Quark Gluon plasma, Heavy ion collisions, Perfect liquids and all that

Giorgio Torrieri

HIC for FAIR
Helmholtz International Center

FIAS Frankfurt Institute for Advanced Studies

All questions to torrieri@th.physik.uni-frankfurt.de

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History:

The quark phase transition <u>before</u> quarks and gluons (and why its relevant now)

What we knew about hadrons before quarks were invented

- There seemed to be infinitely many of them, more and more.
  "Boot-strap ideas" where there is no fundamental particle, but all particles are "made of each other", were popular

- Relation between mass and spin seem to be there (Regge trajectory), roughly $M^2 \sim J$. THis is similar to the vibrating modes of a relativistic string

- Particle slope looked exponential, suggesting that they are close to thermalized. The fact that interactions are strong is in agreement with this, since particles thermalize quickly.

Thermal model of particle production

Fermi Assumed number and momentum of particles would be distributed according to phase space (solvable exactly if pions were massless)

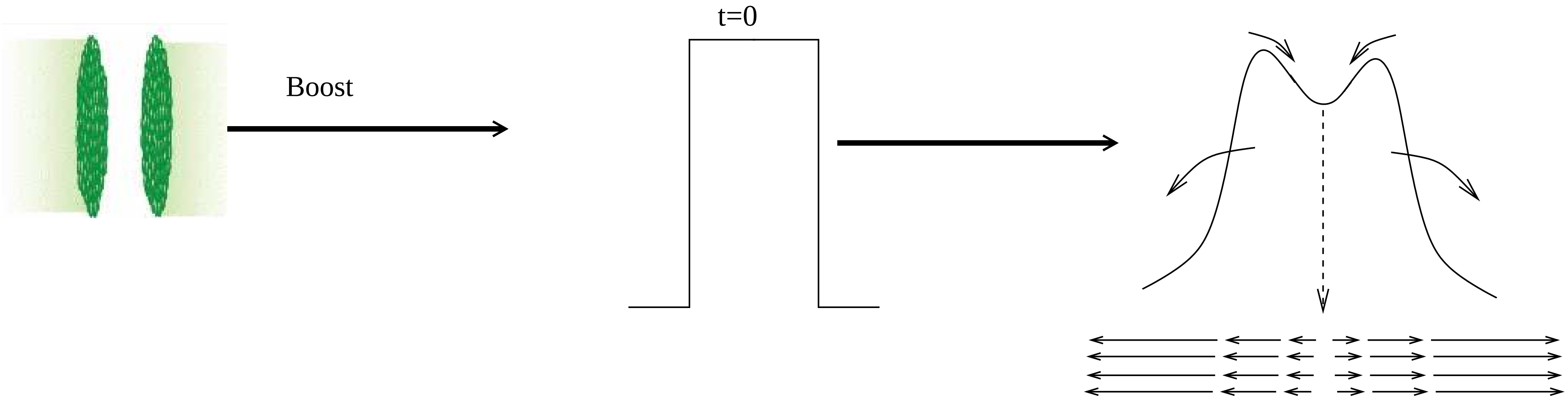
$$\Sigma\left(E_i, \vec{p_i}\right) \propto \int \left[\prod \frac{d^3 p_i}{\sqrt{p_{ix}^2 + p_{iy}^2 + p_{iz}^2}}\right] \delta\left(E_{total} - \sum_i \sqrt{p_{ix}^2 + p_{iy}^2 + p_{iz}^2}\right)$$

$$\sim \exp\left[-\frac{E}{\langle E \rangle}\right]$$

where $\langle E \rangle \sim 3T . T \sim \left(\sqrt{s} * A/\gamma\right)^{1/3}$ But this meant that higher energy collisions looked "hotter", while temperature did not seem to go up that strongly with energy

Landau Realized this could be explained by assuming system is a fluid that expands from initial density and produces particles at a critical density. He solved problem of two Lorentz-contracted "Pancakes sticking together", and expanding as a fluid with the ideal gas equation of state. Considering only longitudinal flow

$$\frac{\partial T_{tt}}{\partial t} - \frac{\partial T_{zz}}{\partial z} = \frac{\partial \left(\gamma^2(e+p)+p\right)}{\partial t} - \frac{\partial \left(\gamma^2 v_z^2(e+p)-p\right)}{\partial z} = 0$$



Together with equation of state ($e = 3p$) and initial conditions ($e(t = 0) = \Theta(\pm z_0 = 1fm m_p/\sqrt{s}, v_z(t = 0) = 0$ non-linear but approximately solvable. If $T_{freeze-out}$ fixed, then so is $\langle E \rangle$ of particles. But

$$N \sim V_{freezeout} T^3 \sim \sqrt{s}^{4/3}$$

(Not really realized experimentally)

What does thermodynamics of all Hadrons look like? $T_{Hagedorn}$:
Total phase space weight $\leftrightarrow$ sum of all hadron states

$$\Omega(V,E) = \sum_{N=1}^{\infty} \frac{1}{N!}\delta^4\left(p - \sum_i p_i\right) \prod_{i=1}^{N} \rho(p_i, m) d^4 p_i$$

The Equation of state of infinitely many hadrons, and the higher a hadron's mass, the higher its spin, and hence degeneracy, $m^2 \propto J$
Above a certain energy, impossible to distinguish highly excited hadron from "fireball" of hadrons. Fireballs are made of fireballs are made of fireballs

$$\Omega(E) \propto \rho(m = E)$$

One can show that only possible $\rho(m))$ satisfying these is exponential

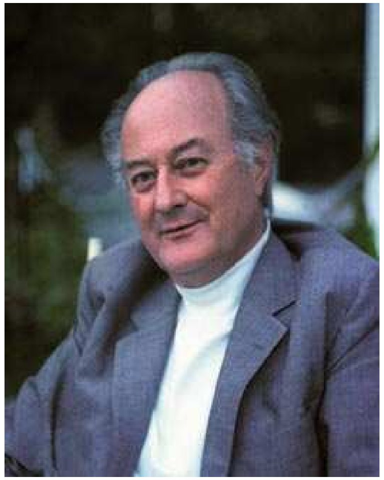
$$\rho(m) \sim \exp(m\beta_H)$$

But then Grand Canonical partition function hehaves funny!

$$Z(V,T) = \int dm \exp\left[\beta_H m - \frac{E}{T}\right]$$

at $T > \beta_H^{-1}$ this <u>diverges</u>!

Using these arguments, before quarks were discovered Hagedorn realized Hadronic matter should "boil": It should be subject to a phase transition, degrees of freedom should change.



Our result does not apply only to Heaven and Earth ~ it also constitutes the first essential progress in Hell research, since Dante ' s beautiful pioneer work (4): Hell being the best of all possible ones, it is clear tha t its hottest parts attain the temperature To ~ 1 . 3 " 1 0 ~2 ~ (*).

(4) DANTE ALIGHIERI: Comedia, preprint (Foligno, 1472).

(') And whosoever does not believe this theory, can go there and check it.

R.Hagedorn,Nuovo Cim.A56:1027−1057,1968.

Youve heard the QCD lectures... how does this old stuff fit in? surprisingly well!

- It has been proven that bound states in $SU(N_c)$ look very much like Regge trajectories. Recently, the existance of a Hagedorn temperature was demonstrated (http://arxiv.org/abs/0901.0494)

- AdS/CFT (See later!)

A post-QCD introduction

What we learned so far (about QCD)

- The fundamental constituents are "Quarks", charged with "color"
  But all we see are colorless quark composites, Hadrons
- Separating free quark from hadron is impossible... Force at large distances $\geq \Lambda_{qcd} \sim 1fm \sim 1GeV$ behaves as a string, which "breaks" when quark pushed with enough energy to create a $q\overline{q}$ pair
  (Mass of hadrons, other than π, set by Λ_{QCD} (up to $O(1)$ corrections)
- In this regime, force is strongly coupled (non-perturbative). So this effect not fundamentally calculated/understood
- For high $> 1GeV, \Lambda_{QCD}$ momentum transfer/short distance, "simple": String disappears at high energy/shorter distances, quarks behave in way that can be calculated from fundamental theory.

What it means

The string holding quarks together is <u>not</u> a "real" force created by the quarks, but a manifestation of the vacuum between the quarks, a collective effect of the infinity infinitely fluctuating quarks and gluons (No one talks about spin chains as a "force"

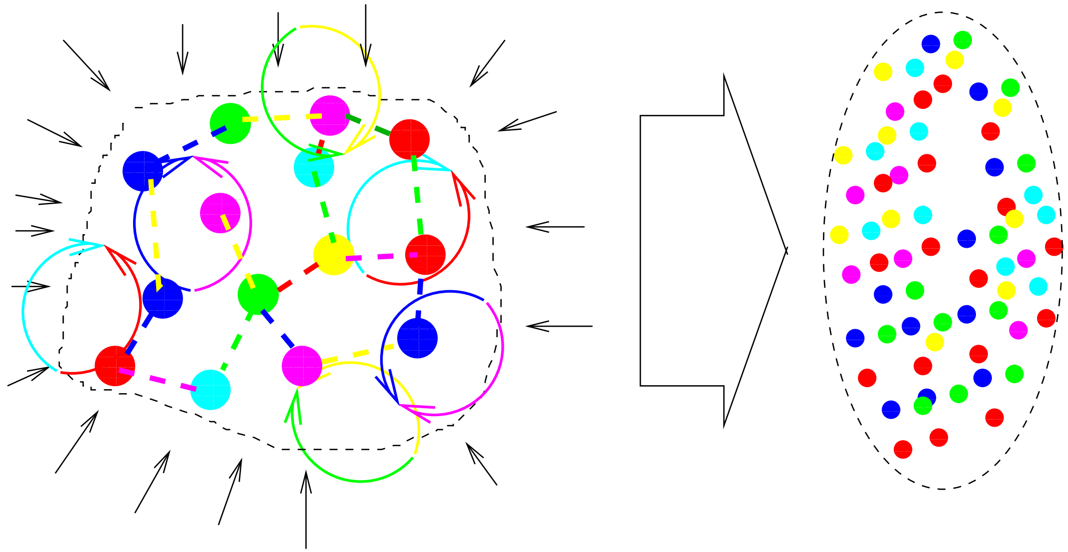
At small distance scales ($\sim$ high momenta a la Heisenberg), this collective effect does not exist (By Asymptotic freedom quantum fluctuations "drowned out")

Since at low energy system is non-perturbative, it or transitions to "high energy" from it <u>not</u> understood.

Let's do the "next best thing": increase Temperature/Quark density/mean collision momentum $\rightarrow$ decrease quark separation

- Small separation $\rightarrow$ no room for chain
- Large temperature $\rightarrow$ more average quark energy
  Quantum fluctuations typically low momentum
  IF a quark carries an energy much higher than the scale of quantum effects, it will "push through" them, much like a fast speedboat pushes through the waves on a choppy sea

D. Gross, D. Politzer and F. Wilczek proved this from first principles (Quantum Chromodynamics). That's why they got the Nobel prize in 2004!



High-temperature nuclear matter → a Quark-Gluon-Plasma, (QGP), where quarks move freely and interact weakly. Properties can be calculated from theory.

How high is this temperature?

- "Back of the envelope" ($R_{hadron} \sim \rho_{hadrons}^{-1/3}$), or equivalently $\Lambda_{QCD} \sim T^2$:
  200 MeV
- Hagedorn limiting Temperature: About the same
- Numerical (Lattice QCD) simulations:
  $\sim$ 190 MeV (Not bad)

That's $\sim$ 1 trillion C (Electron mass = 0.5MeV)
(h=c=k=1 $\Rightarrow$ 200 MeV = $(10^{-15}m)^{-1}$)

- How does a system go from the "cold" state to the "hot state"?
  Is it a smooth transformation or a phase transition (like ice $\Leftrightarrow$ water) where at a critical temperature the proprerties of the system discontinuosuly change? (Latent heat,etc.)
  We don't know!

- What does the Quark-gluon plasma look like? Is it an ideal gas or a strongly interacting liquid? What is it's equation of state? Viscosity? Diffusion properties?
  We don't know... except perhaps in the "infinitely high" temperature limit.

So we don't know a lot of things do we care?

Is this important? YES!

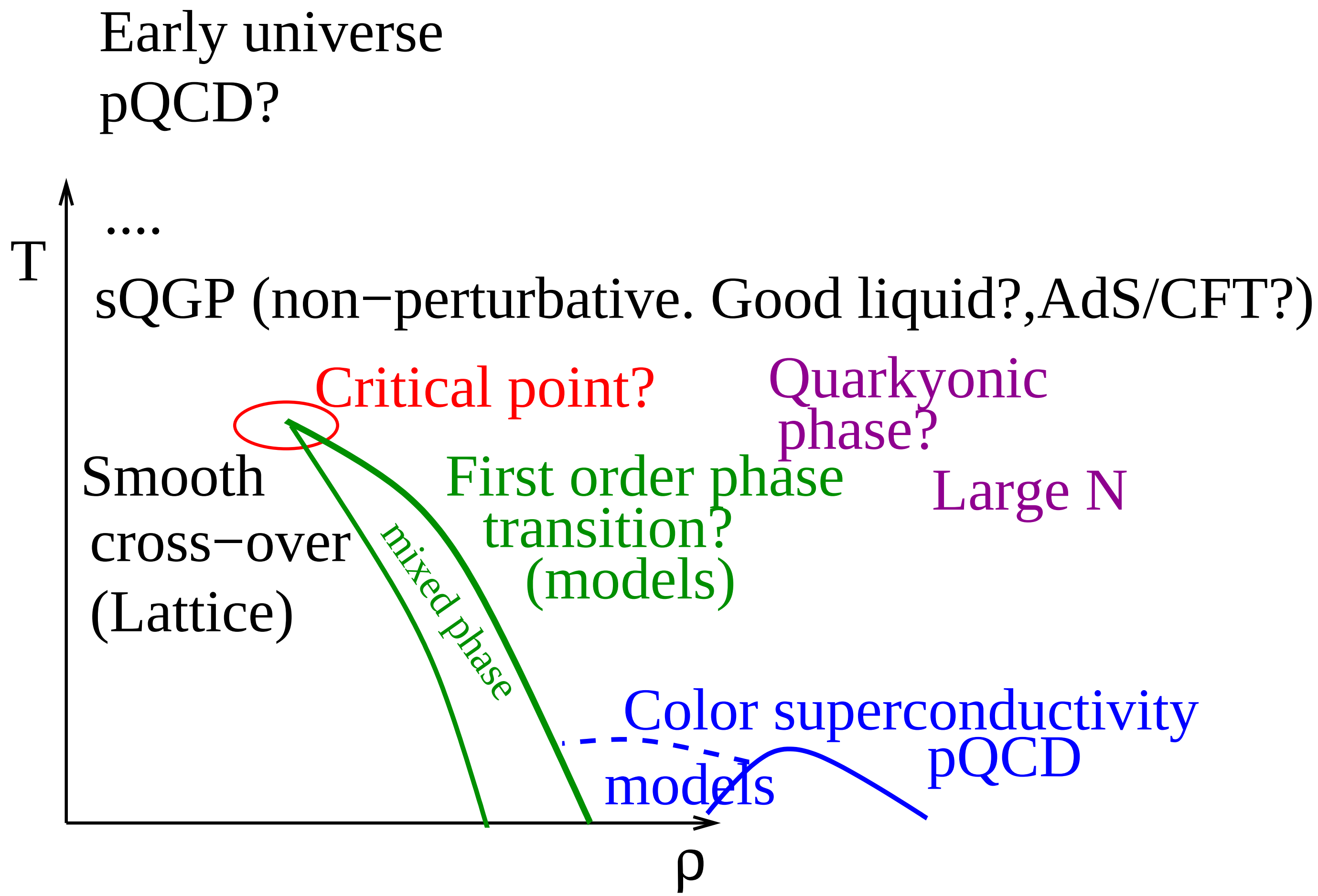
- The early universe was a quark gluon plasma
  Understanding quark-gluon-plasma $\Leftrightarrow$ understanding the big bang!

- Observing the quark-gluon-plasma phase transition gives us a window to study experimentally
  - The structure of the quantum vacuum
    A not-well understood and fascinating field
    I mean... the vacuum, empty space, behaves just like some kind of "material"... In fact, as a superconductor!
  - The structure of strongly interacting systems
    (A very general class of mostly unsolved issues)
  - Confinement/the nuclear force

What we think we know, and how...

Our current undestanding

"?" denotes lack of it!

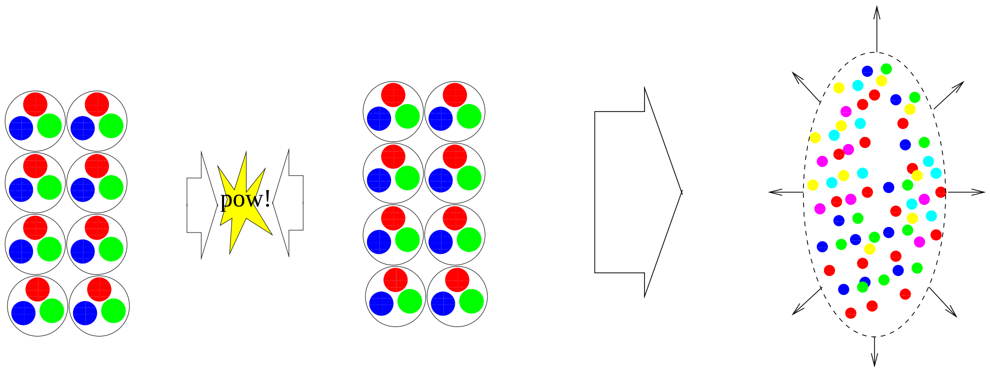


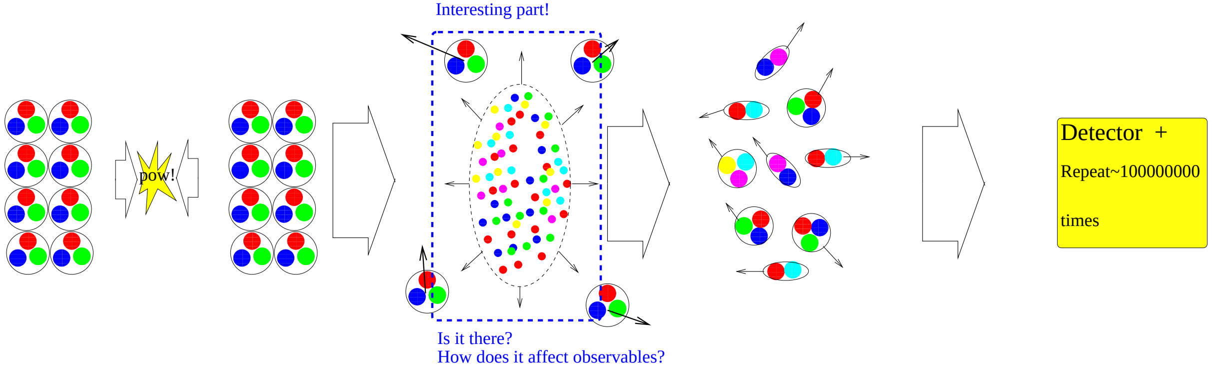
But how do we study this experimentally?

