Observation of the onset of deconfinement
and
Search for the critical point

Past and future of the ion physics at the CERN SPS

M. Gazdzicki
Frankfurt, Kielce

● The problems

PAST

● ● Observation of the onset of deconfinement

FUTURE

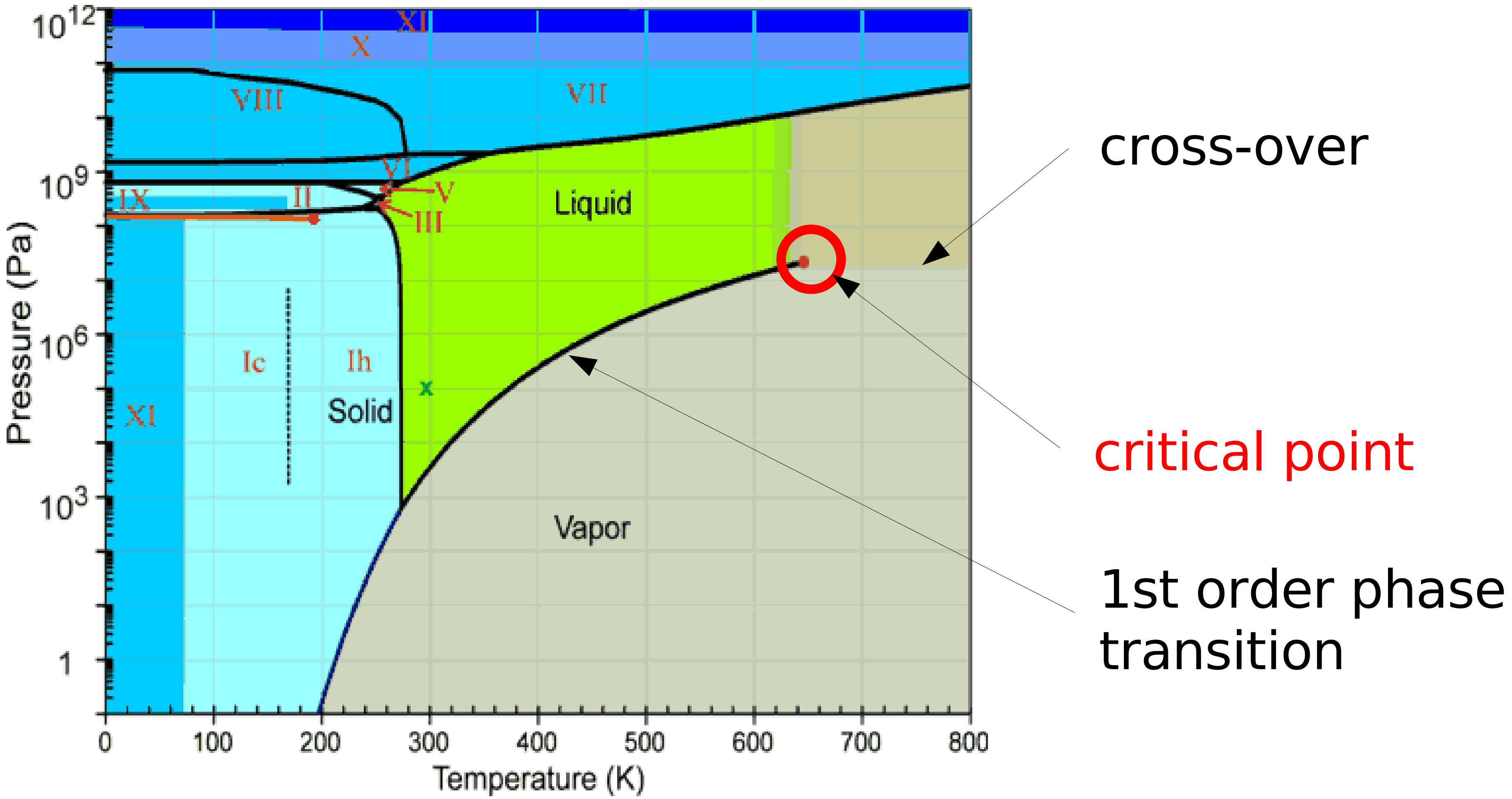
● ● ● Search for the critical point

● The problems

What are the phases of strongly interacting matter?

How do the transitions between them look like?

Phase diagram of water



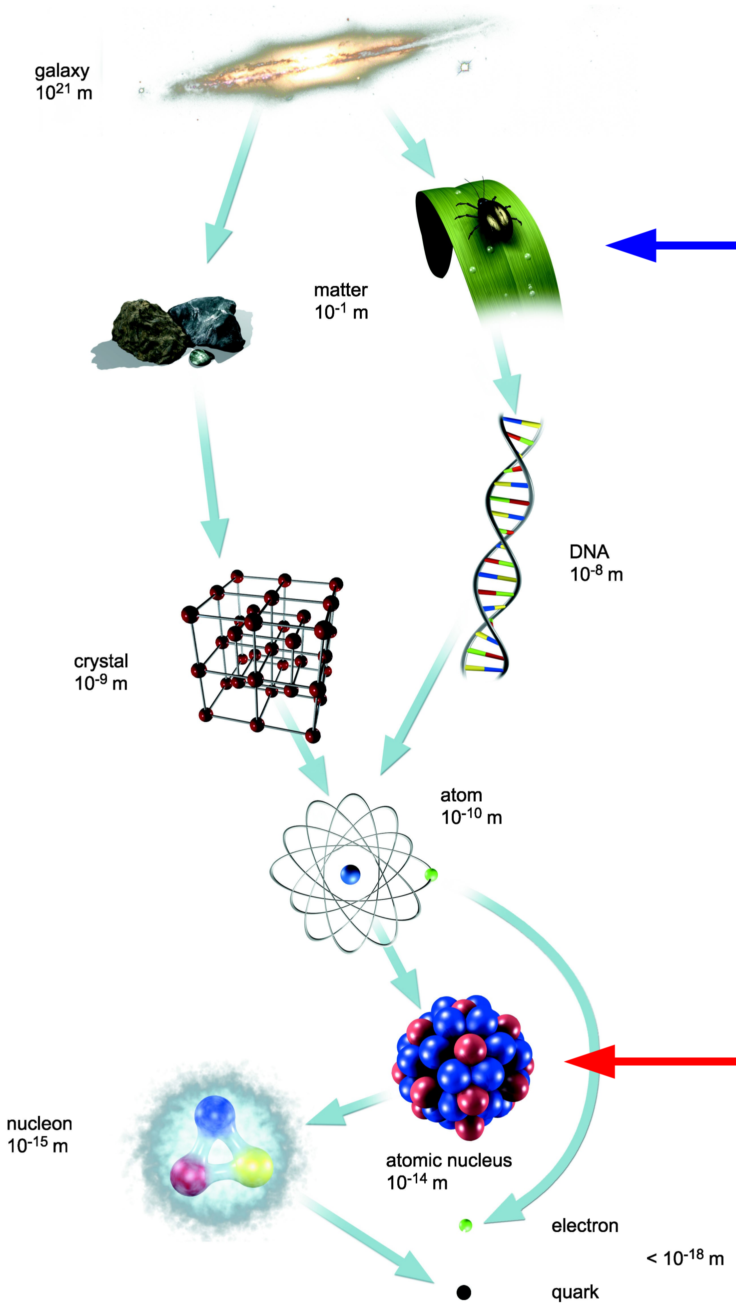
cross-over

critical point

1st order phase transition

the end point of a 1^{st} order line = a critical point of the 2^{nd} order
(at the critical point the phases start to be indistinguishable)

In our daily life ...

