Lecture on Compressed Baryonic Matter

5th International FAIR School
Castiglione della Pescaia
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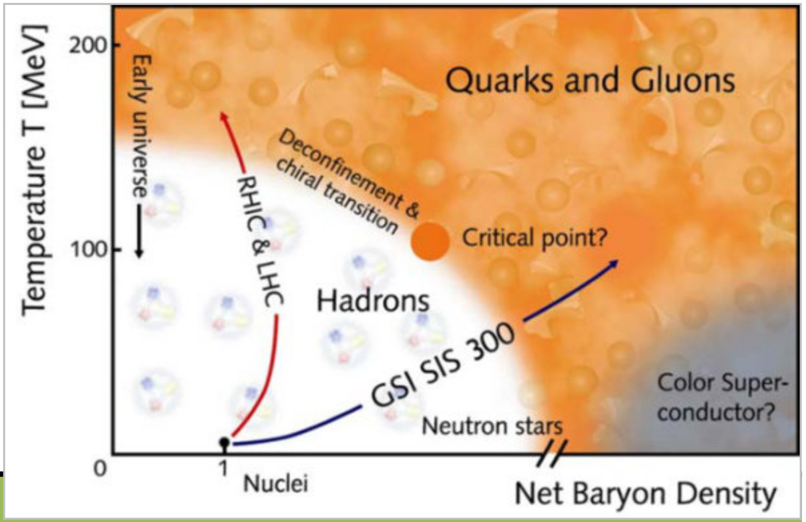

A guided tour
across the QCD phase diagram

Outline

	A brief introduction
Chapter I	Nuclear Matter at (or close to) ground state
Chapter II	Compressed nuclear matter in the universe: Late stages of heavy stars
Chapter III	Exploring dense nuclear matter in the laboratory: Nucleus-nucleus collisions at SIS18
Chapter IV	Exploring the highest net baryon densities in the laboratory

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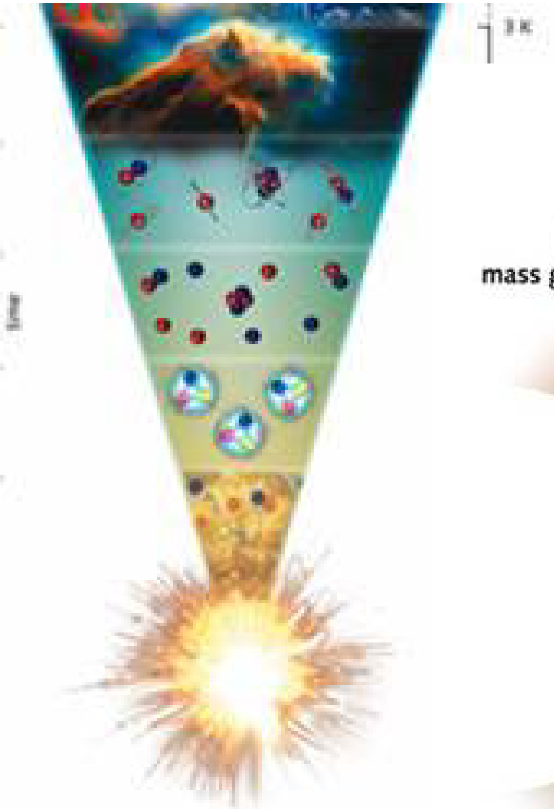
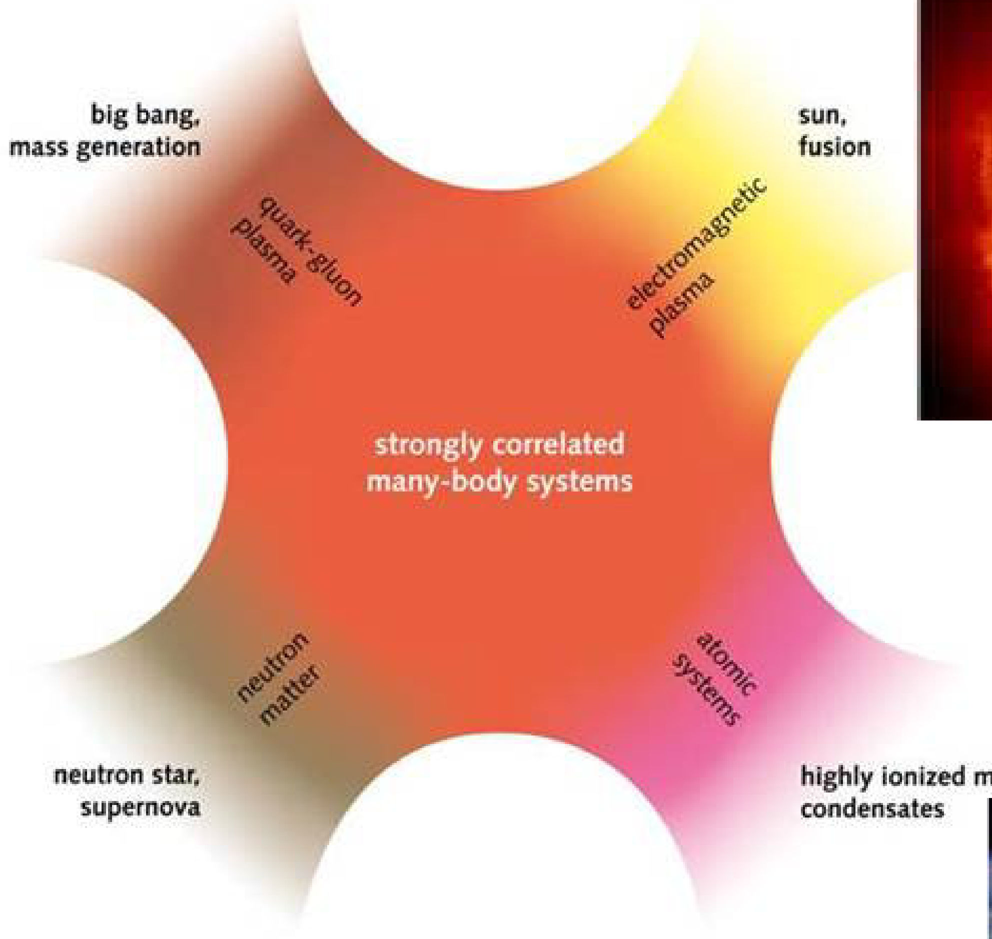
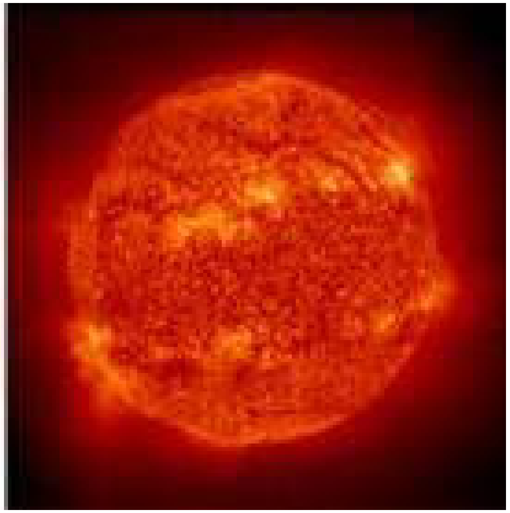
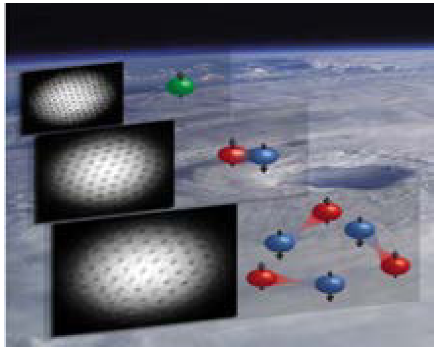
FAIR research topics and inter-links





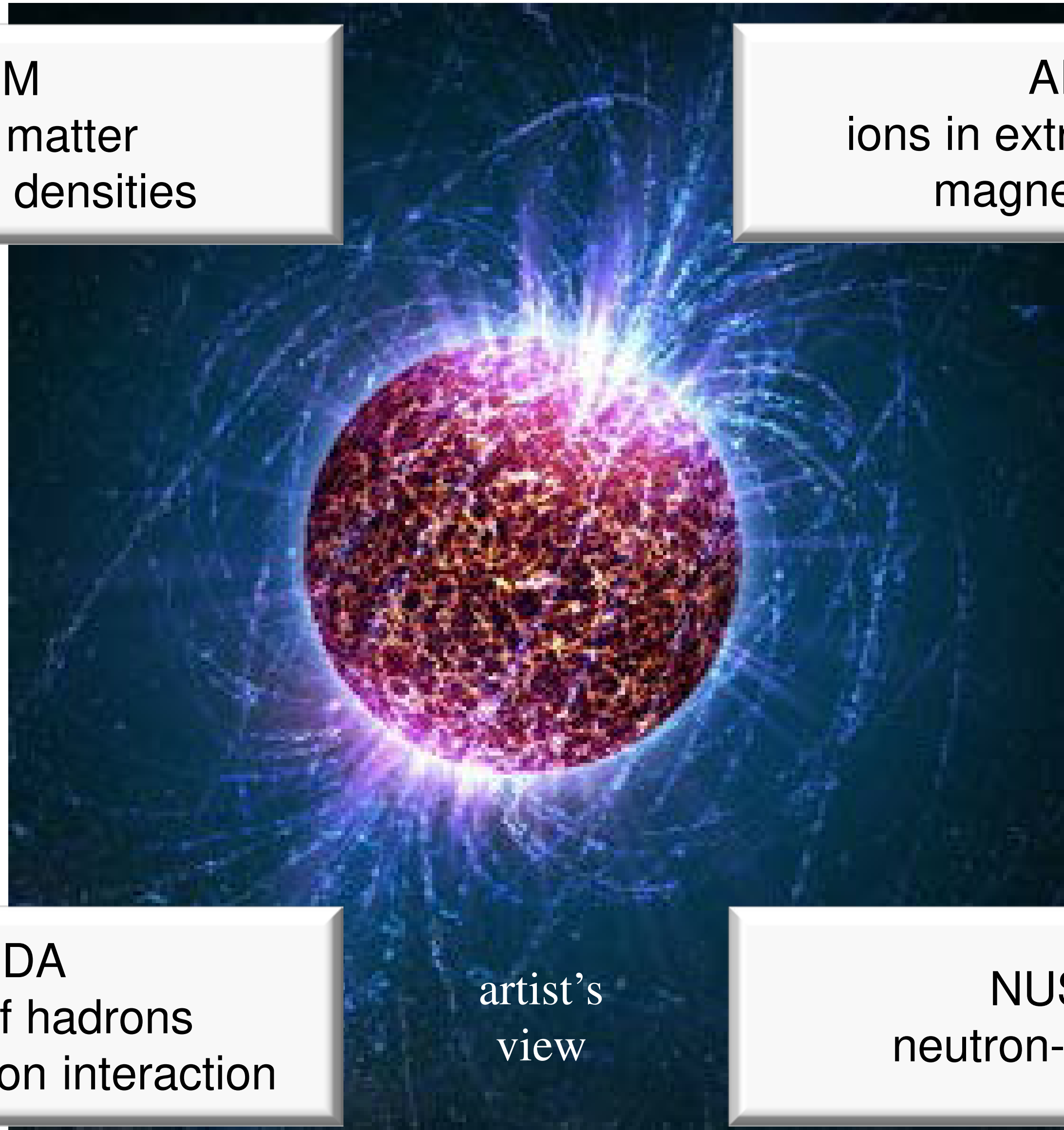




FAIR - Cosmic Matter in the Laboratory

CBM
nuclear matter
at extreme densities

APPA
ions in extreme electro-
magnetic fields

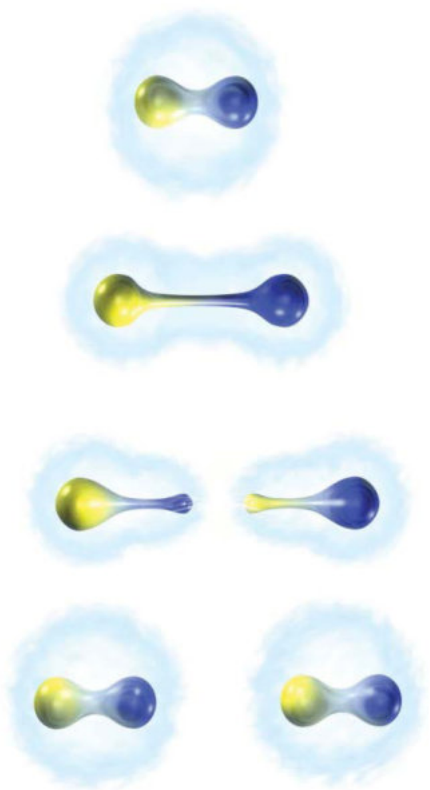


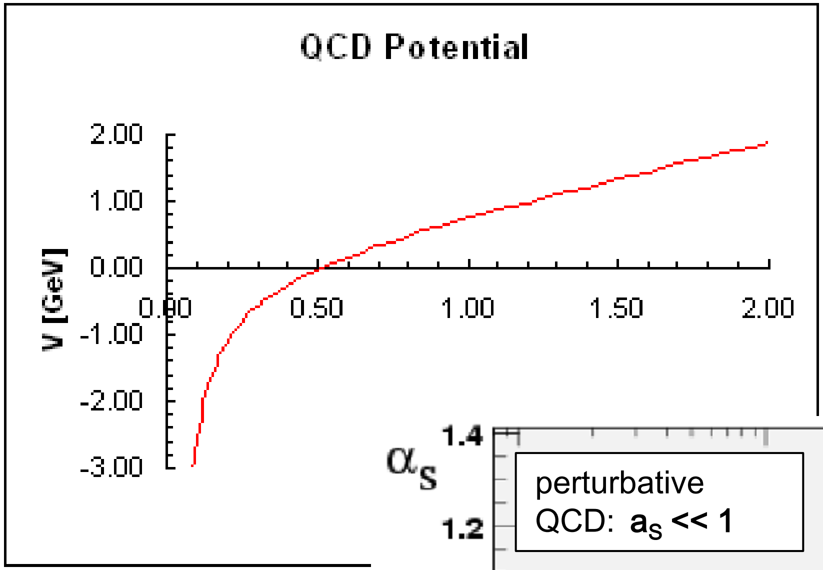
PANDA
structure of hadrons
hyperon-hyperon interaction

NUSTAR
neutron-rich nuclei

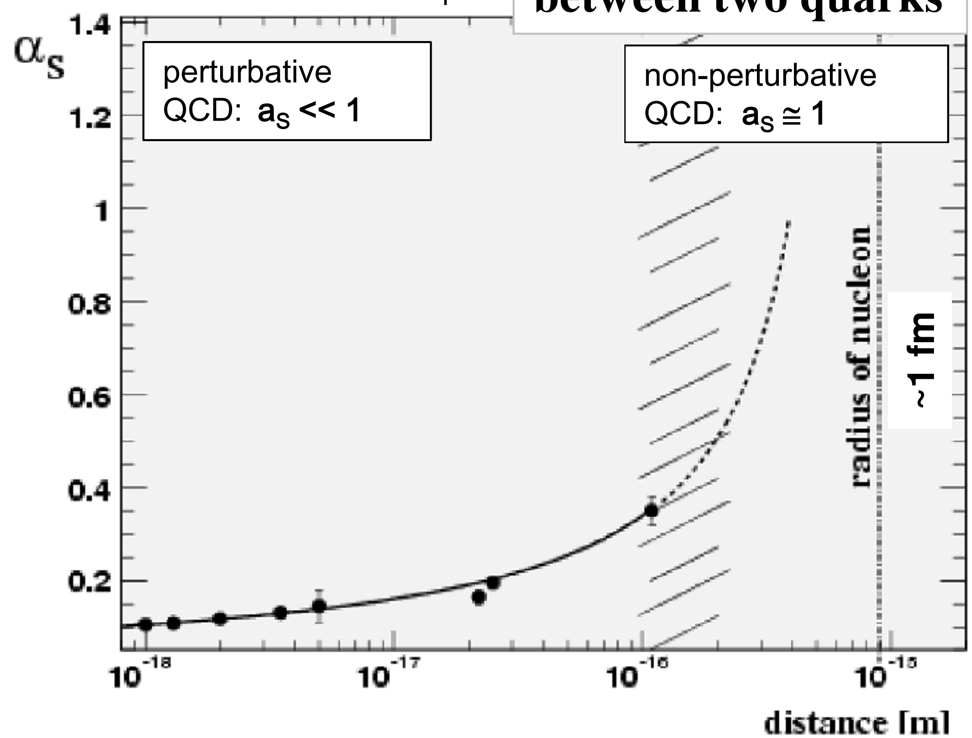
Quarks are confined!

$$V(r) = -\frac{4\alpha_s \hbar c}{3r} + Kr$$



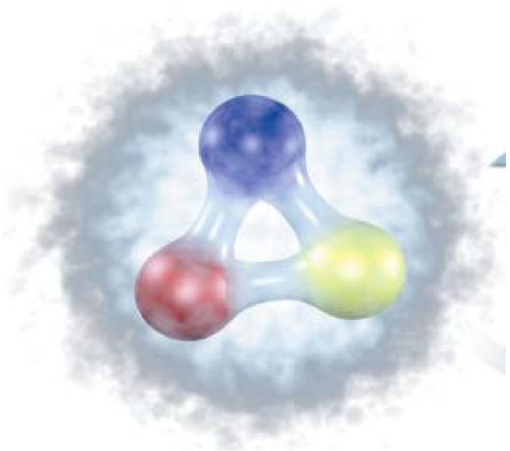


Coupling strength between two quarks

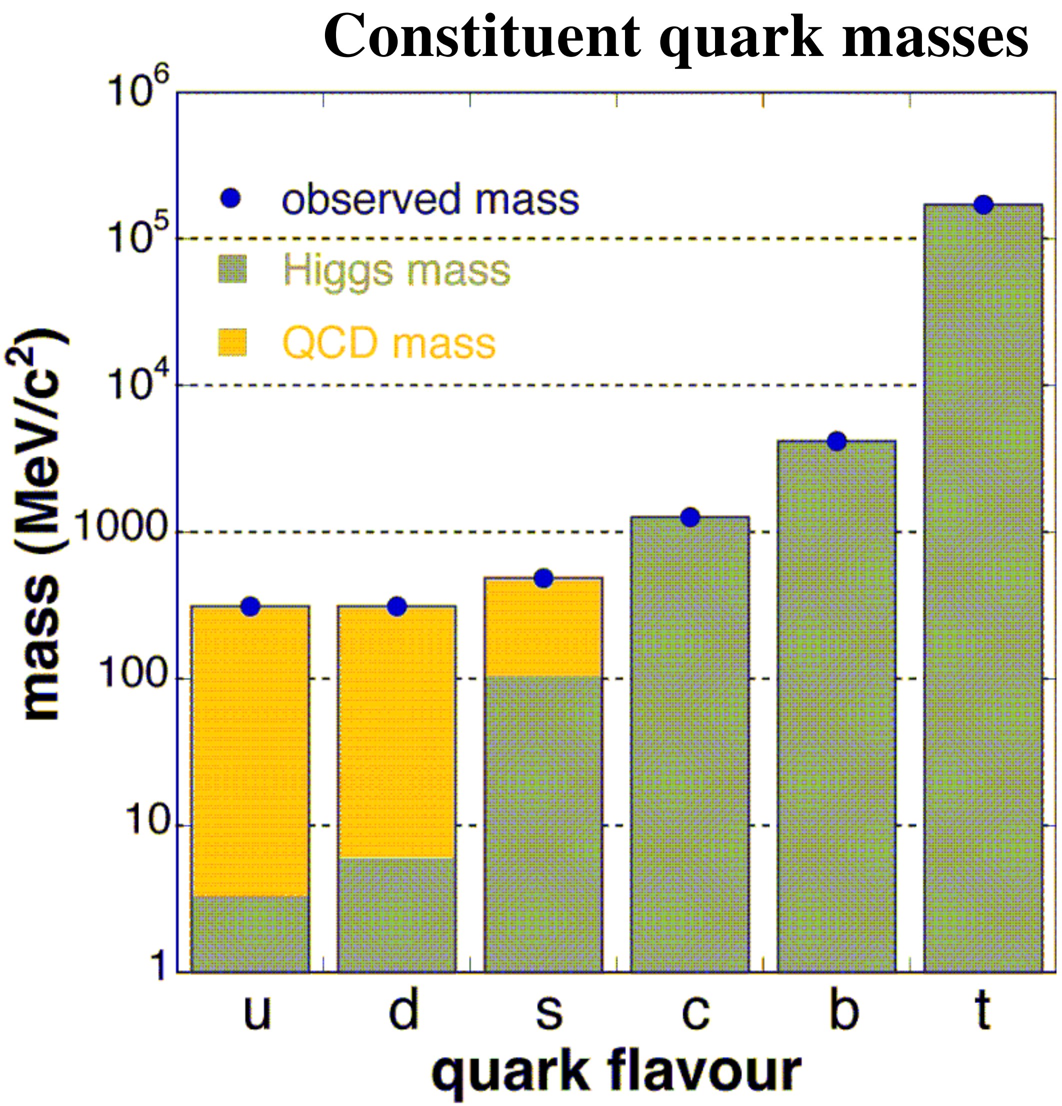


Asymptotic freedom
(Frank Wilczek - Physics Nobel prize 2004)

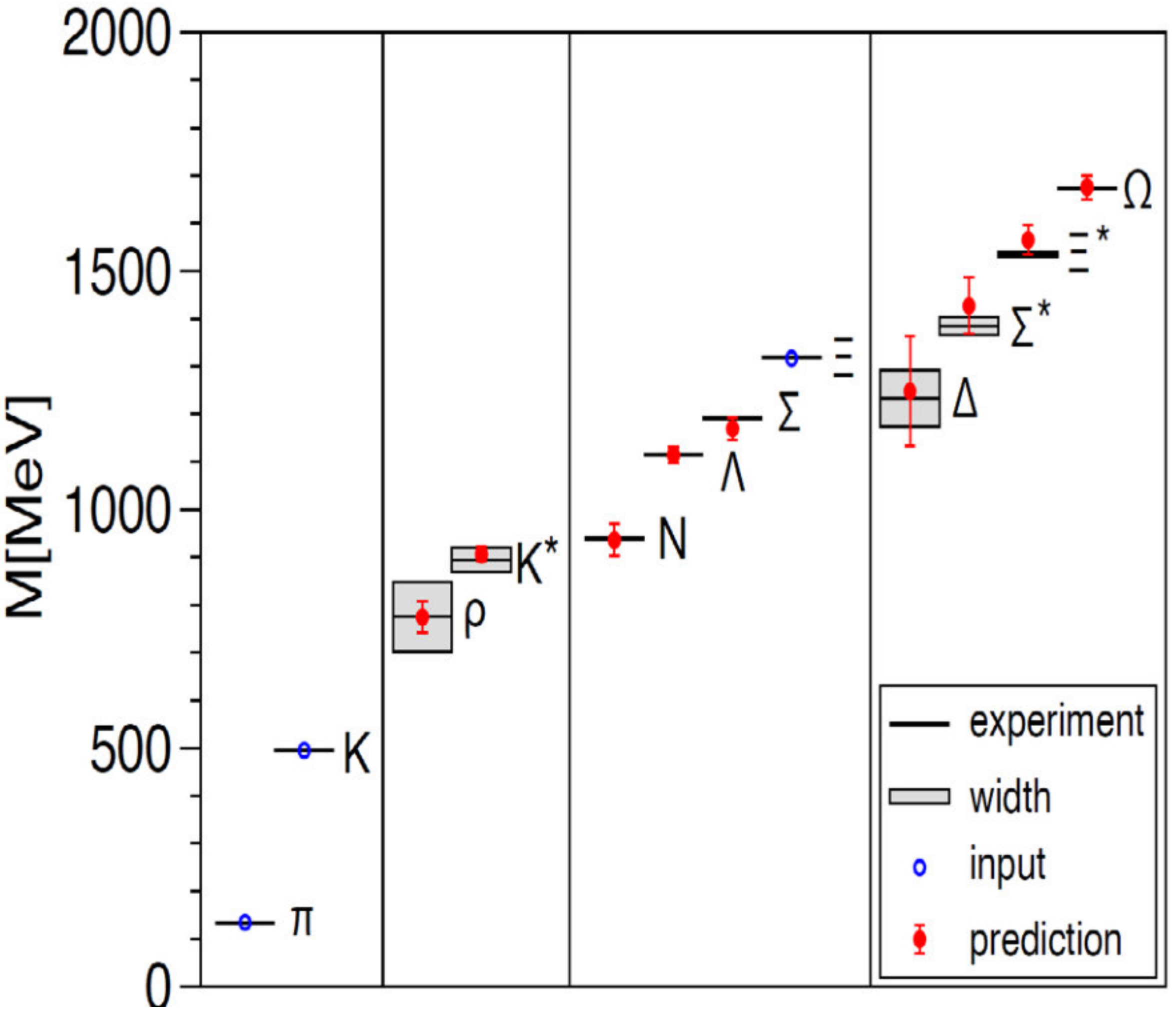
Proton



mass not determined by the sum of current quark masses !!!



The strong interaction and the origin of hadron masses



Δ^+ (1232): uud

p (938): uud

$\rho^+(770)$: $u\bar{d}$

$\eta(548)$: $\frac{u\bar{u} + d\bar{d} - 2s\bar{s}}{\sqrt{6}}$

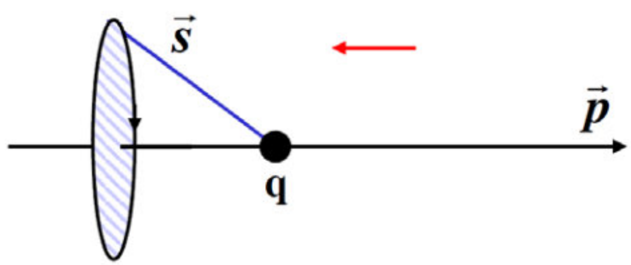
$K^+(494)$: $u\bar{s}$

$\pi^+(140)$: $u\bar{d}$

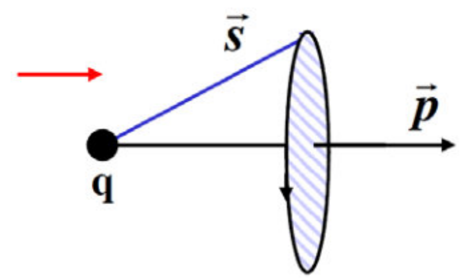
Chiral symmetry in a nutshell

Chiral symmetry = fundamental symmetry of QCD

Chirality: projection of the spin $\vec{s}$ on the momentum $\vec{p}$



left-handed quarks



right-handed quarks

In case of massless quarks:

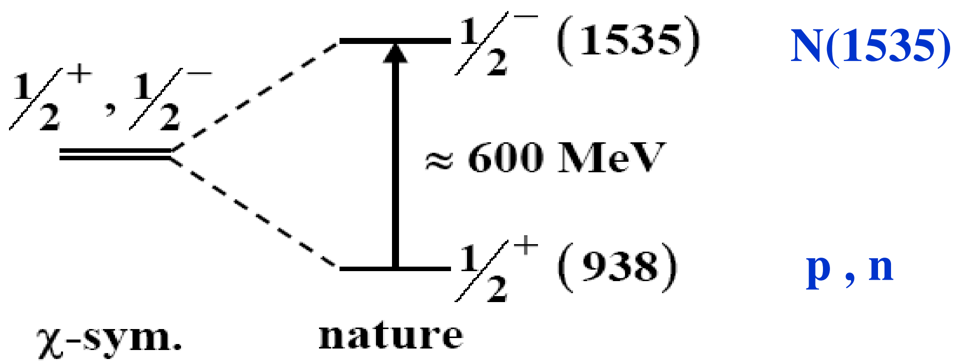
the chirality corresponds to the (conserved) helicity,
left- and right-handed quarks **decouple**

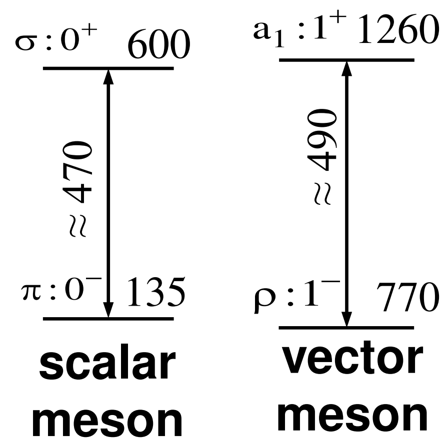
Chiraly symmetric world:

chiral partners with same spin but opposite parity **degenerate in mass**.

The QCD Lagrangian is **chiraly symmetric**
but in "nature" chiral symmetry is broken !

Mass split is large, comparable to hadron masses.



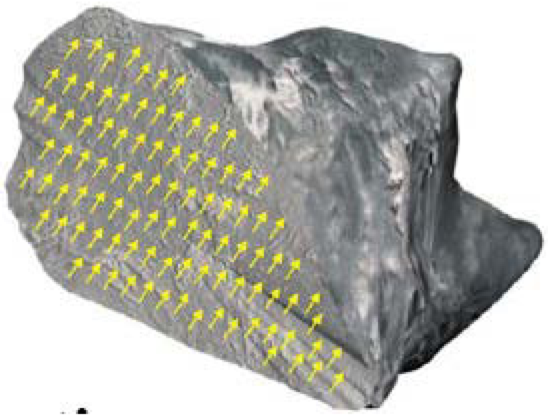


explicit breaking by small but finite quark masses

spontaneous breaking due to the existence of a massless mode ("Goldstone-boson")

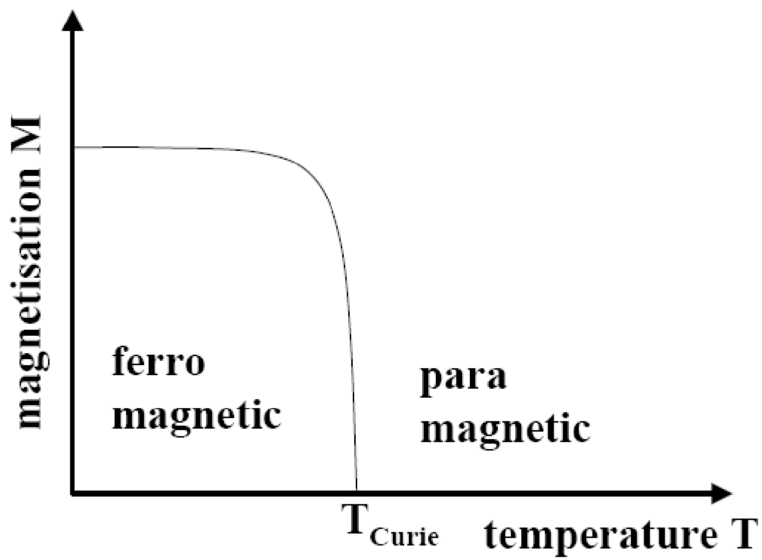
Spontaneous breaking of symmetry

spontaneous breaking of
full rotational symmetry

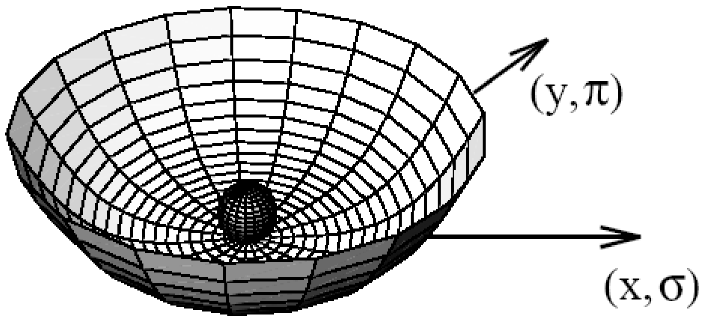


ferromagnetic

paramagnetic

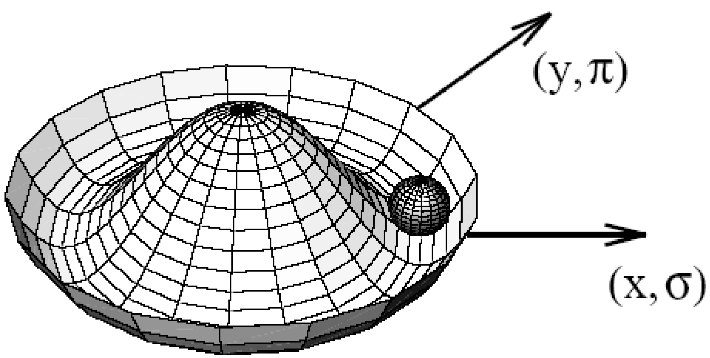


Classical mechanics analogy



ground state: symmetric

rotational symmetry



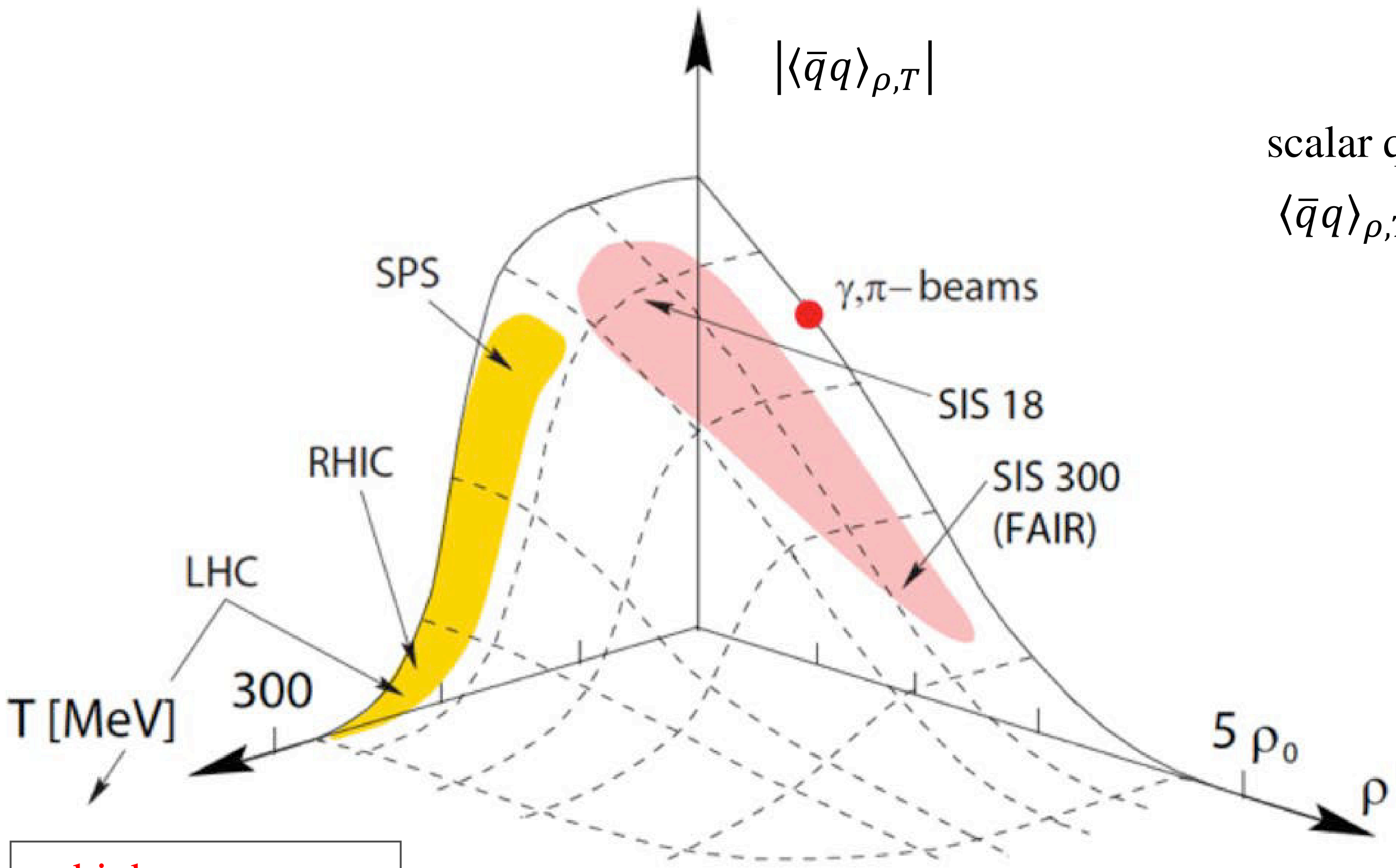
ground state: not symmetric

spontaneously broken rotational symmetry

Chiral symmetry restoration

According to theoretical predictions (i.e. by Lattice QCD)

chiral symmetry can be (partially) restored $\langle \bar{q}q \rangle_{\rho,T} \rightarrow 0$



