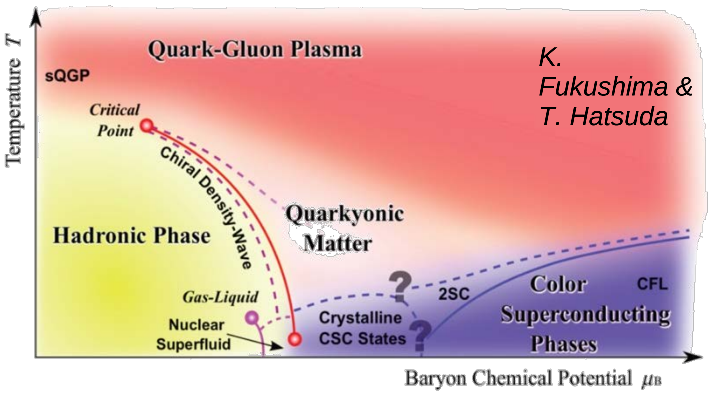
CBM Lecture
Exploring the QCD phase diagram

6th International FAIR School
Castiglione della Pescaia
September 2019

Christian Sturm
GSI Helmholtzzentrum für Schwerionenforschung GmbH



K. Fukushima & T. Hatsuda

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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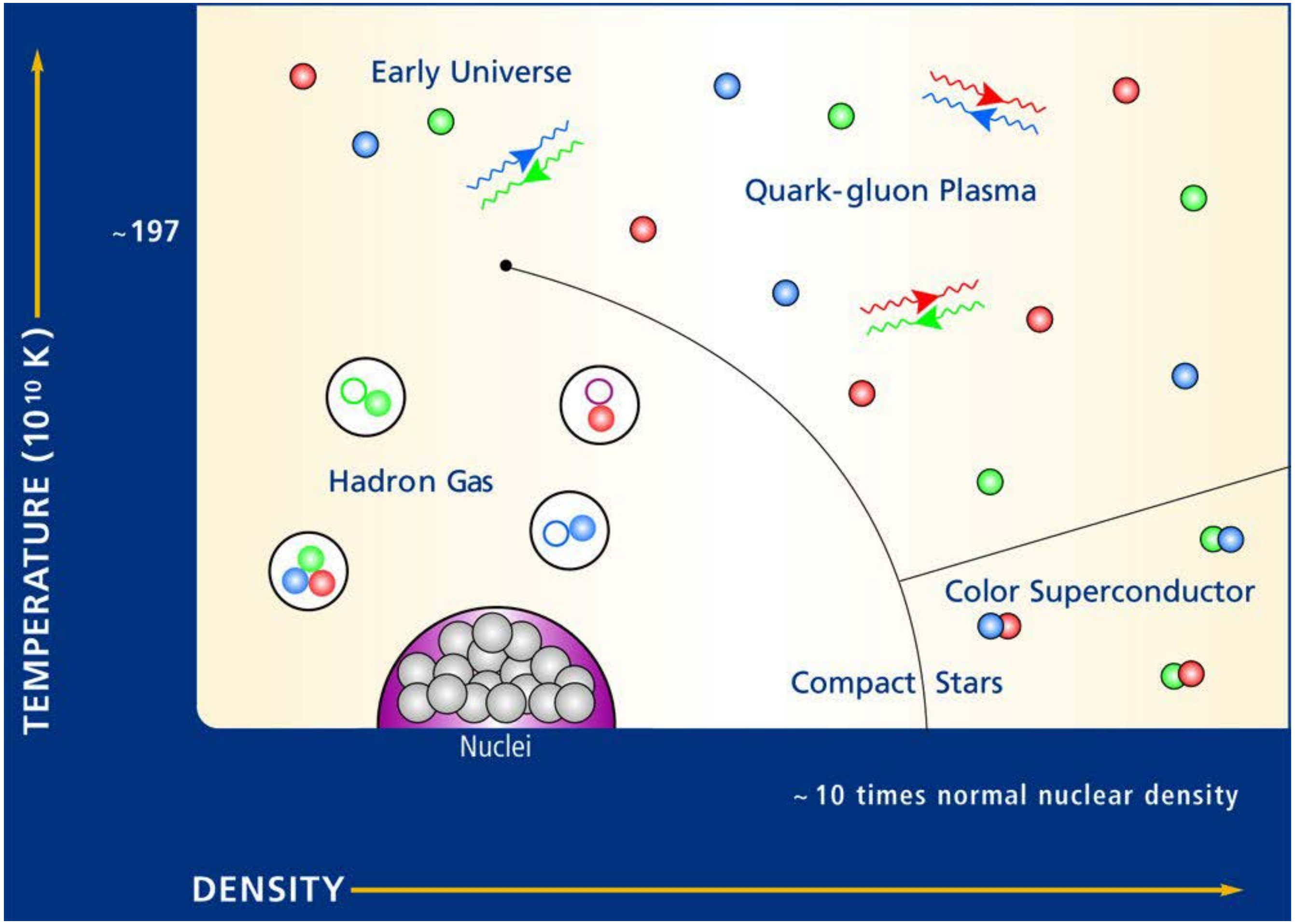
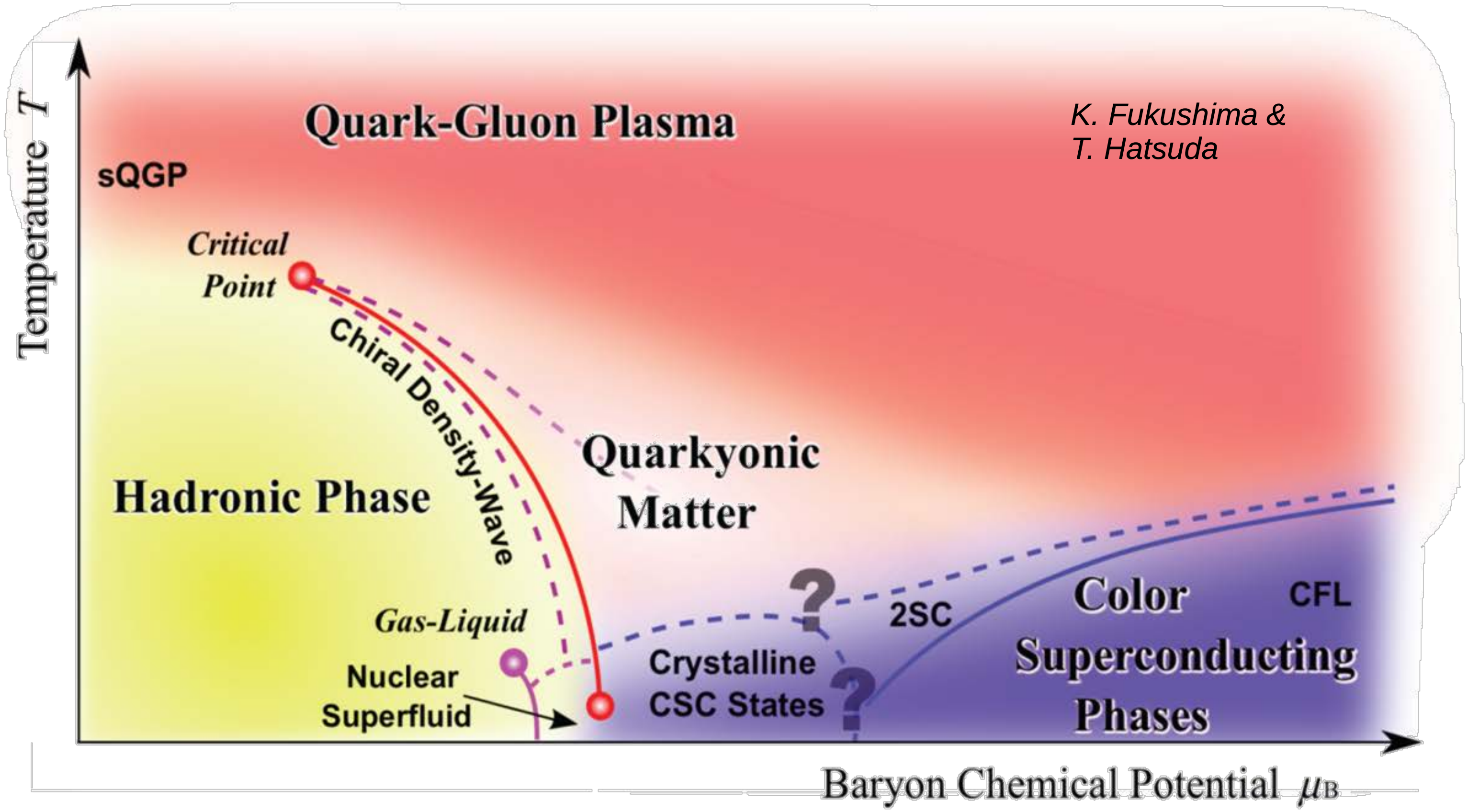
The phase diagram of strongly interacting matter



sketch
shown by Marcus

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

The phase diagram of strongly interacting matter

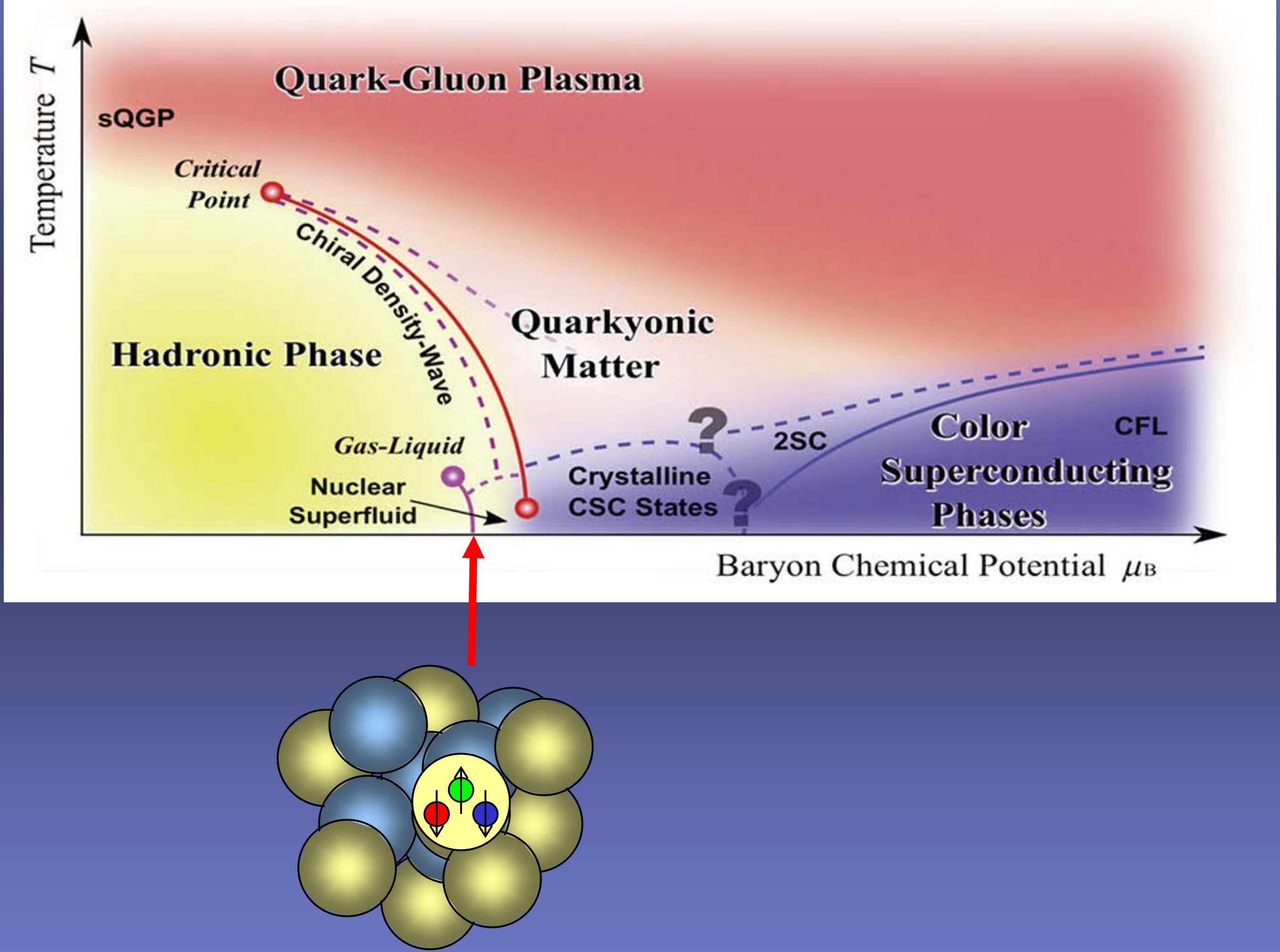


K. Fukushima &
T. Hatsuda

What do we know ?

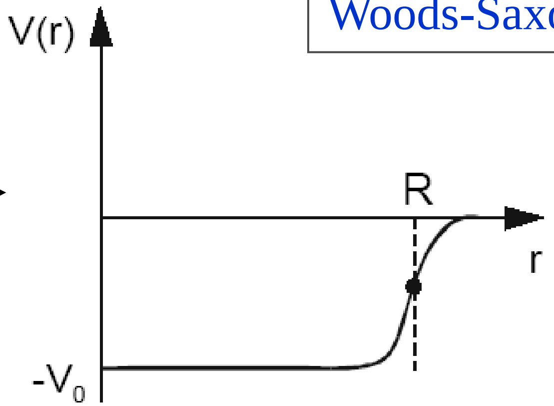
How to scan the phase diagram in the laboratory ?
→ **nucleus-nucleus collisions at various beam energies !**

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



Nuclear matter at ground state: the Nuclear Shell Model

density distribution
of nucleons
inside (heavy) nuclei →



Woods-Saxon Potential

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

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

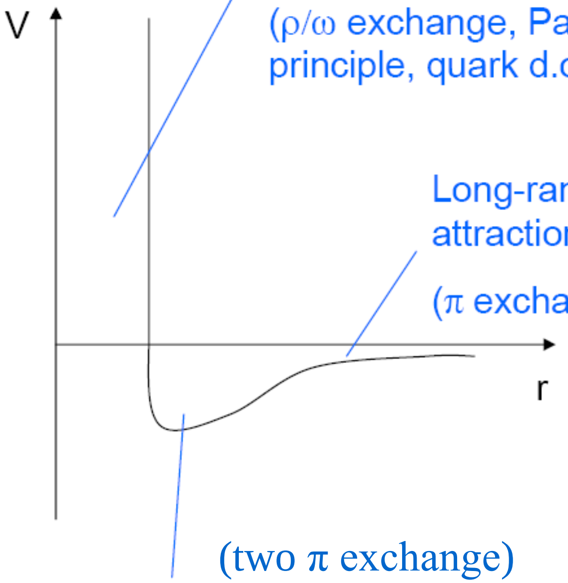
N	2	8	20	28	50	82	126	(184)	(196)
Z	2	8	20	28	50	82	(114)	(164)	

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:

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



Hard-core repulsion for r≤0.4 fm

(ρ/ω exchange, Pauli principle, quark d.o.f.)

Long-range attraction

(π exchange)

(two π exchange)

Binding around ~0.8 fm

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

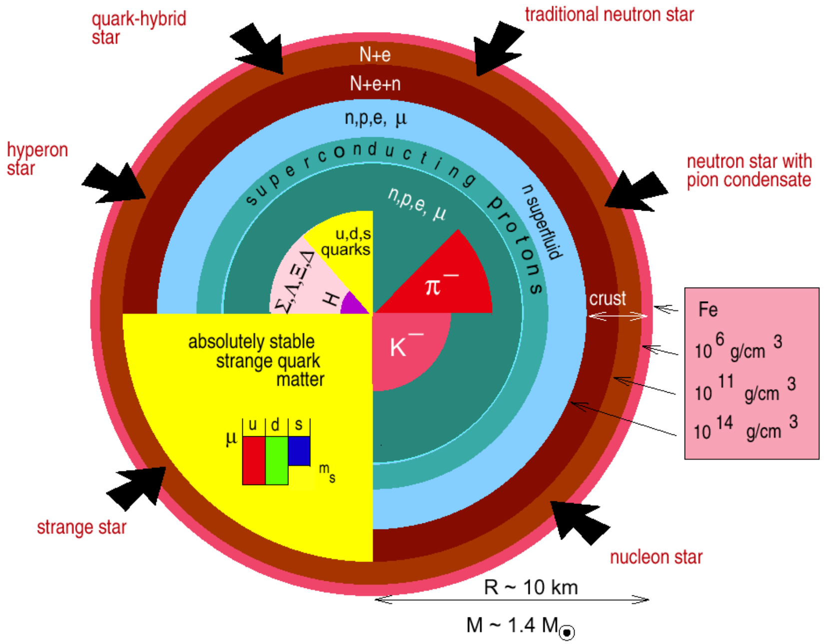
Pion (π-meson):
- pseudo-scalar particle $J^P = 0^-$
- $m_\pi = 140$ MeV

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.

Nucleus

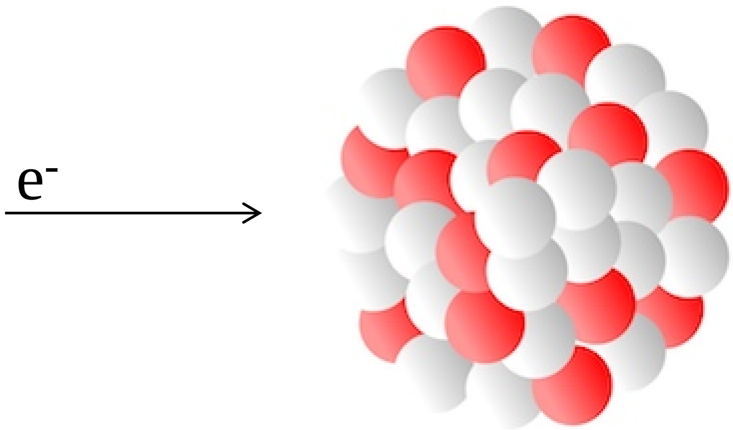
Neutron star

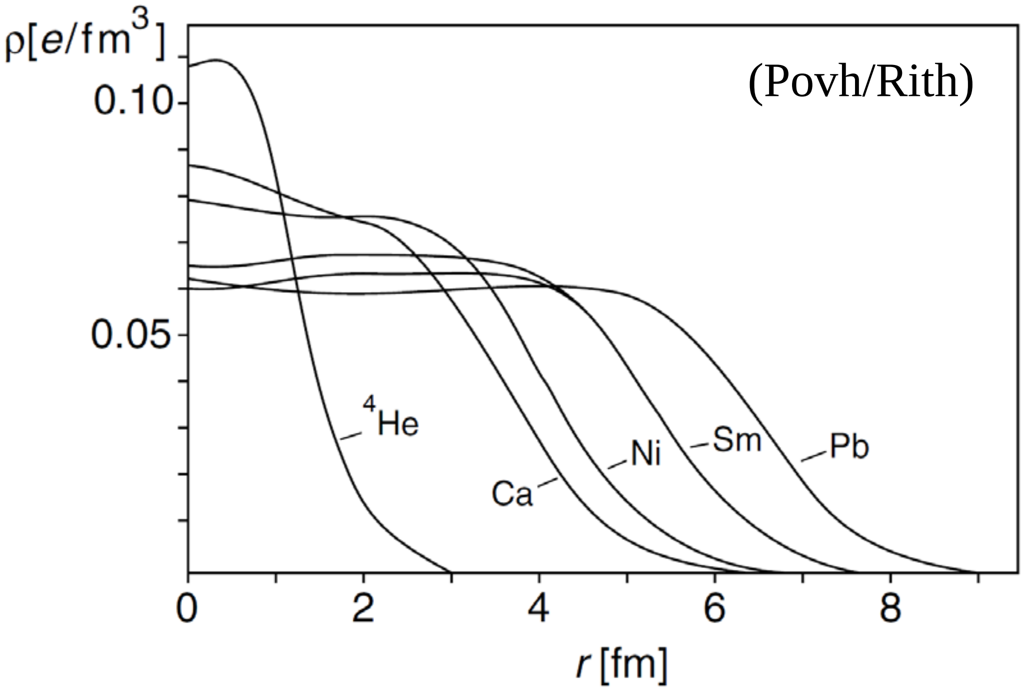


Properties of nuclear matter ?

Nuclear matter at ground state

Charge distribution of nuclei obtained in electron-nucleus scattering





$$\rho_0 = \rho^e(0)\cdot\frac{A}{Z} \qquad {}^{208}_{82}Pb \qquad \frac{A}{Z} = 2.53$$

saturation density $\rho_0 \approx 0.15 - 0.17$ nucleons / fm^3

The equation-of-state of nuclear matter

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

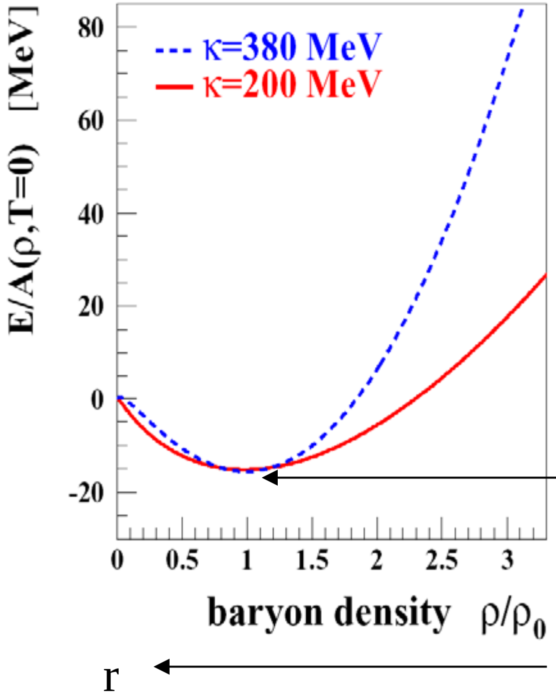
$(\varepsilon = E/A)$ thermal compressional ground state energy

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



curvature at saturation density:
compression modulus

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

Example for a nuclear equation-of-state (EoS)

example for an
effective NN-Potential
(Skyrme type)

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

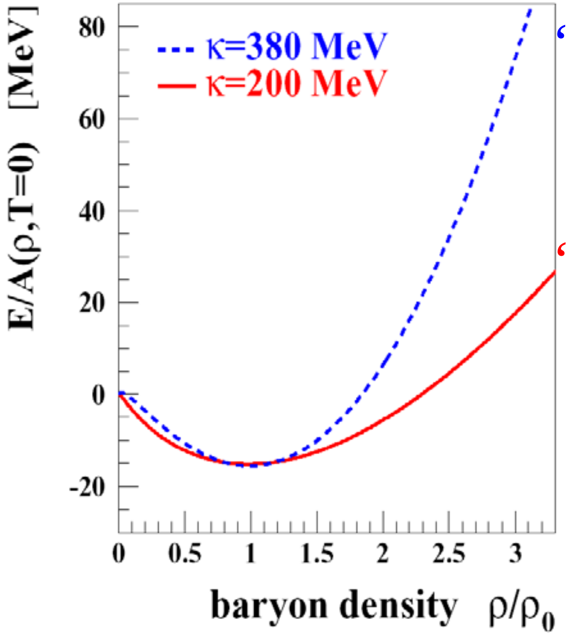
constraints for the parameters
of the potential :

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

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

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

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



“stiff” EoS

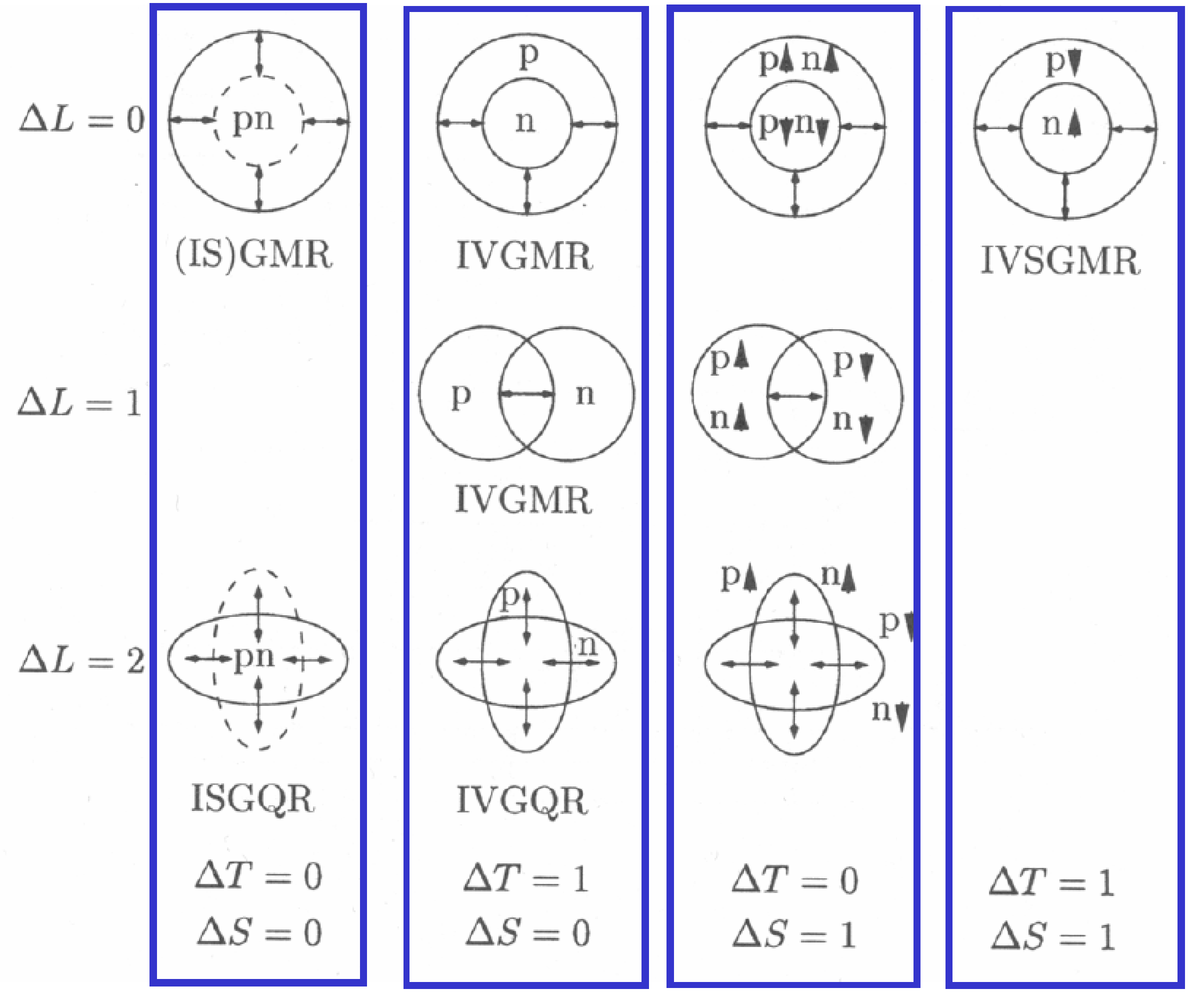
“soft” EoS

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

compression modulus

Nuclear EoS - how to measure ?