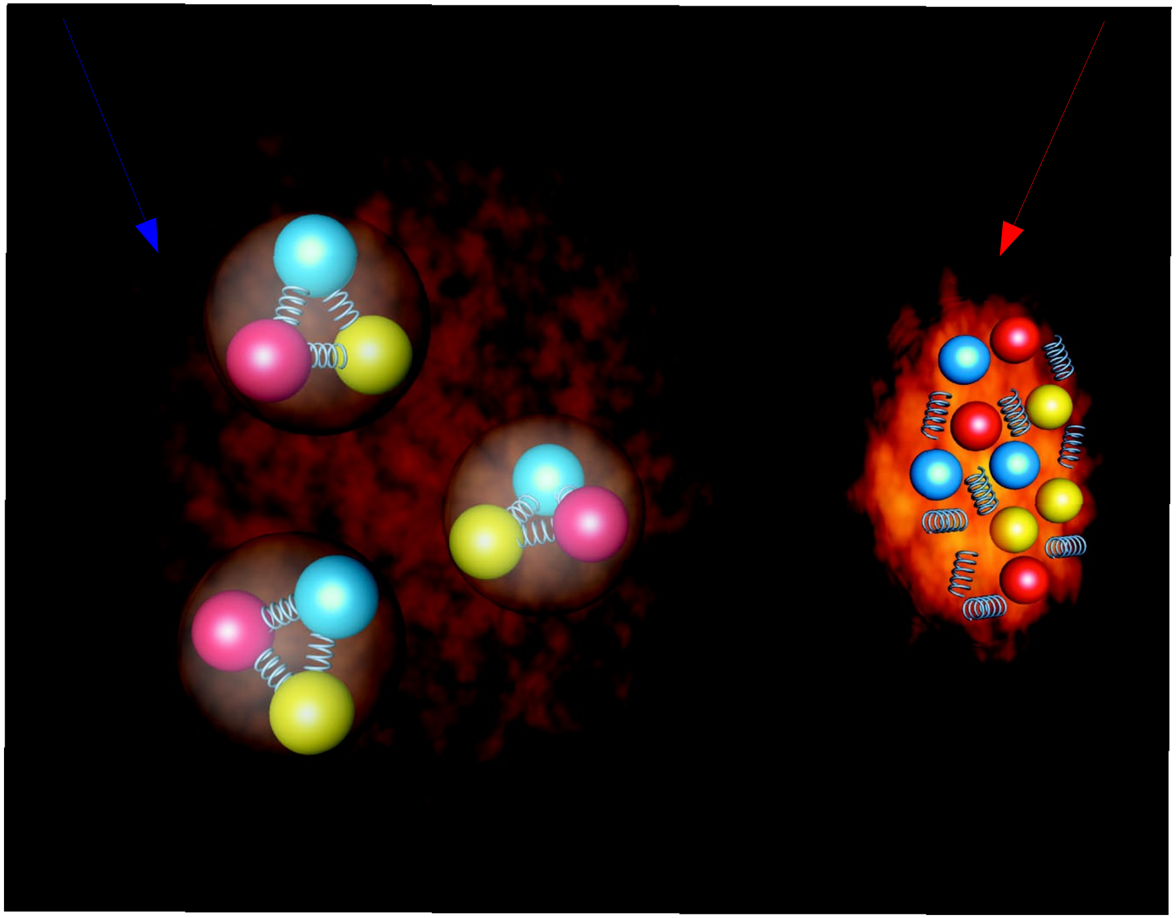


droplets of water

10^{-12}

droplets of strongly interacting matter

Two basic states of strongly interacting matter are expected

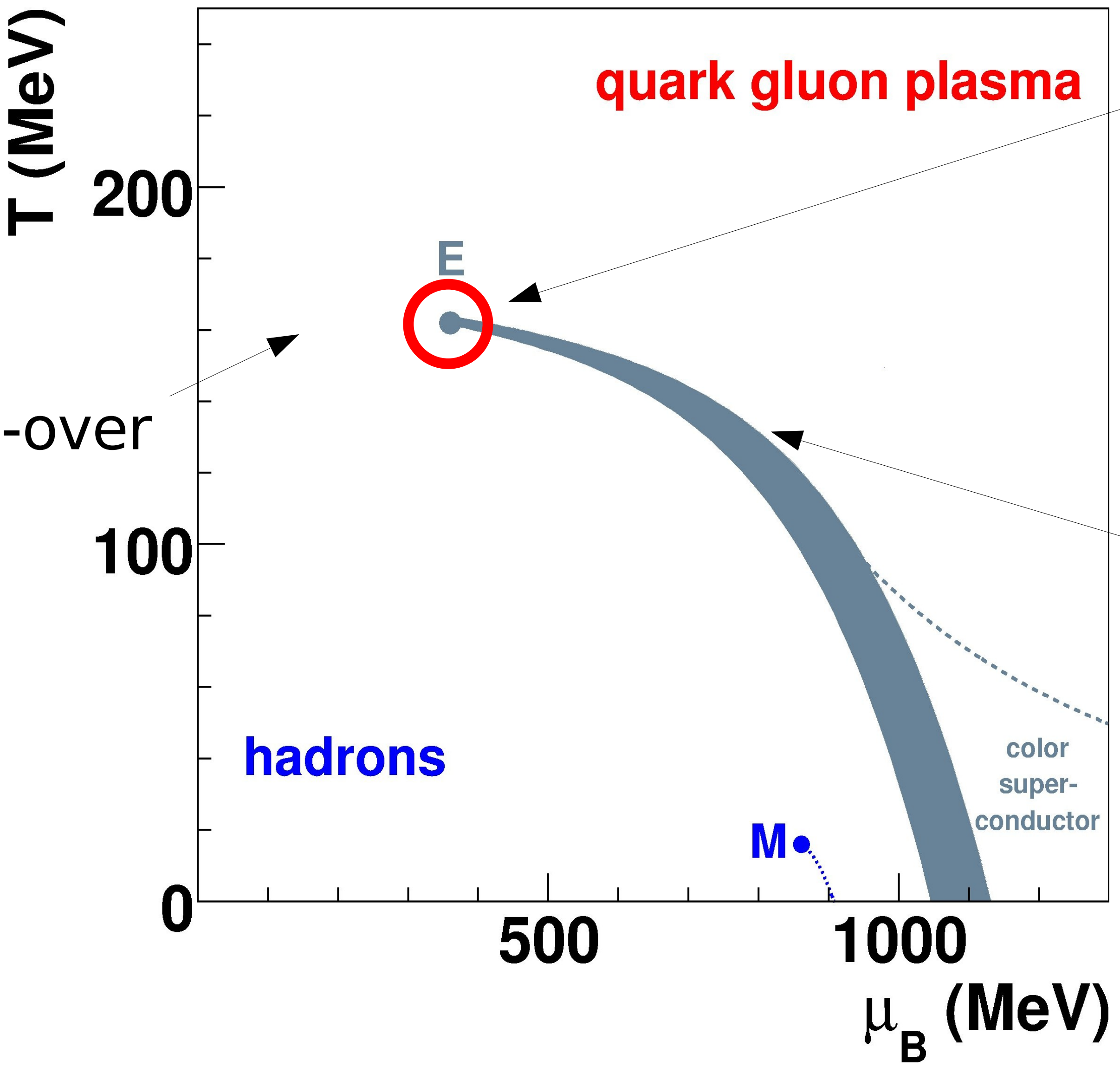


Hadron gas at low densities

Quark-gluon plasma at high densities

Collins, Perry 1975

Hypothetical phase diagram of strongly interacting matter



critical point

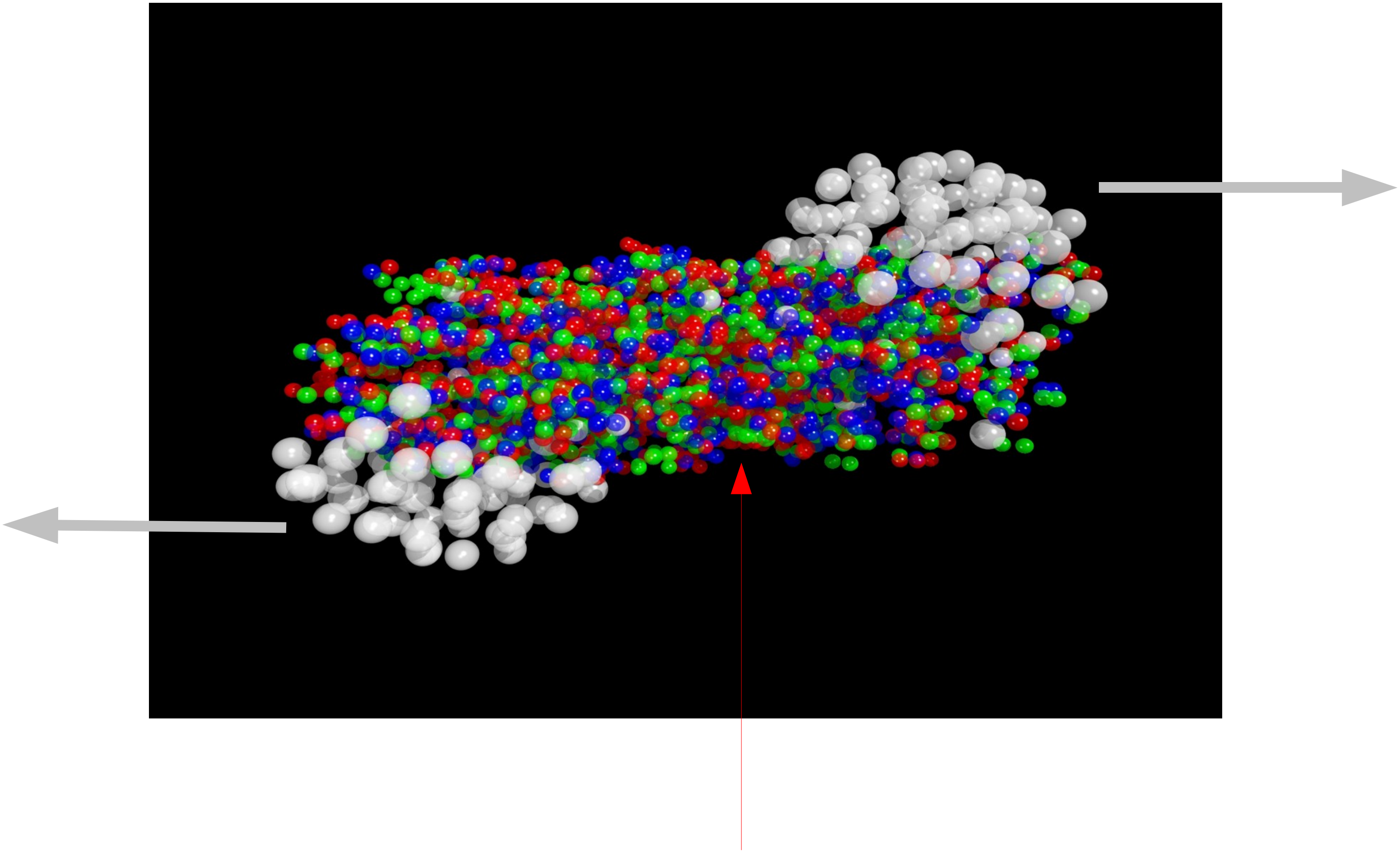
cross-over

1st order phase transition

How does the nature look like? →

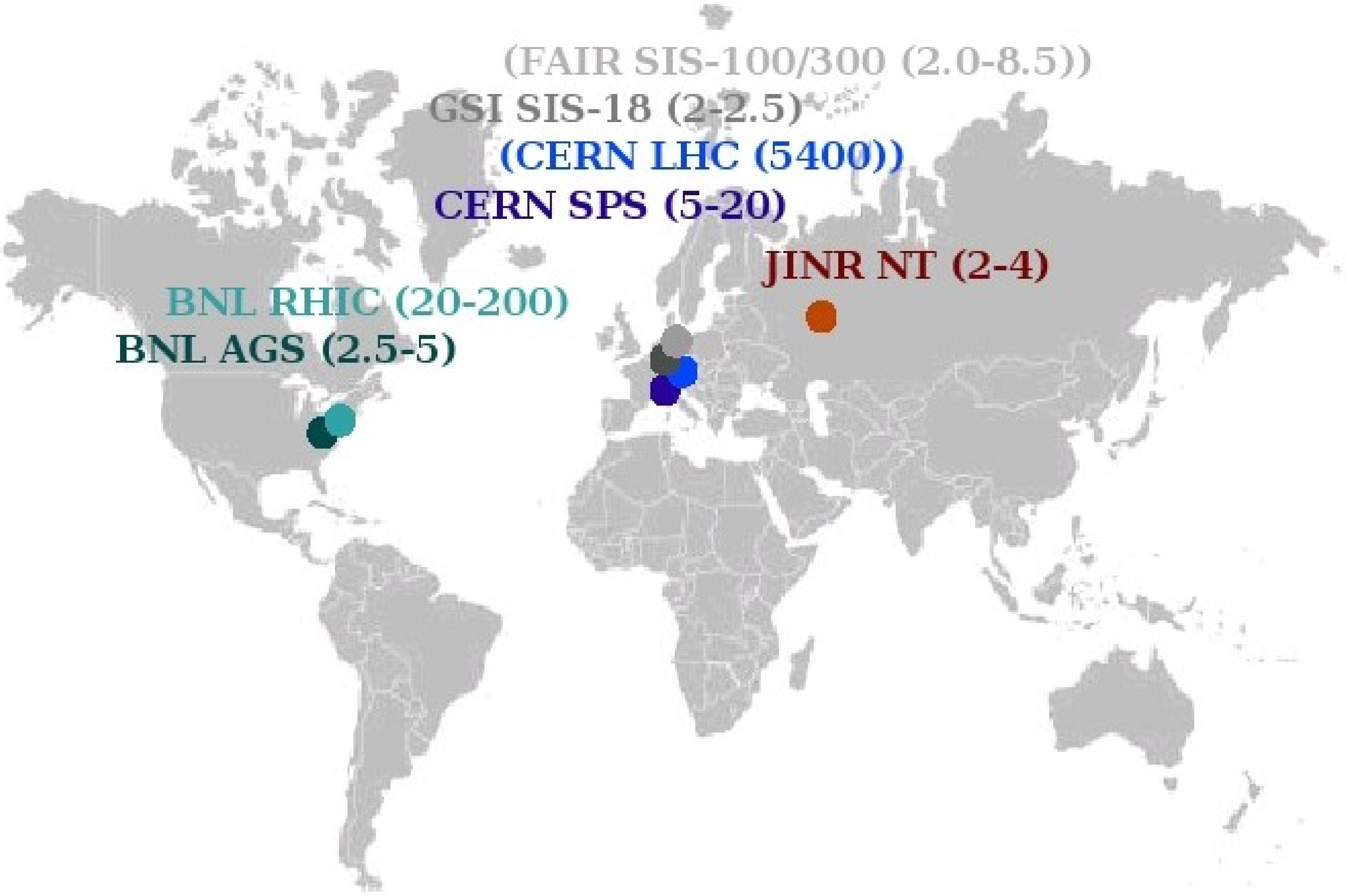
COLLISIONS OF TWO NUCLEI

-the only tool to study properties of strongly interacting matter in laboratory

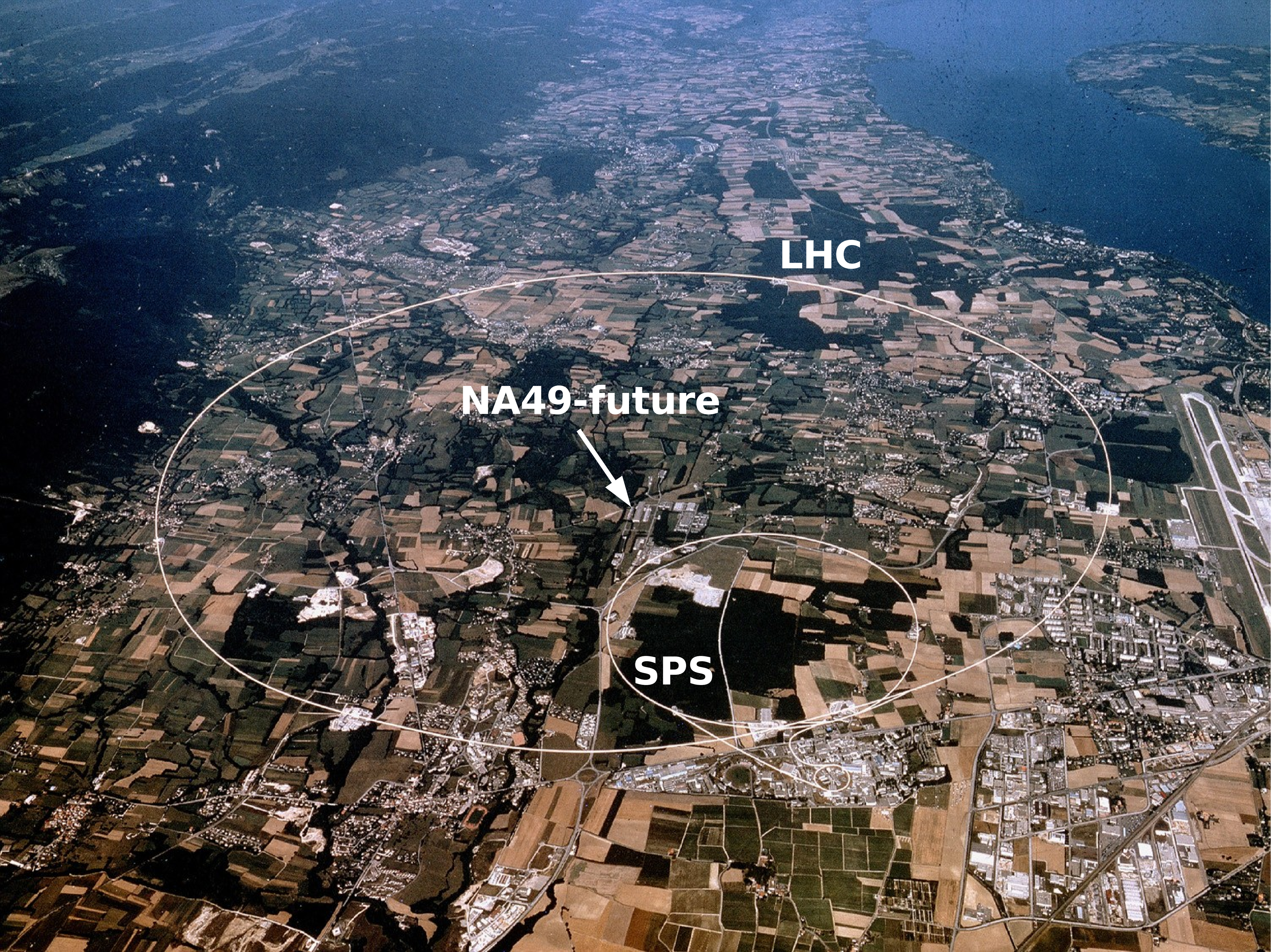


matter at high energy density

Heavy Ion Accelerators

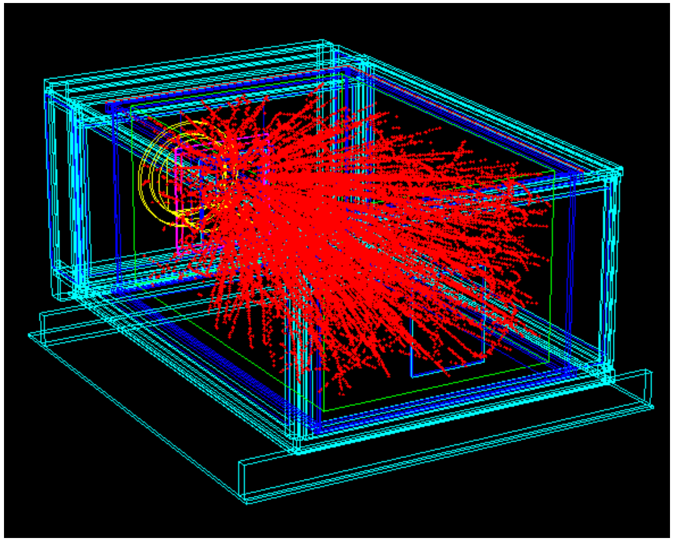


LAB ACC (center of mass energy per nucleon-nucleon pair in GeV)

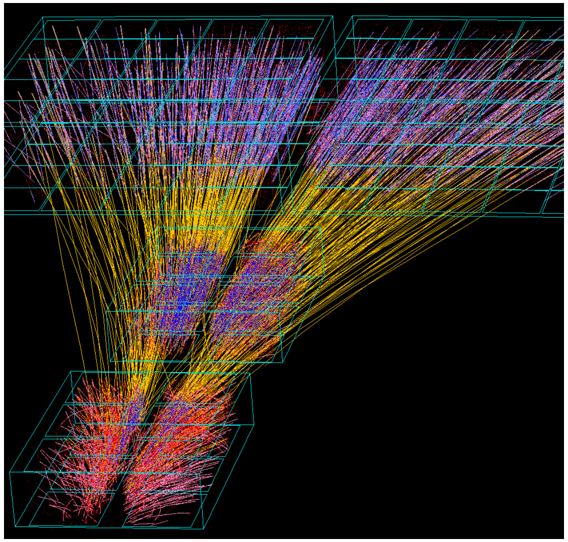

LHC
NA49-future
SPS

Heavy Ion Experiments

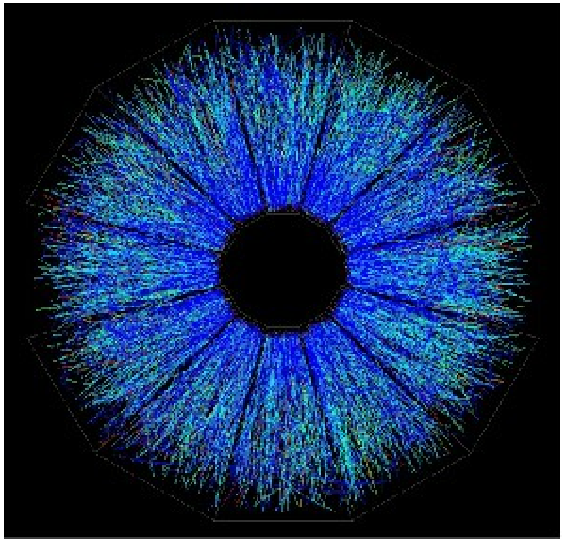
BNL AGS → CERN SPS → BNL RHIC



E895



NA49



STAR

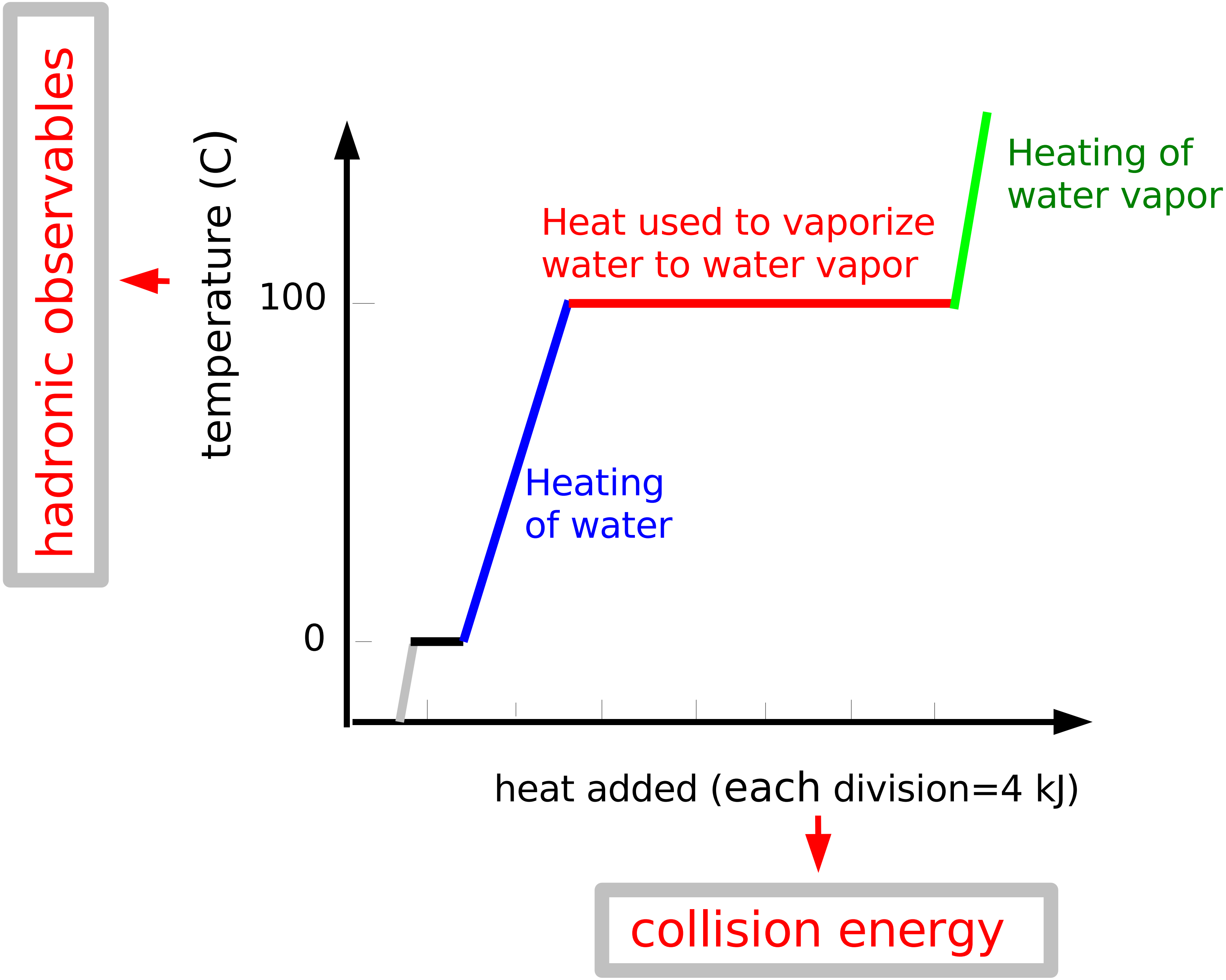
A large acceptance,
a high momentum resolution,
a good particle identification

