Quark Gluon Plasmas

???

Perfect Fluid?

sQGP?

Janus: the doorkeeper of Heaven

AdS_5 Black Hole?

Color Glasma?

Femto Cosmology with A+A @ LHC

M.Gyulassy, Columbia Uni. / Helmholtz Alliance

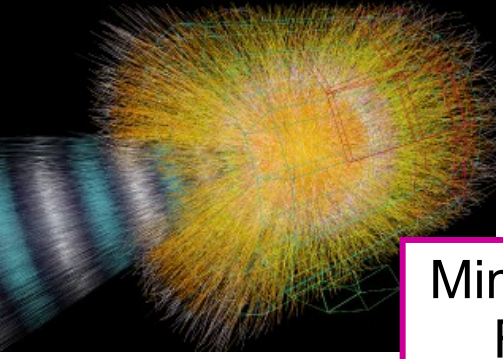
M.G., L. McLerran, Nucl.Phys.A750:30-63,2005

Outline:

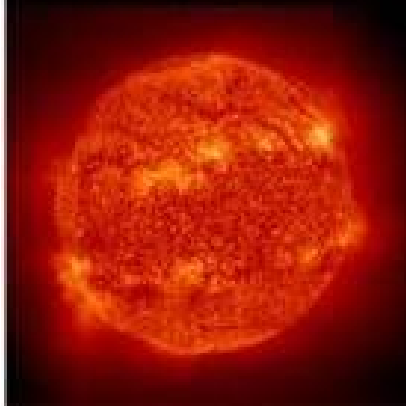
1)The QGP corner of EMMI's Landscape
2) QGP thermodynamics
3) Elliptic Flow Barometer
4) Jet Tomography

Some Startup Homework Problems for EMMI

EMMI Landscape



Mini Bangs
Femto
Cosmology



Plasmas
Lasers

T = ∞

μ = 0

quark-gluon plasma

electromagnetic plasma

strongly correlated many-body systems

$$\Gamma \equiv \frac{\alpha}{(\gamma-1)}\frac{\hbar}{\ell mc} \sim 1$$

μ = ∞

neutron matter

atomic systems

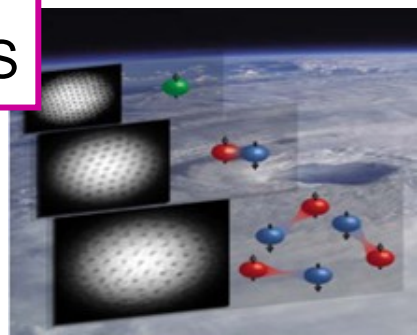
Neutron Star
Super Nova

T = 0

$\hbar$ =1

$Z\alpha_e$ >1
Trapped
BEC, BCS

SU(3) ⟷ U(1)



M.Gyulassy, Columbia/Helmholtz Alliance

Modelling Strongly Interacting Quark Gluon Plasmas

On the Fragile Boundary

between g=0 (wQGP) and g= ∞ (sQGP ~ AdS/CFT)

$$0 \ll \Gamma = \alpha \rho^{1/3} / T \sim 1 \ll \infty$$

The Unexpected Experimental Discoveries* at RHIC inspired a paradigm shift**

weak coupling wQGP => strong coupling sQGP <= AdS/CFT

However, recent 2007 theory advances now challenge this

Lim wQGP ~ Lim sQGP

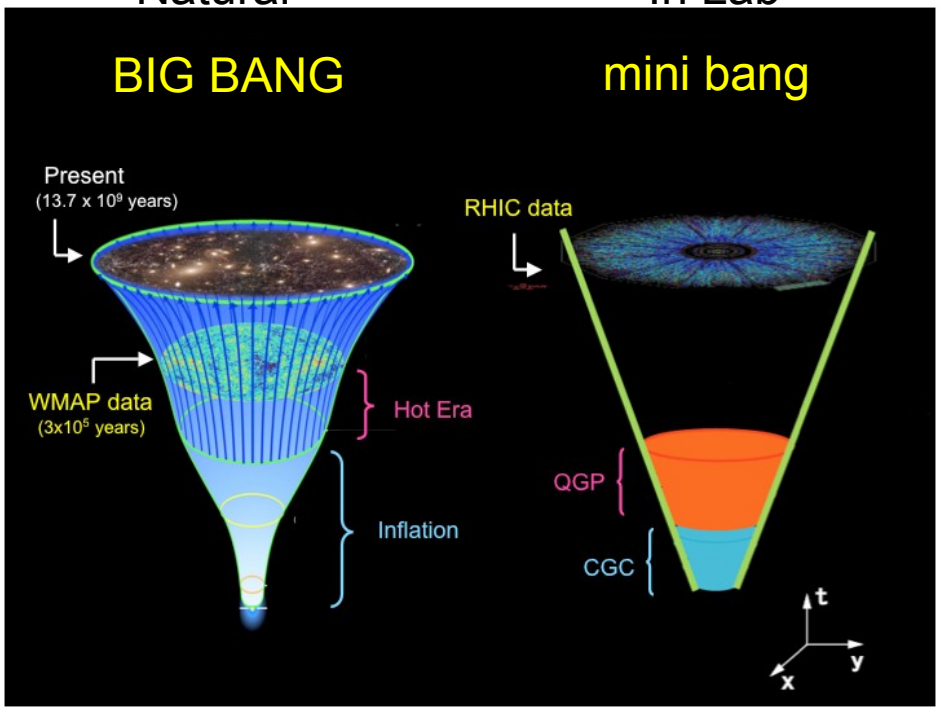
$\alpha_s \sim 0.3\text{-}0.5$

Cosmic vs Nuclear Time Machines

Natural | In Lab

Time

Now



-10^{+17} sec

Time

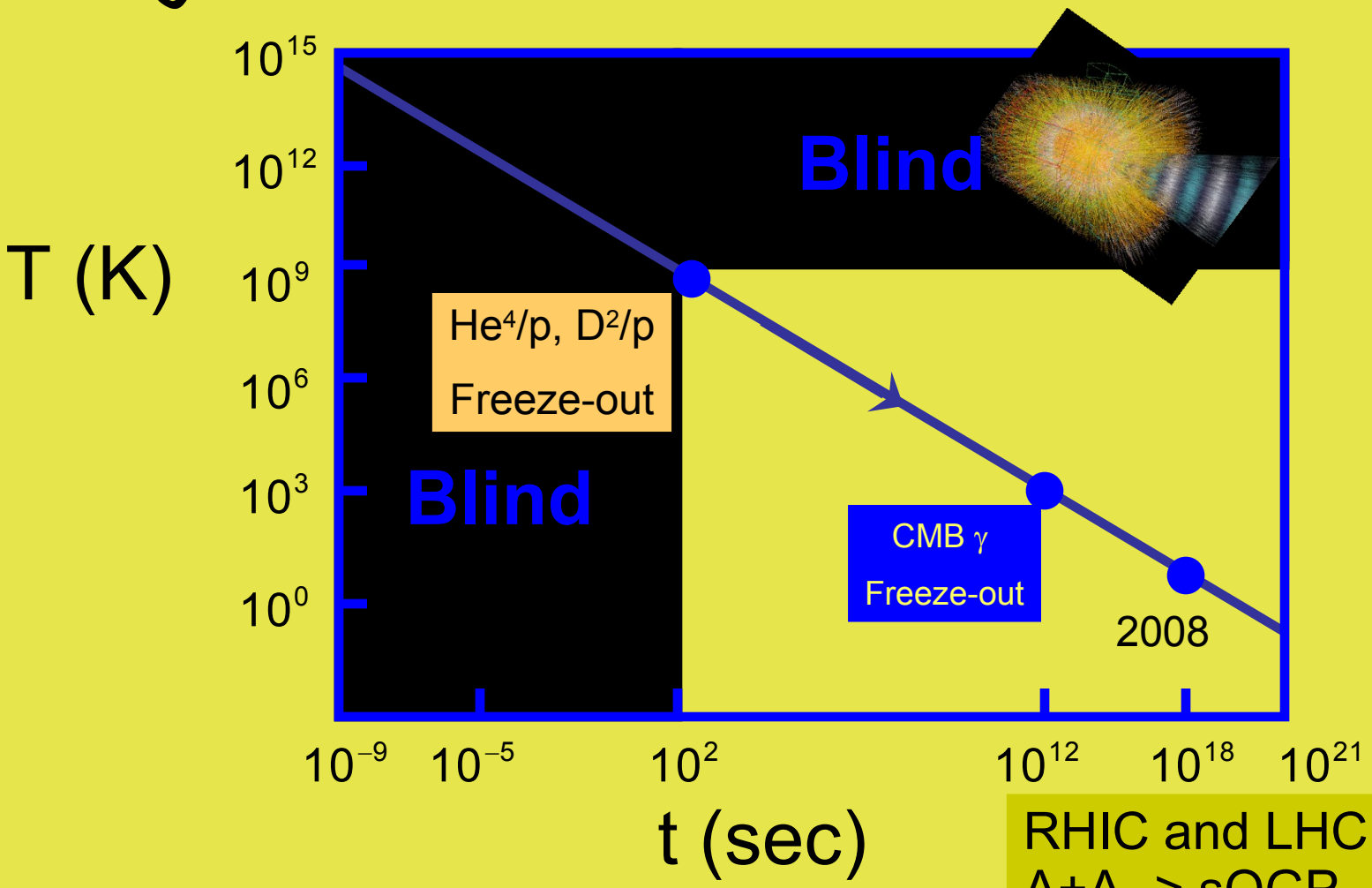
Now

-10^{-23} sec

- 1 BIG BANG event
  - Few probes: γ CMB , He/p,
  - Future:
    Neutrino ICE^3
    Gravity Waves GEO, LIGO

- 10^{10} mini bangs RHIC
  - Many probes: Flow, Jets, Strangeness, Charm, e, μ, γ
  - $0.01-10$ Femto-meters
  - Future: LHC (starts next month)

Nuclear Freeze-out blinds cosmologists to t<3 minutes but is a critical consistency test of BB



RHIC and LHC
A+A -> sQGP
probe matter with
T~ 10^{12} K (t_{BB} ~ 10^{-5} sec)

Experiment ~1600 Pb + Heat --> Au + Stuff ??

Finally succeeded in GSI 375 years later!

RHIC

Relativistic Heavy Ion Collider @ BNL

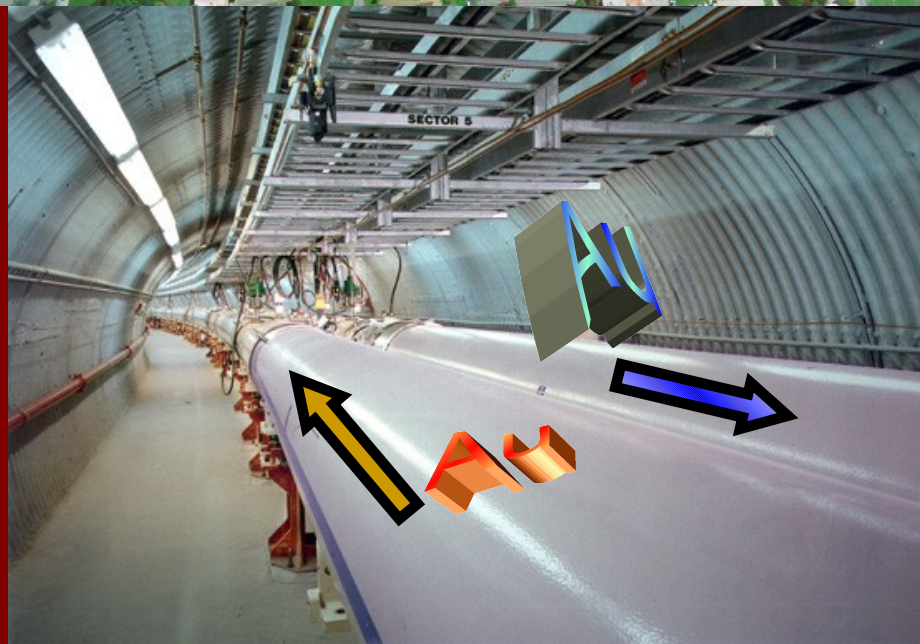
- Since 2000 -
- 3.8 km circ. collider
- 4 Experiments
  - STAR
  - PHENIX:
  - BRAHMS
  - PHOBOS
- p+p, d+A, A+A
- Energy:

