Heavy Ion Physics
Lecture 1: Introduction to Heavy Ion Physics

HUGS 2015

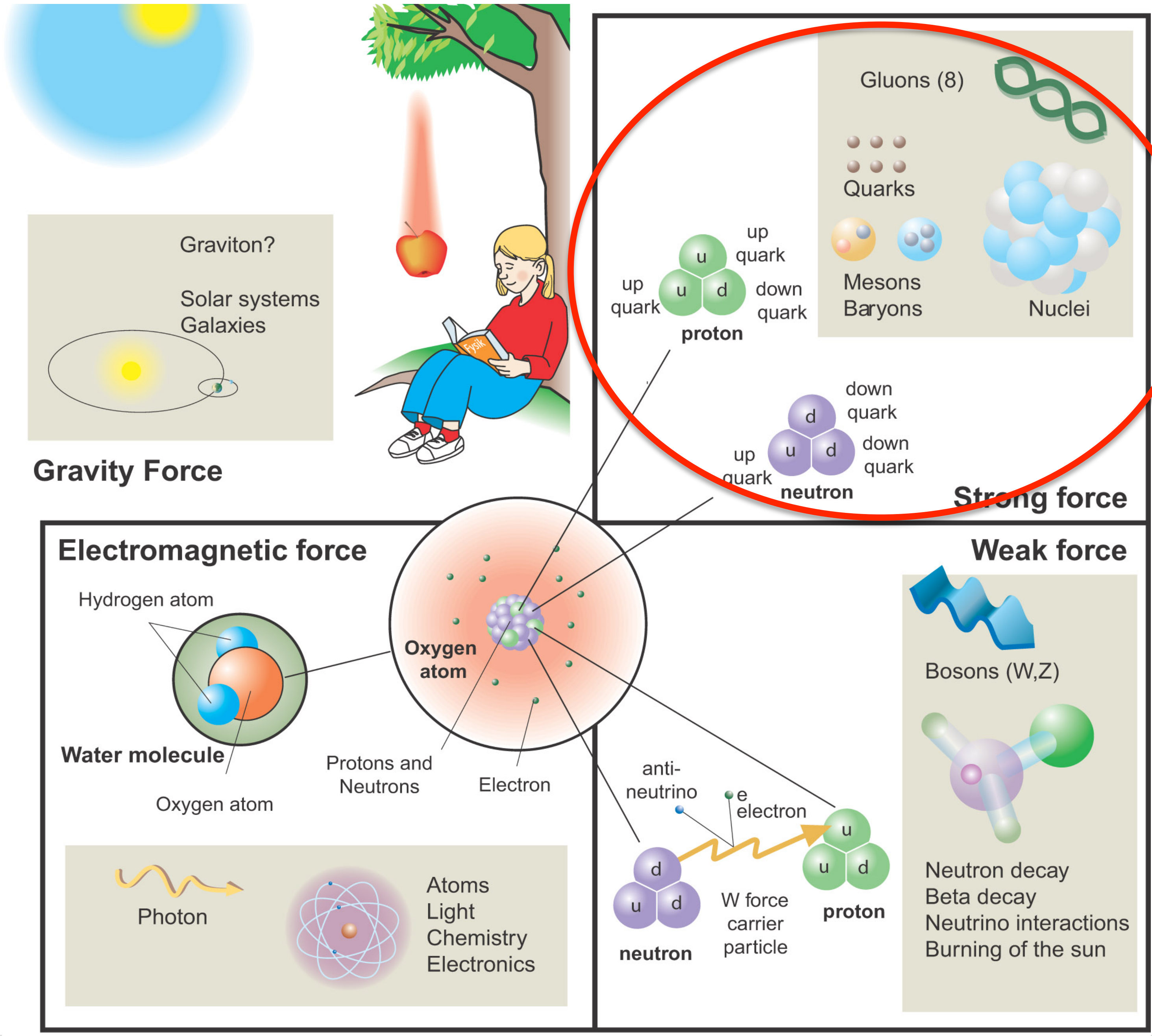
Bolek Wyslouch

Borrowing heavily from Yen-Jie Lee(MIT), Gunther Roland(MIT) and Tom Hemmick (StonyBrook)

Plan of lectures

- Lecture 1: Introduction to heavy ion physics
- Lecture 2: Accelerators and experiments
- Lecture 3: Particle production
- Lecture 4: Elliptic flow and correlations
- Lecture 5: Parton energy loss: jets
- Lecture 6: Quarkonia and heavy quarks

Fundamental Interactions



Constituents of matter

FERMIONS
matter constituents
spin = 1/2, 3/2, 5/2, ...

Leptons spin = 1/2

Flavor	Mass GeV/c^2	Electric charge
ν_e electron neutrino	$<1\times10^{-8}$	0
e electron	0.000511	−1
ν_μ muon neutrino	<0.0002	0
μ muon	0.106	−1
ν_τ tau neutrino	<0.02	0
τ tau	1.7771	−1

Quarks spin = 1/2

Flavor	Approx. Mass GeV/c^2	Electric charge
u up	0.003	2/3
d down	0.006	−1/3
c charm	1.3	2/3
s strange	0.1	−1/3
t top	175	2/3
b bottom	4.3	−1/3

Basic ingredients of nuclear matter

Heavy quarks appear in hot nuclear matter

BOSONS
force carriers
spin = 0, 1, 2, ...

Unified Electroweak spin = 1

Name	Mass GeV/c^2	Electric charge
γ photon	0	0
W^-	80.4	−1
W^+	80.4	+1
Z^0	91.187	0

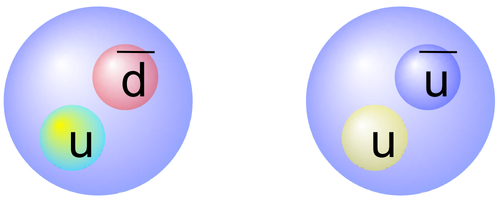
Strong (color) spin = 1

Name	Mass GeV/c^2	Electric charge
g gluon	0	0

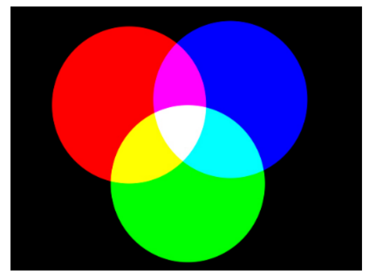
Color confinement in Strong interactions

- Different from EM or Weak Interaction
- Typical hadrons:
  - Mesons: contain a quark and an anti-quark

π^+

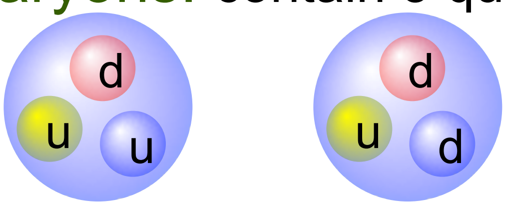


π^0

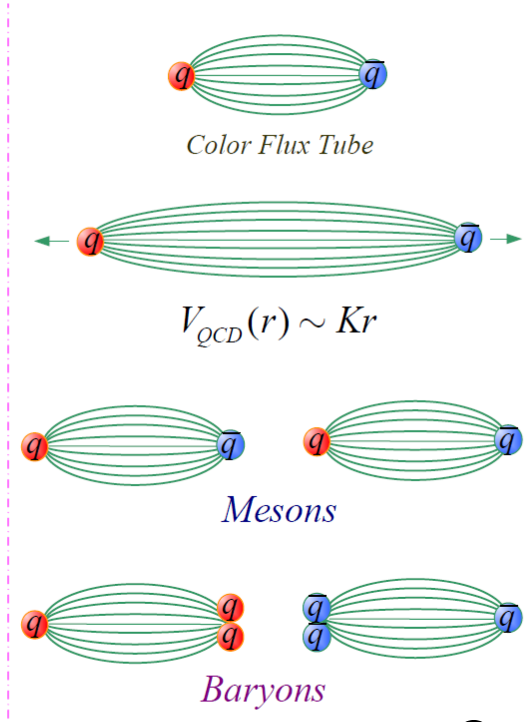


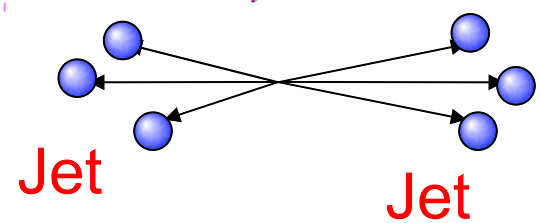
  - Baryons: contain 3 quarks

p



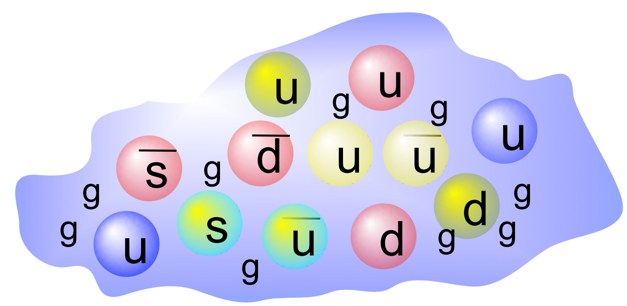
n





- What will happen if we increase the temperature and density? Can we "melt" hadrons?

Quark-Gluon Plasma (QGP)

