ITP: QCD IN THE RHIC ERA

APRIL 2002

# ENERGY LOSS AND QUENCHING OF HADRON SPECTRA

R. BAIER

UNIVERSITY OF BIELEFELD

## CONTENT

- CHARACTERISTICS OF RADIATIVE QCD ENERGY LOSS DUE TO MULTIPLE SCATTERING OF PROPAGATING PARTONS IN A DENSE MEDIUM
- DEPENDENCE ON THE MEDIUM: VIA TRANSPORT COEFFICIENT $\hat{q}$
- HOW TO MEASURE $\Delta E$

⇒ QUENCHING OF LARGE $p_T$ HADRON/PION SPECTRA

- CHALLENGE/DISCUSSION: NON-EQUILIBRATED DENSE GLUONIC SYSTEM

---

COMMON MORE RECENT WORK WITH

YURI DOKSHITZER

AL H. MUELLER

DOMINIQUE SCHIFF

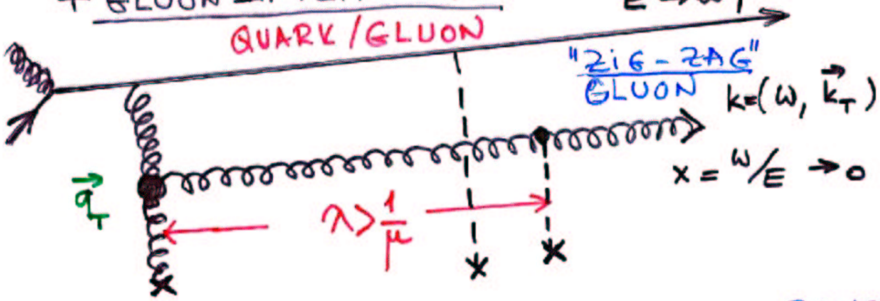
STEPHAN PEIGNÉ

## pQCD RADIATIVE LOSS / MEDIUM INDUCED

HIGH ENERGY PARTON

DOMINANT PROCESS - MULTIPLE SCATTERING + GLUON INTERACTION

$E \to \infty$, LOSS $\Delta E$




SCREENED SCATTERING CENTERS, RANGE ~ $1/\mu$
(M. GYULASSY AND X. N. WANG)

$\mu$ .. TYPICAL KICK IN A SINGLE SCATTERING & RANGE OF INTERACTION

RANDOM WALK: $\langle \vec{k}_T^2 \rangle_L \sim \mu^2 L / \lambda$
LENGTH $L$
$\sim \hat{q} L$
($k_T$ BROADENING)

TRANSPORT COEFFICIENT $\hat{q} \simeq \mu^2 / \lambda$

$$\simeq \rho \int d^2\vec{q}_T \; \vec{q}_T^{\,2} \frac{d\sigma}{d^2\vec{q}_T}$$

$\rho$: NUMBER DENSITY OF MEDIUM

"$\sigma$": GLUON - CENTER INTERACTION

## TIME SCALES:

- FORMATION TIME ON-SHELL GLUON $\quad t_{FORM} \sim \frac{\omega}{\vec{k}_T^2}$

- COHERENCE TIME / LENGTH

$$t_{COH} \sim \frac{\omega}{\langle \vec{k}_T^2 \rangle_{COH}}$$

$$\langle \vec{k}_T^2 \rangle_{COH} \sim N_{COH} \, \mu^2 \sim \hat{q} \, t_{COH}$$

$\Big\}$ $t_{COH} \sim \sqrt{\omega / \hat{q}}$

$N_{COH} \sim \frac{t_{COH}}{\lambda}$ .. NUMBER OF COHERENT SCATTERING CENTERS ACTING AS ONE SOURCE FOR GLUON RADIATION
(MANY)

MEDIUM INDUCED RADIATION SPECTRUM / LENGTH FOR $N_{COH} > 1$, $\omega > \omega_{BH} \sim \lambda \mu^2$

$$\omega \frac{dI}{d\omega\, dz} \sim \left( \omega \frac{dI}{d\omega\, dz} \right)_{BH} \frac{1}{N_{COH}} \sim \frac{\alpha_s}{\pi} C_R \sqrt{\hat{q} / \omega}$$

"SUPPRESSION"