We need compressed nuclear matter, so let's collide 2 large nuclei together! How large is large? Well, large enough for concepts like temperature to make sense. ie, No one knows, and well return to the question again

Analogy: creating water in the cold by squeezing 2 snowballs together.

Problem: At the end of the process, the "water" becomes "snow again".



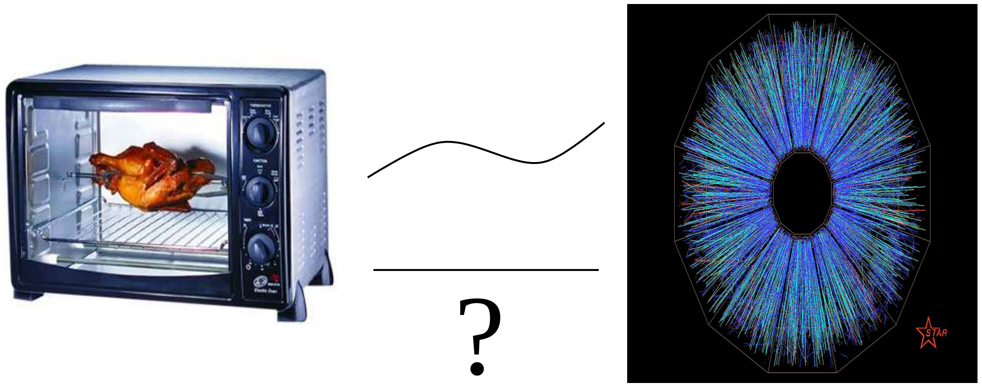


- How do we know a QGP was created?
  Is the circled region in the middle of picture actually there?

- How do we know how long it lasts, and how can we extract its properties?

That is the zillion dollar question! And its still unsolved!

The problem in a nutshell...



We are in the process of producing and studying the quark gluon plasma, a phase of matter. And of studying the phase transitions and in general the thermodynamics of strongly interacting matter.

But we are creating a very violent and fast explosion of particles. Phase transitions and thermodynamics in general are adiabatic phenomena, changes happen infinitely slowly!

These experiments are done at:

CERN, Geneva, Switzerland

Super−Proton Synchtrotron (SPS)

Lead−Lead collisions, 4−19 GeV/nucleon

1990: SPS, 30 GeV per nucleon   CERN,Geneva

Brookhaven National Laboratory, New York

Relativistic Heavy Ion Collider (RHIC)

Gold−Gold collisions, 62−200 GeV/Nucleon

(1 GeV=1.9 10^{-10} Joules)

These experiments are done at:

CERN, Geneva, Switzerland

Super−Proton Synchrotron (SPS)

Lead−Lead collisions, 4−19 GeV/nucleon

2007: Large Hadron Collider (LHC) 7000 GeV/nucleon

FAIR (Darmstadt, Germany): ~ 2014

Different energy/systemsizes, but low, $< SPS_{max}$ with modern detectors.

NICA (Dubna,Russia)

Energy/size similar to FAIR, but collider
See rare signatures, and look for "something special" (onset of deconfinement, critical point)
Similar plan in NICA,in Dubna RHIC,SPS also plan energy scans.

Some more ab initio theory

We know what the phases at high/low T look like

At high temperature Its a nearly ideal gas of quarks (3 flavors, spin $1/2$) and gluons (8 types, spin 1, liek photons)

At Low temperature Its a weakly coupled gas of hadrons $(\pi, K, p, n, ...)$. There is an infinite number of them, mass is proportional to spin, all are color-neutral

What do we expect?Well, the alternatives are...

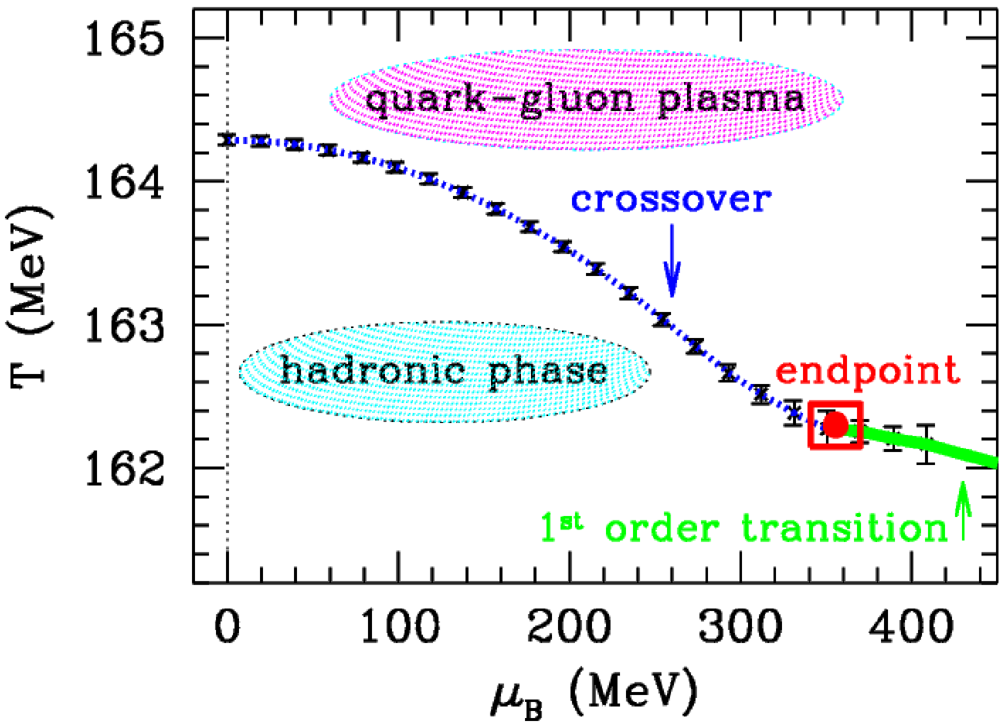
A phase transition (1st order) "order parameter" (OP:density, tension of the string,... has a discontinuity@critical temperature/density. Like water-ice, with a "latent heat" discontinuity at T=0C. Expect bubbling, supercooling, hydrodynamic instability (negative pressure) etc.

A phase transition (2nd order) derivative of OP is discontinuus. eg Spin system Divergence of fluctuations and "large-scale" correlations.

A cross-over Degrees of freedom change continuusly with temperature (like atomic gas-plasma: At all temperatures "some" electrons are free, percentage goes from ~ 0 to ~ 100 as temperature increases

A critical point If in some parts of phase diagram its a transition, in others a cross-over, boundary ($\sim$ 2nd order,water-ice at high p)

The current consesus (not proven!)



How did we arrive at this consensus?

Well, in general, the system experiencing a broken symmetry has to undergo a first or second order phase transition (this can be proven). The opposite, however, is not true: Water-vapour is a phase transition, but no change in symmetries is associated with it.

In QCD, there are not one but two symmetries that are broken badly in some region. Trouble is, they are also nearly but not quite exact

Polyakov Loop/$Z(3)$ is associated with confinement

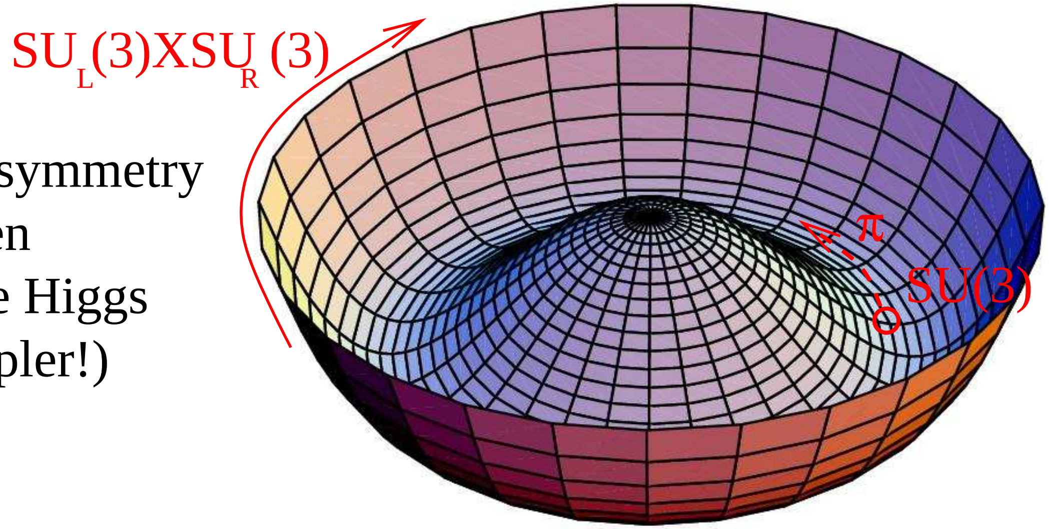
Chiral symmetry Happens at the same time

Chiral symmetry

(A symmetry of QCD, in principle unrelated to confinement)

If quarks were massless, QCD lagrangian would aquire an $SU(3)_L \times SU(3)_R$ symmetry in flavor space. Using these, One can transform eg, $\rho \to a_1, \pi \to f_0$,switch parity , so their mass difference should be $\sim m_q \sim 10 MeV$. Its actually $\sim 250 - 300 MeV$. vice-versamass of $\pi \ll 1 GeV (\Lambda_{QCD})$, the mass of the other particles (associated with the string size).

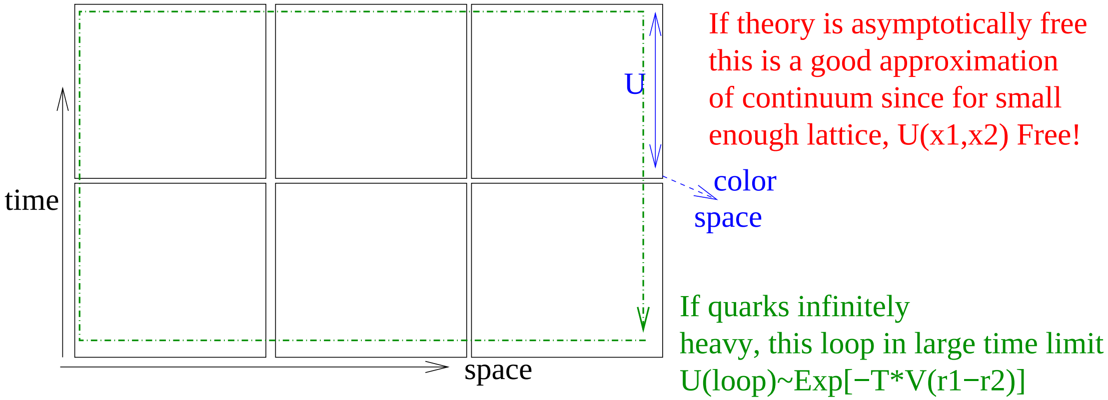
So this symmetry
is broken
(like the Higgs
but simpler!)



The low T QCD ground state is not invariant under $SU(3)_L \times SU(3)_R$, it contains a condensate, "bound state gas", $\langle q_L \overline{q}_R \rangle$. The π is the Goldstone boson of this symmetry (The π is not just a $\langle q\overline{q} \rangle$ bound state, but also a "sound disturbance" of the chiral condensate), so $m_\pi \ll \Lambda_{QCD}$.

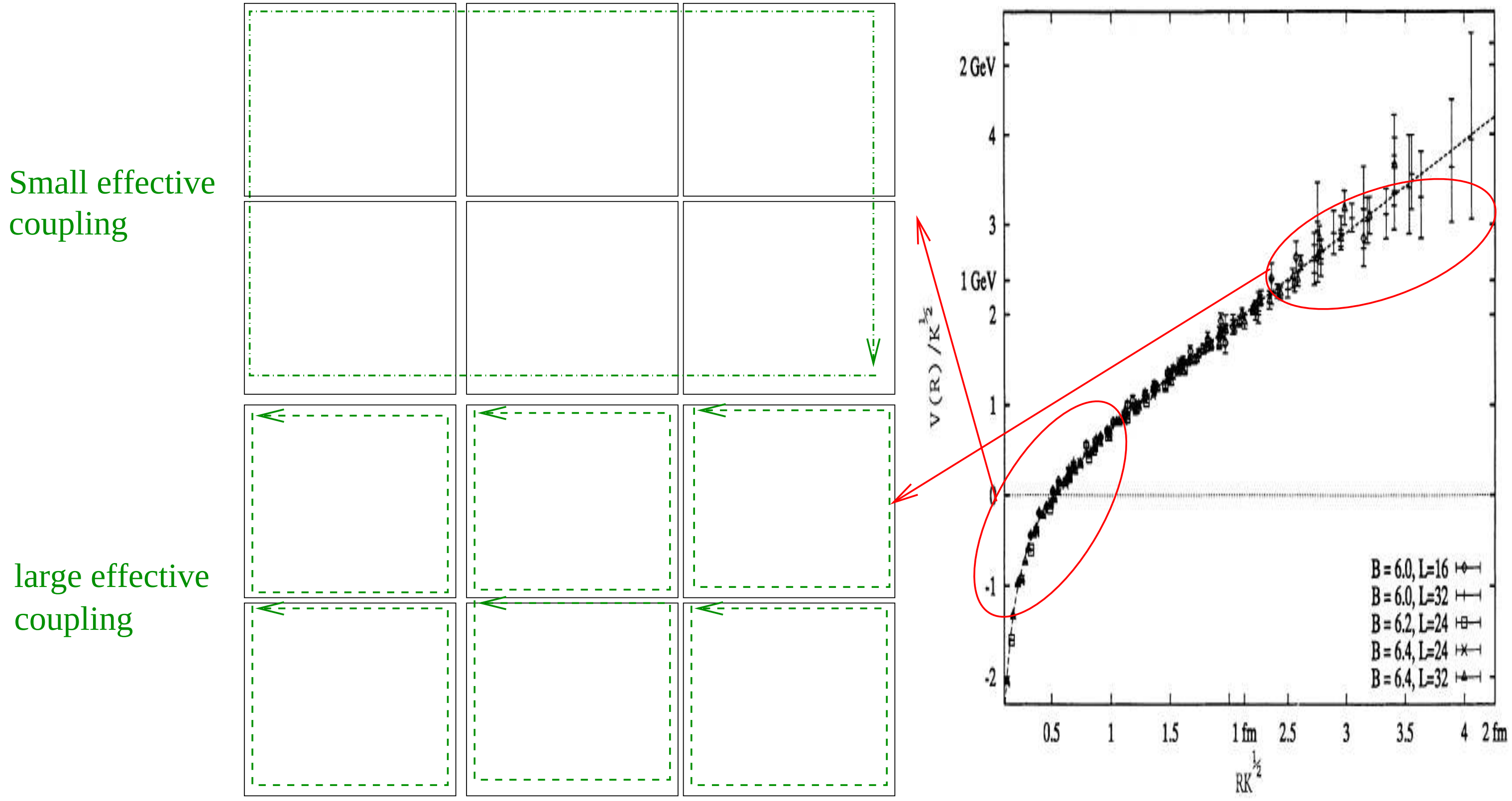
If χ-symmetry was exact, wed know it would be associated with a phase transition. But it is not exact, since quark masses are finite.$m_q \ll \langle q_L q_R \rangle_{T=0}$, but could be enough to transform a transition into cross-over.

Confinement can <u>sort of</u> be seen in the same way



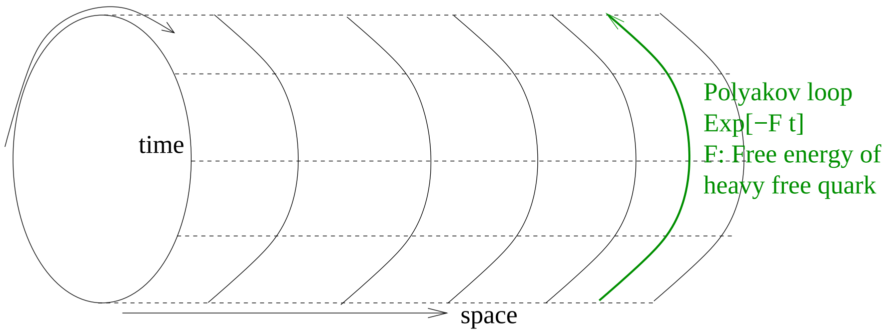
We can get <u>a little</u> theoretical understanding (and <u>a lot</u> of numerical results by integrating out all physics <u>except</u> a set of discrete lattice points. Theory <u>with infinitely heavy quarks</u> written in terms of

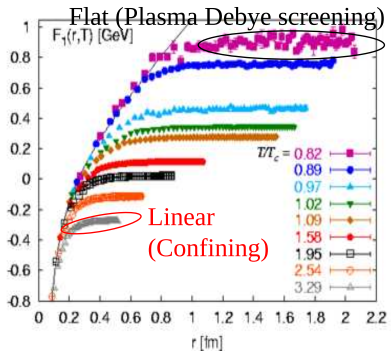
$$S \underbrace{=}_{no\ \ q} \prod_{\forall U} \int_{-\infty}^{\infty} dU_i f(U_i), U_j^{i,i+1} = \exp \int_{x_i}^{x_{i+1}} \left[g A_j^{\mu} dx_{\mu} \right], f(U) = \frac{1}{g^2} \left(\sum_{i=lattice} 1 - \frac{1}{2} Tr_j (U U^{+} U$$



At large distances, such a loop ("the Wilson loop") depends on "area", ie the potential $\propto r$. At low distances, it depends on perimeter, so potential $\propto r^{-1}$

Finite temperature and free quarks





Calculations done in a Vacuum field theory can be generalized to finite temperature by compactifying time. This mathematical trick can be understood by seeing that the partition functions are the same if time is periodic in $1/(2\pi T)$

$$Z_{QM} = Tr_A \left(\exp\left[i \int dx dt \mathcal{L} \right] \right), Z_{Statistical} = Tr_A \left(\exp\left[-\frac{1}{T} \int dx \mathcal{H} \right] \right)$$

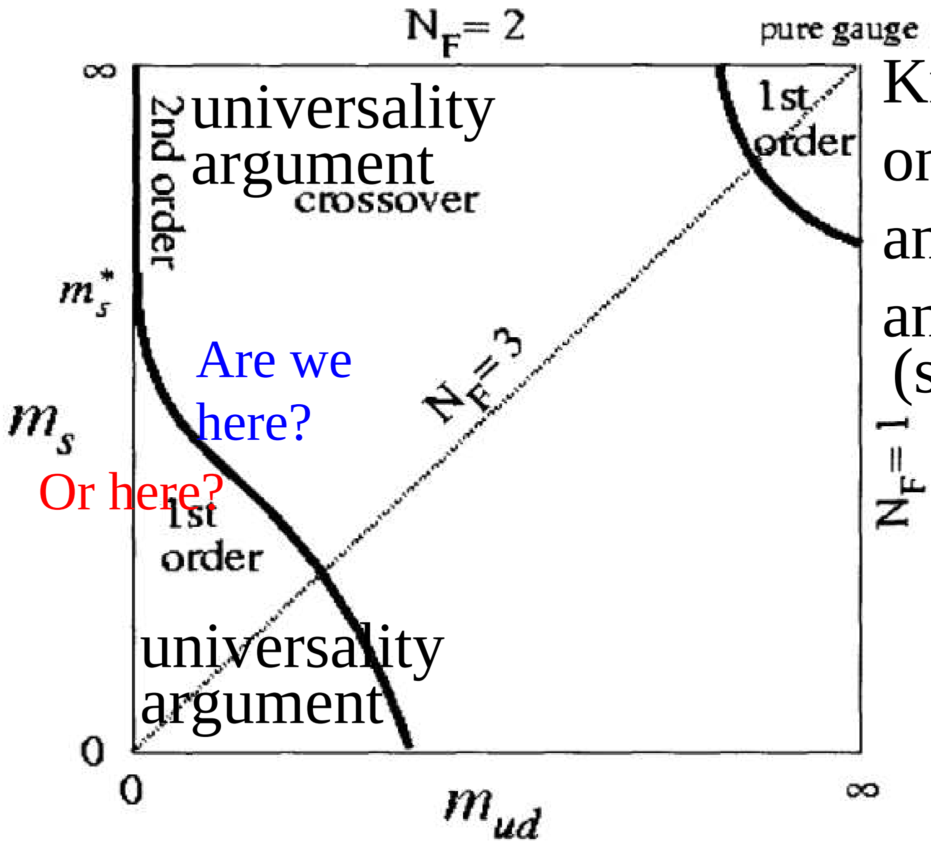
On the lattice without quarks, confinement can be thought of as a global symmetry using Polyakov loop! Condsider Polyakov loop, 1 loop around the "cylindrical time", $\int_0^{1/T} dt \exp[-A_0 dt] \sim \exp[-F/T]|_{free \quad quark \quad in \quad bath}$

- For a confining phase, $\langle L \rangle = 0$ (Free energy of a free quark is infinite)
- For deconfinement, $\langle L \rangle = f(T) \neq 0$ (Free energy of a free quark $\leq \infty$

Note that, unlike most phase transitions, the low-temperature phase is the most symmetric one. But all this is not anymore true if quarks are present. Quark-antiquark pairs break string/Wilson loop/..., break the $Z(3)$ and make the potential not well defined. $\langle L \rangle_{with \quad quarks} (T=0) \sim f(\Lambda_{QCD} > 0$, so transition not necessarily a phase transition!

