Introduction to Quark Gluon Plasma

Mahnaz Q. Haseeb
Department of Physics
CIIT, Islamabad

Topics of lectures on QGP

- Introduction to QGP
- Thermodynamics and Phase Transitions
- Hydrodynamics in QGP

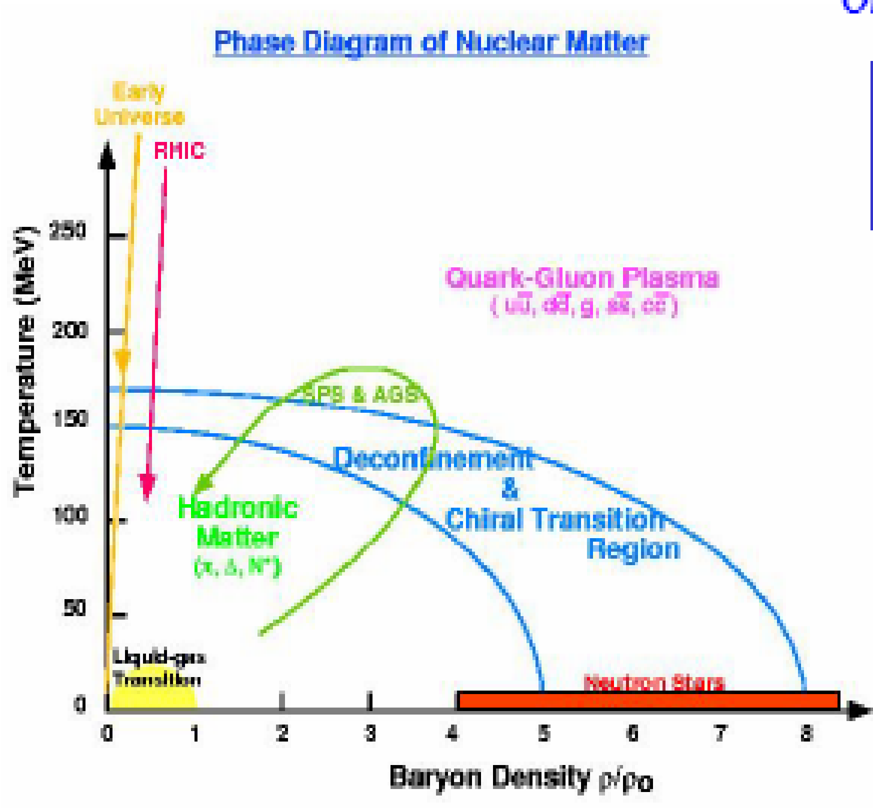
Outline

- Motivation
- An overview of QCD
- What is Quark Gluon Plasma (QGP)?
- How to create QGP?
- Claims about its discovery
- Physical parameters measured
- Expectation from LHC about QGP

Motivation

"To understand the <u>Equation of State of Nuclear, Hadronic & Partonic Matter</u>"

Of cross-disciplinary interest:



Nuclear Physics "NMEOS"

- Collective Nuclear Phenomena
- Effects of the Nuclear Medium

Astrophysics "NMEOS - Matter Incompressibility"

- Neutron Star Stability
- Supernova Expansion Dynamics

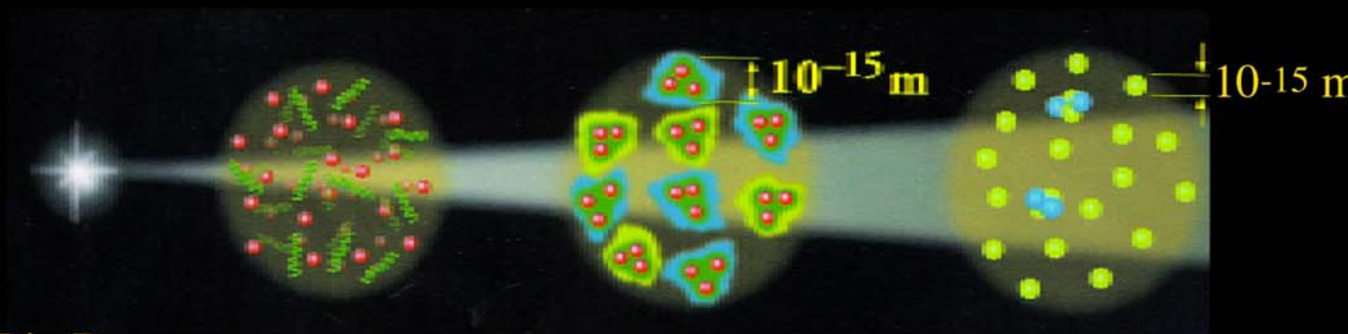
Cosmology "QCD Phase Transition"

- Evolution of Early Universe

Particle Physics "Perturbative QCD Vacuum"

- High (Energy) Density QCD
- Symmetry Breaking Mechanisms
- Particle Masses

History of the Universe

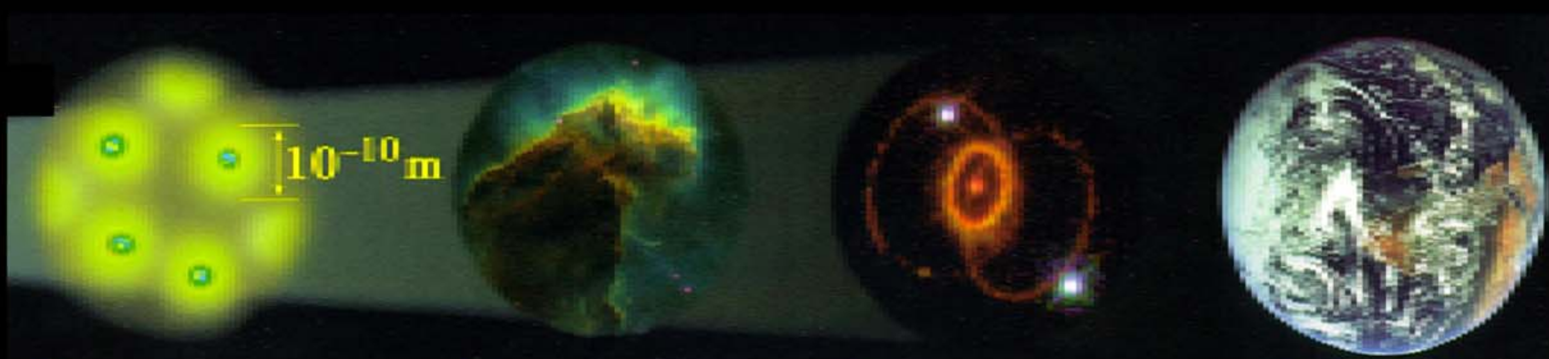


Big Bang

Quark-Gluon Plasma
10^{13}K, 10^{-6}s

Protons& Neutrons
10^{12}K, 10^{-4}s

Low-mass Nuclei
10^{9}K, 3 min



Neutral Atoms
4000K, 10^{5}y

Star Formation
10^{9}y

Heavy Elements
>10^{9}y

Today

Source: Nuclear Science Wall Chart

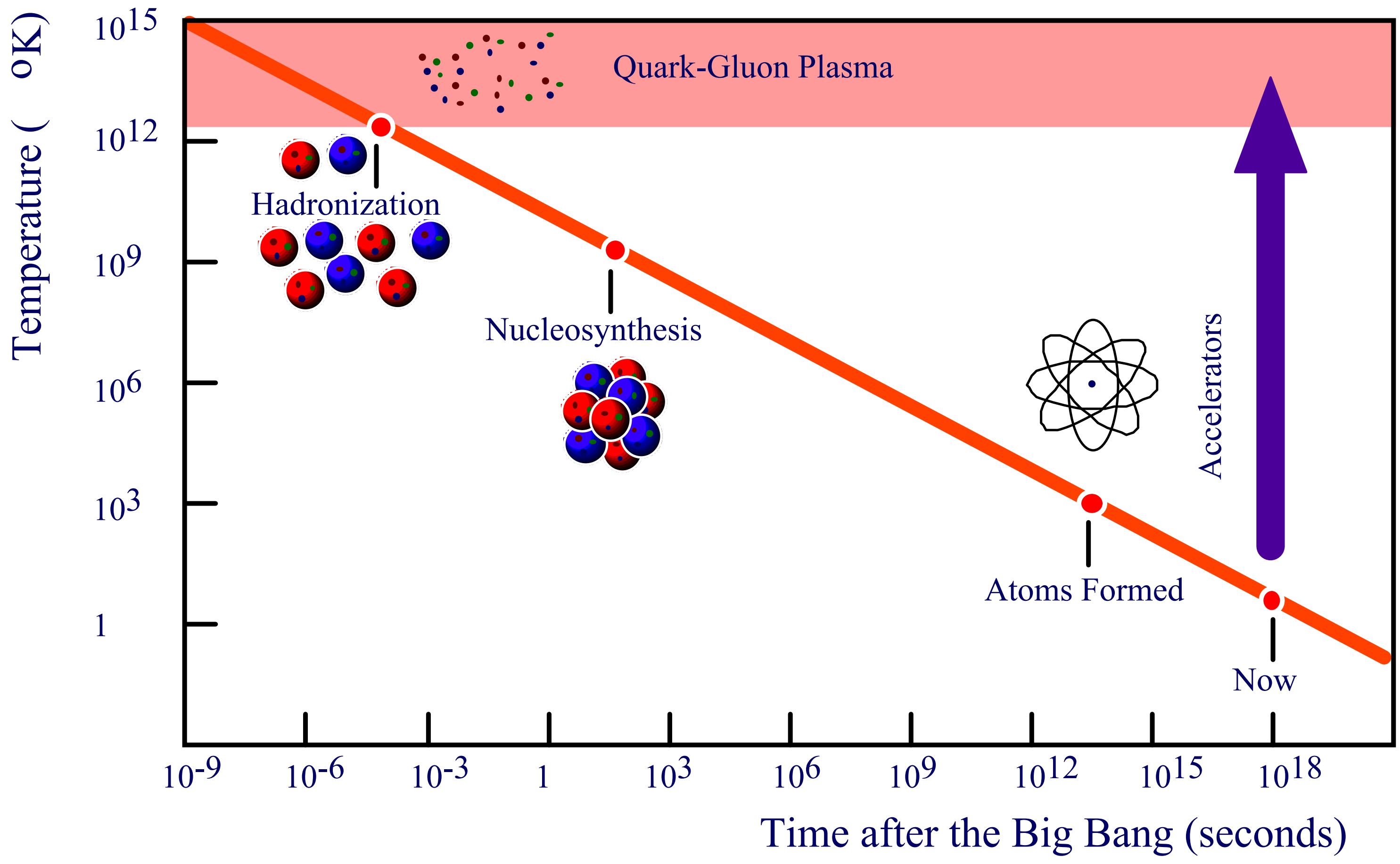
Energy Scales

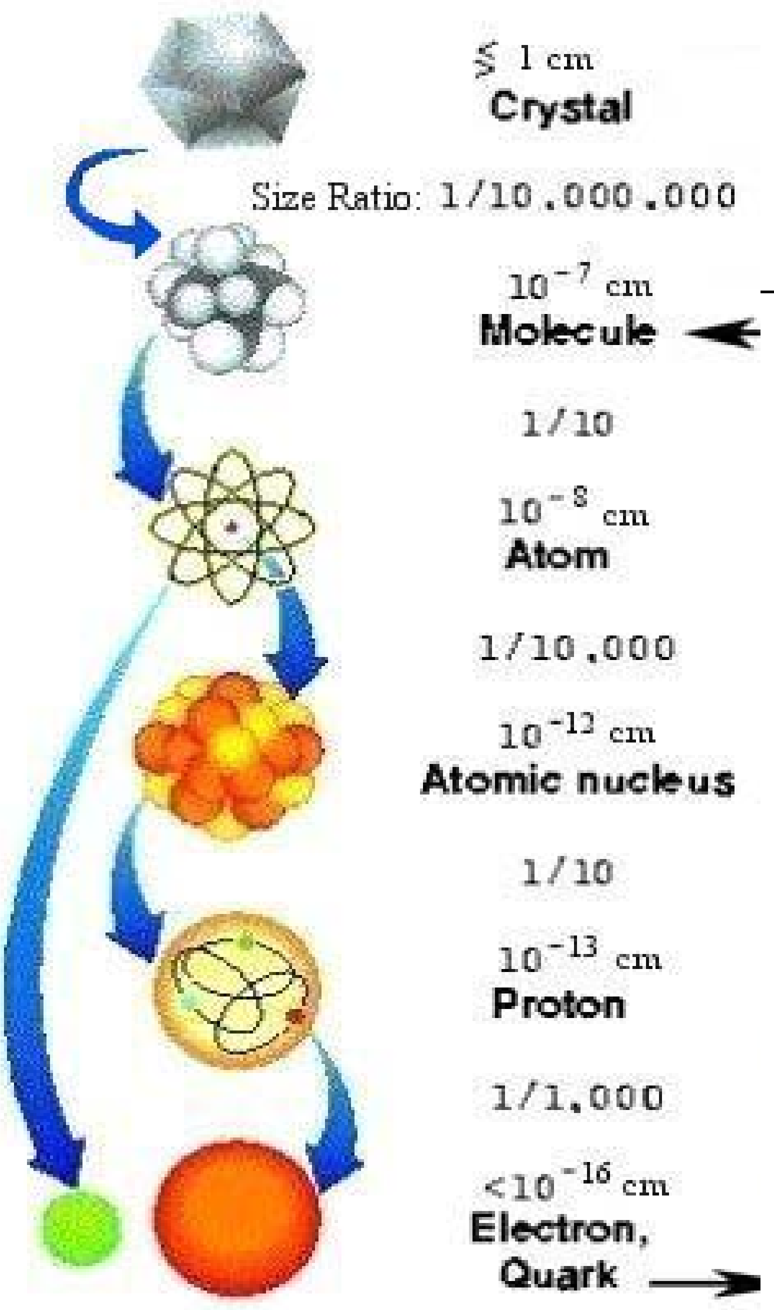
- **The beginning**
  The universe is a hot plasma of fundamental particles … quarks, leptons, force mediating particles (and other particles ?)
  10^{-43} s Planck scale (quantum gravity ?) 10^{19} GeV
  10^{-35} s Grand unification scale (strong+electroweak) 10^{15} GeV
  Inflationary period 10^{-35}-10^{-33} s
  10^{-11} s Electroweak unification scale 200 GeV

- **Micro-structure**
  10^{-5} s QCD scale - protons and neutrons form 200 MeV
  3 mins Primordial nucleosynthesis 5 MeV
  3×10^{5} y Radiation and matter decouple - atoms form 1 eV

- **Large scale structure**
  1 b yrs Proto-galaxies and the first stars
  3 b yrs Quasars and galaxy spheroids
  5 b yrs Galaxy disks
  Today Life !