PAST

● ● Observation of the onset of deconfinement

- The basic idea – the heating curve of water
- ■ The heating curves of strongly interacting matter

The basic idea – the heating curve of water



■ ■ Heating curves of strongly interacting matter

1994-1998: Basic idea and predictions

Statistical Model of the Early Stage → Kink, Horn

M.G., Gorenstein 1994-1999

1998-2002: Pb+Pb collisions at low SPS energies
(energy scan program at the CERN SPS)

Observation of the predicted anomalies in energy dependence of hadron production

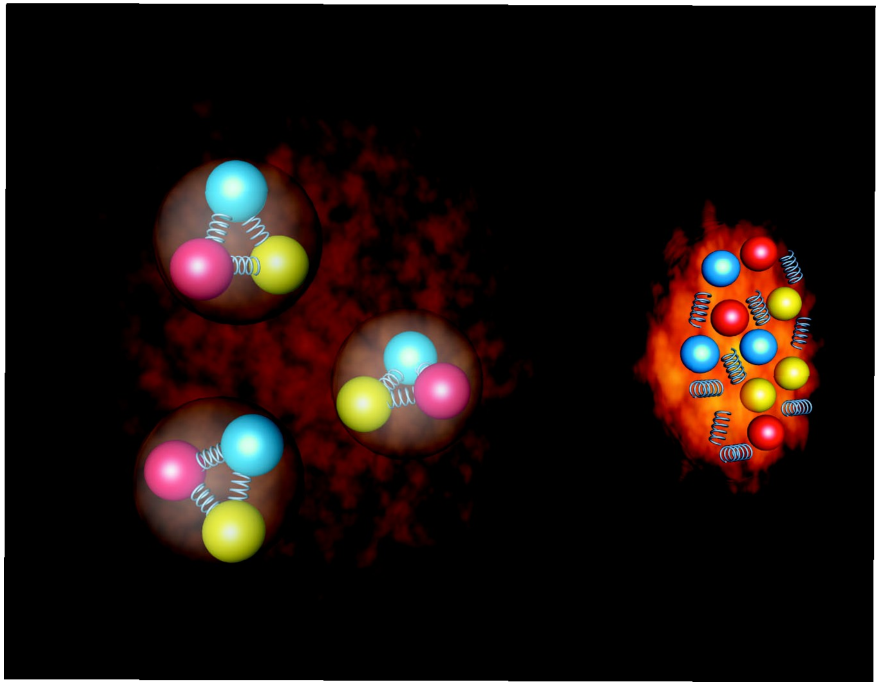
NA49 at the CERN SPS

2002-now: Search for other effects, experimental test

Step ..., more NA49 data, future measurements

Heating curves of strongly interacting matter

hadrons **mixed** **QGP**

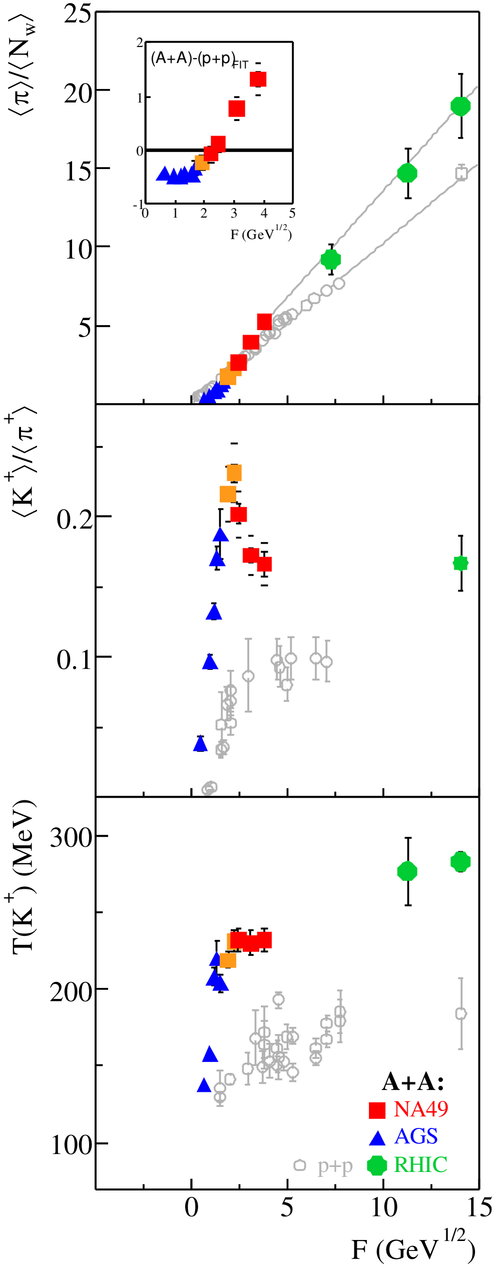


AGS **SPS** **RHIC**

collision energy

AGS **SPS** **RHIC**

hadronic observables



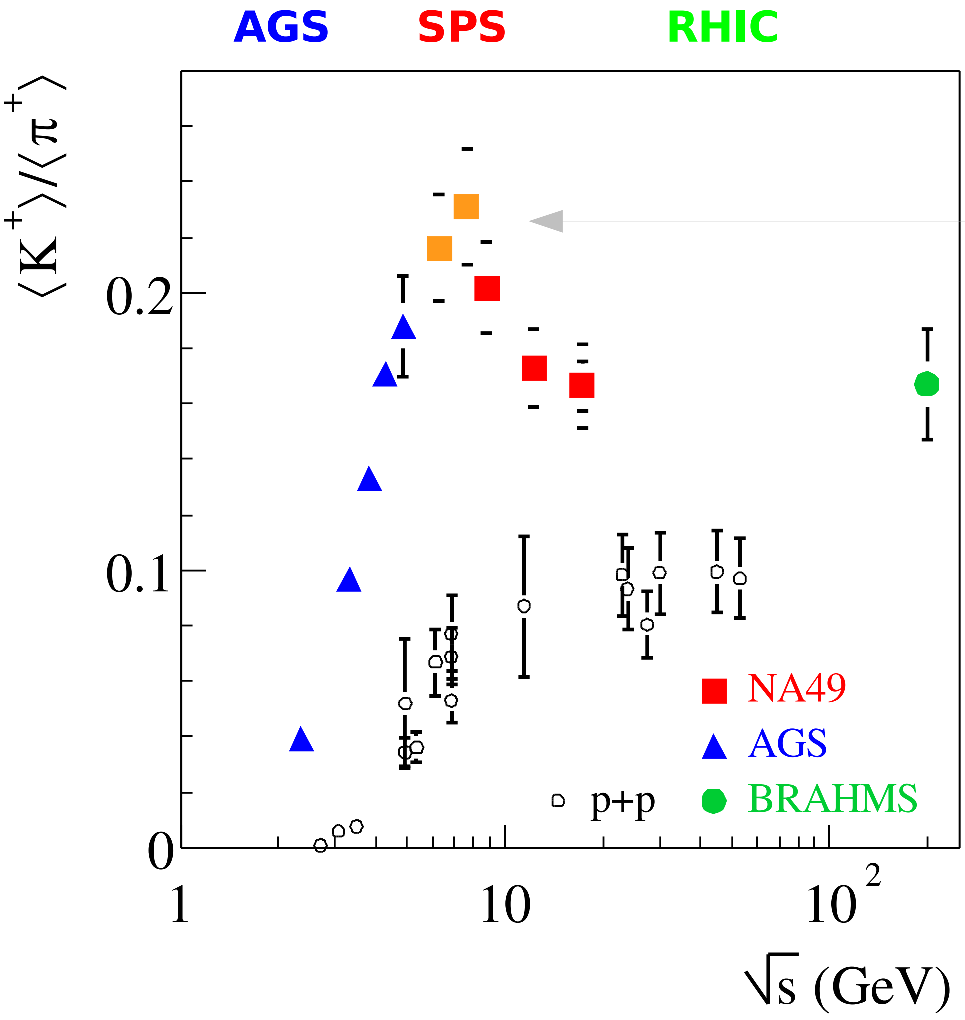
Kink

Horn

Step

collision energy

The horn in strangeness yield



Deconfinement

↓

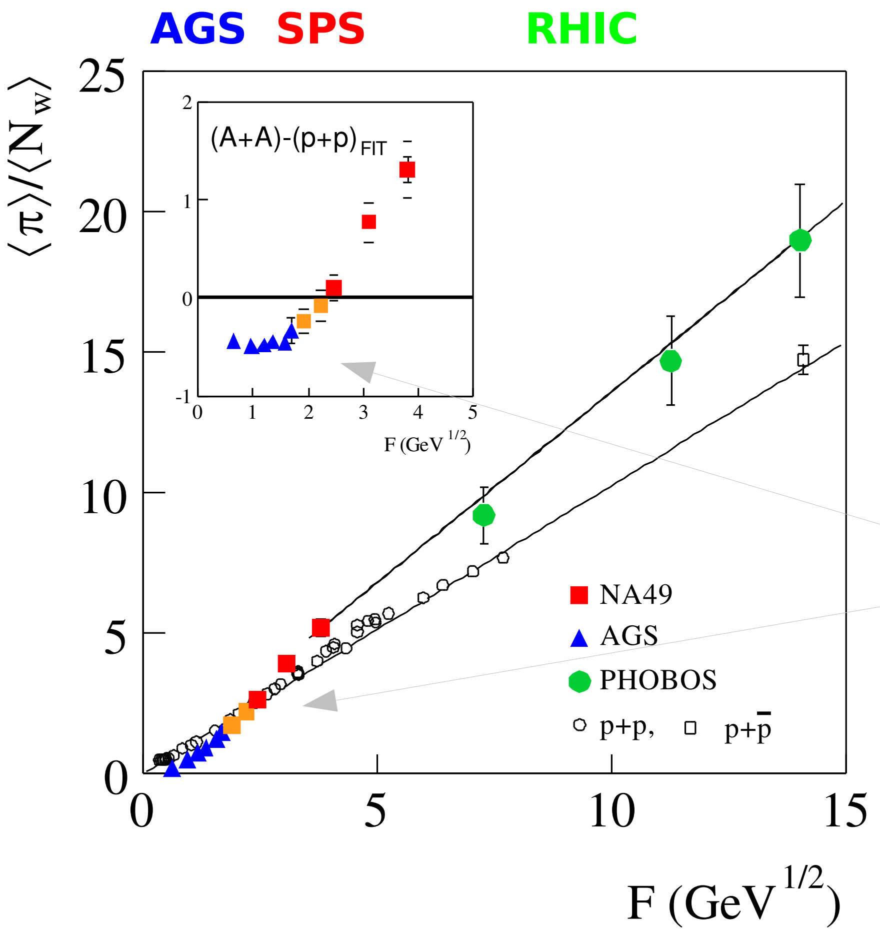
Decrease of masses of strangeness carriers and the number ratio of strange to non-strange degrees of freedom

