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What is the

Quark-Gluon Plasma

and how to measure it?

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OUTLINE

- Recall Quantum Chromo Dynamics
- Creation of Quark-Gluon Plasma
  - Heavy Ion Collisions
  - Space-Time evolution
  - Centrality of Collisions
- Quark-Gluon Plasma signatures
  - Nuclear modification factor
  - Charmonium suppression
  - Strange enhancement
  - Jet quenching
  - Hydrodynamic Flow

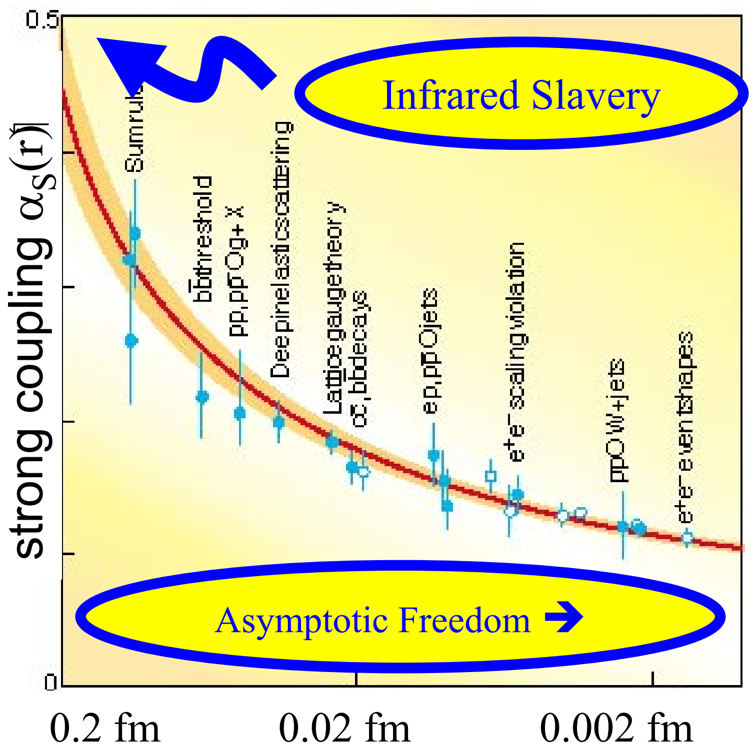
- „What are the building blocks of matter ?“
- „When was matter created ?“

- -> Quark-Gluon Plasma (QGP)
  - helps to understand these questions
  - is primordial form of matter
  - is root of various elements in present universe

Recall QCD

- fundamental theory for strong interaction
  fundamental particles (quarks (q) and gluons (g))
- important characteristics
  - confinement / deconfinemet
  - coupling constant is „running“ with (depends on) r
  - lim $\alpha_s(r) = 0$ for r -> ∞

Confinement / Deconfinement

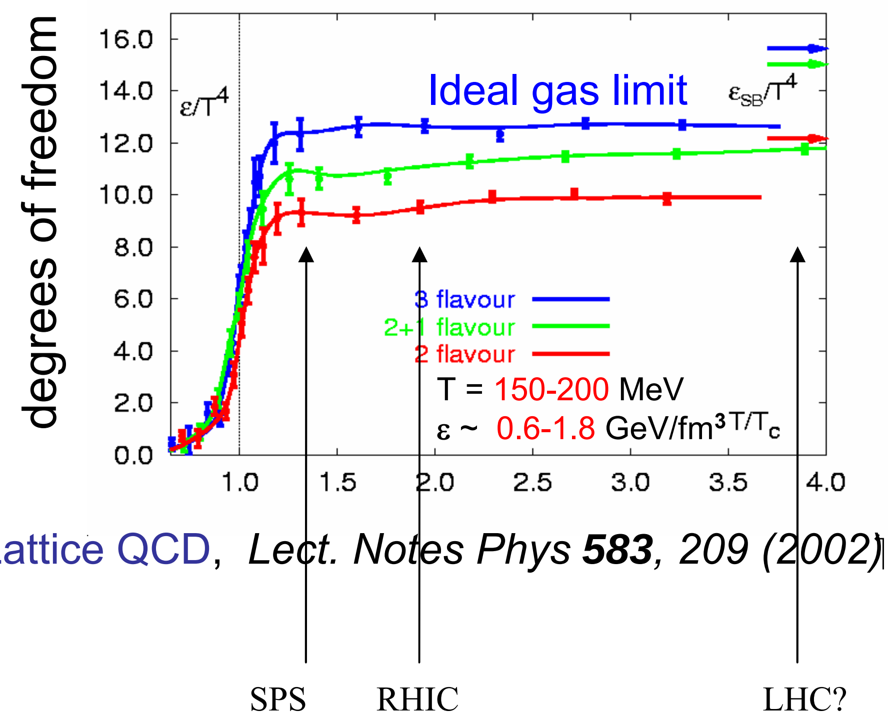


- **Confinement**
  - „infrared slavery“
  - at low energy/temperature
  - large distances
  - q and g interaction strong
  - no free q, g -> bound in colorless particles
  - V_{long} = kr, with k ~ 1GeV/fm
- **Deconfinement**
  - „asymptotic freedom“
  - at high energy/temperature
  - small distances
  - q and g interaction is weak
  - $V_{short} = -4/3\ \alpha_s(r)/\ r$
  - q and g are quasi free

QCD calculation

- Perturbation theory can only be applied at short distance/high momentum transfer
- At scales of the order of the hadron size (~ 1 fm) perturbative methods lose validity
- → Approximate Theory for larger distances
    - 4 dim lattice, with gauge field as lattice links

Lattice QCD

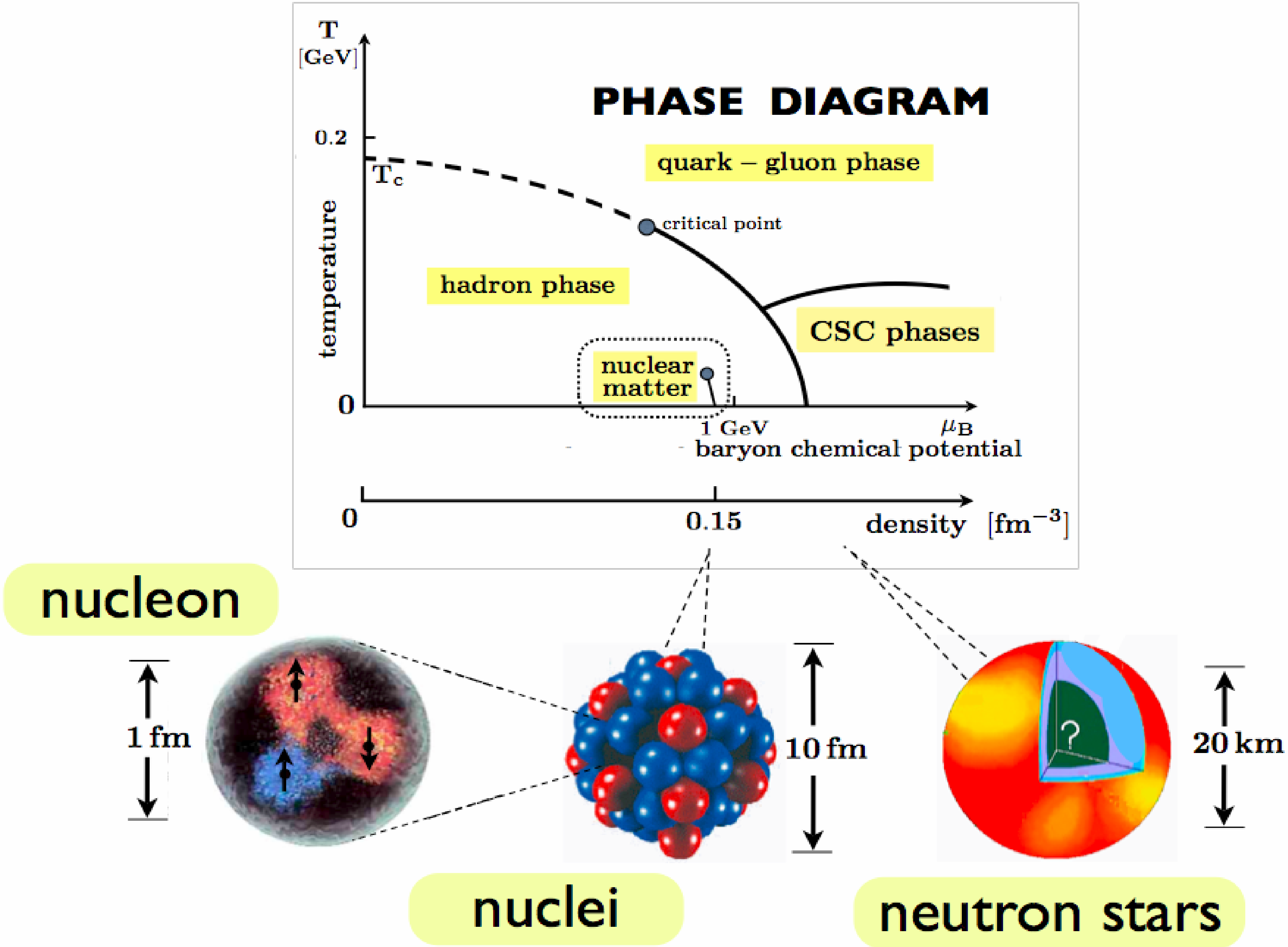


Lattice QCD, *Lect. Notes Phys* ***583***, *209 (2002)*

- **for ideal gas:**
  - **energydensity ε ~T^4**
- **degrees of freedoms**
- **At T/T_c rapid changes**
- **At T~1.2 T_c ε settles at about 80% of the Stefan-Boltzmann value for a ideal gas of q, $\bar{q}$, g (ε_{SB})**

→ phase transistions from hadronic matter to QGP

QCD Phase Diagram

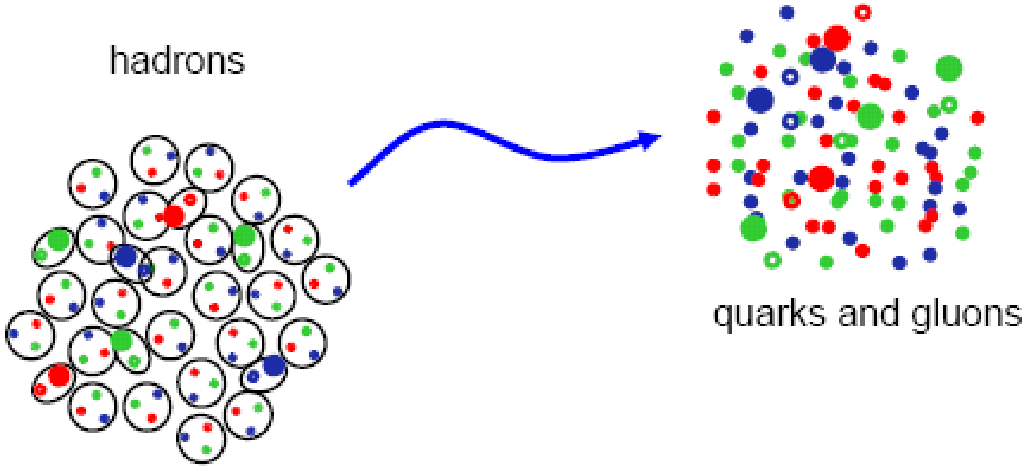


„Why do we need QGP?“

“To understand the strong force and the phenomenon of confinement”