$\frac{\alpha_s C_R}{\pi \lambda}$ ~ $\omega$ INDEPENDENT

**RESULT:** LPM SUPPRESSED (MEDIUM-INDUCED) (SOFT) GLUON SPECTRUM

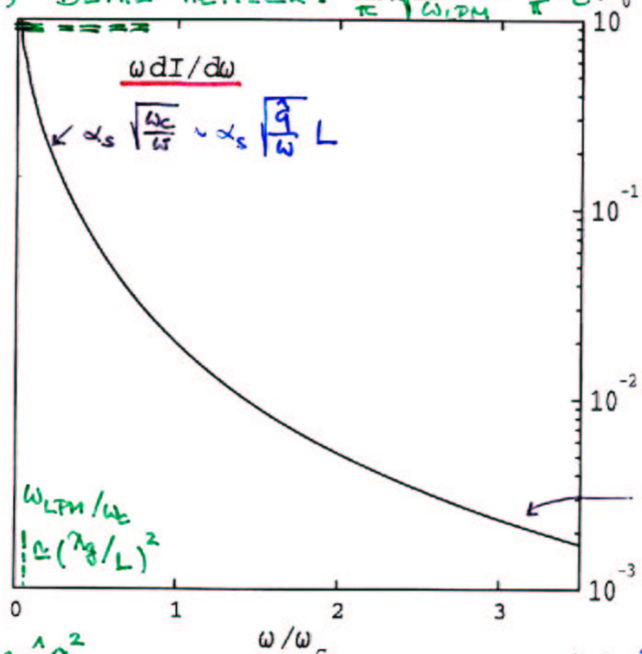
SIZE / LENGTH $L$ FIXED

$\alpha_s = 0.3$

$L/\lambda_g \gg 1$

$\omega \ll E_{PARTON} \to \infty$

(INCOHERENT) BETHE-HEITLER: $\frac{\alpha_s C_R}{\pi} \sqrt{\frac{2\omega_c}{\omega_{LPM}}} = \frac{\alpha_s}{\pi} N_c \left( L/\lambda_g \right)$




$\omega\, dI/d\omega$: $\alpha_s \sqrt{\frac{\omega_c}{\omega}} \sim \alpha_s \sqrt{\frac{\hat{q}}{\omega}}\, L$

$\alpha_s \left( \frac{\omega_c}{\omega} \right)^2$

$\omega_{LPM}/\omega_c \simeq (\lambda_g/L)^2$

$\omega_{LPM} \simeq \hat{q}\, \lambda_g^2$

$\hat{q} \simeq \frac{\mu^2}{\lambda}$ : $\hat{q}$ .. TRANSPORT COEFFICIENT

$\omega_c = \frac{1}{2} \hat{q} L^2$ ... CHARACTERISTIC GLUON ENERGY

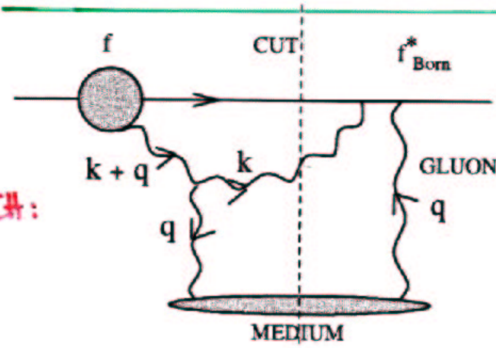
**CRUCIAL OBSERVATION:**

GLUON RADIATION SPECTRUM INDUCED BY MULTIPLE SCATTERINGS IS DOMINATED BY

INTERFERENCE TERM OF AMPLITUDES

⇒ DEPENDENCE ON THE MEDIUM

SKETCH:




$$\frac{\omega dI}{d\omega} \propto \alpha_s \int f \otimes f^*_{BORN}$$

CONTAINS ALL THE MULTIPLE INTERACTIONS

MEDIUM:

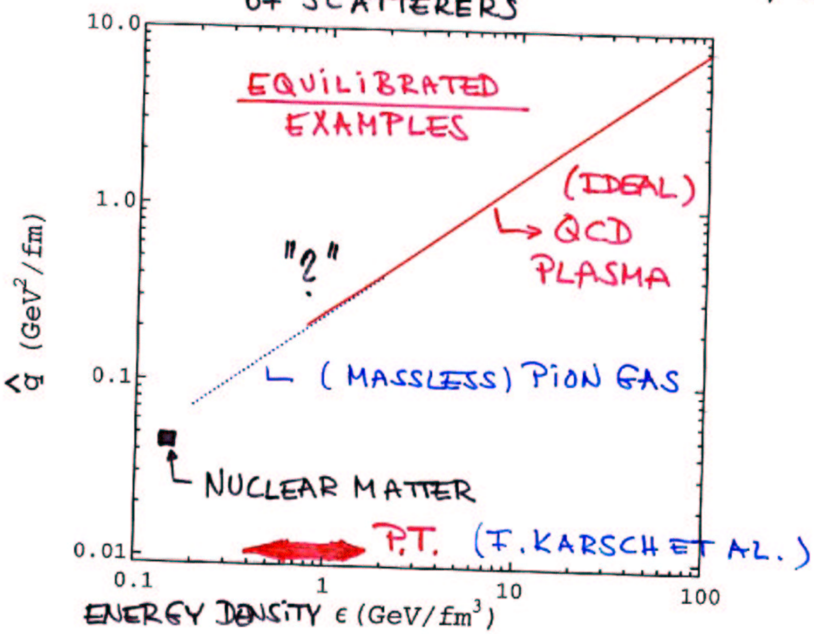
GAS: $\rho(T) \sim T^3 \sim \epsilon^{3/4}$, $xG(x,Q^2) \sim \alpha_s \ln Q^2/\lambda^2$

COLD MATTER: $\rho = \epsilon/m_N$, $x G_N \sim 1-2$: GLUON IN NUCLEON

FOR:

- $\hat{q} \simeq \rho$ × "EFFECTIVE" GLUON-DISTRIBUTION IN MEDIUM, $xG$

  NUMBER DENSITY OF SCATTERERS




- "SMOOTH" INCREASE WITH $\epsilon \uparrow$ FOR $\hat{q}$ AND FOR $\Delta E\,(\hat{\epsilon})$

  NO "JUMPS" IN TERMS OF $\hat{q} = \hat{q}(\epsilon)$

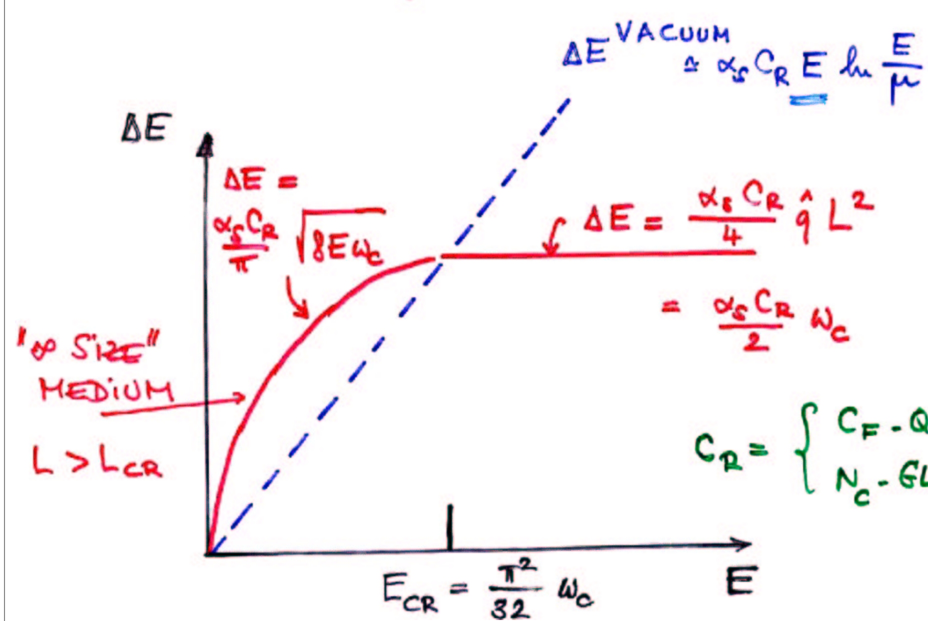
- $\Delta E|_{QCD} \gg \Delta E|$ (COLD) NUCLEAR MATTER

## MEDIUM INDUCED ENERGY LOSS ΔE DUE TO GLUON RADIATION

$$\omega \frac{dI}{d\omega}\Big|_{soft} = \frac{\alpha_s C_R}{\pi} \ln\left[\cosh^2\sqrt{\frac{\omega_c}{2\omega}} - \sin^2\sqrt{\frac{\omega_c}{2\omega}}\right]$$

$$\omega_c = \frac{1}{2}\hat{q} L^2$$

$$\Rightarrow \Delta E = \int_0^{E(\to\infty)} d\omega\, \frac{\omega dI}{d\omega}$$ .. AVERAGE ENERGY LOSS




