Ultra-relativistic Heavy Ion Collisions

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- **Lecture I: Dense Matter and the Quark-Gluon Plasma**
- **Lecture II: Statistical Hadron Production**
- **Lecture III: Heavy Quark and Quarkonia Production**

Lectures assembled in collaboration with Peter Braun-Munzinger

Lecture I:
Dense Matter and the Quark Gluon Plasma

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Outline:

- **Introduction, historical remarks**
- **Early universe**
- **Critical temperature and density**
- **The phases of strongly interacting matter**
- **Results from lattice QCD**
- **Making strongly interacting matter in nuclear collisions**
- **Survey of experiments**

Historical Remarks

- **Pomeranchuk 1951: finite hadron size → critical density n_c.**
  Dokl. Akad. Nauk. SSSR 78 (1951) 889.
- **Hagedorn 1965: mass spectrum of hadronic states $\rho(m) \propto m^{\alpha} \exp{(m/B)}$**
  → critical temperature $T_c = B$. Nuovo Cim. Suppl. 3 (1965) 147.
- **QCD 1973: asymptotic freedom**
  D.J. Gross, F. Wilczek, Phys. Rev. Lett. 30 (1973)1343
  H.D. Politzer, Phys. Rev. Lett. 30 (1973) 1346.
- **asymptotic QCD and deconfined quarks and gluons:**
  N. Cabibbo, G. Parisi, Phys. Lett. B59 (1975) 67.
  J.C. Collins, M.J. Perry, Phys. Rev. Lett. 34 (1975) 1353.

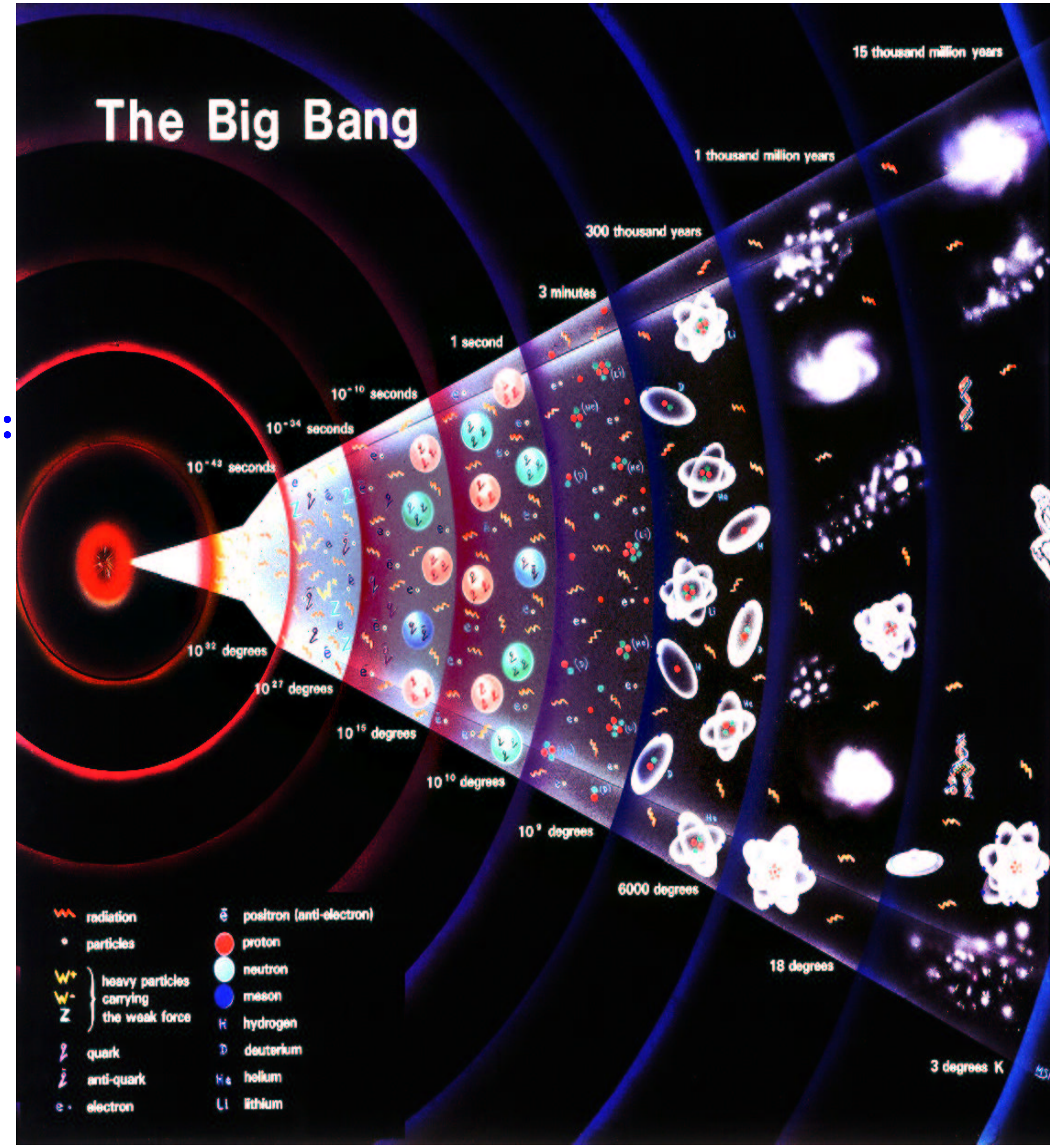
Historical Remarks

- **Bielefeld 1980: start of quark matter conferences.**
- **CERN/BNL 1986: start of nuclear collisions program.**
- **CERN 2000: press release about "New State of Matter".**
- **BNL 2001: first collider experiments.**
- **CERN 2007: start of Pb+Pb collisions at LHC.**
- **GSI 2012: exploration of high baryon density region.**

from the big bang to galaxies

10^{-5} s after big bang:
phase transition from quarks
and gluons to hadronic matter

temperature at phase transition:
T$\approx 2 \cdot 10^{12}$K = 200 MeV



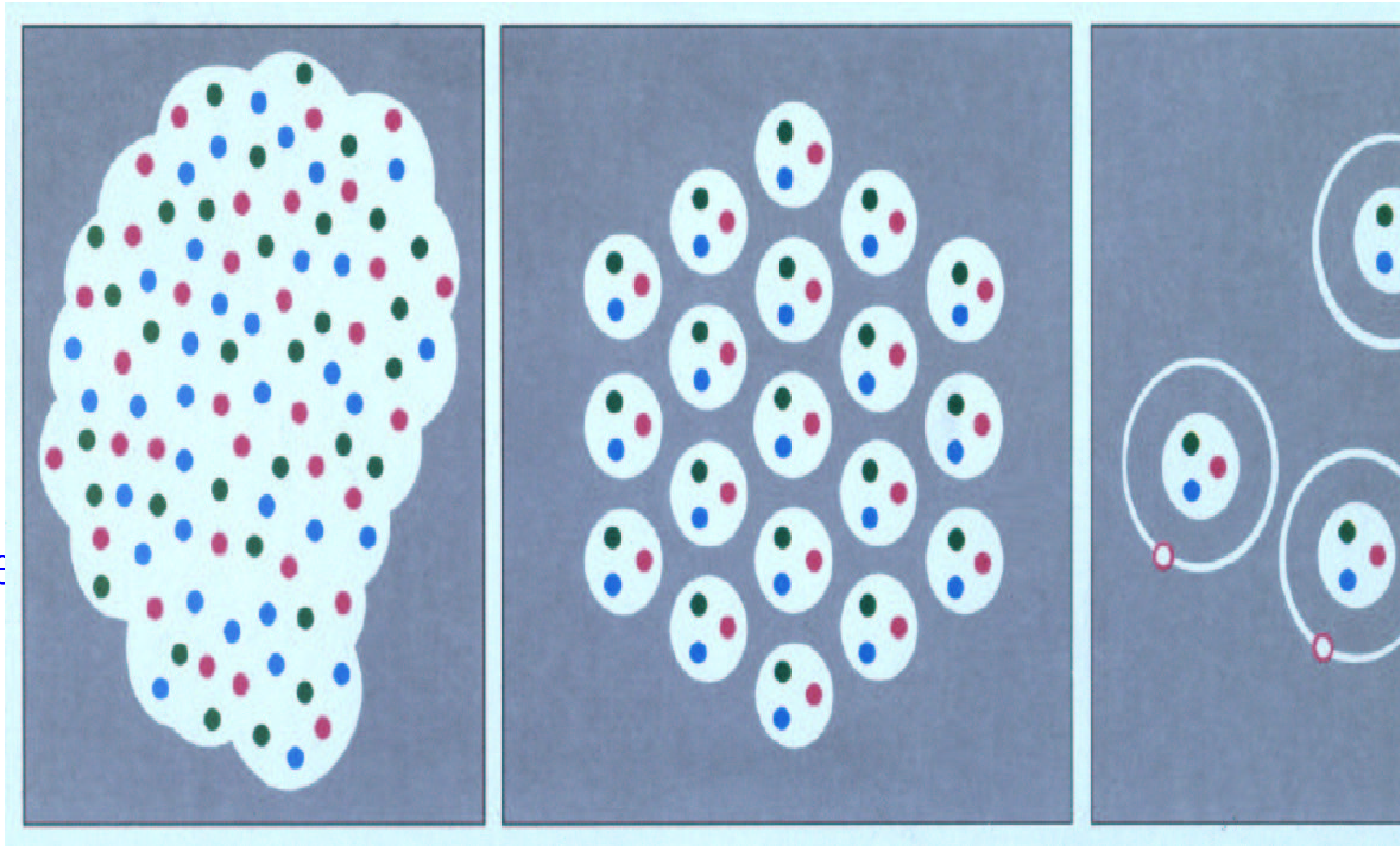
QGP – Deconfined Quarks and Gluons

from nucleons to quark matter

Heating or Compression → Deconfinement

temperature at phase transition:
T $\approx 2 \cdot 10^{12}$**K**
T $\approx$ 200 MeV
(low density)

