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FORMAL REPORT

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Strongly Coupled Plasmas: Electromagnetic, Nuclear & Atomic

December 16 - 17,2004

Organizers:

Barbara Jacak (SUNY, Stony Brook)
Edward Shuryak (SUNY, Stony Brook)
Timothy Hallman (BNL)
Steffen Bass (Duke University / RBRC, BNL)
Ron Davidson (PPPL)

RIKEN BNL Research Center

Building 51OA, Brookhaven National Laboratory, Upton, NY 11973-5000, USA

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Preface to the Series

The RIKEN BNL Research Center (RBRC) was established in April **1997** at Brookhaven National Laboratory. It is funded by the "Rikagaku Kenkyusho" (RIKEN, The Institute of Physical and Chemical Research) of Japan. The Center is dedicated to the study of strong interactions, including spin physics, lattice QCD, and RHIC physics through the nurturing of a new generation of young physicists.

The RBRC has both a theory and experimental component. At present the theoretical group has **4** Fellows and **3** Research Associates as well as **11** RHIC Physics/University Fellows (academic year **2003-2004).** To date there are approximately **30** graduates from the program of which **13** have attained tenure positions at major institutions worldwide. The experimental group is smaller and has **2** Fellows and **3** RHIC Physics/University Fellows and **3** Research Associates, and historically 6 individuals have attained permanent positions.

Beginning in **2001** a new RIKEN Spin Program (RSP) category was implemented at RBRC. These appointments are joint positions of RBRC and RIKEN and include the following positions in theory and experiment: RSP Researchers, RSP Research Associates, and Young Researchers, who are mentored by senior RBRC Scientists. A number of RIKEN Jr. Research Associates and Visiting Scientists also contribute to the physics program at the Center.

RBRC has an active workshop program on strong interaction physics with each workshop focused on a specific physics problem. Each workshop speaker is encouraged to select a few of the most important transparencies from his or her presentation, accompanied by a page of explanation. This material is collected at the end of the workshop by the organizer to form proceedings, which can therefore be available within a short time. To date there are sixty-eight proceeding volumes available.

The construction of a 0.6 teraflops parallel processor, dedicated to lattice QCD, begun at the Center on February **19,1998,** was completed **on** August **28, 1998** and is still operational. A **10** teraflops QCDOC computer in under construction and expected to be completed this year.

N. **P.** Samios, Director
November 2004

***Work performed under the auspices of U.S.D.O.E. Contract No. DE-AC02-98CH10886.**

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Introduction

The Relativistic Heavy Ion Collider (RHIC) was commissioned for heavy ion collisions and for polarized pp collisions in 2001. All principal components of the accelerator chain were operational by the 2003 RHIC run. Approximately 50 papers on RHIC experimental results have been published in refereed journals to date. This is a testament to the vast amount of exciting new information and the unprecedented analysis and publication rate from RHIC. A number of signals of creation of matter at extreme energy density, and of new physics in that matter, have been observed. The RHIC community has been heavily engaged in discussion about these signals, and about the appropriate level of proof for Quark Gluon Plasma discovery at the RHIC. In fact, such discussions were the subject of an earlier RBRC Workshop.

One of the striking results from heavy ion collisions at RHIC is that the quark gluon plasma accessible appears to be strongly coupled. The properties of strongly coupled plasmas are of intense interest in the traditional Plasma Physics community, who have been developing tools to study such matter theoretically and experimentally. Despite the fact that one plasma interacts electromagnetically and the other through the strong interaction, there is tremendous commonality in the intellectual approach and even the theoretical and experimental tools. It is important to broaden the discussion of Quark Gluon Plasma discovery beyond possible signals of deconfinement to also encompass signals of plasma phenomena in heavy ion collisions.

Thus it is imperative establish more direct contact among Nuclear, Plasma and Atomic physicists to share techniques and ideas. RHIC physicists will benefit from familiarity with typical plasma diagnostics and theoretical methods to study strongly coupled plasmas. Plasma and Atomic physicists may find new techniques parallel to the multi-particle correlations used in RHIC data analysis, and theoretical tools to study high energy density matter where the coupling constant is not small.

The goal of this Workshop was to bring together experts at the forefront of theoretical and experimental work on strongly coupled systems in the three communities. From the variety and depth of the presentations at the workshop, we believe that we successfully fostered the exchange of information and ideas. Furthermore, many overlaps and possible exchanges of techniques were identified. Extremely interesting discussions took place, identifying possible avenues for further exchanges and interdisciplinary collaborations.

We are most grateful for the enthusiastic participation in this 2 day Workshop by members of the RHIC, Plasma and Atomic Physics communities. The Workshop would not have been possible without the support of the RIKEN BNL Research Center and National Science Foundation. We thank Brookhaven National Laboratory and the U.S. Department of Energy for providing the facilities for holding this workshop. And, our most sincere thanks go to the RIKEN and BNL administrative staff, especially to Pamela Esposito. Her professional, efficient, and patient work made this Workshop happen.

What is so remarkable about the sQGP discovered at RHIC ?

(strongly coupled Quark Gluon Plasma)

Why are nuclear physicists reading Volume II Of Prof. Ichimaru's Plasma books?

Why are nuclear physicists looking over the shoulders of Prof. Thomson at Liverpool?

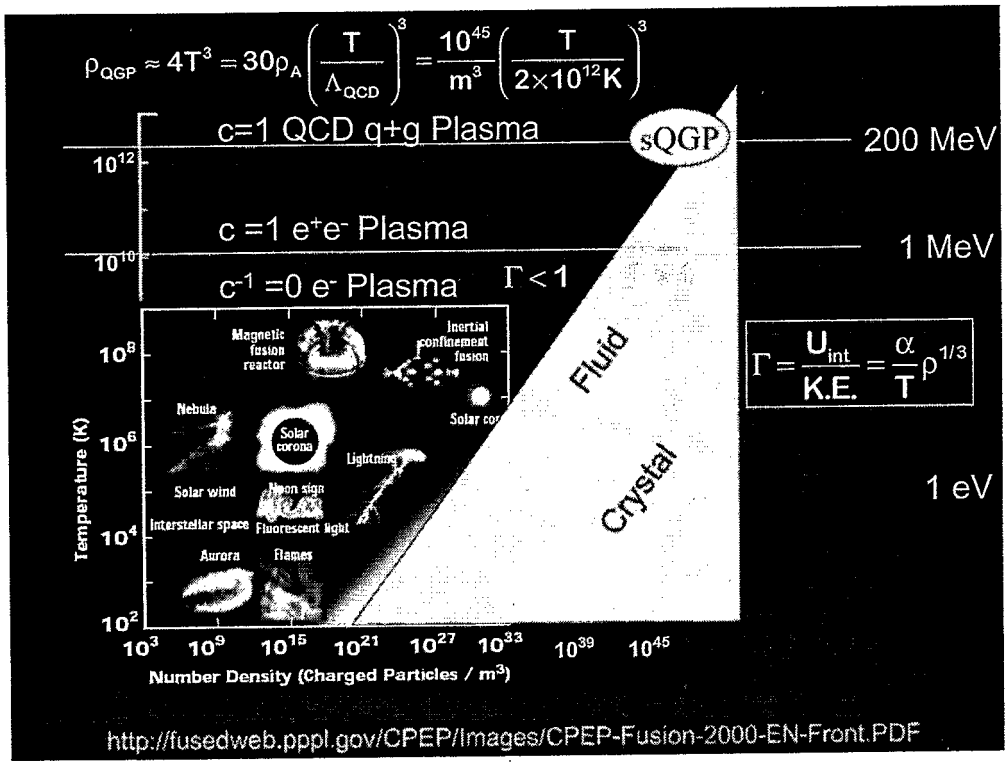
What desperation led them to seek answers In The Elegant adS_5XS_5 Universe ??

See http://nt3.phys.columbia.edu/people/gyulassy/Talks/2004.12.16_RBRC_Plasma/

M.Gyulassy, L. McLerran nucl-th/0405013, Nucl.Phys.A in press

M.Gyulassy: Erice Lectures 8/30/04

http://nt3.phys.columbia.edu/people/gyulassy/Talks/2004.08.30_Erice/



Failure of weak coupling perturbative QCD expansion

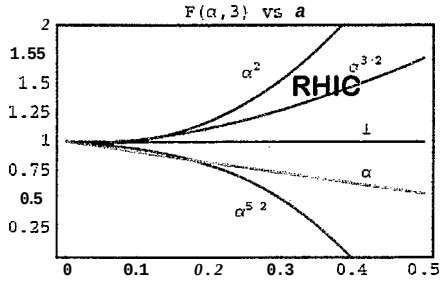
High Temperature QCD Perturbation **Theory**

(E.Braaten and A. Nieto, PRL 76 (96) 1417)
(C.Zhai and B. Kastening, PRD 52 (95) 7232)

Quark – Gluon Plasma Pressure

$$P = \frac{\pi^2}{90} T^4 \left(2_g 8_c + \frac{7}{8} 2_g 3_c 2 n_f\right) F(\alpha, n_f)$$

$$F(\alpha, 3) = 1 - 0.9\alpha + 3.3\alpha^{3/2} + (7.1 + 3.5 \log \alpha)\alpha^2 - 20.8\alpha^{5/2} + (?)\alpha^3 + \ldots$$

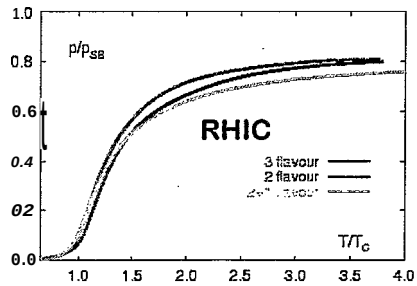


α(T)

Lattice QCD

F.Karsch et al, PLB 478 (00)477
16^6X4 improved gauge and staggered q
$M_{u,b}$~T/4 ,M_s~T

QGP ≠ wQGP



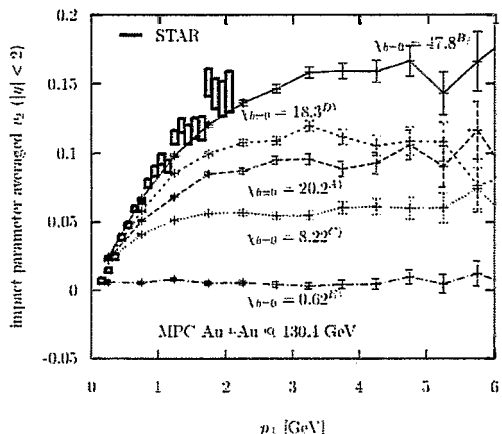
TIT,

Gyuiassy RBRC/BNL 12/16/04

The sQGP must be almost a perfect fluid !

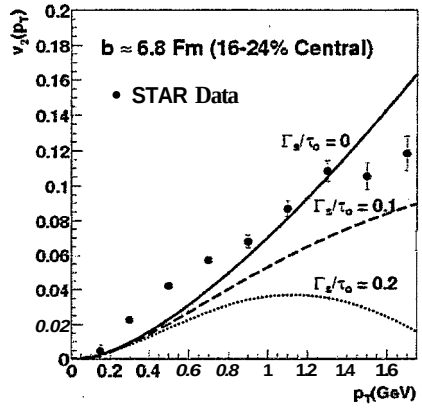
Gluon Transport

D.Molnar, MG (01)



Navier-Stokes

D.Teaney (03)



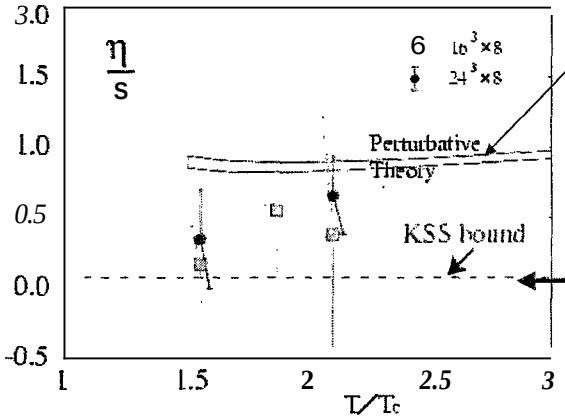
Opacity $\chi = \int d\tau\, \sigma\, \rho \approx \frac{dN_g}{dy} \frac{\sigma_g}{\pi R^2}$ **must be >> pQCD**

Gyulassy RBRC/BNL 12/16/04

Transport coefficients of gluon plasma

Lattice QCD vs pQCD vs N=4 SUSY

Lattice QCD: A.Nakamura and S.Sakai, hep-lat/0406009



P.Arnold et al
JHEP 0305:051,2003

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

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

N=4 SUSY

g^2N_c -> Inf

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

N=4 SUSY: Policastro, Son, Starinets (2001)
Kovtun,Son,Starinets (2004)

pQCD: Danielewics, MG, ... (1985)

Strongly Coupled Plasmas (Ichimaru Vol 2)

Important Role of dynamic correlations at large Γ

$V_i(k) = Z^2 v(k)/\varepsilon_e(k,0)$ represents the Fourier-transformed interionic potential and $\varepsilon_e(k,0)$ static screening function of the electrons, eq. (3.116). They then *evaluated the* shear viscosity η v aid of the collision term in the static LFC approximation, eq. (2.81):

$$\frac{\sigma_{tr}}{T} = \frac{1}{\eta} = \frac{1}{5\pi^2(k_B T)^3}\int_0^\infty dk \int_0^\infty dw \frac{k^3 V_i(k)^2[1 - G_i(k)]}{|\bar{\varepsilon}_i(k,kw)|^2} \exp\left(-\frac{mw^2}{k_B T}\right),$$

where

$$\bar{\varepsilon}_i(k,\omega) = 1 - V_i(k)[1 - G_i(k)]\chi_i^{(0)}(k,\omega)$$

Vol. 1

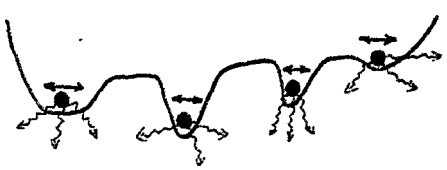
Dielectric screening

and $\chi_i^{(0)}(k,\omega)$ is the free-particle polarizability of the ions, eq. (2.77).

In table 9. we list the computed values of the reduced shear viscosity $\eta^* = \eta/Mn_i\omega_p a^2$

Quasilocalized charge approximation in strongly coupled

Golden, Kalman,
Plas.Phys. 2000



Conclusion Part I:

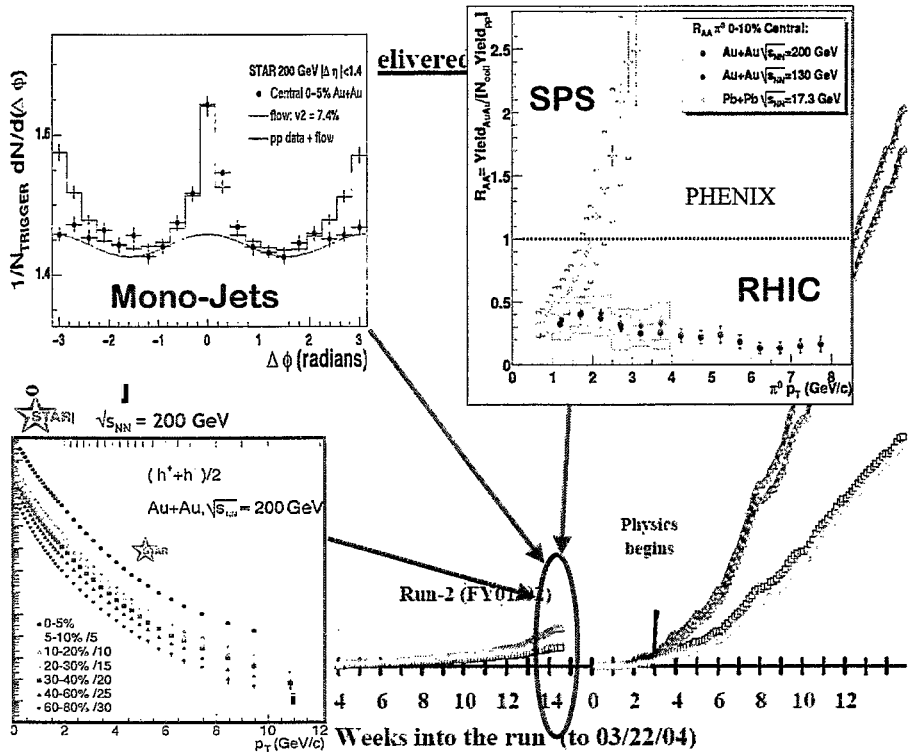
QCD pressure P_{QCD} accounts well for
the fine structure (p_T , m_h) of elliptic flow at RHIC

Even more remarkably, the QGP at $T<3T_c$
Seems to saturate the ***minimal*** viscosity bound!

strongly coupled plasma
sQGP

To understand better the physics we need to study and compare to SCM in other fields

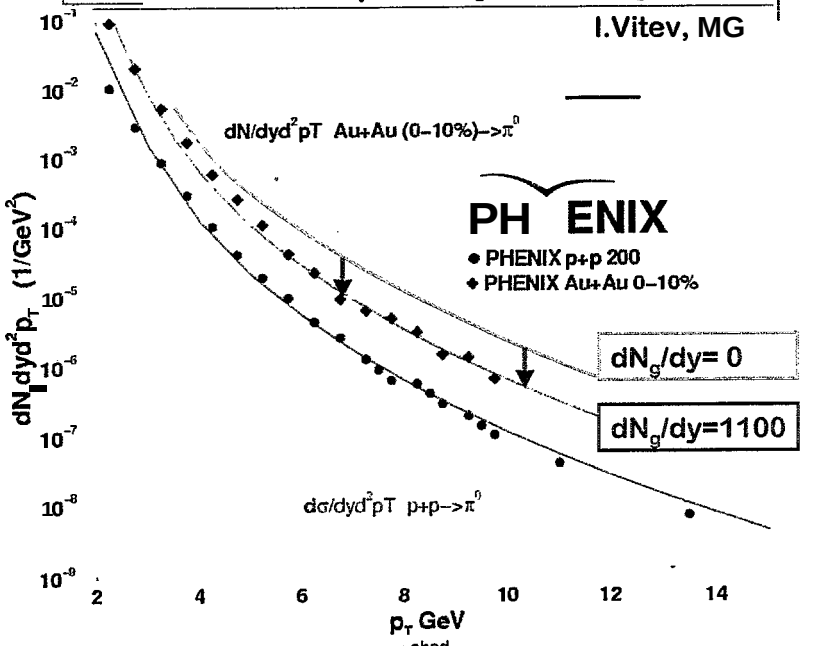
Gyulassy RBRC/BNL **12/16/04**



Absolute scale pQCD jet tomography

I.Vitev, MG

GRV
EKS
BKK
GLV



Gyulassy

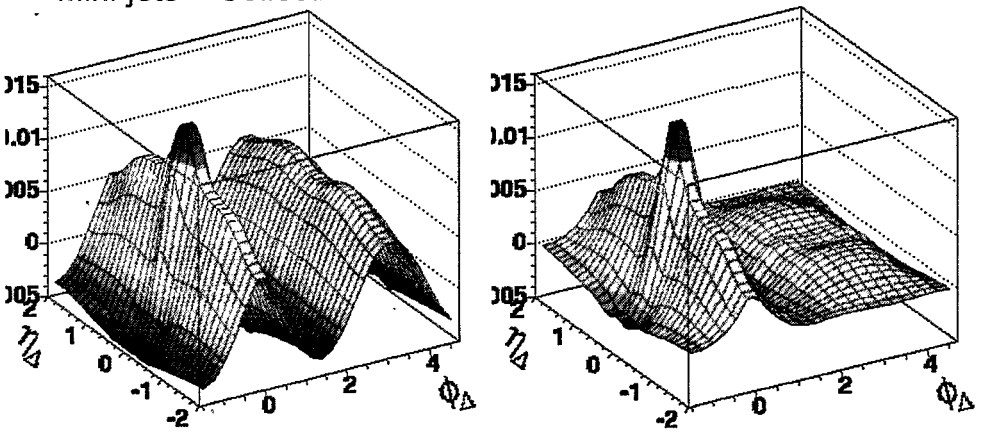
$$dN_{AB\to\pi} = T_{AB} \otimes \left(f_{a/A} \otimes f_{b/B}\right)^{shad}_{\Delta x_T} \otimes d\sigma_{ab\to c} \otimes P(\Delta E) \otimes D_{\pi/c}$$

STAR *Prelim*: p_t Correlations at 200 AGeV

Mid-central Au+Au

Mini-jets + Collective flow

$v_2(y)$ subtracted



New high p_T, rapidity, azimuth correlation tools
M.Daugherity DNP 10/04: Univ. Texas

Gyulassy RBRC/BNL 12/16/04

PHASE TRANSITIONS, TRANSPORT PROCESSES AND DYNAMIC CORRELATION IN STRONGLY COULOMB-COUPLED, ATOMIC PLASMAS

Setsuo Ichimaru

The University of Tokyo, Bunkyo-ku, Tokyo, Japan

Equations of state in various phases of hydrogen matter are evaluated through the dielectric formulation in strong Coulomb coupling as well as by the classical and the quantum-statistical Monte Carlo simulations [1]. The resultant phase diagrams describe phase transitions such as metallization (or ionization), Wigner crystallization and spin-magnetization [2, 3]. We note on the possibility of accounting for the magnetic fields and temperatures observed on the surfaces of magnetic white dwarfs in terms of such a magnetic phase diagram for metallic hydrogen.

A novel theory of dynamic correlation in a viscoelastic one-component plasma (OCP) is developed [4, 5]. Fully convergent kinetic equations are thereby obtained by a fluctuation-theoretic formulation of the collision integrals. A self-consistent solution to the kinetic equations then lead to determination of the dynamic structure factor, $S(k, \omega)$, and the coefficient η of shear viscosity in the ordinary fluid states as well as in the metastable, supercooled states; the results agree with molecular-dynamics simulation data Steep increase in η and the viscoelastic relaxation time, concurrent with appearance of the quasielastic peak in $S(k, \omega)$, implies a possible transition into a glassy state in such a supercooled OCP. Relevance of such a glass transition in laboratory experiments is examined in terms of the lifetimes of metastable states against homogeneous nucleation of a crystalline state.

A cursory remark is made in conjunction with a quark gluon plasma and a color glass condensate with the QCD matter.

[1] See, for example, S. Ichimaru, ***Statistical Plasma Physics. Vol. I: Basic Principles*** (Addison-Wesley, Reading, MA, 1992; Westview, Boulder, CO, 2004); ***Vol. II: Condensed Plasmas*** (Addison-Wesley, Reading, MA, 1994; Westview, Boulder, CO, 2004).

[2] H. Kitamura and S. Ichimaru, J. Phys. Soc. Jpn **67, 950 (1998).**

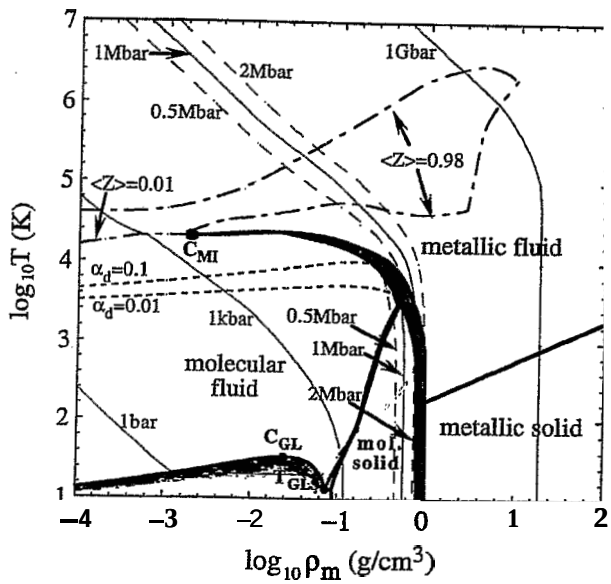
[3] S. Ichimaru, Phys. Plasmas **8**, 48 (2001).

[4] S. Ichimaru and S. Tanaka, Phys. Rev. Lett. **56, 2815** (1986).

[5] S. Tanaka and S. Ichimaru, Phys. Rev. **A 35, 4743 (1987).**

Metal-Insulator Transitions in Hydrogen Matter

H. Kitamura and S. Ichimaru, J. Phys. Soc. Jpn 67, 950 (1998)



C_{MI}

$\rho_m = 0.0019$ g/cm^3

$T = 2.04\times10^4$ K

$P = 3.0$ kbar

Atomic ionization:

$$H \Rightarrow p + e^- - 13.6\,\text{eV}\ (= 1\,\text{Ry})$$

Molecular ionization:

$$H_2 \Rightarrow H_2^+ + e^- - 15.45\,\text{eV}\ (= 1.13\,\text{Ry})$$

Molecular dissociation:

$$H_2 \Rightarrow H + H - 4.447\,\text{eV}\ (= 0.33\,\text{Ry})$$

Molecular-ionic dissociation:

$$H_2^+ \Rightarrow H^+ + p - 2.467\,\text{eV}\ (= 0.18\,\text{Ry})$$

Electronic Screening and Binding Energies

Effective radii, R_b, of bound electrons

Lowering of binding energies $\Leftrightarrow$ Increase in R_b

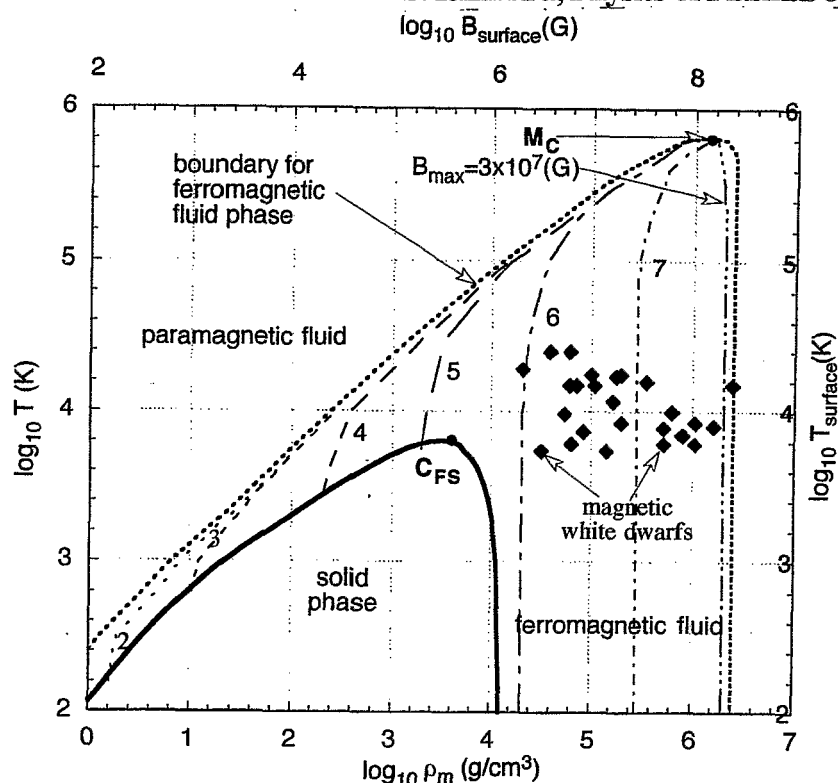
$$f(x) = 1 - 1.9585\,x + 1.2172\,x^2 - 0.24900\,x^3 + 0.012973\,x^4$$

$$f(0) = 1 \qquad f(1.17) = 0$$

$$a/R_b = r_s f(a_B/D_s) = 1, \quad \text{for "pressure ionization"}$$

PHASE DIAGRAM OF METALLIC HYDROGEN AND MAGNETIC WHITE DWARFS

S. Ichimaru, Physics of Plasmas 8, 48 (2001)



	C_{FS}	M_C
ρ_m (g/cm^3)	4.0×10^3	1.4×10^6
R_s	161	22.4
T (K)	6.6×10^3	6.6×10^5
Θ	0.159	0.317
B_M (G)	2.6×10^5	8.0×10^6
Γ_s	517	34.4

strongly coupled degenerate

$B_M = 4\pi\zeta\mu_p n$

($\mu_p = 1.4\times10^{-23}$ erg/G)

Numerals at the dashed and chain curves denote the decimal exponents of B_M in gauss. Diamond markers plot observed surface-field strengths ($B_{surface}$) vs. surface temperatures ($T_{surface}$) for 25 magnetic white dwarfs. [J. Weisheit, in *Elementary Processes in Dense Plasmas :Proc. Oji International Seminar* (eds. S. Ichimaru and S. Ogata) p. 61 (Addison-Wesley, Reading, MA, 1995)]

GENERALIZED VISCOELASTIC THEORY FOR GLASS TRANSITIONS IN STRONGLY COUPLED PLASMAS

S. Ichimaru and S. Tanaka, Phys. Rev. Lett. 56,2815 (1986)

S. Tanaka and S. Ichimaru, Phys. Rev. A 35,4743 (1987)

QUESTION: Can a "glassy plasma" be produced, when a one-component plasma (OCP) is supercooled below a Wigner-transition temperature, sufficiently fast to avoid homogeneous nucleation of crystals?

REMARKS: An OCP is probably a most difficult system to make a glass - - symmetric interaction; point charges; too "elusive" to lock themselves into a glassy state

PURPOSES OF THE STUDY

◊ To develop a theory of dynamic correlation in the strongiy coupled OCP through the generalized viscoelastic formalism, so that the MD simulation results for both $S(\mathbf{k},\omega)$ and η (shear viscosity) are well reproduced.

0 To extend the theory to plasmas in a supercooled, metastable, fluid state ($\Gamma_m \approx 178 < \Gamma < \Gamma_c$ **gt.t. ~10³).**

◊ To analyze a possibility of glass transition, revealed in the formation of a quasi-elastic peak in $S(\mathbf{k},\omega)$.

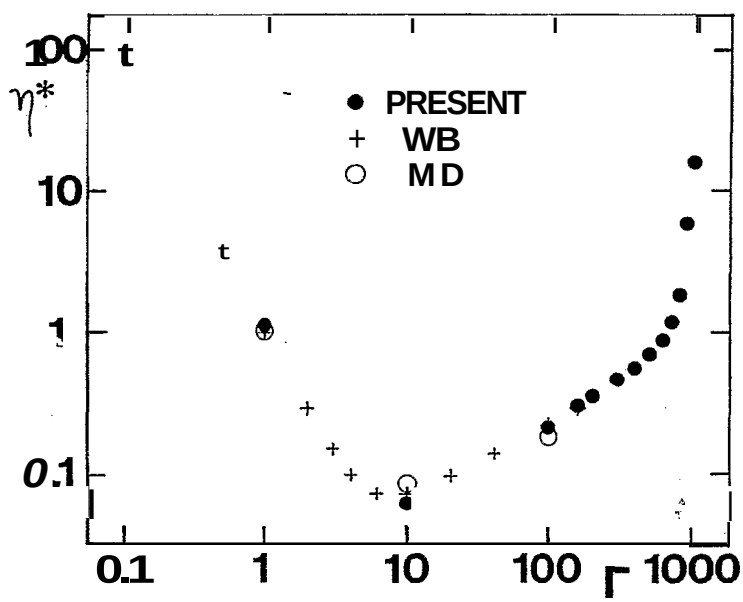
◊ To estimate the lifetime of the metastable fluid in terms of its self-diffusion and the probability of spontaneous nucleation of crystals - rate of "rapid quench" necessary to maintain the glassy state.

6 **To** relate the theory with a possible experiment.

PRINCIPAL RESULTS

◊ Shear viscosity η in supercooled OCP fluids

$$\eta^* \equiv \eta / mn\omega_p a^2 \qquad \omega_p = \sqrt{4\pi n (Ze)^2/m}$$



◊ If a Penning-trapped, non-neutral $^9Be^+$ plasma at $n \approx 10^{10}$ cm^{-3} is laser-cooled to $\Gamma = 900 - 1000$, within a time scale of $2 \times (10 - 10^5)$ sec, the resulting state will be a glass rather than a crystal.

	ATOMIC PLASMAS	QCD MATTER
incoherent thermal limit at high temperatures	IONOZED GAS	Quark Gluon Plasma (QGP)
⇓	{increase in viscosity}	
lowering temperature and/or increase in density	FLUID METALLIC HYDROGEN	
{increase in coupling)	$\Gamma = e^2(4\pi n/3)^{1/3}/k_B T$	
⇓	{increase in viscoelasticity}	
⇓	{glassy state and crystalline nucleation).	
coherent limit at high densities (energies)	SOLID METALLIC HYDROGEN	Color Glass Condensate ? (CGC)

Quark-Gluon Plasma and Lattice QCD

T. Hatsuda (Univ. Tokyo)

1. Progress in lattice QCD
   - equation of state of hot plasma
   - static and dynamic correlations -> strongly coupled plasma ?

