Title: Probing the Properties of Quark-Gluon Plasma

Date: Feb 14, 2007 02:00 PM

URL: http://pirsa.org/07020001

Abstract: Experimentalists at the Relativistic Heavy Ion Collider create exploding droplets of quark-gluon plasma, the stuff which filled the universe for the first microseconds after the big bang. I'll give one theorist's perspective on what we are learning about the properties of quark-gluon plasma from these experiments, including the conclusion that it is closer to an ideal liquid than to an ideal gas and the observation that it "quenches" high energy quarks ("jets") trying to plow through it. The static properties of quark-gluon plasma can be calculated from first principles, but we have no rigorous calculations of what QCD predicts for the viscosity and jet quenching ability of the evidently very strongly interacting quark-gluon plasma that RHIC has discovered. In desperation, theorists are resorting to calculating the properties of quark-gluon plasma in theories other than QCD, wherein difficult dynamical questions like how does a strongly interacting plasma quench jets can be answered by doing easy string theory calculations. I will discuss two examples where such calculations have been compared quantitatively to inferences drawn from existing RHIC data, and close with one prediction for data to come.

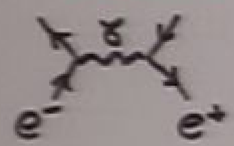
Before we get to quark-gluon plasma .....

- What is QCD?
- What does it describe?
- Why study its phase diagram?

WHAT IS QCD?

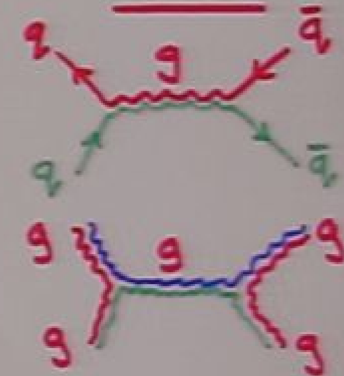
Its Lagrangian suggests it is a theory of quarks and gluons, not too different from QED which is a theory of electrons and photons:

QED



e^-: charge −1
γ : neutral

QCD



q: charge r, g or b
gluons: also colored.

Quarks come in six flavors:

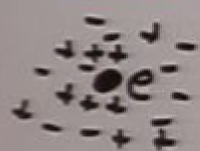
Flavor	Mass (MeV)	
u	5	light. treat as massless to first approx.
d	10	
s	100	← middleweight
c	1500	too heavy to play a role in this talk
b	5000	
t	175000	

ASYMPTOTIC FREEDOM

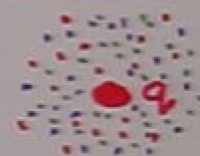
Gross, Wilczek, Politzer (1973)

In quantum field theory, the vacuum is a medium which can screen charge.

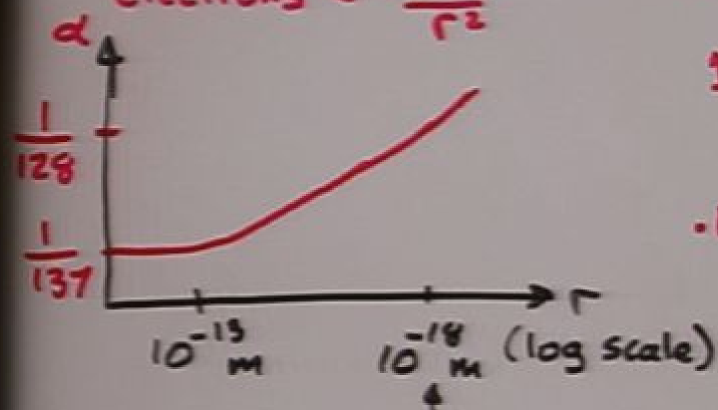
QED

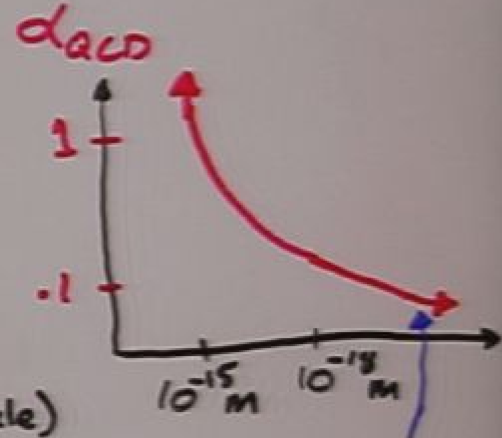


QCD



α: Force between electrons ~ $\frac{\alpha(r)}{r^2}$



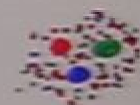


Coupling "constants" not constant. Depend on scale at which you probe.

asymptotic freedom, or anti-screening. (That's why Friedman, Kendall, Taylor were able to see weakly interacting quarks.)

WHAT DOES QCD DESCRIBE?

It is an experimental fact that in the world around us, quarks and gluons occur only in <u>colorless</u> packages:

Protons, neutrons, ... 

Pions, kaons, ... 

These <u>hadrons</u> are the quasiparticles of the QCD vacuum.

They, in turn, make up everything from nuclei to neutron stars, and thus most of the mass of you and me.

Why no colored quasiparticles?

- would disturb vacuum out to ∞, and $\therefore$ have ∞ mass.
- NB: growth of $\alpha(r)$ with $r \Rightarrow$ force between colored objects does not fall off with distance.
- their absence confirmed by direct calculation. (Lattice gauge theory.)

NB: hadrons are <u>heavy</u>. $M_{proton} = 938$ MeV, $M_{u+u+d} \cong 20$ MeV

WHY STUDY QCD?

WHY IS IT A CHALLENGE?

- The only example we know of a strongly interacting gauge theory.
- We understand the theory at short distances
- The quasiparticles – the excitations of the vacuum – are hadrons, which do not look at all like the short distance quark and gluon degrees of freedom.

HOW DO WE RESPOND TO THE CHALLENGE?

- Study the spectrum, properties, and structure of the hadrons.
- Get away from the vacuum. Understand other phases of QCD, and their quasiparticles. Map the QCD phase diagram.

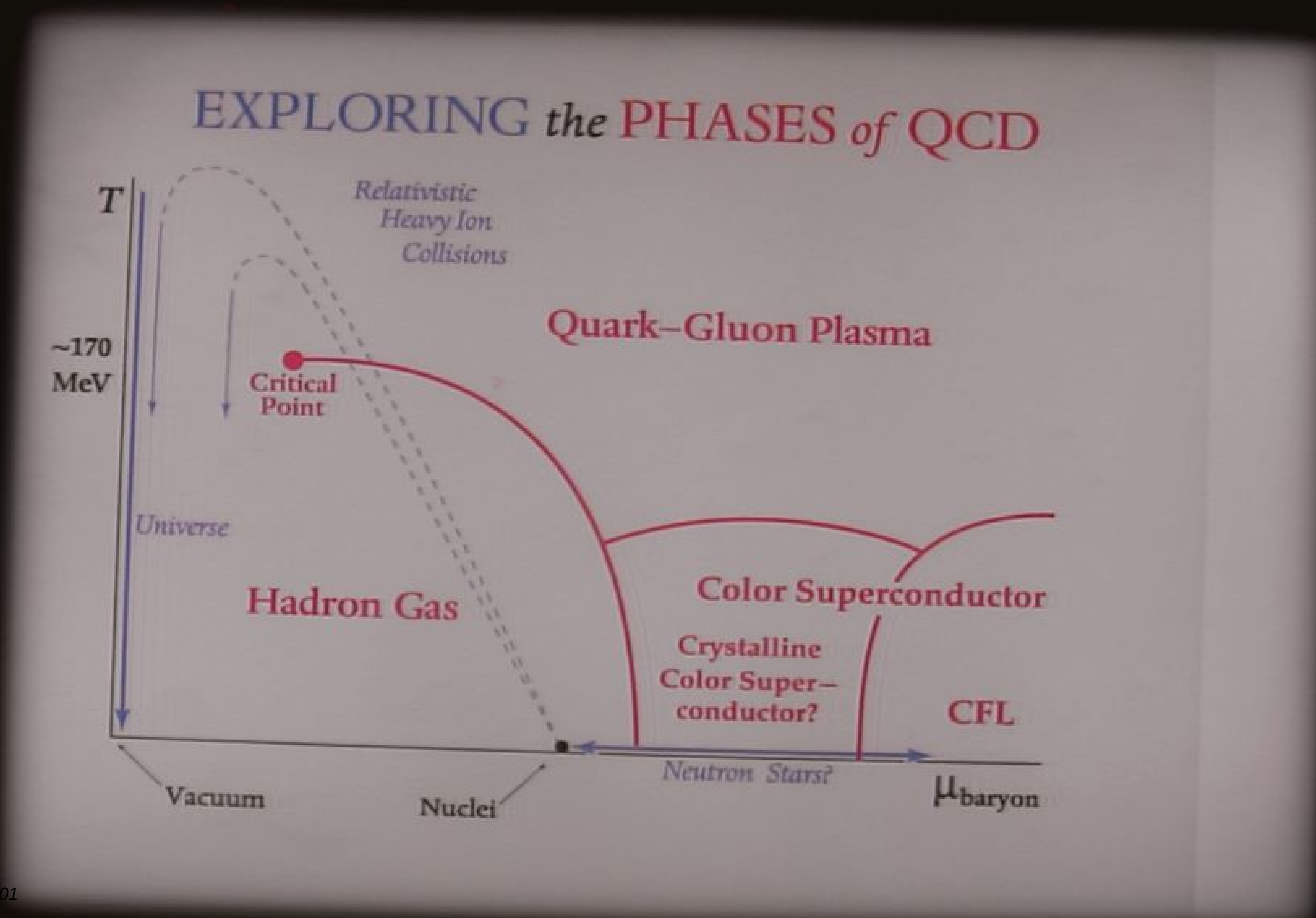
DO OTHER (SIMPLER?) PHASES EXIST?

Do other phases exist whose quasiparticles look more like the quarks and gluons of the QCD lagrangian? And look more like phases familiar from QED?

Asymptotic freedom: quarks and gluons weakly interacting
i) when close together
ii) when interact at large momentum.

Suggests look at high density or high temperature.

NB: condensed matter physics teaches us that phases may be far from simple even for α as small as $\frac{1}{137}$.


EXPLORING the PHASES of QCD
T
Relativistic
Heavy Ion
Collisions
~170
MeV
Critical
Point
Quark–Gluon Plasma
Universe
Hadron Gas
Color Superconductor
Crystalline
Color Super–
conductor?
CFL
Neutron Stars?
Vacuum
Nuclei
μ_{baryon}

$T \neq 0$; $\mu = 0$

- vertical axis
- we know a lot from lattice QCD. eg →
- QCD describes a transition

FROM	TO
gas of hadrons	plasma of quarks and gluons
with chiral symmetry badly broken	with chiral sym. almost restored.

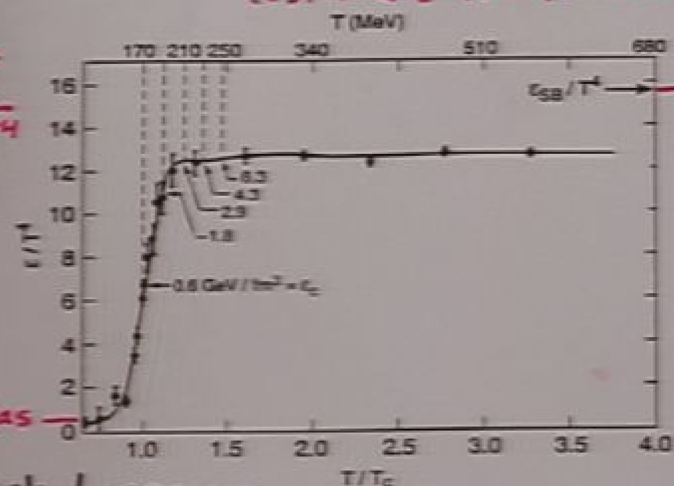
- $T_c \simeq 175 \pm 15$ MeV
- The transition is a smooth crossover, like ionization of a gas occurring in a narrow range of T

IF $m_s \gtrsim \frac{1}{5} m_s^{physical}$, and so in nature

NB: In world with $m_u = m_d = m_s$, crossover if $m_q \gtrsim \frac{1}{15} m_s^{physical}$ Bielefeld Columbia

T(MeV), assuming $T_c = 170$ MeV.
(estimate is $140 < T_c < 190$)

$\frac{\varepsilon}{T^4}$



ideal QGP

pion gas

T/T_c

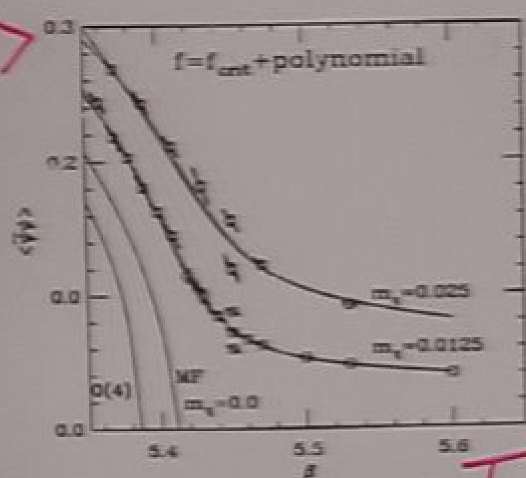
Karsch Laermann
Peikert (Heine)

DECONFINEMENT
(IONIZING
THE
HADRONS)

&

$\langle \bar{\psi}\psi \rangle$

Blum
DeTar
MILC
collab.