A brief history ...




≲ 1 cm
Crystal
Size Ratio: 1/10,000,000
10^{-7} cm
Molecule
1/10
10^{-8} cm
Atom
1/10,000
10^{-12} cm
Atomic nucleus
1/10
10^{-13} cm
Proton
1/1,000
$<10^{-16}$ cm
Electron,
Quark

Building Blocks of Hadron World

- Molecules
  - Atoms
    - Nucleus
      - Proton (uud)
      - Neutron (udd)
    - Electrons
- Hyperons (s…)
- Mesons ($q\text{-}\bar{q}$)
- Exotics ($qqqq\text{-}\bar{q}$,…)

Strong interaction is due to color charges and mediated by gluons. Gluons carry color charges too.

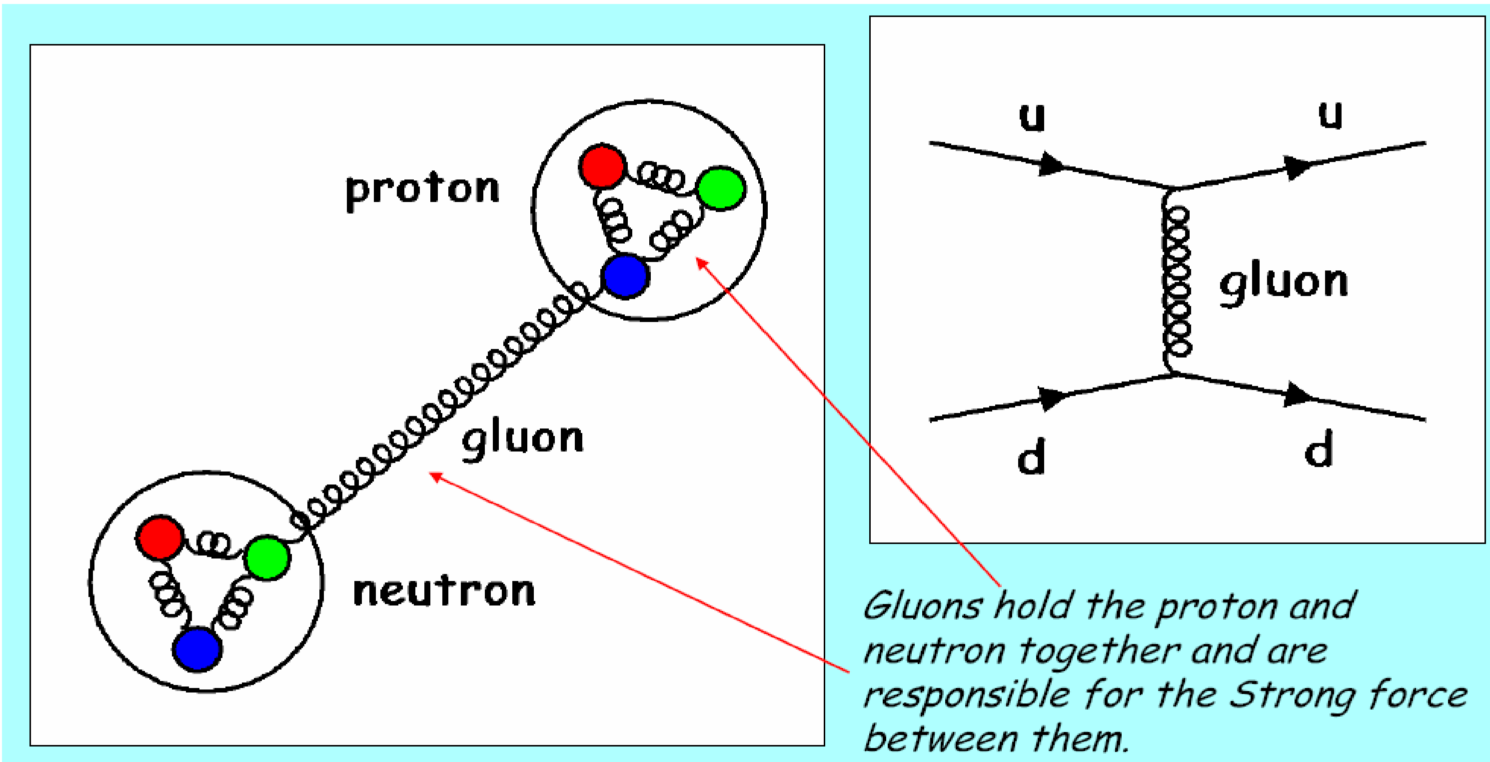
Baryon Density: ρ = baryon number/volume

normal nucleus $\rho_0 \sim 0.15\ /\mathrm{fm}^3 \sim 0.25\mathrm{x}10^{15}\ \mathrm{g/cm}^3$

Temperature: MeV $\sim 1.16 \times 10^{10}$ K

10^{-6} second after the Big Bang T~200 MeV

Interaction between quarks and gluons

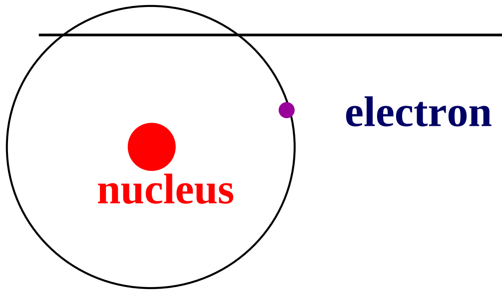


Separate quarks do not exist in nature

- confinement first established as an experimental fact, then by theory of strong interactions **Quantum Chromo Dynamics (QCD)**

Analogies and differences between QED and QCD

to study structure of an atom…



neutral atom

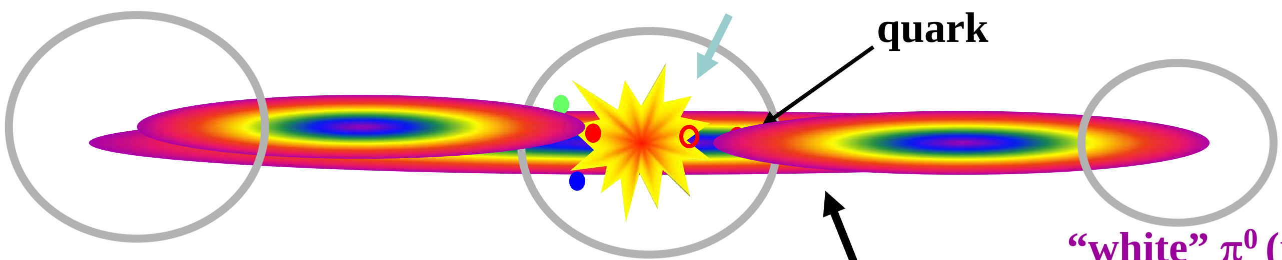
…separate constituents

QED Quantum Electro Dynamics

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

quark-antiquark pair
created from vacuum

quarks
u,d, (s,c,t,b)



"white" proton (baryon)
(confined quarks)

Strong color field
Force *grows* with separation !!!

"white" π^0 (meson)
(confined quarks)

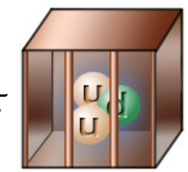
QCD Quantum Chromo Dynamics

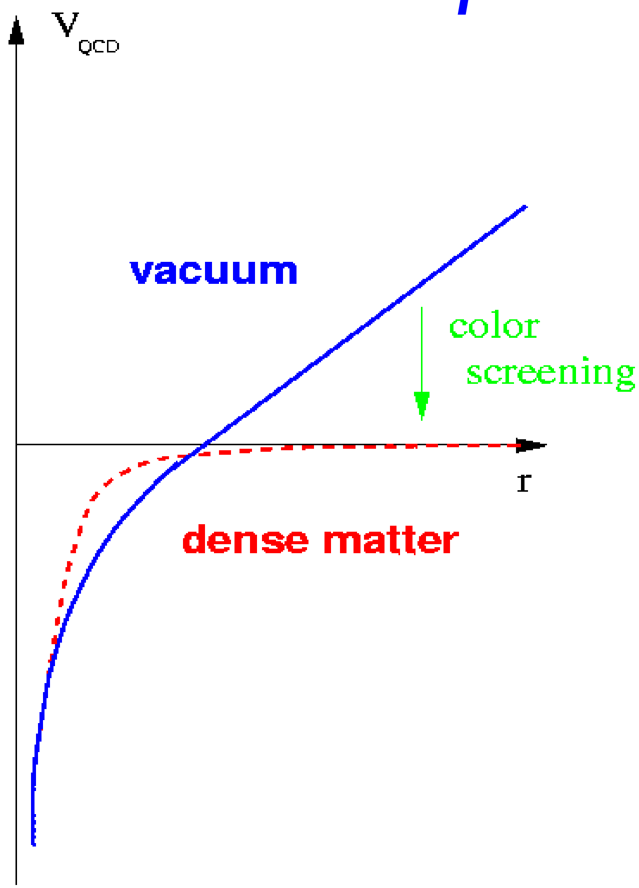
QCD Potential

Coulomb potential

$$V(r) = -\frac{\alpha}{r} + kr$$

Confinement





in vacuum:

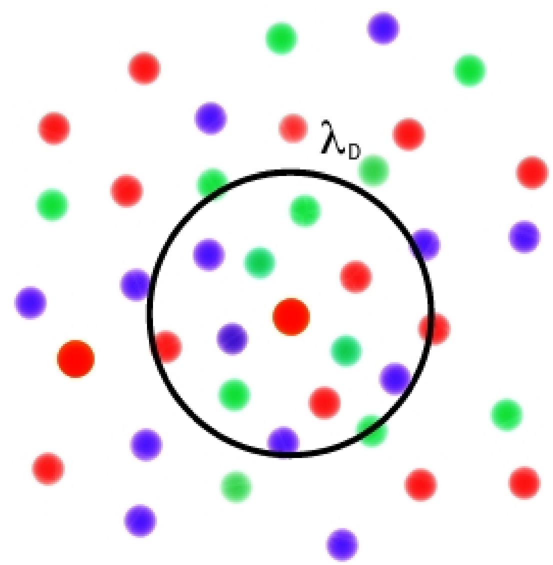
- linear increase with distance, strong attractive force
- confinement of quarks to hadrons

in dense and hot matter

- screening of color charges (similar to Debye screening in dense atomic matter)
- potential vanishes for large distance
- deconfinement of quarks
  $\rightarrow$ QGP

- An electrical plasma is one in which the particles are charged

  \- a nuclear plasma would be one in which the particles possess color charges.
- The charge of one particle is screened by the surrounding charges.
- Debye Screening Radius (λ_D): The distance at which the charge is reduced by 1/e for electromagnetic plasma.



These quarks effectively cannot "see" each other!

Instances of Debye Screening

- **In bulk media**
  - In bulk media, there is an additional charge screening effect.
  - At high charge density, n, the short range part of the potential becomes:

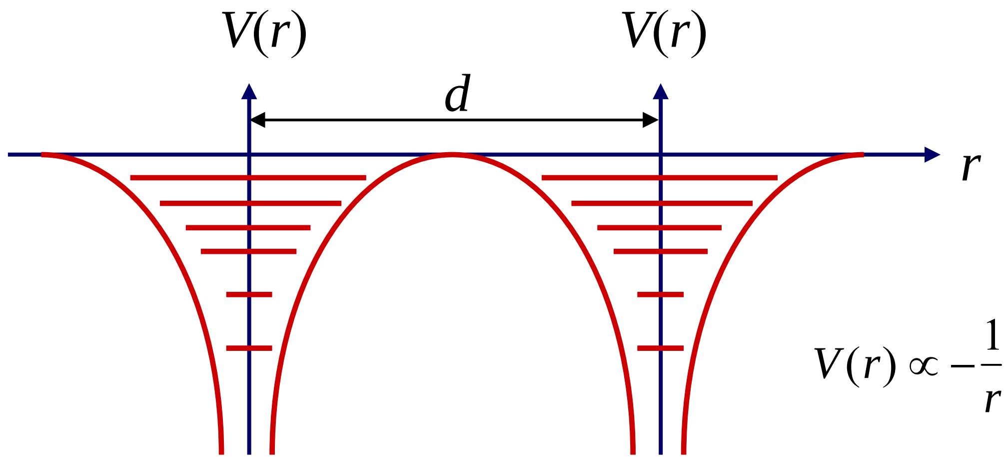
$$V(r) \propto \frac{1}{r} \Rightarrow \frac{1}{r}\exp\left[\frac{-r}{r_D}\right] \quad \text{where} \quad r_D = \frac{1}{\sqrt[3]{n}}$$

    and r_D is the Debye screening radius.
  - Effectively, long range interactions ($r > r_D$) are screened.
- **The Mott transition**
  - In condensed matter, when $r <$ electron binding radius
    $\Rightarrow$ an electric insulator becomes conducting.
- **Debye screening in QCD**
  - Analogously, think of the quark-gluon plasma as a colour conductor.
  - Nucleons (all hadrons) are colour singlets (baryons: qqq, or mesons qqbar).
  - At high (charge) density quarks and gluons become unbound.
    $\Rightarrow$ nucleons (hadrons) cease to exist.