↓

A sharp maximum in the strangeness to pion ratio

M.G., Gorenstein

The kink in pion multiplicity



Deconfinement

↓

Increased entropy production

↓

Steepening of the increase of pion production

$$\langle \pi \rangle \sim g^{1/4} F - \epsilon$$

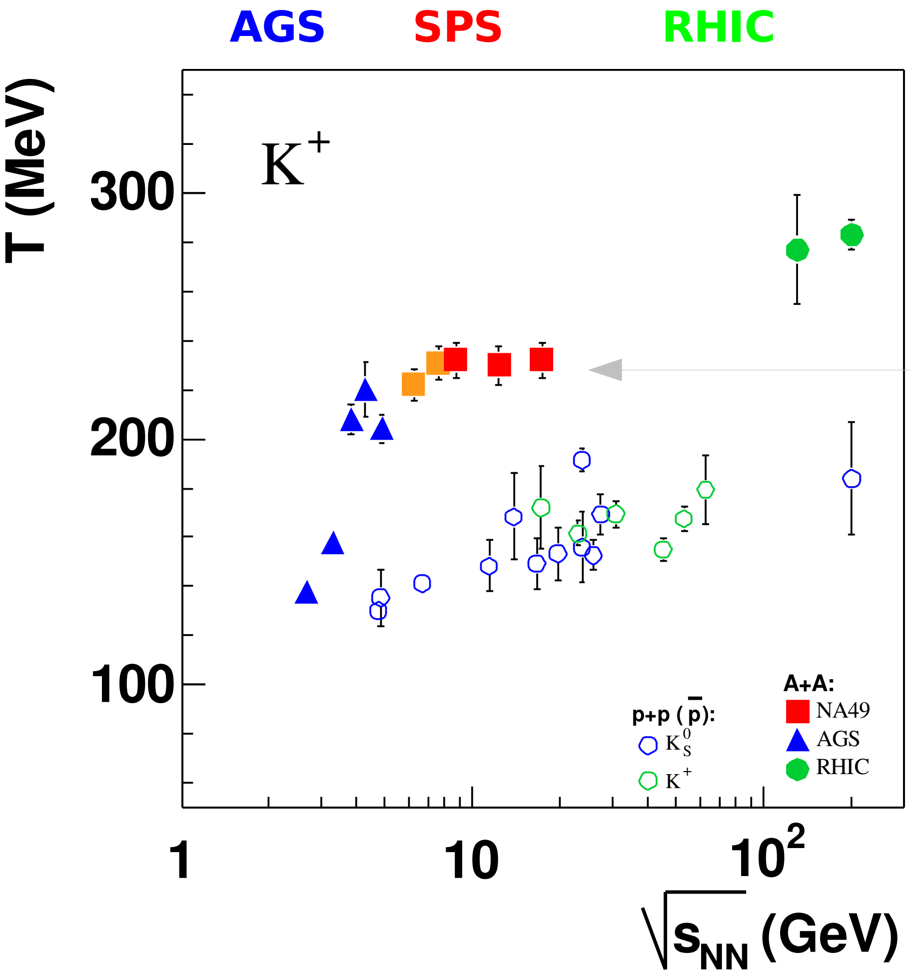
$$F \approx \sqrt{\sqrt{s_{NN}}}$$

$\langle \pi \rangle$ - total pion multiplicity

$\langle N_W \rangle$ - number of interacting nucleons

M.G., Gorenstein

The step in m_T slopes



Deconfinement

↓

Constant temperature and pressure in the mixed phase region

↓

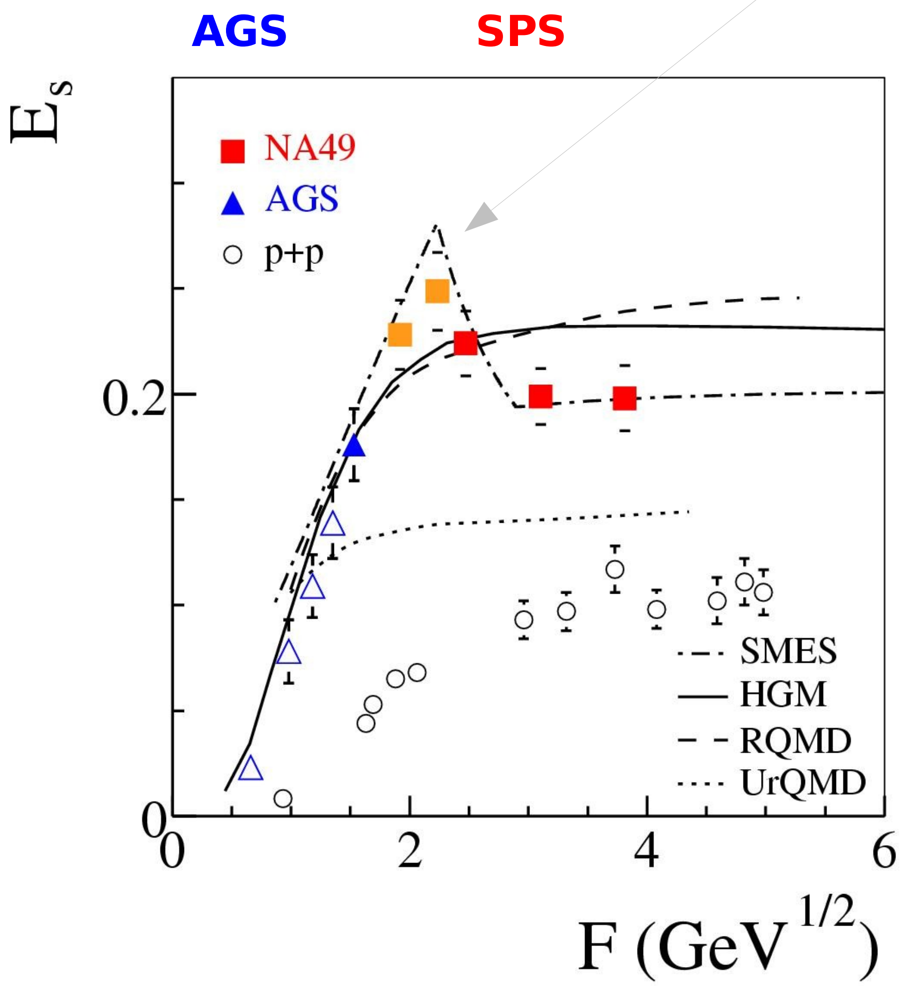
Weaker energy dependence of the shape of transverse mass spectra

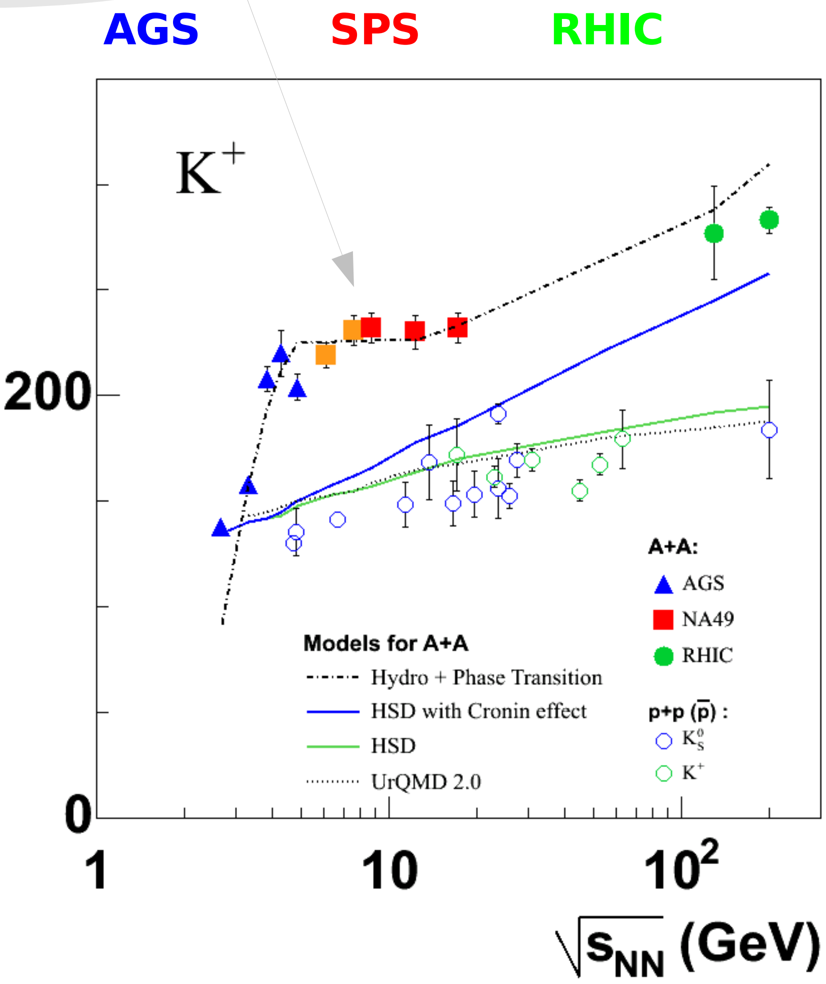
T – inverse slope parameter of transverse mass spectra

Shuryak, van Hove
Gorenstein, M.G., Bugaev

The models

Models with the
1st order phase transition
reproduce the data





$$E_S = (\langle \Lambda \rangle + \langle K + \overline{K} \rangle)/\langle \pi \rangle$$

... but consistent model description is still missing

Searches for further signals of the onset of deconfinement:

+ two-pion correlations

Akkelin, Sinyukov

see Sinyukov's talk

+ longitudinal expansion

Bleicher

+ fluctuations

MIshustin
M.G., Gorenstein

see Mishustin's and MG's talks

Summary of ● ●

I Several anomalies in hadron production are observed at low SPS energies

II The onset of observed anomalies is located at about 30*A* GeV

III The anomalies cannot be reproduced by the models without phase transition

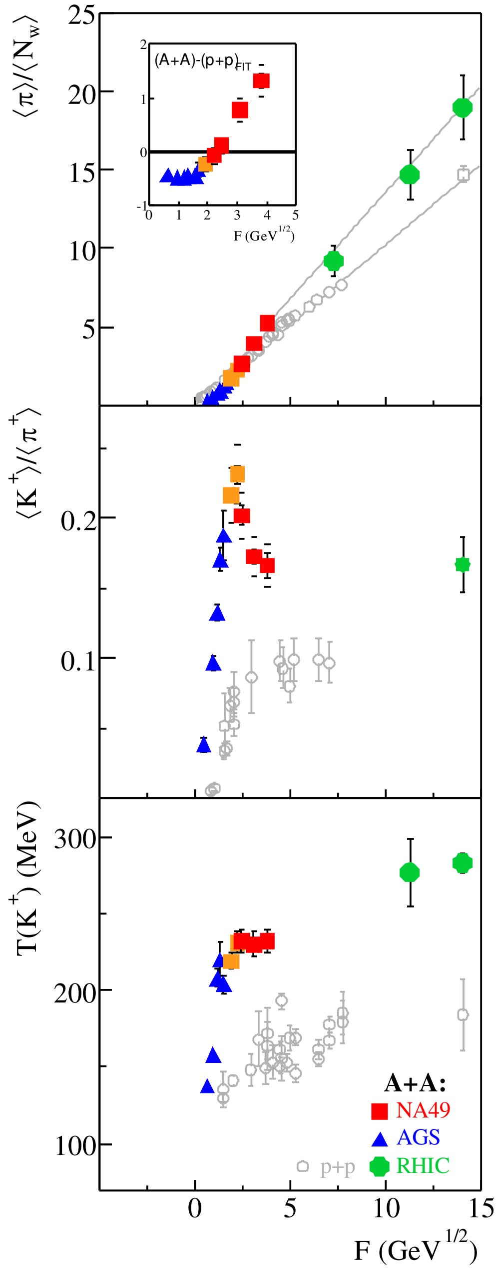
IIII Measured rapid changes are consistent with models assuming 1st order PT

↓

FUTURE

AGS SPS RHIC

hadronic observables



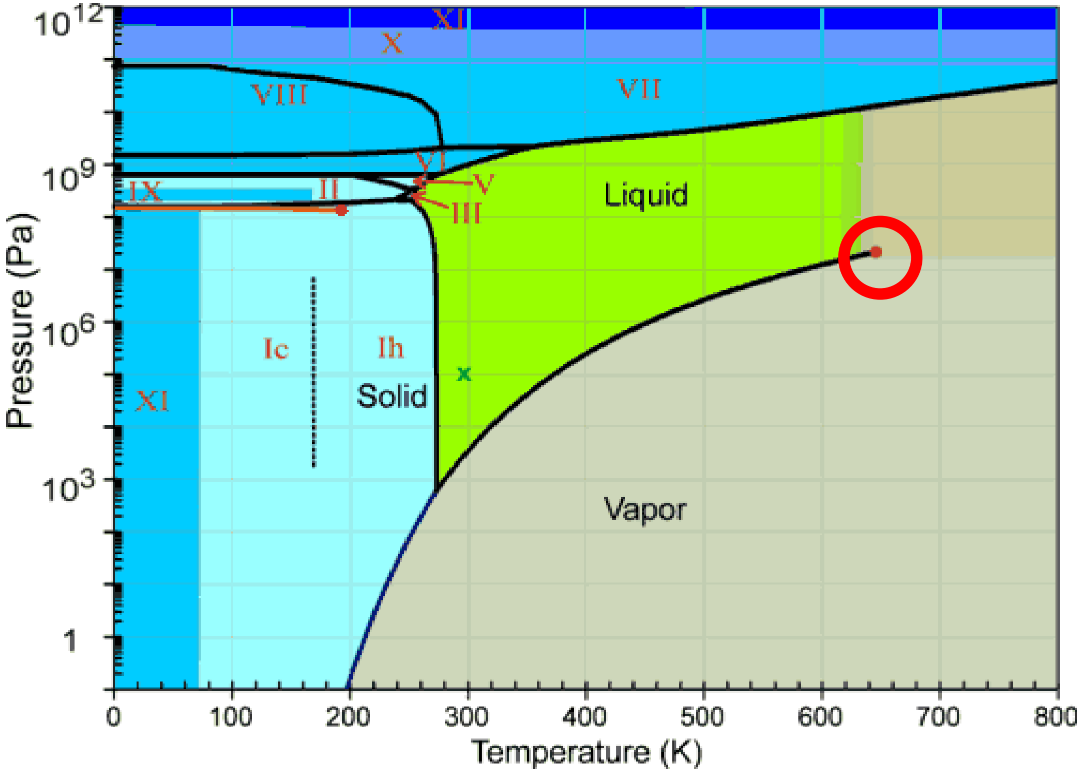
collision energy

FUTURE

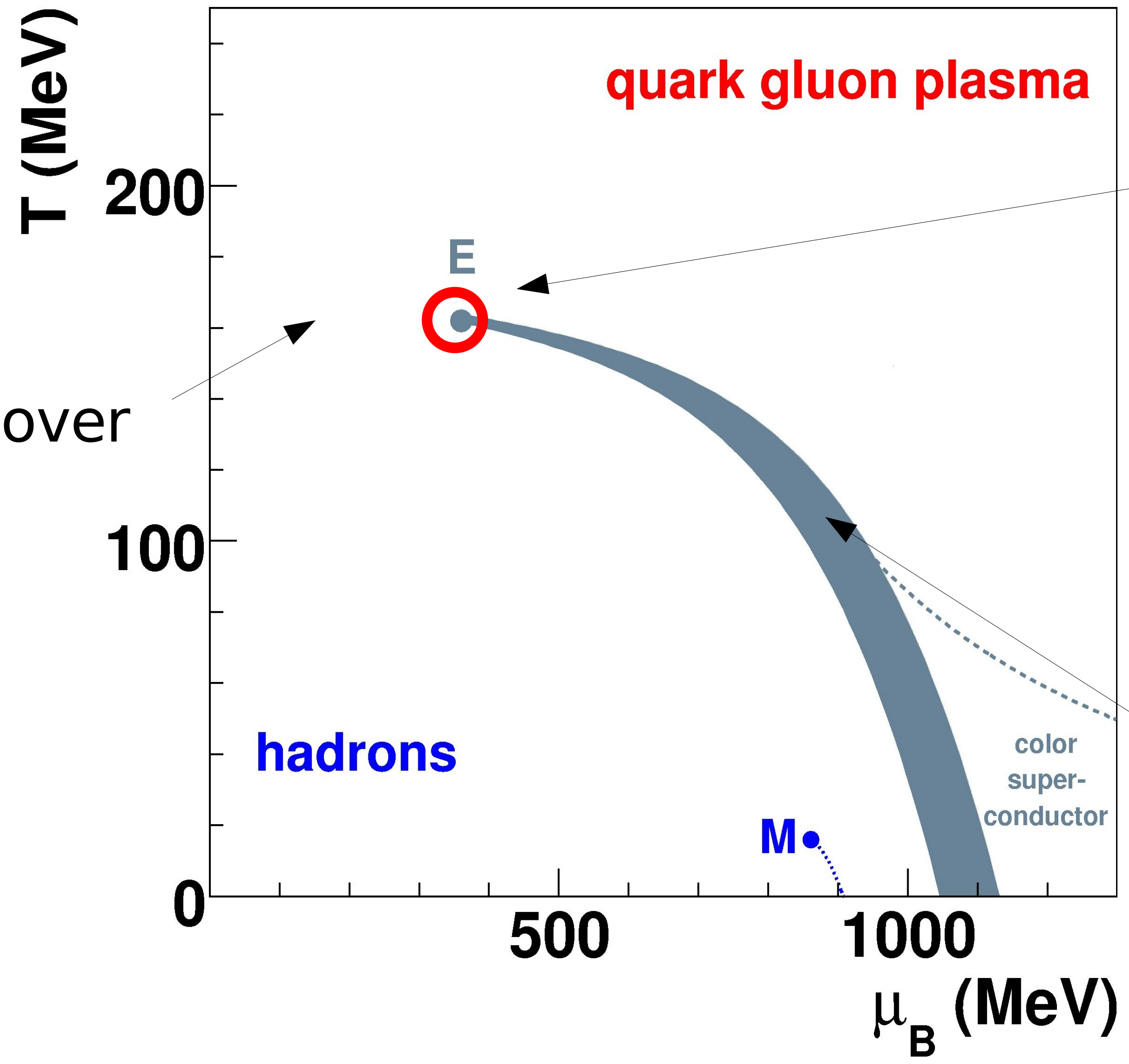
● ● ● Search for the critical point

- The critical point and its location

- Search for the critical point
  of strongly interacting matter



The critical point and its location



critical point

Casalbuoni et al. 1989

and its location
(lattice QCD)