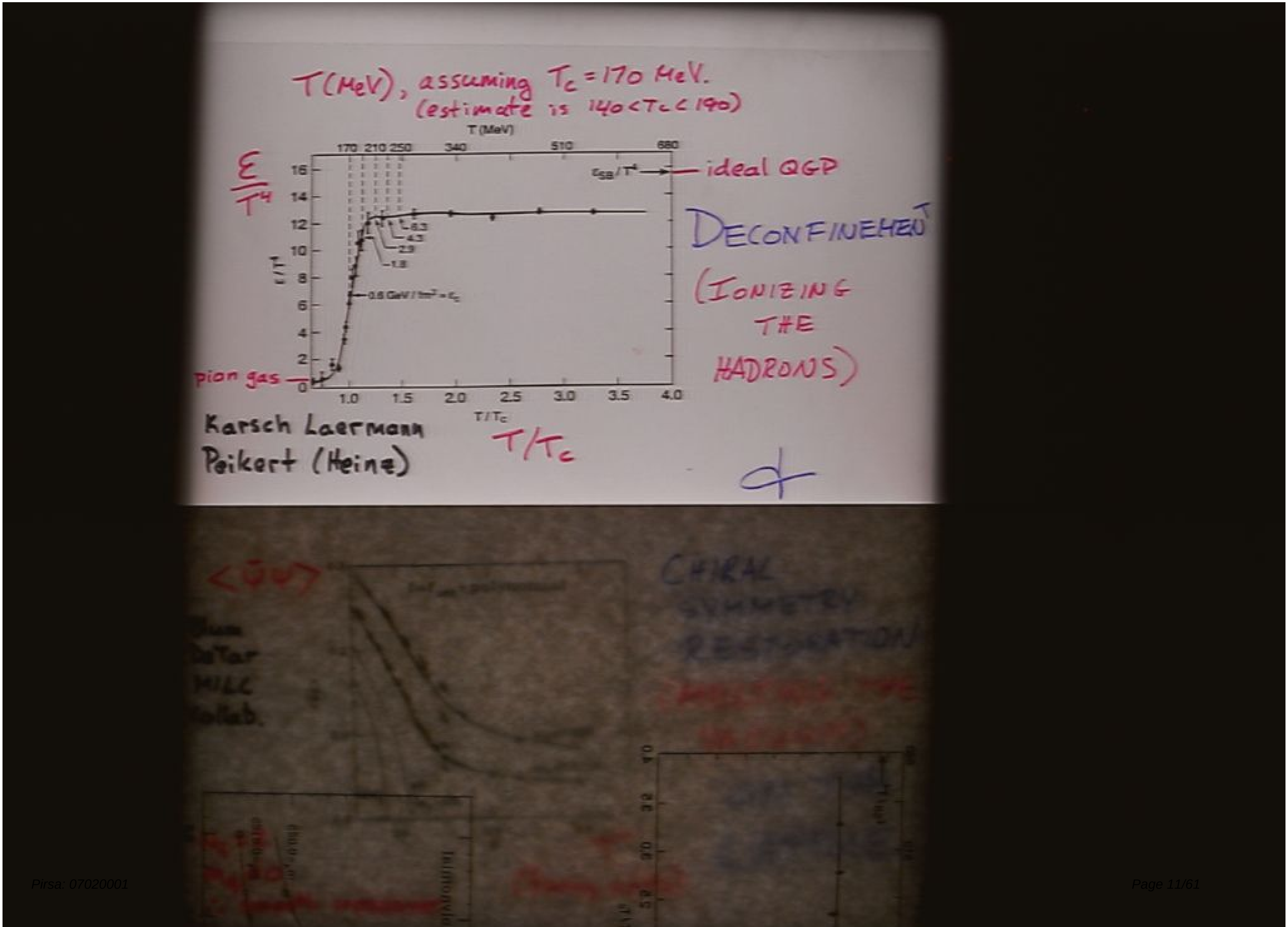


T
(funny units)

CHIRAL
SYMMETRY
RESTORATION
(MELTING THE
VACUUM)

ON THE
LATTICE

$N_f = 2$
$m_q \neq 0$
∴ smooth crossover



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(estimate is 140 < T_c < 190)
T (MeV)
170 210 250 340 510 680
ε/T⁴
ideal QGP
DECONFINEMENT
(IONIZING THE HADRONS)
0.6 GeV / fm³ = ϵ_c
pion gas
T/T_c
Karsch Laermann Peikert (Heine)
CHIRAL SYMMETRY RESTORATION

EXPLORING QGP PROPERTIES

"Making QGP" is not a yes/no question:
No sharp boundary between hadrons, QGP.

Goal of RHIC: create matter ① that is above the crossover ② and study its properties. ③

①: RHIC data (on V_2) tell us interactions sufficient to yield ~equilibrated matter, expanding collectively as a fluid, by a time ~ 0.6 − 1 fm.
After that hydrodynamics (ideal hydro; zero mean free path; ideal liquid not ideal gas) describes "bulk" of particles ($p_T \lesssim 1$-2 GeV) well.

②: RHIC data (dE_T/dy) tell us
$\varepsilon(1\,\text{fm}) > 5\,\text{GeV}/\text{fm}^3 \Rightarrow$ above crossover
(↑ NB)

So, on to ③.....

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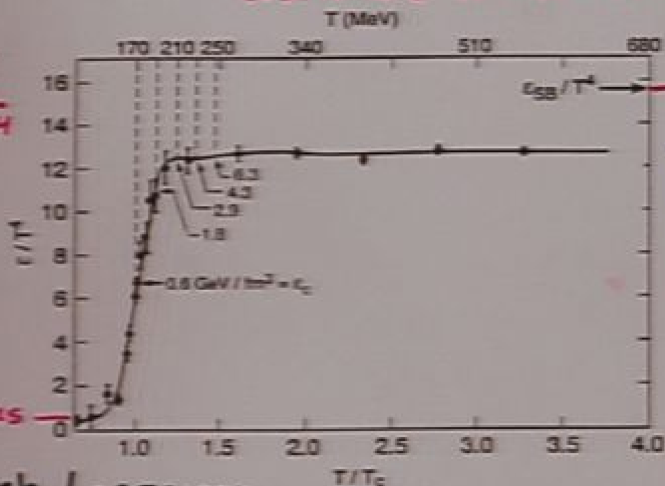
(estimate is $140 < T_c < 190$)

$\frac{\varepsilon}{T^4}$



— ideal QGP

pion gas

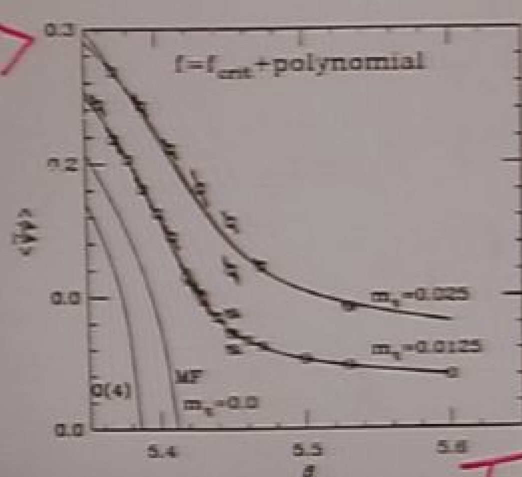
DECONFINEMENT (IONIZING THE HADRONS)

Karsch Laermann Peikert (Heine)

T/T_c

&

$\langle\bar{\psi}\psi\rangle$



Blum DeTar MILC Collab.

CHIRAL SYMMETRY RESTORATION (MELTING THE VACUUM)

ON THE LATTICE

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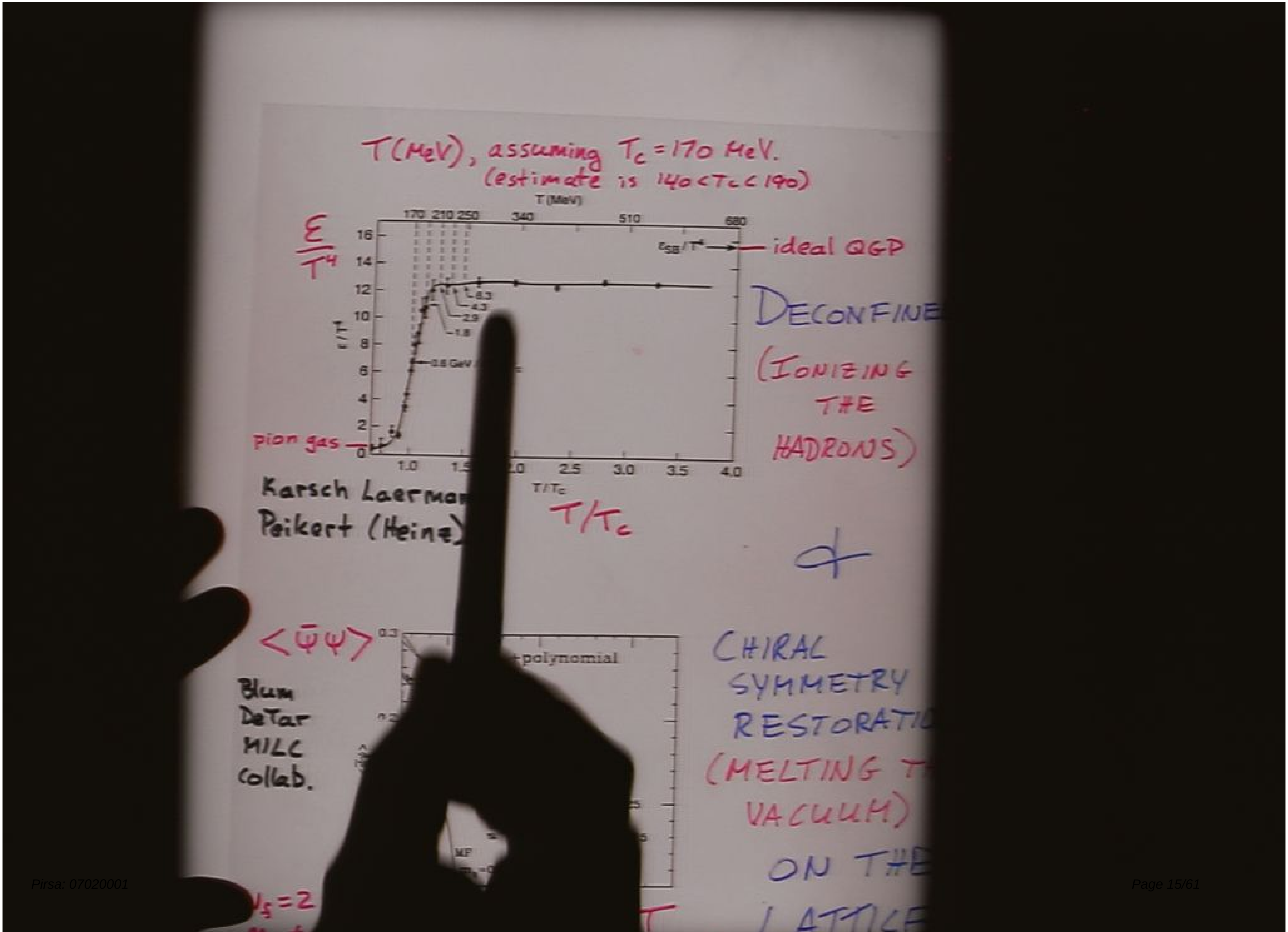
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(estimate is 140 < T_c < 190)
T (MeV)
170 210 250 340 510 680
$\frac{\varepsilon}{T^4}$
16 14 12 10 8 6 4 2 0
ε_{SB}/T^4
ideal QGP
6.3
4.3
2.9
1.8
0.8 GeV
pion gas
1.0 1.5 2.0 2.5 3.0 3.5 4.0
T/T_c
Karsch Laerman
Peikert (Heine)
DECONFINE
(IONIZING
THE
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<$\bar{\psi}\psi$>
polynomial
Blum
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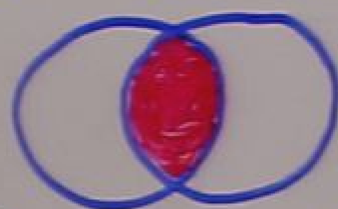
MILC
Collab.
CHIRAL
SYMMETRY
RESTORATI
(MELTING T
VACUUM)
ON THE

TOWARD MEASURING SHEAR VISCOSITY

Elliptic flow indicates extent of early equilibration.

