Der Urknall im Labor
Erforschung von Urknallmaterie mit Schwerionenstoessen

Bad Honnef, April 3-7, 2006

Peter Braun-Munzinger

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Resultate der CERN SPS und RHIC

Experimente

Die Zukunft: Alice am LHC

CBM an FAIR

Ausblick


M100 Spiral Galaxie
50 Millionen LJ


Reise zum Urknall
Zurück zum Urknall
1.000 Millionen Jahre
300.000 Jahre
3 Minuten
Natur
Quark-Gluon Plasma
Nukleonen
Kerne
Atome
Heute
Urknall
10 $^{-6}$ sec
10 $^{-4}$ sec
3 min
15 Mil Jahre
Experiment
10^9 K
Strahlung
Teilchen
W+ W- Z
Schwere Teilchen, die die schwache Kraft vermitteln
Quark
Anti-Quark
Elektron
Positron (Anti-Elektron)
Proton
Neutron
Meson
Wasserstoff
Deuterium
Helium
Lithium
6000 K
18 K
3 K
0 K ≈ -273 °C (absoluter Nullpunkt)

Evidenz für den Urknall

- ✔ Hubble Expansion
- ✔ Kosmische Hintergrundstrahlung
- ✔ Elementsynthese im frühen Universum
- ✔ Entstehung von Galaxien

✔Erzeugung von **Quark-Gluon Materie** im Labor

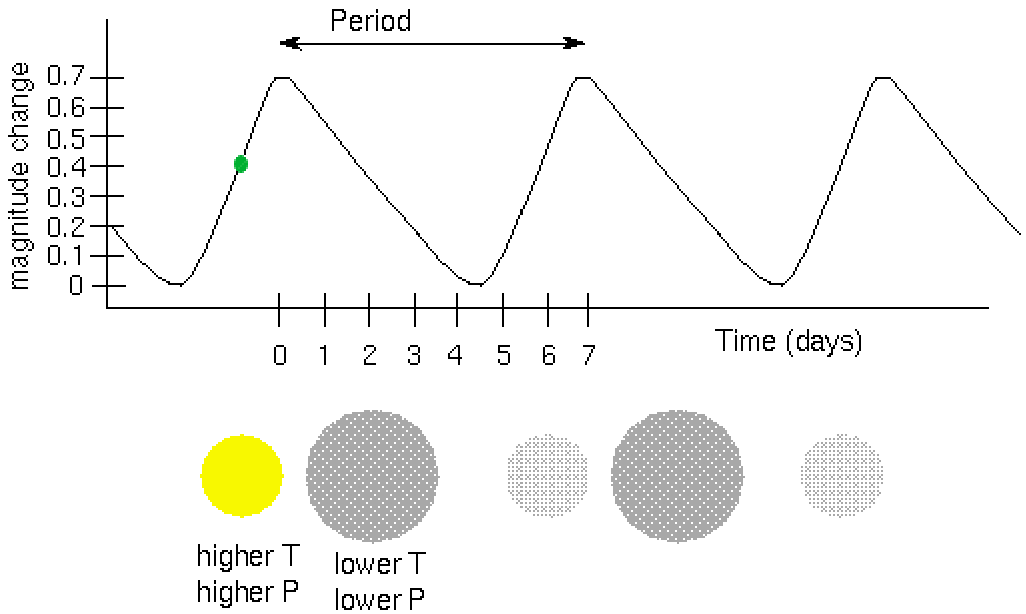
Gibt es Evidenz für die Expansion des Universums?

Messung der **Fluchtgeschwindigkeit** von Sternen
über
die Rotverschiebung der Spektrallinien

Messung der **Distanz**
über
die Helligkeit variabler Sterne (Cepheiden)
und spezieller Supernovae

Physics of Cepheid Variables

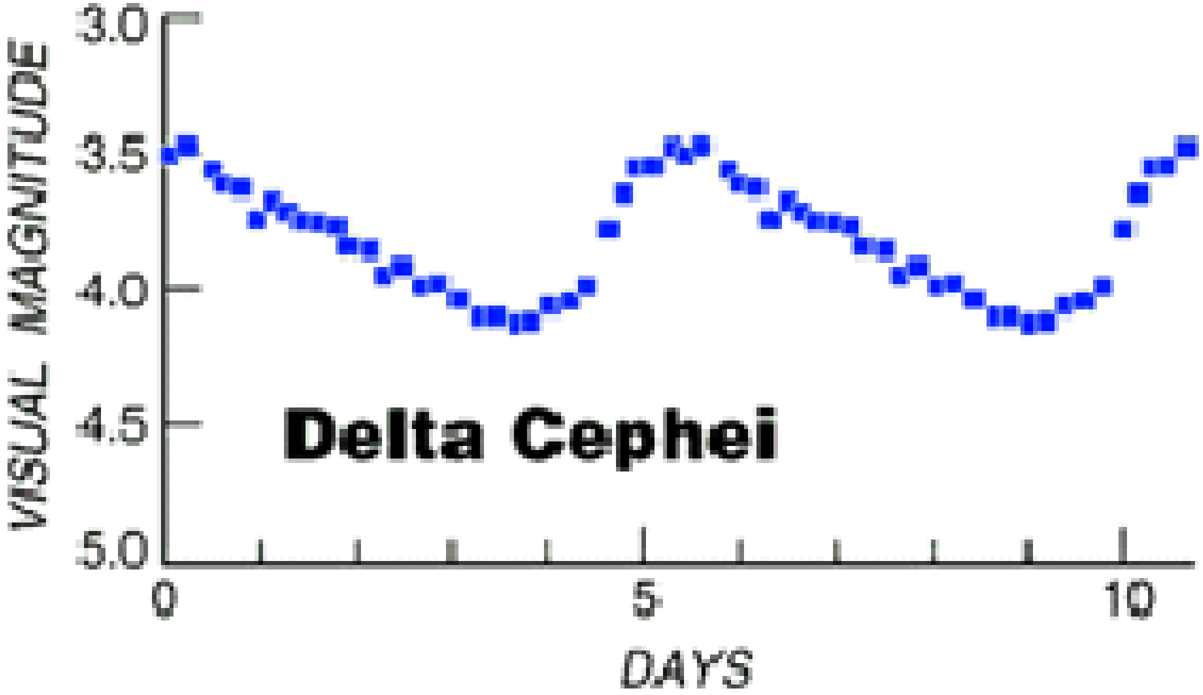
- The variation in the luminosity of Cepheids is caused by variations of surface temperature of the star as well as radius.

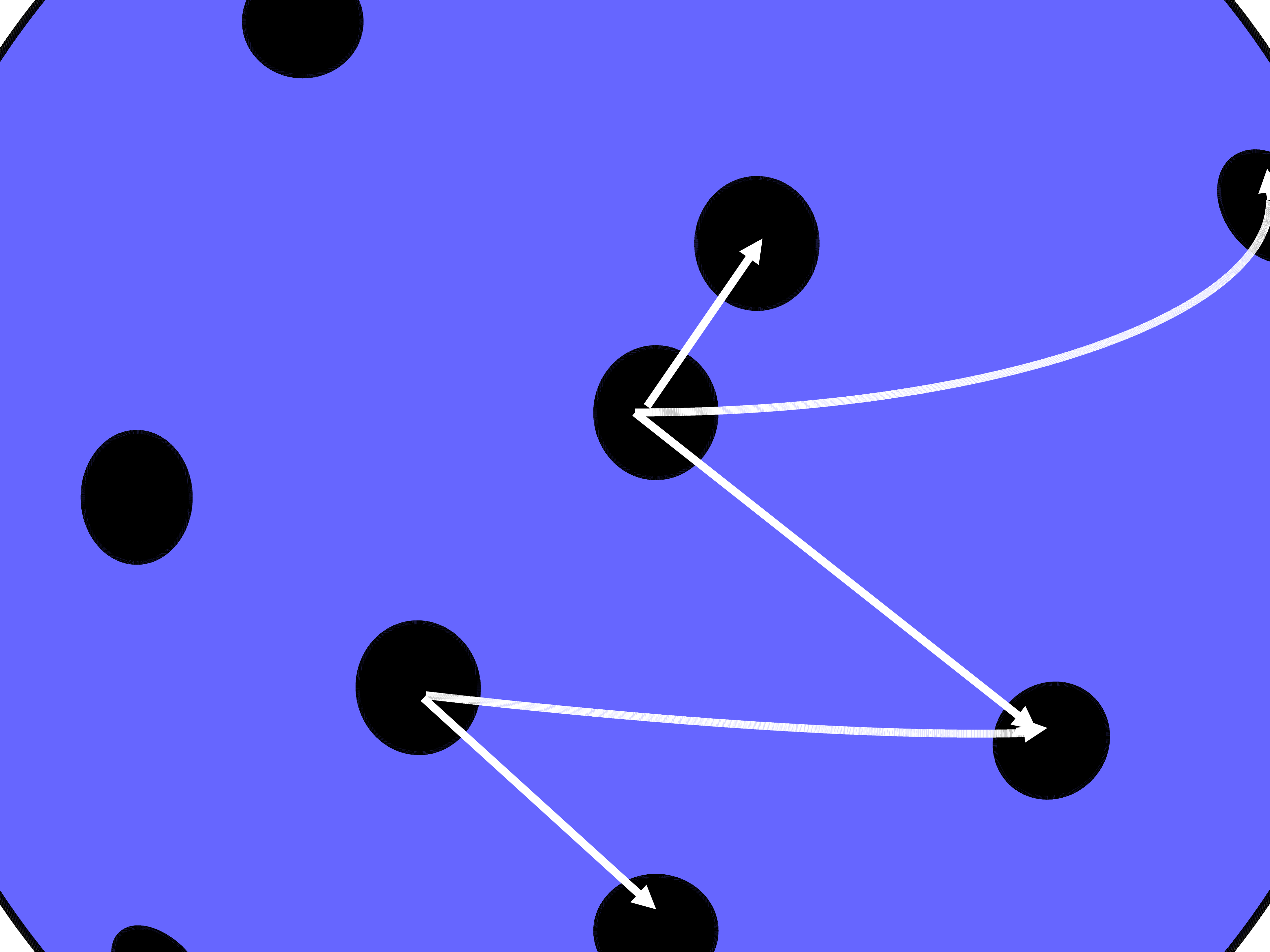


Cepheid variables: outward pressure (P) and inward gravity compression are out of sync, so star changes size and temperature: it **pulsates**. *RR-Lyrae* variables are smaller and have pulsation periods of less than 24 hours. Also, their light curve looks different from the Cepheid light curve.

History of Cepheid Variables

- Cepheid Variable stars are named after Delta Cephei, which was the first star that astronomer's noticed changed in brightness over a period of about 5 days.



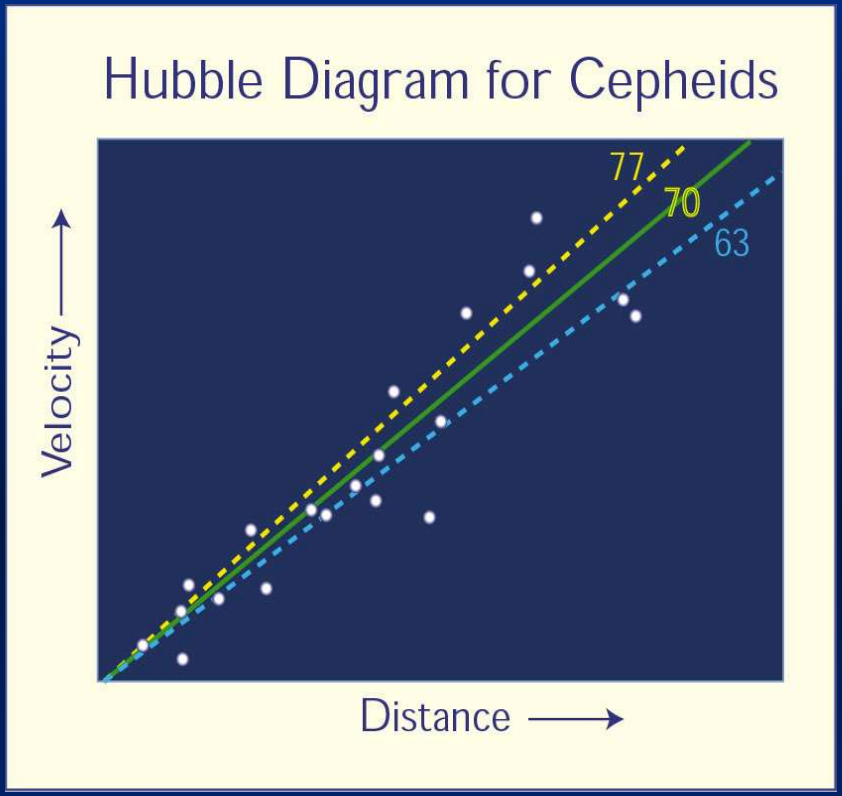


NGC 4603

Die am weitesten entfernte Galaxie in der man Cepheiden beobachtet hat.

Diese veränderlichen Sterne geben ein Mass für die Expansionsgeschwindigkeit des Universums.

Expansion des Universums



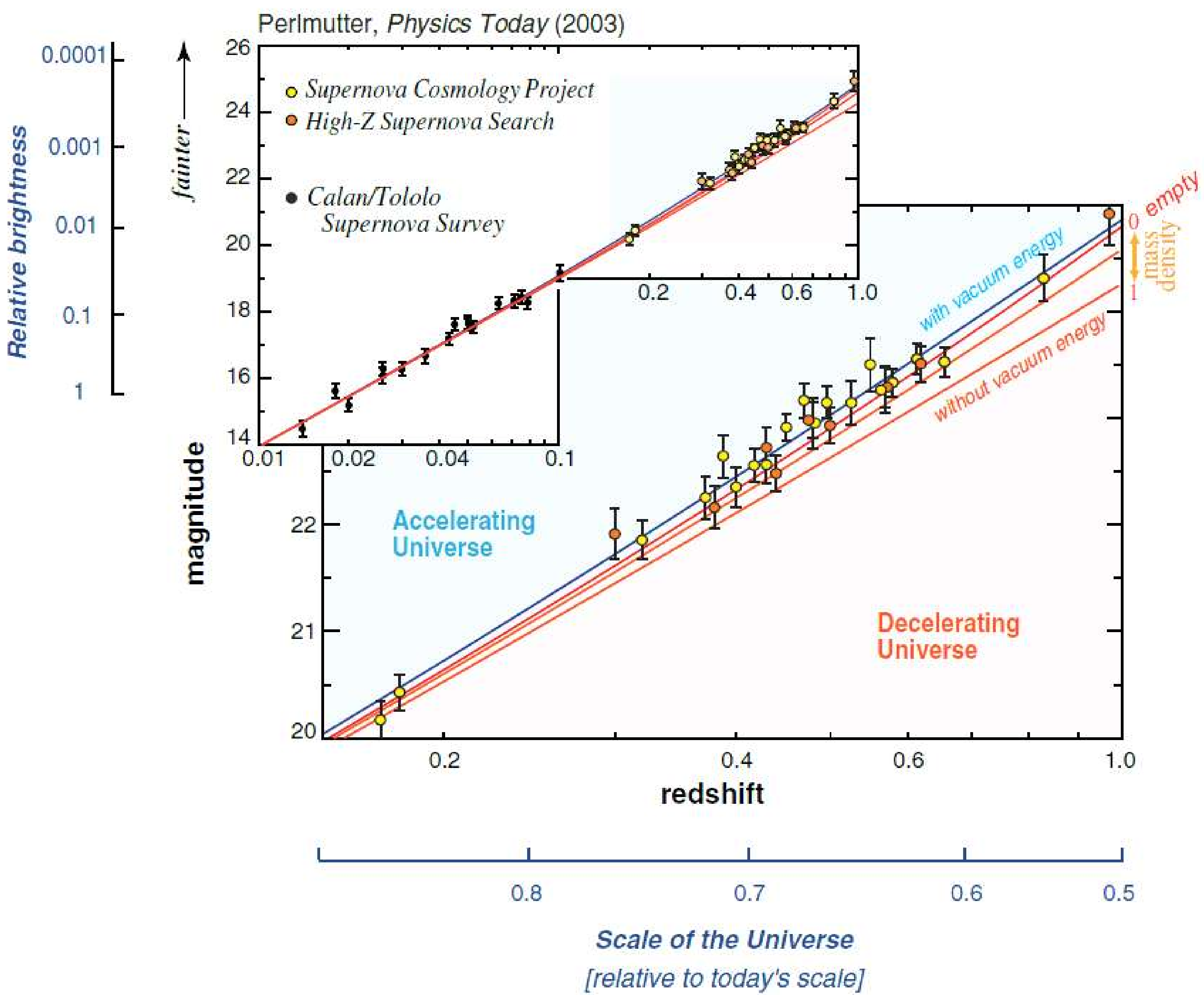
V = H · D

E. Hubble, 1924

<H> = 70 km/s Mpc = 1/15 $\cdot 10^9$ Jahre

Sterne und Galaxien bewegen sich von der Erde weg mit umso grösserer Geschwindigkeit (V) je grösser ihr Abstand (D) ist

Type Ia Supernovae



Urknall

Konstante Expansion impliziert, dass das Universum vor ca 15 Milliarden Jahren in einem Punkt startete.

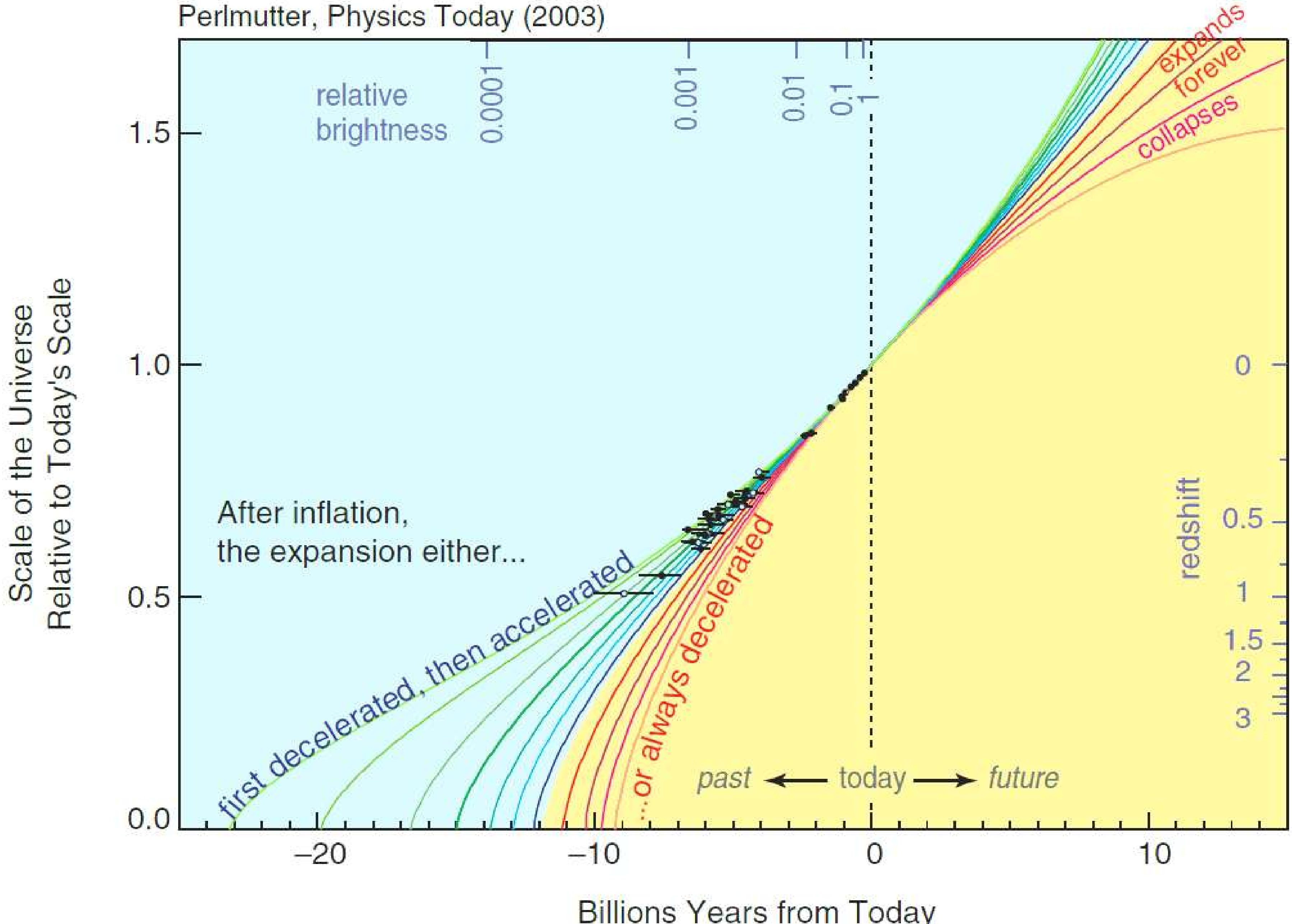
Dauer der Expansion = 15 Milliarden Jahre

$D/V = 1/H$

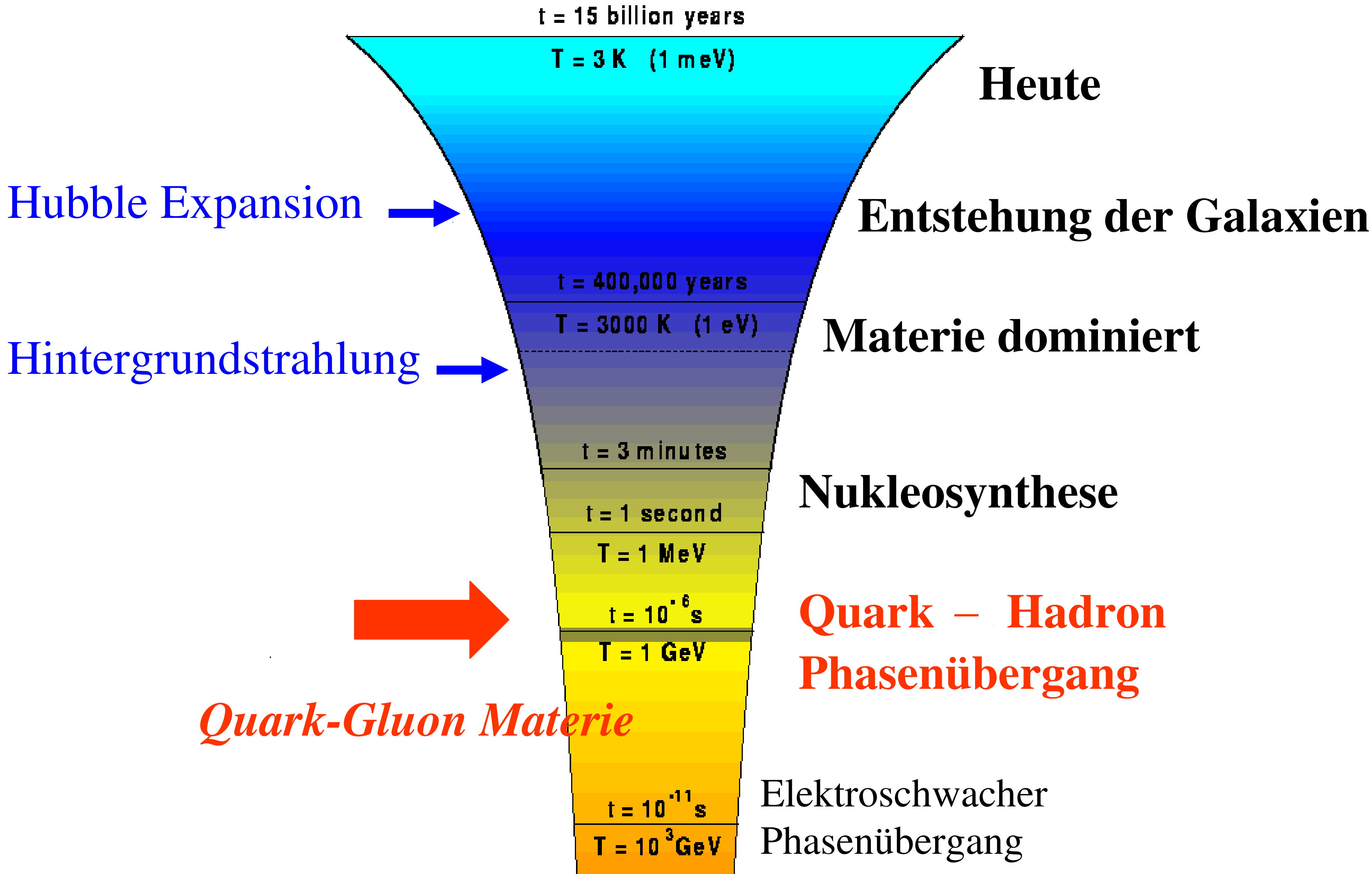
(nicht ganz richtig, s.u.)

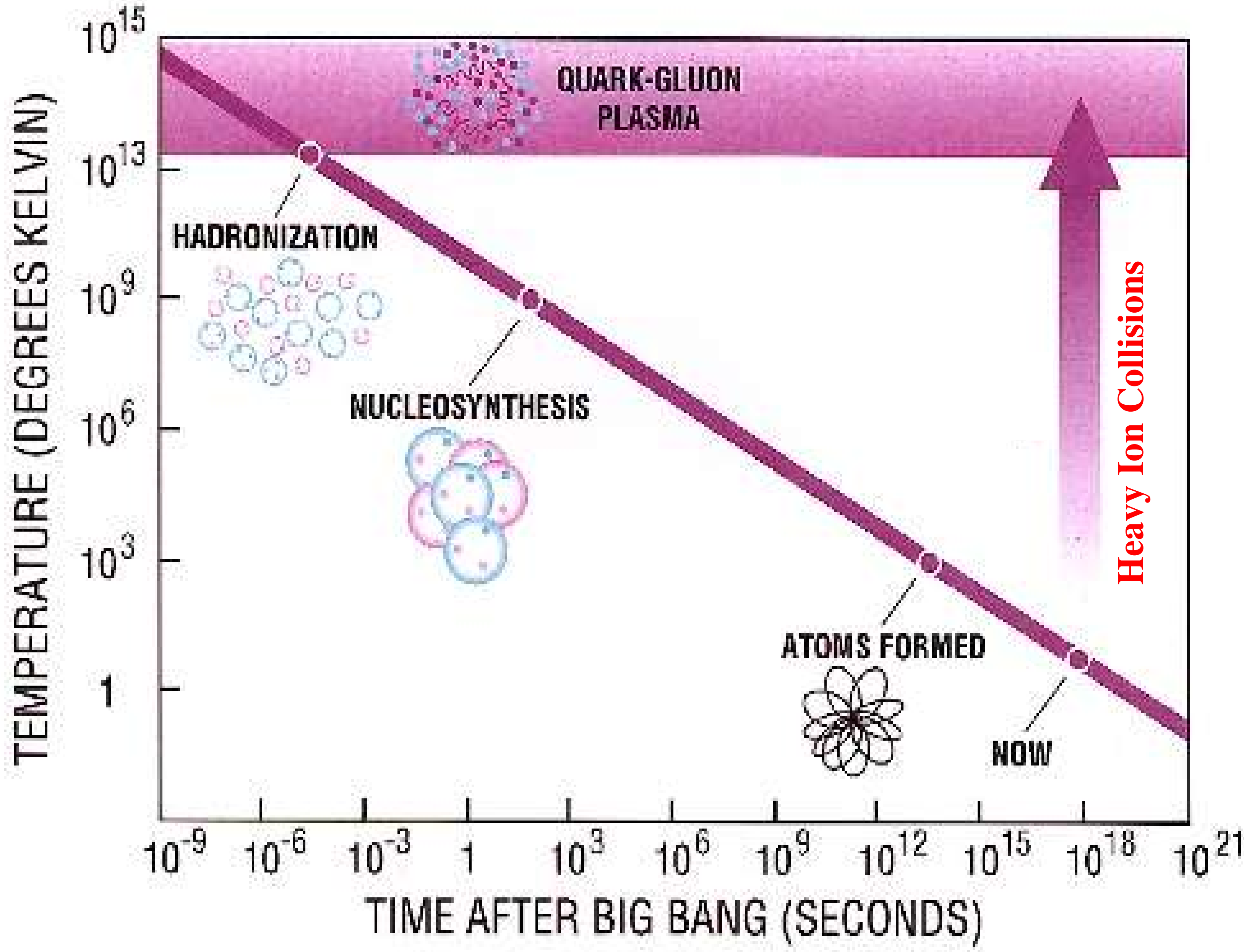
Expansion History of the Universe

Perlmutter, Physics Today (2003)



Wieweit kann man den Urknall zurückverfolgen?