Conclusion: On the lattice, we know that

Lattice
says its
a cross−over
but might
be close to
critical point



Known
on lattice
and semi−
analytically
(symmetry)

Conclusion: On the lattice, we know that

- At low chemical potential the "transitions" for deconfinement and chiral symmetry breaking coincide. That is, quarks become free and nearly massless simultaneusly.
  (this is a numerical result not analytically undersood, through mixing between Polyakov loop (see in a slide) and $\overline{q_L} q_R$ is probably the reason. It might not be universal (quarkyonic phase))

- The transition is not a transition, its a cross-over (probably)

- Other properties of Plasma not well understood
  ($T_c, p(T \sim T_c)$,viscosity,conductivity,...)

On a conceptual level, these two facts are not explained. And they are true "within error bar". So experimental detection of QGP, crucial

The QGP? Have we found it?

MANY ideas to look for QGP

Strangeness enhancement QGP should be more efficient at creating strangeness, so strangeness should quickly thermalize

Charmonium suppression Heavy quarks should break up in QGP

Photons and dileptons QGP should me more efficient than hadron gas at producing photons and dileptons

Fluctuations FLuctuations should diminish in an "ideal" QGP since bigger density of degrees of freedom, be enhanced at the critical point.

...

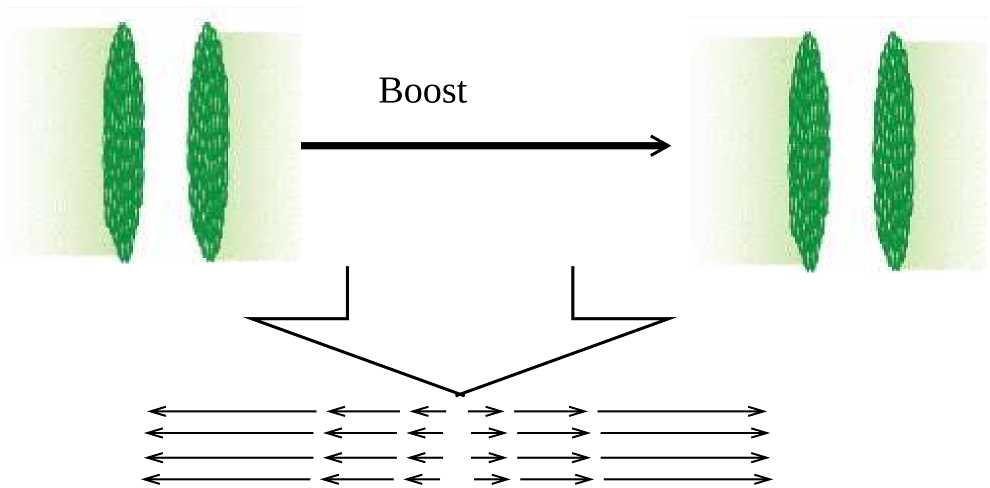
What these have in common is: No convincing scaling violation found in experiment. Newsworthy high energy (RHIC!) signarues (of what?)

Jet suppression

Hydrodynamic behaviour

Characterizing the event:Some basics

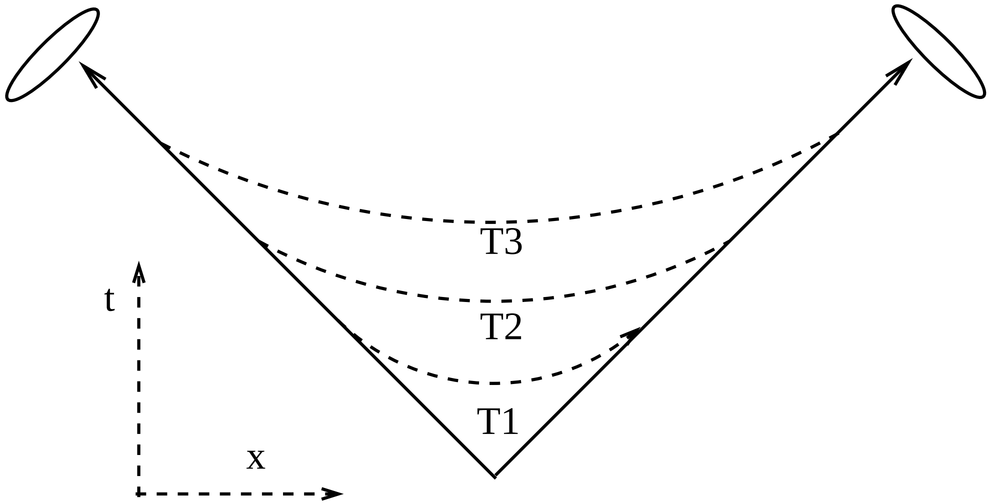
Landau assumed low transparency, nuclei stick together. But asymptotic freedom in QCD means this is unlikely at high $\sqrt{s} \gg m$ energy



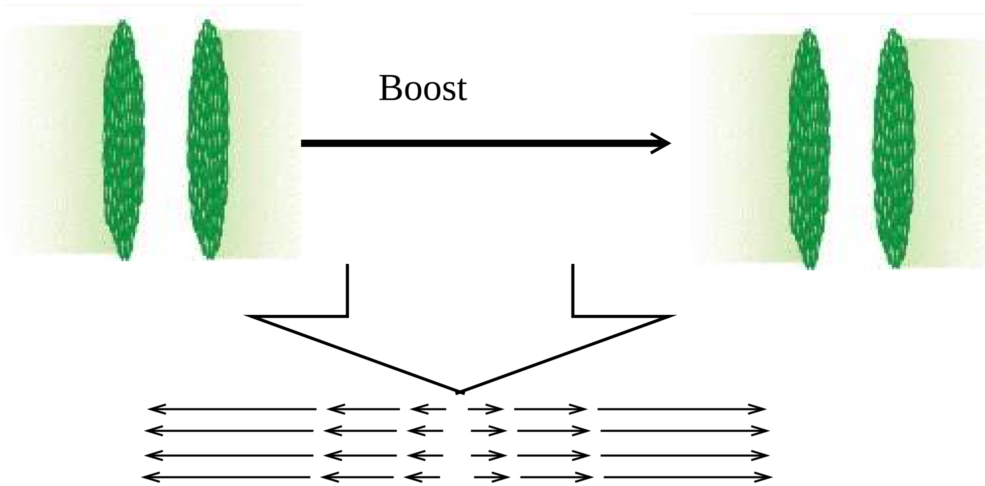
NB This is the consensus. No one actually knows what is the transparency at earlier times, or how it changes with energy!

A good system of coordinates to characterize this system

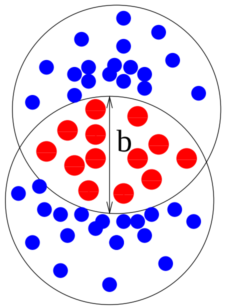
Let z be the beam direction. Rapidity $y = \tanh^{-1} v_z$, Lorentz-additive. p_T Lorentz invariant wrt to the beam. NB Often pseudo-rapidity used, $\eta = \tanh^{-1} p_z/|p|$



At Asymptotically high energies system boost-invariant,exactly solvable in 0+1D,approximately in 1+1D ("Bjorken hydrodynamics")



$$v_z = \frac{z}{t}, \qquad e = e\left(\tau = \sqrt{z^2 - t^2}\right), \qquad \partial_\alpha u^\alpha = \frac{1}{\tau}$$



Transverse initial conditions:
The Glauber model

At high $\sqrt{s}$, correlations between nuclei irrelevant (time dilation)
$\frac{dN}{dy} = aN_{part} + bN_{collisions}$

- "hard" particles form independent superimposed collisions N_{coll}
- "Soft particles from each "participant" (> 1 collision)

a, b fitted to data (Cant calculate energy released into $y = 0$ region)

The Color Glass condensate:an alternative initial condition

Gluons diverge at low x (asymptotic freedom)

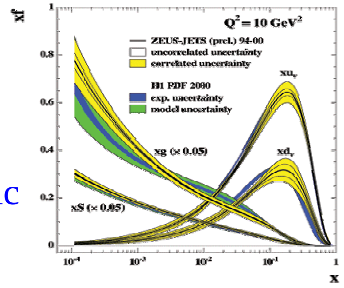
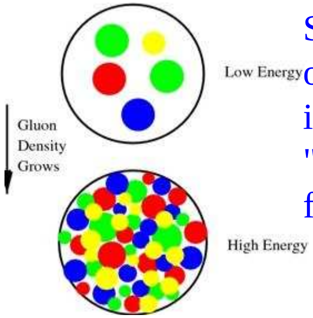


FIG. 2: The gluon distribution function measured at Hera [13].



So gluons overlap into "classical" field

High in $\sqrt{s}$ (RHIC?) soft particle production dominated by Gluons at low x ("Saturation scale"): $Q_s = x_s\sqrt{s}$ set by balance between $gg \leftrightarrow ggg$

- Random (Neighbouring Color vertices point in random directions,)
- Dominated by a "saturation" scale $Q_s = x_s\sqrt{s}$, set by $ggg \leftrightarrow gg$
- As occupation number at x_s large Classical, solvable by $\partial_\mu F^{\mu\nu} = J^\nu|_{random \quad source}$

A brief summary of theoretical methods

All of this is nice, but calculating is a fundamental problem

- (Potentially) non-perturbative
- (Potentially) non-equilibrium
- Certainly non-linear

We can try to calculate, no guarantee well succeed!

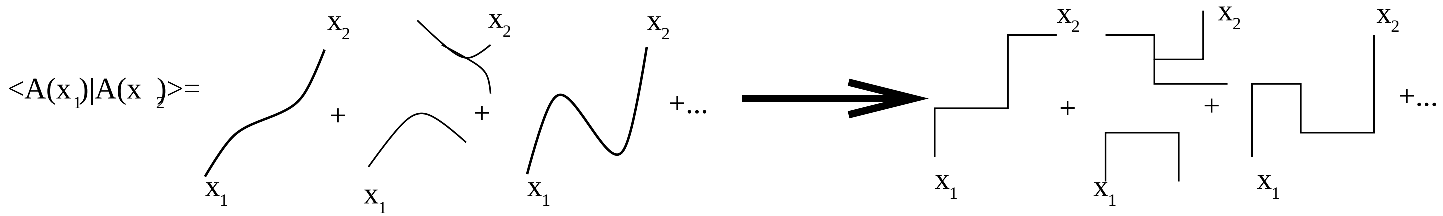
Perturbative QCD just calculate quark-gluon Feynman diagrams

- fundamental
- probably does not work for most particles (all but very high momentum scattering, "jets" and "jet-medium") (Asymptotic freedom)
- maybe does not work for any
  No one knows how asymptotic freedom works in a high temperature many particle system: Even if neighbouring close enough to interact perturbatively, "next-to-nearest" neighbours are not!
  (Easy to see in perturbative quantum mechanics: $V(x) = ax^2 + \alpha x^4$)

$$\forall \alpha \exists \psi_n s.t. \left\langle \psi_n a x^2 \psi_n \right\rangle \ll \left\langle \psi_n \alpha x^4 \psi_n \right\rangle, \rho(T>0) = \sum_n \left|\psi_n\right\rangle \left\langle\psi_n\right| \exp\left[-\frac{E}{T}\right]$$

So small coupling constant+Finite temperature$\neq$ perturbative expansion!!!! see J.P.Blaizot lectures

Lattice QCD Quantum functional integral computed on discretized space



$$Z \simeq \prod_i \sum_{\forall U_i} \exp\left[- \sum_i L(U_i) \right]$$

- Fundamental (if you believe in QCD,you have to believe this!), but heavily numerical (no insights)
- No dynamics, only equilibrium, since need to do Wick transform ($\left[- \int L(U_i)\right]$ Either all real or all imaginary for numerical integrals) (Either static Eigenvalues or thermal equilibrium)

Effective models (NJL,PNJL,Sigma model,effective theories of hadrons,...)

Basic idea: "Integrate out" QCD into a quantum field theory of hadrons with hadronic QCD symmetries (eg chiral)

- Calculate in areas inaccessible to QCD.
- But no one knows effective model which captures most physics
- How does the physics we calculate depend on the assumption we make?

Statistical models Assume equilibrium and non-interacting hadrons. No dynamics

Hydrodynamics Assume (near) equilibrium and Navier-Stokes equations. Dynamics, but when is it realistic?

Molecular dynamics Solve the Boltzmann equation from elementary cross-sections

- Does not rely on equilibrium
- Relies on dilution hypothesis and weak coupling
  Going beyond (Kadanoff/Baym,BBGKY) very difficoult and largely not done
- Same problem as effective models: Cross-sections put in by hand
  How does the physics we calculate depend on the assumption we make?

Gauge/string dualities (Recent and "fancy"):

It seems a 4 dimensional strongly coupled field theory looks like a 5-dimensional weakly coupled string theory (General relativity)

- A thermalized medium looks like a Black hole with the corresponding Hawking temperature
- A quark looks like a moving string
- All described by general relativity in 5 dimensions and a negative cosmological constant (AdS)

Strongly coupled, fundamental, and calculable. But not QCD:Works best with $\mathcal{O}(N) = 4$ supersymmetris (CFT)

What are we looking for?

Charmonium suppression

Idea: Soon after T_c (no one knows when, lattice data not ready) J/ψ should dissociate in medium (in same way as atom in hot plasma), due to Debye theory ($\sim$ EM potential in a hot medium).

$$V\left(r, T > T_c\right) = \frac{e^{-m_D(T)r}}{r} \quad , \quad m_D^2 \sim T^2$$

Bound state $\langle r \rangle$ in radial potential $\sim 1/m$, so interplay between m and T

$m_D > \langle r \rangle$ Bound state stable

$m_D < \langle r \rangle$ Bound state unstable

Different resonances $J/\psi, \psi', \Upsilon, ...$ have different temperatures $\rightarrow$ thermometer.

Nice idea, butnumerics not understood.

- ANY bound state unstable at finite temperature, a thermal fluctuation can break it up
  Spectral function at finite temperature has imaginary part

- Hadron gas dissociation, non-equilibrium effects, might be important

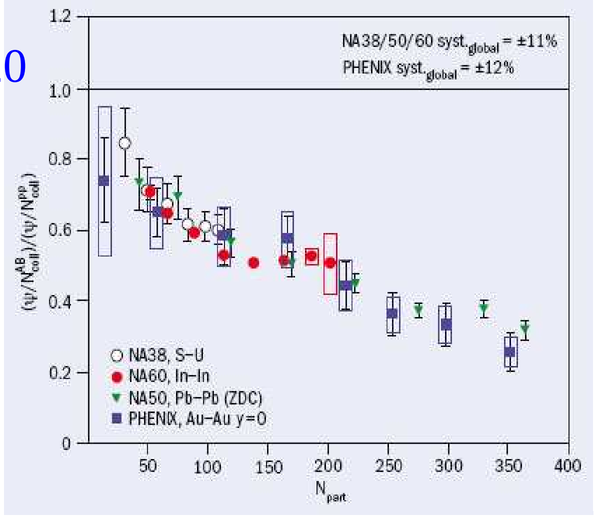
- For bound state survival need $\lim_{x-x'\to\infty} \langle \psi_{c\bar{c}}(x)\psi_{c\bar{c}}(x')\rangle$
  Difficoult on lattice (impossible for imaginary part)

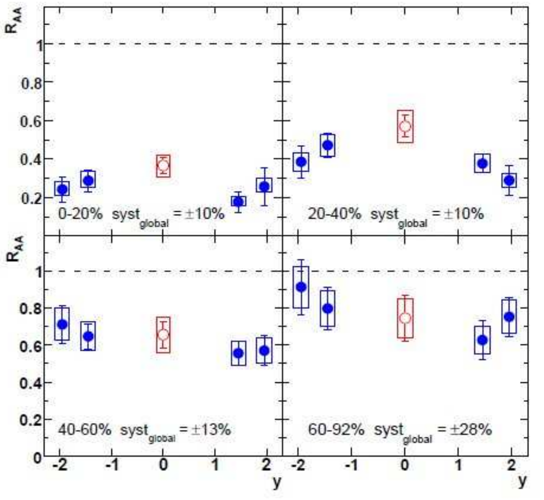
- coalescence of free quarks of a plasma in a J/ψ can lead to J/ψ ehnancement

Experimentally, suppression by factor 4 or so observed by SPS and RHIC. But theoretical interpretation not univocal. And enhancement increases with rapidity.