2. Need to be done
   - full QCD for small m, small a and large L
   - full QCD for dynamic correlations
     (viscosity, colored bound states etc)

3. Computer resources
   - massive computers (>10Tflops) + sharing lattice data
     (see, Lattice QCD simulations via International Research Network,
     Sep. 21-24, 2004, http://www.rccp.tsukuba.ac.jp/workshop/ilft04/)

4. Need new ideas
   - cold degenerate plasma
   - far from equilibrium
   - ideas to and from QED plasma and atomic condensates

QGP for $g \ll 1$ ($T \gg 100$ GeV)

Relativistic plasma :

$$n \sim T^3 \;\rightarrow\; r \sim 1/T$$

$$\lambda_{\rm d} \sim 1/T, \quad \lambda_{\rm D} \sim 1/(gT)$$

$$\frac{1}{T} \ll \frac{1}{gT} \ll \frac{1}{g^2 T}$$

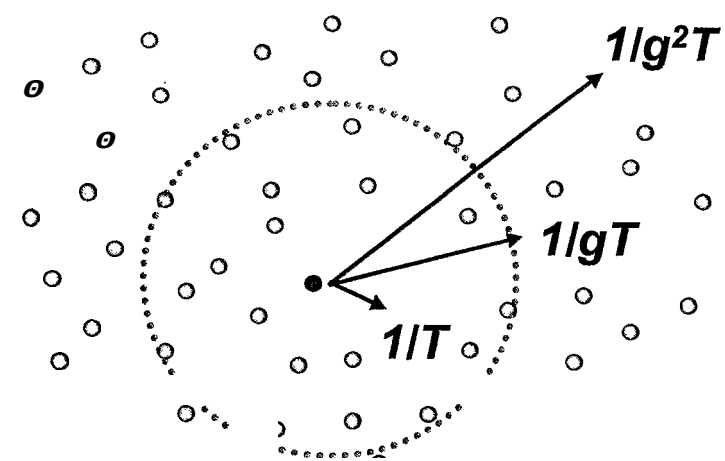
Inter-particle distance | Electric screening | Magnetic screening

Debye number :

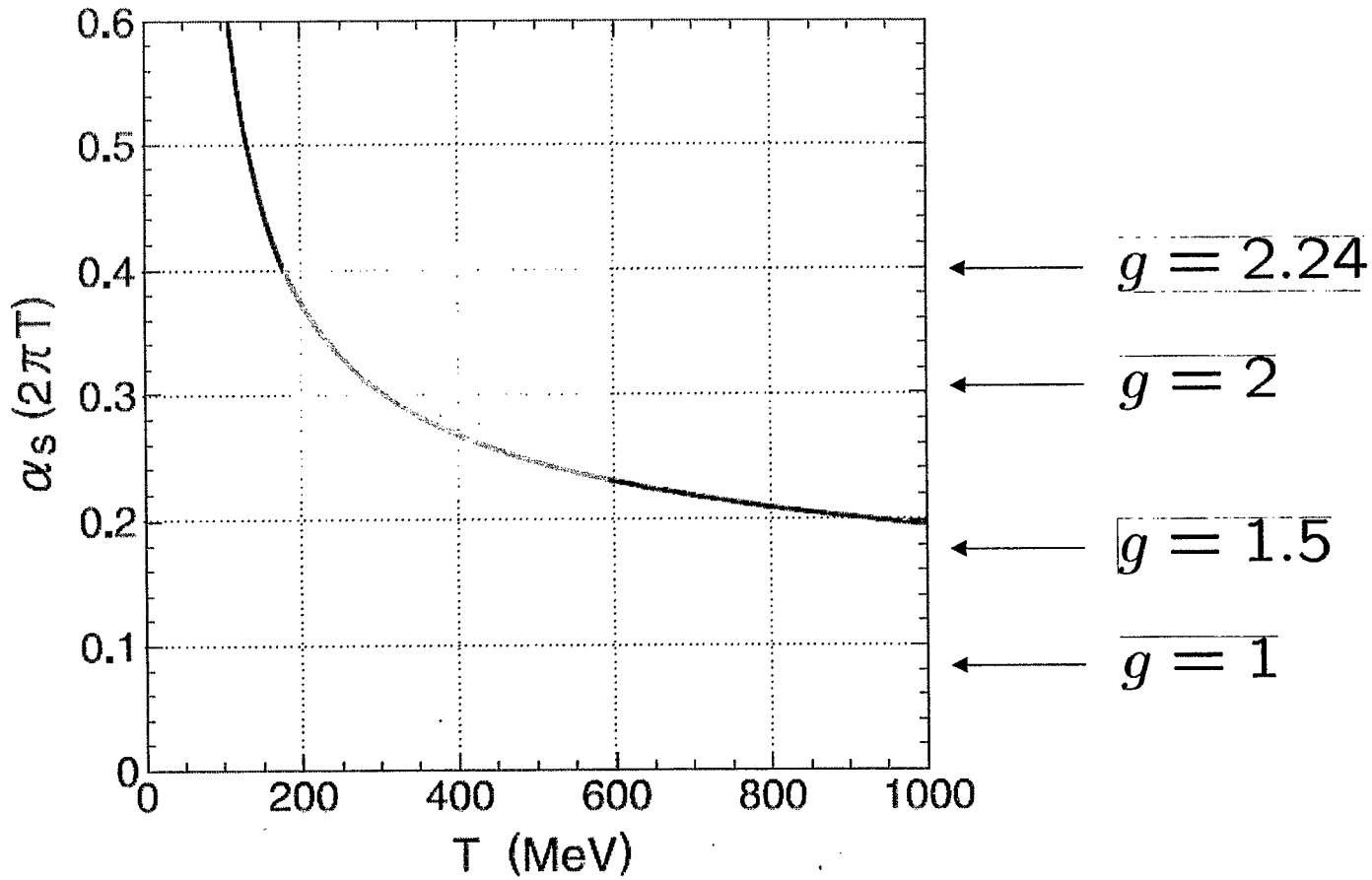
$$N_{\rm D} = \frac{4\pi}{3}\lambda_{\rm D}^3 n \sim (2/g)^3$$

"Coulomb" coupling parameter :

$$\Gamma = \frac{\text{Coulomb}}{\text{Kinetic}} \sim \frac{\alpha_s T}{T} = \frac{g^2}{4\pi}$$



S. Ichimaru, Rev. Mod. Phys. 54 ('82) 1071



1. Strong coupling problem

g ~ 2 for T=200-400 MeV → badly behaved perturbation series

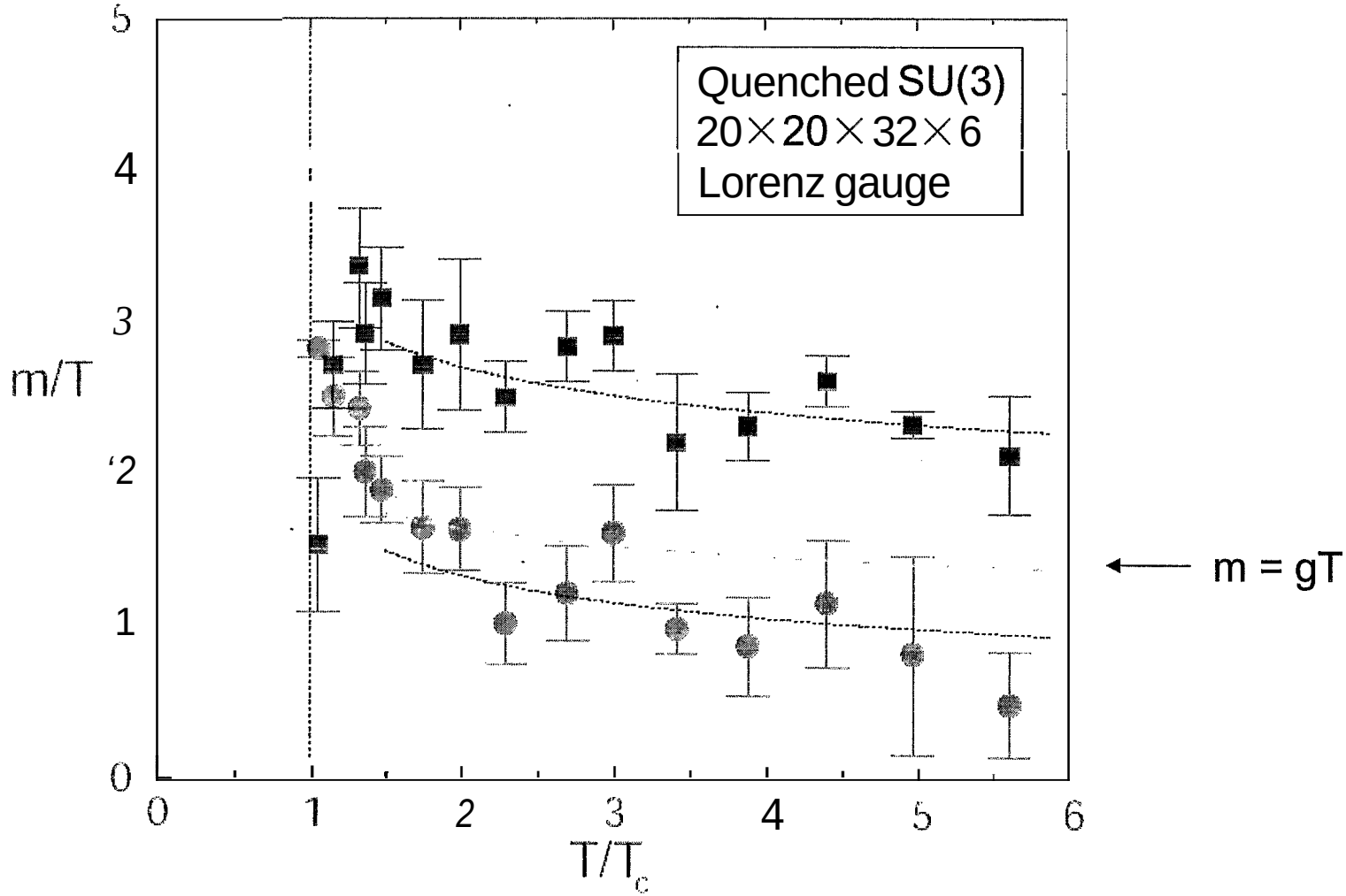
2. Non-Abelian magnetic problem

soft magnetic gluons are always non-perturbativeeven if g → 0

→ ~~pertubation theory~~

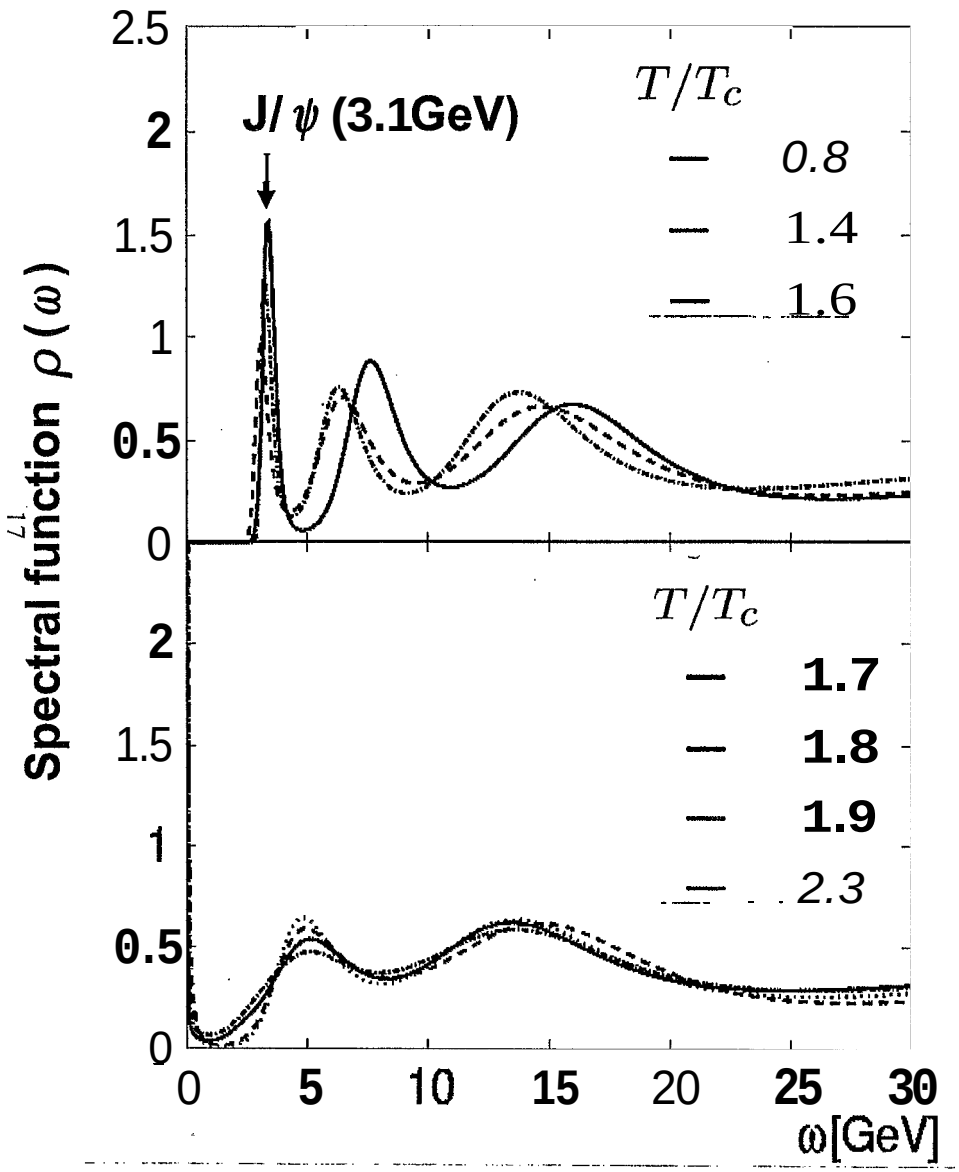
Screening masses at $T>T_c$ (quenched)

$$\langle A_\mu(\mathbf{x}) A_\nu(\mathbf{0}) \rangle \sim e^{-m|\mathbf{x}|}$$



Nakamura, Saito & Sakai, Phys.Rev.D69 ('04) 014506

$c\bar{c}$ bound state above T_c (quenched)



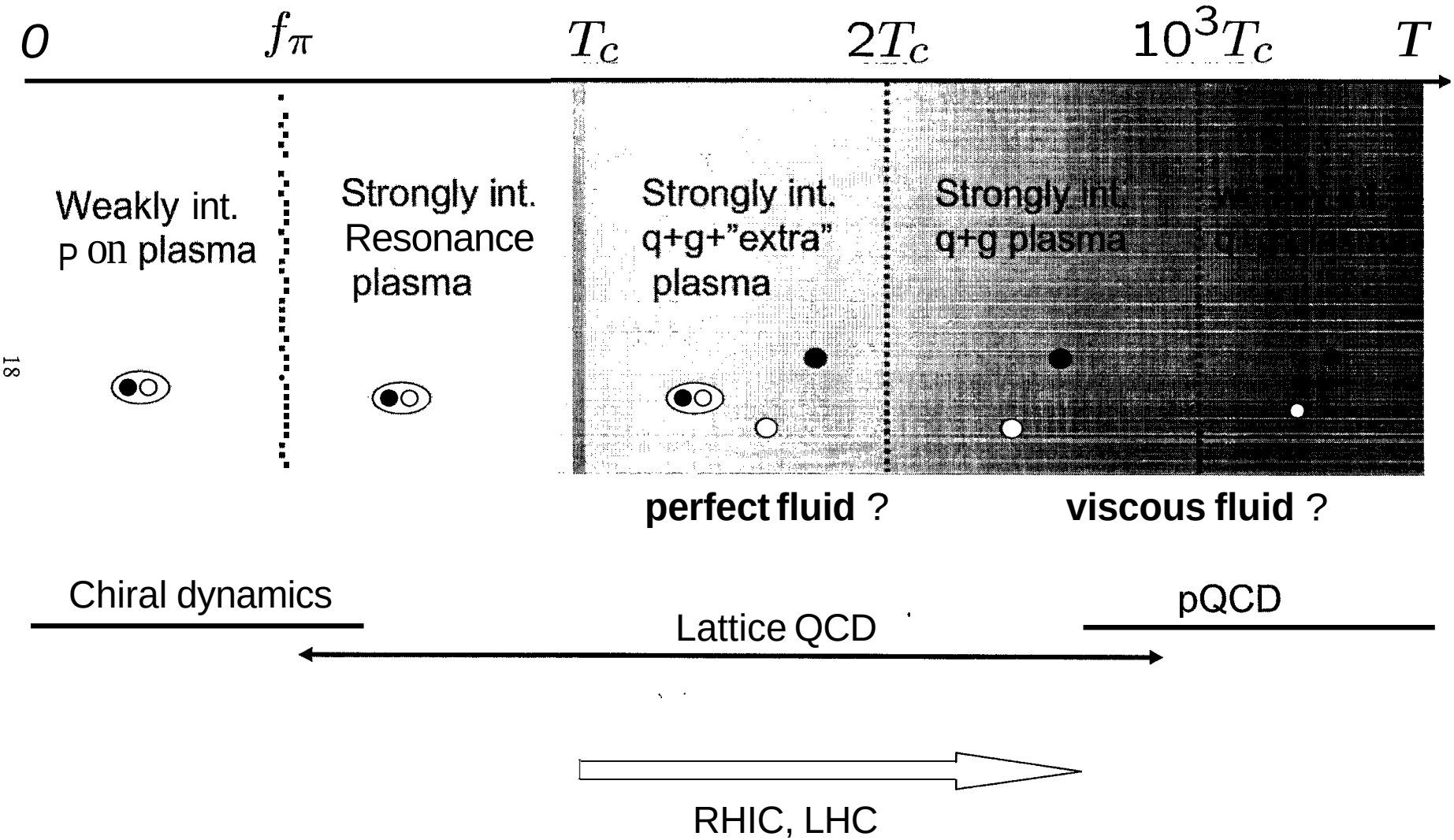
1. J/ψ survives up to 1.6 T_c

2. J/ψ disappears in 1.6 T_c < T < 1.7 T_c

Asakawa & T.H., PRL 92 ('04) 012001

see also,
Umeda et al, hep-lat/0401010
Datta et al., PRD 69 ('04) 094507

Possible hierarchy of QCD plasma



Heavy Ion Collisions as "QGP" Probes – Mark D. Baker – BNL

16 December, 2004

The strong force, governed by Quantum Chromodynamics (QCD), is an important, fundamental force, and is responsible for **99%** of the visible mass in the universe since only about 1% of the mass of normal nuclear matter is due to the Higgs coupling with up and down "current" quarks. The rest is due to confinement and chiral symmetry breaking. At temperatures of around $2x10^{12}$ degrees **K,** normal nuclear and hadronic matter is expected to give way to a deconfined state of matter known as the "Quark Gluon Plasma" (QGP). We attempt to create this matter at the Relativistic Heavy Ion Collider **(RHIC)** at Brookhaven National Laboratory **(BNL)** and study it using two large detectors: PHENIX and STAR, and two small detectors: BRAHMS and PHOBOS.

Slide 1A shows some characteristics of our "plasma experiments. These heavy ion collisions typically occur at a rate of **–9** kHz, with each collision creating matter that lasts for 10s of yoctoseconds (1 ys = 10^{-24} s). A head-on heavy ion collision creates up to 5000 charged particles as shown in slide 1B.

In addition to the large number of particles, we know that we have created bulk matter because we see evidence of pressure in the system. The strongest evidence is the strength **of** the azimuthal asymmetry, known **as** elliptic flow, and characterized by $v_2=\langle\cos 2(\phi-\phi_R)\rangle$, where ϕ is the azimuthal angle around the beam-collision axis, z, and ϕ_R is the reaction plane. This can be seen in slides 2A-2B. Describing this asymmetry requires ideal or almost-ideal hydrodynamics or an anomalously high cross-section in a partonic cascade. Further evidence of rapid expansion (pressure) can be found in the particle spectra and correlations. This matter can be characterized at (chemical) freezeout by a single temperature of **176** MeV (or $2x10^{12}$ degrees K) **as** can be seen in slide 3A.

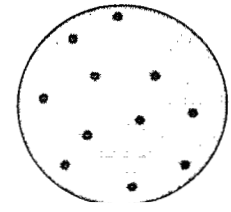
Freezeout only occurs after some cooling of the system. We can also estimate the energy density of this matter (not shown) to be 5-25 GeV/fm^3. Slide 3B shows where this matter falls on the theoretical energy density vs. temperature curve and allows us to estimate the initial temperature of the matter at 250-350 MeV, solidly above the critical temperature. Slides 4A and 4B show where the matter created at RHIC falls in T,μ_B and T,ρ planes: dramatically hotter and denser than any other known plasmas.

Slides 5A and 5B show the evidence that the medium is very dense and is opaque when probed by high momentum partons produced in the initial collision. Instead of back-to-back jets from the entire volume, this matter only emits single jets from the surface.

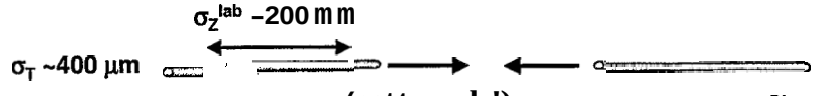
Based on all of this evidence, and accepting input from various approximate solutions to QCD, the simplest explanation is that we have formed **a** deconfined state of matter, which could perhaps be called a "QGP". Further theoretical work and experimental study is needed to overconstrain and really test QCD as well as understanding the nature of this matter.

Bunch-bunch collisions

- Crossings occur at 9 MHz ("shot frequency")
  - 120 x c/(3.83 km)
- Typically (99.9%) nothing happens!
  - 10^9 ions spread out over ~ $\pi(400\mu m)^2$
    - a_{2D} ~ 12 nm = 12 x 10^6 fm
    - d_{Au} ~ 14 fm
  - $10^9 * (d_{Au}/a_{2D})^2 = 10^9 * (10^{-6})^2 = 10^{-3}$
- Collisions at ~ 9 kHz

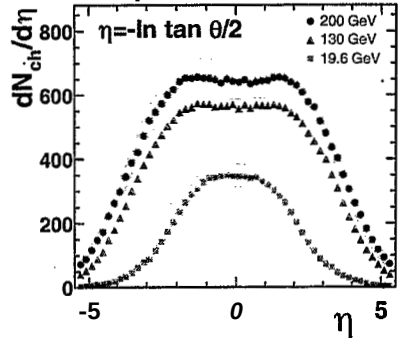


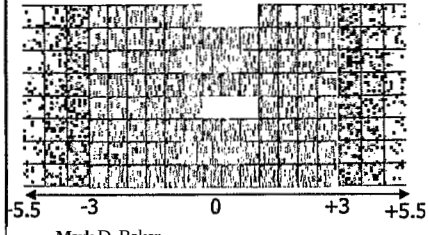
(not to scale!)



(not to scale!)

How many produced particles?





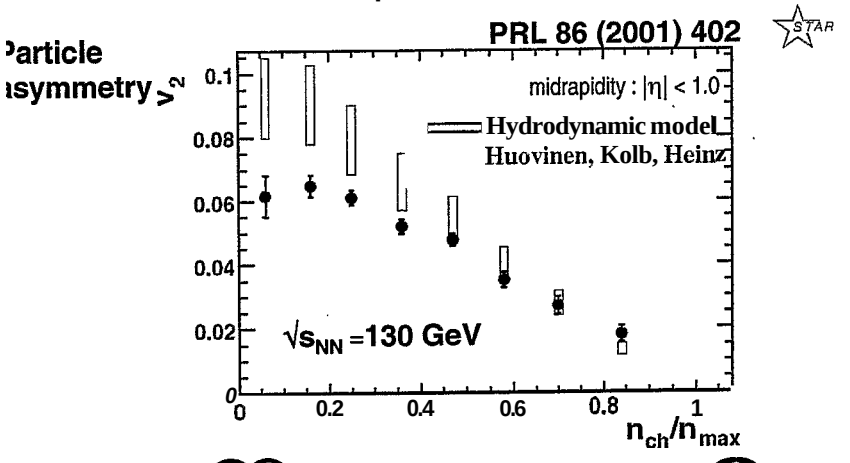
# of charged particles (central collision):

5060±250 @ 200 GeV

4170±210 @ 130 GeV

1680±100 @ 19.6 GeV

Elliptic Flow



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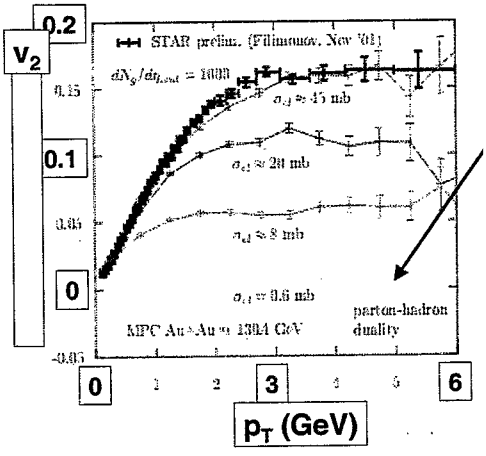
Strongly Coupled Plasmas

Need large σ to describe v_2



Second clue!

Parton cascade using free q,g scattering cross sections underpredicts pressure

Must use hydrodynamics OR very high cross-sections in cascade.

D Molnar, ISMD 2001, arXiv:hep-ph/0111401

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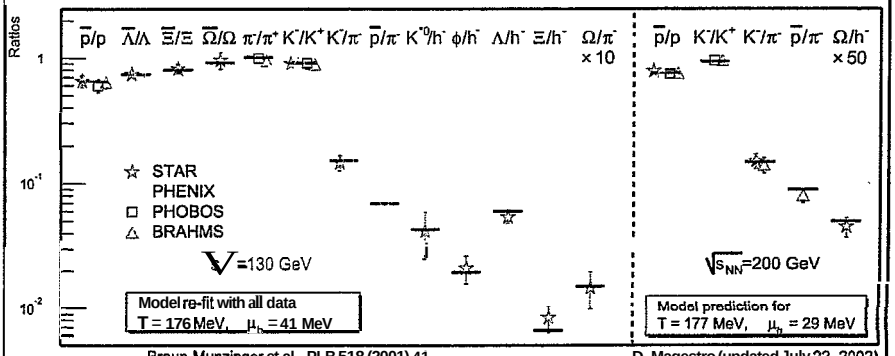
Strongly Coupled Plasmas

Thermometer II: Particle Ratios



Braun-Munzinger et al., PLB 518 (2001) 41

D. Magestro (updated July 22, 2002)

130 GeV: T ~ 176 MeV

200 GeV: T ~ 177 MeV
μ_b ~ 29 MeV

176 MeV ≠110!

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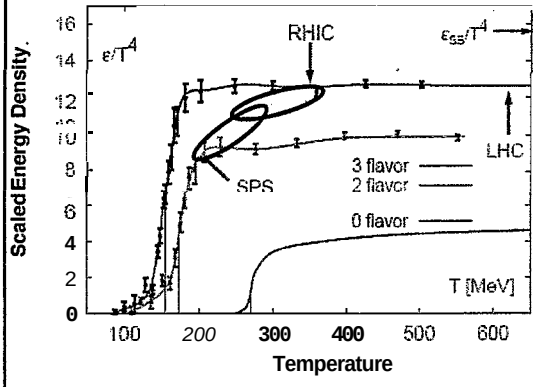
Strongly Coupled Plasmas

Use Lattice QCD

$$\varepsilon(T) \Rightarrow T(\varepsilon)$$



CERN **SPS** (√s = **17** GeV)
ε_i ~ 2-10 GeV/fm³
T_i ~ 190-290 MeV

BNL **RHIC** (√s = **200** GeV)
ε_i ~ 5-25 GeV/fm³
T_i ~ 250-350 MeV

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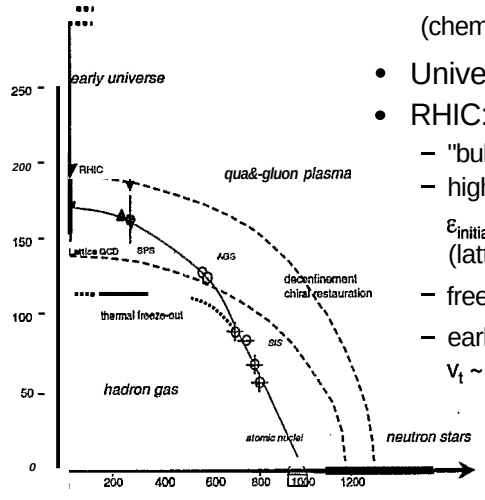
Strongly Coupled Plasmas

Putting it all together



(chemical freezeout)

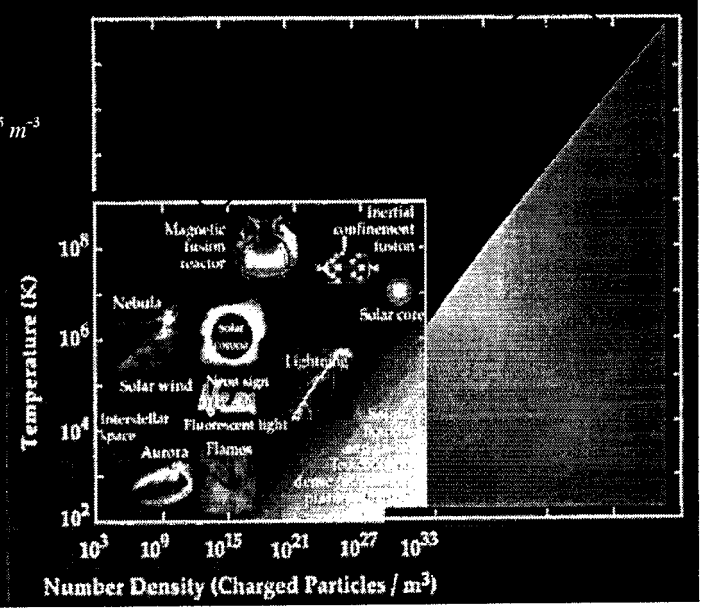
- Universal curve!
- RHIC:
  - "bulk" matter
  - high energy density
    $\varepsilon_{initial}$ ~ 5-25 GeV/fm^3
    (lattice⇒ T_i>250 MeV)
  - freezeout near T_C
  - early collective expansion
    v_t ~ 0.65 c

Mark *D.* Baker

Strongly Coupled **Plasmas**

Plasmas - The 4th State of Matter

$n(T) = 3.6T^3$
(200MeVfm=1),
$T = 200-400$MeV
$\Rightarrow n(T) \sim 4-30\times10^{45}\ m^{-3}$

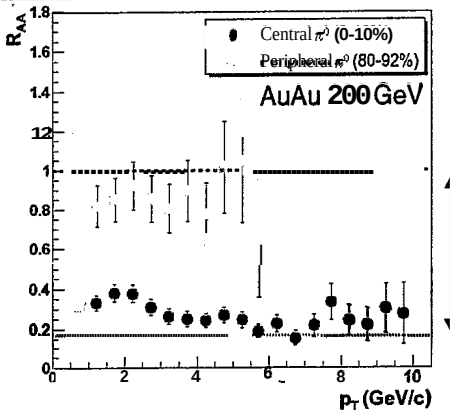


High p_T particles are suppressed!

PRL91, 072301(2003)

PHENIX

$$R_{AA} = \frac{Yield_{AuAu}/\langle N_{binary}\rangle_{AuAu}}{Yield_{pp}}$$



Proportional to the density of scattering centers (gluons)
$\rightarrow dN_g/dy$ –1000

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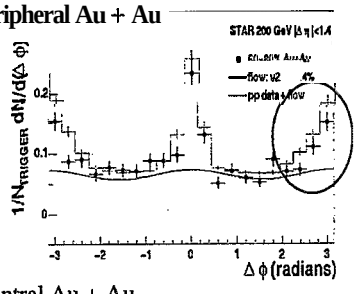
Strongly Coupled Plasmas

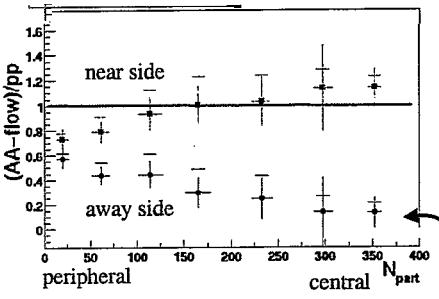
Look for the jet on the other side

Peripheral Au + Au

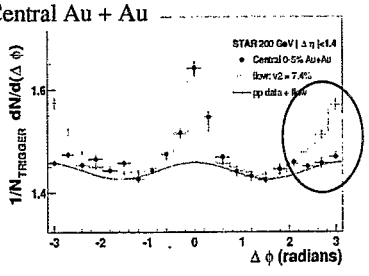
STAR PRL *90,082302* (2003)



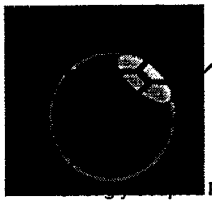
$$D_2(Au+Au) = D_2(p+p) + B(1+v_2^2\cos(2\Delta\phi))$$



Central Au + Au



Medium is opaque!