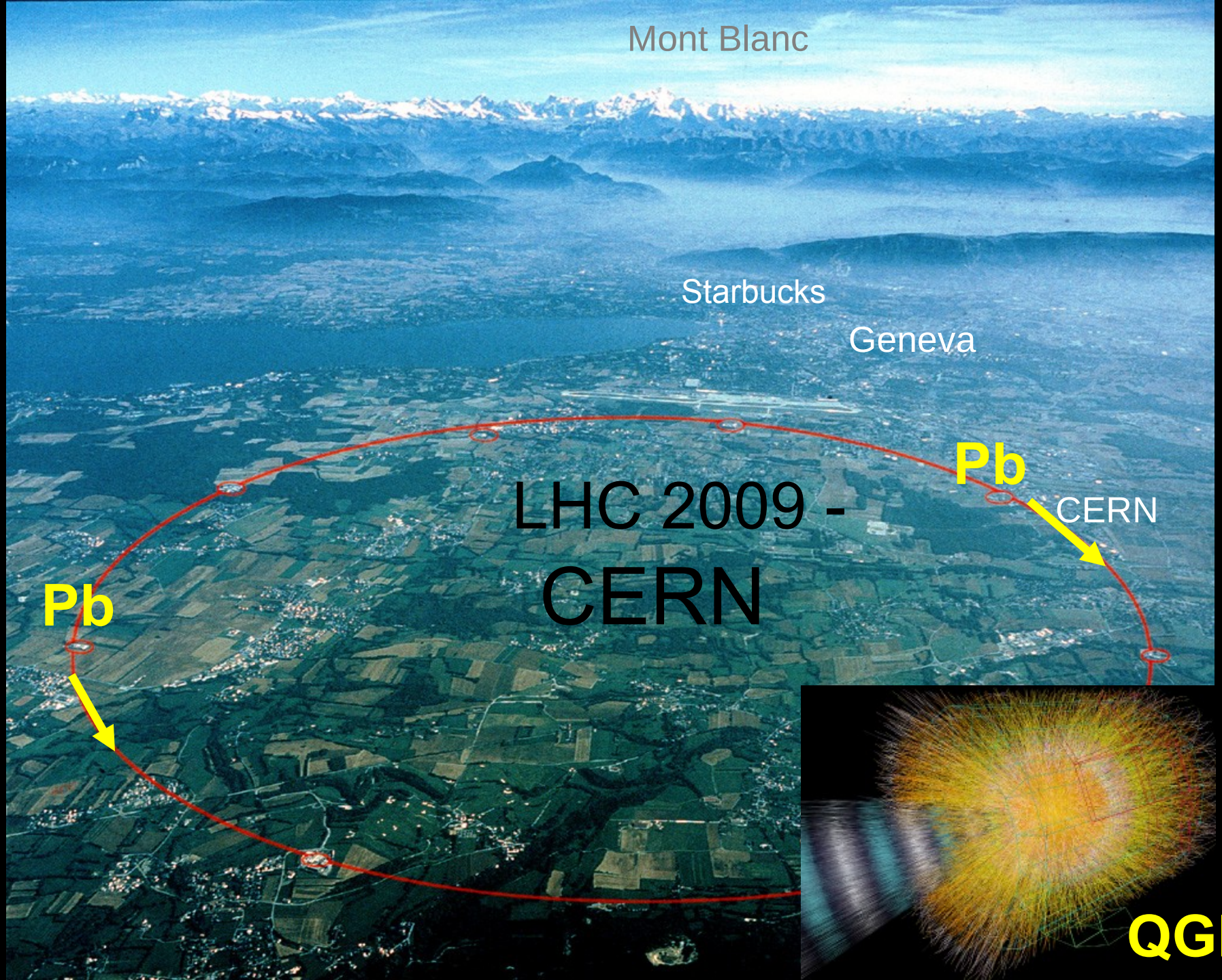
  500 GeV for p-p

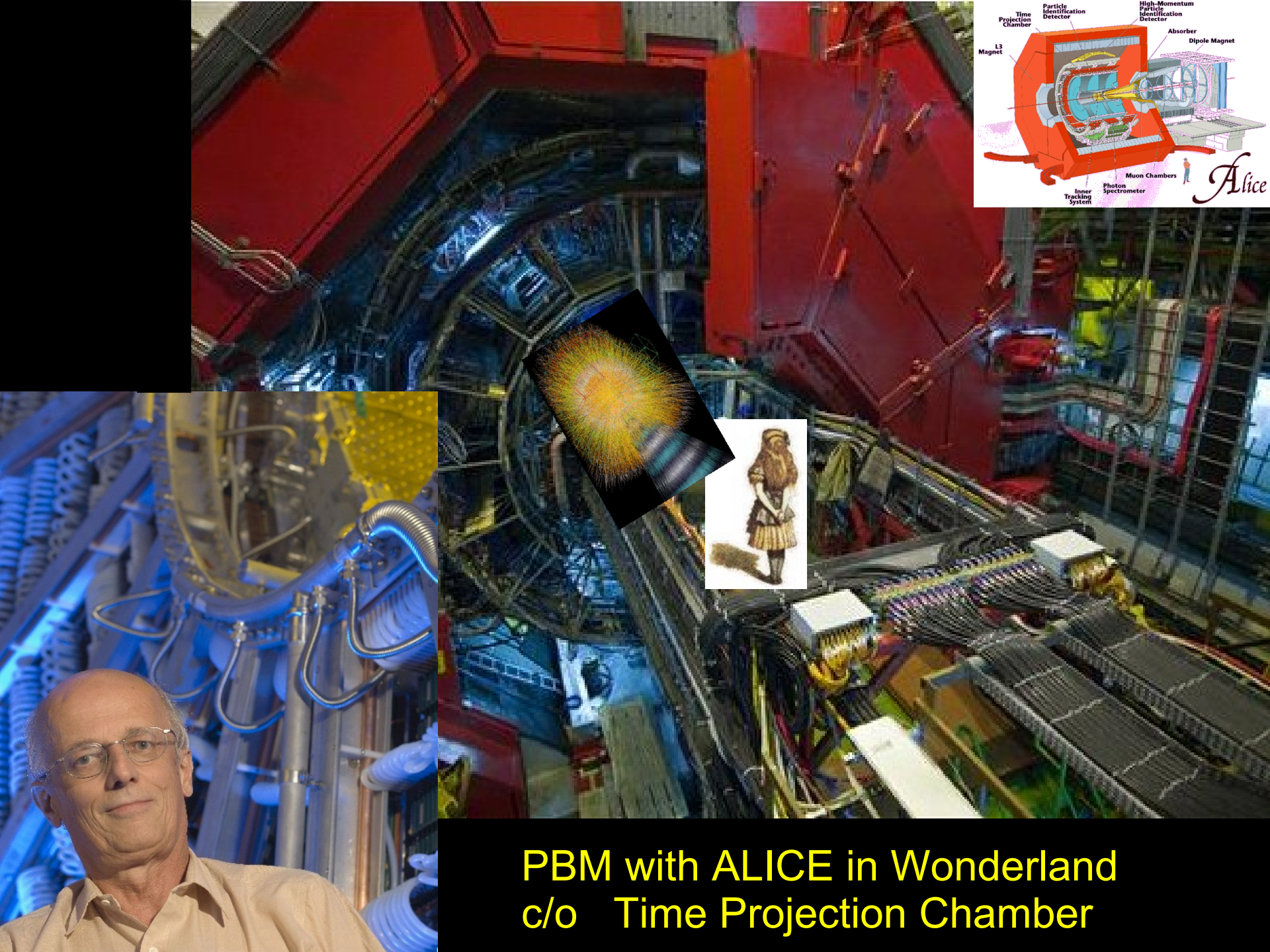
  5-200 AGeV for A+A

  39 TeV Au+Au

  13 TeV Cu+Cu

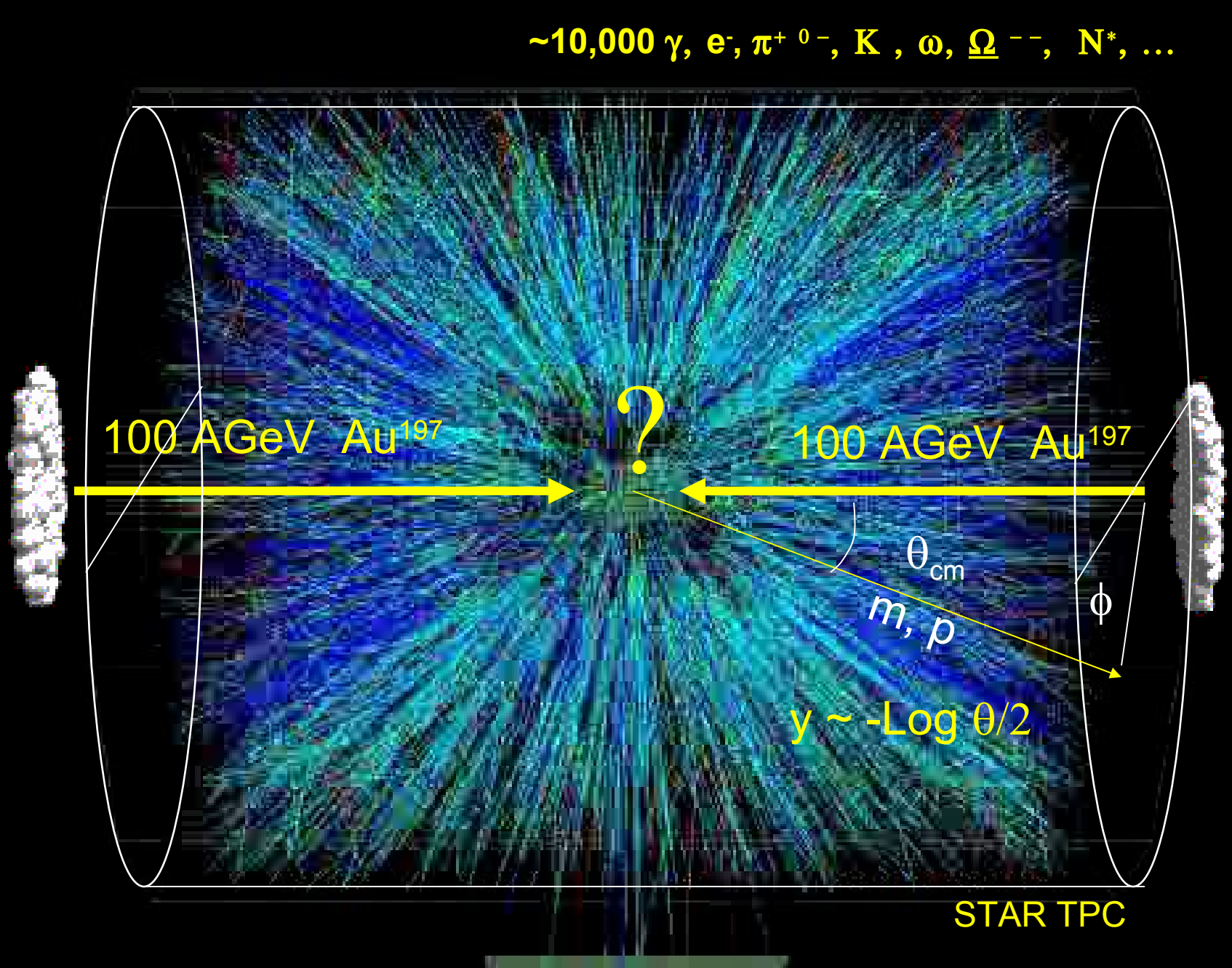



Mont Blanc
Starbucks
Geneva
LHC 2009 -
CERN
Pb
Pb
CERN
QGP



PBM with ALICE in Wonderland
c/o Time Projection Chamber

A typical mini bang at RHIC



Part 2: QCD Thermodynamics

EMMI prob 1: need to break the thermo impass

QCD quasiparticle vs Lattice vs AdS gravity duals vs ....

The ideal Quark Gluon Plasma 1975

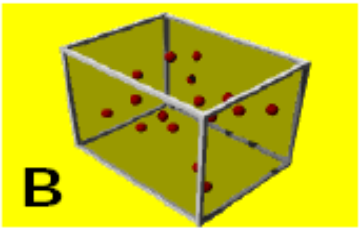
Collins, Perry
Baym, Chin
Freedman,
McLerran,
Shuryak, …

Because QCD is Asymptotically *Free*

$$P_{QCD}(T) \xrightarrow{T \gg \Lambda_{QCD}} P_{SB}(T)$$

1884

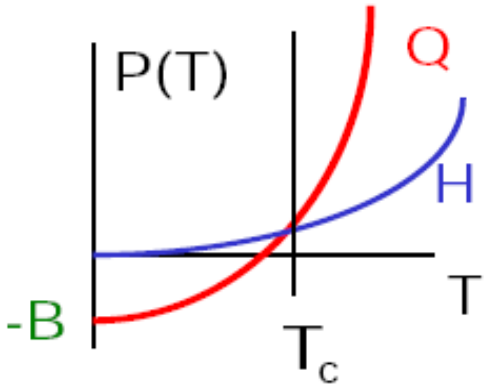
Ideal (Stefan-Boltzmann) Pressure at g→0



$$P^{QCD}_{SB}(T) = \left(\underbrace{2_s \times 8_c}_{\text{gluons}} + \frac{7}{8} \times \underbrace{2_s \times 3_c \times 2_{q\bar{q}} \times n_f}_{\text{quarks}}\right) \frac{\pi^2 T^4}{90} - \underbrace{B}_{\text{vac}}$$

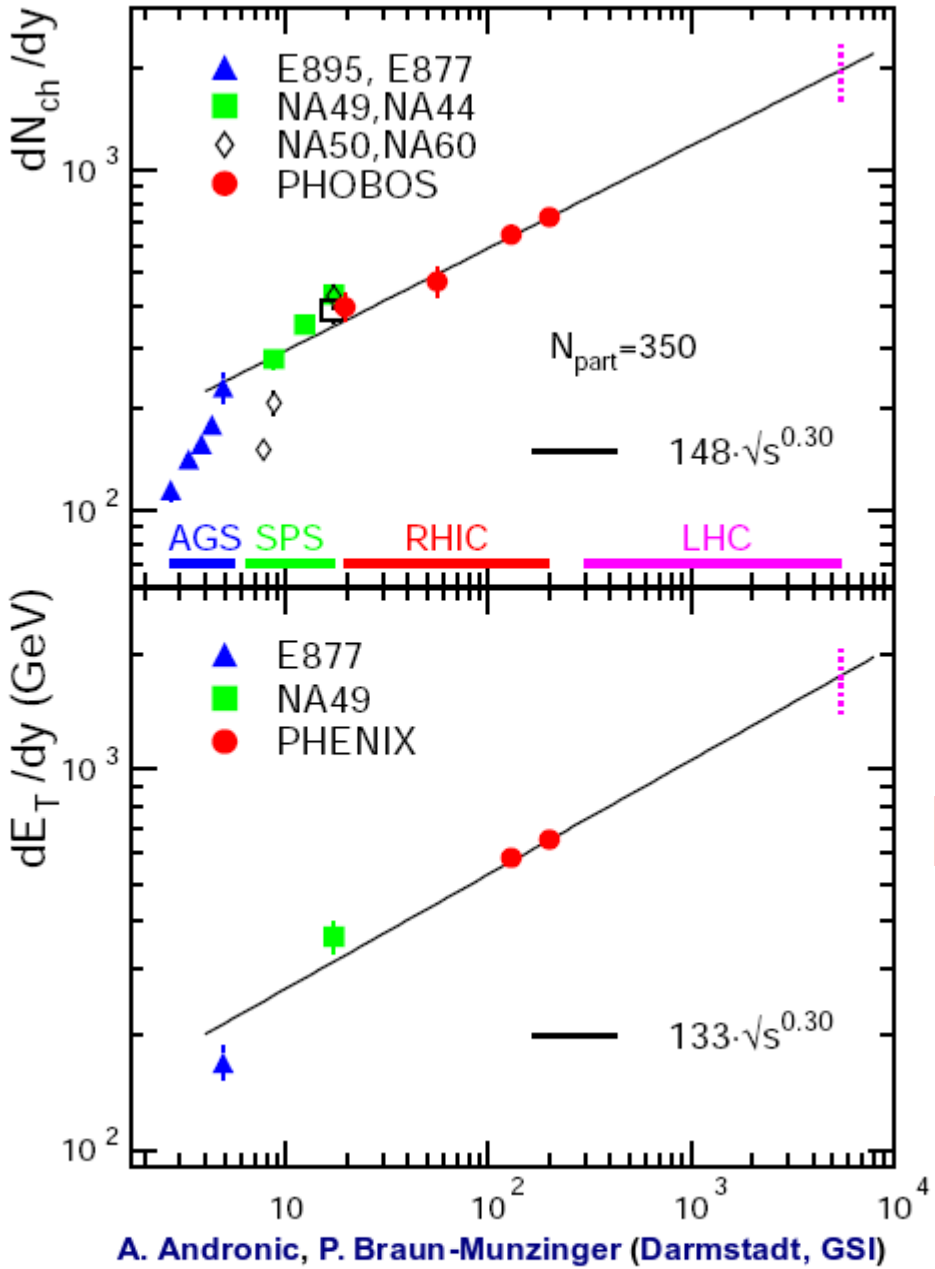
$$P^{H}(T) = \left(\underbrace{3_{iso}}_{\text{pions}} + \underbrace{O(e^{-M/T})}_{\rho,\omega,\cdots}\right) \frac{\pi^2 T^4}{90}$$

$$T_c = \left(\frac{B}{K_Q - K_H}\right)^{1/4} \approx \Lambda_{QCD} \approx 150 - 200\ \text{MeV}$$



Expect a Phase Transition at T_c where confined quarks and gluons inside Hadrons T<Tc are liberated to "Roam Freely" in a QGP

Entropy ~ K T^3 Production in A+A



A. Andronic, P. Braun-Munzinger (Darmstadt, GSI)
Lect.Notes Phys.652:35-68,2004

$$T(\tau) \propto \left(\frac{1}{\tau\pi R^2}\frac{dN}{dy}\right)^{1/3}$$

$$\tau > \hbar/3T \Rightarrow T_{max} \propto A^{1/9}(\log s)^{1/2}$$

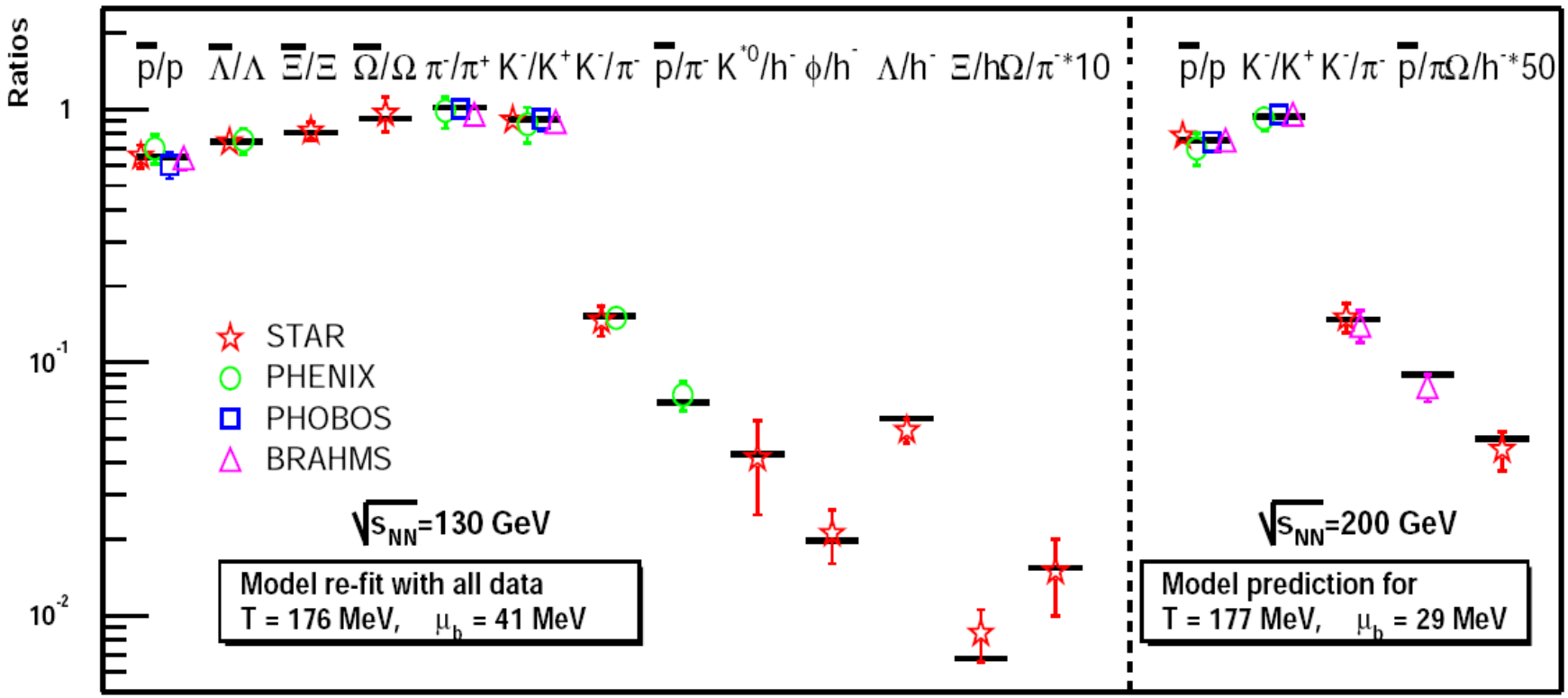
$$\rho_B(\tau) = \frac{1}{\tau\,\pi R^2}\frac{dN^{b-\bar{b}}}{dy}$$

