Multiplicity and flow scaling in rapidity in weakly and strongly coupled systems

(Why hydro bothers me and how NICA could help)

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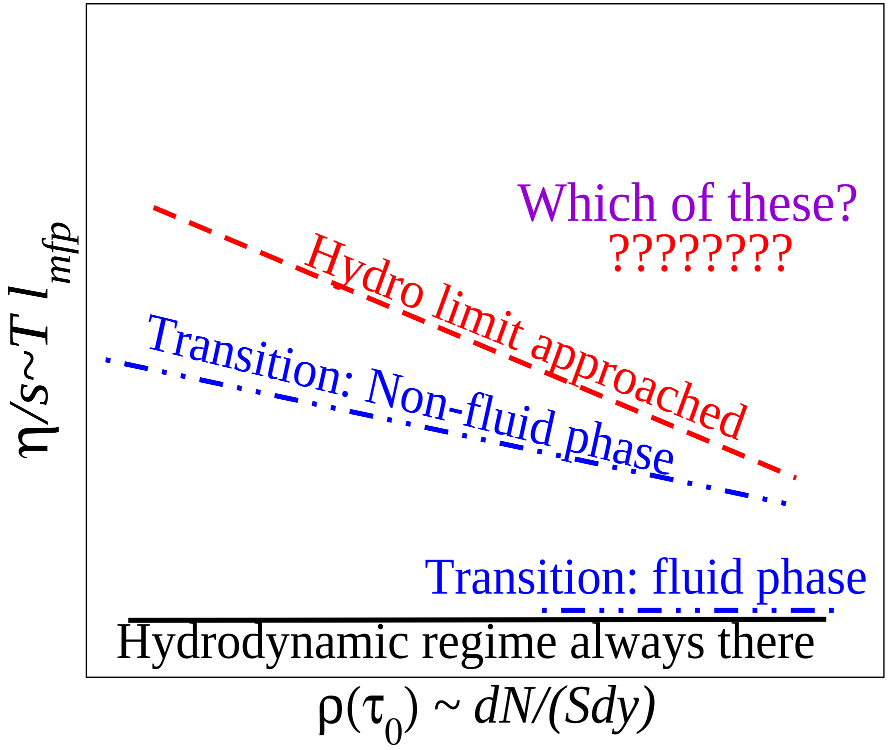
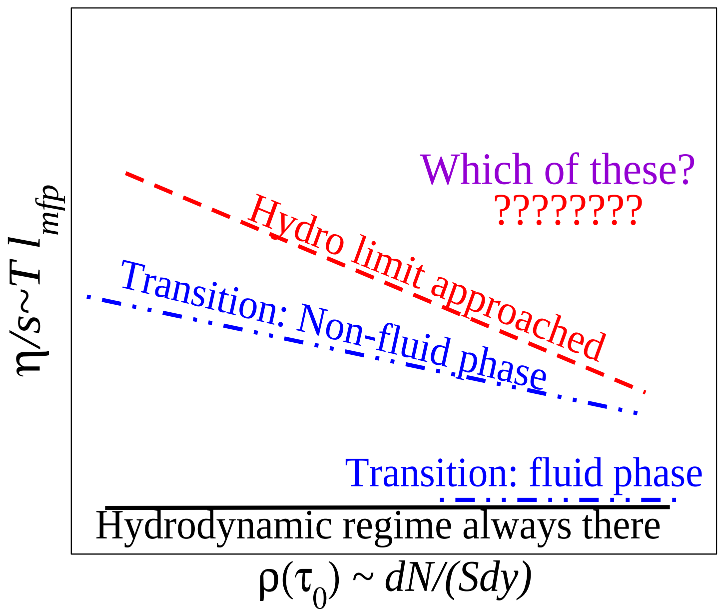
FIAS Frankfurt Institute for Advanced Studies



The most important question facing the study of flow in heavy ion collisions

How does hydro turn on??



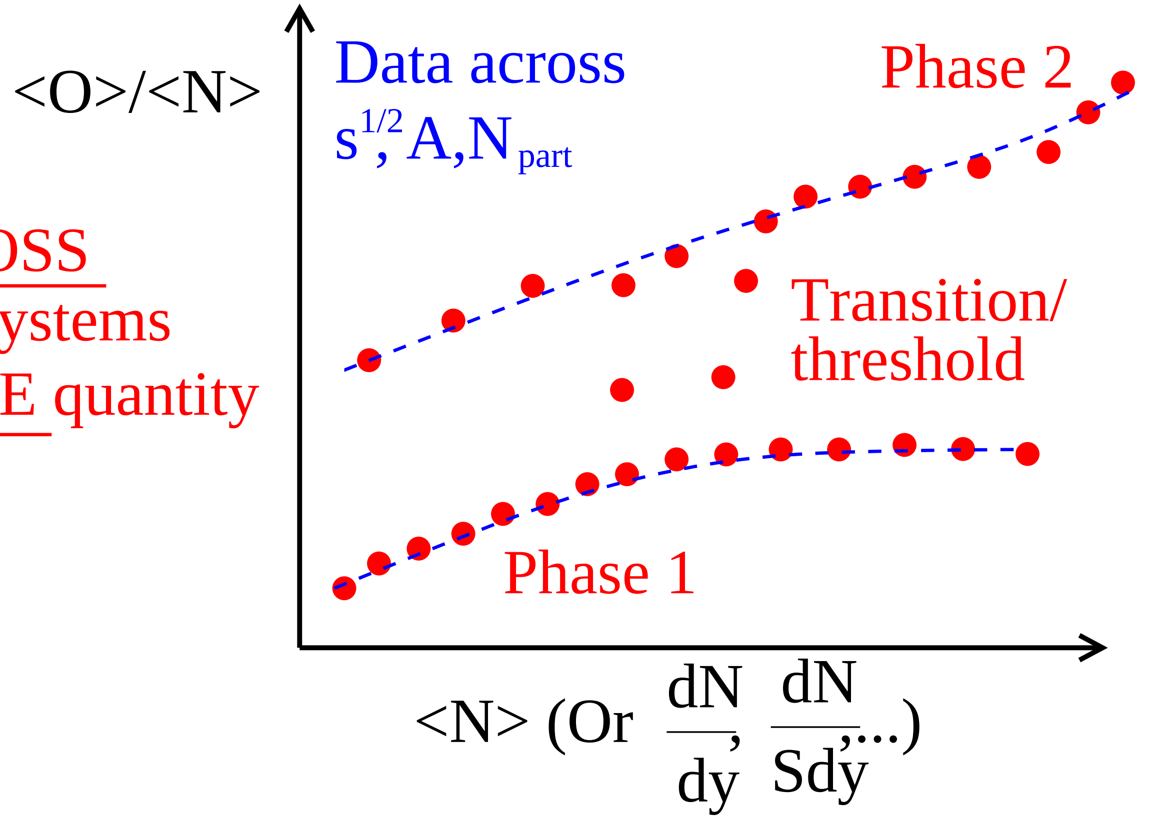
The most important question facing the study of flow in heavy ion collisions

How does hydro turn on??

Naive expectation: At T_c <u>if hydro holds!</u>

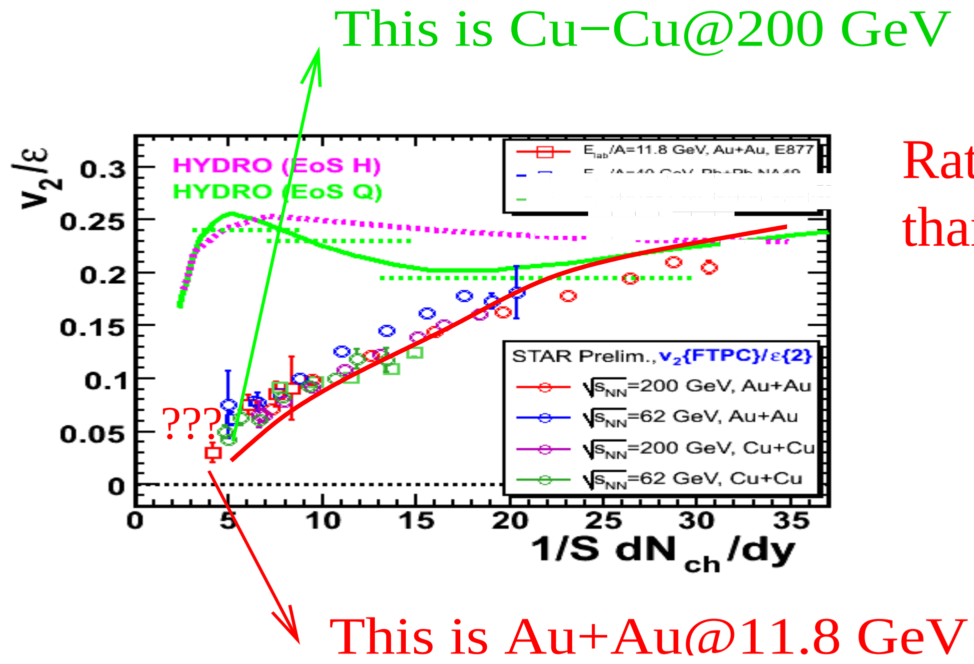
- c_s has a <u>dip</u>, to <u>0</u> (transition) or to a <u>minimum</u> (crossover)
- η/s changes from $\sim N_c^2$ (HG) to $\sim N_c^0$ (QGP) Order of magnitude

The hope

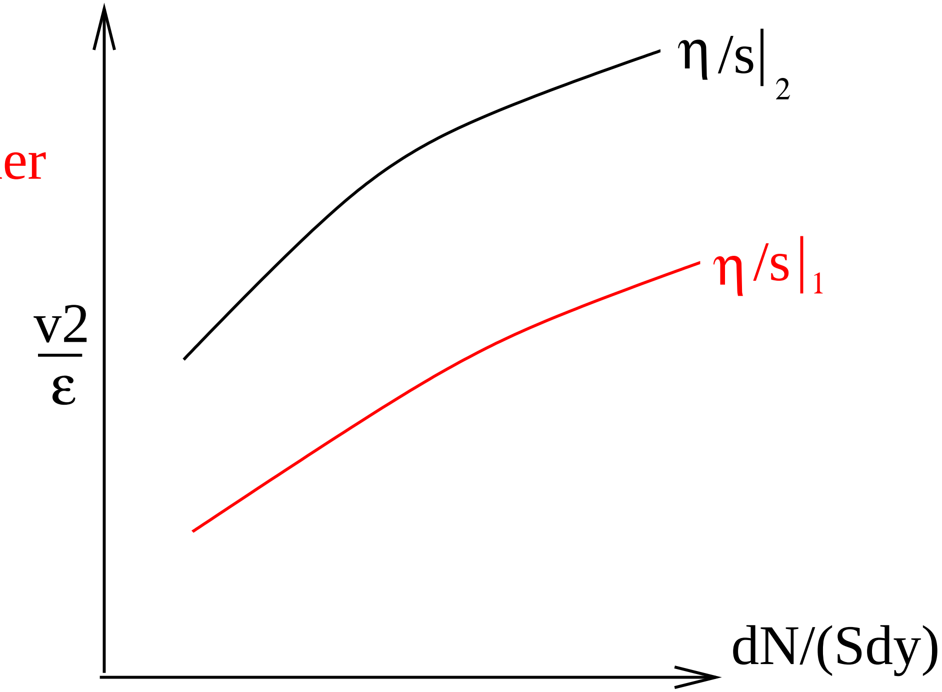


Scaling ACROSS energies and systems of INTENSIVE quantity BROKEN

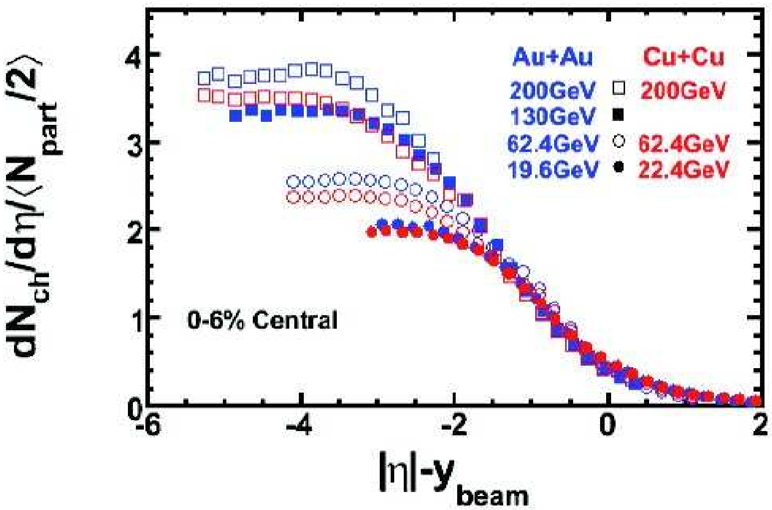
The hope: Flow can lead to something of this type...