Excite collective excitation of nuclei: Giant Resonances



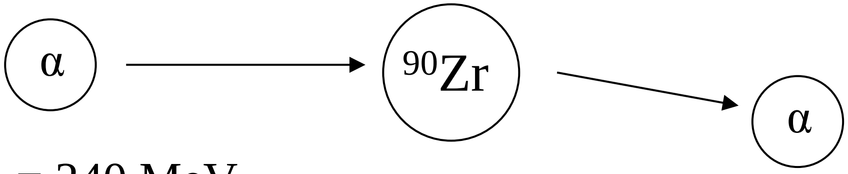
monopole vibration:
"breathing mode" of nuclei

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

quadruple vibrations

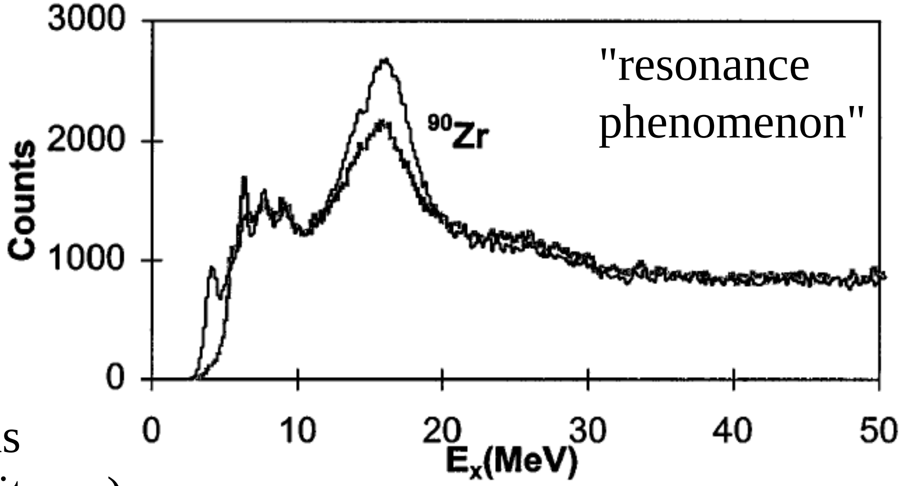
Nuclear EoS - how to measure ?

inelastic scattering of α particles on nuclei



E_{kin} = 240 MeV

measurement:
total energy of outgoing α particle
→ $E_x = E_{in} - E_{out}$



"resonance phenomenon"

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

energy loss of the α particle: 15 – 25 MeV

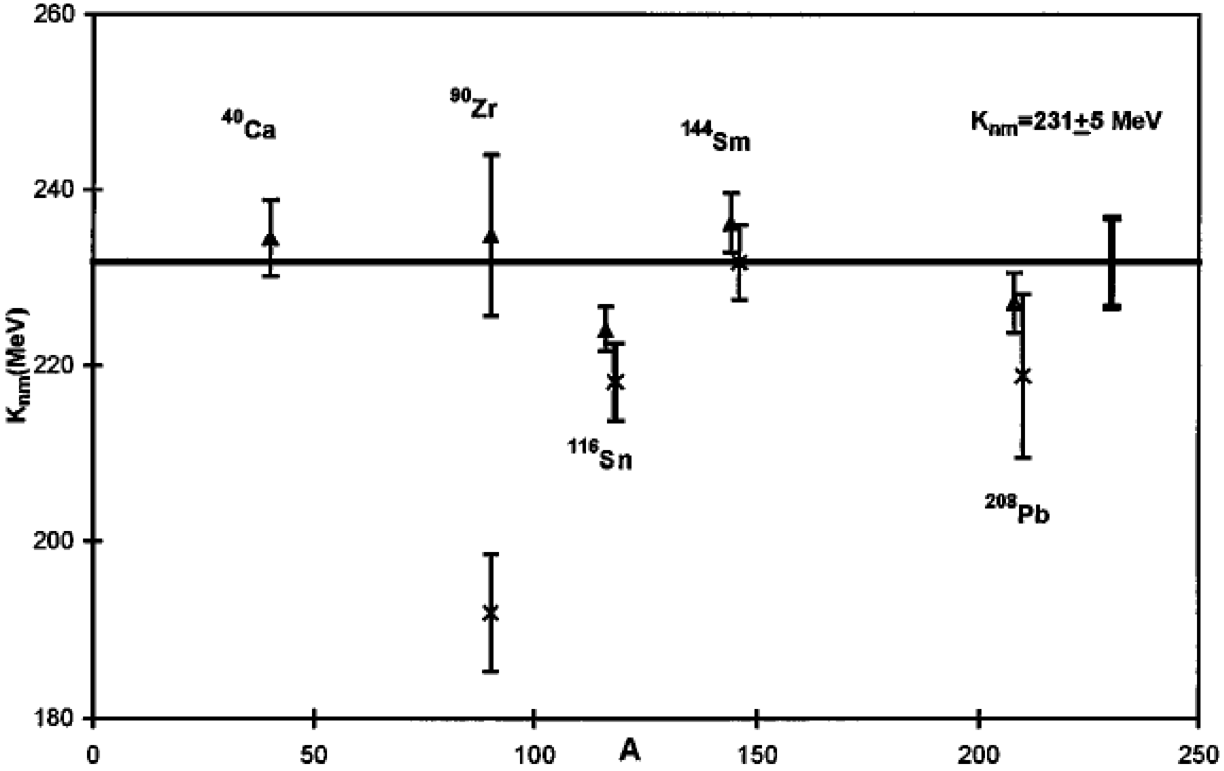
excites slight density oscillations with elongations of about 1/100 – 1/10 ρ_0 (around saturation density ρ_0).
→ **giant monopole resonance**

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

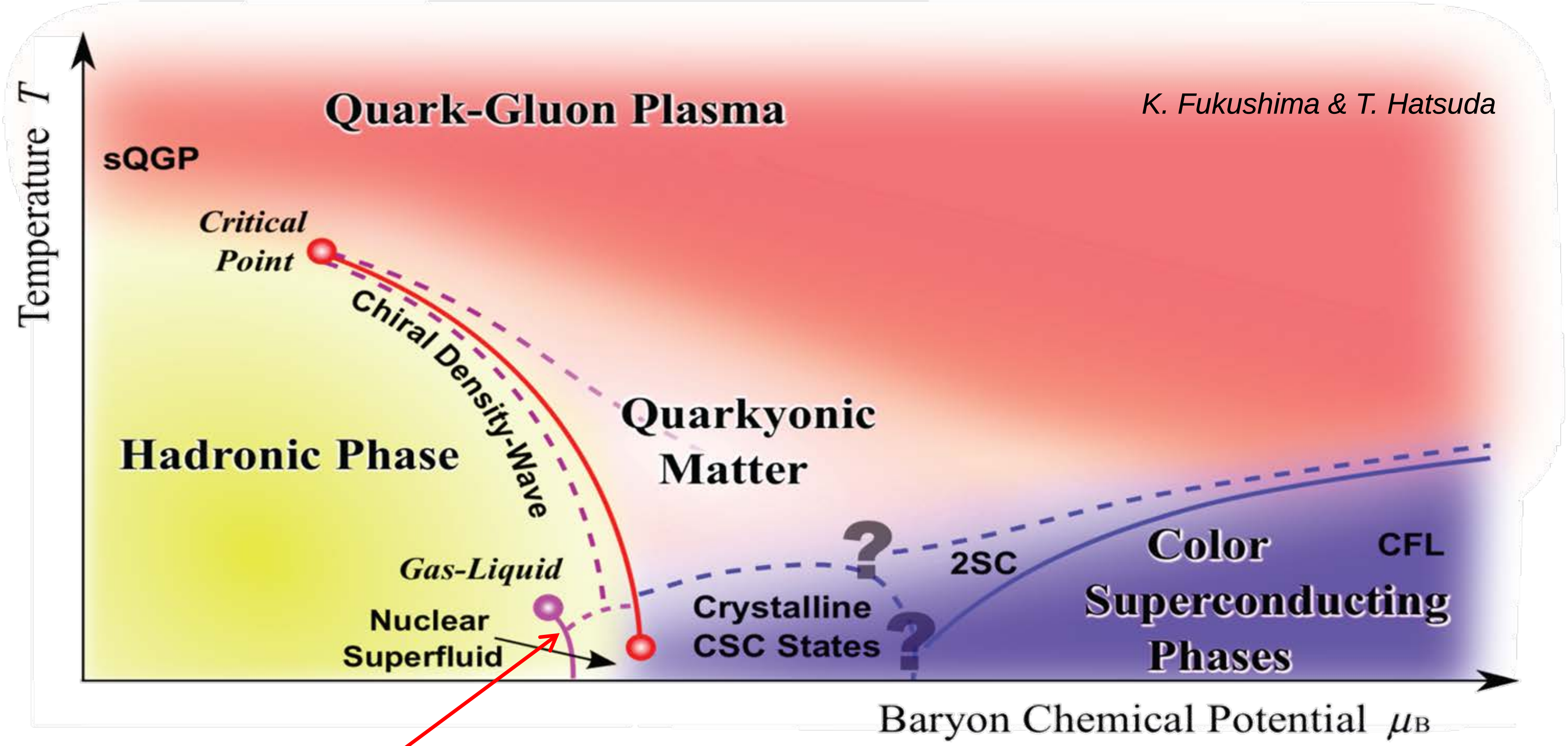
"Excitation of the Giant Monopole Resonance
by inelastic scattering of α particles on nuclei"

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



$\kappa = 231 \pm 5$ MeV

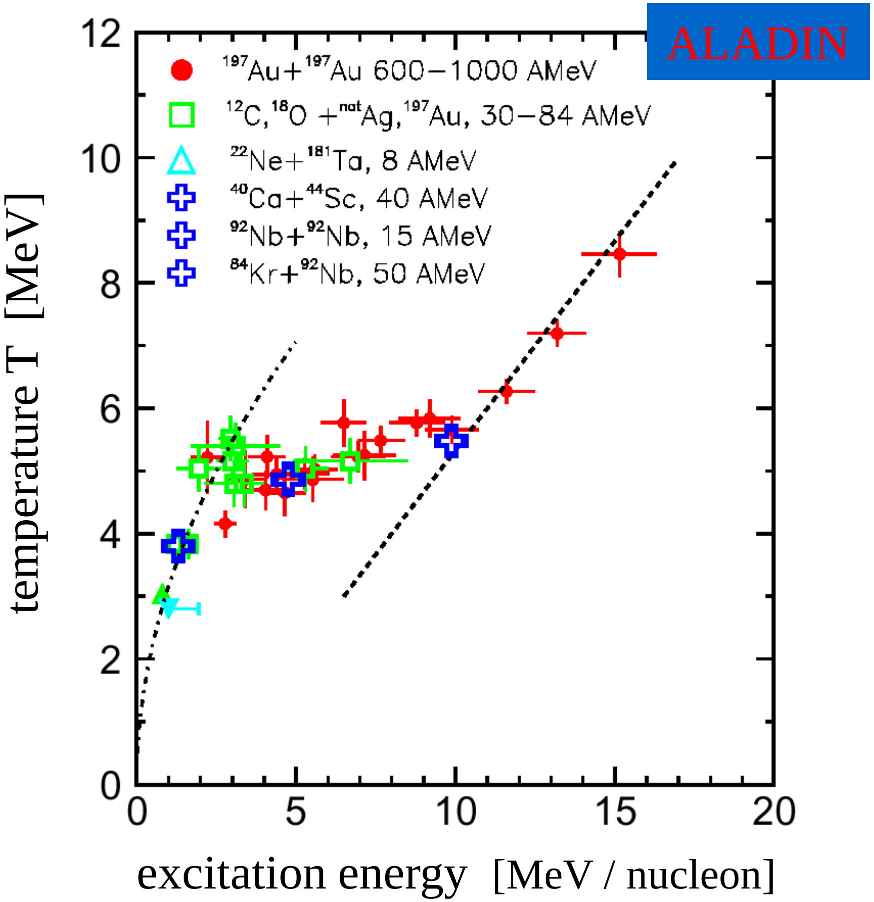
Phases of nuclear matter: the liquid-gas phase transition



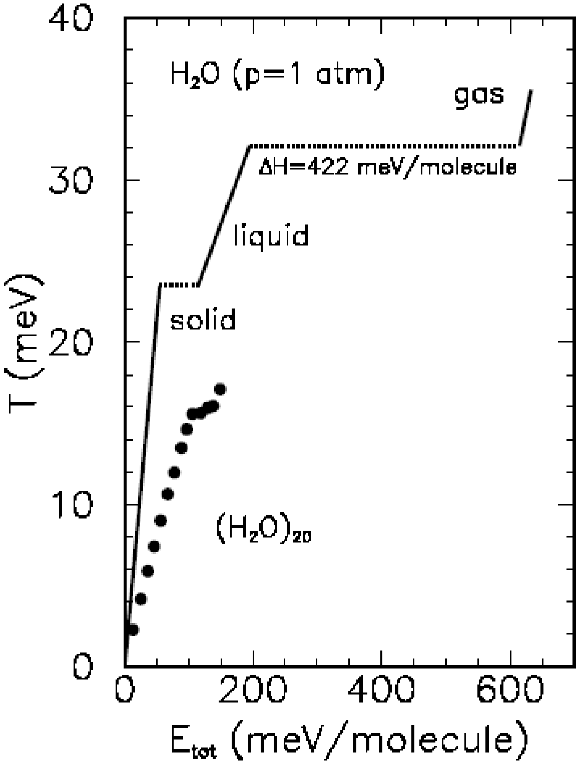
obtained in peripheral nucleus-nucleus collisions at bombarding energies from 8 – 1000 AMeV

The liquid-gas phase transition

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



caloric curve of H_20



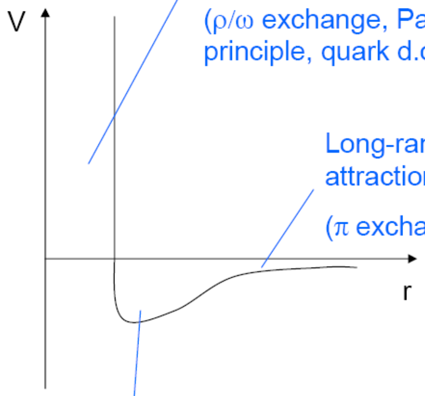
evidence for a
transition from a
liquid to a vapor phase
of nuclear matter

Your 3-minute-discourse

Discuss with your neighbor

Is there a good argument or even an observation that the strong force has a repulsive component ?

Why using a nuclear shell model or an OBE model (like Yukawa) while the well-known theory of strong interaction is QCD ?



Hard-core repulsion for r≤0.4 fm

(ρ/ω exchange, Pauli principle, quark d.o.f.)

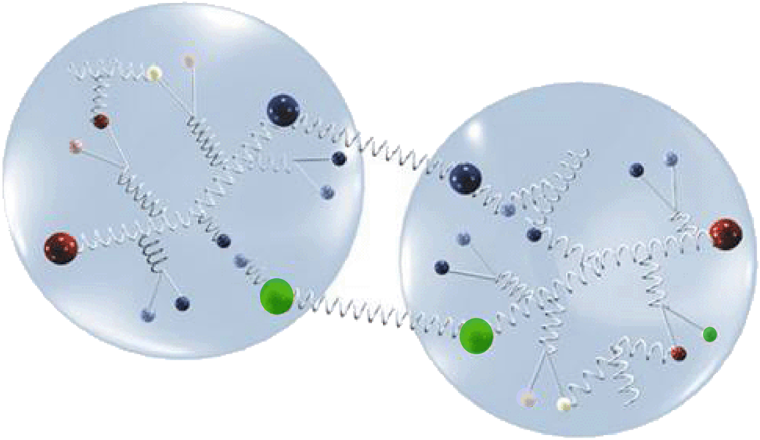
Long-range attraction

(π exchange)

Binding around ~0.8 fm

Nuclear matter in ground state – link to QCD ?

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 → $p_f = 250$ MeV/c .

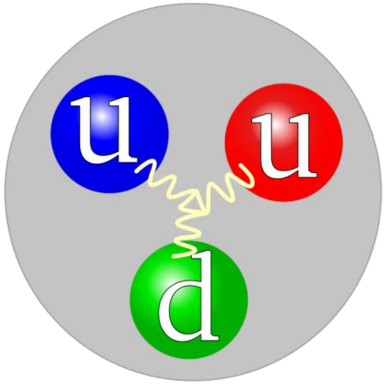
Link to **QCD** ?

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

... since we know that hadrons are composite objects ...

mass of hadrons ?

Proton

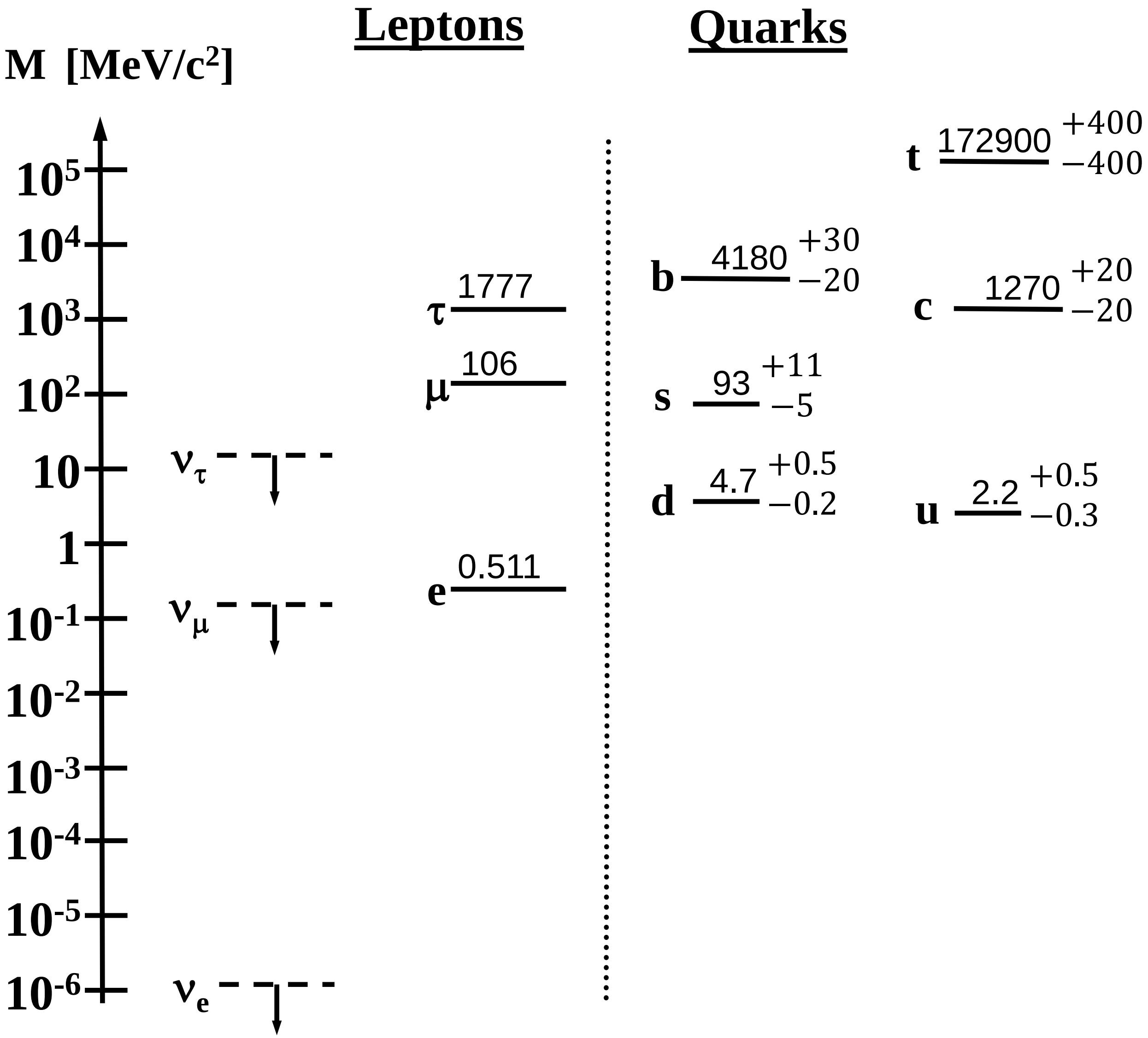


mass **not** determined
by the sum of current quark masses !!!