Mark D. Baker

Plasmas

High Energy Density Physics Experiments with Terawatt to Petawatt Ultrafast, High Intensity Lasers

Presented by:

Todd Ditmire

The Texas Center for High Intensity Laser Science

Department of Physics
University of Texas at Austin

Grad students:
Aaron Edens
Jens Osterhoff
Will Grigsby
Gilliss Dyer
Ariel Surneruk
Alex Maltsev
Greg Hays
Irina Churina
Byong-Ick Cho
Parrish Brady
Rene Hartke
Matthias Hohenberger
Allan Dalton
Brendan Murphy
Robert Morgan
Andreas Henig
Stephan Kneip
Matt Lane

Post ***Docs:***
Kay Hofiman
Dan Symes
Alexy Arefiev (theory)

Undergrad Students;
Michael Garrity
Shawn Alverson
Gaurav Bansal
Jamie Landry
Mark Wu

Petawatt Team
Erhard Gaul
Mike Martinez
Skyler Douglas
Dan Gorski
Jay Campbell
Keith Carter
Watson Henderson

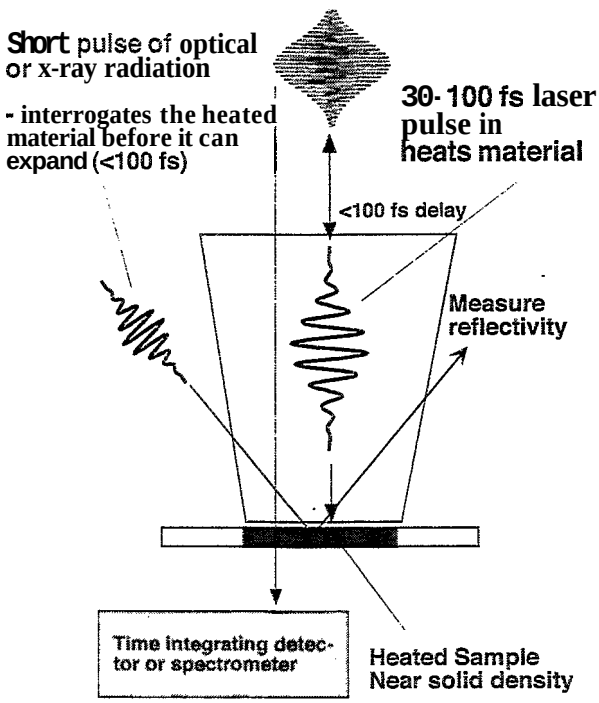
Participating UT Faculty and Senior Scientists:
Boris Breizman
Prashant Valanju
Mike Downer
Roger Bengtson
Michael Marder (CNLD)
Eric Taleff (Mech Eng)
Stephan Bless (IAT)
Richard Hazeltine (IFS)
Charles Chiu
Wendell Horton (IFS)
Richard Fitzpatrick (IFS)
John Keto

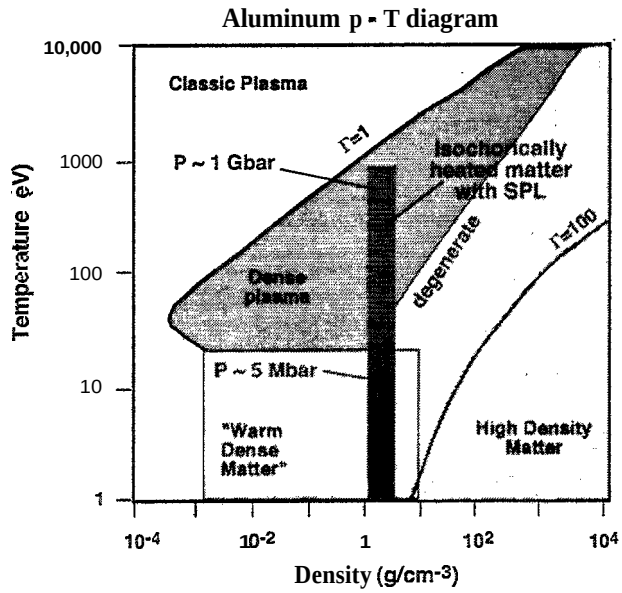
Lawrence Livermore Nat Lab
John Edwards, Freddy Hansen, Prav ***Patel,*** Dwight Price
Bruce Remington, Dick Lee, Jeff ***Colvin***
with additional contributions from Mike Key and Klaus Widmann

Sandia National Lab
John ***Porter,*** Richard Adams, Larry ***Ruggles, Ian*** Smith, Patrick ***Rambo***

FOCUS Frontier Center, U. of Michigan
Tolya Maksimchuk, Victor Yanovsky, Don ***Umstadter, Gerard Mourou***

A short pulse laser can isochorically heat materials to high temperature and pressure



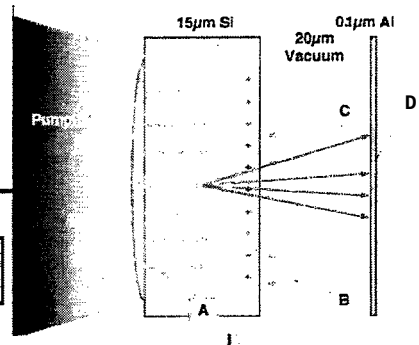


Target expands $\sim d/c_s$
$\sim$ 10 nm/ 5 x 10^6 cm/s (for 100 eV Al)
$\sim$ 200 fs

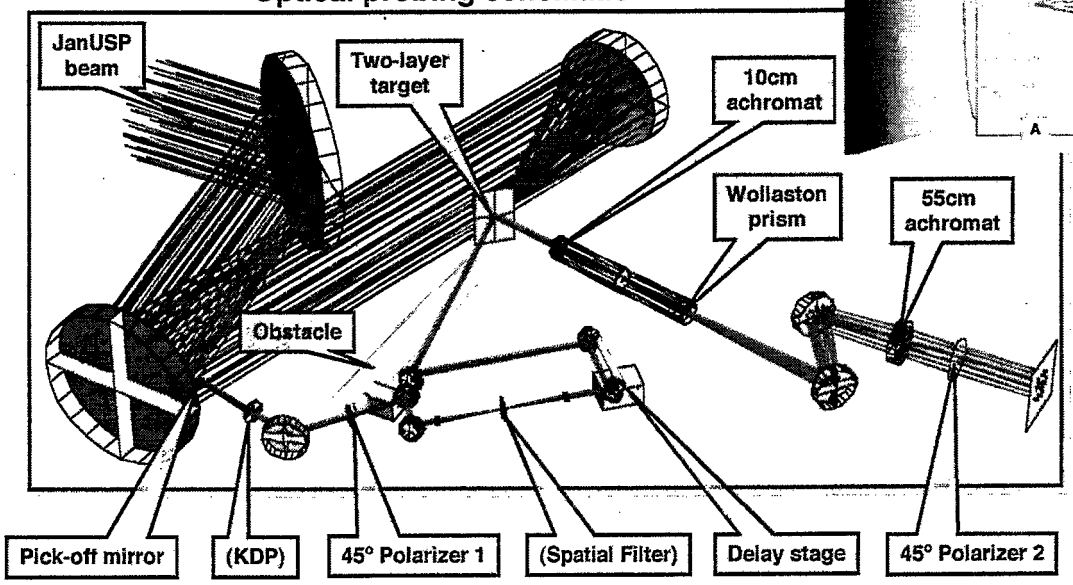
We probe Si K-alpha heating of Al with reflectivity and interferometry

Principal diagnostics include:
Optical probe
X-ray pinhole camera
X-ray CCD as single photon counting spec.
Proton sensitive film

Target Design

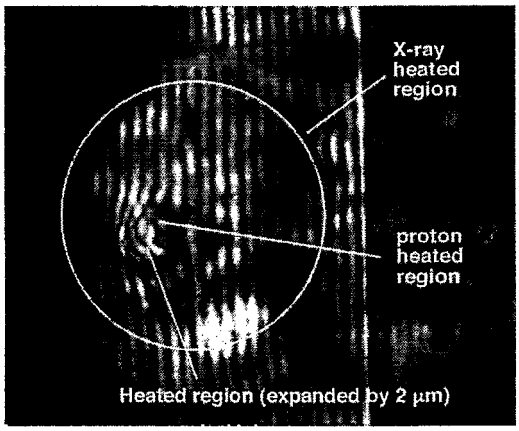


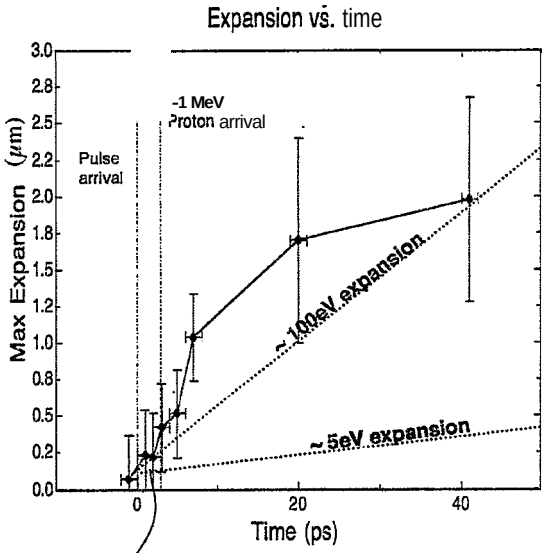
Optical probing schematic



We have observed expansion and reflectivity changes of X-ray heated Al

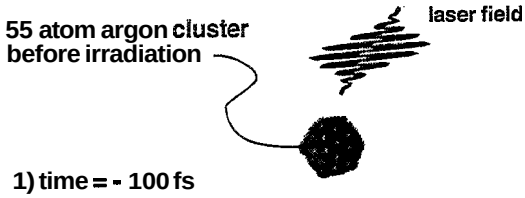
Interferometry image at 40 ps after x-ray irradiation



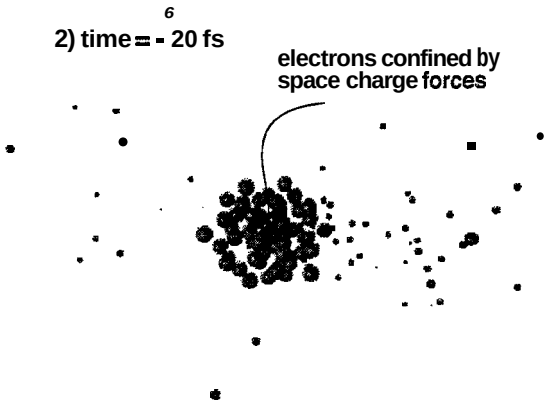


Initial slow expansion is from x-ray pulse arrival

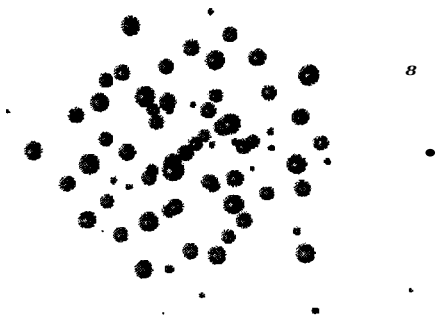
A cluster irradiated by an intense fs laser creates a microplasma which explodes after excitation



Simulation with $I = 10^{16}$ W/cm^2
$\Delta\tau = 50$ fs

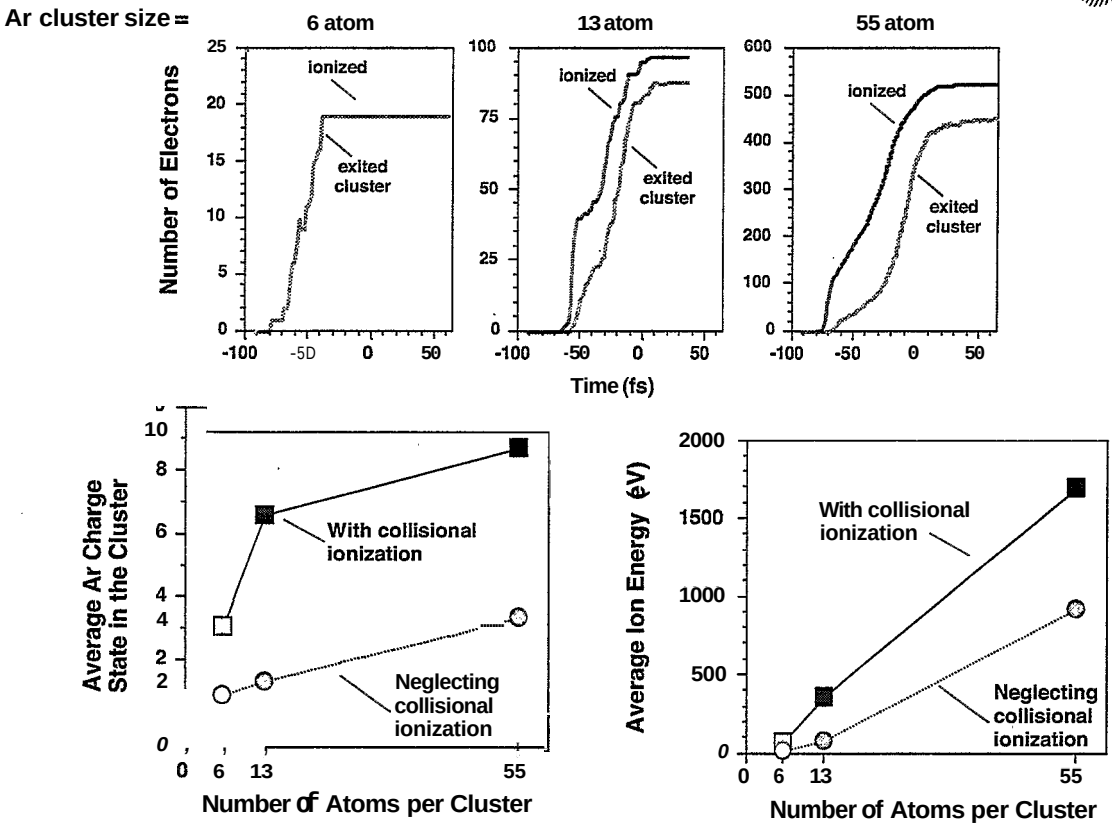


Laser field begins to heat and expel electrons from cluster



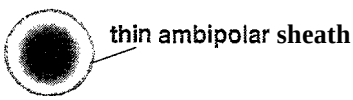
ions explode by Coulomb farces

Simulations indicate that space-charge forces retain electrons within the cluster when the size increases



The explosion of a cluster irradiated at high intensity can often be described by one of two simple models

Hydrodynamic expansion

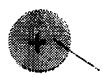


neutral region
charged region

$f(E)dE \sim E^{-1/2}\, e^{-(6E/kT_e)}$

(asymptotic region for a spheri-cat, isothermal expansion)

Coulomb expansion

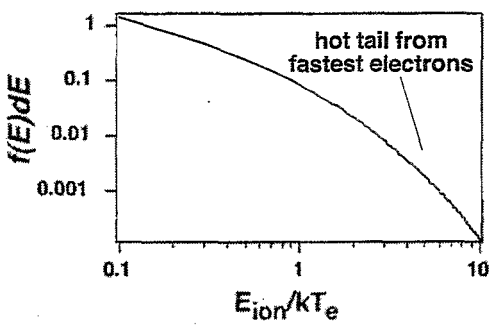


positively charged sphere
with radius r and initial density n

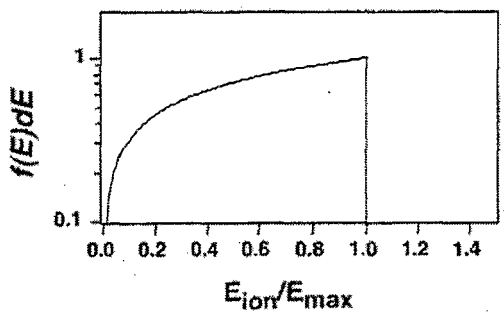
$f(E)dE \sim E^{1/2}\, dE \qquad E<E_{max}$

$E_{max} = (ne^2/3\varepsilon_0)\, r^2$

Hydro expansion reflects electron energy distribution

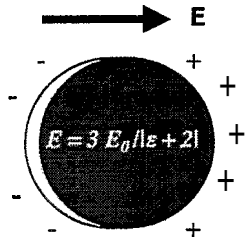


Coulomb expansion reflects only the ion spatial distribution



Collective behavior of the confined electron cloud is important in the laser cluster interaction

We can calculate the natural frequency of a cluster by looking at the response when two solid charge spheres are displaced a small distance x and released



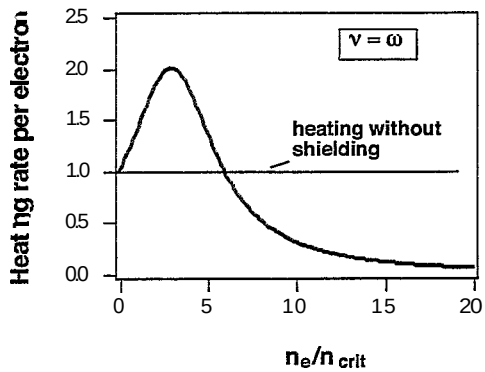
$$E_x = \frac{4\pi e n_e}{3} x$$

$$\frac{d^2x}{dt^2} + \frac{4\pi e^2 n_e}{3m_e} x = 0$$

The solutions to this equation are oscillatory with frequency

$$\omega_{cp} = \sqrt{\frac{4\pi n_e e^2}{3m_e}} = \frac{\omega_p}{\sqrt{3}}$$

The cluster microplasma exhibits a "giant resonance" akin to the giant resonance in nuclear physics

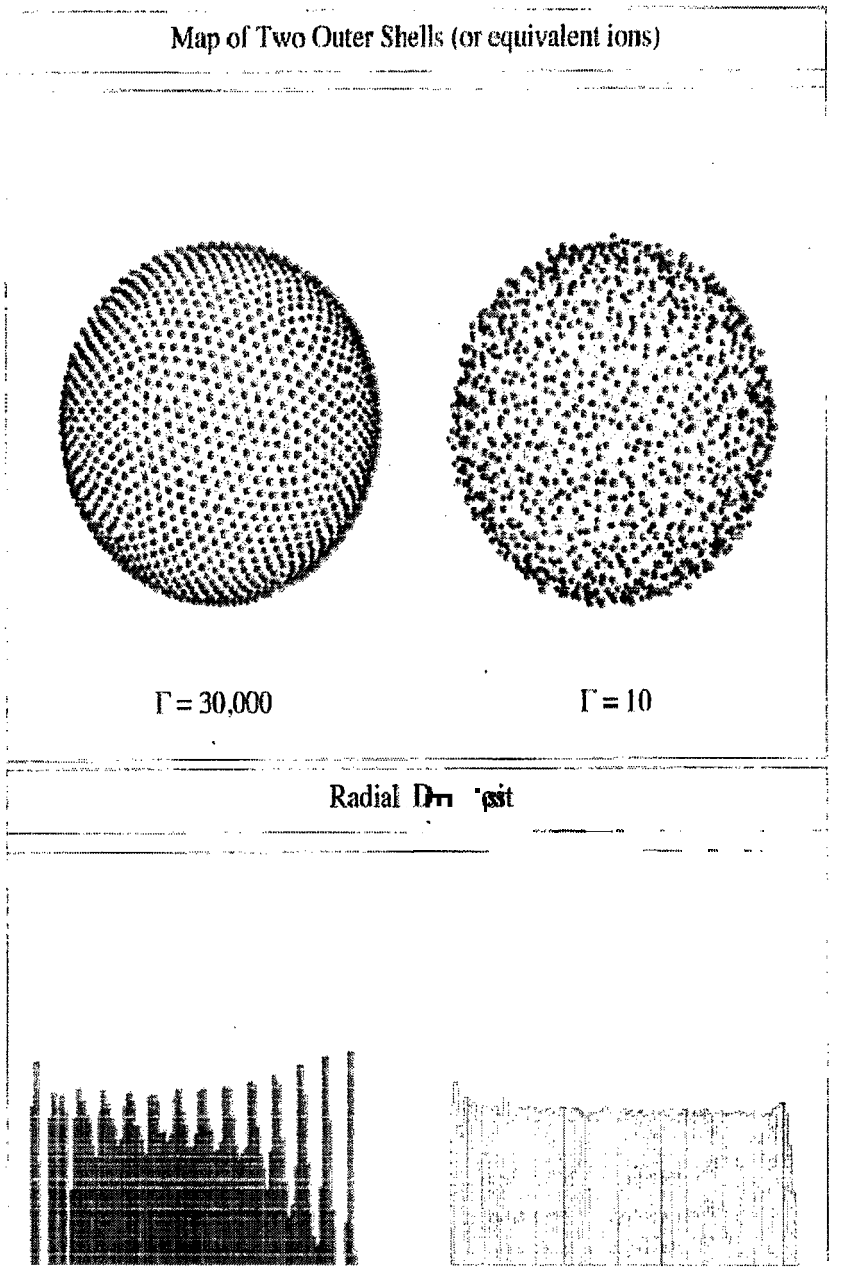


Siiiiulations of Cold, Confined, One-Component Plasmas

John Schiffer, Physics Division, Argonne Nat'l Lab.

Past and current work on simulations of classical one-component plasmas, confined in devices such as ion traps or accelerator storage rings will be summarized. Topics include

- The forms of ordering in cold systems from few particles to many, including the evolution shell structure.
- Dimensional phase transitions induced by the nature of the environment, from one-dimensional systems to two and three, including ordered ion beams.
- The phase transition and latent heat from liquid to solid state for finite systems.
- Systems confined in rf fields, such as quadrupole traps and the concept of temperature in such systems.
- **A** recent attempt at exploring the properties of a cold, confined one-component plasma with a ***logarithmic*** potential shows some similarities and some differences compared to a Coulomb plasma.



For harmonic confinement in 3 dimensions, the density in the interior of a cold plasma cloud is uniform.

At the surface of the cloud

$F_{conf.} = -KR, \quad F_{coul} = N q^2/R^2$

so that

$R = (Nq^2/K)^{1/3}$

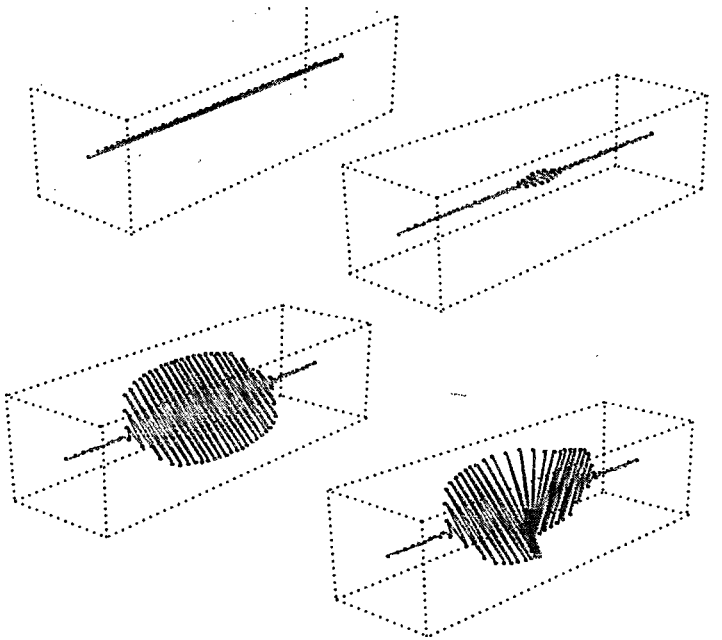
The density is not uniform if

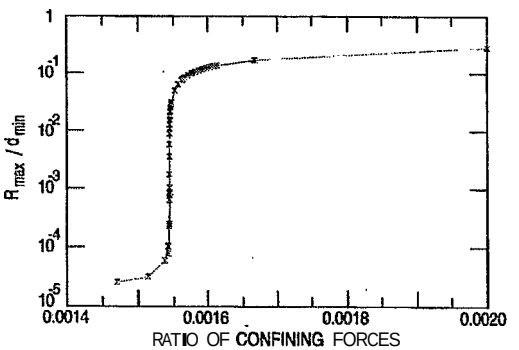
- the confining force is not harmonic,
- the system is confined to fewer than 3 dimensions,
- the force is not Coulomb.

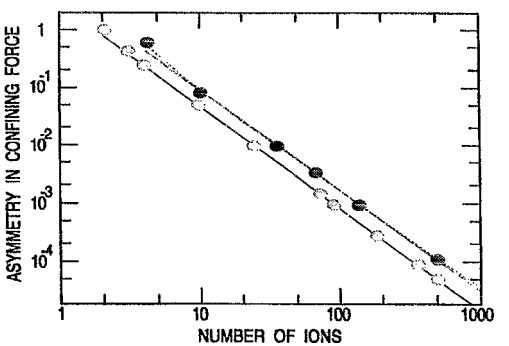
Phase Transitions in Anisotropically Confined Ionic Crystals

J. P. Schiffer
Physics Division, Argonne National Laboratory, Argonne, Illinois 60439
and The University of Chicago, Chicago, Illinois 60637
(Received 17 September 1992)

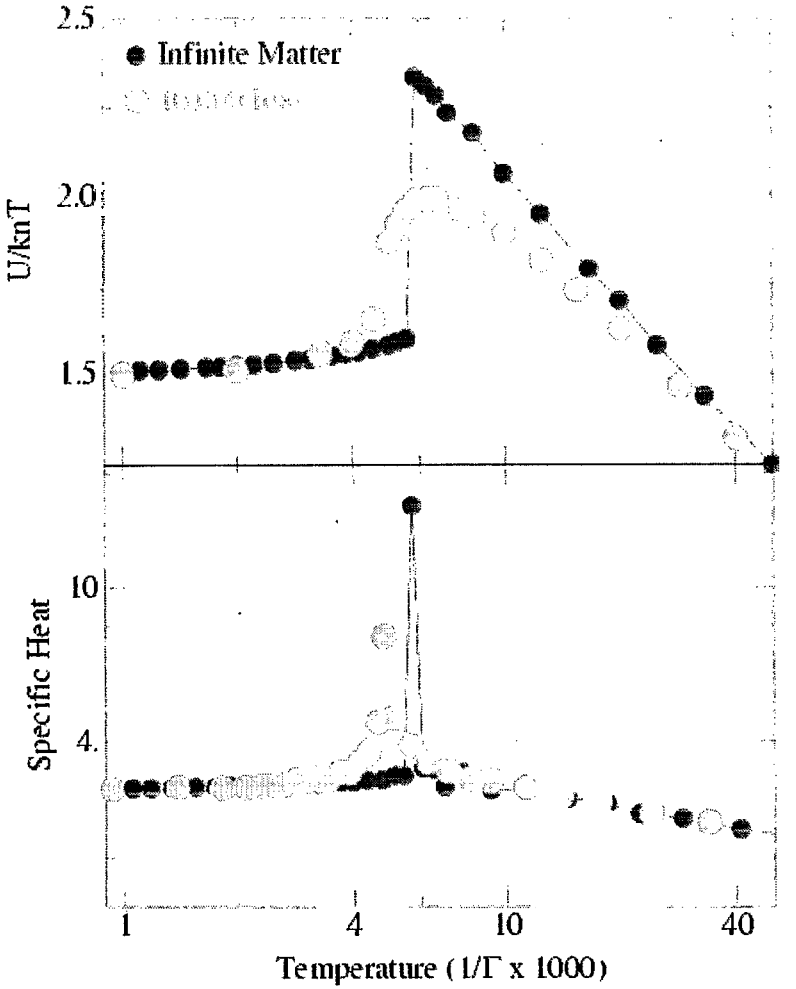
Crystalline, confined ionic systems exhibit well defined phase transitions as a function of the anisotropy of the confining potential. The transitions from one to two dimensions, from two to three, and back from three to two have been investigated as a function of this anisotropy with molecular dynamics simulations. The anisotropy at which such transitions occur seems to be proportional to a power of the number of confined ions.

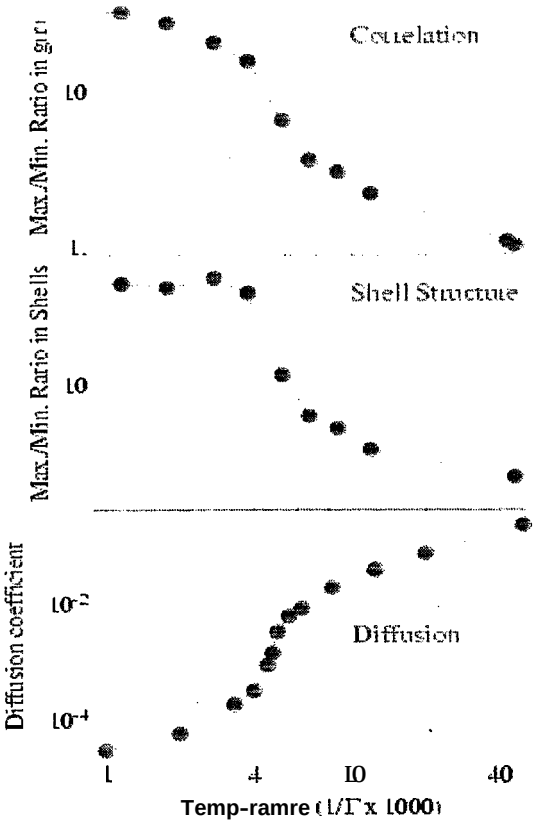






Solid to Liquid Phase Transition



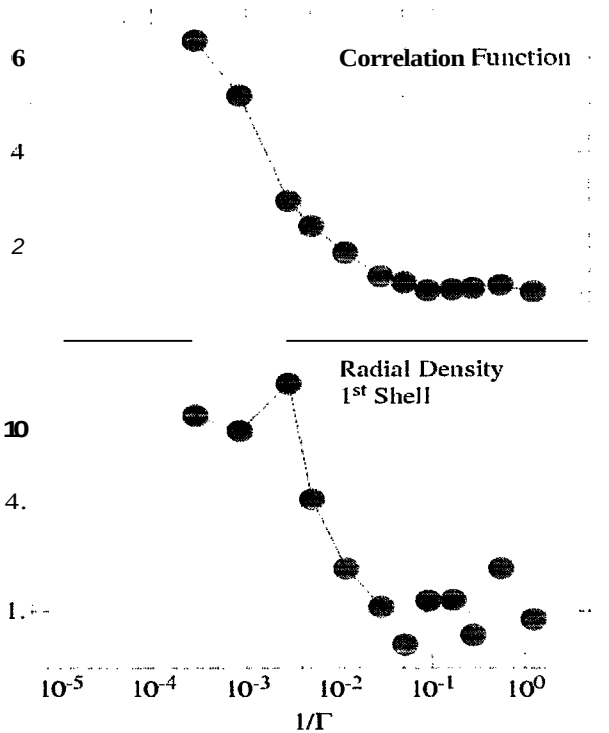


One-Component Coulomb Plasma

Solid-liquid phase transition in 10000 ions confined to a sphere

Tracked in Sharpness of

- Peak in Correlation Function
- Sharpness in Shell Structure
- Diffusion Rate



One-Component Quark Plasma

1000 particles. Here, the solid-to-liquid 'phase transition' seems to occur at about the same temperature ($\Gamma \approx 300$), as that in a corresponding (1000 ion) Coulomb system.

But note that here

$\Gamma \equiv 1/(a_{WS} \log(a_{WS}))$ / kT.

Equations of State
Derived from HED laboratory experiments."
UCRL-PRES-208770

Richard W. Lee and Stephen B. Libby
V Division
Physics and Advanced Technologies
LLNL
University of California

Laboratory experiments focused on understanding of the Equation of State (EOS) in the High Energy Density regime are performed on various high-energy laser and pulse power facilities. The primary effort over the past decade has been the development of experimental techniques to measure the EOS accurately. This has in turn led to the work on perfecting measurement along the primary shock Hugoniot. This approach was clearly motivated by the fact that one only requires the measurement of two variables, e.g., the shock velocity and the pusher velocity, to provide an *absolute* EOS while relative measurement, using a known standard, requires only one variable! However, there is room for deep concern as *in situ* measurements of the state of the shocked material are missing, That is, although one may assume that the Hugoniot conditions are satisfied one must ensure that the shocked matter has equilibrated, that the density – or particle spacing – is measured, and the temperature of the matter is bracketed. Desired in situ measurements'include luminescence spectroscopy to confirm the temperature and x-ray scattering to determine $S(k,\omega)$. The state of play is decidedly worse for measurement off-Hugoniot as all the drawbacks are amplified by having to interrogate an ill-defined hydrodynamic state of the matter.

The positive aspects of the current EOS measurements along the principal Hugoniot are:

1) Systems can be driven to very high pressures (> 10 Mbar)
2) Shocks can be verified to be temporally stable and spatial uniform
3) Two independent variables can be measured to reasonable accuracy
4) Measurements of additional physical parameters can be carried out, including reflectivity (to get at the dielectric function $\varepsilon(\omega)$), and pyrometry (shock temperature).

While, the drawbacks of the technique are understood and numerous:

5) Measurement of *in situ* properties (such as $S(k,\omega)$) have not been achieved
6) Different methods for generating the shocks provide differ results
7) Errors in the state variables are amplified, as these are not measured directly
8) Measurement off-Hugoniot are completely unsatisfactory; but, represent the vast majority of the phase-space

So, progress has been made but much research is needed.

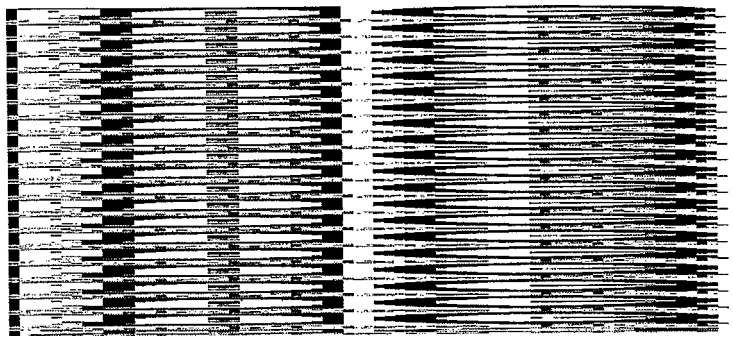
* Work Performed under the auspices of the US Department of Energy by LLNL under contract No. W-7405-ENG-48

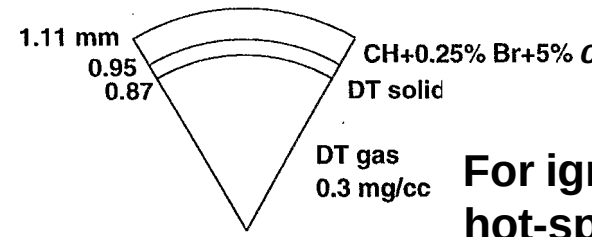
Example of EOS studies: Understanding H_2 EOS important to ICF & Astrophysical systems

- **Inertial Fusion - NIF**
  - Increased compressibility $\Rightarrow$ increased ρ $\Rightarrow$ increased yield
  - Reduced Rayleigh-Taylor growth during implosion $\Rightarrow$ less mixing of pusher and gas
  - Decreased sensitivity to drive $\Rightarrow$ greater margin for ignition

- **Astrophysics - planetary & law-mass stellar atmospheres**
  - No sudden phase transition may $\Rightarrow$ no phase separation
  - Significance now being explored
  - Renewed interest in theory of H EOS at high pressure

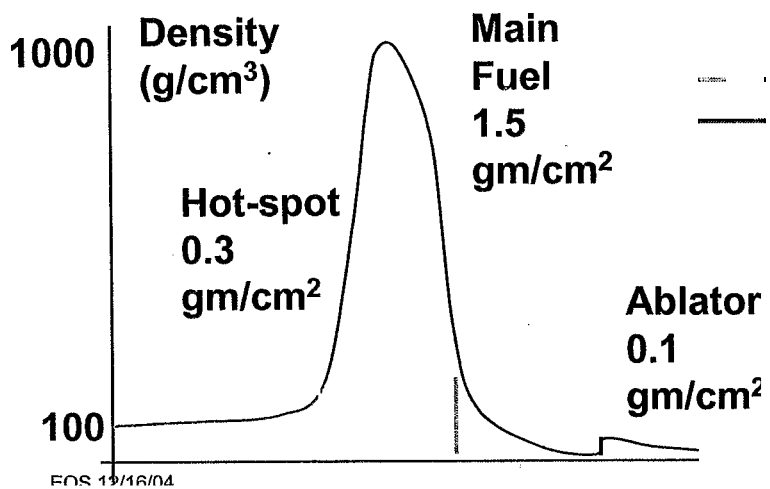
'Hot Spot' Haan Ignition Target Design Relies on EOS and Alpha Particle Stopping in Compressed, Shocked Capsule



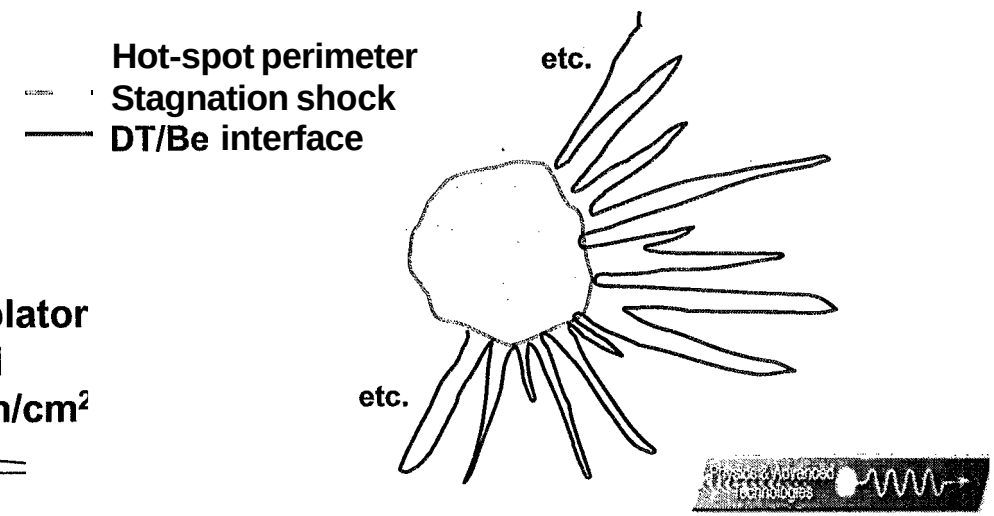


For ignition, need hot-spot with T_{ion} ~ 10 keV, ρR_{HS} ~ 0.3 g/cm^2

I D picture

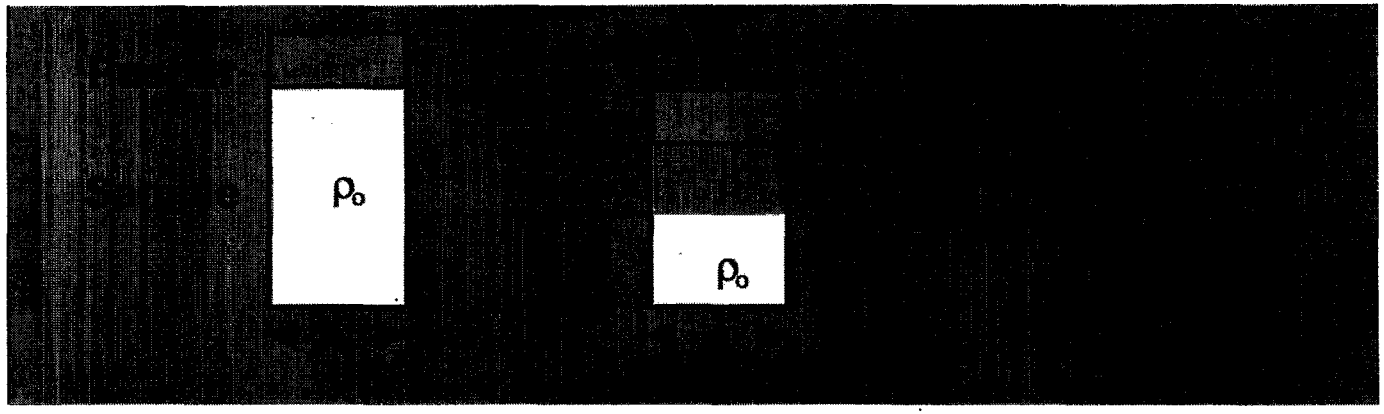


2D or 3D picture



EOS data for extreme pressures are most easily accessible on the Hugoniot

- **Hugoniot is locus of ρ-T points arising from an ideal strong shock**



Mass	Momentum	Energy
$\rho(xA) = \rho_o(LA)$	$F - F_o = \rho_o(LA)(U_p - 0)$	$dQ = dE + PdV$
$\frac{\rho}{\rho_o} = \frac{L}{x} = \frac{U_s}{(U_s - U_p)}$	$P - P_o = \rho_o U_s U_p$	$E - E_o = \frac{u}{\rho_o U_s} - \frac{U_n^2}{2}$

