Properties of sQGP

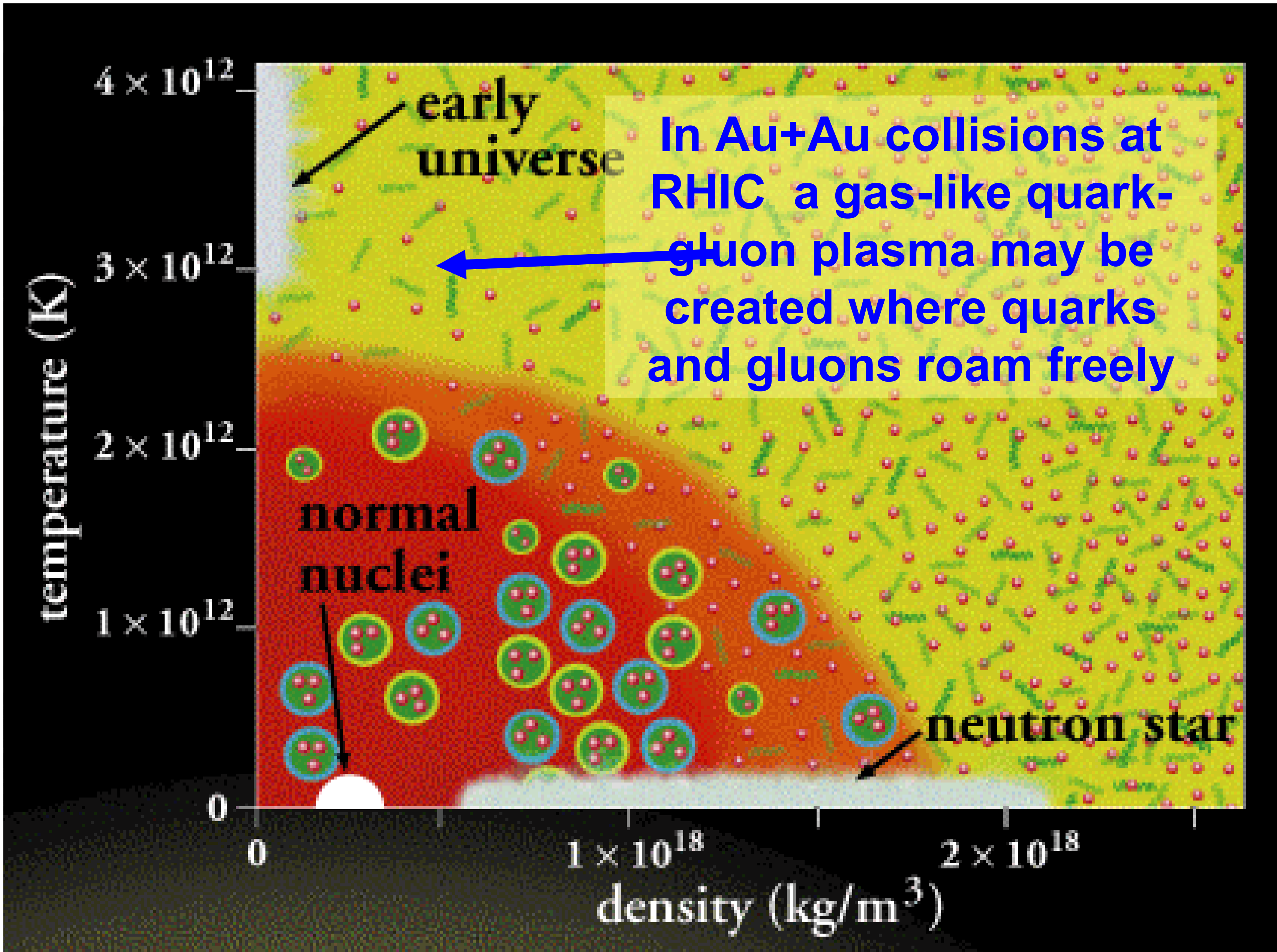
perfect fluid of quarks discovered at RHIC

Csörgő, Tamás

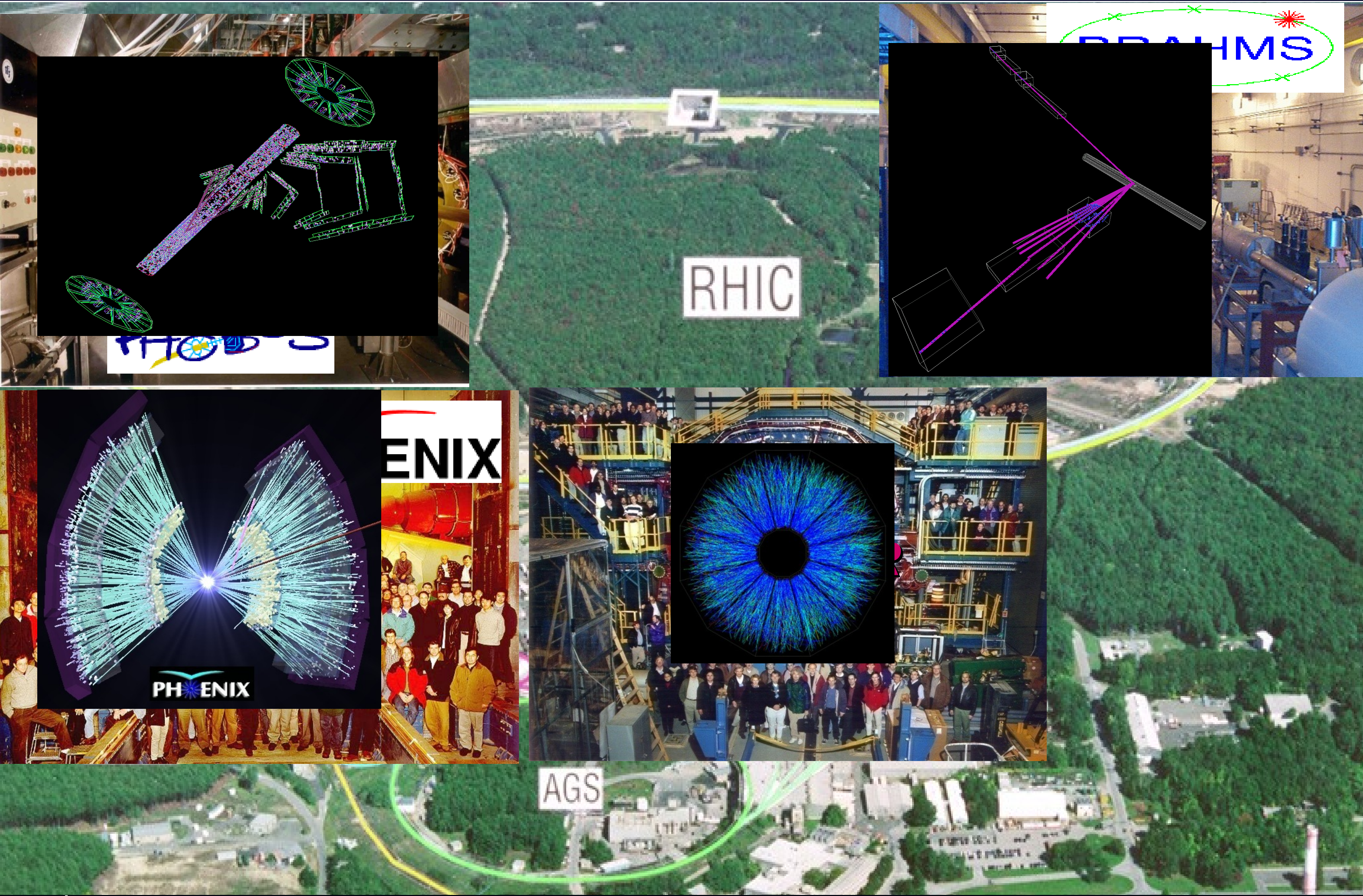
Department of Physics, Harvard University, Cambridge, MA
MTA KFKI RMKI, Budapest

New phenomena
New form of matter
Speed of sound
Perfect fluid
Fluid of quarks
Perfection at limit
Light from Quark-Gluon Plasma
In-medium mass modification of η'
Experimentally: Crossover

Expectations cca 2000



RHIC and the 4 RHIC experiments



RHIC: Plans around 2000 (and 2010)

Utilize the unprecendented capabilities of RHIC

- **Big enough √s**
  - Reliable pQCD probes available
  - Net baryons separated from the produced „glue”
  - Decisive experimental information for or against the existence of QGP
- **Polarized p+p collisions**

Two smaller and two large detectors

- **Complementary and partially overlapping capabilities**
- **Smaller detectors, 3-5 years lifetime: BRAHMS, PHOBOS**
- **Large detectors ~ Facilities: PHENIX, STAR**
  - Significant investments
  - Long life-times (20+ years, currently PHENIX-v3 under desing)
  - Upgrades in response to discoveries
  - (Luminosity enhancement at lowered energies: search for/against a critical point of QCD, direct photons, electron-ion collider ...)

