Compressed Nuclear Matter

GSI Summer Student Program lecture, Darmstadt, 2006

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- **where are our labs - heavy ion accelerator map**
- **what do we do - basics of heavy ion collisions**
- **our tools - basics of particle detectors**
- **why do we do it - nuclear matter and its relations with the real world**
- **examples of heavy ion experiments**

Structure of matter

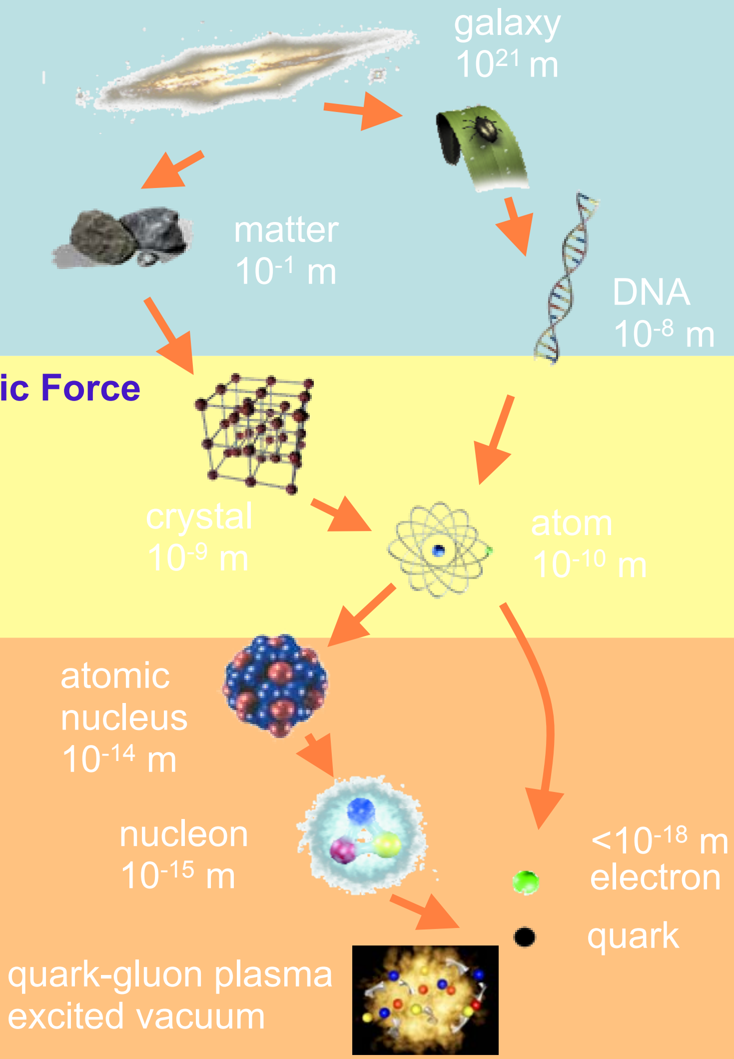
Gravitational Force
General Relativity

Electromagnetic Force
QED

Electroweak Force

Weak Force
Standard Model

Strong Force
QCD



galaxy
10^{21} m

matter
10^{-1} m

DNA
10^{-8} m

crystal
10^{-9} m

atom
10^{-10} m

atomic nucleus
10^{-14} m

nucleon
10^{-15} m

$<10^{-18}$ m
electron

quark

quark-gluon plasma
excited vacuum

Research with Beams of Hadrons and Ions:

Ion-Matter Interactions

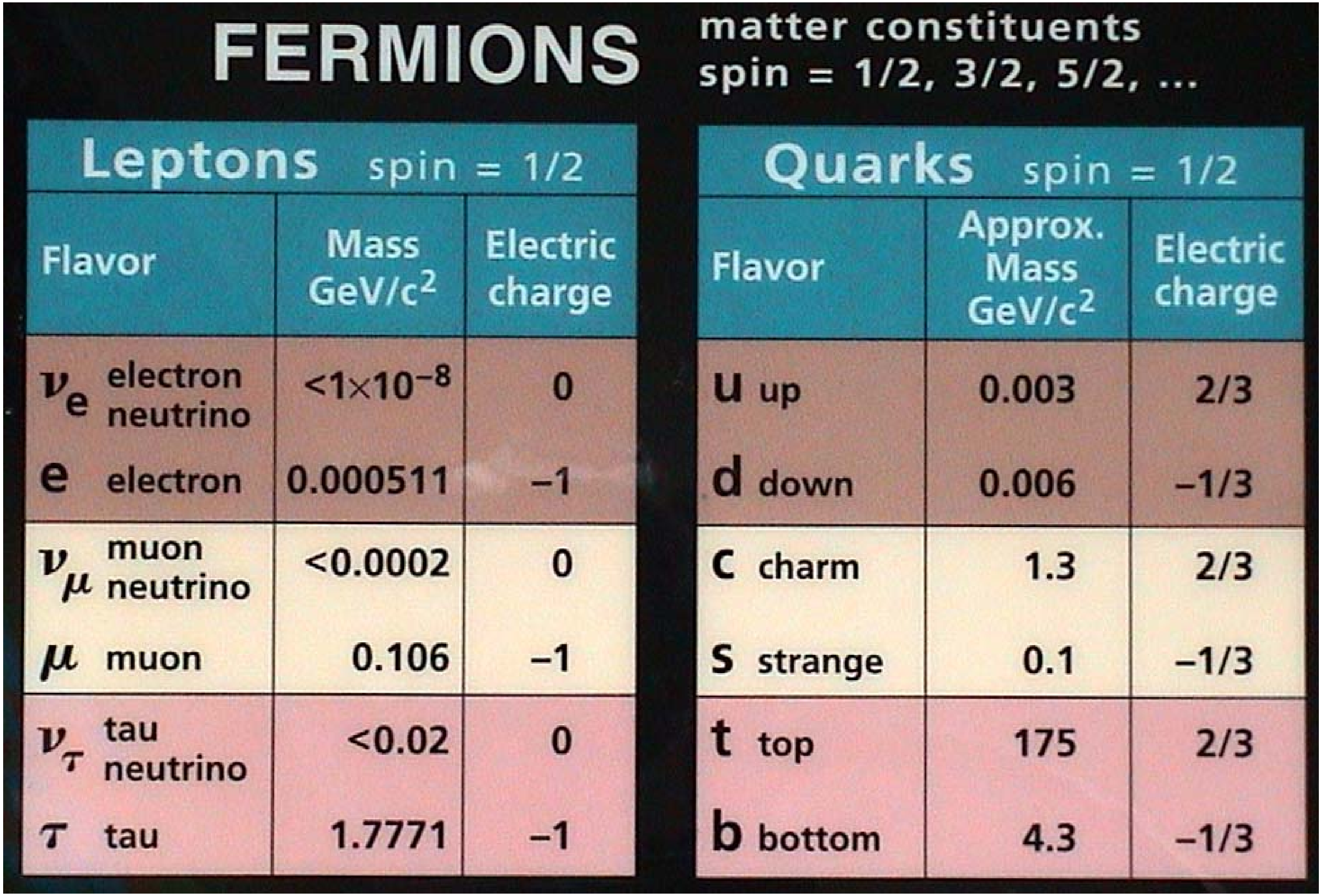
Dense Plasmas

Ultra High EM Fields
Nuclei at the Extremes

Quark Gluon Structure of Hadrons

Quark Matter

“Elementary” consituents



FERMIONS

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

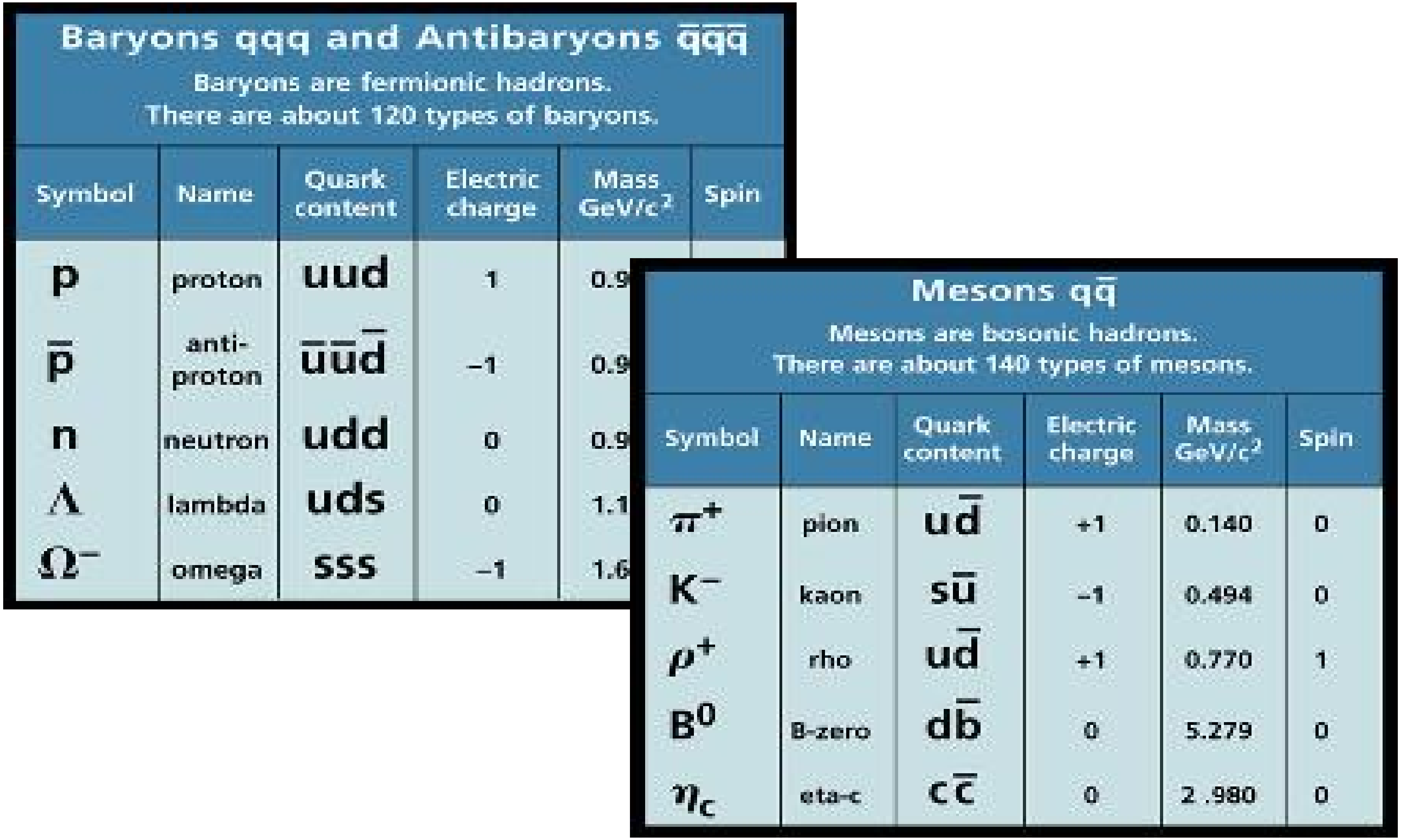
Leptons spin = 1/2

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

Hadrons



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	proton	uud	1	0.9	
$\bar{p}$	anti-proton	$\bar{u}\bar{u}\bar{d}$	–1	0.9	
n	neutron	udd	0	0.9	
Λ	lambda	uds	0	1.1	
Ω^-	omega	sss	–1	1.6	

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
η_c	eta-c	$c\bar{c}$	0	2 .980	0

Relativistic Heavy Ion Accelerators

BERKELEY

Bevalac, $\sqrt{s} = 2.8$

BROOKHAVEN

AGS, $\sqrt{s} = 5.5$
RHIC, $\sqrt{s} = 200$

CERN, GENEVA

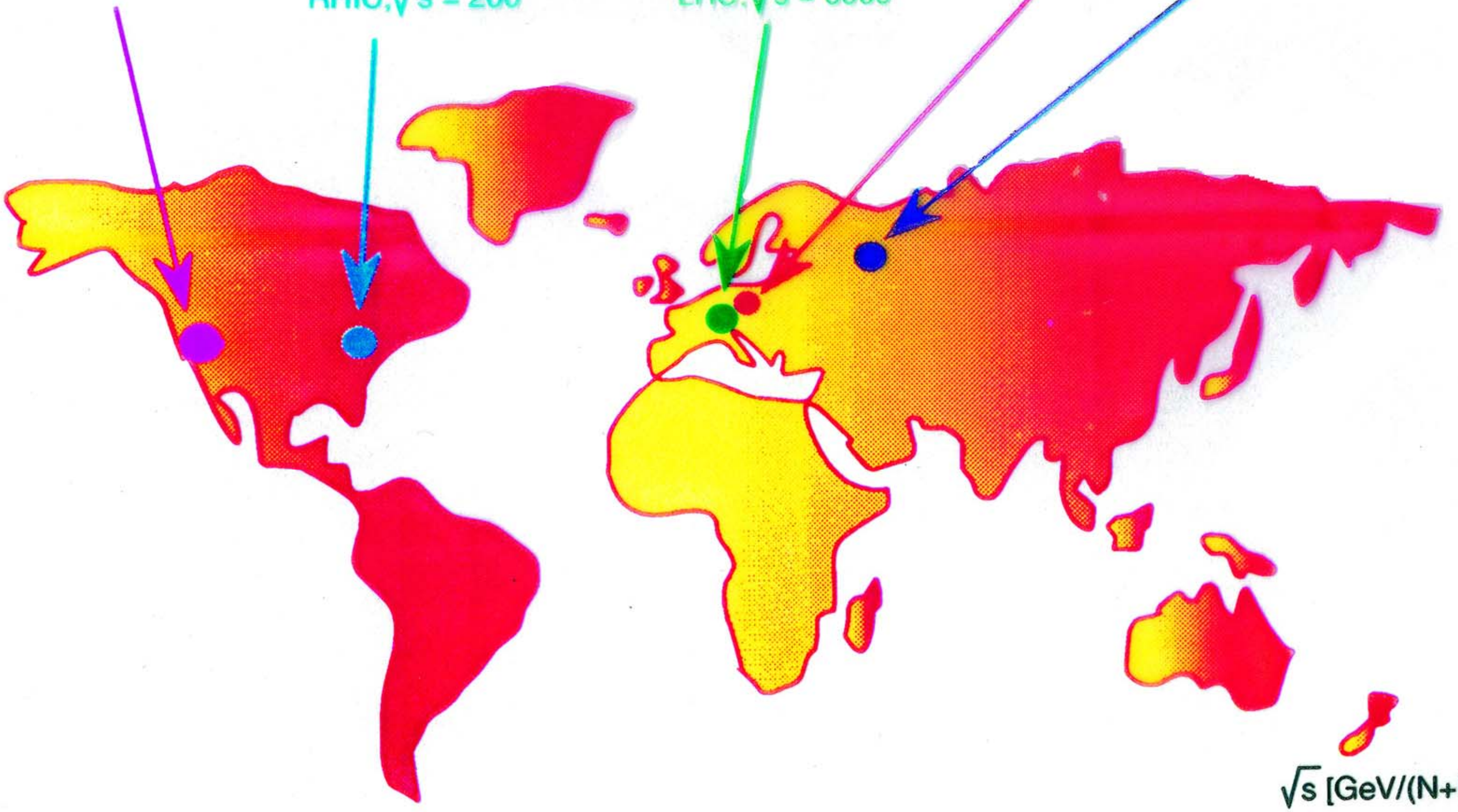
SPS, $\sqrt{s} = 20$
LHC, $\sqrt{s} = 6000$

GSI

SIS, $\sqrt{s} = 2$

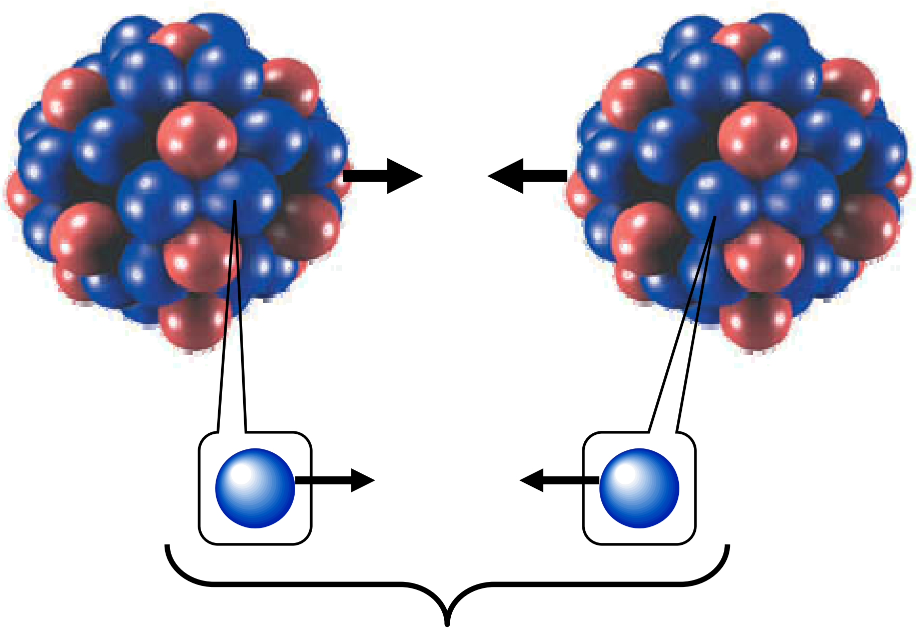
DUBNA

Synchro, $\sqrt{s} = 3.2$



$\sqrt{s}$ [GeV/(N+N)]

Definition of $\sqrt{s}$



colliding nuclei

pair of nucleons

$$\sqrt{s} = \sqrt{\left(E_1 + E_2\right)^2 - \left(\overrightarrow{p_1} - \overrightarrow{p_2}\right)^2}$$

total energy of the two nucleons in pair c.m.s.

invariant mass

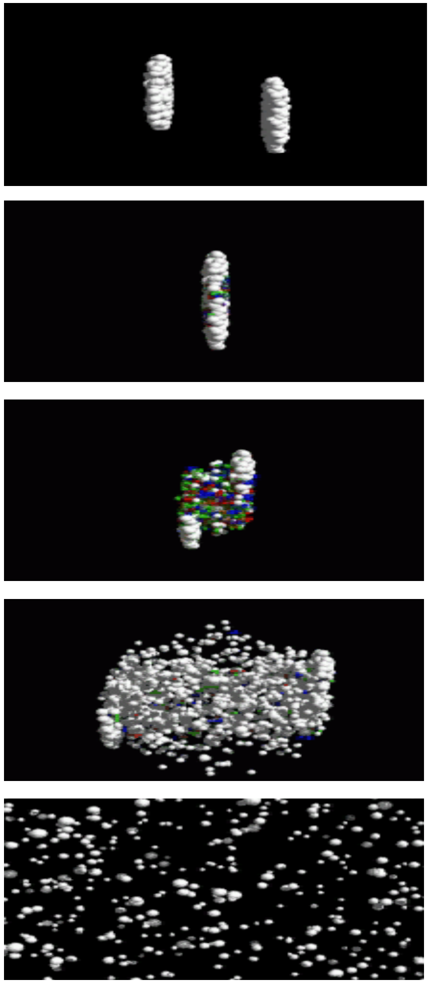
Basics of heavy ion collisions

Terminology, Nomenclature etc.

- c=1, k=1, ...
- energy, momentum, mass in GeV
- space and time in fm, 1 fm = 10^{-15} m
- temperature T in GeV
- $E^2 = m^2 + p^2$
- kinetic energy $T = E - m$
- velocity β relative to velocity of light c
- rapidity $y=1/2 \log((E+pz)/(E-pz))$ used rather than velocity

Phases of heavy ion collision

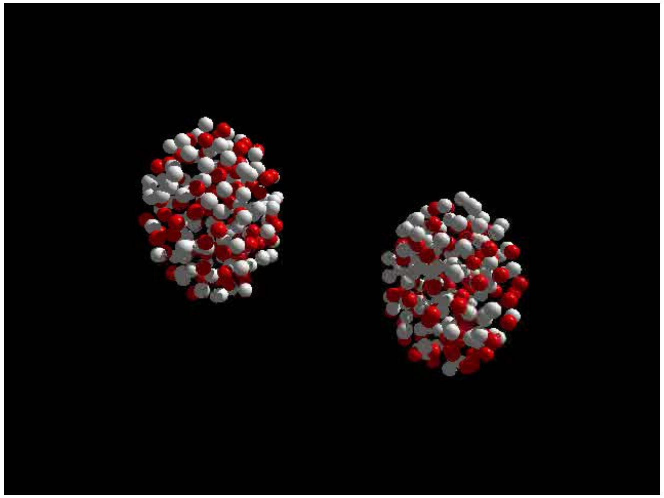
UrQMD 160 GeV Au+Au



- **before collision**
- **compression and heating**
- **thermalization**
- **expansion**
- **chemical freezeout (number of particles frozen)**
- **kinetic freezeout (particle momenta frozen)**

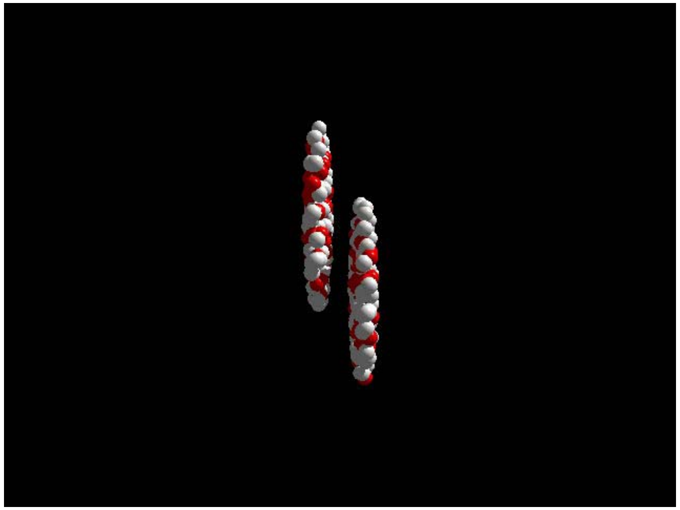
Ultrarelativistic Quantum Molecular Dynamics (UrQMD)

one of the most commonly used theoretical models, Frankfurt University



U+U at 23 GeV collision movie

link to Henning Weber



What are the main features?

- In first approximation, individual NN collisions (like a medieval battle)

- The fireball volume depends on impact parameter
- The direction of particle emission may depend on the orientation of the b-vector
- The fireball exists only for a short time

Bitwa pod Grunwaldem, Wojciech Kossak

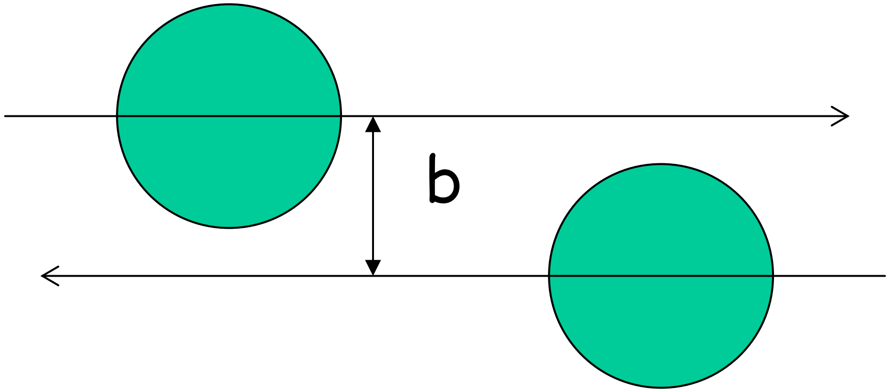
Centrality

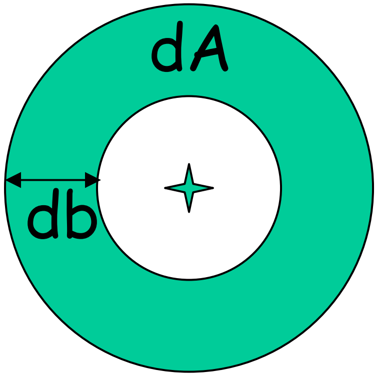
A nucleus is a very small object, how to hit it in the center?

In fact, $\sigma(b=0) = 0$!

σ = geometrical cross section

b = impact parameter

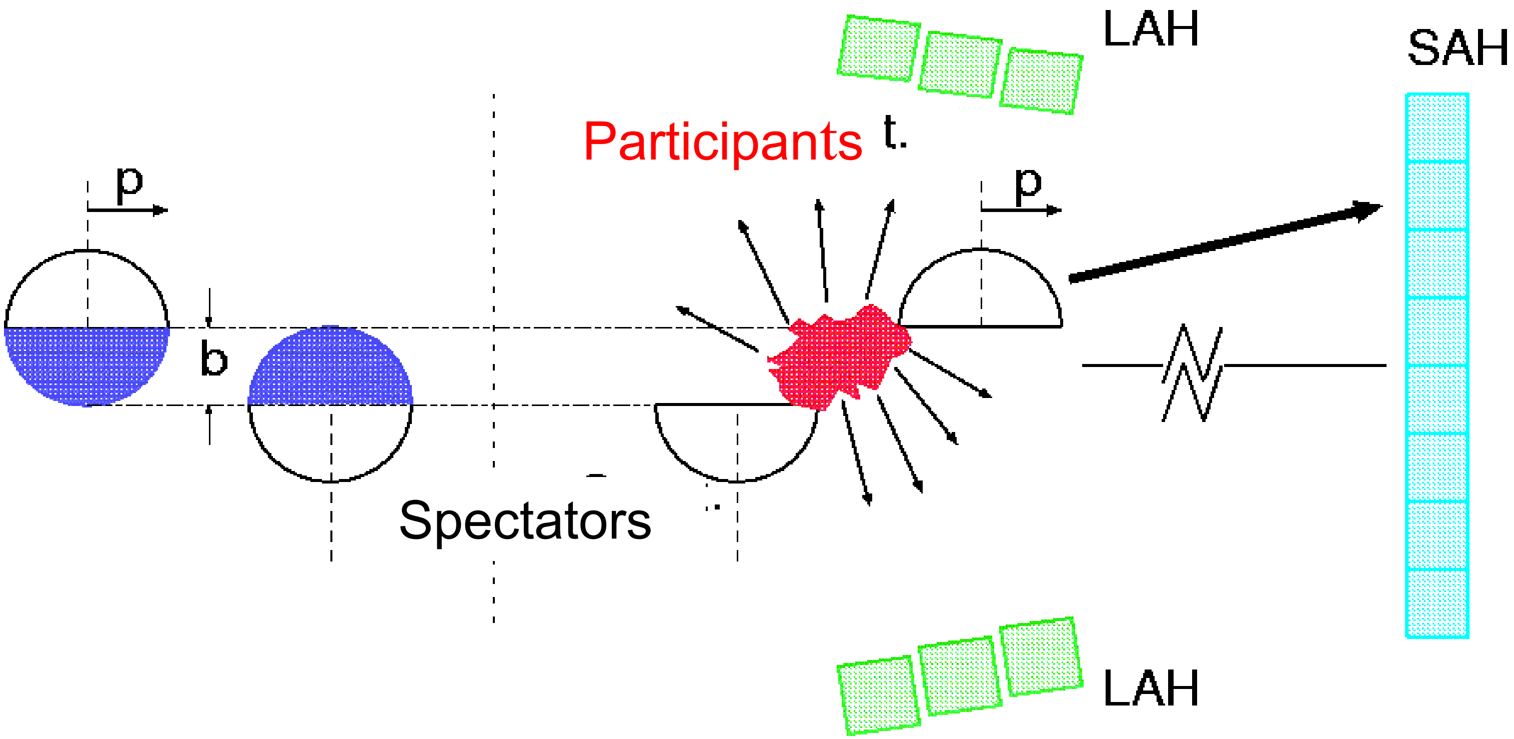




$$d\sigma \propto dA = \pi(b + db)^2 - \pi b^2 \approx 2\pi b db$$

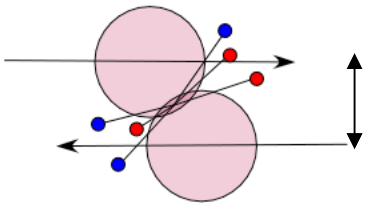
$$\sigma = \int d\sigma \propto 2\pi \int b db = \pi b^2$$

Event characterization

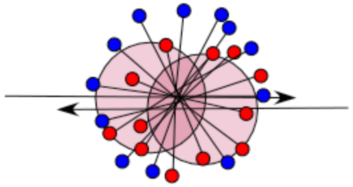


Emission pattern of fragments holds information on number of participating nucleons in A+A collision.

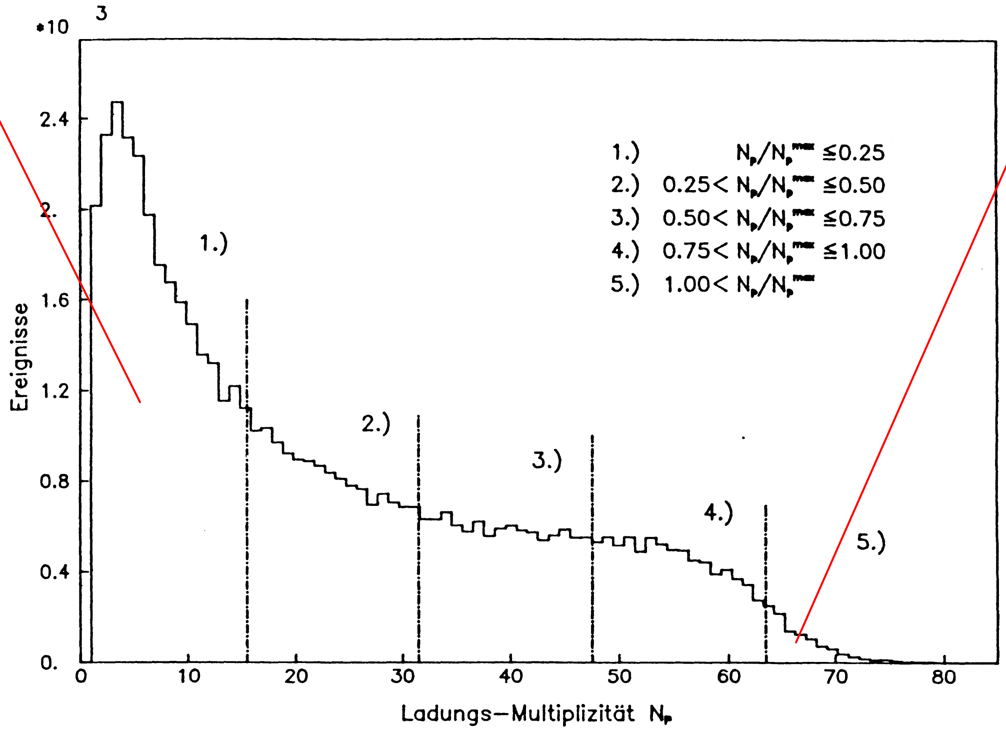
Selecting the impact parameter by multiplicity of particles emitted at large angles



impact parameter b



large b ⇔ few secondary particles ⇔ large cross section

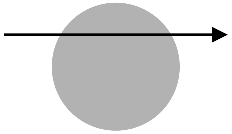


small b ⇔ many secondary particles ⇔ small cross section

Nuclear overlap model

... aka Glauber model aka Wounded Nucleon Model
Calculates N_{part} and N_{coll} for a given impact parameter b

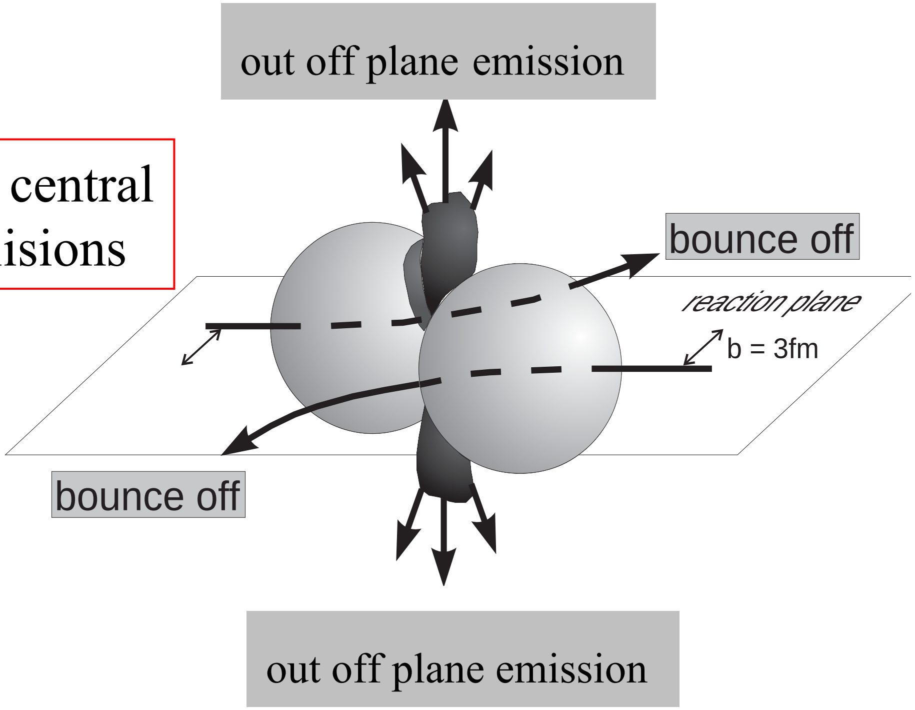
- density $n_A(r) = \dfrac{n_0}{1+\exp\left(\dfrac{r-R}{d}\right)}$
- thickness function $T_A(b) = \int_{-\infty}^{\infty} dz\, n_A\left(\sqrt{b^2+z^2}\right)$



- overlap function $T_{AB}(b) = \int d^2s\, T_A(\vec{s})\, T_B(\vec{s}-\vec{b})$
- number of NN collisions $N_{coll} = T_{AB}(b)\, \sigma_{NN}$
- number of participants $N_{part}^{A} = \int d^2s\, T_A(\vec{s})\, \left\{1-\exp\left(-\sigma_{NN}\, T_A(b)\right)\right\}$
- our implementation

Reaction plane

semi central collisions

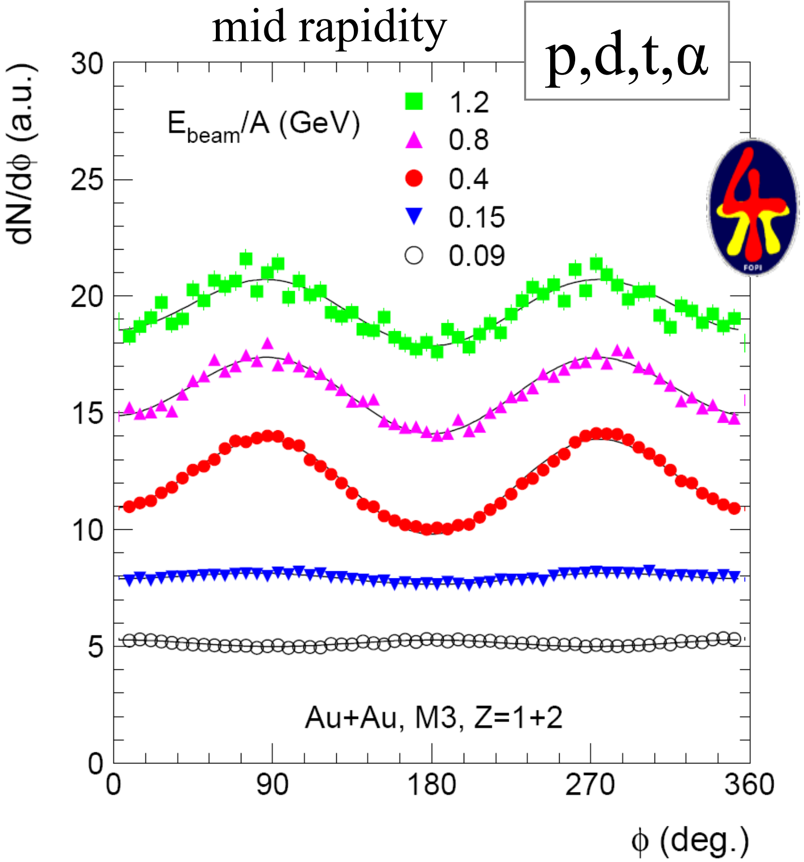


out off plane emission

bounce off

bounce off

out off plane emission



mid rapidity

p,d,t,α

Fourier expansion of the dN/dϕ distribution:

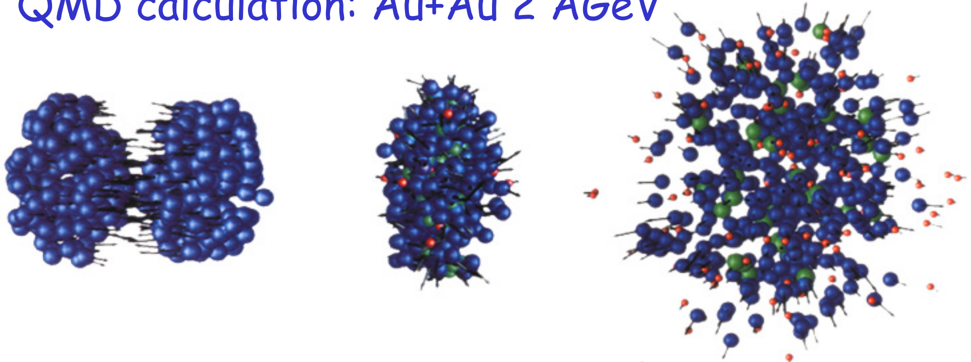
$$\frac{dN}{d\phi} \sim [1 + 2v_1 \cdot \cos(\phi) + 2v_2 \cdot \cos(2\phi)]$$

the coefficients quantify :

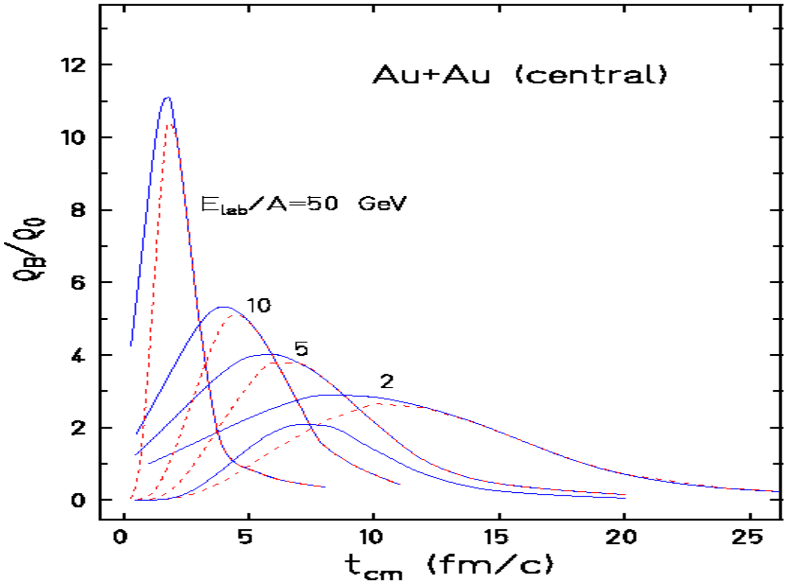
- v_1 the in-plane and
- v_2 the elliptic emission pattern

Transient existence of a dense fireball

QMD calculation: Au+Au 2 AGeV



t = 1 – 10 fm/c



Challenge:

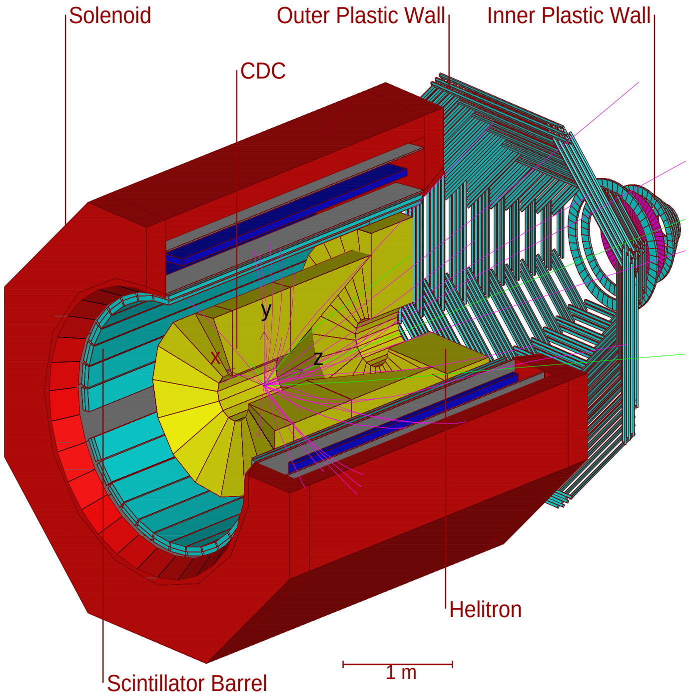
Extract information on the high density phase

Observables:

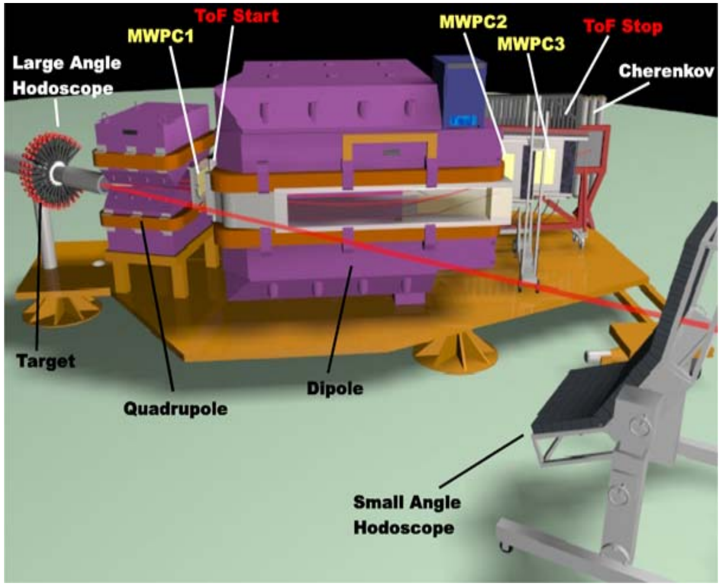
- collective flow of matter → pressure
- particles born in the fireball → temperature

Two ways of measuring particles examples at GSI: FOPI and KaoS

wide (4 pi) acceptance



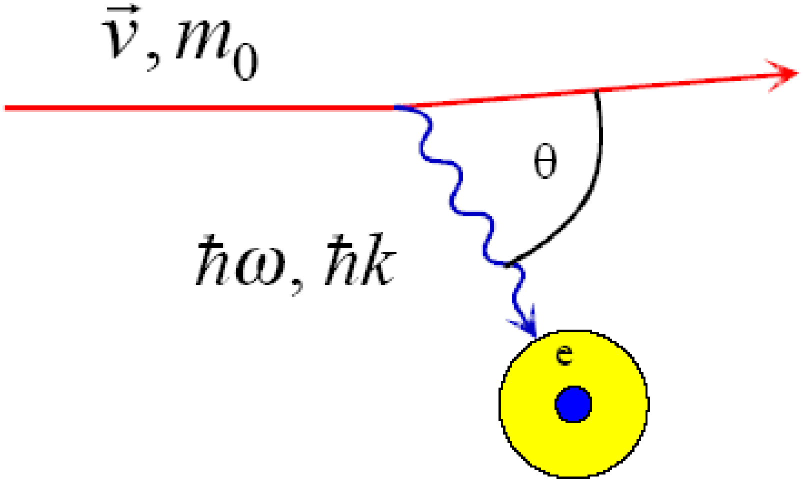
high resolution



Basics of particle detectors

Detecting charged particles

discrete collisions with the atomic electrons of the material

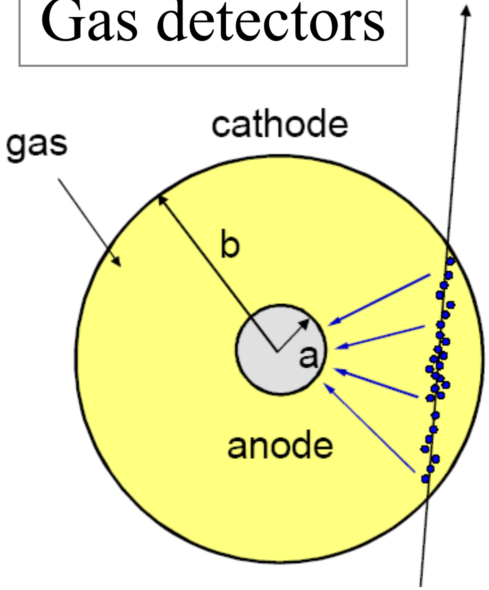


If the energy of the photon (ħω) is big enough → **ionization**.

