

A vibrant, fiery cosmic background with swirling patterns of orange, red, and yellow, resembling a nebula or a star-forming region. The colors are bright and intense, set against a dark, almost black background.

Reise zum Urknall

Peter Braun-Munzinger

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Urknall

Expansion des Universums
Temperaturentwicklung
Frühe Urknall-Materie

Urknall im Labor

Ultrarelativistische Schwerionenstöße
Quark-Gluon Materie
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

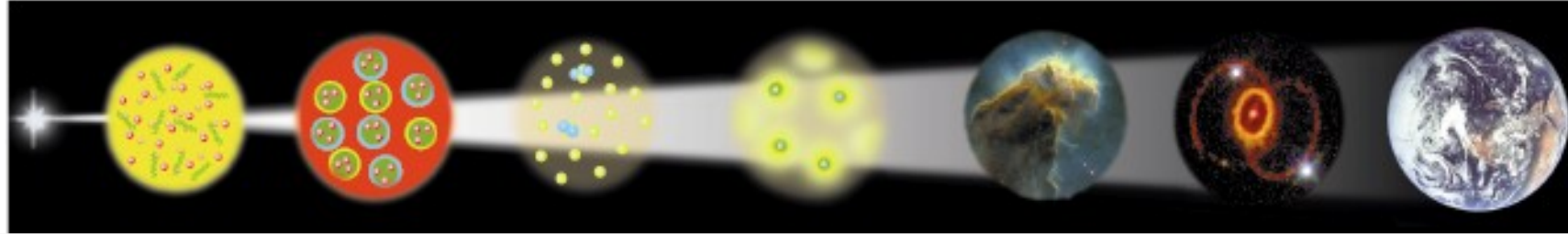
Quark-Gluon
Plasma

Nukleonen Kerne

Atome

Heute

Urknall



10^{-6} sec

10^{-4} sec

3 min

15 Mil Jahre

Experiment

- Strahlung
- Teilchen
- Schwere Teilchen, die die schwache Kraft vermitteln
- Quark
- Anti-Quark
- Elektron
- Positron (Anti-Elektron)
- Proton
- Neutron
- Meson
- Wasserstoff
- Deuterium
- Helium
- Lithium

10^9 K

6000 K

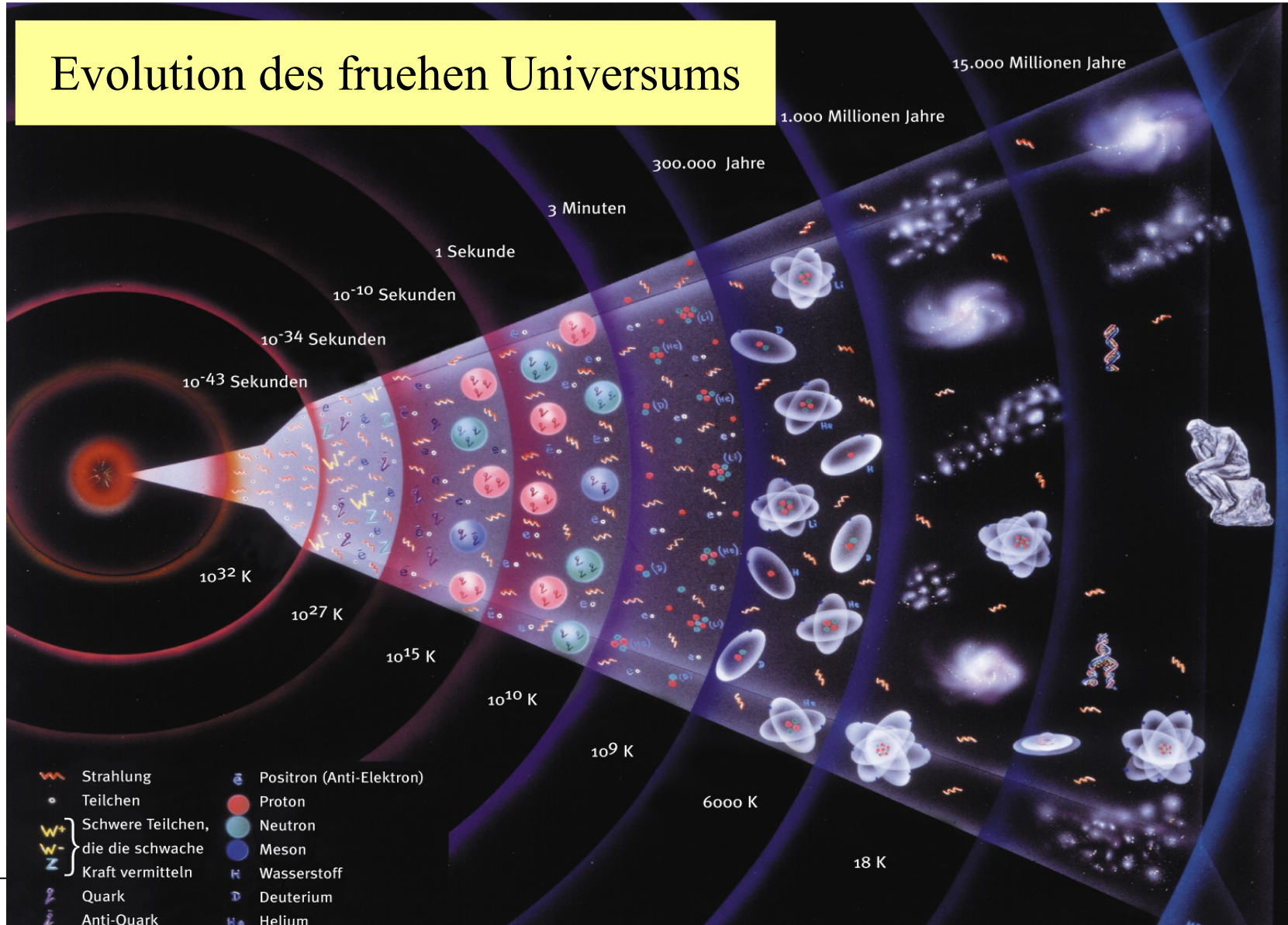
18 K

0 K \approx -273 °C (absoluter Nullpunkt)

3 K

Alle Materie wird an der QCD Phasengrenze produziert

Evolution des fruehen Universums



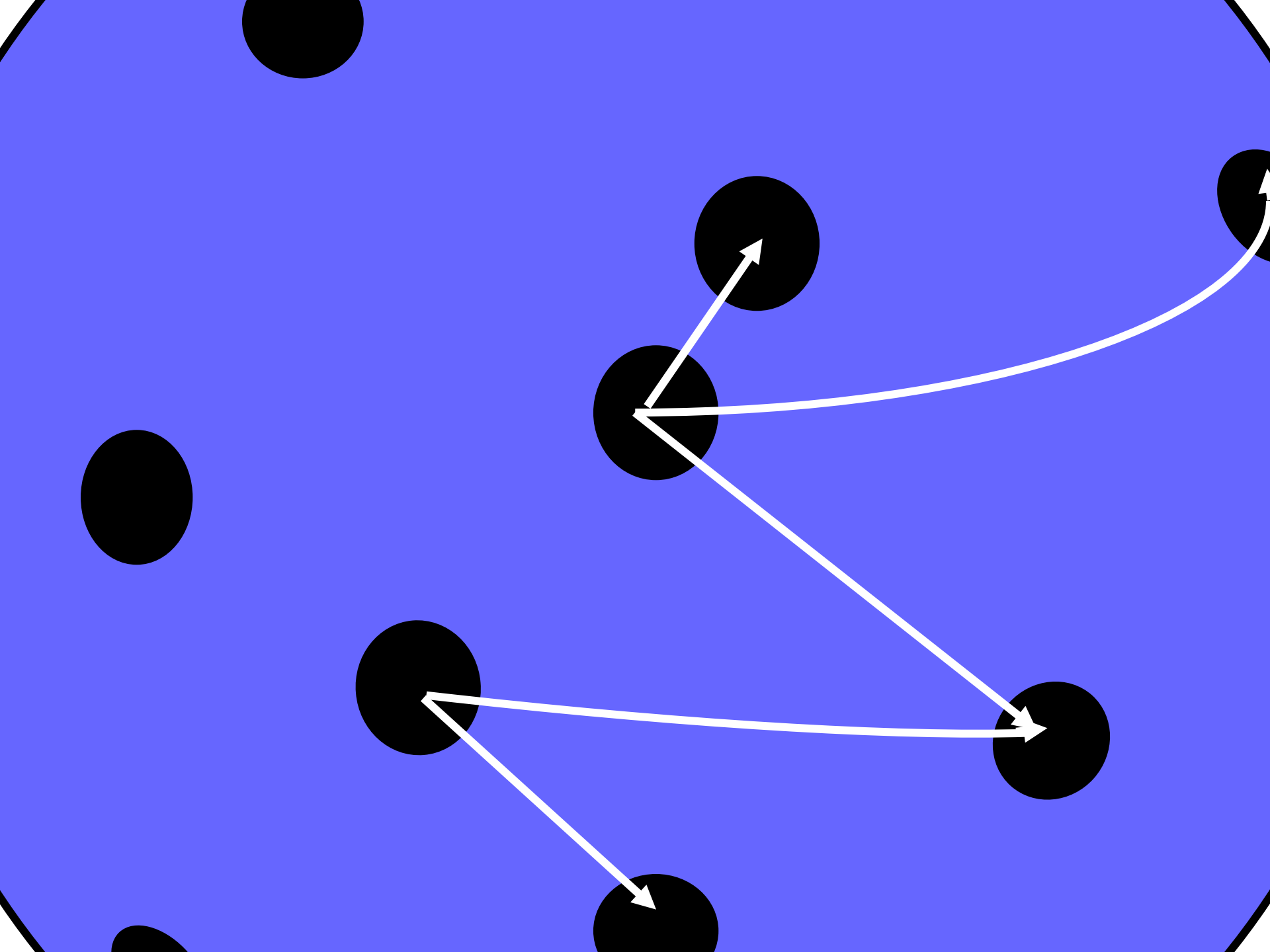
Evidenz für den Urknall

- ✓ Hubble Expansion
- ✓ Kosmische Hintergrundstrahlung
 - Elementsynthese im frühen Universum
 - Entstehung von Galaxien und ausgedehnten Strukturen im All
- ✓ 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

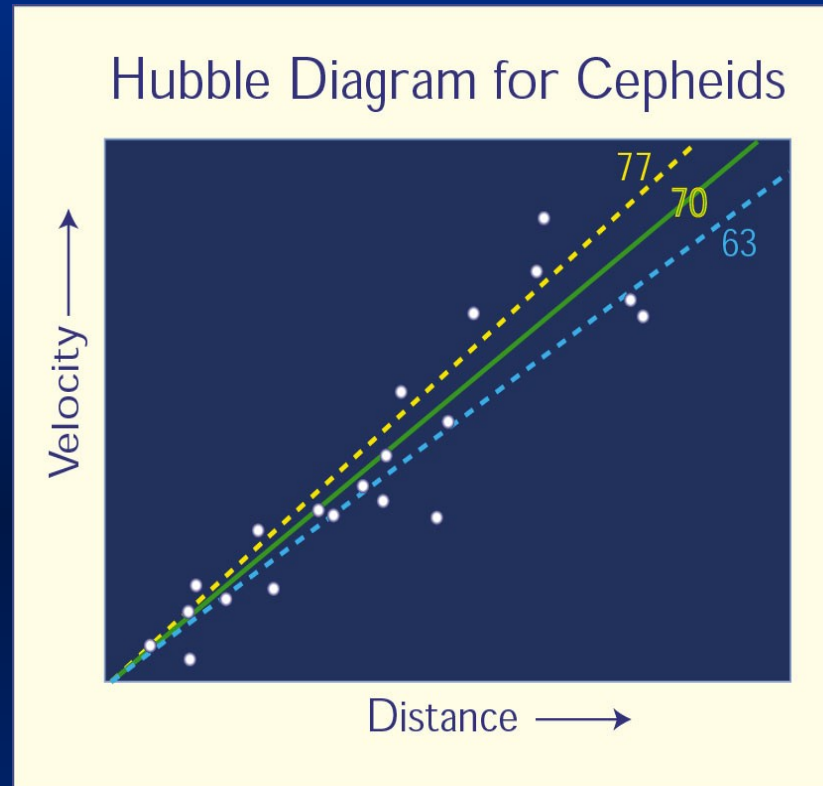


NGC 4603

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



$$V = H \cdot D$$

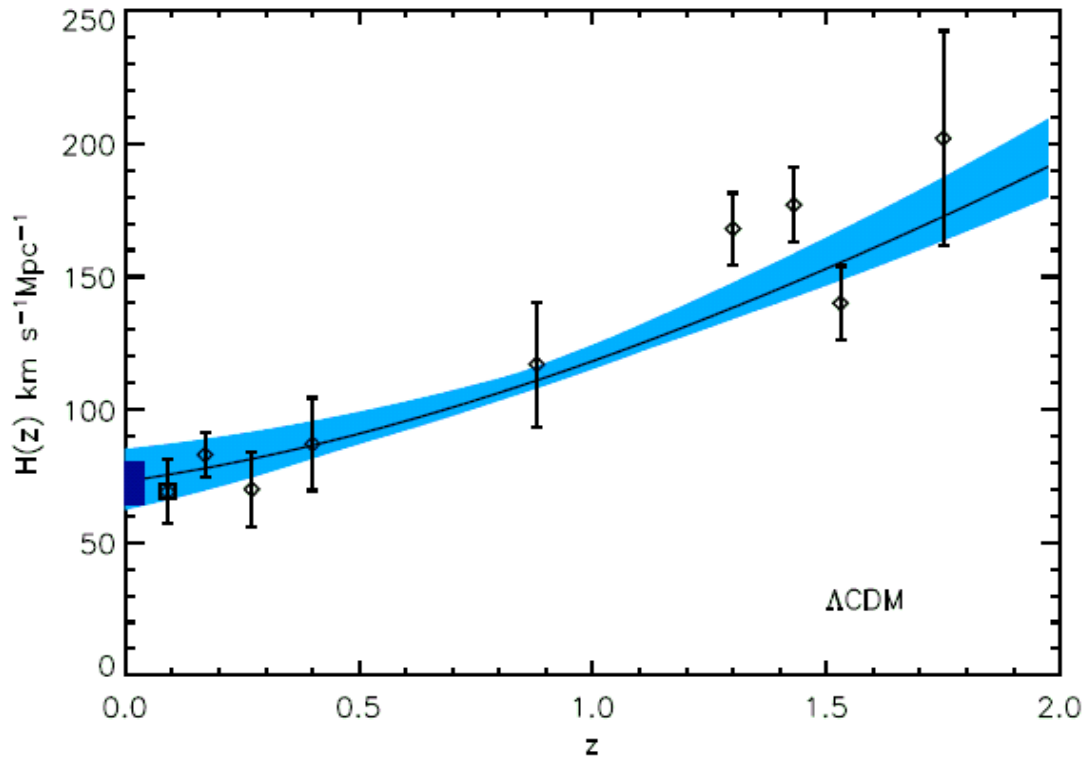
E. Hubble, 1924

$$\langle H \rangle = 72 \text{ km/s Mpc} = 1/15 \cdot 10^9 \text{ Jahre}$$

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

Die Hubble Konstante, WMAP Bestimmung Februar 2007,

arXiv:astro-ph/0603449v2 27 Feb 2007



$$H(0) = 73 \pm 2 \text{ km/(s Mpc)}$$

Urknall

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

Dauer der Expansion = 15 Milliarden Jahre

$$D/V = 1/H$$

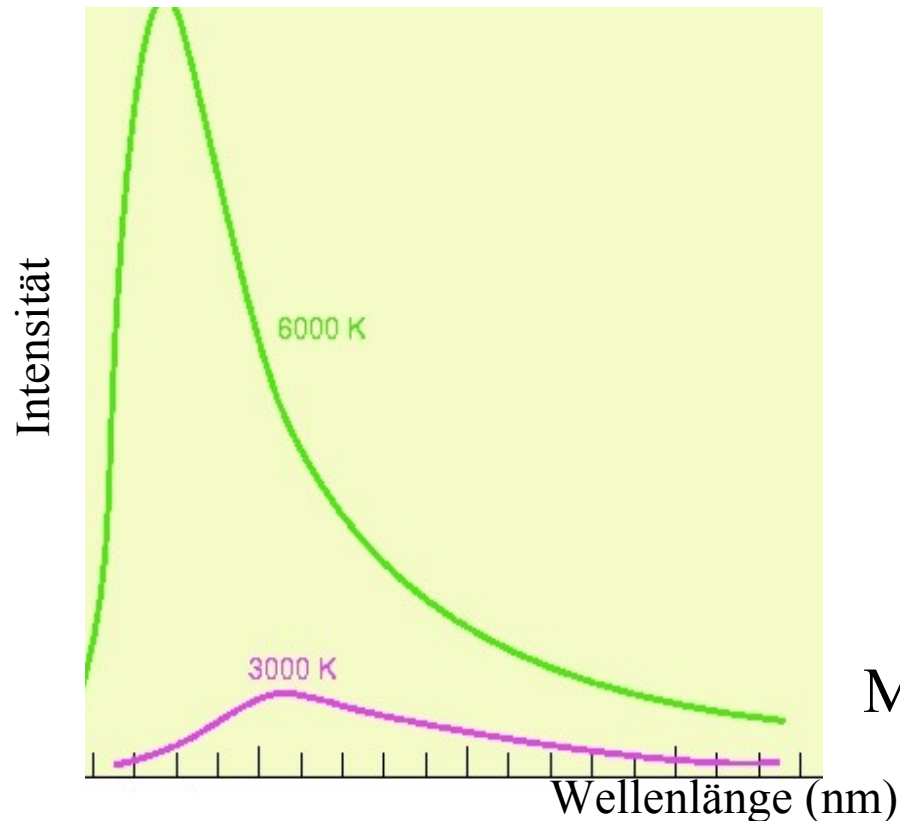
Wie wird die Temperatur bestimmt?