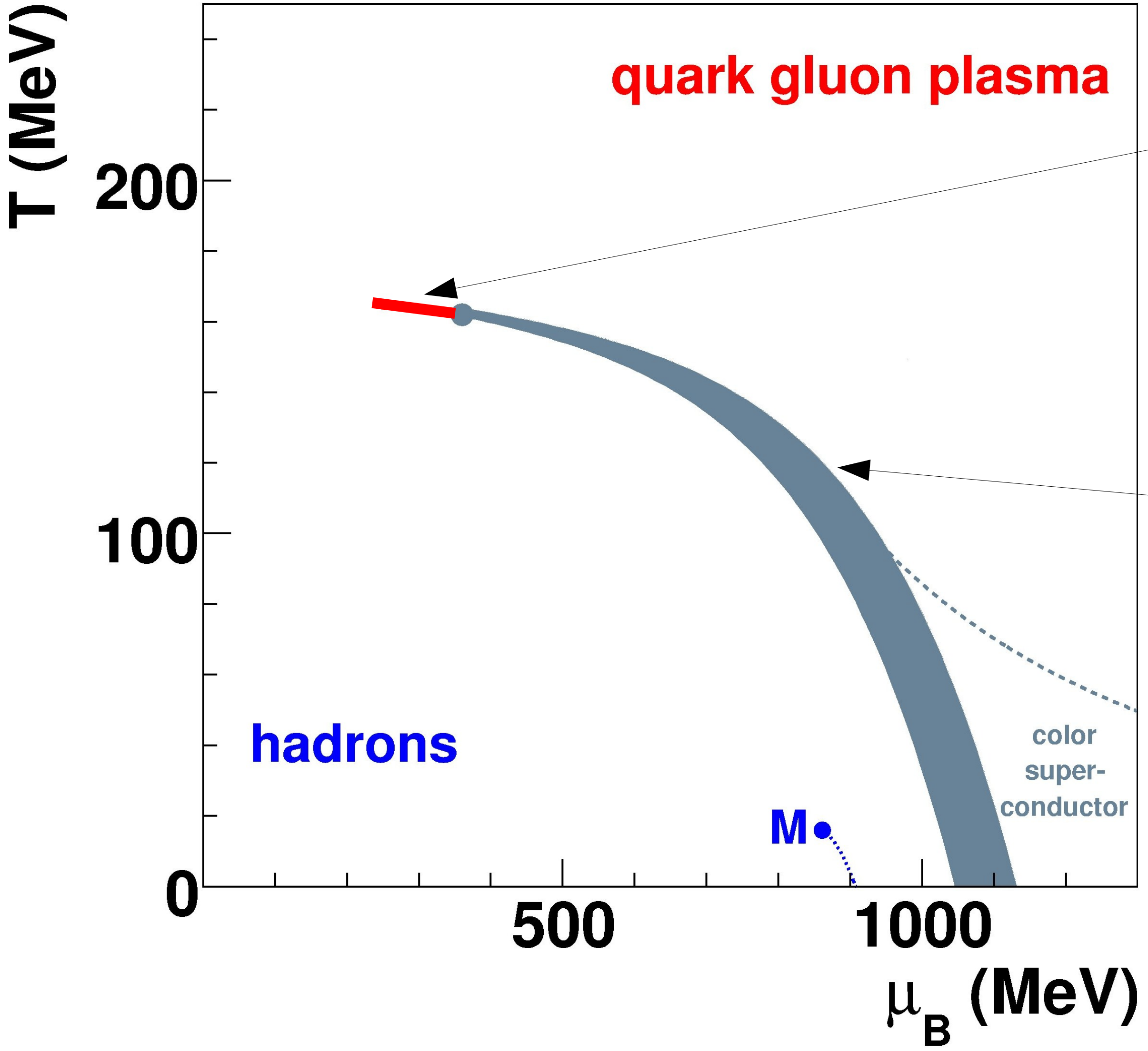
Fodor, Katz,
Ejiri et al. 2005

cross-over

1st order phase
transition

or the critical line?

a quark-gluon bag model



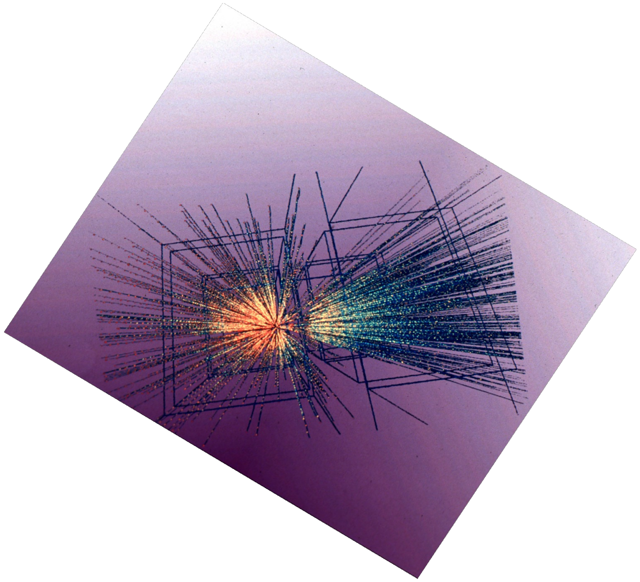
critical line

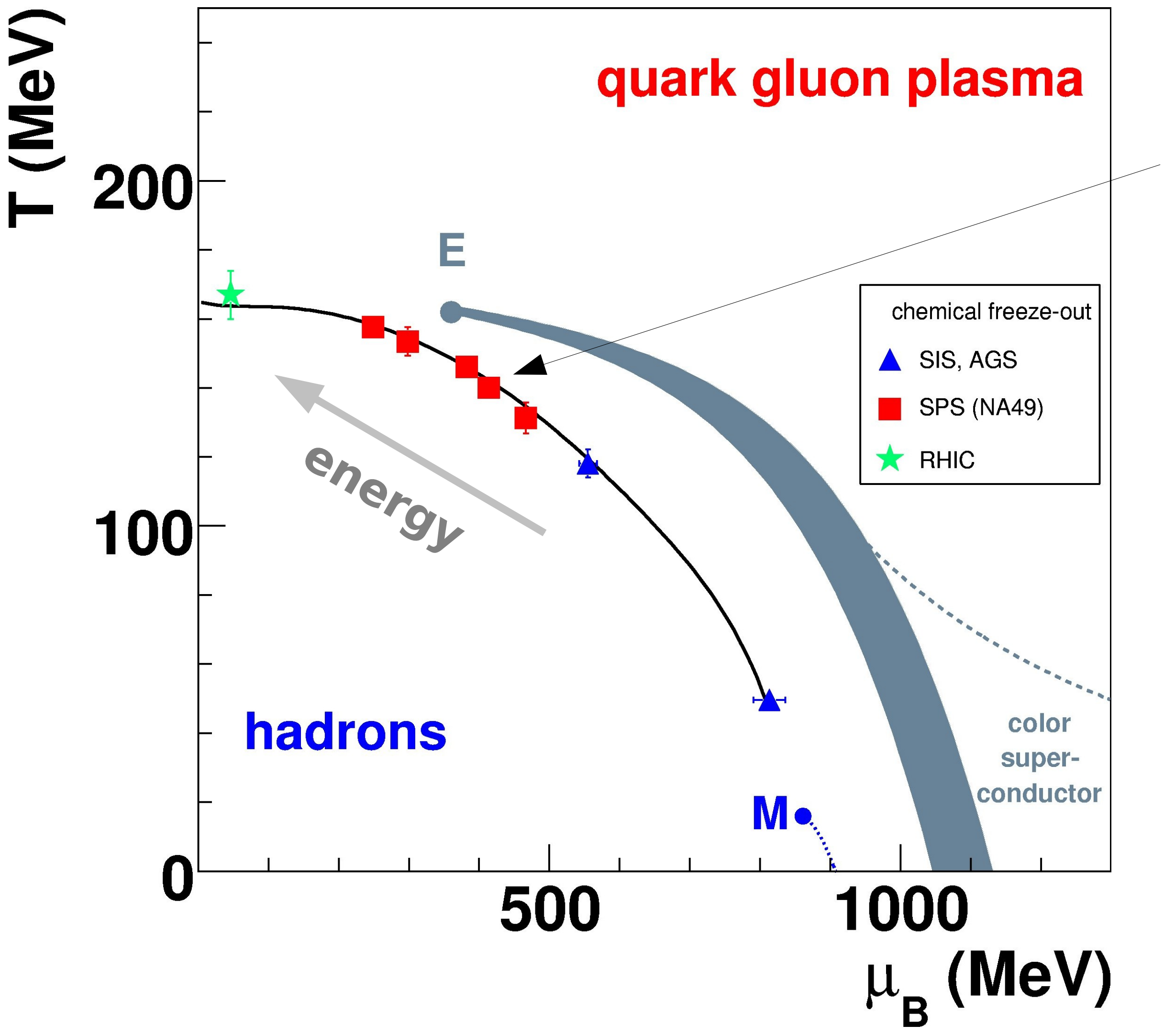
Gorenstein, M.G., Greiner

1st order phase transition

see Gorenstein's talk

Search for the critical point of strongly interacting matter



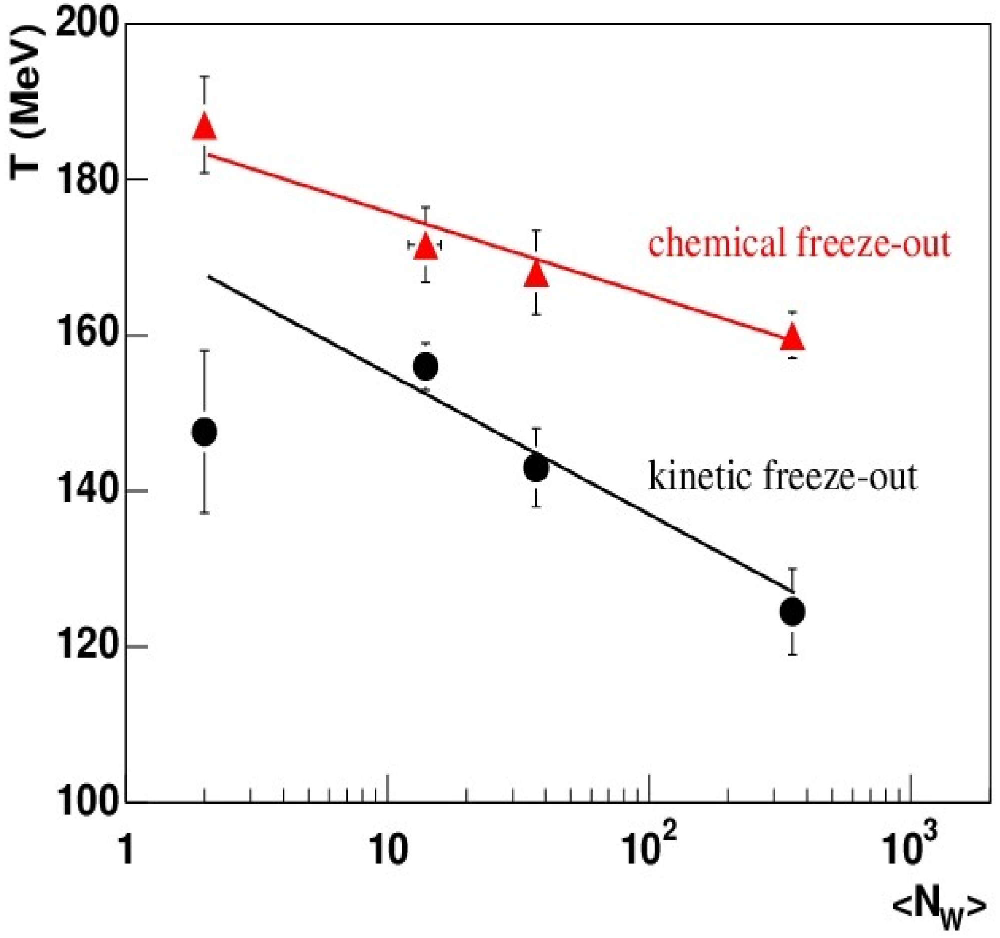


Chemical freeze-out points for central Pb+Pb collisions from the hadron gas fits

Becattini et al. 1999-2005

see Becattini's talk

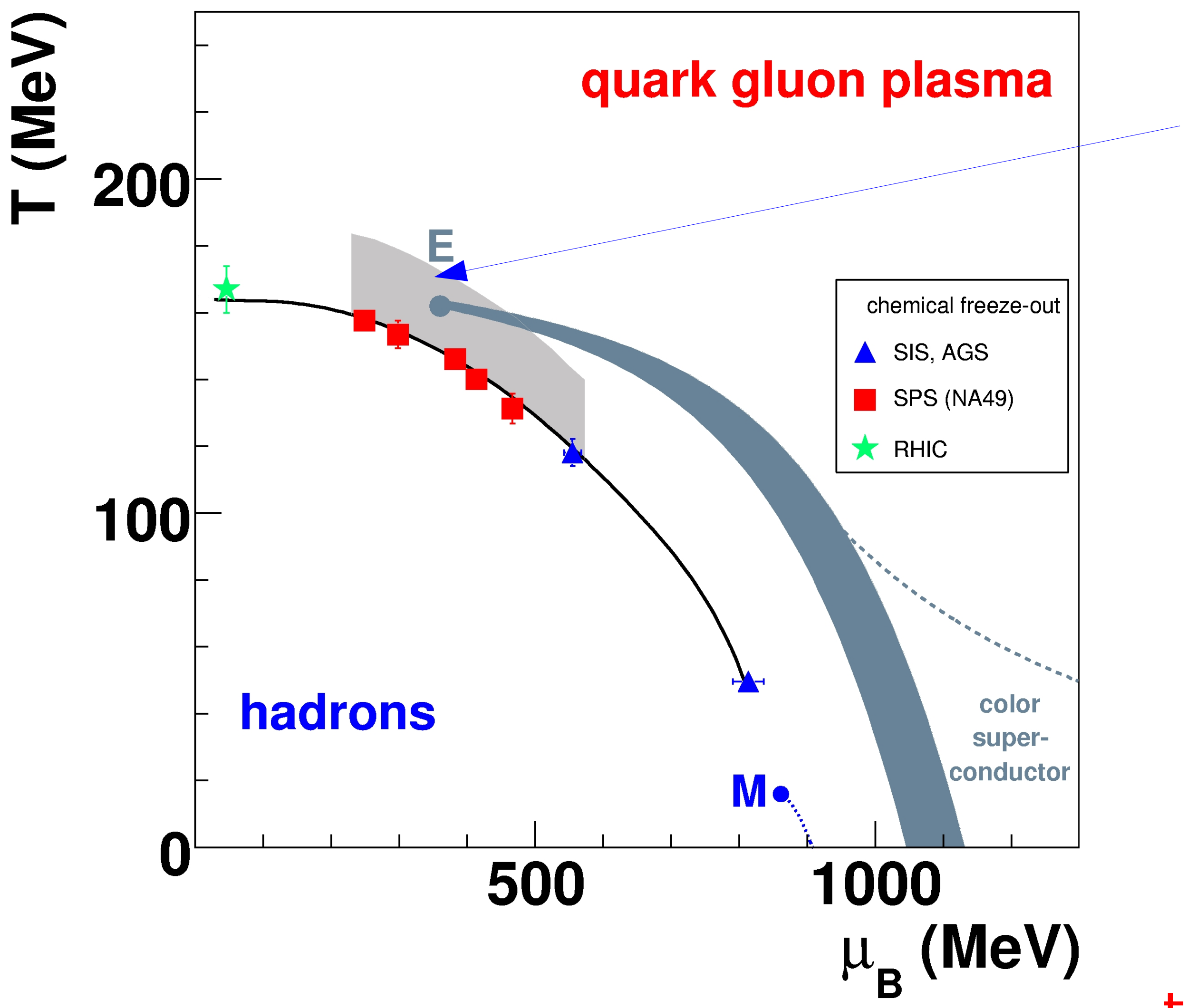
The position of chemical (and kinetic) freeze-out points depends on collision energy and system size



p+p, C+C, Si+Si and
Pb+Pb collisions
at 158*A* GeV

Becattini et al. 2005

(collision energy) - (system size) scan = T - μ_B scan



Phase diagram domain possibly covered by chemical freeze-out points in the future SPS study

Search for the critical point

↓

(collision energy)-
-(system size) scan
at energies higher than
the onset of deconfinement,
i.e. 30*A* GeV