Since then …

A RHIC accelerator komplex

Routine operation at several times desing luminosity, > 4x(Au+Au)

Variable collider parameters

Combinations of beams: Au+Au, d+Au, Cu+Cu, pp+pp

Colliding energies: 22 GeV (Au+Au, Cu+Cu, pp+pp), 7,7, 32, 56 GeV (Au+Au), 62 GeV (Au+Au,Cu+Cu, pp+pp) , 130 GeV (Au+Au), 200 GeV (Au+Au, Cu+Cu, d+Au, pp+pp), 410 GeV (p+p), 500 GeV (pp+pp)

Experiments:

Worked ! PHOBOS and BRAHMS finished data taking in 2005

Scientific results:

1000+ published papers, ~ 40 000 citations by today

SIGNIFICANT **DISCOVERIES**

Future based on:

Proven ability to upgrade PHENIX and STAR

Key scientific questions determined

Accelerator complex and experiments: currently in phase 2.

start for critical point of QCD search:

Phase 3. (5-10 years) in preparation, upgrade plans submitted

Language

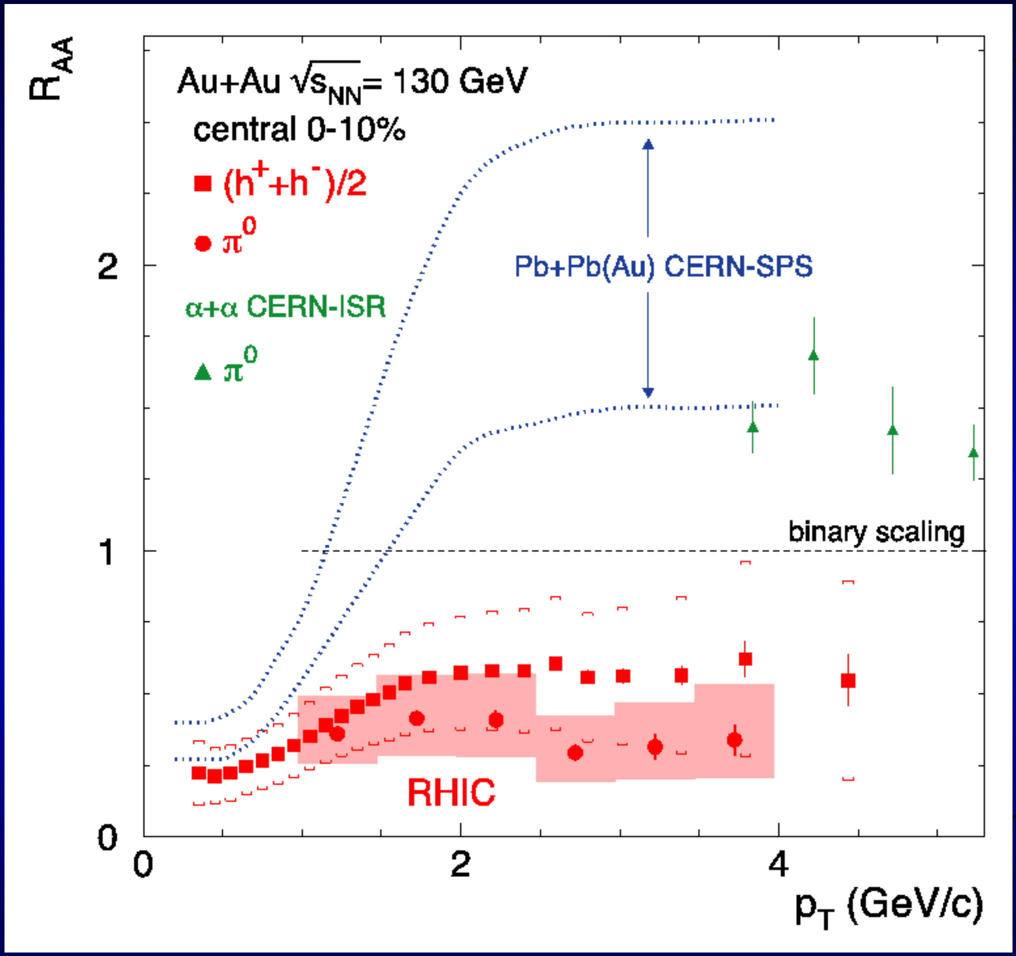
Commonly utilized basic nuclear properties

A, Z ...

Quantities specific to heavy ion physics

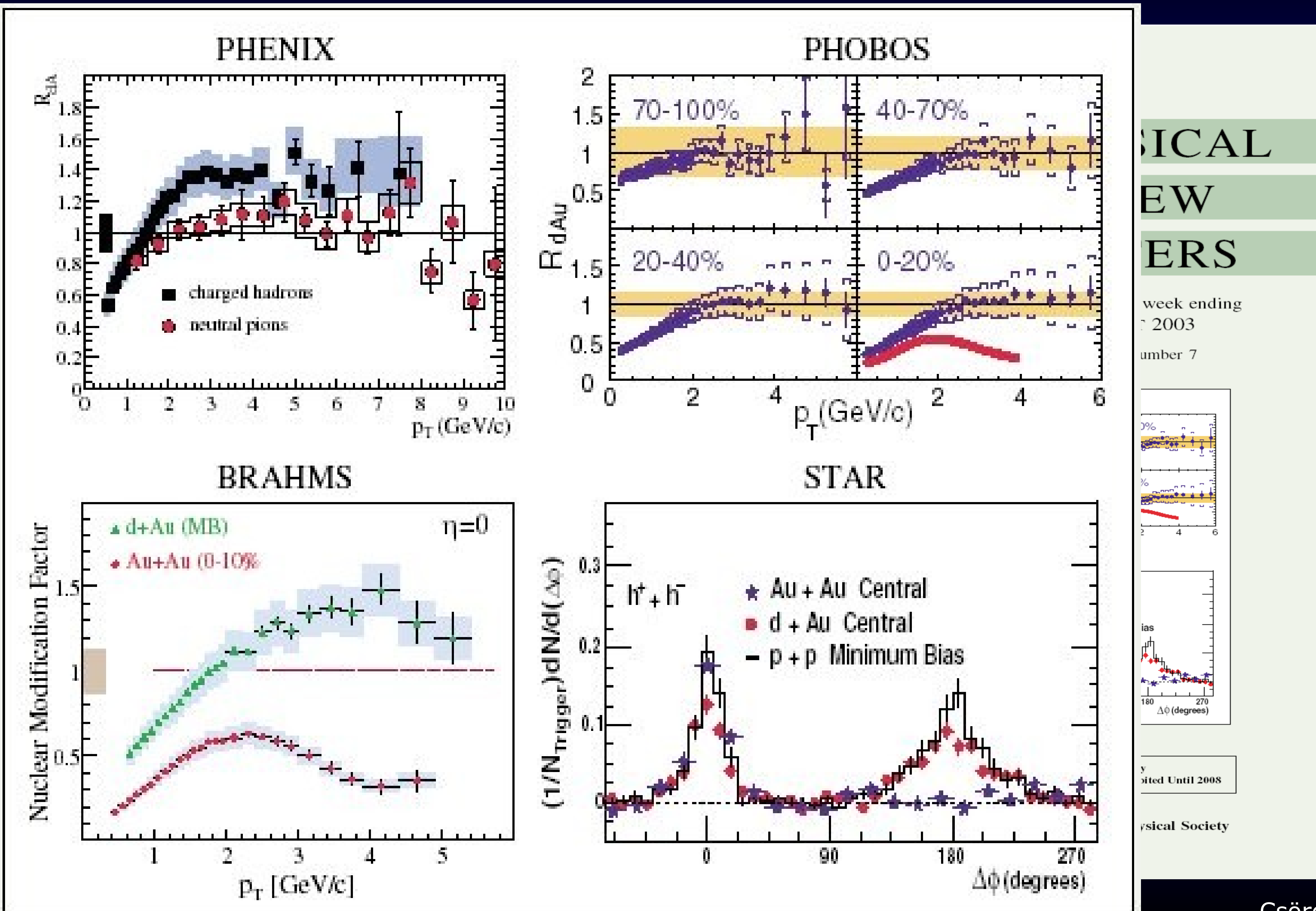
v_2	**Azimuthal anisotropy - Fourier coefficient - "elliptic flow"**
R_{AA}	**Nuclear modification factor, its value is 1 in lack of nuclear effect**
T	**Temperature (MeV)**
μ_B	**Baryon chemical potential (MeV) ~ *net* baryon density**
η	**Shear viscosity (MeV^3)**
s	**Entropy density (MeV^3) ~ "particle" density**