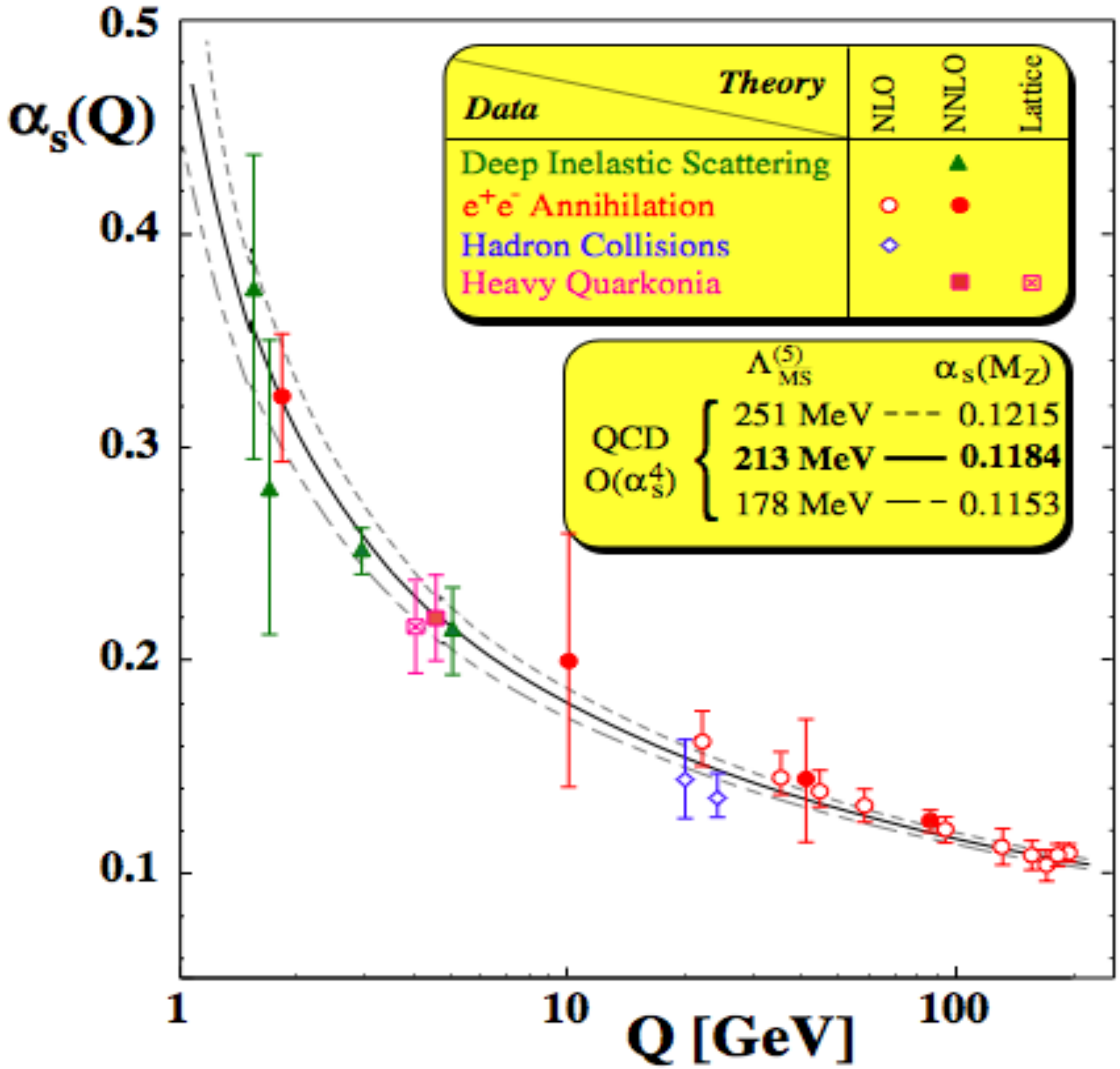


Asymptotic Freedom

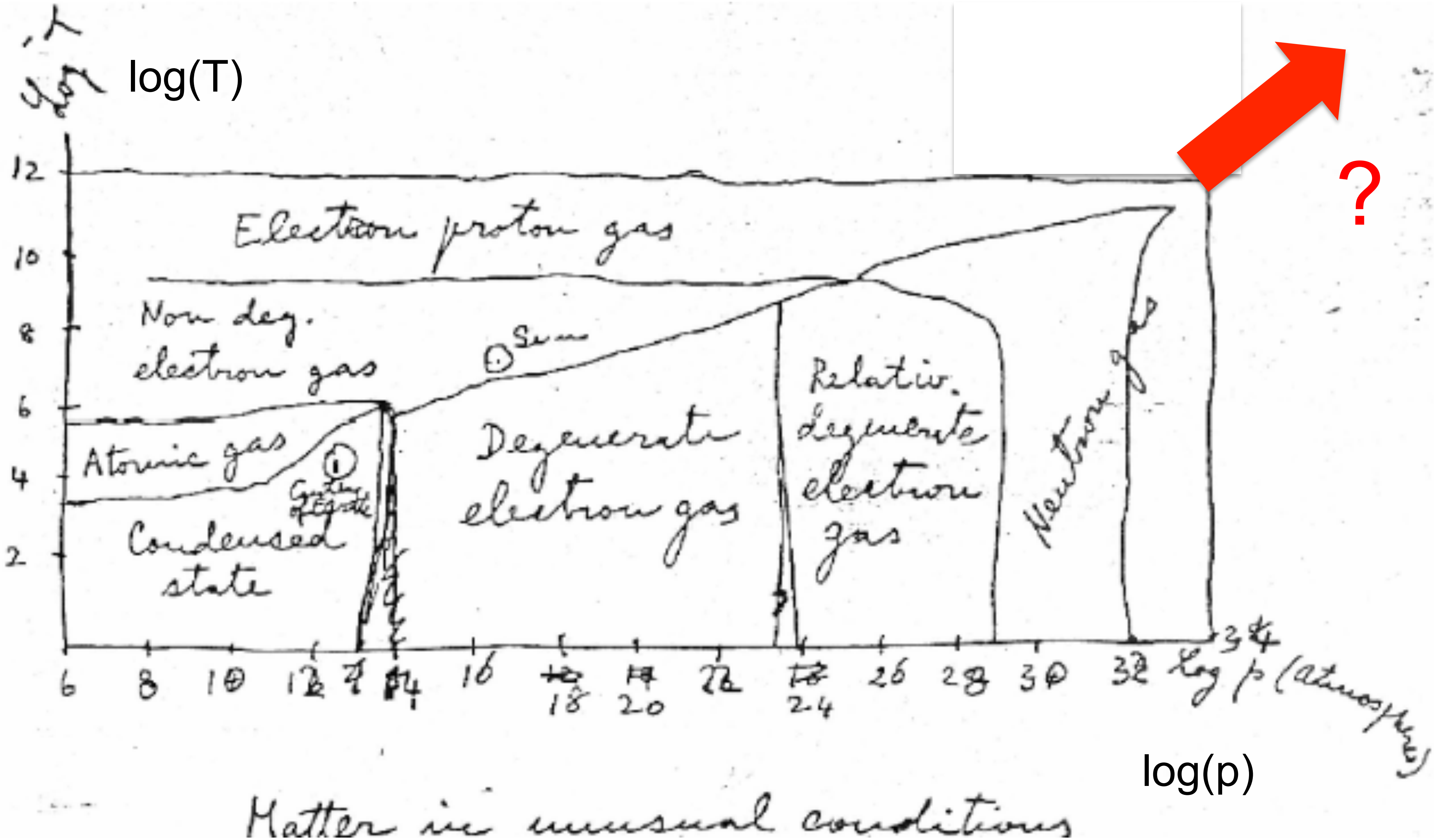
Gross, Politzer, Wilczek 1973: Strong interactions are weak at short distances (high momentum transfers)

Strong Coupling Constant

α_s



Enrico Fermi’s lectures on statistical physics ~1953



Matter in unusual conditions!

Origins of the relativistic heavy ion field

Superdense Matter: Neutrons or Asymptotically Free Quarks?

J. C. Collins and M. J. Perry
Department of Applied Mathematics and Theoretical Physics, University of Cambridge, Cambridge CB3 9EW, England
(Received 6 January 1975)

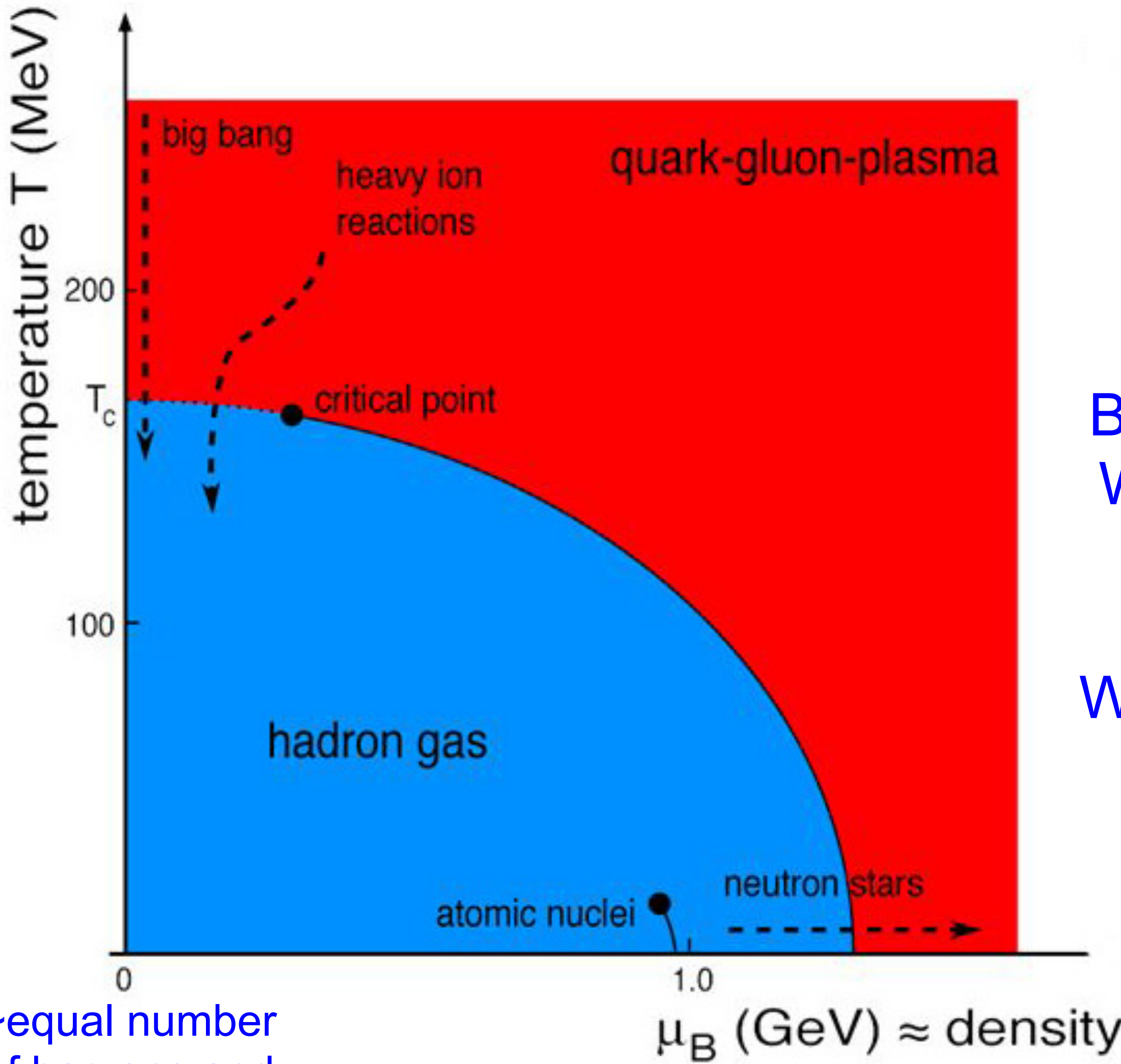
We note the following: The quark model implies that superdense matter (found in neutron-star cores, exploding black holes, and the early big-bang universe) consists of quarks rather than of hadrons. Bjorken scaling implies that the quarks interact weakly. An asymptotically free gauge theory allows realistic calculations taking full account of strong interactions.

PRL 1975

This was one of the original motivations for the field of Relativistic Heavy Ion Collisions

Interestingly, the Nature decided that it wants to do something else with quarks and gluons…

Phase diagram of quark and gluon matter



~equal number of baryons and anti-baryons

dominated by baryons

1 eV ~ 12000 K

100 MeV ~ 1.2 10^{12} K

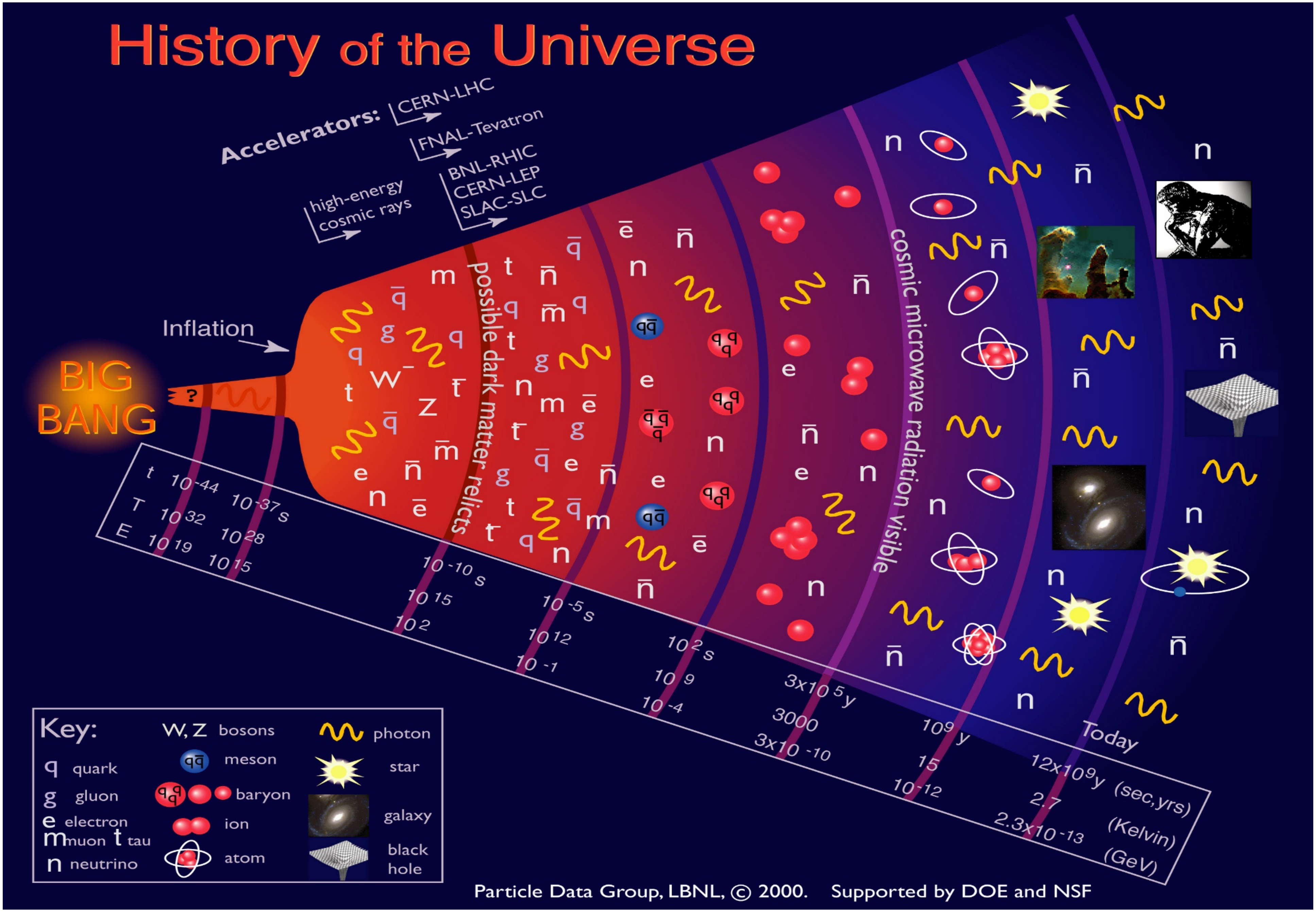
Big questions of our field: What is the nature of the phase transition?

What are the properties of the melted phase?