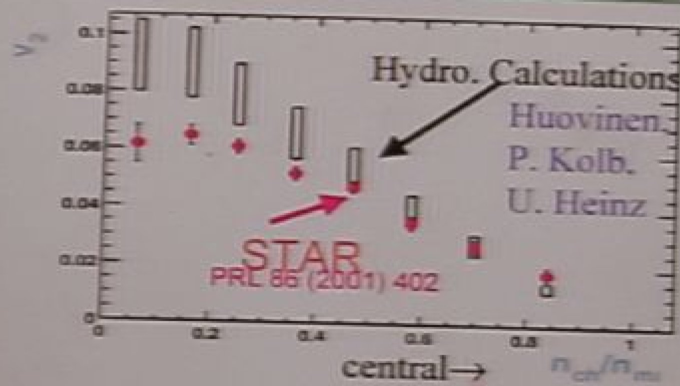
Look at non-head-on collisions:



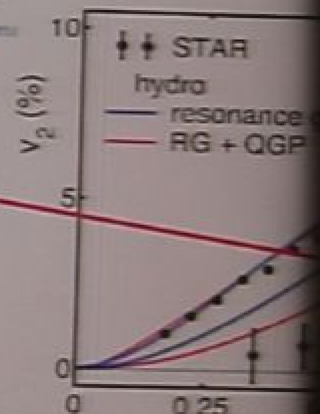
If just lots of p-p collisions followed by free streaming, then final state momenta uniformly distributed in azimuth angle ϕ.

If interaction → equilibration → pressure, pressure gradients → collective flow. If this happens early, before [red ellipse] circularizes by free streaming, then nonzero $V_2 \sim \langle \cos 2\phi \rangle$.

v_2 predicted by hydrodynam



pressure
explosio
happens
early eq



Hydro can reproduce magnitude of elliptic flow for π, p. BUT ***must add QGP to hadronic EOS!!***

Similar conclusion reached by CM Ko, et al., Kapusta, et al., Bleicher, et al., among others…

talk by B. Jacak

- Ideal hydrodynamics based on assumption of local eqbm.
- Hydro never agreed with data before RHIC. (At SPS, $v_2^{data} \sim \frac{v_2^{hydro}}{2}$
- At RHIC, hydro does good job of describing v_2, spectra for $p_T < 1$-2 GeV
- MEANS: "hydro works" by $t \sim 0.6$-1 fm

  Heinz Kolb
- Challenge to theory: how can ~ equilibration occur so quickly? Strong interactions? Strong color fields → plasma instabilities?

  Mrowczynski, Rebhan, Romatschke, Strickland, Arnold Moore Yaffe, ...
- MEANS: "small" shear viscosity η.

  Teaney: $\eta/s < \mathcal{O}(\frac{1}{10})$

  ⌜cf water: $\eta/s > 10$⌟

CHALLENGES: Real extraction of η requires hydro calculations with $\eta \neq 0$.

Muronga; Heinz Song Chaudhuri; Baier Romatschke

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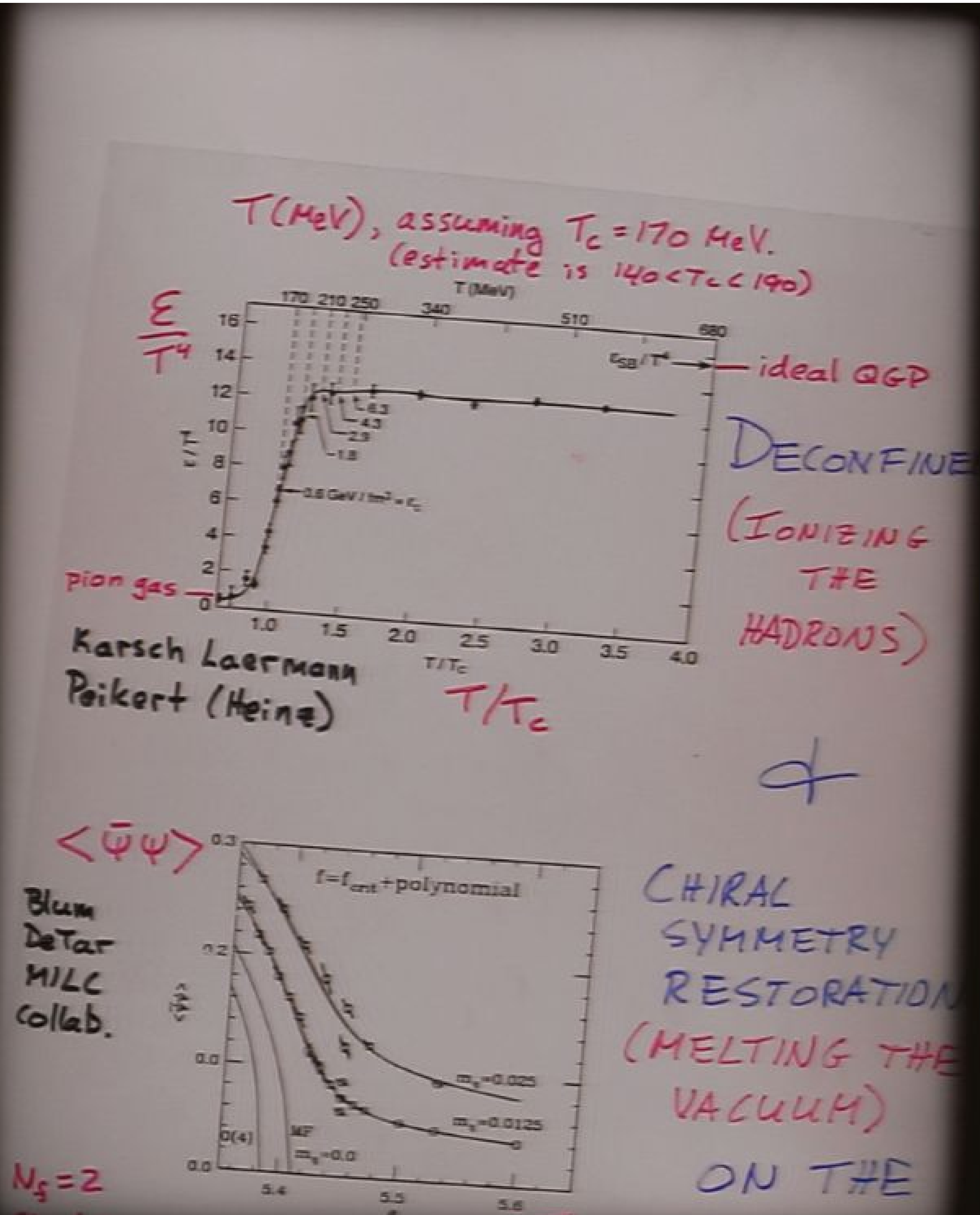
Should we be surprised if/that the QGP turns out to be liquid-like?

1) No. At $T \sim$ few T_c, coupling not small

2) But.... Lattice shows ε/T^4 reaches 80% of its value in an ideal-gas-QGP (ie noninteracting) already just above T_c. Doesn't this imply interactions are "just a 20% correction" ???

3) $N=4$ SUSY QCD can teach us a lesson:

- $\varepsilon/T^4 = 75\%$ of its value in a noninteracting SUSY-QGP (...ubser, ...ebanov, ...eytlin, ...eet)
- interactions <u>very</u> strong.
  - (...licastro, ...on Starinets) $\eta/s = \frac{1}{4\pi} \rightarrow$ m.f.p. $\sim$ spacing
  - (...ovtun, ...Starinets) - a liquid with lower viscosity per entropy than water
  - ideal hydro!
- Teaney uses V_2 data to suggest η/s of real world QGP $\sim$ as small.



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&
⟨ψ̄ψ⟩
f=f_crit+polynomial
Blum
DeTar
MILC
collab.
m_q=0.025
m_q=0.0125
m_q=0.0
O(4)
MF
CHIRAL
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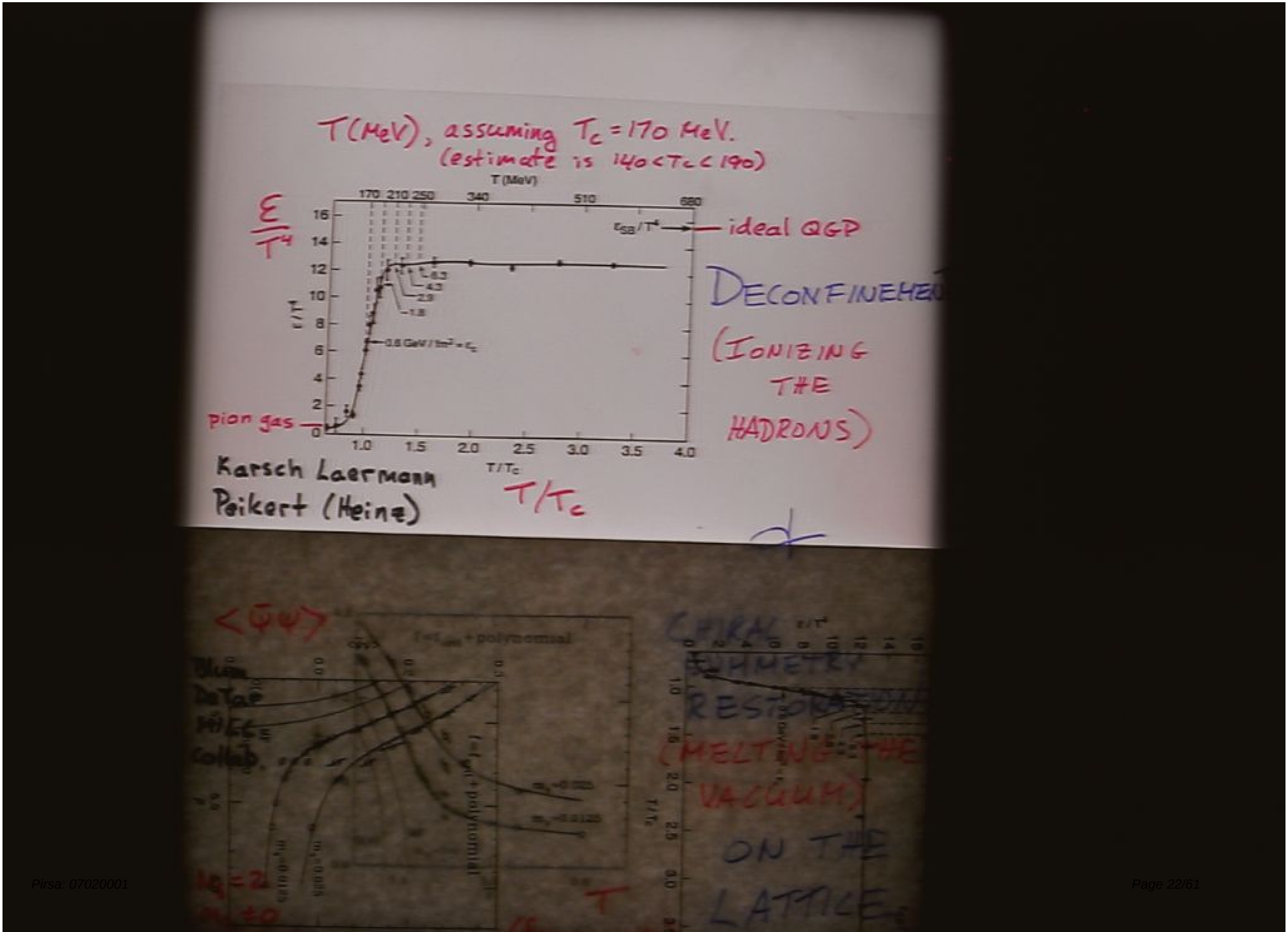
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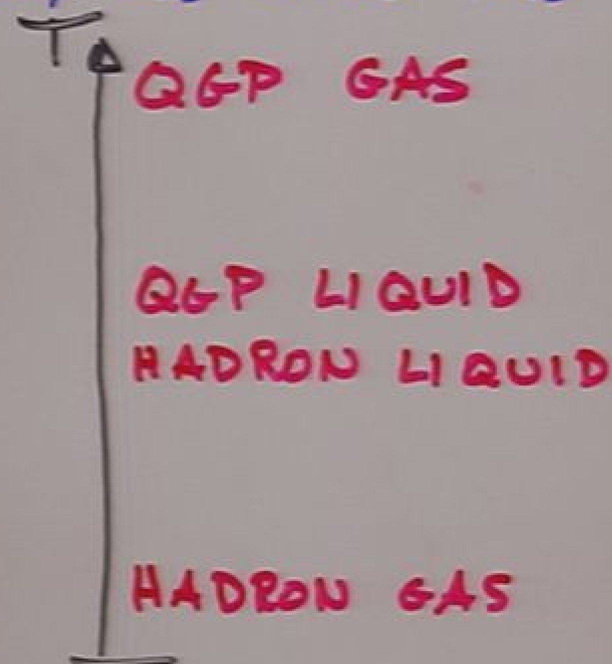
  $\eta/s = \frac{1}{4\pi} \rightarrow$ m.f.p. ~ spacing (Policastro, Son, Starinets)