Machine	AGS	SPS	RHIC	LHC
$\sqrt{s_{NN}}$ (GeV)	4.9	17.3	200	5500
$dE_T/d\eta$ (GeV)	192	363	625	1800 ?
$dN_{b-\bar{b}}/d\eta$	170	100	25	~0 ?
ε (GeV/fm^3)	1.2	2.4	4.1	11.6 ?
n_{baryon} (fm^{-3})	1.1	0.65	0.17	?

$$\varepsilon(\tau) = \frac{1}{\tau\ \pi R^2}\frac{dE_T}{dy}$$

Bjorken 1982

Hadro-synthesis near T ~ 200 MeV ~2x10^{12}K at RHIC is
a prerequisite consistency test of sQGP thermo interpretation AA data

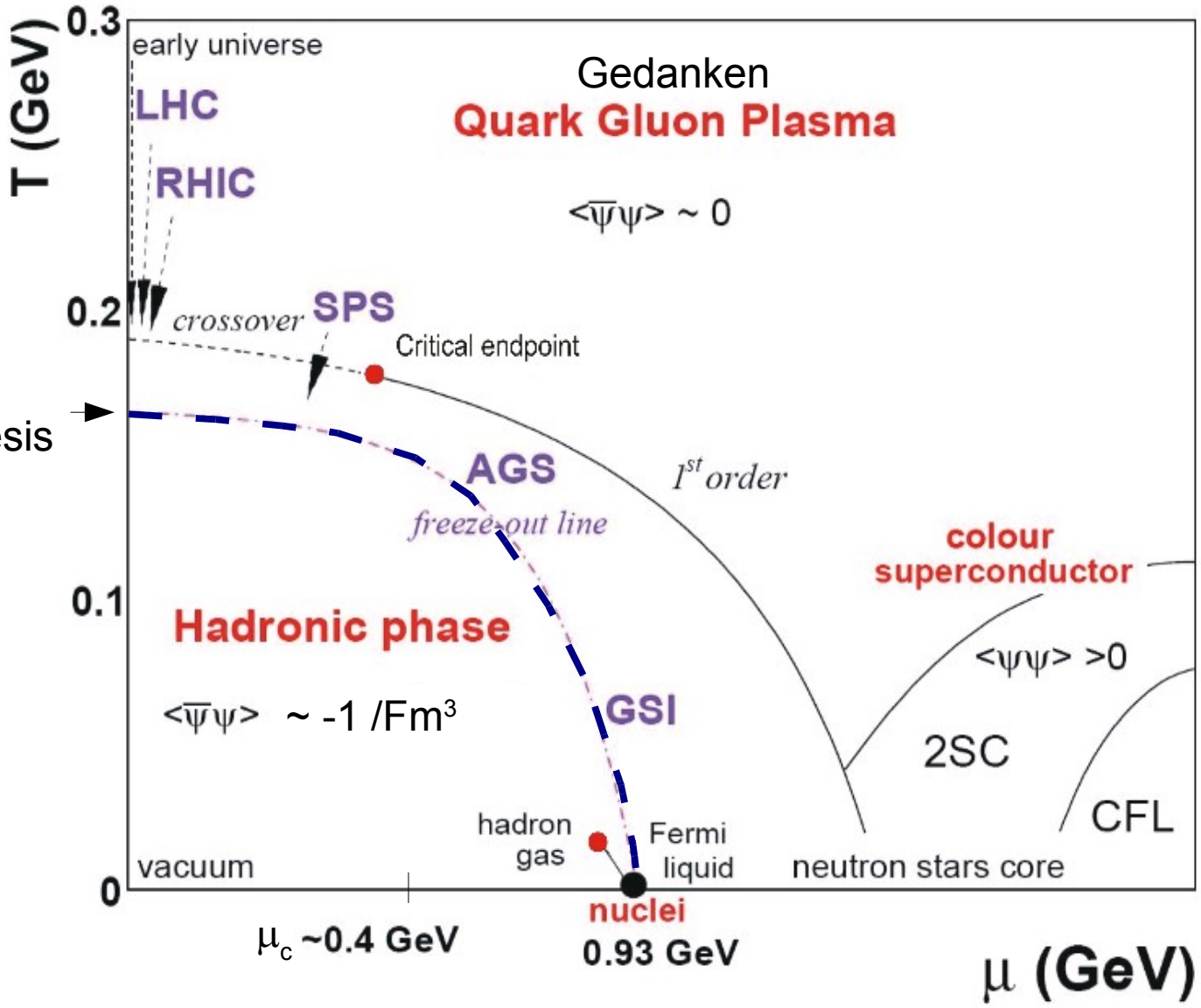


Test at RHIC was past A+. So OK to go onto next tests ...

Test was also past at SPS but 2nd Elliptic Flow Test and 3rd Jet Opacity Test
Unfortunately Failed !

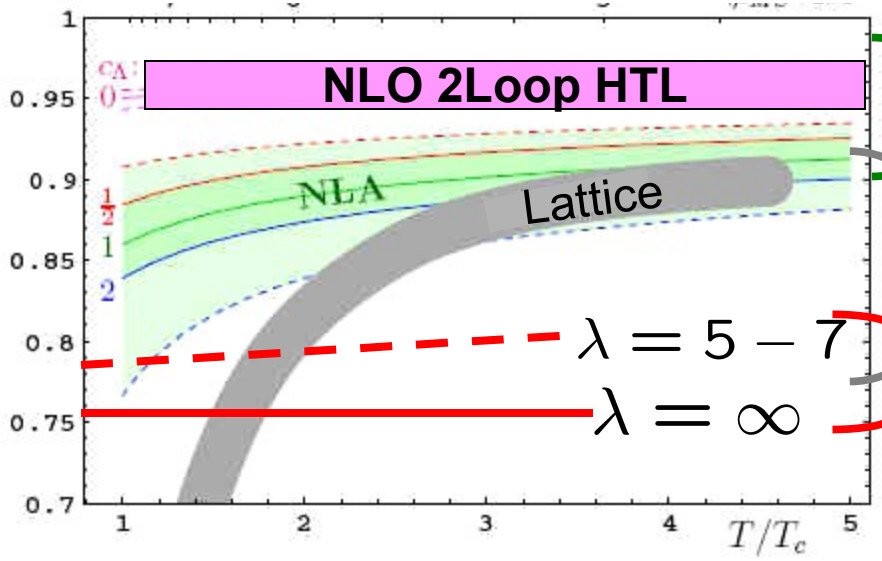
P.Braun-Munzinger, K.Redlich and J.Stachel,
``Particle production in heavy ion collisions," nucl-th/0304013.

Modern Cartoon of QGP Phase Diagram (J.Wambach 2006)



How strongly is the Quark Gluon Plasma coupled ?

S/S_{SB} Entropy/Non Interacting Entropy



weak QCD: Braaten et al

JP. Blaizot et al

lattice QCD: F. Karsch et al

AdS/CFT: Gubser, Klebanov, ...

How to explain 10-20% deviations from g=0 Stefan-Boltzmann?

As a g = ∞ Black Hole in 5D AdS_5 ?

As a dynamically screened g ~ 2 quasiparticle gas?

Lattice "data" indicate that QGP T~3Tc is at the Γ~1 "EMMI" boundary between the pQCD and AdS/CFT worlds: wQGP ~ sQGP

similar to

J.-P. Blaizot, et al **hep-ph/0611393**

THE Idea: Look for soluble field theory analog of the insoluble QCD

More Symmetry => More Constraints => Solutions are easier

well known QM examples: SU(N) Harmonic Oscillator
O(4) Hydrogen Atom

In Field Theory it seems that the SO(2,4) Super-conformal N=4 Super-Symmetric Yang Mills distant cousin of QCD may be ex

$$N_c \to \infty \text{ and } g^2 N_c \to \infty$$

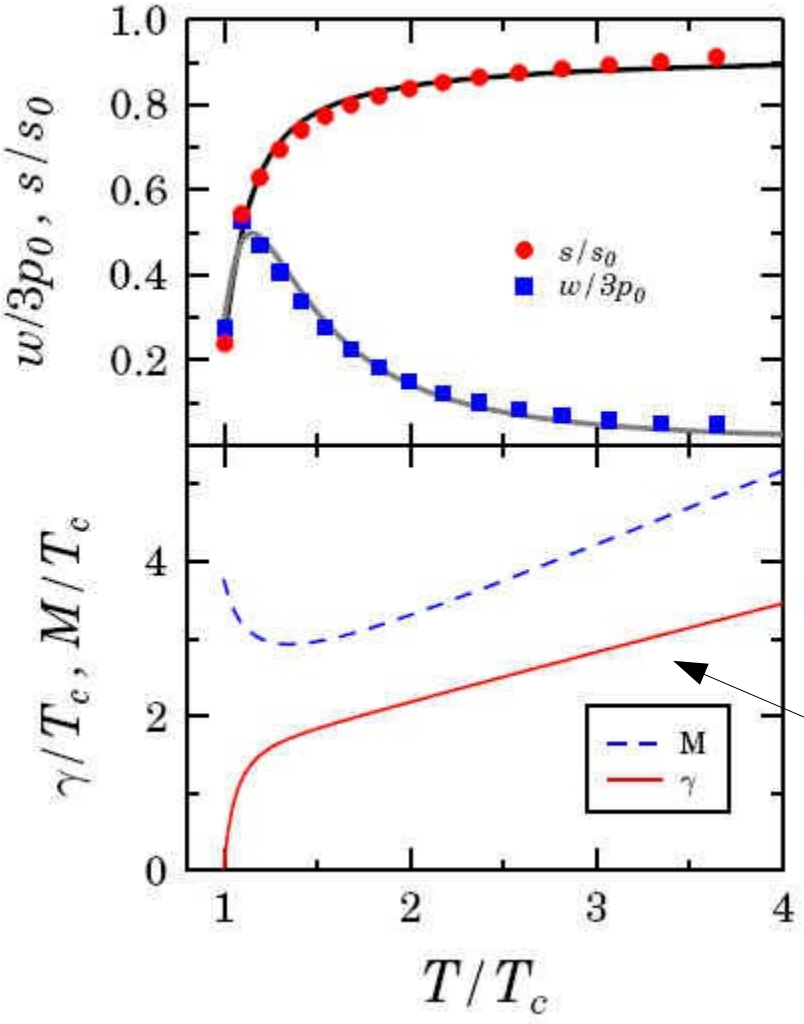
ing limit

(N

Maldecena *Conjecture*d (1998)
In this limit, strongly coupled quantum N=4 SYM in 4D is dual to classical weak gravity in the 10D curved space time:$AdS_5 X S_5$

Conformal SO(2,4) group in 4D ~ Isometry SO(2,4) group of 5Dim AdS

A. Peshier and W. Cassing : hep-ph/0502138

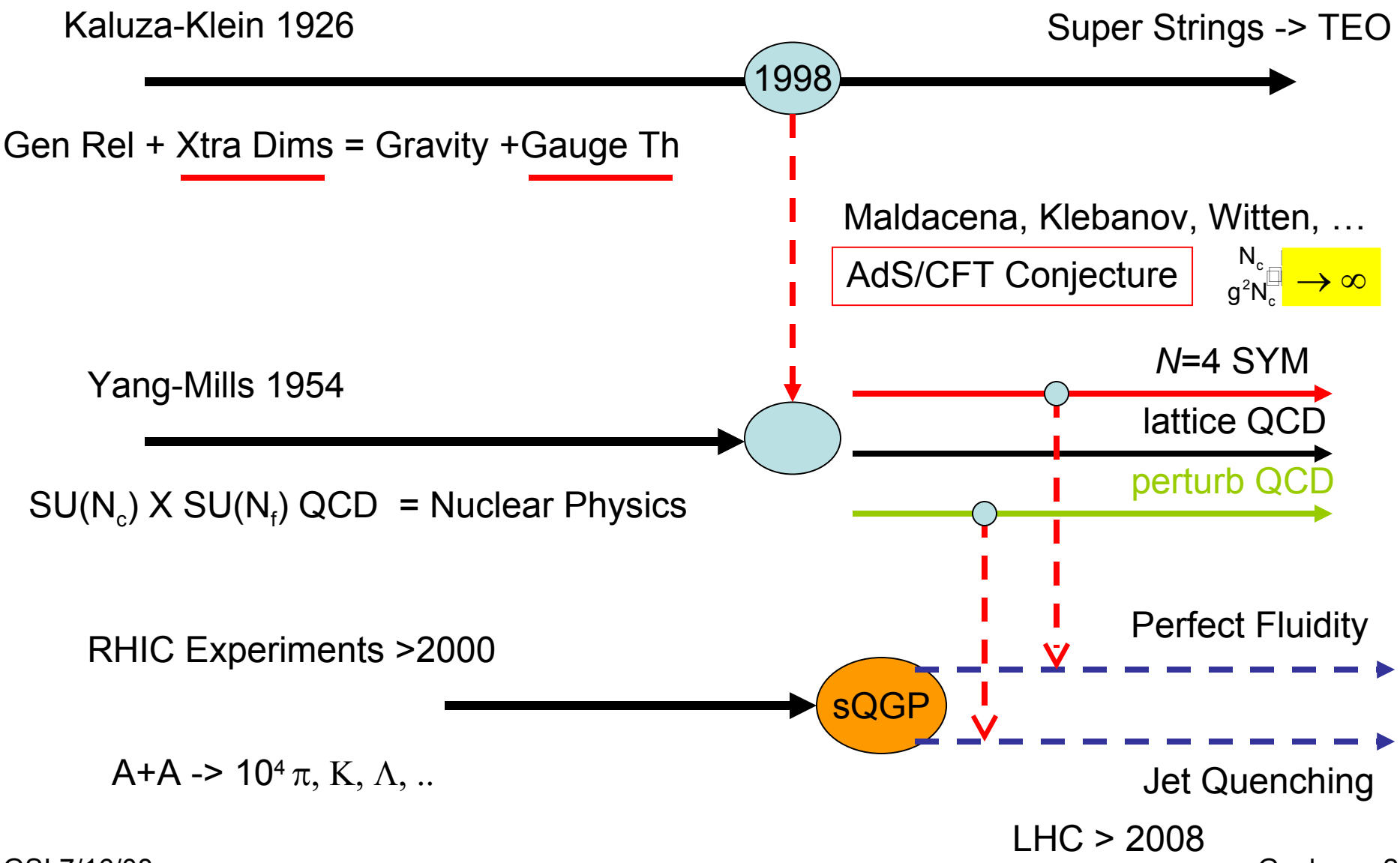


The entropy s(T) and the interaction measure w = e−3p, in units of the Stefan-Boltzmann limits s_0 and p_0, from this fitted dynamical quasiparticle model in comparison to lattice calculations. The lower part shows the adjusted mass M and width .

