Relativistic Heavy Ion Physics

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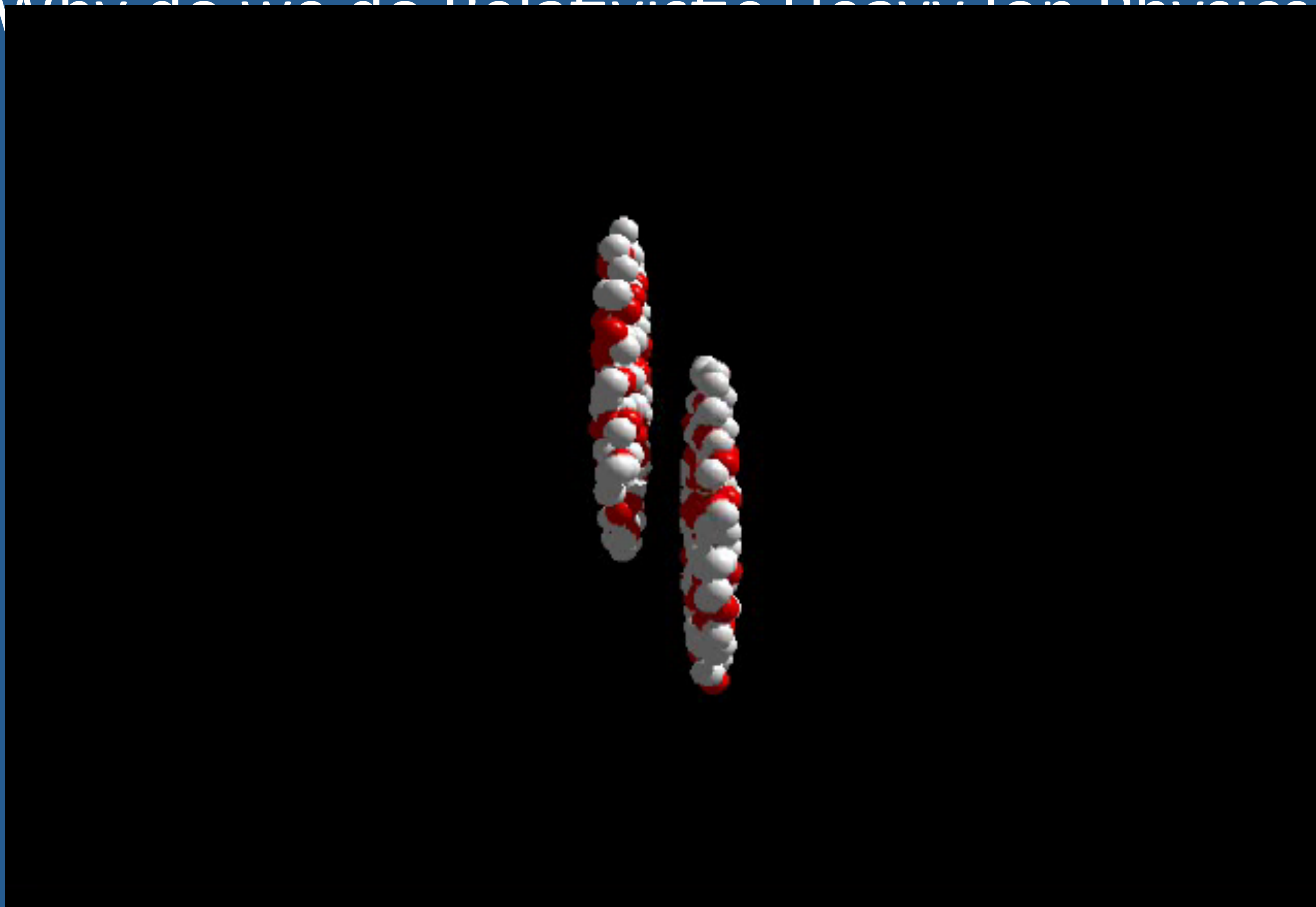
Why do we do Relativistic Heavy Ion Physics?

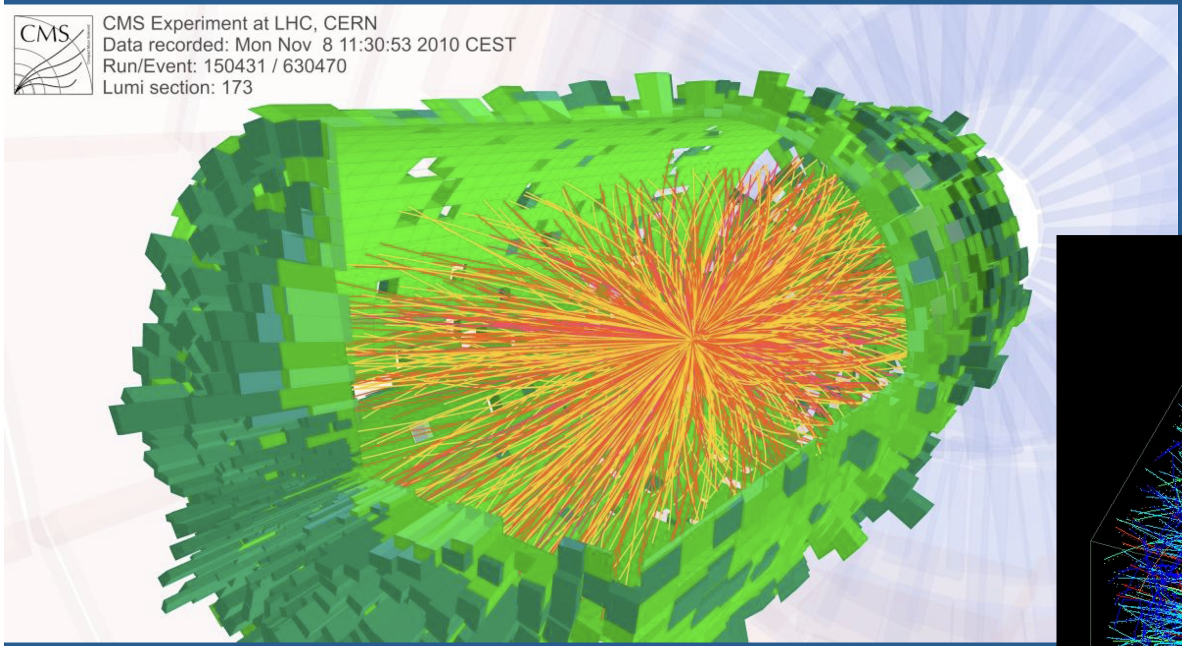
Goal: Create the hottest matter on earth
(Quark-Gluon Plasma)

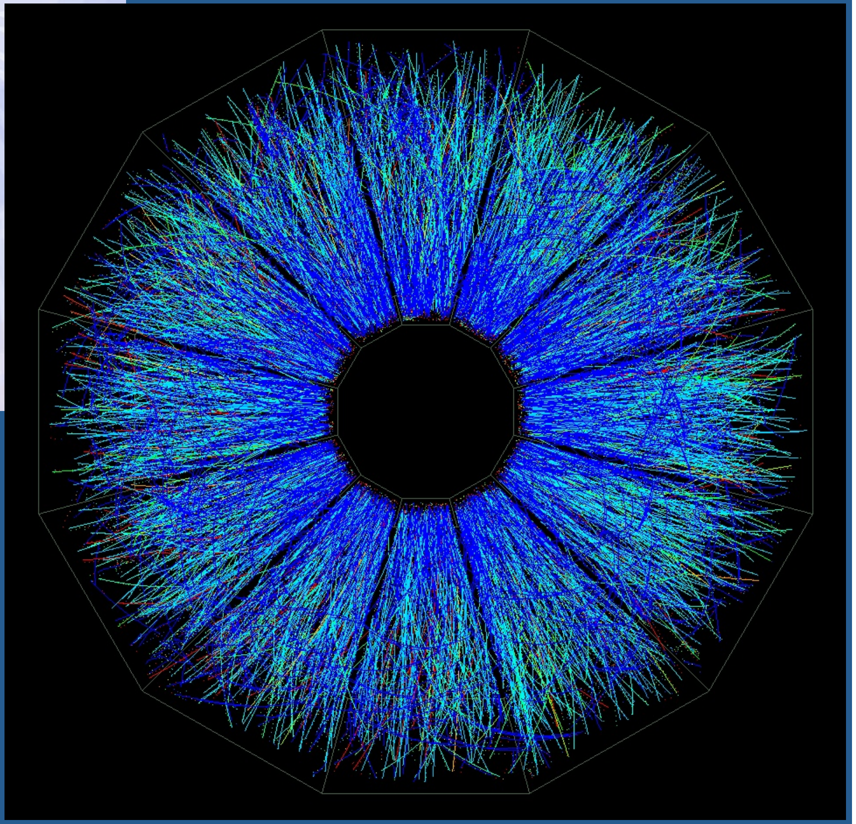
A relativistic heavy ion collision:
Two nuclei colliding at $\sqrt{s}$ ~ 1 – 10000 GeV
Thousands of new particles are produced.
The product of the collision is NOT a simple superposition of elementary nucleon-nucleon collisions.

Why do we do Relativistic Heavy Ion Physics?



Heavy Ion Events in Detectors:



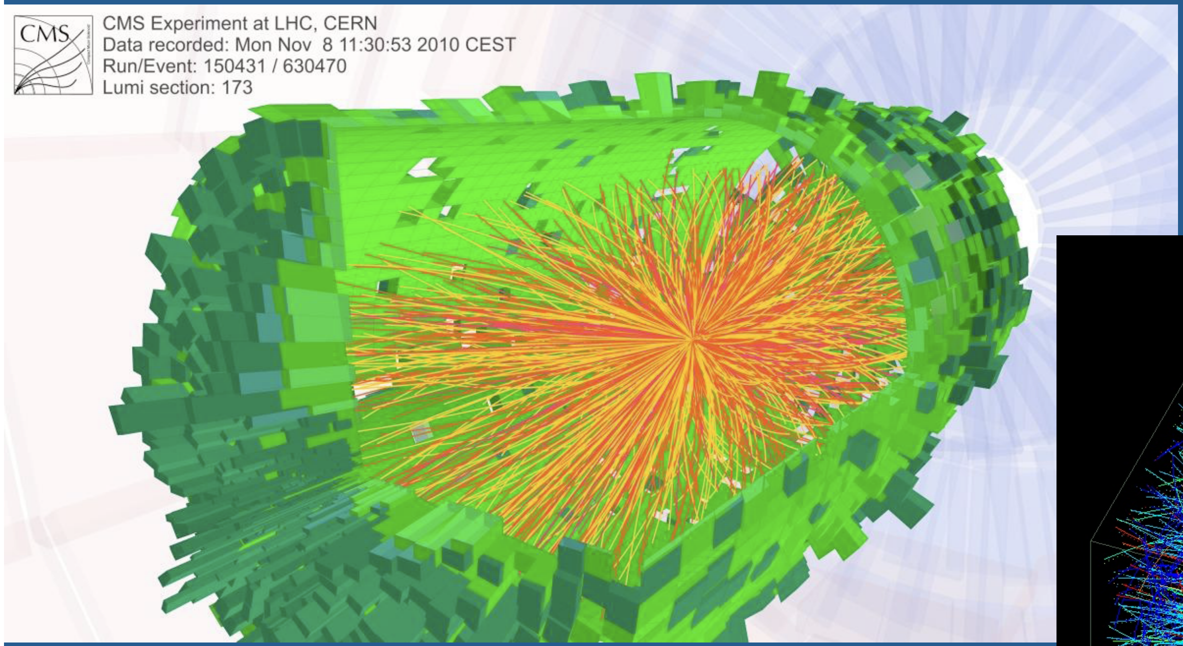


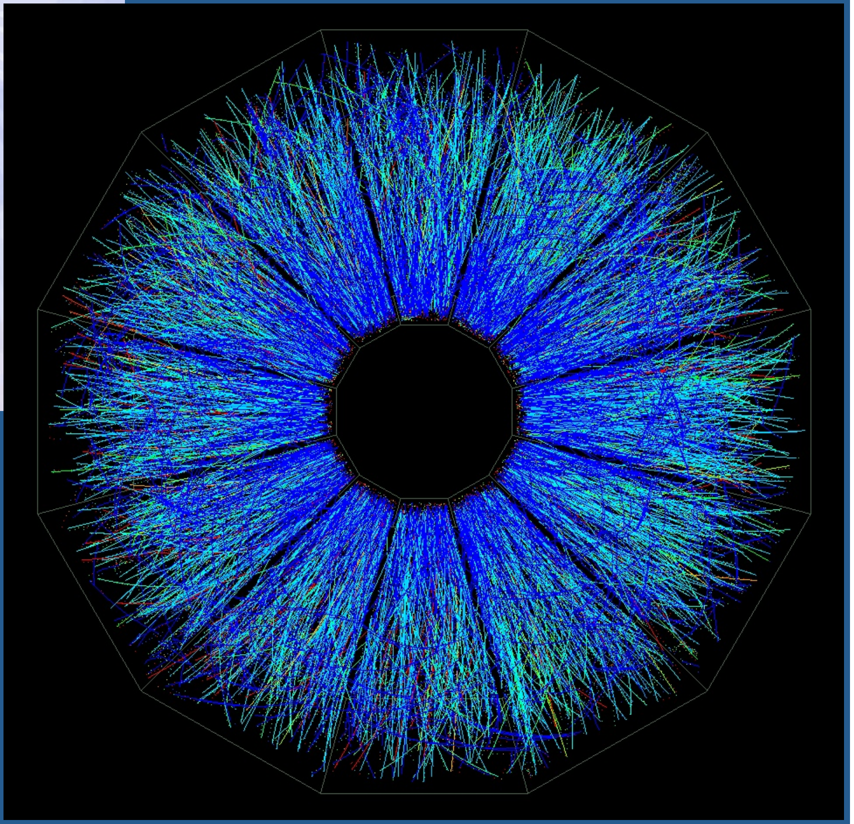
Q1: ***Why*** **measure such complexity?**

Q2: How to measure such complexity?

Q3: What did we learn so far?

Heavy Ion Events in Detectors:



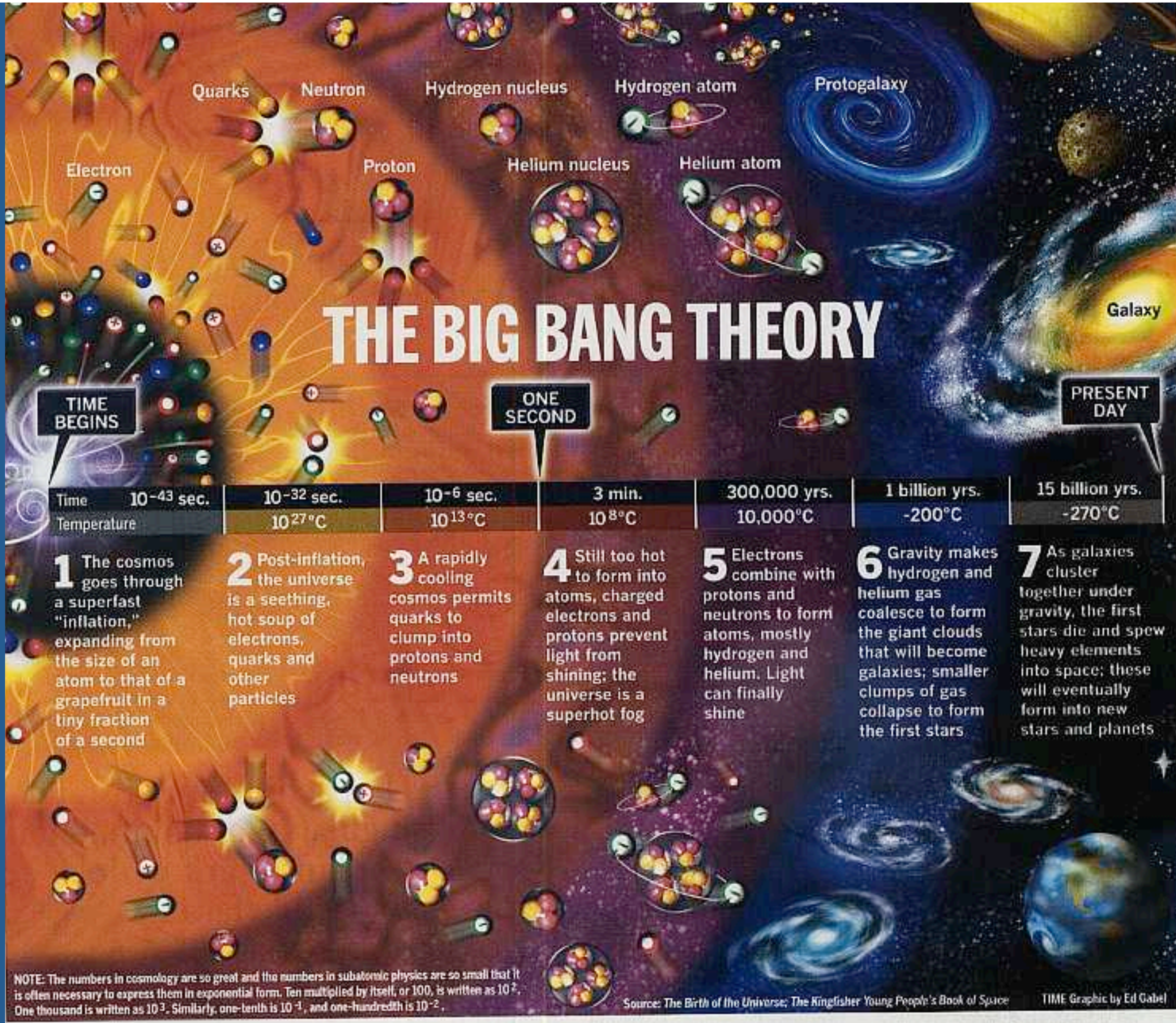


Q1: ***Why*** **measure such complexity?**

Q2: How to measure such complexity?

Q3: What did we learn so far?