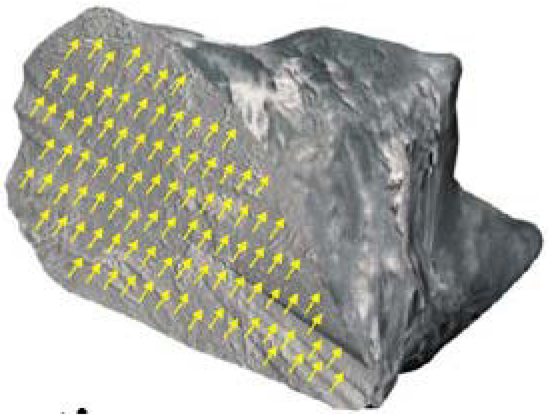
scalar quark condensate $\langle \bar{q}q \rangle_{\rho,T}$

at high temperature

at large baryon density

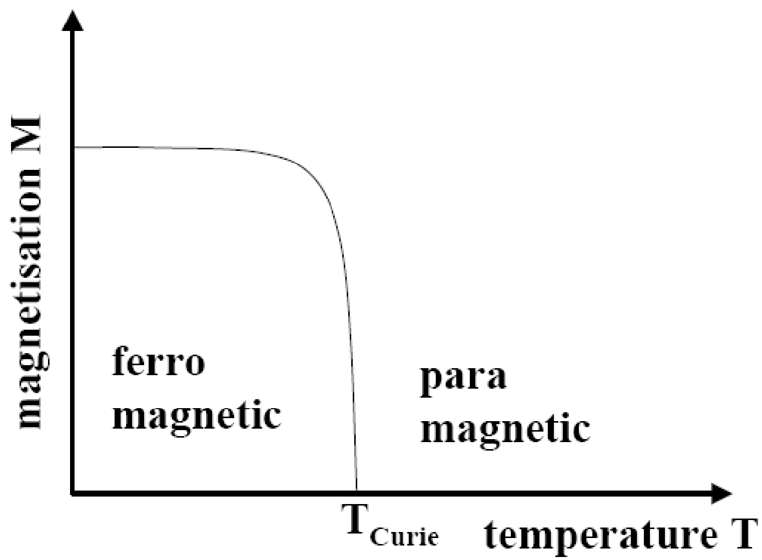
Restoration of symmetry

restoration of the
full rotational symmetry



ferromagnetic

paramagnetic



System: one particle species, P and T constant

Gibbs free energy (= thermodynamical potential)

$$G(T,P) = G_1(T,P) + G_2(T,P) = N_1\mu_1(T,P) + N_2\mu_2(T,P)$$

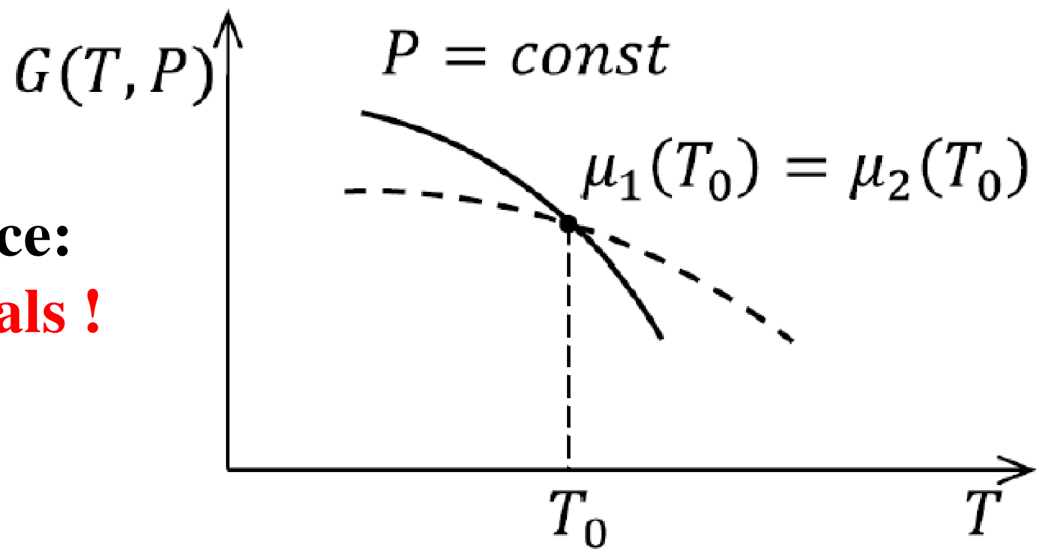
equilibrium: $dG = 0\,,\qquad N = N_1 + N_2 \; fixed \;\rightarrow dN_1 = -dN_2$

$$dG = \mu_1 dN_1 + \mu_2 dN_2 = 0$$

$$\rightarrow \mu_1\,(T,P) = \mu_2(T,P)$$

condition for coexistence:

equal chemical potentials !

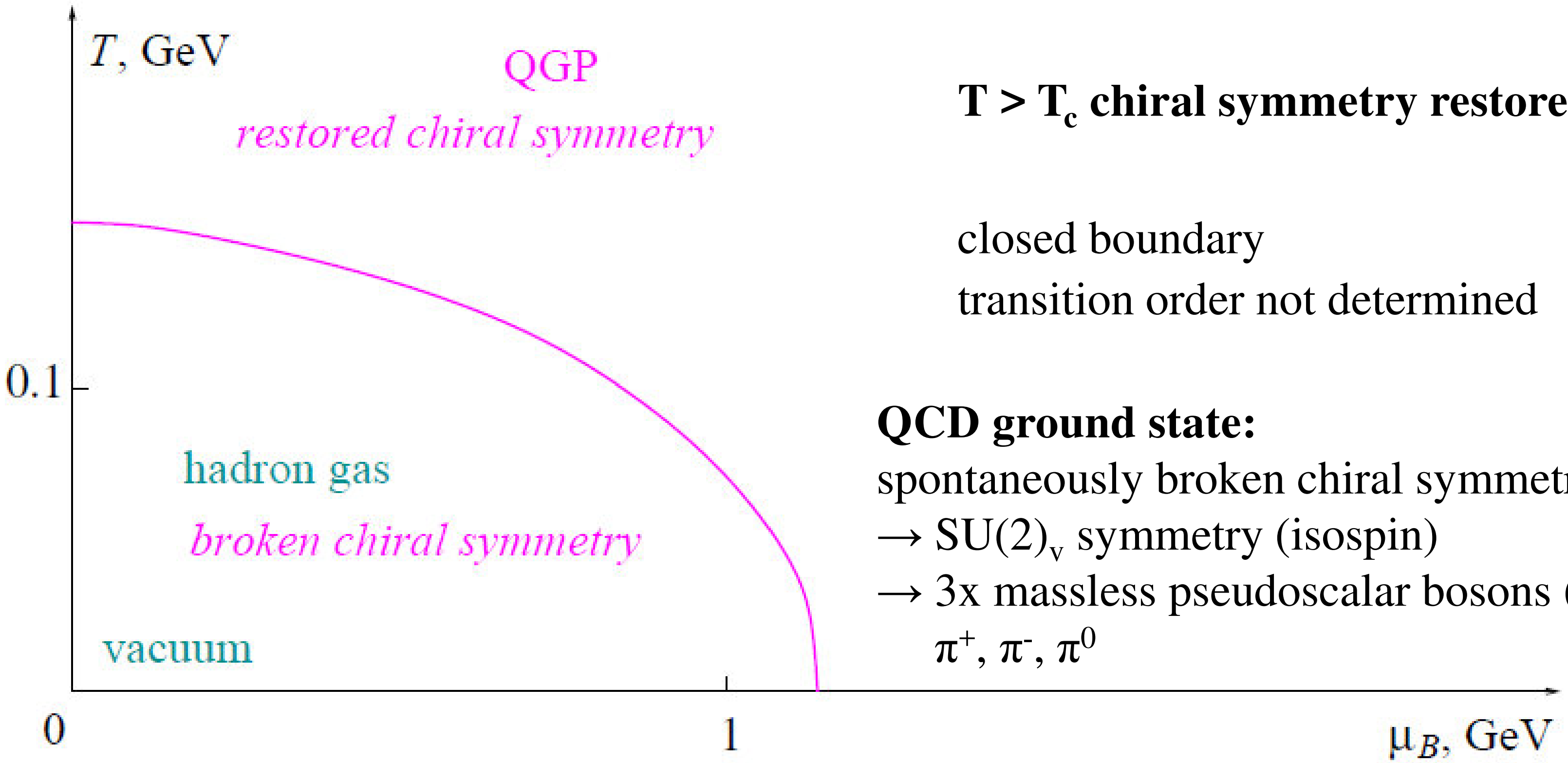


Structures of the QCD phase diagram

Assumption:

2x massless quarks (u,d), chiral limit

the QCD Lagrangian is chiraly symmetric, $SU(2)_L$ x $SU(2)_R$



T > T_c chiral symmetry restored

closed boundary

transition order not determined

QCD ground state:

spontaneously broken chiral symmetry

→ $SU(2)_v$ symmetry (isospin)

→ 3x massless pseudoscalar bosons (Goldstone)

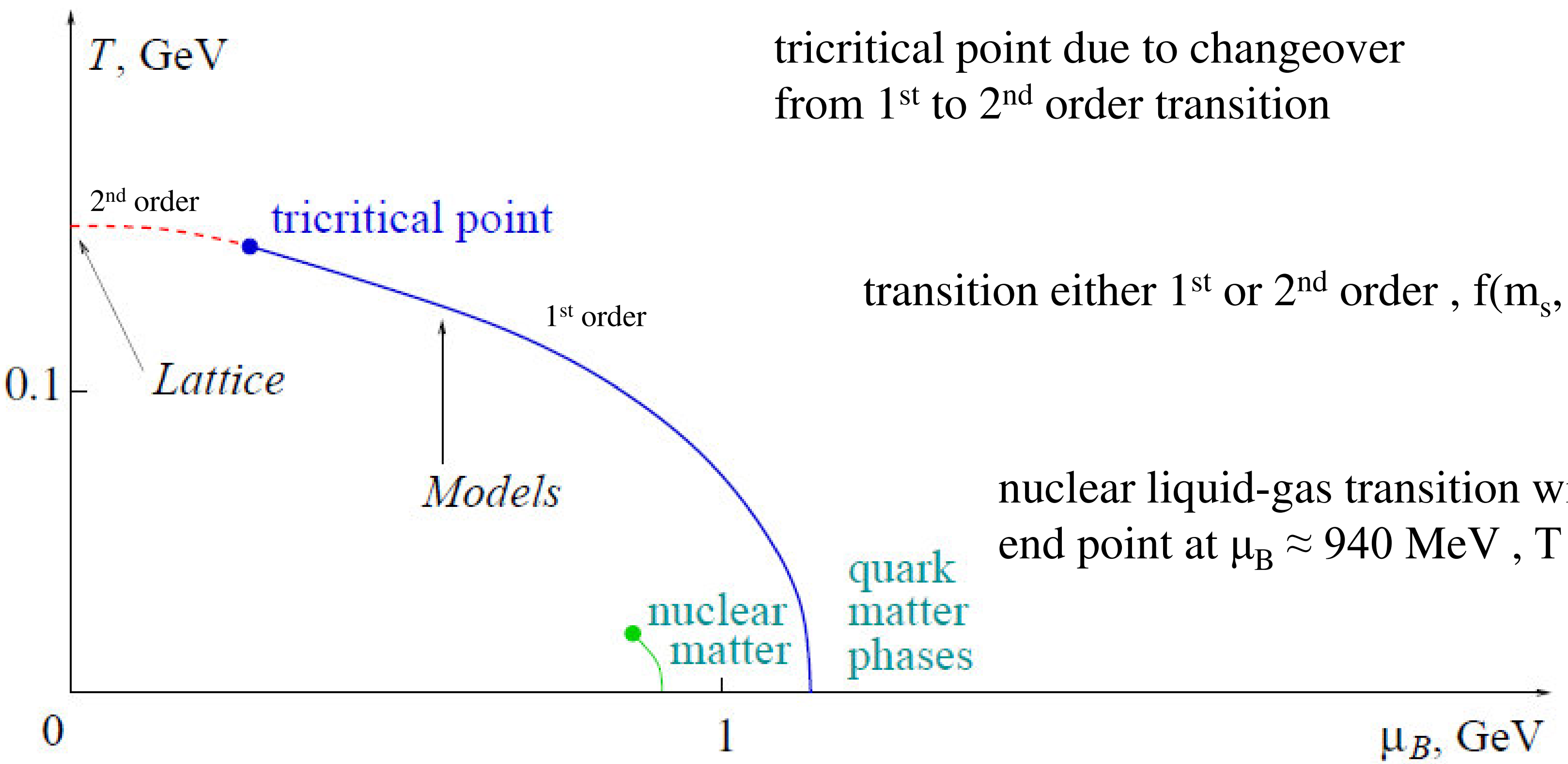
π^+, π^-, π^0

taken from CBM Physics Book

Lecture Notes in Physics, Vol. 814, 2011, Springer

Structures of the QCD phase diagram

Assumption:
2x massless quarks (u,d) + 1x massive quark (s)



tricritical point due to changeover from 1st to 2nd order transition

transition either 1st or 2nd order , f(m_s, μ_B)

nuclear liquid-gas transition with critical end point at $\mu_B \approx$ 940 MeV , T ≈ 15 MeV

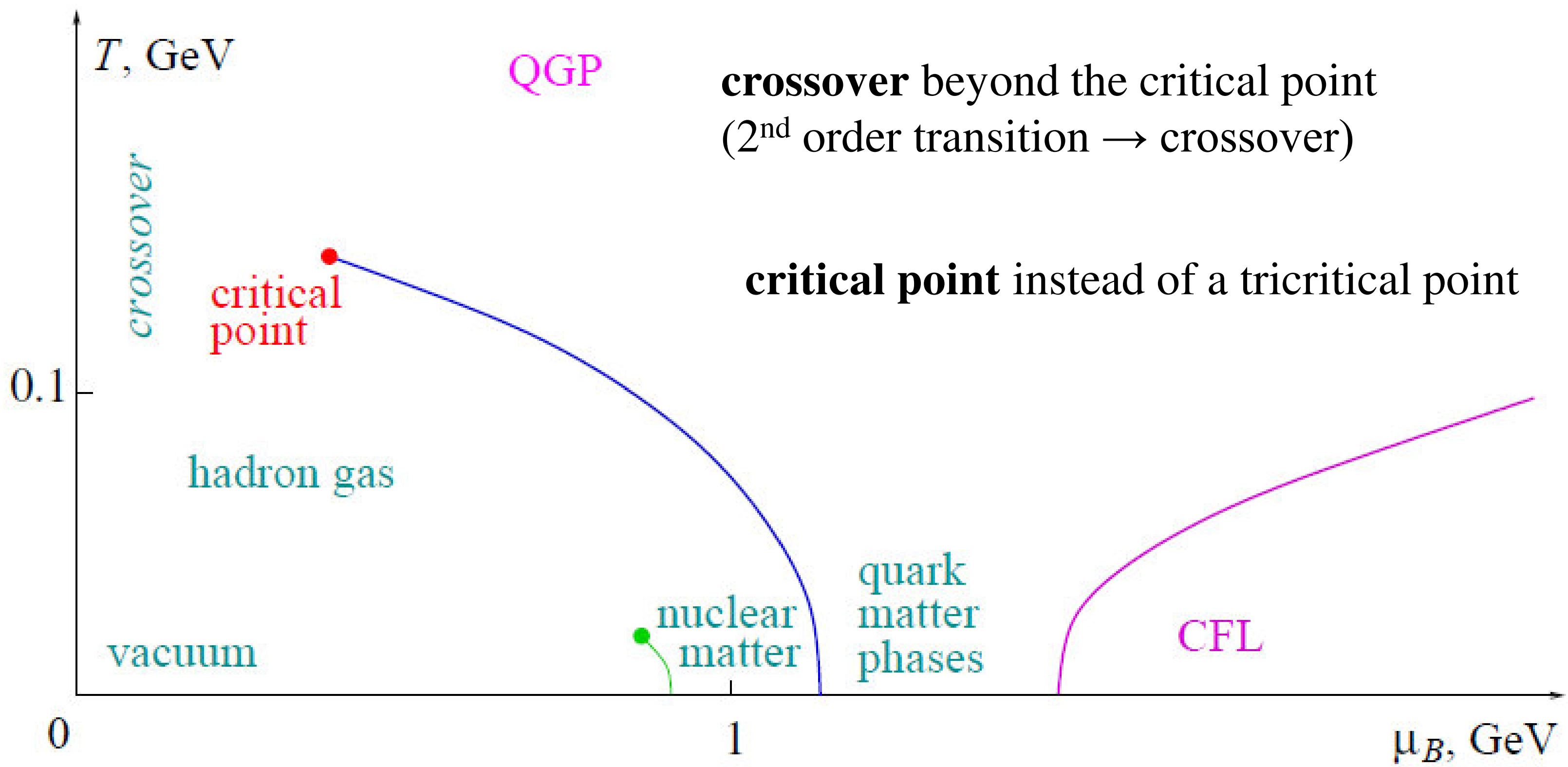
taken from CBM Physics Book
Lecture Notes in Physics, Vol. 814, 2011, Springer

Structures of the QCD phase diagram

masses of light quarks (u,d) set to **(observed) finite values**
→ **explicit breaking of chiral symmetry**

crossover beyond the critical point
(2^{nd} order transition → crossover)

critical point instead of a tricritical point



taken from CBM Physics Book
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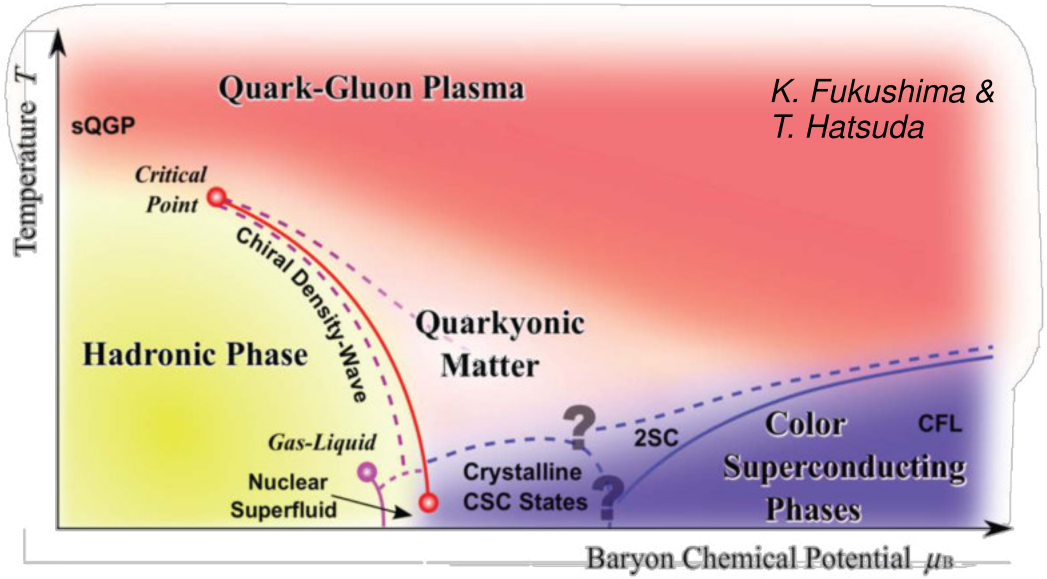
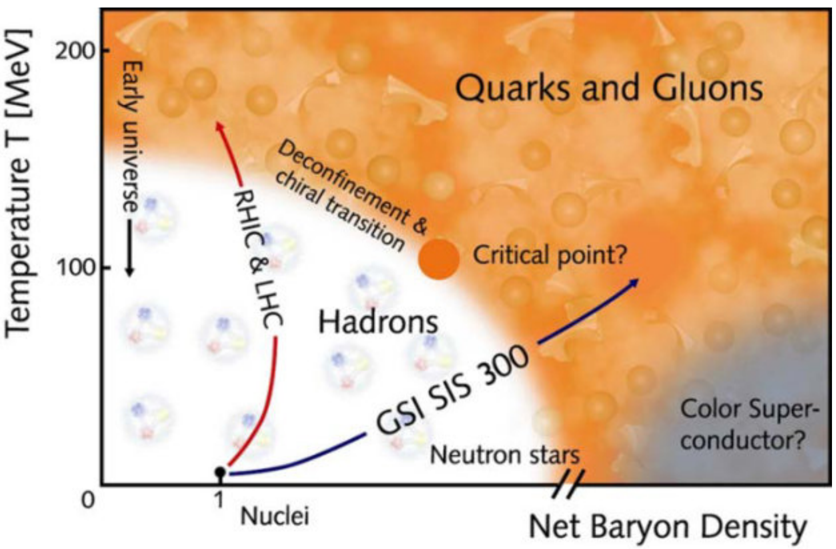
The phase diagram of strongly interacting matter



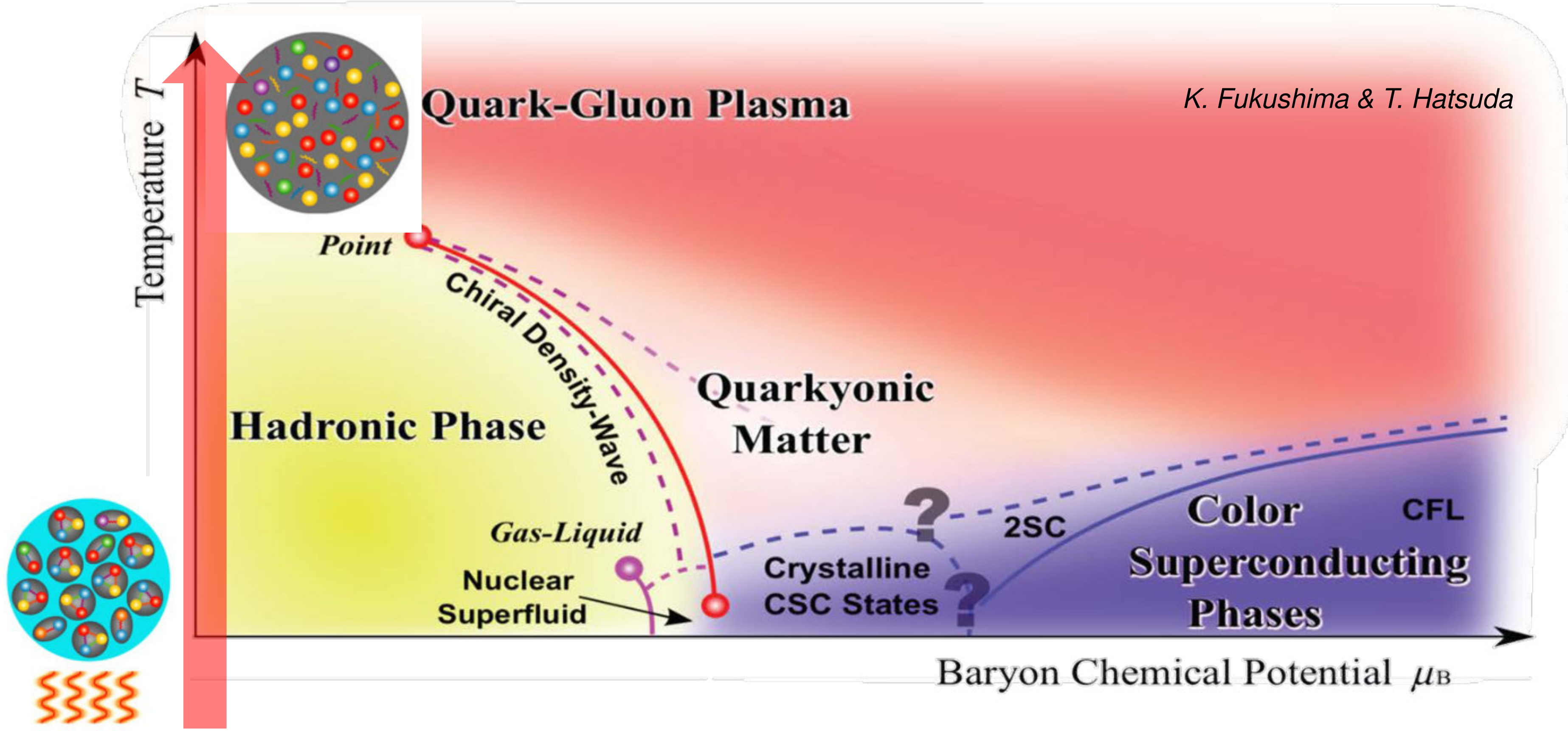


$$= \frac{1}{V}\frac{1}{3}(n_q - n_{\bar{q}})$$

How to scan the phase diagram ?

→ **Nucleus-nucleus collisions at various beam energies !**

Exploring the QCD phase diagram



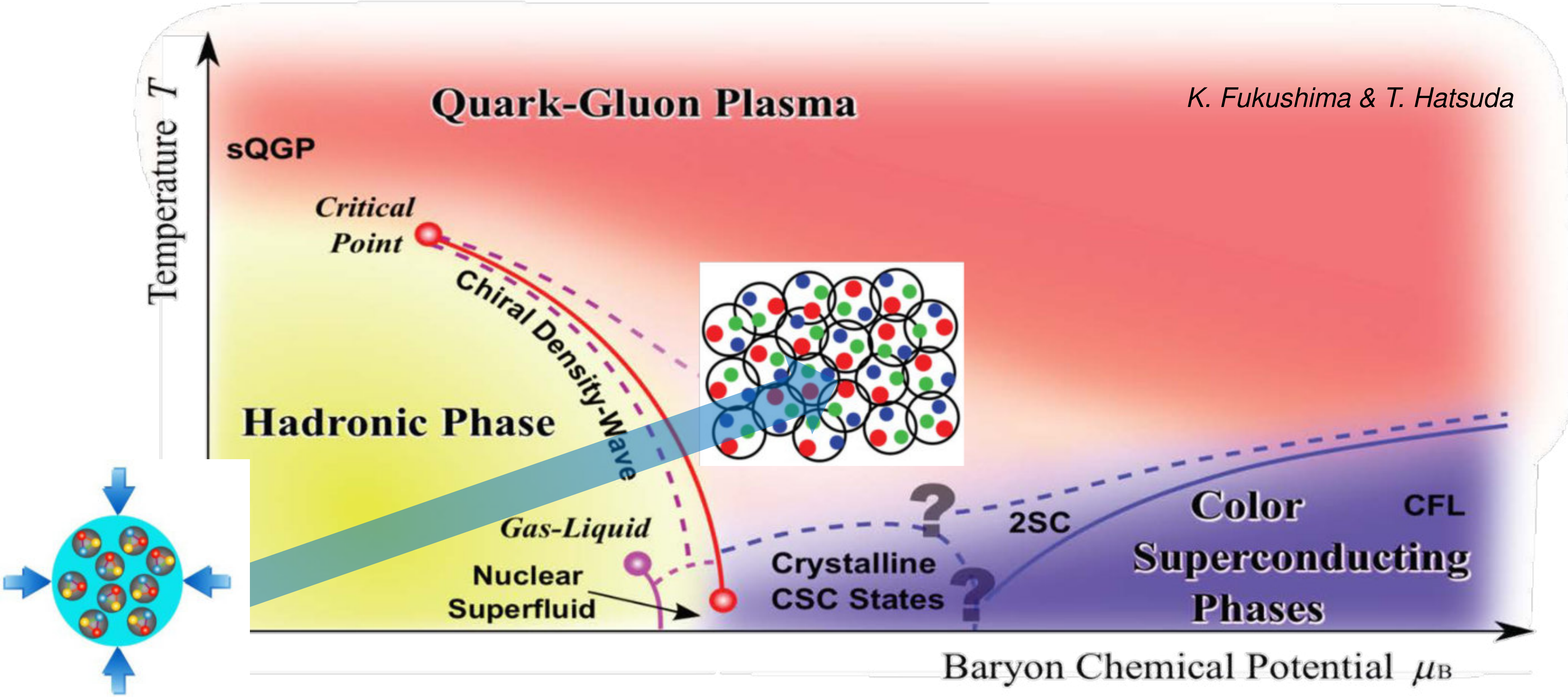
At very high temperature:

N of baryons ≈ N of antibaryons → situation similar to early universe

Lattice QCD: crossover transition Hadronic Matter → Quark-Gluon Plasma

Experiments:

ALICE, ATLAS and CMS at LHC & STAR and PHENIX at RHIC



At high baryon density:

N of baryons >> N of antibaryons , densities like in neutron star cores

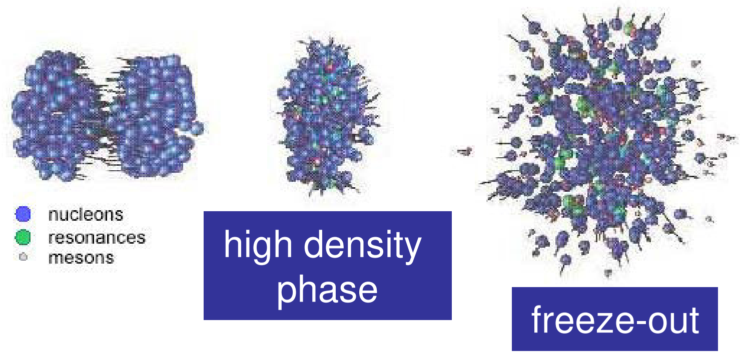
→ Lattice QCD not (yet) applicable

→ Models predict first order phase transition with mixed or exotic phases

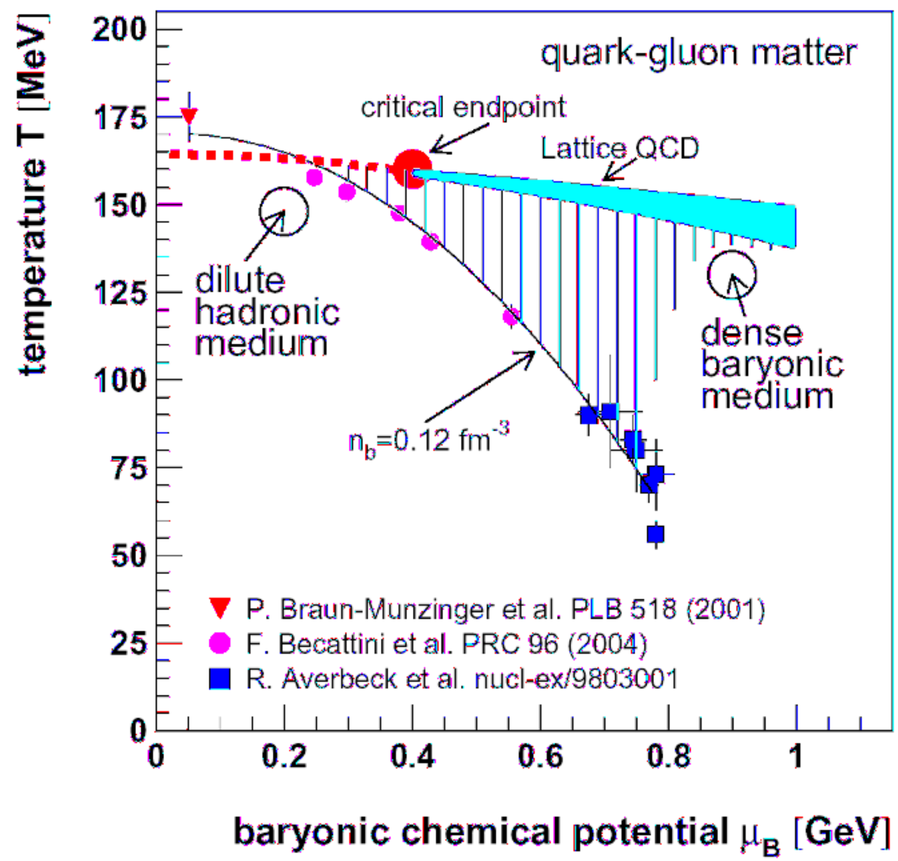
Experiments:

BES at RHIC, NA61 at CERN SPS, NICA at JINR and **CBM at FAIR**

The phase diagram of strongly interacting matter

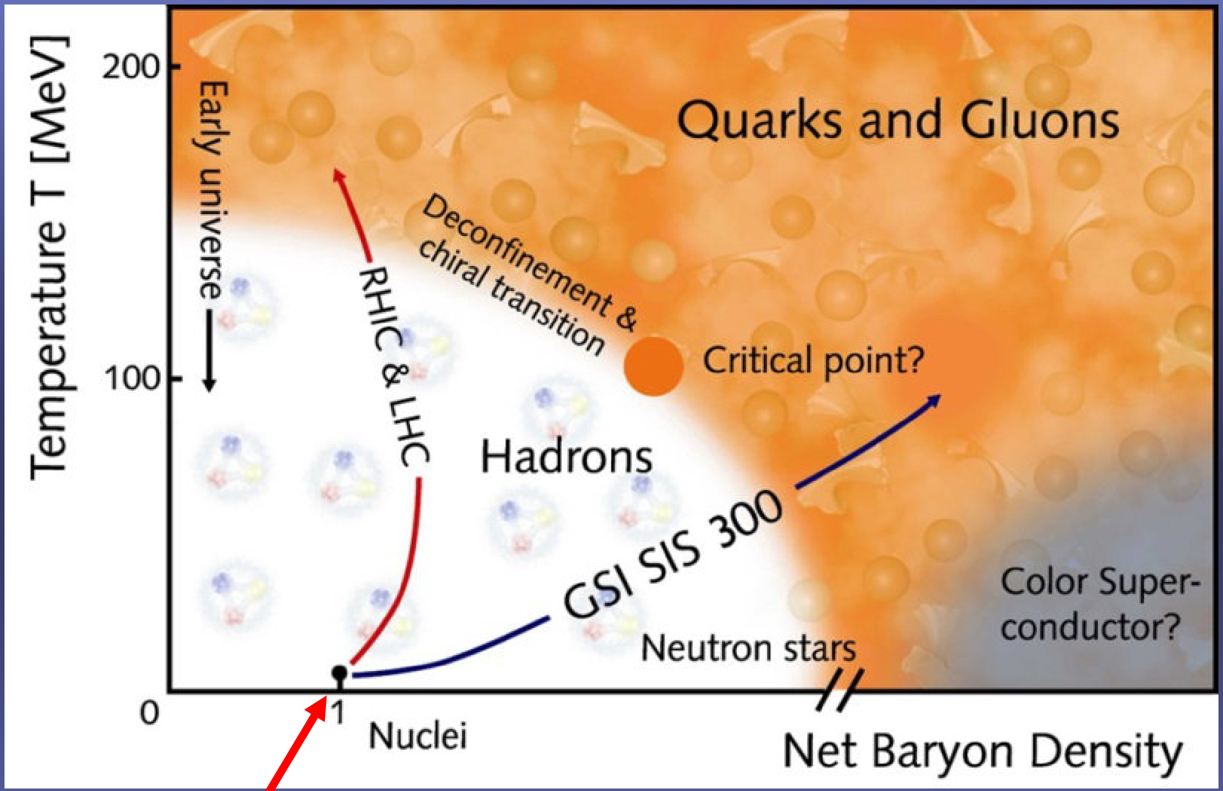


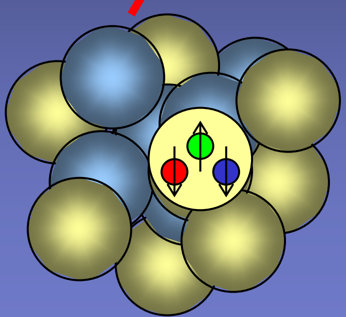
data taken at:
RHIC/LHC SPS AGS SIS



<u>data:</u>
μ_B , T calculated by **statistical models** to describe the **measured particle ratios** (at the freeze-out) such as:
p/d
π/K
...

