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

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How protons and Neutrons are made

How protons and neutrons are made

Ingredients: Quarks (3 colors)

3 light flavors: up,down,strange, 3 heavy: charm,bottom,top

Antiquarks: 3 "anticolors" ,antiflavors

Flavor: Particle ”type” (Mass,electric charge)

Color: A more complicated ”electric charge”: a neutral object can be made by

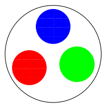
- Combining a ”Color” with Anticolor
- Combining all three colors

Theory: Quantum chromodynamics.In analogy with Quantum electrodynamics

Naive picture (circa '60s): All particles influenced by nuclear force (protons, neutrons,mesons,...) are <u>color-neutral composites</u> (sort of like atoms are charge-neutral composites of protons and electrons)

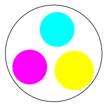
How to make a color−neutral composite:

Baryon
3 quarks



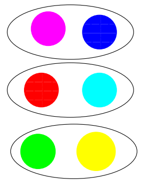
Protons
Neutrons
"strange hyperons"
(Λ,Ξ,Ω)

Antibaryon
3 anti−quarks



Antibaryons

Meson
Quark+Antiquark



π,K,η,ϕ,ρ,...

All particles fall neatly into this <u>classification scheme</u>. Kind of periodic table: Charge, spin, mass correlated. M. Gell-man won Nobel for noticing

Quantum mechanics: Energy and time "uncertain"

Relativity: $E = mc^2$, so particle mass $\Leftrightarrow$ energy

Therefore:
Number of particles in any system is always uncertain. all systems (including empty space) are composed of an "infinite", always fluctuating number of particles.

$$\underbrace{\Delta E}_{Energy\ \ violation} \times \underbrace{\Delta t}_{Fluctuation\ \ duration} \sim \underbrace{h}_{Plank's\ \ constant}$$

this is not good! In Classical mechanics the 3-body problem is unsolvable exactly. In Quantum mechanics all systems are infinite-body problems!

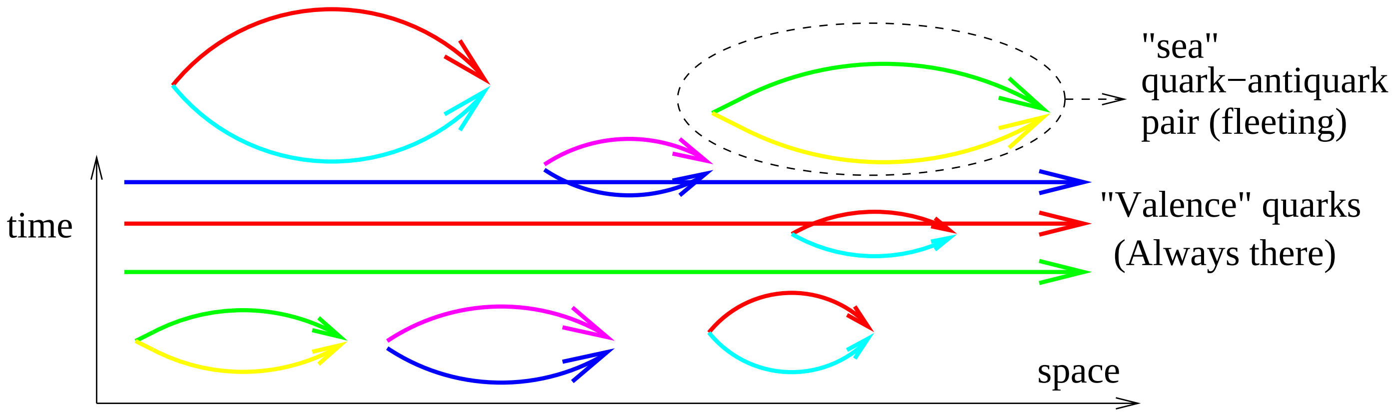
Electromagnetism: Particles are heavy with respect to energy of interaction

$$mc^2 >> \frac{Q^2}{r}$$

fluctuations small, n. of particles "nearly" fixed.
(And calculations possible to any precision)

Inter-Quark force: Fluctuations dominate! Everything (including the vacuum) is a coherent many-body system

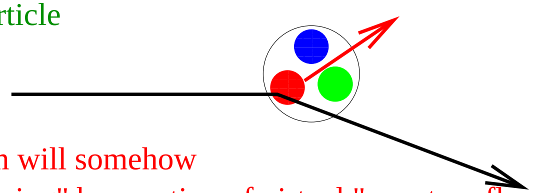
A schematic view of a proton:



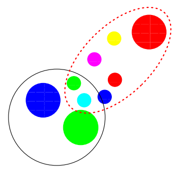
Quarks-Antiquarks is always 3 (or 0 for mesons). But Quarks+Antiquarks can be anything!(In fact, it depends “how” you look at a proton).

One non−trivial effect: Confinement of quarks

If we try to "free" a quark, for instance by "kicking it" with a colliding particle



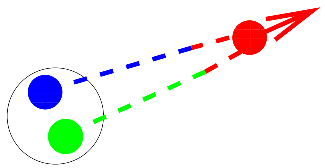
The vacuum will somehow
start "polarizing" by creation of virtual "quantum fluctuations"



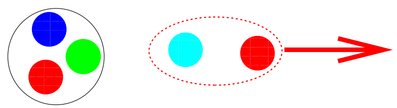
These virtual particles will form some sort of "chain",so,
unlike electromagnetism, quark force INCREASES with distance

Quark force ~ kr

Electromagnetic force: $\frac{k}{r}$



Eventually enough energy will be spent to create EXTRA quark pair



So instead of free quarks, we've made MORE
(Color−neutral) particles.

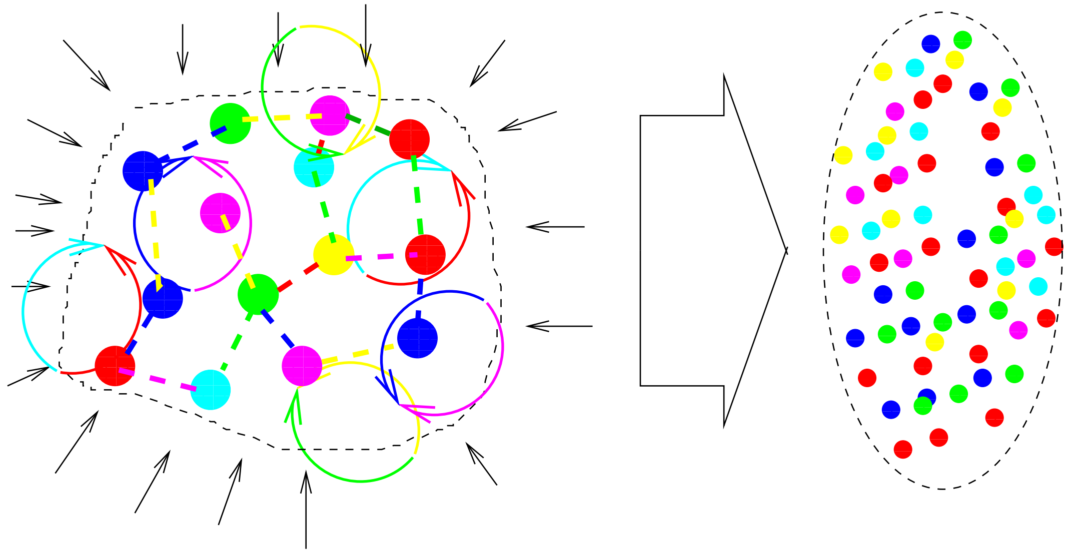
- Bottom line: Color force behaves like a chain:
  - At small distances/large energies force is weak, and similar to electromagnetism (predictive)
    This is how we tested QCD!
  - At large distance, it becomes larger due to infinite particles produced by quantum vacuum excitations
    we can't calculate that from first principles, except with numerical models ("Lattice QCD") hard to connect to physics !
  - The energy within the chain also adds to quark mass, so constituent quarks ~ 300 times heavier than "bare" quarks

If that looks vague, it's because no one really understands how confinement works!
We know quarks are fundamental, but we don't know how to use them to describe composite objects.