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

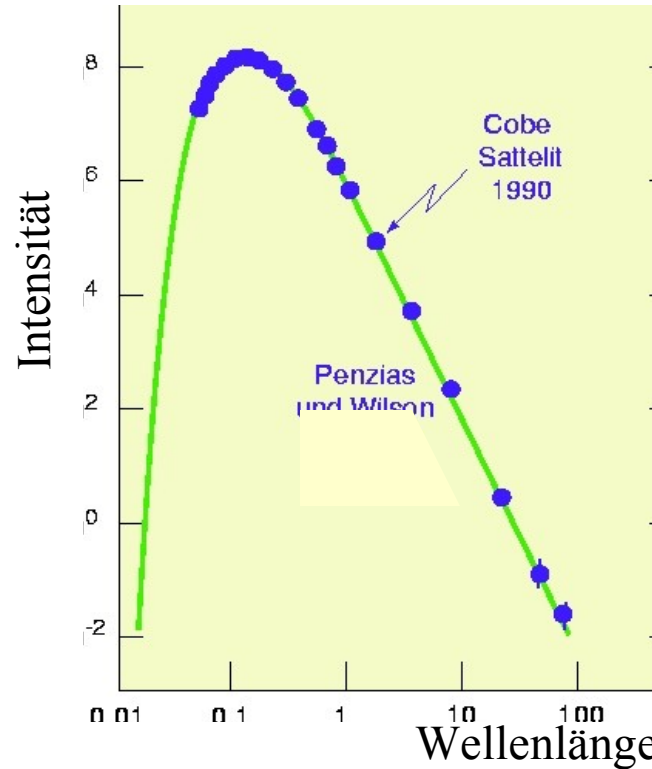
Aus Intensität und Wellenlänge des Sonnenlichts

$$T = 6000 \text{ K}$$

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

Messung der Temperatur im All

Spektrum der kosmischen Hintergrundstrahlung



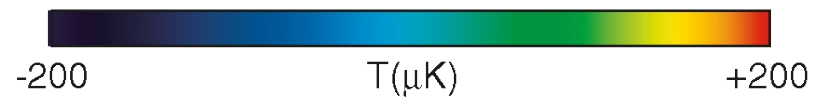
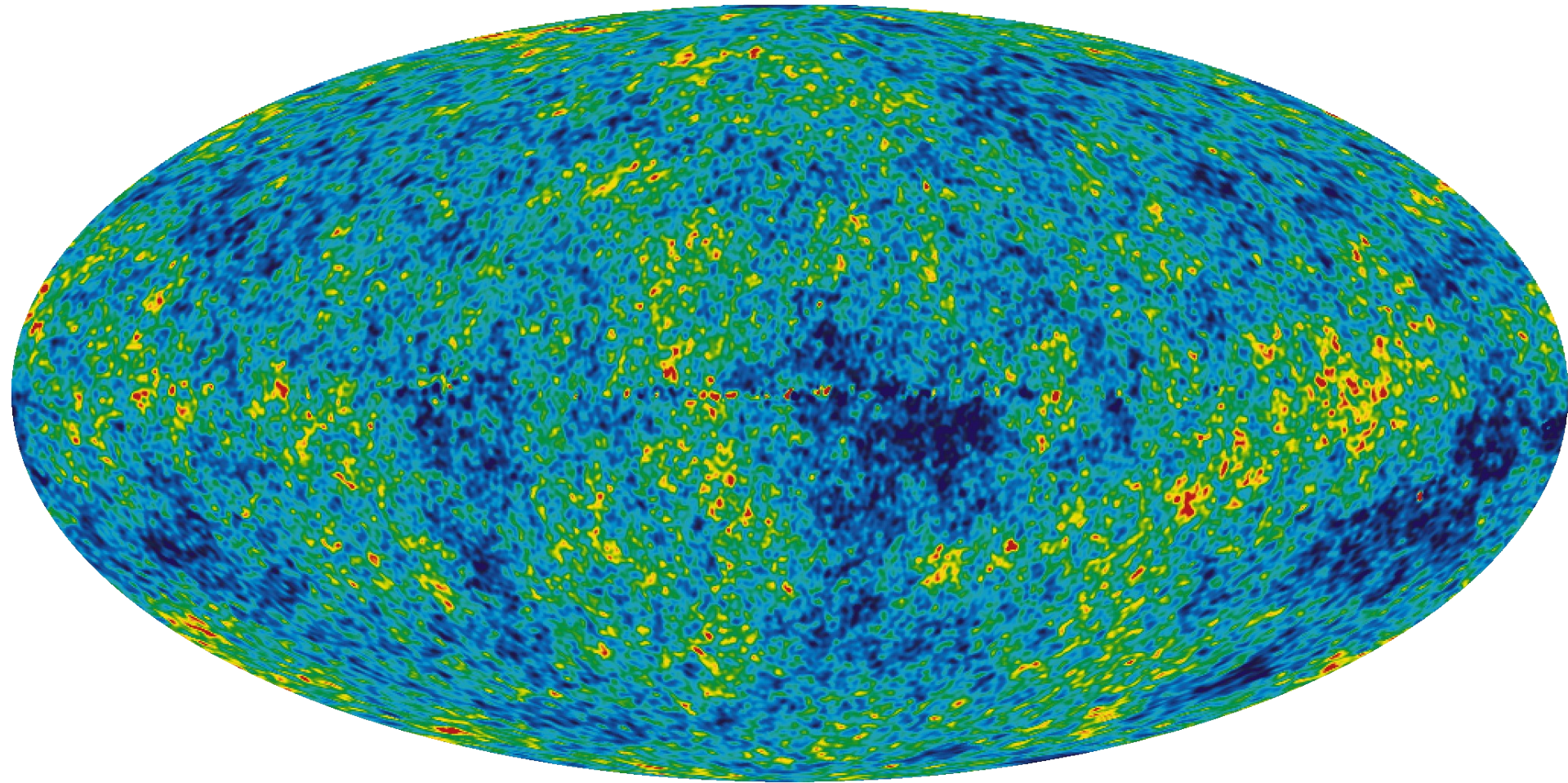
Penzias und Wilson 1965

Aus Intensität und Wellenlänge der Mikrowellen-Hintergrund Strahlung

$$T = 2.736 \pm 0.017 \text{ K}$$

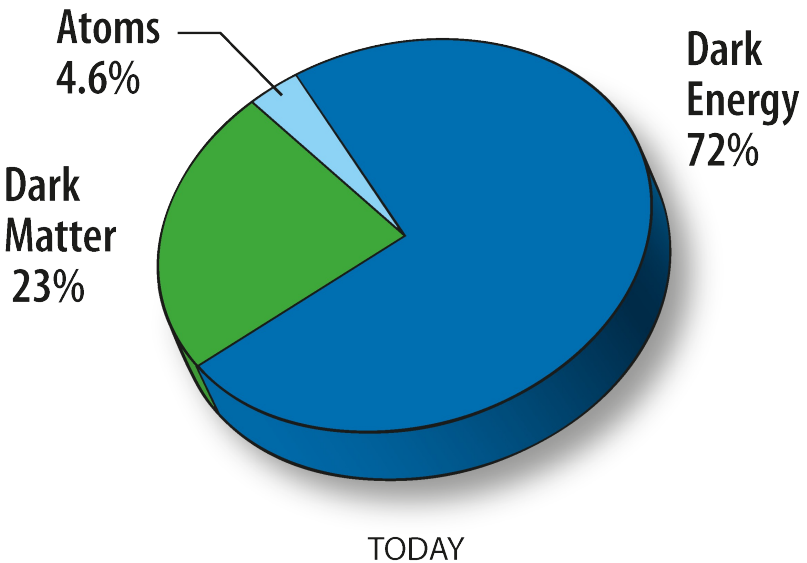
$$\text{Dichte} = 400 \text{ Photonen/cm}^3$$

Temperaturverteilung im Universum -- WMAP Experiment



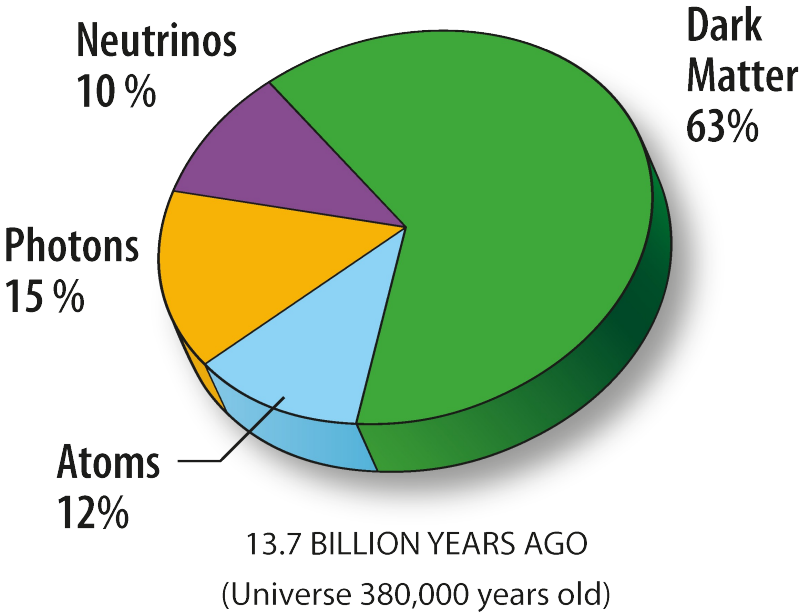
WMAP 5-year

heute

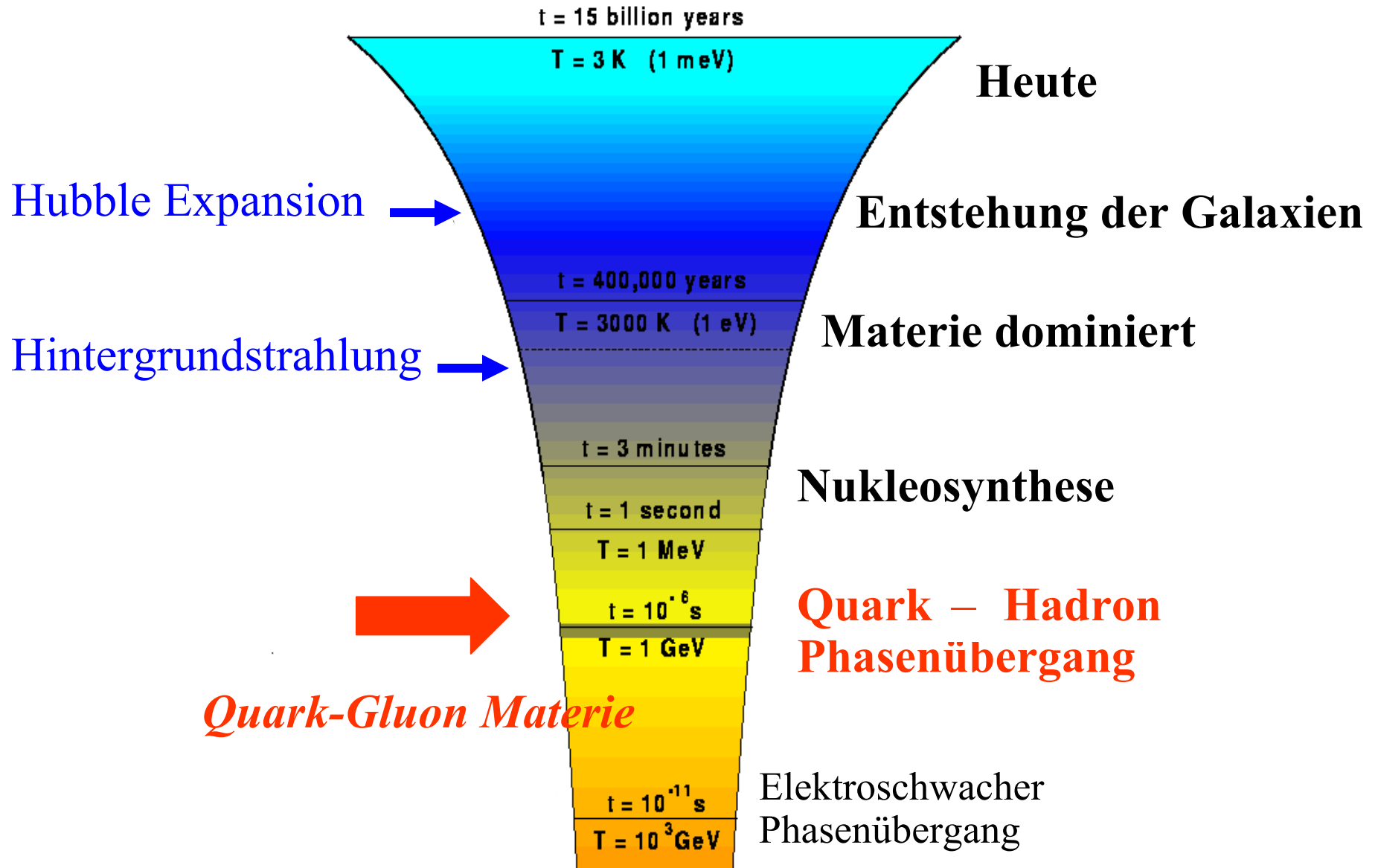


Bestandteile des Universums

vor 13.7 Mill. Jahren

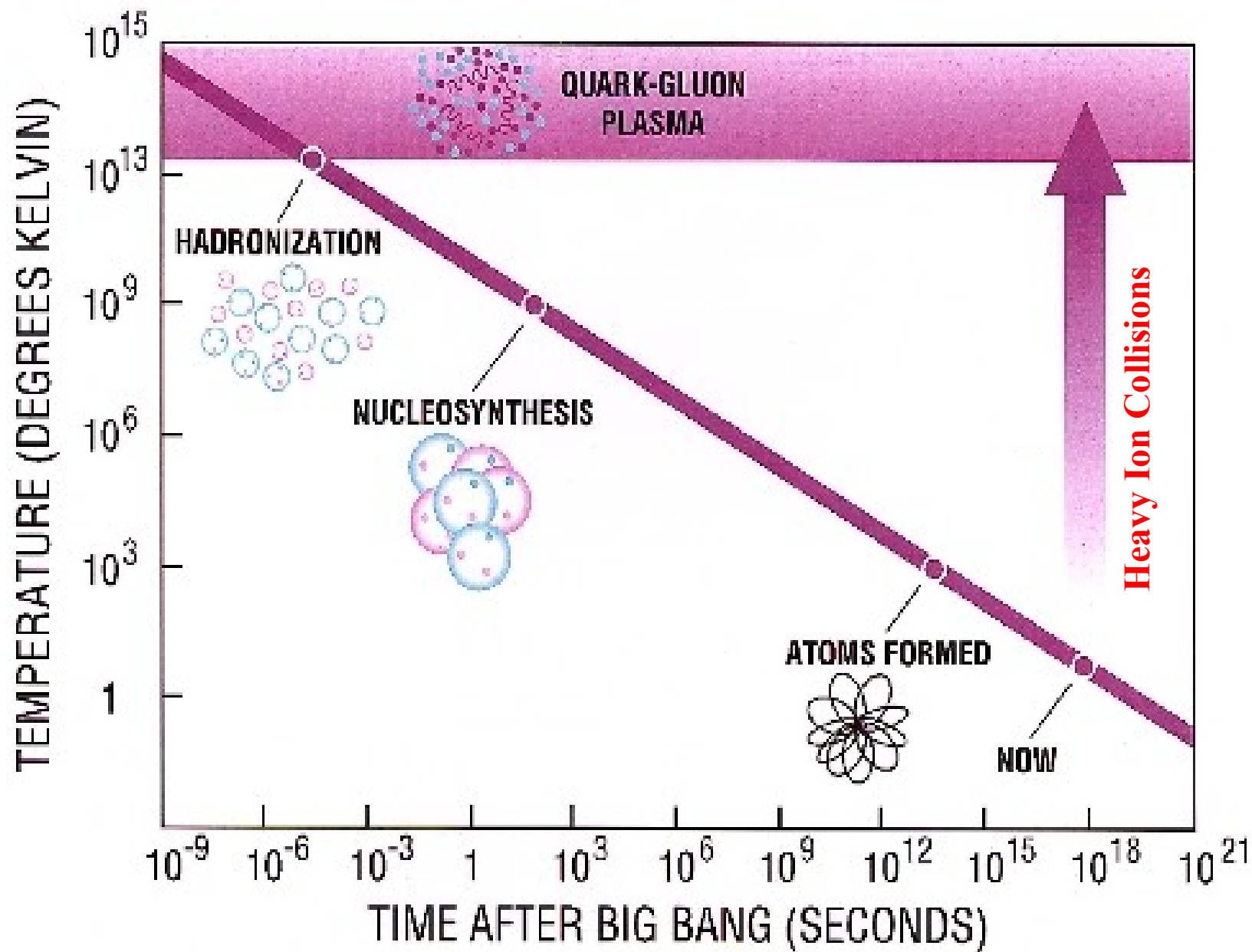


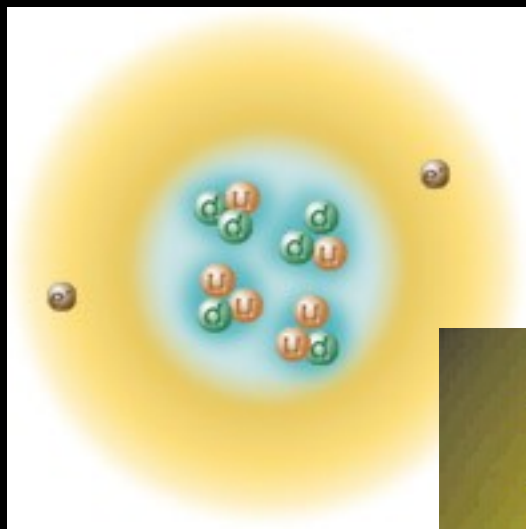
Wieweit kann man den Urknall zurückverfolgen?



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

Mit Schwerionen-Kollisionen
bei
ultrarelativistischen Energien



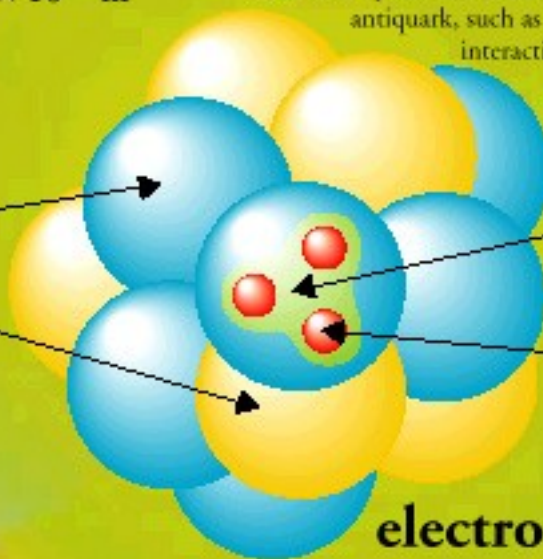


The Nucleus

$(1-10) \times 10^{-15} \text{ m}$

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.

neutron
 10^{-15} m
proton



strong field

quark
 $< 10^{-19} \text{ m}$

electromagnetic field

Der Teilchen-Zoo

BOSONS

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

Unified Electroweak spin = 1

Strong (color) spin = 1

Baryons qqq and Antibaryons $\bar{q}\bar{q}\bar{q}$

Baryons are fermionic hadrons.
There are about 120 types of baryons.

Symbol	Name	Quark content	Electric charge	Mass GeV/c^2	Spin
--------	------	---------------	-----------------	-----------------------	------

p

π

n

Λ

Ω^-

Mesons $q\bar{q}$

Mesons are bosonic hadrons.
There are about 140 types of mesons.