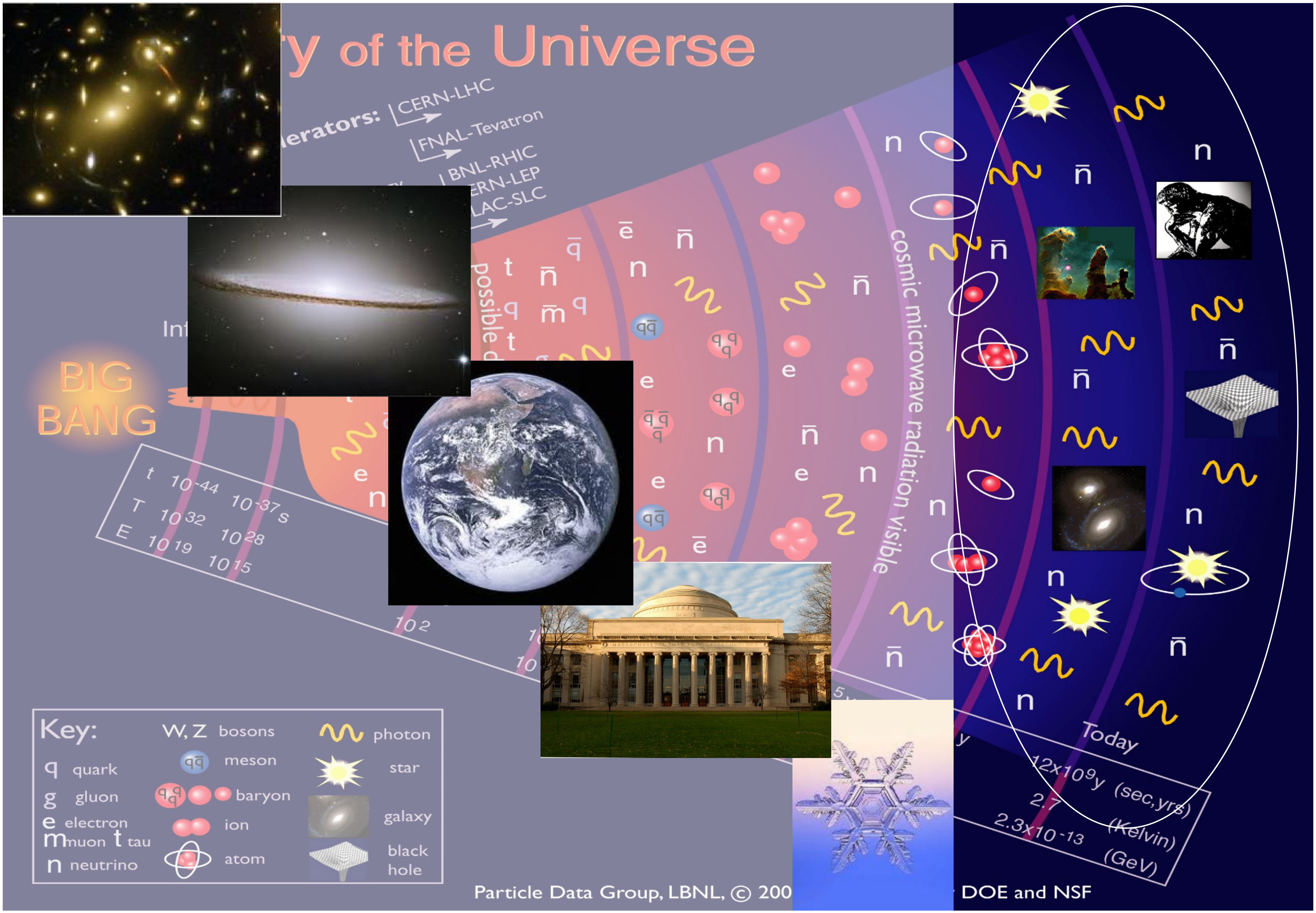
Where could such matter be produced?

- Present understanding holds that all matter and energy of the universe sprang from a single point:
  - Extremely Dense; Extremely Hot
- Since that epoch, the history of the universe is dominated by cooling:
  - Today the universe is mostly ~2.7 K.
  - Exceptions exist in hot spots (like our solar system)
- As the universe cooled, different phases of matter and different forces of nature played the dominant role.

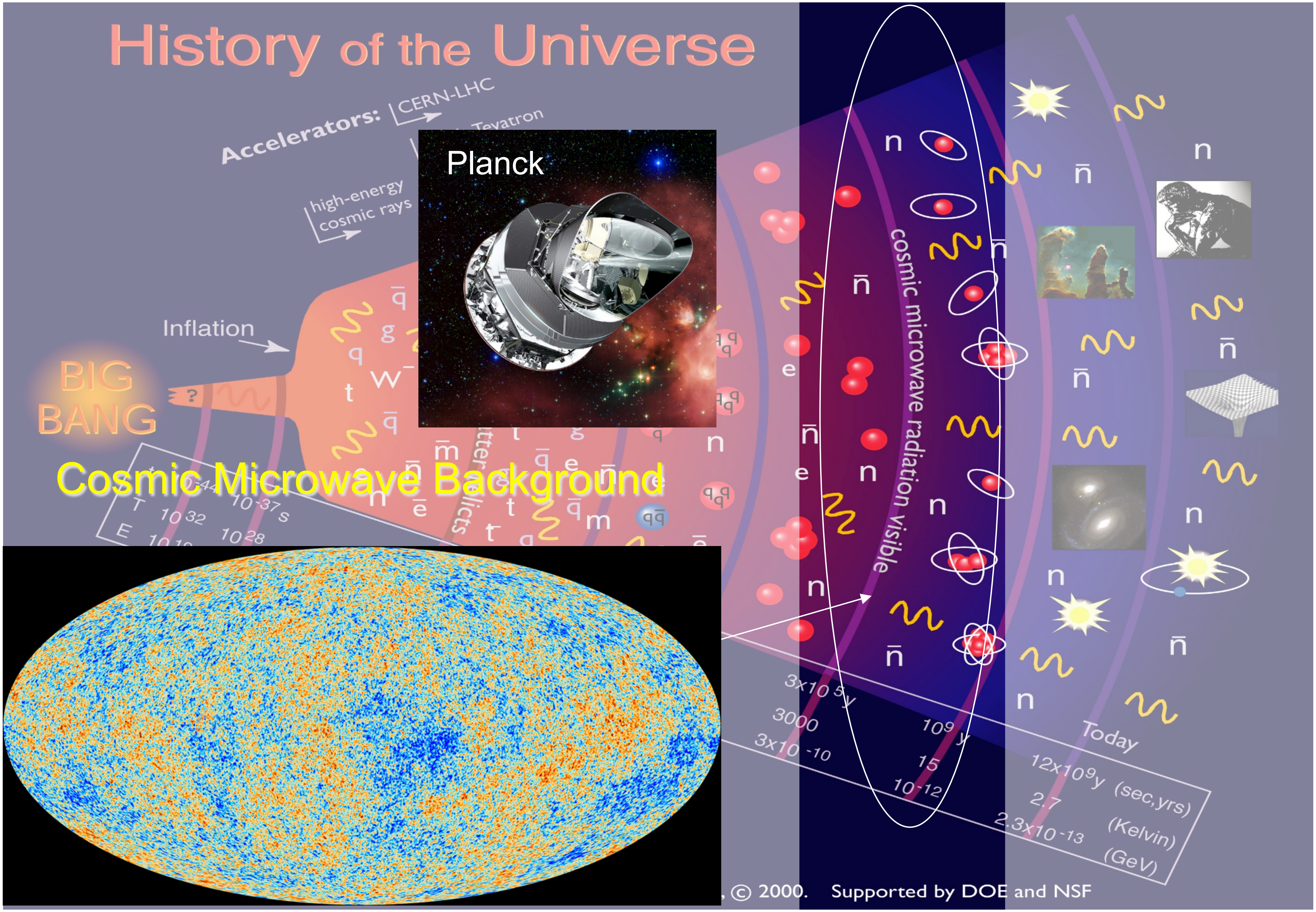
Quarks and Gluons in the Universe



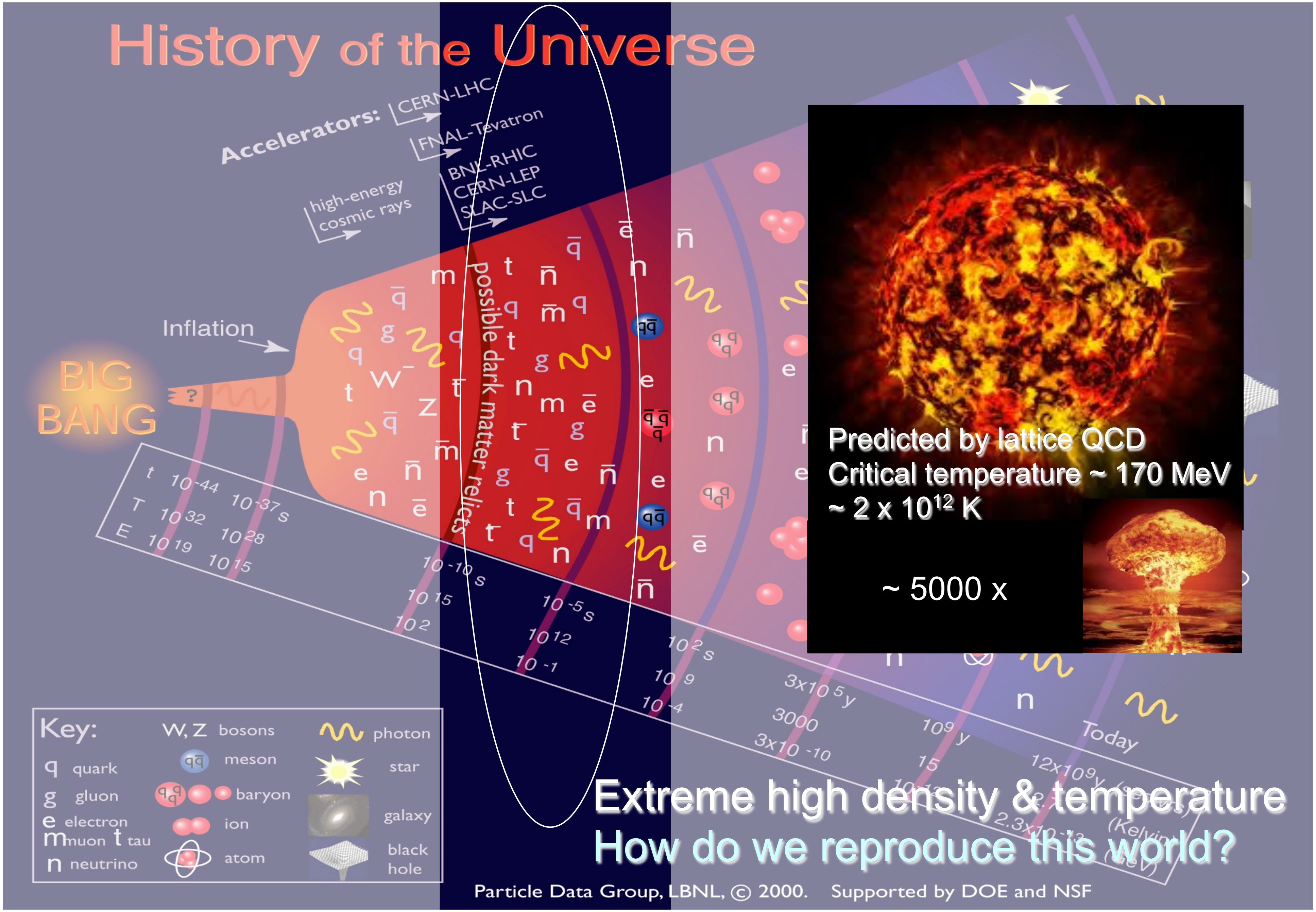
Quarks and Gluons in the Universe



Quarks and Gluons in the Universe



Quarks and Gluons in the Universe



Predicted by lattice QCD
Critical temperature ~ 170 MeV
~ 2 x 10^{12} K

~ 5000 x

Extreme high density & temperature
How do we reproduce this world?

Making Plasma in the Laboratory

- Extremes of temperature and density are necessary to recreate the Quark-Gluon Plasma, the state of our universe for the first few microseconds.
  - Density threshold is when protons/neutrons overlap
    - 4X nuclear matter density = touching.
    - 8X nuclear matter density should be plasma.
  - Temperature/Energy Density threshold:
    - When the temperature exceeds the mc^2 of the lightest meson (pion $m=140$ MeV/c^2)
    - Several light hadrons per volume of light hadron $\varepsilon_c \sim 1$ GeV/fm^3
    - The necessary temperature is $\sim 10^{12}$ Kelvin.

