Relativistic Heavy-Ion Physics

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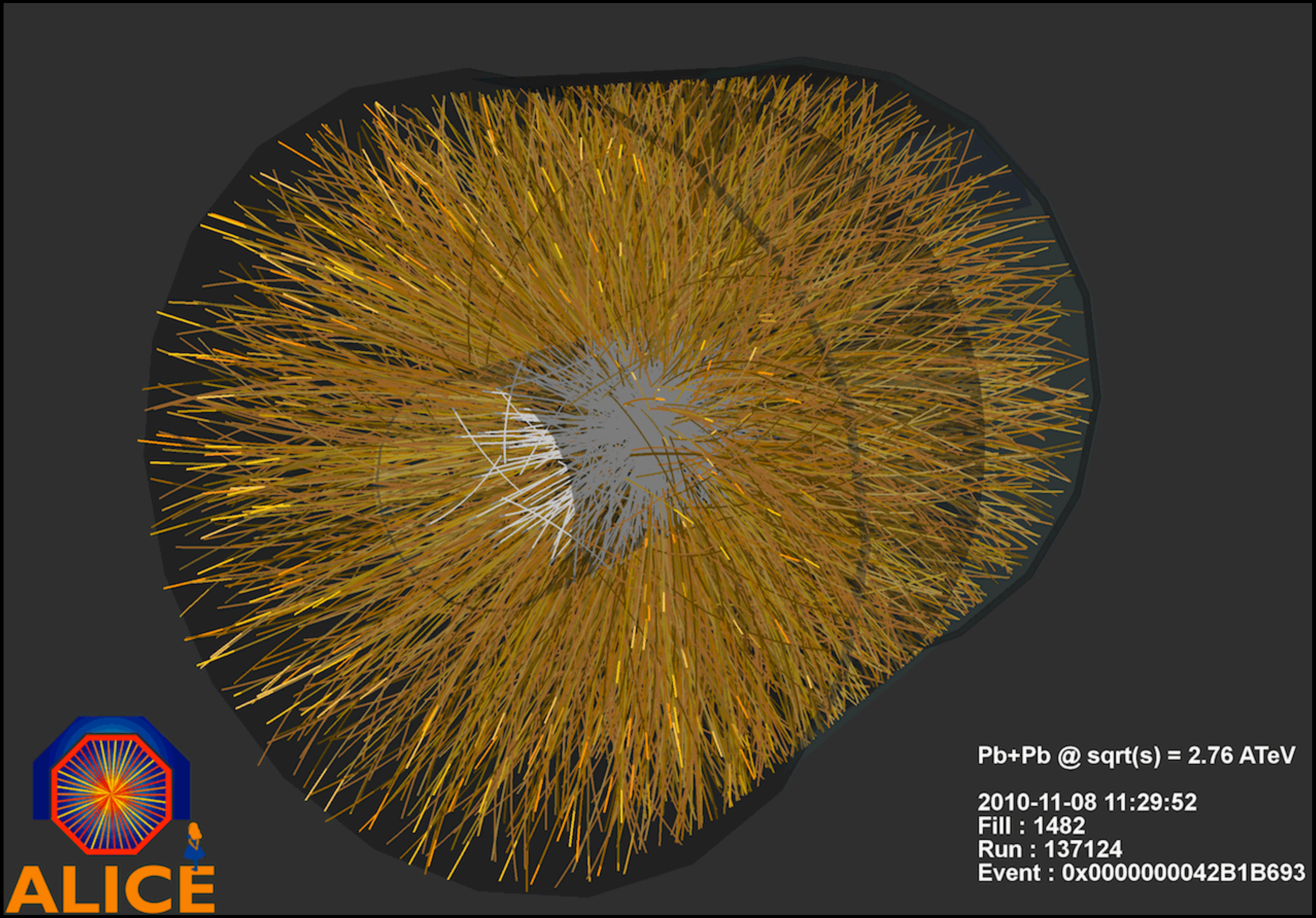
Introduction


ALICE
Pb+Pb @ sqrt(s) = 2.76 ATeV
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What is relativistic heavy-ion physics?

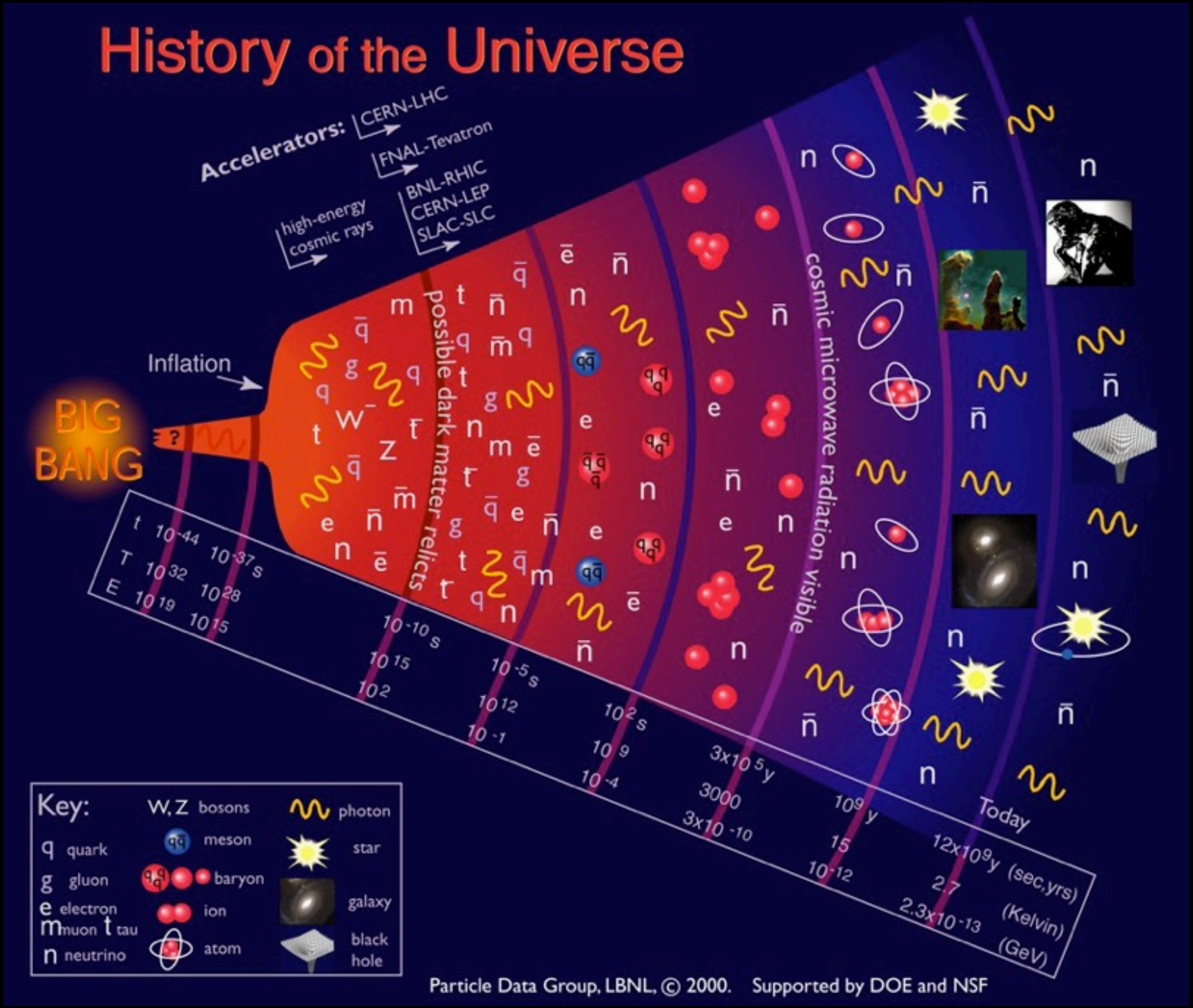
- Multidisciplinary branch of nuclear/high-energy physics
- Uses the **techniques** of high-energy (particle) physics to study the remnants of nuclear collisions
- Uses **concepts** from thermodynamics, fluid dynamics and even string theory to explain the results.
- Ultimately want to understand the behaviour of *bulk* **QCD** matter and learn what goes on at the *microscopic* level.