Stephanov, Shuryak, Rajagopal 1999

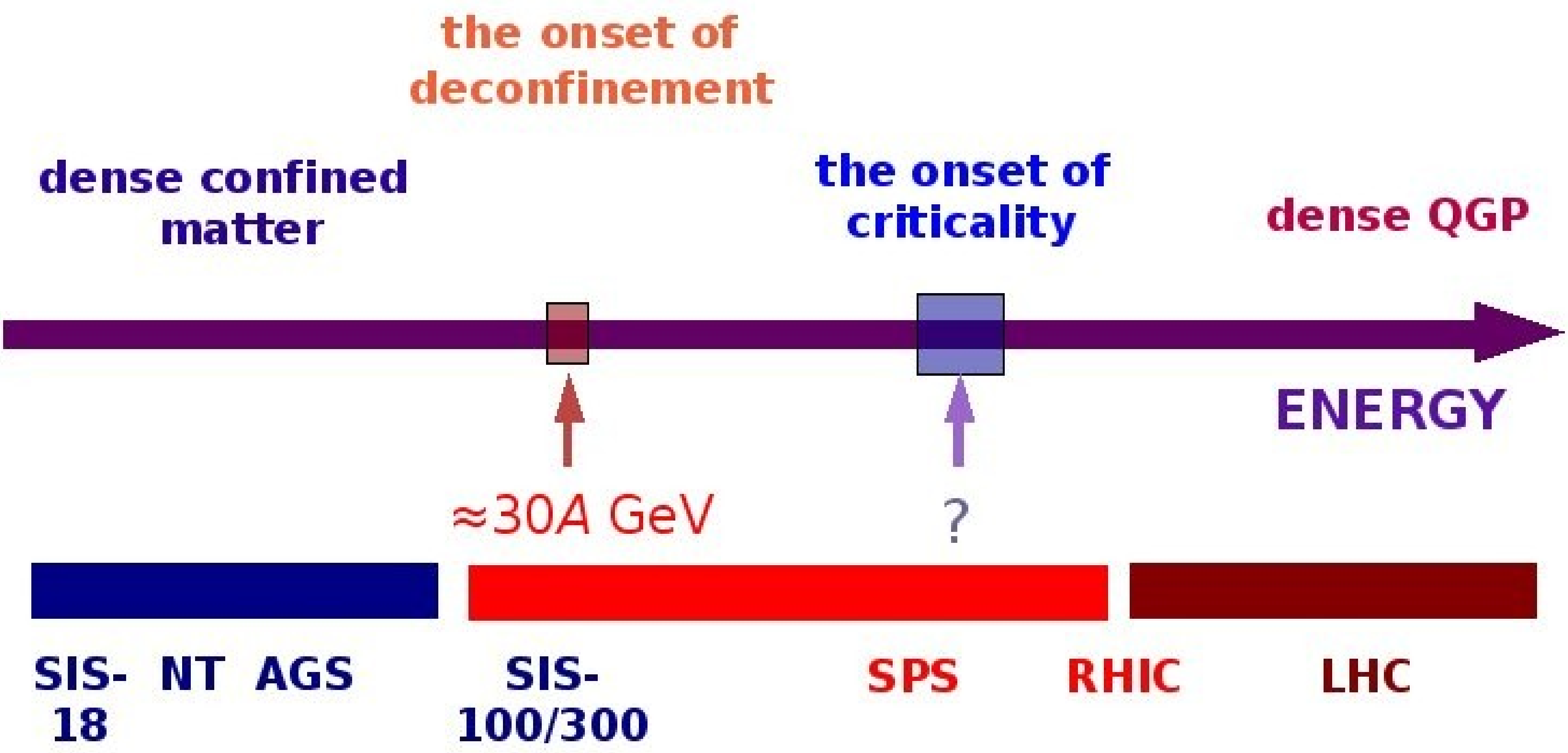
In the “critical” region matter shows anomalous properties

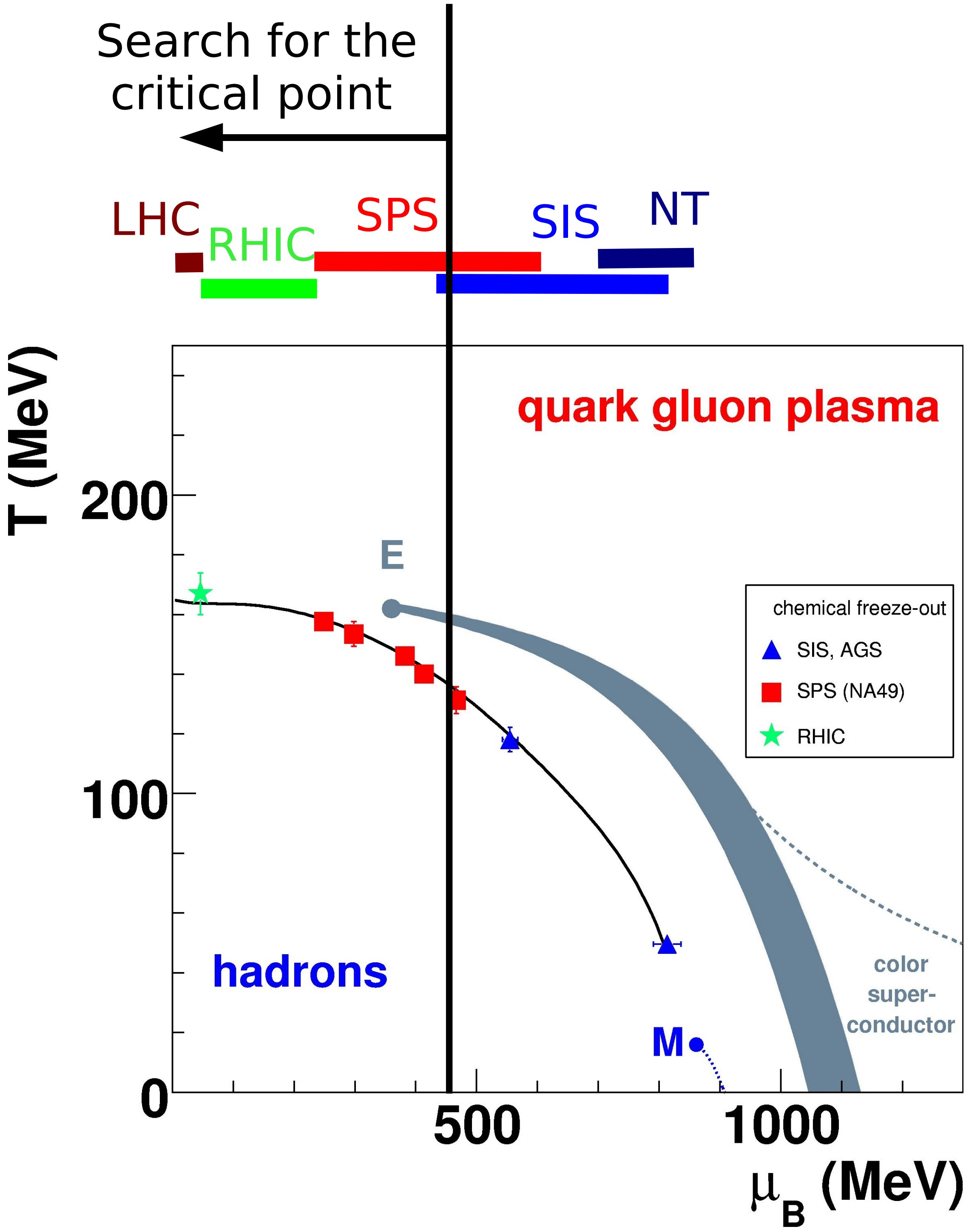
(In the case of water large fluctuations in the size of liquid/vapor domains lead to the critical opalescence)

Large characteristic multiplicity and transverse momentum fluctuations are expected when strongly interacting matter freezes-out close to the critical point

Stephanov, Shuryak, Rajagopal
Antoniou, Kapoyannis

Physics of strongly interacting matter vs accelerators





Search for the critical point

Status of the program at SPS

November 2003:

Expression of Interest (study the properties of deconfinement) submitted to the SPS committee by the proto-collaboration (now 10 institutes from Croatia, Germany, Greece, Hungary, Korea, Norway, Poland, Russia, South Africa and United States)

September 2004:

A special SPSC meeting in Villars (Switzerland)
''Fixed-Target Physics at CERN Beyond 2005''

February 2005

The SPSC conclusions:

''... *Recent developments confirm that heavy ion beams at CERN SPS energies and luminosity remain ideal tools to observe the features of the phase transition between the confined and the deconfined states of hadronic matter known as Quark Gluon Plasma (QGP). ...*
A major step forward in understanding the phase diagram of hadronic matter would be the discovery of a critical point. ...
Once the LHC has been commissioned with ions, an SPS programme aimed at the identification of the critical point, as well as at the study of it properties, is likely to be of substantial significance. ...''

October 2005:

submission of a letter of intent

Summary of

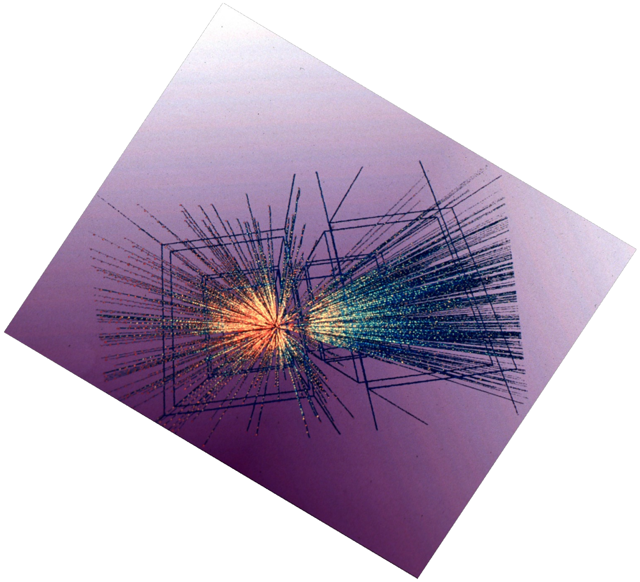
past and future of the ion physics at the CERN SPS