Overdamped Modes !

$$1/\Delta(\omega,k;T) = \omega^2 - k^2 - M^2(T) - i\omega\gamma(T)$$

sQGP at Cross Roads of Physics



· Is the quasiparticle QCD paradigm of QGP really dead † ?

·

· Should we abandon QCD & jump into the **AdS$_5$ Black Hole** † ?

·

· Or have reports of its early demise been *exaggerated* * ?

·

· We need to devise A+A signatures to let RHIC/LHC decide [1] !

EMMI prob 1: How to understand QGP thermo

†) K. Rajagopal , D. Kharzeev, E. Shuryak , D. Son...

*) J.P.Blaizot, A.Rebhan, E.Braaten, L.Mclerran, ...

1) M.G., W. Horowitz, S. Wicks, J. Noronha, ...

Part 3: Elliptic Flow as sQGP Barometer

EMMI prob 2: Initial Condition

EMMI prob 3: QGP ShearViscosity

(EMMI prob 4: Hadronization interface
and bulk viscosity)

Femto Cosmology Probes sQGP Matter Produced in AA

Barometer : Differential Collective Flow
- Azimuthal Elliptic
- Longitudinal Directed
- Transverse Radial

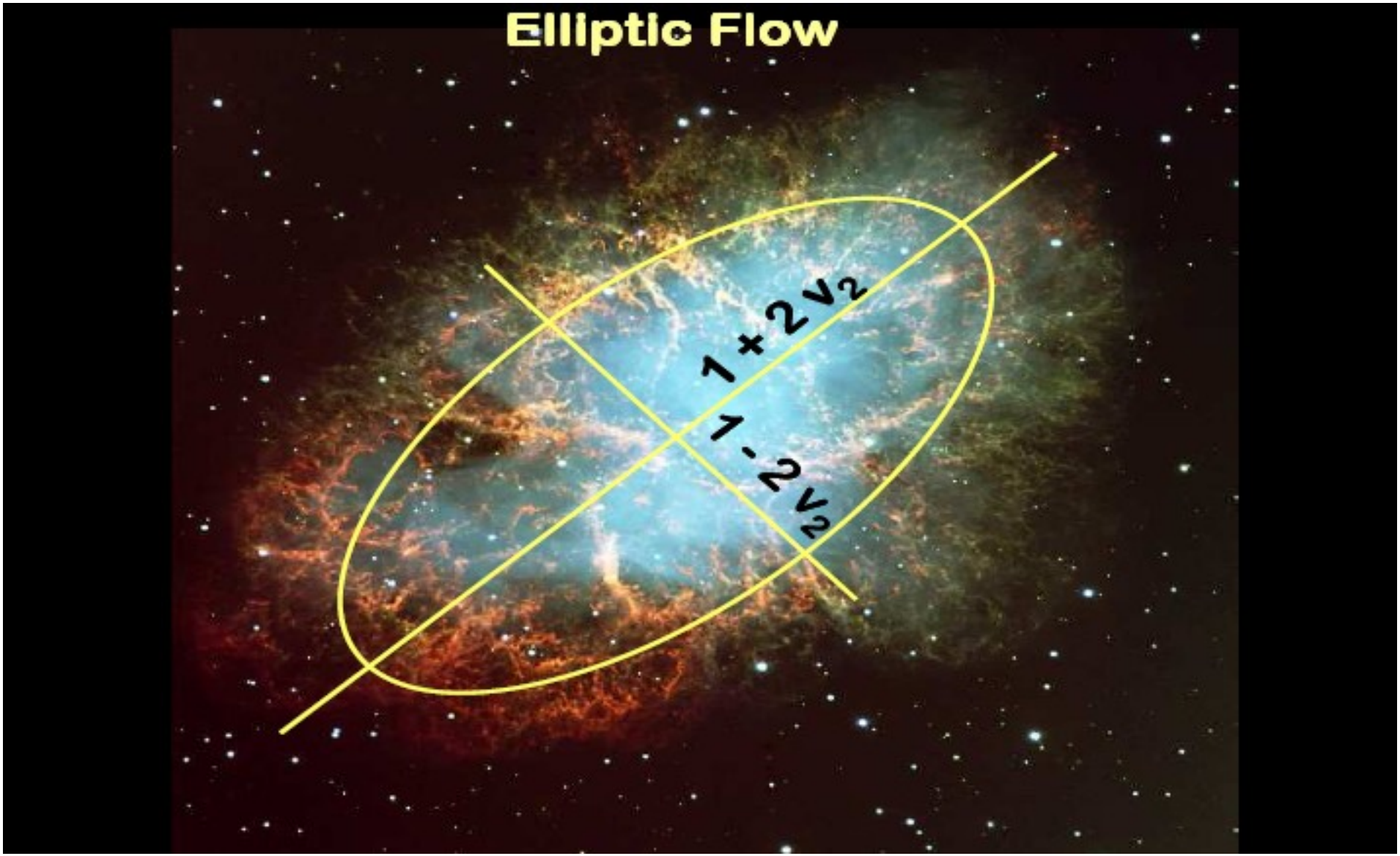
Thermometer: Photons , dilepton Pairs, vector mesons

Critical Phenomena: Hadron Species Ratios and Fluctuations

Tomography : Short wavelength Jets, Heavy Quark Jets

Exotic Searches: Multiquark states, Femto Junction fullerenes, CP violating domains

…



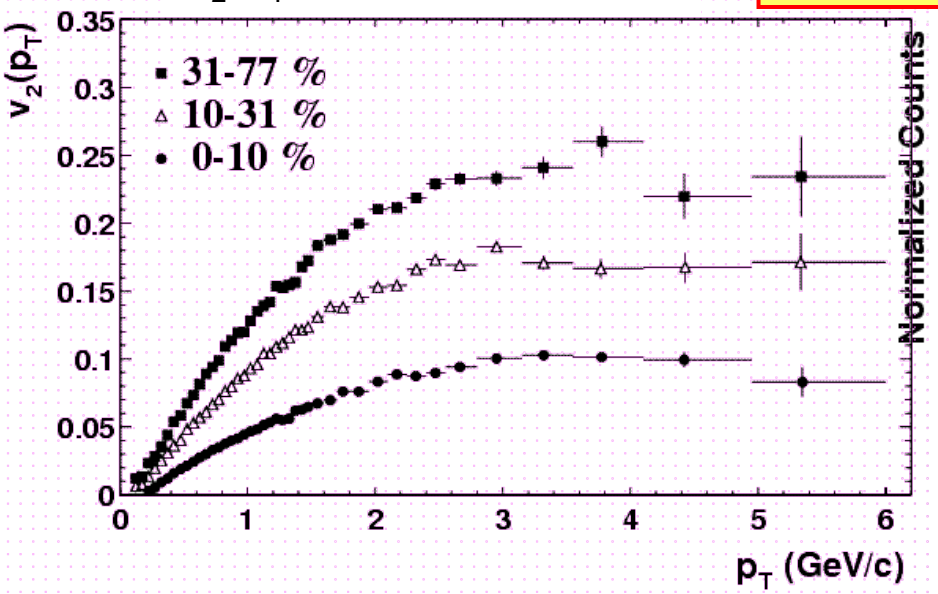
$V_2 = < \mathrm{Cos}(2 \phi) >$

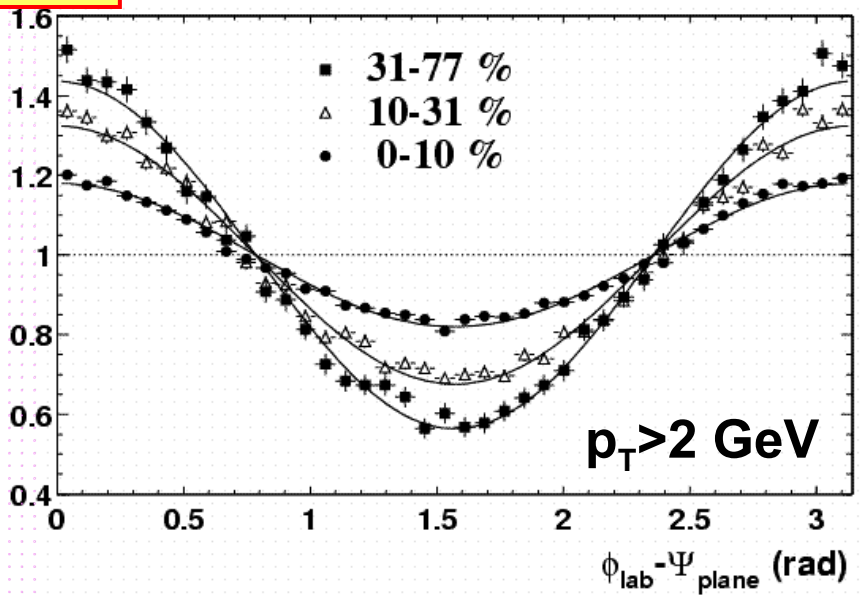
Transverse Elliptic Flow is main Barometric probe of sQGP Pressure

$V_2(p_T) = < \mathrm{Cos}(2 \phi) >$

STAR 2002

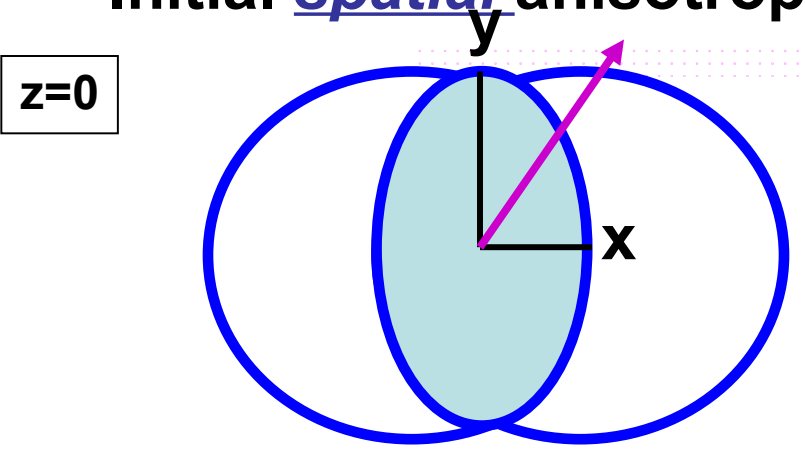
$dN_{ch}(p_\perp, \phi - \psi_{reac})$

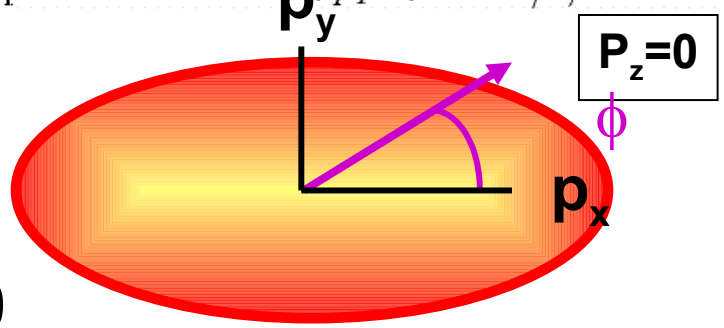




Initial *spatial* anisotropy

Final *momentum* anisotropy



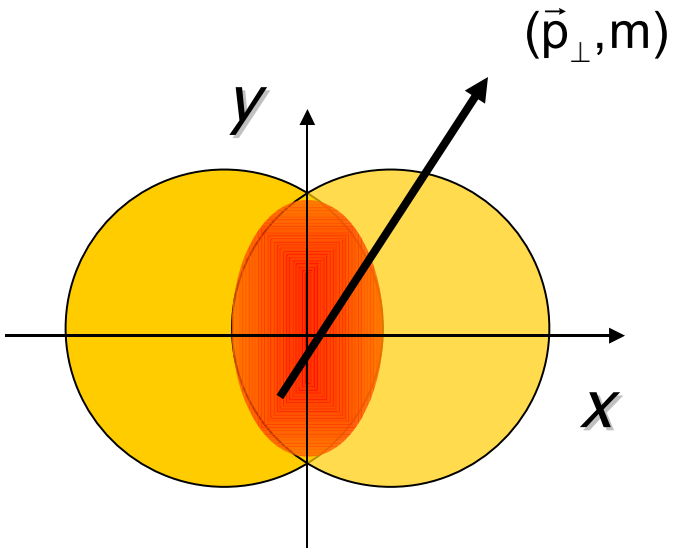


$$\partial_\mu T^{\mu\nu}(x) = 0$$

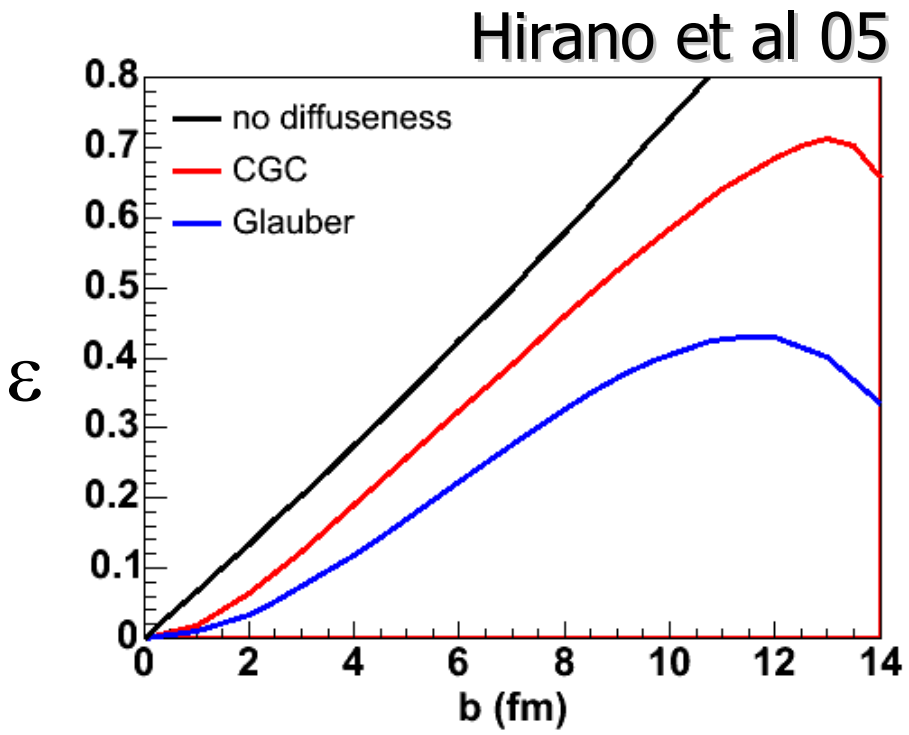
Stoecker, Greiner 84, Ollitrault 92

Elliptic flow is sensitive to Initial AA Geometry :