QUARK-GLUON PLASMA
HADRONIZATION
NUCLEOSYNTHESIS
ATOMS FORMED
NOW
Heavy Ion Collisions
TEMPERATURE (DEGREES KELVIN)
10^{15}
10^{13}
10^{9}
10^{6}
10^{3}
1
TIME AFTER BIG BANG (SECONDS)
10^{-9} 10^{-6} 10^{-3} 1 10^{3} 10^{6} 10^{9} 10^{12} 10^{15} 10^{18} 10^{21}

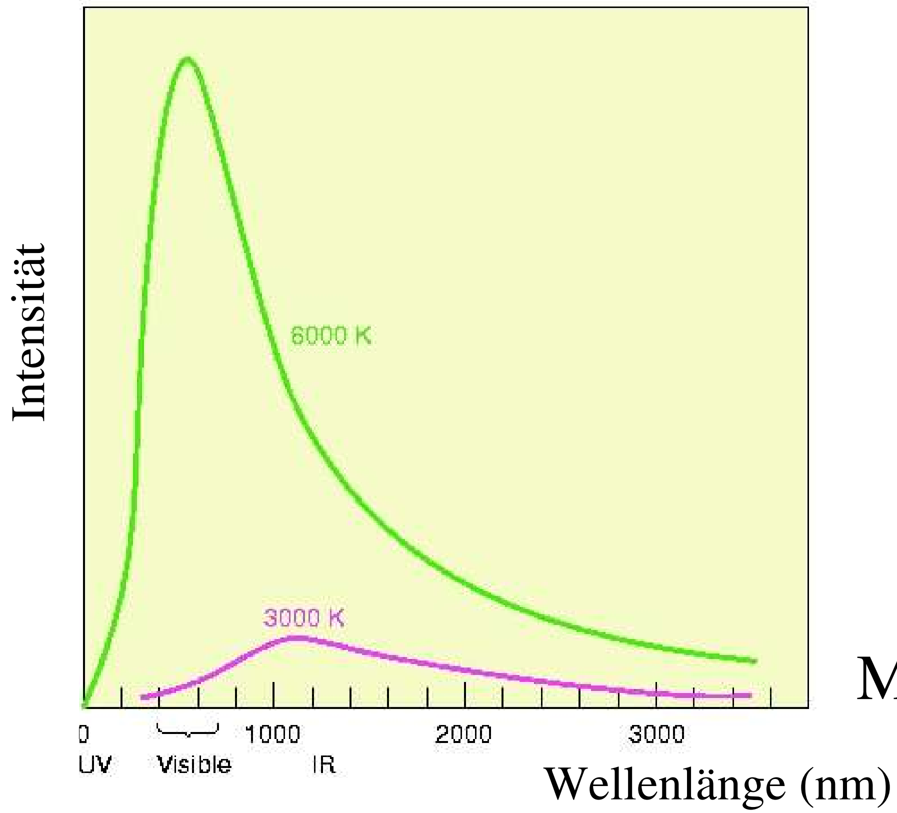
Wie wird die Temperatur bestimmt?

Aus der **Spektralverteilung** der Strahlung,
d.h. aus der Intensität als Funktion der Wellenlänge

- Für die Sonne mit Photonen (Licht) im sichtbaren Bereich
- Für das Weltall heute mit Mikrowellen
  (kosmische Hintergrundstrahlung)

Messung der Temperatur an der Sonnenoberfläche

Photonen Spektrum



M. Planck 1900

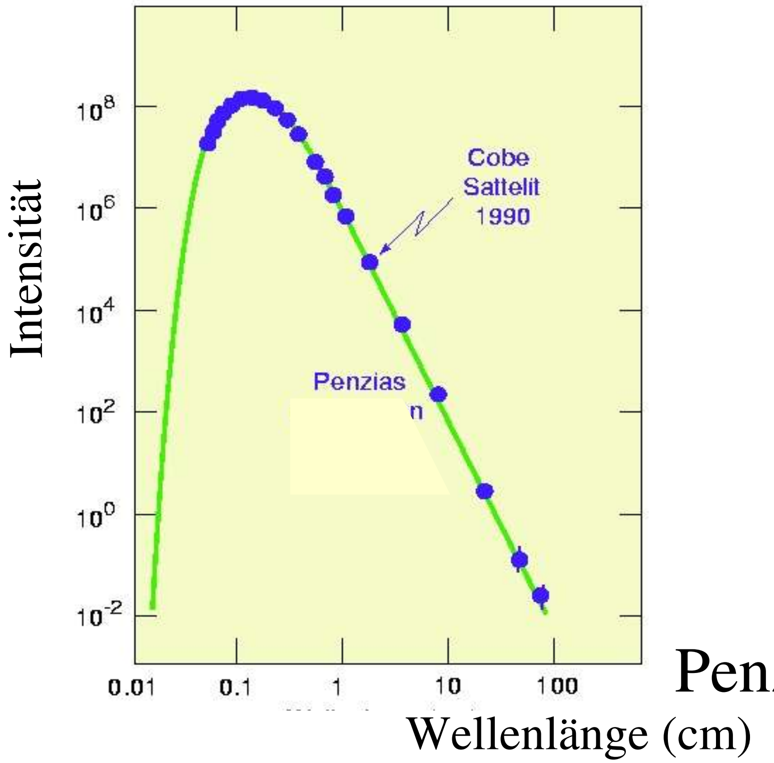
Aus Intensität und Wellenlänge des Sonnenlichts

$T = 6000$ K

Dichte = $4 \cdot 10^{12}$ Photonen/cm^3

Messung der Temperatur im All

Spektrum der kosmischen Hintergrundstrahlung



Penzias und Wilson 1965

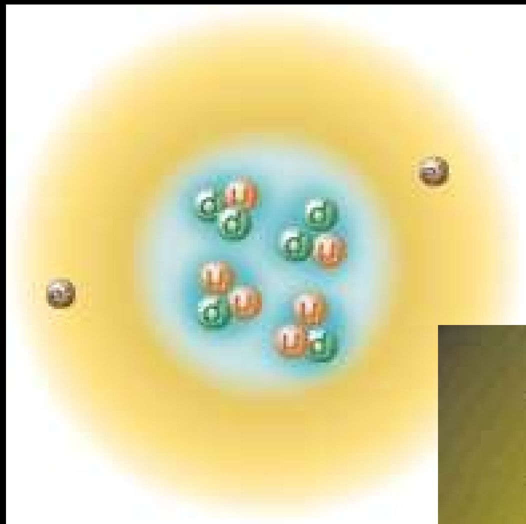
Aus Intensität und Wellenlänge der Mikrowellen-Hintergrund Strahlung

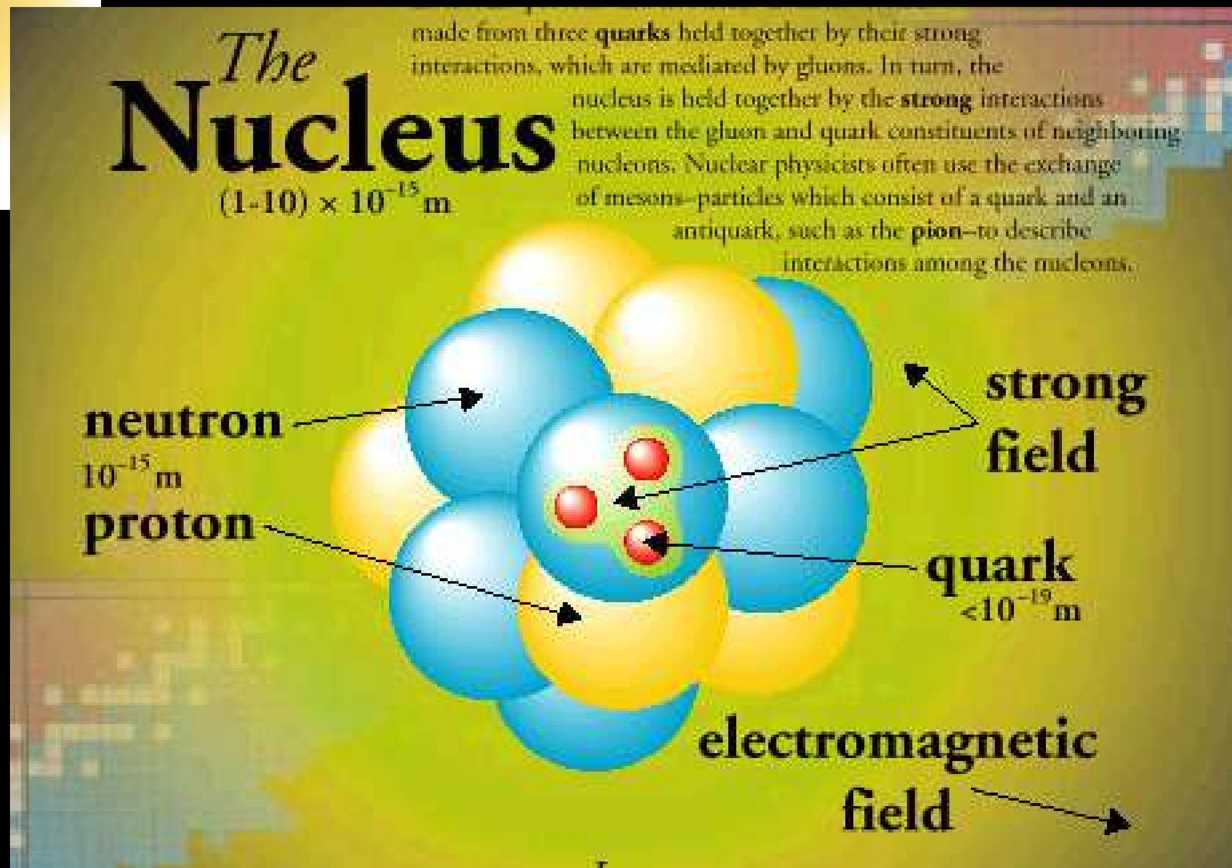
$$T = 2.736 \pm 0.017\ K$$

Dichte = 400 Photonen/cm^3

Wie kann man den Materiezustand, der 10 Mikrosekunden nach dem **Urknall** existierte, produzieren und untersuchen?

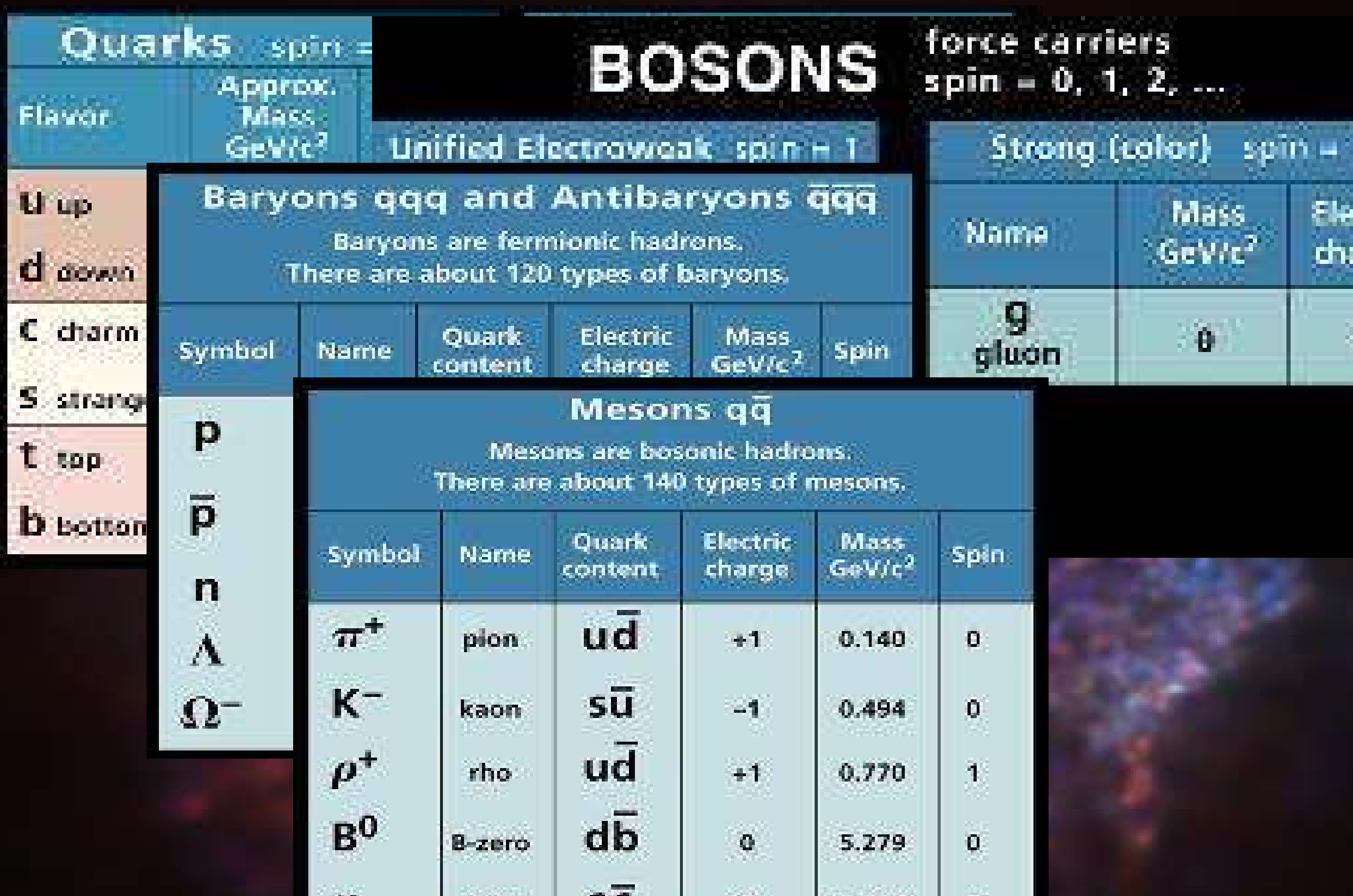
Mit Schwerionen-Kollisionen bei ultrarelativistischen Energien

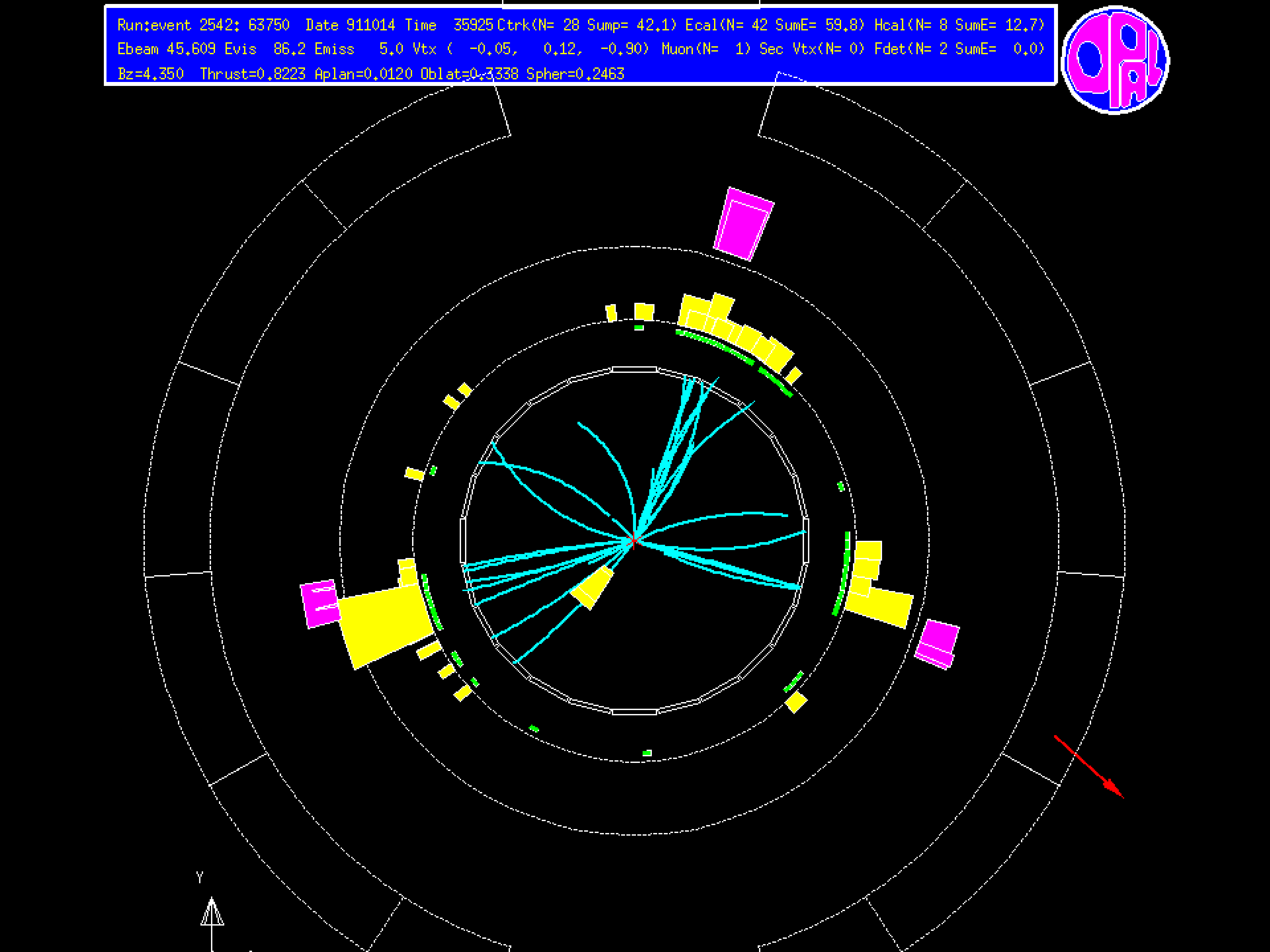


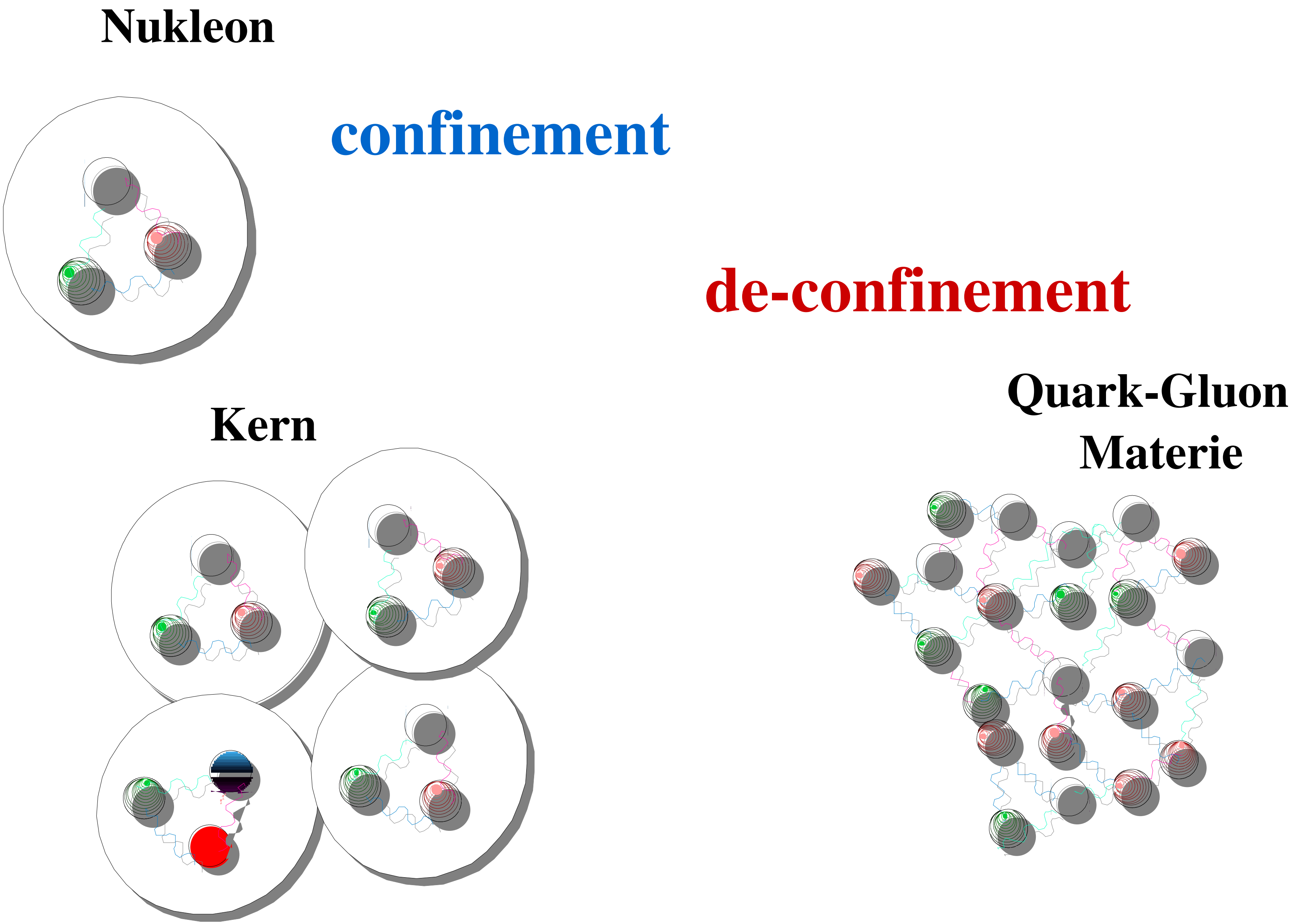


made from three **quarks** held together by their strong interactions, which are mediated by gluons. In turn, the nucleus is held together by the **strong** interactions between the gluon and quark constituents of neighboring nucleons. Nuclear physicists often use the exchange of mesons–particles which consist of a quark and an antiquark, such as the **pion**–to describe interactions among the nucleons.
The Nucleus
(1-10) × 10^{-15} m
neutron
10^{-15} m
proton
strong field
quark
<10^{-19} m
electromagnetic field

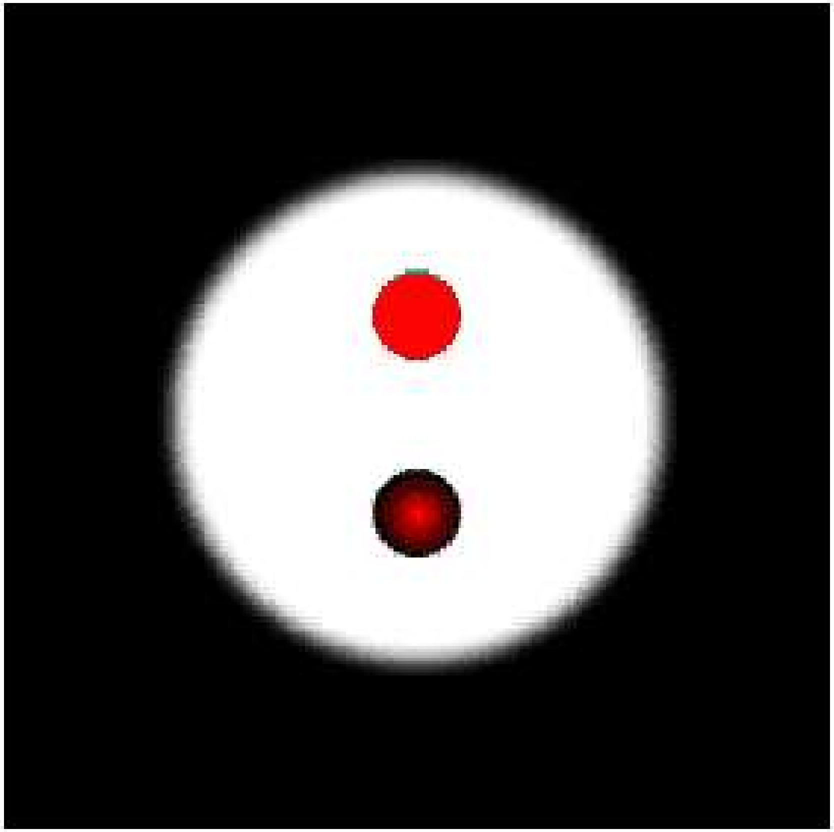
Der Teilchen-Zoo



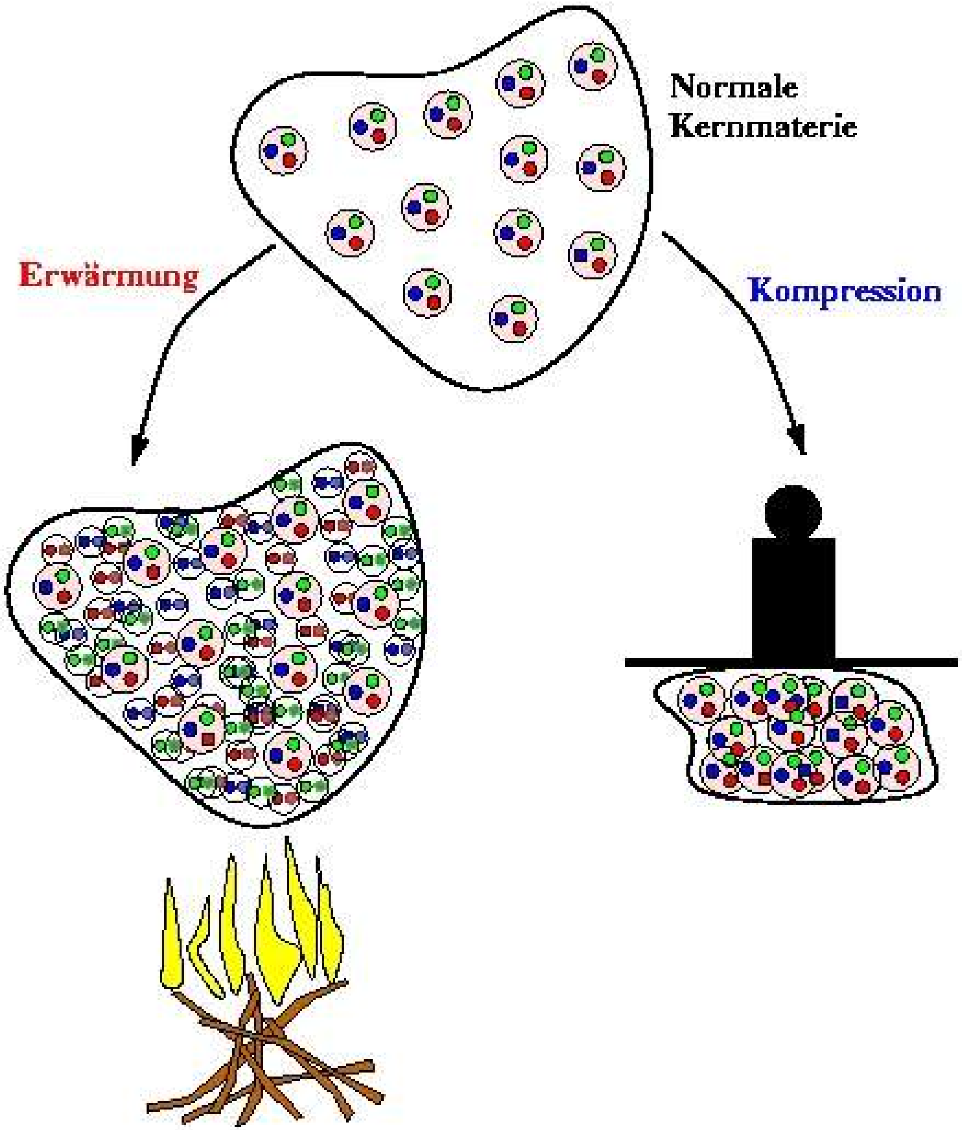

Run:event 2542: 63750 Date 911014 Time 35925 Ctrk(N= 28 Sump= 42.1) Ecal(N= 42 SumE= 59.8) Hcal(N= 8 SumE= 12.7)
Ebeam 45.609 Evis 86.2 Emiss 5.0 Vtx (-0.05, 0.12, -0.90) Muon(N= 1) Sec Vtx(N= 0) Fdet(N= 2 SumE= 0.0)
Bz=4.350 Thrust=0.8223 Aplan=0.0120 Oblat=0.3338 Spher=0.2463
Y