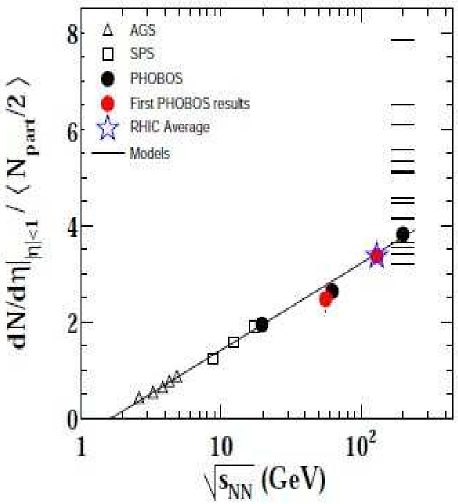


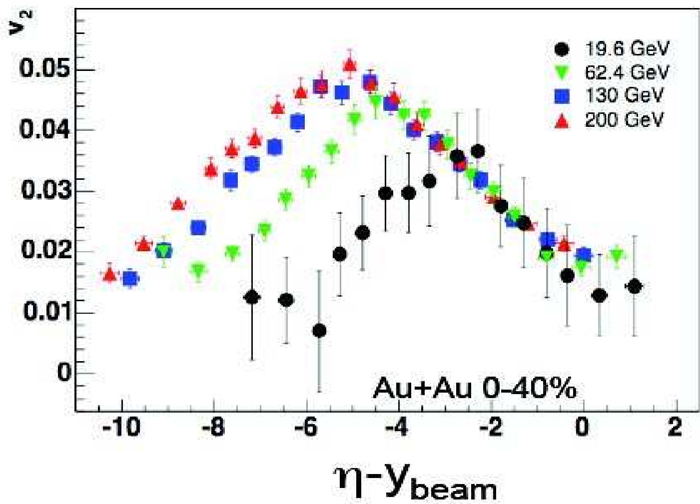
Rather than



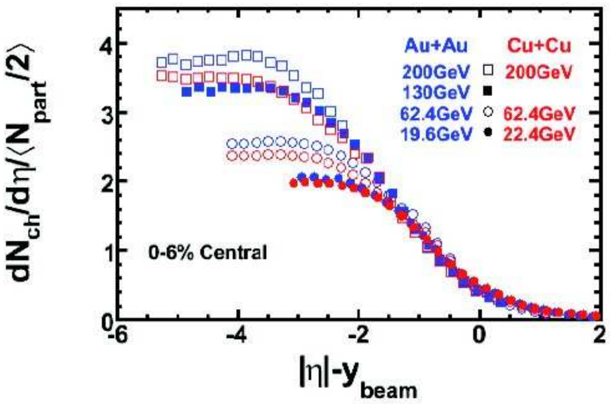
At the moment, v_2 is <u>not</u> it!

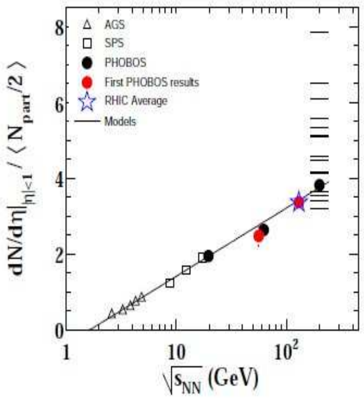


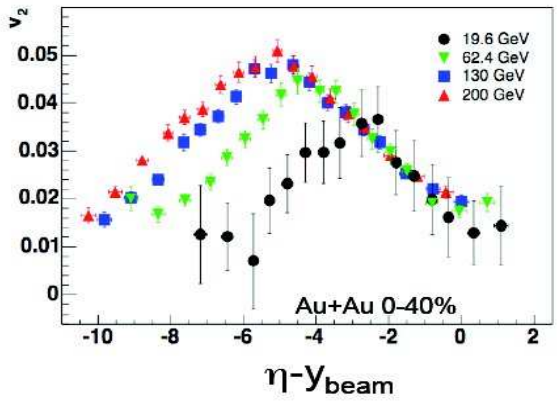




And something funny has certainly been found when scaling in both energy and rapidity





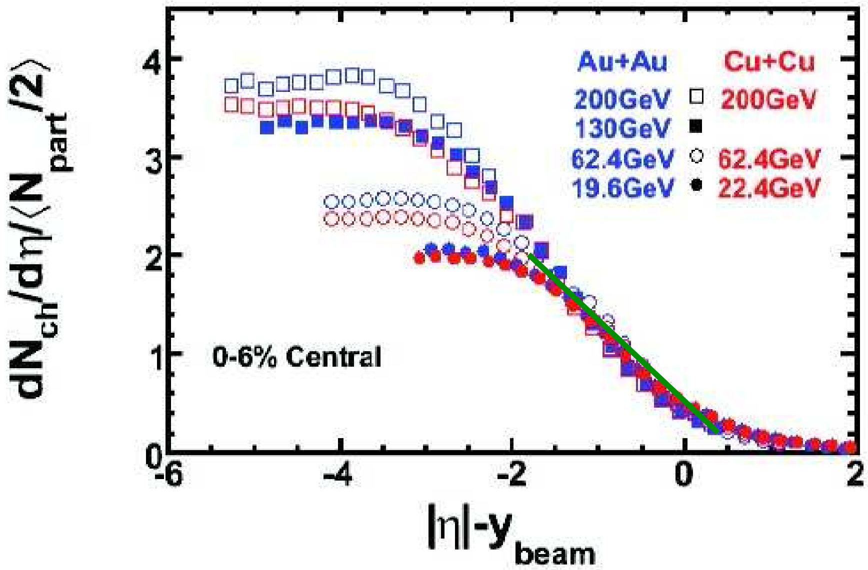


I plan to show you that...

The first scaling follows naturally from QCD-inspired initial conditions

The second scaling Can be accomodated by a not-unreasonable modification of these

The third scaling is very tricky (impossible?) to model within hydro, but arises naturally in weakly coupled systems! ($Kn \geq 1$)



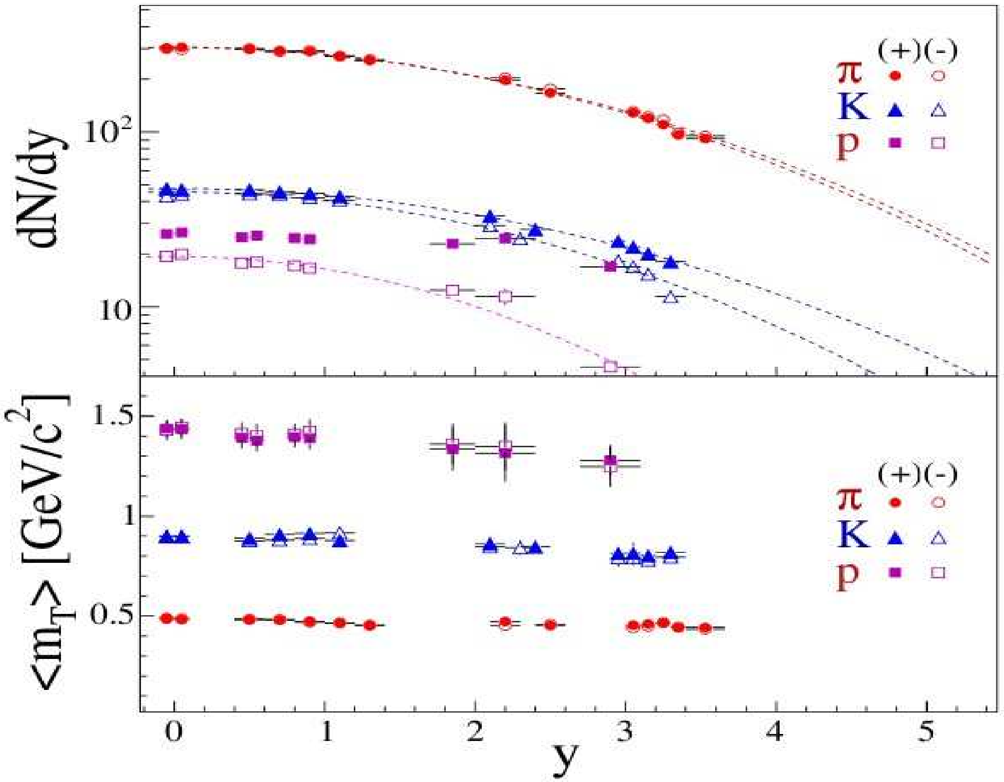
Universal fragmentation
Slope of spectators independent of energy

It is easy to see that, by kinematics, $y_{lim} \sim \log \sqrt{s}$
Universal fragmentation is more involved, but ultimately undestandable within QCD phenomenology

A generic intuitive explanation: Brodsky-Gunion-Kuhn (BGK)!

- Each target-projectile collision produces parton at y^*, uniformly distributed between y^T_{lim} and y^P_{lim}
- Each Target/Projectile (T/P) wounded nucleon produces a string disintegrating between $y^{T,P}_{lim}$ and y^*.
- Total multiplicity $\sim \sum$ independent string fragmentations
  - Number of strings at projectile/target $\sim N^{P,T}_{part}$ of projectile/target (Universal fragmentation for different $\sqrt{s}/y_{lim}$, same N_{part})
  - Density linearly interpolates between them away from limiting rapidities ("Triangle" seen experimentally in $(dN/d\eta)_{AA}/(dN/d\eta)_{pp}$) Initial Bjorken flow ($y = \eta$) but no boost-invariance except for symmetric systems

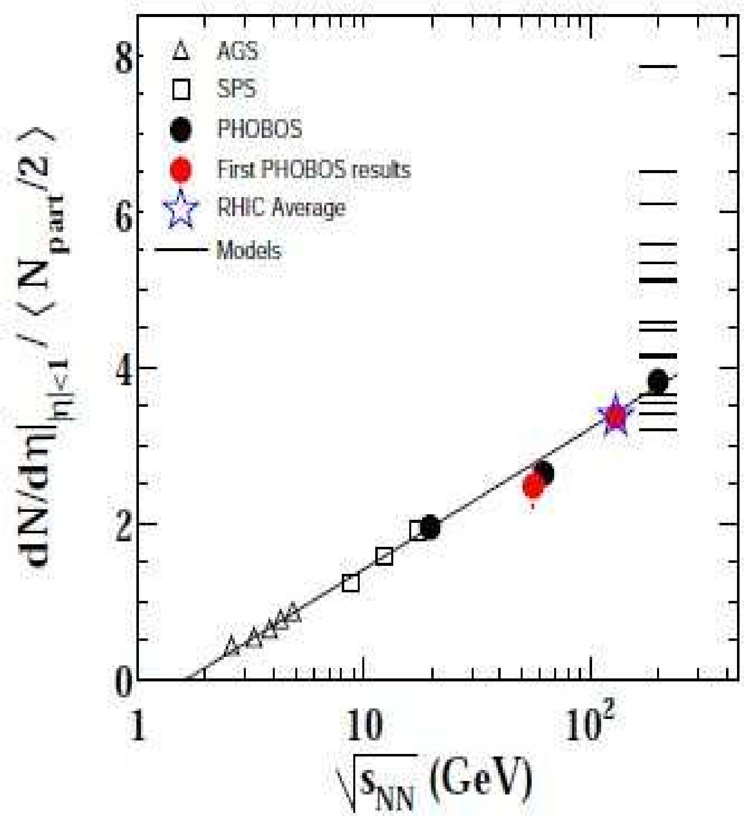
But this picture has a problem I...