Cylinder, Participant Glauber, or Color Glass Condensate



$$\varepsilon = \frac{\langle y^2 - x^2 \rangle}{\langle x^2 + y^2 \rangle}$$



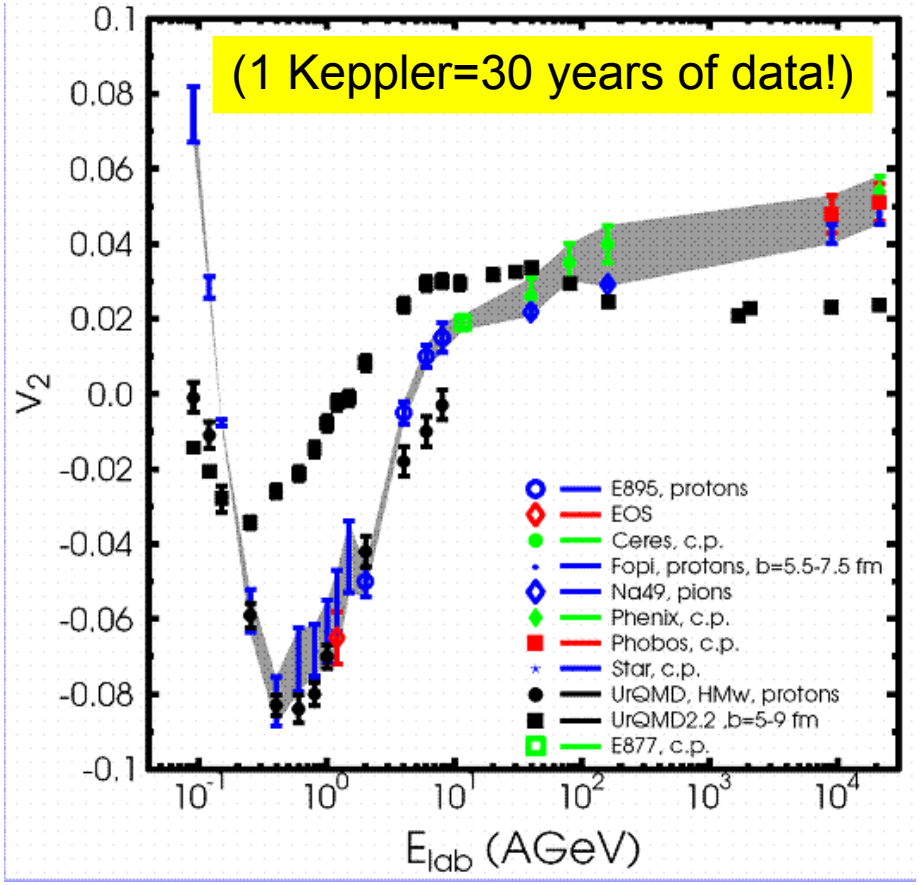
"Perfect Fluid" elliptic flow if $v_2 \sim 0.2\ \varepsilon$

Imperfect viscous flow if $v_2 < 0.2\ \varepsilon$

Perfect Fluidity was not seen before below RHIC energies

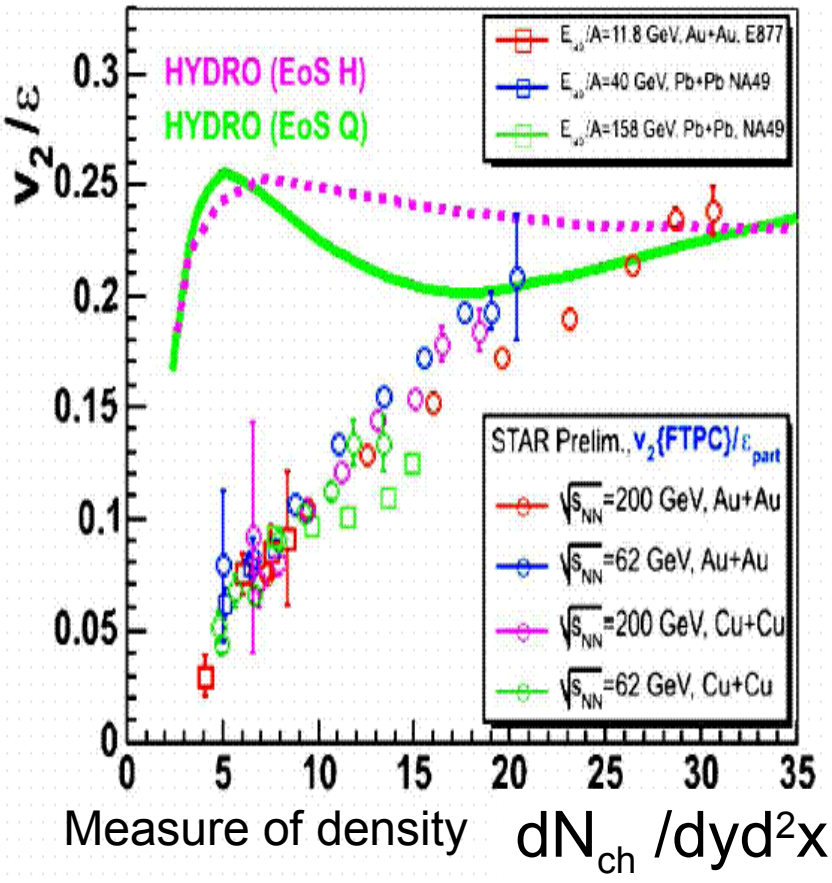
Elliptic v_2 flow seen everywhere

M. Bleichert, et al UrQMD, Transport



~ Perfect fluidity seen only at RHIC

Kolb, Heinz: Euler Hydrodynamics



Ordinary hadron resonance matter is
a poor viscous fluid, while highest density appears to flow ideally

Early Universe was a liquid

Quark-gluon blob surprises particle physicists.

by Mark Peplow
news@nature.com

nature

The Universe consisted of a perfect liquid in its first moments, according to results from an atom-smashing experiment.

Scientists at the Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory on Long Island, New York, have spent five years searching for the quark-gluon plasma that is thought to have filled our Universe in the first microseconds of its existence. Most of them are now convinced they have found it. But, strangely, it seems to be a liquid rather than the expected hot gas.

Contact: 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

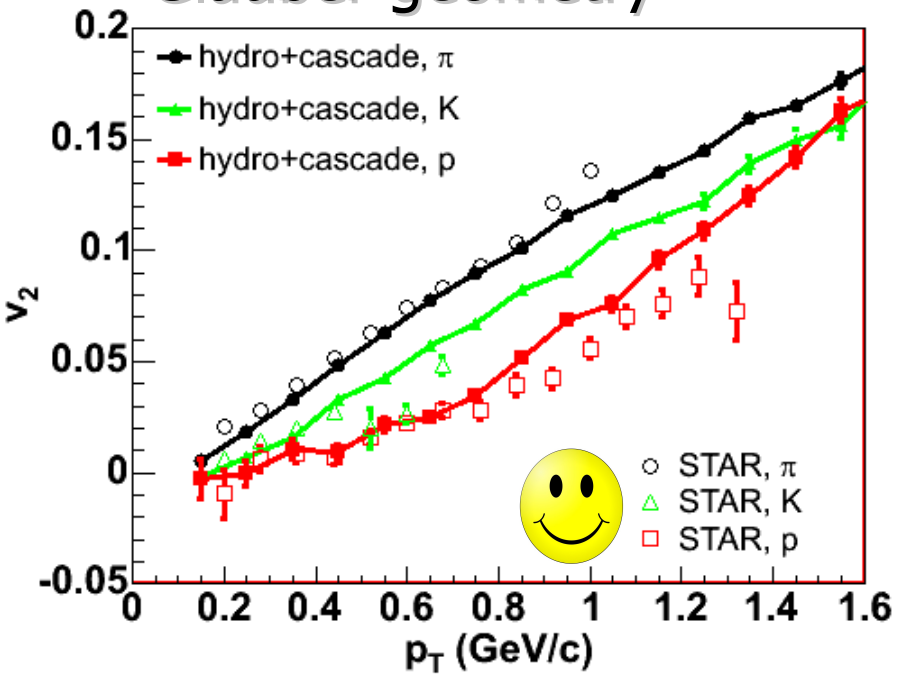
TAMPA, FL -- The four detector groups conducting research at the Relativistic Heavy Ion Collider (RHIC) -- a giant atom "smasher" located at the U.S. Department of Energy's Brookhaven National Laboratory -- say they've created a new state of hot, dense matter out of the quarks and gluons that are the 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

EMMI Prob 2 : AA Initial Geometry and Flow

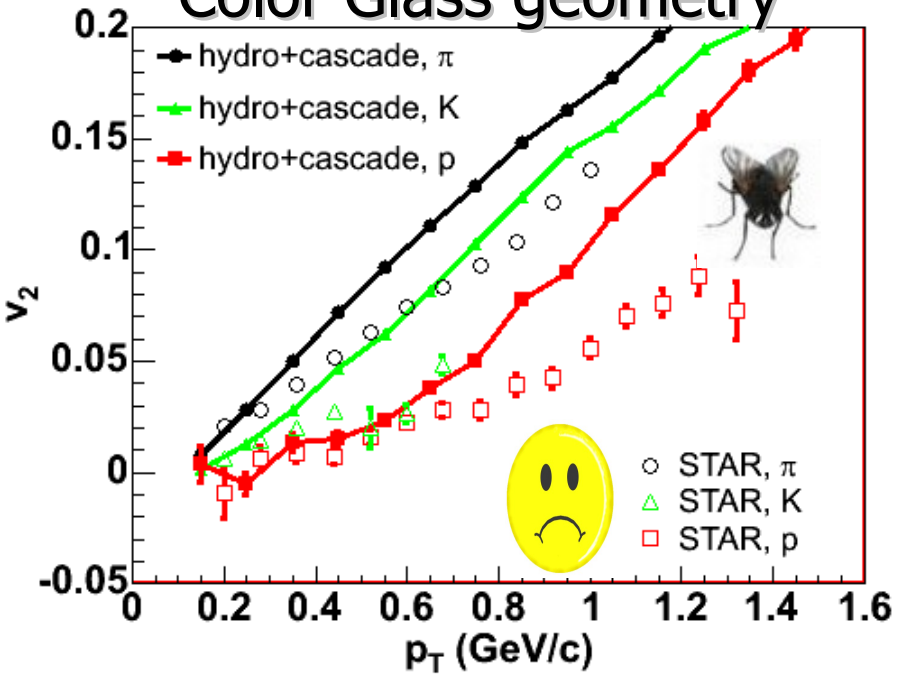
Hirano, Nara, et al 05

$v_2(p_T, m)$ for identified hadrons is very sensitive to A+A-> sQGP Initial Condition Geometry

Glauber geometry



Color Glass geometry



v_2(Glaub) ~ v_2(data)

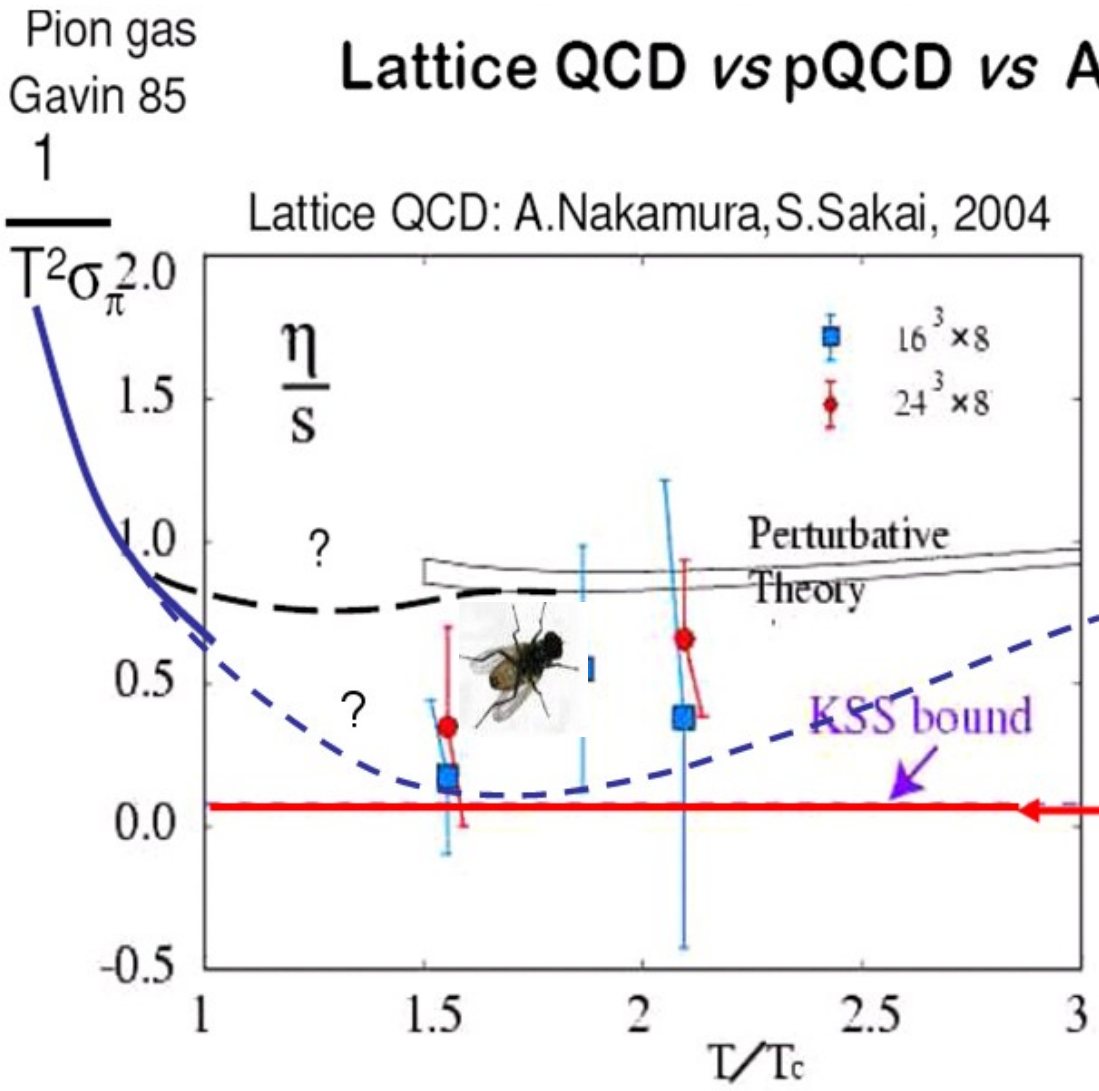
v_2(CGC) > v_2(data) !!

Glauber+Data => "sQGP" is Perfect Fluid

CGC+Data => "sQGP" is Imperfect Fluid !!

EMMI Prob 3: What is Shear Viscosity of sQGP ?