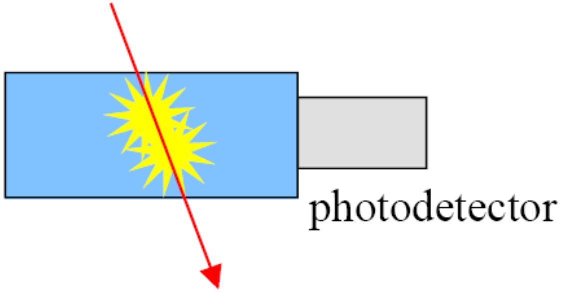
Instead of ionizing an atom the photon can escape from the medium under certain conditions. → Emission of **Cherenkov light**

Detecting charged particles

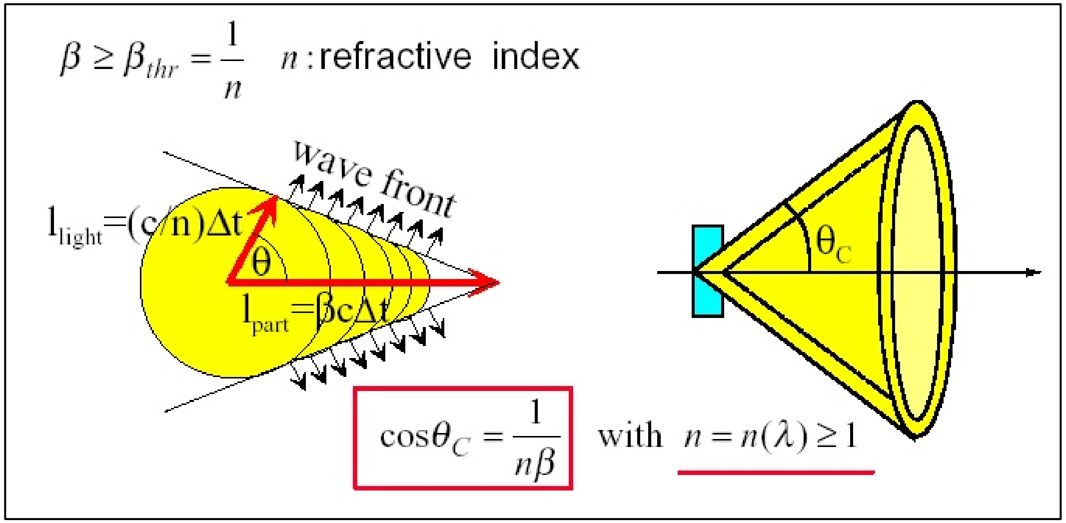
Gas detectors



Scintillation counters



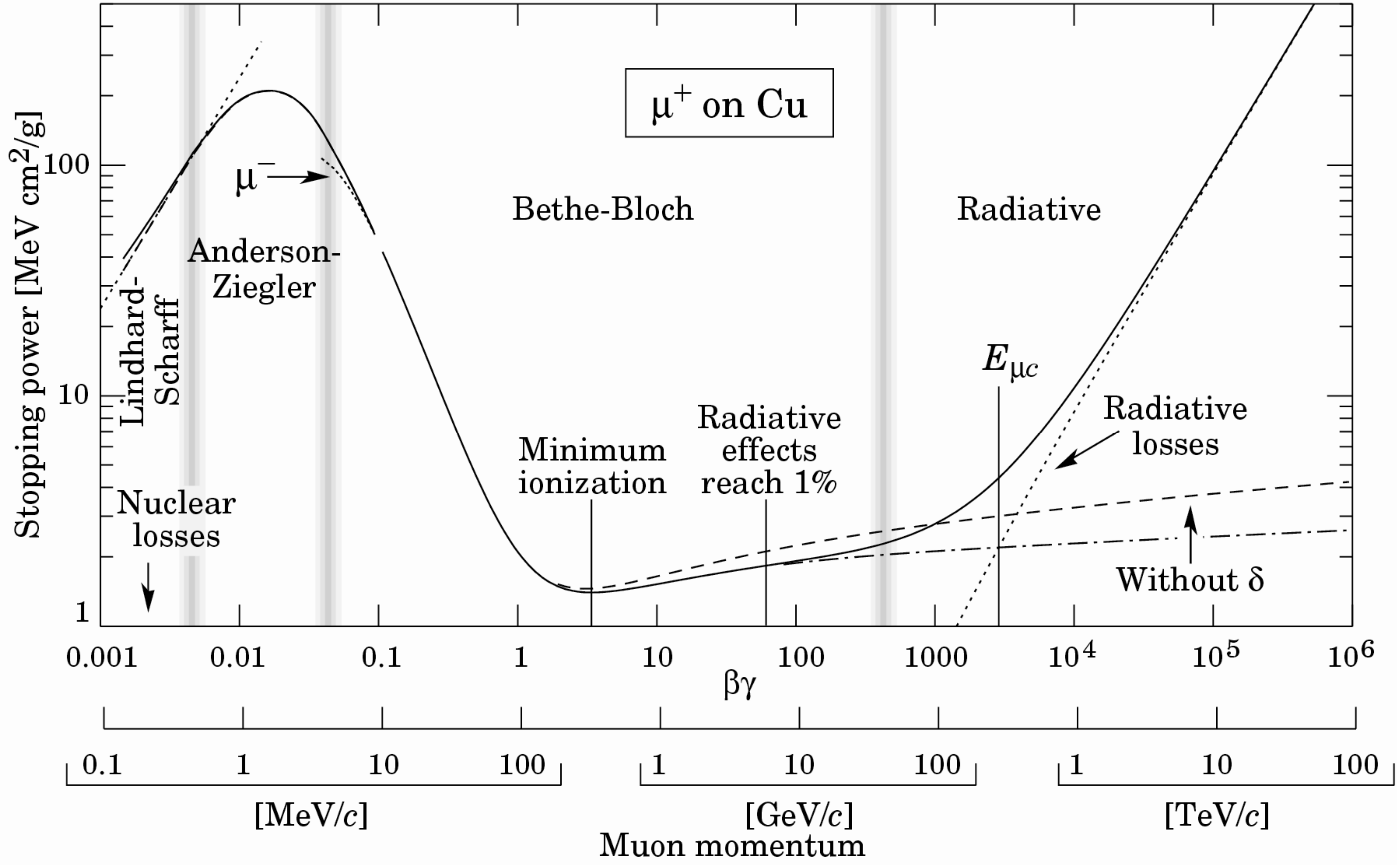
Cherenkov counters



$\beta \geq \beta_{thr} = \frac{1}{n}$ n : refractive index

$\boxed{\cos\theta_C = \frac{1}{n\beta}}$ with $n = n(\lambda) \geq 1$

Specific energy loss of muons in matter

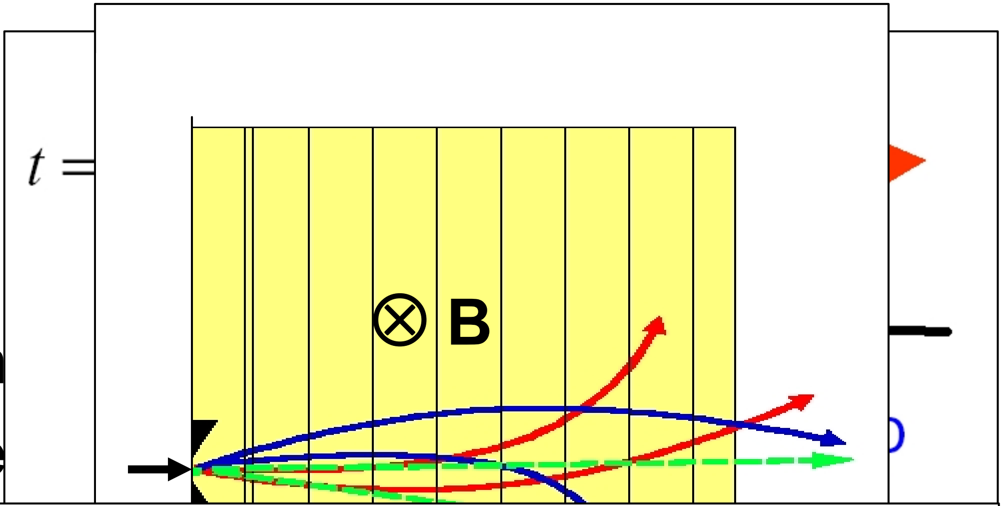


How to identify (charged) particles ?

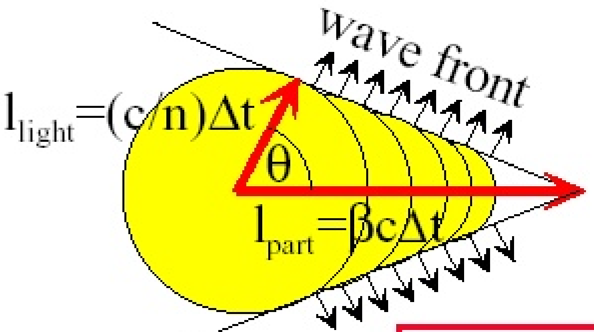
Measure its:

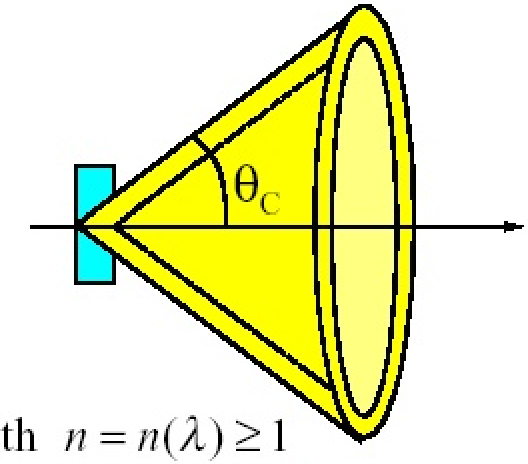
- velocity ***β*** :
- momentum ***p*** :
- Cherenkov radiation
- energy loss in matte

$\Big\}$ $p =$



$\beta \geq \beta_{thr} = \frac{1}{n}$ n : refractive index



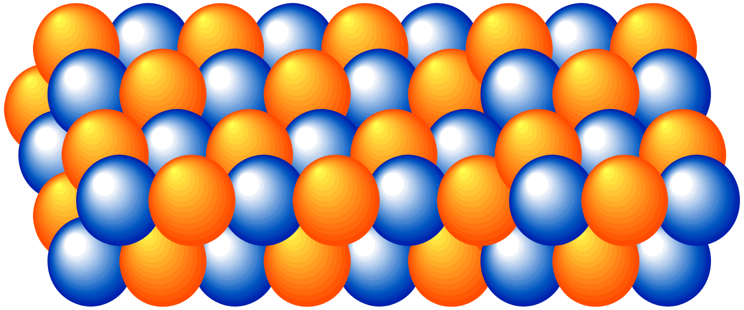


$$\boxed{\cos\theta_C = \frac{1}{n\beta}}$$ with $\underline{n = n(\lambda) \geq 1}$

Getting to the point: nuclear matter

Concept of Nuclear Matter

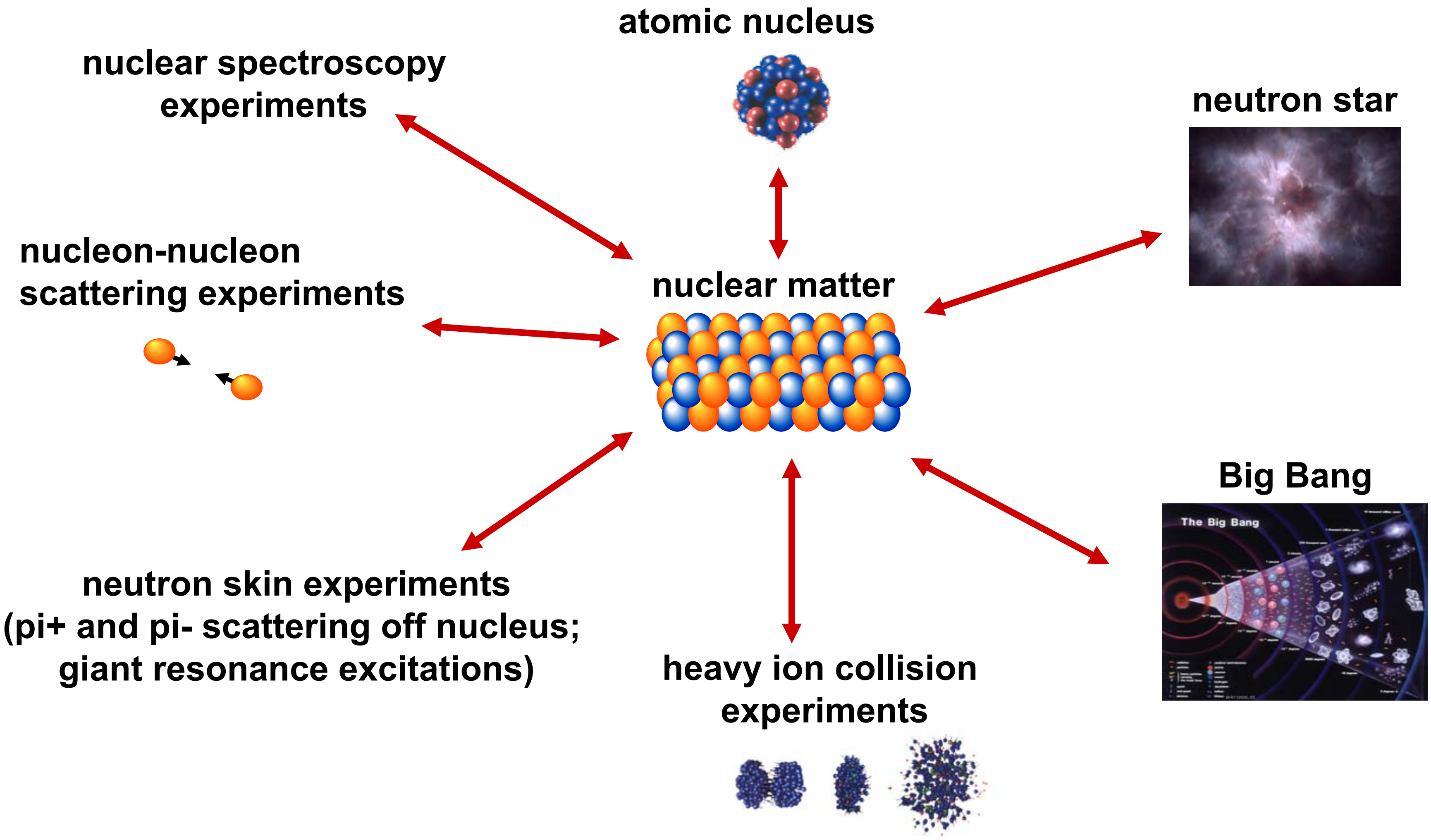
- protons and neutrons
- symmetric: $n_{prot} = n_{neut}$
- infinite in space, stable in time
- interactions: strong, Coulomb, Pauli exclusion principle



PROPERTIES

- density
- binding energy per nucleon
- effective mass of nucleon
- symmetry energy
- structure (crystaline? liquid? gaseous?)
- phase transitions? of what type?
- conductivity (conductor? superconductor?)
- compressibility aka Equation of State

Nuclear matter and its relation with the real world



atomic nucleus

nuclear spectroscopy experiments

neutron star

nucleon-nucleon scattering experiments

nuclear matter

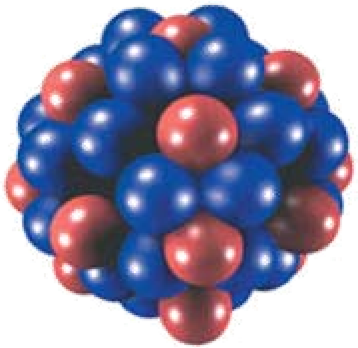
Big Bang

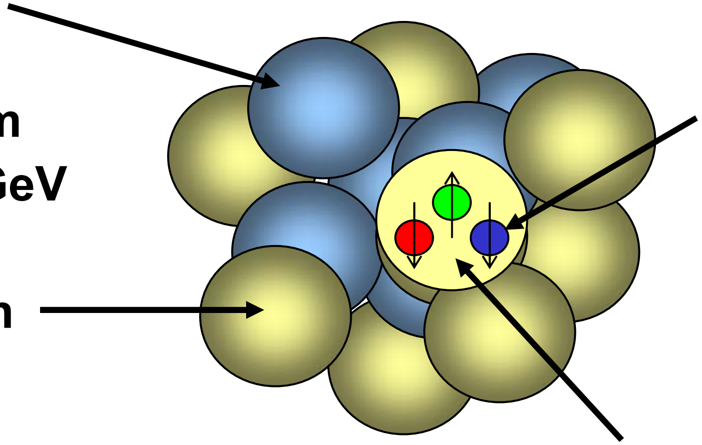
neutron skin experiments
(pi+ and pi- scattering off nucleus;
giant resonance excitations)

heavy ion collision experiments

Atomic Nucleus

radius 1-7 fm → 100 000 times smaller than atom
yet 0.9997 of the atom mass is in its nucleus
density 280 million tons per cm^3





proton

R ≈ 1 fm
m ≈ 1 GeV

neutron

up and down quarks
R < 10^{-4} fm; m ≈ 10 MeV

gluons and quark-antiquark pairs

R(A) = 1.2 fm A$^{1/3}$
ρ = 0.17 / fm^3

Atomic Nucleus

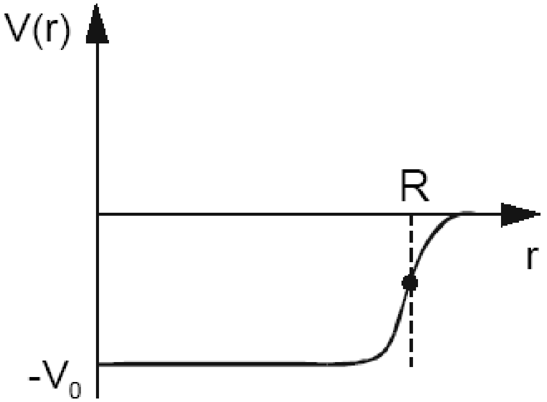
Nuclei form because of the strong effective interaction between nucleons. Although this „residual“ interaction is weaker than the bare strong force between quarks and gluons, it still overcomes Coulomb repulsion of protons by far.

Nuclei can be described assuming nucleons moving independently in a mean nuclear potential:

- **Phenomenological**
  Square-well, Harmonic,
  Woods-Saxon
- **Self-consistent**
  Hartree-Fock

Woods-Saxon Potential

$$V(r) = \frac{-V_o}{1 + \exp\left(\frac{r-R}{a}\right)}$$

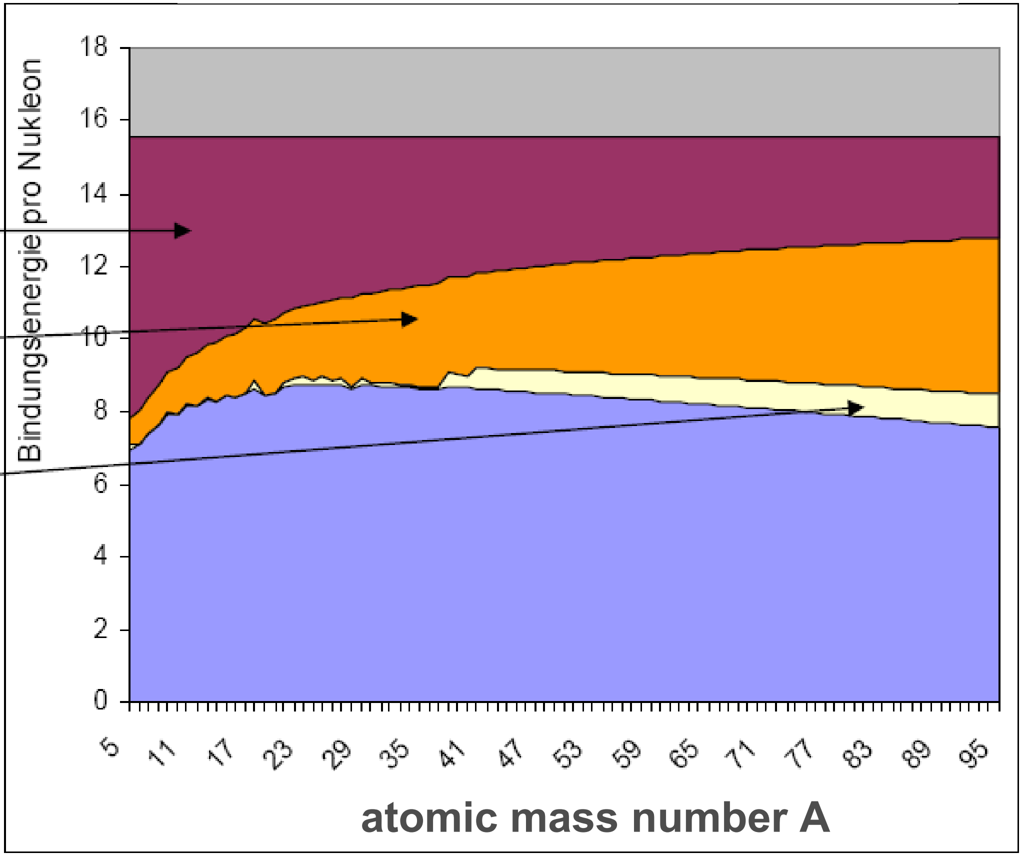


Liquid drop model of atomic nucleus

Bethe & Weizsäcker mass formula
$M_{nucleus} = Z\, m_p + (A-Z)\, m_N - B(Z,A)$
with binding energy B(Z,A)

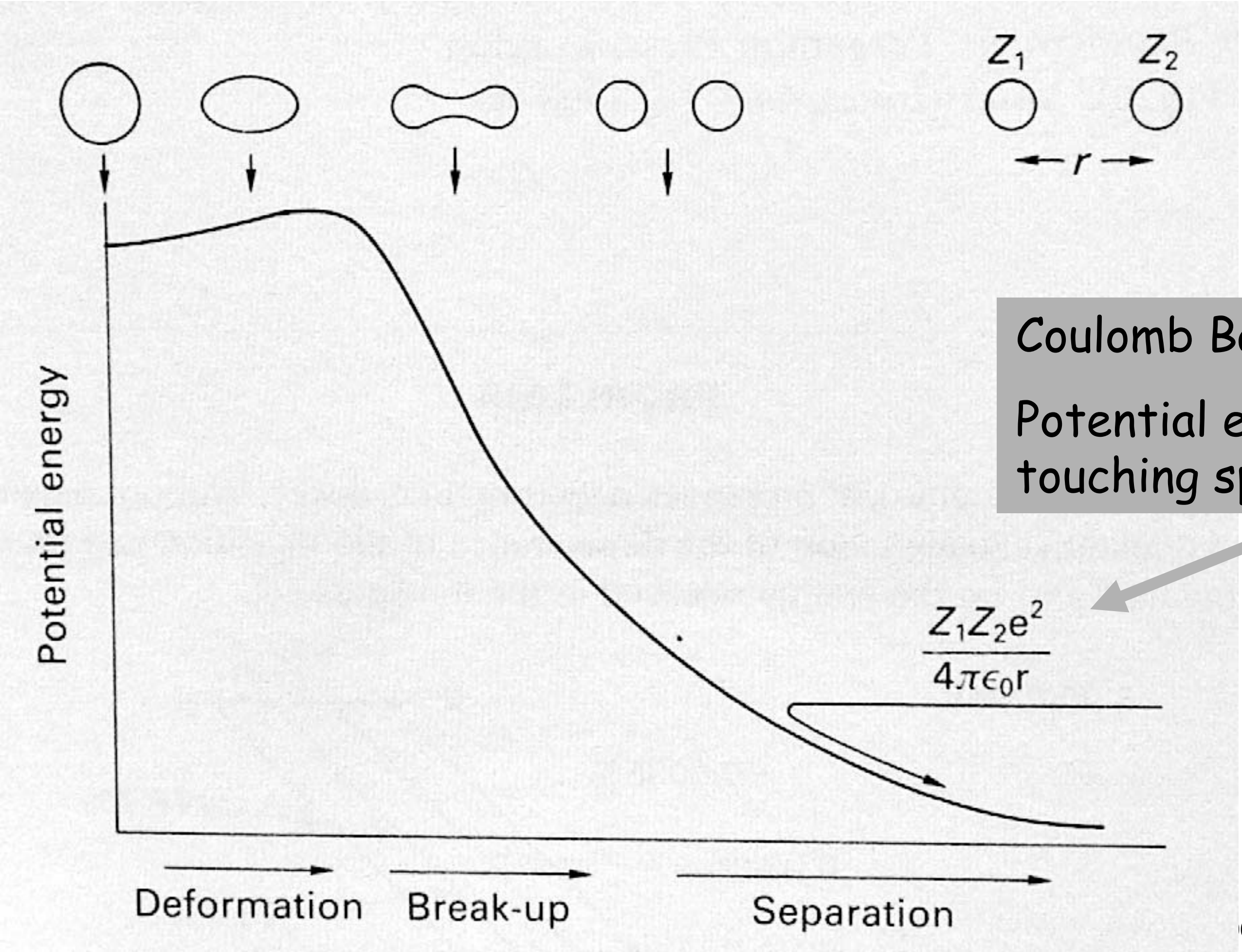
$$\begin{aligned} B(Z,A) = {} & a_V A && \text{volume} \\ & - a_S A^{2/3} && \text{surface} \\ & - a_C \frac{Z^2}{A^{1/3}} && \text{Coulomb} \\ & - a_A \frac{(N-Z)^2}{4A} && \text{asymmetry} \\ & \left\{ \begin{array}{l} - a_P / A^{1/2} \\ + 0 \\ + a_P / A^{1/2} \end{array} \right. && \text{pairing} \end{aligned}$$

binding energy per nucleon B(Z,A)/A



Nuclear fission

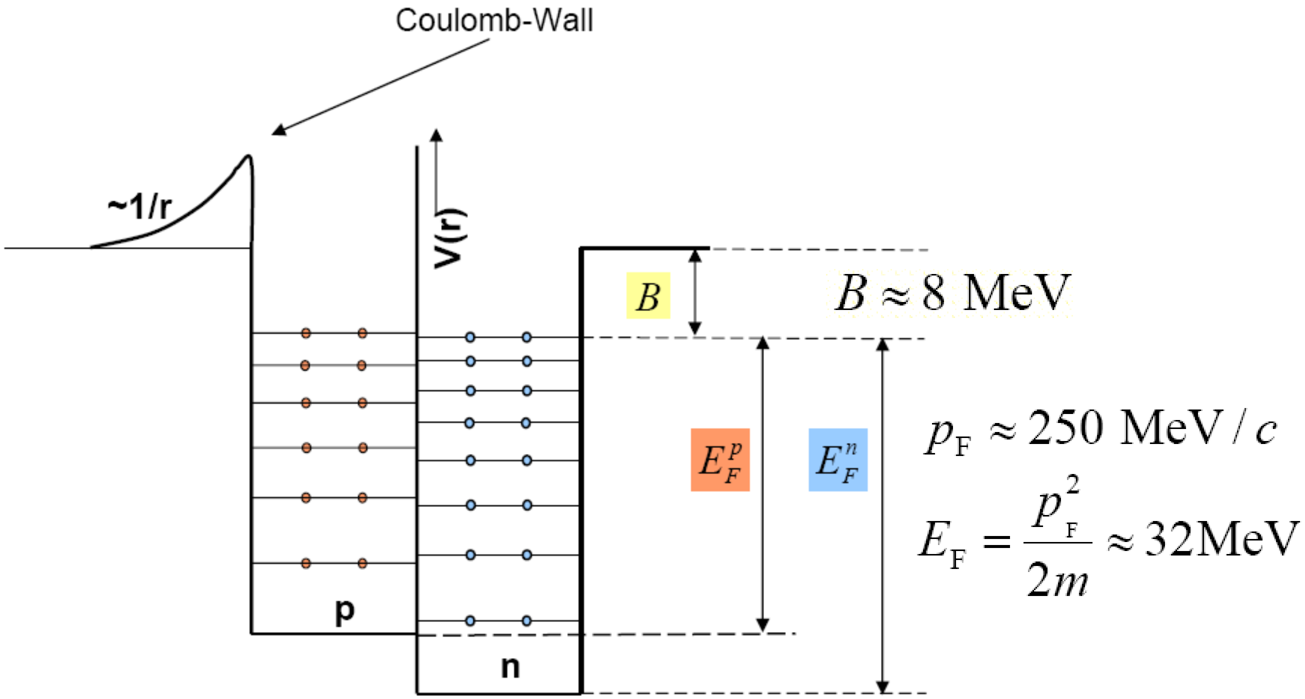
At moderate excitation energies nuclei behave like little droplets of water



Coulomb Barrier:

Potential energy of two touching spheres (if $r=R_0$)

Fermi gas model of atomic nucleus



$$B \approx 8\ \text{MeV}$$

$$p_{\text{F}} \approx 250\ \text{MeV}/c$$

$$E_{\text{F}} = \frac{p_{\text{F}}^2}{2m} \approx 32\text{MeV}$$

protons and neutrons
are Fermions (spin ½)
→ Pauli exclusion principle

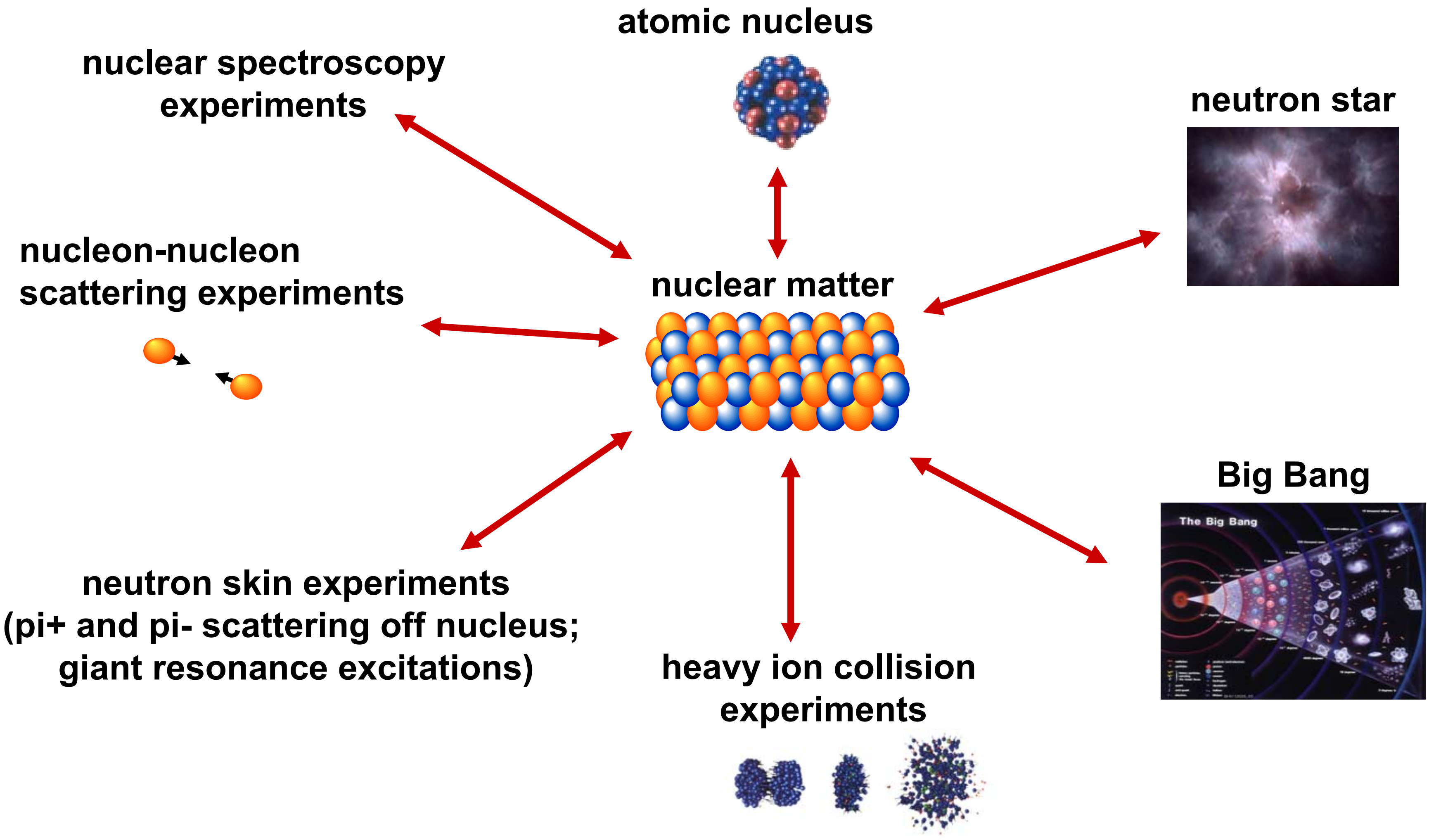
From nucleus to nuclear matter

- phenomenological mean field approach
- examples: Skyrme model, Walecka model
- fit the known ATOMIC NUCLEUS properties

resulting properties of NUCLEAR MATTER:

- density: 0.15-0.16 nucleons / fm^3
- binding energy: 16 MeV per nucleon
- effective mass $m_N^* = 0.7\text{-}\ 0.8\ m_N$
- symmetry energy S = 30 – 35 MeV
- structure: liquid
- EoS: K_0 = 200-300 MeV

