AdS/CFT phenomenology: Mach cones in heavy ion collisions

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An apology: Most of this lecture has nothing to do with AdS/CFT or dualities. I even discuss in detail (gasp!) experimental data

A hope: The problem I am discussing, however, is one that

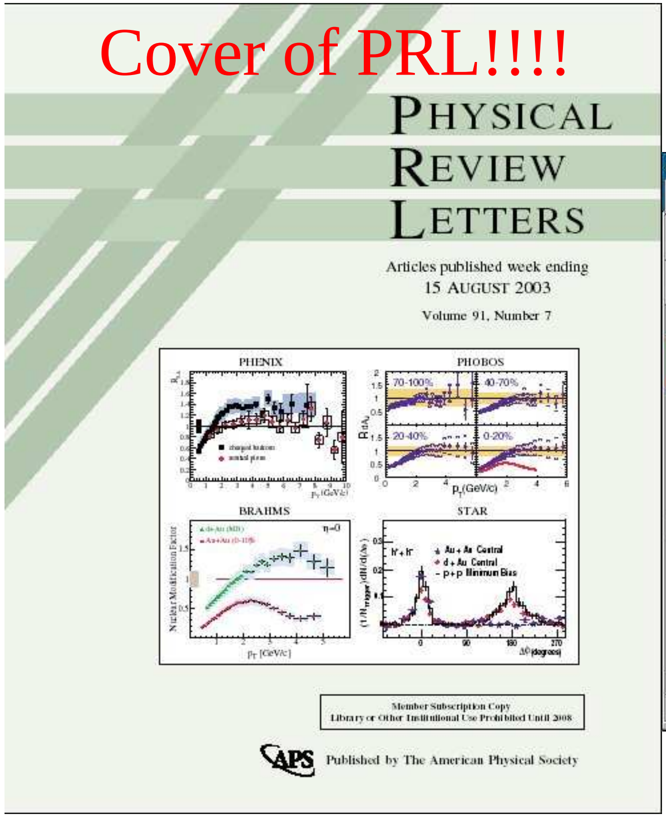
- We hope AdS/CFT will give us insights to
- Might lead to a quantitative phenomenology of AdS/CFT

So I hope its not a total waste of time!

AdS/CFT phenomenology: Mach cones in heavy ion collisions

- A short introduction to RHIC heavy ion collisions
- Mach Cones. What are they and why do we want to see them?
- We think we saw them
- The theory (and why it is not so simple)
- How AdS/CFT can help
- The situation so far, and what to do

Cover of PRL!!!!



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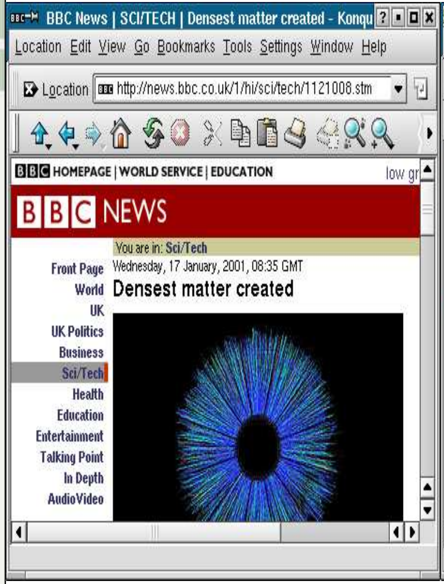
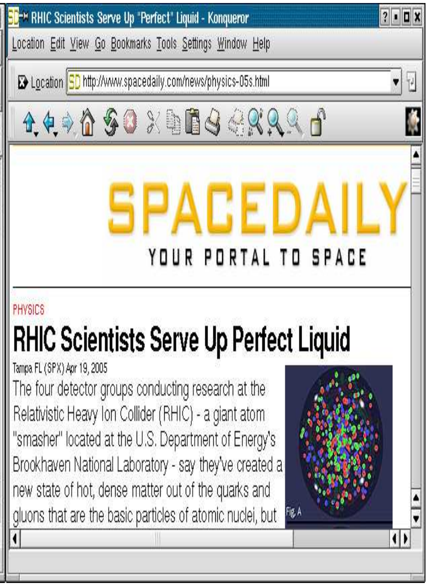
BBC!



Wednesday, 17 January, 2001, 08:35 GMT

Densest matter created

SPACE
DAILY!



RHIC Scientists Serve Up Perfect Liquid

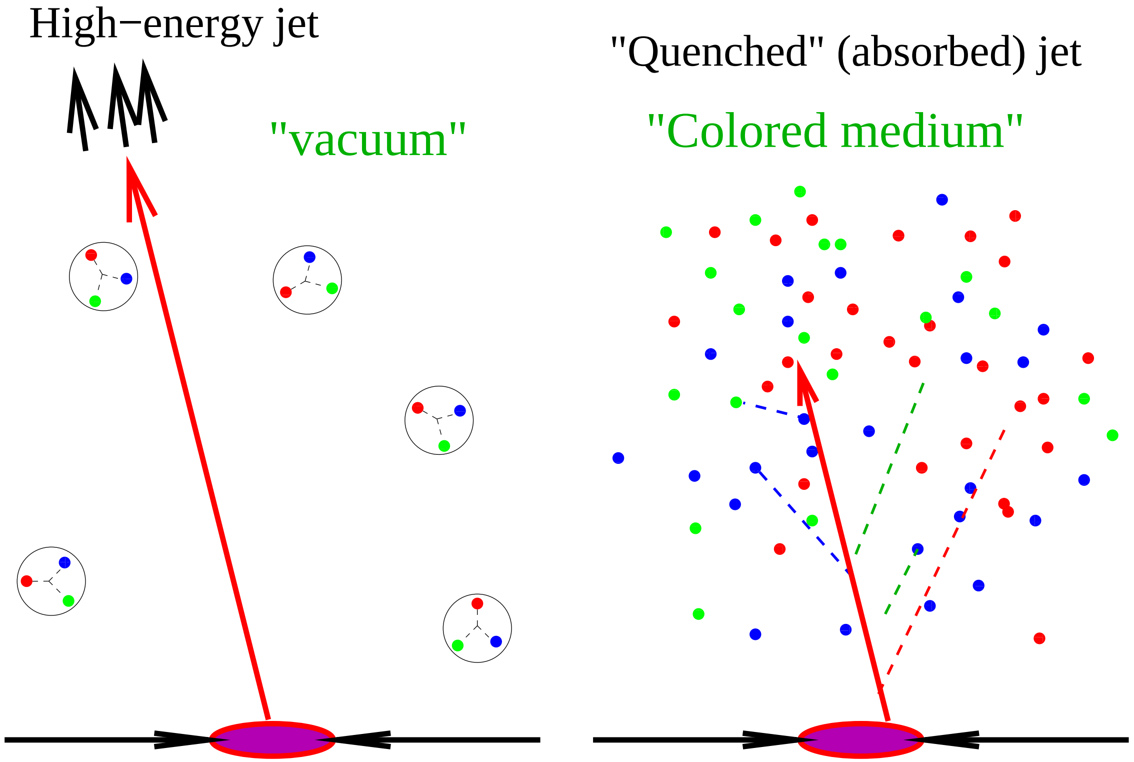
Tampa FL (SPX) Apr 19, 2005

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

RHIC IS FAMOUS! WHY?!

Basically: Jets are suppressed ⇒ System dense and opaque.
Flow sensitive to initial conditions ⇒ System fluid

Jet suppression (Bjorken,many others): Bethe-Bloch energy loss+QCD



High−energy jet

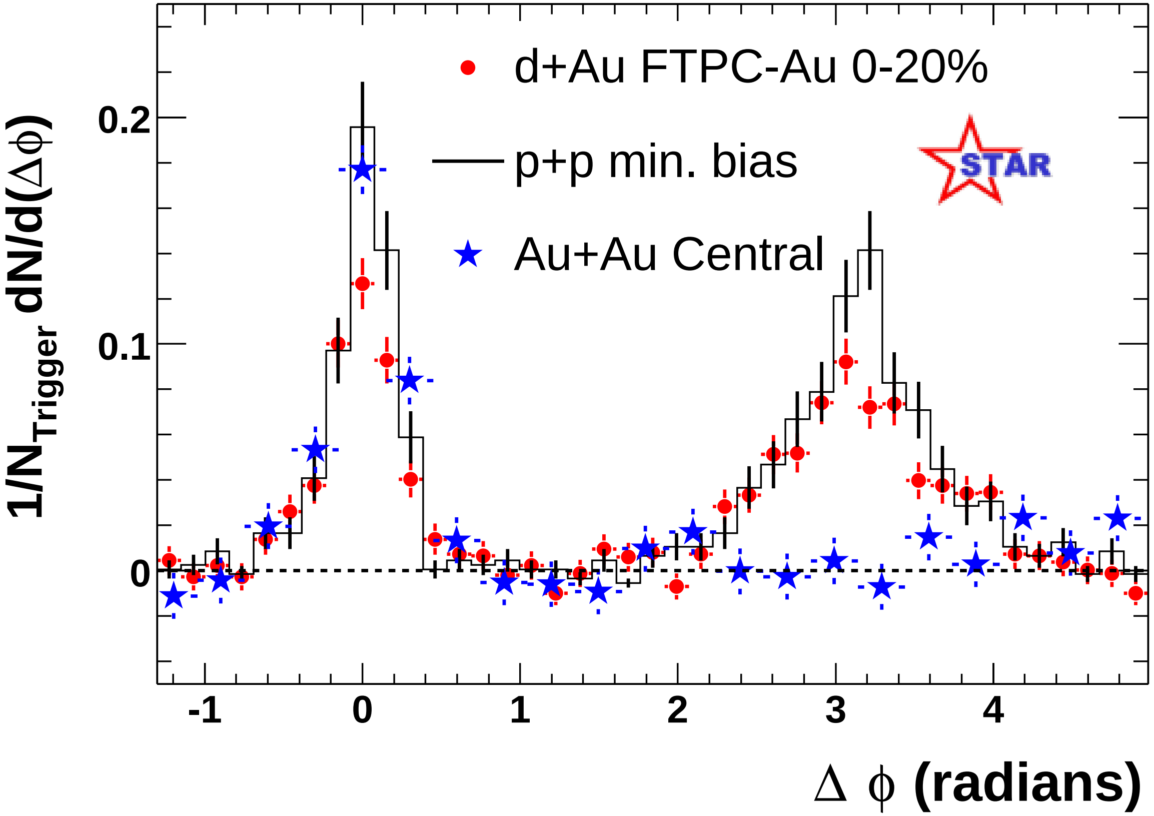
"vacuum"

"Quenched" (absorbed) jet

"Colored medium"

"jets" of fast particles quickly lose energy by medium-induced radiation.

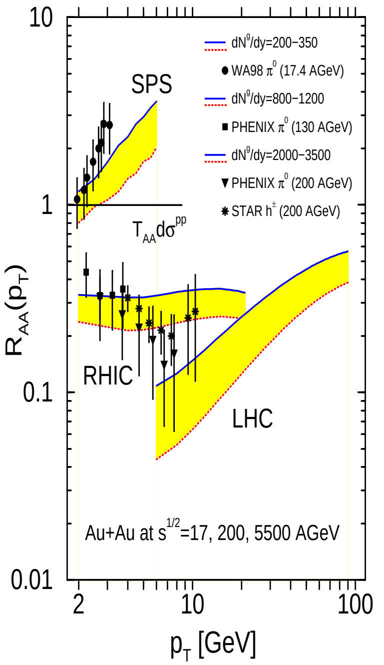
This was conclusively shown to happen! (And made it to PRL cover)
(NB: Jets in HIC ⇒ single high-p_T triggers)



But is it QGP? or close to equilibrium? Difficoult to tell with jets (“Hard” parton-medium interactions dont care about “soft” confining forces). When does this effect ”turn on”? Jet production strongly $\sqrt{s}$-dependant, so energy scan difficult. Models also fit lower energy SPS data (Similar “medium”, nuclear enhancement overcomes loss).

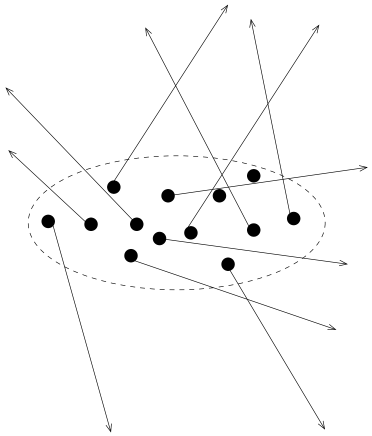
Gyulassy,Levai,Vitev

PRL.85:5535−5538 2000

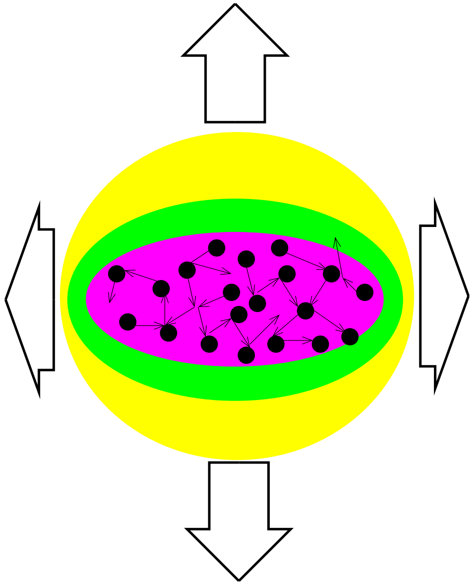


What kind of ”medium” is created in nuclear collisions?