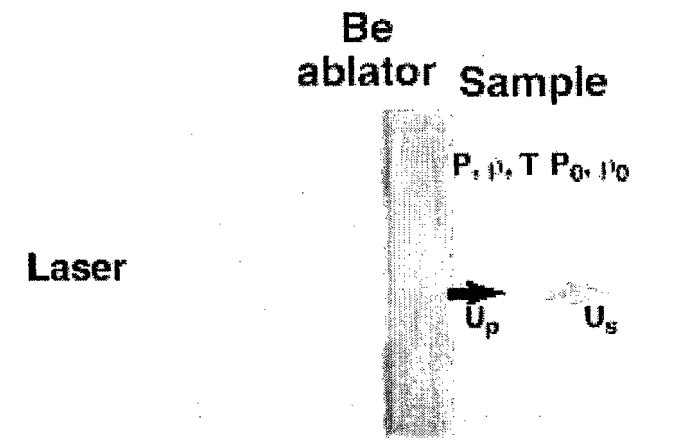
- 4 unknowns (p, P, U_s, U_p) and 2 equations

$\Rightarrow$ need 2 quantities for ***absolute*** measurement

EOS measurements are exacting and current capabilities are good (but not great)

- Basic configuration uses an *absolute* method when shock material can be radiographed

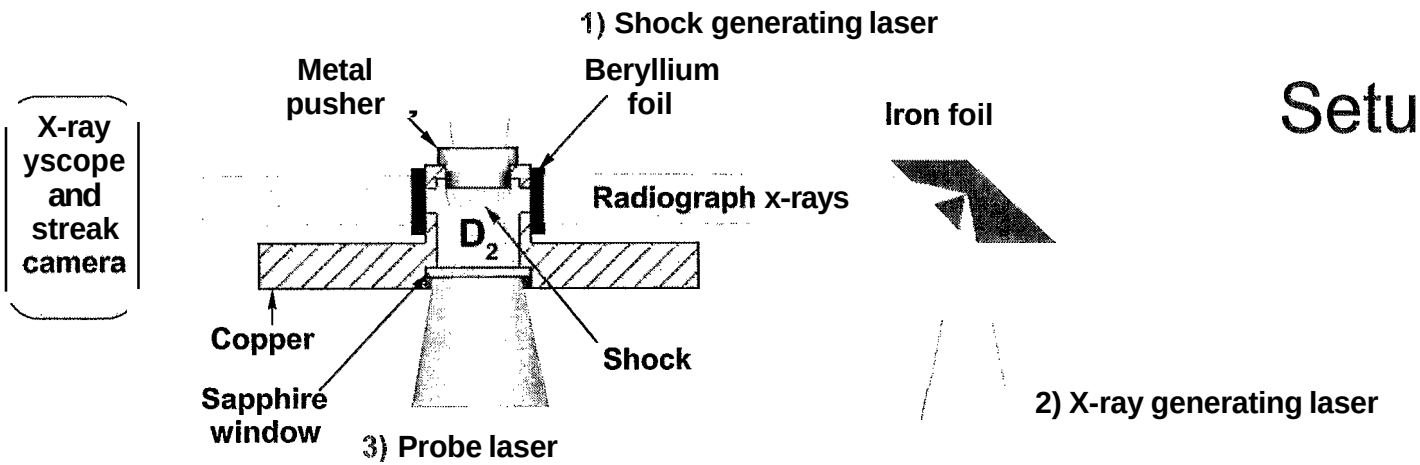
- Preheat: < few hundred C
- Planarity of shock: ~ 0.2%
- Steadiness of shock pressure: ~ 2%
- Accuracy of velocity: $\Delta U_s/U_s$ ~ 2%
- But, there remains no *in situ* probe of the state of the shocked material



basic configuration schematic

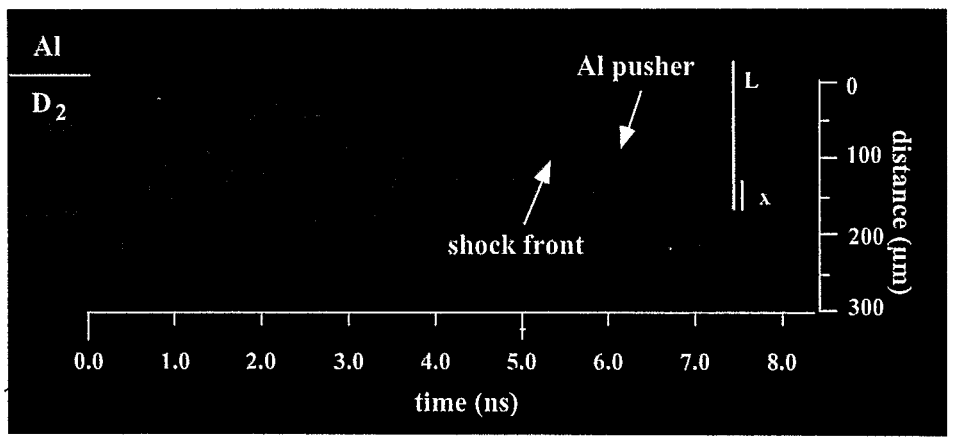
Current improved method uses 3 lasers: 1) create shock, 2) x-rays, and 3) probe sample

Setup



Data

streak camera record

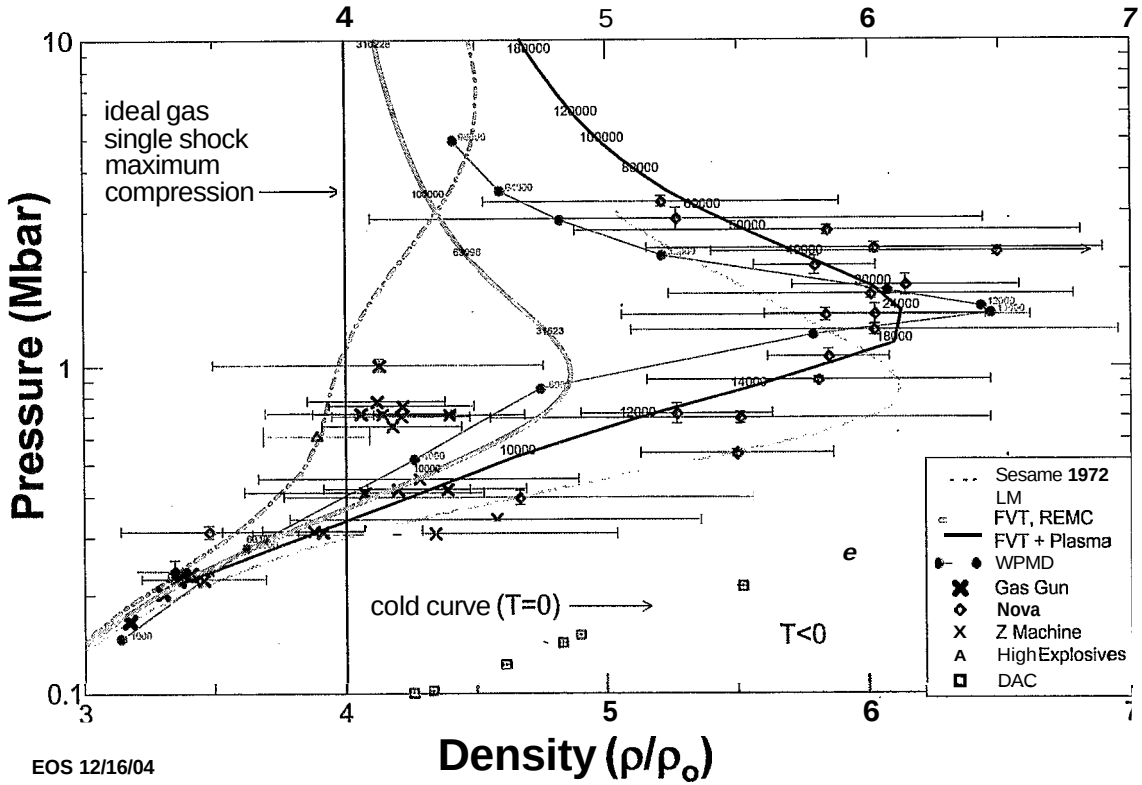


$$\frac{\rho}{\rho_o} = \frac{L}{x} = \frac{U_s}{U_s - U_p}$$

- Slope of shock front yields U_s
- Slope of pusher interface gives U_p

D_2 EOS experiments show strengths and weakness of the current methods

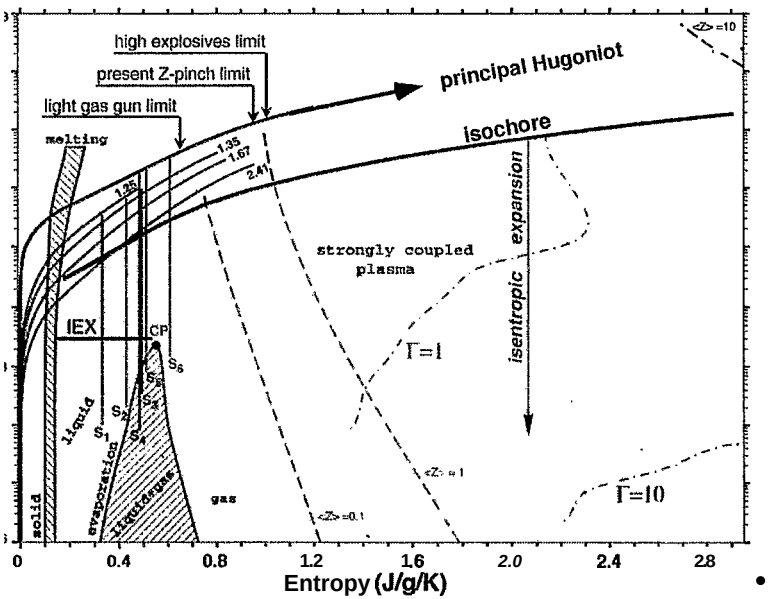
- **Reflectivity, pyrometry, and other laser techniques corroborate D_2 data**
- **Z pulsed power "flyer plate" relative measurements** *do not*



- Theory and simulation are not in agreement with data or each other
- Only the Z pulsed power and larger lasers can access the regime
- Improvements and resolution essential

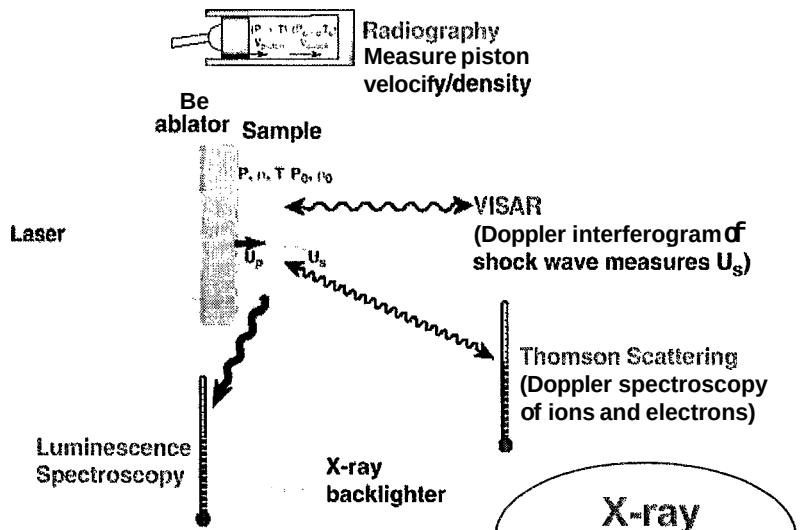
Goals: Increase EOS data and make *in situ* measurements of the HED matter

Pb phase diagram shows paucity of data



- Isochoric heating / isentropic expansion
- Principal and porous Hugoniots shock compression experiments
- Studied release isentropes (S)
- Isobaric expansion (IEX)
- Ionization degree (<Z>) and non-ideality parameter (Γ) are shown

- **Diagnostics for EOS**



- Diagnostic currently include:
  - Luminescence
  - X-radiography
  - Visar Doppler interferometry
  - Pyrometry
  - Reflectivity

X-ray scattering

- Develop x-ray scattering to probe the bulk: measure $S(k,\omega)$

Hydrodynamic Simulation of Relativistic Heavy Ion Collisions

Tetsufumi Hirano

Department of Physics, Columbia University

First data reported by the STAR Collaboration at RHIC [1] are significant meaning because the observed large magnitude of elliptic flow for charged hadrons is consistent with hydrodynamic predictions [2]. This suggests that large pressure, possibly in the partonic phase, is built at the early stage ($\tau \sim 0.6$ fm/c) in Au+Au collisions at $\sqrt{s_{NN}} = 130$ and 200 GeV. This situation at RHIC is in contrast to that at lower energies such as AGS or SPS where hydrodynamics always overpredicts the data [3]. ,Moreover,this also suggests that the effect of the viscosity in the QGP phase is remarkably small and that the QGP is almost a perfect fluid [4]. Hadronic transport models are very good to describe experimental data at lower energies, while they fail to reproduce such large values of elliptic flow parameter at RHIC.So the importance of hydrodynamics is rising in heavy ion physics. To understand these experimental data, hydrodynamic analyses are also performed extensively [5,6]. In this short review, we highlight several results on elliptic flow from hydrodynamic calculations.

References

[1] K. H. Ackermann *et al.* (STAR Collaboration), Phys. Rev. Lett. **86** 402 (2001).

[2] P. F. Kolb, P. Huovinen, U. Heinz and H. Heiselberg Phys. Lett. B ***500*** 232 (2001): P. Huovinen, P. F. Kolb, U. W. Heinz, P. V. Ruuskanen and S. A. Voloshin, Phys. Lett. B **503** 58(2001): P. F. Kolb, U. W. Heinz, P. Huovinen, K. J. Eskola and K. Tuominen, Nucl. Phys. **A696** 197(2001).

[3] C. Alt *et al.* (NA49 Collaboration), Phys. Rev. C **68** 034903 (2003): G. Agakichiev *et al.* (CERES/NA45 Collaboration), Phys. Rev. Lett. **92** 032301 (2004).

[4] E. Shuryak, 2004 J. Phys. G **30** S1221 (2004): D. Teaney, Phys. Rev. C **68** 034913 (2003).

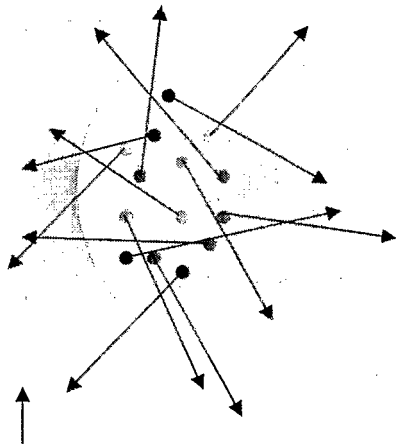
[5] P. Huovinen, in *Quark Gluon Plasma 3* eds. R Hwa and X N Wang (Singapore, World Scientific, 2003)

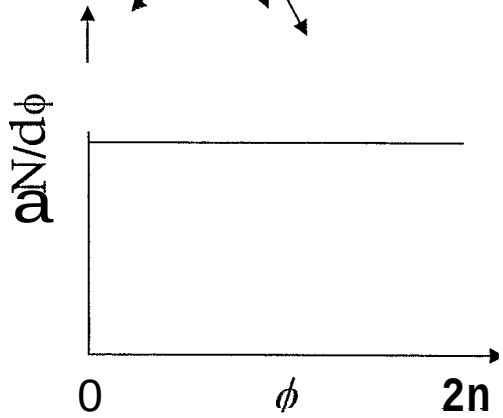
[6] P. F. Kolb and U. Heinz, in *Quark Gluon Plasma 3* eds. R Hwa and X N Wang (Singapore, World Scientific, 2003)

Elliptic Flow

Ollitrault ('92)

No secondary interaction





Input

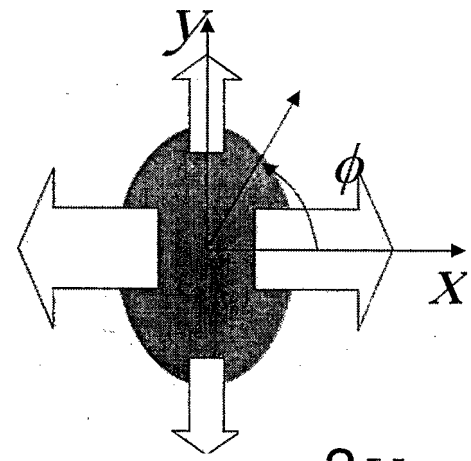
Spatial anisotropy ε

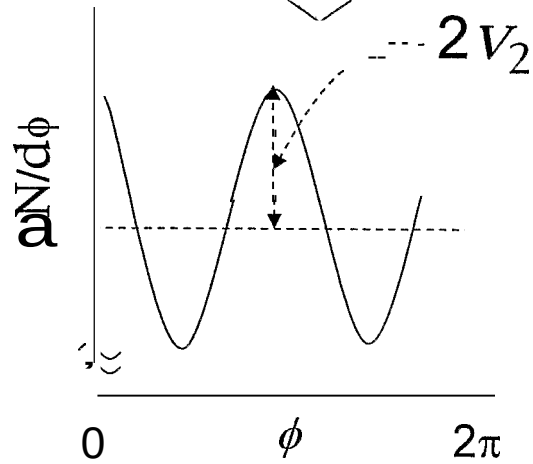
Interaction among produced particles

output

Momentum anisotropy v_2

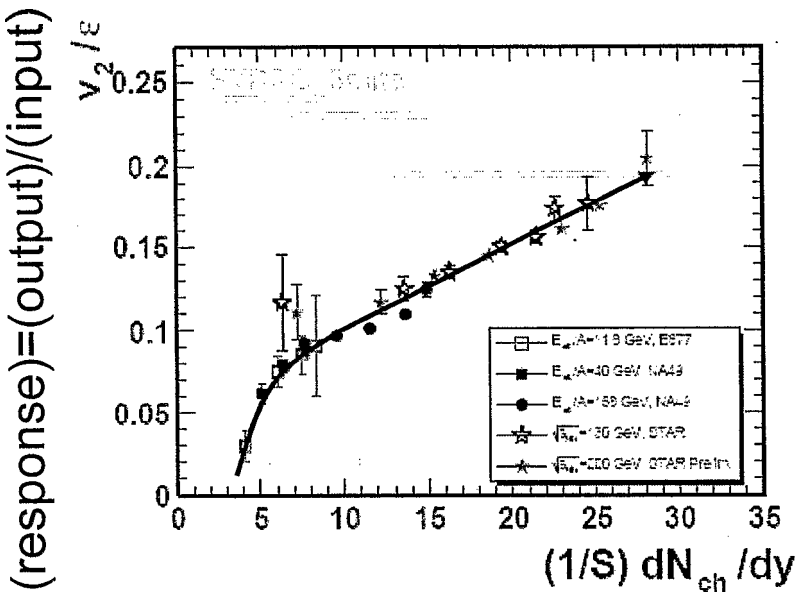
Hydrodynamic behavior





Particle Density Dependence of Elliptic Flow

NA49('03)



Number density per unit transverse area

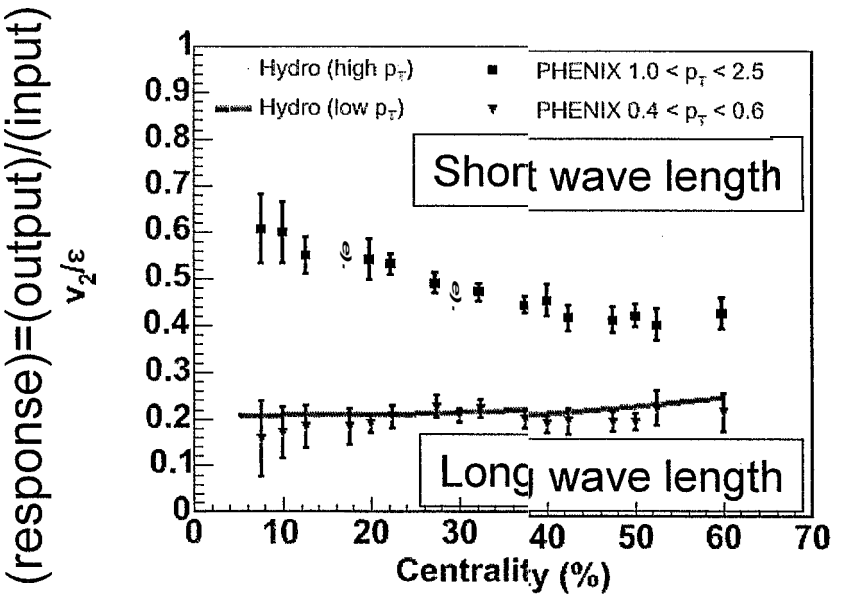
Kolb, Sollfrank, Heinz ('00)

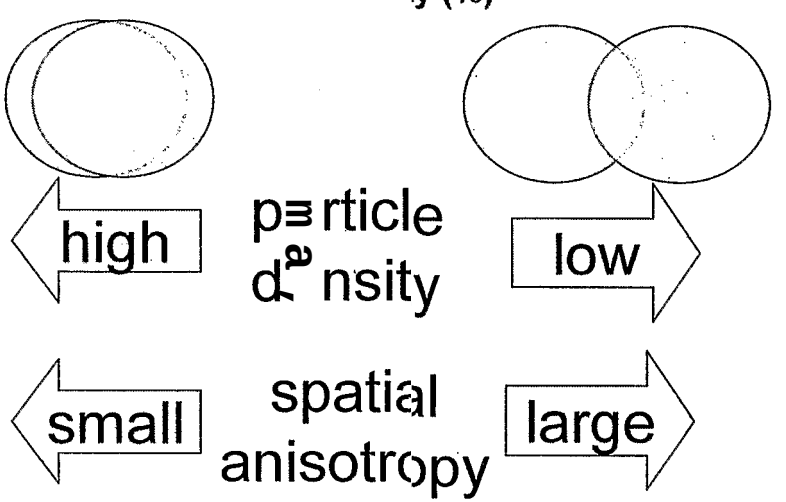
- **Dimension**
  - 2D+boost nv.
- **EoS**
  - QGP + hadrons (chem. eq.)
- **Decoupling**
  - **Sudden freezeout**

•Hydrodynamic response is const. $v_2/\varepsilon \sim 0.2$ @ RHIC
•Exp. data reach hydrodynamic limit at RHIC for the first time.

Dawn of **the** hydro age?

"Wave Length" Dependence





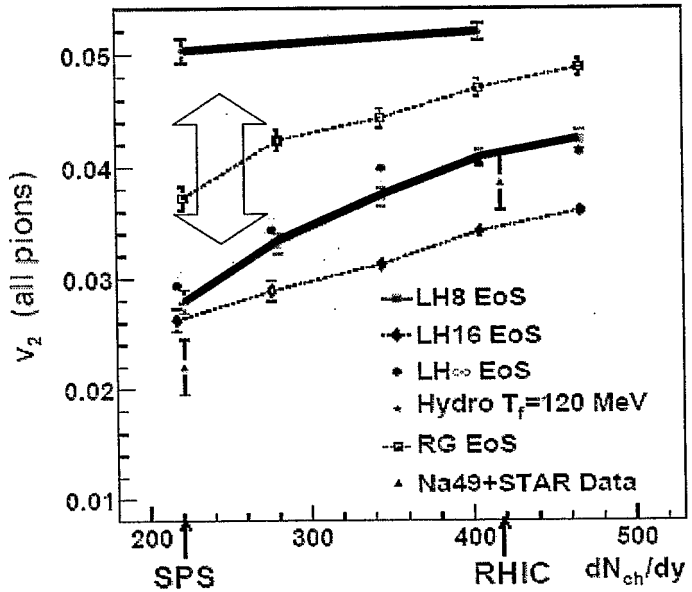
T.H.('04)

- **Dimension**
  - **Full 3D (τ–η_s coordinate)**
- **EoS**
  - **QGP + hadrons (chem. frozen)**
- **Decoupling**
  - Sudden freezeout

•Long wave length components (small transverse momentum) obey "hydrodynamics scaling"

•Short wave length components (large transverse momentum) deviate from hydro scaling.

Particle Density Dependence of [redacted]tic Flow [redacted]d.)



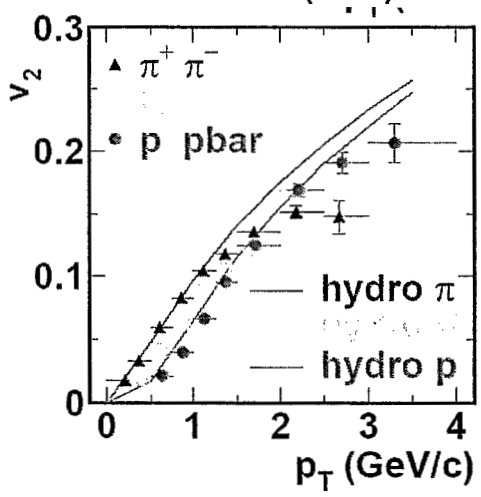
Teaney, Lauret, Shuryak('01)

- **Dimension**
  - 2D+boost inv.
- **EoS**
  - Parametrized by latent heat (**LH8**, LH16, LH-infinity)
  - Hadrons
  - QGP+hadrons (chem. eq.)
- **Decoupling**
  - **Hybrid (Boltzmann eq.)**

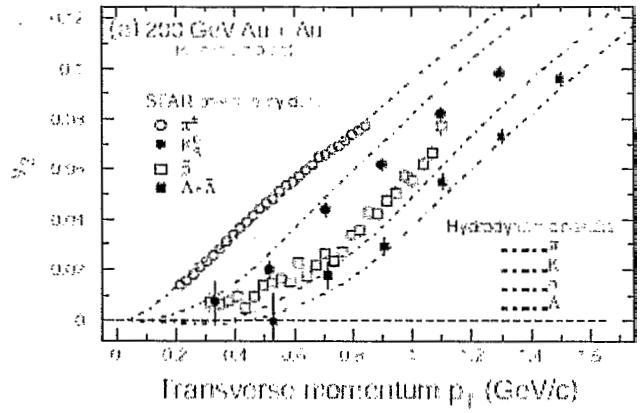
- Deviation at lower energies can be filled by "viscosity" in hadron gases
- Latent heat ~0.8 GeV/fm^3 is favored.

"Fine Structure" of v_2: Transverse Momentum Dependence

PHENIX('03)



STAR('03)

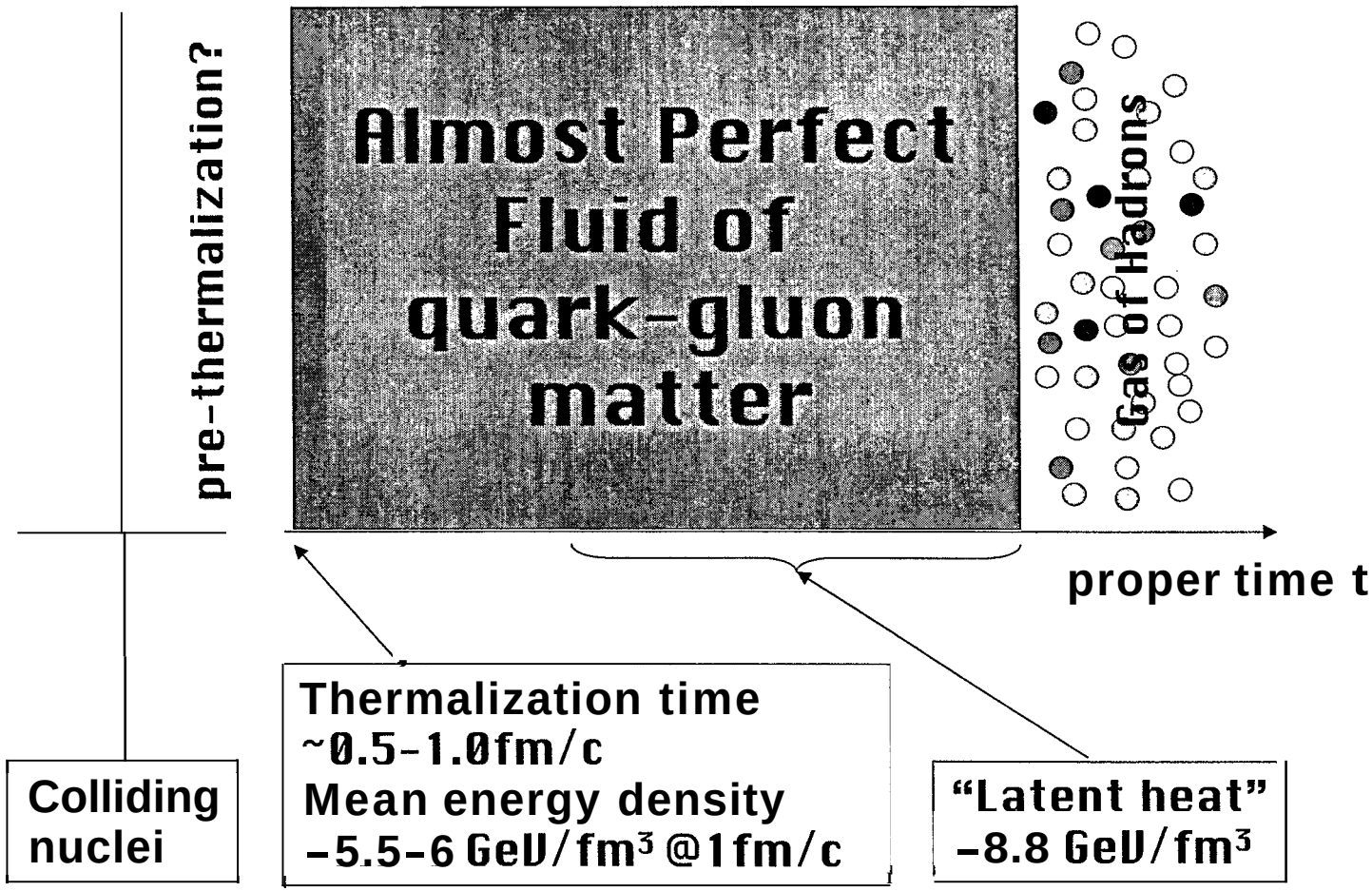


Huovinen et al.('01)

- **Dimension**
  - 2D+boost inv.
- **EoS**
  - QGP + RG (chem. eq.)
- **Decoupling**
  - Sudden freezeout

- Correct p_T dependence up to p_T=1-1.5 GeV/c
- Mass ordering
- Deviation in small wave length regions
  → Effects other than hydro

Summary: A Probable Scenario



Flow in Heavy-Ion Collisions

Kirill Filimonov (LBNL)

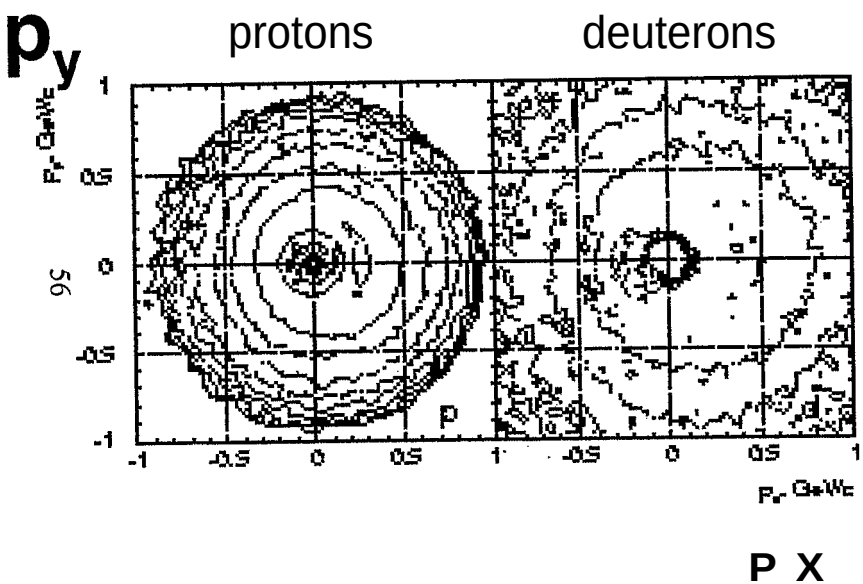
- <u>Collective motion</u> characterized by space-momentum correlation of dynamic origin
- Concept from Hydrodynamics:
  - hot and compressed matter behaves like a compressible fluid

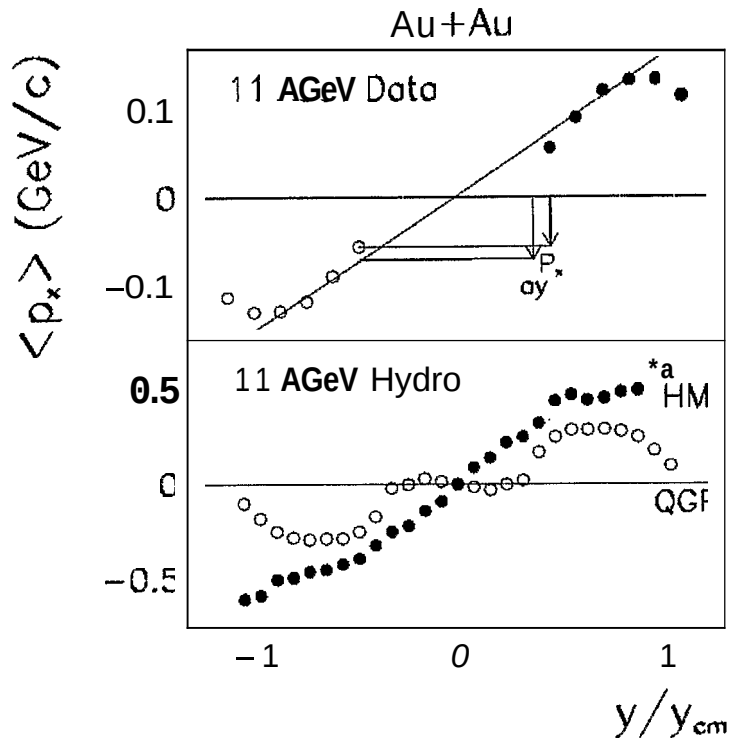
Types of Flow:

- axially symmetric radial flow
- azimuthally anisotropic transverse flow

Directed (sideward) Flow

Example: E877 (AGS, 11 AGeV)





$\langle p_x \rangle \neq 0$

Interplay of passage/expansion times

VOLUME 83, NUMBER 7 PHYSICAL REVIEW LETTERS 16 AUGUST 1999

Elliptic Flow: Transition from Out-of-Plane to In-Plane Emission in Au + Au Collisions