1st milestone: new phenomena

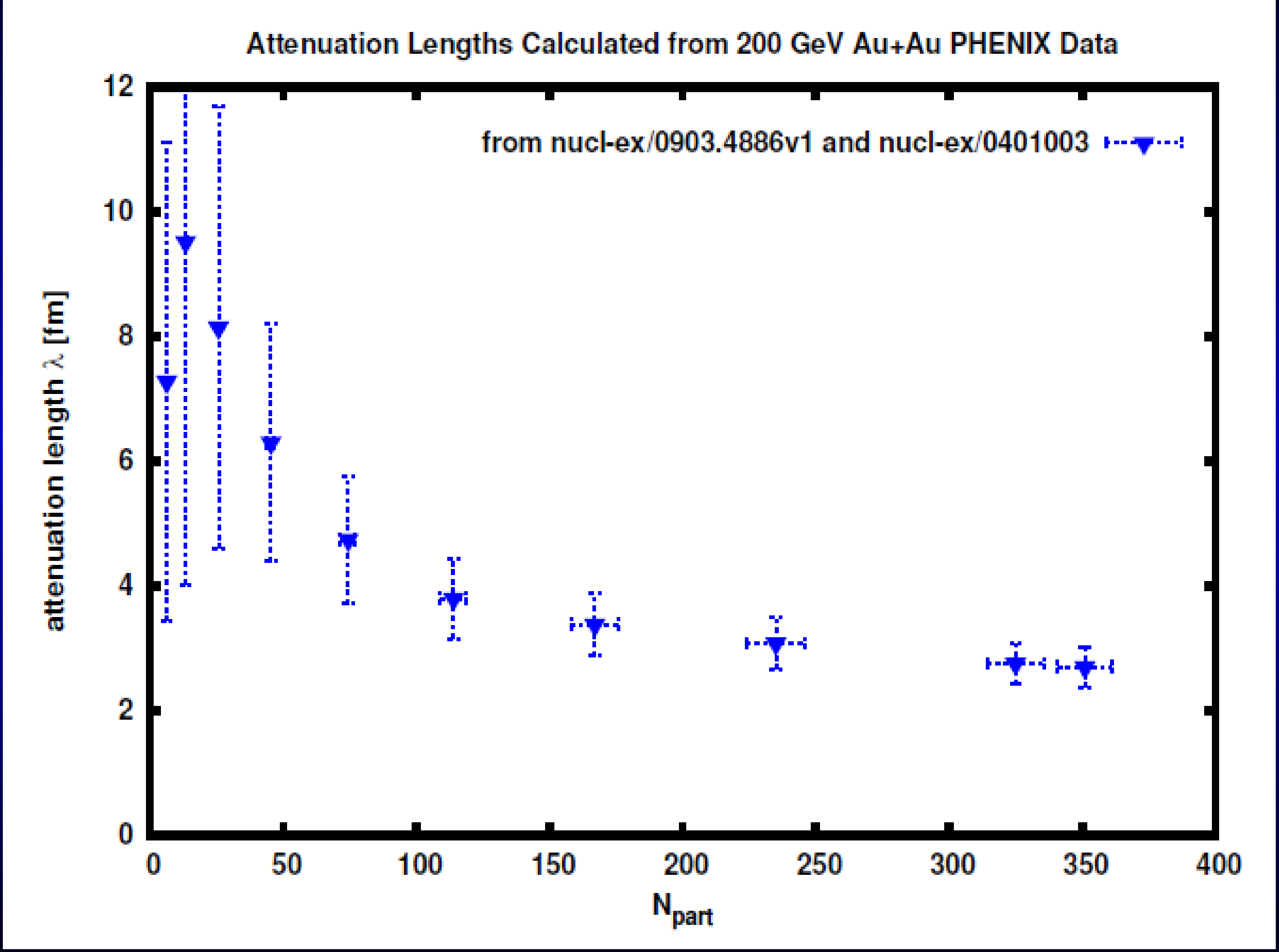


Suppression of particle production in Au+Au collisions at RHIC - a PHENIX discovery (currently 559 citations)

2^{nd} milestone: a new form of matter



Measurement of optical opacity



T. Cs, arXiv:0903.0669 [nucl-th]

3rd milestone: Not a gas, but a liquid!

Cím http://www.aip.org/pnu/2005/split/757-1.html

AMERICAN INSTITUTE OF PHYSICS | SEARCH | advanced search | home

Physics News Update

The AIP Bulletin of Physics News

Subscribe to Physics News Update

Physics News Graphics

Physical Review Focus

Physics News Links

Archives
2006
2005
2004

Number 757 #1, December 7, 2005 by Phil Schewe and Ben Stein

The Top Physics Stories for 2005

At the Relativistic Heavy Ion Collider (RHIC) on Long Island, the four large detector groups agreed, for the first time, on a consensus interpretation of several year's worth of high-energy ion collisions: the fireball made in these collisions -- a sort of stand-in for the primordial universe only a few microseconds after the big bang -- was not a gas of weakly interacting quarks and gluons as earlier expected, but something more like a liquid of strongly interacting quarks and gluons (PNU 728).

Other top physics stories for 2005 include, in general chronological order of their appearance throughout the year, the following:

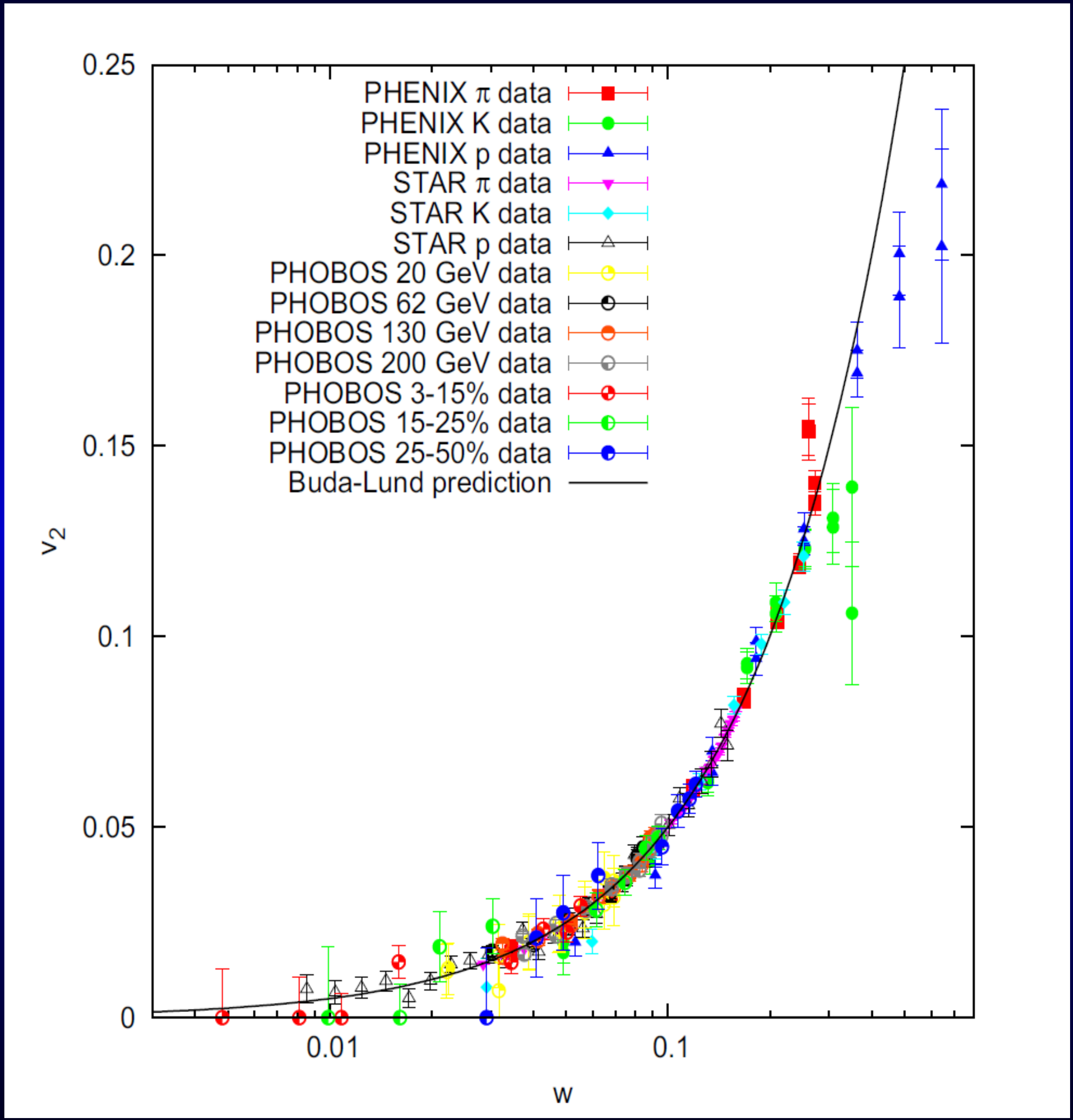
the arrival of the Cassini spacecraft at Saturn and the successful landing of the Huygens probe on the moon Titan (PNU 716);

the development of lasing in silicon (Nature 17 February);