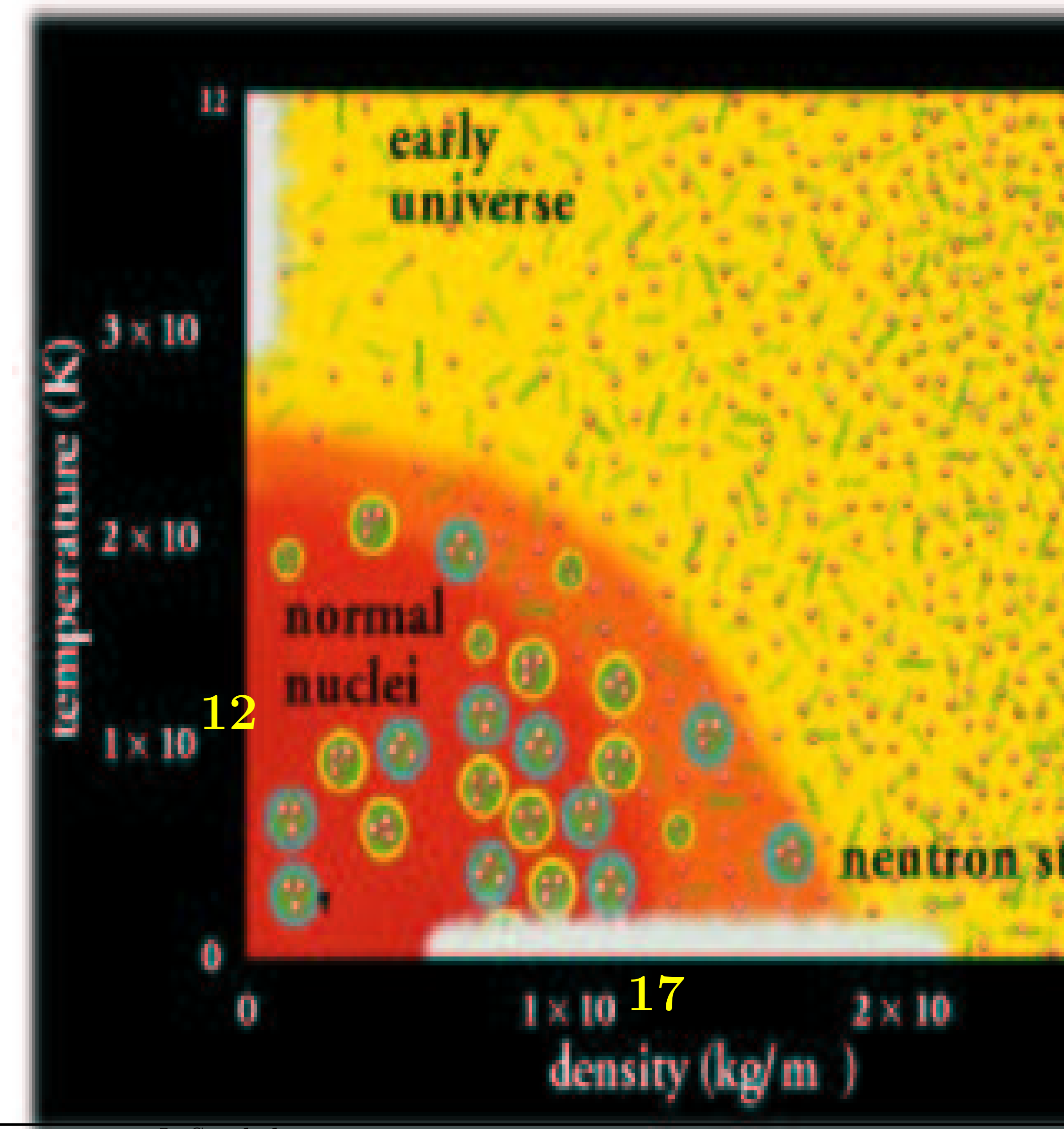
alternatively:
density $\approx 5\rho_0$
(low temperature



Phase Diagram (schematic)

from nuclear to quark matter

phase boundary:
normal nuclear matter →
quark-gluon matter
at high density and/or
temperature

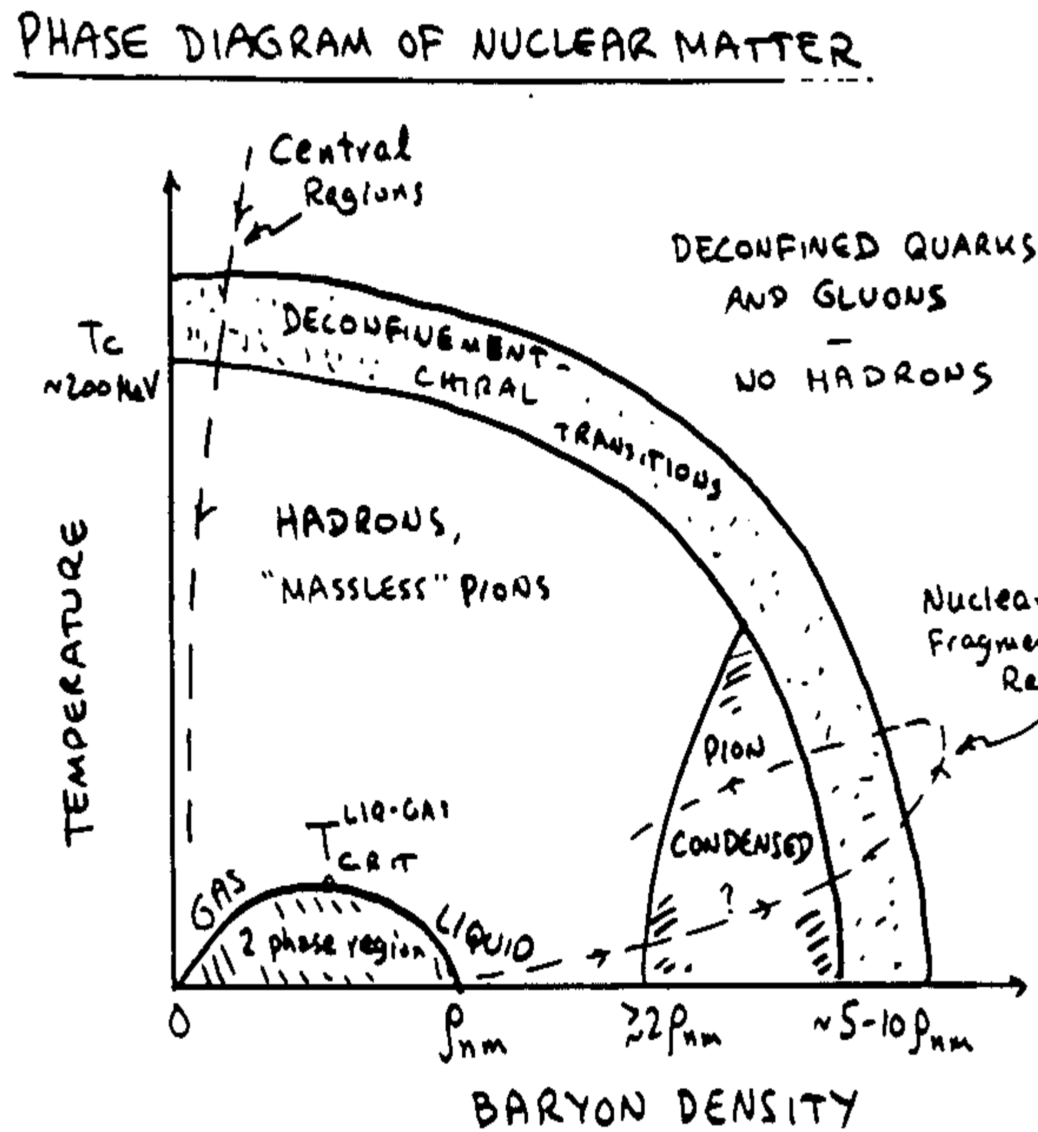


Phase Diagram (historical)

from Gordon Baym 1983

see also: G. Baym
Nucl. Phys. A698(2002)xxiii

most of ingredients there
20 years ago



Simple Estimates of critical conditions

1. deconfinement at high temperature (a la Polyakov 1978):

   $T = 0$

   energy of color string $E_{q\bar{q}}(r) = \sigma\ r$

   with string tension $\sigma \approx 1$ GeV/fm

   $T > 0$

   free energy of string $F_{q\bar{q}}(L) = E_{q\bar{q}}(L) - T\ S(L)$

   $$= \sigma\ L - T \ln N(L)$$

   $$= (\sigma - T/a \ln 5)L$$

   $$= \sigma_{eff}(T)\ L$$

   with number of string configurations: $N(L) = 5^{L/a}$

   and typical stepsize = string thickness ≈ 0.3 fm

   critical temperature when $\sigma_{eff}(T)=0$

   $$\rightarrow T_c = \frac{1\text{GeV}\ 0.3\text{fm}}{\text{fm}\ \ln 5} = 185\ \text{MeV}$$

2. at high baryon density:

- **normal nuclear matter:**

  baryon density $\rho_0 = \frac{\mathrm{A}}{4\pi/3\mathrm{R}^3} = \frac{1}{4\pi/3\mathrm{r}_0^3} \approx \mathbf{0.16\ /fm^3}$

  with $\mathrm{r}_0 = \mathbf{1.15\ fm}$

- **if nuclei are compressed, eventually nucleons start to ove**

  nucleon charge radius $\mathrm{r_n} = \mathbf{0.8\ fm}$

  $\rightarrow \rho_\mathrm{c} = \frac{1}{4\pi/3\mathrm{r_n^3}} \approx \mathbf{0.47/fm^3 = 3}\ \rho_0$

- **more stringent:**

  pressure of quark-gluon bubble has to sustain

  vacuum pressure

  at T=0 with bag constant B = 0.2 GeV/fm^3

  $\rightarrow \mu \geq \mathbf{0.42\ GeV}$

  critical net quark density $\mathrm{n_q - n_{\bar{q}}} \geq \mathbf{1.9/fm^3}$

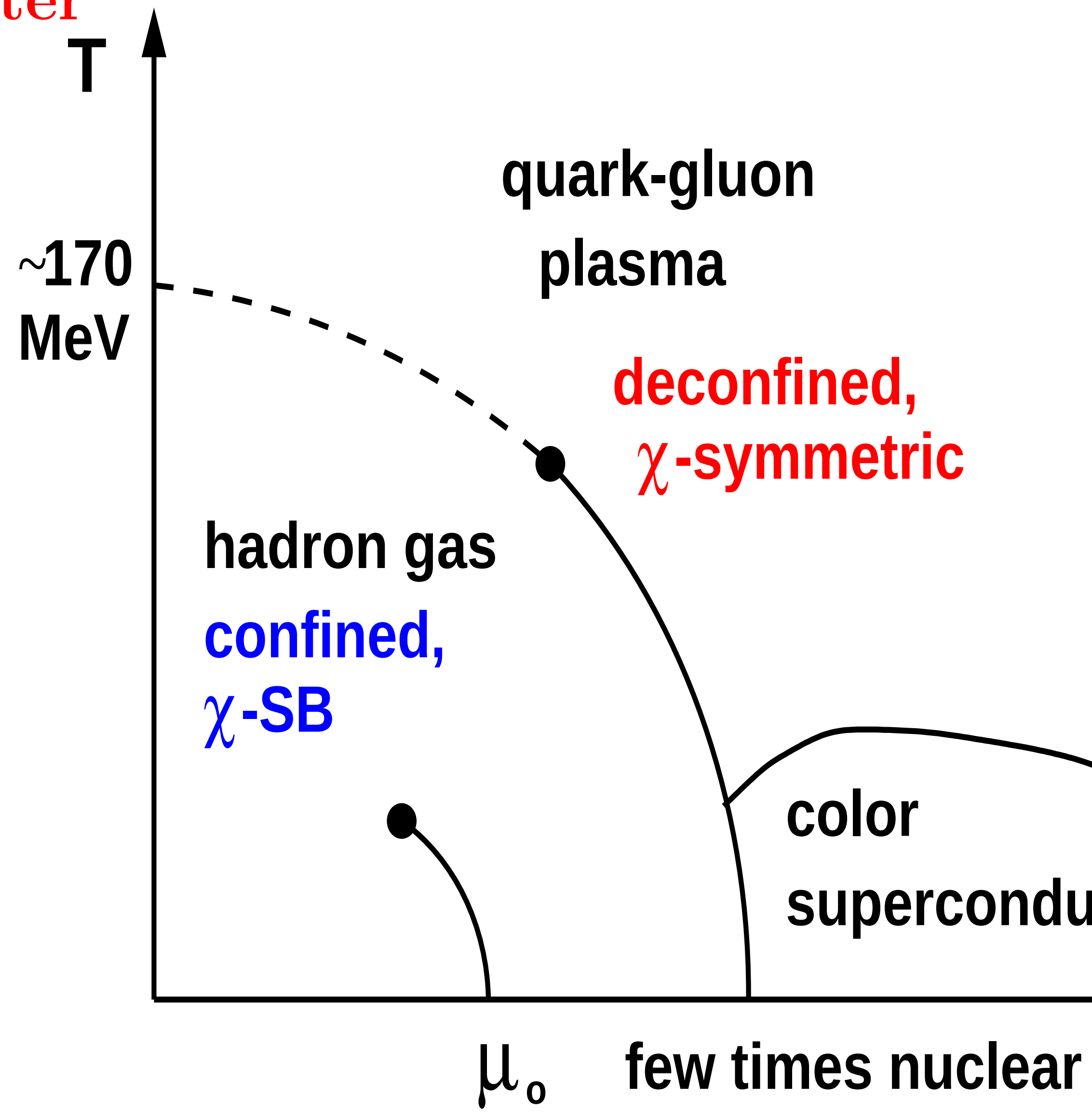
  $\rightarrow \rho_\mathrm{c} = 1/3(\mathrm{n_q - n_{\bar{q}}}) \geq 0.64 = 4\rho_0$