Brahms white paper

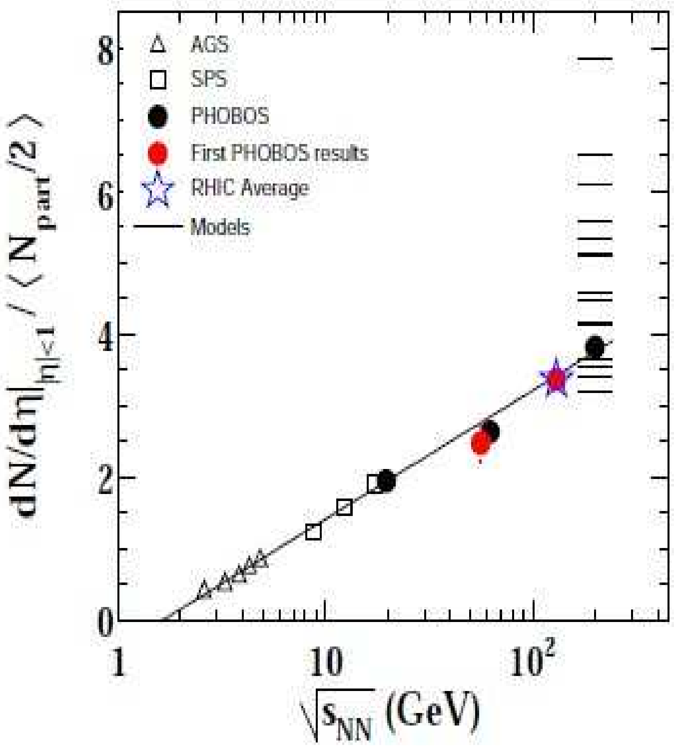
Even at RHIC top centrality there is no boost-invariance!

But this picture has a (related?) problem...



The multiplicity rapidity density at y=0 also scales with $\ln(\sqrt{s})$ at all $\sqrt{s}$

$$\frac{dN}{dy} \sim N_{part} \ln(\sqrt{s})$$



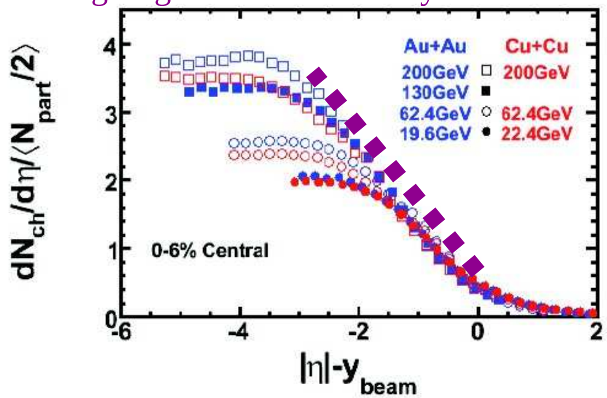
The multiplicity
rapidity density at y=0
also scales with
ln(√s) at all √s

$$\frac{dN}{dy} \sim N_{part} \ln(\sqrt{s})$$

NOT Feynmann scaling! He predicted, from local Boost-invariance and dimensional analysis, $dN/dp_z \sim 1/Q$, that $\langle N_{tot} \rangle \sim \ln\sqrt{s}$. It appears its $\langle N_{tot} \rangle \sim (\ln\sqrt{s})^2$. Does mid-rapidity know about limiting fragmentation?

Not Landau either!

Limiting fragmentation of dN/dy



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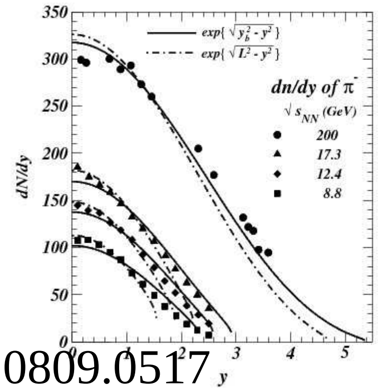


Scaleless EoS no transverse flow

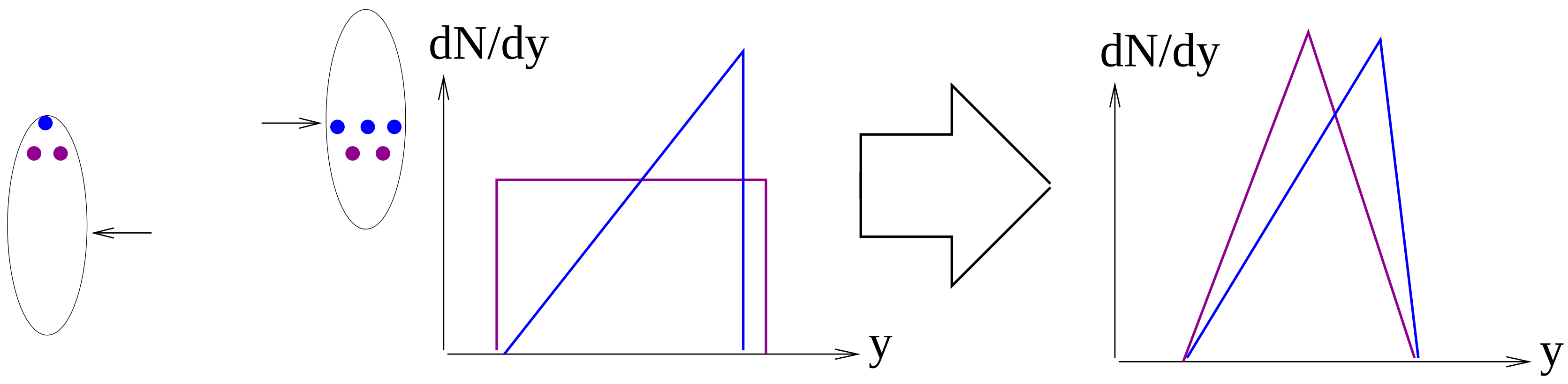
Wong,0809.0517

Landau becomes Bjorken after a few $T_{initial}^{-1} \sim \mathcal{O}(1)/\sqrt{s}$

That means approximate limiting framgnetaiton <u>well away</u> from mid-rapidity (Not perfect, even with ideal EoS,inapplicable in cross-over/hadronic),but <u>not to mid-rapidity</u>, Which is why Landau $dN/dy \neq \ln(\sqrt{s})$

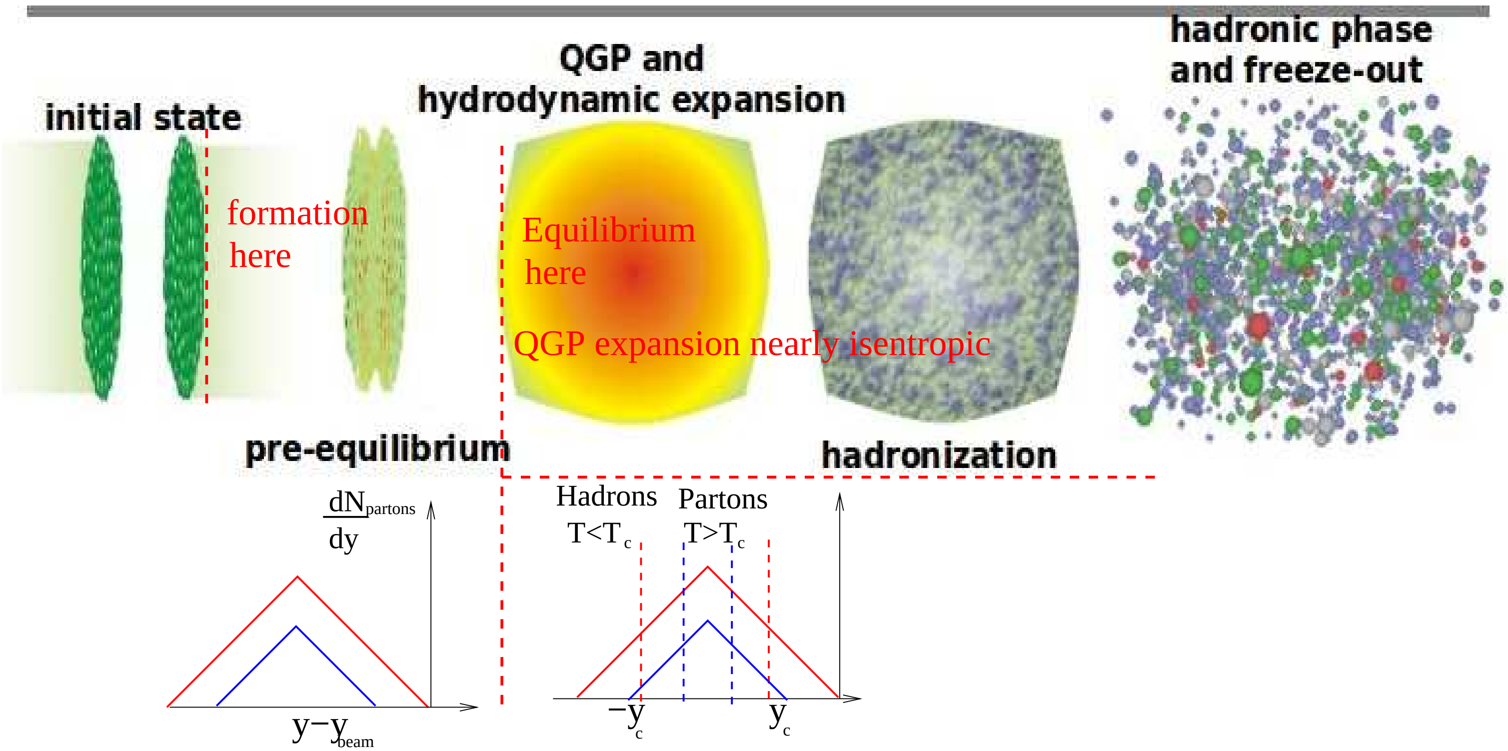
Need initial Boost-invariance $(y = \eta)$ for limiting fragmentation up to mid-rapidity, <u>but</u> large stopping in the middle to account for dN/dy

A simple explanation: limiting fragmentation up to $y = 0 \rightarrow$ triangles!

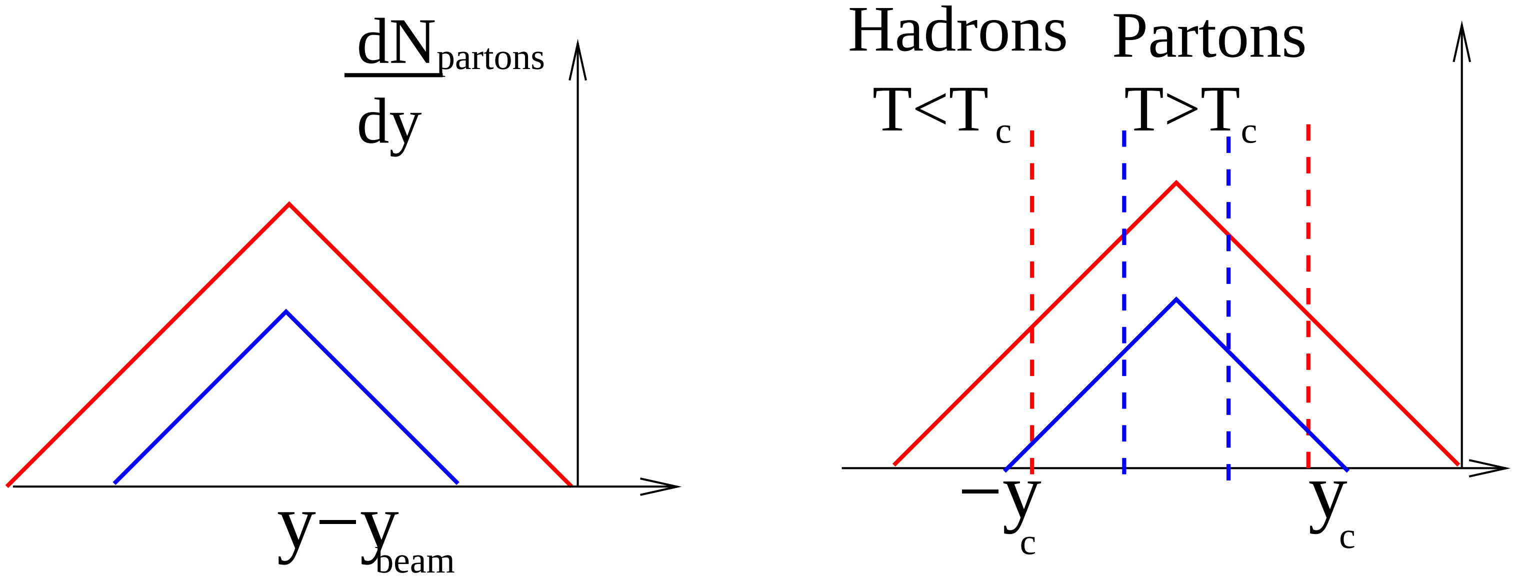


- Slope $\sim N_{Part}^{P,T}$,independent of $\sqrt{s}$
- x-intercept $\sim y_{lim}^{P,T} \sim \ln \sqrt{s}$