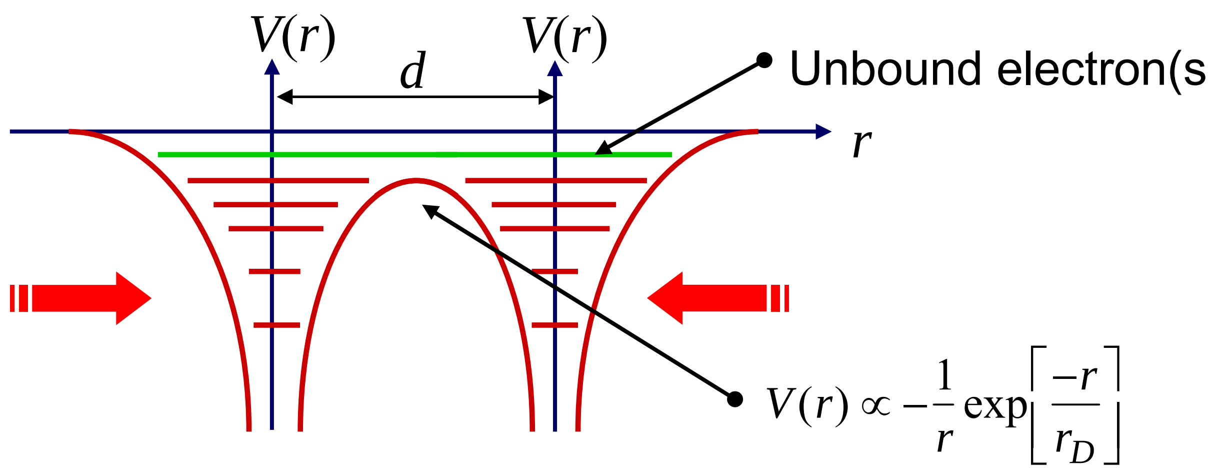
Debye screening

- Modification of V_{em} - the Mott Transition

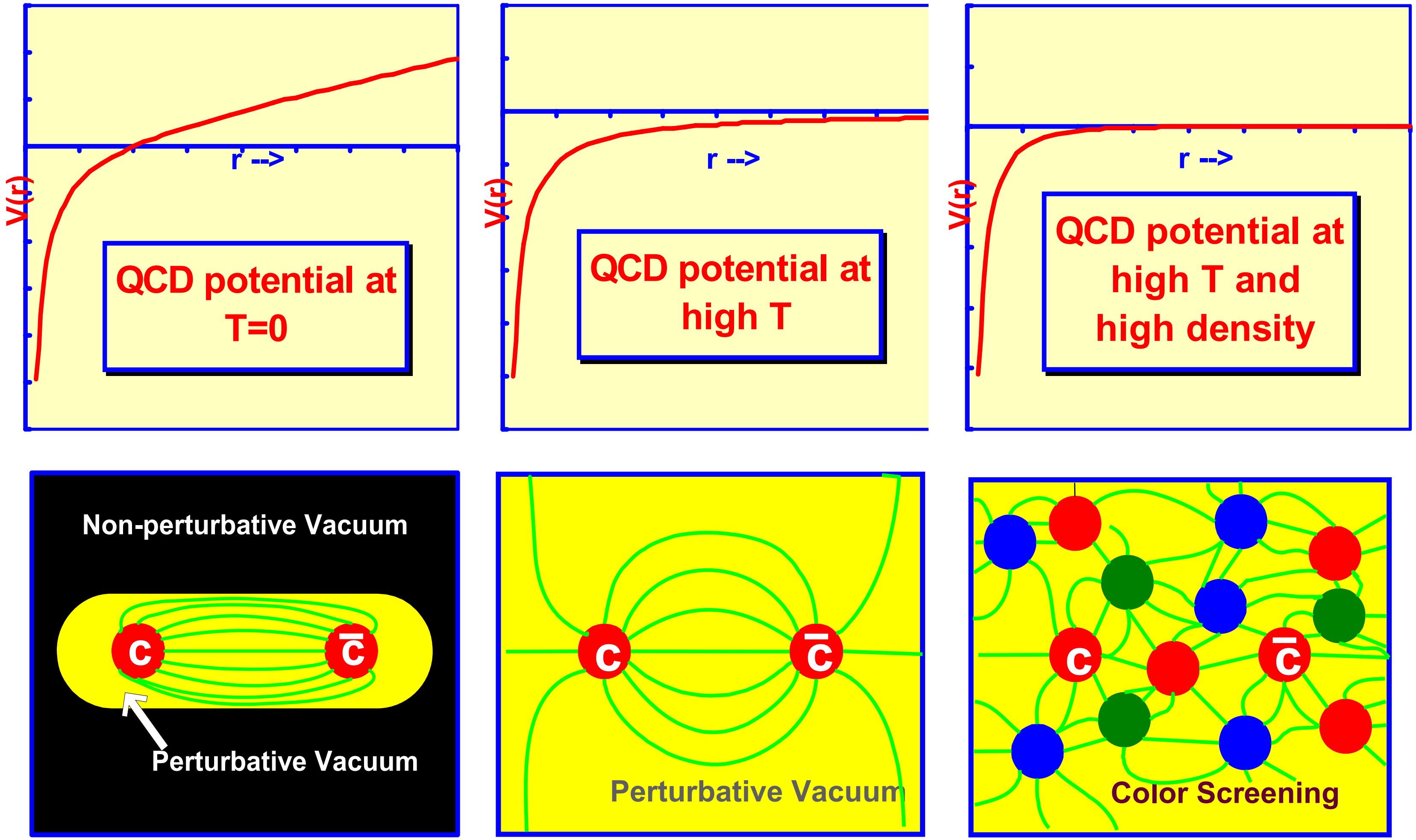
a) $d > r_{\text{D}}$



b) $d < r_{\text{D}}$



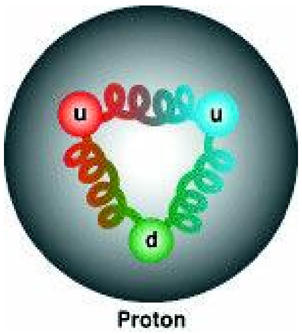
Screening in QCD



What is Quark-Gluon Plasma?

At room temperature, quarks and gluons are always confined inside colorless objects (hadrons):

protons, neutrons, pions, …..

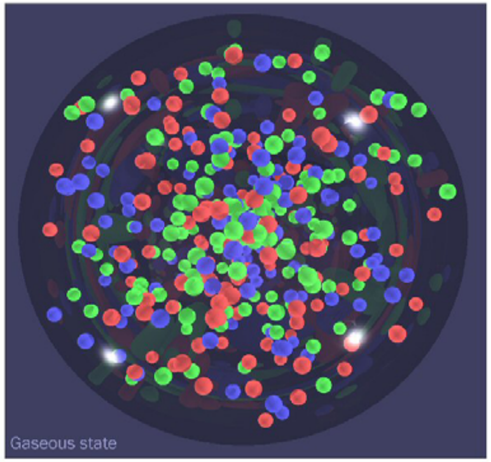


Very high temperature (asymptotic freedom):

→ Interactions become weak

→ quarks and gluons deconfined

→ Quark-gluon plasma (QGP)



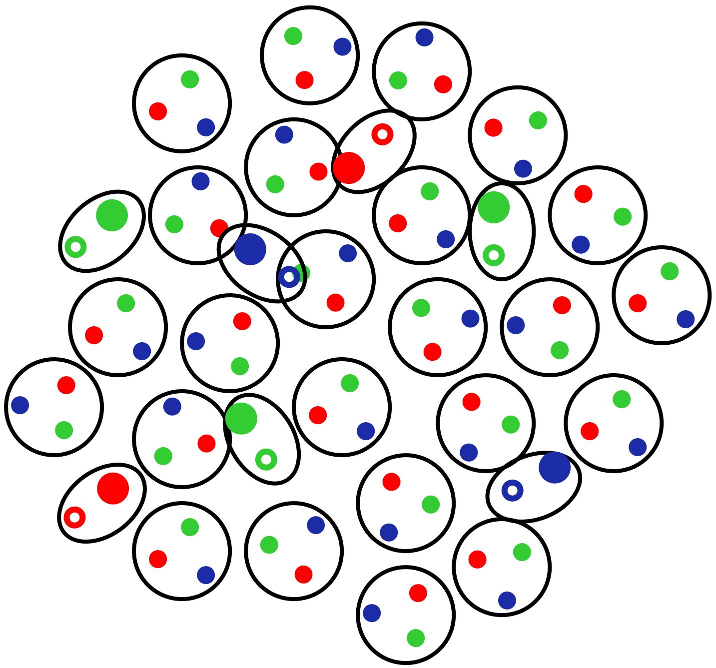
Infinitely high temperature:
QGP may behave like an ideal gas.

Generating a deconfined state

Present understanding of Quantum Chromodynamics (QCD)

- heating
- compression

→ *deconfined matter !*

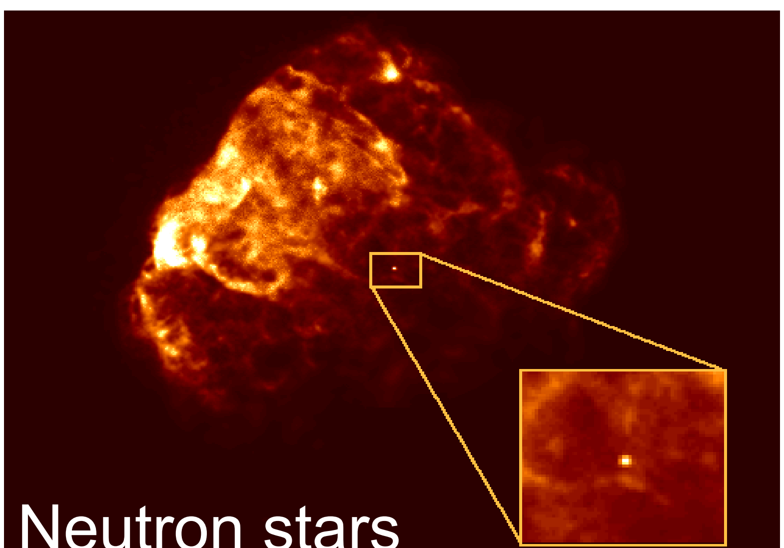


Nuclear Matter (confined)

Hadronic Matter (confined)

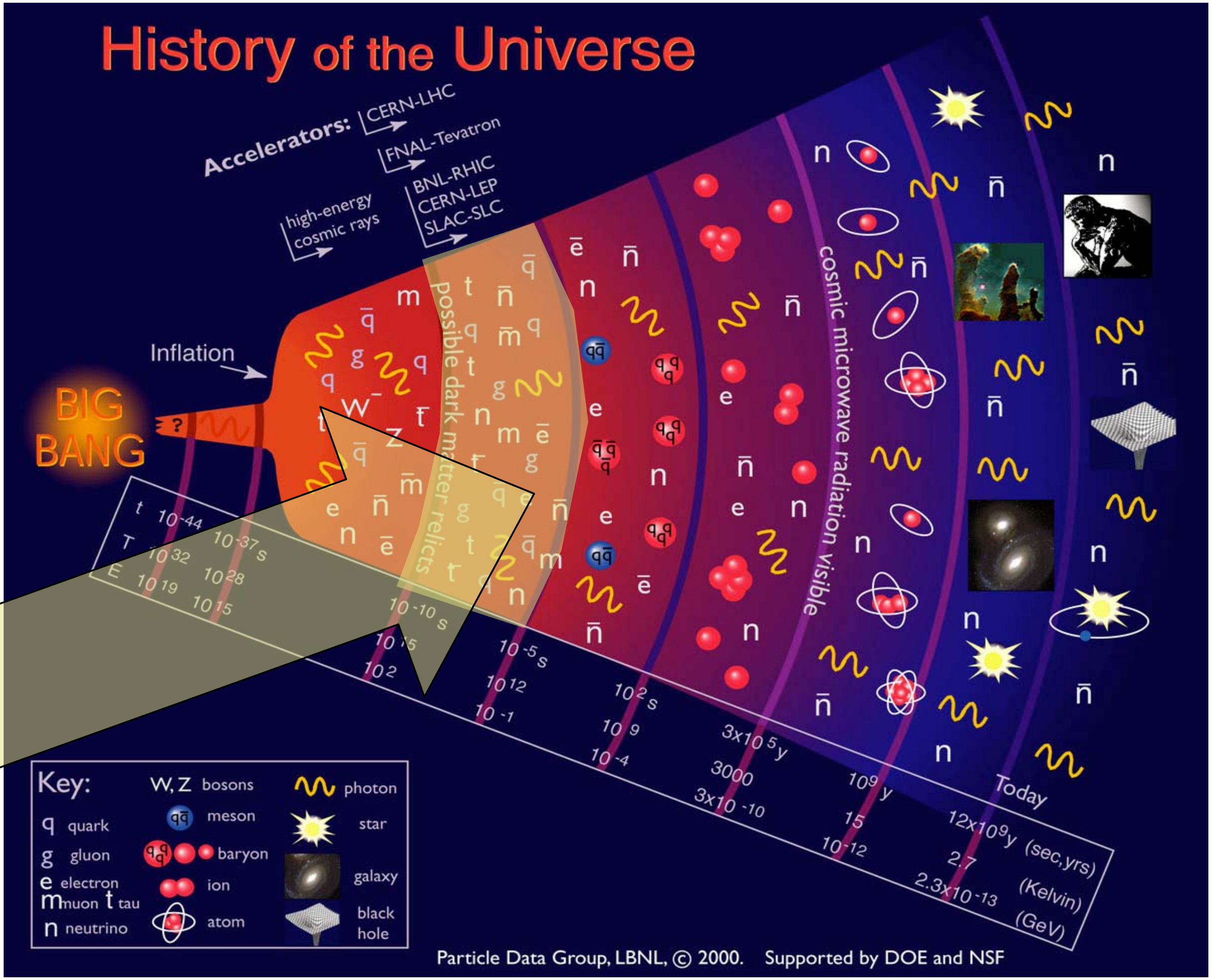
Quark Gluon Plasma deconfined !

Where to study the QGP?