→ **Deconfined colour matter has to be created and studied**

→ **Quark-Gluon Plasma**

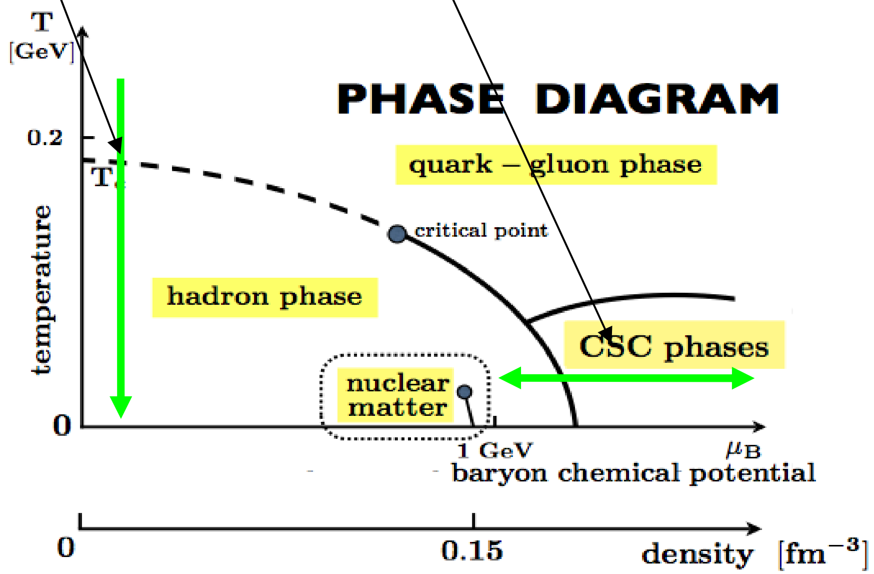


„Recipes“ for quark-gluon plasma

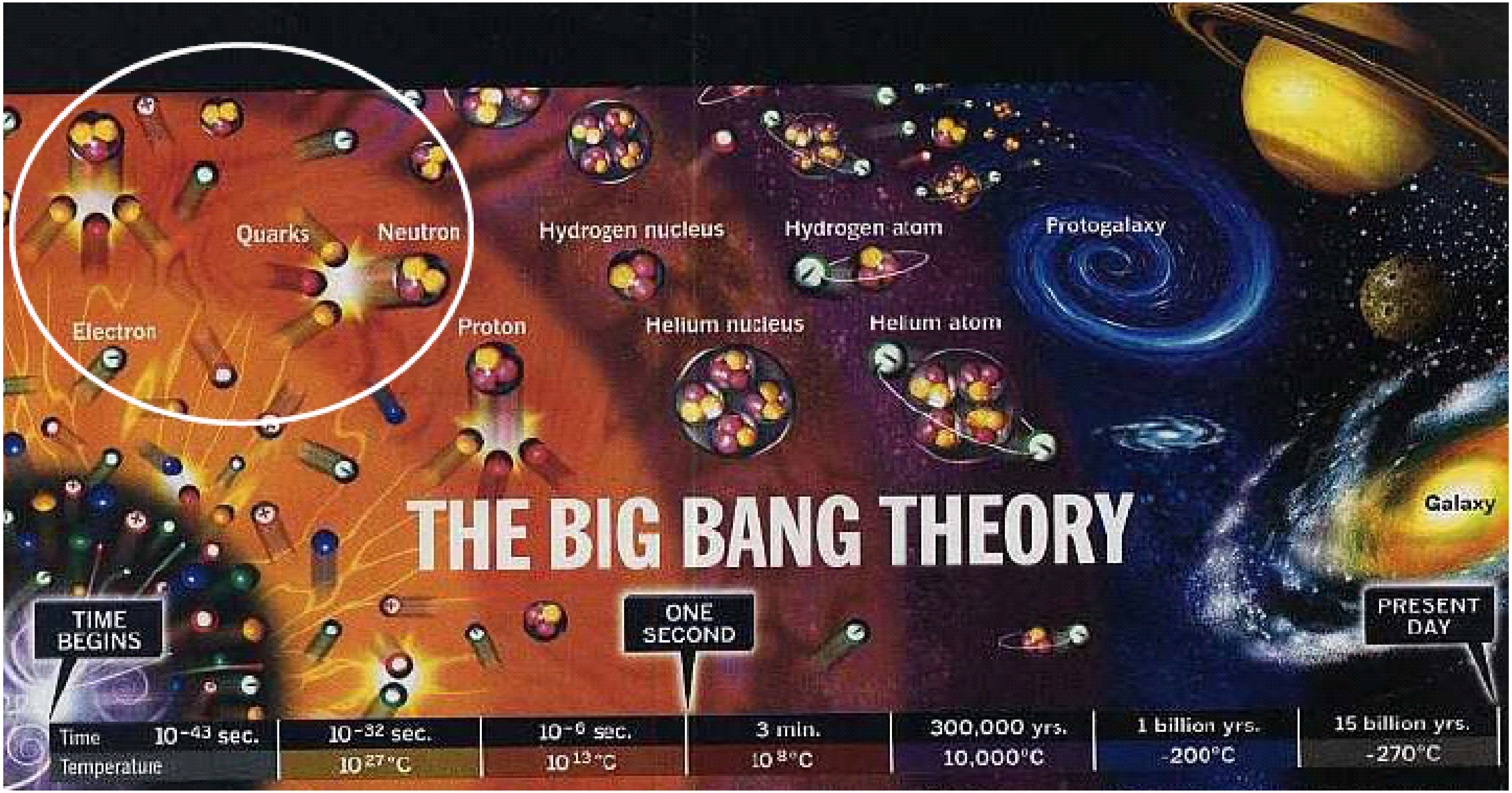
- **Phase Diagram → 2 methods**
  - **High Temperature**
    - all hadrons approx. same size (~ 1 fm)
    - hadrons start to overlap for $T > T_c$
    - lattice QCD: T_c ~170 MeV (sun = 1.3 keV)
    - hadron system disolves into QGP, with $n_q = n_{\bar{q}}$
  - **High baryon density**
    - large number of baryons
    - and compress
    - baryons start to overlap for $\rho > \rho_c$
    - lattice QCD: ρ_c = (several) x ρ_{nm}, with $\rho_{nm} = 0.16\ fm^{-3}$
    - system disolves, with $n_q >> n_{\bar{q}}$

„Where to find it?“ (i)

1. early universe (already too late to observe)
   - 10^{-5}~10^{-4} s after cosmic Big Bang QCD phase transition
2. superdense stars
   - white dwarfs/neutron stars/quark stars?
   - observation not „practical“



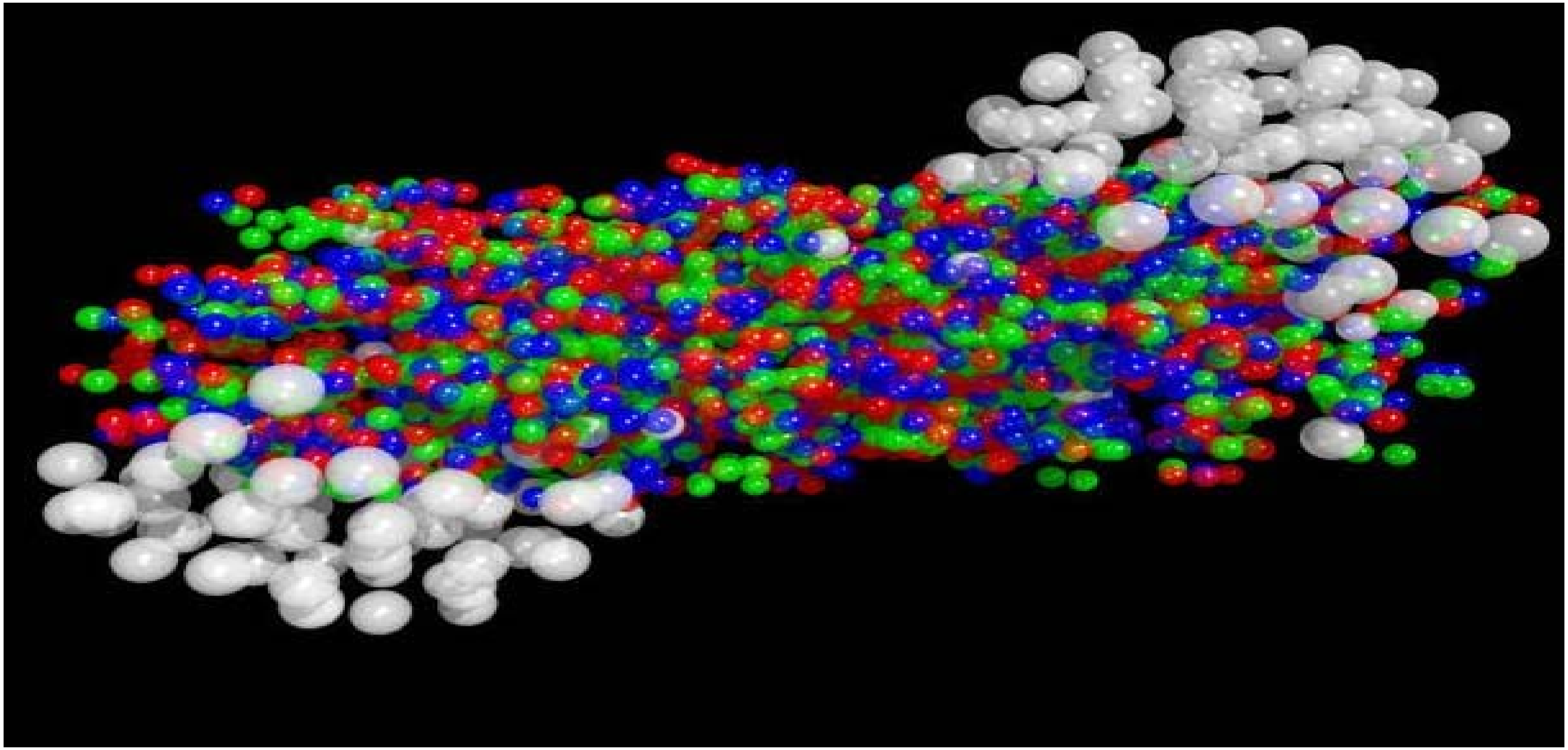
The Big Bang aftermath

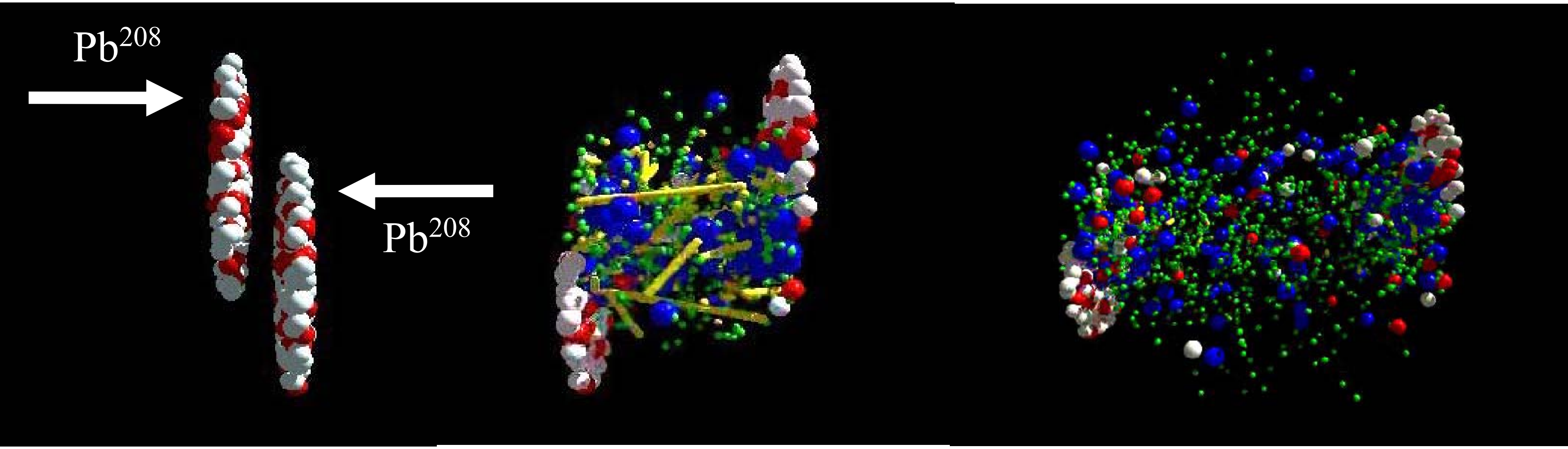


„Where to find it?“ (ii)

3. Heavy Ion Collisions

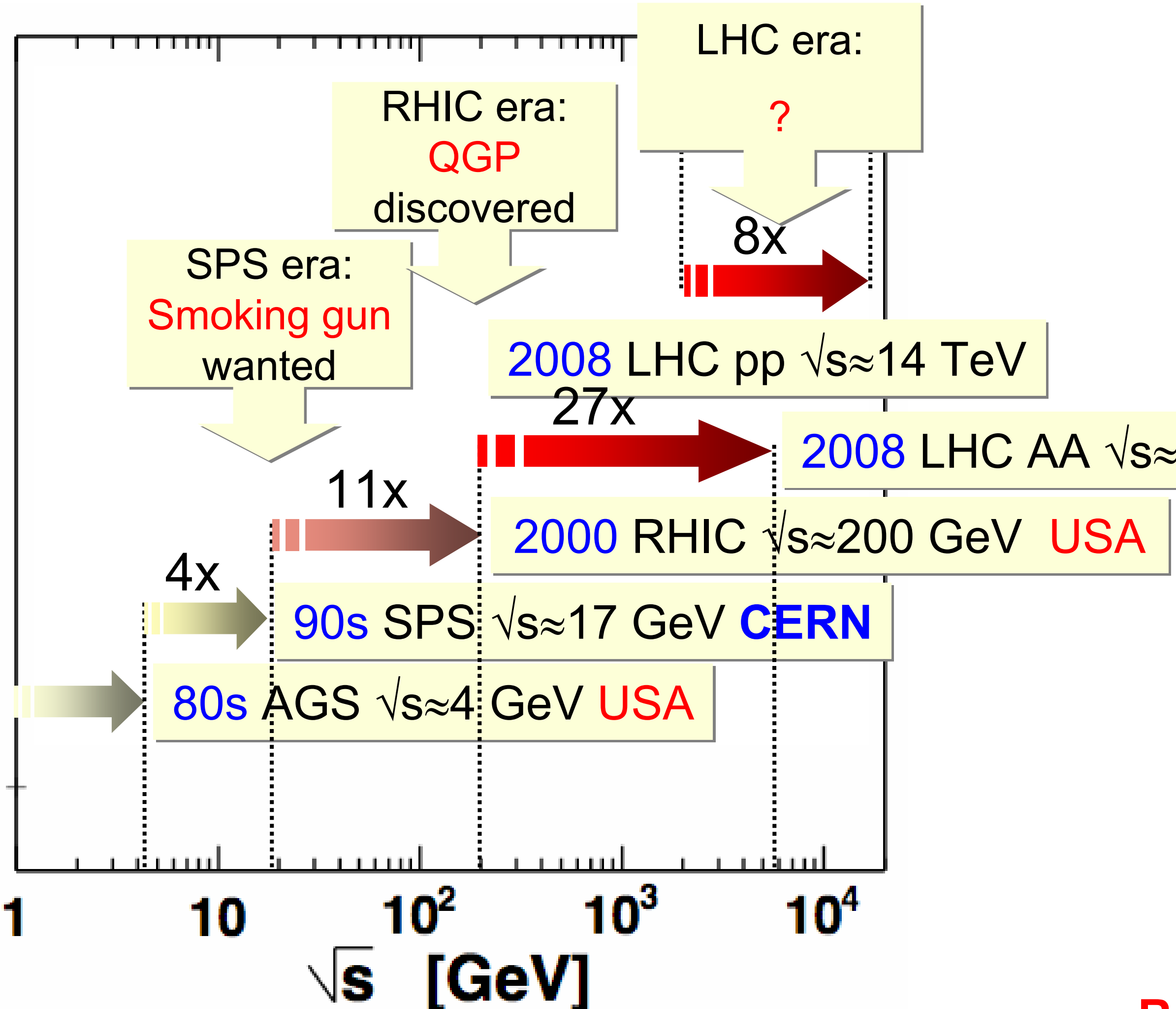
- heat and compress a large volume of QCD matter
- Colliding heavy nuclei at very high energies