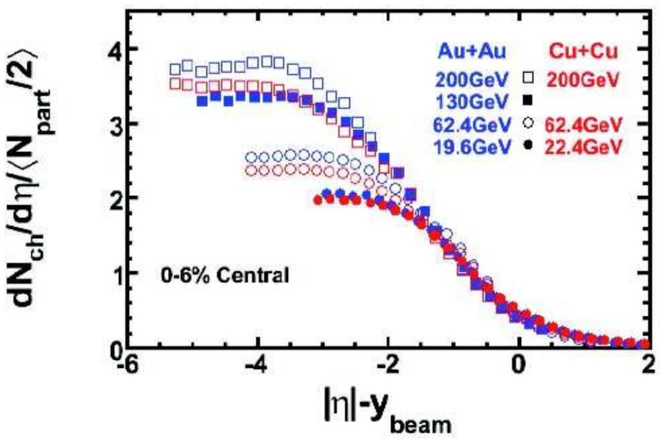
So intersection at maximum, also $\sim \left(N_{part}^{P} + N_{part}^{T}\right) \ln \sqrt{s}$
Boost invariance, even in symmetric collisions, goes away like in data !
Asymmetric systems (eg p-A,A-A at large $r_\perp$)$\rightarrow$ BGK as C of M at large y

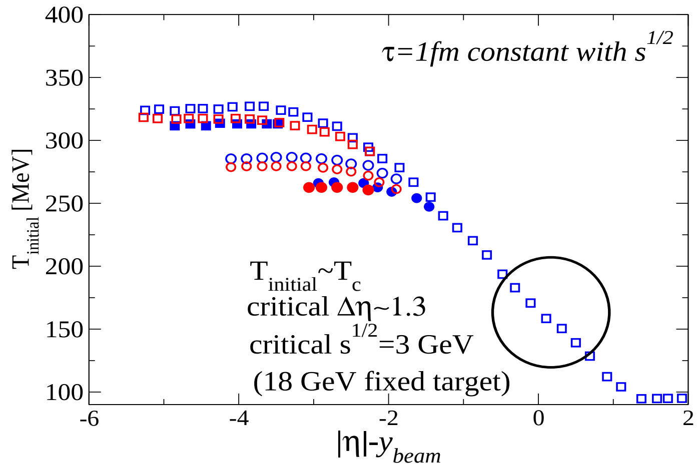


So far everything I told you related to the "formation time", $\sim Q_s^{-1}$ (Or some such scale). At this time, system is partonic everywhere. For system to "know" if its QGP or HG, its pressure gradient and η/s, one has to wait until the later equilibration time $\sim \mathcal{O}(1) \times R \times Kn$ So....



<u>Remember</u> That we have a phase transition!
So, if there is Bjorken flow (distinct slices not talking to each-other), there will be slices dominated by partons and others by hadrons *at equilibrium*





We can estimate this critical rapidity *very roughly*, by just plugging the experimental $\frac{2}{N_{part}}\frac{dN}{d\eta}$ distribution into the back-of-the-envelope entropy formula, $\frac{ds}{dy} = 4\frac{dN}{d\eta} \sim N_{part}\tau f m^2 g T^3$. We get'/usr/share/applications/gnome-screenshot.desktop' The "critical" y should be well within detection (critical $\sqrt{s}$@low energy SPS)

What can these considerations tell us about hydro and phase transitions?

Perhaps very much...

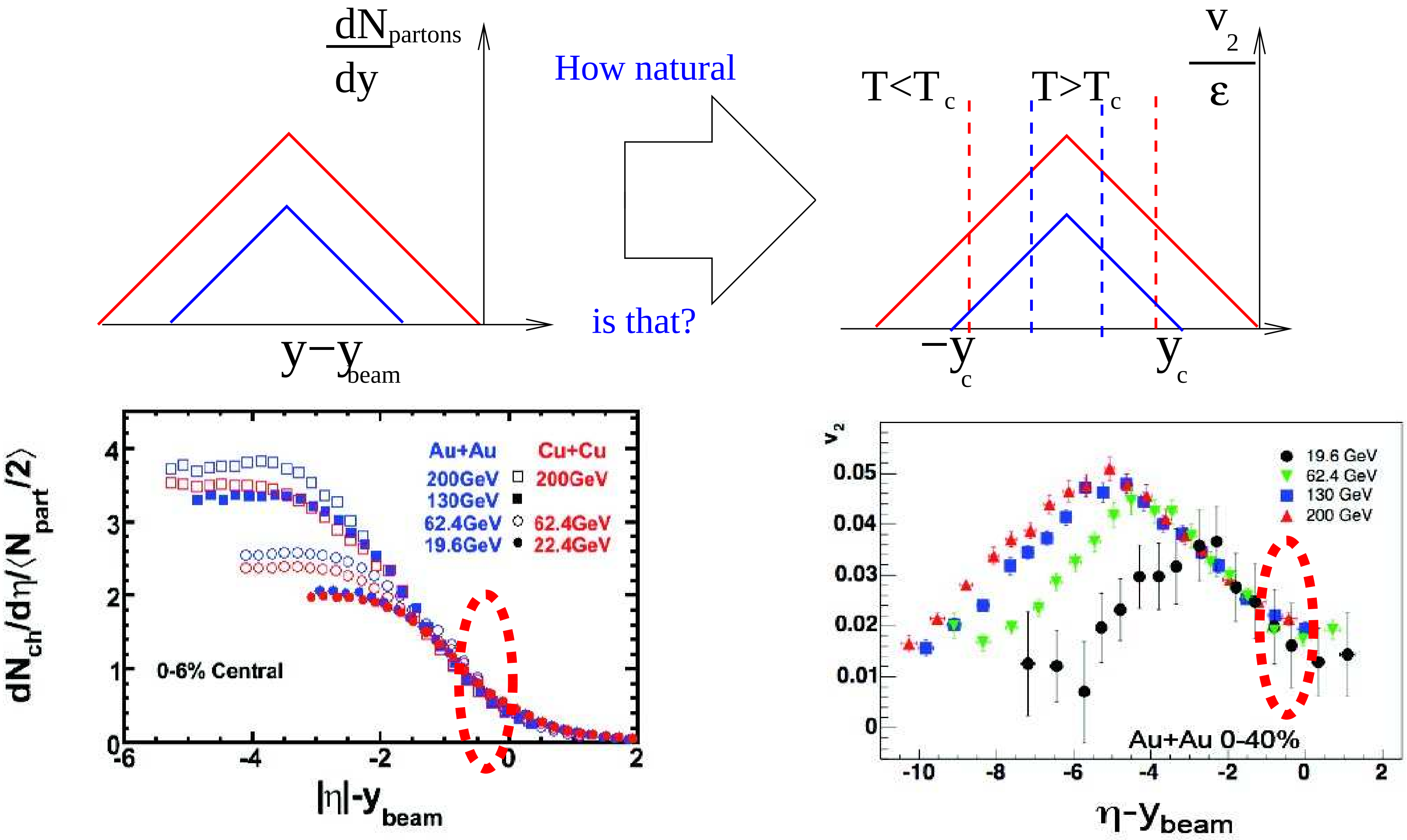
- Initially ("formation time") the system is partonic

- But *at equilibrium* its partonic at $y < y_c(T > T_c)$ and hadronic otherwise

- System "probably" nearly ideal as a QGP $y < y_c$, a lousy liquid $(Kn \sim 1)$ at central rapidity, a lousy hadron gas away

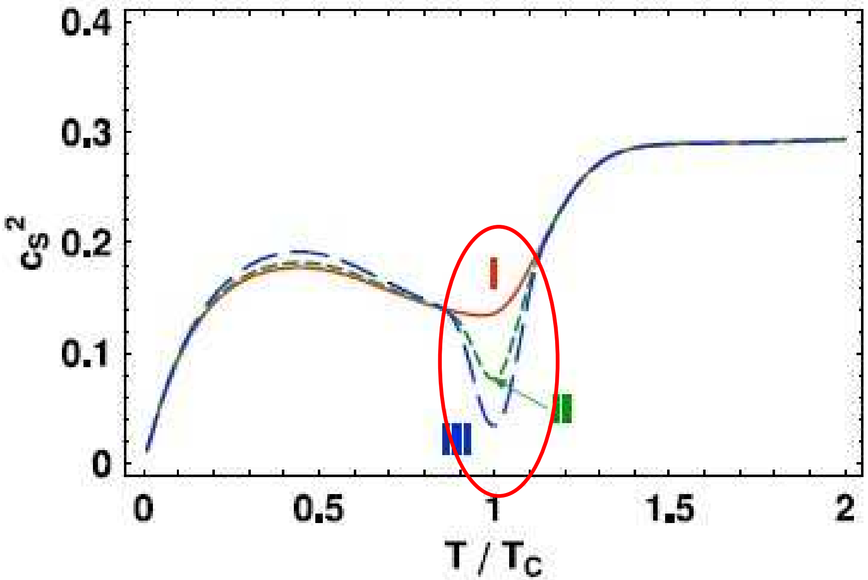
- But both free streaming and ideal liquid conserve entropy, so in those two limits not much should change with dN/dy.

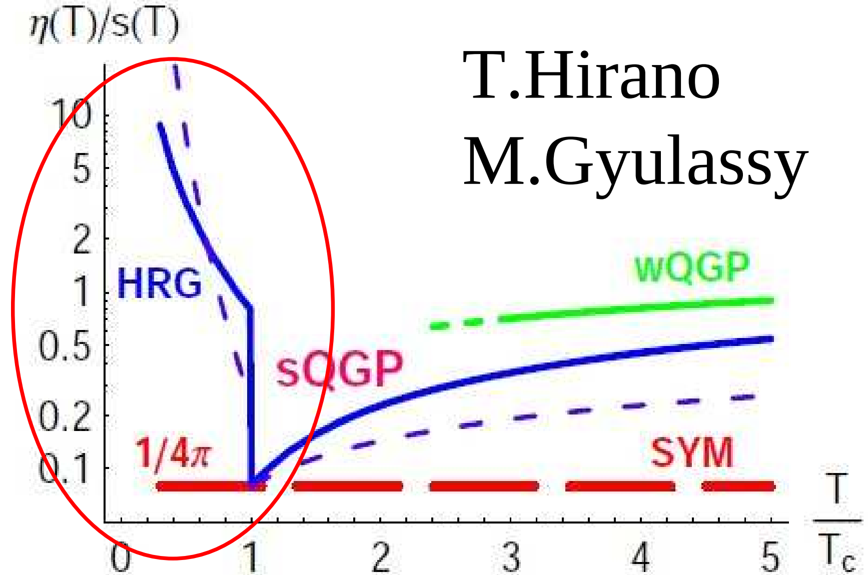
So perhaps very little... but v_2 is a different story!



dN_partons / dy
y−y_beam
How natural
is that?
T<Tc
T>Tc
v2 / ε
−yc
yc
dNch/dη/⟨Npart/2⟩
Au+Au
Cu+Cu
200GeV
130GeV
62.4GeV
19.6GeV
200GeV
62.4GeV
22.4GeV
0-6% Central
|η|-y_beam
v2
19.6 GeV
62.4 GeV
130 GeV
200 GeV
Au+Au 0-40%
η-y_beam

But both EoS and η/s should have a scale, T_c





T.Hirano
M.Gyulassy

At T_c (mixed phase) speed of sound experiences a dip (not to 0,as its a cross-over,but a dip). Above T_c, $\eta/s \sim N_c^0$, below T_c, $\eta/s \sim N_c^2$.