- **Verify existence of QGP**
- **Study properties of QGP**
- **Use external and internal probes**
- Small viscosity perfect liquid.
- Opaque to fast partons


Quarks
Neutron
Hydrogen nucleus
Hydrogen atom
Protogalaxy
Electron
Proton
Helium nucleus
Helium atom
THE BIG BANG THEORY
Galaxy
TIME BEGINS
ONE SECOND
PRESENT DAY
Time | 10-43 sec. | 10-32 sec. | 10-6 sec. | 3 min. | 300,000 yrs. | 1 billion yrs. | 15 billion yrs.
Temperature | 1027°C | 1013°C | 108°C | 10,000°C | -200°C | -270°C
1 The cosmos goes through a superfast "inflation," expanding from the size of an atom to that of a grapefruit in a tiny fraction of a second
2 Post-inflation, the universe is a seething, hot soup of electrons, quarks and other particles
3 A rapidly cooling cosmos permits quarks to clump into protons and neutrons
4 Still too hot to form into atoms, charged electrons and protons prevent light from shining; the universe is a superhot fog
5 Electrons combine with protons and neutrons to form atoms, mostly hydrogen and helium. Light can finally shine
6 Gravity makes hydrogen and helium gas coalesce to form the giant clouds that will become galaxies; smaller clumps of gas collapse to form the first stars
7 As galaxies cluster together under gravity, the first stars die and spew heavy elements into space; these will eventually form into new stars and planets
NOTE: The numbers in cosmology are so great and the numbers in subatomic physics are so small that it is often necessary to express them in exponential form. Ten multiplied by itself, or 100, is written as 10 2. One thousand is written as 10 3. Similarly, one-tenth is 10 -1, and one-hundredth is 10 -2.
Source: The Birth of the Universe; The Kingfisher Young People's Book of Space
TIME Graphic by Ed Gabel

QGP was there on the "First Day"

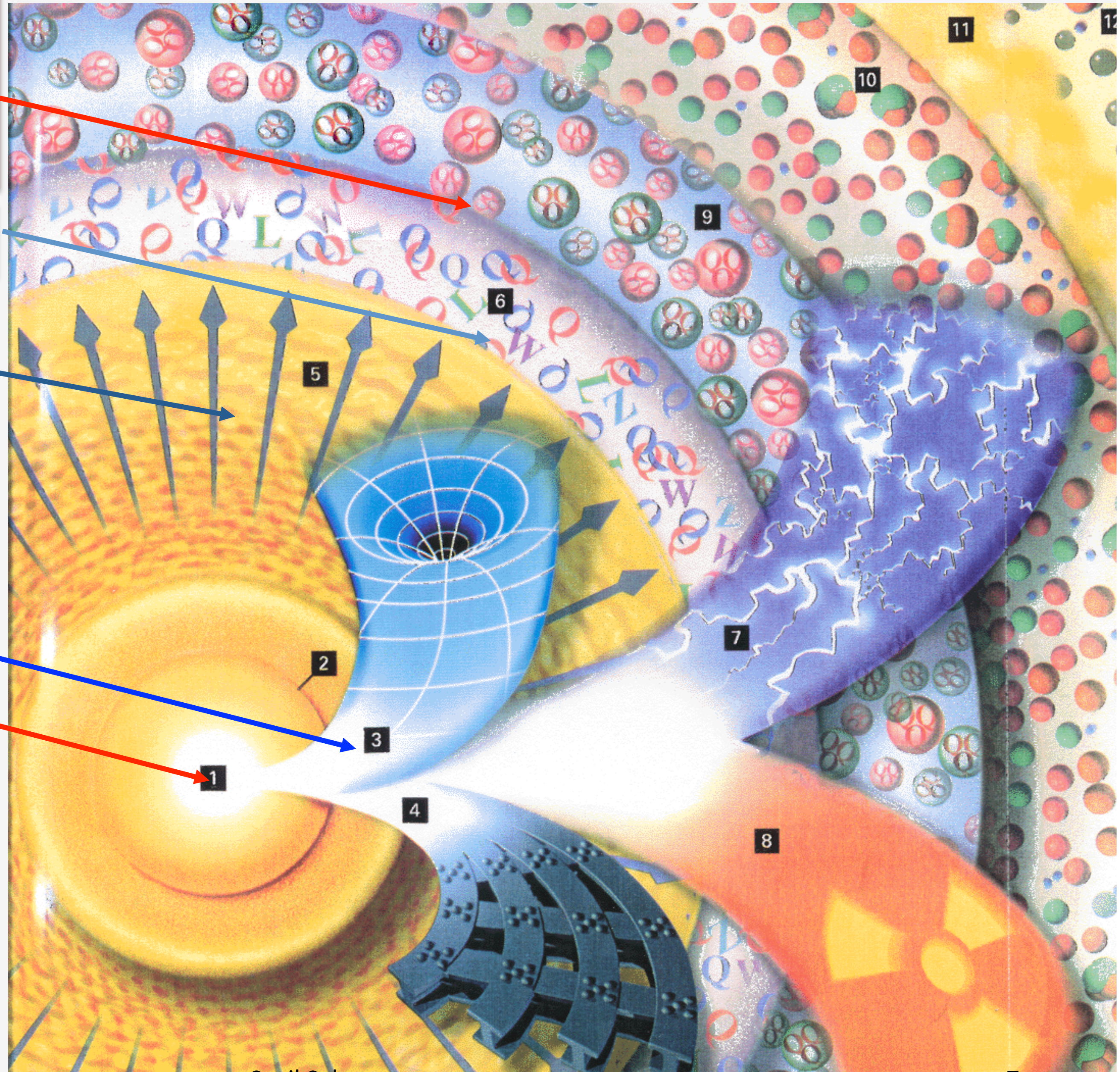
At 10 μ-seconds
& ~ 10^{12} Kelvin
Quark-to-hadron
phase transition

Quark-Gluon Plasma

Rapid inflation

gravity, strong & E-W
forces separate

'Big Bang'



How to measure such a complexity?
An analogy… and a difference!

to study structure of an atom…

electron

separate constituents

To understand the strong force and the phenomenon of confinement:
Create and study a system of deconfined colored quarks (and gluons)

Confinement: fundamental & crucial (but *not* understood!) feature of strong force
- colored objects (quarks) have ∞ energy in normal vacuum

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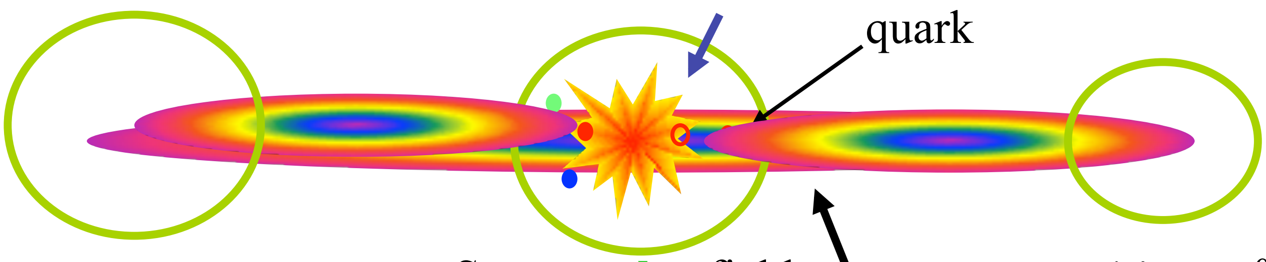
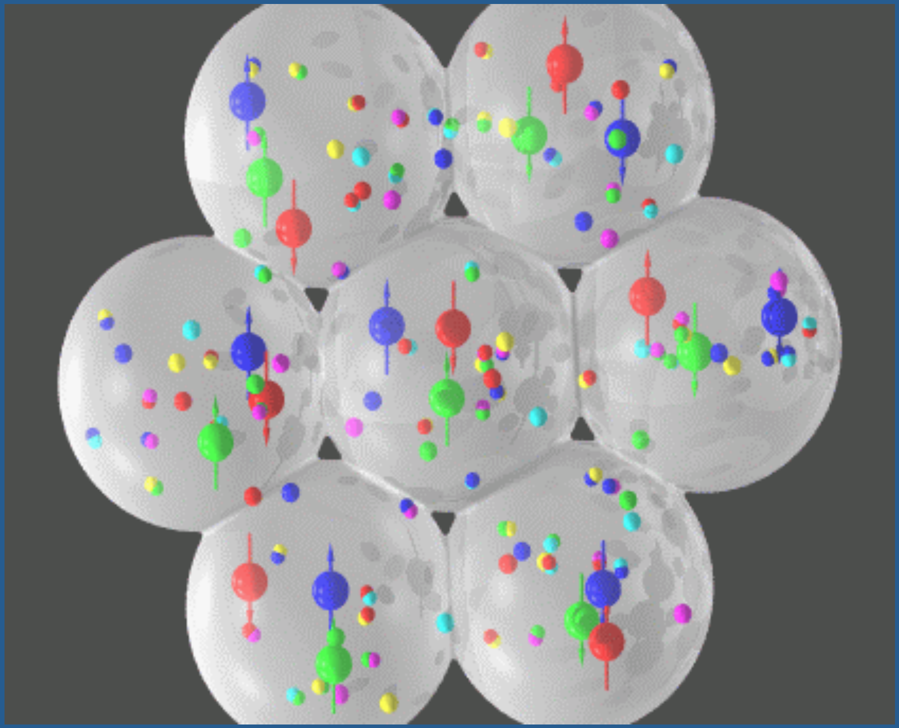


Increase the temperature and pressure.

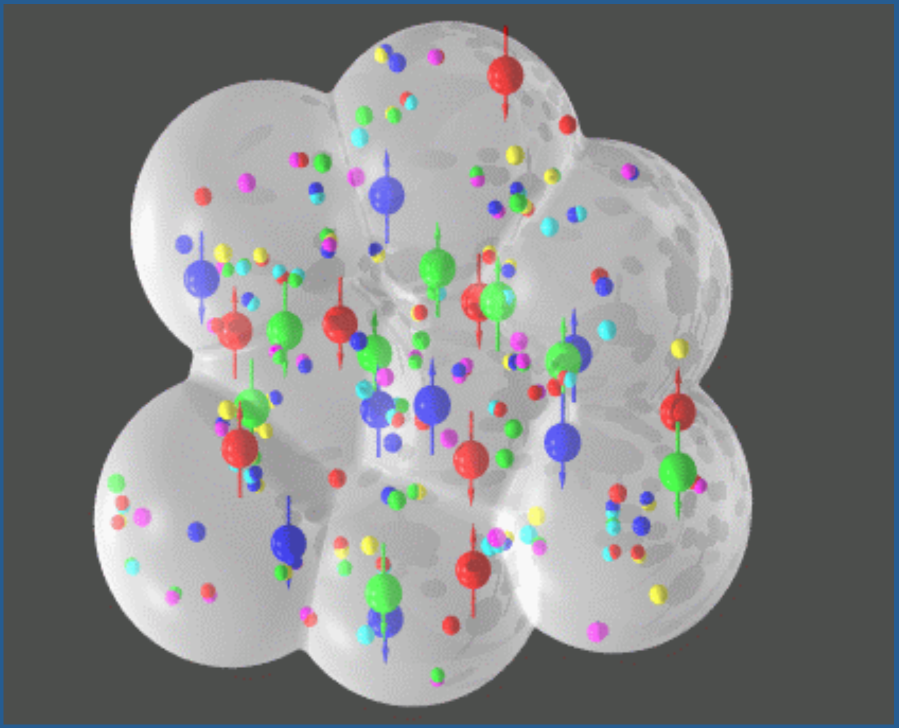
Crush matter into a soup of its constituents.

Hadronic matter

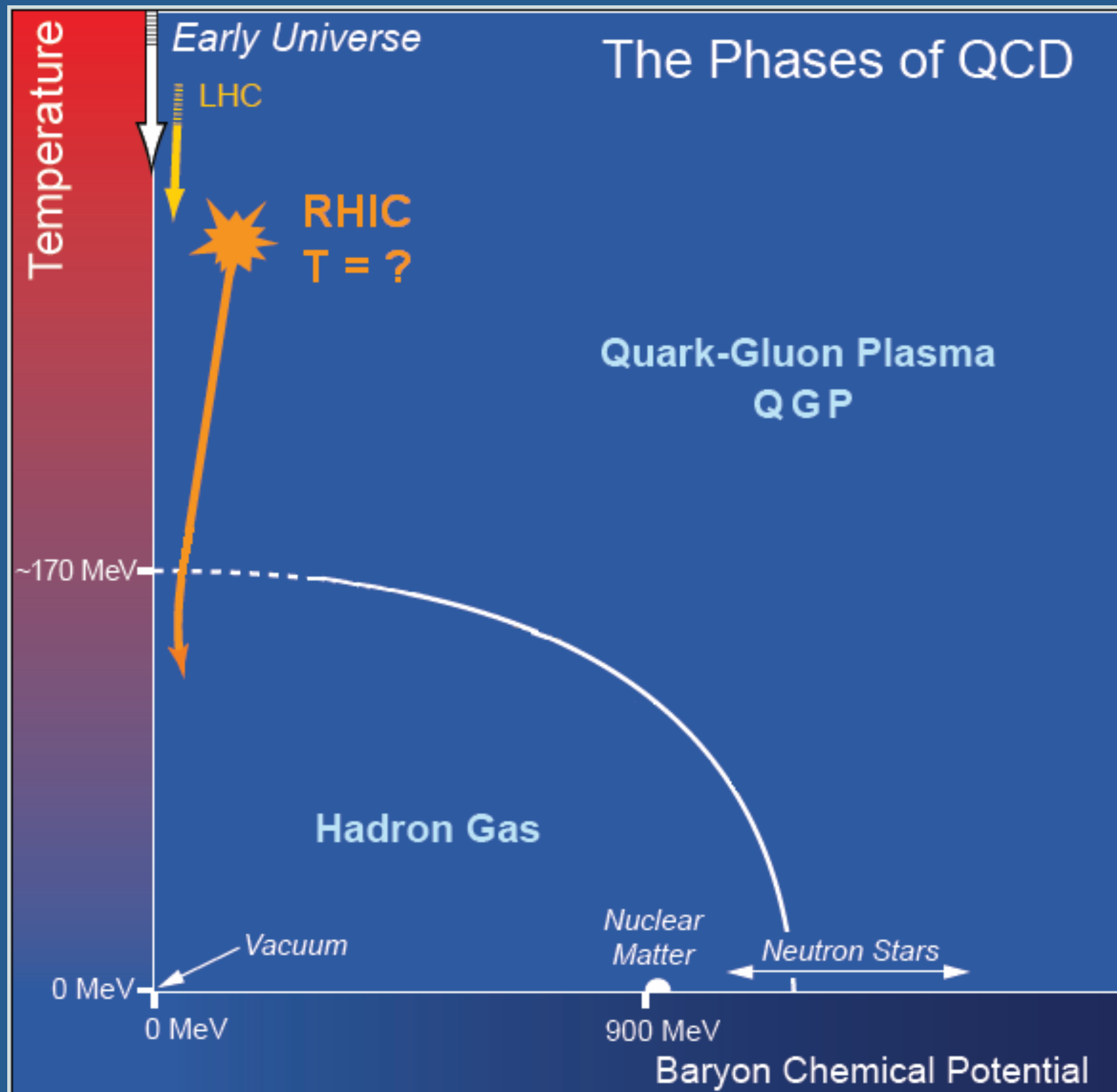


Quark gluon plasma

A very hot soup at ~10^{12}K



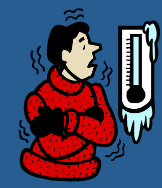
The Landscape of QCD



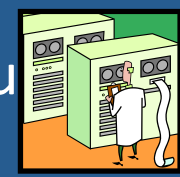
Heavy Ion Collisions at RHIC and LHC create conditions sufficient to "melt" matter into a quark gluon plasma

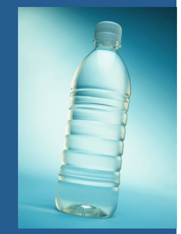
How can we experimentally study the thermodynamics of the STRONG force?

Imagine…



- You know that ice exists…
- Your theory friends with huge computers tell you that there is something called water…

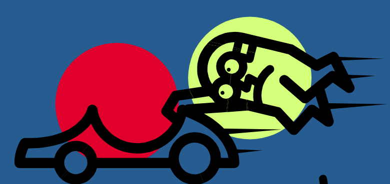




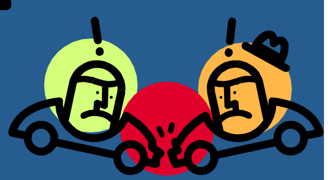
- You don't have a way to heat ice…

- So you put millions of ice cubes in an ice-accelerator

- Send them at 99.995% of the speed of light to collide



- Generating thousands of ice-cube+ice-cube collisions per second…



- And you watch it all from the vicinity of Mars!

Producing "Bulk" nuclear Matter in the laboratory.

We must create/compress/heat a **bulk** (geometrically large) system

Freeze/melt a single H_20 molecule?