Nukleon
confinement
de-confinement
Kern
Quark-Gluon
Materie

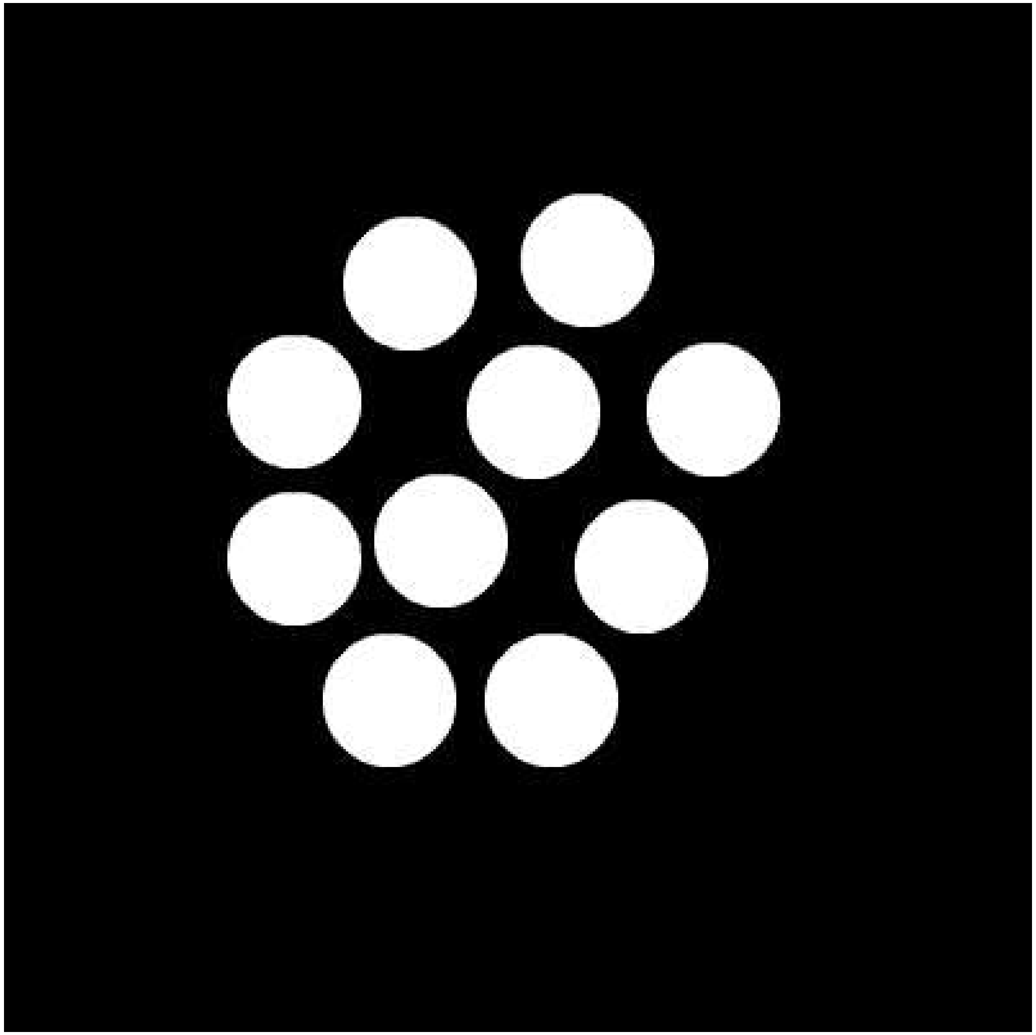
Ein Meson



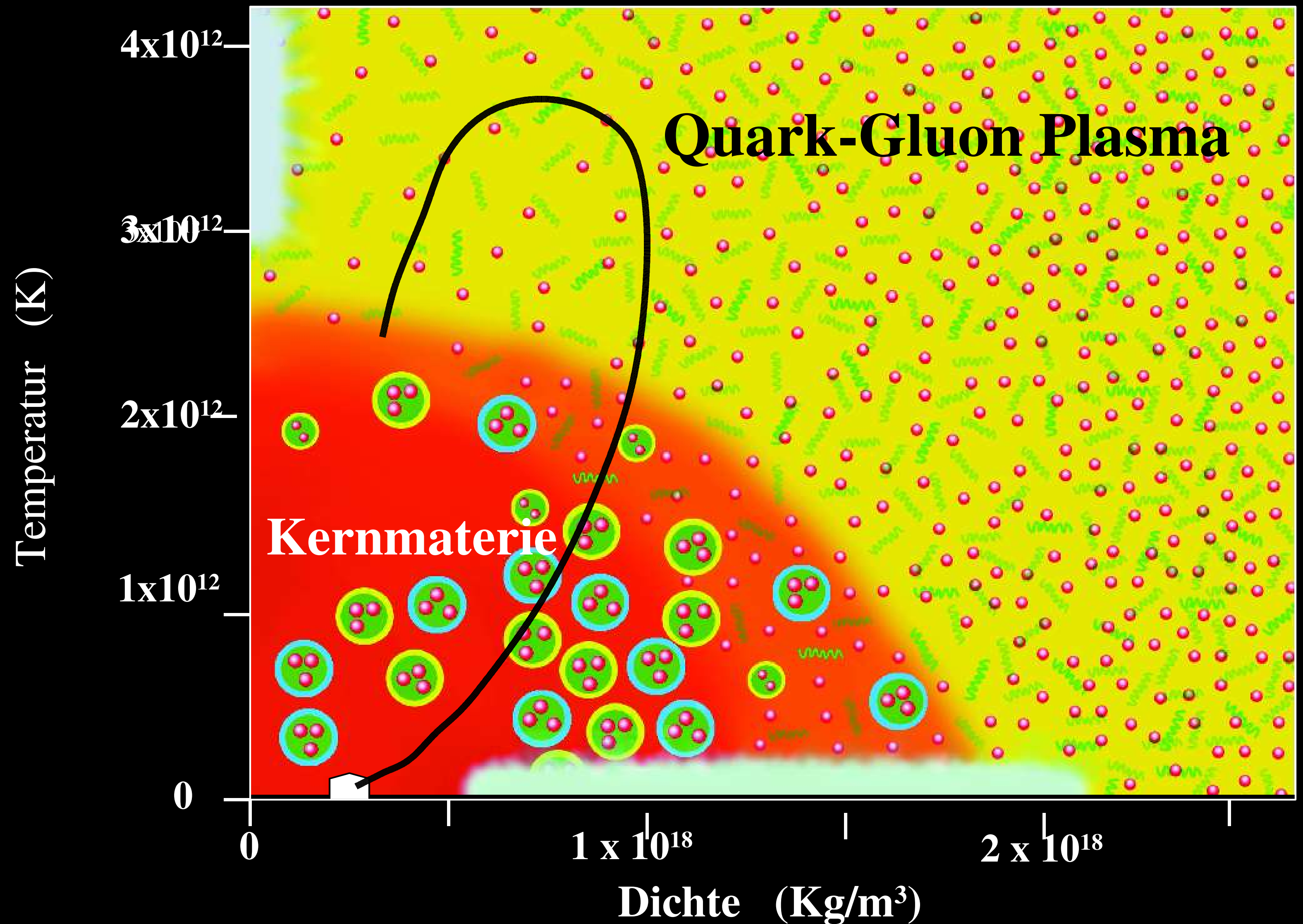
Durch enorme Erwärmung oder Kompression von Materie werden Quarks aus ihrem *"confinement"* befreit:



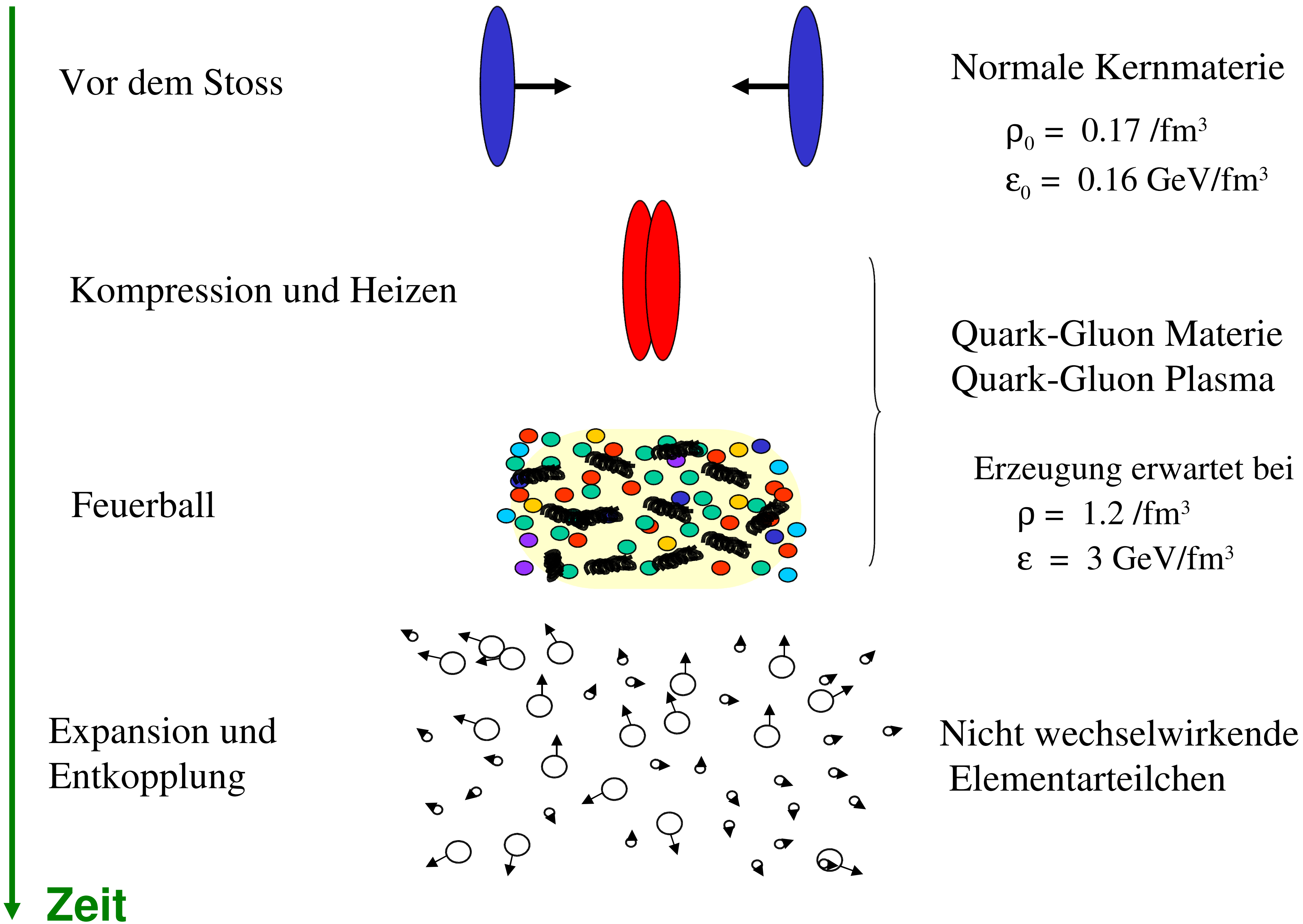
Von Kernmaterie zum Quark Gluon Plasma



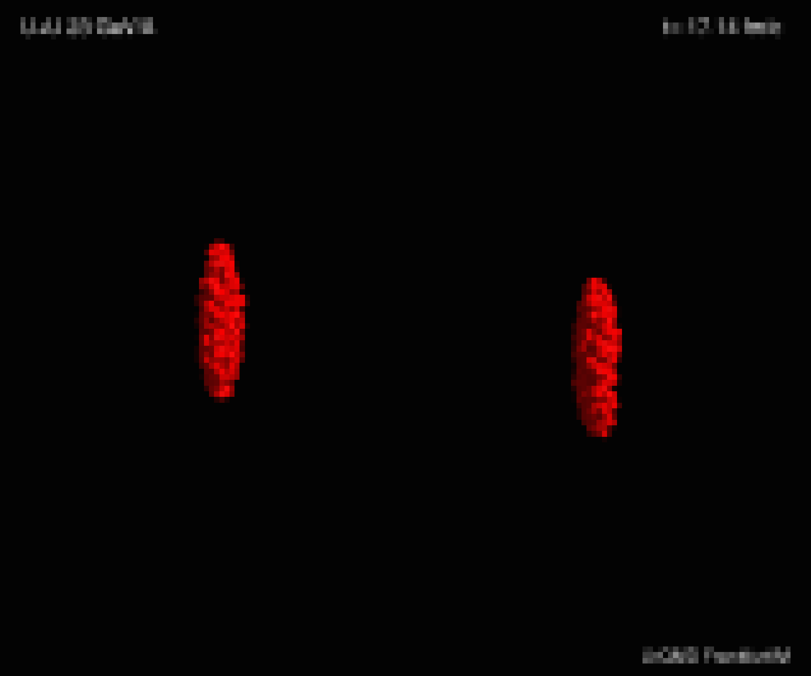
movie mesons

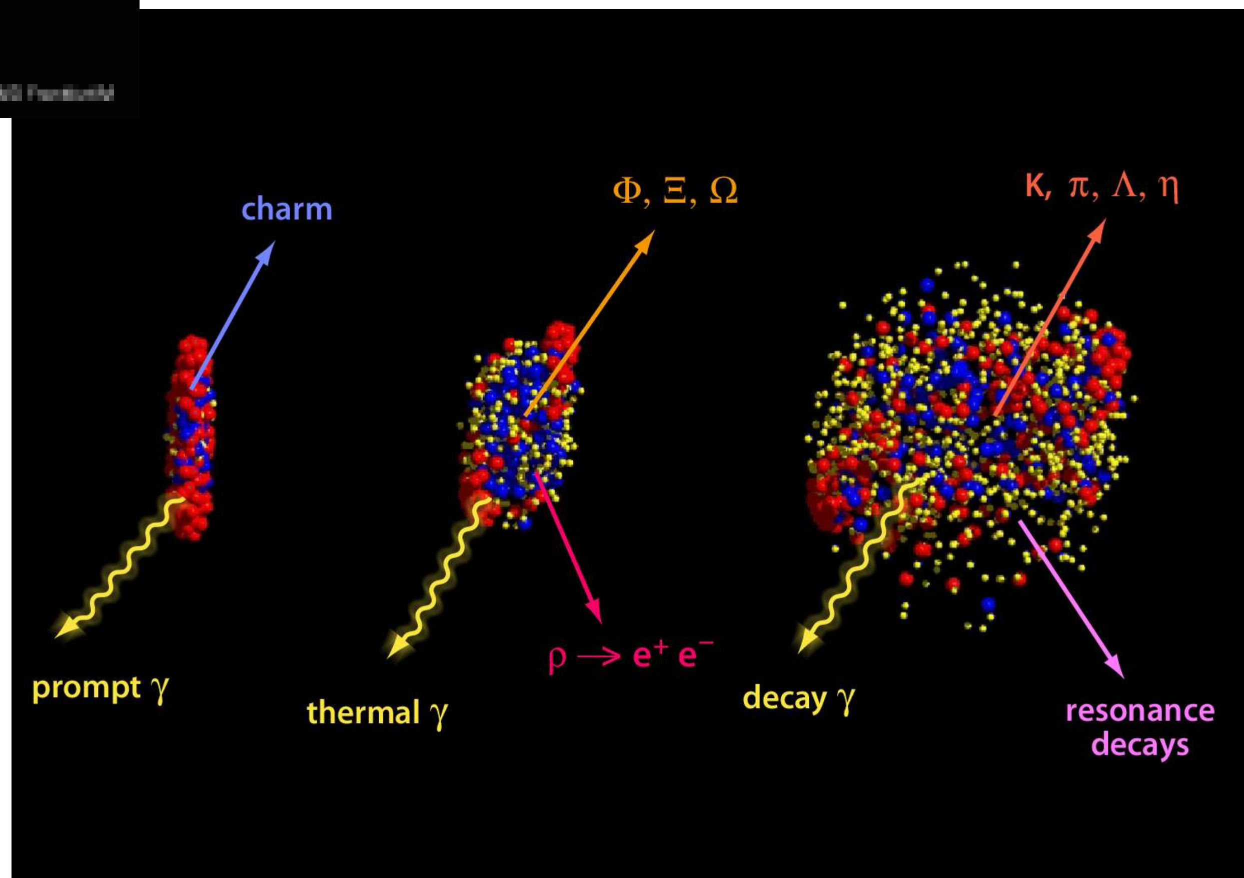


Quark-Gluon Plasma
Kernmaterie
Temperatur (K)
4x10^12
3x10^12
2x10^12
1x10^12
0
0
1 x 10^18
2 x 10^18
Dichte (Kg/m³)

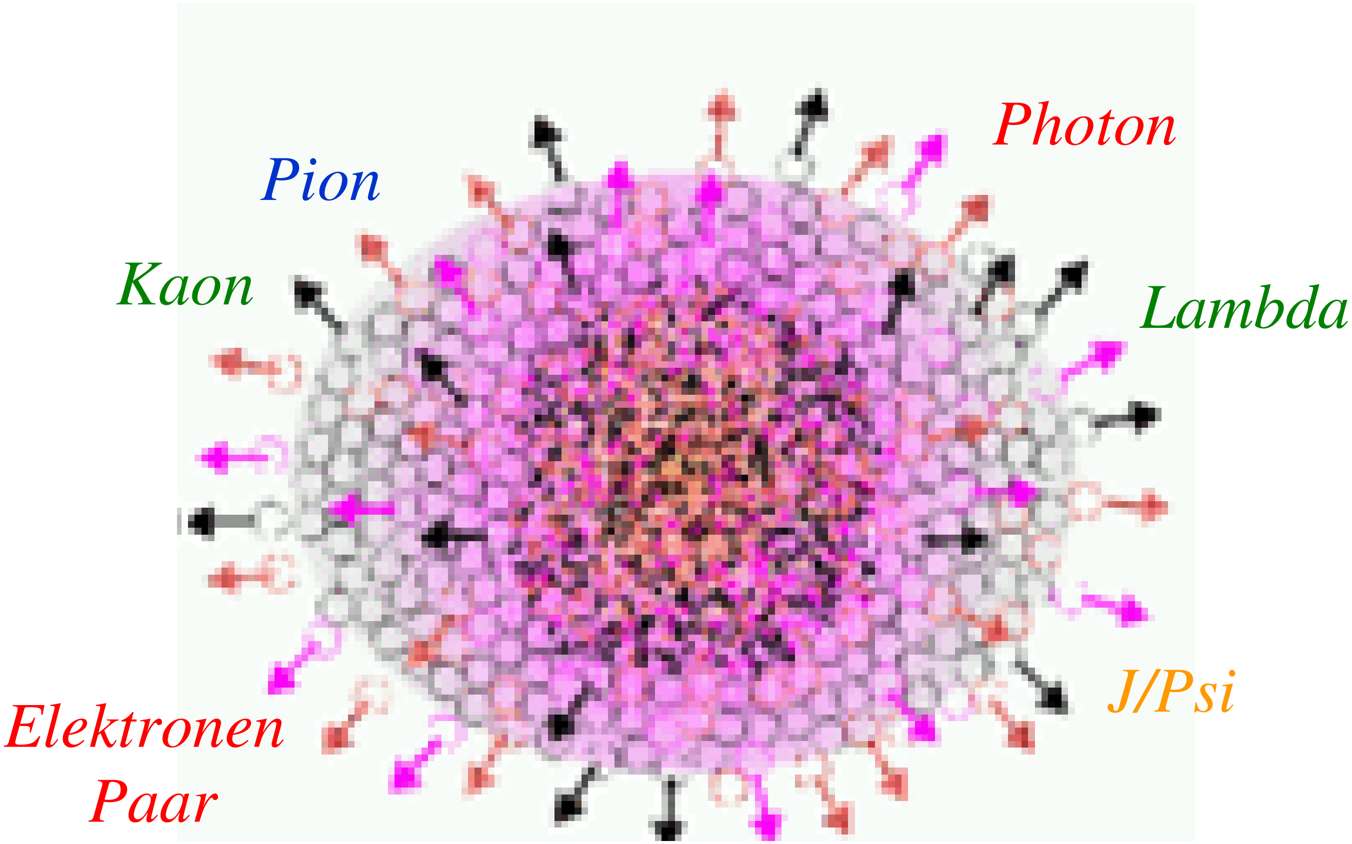

Vor dem Stoss
Normale Kernmaterie
$\rho_0 = 0.17 /fm^3$
$\varepsilon_0 = 0.16 GeV/fm^3$
Kompression und Heizen
Quark-Gluon Materie
Quark-Gluon Plasma
Feuerball
Erzeugung erwartet bei
$\rho = 1.2 /fm^3$
$\varepsilon = 3 GeV/fm^3$
Expansion und
Entkopplung
Nicht wechselwirkende
Elementarteilchen
Zeit

Kollision und Diagnose



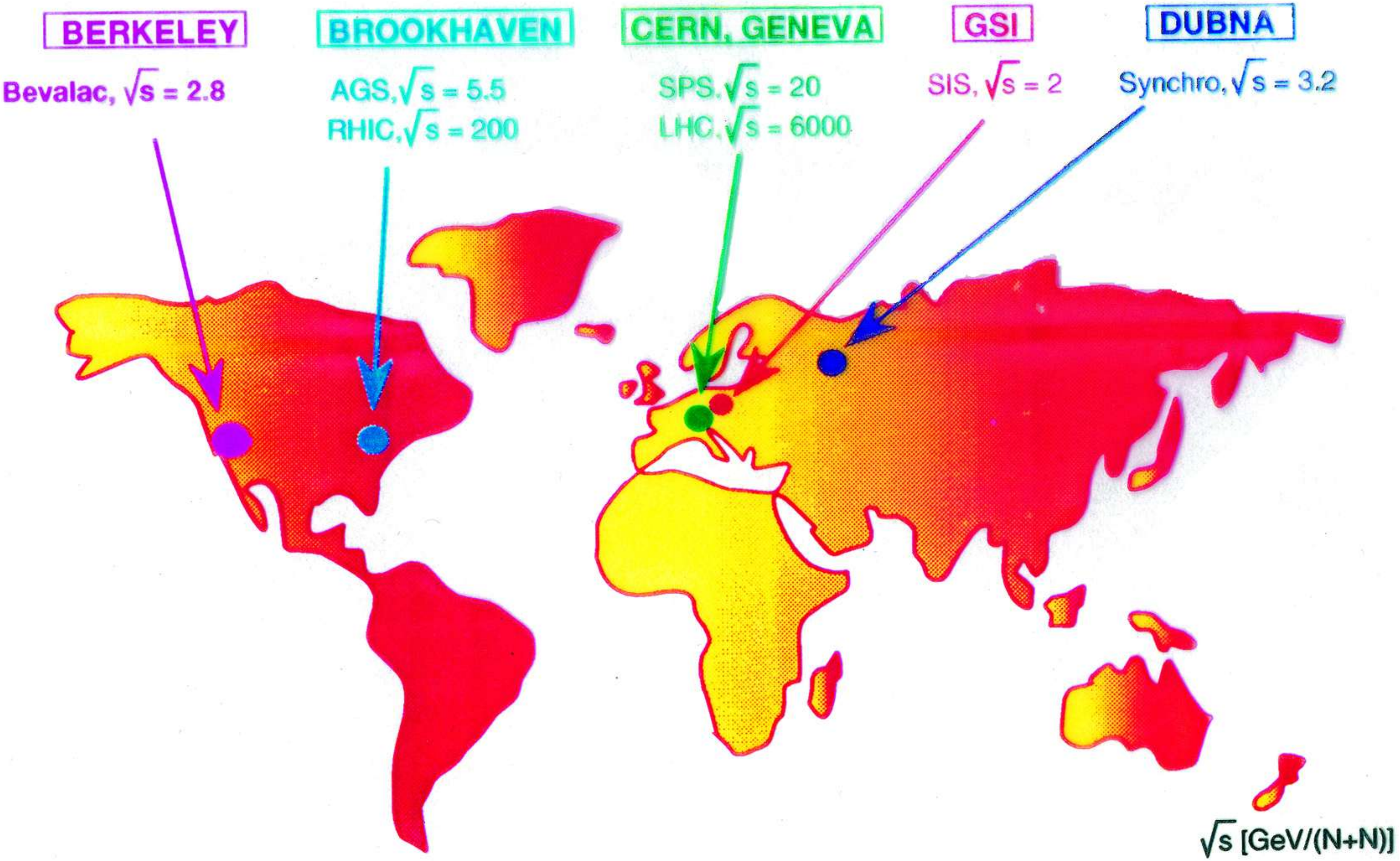


Feuerball



Die Eigenschaften des Feuerballs kann man durch die Messung der emittierten Teilchen bestimmen.

Relativistic Heavy Ion Accelerators



SPS : 1986 - 2003

- S and Pb ; up to √s =**20** GeV/nucl pair
- hadrons, photons and dileptons

LHC : starting 2007

- Pb ; up to √s = **5.5 TeV/nucl pair**
- ALICE and CMS experiments

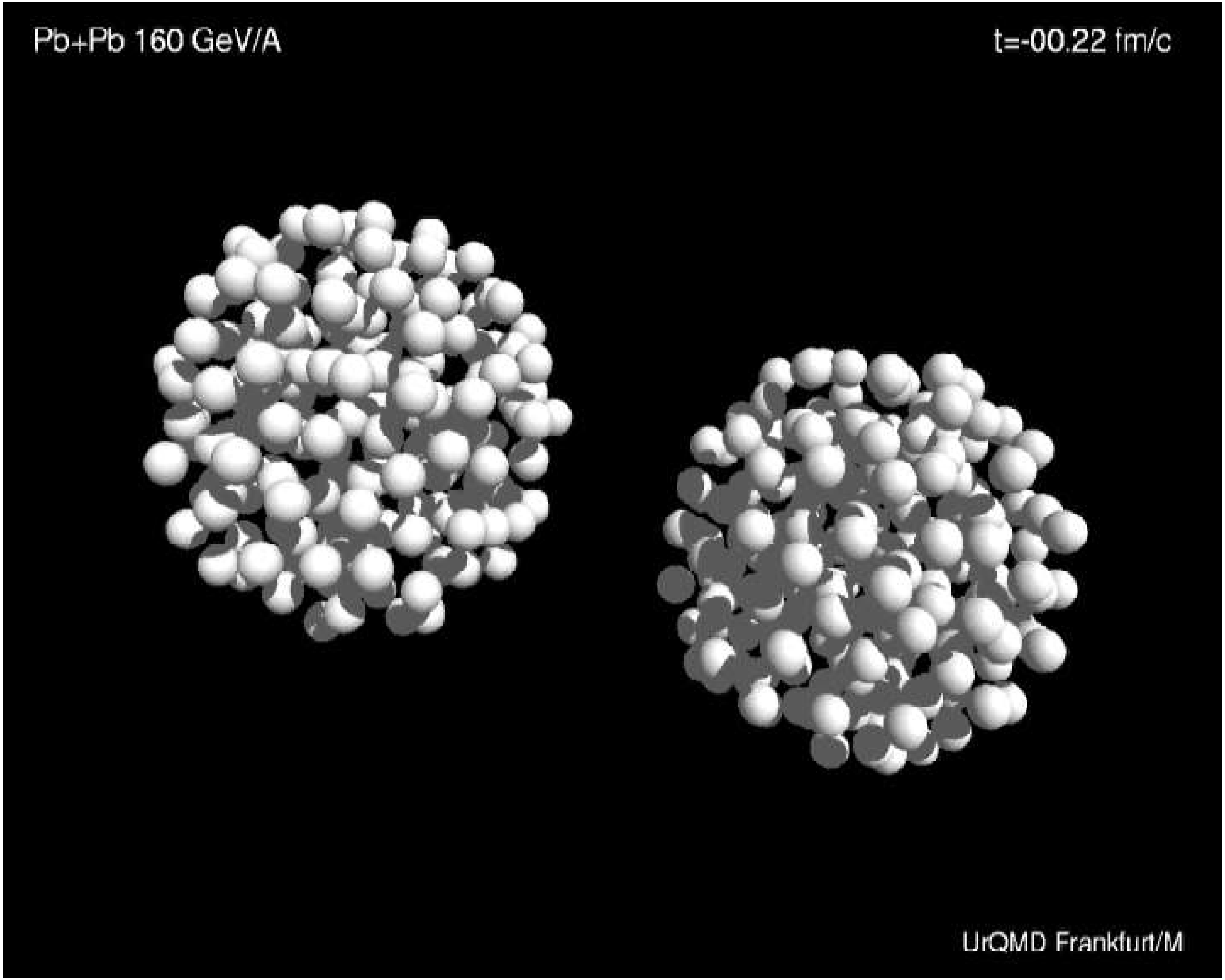
AGS : 1986 - 2000

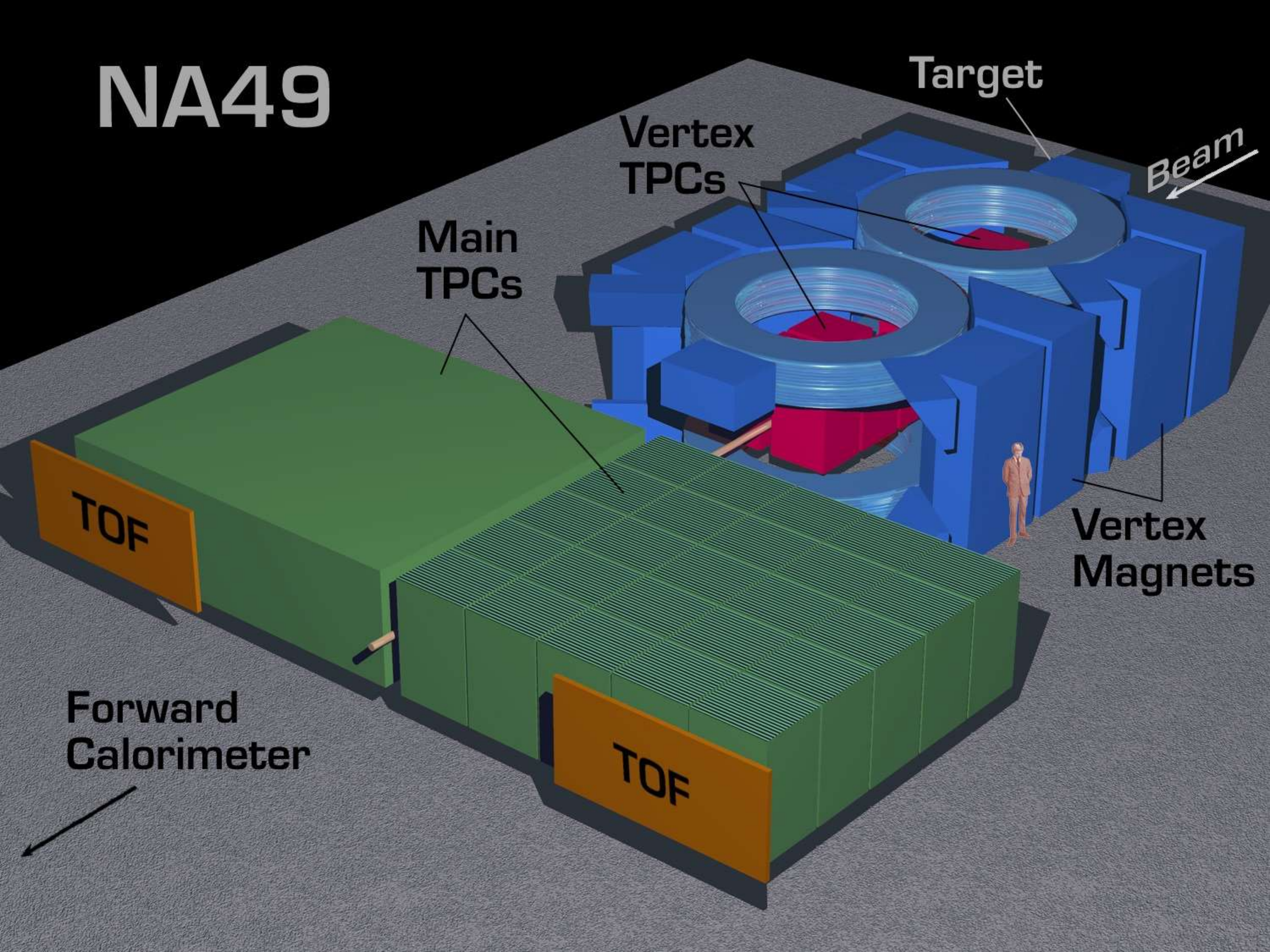
- Si and Au ; up to **√s =5 GeV /nucl pair**
- only hadronic variables