$C_R = \begin{cases} C_F \text{ - QUARK} \\ N_c \text{ - GLUON} \end{cases}$

## HOW TO MEASURE $\Delta E\,(L)$ ?

- INCLUSIVE LARGE $p_T$ HADRONS IN A-A COLLISIONS

"JET QUENCHING": SHIFT OF LEADING PARTICLE / PION SPECTRUM

"VACUUM" ⟶ MEDIUM / PARTON PROPAGATION + RADIATION

$$\frac{d\sigma^{MEDIUM}}{dp_T^2}(p_T) = \underbrace{Q(p_T)}_{\text{QUENCH FACTOR}} \frac{d\sigma^{VACUUM}}{dp_T^2}(p_T)$$

$$\simeq \frac{d\sigma^{VACUUM}}{dp_T^2}\left(p_T + \underbrace{S(p_T)}_{\text{SHIFT}}\right)$$

NOTICE:

BIAS, SUCH THAT $S(p_T) < \Delta E$ (AVERAGE LOSS) DUE TO SHARPLY FALLING

$$\frac{d\sigma^{VACUUM}}{dp_T^2}(p_T) \simeq \frac{CONST}{p_T^n}, \quad \overset{RHIC}{n \gtrsim 8-10}$$

⇒ ADDITIONAL SUPPRESSION OF REAL GLUON EMISSION

WE PROPOSE (DETAILS IN BDMS: JHEP 0109 (2001) 033)

$$\frac{d\sigma^{MEDIUM}}{dp_T^2}(p_T) = \int d\epsilon\, D(\epsilon)\, \frac{d\sigma^{VACUUM}}{dp_T^2}(p_T+\epsilon)$$

$D(\epsilon)$: PROBABILITY THAT THE ENERGY $\epsilon$ IS TAKEN AWAY FROM THE LEADING PARTON BY MEDIUM INDUCED MULTI GLUON RADIATION:

FOR PRIMARY EMITTED (SOFT) GLUONS – POISSON

$$D(\epsilon) = \sum_{n=0}^{\infty} \frac{1}{n!}\left[\prod_i^n \int d\omega_i \frac{dI}{d\omega_i}\right] \delta\left(\epsilon - \sum_i \omega_i\right)$$

$$\times \underbrace{\exp\left[-\int d\omega \frac{dI}{d\omega}\right]}_{\text{ACCOUNTS FOR VIRTUAL RADIATION}}$$

⇒ $Q(p_T)$ AND $S(p_T)$ VIA MELLIN TRANSFORM

USING $\frac{dI}{d\omega}$ LPM SUPPRESSED GLUON SPECTRUM

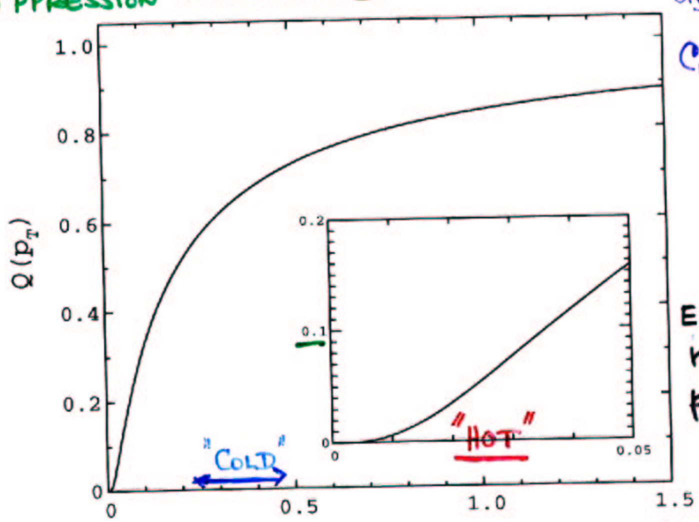
## QUENCHING FACTOR

$$Q(p_T) \xrightarrow[p_T\to\infty,\ n,\omega_c\ \text{FIXED}]{X\to\infty} 1+\mathcal{O}(\alpha_s)$$ "SMALL"