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

- Small separation $\longrightarrow$ no room for chain
- Large temperature $\longrightarrow$ 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 <u>move freely</u> and <u>interact weakly</u>. Properties can be <u>calculated</u> 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!

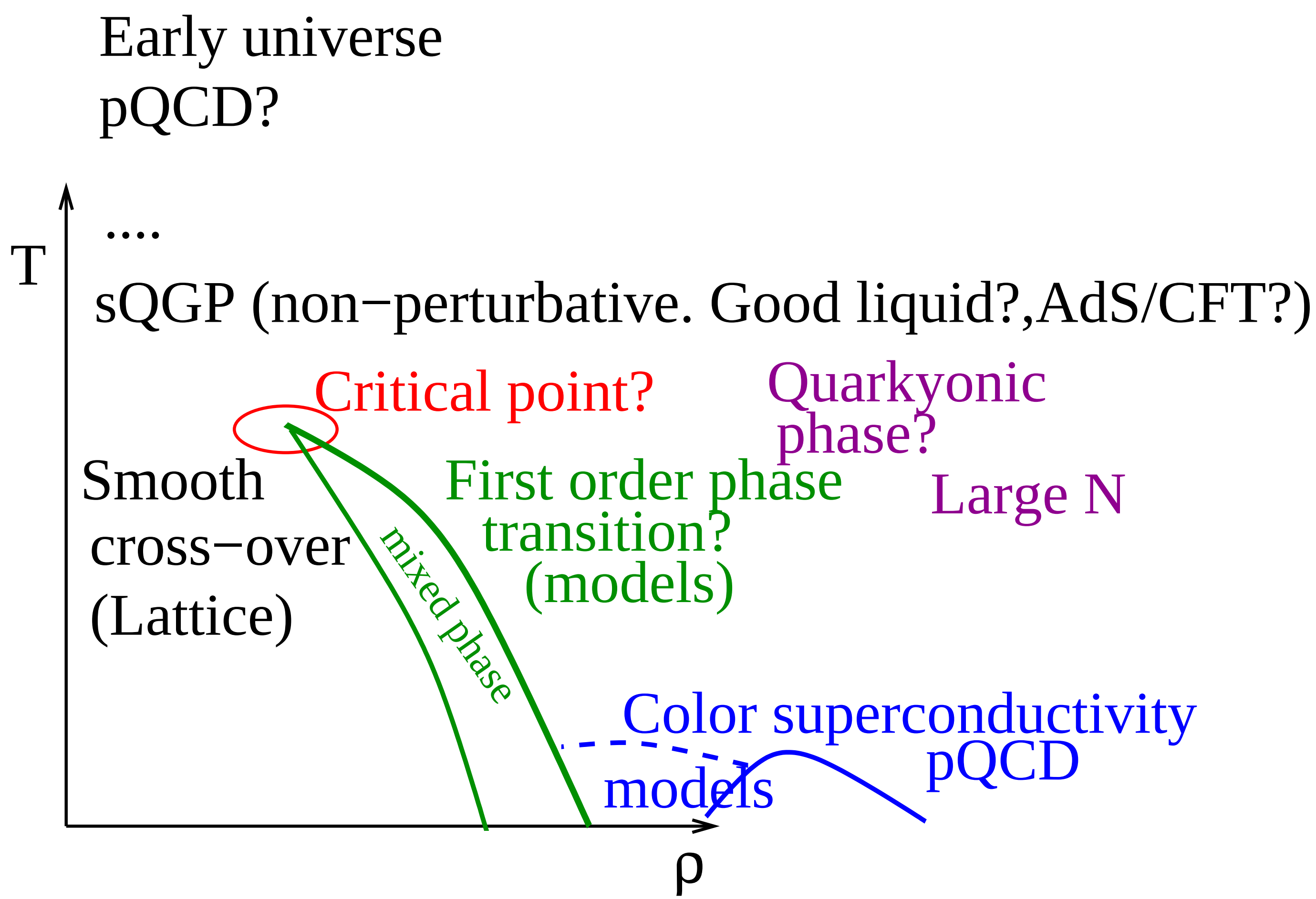
- The early universe was a quark gluon plasma
  Understanding quark-gluon-plasma $\Leftrightarrow$ understanding the big bang!

- 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!

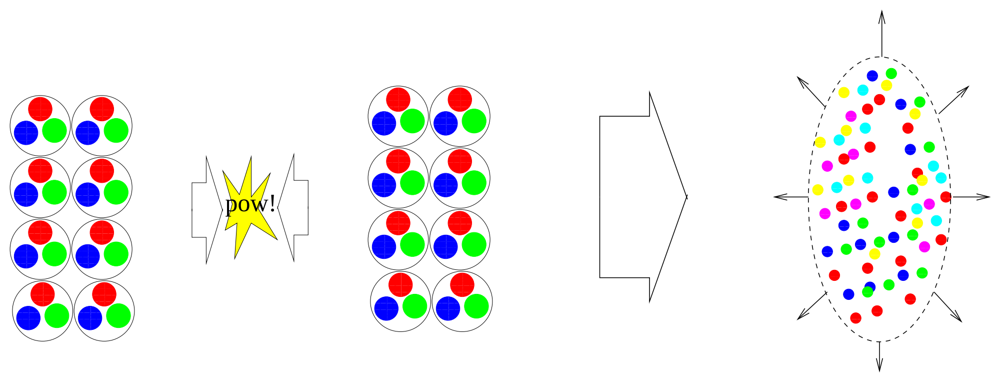


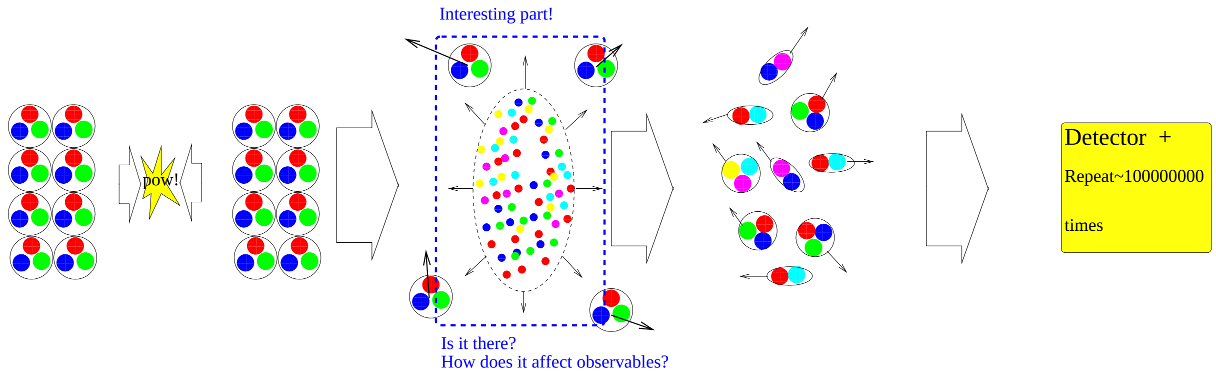
But how do we study this experimentally?

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".