  - a liquid with lower viscosity per entropy than water (Kovtun, Son, Starinets)

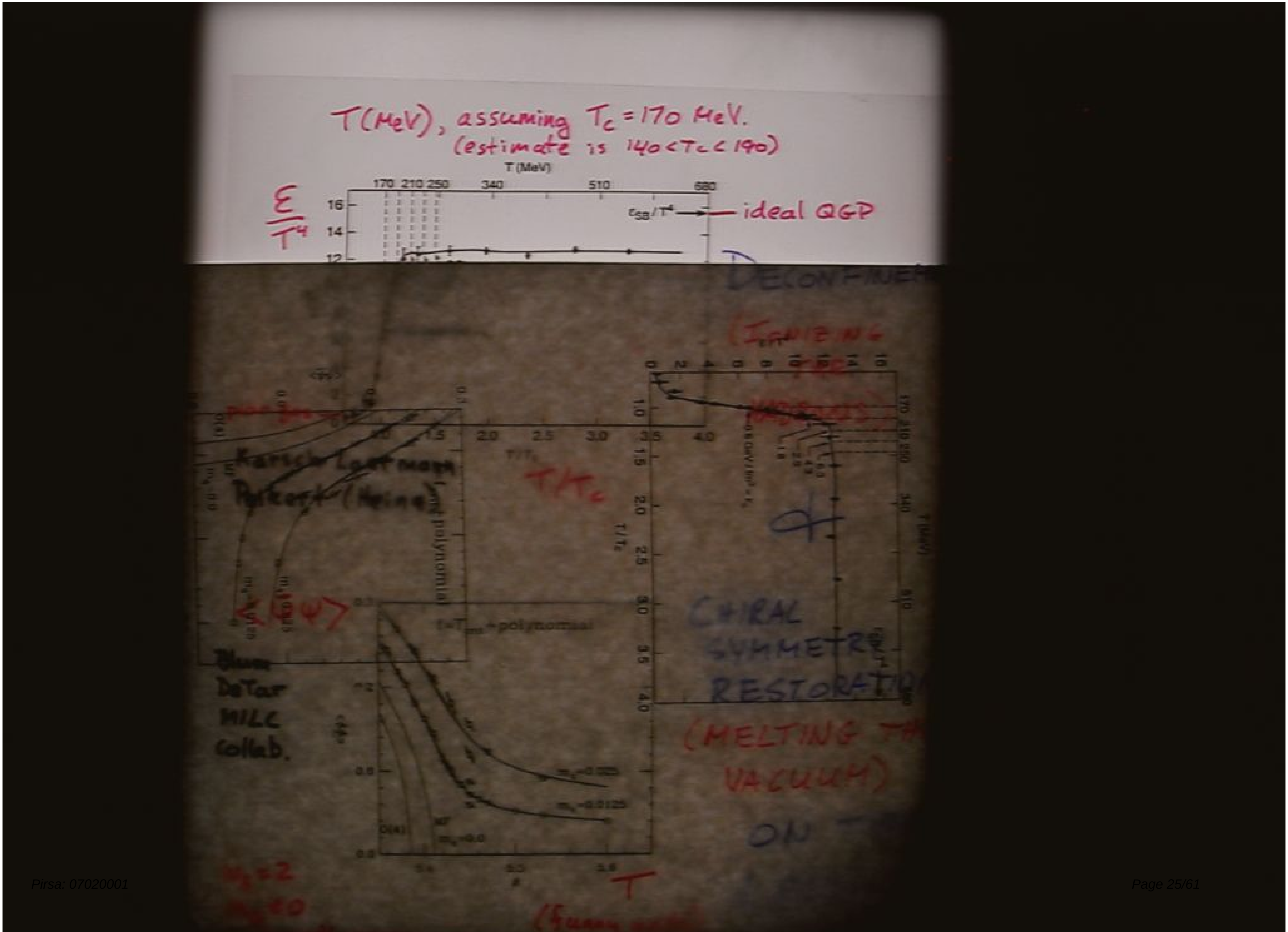
  - ideal hydro!

- Teaney uses v_2 data to suggest η/s of real world QGP ~ as small.

So, a posteriori, (ie after the data) it is not surprising to find a QGP liquid. In fact, given that the transition is a crossover, it probably has to be this way:



Also aposteriori (in this case, after the string theorists) we realize that $\frac{\varepsilon}{T^4} = 80\%$ of noninteracting is closer to 75% (strong coupling) than to 1.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TOWARD MEASURING OPACITY AND PERHAPS v_{sound} AND T^3

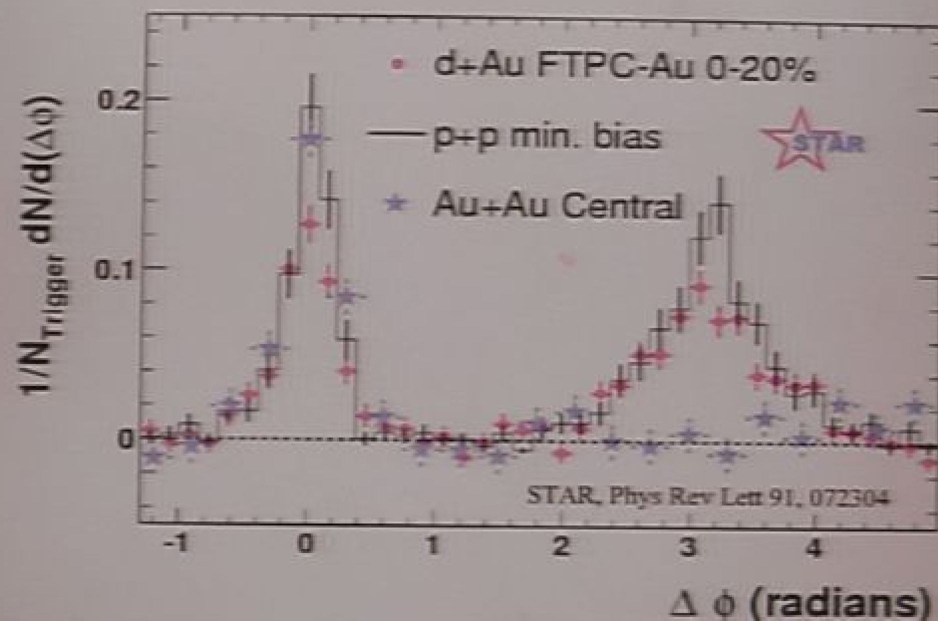
"Jet quenching": RHIC data suggests that the rare high-p_T particles produced in initial hard scatterings are efficiently stopped. "Parton energy loss" to the point that matter is opaque.

Picture Suggested:

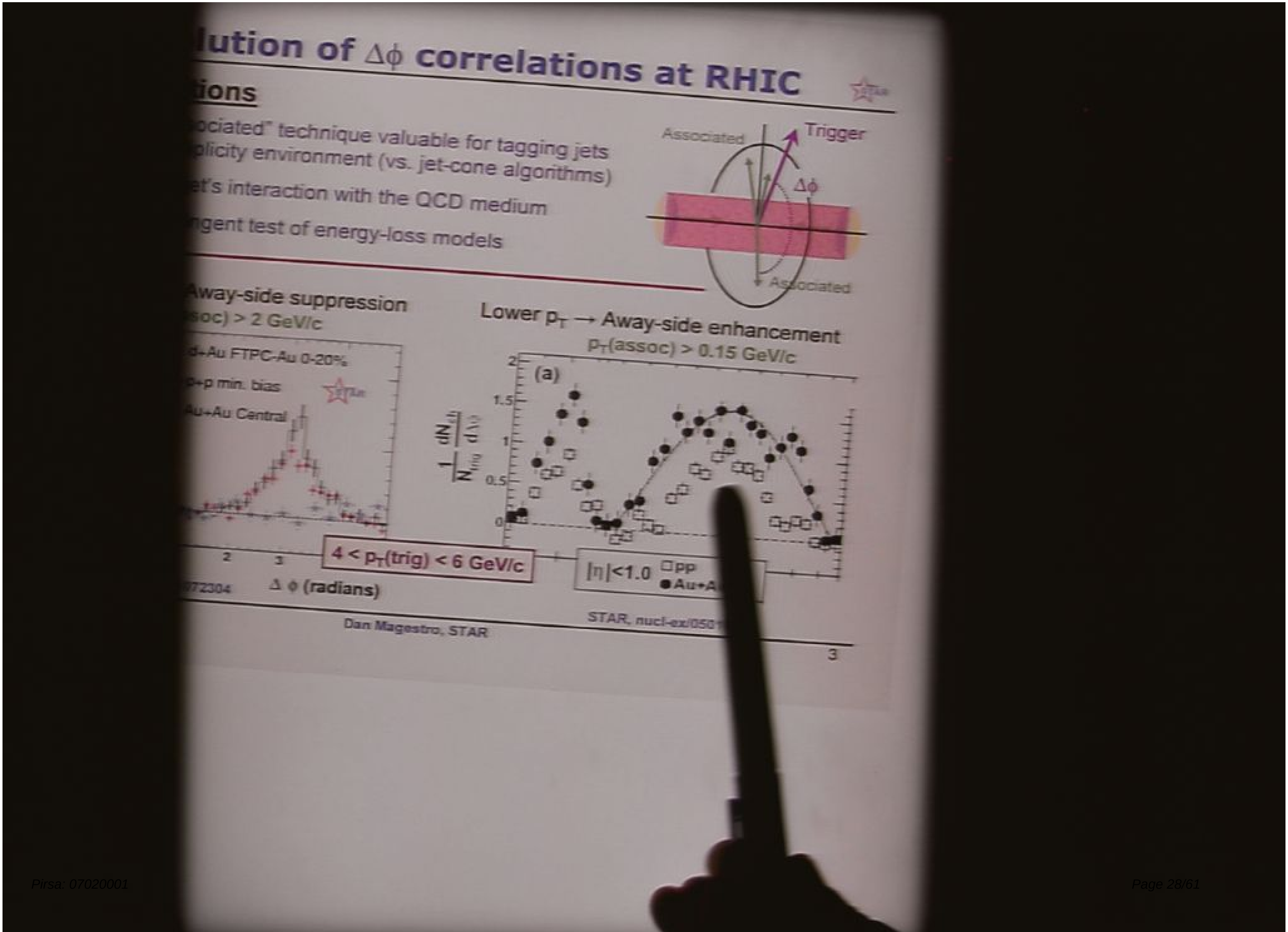
Ingoing, and interior, jets quenched.

Should see some back to back jets at any p_T, and more at higher p_T.