SIGNIFICANT SUPPRESSION FOR SMALL X

$\alpha_S = 0.3$

$C_F = 4/3$




E.G. FOR $n \sim 10$, $p_T \sim 10$ GeV/c

Q SCALES IN: $X = p_T/(n\omega_c)$ .. DIMENSIONLESS

$$\omega_c = \frac{1}{2}\hat{q} L^2$$

TYPICAL VALUES: $L = 5$ fm

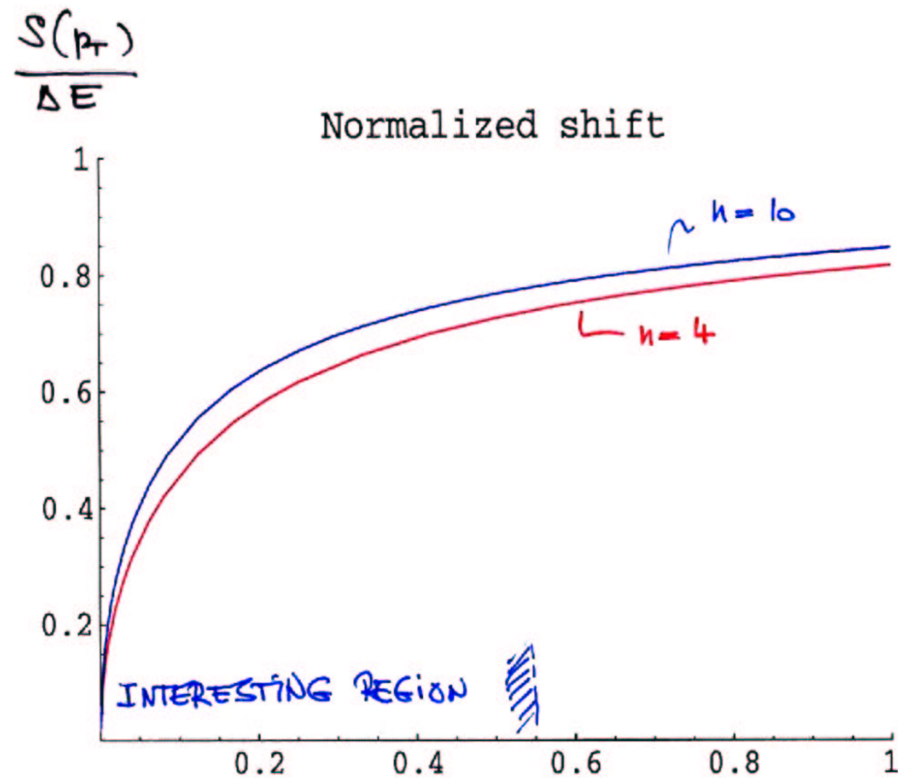
COLD: $\omega_c \simeq 3$ GeV

PION: $\omega_0 \simeq 15$ ($\epsilon = 1$ GeV/fm$^3$) GeV

QGP: $\omega_c \simeq 25$ ($\epsilon = 2$ GeV/fm$^3$) — 80 ($\epsilon = 10$ GeV/fm$^3$)

## $p_T$ DEPENDENCE OF SHIFT

$$S(p_T) < \Delta E \ (\sim L^2)$$




$$X = \frac{p_T}{n\,\omega_c}$$

EFFECTIVELY:

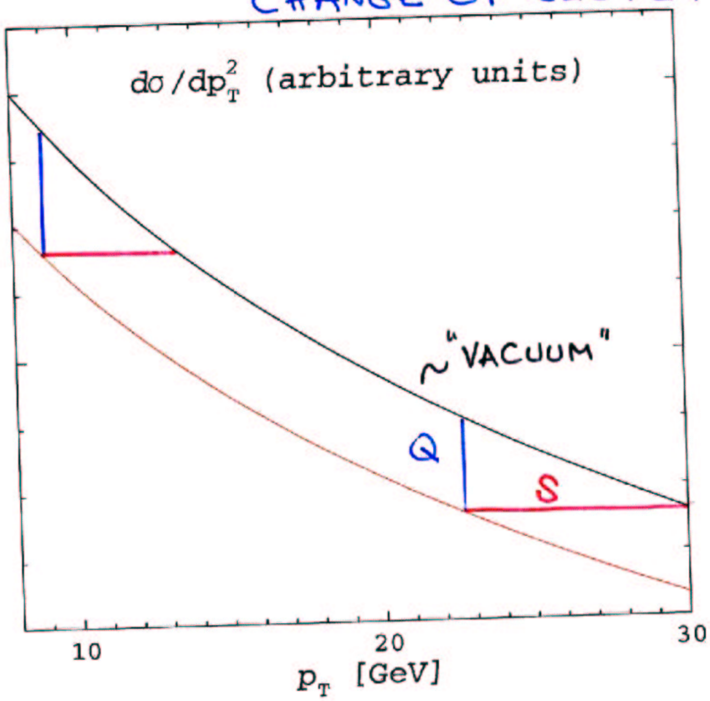
$$S(p_T) \sim L\sqrt{p_T}$$

## ILLUSTRATION: $p_T$ DEPENDENCE

($L = 5$ fm)