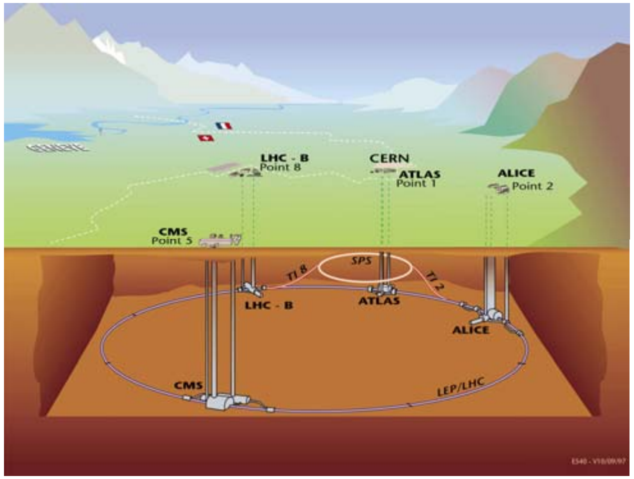




- When 2 nuclei of 208 nucleons collide, each "participating nucleon" interacts around 4 or 5 times, on average!
- At $\sqrt{s}$ = 20 GeV, around 2200 hadrons are produced in central Pb-Pb collisions (to be compared to 8 or so produced in pp) (SPS)
- Create for a short time span (about 10^{-23}s, or a few fm/c) the appropriate conditions for QGP

Heavy Ion Collider

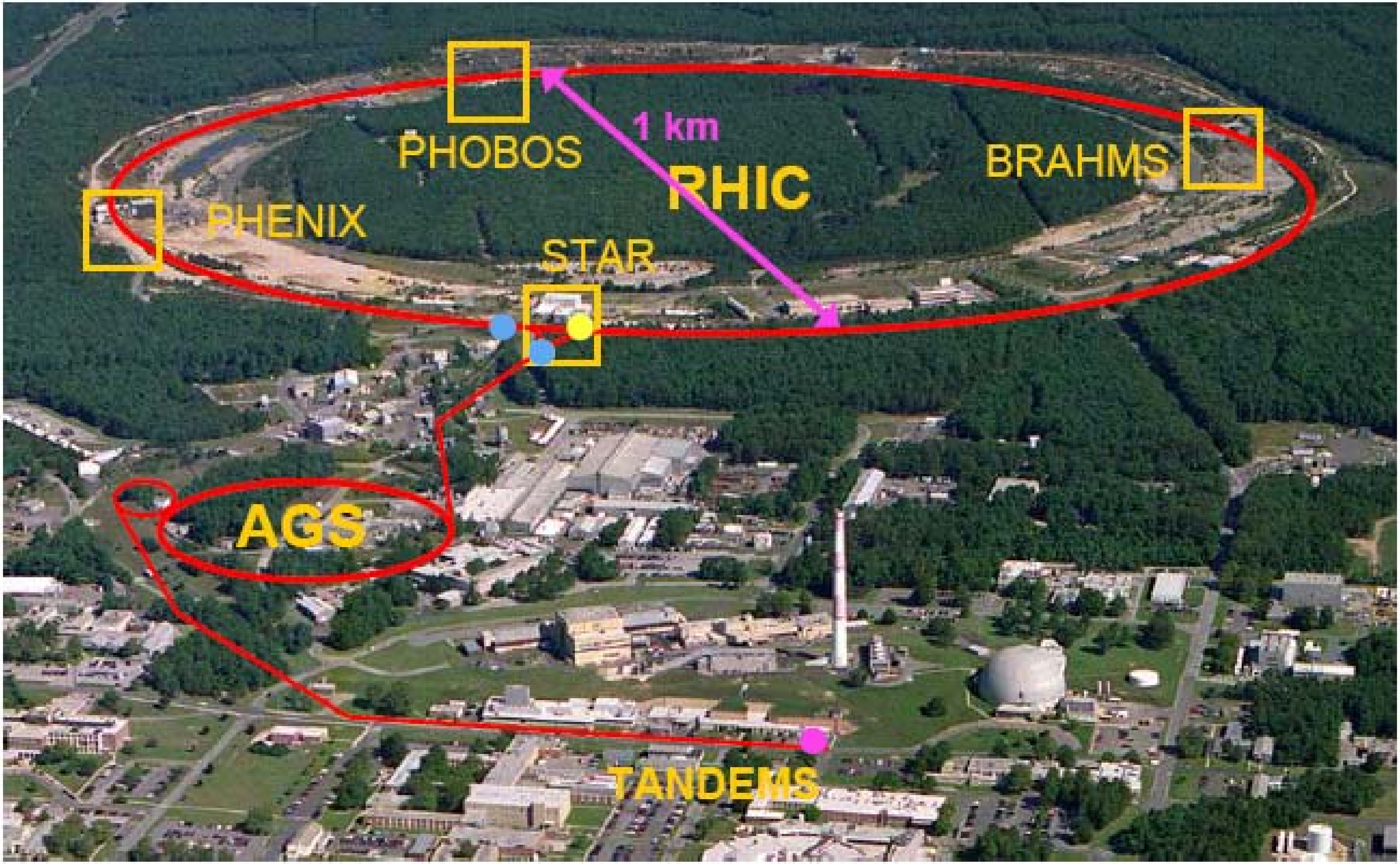




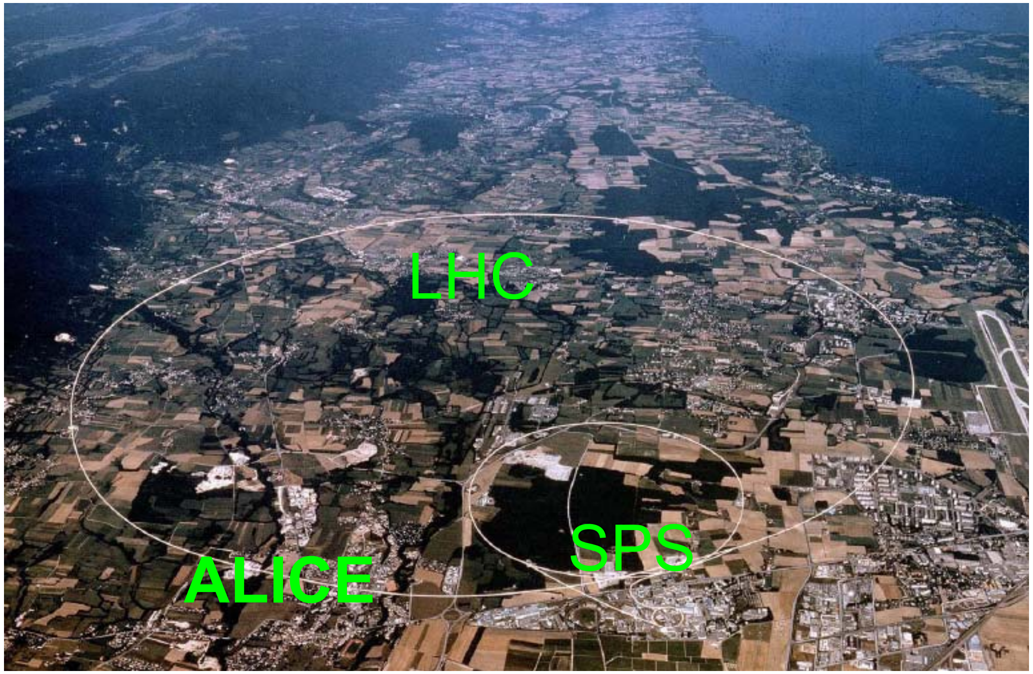
Relativistic **H**eavy **I**on **C**ollider

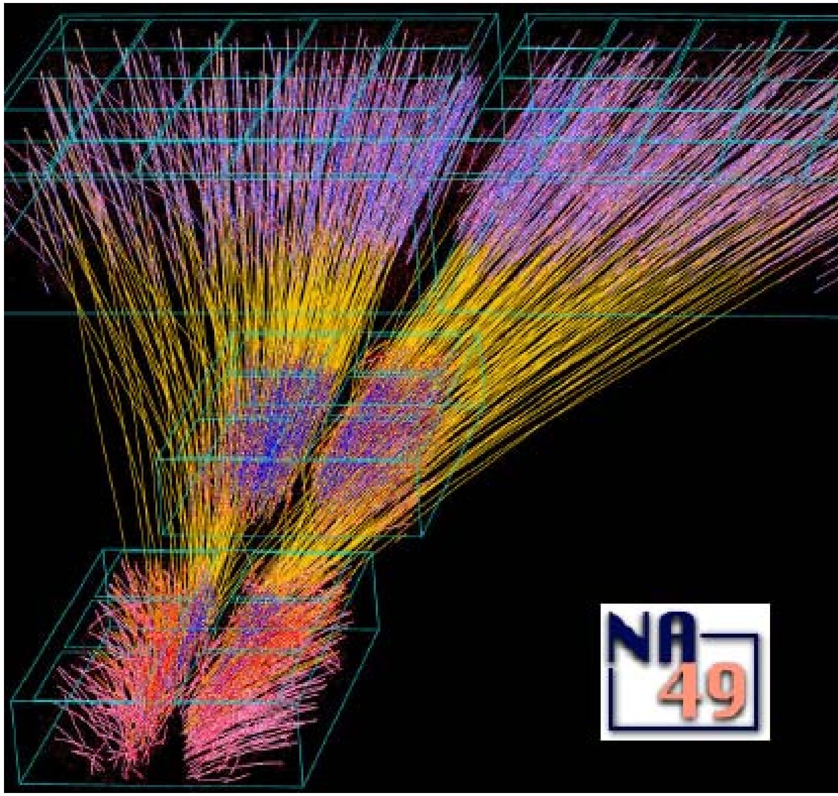
Brookhaven Nat. Lab. Long Island, USA

RHIC



CERN

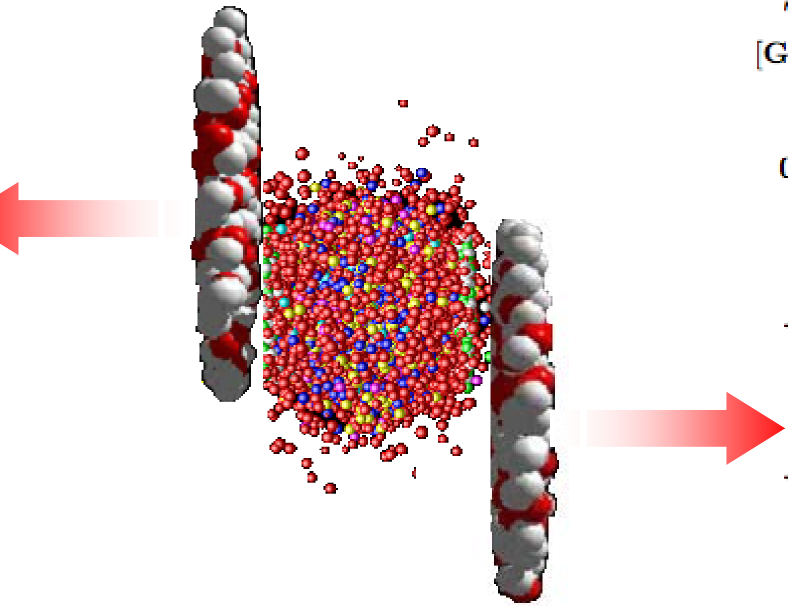


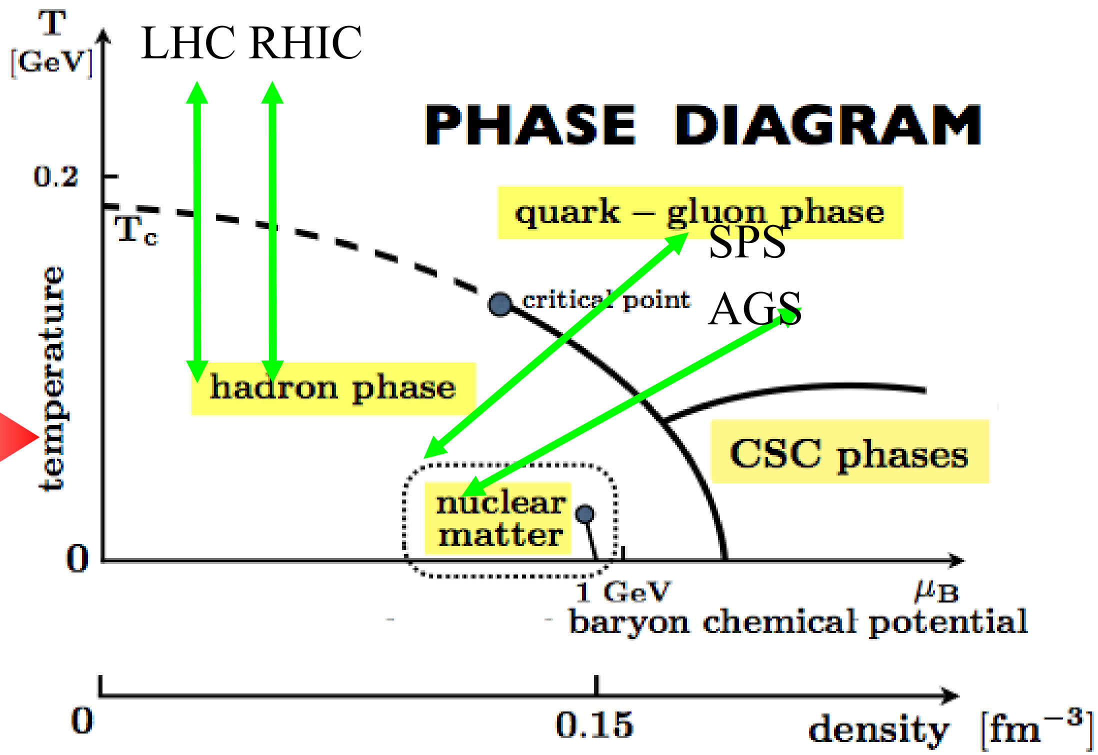


PbPb Collission at SPS

Heavy Ion Collisions

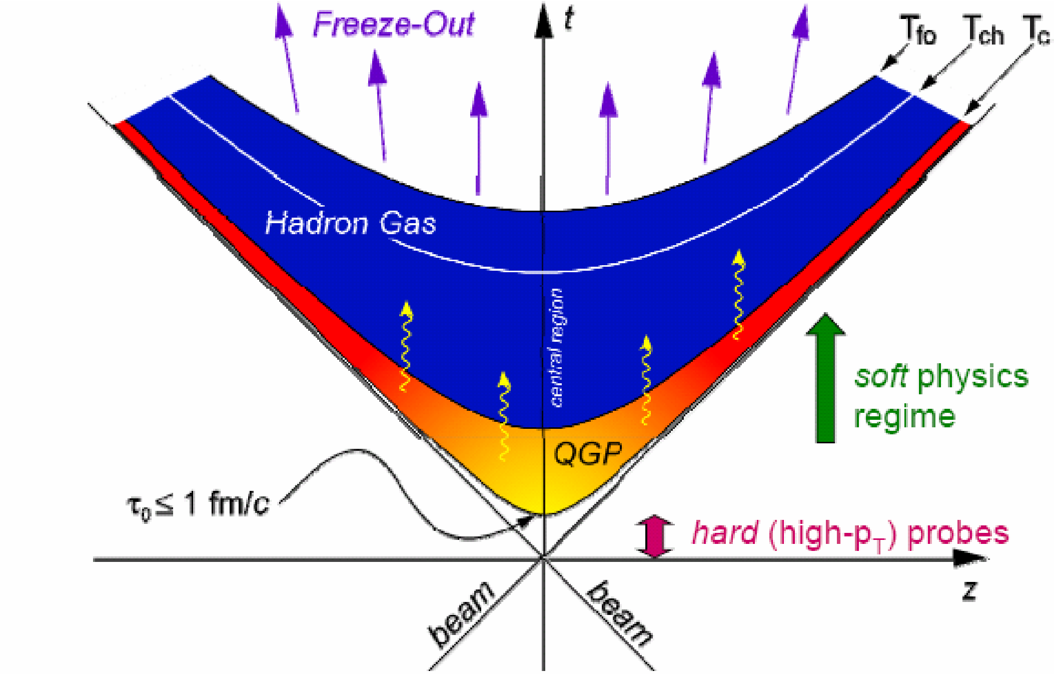
- „exploring the phases and structure of QCD“
- high E, high T, low ρ_{baryon}