What is known: recoiling hadrons are suppresse



Compare to d+Au: suppression is final-state effe


lution of Δφ correlations at RHIC
tions
ociated" technique valuable for tagging jets
plicity environment (vs. jet-cone algorithms)
et's interaction with the QCD medium
ngent test of energy-loss models
Associated
Trigger
Δφ
Associated
Away-side suppression
soc) > 2 GeV/c
d+Au FTPC-Au 0-20%
p+p min. bias
Au+Au Central
2
3
072304
Δ φ (radians)
4 < pT(trig) < 6 GeV/c
Lower pT → Away-side enhancement
pT(assoc) > 0.15 GeV/c
(a)
2
1.5
1
0.5
0
|η|<1.0
pp
Au+A
STAR, nucl-ex/0501
Dan Magestro, STAR
3

lution of Δφ correlations at RHIC

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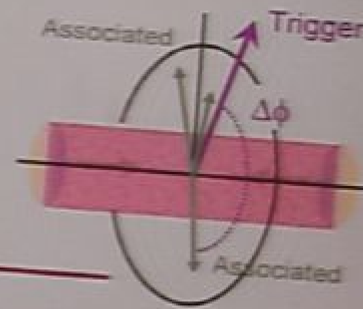
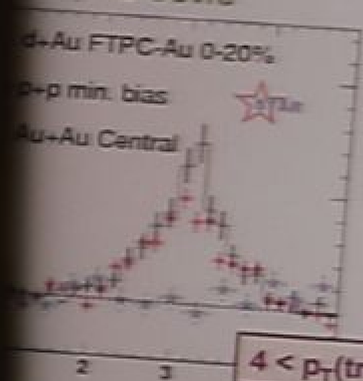


Away-side suppression

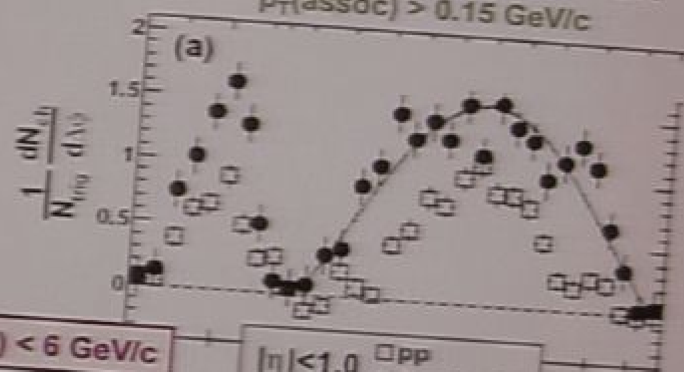
soc) > 2 GeV/c



$4 < p_T(trig) < 6$ GeV/c

Lower $p_T \rightarrow$ Away-side enhancement

p_T(assoc) > 0.15 GeV/c

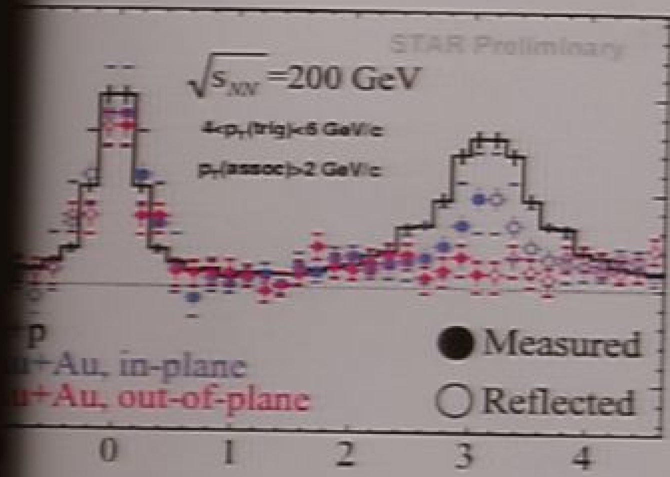


STAR, nucl-ex/0501016

Dan Magestro, STAR

Path Length Dependence

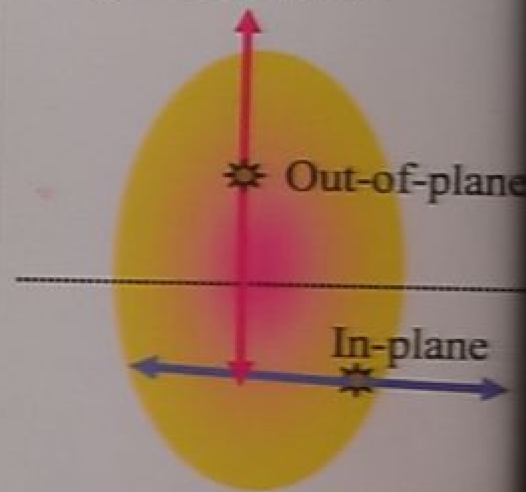
di-hadron, 20-60% Central



imonov DNP03

ssion larger out-of-plane

Background Subtracted
See J. Bielcikova *et al.*, (nucl-ex/0311007) for background derivation



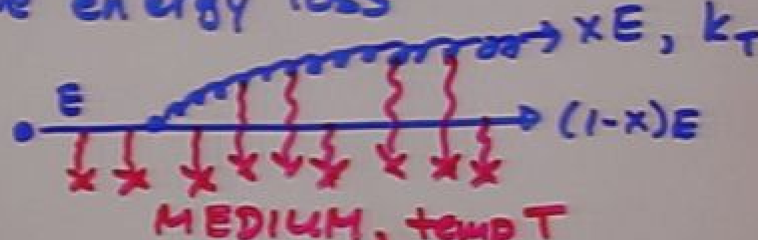
$$\Delta E_{GLV} \sim L^n(\phi)$$

January 2004

JET QUENCHING

QGP @ RHIC surprisingly opaque to hard colored partons.

Radiative energy loss



dominates in high E limit. ($E \gg k_T \gg T$).

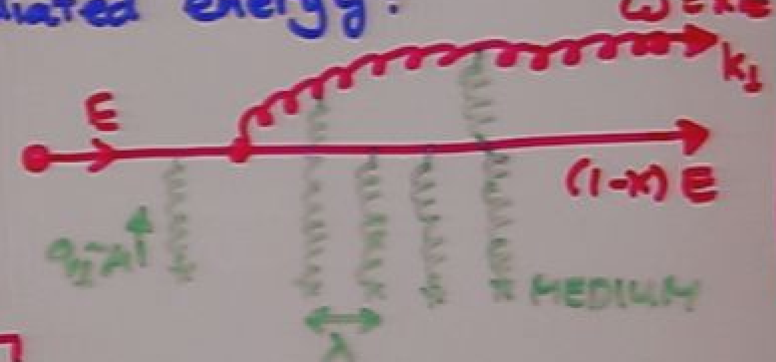
__If__ so, energy loss sensitive to medium through __one__ parameter $\hat{q} \sim \langle p_T^2 \rangle / L$

$\hat{q}$ extracted by comparing to RHIC data (on R_{AA} vs. p_T) seems to be 5-15 times larger than suggested by weak coupling calculations.

WHAT DO WE LEARN ABOUT THE MEDIUM FROM HOW A HARD PARTON LOSES ENERGY PLOWING THROUGH IT?

Perturbative formalism for calculating parton energy loss: Baier Dokshitzer Mueller Peigné Schiff Zakharov Wiedemann Gyulassy Wang Wang Levai Vitev Salgado ...

Energy lost by gluon radiation. Spectrum of radiated energy:

$\omega \frac{dI}{d\omega} \sim \Big|$  $\Big|^2$

$\sim \alpha_s \sqrt{\frac{\hat{q}}{\omega}}\, L$ for $\omega < \hat{q} L^2$

where $\hat{q}$ is p_T^2 picked up per L travelled, so $\sim \mu^2/\lambda$, and L = distance travelled.

ASSUMES: E, $k_\perp$ large, so QCD weakly coupled at these scales. (At RHIC, $E \sim 20\,\mathrm{GeV}$. At LHC, $E \sim 100+\,\mathrm{GeV}$)

Parton energy loss sensitive to the medium (ie to strongly interacting physics at scales $\propto T$) through one parameter: $\hat{q}$.

Energy loss: $\Delta E \sim \alpha_s \hat{q} L^2$.

Intuition: $\hat{q} \sim \frac{\mu^2}{\lambda}$ ← (Debye screening length)$^{-2}$ ← "mean free path"

$\sim n_{\text{scatterers}} \cdot \left(\begin{matrix}\text{Dimensionless} \\ \text{measure of } \sigma\end{matrix}\right)$

Implications of RHIC data: → FIG

Eskola Honkanen Salgado Wiedemann Dainese Loizides Paic

$$\bar{\hat{q}} \sim (5-15)\,\text{GeV}^2/\text{fm}$$

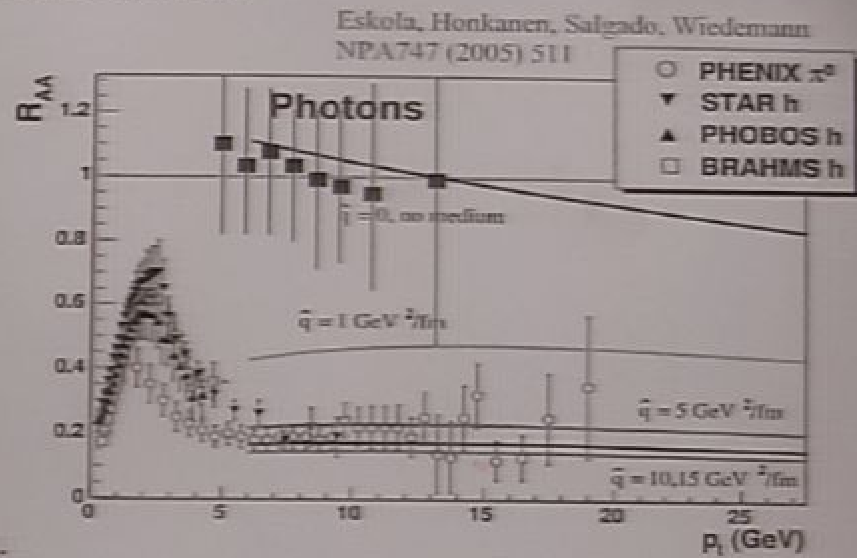
($\bar{\hat{q}}$ is a time-averaged $\hat{q}$. Relation to $\hat{q}(\tau)$ depends on assumptions, but reasonable to think $\bar{\hat{q}} \sim \hat{q}(1\,\text{fm})$.)

WANTED: strong coupling calculation of $\hat{q}$ ....

suppression of leading hadrons

ss calculations account for:

- cation factor
- ndence
- orrelations
- natural limit emission



paque medium.

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Eskola Honkanen Salgado Wiedemann Dainese Loizides Pa

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WANTED: strong coupling calculation of $\hat{q}$ ....

$\hat{q}$ IN N=4 SUSY QCD

Hliu, KR, Wiedemann

- A different strongly interacting gauge theory plasma. ($\eta/s = 1/4\pi$)
- $\hat{q}$ calculable in strong coupling limit:

$$\hat{q} = \frac{2\pi^2 \Gamma(5/4)}{\Gamma(3/4)} \sqrt{\alpha N_c}\, T^3 = 27\sqrt{\alpha N_c}\, T^3$$

N_c ↑ # of colors (3 for QCD)

- $\hat{q}$ is <u>not</u> proportional to s, or to $n_{scatterers}$. Those are $\sim N_c^2 T^3$.
- $\hat{q}$ a measure of T^3!
- Try some numbers: $N_c = 3$, $\alpha = 1/2$
  $\rightarrow \hat{q} = 5\ GeV^2/fm$ for $T = 300\ MeV$
- cf: hydrodynamic modelling suggests $T(1fm) \sim 270\ MeV$. Kolb Heinz; Teaney Shuryak
- So: $\hat{q}_{N=4\ SYM} \sim \hat{q}_{QCD @ RHIC}$
- Weak coupling QCD calculation of $\hat{q}$ is $\sim \frac{1}{5}$ what is needed to fit data.

$$\hat{q}_{\text{weakly coupled QCD}} \simeq 3.1\,\alpha^2 N_c^2 T^3 \simeq 0.9\ GeV^2/fm$$

Baier Schiff — for $\alpha = \frac{1}{2}$, $N_c = 3$, $T = 300$

QUARK-GLUON PLASMAS

- Nature only provides experimentalists <u>one</u> strongly interacting quark-gluon plasma to study, ie that of QCD.
- Would be very helpful to have more examples, to learn what features are <u>characteristic</u> and what are uninteresting details.
- Theorists now finding examples ($N=4$ SYM is simplest) in which calculations become tractable in limit of <u>strong</u> coupling.
  - can compare <u>static</u> (ie thermodynamic) features to QCD theory. (Lattice QCD)
  - can compare some <u>dynamic</u> features (eg η/s, $\hat{q}$, ...) to QCD experiment (RHIC)

QGP@RHIC IS A LIQUID....

- Lattice QCD is perfect calculational method for studying its thermodynamics
  → onward to the continuum limit
- AdS/CFT is perfect calculational method for studying dynamics of quark-gluon plasmas precisely in those regimes in which they are liquid-like. Both η/s and $\hat{q}$ now calculated in <u>many</u> (∞) strongly interacting QGP's, but not in QCD. Both agree better with RHIC data than do weak coupling QCD calculations. What are common characteristics of QGPs?

η/s ? $\hat{q}/\sqrt{\# \text{ of d.o.f.}}$? Quarkonium suppression vs. p_T ?