$Q(p_T)$
AND
SHIFT $S(p_T)$

CHANGE OF SLOPE:




$S(p_T)$ INCREASES WITH $p_T$

QUENCHING FACTOR APPROACHES

$$Q(p_T) \xrightarrow[p_T \to \infty]{} 1 + \underbrace{\mathcal{O}(\alpha_s)}_{\text{SMALL CORRECTION}}$$

## HOW STABLE / RELIABLE ARE THE PREDICTIONS FOR $Q(p_T)$ / $S(p_T)$?

ALTHOUGH $\Delta E$, $Q(p_T)$, $S(p_T)$ ARE IR SAFE

NEVERTHELESS IR SENSITIVE DUE TO "SOFT SINGULARITY" IN

$$\omega \, dI/d\omega \sim 1/\sqrt{\omega}$$

INTRODUCE CUTOFF $\omega \geq \omega_{MIN} \sim 300 - 500$ MeV

↳ "STABLE" RESULT FOR

$p_T \gtrsim 10$ GeV/c at RHIC (i.e. $n \sim 10$)

AT LARGE $p_T$: $Q(p_T) \simeq 1 + \underbrace{\mathcal{O}(\alpha_s)}$

SMALL, i.e.

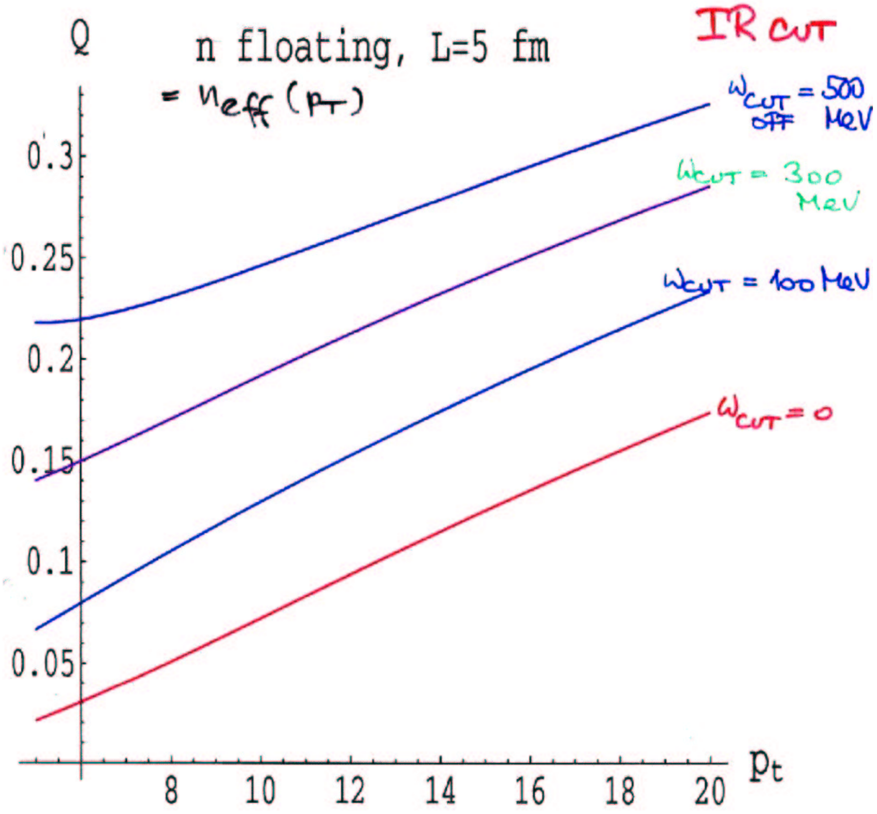
SENSITIVE TO EFFECTS NOT YET UNDER CONTROL

↳ $p_T \lesssim p_T^{MAX} \sim \frac{\alpha_s}{2} C_R \omega_c n$

(RATHER LARGE AT RHIC)