Relation to the Big Bang

- Energy density
  - 1 GeV/fm³ →
    - 1.8x10¹⁵g/cm³
- Temperature
  - 170 MeV →
    - 2.0x10¹² K

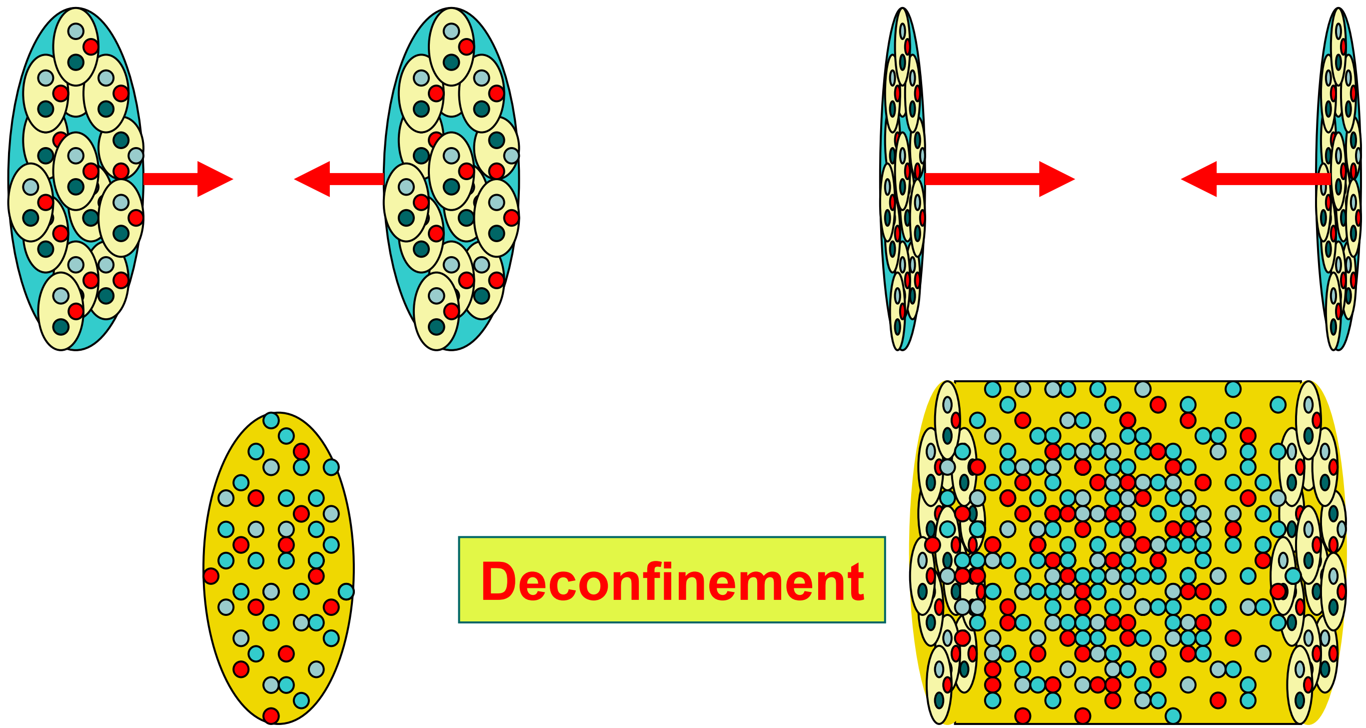


Conditions that prevailed ≈ 10 μs after the Big Bang

The Melting of Quarks and Gluons

Matter Compression:

Vacuum Heating:

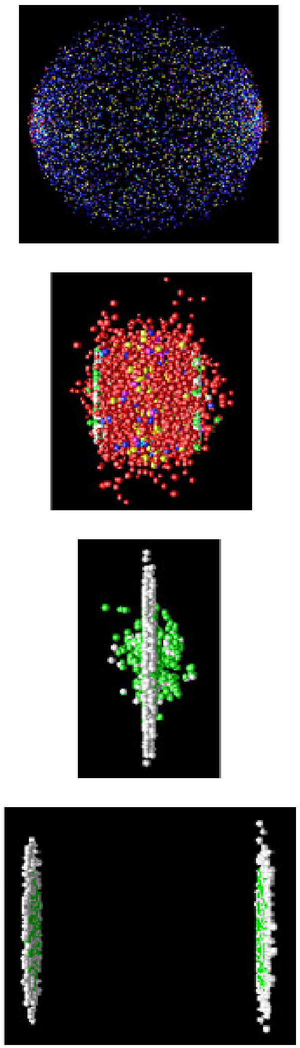


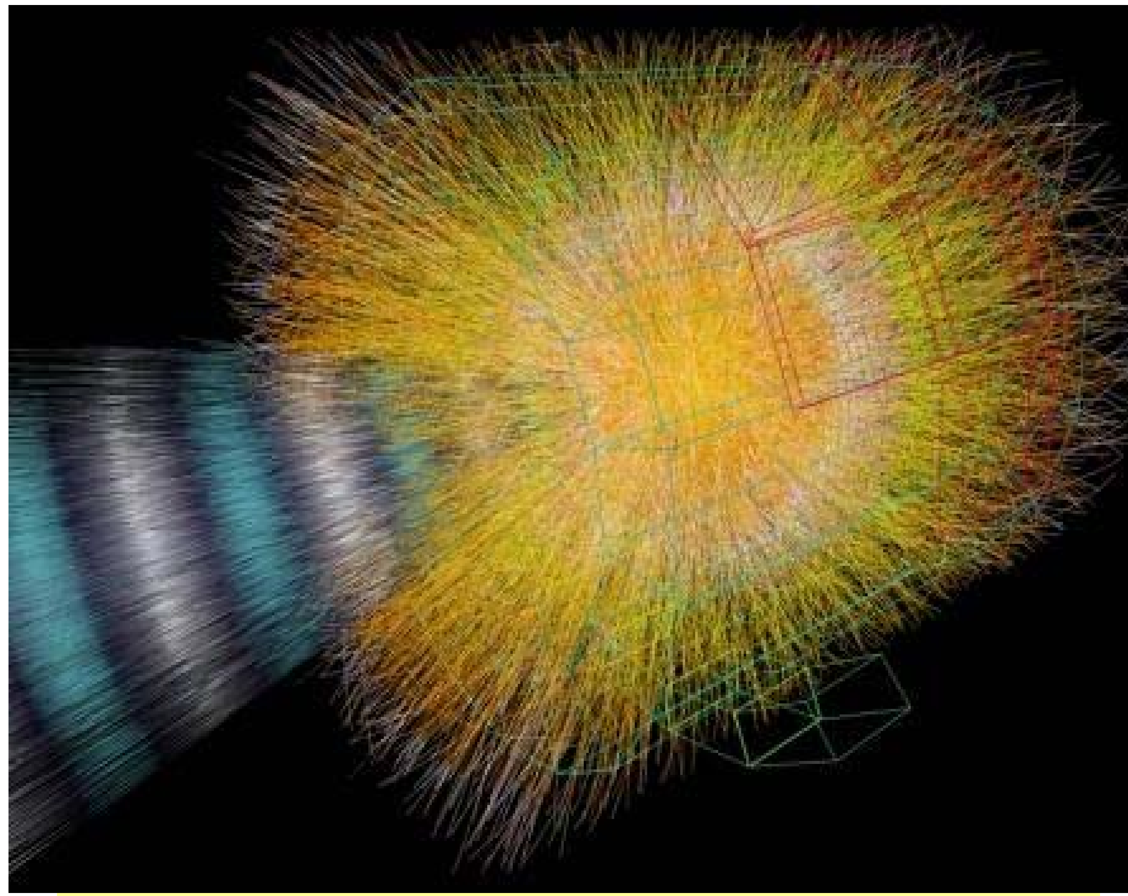
High Baryon Density
-- low energy heavy ion collisions
-- neutron star→quark star