Space-Time evolution

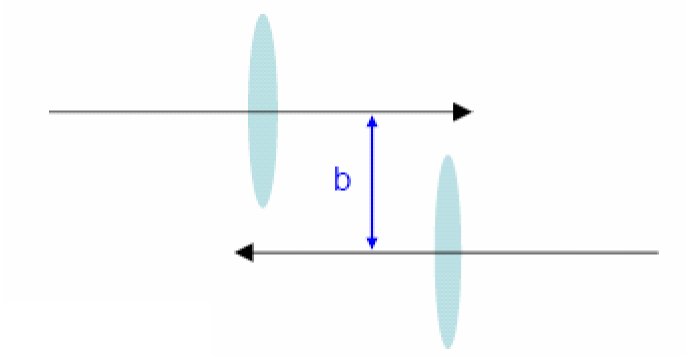
- The “fireball” expands through several phases:
  - Pre-equilibrium state
  - Quark-gluon plasma phase, $T>T_c$
  - At chemical freeze-out, T_{ch}, hadrons stop being produced
  - At kinetic freeze-out, T_{fo}, hadrons stop scattering



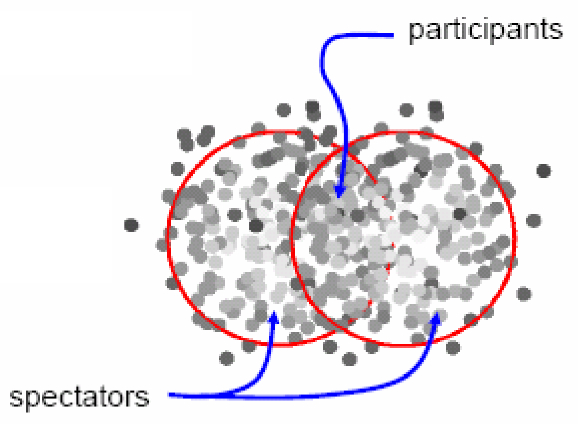
Freeze Out

- In nucleus-nucleus collision we form a strongly interacting “fireball” which expands and cools down
- When finally the system is so dilute (i.e. the mean free path is so large) that interactions among the collision products cease, we have “freeze out”
- From then on the collision products just stream out towards the detector

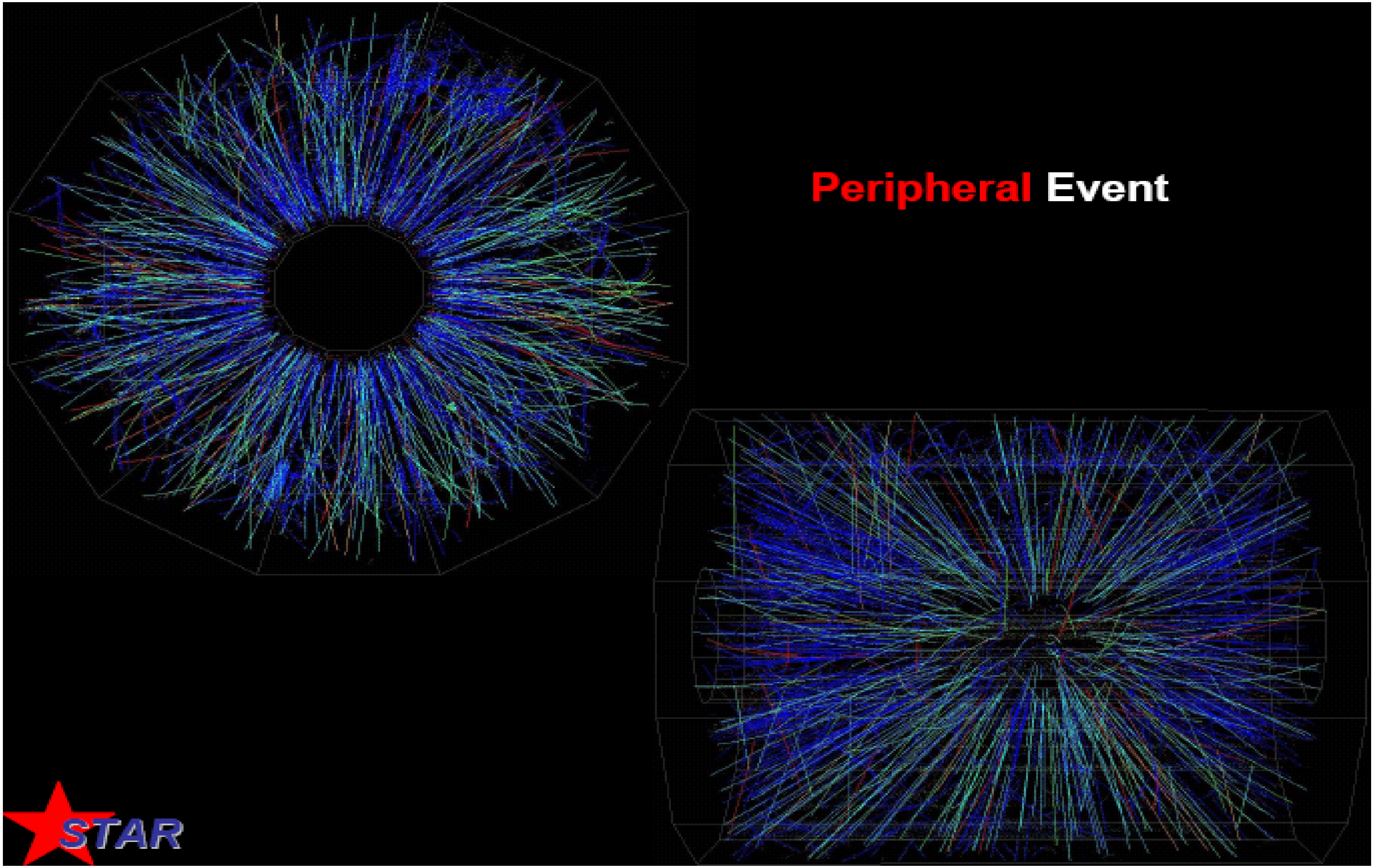
Centrality of nucleus-nucleus collision



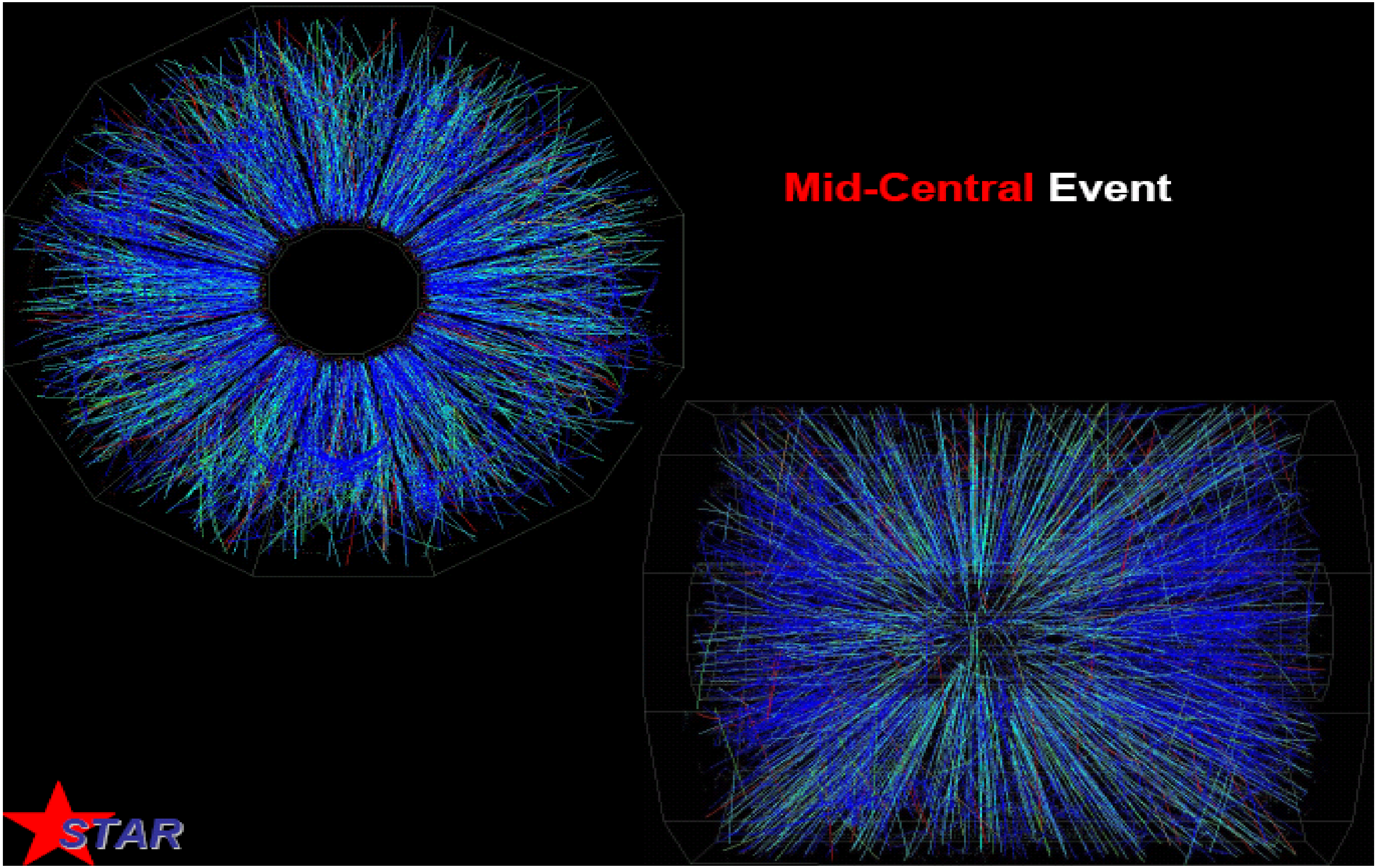
- **b = impact parameter**
- **distance between colliding nuclei, perpendicular to the beam-axis**
  - **large b: peripheral collisions**
  - **small b: central collisions**
- **not measured ! must be derived from measured variables, through models**
- **Quantitative measures of the collision centrality:**
  - **Number of participant nucleons: N_{part}**
  - **Number of binary nucleon-nucleon collisions: N_{coll}**
  - **Multiplicity density of charged particles at mid-pseudo**
  - **Forward hadronic energy: E_{ZDC}**
  - **Transverse energy: E_T**
  - **... among others**