## IR SENSITIVITY

HOT MEDIUM : $\hat{q} \simeq 1\,\mathrm{GeV}^2/\mathrm{fm}$

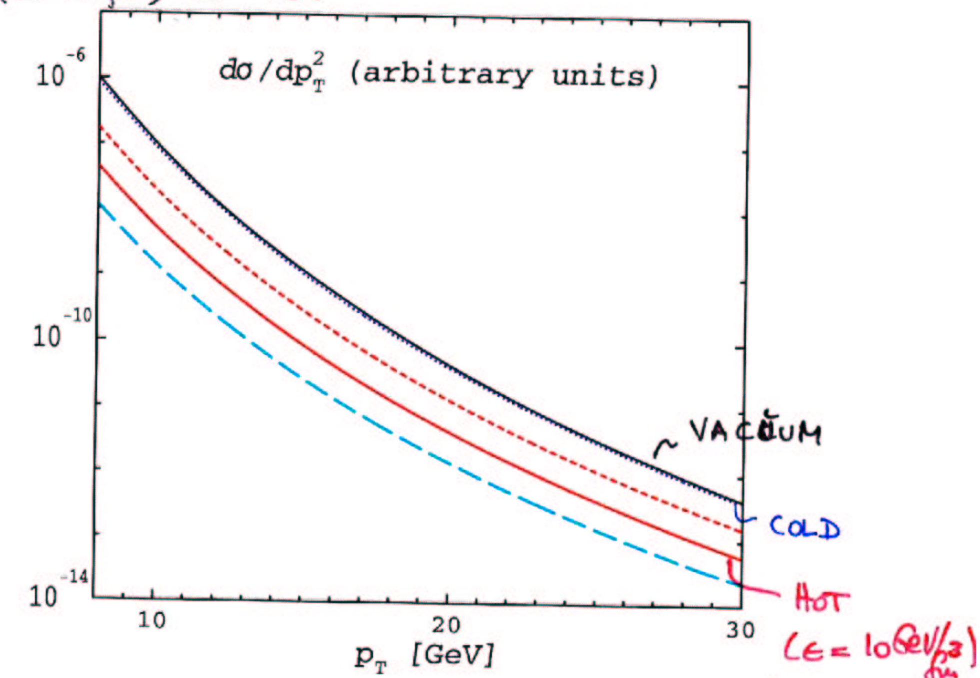



FLOATING : $\frac{1}{(p_T + 1.71)^{12.44}} \hat{=} \frac{1}{p_T^{\,n_{eff}(p_T)}}$

## MEDIUM DEPENDENCE OF QUENCHING

RHIC : $\frac{d\sigma^{VACUUM}}{dp_T^2} \simeq \frac{\mathrm{CONST}}{(p_T + 1.71)^{12.44}}$

$(L = 5\,\mathrm{fm},\ \alpha_s = 1/3)$




"SMOOTH" QUENCHING WITH DENSITY ↑ AT FIXED $p_T$

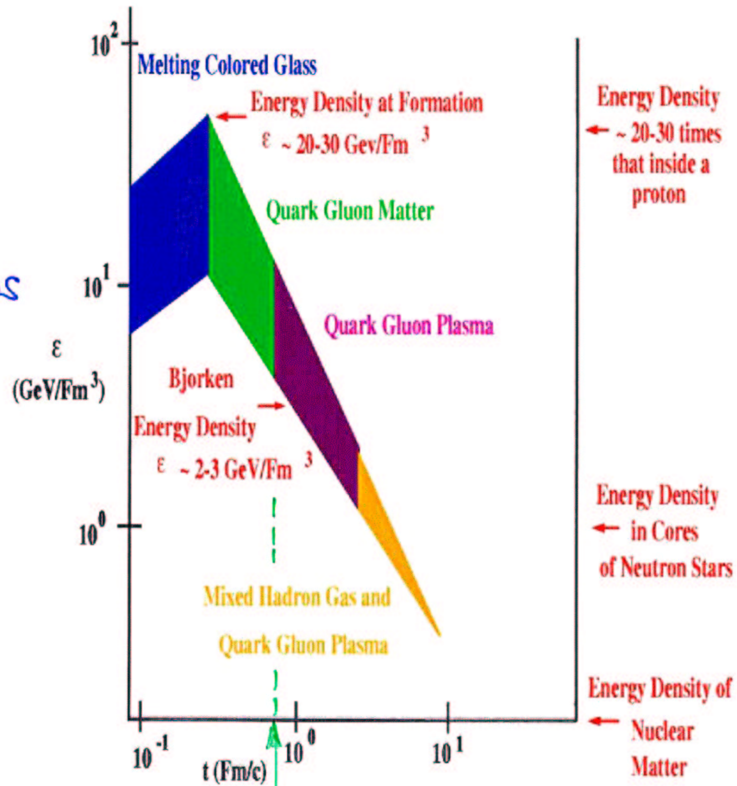
$(\omega_{CUTOFF} = 500\,\mathrm{MeV})$

(FROM McLERRAN'S TALK)

CHALLENGE:

OPEN QUESTION: WHICH MEDIUM IS PROBED BY QUENCHING ?