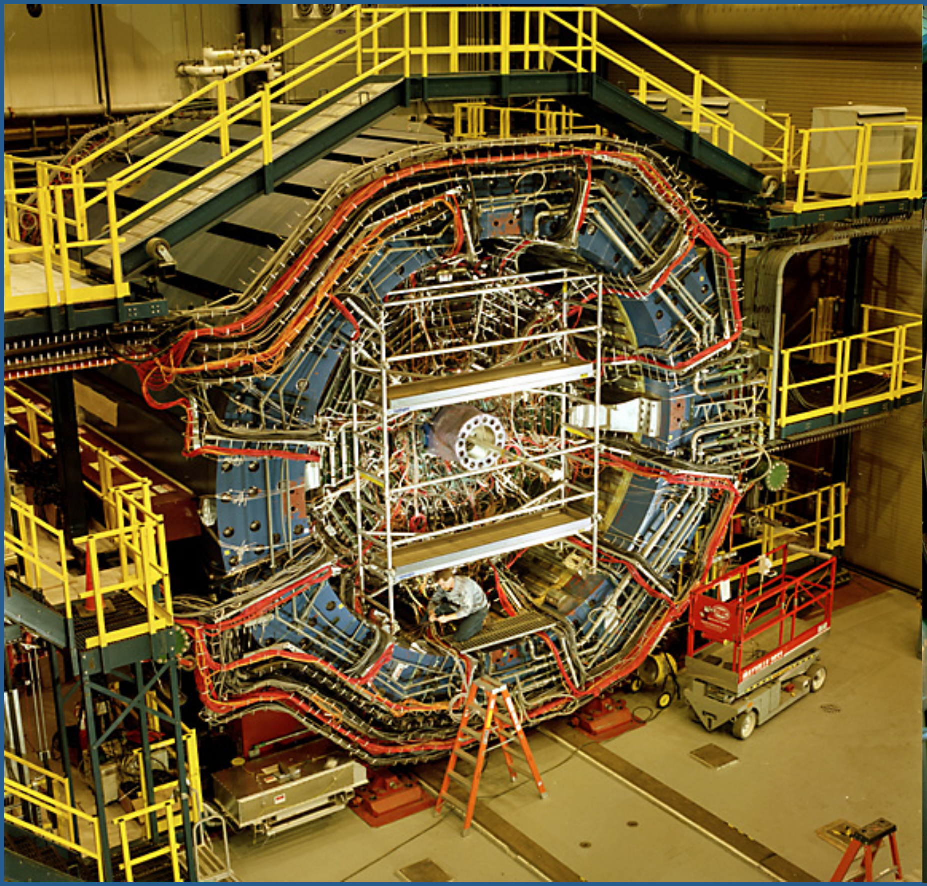
Fundamental distinction from particle physics

Only achievable through collisions of the heaviest nuclei (Au, Pb) at the highest available energy– Relativistic Heavy Ion Collider (RHIC) and Large Hadron Collider (LHC)

- **RHIC ≡ <u>R</u>elativistic <u>H</u>eavy <u>I</u>on <u>C</u>ollider**
  - **3.83 km circumference**
  - **Two independent rings**
    - 120 bunches/ring
  - **Capable of colliding ~any nuclear species on ~any other species**
  - **Energy:**
    - Up to 500 GeV for p+p
    - Up to 200 GeV for Au+Au (per N-N collision)
  - **Luminosity**
    - Au+Au: 2 x 10^{26} cm^{-2} s^{-1}
    - p+p : 2 x 10^{32} cm^{-2} s^{-1} (*polarized*)

200 GeV)

RHIC Experiments



STAR ~550 Collaborators
specialty: large acceptance
Hadronic Observables
Jets & Di-Hadron Physics
High-pT Quarkonia

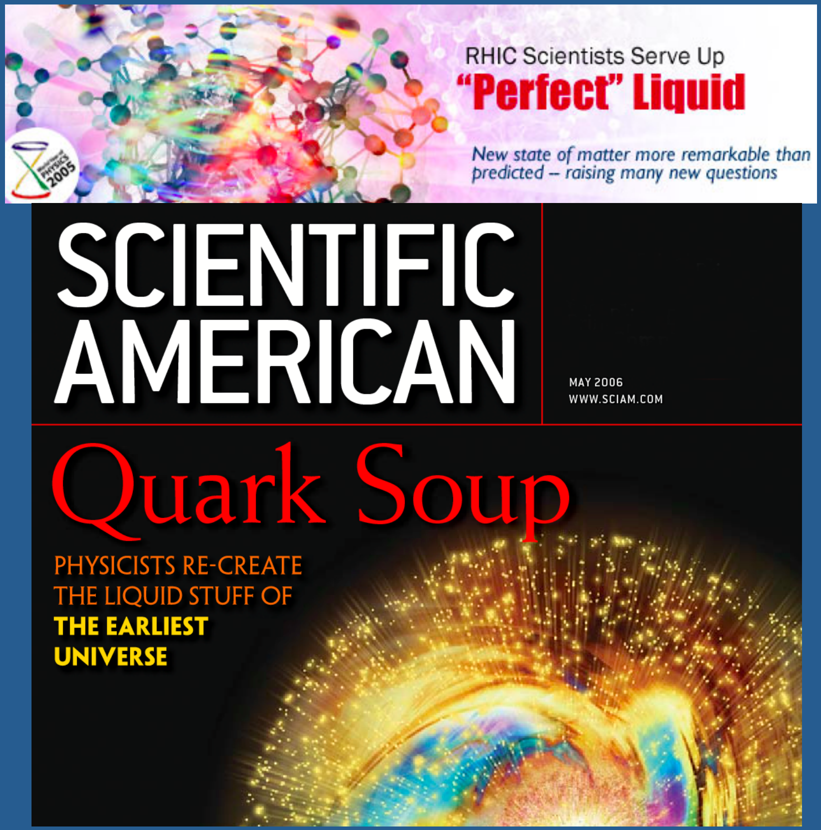
PHENIX ~550 Collaborators
specialty: rare probes, leptons,
and photons

Last 10 Years of Discoveries

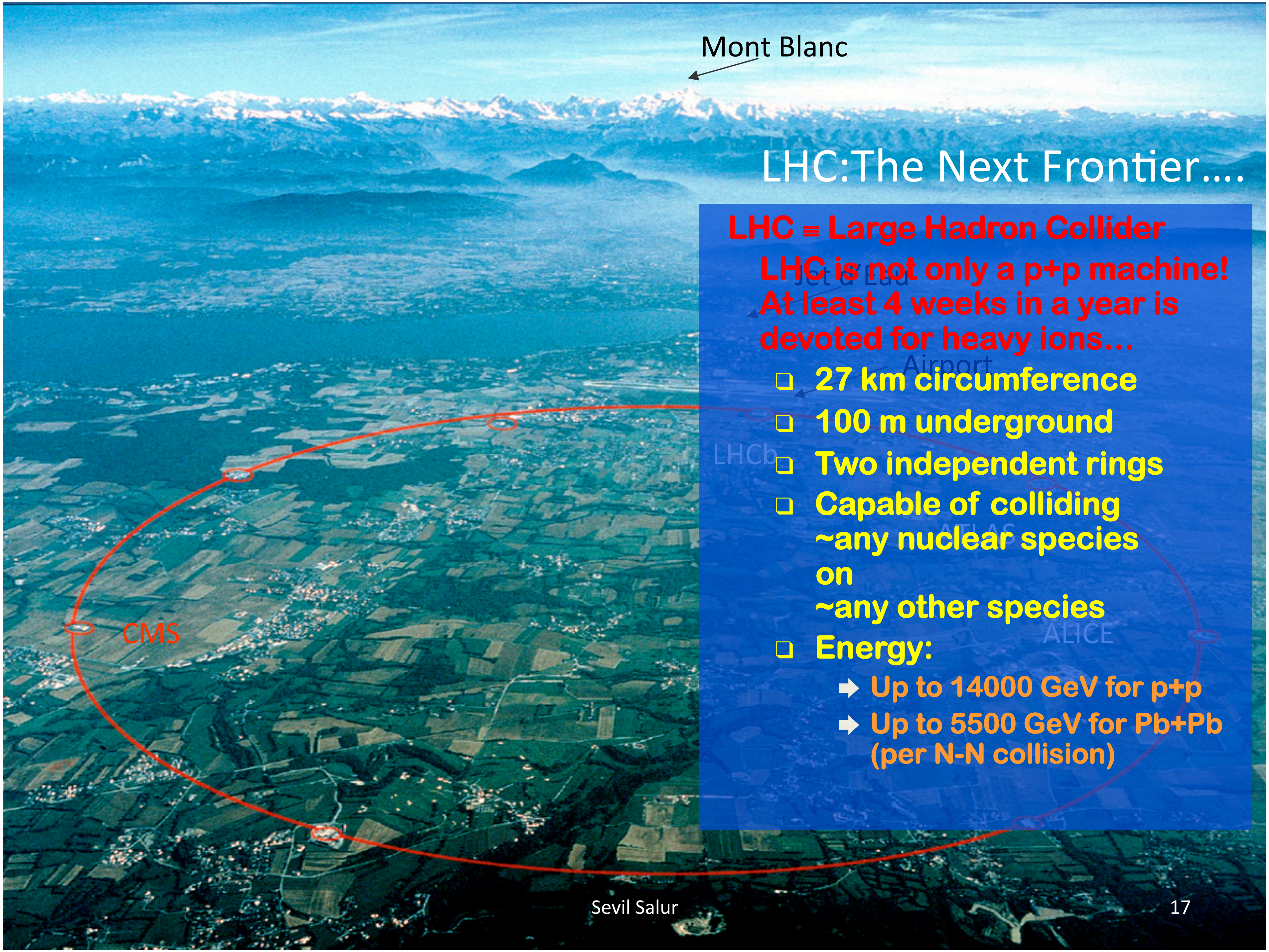
- **Collective Flow:**
  → behaves more like liquid rather than gas.
  → small viscosity perfect liquid.

- **Particle Production:**
  → recombination/ coalescence dominates over fragmentation at medium p_T

- **Jet Quenching:**
  → opaque to fast partons



LHC:The Next Frontier….



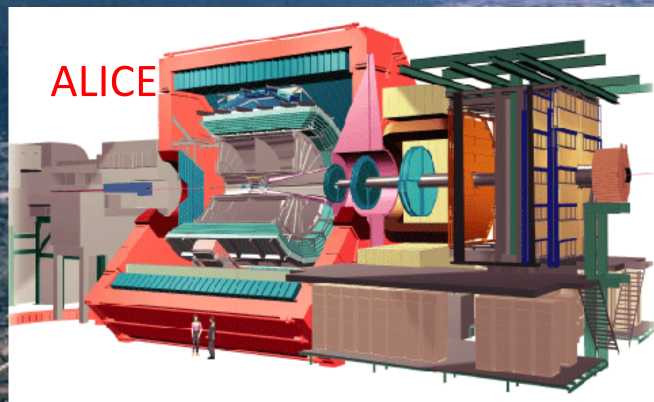
LHC ≡ Large Hadron Collider

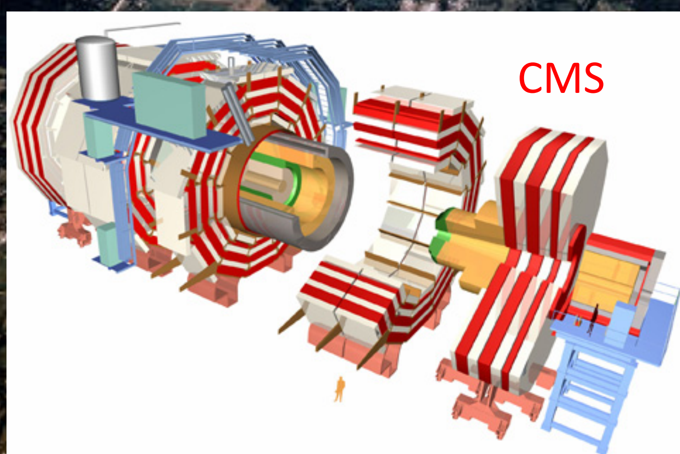
LHC is not only a p+p machine! At least 4 weeks in a year is devoted for heavy ions…

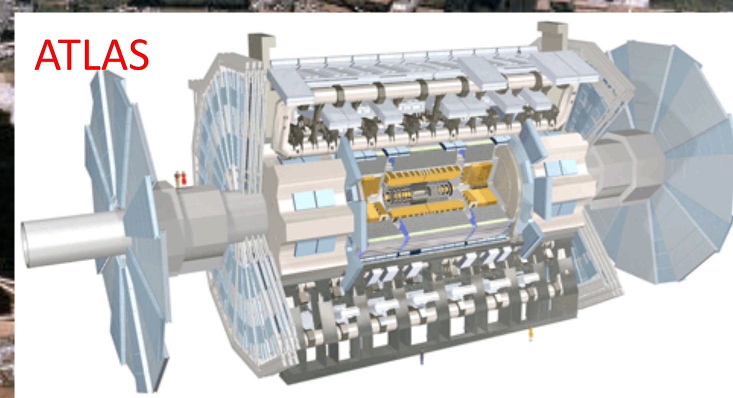
- **27 km circumference**
- **100 m underground**
- **Two independent rings**
- **Capable of colliding ~any nuclear species on ~any other species**
- **Energy:**
  - **Up to 14000 GeV for p+p**
  - **Up to 5500 GeV for Pb+Pb (per N-N collision)**

LHC Experiments

LHC Heavy Ion program started in late 2010 Pb+Pb and p+p at 2.76 TeV per NN!







Why Study Heavy Ion Collisions at LHC ?

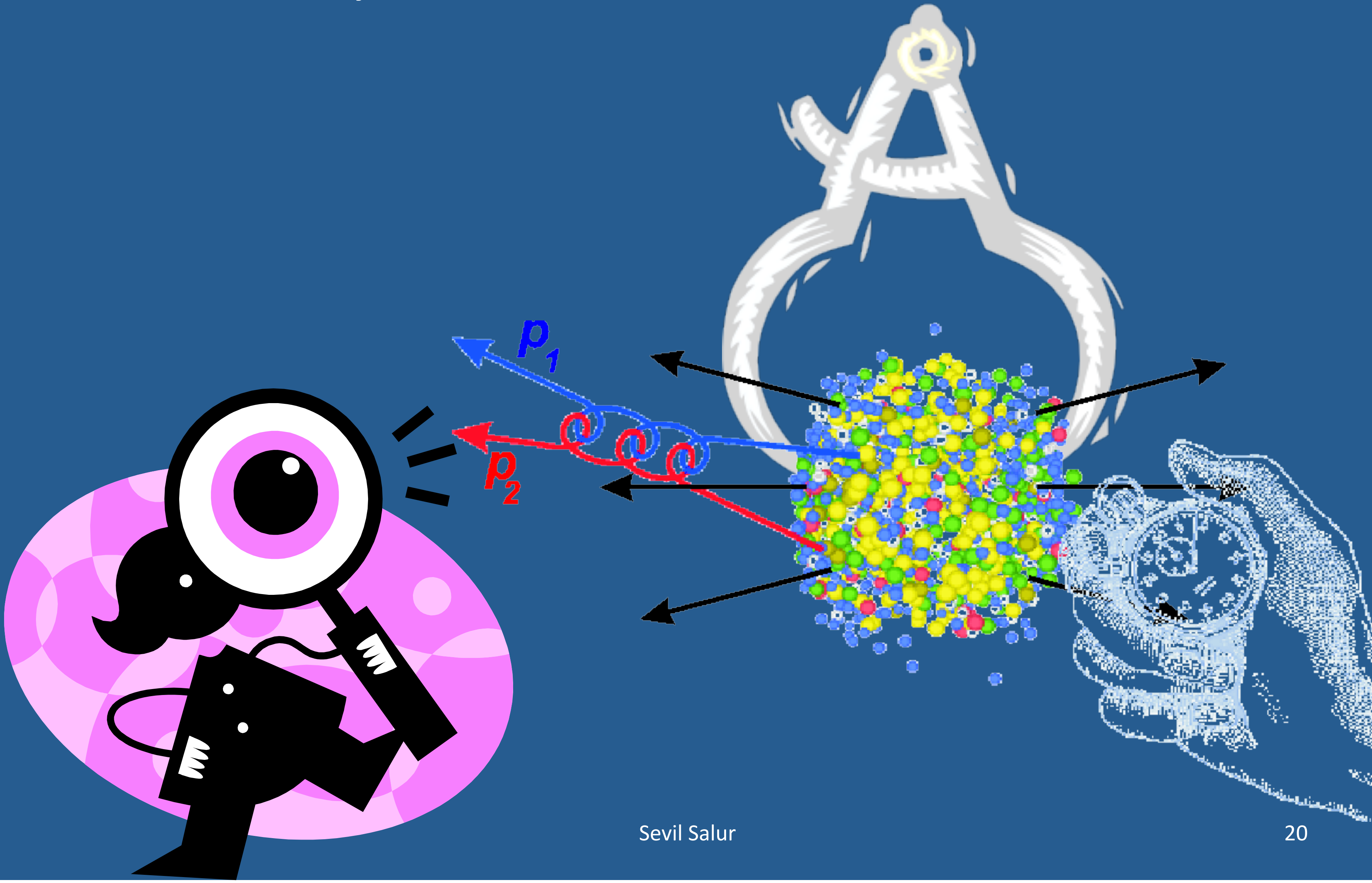
Central collisions	SPS	RHIC	LHC
$s^{1/2}$(GeV)	**17**	**200**	**5500**
dN_{ch}/dy	**500**	**700-1500**	**3-10 x10^3**
ε (GeV/fm^3)	**2.5**	**3.5-7.5**	**15-40**
τ_{QGP} (fm/c)	**<1**	**1.5-4.0**	**4-10**

J. Schukraft QM2001

LHC provides a **critical** lever arm in energy.

LHC : Longer - Hotter – Colossal (Bigger)

So, what have we seen?



Experimental search for "interesting" phenomena

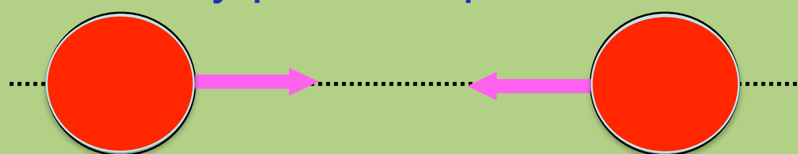
- Look at elementary p+p collisions
  - Measure an observable (e.g. Jet production)
- Look at Heavy Ion collisions
  - Measure the same observable as we do in p+p
- Compare them, is there something new?

Geometry Matters!