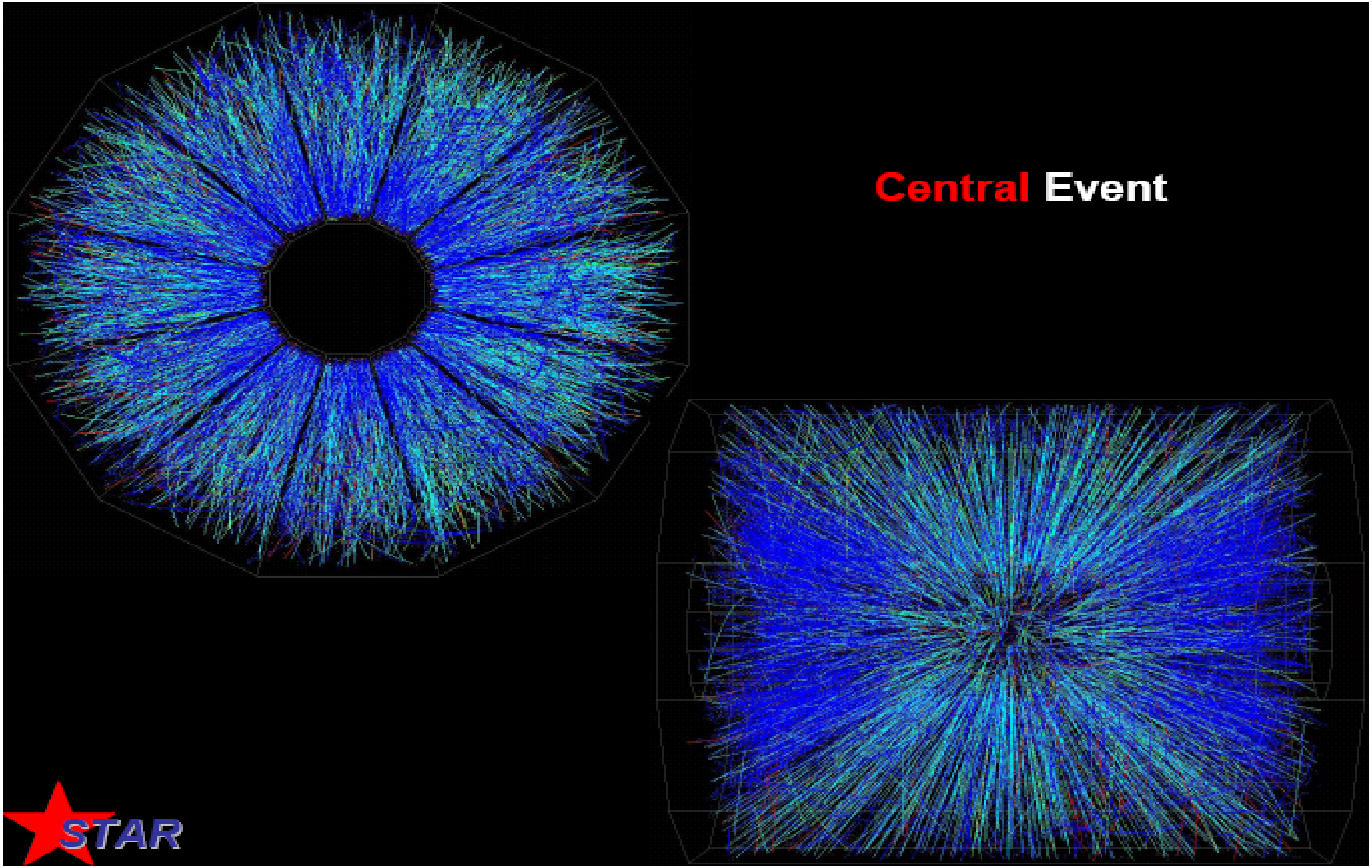
Prepherial Event (STAR)



Mid-Central Event



Central Event



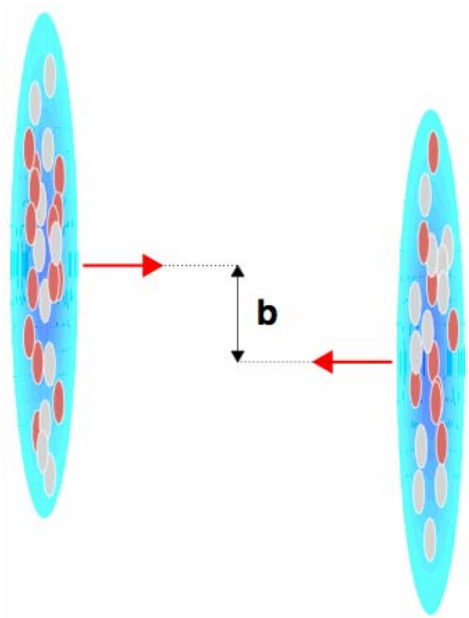
QGP signatures in HIC

- High-pt partons traversing and probing the matter created in the collision
  - Nuclear modification factor
  - Di-jets / Jet quenching
  - Collective behaviour of the matter

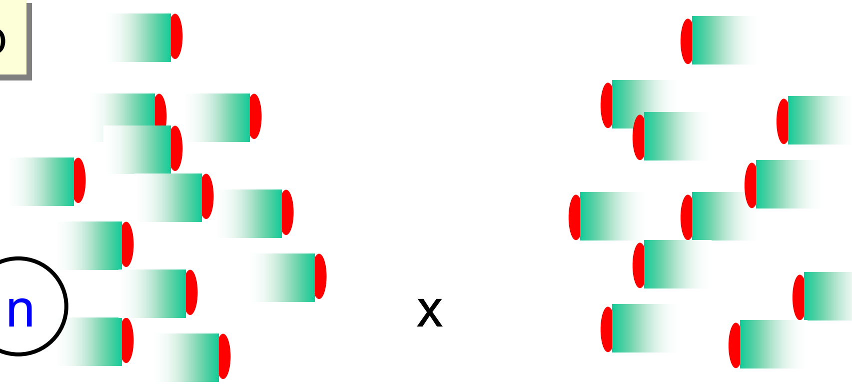
    azimuthal anisotropy of produced hadrons (flow)
  - Quarkonia suppression
  - Strangeness enhancement
- Direct photons
- Particle interferometry (HBT)
- …

Nuclearmodification Factor R_{AA}

A+A



p+p

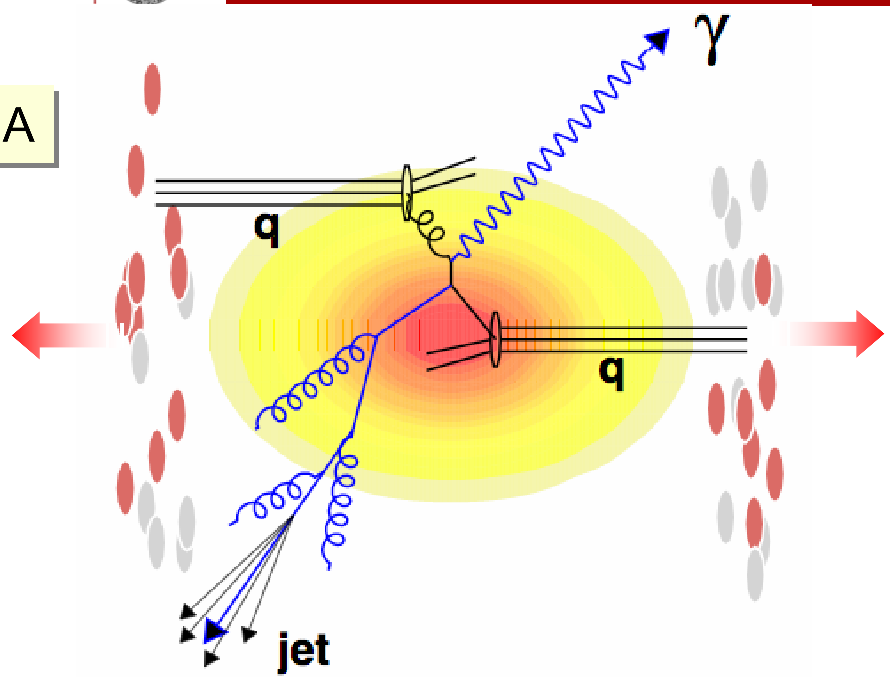


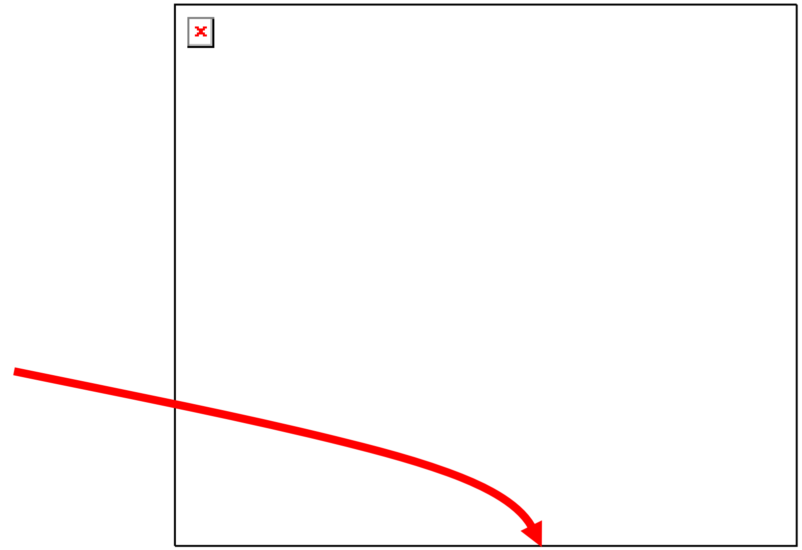
$n \times m \approx \langle N_{binary} \rangle$

varies with impact parameter ***b***

Nuclearmodification Factor R_{AA}

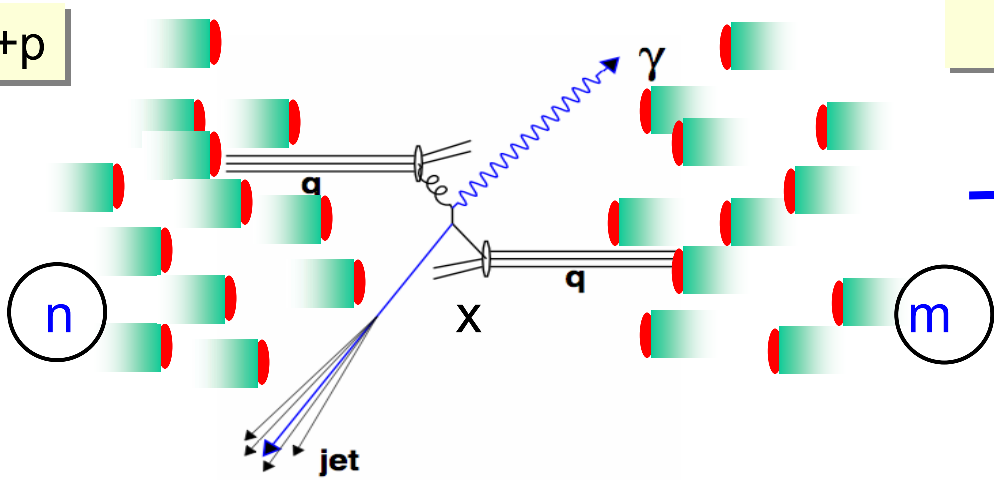
A+A





$$R_{AA}(p_T) = \frac{d^2N^{AA}/dp_T d\eta}{\langle N_{binary}\rangle d^2N^{pp}/dp_T d\eta}$$