Nuclear matter and its relation with the real world



atomic nucleus

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nuclear matter

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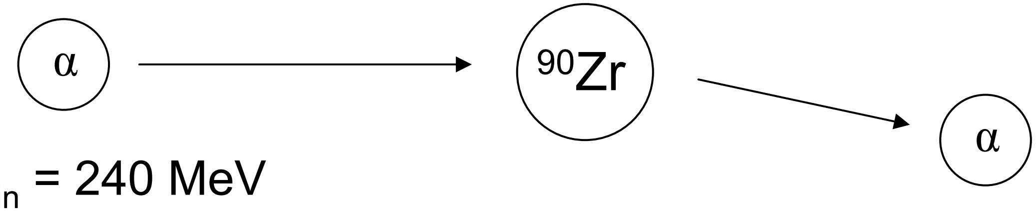
(pi+ and pi- scattering off nucleus;
giant resonance excitations)

heavy ion collision experiments

Big Bang

Excitation of the giant monopole resonance

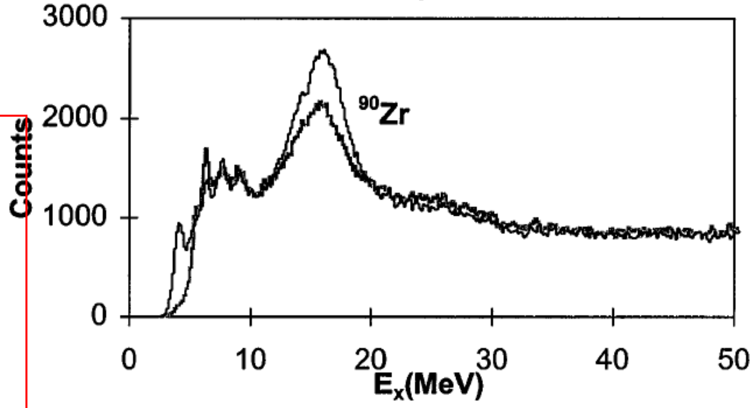
inelastic scattering of α particles on nuclei



measure of the total energy
of the outgoing α particle → E_x

E_{kin} = 240 MeV

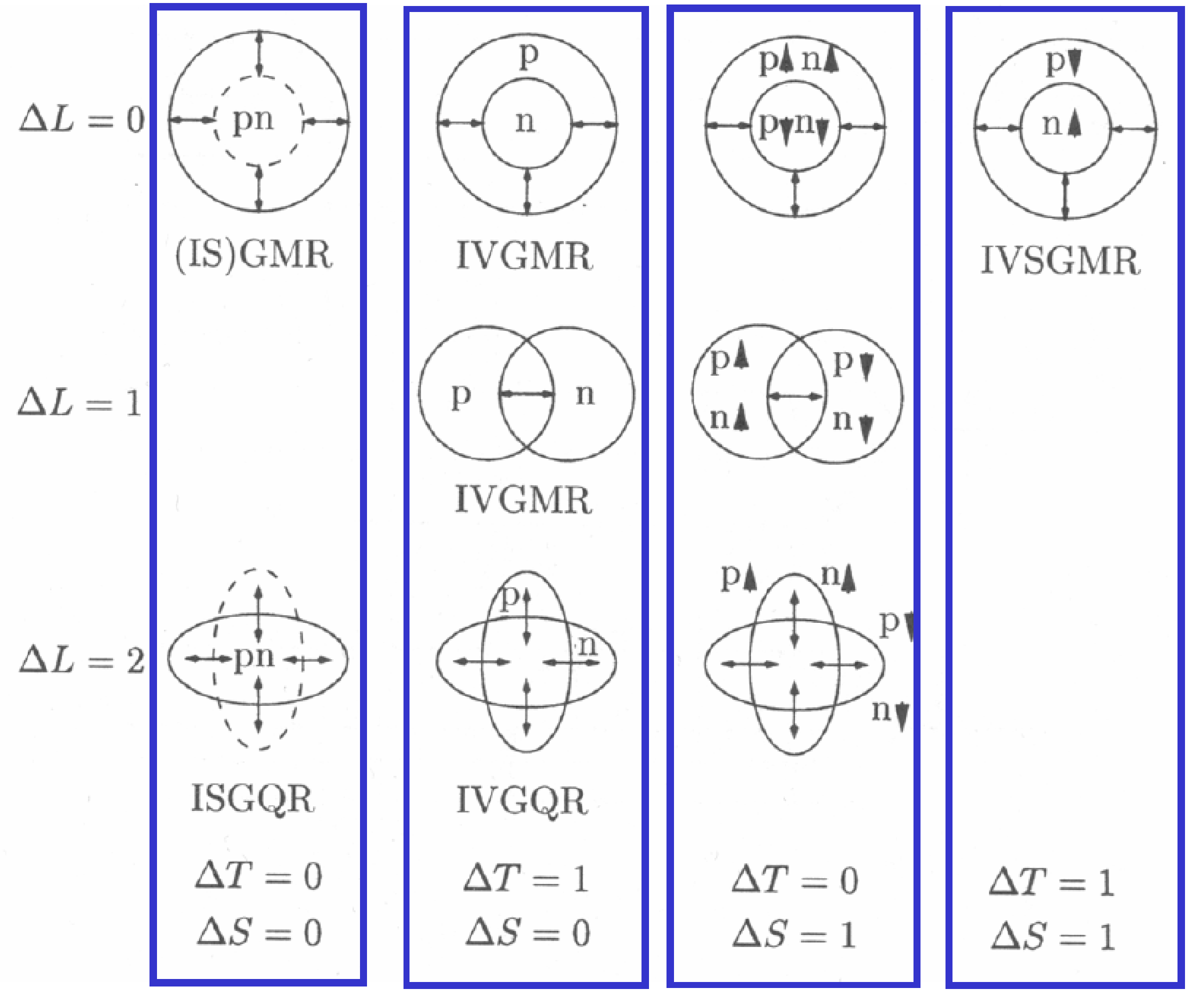
"resonance phenomenon"



The energy loss of the α particle of about 15 – 25 MeV excites slight density oscillations with elongations of about 1/100 ρ_0 (around saturation density ρ_0). It is a collective excitation of the nucleus and calls the Giant Monopole Resonance or the "breathing mode" of nuclei.

From the measured excitation energy distribution E_x :
→ frequency
→ restoring force (potential) of the oscillation
→ "spring constant" κ = compression modulus

Collective excitation of nuclei: giant resonances



monopole vibration:
"breathing mode" of
the nucleus

dipole vibration:
"protons and neutrons
oscillate against each other"

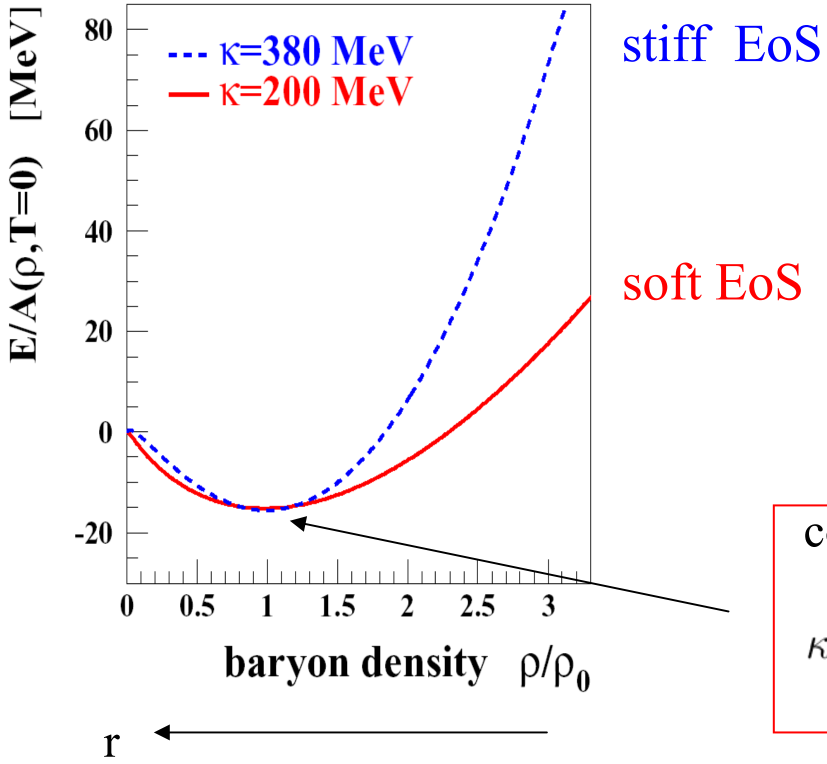
quadruple vibrations

The nuclear equation-of-state (EoS)

$$\varepsilon(\rho,T) = \underbrace{\varepsilon_T(\rho,T)}_{\text{thermal}} + \underbrace{\varepsilon_C(\rho,T=0)}_{\text{compressional}} + \underbrace{\varepsilon_0}_{\text{ground state energy}} \qquad (\varepsilon = E/A)$$

nuclear equation-of-state at T = 0 : the "compressional" energy

$$E/A\,(\rho, T=0) \;=\; \frac{1}{\rho}\int U(\rho)\,d\rho \qquad U(\rho):\ \text{density dependent local potential}$$



constraints for the parameters of the potential :

$$\varepsilon(\rho=\rho_0, T=0) = -16MeV$$

$$\left(\frac{\partial\varepsilon(\rho,T=0)}{\partial\rho}\right)_{\rho=\rho_0} = 0$$

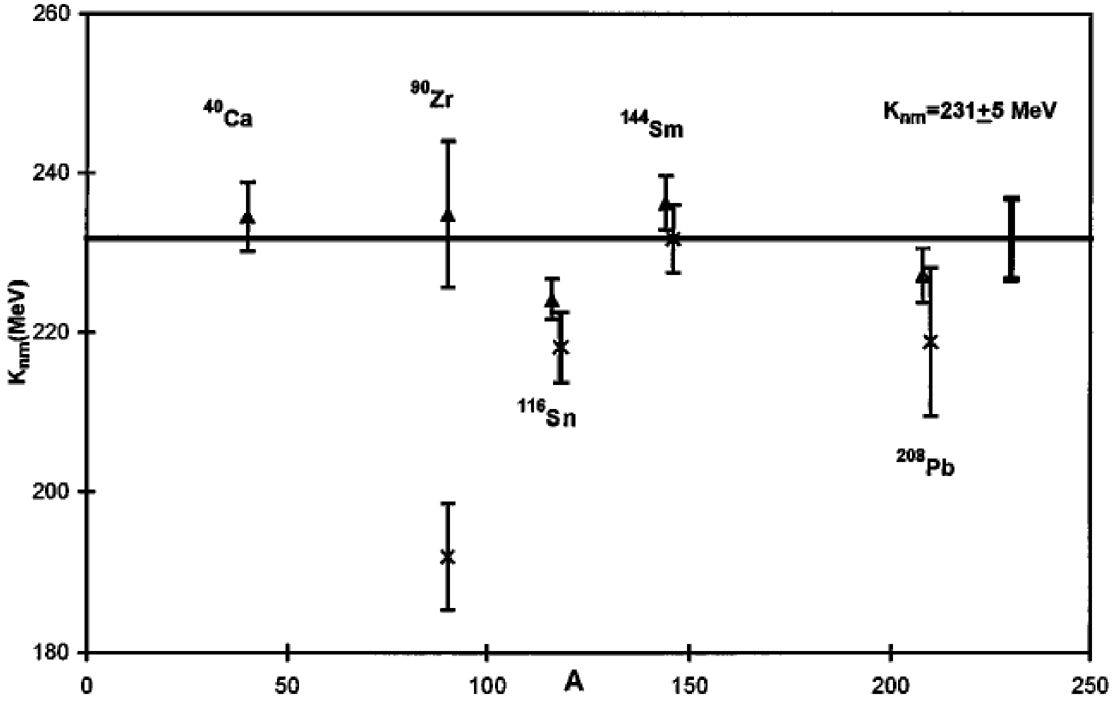
compression modulus

$$\kappa \;=\; \left(9\rho^2\,\frac{\partial^2 E/A(\rho,T=0)}{\partial\rho^2}\right)_{\rho=\rho_0}$$

The compression modulus κ at ρ_0

"Excitation of the Giant Monopole Resonance
by inelastic scattering of α particles on nuclei"

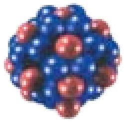
Youngblood et al. , Phys. Rev. Lett. 82 (1999)691



$\kappa = 231 \pm 5$ MeV

Nuclear matter and its relation with the real world

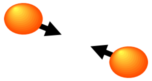
atomic nucleus



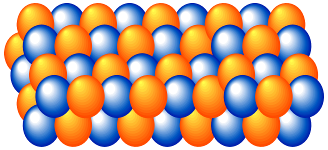
nuclear spectroscopy experiments

neutron star

nucleon-nucleon scattering experiments

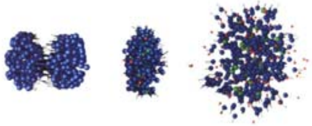


nuclear matter

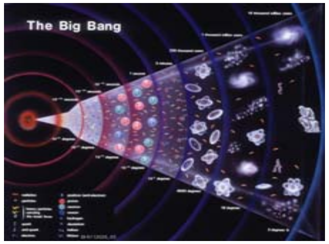


neutron skin experiments (pi+ and pi- scattering off nucleus; giant resonance excitations)

heavy ion collision experiments



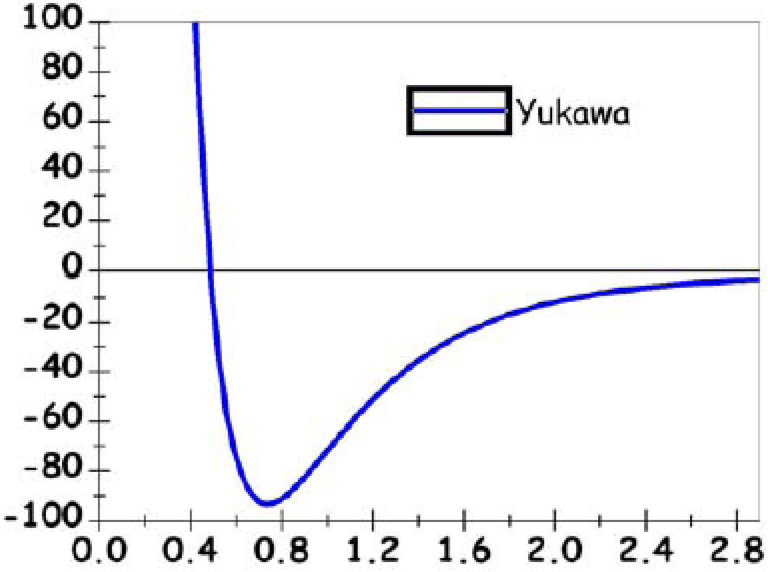
Big Bang

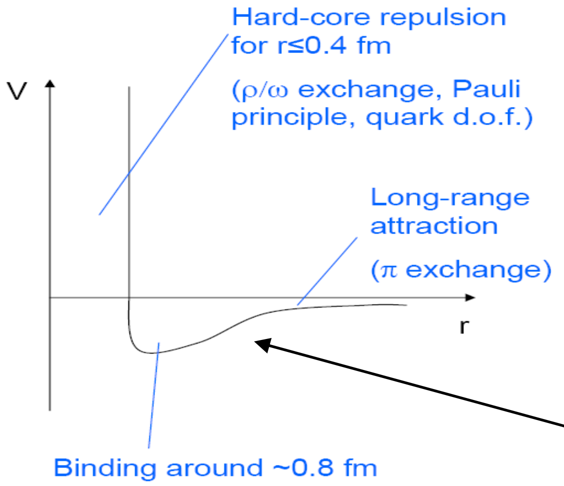


From nucleon-nucleon scattering to nuclear matter

MICROSCOPIC MANY BODY APPROACH

- use NN potential deduced from the scattering data
- use variational or Monte Carlo techniques
- example: Brueckner-Hartree-Fock



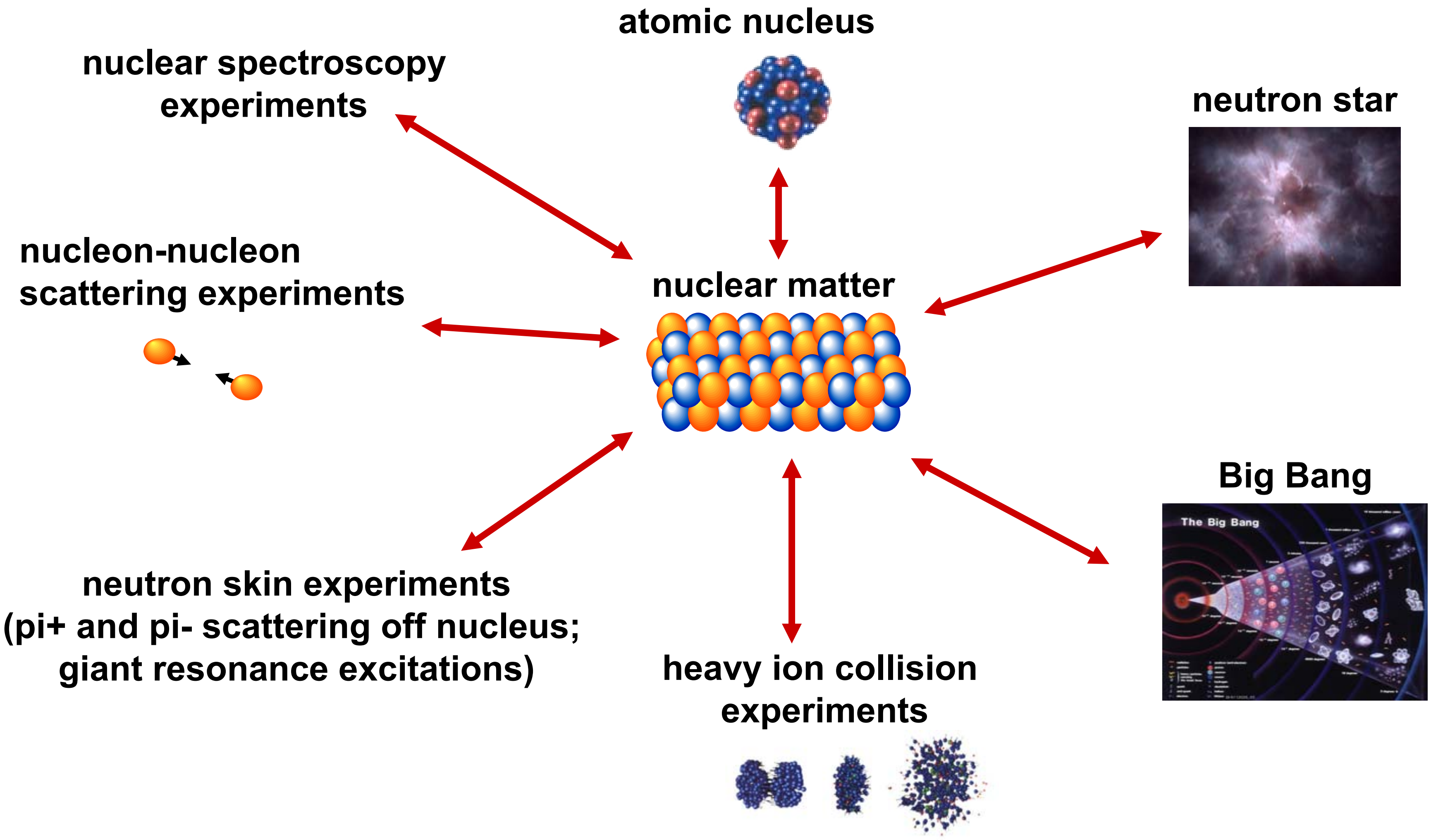


low energy scattering restricts this part

Neutron skin experiments

- neutron-over-proton excess in nucleus
- calculations predict neutron skin
- experimental access via
  - pion-nucleus scattering
  - giant resonance excitations
- → symmetry energy of nuclear matter

Nuclear matter and its relation with the real world



atomic nucleus

nuclear spectroscopy experiments

neutron star

nucleon-nucleon scattering experiments

nuclear matter

Big Bang

neutron skin experiments
(pi+ and pi- scattering off nucleus;
giant resonance excitations)

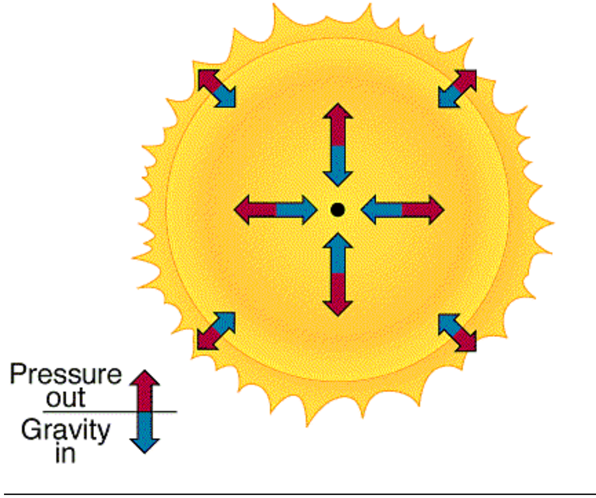
heavy ion collision experiments

Neutron Stars

Evolution of stars

Healthy star

- powered by nuclear fusion reactions
- the nuclear reactions provide the pressure which counteracts gravity



Aged star

- when nuclear fuel is exhausted gravity takes over and the star collapses
- degeneracy pressure of electrons may stop the collapse

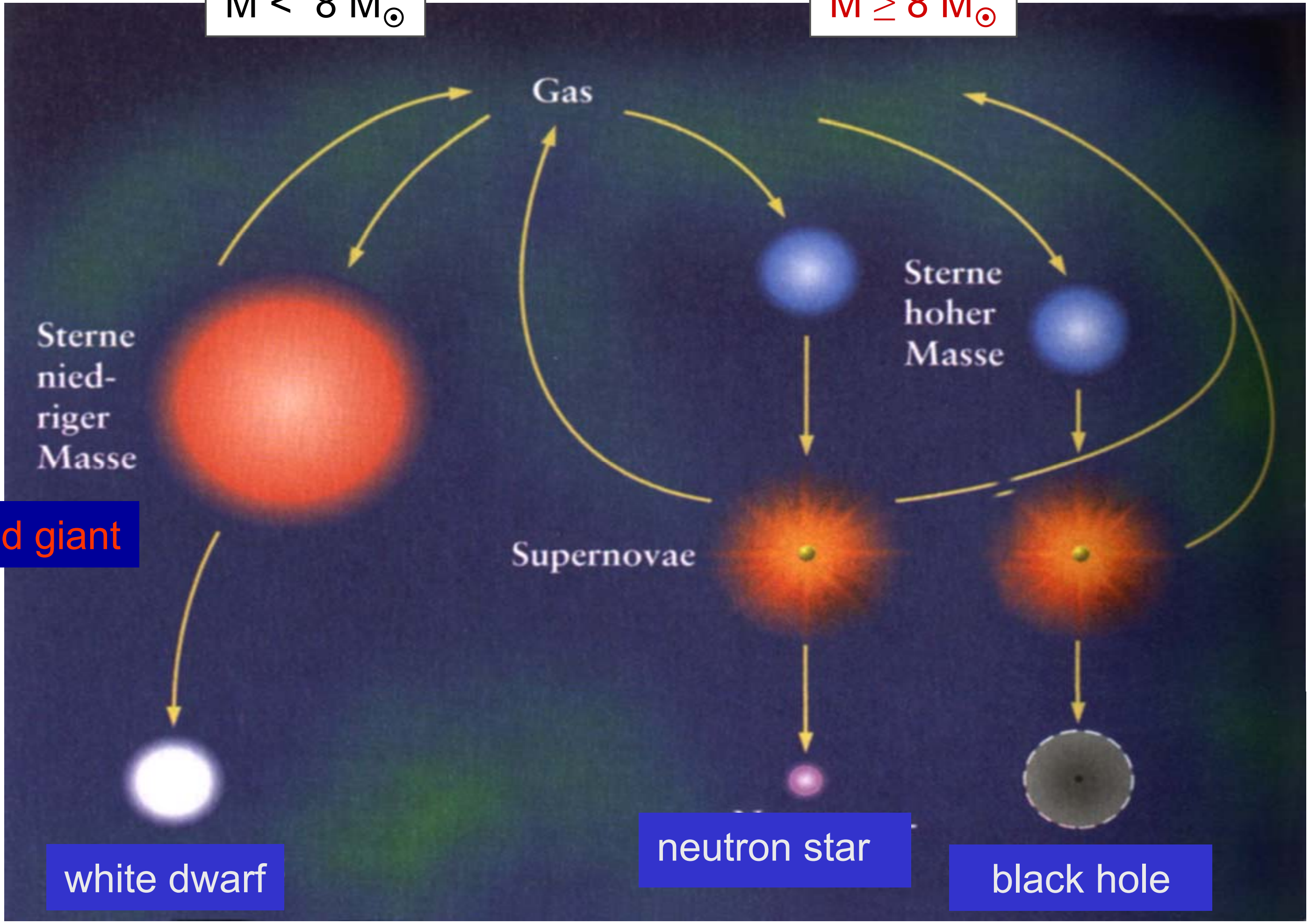
  → crystalline C (and some O) core and electrons, white dwarf
- otherwise, supernova
- degeneracy pressure of neutrons may stop the collapse

  → neutron star
- otherwise black hole

Stellar evolution

$M < 8 M_\odot$

$M \geq 8 M_\odot$



red giant

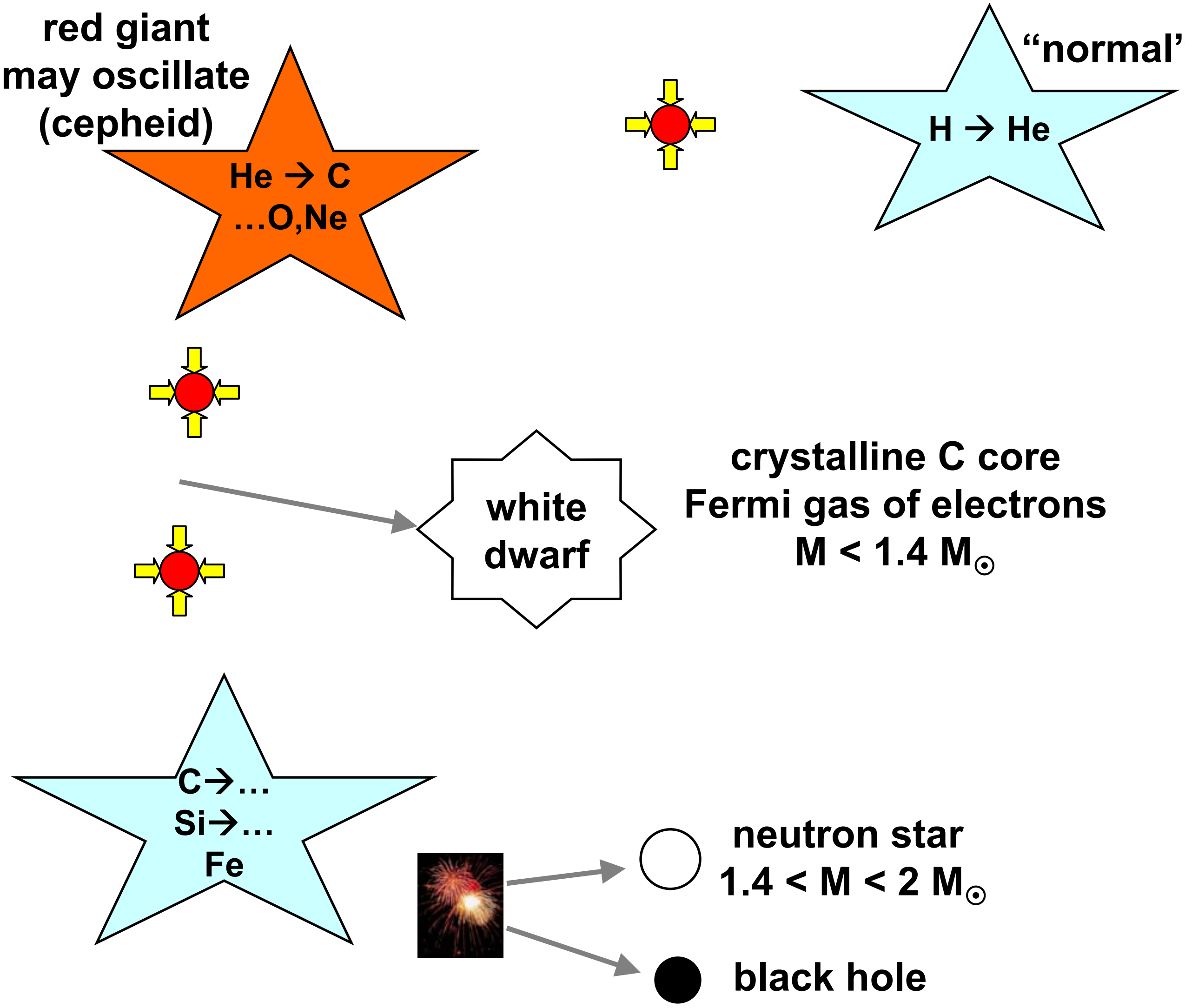
white dwarf

neutron star

black hole

$1.4 M_\odot < M < 2 M_\odot$

Evolution of stars



"normal" star

H → He

red giant
may oscillate
(cepheid)

He → C
…O,Ne

white
dwarf

crystalline C core
Fermi gas of electrons
$M < 1.4\ M_\odot$

C→…
Si→…
Fe

neutron star
$1.4 < M < 2\ M_\odot$

black hole

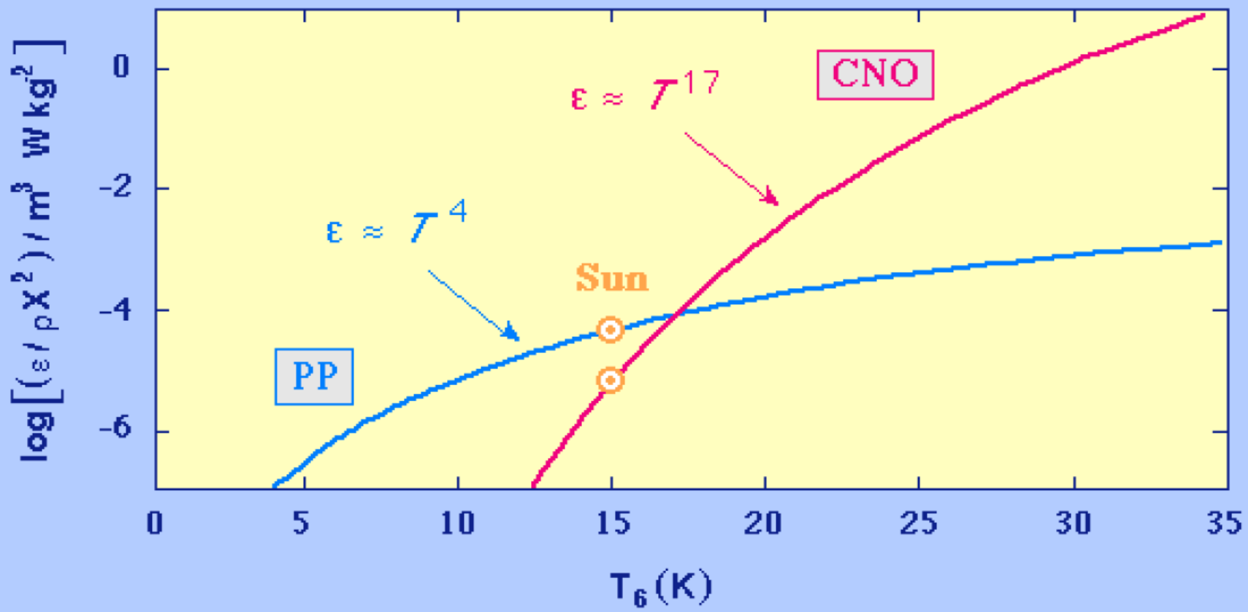
... in more detail

pp-chain $^{1}\mathrm{H}(p,e^{+}\nu_{e})\ ^{2}\mathrm{D}(p,\gamma)\ ^{3}\mathrm{He}(^{3}\mathrm{He},2p)\ ^{4}\mathrm{He}+26.21\,\mathrm{MeV}$

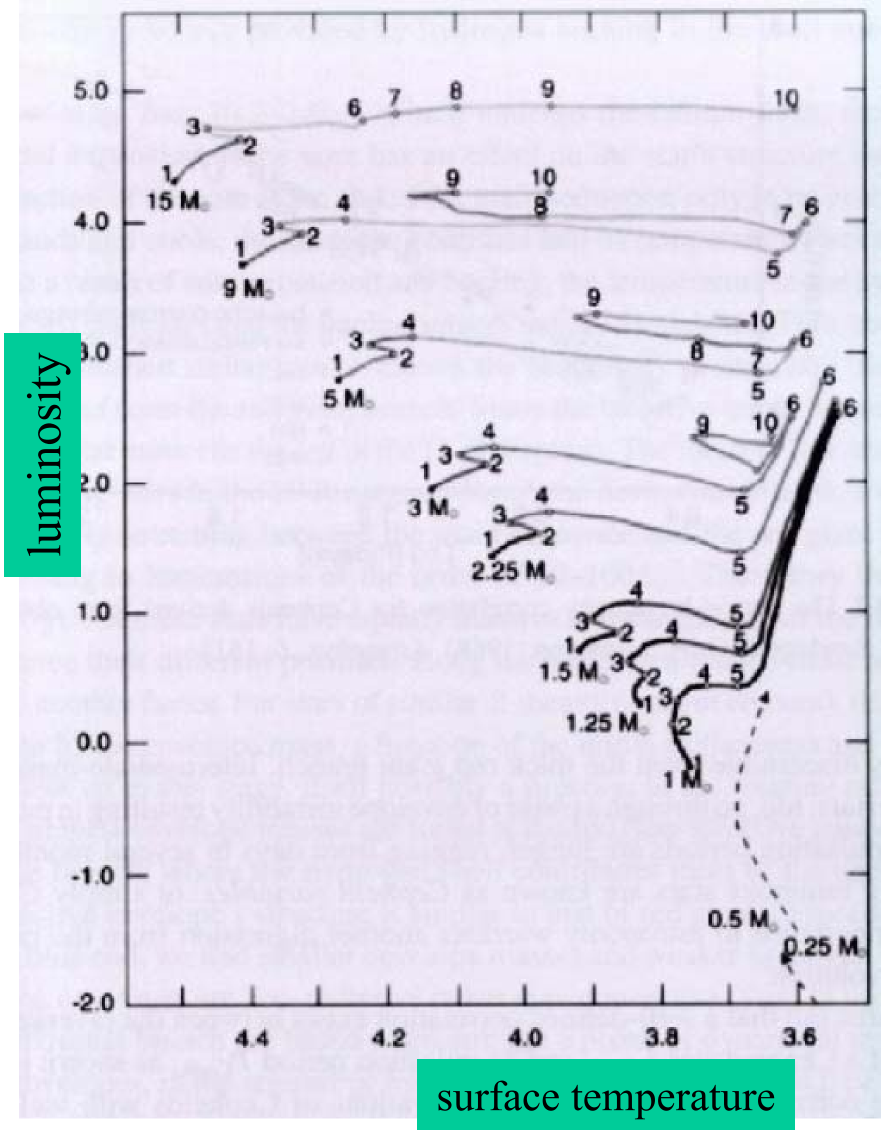
CNO-cycle $^{12}\mathrm{C}(p,\gamma)\ ^{13}\mathrm{N}(,e^{+}\nu)\ ^{13}\mathrm{C}(p,\gamma)\ ^{14}\mathrm{N}(p,\gamma)\ ^{15}\mathrm{O}(,e^{+}\nu_{e})\ ^{15}\mathrm{N}(p,\alpha)\ ^{12}\mathrm{C}+25.0\,\mathrm{MeV}$

(note: carbon, nitrogen and oxygen act only as catalysts !)