High Temperature Vacuum
-- high energy heavy ion collisions
-- the Big Bang

Huan Zhong Huang

Creation of QGP





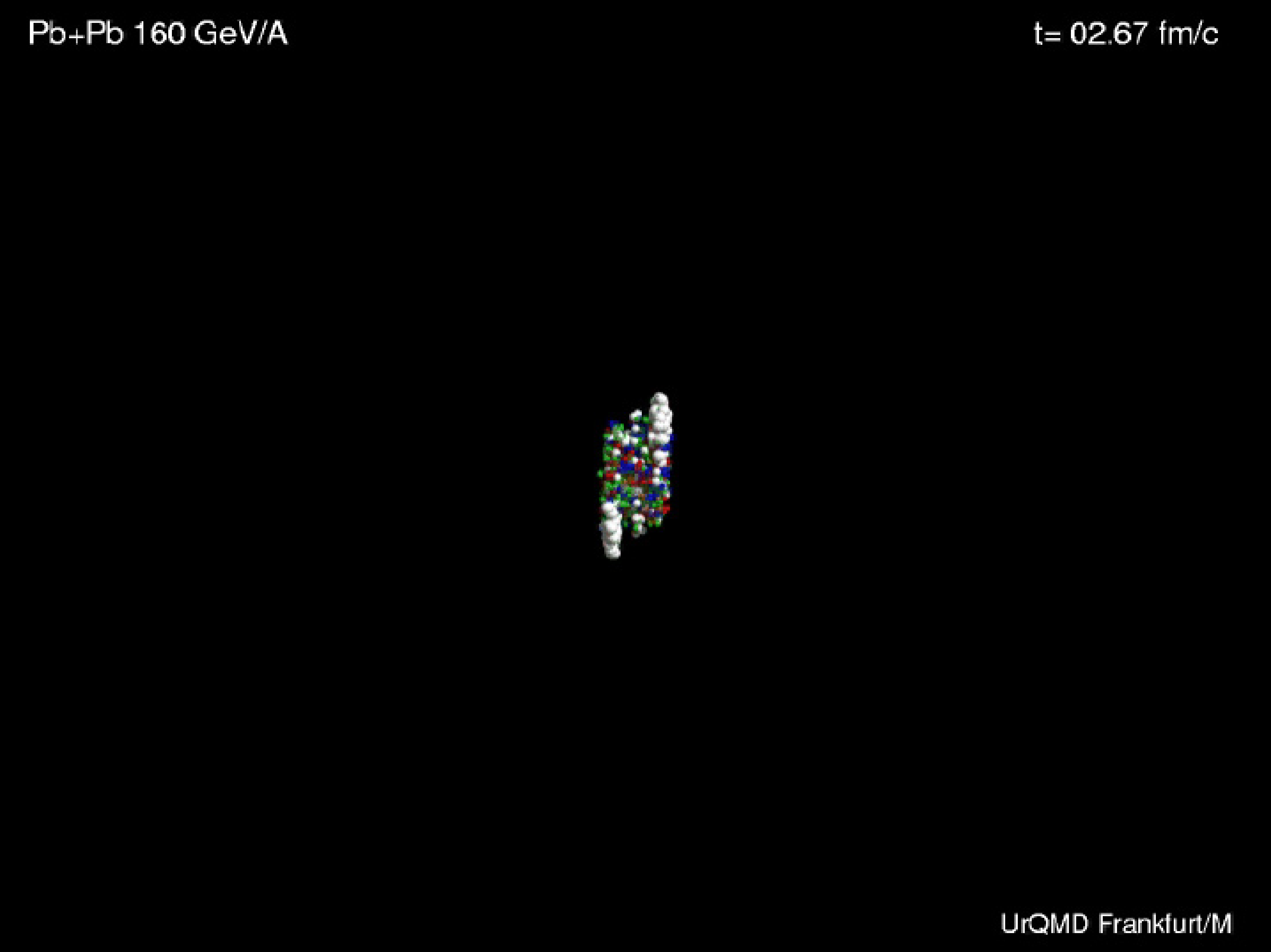
Collide ultra-relativistic heavy ions

Pb+Pb 160 GeV/A
t=-17.33 fm/c
UrQMD Frankfurt/M

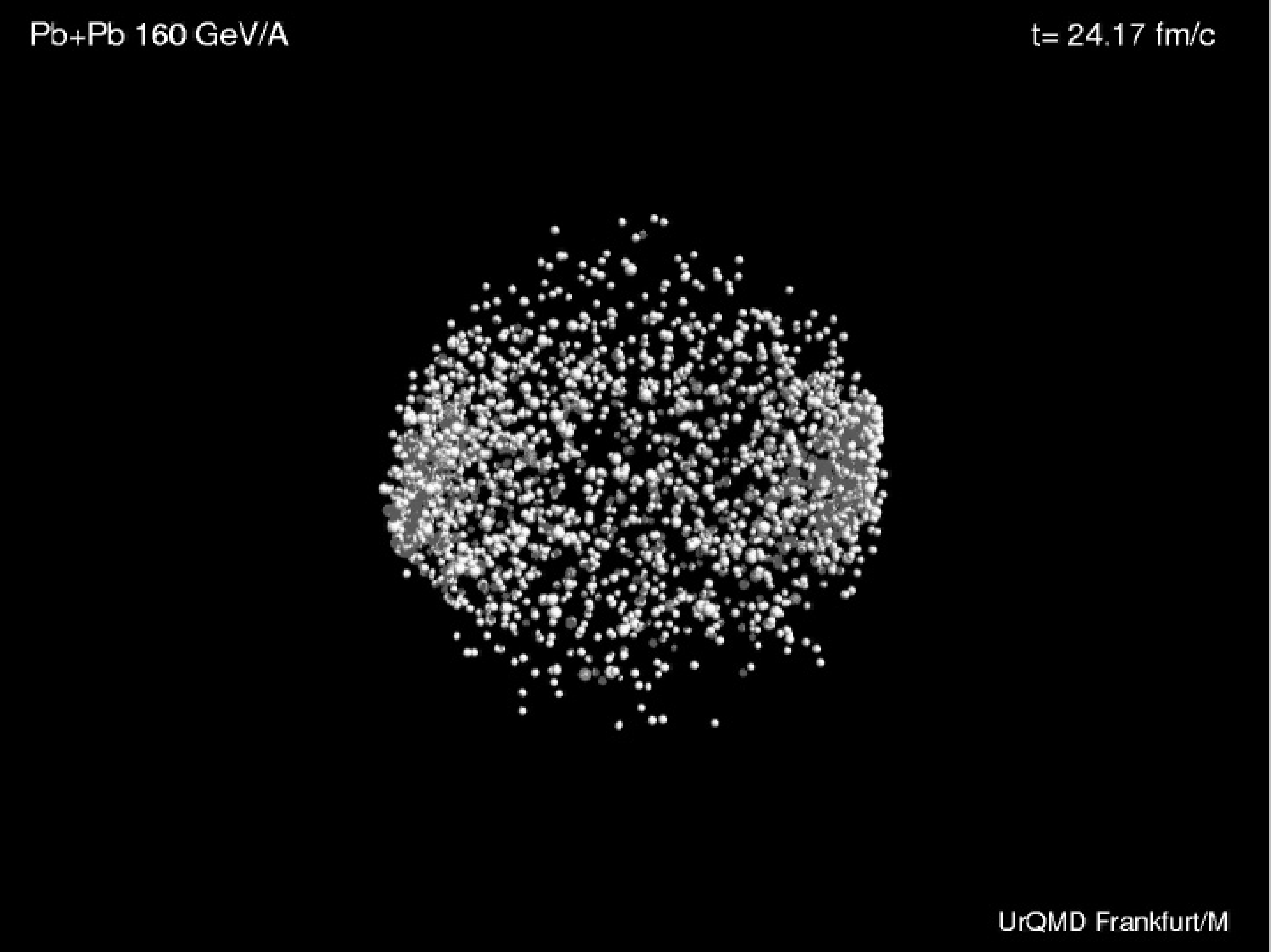

Pb+Pb 160 GeV/A
t=-03.33 fm/c
UrQMD Frankfurt/M

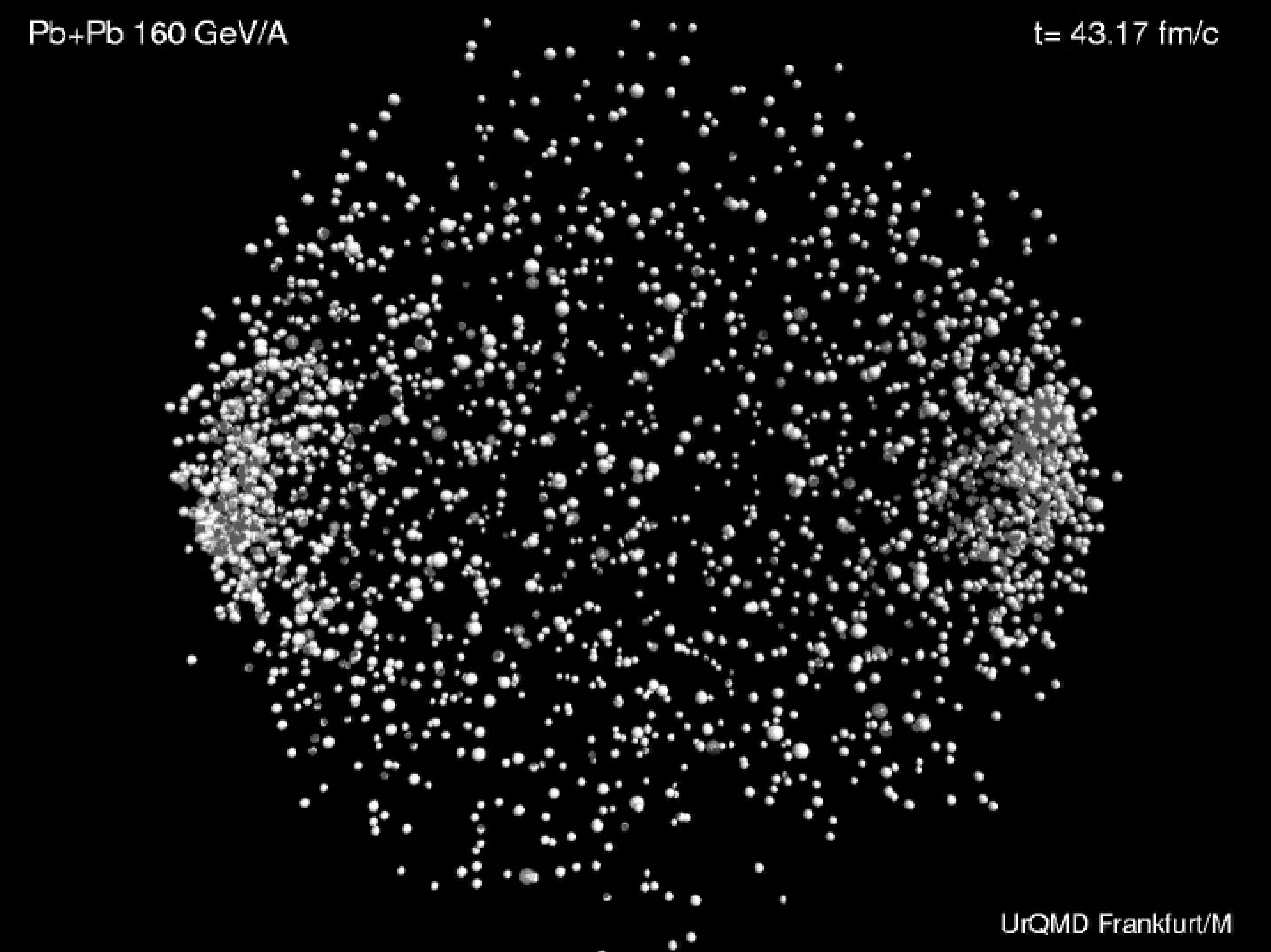

Pb+Pb 160 GeV/A
t=-00.33 fm/c
UrQMD Frankfurt/M


Pb+Pb 160 GeV/A
t= 00.67 fm/c
UrQMD Frankfurt/M


Pb+Pb 160 GeV/A
t= 02.67 fm/c
UrQMD Frankfurt/M

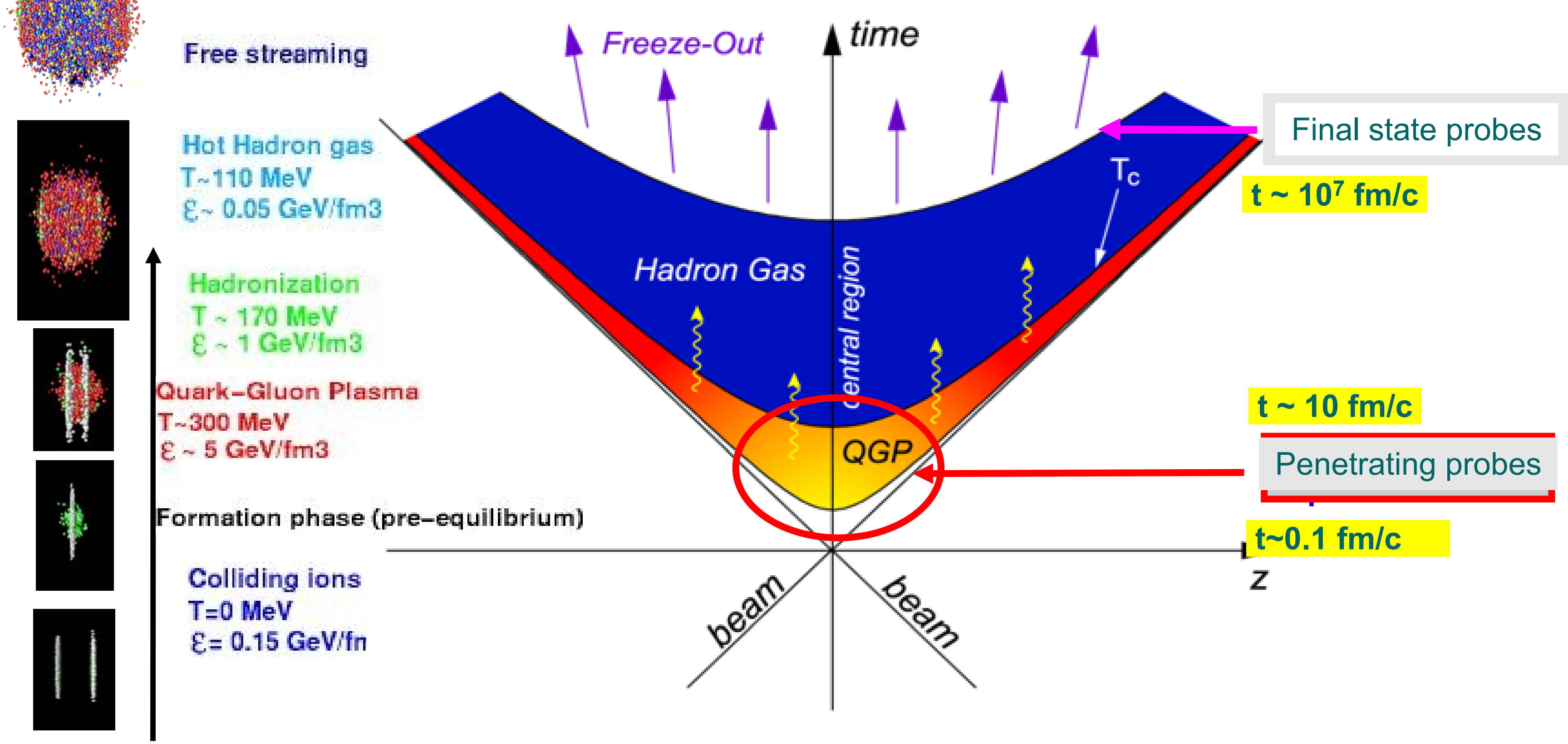

Pb+Pb 160 GeV/A
t= 08.17 fm/c
UrQMD Frankfurt/M

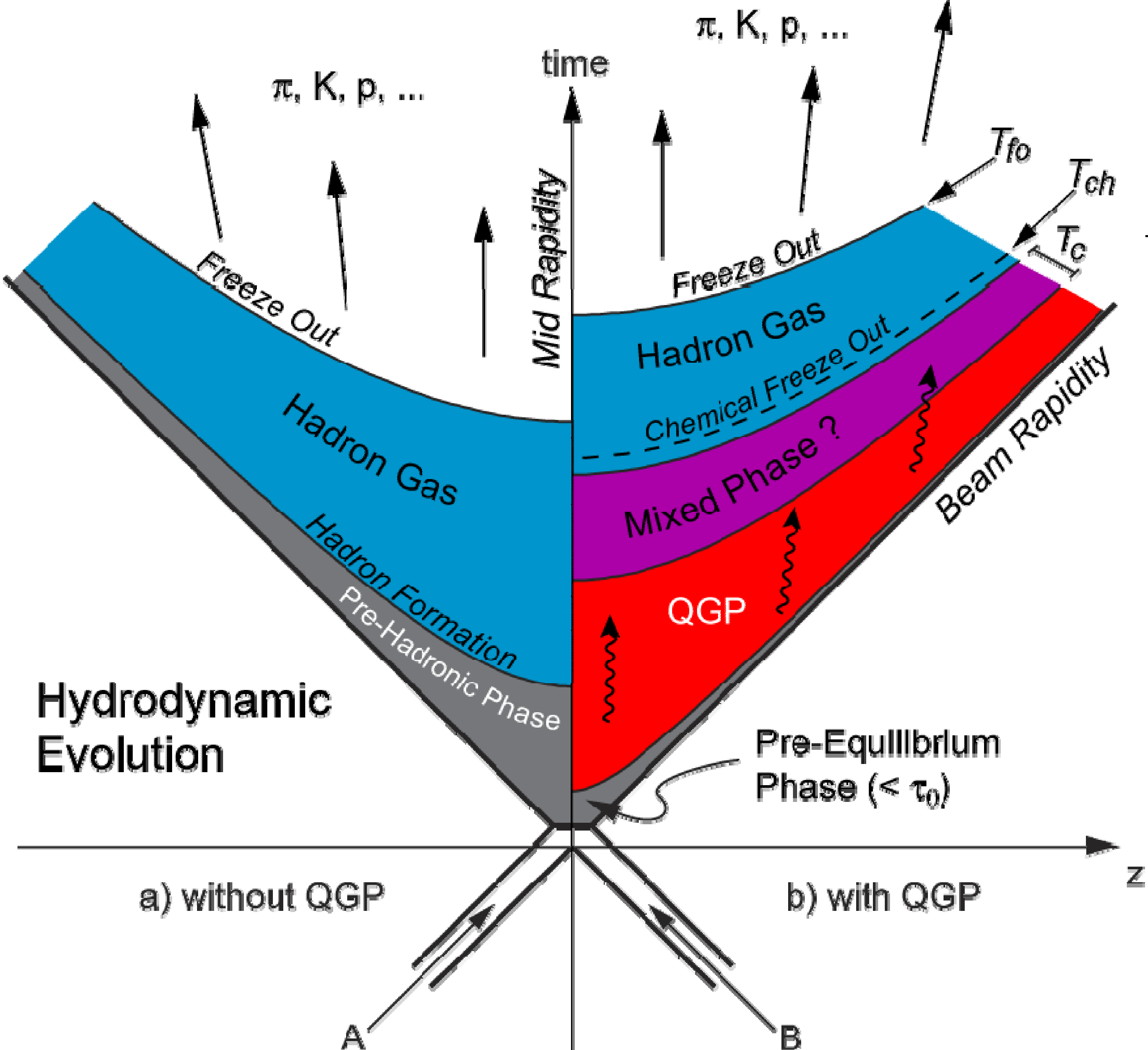

Pb+Pb 160 GeV/A
t= 24.17 fm/c
UrQMD Frankfurt/M


Pb+Pb 160 GeV/A
t= 43.17 fm/c
UrQMD Frankfurt/M

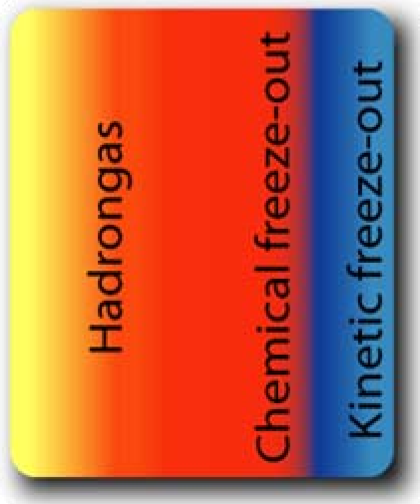
The "Little Bang" in the lab

- *Nucleus-nucleus collisions: fixed-target reactions ($\sqrt{s}$=20 GeV, SPS) or colliders ($\sqrt{s}$=200 GeV, RHIC. $\sqrt{s}$=5.5 TeV, LHC)*
- *QGP expected to be formed in a tiny region (~10^{-14} m) and to last very short times (~10^{-23} s).*
- *Collision dynamics: Diff. observables sensitive to diff. react. stages*




time
π, K, p, ...
π, K, p, ...
Mid Rapidity
Freeze Out
Freeze Out
Hadron Gas
Hadron Gas
Hadron Formation
Pre-Hadronic Phase
Chemical Freeze Out
Mixed Phase ?
QGP
Beam Rapidity
T_{fo}
T_{ch}
T_c
Hydrodynamic
Evolution
Pre-Equlllbrlum
Phase (< τ_0)
a) without QGP
b) with QGP
z
A
B