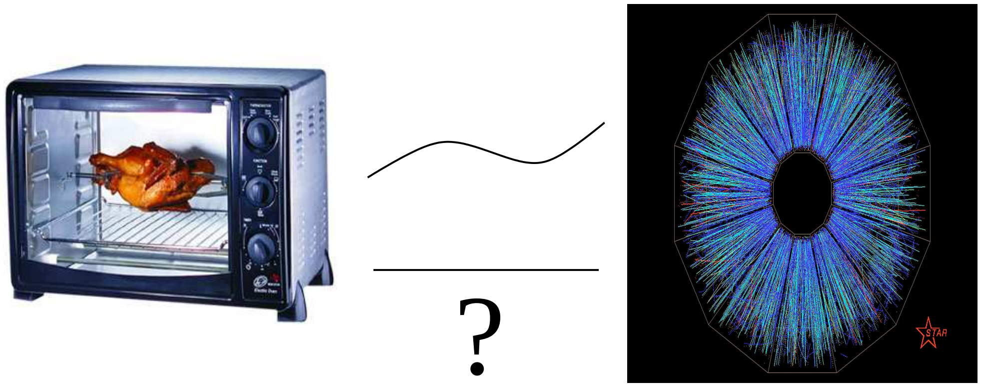


- How do we know a QGP was created?
  Is the circled region in the middle of picture actually there?

- 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!

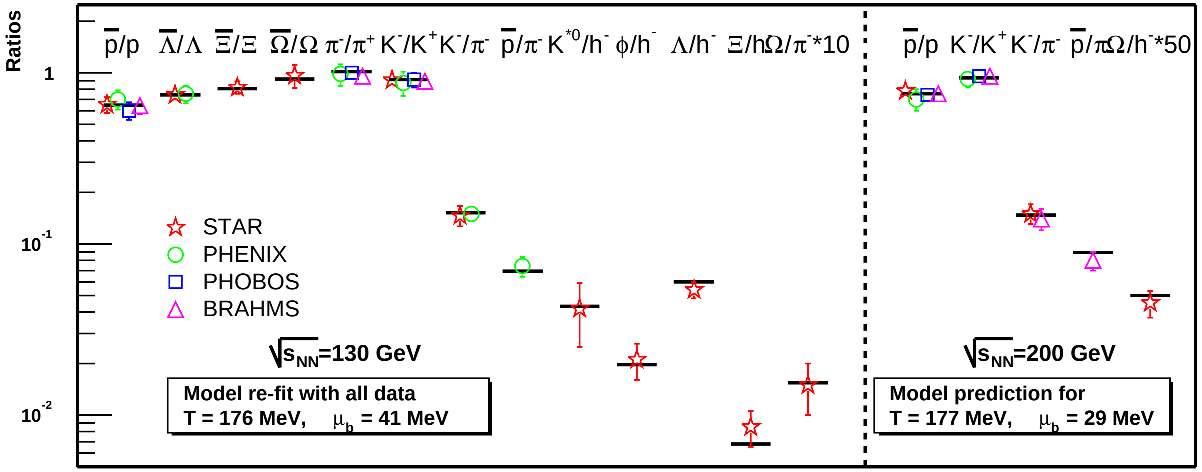
The problem in a nutshell...



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!

A fluid suggests that miscroscopic properties of the system are governed by thermodynamics/statistical mechanics Is that correct?



It seems to be! Fitting particle abundances to temperature gives good description of all particle yields! Final temperature $\sim$ 1 trillion degrees (phase transition temperature).

But questions remain:

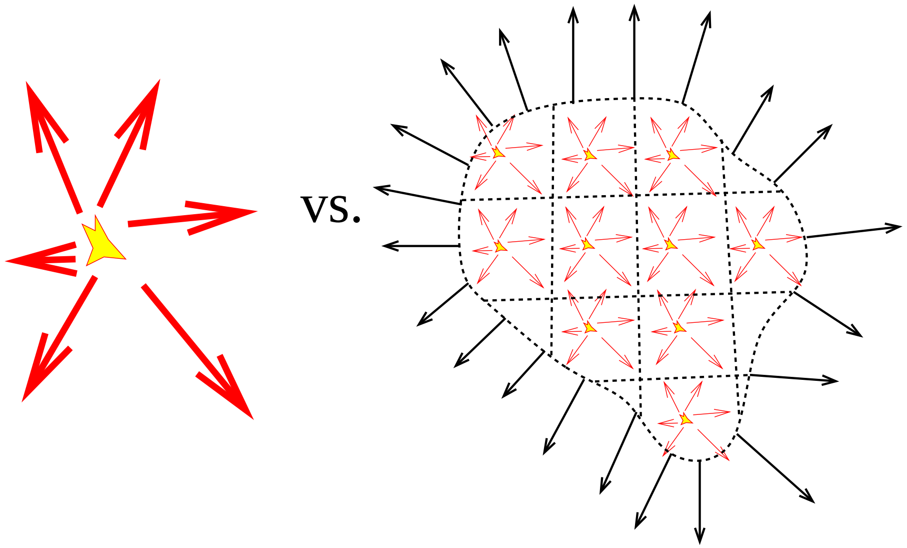
- Many statistical models on the market! (chemical non-equilibrium? What is the decoupling temperature/final system volume?)

- How does the system decouple? What is the role of interactions after particle formation?

- Energy/system size dependance of temperature/density not well understood.

Need a probe capable of killing models.

Equilibration, especially "fake" equilibration, is different from LOCAL equilibration

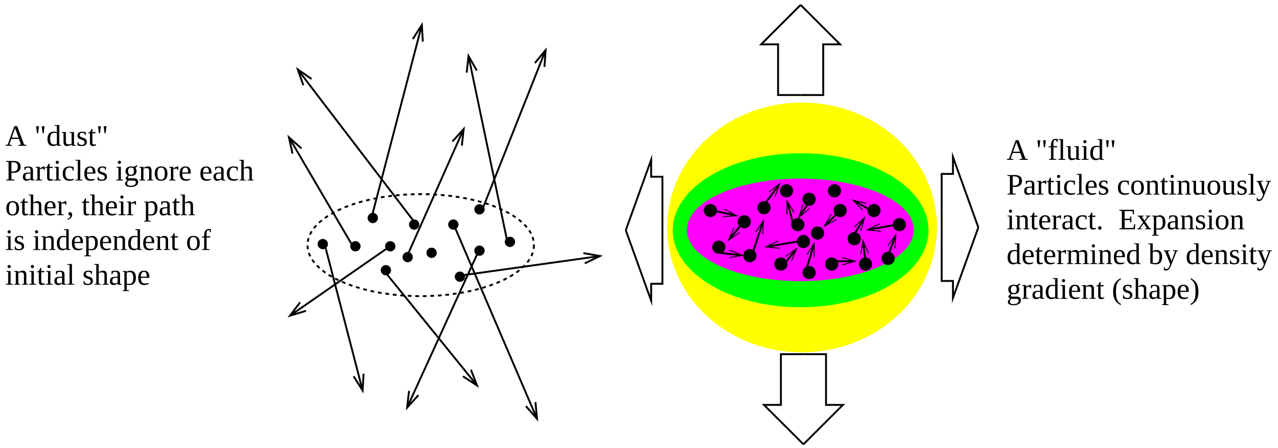


A "Phase transition" only really makes sense in the latter case

Signature of local thermalization: Pressure $\longrightarrow$ collective flow!