http://arxiv.org/abs/nucl-ex/0410003

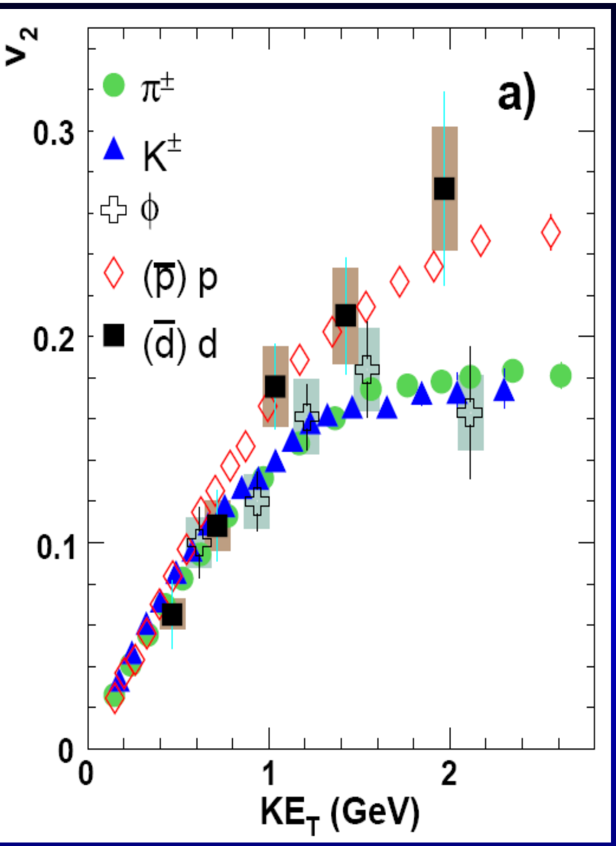
971 citations in ~ 5 years

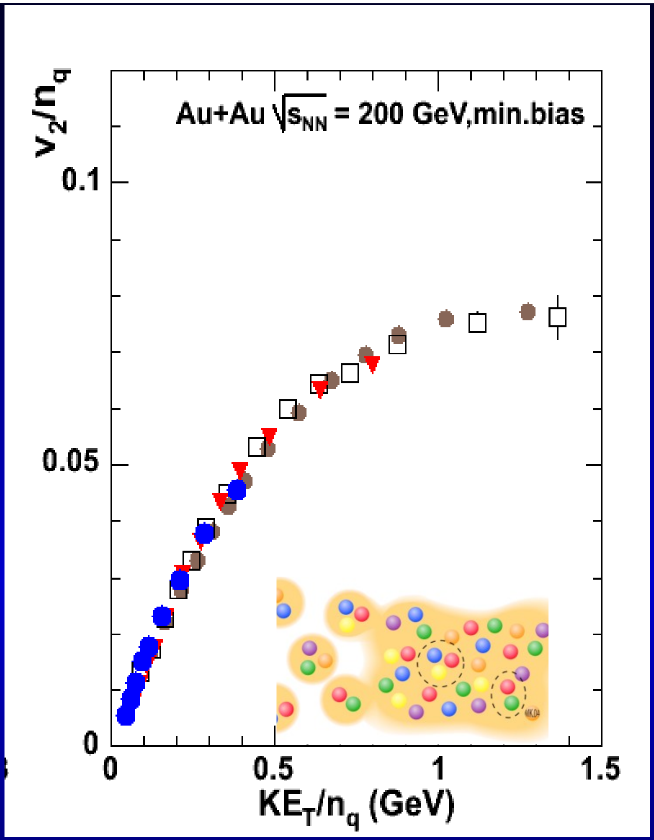
The perfecf fluid at RHIC

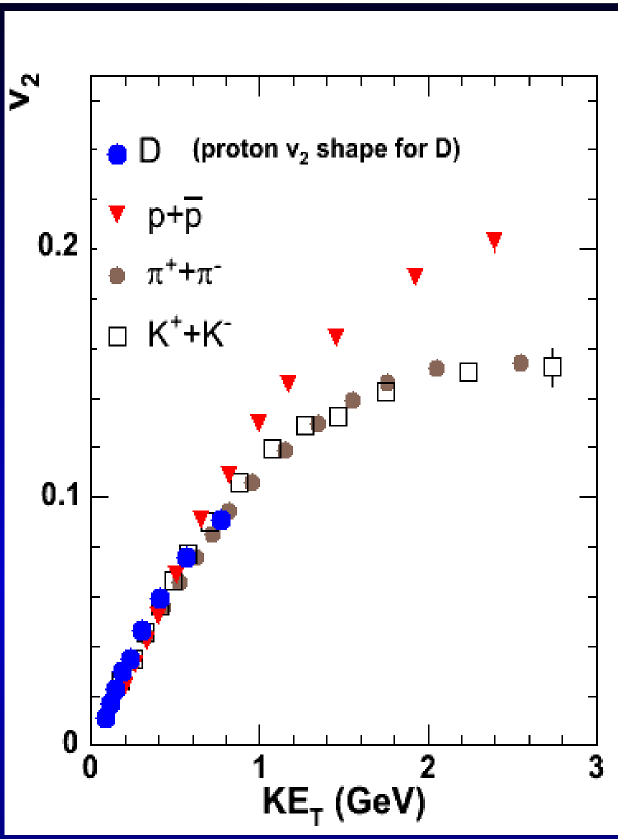


M. Csanád, T. Cs. et al, Eur. Phys.J.A38:363-368,2008

4th milestone: A fluid of quarks







φ meson v_2
follows other mesons

$$v_2^{hadron}\left(KE_T^{hadron}\right) \approx n v_2^{quark}\left(KE_T^{quark}\right)$$
$$KE_T^{hadron} \approx n KE_T^{quark}$$

D meson v_2
follows other mesons

Even strange and charmed quarks participate in the flow

How "perfect" ? Let us measure η/s!

Diffusion of heavy quarks → viscosity ~ η /s

FLOW: *Has the QCD Critical Point Been Signaled by Observations at RHIC?*, R. Lacey *et al*., Phys.Rev.Lett.98:092301,2007 (nucl-ex/0609025)

$$\frac{\eta}{s} = (1.1 \pm 0.2 \pm 1.2)\frac{1}{4\pi}$$

The Centrality dependence of Elliptic flow, the Hydrodynamic Limit, and the Viscosity of Hot QCD, H.-J. Drescher *et al*., (arXiv:0704.3553)

$$\frac{\eta}{s} = (1.9 - 2.5)\frac{1}{4\pi}$$

FLUCTUATIONS: *Measuring Shear Viscosity Using Transverse Momentum Correlations in Relativistic Nuclear Collisions*, S. Gavin and M. Abdel-Aziz, Phys.Rev.Lett.97:162302,2006 (nucl-th/0606061)

$$\frac{\eta}{s} = (1.0 - 3.8)\frac{1}{4\pi}$$

DRAG, FLOW: *Energy Loss and Flow of Heavy Quarks in Au+Au Collisions at $\sqrt{s_{NN}}$ = 200 GeV* (PHENIX Collaboration), A. Adare *et al*., Phys.Rev.Lett.98:172301,2007 (nucl-ex/0611018)

$$\frac{\eta}{s} = (1.3 - 2.0)\frac{1}{4\pi}$$

CHARM!

5^{th} milestone: Perfection at limit

Every "realistic" hydrodynamic calculations assumed zero (0)viscositiy initially

$\eta = 0 \rightarrow$ "perfect fluid"

Note: conjectured quantum limit:

$$\eta \geq \frac{\hbar}{4\pi}(Entropy\ Density) \equiv \frac{\hbar}{4\pi} s$$

"A Viscosity Bound Conjecture", **P. Kovtun, D.T. Son, A.O. Starinets, hep-th/0405231**

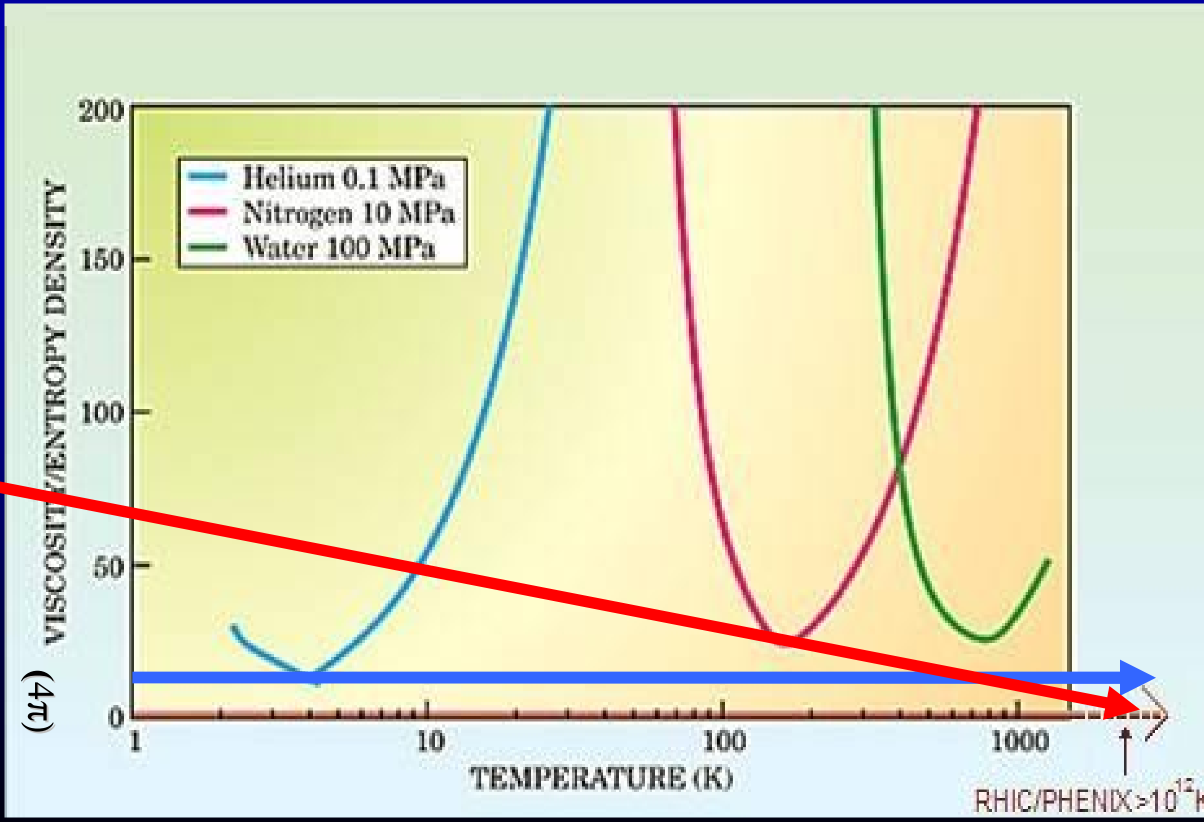
How ordinary fluids compare to this limit?