RHIC : 2000

- **Au ; up to √s = 200 GeV /nucl pair**
- hadrons, photons, dileptons, jets

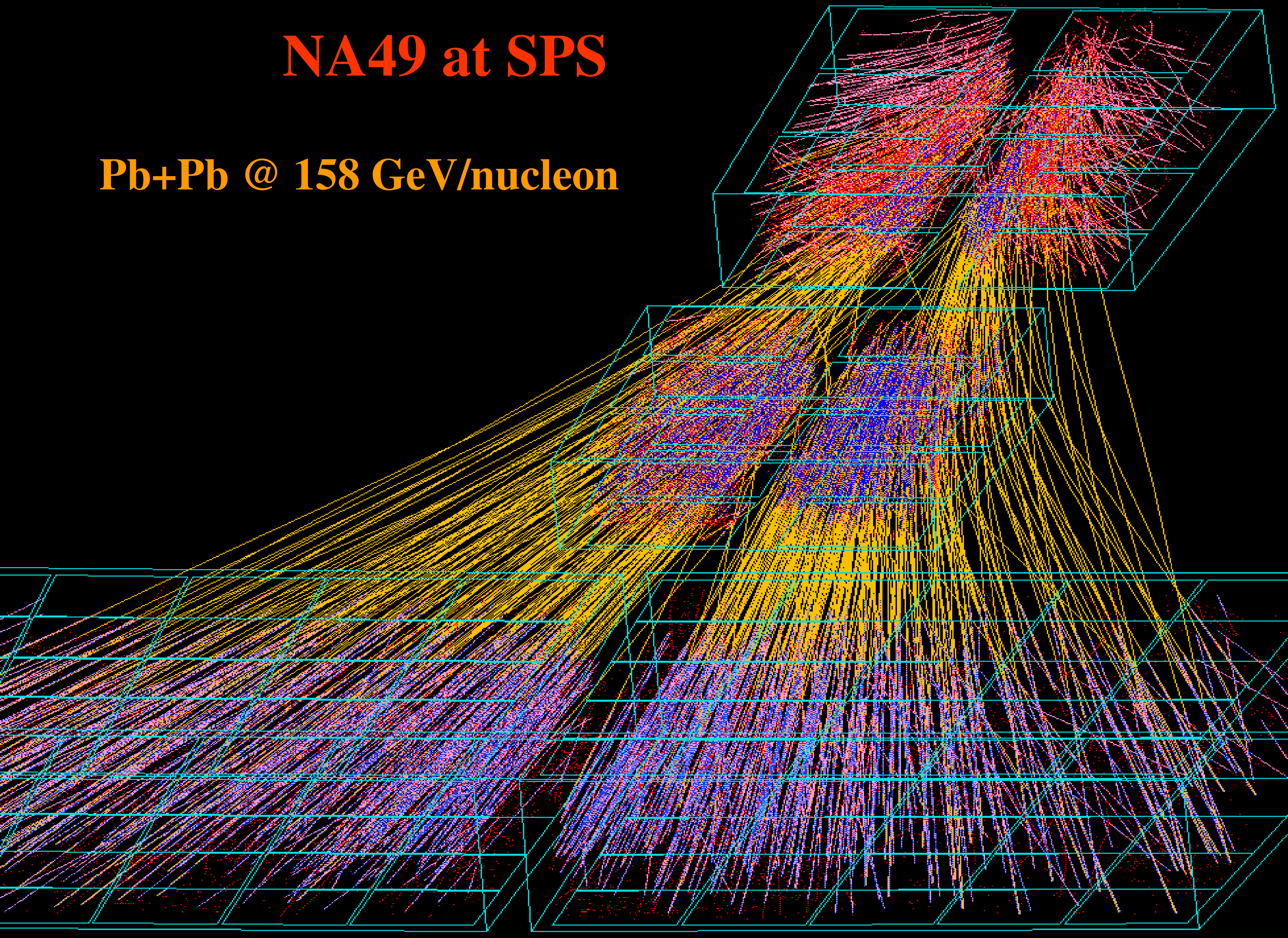

UTO ZURICH
409.04


Pb+Pb 160 GeV/A
t=-00.22 fm/c
UrQMD Frankfurt/M

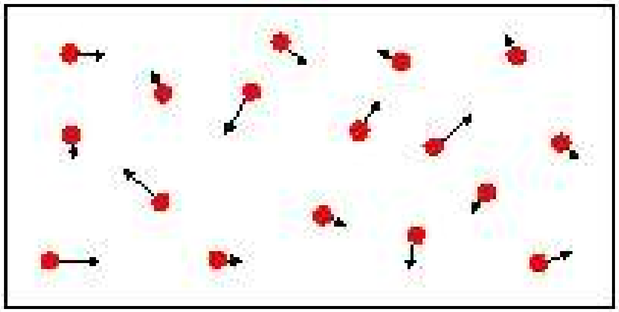

NA49
Target
Beam
Vertex
TPCs
Main
TPCs
TOF
TOF
Vertex
Magnets
Forward
Calorimeter

NA49 at SPS

Pb+Pb @ 158 GeV/nucleon



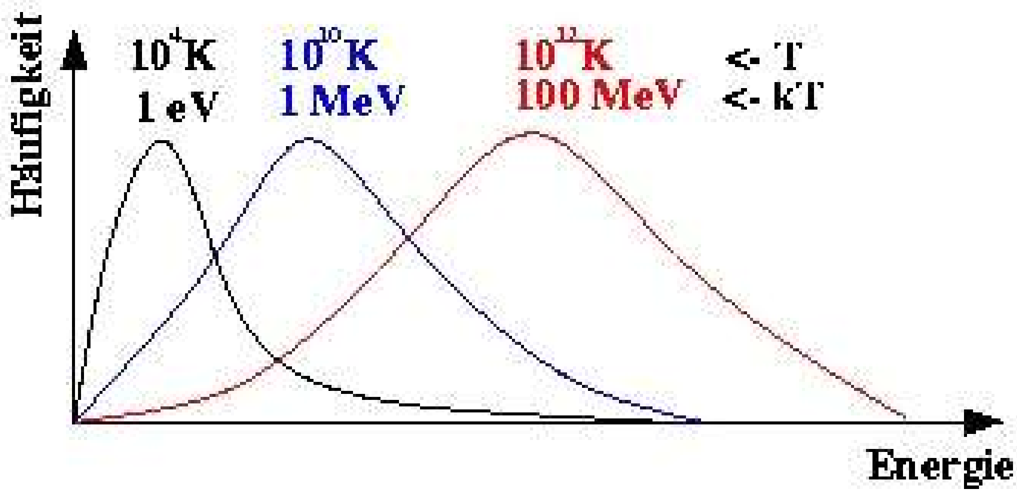
Thermische Energie



Gas mit Temperatur *T*

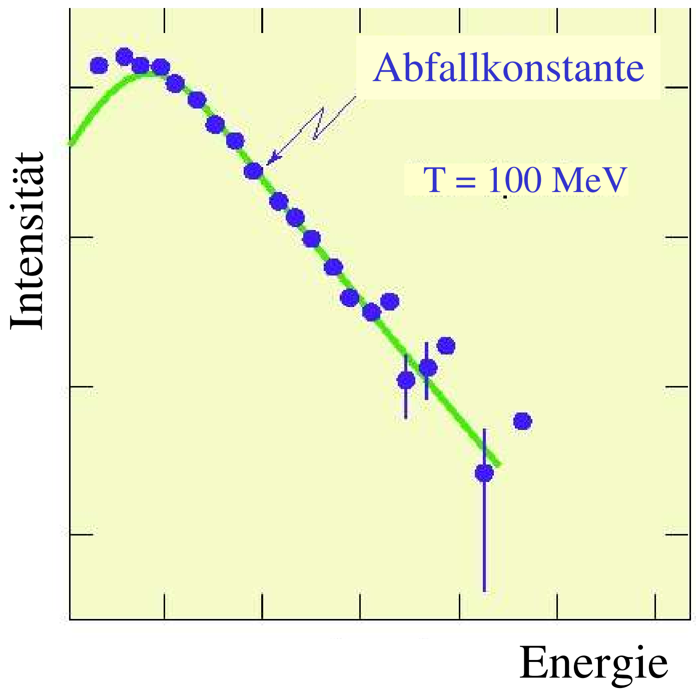
mittlere kinetische Energie
$E_{kin} = 1/2\, mv^2 \sim kT$ ist
proportional zur Temperatur

(kT=*thermische Energie*)



Messung der Temperatur eines Feuerballs aus dem Schwerionenstoss

Pionen Spektrum



Abfallkonstante proportional zur Temperatur

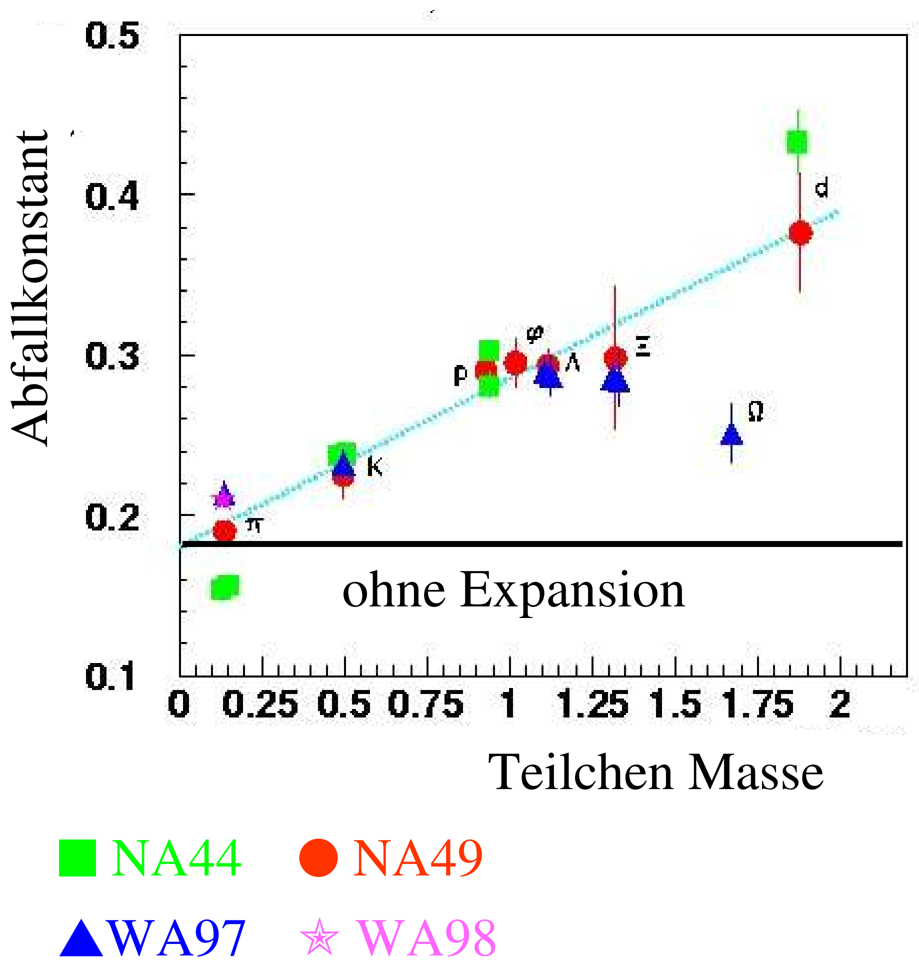
Aus Intensität und Energie der ausgestrahlten Pionen

T = 100 MeV T = 10^{12} K

100 000 mal heißer als im Inneren der Sonne!

Puzzle: die Abfallkonstante ('Temperatur')

hängt von der Masse ab!



Auflösung:

Hubble Expansion
und Abkühlung des
Nuklearen Feuerballs

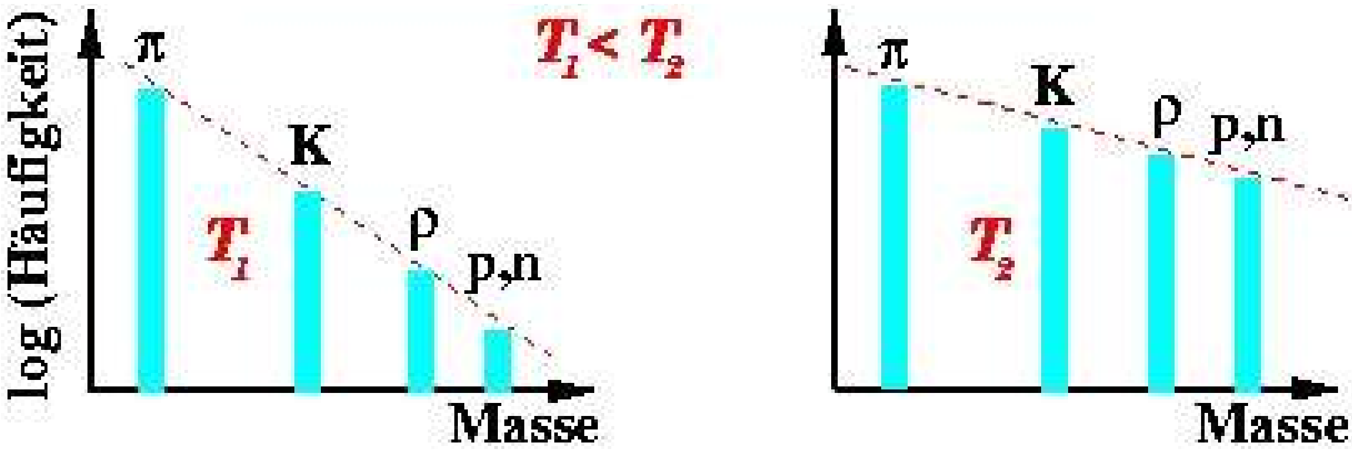
Beim Ausfrieren:

T = 120 MeV

v = 0.55 c

Thermische Energie kann auch zur Besetzung von angeregten Zuständen oder zur Production neuer Teilchen führen

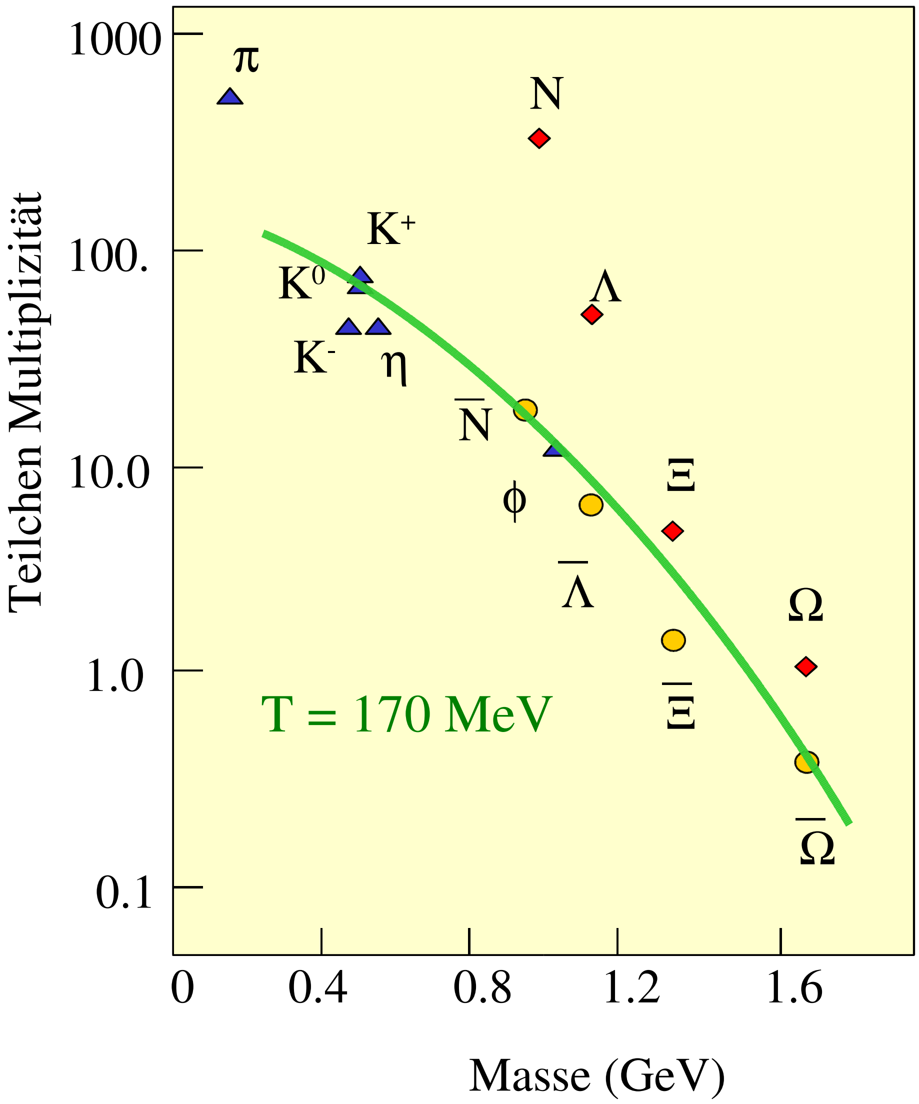
Äquivalenz Energie <=> Masse



Häufigkeit $\sim m^{3/2}\, e^{-m/T}$

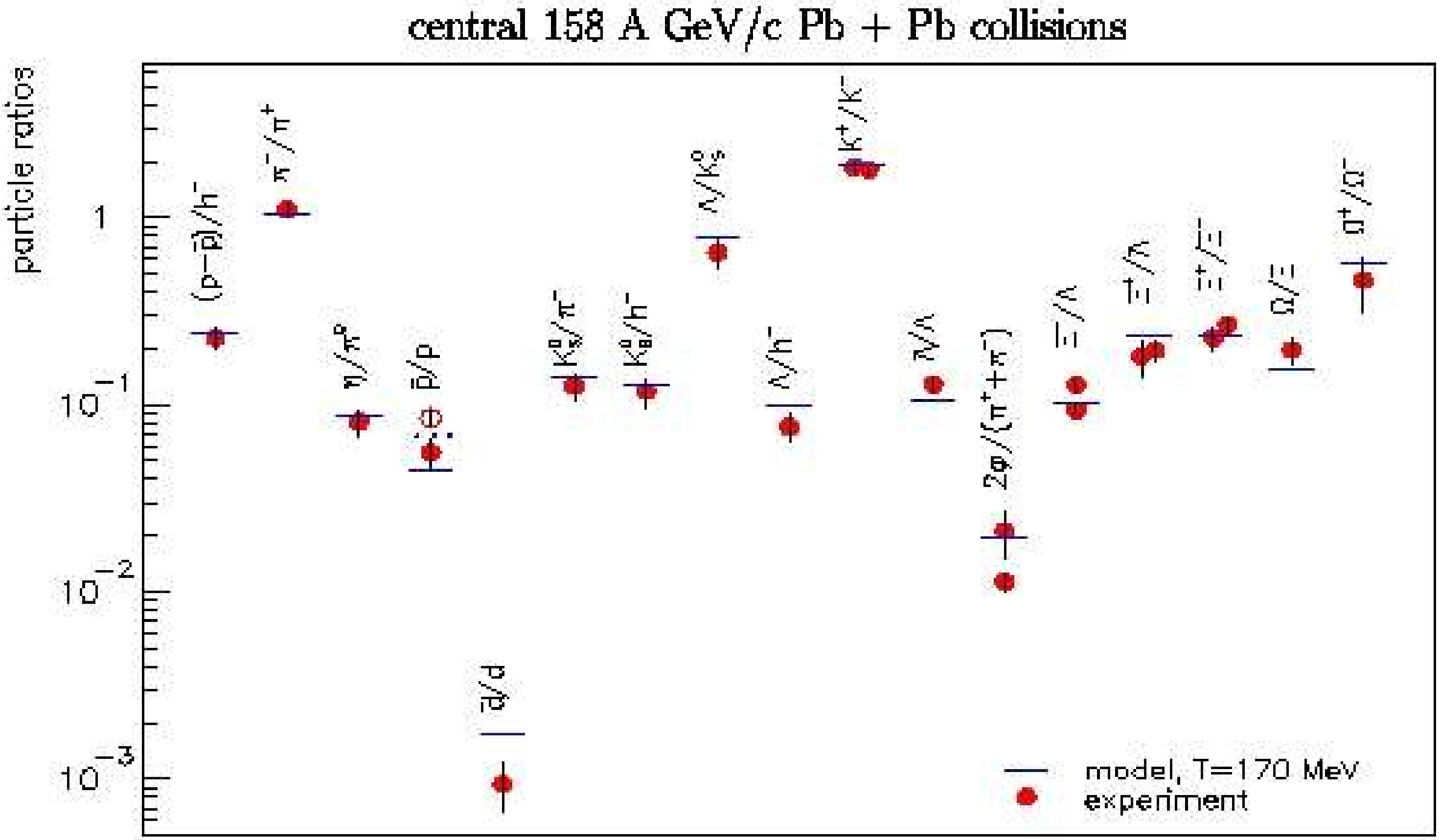
Die gemessenen Teilchenhäufigkeiten erlauben die Bestimmung von Temperatur und Dichte beim Zeitpunkt der Produktion hadronischer Teilchen

Häufigkeit ~ $m^{3/2} e^{-m/T}$



Die gemessene Teilchen-Multiplizität kann man verstehen, wenn alle Teilchen gemeinsam bei einer Temperatur von **170 MeV** produziert werden.

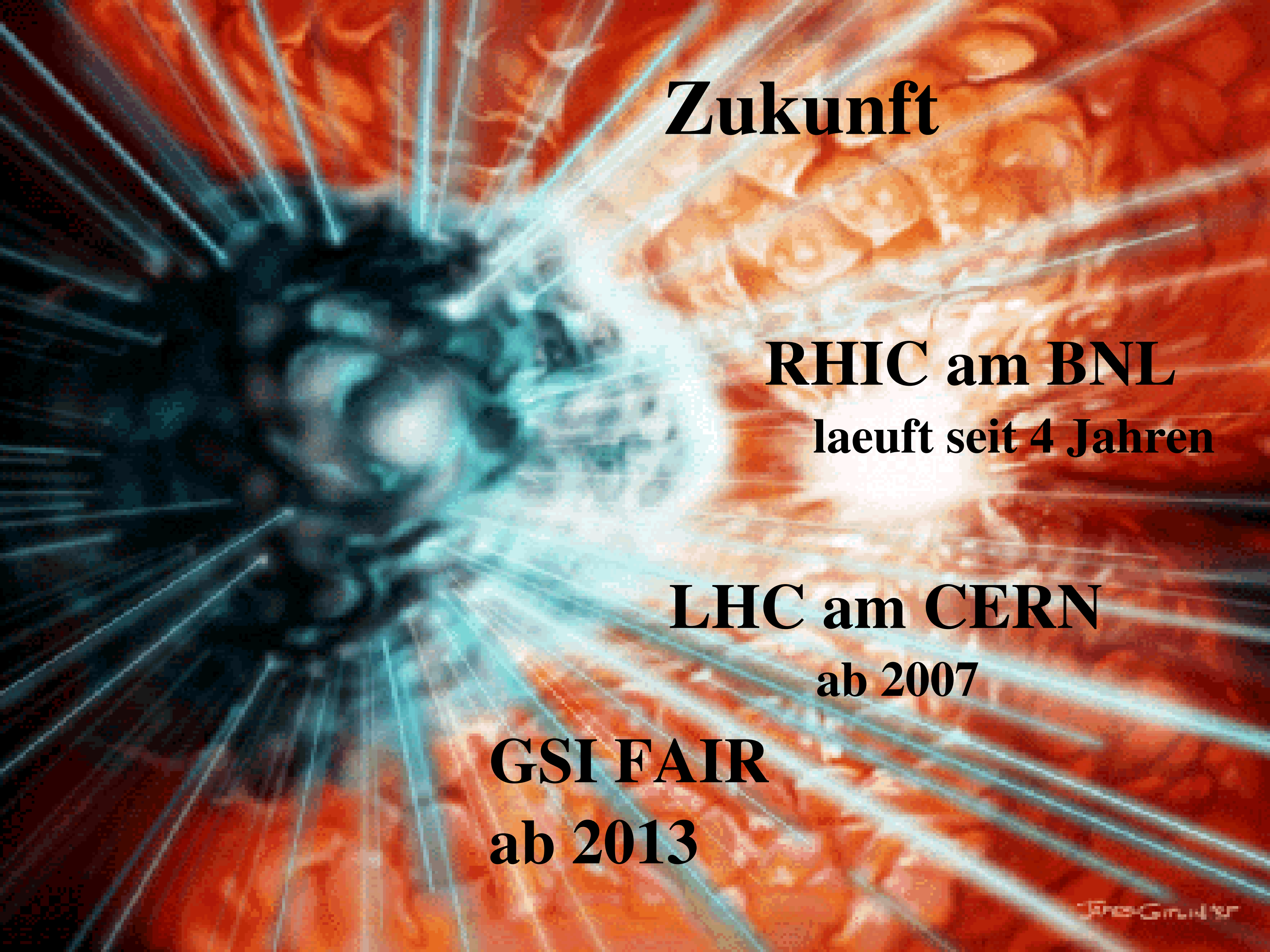
Beschreibung in einem vollständigen thermischen Modell at SPS



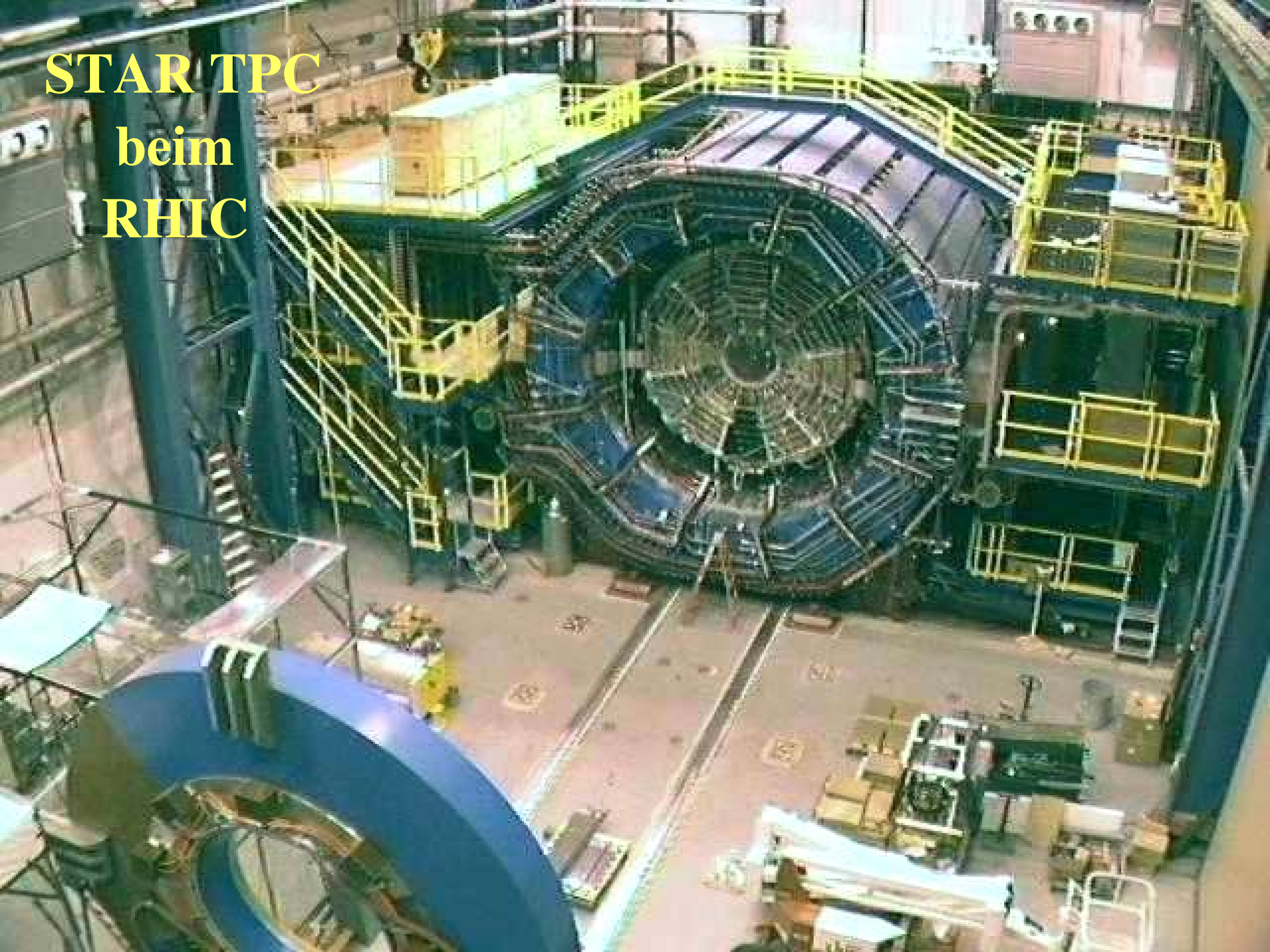
Bestimmung der Temperatur und Dichte zur Zeit der Teilchenproduktion