N=4 SUSY QCD vs. QCD

- N=4 is supersymmetric, but susy is badly broken at $T \neq 0$
- Degrees of freedom at weak coupling differ: Define ν by $\varepsilon = \nu \frac{\pi^2}{30} T^4$

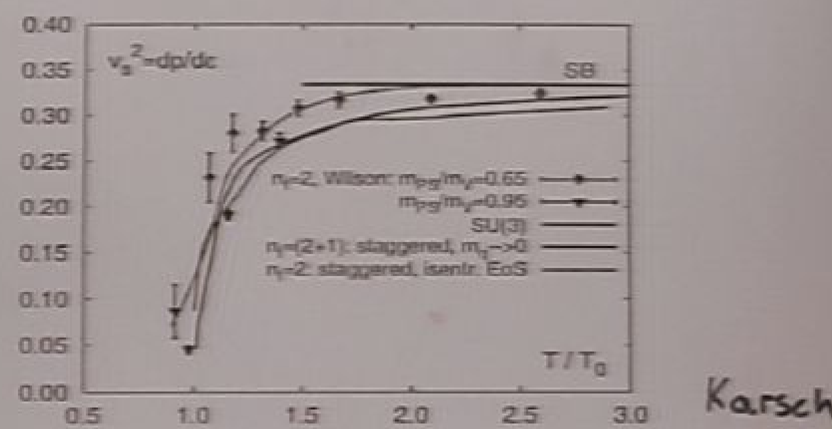
  Then: $\nu_{N=4} = 15(N_c^2 - 1) = 120$

  $\nu_{QCD} = 2(N_c^2 - 1) + \frac{21}{2} N_c = 47.5$

  Need observables (eg ratios like η/s) insensitive to this.
- N=4 is <u>conformal</u>. [No scale except T.]
  - QCD is <u>not</u> conformal for $T < T_c$ or for $T \to \infty$.
  - But, for $2T_c < T < 10 + T_c$, QGP looks quite conformal. [$\varepsilon \sim T^4$, $P \sim T^4$, $V_{sound}^2 \sim \frac{1}{3}$
  - Maybe strongly interacting QGP is well-modelled as conformal
- N=4 calculations tractable when:

  $1/N_c^2 \ll 1$ (In QCD, $1/N_c^2 = 1/9$)

  $g^2 N_c = 4\pi \alpha N_c \gg 1$ (For $N_c = 3$, $\alpha = 1/2$: $g^2 N_c = 6\pi \simeq 19$)



E 6. The velocity of sound in QCD vs. temperature expressed in units of the transitio
Shown are results from calculations with Wilson [22] and staggered fermions [10] as w
U(3) gauge theory [21]. Also shown is the resulting v_s^2 deduced from Eq. 3 [19].

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AdS / CFT

Maldacena ; Witten ; Gubser
Klebanov Polyakov ....

N=4 SYM is equivalent to Type IIB
String theory on $\underbrace{AdS_5}_{\text{4+1 "big" dimensions}} \times \underbrace{S_5}_{\text{5 curled up dimensions}}$

Translation Dictionary:

N=4 SYM gauge theory in 3+1 dim		String theory in 4+1(+5) dim
$\frac{g^2 N_c}{4\pi N_c}$	=	g_{string}

⌈$N_c \to \infty$ at fixed $g^2 N_c$ means $g_{string} \to 0$⌋

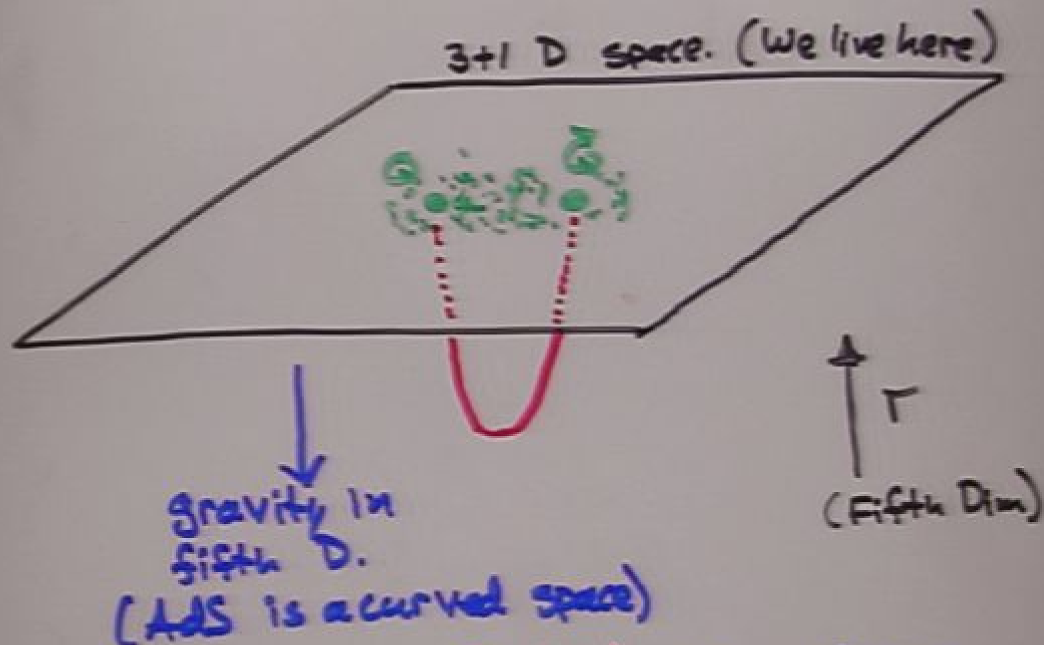
$\sqrt{g^2 N_c}$	=	R^2/α'

⌈R: AdS curvature
$\frac{1}{2\pi\alpha'}$: string tension⌋

Heat the gauge theory to a temperature T.	= Add a Black hole in the 5th dimension, with $T_H = r_0/\pi R^2$

⌈r_0: location of BH horizon in fifth dim.⌋

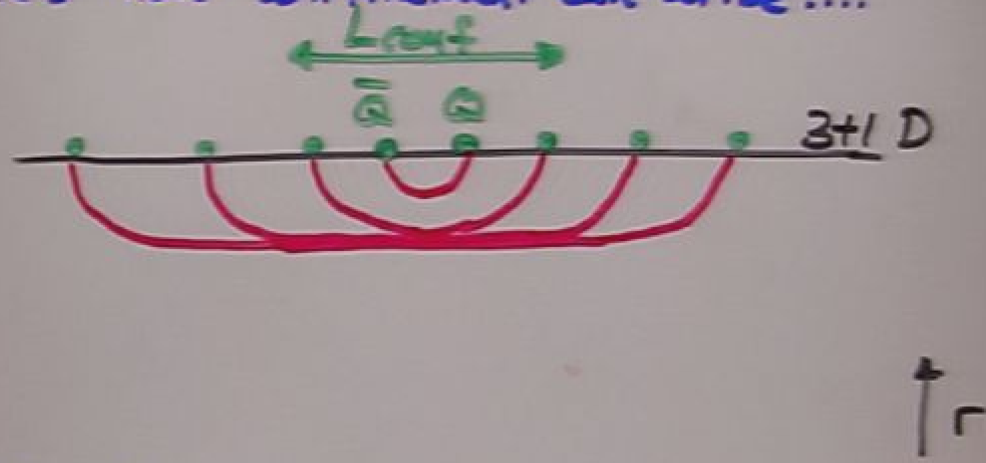
How can strings in 5D describe, say, force between Q and $\bar{Q}$ in a 4D gauge theory?



- Extremize energy of ∪ string. (Like catenary problem, in unusual gravitational field.)
  - Large $g^2 N_c$ → Large tension → no fluctuation
  - Large N_c → small g_{string} → no loops break off.
- Force between Q and $\bar{Q}$ $= \frac{d}{d\ \text{separation}}$ (Energy of string)

CONFINEMENT?

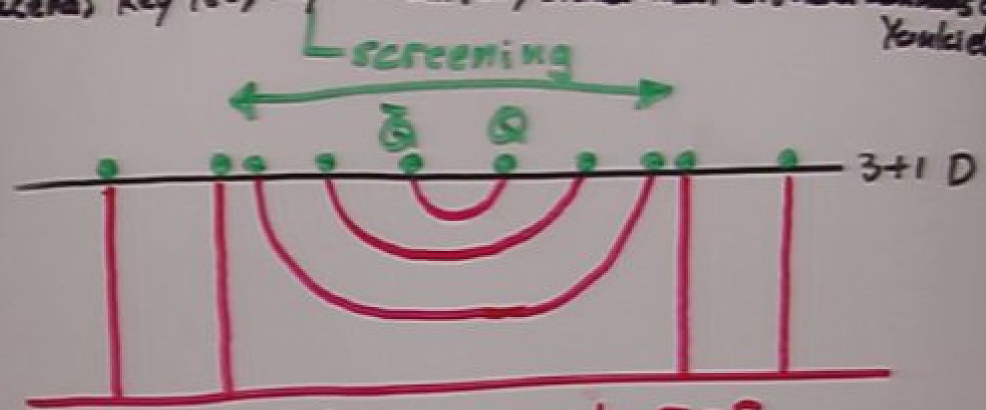
Here's how confinement can arise ....



- This does <u>not</u> happen in N=4
  - shape of string stays same as L increases. (N=4 is conformal)
- Confining gauge theories with dual descriptions like this <u>are</u> known.
- QCD not known to have a description like this.
- Don't use N=4 as a guide to QCD at T=0.

DECONFINEMENT AT $T \neq 0$

Maldacena; Rey Yee; Rey Theisen Yee; Brandhuber Itzhaki Sonnenschein Yankielowicz



Black Hole Horizon at $r = r_0$

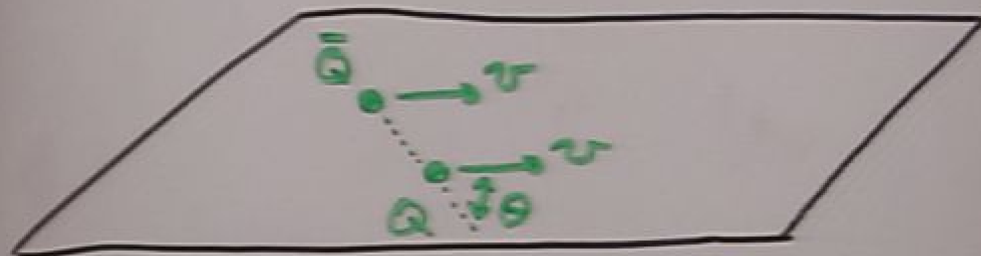
- For $L < L_s$, force between Q & $\bar{Q}$.
- For $L > L_s$, force is screened. Q & $\bar{Q}$ deconfined.
- In $N=4$ SUSY QCD,

$$L_s = \frac{0.277}{T}$$

- In QCD, force between static Q & $\bar{Q}$ in QGP can be calculated. (Lattice QCD) Can define L_s, though it is not a sharp boundary. Find: $L_s \sim \frac{0.5}{T} \rightarrow \frac{0.7}{T}$ Kaczmarek Karsch Zantow Petreczky
- $N=4$ gets this feature of the QCD strongly interacting QGP to within factor of 2!

A PREDICTION FOR EXPERIMENT

H. Liu, KR, Wiedemann



- Calculate force between $Q + \bar{Q}$ <u>moving</u> through the $N=4$ QGP. (Not known how to do this calculation in QCD.) Find:

$$L_s = \frac{f(v,\theta)}{\pi T}(1-v^2)^{1/4}$$

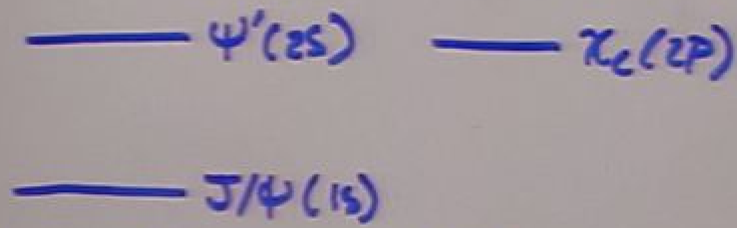
LRW; Peeters et al; Chernicoff et al; Caceres et al

where f is almost a constant. ($f(0,0) = 0.8$[illegible]) $f(0,\frac{\pi}{2}) = .743$

- So, $L_s(v,T) \simeq L_s(0,T)/\sqrt{\gamma}$
- Makes sense if L_s controlled by ε, since $\varepsilon \sim T^4$ and $\varepsilon(v) = \varepsilon(0)\,\gamma^2$.
- J/ψ ($\bar{c}c$) and Υ ($\bar{b}b$) mesons dissociate when T reaches T_{diss}, at which $L_s \sim$ meson size.
- Suggests: $T_{diss}(v) \sim T_{diss}(0)/\sqrt{\gamma}$!

