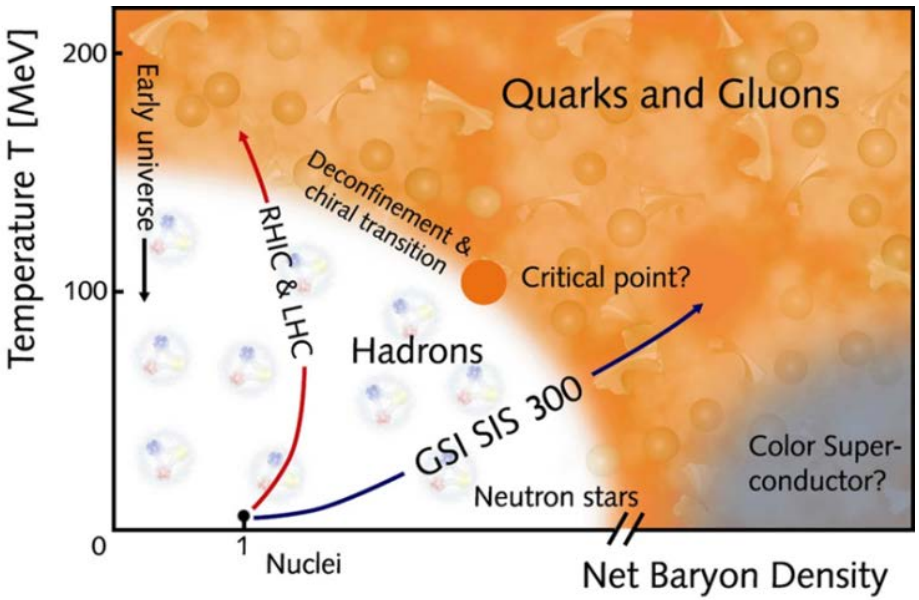
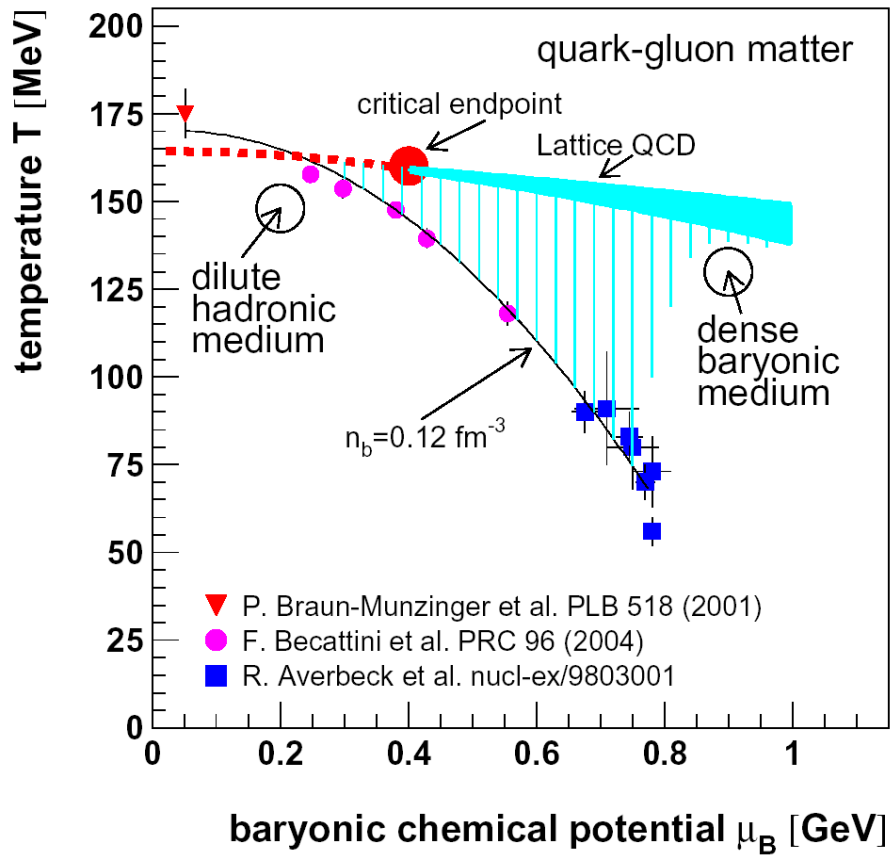
The phase diagram of strongly interacting matter



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

data taken at:
RHIC/LHC SPS AGS SIS



How to scan the phase diagram ?
→ Nucleus-nucleus collisions at various beam energies !

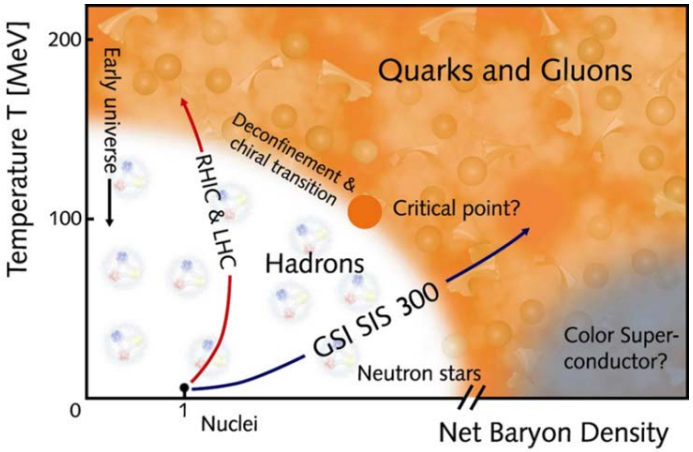
Lecture on Compressed Baryonic Matter

3rd International Conference on New Frontiers in Physics

July/August 2014

Christian Sturm

GSI Helmholtzzentrum für Schwerionenforschung

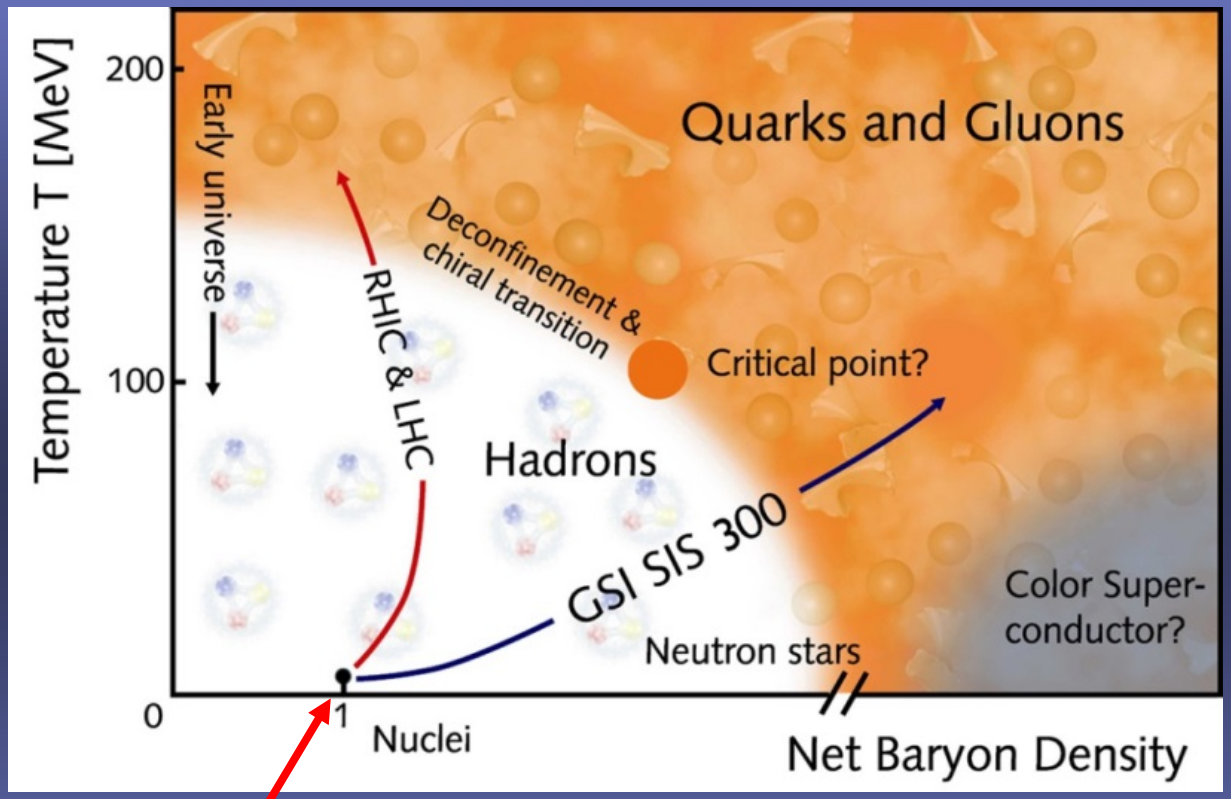


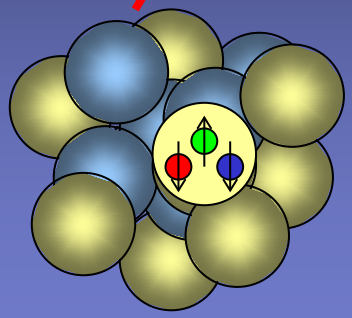
<u>Outline</u>

Part I	Nuclear Matter in (or close to) ground state
Part II	Exploring compressed nuclear matter in "nature"
Part III	Exploring dense nuclear matter in the laboratory
Part IV	Exploring the early universe in the laboratory
Part V	Exploring the highest baryon densities in the laboratory

GSI FAIR Bundesministerium für Bildung und Forschung HIC for FAIR Helmholtz International Center Study of Strongly Interacting Matter HadronPhysics

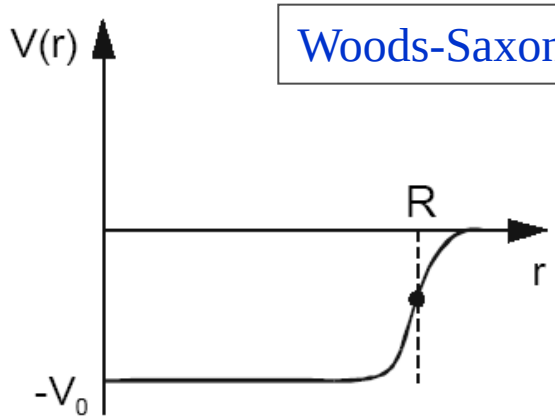
Part I
Nuclear Matter in (or close to) ground state





Nuclear matter in ground state: the Nuclear Shell Model

density distribution of nucleons inside (heavy) nuclei



Woods-Saxon Potential

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

solving the Schrödinger equation

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

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

observed magic numbers

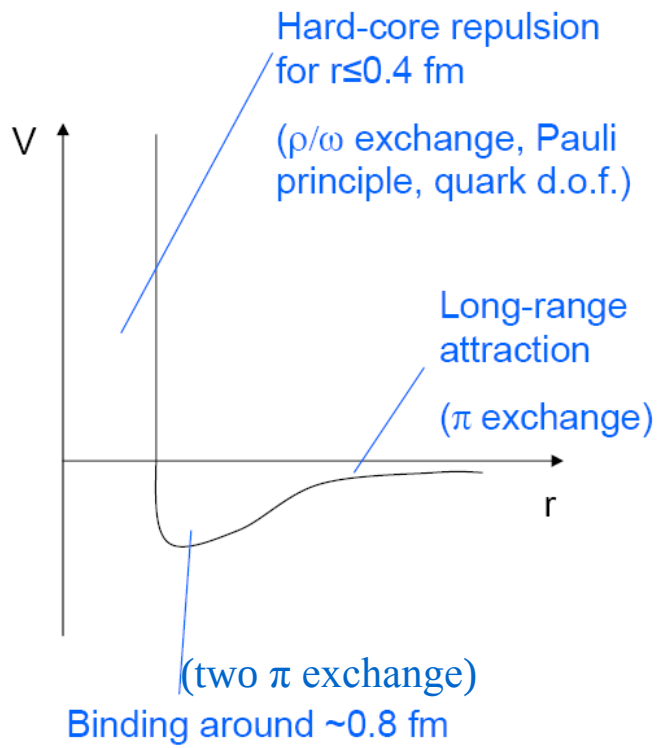
N	2	8	20	28	50	82	126	(184)	(196)
Z	2	8	20	28	50	82	(114)	(164)	

Effective nucleon-nucleon interaction

The meson exchange is a <u>model</u> to describe the effective nucleon-nucleon-interaction

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

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



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

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

note: 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

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

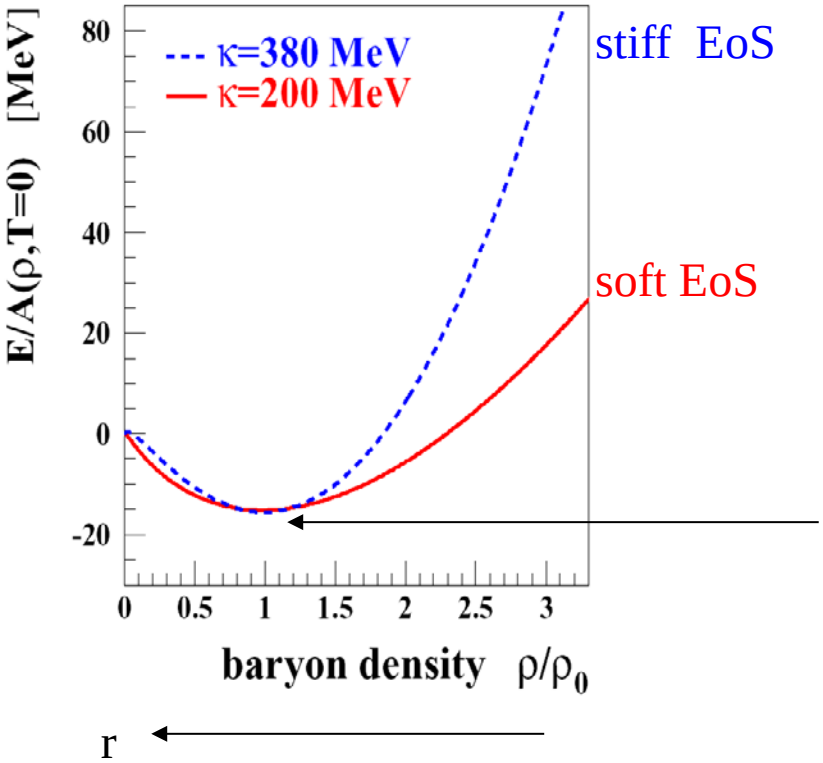
$(\varepsilon = E/A)$ thermal compressional ground state energy

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

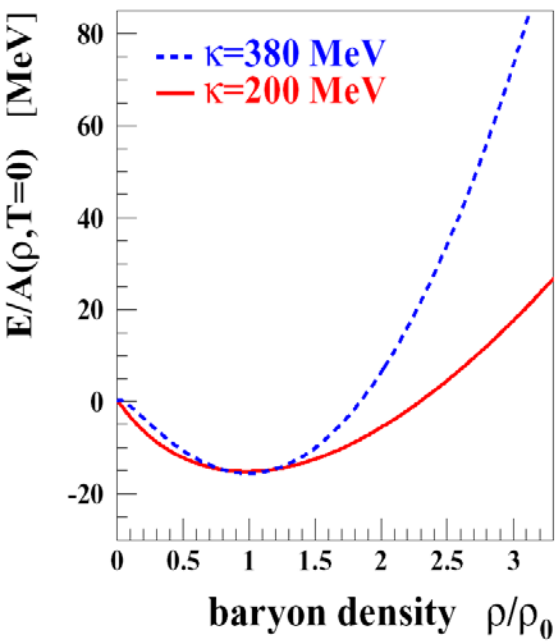


compression modulus

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

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)

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

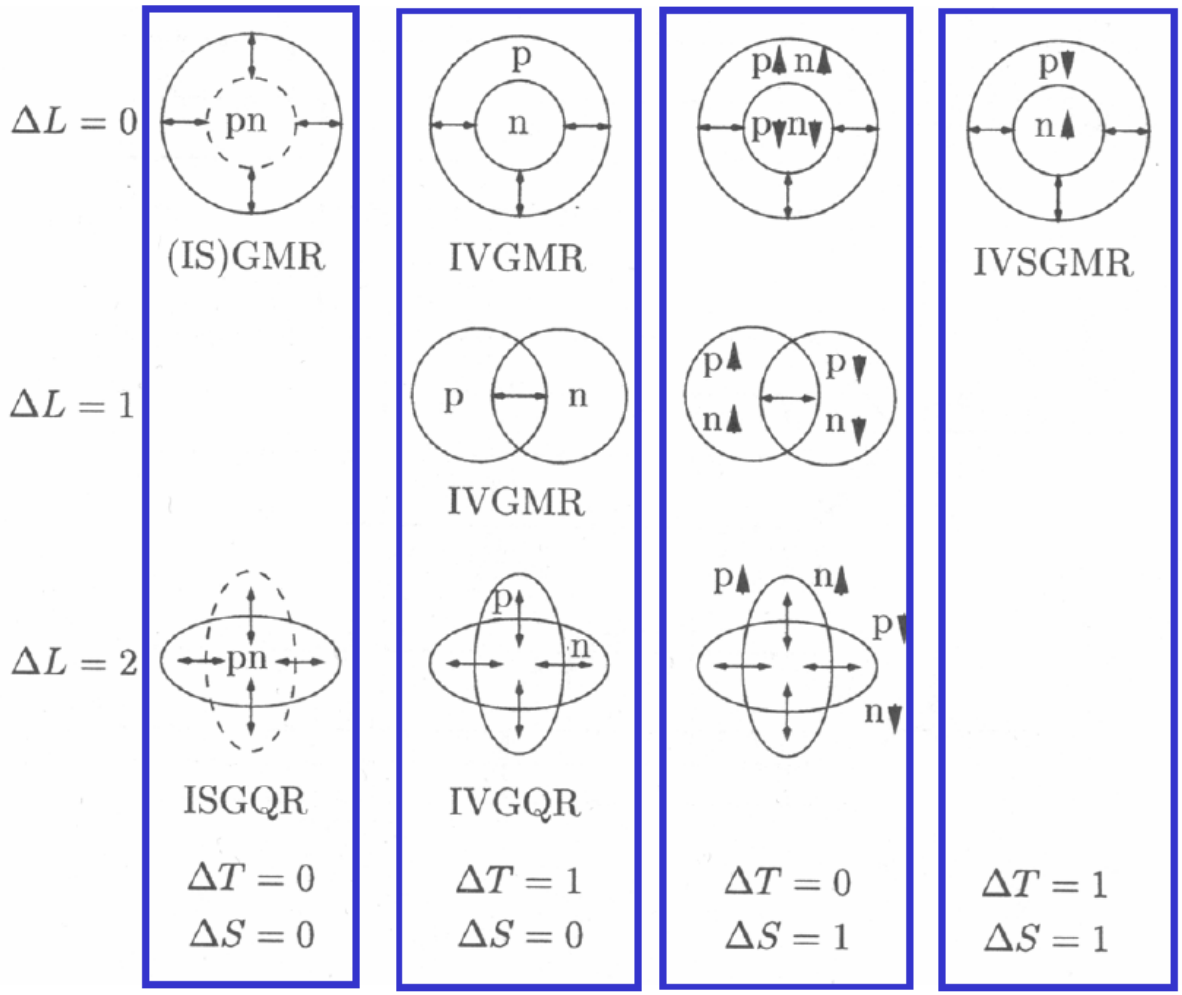
constraints for the parameters of the potential :

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

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

	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



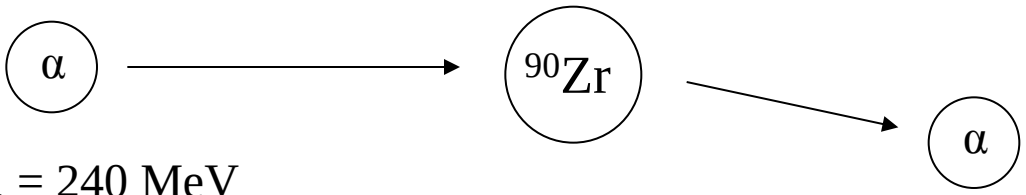
monopole vibration:
"breathing mode" of the nucleus

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

quadruple vibrations

Excitation of the giant monopole resonance

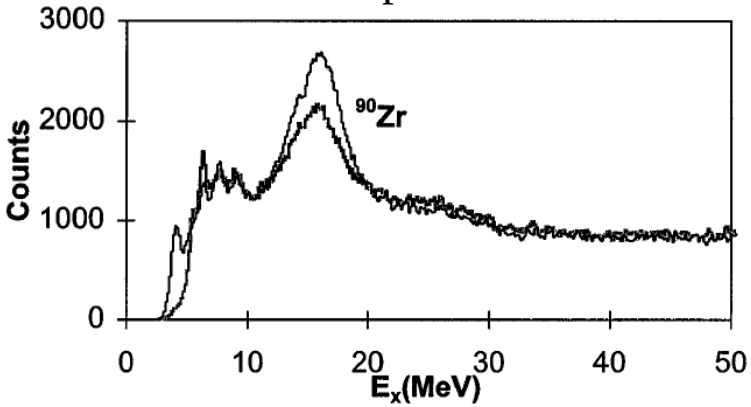
inelastic scattering of α particles on nuclei



E_{kin} = 240 MeV

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

"resonance phenomenon"



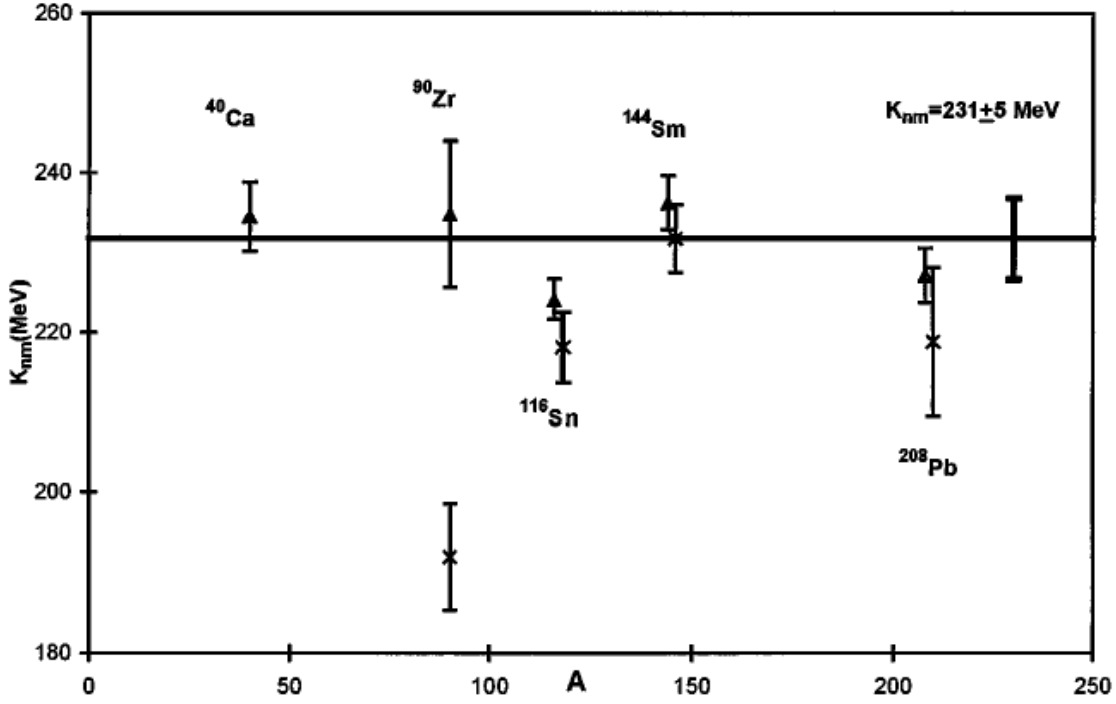
The energy loss of the α particle of about 15 – 25 MeV excites slight density oscillations with elongations of about 1/100 ρ_0 (around saturation density ρ_0). It is a collective excitation of the nucleus and calls the Giant Monopole Resonance or the "breathing mode" of nuclei.