T = 170 MeV

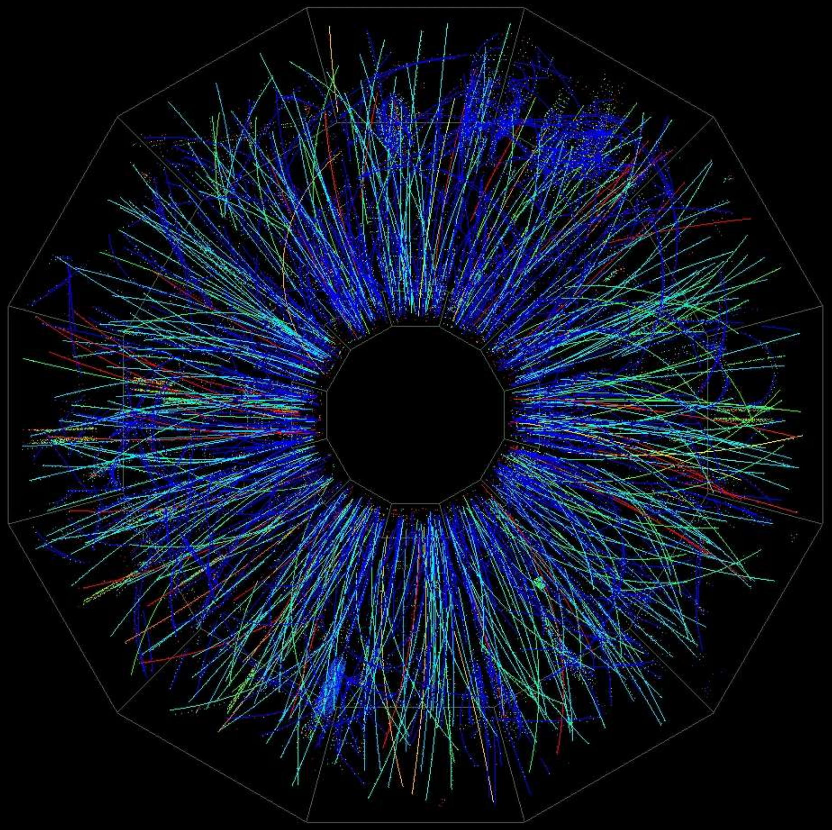
μ_B = 266 MeV


Zukunft
RHIC am BNL
laeuft seit 4 Jahren
LHC am CERN
ab 2007
GSI FAIR
ab 2013

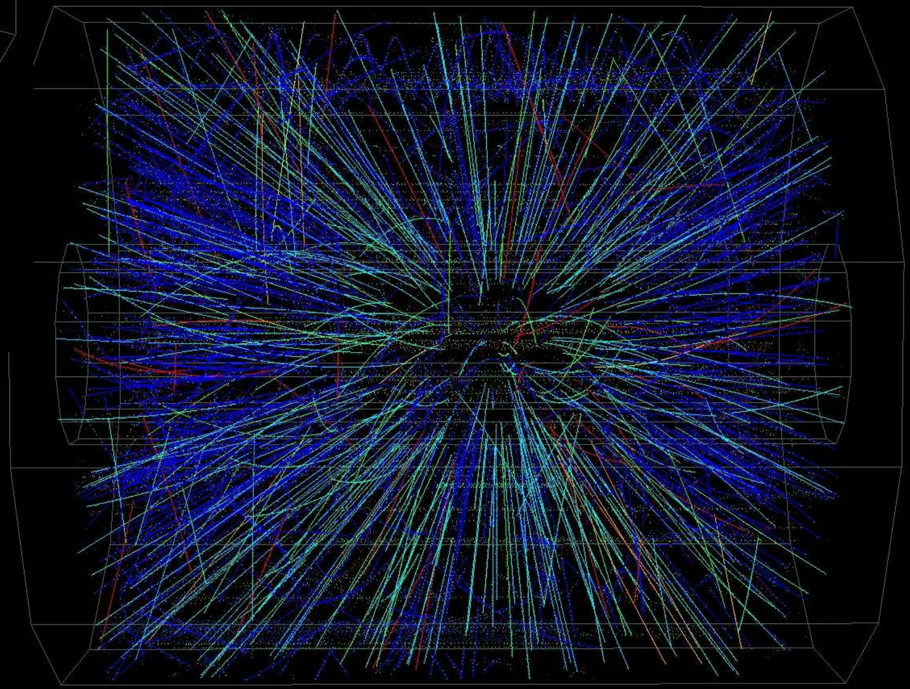
Relativistic Heavy Ion Collider


STAR TPC
beim
RHIC

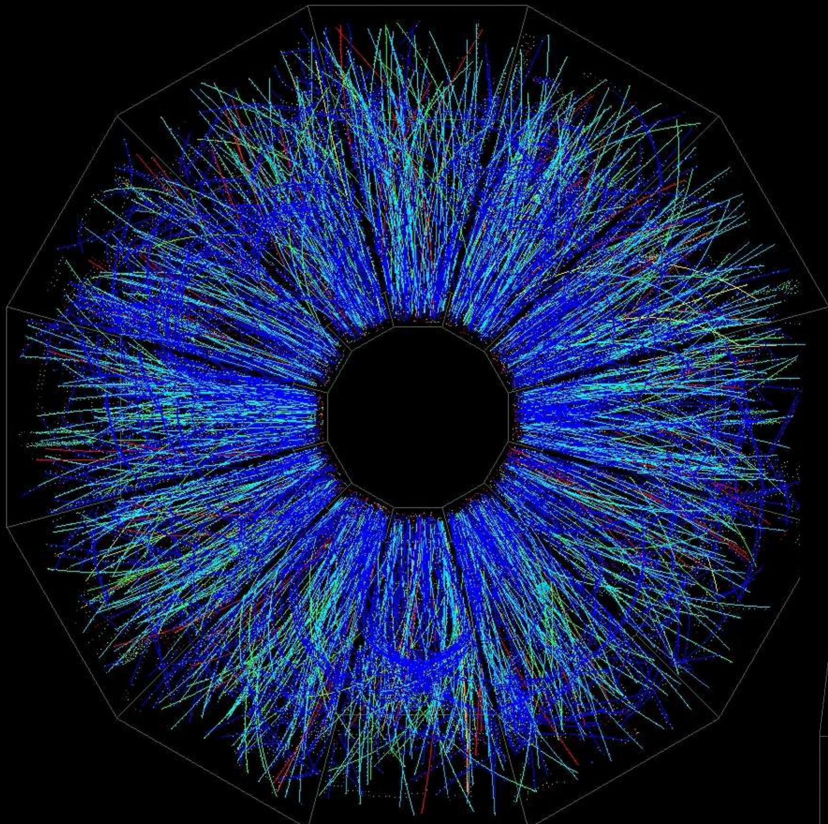
Au on Au Event at CM Energy ~ 130 A-GeV



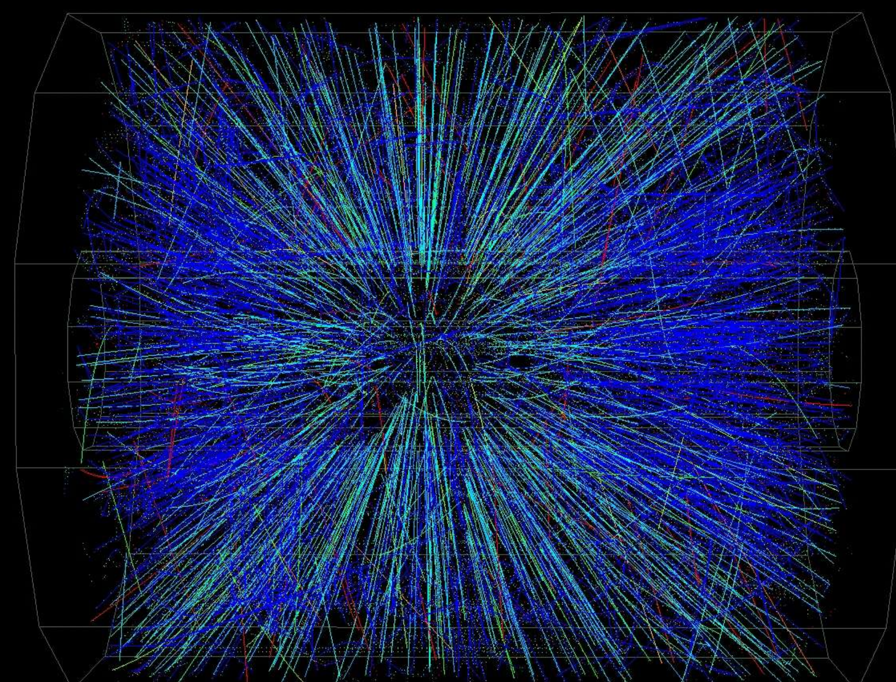
Peripheral Event



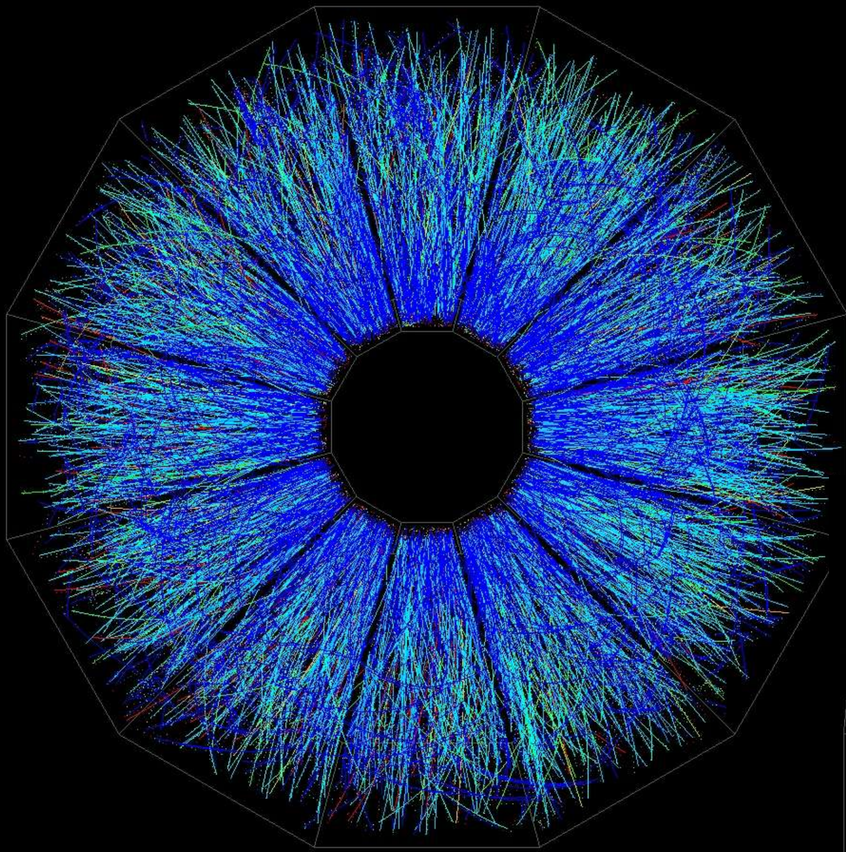
Au on Au Event at CM Energy ~ 130 A-GeV



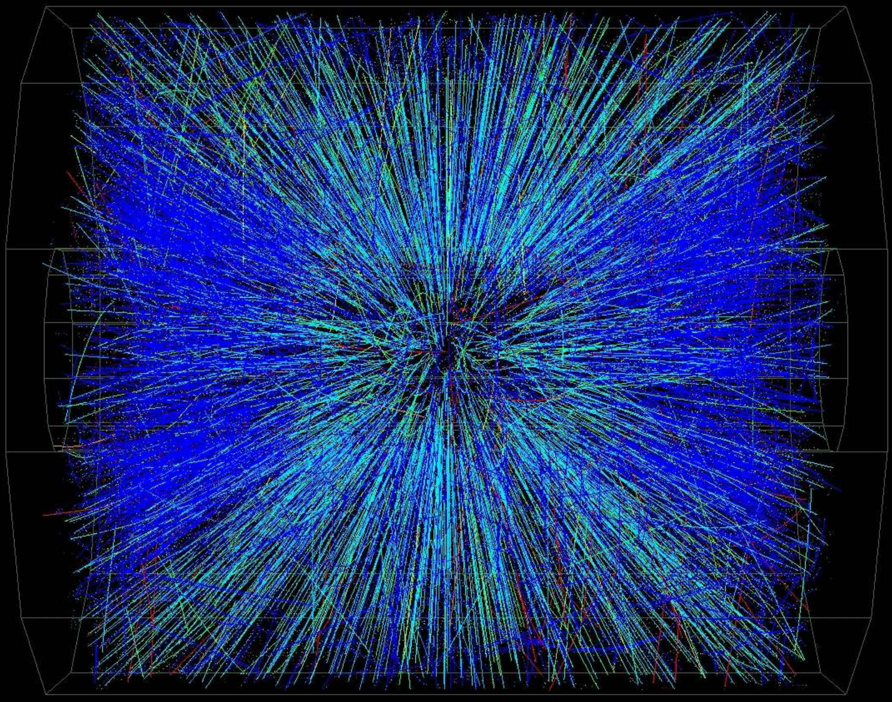
Mid-central Event



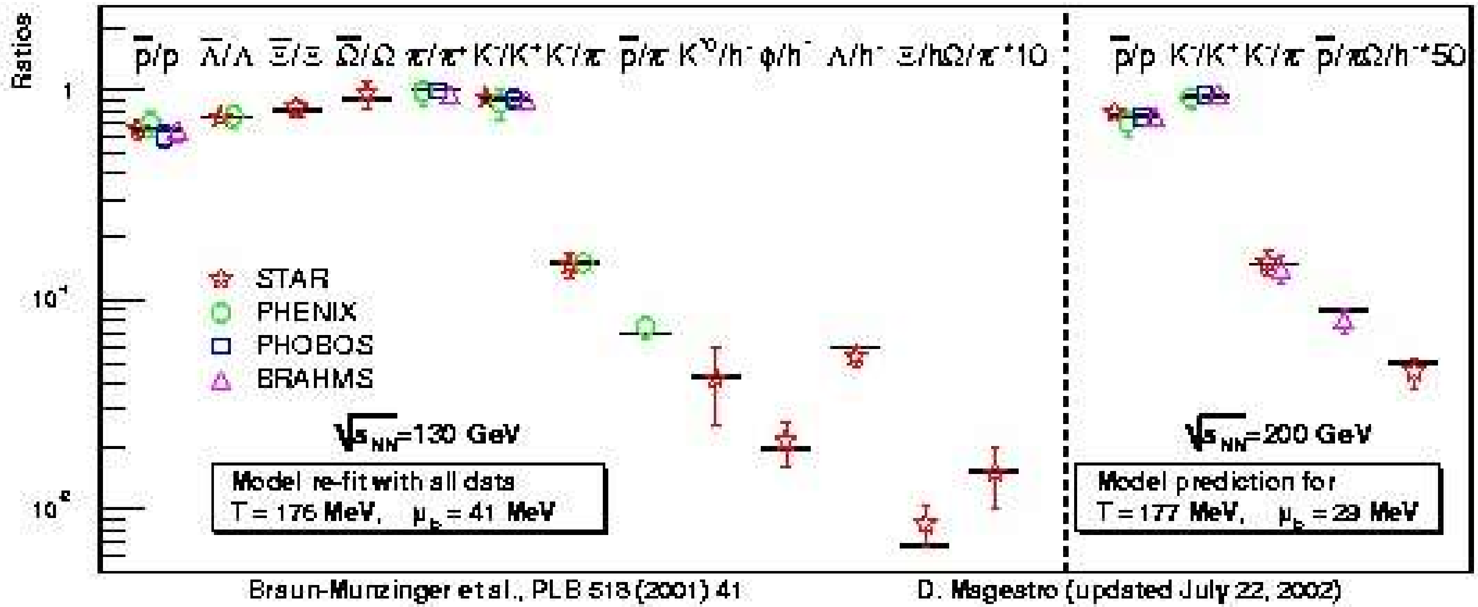
Au on Au Event at CM Energy ~ 130 A-GeV



Central Event



Beschreibung in einem vollständigen thermischen Modell beim RHIC

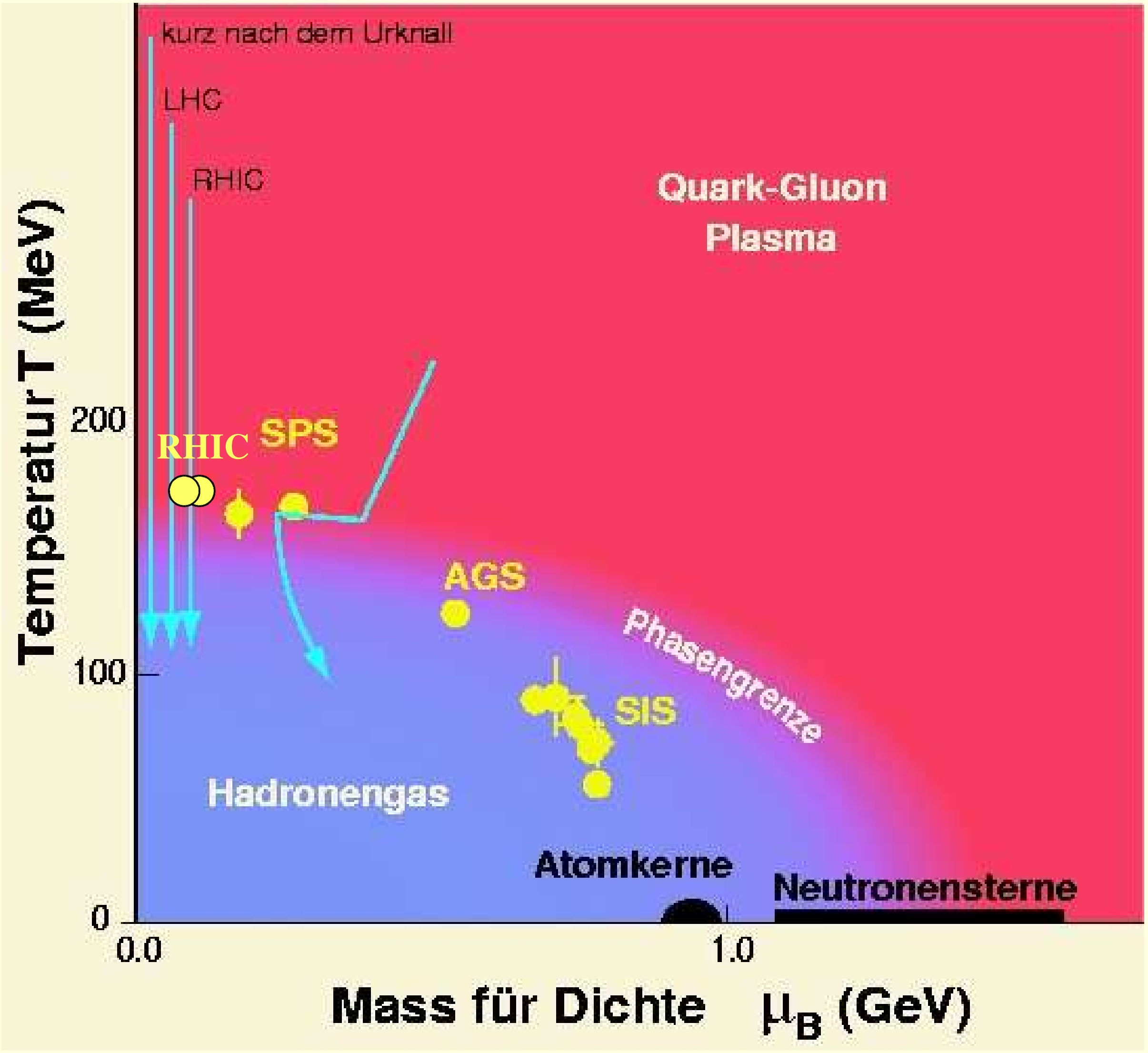


Bestimmung der Temperatur und Dichte zur Zeit der Teilchenproduktion

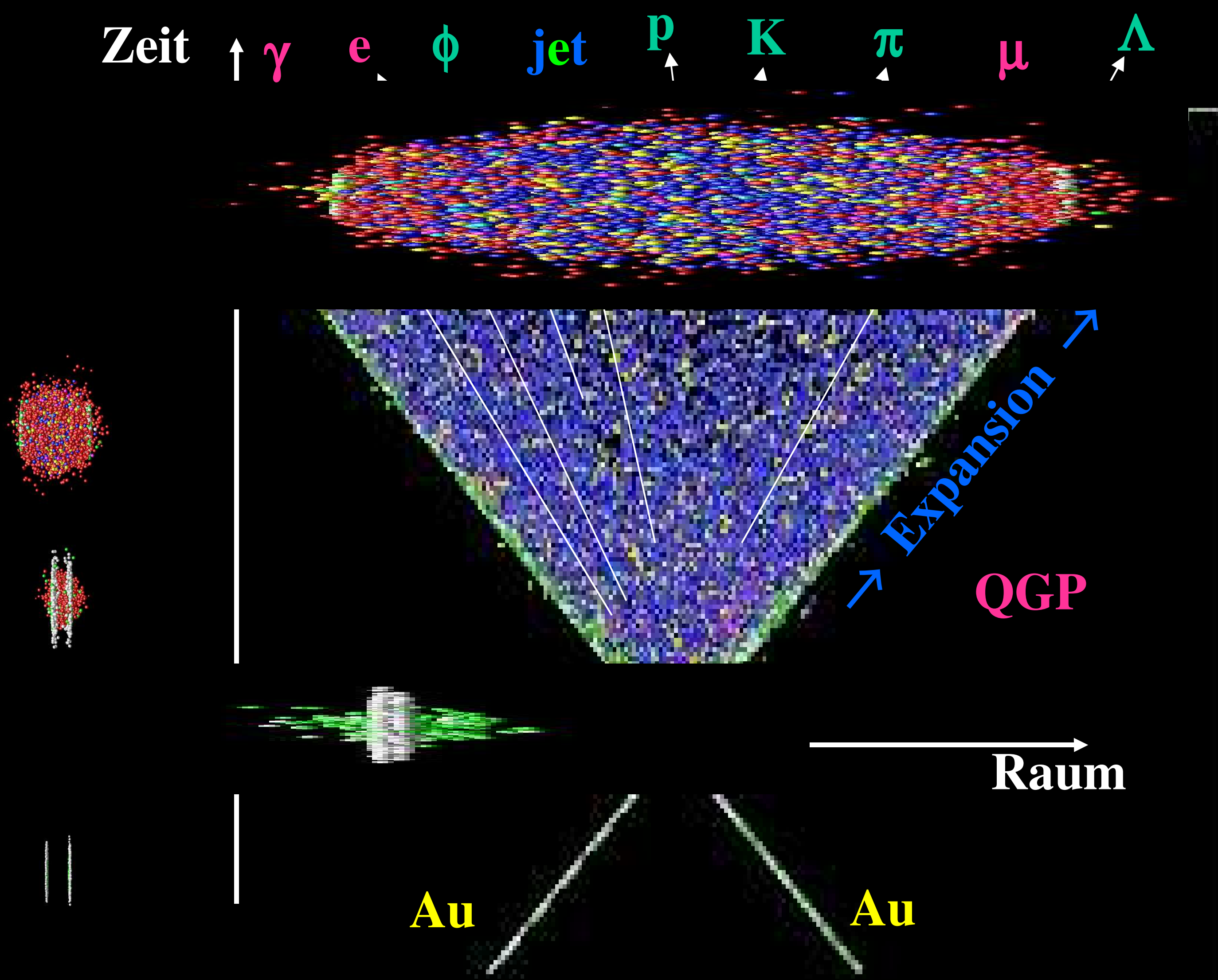
$T = 175$ MeV
$\mu_B = 41$ MeV

$T = 177$ MeV
$\mu_B = 29$ MeV

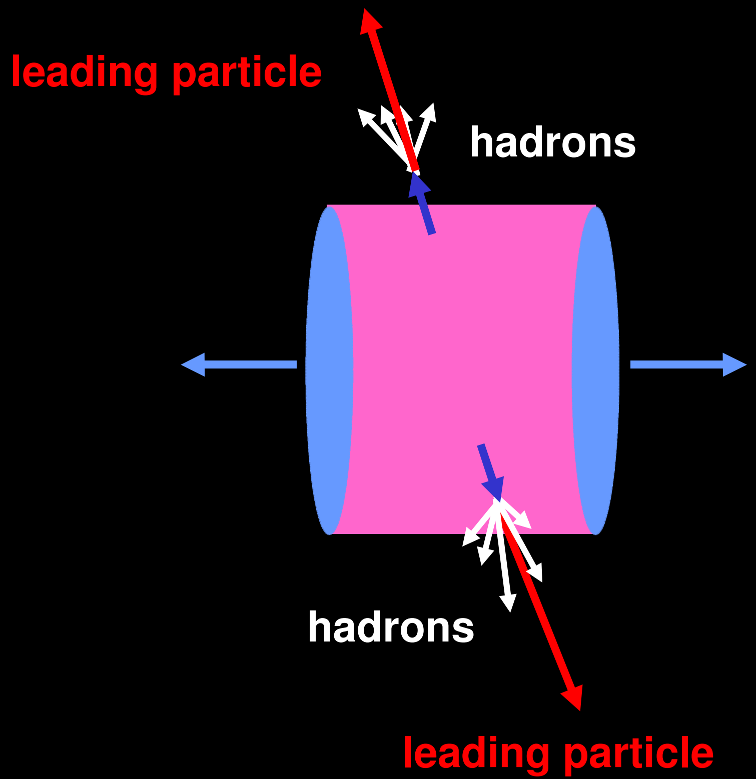
Phasendiagramm



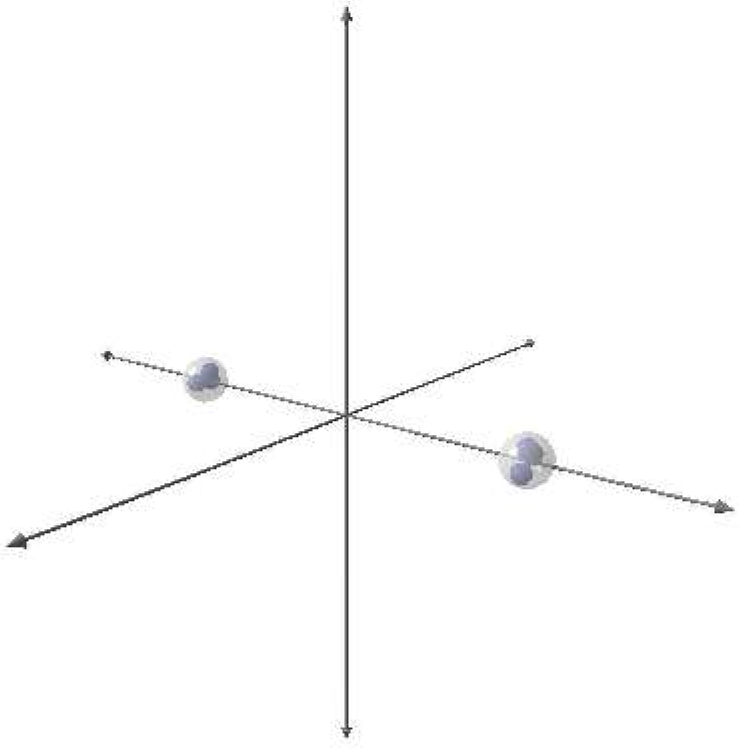
Zeitliche Entwicklung des Feuerballs



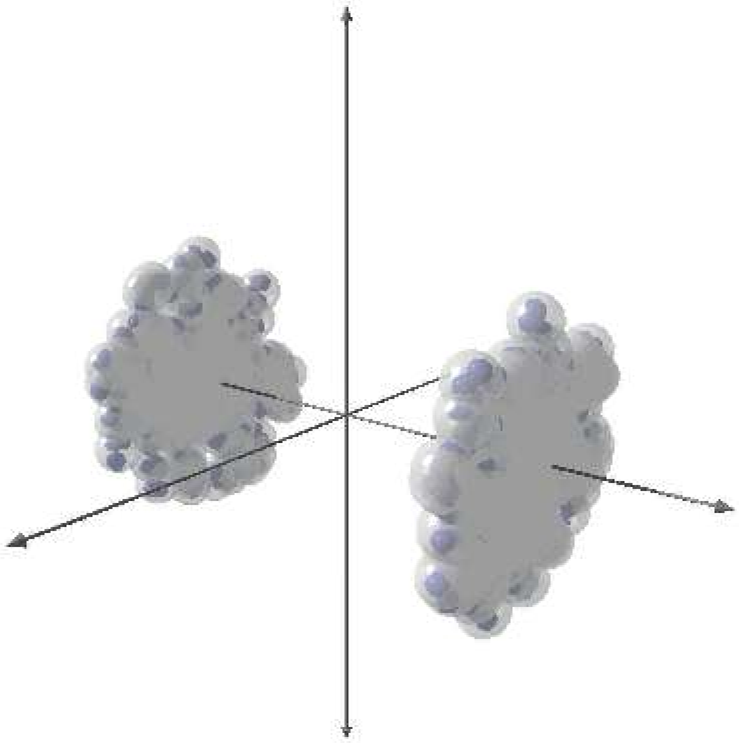
Jets in hoch-dichter Materie



Kein Energieverlust im Vakuum

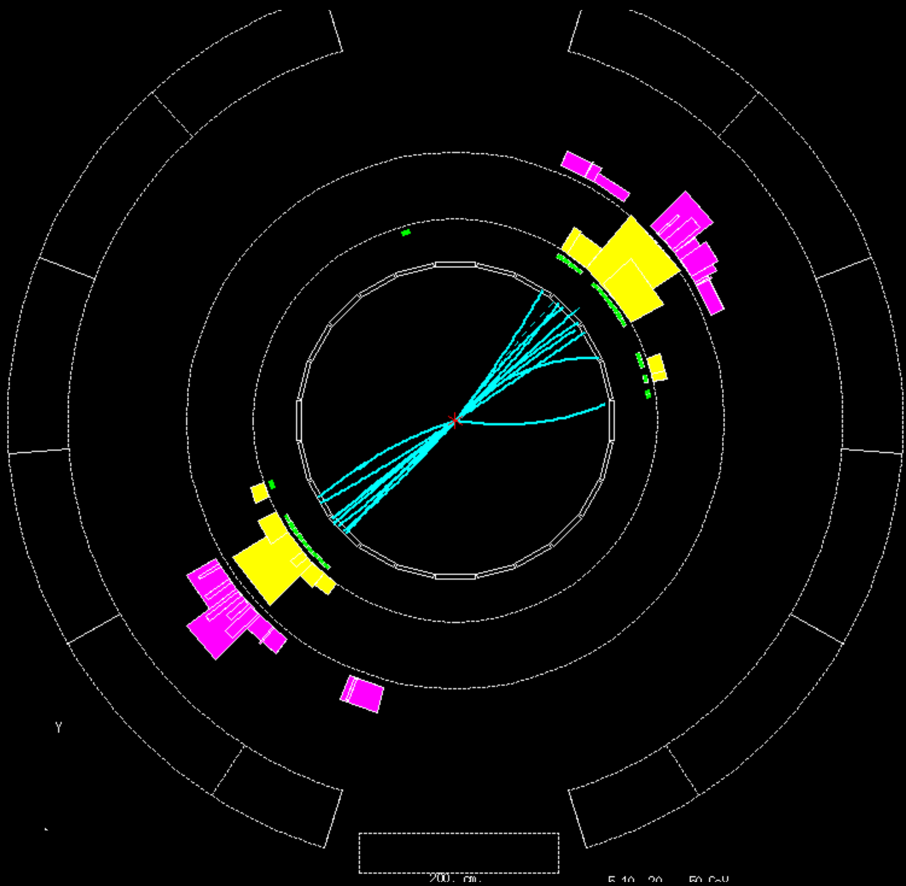


Energieverlust in dichter Materie

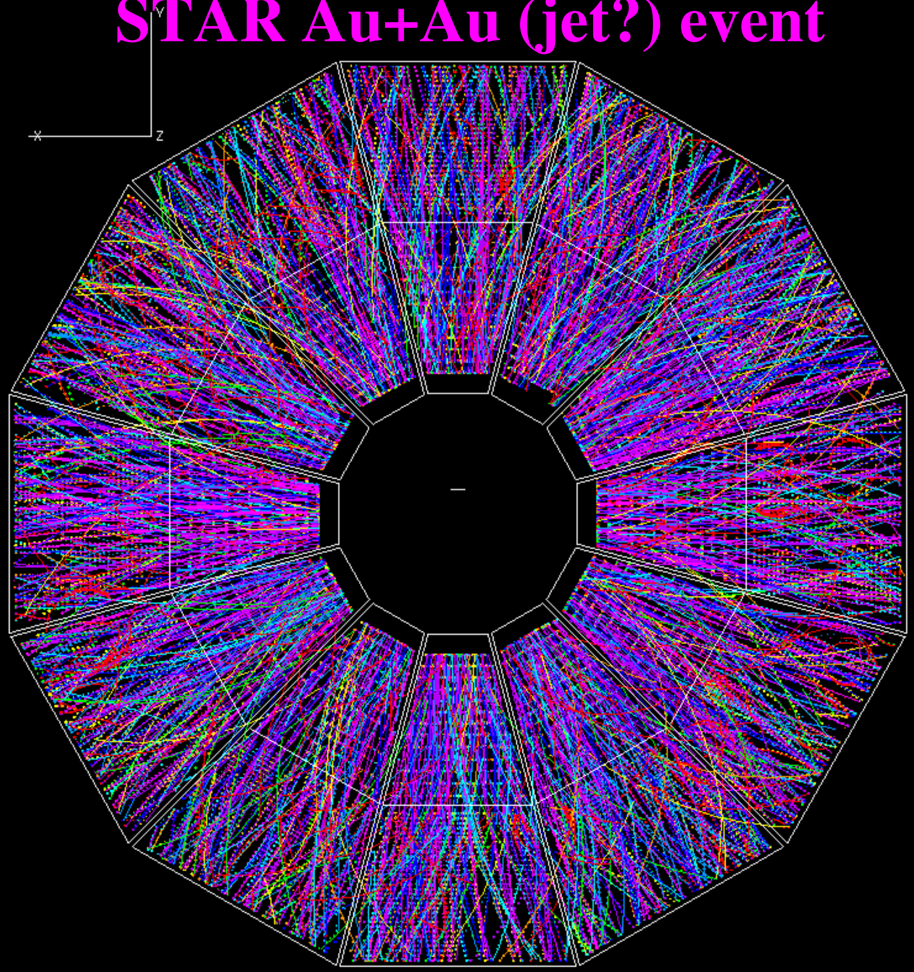


Jets at RHIC

Jet event in e^+e^- collision

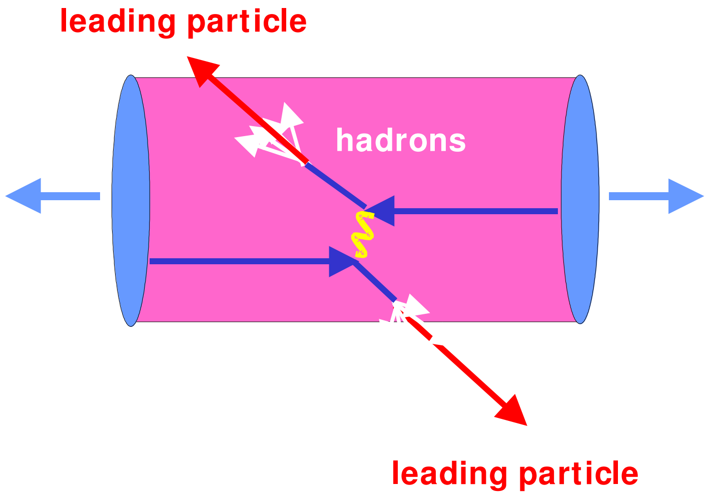


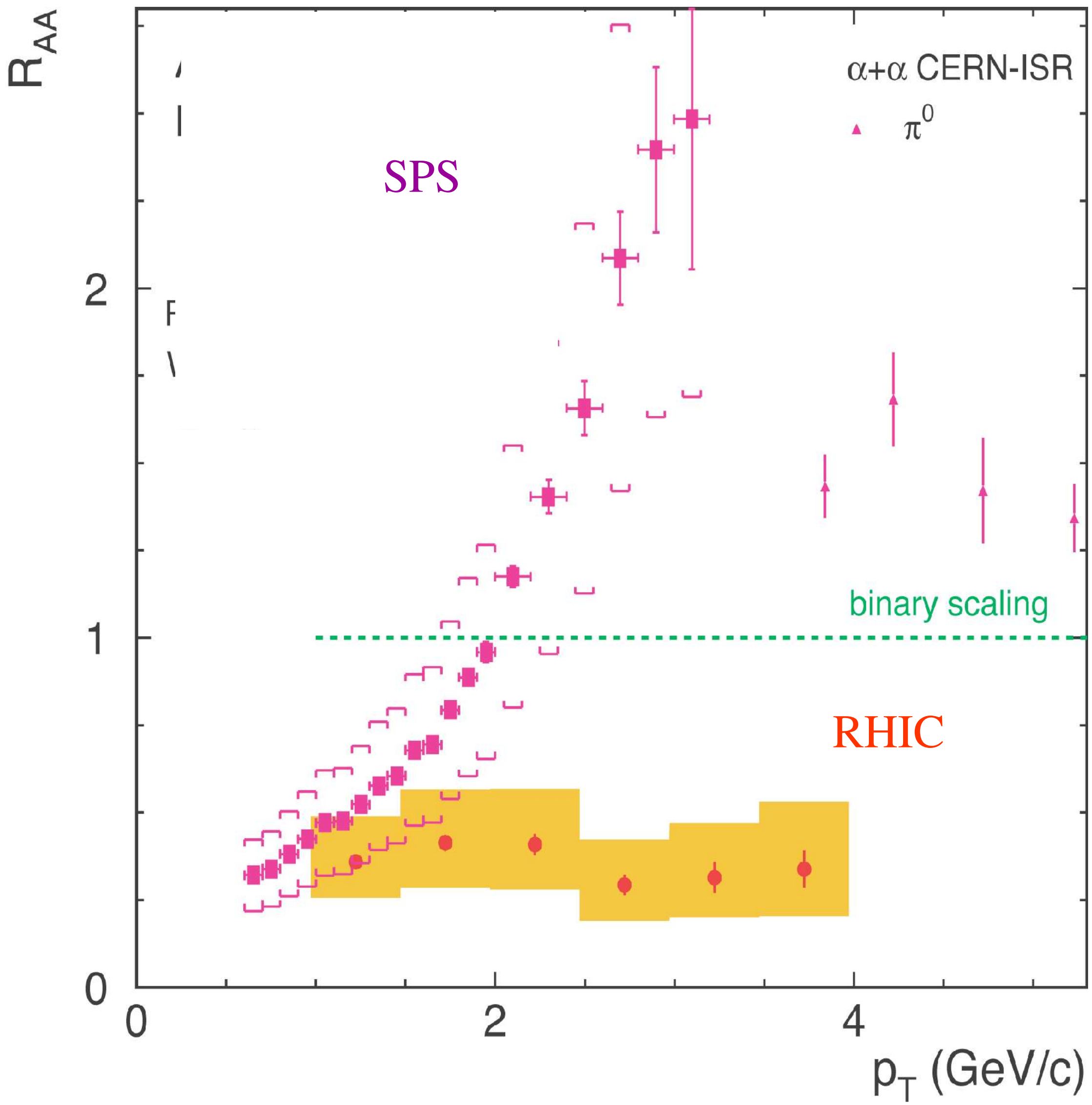
STAR Au+Au (jet?) event



Can we see jets in high energy Au+Au?

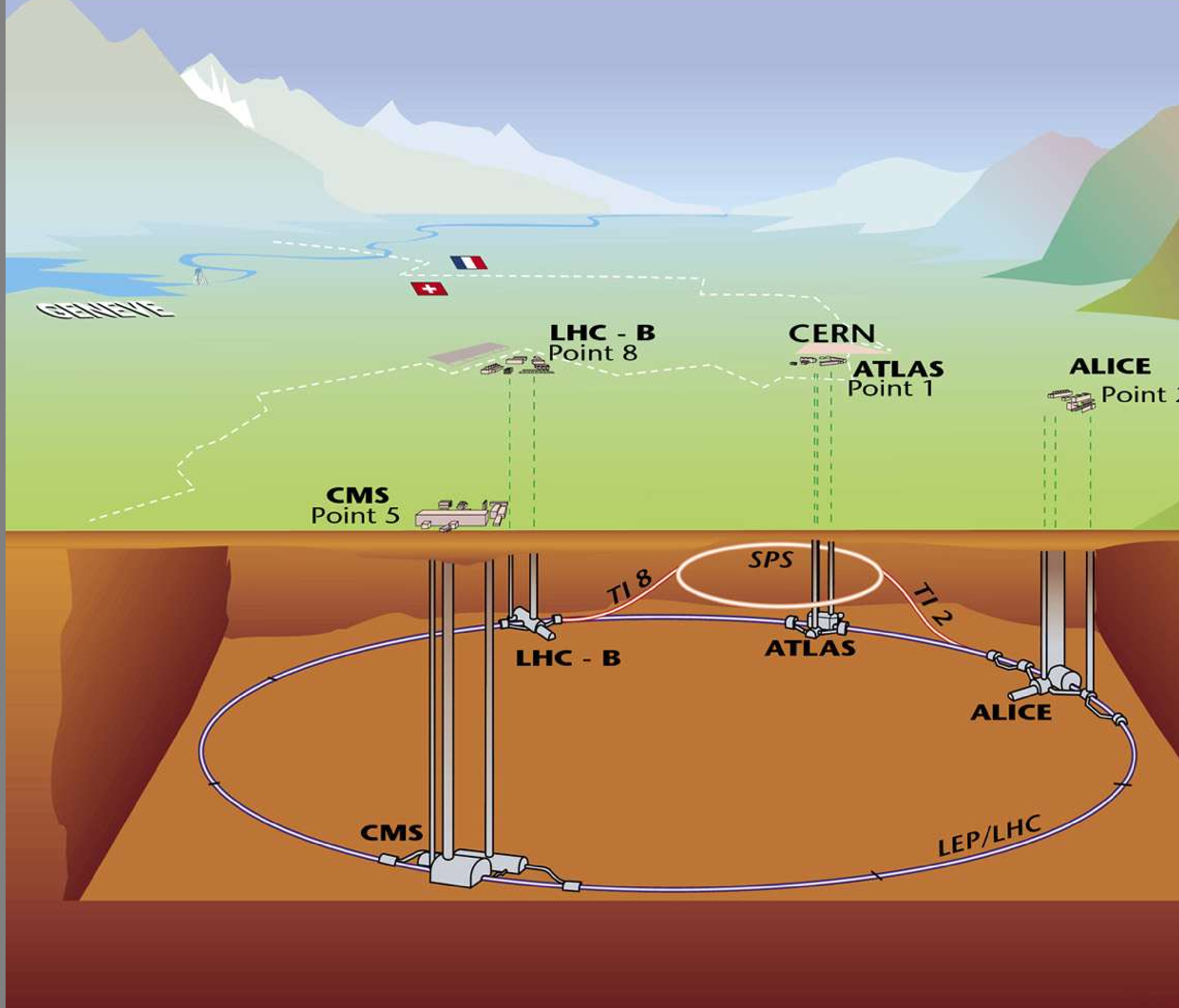
Suppression of Hadron Production





Energieverlust und Gluon-Dichte

- 5-fache Unterdrueckung von Jets in zentralen Au-Au Stoessen
- Modell: Energieverlust in dichter Gluon-Materie
- Quantitativ: Daten implizieren Gluon-Dichte von $7/fm^3$
- Feuerball-Temperatur $T > 500$ MeV
- Feuerball ist QGP!


GENEVE
LHC - B
Point 8
CERN
ATLAS
Point 1
ALICE
Point
CMS
Point 5
SPS
TI 8
TI 2
LHC - B
ATLAS
ALICE
CMS
LEP/LHC