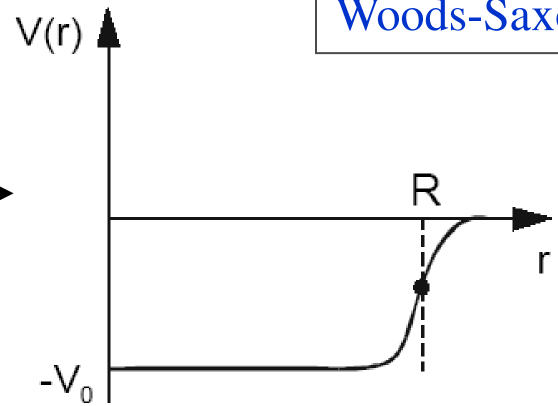
Chapter I
Nuclear Matter at (or close to) ground state





Woods-Saxon Potential

density distribution of nucleons inside (heavy) nuclei →



$$V(r) = \frac{-V_0}{1 + \exp\left(\frac{r - R}{a}\right)}$$

solving the Schrödinger equation

$$\left\{ \frac{\hbar^2}{2m} \Delta + \left[E - V(r) \right] \right\} \Psi = 0$$

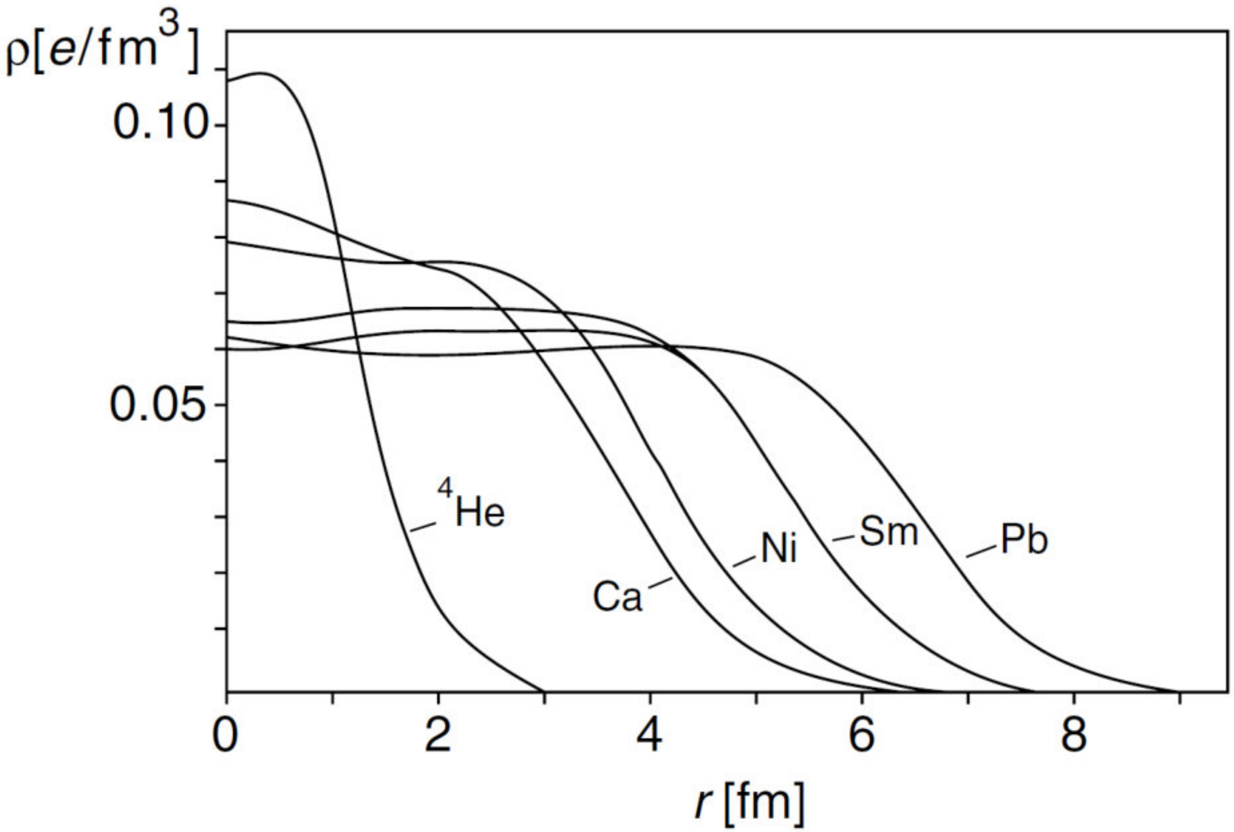
splitting of shells due to the spin-orbit coupling has to be taken into account !

observed magic numbers

N	2	8	20	28	50	82	126	(184)	(196)
Z	2	8	20	28	50	82	(114)	(164)	

Nuclear matter at ground state

Charge distribution of nuclei obtained in electron-nucleus scattering



(Povh/Rith)

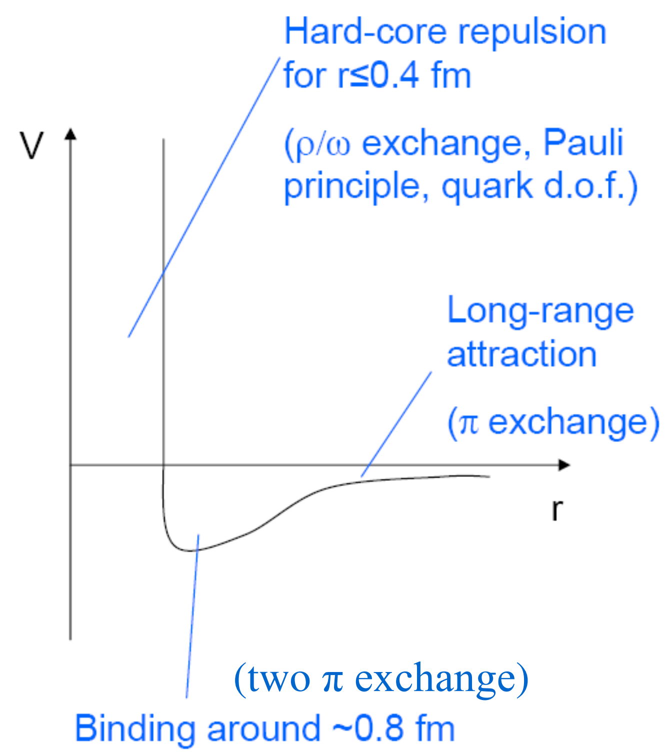
$\rho^e(0) \cdot \frac{A}{Z} \rightarrow$ saturation density $\rho_0 \approx 0.17$ nucleons / fm^3

Effective nucleon-nucleon interaction

The meson exchange is a model to describe the effective nucleon-nucleon-interaction

range R of the interaction is determined by the uncertainty principle:

$$R = c\Delta t = \frac{\hbar c}{m_x c^2} = \frac{197 MeV \bullet fm}{m_x c^2}$$



ρ- , ω-meson:
- vector particle $J^P = 1^-$
- $m_{\rho,\omega} \approx 780$ MeV

Pion (π-meson):
- pseudo-scalar particle $J^P = 0^-$
- $m_\pi = 140$ MeV

Link to QCD

In QCD one important contribution to the description of the nucleon-nucleon interaction is given by **color neutral quark-antiquark exchange** (sea quarks) which can be understood as a meson exchange between nucleons.

The equation-of-state of nuclear matter

$$\varepsilon(\rho,T) = \varepsilon_T(\rho,T) + \varepsilon_C(\rho,T=0) + \varepsilon_0$$

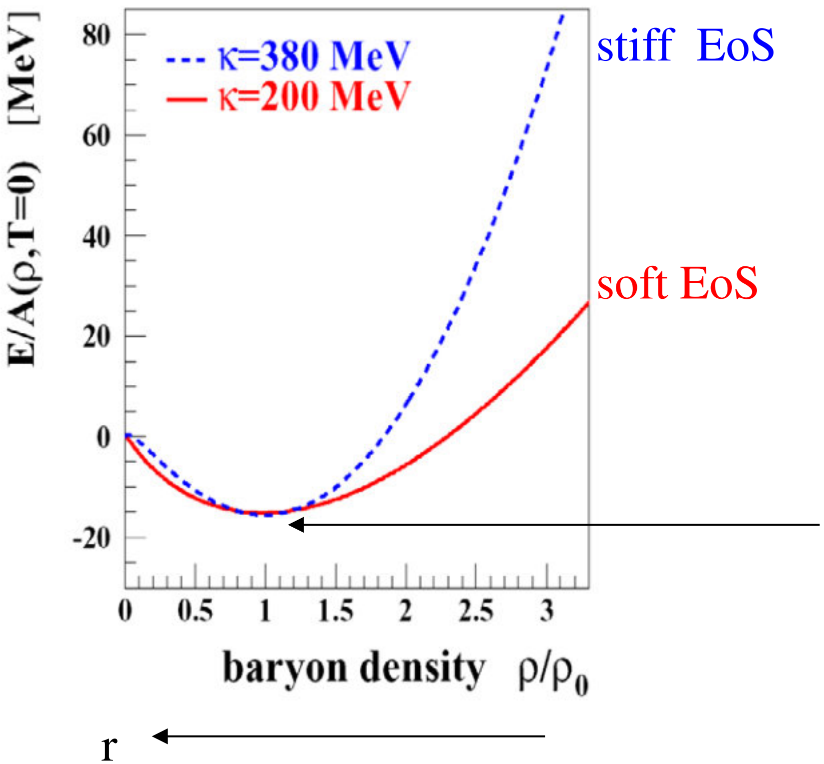
$(\varepsilon = E/A)$ thermal compressional ground state energy

thermodynamical concept

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

$$E/A(\rho,T=0) = \frac{1}{\rho}\int U(\rho)\,d\rho$$

$U(\rho)$: density dependent local potential

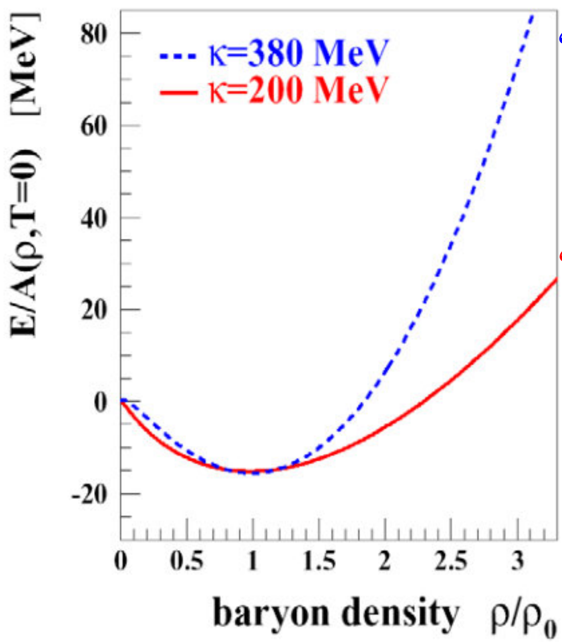


compression modulus

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

The nuclear equation-of-state (EoS)

$$E/A\,(\rho, T=0) \;=\; \frac{1}{\rho}\int U\,(\rho)\,d\rho$$



"stiff" EoS

"soft" EoS

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

compression modulus

effective NN-Potential (Skyrme)

$$U\,(\rho) \;=\; \alpha\left(\frac{\rho}{\rho_0}\right) \;+\; \beta\left(\frac{\rho}{\rho_0}\right)^{\gamma}$$

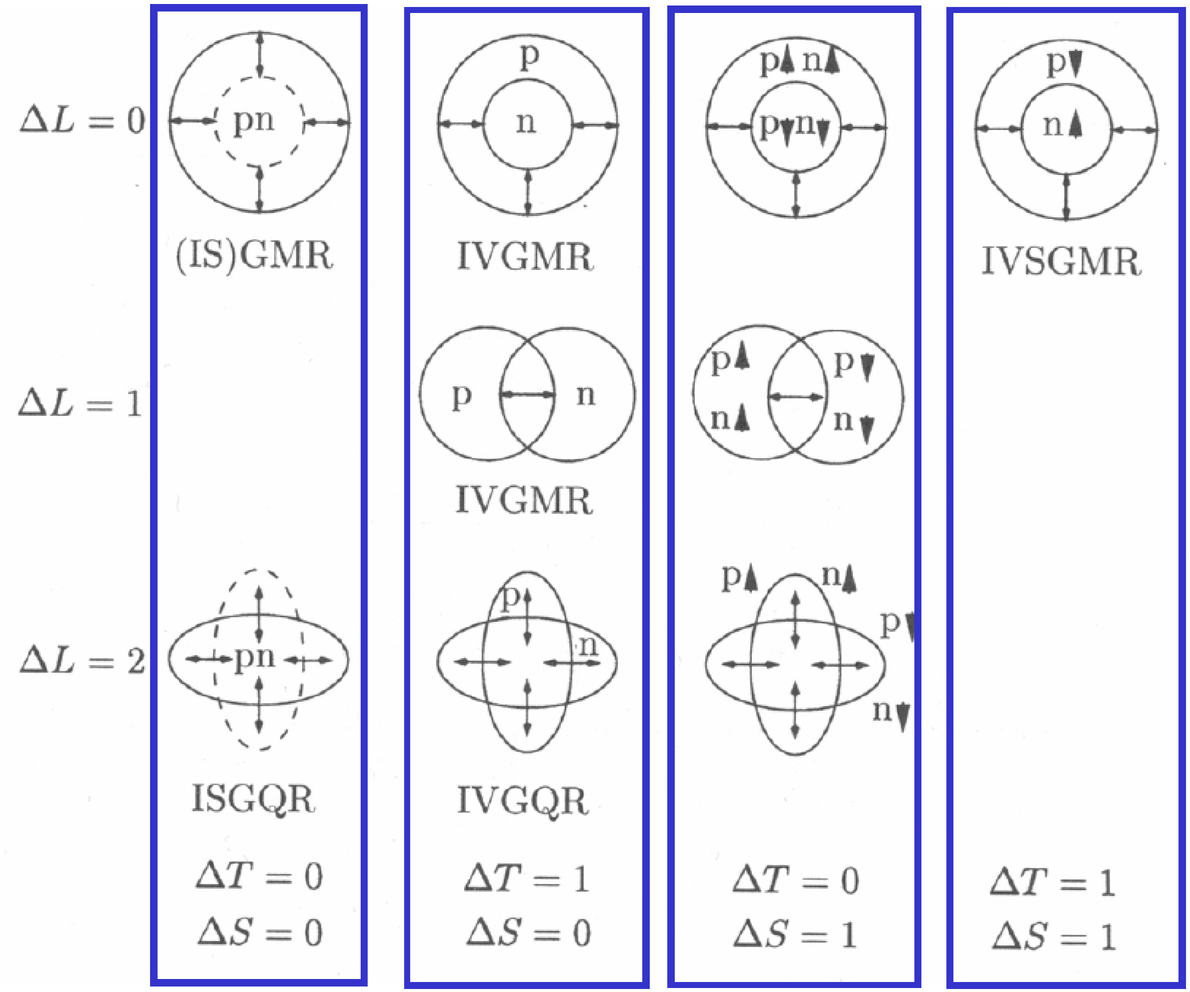
constraints for the parameters of the potential :

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

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

	α [MeV]	β [MeV]	γ
κ = 380 MeV	**-124**	**70.5**	**2**
κ = 200 MeV	**-356**	**303**	**7/6**

Collective excitation of nuclei: Giant Resonances



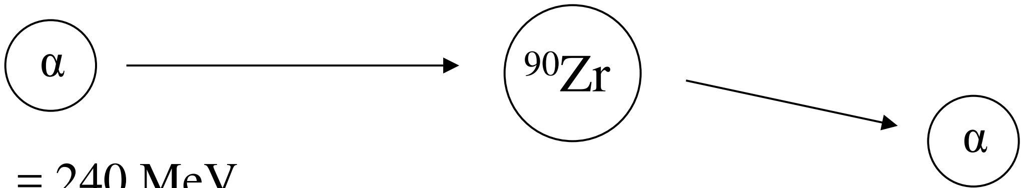
monopole vibration:
"breathing mode" of
the nucleus

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

quadruple vibrations

Excitation of the giant monopole resonance

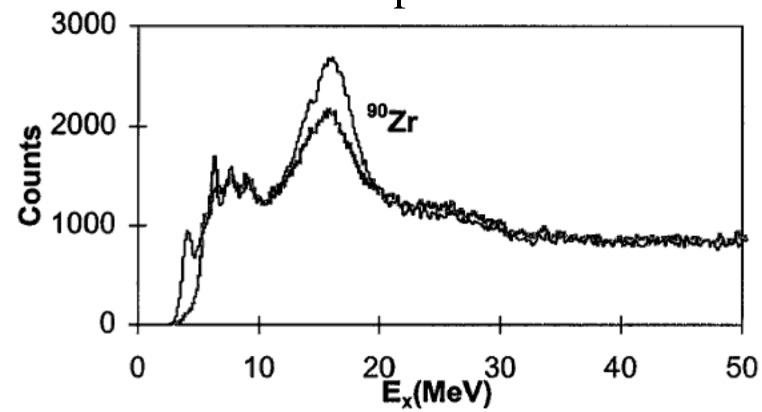
inelastic scattering of α particles on nuclei



E_{kin} = 240 MeV

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

"resonance phenomenon"



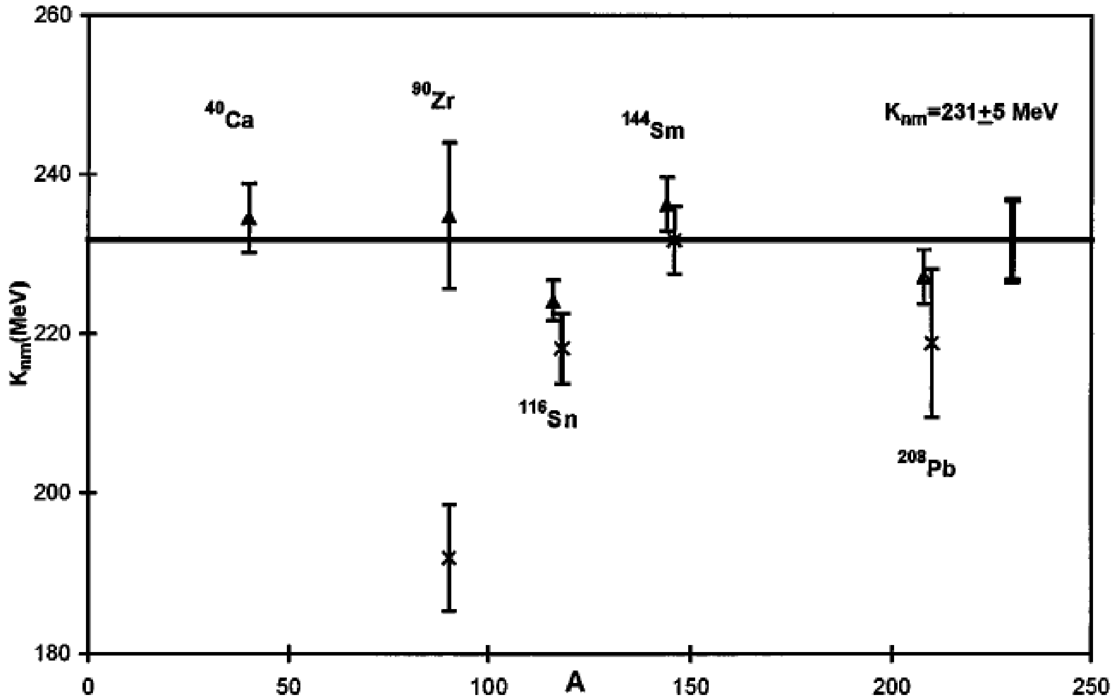
The energy loss of the α particle of about 15 – 25 MeV excites slight density oscillations with elongations of about 1/100 ρ_0 (around saturation density ρ_0). It is a collective excitation of the nucleus and calls the Giant Monopole Resonance or the "breathing mode" of nuclei.

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

The compression modulus κ at saturation density ρ_0

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

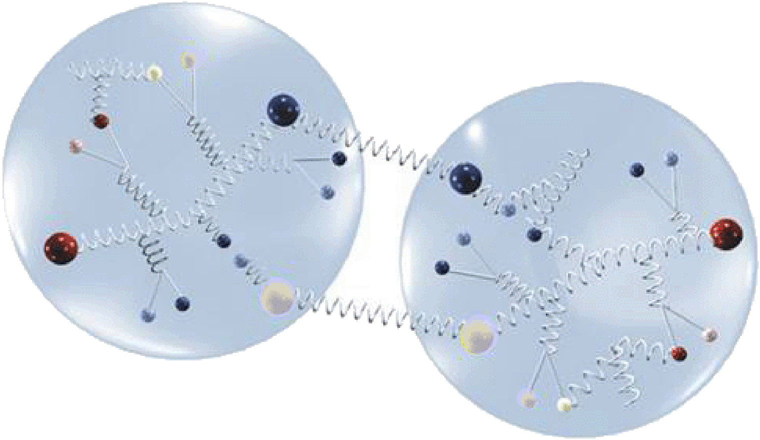
Youngblood et al. , Phys. Rev. Lett. 82 (1999)691



$\kappa = 231 \pm 5$ MeV

Summary: effective nucleon-nucleon interaction

The **bonds** between nucleons inside the nucleus are **relatively "weak"**.
The average distance is much larger than the hard core radius of the nucleon.

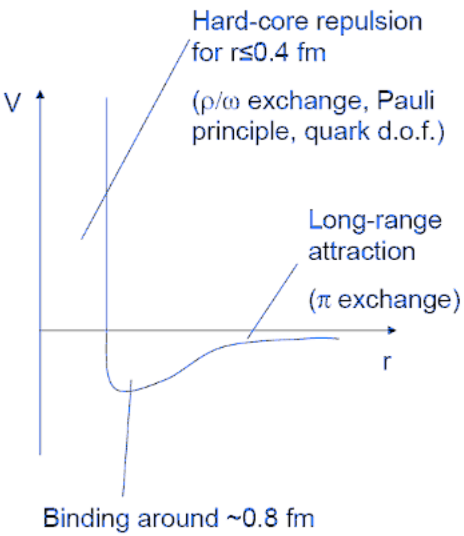


Nucleons are not localized inside the nucleus - they can move almost free inside the nucleus $\rightarrow p_f = 250$ MeV/c .

Link to **QCD** ?

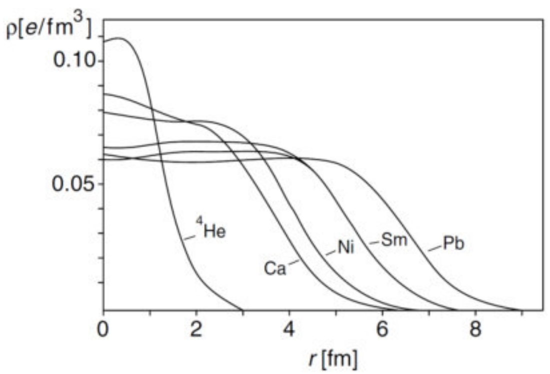
Quarks and gluons are not the relevant degree of freedom (in this regime).
The largest fraction of the interaction strength is shielded because quarks and gluons are bound to color-neutral hadrons.

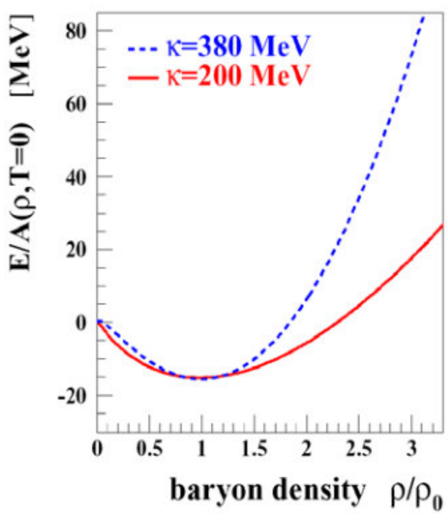
Summary: effective nucleon-nucleon interaction



The effective NN-potential has an **attractive** and a **repulsive** component.

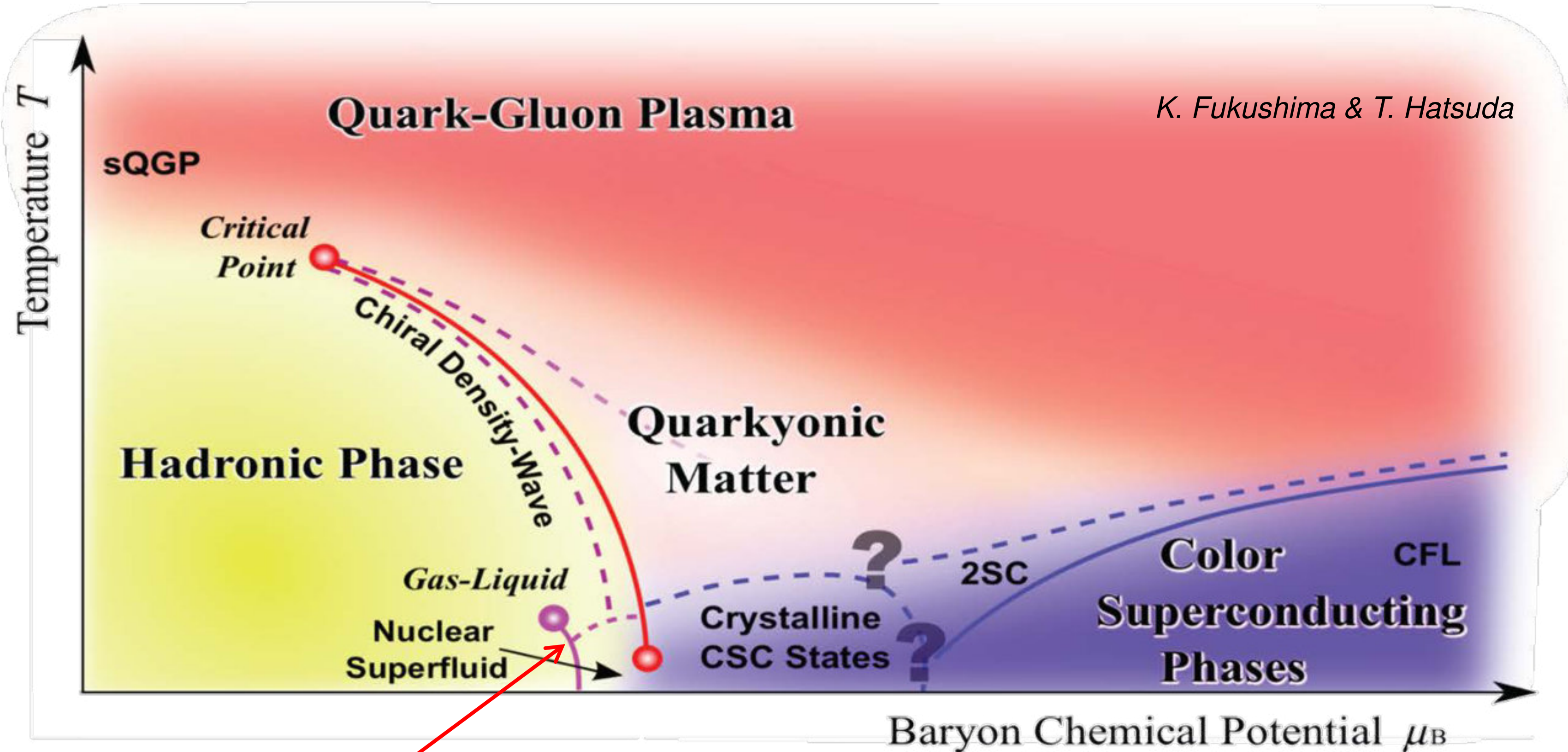
It saturates at $\rho_0 = 0.17\ \mathrm{fm}^{-3}$





The equation-of-state of nuclear matter:
$\kappa = 231 \pm 5$ MeV at saturation density ρ_0

The liquid-gas phase transition

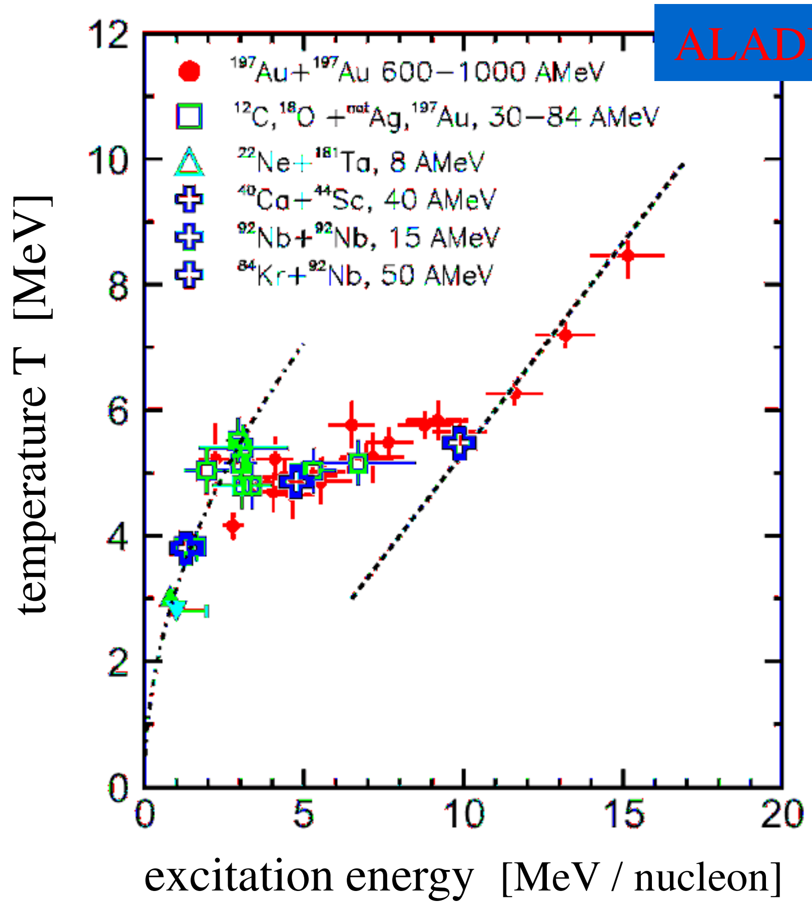


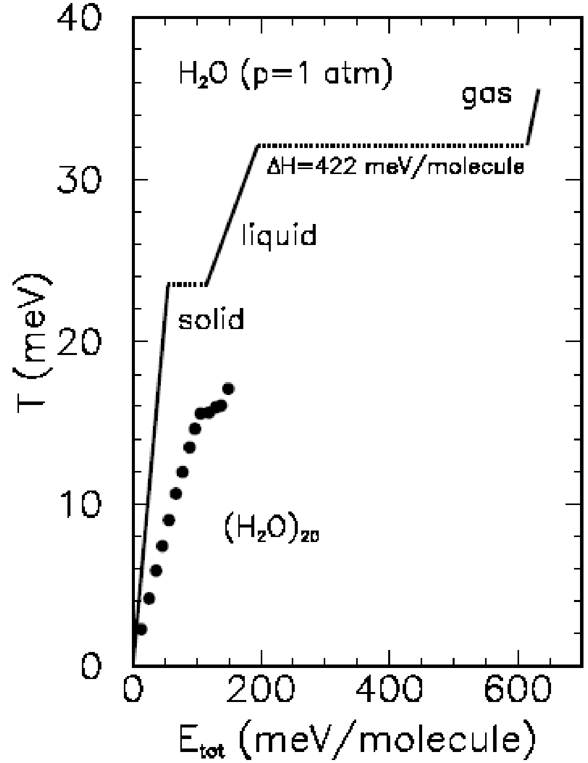
obtained in peripheral nucleus-nucleus collisions at bombarding energies from 8 – 1000 AMeV

The liquid-gas phase transition

peripheral nucleus-nucleus collisions

- temperature: MB distr. of the decay products
- excitation energy: total energy of **all** particles

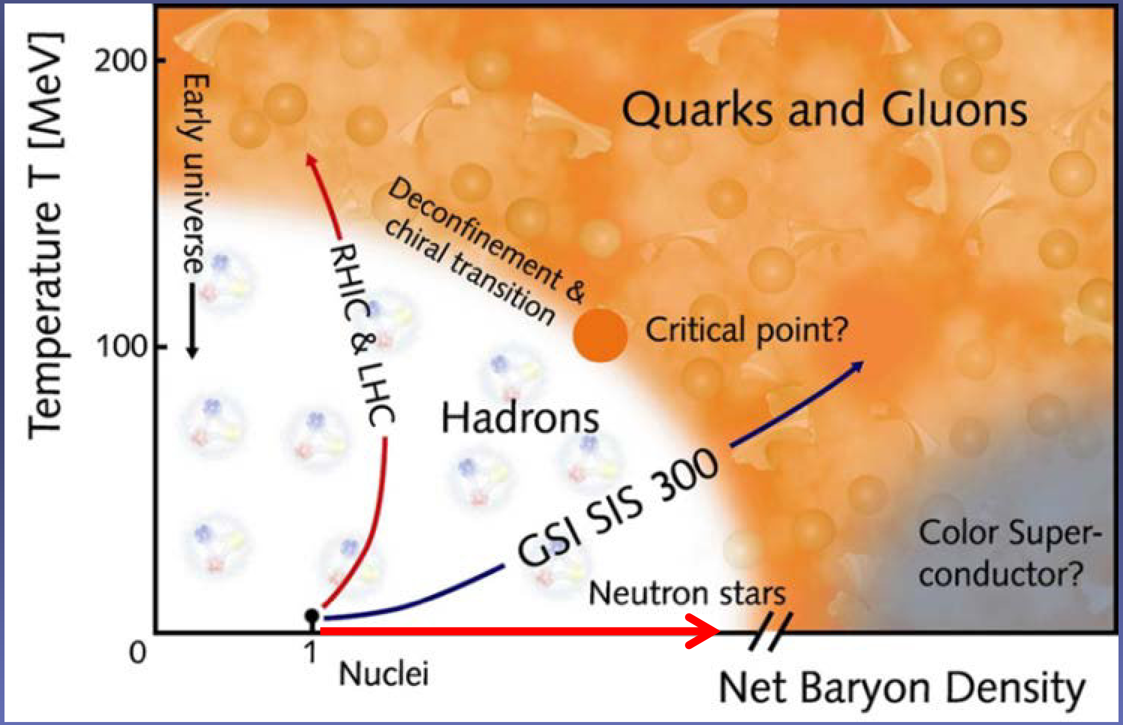




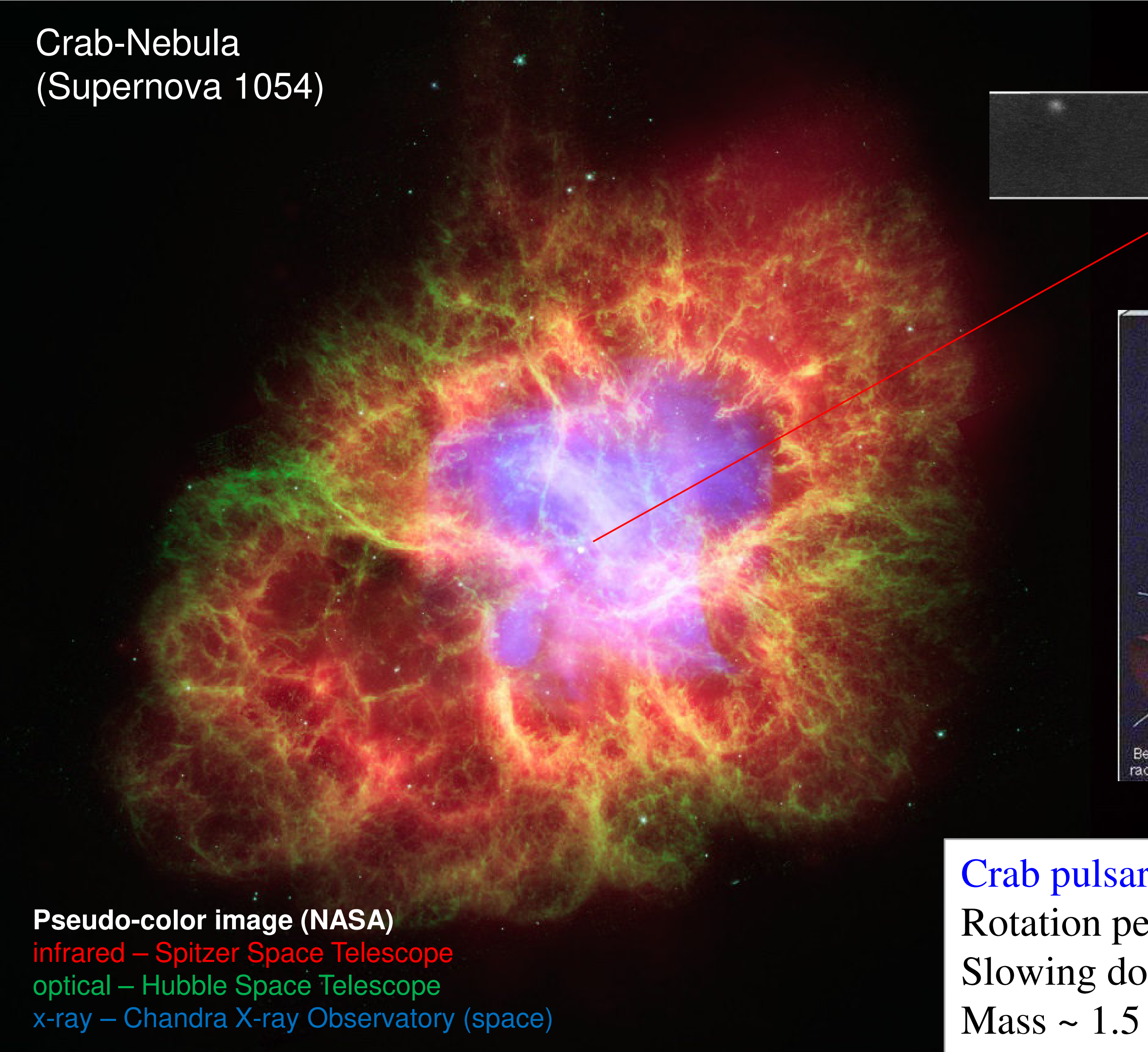
Results of the ALADIN collaboration show evidence for a transition from a liquid to a vapor phase of nuclear matter.