Masses of elementary particles

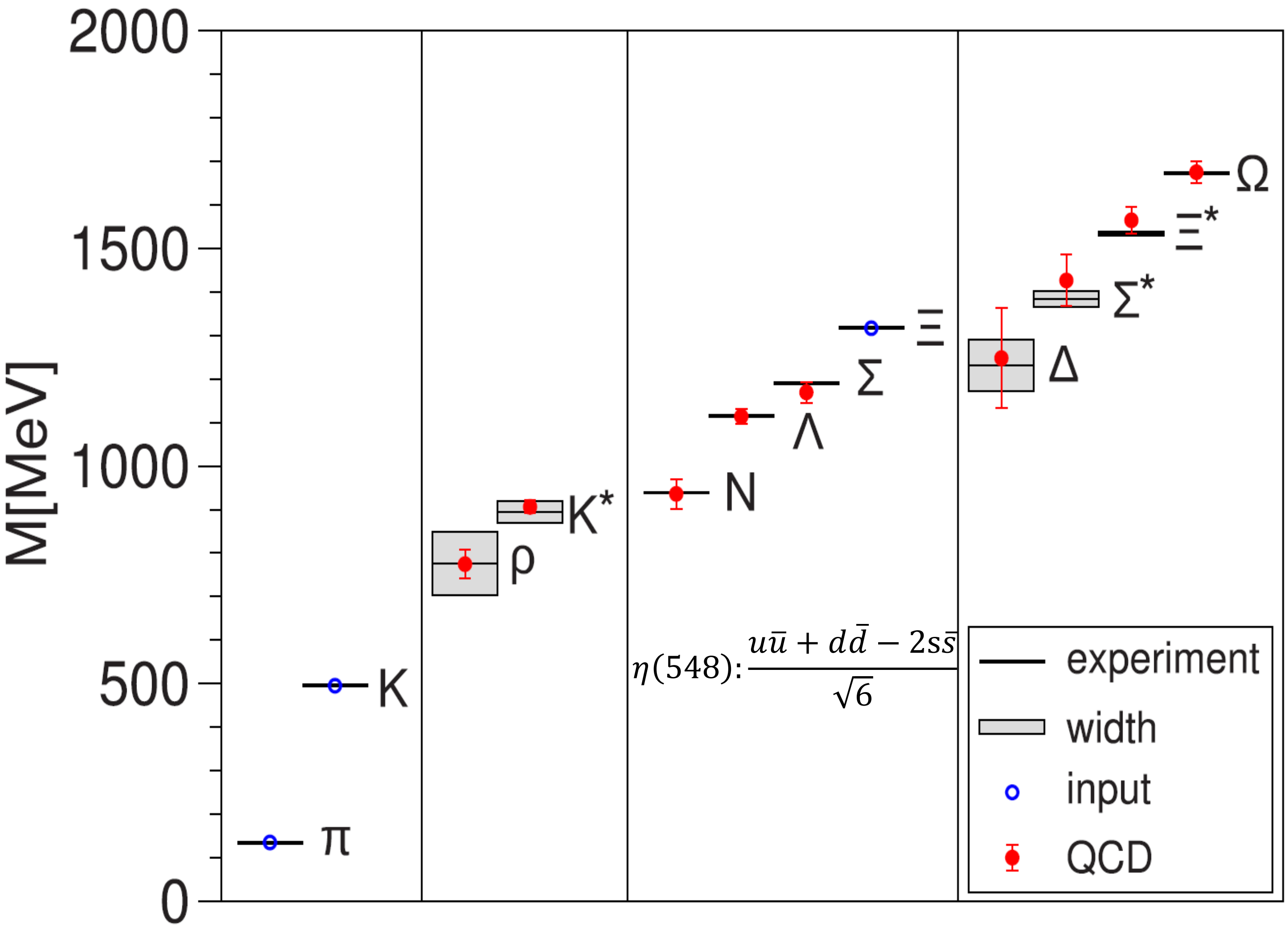
PDG PHYSICAL REVIEWD 98, 030001 (2018)

"mass" means:
current mass = weak mass



Observation: the hadronic mass spectrum

Lattice QCD
S. Dürr et al., Science 322, 1224 (2008)
Ab Initio Determination of Light Hadron Masses



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

Δ^{+} (1232): uud

p (938): uud

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

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

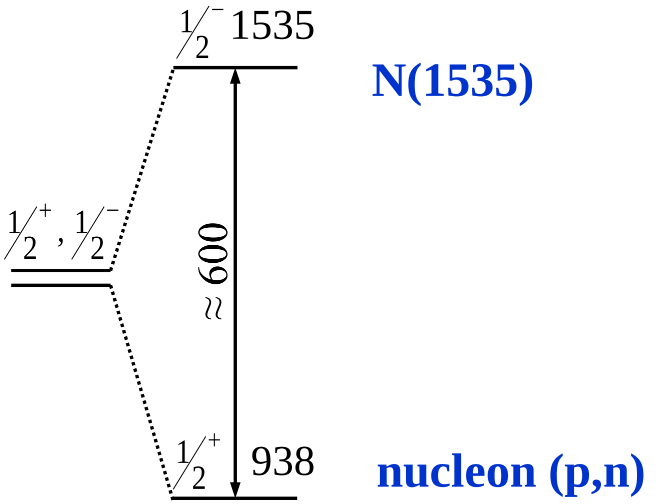
$\pi^{+}(140)$: $u\bar{d}$

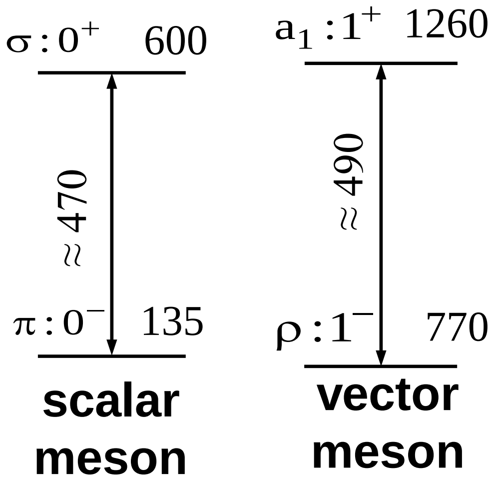
Observation: broken chiral symmetry

The QCD Lagrangian is **chirally symmetric**

“chiral” partners: same spin but opposite parity
should degenerate in mass

p,n ↔ N(1535) (baryons) or $\pi \leftrightarrow \sigma$ (mesons)





but in "nature" chiral symmetry **is obviously broken**!

Mass split is large, comparable to hadron masses

Broken chiral symmetry

Aspects of Chiral Symmetry
Volker Koch, BNL
arXiv:nucl-th/9706075v2

Consequence* of the spontaneous breakdown of a symmetry: existence of a massless mode – the Goldstone-boson

* Goldstone's theorem

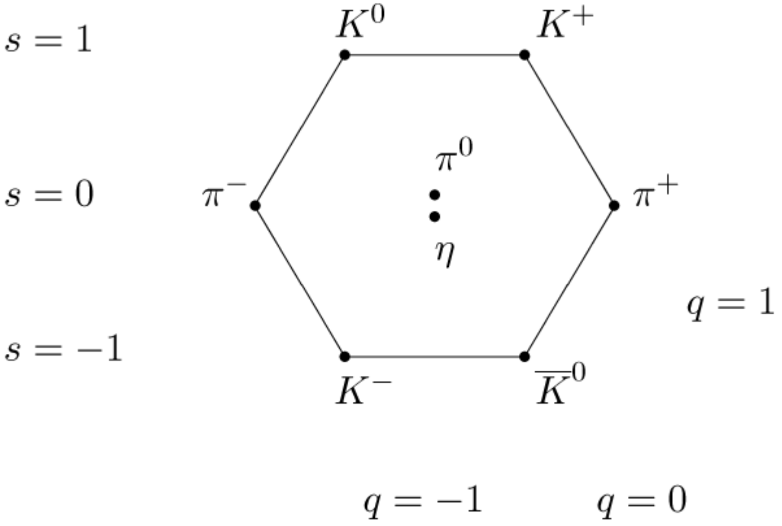
In QCD: Pion

(1) If chiral symmetry would be a perfect symmetry of QCD
→ Pion massless

(2) **But chiral symmetry is only an approximate symmetry of QCD**
→ Pion should have a finite but small mass

$SU(2)$: π^0, π^+, π^-

$SU(3)$: $\pi^0, \pi^+, \pi^-, K^0, \overline{K}^0, K^+, K^-, \eta$



Chiral symmetry

explicitly broken

by small but finite quark masses

and

spontaneously broken

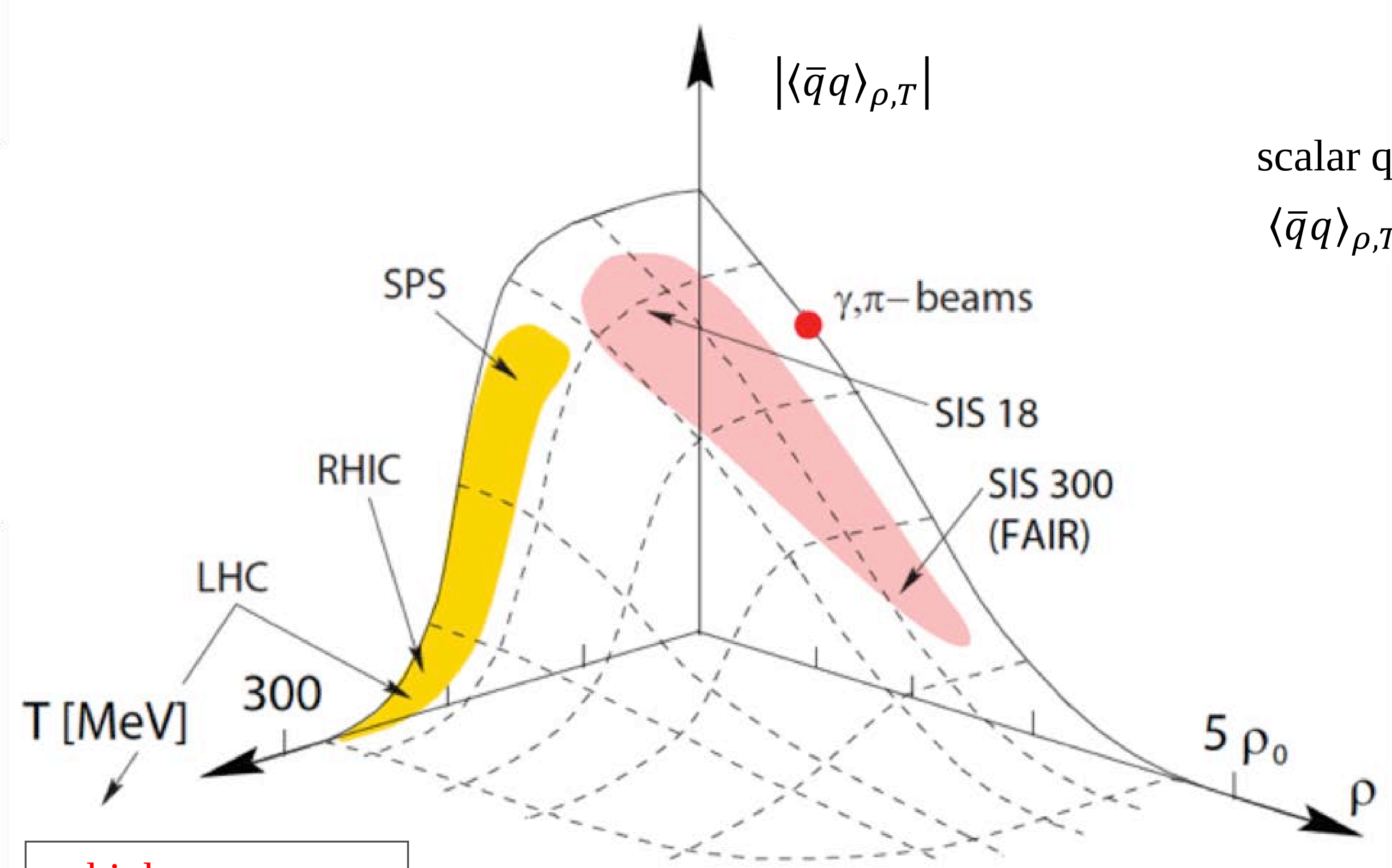
due to the existence of a massless mode (Goldstone-boson*)

* Nambu-Goldstone boson

Consequence: chiral symmetry can be restored

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

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



scalar quark condensate

$\langle\bar{q}q\rangle_{\rho,T}$

at high temperature

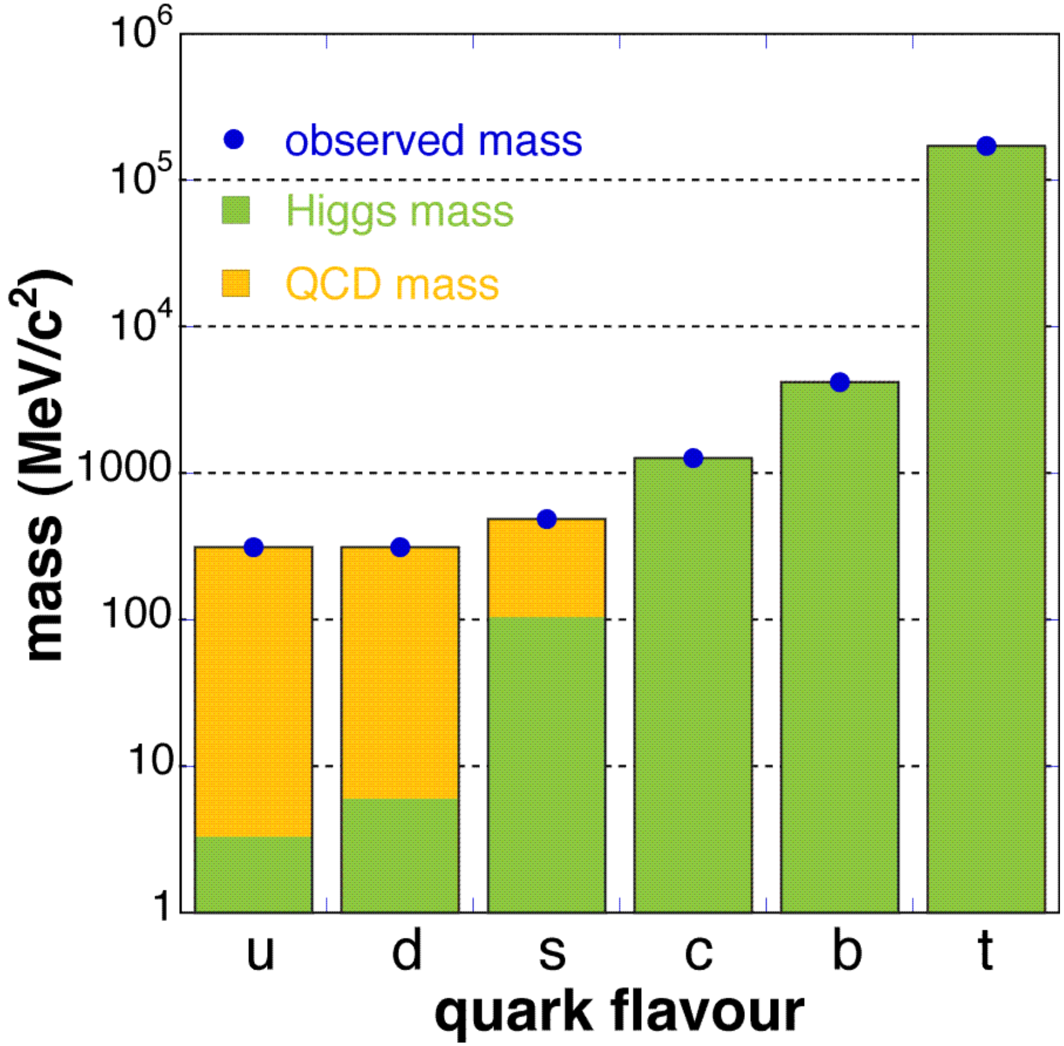
at large baryon density

Your 3-minute-discourse

Discuss with your neighbor

What generates the mass of the visible universe ?

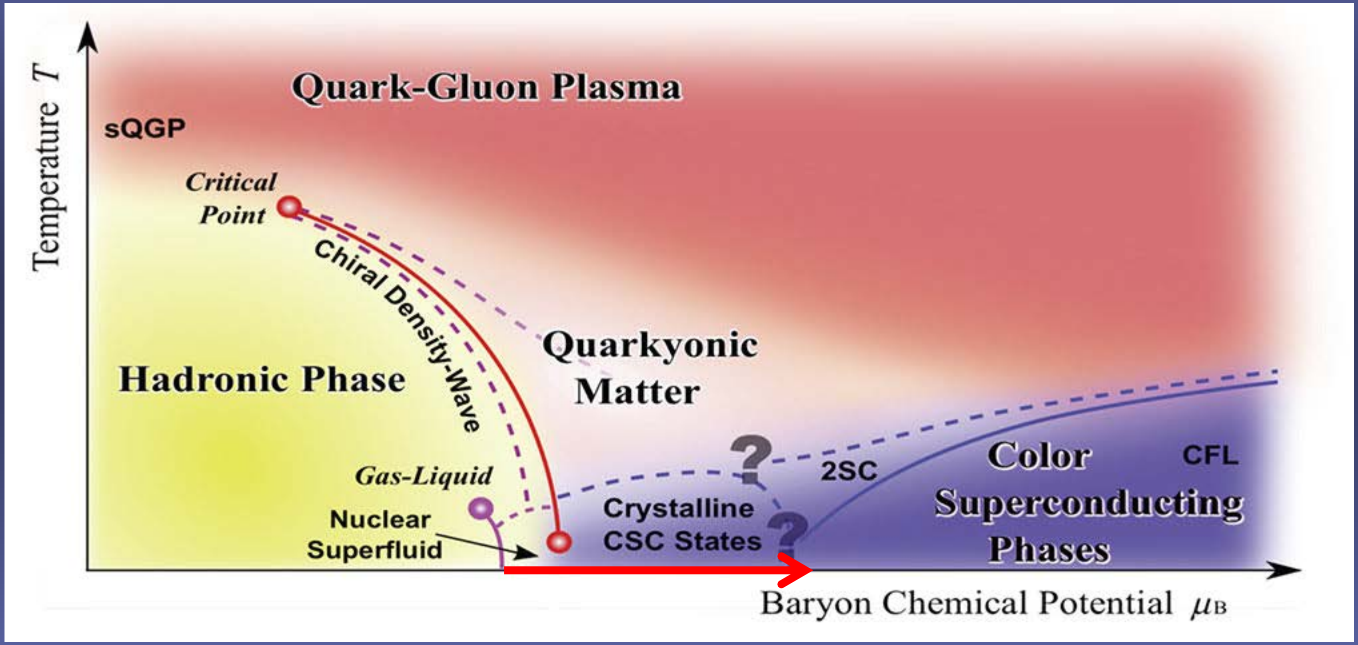
The strong interaction and the origin of hadron masses



not valid
for the light
pseudo-scalar mesons
π , η and K

Chapter II
Compressed nuclear matter in the universe

Late stages of heavy stars



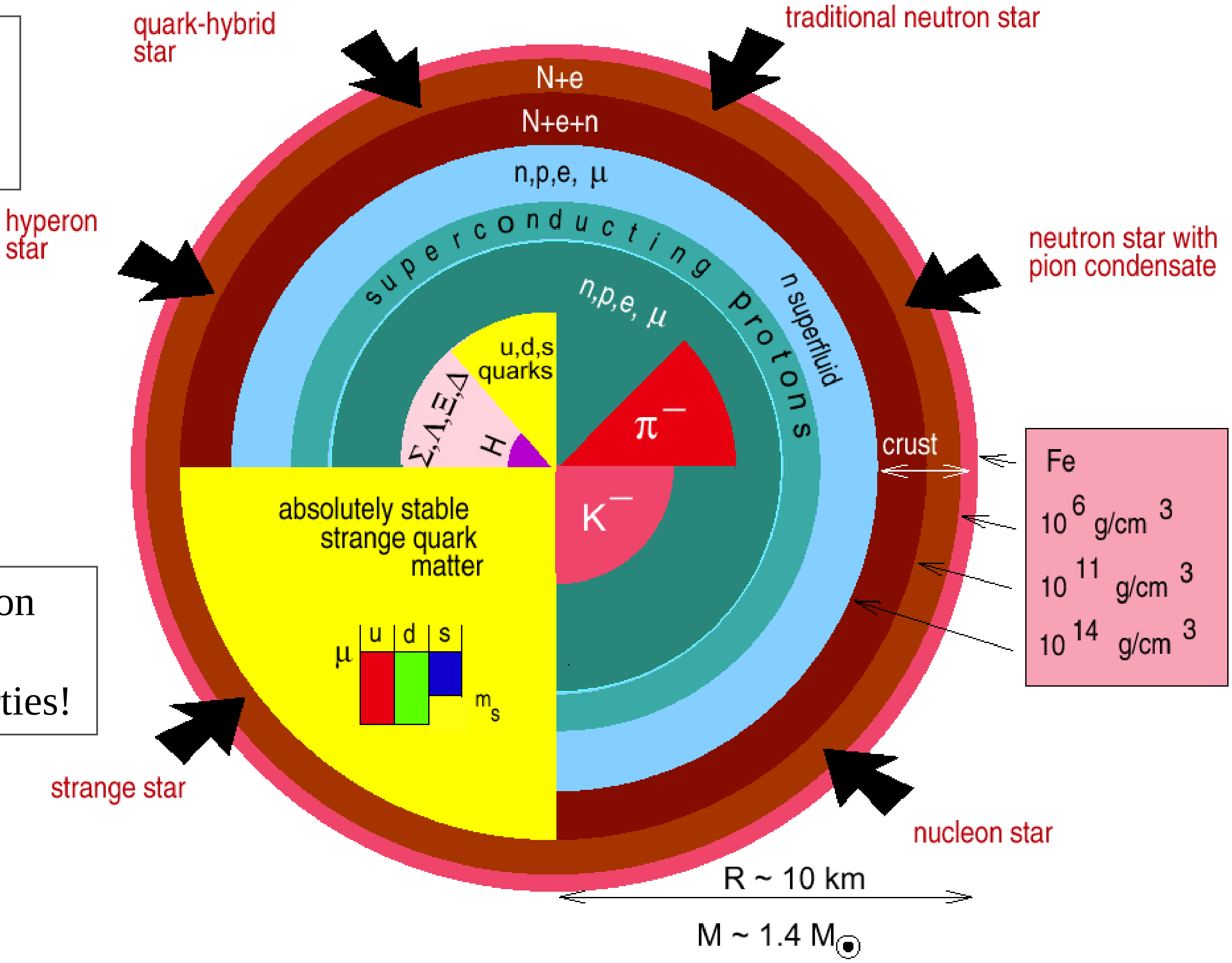
$T \approx 0\,,\ \rho \rightarrow 5\text{-}10\ \rho_0$

→ Lecture by Jürgen Schaffner-Bielich, Monday, 11:00

Composition of a neutron star

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

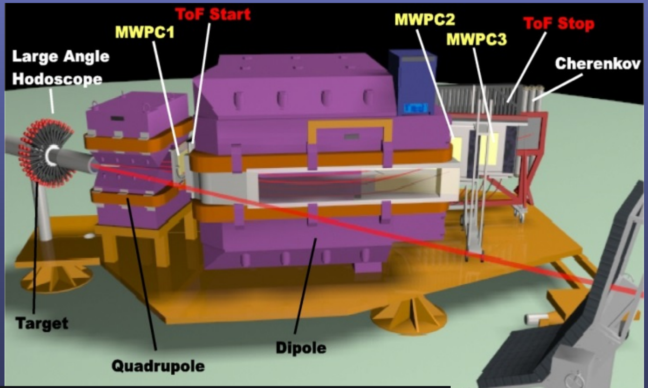
Each arrow indicates a different model for the neutron star.

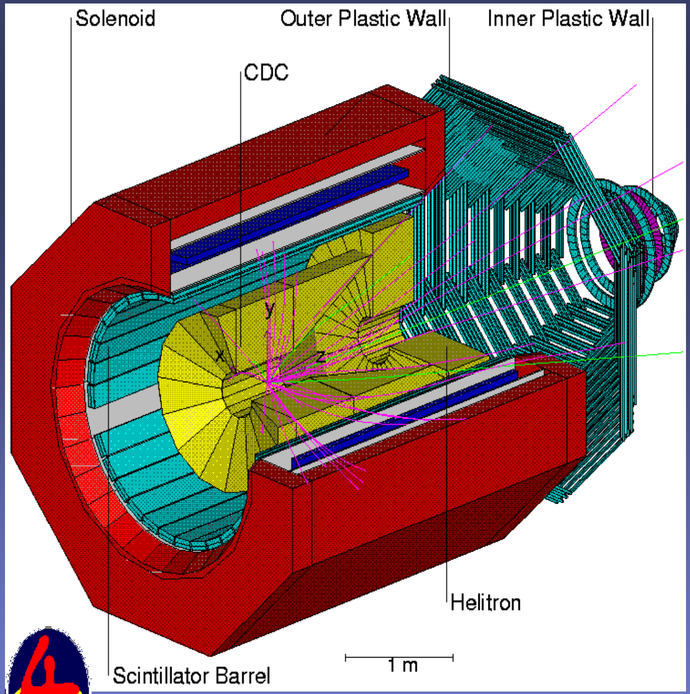


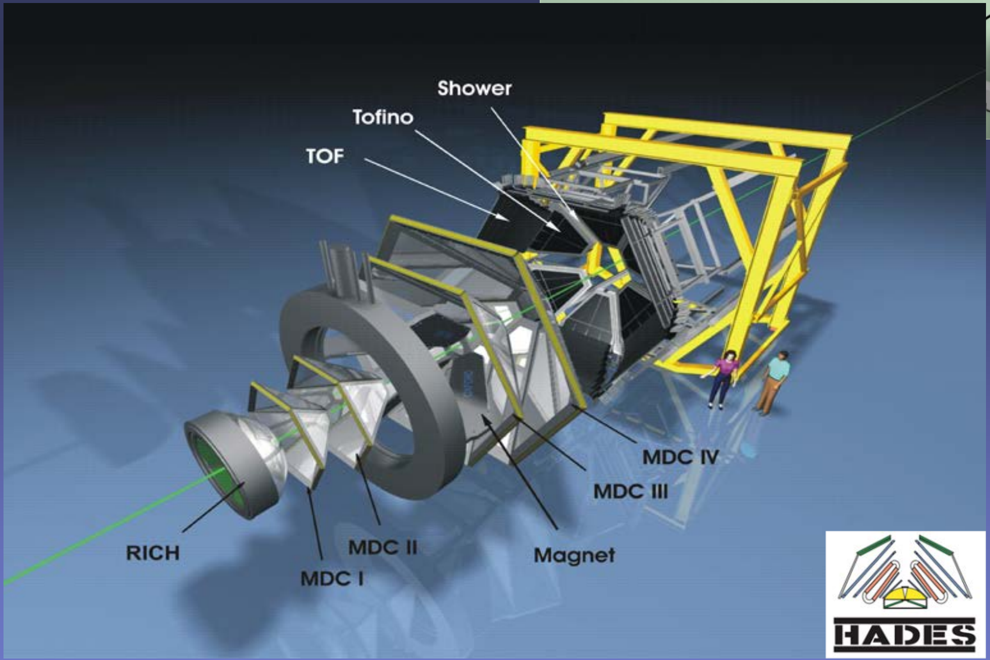
Each model is based on assumptions on nuclear matter properties!