Phase transition

- Count the degrees of freedom of a gas of fermions and bosons.
- Each bosonic degree of freedom contributes $\frac{\pi^2}{30}T^4$ to the energy density and each fermionic DOF contributes 7/8 of this:

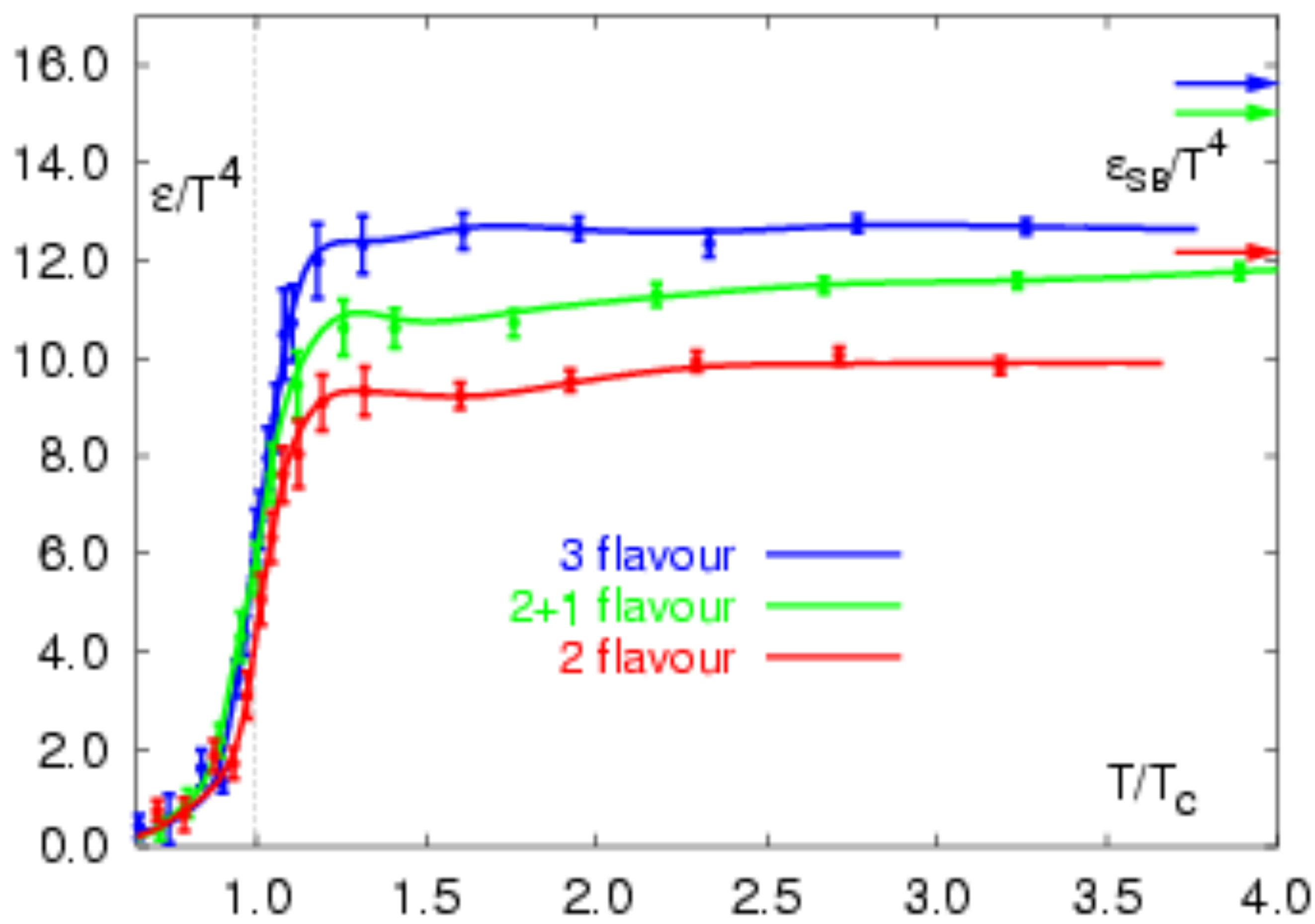
$$\varepsilon_{2-flavor} = \left(2_f \cdot 2_s \cdot 2_q \cdot 3_c \frac{7}{8} + 2_s \cdot 8_c\right)\frac{\pi^2}{30}T^4 = 37\frac{\pi^2}{30}T^4$$

$$\varepsilon_{3-flavor} = \left(3_f \cdot 2_s \cdot 2_q \cdot 3_c \frac{7}{8} + 2_s \cdot 8_c\right)\frac{\pi^2}{30}T^4 = 47.5\frac{\pi^2}{30}T^4$$

- A pure pion gas would have only 3 DOF (π^+,π^-,π^0)
- Pressure = $\varepsilon/3$.

Lattice Calculations

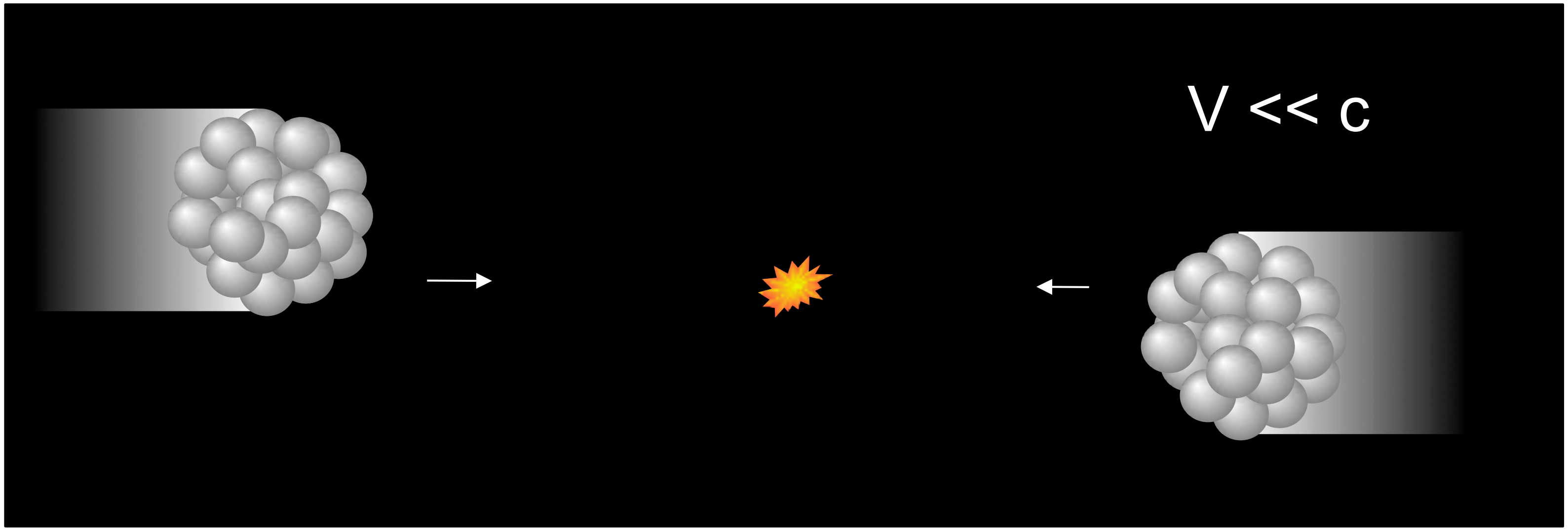
- The onset of QGP is far from the perturbative regime (α_s~1)
- Lattice QCD is the only 1st principles calculation of phase transition and QGP.



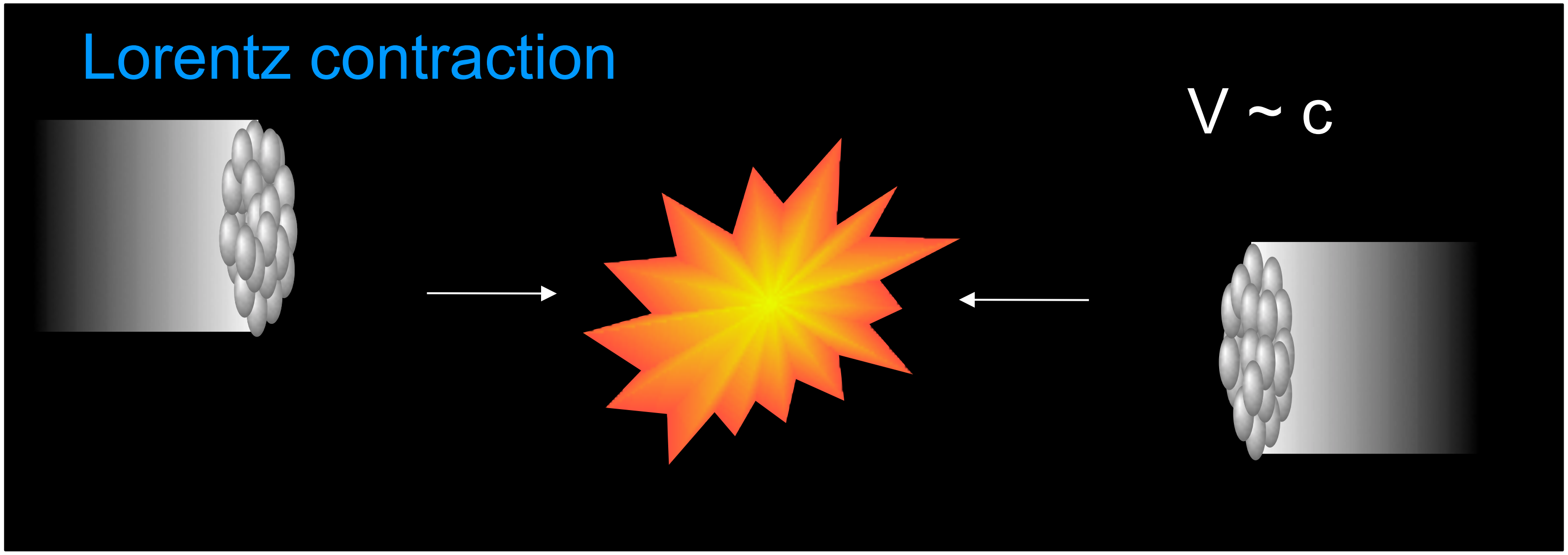
- **Lattice Calculations indicate:**
  - **T_C~170 MeV**
  - **ε_C~1 GeV/fm^4**

How can we “melt” nuclear matter in the laboratory?

Collisions of energetic, large nuclei



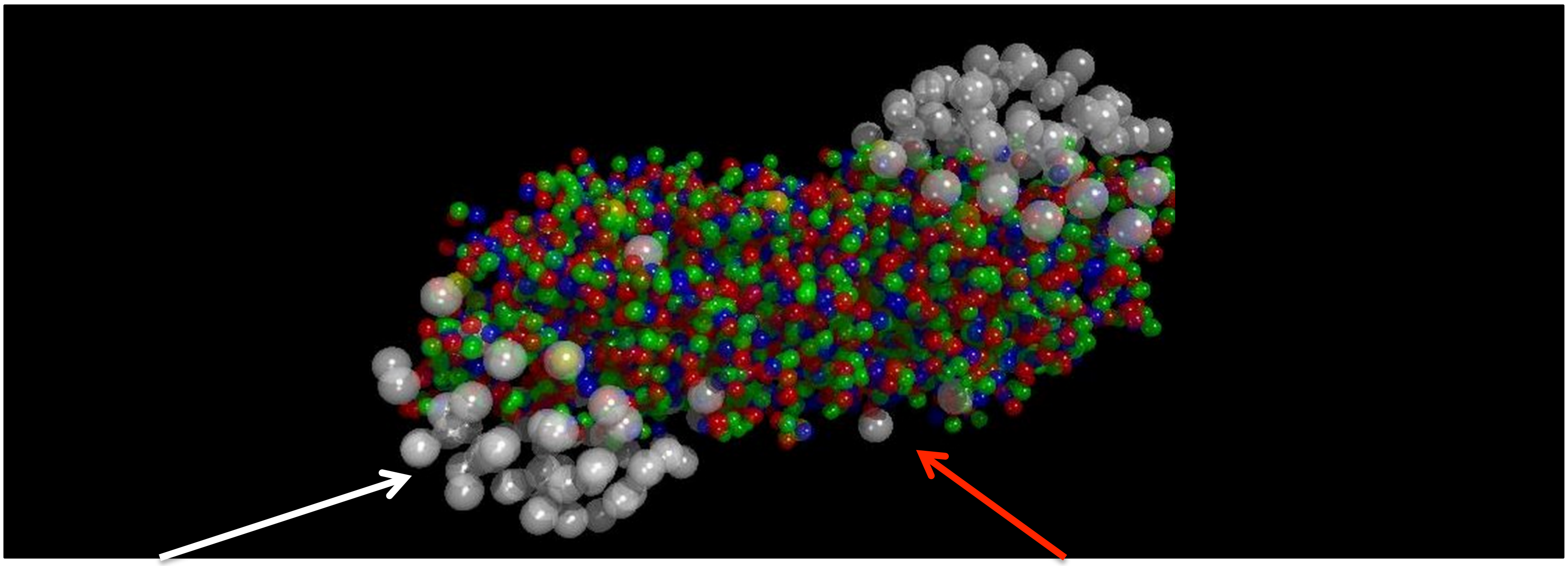
Collisions of relativistic, large nuclei



Energy is usually released in collisions..