Symbol	Name	Quark content	Electric charge	Mass GeV/c^2	Spin
π^+	pion	$u\bar{d}$	+1	0.140	0
K^-	kaon	$s\bar{u}$	-1	0.494	0
ρ^+	rho	$u\bar{d}$	+1	0.770	1
B^0	B-zero	$d\bar{b}$	0	5.279	0
		$c\bar{u}$			

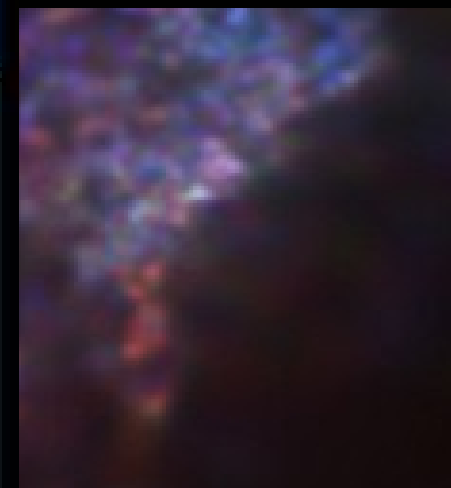
Name

Mass GeV/c^2

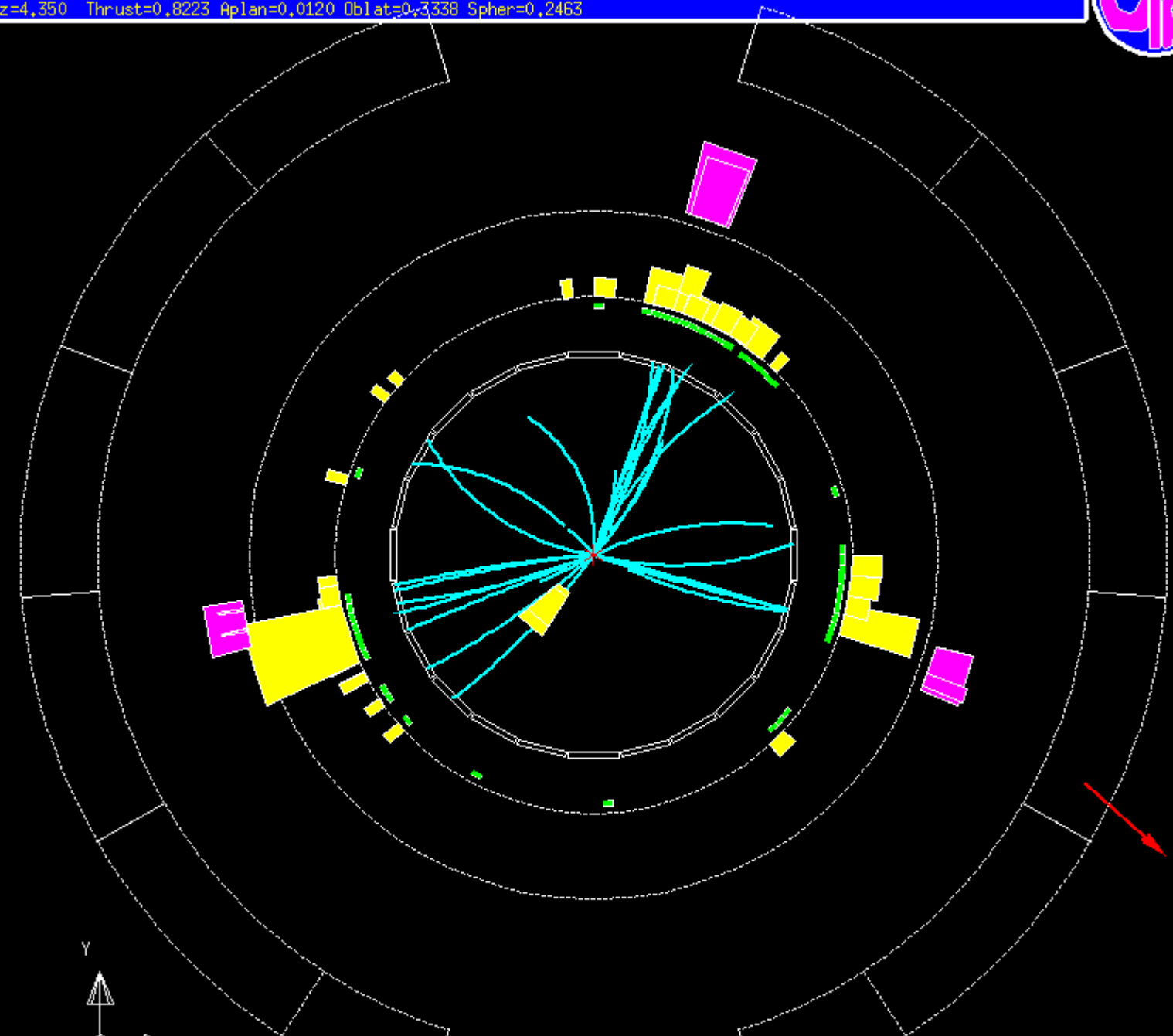
Electric charge

g
gluon

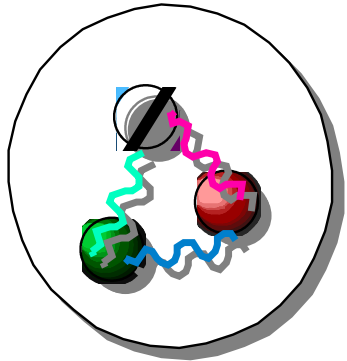
0



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



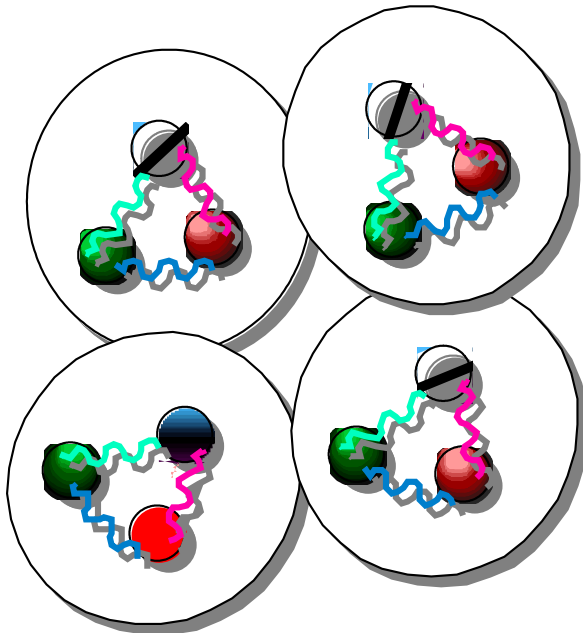
Nukleon



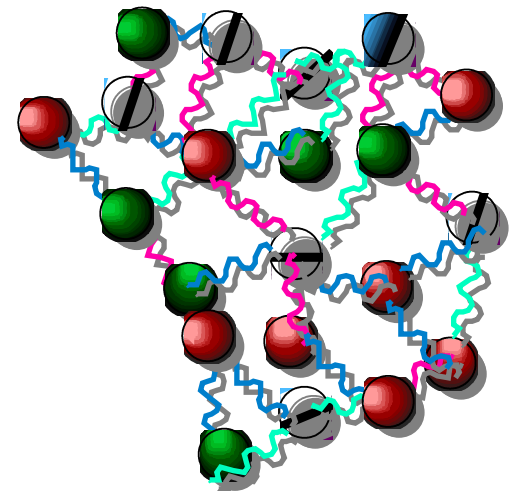
confinement

de-confinement

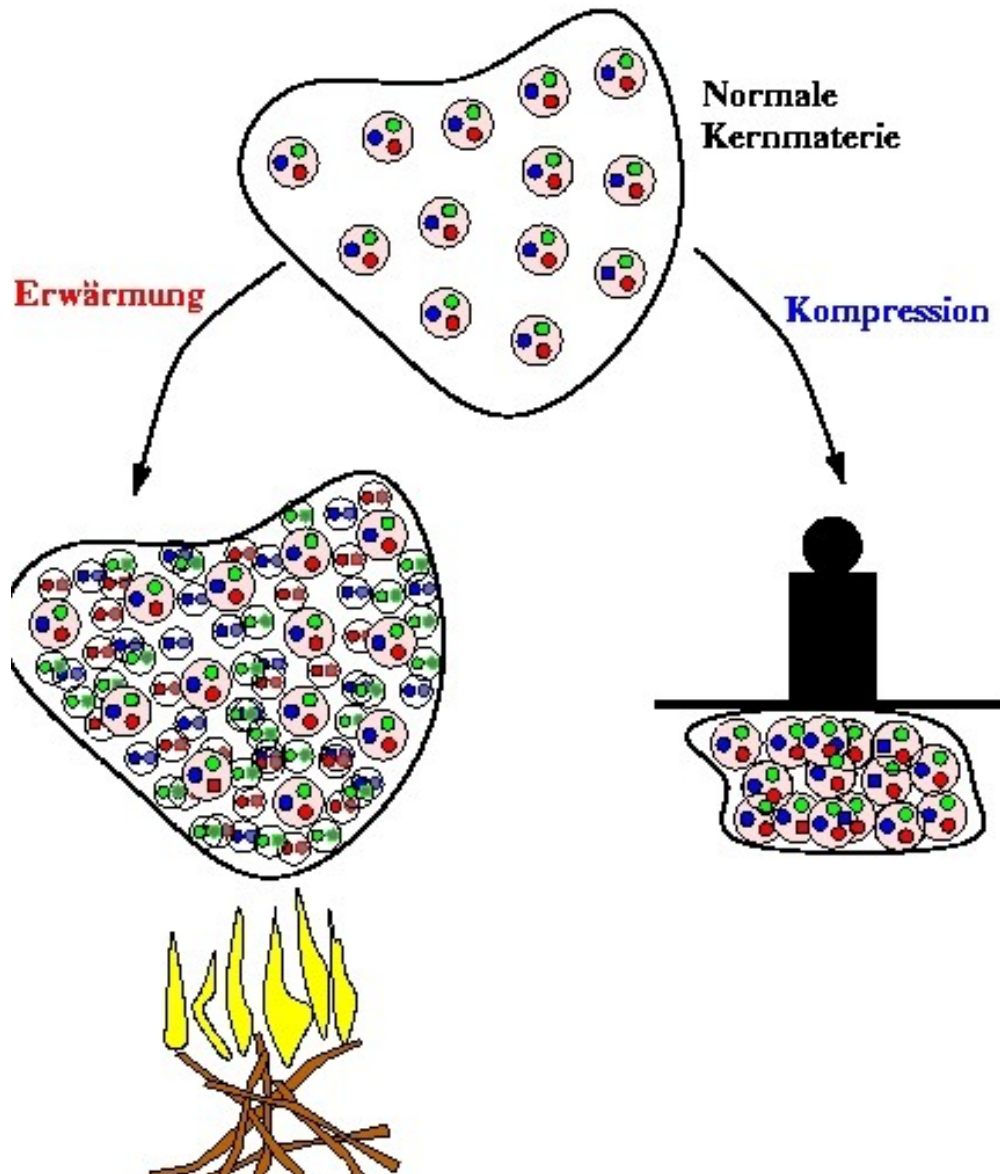
Kern

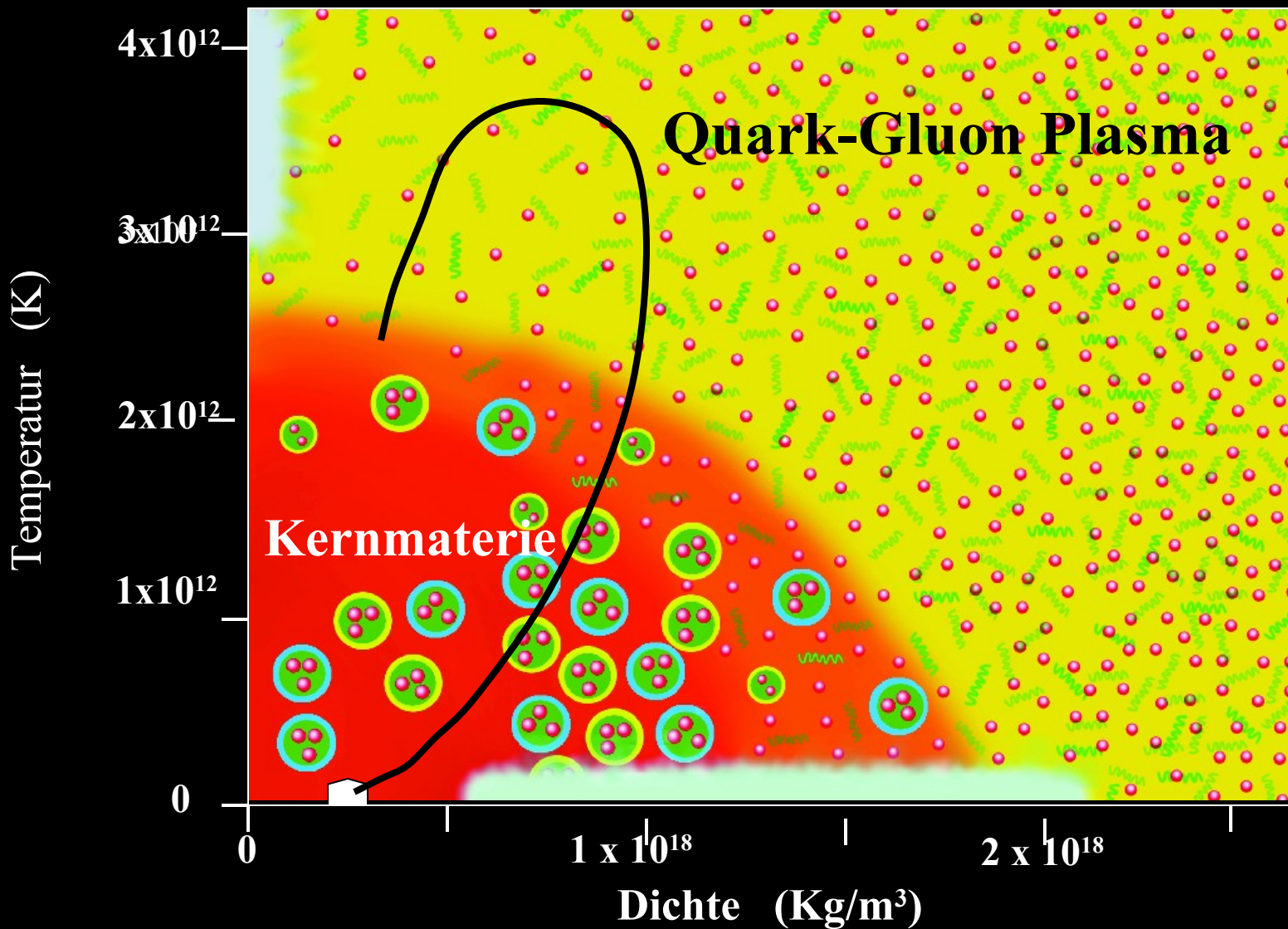


Quark-Gluon Materie



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





Vor dem Stoss

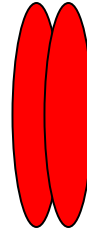


Normale Kernmaterie

$$\rho_0 = 0.17 \text{ /fm}^3$$

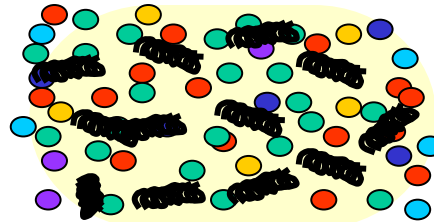
$$\varepsilon_0 = 0.16 \text{ GeV/fm}^3$$

Kompression und Heizen



Quark-Gluon Materie
Quark-Gluon Plasma

Feuerball

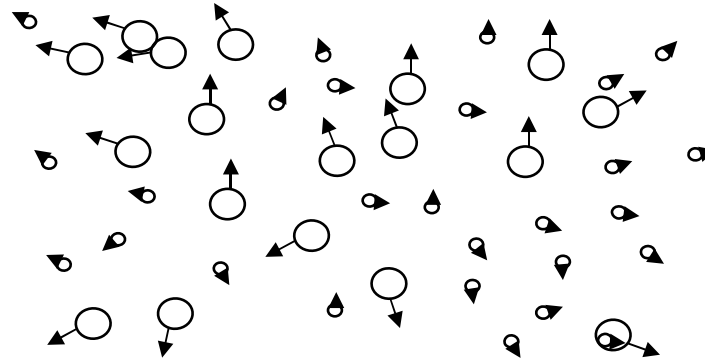


Erzeugung erwartet bei

$$\rho = 1.2 \text{ /fm}^3$$

$$\varepsilon = 3 \text{ GeV/fm}^3$$

Expansion und
Entkopplung

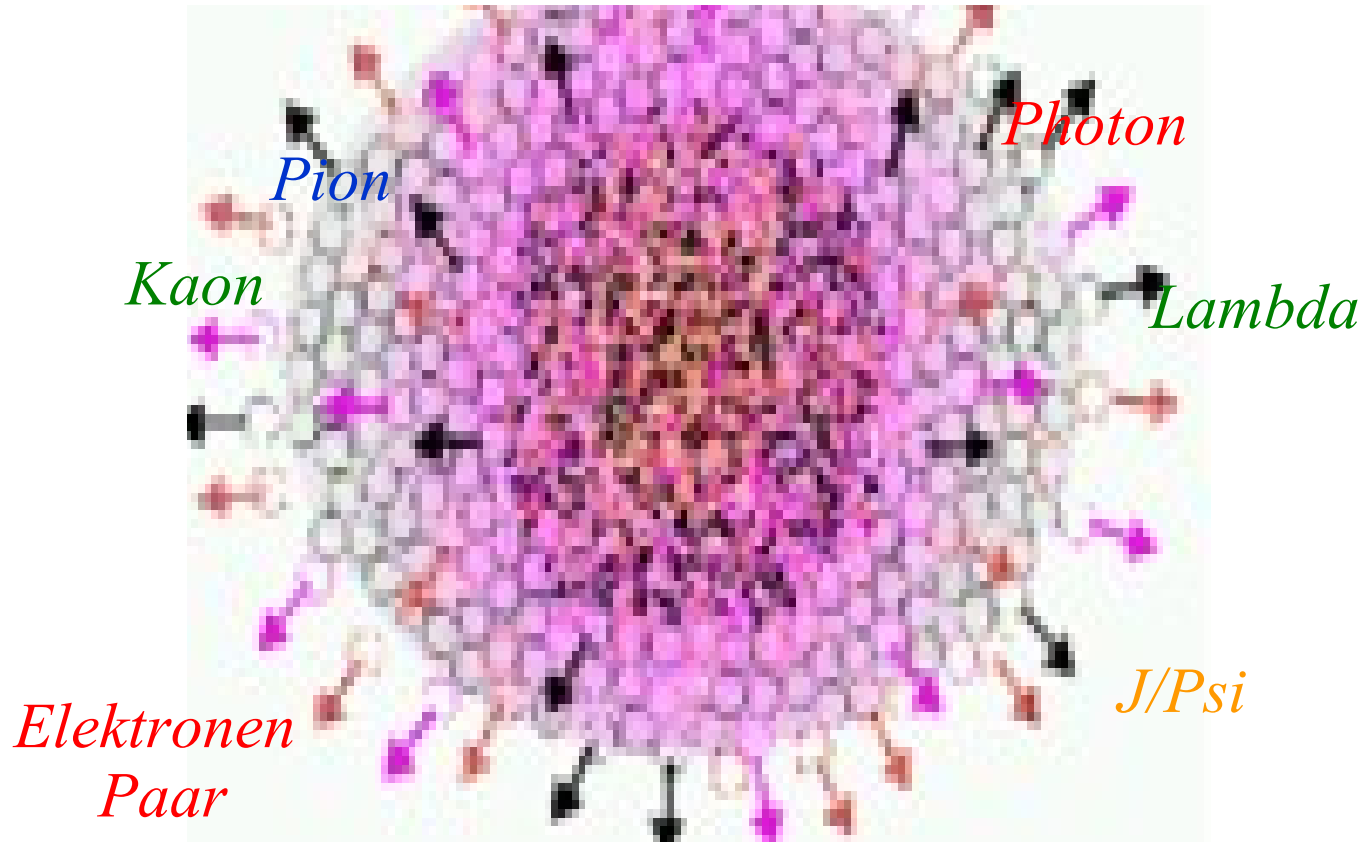


Nicht wechselwirkende
Elementarteilchen

Zeit

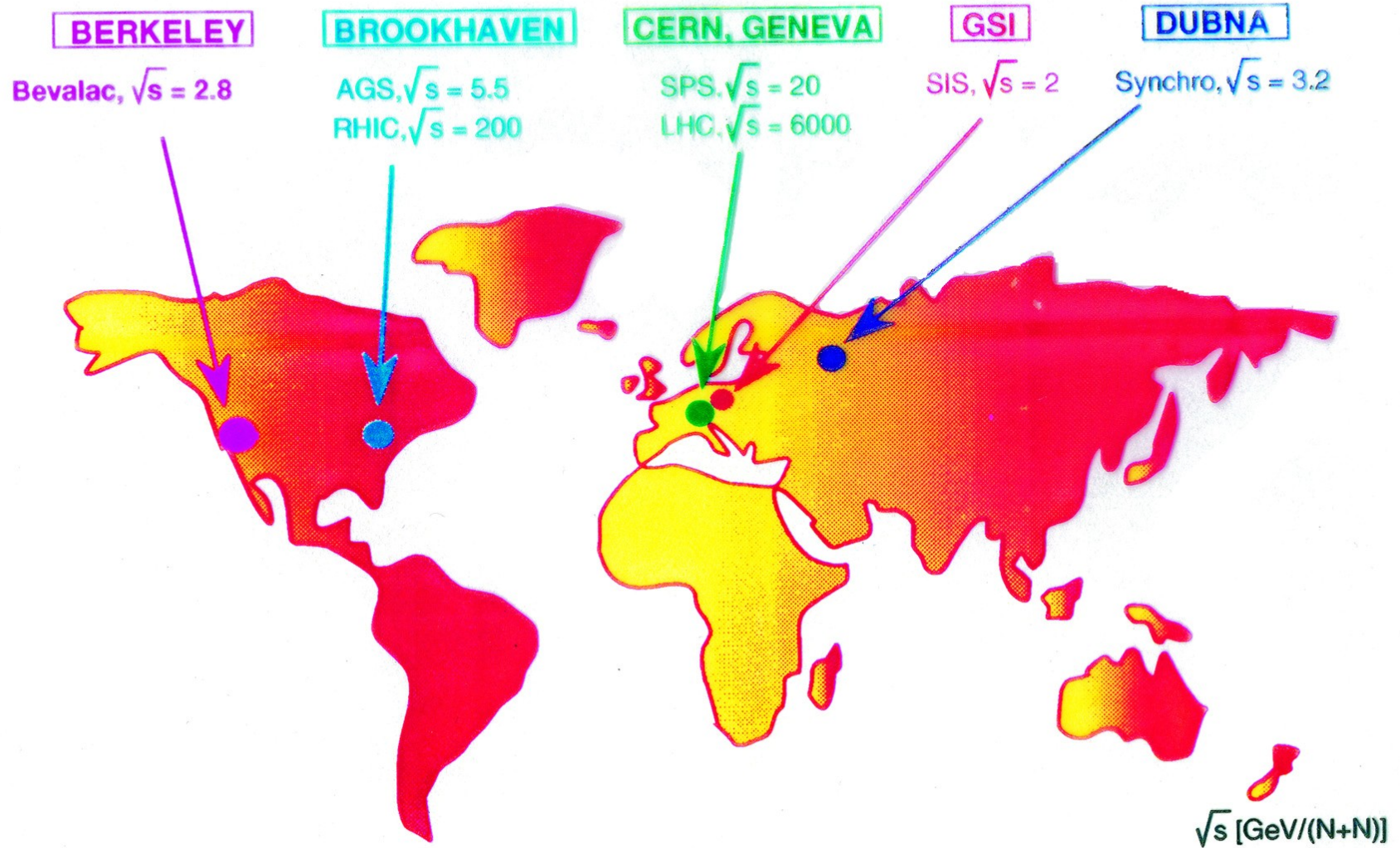


Feuerball



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

Relativistic Heavy Ion Accelerators





CERN

SPS : 1986 - 2005

- S and Pb ; up to $\sqrt{s} = 20$ GeV/nucl pair
- hadrons, photons and dileptons