CENTRAL COLLISIONS

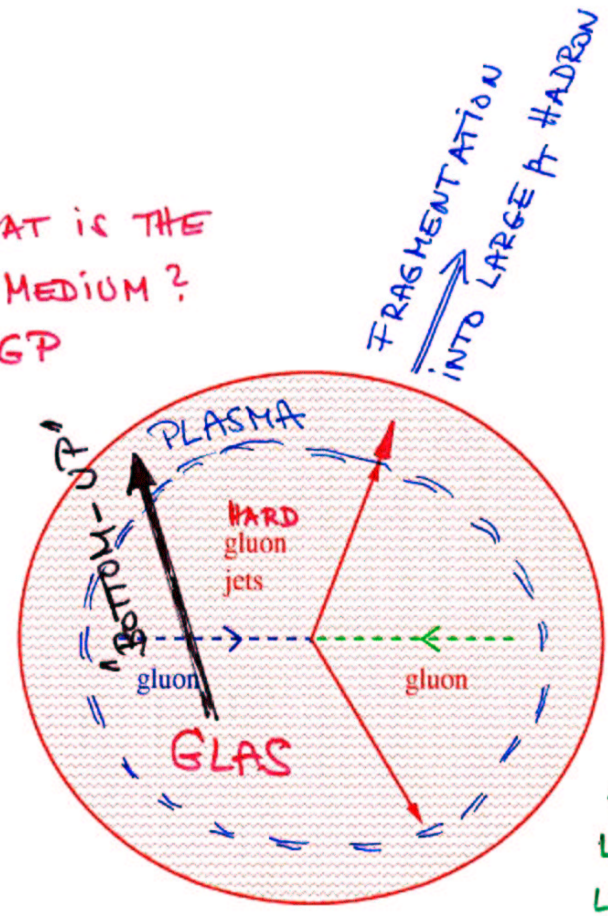



OPTIMISTIC: SHORT EQUILIBRATION TIME

MORE REALISTIC: $t_{eq} \sim \mathcal{O}(R_{Au}) \sim 5\,fm$ (!)

("bottom-up" SCENARIO
R.B., A.H.M., D.T.S., AND D.S.)

WHAT IS THE MEDIUM ? QGP




Gluon jets produced in a medium will scatter on the media;

The high momentum component of the jet spectrum will be depleted.

HADRONS AT LARGE $p_T$ ARE LESS ENERGETIC DUE TO MEDIUM INDUCED RADIATION

COLORED GLASS CONDENSATE
(L. McLERRAN AND R. VENUGOPALAN, ...)

(FROM McLERRAN'S TALK)

MANY QUESTIONS:

- COLORED GLAS / NONEQUILIBRIUM
  VS.
  QGP / EQUILIBRIUM

AT RHIC: ENERGY DENSITIES $\epsilon > 20\text{-}30\,\mathrm{GeV}/\mathrm{fm}^3$
IN CENTRAL COLLISIONS

- HOW TO DISTINGUISH ?
- LIFE TIMES / EQUILIBRATION TIME / THERMALIZATION
- PARTON PROPAGATION IN A MEDIUM WITH OCCUPATION NUMBER $1/\alpha_s$, $\alpha_s \ll 1$ ?
- A - DEPENDENCE OF $\hat{q}$ ($\hat{q} \sim A$, $Q_s \sim A^{1/3}$, ..)
- SIGNATURES
-

## SUMMARY / CONCLUSIONS

STUDY OF HARD / LARGE $p_T$ PROCESSES IN A-A COLLISIONS IS BECOMING EXCITING: (p) QCD PLAYS THE CENTRAL ROLE

ALREADY A FEW RESULTS:

- RADIATIVE ENERGY LOSS >> ELASTIC ONE IN DENSE MEDIA
- LARGE $p_T$ HADRONS - 'WINDOW' OF STABLE PREDICTIONS $p_T \gtrsim 10$ GeV/c (RHIC) AND WHEN $Q(p_T)$ SIGNIFICANTLY DIFFERS FROM 1; $S(p_T)$ DEPENDS ON $p_T$, $S(p_T) \sim L\sqrt{p_T}$.
- INDICATION THAT $\hat{q}(\epsilon)$ SMOOTH IN $\epsilon$
- RELATED ANALYSIS FOR JETS / CONE

MANY OPEN QUESTIONS:

- EQUILIBRATED QGP VS. CGC, OR SCENARIO BY E. SHURYAK
- QUANTITATIVE PREDICTIONS (KINEMATICS, $\vec{B}$-SPACE GEOMETRY, .. CRONIN EFFECT, .... )