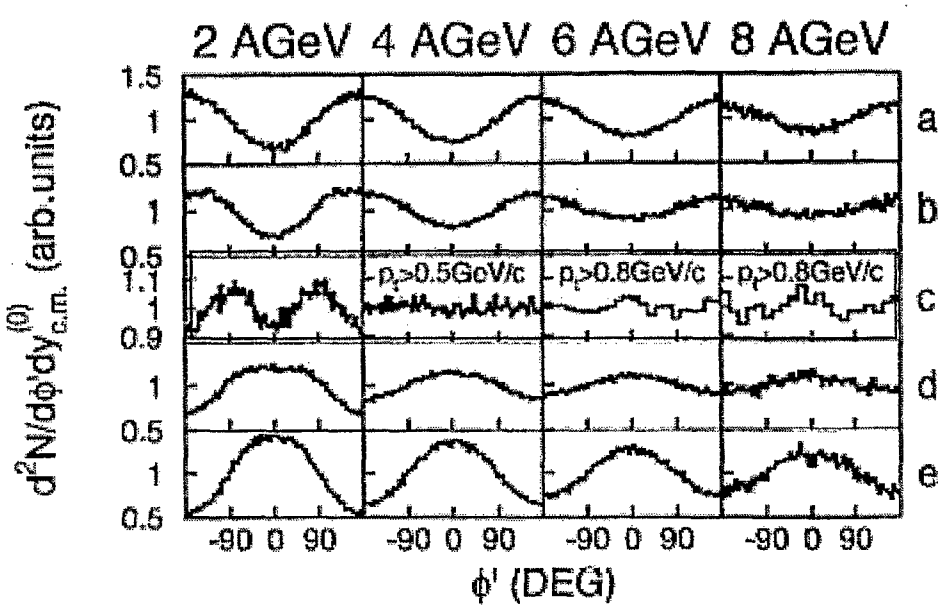
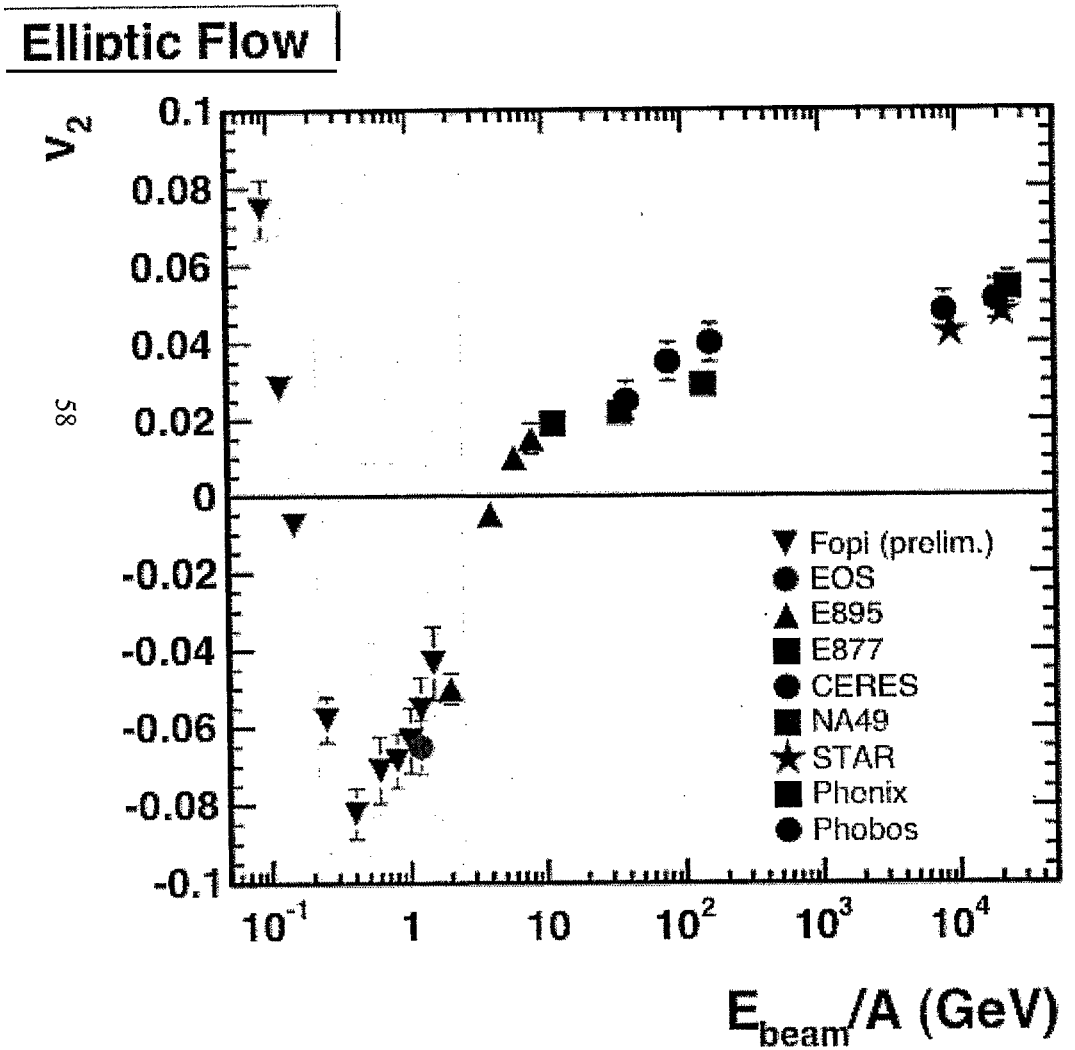


FIG. 2. Azimuthal distributions (with respect to the reconstructed reaction plane) for 2A, 4A, 6A, and 8A GeV Au + Au.

Passage time: $2R/(\beta_{cm}\gamma_{cm})$
Expansion time: R/c_s
$c_s = c\sqrt{dp/d\varepsilon}$ - speed of sound

v_2 Excitation Function



Rich structure

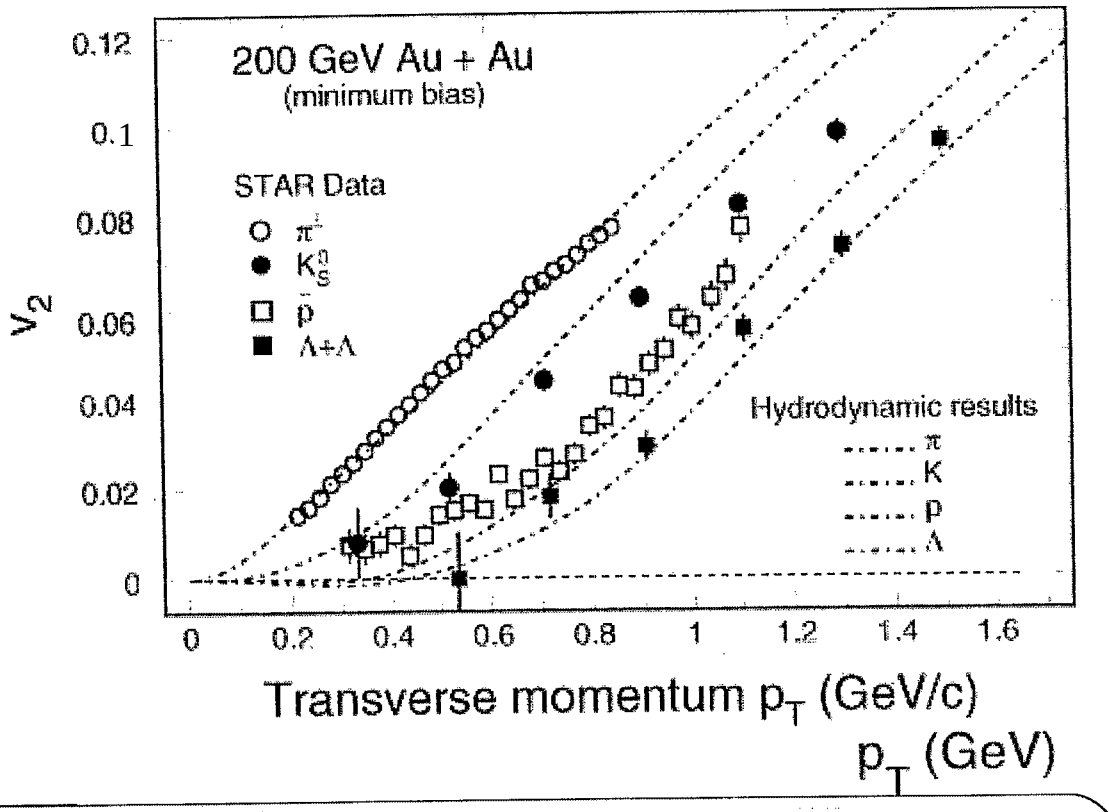
Transition from in-plane to out-of-plane and back to in-plane emission

Geometry effect in addition to (smooth?) change in pressure

Elliptic flow => sensitivity to *early* system

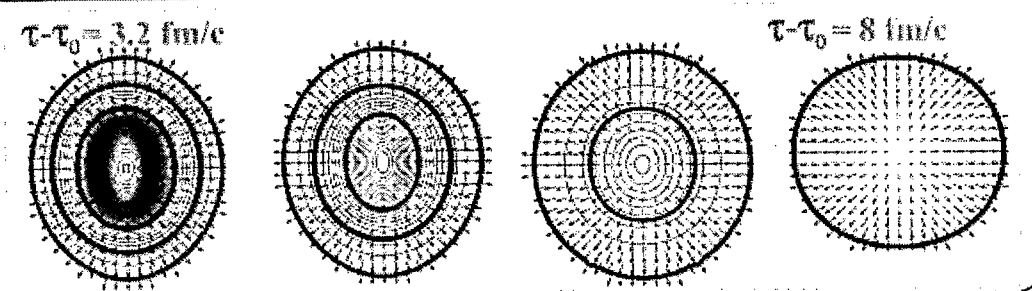
"Elliptic flow"

- evidence of *collective* motion
- sensitive to *early* pressur
- evidence for
  - early thermalization
  - QGP in early stage



p_T (GeV)

Hydrodynamic calculation of *system* evolution



Conclusions and Outlook

- Elliptic flow at RHIC => Evidence for early pressure
- First time hydro works in heavy ion collisions!
- Indications of re-interaction between constituent quarks
- Will charm flow at RHIC?

Jet Quenching: Energy Loss of Color-Charged Probes

Axel Drees, University Stony Brook, RBRC workshop at BNL

Strongly Coupled Plasmas: Electromagnetic, Nuclear and Atomic; December 16-17 2004

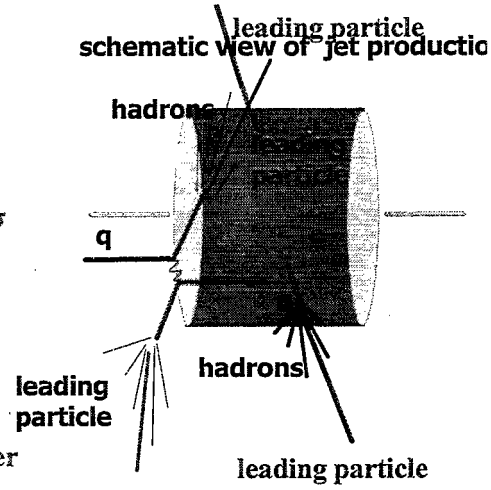
Typical external probes in plasma physics are short in wavelength compared to the characteristic wavelength of the plasma. Measurement of their transmission yields information about the opacity and density of the plasma. In heavy ion collisions, the timescale is too short to use an external probe source, but quarks and gluons scattered with high momentum transfer in the initial nucleon-nucleon collisions are short wavelength probes which carry color charge. The production rate and distribution of these probes can be calculated with QCD, and their fragmentation into jets of hadrons benchmarked in p+p collisions. Using these, transmission through the Quark Gluon Plasma can be measured.

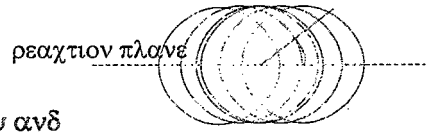
A large suppression in the production of high momentum hadrons from such jets is observed in central Au+Au collisions. This suppression is seen also for the partner parton for jets emitted from the surface of the collision. No suppression is seen in d+Au collisions, indicating that the suppression is an effect of the hot, dense system present in Au+Au collisions but absent in d+Au. Using an opacity expansion, the observed suppression factor indicates that a system with 1000 gluons per unity rapidity at an initial energy density of $\sim$15 GeV/fm3 is formed.

This kind of probe should also allow measurement of plasma properties, using coincidences of two or more hadrons to track interactions of the probe with the medium. It may be possible to elucidate the speed of sound in the quark gluon plasma from a "splash" pattern on the away side, or probe the coupling strength by detecting jet fragments which have been boosted by the expanding medium.

Jets: A Penetrating Probe for Dense Matter

- Ωηατ ισ α φετ?
  - Ινχομινγ παρτονσ μαψ χαρρψ λαργε φραχτιον ξ οφ βεαμ μομεντυμ
  - Τηεσε παρτονσ χαν σχαττερ ωιτη λαργε μομεντυμ τρανσφερ
  - Ρεσυλτσ ιν λαργε π_T οφ σχαττερεδ παρτονσ
  - αππεαρσ ιν λαβορατορψ ασ "φετ" οφ παρτιχλεσ
- ϑετ προδυχτιον χαν βε οβσερωεδ ασ
  - ηιγη π_T λεαδινγ παρτιχλεσ
  - ανγυλαρ χορρελατιον
- **In a gold gold collision**
  - **Scattered partons travel through dense matter**
  - **Expected to loose a lot of their energy**
- **Energy loss observed as**
  - **suppression of high p_T leading particles**
  - συππρεσσιον οφ ανγυλαρ χορρελατιον
  - Δεπενδινγ ον πατη λενγτη, ι.ε. χεντραλιτψ ανδ ανγλε το ρεαχτιον πλανε





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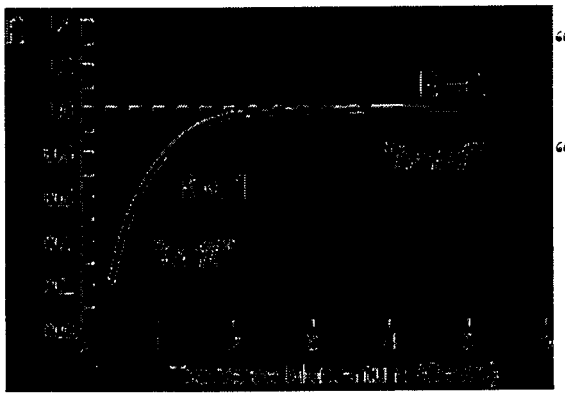
Investigate Medium Modification of Spectra

Compare Au+Au to nucleon-nucleon particle spectra:

Nuclear Modification Factor:

$$R_{AA}(p_T) = \frac{yield(AuAu)/N_{coll}}{yield(pp)}$$



"Soft" or bulk particle production
R < 1 scales with ~N_{part}

"Hard" or jet-like particle production

R = 1 expected scaling with N_{coll}
R > 1 enhancement, e.g. Cronin effect

R < 1 suppression or jet quenching

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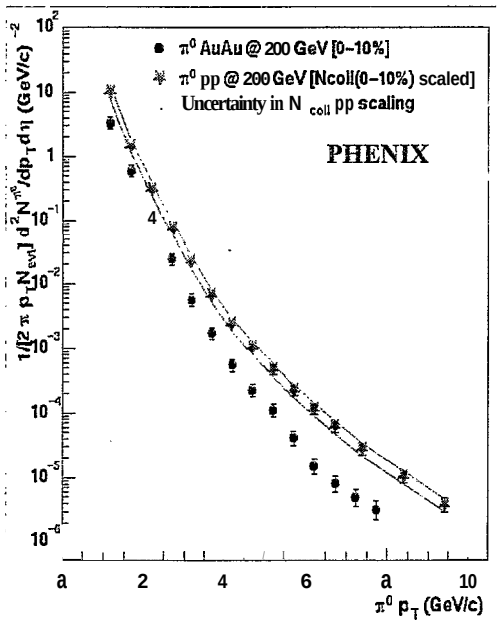
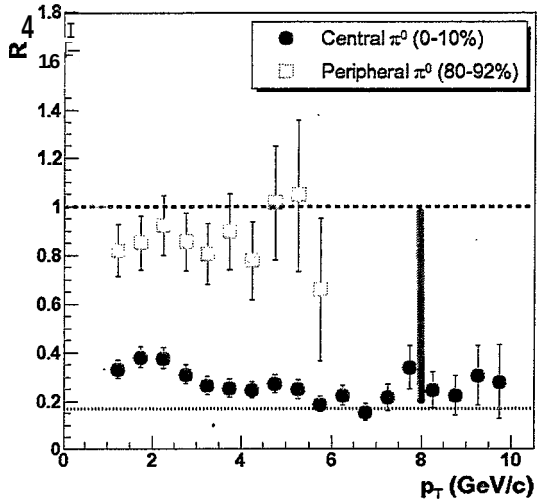
Axel Drees

Suppression of π^0 in Central AuAu Collisions

PRL 91 (2003) 72301



Nuclear modification factor:



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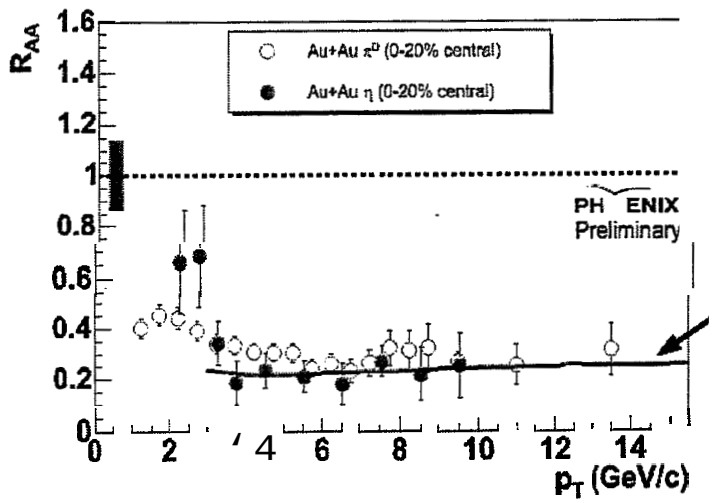
High p_T suppressed by factor ~ 5
pp to central AuAu and peripheral to central Au-Au

Drees

Energy Loss Analysis of π^0 P_{AA}



GLV calculation:
$dN_g/dy \sim 1100$
$e \sim 15$ GeV/fm^3

Medium with extremely opaque core
Jets biased towards surface emission

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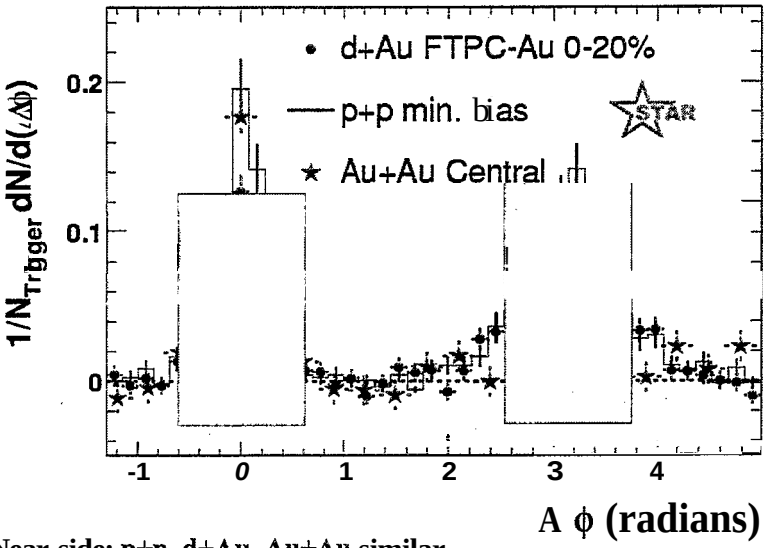
Axel Drees

Disappearance of the "Away-Side" Jet



trigger 6 <pt< 8 GeV
partner 2 < pt < 6 GeV

Integrate yields in some ϕ window on near and away side

Near-side: p+p, d+Au, Au+Au similar
Back-to-back: Au+Au strongly suppressed relative to p+p and d+Au

Suppression of the away side jet in central Au+Au

STONY BROOK

Axel Drees

Heavy Quarkonium and Color Screening

Dmitri Kharzeev

Nuclear Theory Group,

***Physics** Department,*

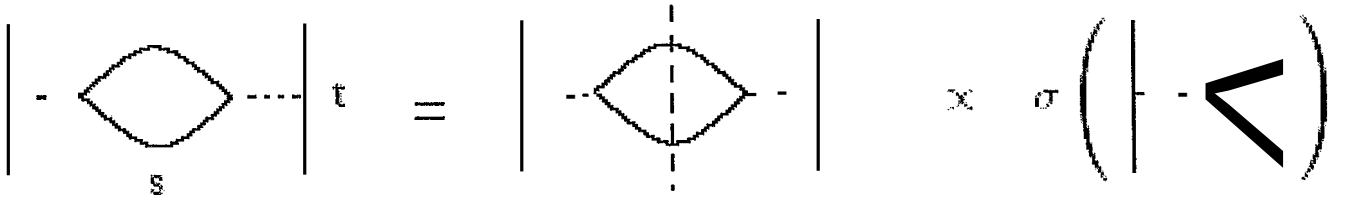
Brookhaven National Laboratory,

Upton, NY 11973-5000, USA

QCD has a remarkable property of color anti–screening, or the "asymptotic freedom". As a result, the bound states of heavy quark and anti-quark (heavy quarkonia) may in the first approximation be described with the use of a Coulomb potential generated by perturbative gluon exchanges. In quark-gluon plasma, due to the scattering of Coulomb gluons off the heat bath, the heavy quark potential gets screened; therefore at sufficiently high temperatures the bound states will dissolve. Another dissociation mechanism is "ionization" of the bound states by thermal gluons, similar to photo-effect. This talk discusses the relative importance of the two mechanisms in view of the recent lattice results and the experimental data from RHIC and SPS.

Coulomb potential in QCD

Spectral representation in the t-channel: $V(R) = \sum_m \sigma(r \quad) \, \frac{\exp(-mR)}{R}$

Disc$_t$ 

If physical particles can be produced (positive spectral density), then unitarity implies screening

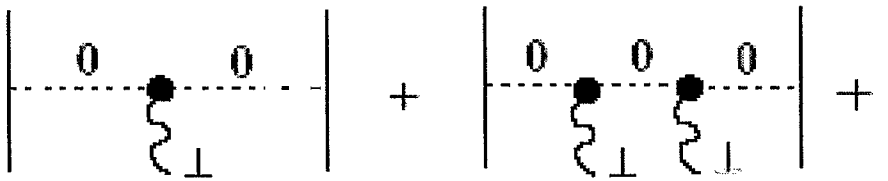
$$\left\{ \frac{d\,\alpha_s^{-1}(R)}{d\ln R} \right\}^{\text{phys}} \propto \frac{1}{3} N + \frac{2}{3} n_f$$

Gluons (transverse) Quarks

Coulomb potential in QCD - II

Missing non-Abelian effect: instantaneous Coulomb exchange dressed by (zero modes of) transverse gluons

$$\sum_n \left[0 + \perp - 0\right]^n =$$



Negative sign
(the shift of the ground level
due to perturbations - unstable vacuum!):

$$\delta E \equiv E - E_0 = \sum_n \frac{|\langle 0|\delta V|n\rangle|^2}{E_0 - E_n} < 0$$

Gribov '78

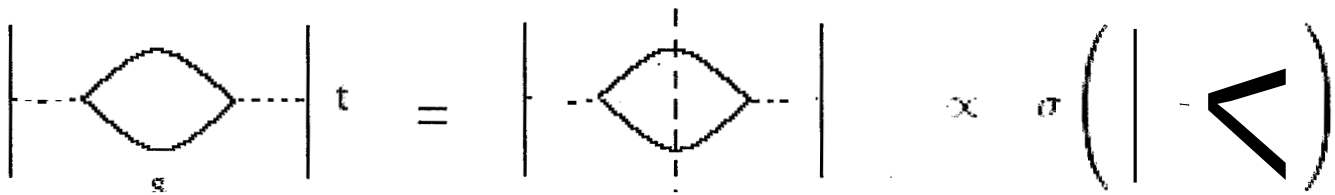
Anti-screening

$$\left\{ \frac{d\,\alpha_s^{-1}(R)}{d\ln R} \right\}^{\rm stat} \propto -4N$$

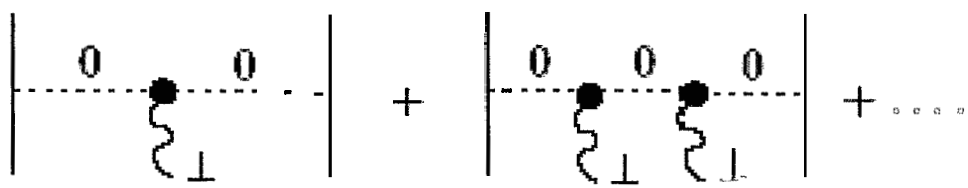
Review:
Yu.Dokshitzer & DK,
hep-ph/0404216

Screening in Quark-Gluon Plasma

These diagrams are enhanced at finite temperature:
(scattering off thermal gluons and quarks)

Disc_t 

This diagram is not:

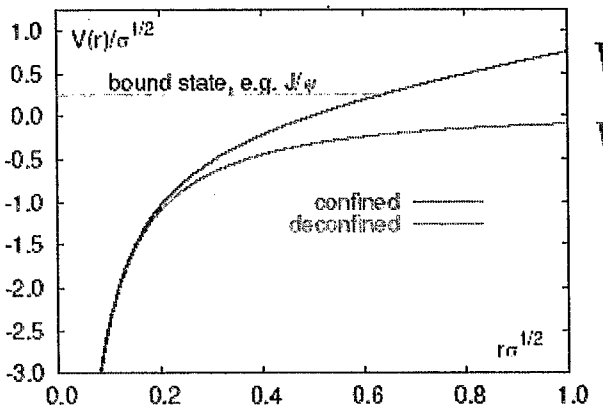
$\sum_n \left[0 + \perp \to 0\right]^n =$ 

=> At high enough T, screening wins

Heavy quarkonium as a probe

The Matsui-Satz argument:

- deconfinement $\Rightarrow$ screening
  $\Rightarrow$ no heavy quark bound states in a QGP

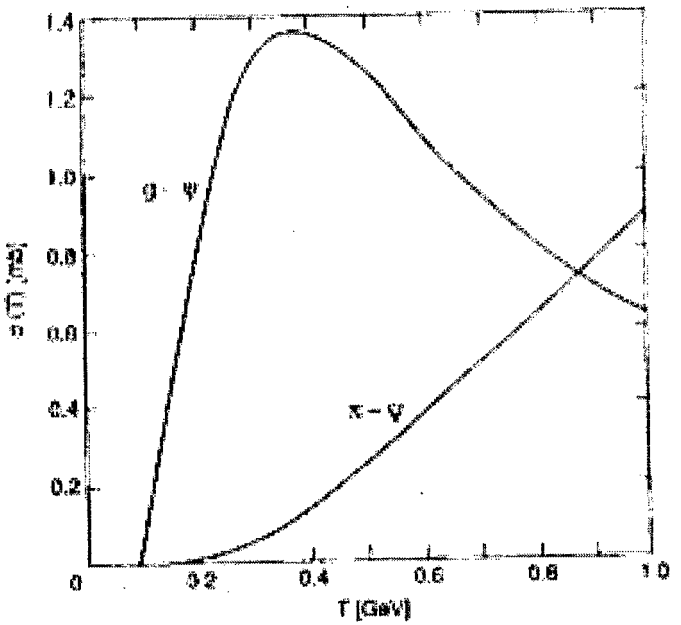


$V_{\bar{q}q}(r,T) \to \infty$ confinement

$V_{\bar{q}q}(r,T) < \infty$ deconfinement

the link between the observables and the McLerran-Svetitsky confinement criterion

What mechanism is more important?



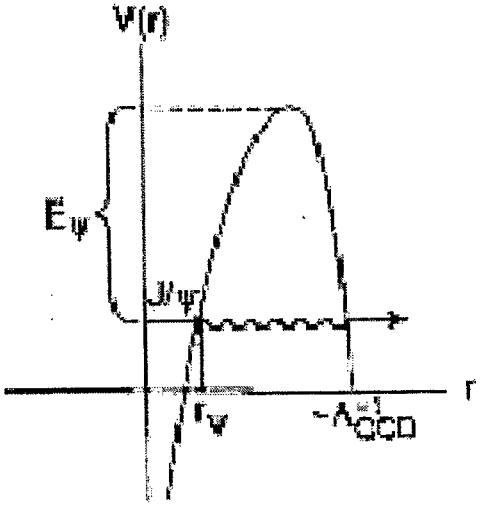
DK, H.Satz, hep-ph/9505345

Strongly coupled regime:
$\Delta E/T >> 1$
Ionization

Weakly coupled regime:
$\Delta E/T << 1$
Screening

What mechanism is more important?

DK, L.McLerran, H.Satz
hep-ph/9504338



$$R_{act} = \frac{1}{Z(T)} \frac{V}{L} \left(\frac{c}{\pi^2} MT^2 \right) e^{\frac{-E_{J/\psi}}{T}}$$

Weak coupling:

$$R_{act} = \frac{4}{L} \sqrt{\frac{T}{2\pi M}} = \frac{v(T)}{L}$$

Strong coupling:

$$R_{act} = \frac{(LT)^2}{3\pi} M e^{-E_{J/\psi}/T}$$

Diagnosing Collective Plasma Modes

We are interested in modeling the dynamical properties of dense, strongly coupled plasmas. These plasmas are characterized by ratio of the potential to the kinetic energy per particle being greater than one and, at large enough density and/or low enough temperature, by the degeneracy of the free electron gas. The dynamics of dense, strongly coupled plasmas is characterized by collective modes, such as the ion-acoustic wave or the electron plasma wave, whose spectra contain a wealth of information about the equilibrium and transporf properties of the plasma. Light scattering experiments (Thomson scattering) from free electrons constitute a probe of the collective behavior of the plasmas and, in principle, a diagnostic of the plasma if the scattered spectrum of radiation can be predicted. An important quantity is the spectrum of the electron density-density fluctuations, the so-called dynamic structure factor $S_{ee}(k,\omega)$, since it is directly probed in Thomson scattering (here k and ω are, respectively, the wave-vector annd the frequency of the electron density fluctuations). We illustrate the difficulty of constructing a theory of $S_{ee}(k,\omega)$ by constructing gradually more complicated models and comparing their predictions to molecular dynamics calculations, which play a crucial role in calibrating our understanding of dynamical properties. First, we consider two simple sum-rule models to show how strong coupling manifests itself in the dispersive properties of the collective modes: here, the screened one-component plasma model (Yukawa) is used, which has ion-acoustic wave dispersion. These models contain exact information on the structural (liquid-like) properties of the system, and are able to reproduce qualitatively the dispersion of the mode. However, purely static information is not enough to model the collisional mechanisms (such as viscosity, heat transport...) responsible for the width of the modes. In order to go beyond these simple models, one uses the fluctuation-dissipation, which connects $S_{ee}(k,\omega)$ to the electron-electron response function $\chi_{ee}(k,\omega)$. $\chi_{ee}(k,\omega)$ is written exactly in terms of the ideal gas response function, the interaction potential between particles, and the so-called dynamical local-field correction $G(k,\omega)$. As such, the model reproduces the independent particle system behavior when the system is probed at large momentum transfer k, as well as collective effects at smaller wave-vector because of the presence of the mean-field. The difficulty resides in modeling $G(k,\omega)$, which contains both the structural and collisional information of the system, that strongly affect the position as well as the width of the modes. We show that frequency-independent models, based on the satisfaction of basic sum-rules, is not enough to reproduce the position and the shape of fhe resonances. A calculation for a dense aluminum plasma show the strong sensitivity of the ion-acoustic peak to the models. This is important because the ion-acoustic peak is likely to display the effects of strong coupling more prominently than the electron wave, since the ions are often cooler and have higher charge states Z. $G(k,\omega)$ is a truly frequency dependent quantity, and even a viscoelastic model is not able to reproduce the simulation data. We also illustrate the impact of degeneracy on the shape of the spectrum: as the temperature decreases, properties become insensitive to the temperature and depend essentially on the density.