	T_{thr} [K]	mass limit
H-burning	**$2-5\cdot10^{7}$**	**$M\geq0.1\,M_{\odot}$**
He-burning	**$1\cdot10^{8}$**	**$M\geq0.5\,M_{\odot}$**
C-burning	**$6\cdot10^{8}$**	**$M\geq5\,M_{\odot}$**
O-burning	**$2\cdot10^{9}$**	
$^{28}\mathrm{Si}\rightarrow{}^{56}\mathrm{Ni}\rightarrow{}^{56}\mathrm{Co}\rightarrow{}^{56}\mathrm{Fe}$	**$4\cdot10^{9}$**	

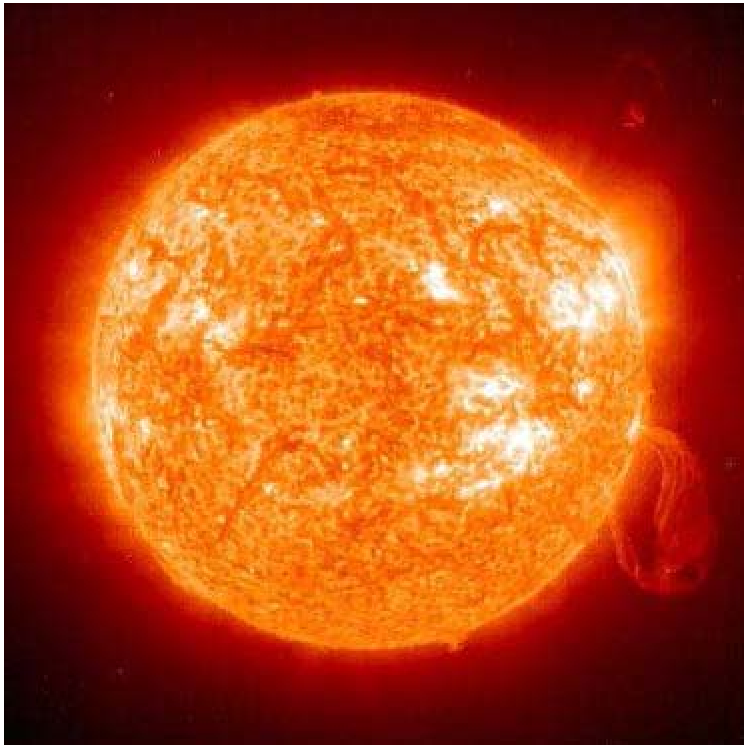


Hertzsprung-Russel diagram



mass	life time [years]
main sequence (1 – 3)	
1.0 $M_\odot$	$9.0 \cdot 10^9$
2.2 $M_\odot$	$5.0 \cdot 10^9$
15. $M_\odot$	$1.0 \cdot 10^7$
giant branch (5 – 6)	
1.0 $M_\odot$	$1.0 \cdot 10^9$
2.2 $M_\odot$	$3.8 \cdot 10^7$
15. $M_\odot$	$1.5 \cdot 10^6$ +(6-10)

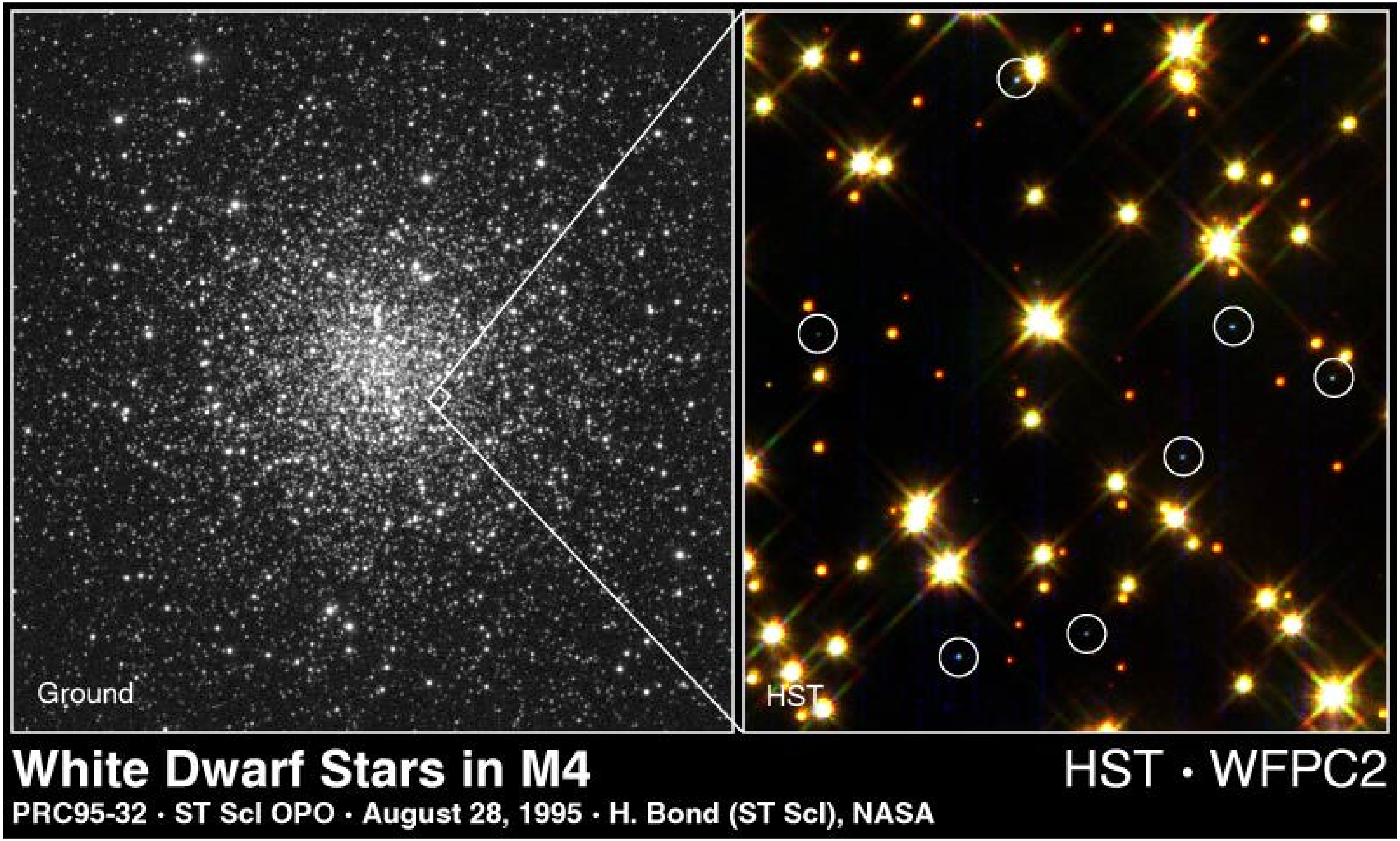
Stellar evolution: $M < 8\ M_\odot$



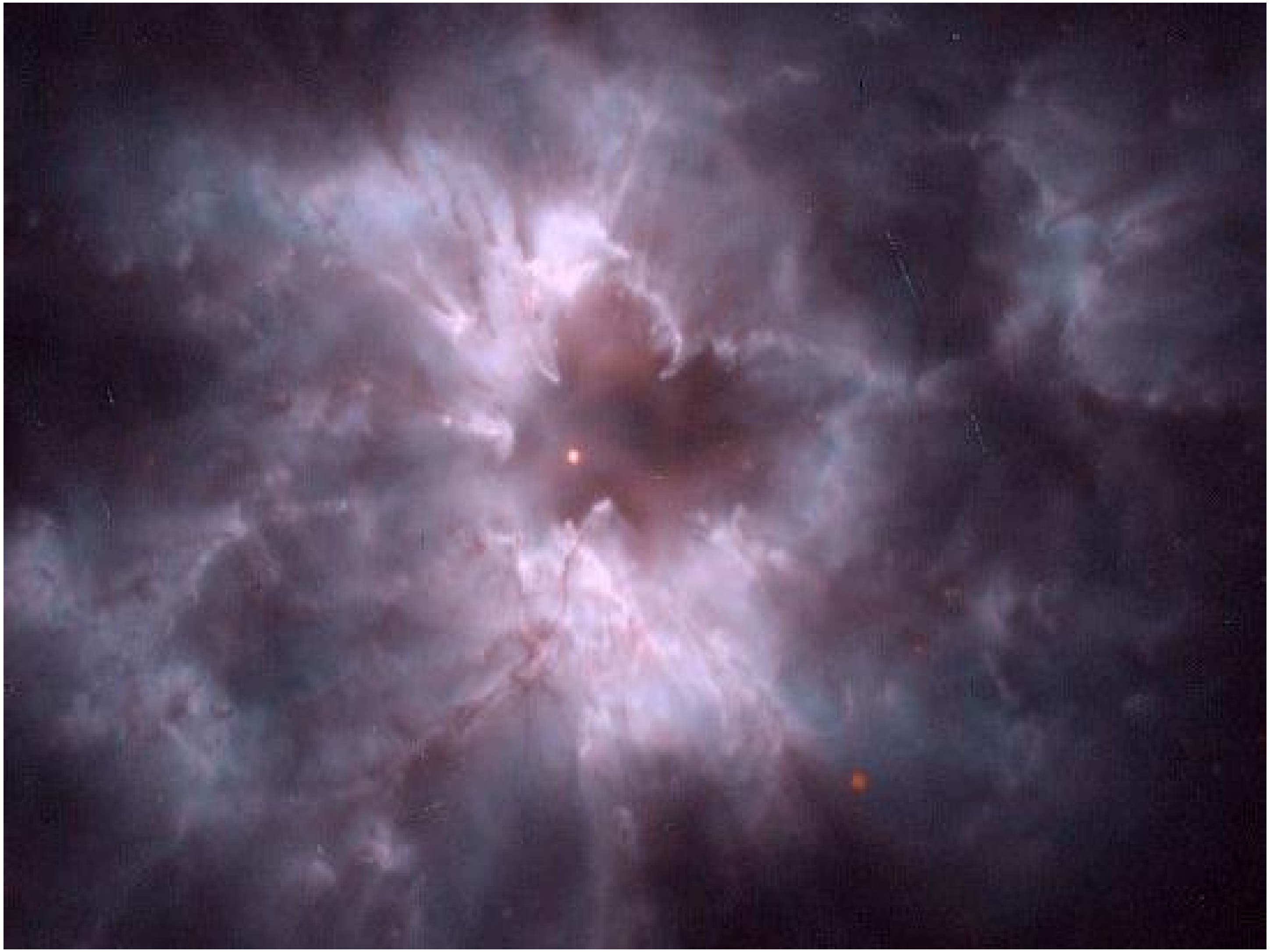
The Sun will reach the read giant stage in about 4 - 5 x 10^9 years

10^9 years later it will become a white dwarf

White dwarfs



White dwarf



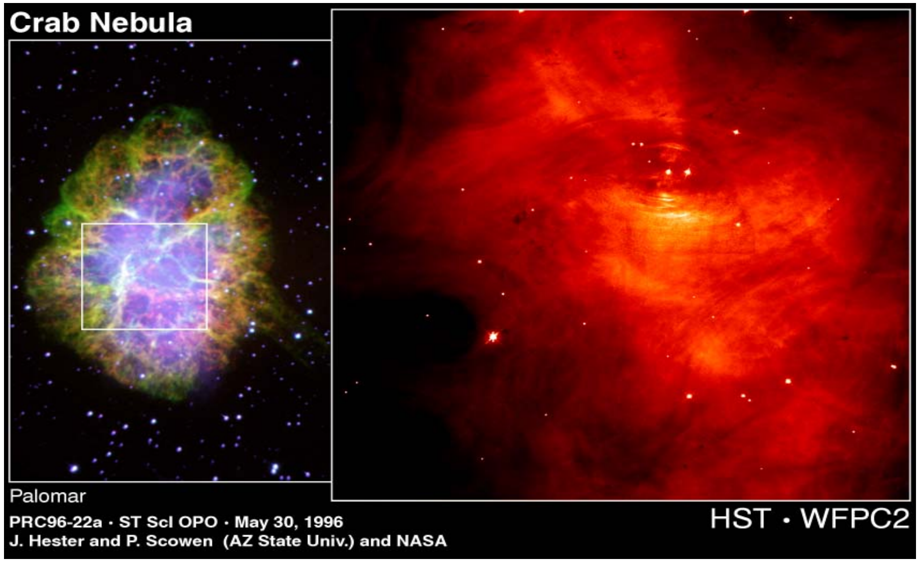
Supernova 1987A

near the Tarantula nebula
in the Large Magellanic Cloud

CRAB nebula

SUPERNOVA in 1054

In **1054** chinese astronomers for 1 month observed a "visiting star", as bright as the full moon



PRC96-22a · ST ScI OPO · May 30, 1996
J. Hester and P. Scowen (AZ State Univ.) and NASA

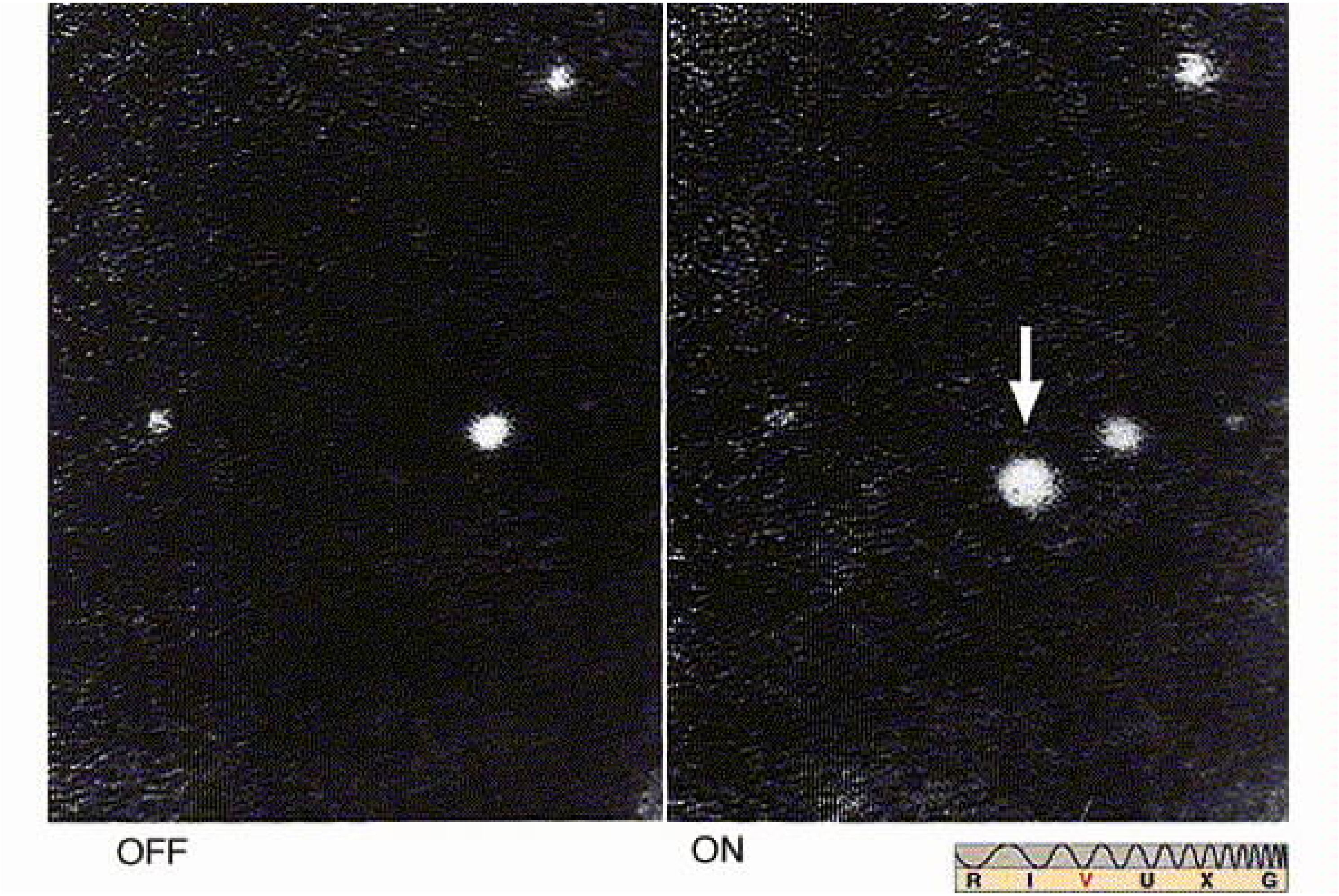
REMNANTS in 2006

distance about 7000 light years
diameter about 10 light years
expansion about 1000 Km/s

In **1968/69** discovery of a pulsating radio source (30 Hz) at that location in the sky:

A rotating neutron star with strong magnetic field emitting synchrotron radiation from high energy electrons: **a pulsar**

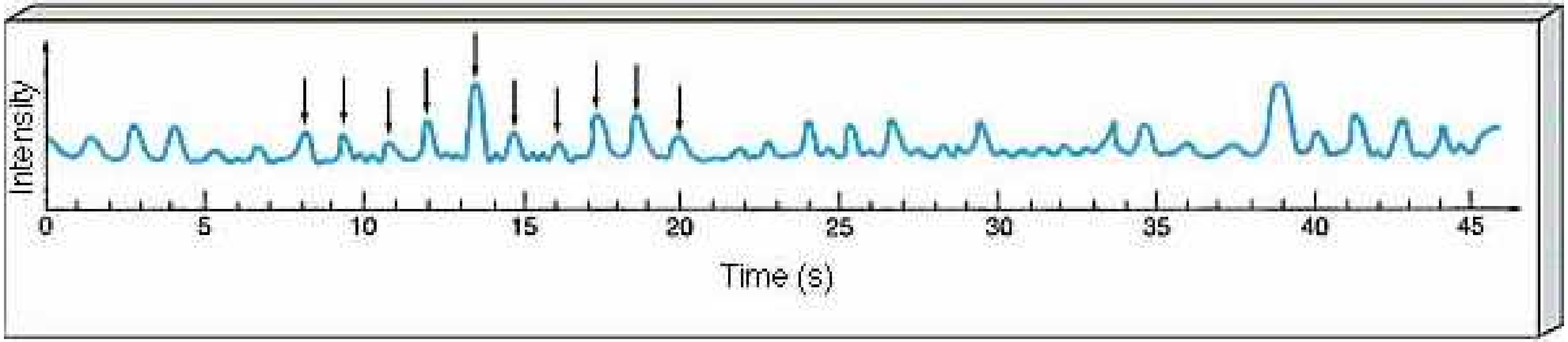
CRAB nebula pulsar



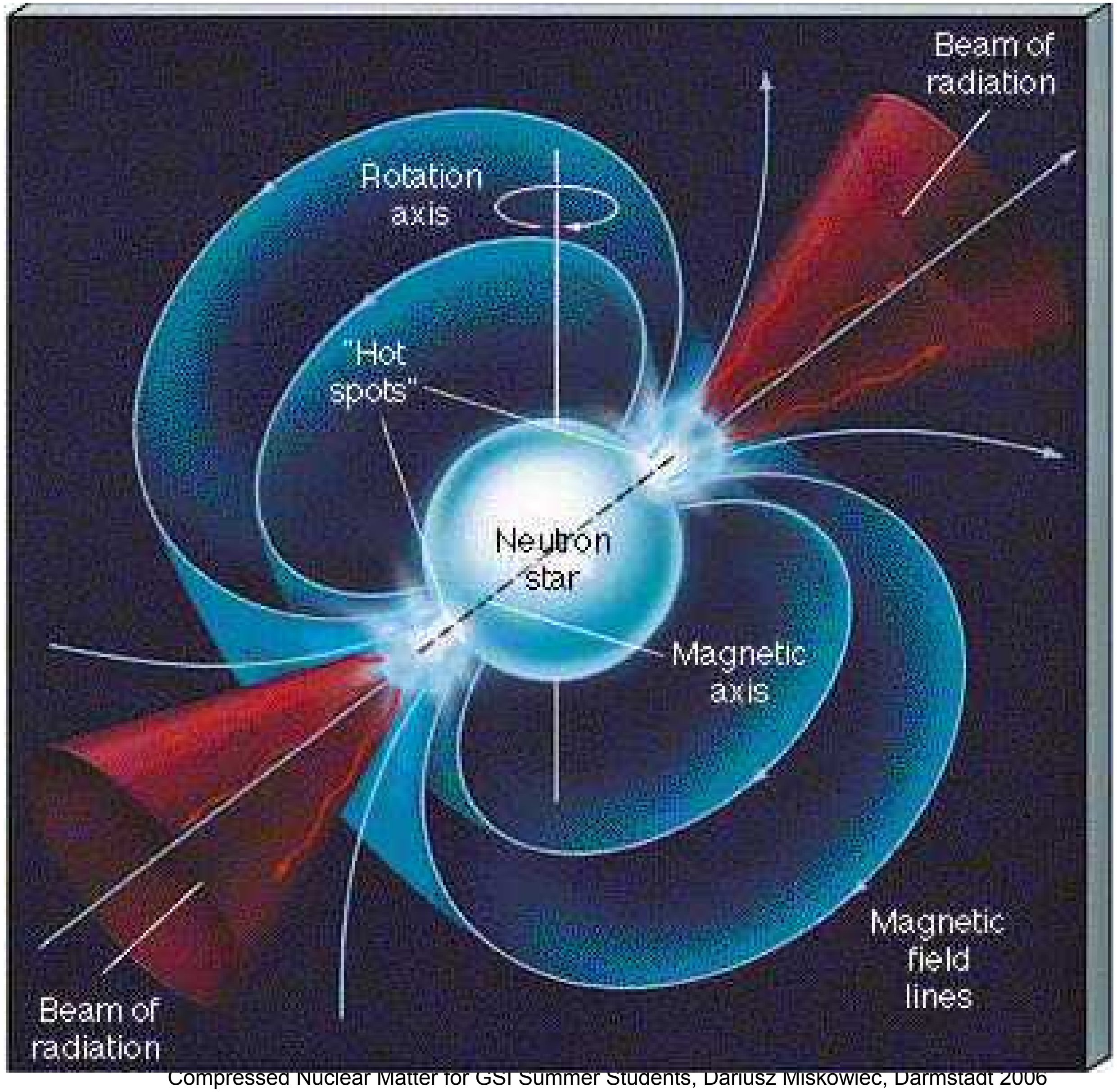
Pulsars: rotating neutron stars

- How to detect neutron stars?
- By their synchrotron radiation!

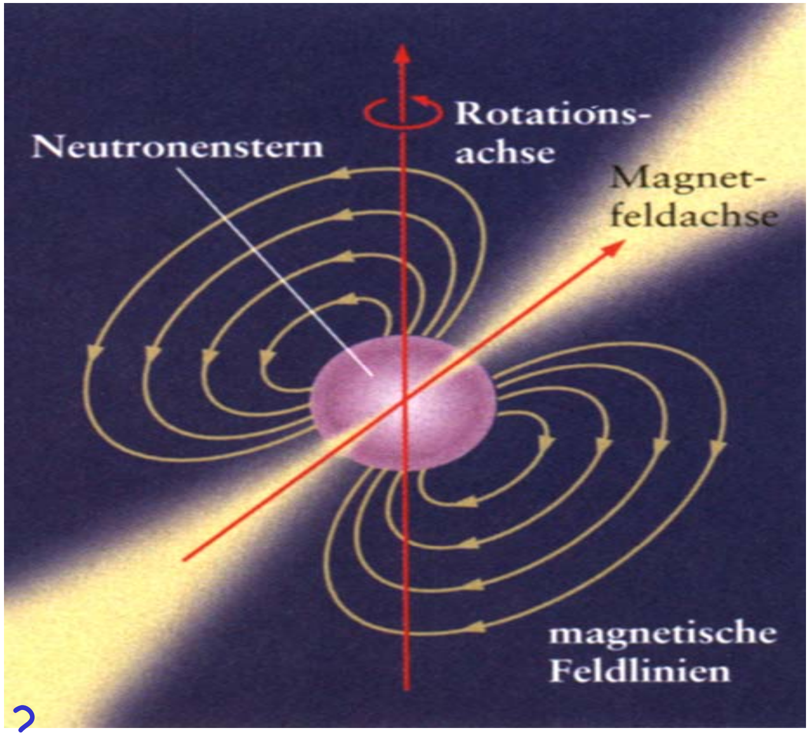
- **In 1937 two astronomers, working with a radio-telescope, discovered a source of intense periodic radio emission with**
- **period 1.33730113 (extremely accurate).**
- **PSR 137+214 slows down by 3.2 × 10^{-12} ms/year**



Light-House pulsar model



Pulsars: young neutron stars



- focused radiation (x-ray to radio)
- frequency $f = 0.25 - 1000$ Hz
- "age" $\tau = P/(2\, dP/dt)$
- radius = approx. 10 km
- mass = about 1.5 solar masses

  ⇒ 3-10 times the density of an atomic nucleus (3-10 ρ_0)
- structure: iron crust + core of

  90% neutrons, 10% protons + electrons

  Maybe pions ? strange particles? quarks ?
- magnetic field $5 \cdot 10^{12}$ Gauss
- abundance: about 1000 observed, but estimated about 100 Mio in our galaxy

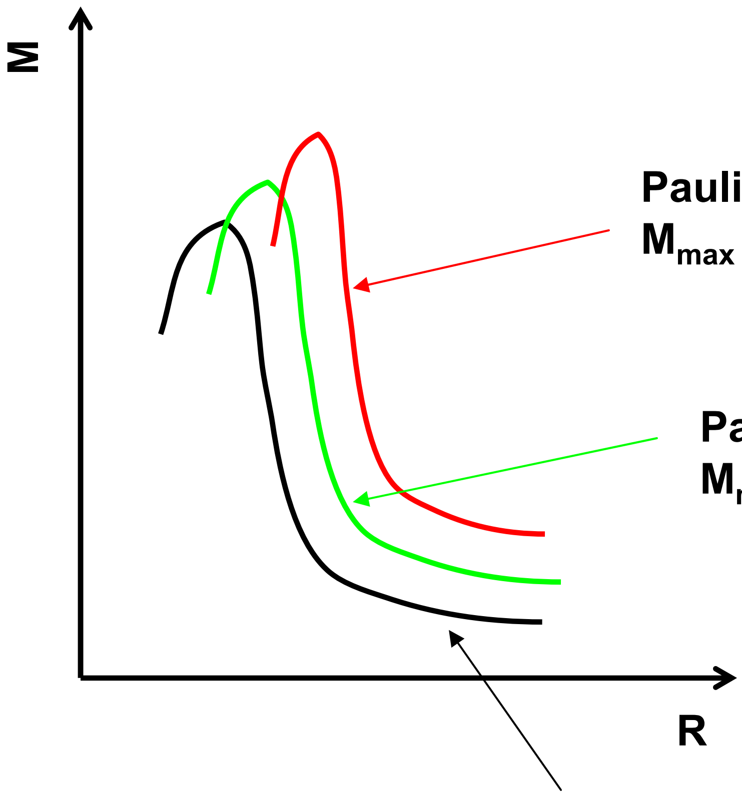
Neutron star radius

typical neutron star
$(d \approx 10\ \text{km}, M \approx 1\text{-}2M_\odot)$

typical city

$\Rightarrow$ neutron stars are optically **not** visible (with a few exceptions)

Mass - radius relation for a neutron star

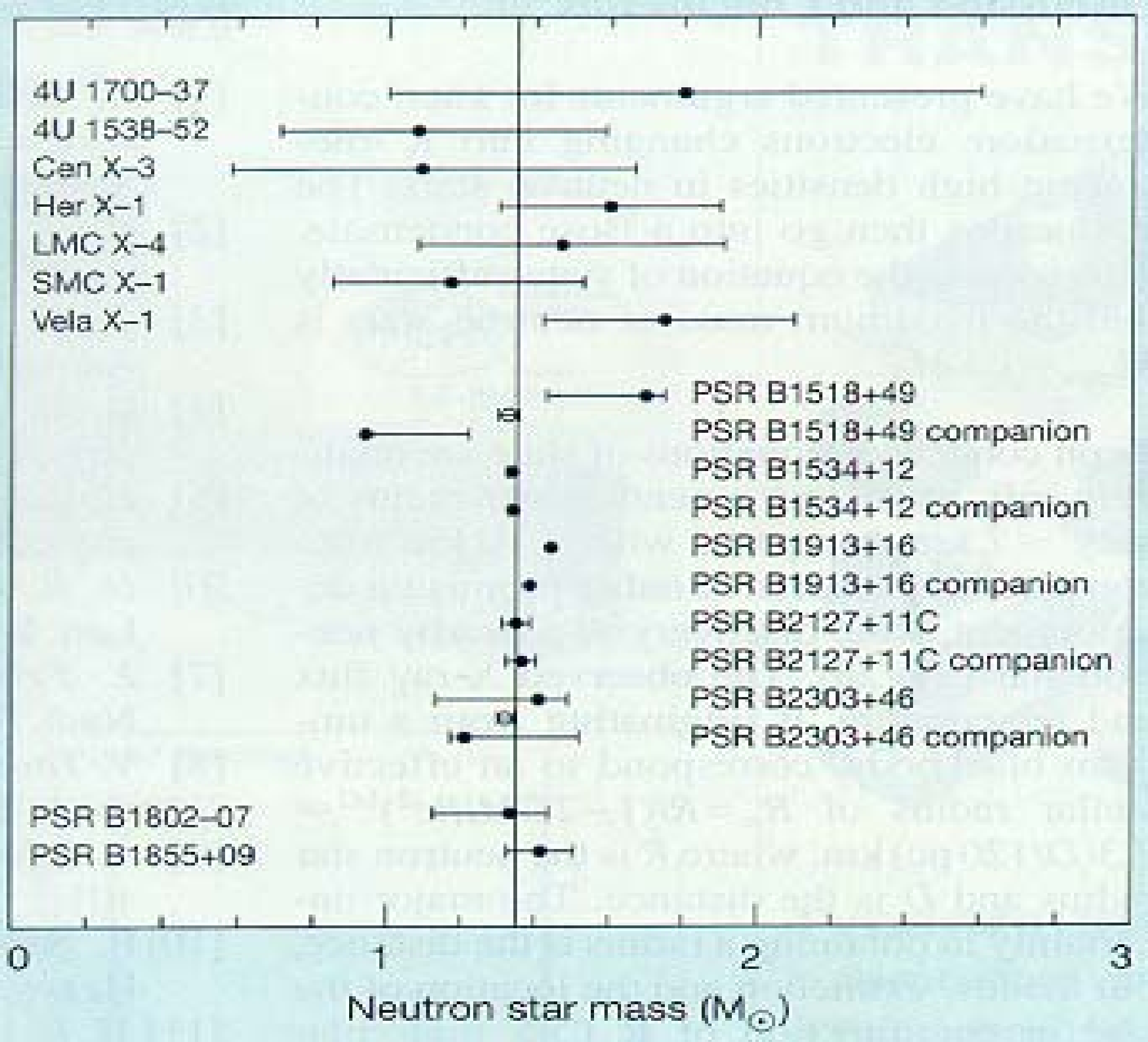


Pauli + hard EoS
$M_{max} \approx 2.7\ M_{\square}$

Pauli + soft EoS
$M_{max} \approx 2\ M_{\square}$

only Pauli
$M_{max} \approx 1.8\ M_{\square}$

Observed neutron star masses

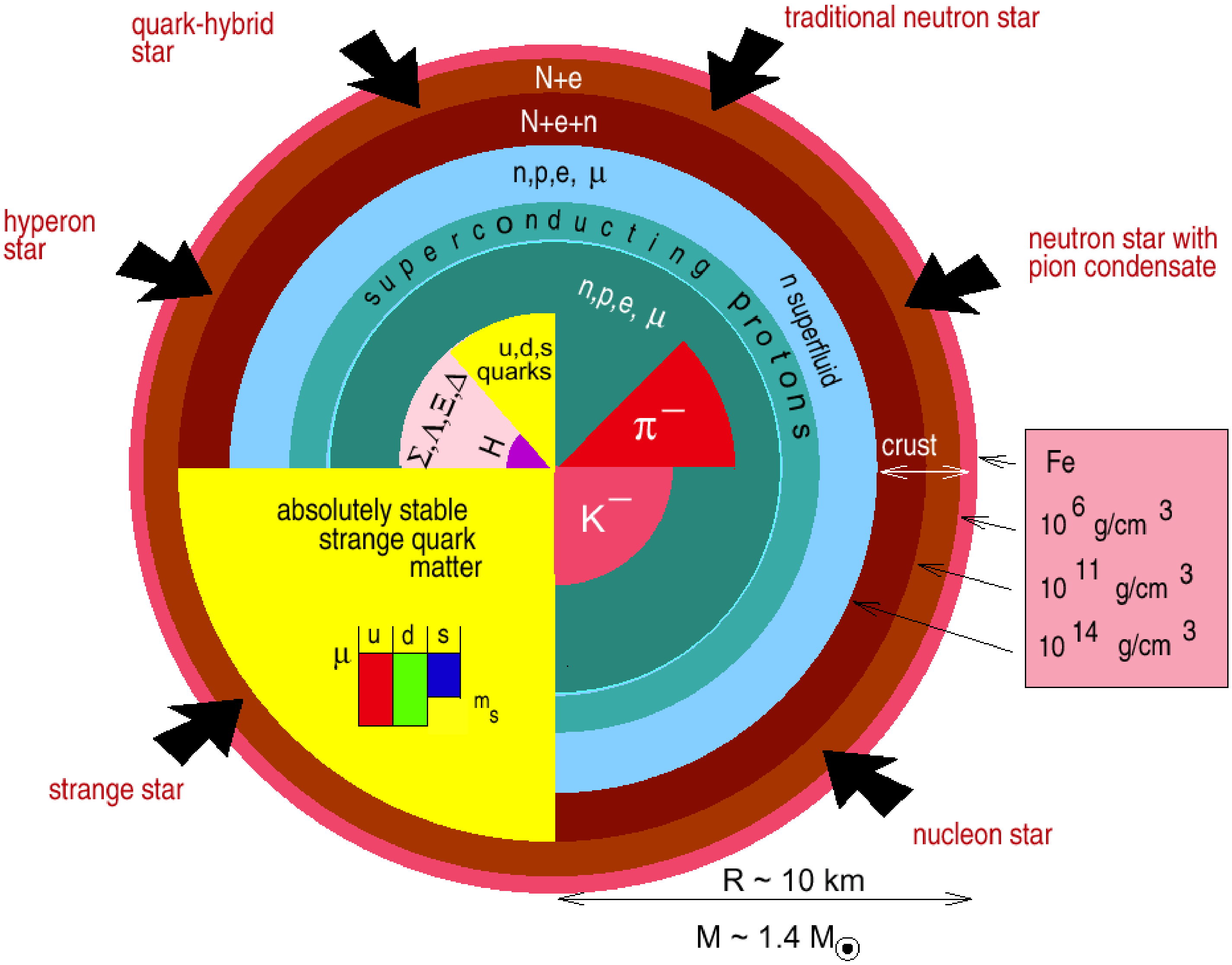


- **>1500 pulsars known**
- **rotation period > 1.5 ms**
- **M < 2.5 $M_\odot$ (2 σ)**

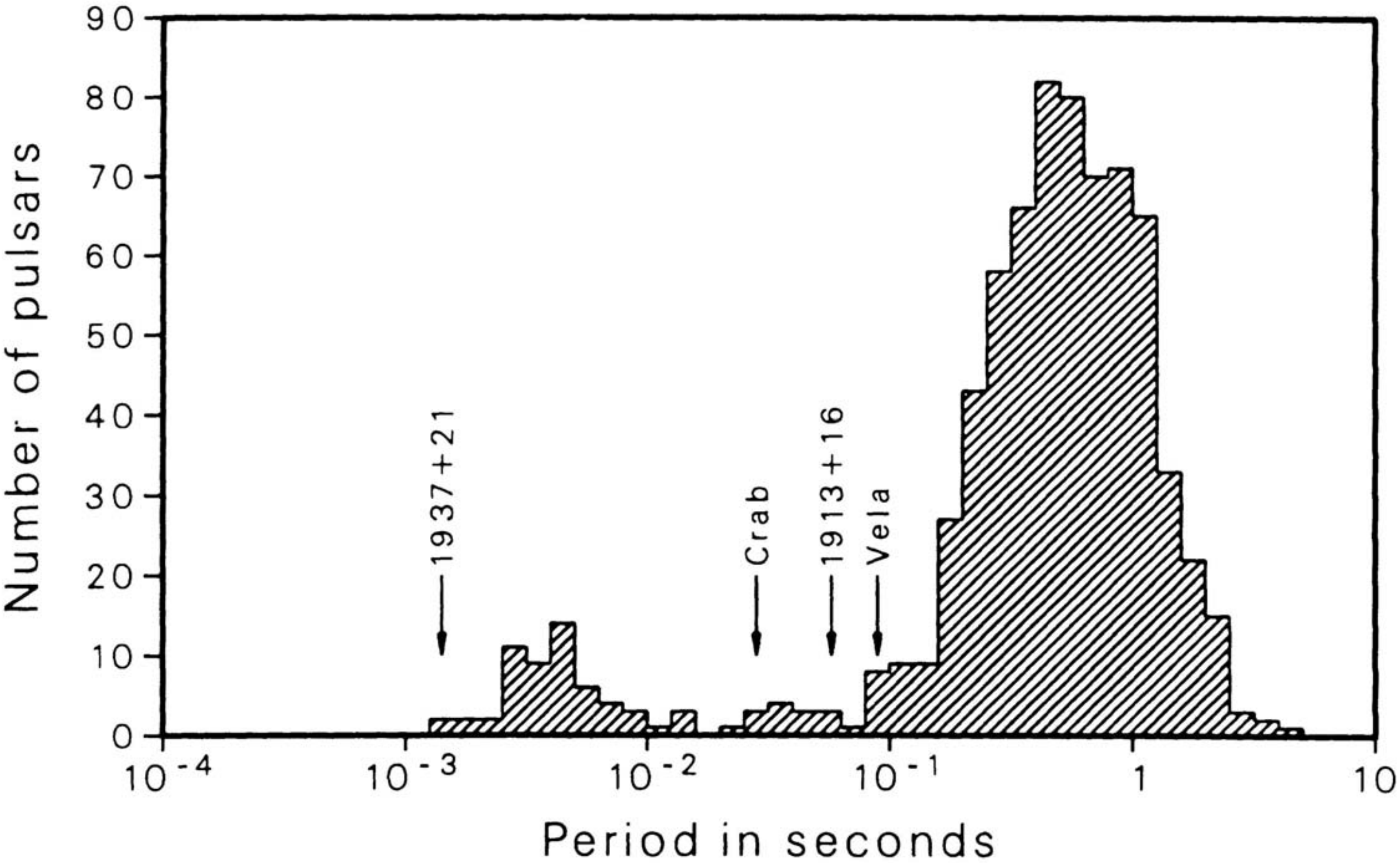
Actual structure of the neutron star can be much more complex