Changes in equation of state, viscosity etc. $\longrightarrow$ transition

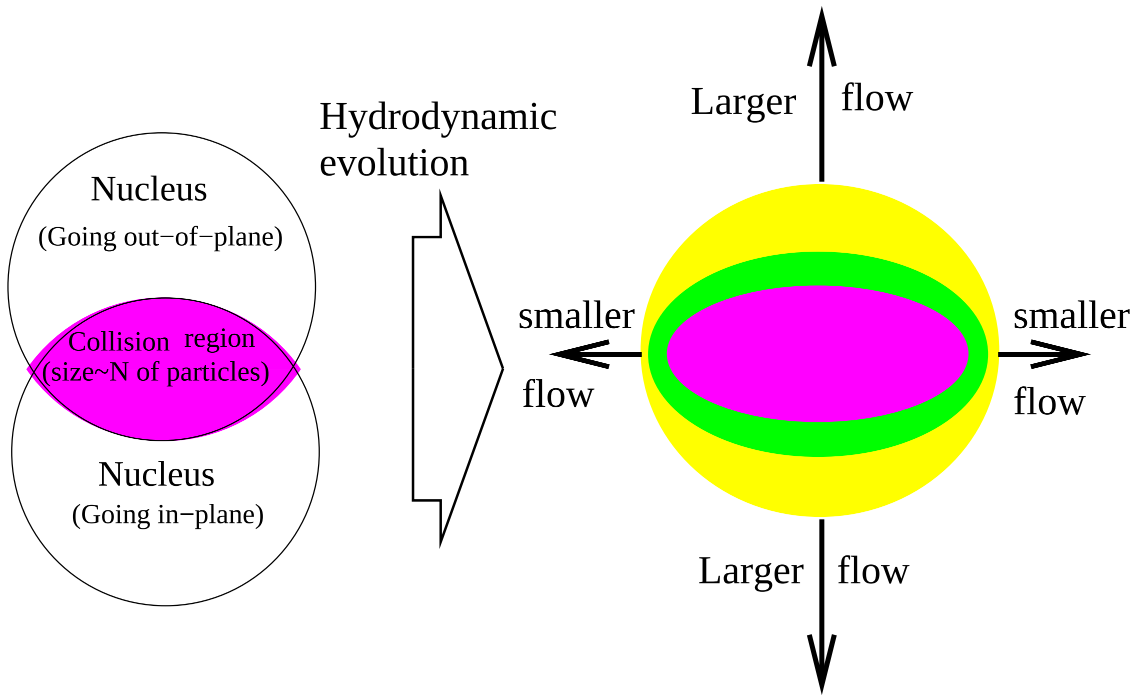
What kind of "medium" is created in nuclear collisions?

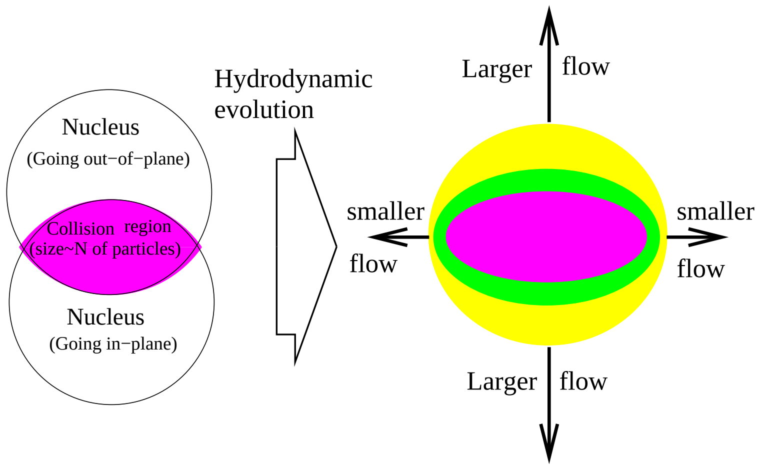


Is it a dust or a fluid? <u>Quantitatively distinguished by</u>

- "mean free path" between collisions (0 for fluid, infinite for dust)
- viscosity, "friction" of response to shape changes (zero for "perfect fluid").

This question can be quantitatively investigated:

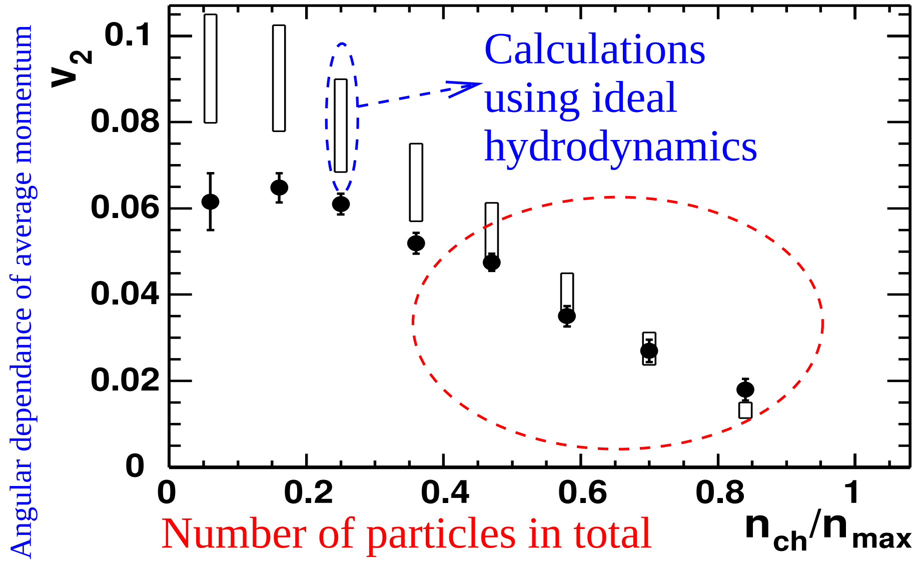




Hydrodynamics predicts flow eccentricity as a function of number of particles ($\sim$ area of overlap region). Parametrized by 2nd Fourier component, v_2

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

Input in hydro: Equation of state (lattice), viscosity (parameter, not really known), initial conditions (Potentially big systematic error)



- Data described by ideal hydrodynamics (mean free path between particle collisions is zero! (Viscosity not much bigger than “lowest viscosity” conjectured by string theory!)

- But QGP should naively <u>not</u> be like that: Ideal gas $\longrightarrow$ large mean free path

Apparent speed of thermalization of matter formed@RHIC still a mistery (strong coupling? Plasma instabilities?)