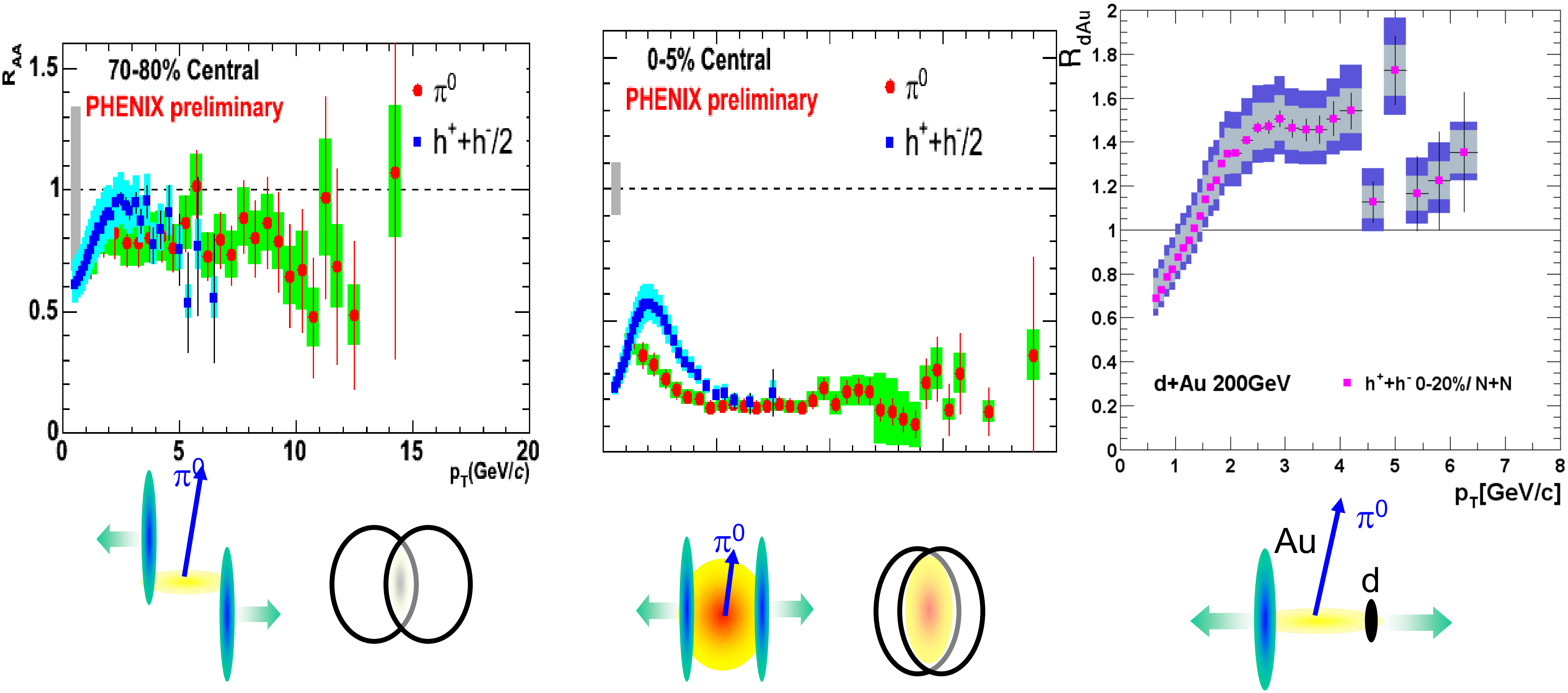
p+p



$\approx \langle N_{binary} \rangle$

varies with impact parameter ***b***

RHIC $\sqrt{s}$ = 200 π^o and h^++h^- data



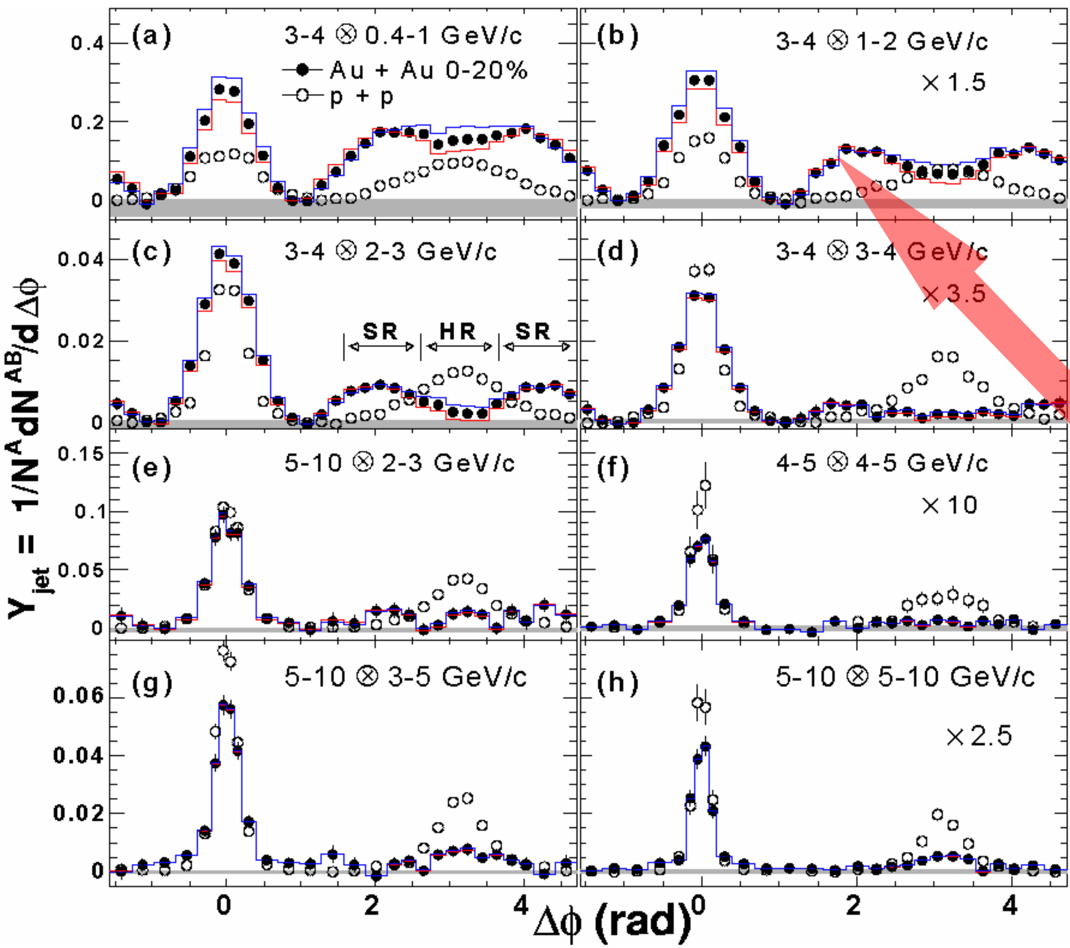
- Strong suppression (x5) in central Au+Au coll.
- No suppression in peripheral Au+Au coll.
- No suppression (Cronin enhancement) in control d+Au exp.

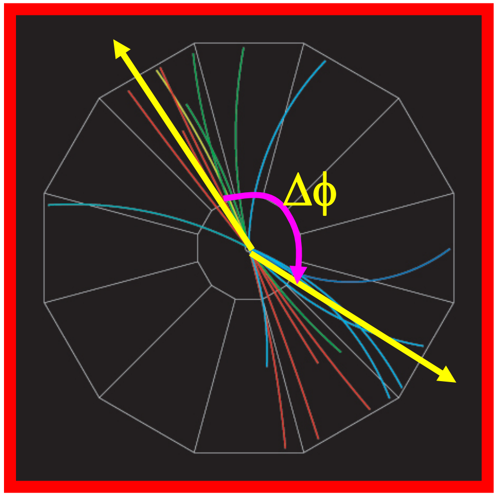
Scattering for partons before hard collision

Convincing evidence for the **final state partonic** interaction - emergence of **QGP**

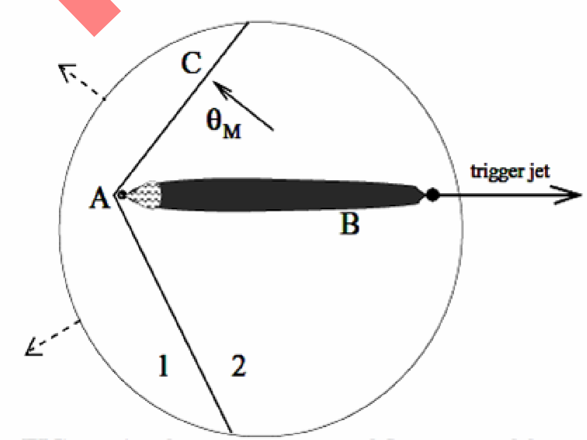
Jet shape evolution with trigger and assoc. p_T

Au+Au / p+p √s = 200 GeV





p + p → jet + jet

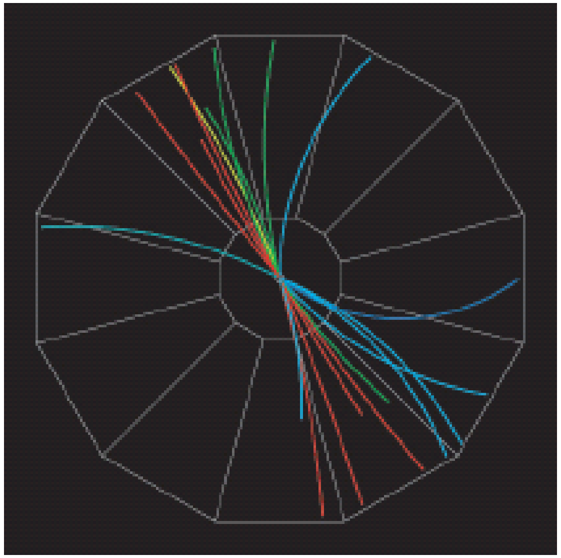


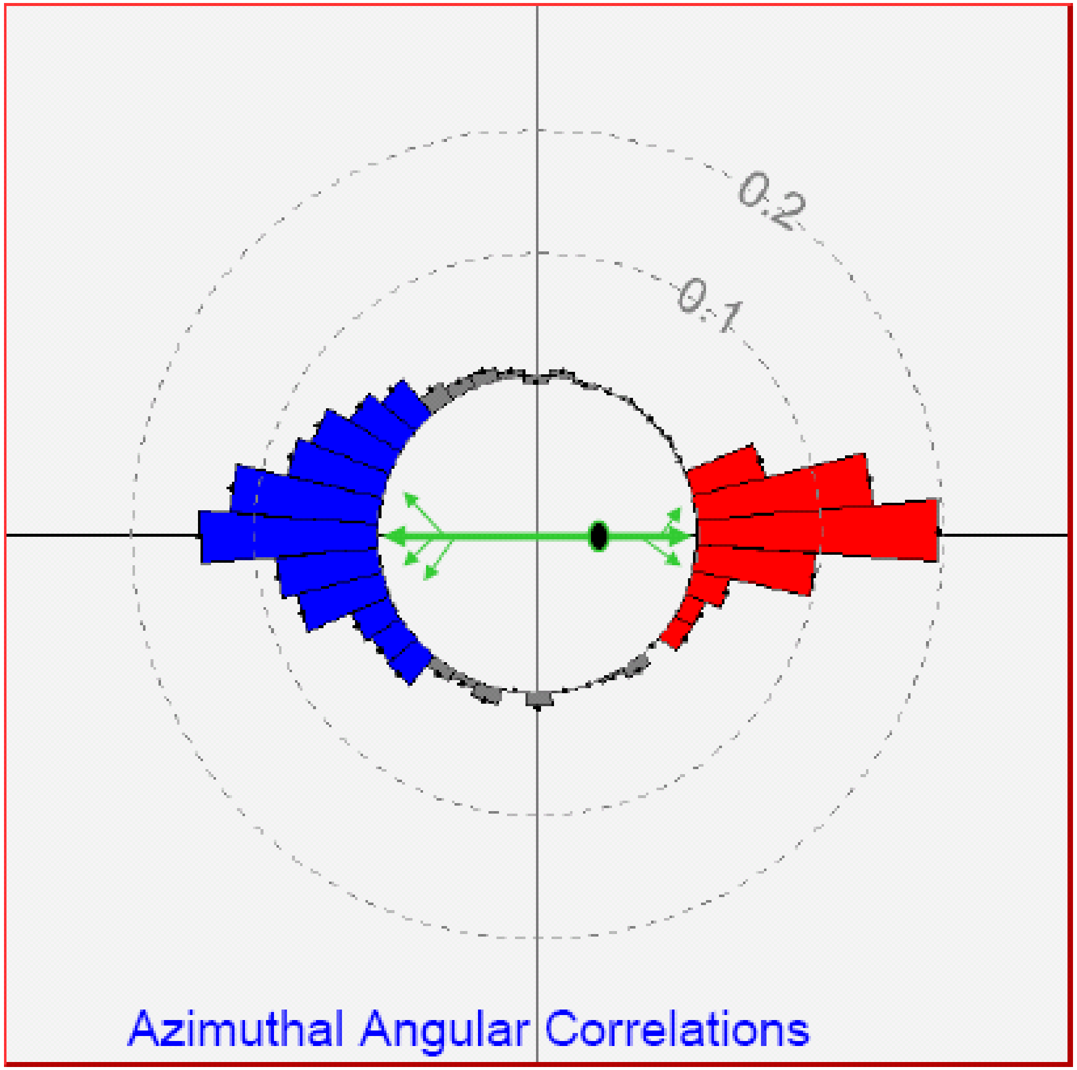
Per-trigger yield vs. $\Delta\phi$ for various trigger and partner p_T ($p^A_T \otimes p^B_T$), arranged by increasing pair momentum ($p^A_T + p^B_T$)

arXiv:0705.3238 [nucl-ex]

Jet Quenching, pp

Azimuthal correlations show strong back-to-back peaks

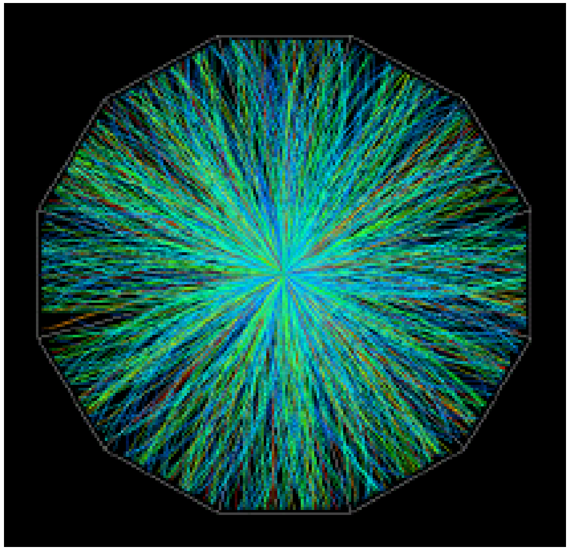


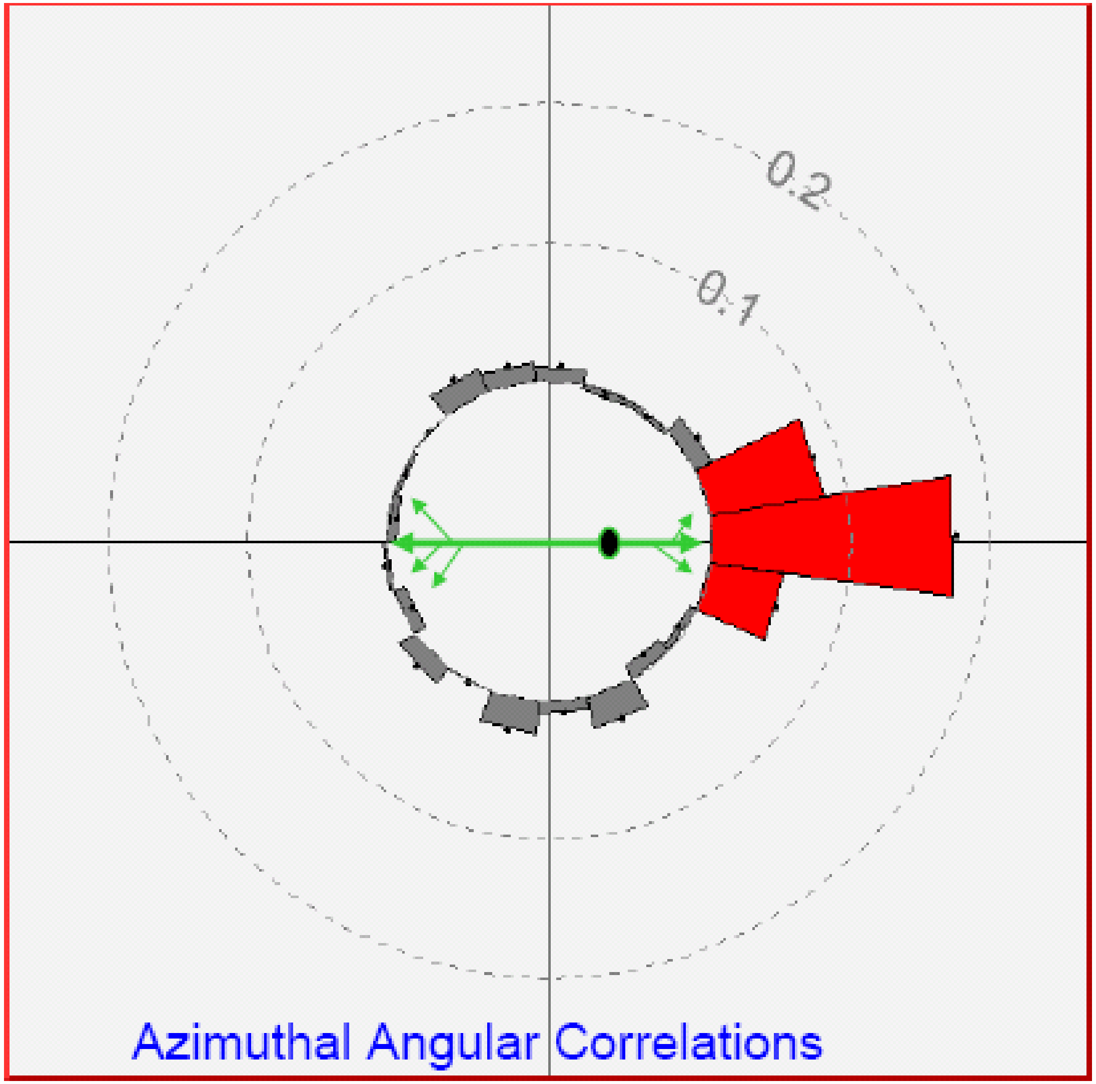


Jet Quenching, PbPb

Azimuthal correlations show that the "away-side jet" has disappeared...