PHENIX nucl−ex/0611020 (PRL)

Suppression of charmonium scales well with multiplicity

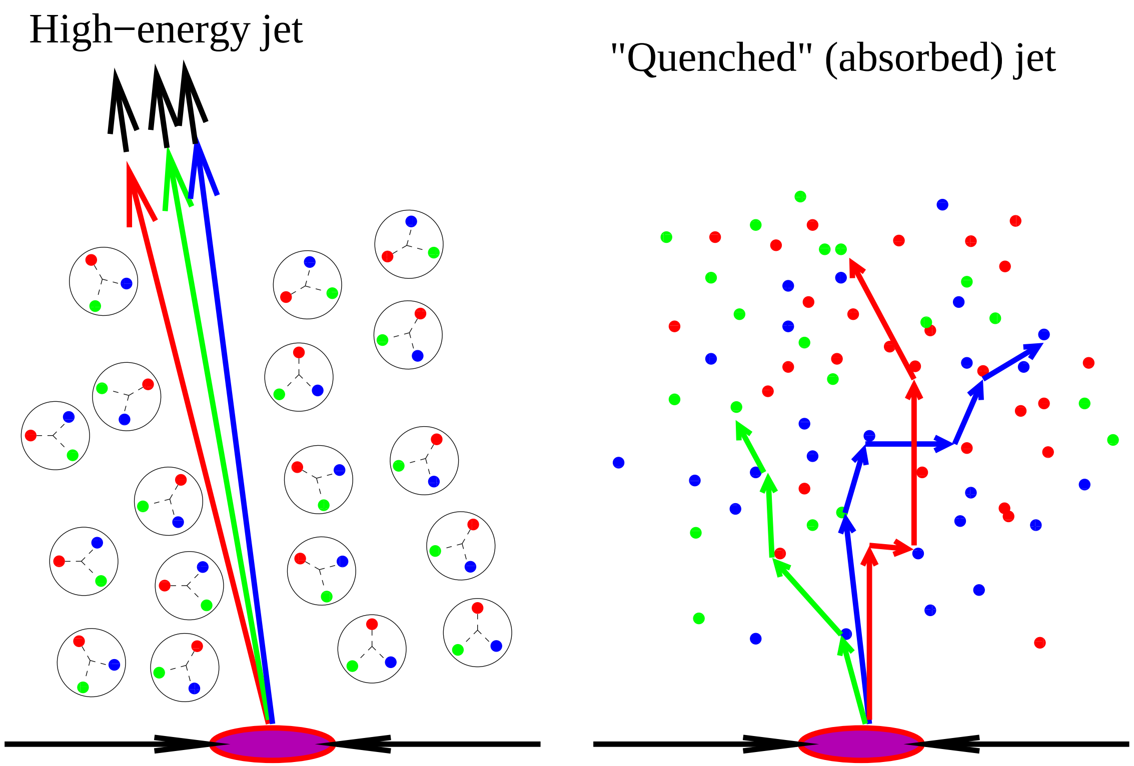




And INCREASES with rapidity!

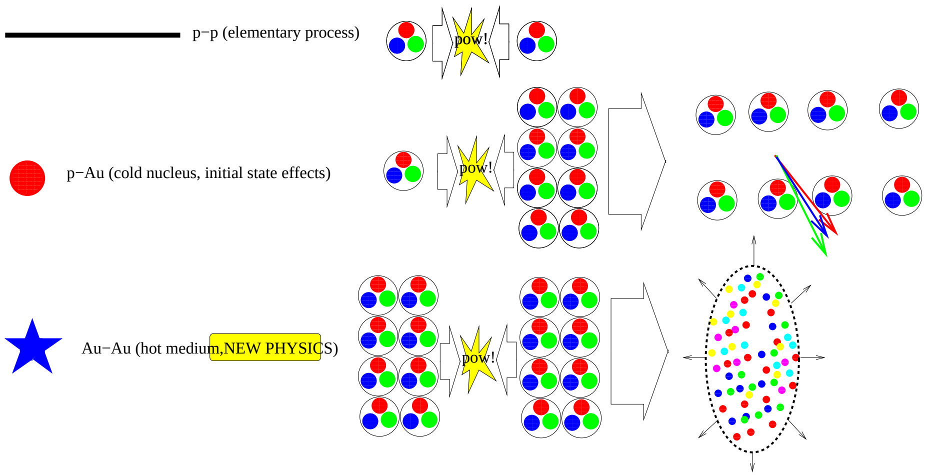
No transition evidence as yet!

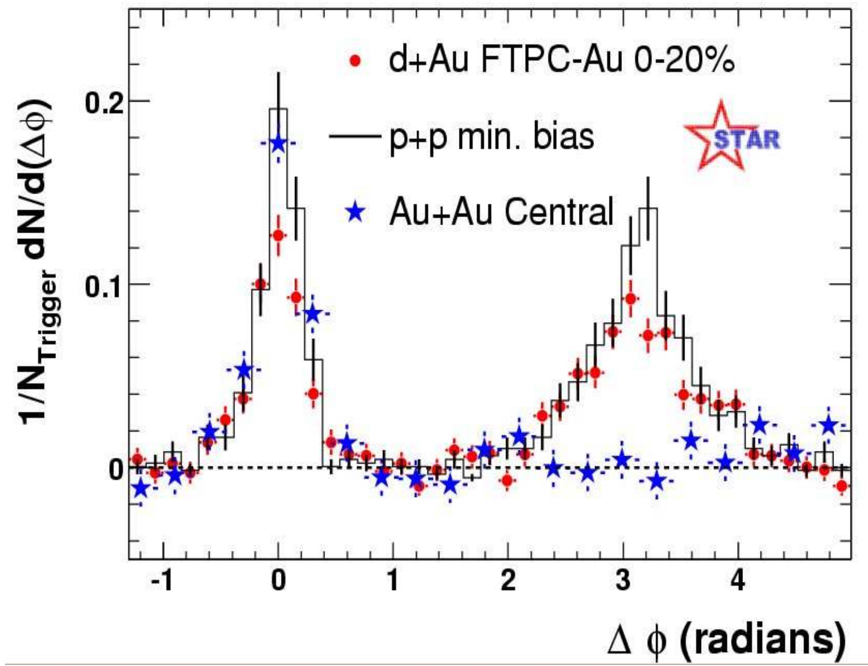
Jet suppression (Bjorken,many others): Bethe-Bloch energy loss+QCD



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

This was conclusively shown to happen,and to be due to the medium! (NB: Jets in HIC ⇒ single high-p_T triggers)



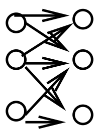


But is it QGP? or close to equilibrium? Difficoult to tell with jets (“Hard” parton-medium interactions dont care about “soft” confining forces).
When does this effect ”turn on”? Jet production strongly $\sqrt{s}$-dependant, so energy scan difficult. Models also fit lower energy SPS data (Similar “medium”,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

Gyulassy,Levai,Vitev

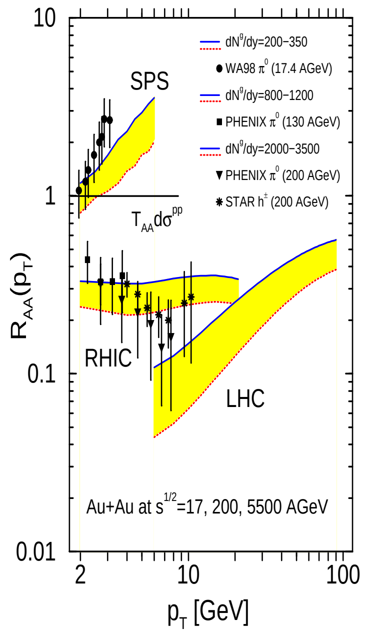
PRL.85:5535−5538 2000

Low energy: Nuclear enhancement (combinatoric) dominates

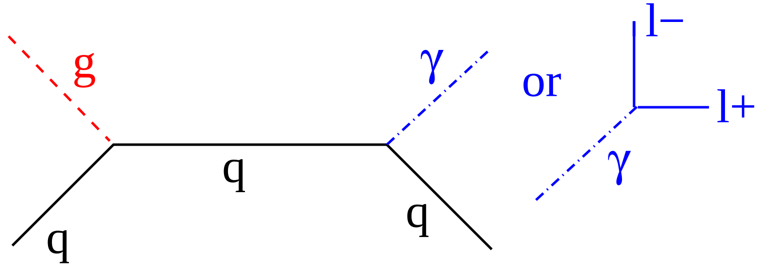


High energy: Medium suppression dominates

Interplay can give scaling violation
even if intensive properties of medium unchanged



Photon and dilepton QGP production



"THermal" radiation from initial QGP stage. System electromagnetically transparent, so can probe "early" phase. But a lot of background due to, eg, $\eta \rightarrow \gamma$

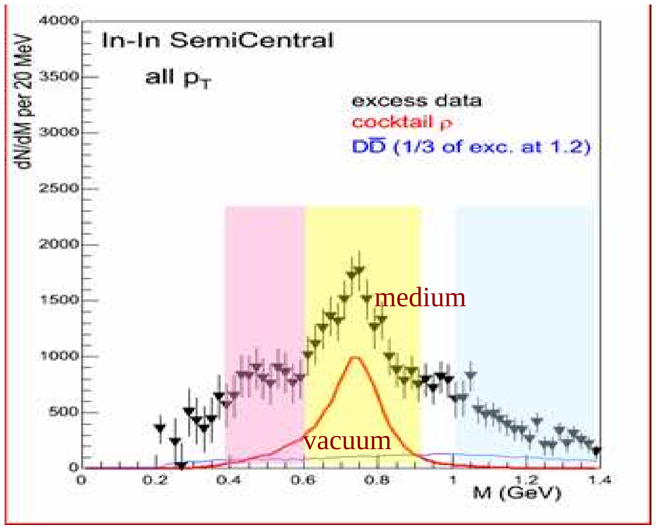
Dilepton chiral symmetry restoration signature

If chiral symmetry is restored or on the way to be restored, resonances such as the $\rho, a_1, ...$ should be modified: Either shift in mass or change in width (melting). Details <u>not</u> understood (most models get melting).

Experimentally, ρ found to be broadened at SPS (RHIC ρ not seen yet). But many contributions to the signal, interpretation once again controversial.

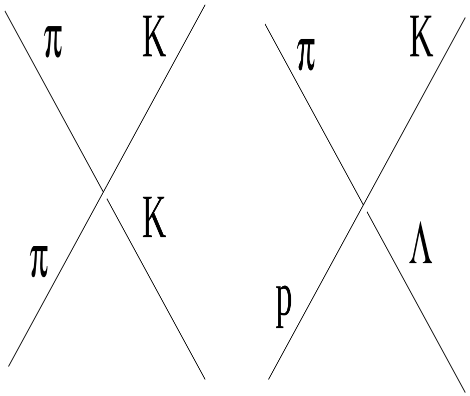
NA60
collaboration
Indium−Indium

160 GeV
fixed target



Strangeness Enhancement: Theoretical motivation

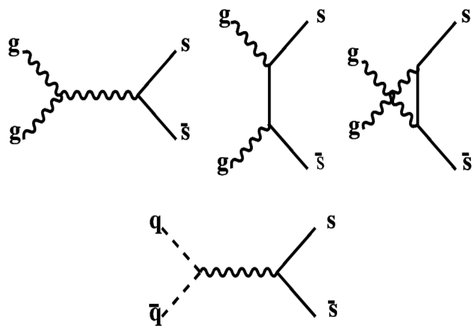
Hadronic production



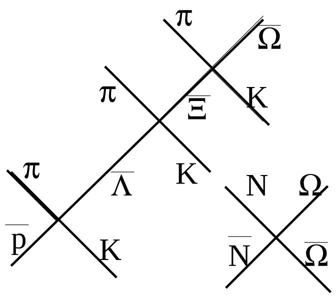
Strangeness equilibration:

Vs

Quark gluon plasma:



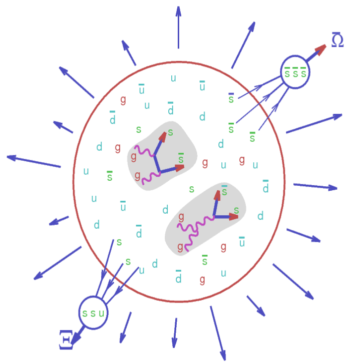
Hadronic production



Multistrange baryons:

Vs

Quark coalescence:



Strangeness Enhancement: Theoretical motivation

B.Muller,P.Koch J.Rafelski observed that

- Strange Quarks in QGP reach chemical equilibrium faster than HG at same density
  γ_s closer to 1 for system initially at QGP w.r.t. system at HG

- The equilibrium QGP strangeness abundance is greater than HG at same density
  γ_s could be > 1

Hence, the enhancement of strange quarks w.r.t. "expectation" could signal a transition to the new phase of matter.

What is enhancement?

Defined as

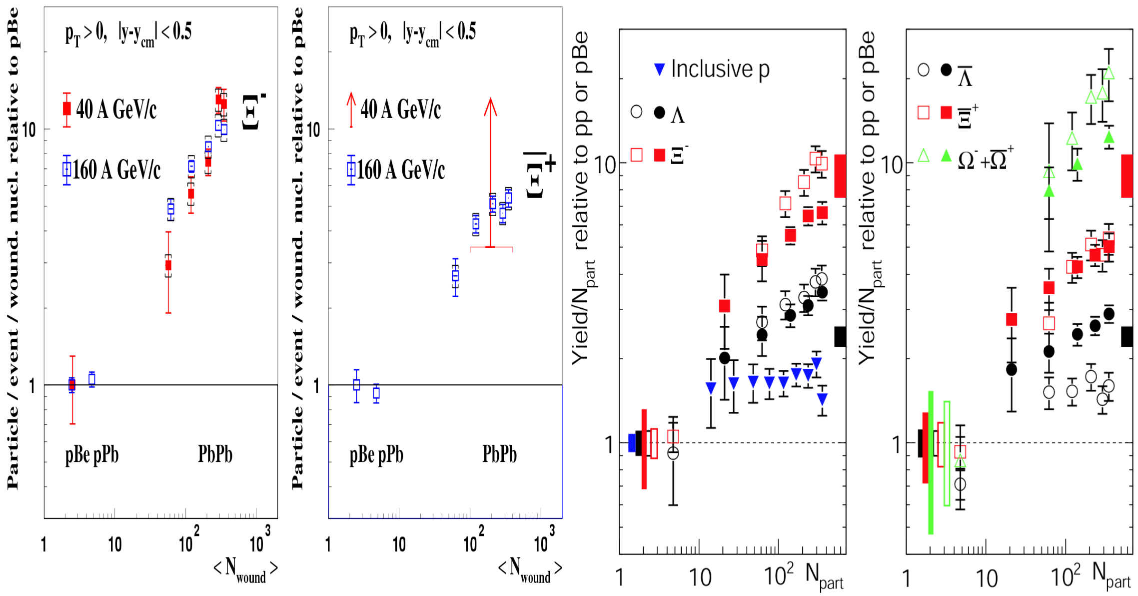
$$Y = \frac{\left[\langle N \rangle / N_p \right]_{A-A}}{\left[\langle N \rangle / N_p \right]_{p-p,p-A,d-A,...}}$$

Parametrizes "extra" strangeness (or any yield) w.r.t. "small" system (no "medium"). Soft equivalent to $R_{AA,CP}$.

Some model dependence in definition of N_p (CGC? Effect of η in hydro? Normalize by dN/dy (strictly $\sim$ volume if $T_{f.o.}$ constant or do "enhancement" of N_{ch}

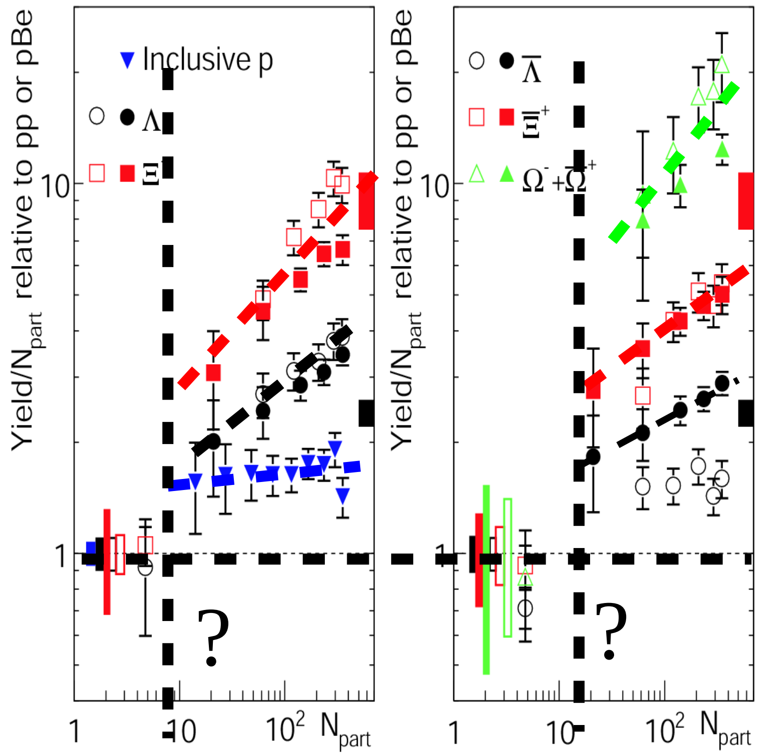
Strangeness enhancement: the present situation

One of the few signatures (the only?) where something local is qualitatively different between p-(p,Au),Au-Au. Something that breaks the scaling between "small" and "large" systems



p-A seems to be qualitatively similar to p-p. something connected with strangeness is enhanced at A-A. What?

Some important things can be seen by eye

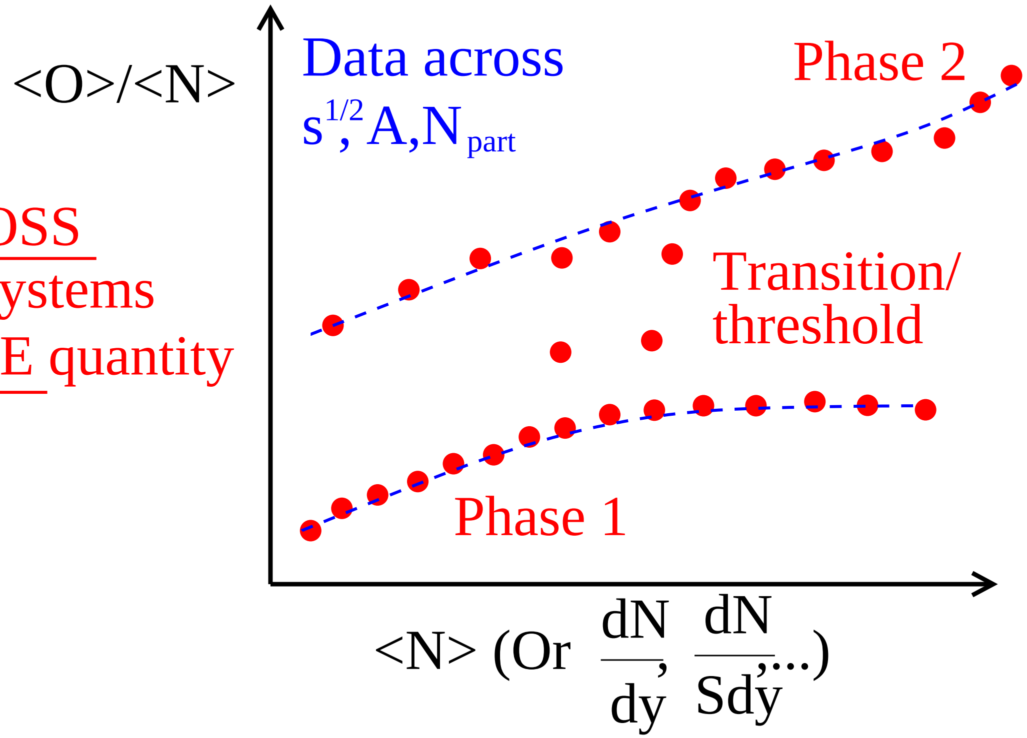


NB: higher $s^{1/2}$ SPS data very similar

No enhancement in small systems. Above "critical" size (??), $Enhancement \propto N_{part}$ but slope $\propto s$ $\Rightarrow$ Thermodynamic limit (and isenthropic expansion?), and local chemistry changes (turning on when?).