Chapter II
Compressed nuclear matter in the universe

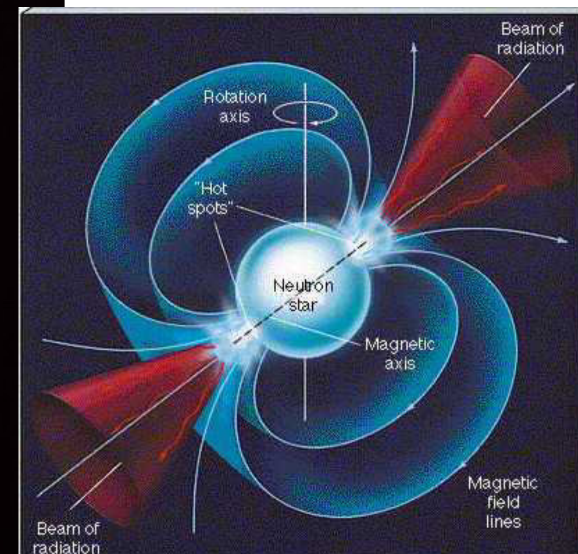
Late stages of heavy stars



$T \approx 0$, $\rho \rightarrow$ 5-10 ρ_0



slow motion



Crab pulsar

Rotation period $T = 33.4$ ms

Slowing down rate $\Delta T/\Delta t = 3 \cdot 10^{-8}$ s/a

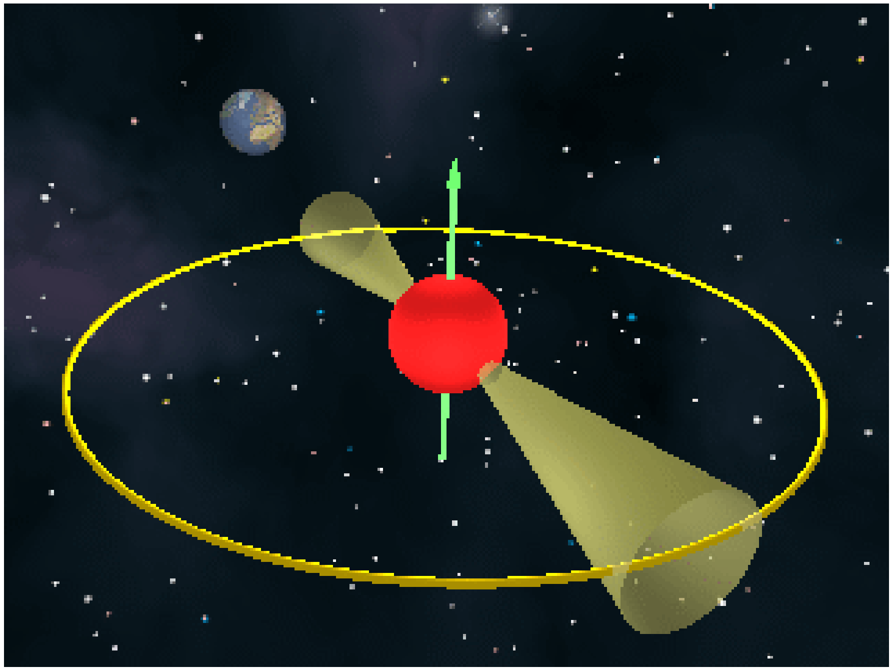
Mass ~ $1.5\ M_{\odot}$

Radius ~ 15 km

Density $3 - 10\ \rho_0$

Pulsars

"The Sounds of Pulsars" http://www.jb.man.ac.uk/~pulsar/Education/Sounds/sounds.html



PSR B0531+21 (Crab Pulsar)
rotation: 30 times a second

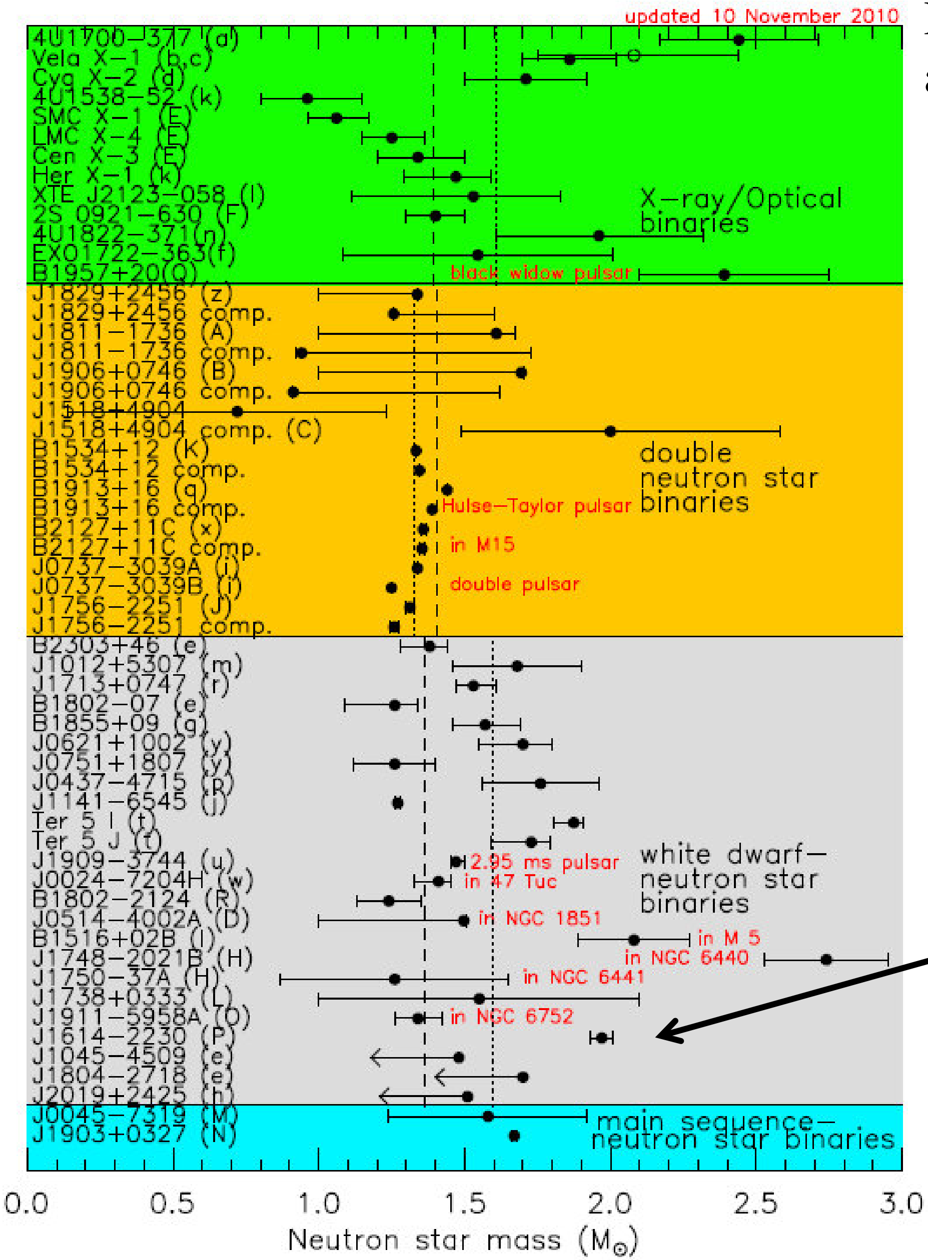
PSR B1937+21
rotation: 642 times a second

Fastest-rotating pulsar: PSR J1748-2446ad
rotation: 716 times a second

The surface of the fastest-rotating pulsars are moving at about 14% of the speed of light !

Enormous gravitational forces which prevent it flying apart due to the immense centrifugal forces !

Observed neutron star masses



Lattimerand Prakash, arXiv:1012.3208 [astro-ph.SR]

PSR J1614-2230

Green Bank Radio Observatory (2010)

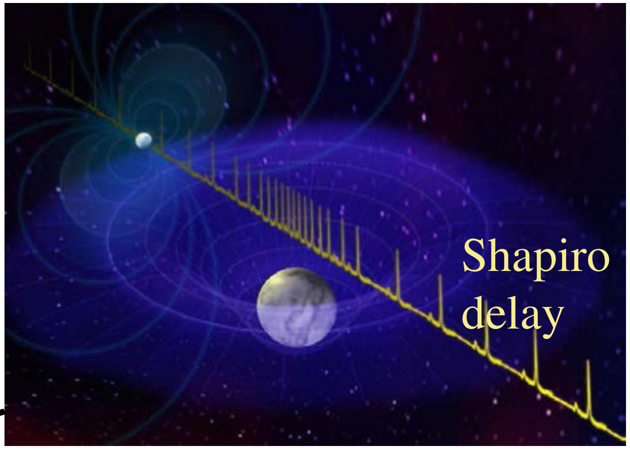
Mass: (1.976 ± 0.04) $M_\odot$

Distance: ~1 kPc (~3200 Ly)

Pulsar spin period: 3.1508076534271(6) ms

Companion mass: 0.5 $M_\odot$

Orbital period: 8.6866194196(2) d



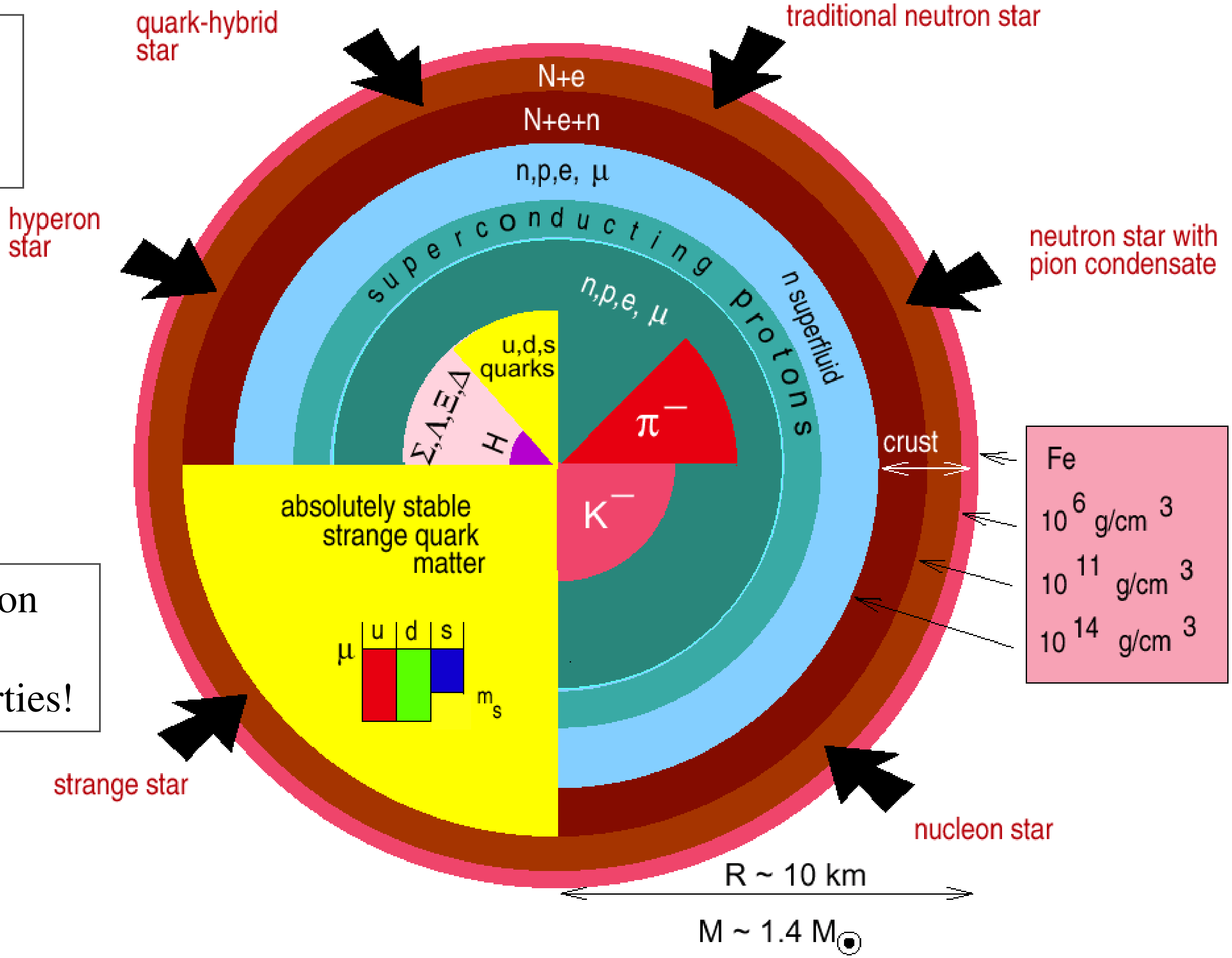
Shapiro delay – a general relativistic effect ! Time signal is getting delayed when passing near massive object - size of the effect depends on mass and inclination angle.

Composition of a neutron star

F. Weber, J.Phys. G27 (2001) 465

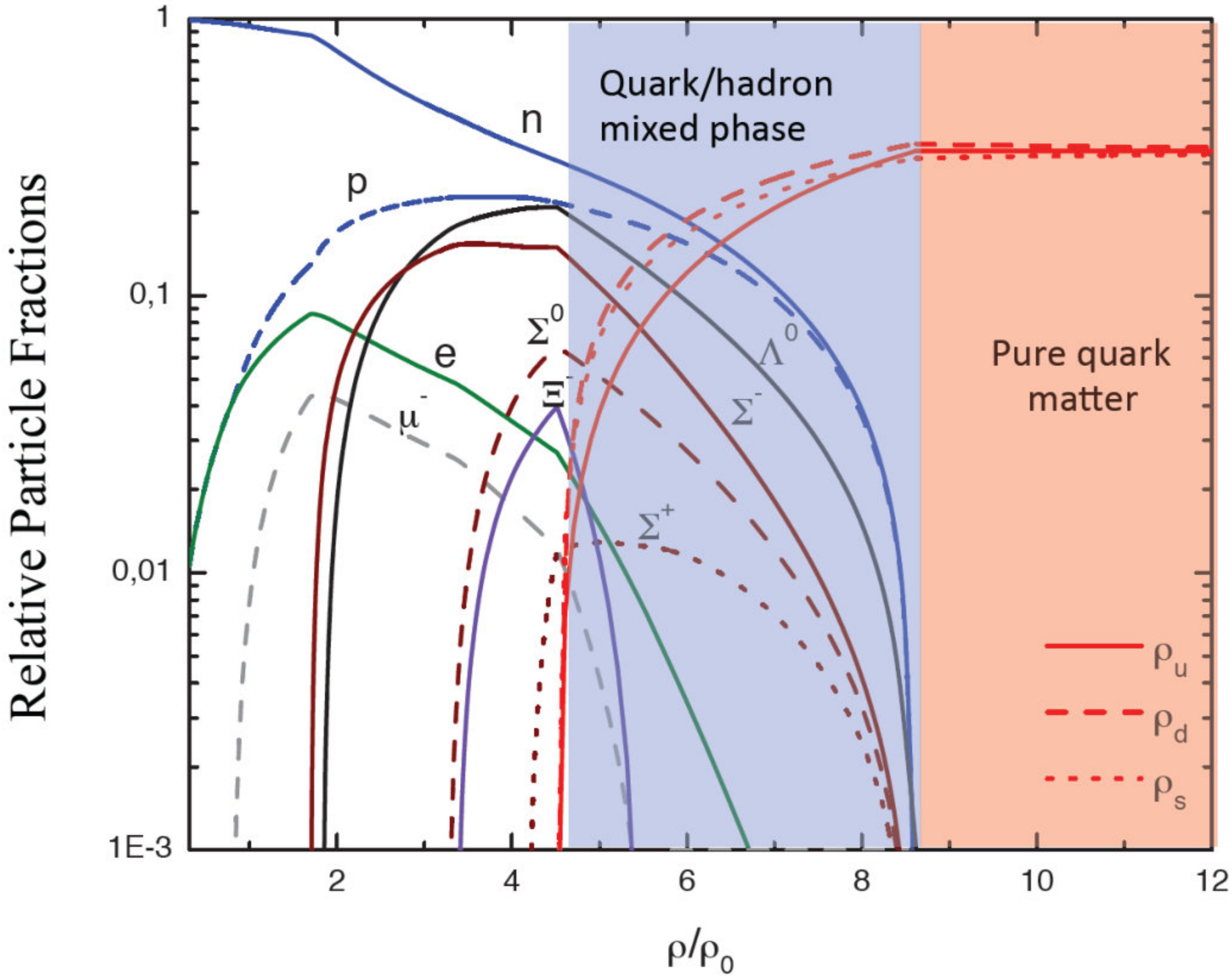
Each arrow indicates a different model for the neutron star.

Each model is based on assumptions on nuclear matter properties!



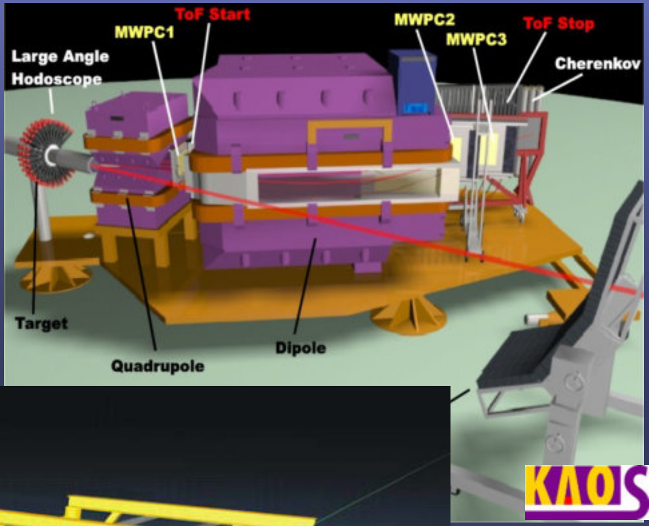
Quark matter in massive neutron stars?

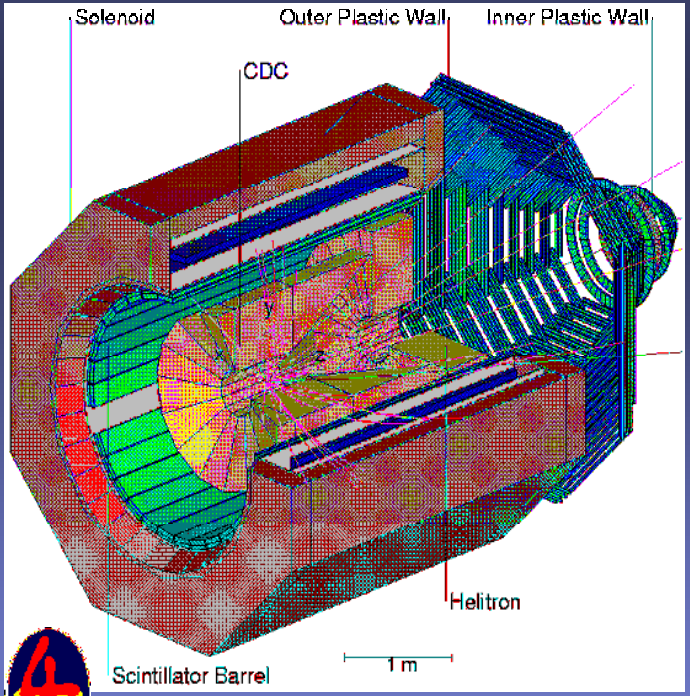
Equation-of-state: Non-local SU(3) NJL with vector coupling
M. Orsaria, H. Rodrigues, F. Weber, G.A. Contrera, arXiv:1308.1657

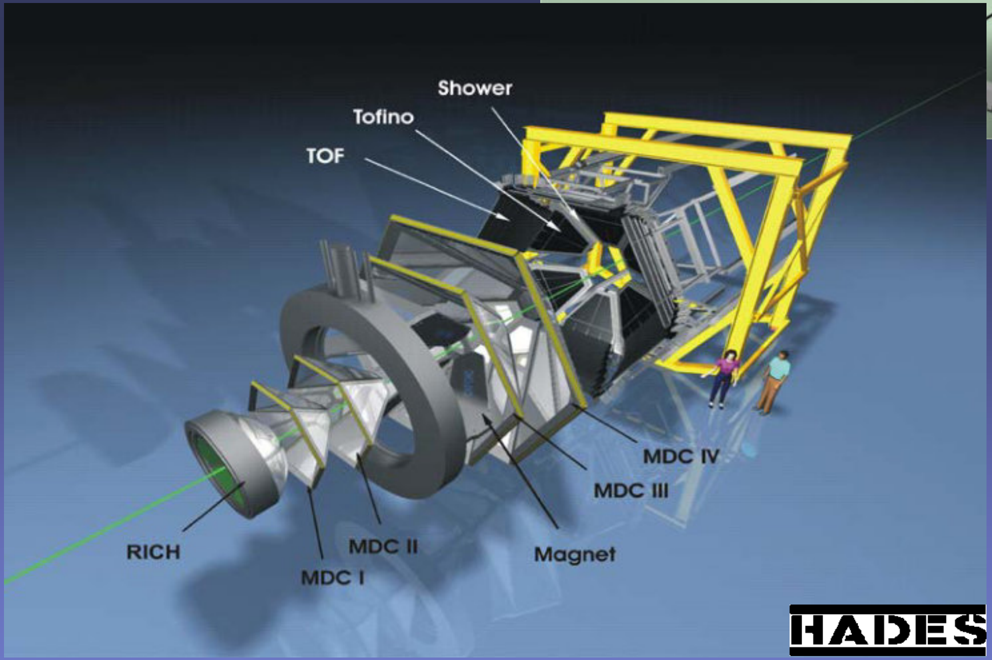


Chapter III
Exploring dense nuclear matter in the laboratory

Nucleus-nucleus collisions at SIS18



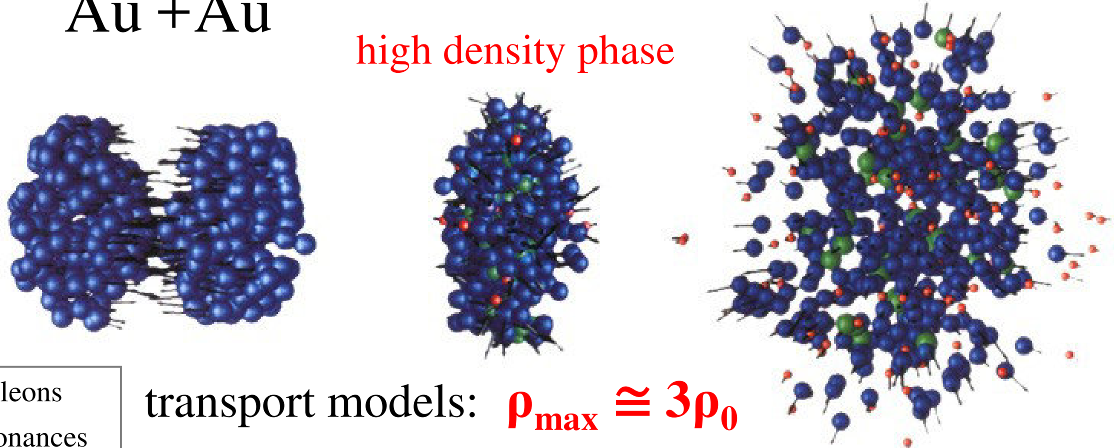




Relativistic nucleus-nucleus collisions at SIS18

QMD , S. Bass , Uni. Frankfurt

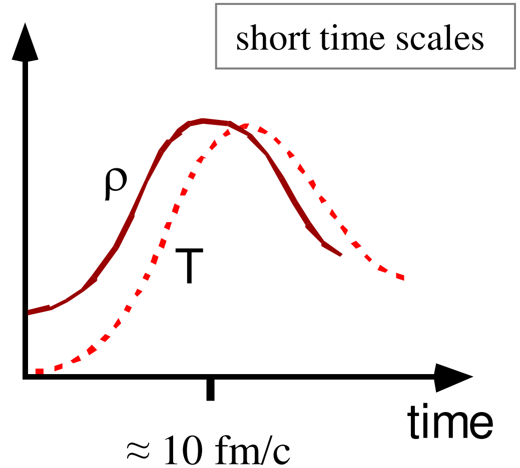
Au +Au

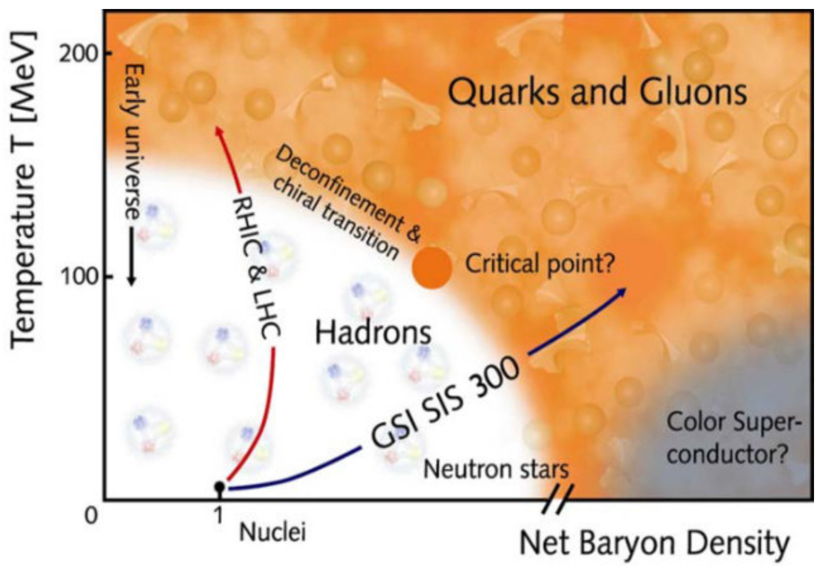


- nucleons
- resonances
- mesons

transport models: $\rho_{max} \cong 3\rho_0$

t — $\approx 10^{-22}$ s =100 fm/c





at SIS18 (max. 2 AGeV in A+A):
$\rho_B \approx 1 - 3\ \rho_0$
$T \approx 70 - 100$ MeV

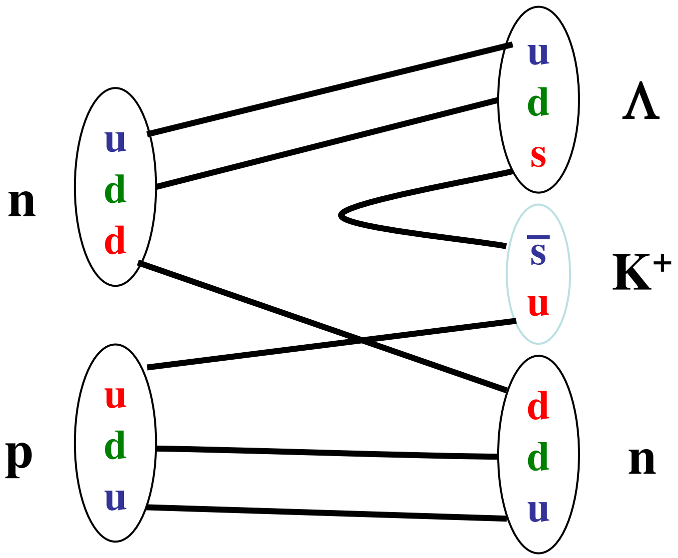
<u>note:</u>
system not necessarily equilibrated

The creation of strange mesons in elementary reactions

associate production !

K^+ mesons

$m = 493.7\ MeV/c^2$

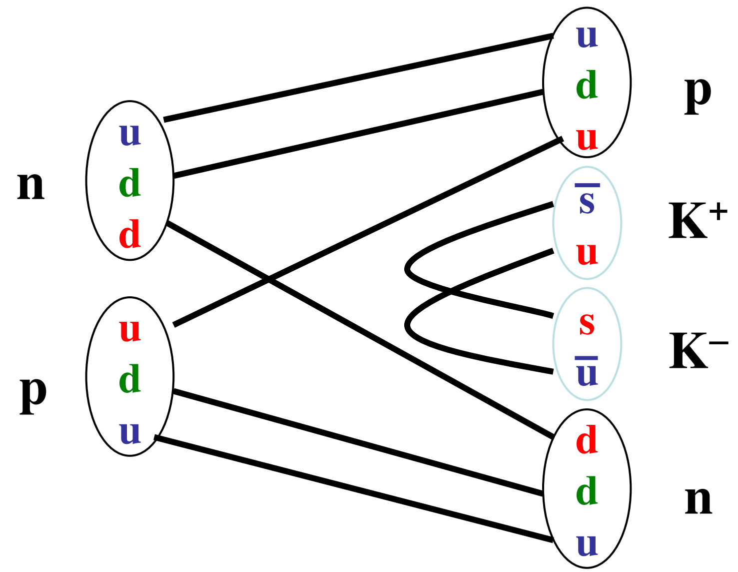


production threshold

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

K^- mesons

$m = 493.7\ MeV/c^2$



production threshold

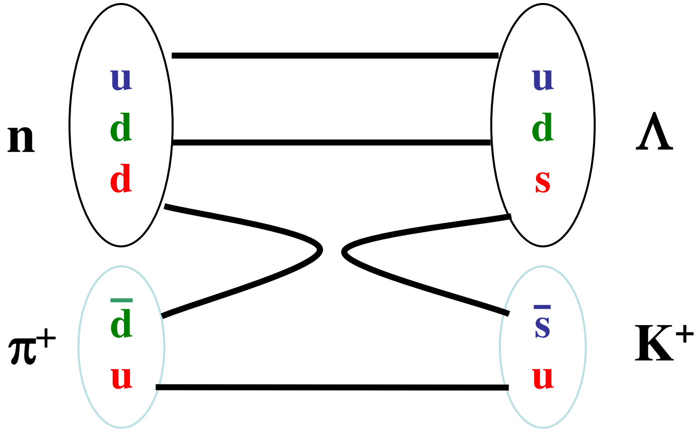
$$E_{lab} = 2.5\ GeV$$

e.g.

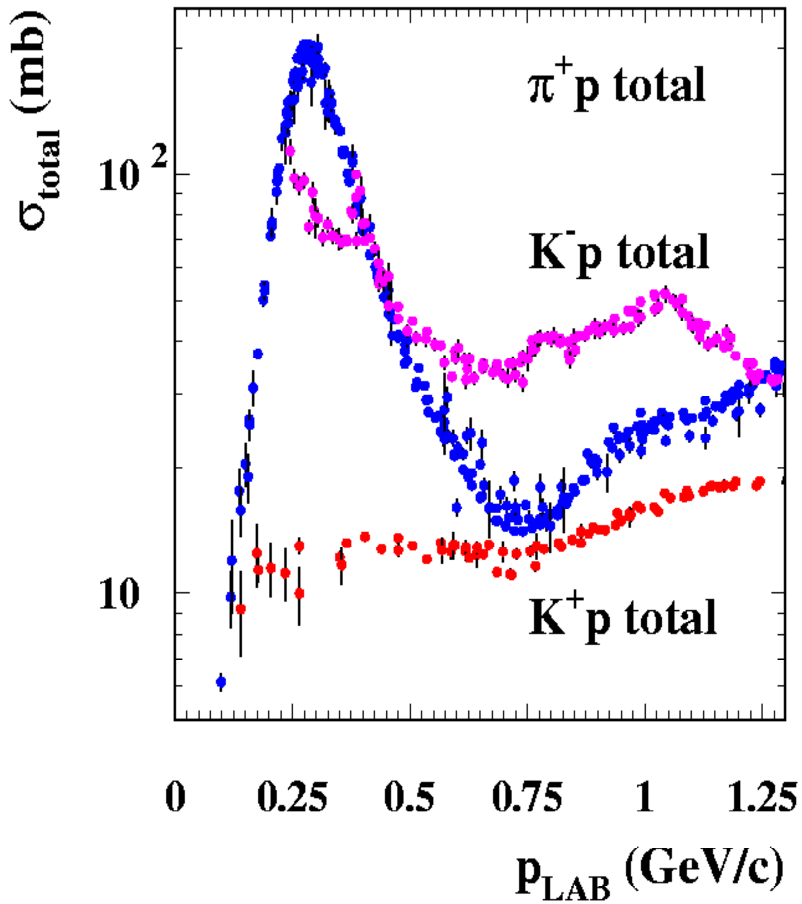
$$NN \rightarrow N\Delta$$
$$N\Delta \rightarrow NK^+Y$$
$$\pi N \rightarrow K^+Y$$

(Y=Λ,Σ)

multi step processes !