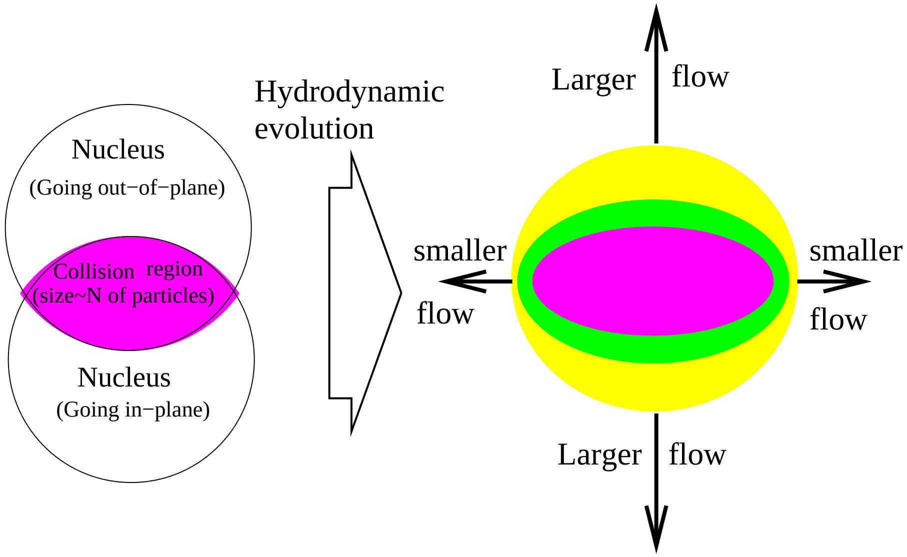
A "dust"
Particles ignore each
other, their path
is independent of
initial shape



A "fluid"
Particles continuously
interact. Expansion
determined by density
gradient (shape)



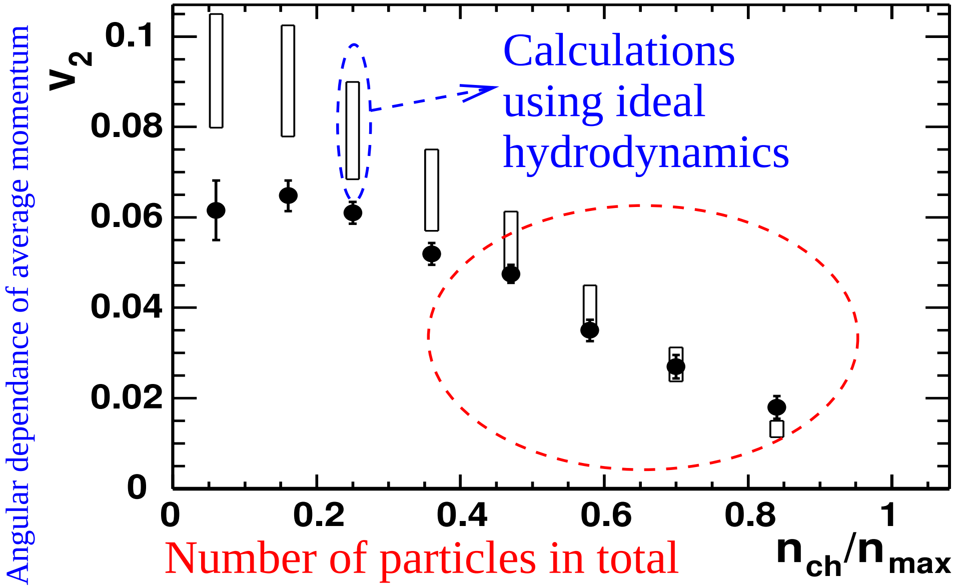
Quantitatively distinguished by mean free path, viscosity



Hydrodynamics predicts flow eccentricity as a function of number of particles ($\sim$ area of overlap region). Parametrized by 2nd Fourier component, v_2

$$E\frac{dN}{d^3p} = \sum_n E\frac{dN}{dp_z p_T dp_T}\left(1+2v_n\cos(n\phi)\right)$$

P.Kolb and U.Heinz,Nucl.Phys.A702:269,2002.

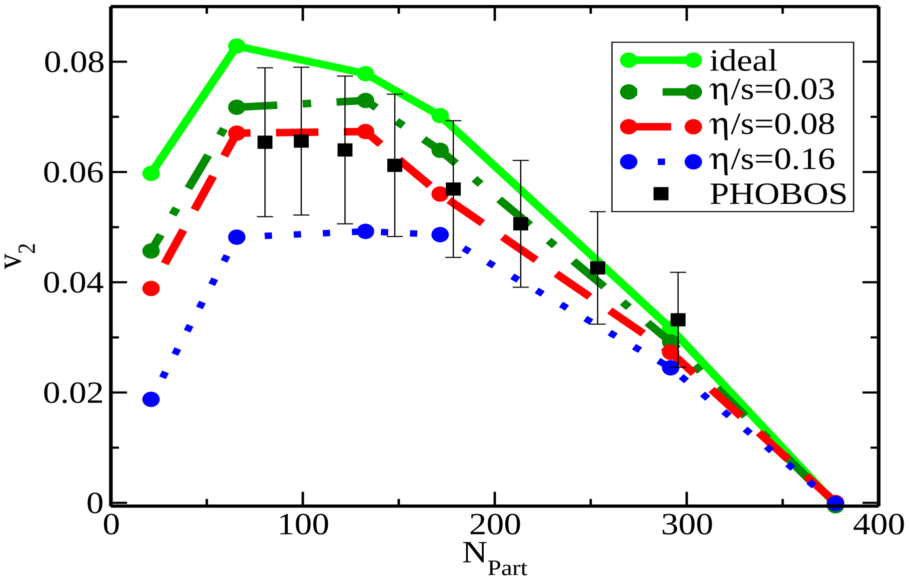


Calculations using ideal hydrodynamics

Angular dependance of average momentum

Number of particles in total

P.Romatschke,PRL99:172301,2007



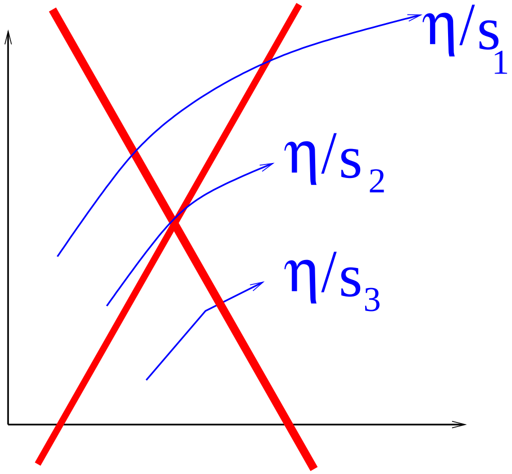
Data described by ideal hydrodynamics (mean free path between particle collisions is zero! THis is where “ideal liquid” headline from!

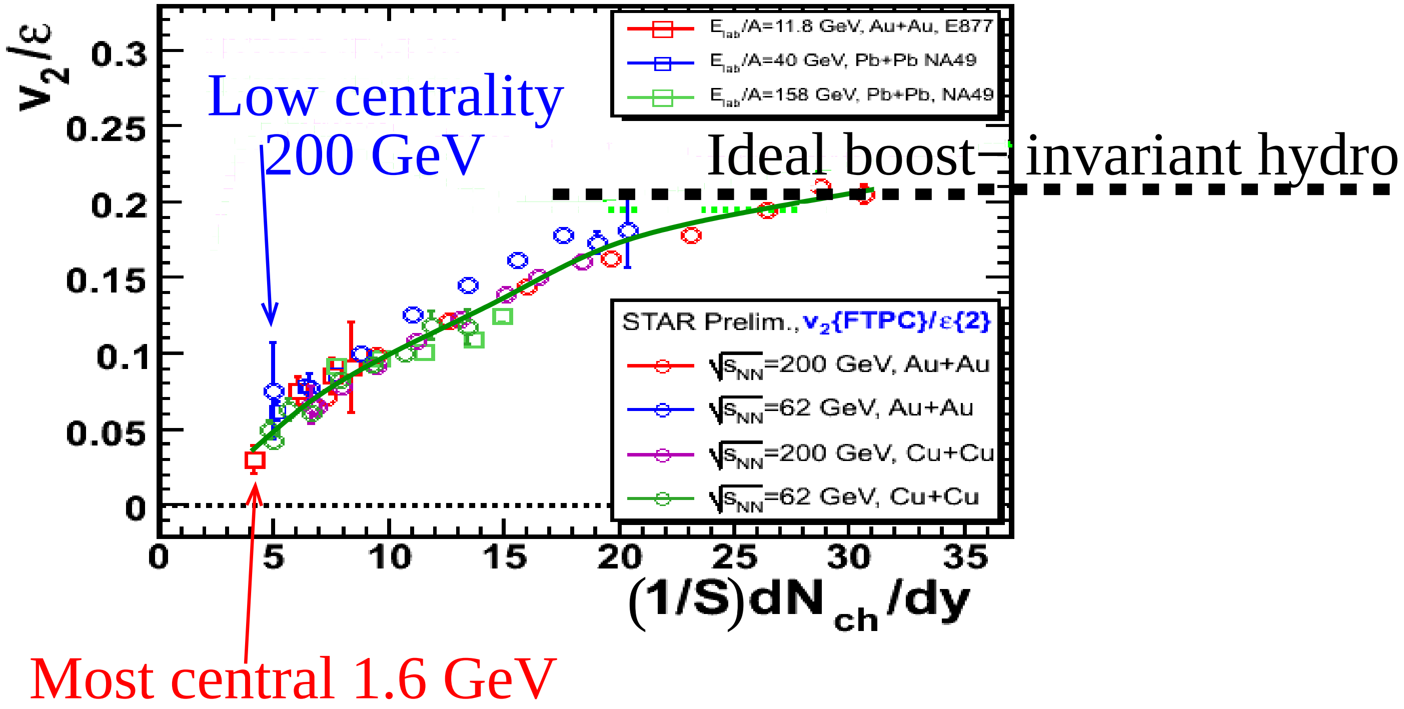
(Viscosity not much bigger than “lowest viscosity” conjectured by string theory!!!!!(more on that later))

But...

While lower energy (SPS,RHIC) has v_2 below ideal hydro, no transition observed (v_2 becomes higher smoothly with multiplicity at all energies).

Song, Heinz
arXiv:0805.1756
GT
PRC76:024903,2007





More but...

- No one predicted the QGP would be an ideal liquid, and not clear why this would be the case.
- Hydrodynamics has parameters put in by hand: A lot of assumptions go into initial conditions (Temperature, degree of transparency). Wrong initial conditions lead to wrong viscosity!
- Other observables, more sensitive to final interactions, at best indifferent to hydro. Can we claim ideal fluid with just one observable?

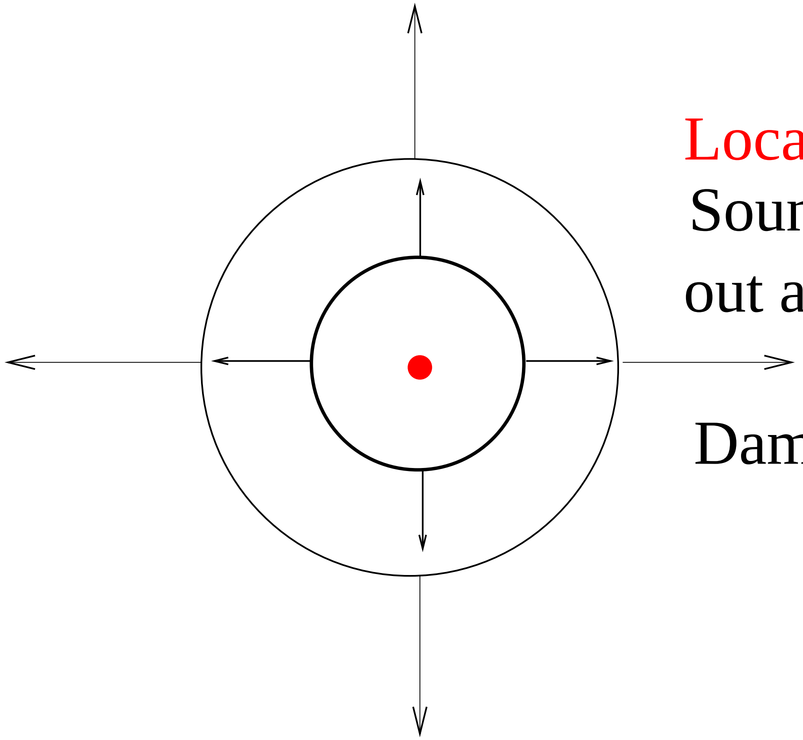
What is needed...

- Develop a coherent falsifiable picture
  We know jets lose energy. Assume the system is a fluid. What then?

- Can the energy lost from jets to the fluid tell us something about the fluid's properties (EoS? Viscosity? Density during deposition?)?