Each arrow indicates a different model for the neutron star

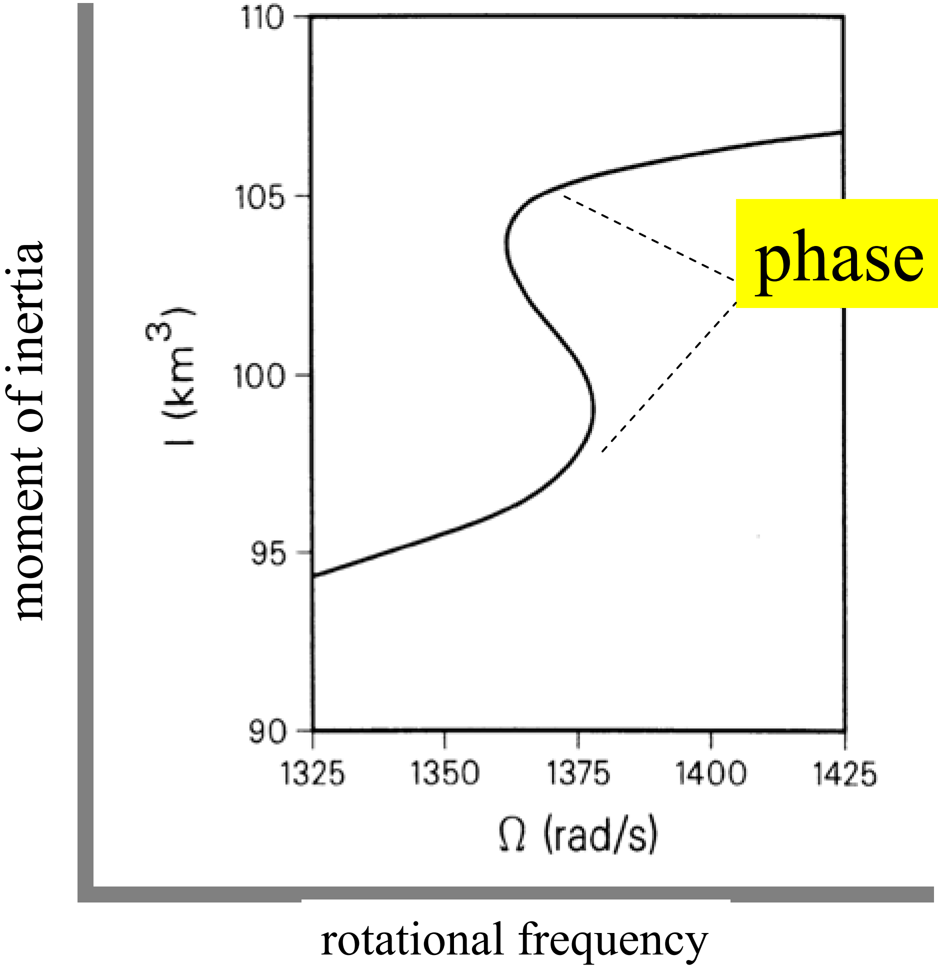
Each model represents a different EoS



Rotational frequencies of pulsars



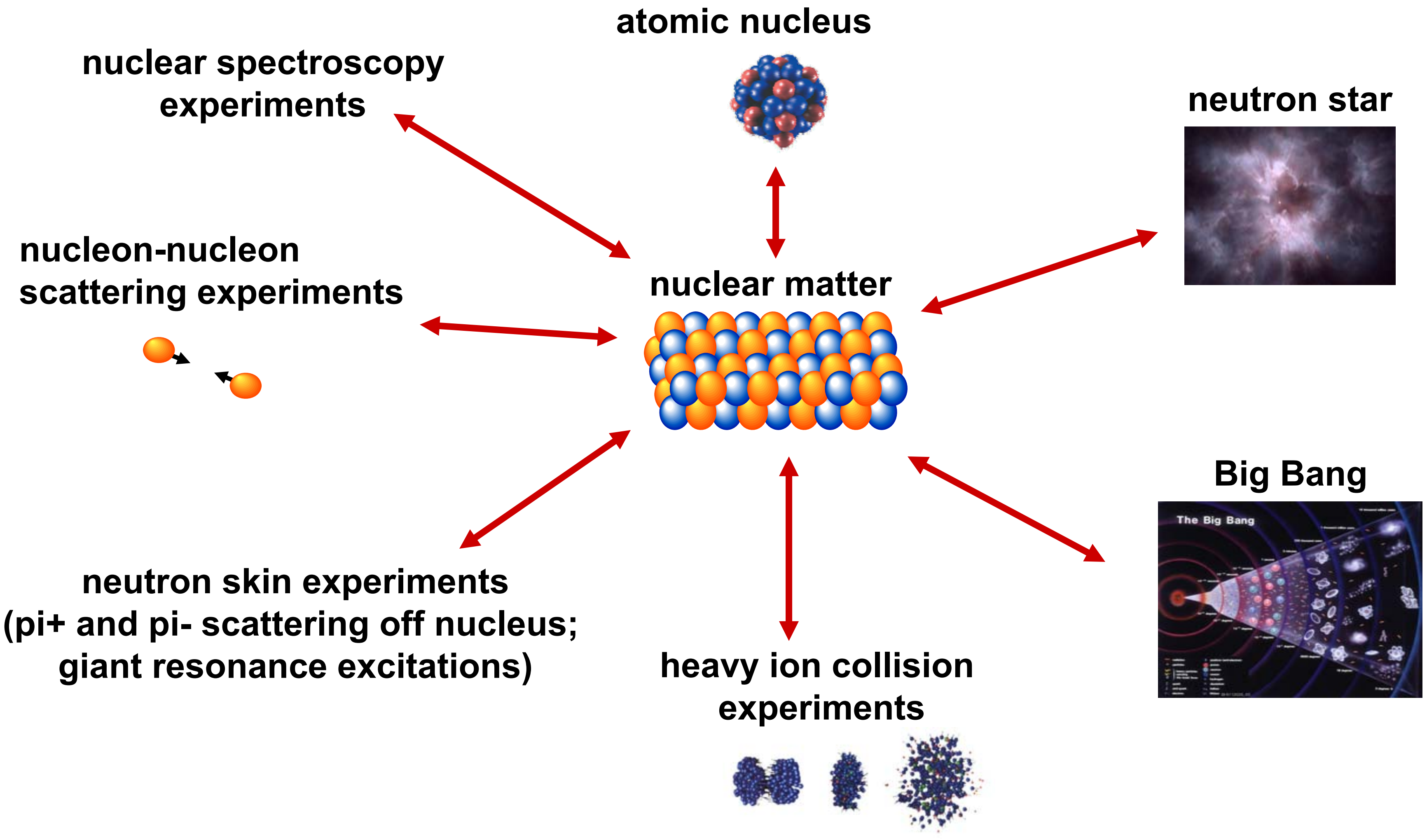
Rotational frequencies of pulsars



phase transition - 10^7 years

- **transition from neutron matter to Quark Gluon Plasma?**

Nuclear matter and its relation with the real world



atomic nucleus

nuclear spectroscopy experiments

neutron star

nucleon-nucleon scattering experiments

nuclear matter

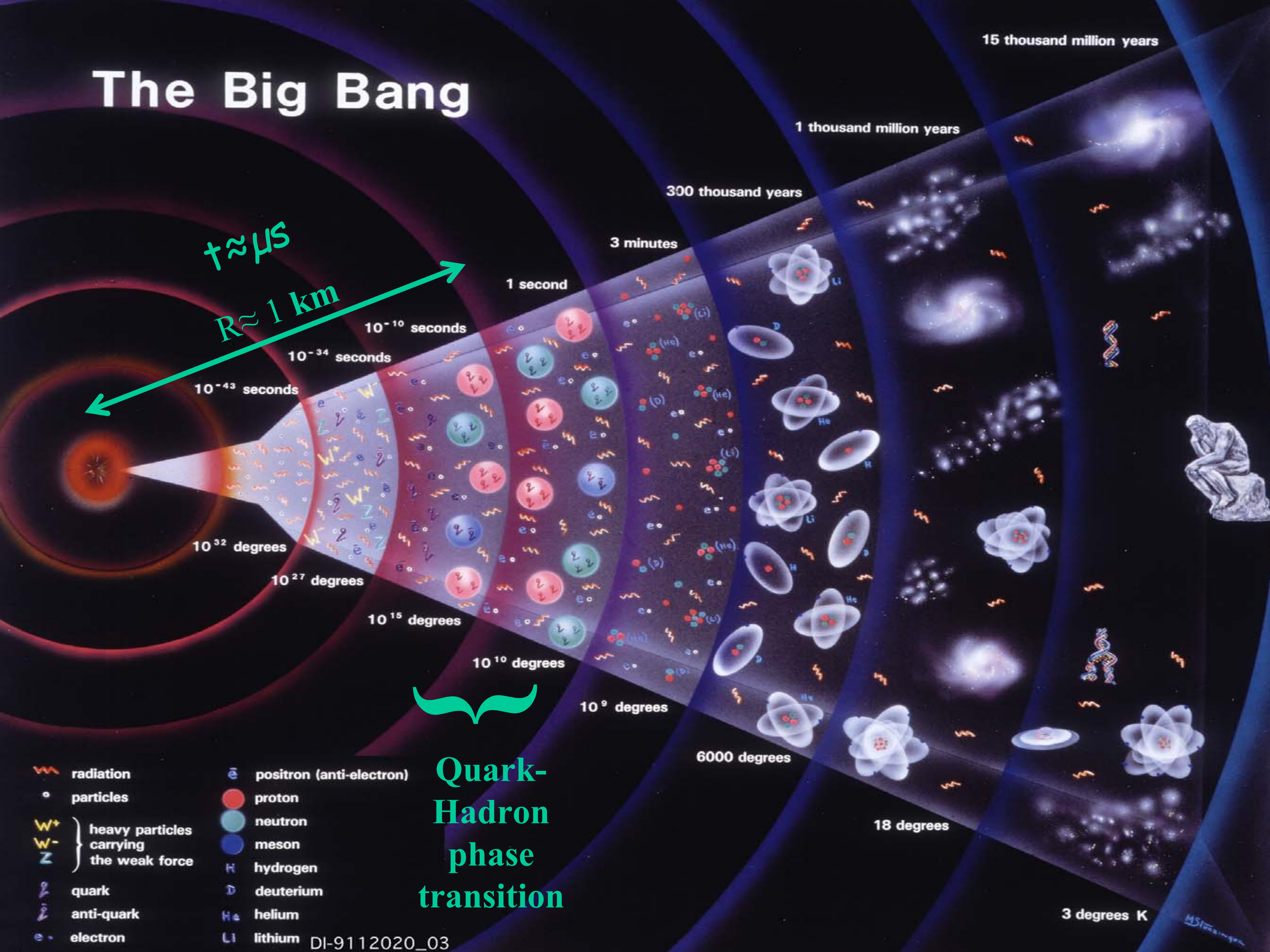
Big Bang

neutron skin experiments (pi+ and pi- scattering off nucleus; giant resonance excitations)

heavy ion collision experiments

The Big Bang and Quark Gluon Plasma

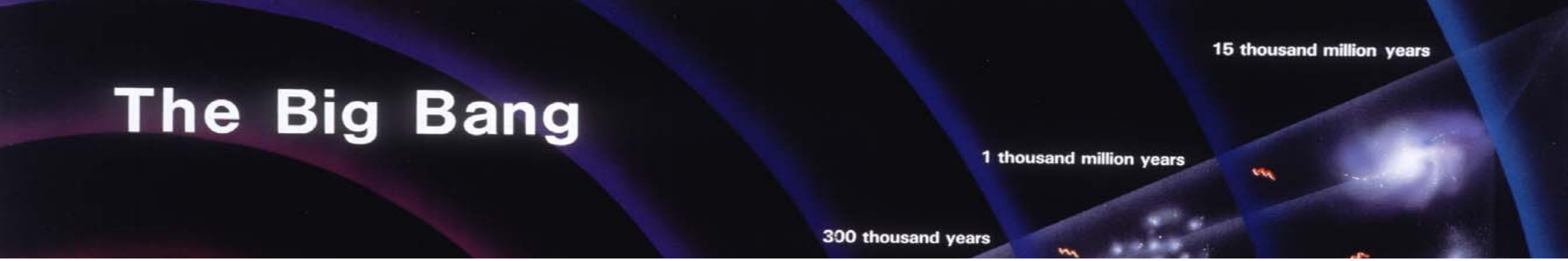
The Big Bang

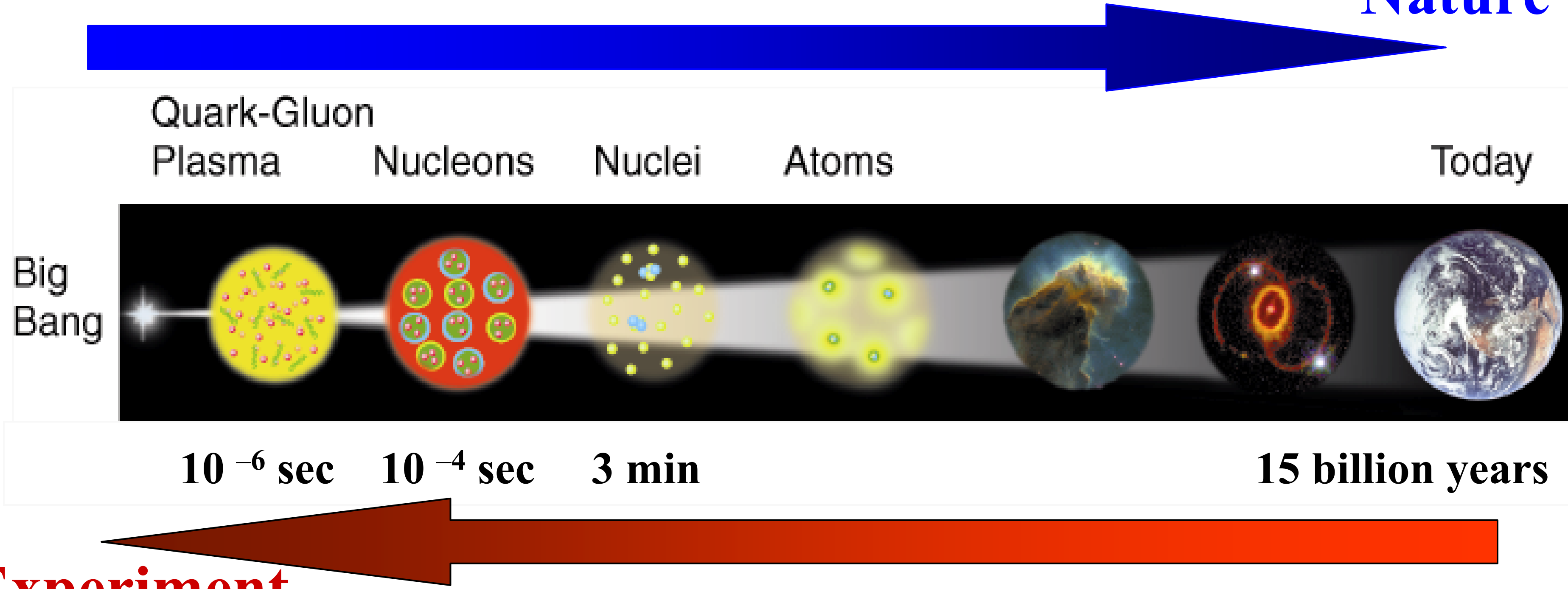


$t \approx \mu s$

$R \approx 1$ km

Quark-Hadron phase transition





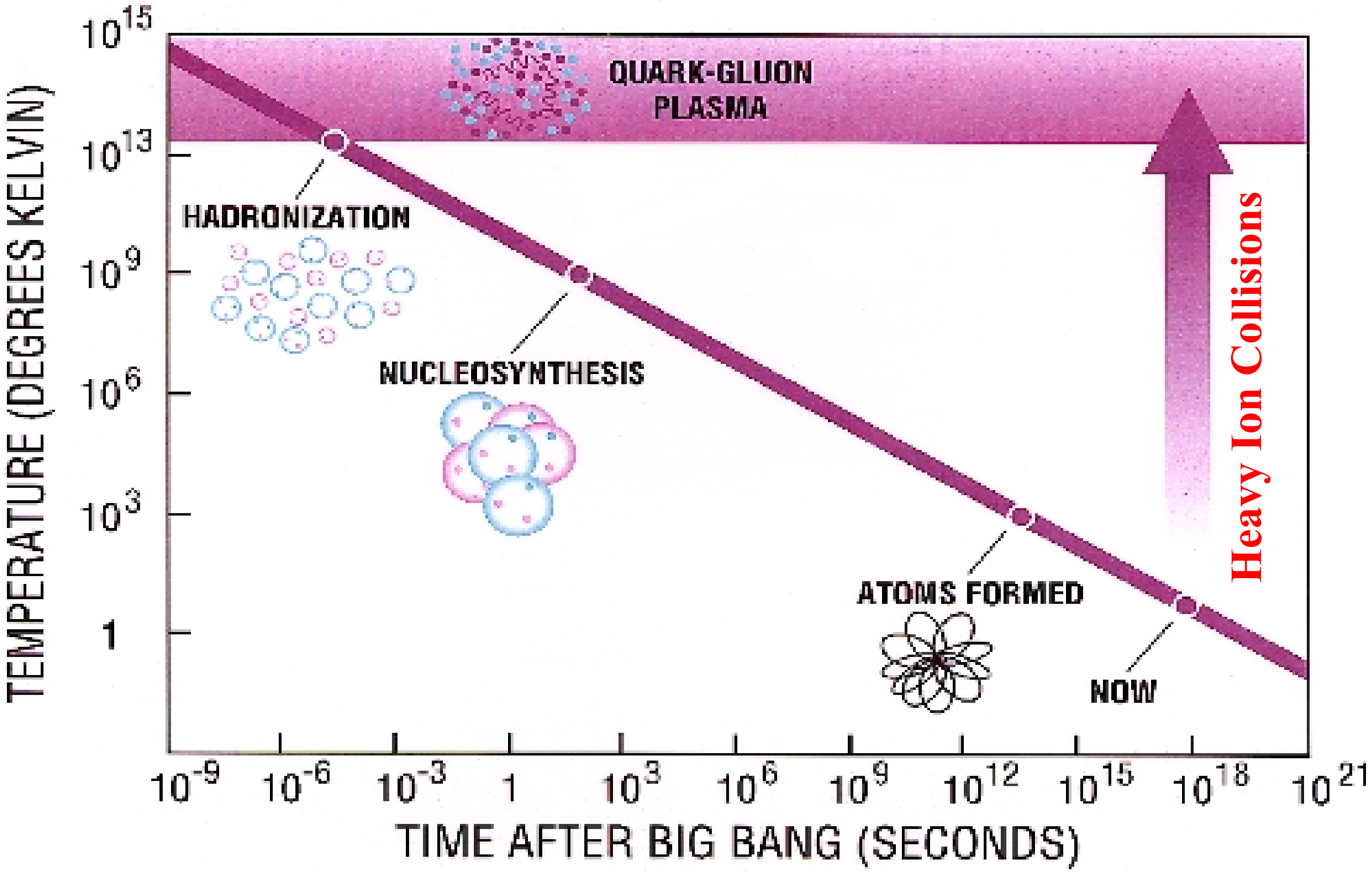
Nature

10^{-6} sec **10^{-4} sec** **3 min** **15 billion years**

Experiment

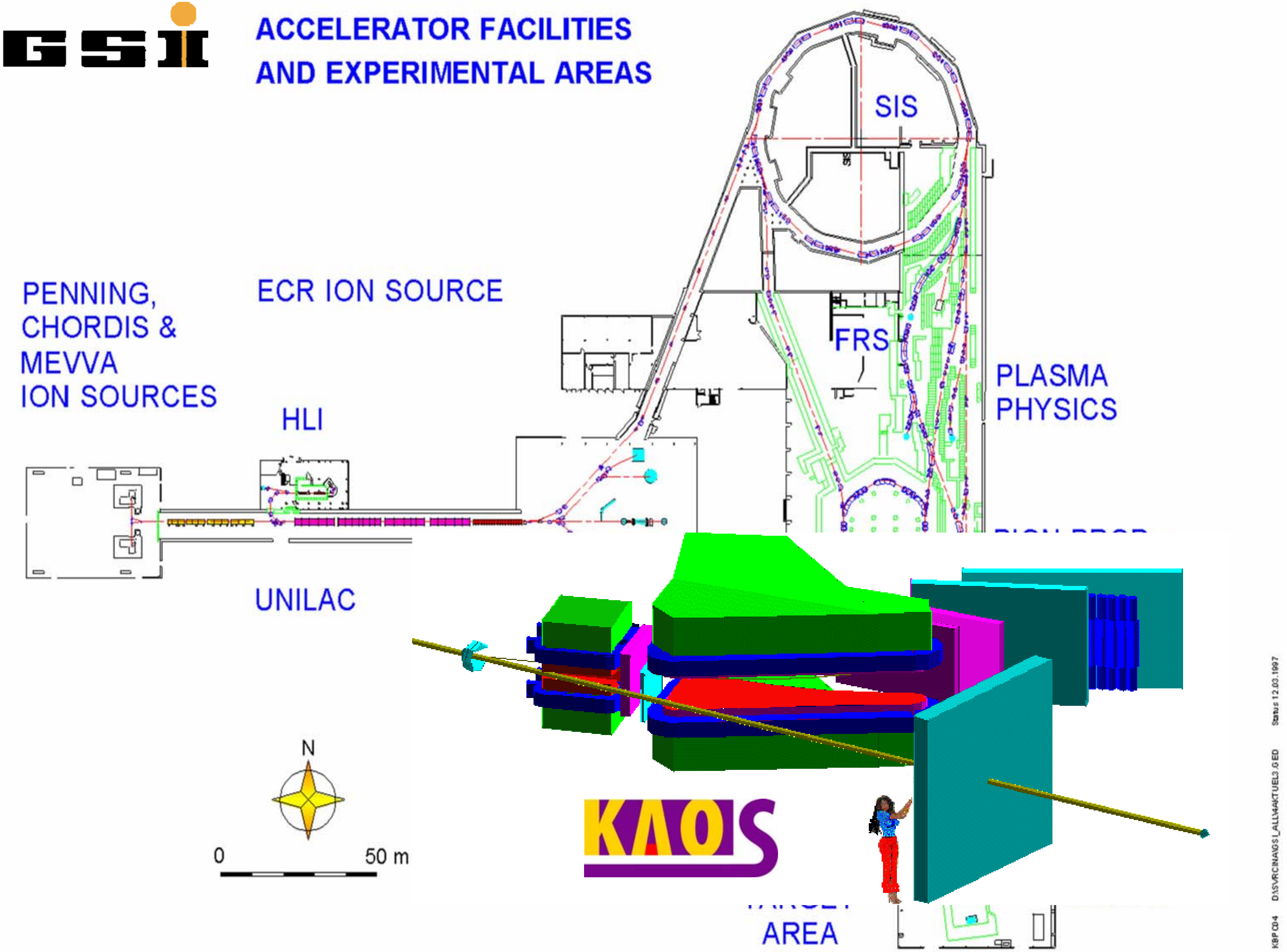
Quark-Hadron phase transition

Temperature evolution of universe



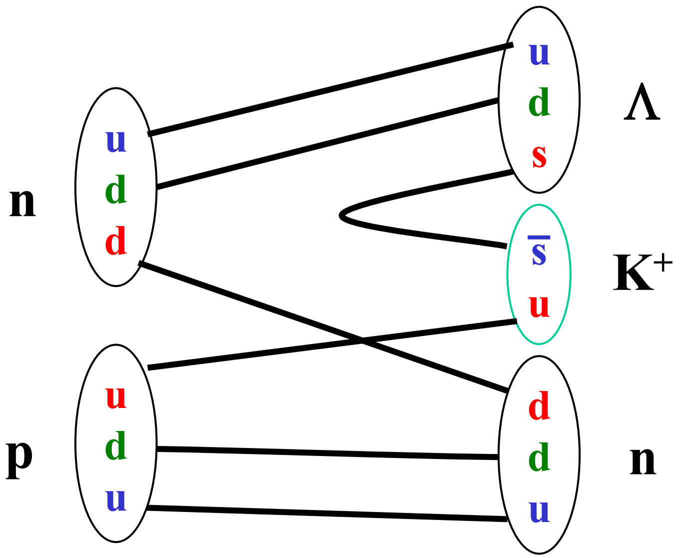
The KaoS experiment and the Equation of State of nuclear matter

ACCELERATOR FACILITIES AND EXPERIMENTAL AREAS



The creation of strange mesons in NN reactions

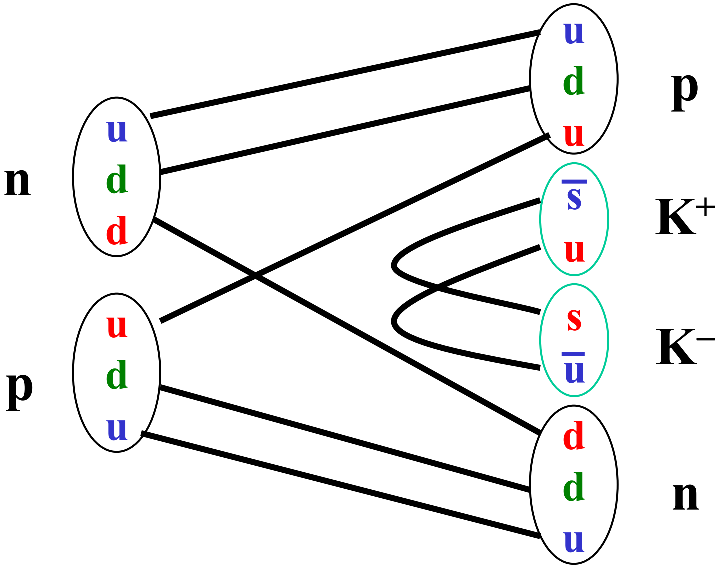
K^+ mesons



production threshold

$$E_{lab} = 1.58\,GeV$$

K^- mesons



production threshold

$$E_{lab} = 2.5\,GeV$$

Additional channels in A+A collisions

e.g.

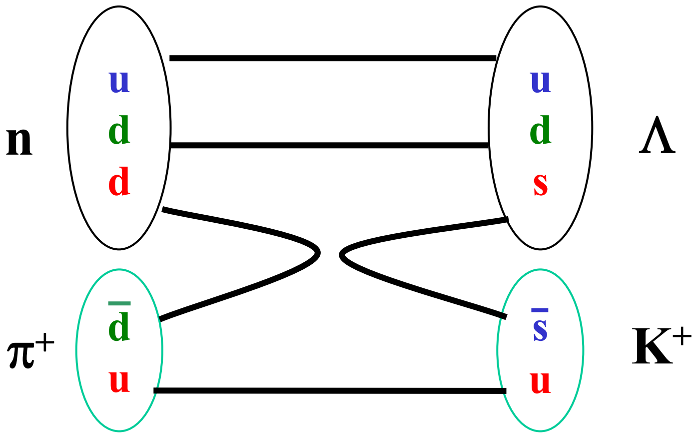
$$NN \rightarrow N\Delta$$

$$N\Delta \rightarrow NK^+Y$$

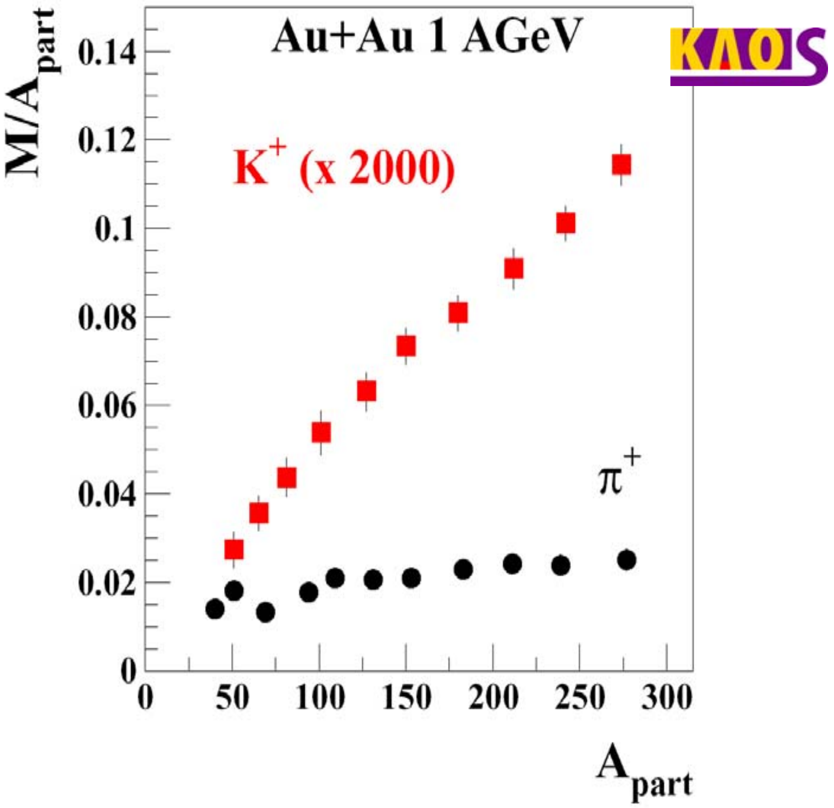
$$\pi N \rightarrow K^+Y$$

$(Y=\Lambda,\Sigma)$

multi step processes !



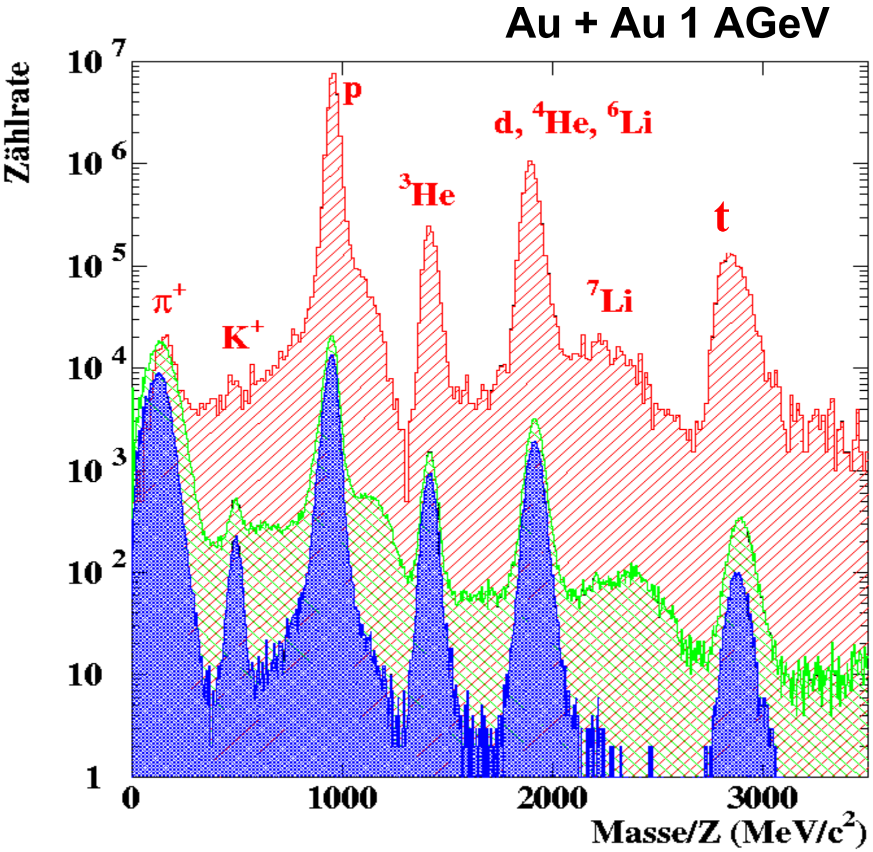
M: multiplicity = number / per collision

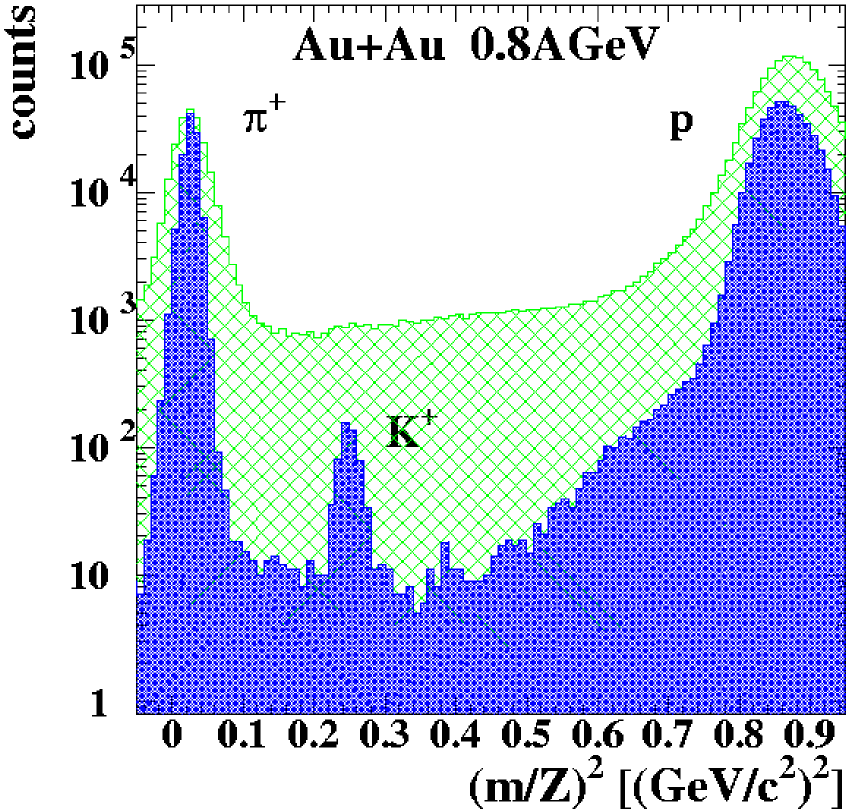


peripheral → central collisions

A_{part} : number of participating nucleons

Particle identification with KaoS





1. Any-charged-particle trigger
2. Kaon trigger (TOF & Cherenkov)
3. Kaon trigger & tracking & 2xTOF

$p / \pi^+ / K^+ \approx 2 \cdot 10^4 / 10^3 / 1$

Soft/hard EoS – more/less subthreshold kaons

Approach A

- The density reached in both cases is the same
- If the EoS is soft, more energy remains for producing kaons

Approach B

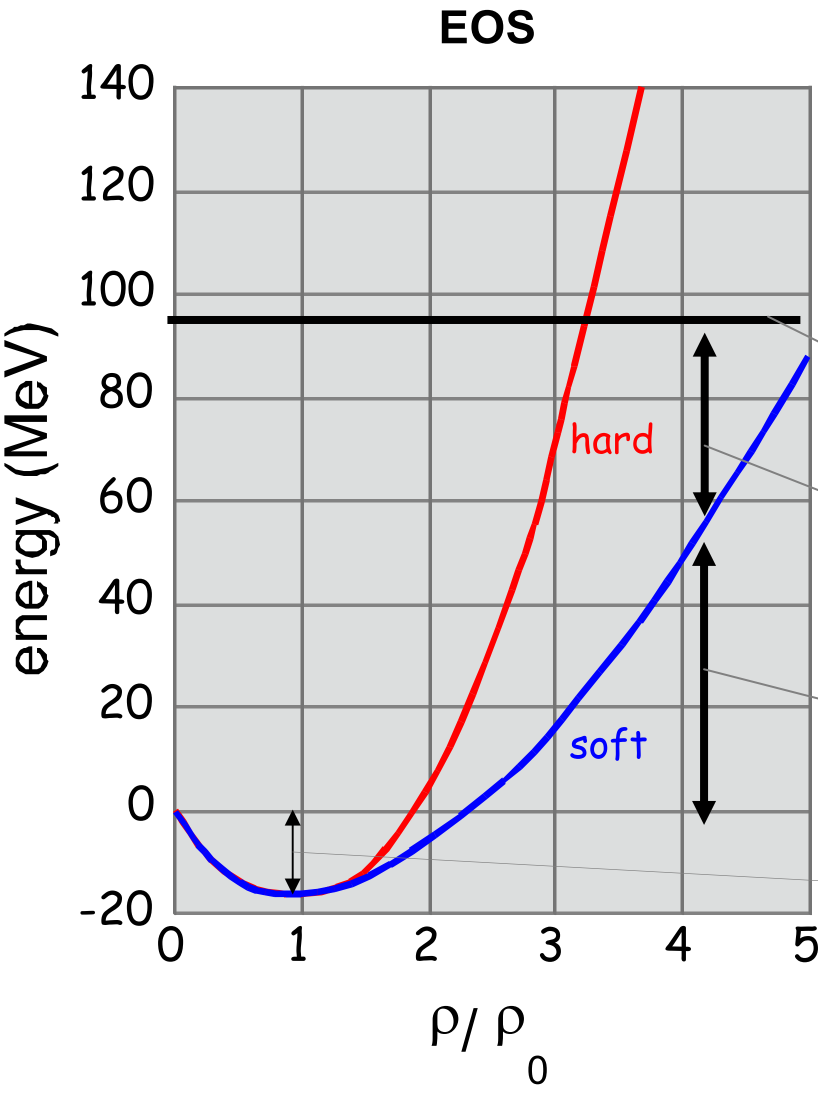
- The density reached in case of soft EoS is higher so two-step processes run at a higher rate
- The two-step processes contribute significantly to subthreshold kaon production

→ somewhat model dependent…

Model dependence can be reduced by taking ratios

Subthreshold kaons and EoS – approach A

$$\varepsilon_{\text{particle}} = \varepsilon_{\text{thermal}} + \varepsilon_{\text{compression}} + \varepsilon_{\text{binding}}$$



$$\varepsilon = E^{\text{cm}}_{\text{beam}} \big/ \text{particle} = 100\ \text{MeV}$$

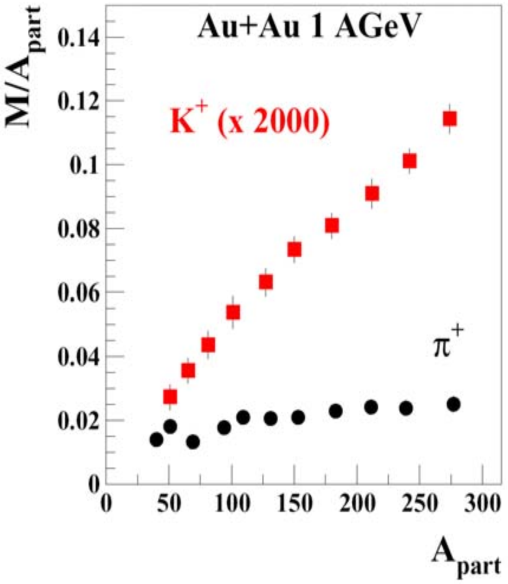
$$\varepsilon_{\text{thermal}} = 40\ \text{MeV}$$

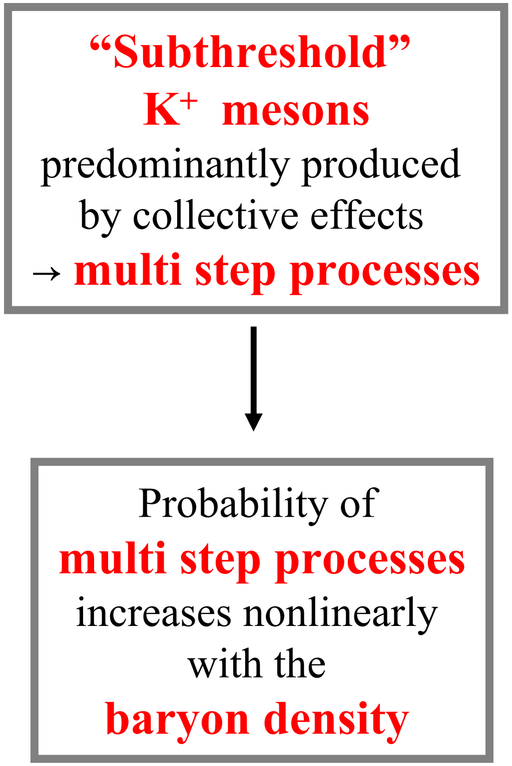
$$\varepsilon_{\text{compression}} = 60\ \text{MeV}$$

$$\varepsilon(\rho_0) = -16\,\text{MeV}$$

Subthreshold kaons and EoS – approach B

production threshold: E_{lab}= 1.58 GeV





"Subthreshold"
K^+ mesons
predominantly produced
by collective effects
→ **multi step processes**

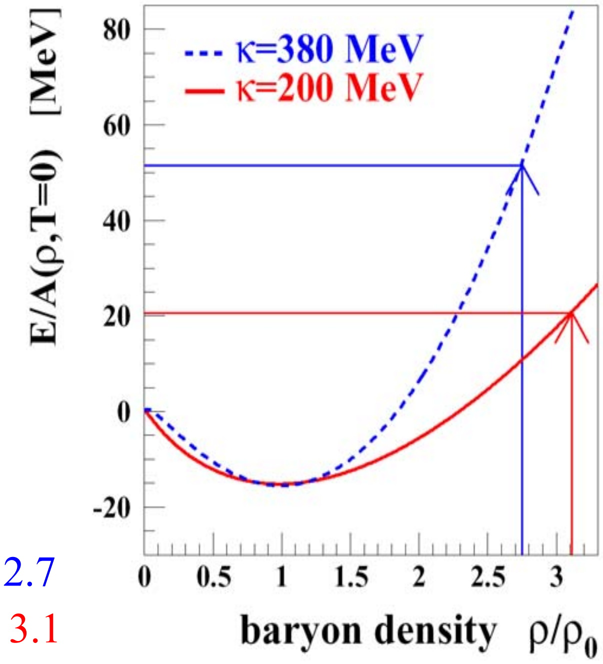
Probability of
multi step processes
increases nonlinearly
with the
baryon density

e.g.

$$NN \rightarrow N\Delta$$
$$N\Delta \rightarrow NK^+Y$$
$$\pi N \rightarrow K^+Y$$
(Y=Λ,Σ)

IQMD:
Au+Au
1AGeV

stiff EoS $\rho_{max} / \rho_0 \cong 2.7$
soft EoS $\rho_{max} / \rho_0 \cong 3.1$



Compression modulus of nuclear matter (ρ > ρ0)