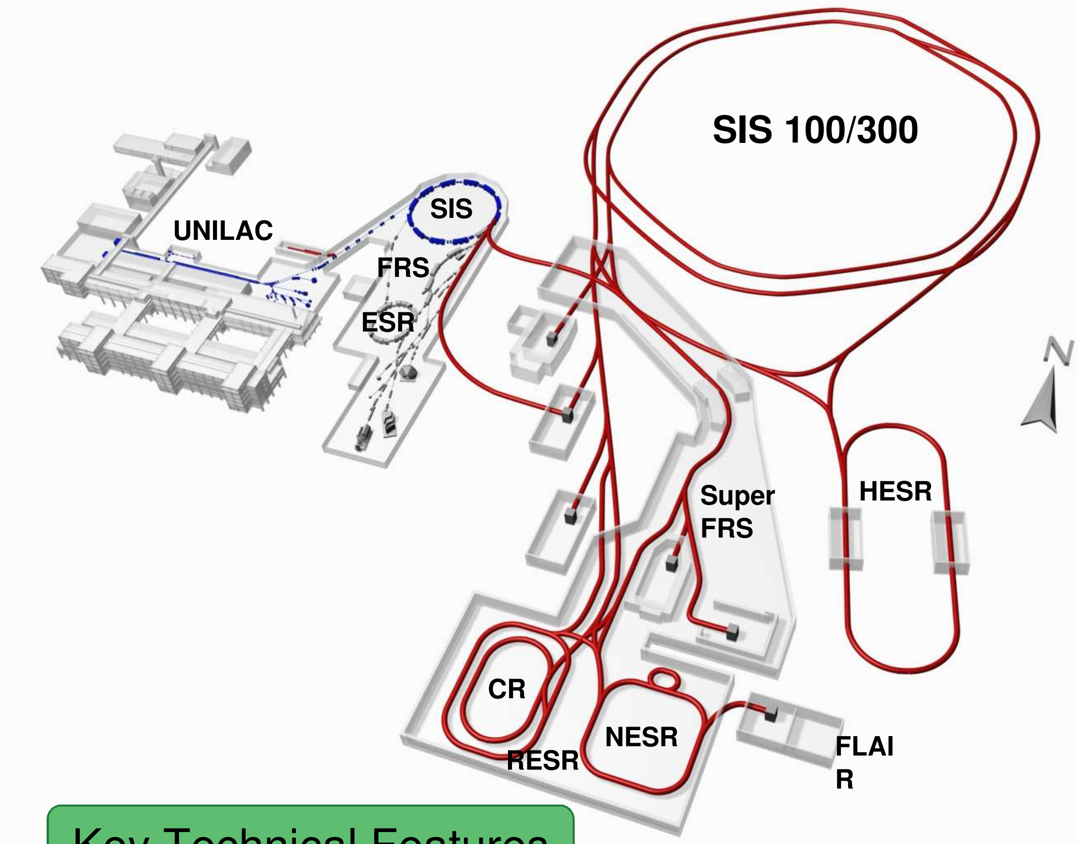
ALICE beim LHC

Bis zu 60000 geladene Teilchen

Faktor 25 höher als beim SPS

The International FAIR Project at GSI

Facility Characteristics



Primary Beams

- 10^{12}/s; 1.5-2 GeV/u; $^{238}U^{28+}$
- Factor 100-1000 over present in intensity
- $2(4)x10^{13}$/s 30 GeV protons
- 10^{10}/s $^{238}U^{73+}$ up to 35 GeV/u
- up to 90 GeV protons

Secondary Beams

- Broad range of radioactive beams up to 1.5 - 2 GeV/u; up to factor 10 000 in intensity over present
- Antiprotons 3 - 30 GeV

Storage and Cooler Rings

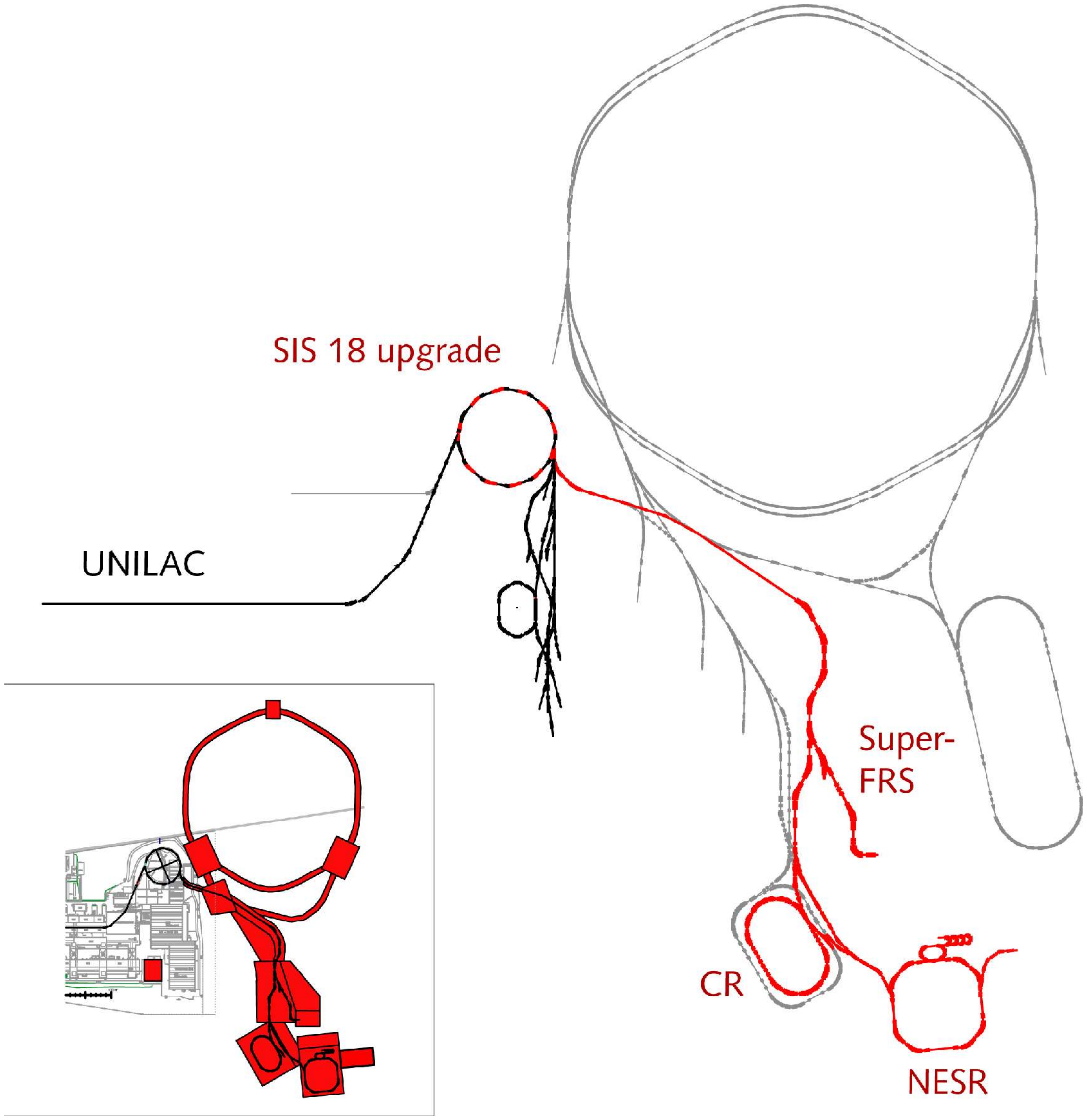
- Radioactive beams
- e^- – A (or Antiproton-A) collider
- 10^{11} stored and cooled 0.8 - 14.5 GeV antiprotons

Key Technical Features

- Cooled beams
- Rapidly cycling superconducting magnets

THE END

Stage 1



Civil Construction

- Ringtunnel for double ring synchrotron incl. technical buildings
- Buildings housing the SFRS, the CR and NESR plus nuclear structure and atomic physics experiments
- Office building

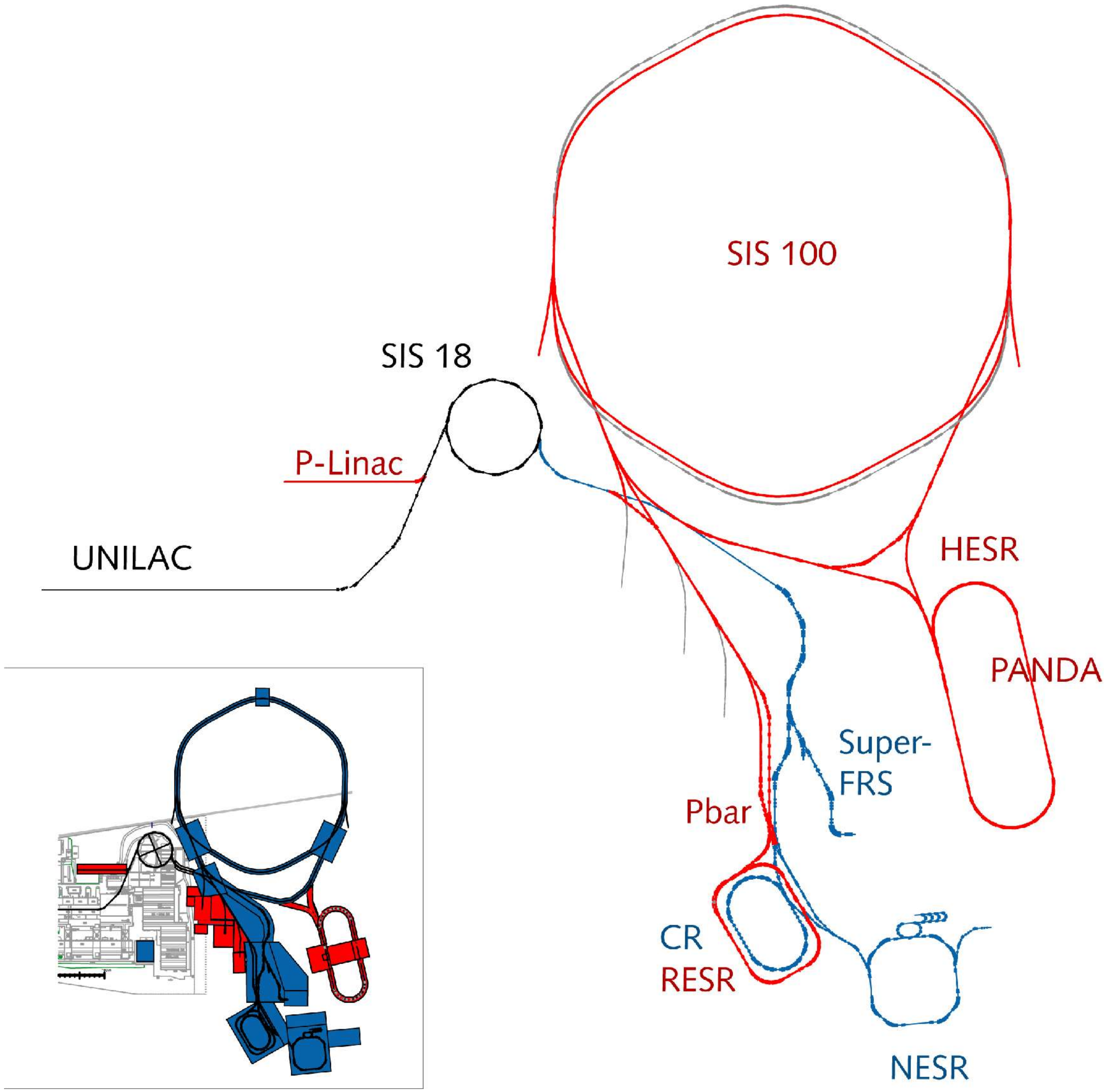
Accelerator

- 2 x 10^{11}/puls U^{28+} at 200 AMeV
- 4 x 10^{10}/puls U^{73+} at 1000 AMeV
- 4 Hz up to 12 Tm; 1 Hz up to 18 Tm
- Bunch compression to 70 ns

Research

- Nuclear structure and nuclear astrophysics (gain factor in intensities for radioactive secondary beams: ~100)
- Plasma physics at 'old' facility (gain factor in power density: ~200)
- Atomic physics studies with highly charged/radioactive ion beams)

Stage 2



Civil Construction (completed)

- p linac building
- HESR building
- Buildings housing nuclear collision, plasma physics and atomic physics experiments

Accelerator

- 1 x 10^{12}/puls U^{28+} at 2,7 AGeV
- 1 x 10^{11}/puls U^{73+} at 8,3 AGeV (Ne^{10+} bis 14 AGeV)
- Bunch compression to 50 ns
- 2,5 x 10^{13}/puls protons up to 29 GeV
- up to 10^{11} antiprotons accumulated, stored and cooled in the HESR up to 15 GeV
- low (down to zero) energy antiprotons at NESR and HITRAP