LHC : starting 2009

- Pb ; up to $\sqrt{s} = 5.5$ TeV/nucl pair
- ALICE, ATLAS, CMS experiments

AGS : 1986 - 2000

- Si and Au ; up to $\sqrt{s} = 5$ GeV /nucl pair
- only hadronic variables

RHIC : 2000

- Au ; up to $\sqrt{s} = 200$ GeV /nucl pair
- hadrons, photons, dileptons, jets



BNL

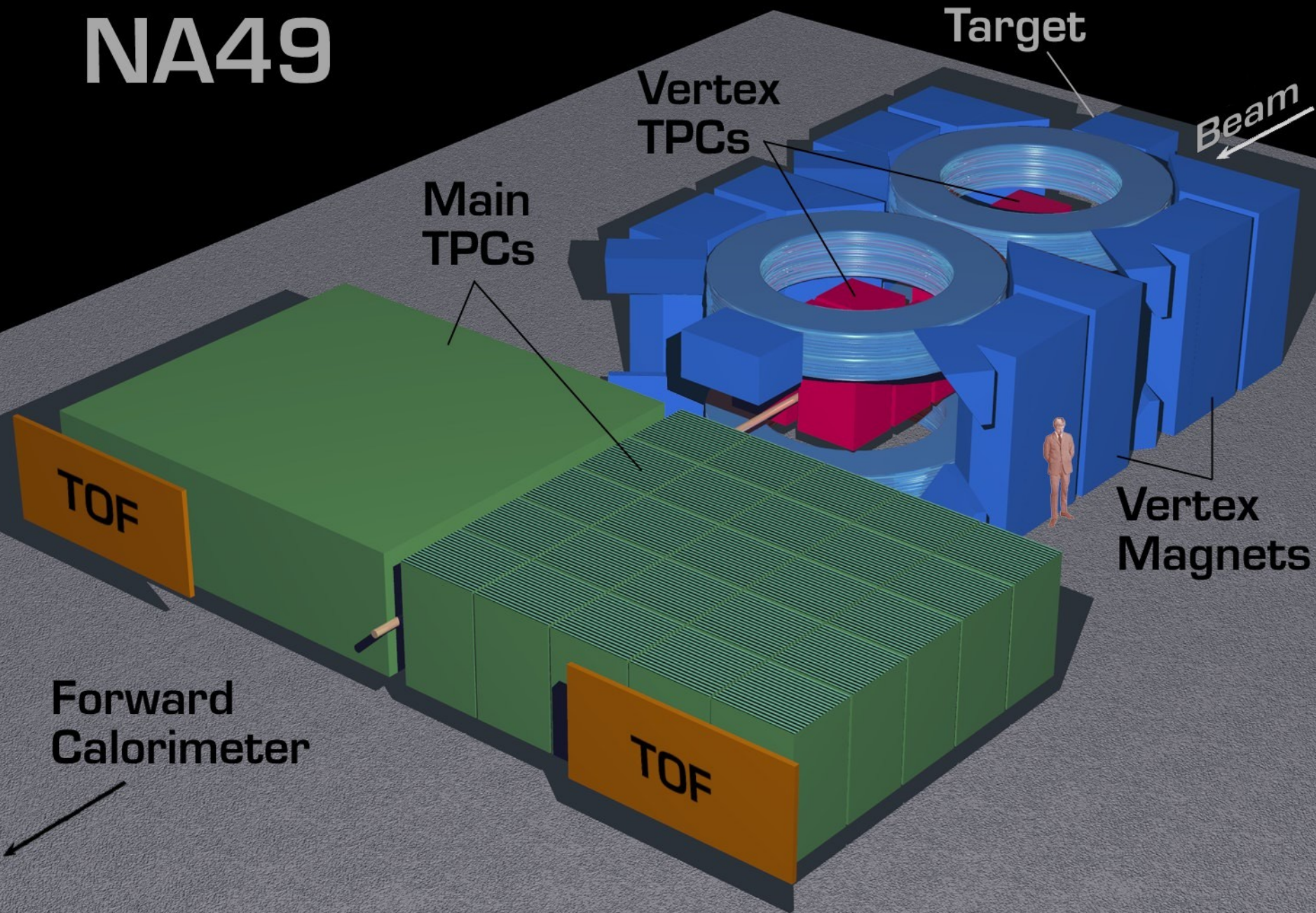
RHIC



UTO DIREC
7500 kg

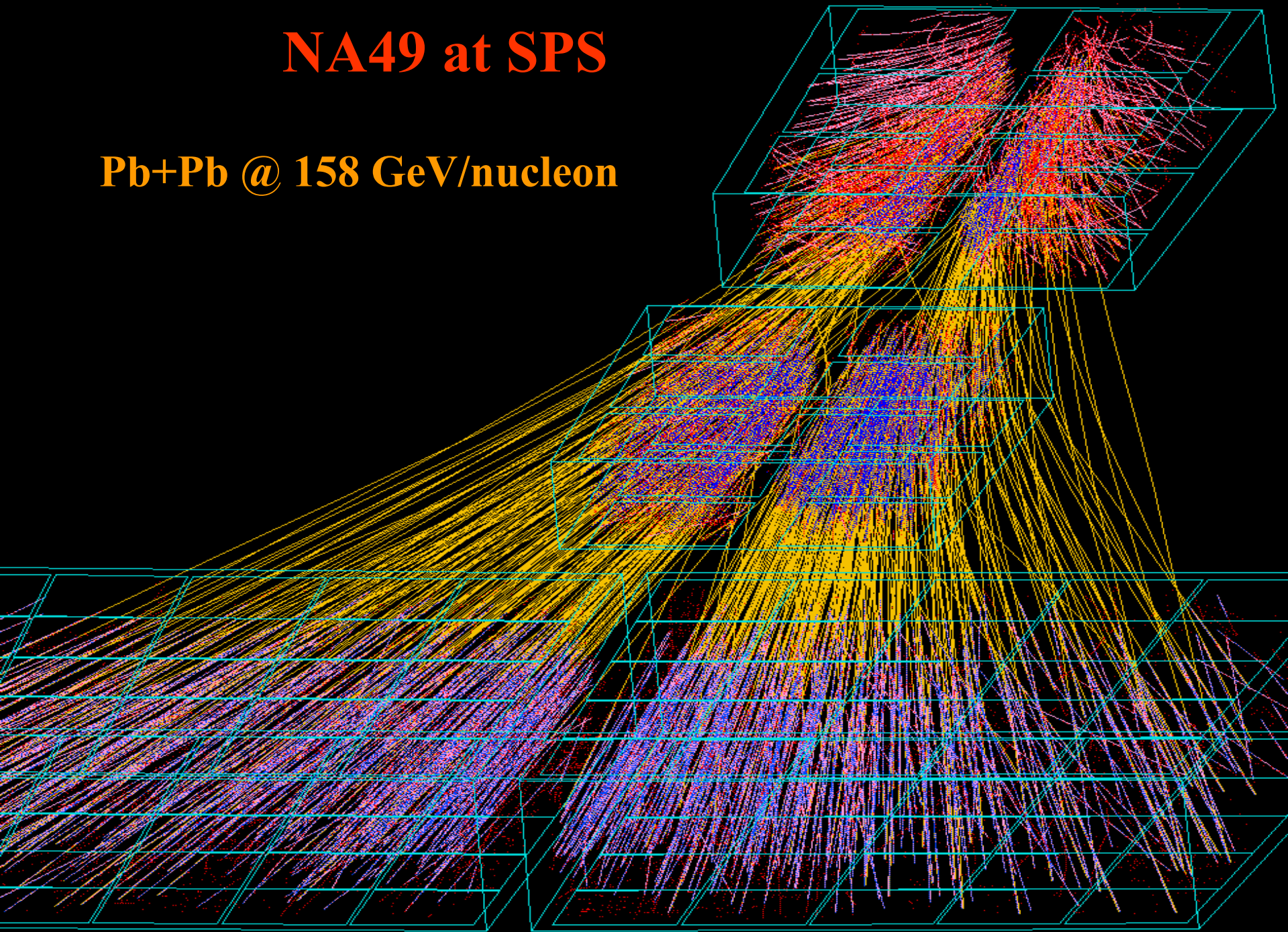
403.04

NA49

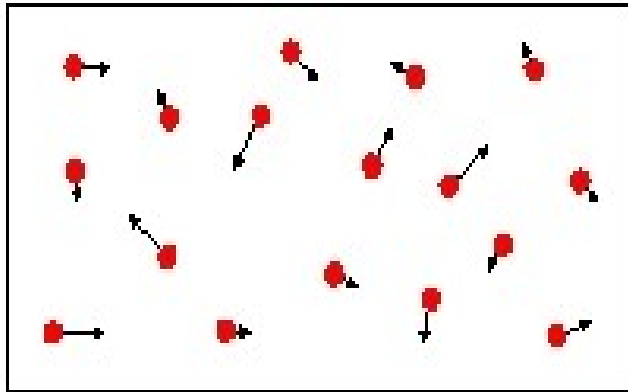


NA49 at SPS

Pb+Pb @ 158 GeV/nucleon



Thermische Energie



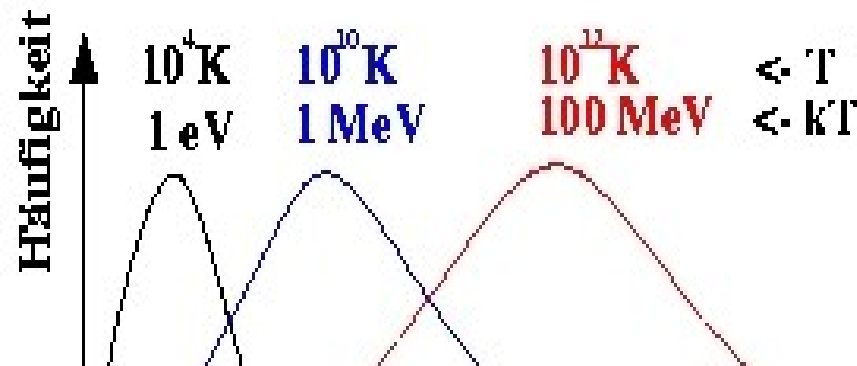
Gas mit Temperatur T

mittlere kinetische Energie

$$E_{\text{kin}} = \frac{1}{2} m \bar{v}^2 \sim kT \text{ ist}$$

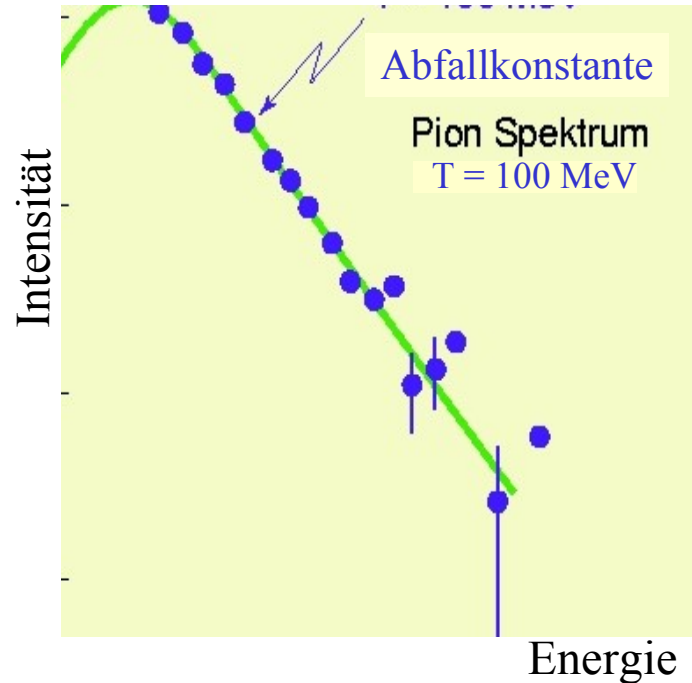
proportional zur Temperatur

($kT = \textit{thermische Energie}$)



Messung der Temperatur eines Feuerballs aus dem Schwerionenstoss

Pionen Spektrum



Abfallkonstante
proportional zur
Temperatur

Aus Intensität und Energie der ausgestrahlten Pionen

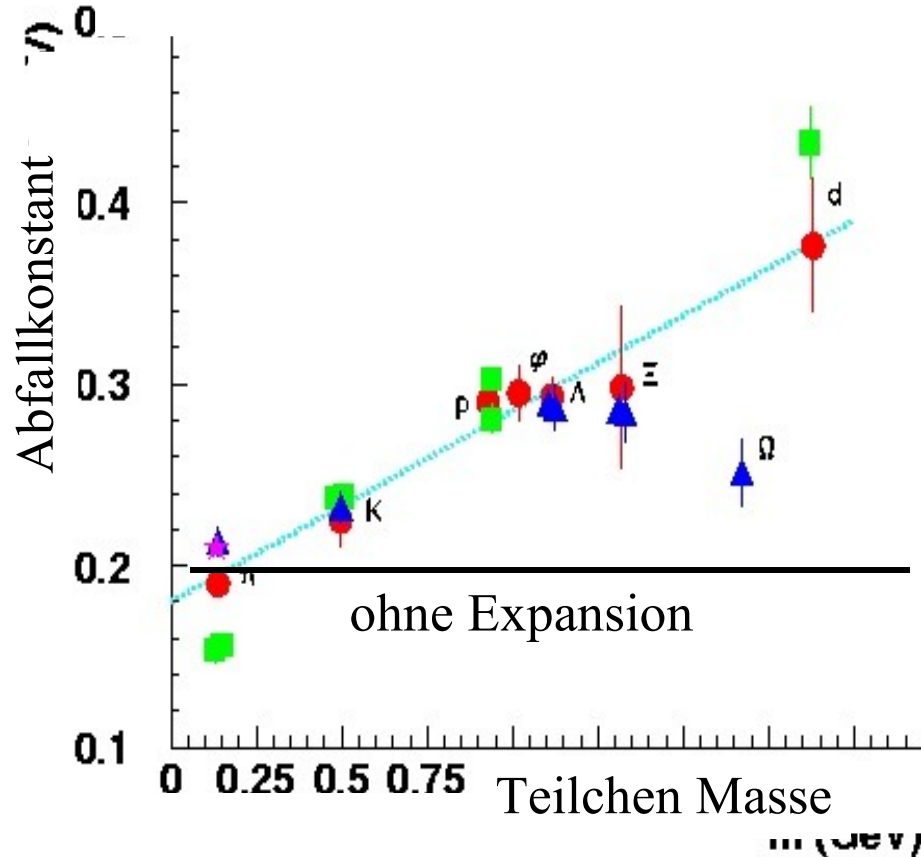
$$T = 100 \text{ MeV} \quad T = 10^{12} \text{ K}$$

100 000 mal heißer als im Inneren der Sonne!

Puzzle: die Abfallkonstante ('Temperatur')

mass dependence of inverse slopes

hängt von der Masse ab!