Model dependence can be somewhat reduced by considering ratios

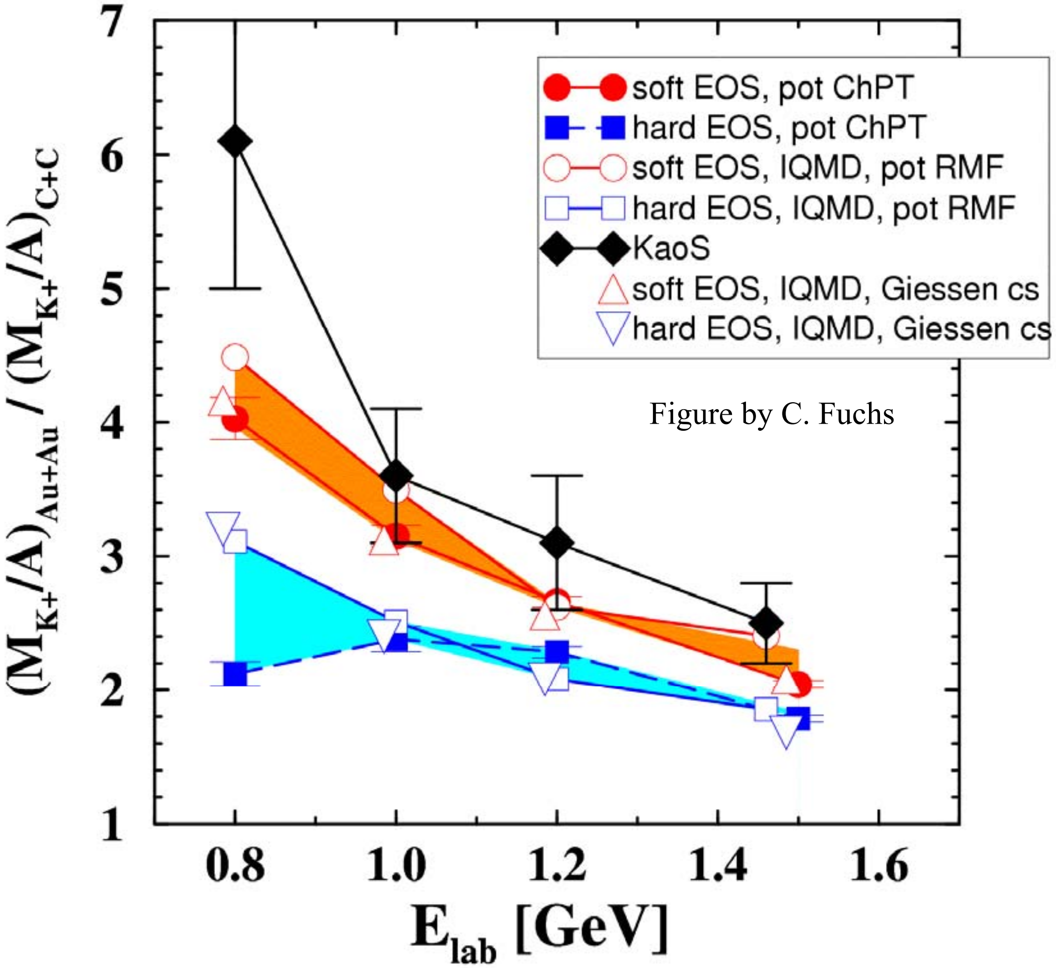


Figure by C. Fuchs

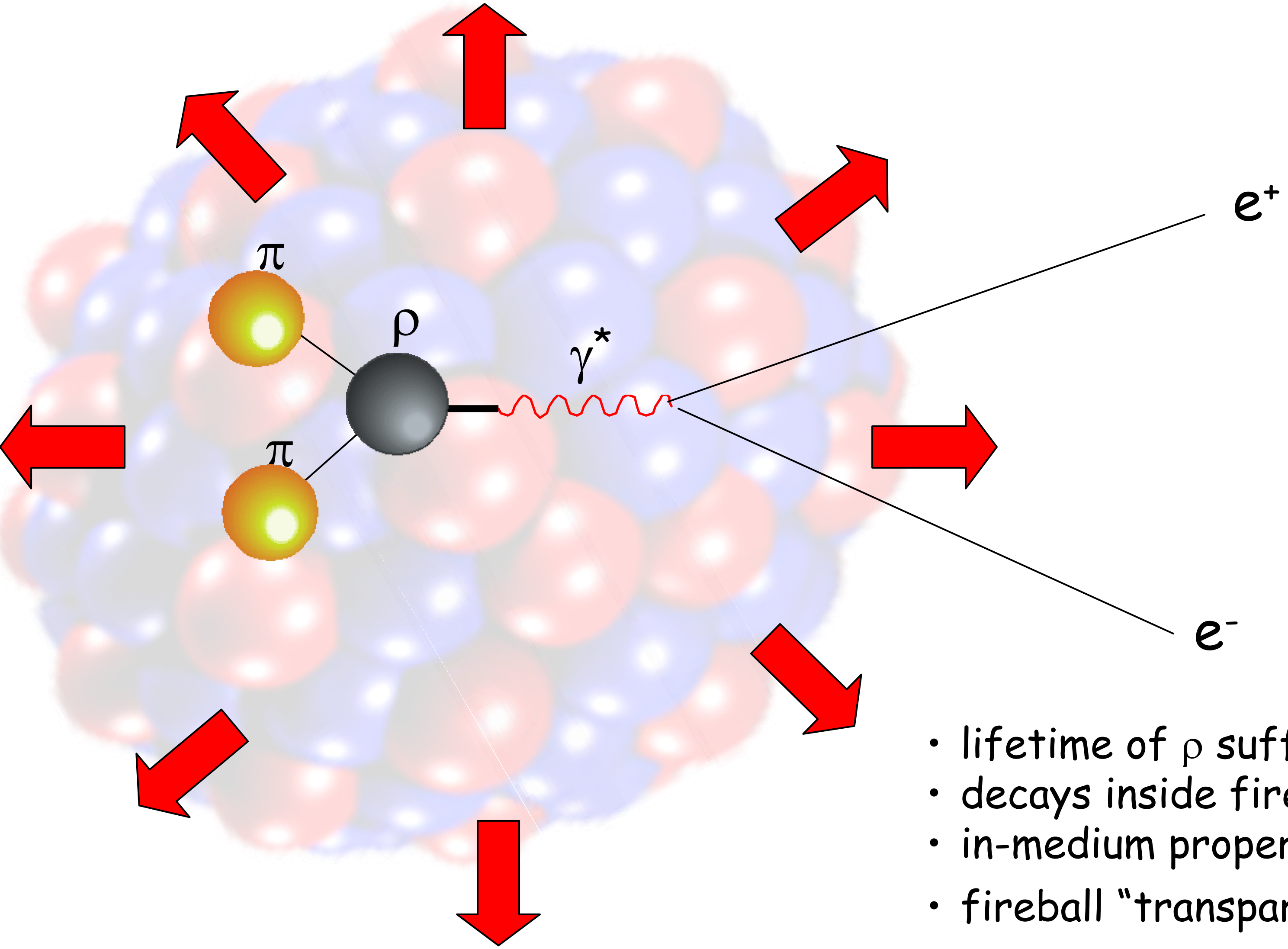
$\kappa \approx$ 200 MeV
soft EoS

Experiment:
C. Sturm et al., Phys. Rev. Lett. 86 (2001) 39

Theory:
QMD C. Fuchs et al., PRL 86 (2001) 1974
IQMD Ch. Hartnack, J. Aichelin,
J. Phys. G 28 (2002) 1649

CERES and mass modification of the ρ-meson in medium

Probing the interior of the fireball via vector mesons & lepton pairs



- lifetime of ρ sufficiently short
- decays inside fireball
- in-medium properties conserved
- fireball “transparent” for electrons

How to measure e^+e^- pairs?

the reaction $\pi\pi \rightarrow \rho \rightarrow e^+e^-$ in AA collisions is

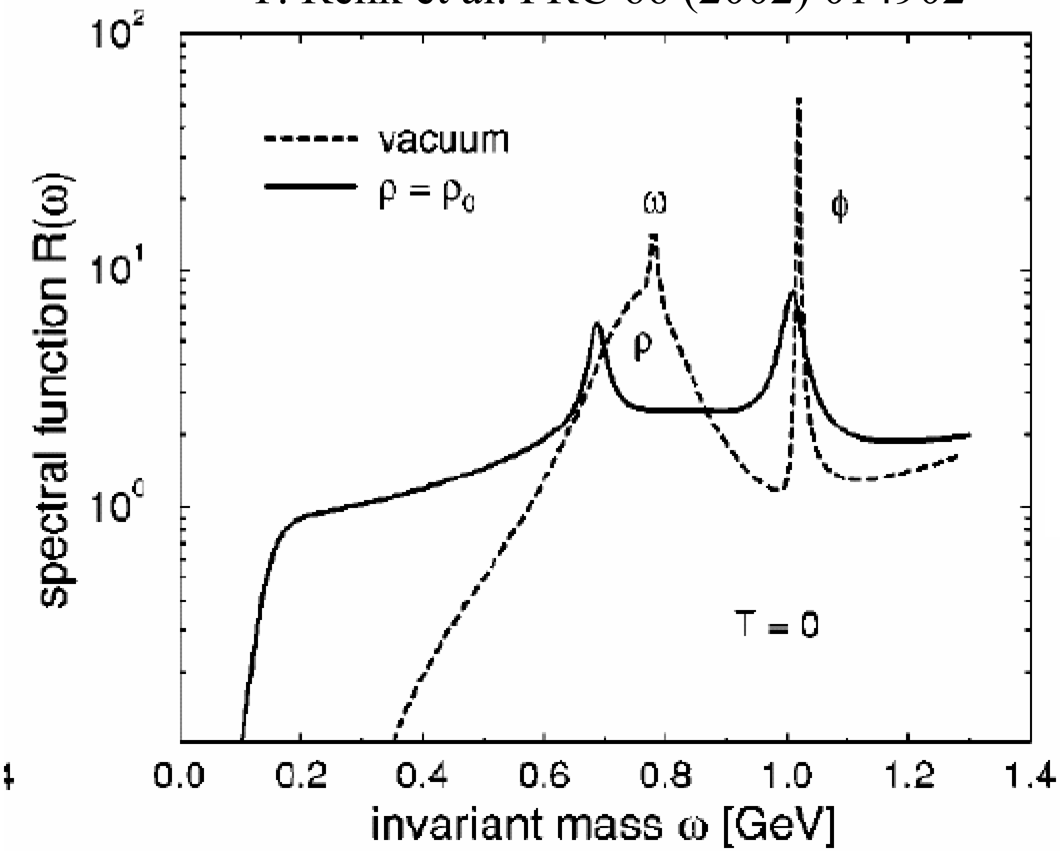
a) extremely rare ($\Gamma_{\rho \rightarrow e^+e^-}/\Gamma$ = 4.5 10^{-5})
b) very difficult to measure/trigger on

why:

a) electrons are easily confused with the relatively copiously produced pions (large background)
b) pair production $\gamma \rightarrow e^+e^-$ very common reaction of photons with any type of material (huge background)
c) Dalitz-decays (e.g. $\pi \rightarrow \gamma e^+e^-$, gigantic background)
d) dramatic combinatorial background

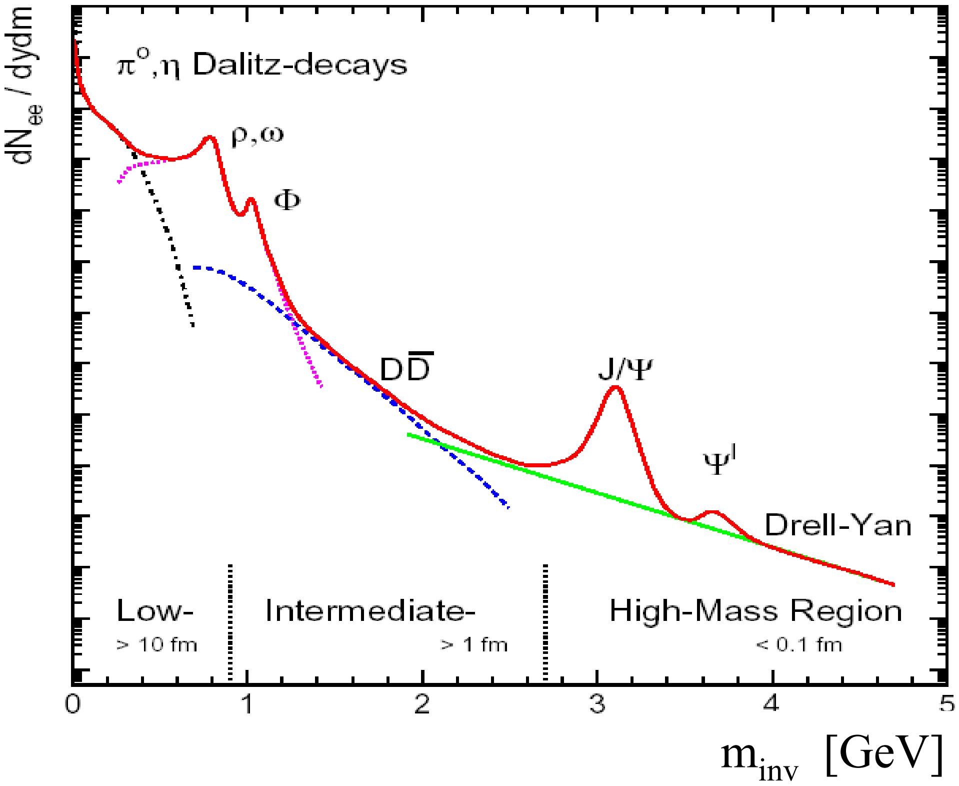
Model predictions for vector mesons

T. Renk et al. PRC 66 (2002) 014902



- melting of the ρ-meson
- mass shift and broadening of the ω-meson
- small effects on the ϕ-meson

Dilepton sources in heavy ion collisions

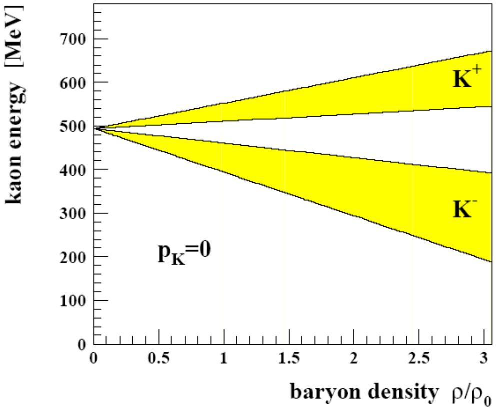


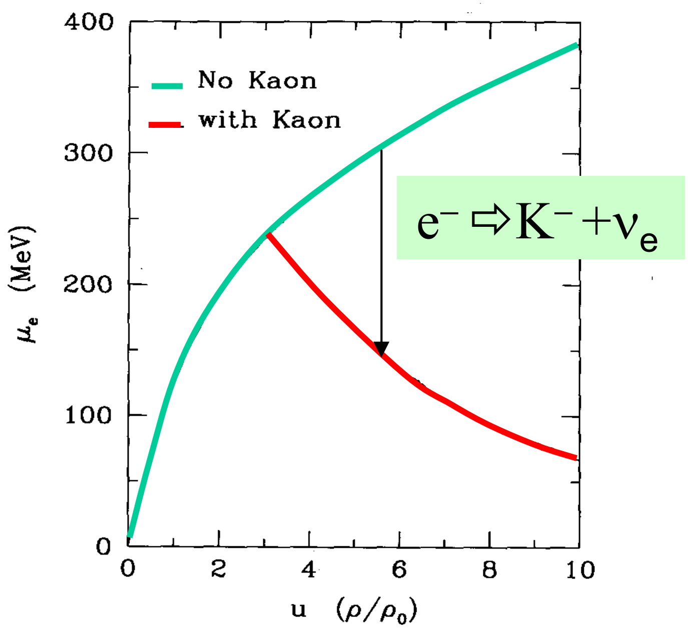
	mass [MeV/c^2]	cτ [fm]	dominating decay	e^+e^- branching ratio
ρ	768	1.3	ππ	4.4×10^{-5}
ω	782	23.4	$\pi^+\pi^-\pi^0$	7.2×10^{-5}
Φ	1019	44.4	K^+K^-	3.1×10^{-4}

E_{thr} (NN)
1.7 GeV
1.8 GeV
2.6 GeV

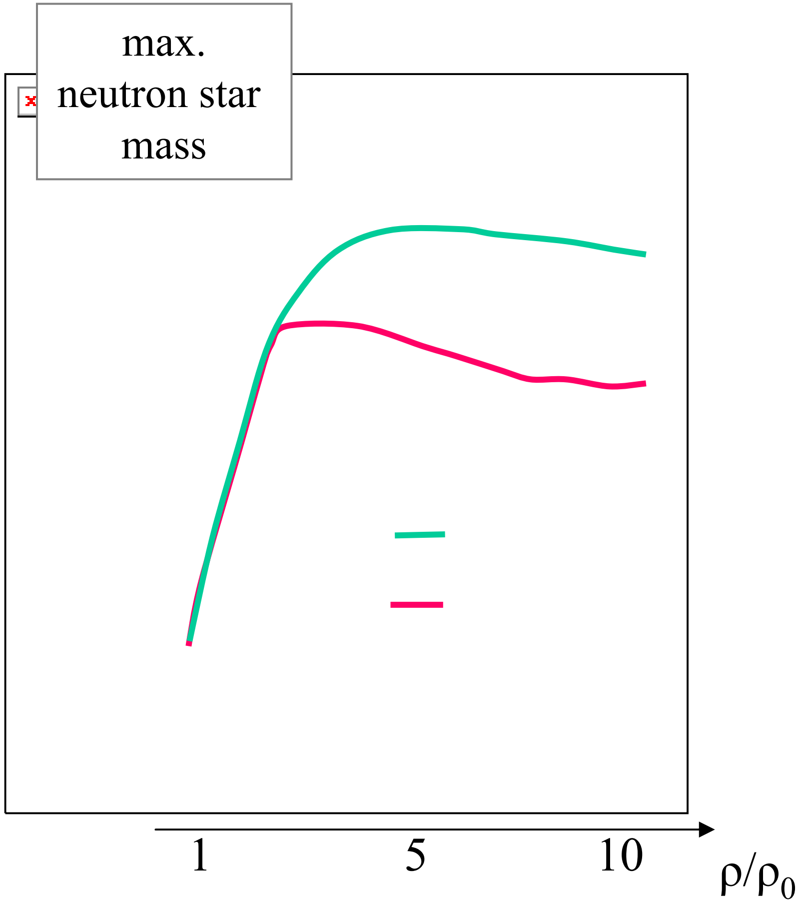
Mass modifications may be of relevance for neutron stars, example: K^- condensation

due to a dropping K^- mass : $e^- \Rightarrow K^- + \nu_e$, $n \Rightarrow p + K^-$) ?





$e^- \Rightarrow K^- + \nu_e$



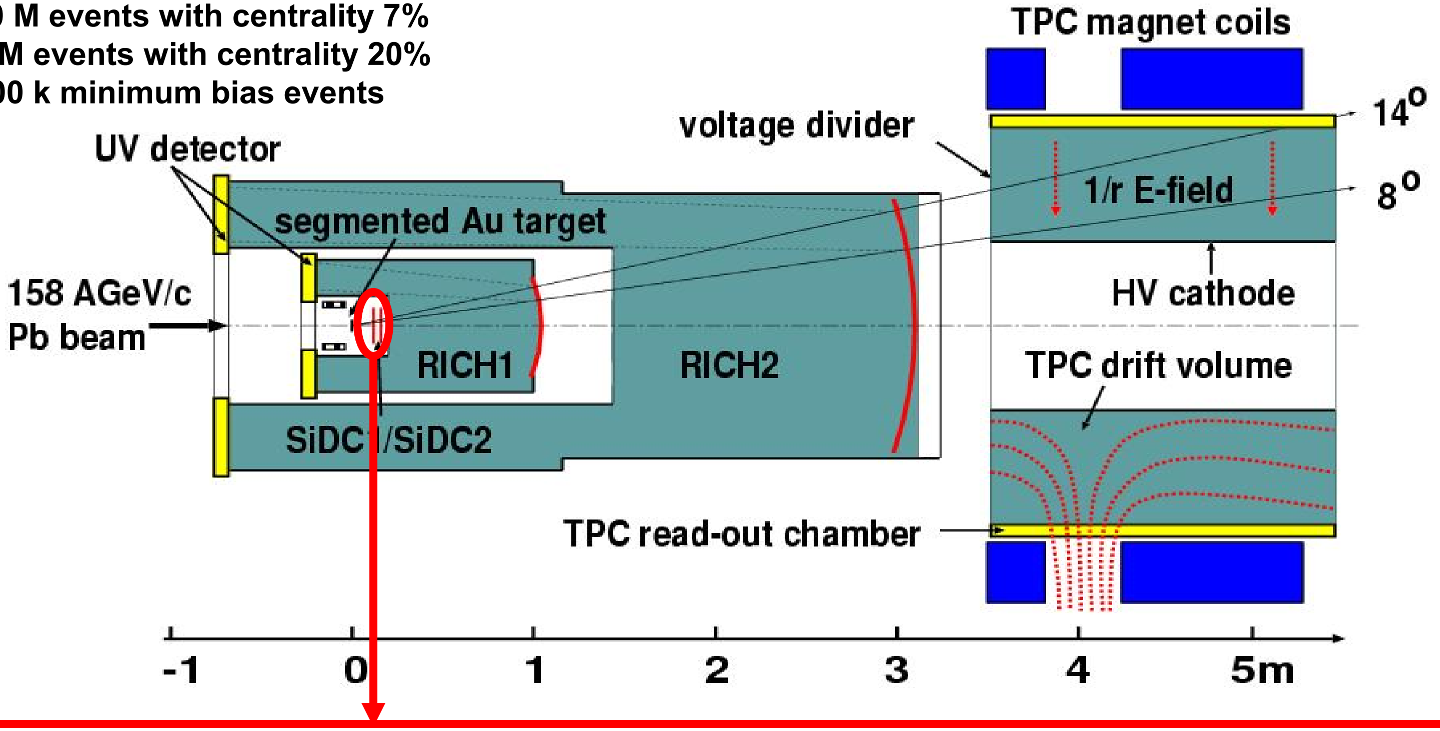
max. neutron star mass

G.E. Brown, H.A. Bethe, Astrophys. Jour. 423 (1994) 659

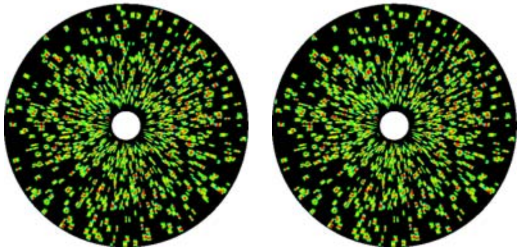
G.Q.Li, C.H. Lee, G.E. Brown , Nucl. Phys. A 625 (1997)

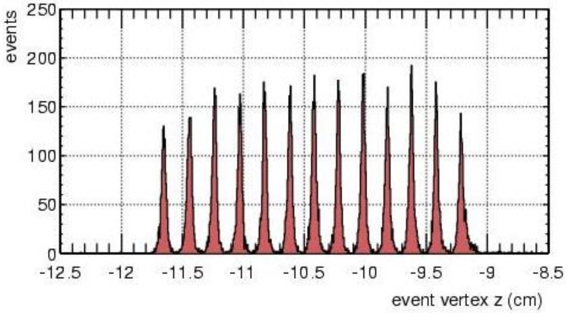
setup with TPC: 1999 and 2000

run 2000: 30 M events with centrality 7%
2 M events with centrality 20%
500 k minimum bias events



SD: event vertex, track vertex and angle

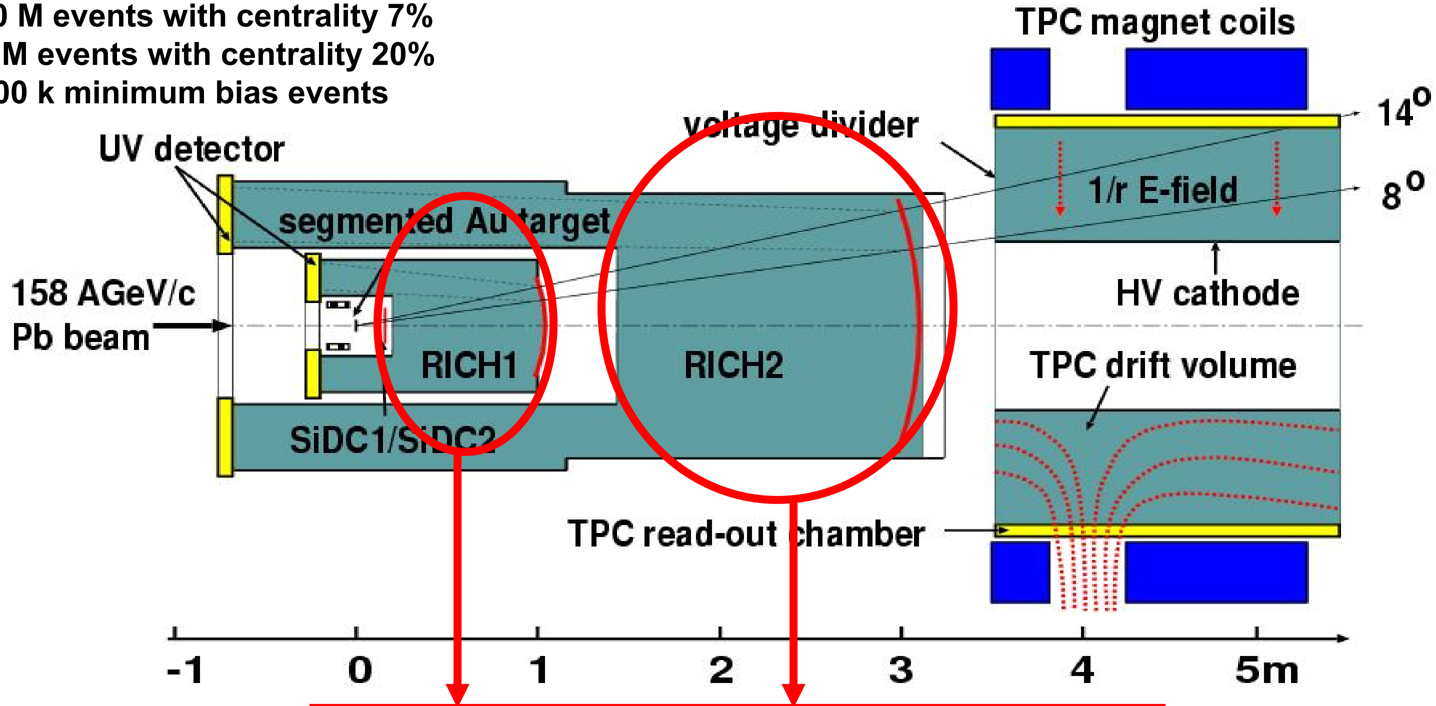




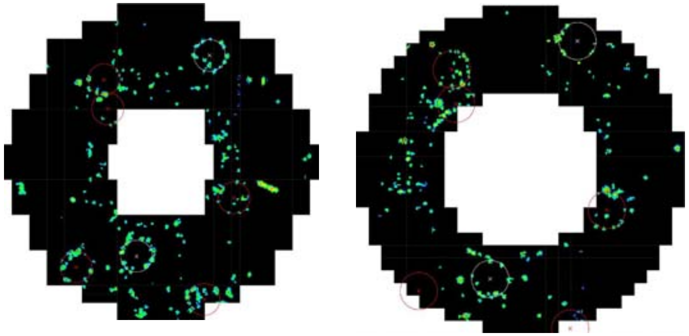
event Δz = 0.2 mm
track $\Delta\theta$ = 0.2 mrad
$\Delta\varphi$ = 2 mrad

setup with TPC: 1999 and 2000

run 2000: 30 M events with centrality 7%
2 M events with centrality 20%
500 k minimum bias events

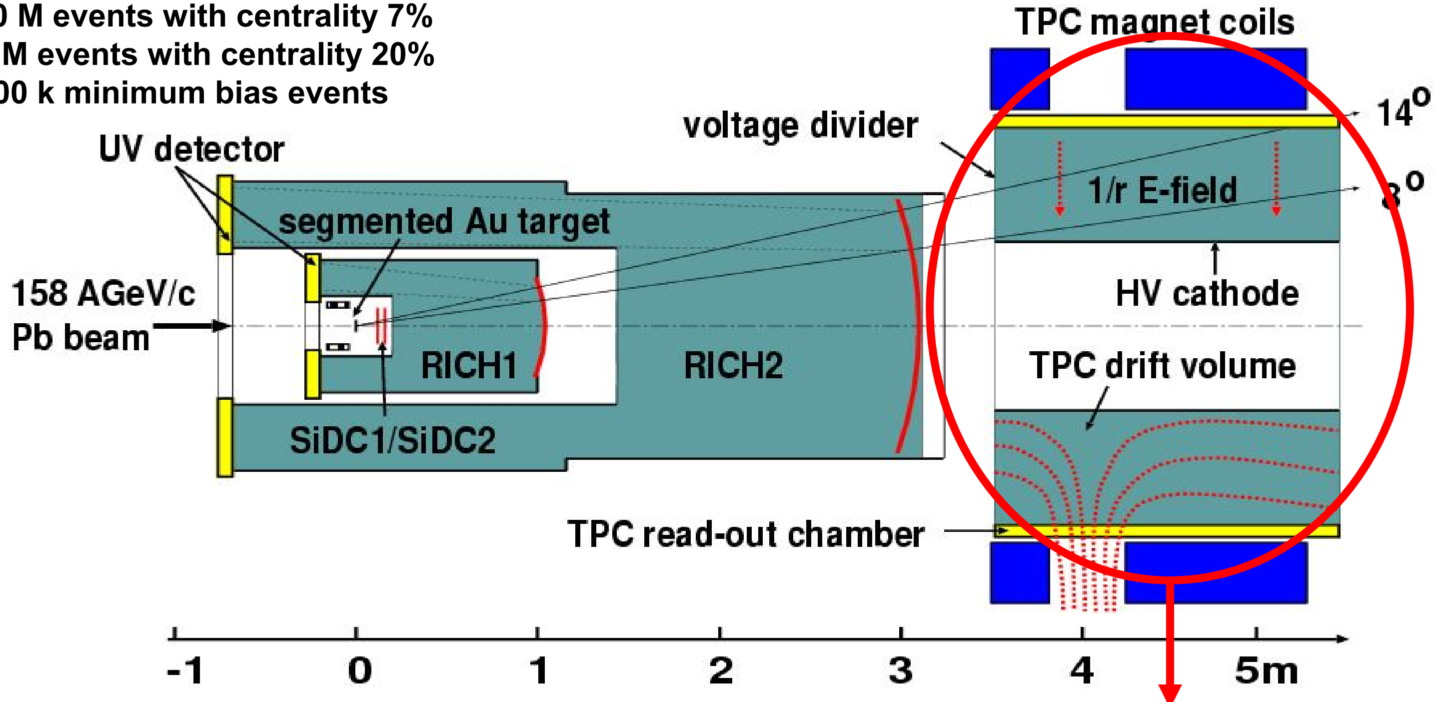


RICH's: electron identification

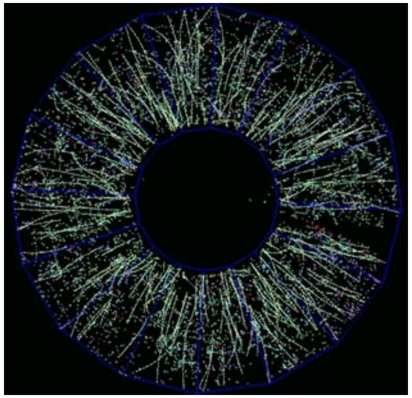


setup with TPC: 1999 and 2000

run 2000: 30 M events with centrality 7%
2 M events with centrality 20%
500 k minimum bias events



radial drift TPC: momentum and energy loss

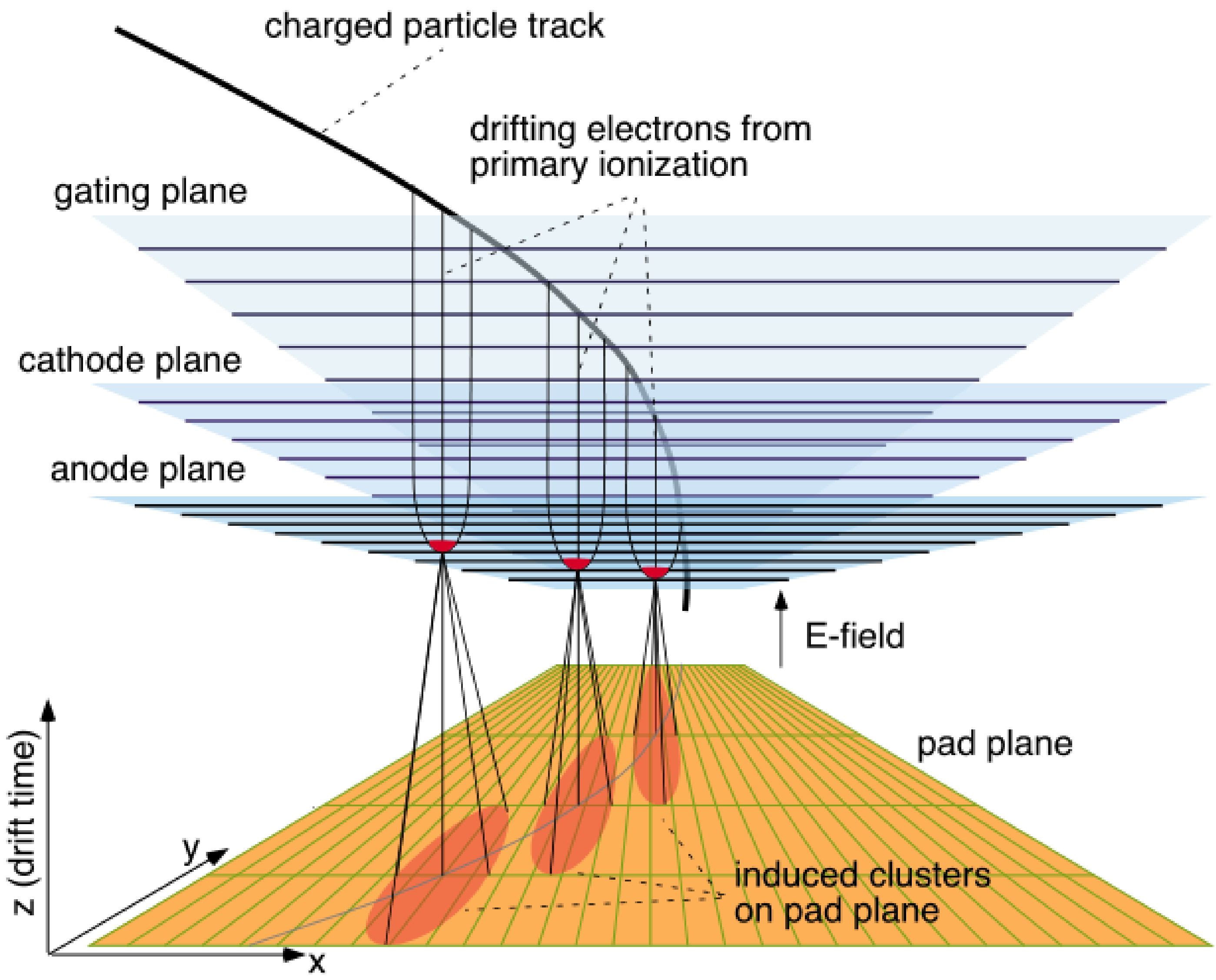


$\Delta p/p = 2\% \oplus 1\% * p/\mathrm{GeV}$

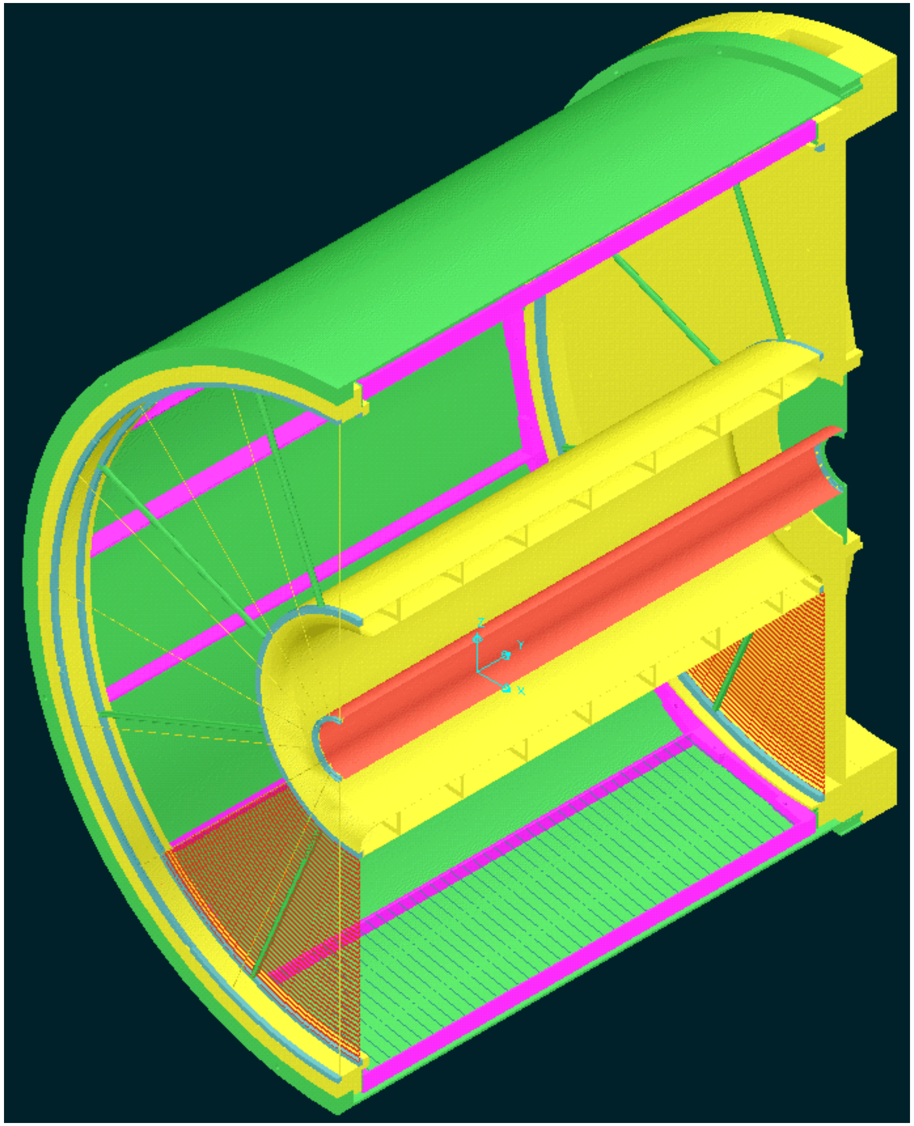
$\Delta m/m = 3.8\ \%$ for ϕ

$\Delta(dE/dx)/(dE/dx) = 10\%$

TPC working principle - 3D-imaging



CERES TPC



cylinder Φ 2.6 m x 2 m

gas Ne:CO2 (80:20)

radial E-field ER~1/r with E=200-600 V/cm

radial drift with v=0.7-2.4 cm/μs

centrality determination

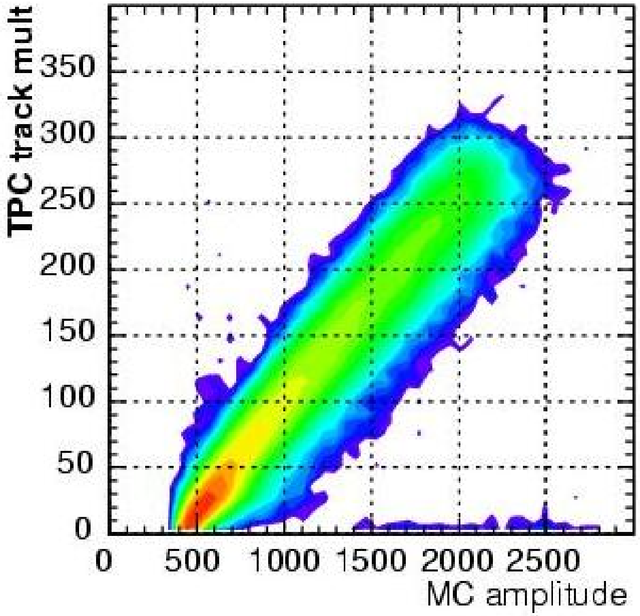
Pb+Au at 158 GeV per nucleon

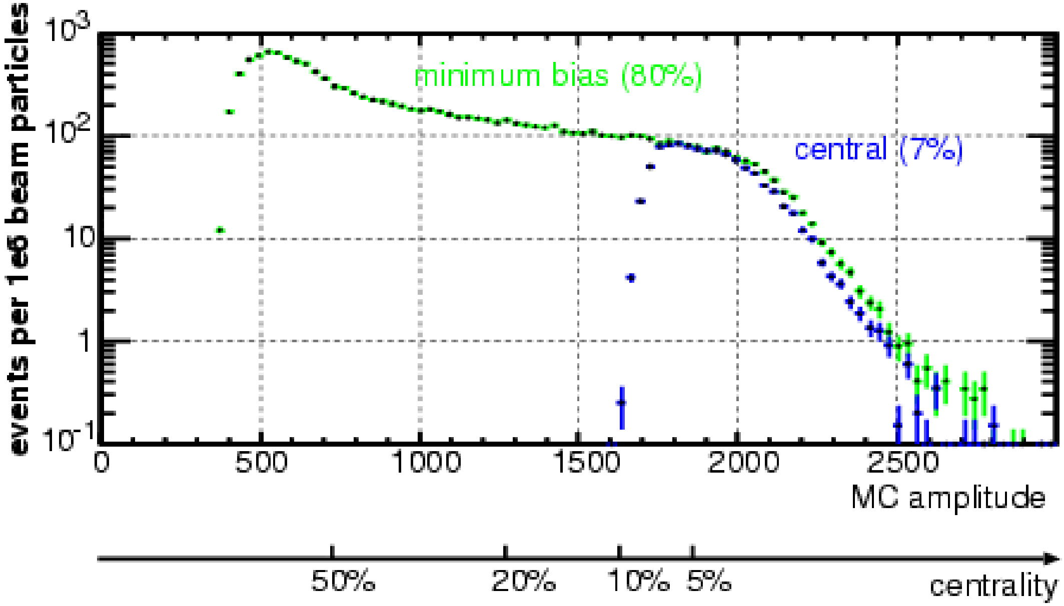
centrality deduced from the multiplicity of charged particles around mid-rapidity