The common problem:What is the ideal QGP signature?

Scaling ACROSS energies and systems of INTENSIVE quantity BROKEN



There are good reasons to fear that such a signature is unrealistic. But without it, how could we be convinced?

Integrating all momenta we get...

$$\langle N_i \rangle \sim V \Pi_i \lambda_q^{q_i - \overline{q}_i} \gamma_q^{q_i + \overline{q}_i} F\left(\frac{m}{T}\right) + \sum_{j \to i} b_{j \to i} \langle N_j \rangle$$

where $F(x) = x^2 K_2(x)$

all details of flow, hadronization surface integrate out!

Parameters characterizing the system...

“Temperature” T Drives particle abundance w.r.t. mass

Fugacity λ_q Estabilishes density of conserved charge q (Strangeness,etc.)

“Phase space occupancy” γ_q estabilishes density of $q\overline{q}$ pairs $\left(= 1|_{equilibrium}\right)$

Local/chemical scale of strangeness abundance

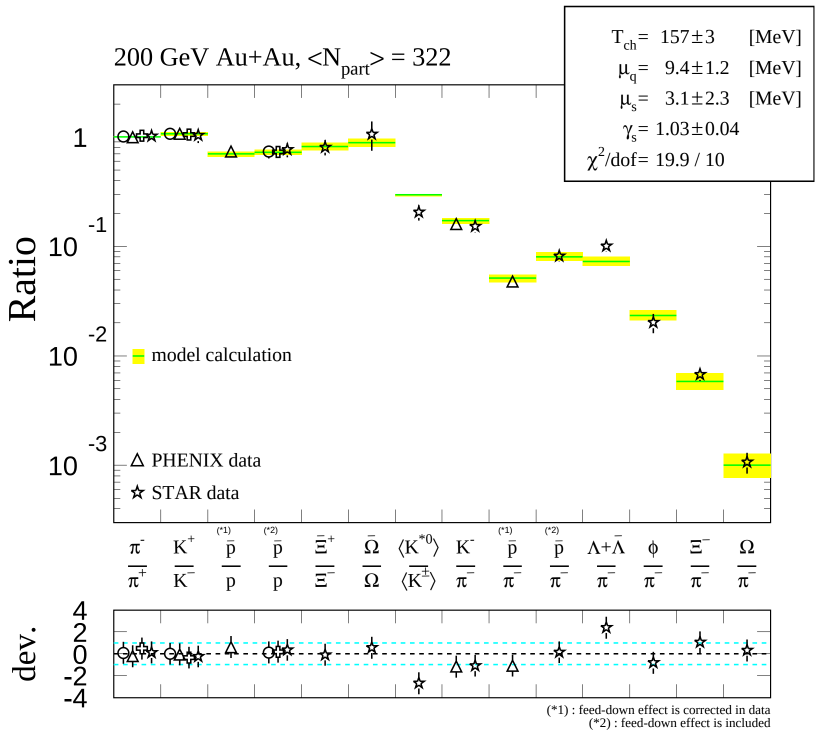
“Volume” V total multiplicity at chemical freeze-out (also acceptance)

Equilibrium phase space (Canonical) scale of strangeness abundance

“Lifetime τ Reinteraction <u>after</u> chemical freeze-out.

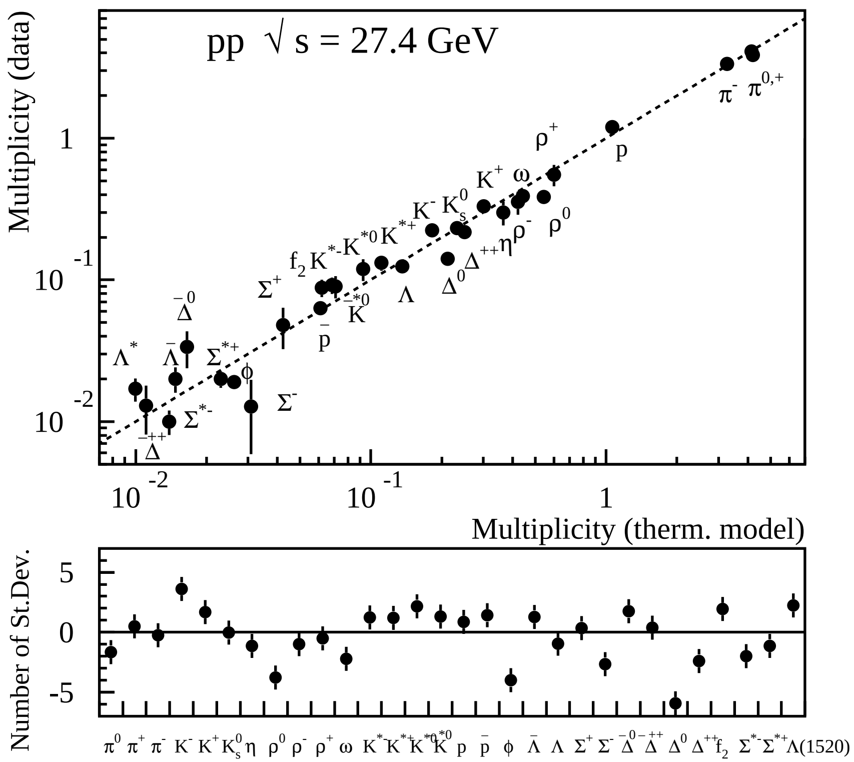
Assuming statistical model approximately valid at chemical f.o. Assuming statistical model approximately valid at chemical f.o.

What we know... (this plot from Kaneta and Xu, nucl-th/0405068, also Braun-Munzinger,Stachel,Becattini,Rafelski,GT,...)

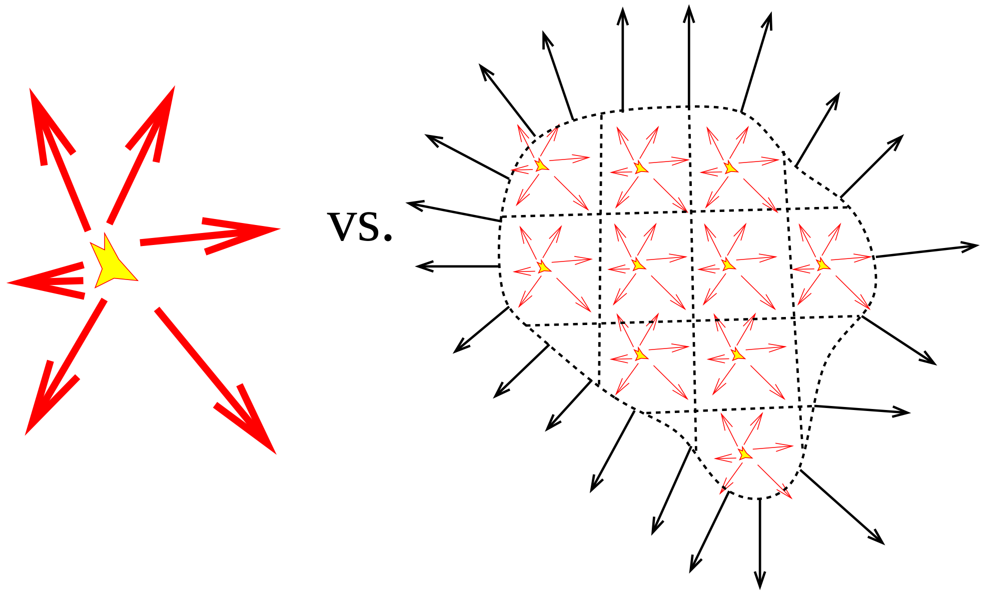


This will probably also happen at the LHC!

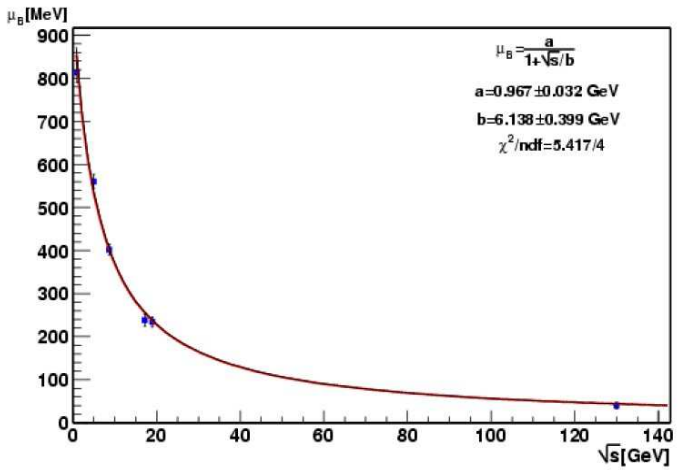
...But it also happens in $e^+e^-, p-p$! (Becattini, hep-ph/9701275)

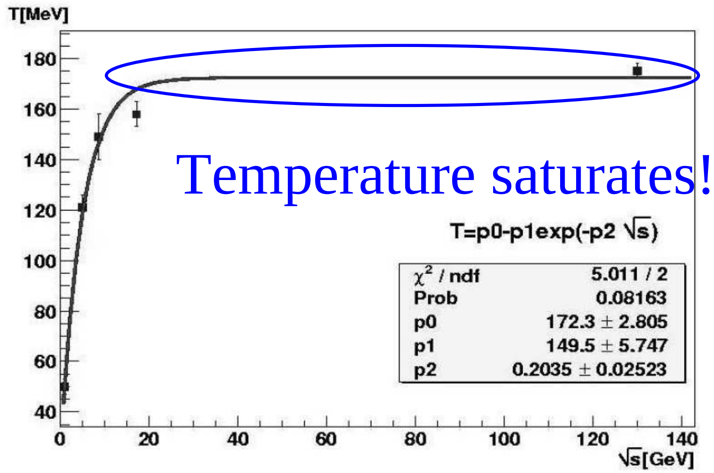


What is not necessarily Hydrodynamics:
Global "Equilibration" different from LOCAL equilibration



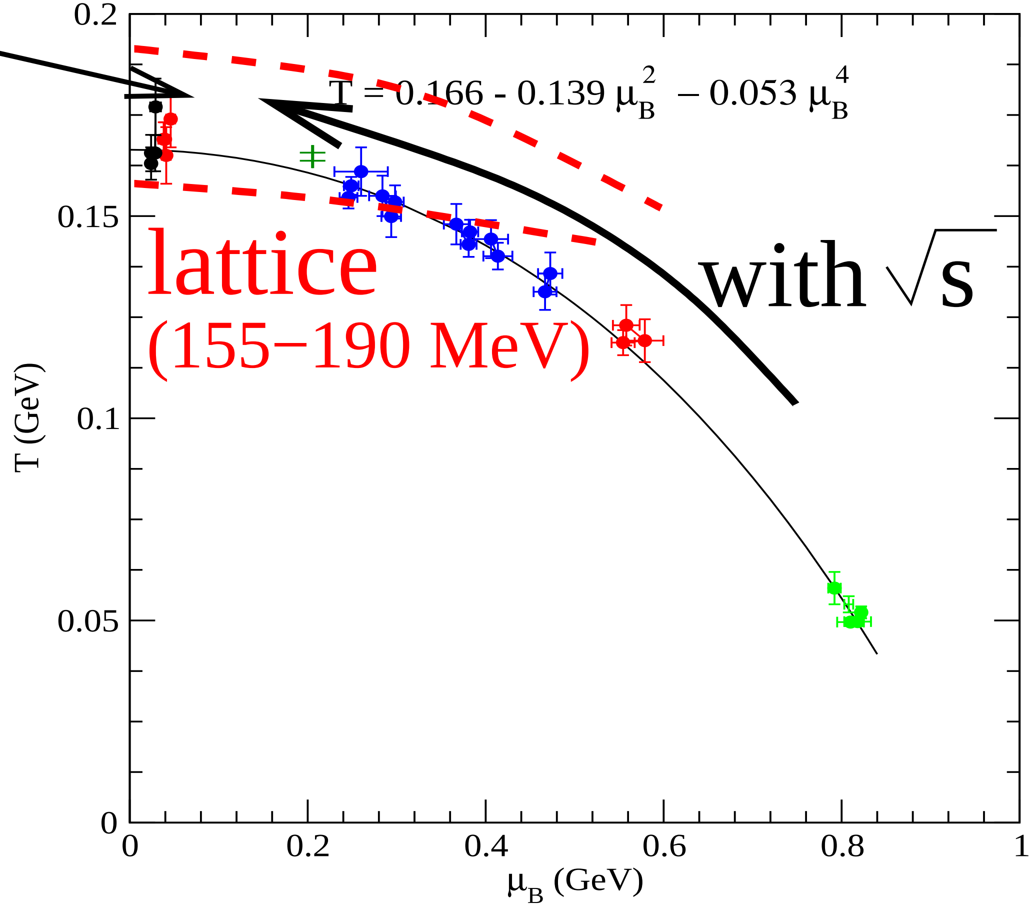
Many explanations, from mundane Phase space to esoteric QCD-black hole equivalence . But in chemical parameters, is there any difference in energy/system size/...?





Are we seeing the phase transition? Or....

p−p,e−e also here:



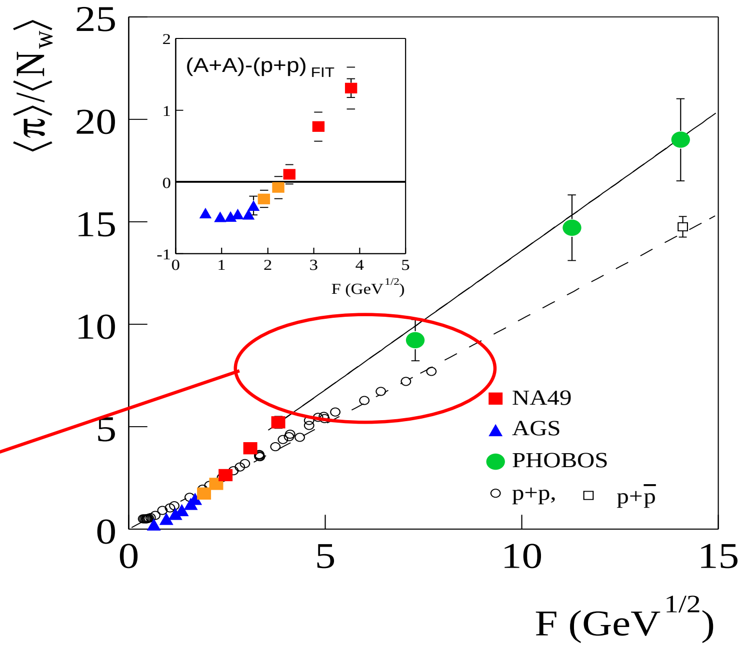
Or simply greater transparency with higher energy?

Can we see a "phase transition" in the thermal parameters?

How does a phase transition manifest itself?

- Through latent heat (if first order)
- Through an enhancement in fluctuations (if second order)
- Through a change in the entropy content of the system
- Through a change in chemical content of the system

Jump
in entropy
produced
in A−A
system?



watch the Variable. It is the "Fermi Variable", defined as $N_{part} \frac{(\sqrt{s} - 2m_N)^{3/4}}{\sqrt{s}^{1/4}} =$

Assume <u>no</u> transparency. By Lorentz contraction, $V = V_0 m_N / sqrts$ where V_0 is the proton volume. The energy density, therefore, is

$$\rho = \frac{E}{V} = \frac{\left(\sqrt{s} - 2m_N\right)\sqrt{s}}{2m_N V_0}$$

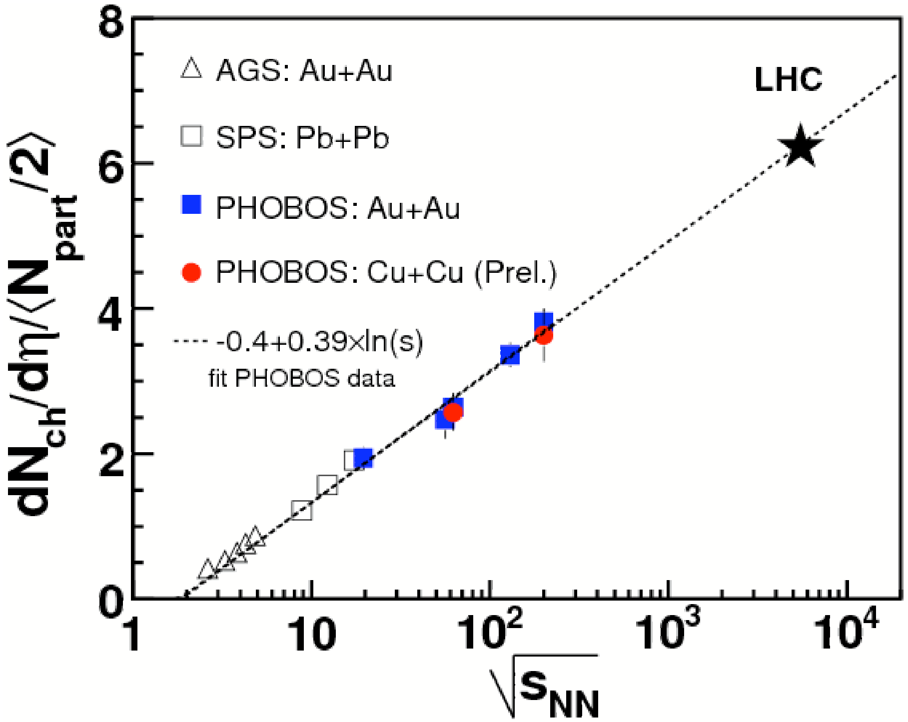
Now assume an ideal gas equation of state, so

$$p = \frac{1}{3}\rho, \rho \sim T^4 s = \frac{e+p}{3} \sim \rho^{3/4}$$

putting everything together, the entropy density is given by Fermi's formula, giving entropy in terms of "global" quantities.

$$s \sim \frac{(\sqrt{s} - 2m_N)^{3/4}}{\sqrt{s}^{1/4}}$$

But assumptions unrealistic: In particular, transparency strongly increases with Energy (remember Bjorken!)