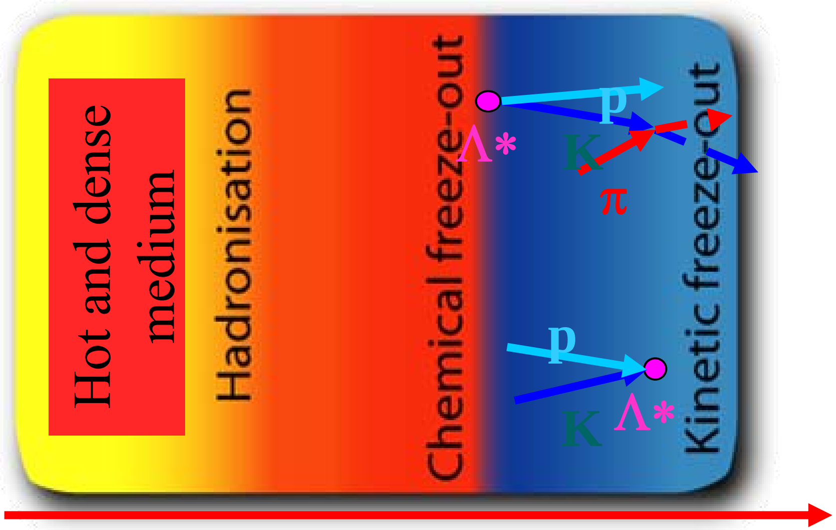
Time in Heavy Ion Reactions



p+p interactions:
- No extended initial medium
- Chemical freeze-out (no thermalization)
- Kinetic freeze-out close to chemical freeze-out

Particle yields

Particle spectra

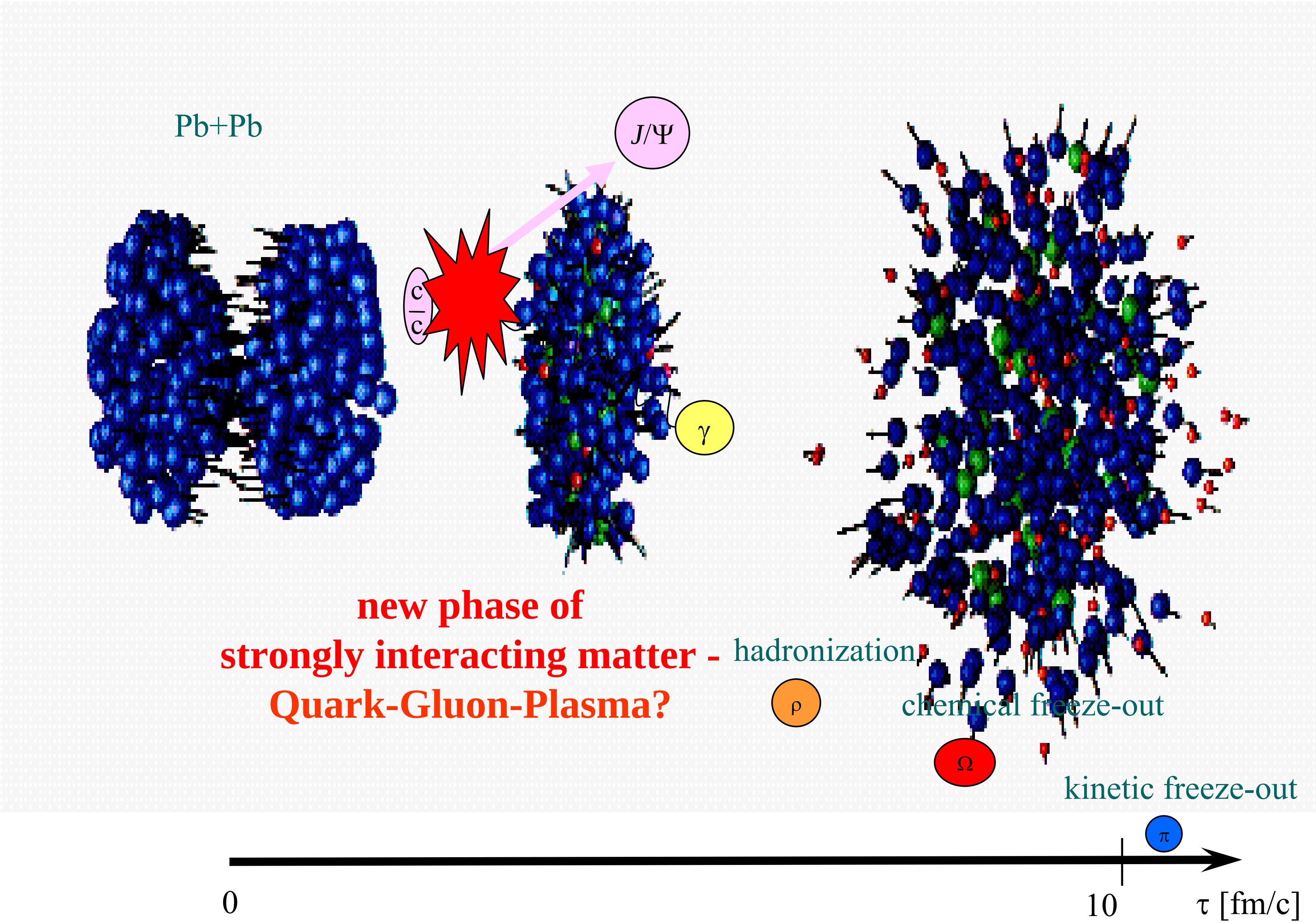


time

Au+Au interactions:
- Extended hot and dense phase
- Thermalization at chem. freeze-out
- Kinetic freeze-out separated from chemical freeze-out

Christina Markert 2006

Ultrarelativistic Heavy Ion Collisions



End of the World!

J. Nagle

Can be dismissed with some basic General Relativity

$$R_S = {2GM}/{c^2} = 10^{-49}\, meters$$

$$R = 10^{-15}\, meters$$

much less than Planck length !

Even if it could form, it would evaporate by Hawking Radiation in 10^{-83} seconds !

A little of search history

1951-1975
Pomeranchuk, Hagedorn, Fubini, Veneziano, Mandelstam, Cabibbo, Parisi et al:

Critical temperature for phase transition to QGP with free color quarks and gluons

T_c= 150-180 MeV

1986/1987
Experimental research of AA interactions:
Creation of new state of matter – Quark Gluon Plasma at AGS and SPS, since 2000 at RHIC and now shortly in LHC

Density of energy in point of transition

0.7-1.0 GeV/fm^3

AGS : $\sqrt{S_{NN}}$ = 5 GeV
SPS : $\sqrt{S_{NN}}$ = 20 GeV
RHIC : $\sqrt{S_{NN}}$ = 200 GeV

Facilities to hunt the QGP and its signatures

The Future Experiment
CBM: Fixed Target
U^{235} @ 2-45 GeV/A

-What were the expectations in the beginning?

Little Bang

2009-10
LHC: Collider
Pb+Pb @5.5TeV/A

2000
RHIC: Collider
Au+Au @ 200GeV/A

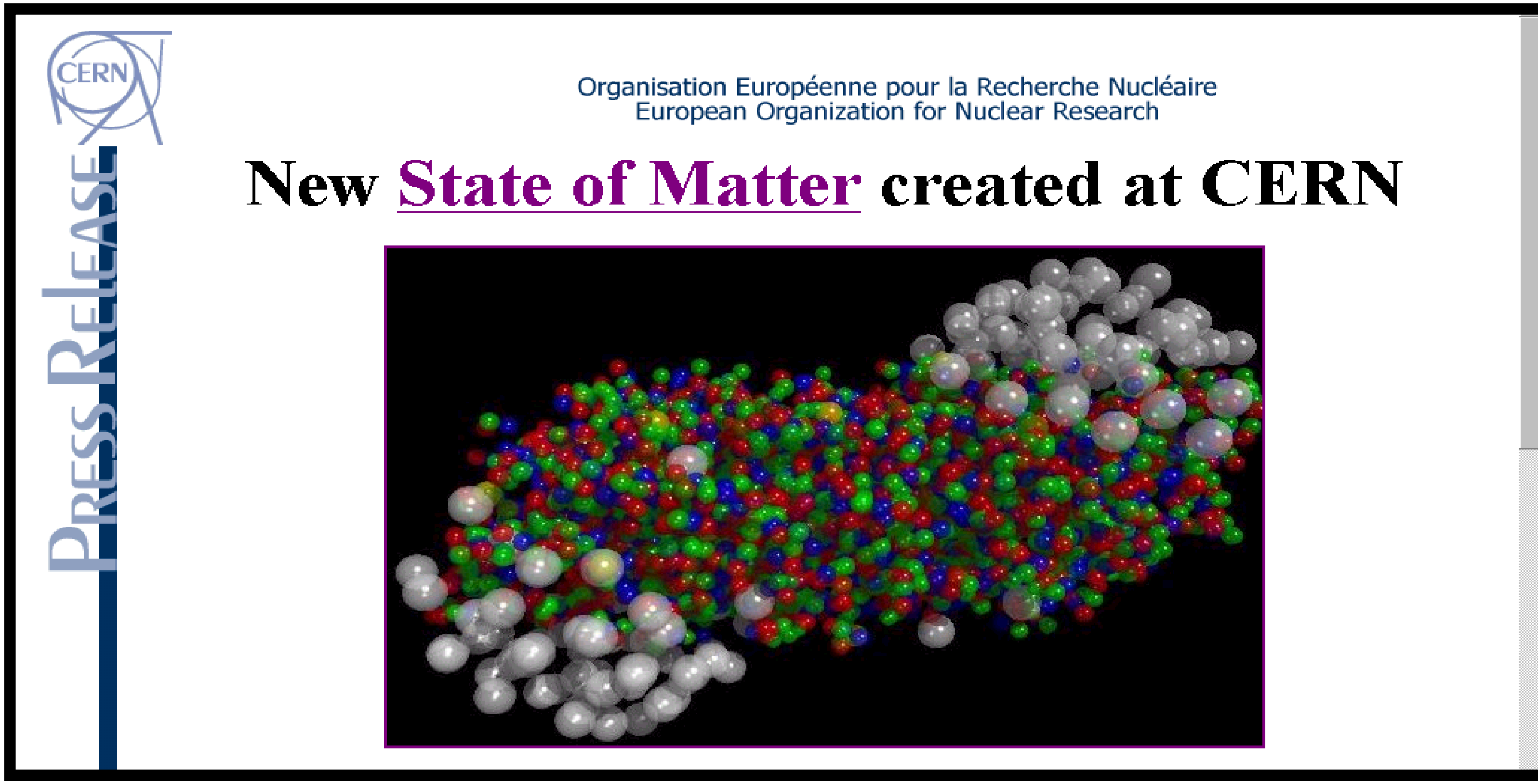
1996
SPS: Fixed Target
Pb at 158GeV/A
(Ec.m.=17.3GeV)

1991
AGS: Fixed Target
Au at 11.7 GeV/A
(Ec.m.=4.86GeV)

1984
Bevalac:
Fixed Target
Au at
1GeV/A

- What have we learned so far?
- What are the prospects for the future?

QGP: A new state of matter



"The combined data coming from the seven experiments on CERN's Heavy Ion programme have given a clear picture of a new state of matter. . . . We now have evidence of a new state of matter where quarks and gluons are not confined. There is still an entirely new territory to be explored concerning the physical properties of quark-gluon matter." [L. Maiani, 2000]

Research results, SPS:

February 2000

Ulrich Heinz and Maurice Jacob Theoretical Physics Division, CERN CH-1211 Geneva 23, Switzerland:

Evidence for a New State of Matter:

An Assessment of the Results from the CERN Lead Beam

… Present theoretical ideas provide a more precise picture for this new state of matter: it should be a quark-gluon plasma (QGP), in which quark and gluons, the fundamental constituents, are no longer confined within the dimensions of the nucleon, but free to move around over a volume in which a high enough temperature and/or density prevails…

… A common assessment of the collected data leads us to conclude that we now have compelling evidence that a new state of matter has indeed been created… The new state of matter found in heavy ion collision at the SPS features many of the characteristics of the theoretically predicted quark-gluon plasma…

For last 9 years there has been a significantly increased interest in HIC

- **New beautiful results from RHIC (STAR, PHENIX, BRAHMS, PHOBOS), and also new results from experiments at SPS (NA49, NA50, NA57 and NA60).**

- **Ability to deliver physics at ~ all scales**

Research program on nucleus-nucleus collisions at the new accelerator facility at GSI (FAIR) and LHC

- **There is very fast development of theory and preparation of new experiments**

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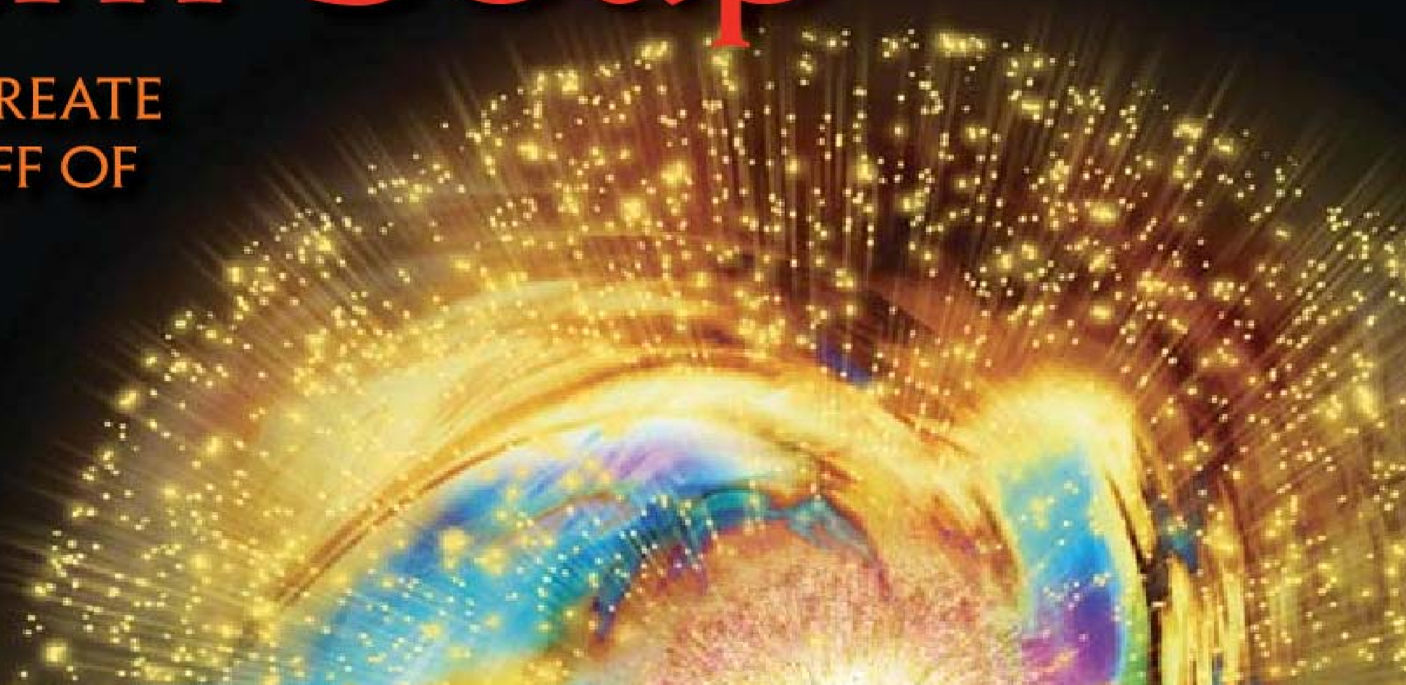
Quark Soup