Auflösung:

Hubble Expansion
und Abkühlung des
Nuklearen Feuerballs

Beim Ausfrieren:

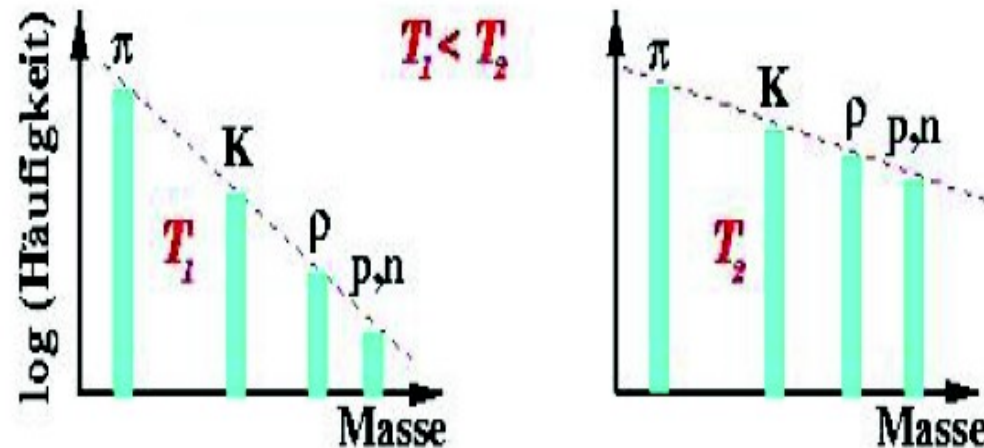
$$T = 120 \text{ MeV}$$

$$v = 0.55 c$$

■ NA44 ● NA49
▲ WA97 ☆ WA98

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

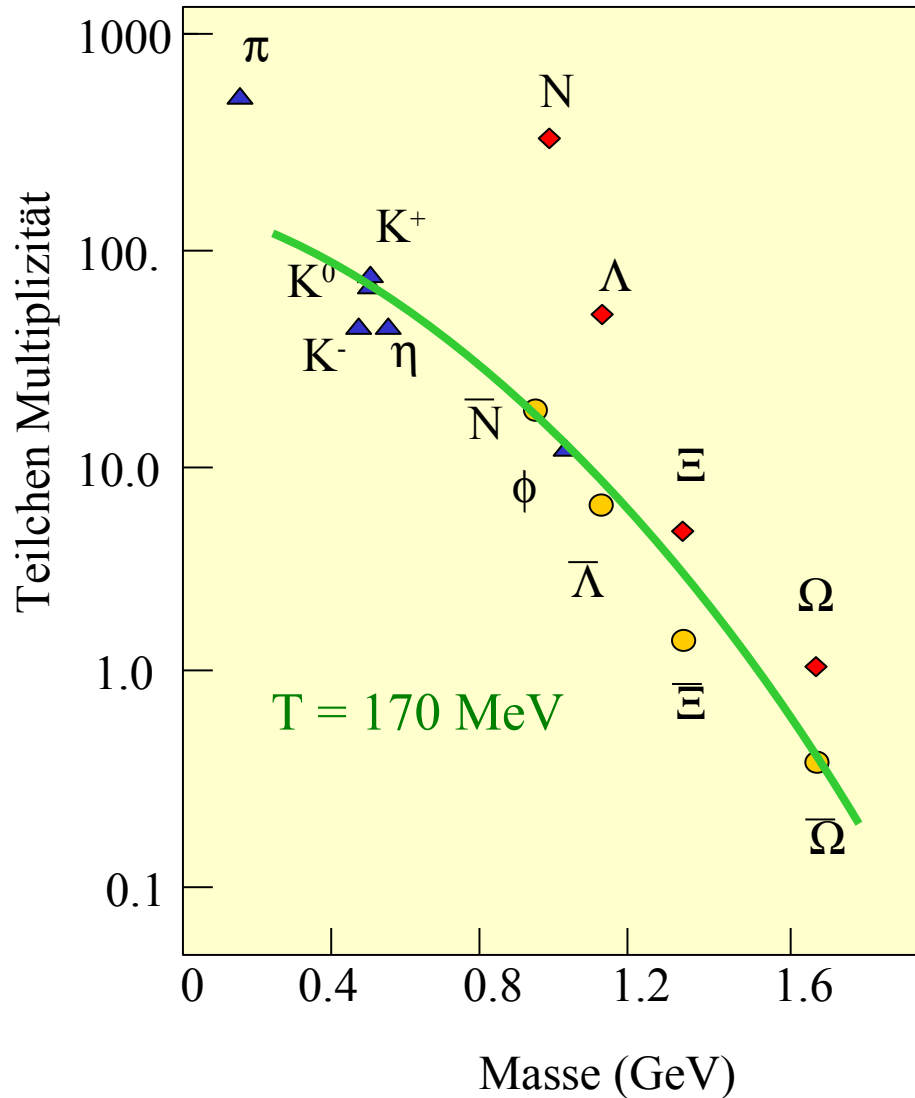
Äquivalenz Energie \Leftrightarrow Masse



$$\text{Häufigkeit} \sim m^{3/2} e^{-m/T}$$

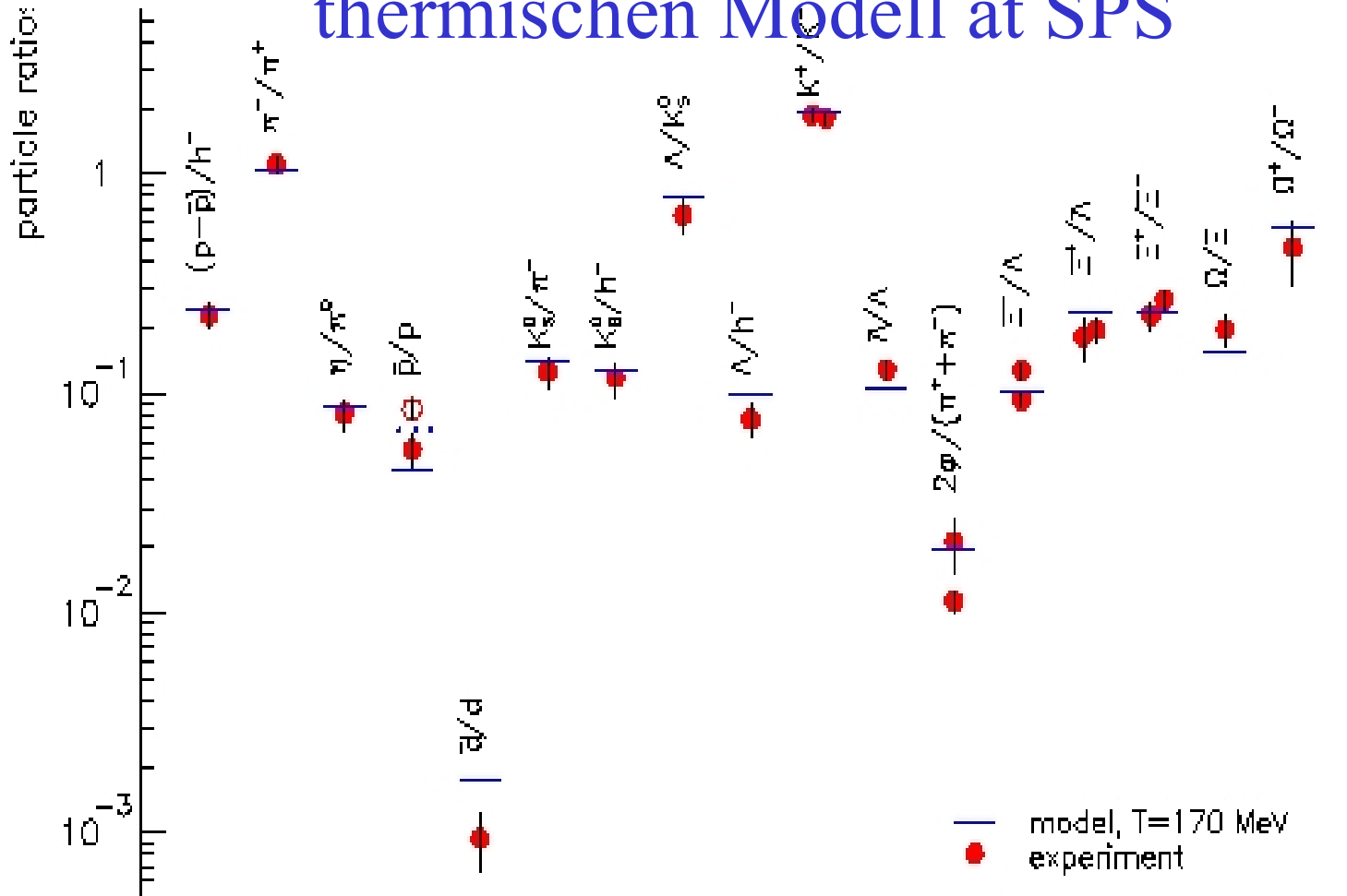
Die gemessenen Teilchenhäufigkeiten erlauben die Bestimmung von Temperatur und Dichte beim Zeitpunkt der Produktion hadronischer Teilchen

$$\text{Häufigkeit} \sim m^{3/2} e^{-m/T}$$



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
 $\mu_B = 266$ MeV

Zukunft

RHIC am BNL
läuft seit 8 Jahren

LHC am CERN
Ab 2009 – jetzt

GSI FAIR
ab 2016

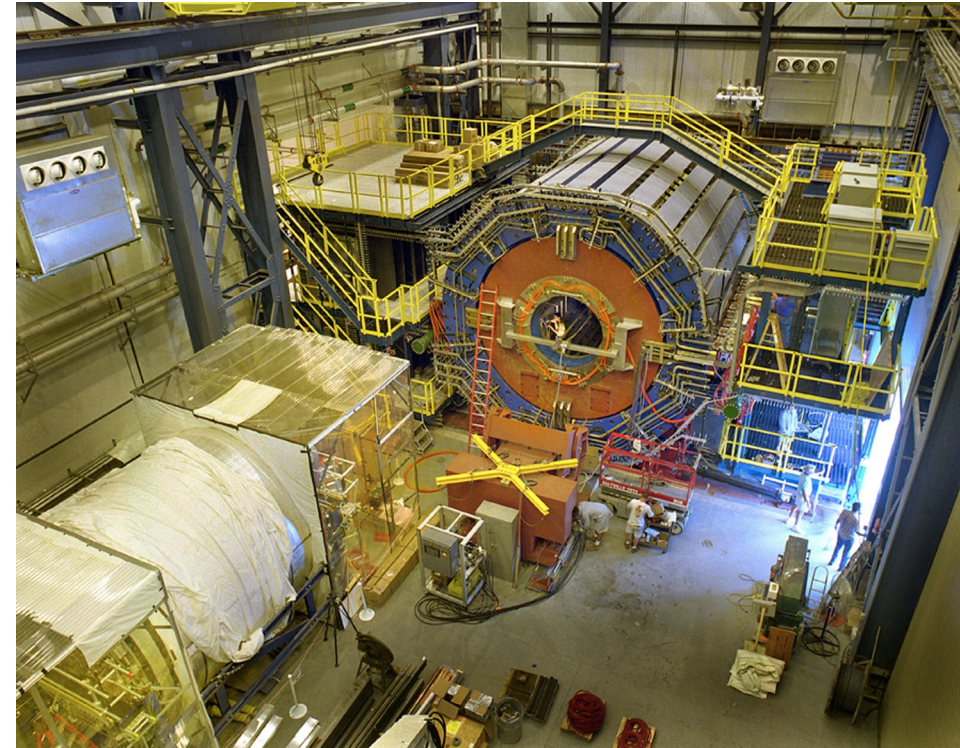
Relativistic Heavy Ion Collider



RHIC experiments: 2 large and 2 small

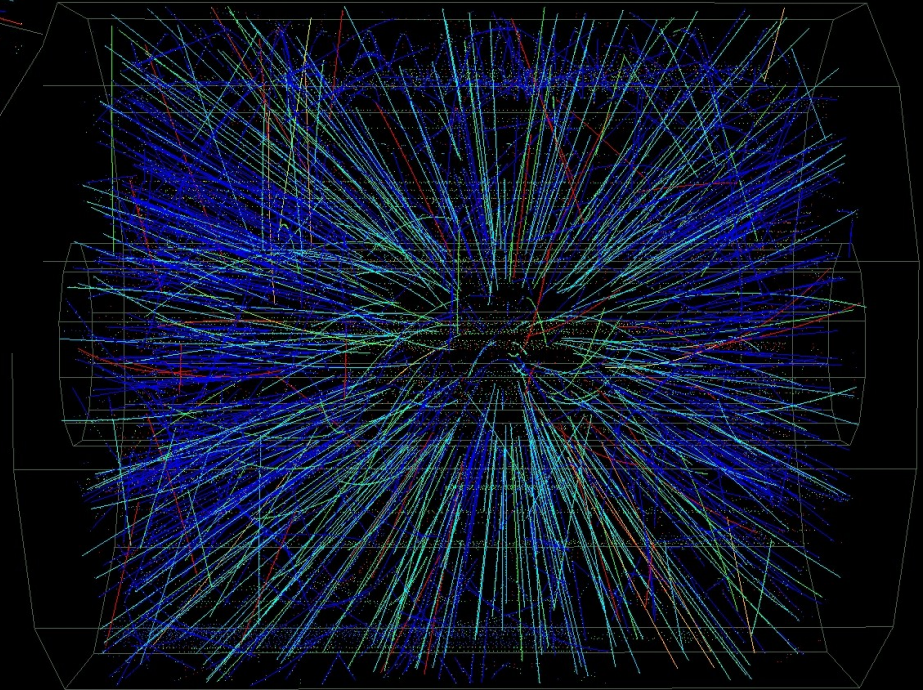
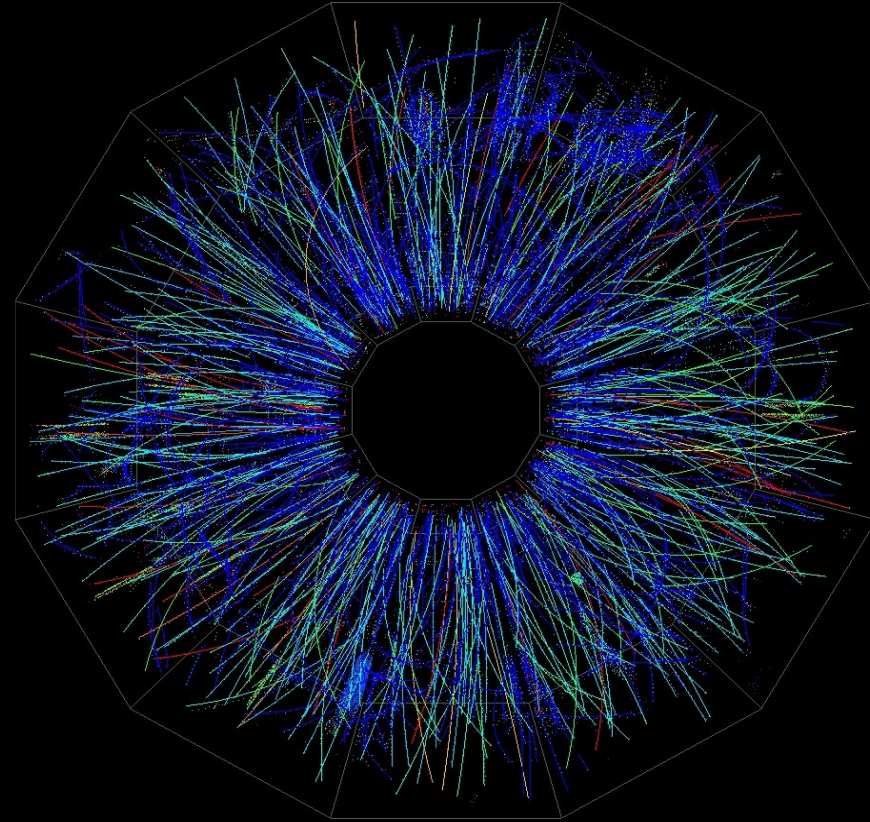
STAR: large TPC at central rapidity