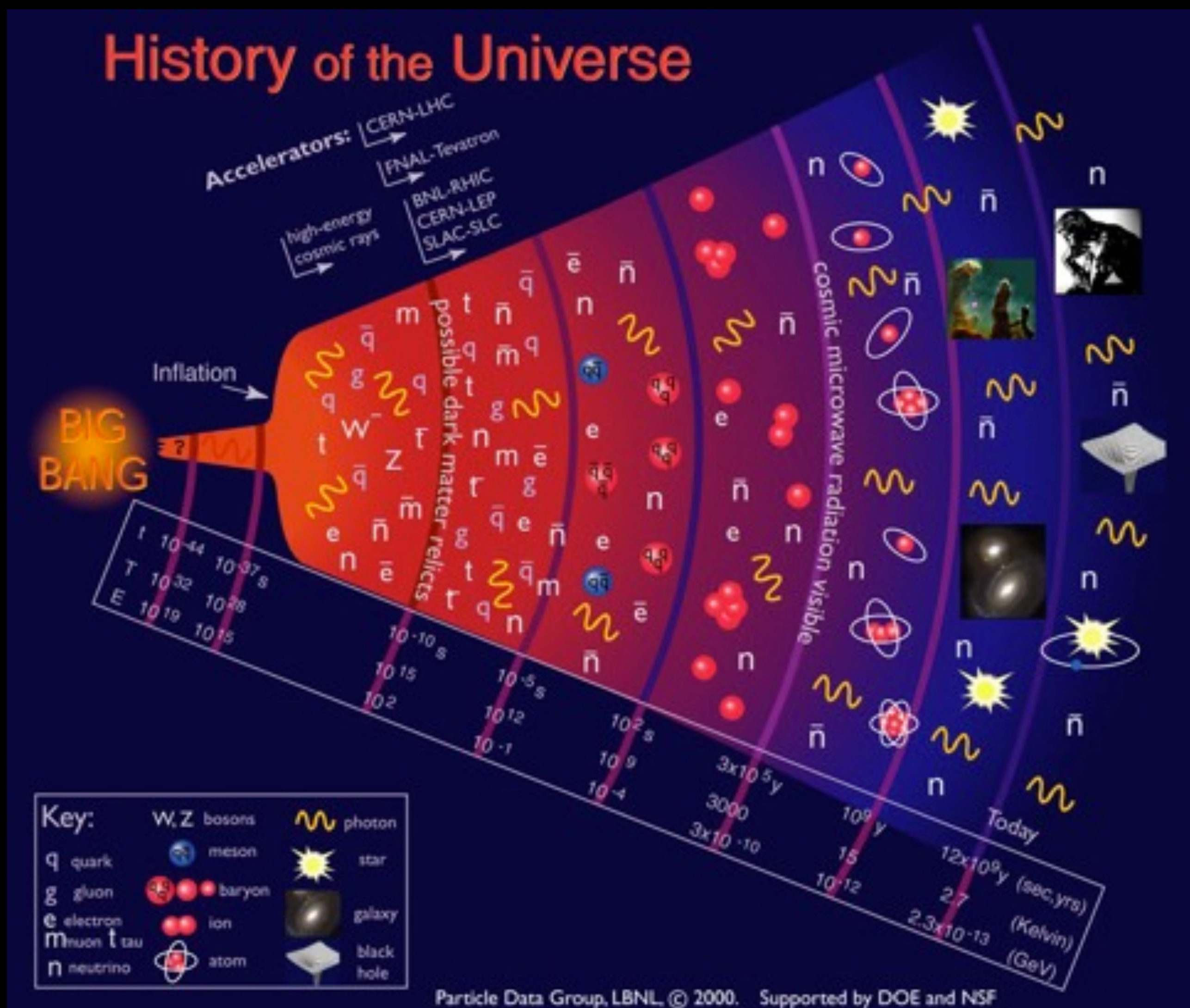
And what is it not?!

- It has not much to do with ‘traditional’ nuclear physics
  - No shell models, γ-ray level schemes, or decay chains
- However we will need an approximate description of the nucleus as an extended object
- *Extends* study of nuclear matter to high T

Motivations

- Cosmological
- The origin of (most of) the mass
  - QCD Confinement
  - chiral symmetry restoration
- Studying the hadronization phase transition
- Extracting the bulk properties of strongly coupled quark/gluon matter

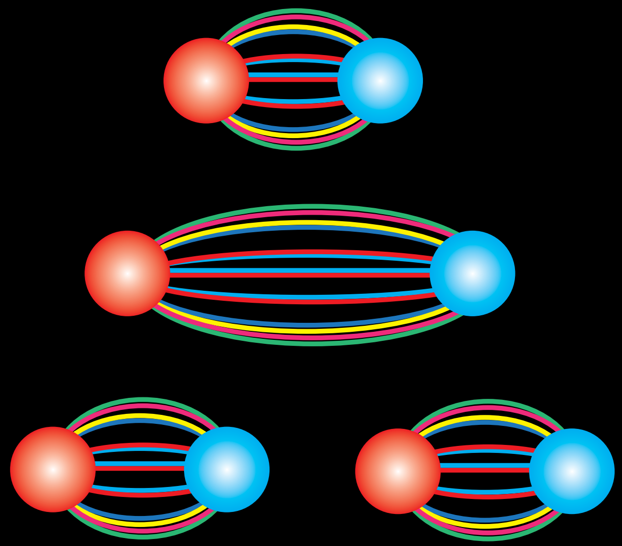

History of the Universe
Accelerators:
CERN-LHC
FNAL-Tevatron
BNL-RHIC
CERN-LEP
SLAC-SLC
high-energy cosmic rays
Inflation
BIG BANG
possible dark matter relics
cosmic microwave radiation visible
t 10-44 10-37 s
T 10 32 10 28
E 10 19 10 15
10-10 s
10 15
10 2
10-5 s
10 12
10 -1
10 2 s
10 9
10 -4
3x10 5 y
3000
3x10 -10
10 9 y
15
10-12
Today
12x10 9 y (sec,yrs)
2.7 (Kelvin)
2.3x10 -13 (GeV)
Key:
q quark
g gluon
e electron
m muon t tau
n neutrino
W,Z bosons
meson
baryon
ion
atom
photon
star
galaxy
black hole
Particle Data Group, LBNL, © 2000. Supported by DOE and NSF



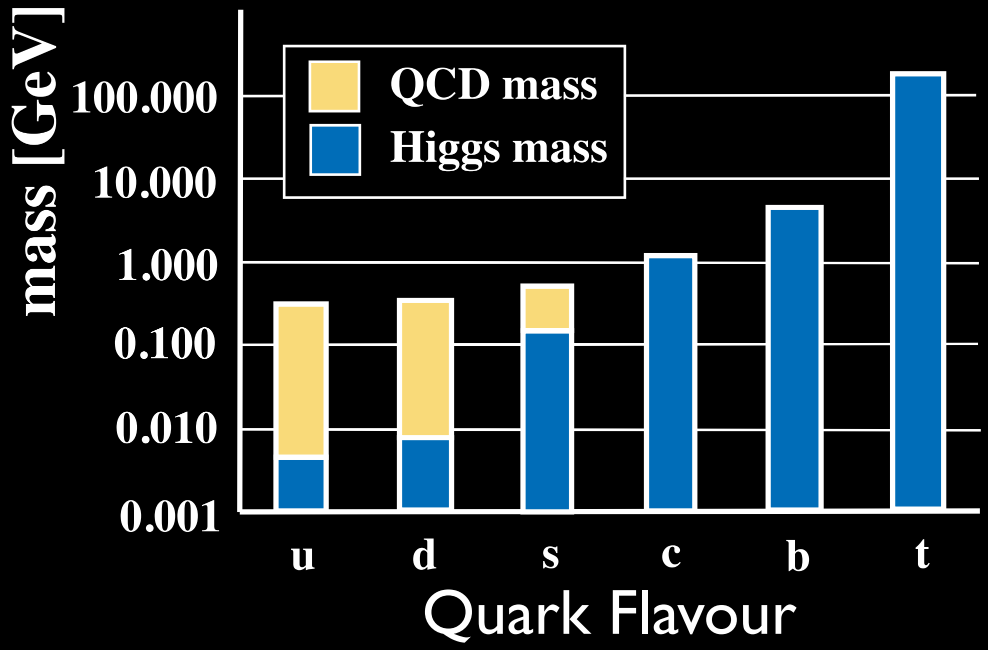
- 10 μs after Big Bang universe had a temperature of 10^{12} K
- Particles had typical energies 100 MeV

The macroscopic quantities of the QGP will give us better understanding of the underlying microscopic theory (QCD) in the non-perturbative regime

mechanism of confinement



mass generation in the strong interaction

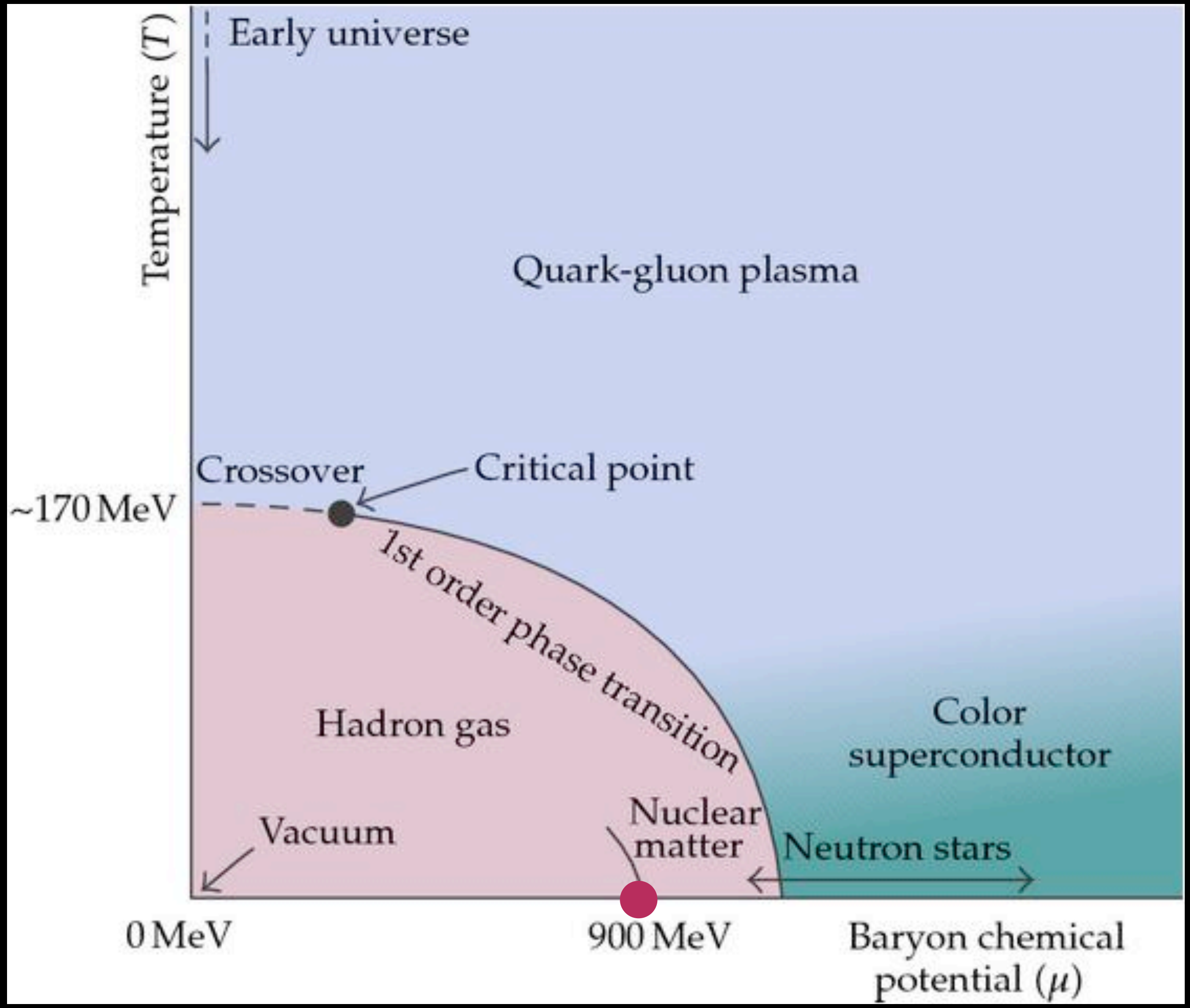


No free quarks observed in experiments

Observed hadrons M >> than quarks

QCD Phase Diagram

- Increasing temperature or (a variable related to) density leads to new stable phases