A summary of what we know

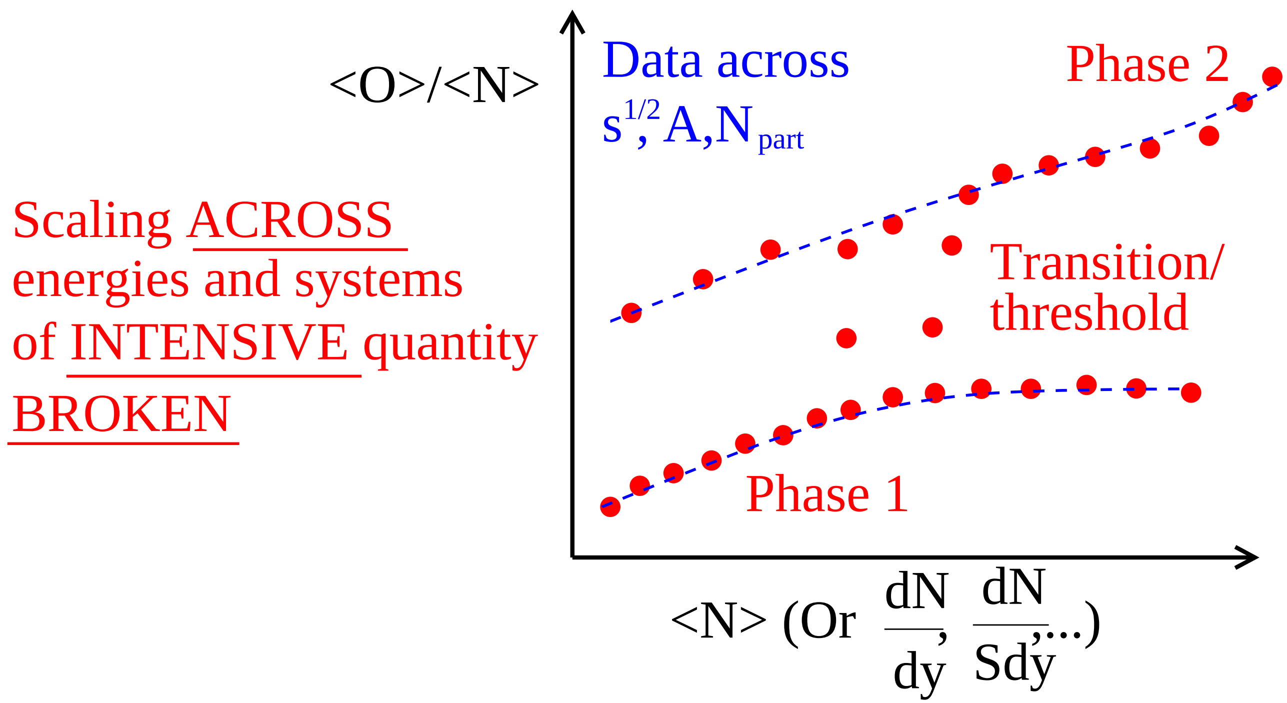
- The system seems to be locally thermalized and strongly (non-perturbatively) coupled
- It is most likely a system of quarks, since hadrons thought to be weakly coupled. Beside... density is thought to be way too high for hadronic degrees of freedom to be relevant

What we do not know

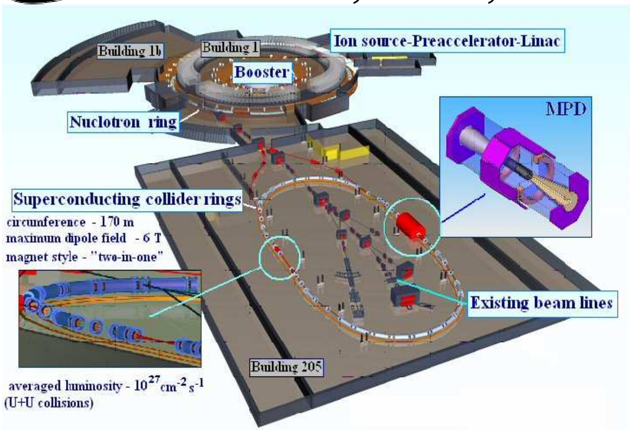
- What is the threshold for this fluid regime in energy and system size?
- Is it associated with a phase transition? Lattice simulations say its not a phase transition at small chemical potential. Analytically, its likely to be at large chemical potential. critical point?

How could we find out?

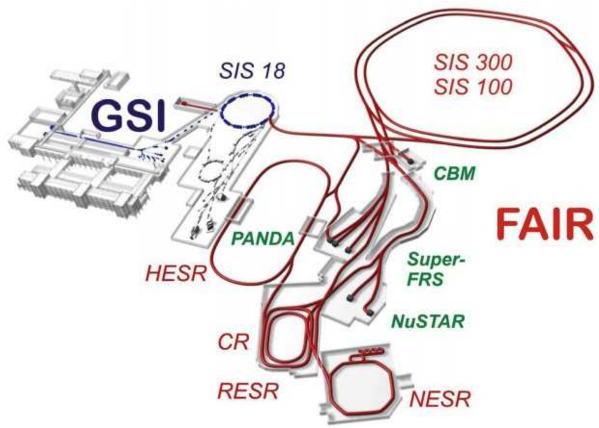
Vary Energy, impact parameter, system size etc... as much as possible.
Look for scaling violations.