Chapter III
Exploring dense nuclear matter in the laboratory

Nucleus-nucleus collisions at SIS18

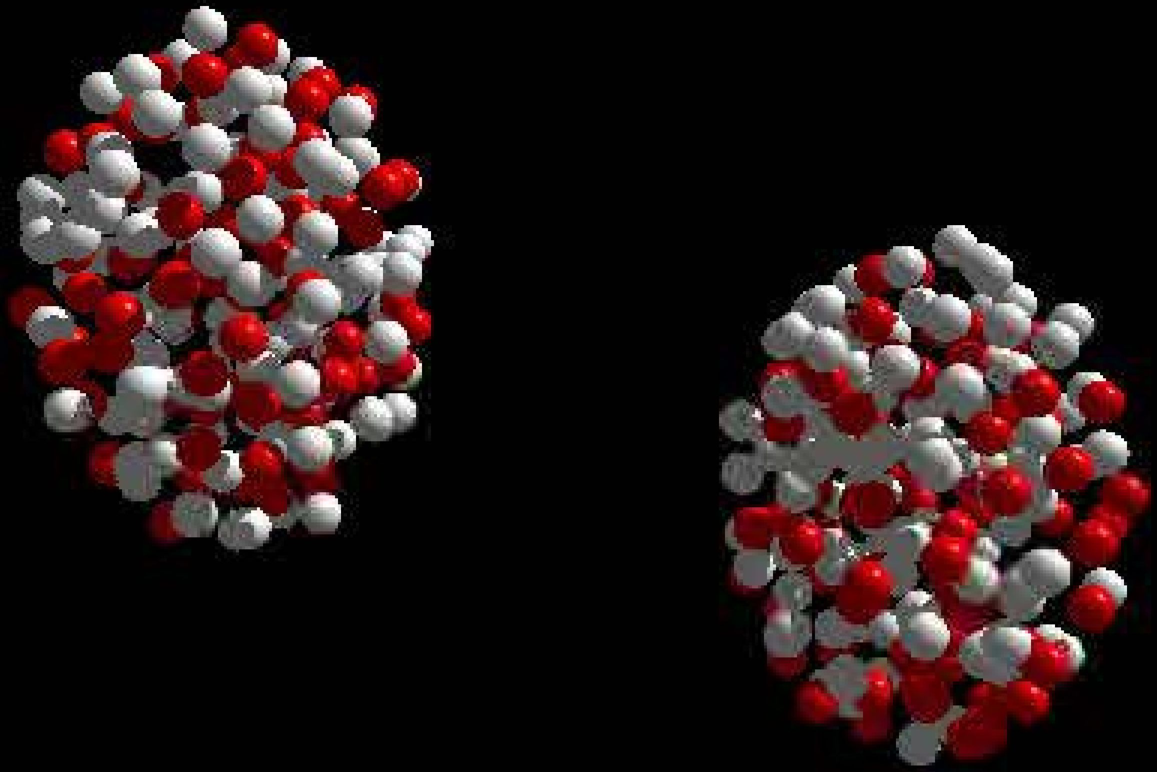






UrQMD

Au +Au   1.5 AGeV

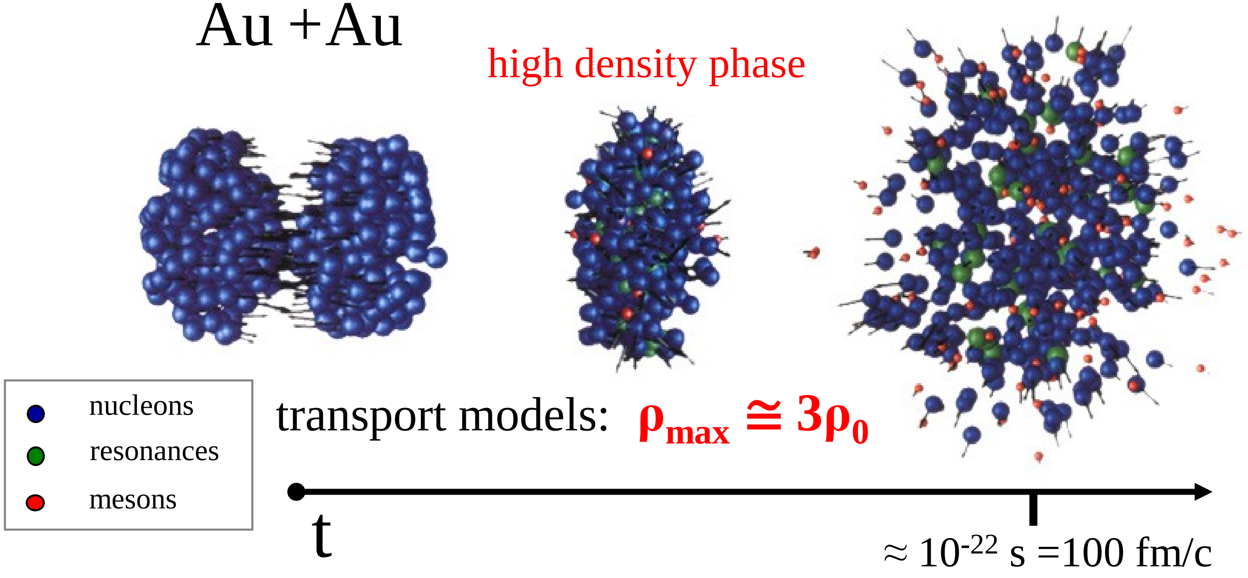


Relativistic nucleus-nucleus collisions at SIS18

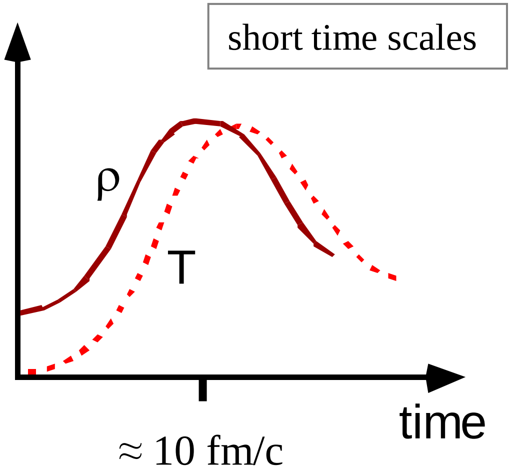
QMD , S. Bass , Uni. Frankfurt

Au +Au

high density phase

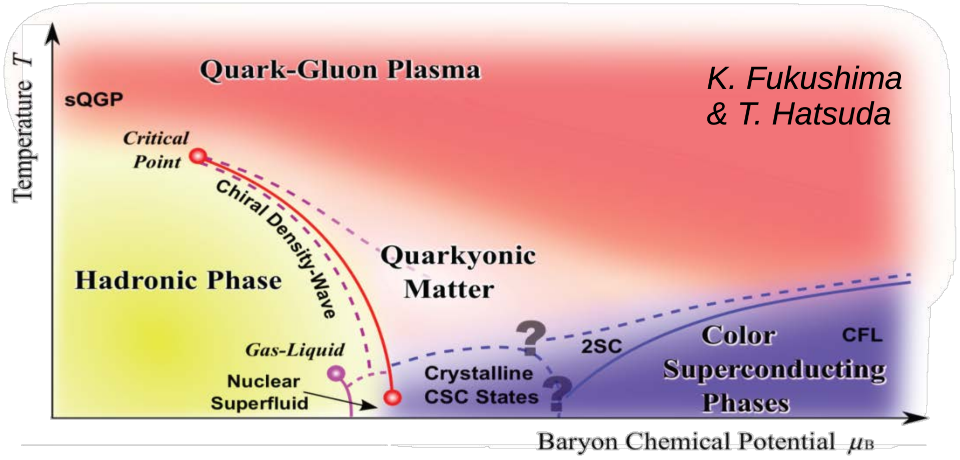


transport models: $\rho_{max} \cong 3\rho_0$



at SIS18 (max. 2 AGeV in A+A):
$\rho_B \approx 1 - 3\ \rho_0$
$T \approx 70 - 100$ MeV
→ hadronic phase
no evidence for phase transition

note:
system not necessarily equilibrated



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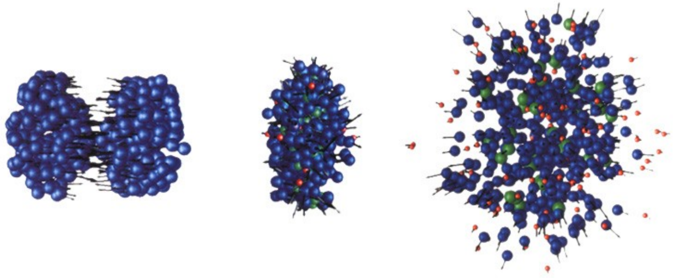
& T. Hatsuda

Observables at SIS18 energies



Selected observables:

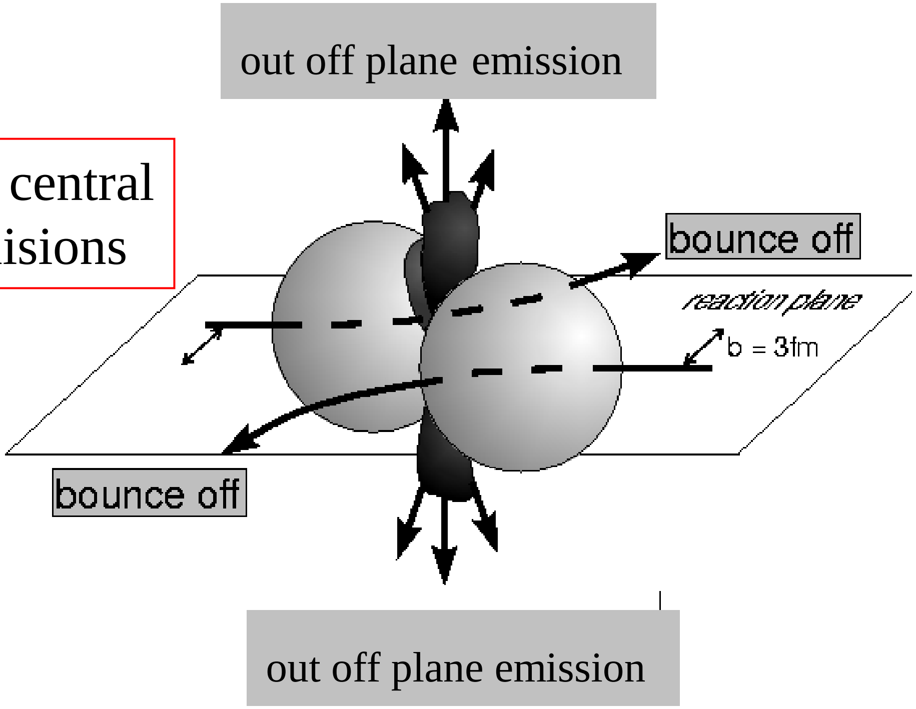
Collective motion of particles (flow)

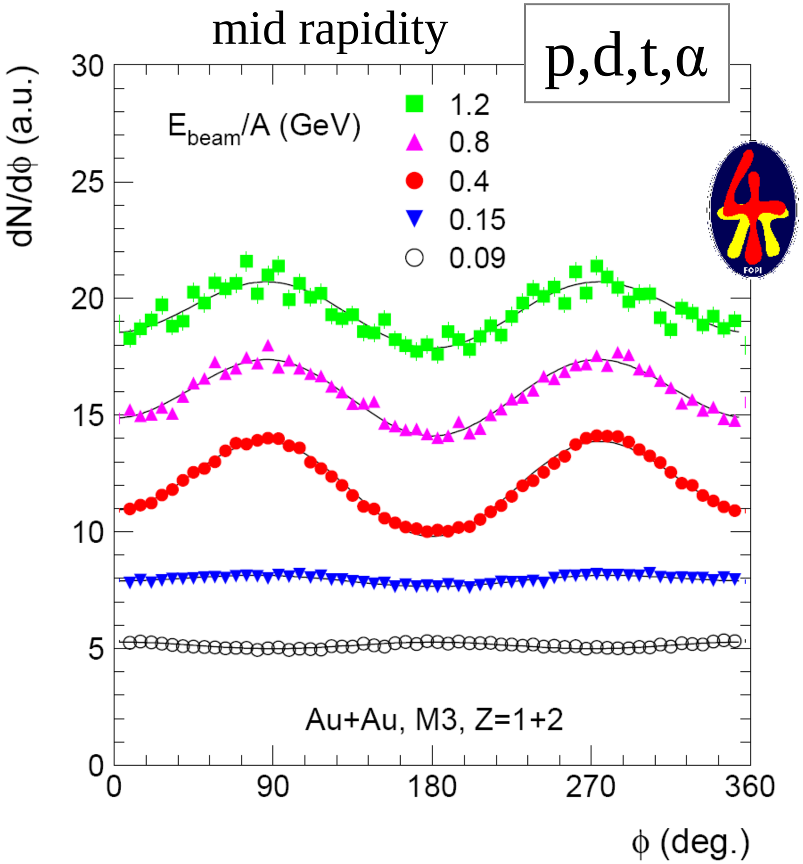
Strangeness production and propagation

Di-lepton production

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 :

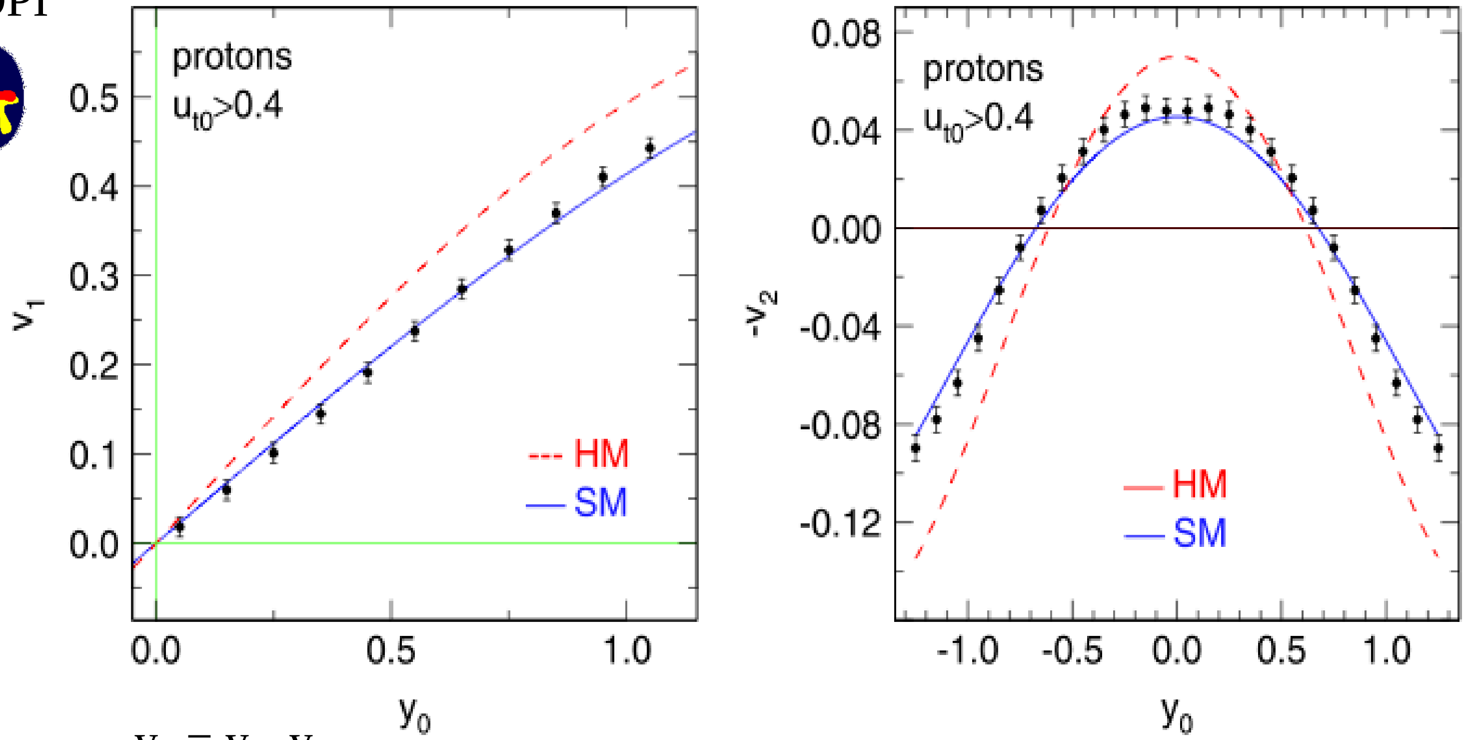
- v_1 the in-plane and
- v_2 the elliptic emission pattern

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

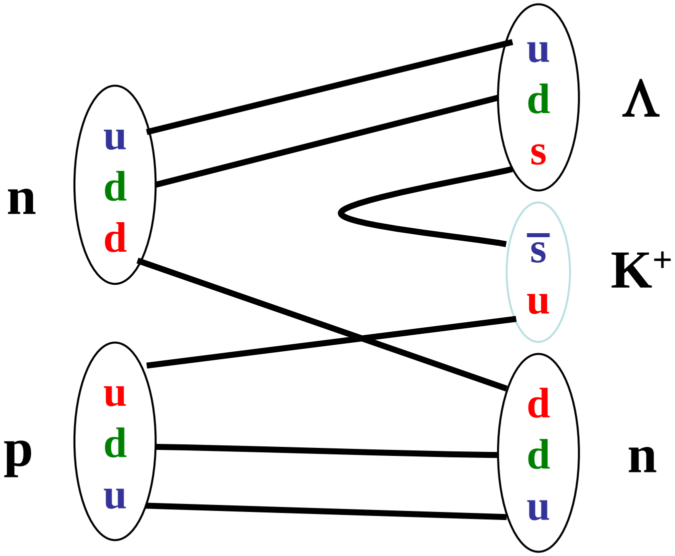
→ IQMD-SM describes $v_2(y_0)$ for $E_{lab} = 0.15$ AGeV to 1.5 AGeV !

The creation of strange mesons in elementary reactions

associate production !

K^+ mesons

m = 493.7 MeV/c^2

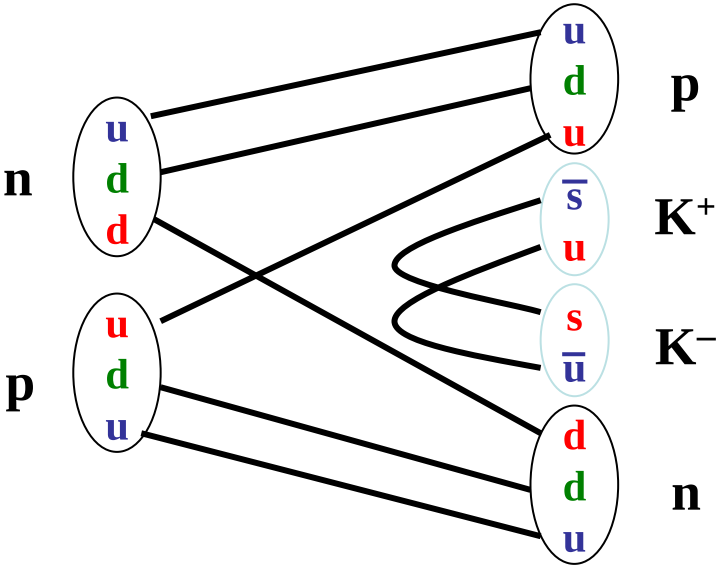


production threshold
(in lab. frame)

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

K^- mesons

m = 493.7 MeV/c^2



production threshold
(in lab. frame)

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

Additional channels in A+A collisions

e.g.

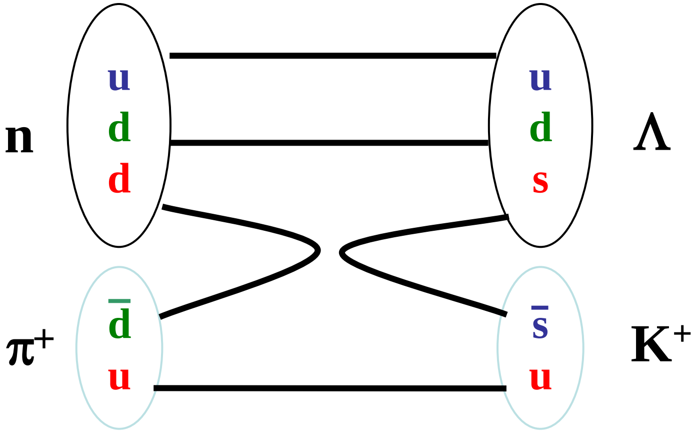
$$NN \rightarrow N\Delta$$

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

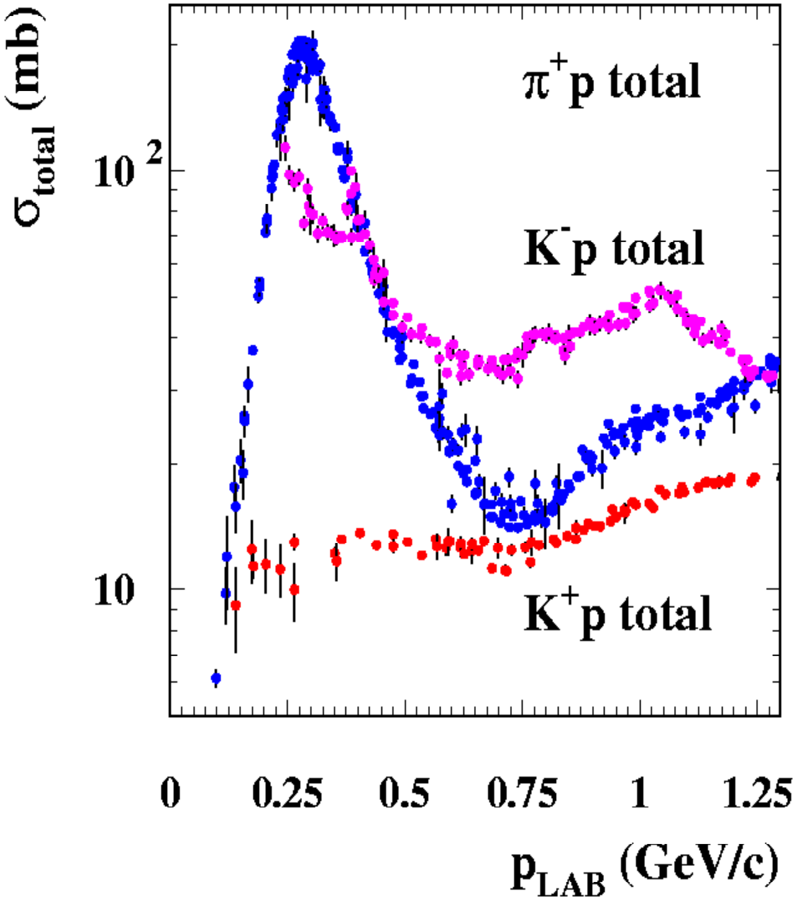
$$\pi N \rightarrow K^+Y$$

$(Y=\Lambda,\Sigma)$

multi step processes !



… and final state interaction !