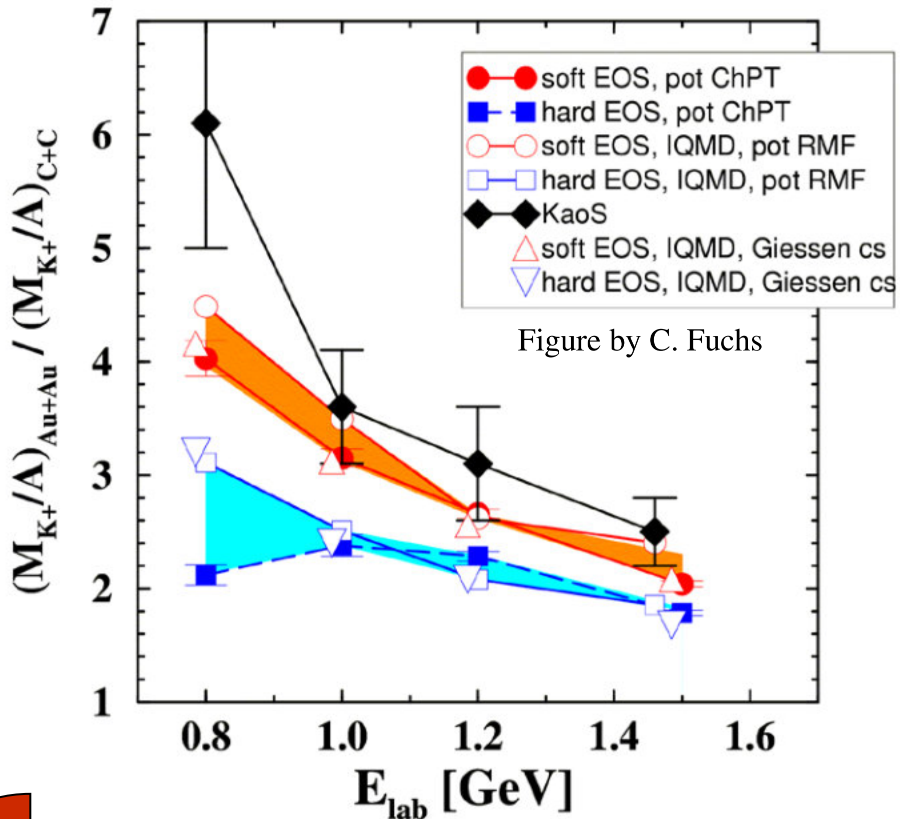
... and final state interaction !

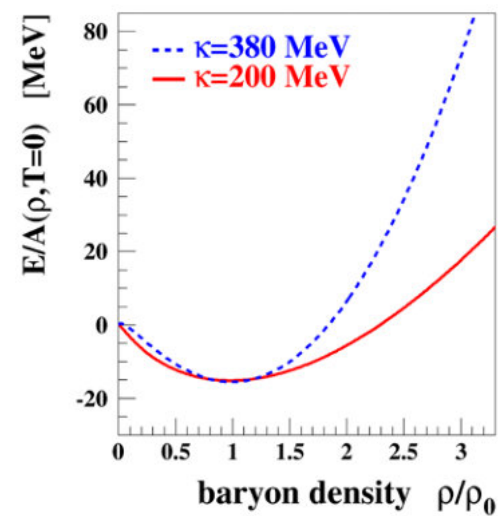


The compression modulus of nuclear matter (ρ > ρ0)

Experiment: Phys. Rev. Lett. 86 (2001) 39

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

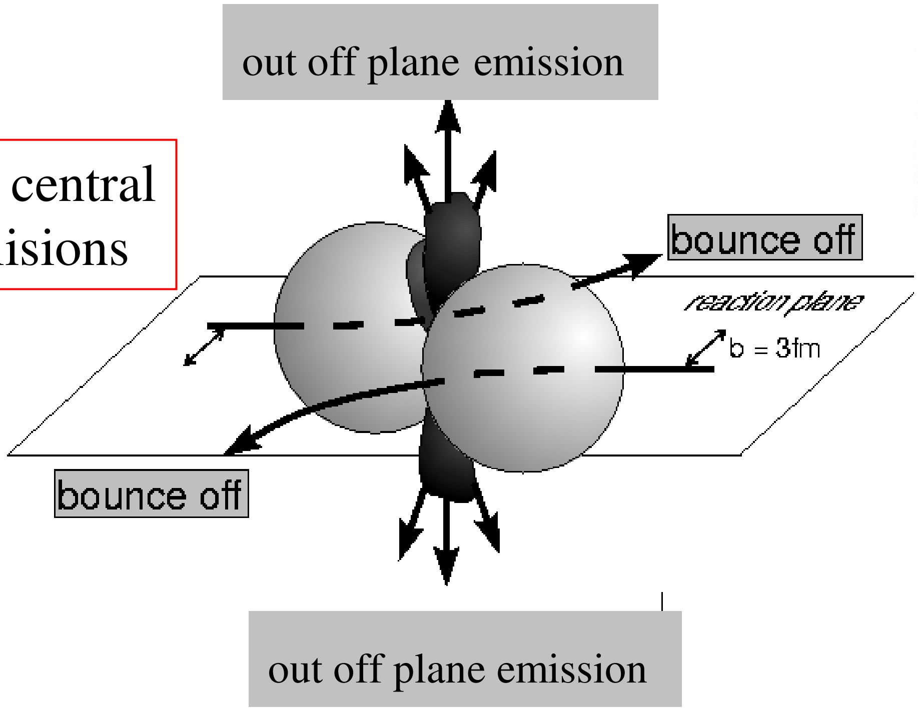


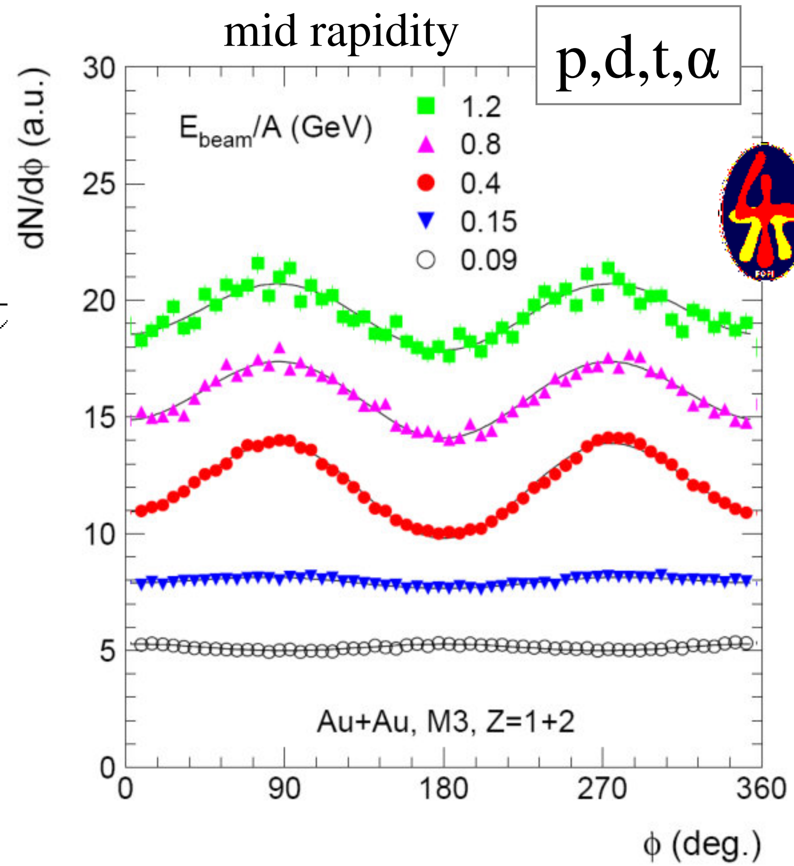


"soft" nuclear equation-of-state: κ ≈ 200 MeV

Azimuthal particle emission

semi central collisions





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

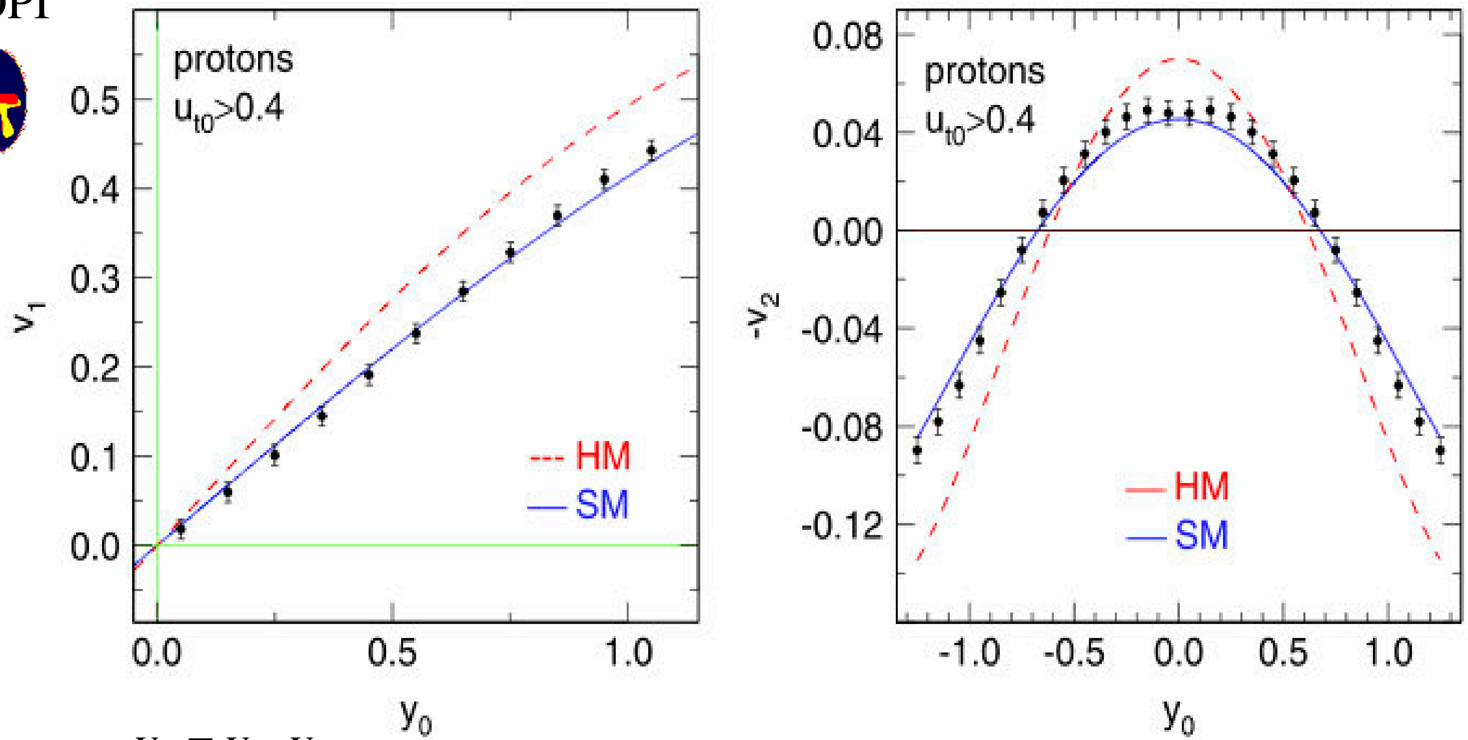
named as well as: v_1 directed flow , v_2 elliptic flow

Elliptic flow and the nuclear equation-of-state

W. Reisdorf et al. (FOPI), Nucl. Phys. A 876 (2012) 1

FOPI

Au+Au 1.5 AGeV



$y_0 = y - y_b$

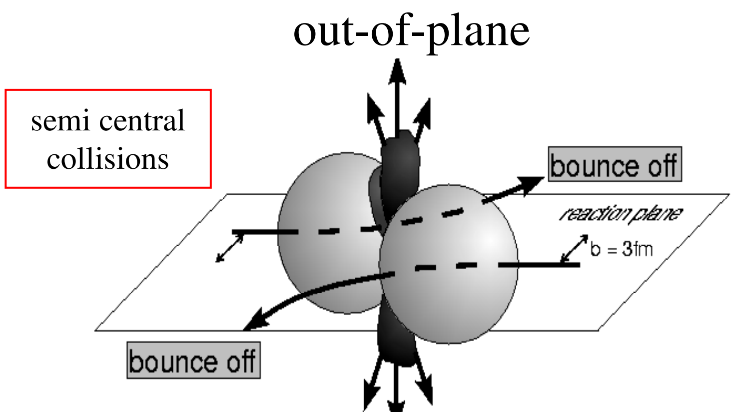
IQMD transport calculation

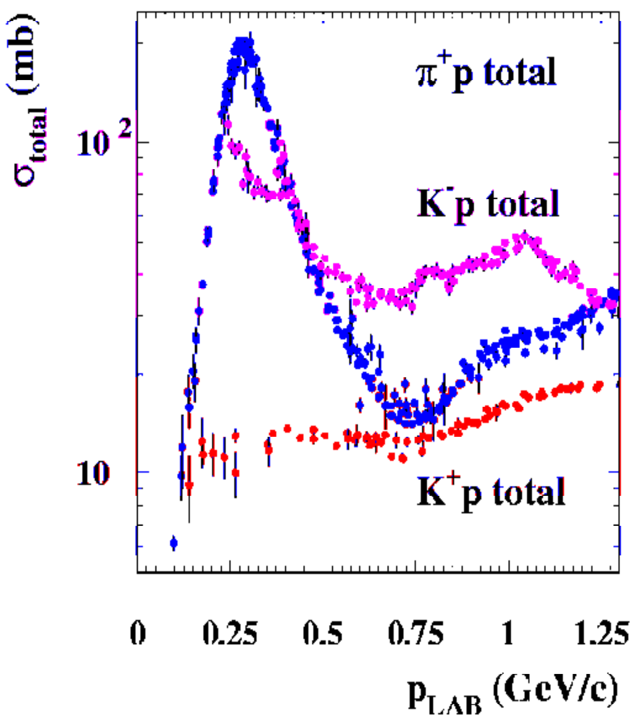
SM: soft equation-of-state (by effective NN force), momentum dependent force

→ IQMD-SM describes $v_2(y_0)$ for E_{lab} = 0.15 AGeV to 1.5 AGeV !

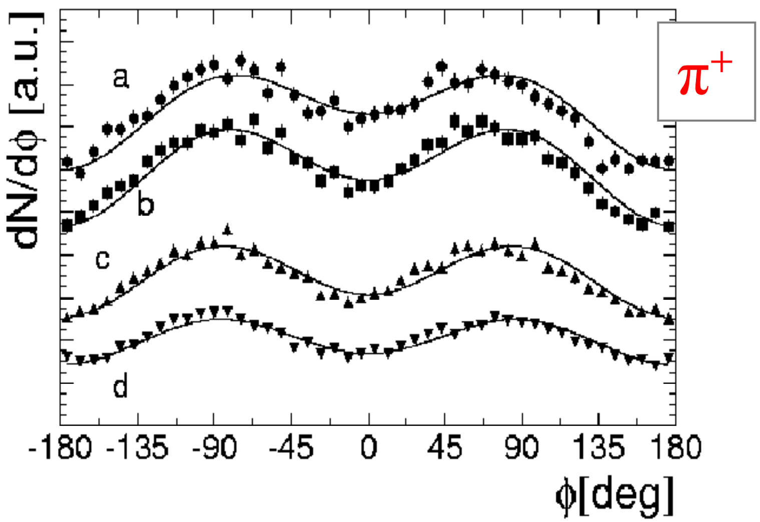
consistent picture at
SIS18 energies ($1.5 < \rho / \rho_0 < 3.0$)

Azimuthal particle emission





Bi+Bi 0.7AGeV, semi central

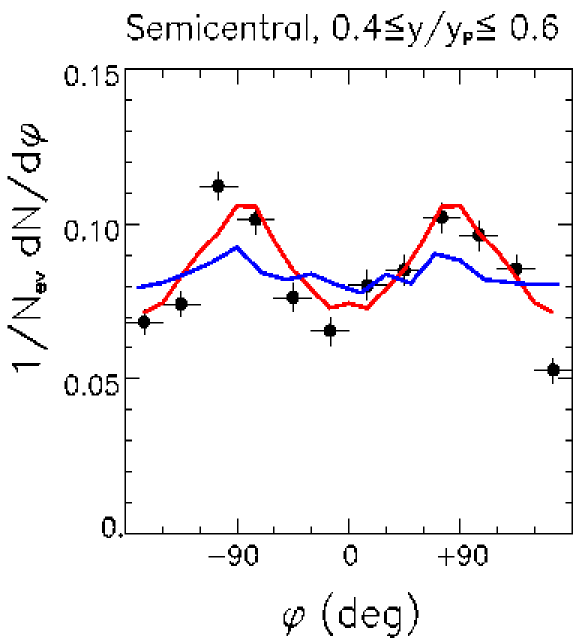


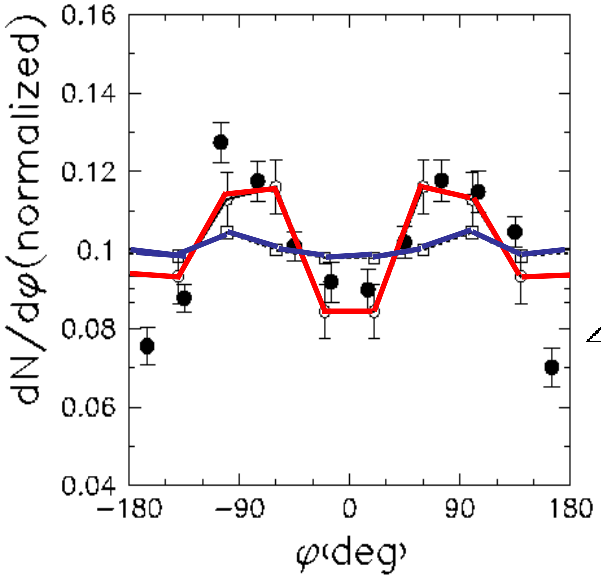
D. Brill et al.
ZPA355 (1996) 61
ZPA357 (1997) 207

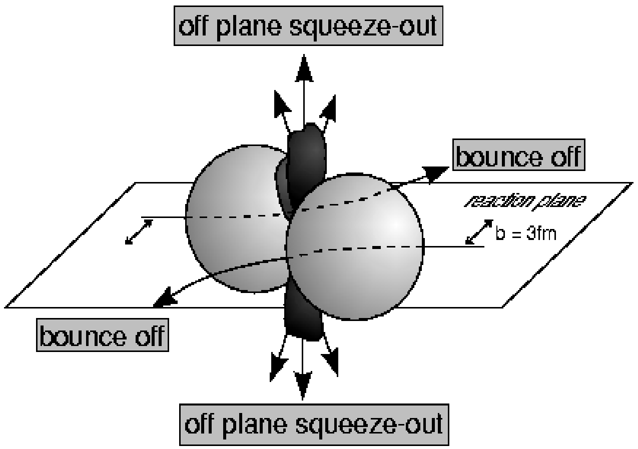
Pions are enhanced emitted perpendicular to the reaction plane.
What would you expect how the K^+ emission pattern looks like ?

K+ emission pattern in Au+Au collisions at 1 AGeV

Data: Y. Shin et al., Phys. Rev. Lett. 81 (1998) 1576







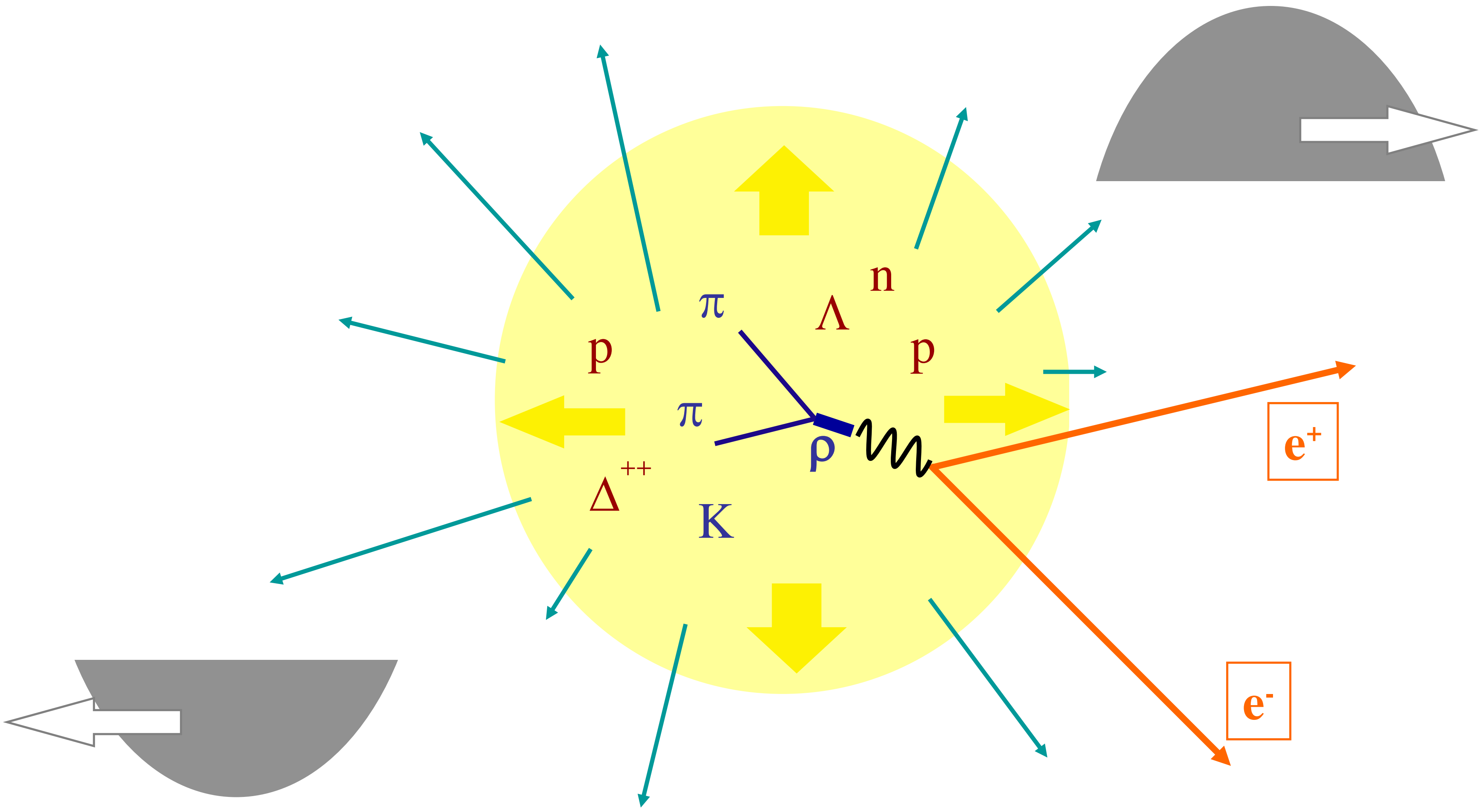
RBUU Stony Brook:
G.Q.Li et al.,
Phys. Lett. B 381 (1996)

QMD Tübingen:
Z.S. Wang et al.,
Eur. Phys. J. A5 (1999) 275

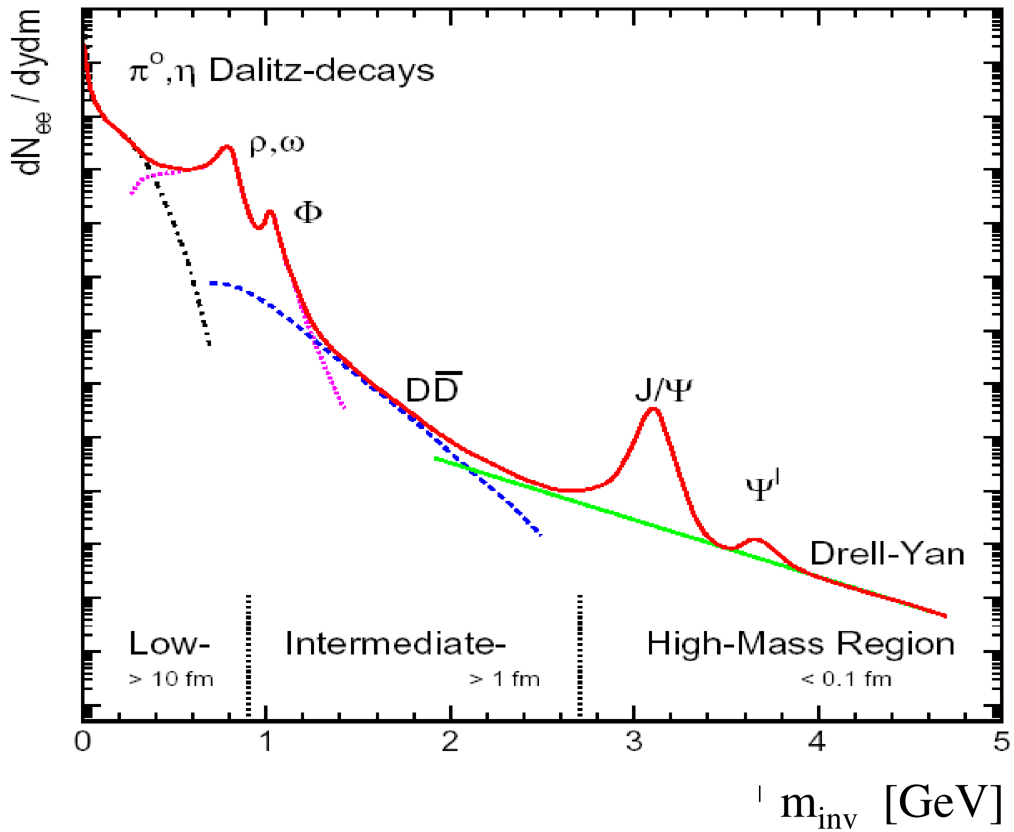
Transport models:

with K+N potential
no K+N potential

e^+e^- pairs – penetrating probes



Di-lepton sources



	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

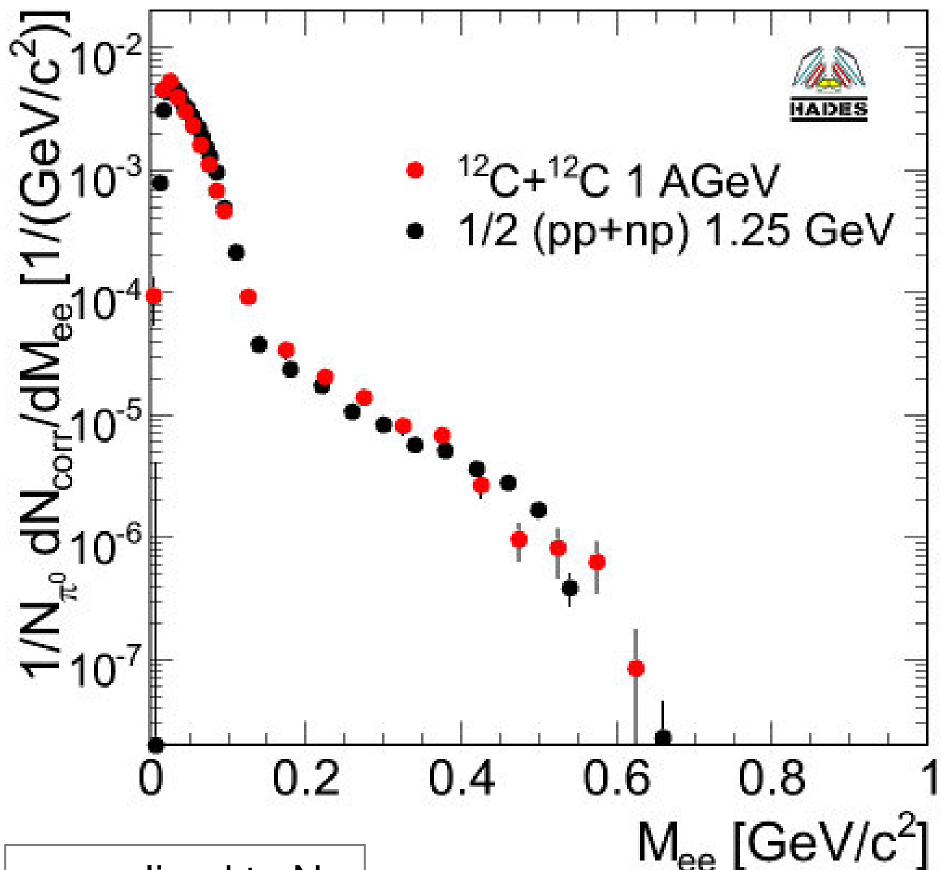
2.6 GeV

C+C vs. N+N results

Comparison of C+C data to average of pp and np collisions:

PLB 690 (2010) 118

PL.B 663 (2008) 43

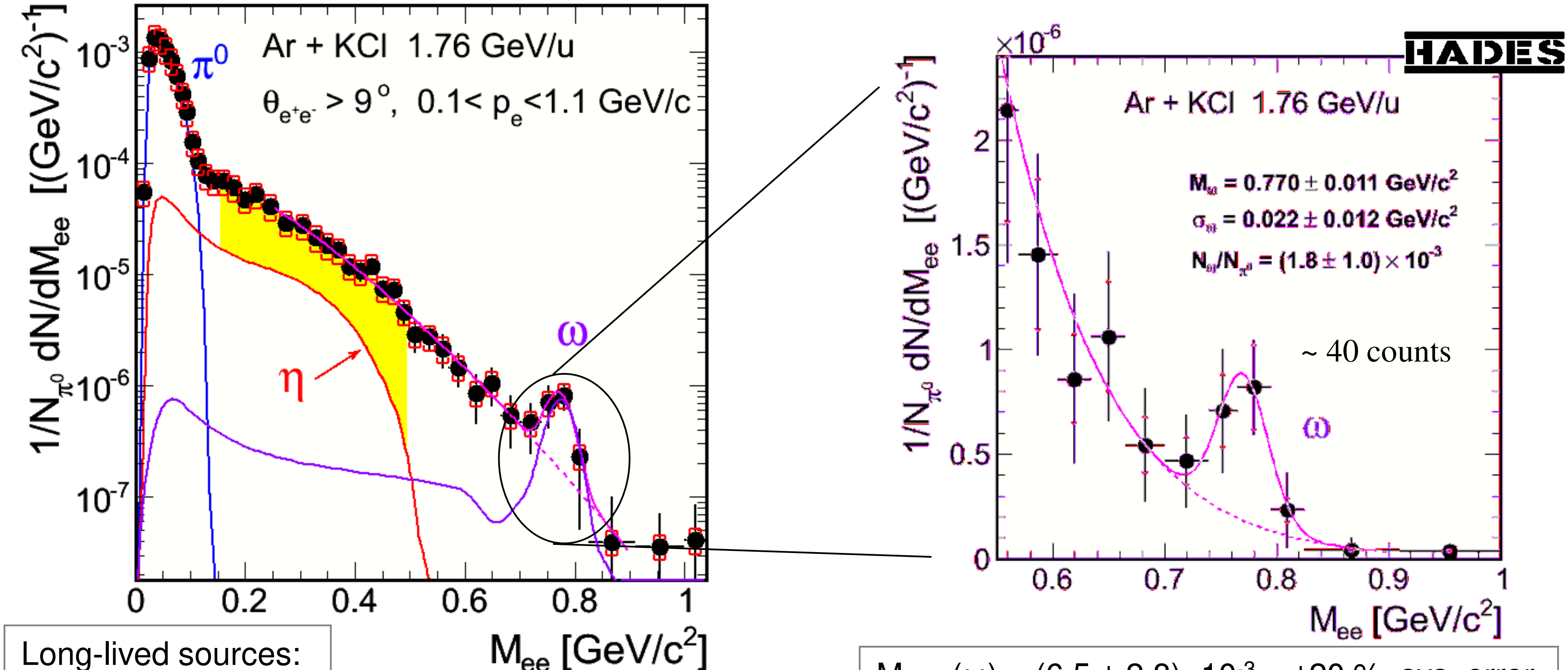


normalized to N_π

- C+C data reproduced (within 20%) by **superposition** of pp and np data
- Pair “excess” observed in C+C data can be traced back to enhanced pair production in n+p collisions (DLS puzzle solved)

e^+e^- Production in Ar + KCl

PRC 84 (2011) 014902



Long-lived sources:
π^0, η, and ω

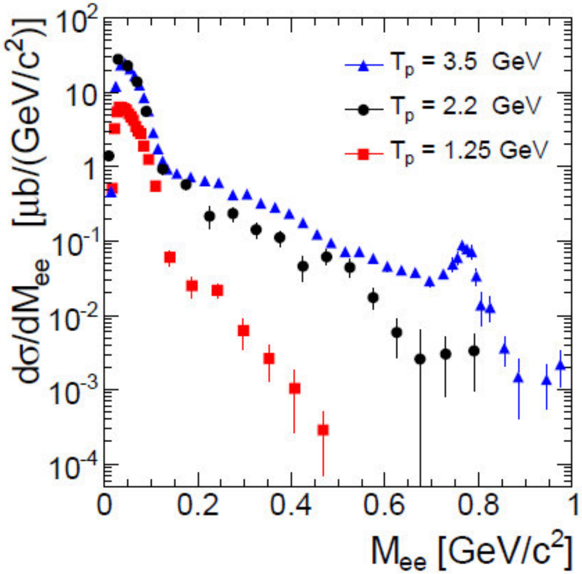
$M_{LVL1}(\omega) = (6.5 \pm 2.8) \cdot 10^{-3}$ ±20 % sys. error

η mass region: strong overshoot above the cocktail of long-lived sources!

ρ/ω mass region: strength of ρ meson ?

