accordo con equilibrio termico locale e T_{chem}(165 MeV) > T_{kin}(130 MeV)
- Flusso ellittico grande (circa il doppio che a SPS) spiegabile soltanto con termalizzazione veloce (< 1 fm/c) e comportamento idrodinamico quasi ideale (s-QGP)
- Jet quenching = perdita di energia dei partoni duri in un mezzo opaco
- Segnali di meccanismo di adronizzazione per coalescenza
- Soppressione del charmonio circa dello stesso ordine di quella osservata a SPS

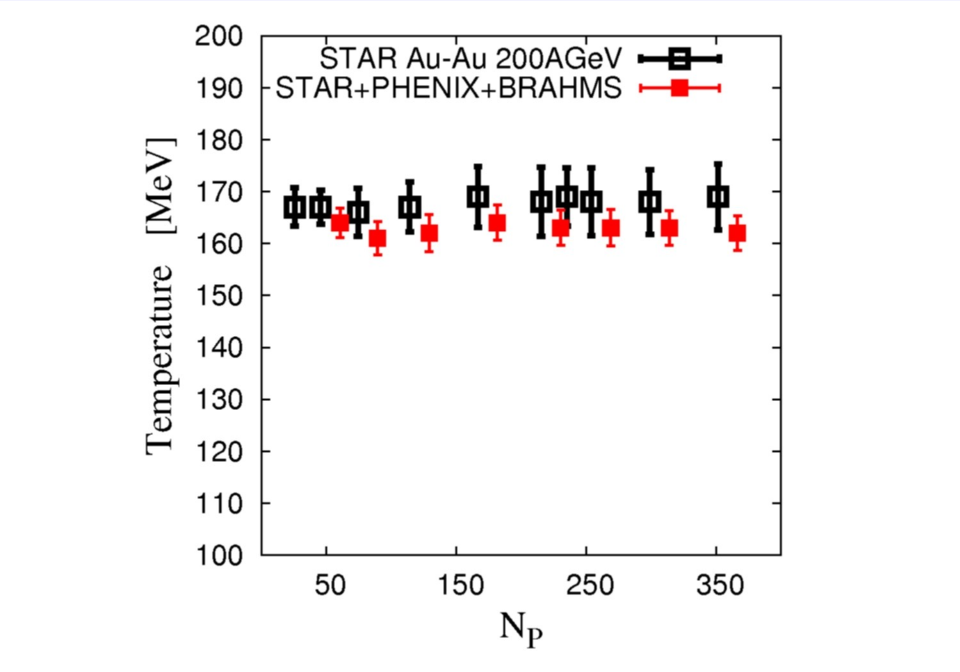
Evidenza di equilibrio chimico

F. B., J. Manninen, presented at QM08





Is the “statistical model” fit perfect?



La temperatura di freeze-out chimico e' indipendente dalla centralita'

F. B., J. Manninen, presented at QM08

La stranezza e' completamente saturata nelle collisioni piu' centrali