Phase Diagram (modern)

from nuclear to quark matter

at low temperatures:
color is confined
and
chiral symmetry is broken

temperature at
phase transition:
T≈ 170 MeV for $\mu = 0$



Hagedorn's Limiting Temperature

all thermodynamical quantities diverge at T_{limit}

(R. Hagedorn, Suppl. Nuovo Cim. 3 (1965) 147)

assume $\rho_m \propto (m_0^2 + m^2)^{(-5/4)} \exp(m/b)$

take energy density of hadron gas, $\epsilon(\mathrm{T})$

$\epsilon(\mathrm{T}) = \Sigma_{\mathrm{m}_\pi}^{\mathrm{M}} \epsilon(\mathrm{m_i}, \mathrm{T}) + \int_{\mathrm{M}}^{\infty} \epsilon(\mathrm{m}, \mathrm{T})\rho(\mathrm{m})$**,**

but for large masses $m > M$**,** $\epsilon(m, \mathrm{T}) \propto \exp(-\mathrm{m}/\mathrm{T})$

$\rightarrow$ **integral diverges if T > b**

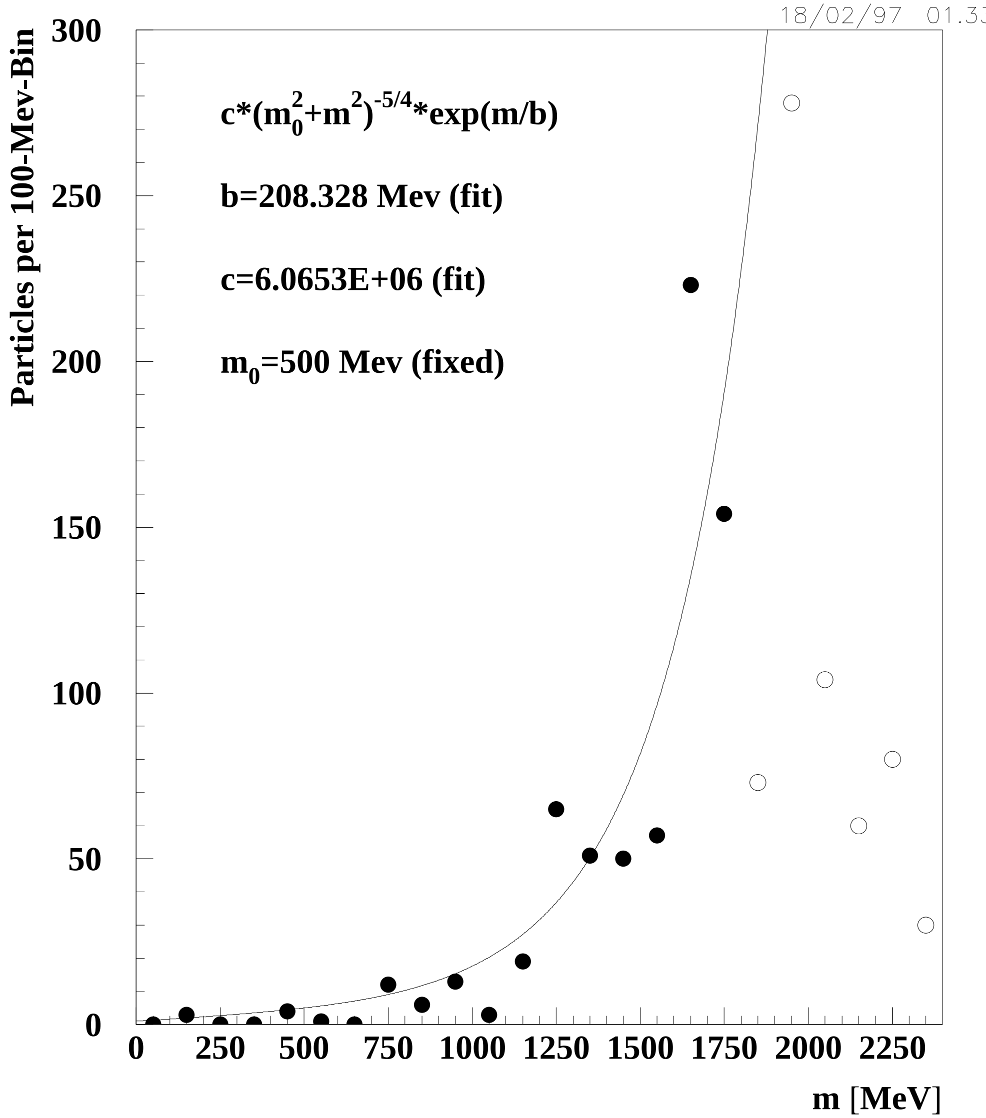
hadronic mass spectrum as of 1997

fit with

Hagedorn mass formula

$$\rho_m \propto (m_0^2 + m^2)^{(-5/4)} \exp{(m/b)}$$

b = T_{limit} = 200 ± 30 MeV



Simple Construction of Phase Transition

Basis: MIT bag model with bag constant B

B is energy density of QCD vacuum (see above)

energy density of quark-gluon matter: $\epsilon = \epsilon_{thermal} + B$

pressure: P = 1/3 (ϵ - 4 B)

with $\epsilon_{thermal} \propto n_{thermal}^{4/3}$ **and** $P = n^2 \partial(\epsilon/n)/\partial n$

note: at T = 0, P = -B!

energy density (pressure) of hadron gas:

sum up energy density (pressure) due to each particle

Gibbs criterion for phase transition:

$P_{had} = P_{QGP}$ **and** $\mu_{had} = \mu_{QGP}$

Constructing the Phase Boundary

compute P as above and

look for the crossing points

first order phase transition

by construction

$B = 250\ \text{MeV/fm}^3$

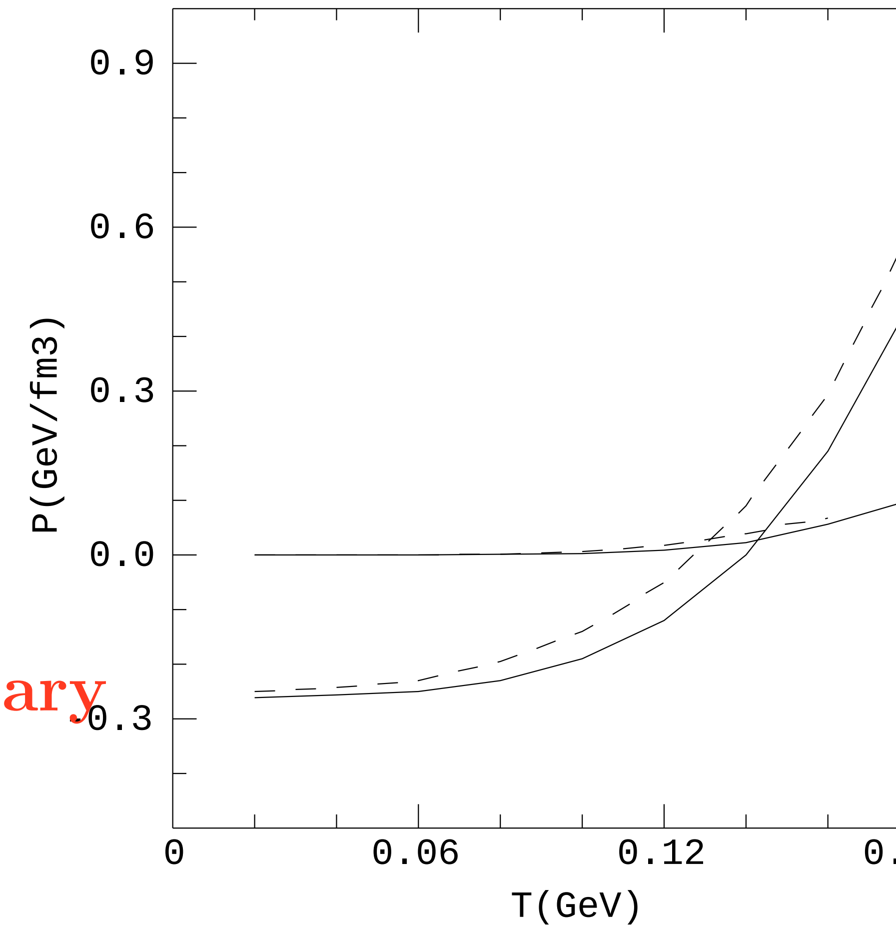
from lattice QCD

determination of the phase boundary

in the $T - \mu$ plane

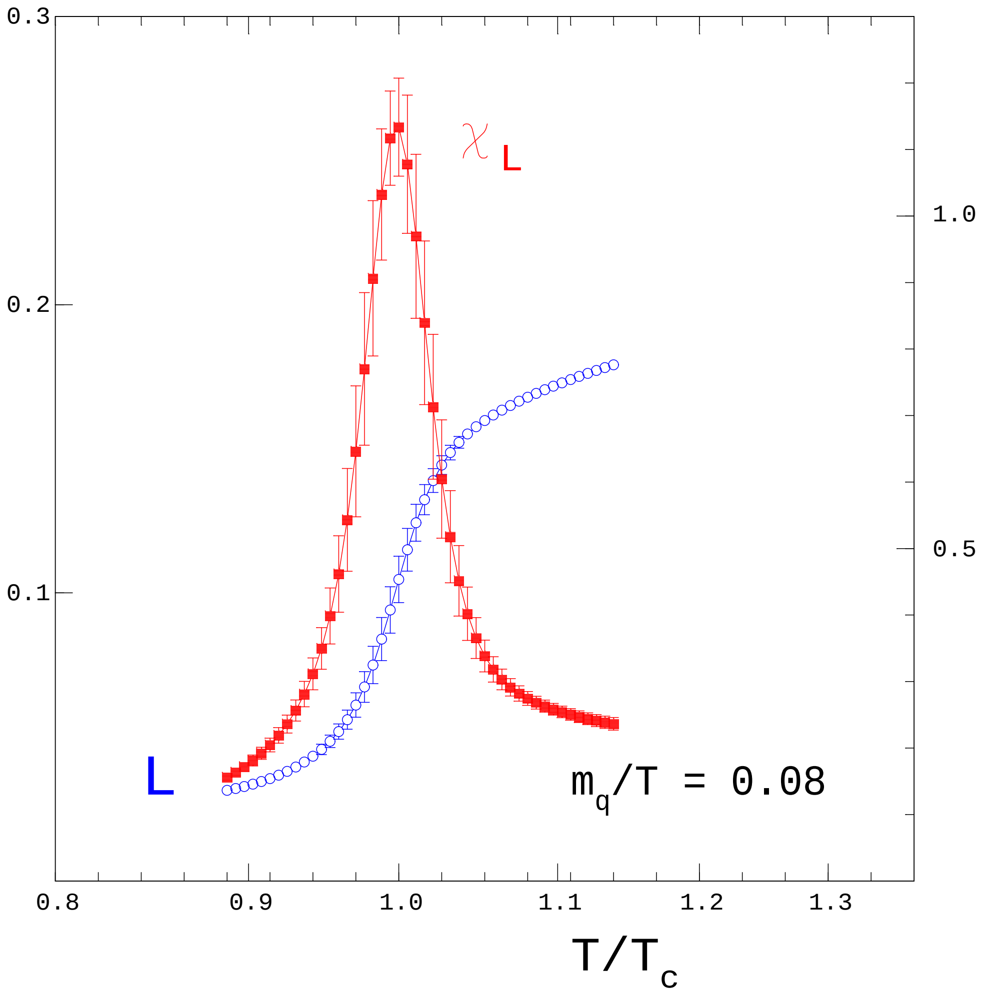
solid lines: μ =170 MeV

dashed lines: $\mu = 540$ MeV

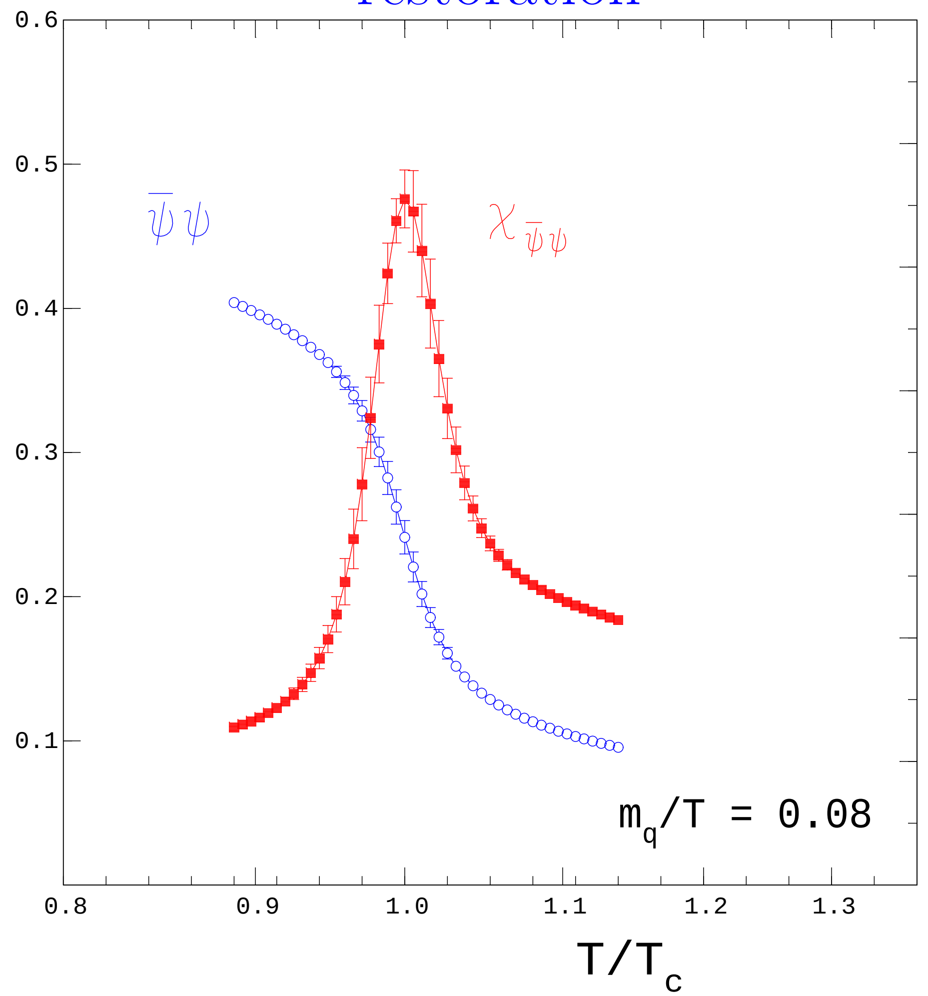


Results from "Lattice QCD"

Polyakov loop - deconfinement



quark condensate - chiral sym. restoration

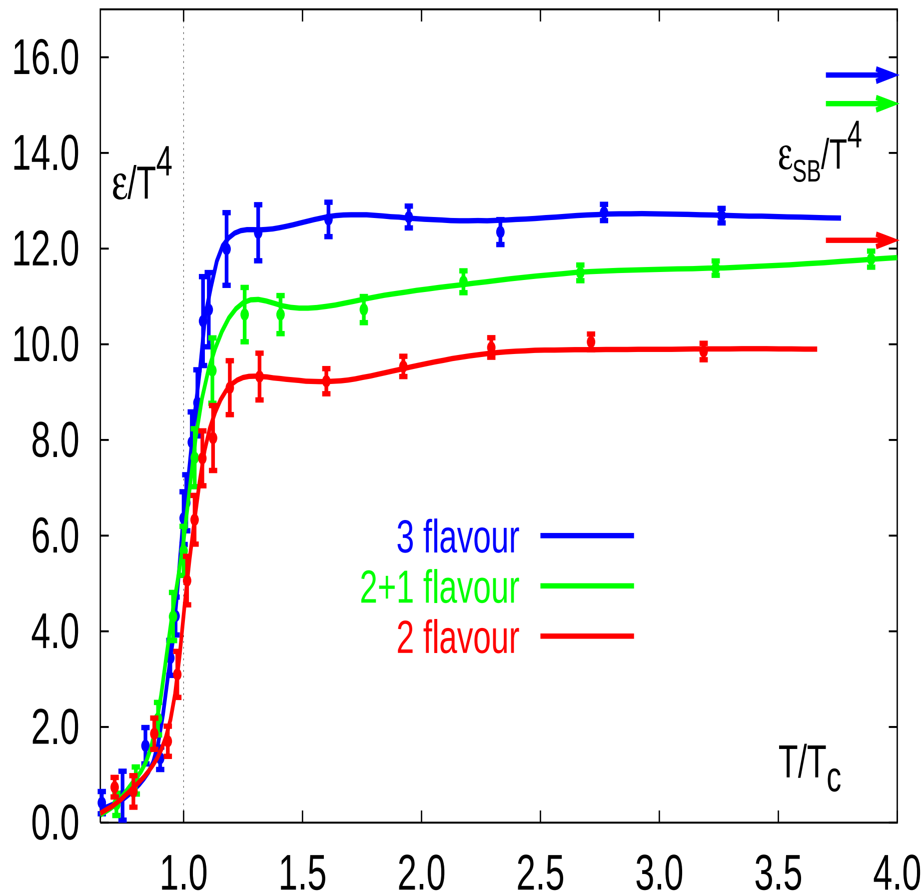


Suceptibilities χ: measure of fluctuations

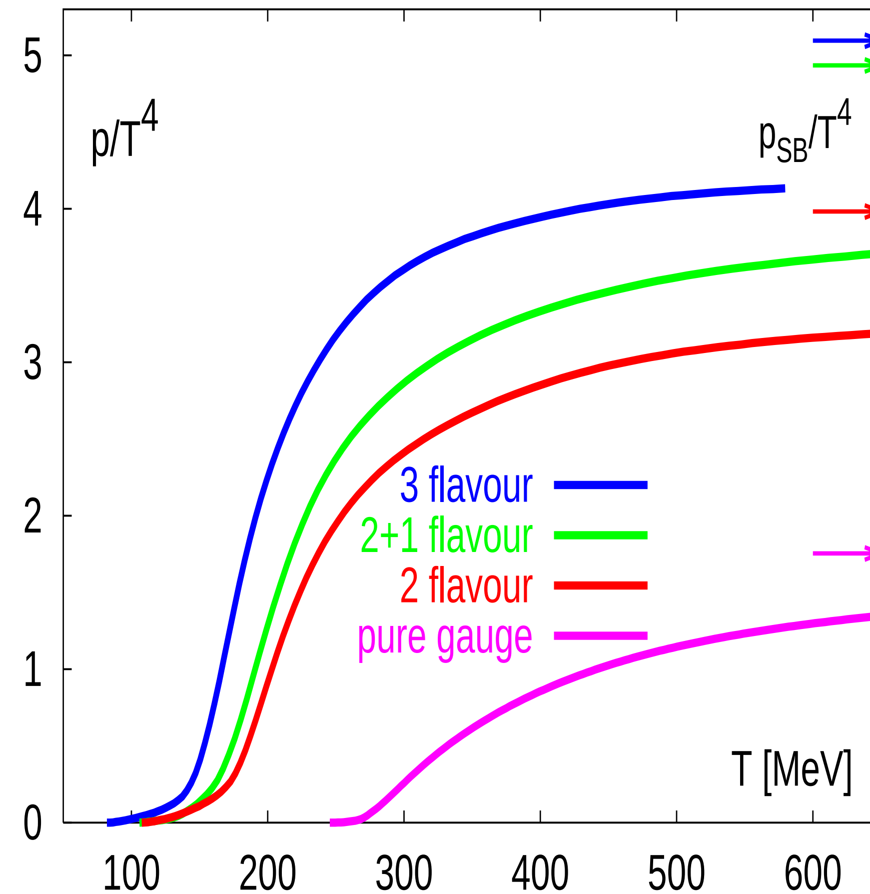
F. Karsch, E. Laermann, hep-lat/0305025

Results from "Lattice QCD"

energy density



pressure

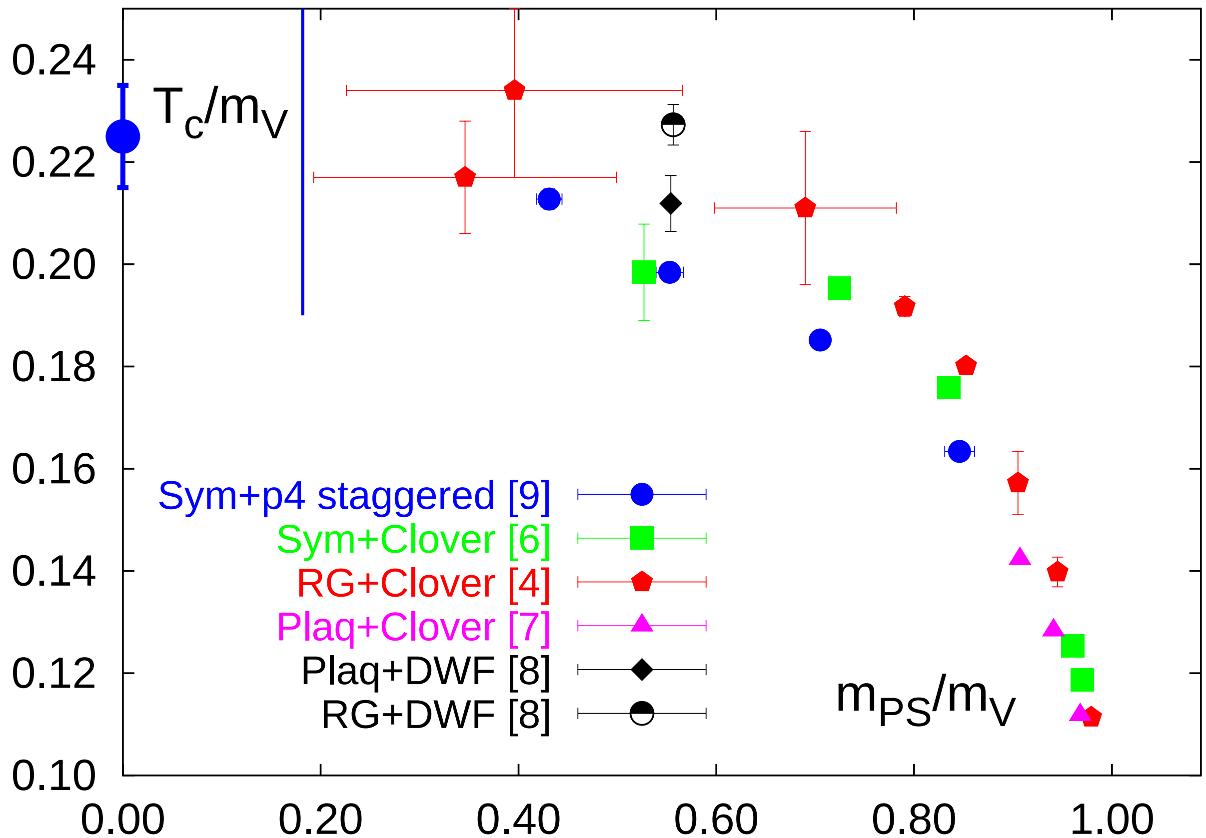


F. Karsch et al. Bielefeld group, Phys. Lett. B478(2000)447 and Nucl. Phys. A698(2002

$16^3\times$ 4 lattice, m_{ql}/T=0.4, m_{qh}/T=0.1

Critical Temperature from “Lattice QCD”