J/ψ SUPPRESSION

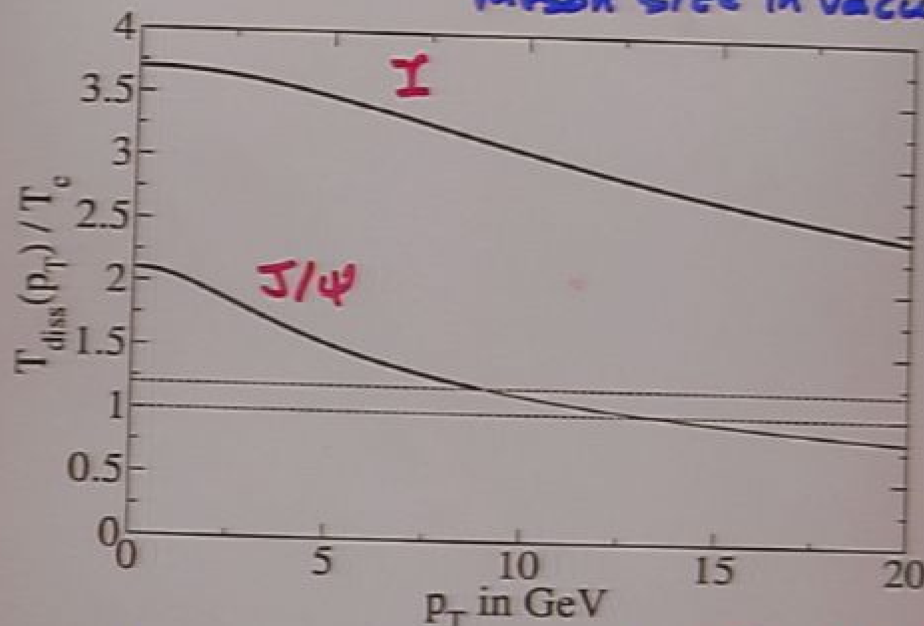
- A long story, which I will oversimplify.
-



- 40% of observed J/ψ were produced as ψ' or χ_c.
- $T_{diss} = 2.1\, T_c$ for J/ψ
  $T_{diss} = 1.1 - 1.2\, T_c$ for ψ', χ_c } at v=0. Lattice QCD
- At both RHIC and SPS (lower energy heavy ion collisions at CERN), J/ψ yield between 100% + 60% expected, as function of impact parameter →
- Suggests RHIC does not reach $2.1\, T_c$.
- Prediction: suppression will increase for high enough P_T J/ψ's : moving through QGP, and $T_{diss}(v)$ drops with v, at some v becoming = to T !

$T_{dissociation}$ vs. P_T

- At $P_T=0$, $T_{diss}^{J/\psi} \simeq 2.1\, T_c$, from lattice QCD
- Υ curve schematic. (Scaled rel. to J/ψ by meson size in vacuum.)



- Our velocity scaling: $T_{diss}(v) \simeq T_{diss}(0)/\sqrt{\gamma}$

+ Karsch Kharzeev Satz model
  (ie $2.1\,T_c < T_{RHIC} < 1.2\,T_c$)

$\Rightarrow$ J/ψ themselves dissociate for
$P_T > 5\,\text{GeV}$ if $T_{RHIC} \sim 1.5\,T_c$
$P_T > 9\,\text{GeV}$ if $T_{RHIC} \sim 1.2\,T_c$

CALCULATION OF $\hat{q}$

- Boils down to "a catenary problem".
  - this time, string hanging between Q & $\bar{Q}$ separated by L, where $L \sim \frac{1}{k_T}$ with k_T the transverse momentum of radiated gluon, moving at speed of light.

CALCULATION OF η/s

- Not analogous to calculation I have described. (Involves calculation of $\langle T_{\mu\nu}(x)\, T_{\mu\nu}(0)\rangle$ correlation function.) Not as simple as "a catenary problem" but still do-able.

$\hat{q}$ ISSUES

We have found $\hat{q}_{N=4\ SYM} \sim \hat{q}_{QCD@RHIC}$.

What are the issues on both sides of this comparison?

$\hat{q}$ EXTRACTED FROM RHIC DATA

- Extraction neglects energy loss by processes other than gluon radiation. Gluon radiation does dominate for high enough energy jets, but do RHIC collisions provide high enough energy jets?
- LHC will help
  - 100+ GeV jets
  - Will be able to see jets, and hence study their modification
    → more discriminating observables
  - Study back to back γ+jet, Z+jet.
    → know initial jet energy

FROM $\hat{q}_{SYM}$ TOWARDS $\hat{q}_{QCD}$

- For <u>any</u> CFT with a gravity dual,

$$\frac{\hat{q}_{CFT}}{\hat{q}_{N=4}} = \sqrt{\frac{S_{CFT}}{S_{N=4}}}$$

Liu, KR Wiedemann

in $N_c^2 \to \infty$, $g^2 N_c \to \infty$ limit. Confirms that weak coupling intuition not a good guide. Suggests:

$$\frac{\hat{q}_{QCD}}{\hat{q}_{N=4}} \sim \sqrt{\frac{47.5}{120}} \sim 0.63$$

- Corrections due to nonconformality calculated in one example: Buchel

$$\hat{q}_{KW} = \sqrt{\frac{27}{16}}\, \hat{q}_{N=4}$$ KW: a conformal th.

$$\hat{q}_{KS} = \left[1 + 3.1\left(c_s^2 - 1\right)\right] \hat{q}_{KW}$$ KS: nonconformal

$= 0.85\, \hat{q}_{KW}$ for $c_s^2 = 0.28$ as in QCD at $T \sim 1.5\, T_c$.

Wanted:

- Examples where $\hat{q}$ calculated as # of d. of f. is reduced
  → Calculate $\hat{q}$ in $N=2^*$.
- Examples where QGP includes fundamentals as well as adjoints.
- Corrections to $g^2 N_c \to \infty$
  - one contribution to these is calculated, and is ~2% for $g^2 N_c = 6\pi$. Armesto Edelstein Mas
- Corrections to $N_c^2 \to \infty$

- Suppose that after calculating $\hat{q}$ in many, and varied, gauge theories with dual descriptions of their quark-gluon plasmas we understand enough to conjecture

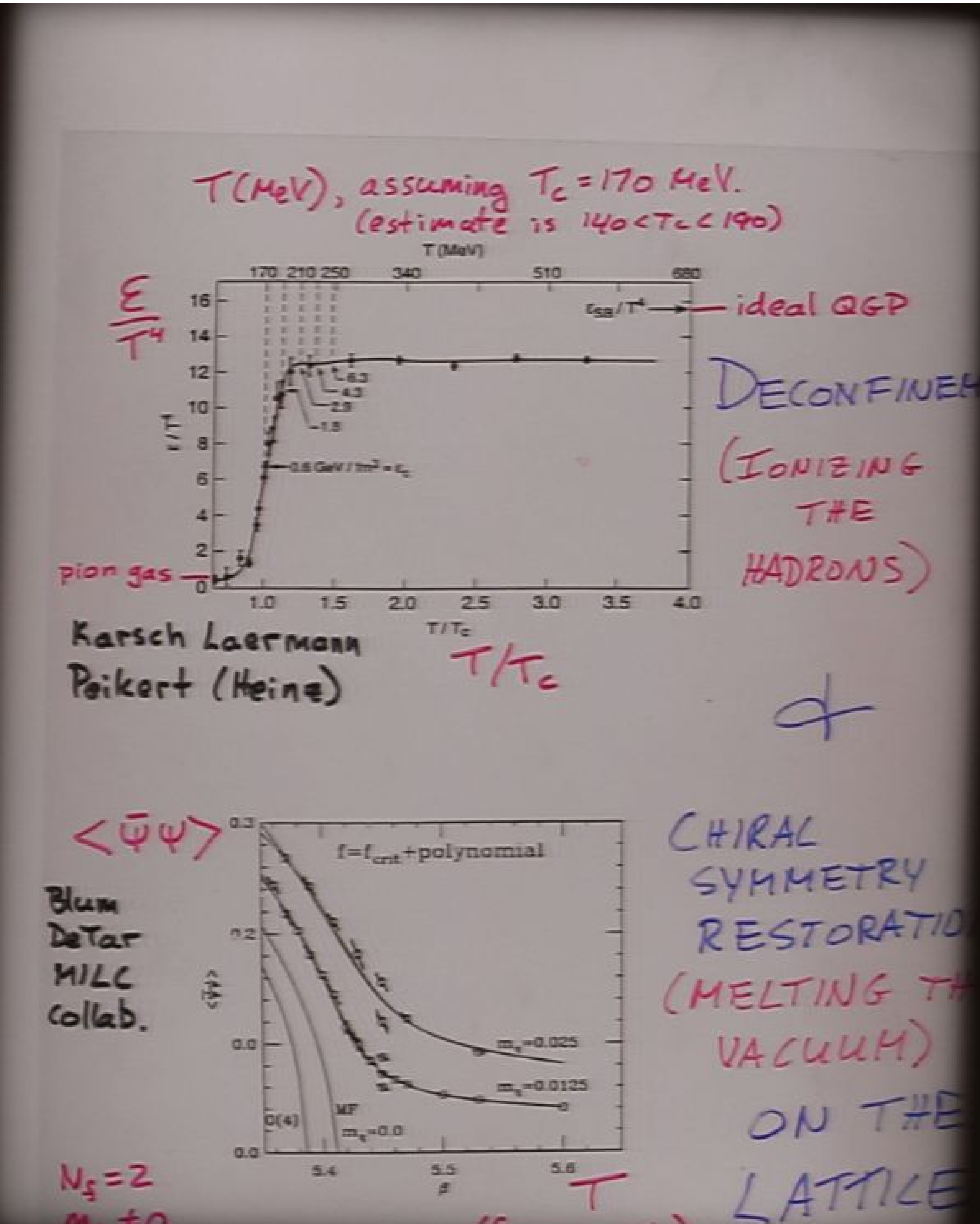
$$\hat{q}_{QCD} = b\sqrt{g^2 N_c}\, T^3$$

with an estimate of b that we trusted at the factor of two level.

This would have a <u>big</u> impact:

$\hat{q}$ would serve as a <u>thermometer</u> for early times with a calibration uncertainty only of order $2^{1/3}$.

→ Allow to <u>measure</u> ε/T^4 and <u>test</u> the lattice QCD calculations from which we began.


T(MeV), assuming T_c = 170 MeV.
(estimate is 140 < T_c < 190)
T (MeV)
170 210 250 340 510 680
ε / T^4
ε_{SB}/T^4
ideal QGP
6.3
4.3
2.9
1.9
0.6 GeV / fm³ = ε_c
pion gas
1.0 1.5 2.0 2.5 3.0 3.5 4.0
T / T_c
Karsch Laermann Peikert (Heine)
DECONFINEM
(IONIZING THE HADRONS)
$\langle \bar{\psi}\psi \rangle$
f = f_{crit} + polynomial
Blum DeTar MILC collab.
CHIRAL SYMMETRY RESTORATIO
(MELTING TH VACUUM)
ON THE LATTICE
m_q=0.025
m_q=0.0125
O(4)
MF
m_q=0.0
5.4 5.5 5.6
β
T
N_f = 2

OTHER DIRECTIONS BEING INVESTIGATED WITH AdS/CFT

- Calculate drag on quark moving through $N=4$ plasma. Herzog Karch Kovtun Kozcaz Yaffe; Gubser; Casalderrey Teaney

  Ie treat whole process of energy loss at strong coupling in $N=4$, rather than just calculation of $\hat{q}$. This is not a good description for high enough energy partons in QCD (eg at LHC). It is plausibly relevant at RHIC, particularly for heavy quarks.
- Modelling jet quenching as drag allows to address further questions like "where does energy go?" Friess Gubser Pufu Michalogiorgakis
- Photon emission rate from $N=4$ plasma. Caron-Huot, Kovtun Moore Starinets Yaffe