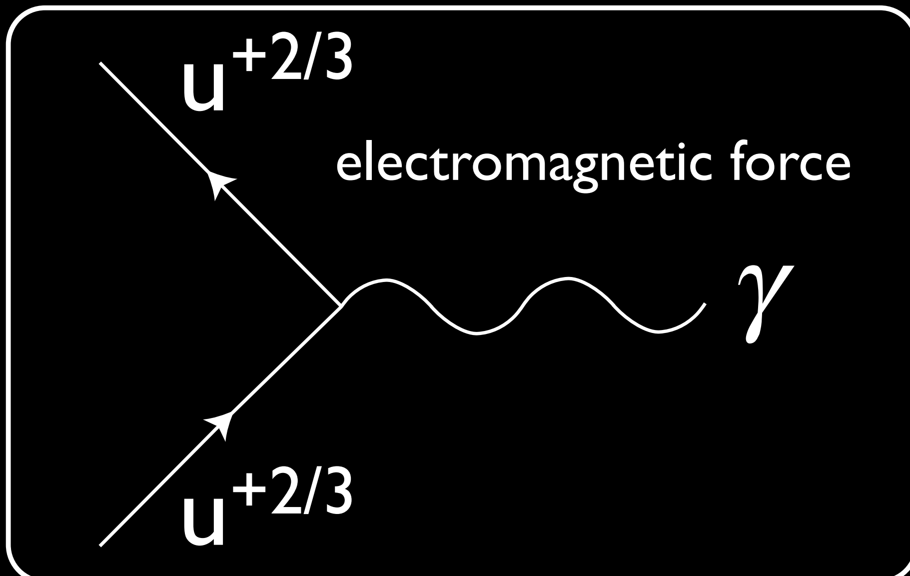
K. Rajagopal and F. Wilczek, Handbook of QCD

Thermodynamic Properties of Matter

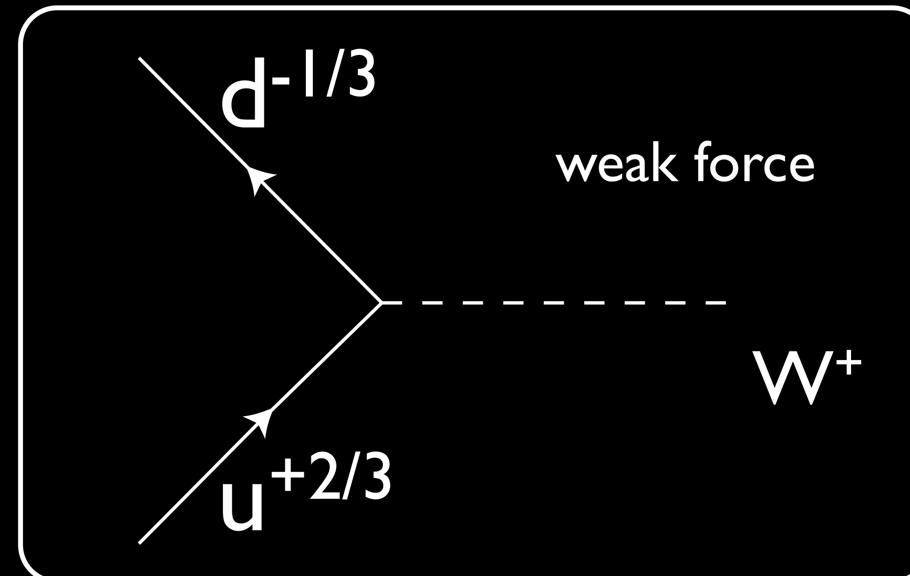
- Specific heat capacity
  - Energy required to change temperature
- Conductivity (to charge, colour,…)
- Speed of sound
- Viscosity
  - resistance to flow

QCD Concepts

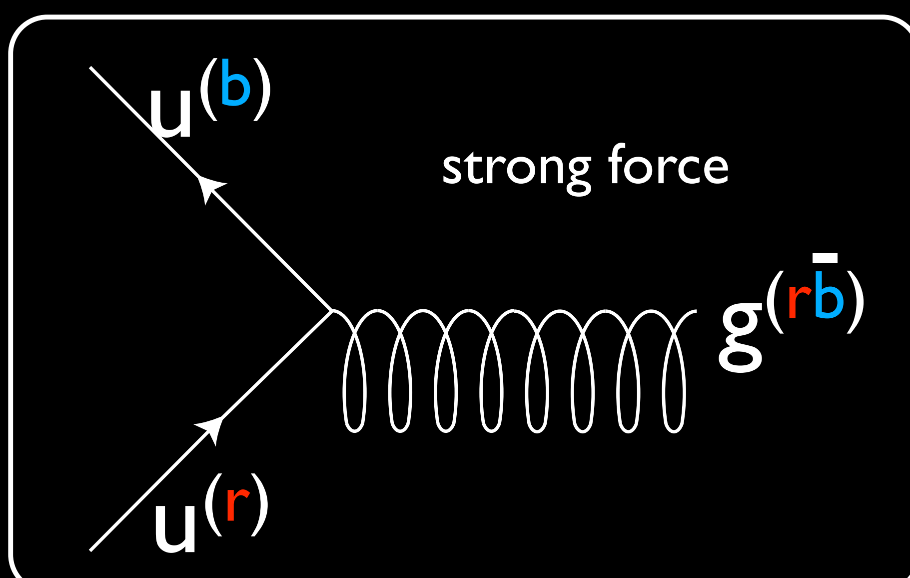
Forces compared



Quantum Electro Dynamics (QED)



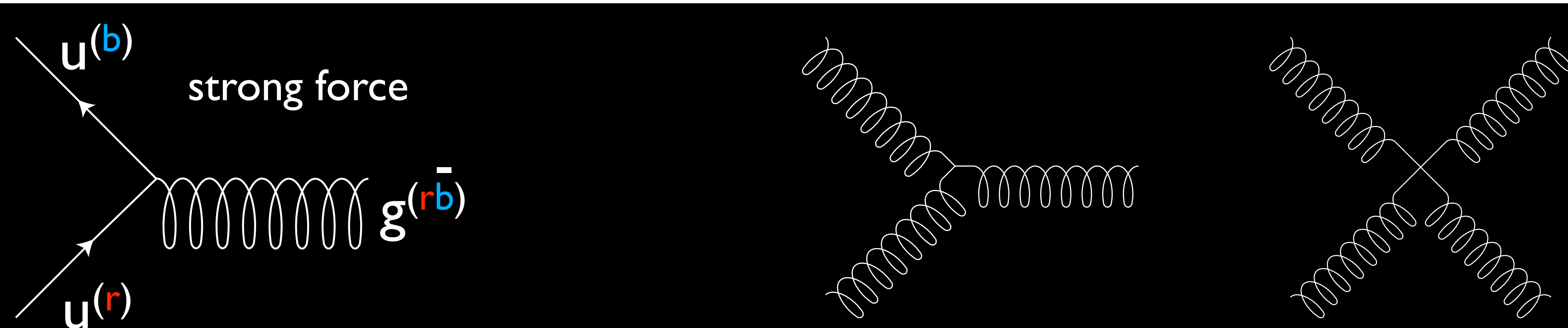
Quantum Flavor Dynamics (QFD)



Quantum Chromo Dynamics (QCD)