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 .

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

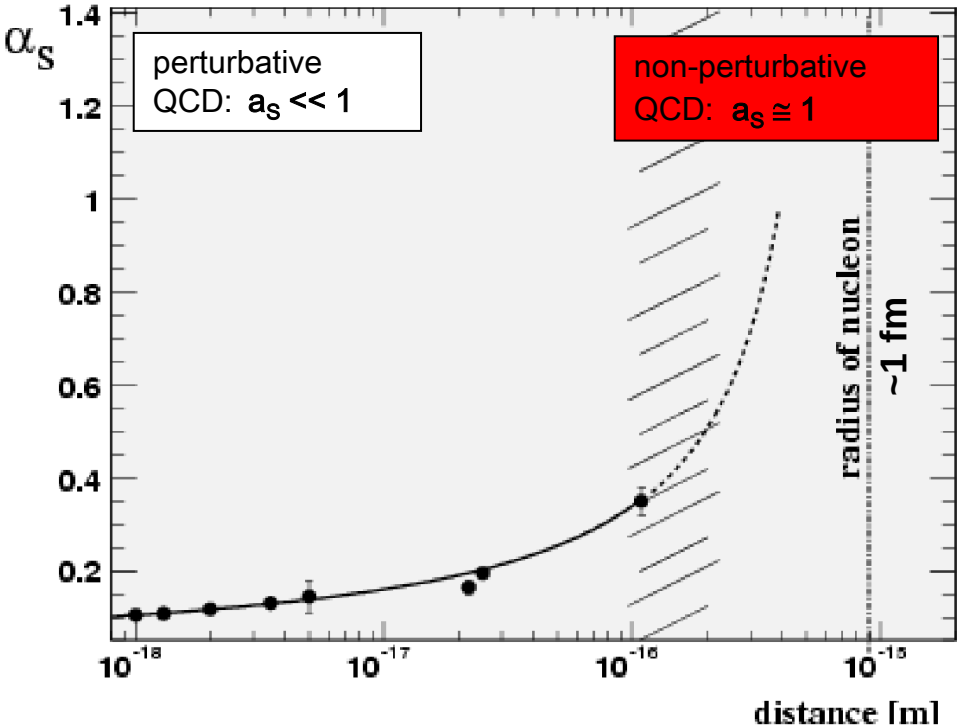
The equation-of-state of nuclear matter:
$\kappa = 231 \pm 5$ MeV at saturation density ρ_0

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.

QCD: running coupling constant α_s

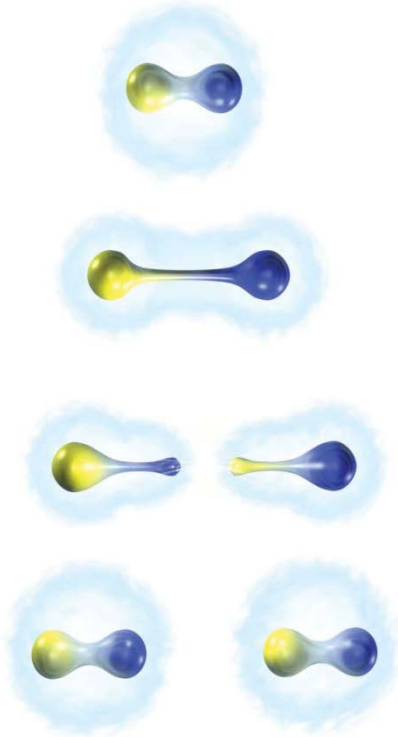
Coupling strength between two quarks



Asymptotic freedom
(Frank Wilczek - Physics Nobel prize 2004)

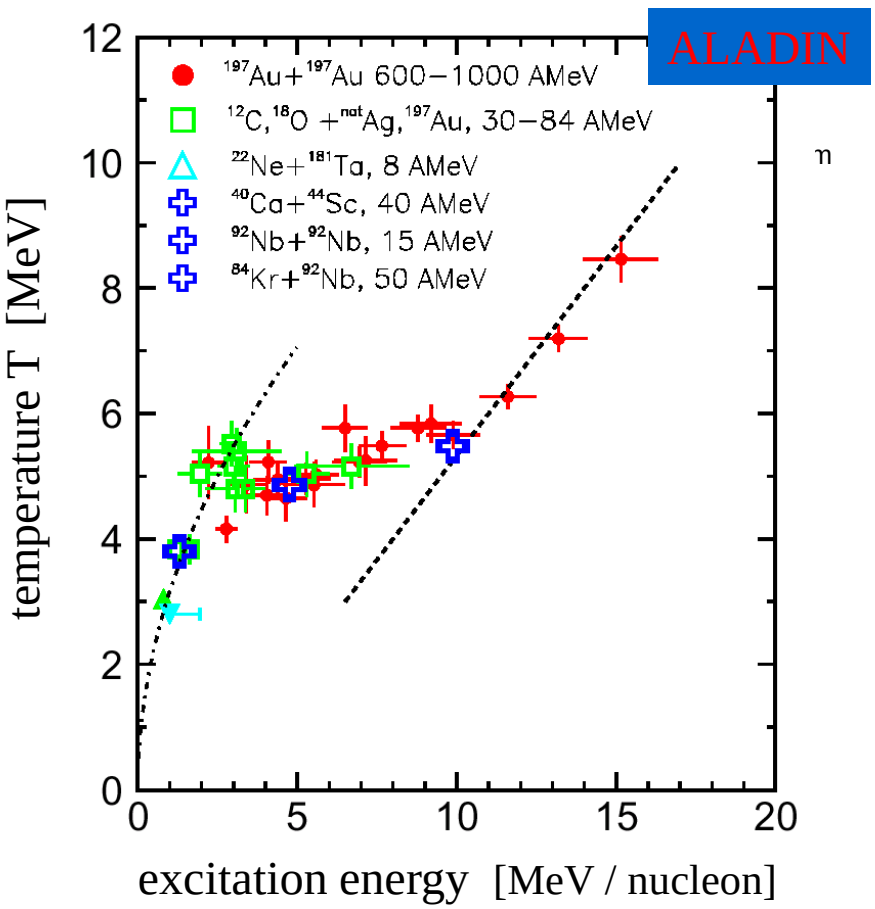
Quarks are confined!

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

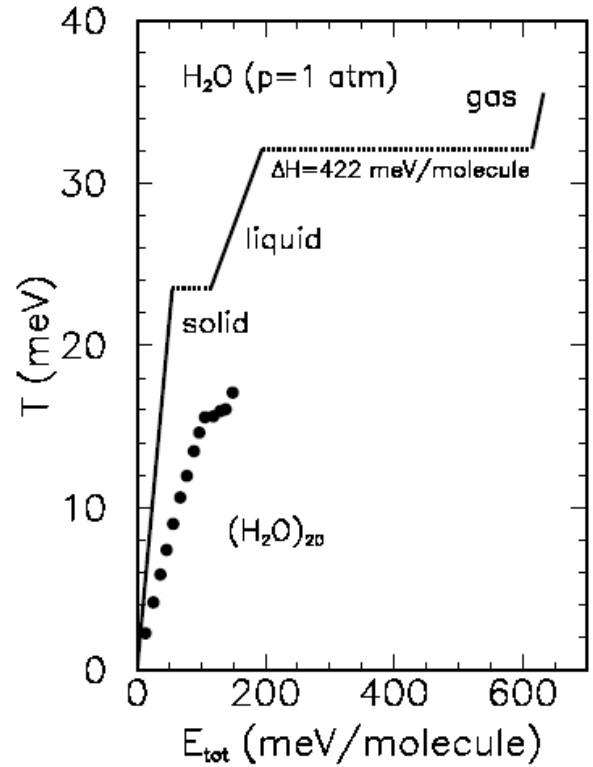


The liquid-gas phase transition

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



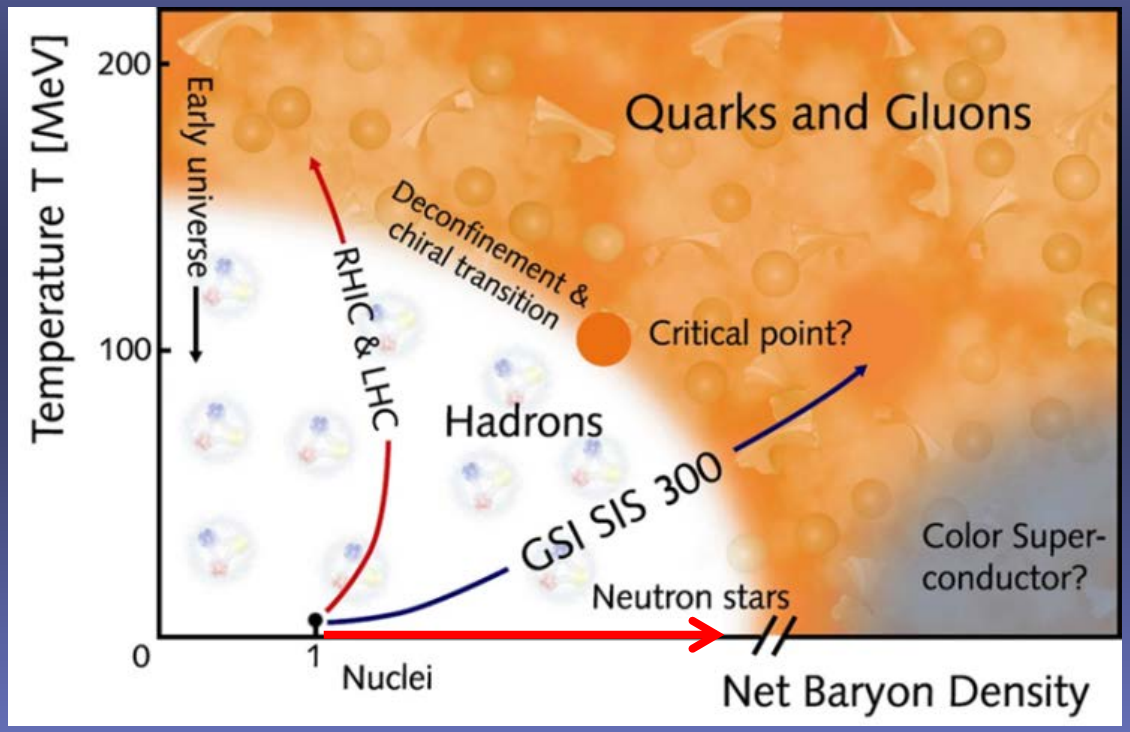
caloric curve of H_20



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

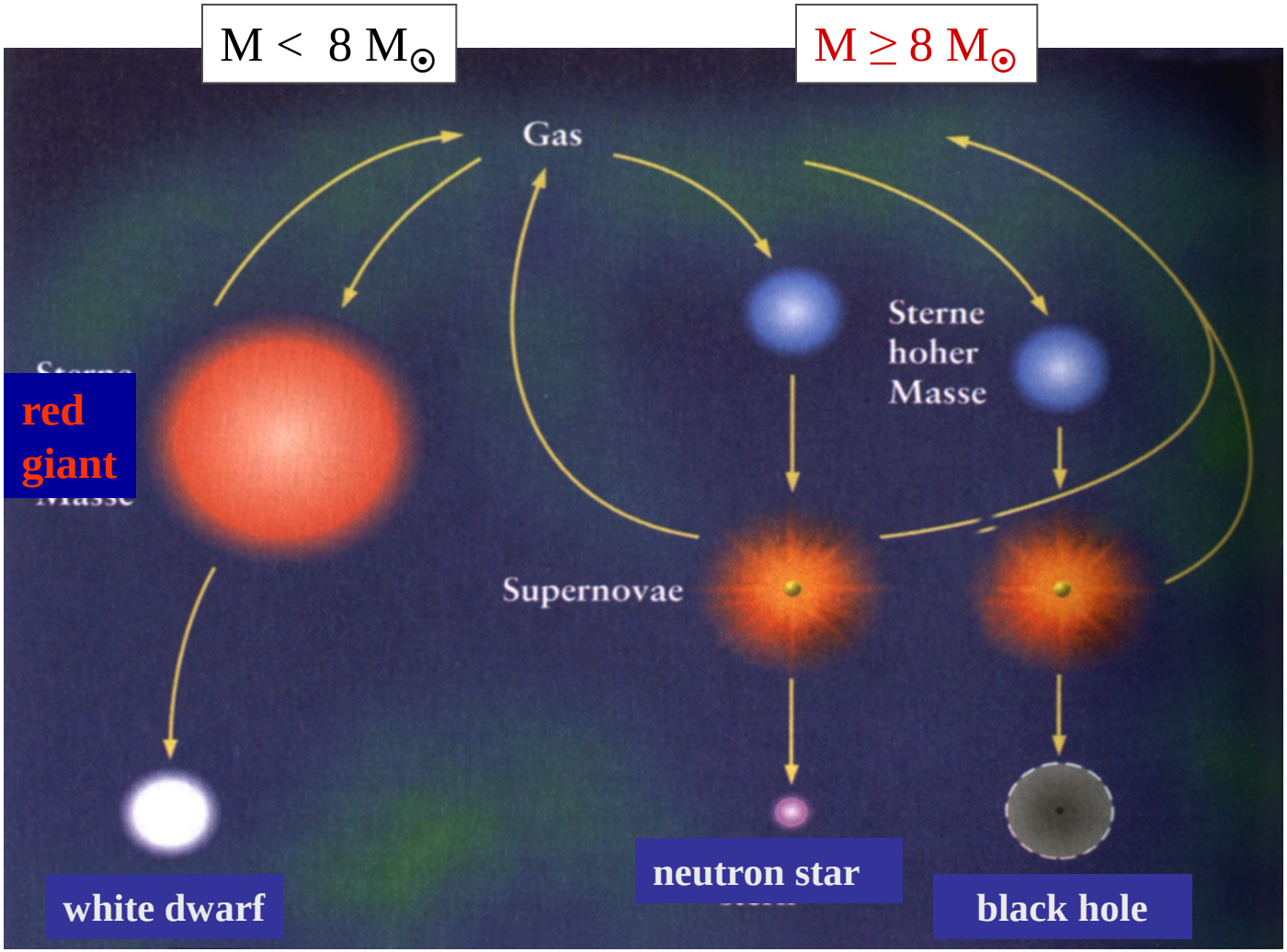
Part II
Exploring compressed nuclear matter in “nature”

Late stages of heavy stars



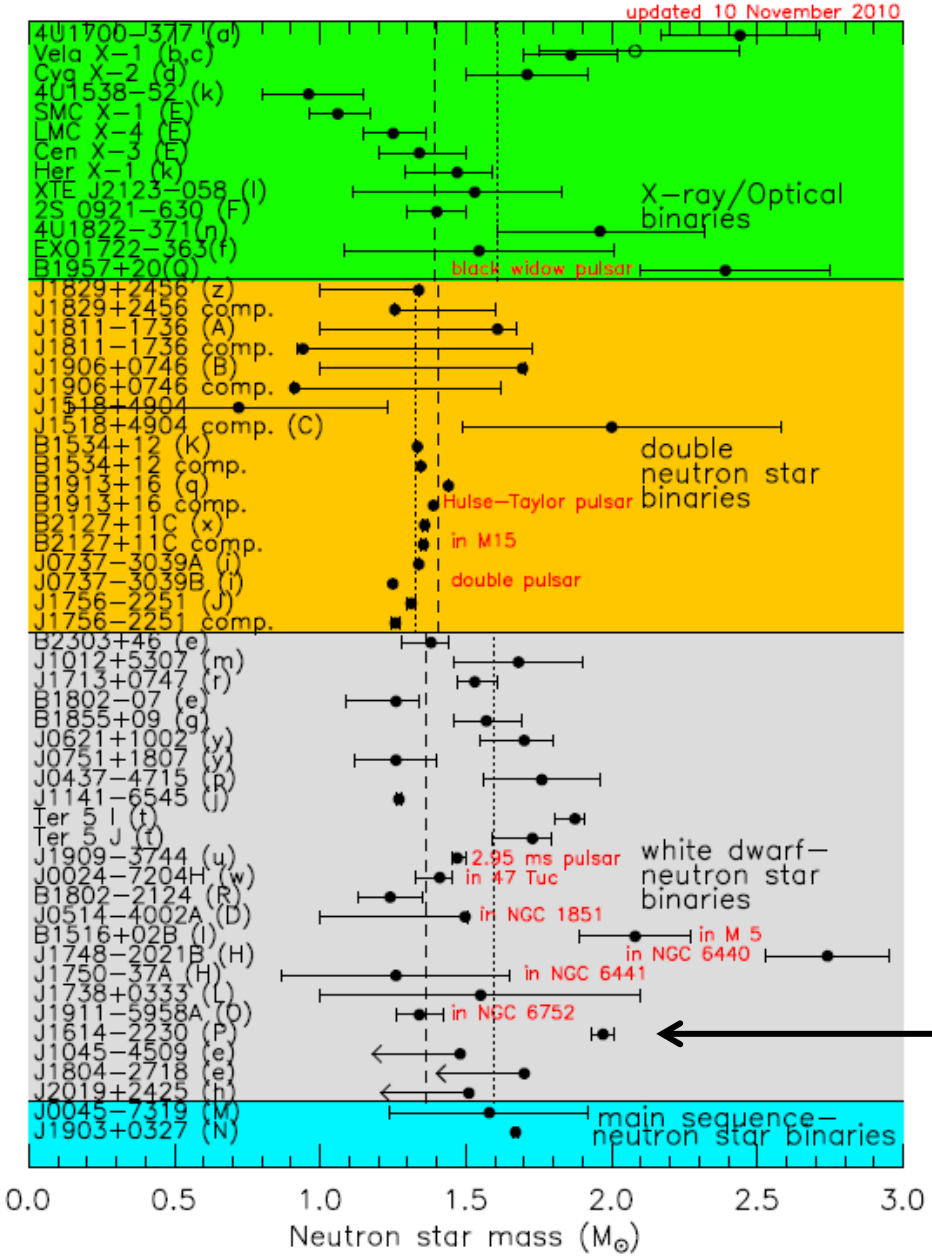
$T \approx 0$, $\rho \rightarrow 5\text{-}10\ \rho_0$

Stellar evolution



note: $M_\odot \equiv M_{sun}$

Observed neutron star masses



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

PSR J1614-2230

Green Bank Radio Observatory (2010)

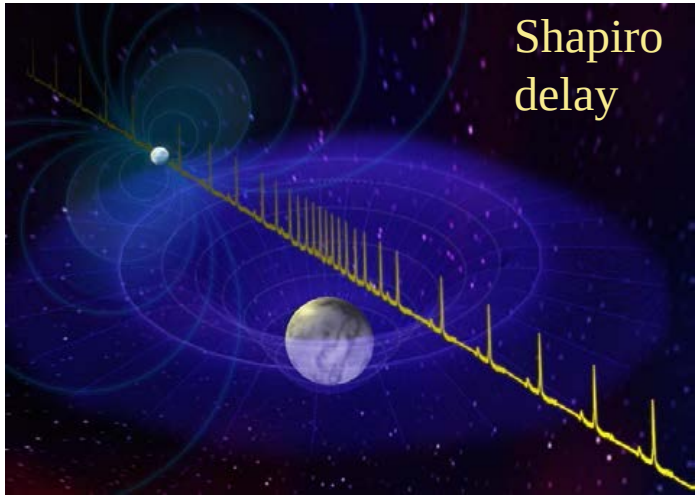
Mass: $(1.976 \pm 0.04)\ M_\odot$

Distance: ~1 kPc (~3200 Ly)

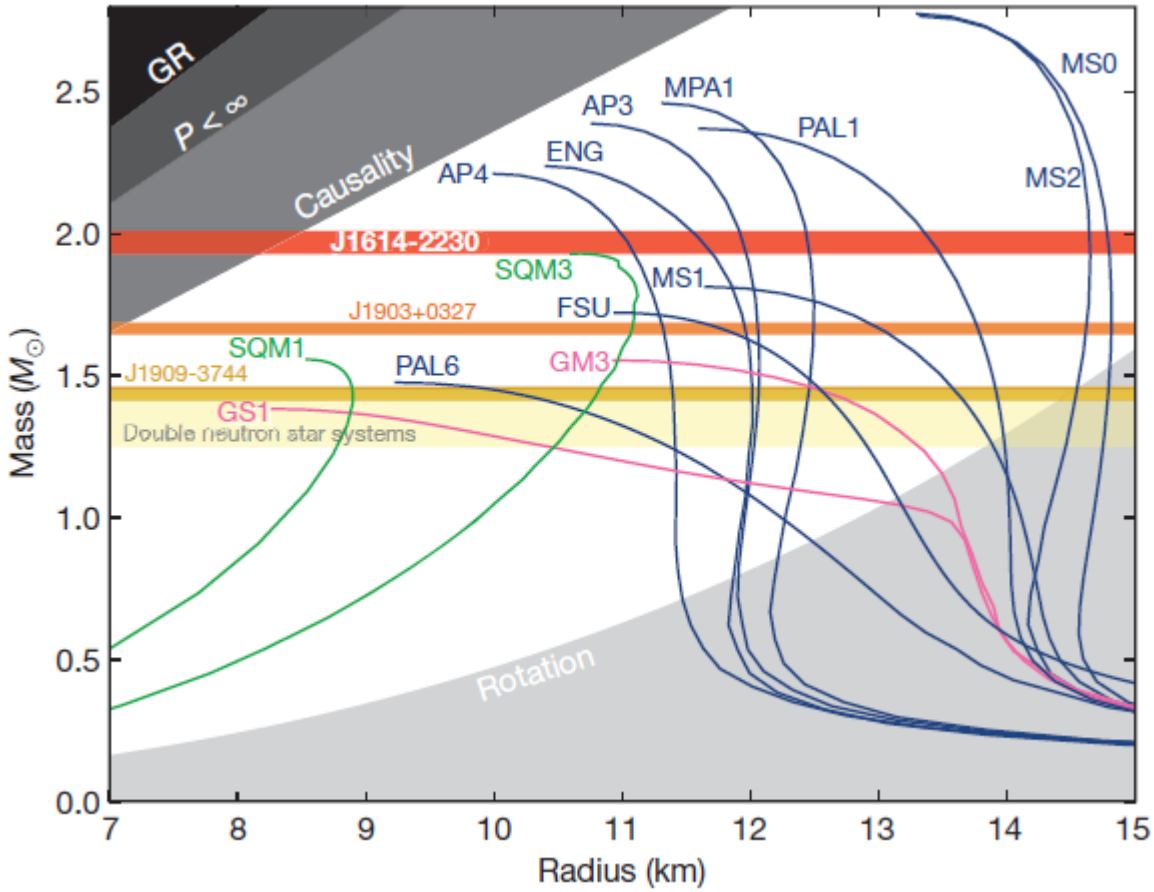
Pulsar spin period: 3.1508076534271(6) ms