F. Karsch, Nucl. Phys. A698(2002)199c and E. Laermann, Proc. Hirschegg 2002



fix temperature scale with mρ $\longrightarrow$ $\mathbf{T}_c = 173 \pm 8$ **MeV**

First Extensions into Region of Finite Net Baryon Densit

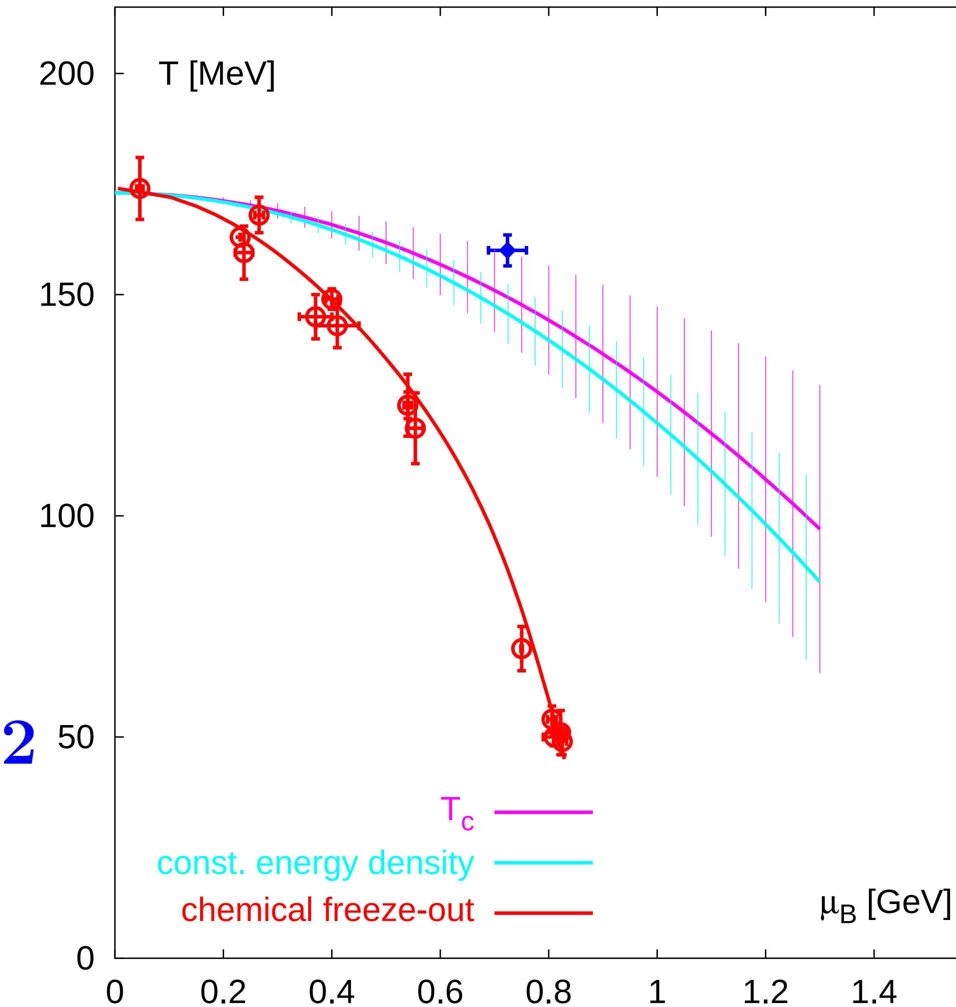
red data points:

chemical freeze-out points from

analysis of data

blue: critical point

Fodor and Katz, hep-lat/0106002



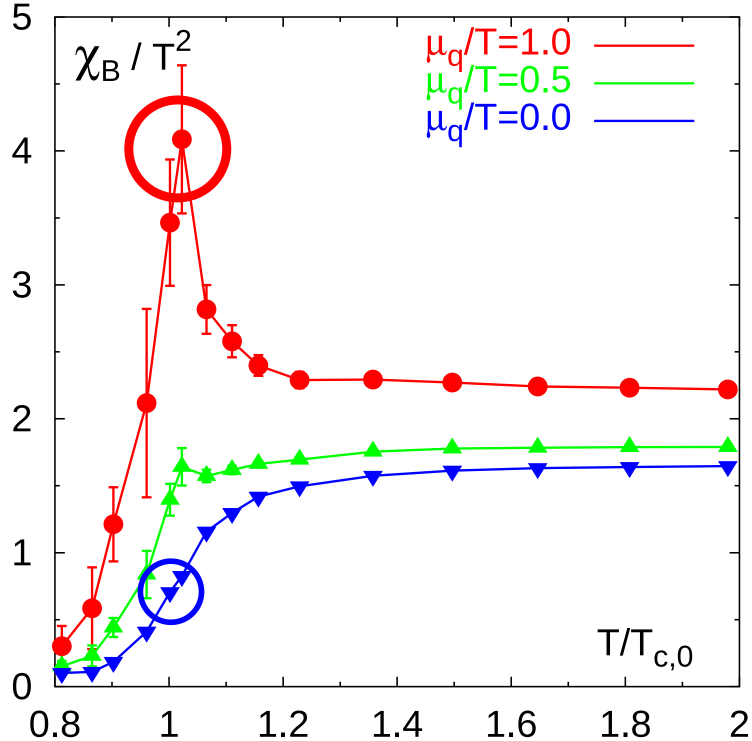
hatched: C.R.Allton et al. Bielefeld/Swansea, hep-lat/020401

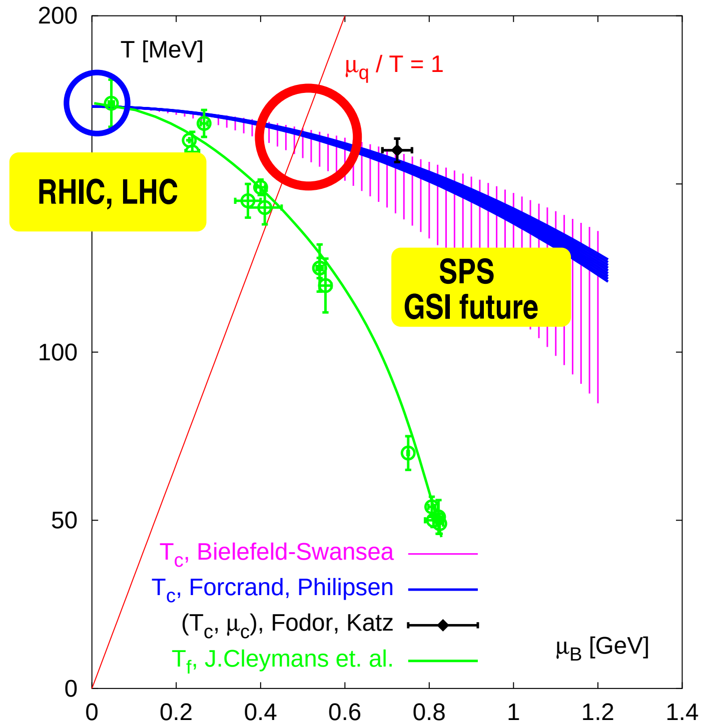
and P.de Forcrand, O. Philipsen, hep-lat/0209084

Fluctuations of the baryon number density ($\mu > 0$)

baryon number density fluctuations:
(Bielefeld-Swansea, in preparation)

$$\frac{\chi_B}{T^2} = \left(\frac{\mathrm{d}^2}{\mathrm{d}(\mu/T)^2} \frac{p}{T^4} \right)_{T \text{ fixed}}$$