If usual definition of energy used ($\sqrt{s}$) scaling remarkably smooth.

From thermodynamics to Hydrodynamics

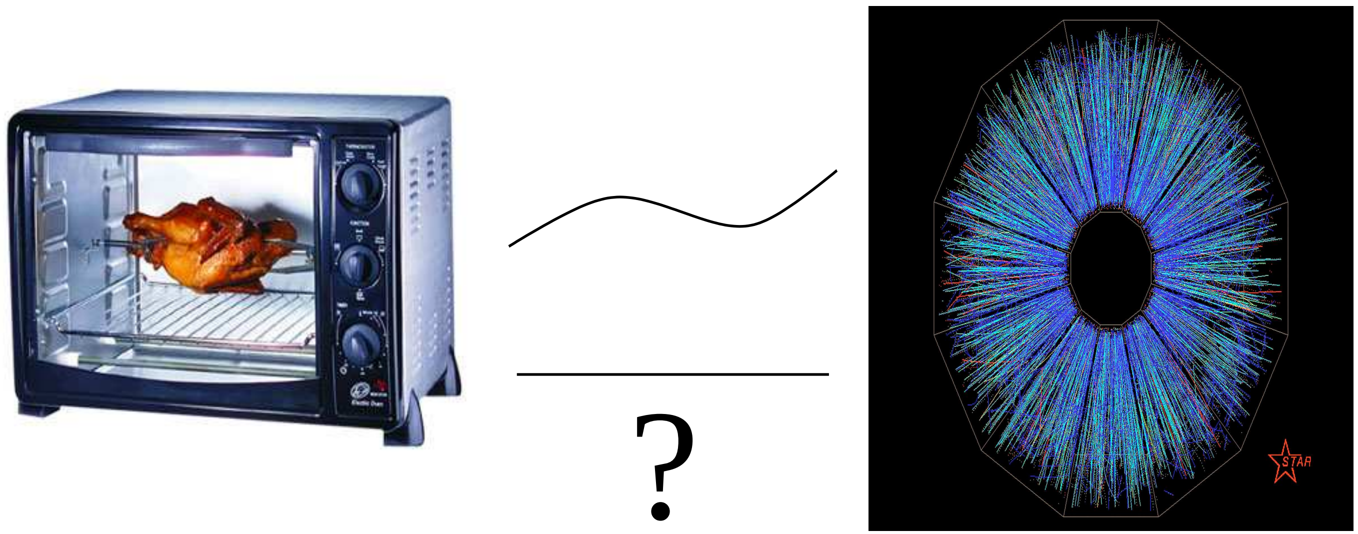
Dynamics If system locally in termal equilibrium,

$$T^{\mu\nu} = T^{\alpha\beta}\Big|_{rest} \Lambda^{\mu}_{\alpha}\Lambda^{\nu}_{\beta} = (e+P)u_{\mu}u_{\nu} - pg_{\mu\nu}$$

together with the equation of state, $P(\rho(T,\mu))$ we have 5 equations,5 unknowns . Ie can solve from any initial condition

At the end we do not see a fluid but particles. Assume "mean free path" goes from 0 to ∞ fast. Production of particles from comoving thermally equilibrated particles... Cooper-Frye formula

$$\left(E\frac{dN}{d^3p}\right)_i = \int d \underbrace{\Sigma_{\mu} p^{\mu} f(p_{\mu}u^{\mu}, T, \mu)}_{ideal} \underbrace{\left[1 + \frac{p_{\mu}p_{\nu}\Pi^{\mu\nu}}{2T^2(e+p)}\right]}_{viscosity} + \underbrace{\left(E\frac{dN}{d^3p}\right)_{j\to i}}_{resonances}$$



Big advantage (?) Can get the dynamics from thermodynamics, can explore phase transitions

Big disadvantage Fast local equilibration is a big approximation. How good is it? Can extend with viscous terms, but gets very compicated

Hydrodynamic based signatures... a brief intro

transverse flow as a probe of the Equation of state

Elliptic flow as a probe of viscosity

HBT (Hanbury-Brown-Twiss) as a probe of spacetime (also the equation of state)

Transverse flow: Boosted thermal distribution

$$\exp\left[-\frac{E}{T}\right] \Rightarrow \exp\left[-\gamma\frac{E-\vec{v}.\vec{p}}{T}\right]$$

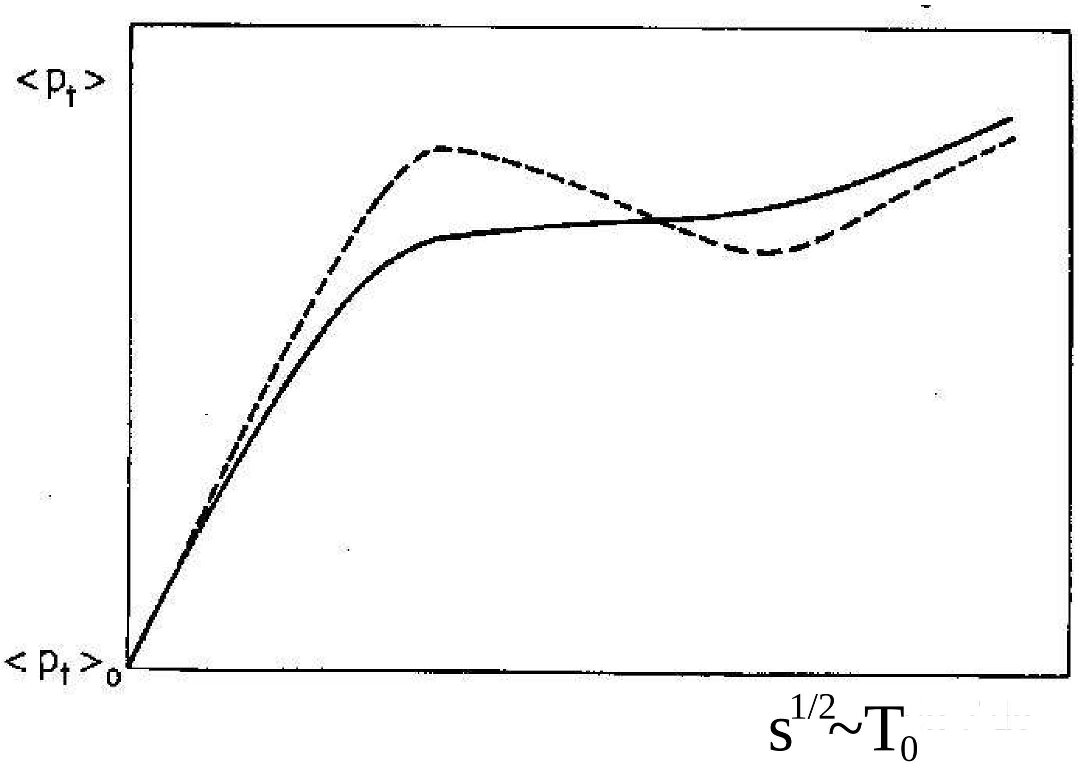
Boost in $\langle p_T \rangle$ for all particles

Higher mass particles boosted more

Flow depends on the equation of state.

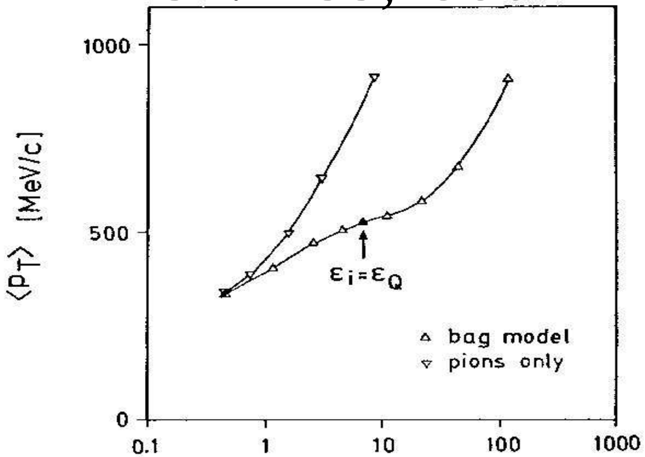
"Mixed phase" $\Leftrightarrow$ no flow $\Rightarrow$ smaller $\langle p_T \rangle$

Bad news



L.Van Hove Phys.Lett.B 118:138,1982

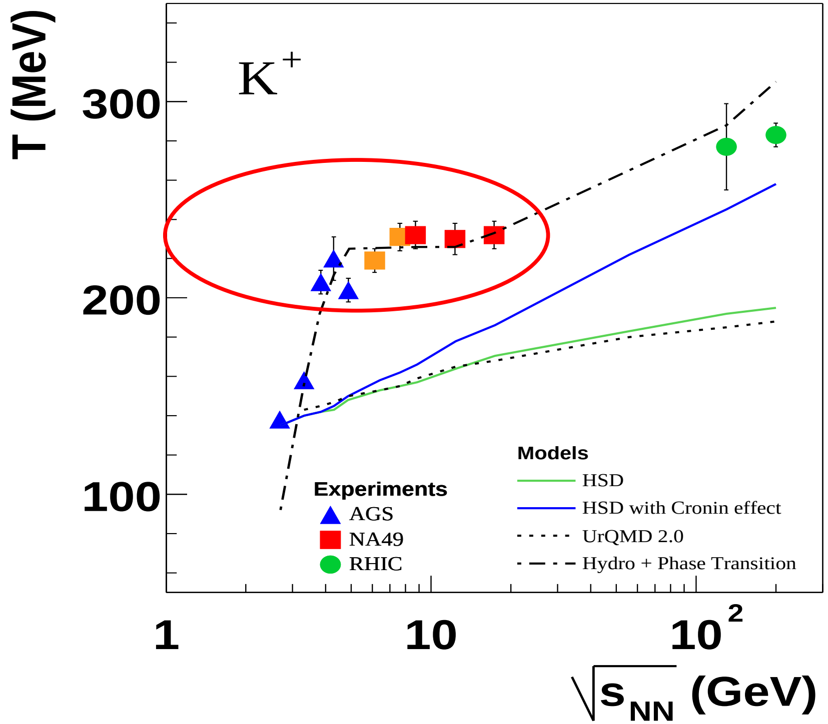
Mclerran et al PRD34:2755,1986



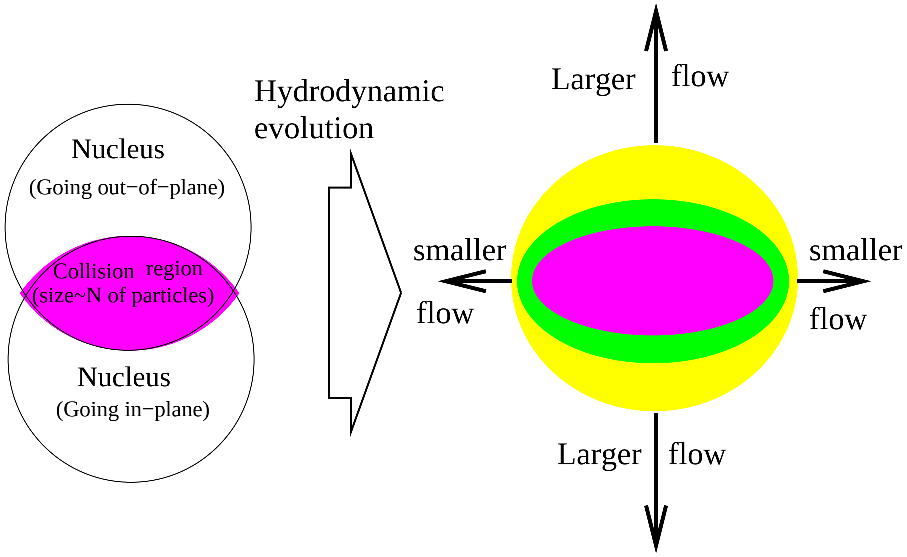
Signature investigated since the '80s. "Lumpy" initial conditions drastically decreases effect

Good news

T−>Slope includes flow



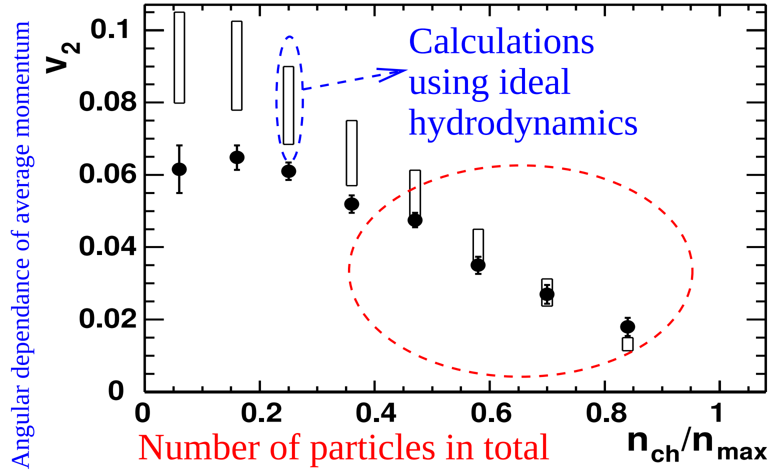
“step” found for Kaons Other scaling violations?



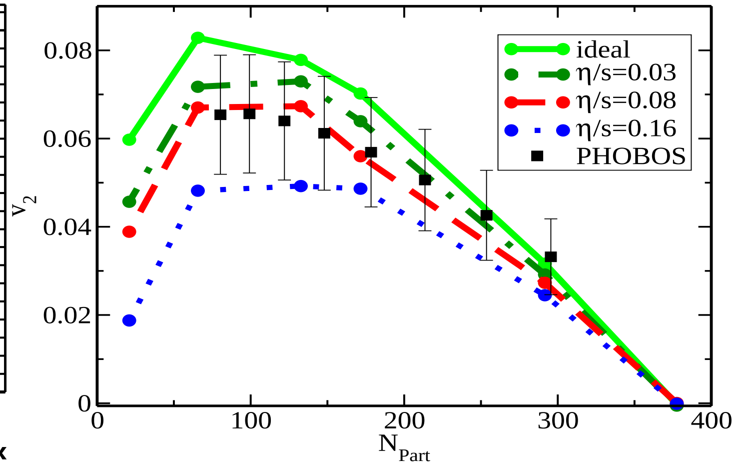
Hydrodynamics predicts flow eccentricity as a function of number of particles ($\sim$ area of overlap region). Parametrized by 2nd Fourier component, v_2

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

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



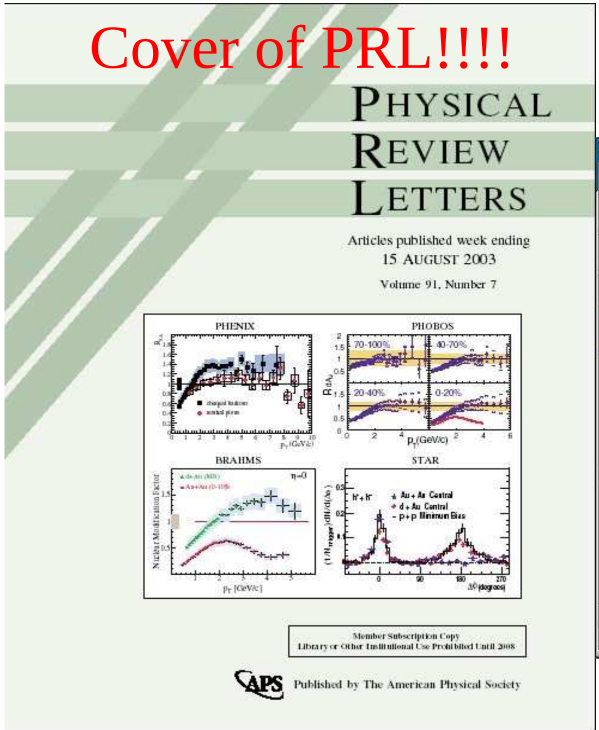
P.Romatschke,PRL99:172301,2007



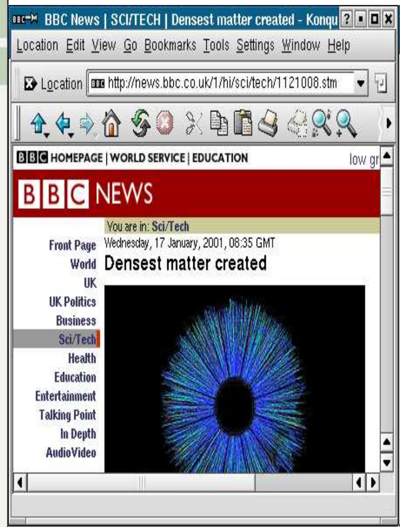
Data described by ideal hydrodynamics (mean free path between particle collisions is zero! THis is where "ideal liquid" headline from!
(Viscosity not much bigger than "lowest viscosity" conjectured by string theory!!!!!(more on that later))

Result is very interesting

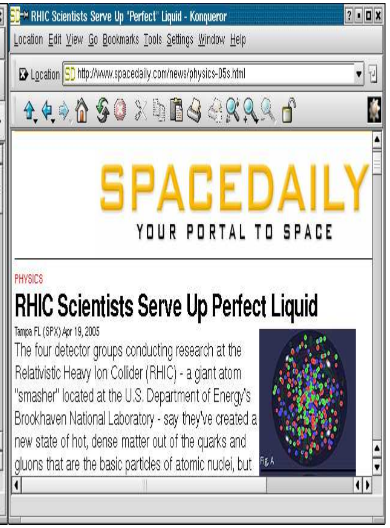
Cover of PRL!!!!



BBC!



SPACE DAILY!

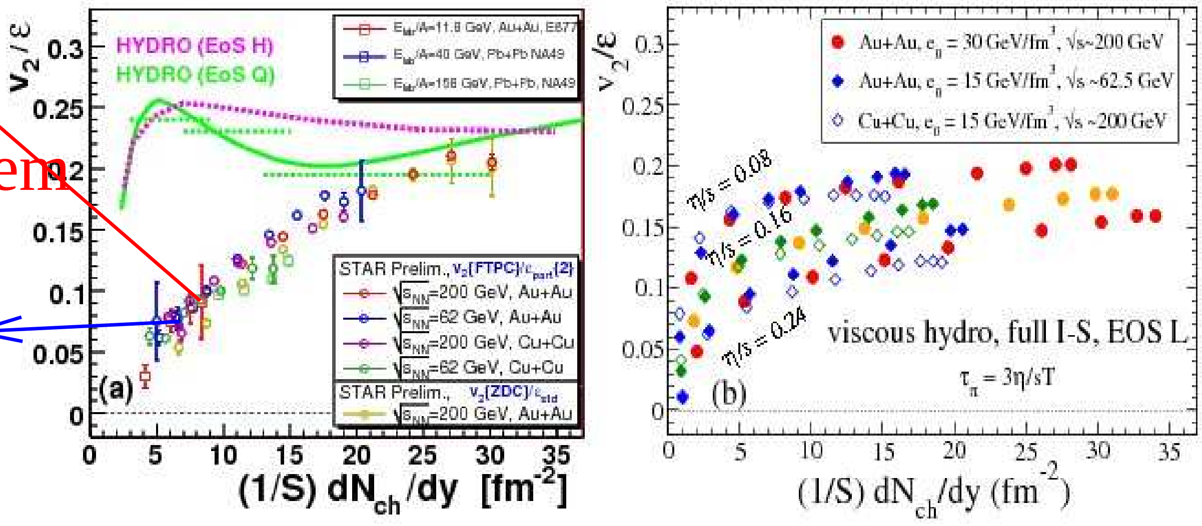


RHIC IS FAMOUS! WHY?!