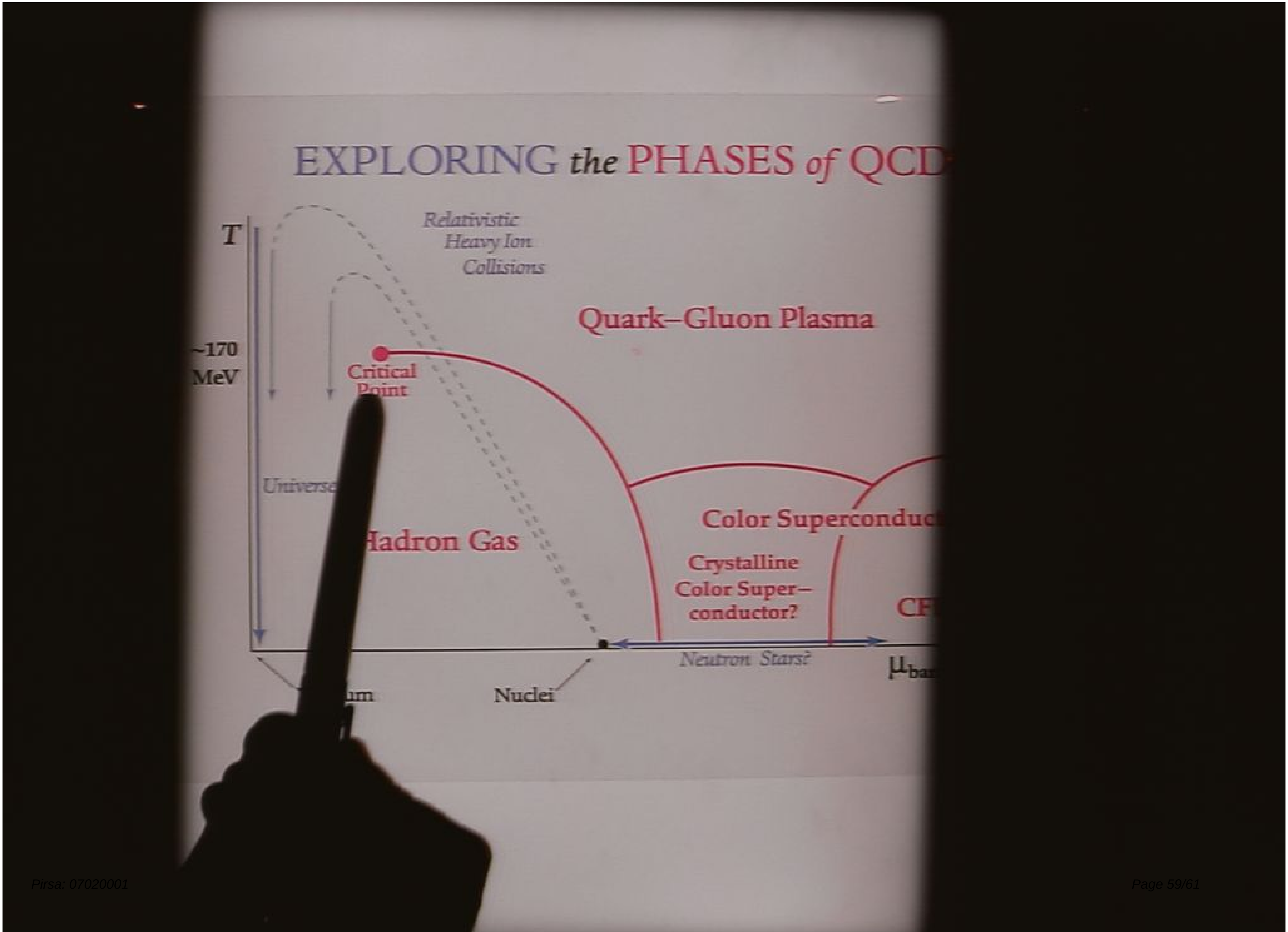
  [Measurement of photon emission from QGP @ RHIC remains an experimental challenge.]

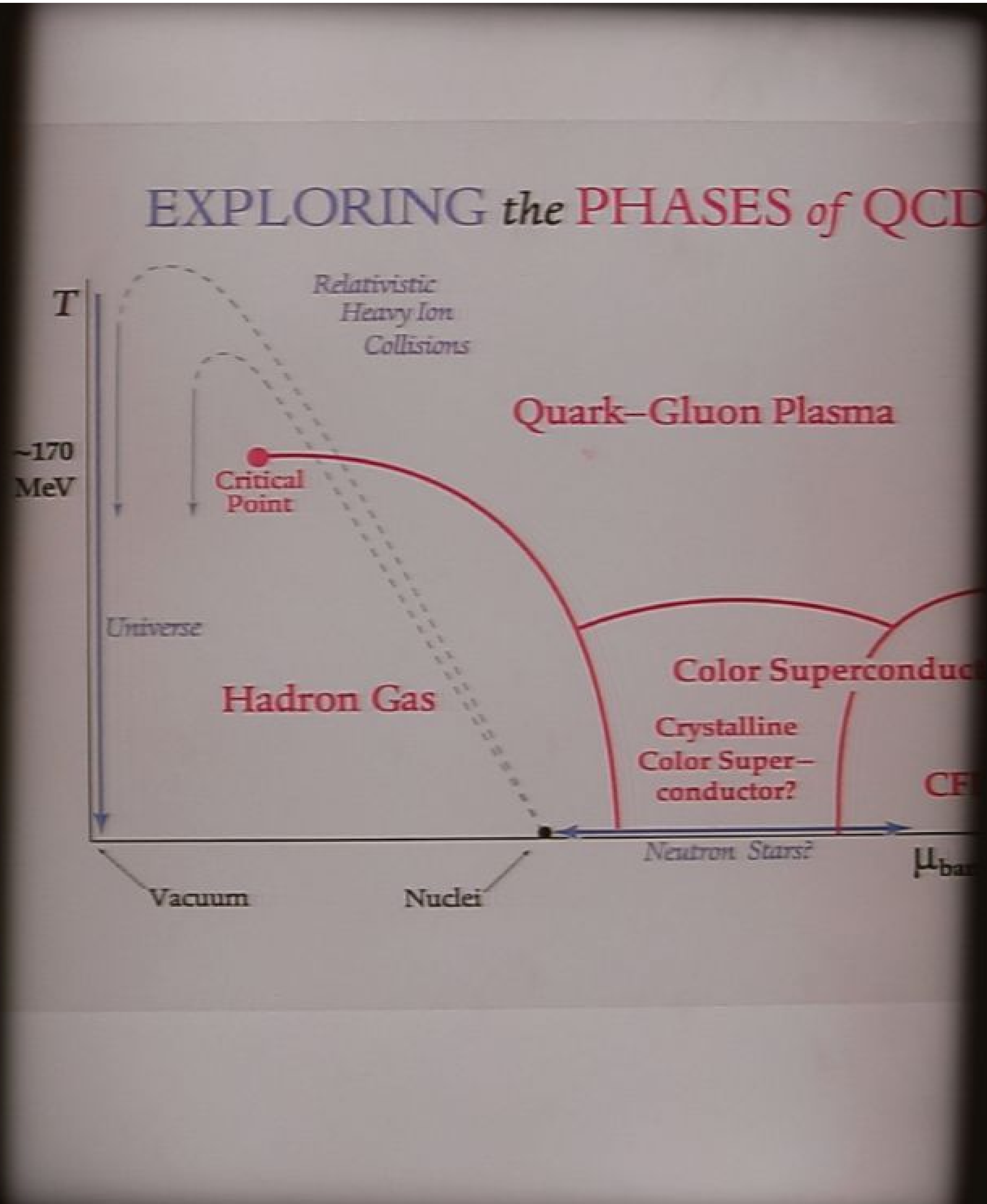
TWO BEST STUDIED STRONGLY INTERACTING QUARK-GLUON PLASMAS

	$N=4$	QCD	
STATIC: $\varepsilon/\varepsilon_{SB}$	$3/4$	~ 0.8 for $T \gtrsim 1.2 T_c$	Lattice QCD
P/P_{SB}	$3/4$	~ 0.8 for $T \gtrsim 2 T_c$	Lattice QCD
C^2_{sound}	$1/3$	$\sim 1/3$ for $T \gtrsim 1.5 T_c$	Lattice QCD
Static screening length L_S	$\frac{0.28}{T}$	$\sim \frac{0.5-0.7}{T}$	Lattice QCD
η/s	$1/4\pi$	$< \mathcal{O}(0.1)$	
$\hat{q}$ at $t \sim 1$ fm, $T \sim 300$ MeV	$5\,\mathrm{GeV}^2/\mathrm{fm}$	$5-15\,\mathrm{GeV}^2/\mathrm{fm}$	
$L_S(v)$	$L_S(0)/\sqrt{\gamma}$	data to come	
Photon emission	Calculated	Measurable?	
Fraction of jet energy going into Mach cone	calculable	Measurable?	

WHAT IS TO COME... ⌈A SELECTION⌋

- Study how higher (RHIC-II) and <u>much</u> higher (LHC) energy partons lose energy, probing QGP.
  → better extraction of $\hat{q}$; more observables
- Calculation of $\hat{q}$ in other more QCD-like strongly interacting QGP.
  - how does it change from theory to theory?
- Explore the phase diagram at $T \sim T_c$, $0 < \mu_B < 3T_c$.
  - low energy collisions at RHIC
  - look for fluctuations that characterize those collisions near critical point
  - ∃ hints in SPS data. RHIC can find critical point if $\mu_{CP} < 500$ MeV
  - progress in lattice QCD too


EXPLORING the PHASES of QCD
T
~170 MeV
Relativistic Heavy Ion Collisions
Quark–Gluon Plasma
Critical Point
Hadron Gas
Color Superconduct
Crystalline Color Super–conductor?
Neutron Stars?
Nuclei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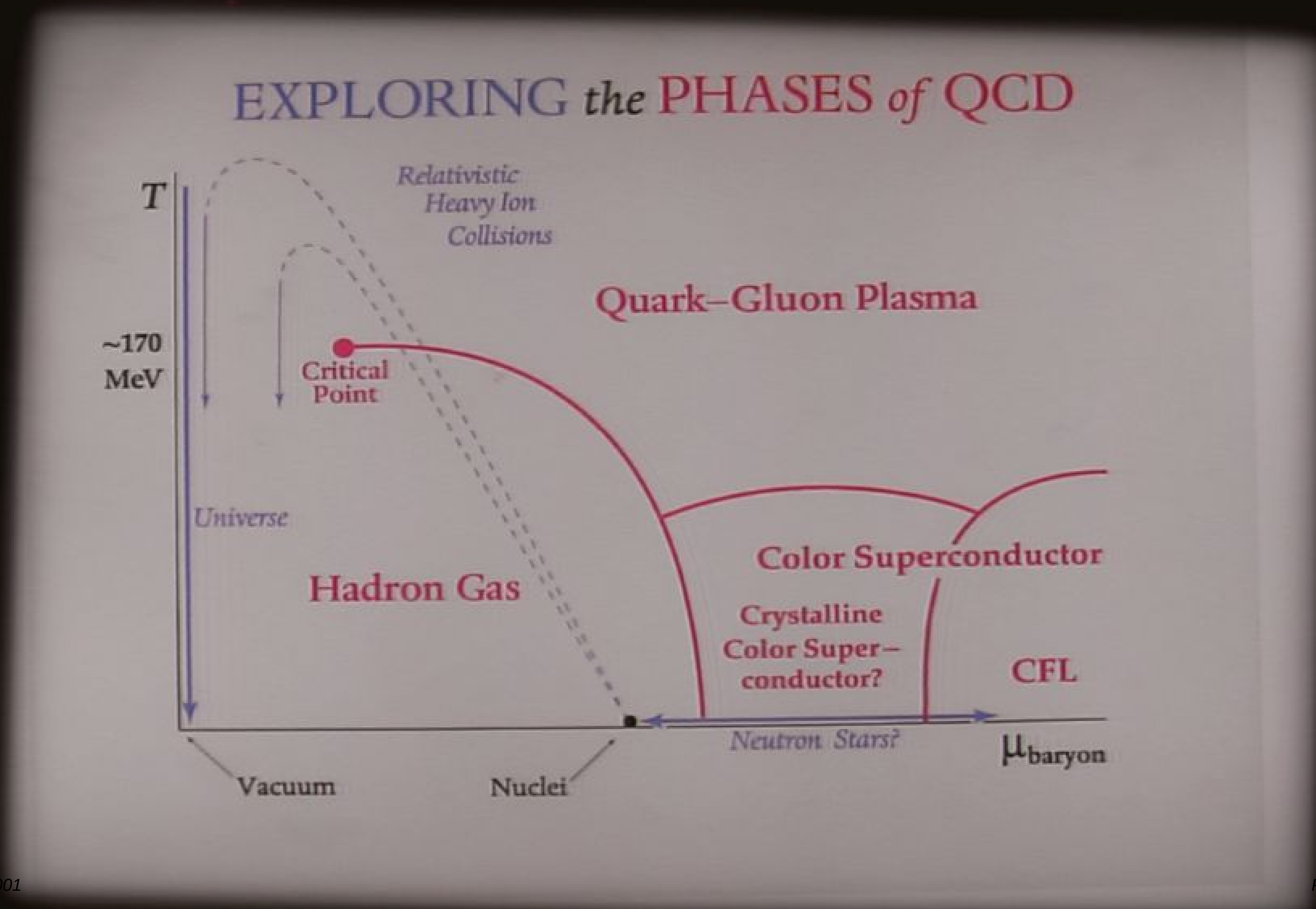
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Color Super–
conductor?
CFL
Neutron Stars?
μbaryon
Vacuum
Nuclei