Lattice QCD *vs* pQCD *vs* AdS/CFT N=4 SYM



Danielewicz, MG, (1985) *

Perturbative QCD

$$\frac{T\,\lambda_{pQCD}}{5} \approx \frac{(0.3)^2}{\alpha^2 \log 1/\alpha} \sim 1$$ *

$$\left(\frac{\eta}{s}\right)_{adS/CFT} = \frac{1}{4\pi}$$

N=4 SUSY

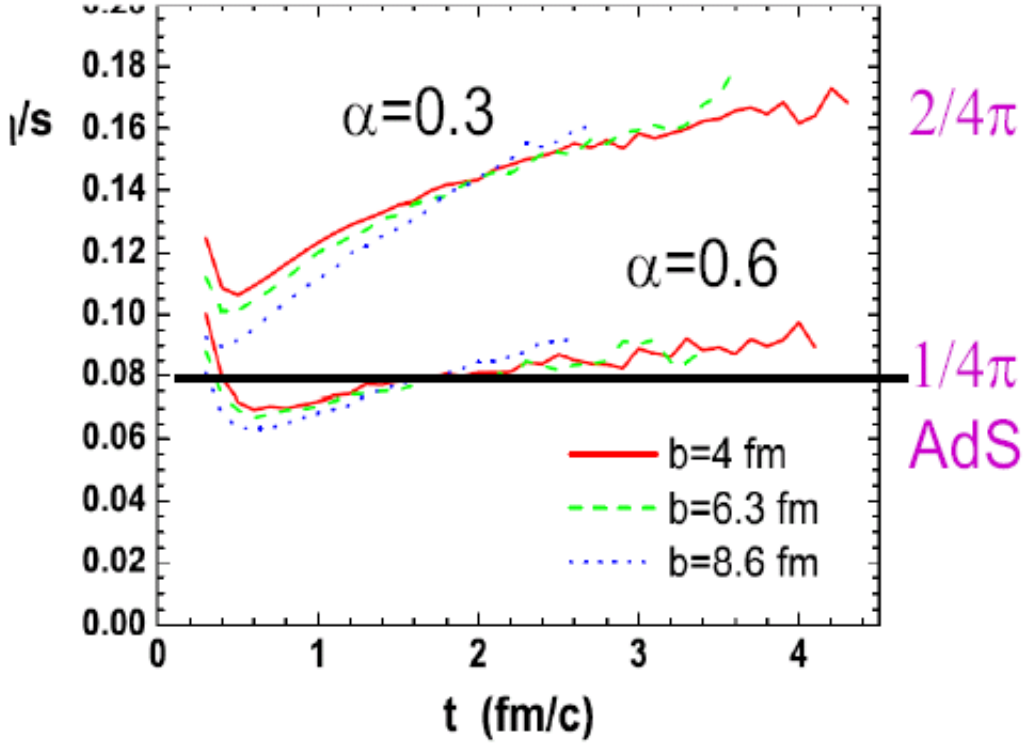
$g^2N_c \rightarrow \infty$

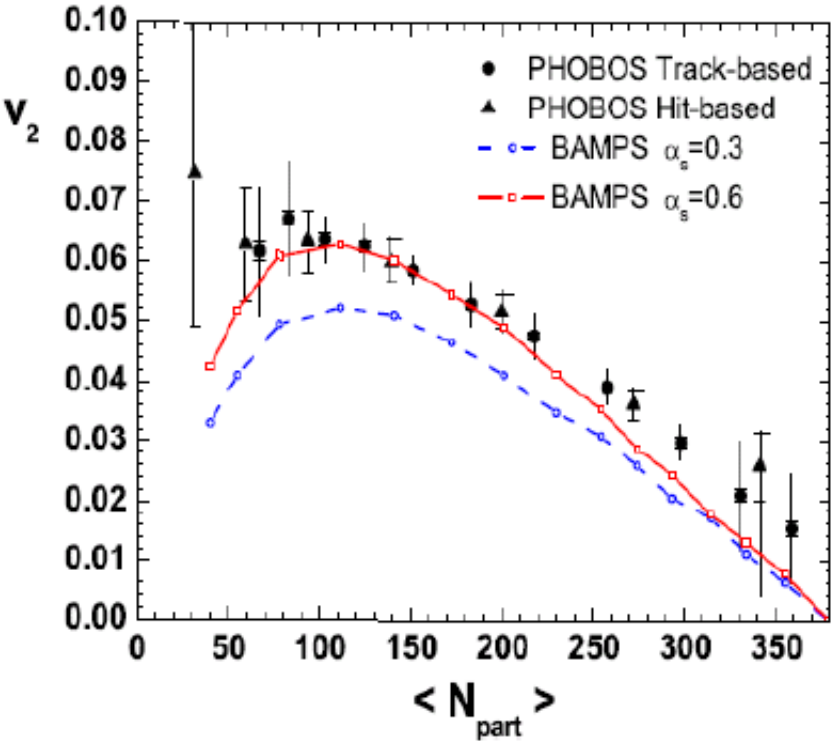
$$\frac{T\lambda_{min}}{5} \approx \frac{\hbar = 1}{15}$$ *

N=4 SUSY KSS: Kovtun, Son, Starinets 04

A recent challenge to the strong coupling paradigm from quasiparticle Radiative Gluon Transport,

Zhe Xu, Carsten Greiner and Horst Stoecker,
arXiv:0711.0961 [nucl-th]

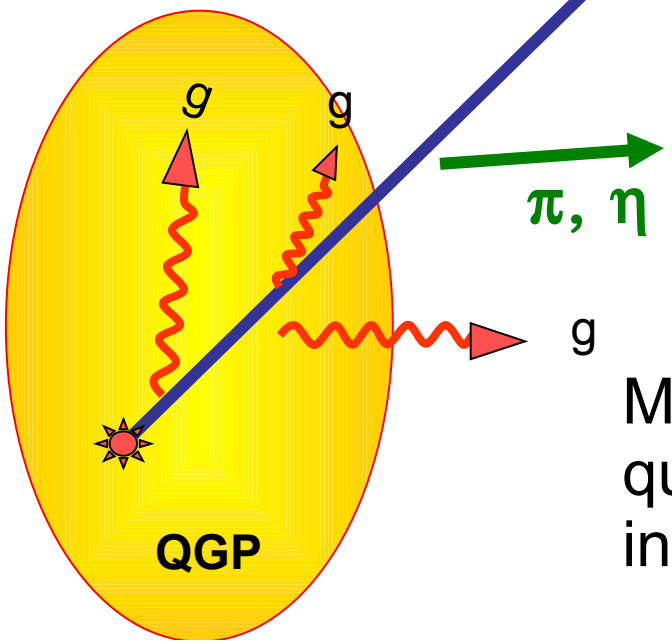




$$\eta \cong \frac{1}{5} n \frac{\langle E(\frac{1}{3} - v_z^2) \rangle}{\frac{1}{3} - \langle v_z^2 \rangle} \frac{1}{\sum R^{\mathrm{tr}} + \frac{3}{2} R_{23} - R_{32}}$$

Part 4 A: Single Jet Tomography of the QGP

(MG, Levai Vitev, Djordjevic, Wicks, Horowitz, ...)



Quark or Glue Jet probes:

$$(\eta,\ p_T,\ \phi - \phi_{reac},\ M_Q)_{init}$$

Hadron jet fragments:

$$(\eta',\ p_T',\ \phi' - \phi_{reac})_{final}$$

Measurements of hadronic/leptonic quenching patterns provides information about QGP density

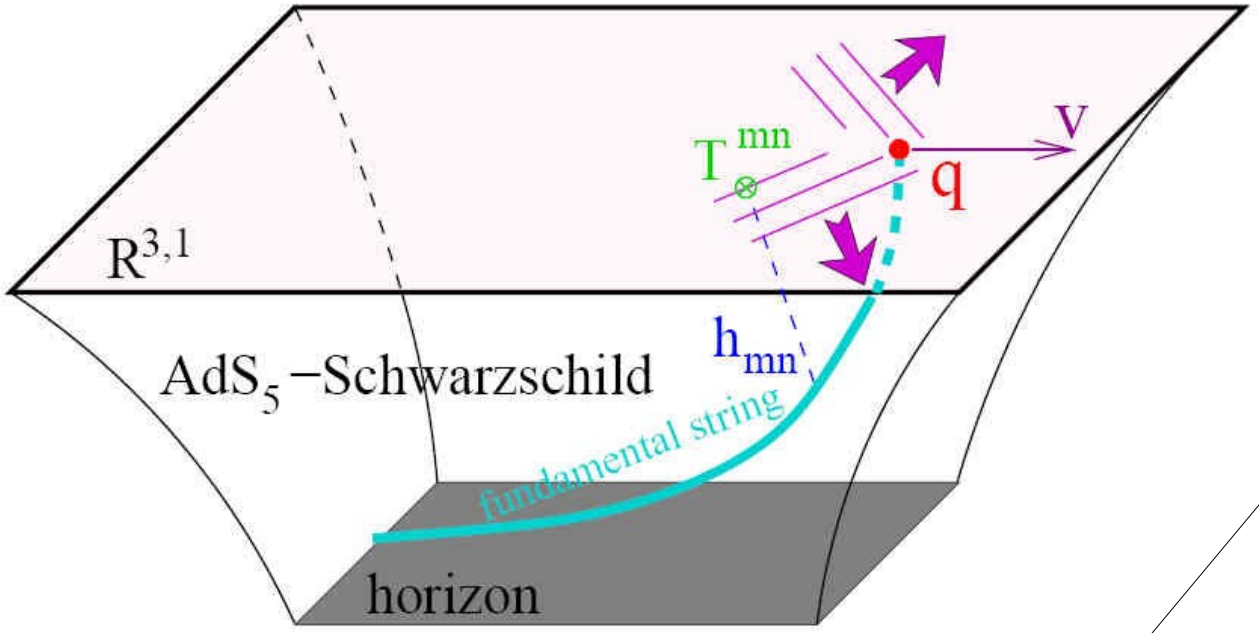
$$a)\ \Delta E^{rad} \propto \alpha_s^3 \int d\tau\ \tau\ \rho_{QGP}\left(\tau, \vec{r}(\tau)\right) Log\left(\frac{E_{Jet}}{\mu^2 L}\right)$$

$$b)\ \Delta E^{elas} \propto \alpha_s^2 \int d\tau\ \rho_{QGP}^{2/3}\left(\tau, \vec{r}(\tau)\right) Log\left(\frac{T\,E_{Jet}}{M(T)}\right)$$

$$c)\ \Delta p_T^{\ 2} \propto \alpha_s^2 \int d\tau\ \rho_{QGP}\left(\tau, \vec{r}(\tau)\right) Log\left(\frac{E_{Jet}}{\mu}\right)$$

3. Jet Quenching in AdS/CFT

Gubser et al
Herzog et al



Very different from pQCD

$$\frac{dp_T}{dt} = -\mu_Q p_T = -\frac{\pi\sqrt{\lambda}(T^*)^2}{2M_Q} p_T, \qquad (1)$$

where T^* is the temperature of the SYM plasma as fixed by the Hawking temperature of the dual D3 black brane.

Nuclear Modification (Jet Suppression) Factor for

$$Q(E) + (AA) \rightarrow Q(E'=E - \Delta E) + X \rightarrow \text{Hadron } H + X'$$

$$R_{AA}(E', M_{H/Q}) = \frac{\text{Num}(E' \text{ in } A+A)}{\text{Binary}(p+p;\, A+A)\ \text{Num}(E' \text{ in } p+p)}$$

$$= (1 - \Delta E/E)^{nQ}$$ QCD Spectral Index

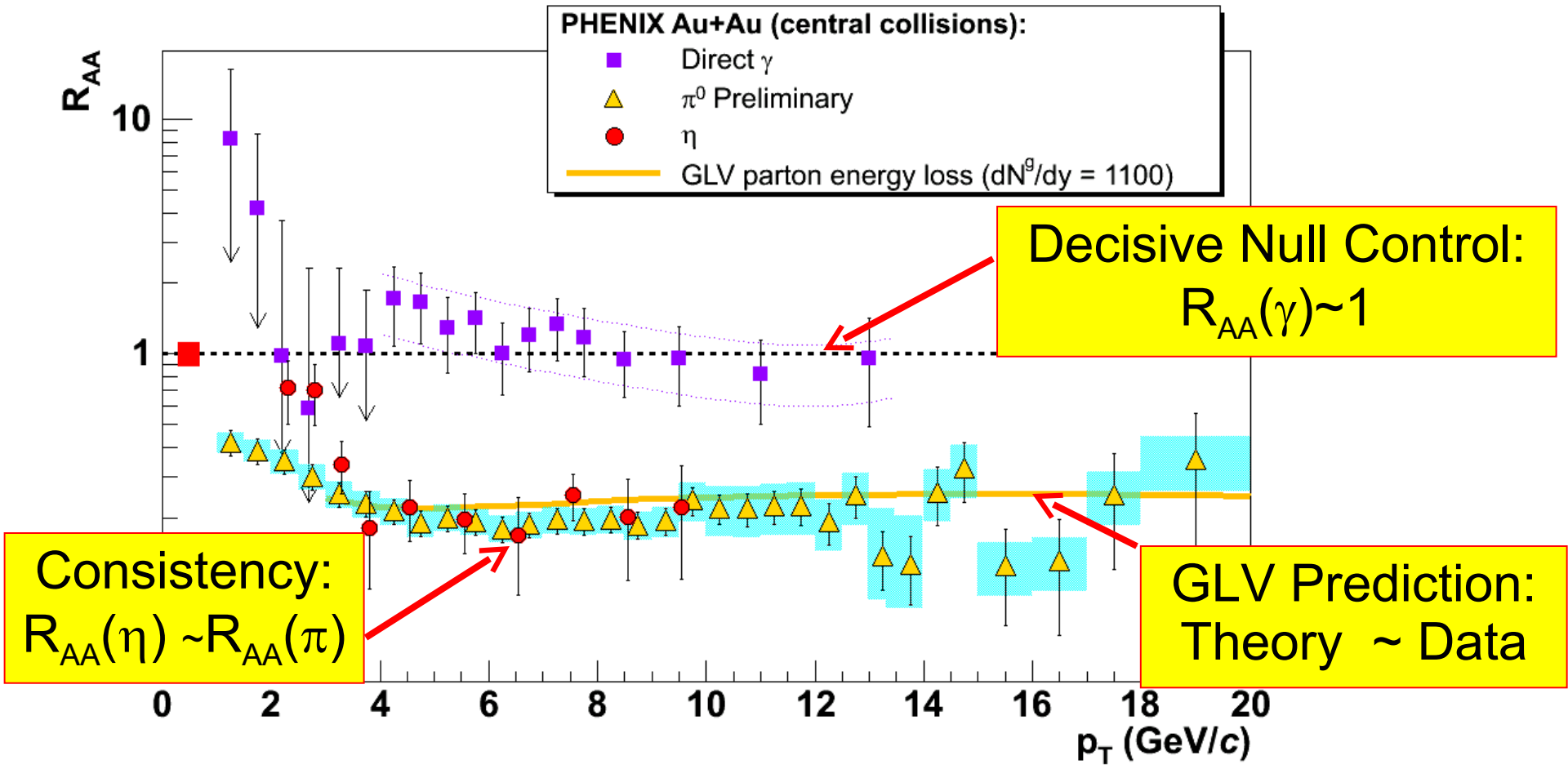
ΔE proportional to opacity $L/\lambda = \sigma\rho L$

Thus R_{AA} is tomographic probe of the density evolution of the QGP

Pions are fragments of (massless) up+down+glue jets

Direct Electrons are fragments of Massive Charm+Bottom quark jets

QGP is opaque to even 20 GeV jets



Suppression is very strong (R_{AA}=0.2!) and flat up to 20 GeV/c

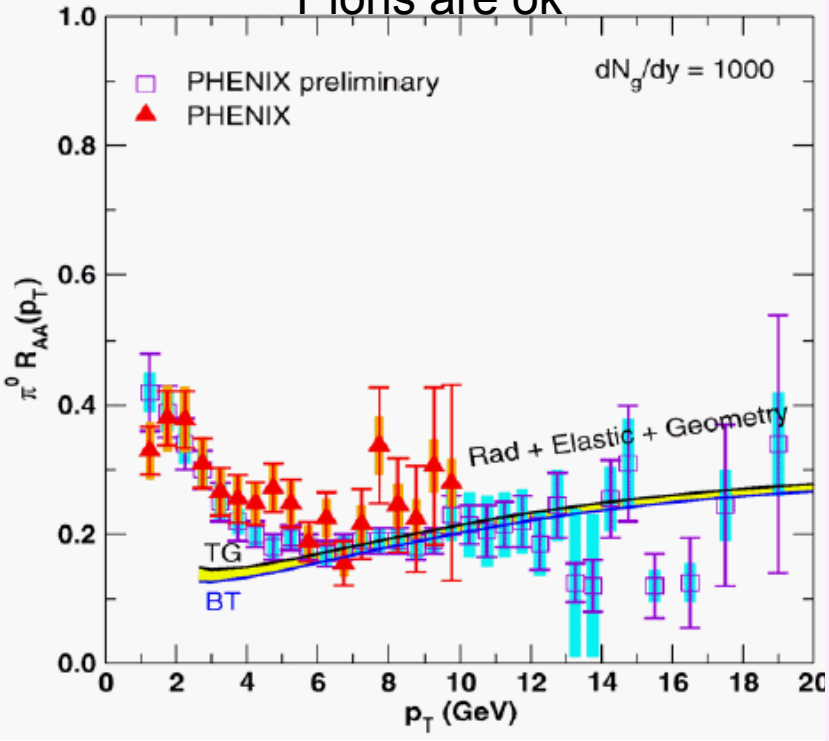
Common suppression for π^0 and η; it is at partonic level

$\varepsilon > 15$ GeV/fm^3

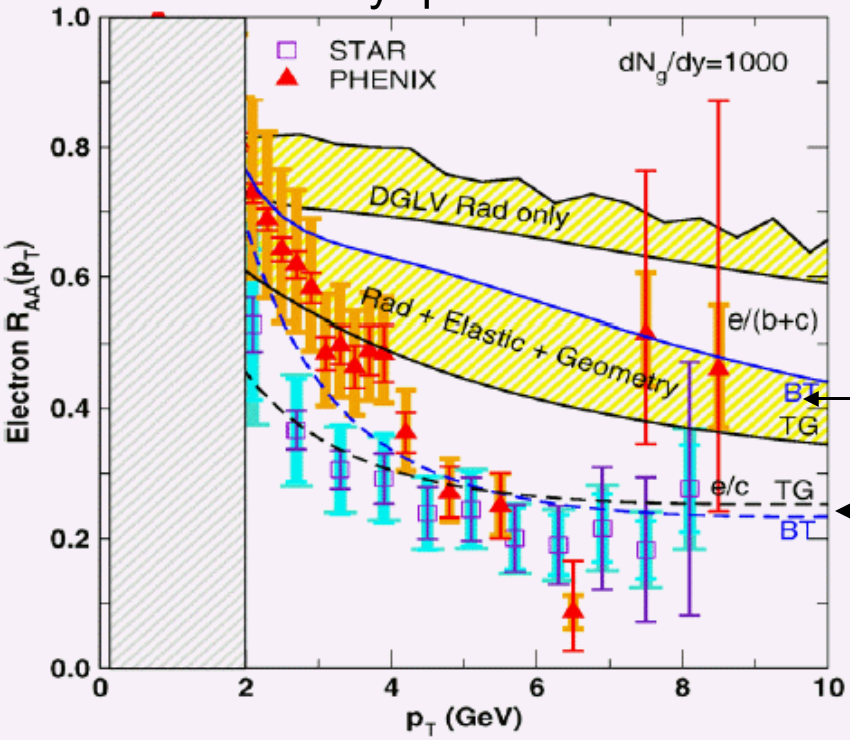
EMMI Prob 4: Heavy quark jet tomography

WHDG:S.Wicks, W. Horowitz, M. Djordjevic, M.Gyulassy, NPA784 (2007) 426

Pions are ok



But Heavy quarks are not!