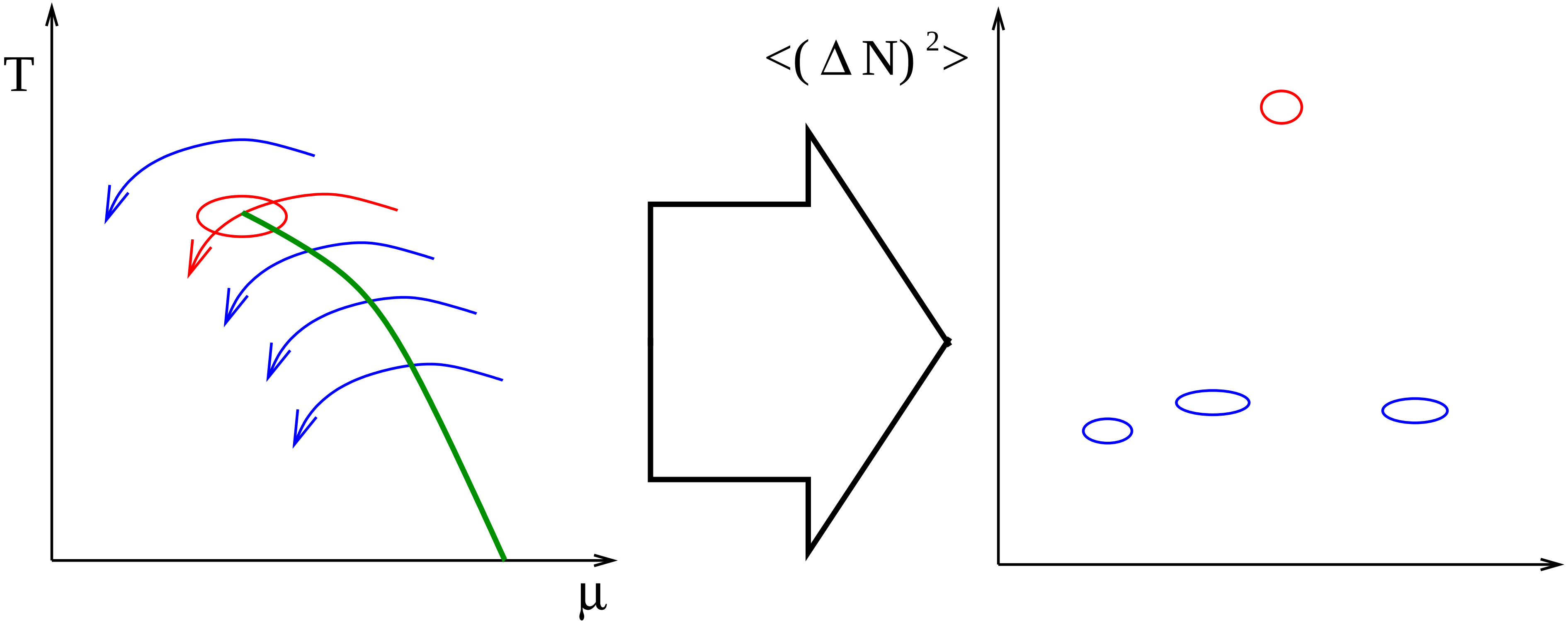
NICA,Dubna,Russia



FAIR,GSI,Germany

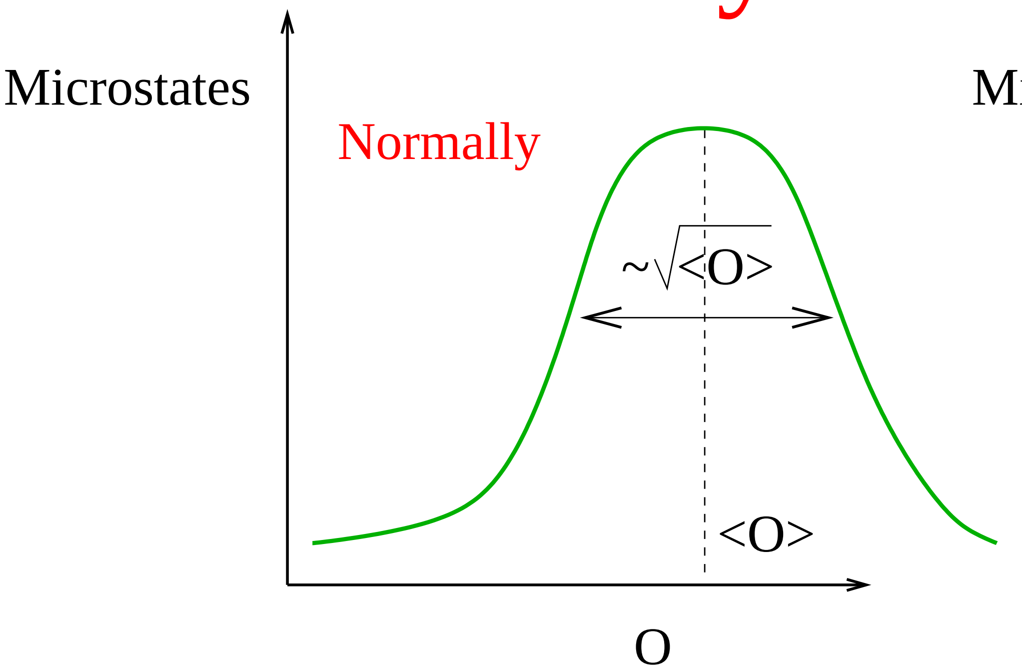


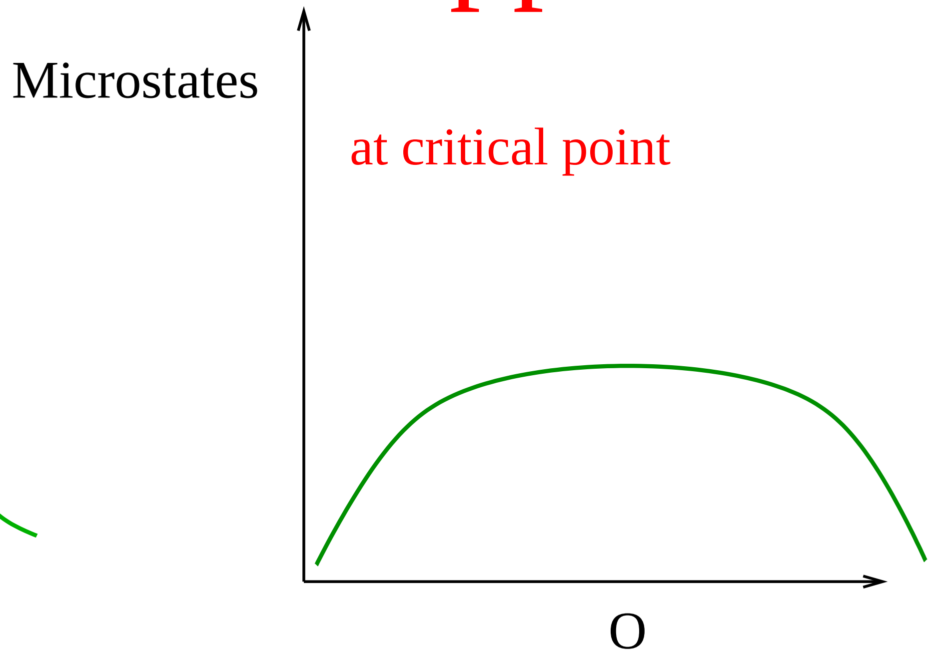
Things to watch out for... fluctuations



Why does this happen?

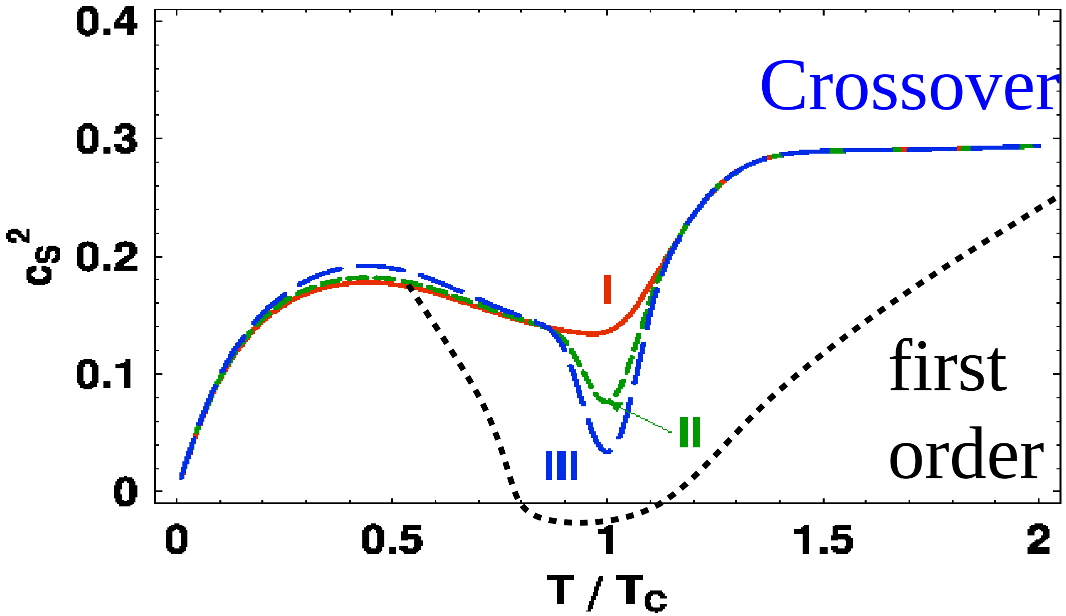
Why does this happen?