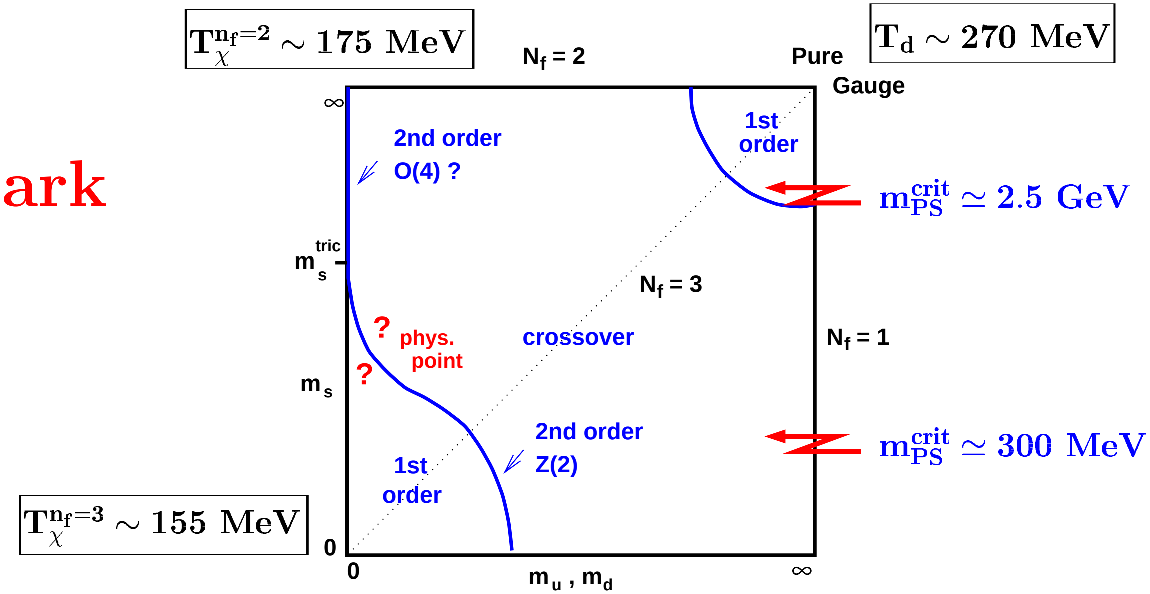




Order of the Phase Transition

key role of strange quark

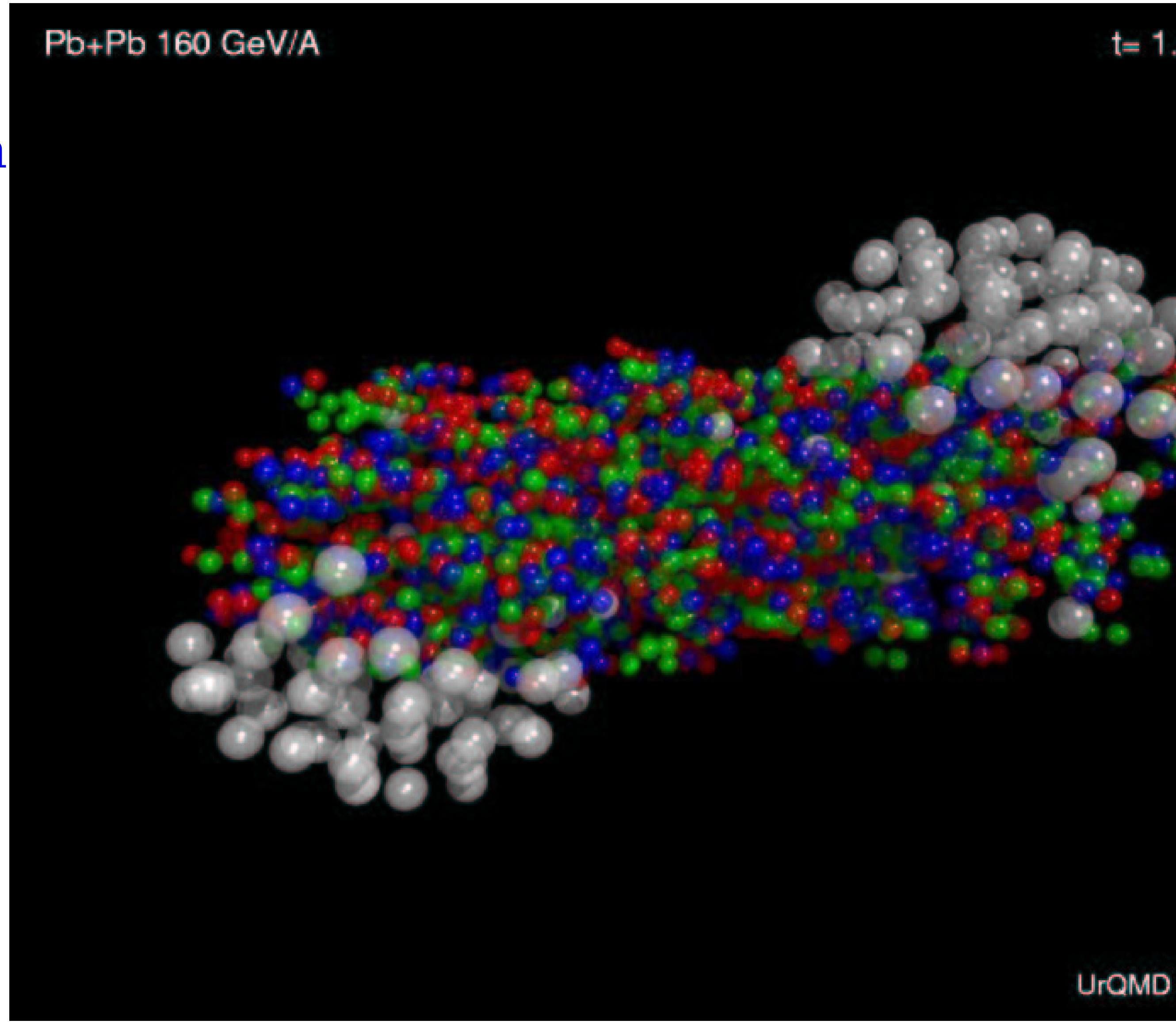
3-flavour phase diagram



Snapshot of a Pb – Pb Collision

SPS Energy

semi-central collision



white: hadrons colored: quarks and gluo

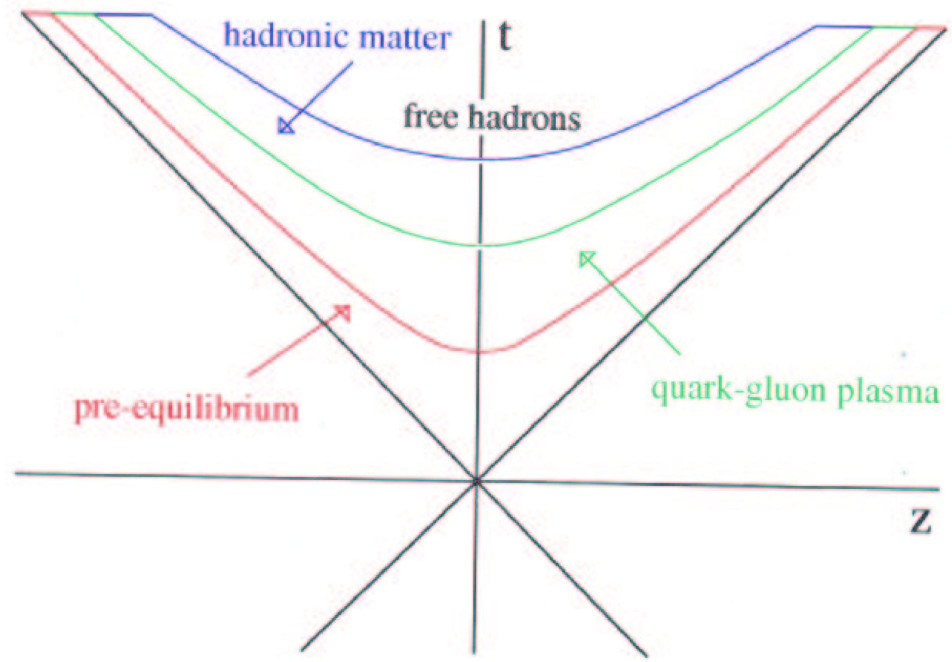
Space Time Development

1st stage: liberation of quarks and gluons

2nd stage: equilibration of quarks and gluons
→ QGP

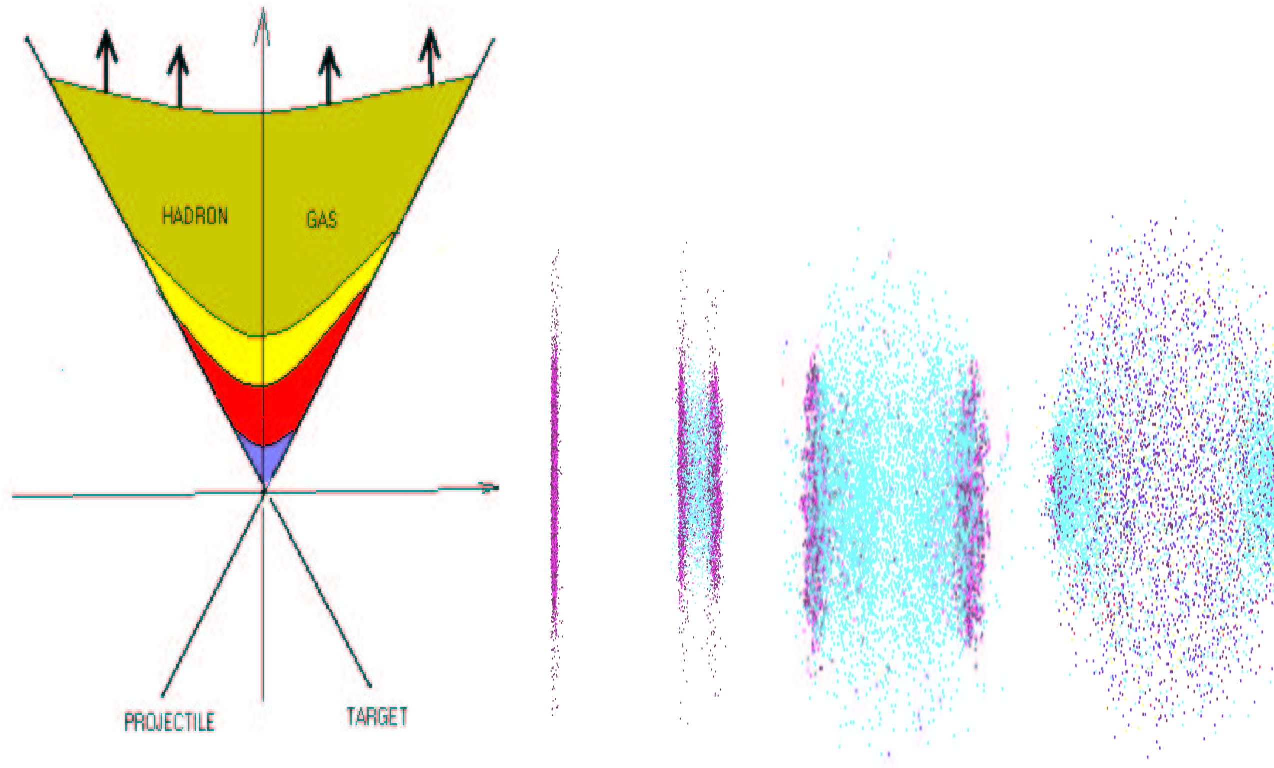
3rd stage: hadronization

4th stage: freeze-out



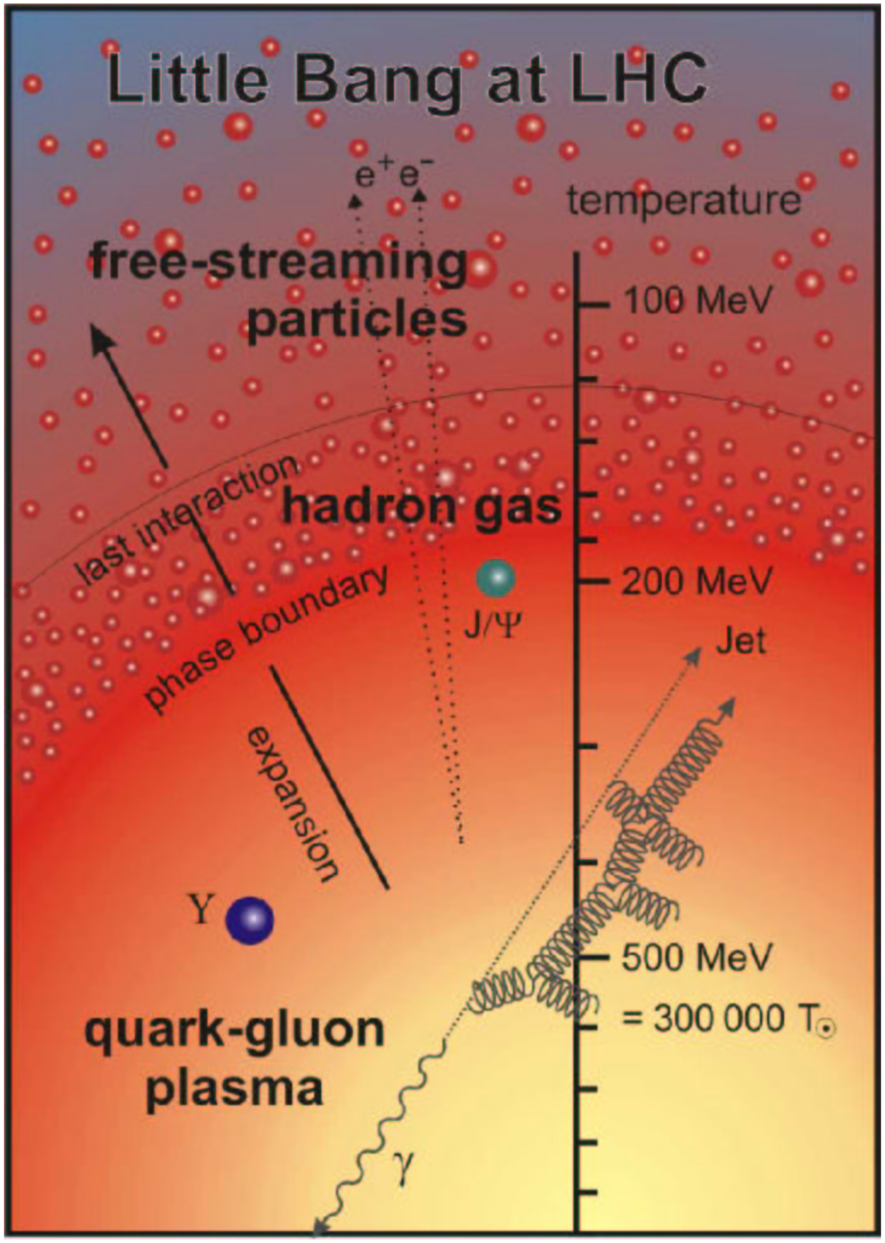
Schematics of Particle Production

development of "central region"