PHENIX: central 2 arm spectrometer
plus forward/backward muon arms

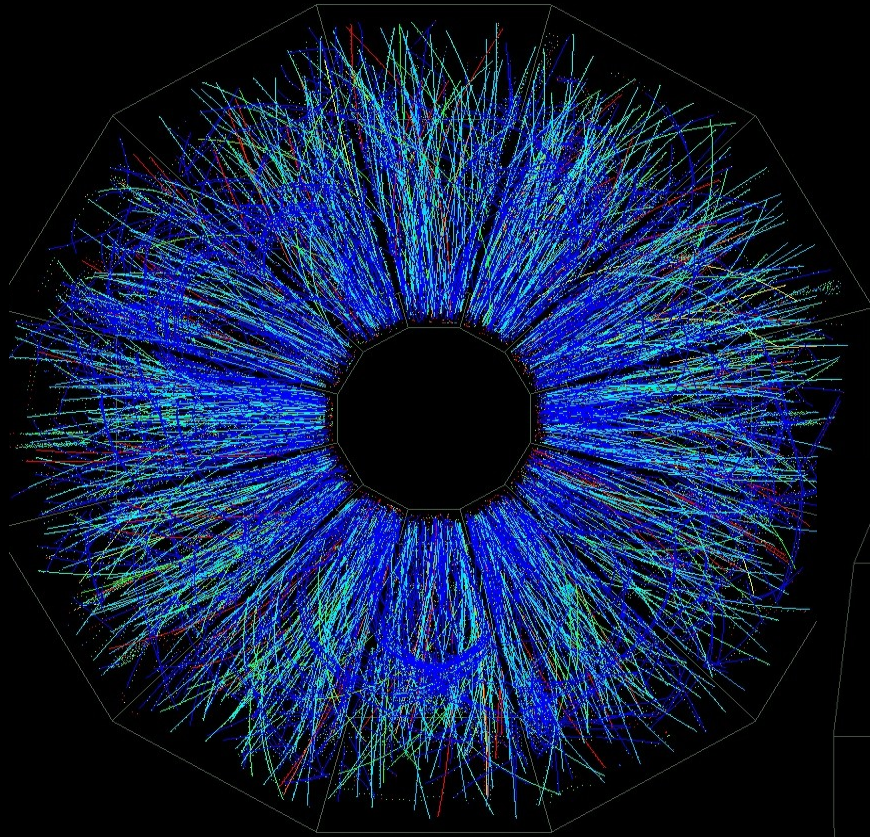


Au on Au Event at CM Energy ~ 130 A-GeV

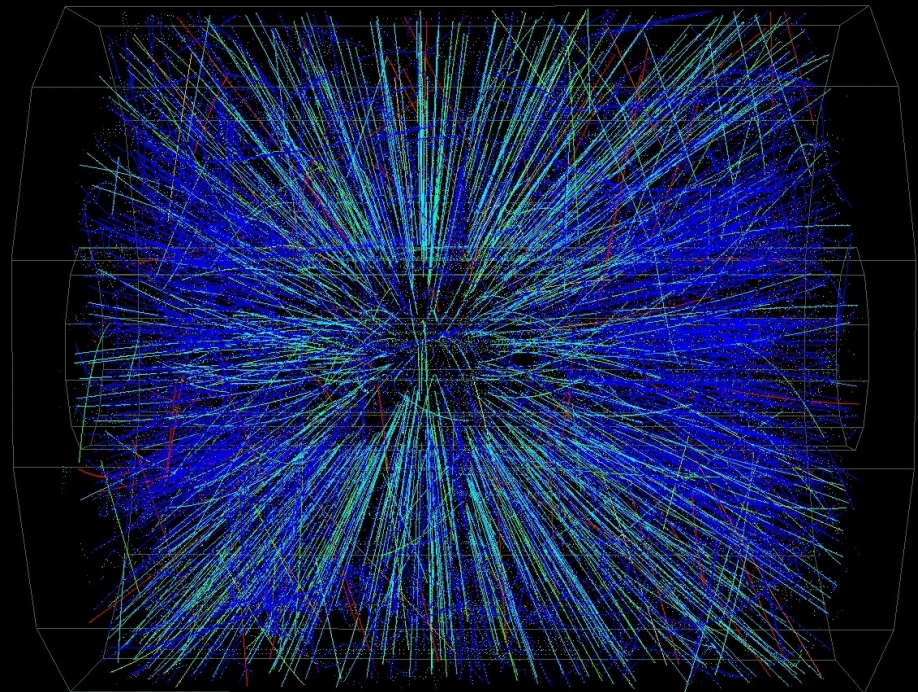
Peripheral Event



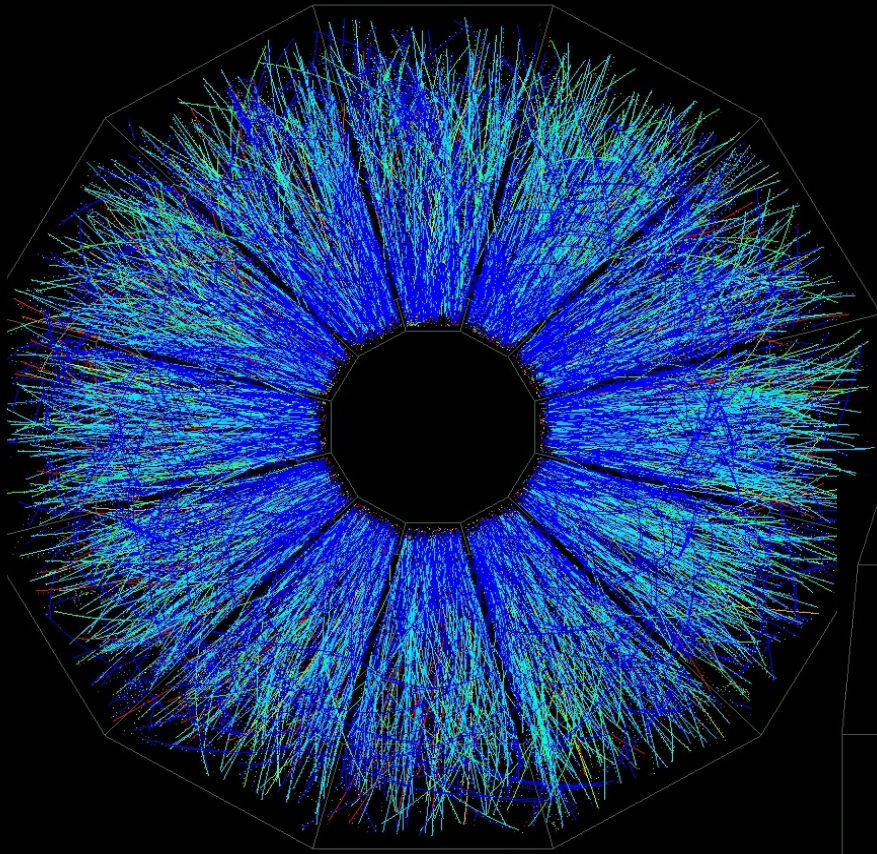
Au on Au Event at CM Energy ~ 130 A-GeV



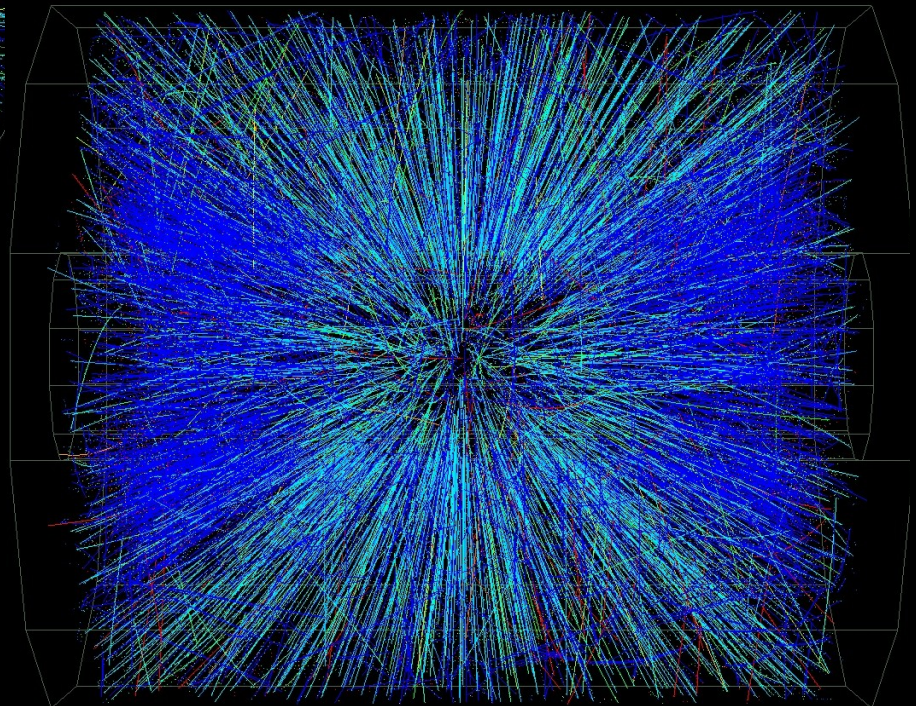
Mid-central Event



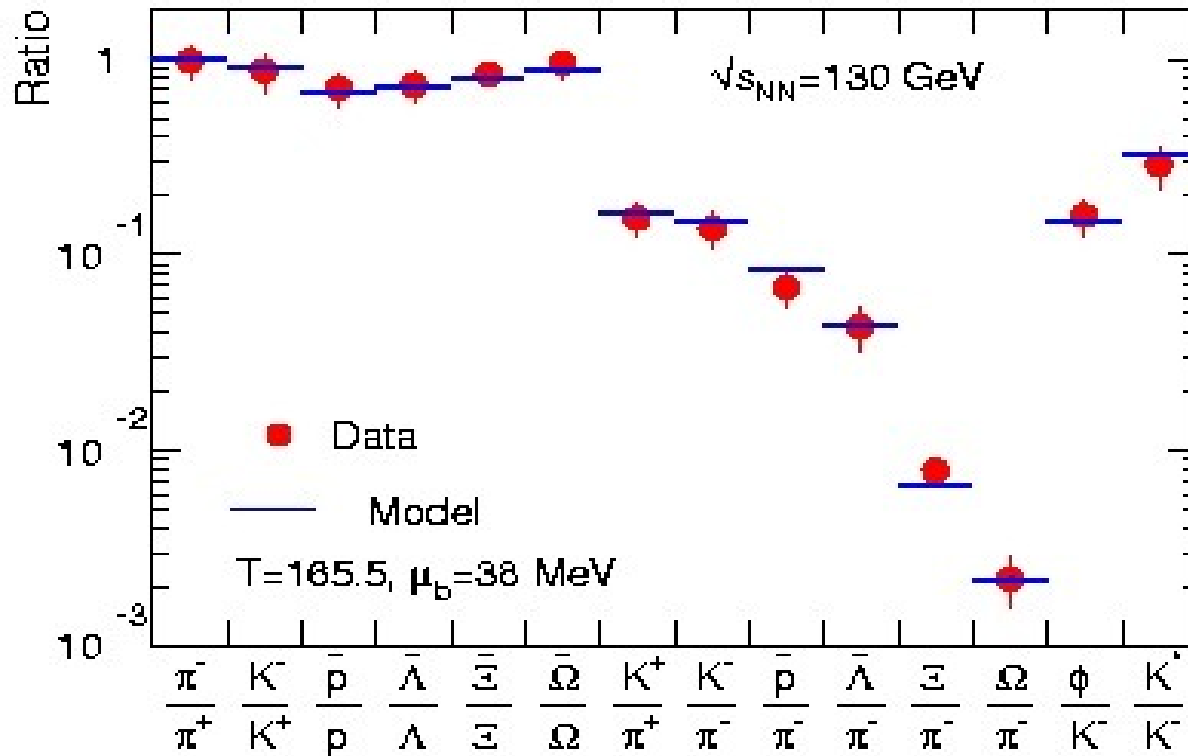
Au on Au Event at CM Energy ~ 130 A-GeV



Central Event



Beschreibung in einem vollständigen thermischen Modell beim RHIC

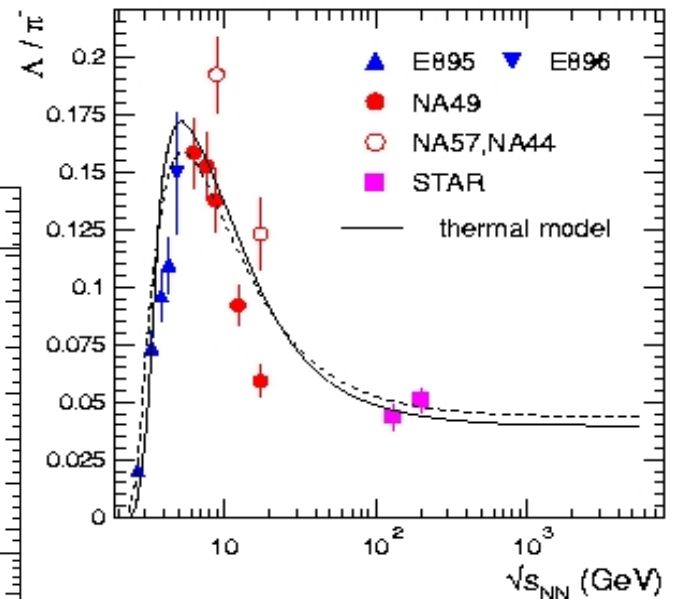
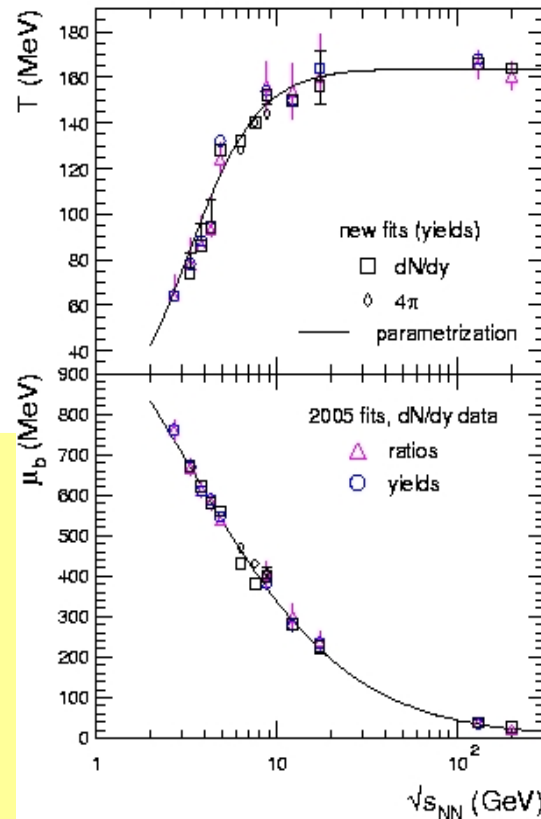
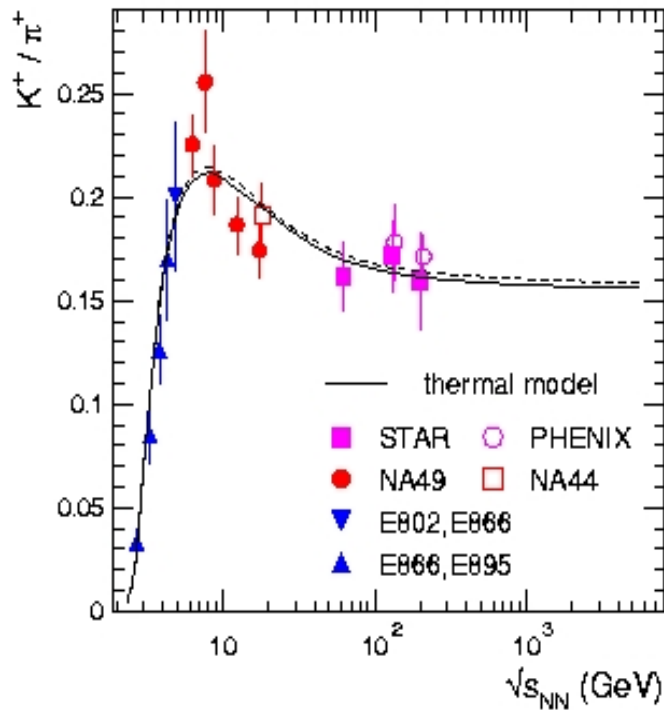


Bestimmung der Temperatur und Dichte zur Zeit der Teilchenproduktion

$$T = 165 \text{ MeV}$$

$$\mu_B = 38 \text{ MeV}$$

neueste Resultate: vollstaendige Beschreibung der Teilchenproduktion



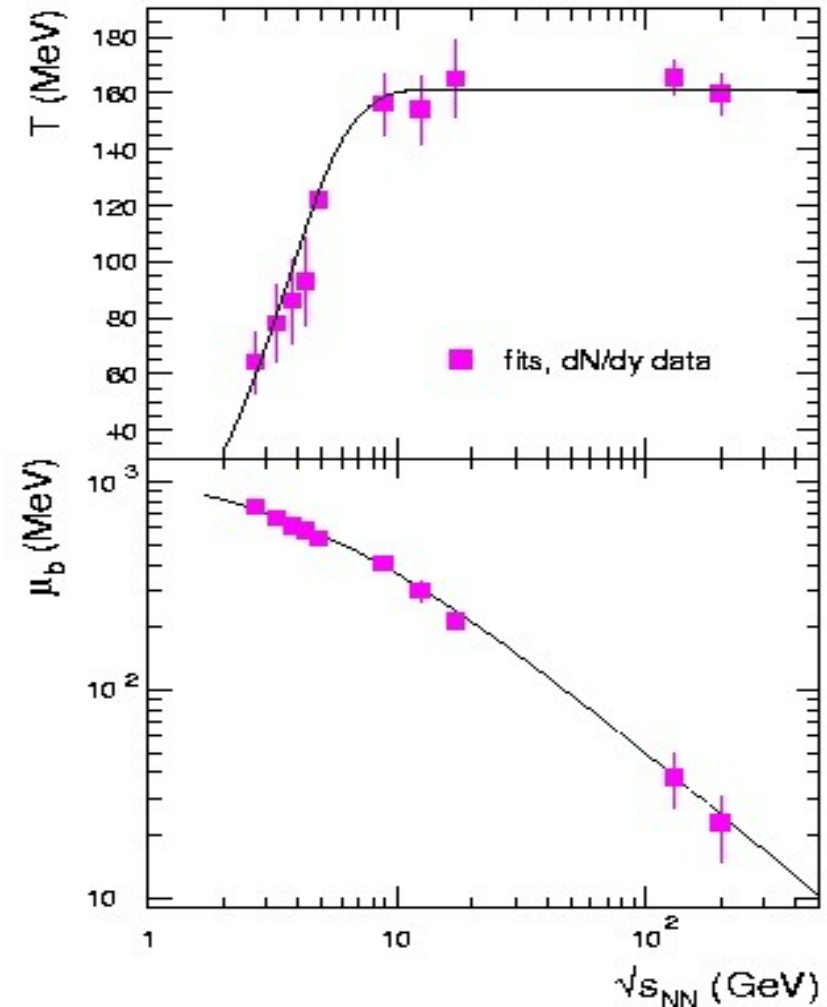
A. Andronic, pbm, J. Stachel
 arXiv:0812.1186

Evidenz fuer Phasenuebergang

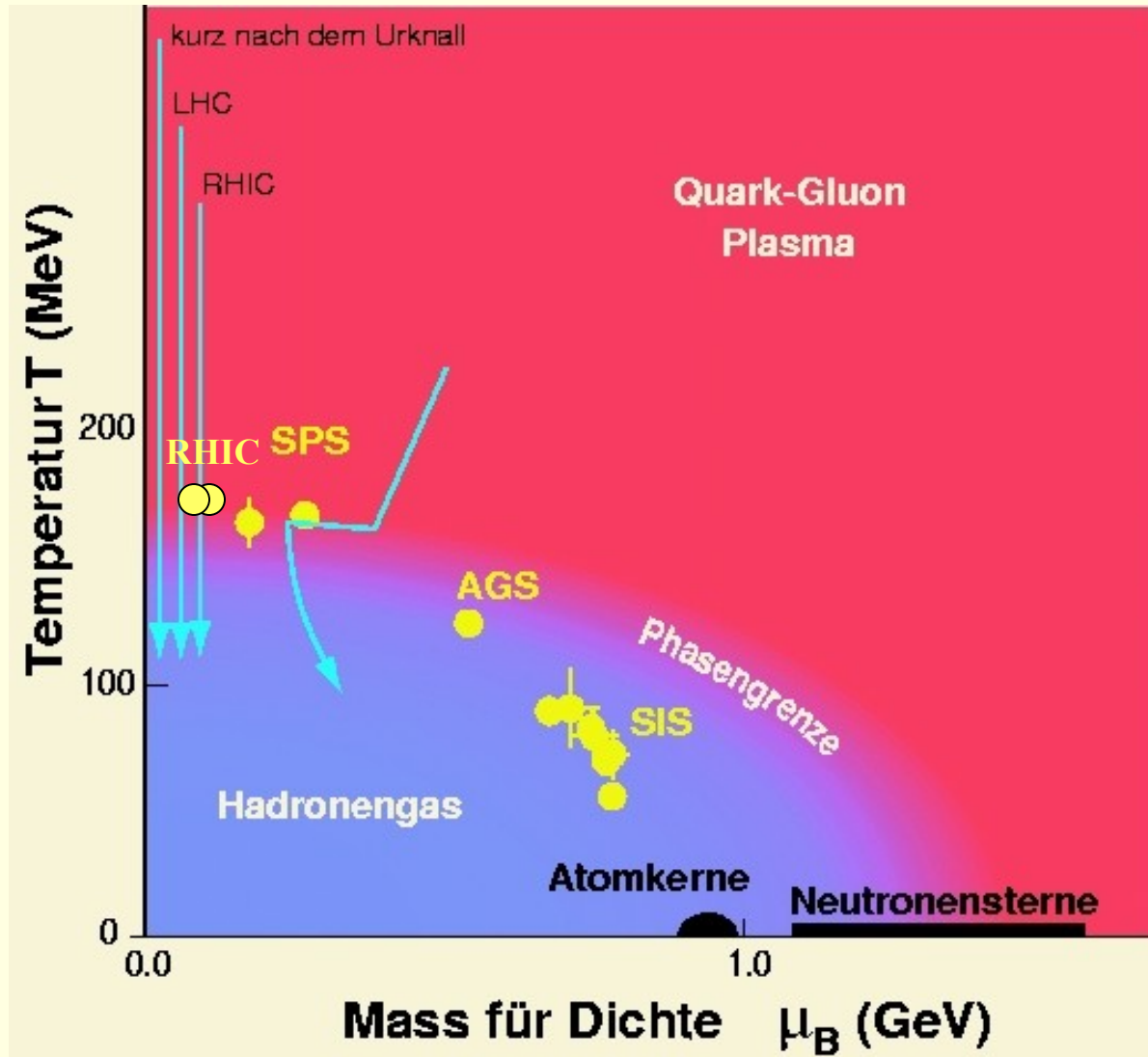
wie Wasser kocht hadronische
Materie bei fester Temperatur