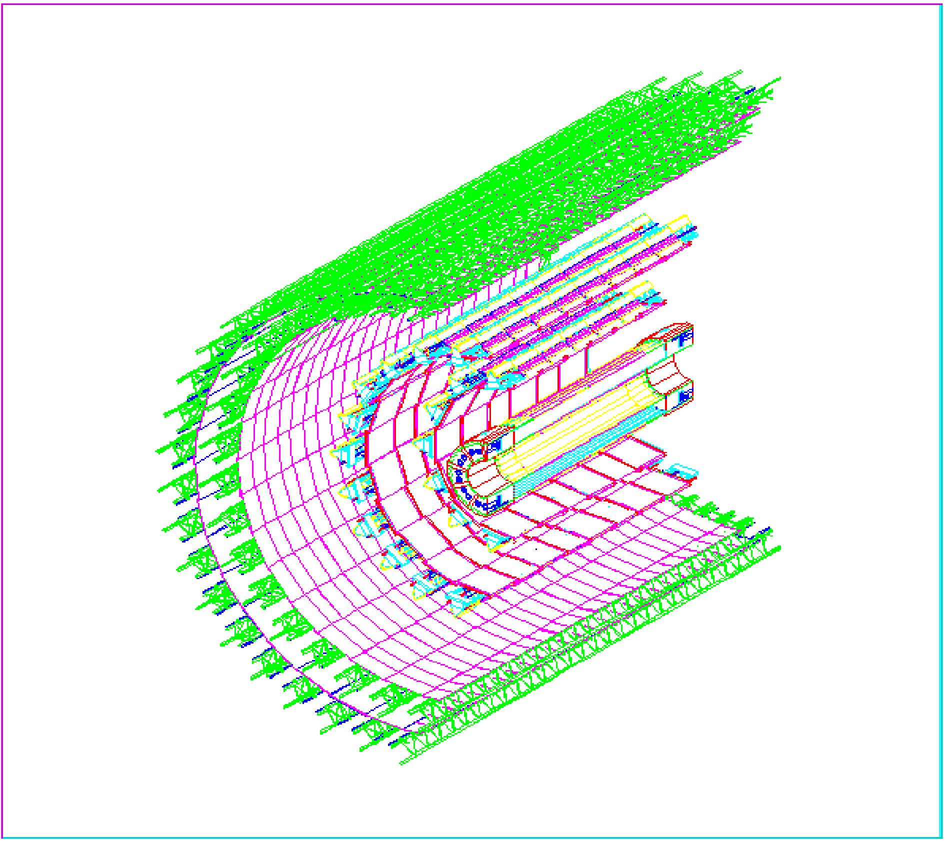
Research

- Nuclear structure and nuclear astrophysics (full gain factor in intensities for radioactive secondary beams: ~1000-10000)
- QCD studies with protons and antiprotons
- precision studies with antiprotonn beams addressing fundamental symmetries and interactions

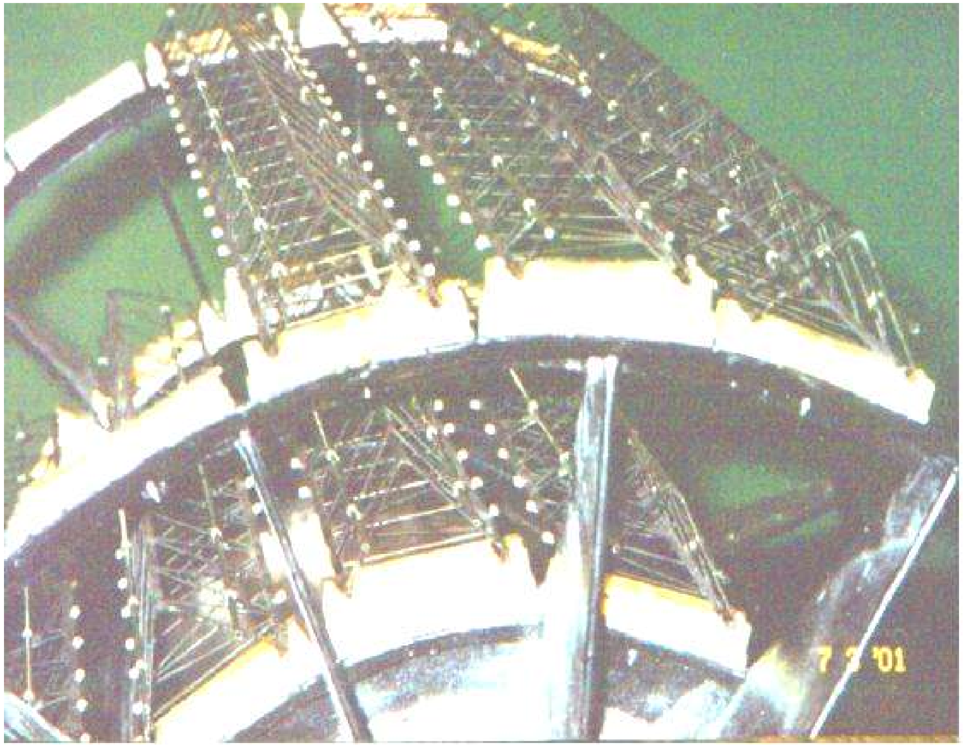

ready to move in

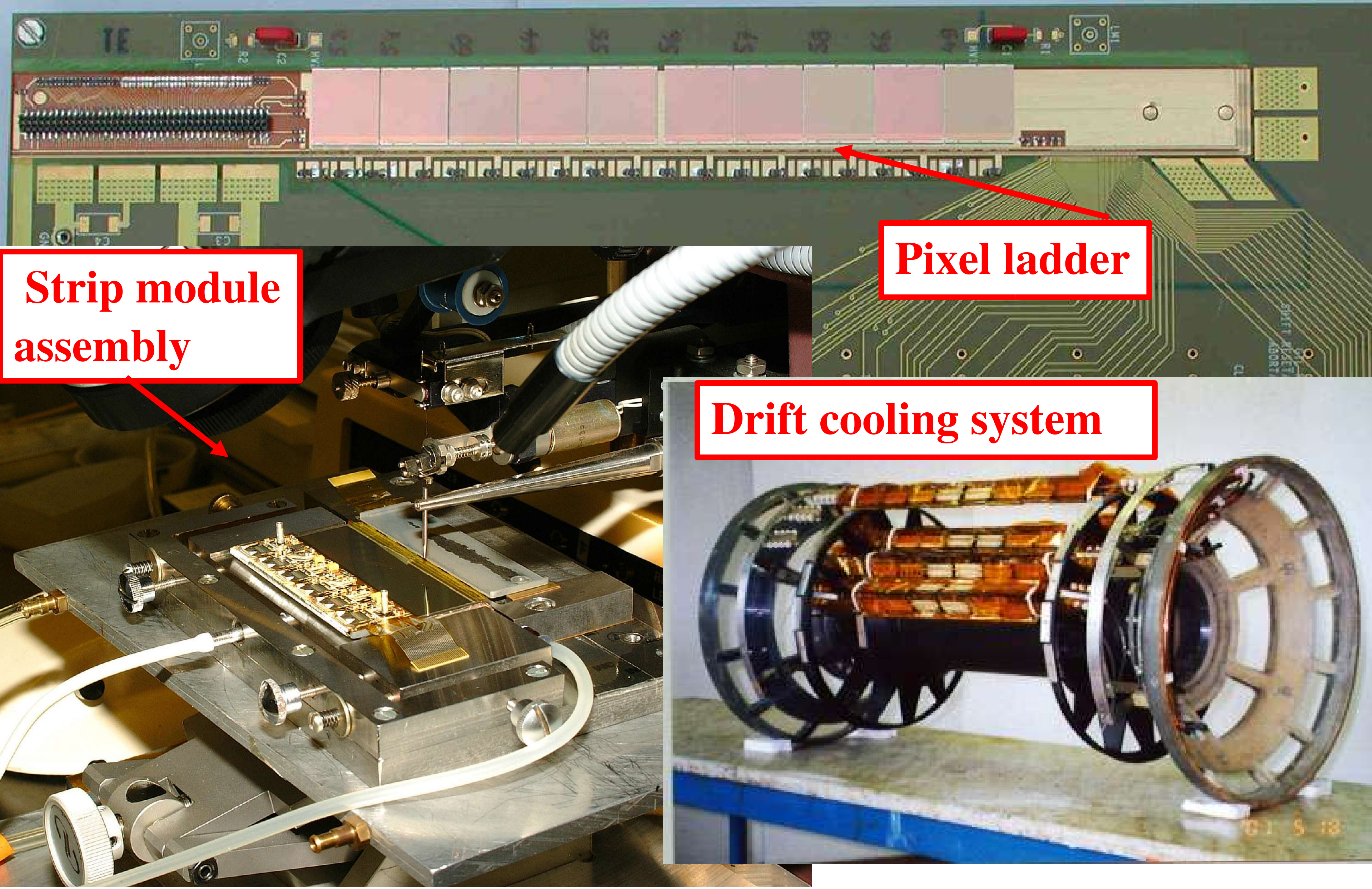
Inner Tracking System

Lay-out des inneren Detektors



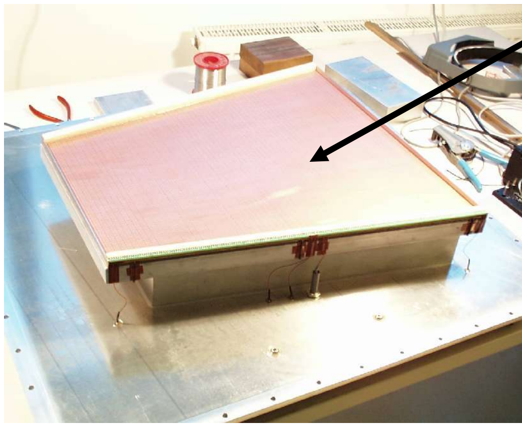
Si Detektor Prototyp

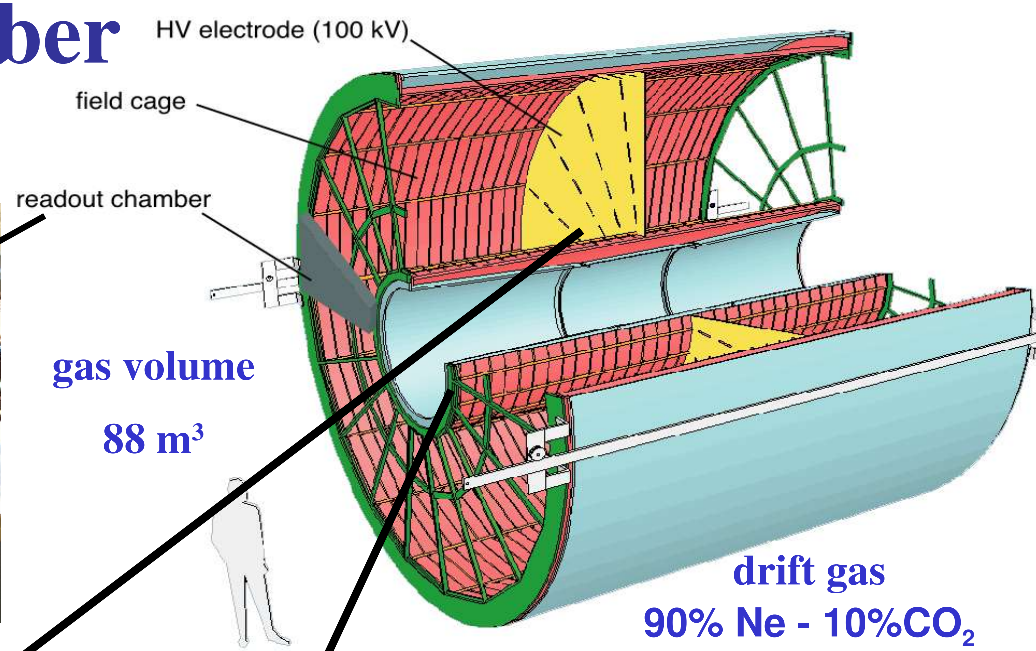




System testing and setting up of series production

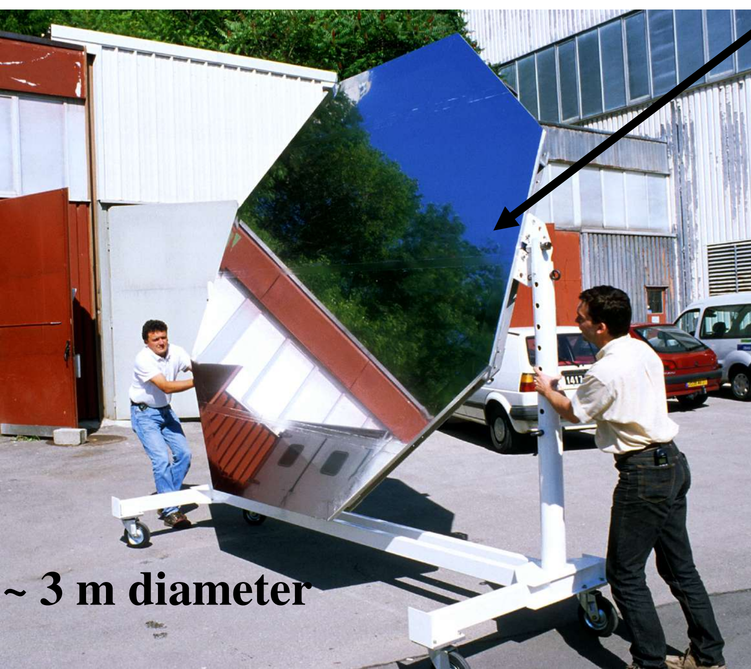
Time Projection Chamber





Central Electrode Prototype

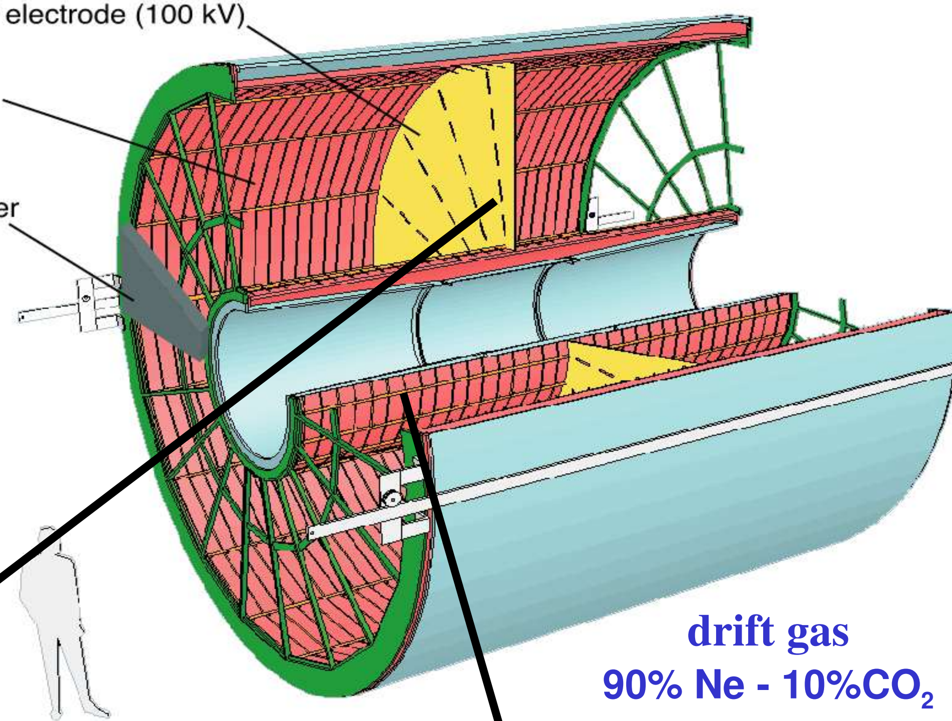
25 µm aluminized Mylar on Al frame

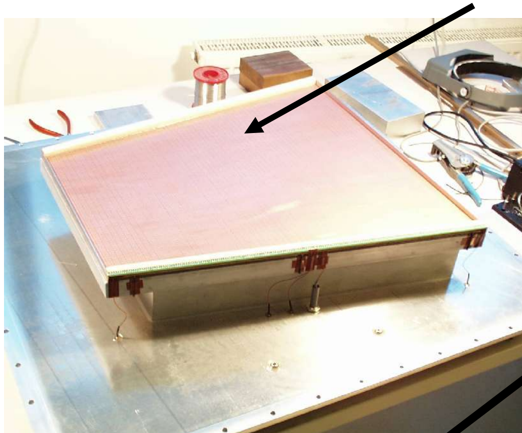


Field Cage Inner Vessel

Time Projection Chamber

largest ever: 88 m³, 570 k channels





for tracking and PID via dE/dx

$-0.9 < \eta < 0.9$

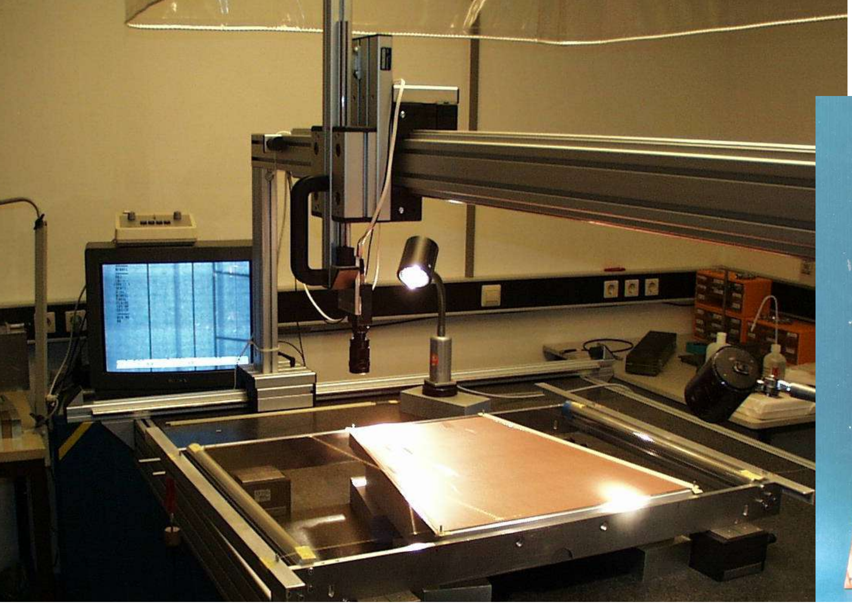
drift gas
90% Ne - 10%CO_2

Central Electrode Prototype
25 µm aluminized Mylar on Al frame

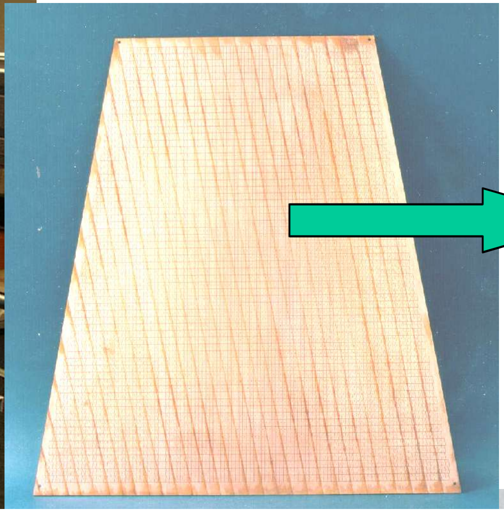
~ 3 m diameter

The ALICE TPC becomes real

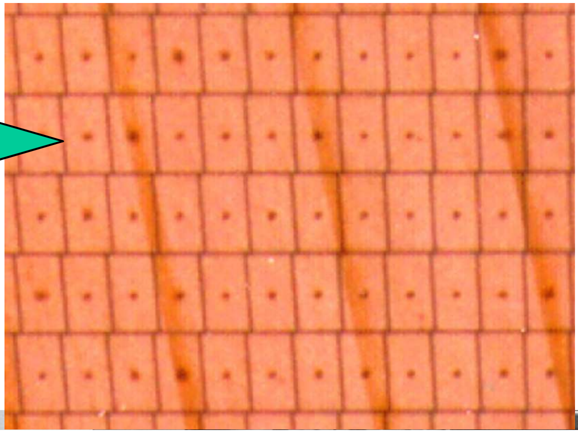
(outer field cage and end plates)



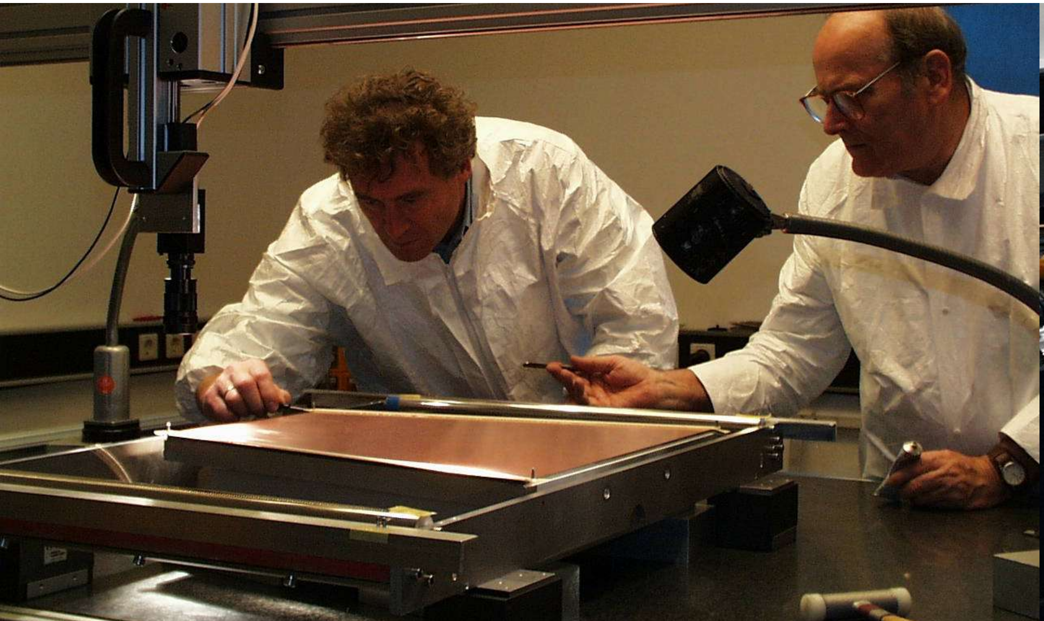
Pad Plane: 5504 pads (4x7.5 mm^2)

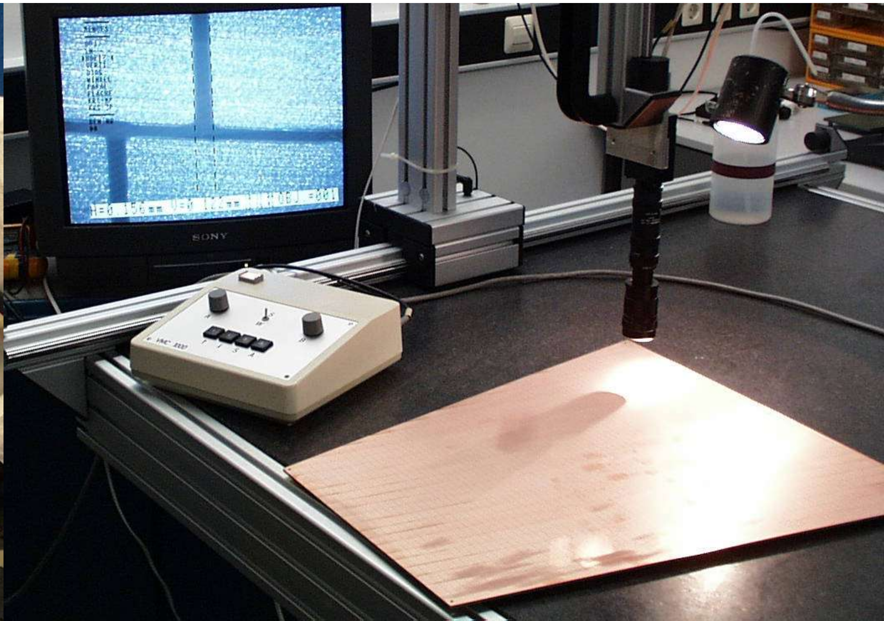


CLOSE-UP ON THE PADS



Construction of the TPC readout chambers: more than half of the inner ones already completed!