The compression modulus of nuclear matter (ρ > ρ0)

Experiment: CS, 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

KAOS

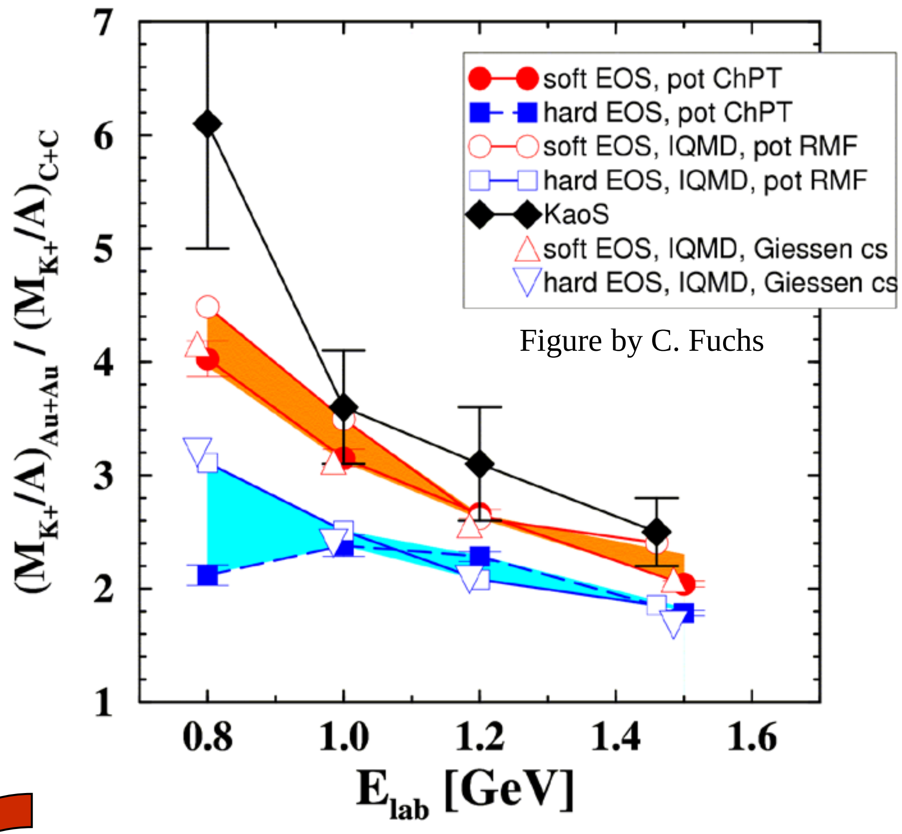
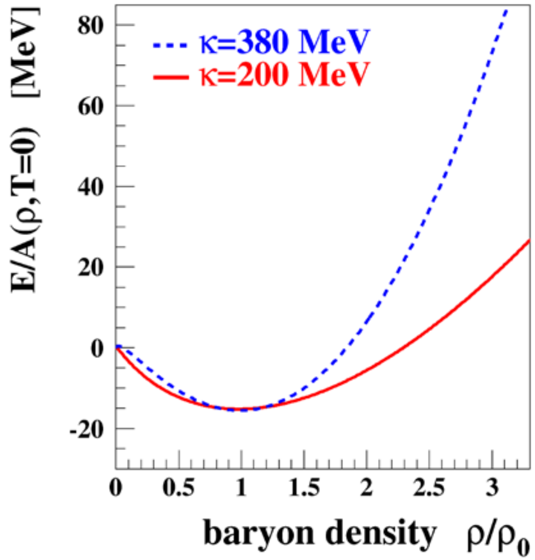


Figure by C. Fuchs

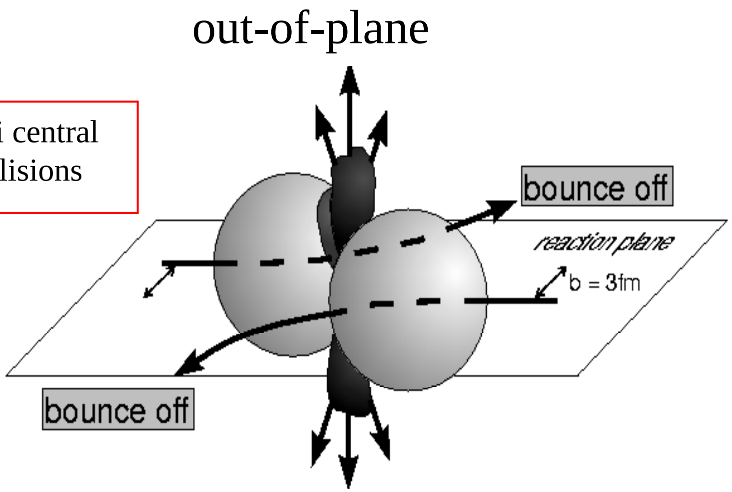


“soft” nuclear equation-of-state: $\kappa \approx 200$ MeV

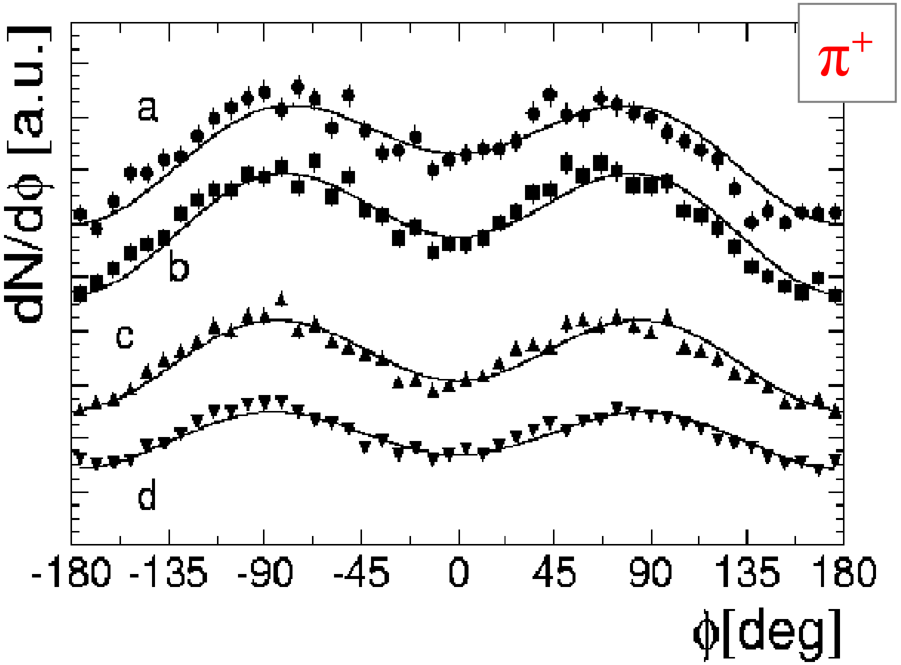
Azimuthal particle emission

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

semi central collisions



Bi+Bi 0.7AGeV, semi central

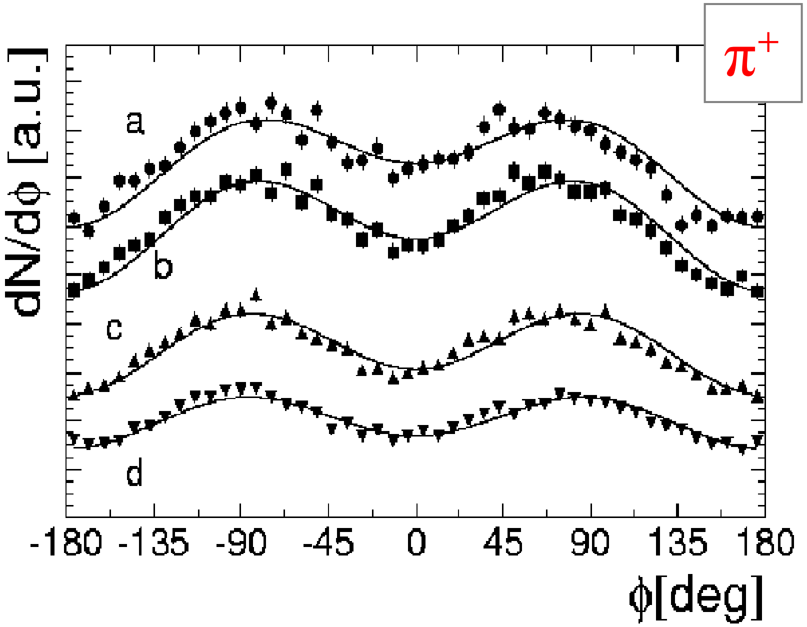


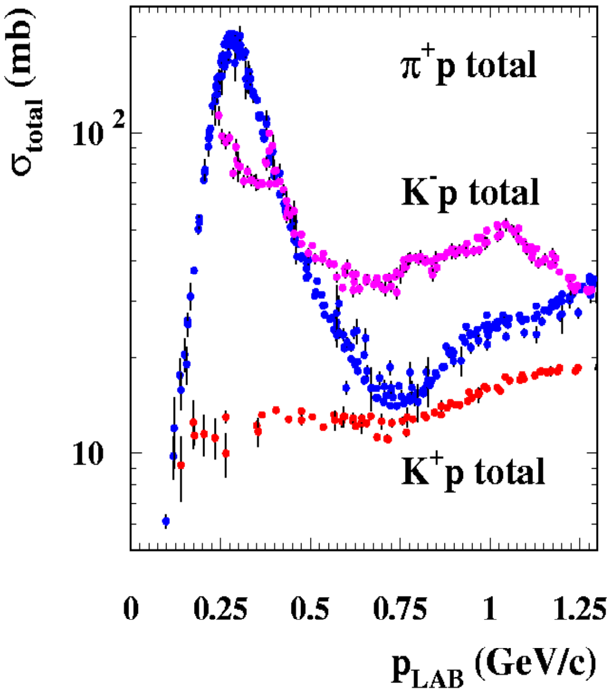
Your 3-minute-discourse

Discuss with your neighbor

Pions are enhanced emitted perpendicular to the reaction plane.

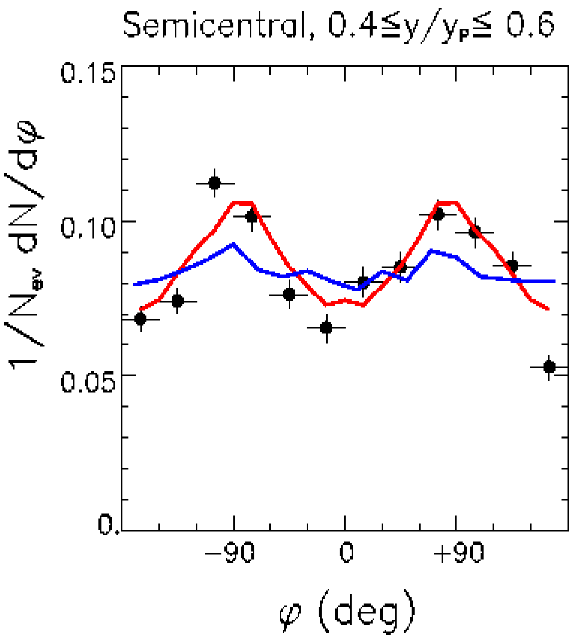
What would you expect how the K^+ emission pattern looks like ?

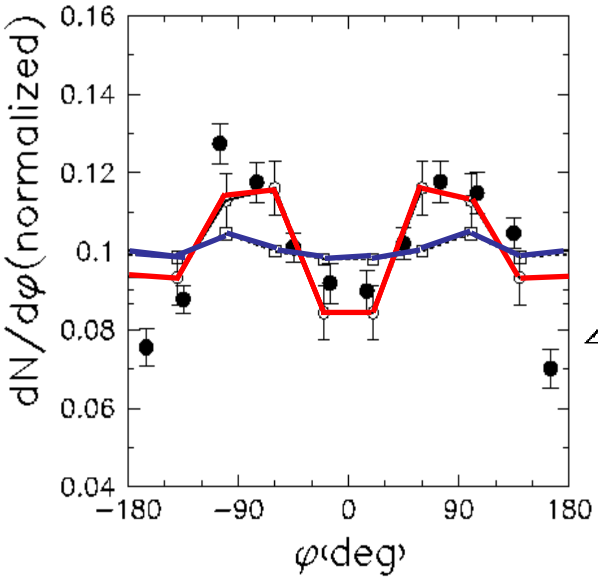


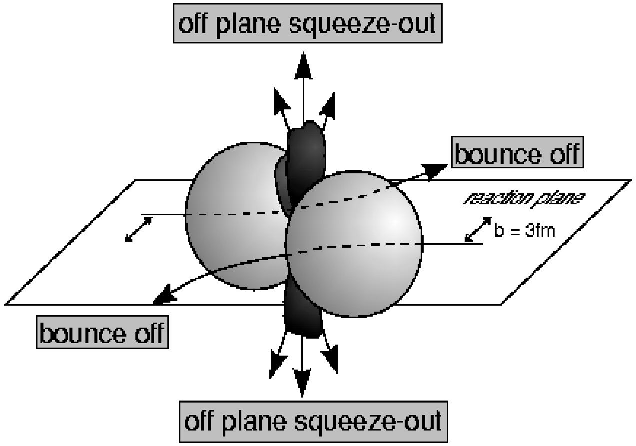


K^+ emission pattern in Au+Au collisions at 1 AGeV

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:

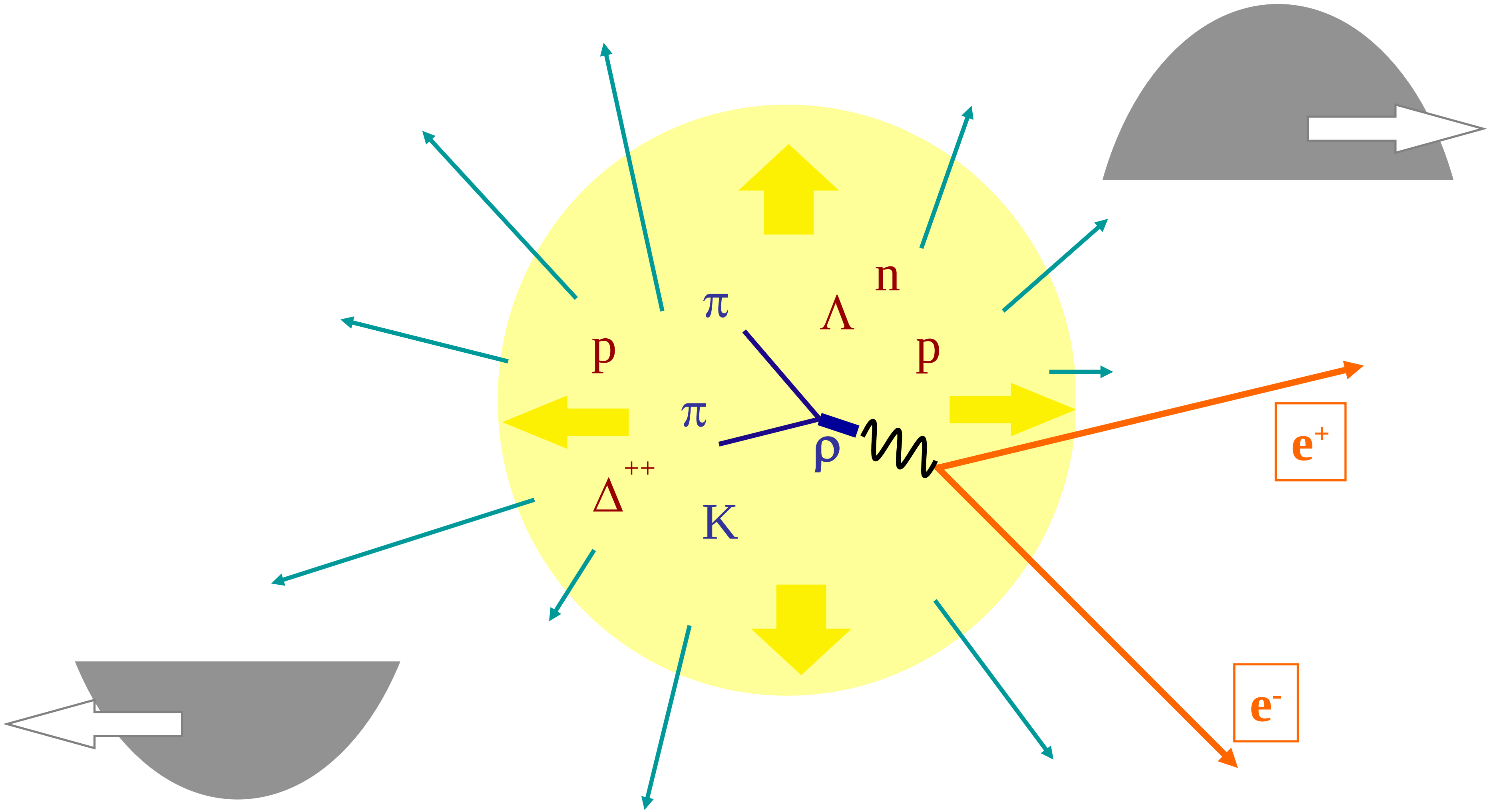
Z.S. Wang et al.,
Eur. Phys. J. A5 (1999) 275

Transport models:

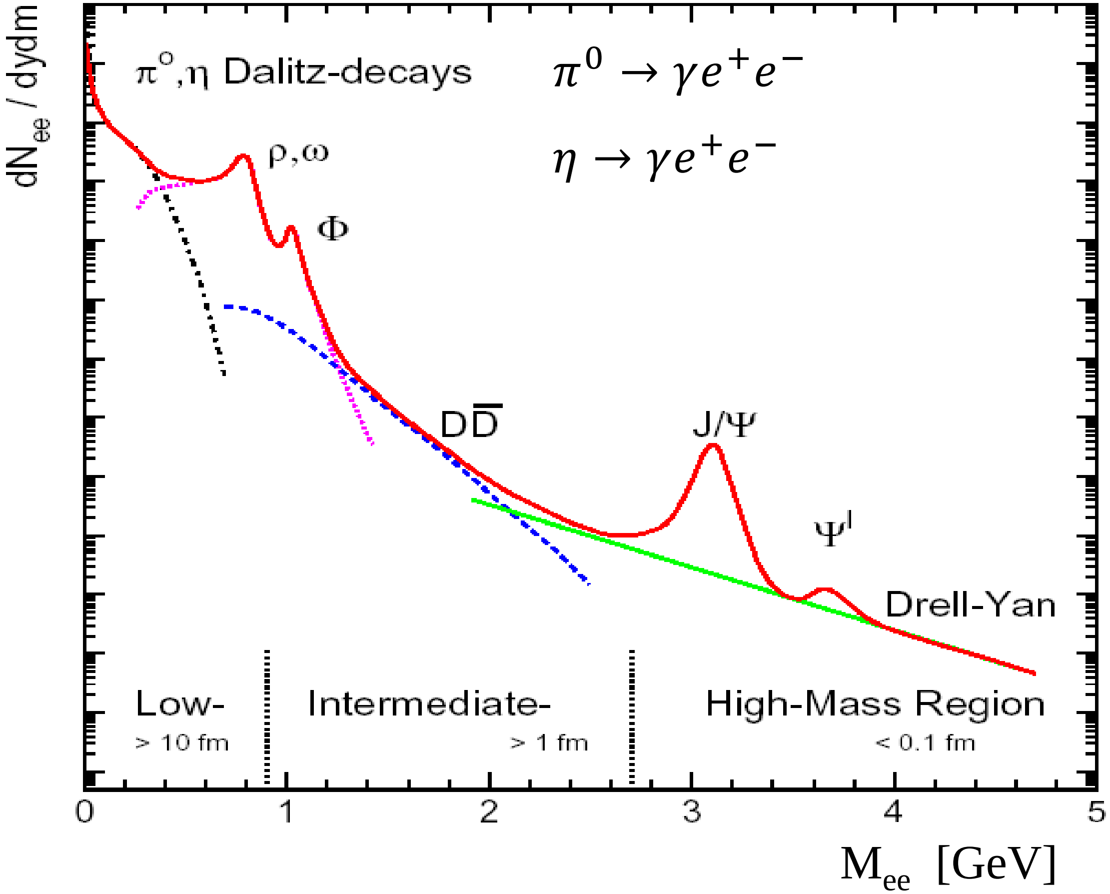
— with K^+N potential

— no K^+N potential

e^+e^- pairs (dileptons) – penetrating probes



Sources of e^+e^- pairs (dileptons)



invariant mass

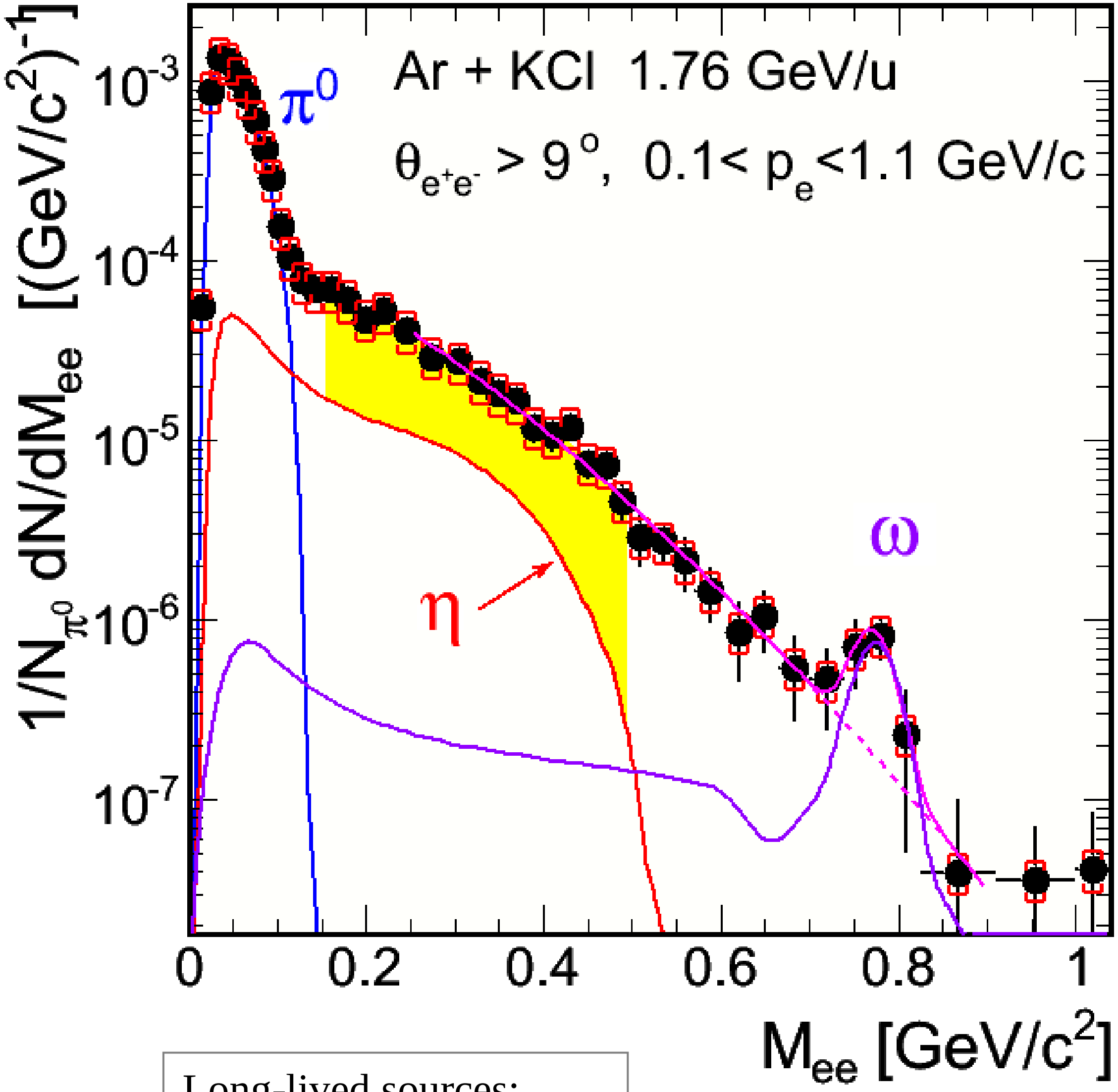
$$M_{ee} = \sqrt{p_{e+} p_{e-}} \sin \frac{\vartheta_{e+e-}}{2}$$

	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}

$E_{thr,lab}$ (NN)
1.7 GeV
1.8 GeV
2.6 GeV

Dileptons in **nucleus-nucleus** collisions at SIS18

HADES, PRC 84 (2011) 014902



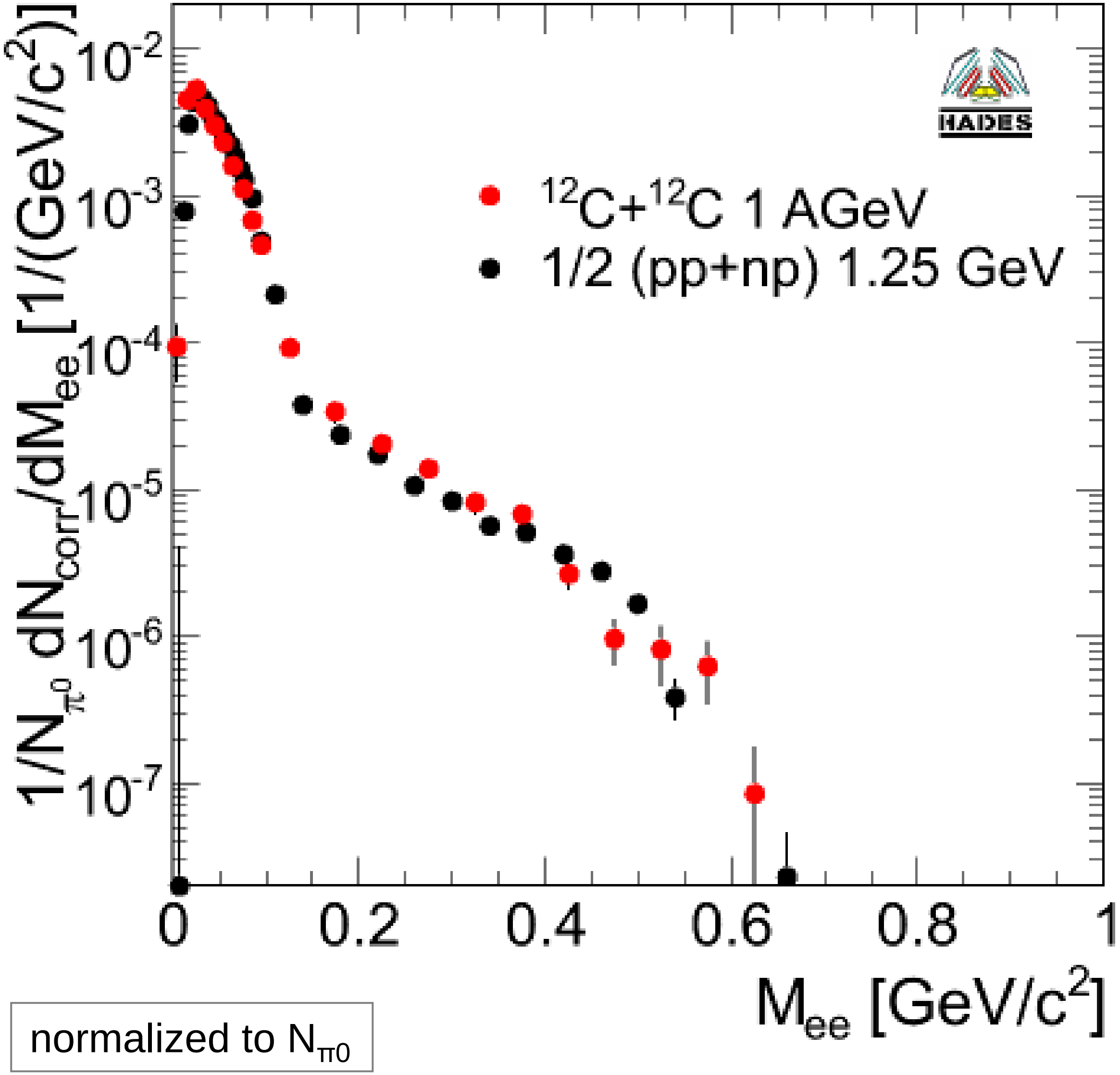
Long-lived sources:
π^0, η, and ω

ρ/ω mass region:
strength of ρ meson ?

melting ρ meson ?