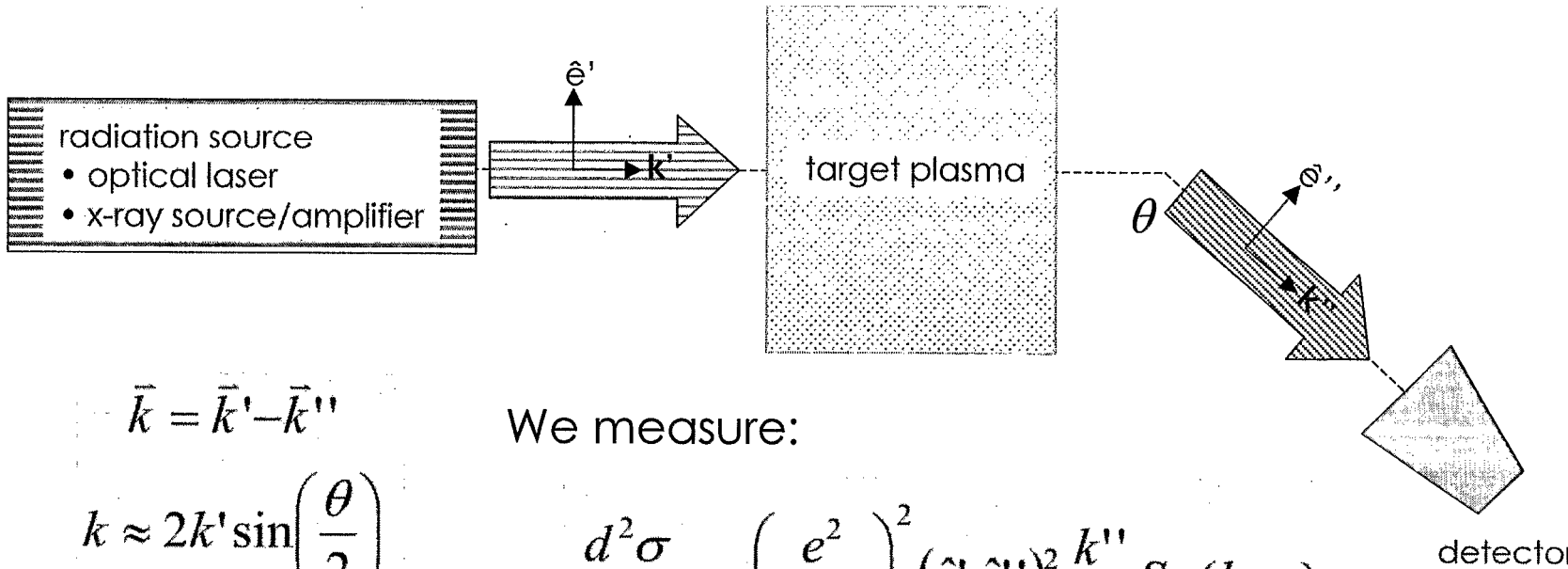
Michael S. Murillo & Jérôme Daligault

Theoretical Division

Los Alamos National Laboratory

Los Alamos

Experimental Configuration: Thomson Scattering



$$\vec{k} = \vec{k}' - \vec{k}''$$

$$k \approx 2k' \sin\left(\frac{\theta}{2}\right)$$

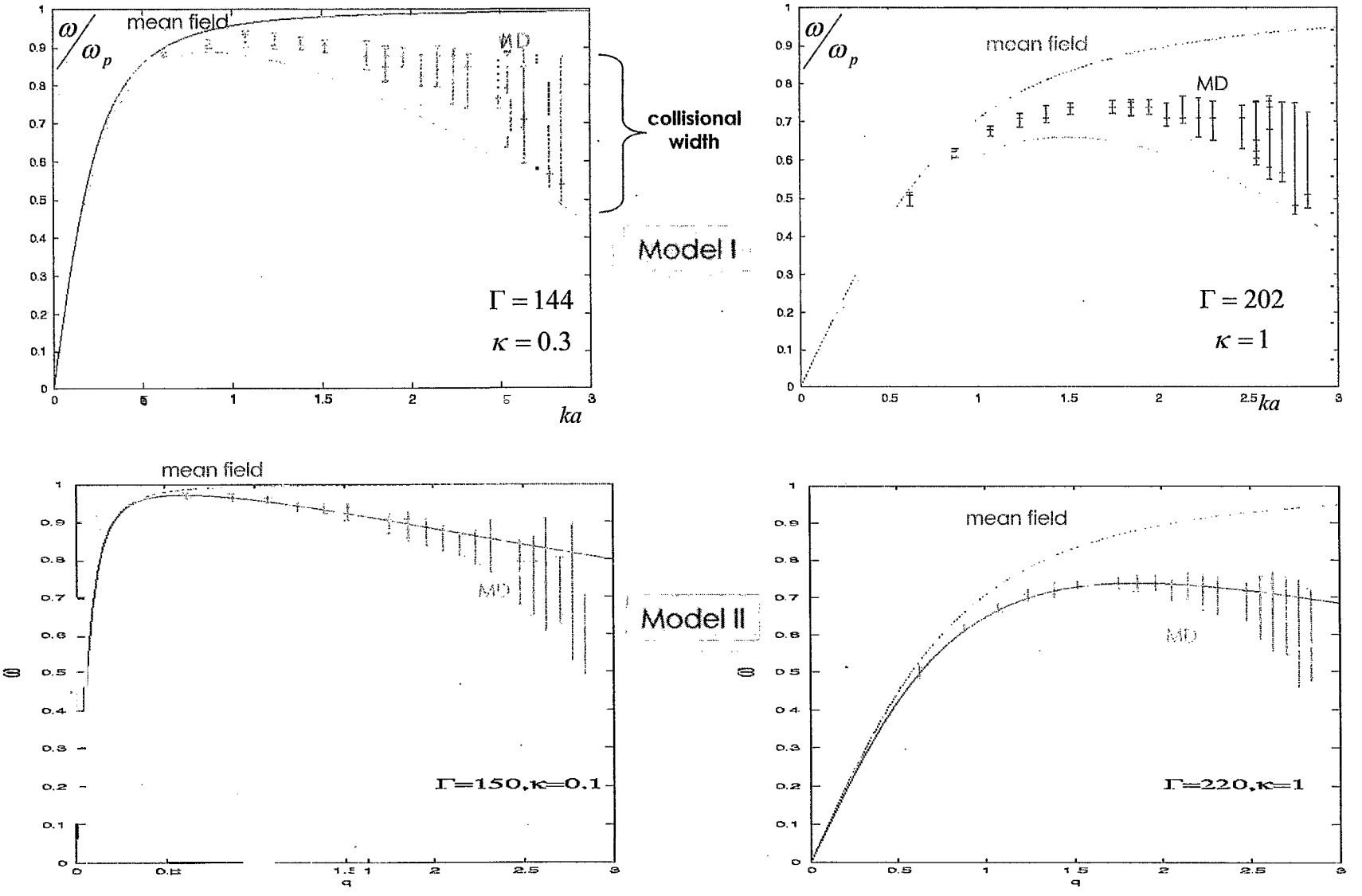
$$\alpha = (k\lambda_D)^{-1}$$

We measure:

$$\frac{d^2\sigma}{d\Omega d\omega} = \left(\frac{e^2}{mc^2}\right)^2 (\hat{e}' \cdot \hat{e}'')^2 \frac{k''}{k'} S_{ee}(k,\omega)$$

Different source properties and observation angles explore different physics:

Sum-Rule Models Compared with Simulation



MD data courtesy: S. Hamaguchi (Univ. of Kyoto)

Beyond Mean-Field: Local Field Corrections

A common representation is in terms of the susceptibility: $\delta n(k,\omega) = \chi(k,\omega) U_{ext}(k,\omega)$

"susceptibility"

Since the susceptibility is well known, we can immediately write down many results:

$$S(k,\omega) = -\frac{2T}{n\omega}\mathrm{Im}\left[\chi(k,\omega)\right]$$ fluctuation-dissipation theorem

$$S_{IG}(k,\omega) = -\frac{2T}{n\omega}\mathrm{Im}\left[\chi^{(0)}(k,\omega)\right]$$ ideal gas

$$S_{RPA}(k,\omega) = -\frac{2T}{n\omega}\mathrm{Im}\left[\frac{\chi^{(0)}(k,\omega)}{1-u(k)\chi^{(0)}(k,\omega)}\right]$$ mean field

$$\omega^2(k) = \frac{4\pi e^2 n_e}{m} + 3\frac{T}{m}k^2$$

$$S(k,\omega) \equiv -\frac{2T}{n\omega}\mathrm{Im}\left[\frac{\chi^{(0)}(k,\omega)}{1-u(k)\left(1-G(k,\omega)\right)\chi^{(0)}(k,\omega)}\right]$$

"local field correction"

$$\int\frac{d\omega}{2\pi}S(k,\omega) \Rightarrow G(k,0)$$

$$\int\frac{d\omega}{2\pi}\omega^4 S(k,\omega) \Rightarrow G(k,\infty)$$

Dynamic Local Field Corrections: Viscoelasticity

$$\Gamma = 9.7$$

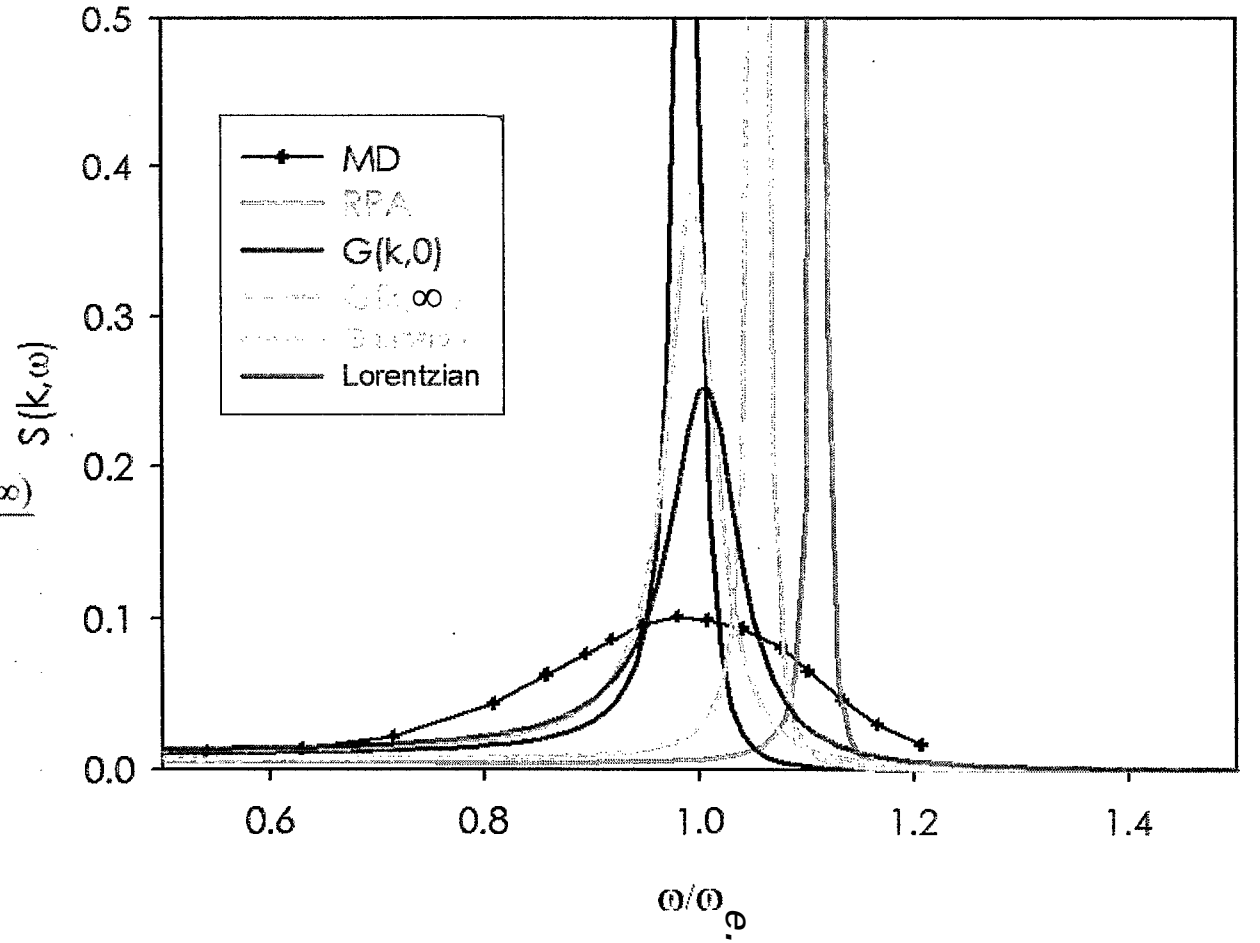
$$ka = 1.38$$

$$G_l(k,\omega) = \frac{G(k,0) - i\omega\tau(k)G(k,\infty)}{1 - i\omega\tau(k)}$$

$$\tau_L(k) = \frac{\tau(0)}{\sqrt{1 + k^2/k_L^2}}$$

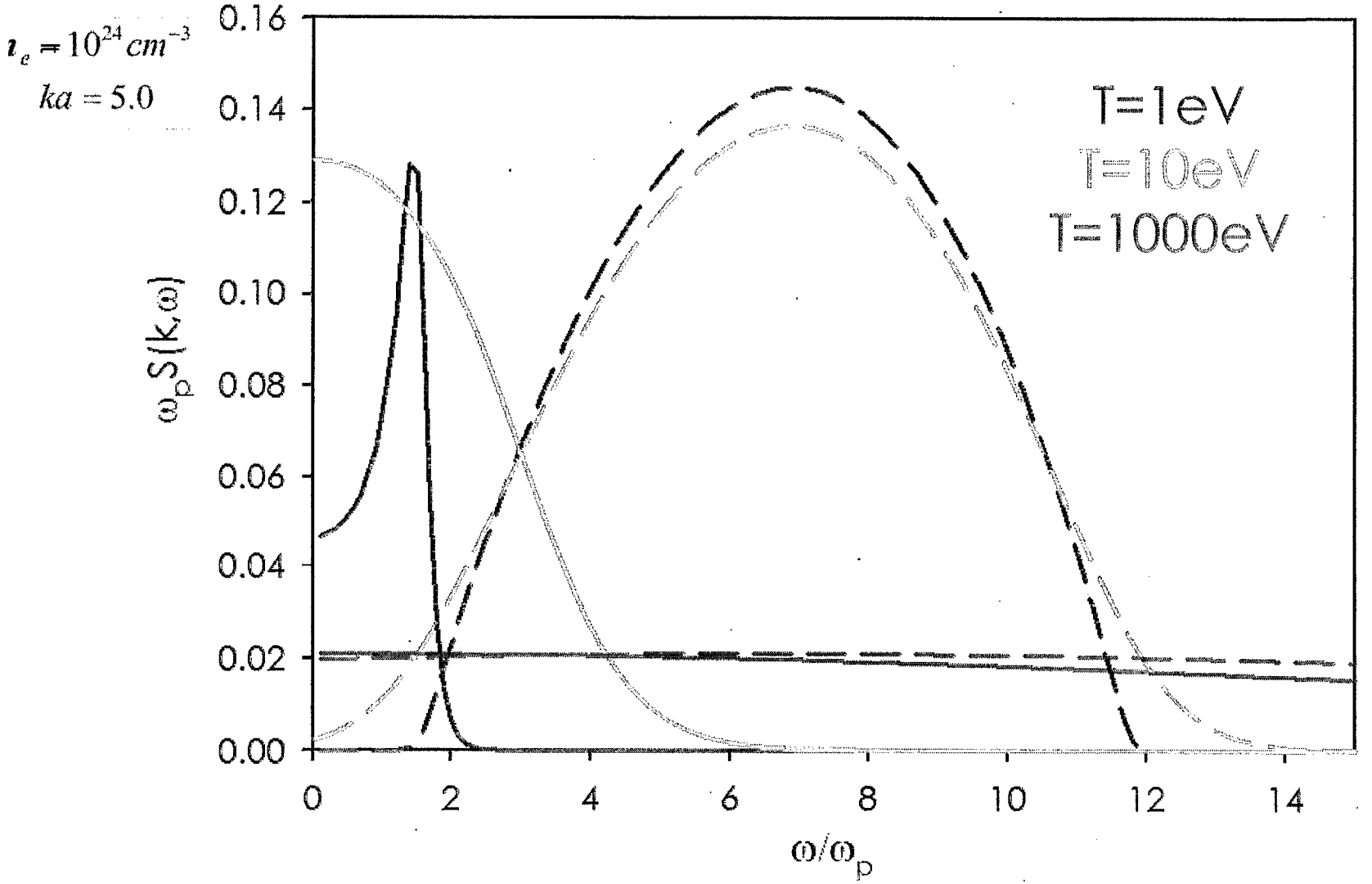
$$\tau_G(k) = \tau(0)\exp\left(-k^2/k_G^2\right)$$

$$\tau(0) = \frac{\eta/nT}{1 - \left(\frac{\partial P}{\partial n}\right)_T / T + \frac{4}{15}U_{ex}}$$



S. Tanaka and S. Ichimaru, *PRA* **35**, 4743 (1987).

Warm Dense Matter: Quantum Gas In Mean Field



Anisotropic Colored Plasmas in Heavy Ion Collisions

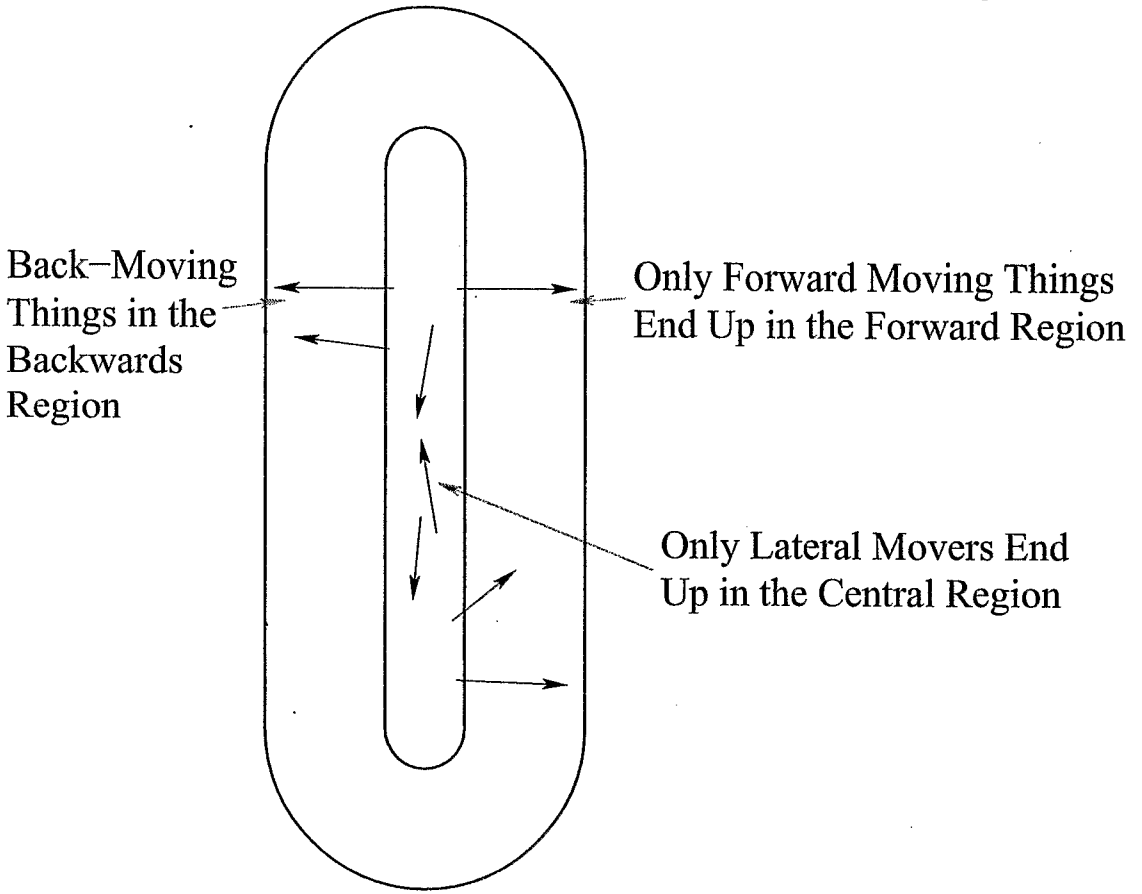
- Why they should (?) be expected
- Similarities and Differences with conventional plasmas
- Possible implications
- Directions for further research

Is a weak-coupling treatment really in contradiction with hydrodynamic behavior as observed at RHIC?

Guy D. Moore P. Arnold, J. Lenaghan, L. Yaffe

Stanislaw Mrówczynski, Mike Strickland, P. Romatschke, A. Rebhan

In the Absence of Further Scattering:



Central plasma is anisotropic (Oblate p distribution).

Quark-Gluon Plasma is –Sort Of– like conventional plasma

There are gluonic fields which obey Maxwell equations.

Small deBroigle wavelength quarks (and gluons!) act like point-particle charges for these gluonic fields

Classical particle + classical field description is justified at leading order in α_s (and underlies Saturation/CGC picture)

Maxwell + Anisotropy $\Longrightarrow$ Weibel Instability

Does instability matter?

If I assume

1. Saturation picture, $f(Q_s) \sim \alpha_s^{-1}$ at $t \sim Q_s^{-1}$
2. $\alpha_s \ll 1$
3. Bjorken hydrodynamics (1-dimensional expansion)
4. No (other) fast isotropization mechanism

Then exponentiation timescale for instability always shorter than age of plasma for all $t > Q_s^{-1}$. Probably.

Arnold, Lenaghan, GDM hep-ph/0307325 (JHEP0308:002)

Key Dynamical Question

Do soft $\boldsymbol{B}$ fields grow to the scale

$$A_\mu \sim \frac{p_{\rm typical}}{g} (= Q_s/g), \quad B \sim \frac{m_{\rm D}\, p_{\rm typical}}{g}$$

the scale where $R_{\rm Lamor} \sim m_{\rm D}^{-1}$ the coherence length, and where $B^2 = \rho_B \sim \rho_{\rm total}$,

Or do they saturate at

$$A_\mu \sim \frac{m_D}{g}, \qquad B \sim \frac{m_{\rm D}^2}{g}$$

where nonabelian interactions become important (gauge fields mutually interact, charges color-rotate on the $\boldsymbol{A}$ field coherence length, *etc)?*

Preliminary results

A appears to saturate at the nonabelian scale

Subsequent cascade of energy from m_{D} scale to larger k gauge fields

Totally different dynamics than in Abelian plasma

Enough for isotropy at all timescales? Not clear

Three Vignettes of the Equation of State and Transport in Dense Plasmas*

Stephen B. Libby
V Division
Physics and Advanced Technologies
LLNL
University of California

Three basic laser-plasma situations were used to illustrate the measurement, computation, degree of control and understanding of basic transport and equation phenomena in high energy density physics. These were: 1-two modes of inertial fusion - 'hot spot' ignition driven by convergent shocks, and 'fast ignition' driven by a short pulse laser generated relativistic electron beam. A related topic is the development of K-alpha sources both for investigating relativistic electron propagation in dense plasmas and using the K-alpha x-rays as a backlighter. 2 – the dielectric function and electrical conductivity of short pulse driven plasmas and exploding wires. 3 – laser-plasma x-ray conversion, necessitating understanding the dynamics of non equilibrium radiative behaviors – "NLTE" physics.

In the first instance, both fusion schemes and K-alpha production rely on the understanding of dE/dx for both slow, heavy ions, and relativistic electrons in hot dense media. As might be expected for a Coulomb scattering problem, dE/dx is complicated by the subtle interplay of infrared and ultraviolet divergences. L. Brown has shown recently that dimensional regularization is a useful way to sort out these effects. It is also important to stress the fact (due to kinematics) that particle ranges increase enormously as the average plasma electron velocity exceeds that of the projectile in question.

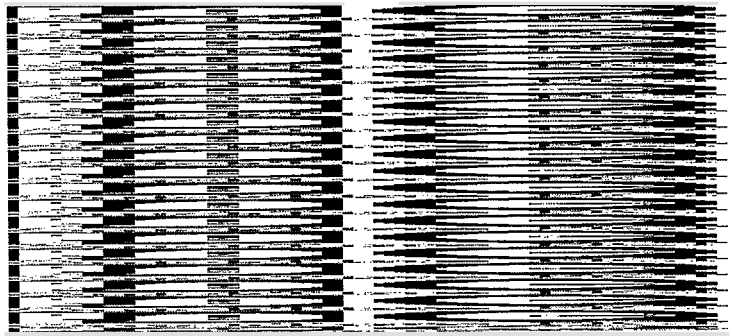
Electrical conductivity importantly enters the applications and study of both pulsed power and laser produced high energy density plasmas. Several reasonably effective methods exist for computing plasma electrical conductivities in the strongly coupled, dense plasma regime. For example, the 'Ziman formula' is applicable for liquid metals and dense plasmas because the static structure factor S(q) and the screened pseudopotential $v_s(q)$ seen the by conduction electrons are peaked in the same q region. However, such methods are all effectively 'Boltzmann closures' enforcing average relaxation times at the expense of effects such as possible coherent backscattering. These issues require the use of the linear response Kubo formula, and carefully assessing the role of all diagrams. Surprisingly, recent experiments in both exploding wires and short pulse laser-plasma reflectivity have given preliminary evidence that such effects (more typical of low temperature condensed matter physics) may occur in few volt plasmas at densities between .1 gr/cc and .0001 gr/cc.

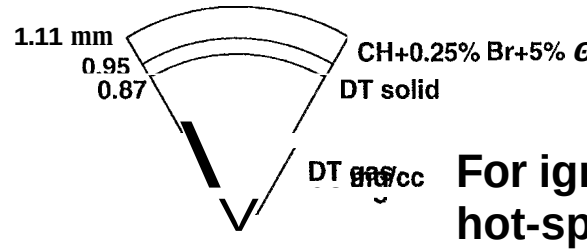
Non-local thermal equilibrium (NLTE) radiation transfer is ubiquitous in laser-plasma applications. Unlike 'local thermal equilibrium' (LTE) where all ion populations and the Maxwellian continuum are characterized by a single electron temperature, in NLTE the ion populations depend on the full non-Planckian radiation field. While arbitrary transient NLTE phenomena remain quite difficult to compute, the special case of near equilibrium steady state NLTE can be treated with a 'linear response' method that effectively determines all possible atomic ion responses in terms of a single precomputed matrix that captures the entropy flow.

Finally, several important topics were left out because of time constraints. These include the Dharmawardana – Perrot theory of non-equilibrium relaxation in multi-temperature plasmas as well as the Dashen-Ma-Bernstein-Rajaraman theory of the equilibrium equation of state in terms of the relevant S-matrix elements. F. Rogers's ACTEX (activity expansion) plasma EOS code is a practical implementation of the latter philosophy for dense plasmas where it is crucial to consistently include both ionic bound and continuum scattering states.

* UCRL-PRES-208781. Work Performed under the auspices of the US Department of Energy by LLNL under contract No. W-7405-ENG-48

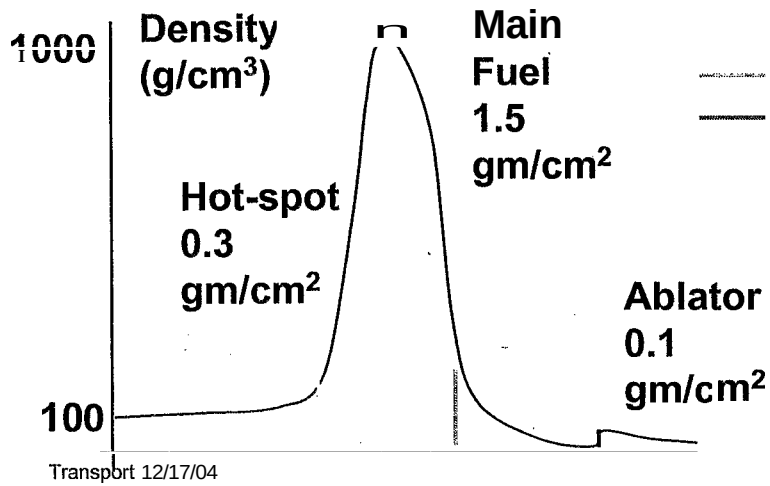
Ignition Target Designs Rely on EOS and Alpha Particle Stopping (dE/dx) in Compressed, Shocked Capsule. Alpha Particle Ranges are Sensitive to Coulomb 'Divergences' and are Strongly Temperature Dependent



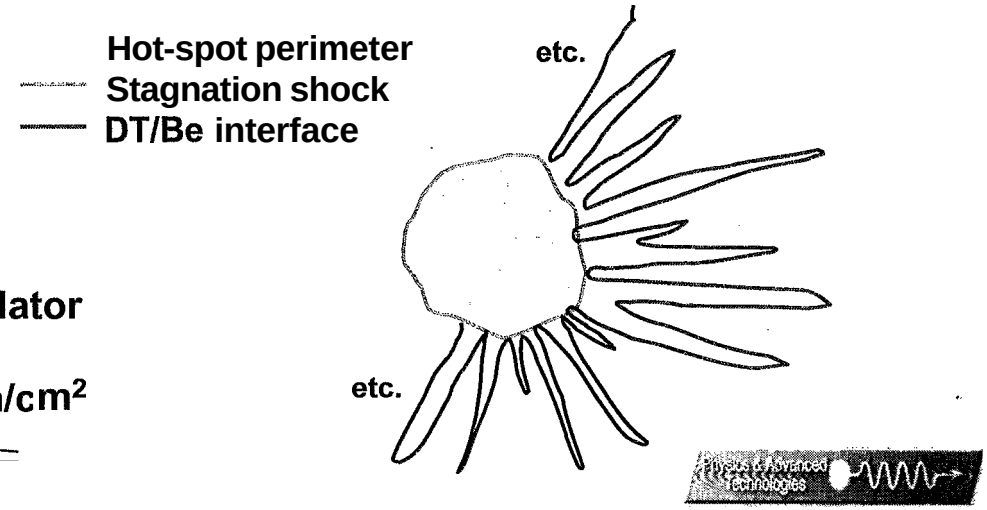


For ignition, need hot-spot with $T_{ion} \sim 10$ keV, $\rho R_{HS} \sim 0.3$ g/cm^2

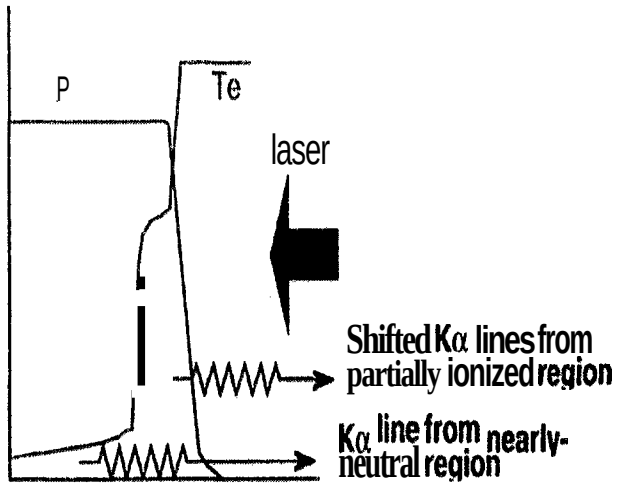
I D picture



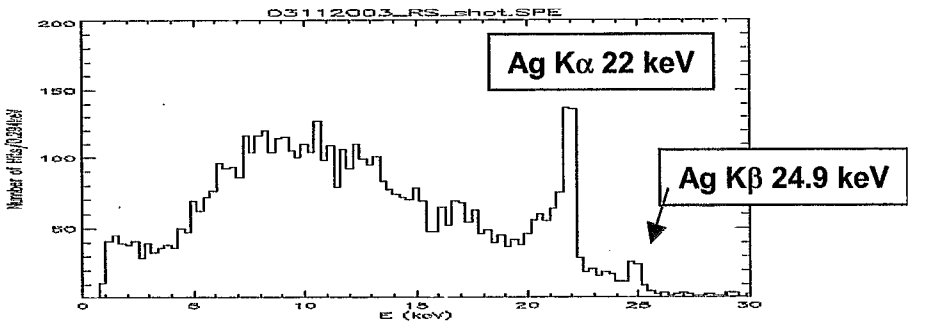
2D or 3D picture



Atomic Physics Considerations for Kα Emission



Ag 192 J Vulcan $2x10^{17}$ W/cm^2 (H-S Park '03)



- K_α experiments serve both a fast electron velocity distribution and dE/dx diagnostic and for the development of petawatt driven hard x-ray backlighters. Interpretation of experiments requires attention to atomic physics issues.
  - Detailed relativistic energy shifts and electron impact cross sections are required to get an accurate picture of the emission spectra and fluorescent yield.
  - The problem of the relaxation of a non-Maxwellian electron distribution in the presence of NLTE atomic physics is analogous to that of NLTE radiation transfer.
  - Radiation trapping?

Ka emission depends on e-transport and atomic processes over
a wide temperature range

The 'Ziman Formula' for Resistivity is the Workhorse for Liquid Metals and Warm Dense Plasmas – However it is an effective 'Boltzmann closure' - Contrast with the Exact Kubo Formula

- Ziman formula utility: typical structure factors S(q) for dense disordered 'metallic' media are peaked at the peak of the screened pseudopotential $v_s(q)$ seen by conduction electrons

$$\rho = \frac{6\pi^2}{h}\frac{1}{j_f^2}\frac{1}{N}\int_0^1 |v(q)|^2 S(q) 4\left(\frac{q}{2k_f}\right)^3 d\left(\frac{q}{2k_f}\right)$$

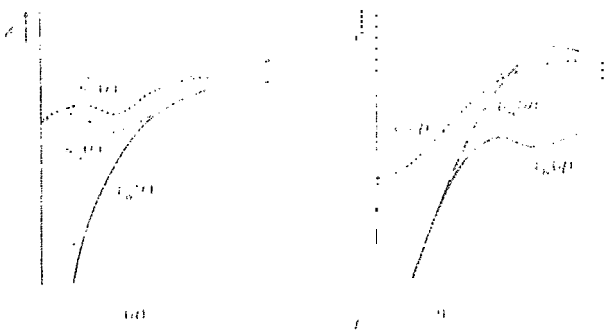


Fig. 10.3. Bare and screened pseudopotentials (a) in real space (b) in reciprocal space

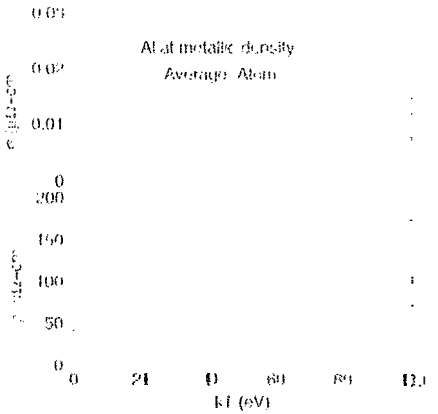


Figure 2. Conductivity and resistivity of Al from the Ziman formula in the plasma state from the average atom code

via G. Bertsch, C. Guet, and W. Johnson, finite temperature DFT-Ziman calculation.

- Kubo Formula for Linear Response Treatment of Conductivity (exact):

$$\sigma = \frac{\pi e^2}{m\Omega}\sum_{\alpha}\sum_{\beta\neq\alpha}(p_x)_{\alpha\beta}(p_x)_{\beta\alpha}\,\delta\left(E_\alpha - E_\beta - \frac{h\omega}{2\pi}\right)\frac{f_\beta - f_\alpha}{\omega}$$

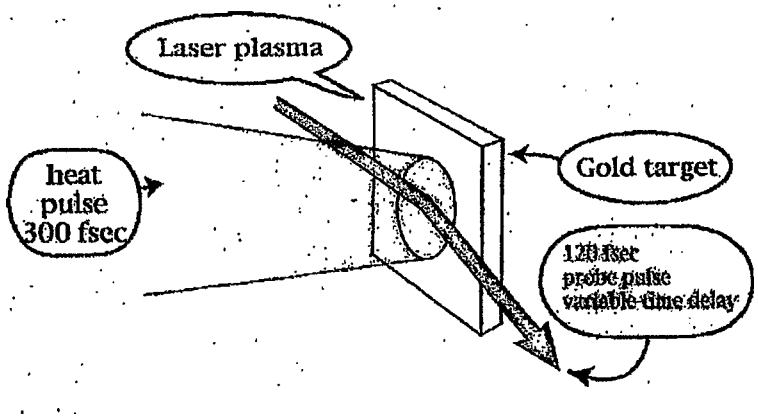
Short Pulse Laser and Pulsed Wire Array Experiments Producing 1- 5 eV expanded plasmas give surprising evidence for unusually low, finite ω, conductivities

- **Present Motivation:**
  - **Theory and experiment give evidence for conductivities below 'Ioffe-Regel' minimum 'metallic' conductivity for a variety of plasmas with**

$$\frac{1}{2}eV \le kT \le 5eV \qquad .0001 \le \frac{\rho}{\rho_{solid}} \le .1$$

  - **M. Desjarlais et. al., *Contrib. Plasma Phys.* 41 (2001), H. Yoneda et. al., *Phys. Rev. Lett.* 91, 075004 (2003).**
  - **Ioffe-Regel d.c. metallic conductivity minimum is**

$$\sigma = \frac{2e^2 k_f^2 l}{3\pi h} \quad k_f l_{mfp} \approx 1 \Rightarrow \sigma = \frac{2e^2}{3\pi h l_{mfp}} \approx 10^2\,(ohm-cm)^{-1}$$



$$\varepsilon(\omega) = 1 + 4\pi n_a \alpha(\omega) + \frac{4\pi i \sigma(\omega)}{\omega}$$

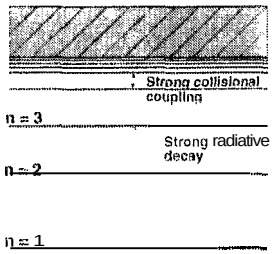
Evidence that the conductivity component σ is anomalously small even after taking into account ionization balance!