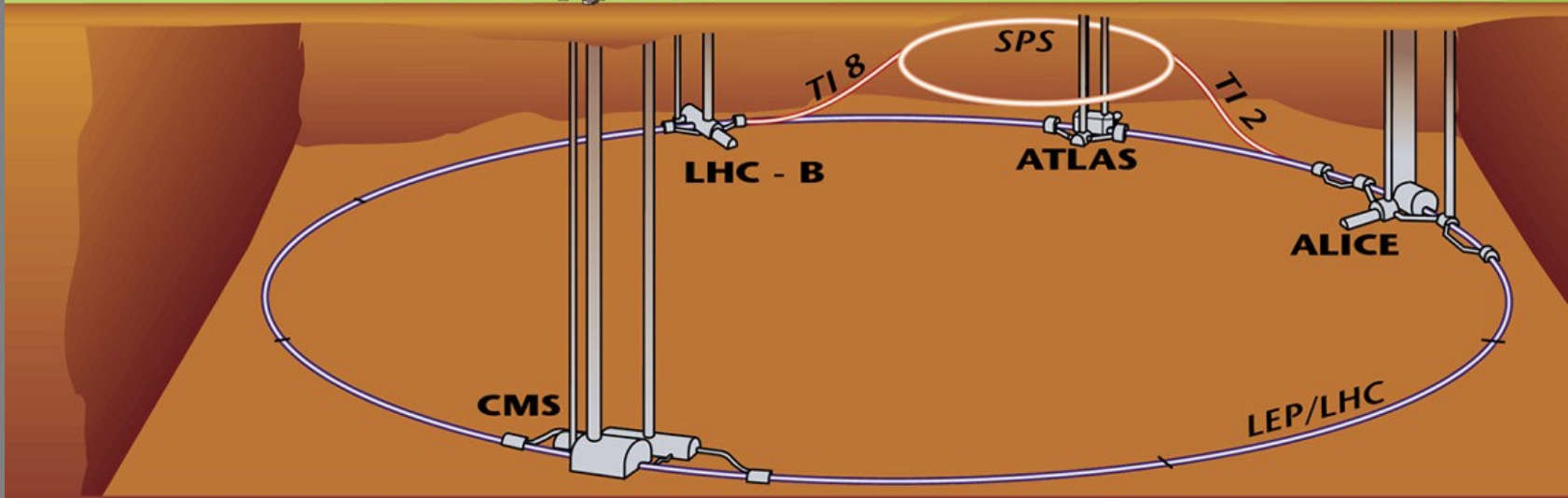
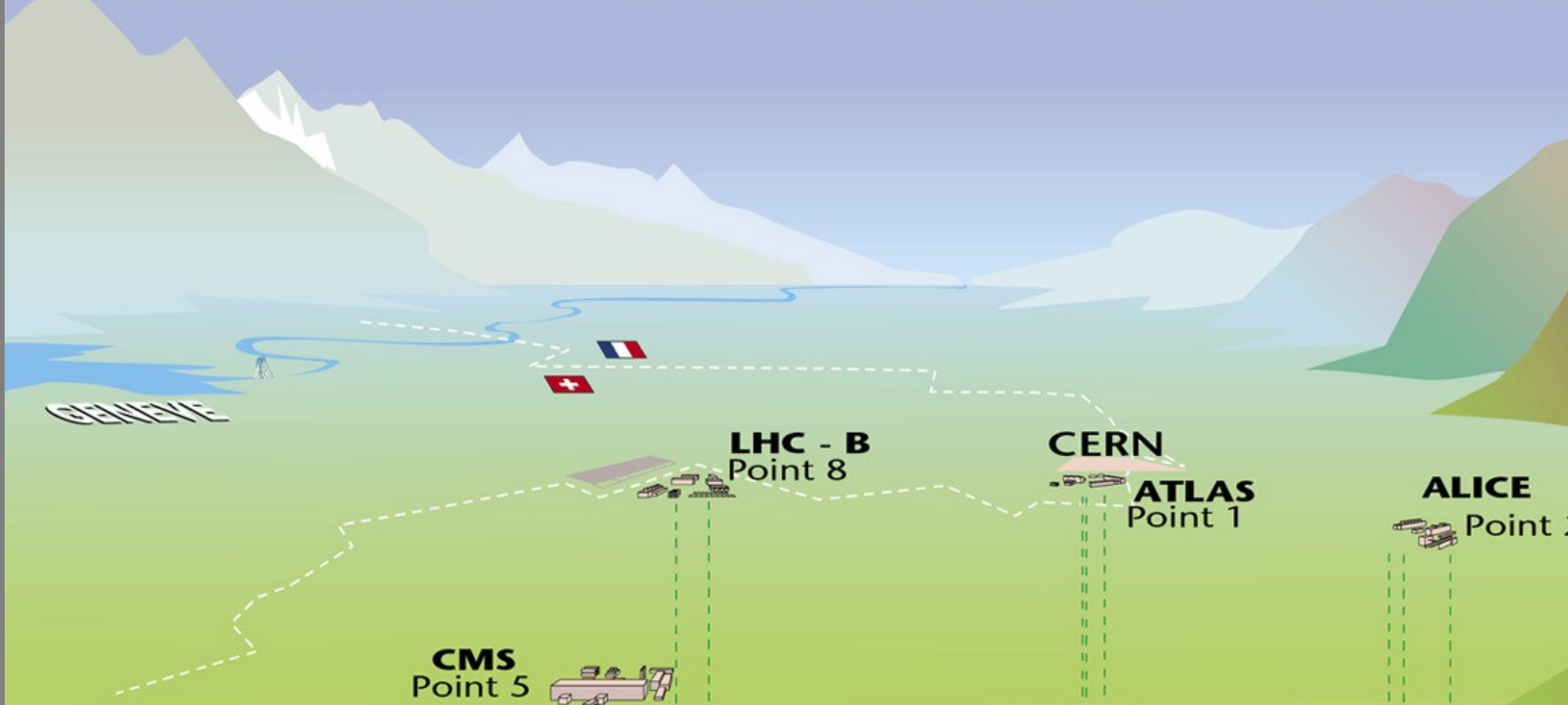
$$T_{\text{lim}} = 160 \text{ MeV} \\ = 2 \times 10^{12} \text{ K}$$

experimentelle Bestimmung
der Phasengrenze

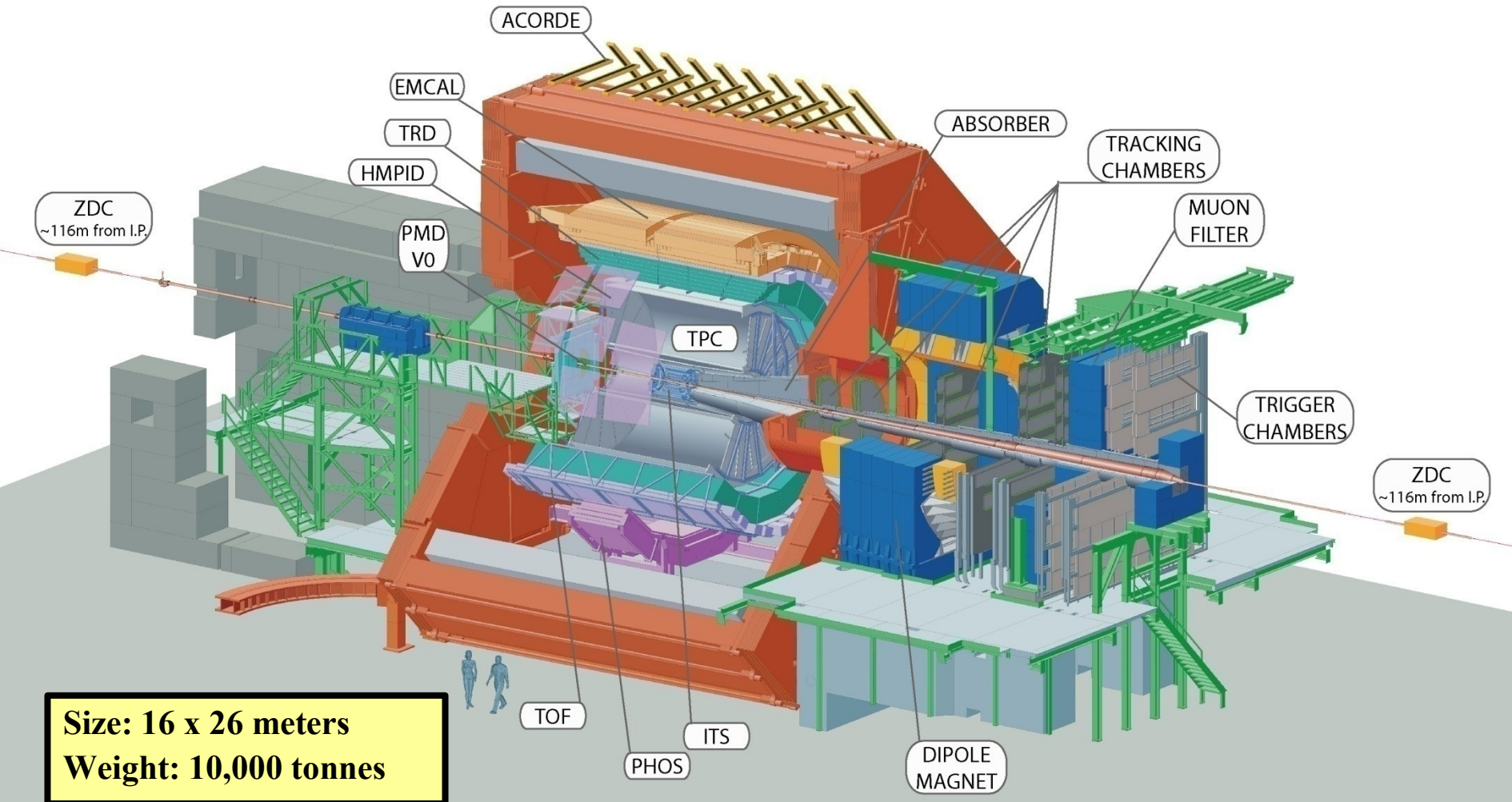


Phasendiagramm





ALICE: A Large Ion Collider Experiment at CERN-LHC



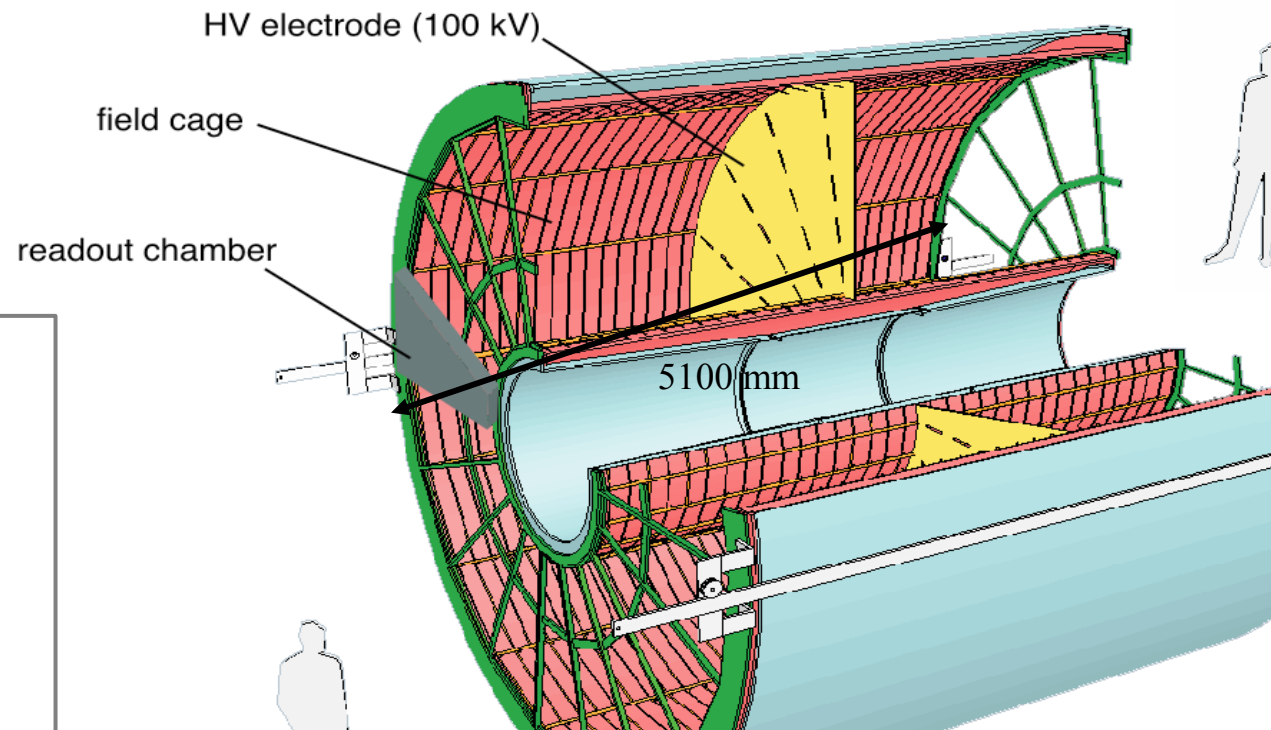
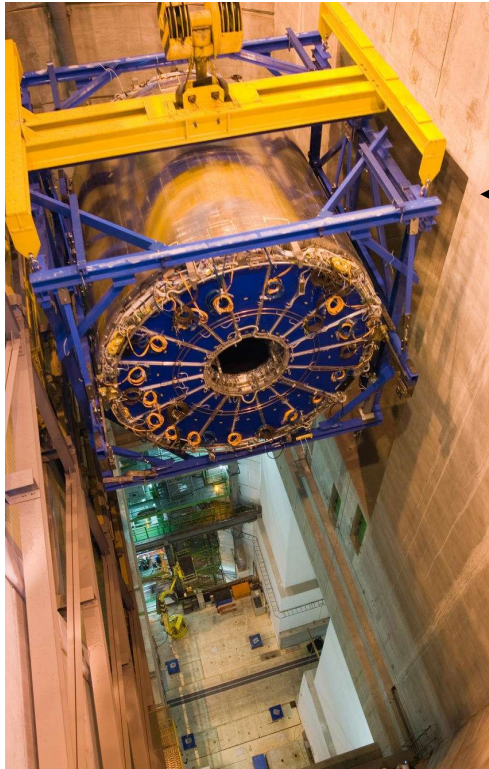
A large industrial facility, possibly a nuclear reactor or a large-scale manufacturing plant, is shown at night. The central feature is a massive, octagonal opening, which is brightly lit from within, creating a strong contrast with the dark exterior. The structure is made of dark, heavy metal, with various pipes, ladders, and scaffolding visible around the opening. The text "ready to move in" is overlaid in a stylized, orange font with a black outline, centered over the opening. The overall atmosphere is one of industrial readiness and scale.

ready to move in

The ALICE Experiment

Time Projection Chamber (TPC)