Both c+b

c only

Electron data seems to falsify pQCD HQ dynamics

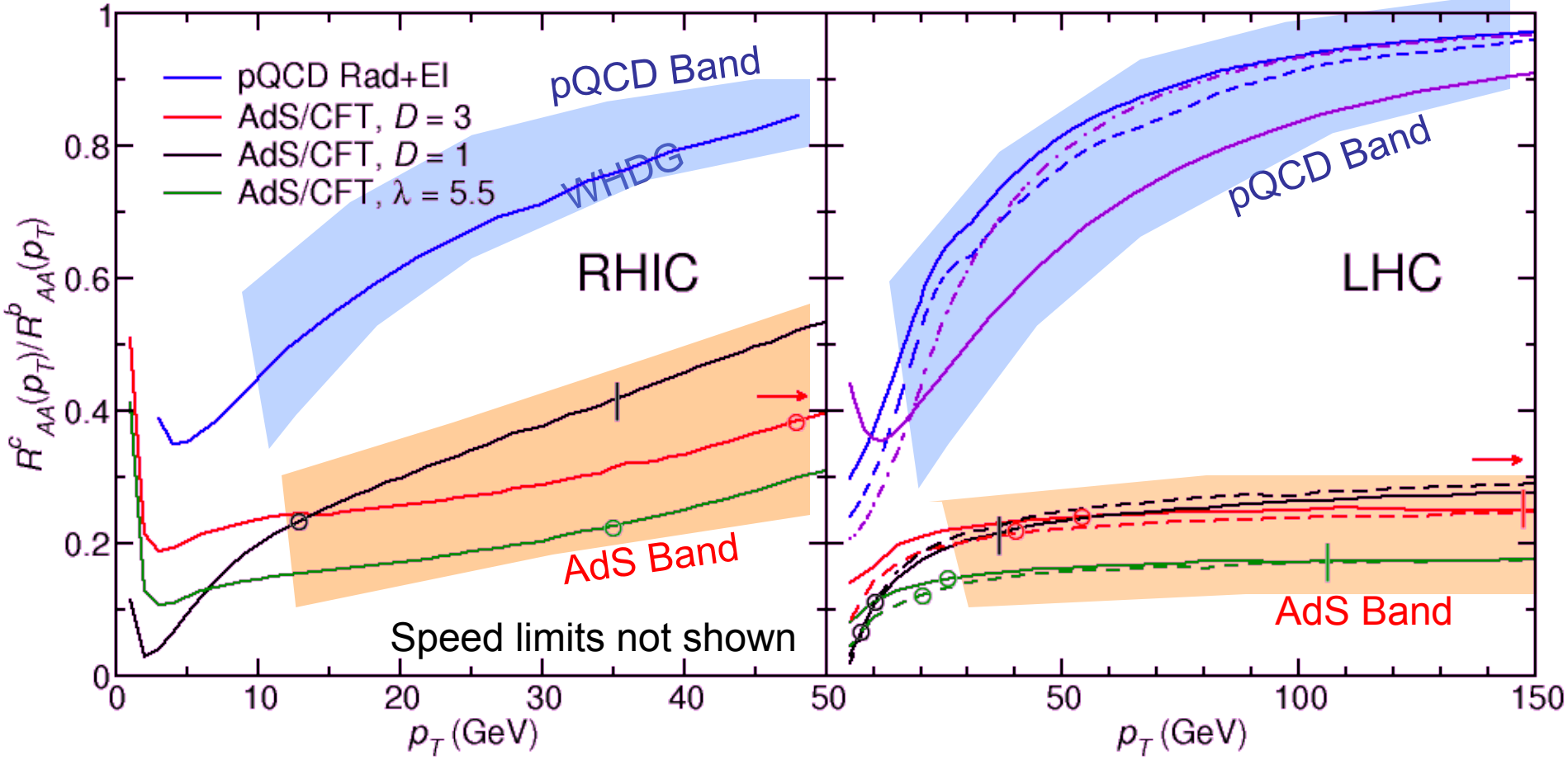
unless:

(1) bottom production is suppressed or

(2) $\alpha_s \to \alpha_c \sim 0.5$, $\Gamma \to 1$ (EMMI Landscape)

RHIC and LHC $R^{cb} = R^{c}_{AA}(p_T)/R^{b}_{AA}(p_T)$

Horowitz, Gyulassy: nucl-th/**0706.2336, PLB**



Bunching into "pQCD band" vs "AdS/CFT band" make this *Double* ratio of charm and bottom jet nuclear modification factors a definitive test of pQCD vs AdS/CFT dynamical modeling of sQGP at RHIC and LHC

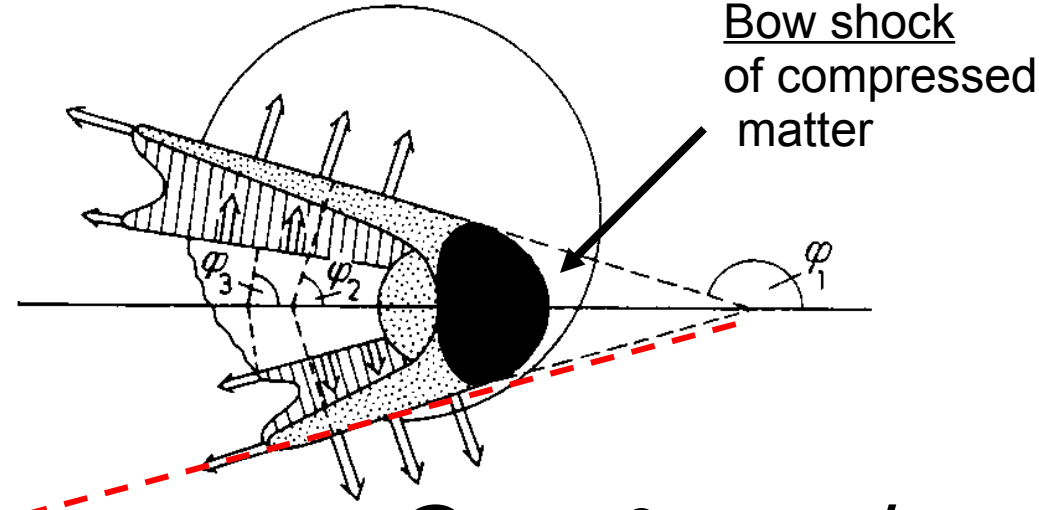
Part 4.2 : Di-Jet Tomography

(J.Noronha, G. Torrieri, B. Betz, MG)

- Conical Mach-like associated correlations
- novel Non-Mach Conical AdS solutions

Nuclear Mach Cone Theory 1973

RHIC Discoveries 2004 :nucl-th/0406018



$$\text{Cos } \theta_M = v_s/v$$

Supersonic probes
Leads to Mach-wakes
(Angular Correlation)

Director Stoecker

But also to probe dependent Neck+Head sources

Di-jet correlations PHENIX J.Jia Int.J.Mod.Phys.E16:3058,2008

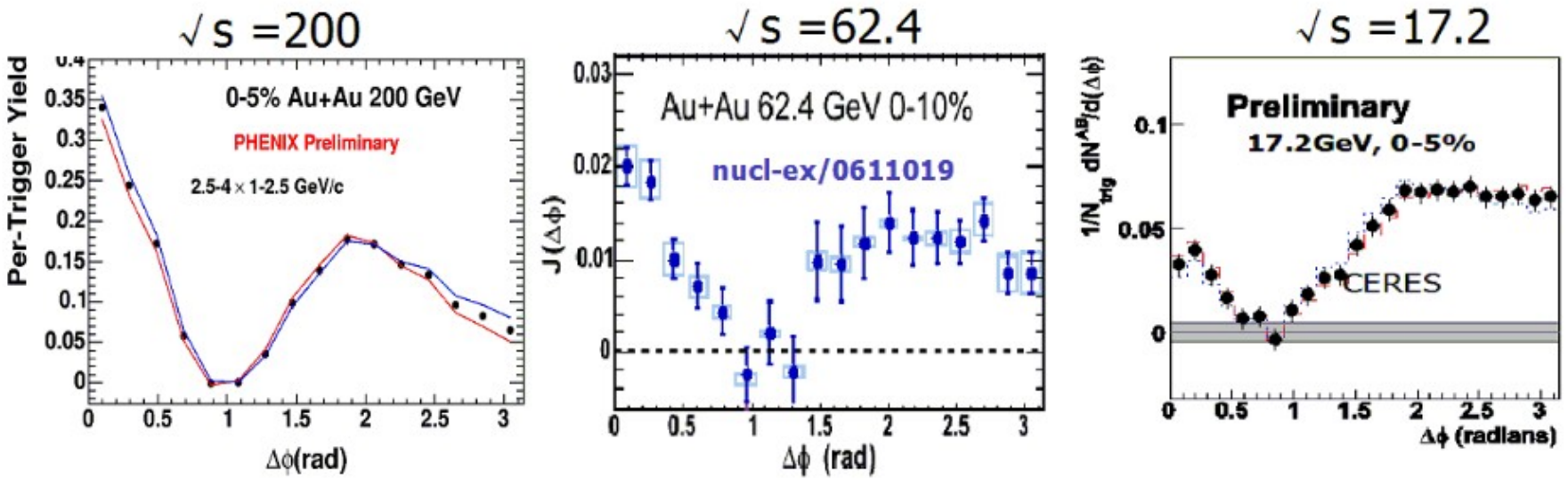
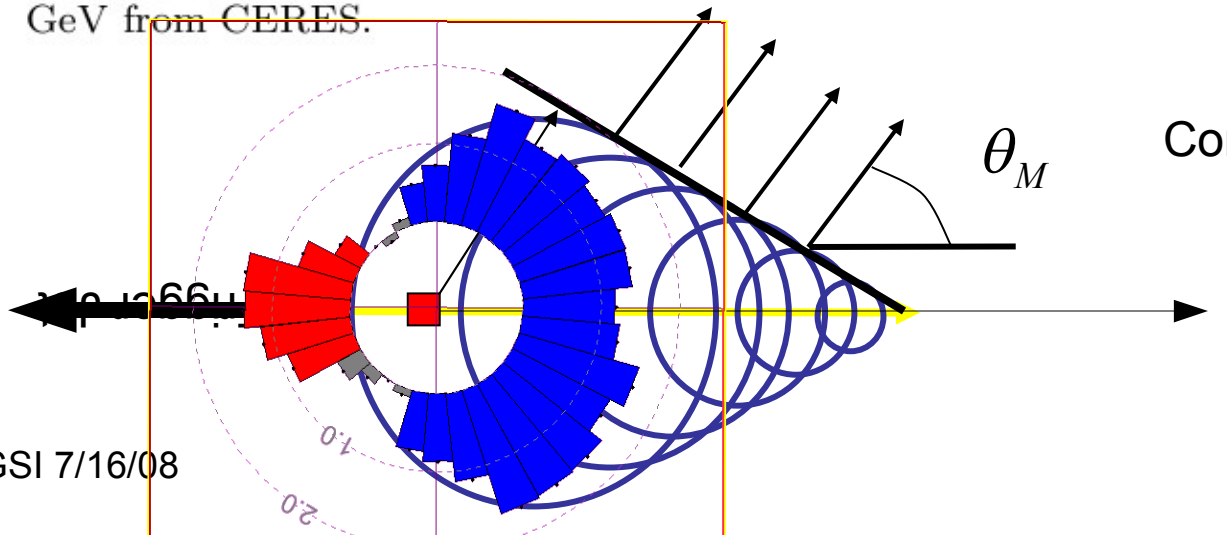


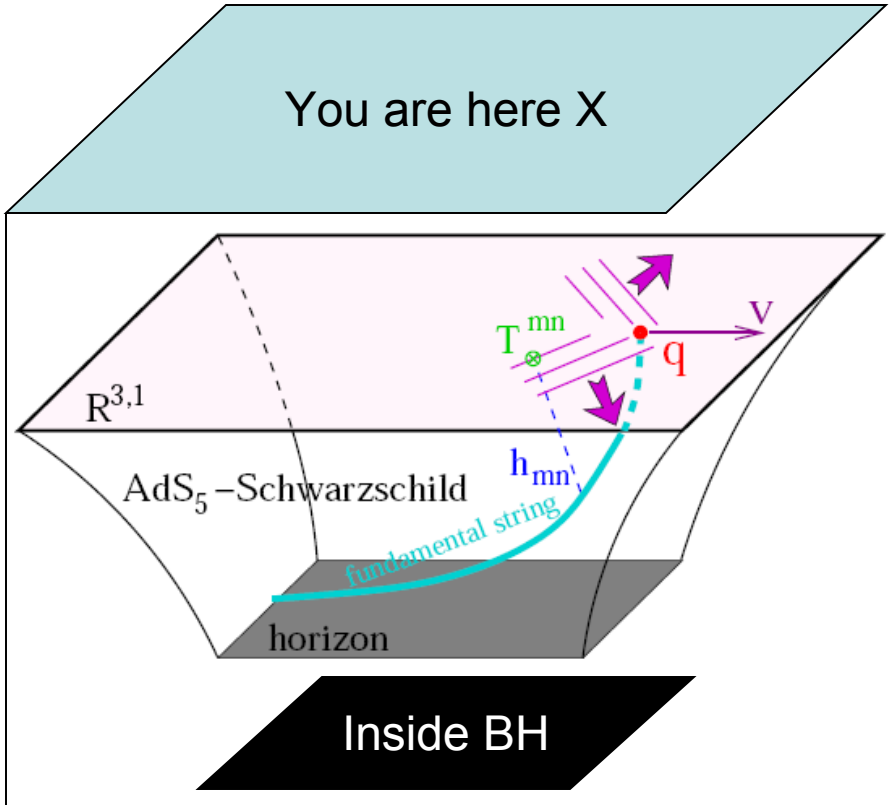
Fig. 7. a) Per-trigger yield in central Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV from PHENIX. b) The extract jet function at $\sqrt{s_{NN}} = 62.4$ GeV from PHENIX. c) Per-trigger yield at $\sqrt{s_{NN}} = 17.3$ GeV from CERES.