Non-Local Thermal Equilibrium States of Plasmas Depend on the Number of Photons per Mode at Every Energy

Local Thermal Equilibrium (LTE) occurs when the ion populations are thermally characterized by the Maxwellian electron temperature T_e. Non-LTE occurs when this hypothesis fails.

- A simple model (Griem) for the electron density required to drive a given level n to LTE is

$$\sum_m C(n,m) + I(n) \geq 10 \sum_{m<n} A(n,m)$$



Electron continuum and ion charge state Q + 1

} Rydberg states near LTE

"Isolated" levels often non-LTE unless sufficient collisions and/or radiation

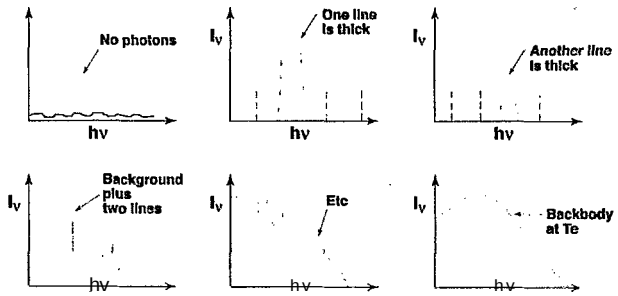
$$N_e(cm^{-1}) \geq \frac{7 \times 10^{18}}{n^{6.5}} Z^7 \left(\frac{KT_e}{Z^2 E_H} \right)^{1/2}$$

Ground state of ion charge state Q

- Radiative effects play a key role in driving LTE in many situations
- Non-LTE effects are significant in laser-plasma experiments
- Our radiation transfer models often need to account for NLTE

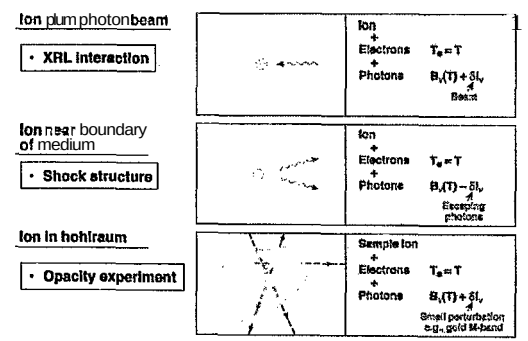
P02274-abl-u-003

Non-LTE In a mufti-dimensional space?



- Each photon frequency-group is another degree of freedom
- The state of the atom is determined by the set of variables ρ, Te, $\{I_\nu\}$

Many near-LTE plasmas can be analyzed using the linear-response method



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Near-LTE non-LTE is a precisely-defined class of states

$\rho, T_e, \{I_\nu\}$ — for 50 groups, a 52-dimensional space

Write $I_\nu = B_\nu(T_\nu)$

Near LTE, photon group temperature $T_\nu = T_e + \delta T_\nu$

Near LTE, expect

$$(\kappa_\nu^a - \kappa_\nu^e) B_\nu = \sum_{\nu'} R_{\nu,\nu'} \delta T_{\nu'} + O(\delta T^2)$$

$R_{\nu,\nu'}$ = linear response matrix for near-LTE non-LTE

$R_{\nu,\nu'}$ r ion in LTE with per $\delta T_{\nu'}$

Photons at energy hν' change t

P03364-mm-u-032

The effect of radiation on non-LTE atomic kinetics in hot dense plasmas can be understood from the view point of non-equilibrium thermodynamics*

- Our Strategy: extract NLTE physics in simpler way near LTE limit avoiding computational explosion (complexity example: M shell iron - 10^3 configurations like $1s^2 2s^2 2p^6 3s3p^2 3d5d \rightarrow 10^6$-$10^7$ lines – as Z increases the number of lines grows fast!)
- Earlier ideas: for electron dominated plasmas, Pitaevski, Gurevich, and Beigman studied electron currents in principal quantum number space (L&L vol. 9); also Scovil and Schulz-Dubois analyzed the steady state maser as a Carnot engine, PRL 2,1959. (also note analogous treatment of the Overhauser effect).
- We study the linear response of an LTE atom (ion) subject to a steady imposed radiation spectrum I, constituting effective temperature shifts δT_ν away from $B_\nu(T_e)$.
- The resulting Response Matrix in frequency group space $R_{\nu\nu'}$ naturally separates the problem of radiation – hydrodynamics from the underlying kinetics and lines.
- Because $R_{\nu\nu'}$ expresses entropy flow, it obeys Onsager constraints.
  - $R_{\nu\nu'}$ is symmetric and has a straightforward form in terms of the plasma rate coefficients. Consistency test for NLTE codes.
  - The principle of minimum entropy production is obeyed.
  - Computed examples in 3 NLTE models show a large range of linear response.
  - Inline $R_{\nu\nu'}$ tabulation scheme offers enormous NLTE rad-hydro acceleration.

- * Libby, Graziani, More, Kato, 13th conf. LIRPP, AIP 1997; More, Kato, Faussurier. Libby. JQSRT, 2001; DeCoster, JQSRT, 2001.

MEASUREMENT OF SCREENING EHHANCEMENT TO NUCLEAR REACTION RATES USING A STRONGLY-MAGNETIZED, STRONGLY CORRELATED NONNEUTRAL PLASMA

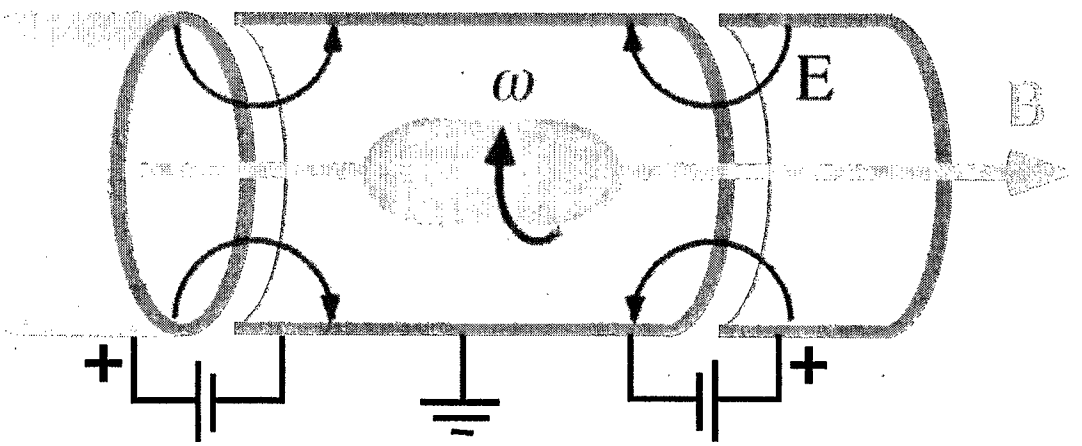
Dan Dubin, Dept. of Physics UCSD
Supported by the NSF/DOE partnership

ABSTRACT:
In the hot dense interiors of stars and giant planets, nuclear reactions are predicted to occur at rates that are significantly enhanced compared to the low density Gamow rates. As first discussed by Salpeter and others around 50 years ago, the reason for the enhancement is that the surrounding plasma screens colliding pairs, increasing the probability of the close collisions that are required for nuclear reactions. In two manuscripts Dubin PRL, Jensen PRL, in press 2004) we show how this predicted enhancement can be studied and experimentally tested over a wide range of parameters for the first time. The tests can be done at low energy by studying the energy equipartition rate of ions stored in a Penning trap and laser cooled to milliKelvin temperatures, where the ions form a strongly coupled plasma. In the strong magnetic field of the Penning trap the the trapped ions execute rapid cyclotron motion. The kinetic energy of this motion is an "adiabatic invariant". Like nuclear energy, this cyclotron energy is released only through rare close collisions between ions that break the adiabatic invariant. When the plasma is strongly correlated, close collisions are more likely because of plasma screening and the rate of cyclotron energy release is enhanced, in just the same manner as for nuclear reactions. Experiments at NIST with laser cooled Be* ions have observed a release of cyclotron energy which is more than 10 orders of magnitude faster than that predicted by theory without the enhancement factor

How can a nonneutral plasma have anything to do with nuclear reaction rates??

Nonneutral plasma:
collection of charges of like sign :
eg. pure ion plasma (Be^+)

pure ion plasmas can be confined for *days* in the static electric and magnetic fields of a Penning trap

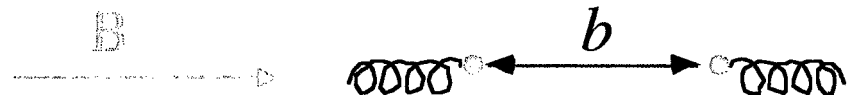


B ~ 4 Tesla
E ~ 10Volt/cm
ω ~ 30 kHz
n ~ 10^8 cm^{-3}
T ~ 0.001K - 10^4 K

Nuclear reactions are NOT happening.

But something analogous to nuclear reactions IS happening!

Higher parallel energy collision:



Release of cyclotron energy requires close collisions to break the adiabatic invariant :

$$\boxed{b/v_{\parallel} \lesssim 1/\Omega_c} \quad \text{or} \quad \boxed{b\Omega_c/v_{\parallel} \lesssim 1}$$

Collision timescale

Adiabaticity **parameter**

So $K_{\perp}$ is internal energy, like nuclear energy.

Close collisions release this energy

In cold, strongly-magnetized plasma, most collisions have $b\Omega_c/v_{\parallel} >> 1$
Only supertherrnal ions release the cyclotron energy

What effect does Debye screening have on the rate (nuclear or equipartition)?

Debye screening decreases energy required for a given distance of closest approach b

No screening:

$$E_{\|} = e^2/\mathfrak{b}$$

$$\nu = \int dE_{\|} \frac{1}{T} e^{-E_{\|}/T} \sigma(E_{\|})$$

$$\equiv \nu_o$$

Debye screening:

$$E_{\|} = e^2 e^{-b/\lambda_D}/b$$

$$\cong e^2(1 - b/\lambda_D)/b, \quad \mathfrak{b} << \lambda_D$$

$$= e^2/b - e^2/\lambda_D$$

less energy needed to get the same differential rate

$$\nu = \int dE_{\|} \frac{e^{-(E_{\|} - e^2/\lambda_D)/T}}{T} \sigma(E_{\|})$$

enhancement factor f

$$= e^{e^2/(\lambda_D T_{\|})} \nu_o$$

rate for no shielding

Salpeter '55

$\Gamma >> 1$ in a white dwarf, a giant planet interior, or a nonneutral plasma:

f is very large (Salpeter and van Horn, 1969)
and has never been verified experimentally

I. Strong shielding regime : close collisions still dominate:

$$\frac{e^2}{E_{Gamow}} << a \leftarrow \text{interparticle spacing}$$

$$\Rightarrow \frac{e^2}{T\,\kappa^{2/5}} << a \qquad \boxed{1 << \Gamma << \kappa^{2/5}}$$

Rate is still given by $\boxed{\nu = f(\Gamma)\,\nu_0}$ (Proof: see Dubin, PRL in press)

Ichimaru and Iyetomi: $\boxed{\ln f(\Gamma) = 1.148\Gamma - 0.00944\Gamma \ln\Gamma - 0.000168\Gamma(\ln\Gamma)^2}$

DeWitt and Slattery: $\boxed{\ln f(\Gamma) = 1.05\Gamma - 0.299\Gamma + 1.039957\,\Gamma^{0.323064} - 0.545823\ln\Gamma - 1.13232}$

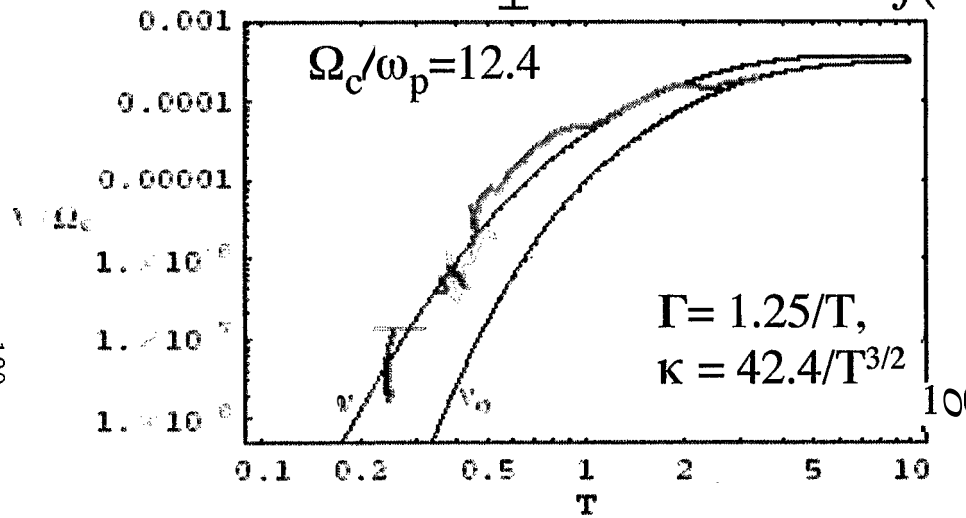
II. Pycnonuclear regime: $\Gamma > \kappa^{2/5}$: theory TBD

Measured equipartition rate
for several simulations:

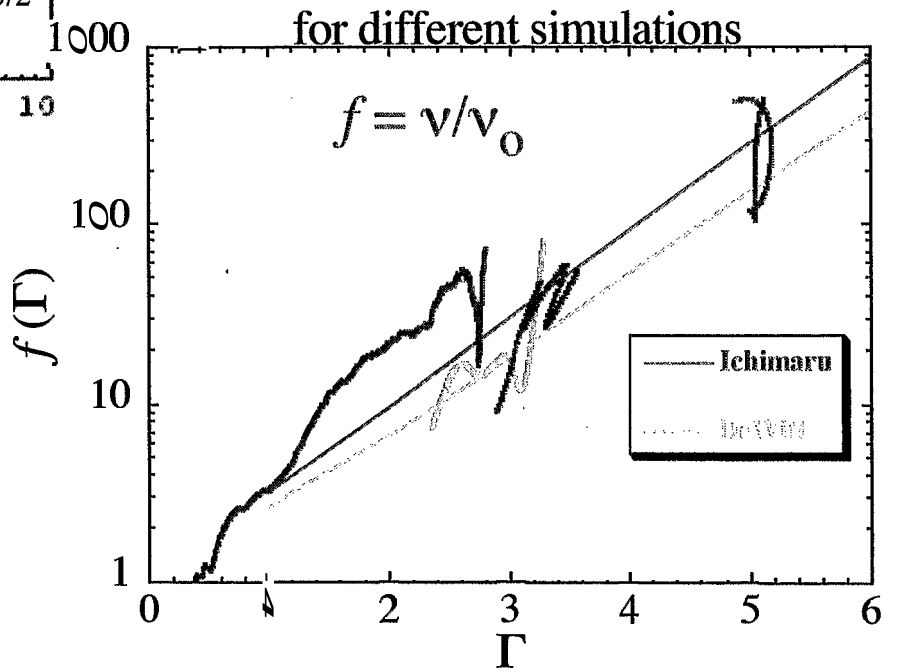
$$\nu = \frac{dT_\perp / dt}{T - T_\perp}$$

ν_o : theory for 2-body equipartition rate

$\nu = f(\Gamma)\, \nu_o$



measured enhancement factors
for different simulations



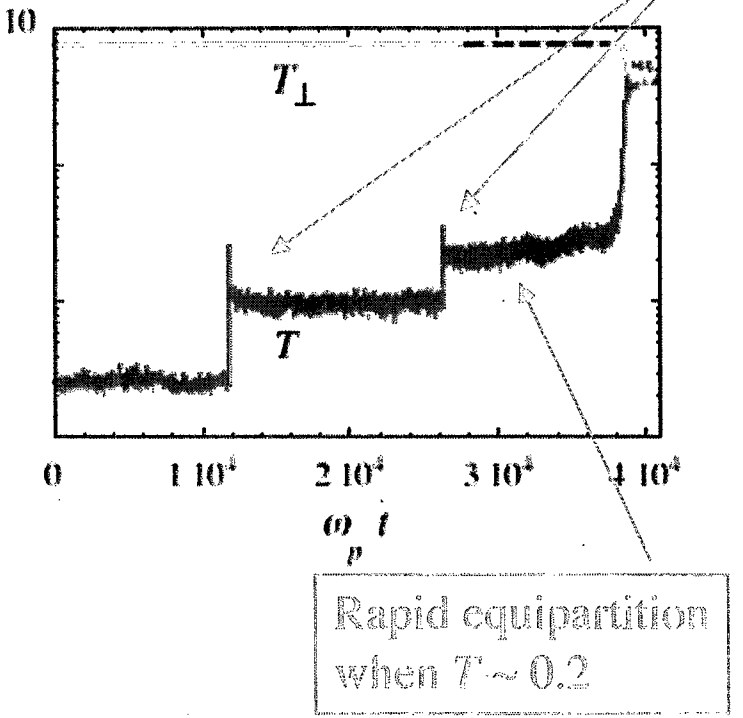
Dubin, PRL in press

MD Simulations of equipartition can measure the rate enhancement factor $f(\Gamma)$

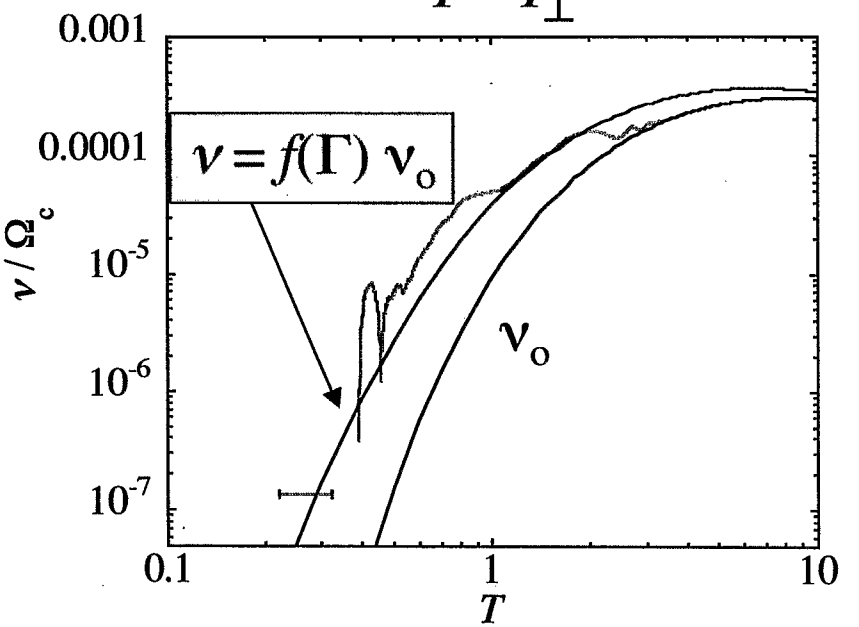
N=200 ions, $\Omega_c/\omega_p = 12.4$.

Parameters chosen so that $\Gamma = 1.25/T$

Start with $T_\perp >> T$. Increase T instantaneously, twice.



$$\nu = \frac{dT_\perp / dt}{T - T_\perp}$$



Strongly-Interacting Cold Atoms

J. E. Thomas

Physics Department, Duke University, Durham, North Carolina 27708-0305

We produce and study a degenerate, strongly-interacting Fermi gas of ^{6}Li atoms. In the experiments, a 50-50 mixture of spin-up and spin-down atoms is magnetically tuned to a Feshbach resonance, where strong interactions are observed, and then cooled by evaporation in a stable optical trap [1, 2].

Near the resonance, the zero-energy s-wave scattering length is large compared to the interparticle spacing, which in turn is large compared to the range of the two-body interaction potential. Under these conditions, the gas is unitary and mechanically stable. Strongly interacting Fermi gases exhibit universal behavior, and therefore provide a paradigm for strong interactions in nature, such as pairing interactions in high temperature superconductors and hydrodynamics in nuclear matter.

We have studied the hydrodynamics of the gas, both in the expansion dynamics and in the collective modes of the trapped cloud. Upon release from a cigar-shaped trap, the cloud exhibits highly anisotropic expansion, standing nearly still in the axial direction, while expanding rapidly in the transverse direction [2]. This behavior is analogous to the "elliptic flow" which is believed to occur in a quark-gluon plasma.

A radial breathing mode is excited in the trapped gas by releasing the cloud for a short time, and then recapturing it. By precisely measuring the frequencies and damping times of this mode as a function of magnetic field and temperature, we test state-of-the-art predictions of the equation of state for this strongly-interacting many-body system. We observe a breakdown in hydrodynamics at high magnetic field and we find that the damping rate decreases linearly with temperature at low temperature. Both of these observations provide evidence for the onset of superfluid hydrodynamics at a high reduced temperature [3, 4].

Recently, we have made the first attempt to measure the heat capacity of a strongly-interacting Fermi gas [5]. We first add a precisely determined energy to the gas. Then, a temperature parameter is determined from the spatial profile of the heated gas. We plot the total energy as a function of the measured temperature pa-

rameter and observe a transition in behavior at a reduced temperature of 0.3. Above this temperature, the gas behaves as a normal Fermi gas of particles with increased mass. Below this temperature, the energy versus temperature exhibits an abrupt change in slope. Using a pseudogap model, which originated in the study of high temperature superconductivity, this change in slope has recently been interpreted as a consequence of high temperature superfluidity [6].

---

[1] J. E. Thomas and M. E. Gehm, "Optically trapped Fermi gases," Amer. Sci. 92, 238–245 (2004).

[2] K. M. O'Hara, S. L. Hemmer, M. E. Gehm, S. R. Granade, J. E. Thomas, "Observation of a strongly interacting, degenerate, Fermi gas of atoms: *Science* 298, 2179 (2002).

[3] J. Kinast, S. L. Hemmer, M. E. Gehm, A. Turlapov, J. E. Thomas, "Evidence for superfluidity in a resonantly interacting Fermi gas," *Phys. Rev. Lett.* **92**, 150402 (2004).

[4] J. Kinast, A. Turlapov, J. E. Thomas, "Breakdown of hydrodynamics in the radial breathing mode of a strongly interacting Fermi gas," *Phys. Rev. A* **70**, 051401(R) (2004).

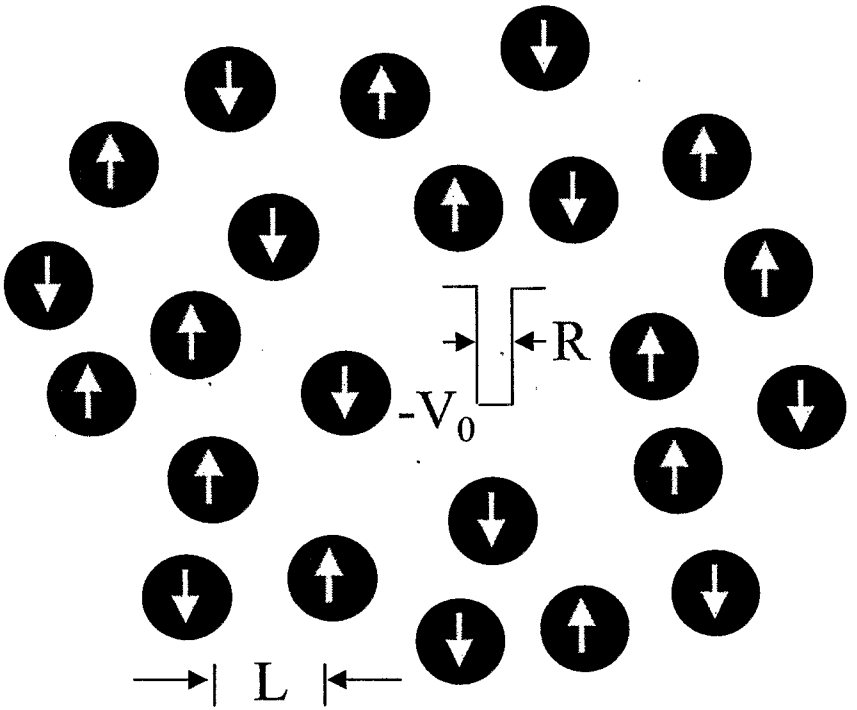
[5] J. Kinast, A. Turlapov, and J. E. Thomas, "Measurement of the heat capacity of a strongly-interacting Fermi gas," arXiv:cond-mat/0409283 (2004).

[6] Q. Chen, J. Stajic, K. Levin, "Thermodynamics of ultracold fermions in traps," arXiv:cond-mat/0411090 (2004).

Universal Interactions at T=0

Duke Physics
Atom Cooling and Trapping

George Bertsch's problem: Furnstahl $a \to \infty >> L >> R \to 0$



$$p_F = \frac{\hbar}{L} \equiv \hbar k_F$$

$$(1+\beta)\frac{\hbar^2 k_F^2(\mathbf{x})}{2M} + U_{\text{Trap}}(\mathbf{x}) = \mu_0$$

O'Hara et al., Science 2002
Heiselberg PRA 2001

$$\boxed{\frac{\hbar^2 k_F^2(\mathbf{x})}{2M^*} + U_{\text{Trap}}(\mathbf{x}) = \mu_0}$$

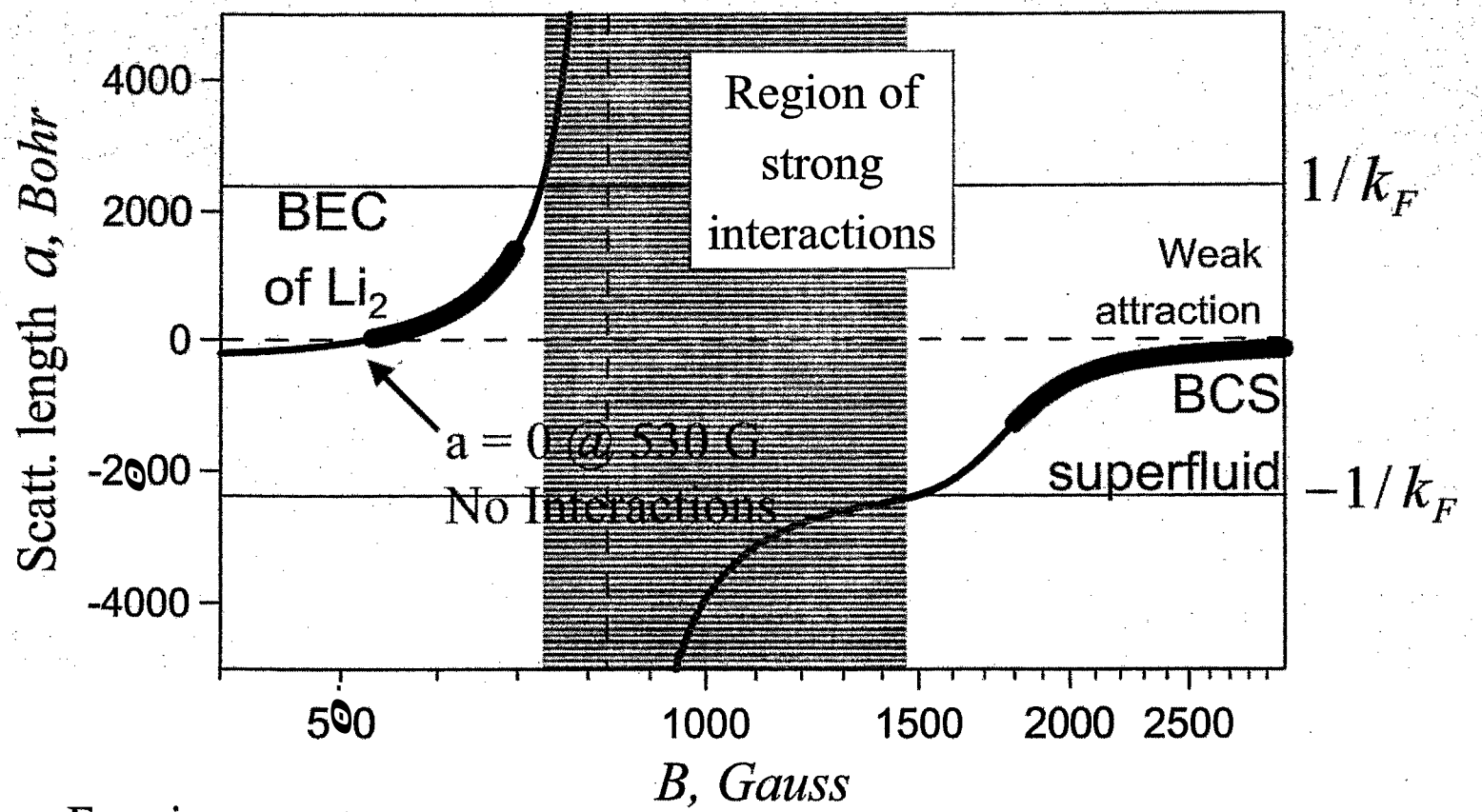
Effective mass: $M^* = \dfrac{M}{1+\beta}$
Baker 1999

Carlson (2003): β = - 0.560
Strinati (2004): β = - 0.545

M* = 2.3 M

Fermi atoms near Feshbach resonance

Duke Physics
Atom Cooling and Trapping



$\hbar k_F$ - Fermi momentum

$1/k_F \sim$ int eparticle distance

Transverse Expansion

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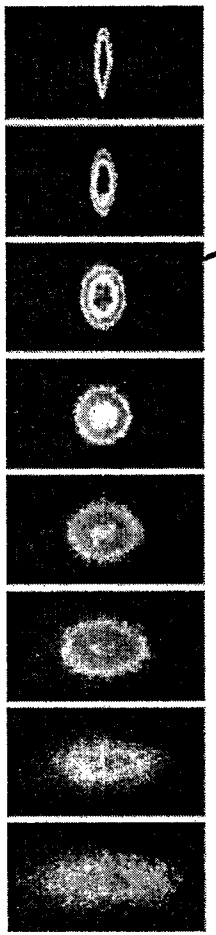
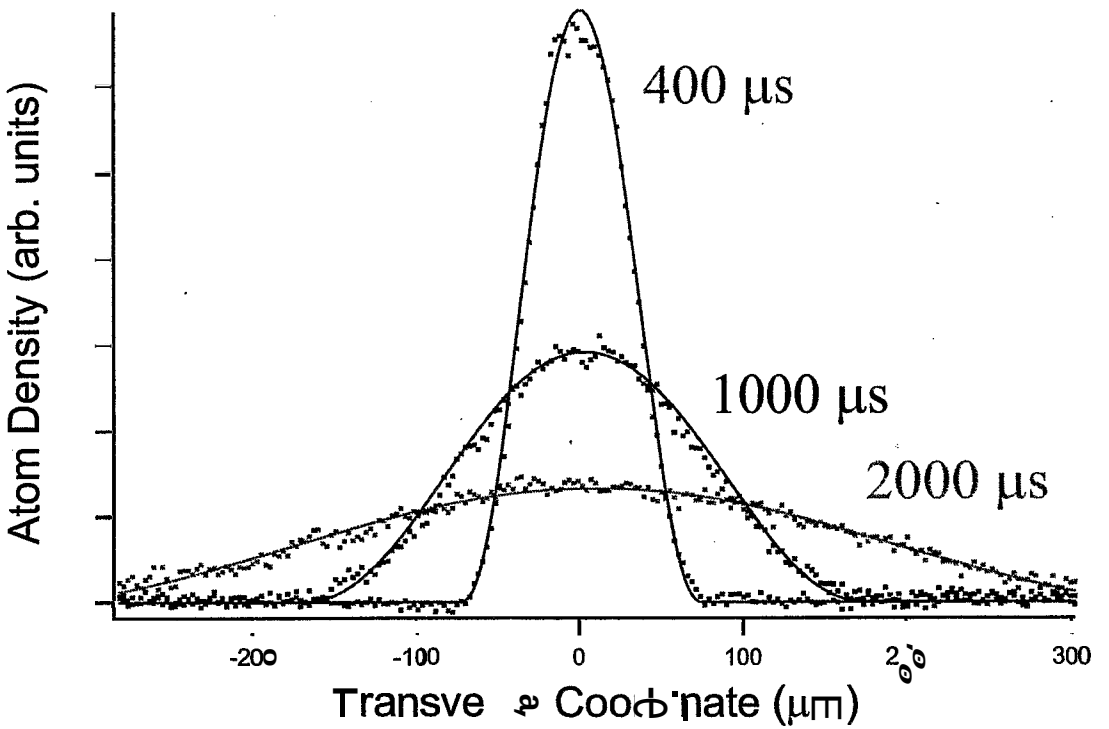


Still Interacting!