We need to analyze the problem of fast energy deposition in hydrodynamics

If Hydro linear



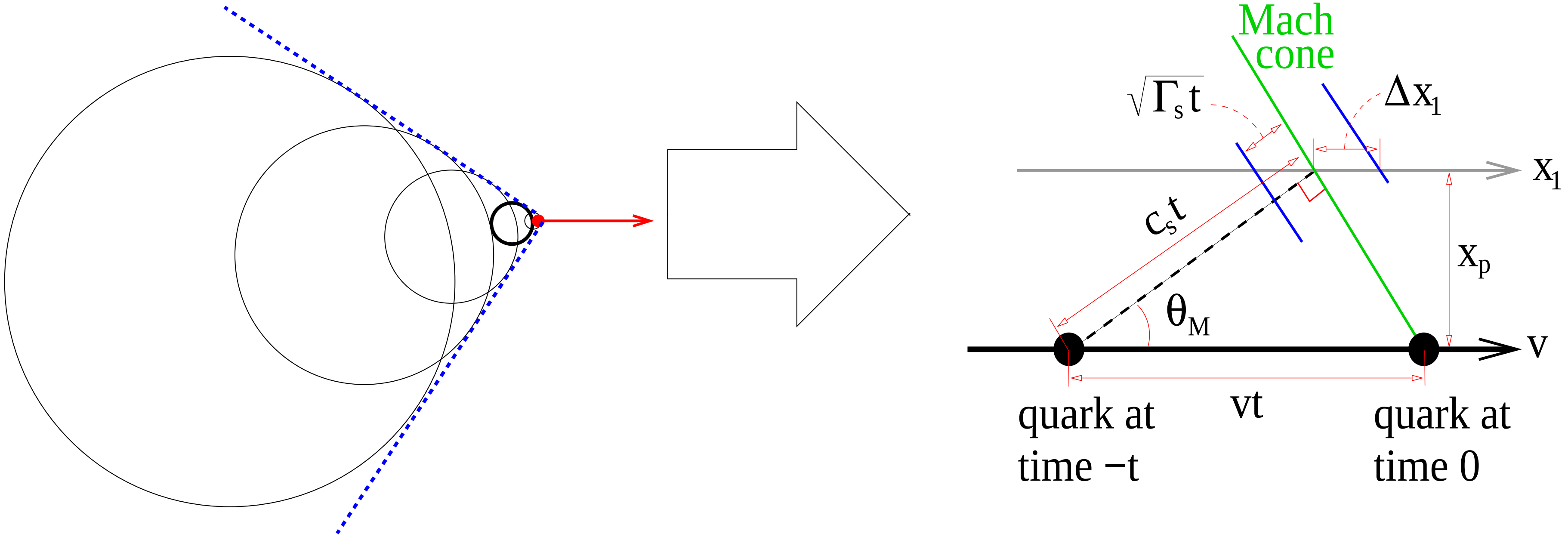
Locally deposited energy:

Sound wave expanding

out at speed $c_s^2 = dp/de$

(Link to EOS!:QGP,HG,Mixed?)

Damping at scale $4\eta/(e+p)$

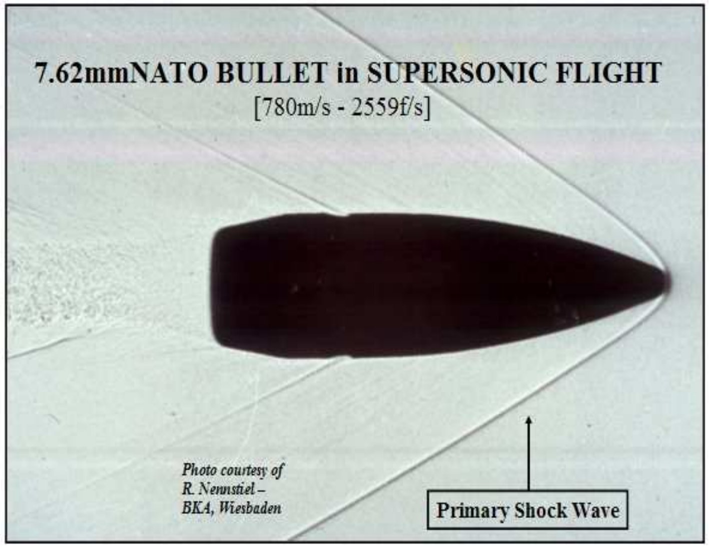


Mach cone angle Sensitive to EoS, $\cos\theta = c_s/v$

Cone killed by high viscosity

IF we see this, we confirm fast thermalization and study fluid's EoS!

This phenomenon is well known



But is it relevant and observable in heavy ion collisions?

First suggested by Horst Stoecker, W. Scheid, W. Greiner,... ,1975

What does this have to do with AdS/CFT?

- AdS/CfT was used to calculate the viscosity of an infinitely-strongly coupled gas, $\eta/s = 1/4\pi$
- THis is very low (η/s for water ~ 10), so, unsurprisingly, strongly coupled CFT is a good fluid ("perfect?" Conjectured lower bound for η/s)
- People got very excited that η/s at RHIC can not be much lower than the bound. Have we "seen string theory" in the (s)QGP?!

AdS/CFT could be used to calculate RHIC observables
...And Mach Cones might be the first place where this is feasible.

At least We can check our hydrodynamic/phenomenological description makes sense,ie its a good limit of the QFT (as youll see its not obvious

At best we build a Falsifiable AdS/CFT phenomenology.
Lets assume that RHIC sQGP $\sim \lim_{\lambda\rightarrow\infty}$ CFT. What can we expect from experiment? Hopefully more precise than "a low viscosity"!

Freeze-out: How to get from fluid to particles

Assume $l_{mfp} \sim$ system sizeat some spacetime locus $\Sigma^\mu = (t, \vec{x})$ chosen according to some criterion (critical time, temperature,...). Conservation of energy+local equilibrium... Cooper-Frye formula

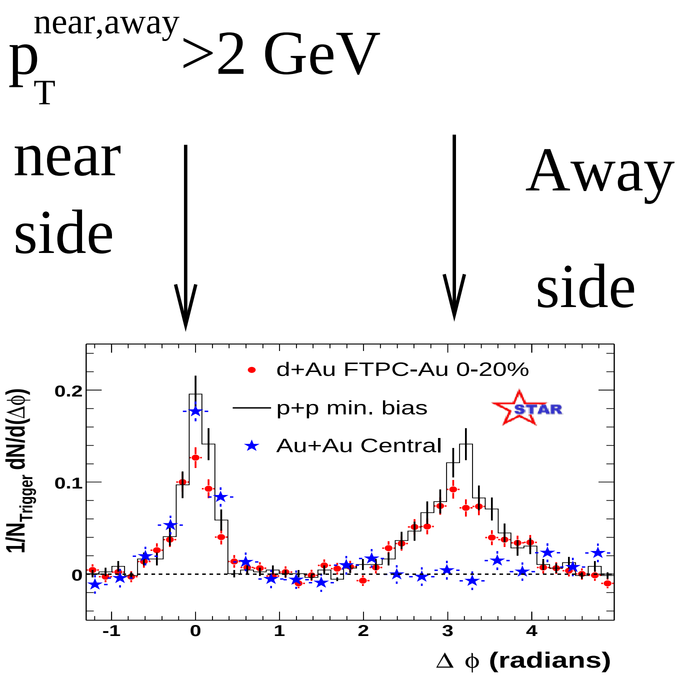
$$E\frac{dN}{d^3p} = \int p_\mu d\Sigma^\mu f_{FD/BE}(p_\mu u^\mu, T, \mu_B)$$

Hydrodynamics+freeze-out criterion give flow u_μ, Σ_μ. Currently Σ^μ choice ad-hoc. Resonances decay after freeze-out.

Generally: "Hot spots" give strongly Σ-dependent signal. "Extra Flow" better, as momentum conservation always results in boost

The result: correlation $\frac{d^nN}{d^n(\phi_i - \phi_{jet})}$(NB: Generally n-particle correlation in theory, n+1-particle in experiment!) For 2 particles we get...

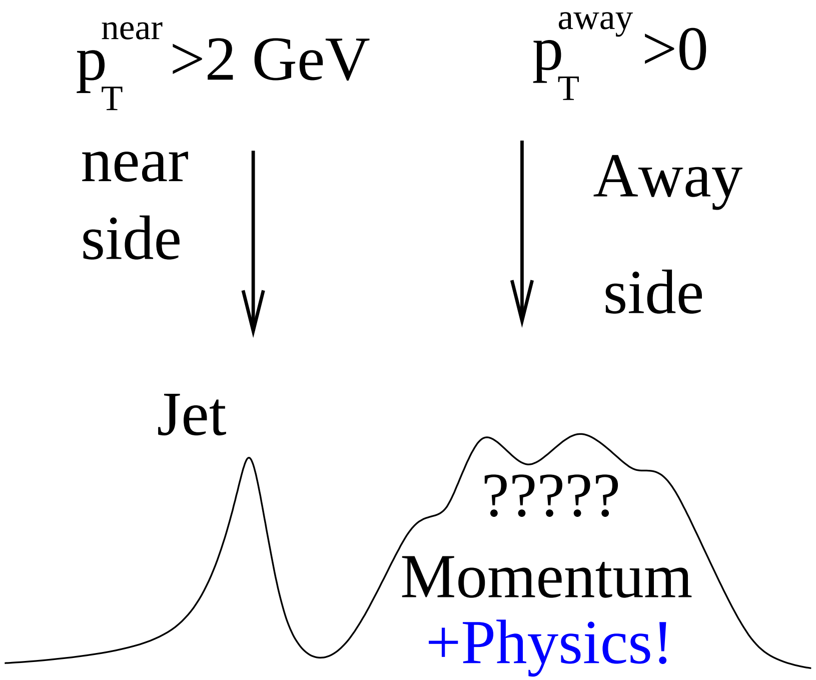
Jet suppression revisited: Softening the away−side trigger



$p_T^{near,away}$ >2 GeV

near side

Away side



p_T^{near} >2 GeV

p_T^{away} >0

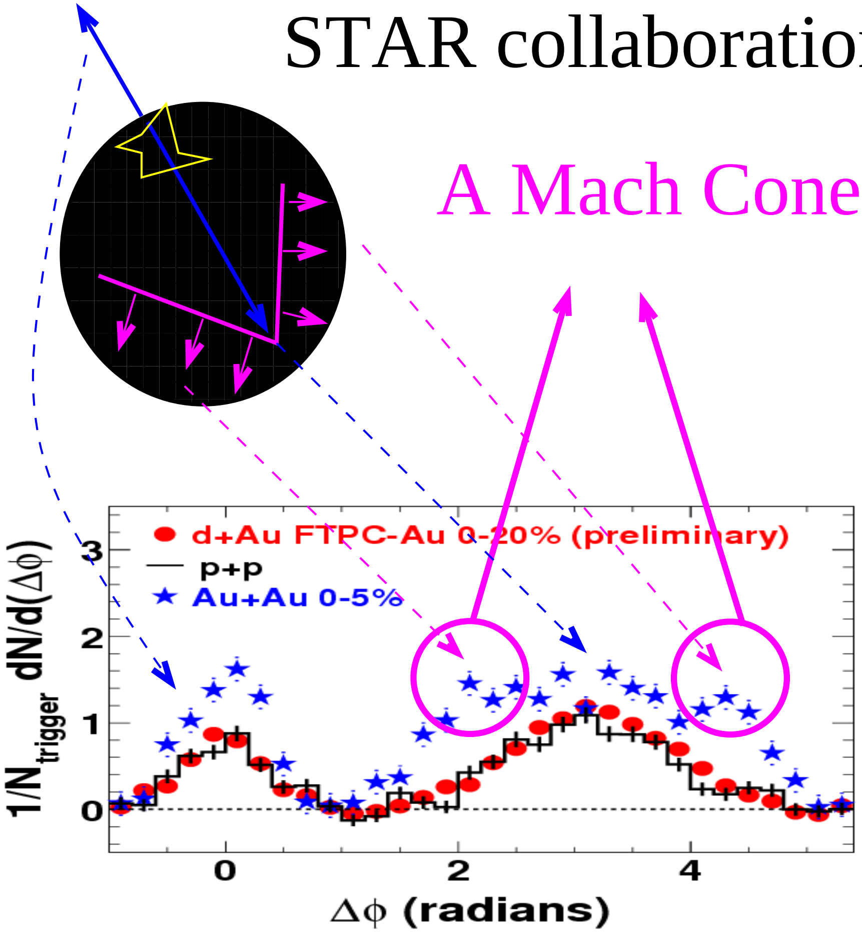
near side

Away side

+Physics!

Correlations between <u>hard</u> particles ($p_T^{near,away} > 2$ GeV) suppressed. By conservation of momentum correlation should <u>reappear</u> when p_T^{away} lowered, hopefully with interesting structures!

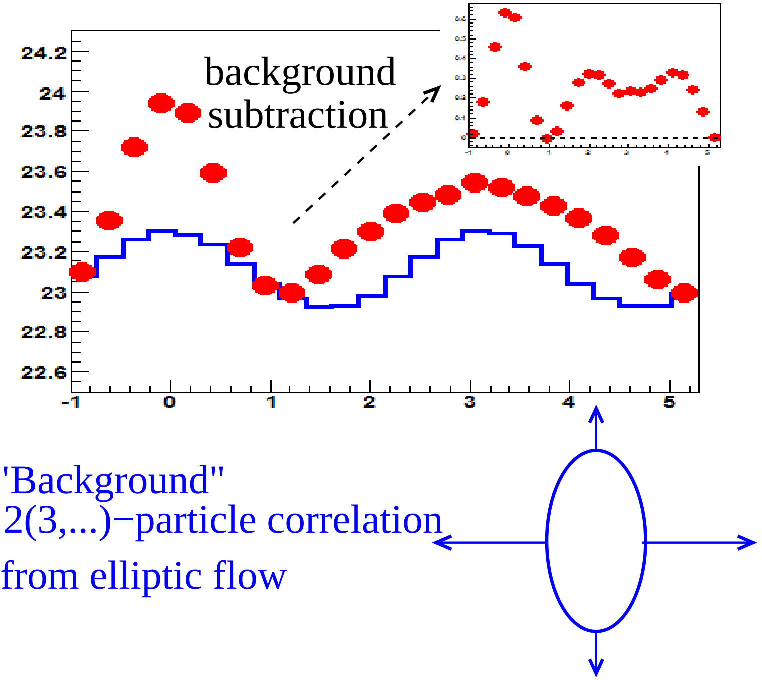
Experiment:If we lower trigger, away-side peak reappears and...