Production of particles

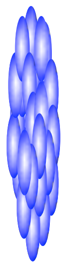
- Energy deposited in the collision region results in large multiplicity of produced particles

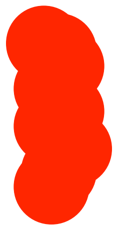


Spectator particles, protons and neutrons from the original nuclei

New particles, created out of the vacuum

Visualization of the collision

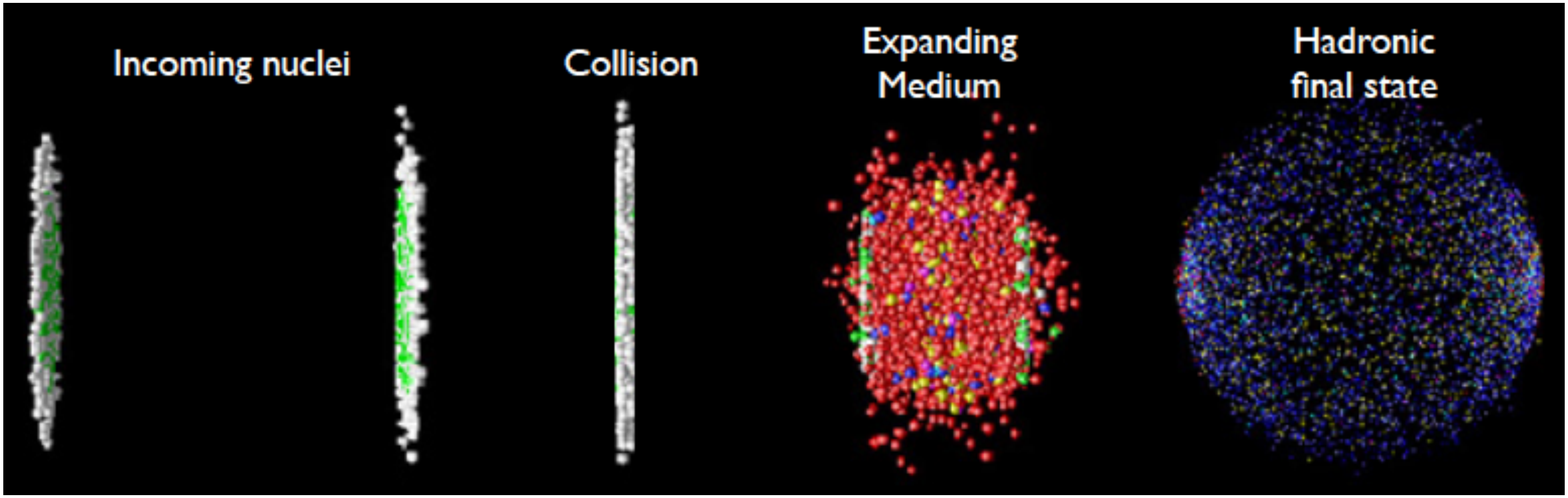

Heavy Ion


Particles before hadronization
(Quark gluon plasma)


Meson


Baryon

Stages of the heavy ion collision



- Initial state: parton distributions inside nuclei
- Hot and dense, expanding medium: energy density
- Final state: fragmentation of partons into hadrons, experimental detection

More detailed sequence of events

- At first an out-of-equilibrium, high density state is created, expands longitudinally
- The system undergoes rescattering, achieves local thermodynamic equilibrium, cools and expands like a fluid (hydrodynamically)
- When the temperature drops to below T_c~170 MeV system is in hadron gas phase
- Hadron gas undergoes freeze-out and particles stream towards the detector

Kinematic Variables

Rapidity:

$$y = \frac{1}{2}\ln(\frac{E + P_Z}{E - P_Z})$$

Pseudo-rapidity:

$$\eta = \frac{1}{2}\ln(\frac{P + P_Z}{P - P_Z}) = -\ln(\tan\frac{\theta}{2})$$

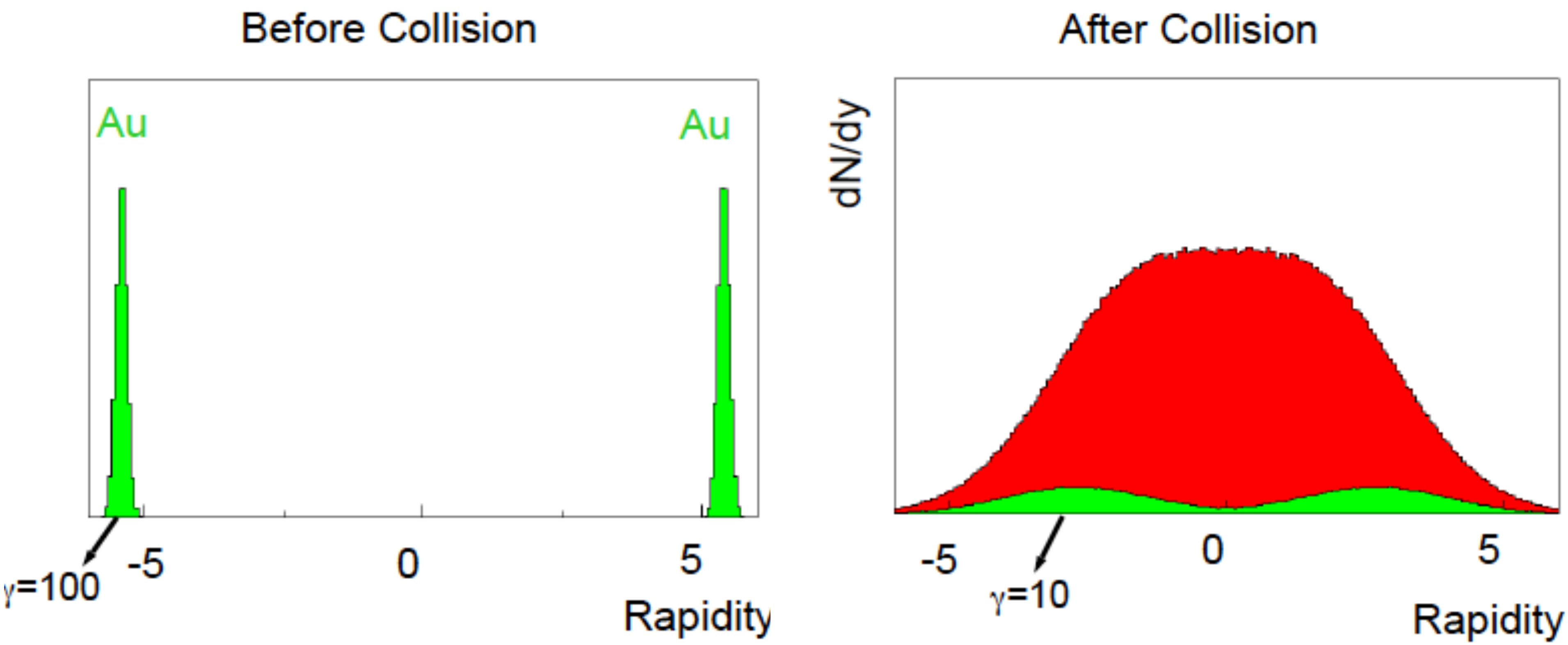
Transverse Momentum:

$$p_T = \sqrt{p_X^2 + p_Y^2}$$

Transverse Mass:

$$m_T = \sqrt{p_T^2 + m_0^2}$$

Kinematics of Au-Au collision at 200 GeV/A

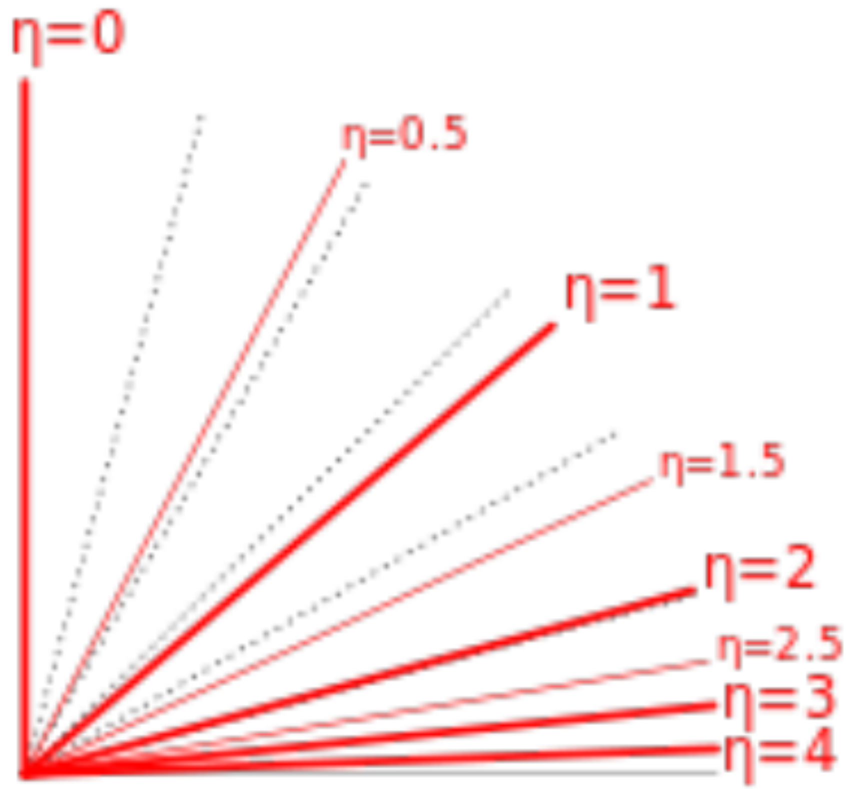


Rapidity $y = \frac{1}{2}\ln\left(\frac{E+p_z}{E-p_z}\right)$

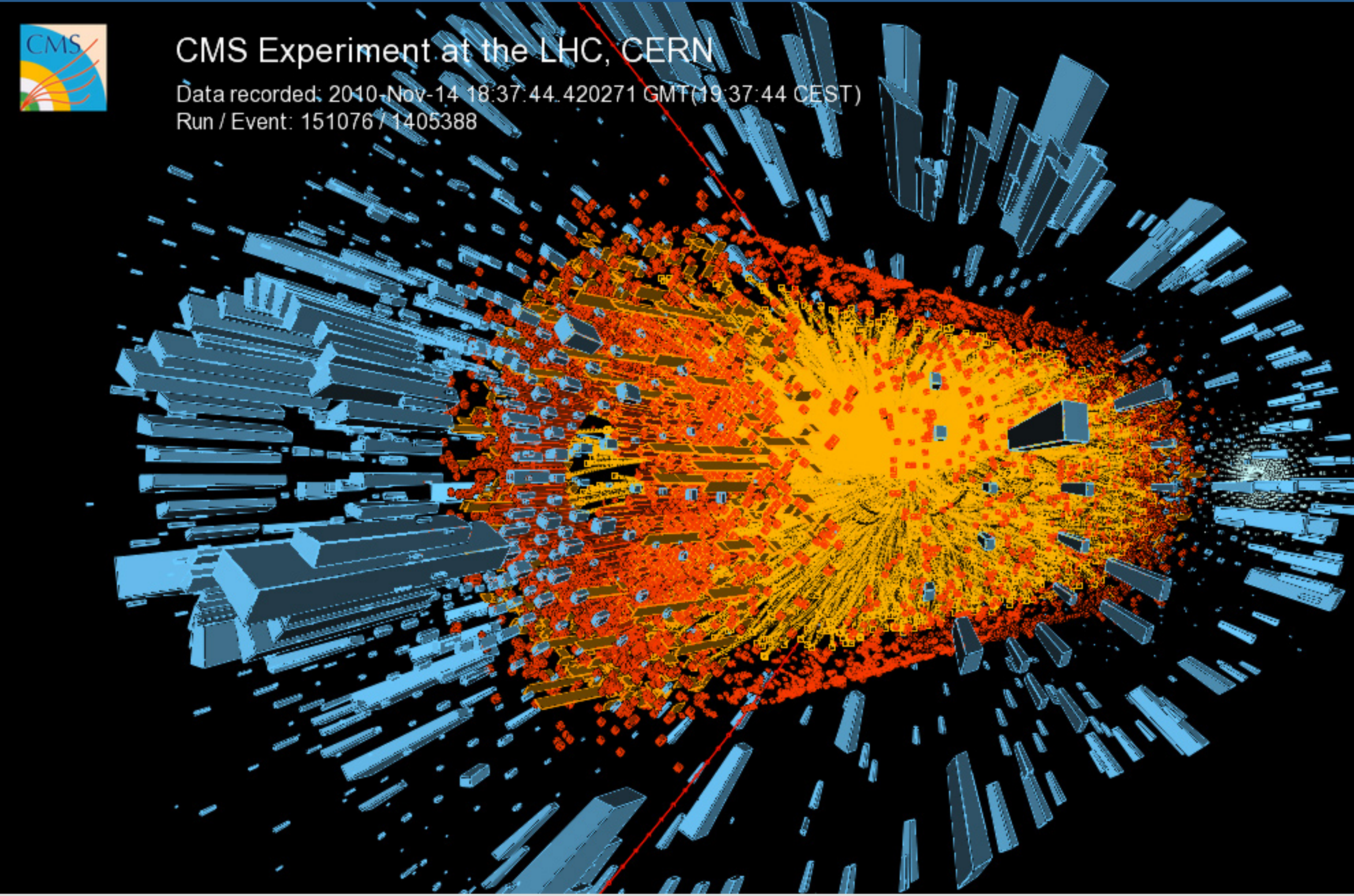
Measures longitudinal velocity
Logarithmic: CMS region is magnified
Lorentz-boost in beam-direction: Shift in y

Pseudorapidity "cheat sheet"

$$\eta = \frac{1}{2}\ln\left(\frac{P + P_Z}{P - P_Z}\right) = -\ln\left(\tan\frac{\theta}{2}\right)$$



Heavy Ion Collision Recorded by the CMS Detector (2010)



Orders of magnitude

Geometrical cross section:
pp $\pi r^2 = \pi(1fm)^2 = 32$ mb

Au+Au Collisions (200 GeV):
$R_{au} = 1.2\ A^{1/3} = 6.98$ fm
$\pi b_{max} = \pi(2R)^2 = 6$ barn