$(4\pi)\,\eta/s > 10$!

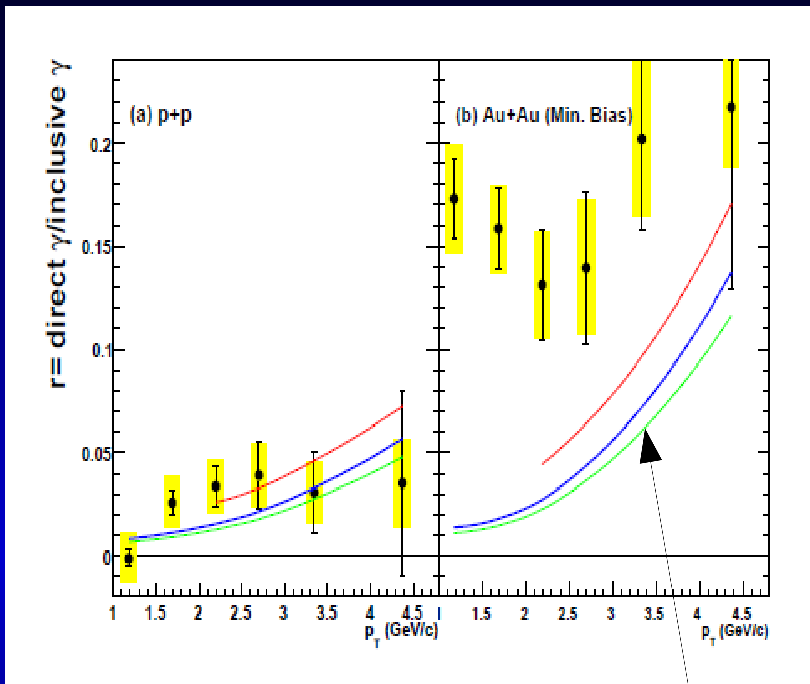
Perfect fluid at RHIC

$(4\pi)\,\eta/s \sim 1$

The hottest (T > 4 Terakelvin) and the most perfect man-made matter…

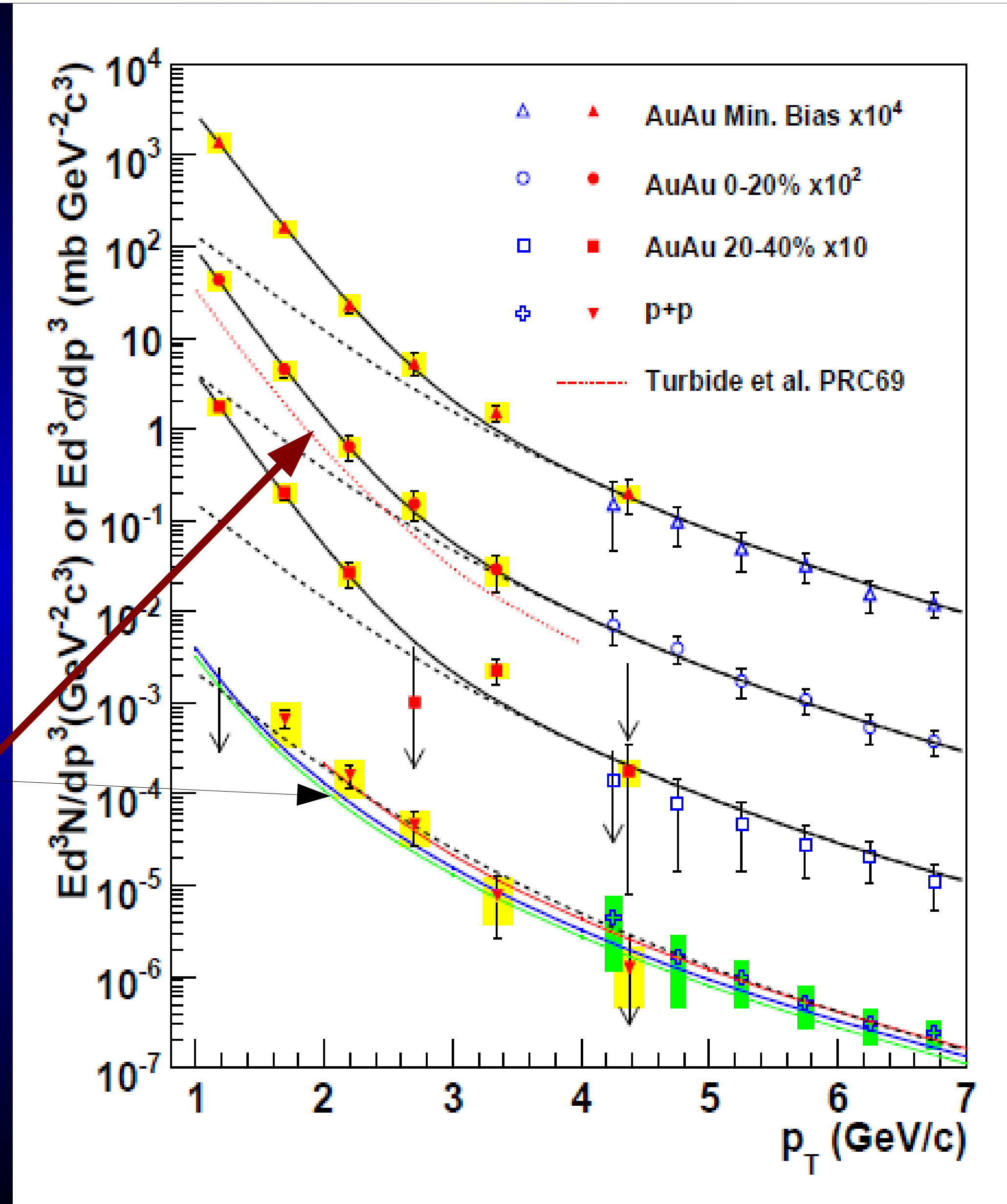


6^{th} milestone: Initial temperature



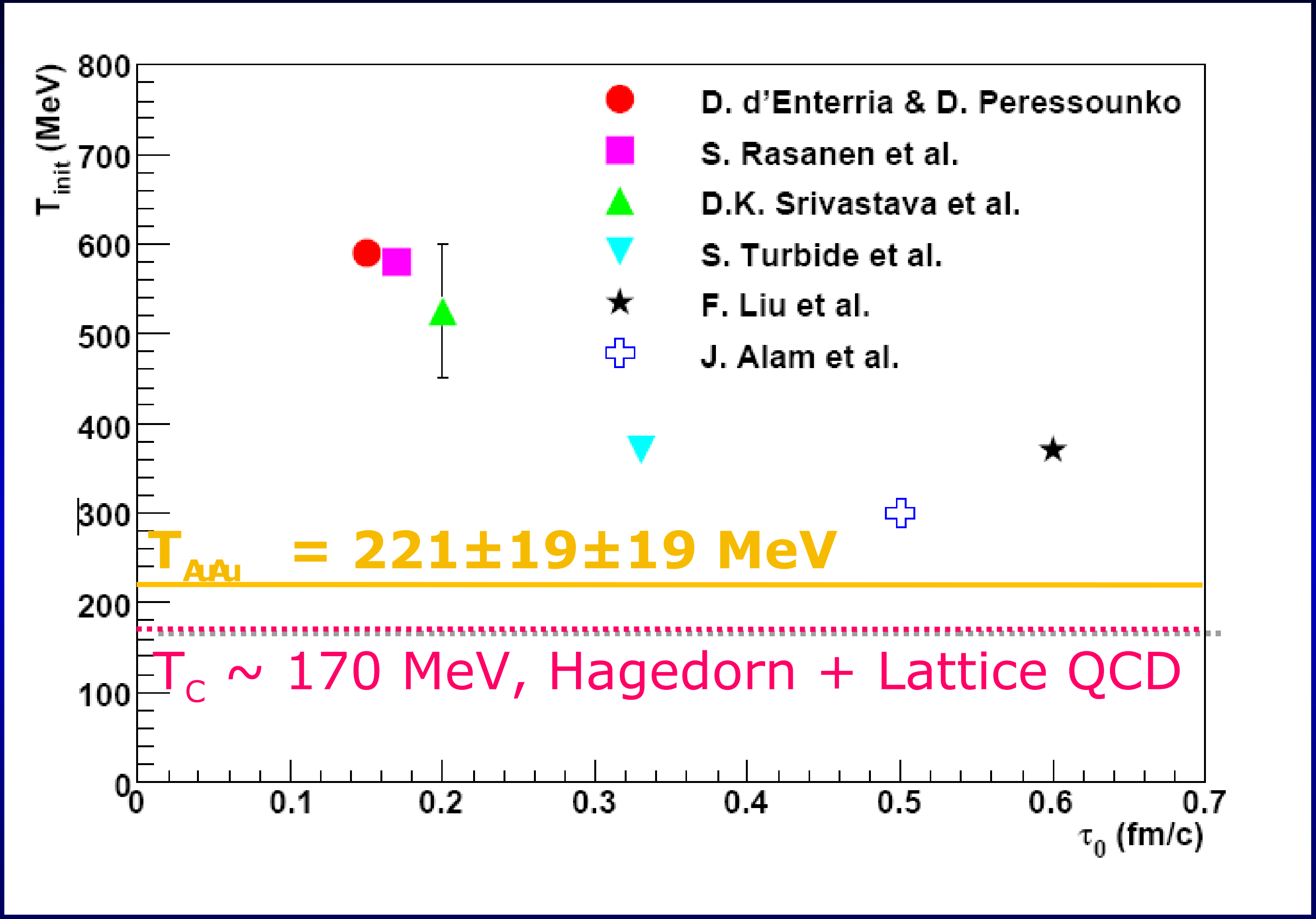
NLO pQCD calculations

Hydro + direct photons
with T_{init} ~ 360 MeV



A.Adare et al.PHENIX Collaboration,
arXiv:0804.4168 [nucl-ex]
Phys.Rev.Lett.104:132301 (2010)
Phys. Rev. C 81, 034911 (2010)

6^{th} milestone: Initial temperature



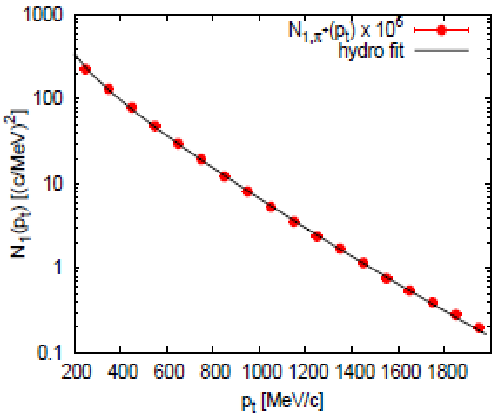