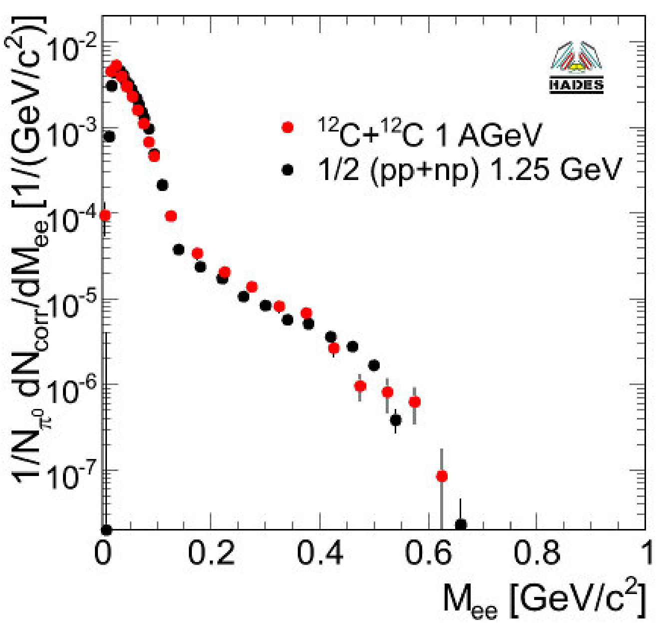
Dileptons - Excess yield at SIS18

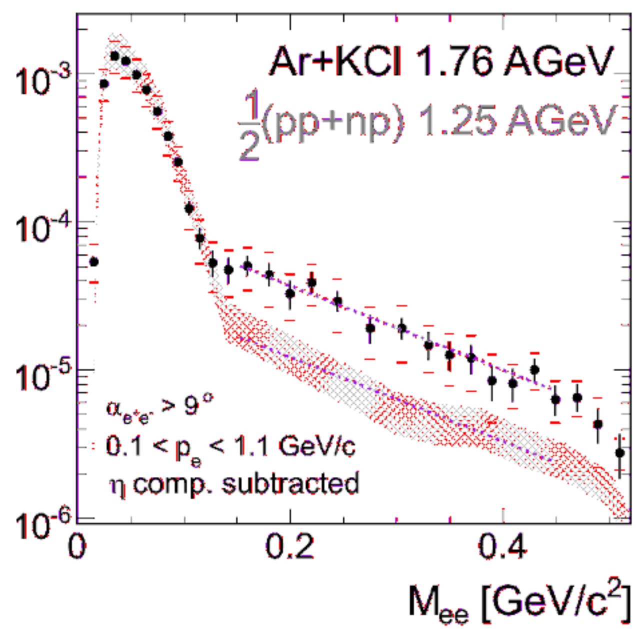
HADES@SIS18



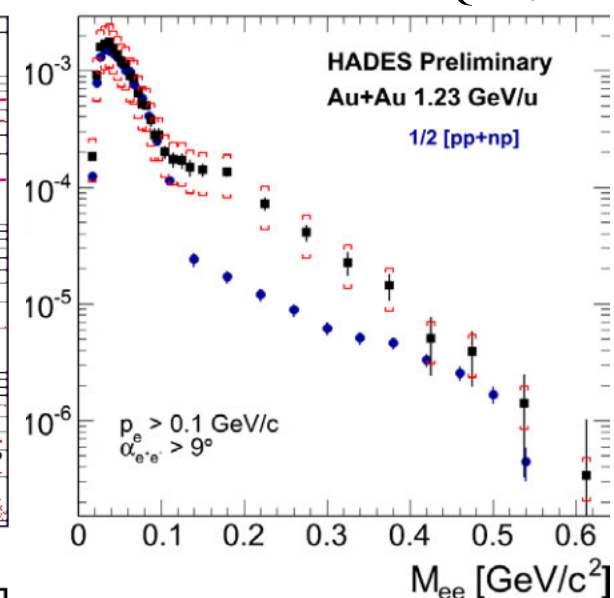
Ar+KCl:
G. Agakishiev et al.PRC 84 (2011) 014902

Au+Au:
preliminary, QM2014





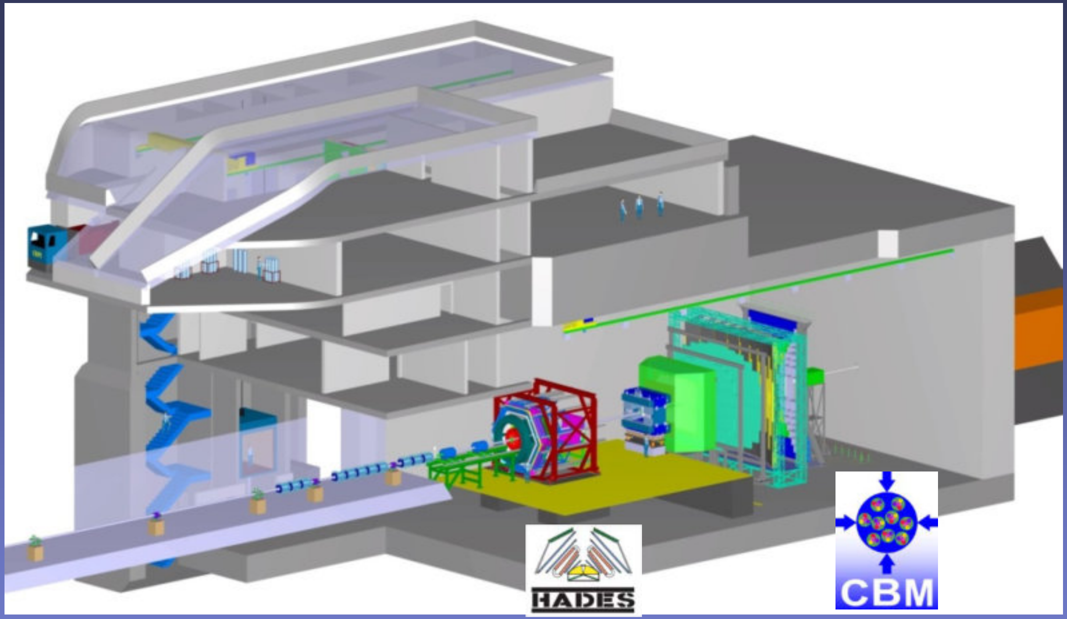
QM 2014



Part IV
Exploring the highest baryon densities in the laboratory

Nucleus-nucleus collisions

- at the Nucletron-M with BM (1 – 4 AGeV)
- at NICA with MPD
- at SPS with NA61/Shine and NA60’
- at RHIC/BES
- **at FAIR with CBM & HADES (2 – 44 AGeV)**

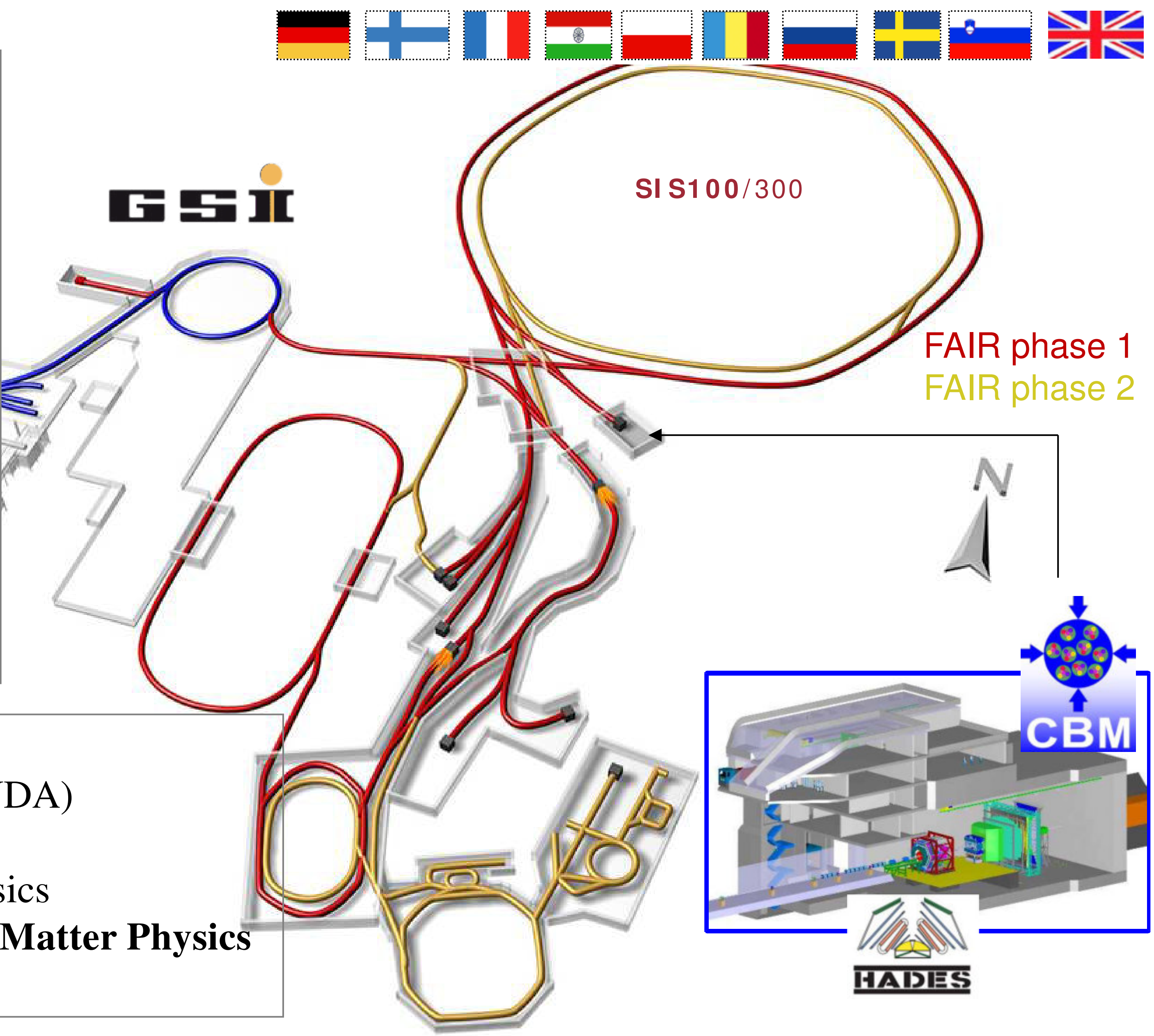


The Facility for Antiproton and Ion Research

Using beams from two synchrotrons for parallel operation :

SIS100:
2-29 GeV (protons)
2-14 A GeV (Ca)
2-11 A GeV (Au)

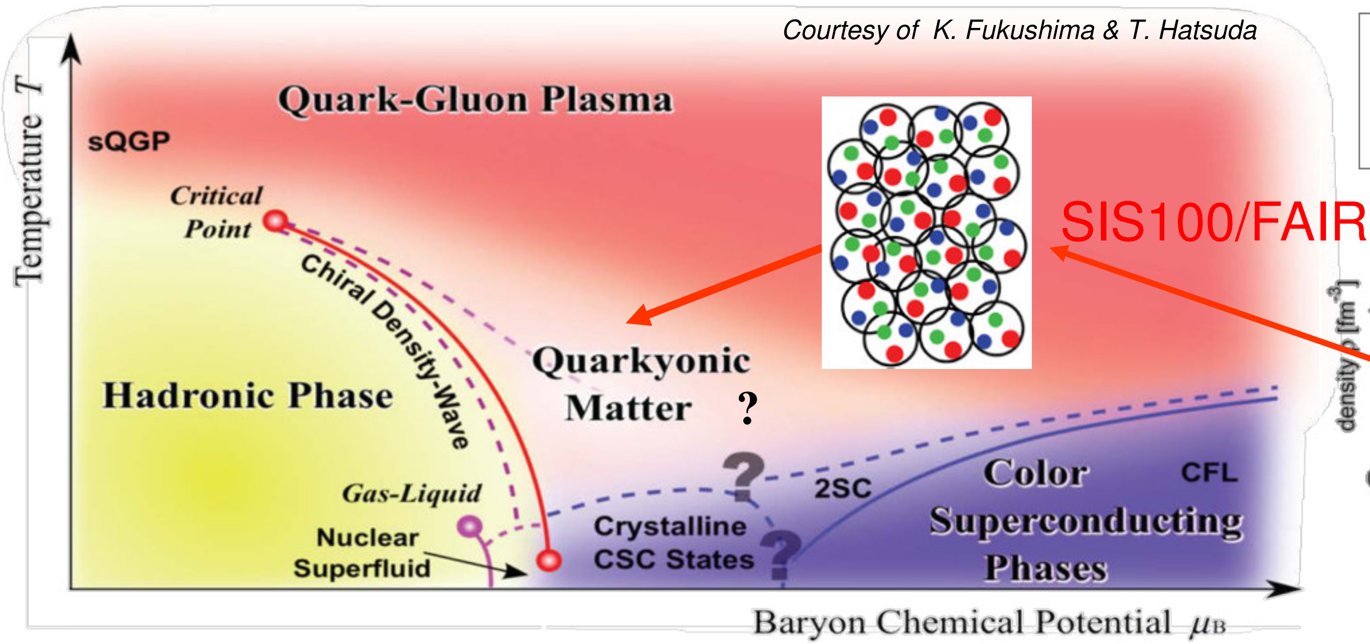
SIS300:
2-89 GeV (protons)
2-44 A GeV (Ca)
2-35 A GeV (Au)



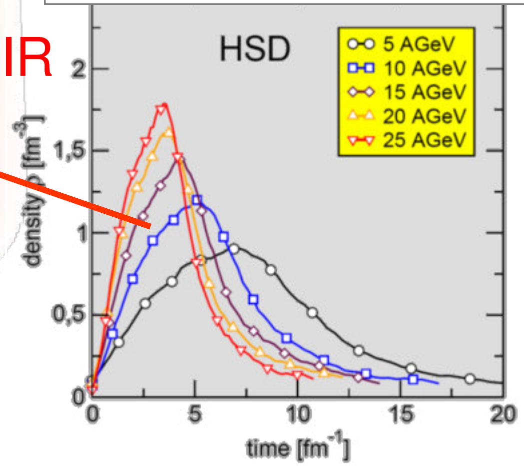
- Hadron spectroscopy with anti-protons (PANDA)
- Rare Isotope beams
- Atomic & Plasma Physics
- **Compressed Nuclear Matter Physics** **CBM & HADES**

The CBM experimental site

Exploring the QCD phase diagram at FAIR energies



Baryon density in central Au+Au collisions (HSD transport code)



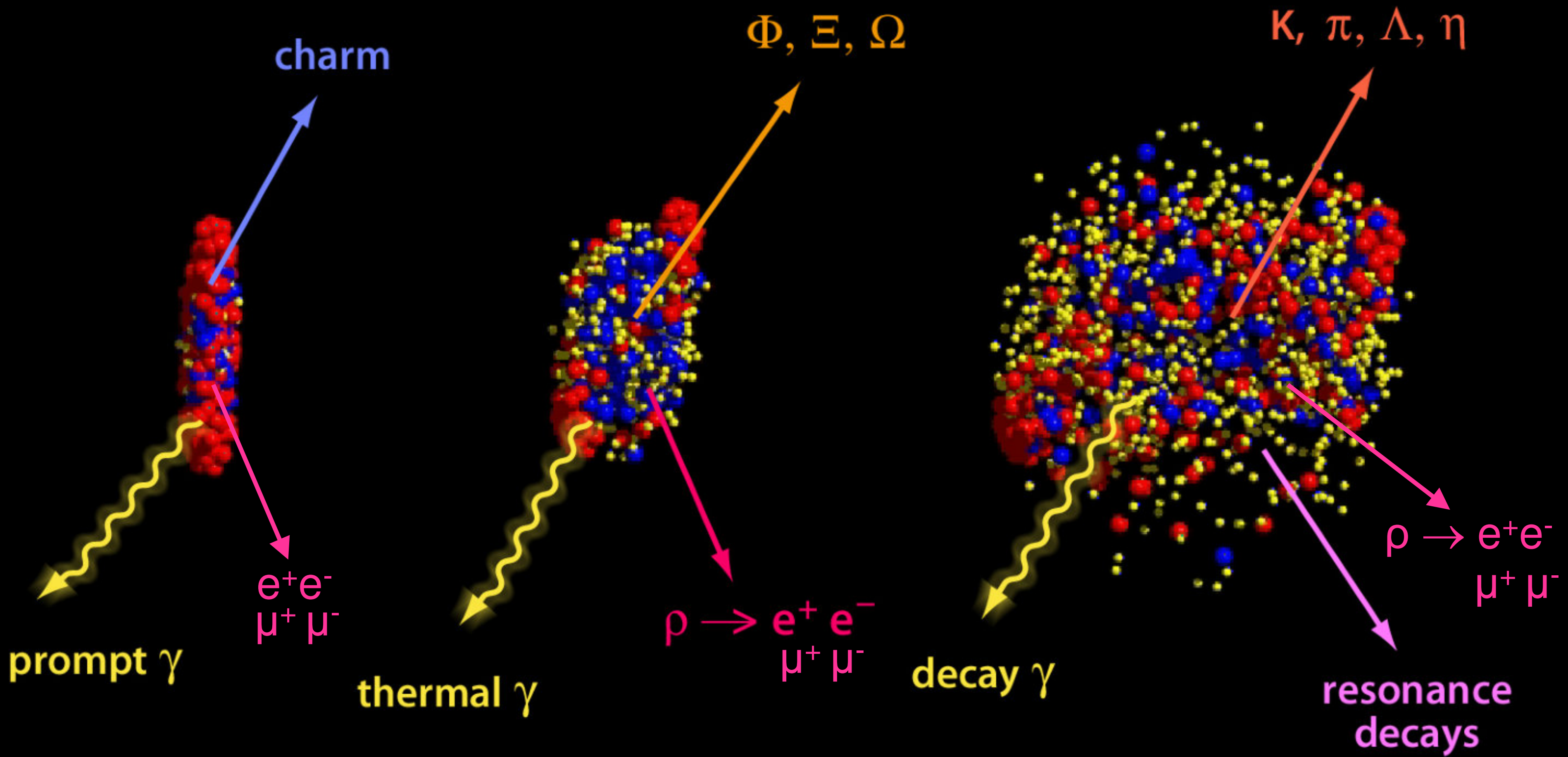
Open questions at high net baryon densities:
- Phase transition from hadronic matter to quarkyonic or partonic matter ?
- Chiral phase transition ? Chiral restoration ?
- In-medium modification of hadrons ?
- Nuclear Equation-of-State at neutron star core densities ?

→ **substantial discovery potential at SIS100 / 300**

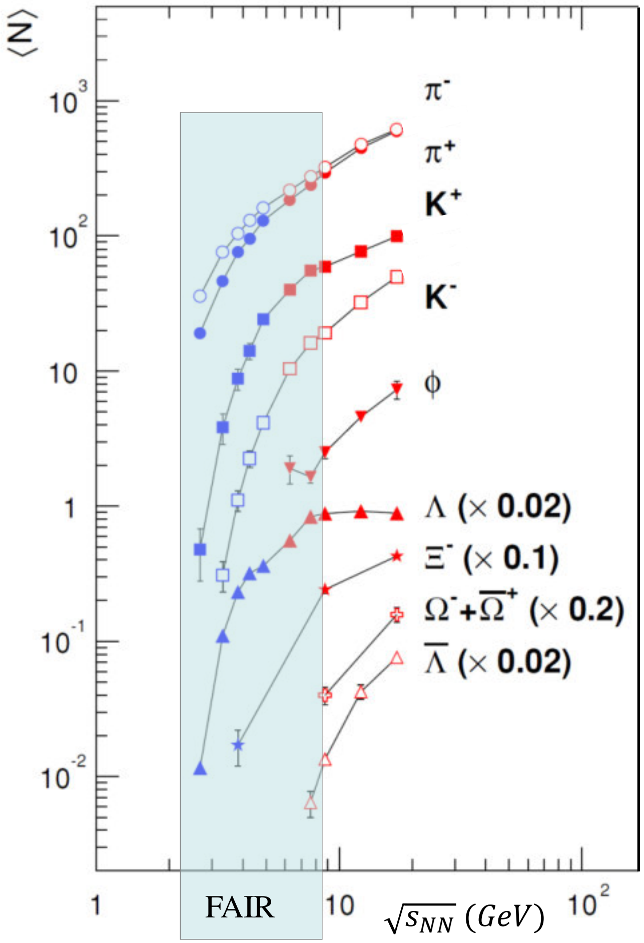
Field driven by experimental data !

Messengers from the dense fireball

UrQMD transport calculation U+ U 23 AGeV



CBM physics observables
Production excitation function of multi-strange baryons



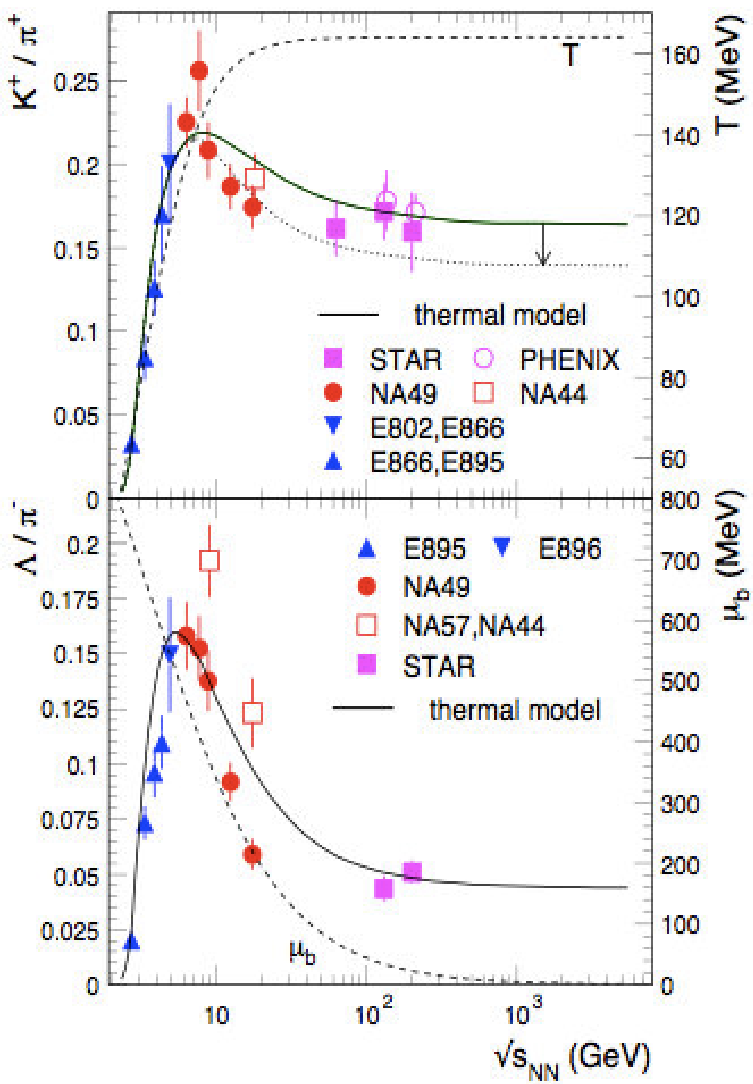
direct production
in nucleon-nucleon collisions:

$pp \rightarrow \Xi^- K^+ K^+ p$ $E_{thr}=3.7$ GeV
$pp \rightarrow \Omega^- K^+ K^+ K^0 p$ $E_{thr}=7.0$ GeV

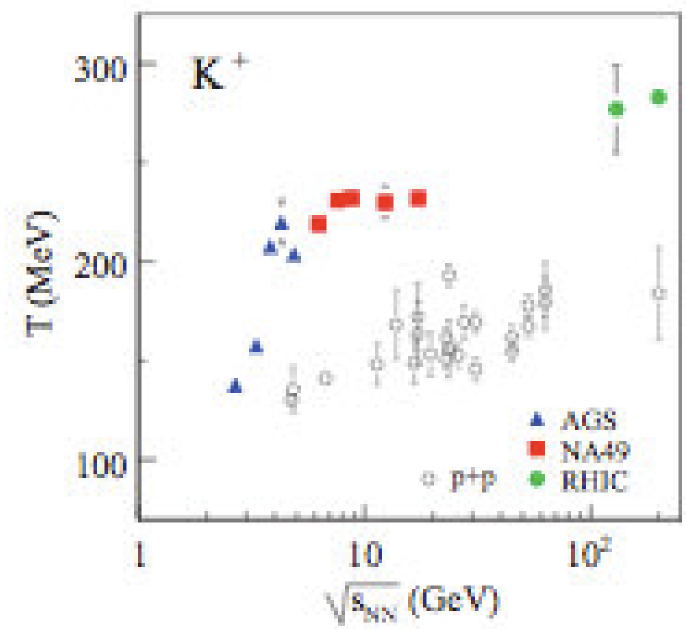
Knowledge about multi-strange baryons at energies below 10 AGeV very limited

→ multi-step production ?
→ production via strangeness exchange channels ?
→ enhanced production in dense medium ?

Strangeness – particle yields

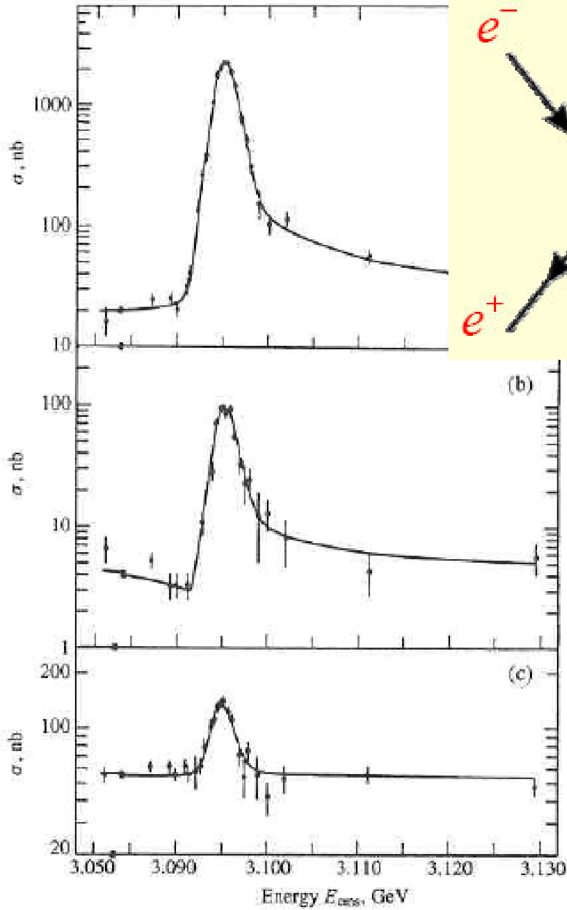


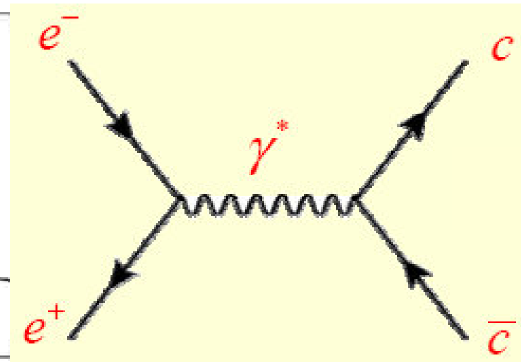
Maximum in K/pi at 30 AGeV
explained by statistical model (?)

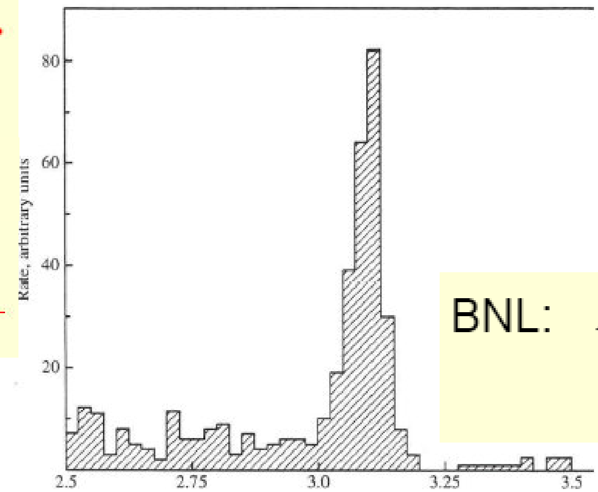


Plateau in apparent temperature above 30 AGeV
indicative of 1st order phase transition (latent heat) ?

1974: J/ψ discovery at SLAC and BNL







BNL: $p + Be \rightarrow \underbrace{J/\Psi}_{\hookrightarrow e^+e^-} + X$

SLAC: $e^+e^- \rightarrow J/\Psi \rightarrow$ **Hadronen**

$\rightarrow e^+e^-$

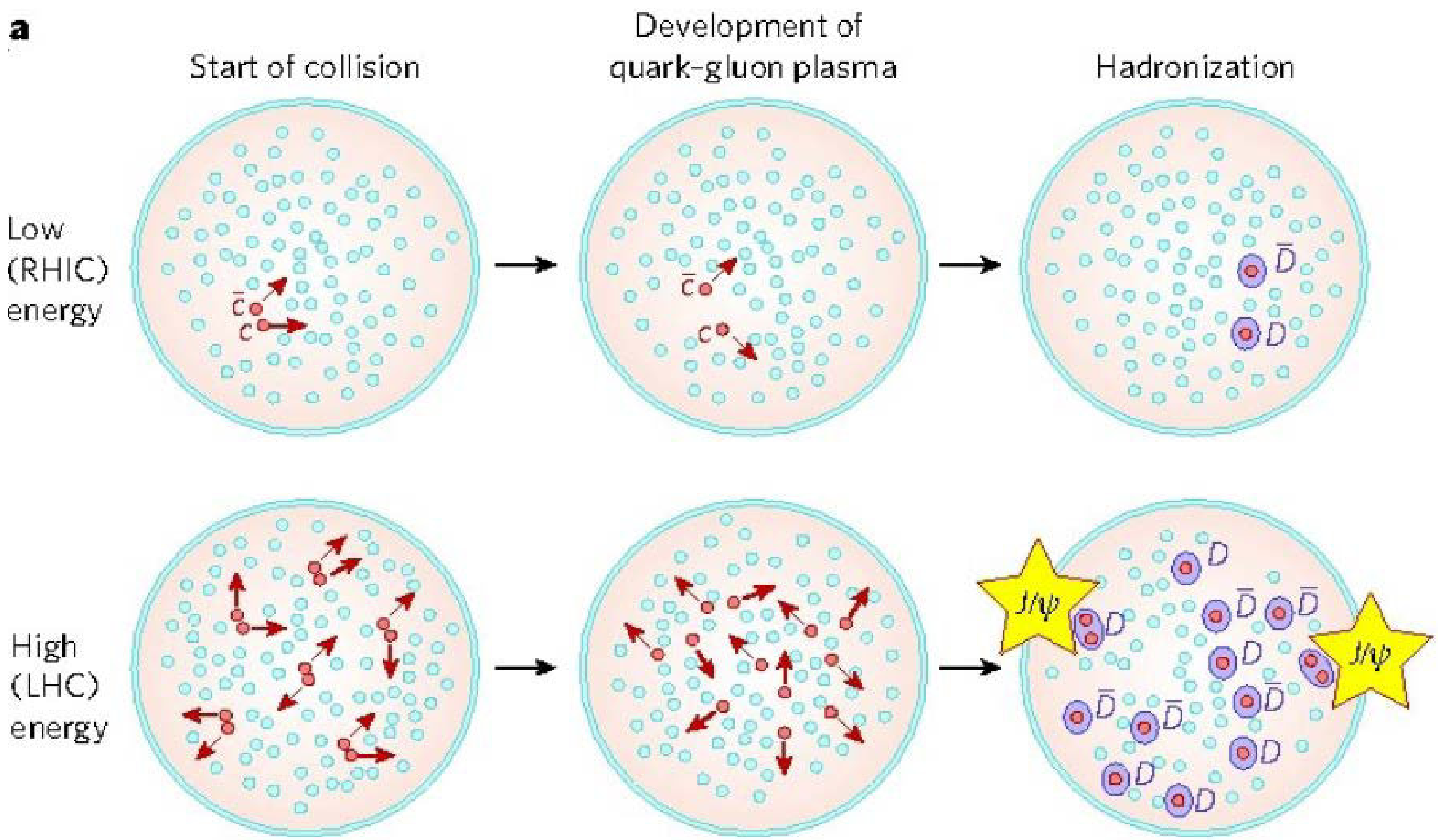
$\rightarrow \mu^+\mu^-$

- bound state of heavy quarks: $c\bar{c}$
- quantum numbers as the photon: $J^p = 1^-$
- J/ψ mass: 3.1 GeV
- c mass: ~1.3 GeV
- bindung energy ~600 MeV
- width: 93 keV (life time: 10^{-20}s)

J/ψ production in nucleus-nucleus collisions

signature of deconfinement ?

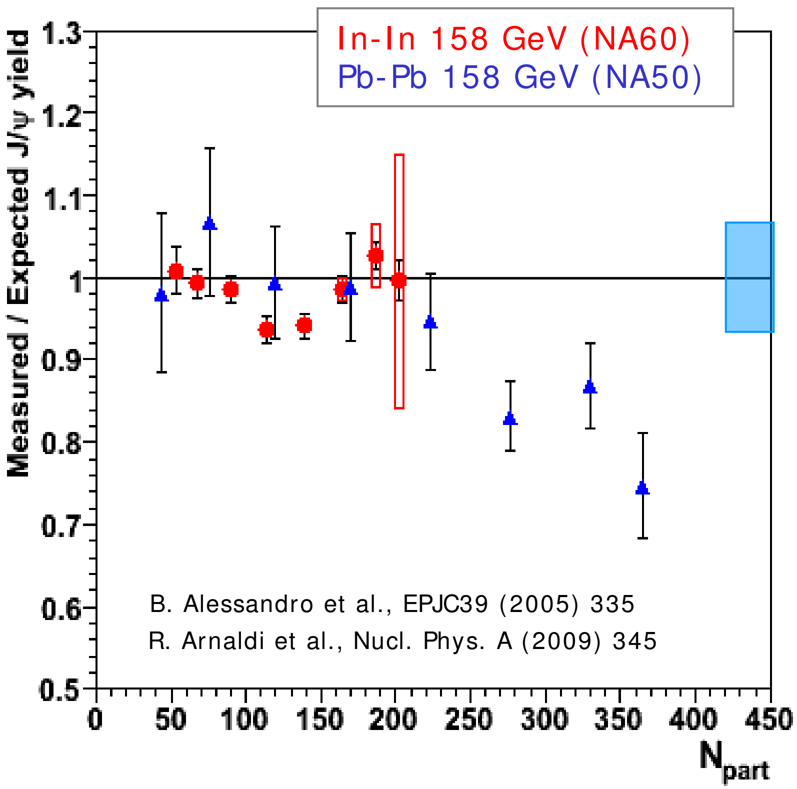
J/ψ suppression



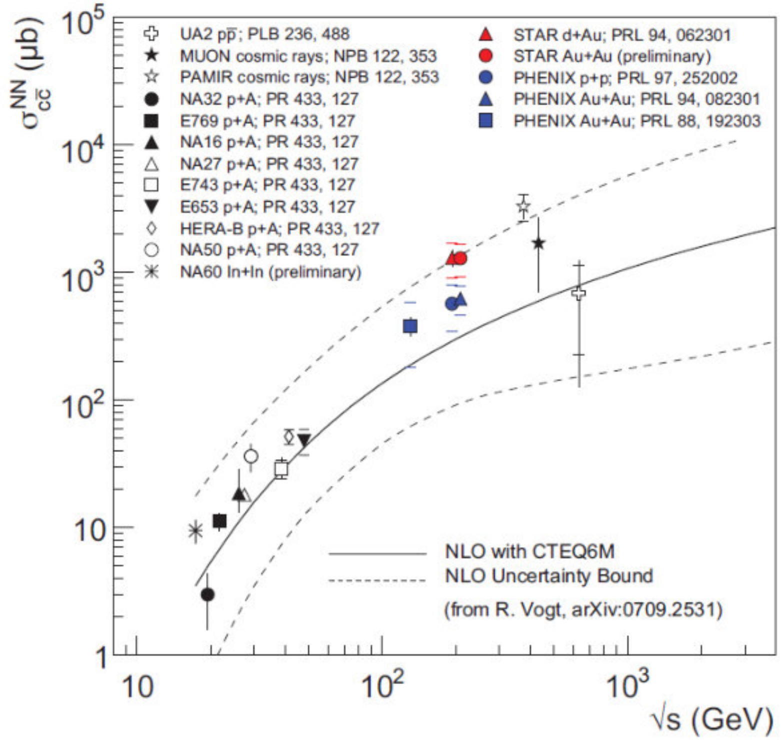
J/ψ regeneration

CBM physics observables: Charmonium (J/ψ)

CERN/ SPS experiments



A.Frawley,T.Ulrich,R.Vogt Phys.Rept.462:125-175,2008



No data available below top SPS energies !

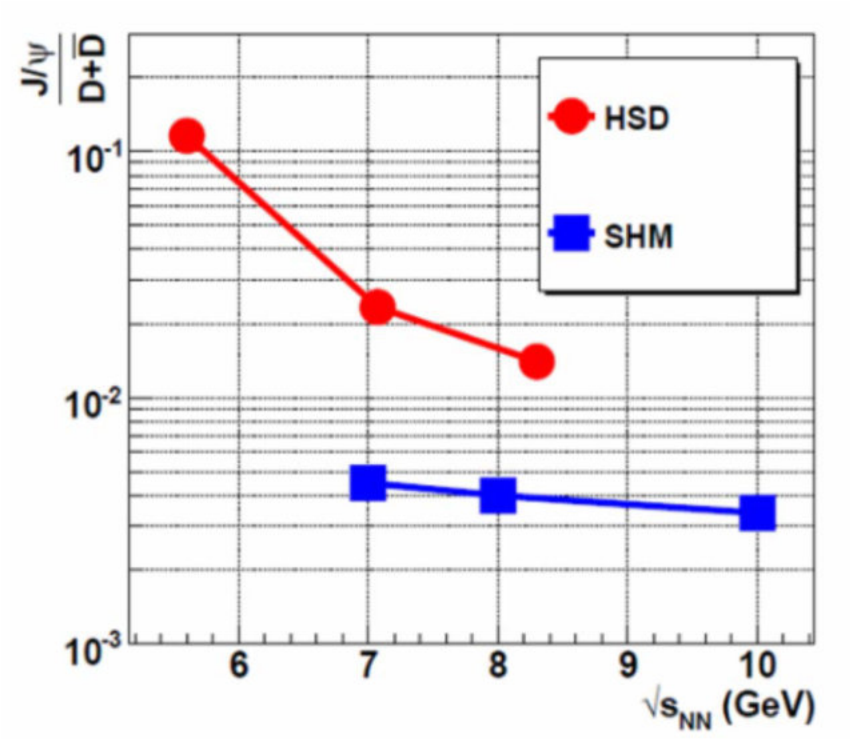
Excitation function of J/ψ production at SIS100/300 energies

→ production mechanism ?

→ J/ψ suppression ?