Pb+Pb (2.76 TeV) 7.7 barn

1 barn = 10^{-24} cm^2

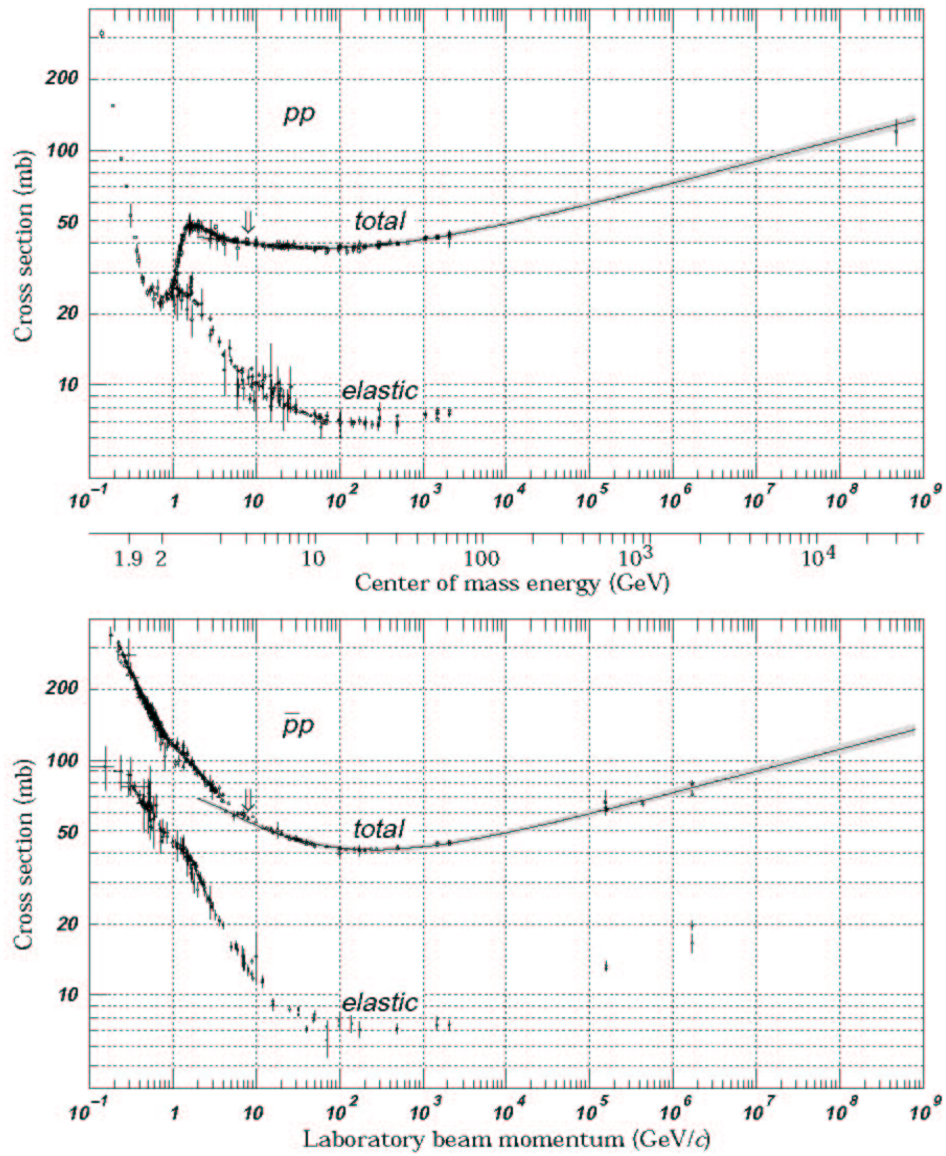


Figure 38.9: Total and elastic cross sections for pp and $\bar{p}p$ collisions as a function of laboratory beam momentum and total center-of-mass energy. Corresponding computer-readable data files may be found at http://pdg.lbl.gov/xsect/contents.html (Courtesy of the COMPAS Group, IHEP, Protvino, Russia, August 1999.)

Orders of magnitude

- To study "matter" it would be nice to have a substantial chunk of "stuff" with well defined temperature, volume, pressure: thermalized matter
- Typical hadron has radius of ~1 fm, fills effectively about 5-6 fm^3 volume so hadronic matter density is about n~0.2 $1/fm^3$
- Typical cross section of hadron interaction at high energies is about is about 50 mbarn (5 fm^2) or more
- Collisions of heavy ions increase the density by at 1-2 orders of magnitude to n~O(10) $1/fm^3$
- Mean free path $\lambda \sim \left(n\sigma\right)^{-1}$ is about 0.02 fm !

- Expect multiple hadronic interactions within the collision volume: thermalization!

Energy Density (Bjorken)

- At $t=t_{form}$, the hatched volume contains all particles with $\beta_{\|} < dz/t_{form}$

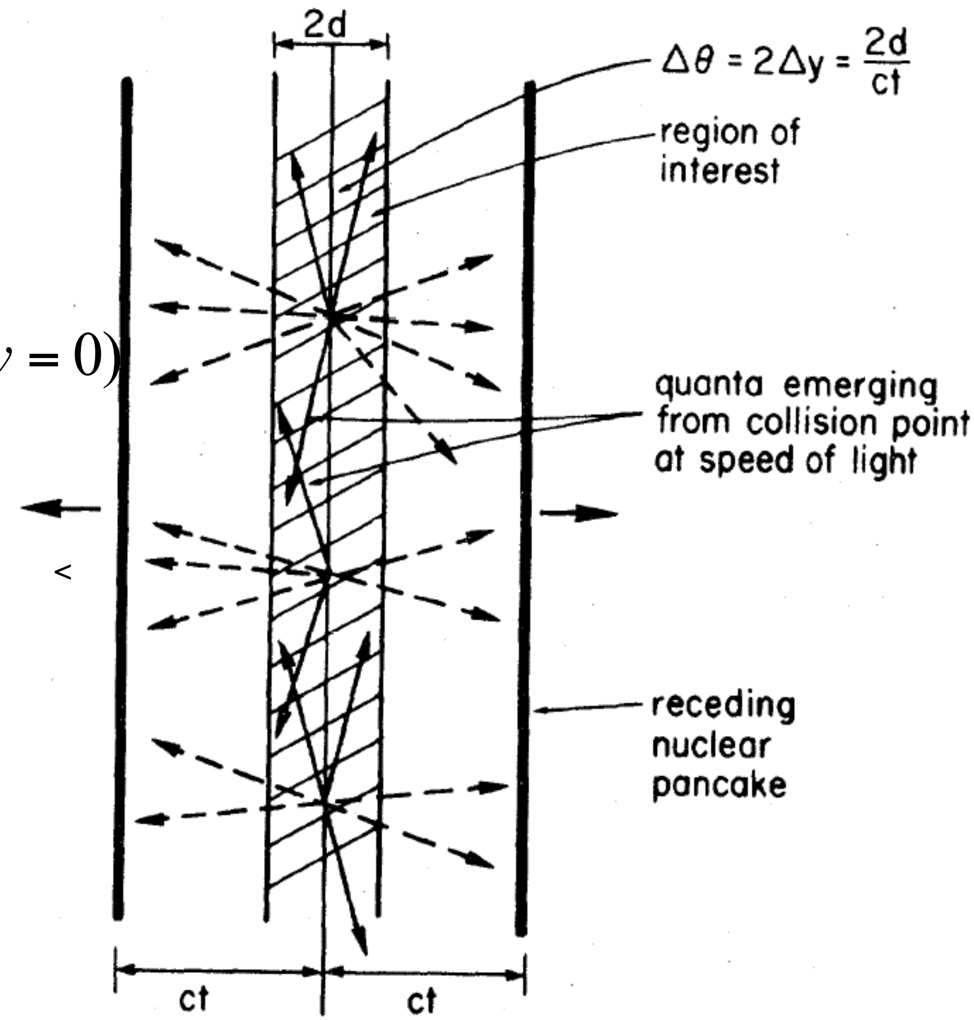
$$dN = \frac{dz}{t_{form}} \frac{dN}{d\beta_{\|}} = \frac{dz}{t_{form}} \frac{dN}{dy} ;(dy = d\beta_{\|} @ y = 0)$$

- At $y = \beta_{\|} = 0$ $E = m_T$, thus:

$$\langle \varepsilon(t_{form}) \rangle = \frac{E}{V} = \frac{dN < m_T >}{dz \cdot A} = \frac{dN(t_{form})}{dy} \frac{< m_T >}{t_{form} \cdot A}$$

- We can equate $dN \langle m_T \rangle$ and dE_T and have:

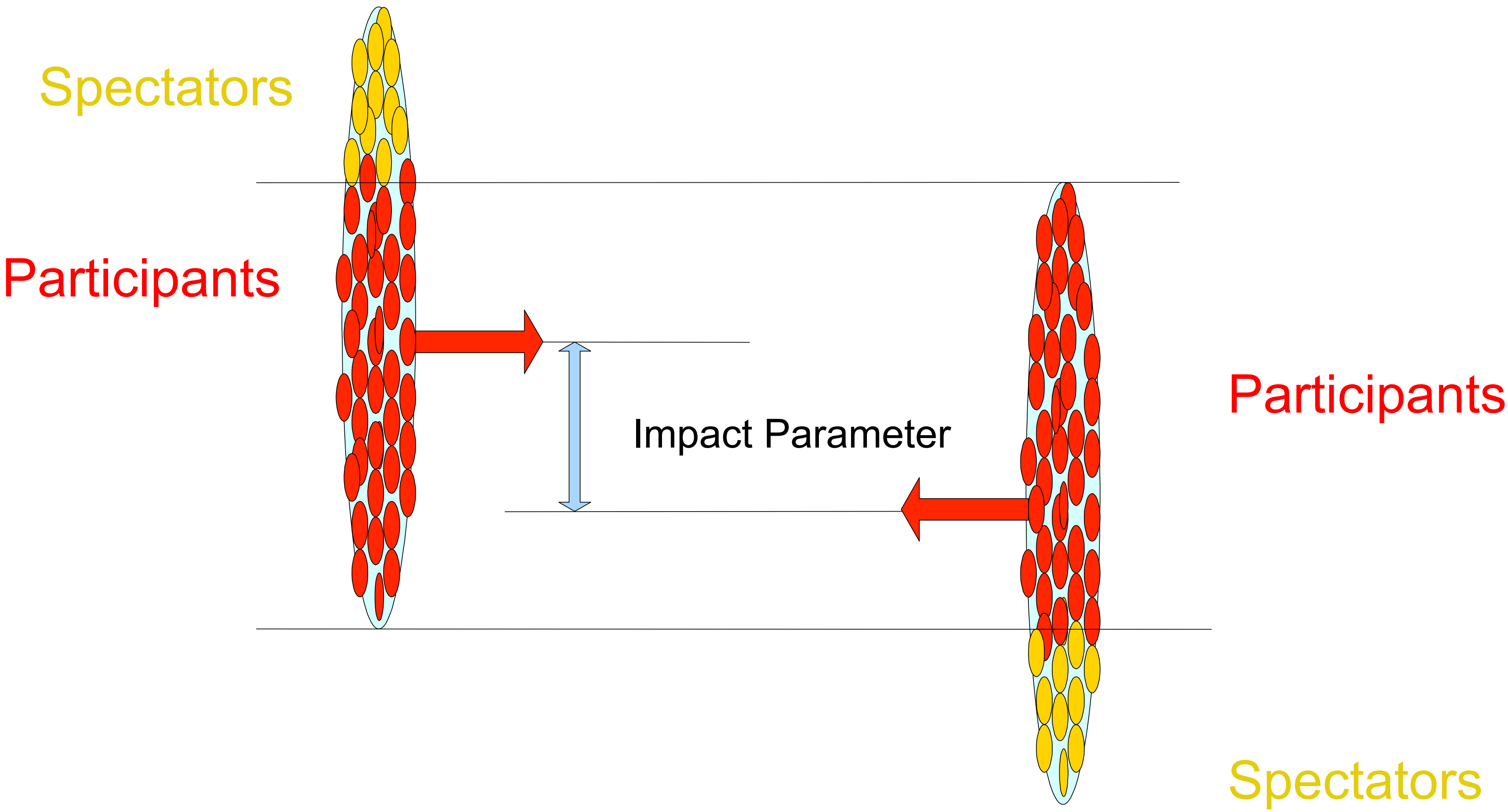
$$\langle \varepsilon_{BJ}(t_{form}) \rangle = \frac{1}{t_{form} \cdot A} \frac{dE_T(t_{form})}{dy}$$



Two nuclei pass through one another leaving a region of produced particles between them.