A.Adare et al.PHENIX Collaboration, Phys.Rev.Lett.104:132301 (2010)

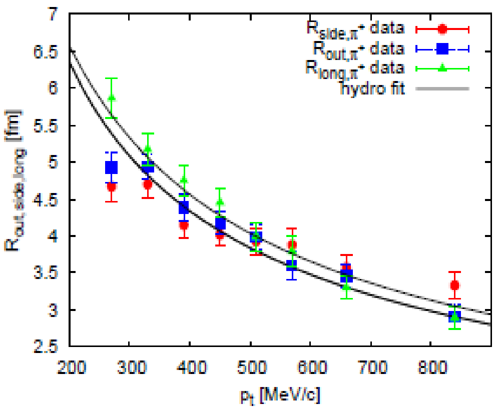
Directly from data: T_{ini} > T_{AuAu} ~ 221 MeV

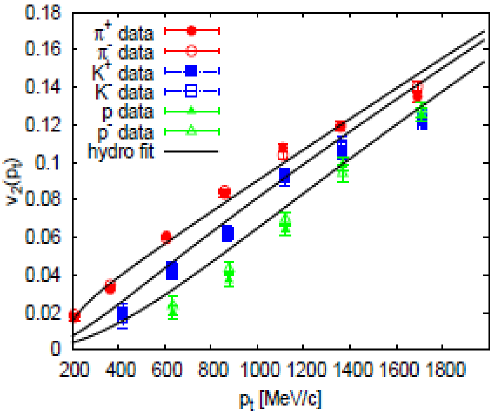
Model calculations: T_{ini} = 300 - 600 MeV, if τ_0 = 0.15 - 0.6 fm/c

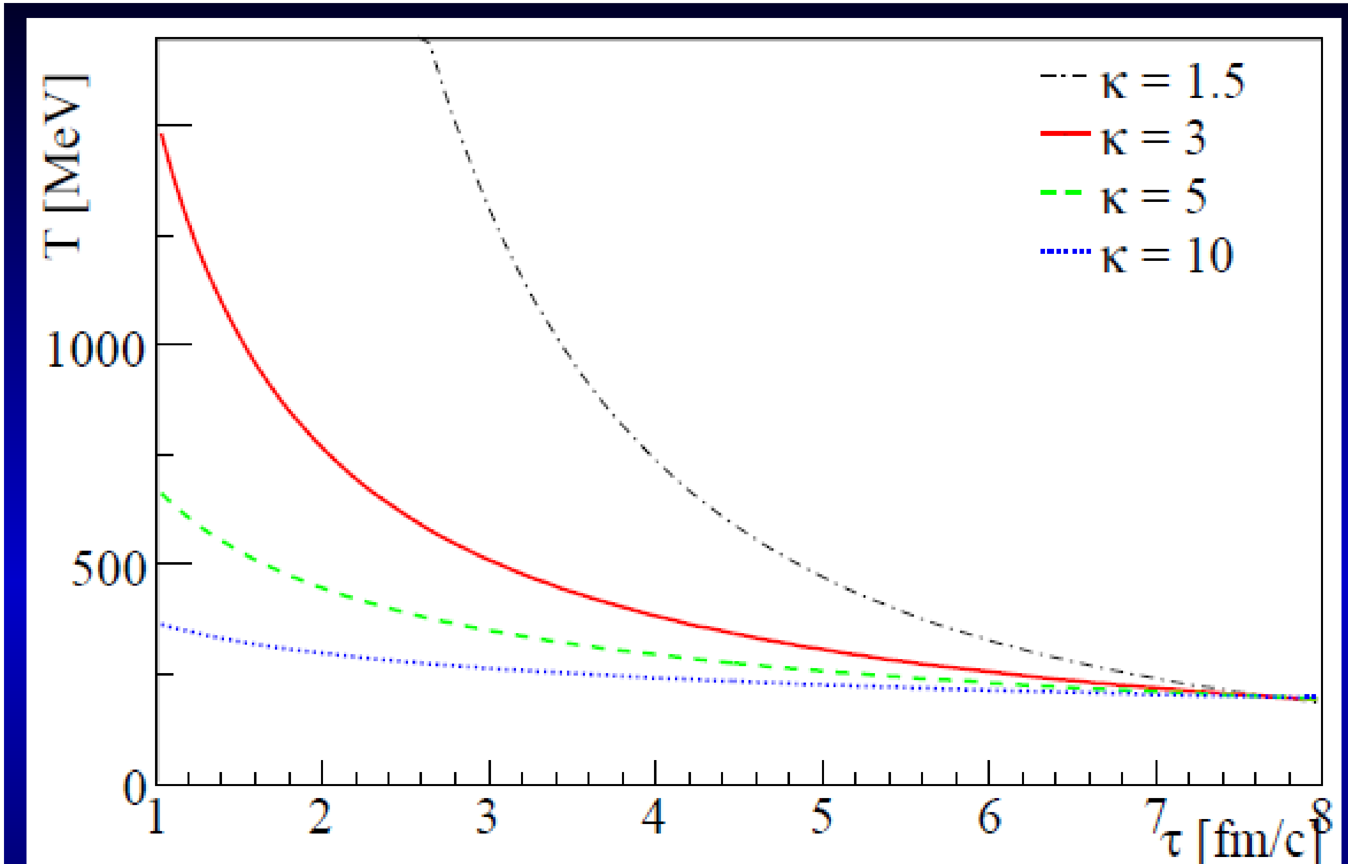
lattice QCD and data on Hagedorn spectra: T_c ~ 170 MeV

Confirmation: Initial temperature









Exact hydro solution: T_{ini} > 340 MeV at τ = 1 fm/c
using simultaneous fits to spectra, v2, HBT radii
and any reasonable EoS with κ = e/p < 10

M. Csanád, M. Vargyas, Eur.Phys.J.A44:473-478,2010

Csörgő T.