STAR collaboration

A Mach Cone?

But the raw plot
Looks like this



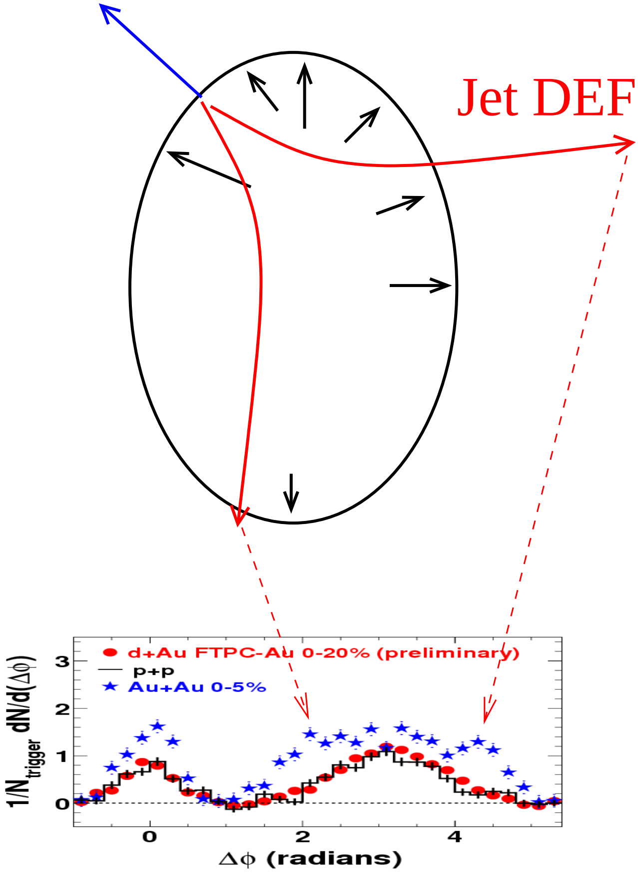
"Background"
2(3,...)−particle correlation
from elliptic flow

Assume correlations from flow anisotropy and from jet uncorrelated (ZYAM). This is model dependent. At best an approximation in full hydrodynamics

In central collisions, peak appears bigger than correction, but are initial fluctuations understood?

Other explanation possible

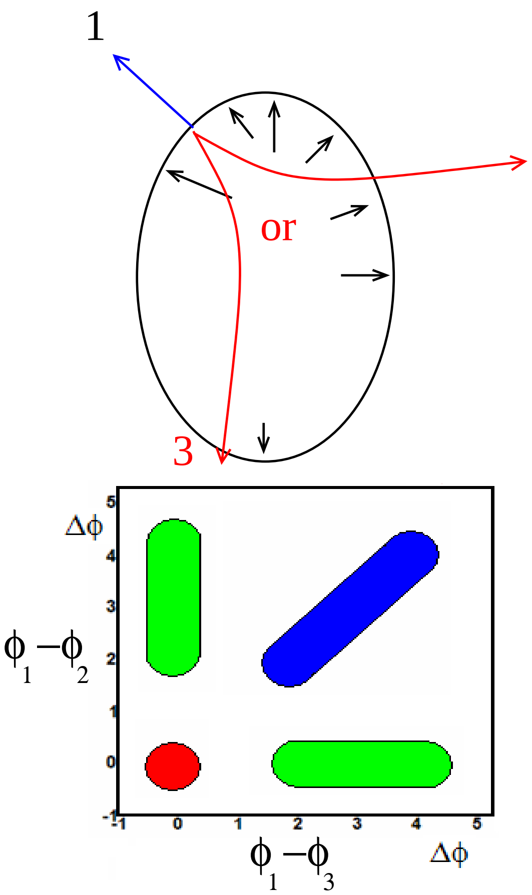
Armesto,Salgado,Wiedemann,PRL93:242301,2004



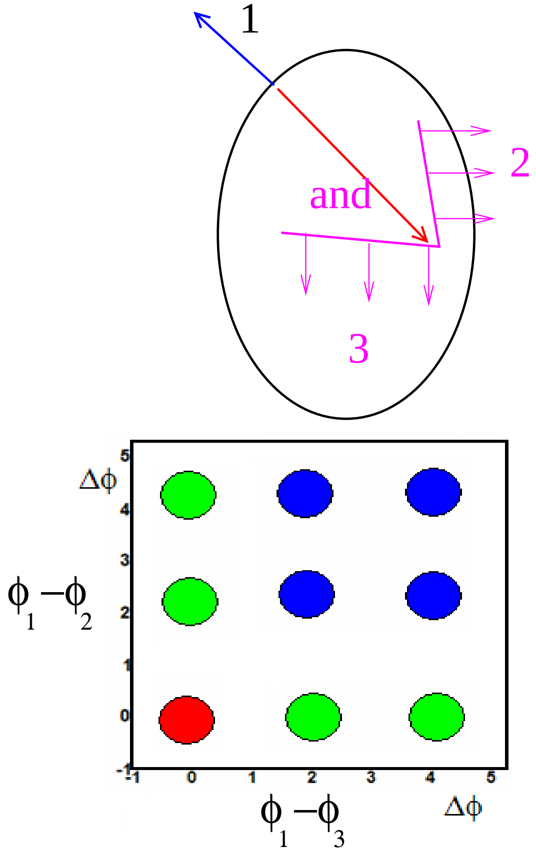
Jet DEFLECTED by

flow anisotropy

But distinguishable:3-particle correlations

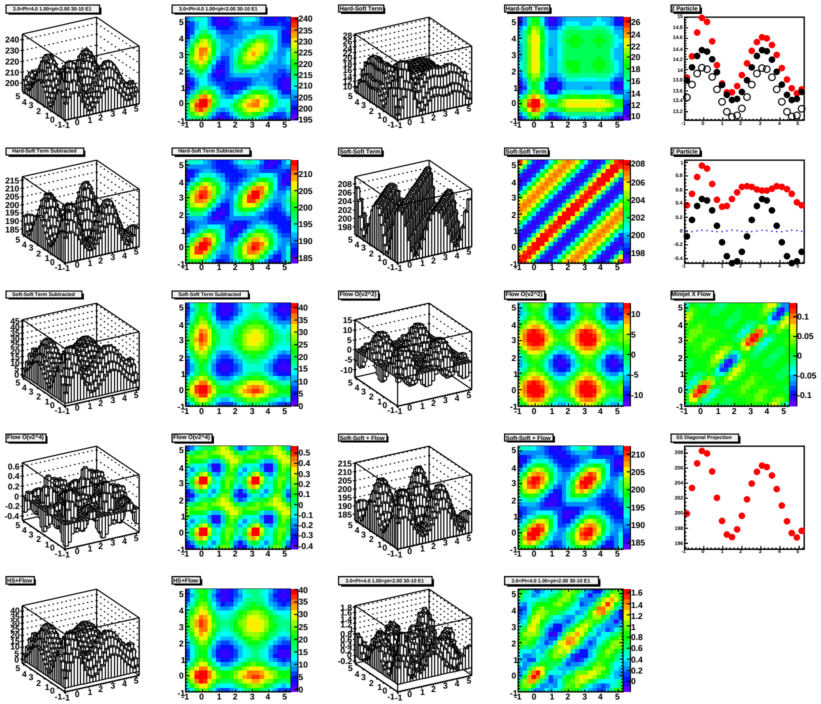


Either 1 or other peak



Both peaks there

Background becomes more tricky... Still use ZYAM to resolve all combinations (Jet×flow,Flow×Flow etc.)

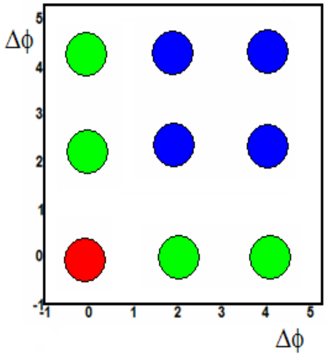


(J.Ulery,PhD thesis)

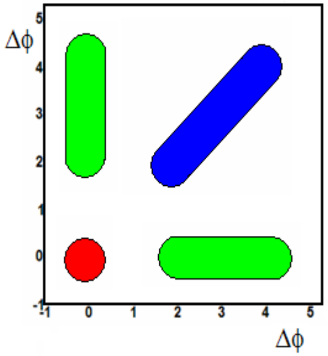
Results look like mixture of Mach and deflected (and why not?)

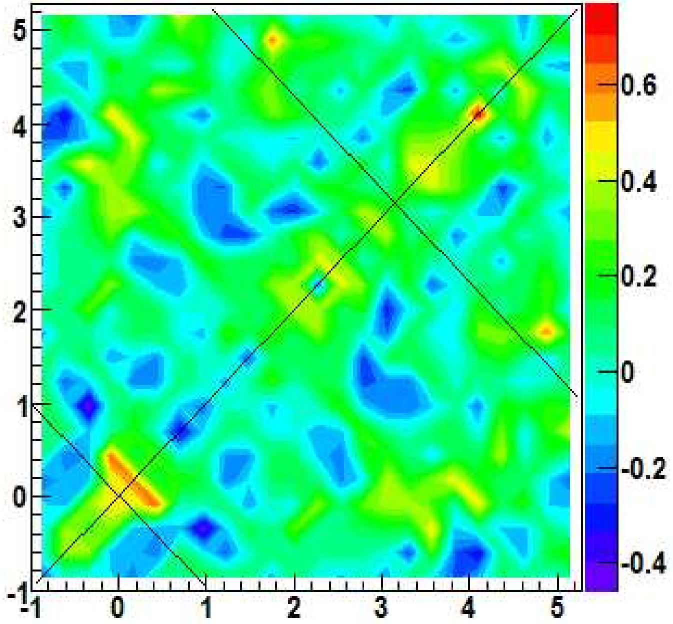
STAR collaboration (PHENIX similar)

Mach

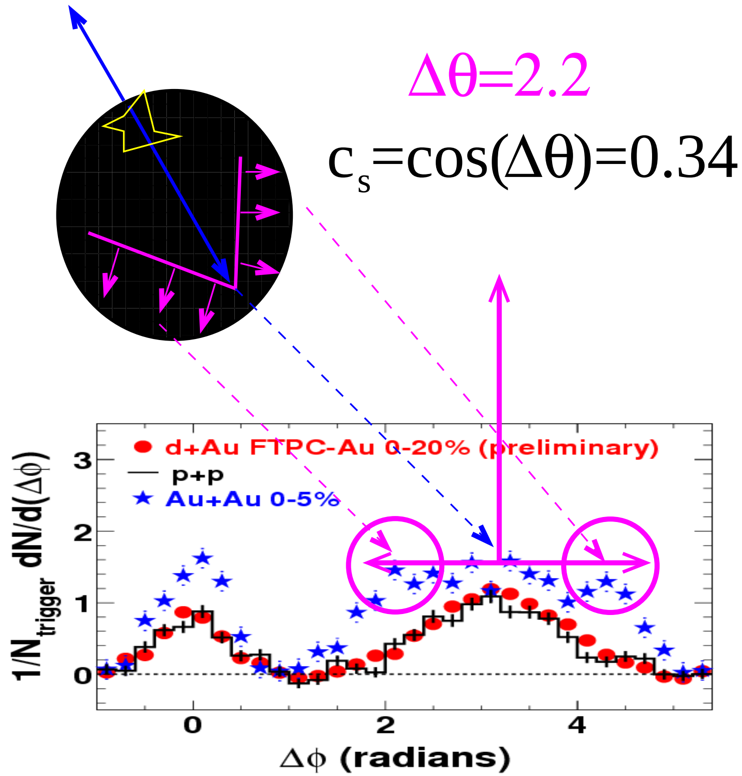


Deflected





If this is a cone
What does the
angle tell us?



$\Delta\theta=2.2$

$c_s=\cos(\Delta\theta)=0.34$

Intriguingly low
Probing transition
region?

(Angle invariant with p_T, as expected in Mach cone with isochronous freeze-out).

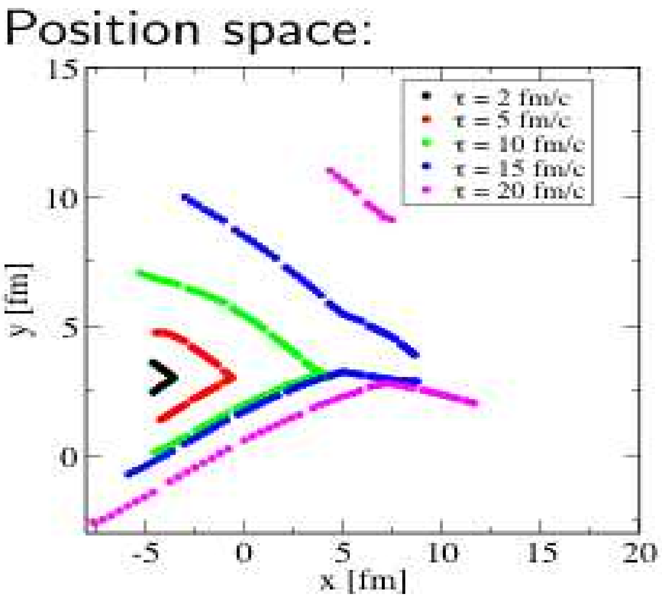
Problem is... heavy ion collisions $\neq$ "textbook"

- Background non-trivial (flowing, phase transition)
- Non-linear hydrodynamics
- Energy-momentum deposition not trivial, and not well understood.