Evolution of the Fireball

signals of hot phase:
penetrating probes
jets, γ, lepton pairs



information on
phase boundary:
yields of produced hadons

Experimental Facilities

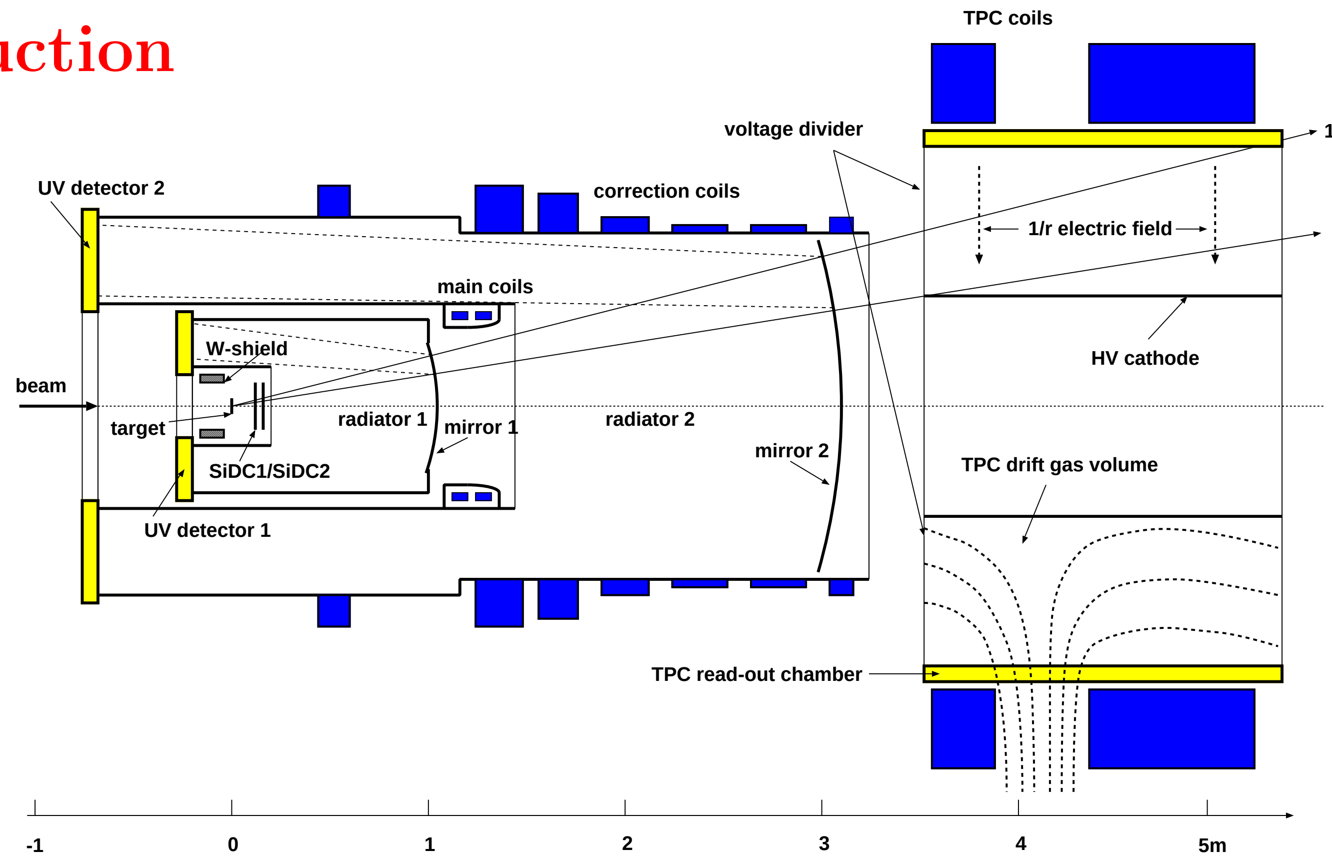
	fixed target		collider	
	AGS	SPS	RHIC	LHC
beam momentum	29 ·Z GeV/c	450 ·Z GeV/c	ea250·Z GeV/c	ea7000·Z GeV/c
projectile	p...Au	p...Pb	p...Au	p...Pb
energy available in c.m. system	Au+Au 600 GeV	Pb+Pb 3200 GeV	Au+Au 40 TeV	Pb+Pb 1150 TeV
hadrons produced per collision	900	2400	5500	30000

Accelerators and Experiments

- **BNL-AGS (1986 - 2002): $\sqrt{s} = 5.5$ GeV, Au + Au collisions**
  5 large experiments: E802/866/917, E810, E814/877, E864, E895.
- **CERN-SPS (1986 - 2004): $\sqrt{s} = 17$ GeV, Pb + Pb collisions**
  7 large experiments: WA80/98, NA35/49, NA38/50/60, NA NA45/CERES, WA97/NA57, NA52.
- **BNL-RHIC (from 2000): $\sqrt{s} = 200$ GeV, Au + Au collisions**
  4 large experiments: BRAHMS, PHENIX, PHOBOS, STA
- **CERN-LHC (from 2007): $\sqrt{s} = 5.5$ TeV, Pb + Pb collisions**
  3 large experiments: ATLAS, ALICE, CMS

NA45/CERES Experiment at CERN SPS

Study of e^+e^- Production



Since 1999:

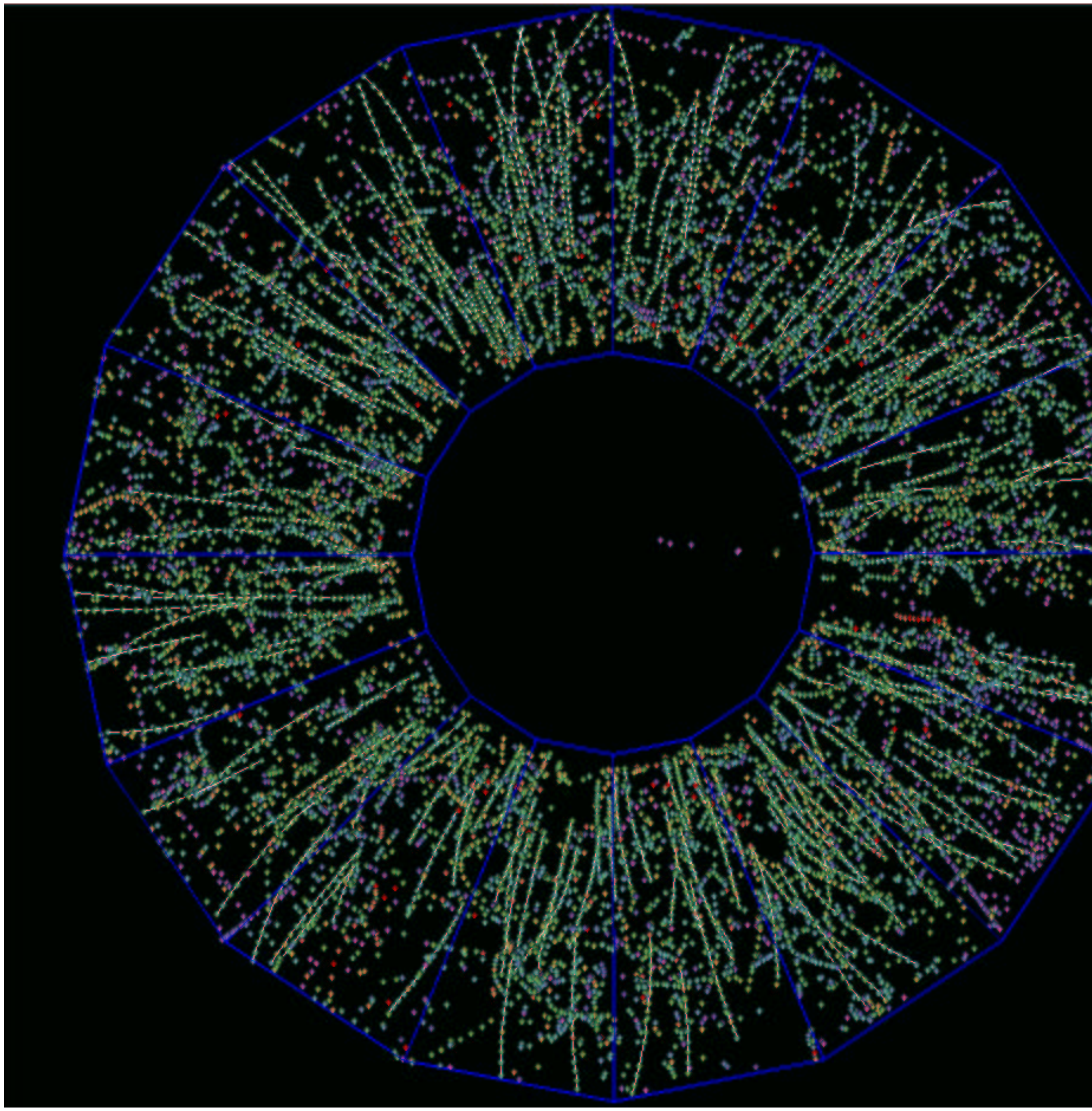
also hadronic observables

mass shift/width increase of ρ meson in hot medium

CERES Event Display

charged particle tracking
with TPC
10 m^3, $4{\cdot}10^6$ pixels

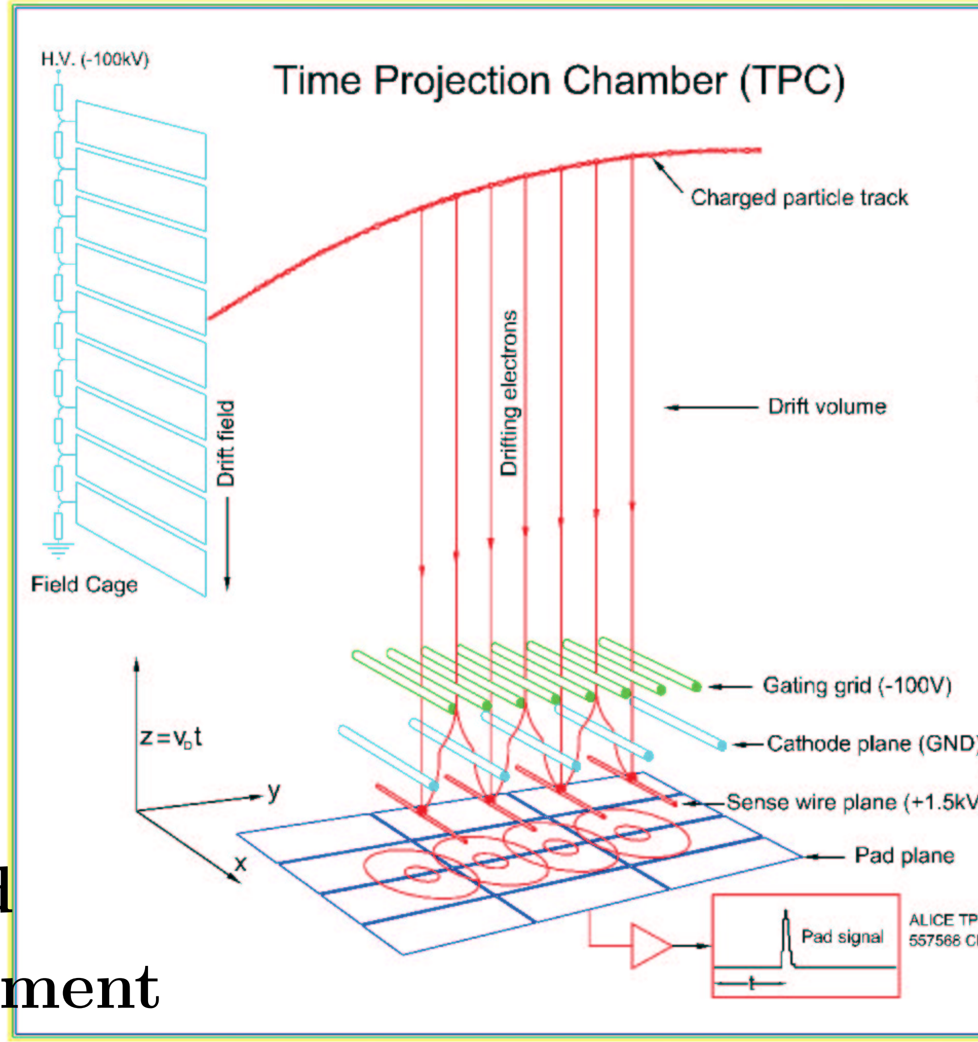
up to 400 charged particles



Time Projection Chamber (TPC) Principle

3-dimensional tracking

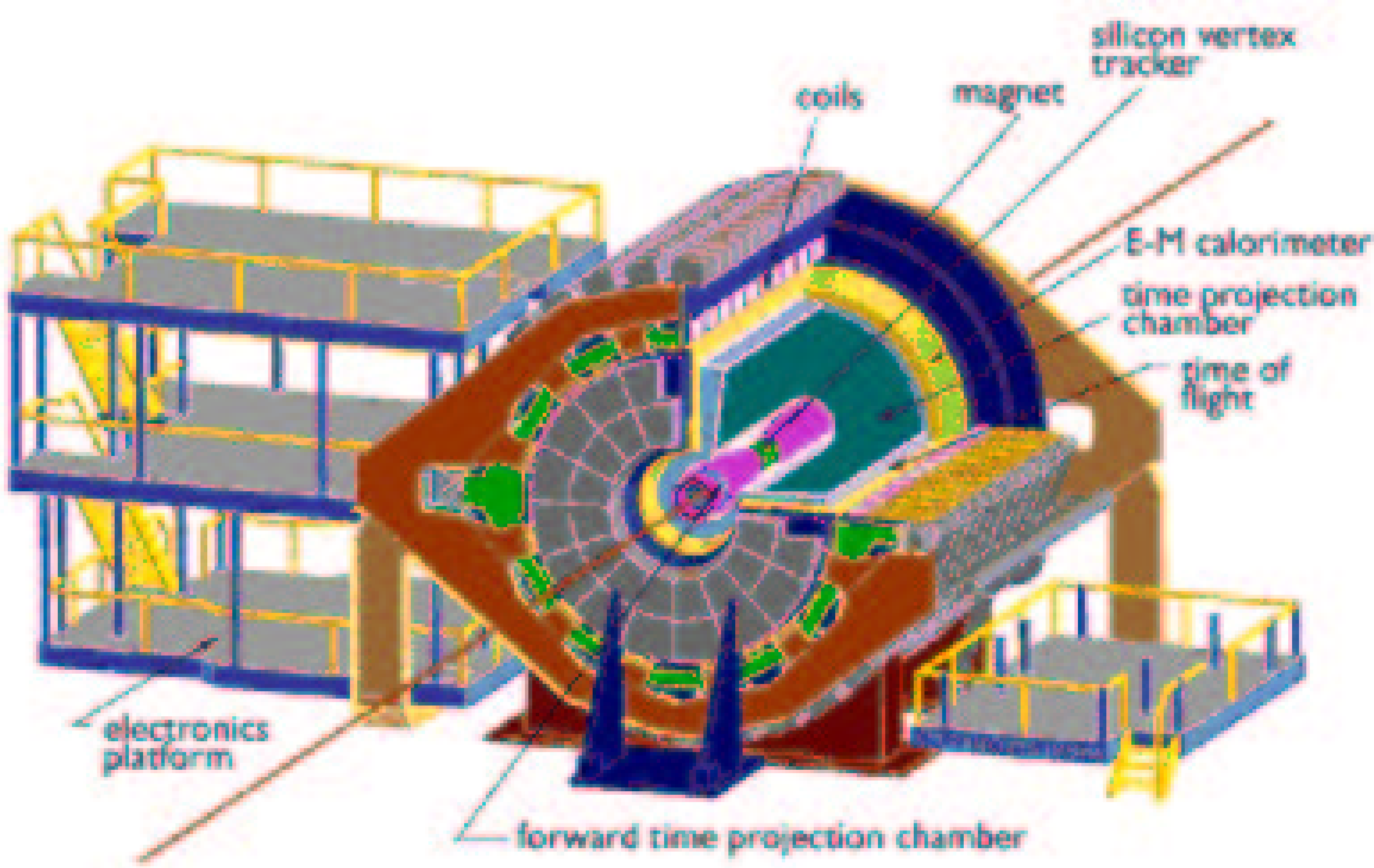
large volumes possible
90 m^3 and
$3 \cdot 10^8$ read out pixels
for ALICE TPC



information from drift time and
2-dimensional position measurement

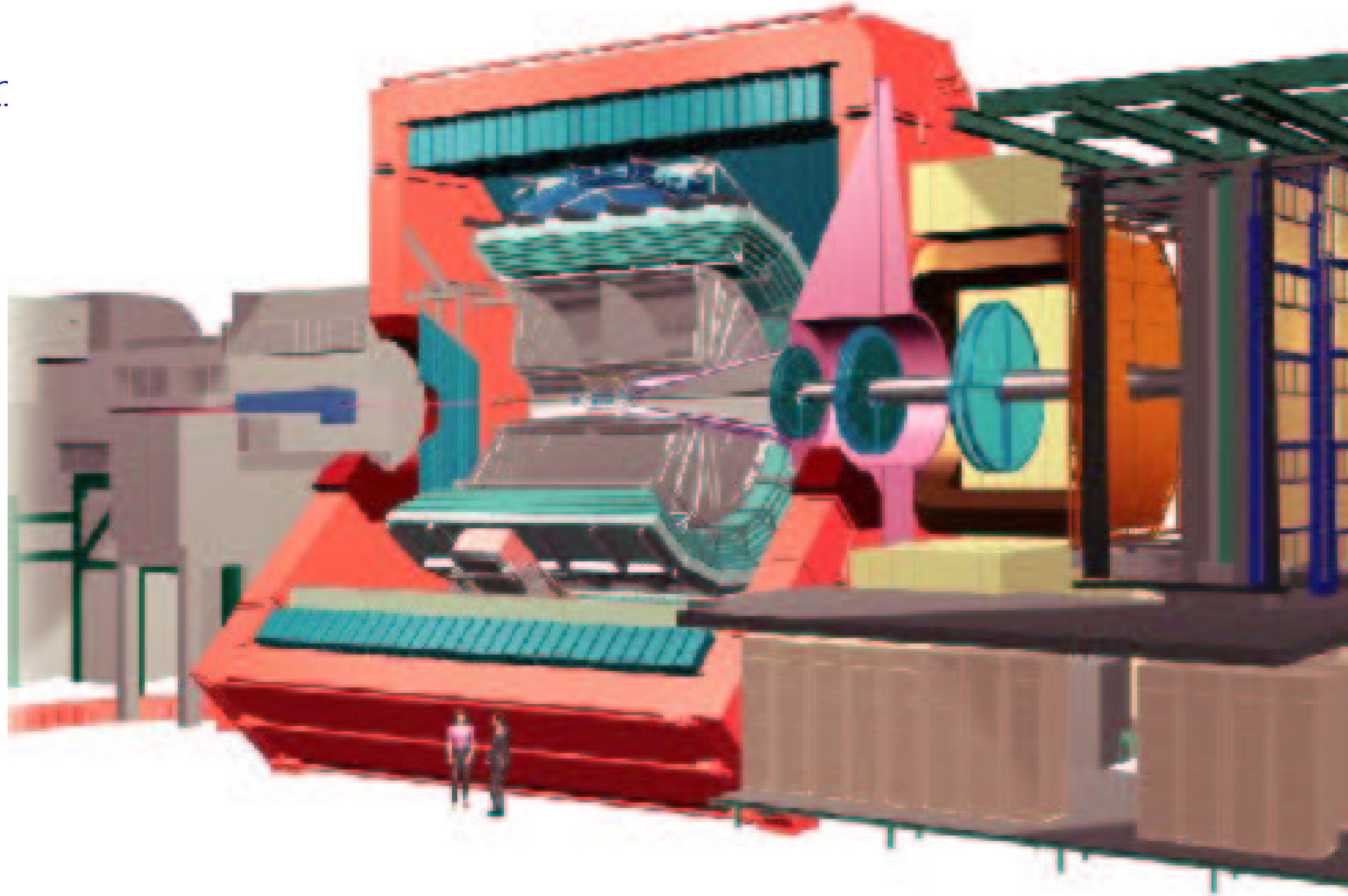
The STAR Experiment at RHIC

running since 2000 **Si Tracker + TPC + EM calorimeter**



The ALICE Experiment at LHC

running from
2007



central barrel: ITS, TPC, TRD, TOF +
forward muon detector

Estimates of Maximum Density from Data

1. from transverse energy distributions $\mathbf{dE_T/d}\eta$

   $\rightarrow$ **max. energy density** ϵ_{max}

2. use Bjorken formula

   $$\epsilon = \frac{1}{A_\perp} dE_T/d\eta \; d\eta/dz$$

3. from net baryon rapidity distribution $\mathbf{dN_{b-\bar{b}}/d}\eta$,

   $\rightarrow$ **max. baryon density** $\mathbf{n}_{baryon}^{max}$

4. again Bjorken formula

   $$\mathbf{n}_{baryon} = \frac{1}{A_\perp} dN_{b-\bar{b}}/d\eta \; d\eta/dz$$

5. maximal values at initial time given by $\mathbf{d}\eta/\mathbf{dz} = \mathbf{1}/\tau$

   with $\tau \approx 1\mathbf{fm}$.

Estimate of Initial Conditions

energy and baryon density a la Bjorken:

$$\epsilon = \frac{1}{A_\perp}\frac{dE_t}{d\eta}\frac{d\eta}{dz} \qquad \text{and} \qquad \rho_b = \frac{1}{A_\perp}\frac{dN_b}{d\eta}\frac{d\eta}{dz}$$

$d\eta/dz$ typically 1 fm for AGS and SPS

- **AGS 11 A GeV/c Au+Au**

$$dE_t/d\eta = 200\text{GeV} \quad dN_b/d\eta = 150$$

$\rightarrow \epsilon = 1.4\ \text{GeV/fm}^3$ **and** $\rho_b = 1.0/\text{fm}^3 \approx 6\rho_0$

T_i = 170 MeV

- **SPS 158 A GeV/c Pb+Pb**

$$dE_t/d\eta = 450\text{GeV} \quad dN_b/d\eta = 80$$

$\rightarrow \epsilon = 3\ \text{GeV/fm}^3$ **and** $\rho_b = 0.5/\text{fm}^3 \approx 3\rho_0$

T_i = 210 MeV

p = 0.7 GeV/fm^3 = 10^{35} Pa