What does v_2 depend on? follow Gombeaud+Borghini+Ollitraut

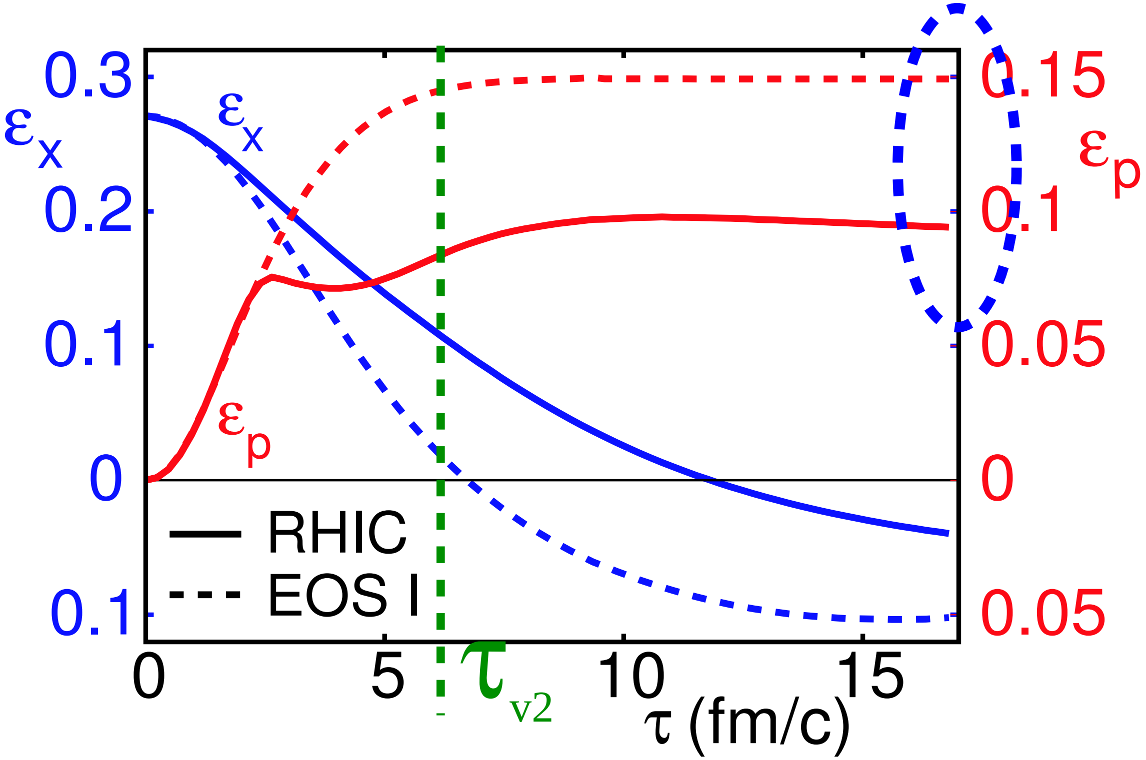
Eccentricity $\left. v_2 \right|_{ideal} \propto \epsilon + \mathcal{O}\left(\epsilon^2\right)$ since ϵ small and dimensionless

Knudsen number $\frac{v_2}{\epsilon} = \left.\frac{v_2}{\epsilon}\right|_{ideal} \left(1 - \mathcal{O}\left(1\right) Kn\right) \sim \left.\frac{v_2}{\epsilon}\right|_{ideal} \left(1 - \mathcal{O}\left(1\right) \frac{\eta}{s} \frac{c_s}{TR}\right)$

speed of sound From what we know of shock-wave expansion

$\left.\frac{v_2}{\epsilon}\right|_{ideal,\tau\rightarrow\infty} \sim c_s$ and $\tau \rightarrow \infty$ is an OK approximation since anisotropy in flow saturates quickly wrt lifetime of system

Beyond linearity... v_2 saturates!,on a scale τ_{v2}

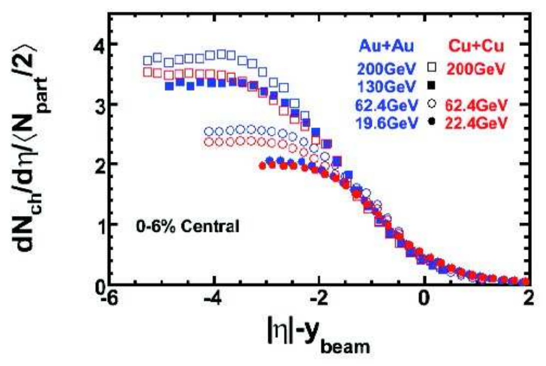


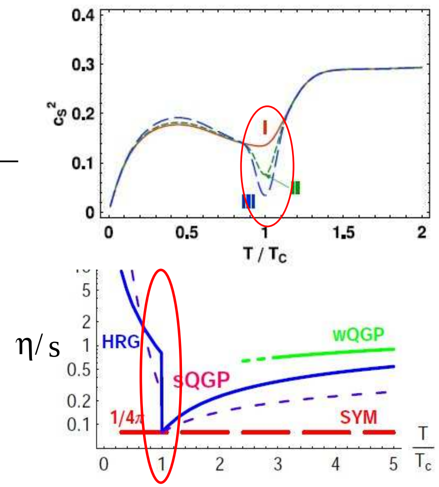
+Freezeout effects

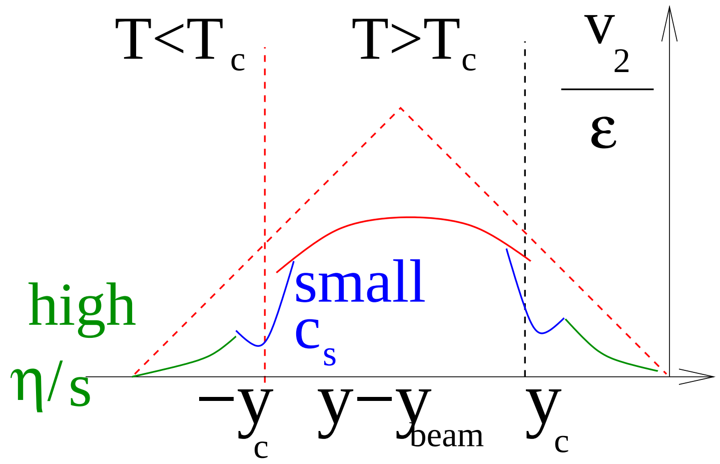
U. Heinz
P.Kolb
nucl−th/0305084

If you dont change η/s but increase lifetime, you generally get same v_2/ϵ.

Putting everything together...

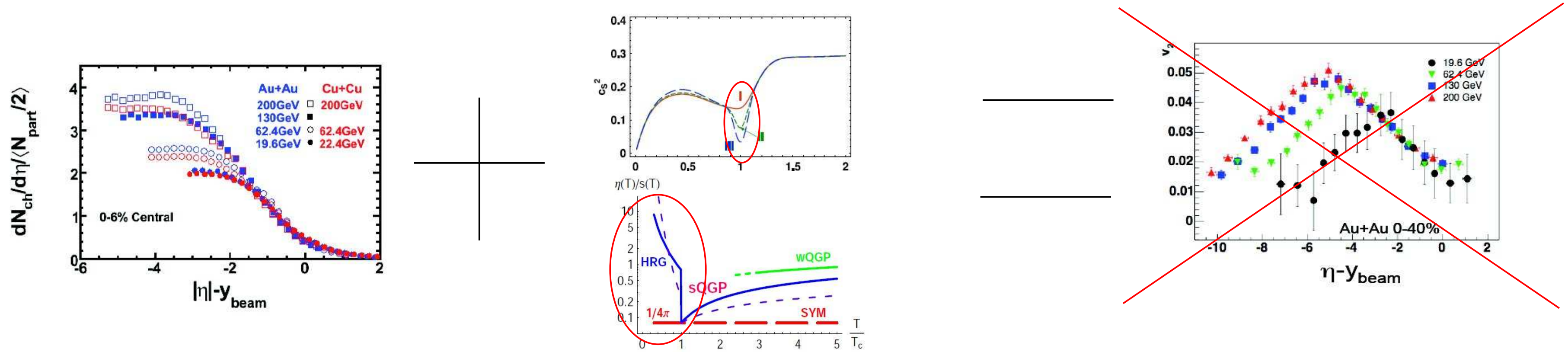






$$\frac{v_2}{\epsilon} \sim \underbrace{c_s}_{Dips@T_c} \left(1 - \mathcal{O}(1) \underbrace{\frac{\eta}{c_s s}}_{Changes@T_c} \underbrace{\frac{1}{TR}}_{Smooth\ \ with\ \ y} \right) \underbrace{\tanh\left(\frac{\tau}{\tau_{v2}}\right)}_{saturation}$$

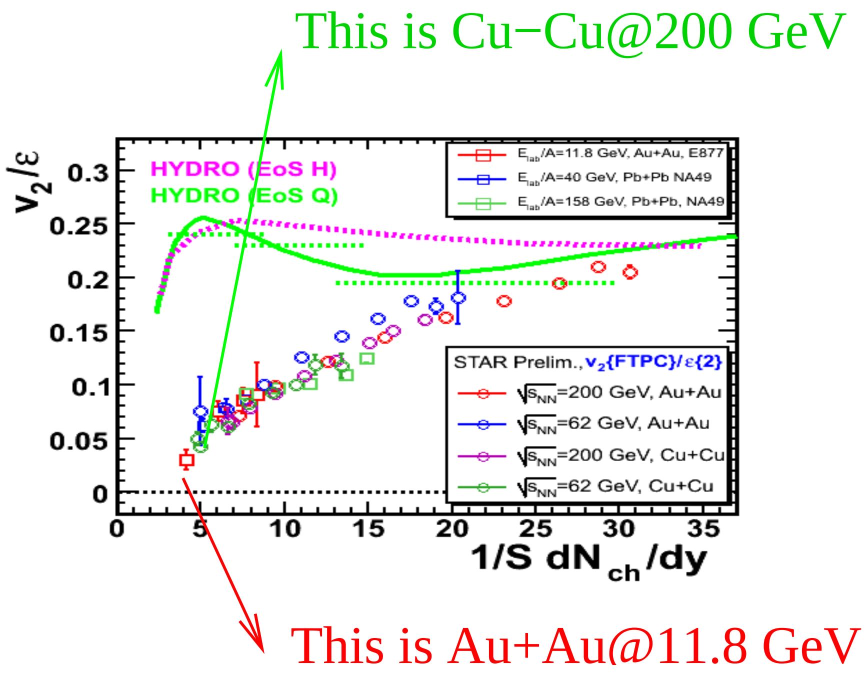
To describe universal fragmentation in $dN/d\eta$, T changes smoothly with η , R independet of it. This destroys universal fragmentation of v_2/ϵ !



It is difficoult to see how any initial condition describing universal fragmentation in $dN/d\eta$ with an an EoS and set of transport coefficients containing T_c can also describe universal fragmentation in v_2/ϵ

For this, One would have to have non-scaling in initial conditions where the effects of longitudinal flow and entropy production at high η/s would "miraculously" cancel out. This is unnatural (see earlier def.)