if we only detect high-p_T particles, p_T > 2 GeV/c

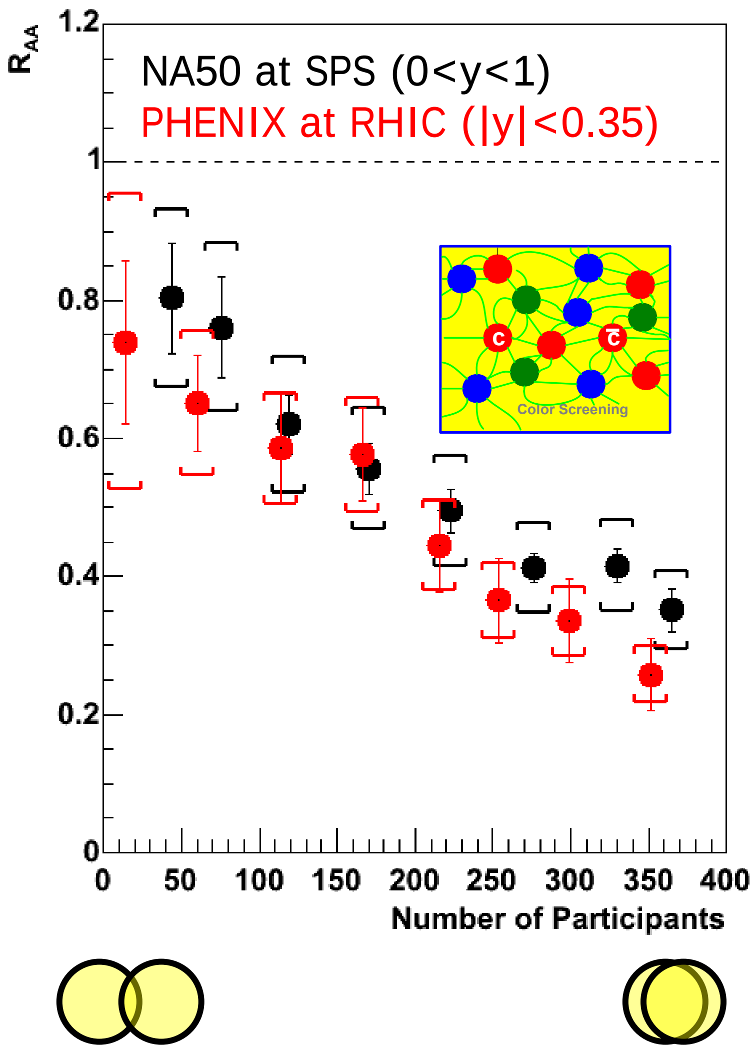




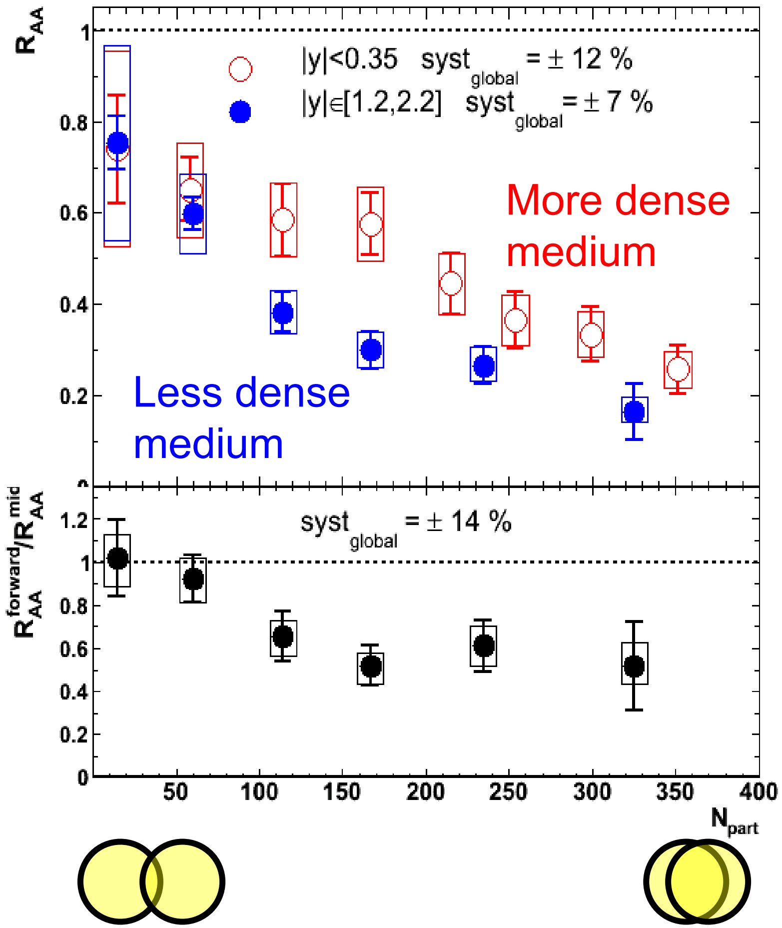
Charmonium Suppression

- QGP signature proposed by Matsui and Satz, 1986
- Interaction potential is expected to be screened beyond the Debyelength λ_D (analogous to e.m. Debyescreening):
- Charmonium($c\bar{c}$) and bottonium($b\bar{b}$) states with $r > \lambda_D$ will not bind; their production will be suppressed
- Reason
  - If probability of combining an uncorrelated $q\bar{q}$ pair at the hadronization stage is negligible
  - then only chance of producing a $q\bar{q}$ bound state is shortly after the pair is produced, while the two quarks are still correlated in phase space
  - Debyescreening allows the two quarks to “forget” about each other’s existence, and to loose the correlation

J/Ψ Suppression - R_{AA}



Suppression increases at more forward rapidity
PHENIX PRL **98**, 232301 (2007)



PHENIX mid-rapidity (e+e-) the same as NA50!!!

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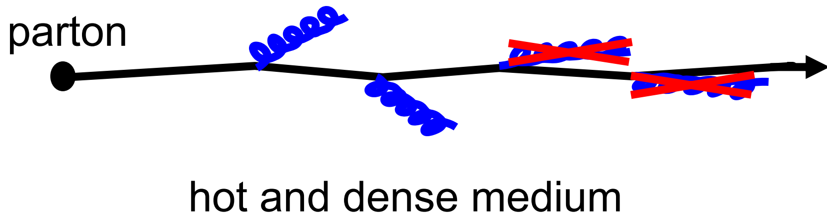
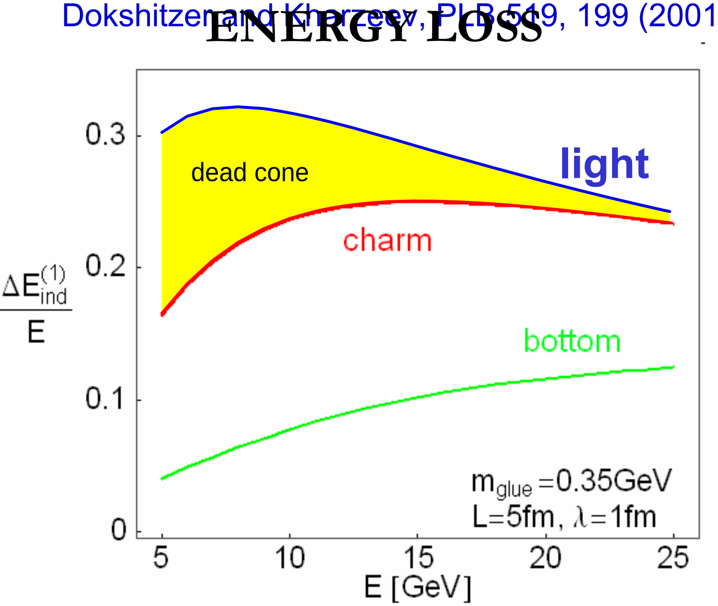
Heavy quarks as a probe (suppression)

•Due to large mass heavy quarks are primarily produced by gluon fusion
→ sensitive to initial gluon distribution
M. Gyulassy and Z. Lin, PRC 51, 2177 (1995)

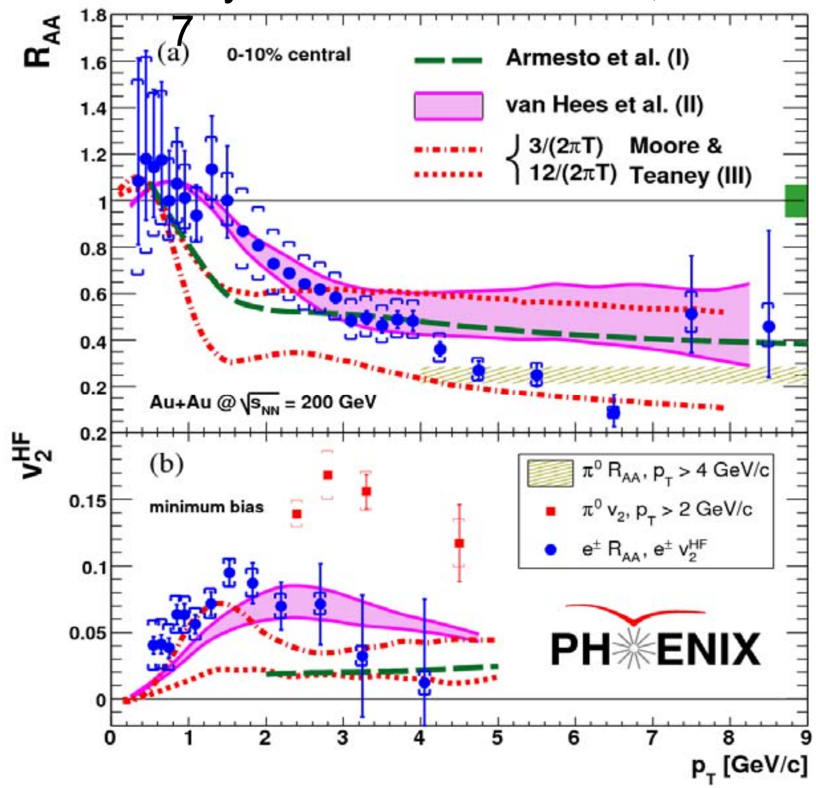


• Heavy quarks lose less energy due to suppression of small angle gluon radiation (dead-cone effect)
Dokshitzer and Kharzeev, PLB 519, 199 (2001)



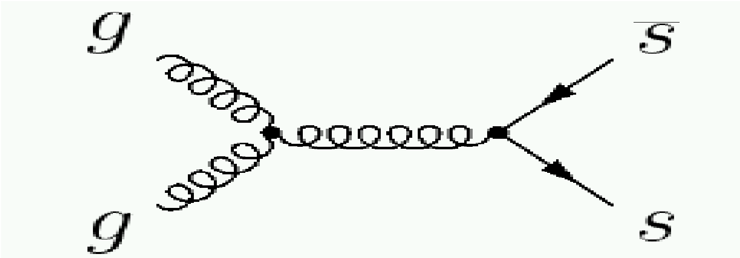
M.Djordjevic PRL 94 (2004)

Phys.Rev.Lett.98:172301,2007



Strangeness enhancement

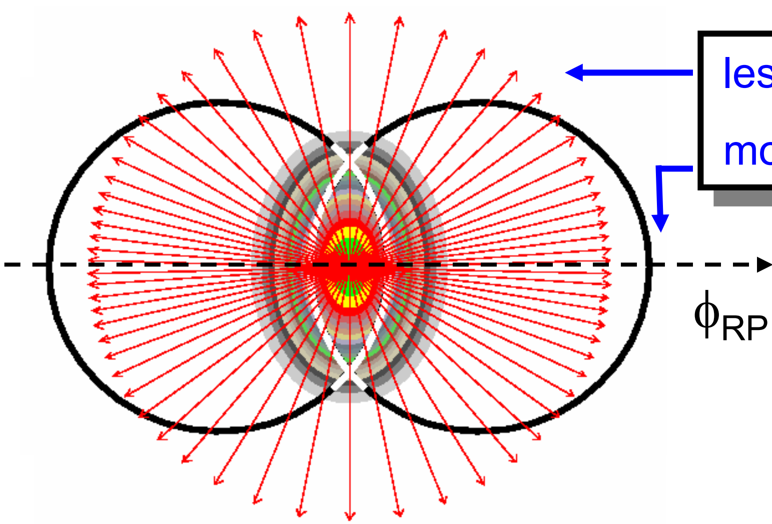
- QGP signature proposed by Rafelski and Müller, 1982
- The masses of deconfined quarks are expected to be about 350 MeV lower than when quarks are confined within hadrons
- T_c ~ 100-200 MeV: the strange quark should be very sensitive!
- m_s(constituent) ~ 500 MeV → m_s(bare) ~ 150 MeV:
- Produced via g-g fusion