Collision Geometry

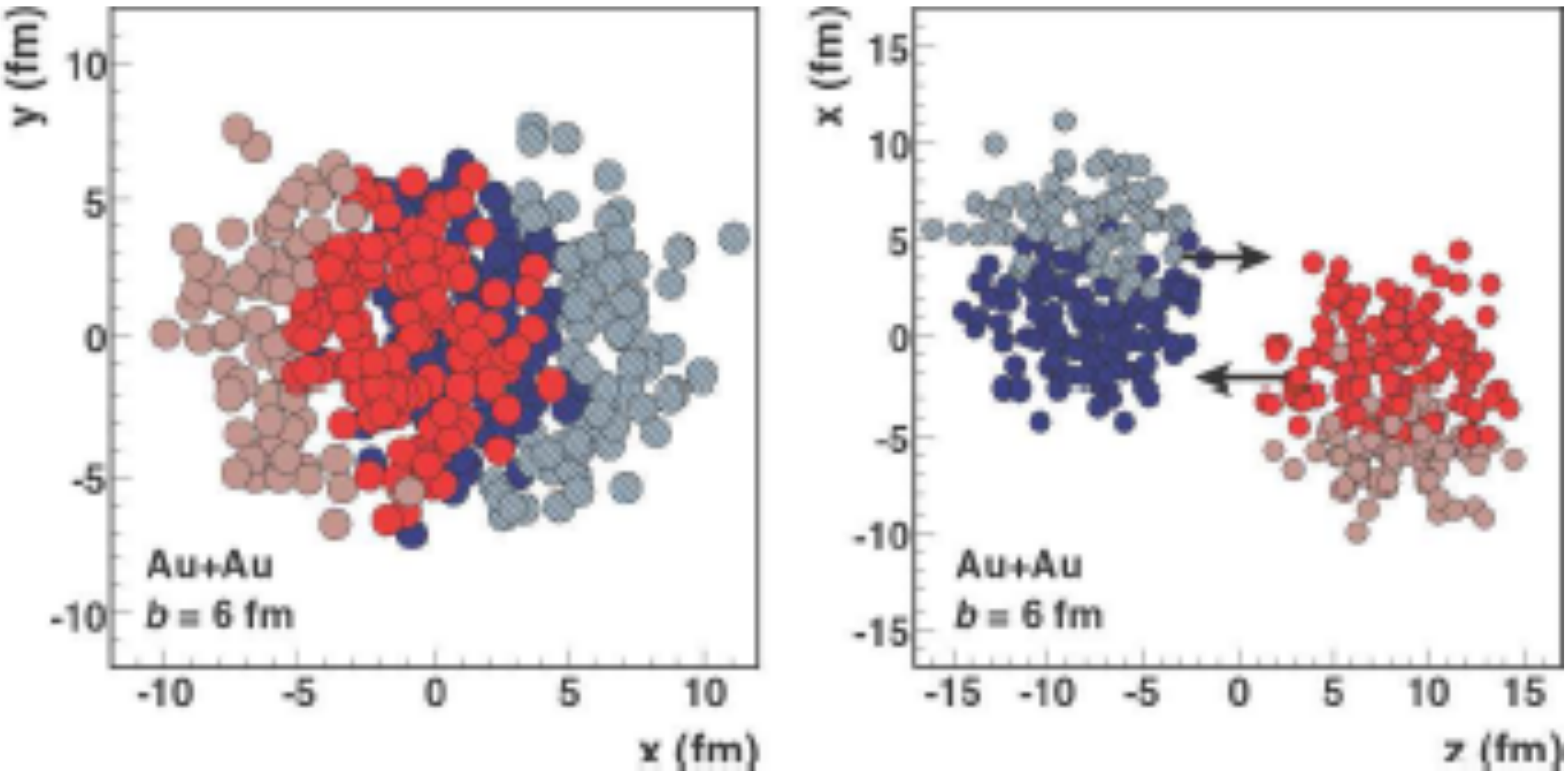
Number of produced particles ~ max. energy density ~ number of participating nucleons



Most central collisions: impact parameter (b) ~ 0 fm

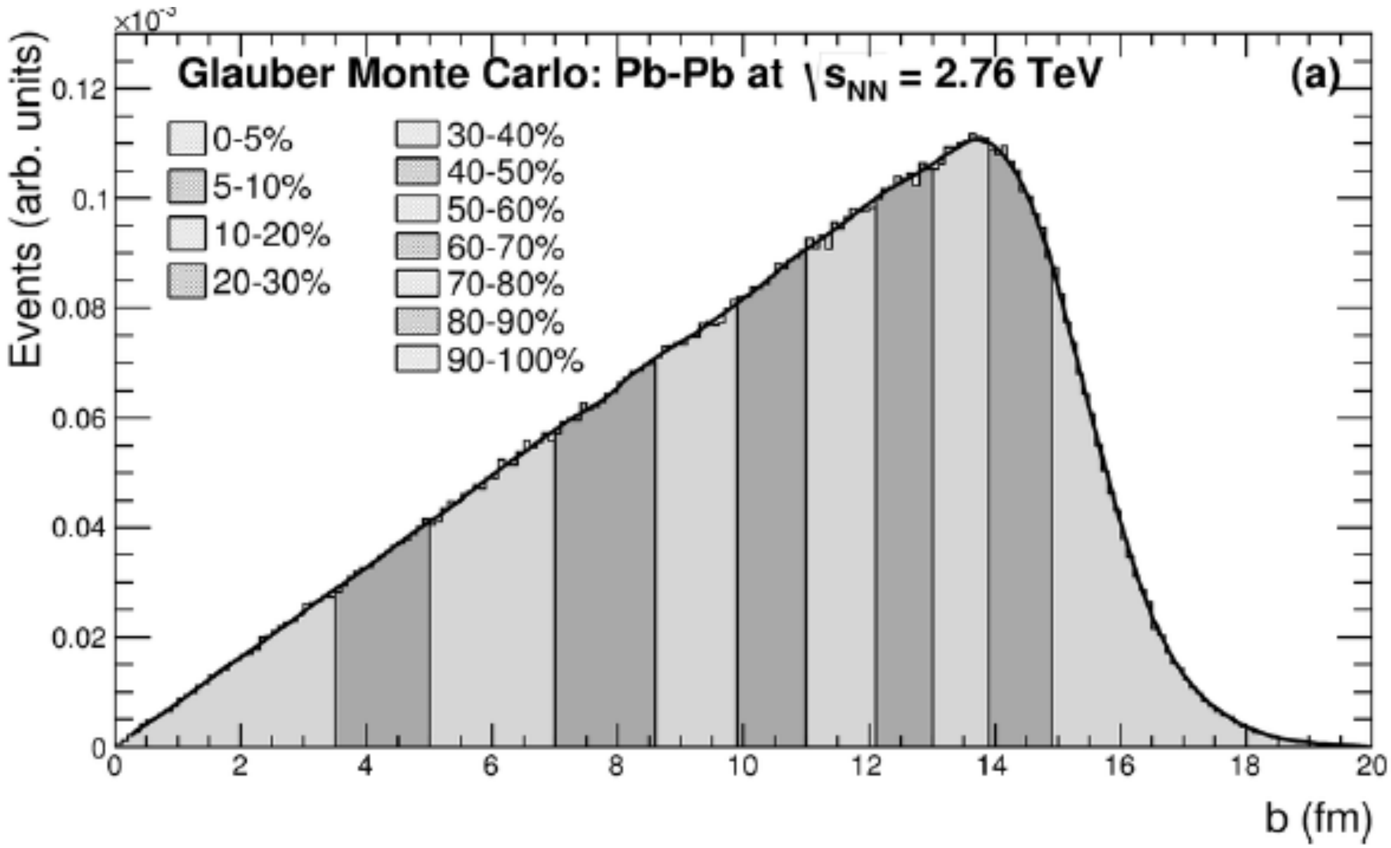
Most peripheral collisions: impact parameter (b) ~ R_{ion} fm

Estimation of collision centrality: Glauber model



- Monte Carlo technique: generate random positions of constituent nuclei
- Follow their trajectory and count interactions
- Use nucleon-nucleon cross section

Collision "centrality"

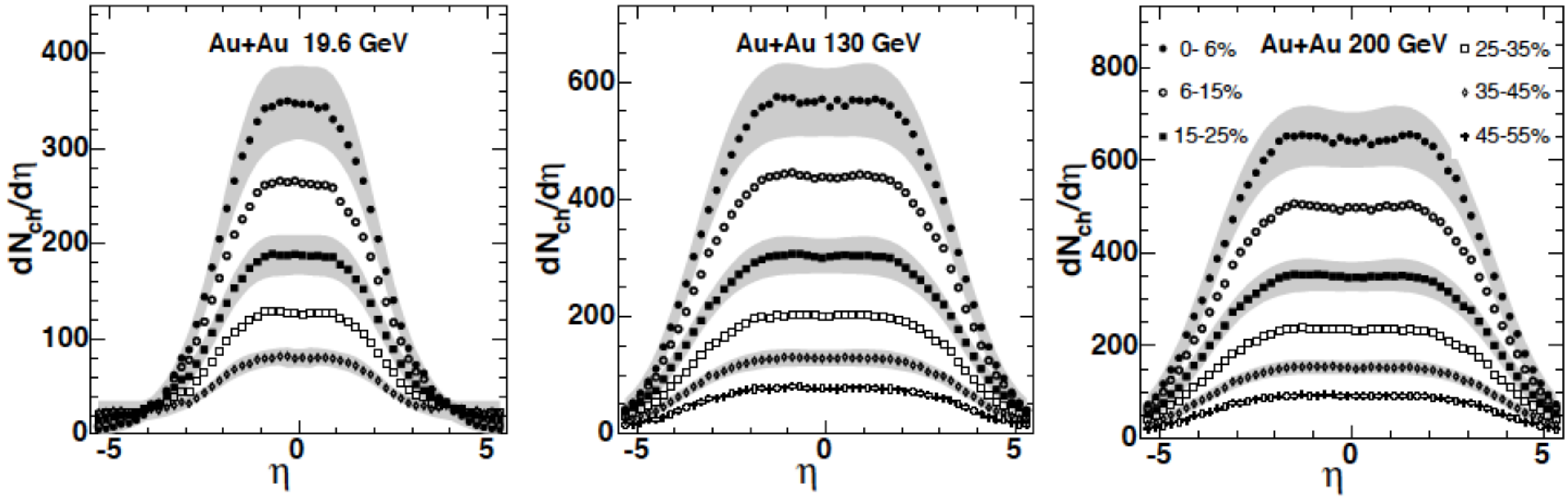


"Centrality" usually characterized by percentile, e.g. the "5% most central collisions"