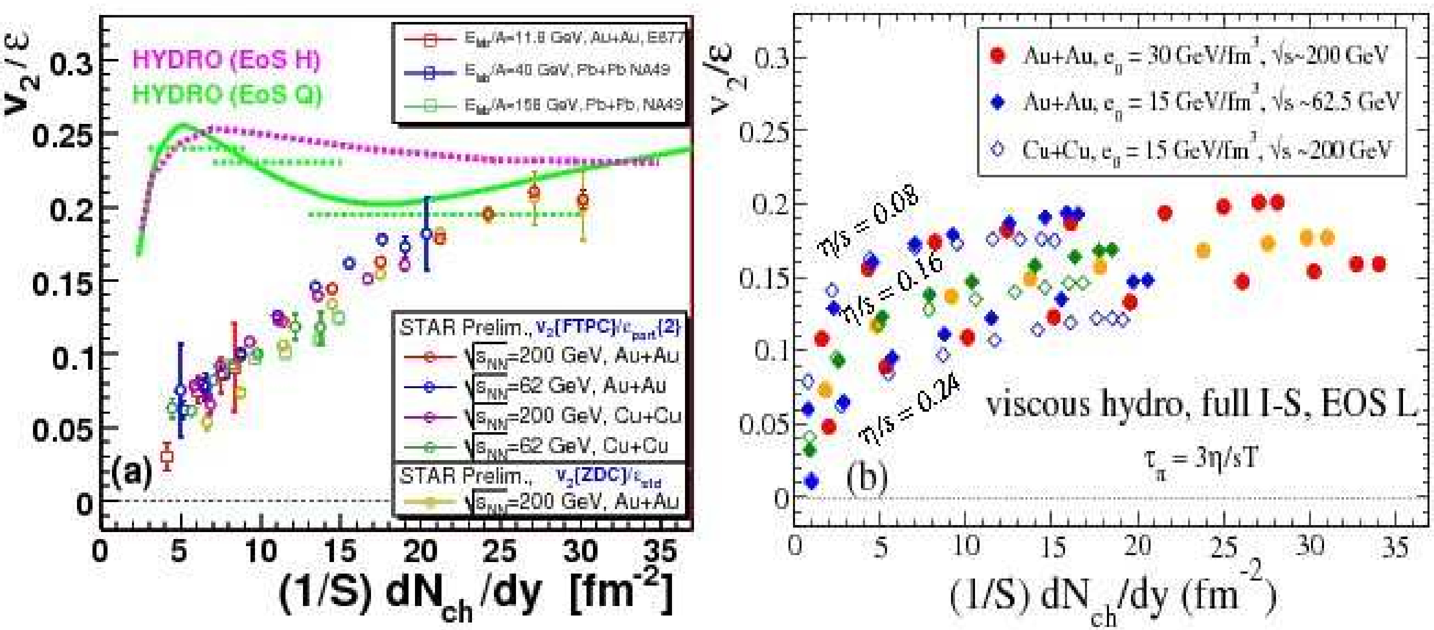
For lower energies... Integrating over all rapidity...



v_2/ϵ is the same for a given $\frac{1}{S}\frac{dN}{dy}$, even if the energy is very different!!!!

Expected from $v_2 \sim \epsilon \frac{dN}{dy}$+universal fragmentation, but...

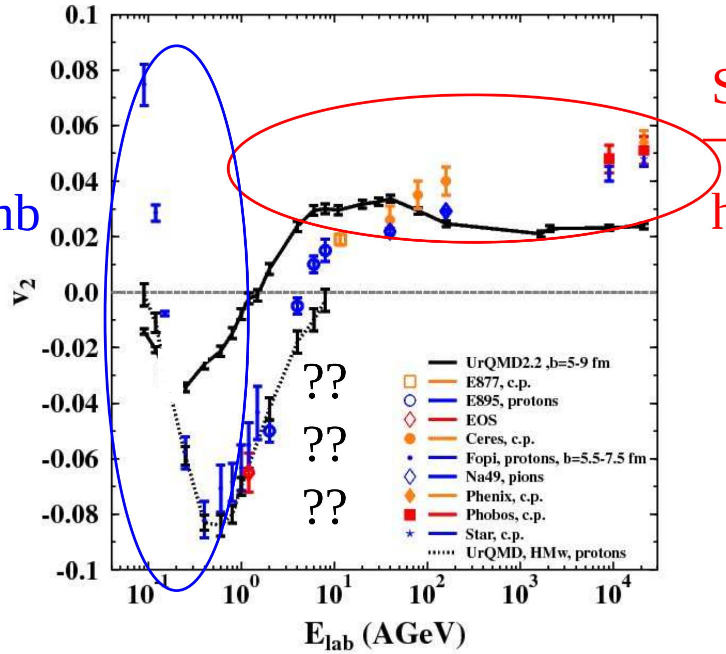
simulation
by
U.Heinz
H.Song



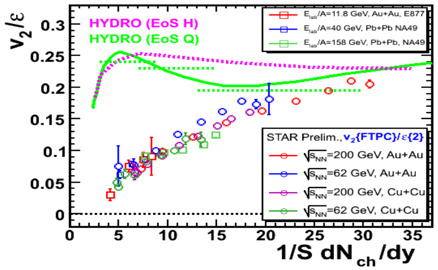
same η/s +Bjorken-type Initial conditions at from AGS to RHIC

Lower energy scans can help!

Coloumb barrier



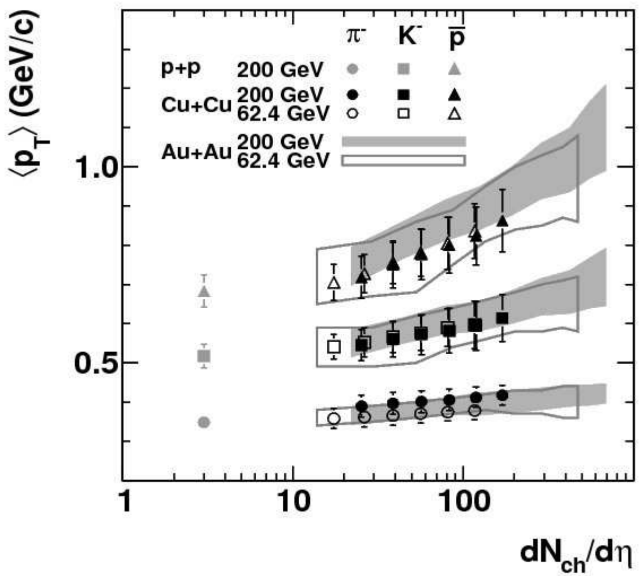
Scaling here



- When does this scaling turn on?
- What else scales?

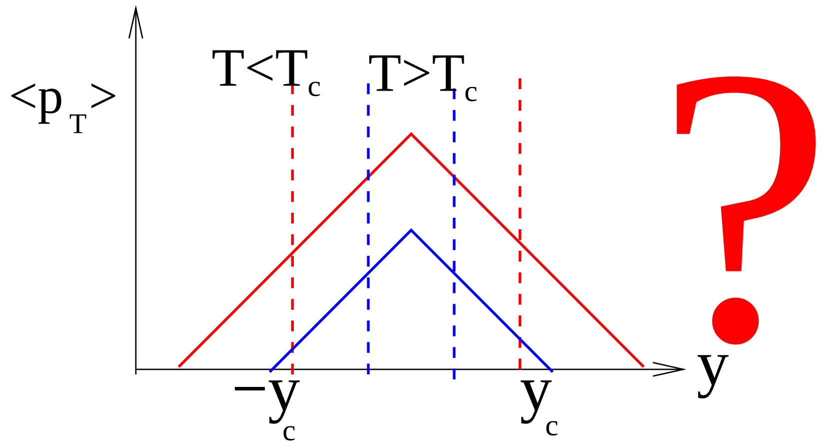
Experimental: Do observables <u>dependent on flow</u> know about EoS, η/s, or do they just universally fragment?

- $\langle p_T \rangle$ ... universal fragmentation?

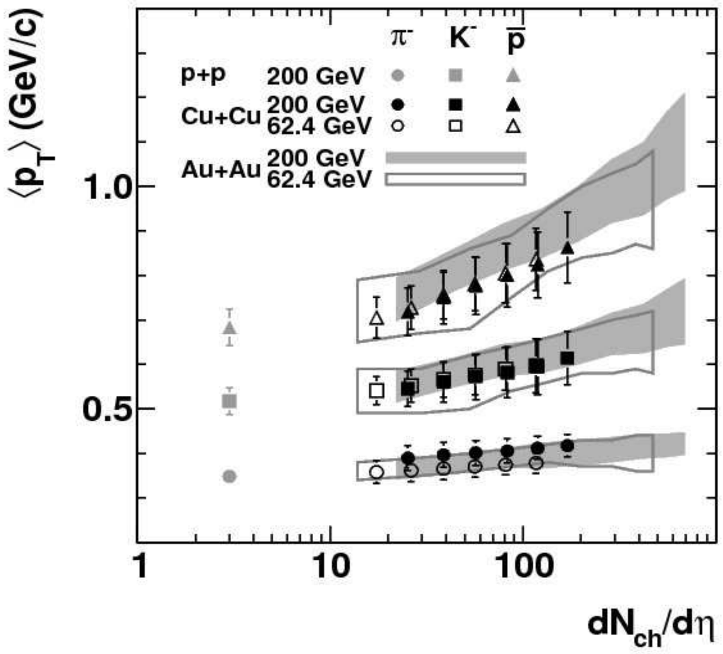


STAR collaboration

1008.3133



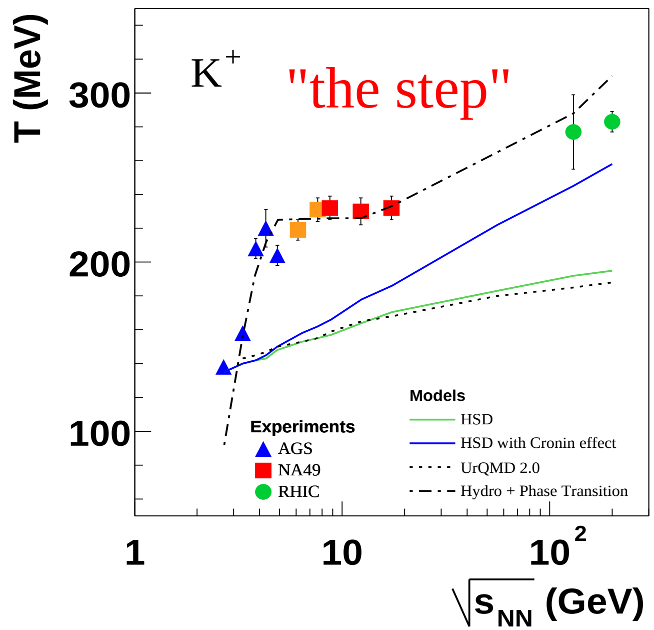
...or the step in rapidity?



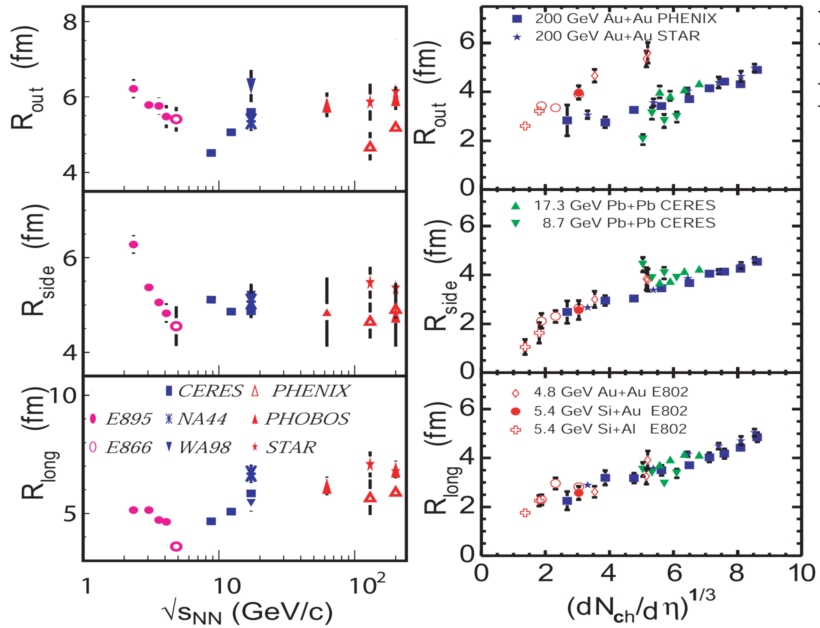
STAR
collaboration

1008.3133

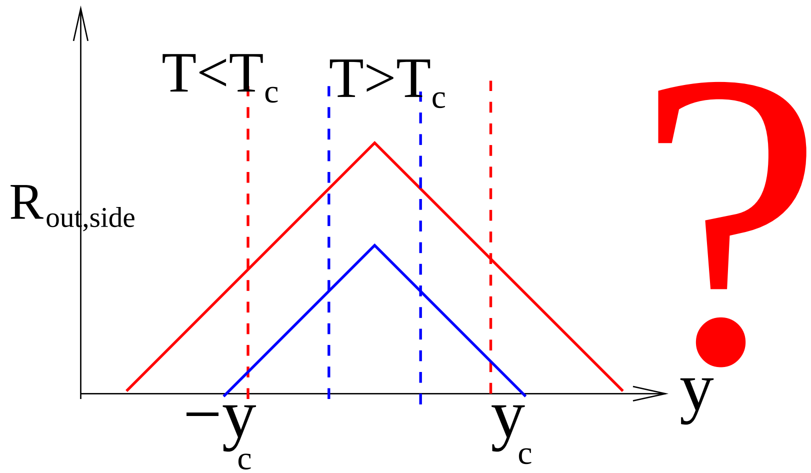
vs



- HBT $R_{o,s}$ any softening in EoS?