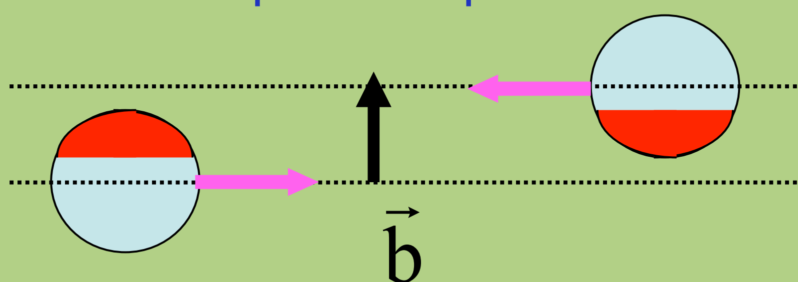
Impact parameter vector $\vec{b}$:

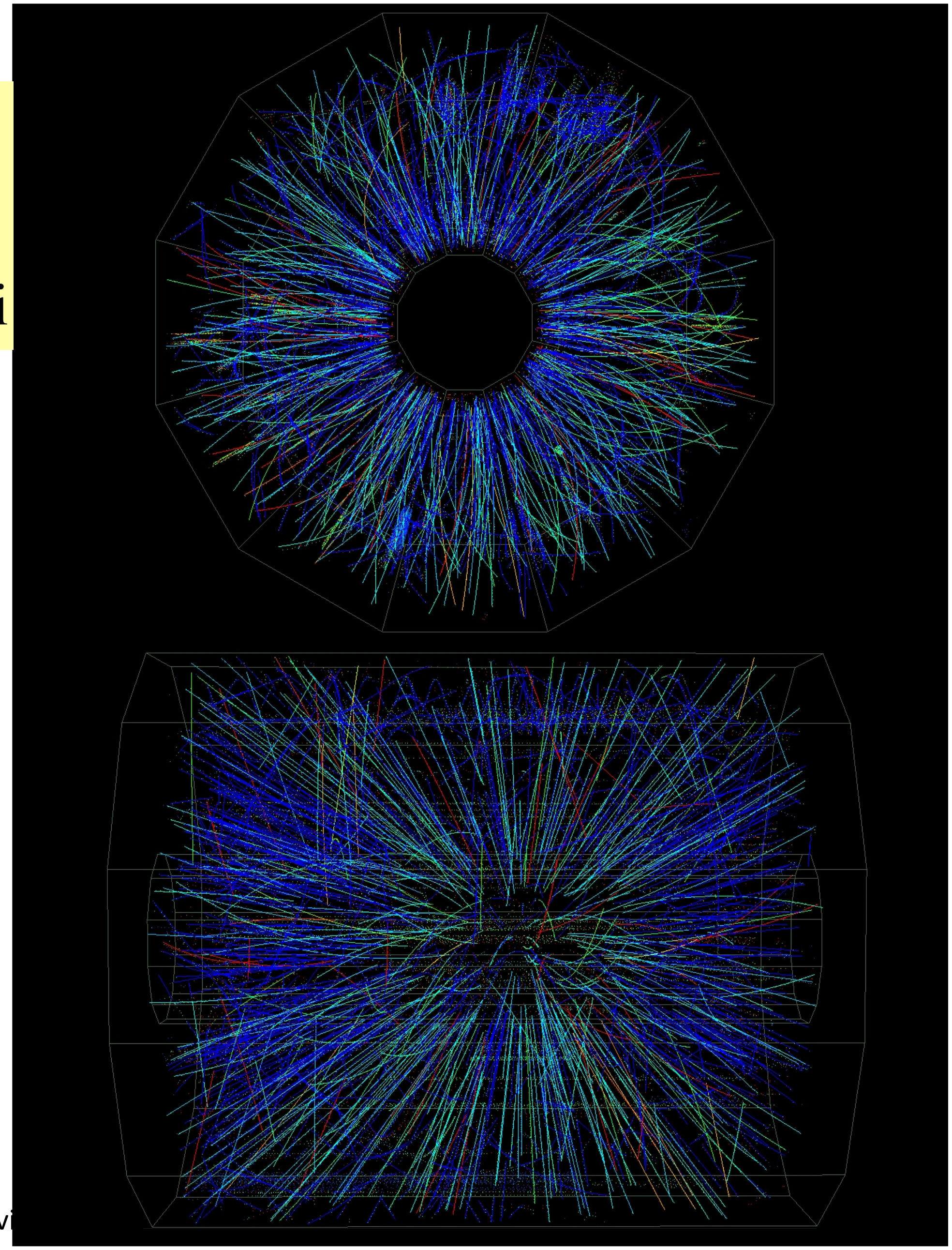
- $\perp$ beam direction
- connects centers of colliding nuclei

$b = 0 \leftrightarrow$ "central collision"
many particles produced



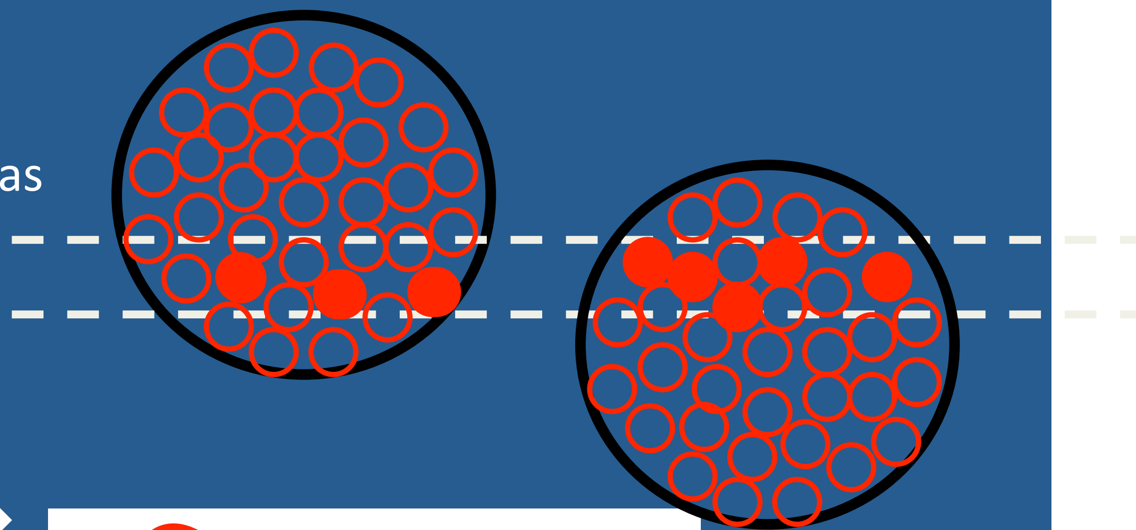
"peripheral collision"
fewer particles produced



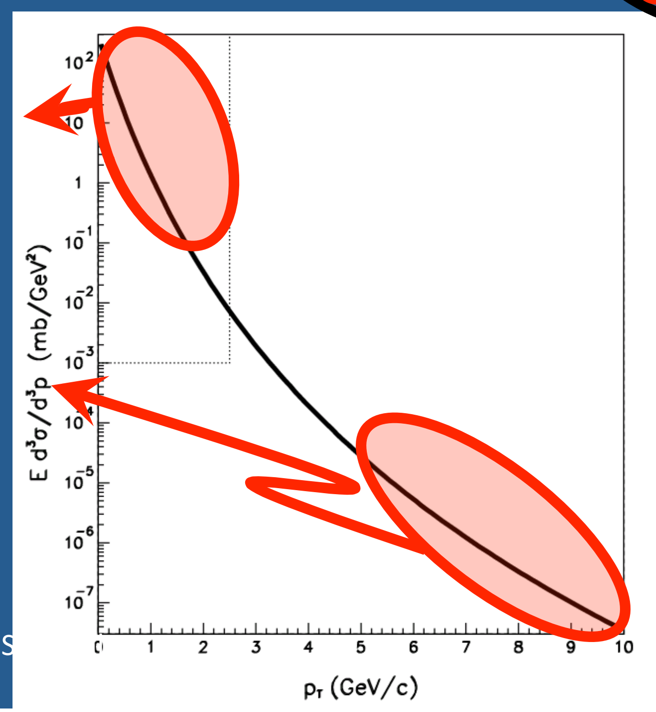


Geometry Matters!

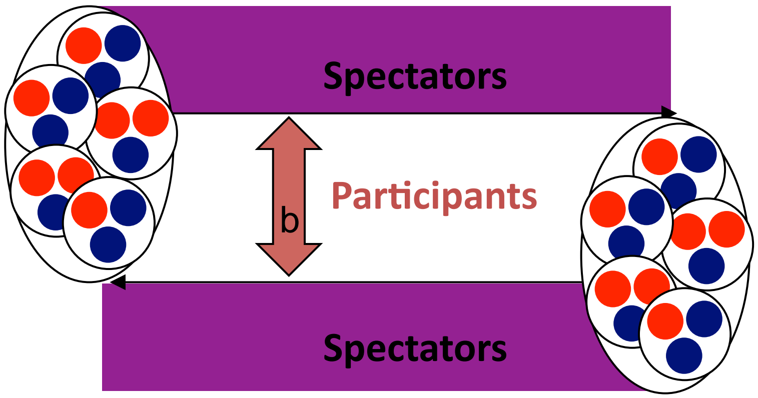
- Focus on some slice of the collision:
  - Assume 3 nucleons struck in A, and 5 in B
  - Do we weight this contribution as
    - N_{part} (= 3 + 5) ?
    - N_{Bin} (= 3 x 5) ?



- Answer is a function of p_T :
  - Low p_T ➡ large cross sections ➡ yield ~N_{part}
    - Soft, non-perturbative, “wounded nucleons”, …
  - High p_T ➡ small cross sections ➡ yield ~N_{Bin}
    - Hard, perturbative, “binary scaling”, point-like, A*B, …

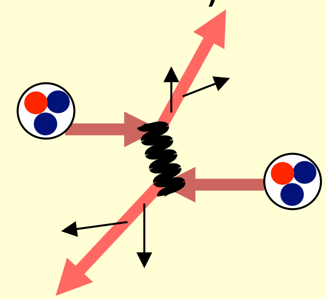


Terminology: Centrality of A+A Collisions



Number of Binary Collisions:
(# of inelastic nucleon+nucleon collisions)

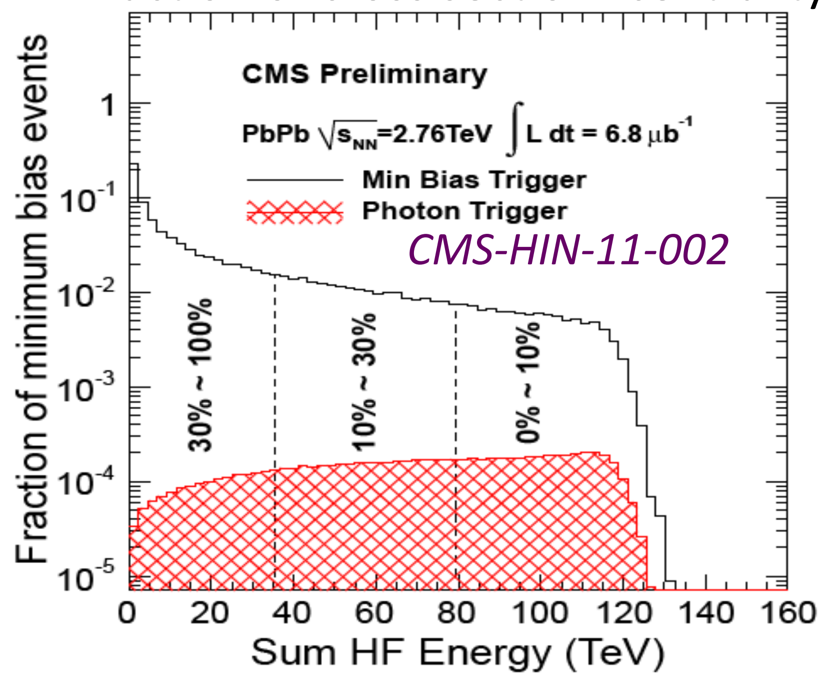
1. Jet Production
2. Heavy Flavor (s,c,b)



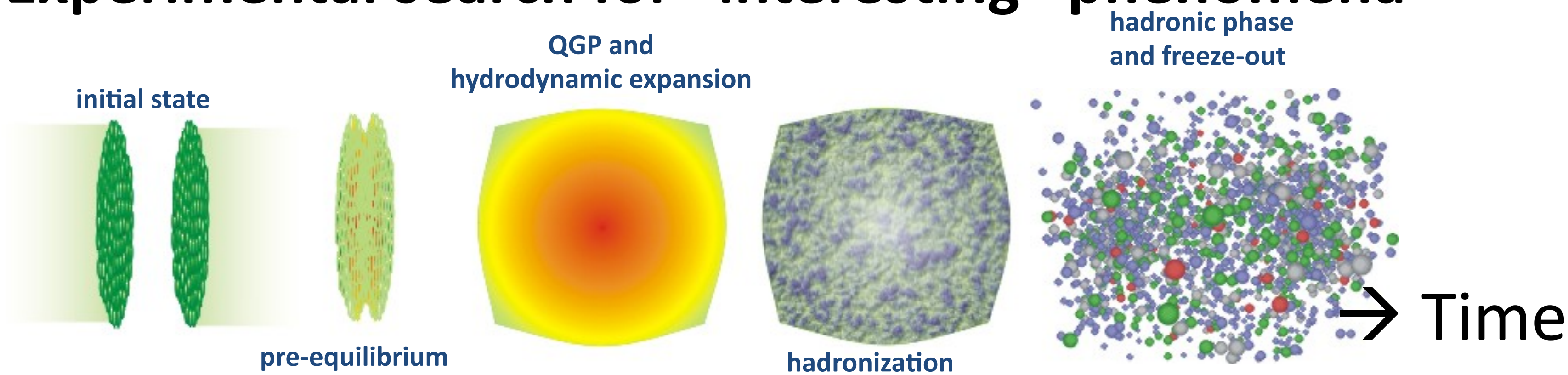
Number of Participant:
(# of incoming nucleons in the overlap area)

1. Soft Hadron Production
2. Transverse Energy

Fraction of cross section "centrality"



Experimental search for "interesting" phenomena



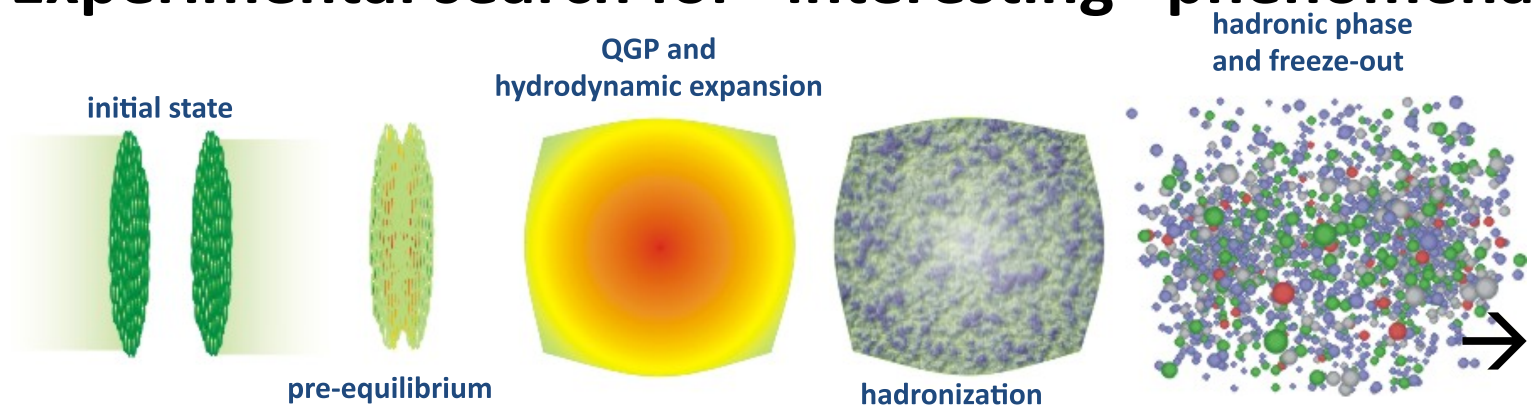
Hard scattered q,g
– penetrating probes

QGP

thermal radiation
(γ, $\gamma^* \rightarrow e^+e^-$, $\mu^+\mu^-$)

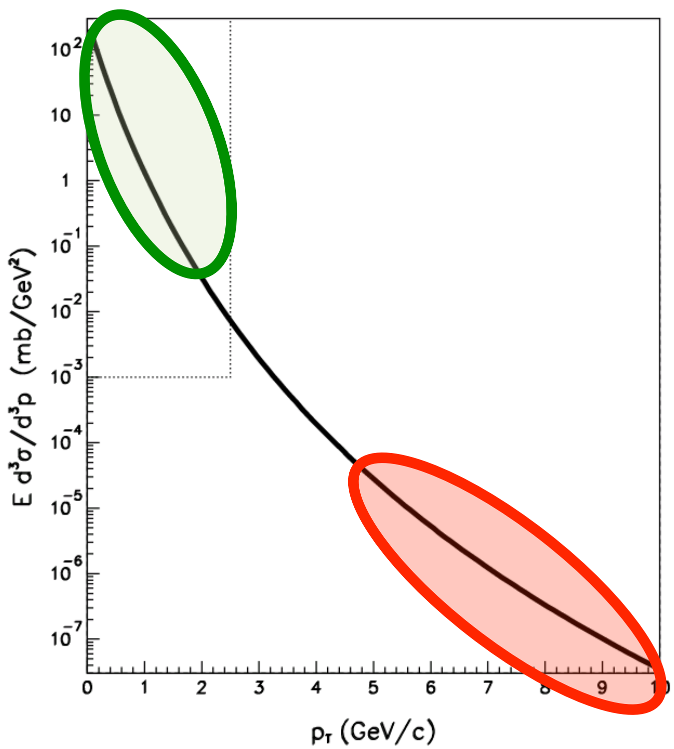
π, **K**, **p**, **n**, ϕ, Λ, Δ, Ξ, Ω, **d**,
Formation of Hadrons
-soft physics