Dileptons - reference measurements at SIS18

HADES, PL.B 663 (2008) 43 & PLB 690 (2010) 118



normalized to $N_{\pi 0}$

Reference measurements:

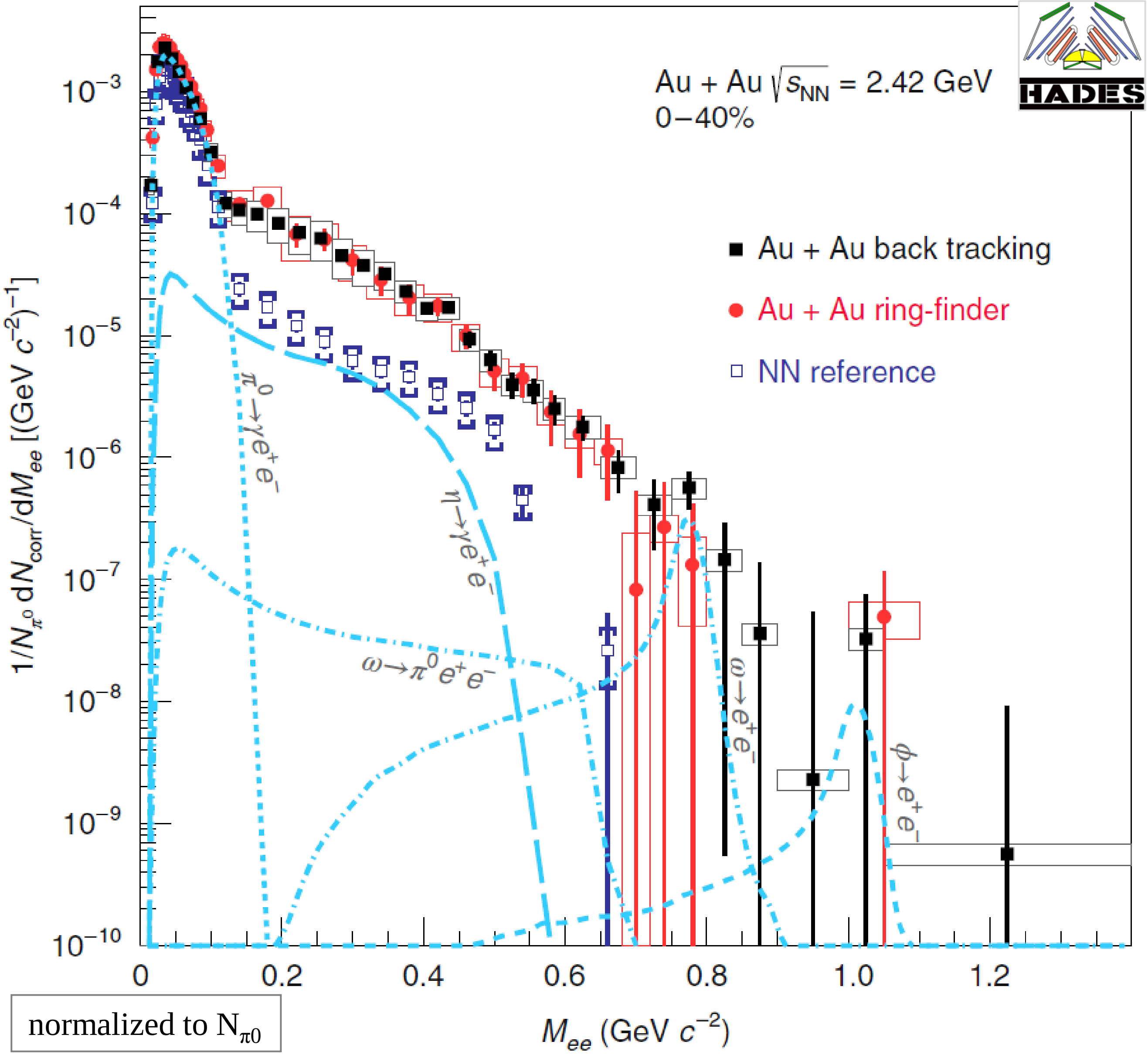
- ● C+C collisions
  (= light symmetric collision system)
- ● p+p and n+p collisions

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 !**)

Dileptons in **nucleus-nucleus** collisions at SIS18

HADES, Nature Physics, 2019, https://doi.org/10.1038/s41567-019-0583-8



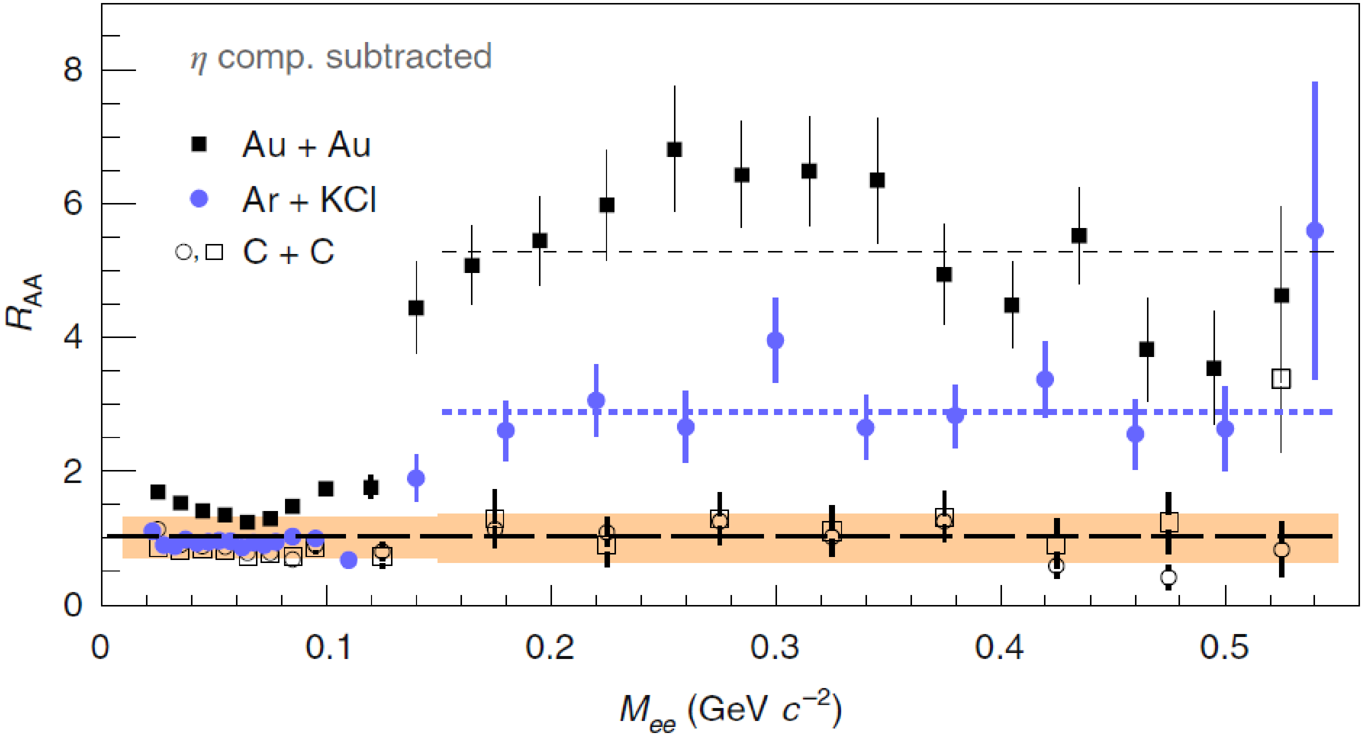
normalized to $N_{\pi 0}$

Dileptons - excess yield at SIS18

HADES, Nature Physics, 2019, https://doi.org/10.1038/s41567-019-0583-8

$$R_{AA} = \frac{1}{\langle A_{part} \rangle} \frac{dN^{AA}}{dM_{ee}} \left(\frac{dN^{NN}}{dM_{ee}} \right)^{-1}$$

"excess" over long-lived e^+e^- sources



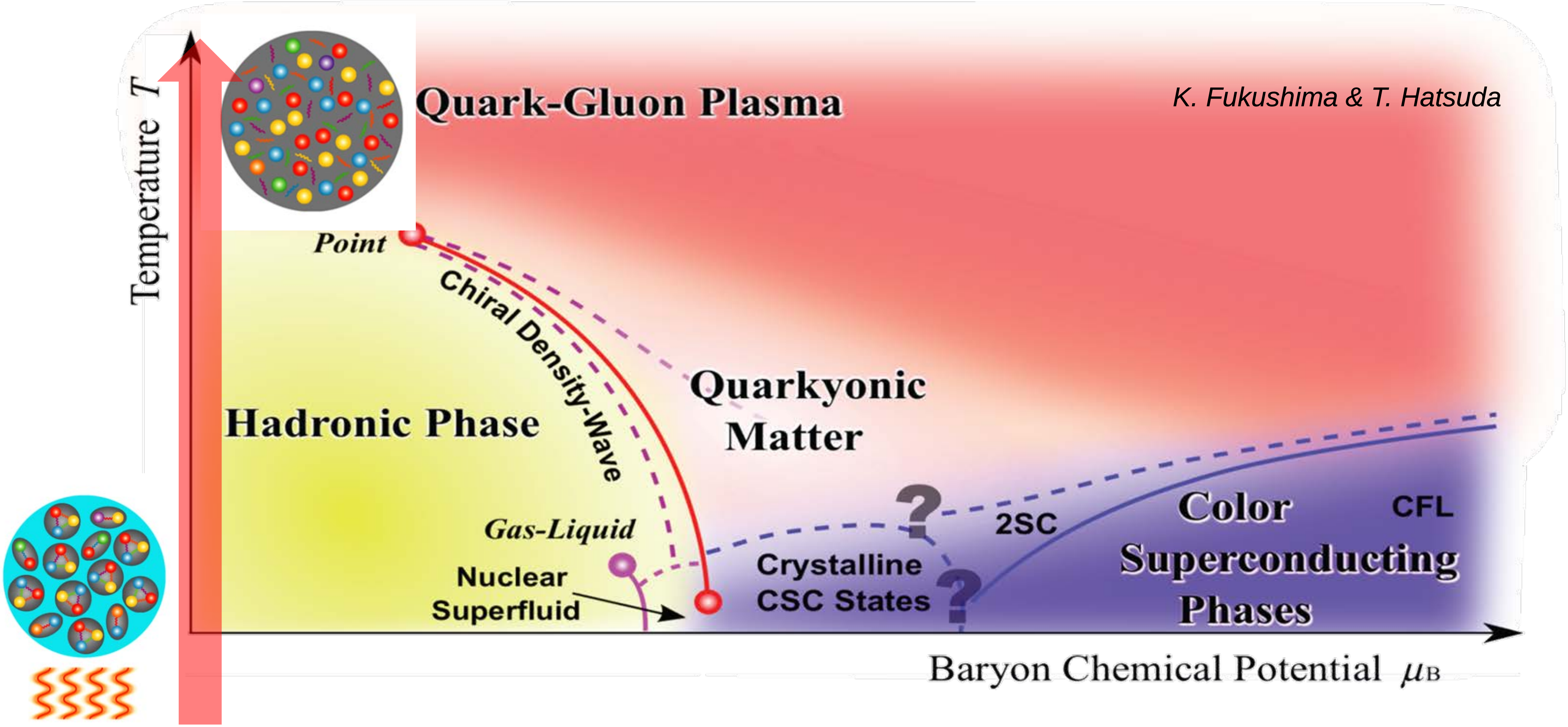
melting ρ ?

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)**

Exploring the QCD phase diagram



At very high temperature:

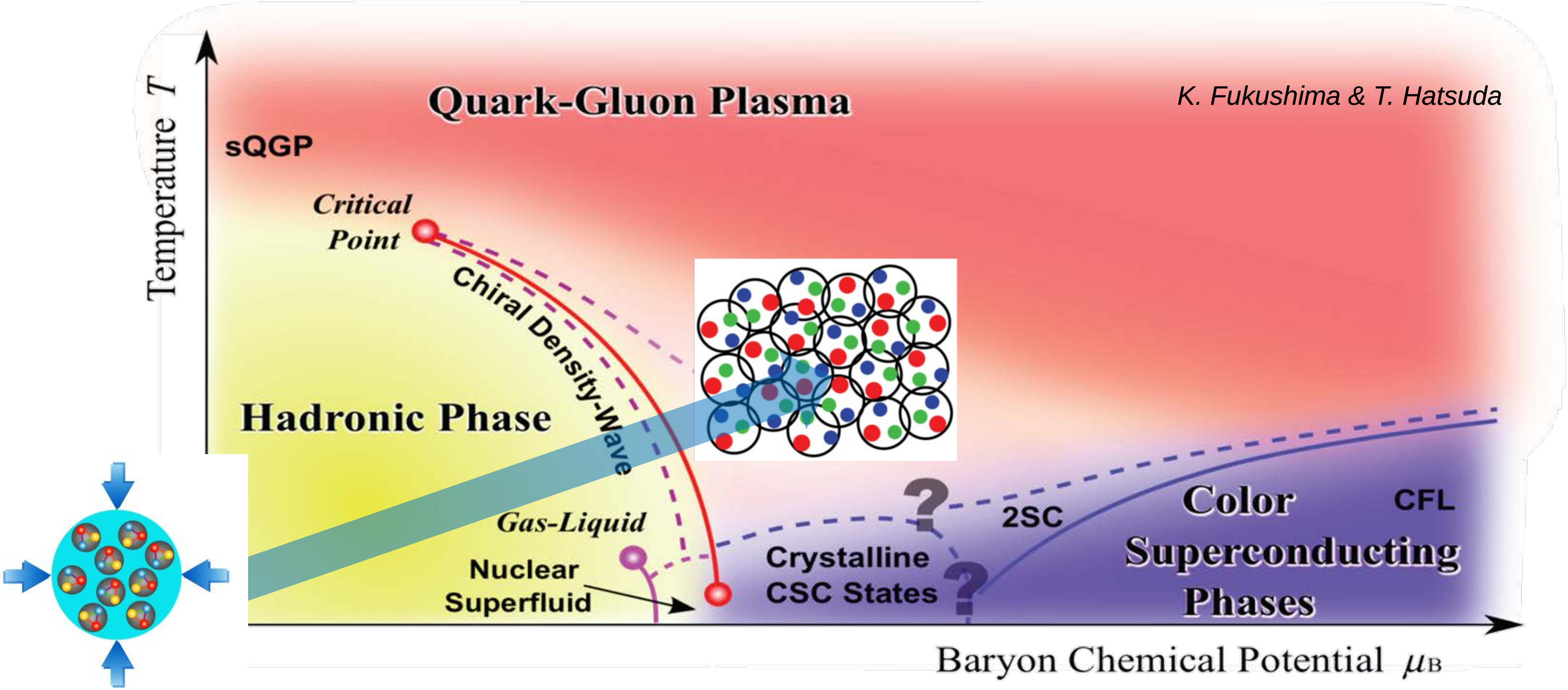
N of baryons ≈ N of antibaryons → situation similar to early universe

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

Experiments:

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

Exploring the QCD phase diagram



At high baryon density:

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

→ Lattice QCD not (yet) applicable

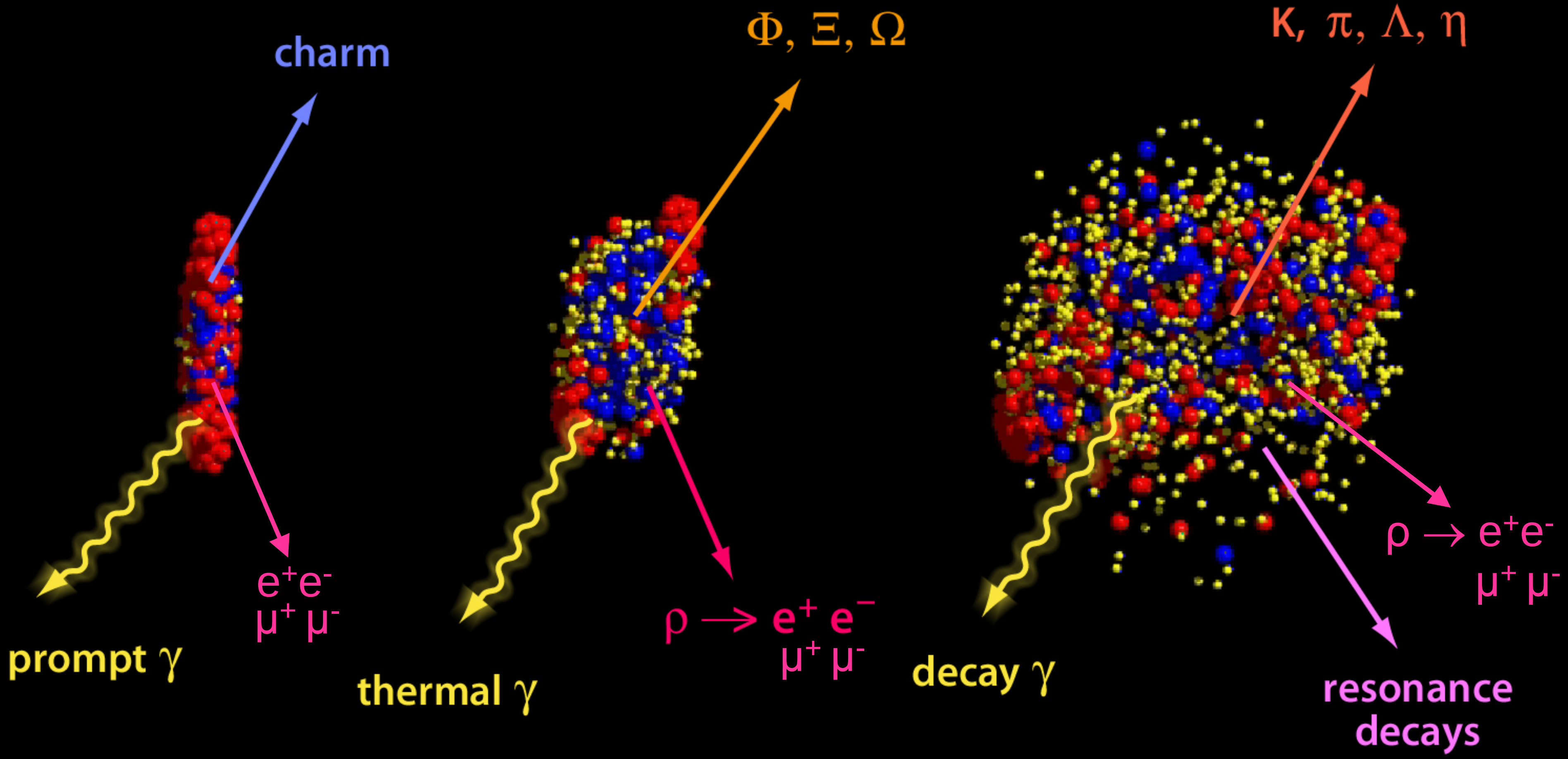
→ Models predict first order phase transition with mixed or exotic phases

Experiments:

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


U+U 23 GeV/A
t=-17.14 fm/c
UrQMD Frankfurt/M

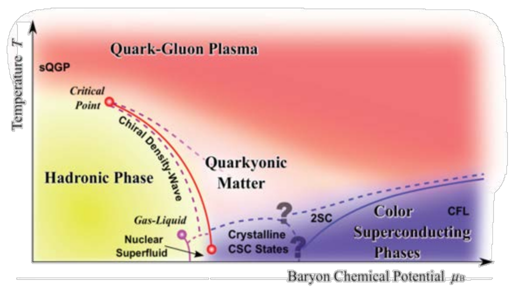
Messengers from the dense fireball



UrQMD transport calculation U+U 23 AGeV

CBM physics case and **observables**

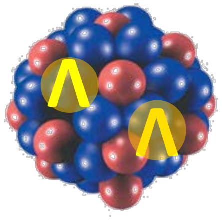
New phases of strongly-interacting matter ?
- excitation function and flow of lepton pairs
- excitation function and flow of strangeness (K, Λ, Σ, Ξ, Ω)



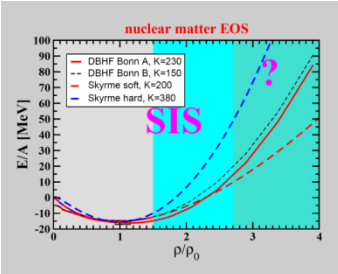
Deconfinement phase transition at high ρ_B ?
- excitation function and flow of charm (J/ψ, ψ', D^0, $D^\pm$, Λ_c)
- anomalouus charmonium suppression
- event-by-event fluctuations of conserved quantities

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

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

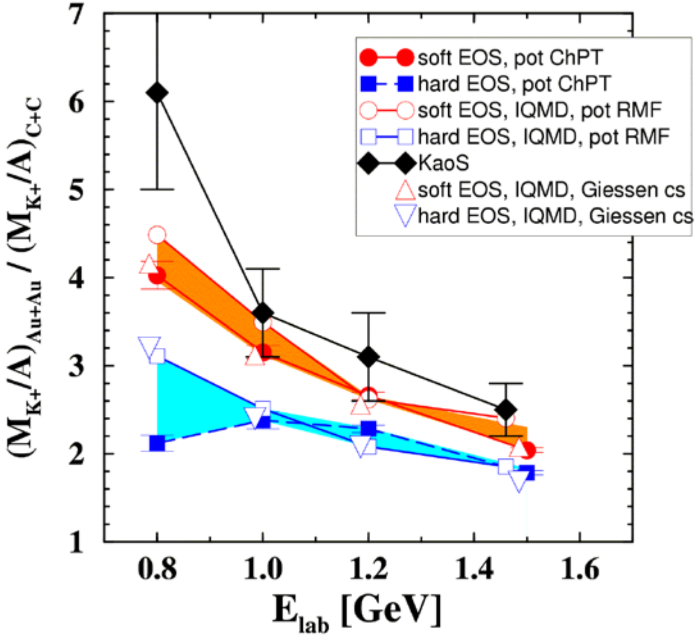


The equation-of-state at neutron star core densities
- collective flow of hadrons
- particle production at threshold energies (multi-strange hyperons)