MC scintillator amplitude $2.95 < \eta < 4.05$

TPC track multiplicity $2.10 < \eta < 2.80$

mid-rapidity $y = 2.91$



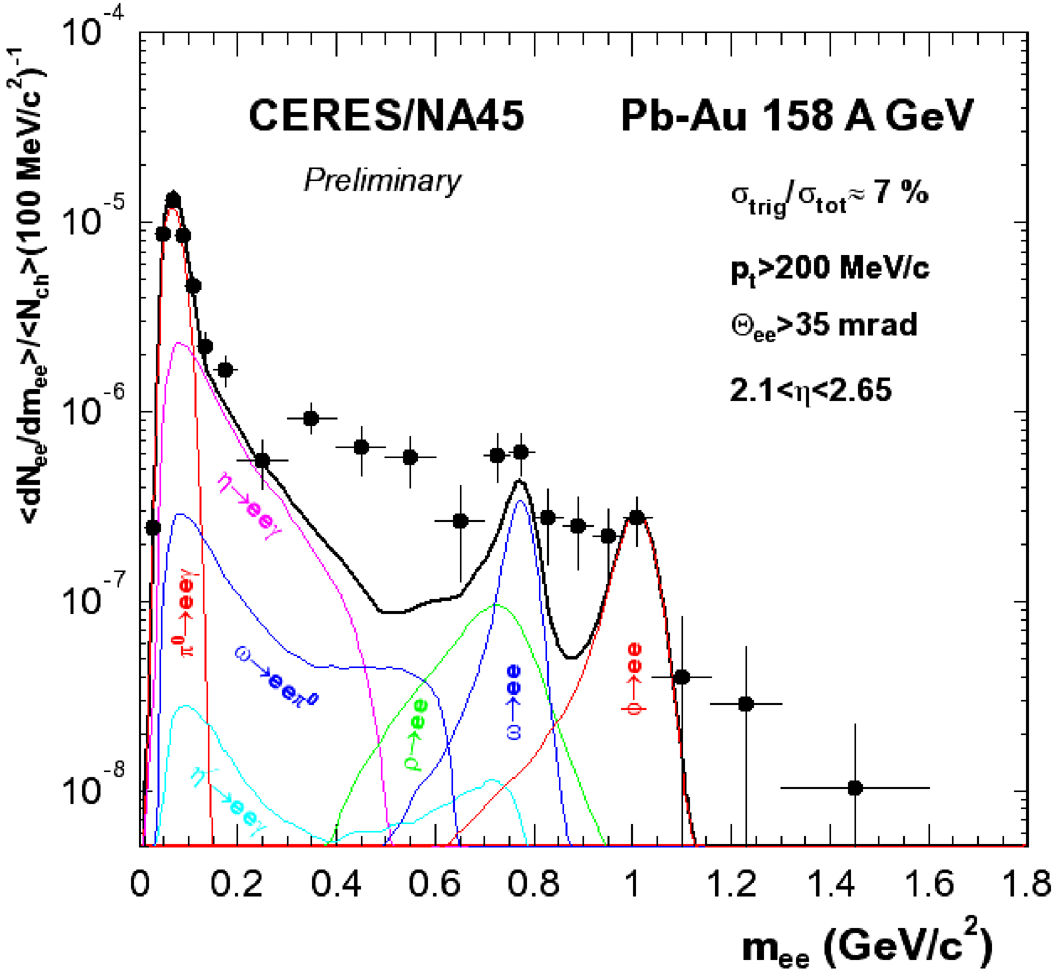


e^+e^- mass spectrum: enhancement

Pb+Au at 158 GeV per nucleon

Sergey Yurevich

comparison to the hadron decay cocktail



enhancement over hadron decay cocktail

for 0.2 GeV < m_{ee} < 1.1 GeV:
2.35±0.31 (stat)

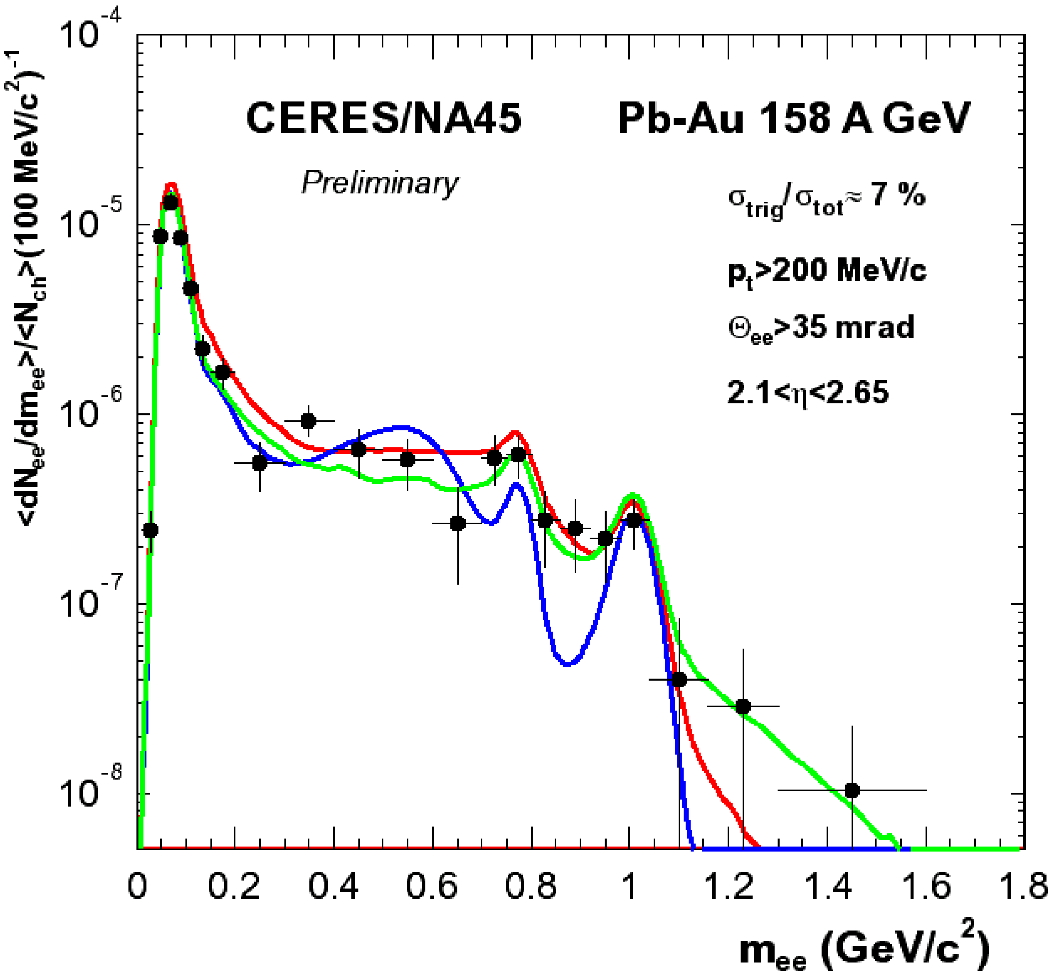
for 0.2 GeV < m_{ee} < 0.6 GeV:
2.80±0.50 (stat)

overall systematic uncertainty of normalization: 21%

e+e- mass spectrum: comparison to the models → indication for mass modification of ρ

Pb+Au at 158 GeV per nucleon

Sergey Yurevich



calculation by R.Rapp using Rapp/Wambach medium modification of rho spectral function

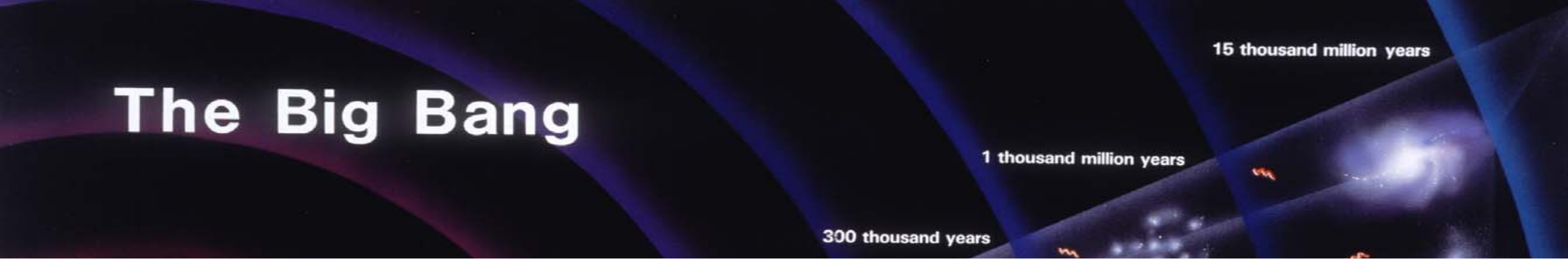
calculation by R.Rapp using Brown-Rho scaling

B. Kämpfer, thermal emission

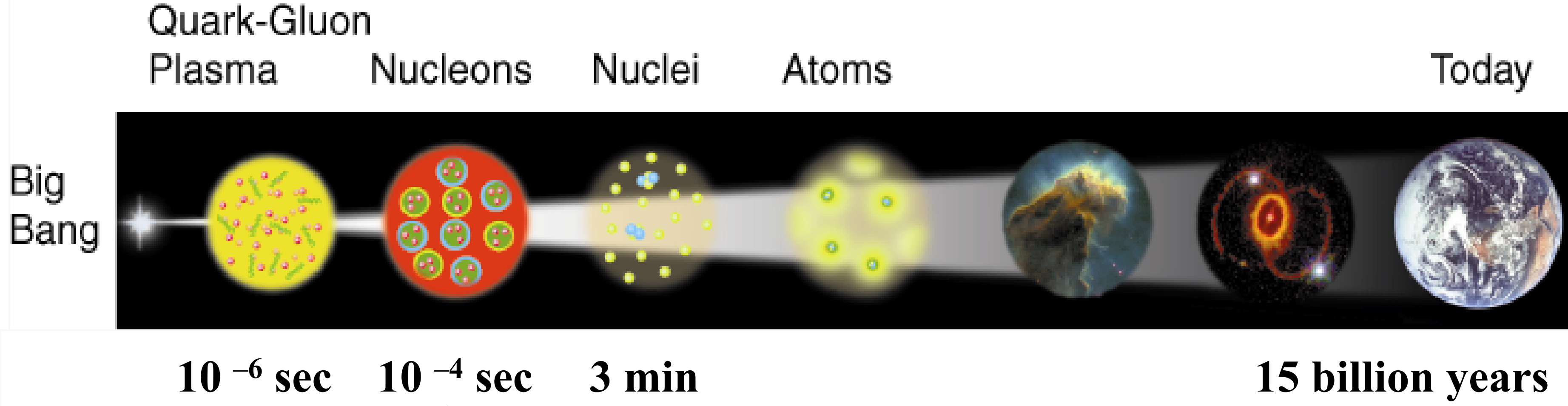
...added to the cocktail.

in the 0.8 < m < 0.98 GeV region:
Brown-Rho curve: $\chi^2/n = 2.4$
the other two curves: $\chi^2/n \sim 0.3$

ALICE and the Early Universe



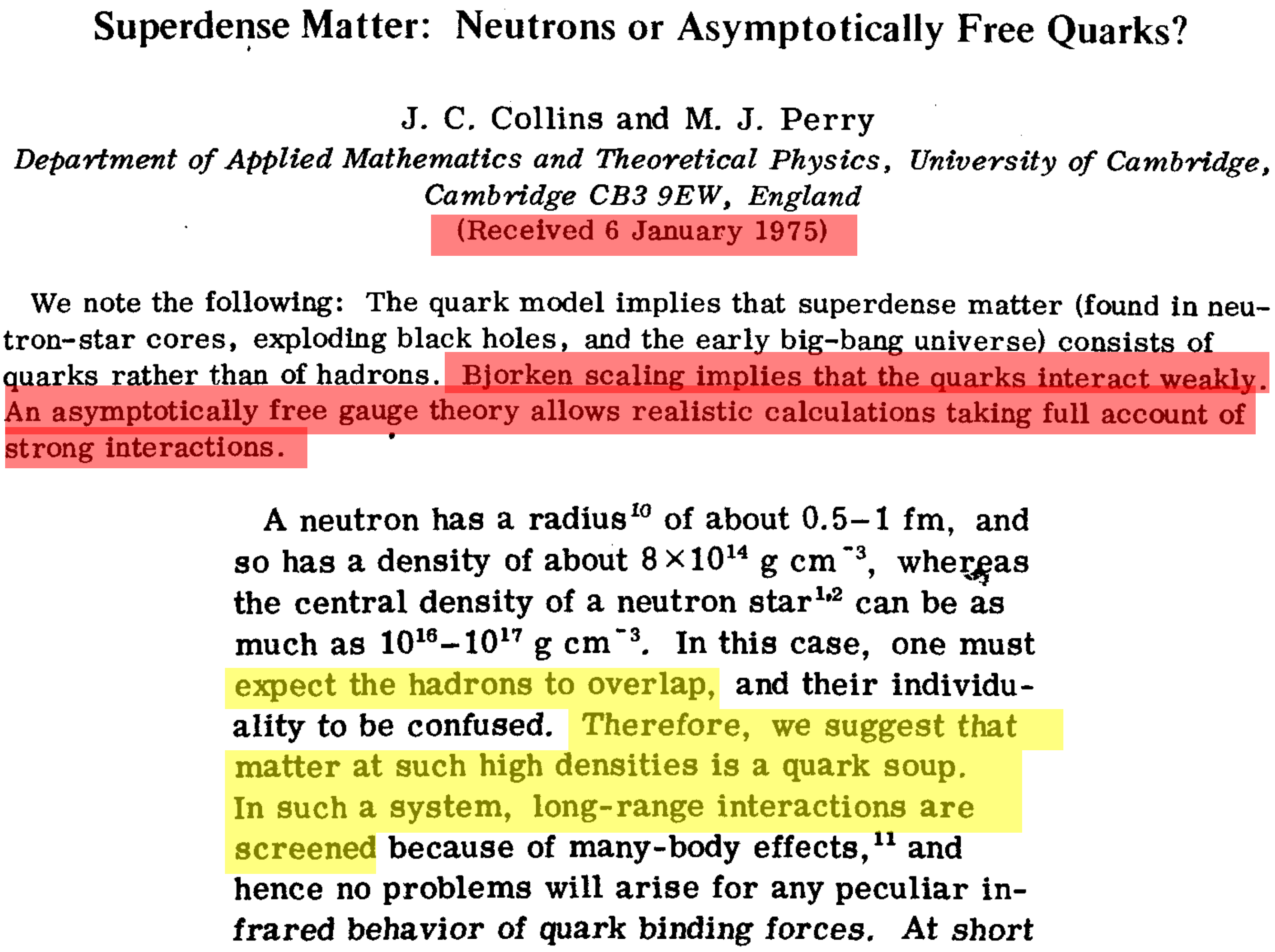
Nature



Experiment

Quark-Hadron phase transition

First mentioned...



Superdense Matter: Neutrons or Asymptotically Free Quarks?

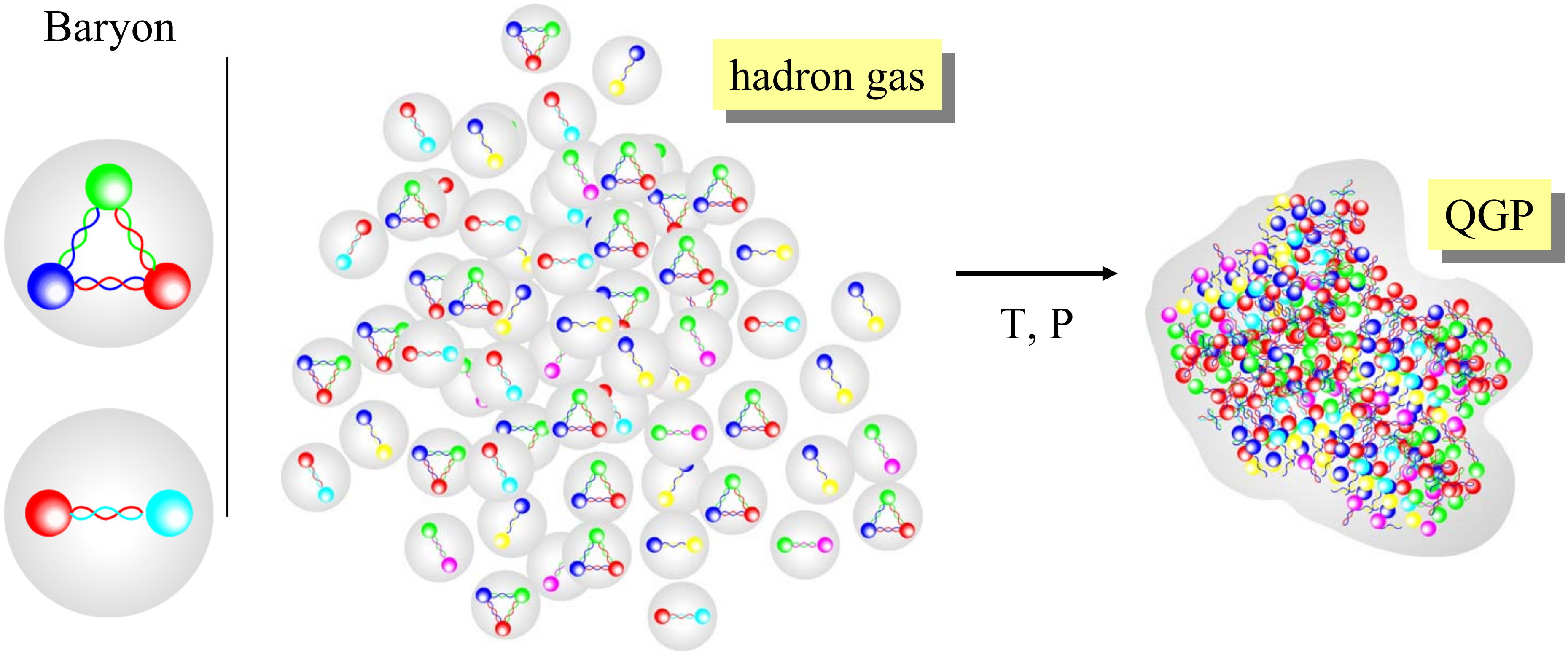
J. C. Collins and M. J. Perry
Department of Applied Mathematics and Theoretical Physics, University of Cambridge, Cambridge CB3 9EW, England

(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.

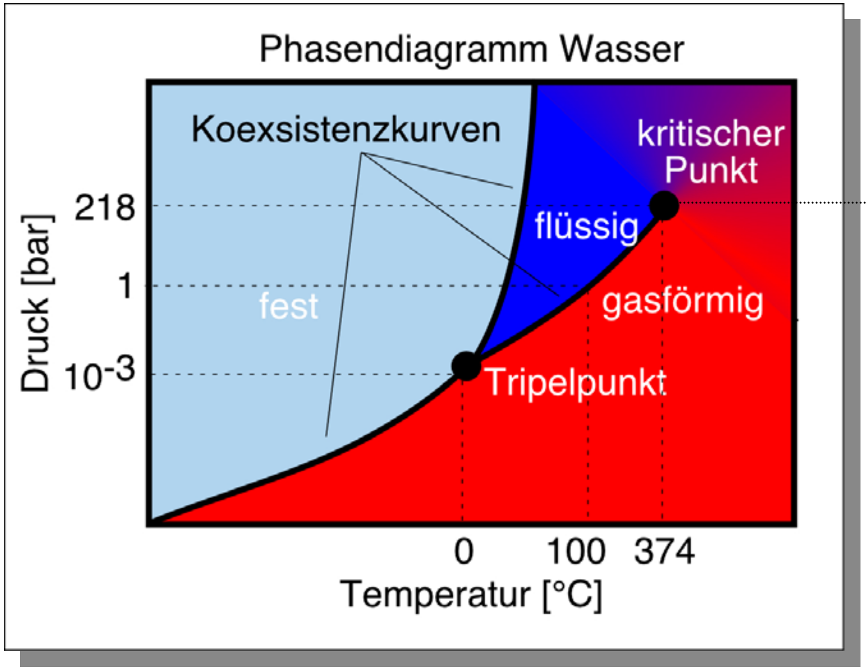
A neutron has a radius[10] of about 0.5–1 fm, and so has a density of about 8×10^{14} g cm^{-3}, whereas the central density of a neutron star[1,2] can be as much as 10^{16}–10^{17} g cm^{-3}. In this case, one must expect the hadrons to overlap, and their individuality to be confused. Therefore, we suggest that matter at such high densities is a quark soup. In such a system, long-range interactions are screened because of many-body effects,[11] and hence no problems will arise for any peculiar infrared behavior of quark binding forces. At short

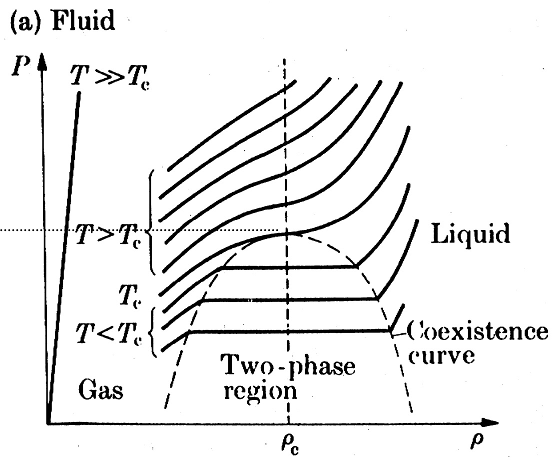
What is the Quark-Gluon Plasma?



- in „normal“ nuclear matter quarks are confined
- hadrons are “melted” via an increase in temperature and/or density → phase transition to a plasma state with fundamentally new properties:
  - color conductivity (quark are“deconfined“)
  - chirale symmetry ($m_{u,d} \approx 5$ MeV/c^2; in nucleon $m_{u,d} \approx 1/3\ m_N \approx 300$ MeV/c^2)

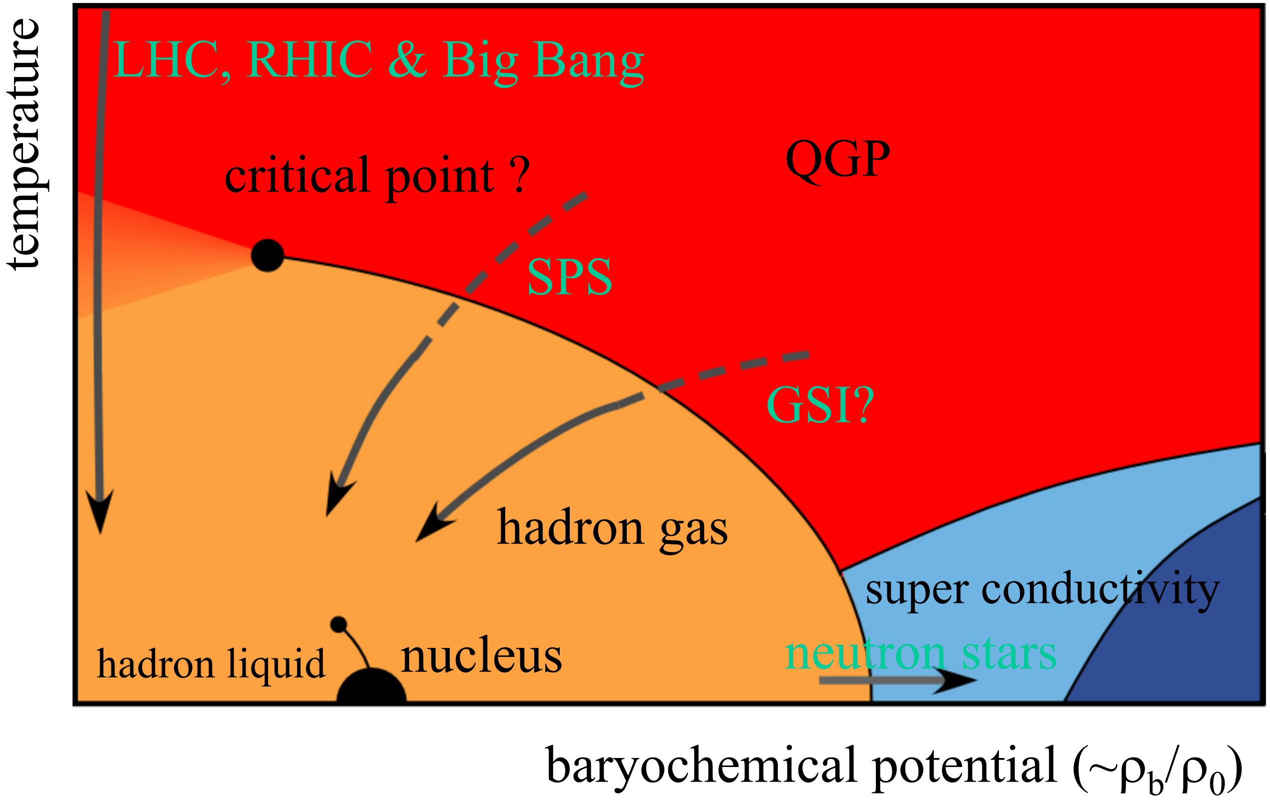
Phase Diagram of Water



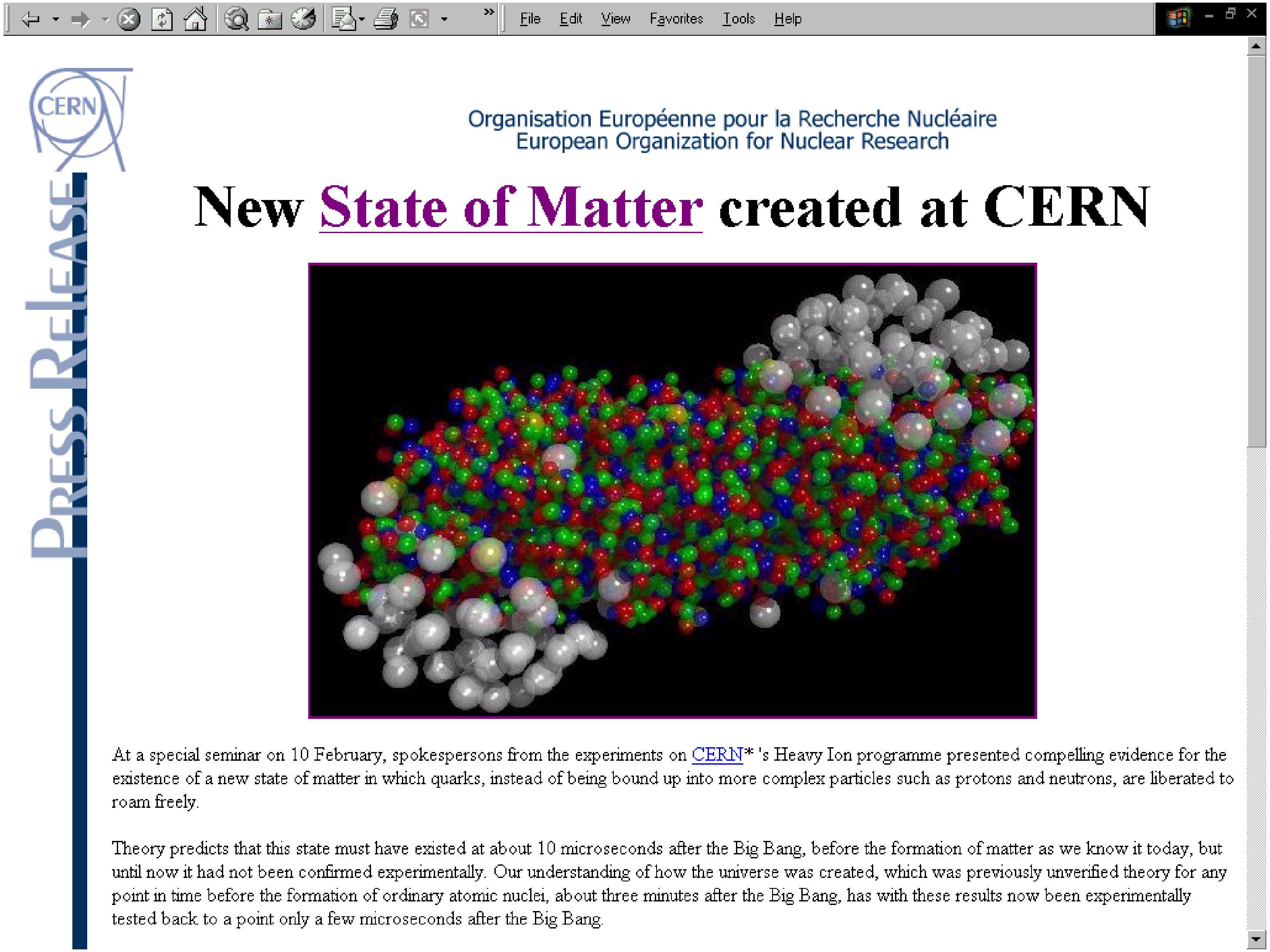


Phase Diagram

K.Rajagopal, Nucl. Phys. A661 (1999) 150



CERN press statement 1.2.2000



Organisation Européenne pour la Recherche Nucléaire
European Organization for Nuclear Research

New State of Matter created at CERN

At a special seminar on 10 February, spokespersons from the experiments on CERN* 's Heavy Ion programme presented compelling evidence for the existence of a new state of matter in which quarks, instead of being bound up into more complex particles such as protons and neutrons, are liberated to roam freely.

Theory predicts that this state must have existed at about 10 microseconds after the Big Bang, before the formation of matter as we know it today, but until now it had not been confirmed experimentally. Our understanding of how the universe was created, which was previously unverified theory for any point in time before the formation of ordinary atomic nuclei, about three minutes after the Big Bang, has with these results now been experimentally tested back to a point only a few microseconds after the Big Bang.