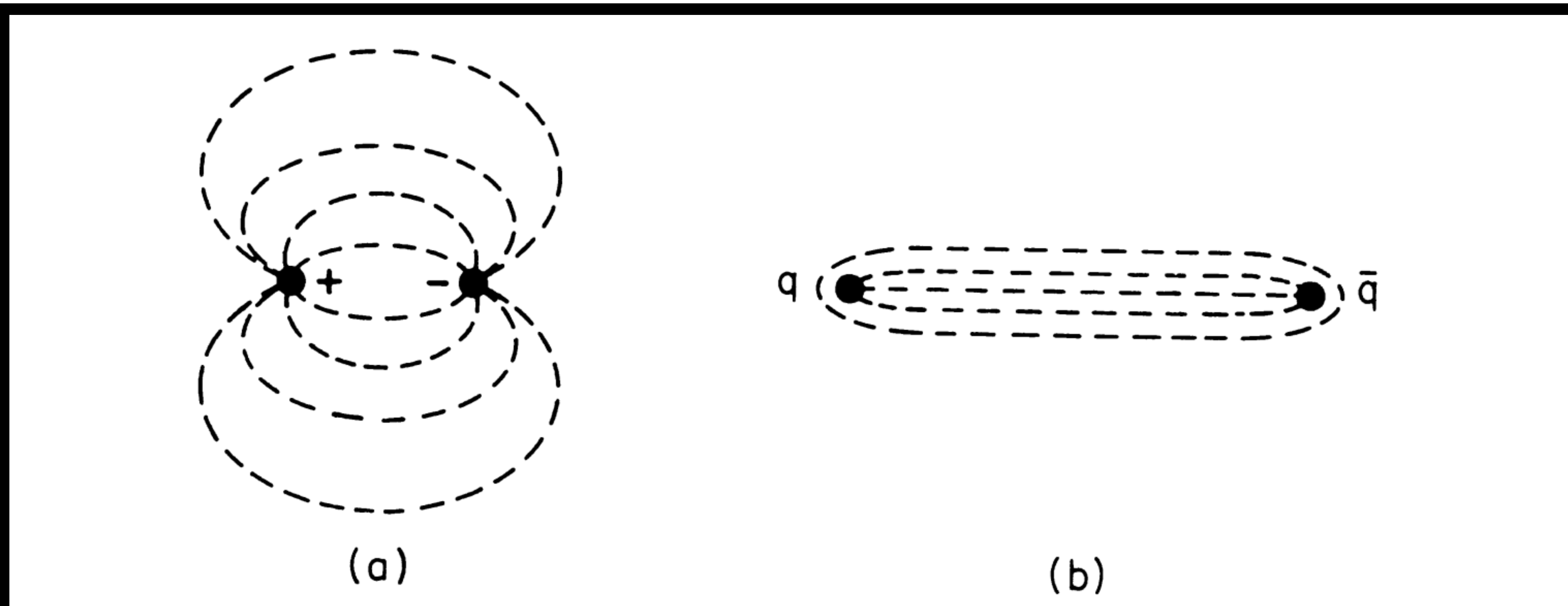
3 colour charges
red, green, blue

Forces compared (2)



gluons carry colour!

gluon self-coupling!



QED
(electromagnetism)

QCD

QCD Confinement

$$V(r) = -\frac{A}{r} + k \cdot r$$

- Additional linear term in potential due to 'flux tube' (or 'string')
- k ~ 1 GeV/fm
- Increasing separation results in a new q-$\bar{q}$ pair

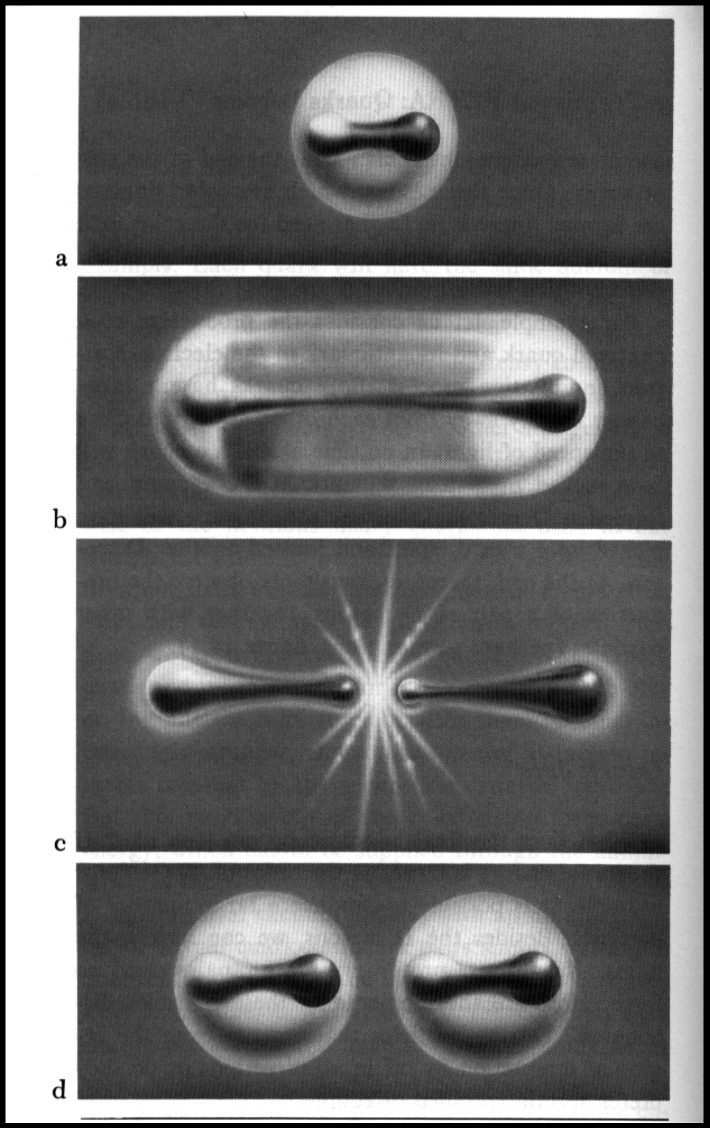
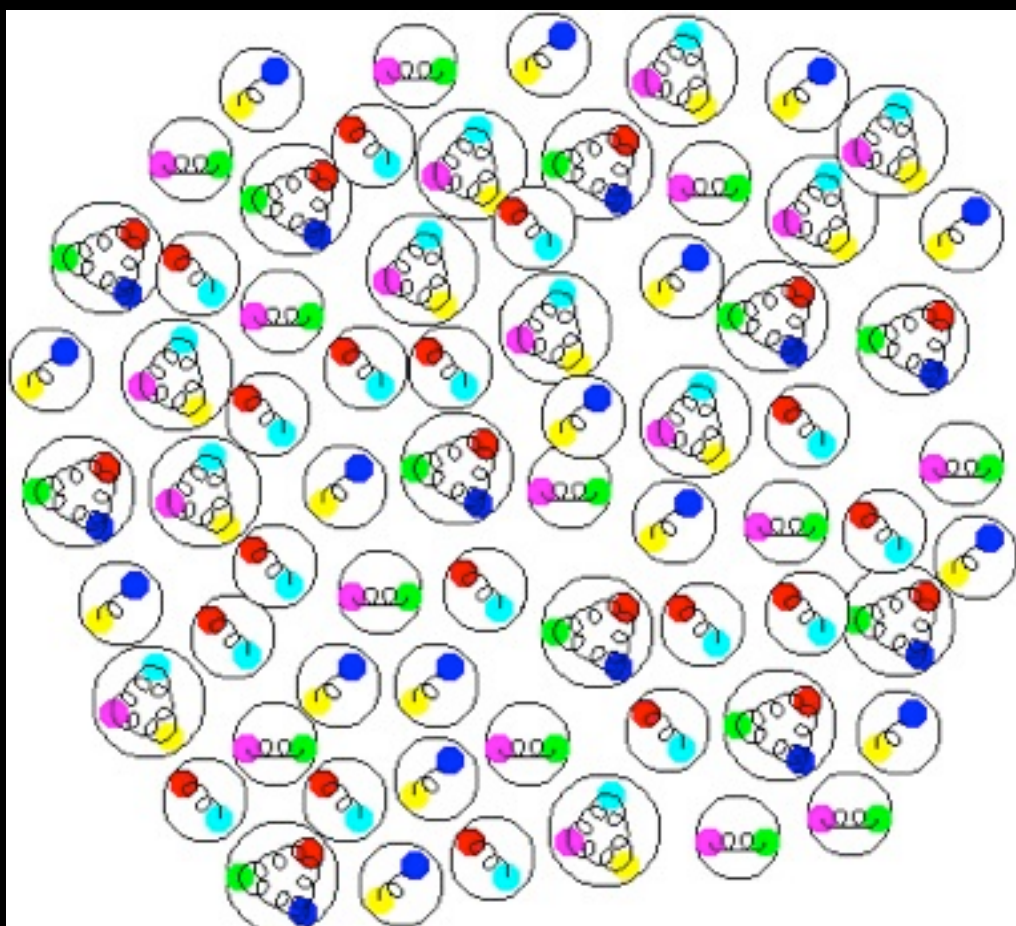
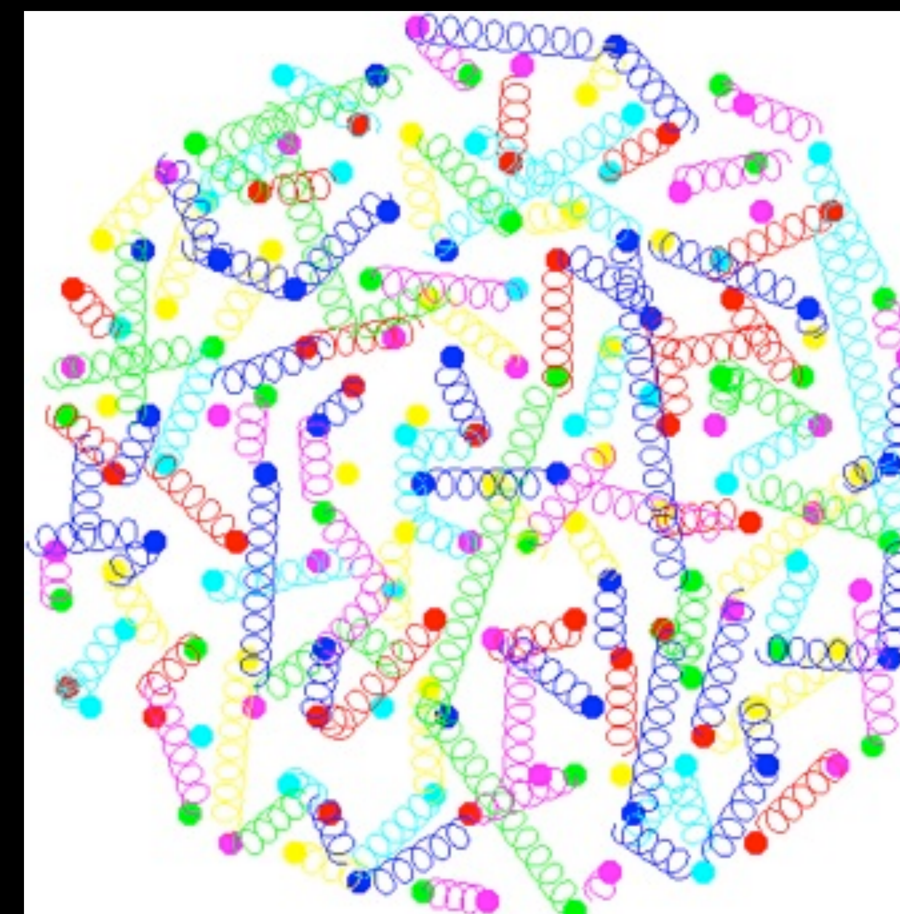


illustration from Fritzsch

Deconfinement



Heating →



Hadrons:
Meson, (anti-)baryons

(anti-)Quarks and gluons

Equation of state

ideal gas Equation of State: $p = \frac{1}{3}\varepsilon = g\frac{\pi^2}{90}T^4$

$$\frac{\varepsilon}{T^4} = g\frac{\pi^2}{30}$$

➡ energy density of g massless degrees of freedom

$$\frac{\varepsilon}{T^4} = 3\frac{\pi^2}{30}$$

➡ hadronic matter dominated by lightest mesons (π^+, π^-, and π^0)