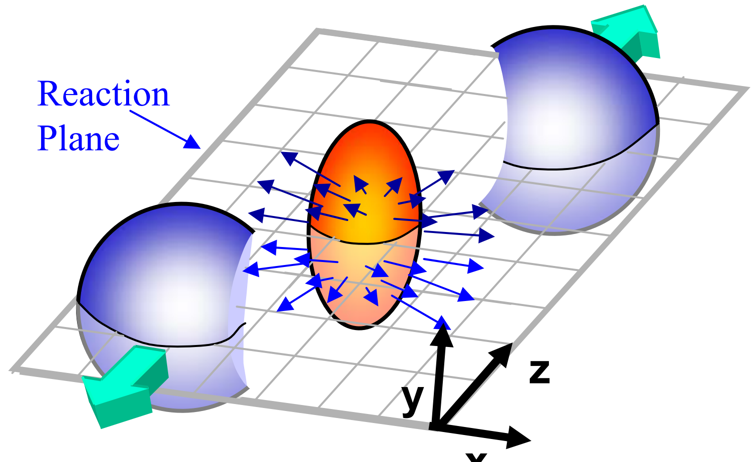


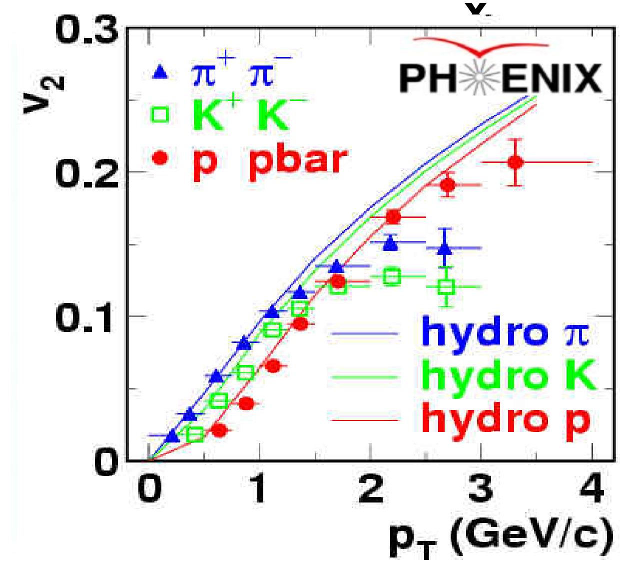
- Strangeness production should be enhanced if the system is deconfined

Nuclear Geometry and Hydrodynamic flow

multiple scattering → larger pressure gradient in plane → less yield out, more in plane







Spatial asymmetry
eccentricity

$$\varepsilon = \frac{\langle y^2\rangle - \langle x^2\rangle}{\langle y^2\rangle + \langle x^2\rangle}$$

Mom. Asymmetry
elliptic flow

$$v_2 = \frac{\langle p_x^2\rangle - \langle p_x^2\rangle}{\langle p_x^2\rangle + \langle p_x^2\rangle}$$

$$\frac{d^3N}{p_T\,dp_T\,dy\,d\varphi} \propto [1 + 2v_2(p_T)\cos 2(\varphi - \phi_{RP}) + \ldots]$$

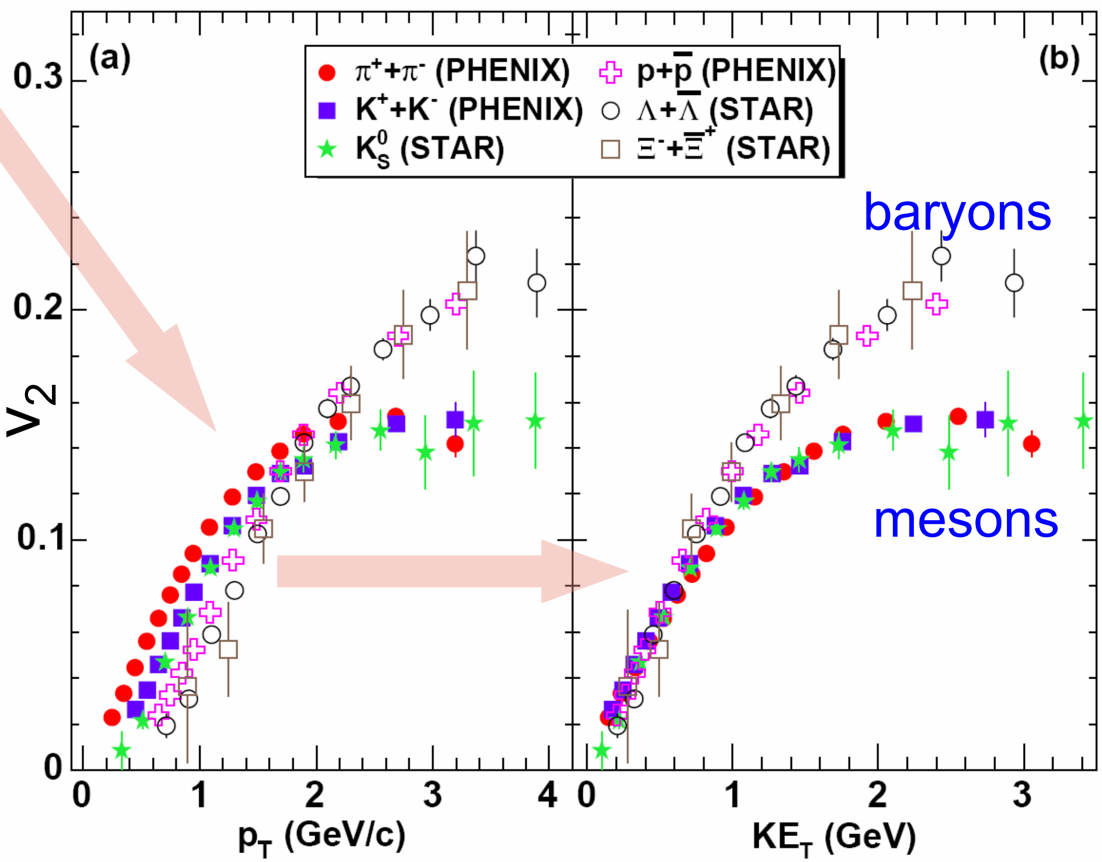
What are the relevent DOF's in "Flow" ?

"Fine structure" of v2(pT) for different mass particles.

$$\partial_\nu T^{\mu\nu} = 0 \quad \rightarrow \quad \text{Work-energy theorem}$$
$$\rightarrow \int_{vol} \nabla P dV = \Delta E_K =$$
$$= m_T - m_0 \equiv \Delta KE_T$$

$v_2(p_T) \rightarrow v_2(KE_T)$

Phys. Rev. Lett., 2007, 98, 162301



v2(KET) universal for baryons
v2(KET) universal for mesons

Do we have an even more universal scaling?

$$v_2^{meson}(p_T) \approx 2 \cdot v_2^{quark}\left(\frac{p_{T,quark}}{2}\right) \qquad v_2^{baryon}(p_T) \approx 3 \cdot v_3^{quark}\left(\frac{p_{T,quark}}{3}\right)$$

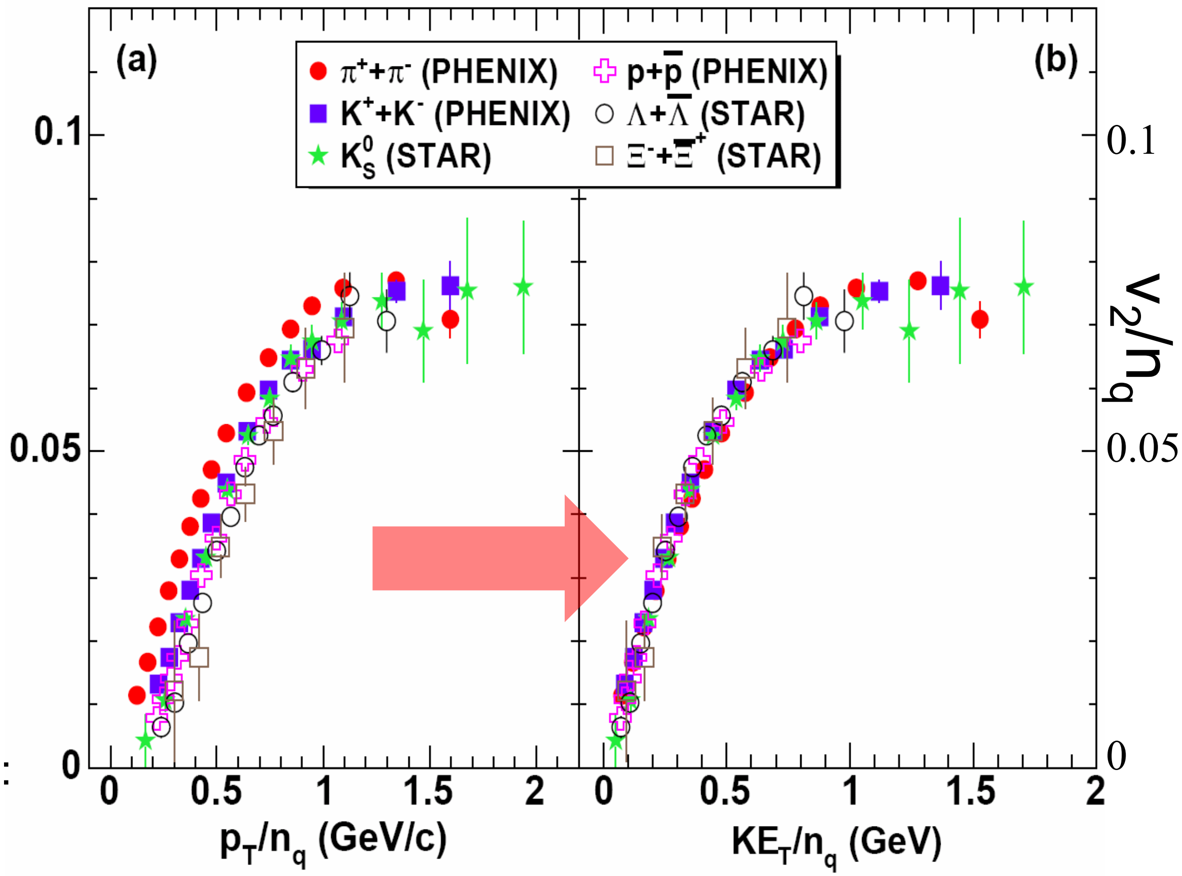
Phys.Rev.Lett.91:092301,2003

The "Flow" Knows Quarks

Assumption:

all bulk particles are coming from recombination of flowing partons

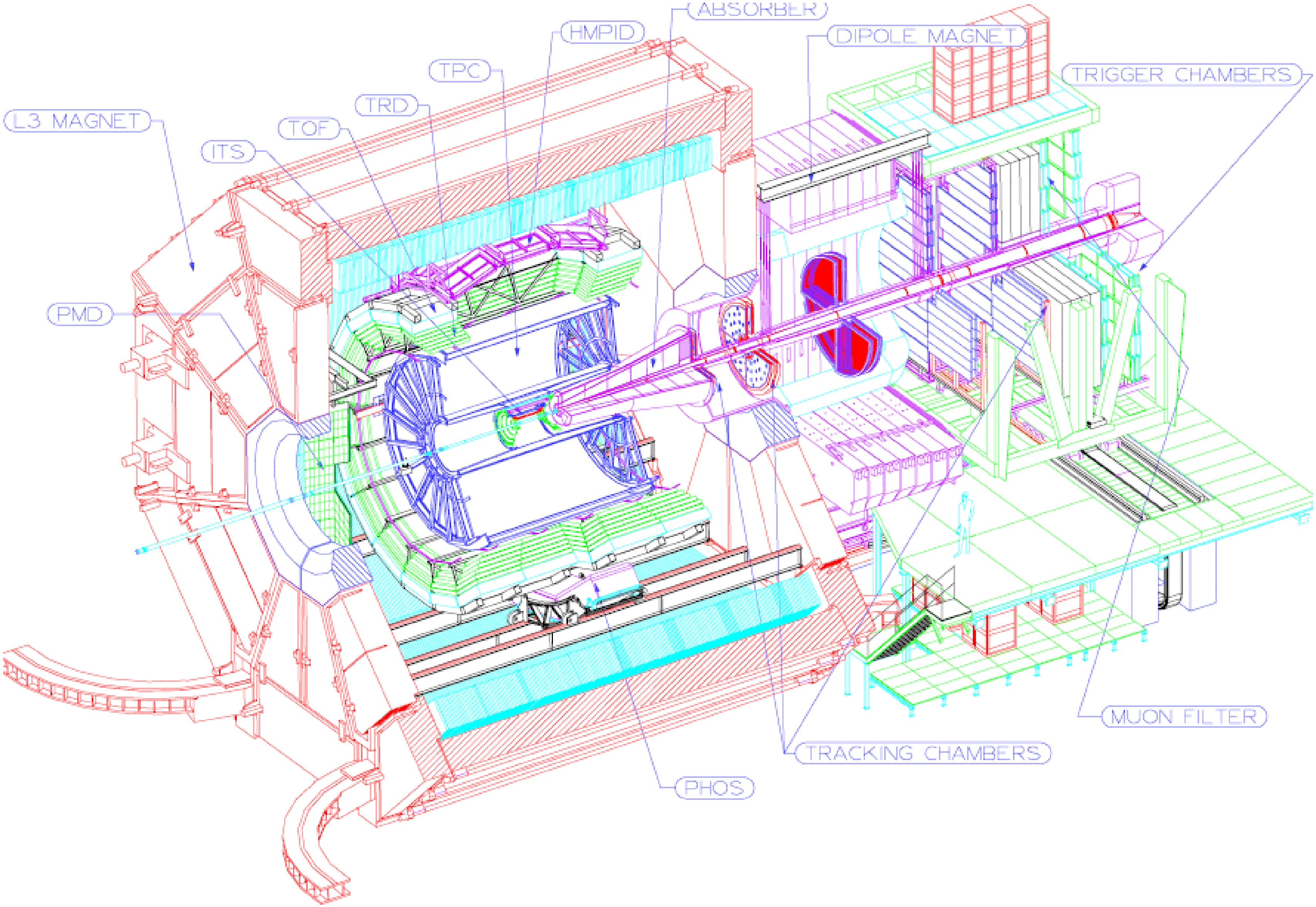
$$v_2(p_T) \rightarrow n_q \cdot v_2\left(\frac{KE_T}{n_q}\right)$$



Discovery of universal scaling:

- flow parameters scaled by quark content n_q resolves meson-baryon separation of final state hadrons. Works for strange and even charm quarks.
- strongly suggests the early thermalization and **quark degree of freedom**.

A Large Ion Collider Experiment



Summary (RHIC && SPS)

Observed:

- Huge suppression of light mesons in central Au+Au collisions
- No suppression in d+Au and peripheral Au+Au coll.
- Similar suppression of J/Ψ at RHIC as at SPS
- Similar suppression for heavy and light quarks

Concluded:

Deconfined opaque partonic matter has been produced.

Observed:

- Flow parameters scaled by quark content n_q resolves meson-baryon separation of final state hadrons
- Works for strange and even charm quarks

Concluded:

- Early thermalization
- Quark degree of freedom
- Small viscosity (strongly coupled matter)

QGP

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