Effect of flow : Just sobstitute $(+,-,-,-)$ metric for u_μ: Usual relationships with frame co-moving with flow (Satarov, Stoecker,Mishustin,PLB627(2005)) In linearized limit, for $v_{jet} \sim 1$

$$\theta = \sin^{-1}\left(c_s / v_{jet}^{comoving \;\; frame}\right) \rightarrow \sin^{-1}\left(c_s \sqrt{\frac{1-v^2}{1-v^2 c_s^2}}\right)$$

flow $\vec{v}$, given by global hydrodynamics, narrows cone.


Position space:

Renk, Ruppert, PRC73:011901,2006

disentangling effect of flow from angle to get EoS

might be non−trivial

full hydrodynamics in a nutshell

Conservation equations of energy-momentum coupled to source (jet)

$$\partial_\nu \underbrace{T^{\mu\nu}}_{energy-momentum\ \ tensor} = \underbrace{J^\mu}_{energy-momentum\ \ source}$$

Use local isotropy in frame co-moving with flow (u_μ) to fix $T_{\mu\nu}$

$$T_{\mu\nu} = (e+P)u^\mu u^\nu - pg^{\mu\nu}$$

Use equilibrium EOS to close system of equations,$p = p(e)$ (5 equations to solve for $p, e, u^{x,y,z}$.

Viscosity:

$$T_{\mu\nu} = T_{\mu\nu} + \Pi_{\mu,\nu}(\zeta(e), \eta(e), \partial_\mu u_\nu)$$

This is complicated (Nonlinear, few analytic solutions) To get insights, use linearized hydro (Casadellrey-Solana,Shuryak,Renk,Ruppert).

$$T^{\mu\nu} = \underbrace{T_0^{\mu\nu}}_{diag[e,p,p,p]} + \underbrace{\delta T^{\mu\nu}}_{\ll T_0^{\mu\nu}}$$

Flow small, only pressure/density (sound waves):In terms of $\epsilon = \delta T^{00}, g_L = T^{0L}, \vec{g}_T = T^{0T}$ where L and T are parallel/perpendicular to jet

$$\partial_t \epsilon + ikg_L = J^0$$

$$\partial_t g_L + ic_s^2 k_L \epsilon + \frac{4}{3}\frac{\eta}{e_0 + p_0} k^2 g_L = J^L$$

$$\partial_t \vec{g}_T + \frac{4}{3}\frac{\eta}{e_0 + p_0} k^2 \vec{g}_T = \vec{J}^T$$

Solvable for ϵ, g_L, g_T with Green's function technology What is J^μ? Well, we don't know!

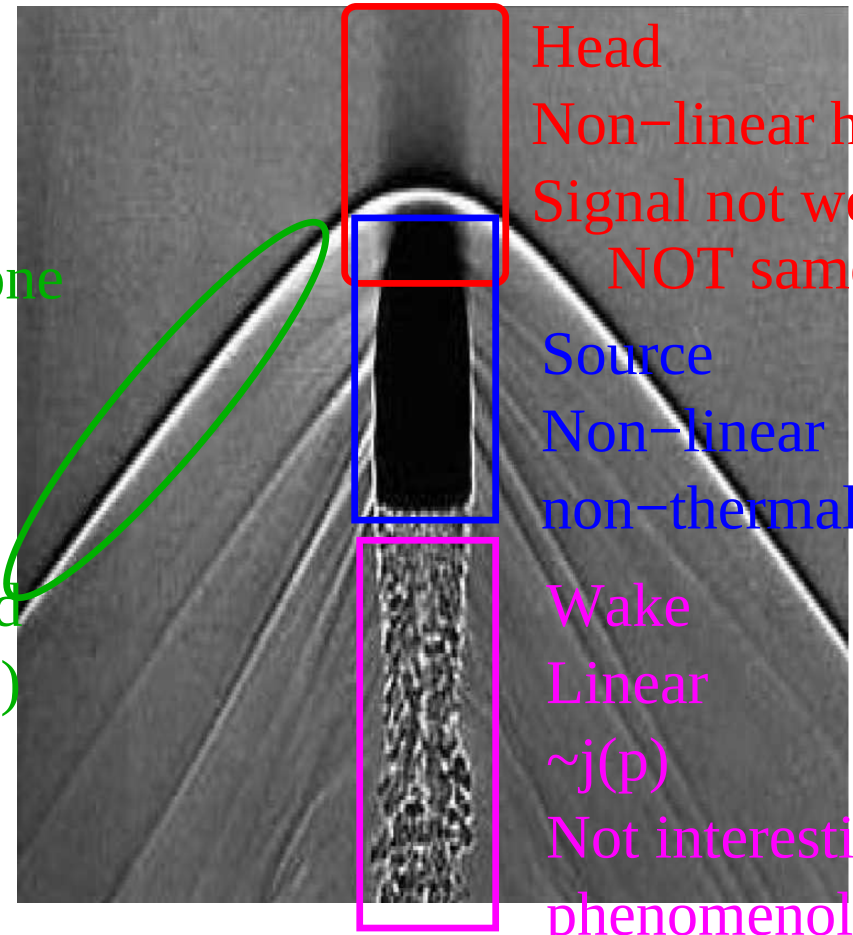
Textbook $J^\mu = (e, 0, 0, 0)\delta(\vec{x} - \vec{v}t)$

On-shell: $J^\mu = (e, e\vec{v}/|v|)\delta(\vec{x} - \vec{v}t)$But parton does not have to be on-shell:

Weakly coupled jet-medium (NB: not inconsistent with hydro: for hydro medium has to be strongly coupled,jet-medium can be anything!) $J^\mu \sim \frac{dE}{dz} \sim L$ for dense medium $(l_{coherence} > l_{scattering}$)

Need consistent picture of the system, interpolating between fully unthermalized jet and thermalized strongly coupled medium. And it's a non-perturbative non-equilibrium non-linear problem!

Is linearized hydro good? probably not



Head

Non−linear hydrodynamics

Signal not well undestood

NOT same as cone angle

Mach Cone

Linear

Useful

(Angle

connected

with EoS)

Source

Non−linear

non−thermalized

Wake

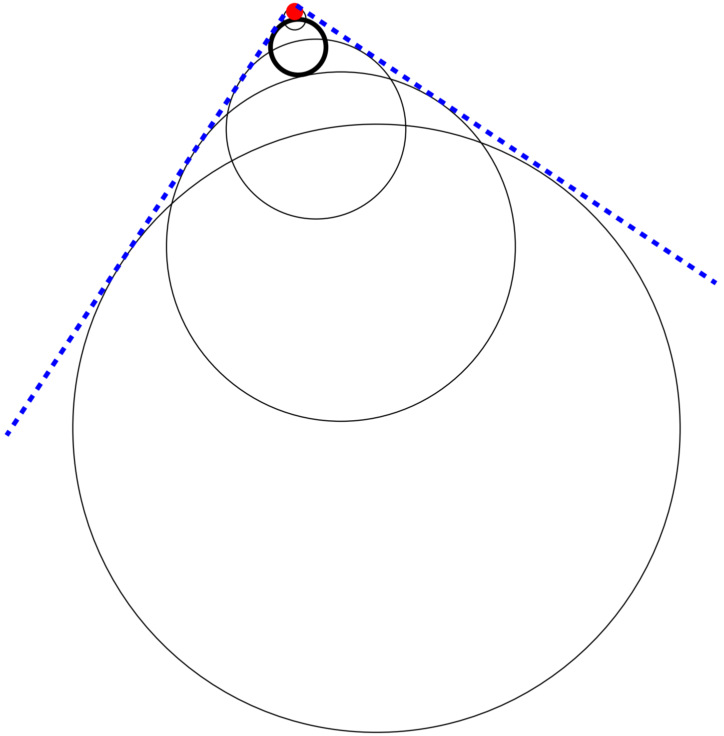
Linear

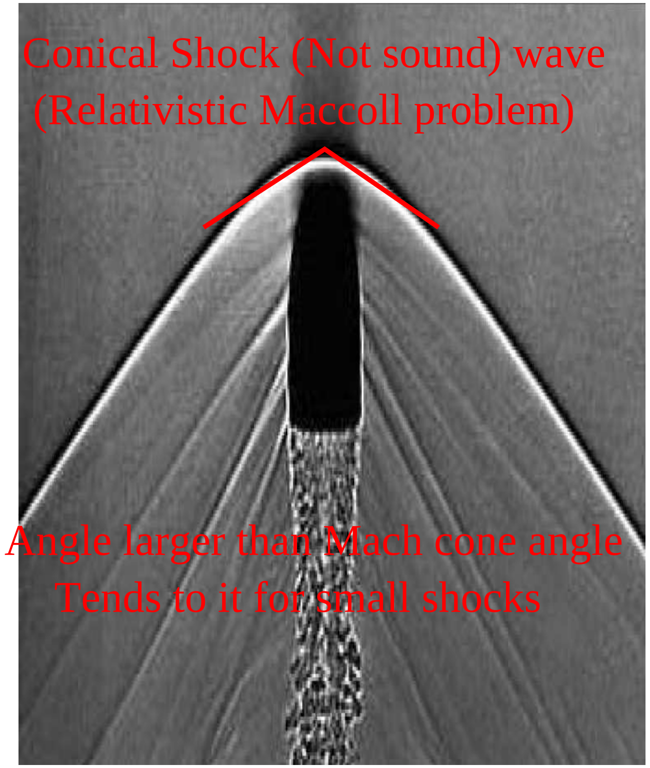
~j(p)

Not interesting

phenomenologically

Pileup of waves at head





Conical Shock (Not sound) wave
(Relativistic Maccoll problem)

Angle larger than Mach cone angle
Tends to it for small shocks

Source usually (a la Lifshitz-Landau) local

$$J^{\mu} \sim J_0^{\mu} \delta(x - vt)$$

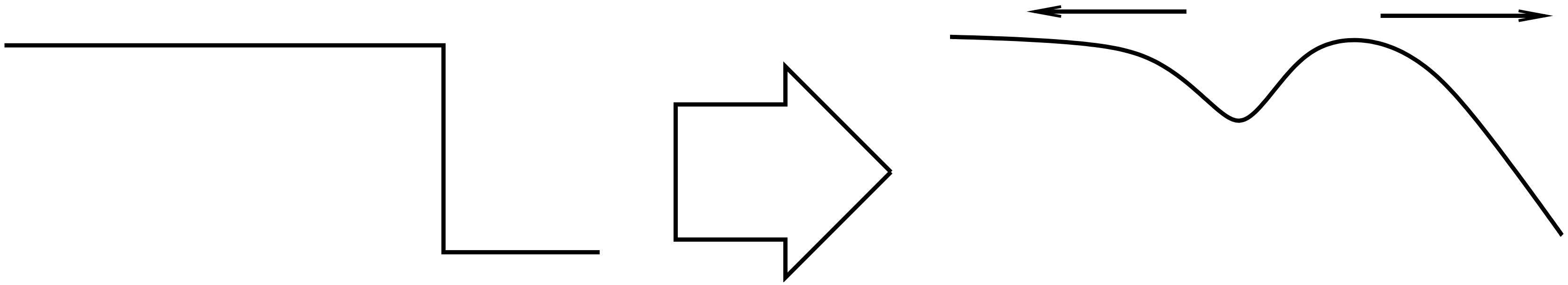
For an infinite δ-function, linearization $\delta T^{\mu nu}/T^{\mu nu} \ll 1$ badly broken. Of course, the δ-function approximation of smeared non-equilibrium distribution

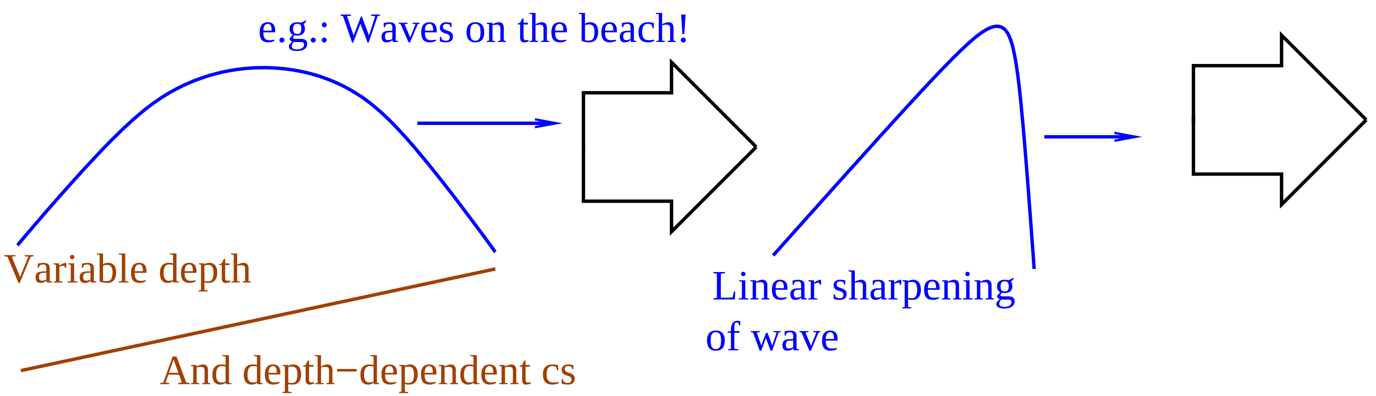
$$\delta(x - vt) \simeq f\left(x - vt, \sigma\right)$$

Because full hydrodynamics is non-linear, form of f where $\delta T^{\mu nu}/T^{\mu nu} \sim 1$ can have effects in the linearized $(x \gg \sigma, \delta T^{\mu nu}/T^{\mu nu} \ll 1)$ region.

Perhaps when $x \gg \sigma$ these effects go away, but this might be too big. (In AdS/CFT Far-away dynamics does depend on weather source is a heavy quark or a meson. So near-side dynamics changes far-away result)

Small perturbations $\neq$ Linear hydro Perturbations must also be stable!





e.g.: Waves on the beach!