Experimental search for "interesting" phenomena



Hard Probes –
penetrating probes

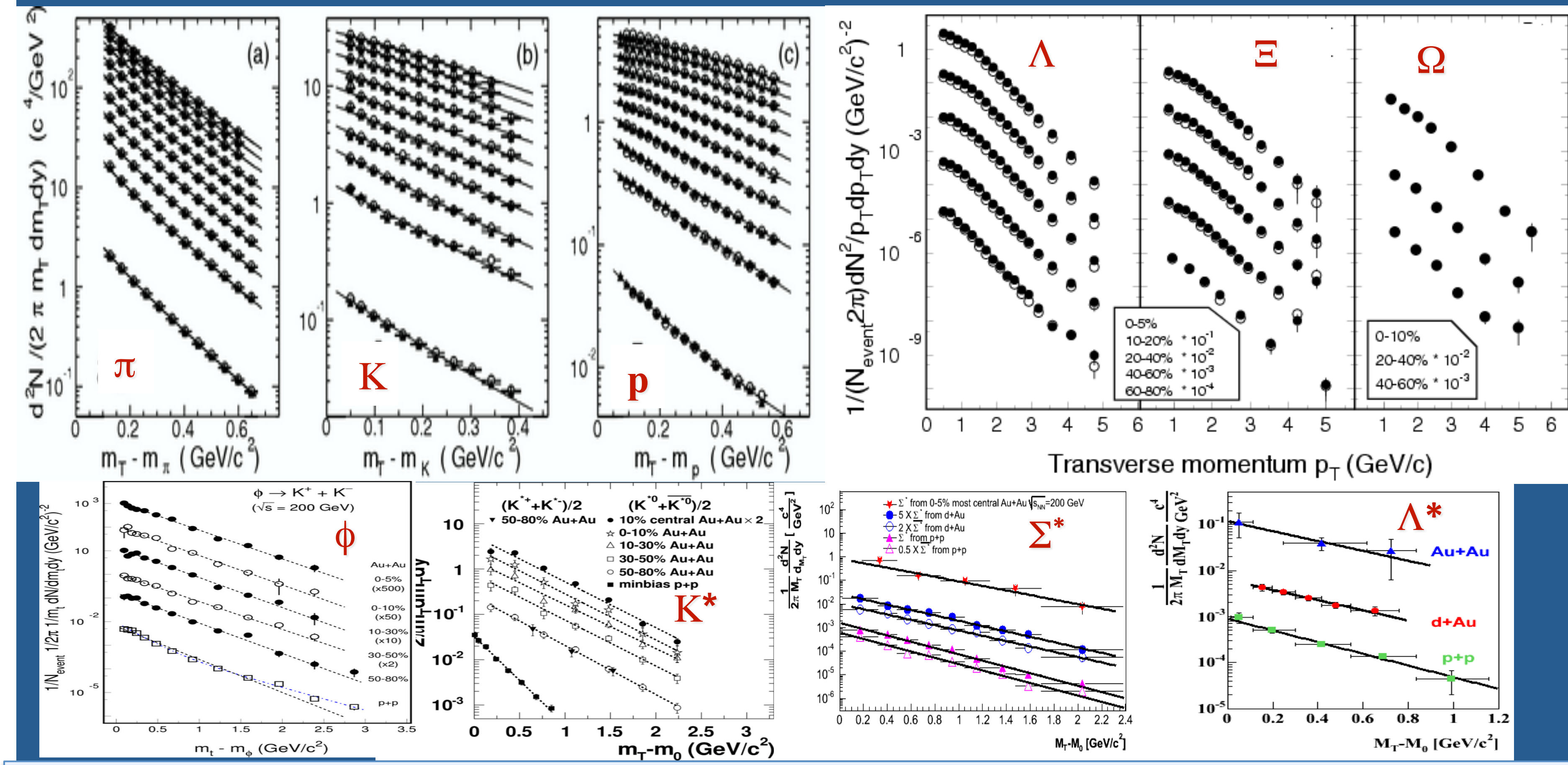
soft physics



Soft Physics: p_T < ~1.5 GeV/c:
"thermal" particles radiated
from bulk medium "internal"
plasma probes

Hard Probes: p_T > 3 GeV/c:
large E_{tot} (high p_T or M)
autogenerated "external" probe
describe by perturbative QCD

Lots of particles…



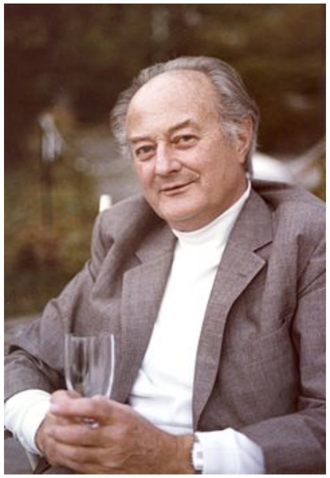
$e^{\pm}$, $\pi^{\pm}$, π^0, $K^{\pm}$, K^{*0}(892), K_s^0, η, p, d, ρ^0, ϕ, Δ, Λ, Σ^*(1385), Λ^*(1520), $\Xi^{\pm}$, Ω, **D^0, $D^{\pm}$, D_s, J/Ψ's, ϒ's** (+ anti-particles) …

How to characterize this richness of data?

Particle Production and Volume

Particle production can be described by phase space!

Pointed out by Fermi and Hagedorn in 50-60's
(and discussed much more since)



Assume: Ideal hadron resonance gas thermally and chemically equilibrated

Recipe: Canonical (small system i.e. pp):
Quantum Numbers conserved exactly.
Grand Canonical limit (large system i.e. central AA):
Quantum Numbers conserved on average via chemical potential
$\Rightarrow$ partition function $\Rightarrow$ density of particles of species ρ_I

Output: temperature T, chemical potential μ_i which generates particle-antiparticle difference and γ_i which regulates the sum of particle-antiparticle pairs

A multi-hadron state should be described by thermodynamics with a limiting temperature. If spectrum of resonant states is exponential, as higher states are populated, T increases.
If number of states increases exponentially, T saturates!

Particle Production and Volume

Particle production can be described by phase space!

Pointed out by Fermi and Hagedorn in 50-60's
(and discussed much more since)

Statistical models are used to estimate the equilibrium properties

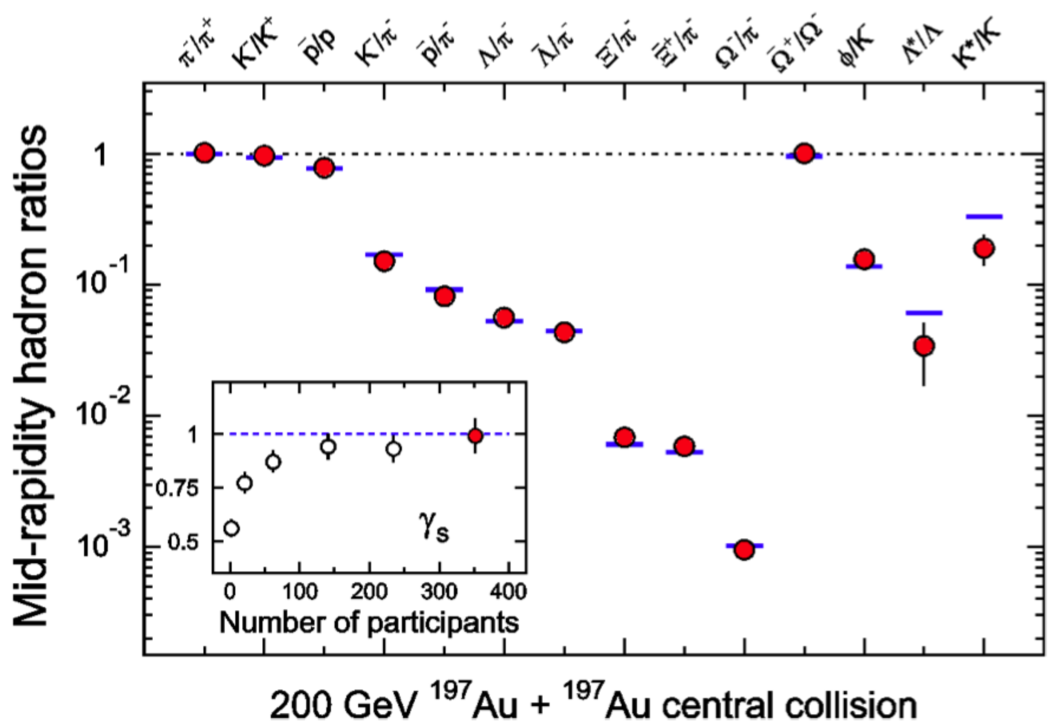
Assume: Ideal hadron resonance gas thermally and chemically equilibrated

Input: measured particle ratios

$$\frac{\bar{p}}{p} = \frac{e^{-(E+\mu)/T}}{e^{-(E-\mu)/T}} = e^{-2\mu/T}$$

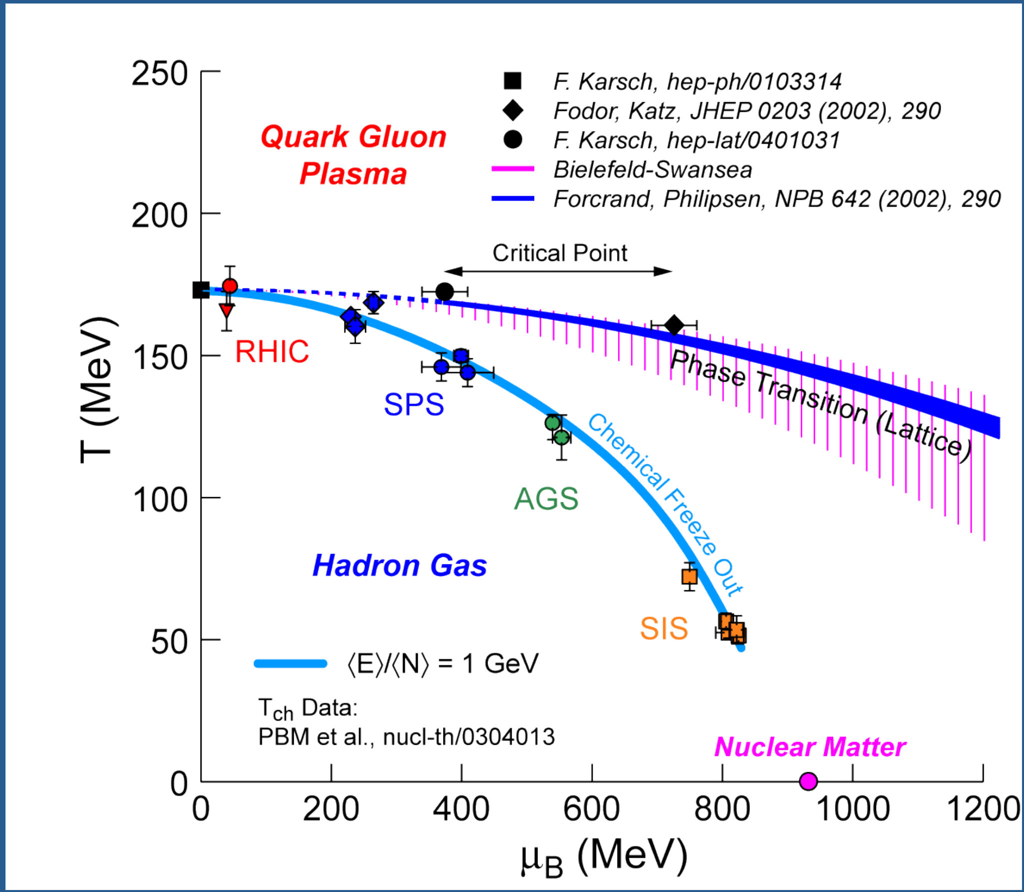
Output: **T = 163 ± 4 MeV,**
μ_B = 24 ± 4 MeV

STAR Collaboration / Nuclear Physics A 757 (2005) 102–183



The Limits of Thermodynamics

- This exercise in "hadro-chemistry"
  - Applies to final-state (ordinary) hadrons
  - Does not (necessarily) indicate
    - QGP formation
    - De-confinement
    - New state of matter



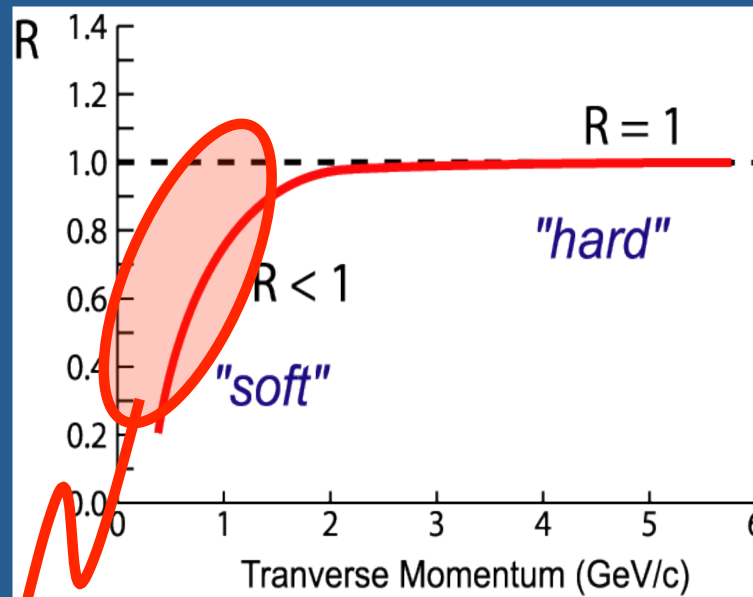
- A smooth continuation of trends seen
  - at lower energies
  - in p-p, even e^+e^-

Systematizing Our Expectations: Compare with p+p

- Describe in terms of *scaled ratio* R_{AA}

$$\equiv \frac{\text{Yield in Au+Au Events}}{N_{Bin}\left(\text{Yield in p+p Events}\right)}$$

= 1 for "baseline expectations"



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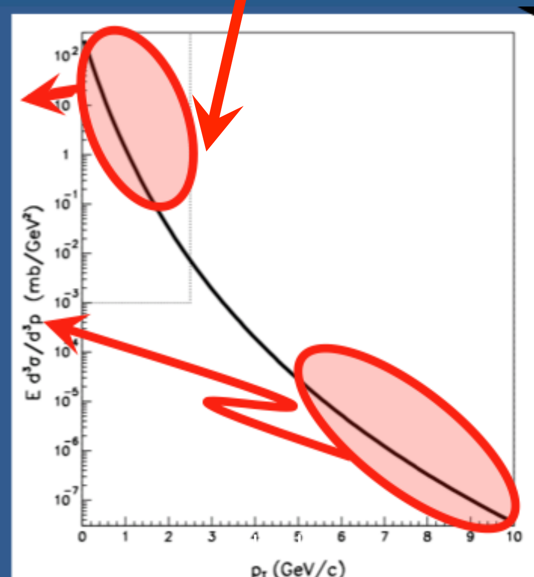
  - Hard, perturbative, "binary scaling", point-like, A*B, …

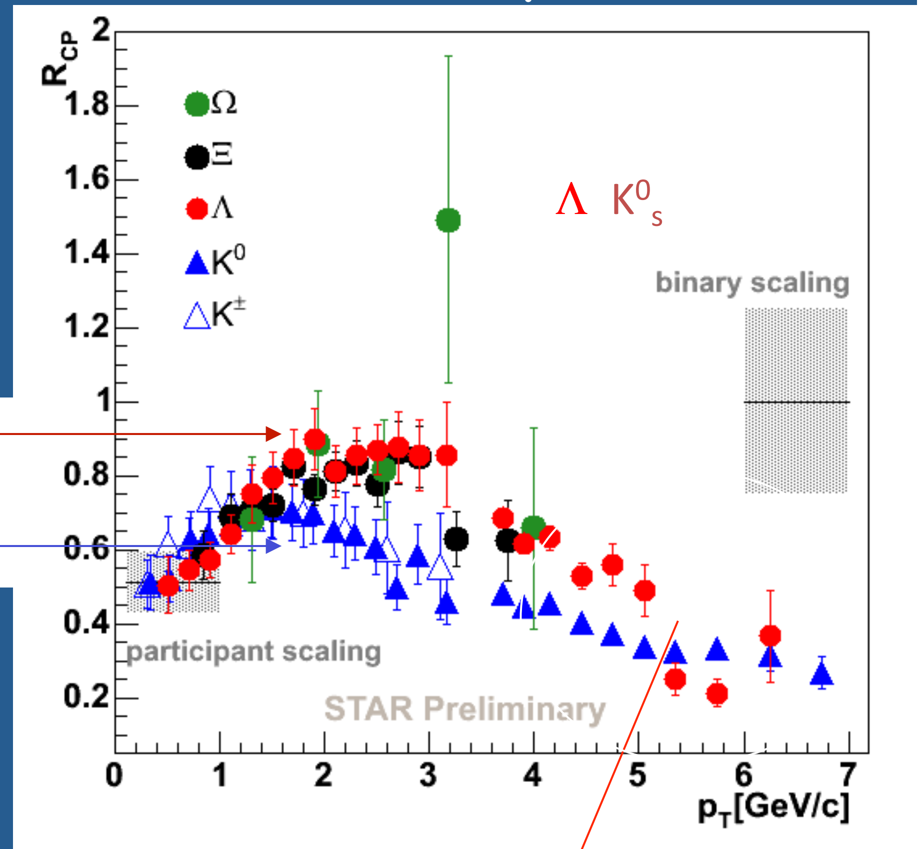


Nuclear Modification Factors R_{cp}

$$R_{CP}^{h}(p_T) = \frac{\dfrac{dN_h}{dp_T}\dfrac{1}{\langle N_{Coll}\rangle}(central)}{\dfrac{dN_h}{dp_T}\dfrac{1}{\langle N_{Coll}\rangle}(peripheral)}$$

Baryons

Mesons



The ‘quenching’ of high pt particles due to partonic energy loss. (Lecture 2)

Parton recombination at intermediate p_T

• in vacuo fragmentation of a high momentum quark to produce hadrons competes with in medium recombination of lower momentum quarks to produce hadrons

•6 GeV/c particle via :

fragmentation from high p_T

meson

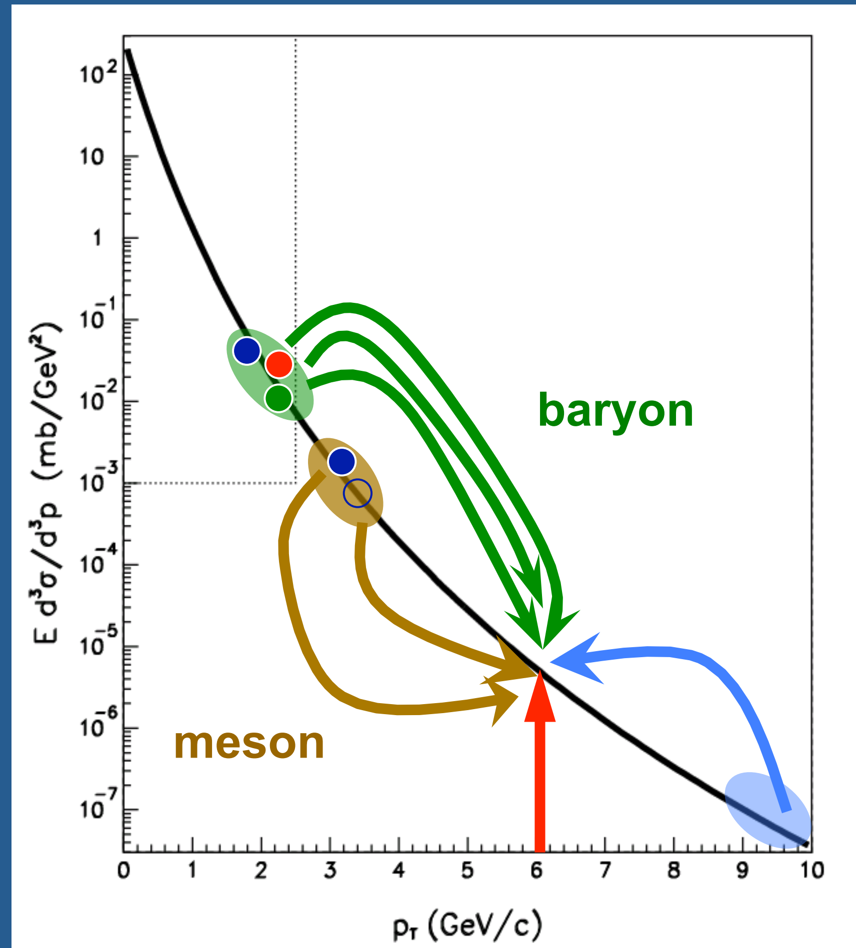
- 2 quarks at p_T~3 GeV/c

baryon

- 3 quarks at p_T~2 GeV/c

Recombination produces more baryons than mesons at intermediate p_T

Quarks Degrees of freedom



R.J. Fries et al., PRL 90 (202303) 2003
V. Greco et al., PRL 90 (202302) 2003

Bulk Behaviour

Energy is deposited in small volume.
~ size of Lorentz-contracted nuclear overlap.
→Leads to formation of transient state.