➡ deconfined matter, quarks and gluons

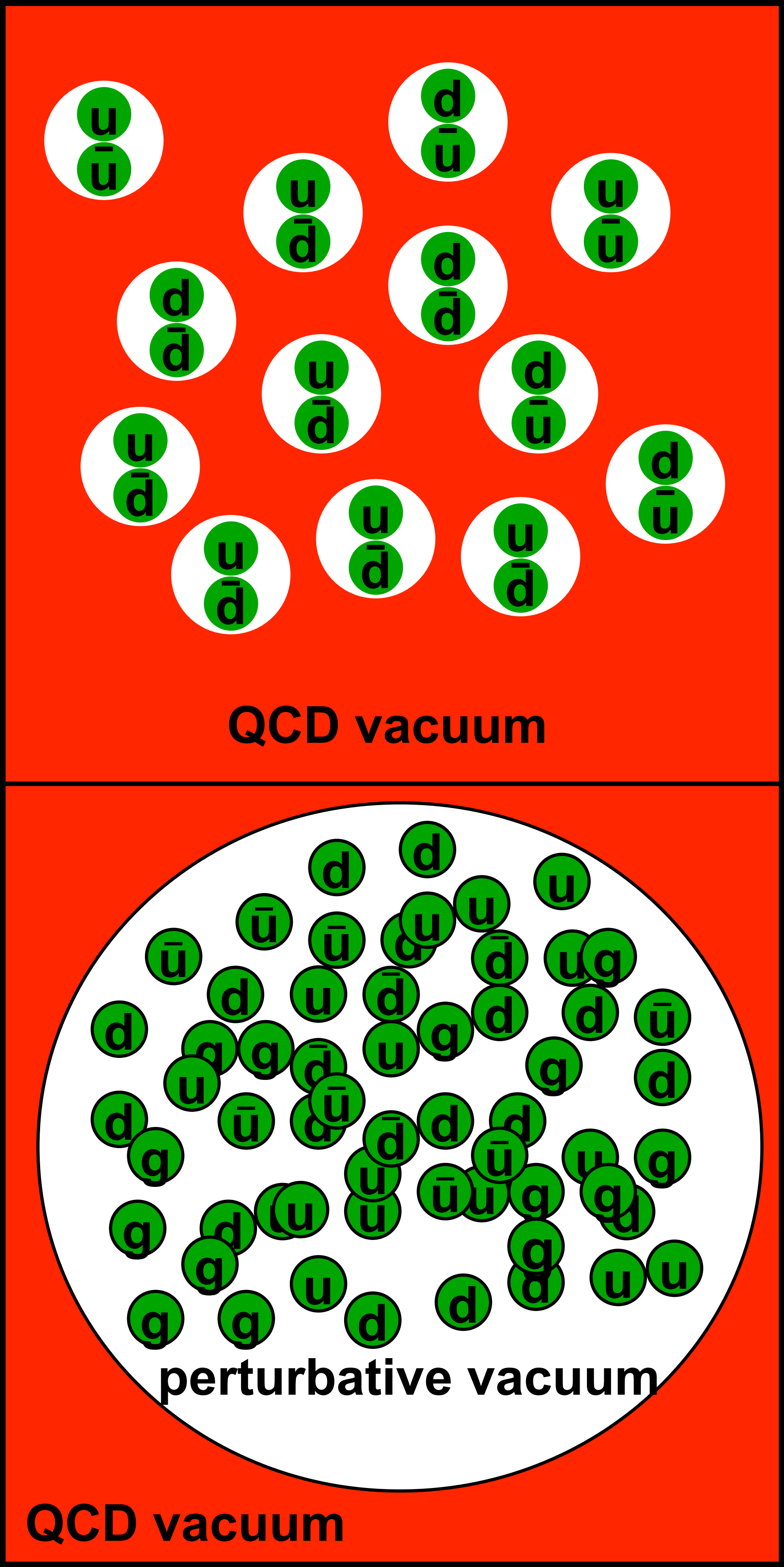
$$g = 2_{\text{spin}} \times 8_{\text{gluons}} + \frac{7}{8} \times 2_{\text{flavors}} \times 2_{\text{quark/anti-quark}} \times 2_{\text{spin}} \times 3_{\text{color}}$$

$$\frac{\varepsilon}{T^4} = 37\frac{\pi^2}{30}$$

➡ during phase transition large increase in degrees of freedom !

Bag pressure

- Gibbs' criterion: the stable phase is the one with the largest pressure
    - i.e larger number d.o.f.
- Vacuum exerts pressure due to virtual particles
    - ΔEΔt ~ h fluctuations



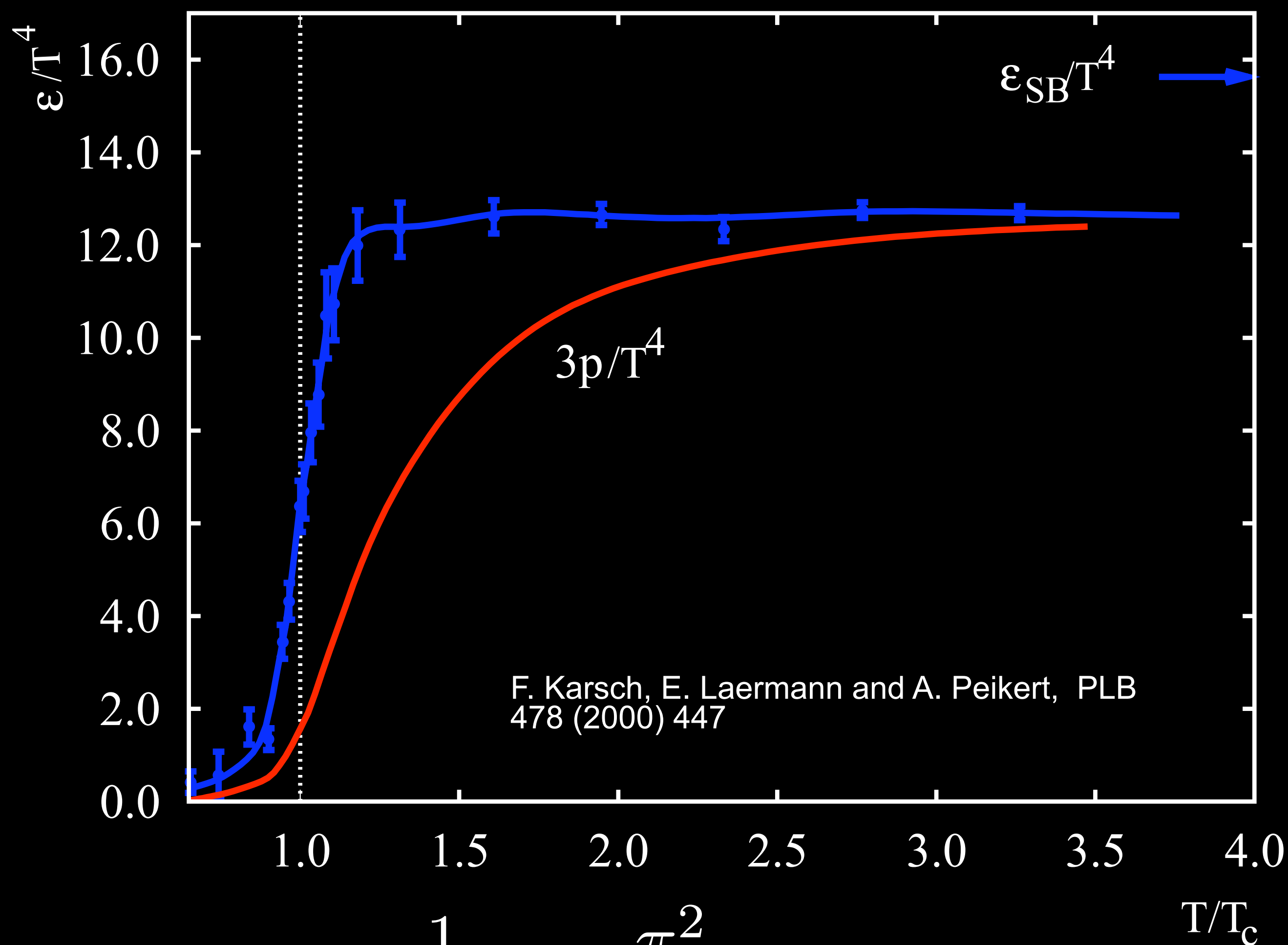
Rough estimate of T_c

- confinement due to bag pressure B (from the QCD vacuum)
    - $B^{1/4} \sim 200$ MeV
- deconfinement when thermal pressure is larger than bag pressure

$$
\begin{aligned}
p &= \frac{1}{3}\epsilon = g\frac{\pi^2}{90}T^4 \\
T_c &= \left(\frac{90B}{34\pi^2}\right)^{1/4} = 150 \text{ MeV}
\end{aligned}
$$

crude estimate!