Nuclear equation-of-state at high (net) baryon densities

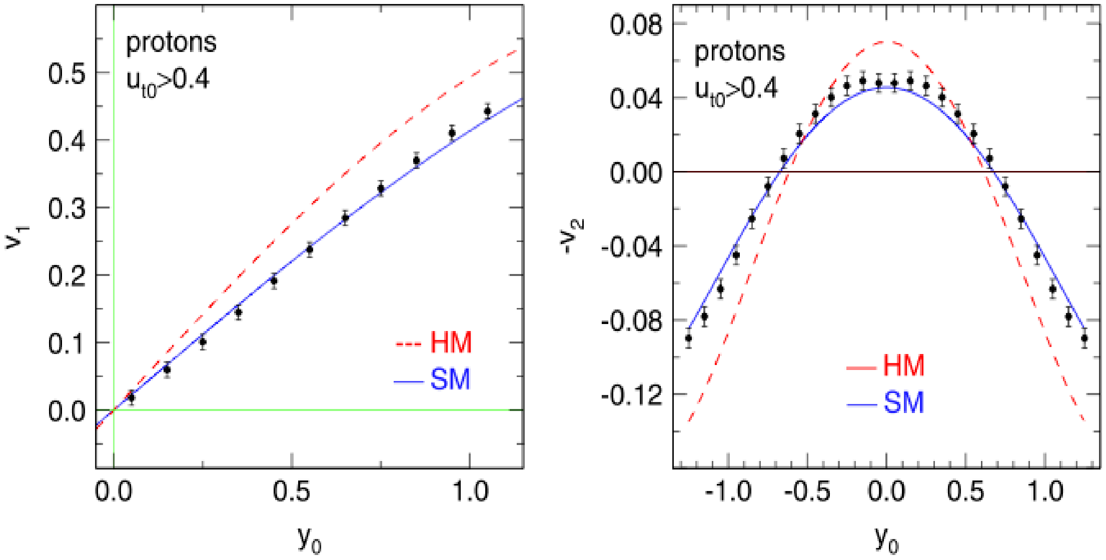
Experiment: CS et al., Phys. Rev. Lett. 86 (2001) 39
Theory: RQMD C. Fuchs et al., Phys. Rev. Lett. 86 (2001) 1974
IQMD Ch. Hartnack, J. Aichelin, J. Phys. G 28 (2002) 1649



FOPI

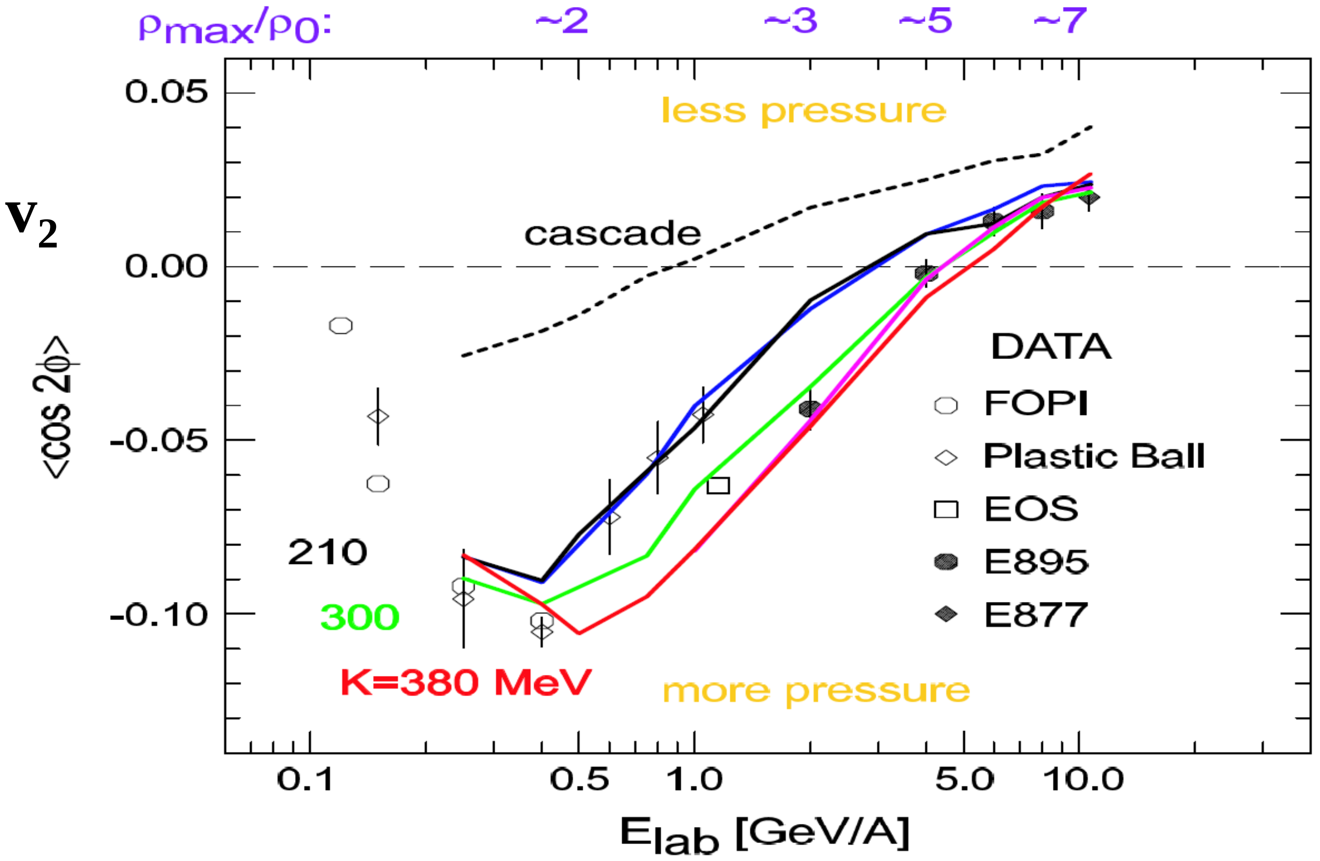
Au+Au 1.5 AGeV

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



Nuclear equation-of-state at high (net) baryon densities

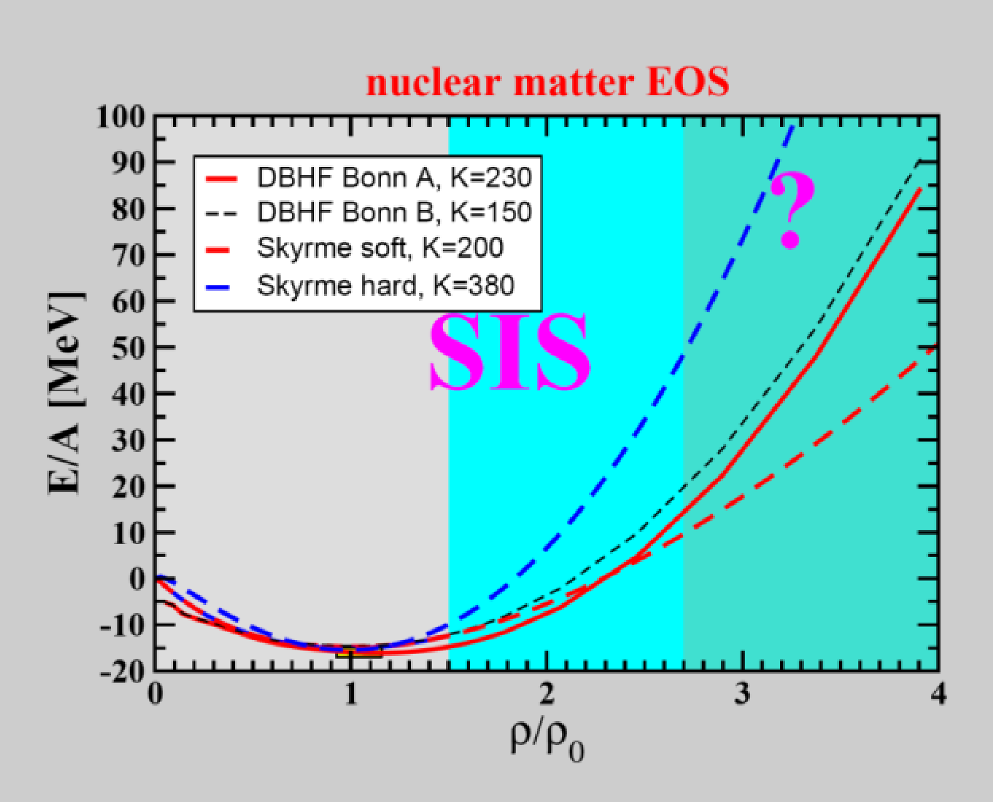
P. Danielewicz et al., Science 298 (2002) 1592



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

inconclusive at AGS energies

Nuclear equation-of-state at the **highest** (net) baryon densities

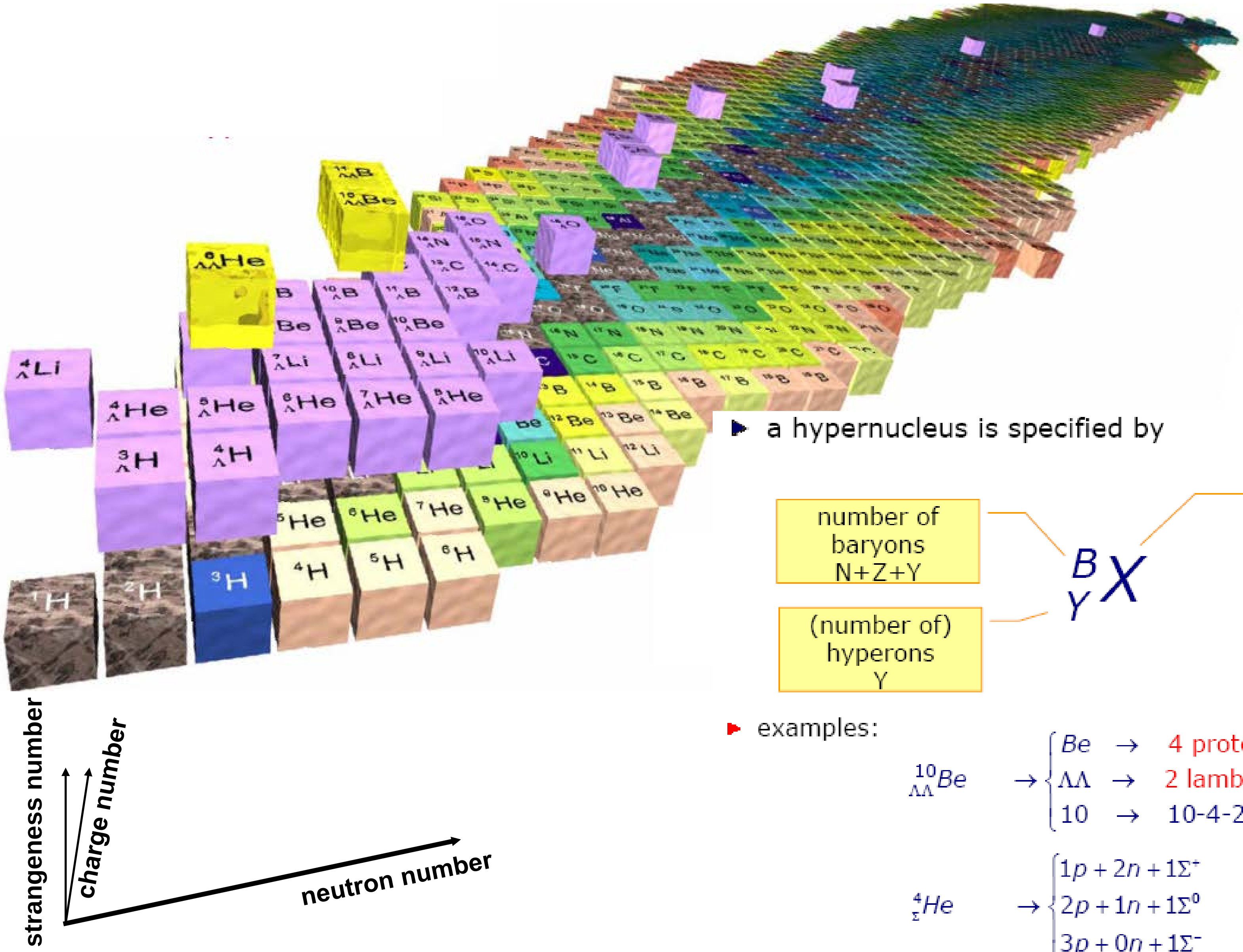


equation-of-state
at
neutron star core densities ?

→ (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)

Strange matter - hypernuclei



- a hypernucleus is specified by

$${}^{B}_{Y}X$$

number of baryons N+Z+Y

(number of) hyperons Y

element = total charge (not number of protons)

- examples:

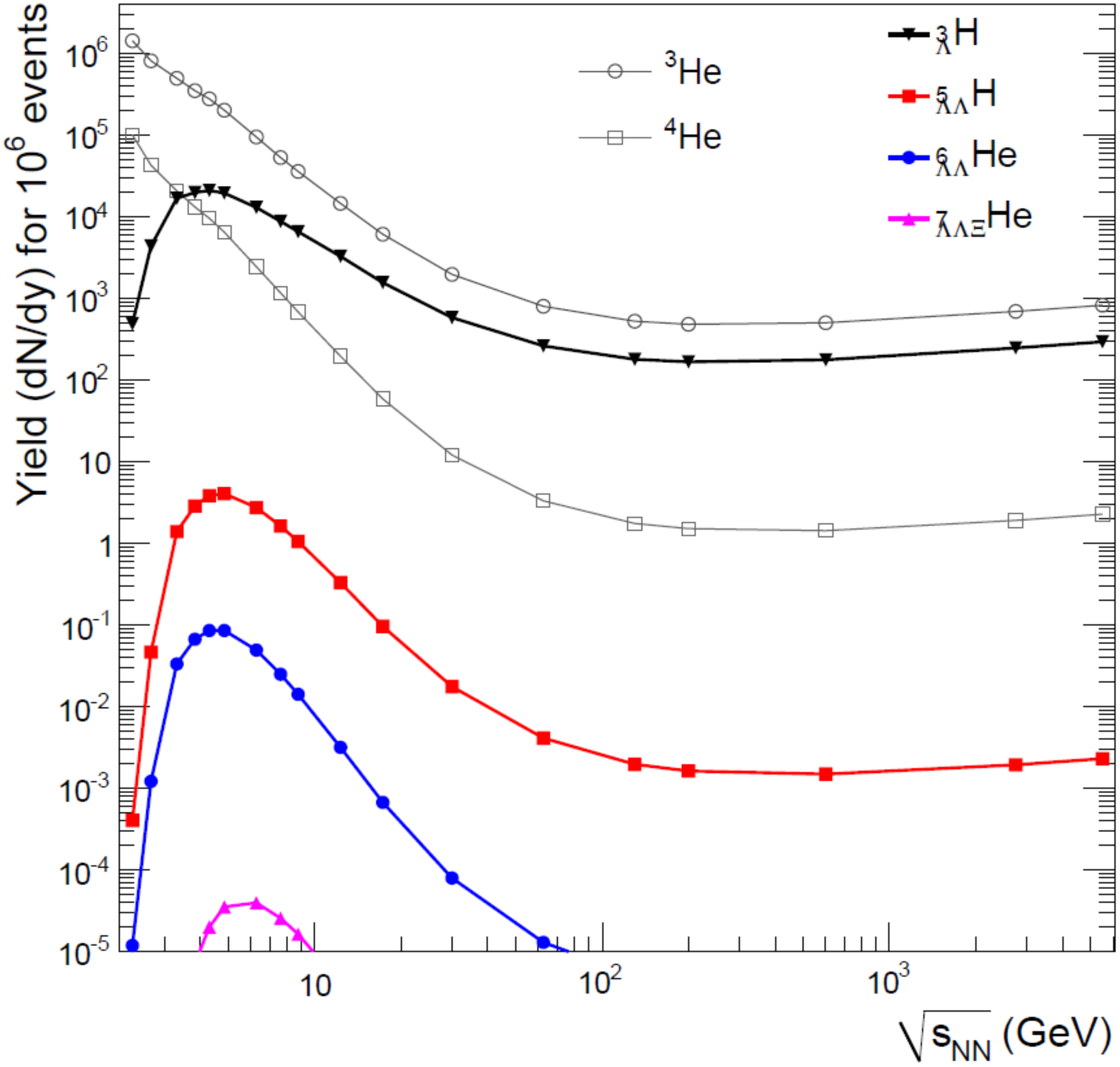
$$^{10}_{\Lambda\Lambda}Be \rightarrow \begin{cases} Be & \rightarrow \quad 4 \text{ protons} \\ \Lambda\Lambda & \rightarrow \quad 2 \text{ lambdas} \\ 10 & \rightarrow \quad 10\text{-}4\text{-}2=4 \text{ neutrons} \end{cases}$$

$$^{4}_{\Sigma}He \rightarrow \begin{cases} 1p+2n+1\Sigma^{+} \\ 2p+1n+1\Sigma^{0} \\ 3p+0n+1\Sigma^{-} \end{cases} \quad \text{indistinguishable}$$

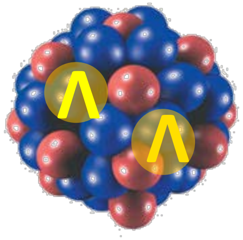
Strange matter – predictions at FAIR energies

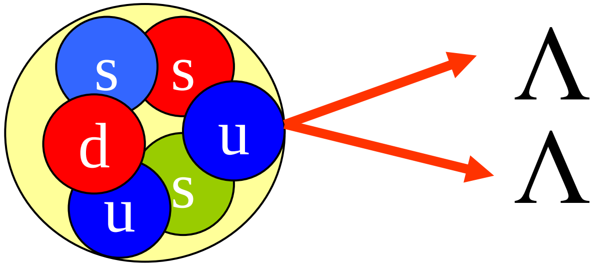
Statistical model

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



Strange matter





double hypernuclei

strange dibaryon

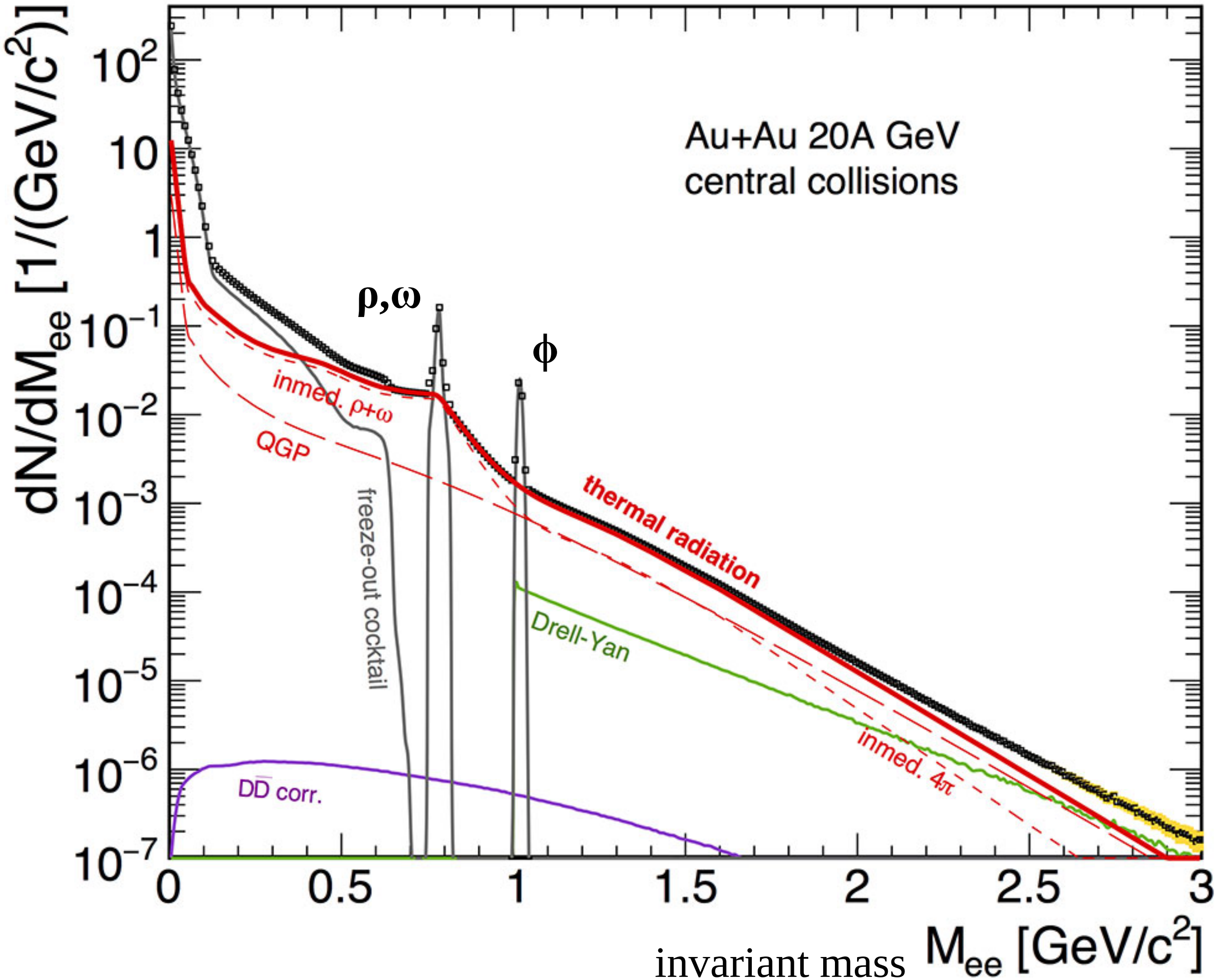
Search for strange matter in the form of strange dibaryons and heavy multi-strange short-lived objects

Production in nucleus-nucleus collisions via coalescence of hyperons and light nuclei

→ existence and yield of (exotic) strange objects ?
→ ΛΛ, NΛ interactions ?
→ remnants of dense (chirally restored?) matter?