And received quite a bit of press coverage

Lower energy larger system

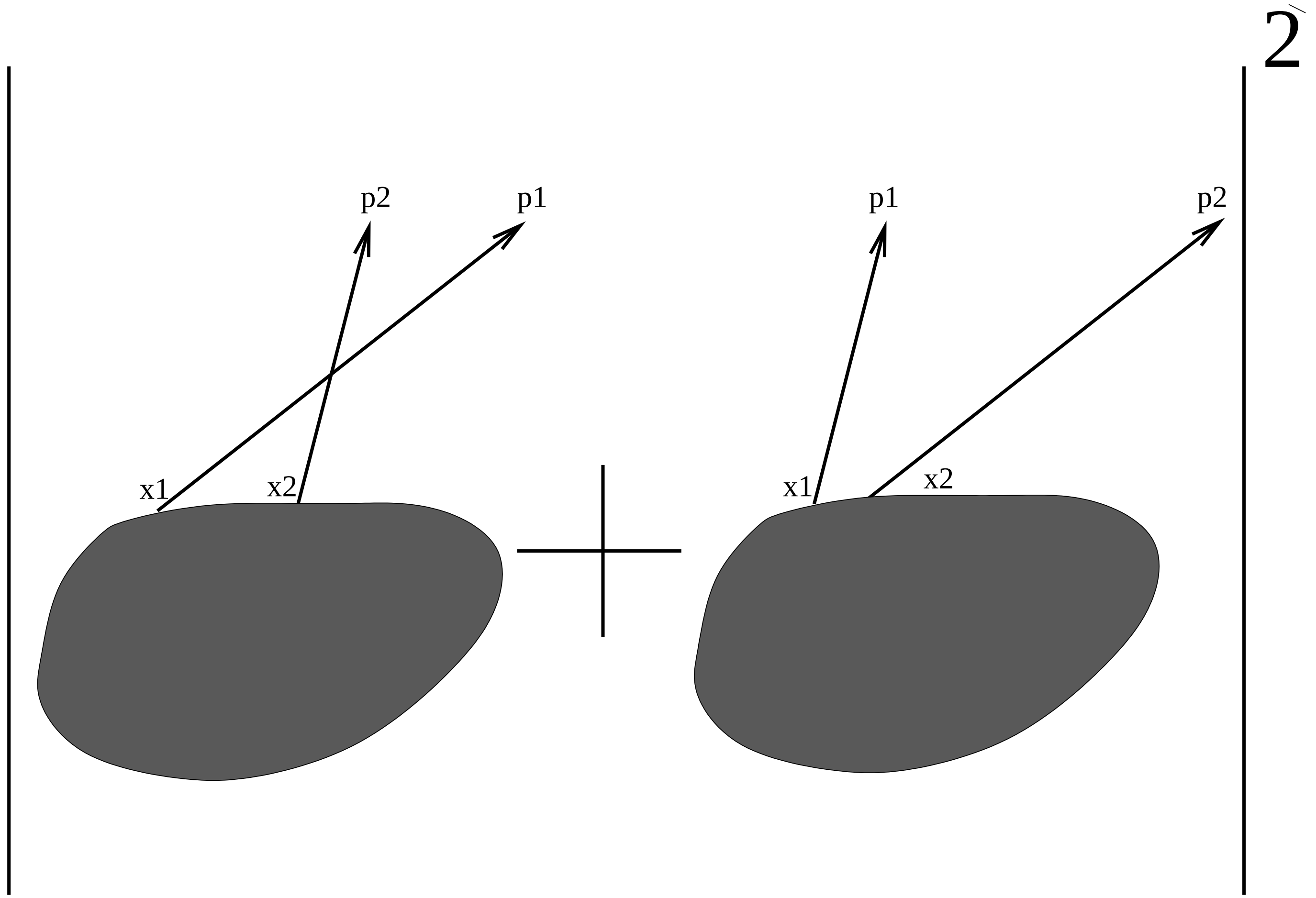
Higher energy smaller system



simulation by U.Heinz H.Song

But once again, interpreting it is difficult In both energy and rapidity, experimentally $v_2 \sim 1/SdN/dy$. Theoretically, v_2 should jump when η/s changes . When does this occur?

HBT: classical source emitting quantum free particles



$$\Psi(x_{1,2},p_{1,2}) = \frac{1}{\sqrt{2}}\left(S(x_1,p_1)S(x_2,p_2)e^{i(p_1x_1+p_2x_2)} \pm S(x_2p_1)S(x_1p_2)e^{i(p_2x_1+p_1x_2)}\right)$$

Measurement of $C(p_1,p_2)$ gives handle on $S(x,p)$

$$C(p_1,p_2) \sim |\tilde{S}(p_1-p_2,p_2)|^2$$

Where the momentum correlation coefficient $C(p_1,p_2)$ is

$$C(p_1,p_2) = \frac{\rho(p_1,p_2)-\rho(p_1)\rho(p_2)}{\rho(p_1)\rho(p_2)}$$

And $\tilde{S}(k,q) = \int d^4xS(x,q)e^{ikx}$, $S(x,p) = d\Sigma_\mu p^\mu f(p_\mu u^\mu, T)$ given by the differential Cooper-Frye formula

Usually $\tilde{S}(q,p) \sim$ Gaussian $\Rightarrow$ parametrization in terms of $R_{out}, R_{side}, R_{long}$

$$S(\underbrace{k}_{p_1+p_2}, \underbrace{q}_{p_1-p_2}) \simeq N(k)\exp\left[R_o^2(k)q_o^2 + R_s^2(k)q_s^2 + R_l^2(k)q_l^2 + R_{ij}(k)q_iq_j\right]$$

S.Pratt, PRD33, 1314 (1986), G. F. Bertsch, NPA498, 173c (1989).

"long" Beam direction $(\vec{z})$

"out" $(\vec{p}_1 + \vec{p}_2) \times \vec{z}$

"side" "out" $\times$ "long"

$k_{side} = 0$ by construction

This parametrization is useful because...

If

$$\left\langle (\Delta x^{\mu})^2 \right\rangle (p) = \int d^4 x S(x,p)(x - \langle x \rangle)^2$$

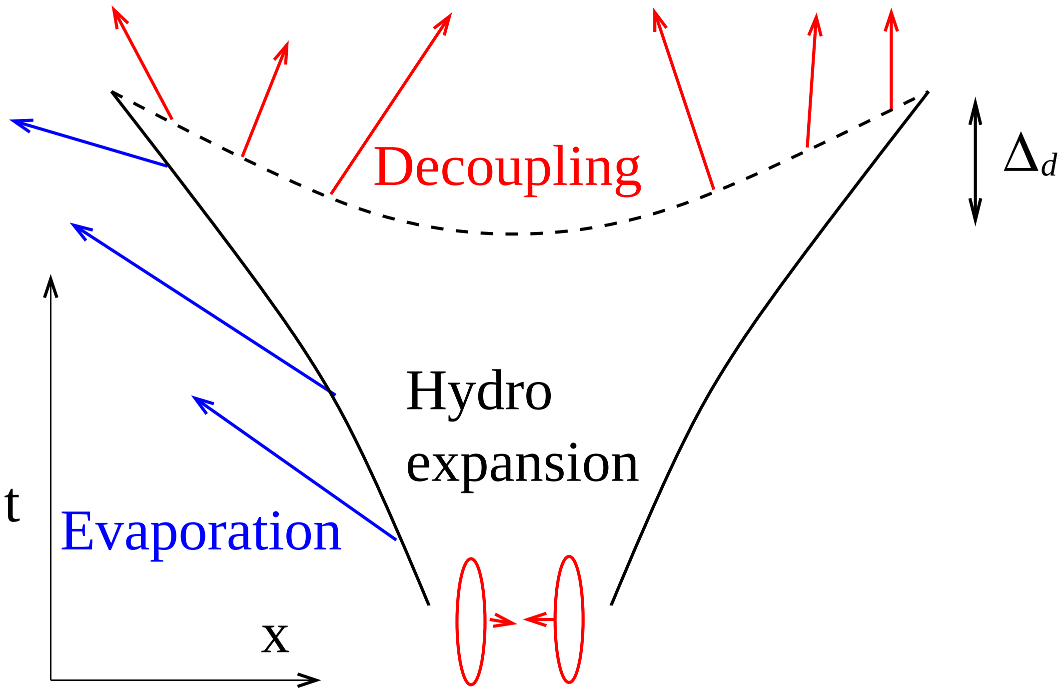
then

$$R_o^2 = \left\langle \left(\Delta r - \frac{k_o}{k_0} \Delta t \right)^2 \right\rangle$$

$$R_s^2 = \left\langle (\Delta r)^2 \right\rangle$$

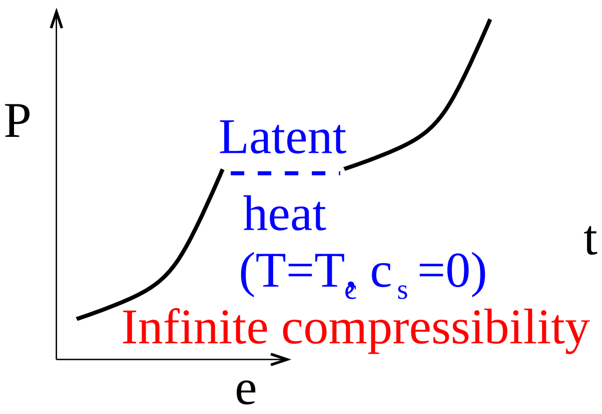
Comparing R_0 and $R_s \rightarrow$ emission time. This was "the" signature for deconfinement!

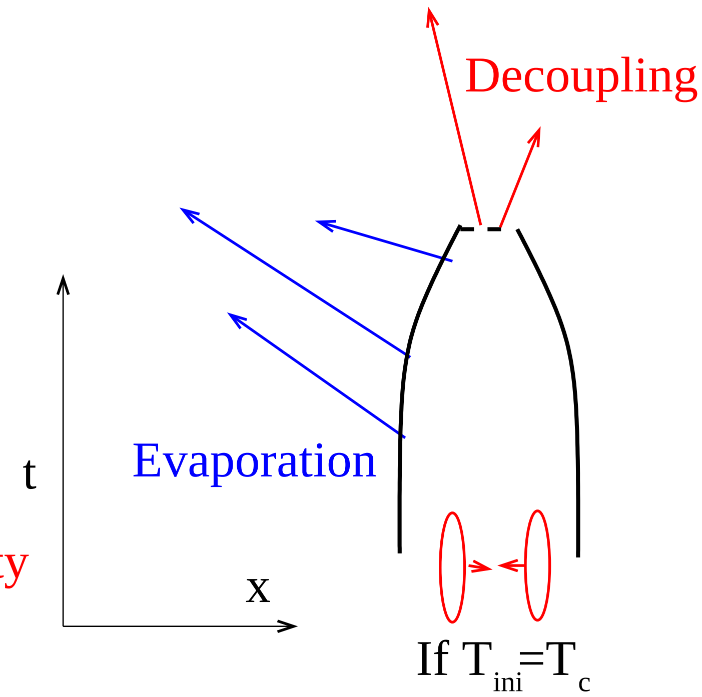
"generic" fireball (starting energy away from T_c), evolution by hydrodynamics, $d\Sigma^\mu$ given by critical $T \sim 100$ MeV

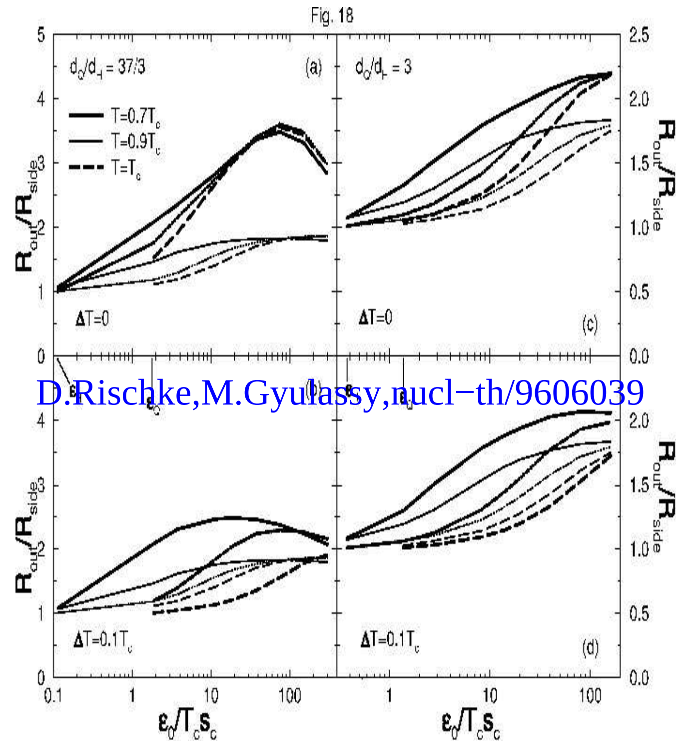


Evaporation suppressed w.r.t. decoupling, , so $\left\langle (\Delta t)^2 \right\rangle \sim \Delta_d$. Higher $\sqrt{s}(\sim T_{initial})$,larger $\left\langle (\Delta x)^2 \right\rangle, \left\langle (\Delta t)^2 \right\rangle$. R_0 and R_s increase, but R_o more.

But if $T_{initial} \simeq T_c$ with a 1st order phase transition, things get interesting!

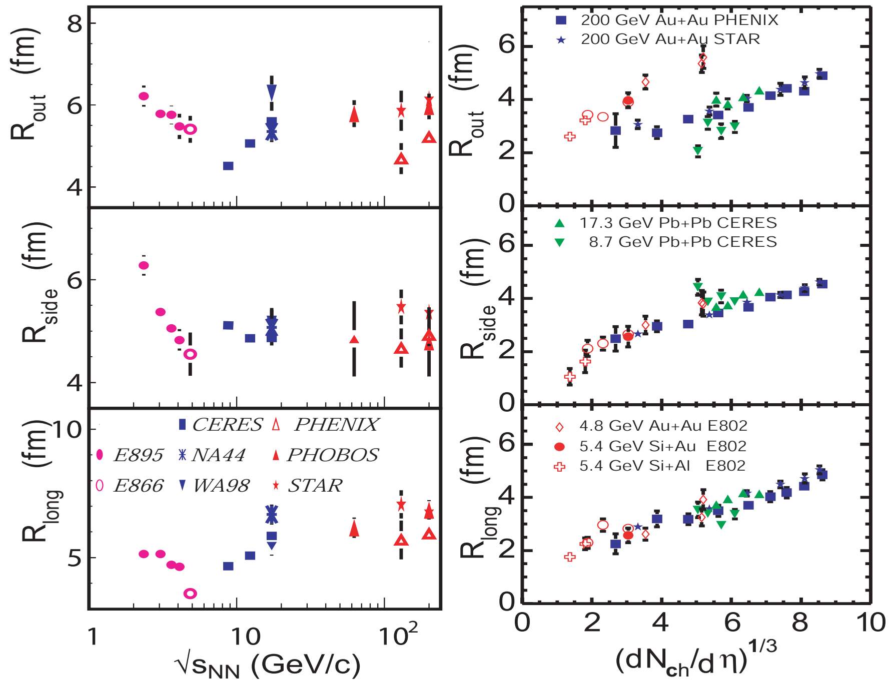






D.Rischke,M.Gyulassy,nucl−th/9606039

The HBT puzzle I We should have hit the transition temperature, but nothing interesting happens to R_o



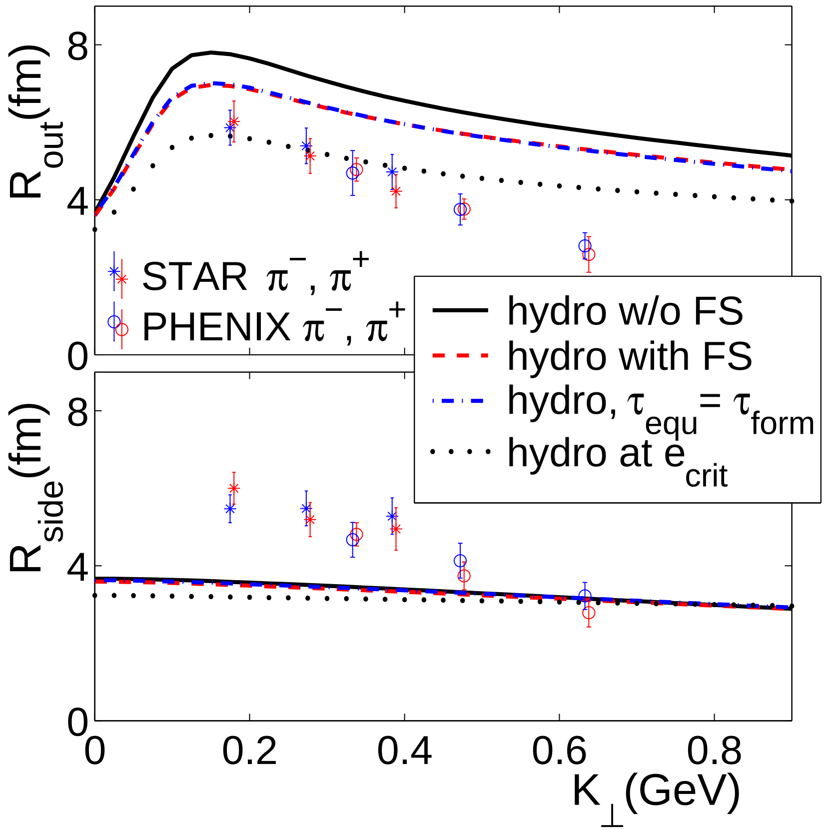
All radiuses constant with energy

(Scale well with $(dN/dy)^{1/3}$)

M. Lisa nucl−th/0701058

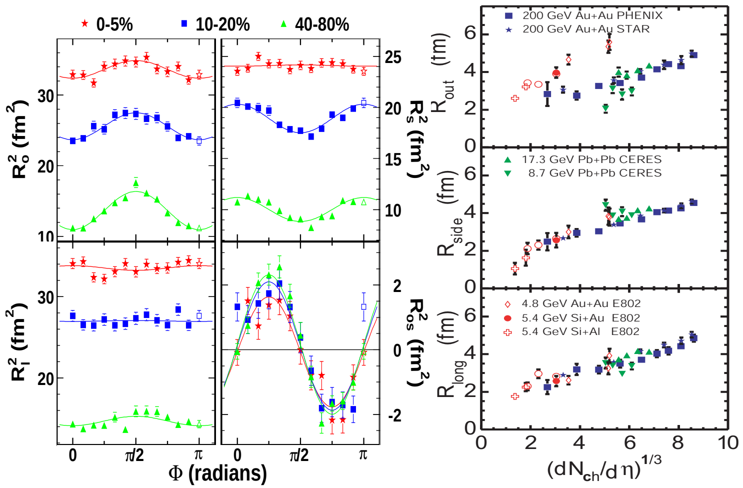
We now know (think?) that it's a corss-over, but an increase in R_o/R_s should still happen

The HBT puzzle II Parameters describing flow do not fit HBT!