QCD on the Lattice



$T_C \sim 170$ MeV, $\varepsilon_C \sim 0.6$ GeV/fm^3

at the critical temperature a strong increase in the degrees of freedom

✓ gluons, quarks & color!

not an ideal gas!

✓ residual interactions

at the phase transition dp/dε decreases rapidly

$$p = \frac{1}{3}\epsilon = g\frac{\pi^2}{90}T^4$$

$$g_{\mathrm{H}} \approx 3 \quad g_{\mathrm{QGP}} \approx 37$$

$$g = 2_{\mathrm{spin}} \times 8_{\mathrm{gluons}} + \frac{7}{8} \times 2_{\mathrm{flavors}} \times 2_{q\bar{q}} \times 2_{\mathrm{spin}} \times 3_{\mathrm{color}}$$

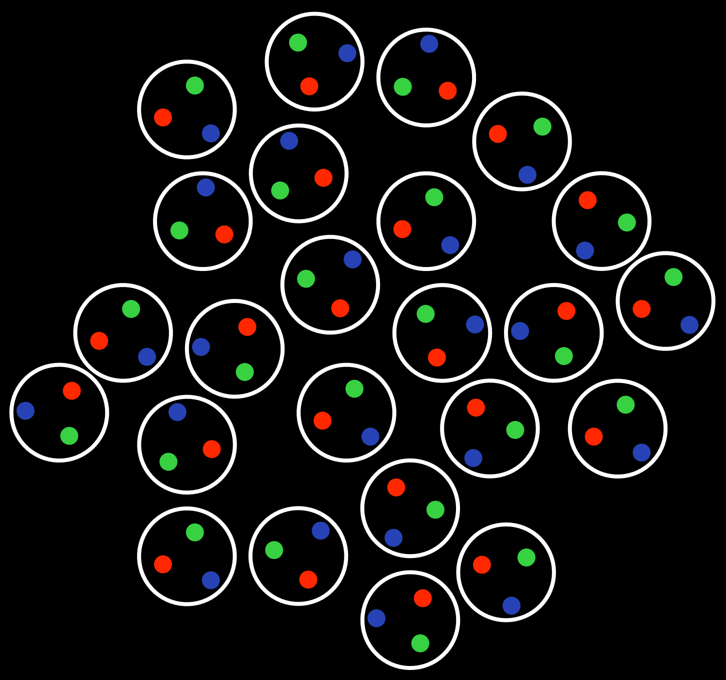
Debye Screening

- Modification of *short range term* in potential due to high colour charge density
  - Debye radius r_D
- Compare to Mott transition to conductor under pressure

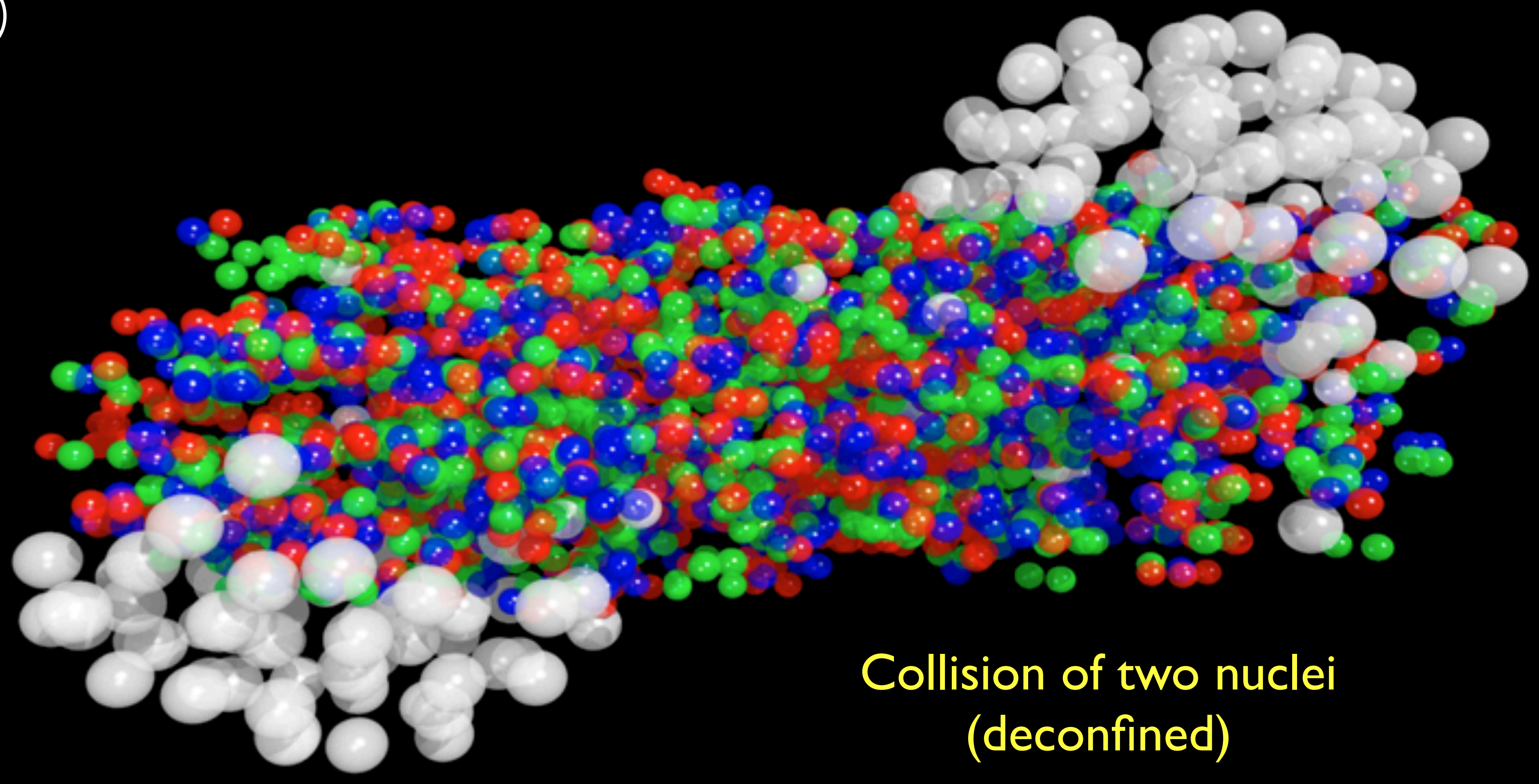
$$V(r) = -\frac{A}{r} \cdot \exp \frac{-r}{r_D}$$

$$r_D = \frac{1}{\sqrt[3]{n}}$$

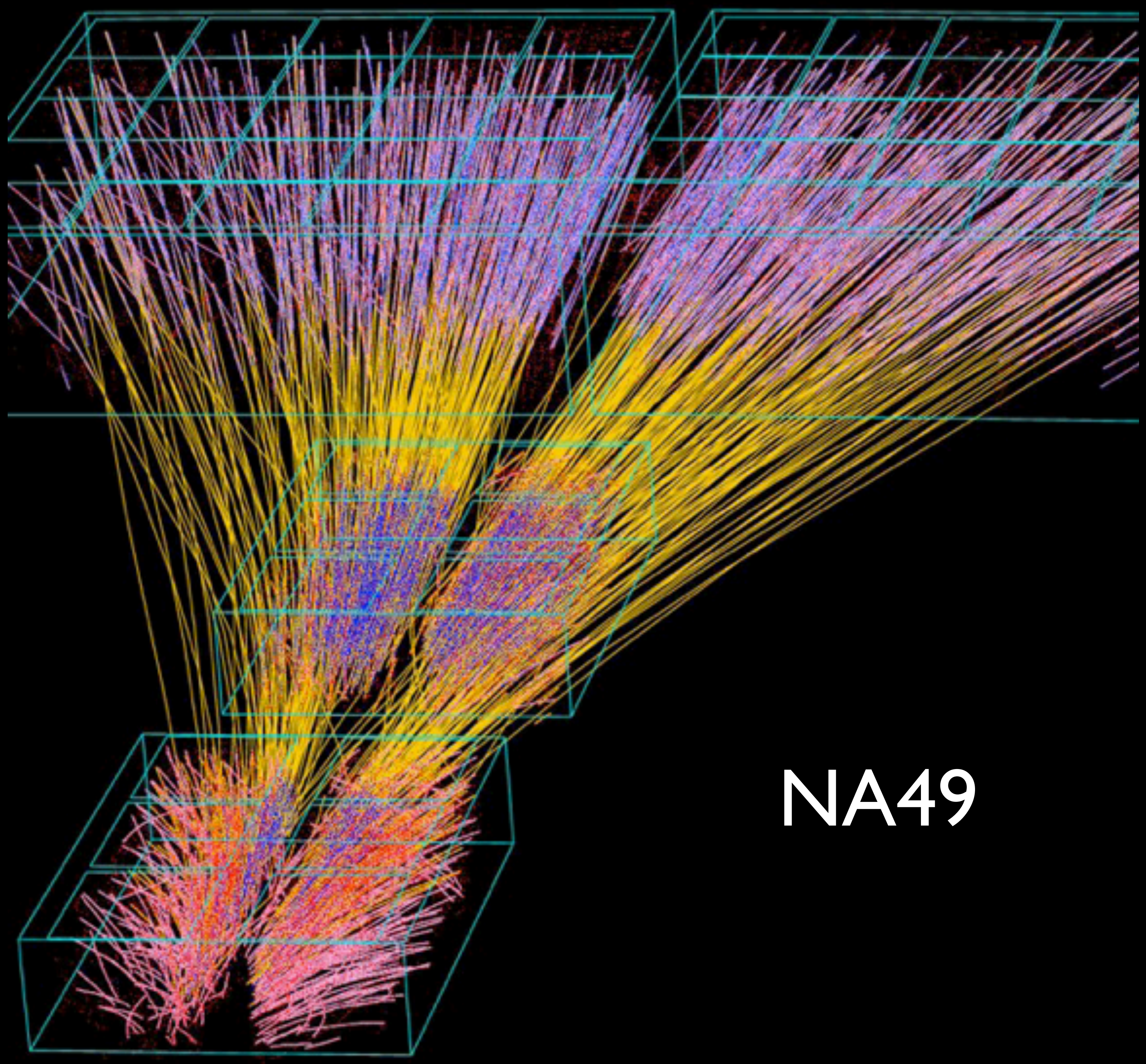
How to do this?