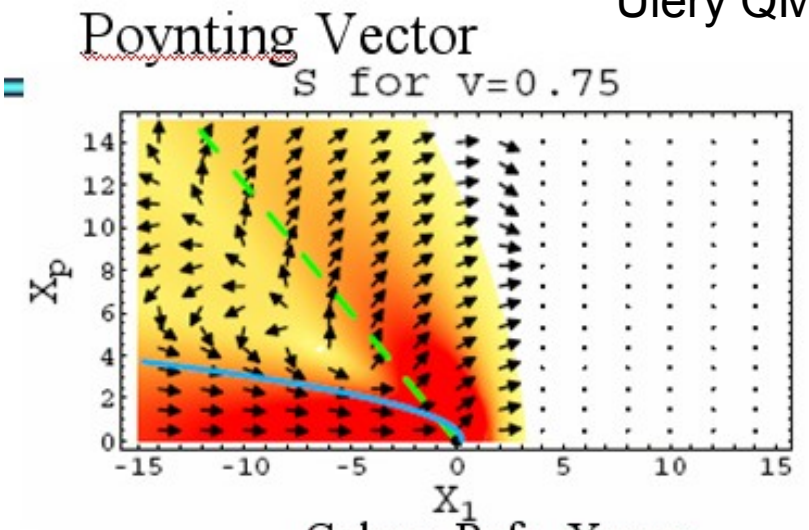
Conical emission

Away Side Jet

Mach Cones in infinite coupled SYM Plasmas via the AdS/CFT conjecture
Heavy Quark String Drag Picture

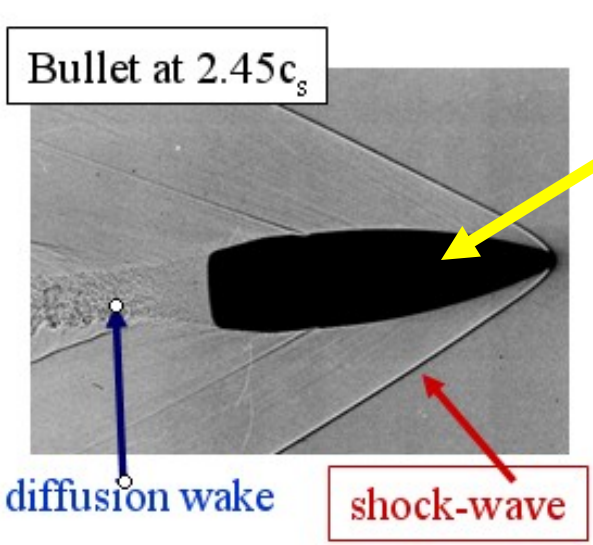


Ulery QM08

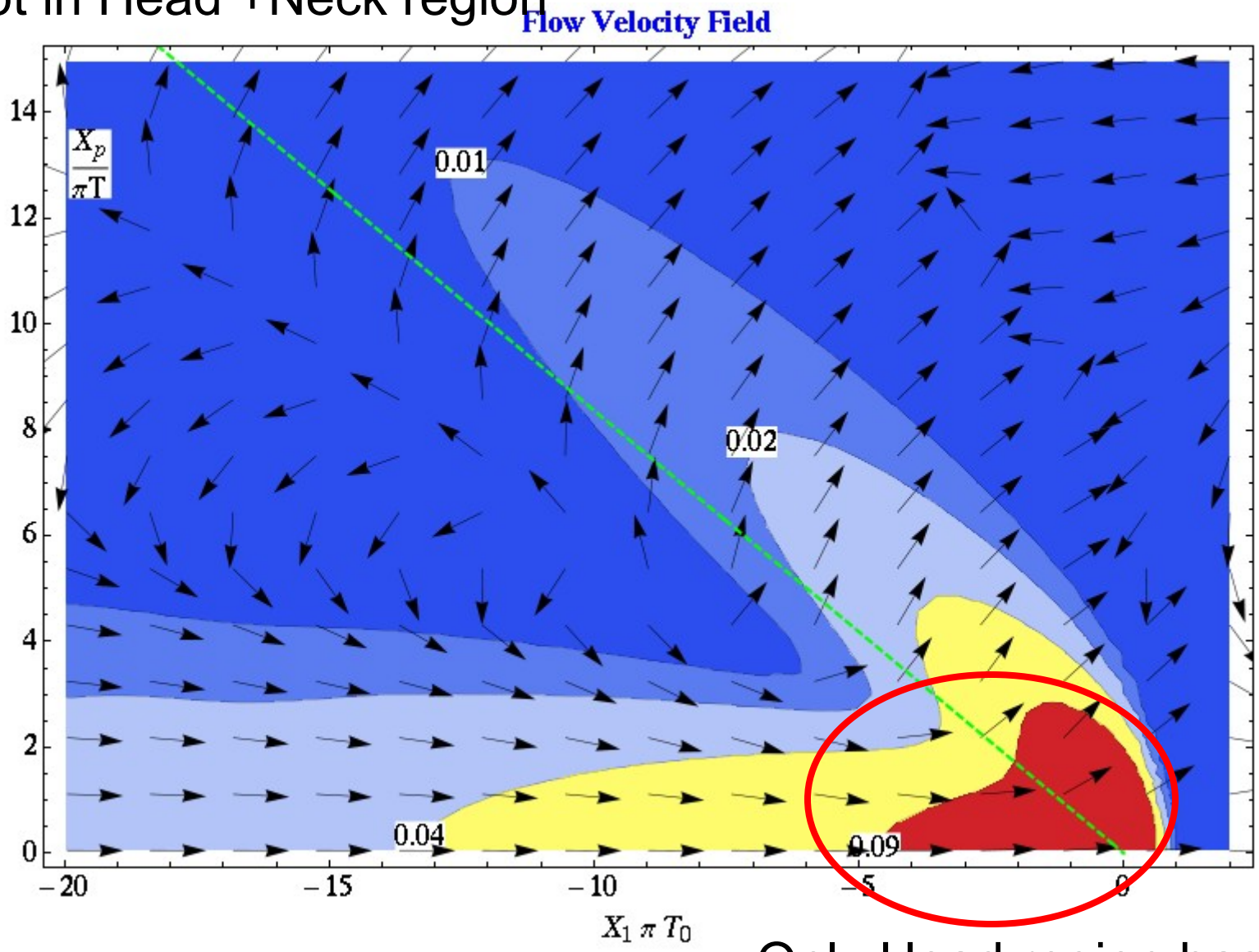


Gubser, Pufu, Yarom
arXiv:0706.4307v1 (2007)

2006-
Herzog et al
Gubser et al
Yaffe et al



Flow velocity field is also small $\Delta v < 0.1$ even for v_Q=0.9c
Except in Head +Neck region



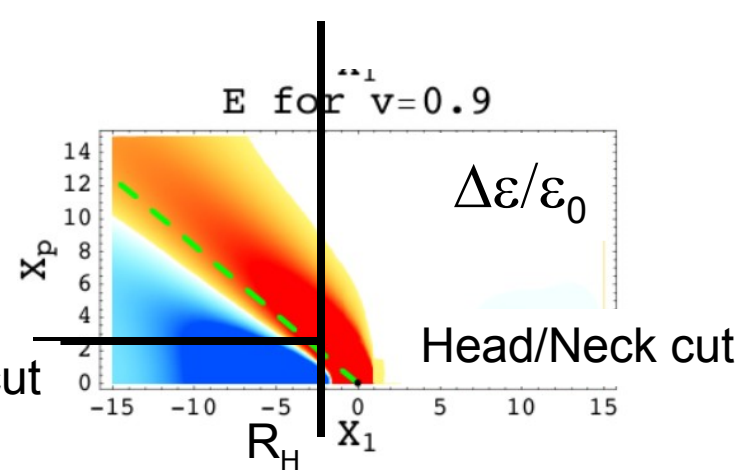
Bow Shock

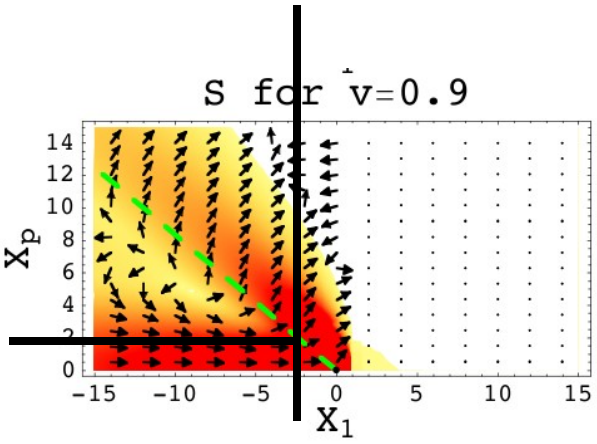
Only Head region has v>0.1

To convert AdS $T^{\mu\nu}(x)$ stress information
into Hadron angular and spectral intensities

$$(T(x), \vec{v}(x)) \xrightarrow{\text{Cooper–Frye}} dN^m / d^3p$$

We used full numerical AdS solution of Gubser, Pufu, Yarom (http://arxiv.org/pdf/0706.4307) with Causal and Head cuts

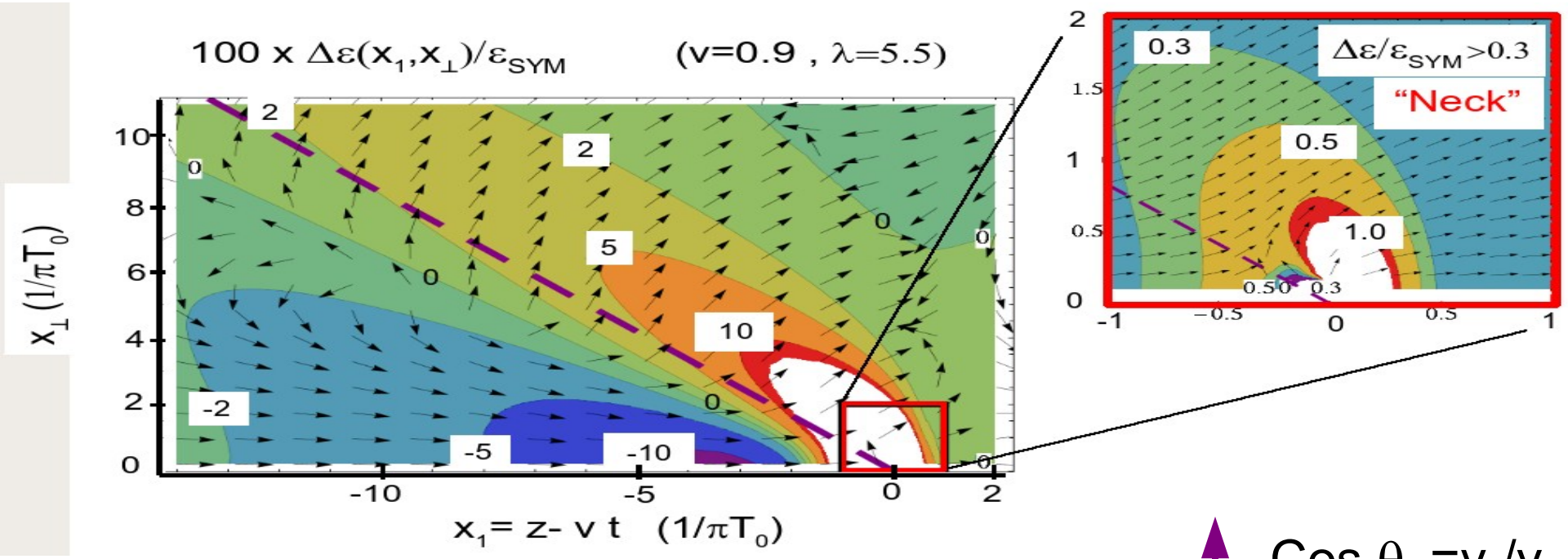




$$\left.\frac{dN}{d\varphi dy}\right|_{y=0} = \frac{g}{(2\pi)^3}\int dV \int dp_\perp \sqrt{p_\perp^2 + m^2}\, p_\perp \exp\left\{-\frac{\gamma}{T}\left[\sqrt{p_\perp^2 + m^2} - p_\perp\left(v_x \cos\varphi + v_y \sin\varphi\right)\right]\right.$$

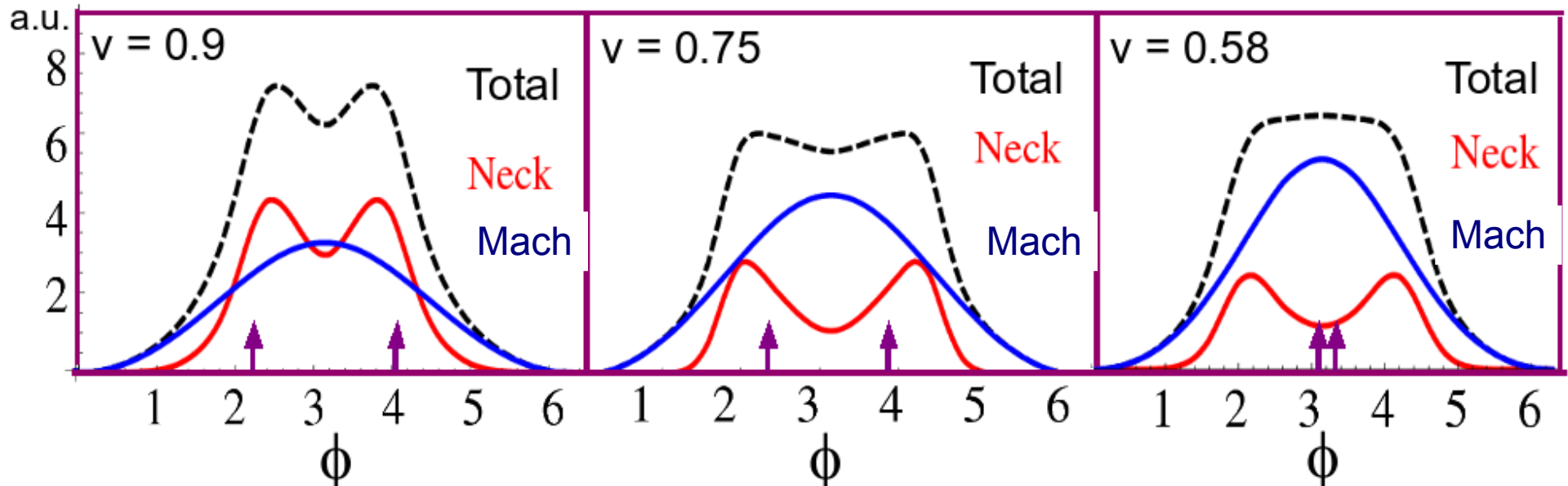
In AdS ~ static SYM plasma assume an isochronous freeze-out

Non-Mach Conical Correlations from AdS Drag, J. Noronha, MG, G. Torrieri 2008



$\cos\theta_M = v_s/v$

$dN(\phi)/d\phi - dN(0)/d\phi$



Di-Jet Correlations provide a second opportunity, besides $R_{c/b}(pT)$, to falsify AdS String Drag dynamics at RHIC and LHC .

Need c or b identified supersonic but not ultra-relativistic heavy quarks

Look for velocity independent conical wave associated correlations

that contradict Mach's law.

The new physics in AdS String Drag picture is a nonequilibrium

“chromo viscous” dynamics Neck zone surrounding the heavy quark,

where stress proportional to T^2/x^2 rather than the bulk T^4

Summary: EMMI's QGP quadrant addresses fundamental questions related to the properties of extreme energy density matter inaccessible through Big Bang Cosmology.

To realize the “femto cosmology” power of A+A at RHIC and LHC problems including those discussed here need to be solved

1) To devise exp or lattice falsifiable observables to test the competing paradigms proposed to explain QGP thermodynamics (as measured by lattice QCD)

2) To constrain the ensemble of Initial Geometric and Flow Conditions (as function of s, b and y) needed by hydro/transport theory to interpret (elliptic, radial, and directed) flow observables

3) Place narrower bounds on the shear and bulk QGP transport coefficients required to invert flow data to extract the QGP equation of state

4) Develop a consistent theory of light and heavy quark jet and dijet observables and calibrate its tomographic power.