Freeze-out proceeds too fast

HBT in some ways too simple



- The scaling with $(dN/dy)^{1/3}$ is just what one would expect for a gas that expands isotropically to a critical average density, and instantaneusly breaks apart.

- Comparing angular HBT with v_2, we see that the time-scale of the collision measured in the two approaches matches.

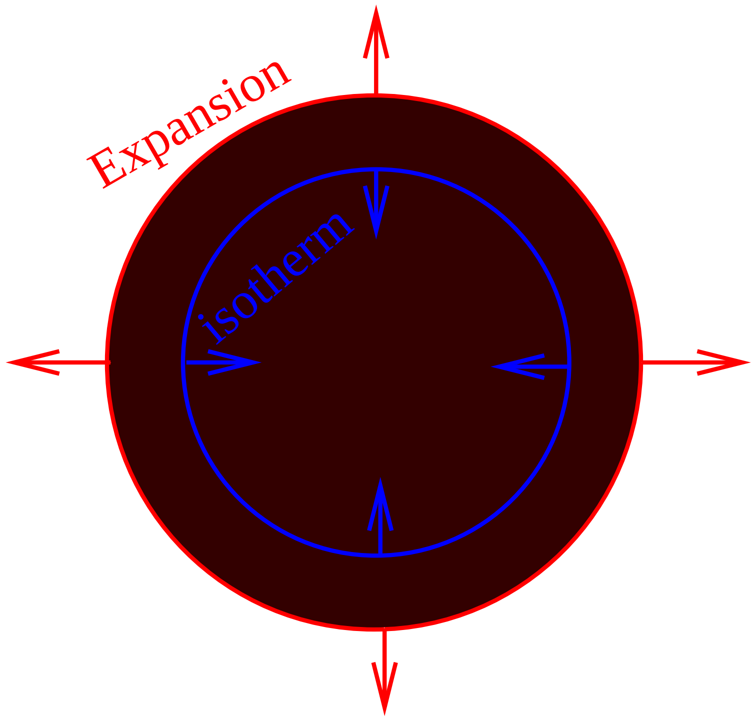
Why not (a) (don't get complacent!)

- That instantaneusly (in lab frame!) is problematic to model within hydro, no matter how many refinements (viscosity, pre-existing flow,afterburner,...) one adds

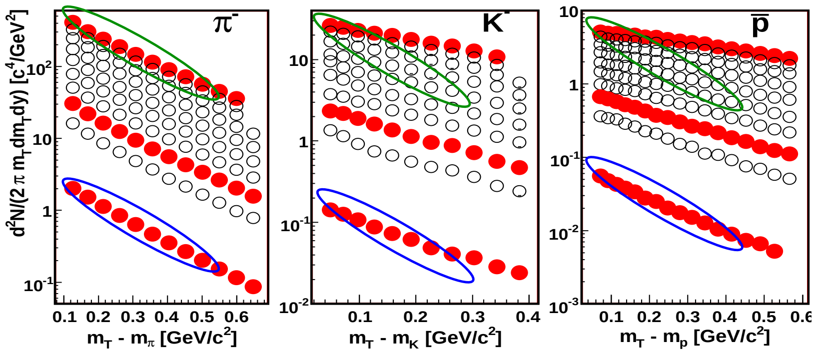
- Its not just that it fails, its how it fails

$$R_o \sim \left\langle (\Delta R)^2 \right\rangle - 2\frac{k_o}{k_0} \langle (\Delta R)(\Delta t) \rangle + \left\langle (\Delta t)^2 \right\rangle \quad , \quad R_s \sim \left\langle (\Delta R)^2 \right\rangle$$

Isotherms usually travel "inwards"
so $\langle \Delta t \Delta x \rangle < 1$,further increasing R_o/R_s . Flow (Lorentz time-dilation) helps, but only so much, at least with approximate boost-invariance.



So do p-p collisions flow??!?!



Not parallel (T and flow)

Nearly parallel (only T)

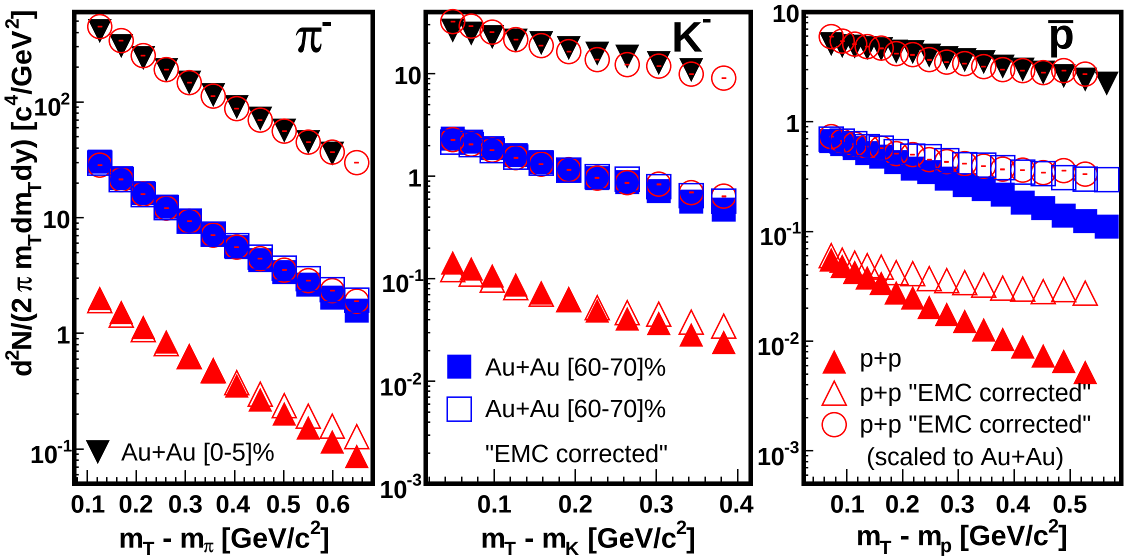
M.Chajecki and M.Lisa, 0807.3569

Does not look like... slopes nearly parallel

...<u>but</u> conservation laws, suppressing higher momentum particles, more important in smaller systems!

$$f(p) \rightarrow \tilde{f}_c(p_1) = \tilde{f}(p_1) \times \frac{\int \left(\prod_{j=2}^{N} d^4 p_j \delta\left(p_j^2 - m_j^2\right) \tilde{f}(p_j) \right) \delta^4 \left(\sum_{i=1}^{N} p_i - P \right)}{\int \left(\prod_{j=1}^{N} d^4 p_j \delta\left(p_j^2 - m_j^2\right) \tilde{f}(p_j) \right) \delta^4 \left(\sum_{i=1}^{N} p_i - P \right)}$$

Correcting flowing distribution for this effect, with same flow assumed between p-p and A-A, gets most p-p spectrum (Z.Chajecki,M.Lisa, 0808.356)



Bottom line: we do not know weather p-p and A-A are different or A-A is merely bigger!!!!

The future: 10 TeV collisions at the LHC.
What do we expect?

$$Bjorken + dN/dy \sim N_{part} \ln s \to T_{LHC} \sim 2 - 3T_{RHIC}$$

Likely (through not certain) coupling constant still strong, so LHC should behave as a “big RHIC”: Soft observables should not change much (Models do exist where increase in T to $\sim 10T_c$) enough for viscosity increase.

But many more jets, at much higher energies. So much more statistics for jet related observables. We hope to understand jet suppression much better

Making predictions is uncertain, especially about the future! Expect surprises!

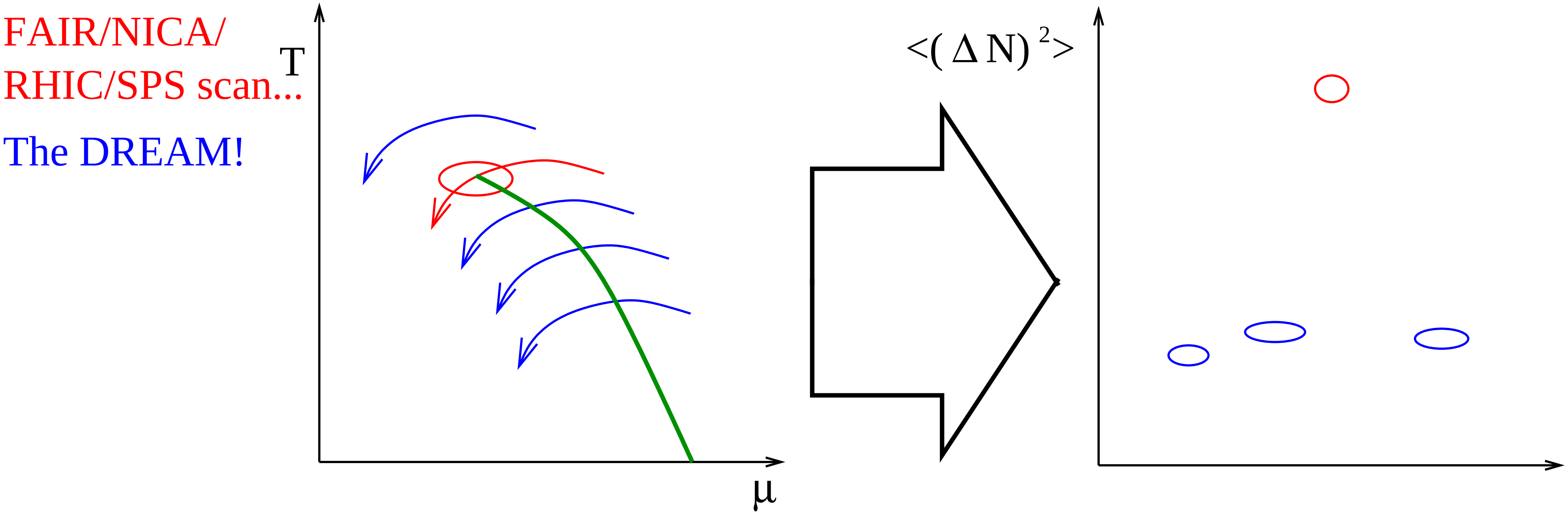
The future: FAIR (Darmstadt),NICA (Dubna) low energy scans at RHIC/SPS
Will hopefully shed some light on the scaling puzzles
Modern detectors, with capability for rare probes (charm,photons etc), making low energy Scans

deconfinement When are quarks really freed?

Critical point searches where is the critical point? How does it manifest itself?

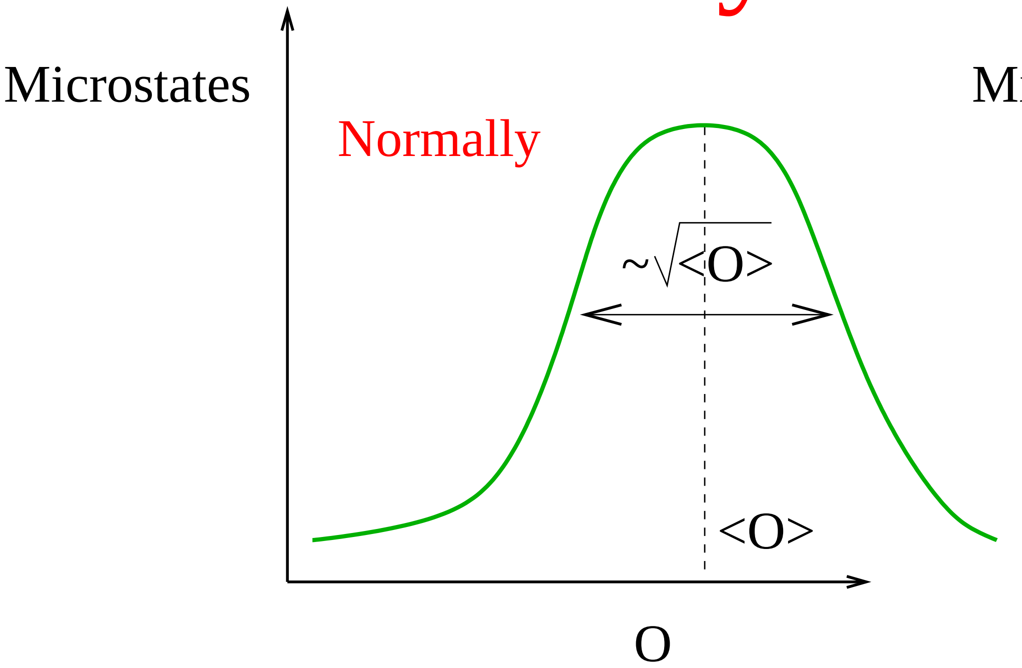
High density quark matter First order phase transition? New phases? (Precursors to color superconductivity?)

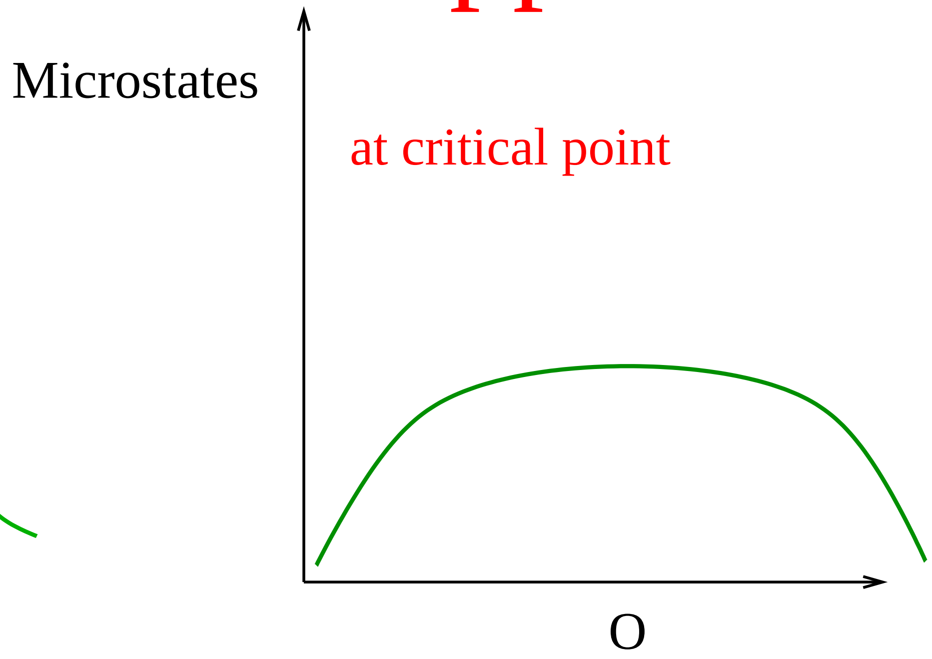
Several projects, expected to start in next decade, in Germany, Russia, existing facilities


FAIR/NICA/
RHIC/SPS scan...
The DREAM!
T
μ
<(Δ N) 2>

Why does this happen?

Why does this happen?





Lots of not so very well understood issues...

Non-equilibrium If system is not in global equilibrium (and connected to a large bath), how do fluctuations evolve?

Other sources of fluctuations Clustering in first order phase transition...

Life time,initial temperature How easy is it to "Miss"/"hit" critical point

In short...

Suprises at high chemical potential?

L.McLerran and R.Pisarski, 0706.2191, asked a very good question!

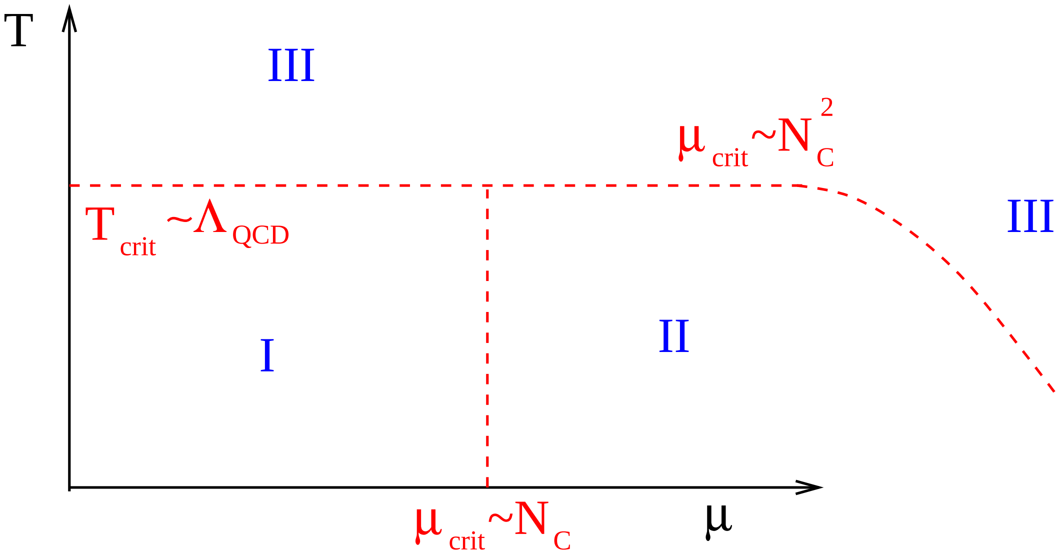
At large N_c

Baryon size stays constant, fixed by confinement scale

Baryon quark number diverges, $\sim N_c$

So inside hadron inter-quark separation $\rightarrow 0$ (Asymptotic freedom, weakly interacting quarks), yet hadrons confined! How is that possible?

Their speculative answer: The Quarkyonic phase (II)



At moderate chemical potential, quarks "inside the fermi sphere" free ($P \sim N_c$), but dynamics entirely hadronic. Possibly, chiral symmetry broken.

No phenomenology yet! But an interesting topic, so experimentalists should expect suprises

To understand whats really going on in heavy ion collisions

To understand strongly coupled field theories

To devise a clear way in which a new state of matter can be experimentally demonstrated

because at the moment, we dont!

This field has a lot of experimental data (existing or to be collected/analyzed), and very profound theoretical puzzles. It needs <u>new</u> minds and <u>new</u> thinking. Lots of research groups all over the world do research in this subject, and there are ample possibilities to join! Almost uniquely, a lot of <u>collaboration</u> between theory and experiment on <u>existing</u> data/puzzles

Spare slides