Nuclear Matter
(confined)

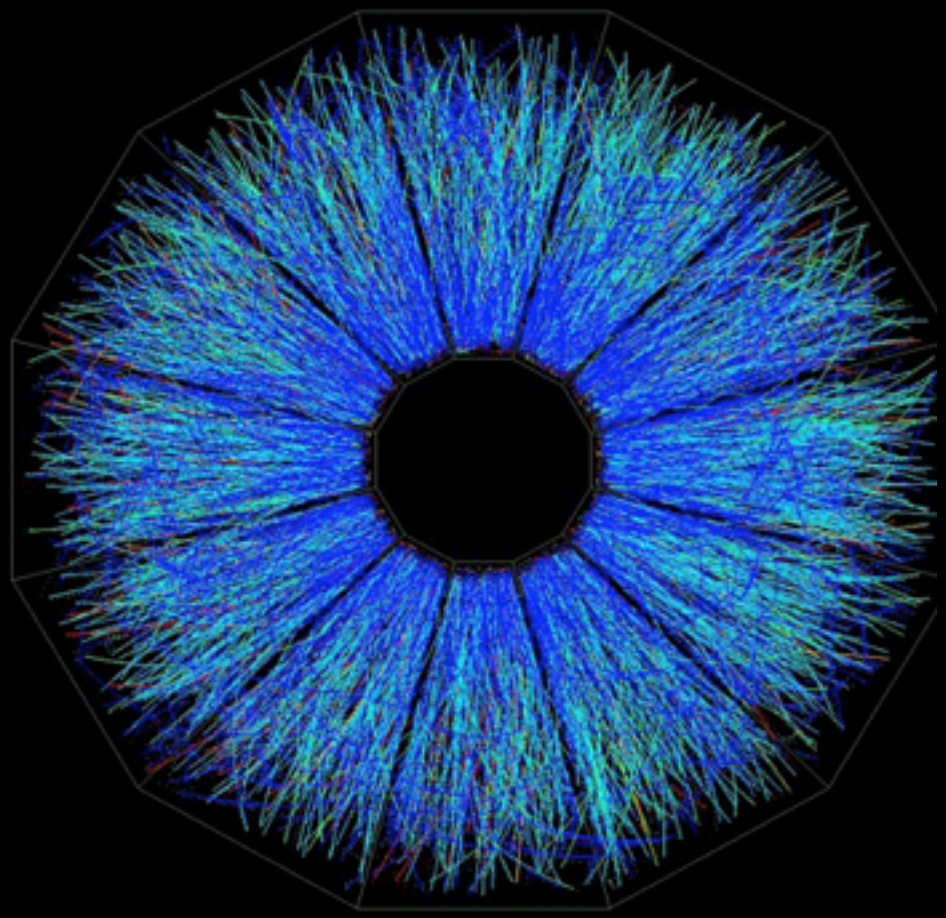


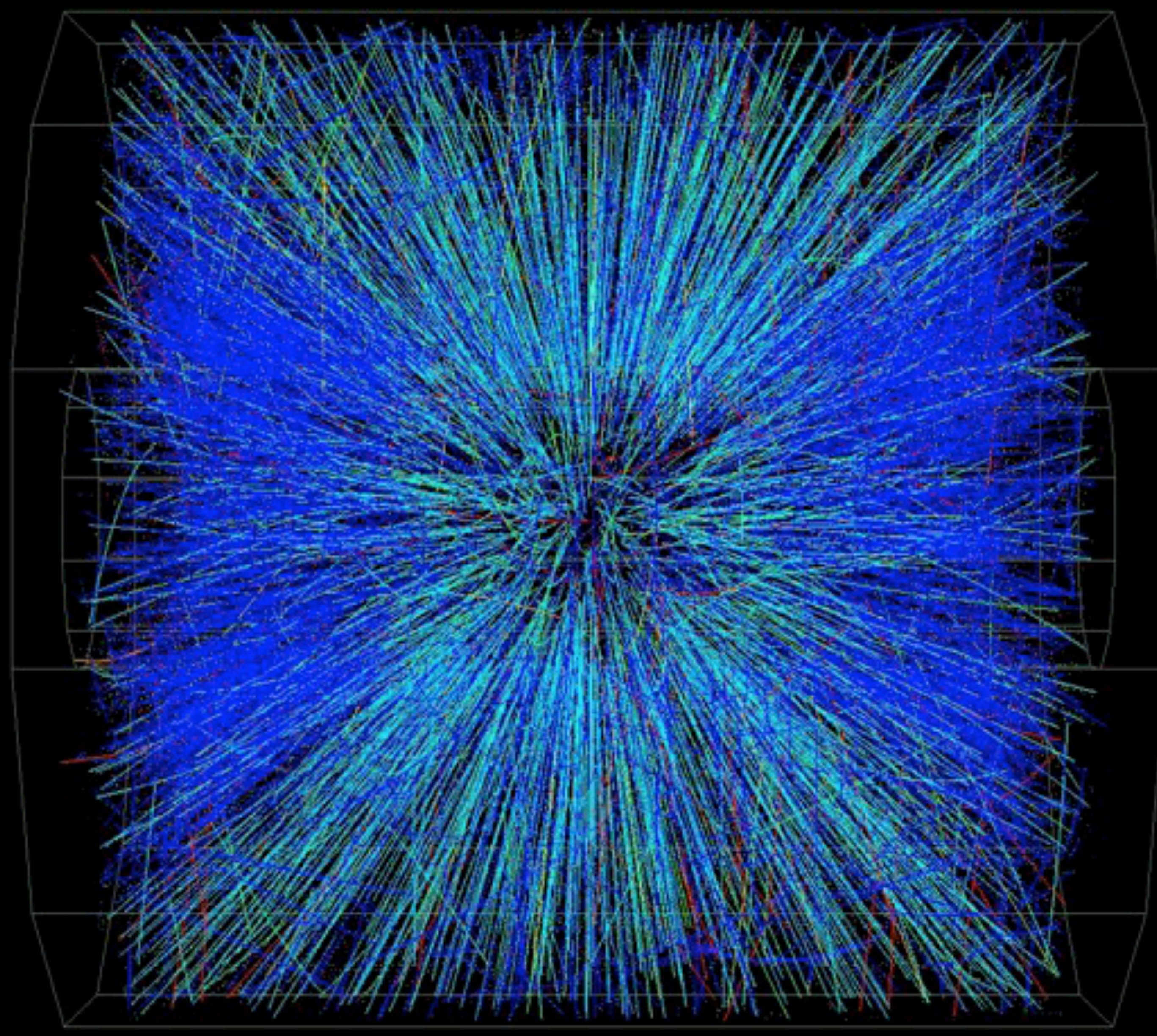
Collision of two nuclei
(deconfined)



Early experiment (SPS 1995)