PAST

● ● Observation of the onset of deconfinement at low CERN SPS energies

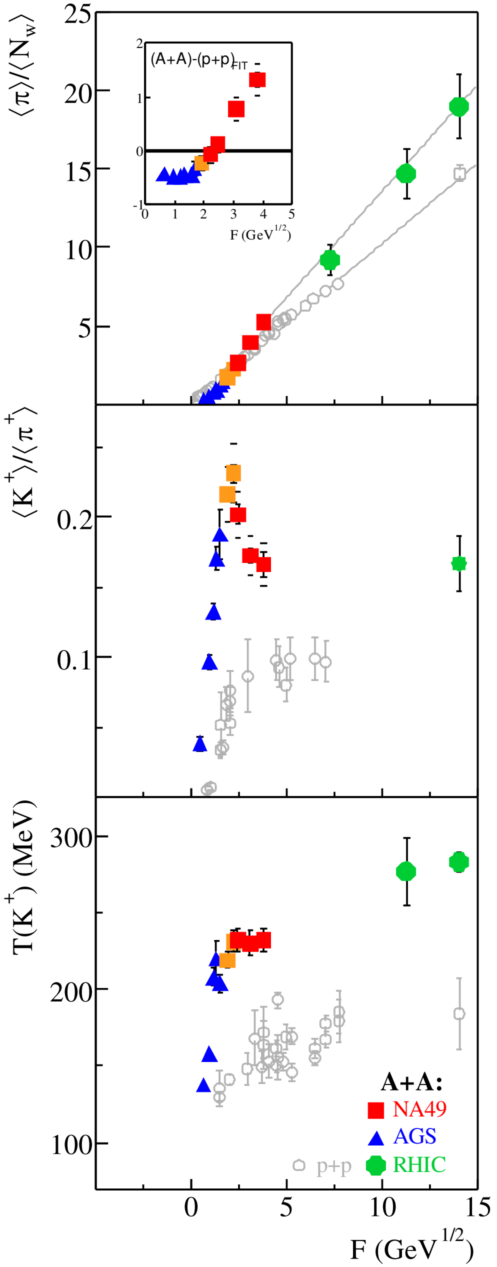
FUTURE

● ● ● Search for the critical point at the CERN SPS

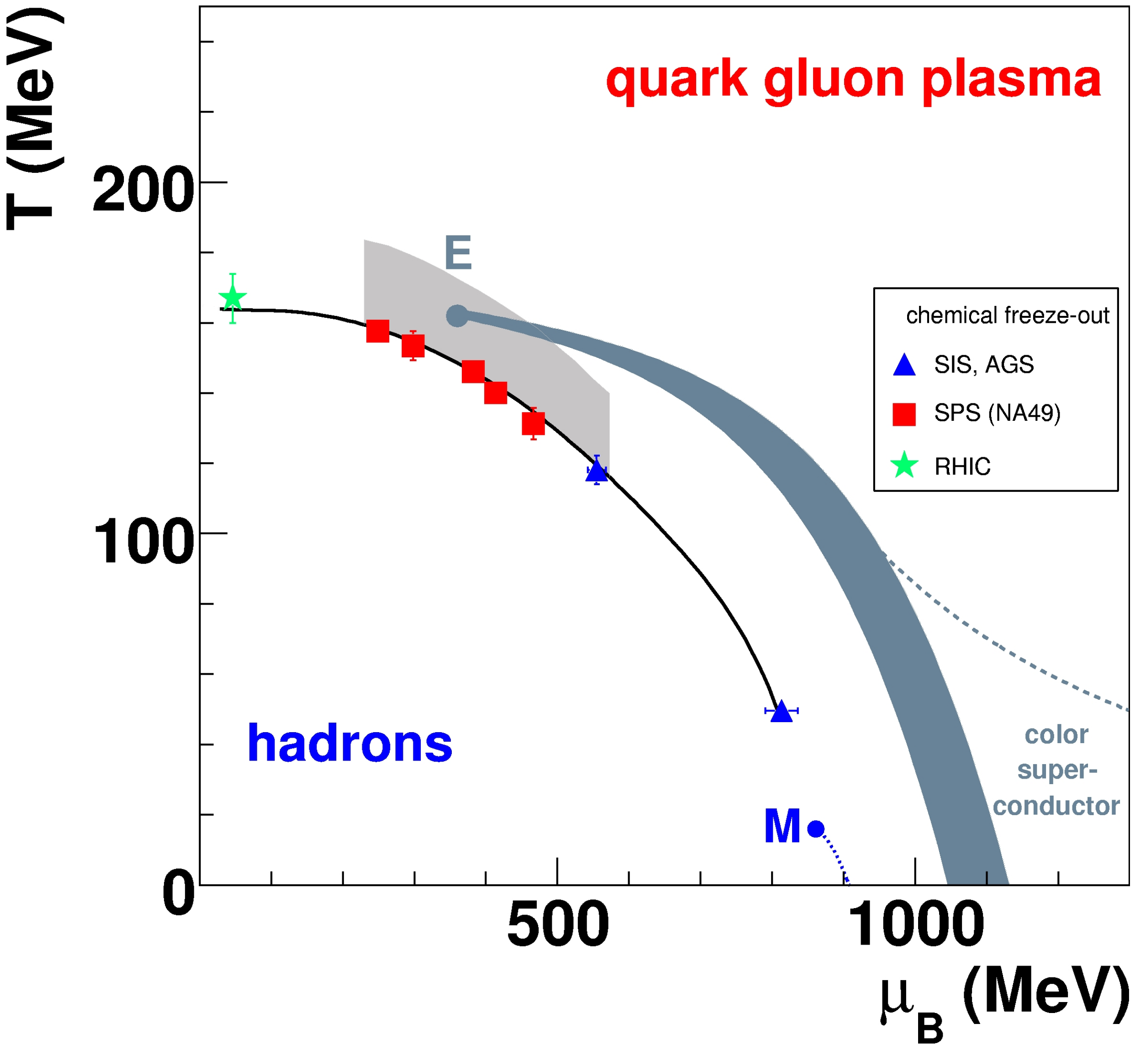


AGS **SPS** **RHIC**

hadronic observables

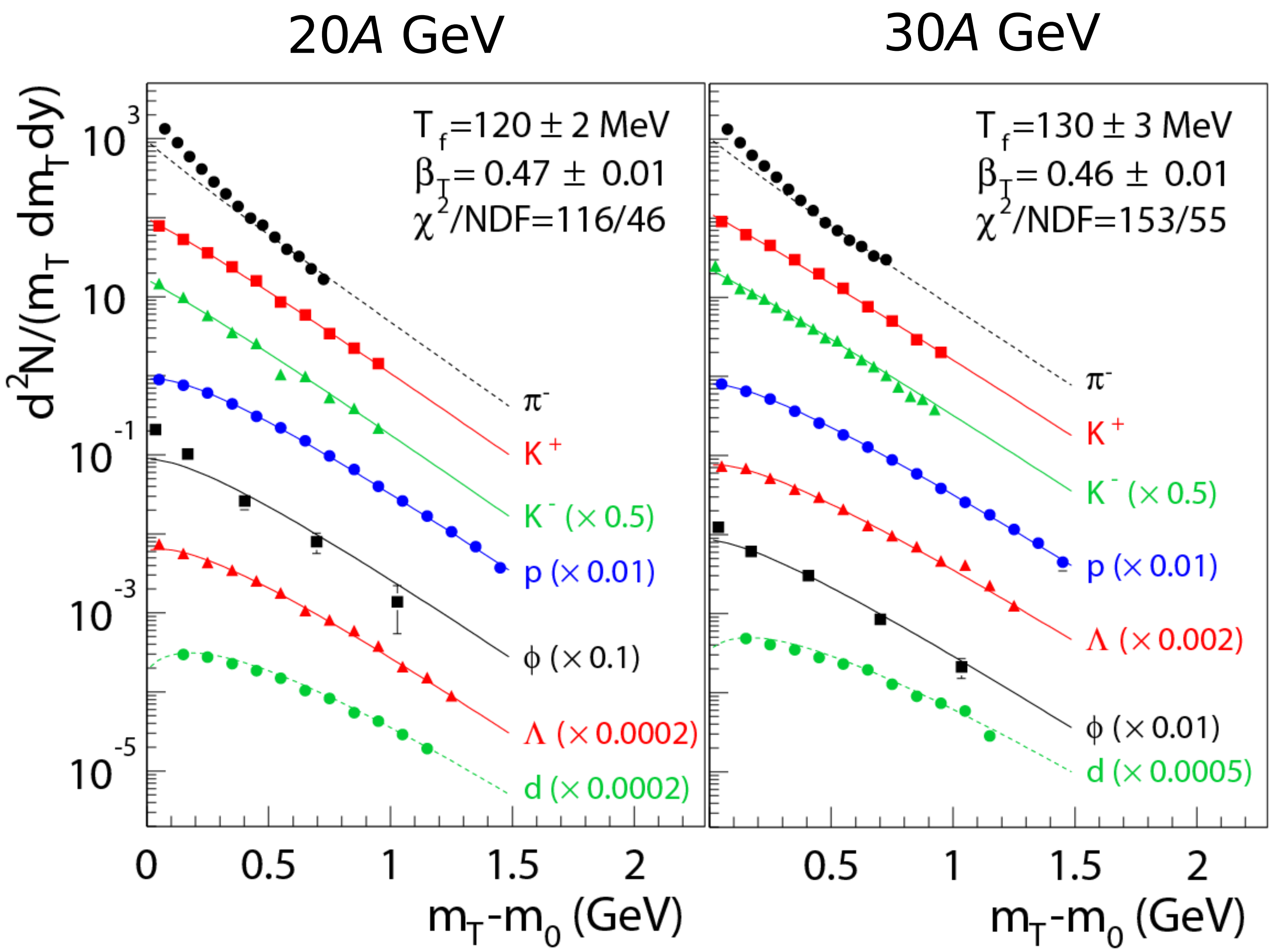


collision energy



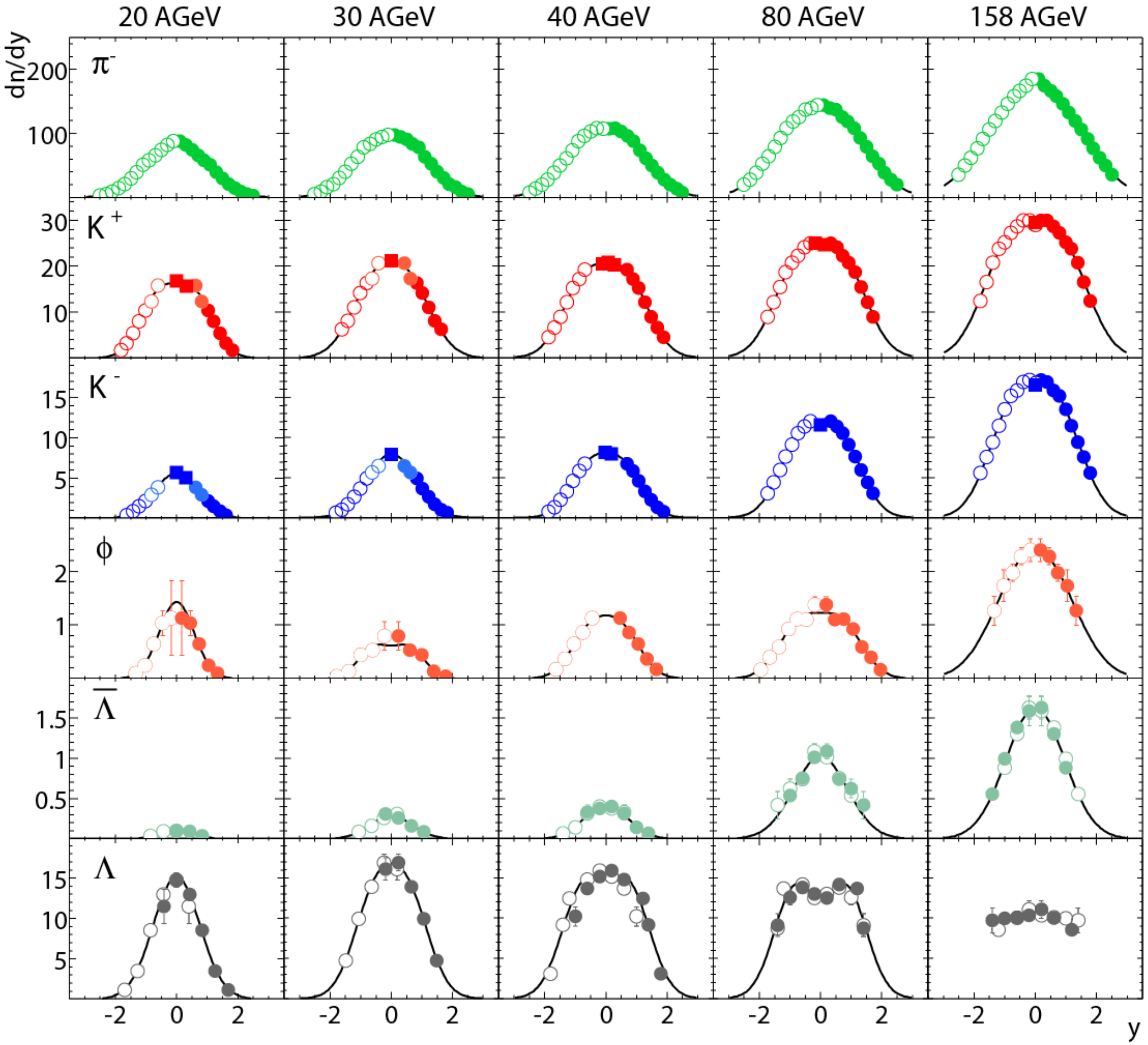
Examples of the "raw" data: transverse mass spectra

(central Pb+Pb collisions)

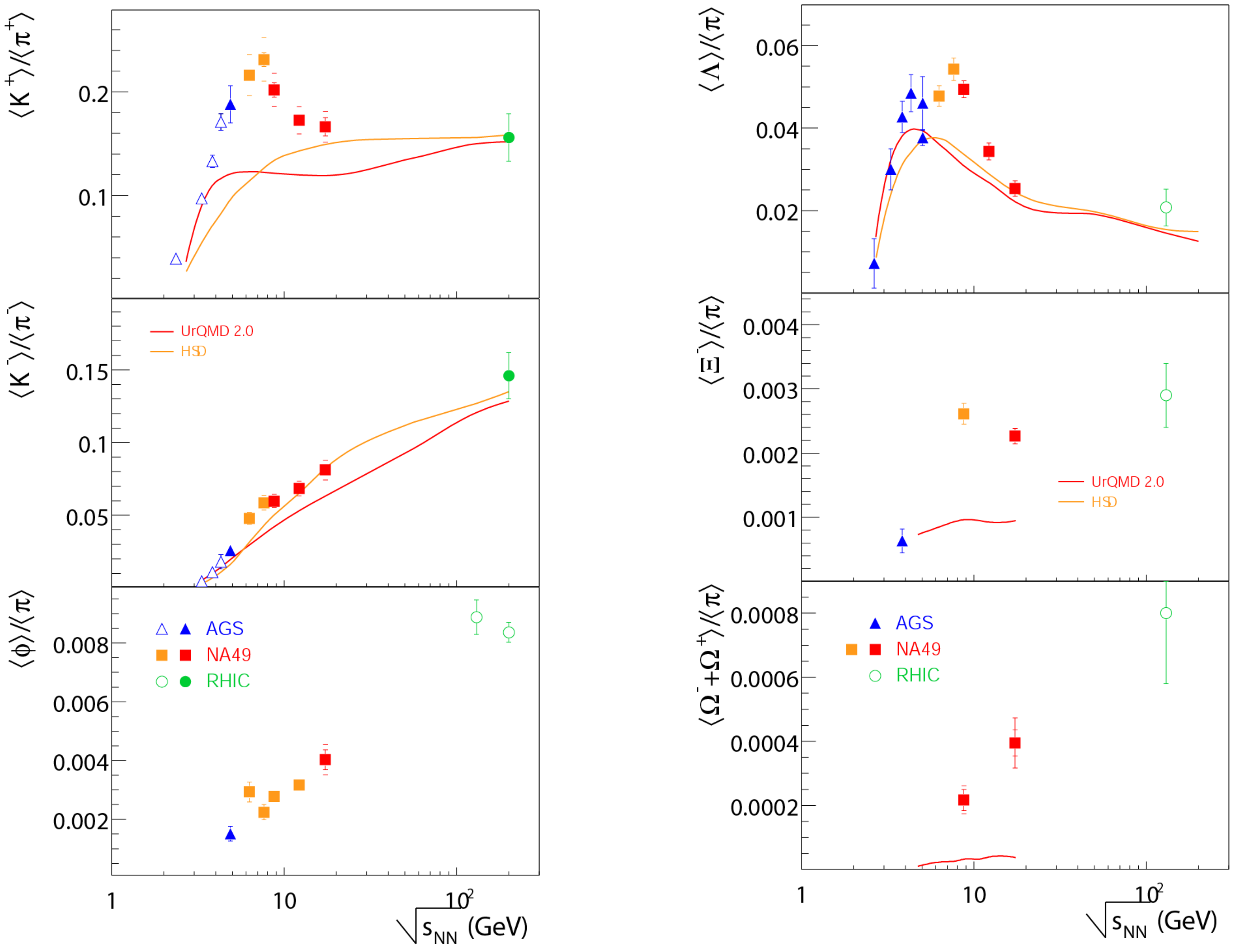


Examples of the "raw" data: rapidity spectra

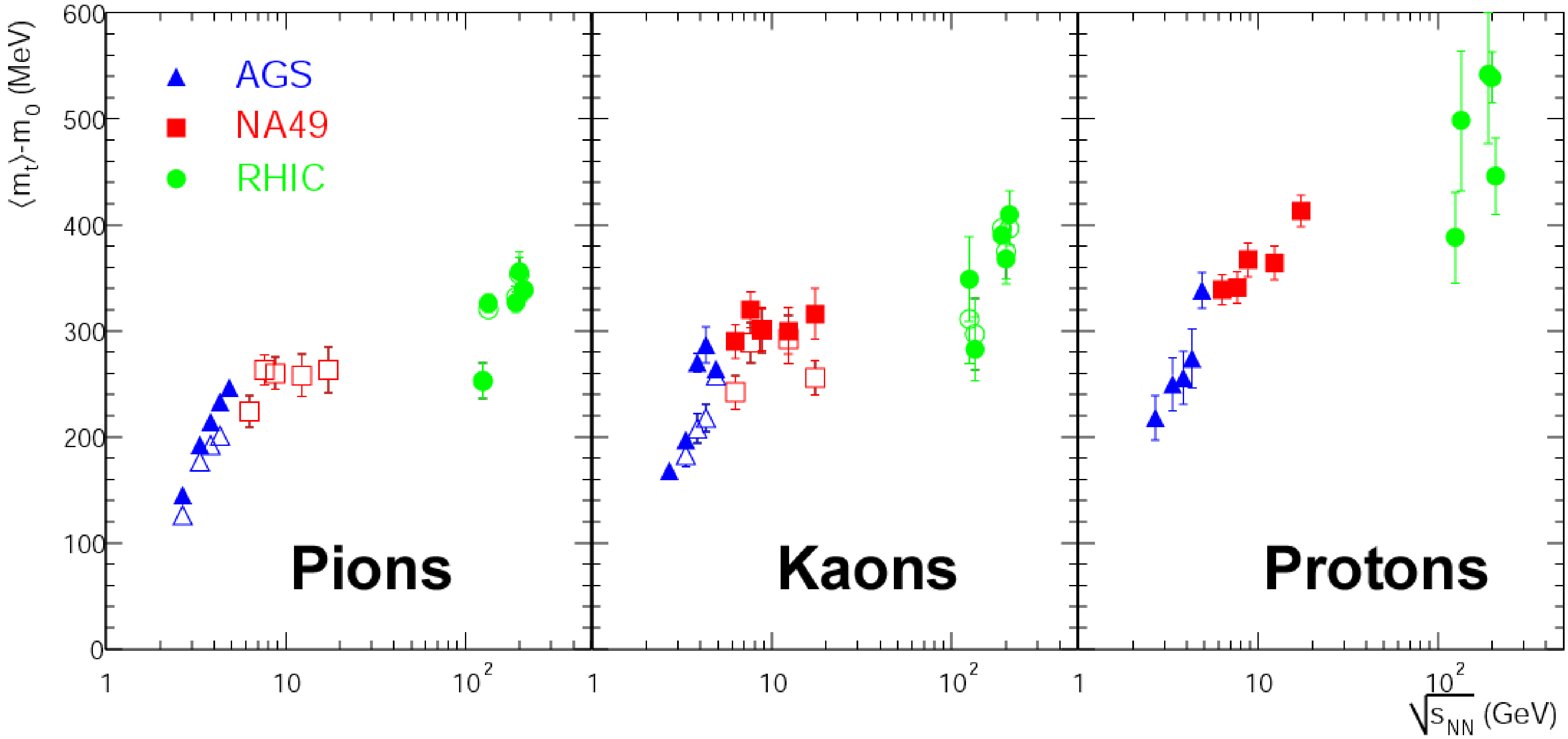
(central Pb+Pb collisions)



...and energy dependence of various strange hadrons



... and in $<m_T>$ of various hadrons



VOLUME 34, NUMBER 21 PHYSICAL REVIEW LETTERS 26 MAY 1975

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.

We first give arguments leading to this idea. It is commonly believed that hadrons consist of quarks[5-7] despite the apparent nonexistence of free quarks.[8] There are two main reasons for this belief. First, a quark model explains[5,6] many properties of the hadron spectrum, and of strong-interaction decays. Secondly we have Bjorken scaling[7] in the deep inelastic scattering of leptons by nucleons. Basically, this indicates that hadrons consist of pointlike objects (partons) which interact weakly with each other when close together. Analysis of the data indicates that partons are the fractionally charged spin-$\frac{1}{2}$ Gell-Mann–Zweig quarks. Since free quarks are not observed,[8] it is assumed that they are permanently bound in hadrons[9] by a mechanism as yet unknown, but much speculated on.

A neutron has a radius[10] of about 0.5–1 fm, and so has a density of about 8×10^{14} g cm^{-3}, whereas the central density of a neutron star[1,2] can be as much as 10^{16}–10^{17} g cm^{-3}. In this case, one must expect the hadrons to overlap, and their individuality to be confused. Therefore, we suggest that matter at such high densities is a quark soup.