Companion mass: $0.5\ M_\odot$

Orbital period: 8.6866194196(2) d

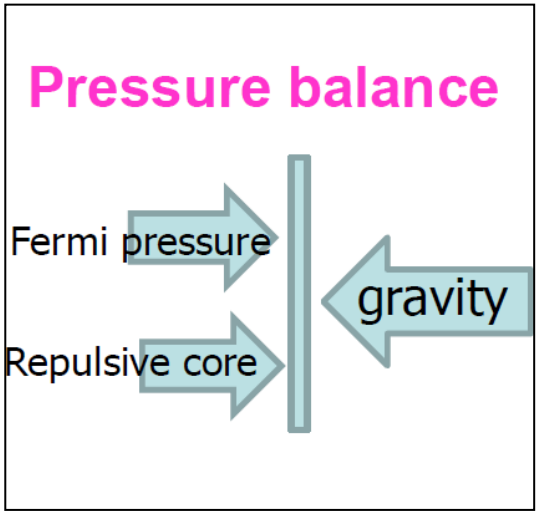


Neutron star mass-radius relation



constraints to EoSs

- nucleons
- nucleons + exotic matter
- strange matter



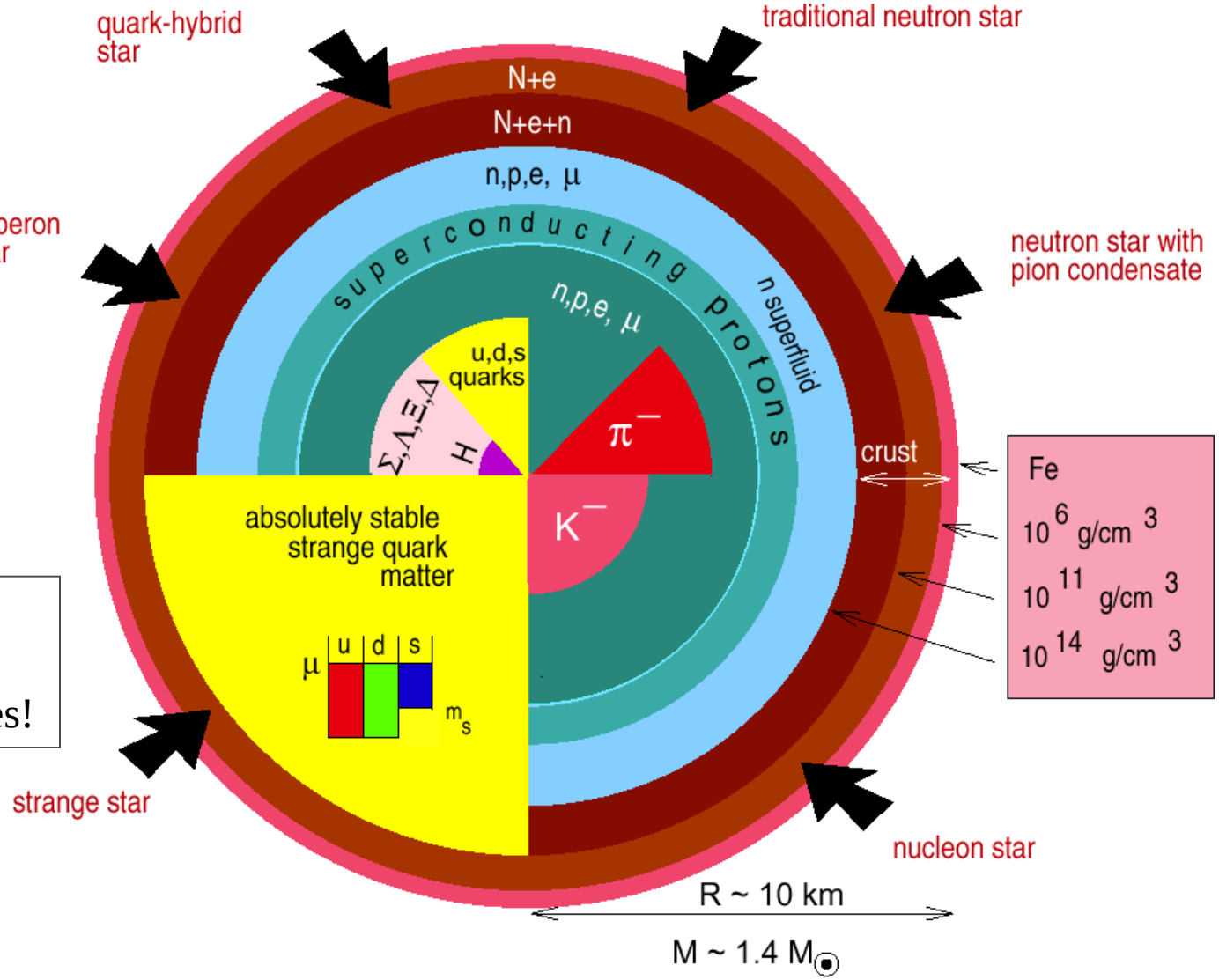
doi:10.1038/nature09466

Composition of a neutron star

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

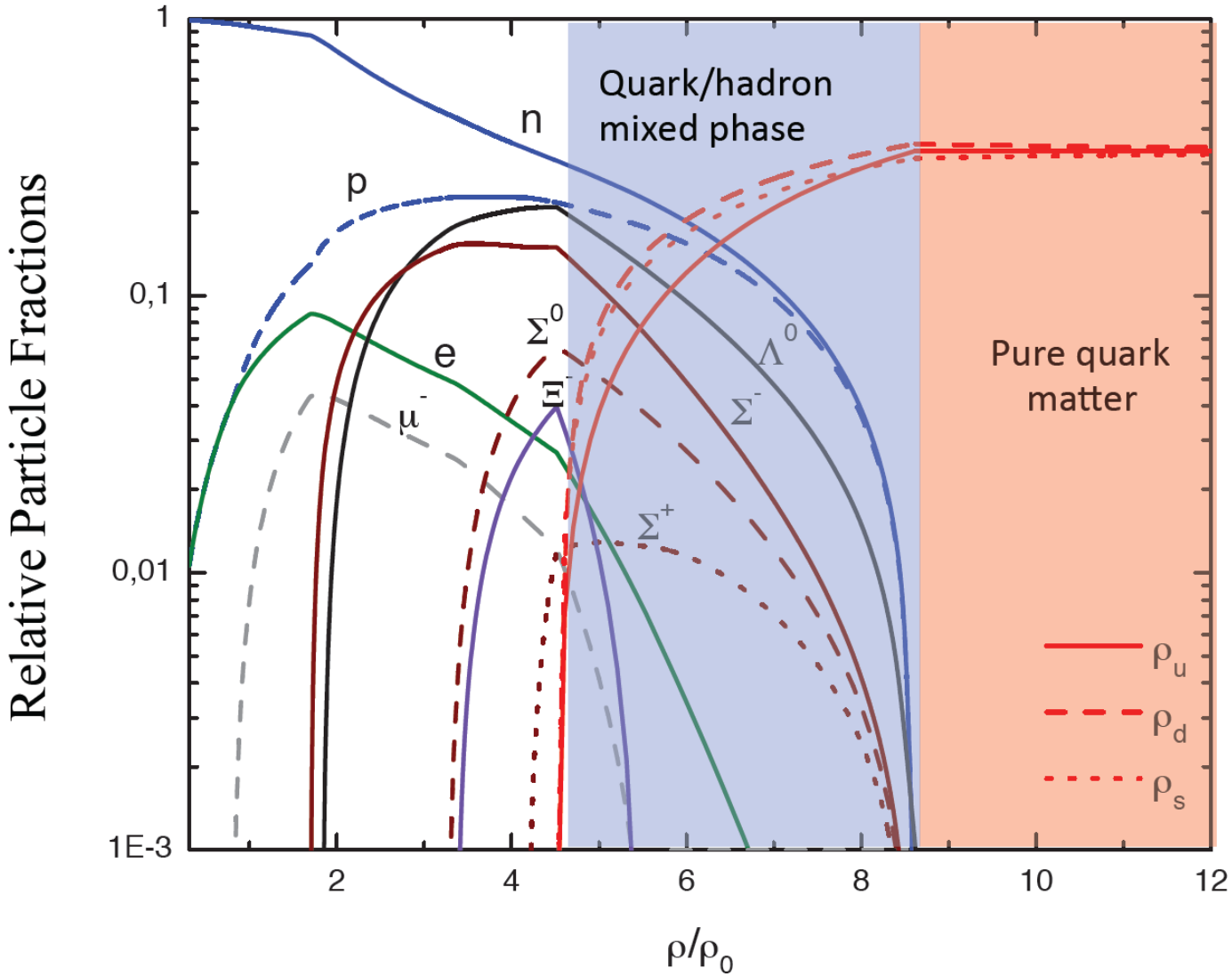
Each arrow indicates a different model for the neutron star.

Each model is based on assumptions on nuclear matter properties!



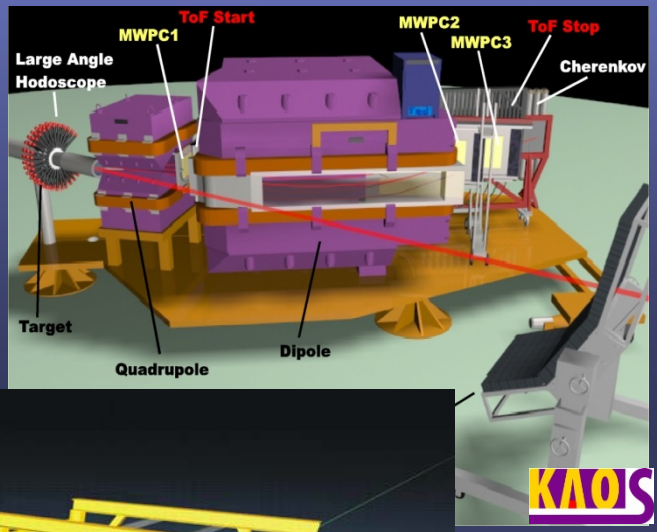
Quark matter in massive neutron stars?

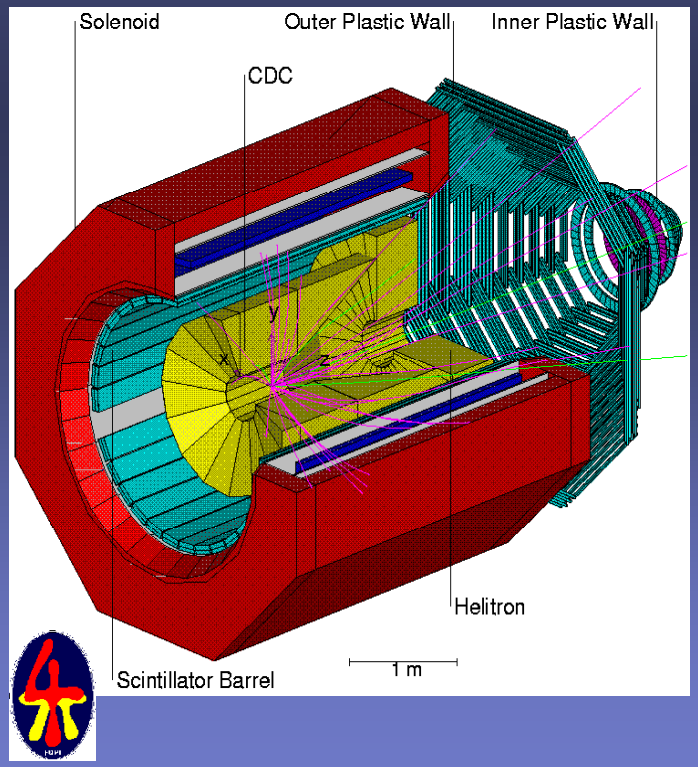
Equation-of-state: Non-local SU(3) NJL with vector coupling
M. Orsaria, H. Rodrigues, F. Weber, G.A. Contrera, arXiv:1308.1657

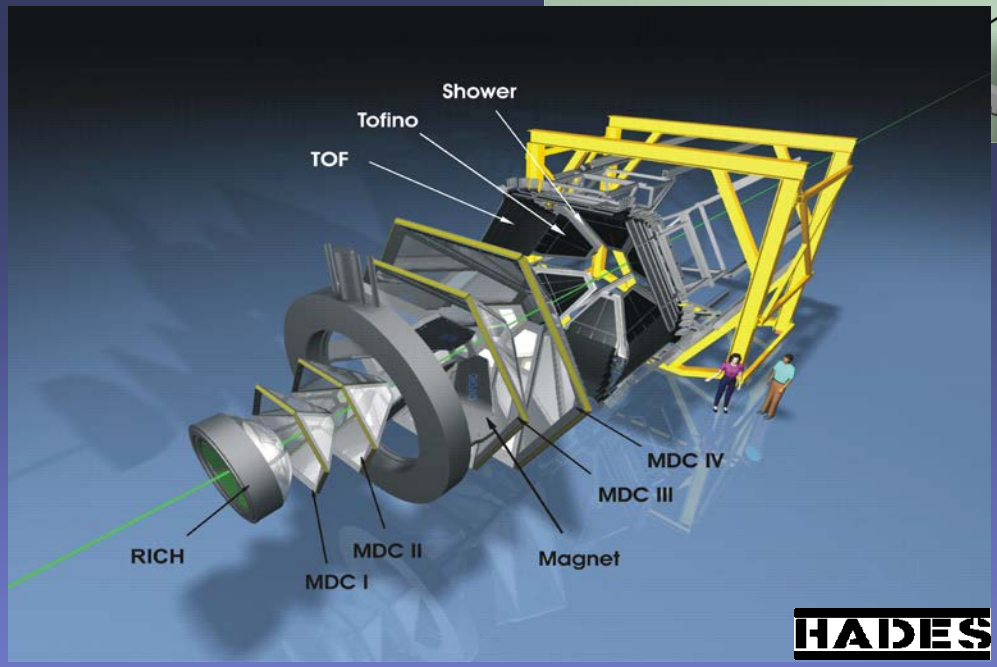


Part III
Exploring dense nuclear matter in the laboratory

Nucleus-nucleus collisions at SIS18





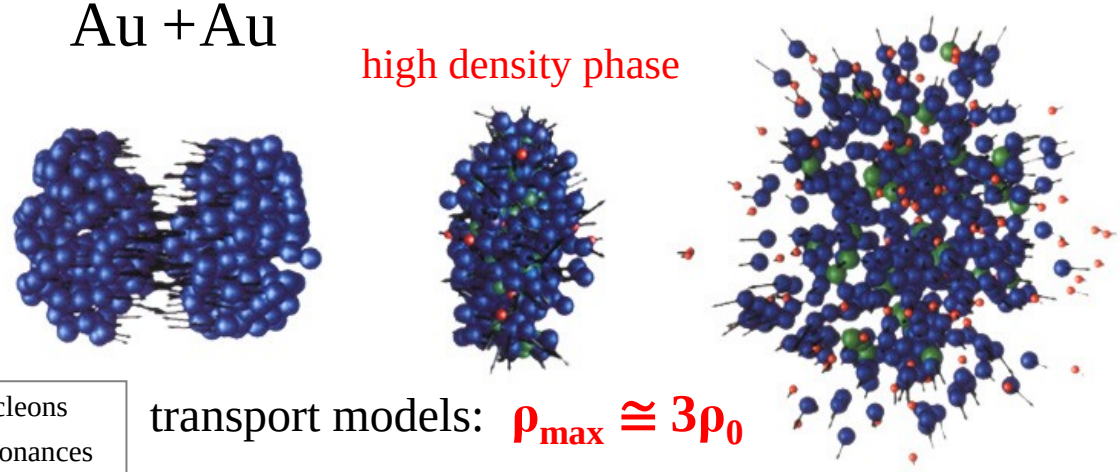


Relativistic nucleus-nucleus collisions at SIS18

QMD , S. Bass , Uni. Frankfurt

Au +Au

high density phase

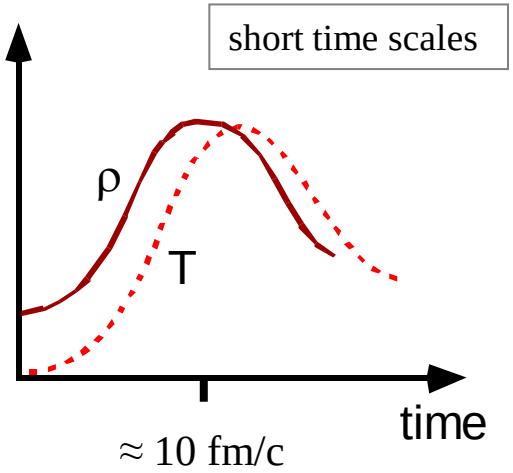


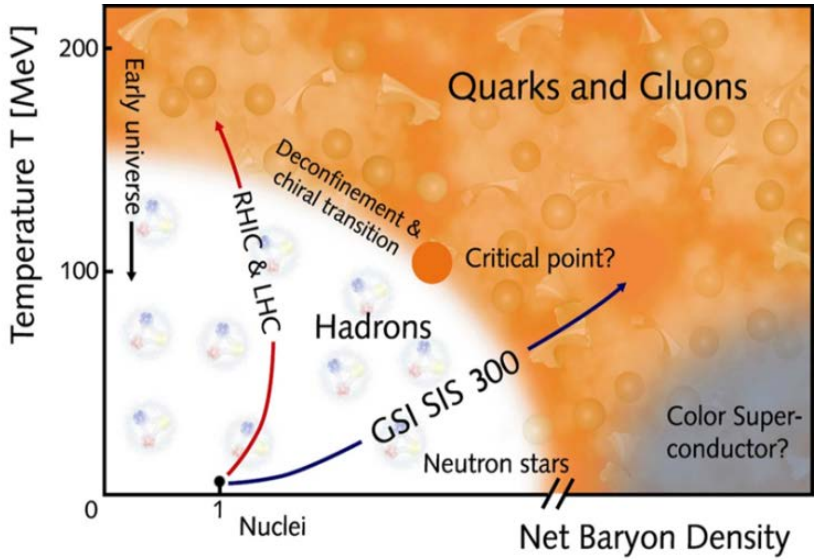
- nucleons
- resonances
- mesons

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

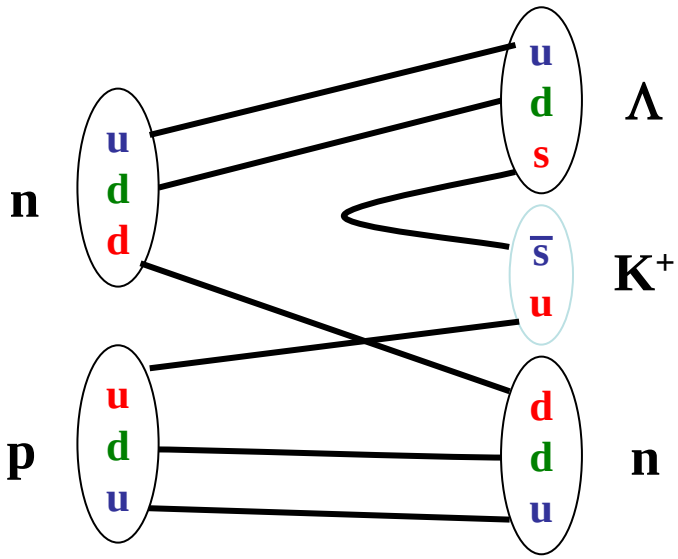
<u>note:</u>
system not necessarily equilibrated

The creation of strange mesons in elementary reactions

associate production !

K^+ mesons

m = 493.7 MeV/c²

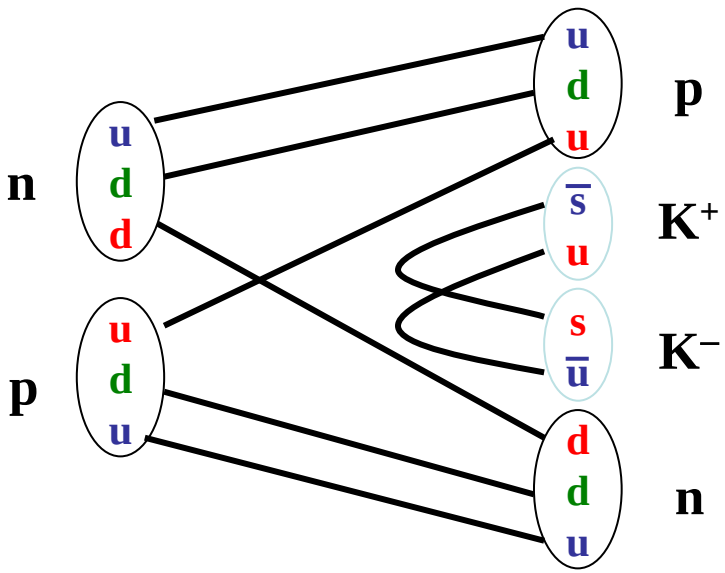


production threshold

$E_{lab} = 1.58\ GeV$

K^- mesons

m = 493.7 MeV/c²



production threshold

$E_{lab} = 2.5\ GeV$

Additional channels in A+A collisions

e.g.

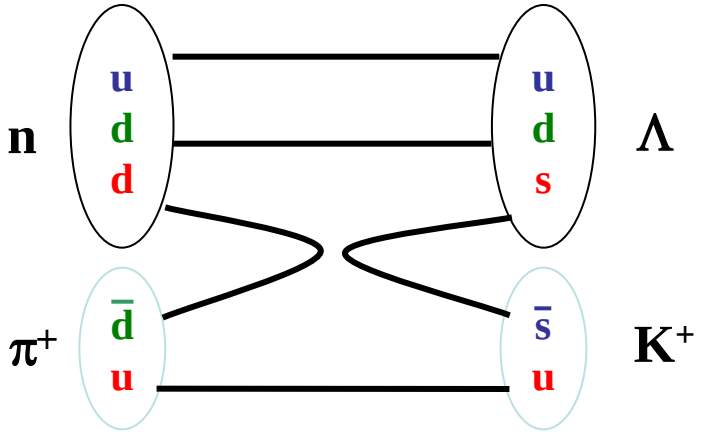
$$NN \rightarrow N\Delta$$

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

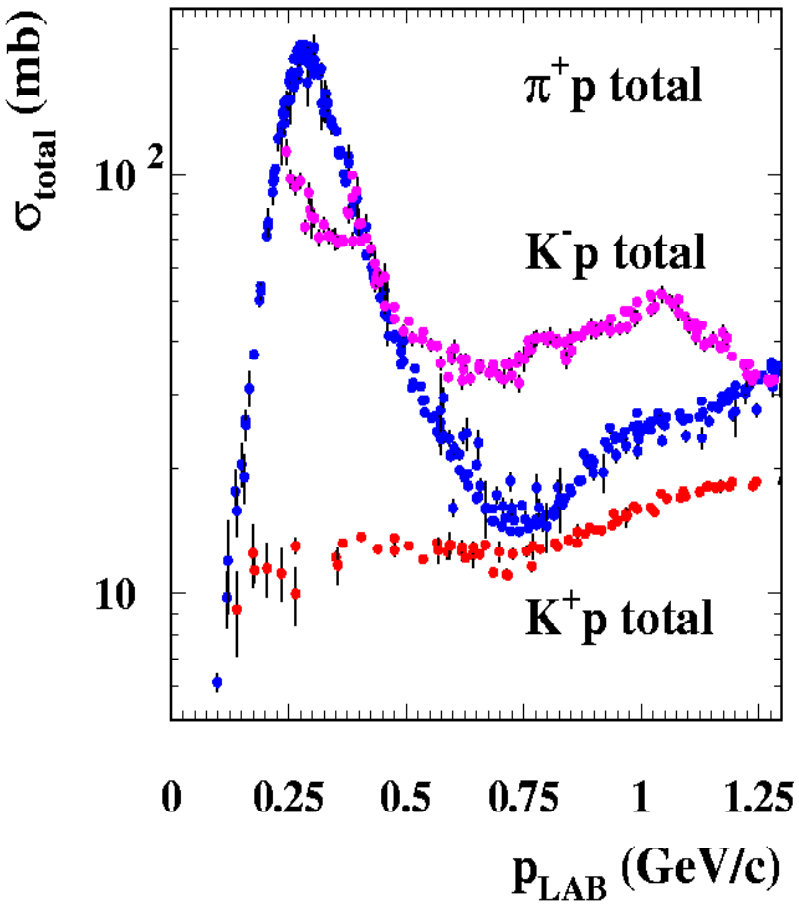
$$\pi N \rightarrow K^+Y$$

(Y=Λ,Σ)

multi step processes !