CBM physics observables

Charmonium (J/ψ) and open charm ($D\overline{D}$) production



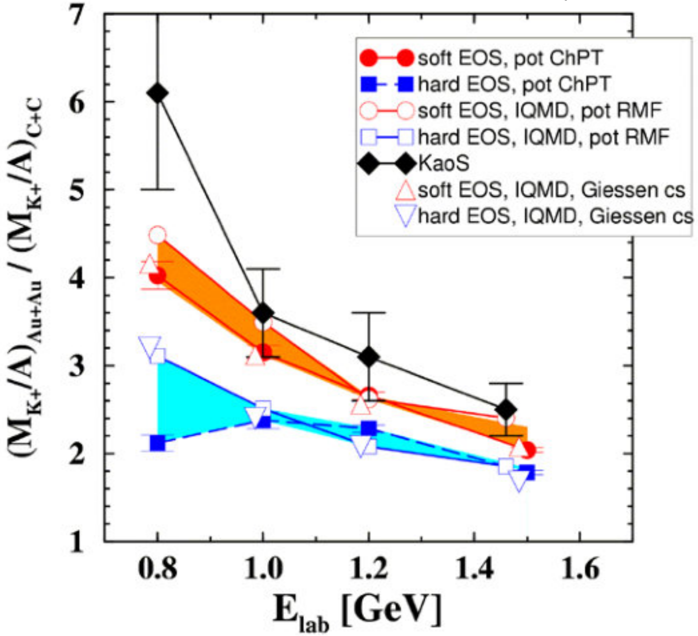
HSD "hadronic"
O. Linnyk et al.,
Int.J.Mod.Phys. E17, 1367 (2008)

SHM "partonic"
A. Andronic et al.,
Phys. Lett. B 659 (2008) 149

J/ψ suppression ?

Nuclear equation-of-state – data situation at FAIR energies

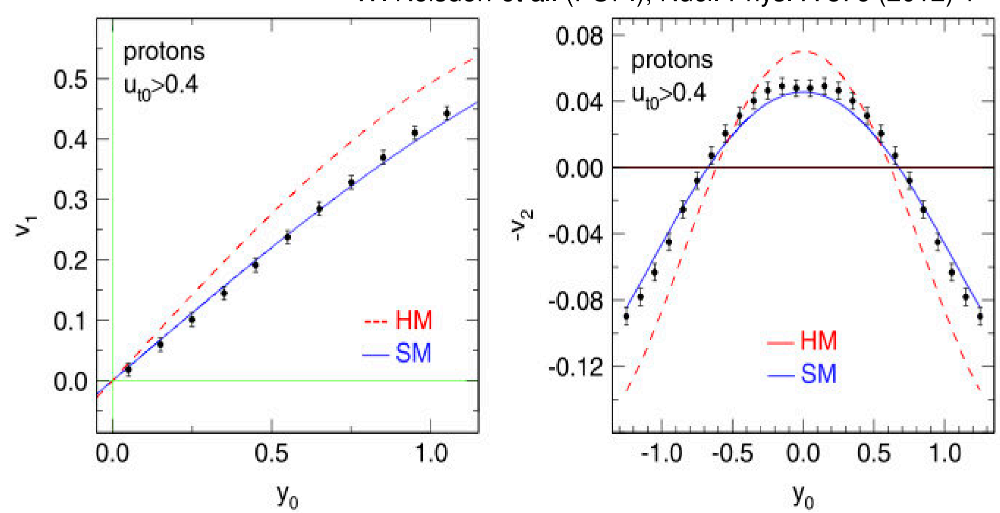
Experiment: CS et al., Phys. Rev. Lett. 86 (2001) 39
Theory: RQMD C. Fuchs et al., Phys. Rev. Lett. 86 (2001) 1974
IQMD Ch. Hartnack, J. Aichelin, J. Phys. G 28 (2002) 1649

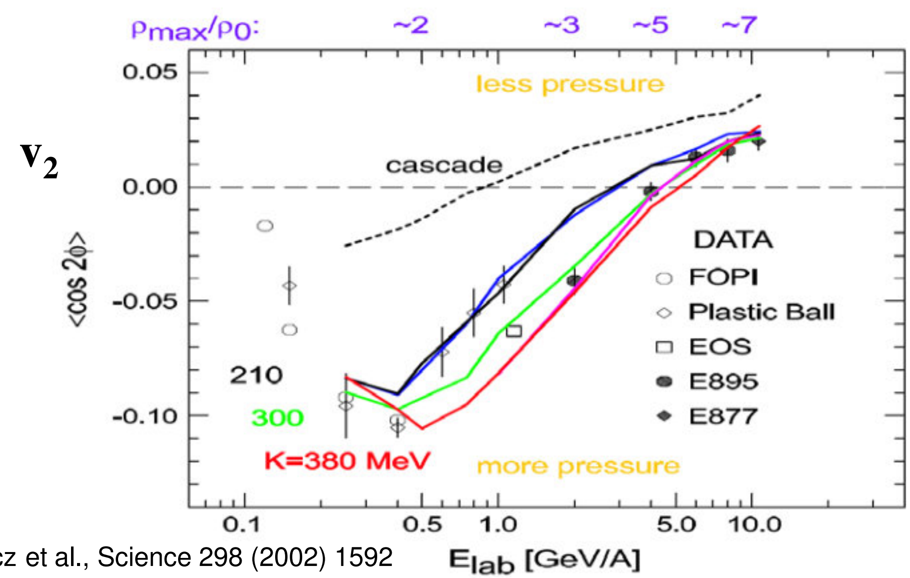


FOPI

Au+Au 1.5 AGeV

W. Reisdorf et al. (FOPI), Nucl. Phys. A 876 (2012) 1



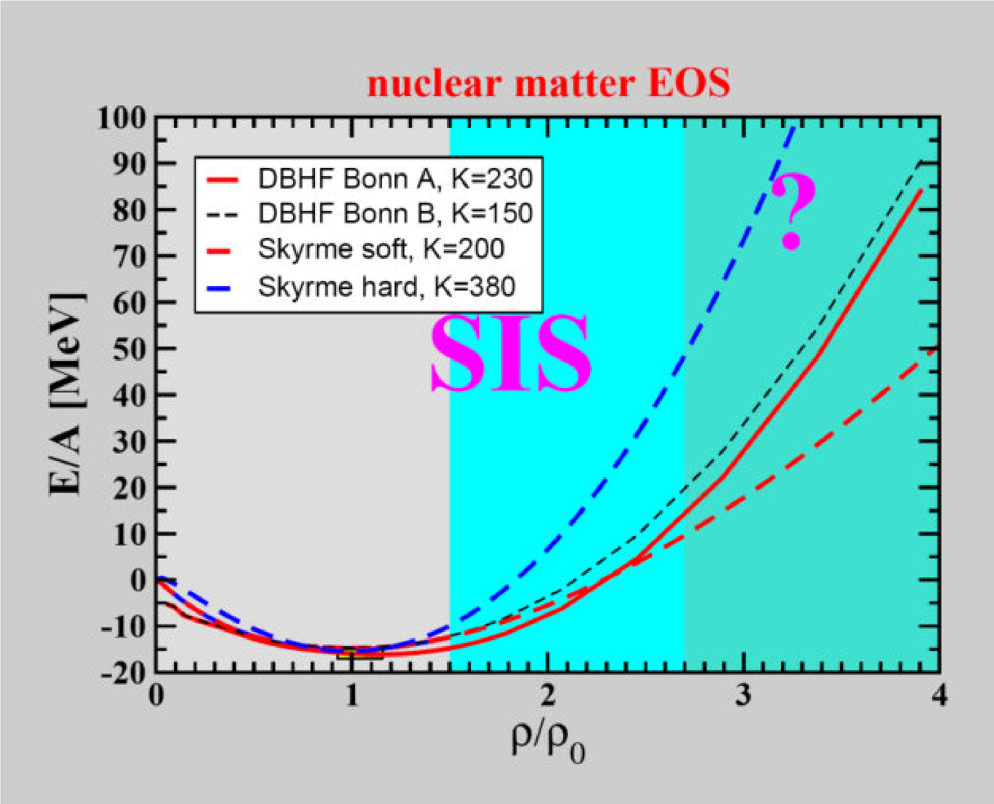


P. Danielewicz et al., Science 298 (2002) 1592

consistent picture at
SIS18 energies ($1.5 < \rho / \rho_0 < 3.0$)

inconclusive at AGS energies

Nuclear equation-of-State – data situation at FAIR energies



equation-of-state
at
neutron star core densities ?

→ (sub-threshold) production
of $\Omega^{+}(\bar{s}\bar{s}\bar{s})$ at FAIR energies
- refined to the high-density phase
- small final-state interaction

DBHF: E. N. E. van Dalen, C. Fuchs, A. Faessler
EPJ. A 31,29 (2007)

Physics Questions

→ existence and yield of (exotic) strange objects?

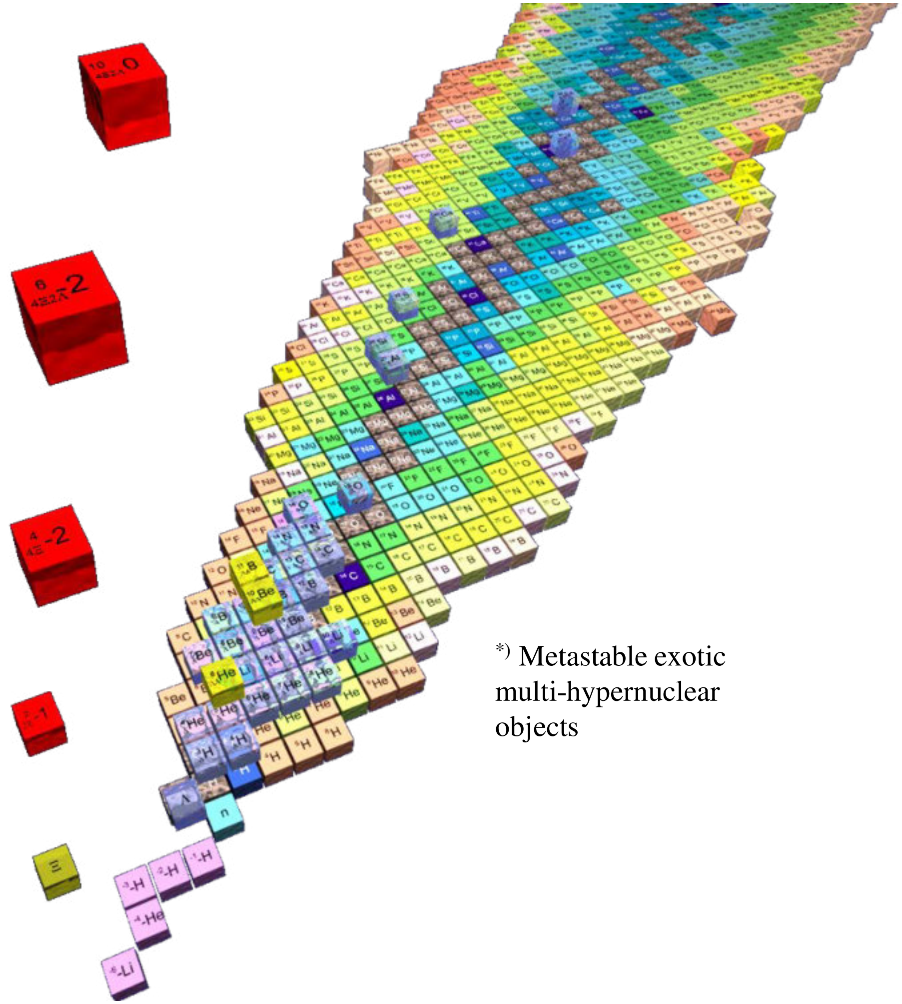
→ ΛN, ΛΛ potential ?

→ remnants of dense, chirally restored or strange matter?

Single and double hypernuclei in nucleus-nucleus collisions

Search for strange matter in the form of strange dibaryons and heavy multi-strange short-lived objects

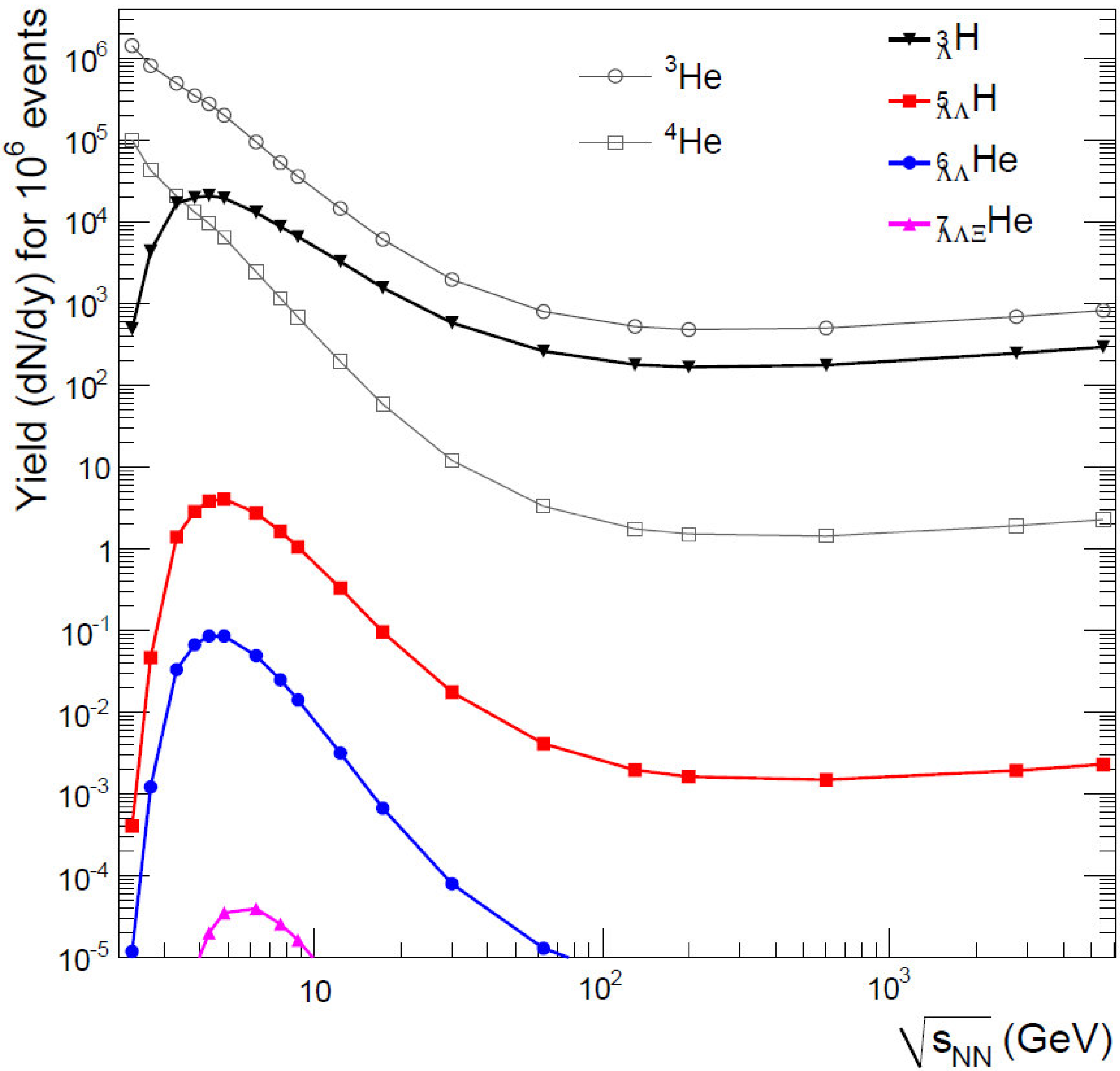
→ Production of hypernuclei via coalescence of hyperons and light nuclei



*) Metastable exotic multi-hypernuclear objects

CBM physics observables
Hypernuclei, strange dibaryons and massive strange objects

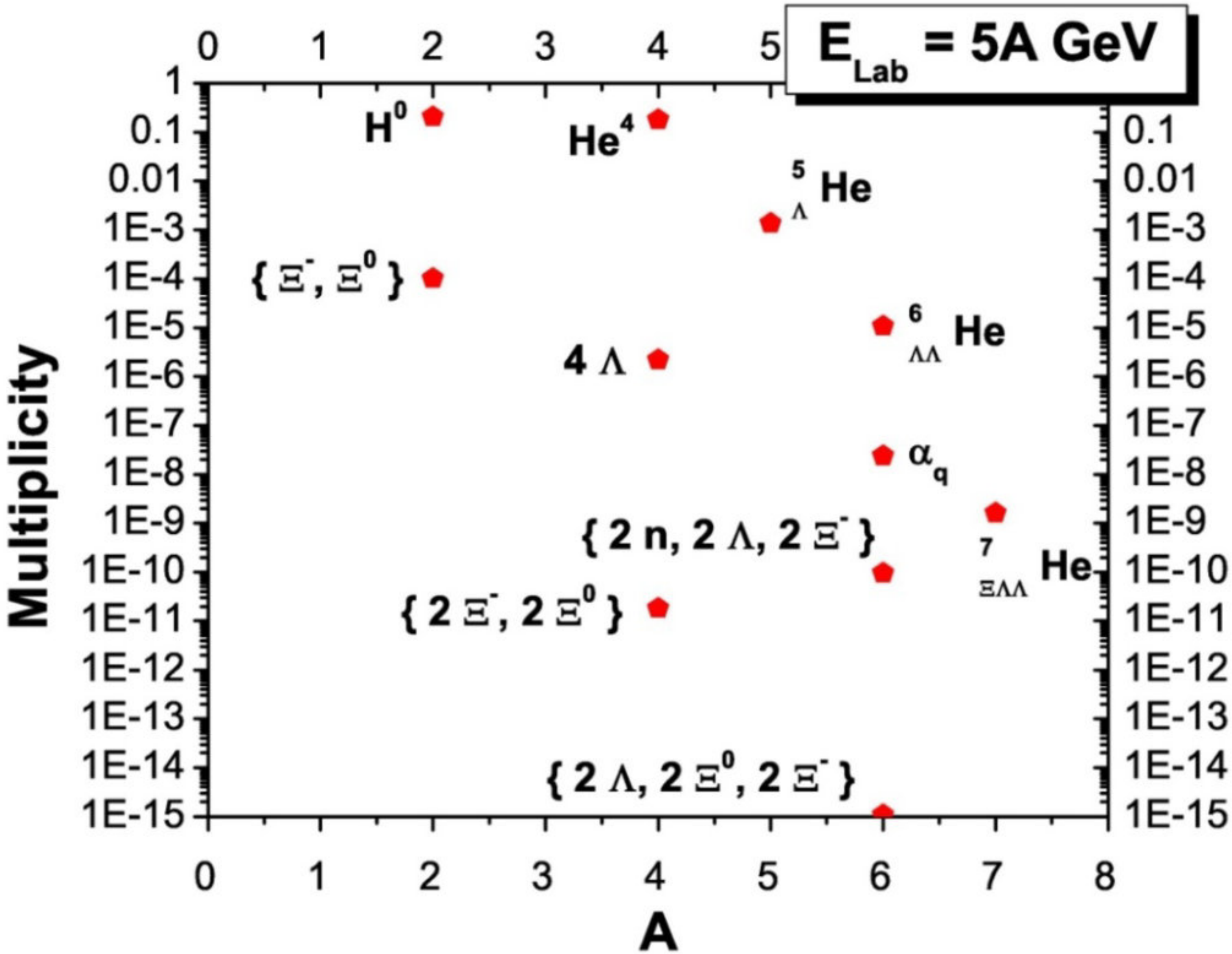
A. Andronic, P. Braun-Munzinger, J. Stachel, H. Stöcker, Phys. Lett. B697 (2011) 203



statistical model

Hypernuclei, strange dibaryons and massive strange objects

J.Steinheimer et. al. , Phys.Lett. B676 (2009) 126-131

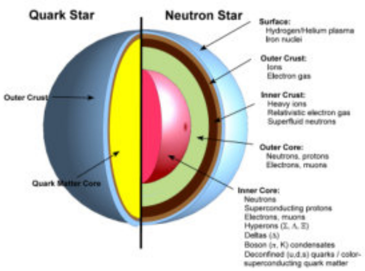


model

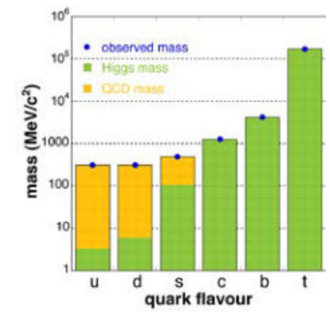
transport
+
hydrodynamics

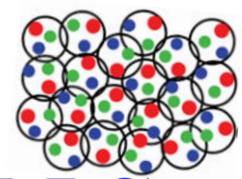
Summary: CBM physics case and observables

The equation-of-state at neutron star core densities
- collective flow of hadrons
- particle production at threshold energies
  (multi-strange hyperons)

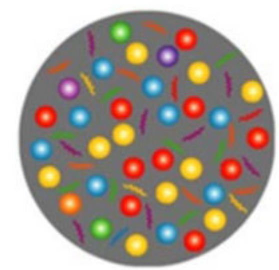


Onset of chiral symmetry restoration at high ρ_B
- in-medium modifications of hadrons ($\rho,\omega,\phi \rightarrow e^+e^-(\mu^+\mu^-)$)



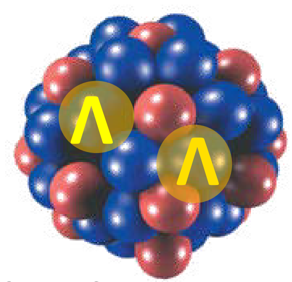


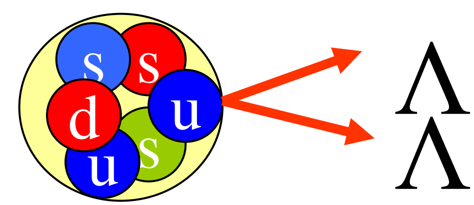
New phases of strongly-interacting matter
- excitation function and flow of lepton pairs
- excitation function and flow of strangeness (K, Λ, Σ, Ξ, Ω)



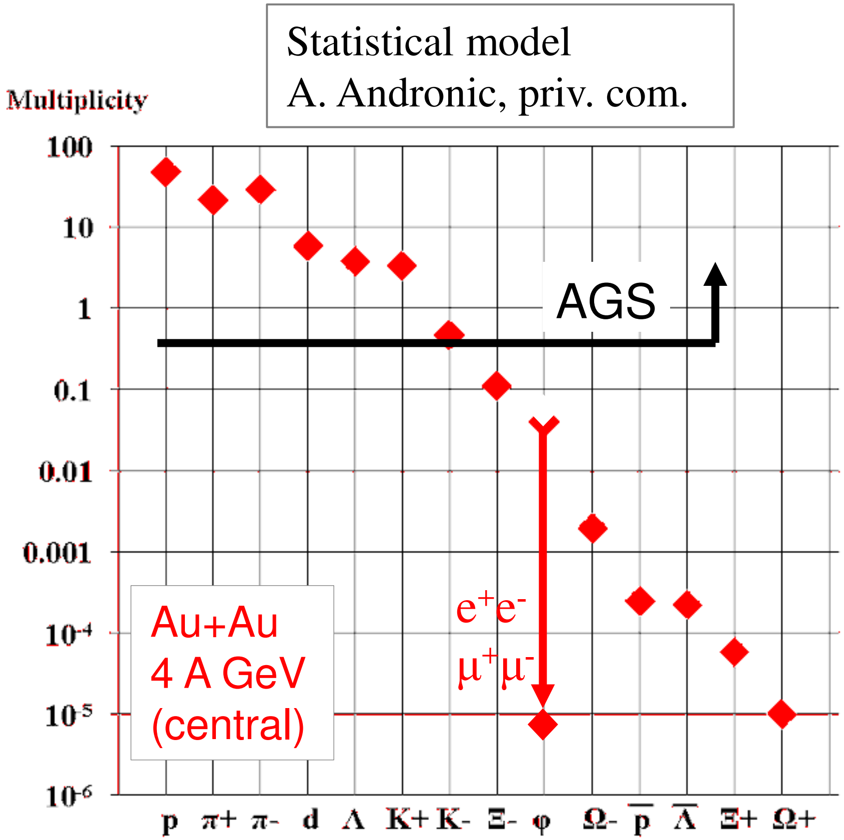
Deconfinement phase transition at high ρ_B
- excitation function and flow of charm (J/ψ, ψ', D^0, $D^\pm$, Λ_c)
- anomalouus charmonium suppression

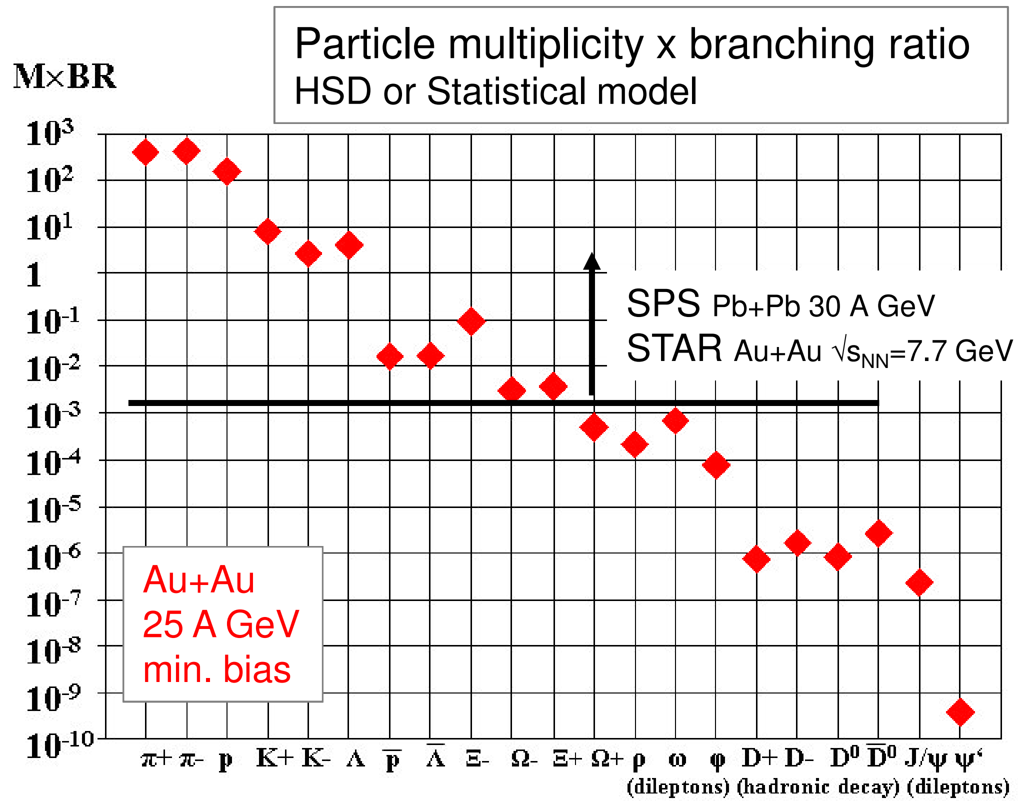
Strange matter
- (double-) lambda hypernuclei
- strange meta-stable objects
  (e.g. strange dibaryons)





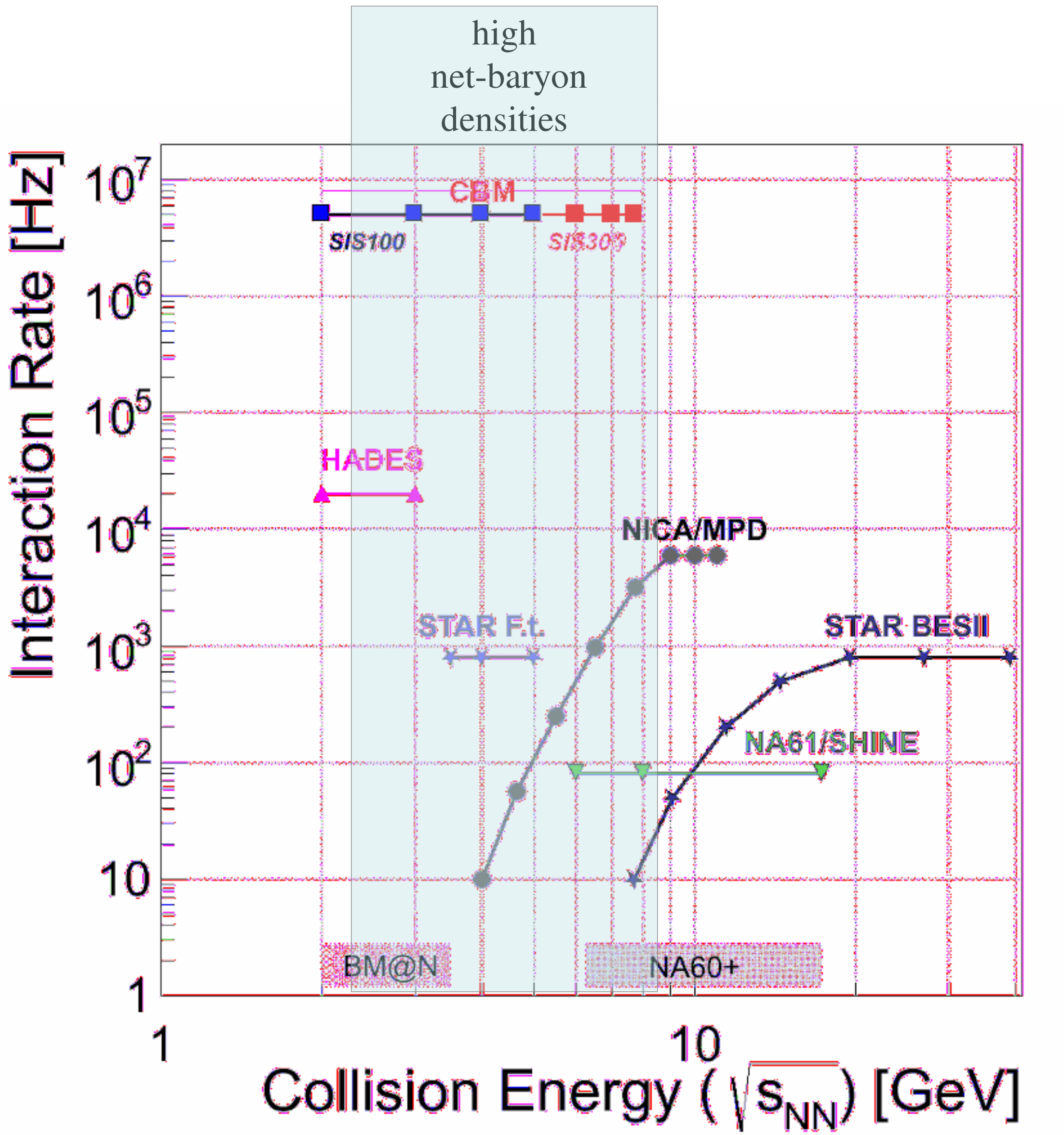
Experimental challenges





rare probes → extremely high interaction rates required !