Exact hydro → initial energy density

$$v = \tanh \lambda\eta,$$
$$p = p_0 \left(\frac{\tau_0}{\tau}\right)^{\lambda d \frac{\kappa+1}{\kappa}} \left(\cosh \frac{\eta}{2}\right)^{-(d-1)\phi_\lambda}$$

Possible cases (one row of the table is one solution):

Case	λ	d	κ	ϕ_λ
a.)	2	$\in \mathbb{R}$	d	0
b.)	$\frac{1}{2}$	$\in \mathbb{R}$	1	$\frac{\kappa+1}{\kappa}$
c.)	$\frac{3}{2}$	$\in \mathbb{R}$	$\frac{4d-1}{3}$	$\frac{\kappa+1}{\kappa}$
d.)	1	$\in \mathbb{R}$	$\in \mathbb{R}$	0
e.)	$\in \mathbb{R}$	1	1	0

Nagy, Cs.T., Csanád: nucl-th/0605070, arXiv:0709.3677v1, arXiv:0805.1562

→ *New, accelerating, d dimension*

↘ d dimensional with $p=p(\tau,\eta)$
↗ (thanks T. S. Biró)

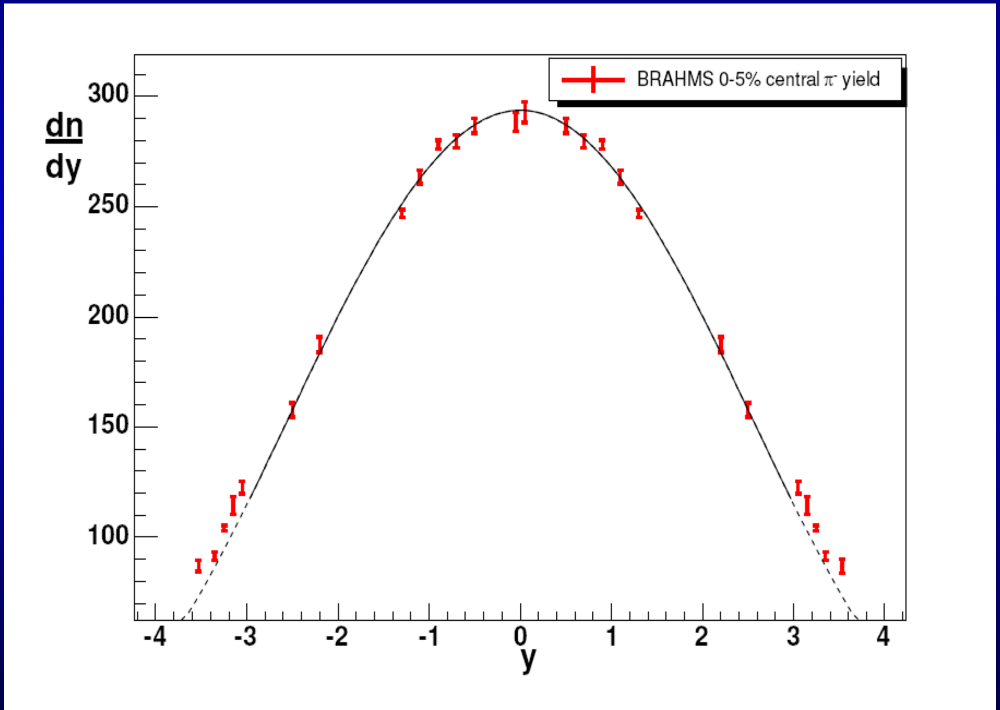
→ Hwa-Bjorken, Buda-Lund

→ Special EoS, but general velocity

If $\kappa = d = 1$, general solution is obtained, for ARBITRARY initial conditions. It is STABLE !

BRAHMS rapidity distribution fitted

$$\frac{dn}{dy} \approx \left.\frac{dn}{dy}\right|_{y=0} \cosh^{\pm\frac{\alpha}{2}-1}\left(\frac{y}{\alpha}\right) e^{-\frac{m}{T_f}\left[\cosh^{\alpha}\left(\frac{y}{\alpha}\right)-1\right]},$$



$$\lambda = \frac{\alpha-1}{\alpha-2}.$$

α	7.4 ± 0.13
$\left.\frac{dn}{dy}\right\|_{y=0}$	294 ± 1
χ^2/NDF	$30.6/14$
CL	0.6%
T_f (MeV)	200 (fixed)
m (MeV)	140 (fixed)
λ	1.18 ± 0.01 (derived)

BRAHMS data fitted with exact hydro solution

Conjecture: EoS dependence of ε_0

Four constraints

1) ε_{Bj} is independent of EoS (λ = 1 case)

2) c_s^2= 1 case is solved for any λ > 0.5

$$\frac{\varepsilon_c}{\varepsilon_{Bj}} = (2\lambda - 1)\left(\frac{\tau_f}{\tau_0}\right)^{\lambda-1}$$

M. I. Nagy, Cs.T., M. Csanád: nucl-th/0605070, arXiv:0709.3677v1, arXiv:0805.1562

Corrections due to respect these limits.

3) c_s^2 dependence of $\varepsilon(\tau)$ is known

4) Numerical hydro results

Conjectured formula – given by the principle of Occam's razor:

$$\frac{\varepsilon_{c_s^2}}{\varepsilon_{Bj}} = (2\lambda - 1)\left(\frac{\tau_f}{\tau_0}\right)^{\lambda-1}\left(\frac{\tau_f}{\tau_0}\right)^{(\lambda-1)(1-c_s^2)}$$

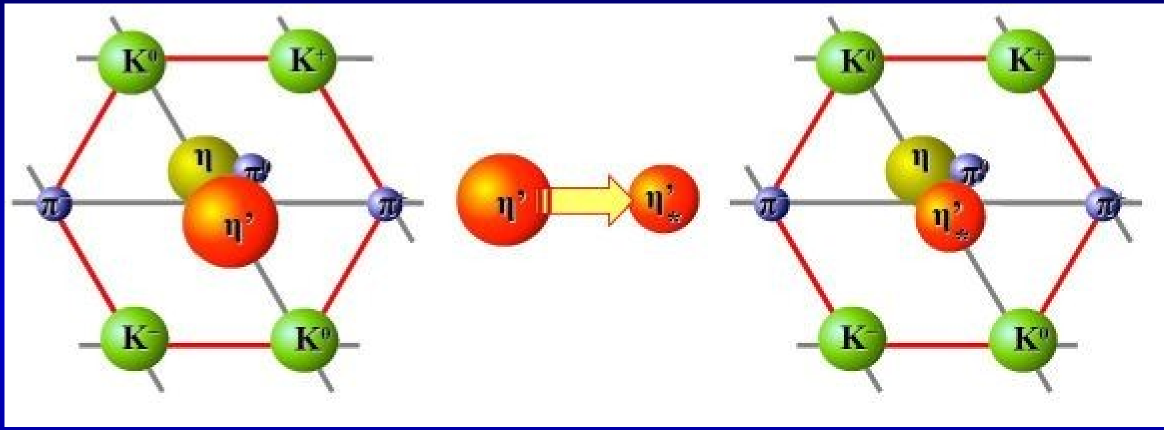
Using λ = 1.18, c_s = 0.35, τ_f/τ_0 = 10, we get e_{cs}/e_{Bj} = 2.9

ε_0 = 14.5 GeV/fm^3 in 200 GeV, 0-5 % Au+Au at RHIC

Summary: Light of Au+Au at RHIC

In Au+Au at RHIC
- New phenomena
- New form of matter
- Perfect fluid
- Fluid of quarks

η' meson mass drop by 200 MeV
a lost symmetry is restored



Properties:

Opaque, R_{AA} ~ 0.2
Attenuation ~ 2 fm
C_s = 0.35 ± 0.05
η/s ≤ superfluid He/5
T_{init} ≥ 300 MeV
ε_{init} ≥ 10-15 GeV/fm³
p_{init} ≥ 1 GeV/fm³

this happens in hadronic matter
deconfinement and $U_A(1)$
restoration happens at different T!

T. Cs, R. Vértesi, J. Sziklai
Phys.Rev.Lett.105:182301,2010

Cross-over transition!

$\Delta m_{\eta'}$ ≥ 200 MeV

see R. Vértesi's talk

APS 2010 announcement related articles (non - Englis

Media	Headline
Deutschlandfunk	Am Anfang war der Symmetriebruch, Vier Billionen Grad heiße Urknall-Suppe untersucht von Jan Lublinski
Yomiuri Online	Successfully achieved four trillion degrees! Reproduced right-after-BigBang
gazeta.ru Science	It was hot in the beginning
Russian Academy of Science	Physicists have measured temperature of the Universe an it's first moments of life
Index.hu	Biggest heat since the Big Bang
Hungarian Academy of Sciences	Temperature of the Hottest Matter Measured
Origo.hu (Hungarian Portal, Science	Creation of the Original Matter of the Universe
Cemblog.wordpress.com (Hungarian)	Results from America on the Original Matter of the Universe
Cemblog.wordpress.com (Hungarian)	At least 4 Trillion Celsius: Temperature of the Primordial Matter of the Universe
Cemblog.wordpress.com (Hungarian)	Bubbles of Violate Symmetry in the Quark Soup of RHIC
HirExtra.hu (Hungarian)	Primordial Soup Boiling Again
Hirado.hu (Hungarian National Television)	Hungarian Researchers in Experiments Studying Post Big Bang State
Epresso.hu (Hungarian Education Portal)	Hungarian Participants in Measurement of Hottest Matter Ever
The-online.hu (Hungarian Science Portal)	Temperature of Hottest Ever Matter Measured

Last Updated on Tuesday, 06-Apr-2010 10:26:49 EDT by A. Franz

QGP at RHIC introduction for students

A KVARKOK FOLYADÉKÁNAK MEGLEPŐ TULAJDONSÁGAI

MÉRFÖLDKÖVEK

A nagyenergiás magfizikában a legfontosabb és legérdekesebb kérdéseket óriási gyorsítók, az úgynevezett relativisztikus nehézion-ütköztetők segítségével tehetjük fel a Természetnek. A fénysebességhez igen közeli sebességű nehézionokat, azaz héliumnál nehezebb atommagokat ütköztetünk egymással. Ezen ütközések során az anyag olyan állapotba jut, amilyen egy szempillantással a Világegyetemünk keletkezése, azaz néhány mikromásodperccel a Nagy Bumm után uralkodott. Emiatt a nagyenergiás gyorsítókban zajló nehézion-ütközéseket – a bennük uralkodó óriási energiasűrűség és hőmérséklet miatt – Kis Bummoknak is nevezhetjük.