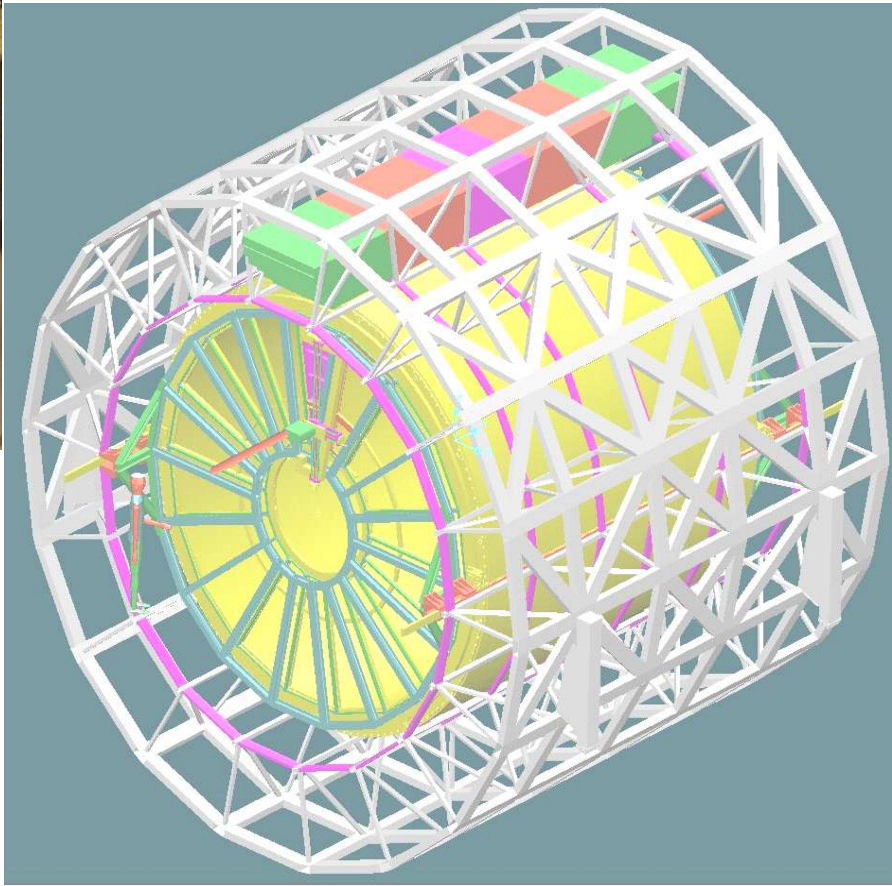




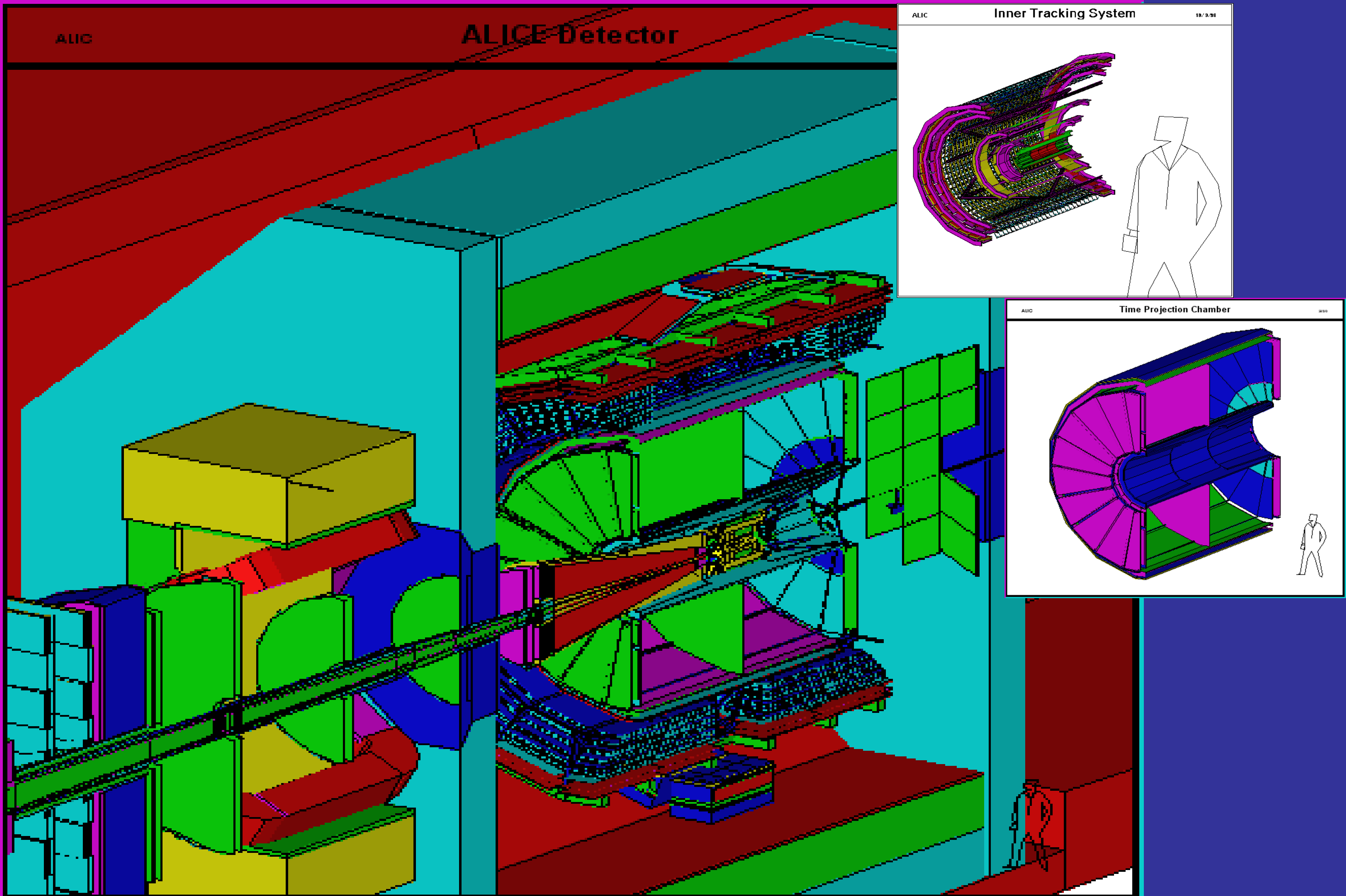
Transition Radiation Detector

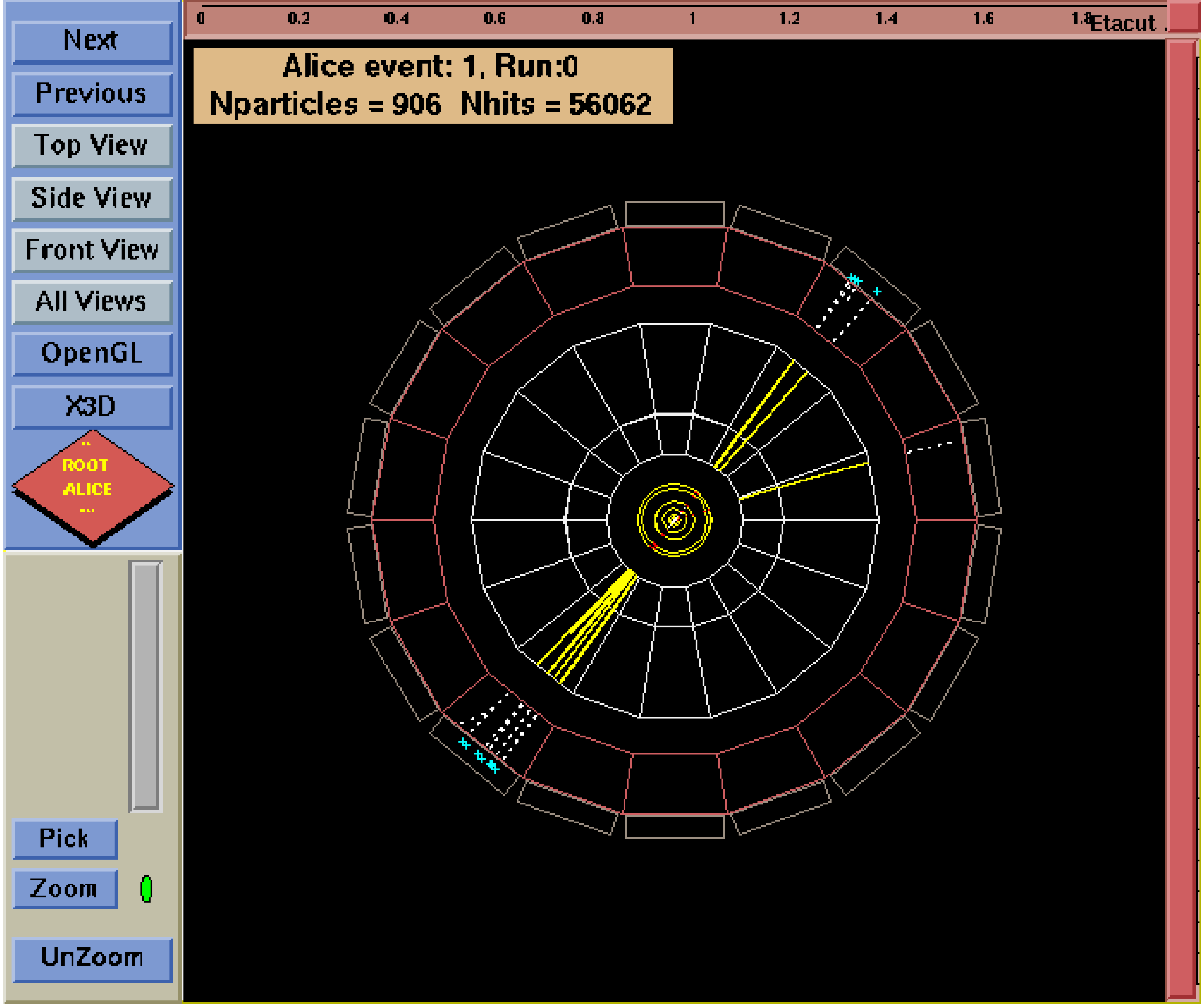
Full scale prototype

supermodule in space frame



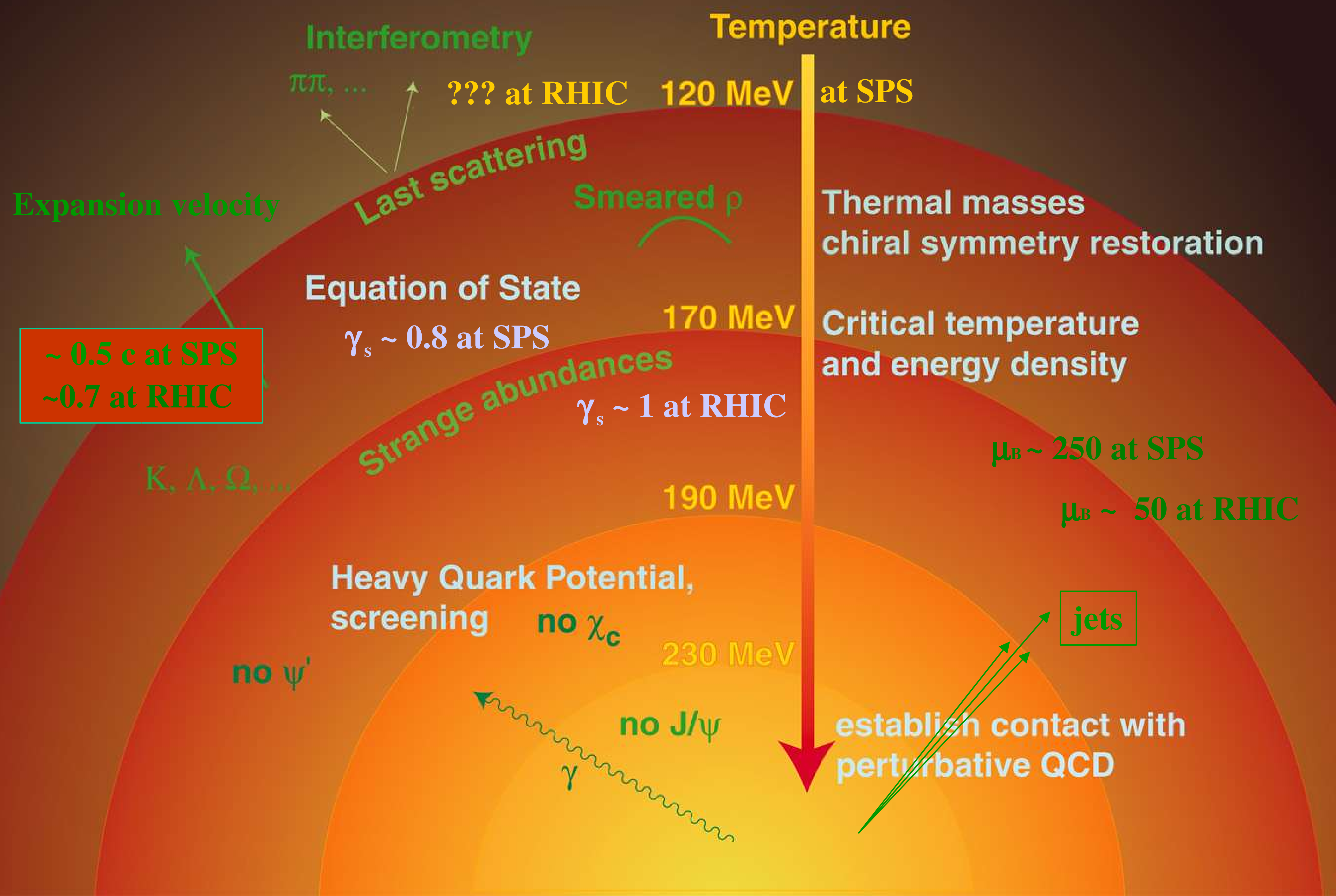
Computer representation of ALICE

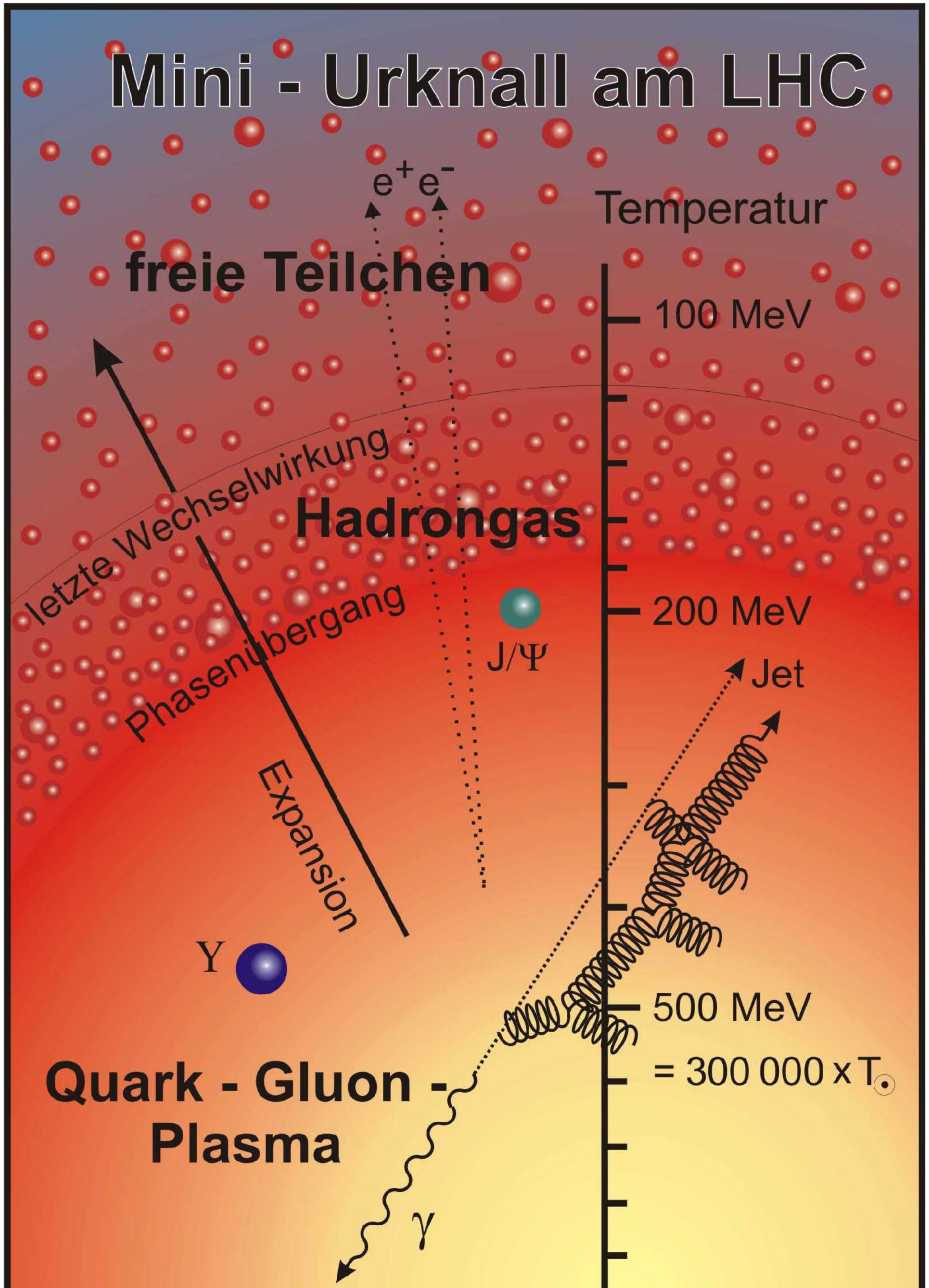




Next
Previous
Top View
Side View
Front View
All Views
OpenGL
X3D
ROOT
ALICE
Pick
Zoom
UnZoom
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
Etacut
Alice event: 1, Run:0
Nparticles = 906 Nhits = 56062

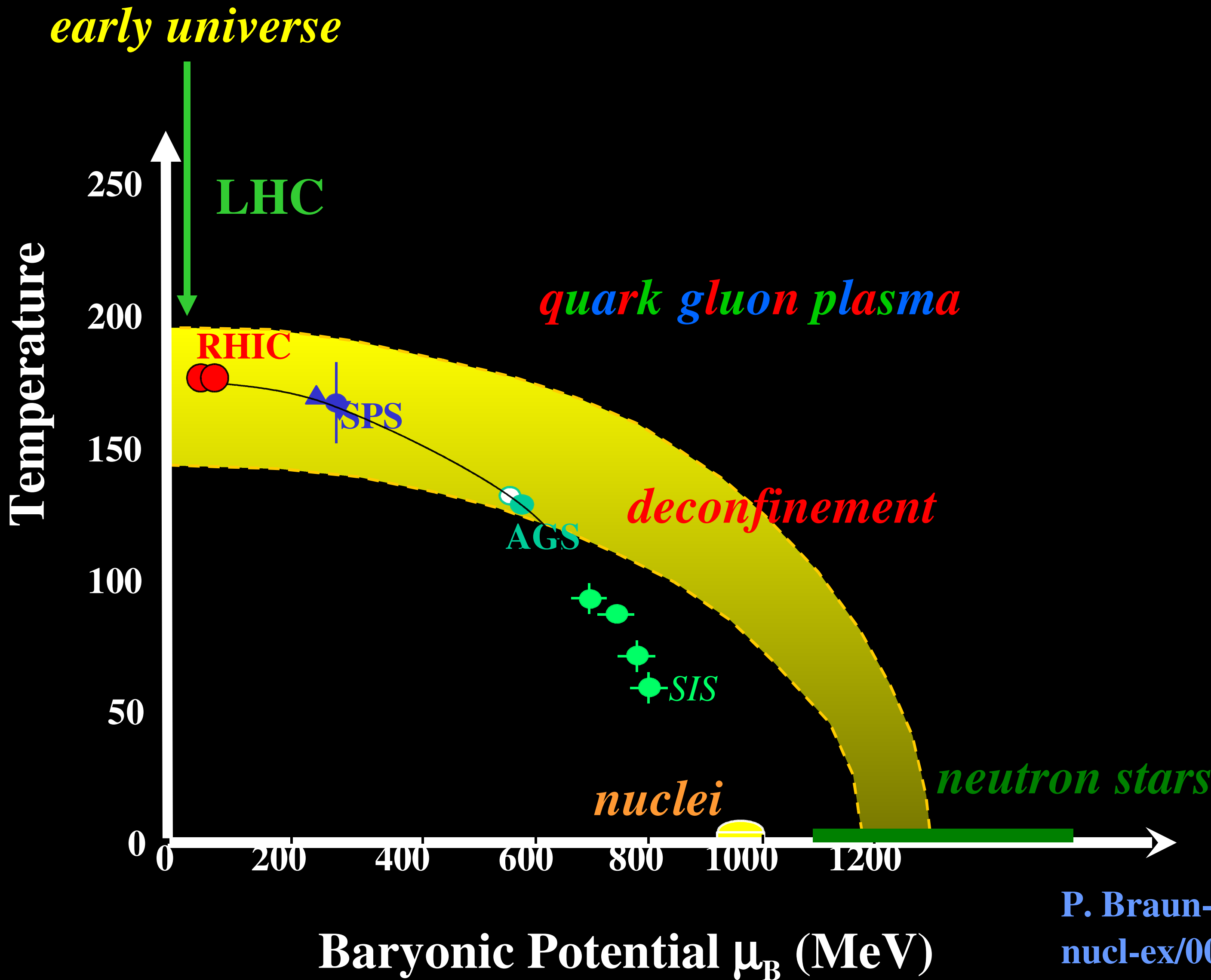
Observables – Lattice Thermodynamics



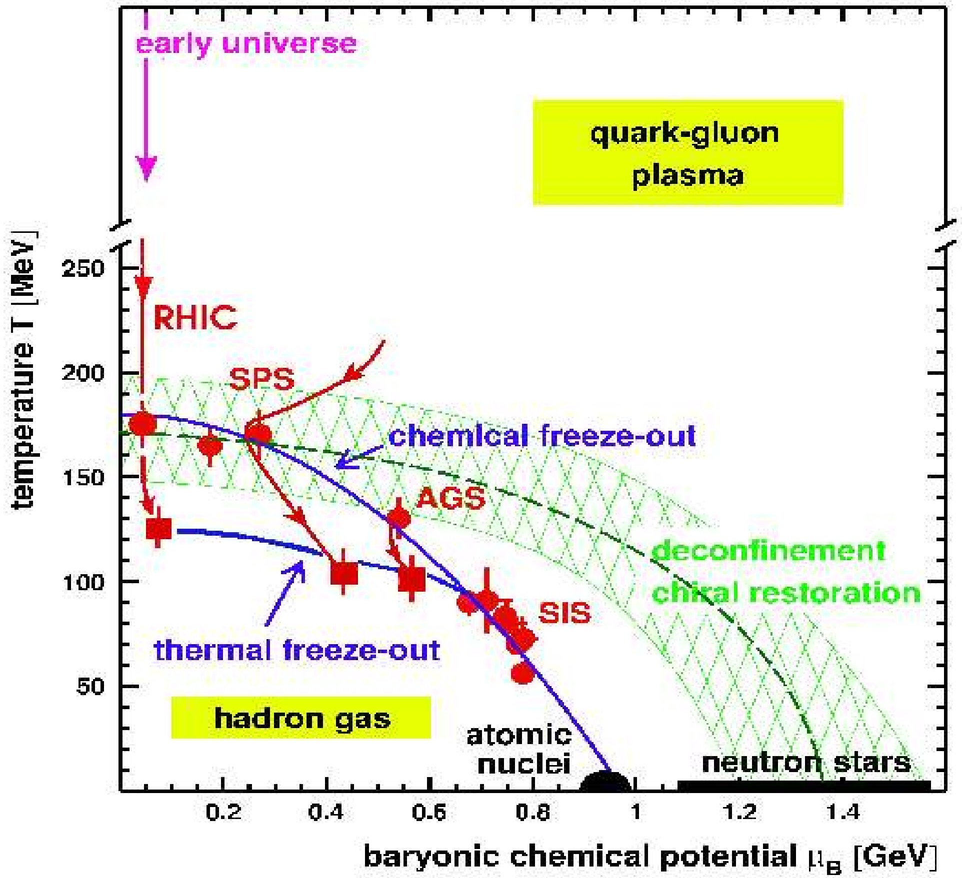


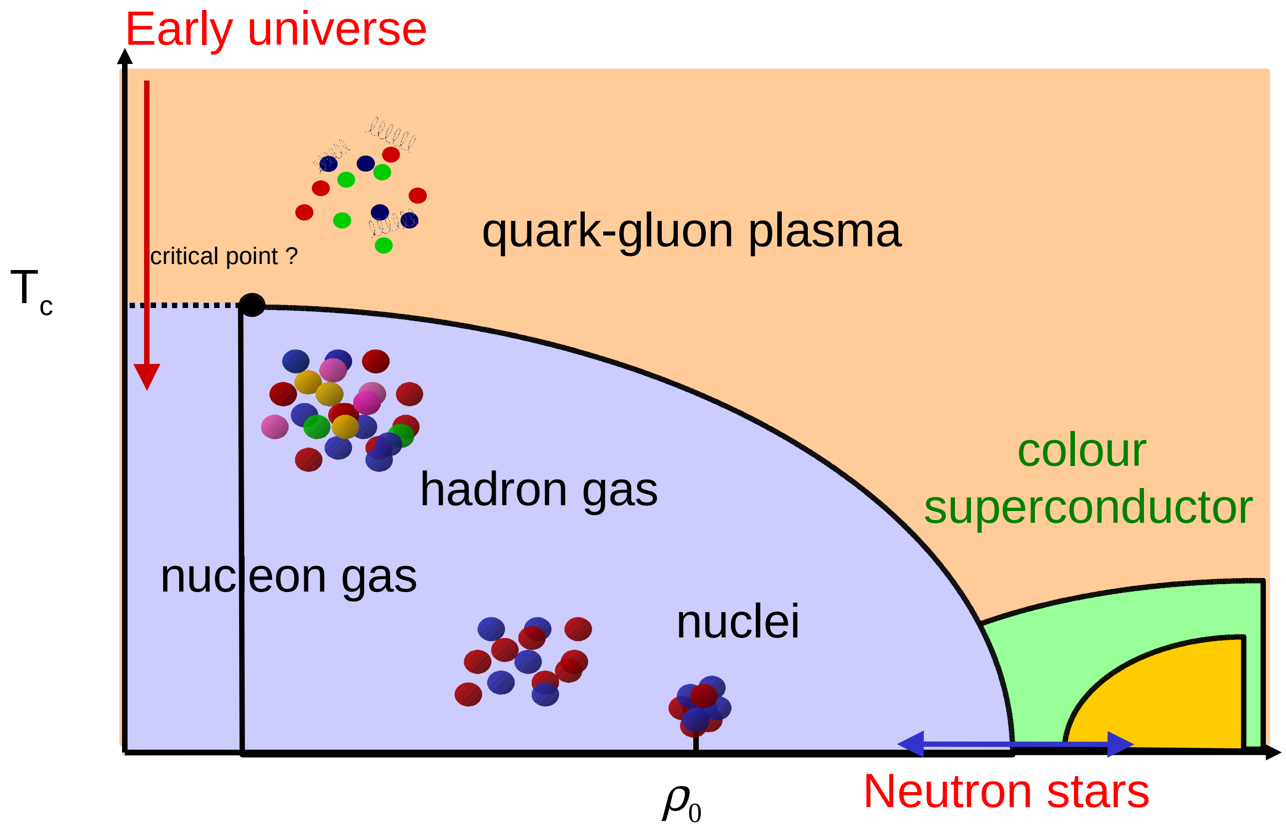
Mini - Urknall am LHC
e+e-
Temperatur
freie Teilchen
100 MeV
letzte Wechselwirkung
Hadrongas
Phasenübergang
200 MeV
J/Ψ
Jet
Expansion
Υ
500 MeV
= 300 000 x T☉
Quark - Gluon - Plasma
γ

Phase Diagram

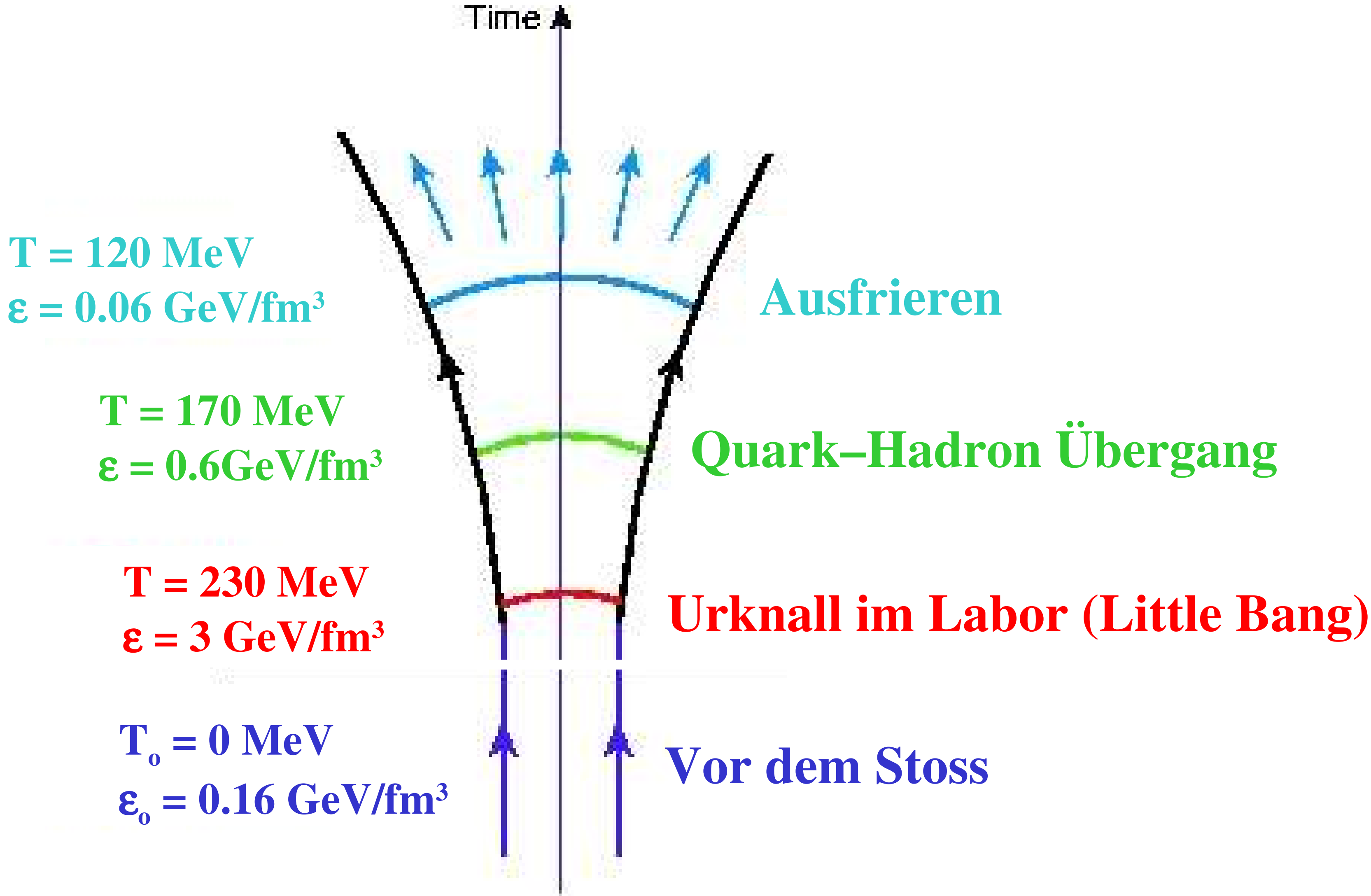


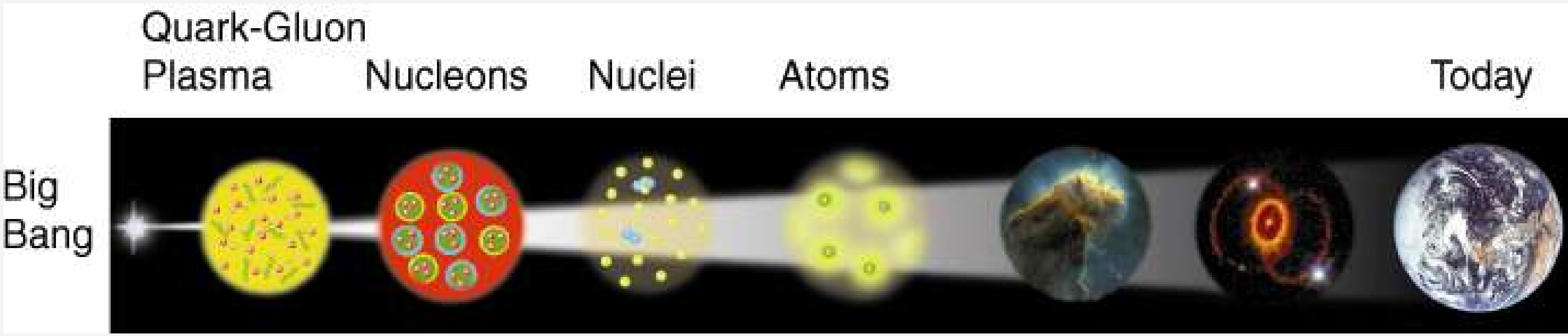
P. Braun-Munzinger
nucl-ex/0007021


early universe
quark-gluon plasma
temperature T [MeV]
250
200
150
100
50
RHIC
SPS
AGS
SIS
chemical freeze-out
thermal freeze-out
deconfinement
chiral restoration
hadron gas
atomic nuclei
neutron stars
0.2
0.4
0.6
0.8
1
1.2
1.4
baryonic chemical potential μ_B [GeV]



Early universe
critical point ?
quark-gluon plasma
T_c
hadron gas
colour
superconductor
nucleon gas
nuclei
ρ_0
Neutron stars


Time
T = 120 MeV
ε = 0.06 GeV/fm³
Ausfrieren
T = 170 MeV
ε = 0.6GeV/fm³
Quark–Hadron Übergang
T = 230 MeV
ε = 3 GeV/fm³
Urknall im Labor (Little Bang)
T₀ = 0 MeV
ε₀ = 0.16 GeV/fm³
Vor dem Stoss



10^{-6} sec	10^{-4} sec	3 min
> 10^{12} K	10^{12} K	10^{9} K
> 150 MeV	100 MeV	100 KeV