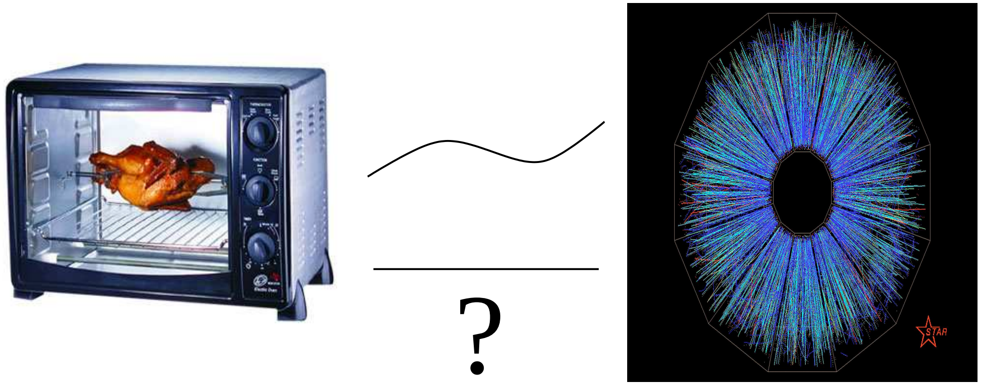
Things to watch out for... latent heat

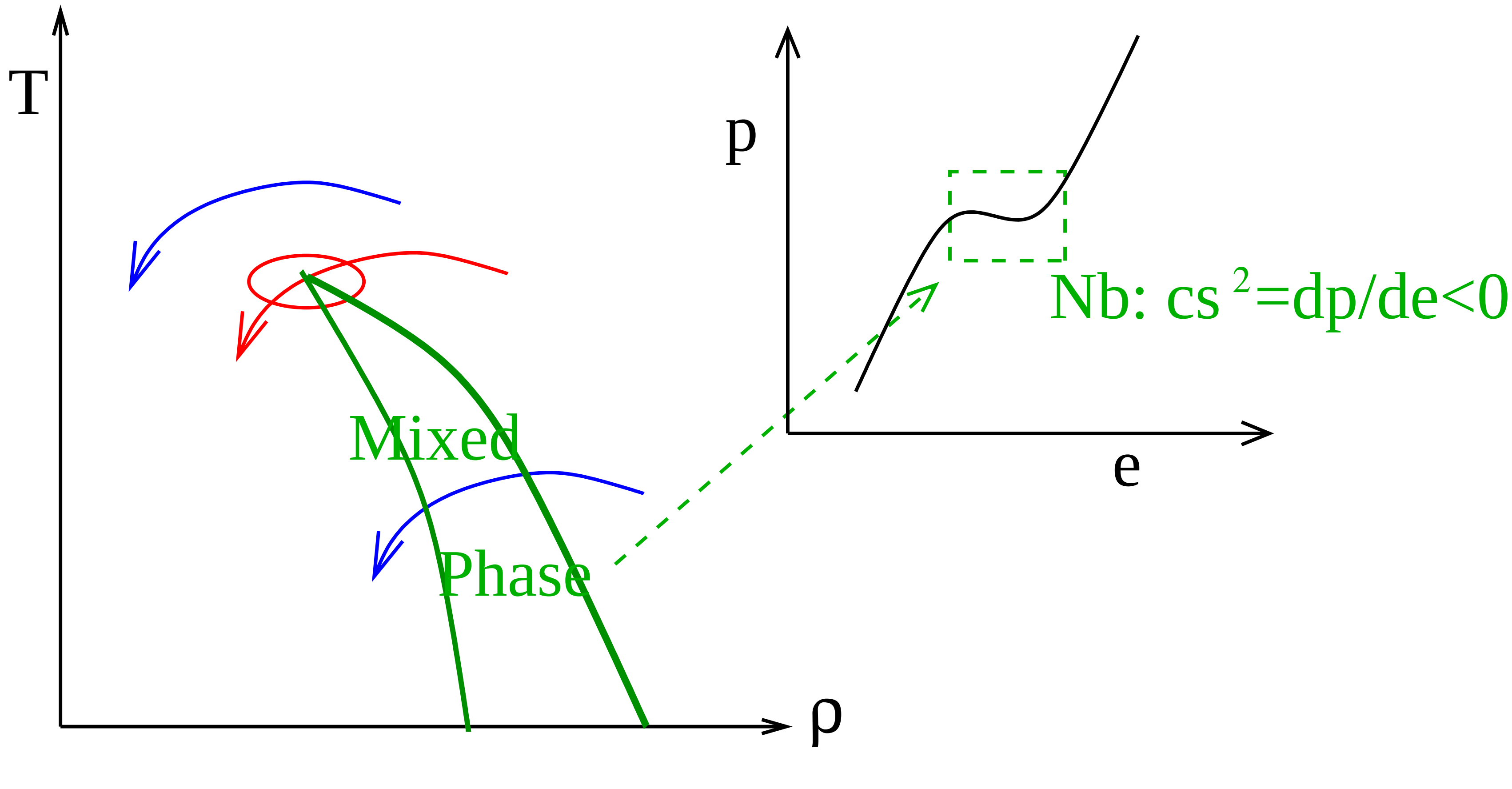
Speed of sound collapses in mixed phase



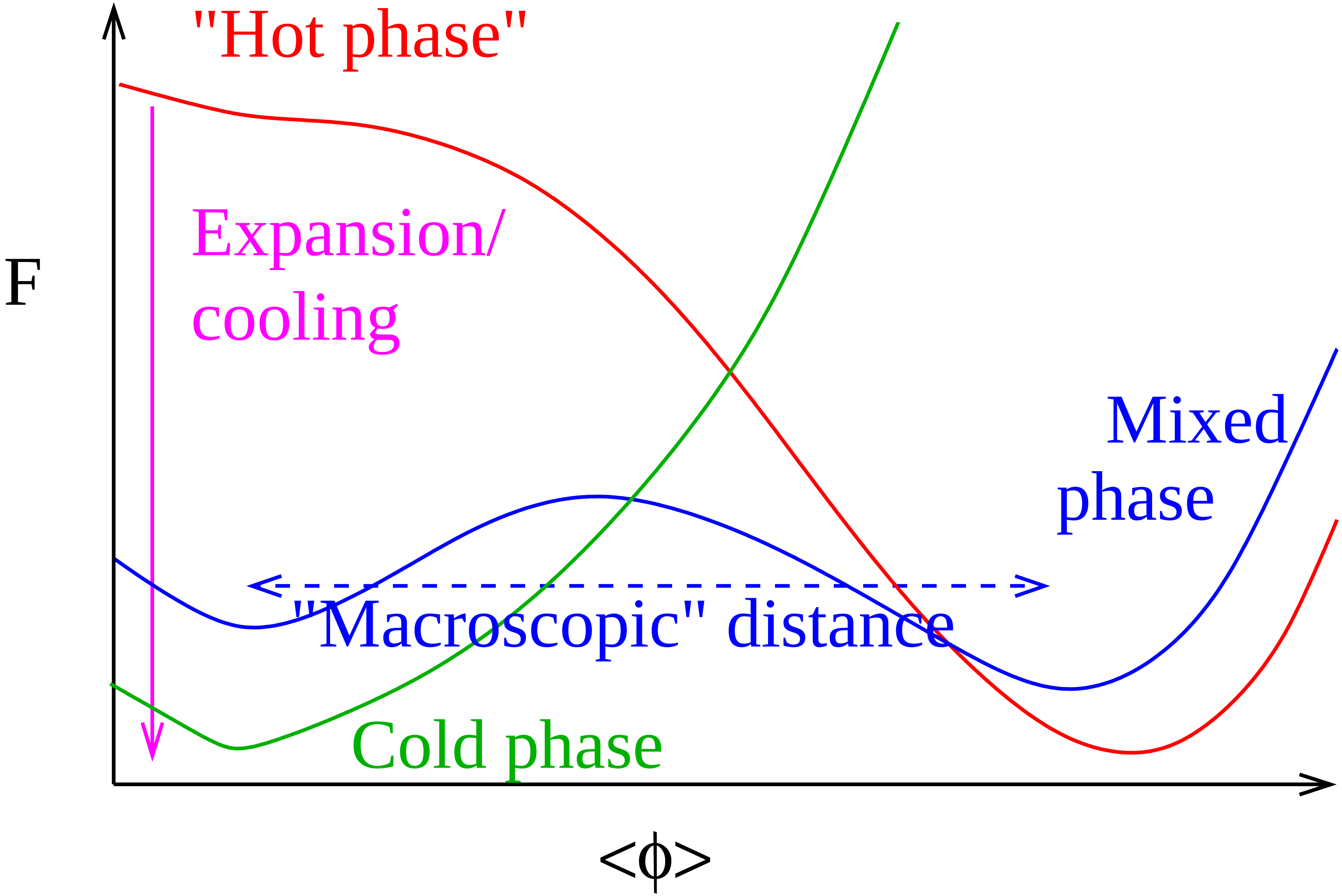
Latent heat characterized by vanishing speed of sound, which determines expansion velocity of shocks. Expect flow phenomena (Slope of p_T distribution, v_2) to suddendly collapse