State undergoes hydrodynamical expansion.
System cools down while expanding. →
Reaches a freeze out temperature. $T_f \sim m_\pi$
Below T_f, hadrons become free particles.

Landau

Hydrodynamics:

Assume: local thermal equilibrium (zero mean-free-path limit)

Solve: equations of motion for fluid elements (not particles)

Hydrodynamic Equations

$$\partial_\mu T^{\mu\nu} = 0,$$ Energy-momentum conservation

$$\partial_\mu n_i^\mu = 0$$ Charge conservations (baryon, strangeness, etc…)

For perfect fluids (neglecting viscosity!),

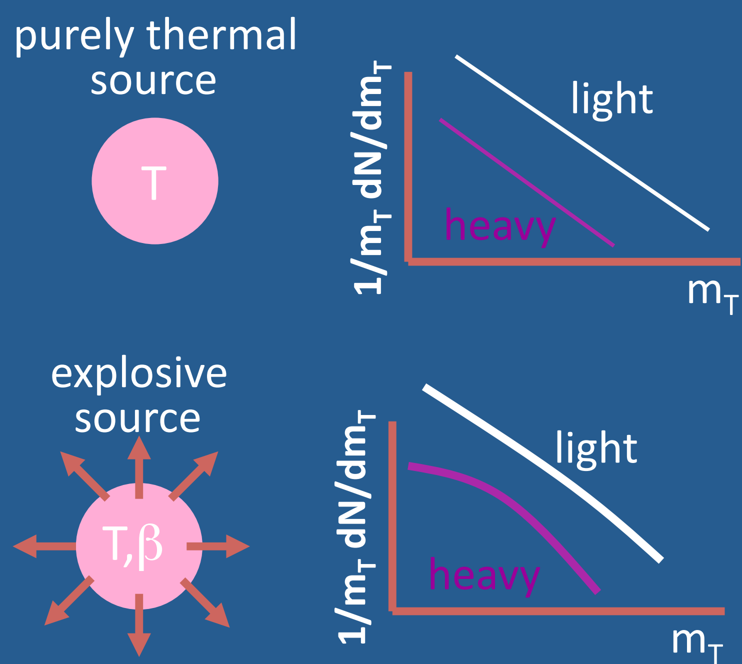
$$T^{\mu\nu} = (e + P)u^\mu u^\nu - P g^{\mu\nu}$$

Energy density   Pressure   4-velocity

Within ideal hydrodynamics, pressure gradient *dP/dx* is the driving force of collective flow.

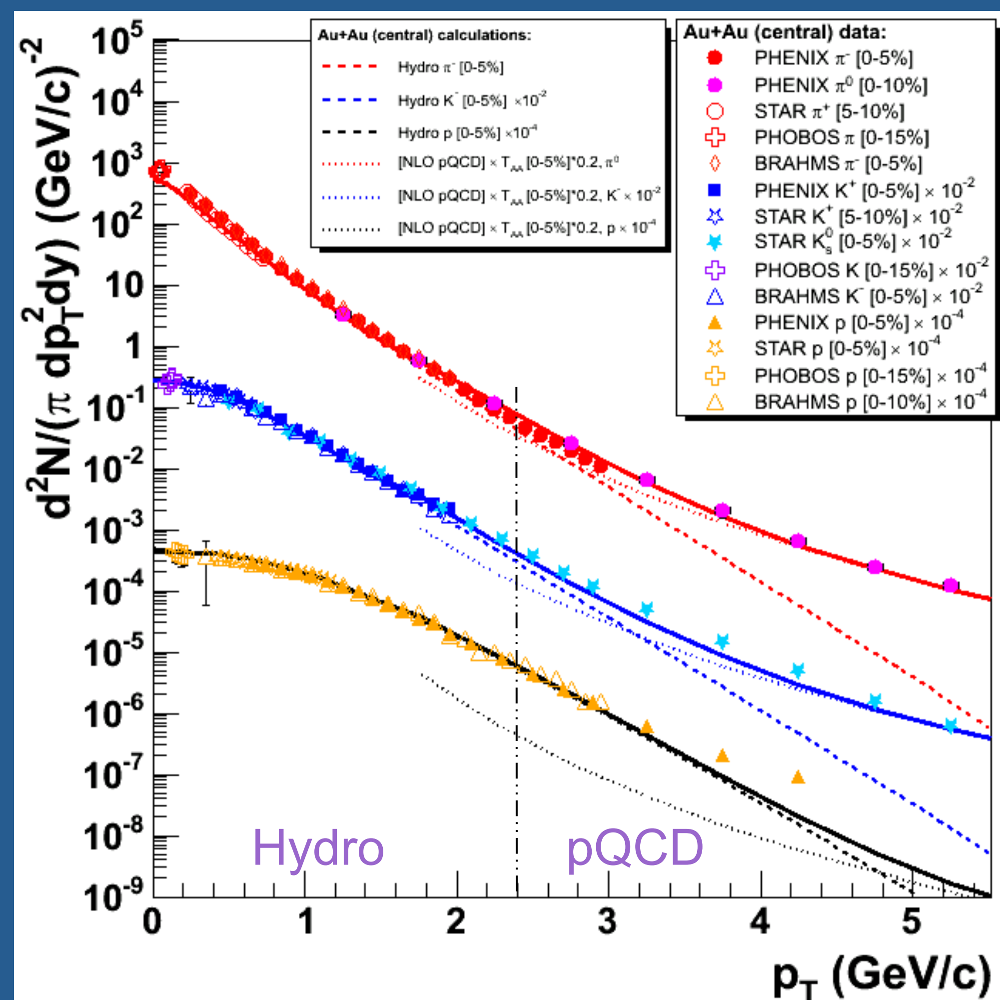
Strong Collective Radial Expansion

Different spectral shapes for particles of differing mass
→ strong collective radial flow



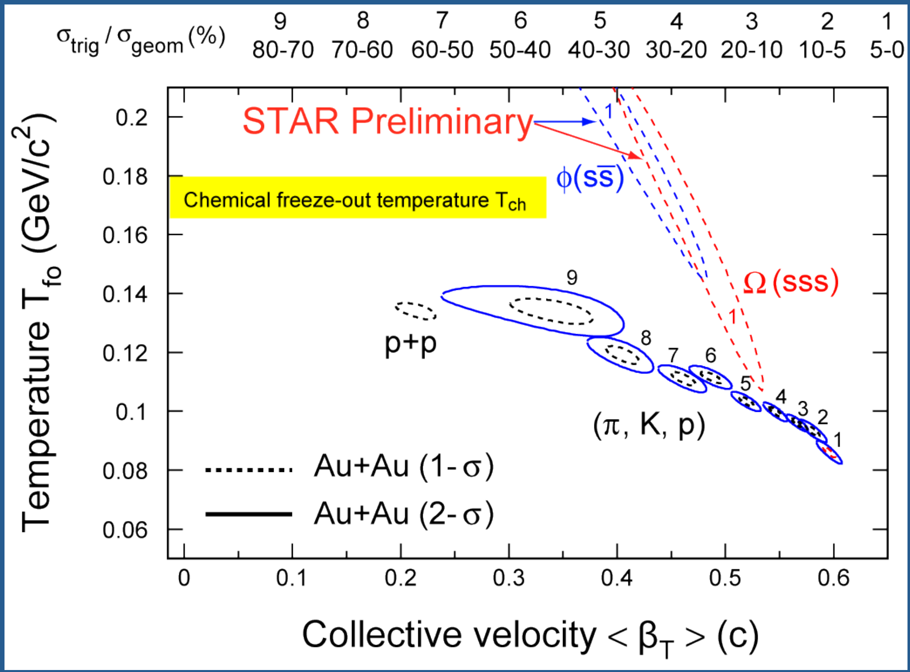
$m_T = (p_T^2 + m^2)^{½}$

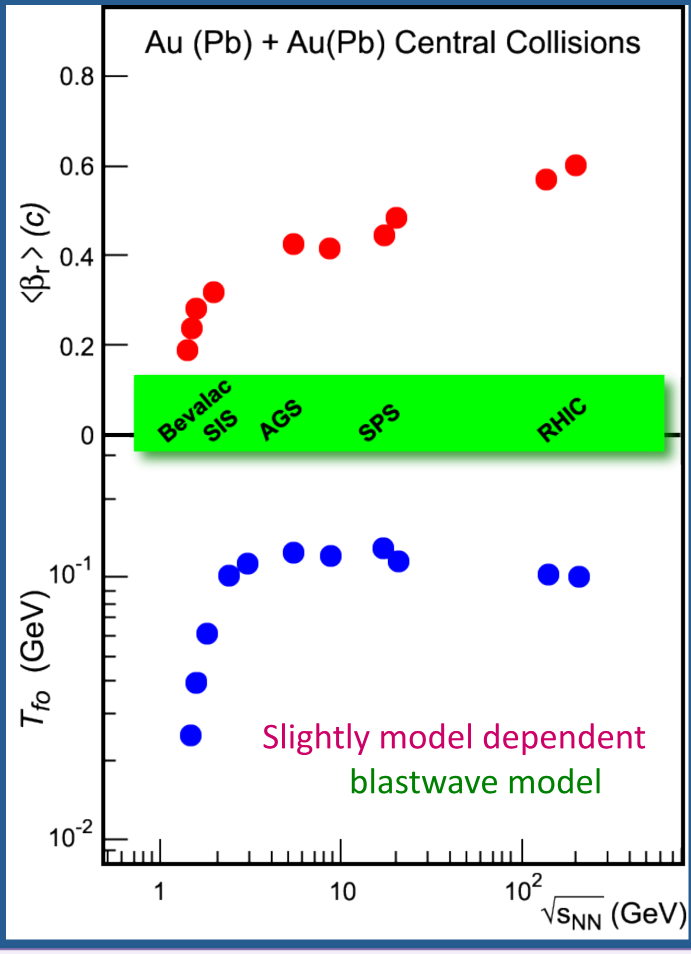
Au+Au central , √s = 200 GeV



T_{fo} ~ 100 MeV & $\langle \beta_T \rangle$ ~ 0.55 c

Kinetic Freeze-Out @ 200 GeV

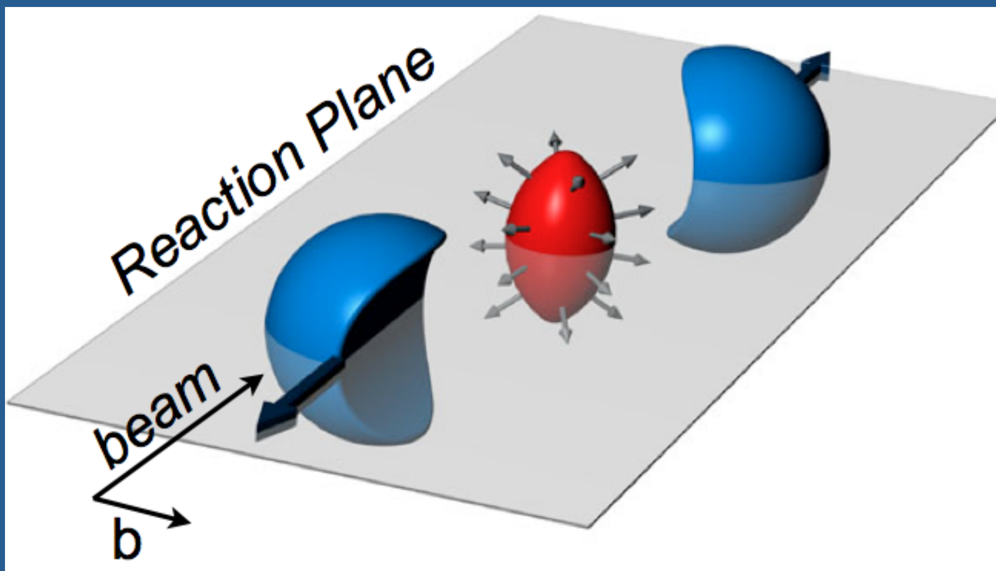


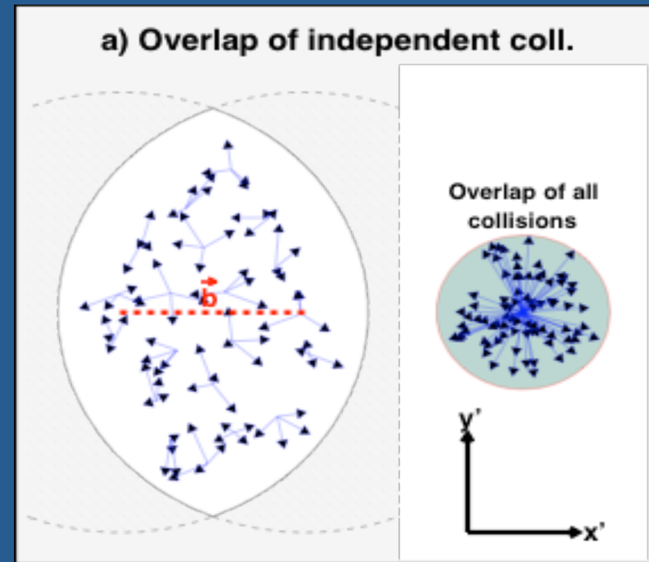


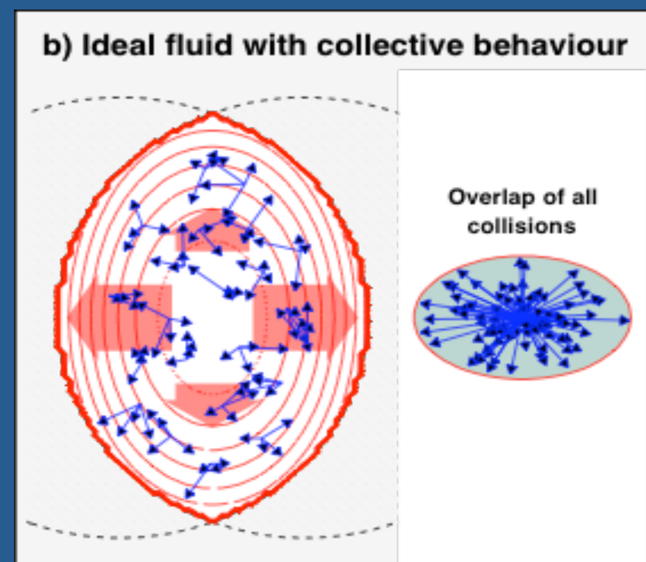
Strong collective radial expansion
⇒ high pressure
⇒ high rescattering rate

Radial flow β_T: increases with √s and centrality
Freeze-out Temperature T_{fo}: decreases with centrality, constant in √s
(bigger systems freeze out later)

Utilize Azimuthal Anisotropy



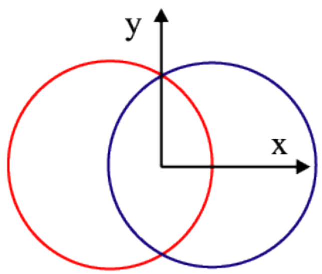




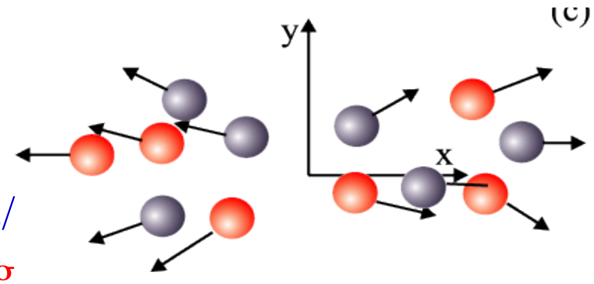
Expansion is driven by a gradient of pressure

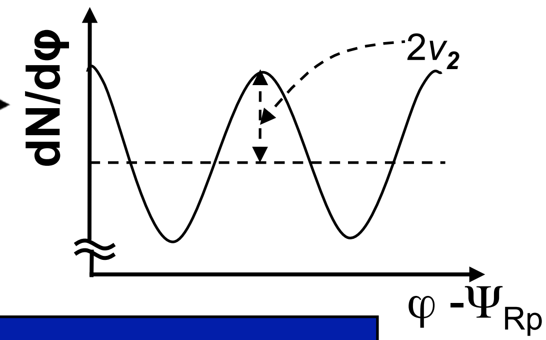
There is a preferential direction for particle emission (Anisotropy in momentum space)