Variable depth

And depth−dependent cs

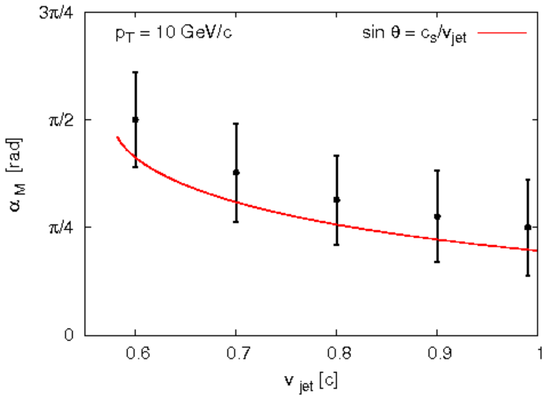
Linear sharpening of wave

Rischke,Stoecker,Greiner: PRD42:2283-2292,1990: Angle in Shocks $\neq c_s/v$

Option I:Explore range of J^μs systematically with full hydro;$\sim$ conical, but...

Betz,Gyulassy,Stoecker,Rischke,Torrieri,QM2008 presentation,coming paper
Also J.Casalderrey−Solana, E.V. Shuryak,PRD74 (2006) 085012

(Probably) invisible T pattern independent of source



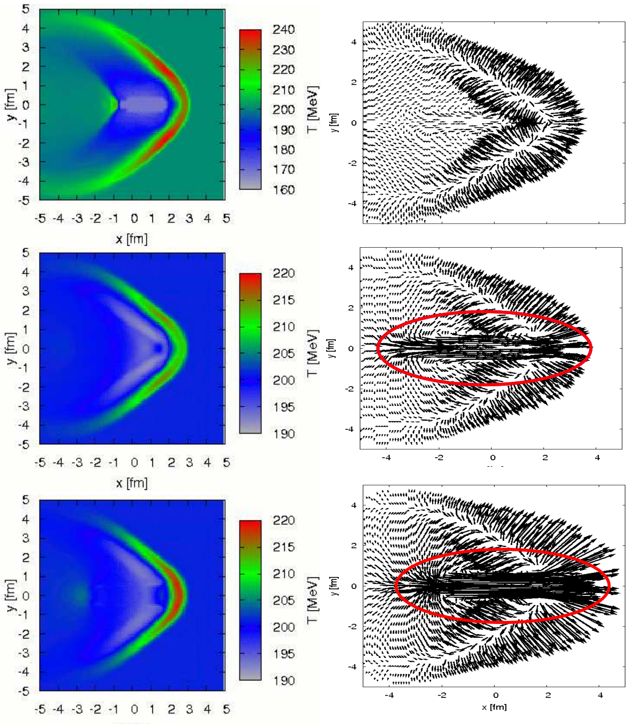
T

$\vec{v}$

Pure Energy

Mixed

Pure $\vec{p}$

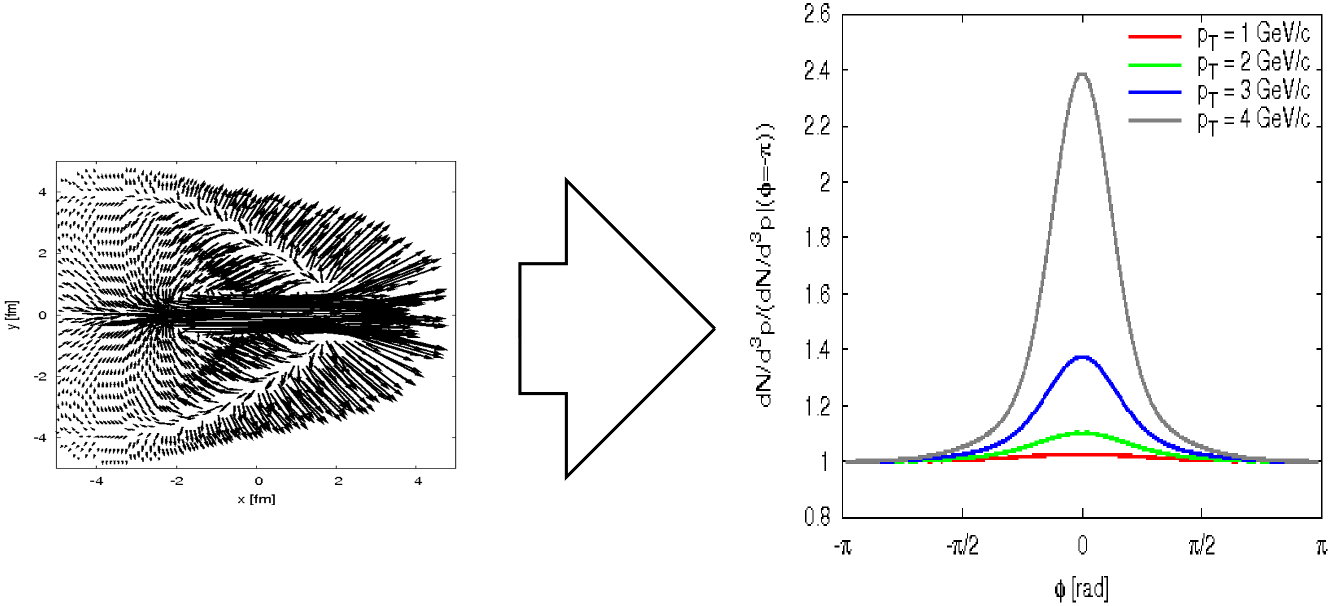


But flow pattern depends on it A LOT!

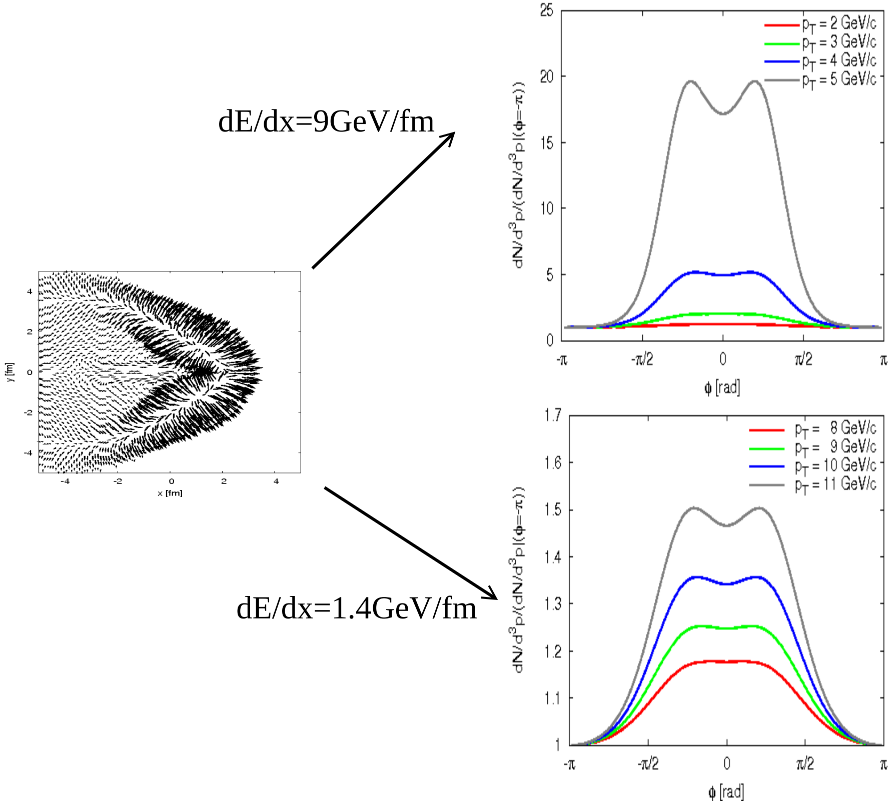
Momentum deposition creates un−conical "diffusion shock", taking most of the source’s energy/momentum

Mach cone angle survives in full hydro (Non linearities no problem. Numerical viscosity?)

"Realistic" GLV/BDMPS calculation forthcoming; LPM effect also likely to spoil Mach signal



Betz,Gyulassy,Stoecker,Torrieri: As expected, diffusion wakes are phenomenologically useless! Yield a generic “peak” indistinguishable from any other jet energy loss mechanism!



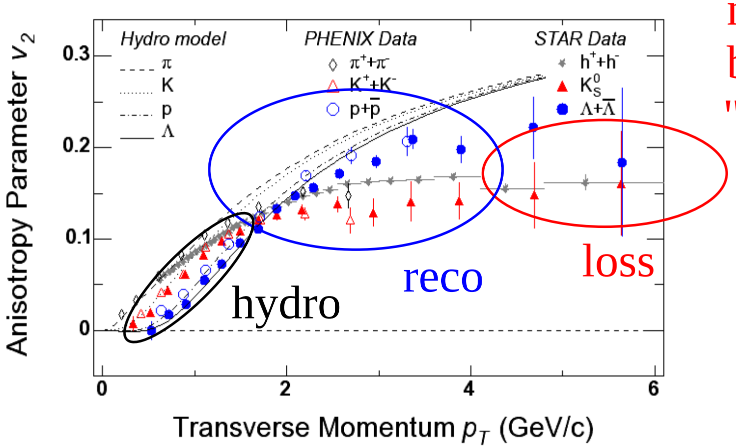
dE/dx=9GeV/fm

dE/dx=1.4GeV/fm

Energy deposition works better:Cone structure, correct angle. Signal increases with p_T (Blue-shift), only strong at very high away-side p_T

But...p_T of “soft” associated particle needs to be huge unless jet energy deposition is large!Since $\langle\sigma\rangle \sim 1/\langle Q\rangle^n$, harder particles less thermalized, (medium is more transparent to them)

away−side should
be "firmly" in "hydro
region



near−side should
be "firmly" in
"loss" region

Exclude Reco by Binning by species? (Meson/Beryon ⇔ Recombination, None/Mass ⇔ Hydro)

Insights from string theory: The good part

The AdS/CFT correspondence gives un an opportunity to solve and study analytically a system that is

- Strongly coupled
- Non-equilibrium

(Not quite non-linear, see in a moment). We therefore have a toy model on which to explore the points we do not understand (i.e., when does the system become equilibrated/ideal)

BUT This is NOT QCD (4 SUSYs, no quarks, $N_c, \lambda \to \infty$).
This has the potential of introducing qualitative subtle differences.

CFT The theory is conformally invariant. No running coupling, no phase transition, no hadrons, no bulk viscosity

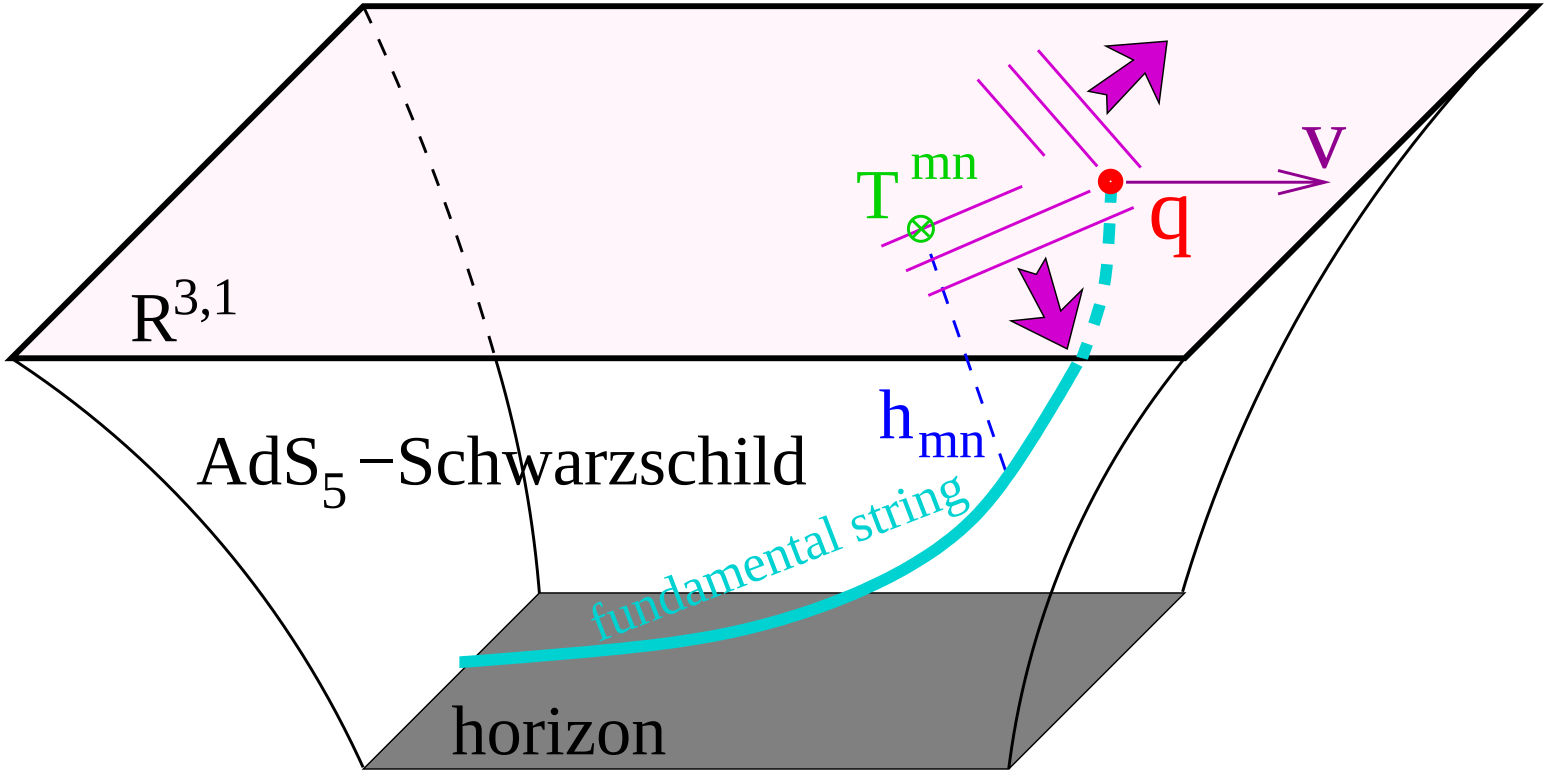
QCD Is approximately conformally invariant at weak coupling, big-time non-invariant at strong coupling

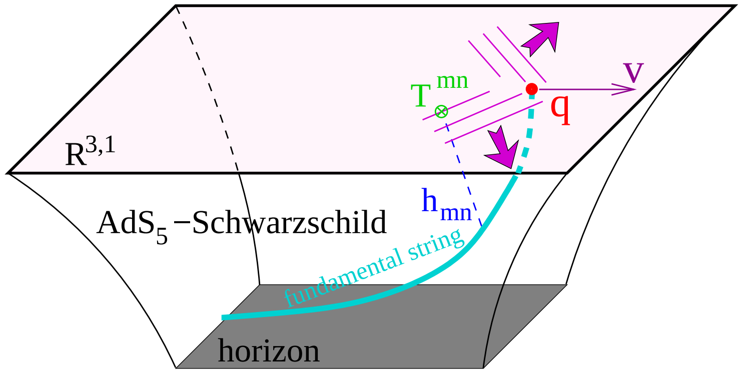
For our problem (Understanding the probe-medium correlation in the strong-field limit), this might be OK.