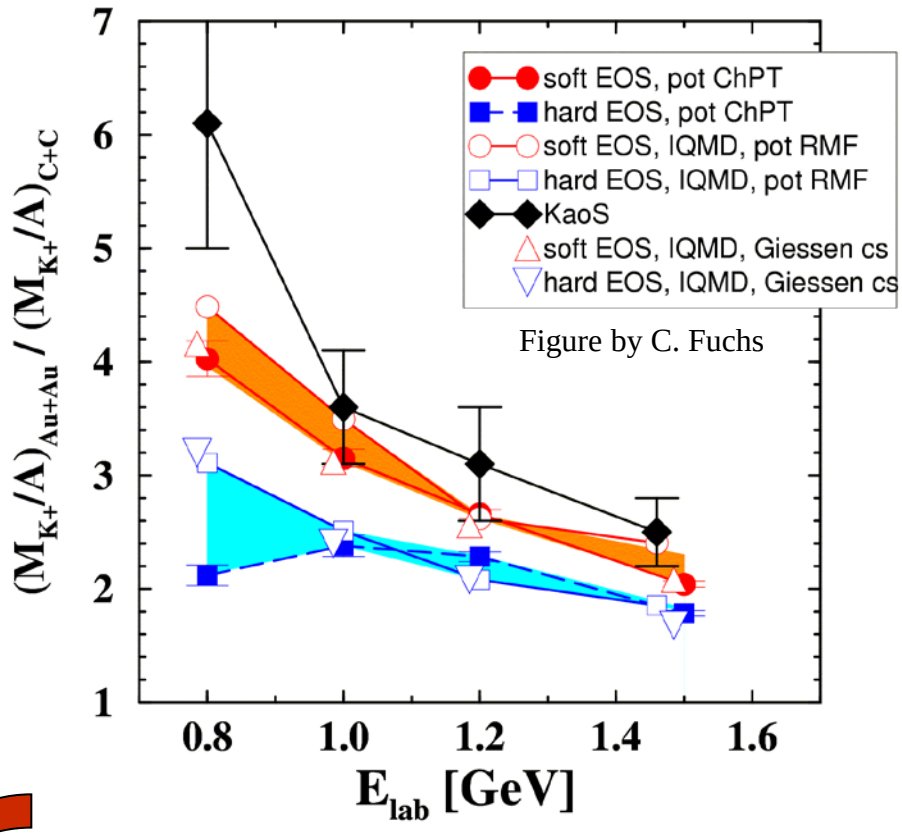
... and final state interaction !

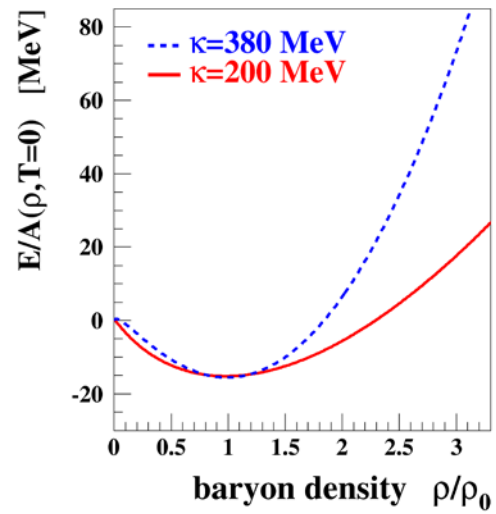


The compression modulus of nuclear matter (ρ > ρ0)

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

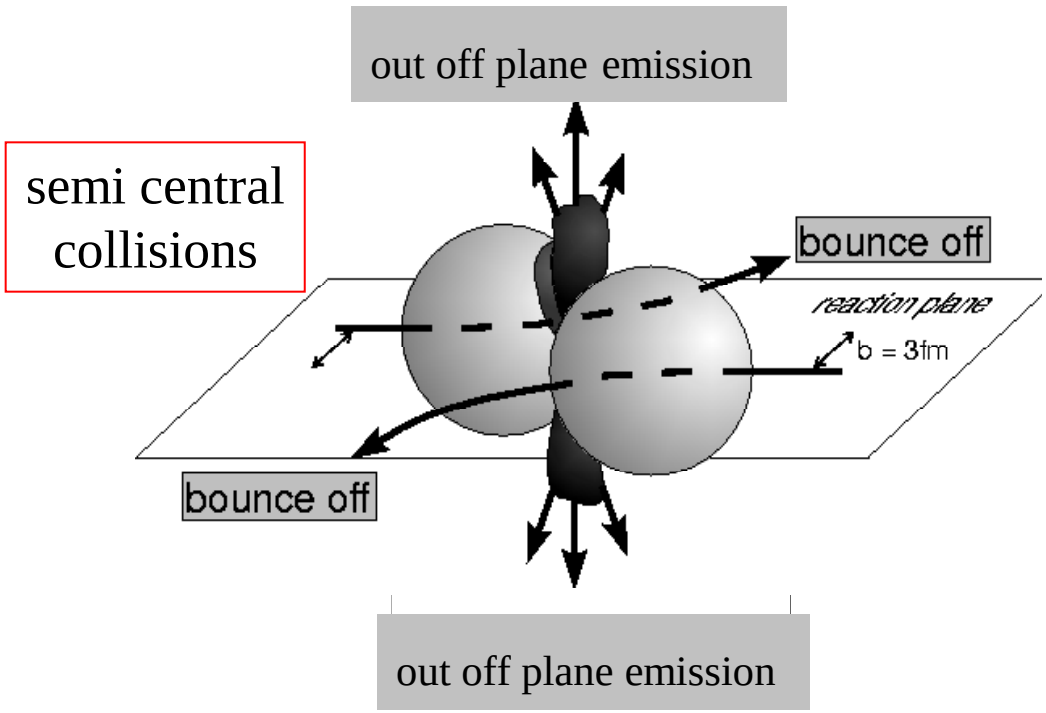
Theory: QMD C. Fuchs et al., Phys. Rev. Lett. 86 (2001) 1974
IQMD Ch. Hartnack, J. Aichelin, J. Phys. G 28 (2002) 1649

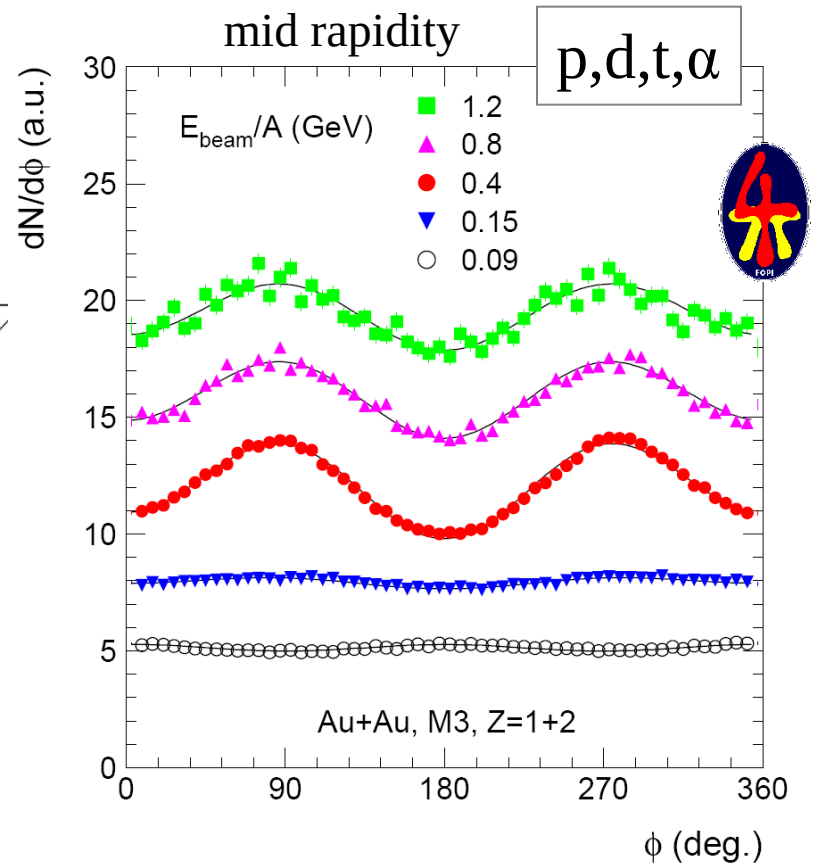




soft nuclear equation-of-state: $\kappa \approx 200$ MeV

Azimuthal particle emission





Fourier expansion of the dN/dϕ distribution:

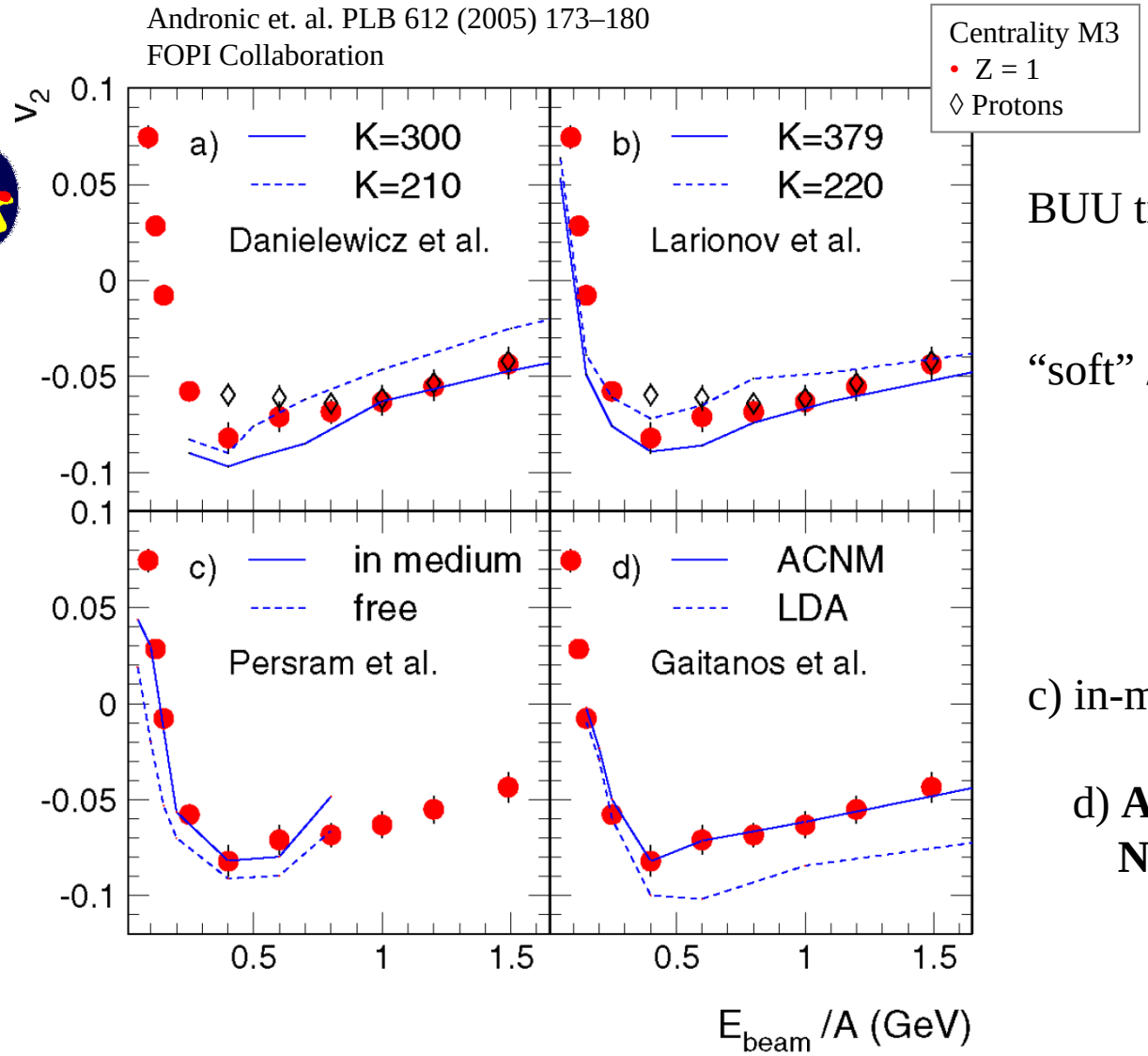
$$\frac{dN}{d\phi} \sim [1 + 2v_1 \cdot \cos(\phi) + 2v_2 \cdot \cos(2\phi)]$$

the coefficients quantify :

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

Elliptic flow and the Nuclear EoS

Andronic et. al. PLB 612 (2005) 173–180
FOPI Collaboration



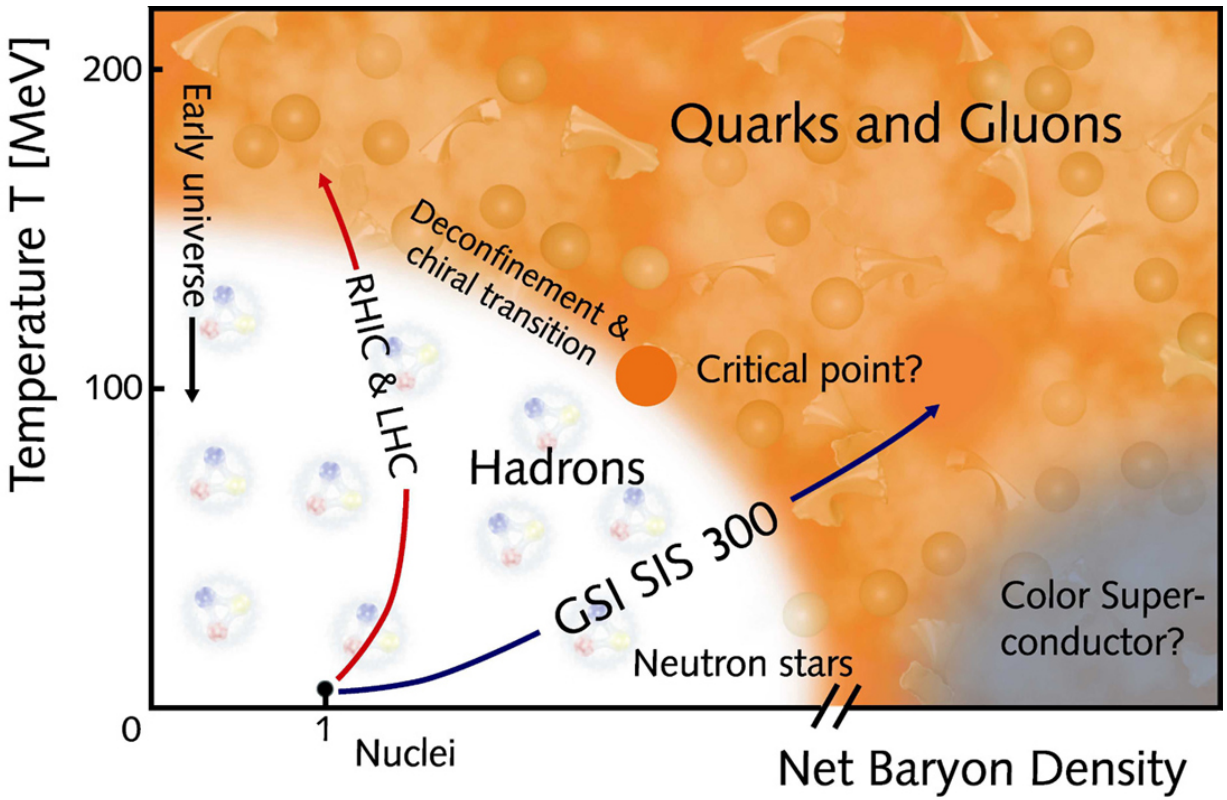
BUU transport models:

“soft” / “stiff” EoS

c) in-medium NN cross section

d) **A**symmetric **C**olliding **N**uclear **M**atter approximation

The phase diagram of strongly interacting matter

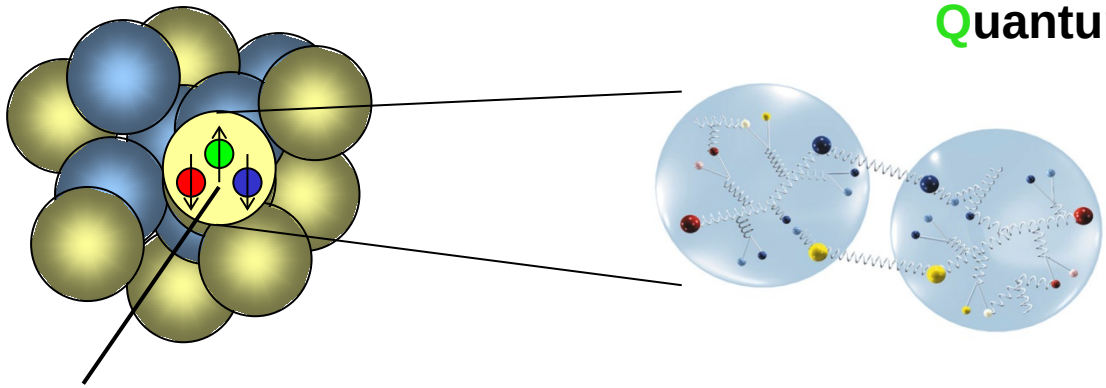


onset of chiral transition visible at SIS18 ?
→ generation of mass ?

- antikaon production
- dileptons

The strong interaction and the origin of hadron masses

Nucleus (R ≈ 1-10 fm; M ≈ A x GeV)

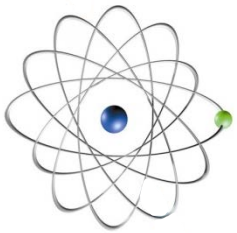


Quarks (R < 10^{-4} fm; M ≈ 10 MeV)

Theory the strong interaction:

Quantum Chromo Dynamics (QCD)

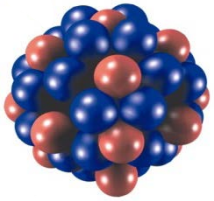
atom
10^{-10} m



$M \approx \Sigma m_i$

binding energy effect ≈ 10^{-8}

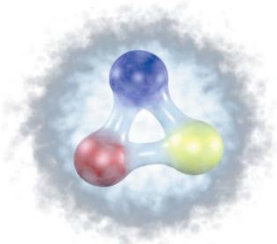
nucleus
10^{-14} m



$M \approx \Sigma m_i$

binding energy effect ≈ 10^{-2}

nucleon
10^{-15} m



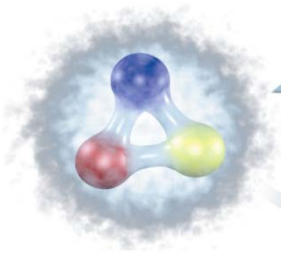
$M \gg \Sigma m_i$

1 GeV >> 20 MeV

<u>nucleon</u>:
mass not determined by sum of current quark masses !!!

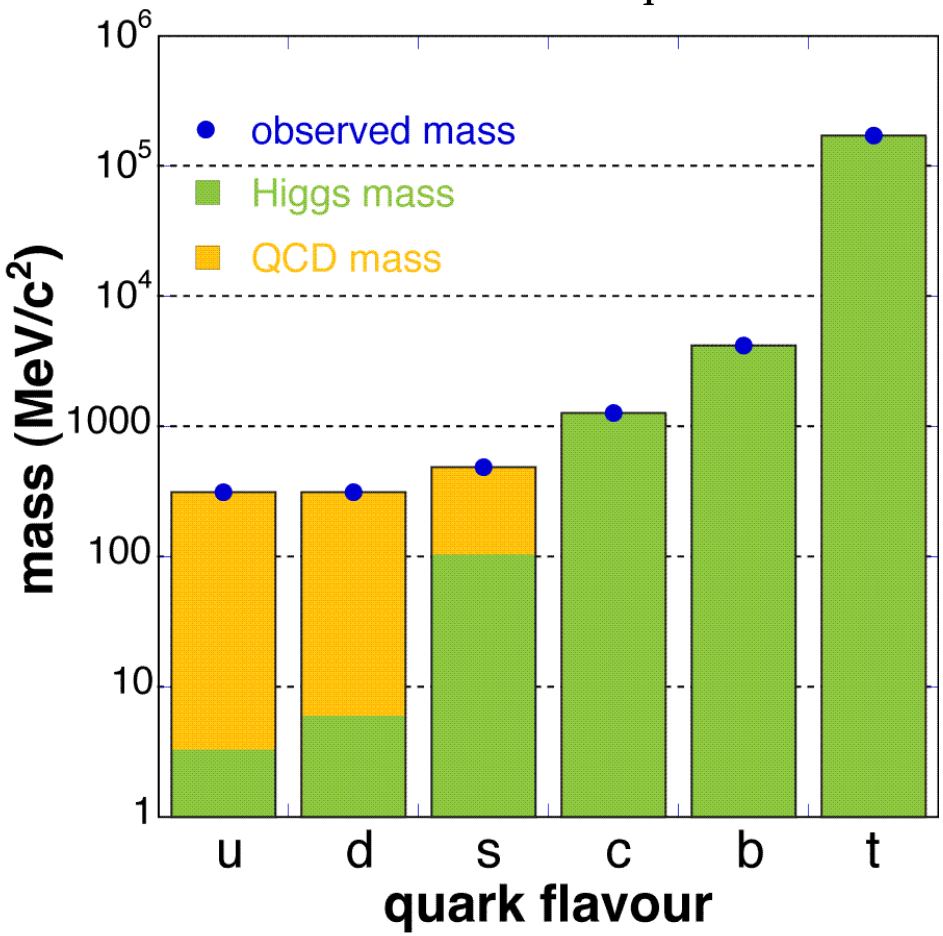
Simple minded view:
mass given by energy stored in motion of quarks and by energy of gluon fields (m = E/c^2)