PHYSICISTS RE-CREATE THE LIQUID STUFF OF **THE EARLIEST UNIVERSE**



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Print-friendly E-mail Article

RHIC Scientists Serve Up "Perfect" Liquid

New state of matter more remarkable than predicted -- raising many new questions

April 18, 2005

TAMPA, FL -- The four detector groups conducting research at the Relativistic Heavy Ion Collider (RHIC) -- a giant atom "smasher" located at the U.S. Department of Energy's Brookhaven National Laboratory -- say they've created a new state of hot, dense matter out of the quarks and gluons that are the basic particles of atomic nuclei, but it is a state quite different and even more remarkable than had been predicted. In peer-reviewed papers summarizing the first three years of RHIC findings, the scientists say that instead of behaving like a gas of free quarks and gluons, as was expected, the matter created in RHIC's heavy ion collisions appears to be more like a *liquid*.

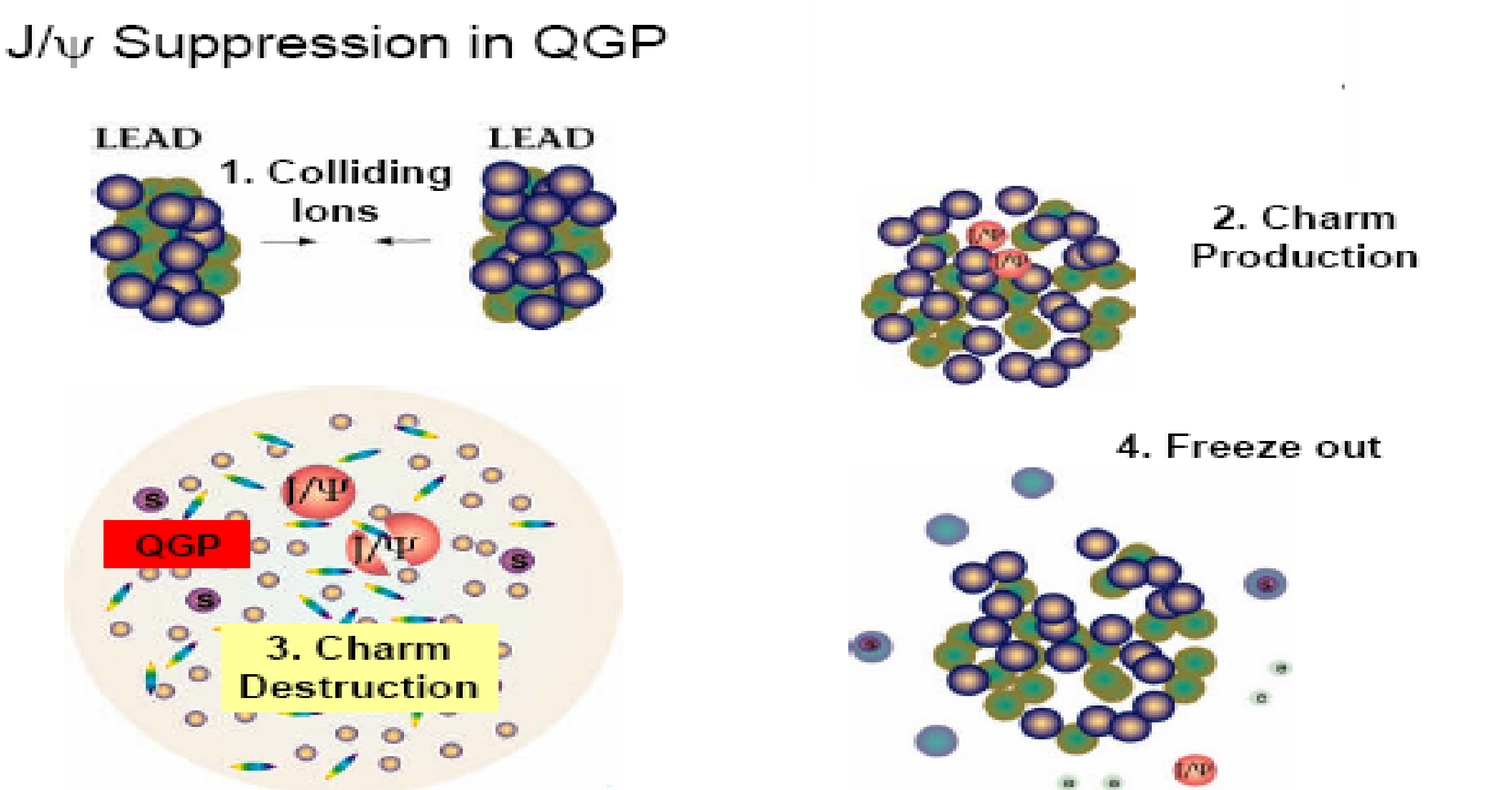
"Once again, the physics research sponsored by the Department of Energy is producing historic results," said Secretary of Energy Samuel Bodman, a trained chemical engineer. "The DOE is the principal federal funder of basic research in the physical sciences, including nuclear and high-energy physics. With today's announcement we see that investment paying off."

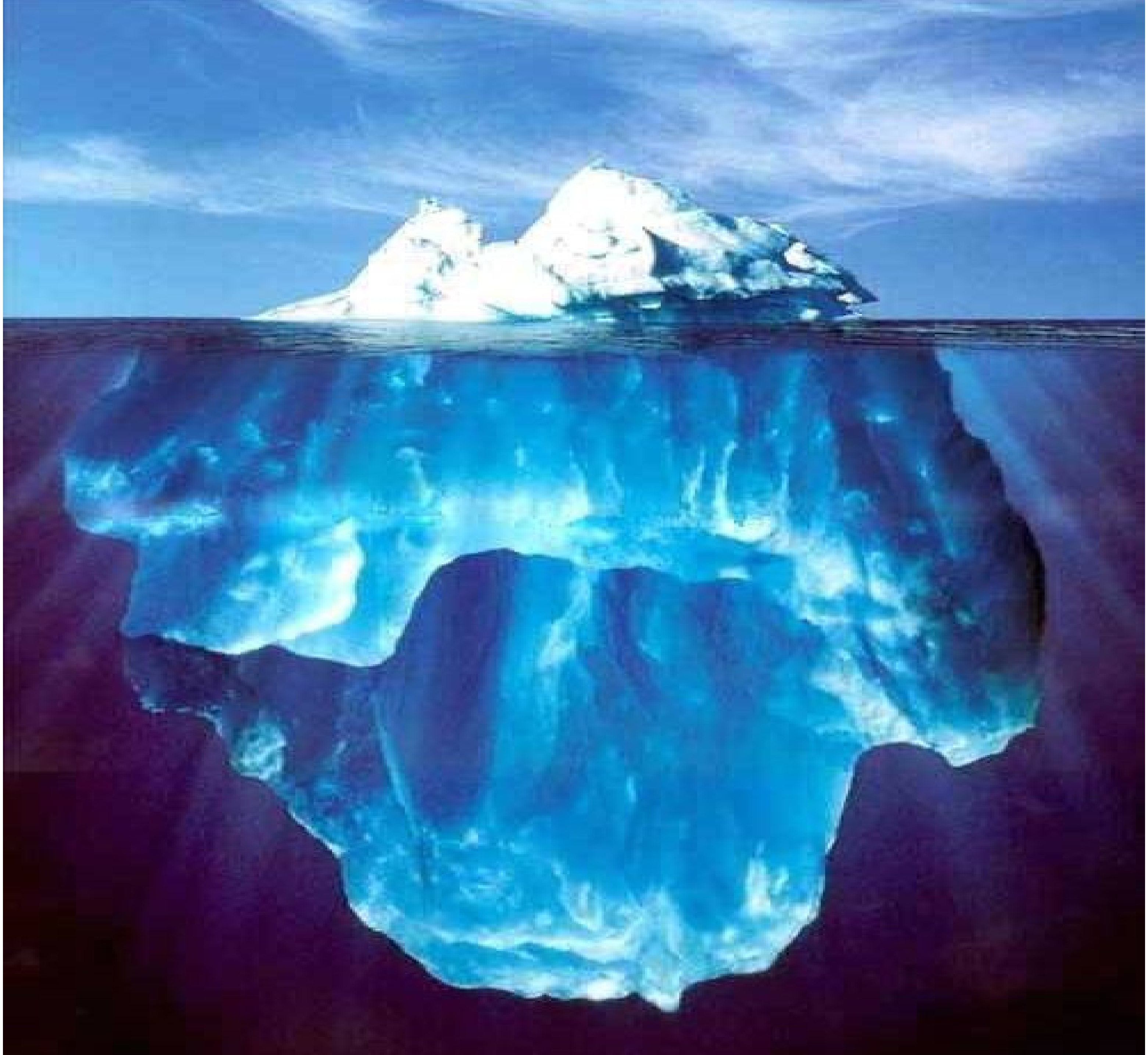
"The truly stunning finding at RHIC that the new state of matter created in the collisions of gold ions is more like a liquid than a gas gives us a profound insight into the earliest moments of the universe," said Dr. Raymond L. Orbach, Director of the DOE Office of Science.

Key Results from SPS & RHIC

- **SPS** (1986-2003) – QGP signatures seen e.g.
  - **Enhancement of strangeness** (up to a factor of ~20).
  - **Suppression of J/Ψ (c c-bar meson)**.
- **RHIC** (2000 onwards) – results from SPS exps confirmed, plus
  - **Elliptic flow**: collective flow of final state hadrons w.r.t. the reaction plane – medium behaves like an ideal liquid rather than a gas as expected.
  - **Jet quenching**: suppression of high p_T hadrons w.r.t. yield expected from superposition of nucleon-nucleon collisions.

- Charmonium states are screened in QGP
  - J/ψ suppression





Large quantitative gains

Increasing the center of mass energy implies

→ Denser initial system

→ Longer lifetime

→ Bigger spatial extension

→ Stronger collective phenomena

A large body of experimental data from the CERN SPS and RHIC supports this argument.

ALICE - A Large Ion Colliding Experiment

- LHC is **ultimate machine** for Heavy Ion Collisions
  - very **significant step** beyond RHIC
  - excellent conditions for **experiment & theory** (QCD)
  - not only latest, but **possibly last** HIC setup at the energy frontier
- ALICE is a powerful **next generation detector**
  - first truly **general purpose** Heavy Ion experiment
  - many **evolutionary** developments
    - SSD, SDD, TPC, em cal, …
  - some **big advances** in technology
    - electronics, pixels, TOF, computing

Pb+Pb Collisions at LHC

- cm-energy $\sqrt{s}$ = 1150 TeV = 0.18 mJ
- energy density ε = 1000 GeV/fm^3

  (ε_{Pb} = 0.15 GeV/fm^3)
- initial temperature T = 1 GeV

  ($T_{critical}$ = 0.15 GeV)
- total multiplicity = 60000
- total volume at freeze-out V = 6 • 10^5 fm^3

  (V_{Pb} = 1500 fm^3)
- lifetime until freeze-out τ = 50 fm/c

ALICE Program and Outlook

Safarik, 09

- first pp run
  - **important pp reference data for heavy ions**
  - **unique physics to ALICE**
    - **minimum-bias running**
    - **fragmentation studies**
    - **baryon-number transport**
    - **heavy-flavour cross sections**
- first few heavy-ion collisions
  - **establish global event characteristics**
  - **important bulk properties**
- first long heavy-ion run
  - **quarkonia measurements**
  - **Jet-suppression studies**
  - **flavour dependences**

Outlook

- high luminosity heavy ion running ($1nb^{-1}$)
  - **dedicated high p_t electron triggers**
  - **jets > 100 GeV (EMCAL)**
  - **Y - states**
  - **γ - jet correlations**
  - **...**
- pA & light ion running

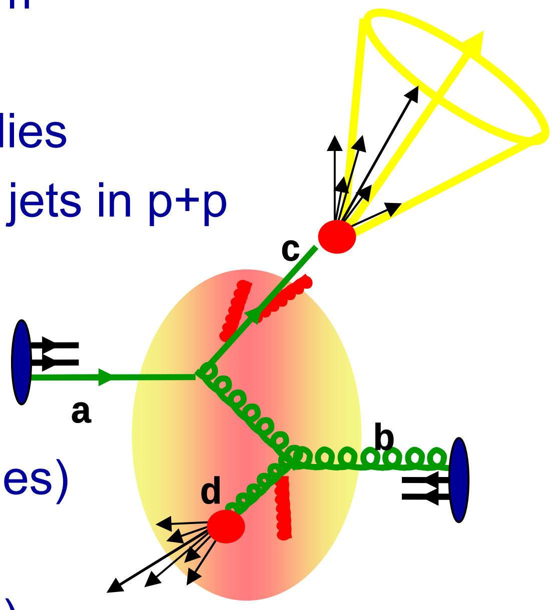
ALICE @ LHC

- Evidence for QGP formation at CERN SPS and RHIC energies.
- ALICE will be able to study the physics of quark matter in detail.
  - almost all known observables
  - from early to late stages of QGP
- ALICE to study pp physics in its own right
- ALICE is ready for first physics