Fraction of the total cross section

Charged Multiplicity

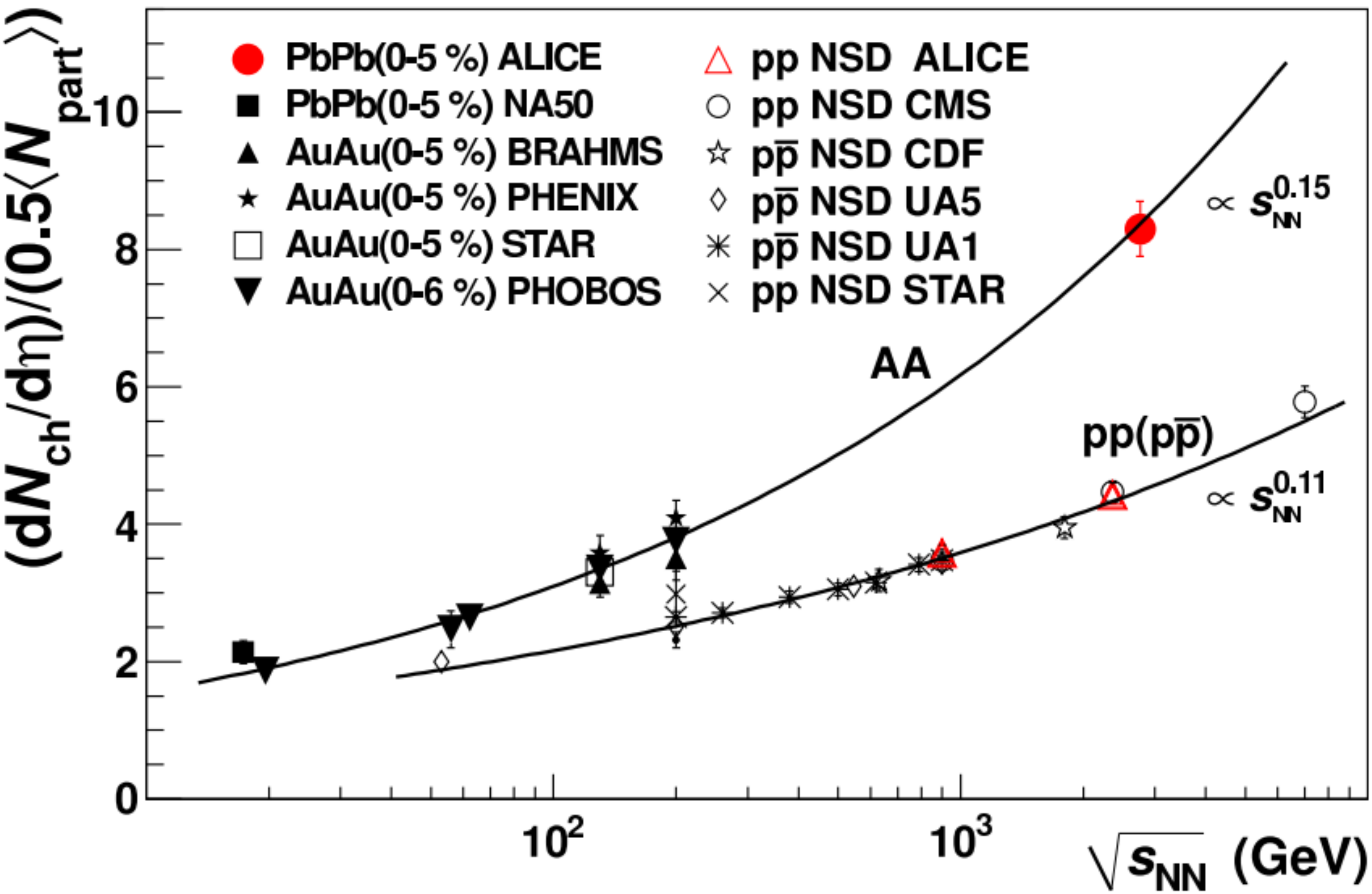
PHOBOS experiment at RHIC accelerator



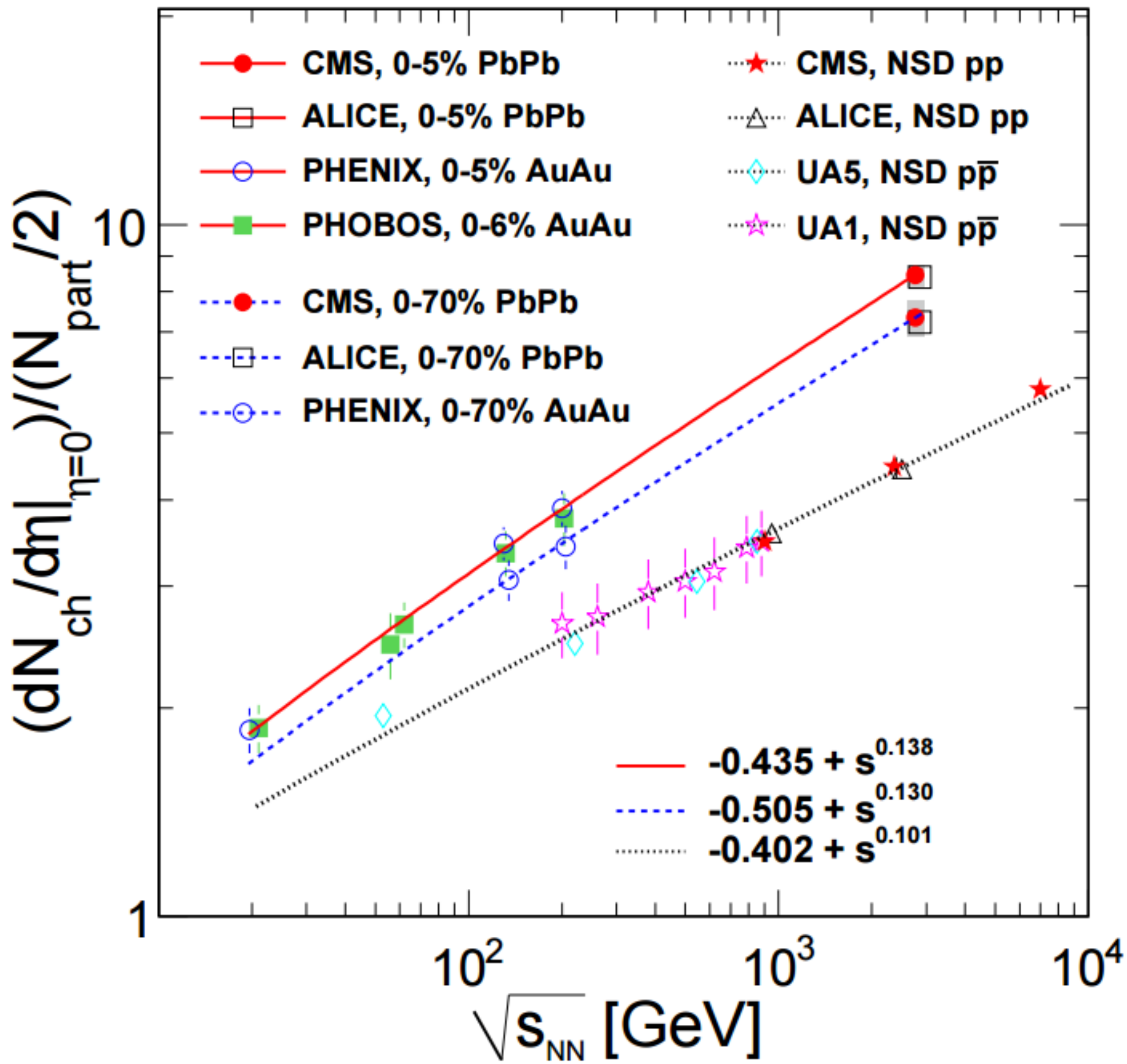
- Charged particle multiplicity as a function of pseudorapidity
- Increasing collision energy: 19, 130, 200 GeV/A
- Different centrality: peripheral to central

- Very clear increase in multiplicity with energy and centrality

Charged multiplicity at η=0 vs $\sqrt{s}$



Charged multiplicity η=0 vs √s



Initial energy density

What time do we assume?

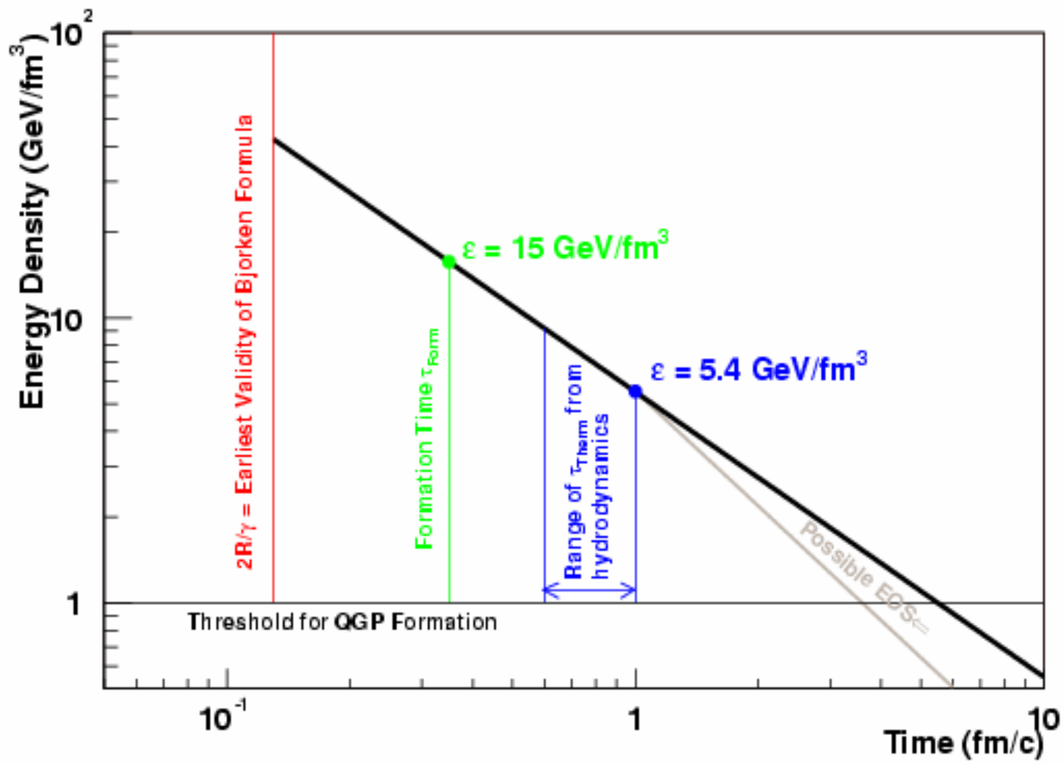
- Two values of $\tau_{0:}$
  - $\tau_{form} = \hbar/\langle m_T \rangle(\tau_{form})$
    $\leq \hbar/\langle m_T \rangle^{final} = 0.35$ fm/c
  - $\tau_{therm} \leq 1$ fm/c (hydro)

- We derive conservative *lower limits* energy density at formation and thermalization

  ε(form) > 15 GeV/fm^3 (RHIC)

  ε(therm) > 5 GeV/fm^3 (RHIC)

  ε(therm) > 16 GeV/fm^3 (LHC)

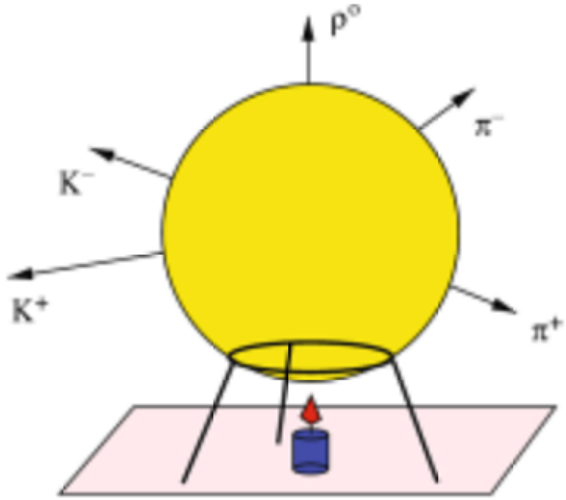


These values are well in excess of ~1 GeV/fm^3 obtained in lattice QCD as the energy density needed to form a deconfined phase.

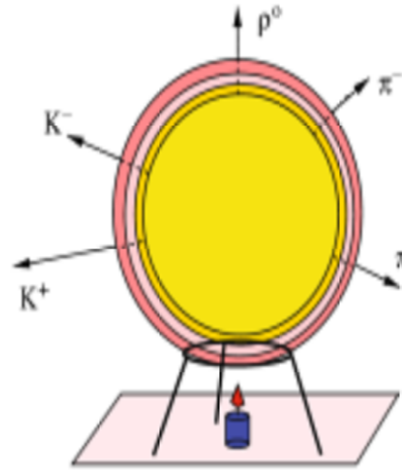
Summary so far

- Heavy ion collisions clearly produce hot region of space with energy densities sufficiently high to enter the quark-gluon plasma phase
- The mean free path for the ingredients seems to be much smaller than the size of the hot region, implying thermalization
- The hot matter expands and cools very fast, the measurements have to be done very quickly

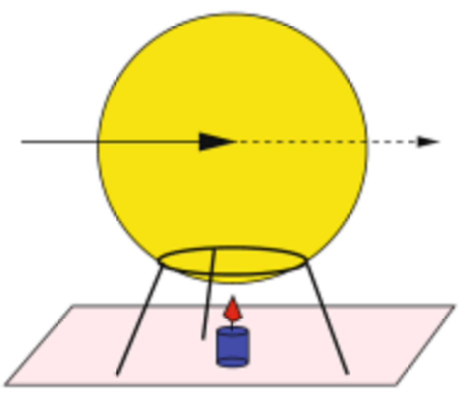
Techniques to study the plasma



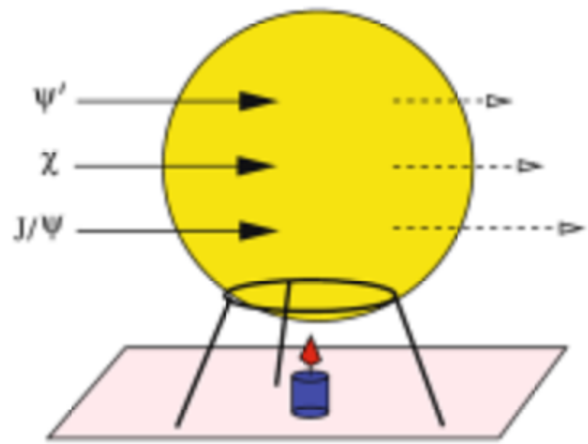
Radiation of hadrons



Azimuthal asymmetry and radial expansion



Energy loss by quarks, gluons and other particles



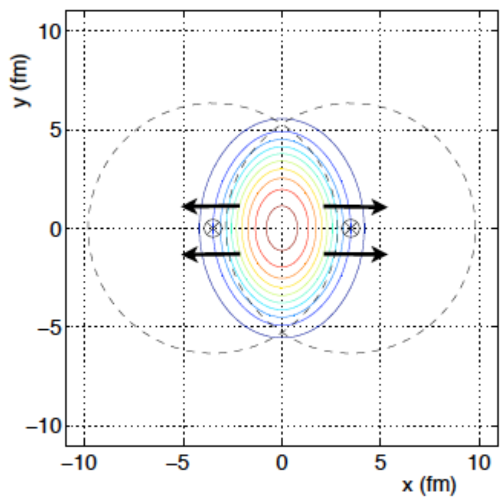
Suppression of quarkonia

Radiation of hadrons and photons

- Effects dependent on energy density
  - Charged multiplicity
  - Energy distribution
- Measuring the “chemistry” of collision, quark content of the plasma, temperature, speed of expansion
  - Momentum spectrum
  - Particle composition: π, K, p, γ
  - Comparison of particle content in nuclear and proton-proton collisions

Azimuthal asymmetry and radial expansion

- Exploit the fact that there are many peripheral collisions that are azimuthally asymmetric



- The pressure in the hot drop of strongly interacting fluid affects the momentum of emitted particles

Energy loss by quarks, gluons and other particles

- Equivalent of x-ray of the plasma, the loss of energy can tell us about the density, composition and the microscopic structure of the plasma
- We use probes created during the elementary collisions between the initial quarks and gluons
  - Large transverse momentum quarks or gluons appearing as jets
  - Particles that do not interact strongly can be used as a reference: Z, W, photon

Production and suppression of quarkonia

- Bound states of heavy quarks produced inside plasma are being used as an indicator of plasma temperature and density
- Comparison of production of quarkonia between ion-ion, proton-ion and proton-proton collisions show several interesting effects that can be interpreted in terms of plasma properties
  - J/ψ, ψ' suppression and recombination
  - Properties of Υ family