The strong interaction and the origin of hadron masses

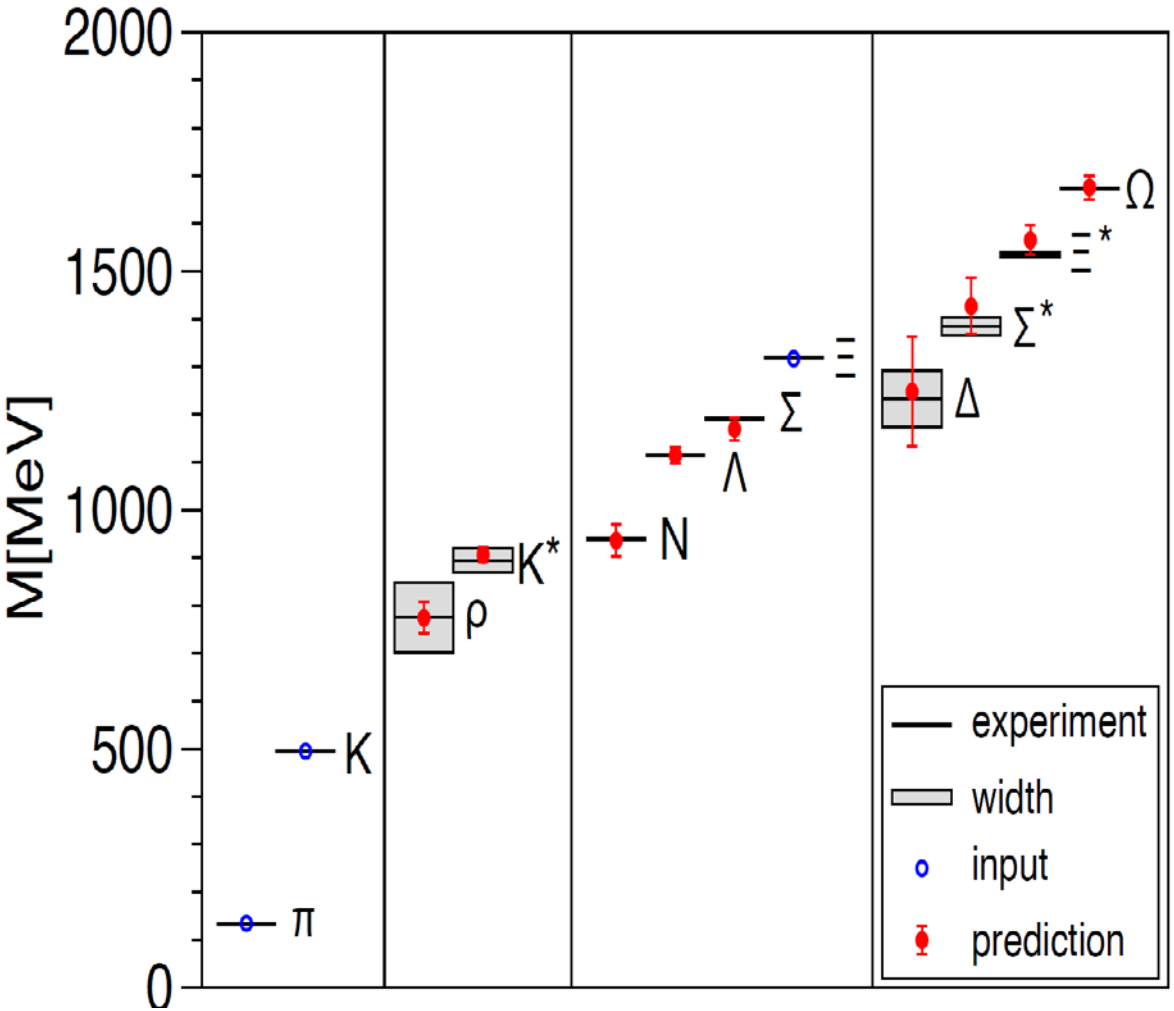


Proton

Constituent quark masses



The strong interaction and the origin of hadron masses



Δ^+ (1232): uud

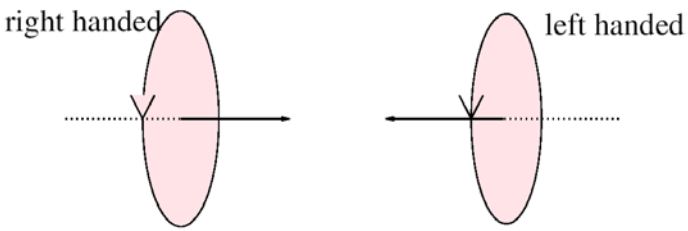
p (938): uud
$\rho^+(770)$: $u\bar{d}$

$\eta(548)$: $(u\bar{u} + d\bar{d} - 2s\bar{s})/\sqrt{6}$
$K^+(494)$: $u\bar{s}$

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

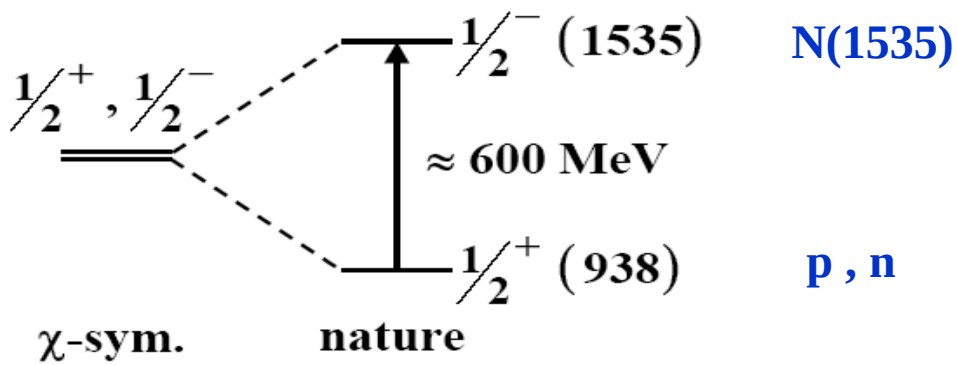
Chiral symmetry in a nutshell

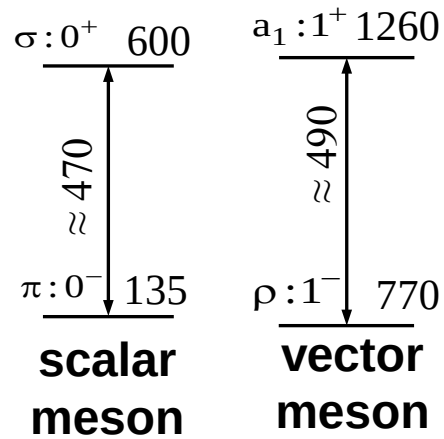
Chiral symmetry = fundamental symmetry of QCD



In case of mass less quarks :
the chirality corresponds to the (conserved) helicity,
left- and right-handed quarks decouple

Chirally symmetric world: chiral partners with same spin but opposite parity degenerate in mass.

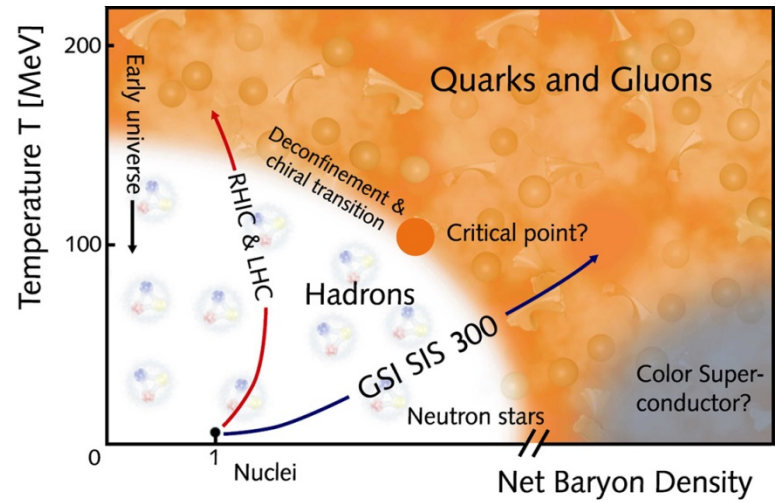




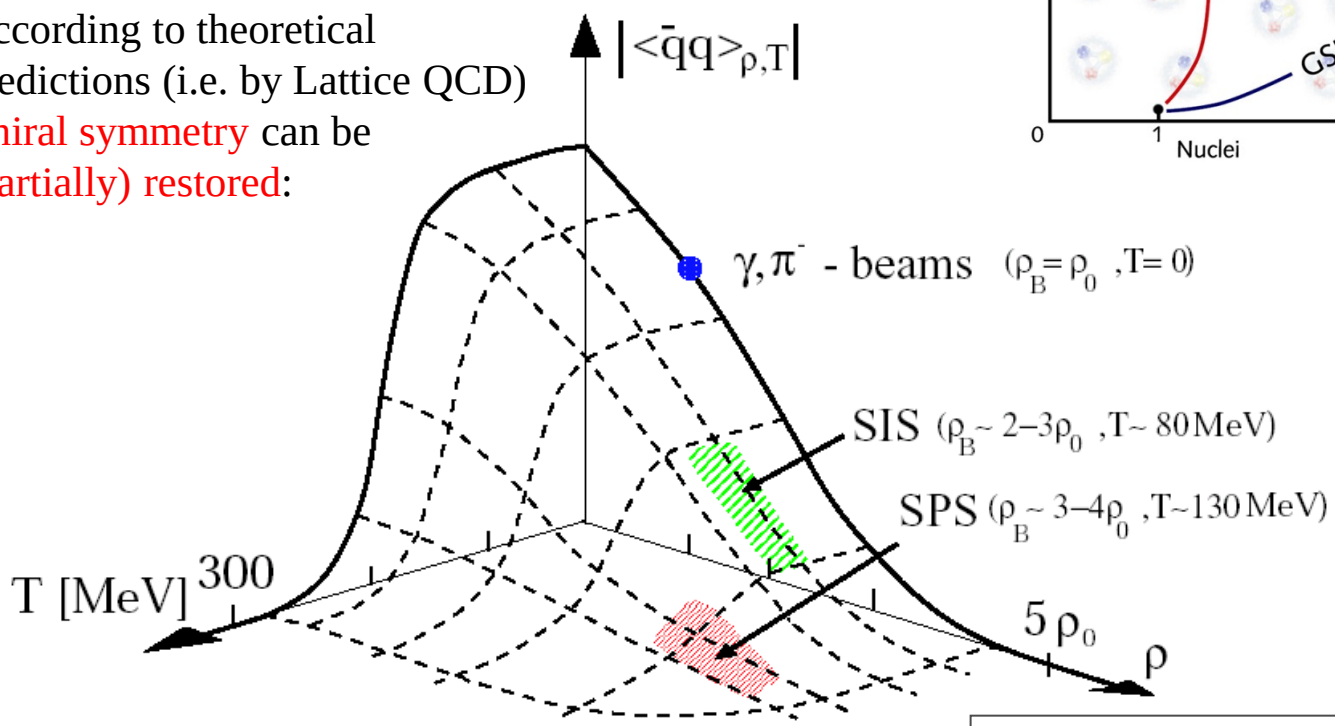
The QCD Lagrangian is chirally symmetric but in "nature" chiral symmetry is broken !
Mass split is large, comparable to hadron masses.

- explicit breaking by small but finite quark masses
- spontaneously broken due to the existence of a mass less mode ("Goldstone-boson"): the pion

Chiral symmetry restoration



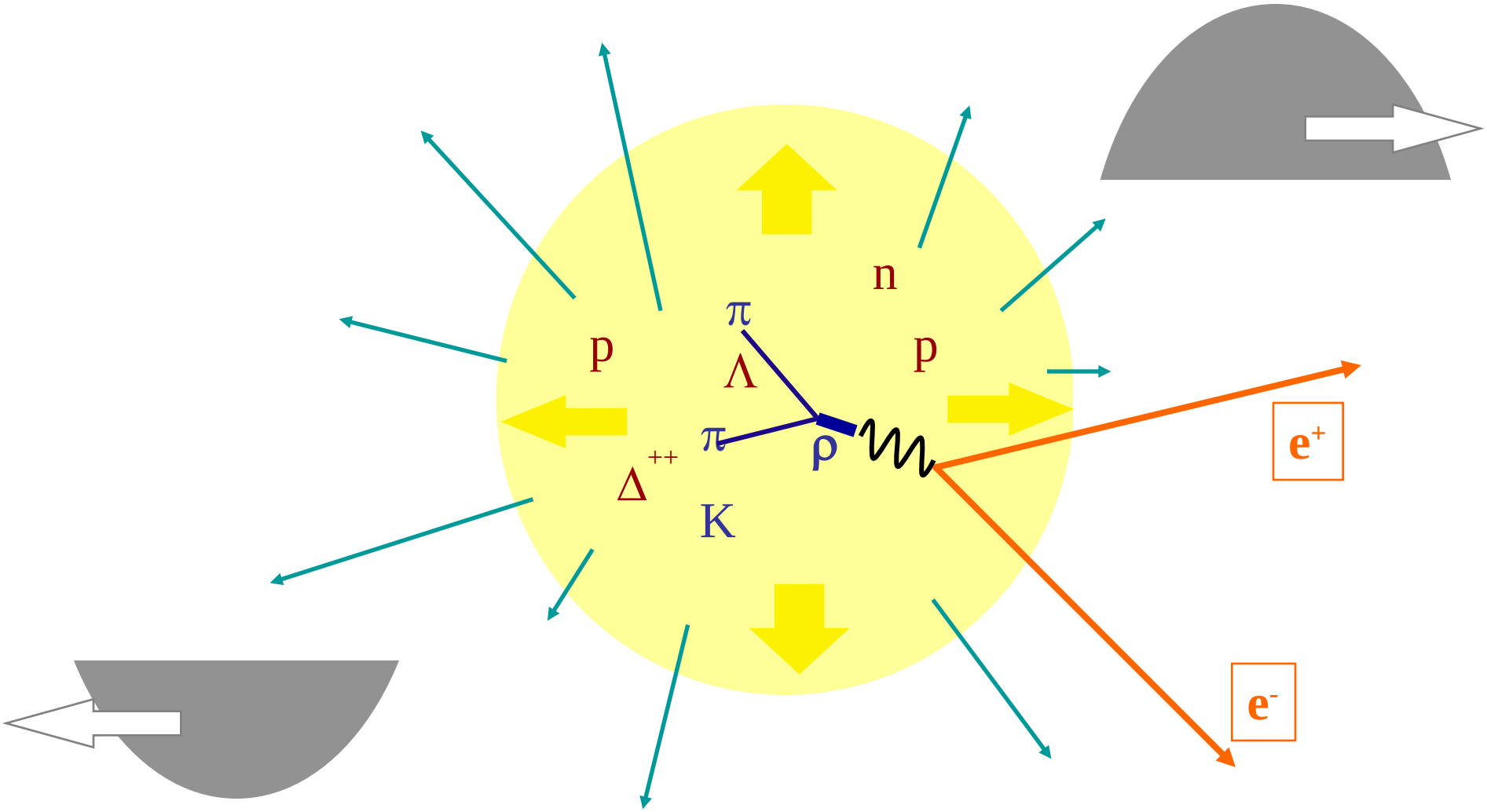
According to theoretical predictions (i.e. by Lattice QCD) Chiral symmetry can be (partially) restored:



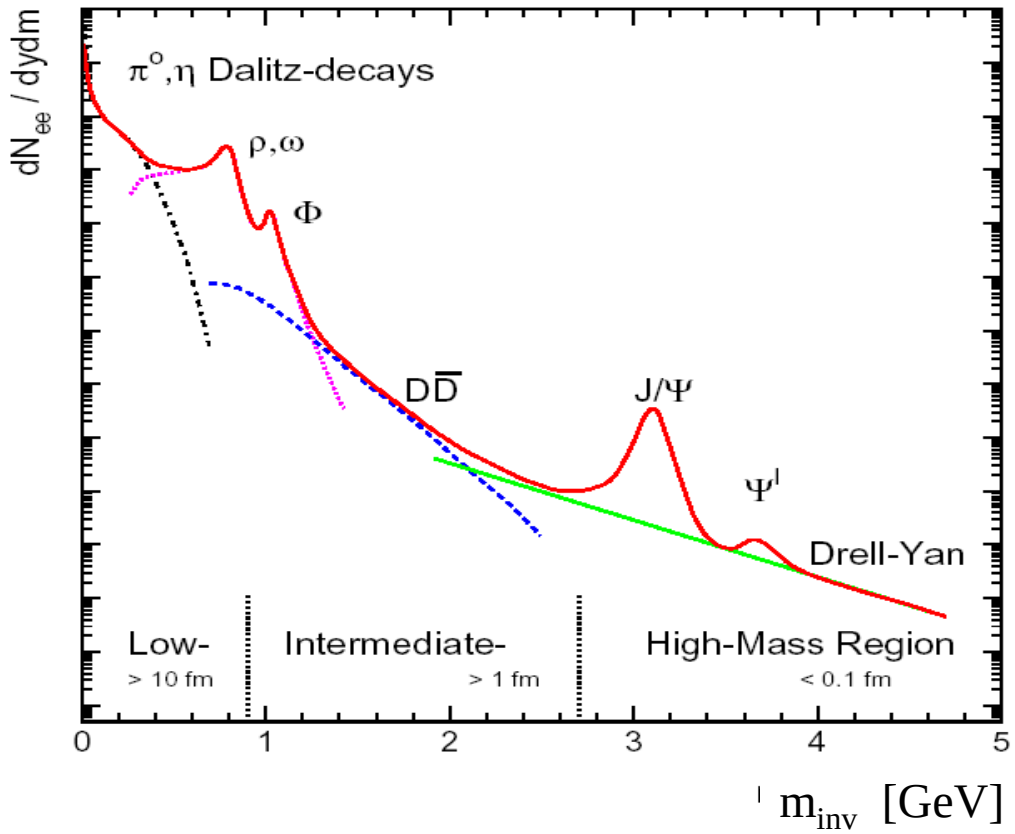
at high temperature

at large baryon density

e^+e^- pairs – penetrating probes !



Di-lepton sources



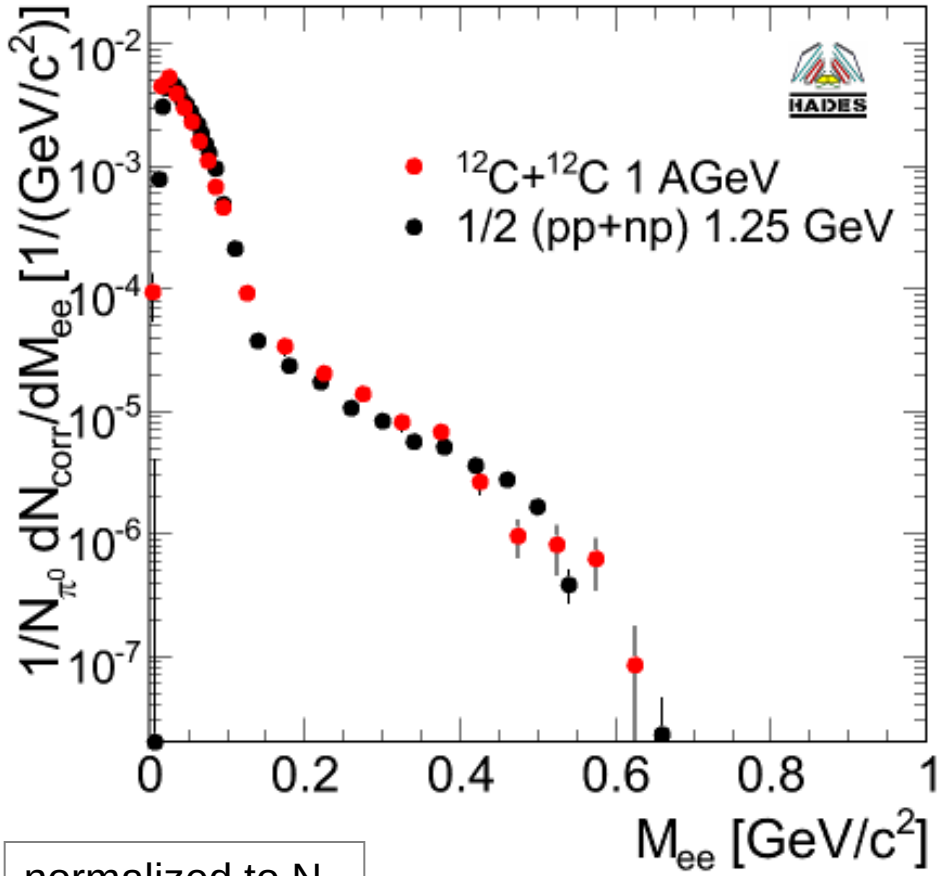
	mass [MeV/c^2]	cτ [fm]	dominating decay	e^+e^- branching ratio	E_{thr} (NN)
ρ	768	1.3	ππ	4.4×10^{-5}	1.7 GeV
ω	782	23.4	$\pi^+\pi^-\pi^0$	7.2×10^{-5}	1.8 GeV
Φ	1019	44.4	K^+K^-	3.1×10^{-4}	2.6 GeV

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

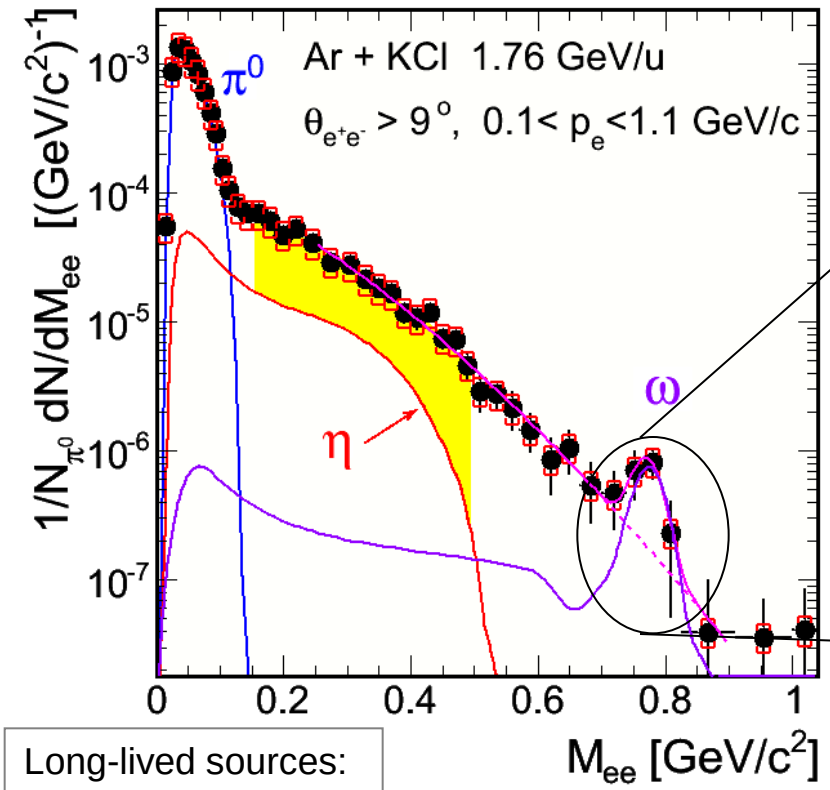


normalized to N_{π}

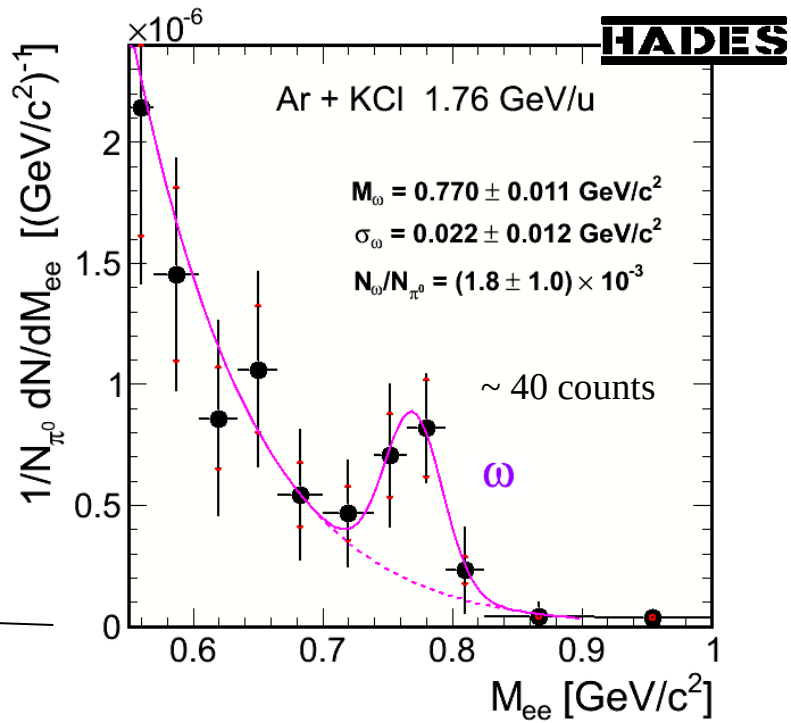
- C+C data reproduced (within 20%) by **superposition** of pp and np data
- Pair "excess" observed in C+C data can be traced back to enhanced pair production in n+p collisions (DLS puzzle solved)

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.