Azimuthal Anisotropy of Emission: Elliptic Flow



Interactions/
Rescattering





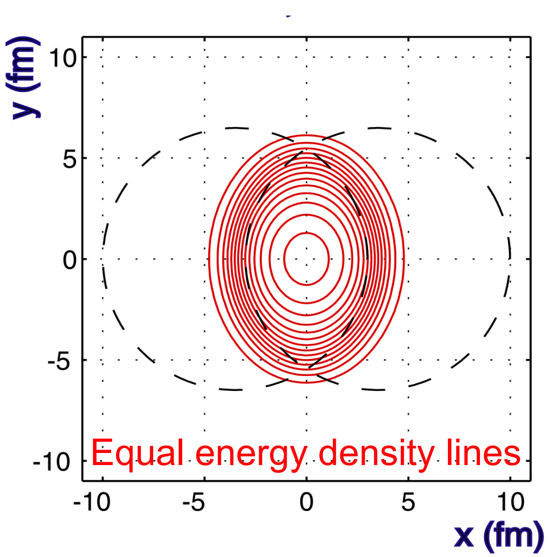
Almond shape overlap
re

Anisotropy in

Elliptic flow observable sensitive to early evolution of system

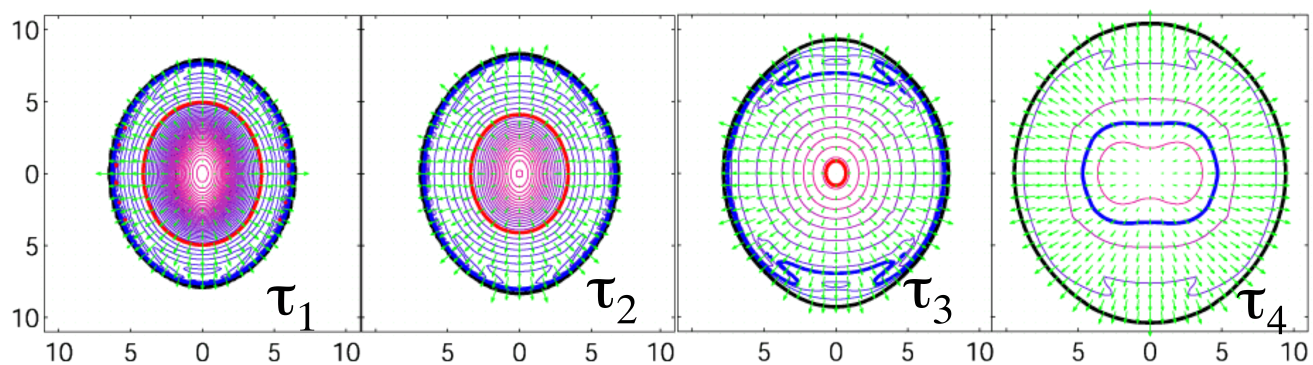
Large v_2 is an indication of ***early*** thermalization

v_2: 2^{nd} harmonic Fourier coefficient in dN/dϕ with respect to the reaction plane

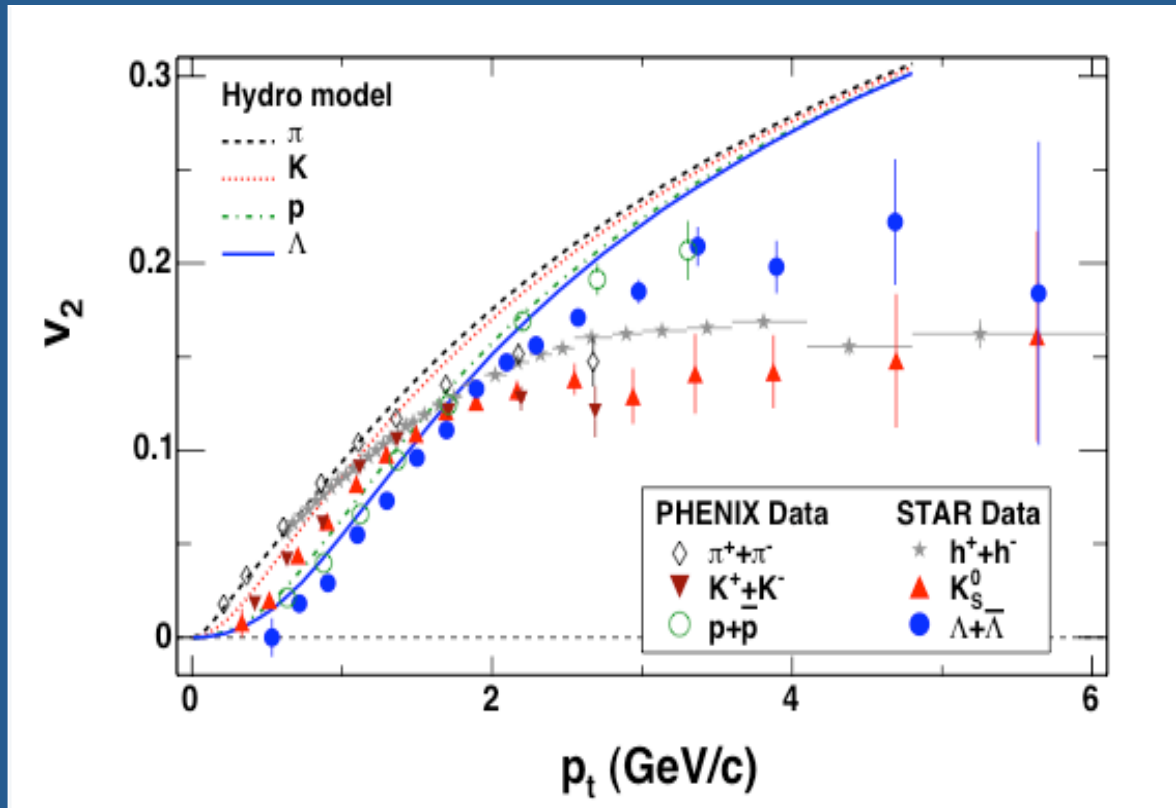


Au+Au at b=7 fm

P. Kolb, J. Sollfrank, and U. Heinz



Flows like a liquid



Phys. Rev. C 72 (2005) 014904

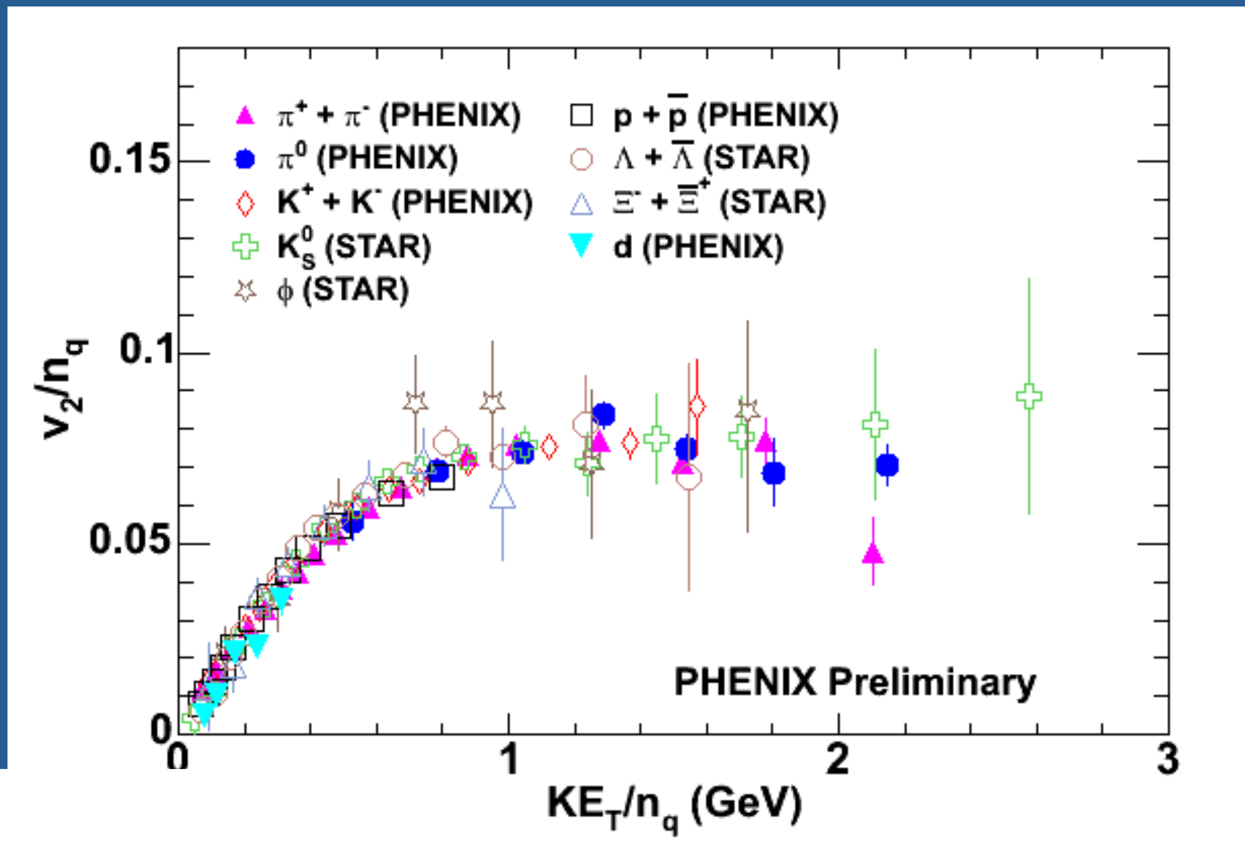
Hydrodynamical models describe data well for p_T (< 2.5 GeV/c)

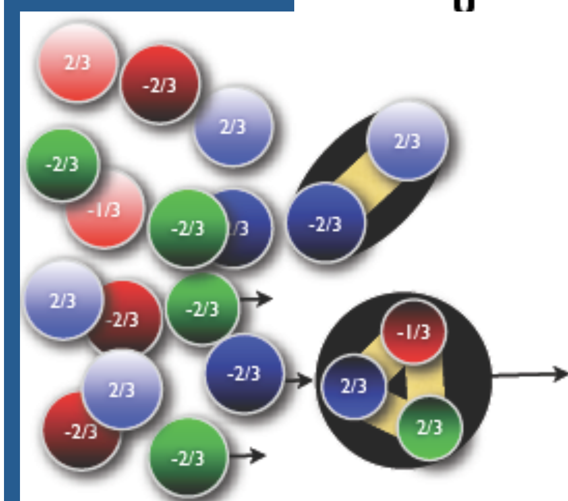
$v_2(\pi) > v_2(K) > v_2(p) \sim v_2(\Lambda)$

⇒ compatible with early equilibration

Strongly suggests that this is *not* just a superposition of p+p collisions

Quarks Flow

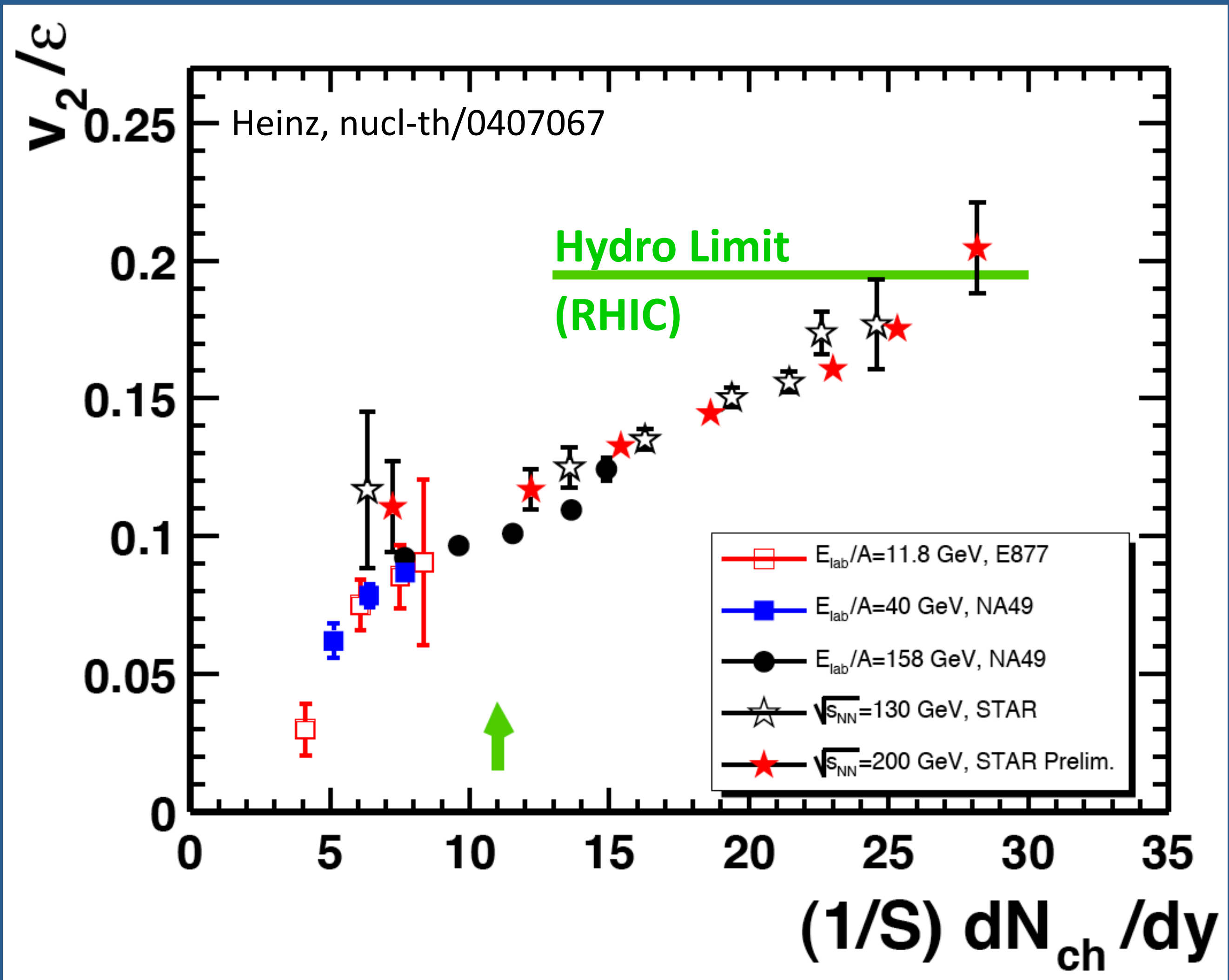




Phys. Rev. C 72 (2005) 014904
Phys. Rev. Lett. **95** (2005) 122301
D. Molnar, S.A. Voloshin Phys. Rev. Lett. 91, 092301 (2003)
V. Greco, C.M. Ko, P. Levai Phys. Rev. C68, 034904 (2003)
R.J. Fries, B. Muller, C. Nonaka, S.A. Bass Phys. Rev. C68, 044902 (2003)
Z. Lin, C.M. Ko Phys. Rev. Lett. 89, 202302 (2002)

implication: valence quarks, not hadrons, are relevant pressure builds early, dressed quarks are born of flowing field

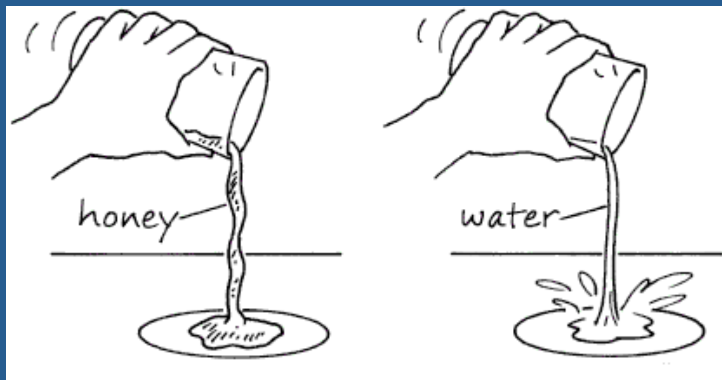
Hydro Limits: Like a Perfect Liquid?



hydro- dynamics without any viscosity describes heavy ion reactions: Thermalization time τ = 0.6 fm/c, Energy Density: ε=20 GeV/ fm^3

ε=spatial eccentricity = $\langle y^2-x^2\rangle/\langle y^2+x^2\rangle$
S=overlap area

Small Viscosity:



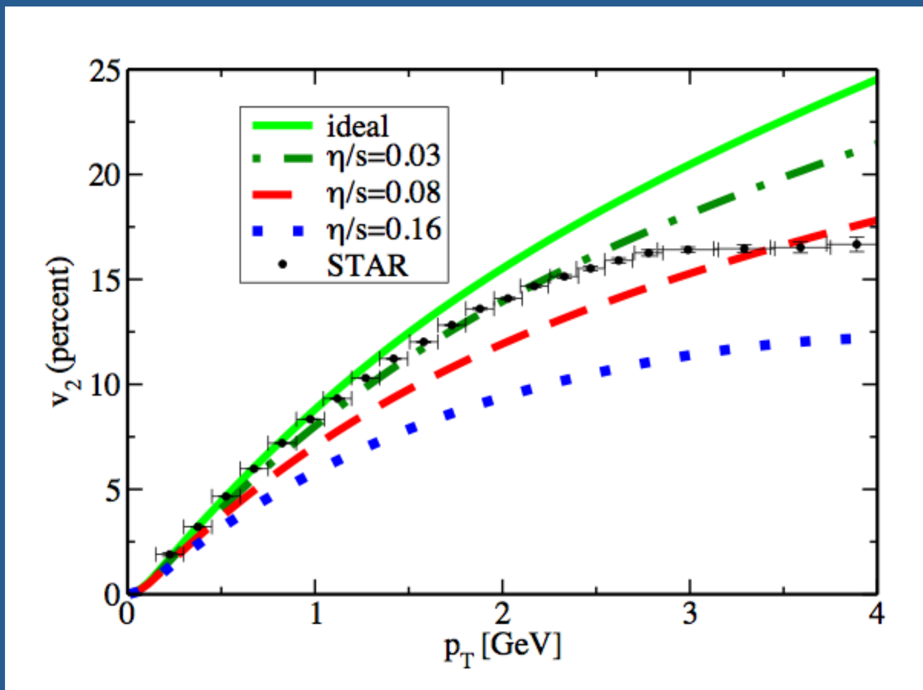
Viscosity describes a fluid's internal resistance to flow - inability to transport momentum & sustain a wave

Viscosity/entropy (η/s) ~1/4π limit
→ liquid at RHIC is "perfect" !