■ Brief history of the CERN SPS ion programs

Rafelski, Muller
Matsui, Satz

1986-1991: Pioneering study with O and S beams

Strangeness enhancement and J/ψ suppression

⇒ Simple superposition models do not work

↓

1994-2000: Pb+Pb collisions at the top SPS energy

anomalous J/ψ suppression, statistical properties of hadron production, direct photons

⇒ Is a new state of matter created?

↓

M.G., Gorenstein

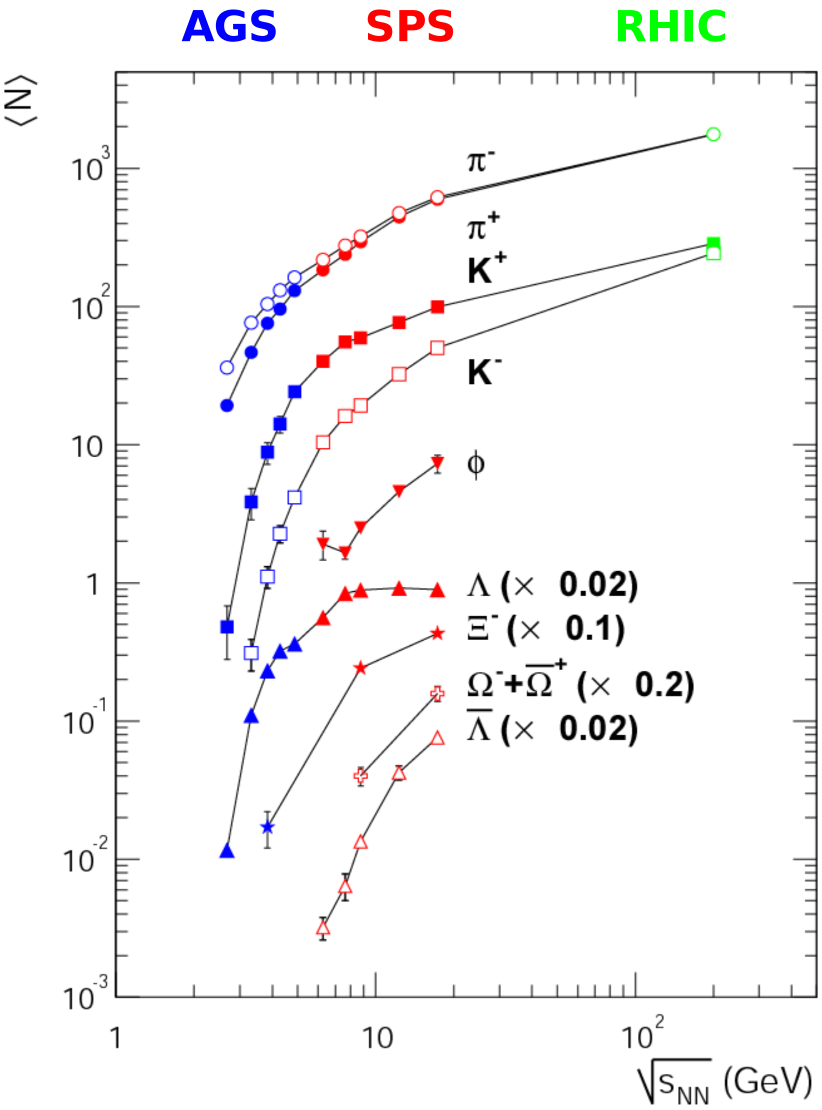
1998-2002: Pb+Pb collisions at low SPS energies
(energy scan program at the CERN SPS)

Anomalies in energy dependence of hadron production

⇒ Observation of the onset of deconfinement?

Examples of the "raw" data: mean multiplicities

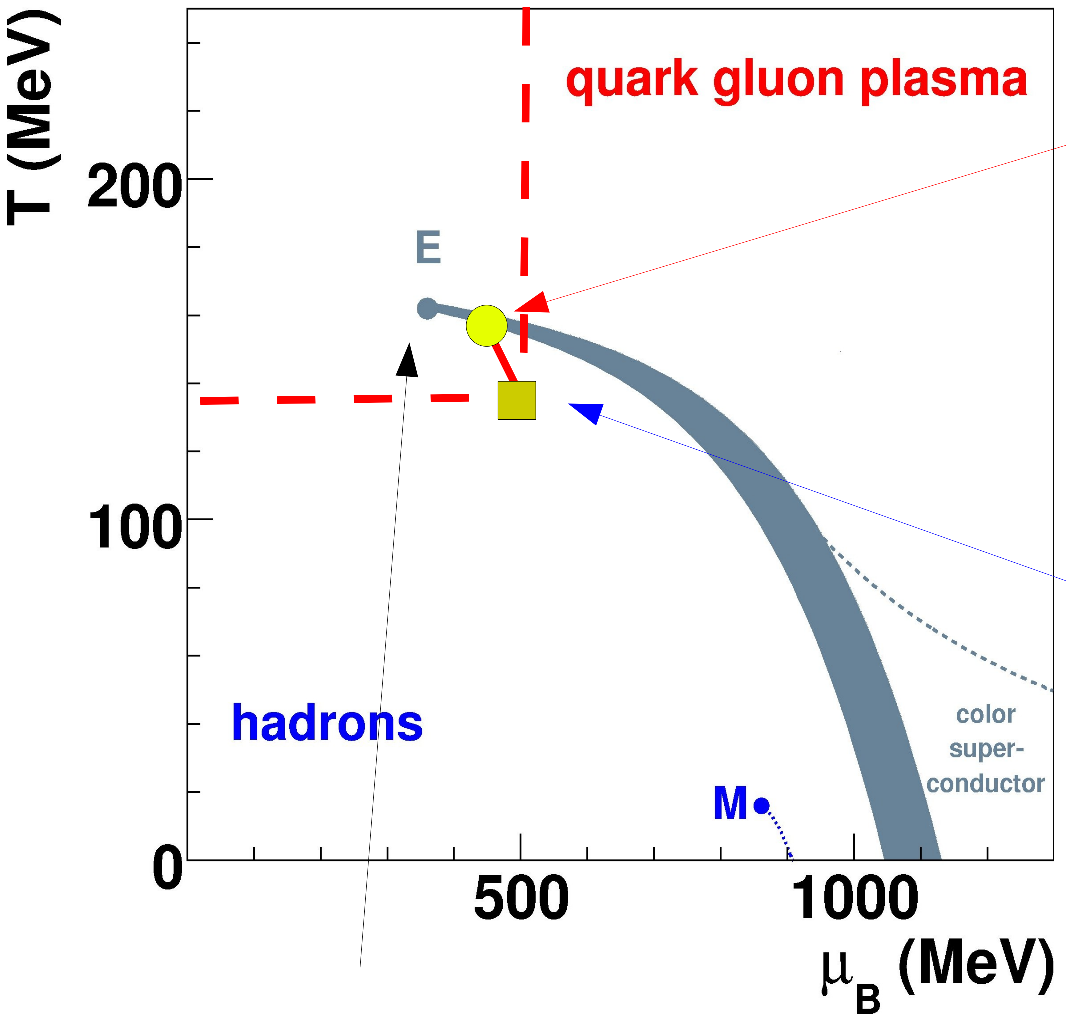
(central Pb+Pb collisions)



“... The discovery of the critical point would in a stroke transform the map of the QCD phase diagram which we sketch below from one base only on reasonable inference from universality, lattice gauge theory models into one within a solid experimental basis. ...”

K.Rajagopal, M. Stephanov, E. Shuryak and F. Wilczek (Nobel 2004)
supporting the NA49 program

... and its location: experiment vs theory



the early stage of central Pb+Pb collisions at 30A GeV hits the transition line (the position of the measured anomalies in the energy dependence)

the chemical freeze-out point of central Pb+Pb collisions at 30*A* GeV (hadron gas analysis of the measured multiplicities: T = 140 MeV, μ_B = 430 MeV)

Becattini et al.

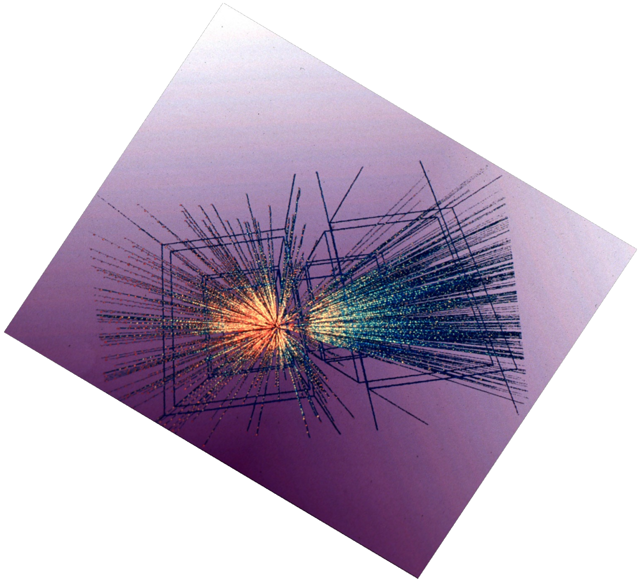
the most recent lattice QCD results (T = 160 MeV, μ_B = 360 MeV)

Fodor, Katz,
Ejiri et al.

The best experimental and theoretical estimates are consistent:

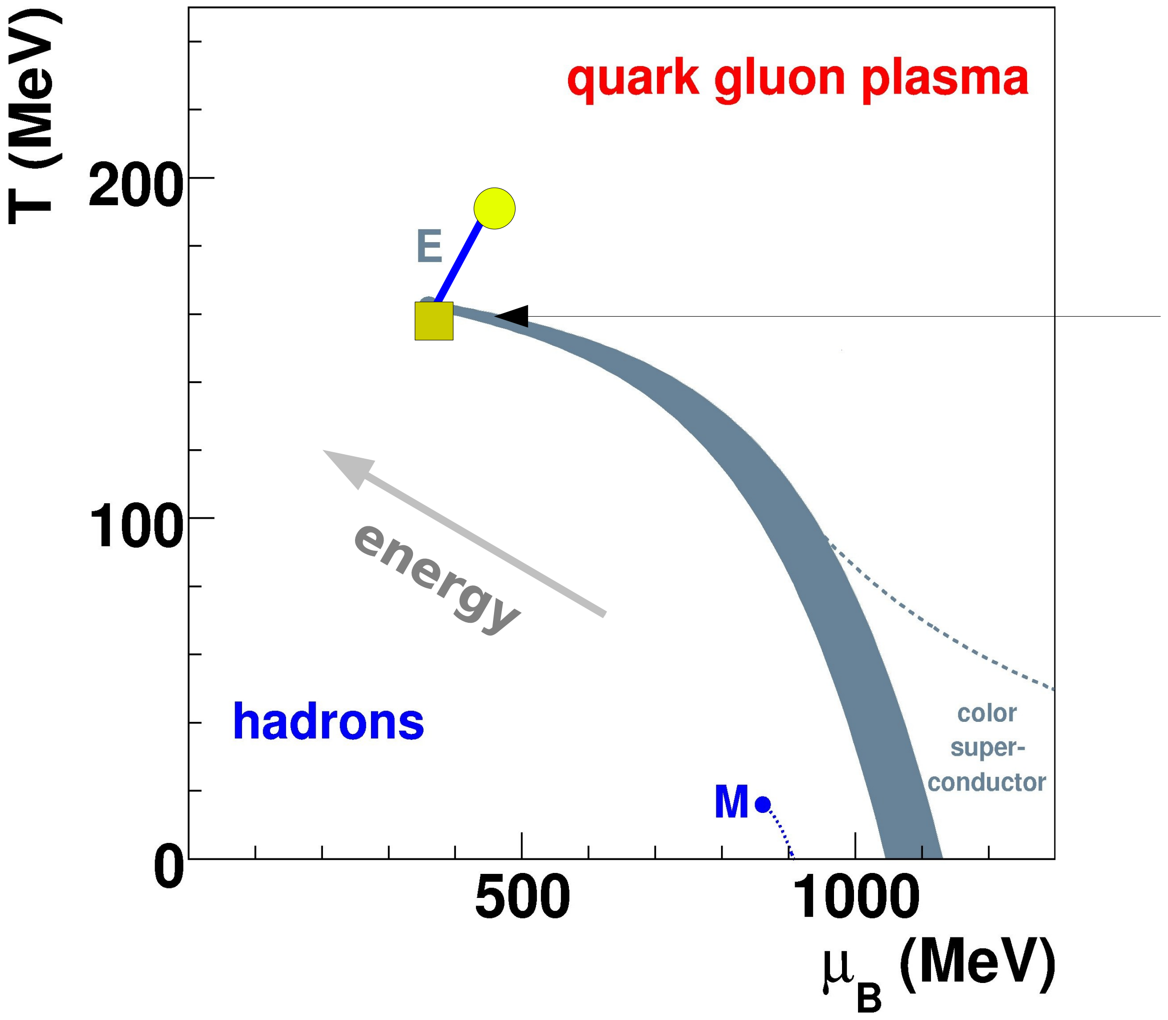
the critical point, if exists, can be observed at energies higher/equal 30A GeV

($T > 140$ MeV, $\mu_B < 430$ MeV)



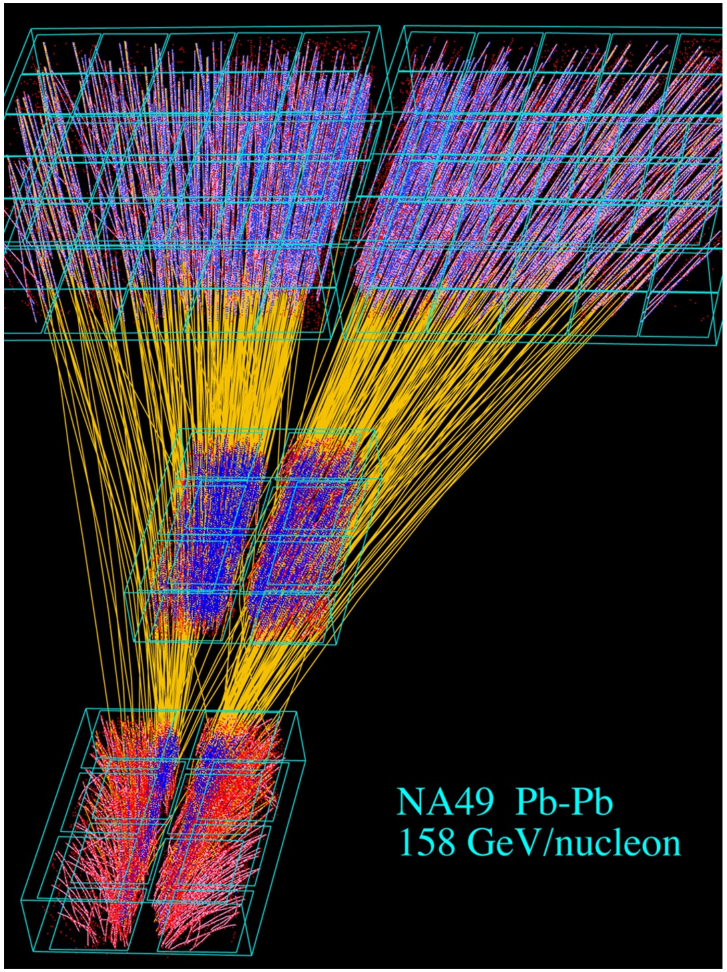
Search for the critical point of strongly interacting matter

Search for a maximum of fluctuations
in the two-dimensional space,
temperature – baryo-chemical potential,
of the freeze-out points



A maximum in fluctuations:
the freeze-out point hits
the critical point

NA49 at the CERN SPS



→ A large acceptance: ≈50%

→ A high momentum resolution:

$$\sigma(p)/p^2 \approx 10^{-4} \quad ((GeV/c)^{-1})$$

→ A good particle identification:

$$\sigma(TOF) \approx 60\,ps,$$
$$\sigma(dE/dx)/\langle dE/dx\rangle \approx 0.04,$$
$$\sigma(m_{inv}) \approx 5\,MeV$$