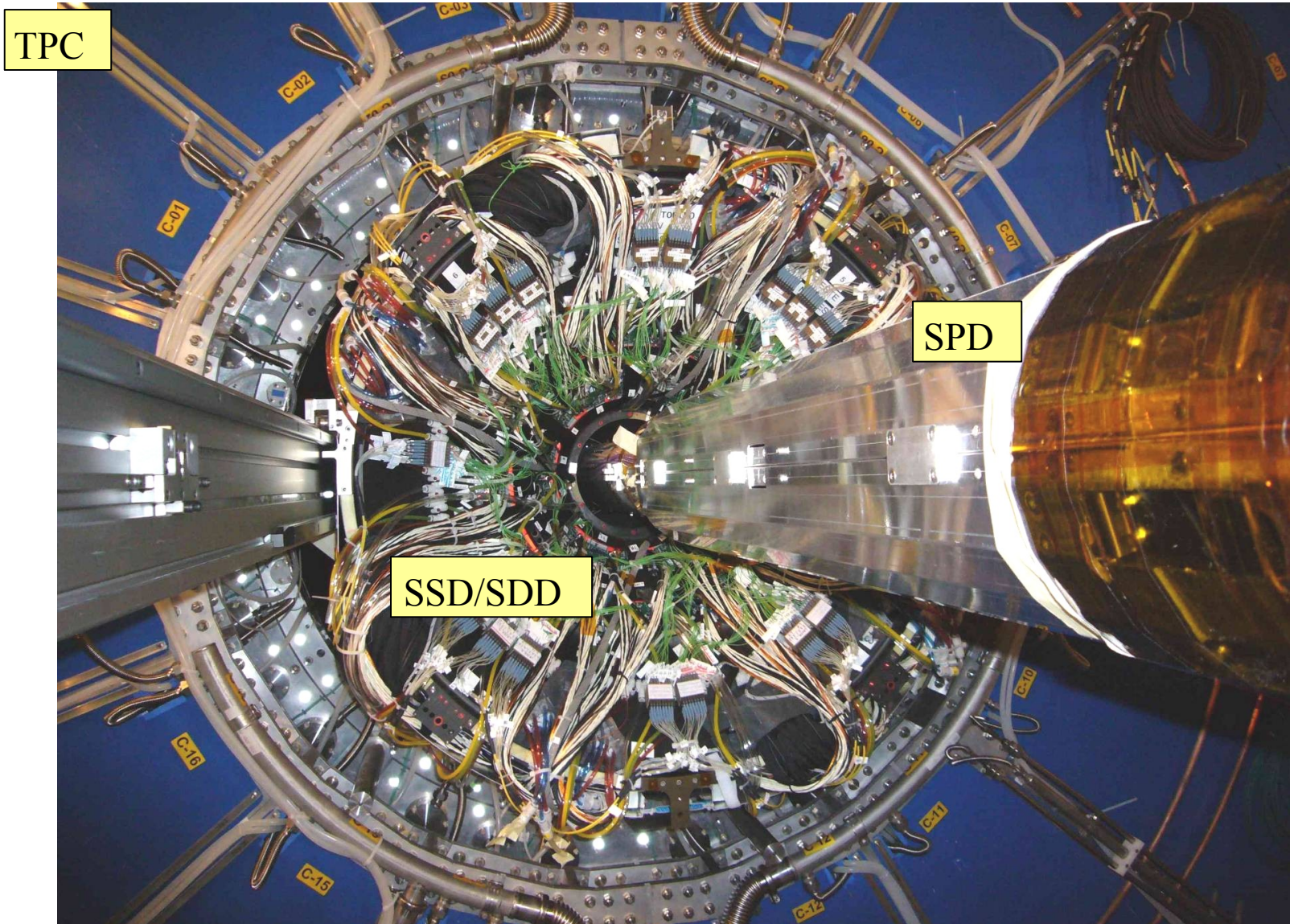
TPC on its way into the ALICE cave

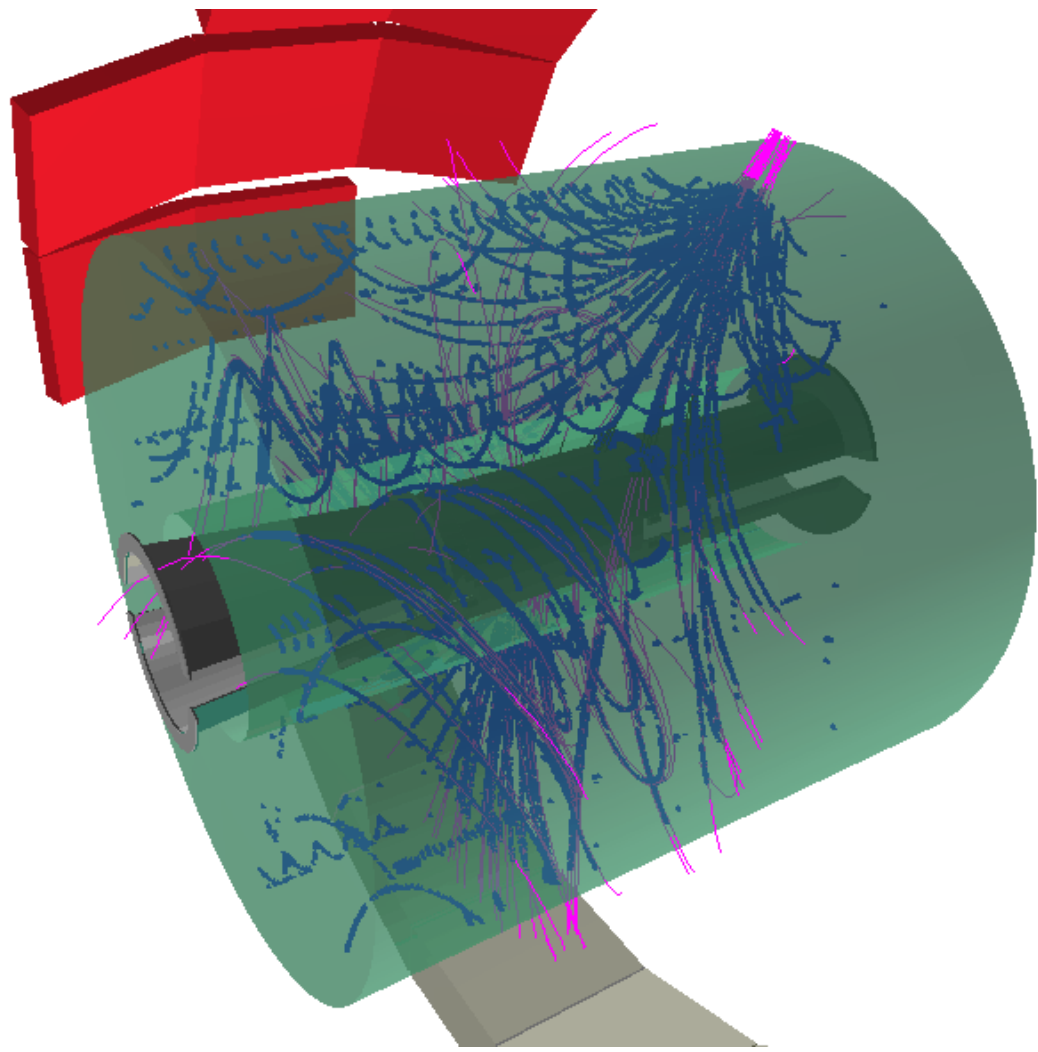


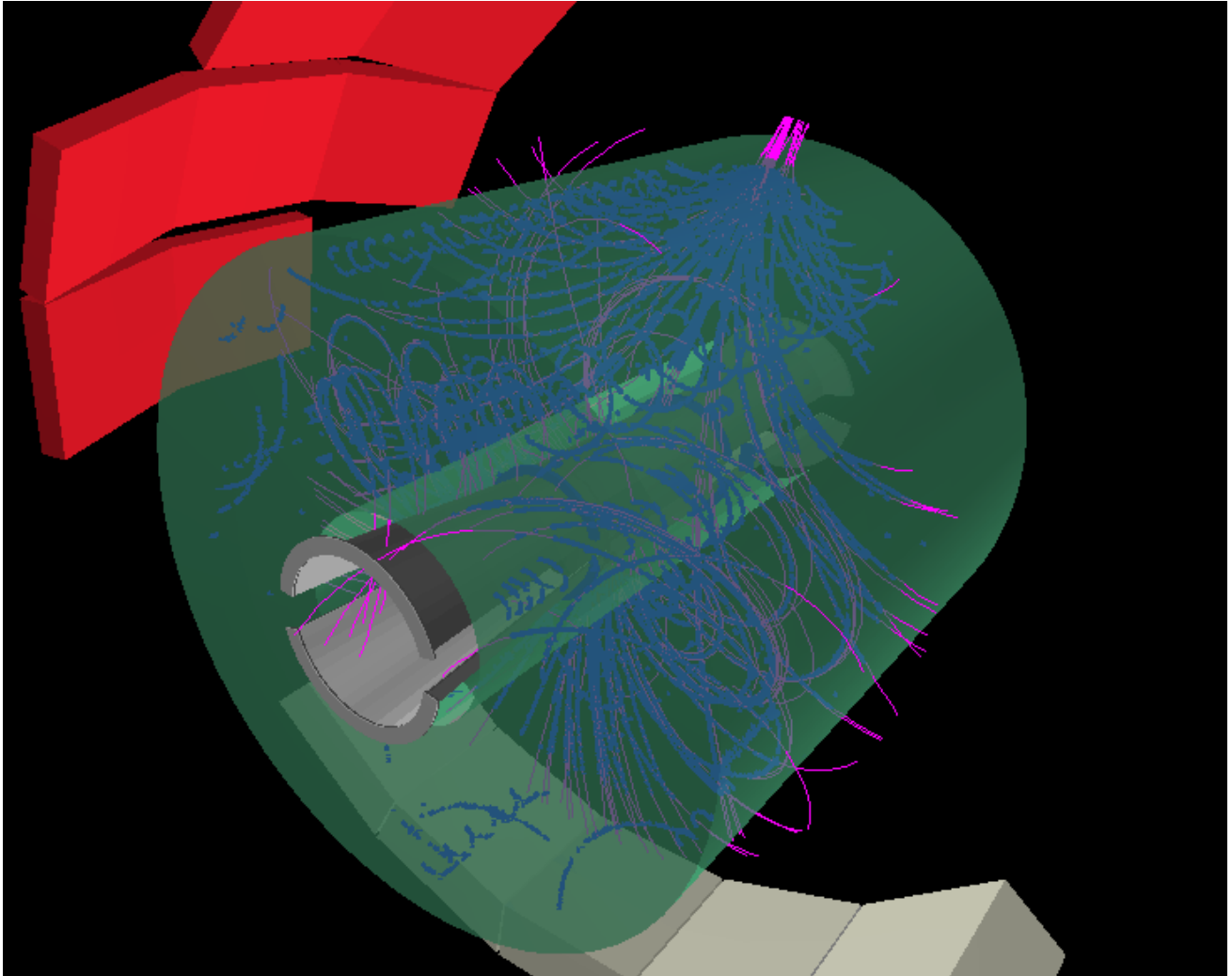
Largest TPC ever built

Radius: 845 - 2466 mm
Drift length: 2 x 2500 mm
Drift time: 92 μ s
Drift gas Ne-CO₂-N₂
Gas volume: 95 m³
557568 readout pads

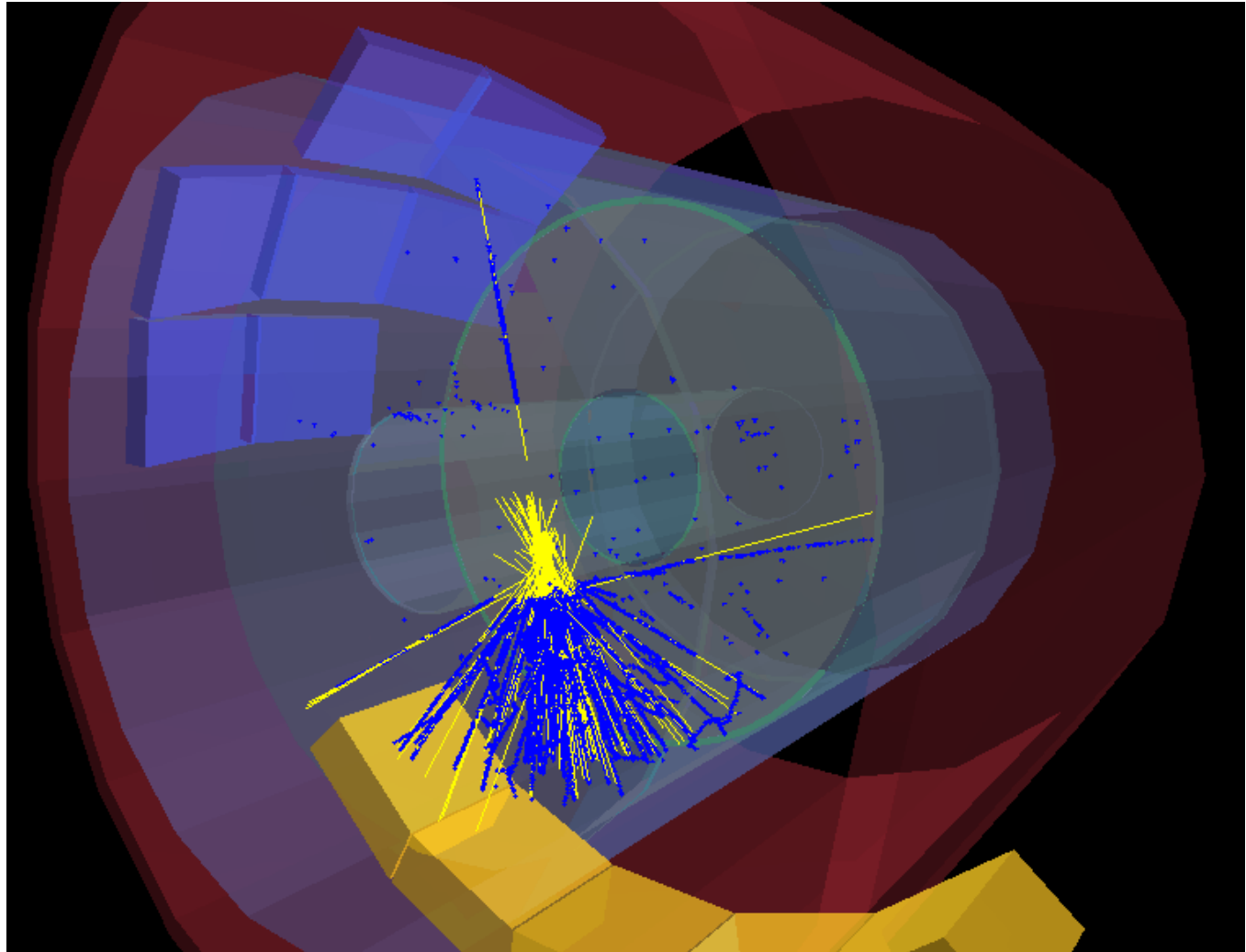
Insertion of the Inner Tracking Detector into the TPC







TPC fully operational and ready to take data



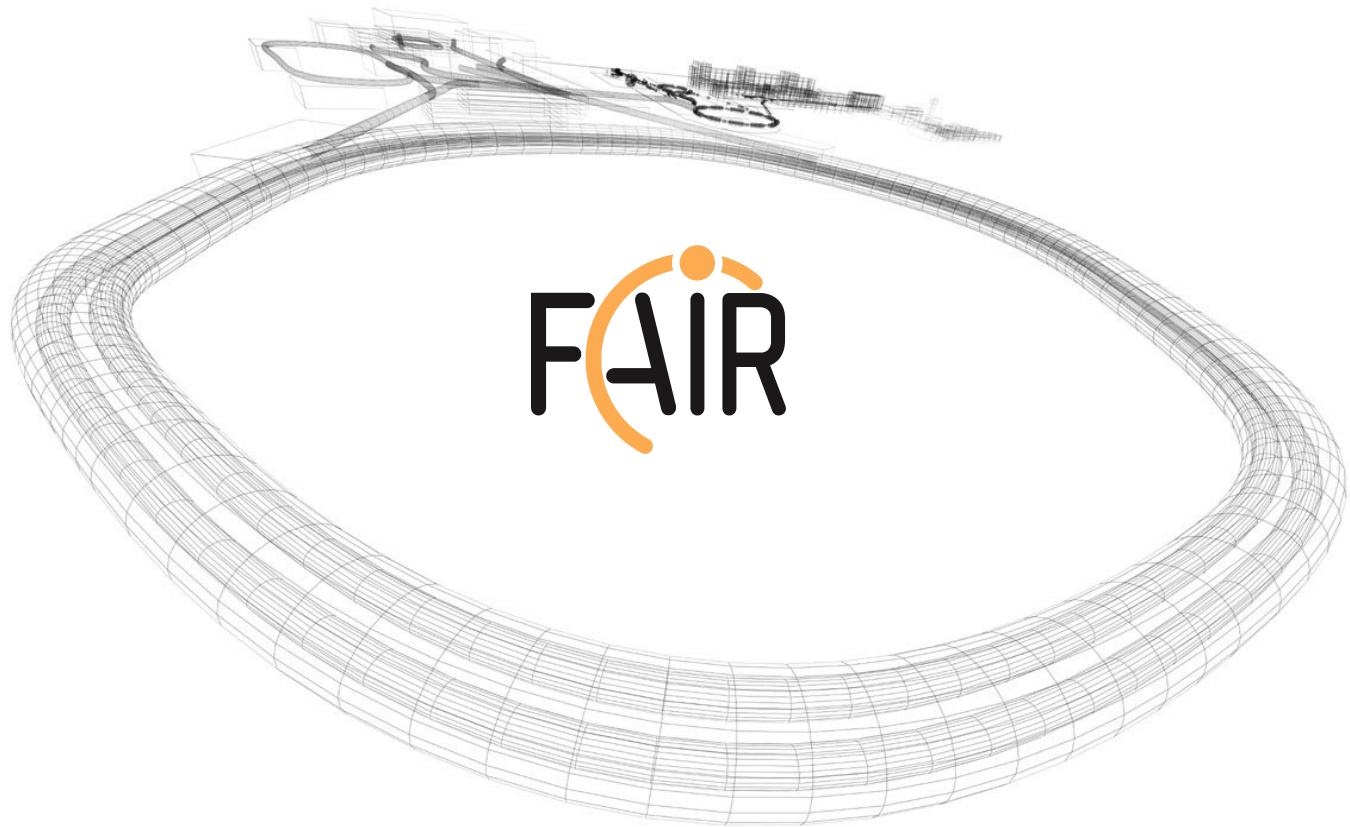
a large cosmic shower in the muon absorber fully tracked



**The International FAIR Project
at GSI**

FAIR – Facility for Antiproton and Ion Research

Facility, Physics Overview Focus on Strong Interactions



FAIR

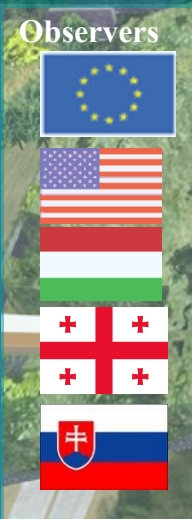


Helmholtz Centre for Ion Research



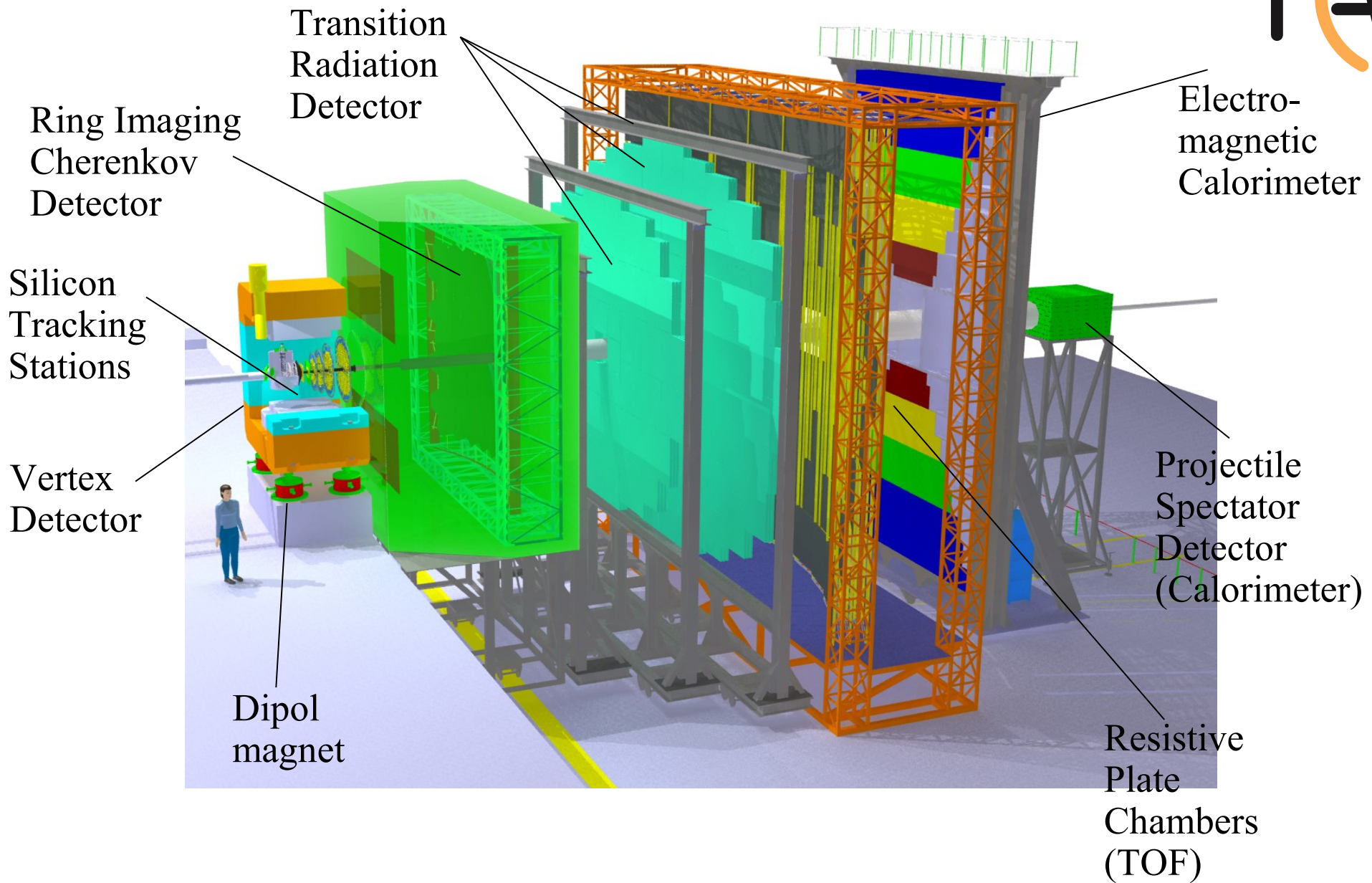


major international basic research project with 15 member states and 5 observers

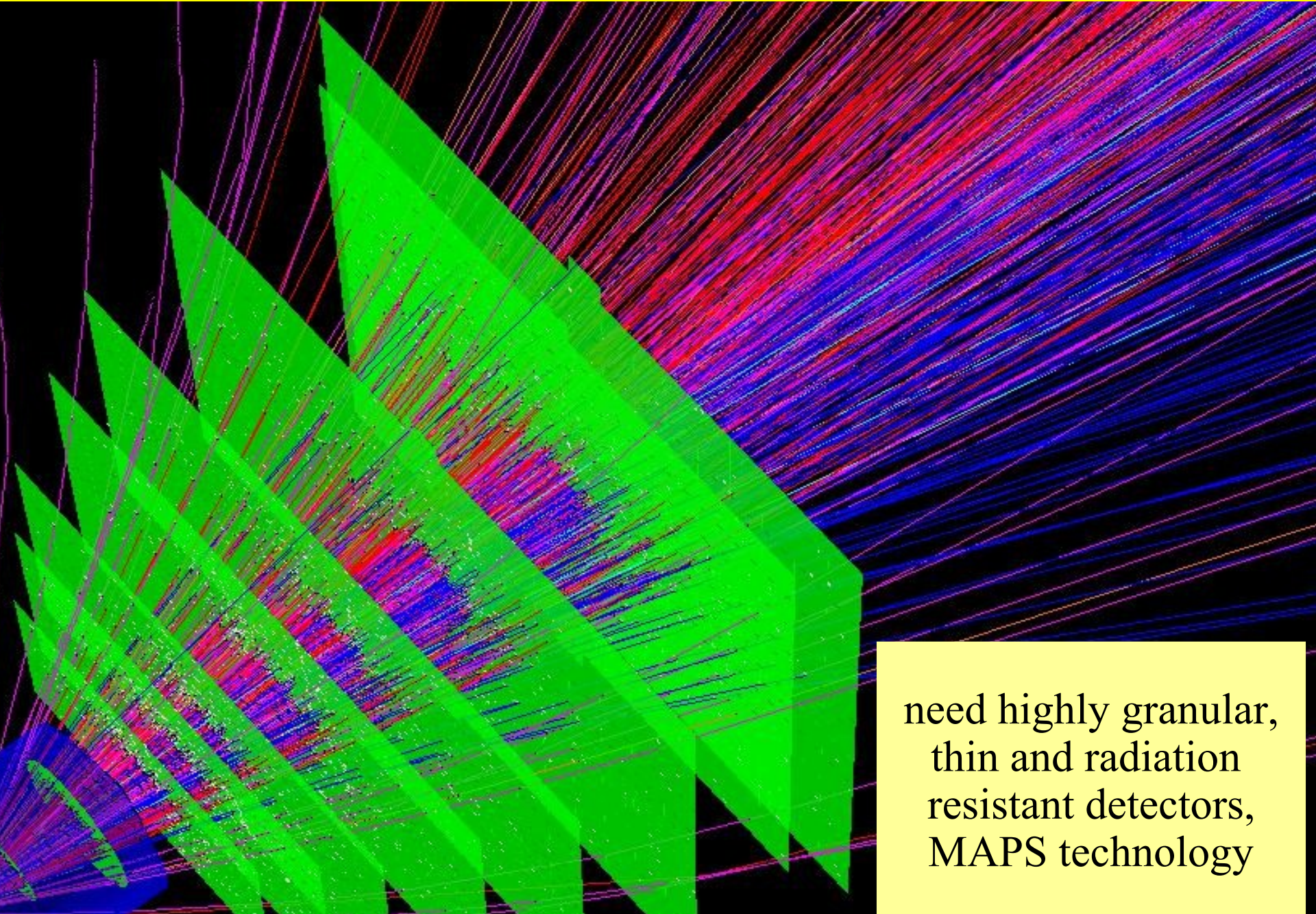


Austria China Finland France Germany Greece India Italy Poland Slovenia Spain Sweden Romania Russia UK

The Compressed Baryonic Matter Experiment



Experimental challenges



need highly granular,
thin and radiation
resistant detectors,
MAPS technology

THE END