STAR



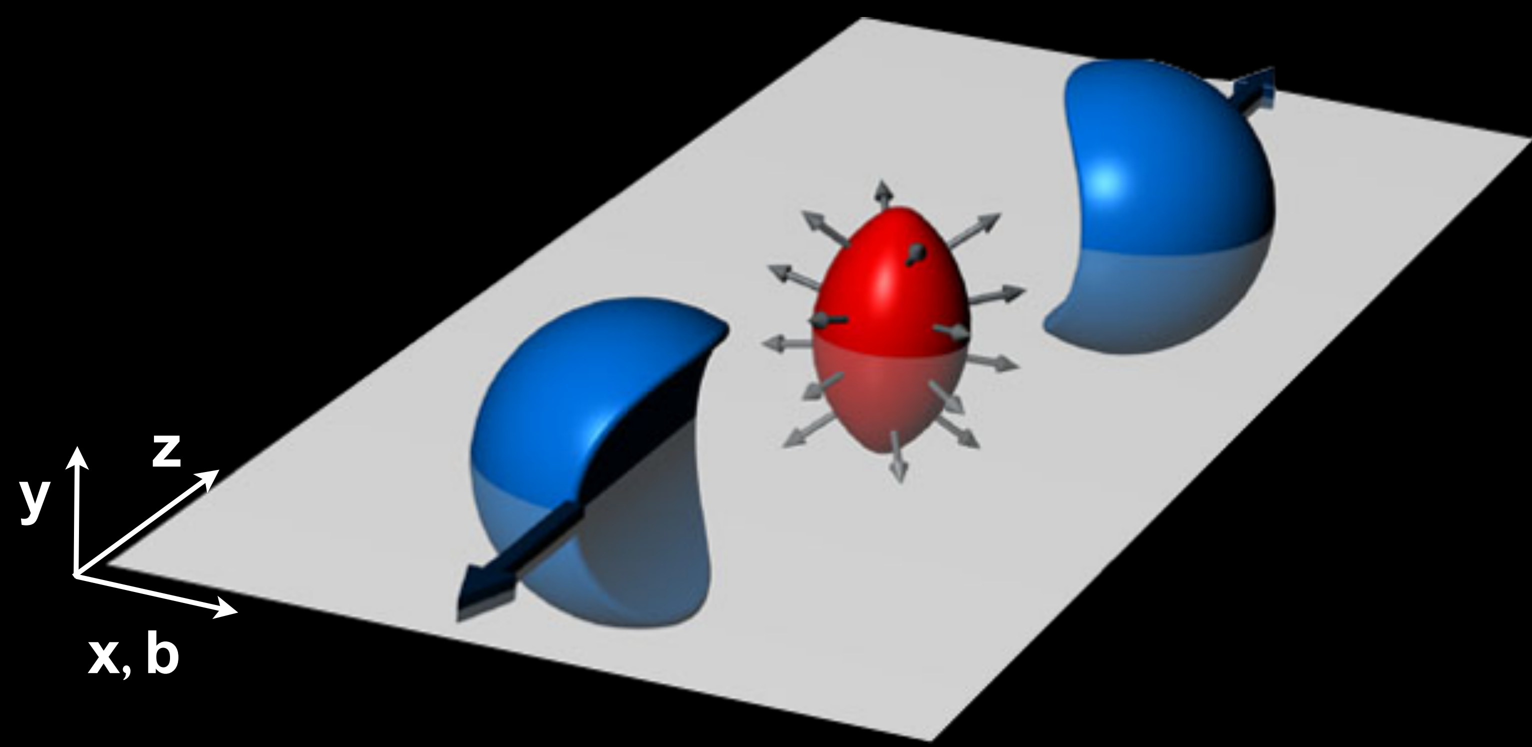


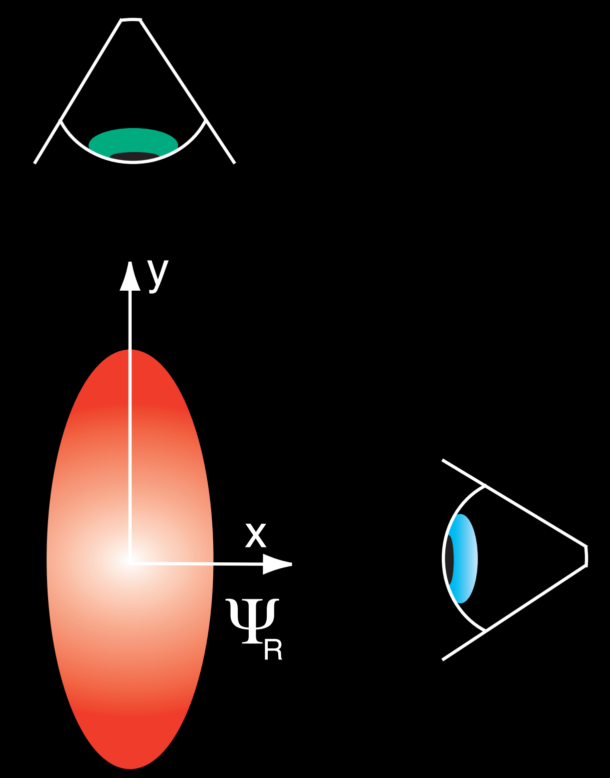
RHIC experiment (2000)

Next lecture

- We will use the concepts covered here to understand what we see in relativistic heavy-ion collisions

The Reaction Plane



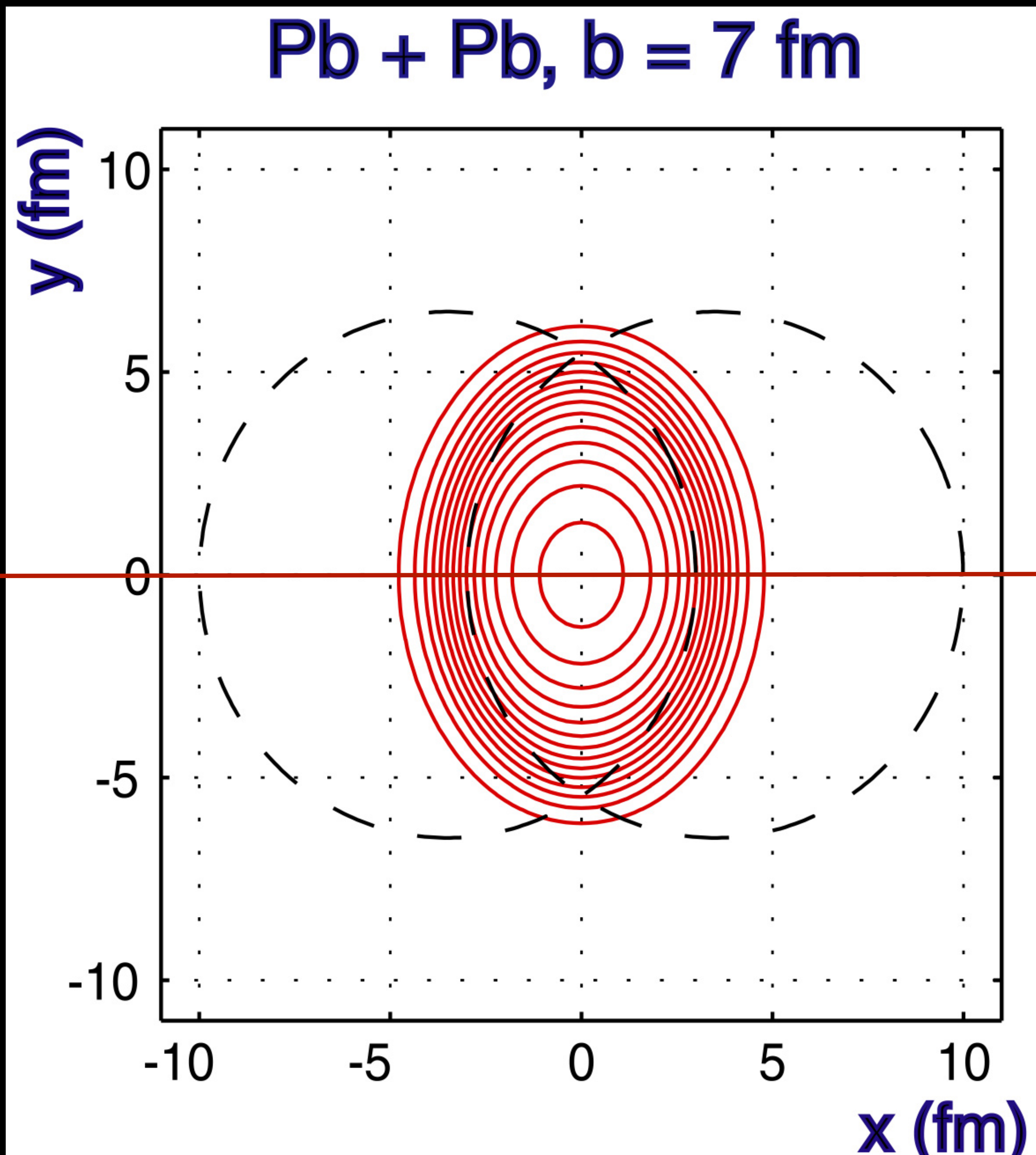


$$E\frac{d^3N}{d^3p} = \frac{d^3N}{p_t dp_t dy d(\phi - \Psi_R)}$$

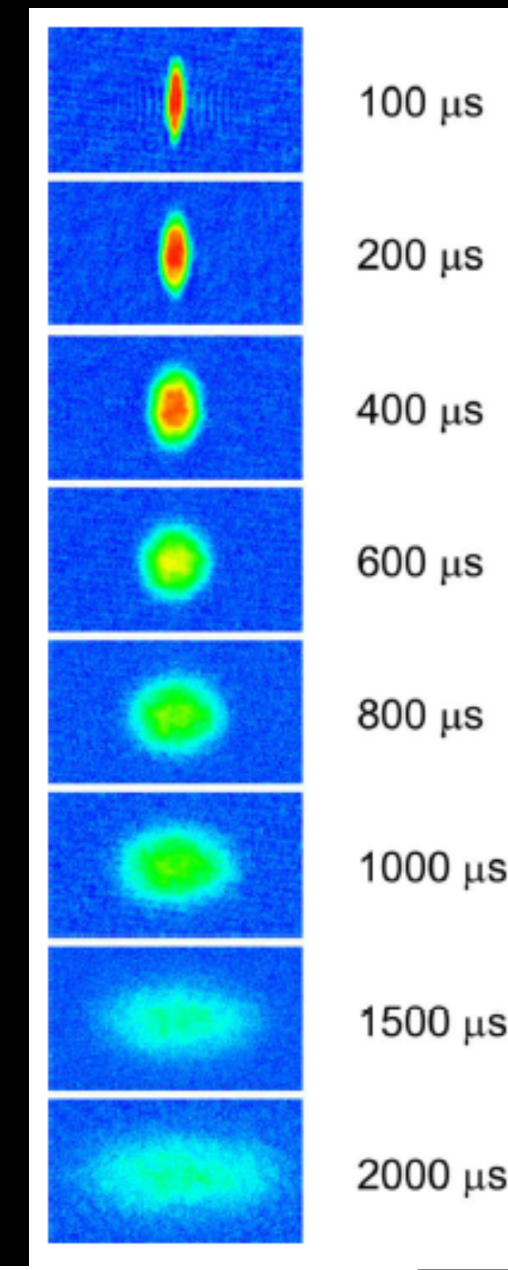
determine the angle of the reaction plane ψ_R

Flow concept

Example from another field: Ultra cold atoms



Reaction plane



$$E\frac{d^3N}{d^3p} = \frac{1}{2\pi}\frac{d^2N}{p_T dp_T dy}\left(1+\sum_{n=1}^{\infty}2v_n\cos\left[n\left(\phi-\Psi_r\right)\right]\right)$$

Acknowledgements

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