Good momentum transport:
neighboring fluid elements "talk" to each other

Can we do better? How to quantify?
- Use hydrodynamics
- Set initial energy density to reproduce observed particle multiplicity
- Use various values of η/s
- Constrain with data

Viscous hydrodynamics & RHIC data



P. Romatschke et al.
Phys. Rev. Lett. 99:172301 (2007)

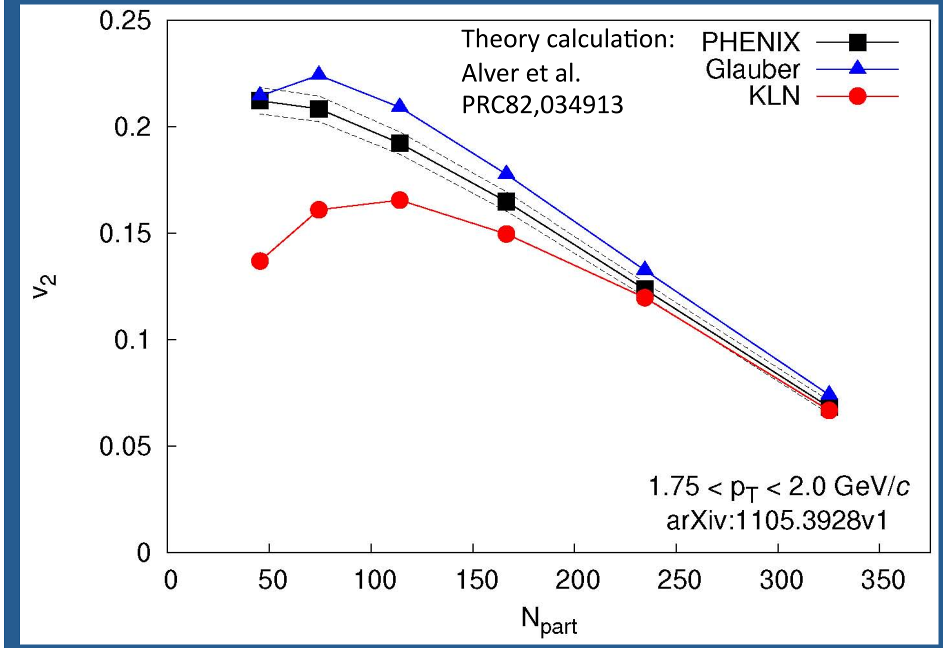
mum bias v_2 seems to favor $\eta/s \simeq 0.03$, at least at low momenta, where hydrodynamics is supposed to be most applicable. Note that this result could change drastically if the minimum bias data were decreased by 20%, which is the estimated systematic error quoted in [25].

There are, however, a number of caveats that should be considered before taking the above numbers literally. Firstly, we have only considered Glauber-type initial conditions, and assumed $\Pi^{\mu\nu}(\tau_0) = 0$. It has been suggested that CGC-type initial conditions lead to larger overall v_2 [33] which in turn would raise the allowed values for η/s in our calculation. This is due to the larger eccentricities in this model [34] (note the issues raised in [35]). How-

Caveats: Details of hydro code, Viscous correction, Initial conditions, freezeout particle mix, What is η/s?

Viscous hydrodynamics & RHIC data

2 models with: Different fluctuations, Eccentricity, ρ distribution



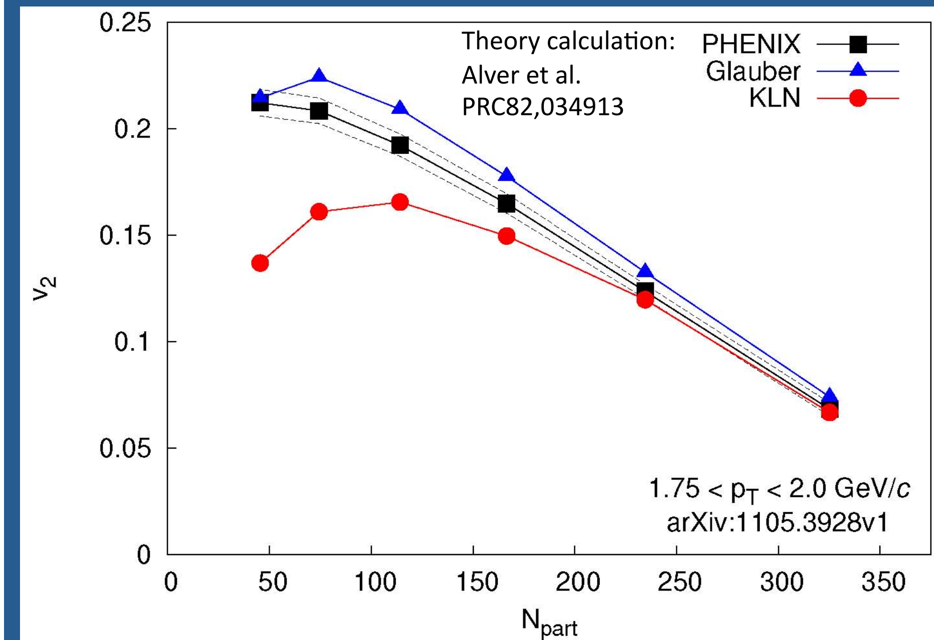
***v_2* described by both Glauber and CGC**

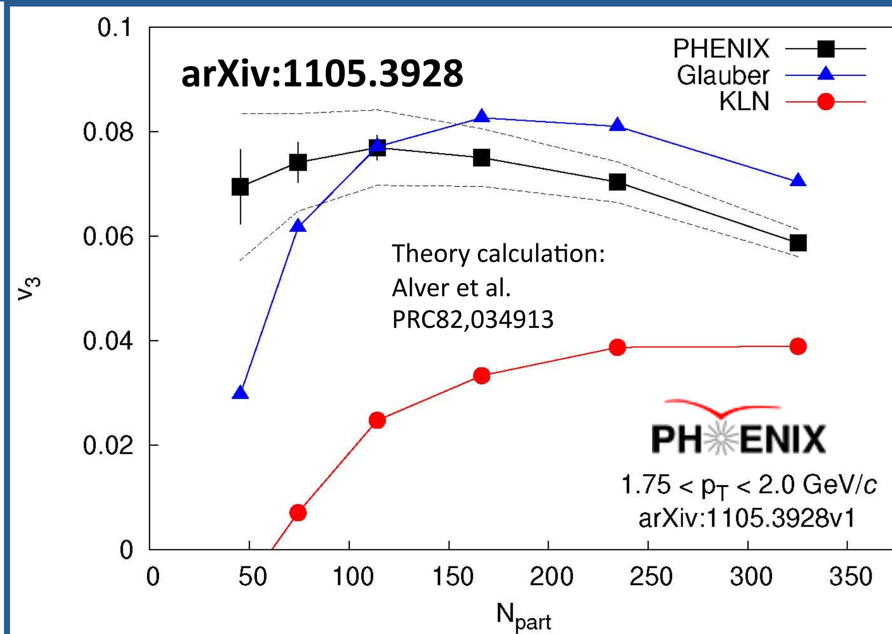
but different values of η/s

Lappi, Venugopalan, PRC74, 054905
Drescher, Nara, PRC76, 041903

Viscous hydrodynamics & RHIC data

2 models with: Different fluctuations, Eccentricity, ρ distribution





v_2 described by both Glauber and CGC

but different values of η/s

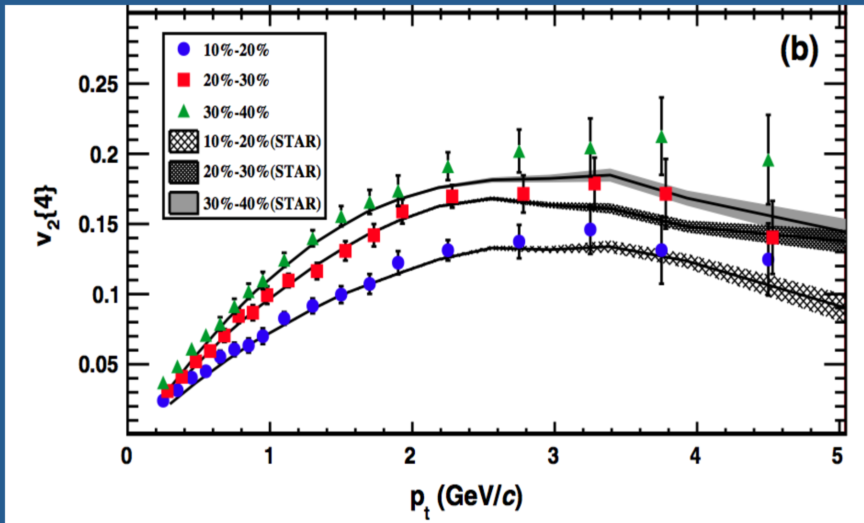
v_3 described only by Glauber

breaks degeneracy

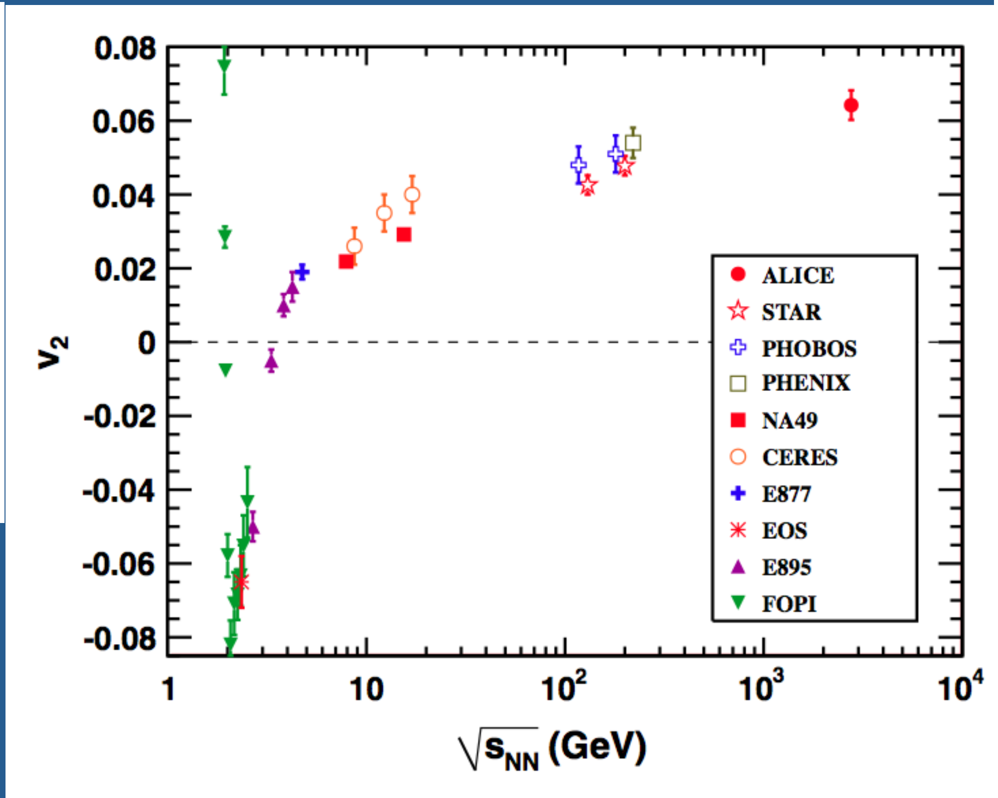
Lappi, Venugopalan, PRC74, 054905
Drescher, Nara, PRC76, 041903

Initial conditions & hydro details are still on the works!

Hydrodynamics at LHC



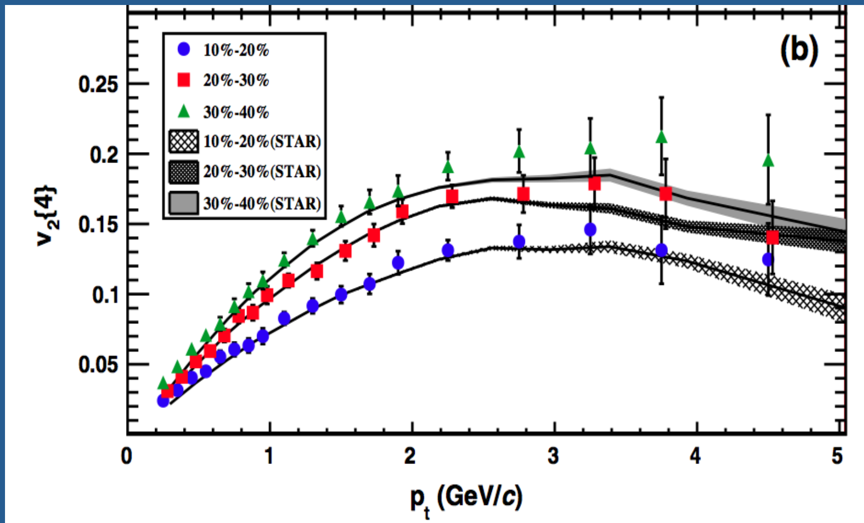
Pb+Pb at LHC flows similarly



the integrated elliptic flow increases 30% (caused by the increase in the mean pt)

ALICE Phys. Rev. Lett. 105, 252302 (2010)
PRL 107, 032301 (2011)

Hydrodynamics at LHC



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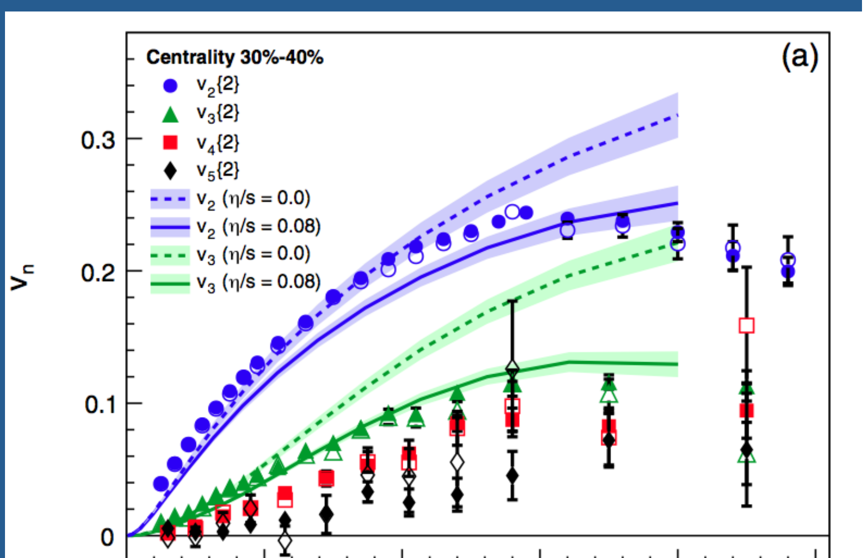

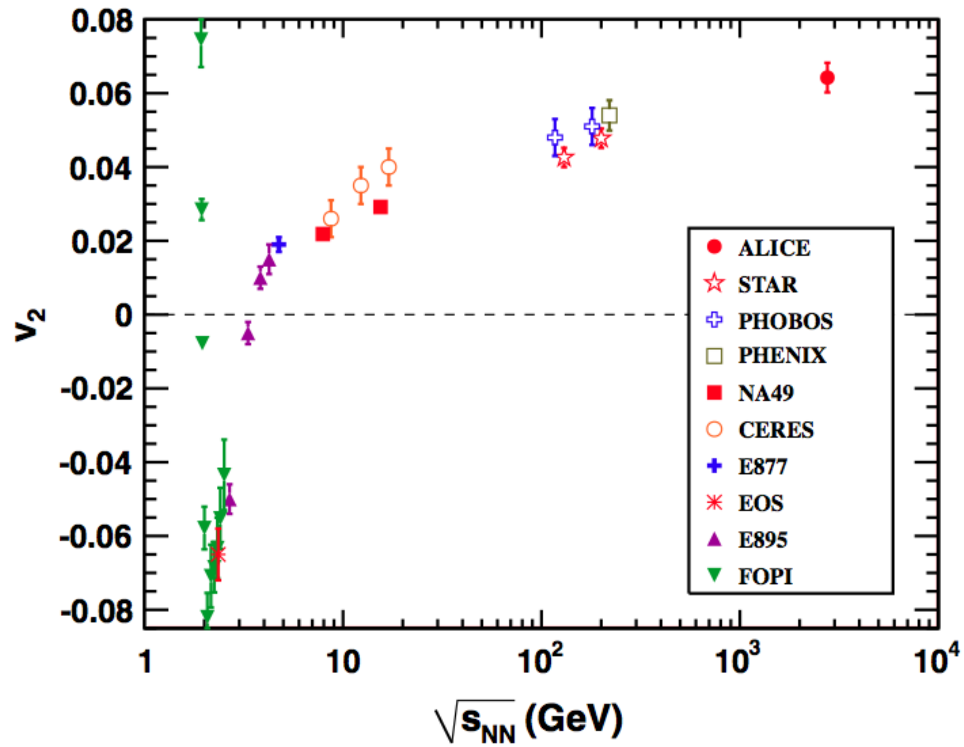

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ALICE Phys. Rev. Lett. 105, 252302 (2010)
PRL 107, 032301 (2011)

Favors a small value of Viscosity/entropy (η/s)

Last 10 Years of Discoveries

- **Collective Flow:**
  → behaves more like liquid rather than gas.
  → small viscosity perfect liquid.

- **Particle Production:**
  → recombination/ coalescence dominates over fragmentation at medium p_T

- **Jet Quenching:**
  → opaque to fast partons