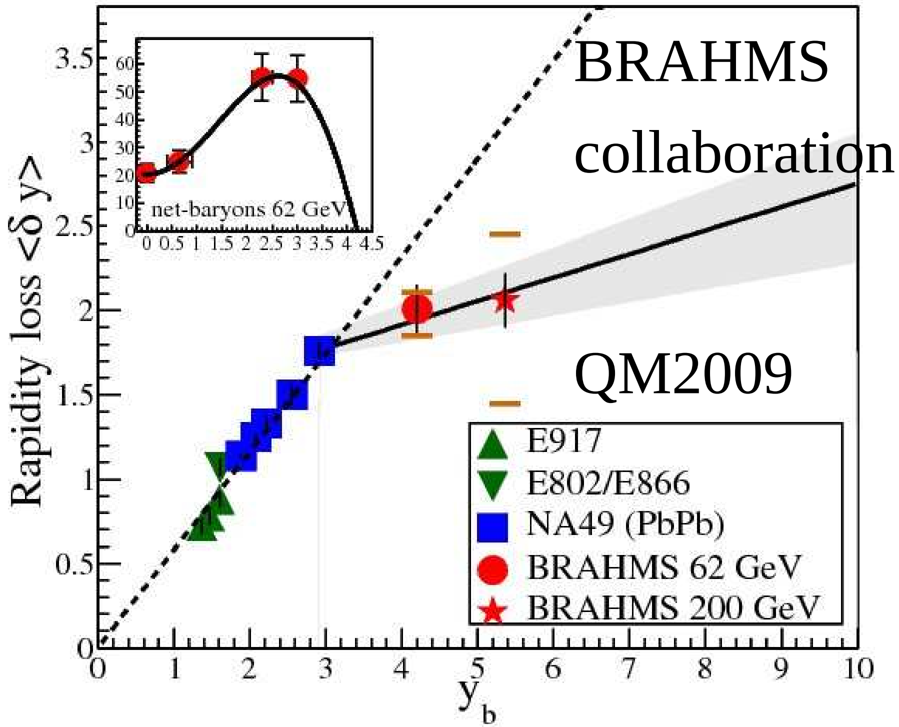
M.Lisa
nucl−ex/0512008



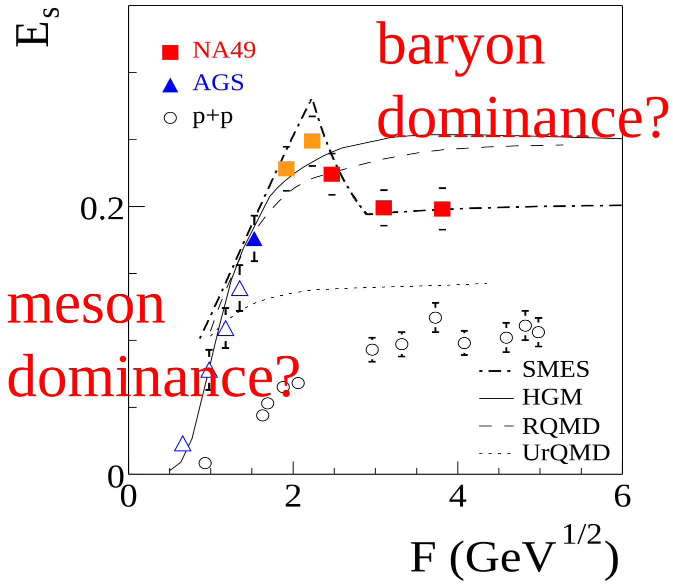
y-integrated scaling of HBT radii very simple (consistent with "fast break-up at critical energy), but some structure with R_o at low energy. Hydro explains this by a combination of factors (S.Pratt,0907.1094)
What happens locally in rapidity?

- Particle species (No limiting fragmentation for baryons. Is appearance of scaling connected to "horn" baryon/meson anomaly?)

$$\langle \Delta y \rangle = y_{beam} - \langle |y| \rangle_{B-\bar{B}}$$



vs



Theory: Hydrodynamic assessment of scaling with non-boost invariant initial conditions: How serious are the effects elucidated here

- Scaling naturalness should be demanded of any model, especially "complicated" ones
- New ideas for viscosity measurements...

v_2 fluctuations (http://arxiv.org/nucl-th/0703031)

Initial eccentricity fluctuations If hydro not turbulent

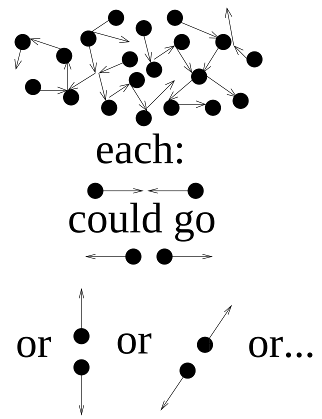
$$\delta v_2 = a_1 \delta\epsilon + a_2 (\delta\epsilon)^2 + ...$$

(chaos would imply something like $\delta v_2 \sim \delta\epsilon e^{\tau} \sim \delta\epsilon e^{dN/dy}$)
Boost-invariant simulations show that $v_2 \propto \epsilon$ (2nd order coefficient small) so

$$\frac{\delta v_2}{v_2} = \frac{\delta\epsilon}{\epsilon}$$

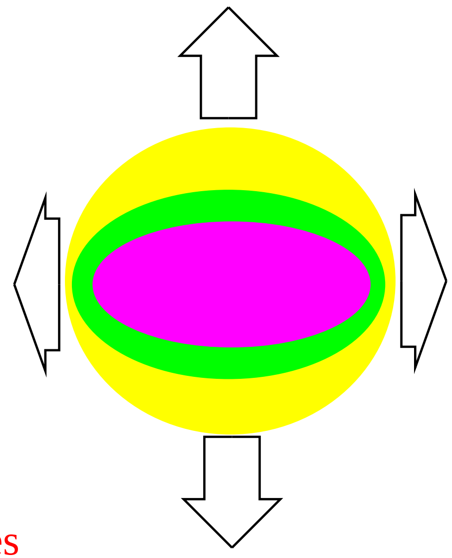
but this is not the only source of fluctuations!

A "dust"



BIG fluctuations
in all collective observables

A "fluid"



deterministic!

finite mean free path

Imperfection of fluid $\Rightarrow$ fluctuation in momentum observabled due to <u>random</u> nature of microscopic dynamics

How big?

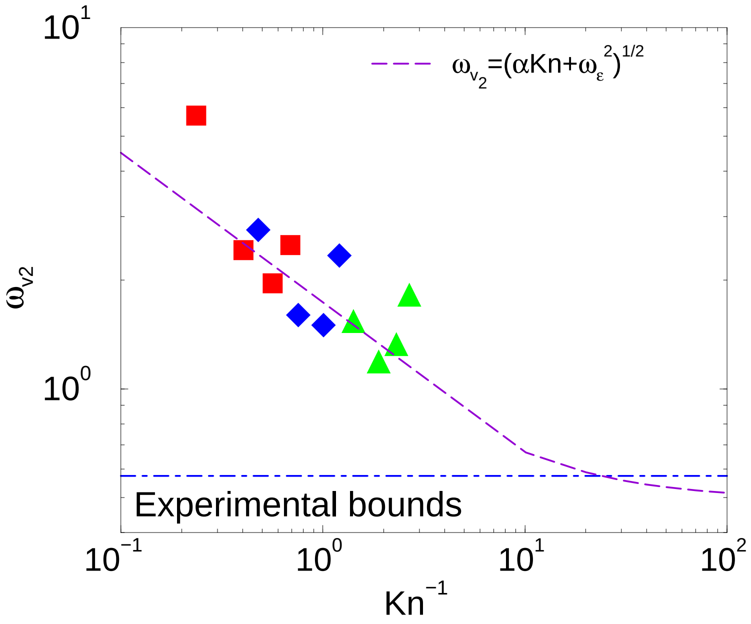
Assume no correlations between initial state and "dynamical" fluctuations, and "Poissonian" scaling of fluctuations with inverse Knudson number

$$\left\langle (\Delta v_2)^2 \right\rangle = \sqrt{\langle (\Delta \epsilon)^2 \rangle + \frac{\alpha}{N_{collisions}^2}}$$

$$\left\langle (\Delta v_2)^2 \right\rangle = \sqrt{\frac{\langle (\Delta \epsilon)^2 \rangle}{\langle \epsilon \rangle^2} + \beta \frac{l_{mfp}}{L}}$$

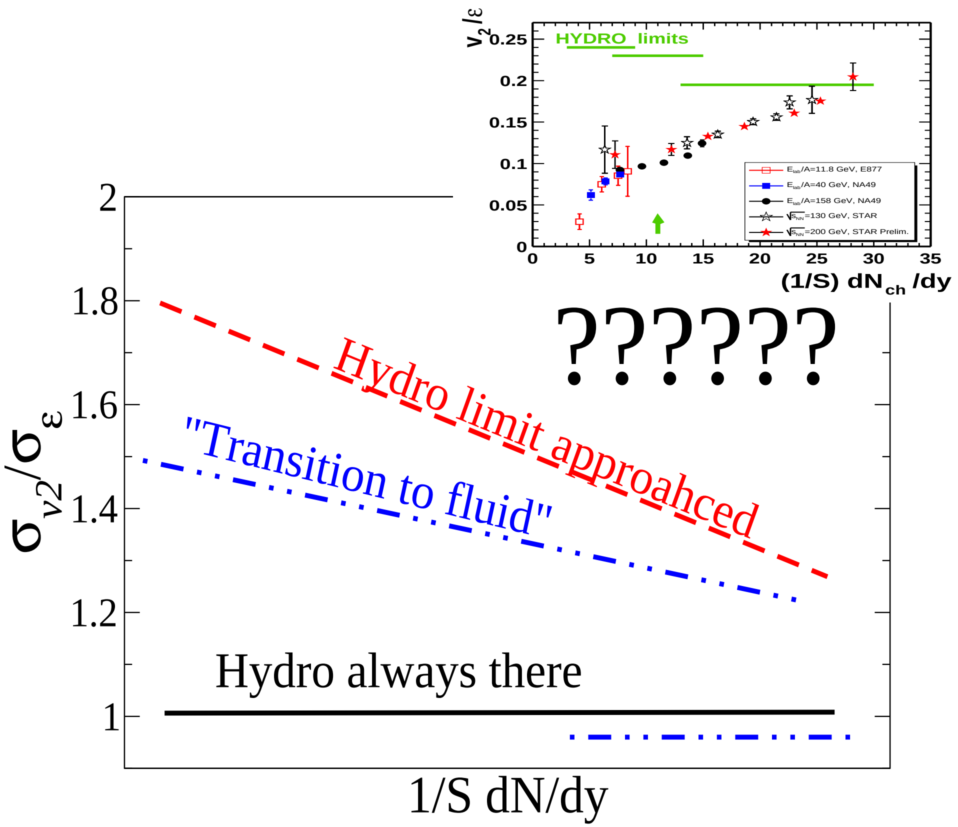
use molecular dynamics to tune β and mean free path.

uRQMD with "tuned" σ (as a toy model)



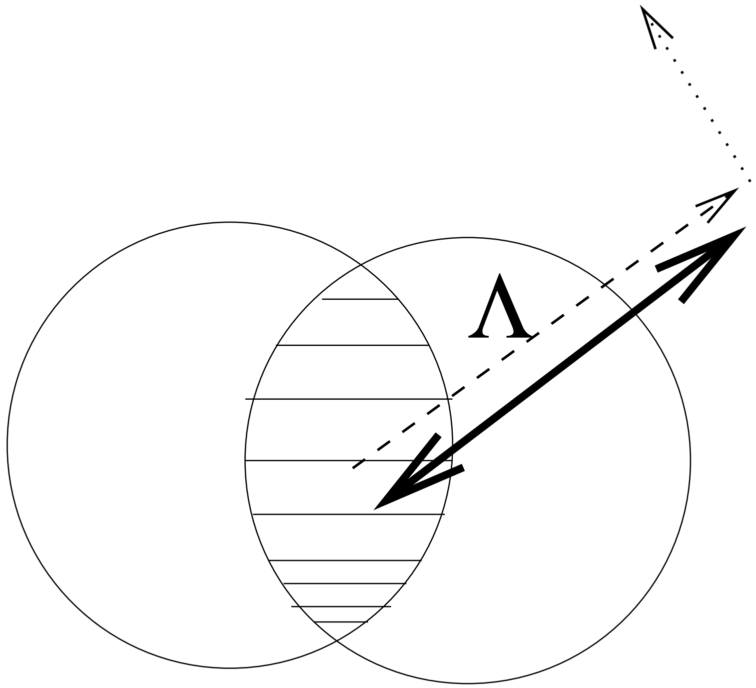
work in progress (comparison with partonic QMD), but in principle could be a powerful indicator of good fluidity.