But thread with caution: for instance, in CFT jet-medium coupling not so different than medium-medium. probably not so in QCD! Bethe-Heitler/LPM/Factorization limits different?

Ads Equivalent of heavy quark moving in a strongly coupled medium

Joshua J. Friess, Steven S. Gubser, Georgios Michalogiorgakis, Silviu S. Pufu,PRD75:106003,2007 Also A. Yarom





$g_{\mu\nu} \Leftrightarrow T_{\mu\nu}$, Quark $\Leftrightarrow$string

Finite T background $\Leftrightarrow$Black hole in AdS space

$\lambda \rightarrow \infty$ $\Leftrightarrow$Classical geometry (Einstein's equations for $g^{\mu\nu}$)

For String (quark) moving at constant velocity, problem solved analytically (and drag force on quark derived). Steady state, no quark energy loss (Unphysical, but not much so if deceleration is small).

Static force (up to $\sim \lambda_{GB}$),

Energy not conserved, quark "pulled by string"
(Brigante et al, 0712.0805, Vazquez-Poritz, 0803.2890)
(good approximation if accelleration small)

$$F_{drag} = -\frac{\sqrt{lm}\pi T^2 v}{\sqrt{1 - v^2 a_2 + \lambda_{GB} v^4/a_2^2}}$$

$$a_2 = \frac{1}{2}(1. + \sqrt{1. - 4. * \lambda_{GB}}) \qquad \frac{\eta}{s} = \frac{1}{4\pi}(1 - \lambda_{GB})$$

- Drag force related to η/s (which depends on λ_{GB}, maybe not bounded)

- finite (and short) momentum-dependent skin depth, surface emission!

Powerful quantitative constraints

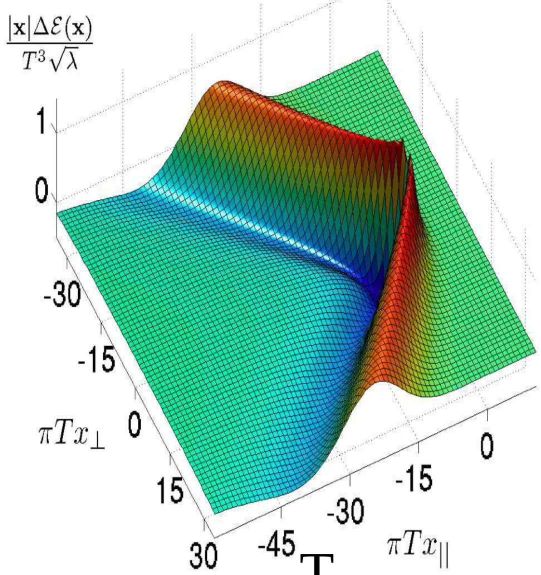
Expansions and approximations

$k/T \ll 1$ Long-lived modes, relevant for hydrodynamics. Close to quark not described.

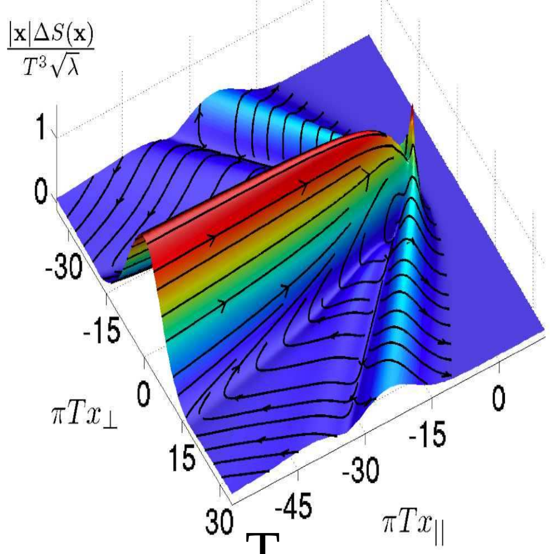
$N_c >> 1$ Signal $\sim N_c$, background $\sim N_c^2$. So hydro forced to be linear by approximation.

At the moment we can only confirm (or rule out!) "textbook" hydro/Mach cone behaviour rather than get insights on what "beyond textbook" looks like.

Chesler,Yaffe:arXiv:0712.0050
Also Yarom,Gubser,Noronha,GT,Gyulassy



T_{00}

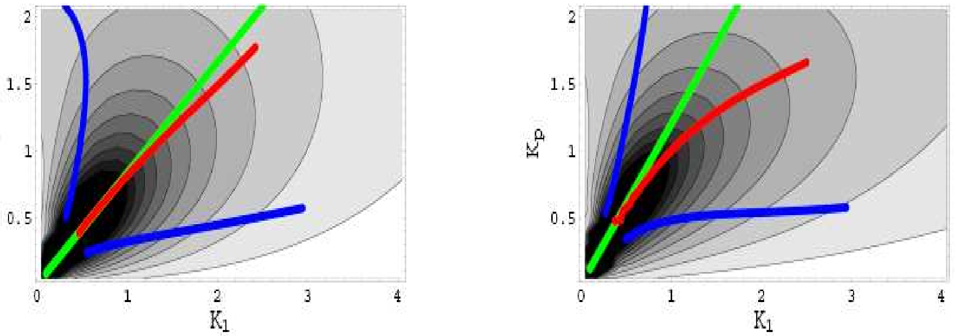


T_{0i}

This is a solution to $T_{\mu\nu}$ from QFT, looks like Mach cone to me!

- The ratio of sound to dissipated energy is $\frac{P_s}{P_d} = 1 + v^2$
(Indipendent of viscosity: "diffusion" wake arises from momentum!

- Angle nearly correct but not quite, even in far field



- Energy-momentum source $J^\mu = (v\Pi(\lambda), \Pi(\lambda), 0)$

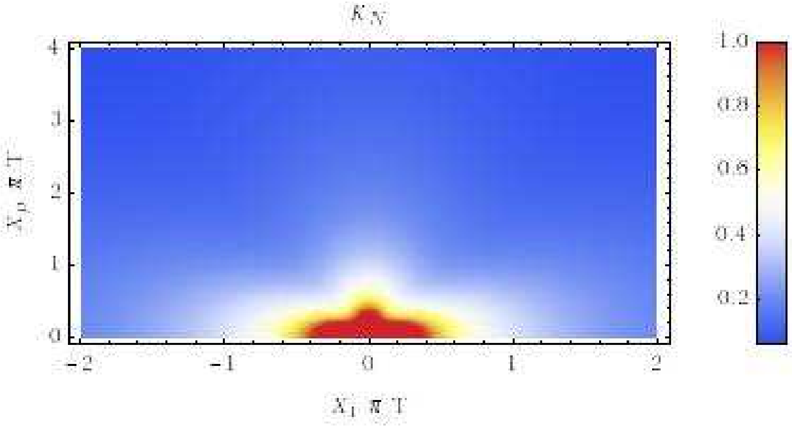
- But details sensitive to source: quarkonium rather than quark has no diffusion wake (Gubser et al, 0711.1415)

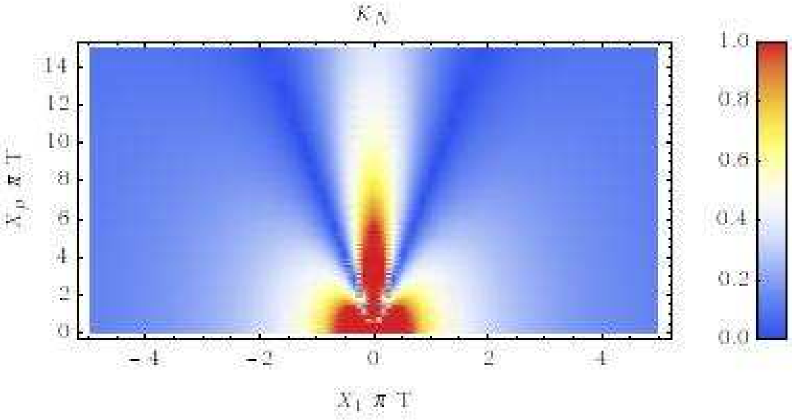
GT,J.Noronha,Gyulassy: arXiv:0712.1053: A more detailed analysis: The "Knudsen number"

Assume "mean free path" $\sim \Gamma_s = \frac{3\eta}{4(e+p)}$, and

$$Kn = \left| \gamma_s \frac{\vec{\nabla} S}{S} \right| (\ll 1)_{hydro}$$

Plots for $v = 0.75, 0.99$:Even for 0.99 $10/T$ thermalized





If

$$T_{\mu\nu} = (p+\rho)u^\mu u^\nu - p g^{\mu\nu} + \eta \left\langle \partial^\mu u^\nu \right\rangle$$

then in Landau frame ($T^{0i}=0$) the system should look be

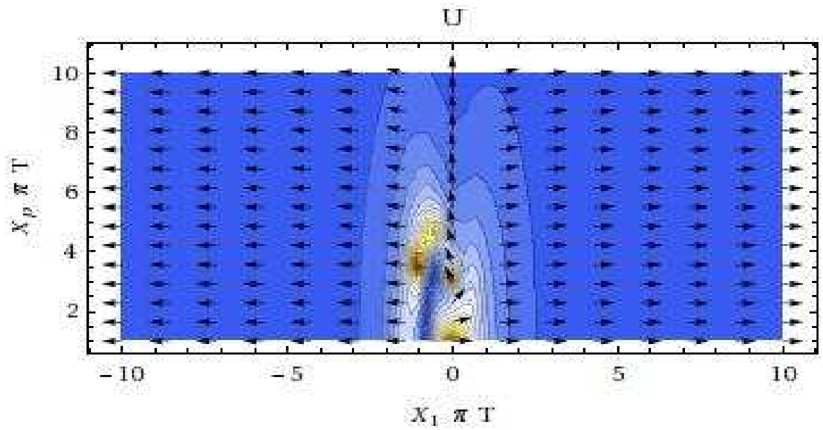
$$T_{\mu\nu}^{landau} = \left(\begin{array}{cccc} e & 0 & 0 & 0 \\ 0 & -e/3 & 0 & 0 \\ e & 0 & -e/3 & 0 \\ 0 & 0 & 0 & -e/3 \end{array} \right) + \frac{e+p}{4\pi T} \left\langle \partial^\mu u^\nu \right\rangle_{Landau}$$

where u_μ is the boost bringing the system to Landau frame

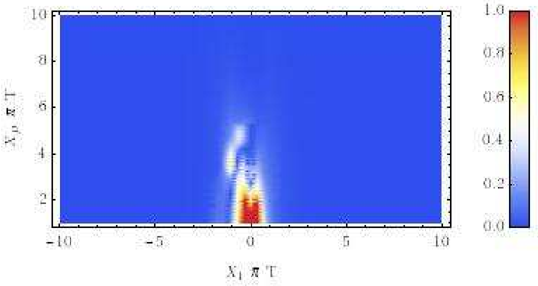
No unknowns, so can be tested!

Linearized ansatz works after $5/\pi T$ fm or so.