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

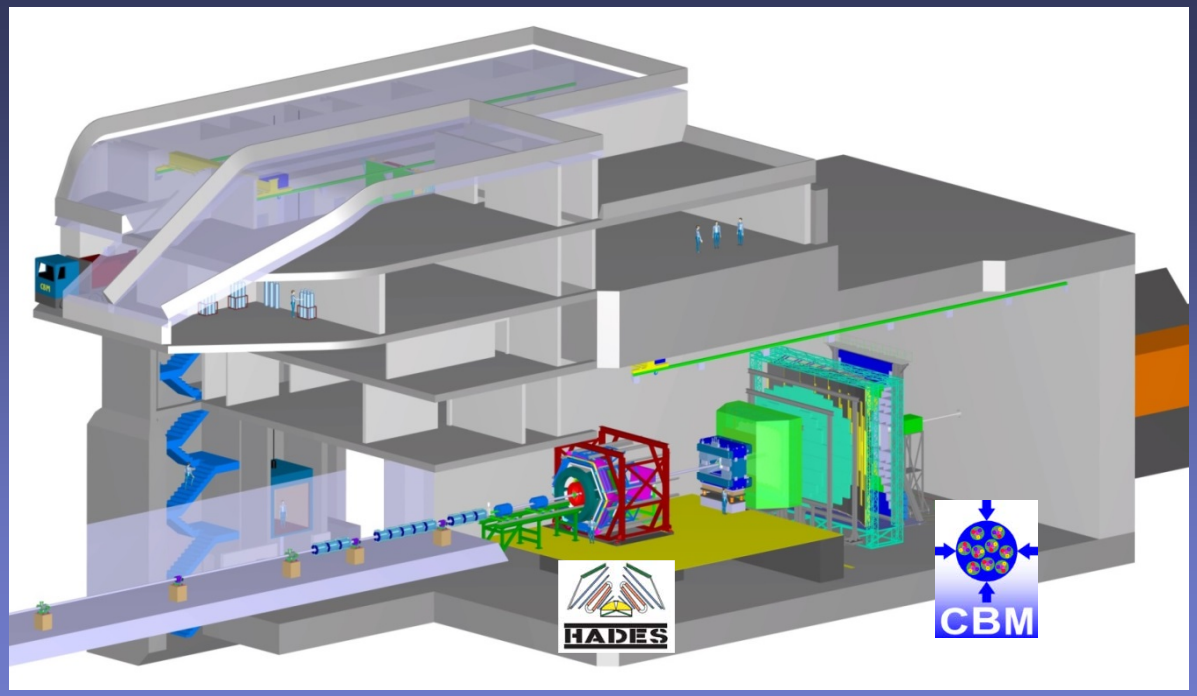
ρ/ω mass region: strength of ρ meson ?

Part V

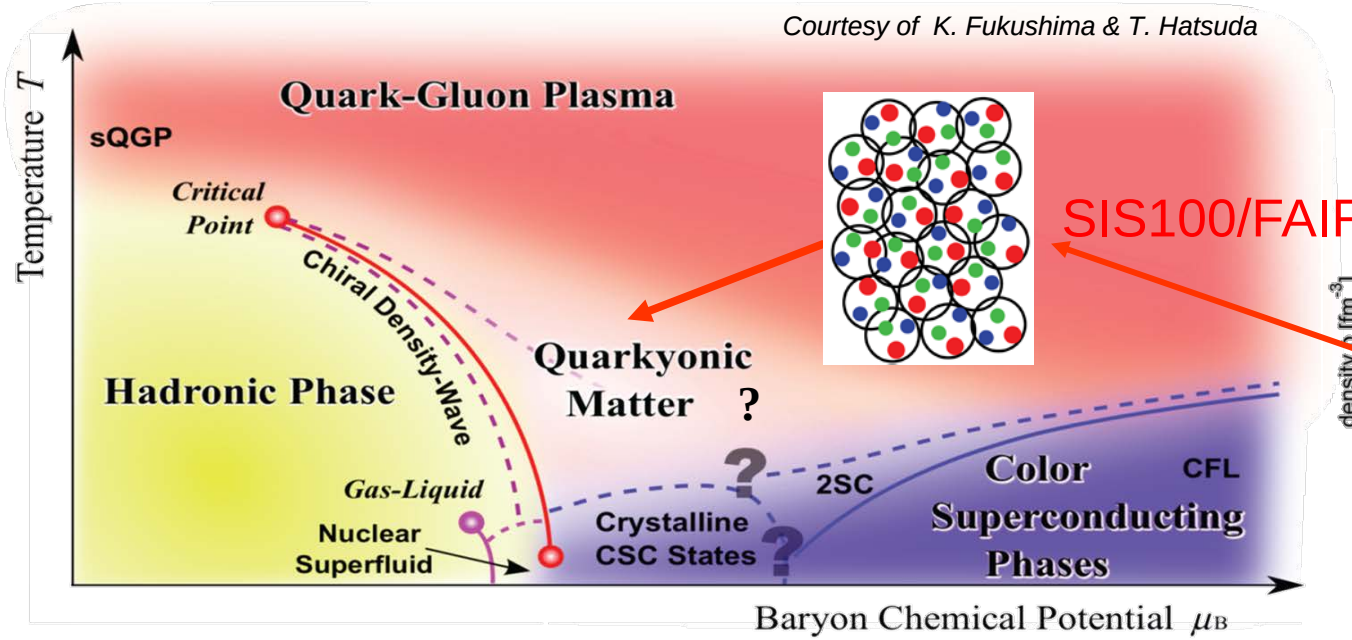
Exploring the highest baryon densities in the laboratory

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 – 45 AGeV)**

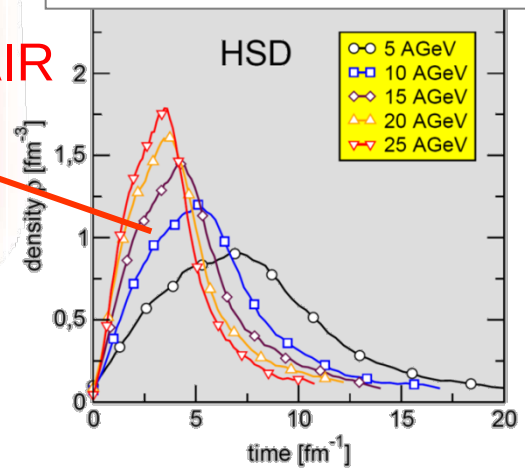


Exploring the QCD phase diagram at FAIR energies



SIS100/FAIR

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



Open questions at high net baryon densities:

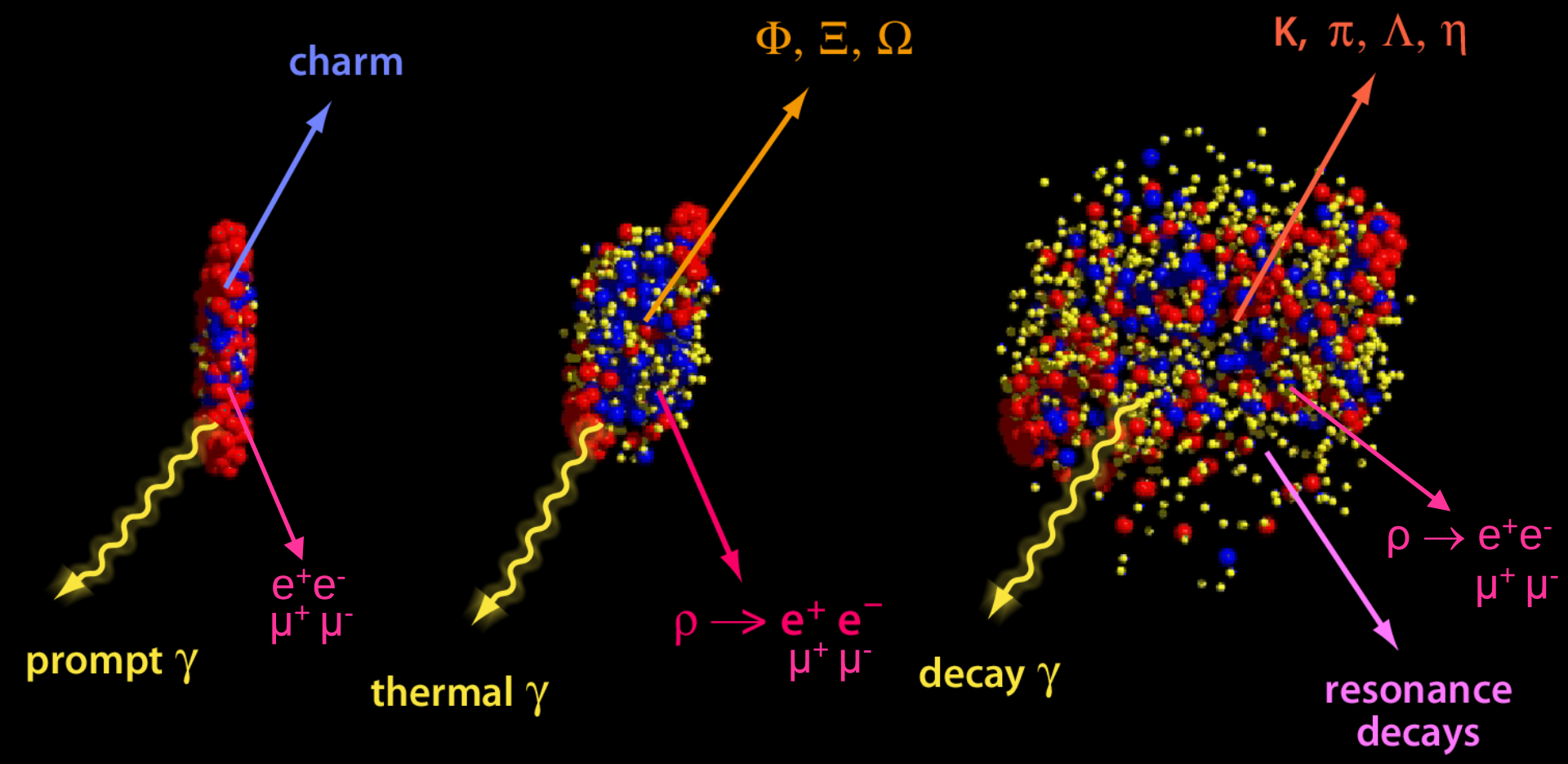
- Phase transition from hadronic matter to quarkyonic or partonic matter ?
- Chiral phase transition ? Chiral restoration ?
- In-medium modification of hadrons ?
- Nuclear Equation-of-State at neutron star core densities ?

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

Field driven by experimental data !

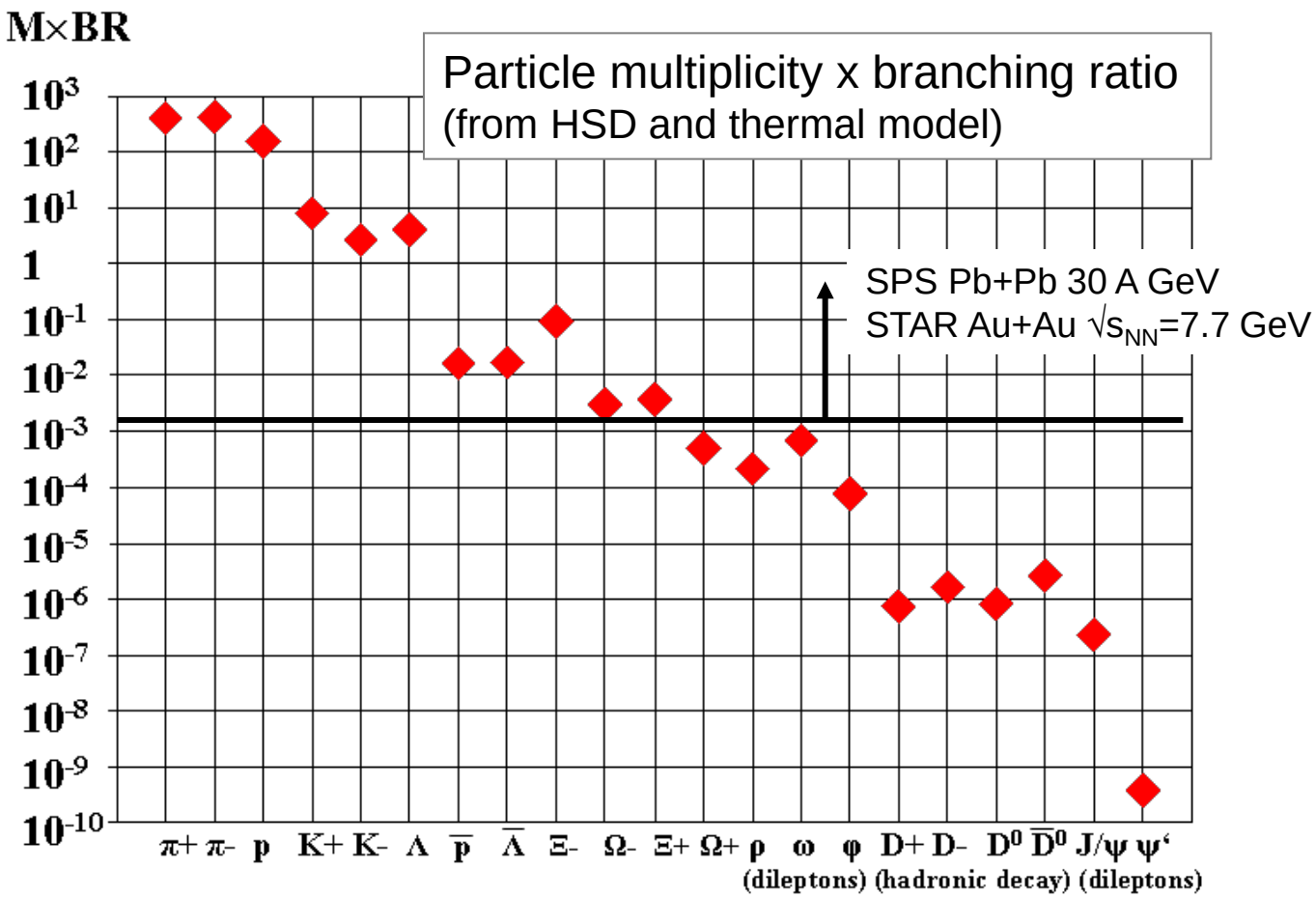
Messengers from the dense fireball

UrQMD transport calculation U+U 23 AGeV



Experimental challenges

Au+Au
25 A GeV
min. bias

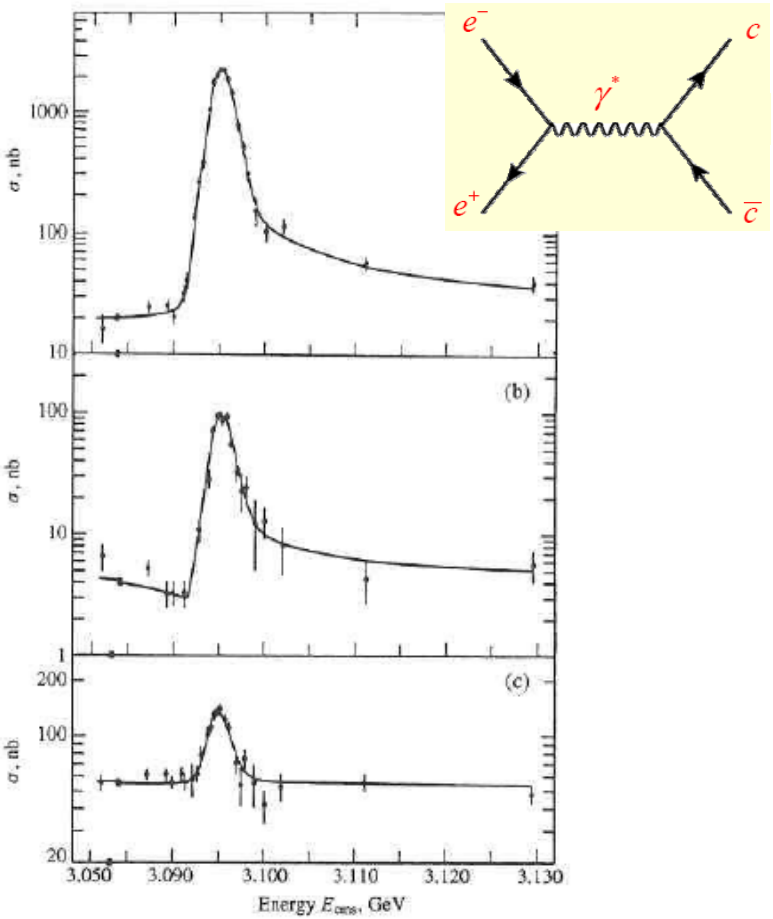


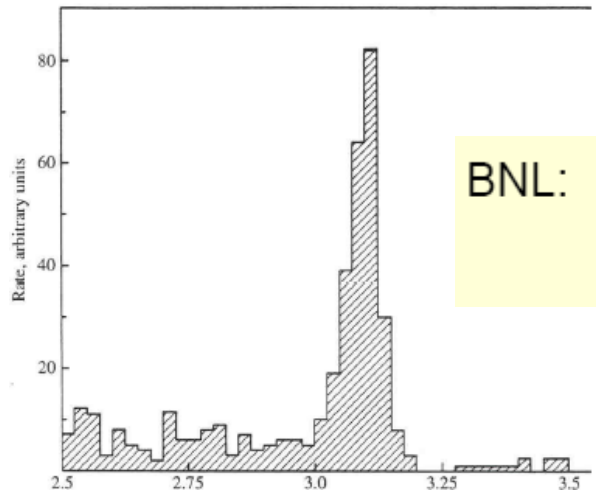
CBM experimental program

Systematic measurement of excitation functions of (**rare**) probes with full event characterization for a variety of beam energies and collision systems

π^{+-}, η, ρ, ω, φ, K^{+-0}, p, $\bar{p}$, Λ, $\bar{\Lambda}$, Σ*, Ξ^{+-}, Ω^{+-}, D^{+-0}, J/ψ, ψ'.

1974: J/ψ discovery at SLAC and BNL





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

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

$\rightarrow e^+e^-$

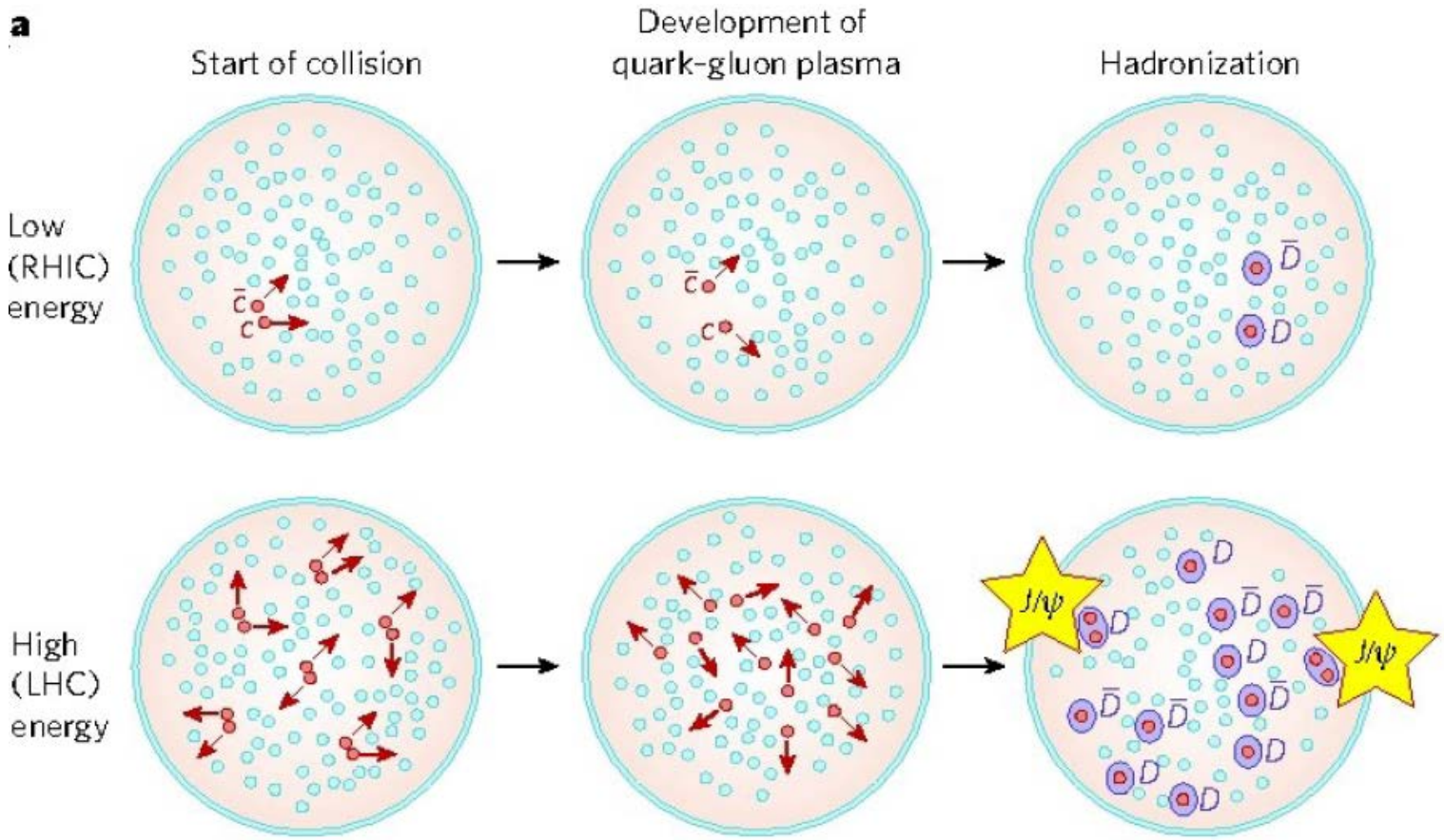
$\rightarrow \mu^+\mu^-$

- 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 ?