BNL press release on July 18, 2003

…In comparing these very different types of collisions, scientists have seen distinctions that clearly show that head-on gold-gold collisions are producing a nuclear environment quite different from that of deuteron-gold collisions. Although RHIC scientists are not ready to claim success, they are confident that RHIC collisions of gold ions have created unusual conditions and that they are on the right path to the discovery of quark-gluon plasma…

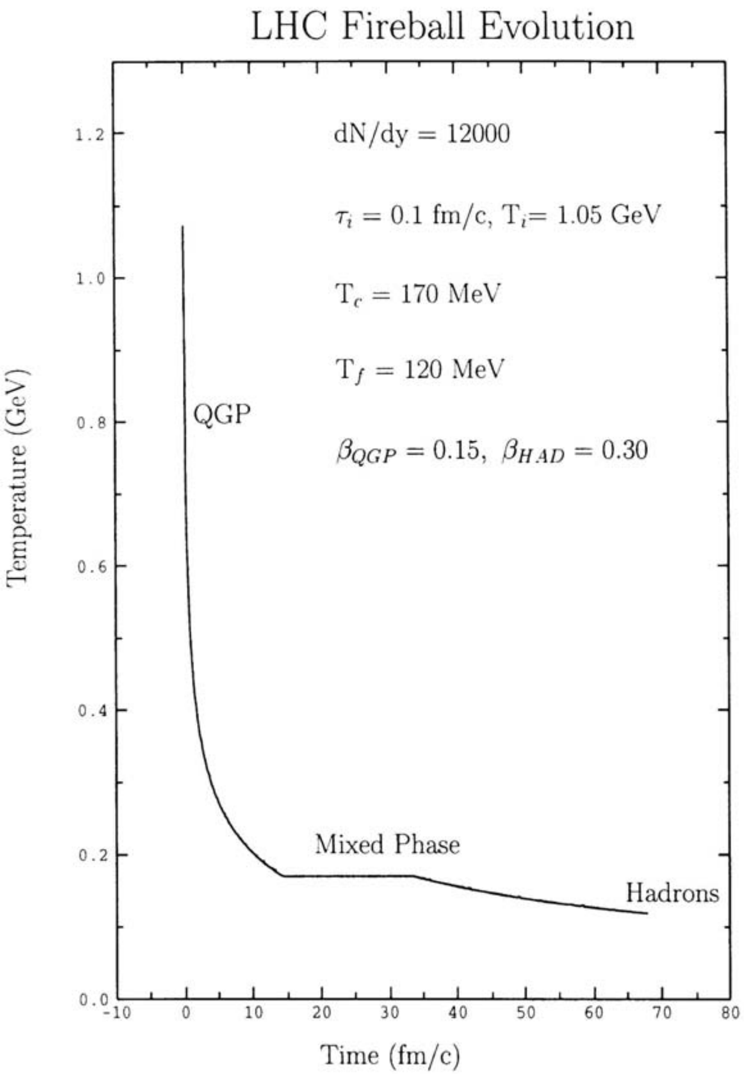
Comparison SPS-RHIC-LHC

Pb+Pb, central collision

	SPS	**RHIC**	**LHC**
E_{cm} [GeV]	**17**	**200**	**5500**
dN_{ch}/dy	**500**	**700**	**3000 - 8000**
E [Gev/fm^3]$_{t_0=1fm/c}$	**≈2.5**	**≈3.5**	**15 - 40**
t_{QGP} [fm/c]	**<1**	**≈1**	**≈4.5-12**

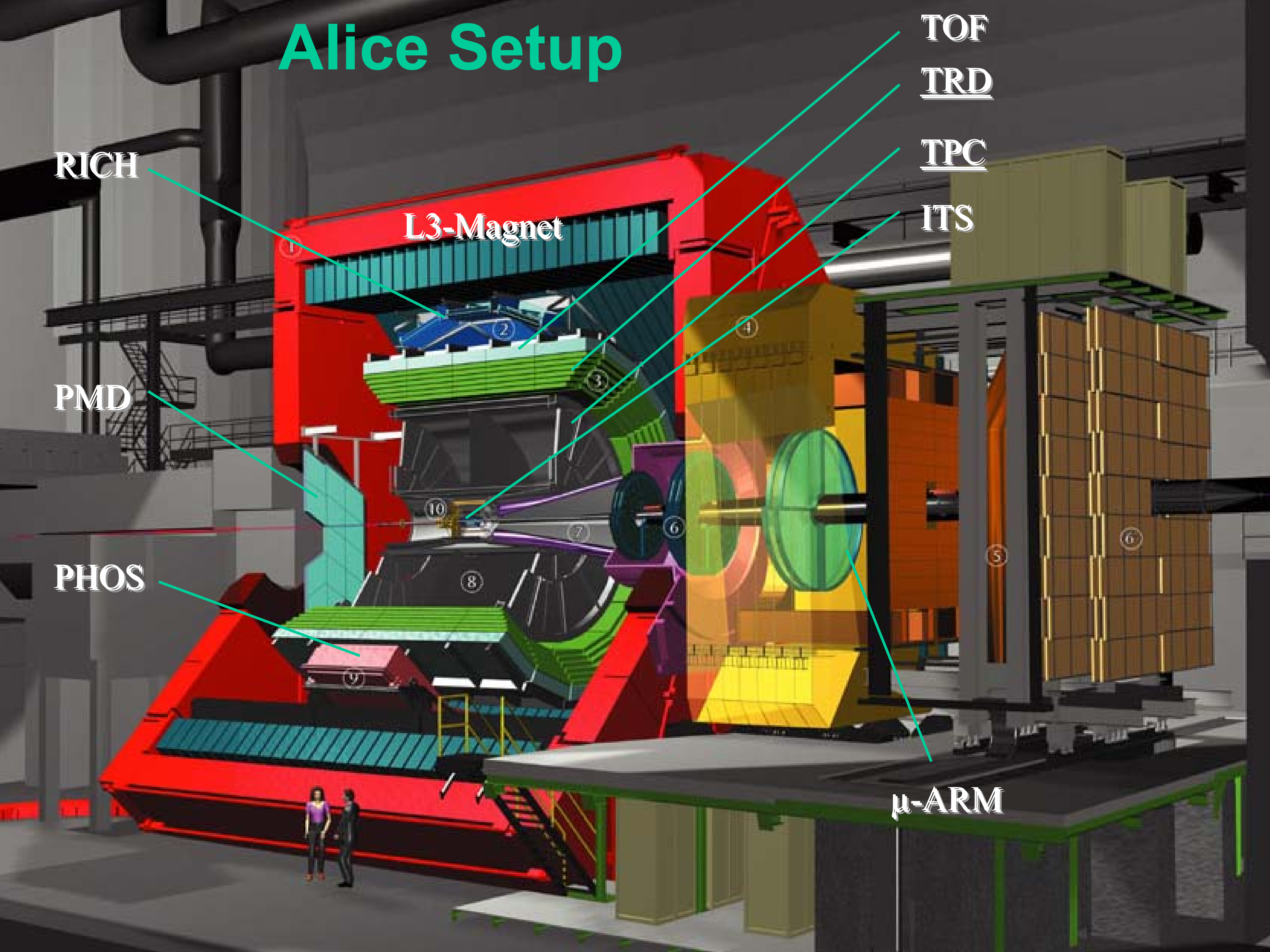
⇒ significant increase in relevant parameters (ε, V, τ): factor 10 from SPS to LHC

Fireball Evolution of Pb+Pb Collisions at the LHC

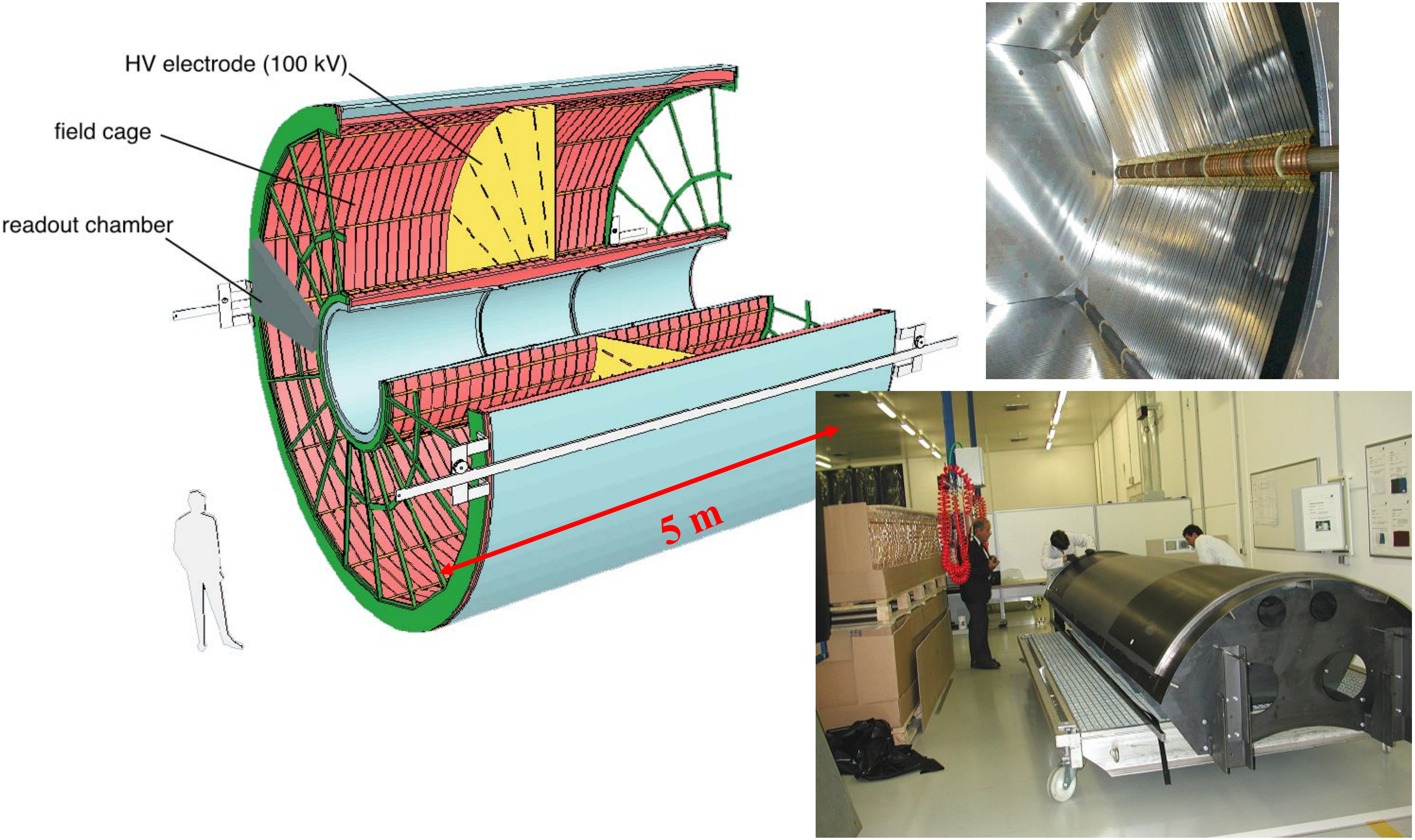


- high energy densities:
  - ✓ $\varepsilon_{\square} \approx$ 1000 GeV/fm^3
  - ✓ $\varepsilon_{\tau=1\ \mathrm{fm/c}} \approx$ 40 GeV/fm^3
- long life times:
  - ✓ τ_{QGP} >10 fm/c
  - ✓ $\tau_{freeze} \approx$ 70 fm/c
- large volumes:
  - ✓ $dN_{ch}/dy \approx$ 8000
  - ✓ $V_{freeze}(\Delta y=1)$ =10^5 fm^3

Alice Setup

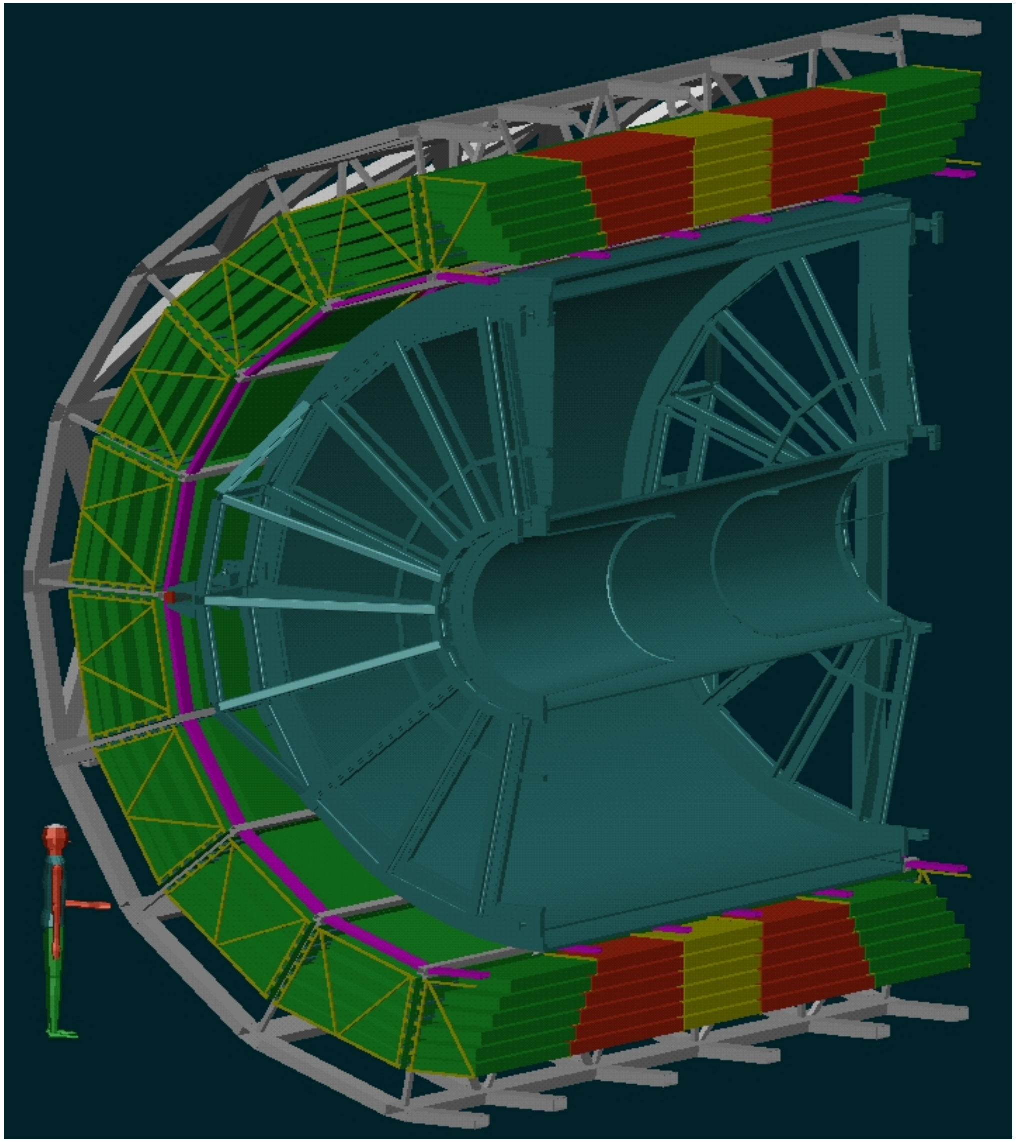


ALICE Time Projection Chamber



ALICE Transition Radiation Detector

Clemens Adler, Uni Heidelberg

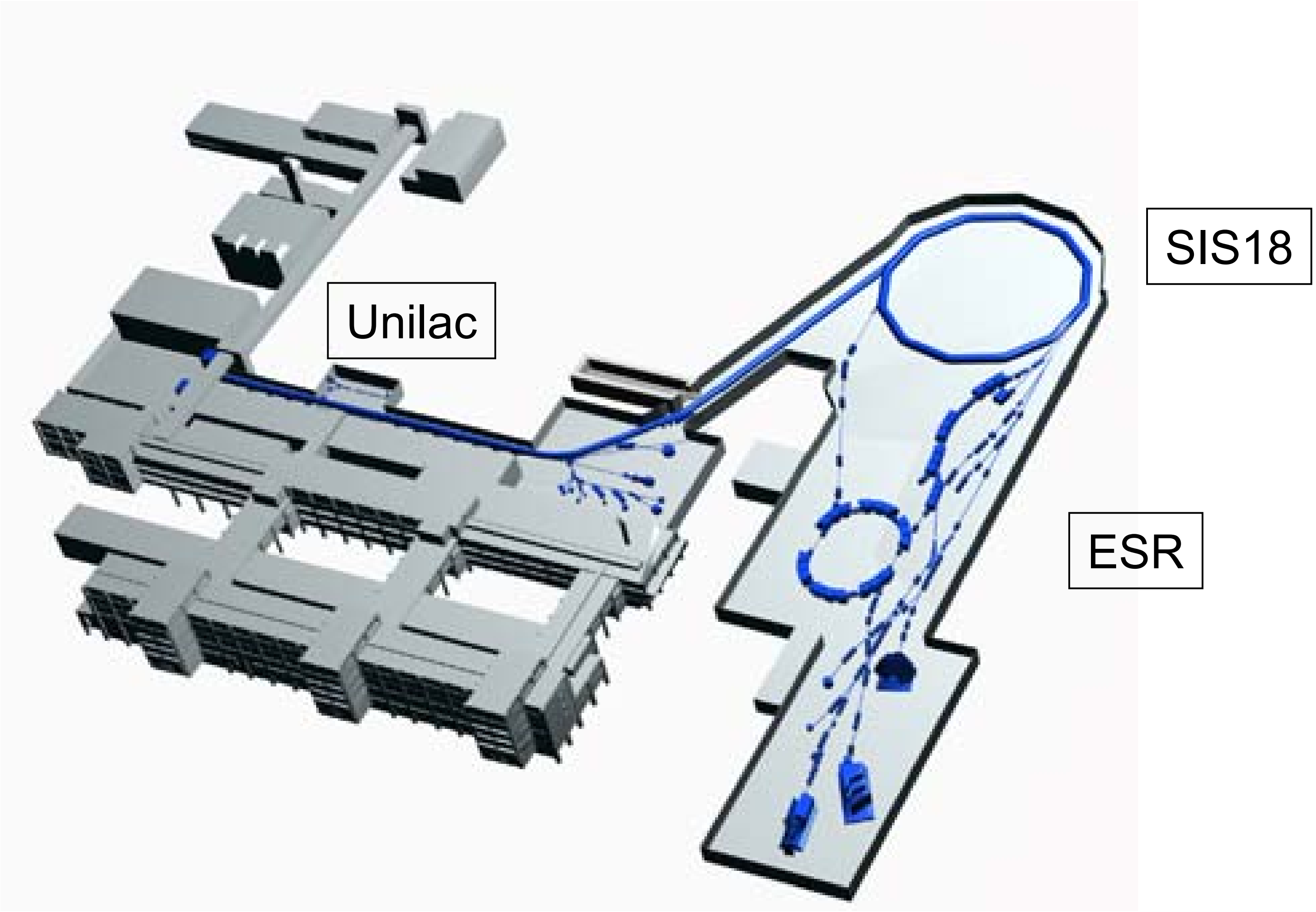


- **Purpose:**
  - **Electron ID in the central barrel**
    at *p* > 1 GeV/*c*
  - **Fast (6 μs) trigger for high-p_t**
    Particles (p_t > 3 GeV/*c*) +PID
- **Parameters:**
  - **540 modules → 767 m^2 area**
  - **18 “supermodules”**
  - **6 layers, 5 longitudinal stacks**
  - **Length: 7 m**
  - **28 m^3 Xe/CO_2 (85:15)**
  - **1.2 million read out channels**
  - **15 TB/s on-detector bandwidth**

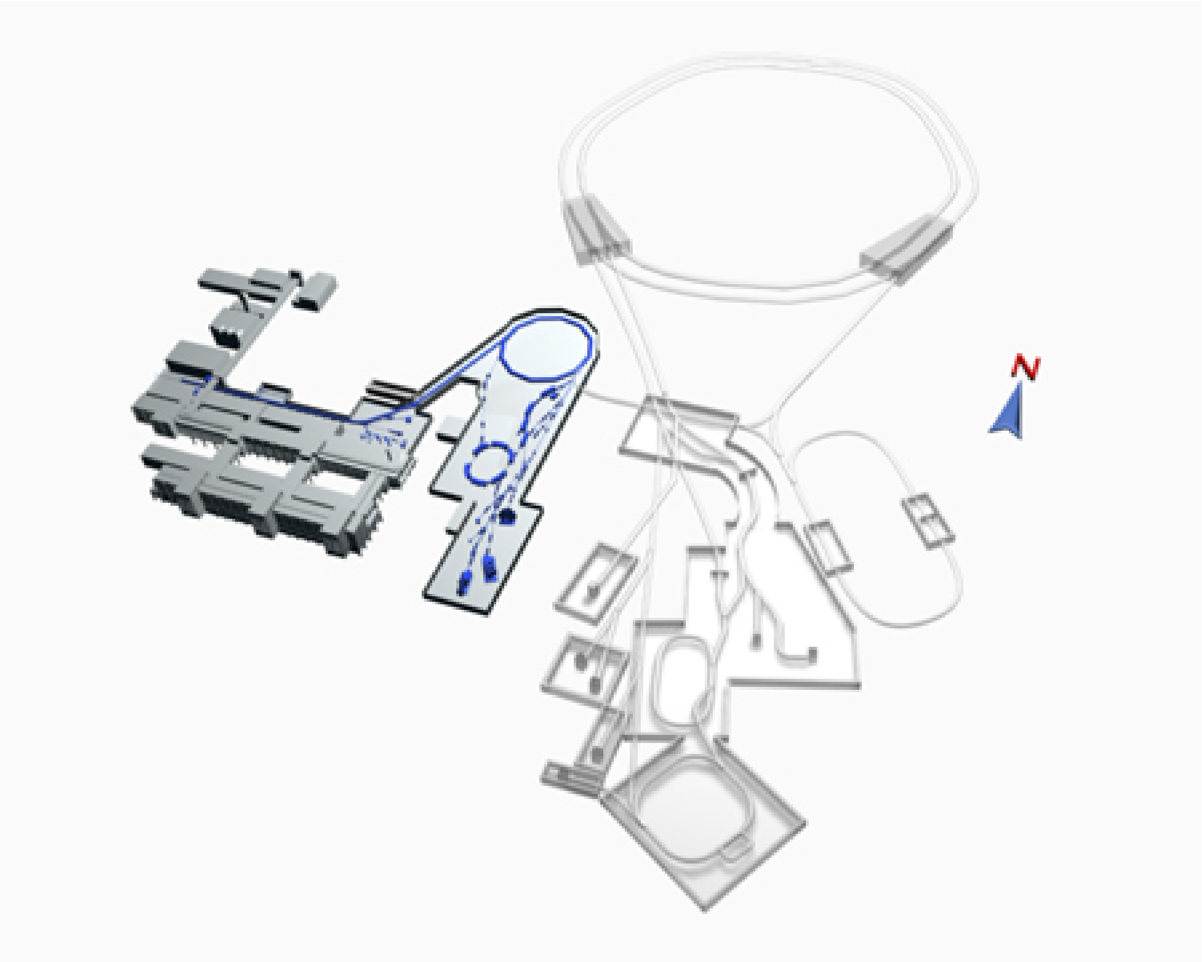
web cam

CBM and high density baryonic matter

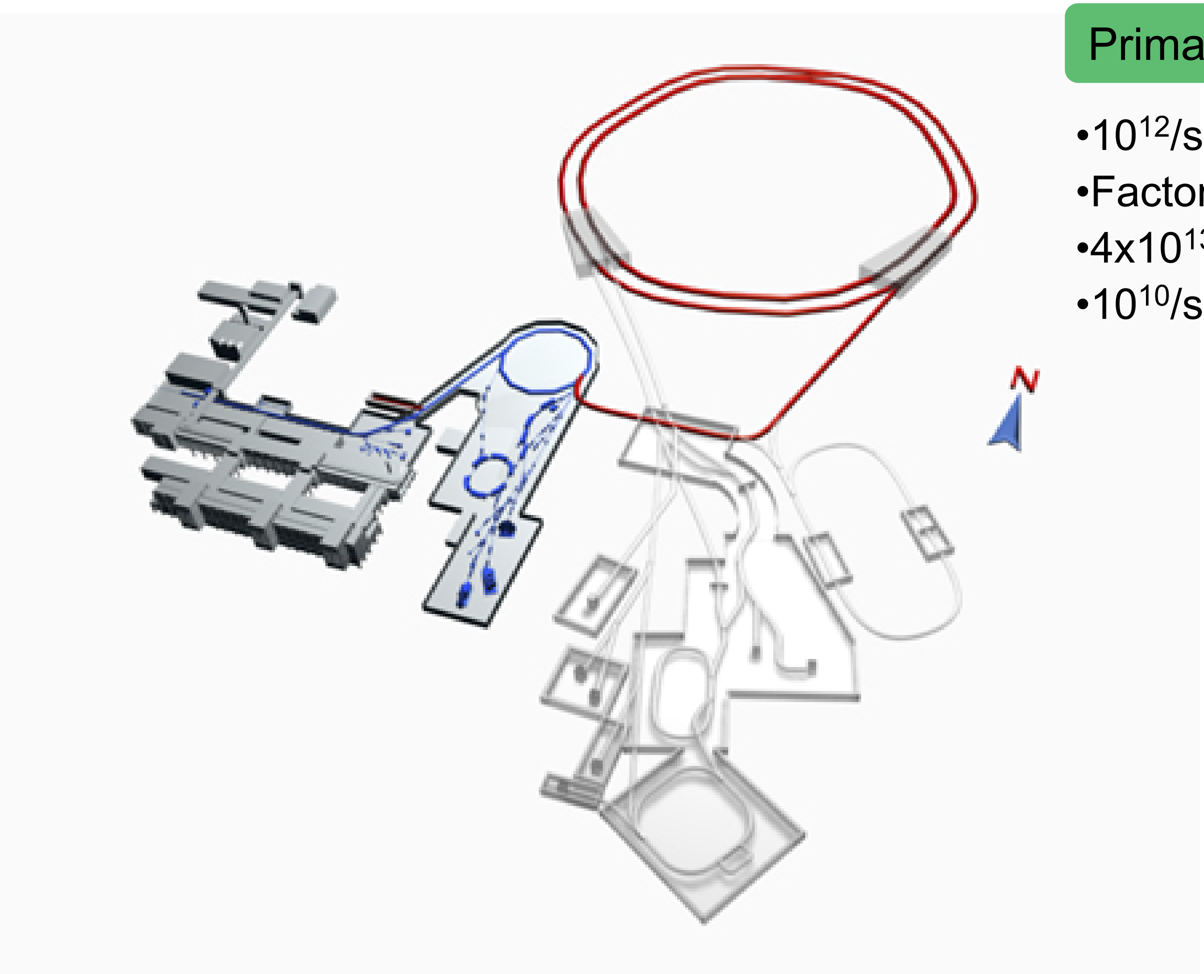
Present GSI accelerator facilities



Future GSI facility characteristics



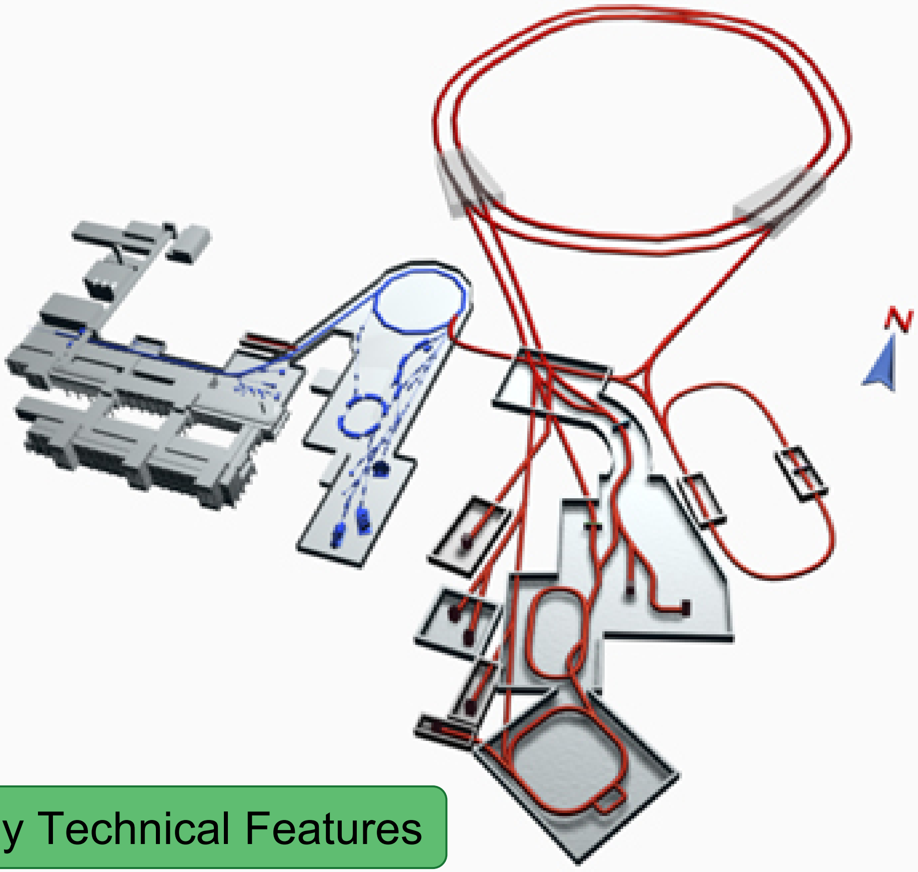
Future GSI facility characteristics



Primary Beams

- 10^{12}/s; 1.5 GeV/u; $^{238}U^{28+}$
- Factor 100-1000 over present in intensity
- 4×10^{13}/s 30 GeV protons
- 10^{10}/s $^{238}U^{73+}$ up to 25 (- 35) GeV/u

Future GSI facility characteristics



Primary Beams

- 10^{12}/s; 1.5-2 GeV/u; $^{238}U^{28+}$
- Factor 100-1000 over present in intensity
- $4(2)\times10^{13}$/s 30 GeV protons
- 10^{10}/s $^{238}U^{73+}$ up to 25 (- 35) GeV/u

Secondary Beams

- Broad range of radioactive beams up to 1.5 - 2 GeV/u; up to a factor 10 000 in intensity over present
- Antiprotons 3(0) - 30 GeV

Storage and Cooler Rings

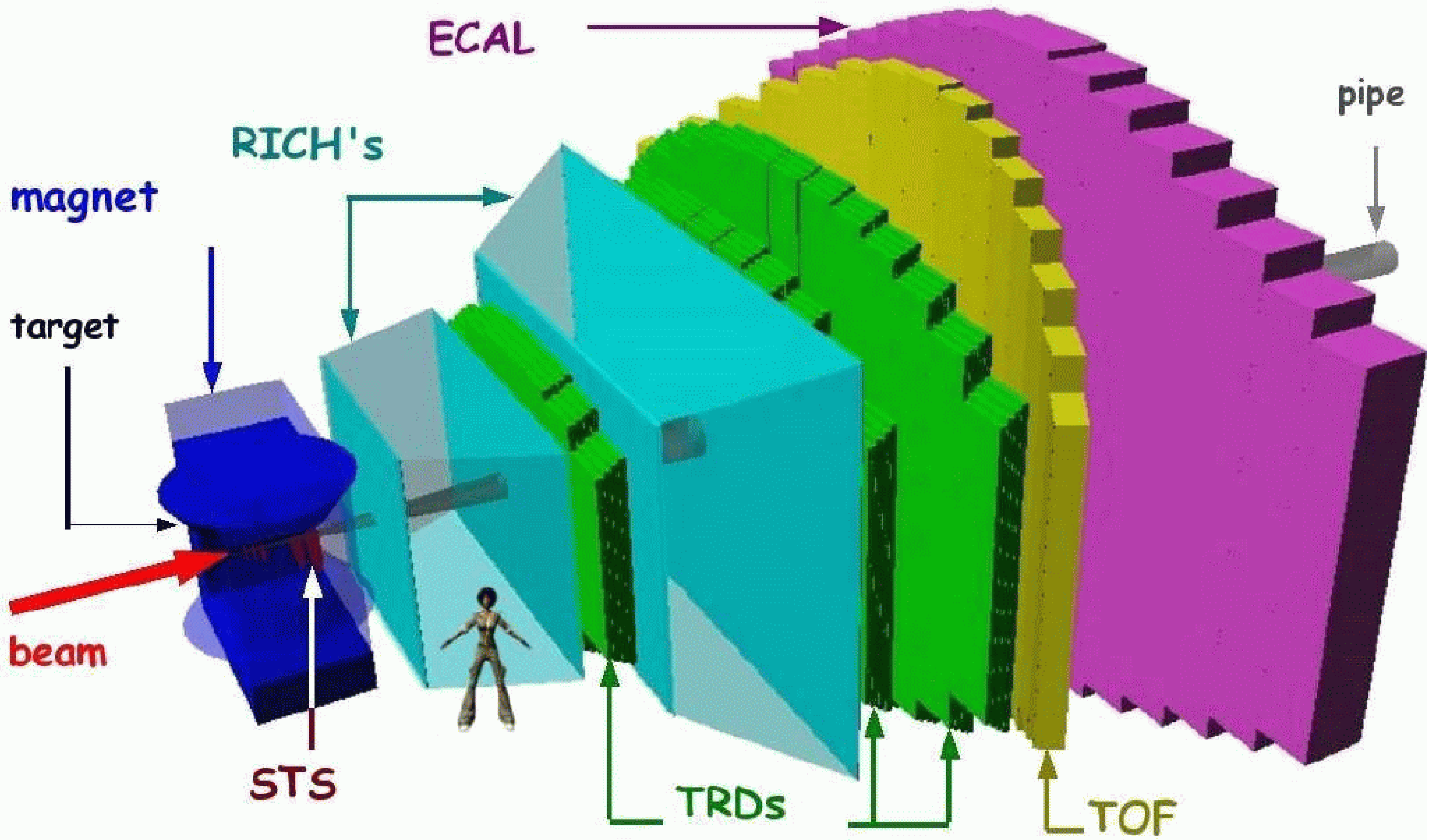
- Radioactive beams
- e – A(RIB) collider
- 10^{11} stored and cooled 3(0) - 15 GeV antiprotons

Key Technical Features

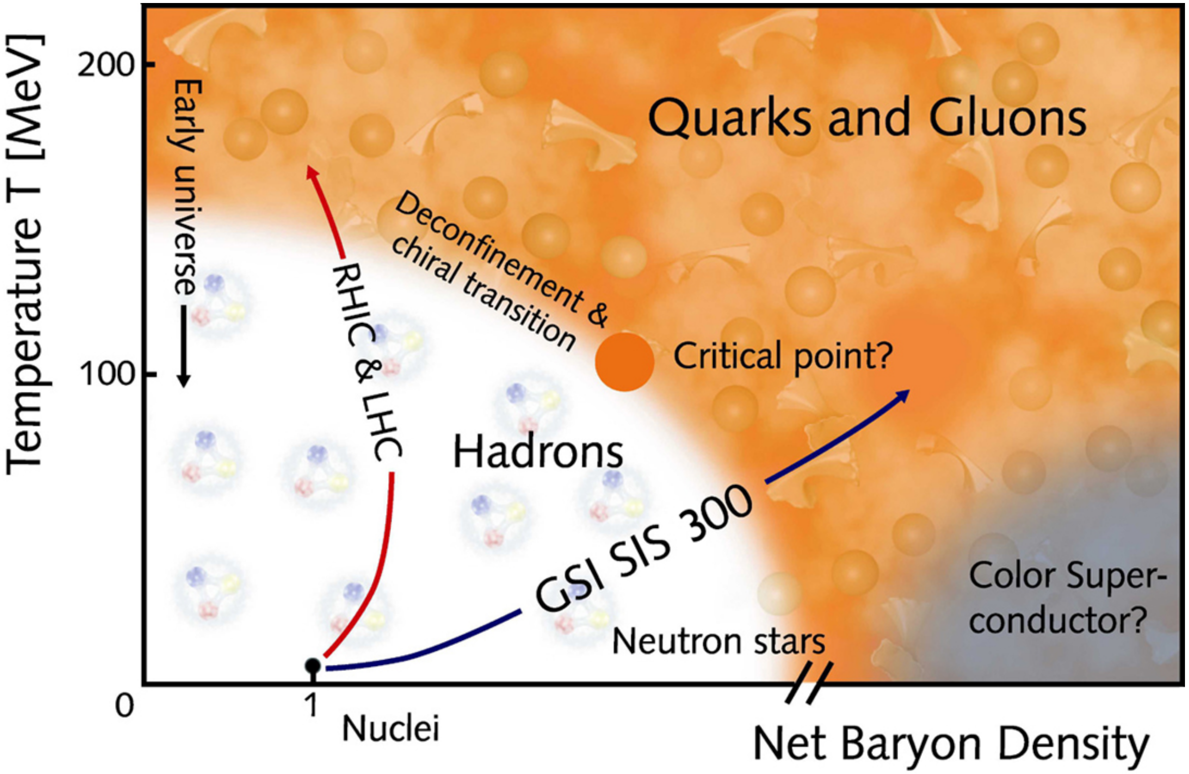
- Cooled beams
- Rapidly cycling superconducting magnets

International Accelerator Facility for beams of Ions and Antiprotons

Compressed Baryonic Matter (CBM) experiment

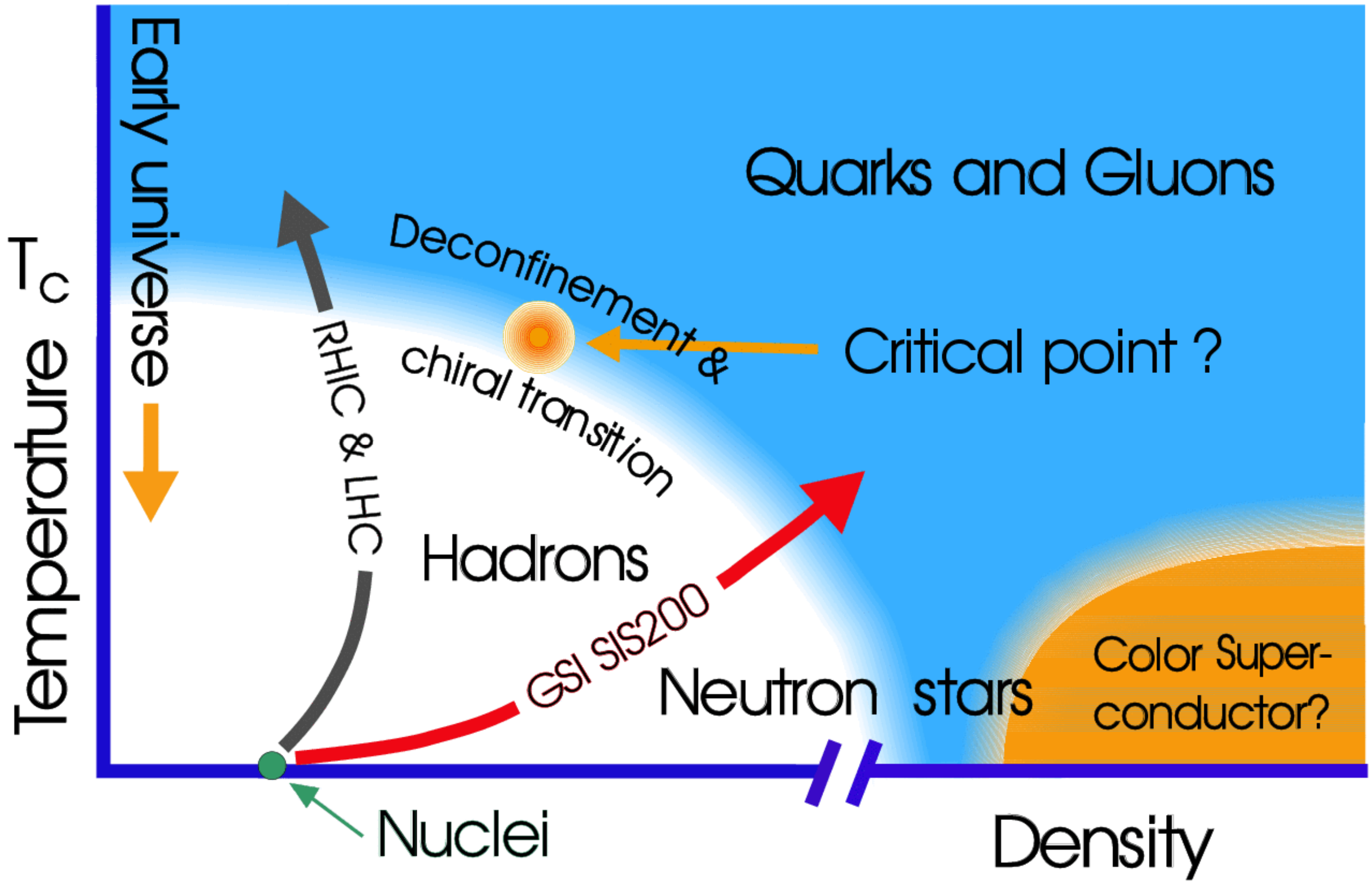


One more version of the QCD phase diagram



of course not complete !!!

QCD phase diagram

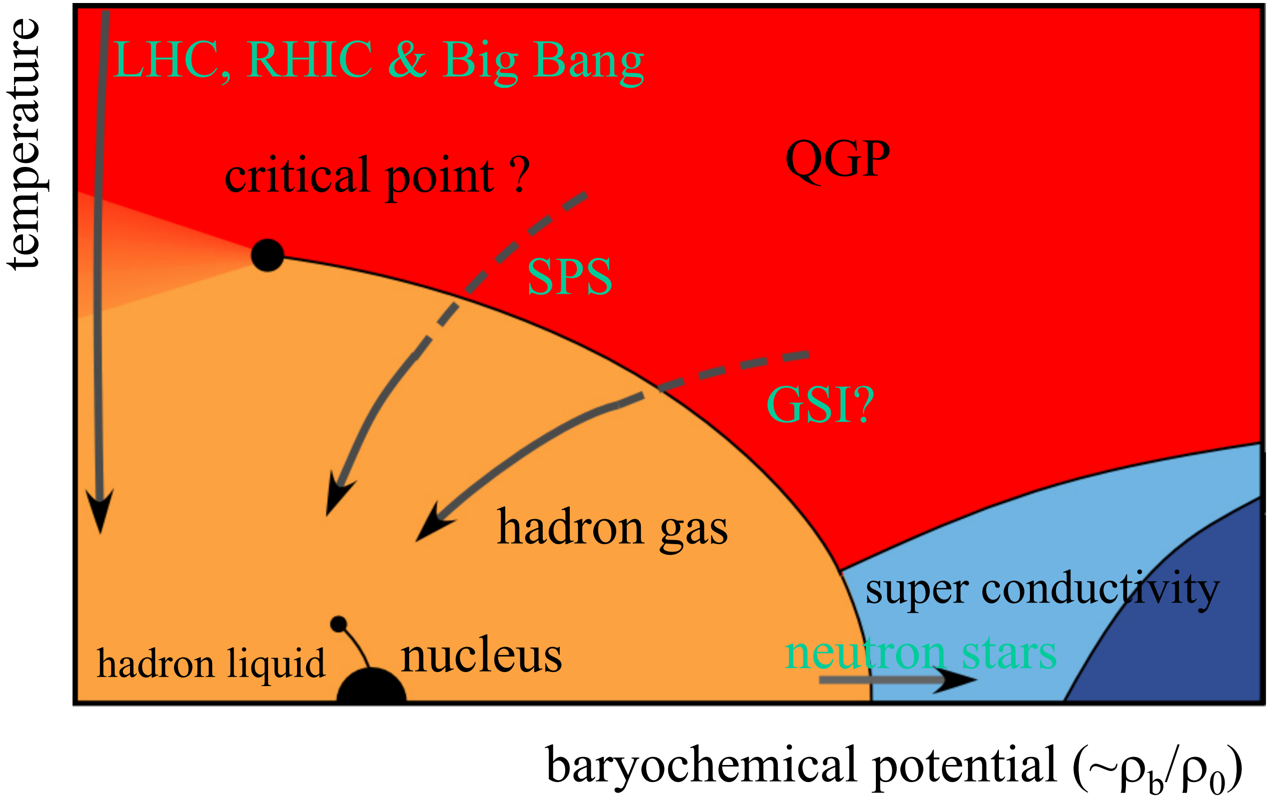


CERN-SPS, RHIC, LHC: high temperature, low baryon density

AGS, GSI (SIS200): moderate temperature, high baryon density

Phase Diagram

K.Rajagopal, Nucl. Phys. A661 (1999) 150



thanks

This lecture heavily uses slides from:

- Christian Sturm
- Anton Andronic
- Romain Holzmann
- Rudi Schmidt
- Joachim Stroth