Flow (Color:Magnitude)



$|\vec{U}-\vec{S}/(3P)|$



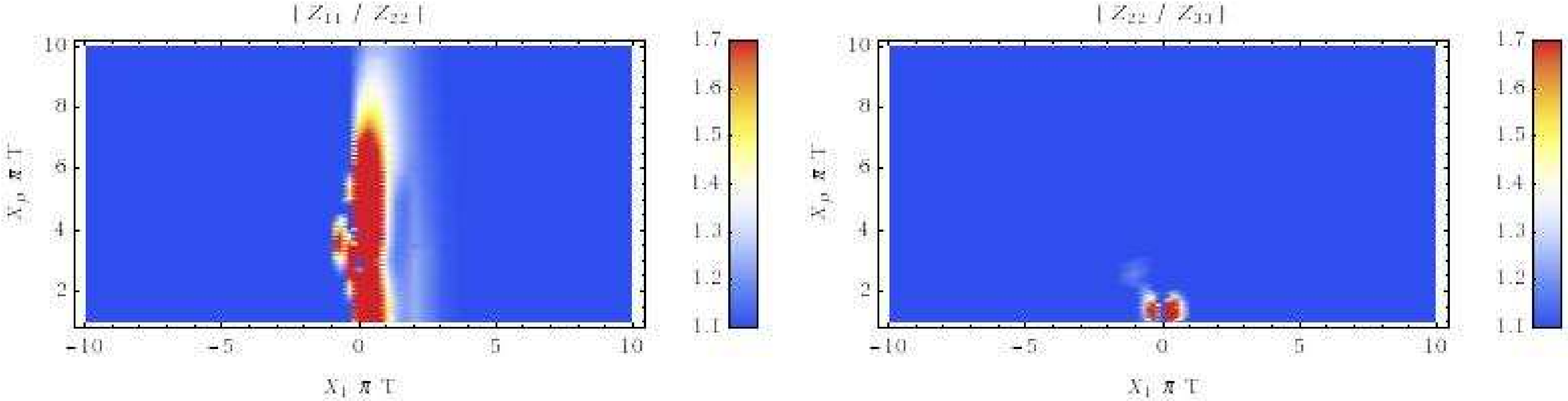
Deviation from Hydro?

Non−linearities?

Testing isotropy

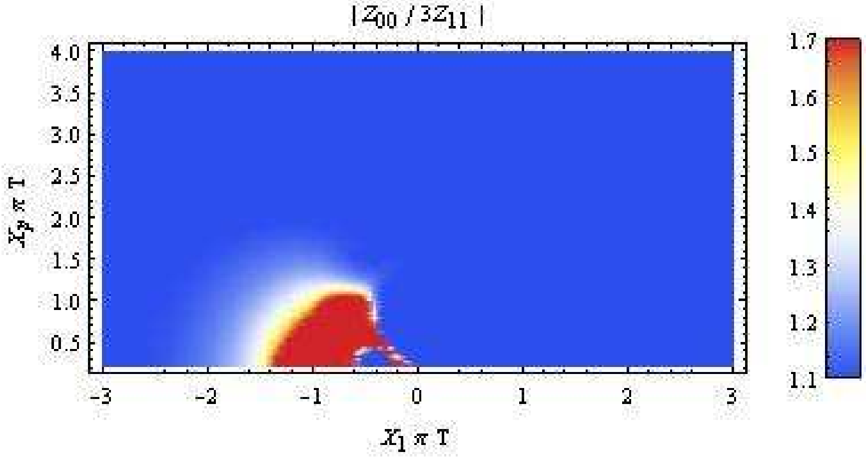
$$Z_{\mu\nu} = T_{\mu\nu}^{landau} - \langle \partial^{\mu} u^{\nu} \rangle_{Landau} \left(= Diag[3p, p, p, p]_{Navier-Stokes}\right)$$

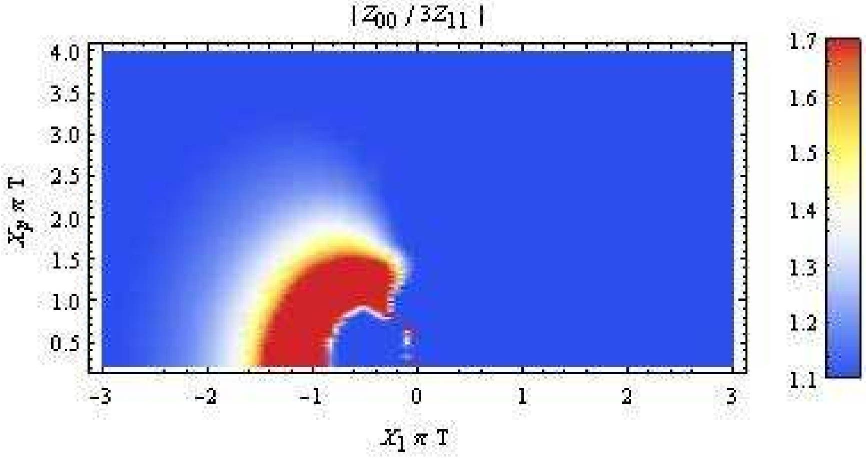
Isotropy: Z11/Z22,Z22/Z33



System a lot more locally isotropic perpendicular to jet.

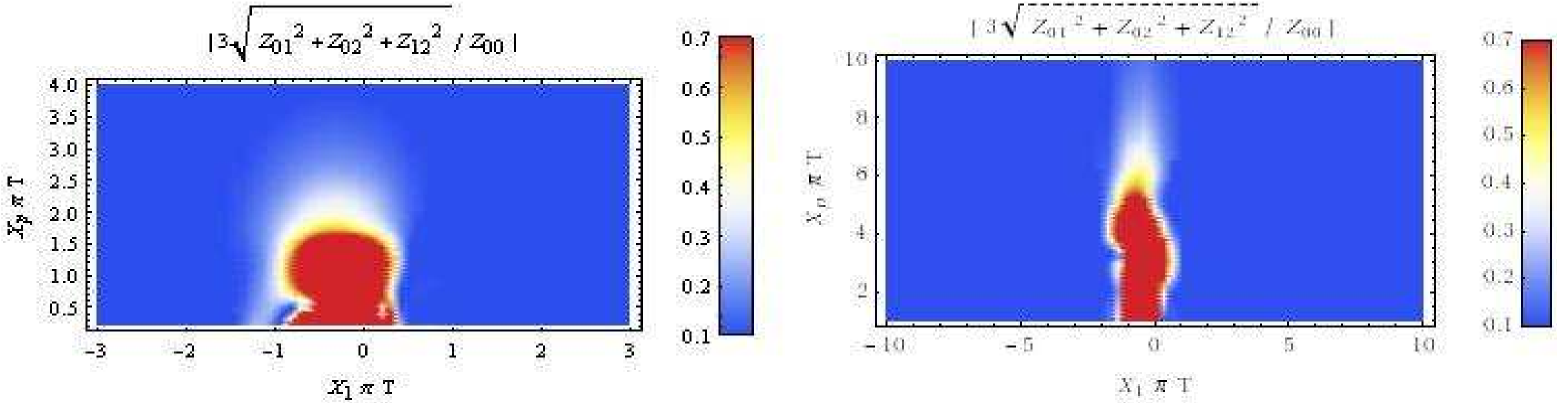
EoS: Z00/3Z11, v=0.75,0.99





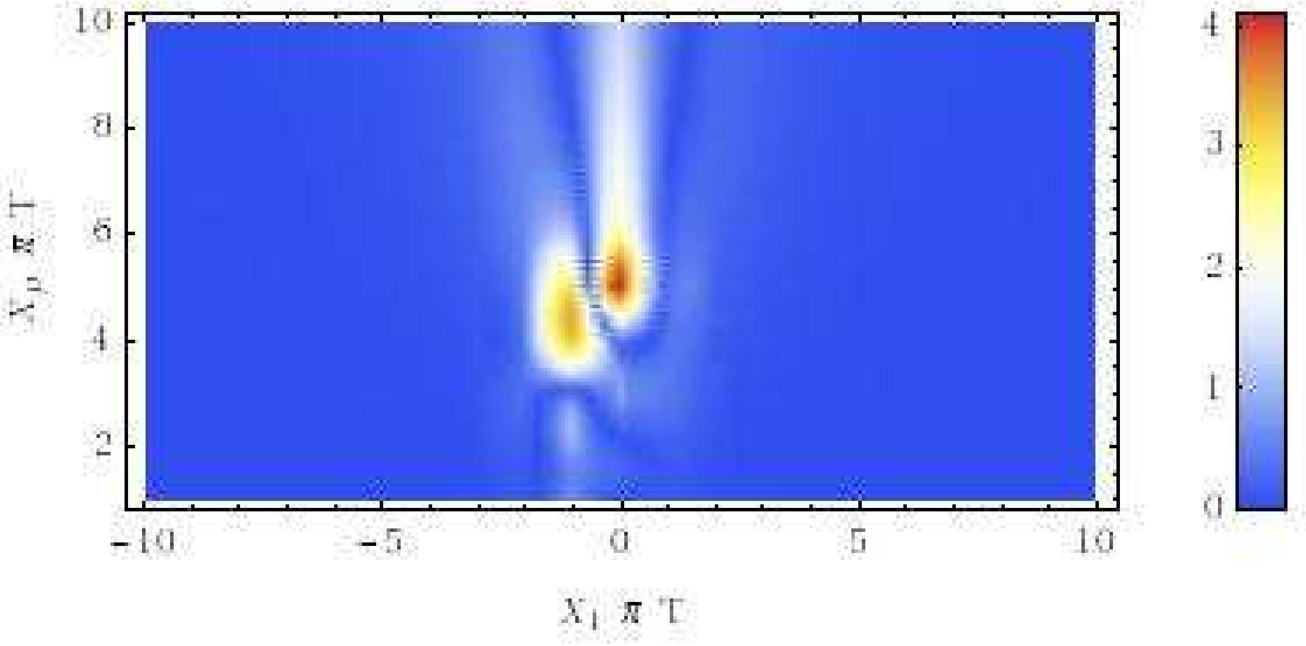
System slightly more thermalized for slower jet

Off diagonal compared to diagonal Z, v=0.90,0.99



Faster jet less thermalized, but non−thermalized area more focused

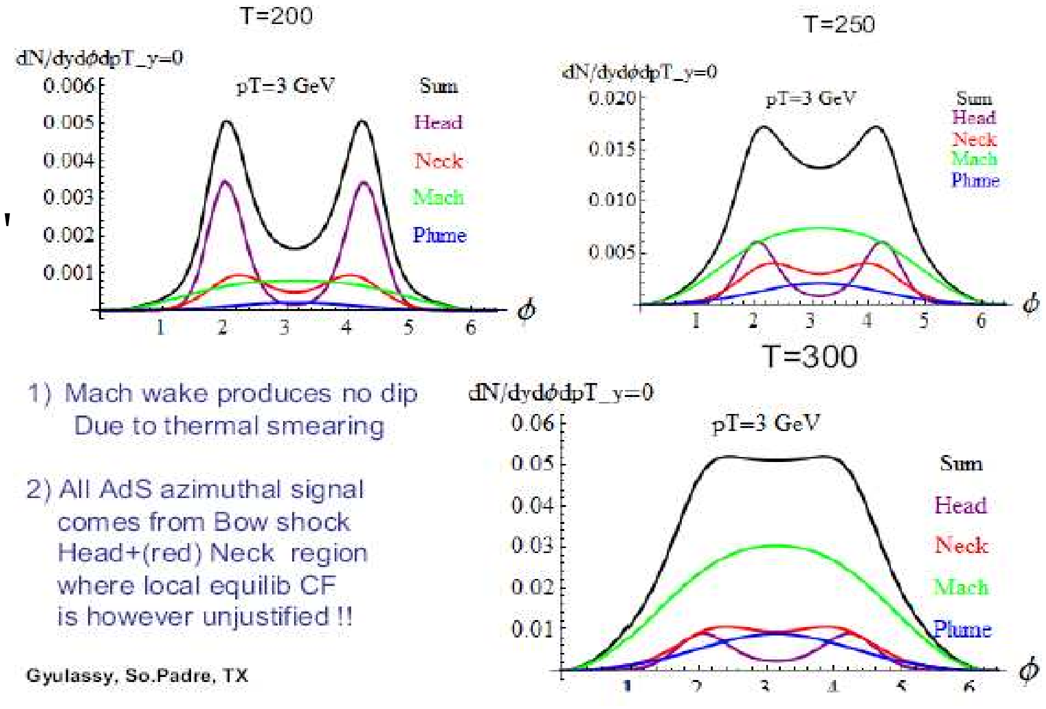
Relative importance of viscosity, $\frac{\Pi_{\mu\nu}\Pi^{\mu\nu}}{sum Z_{ii}^2}$



When hydro description applies viscous tensor unimportant

Freezing out the AdS/CFT Mach cone

At moderate
temperatures
the signal
from the "head"
dominates
and breaks
the signal!



1) Mach wake produces no dip
Due to thermal smearing

2) All AdS azimuthal signal
comes from Bow shock
Head+(red) Neck region
where local equilib CF
is however unjustified !!

Gyulassy, So.Padre, TX

But Cooper−Frye
description
(Instantaneus
liquid−>Particles
transition)
really makes no sense
in this context
(+Head is NOT
thermalized)

Correlation in ENERGY
more model−independent?

What next?

Non-linear hydrodynamics : Non-linear GR, or Gauss-Bonnet terms. As a “preview”, analyze linear solution for stability (turbulence?)

Break CFT and study a “realistic” EoS

2nd order hydrodynamics : But first order allready irrelevant after a few fm. Unlikely to make big difference.
But, by power-counting of coupling constant, non-linearities $\sim$ higher order expansion.

(few) conclusions!

- Mach cone-like patterns arise in a variety of hydro-like models
- Link between features and "fundamental" physics weakened by many not understood parameters
- Experimentalists found something that looks like a Mach cone. But we are not quite certain how to interpret it within the "big RHIC picture", and say something about the medium

Lots of work to do

Theory

- Systematic study of deposition mechanisms
- Freeze-out(Resonances, Σ_μ)
- Flowing background. Other observables needed to determine which flow
- Transport (Also consistent way to couple jet and medium)

Experiment

- Higher $p_T^{trigger}$,lower $p_T^{associate}$.
- Chemical composition and thermal structure of associates. Are they "jetty" or "mediumy"?
- Continue scan in energy/system size. Sudden appearence or smooth excitation? Angle dependence on system size/jet-reaction plane?

BACKUP SLIDES