Experiments exploring dense QCD matter
Rate capabilities

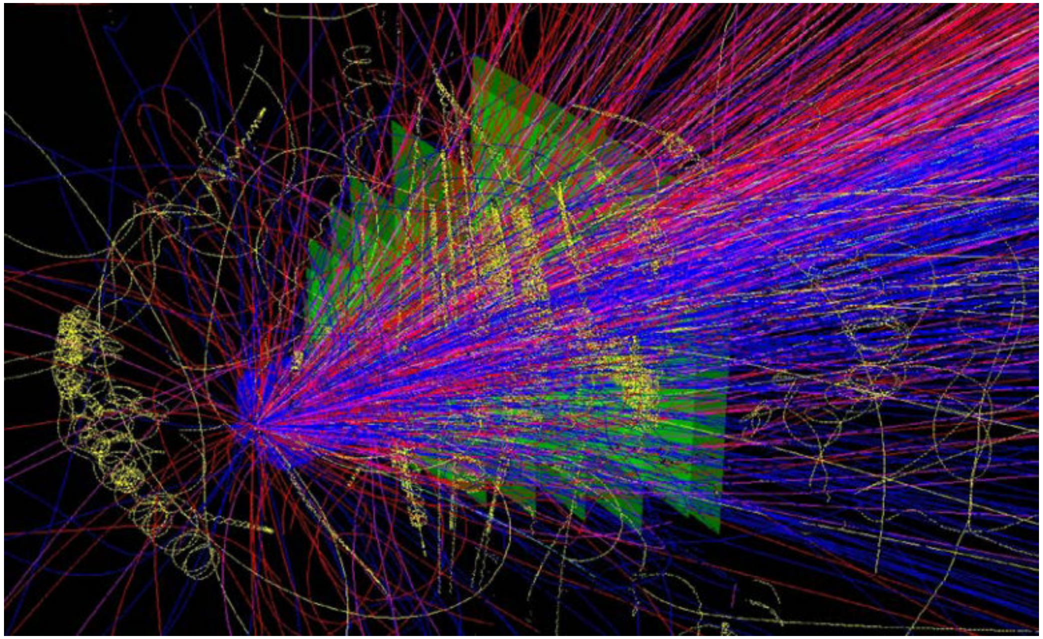


FAIR energies
(Au ions)

E_{kin}^{lab} [A·GeV]	$\sqrt{s_{NN}}$ [GeV]
2	2.7
11	4.9
14 (Ca @ SIS100) 29 (p @ SIS100)	5.5 7.6
30	7.7
35	8.3
44 (Ca @ SIS300) 89 (p @ SIS300)	9.3 13.0

CBM experimental challenges

Perform measurements at unprecedented reaction rates
10^5 - 10^7 Au+Au reactions/sec
→ fast and radiation hard detectors
→ free-streaming read-out electronics
→ high speed data acquisition and
high performance computer farm for online event selection
→ 4-D event reconstruction



Identification
of leptons and hadrons

Determination of
(displaced) vertices ($\sigma \approx 50$ μm)

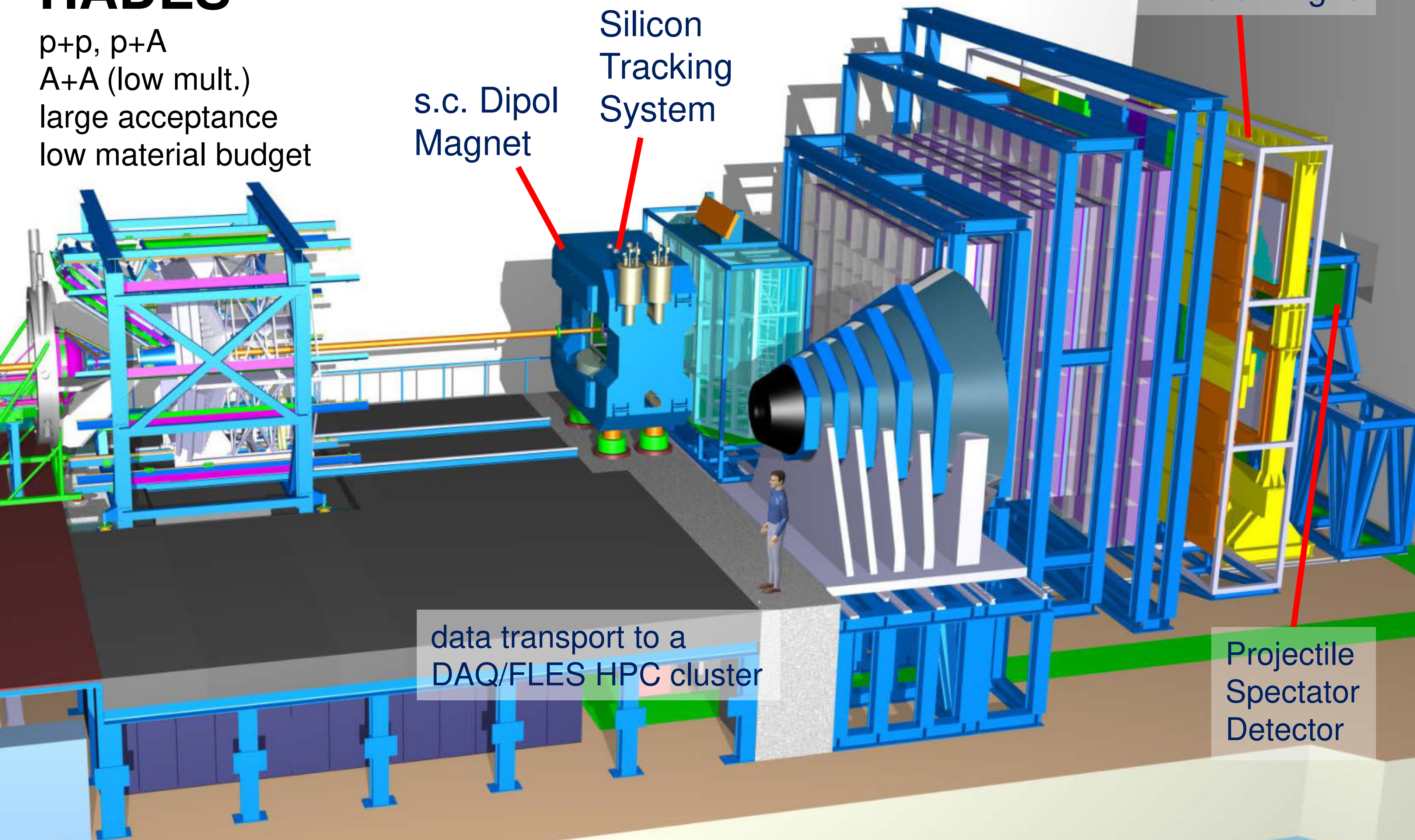
Central Au+Au at 25 A GeV / UrQMD+GEANT4 : 160 p, 400 π^+, 400 π^+, 44 K^+, 13 K^-

HADES

p+p, p+A
A+A (low mult.)
large acceptance
low material budget

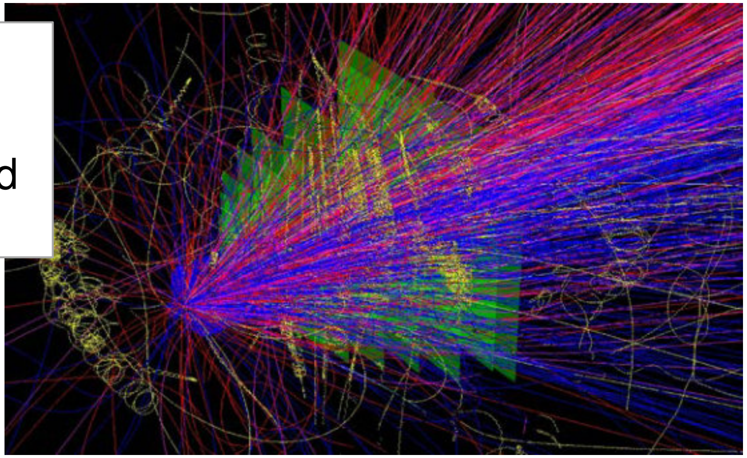
CBM

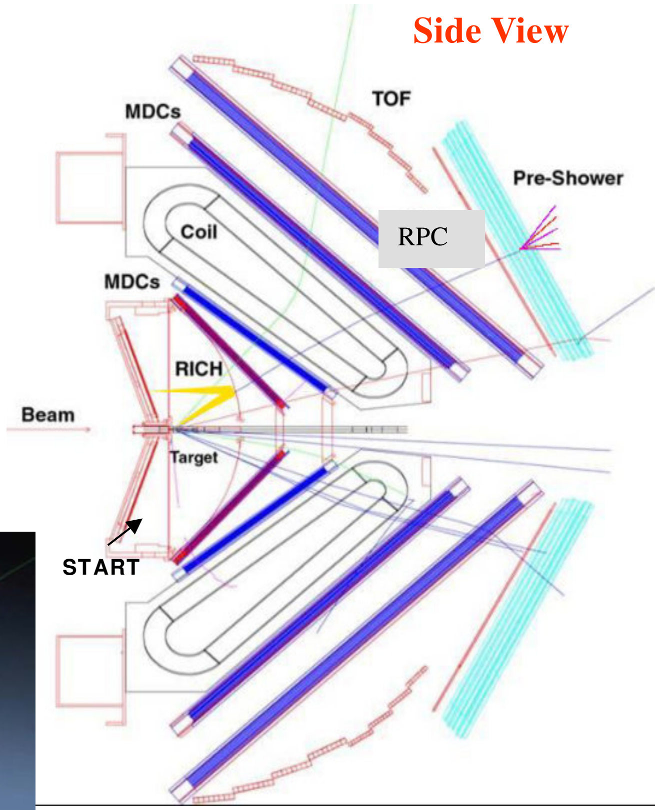
hadrons

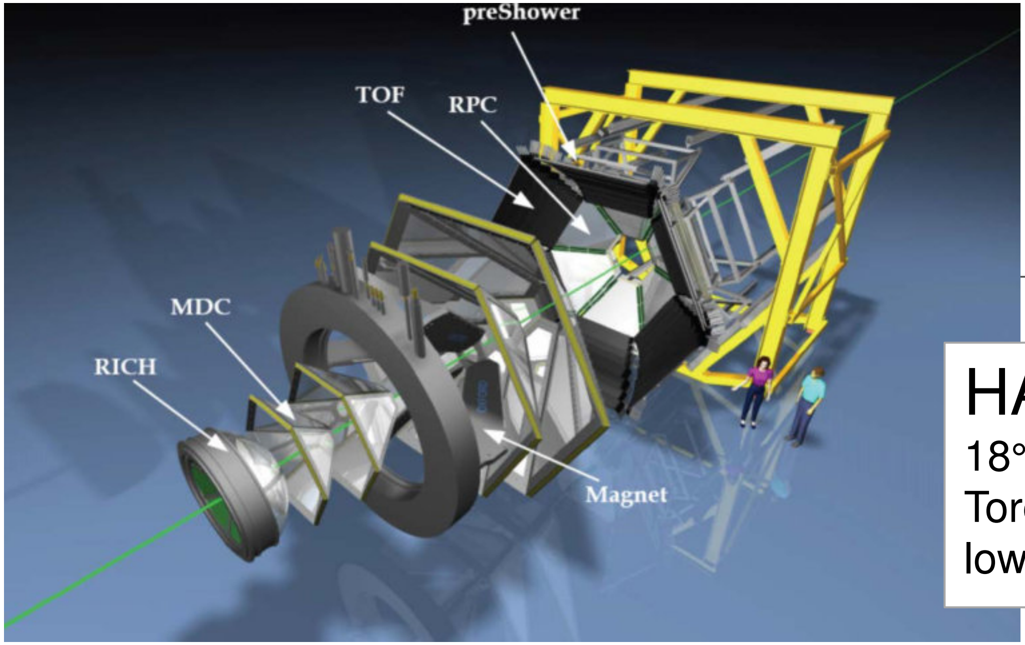


CBM & HADES: complementary experiments

CBM
3° - 25°
Dipole field
high rate

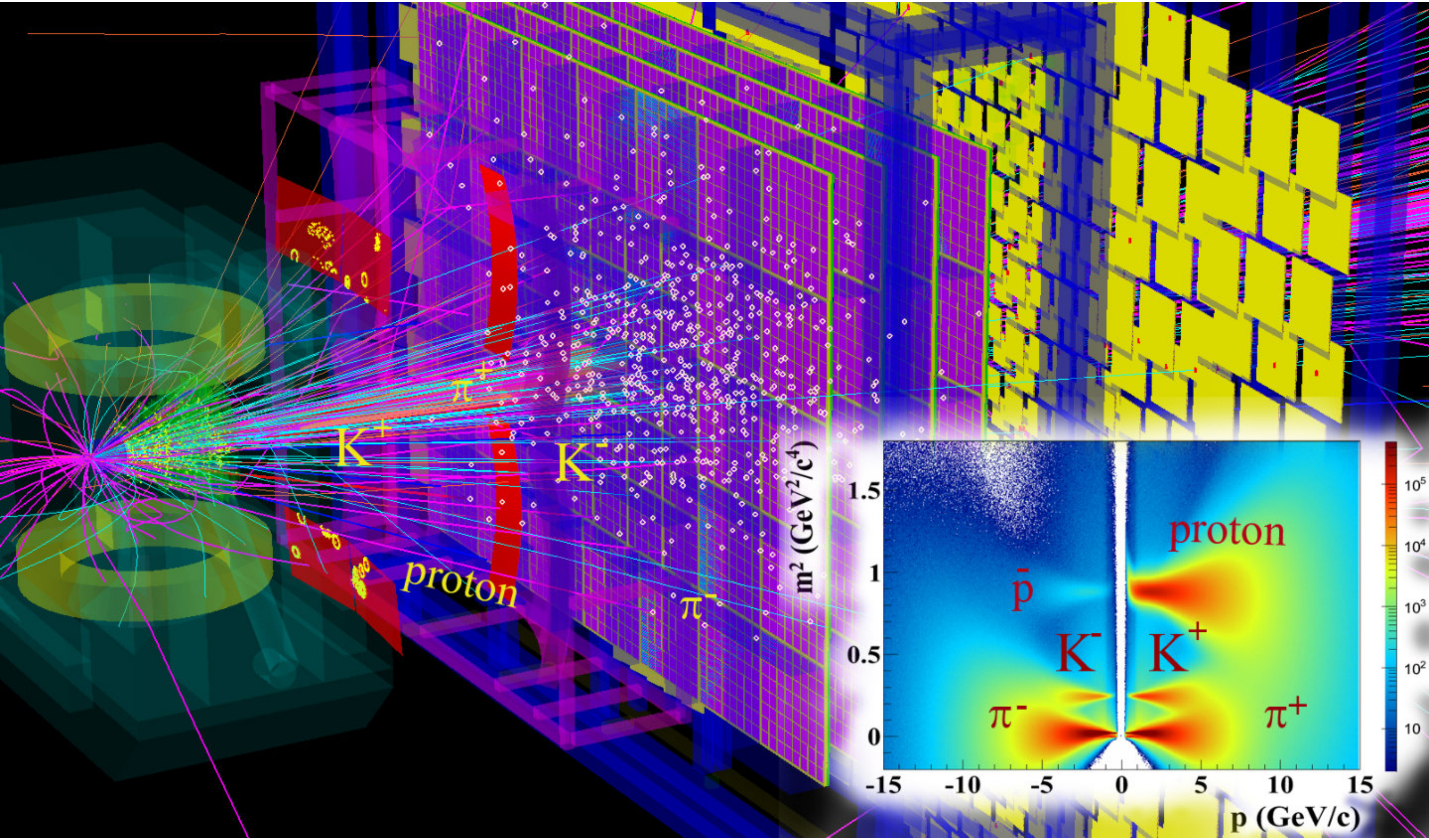




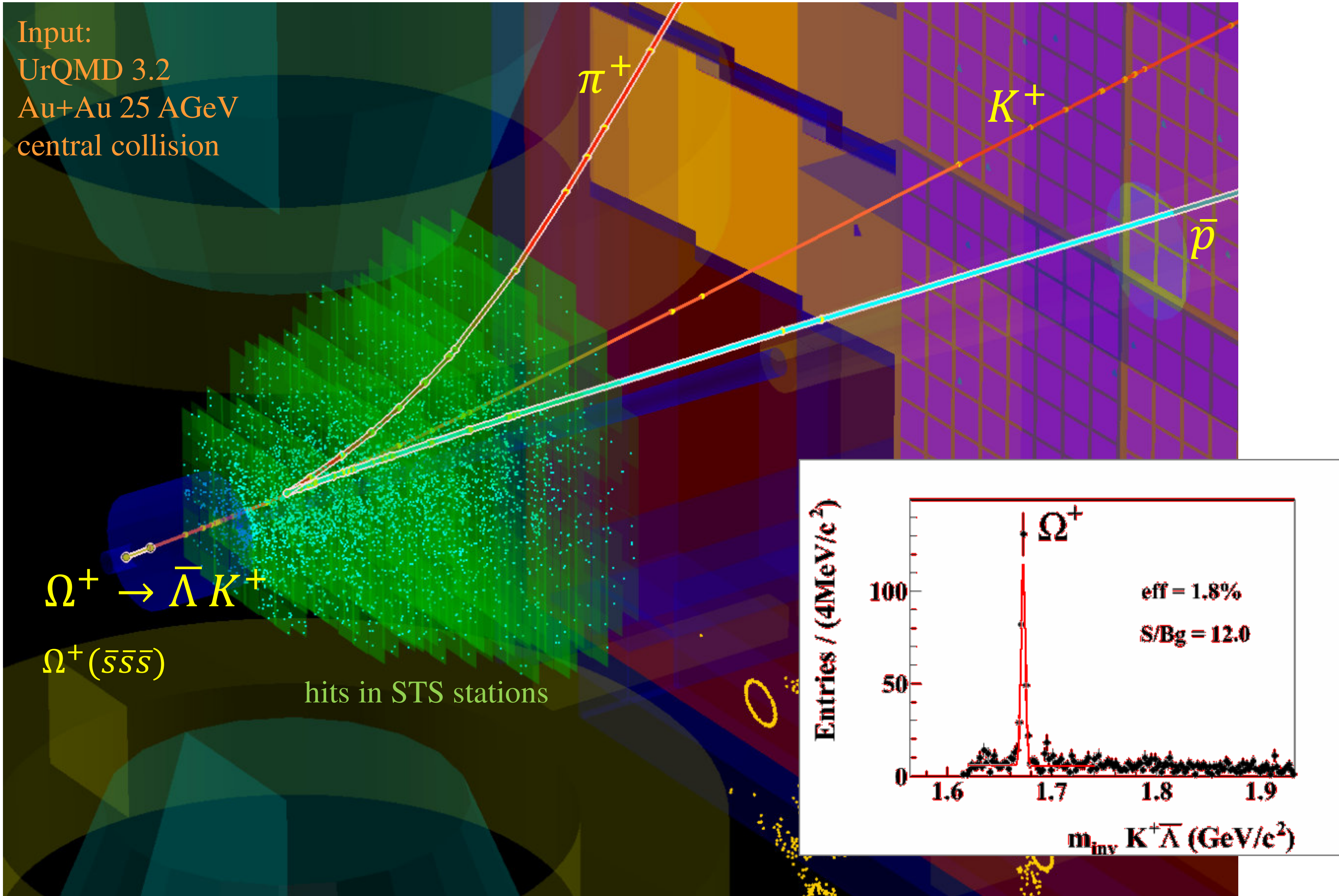


HADES
18° - 85°
Toroidal field
low mass; high res

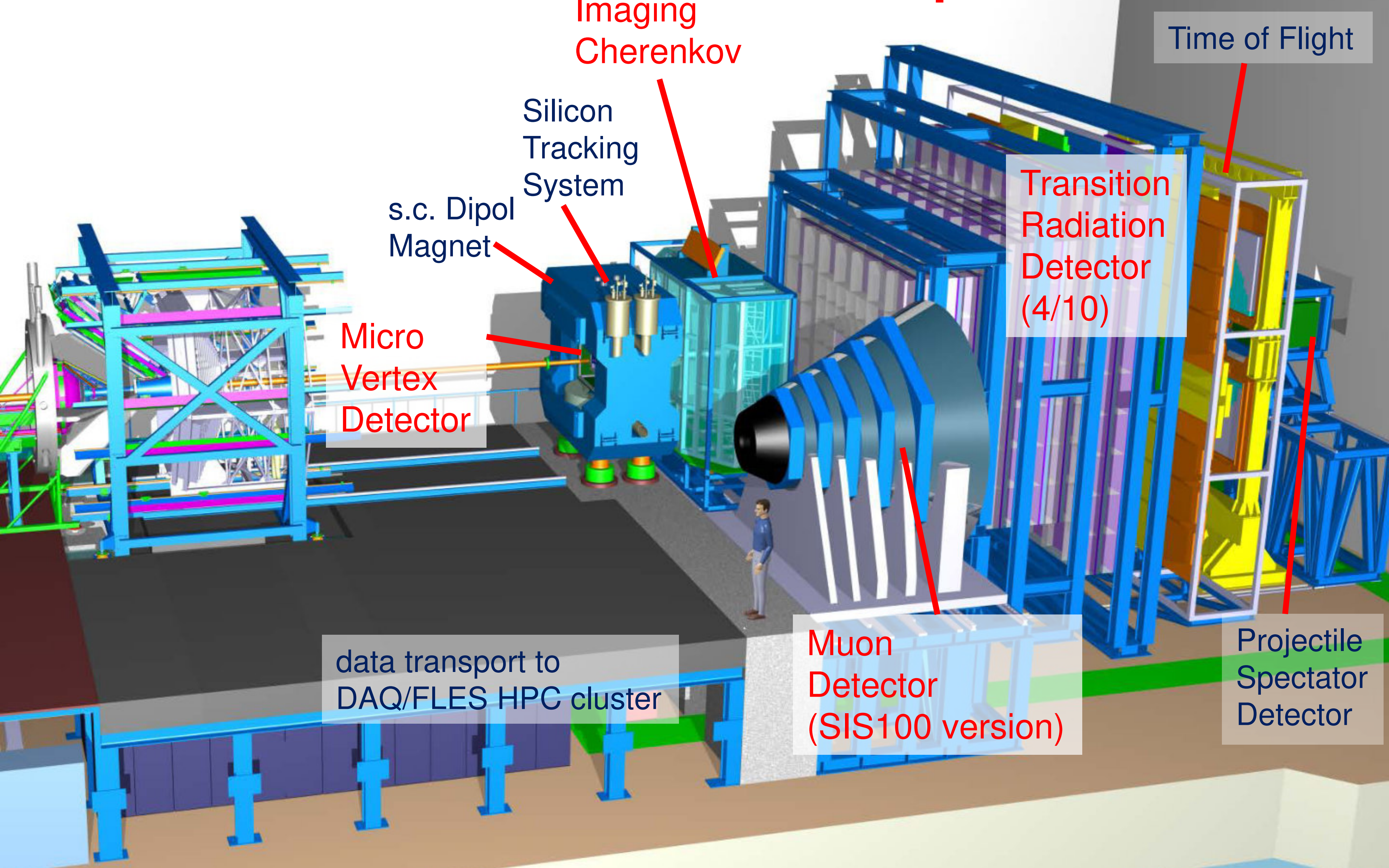
Particle identification



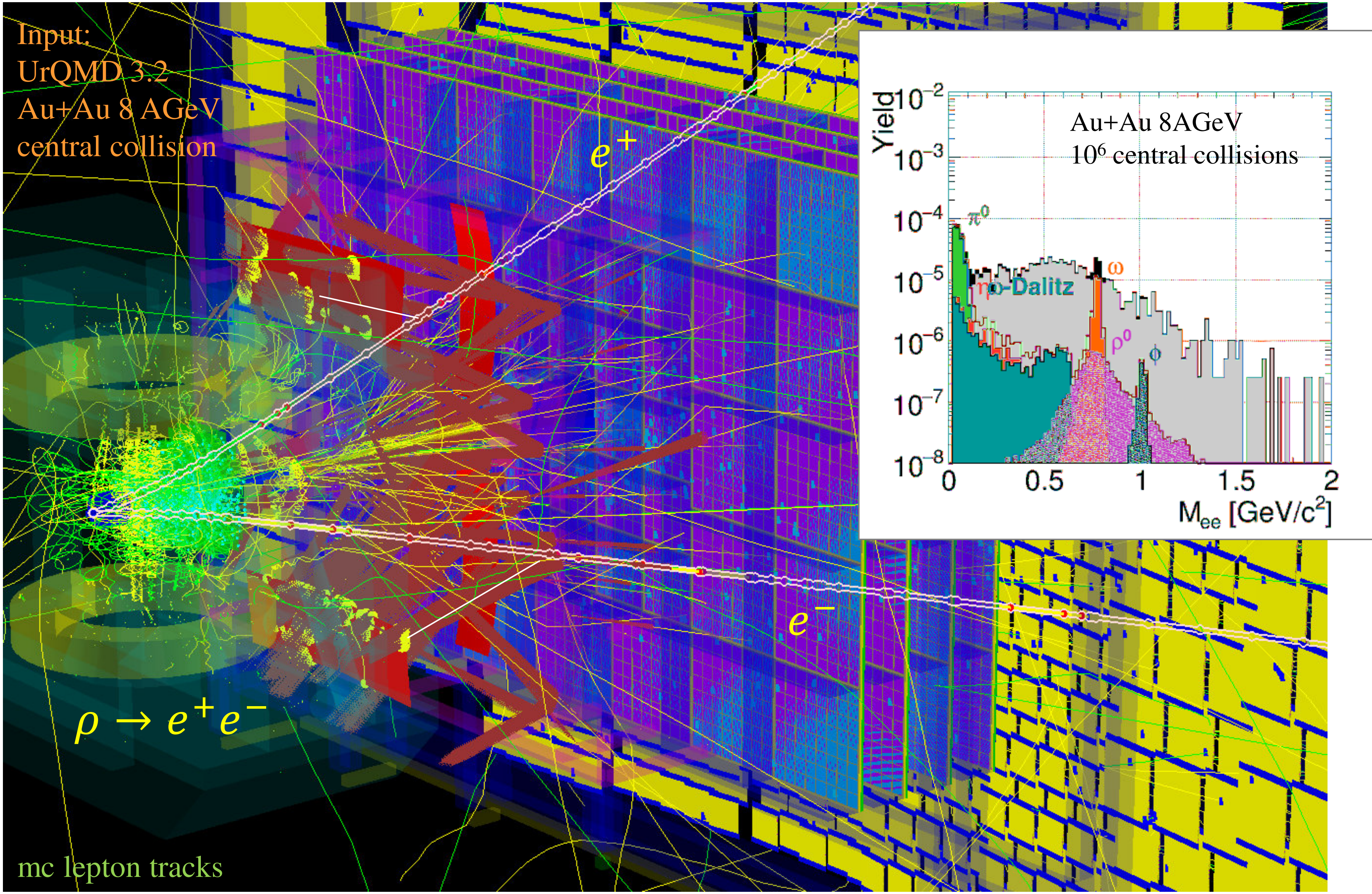
Anti-hyperon reconstruction



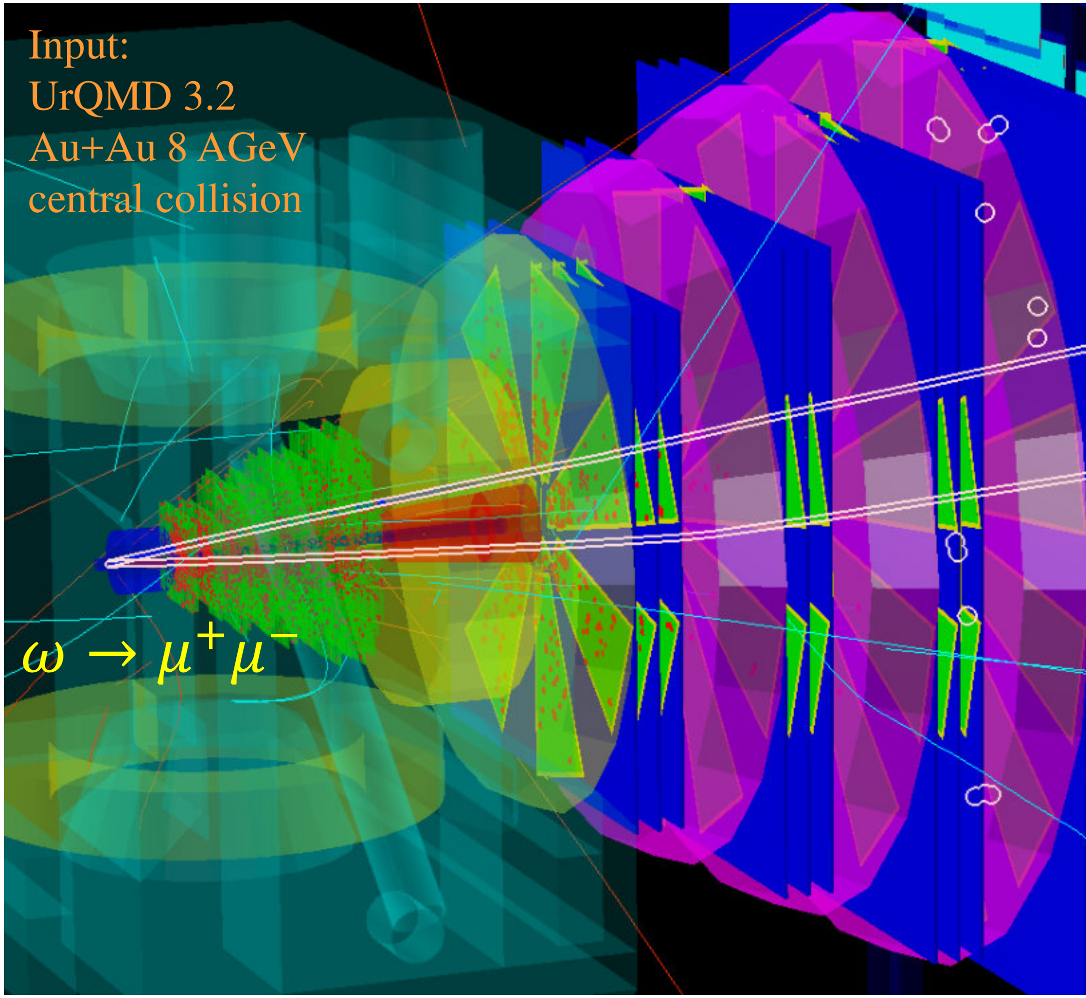
CBM
dileptons

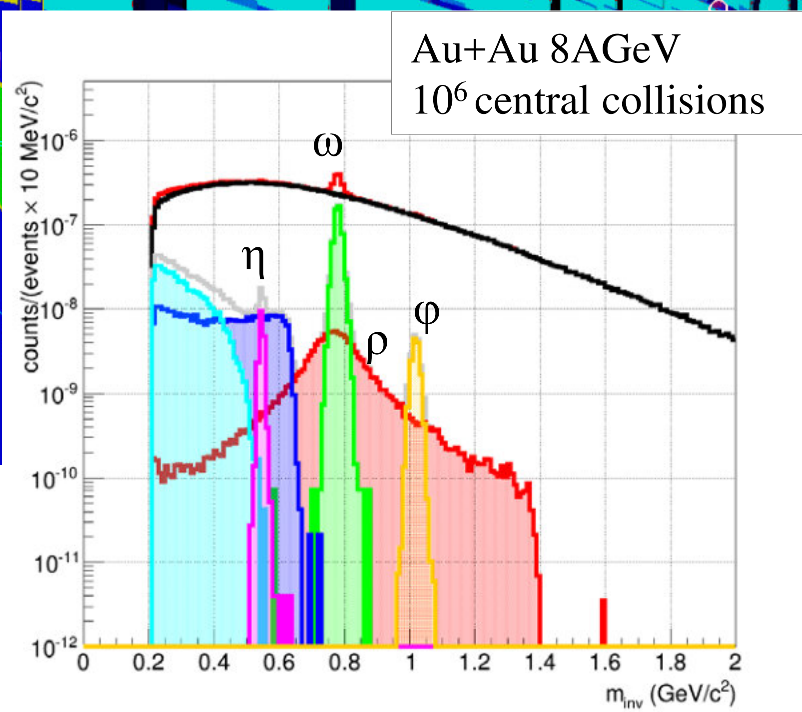


Di-electron reconstruction



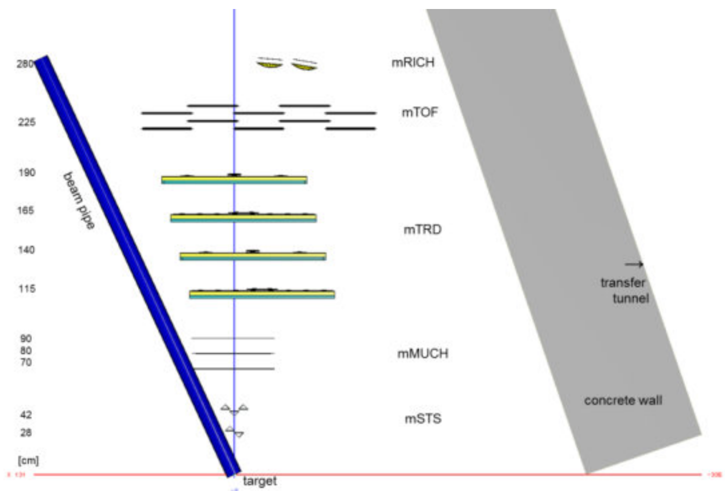
Di-muon reconstruction

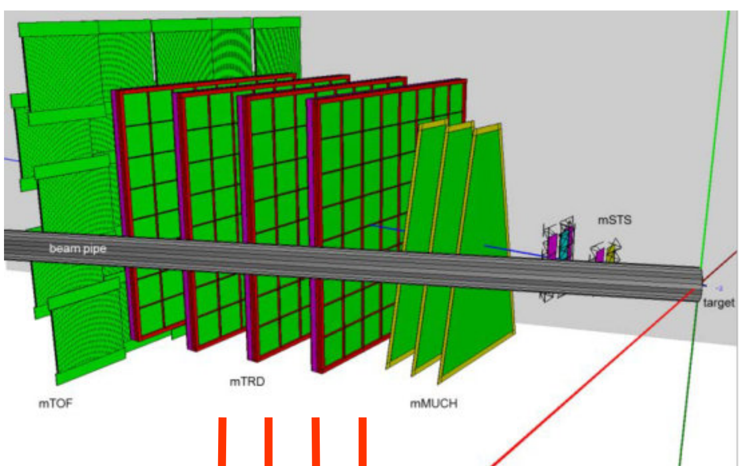




Simulation: signal yields from HSD
background from UrQMD

A CBM full system test-setup for high-rate nucleus-nucleus collisions at GSI/FAIR

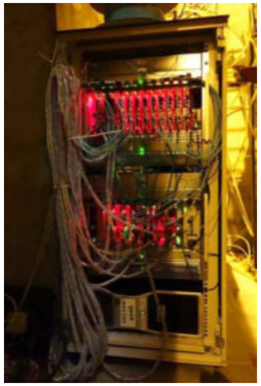


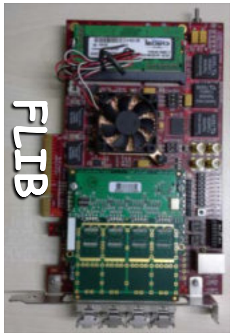


the mCBM test-setup ("mini-CBM") will focus on the

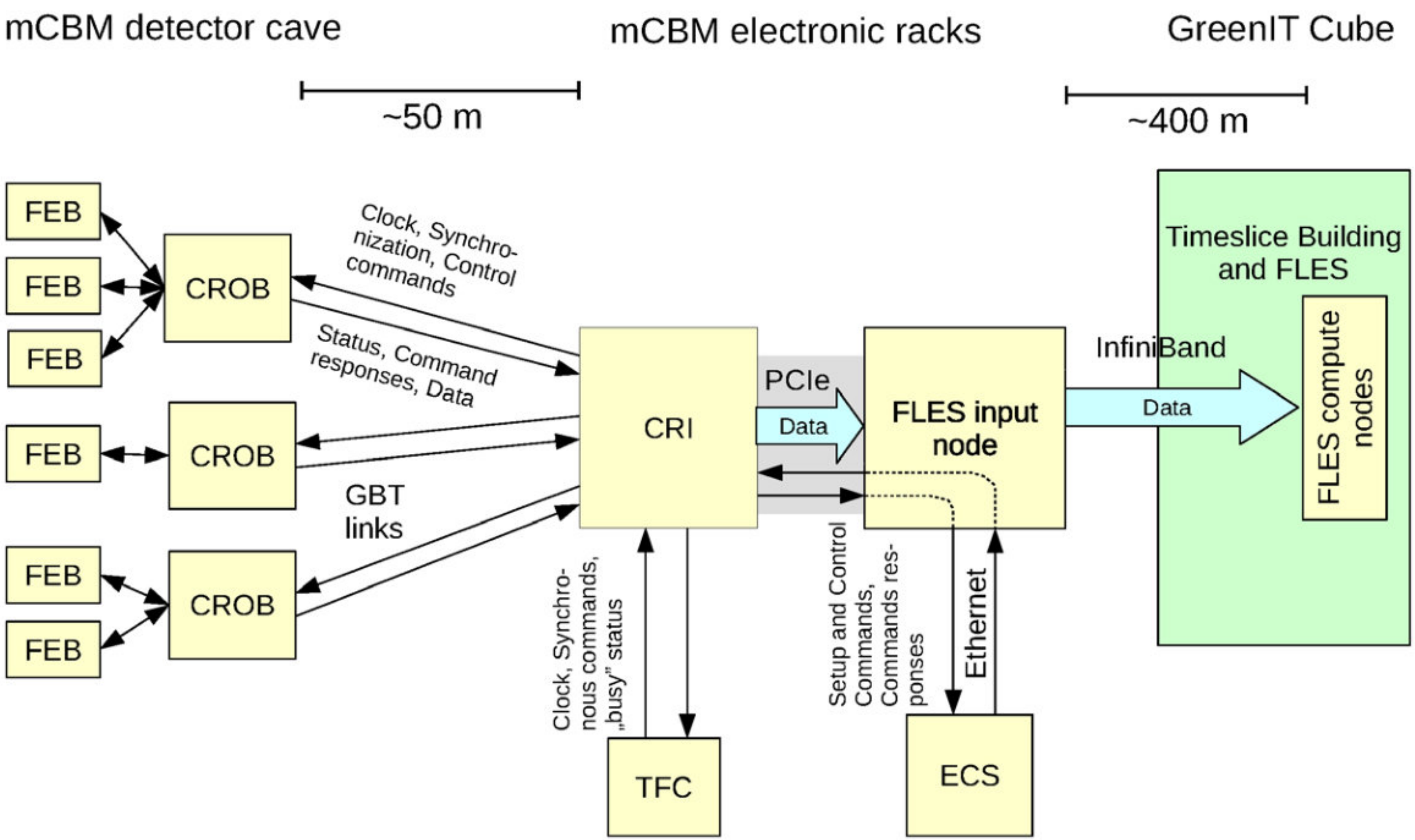
- test of final detector prototypes
- **free streaming data transport to a computer farm**
- **online reconstruction and event selection**
- **offline data analysis**

10/2017	vacuum chamber for switching magnet ordered
11/2017	cave and beam line preparation started
02/2018	mFLES cluster in Green IT Cube operational
03/2018	ready for installation of detector subsystems
05/2018	start commissioning w/o beam
09/2018	start commissioning with beam



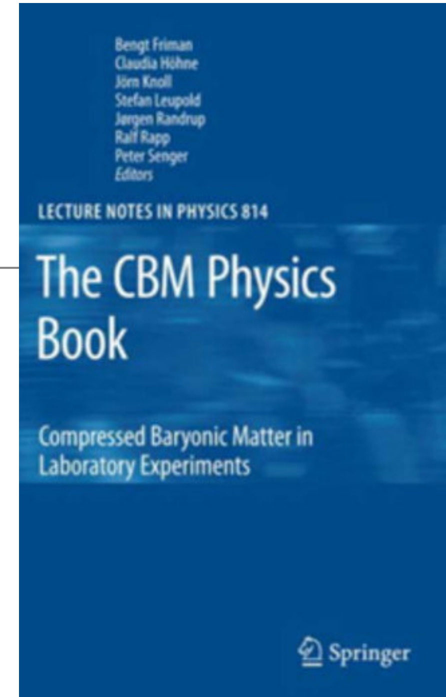


mCBM read-out and data transport - final version



CBM physics observables

Lecture Notes in Physics
Vol. 814 1st Edition., 2011, 960 p.,
Hardcover ISBN: 978-3-642-13292-6



Production excitation function
in nucleus-nucleus collisions at SIS100/300 of
- **multi-strange baryons**
- **anti-protons and anti-hyperons**
- **single and double hypernuclei**

Search for strange matter in the form of strange dibaryons and heavy multi-strange short-lived objects

High precision collective flow excitation function at SIS100/300

Excitation function of J/ψ production at SIS100/300 energies

Excitation function of lepton pair production and in-medium mass distributions of light vector mesons (2 – 35 A GeV)

(not complete)