---- looking forward to lots of exciting physics shortly

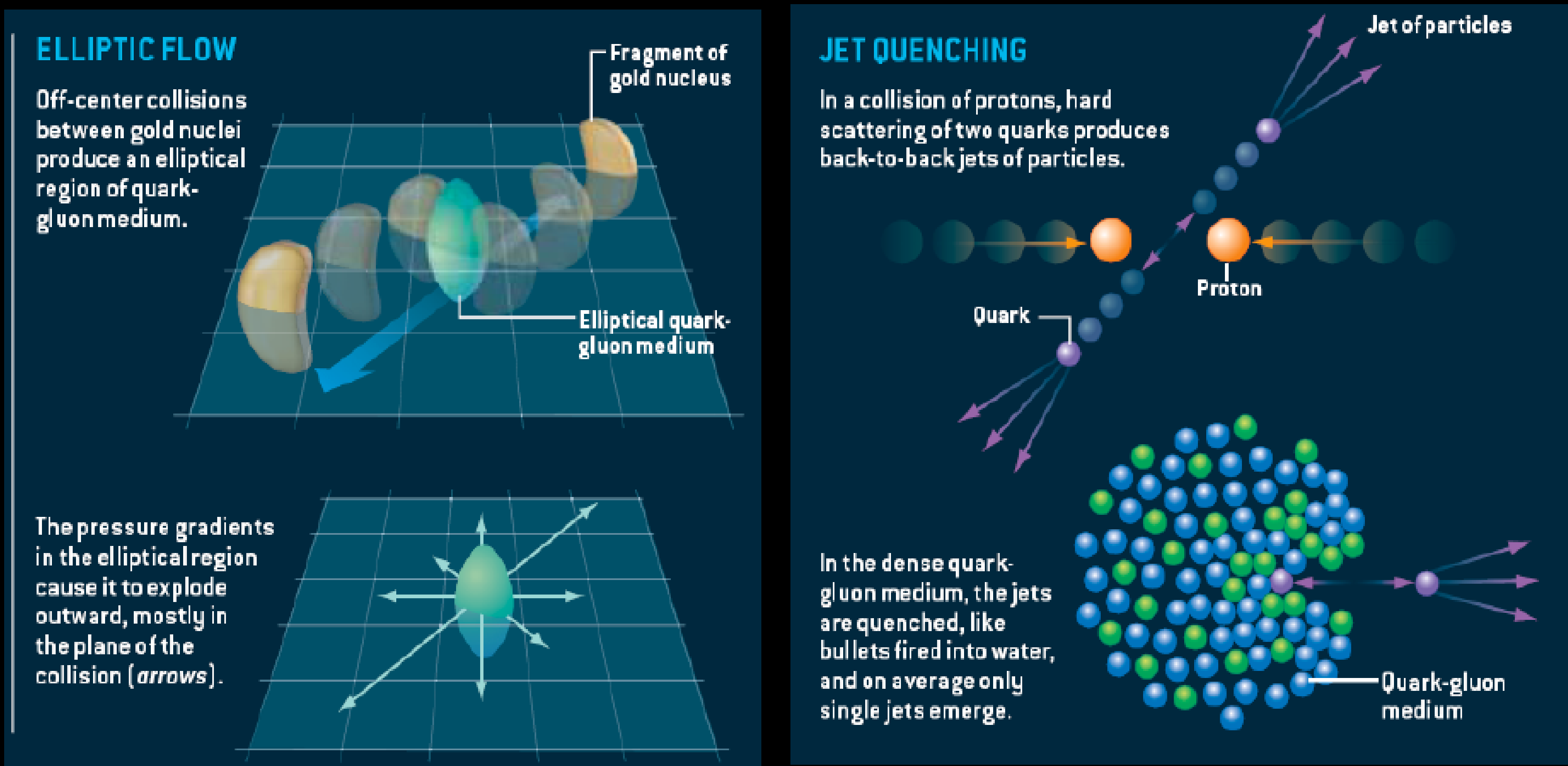
Jets – a new observable at LHC

- Hard, perturbative scale: $Q \gg \Lambda_{QCD}$.
- Parton shower development affected by the medium
- At LHC in Pb+Pb collisions:
  - wider p_T range for suppression, quenching studies
  - jet structure will likely be modified compared to jets in p+p
    - comparison to p+p and p+A is essential
- Observables:
  - High p_T particles and particle correlations
  - Jet rates: single and multi-jets (quenching studies)
  - Jet fragmentation and shape:
    - Distance R to leading particle (in η-φ space)
    - forward-backward correlation: $\Delta\phi$ (particle, jet axis)
    - Fragmentation function: $F(z)=1/N_j \times dN_{ch}/dz$ where $z=p_t/p_{jet}$
  - correlations with non-hadronic particles: jets+γ, jets+Z
  - Jets originating from heavy quarks (b, c)



EVIDENCE FOR A DENSE LIQUID (from Riordan and Zajc, Scientific American, May 2006, p. 34a.)

Two phenomena in particular point to the quark-gluon medium being a dense liquid state of matter: jet quenching and elliptic flow. Jet quenching implies the quarks and gluons are closely packed, and elliptic flow would not occur if the medium were a gas.



Finally, lots of exciting and challenging physics expected from LHC experiments …

Best summarised by the following:

“Traveller, road is nothing more than your footprints;
Traveller, there is no road, you make it as you go”.

H. Satz *(hep-ph/0209181)*

Thankyou

Heavy-ion physics with ALICE

- fully commissioned detector & trigger
  - alignment, calibration available (pp)
- first 10^5 events: global event properties
  - multiplicity, rapidity density
  - elliptic flow
- first 10^6 events: source characteristics
  - particle spectra, resonances
  - differential flow analysis
  - interferometry
- first 10^7 events: high-p_t, heavy flavours
  - jet quenching, heavy-flavour energy loss
  - charmonium production
- yield bulk properties of created medium
  - energy density, temperature, pressure
  - heat capacity/entropy, viscosity, sound velocity, opacity
  - susceptibilities, order of phase transition

- early ion scheme
  - 1/20 of nominal luminosity
  - $\int Ldt = 5 \cdot 10^{25}$ cm^{-2} s^{-1} x 10^6 s
    0.05 nb^{-1} for PbPb at 5.5 TeV
    $N_{pp\ collisions} = 2 \cdot 10^8$ collisions
    400 Hz minimum-bias rate
    20 Hz central (5%)
  - muon triggers:
    ~ 100% efficiency, < 1kHz
  - centrality triggers:
    bandwidth limited
    $N_{PbPbminb} = 10^7$ events (10Hz) $N_{PbPbcentral} = 10^7$ events (10Hz)

Status: Was The QGP Seen?

- observations at SPS
  - initial energy density above critical value
  - strong collective effects
    - strongly interacting system
  - strangeness enhancement
    - close to equilibrium - possible in hadronic system?
  - photon radiation?
    - hot system in initial state - nature of system not conclusive

- modified vector meson spectra
  - relation to chiral symmetry restoration?
- J/ψ- suppression
  - currently better explained by QGP - unique?
- no jet quenching
  - no strong effect expected

- observations at RHIC
  - initial energy density high above critical value
- very strong collective effects
  - early equilibration
- strangeness enhancement
  - as at SPS
- photon radiation not yet observed
- vector meson spectra not yet observed
- J/ψ - suppression not yet observed
- jet quenching
  - high color charged density - nature of system not conclusive

ALICE Summary & Outlook

- first pp run
  - **important pp reference data for heavy ions**
  - **unique physics to ALICE**
    - **minimum-bias running**
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Outlook

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  - **Υ - states**
  - **γ - jet correlations**
  - **...**
- pA & light ion running

Why Heavy Ions?

• Higher energy density may be achieved in proton-proton, but the partonic re-interaction time scale of order 1 fm/c.

• It is difficult to select events with different geometries and avoid autocorrelations.

• We will see that probes with long paths through the medium are key.

We should not rule out pp reactions, but rather study the similarities and differences with AA reactions.

@ SPS

- All indications are that deconfinement is seen @SPS
- strangeness enhancement and J/Ψ suppression are correlated (γ_S. vs centrality) !!
- SPS offers the unique possibility to study precisely the onset of deconfinement....
- to be considered in long term planning of the SPS!

@ RHIC

- Deconfined phase is showing unexpected properties
- New phenomena, new probes:
  - jet tomography
  - collective motion
  - b-quarkonia could be a useful probe
- Initial quanta: Color Glass Condensate?
- A very dense, fluid phase: strongly interacting Quarks and Gluons?
- Which excitations populate the QG Liquid?

- RAPIDITY.

  The rapidity is a generalization of the velocity.

$$y \equiv \operatorname{arcth}(v_{\|}) \quad = \operatorname{arcth}(\frac{p_{\|}}{p^0}) \quad = \quad \frac{1}{2}\ln(\frac{p^0 + p_{\|}}{p^0 - p_{\|}}) \tag{2.5}$$

  This definition uses the components of vectors $\vec{v}$ and $\vec{p}$

2.1.2 Properties of the rapidity

For small velocities: $y \approx v_{\|}$. Particle after the collision moves with $\vec{v}$.
It is customary to decompose $\vec{v}$ to coordinates $(y, \vec{p}_\perp/m)$.
$\vec{p}$ can also be decomposed as $p^\mu = (p^0, p_{\|}, \vec{p}_\perp)$.
The limit of rapidity coordinates for non-relativistic velocities: $(y, \vec{p}_\perp/m) \longrightarrow (v_{\|}, \vec{v}_\perp)$.
While the velocity is limited to 1 (c), the rapidity y may vary between $(-\infty, \infty)$. See Fig. 2.4.

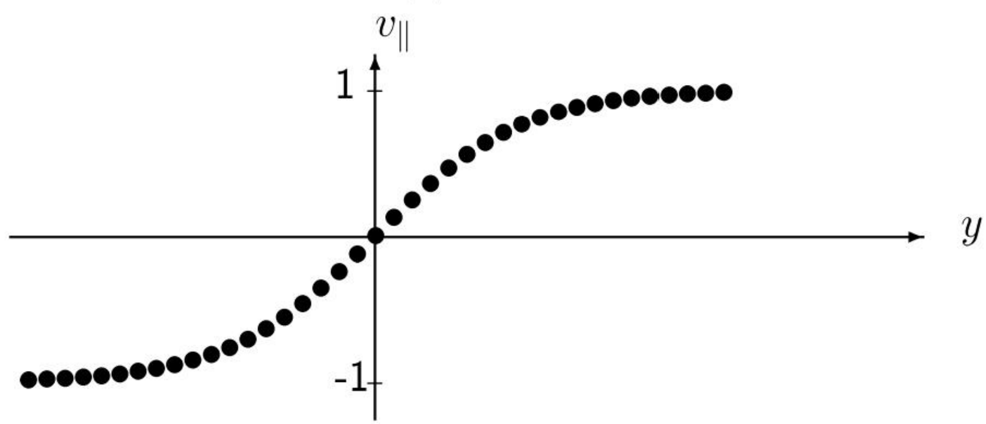

Figure 2.4 *The beam-parallel component of the velocity as function of the rapidity y, [2]*

Review of last lecture: Photons

- A hot QGP will emit photons
- Once emitted, photons leave system
- But any hot system, QGP or hadrons, will emit photons
  - if contained in box, cannot use photon spectrum to distinguish QGP vs. hadrons
  - if T_{photon} >200 MeV unlikely to be from hadrons
  - closer analogy is box with transparent walls
    - photons not in thermal equilibrium
- photons extremely difficult to measure
  - large background of e.g. $\pi^0 \rightarrow 2\gamma$

Today

- High p_t signals of QGP
  - energy loss of partons within a plasma

- Schedule
  - Nov 11 J/ψ
  - Nov 18 strangeness
  - Nov 25 Thanksgiving - no class
  - Dec 2 HBT
  - Dec 9 low-p_t and DCC

Summary

- High pt partons lose energy in a plasma
  - scattering and produced gluons
  - amplitudes interfere (LPM effect)
    - lowers e-loss, dE/dx ~ length
- Softens hadron spectra from fragmented parton
  - measure centrality dependence, periph. baseline
  - uncertainties, establish from p+A
    - pre-scattering: Cronin effect
    - gluon structure functions in Au: initial state
- Sensitive to density of colored-scattering centers

Summary

- Charmonium states screened in a QGP => suppression
- pp reactions produce pre-resonant, color octet state => evolves into J/ψ, χ etc.
- Explains pp, pA and A+A data for A<sulphur
- NA50 Pb+Pb data has fewer J/ψ
  - smooth dependence with E_t, no discontinuity
  - hadronic model reproduces data
    - early role of heavy hadrons, formation time of hadrons?
  - QGP 'model' reproduces data
    - can plasma be opaque to J/ψ, no e-loss of hard partons ?
  - measure pt spectra of J/ψ

Summary

- Strangeness enhancement largest at lower E_{beam}
  - hadronic mechanisms dominate
- Any QGP signal would sit on this baseline
  - strange-yields not reproduced by hadronic transport models
  - but without a definitive ‘smoking gun’, how bad a failure before you ‘need’ a QGP
  - key is excitation function 1-10, 40, 160 AGeV
    - ideal would be a minimum in enhancement
    - imply a QGP-driven enhancement above minimum

Summary

- low-pt sensitive to large-scale phenomena
  - emission from cold QGP
  - collective motion in plasma
  - decay of disoriented vacuum
- any scattering after hadronization will remove info.
- low-pt in pA, AA, consistent decay of resonances
  - difference π^-, π^+ Coulomb interaction => size
- experimental difficulties
- RHIC: opportunities across several experiments

Statistical QCD

$$\varepsilon_{QED} = \frac{\pi^2}{30}\left[\underbrace{2}_{\text{photon spin}} + \frac{7}{8}\underbrace{2\times 2}_{\text{electrons spin}}\right]T^4$$

$$\varepsilon_{QCD} = \frac{\pi^2}{30}\left[\underbrace{3\times 8}_{\text{gluon spin, color}} + \frac{7}{8}\times\underbrace{2\times 2\times 3\times 3}_{\text{quarks spin, color, flavor}}\right]T^4$$

Energy density reflects the information on what the matter is made of !