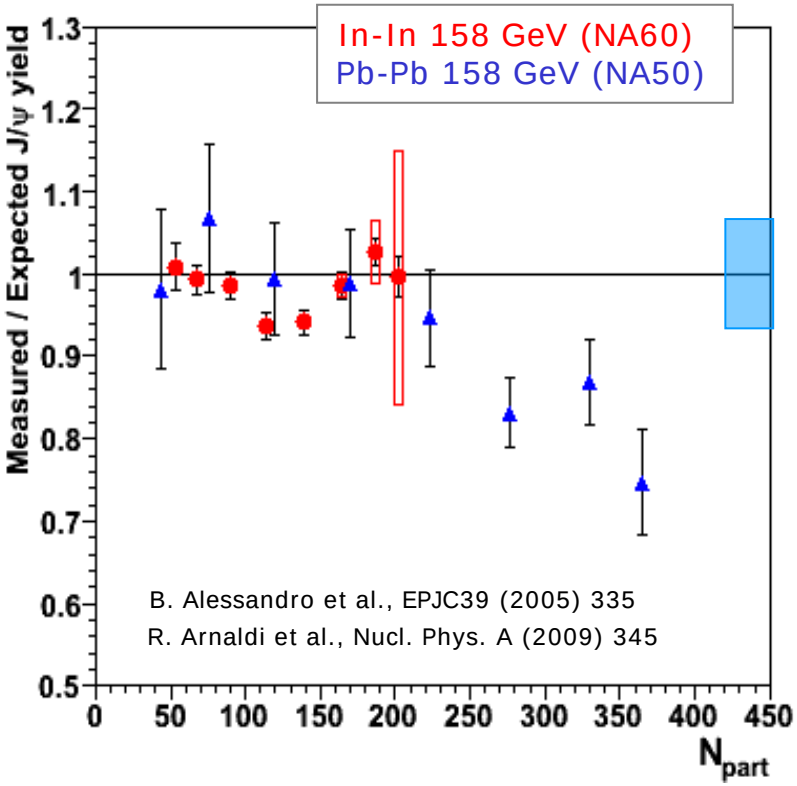
J/ψ suppression



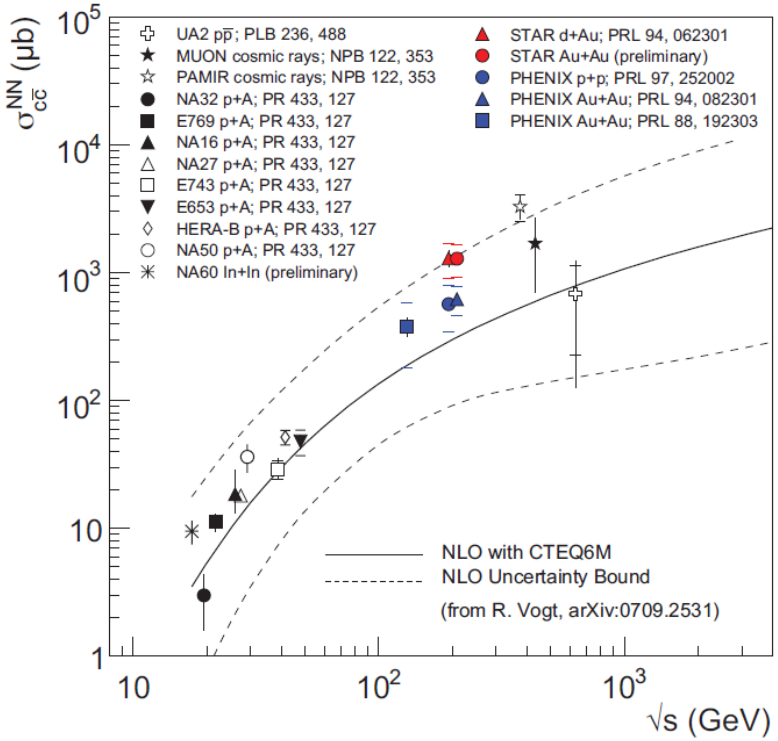
J/ψ regeneration

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 !

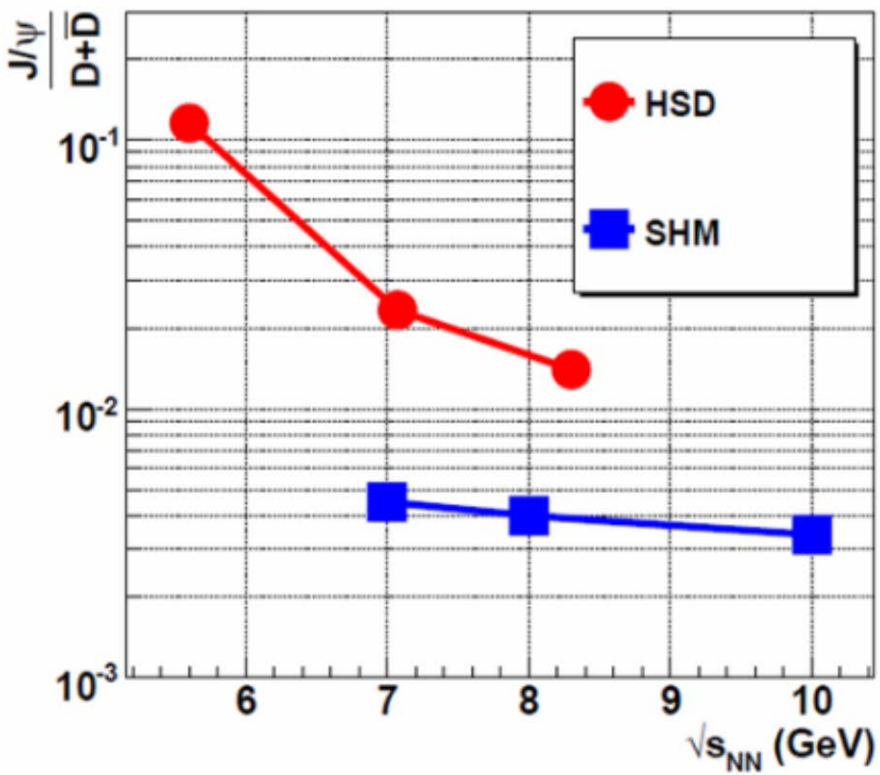
Excitation function of J/ψ production at SIS100/300 energies

→ production mechanism ?

→ J/ψ suppression ?

CBM physics observables

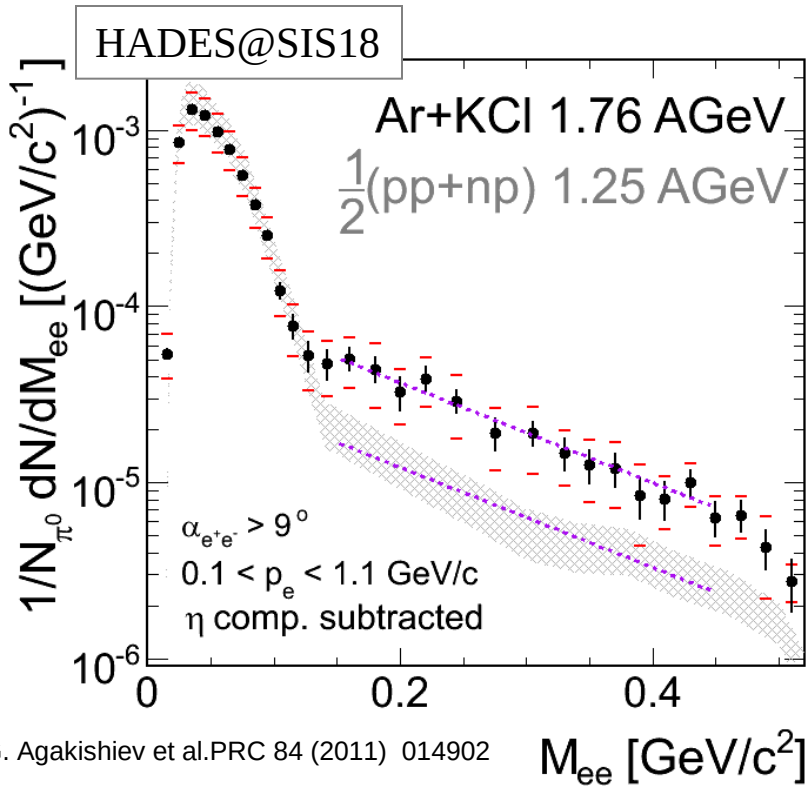
Charmonium (J/ψ) and open charm ($D\overline{D}$) production



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

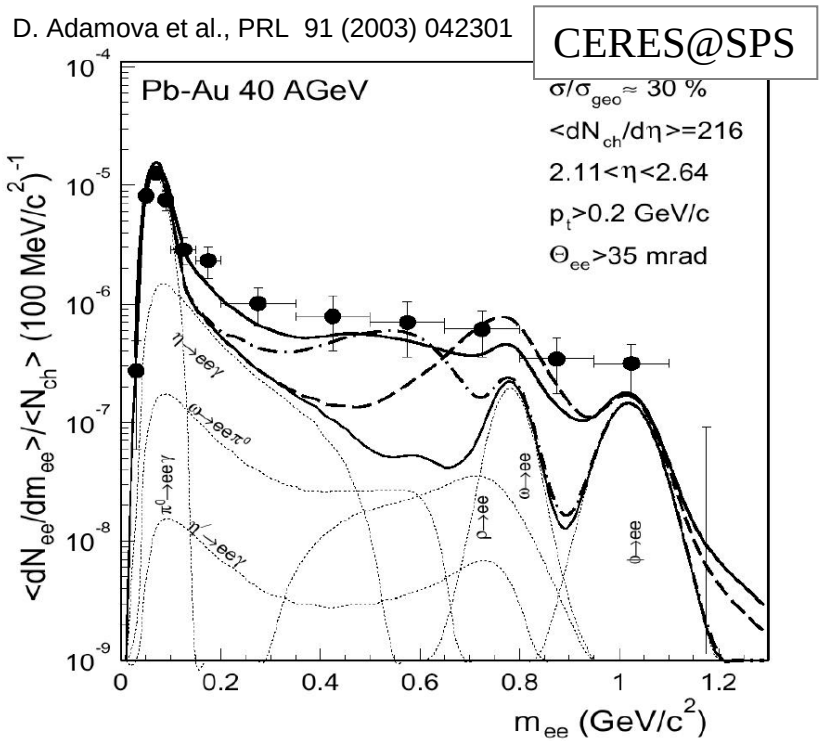
SHM "partonic"
A. Andronic et al.,
Phys. Lett. B 659 (2008) 149

CBM physics observables
Electromagnetic radiation from the dense fireball



G. Agakishiev et al.PRC 84 (2011) 014902

D. Adamova et al., PRL 91 (2003) 042301



No data available in SIS100 / SIS300 energy range !

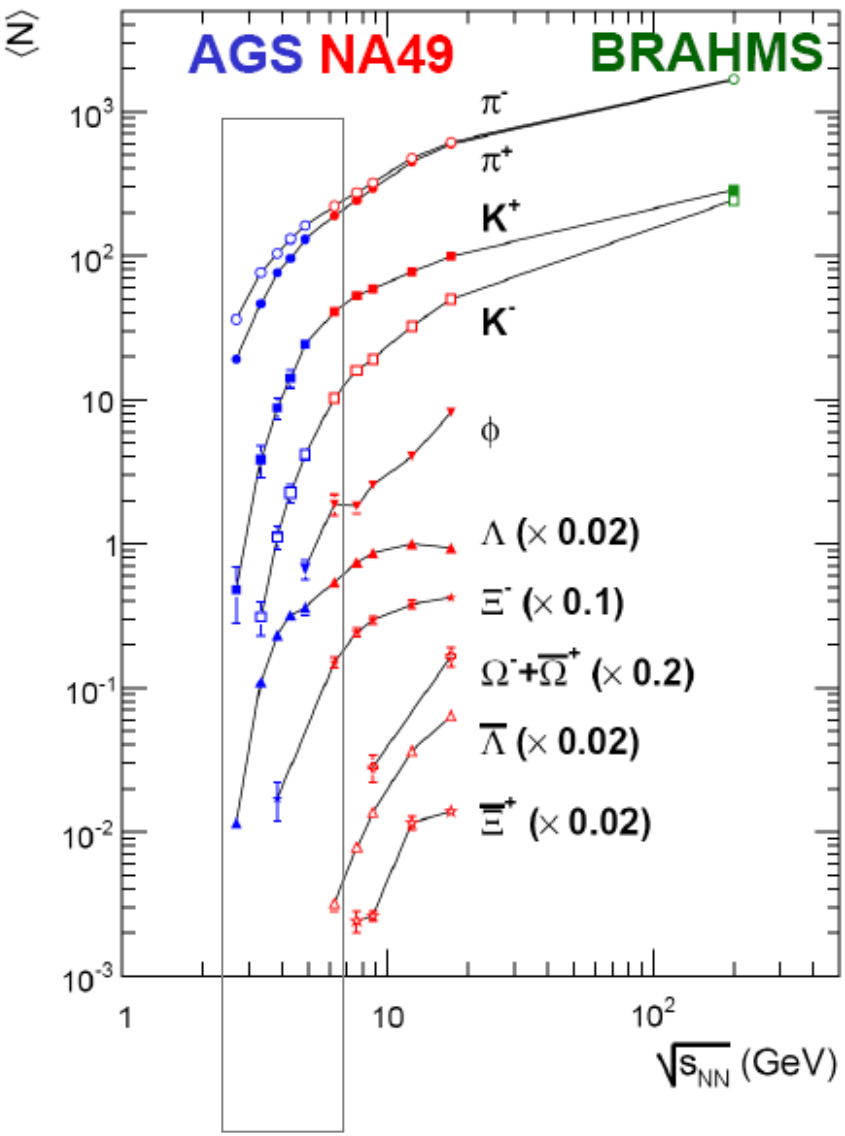
Excitation function of lepton pair production (2 – 45 A GeV)

→ excess ?

In-medium mass distributions of light vector mesons (2 – 45 A GeV)

→ in-medium modification of light vector mesons ?

CBM physics observables
Production excitation function of multi-strange baryons



direct production:

$pp \rightarrow \Xi^- K^+ K^+ p$ 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

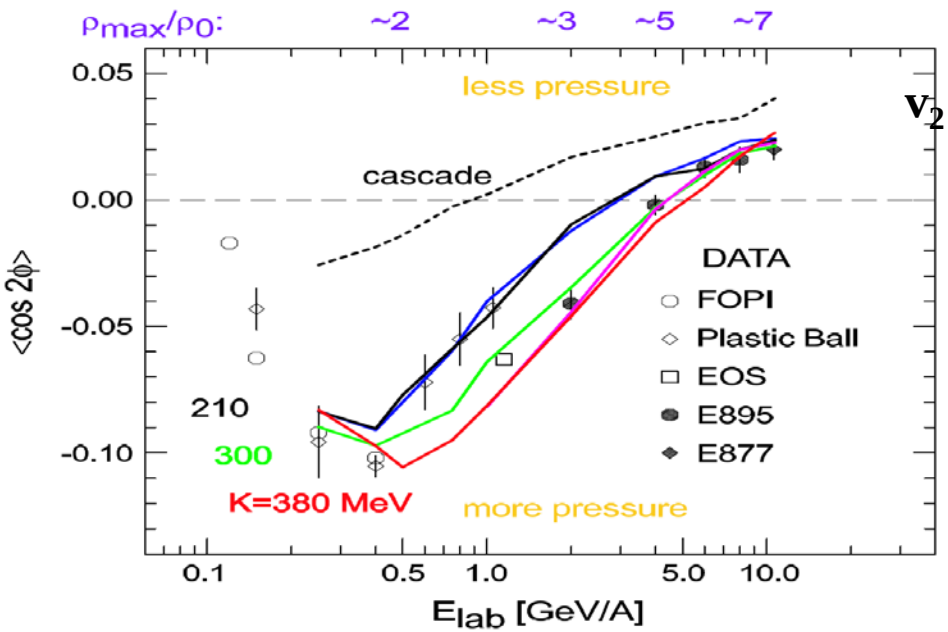
→ multi-step production ?

→ production via strangeness exchange channels ?

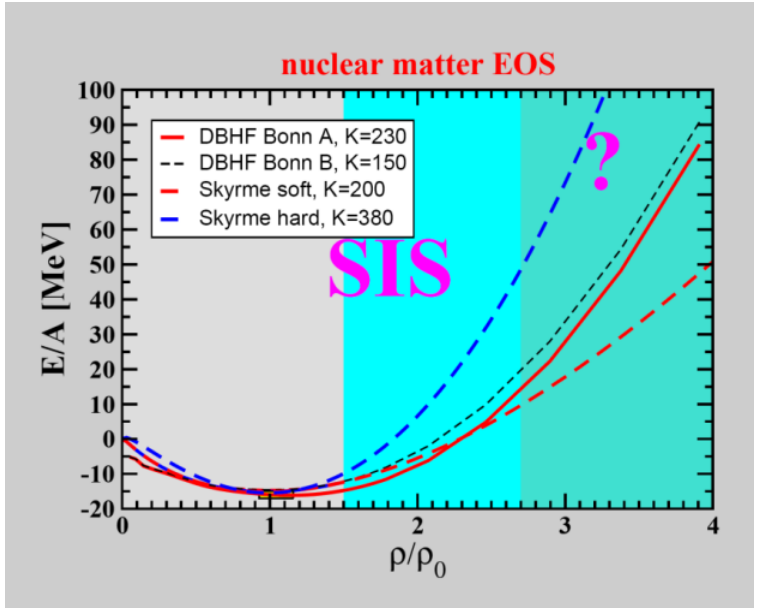
→ enhanced production in dense medium ?

CBM physics observables
Excitation function of collective flow

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



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



Present data sets are not conclusive due to large uncertainties

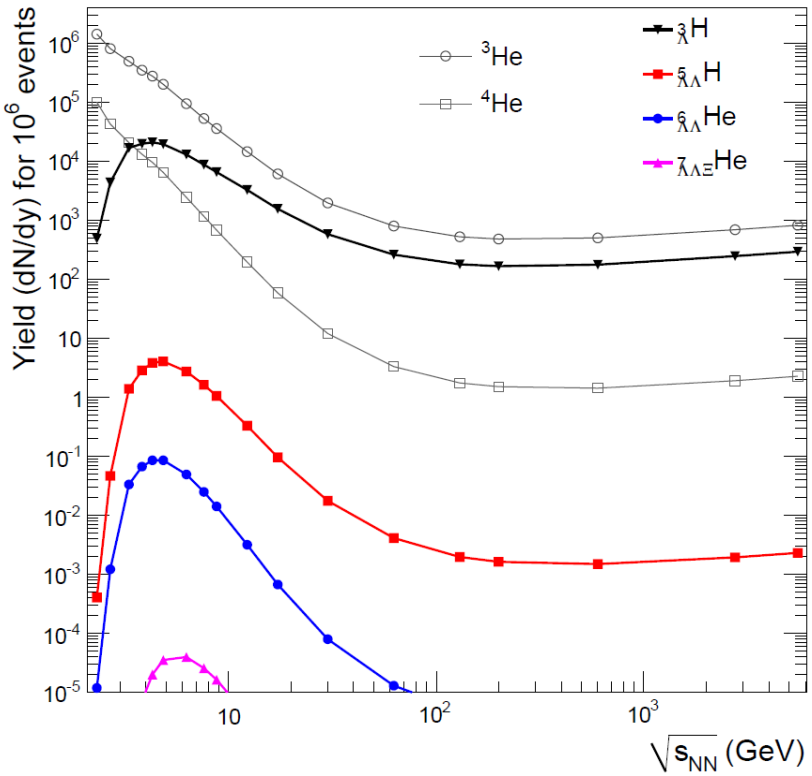
High precision collective flow excitation function at SIS100/300
→ equation-of-state at neutron star core densities

CBM physics observables
Hypernuclei, strange dibaryons and massive strange objects

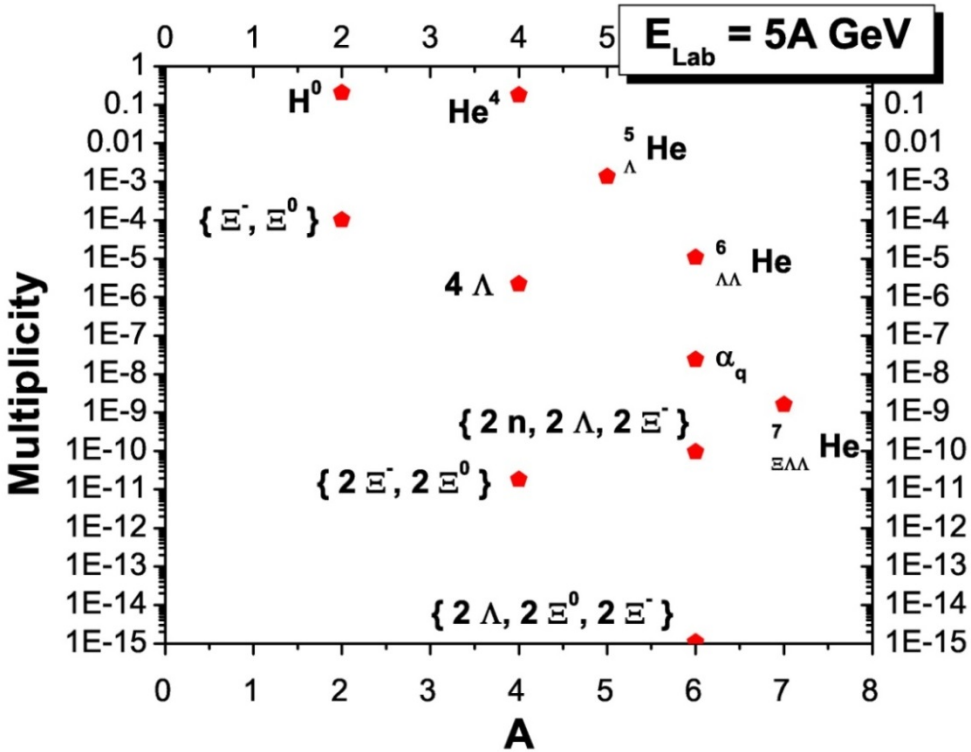
Single and double hypernuclei in nucleus-nucleus collisions

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



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

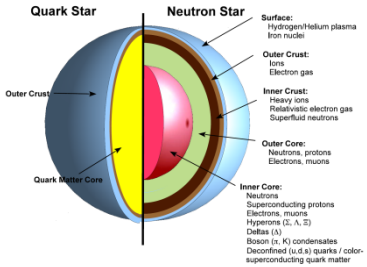


H. Stöcker et al., Nucl. Phys. A 827 (2009) 624c

Summary: CBM physics case and observables

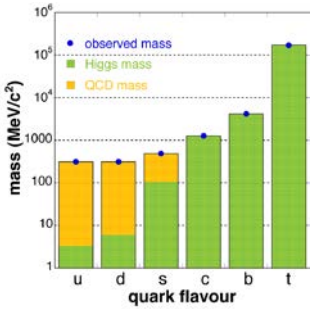
The equation-of-state at neutron star core densities

- collective flow of hadrons
- particle production at threshold energies
  (multi-strange hyperons)



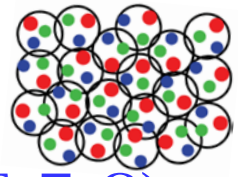
Onset of chiral symmetry restoration at high ρ_B

- in-medium modifications of hadrons ($\rho,\omega,\phi \rightarrow e^+e^-(\mu^+\mu^-)$)



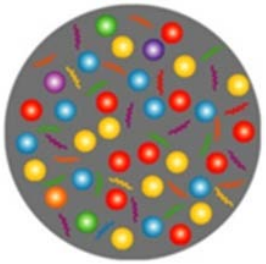
New phases of strongly-interacting matter