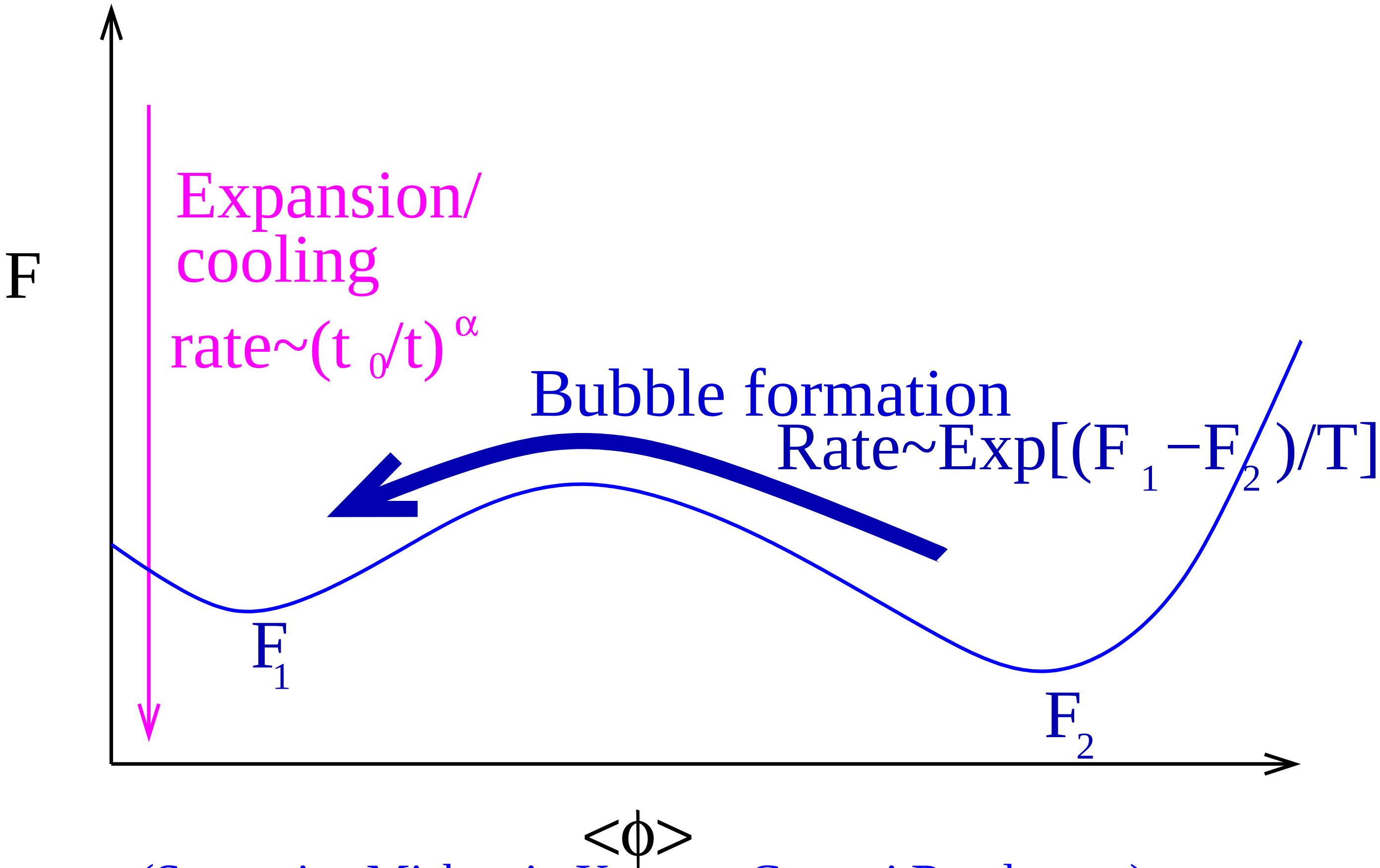
Problem...





T
ρ
Mixed
Phase
p
e
Nb: cs 2=dp/de<0


"Hot phase"
F
Expansion/
cooling
Mixed
phase
"Macroscopic" distance
Cold phase
<ϕ>

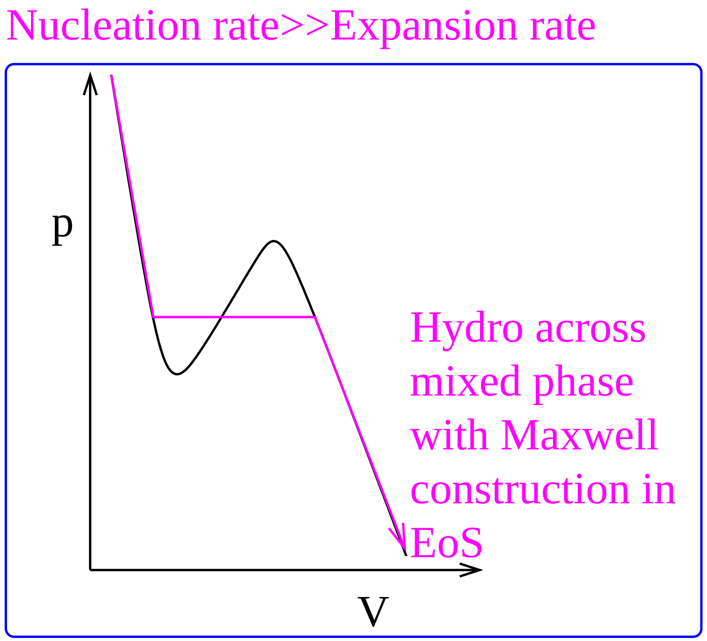


(Scavenius,Mishustin,Kapusta,Csernai,Randrup,...)

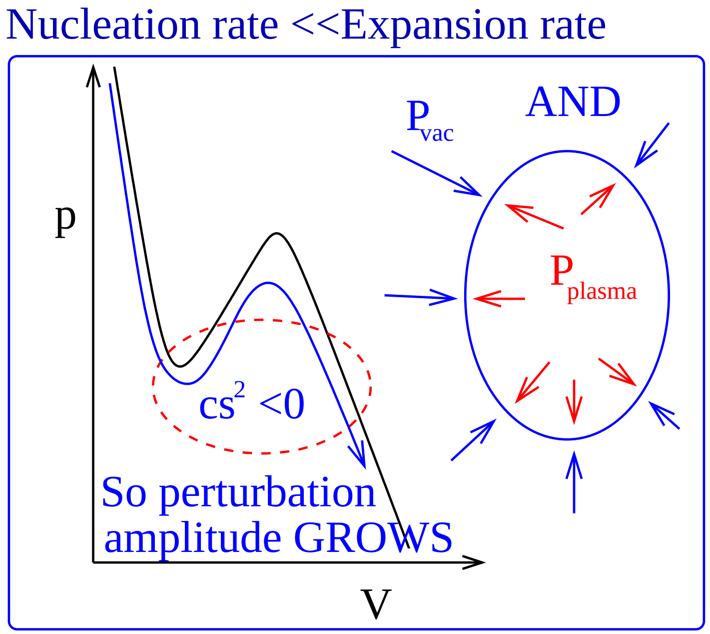
NOT necessarily fast w.r.t. cooling

i.e. no scale separation even for low Kn

Can seed "Large" event−by−event perturbations



Generally stable



Generally unstable

Instability <u>not</u> the same as the critical point fluctuations, NOT an equilibrium process at a global scale. It requires time to build up. But <u>phenomenologically</u> distinguishing them nontrivial. Need a <u>full</u> calculation of instability building rate. $A_0 \exp\left[cs^2 t_{mixed\ \ phase}\right] > A_{background}$?

Conclusions

- Statistical mechanics and hydrodynamics look applicable
  We seem to have created a thermalized system

- How does this "switches on" as conditions (energy and size are changed?)
  Where are we in the phase diagram? And can we study its features?We dont know!