Rise of $\frac{\left\langle (\Delta v_2)^2 \right\rangle}{v_2}$ at lower $\sqrt{s}$ <u>ABOVE</u> $\frac{\left\langle (\Delta \epsilon)^2 \right\rangle}{\epsilon}$ $\rightarrow$ transition to fluid?



An energy/size scan of the v_2 fluctuation would help clarifying weather the "perfect fluid" is transition,approach,or is always there! Polarization and perfect fluidity

(P.Hoyer, PLB187 162 (1987) (a pretty prophetic paper): In a perfect fluid, because of local isotropy, no polarization production is possible. Hoyer suggested measuring production plane since its $\neq 0$ in p-p

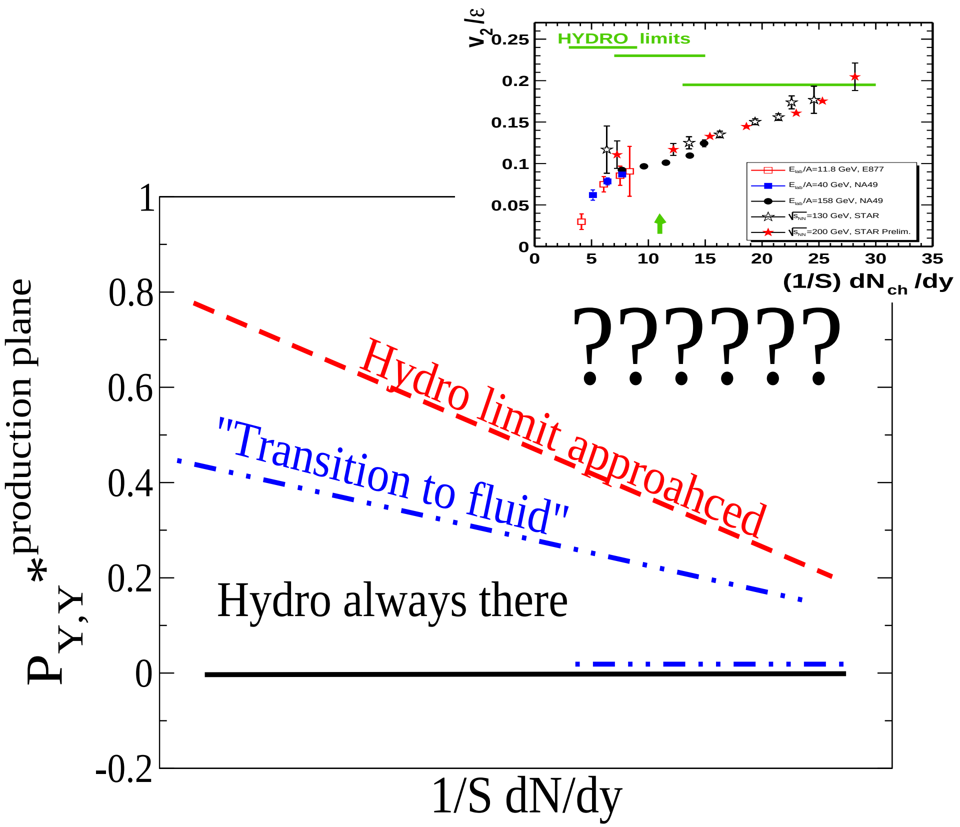


So far measured at AGS only, and compatible with $p - p$.
Order of magnitude estimate for mean free path correction and local vorticity:

$$P_q^i \sim \tanh\left[\frac{l_{mfp}}{T}\left(\epsilon_{ijk}\frac{d\left\langle \vec{p}_i \right\rangle}{d\vec{x}_j}\right)\right]$$

Sudden jumps in polarization observable in $\sqrt{s}$ OR A $\leftarrow$ transition!

Problem:This probes the mean free path,potentially, at the very end including hadronic phase. A locally isotropic QGP followed by an succession of elementary hadronic collisions could produce polarization (Barros and Hama, 0712.3447)
Zero result $\rightarrow$ "perfect fluid",fast f.o.
Sudden transitions with $\sqrt{s} \rightarrow$ transition to fluid



Potentially this is <u>exactly</u> what we are looking for! A signature for fluidity <u>not</u> requiring a large system!

Polarization (GT et al,PRC76:044901,2007)

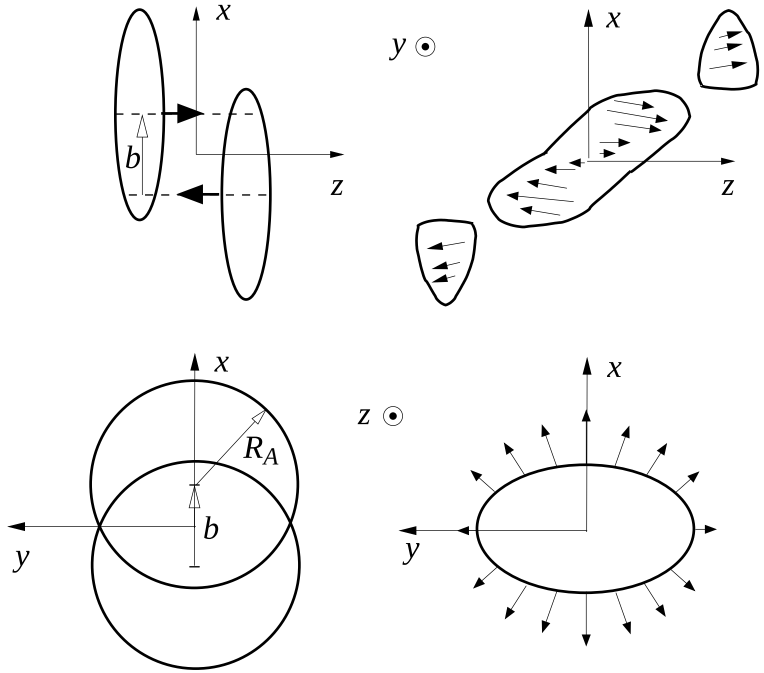
Bad news: Polarization is a mess
many factors, at all stages of collision, contribute to the final observable

Good news: Polarization is a

$$m\vec{e}ss = \begin{pmatrix} mess \\ mess \\ mess \end{pmatrix}$$

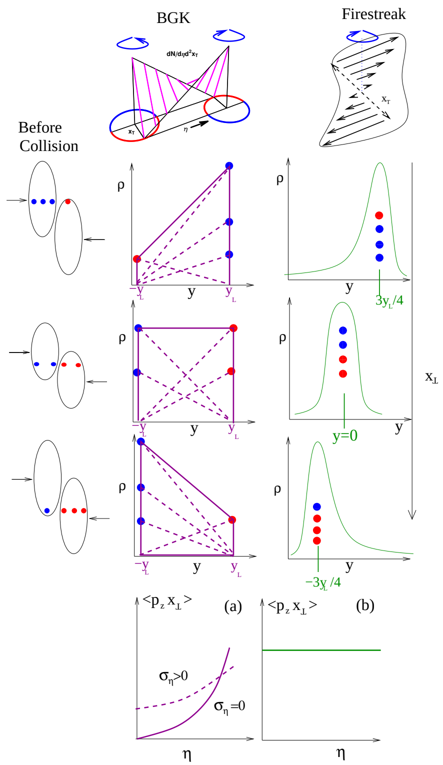
Many directions possible. Comparing directions $\rightarrow$ understanding physics

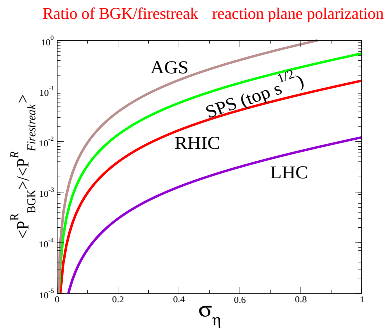
Global polarization and initial conditions (Liang et al,PRL, nucl-th/0410079)



Initial angular momentum in non-central collisions ⇒ quark polarization due to QCD spin-orbit interactions ⇒ hadron polarization due to local hadronization (coalescence? angular momentum conservation?)

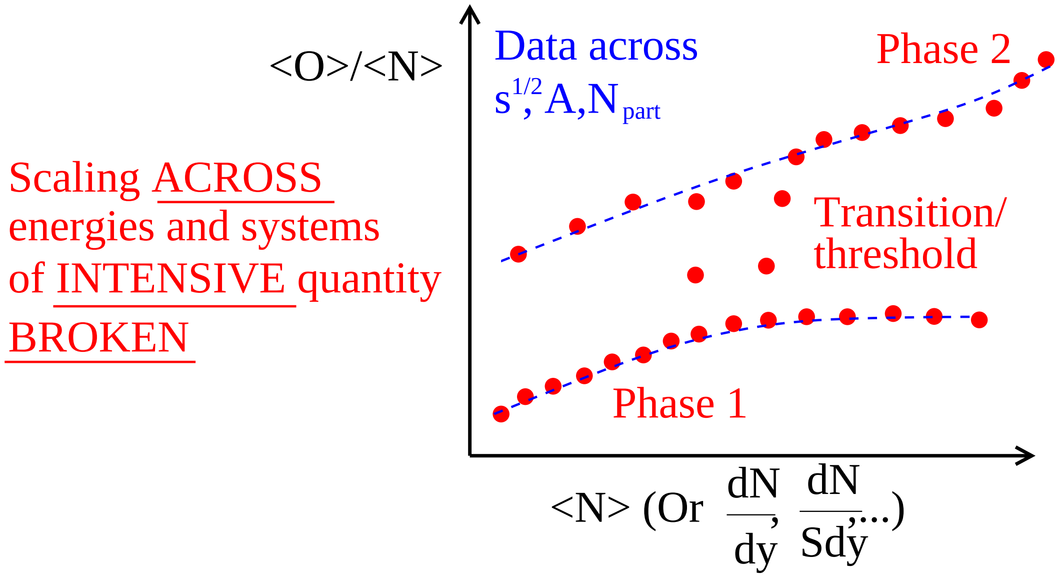
But signature depends crucially on <u>localization</u> of produced partons in z (Firestreak/Bjorken initial condition).





Probe of “Bjorken” conditions, if not of hydro. Small mfp could spoil it.

(very few!!!) conclusions



This would be the ideal QGP signature... and we are not there yet! There are good reasons to fear that such a signature is unrealistic. Certainly, jet suppression and elliptic flow do not qualify. But the scaling suggests they might at some point, if we find where/how it breaks

(very few!!!) conclusions

- Simple scalings have been found to hold for $\frac{dN}{dy}, \left.\frac{dN}{dy}\right|_{y=0}, v_2$

  $\frac{dN}{dy}$ natural within our understanding of QCD

  $\left.\frac{dN}{dy}\right|_{y=0}$ is also natural, provided interesting dynamics happens in the overlap region (non-pQCD)

  v_2 unnatural within hydrodynamics, alternatives need to be looked into (scaling more natural in a weakly coupled system)

- Experimental measurements of limiting fragmentation in other soft observables ($\langle p_T \rangle$, $R_{out,side}$) could help clarify the situation.

- 3D viscous hydro needed to make these statements more quantitative