- excitation function and flow of lepton pairs
- excitation function and flow of strangeness (K, Λ, Σ, Ξ, Ω)



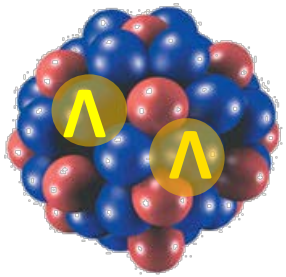
Deconfinement phase transition at high ρ_B

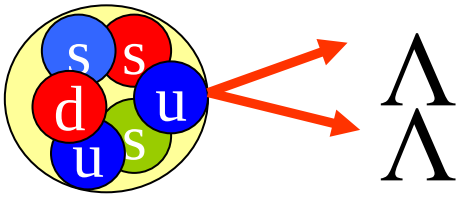
- excitation function and flow of charm (J/ψ, ψ', D^0, $D^\pm$, Λ_c)
- anomalouus charmonium suppression



Strange matter

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





CBM experimental challenges

Perform measurements at unprecedented reaction rates

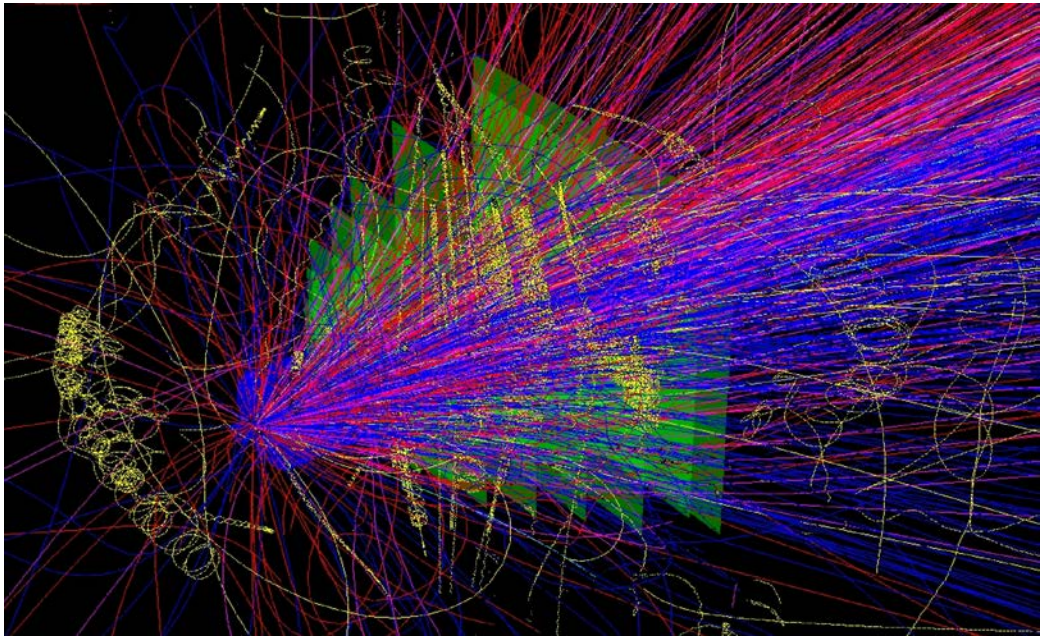
10^5 - 10^7 Au+Au reactions/sec

→ 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

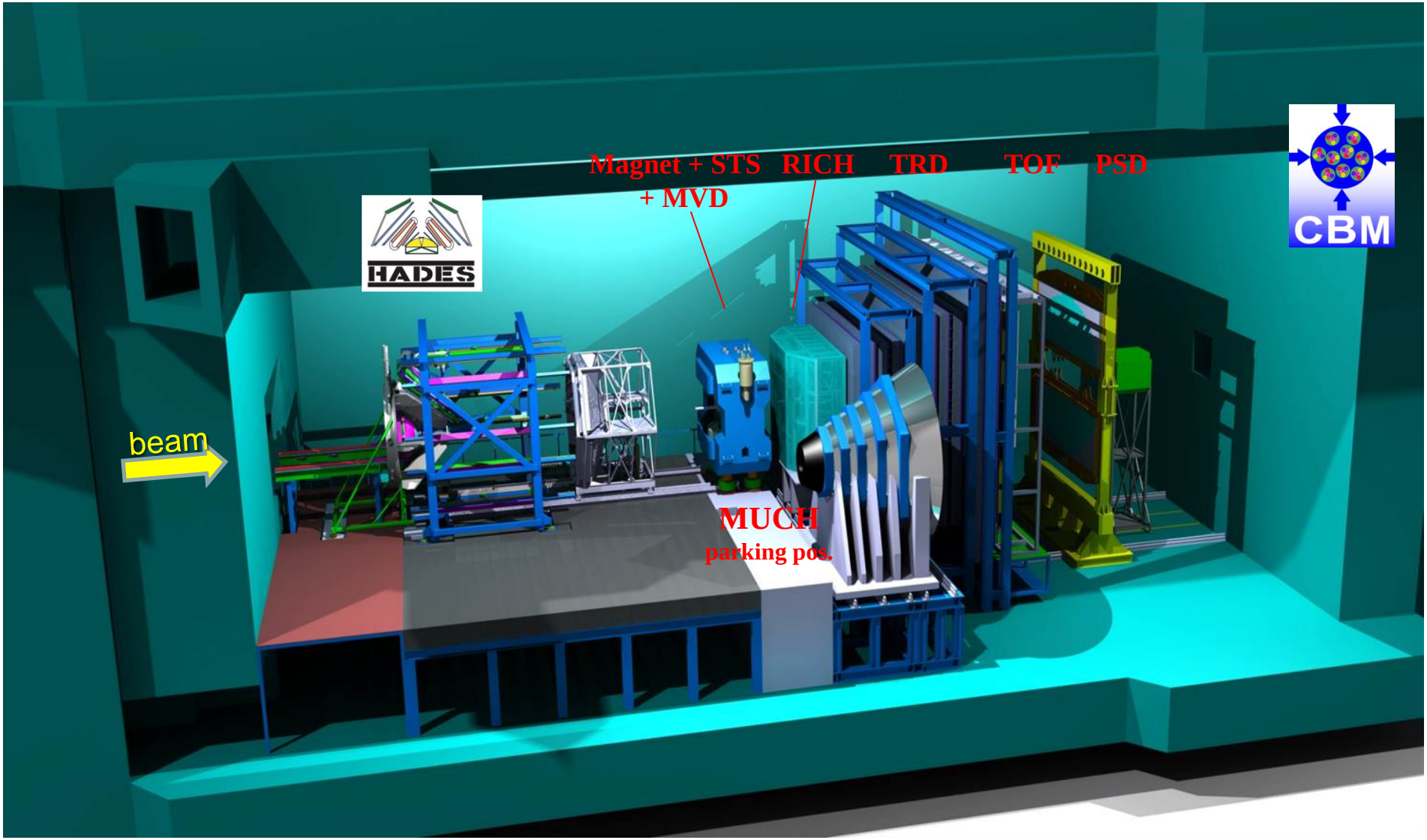


Identification
of leptons and hadrons

Determination of
(displaced) vertices ($\sigma \approx 50\ \mu m$)

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

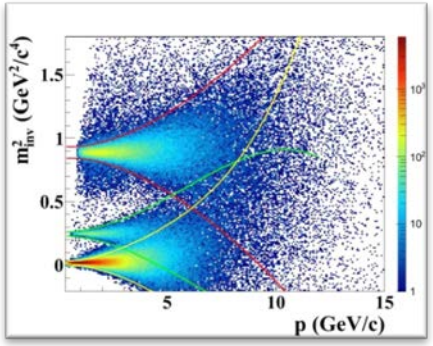
The CBM cave at FAIR

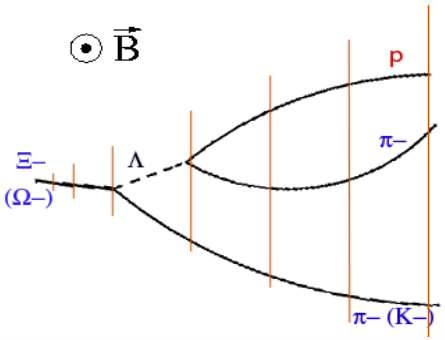


Performance of hyperon identification

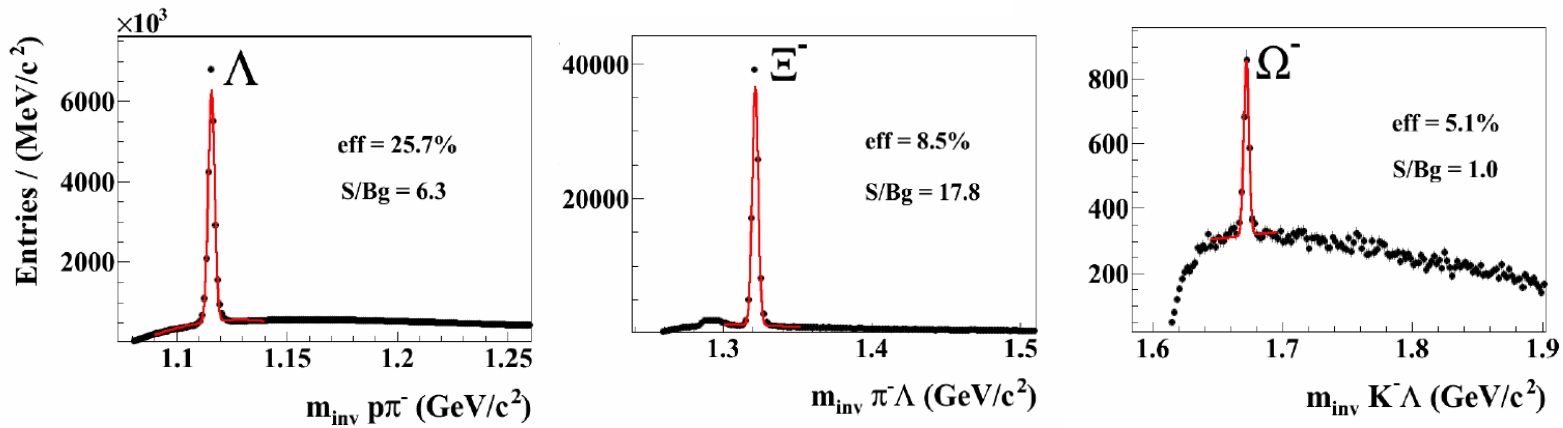
Simulations:

- STS with realistic geometry, material budget, and detector response
- TOF at 10 m, time resolution 80 ps

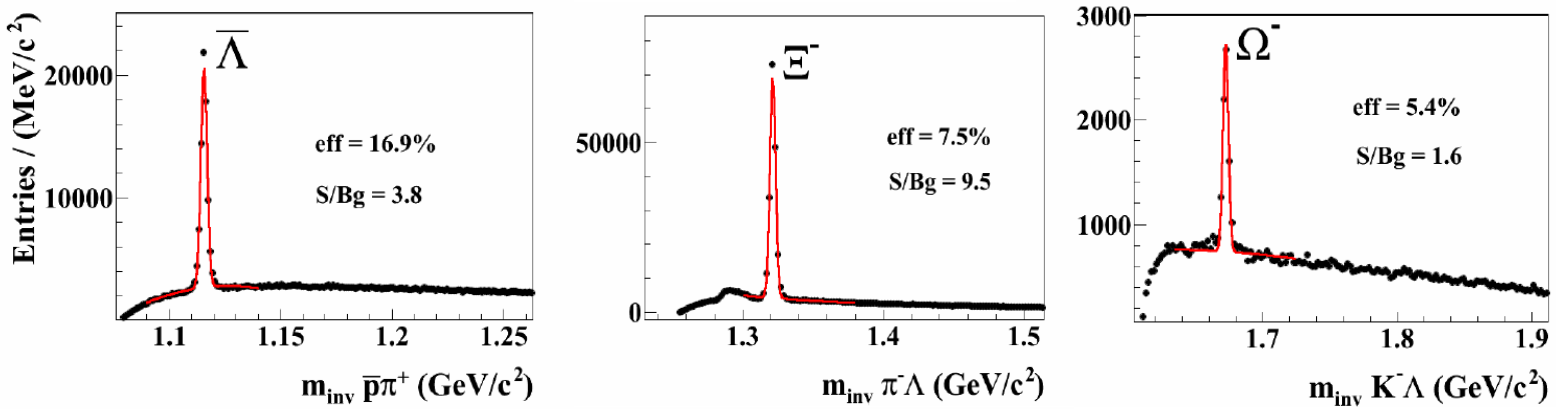




$5 \cdot 10^6$ Au+Au central **10 AGeV**



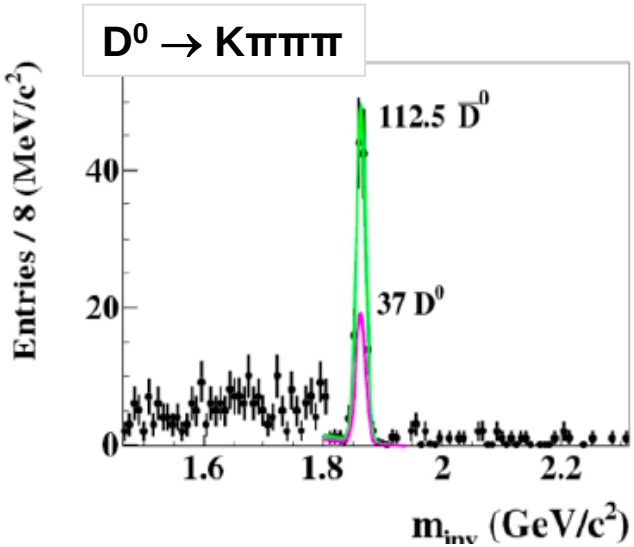
$5 \cdot 10^6$ Au+Au central **25 AGeV**

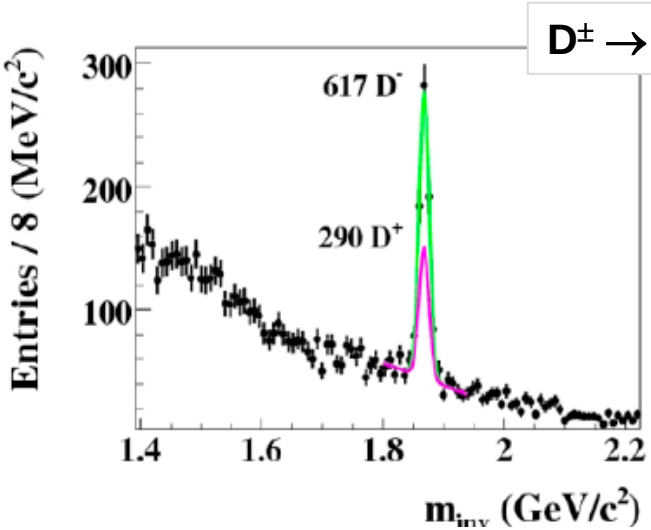


Performance of open charm identification

no particle identification by time-of-flight

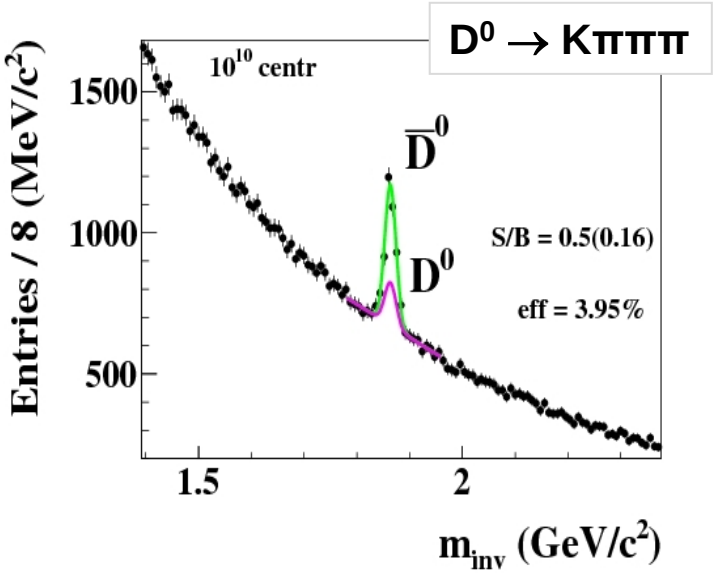
p+C
30 GeV

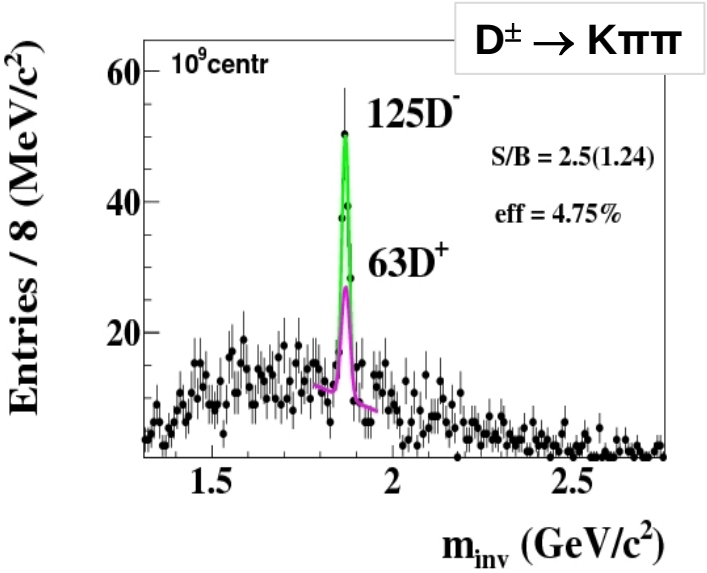




10^{12} centr.

Au+Au
25 AGeV

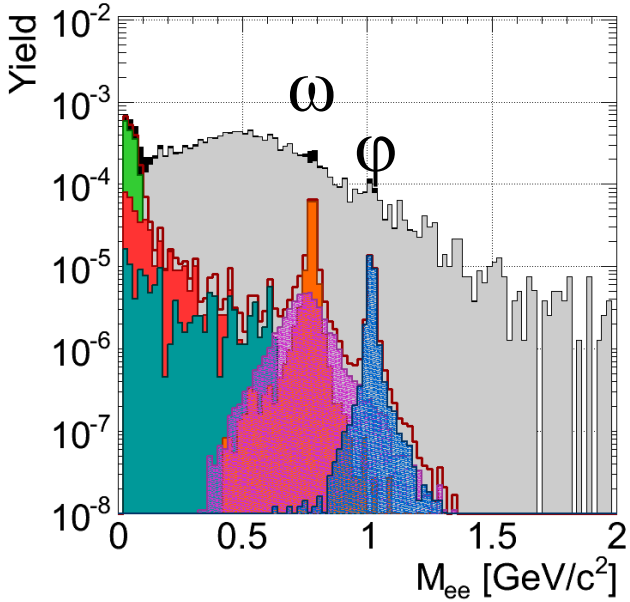




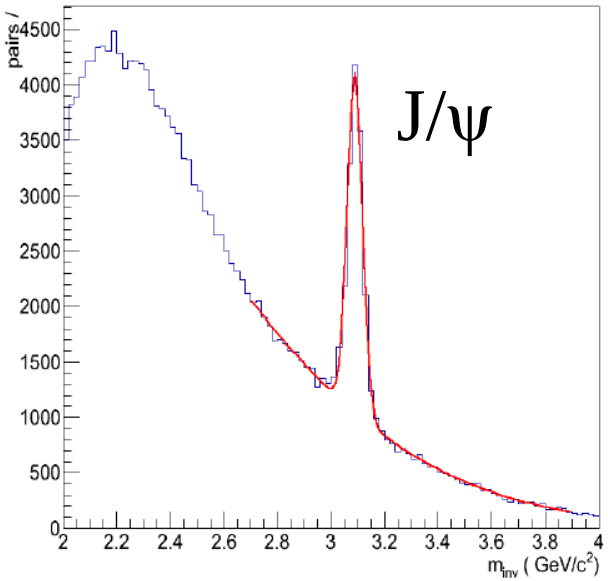
Di-lepton invariant mass spectra

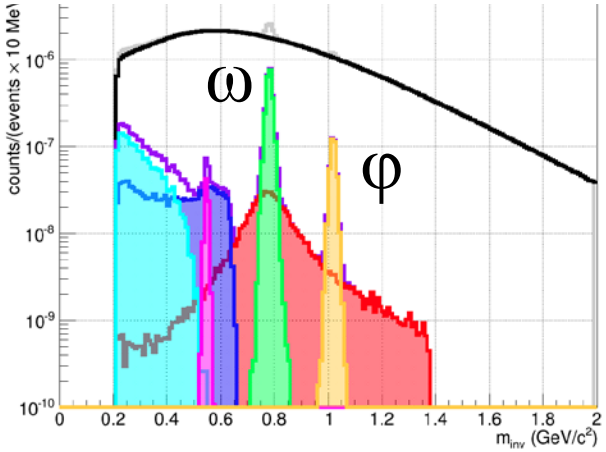
central Au+Au collisions at 25 A GeV

Detector systems: STS, RICH+TRD or MUCH, ToF

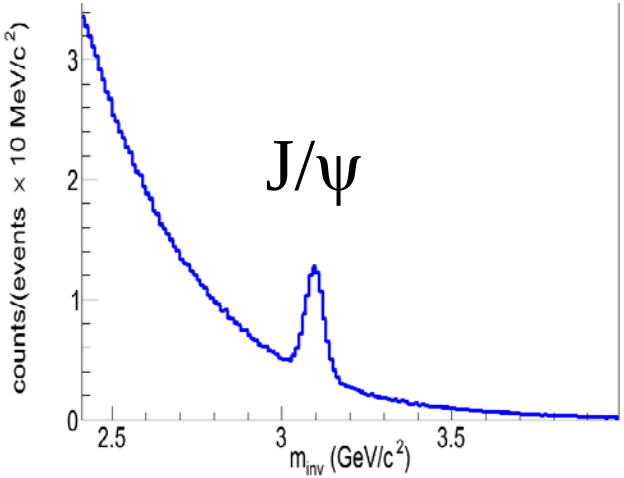


e^+e^-





$\mu^+\mu^-$



CBM physics observables

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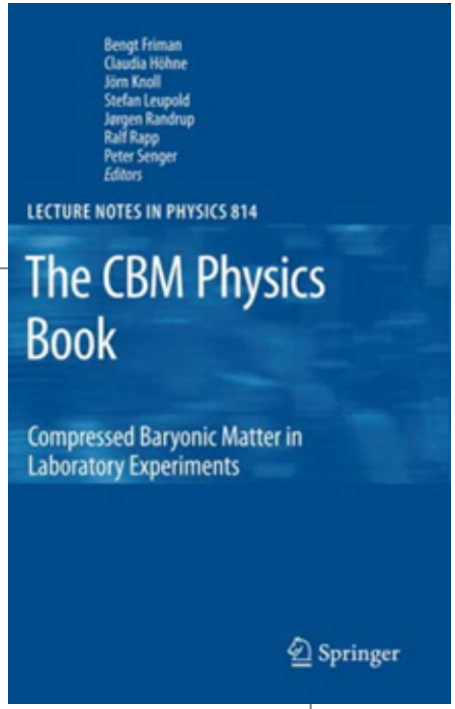

Production excitation function
in nucleus-nucleus collisions at SIS100/300 of
- **multi-strange baryons**
- **anti-protons and anti-hyperons**
- **single and double hypernuclei**

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)