OTKA

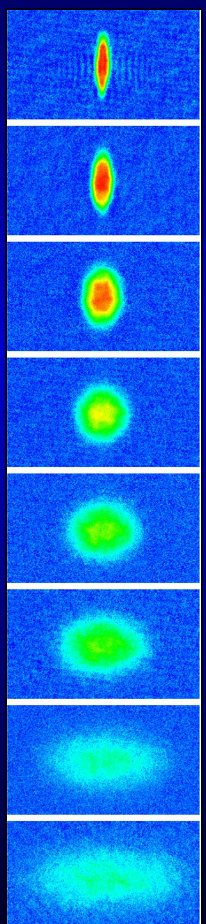
A cikk az OTKA és az Élet és Tudomány közös pályázatán első helyezést ért el.

First prize, OTKA = Hungarian NSF + Hungarian „Life and Sciences” magazin

November-december 2010 issue, this week

Strongly interacting matters

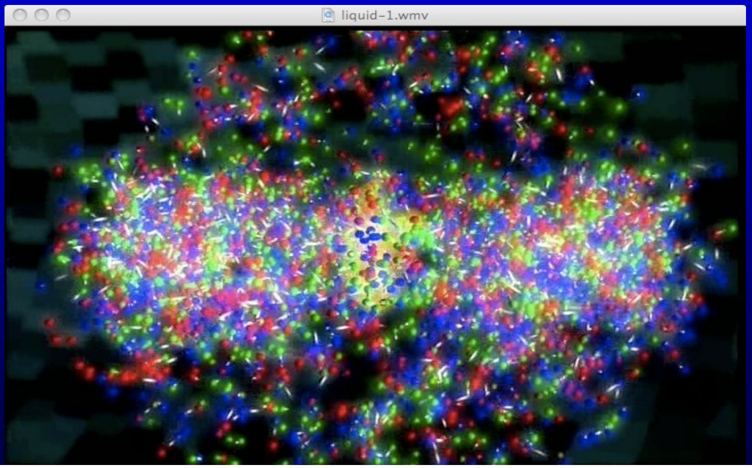
- Ultra-cold atomic ^{6}Li gas
- Perfectly flowing Quark-Gluon Plasma (RHIC)
- High T_c Szuperconductors
- Neutron stars
- Black holes in string theory



Strongly coupled ^{6}Li gas,

$T = 10^{-7}$ K

J. Thomas et al, Science (2002)



Quark-gluon plasma, $T>4\times10^{12}$ K

Similar “Elliptic” flow pictures

Acknowledgments:

DOE, Fulbright, HAESF, MTA, NSF,OTKA

Universidade de São Paulo, Instituto de Física, Caixa Postal 66318, São Paulo CEP05315-970, Brazil
Institute of Physics, Academia Sinica, Taipei 11529, Taiwan
China Institute of Atomic Energy (CIAE), Beijing, People's Republic of China
Peking University, Beijing, People's Republic of China
Charles University, Ovocnytrh 5, Praha 1, 116 36, Prague, Czech Republic
Czech Technical University, Zikova 4, 166 36 Prague 6, Czech Republic
Institute of Physics, Academy of Sciences of the Czech Republic, Na Slovance 2, 182 21 Prague 8, Czech Republic
Helsinki Institute of Physics and University of Jyväskylä, P.O.Box 35, FI-40014 Jyväskylä, Finland
Dapnia, CEA Saclay, F-91191, Gif-sur-Yvette, France
Laboratoire Leprince-Ringuet, Ecole Polytechnique, CNRS-IN2P3, Route de Saclay, F-91128, Palaiseau, France
Laboratoire de Physique Corpusculaire (LPC), Université Blaise Pascal, CNRS-IN2P3, Clermont-Fd, 63177 Aubiere Cedex, France
IPN-Orsay, Universite Paris Sud, CNRS-IN2P3, BP1, F-91406, Orsay, France
SUBATECH (Ecole des Mines de Nantes, CNRS-IN2P3, Université de Nantes) BP 20722 - 44307, Nantes, France
Institut für Kernphysik, University of Münster, D-48149 Münster, Germany
Debrecen University, H-4010 Debrecen, Egyetem tér 1, Hungary
ELTE, Eötvös Loránd University, H - 1117 Budapest, Pázmány P. s. 1/A, Hungary
KFKI Research Institute for Particle and Nuclear Physics of the Hungarian Academy of Sciences (MTA KFKI RMKI), H-1525 Budapest 114, POBox 49, Budapest, Hungary
Department of Physics, Banaras Hindu University, Varanasi 221005, India
Bhabha Atomic Research Centre, Bombay 400 085, India
Weizmann Institute, Rehovot 76100, Israel
Center for Nuclear Study, Graduate School of Science, University of Tokyo, 7-3-1 Hongo, Bunkyo, Tokyo 113-0033, Japan
Hiroshima University, Kagamiyama, Higashi-Hiroshima 739-8526, Japan
KEK, High Energy Accelerator Research Organization, Tsukuba, Ibaraki 305-0801, Japan
Kyoto University, Kyoto 606-8502, Japan
Nagasaki Institute of Applied Science, Nagasaki-shi, Nagasaki 851-0193, Japan
RIKEN, The Institute of Physical and Chemical Research, Wako, Saitama 351-0198, Japan
Physics Department, Rikkyo University, 3-34-1 Nishi-Ikebukuro, Toshima, Tokyo 171-8501, Japan
Department of Physics, Tokyo Institute of Technology, Oh-okayama, Meguro, Tokyo 152-8551, Japan
Institute of Physics, University of Tsukuba, Tsukuba, Ibaraki 305, Japan
Chonbuk National University, Jeonju, Korea
Ewha Womans University, Seoul 120-750, Korea
Hanyang University, Seoul 133-792, Korea
KAERI, Cyclotron Application Laboratory, Seoul, South Korea
Korea University, Seoul, 136-701, Korea
Myongji University, Yongin, Kyonggido 449-728, Korea
Department of Physocs and Astronomy, Seoul National University, Seoul, South Korea
Yonsei University, IPAP, Seoul 120-749, Korea
IHEP Protvino, State Research Center of Russian Federation, Institute for High Energy Physics, Protvino, 142281, Russia
Joint Institute for Nuclear Research, 141980 Dubna, Moscow Region, Russia
Russian Research Center "Kurchatov Institute", Moscow, Russia
PNPI, Petersburg Nuclear Physics Institute, Gatchina, Leningrad region, 188300, Russia
Saint Petersburg State Polytechnic University, St. Petersburg, Russia
Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Vorob'evy Gory, Moscow 119992, Russia
Department of Physics, Lund University, Box 118, SE-221 00 Lund, Sweden

PHENIX **14 Countries; 71 Institutions**

Abilene Christian University, Abilene, TX 79699, U.S.
Baruch College, CUNY, New York City, NY 10010-5518, U.S.
Collider-Accelerator Department, Brookhaven National Laboratory, Upton, NY 11973-5000, U.S.
Physics Department, Brookhaven National Laboratory, Upton, NY 11973-5000, U.S.
University of California - Riverside, Riverside, CA 92521, U.S.
University of Colorado, Boulder, CO 80309, U.S.
Columbia University, New York, NY 10027 and Nevis Laboratories, Irvington, NY 10533, U.S.
Florida Institute of Technology, Melbourne, FL 32901, U.S.
Florida State University, Tallahassee, FL 32306, U.S.
Georgia State University, Atlanta, GA 30303, U.S.
University of Illinois at Urbana-Champaign, Urbana, IL 61801, U.S.
Iowa State University, Ames, IA 50011, U.S.
Lawrence Livermore National Laboratory, Livermore, CA 94550, U.S.
Los Alamos National Laboratory, Los Alamos, NM 87545, U.S.
University of Maryland, College Park, MD 20742, U.S.
Department of Physics, University of Massachusetts, Amherst, MA 01003-9337, U.S.
Morgan State University, Baltimore, MD 21251, U.S.
Muhlenberg College, Allentown, PA 18104-5586, U.S.
University of New Mexico, Albuquerque, NM 87131, U.S.
New Mexico State University, Las Cruces, NM 88003, U.S.
Oak Ridge National Laboratory, Oak Ridge, TN 37831, U.S.
Department of Physics and Astronomy, Ohio University, Athens, OH 45701, U.S.
RIKEN BNL Research Center, Brookhaven National Laboratory, Upton, NY 11973-5000, U.S.
Chemistry Department, Stony Brook University,SUNY, Stony Brook, NY 11794-3400, U.S.
Department of Physics and Astronomy, Stony Brook University, SUNY, Stony Brook, NY 11794, U.S.
University of Tennessee, Knoxville, TN 37996, U.S.
Vanderbilt University, Nashville, TN 37235, U.S.

RHIC decadal plan

ALD Steve Vigdor has charged PHENIX and STAR to write decadal plans – submitted in fall 2010.

1. Summarize detector upgrades underway and to be utilized in the next 5 years.

2. Compelling science beyond 5++ years that require additional detector upgrades and machine capabilities.

3. Prioritize the physics and the upgrades above.

4. Discuss the option of an electron beam in the tunnel and thus an ePHENIX and eSTAR in the MeRHIC and EIC era.

5. Discuss the evolution of the collaboration and experimental effort.