Radial Breathing Mode: Damping Rate vs Temperature

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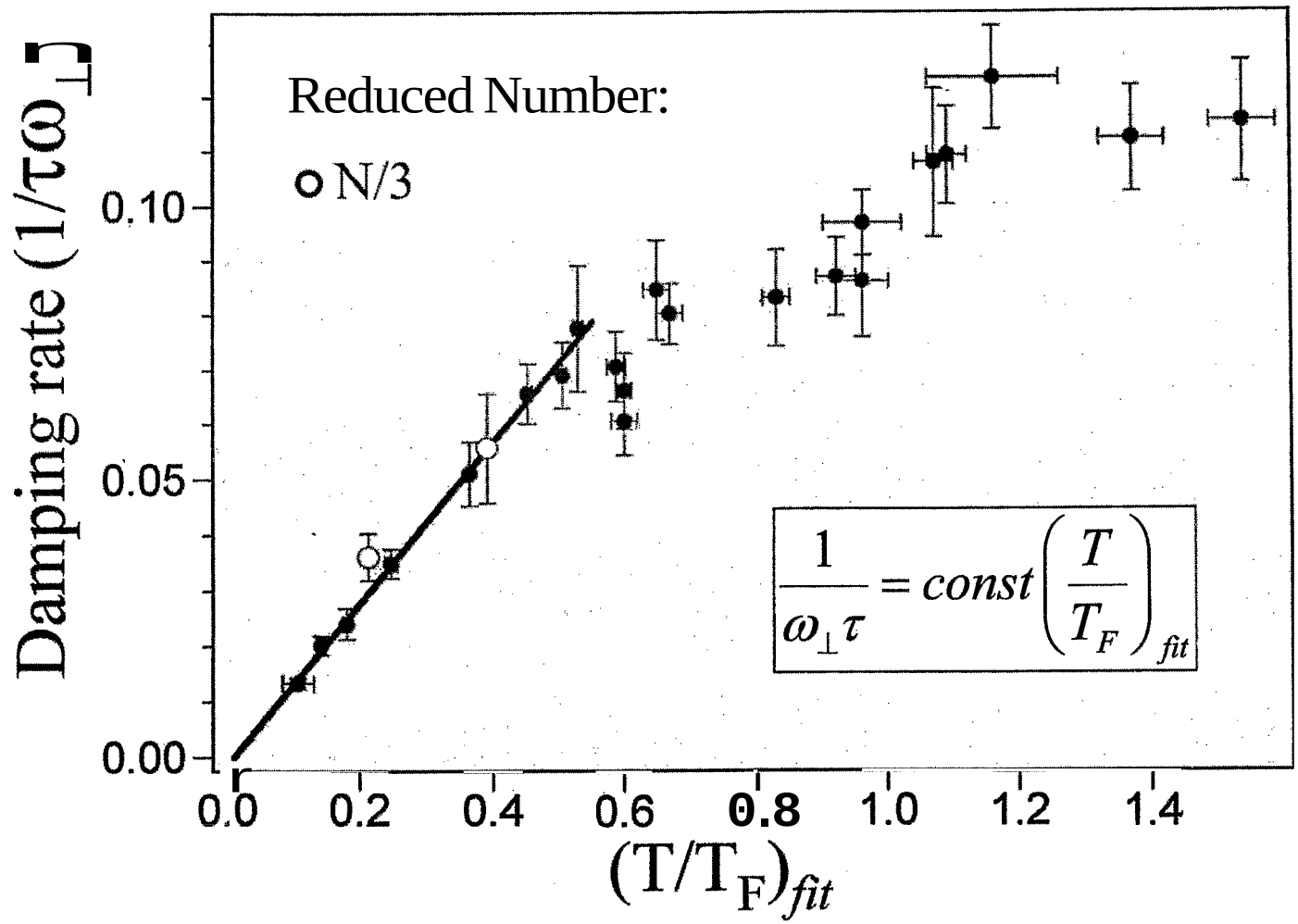
Atom Cooling and Trapping



Input Energy vs Measured Temperature

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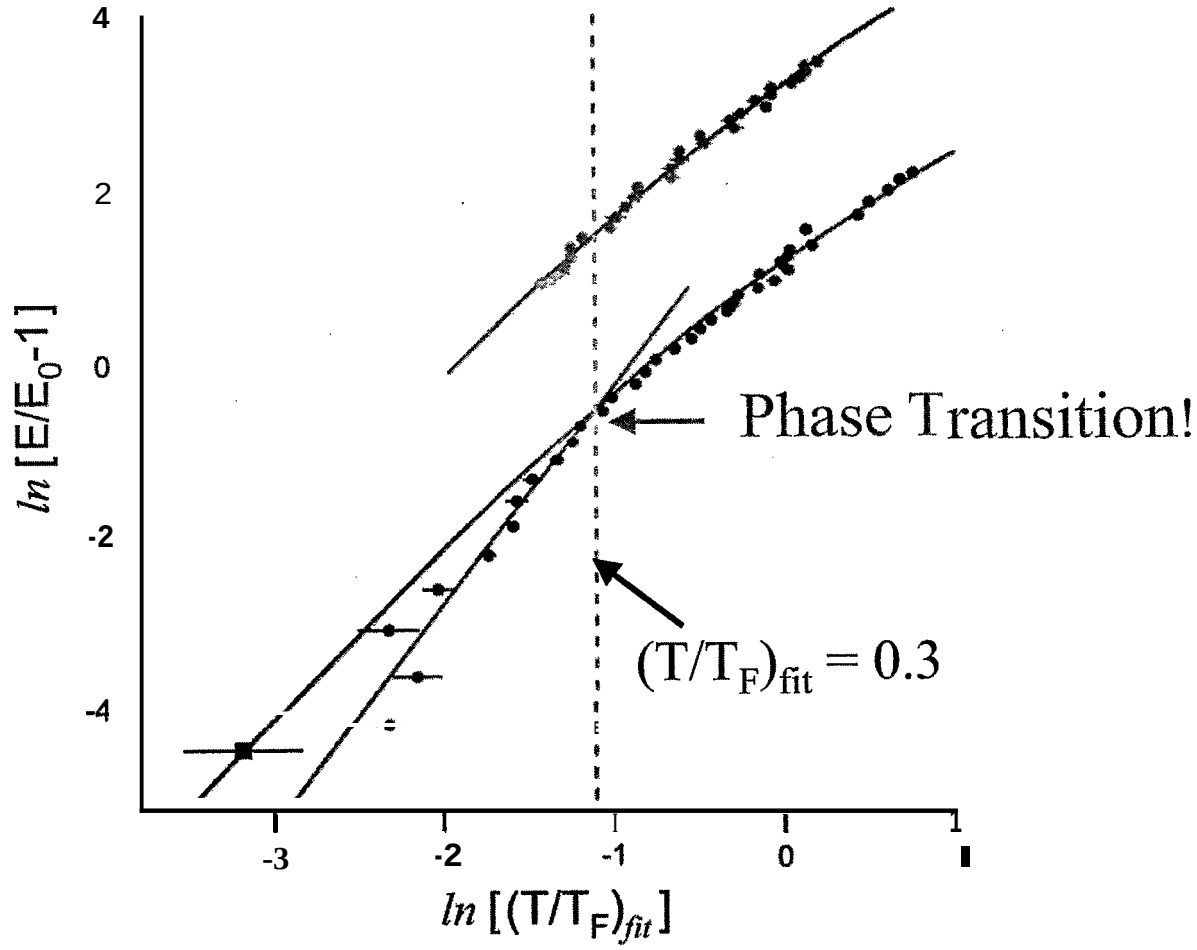
Atom Cooling and Trapping

ln-ln Plot:

— ideal gas
— 5/2 power law



What is common between cold trapped atoms and QGP?

E.Shuryak

Both are near-perfect liquids in strongly coupled regime.

QGP:

- **Potentials strong enough to have multiple bound states, including mostly colored channels. Including those one can understand why**
- EoS is $p/p_{ideal\ gas} \approx .8$ at $T>2T_c$
- QGP seems to be near-perfect fluid

$\eta/\hbar s \sim .1 \sim 1/(4\pi)$ (Ads/cdt result from D.Son et al)

Marginal states? (ESS+Zahed,2003)

Cold atoms:

•Feshbach resonance makes large scattering length

•Universality:

pressure$\approx .5$ of that of ideal Fermi gas at resonance, Although it is mainly made of cooper pairs/molecules and is bosonic in nature

•trapped atoms in a strong coupling regime is a very good liquid as well! We extracted its viscosity $\eta/\hbar n \sim .5 \pm .3$. ``Quantum viscosity" due to uncertainty Relation is a new consept.

- Weak coupling versus strong coupling regime

$n^{1/3}a \ll 1$	$n^{1/3}a \gg 1$
* dilute gas; effective range of inter-atomic forces $r_0 \sim a \ll l \sim n^{-1/3}$	* "densely-packed" liquid $r_0 \sim l \sim n^{-1/3}$ $l -$ *mean free path*
* collisions are infrequent; kinetic description works;	* collisions are frequent; description is in terms of (viscous) hydrodynamics
* viscosity $\eta \sim mn\bar{v}l$ diffusion $D \sim \bar{v}l$	* Fermi liquid picture with weakly interacting quasi-particles breaks down
* at low T system is a weakly interacting gas of (quasi)particles; in Fermi systems Pauli blocking reduces the collision rate: $\eta \sim T^{-2}$	* at $T = 0$ universal relations for transport coefficients: $\eta \sim \hbar n$

Smooth transition from fermi (BCS) to bose (BEC)

(A.Legett,1985)

- The main variable $x=1/ap_F$

X<<-1
Weakly attractive, molecular bound states Which at zero energy is Bose-condensed

X close to 0
The Feshbach Resonance, Here we expect the strongly coupled liquid

X>>1
Fermi side, Attraction only near fermi surface BCS and Cooper pairs

Viscosity and universality

- **There is no need to specify constituents or a mean free path:**
- **Hydro: damping of sound waves can provide a definition**

$$\omega = c_s k + \frac{i}{2}\frac{4\eta}{3mn}k^2$$

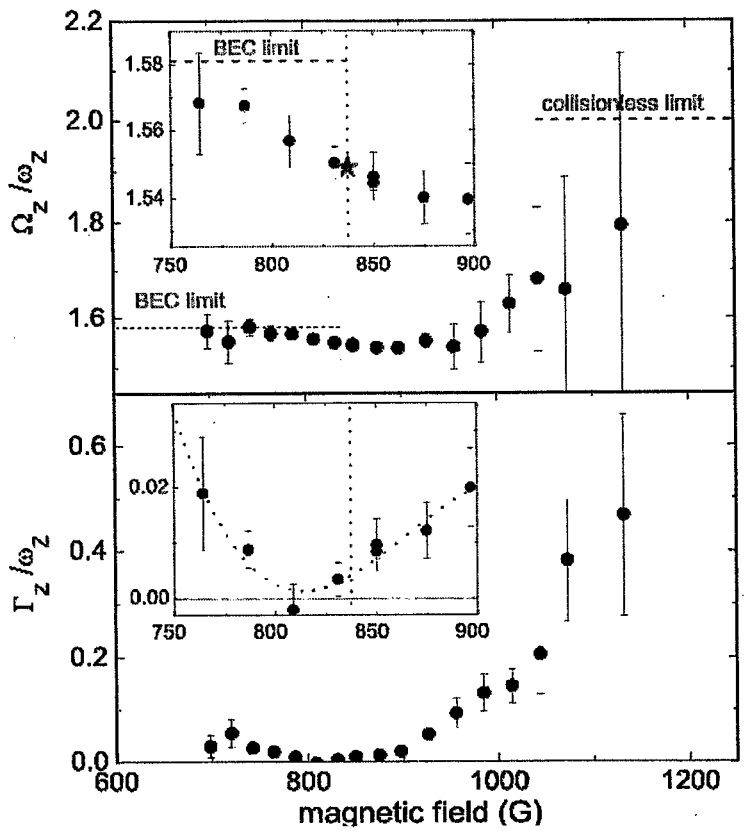
- **For cold atoms quantum viscosity**
- $\eta / \hbar$ **n=**α_η

Should be the universal dimensionless constant

- **Scattering rate must be** $\tau^{-1} \sim \hbar/\varepsilon_F$ **....**

Hydro works for up to 1000 oscillations! The z mode frequency agrees with hydro **(red star)** at resonance, with universal EoS

Viscosity has a strong **minimum there**

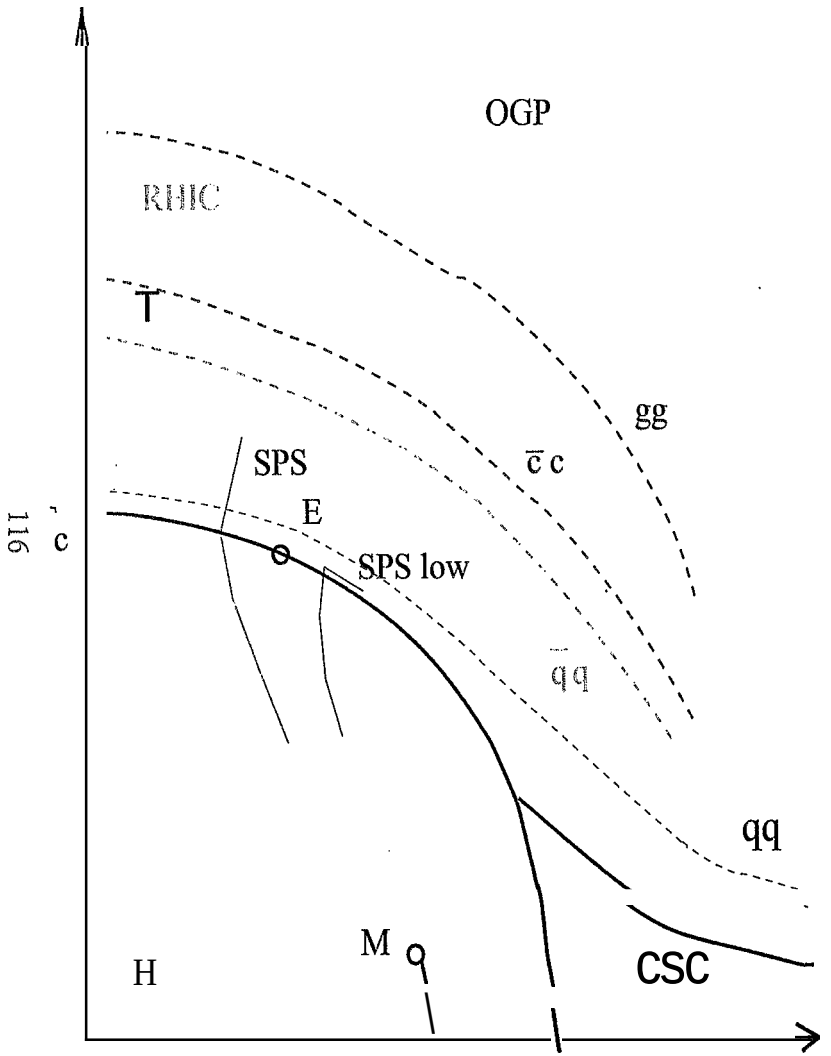


B.Gelman, ES,I.Zahed nucl-th/0410067

$\approx .5 \pm .3$ is reached at the experimental minimum.

•Is it indeed a quantum viscosity?

Bartenstein et al cond-mat/0403716



New QCD Phase Diagram, which includes ``zero binding lines" at which σ can be large! (ES+I.Zahed hep-ph/030726)

The lines marked RHIC and SPS show the paths matter makes while cooling, in Brookhaven (USA) and CERN (Switzerland)

Chemical potential μ_B related to baryon charge

Bound States **Above** T_c

Hong-Jo Park,[a] Chang-Hwan Lee,[a]
presented by Gerald E. Brown[b]

[a] Department of Physics, Pusan National University, Pusan 609-735, Korea
(E-mail: hongjopark@pusan.ac.kr, clee@pusan.ac.kr)

[b] Department of Physics and Astronomy,
State University of New York, Stony Brook, NY 11794, USA
(E-mail: Ellen.Popenoe@sunysb.edu)

Abstract

We discuss the problem of mass, noting that meson masses decrease with increasing scale as the dynamically generated condensate of "soft glue" is melted. We then extend the Bielefeld LGS color singlet interaction computed for heavy quarks in a model-dependent way of including the Ampére law velocity-velocity interaction. Parameterizing the resulting interaction in terms of running coupling constants and including screening, we find that the masses of π, σ, ρ and A_1 excitations, 32 degrees of freedom in all, go to zero (in the chiral limit) as $T \to T_c$ essentially independently of the input quark (thermal) masses, as long as the latter is in the range of $1-2$ GeV, calculated also in Bielefeld. We discuss other LGS which show $\bar{q}q$ bound states, which we interpret as our chirally restored mesons, for $T > T_c$.

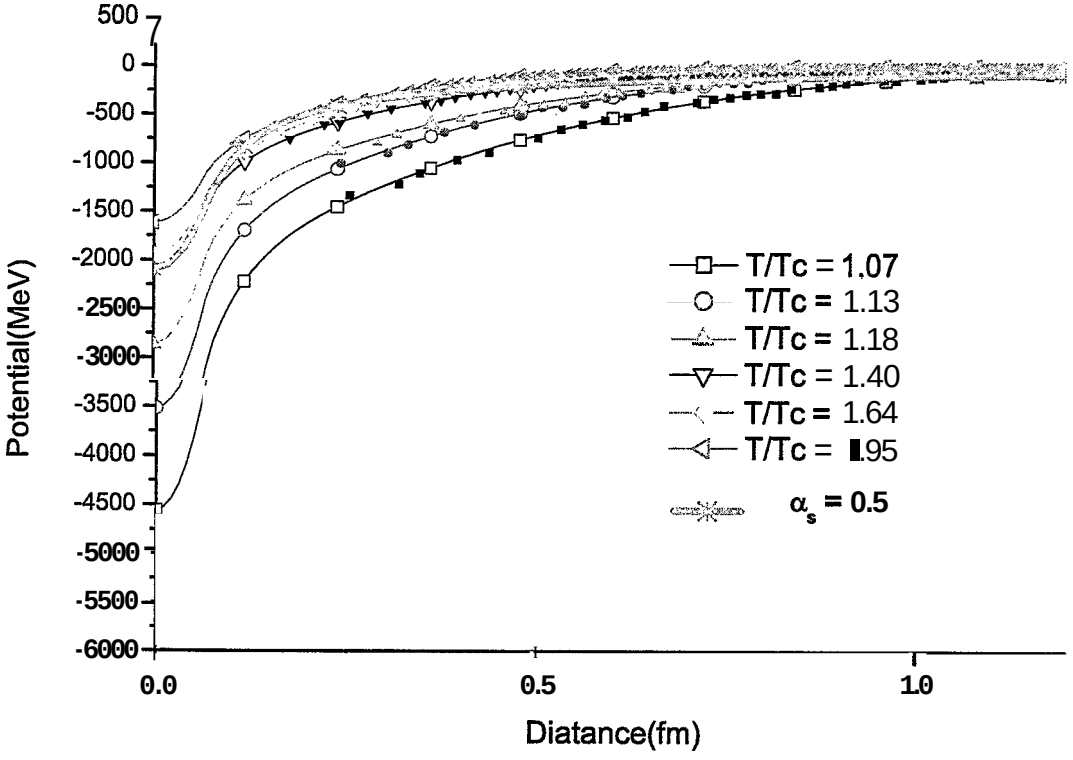


Fig. 1. Potentials from LGS for various T. The Thick line correspond to the Coulomb interaction with constant coupling $\alpha_s = 0.5$. Note that $m_q = 1.4$ GeV is used for the finite quark size effect. The LGS results for $\mathrm{T} = 1.4T_c$ (downward triangle) is close to the Coulomb potential.

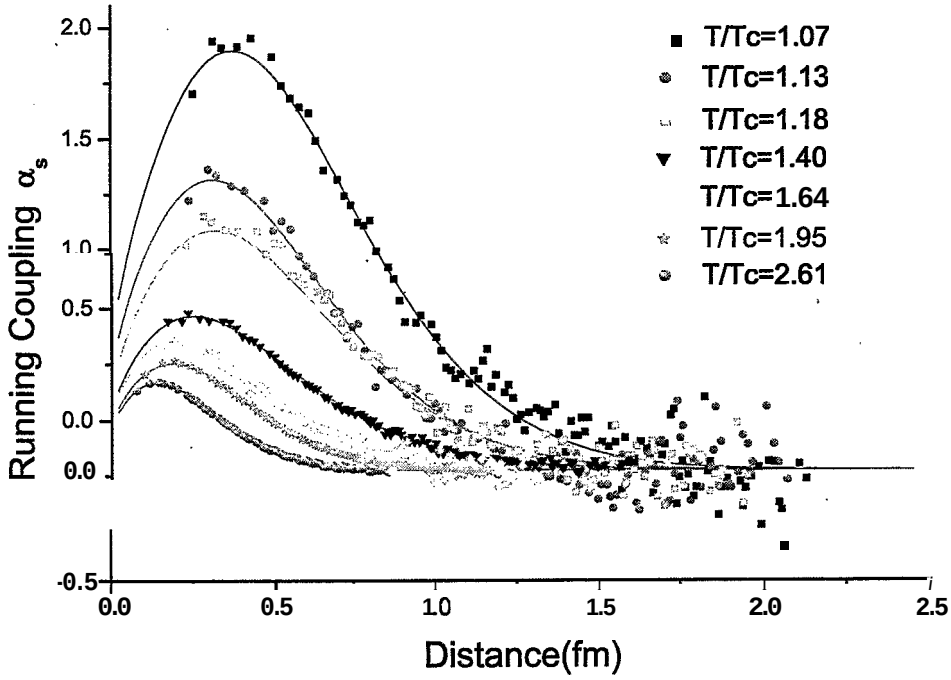


Fig. 2. "Effective Running Coupling"

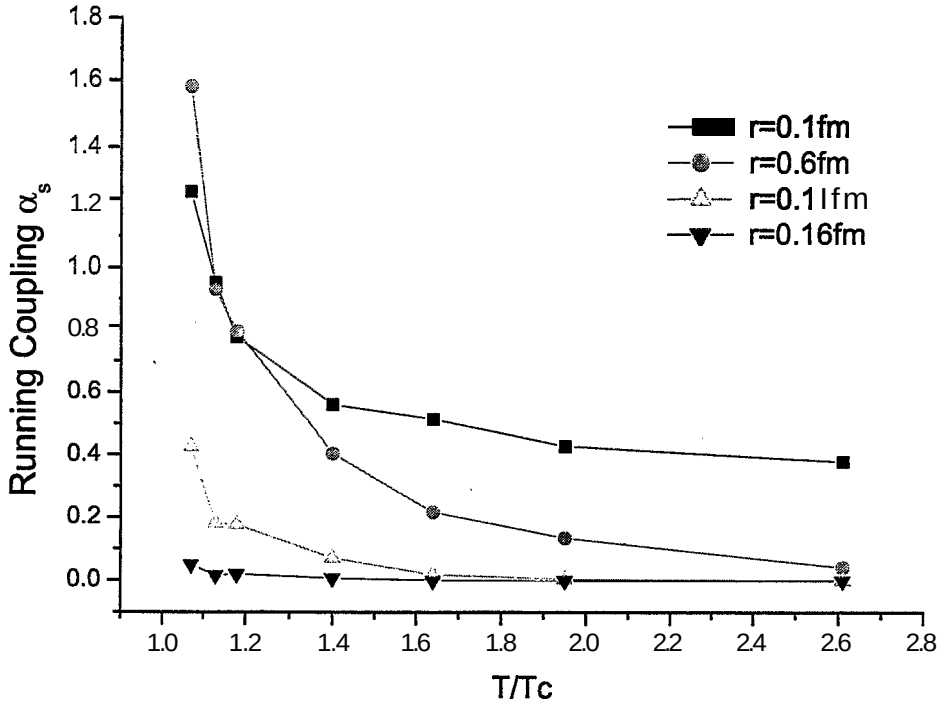


Fig. **3.** "Effective Running Coupling''

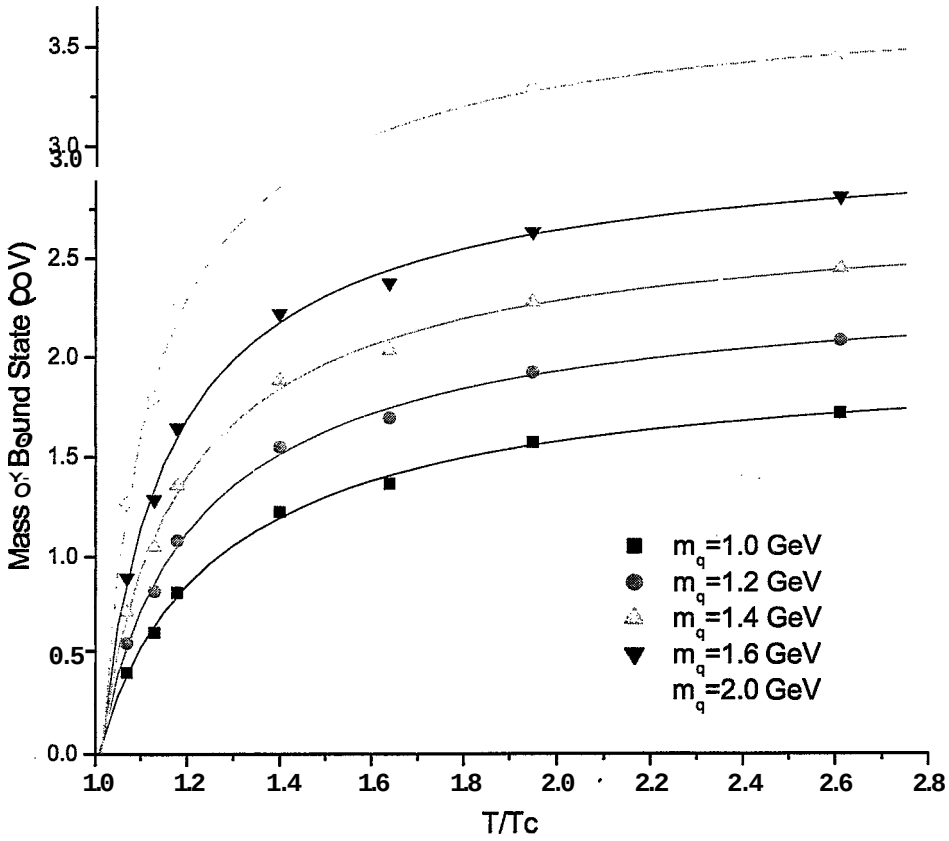


Fig. **4.** Mass of bound states. The fitting curves show that the mass of bound states approaches to zero as T goes to T_c.

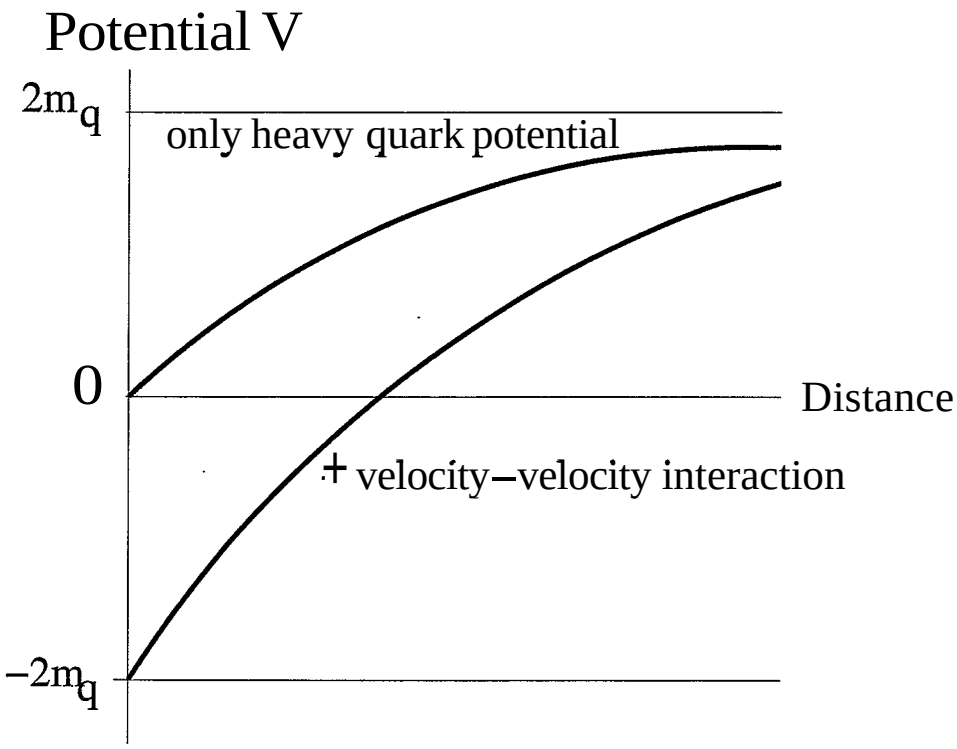


Fig. 5. Schematic model of the color singlet potential and the meson binding

Strongly Coupled Plasmas: Electromagnetic, Nuclear and Atomic

Participant List as of December 6, 2004

Name	Affiliation	E-Mail Address
Peter Adams	LANL	pja@lanl.gov
Yasuyuki Akiba	RBRC/BNL	akiba@rcf.rhic.bnl.gov
Masayuki Asakawa	Osaka University	yuki@phys.sci.osaka-u.ac.jp
Mark Baker	BNL	mdbaker@bnl.gov
Steffen Bass	RBRC / Duke University	bass@phy.duke.edu
Gordon Bavm	University of Illinois	bavm@bethe.Dhvsics.uiuc.edu
Gerry Brown	SUNY, Stony Brook	gerald.brown@sunysb.edu
Zhengwei Chai	BNL	zwchai@bnl.gov
Chan Choi	Purdue University	choi@purdue.edu
Jerome Daligault	LANL	daligaul@lanl.gov
Ron Davidson	Princeton Plasma Physics Lab	rdavidson@pppl.gov
David d'Enterria	Columbia University	denterria@nevis.columbia.edu
Abhay Deshpande	RBRC / SUNY, Stony Brook	abhay@bnl.gov
Todd Ditmire	Universitv of Texas at Austin	tditmire@Dhvsics.utexas.edu
Axel Drees	SUNY, Stony Brook	drees@skipper.physics.sunysb.edu
Dan Dubin	UC, San Diego	ddubin@ucsd.edu
Kirill Filimonov	LBNL	kvfilimonov@lbl.gov
Rainer Fries	University of Minnesota	fries@Dhysics.umn.edu
Boris Gelman	SUNY, Stony Brook	gelman@tonic.physics.sunysb.edu
Rajan Gupta	LANL	rajan@lanl.gov
Sourendu Gupta	Tata Inst of Fundamental Res	sgupta@tifr.res.in
Miklos Gyulassy	Columbia University	gyulassy@mail-cunuke.phys.columbia.edu
Tim Hallman	BNL	hallman@bnl.gov
Tetsuo Hatsuda	University of Tokyo	hatsuda@phys.s.u-tokyo.ac.jp
Ulrich Heinz	Ohio State University	heinz@mps.ohio-state.edu
Tetsufumi Hirano	Columbia University	th2155@columbia.edu
Bei-Lok Hu	University of Maryland	hub@physics.umd.edu
Setsuo Ichimaru	The University of Tokyo	STIchimaru@aol.com
Kei Iida	RBRC	keiiida@quark.phy.bnl.gov
Barbara Jacak	SUNY, Stony Brook	barbara..iacak@stonybrook.edu
Jiangyong Jia	Columbia University	jjia@rcf2.rhic.bnl.gov
Igor Kaganovich	Princeton Plasma Physics Lab	ikaganov@pppl.gov
Masashi Kaneta	RBRC	kaneta@bnl.gov
Thomas Killian	Rice University	killian@rice.edu
Dima Kharzeev	BNL	kharzeev@bnl.gov
Roy Lacey	SUNY, Stony Brook	Roy.Lacey@stonybrook.edu

Strongly Coupled Plasmas: Electromagnetic, Nuclear and Atomic

Name	Affiliation	E-Mail Address
Stephen Libby	LLNL	libby1@llnl.gov
Travis Mitchell	University of Delaware	tbmitche@udel.edu
Denes Molnar	Ohio State University	molnard@pacific.mps.ohio-state.edu
Guy Moore	McGill University	guymoore@hep.physics.mcgill.ca
Berndt Mueller	Duke University	muller@phy.duke.edu
Carter Munson	LANL	cmunson@lanl.gov
Michael Murillo	LANL	murillo@lanl.gov
James Nagle	University of Colorado	jamie.nagle@colorado.edu
Robert Pak	BNL	pak@bnl.gov
Rob Pisarski	BNL	pisarski@quark.phy.bnl.gov
John Schiffer	ANL	schiffer@anl.gov
Edward Shuryak	SUNY, Stony Brook	edward.shuryak@sunysb.edu
Anne Sickles	SUNY, Stony Brook	sickles@skipper.physics.sunysb.edu
Ron Soltz	LLNL	soltz@llnl.gov
Seunghyeon Son	Princeton Plasma Physics Lab	sson@Princeton.edu
Edward Startsev	Princeton Plasma Physics Lab	estarts@pppl.gov
Anna Stasto	BNL	stasto@quark.phy.bnl.gov
Mike Tannenbaum	BNL	mjt@bnl.gov
Francis Thio	USDOE	francis.thio@science.doe.gov
John Thomas	Duke University	jet@phy.duke.edu
Gene Van Buren	BNL	gene@bnl.gov
Harmen Warringa	Vrije Universiteit Amsterdam	harmen@nat.vu.nl
Wei Xie	RBRC/BNL	xiewei@rcf.rhic.bnl.gov

Strongly Coupled Plasmas: Electromagnetic, Nuclear & Atomic

Physics Large Seminar Room
December 16 – 17, 2004

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Thursday, December 16

Morning Chair: Ron Davidson
Afternoon Chair: Edward Shuryak

8:00	Registration
8:45	Welcome
9:00	Miklos Gyulassy – Theoretical Overview of the Quark–Gluon–Plasma (40+15)
9:45	Setsuo Ichimaru – Theory of Strongly Coupled Plasmas (40+15)
10:50	Coffee Break
11:10	Tetsuo Hatsuda – Lattice Gauge QCD (40+15)
12:05	Lunch
13:15	Mark Baker – Heavy–Ion Collisions as QGP Probes (35+10)
14:00	Todd Ditmire – Laser Driven Plasma Experiments (35+10)
14:45	John Schiffer – Order & Melting in Confined, Finite One Component Plasmas (35+10)
15:30	Coffee Break
16:00	Steve Libby / Richard Lee – Plasma Equation of State (35+10)
16:45	Tetsufumi Hirano – Hydrodynamical Simulation of Heavy Ion Collisions (35+10)
17:15	Kirill Filimonov – Collective Flow in Heavy Ion Collisions (35410)
18:00	Adjourn

Strongly Coupled Plasmas: Electromagnetic, Nuclear & Atomic

Physics Large Seminar Room
December 16 – 17, 2004

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Friday, December 17

Morning Chair: Tim Hallman
Afternoon Chair: Steffen Bass

9:00	Axel Drees – Jet Quenching: Energy Loss of Color–Charged Probes (35+10)
9:45	Dima Kharzeev – Heavy Quark Probes and Color Screening (35+10)
10:30	Coffee Break
10:50	Michael Murillo – Diagnosing Collective Plasma Modes (35+10)
11:35	Guy Moore – Plasma Instabilities in the Quark Gluon Plasma (35+10)
12.20	Lunch
13:30	Steve Libby Transport in Strongly Coupled Plasma (35+10)
14:15	Dan Dubin – Measurement of Screening Enhancement to Nuclear Reaction Rates Using a Strongly–Magnetized, Strongly–Correlated Nonneutral Plasma (35+10)
15:00	Coffee Break
	John Thomas – Strongly Interacting Cold Atoms (40+15)
16.25	Edward Shuryak – Strongly Interacting Atoms Make a Near–Perfect Fluid (35+10)
17:10	Gerry Brown – Bound States Above T_C (35+10)
18:00	Adjourn

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Volume 67 – High Performance Computing with BlueGene/L and QCDOC Architectures – BNL-
Volume 66 – RHIC Spin Collaboration Meeting XXIX, October 8-9,2004, Torino Italy – BNL-73534-2004
Volume 65 – RHIC Spin Collaboration Meetings XXVII (July 22, 2004), XXVIII (September 2, 2004), XXX . (December 6,2004) - BNL-73506-2004
Volume 64 – Theory Summer Program on RHIC Physics – BNL-73263-2004
Volume 63 – RHIC Spin Collaboration Meetings XXIV (May 21, 2004), XXV (May 27, 2004), XXVI (June 1, 2004) – BNL-72397-2004
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Volume 39 – RHIC Spin Collaboration Meeting VII – BNL-52659
Volume 38 – RBRC Scientific Review Committee Meeting – BNL-52649
Volume 37 – RHIC Spin Collaboration Meeting VI (Part 2) – BNL-52660

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For information please contact:

Ms. Pamela Esposito
RIKEN BNL Research Center
Building 51OA
Brookhaven National Laboratory
Upton, NY 11973-5000 USA

Phone: (631) 344-3097
Fax: (631) 344-4067
E-Mail: pesposit@.bnl.gov

Mrs. Tammy Stein
RIKEN BNL Research Center
Building 51OA
Brookhaven National Laboratory
Upton, NY 11973-5000 USA

(631)344-5864
(631)344-2562
tstein@bnl.gov

Homepage: http://www.bnl.gov/riken

RIKEN BNL RESEARCH CENTER

Strongly Coupled Plasmas: Electromagnetic, Nuclear & Atomic

December 16 – 17,2004

Li Keran

Nuclei as heavy as bulls
Through collision
Generate new states of matter.
*T.D. **Lee***

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Speakers:

Mark Baker	Gerry Brown	Todd Ditmire	Axel Drees	Dan Dubin
Kirill Filimonov	Miklos Gyulassy	Tetsuo Hatsuda	Tetsufumi Hirano	Setsuo Ichimaru
Dima Kharzeev	Stephen Libby	Guy Moore	Michael Murillo	John Schiffer
Edward Shuryak	John Thomas			

Qrganizers: B. Jacak, E. Shuryak, T. Hallman, S. Bass, and R. Davidson