Deconfinement phase transition at high μ_B ?

e^+e^- pairs



ρ,ω

ϕ

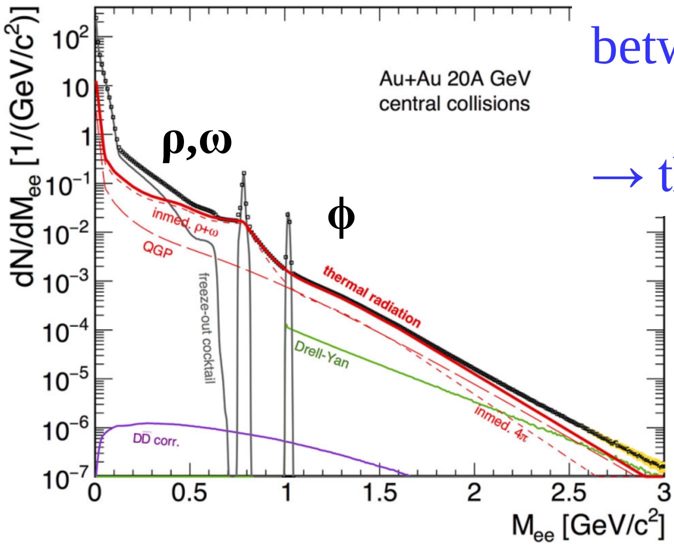
invariant mass

simulation

within
CBM acceptance

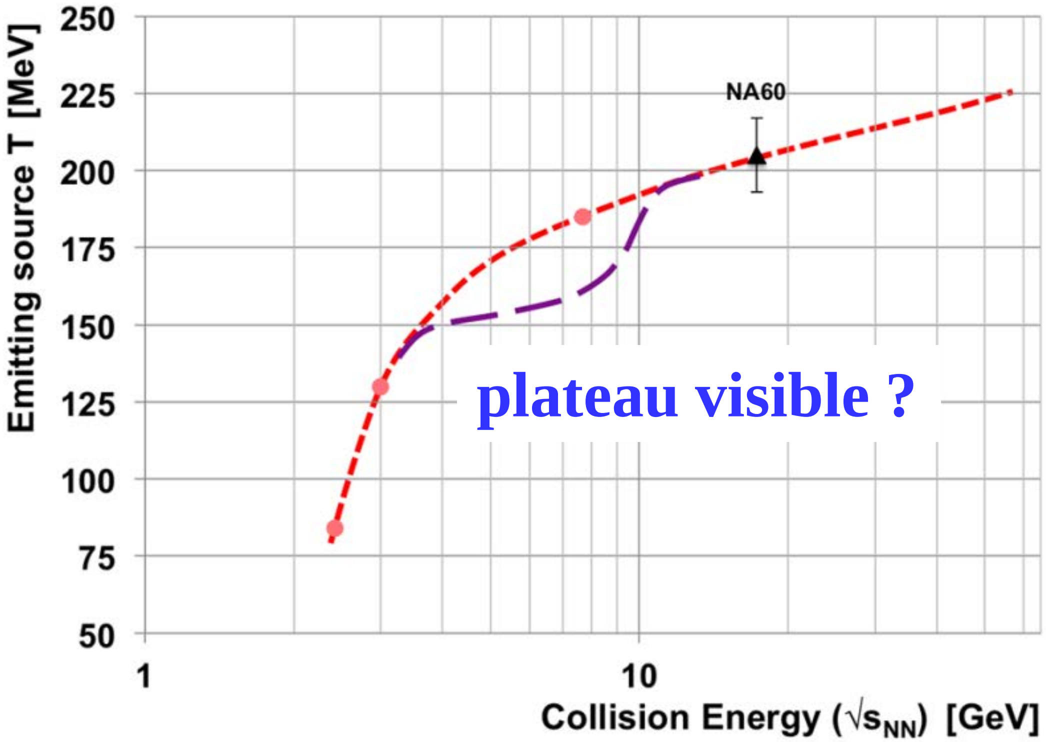
Deconfinement phase transition at high μ_B ?

e^+e^- pairs



measurement of the di-lepton invariant-mass distribution between **1 and 2.5 GeV/*c*2 for different beam energies**

→ thermal radiation T



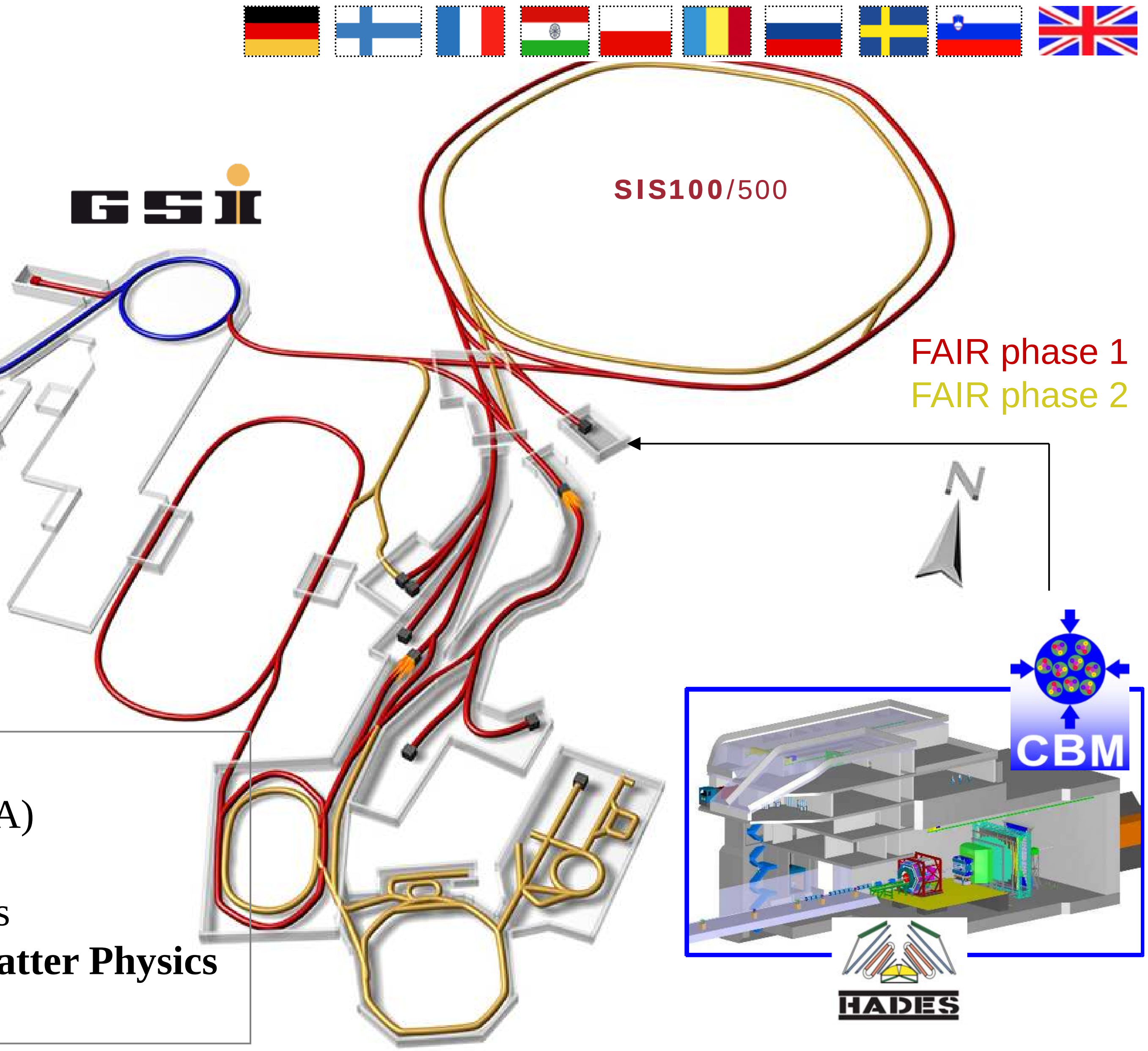
plateau visible ?

The Facility for Antiproton and Ion Research

Using beams from two synchrotrons for parallel operation :

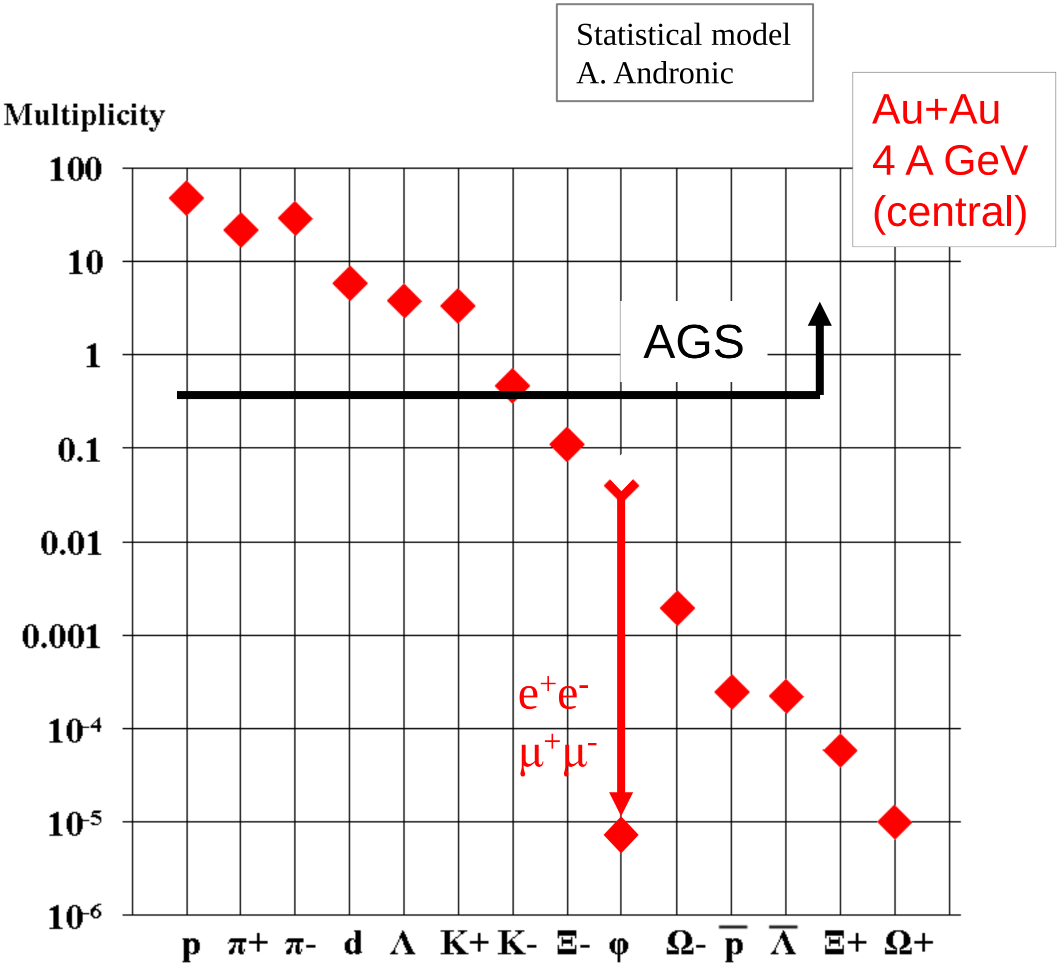
SIS100:
2-29 GeV (protons)
2-14 A GeV (Ca)
2-11 A GeV (Au)

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

Experimental challenge ?



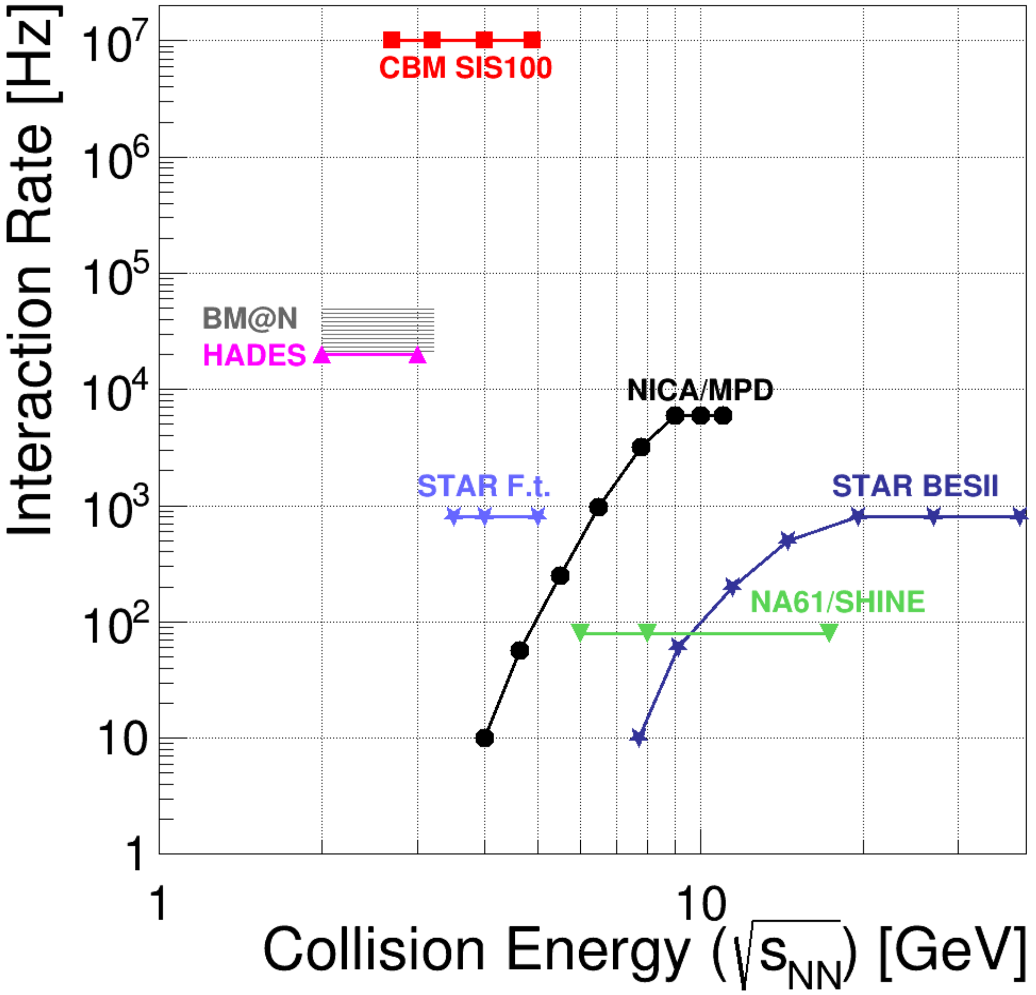
Statistical model
A. Andronic

Au+Au
4 A GeV
(central)

Rare probes → extremely high interaction rates required !

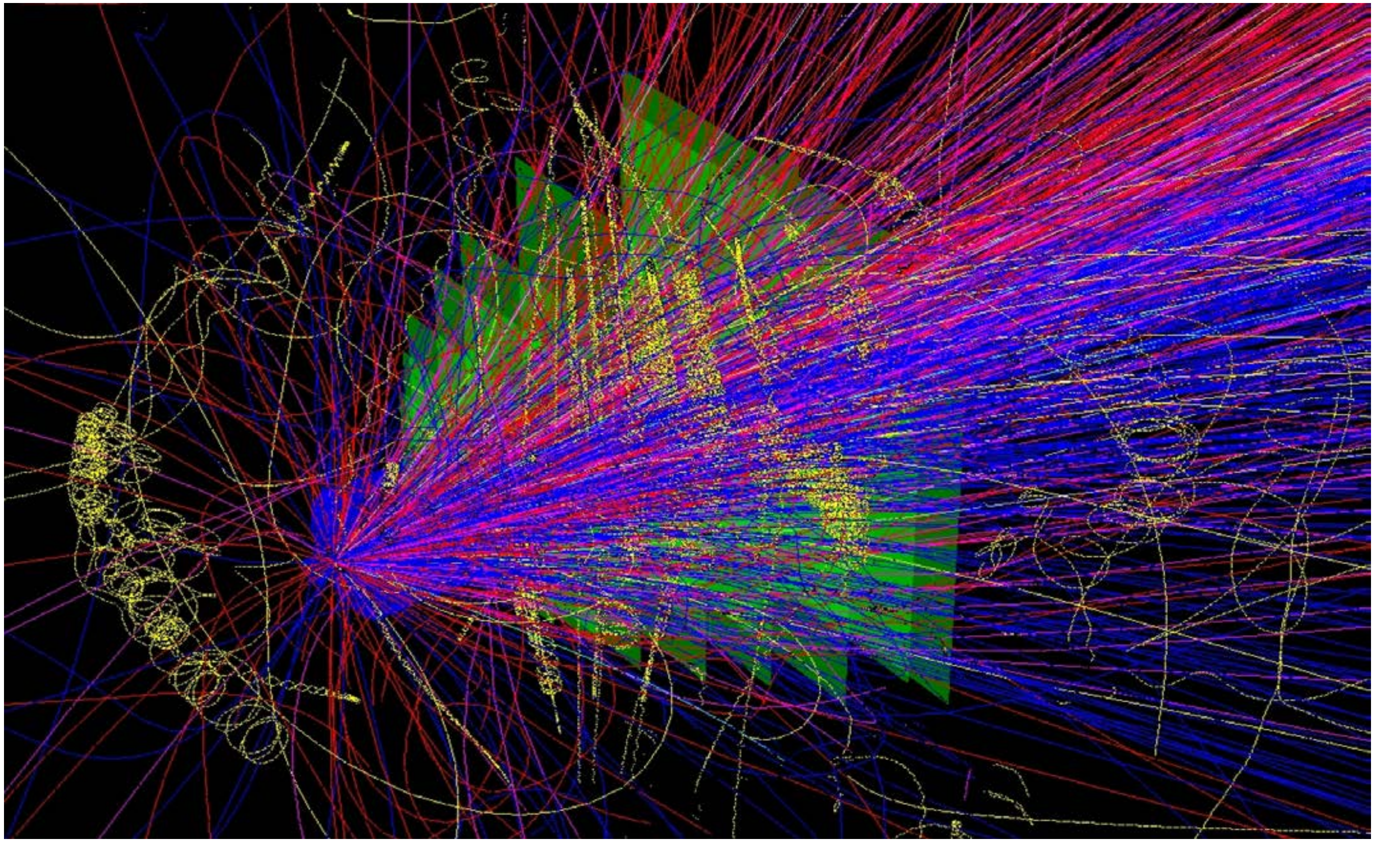
Experiments exploring dense QCD matter

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
phase 2 (SIS300):	
30	7.7
35	8.3
44 (Ca @ SIS300) 89 (p @ SIS300)	9.3 13.0

CBM experimental challenges



Simulation
Au+Au at 25 AGeV
UrQMD+GEANT4:
160 p,
400 π^+, 400 π^-,
44 K^+, 13 K^-

Unprecedented collision rates: 10^5 - 10^7 Au+Au collisions / sec

→ fast and radiation hard detectors

→ free-streaming read-out electronics

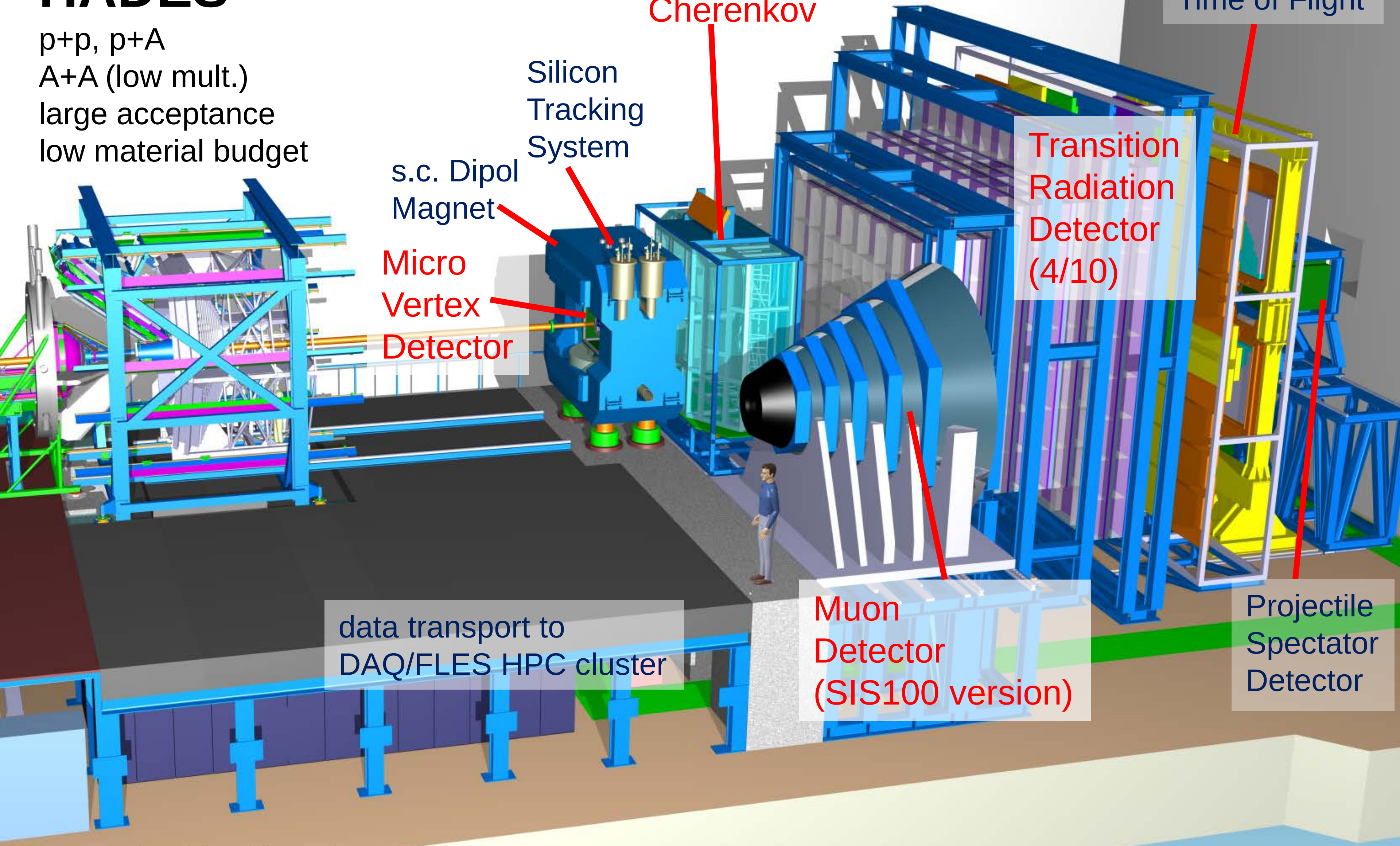
→ high speed data acquisition and
high performance computer farm for online event reconstruction and selection

→ 4-D event reconstruction

CBM

HADES

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



dileptons:

Ring Imaging Cherenkov

Time of Flight

Silicon Tracking System

s.c. Dipol Magnet

Micro Vertex Detector

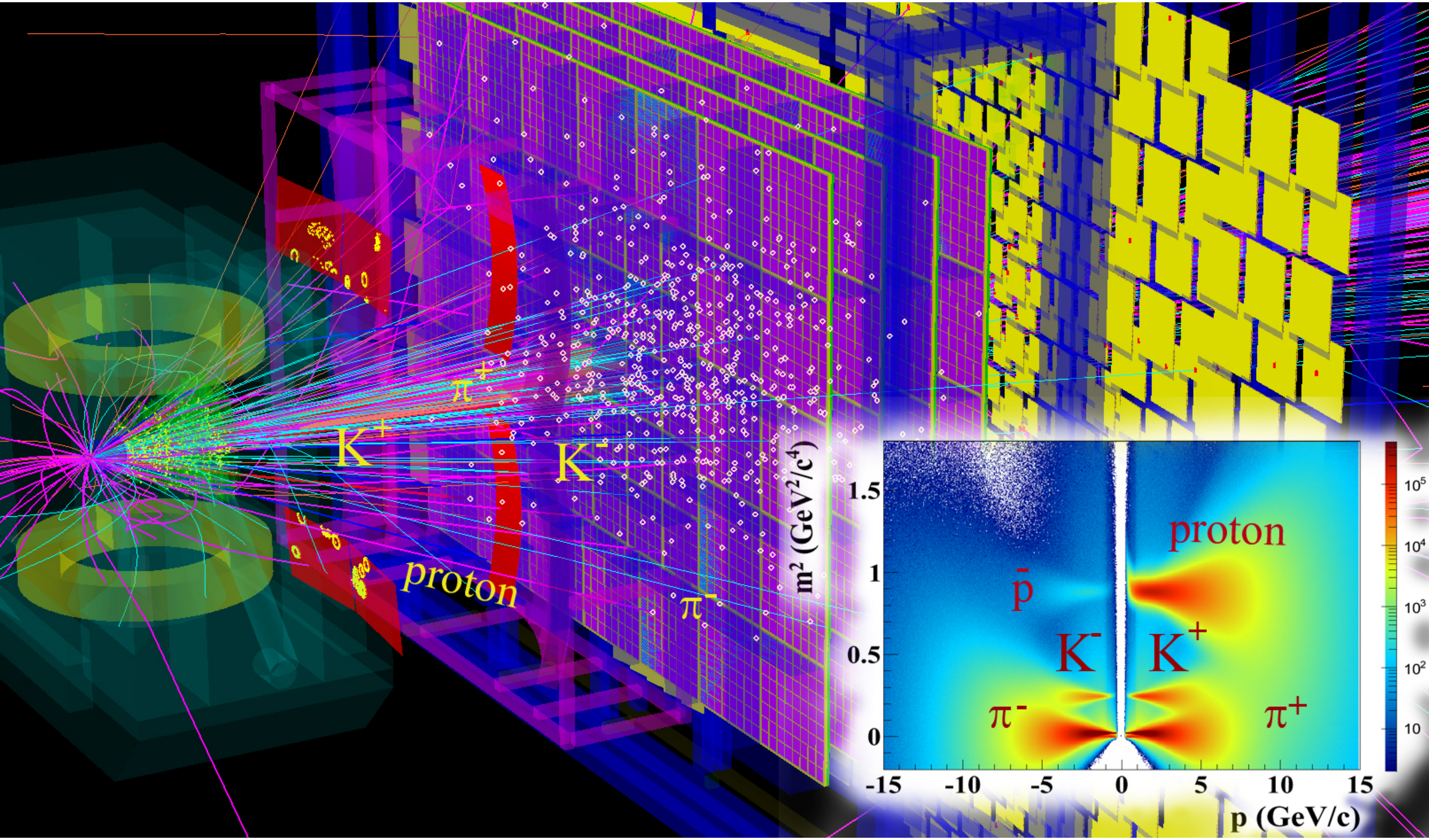
Transition Radiation Detector (4/10)

Muon Detector (SIS100 version)

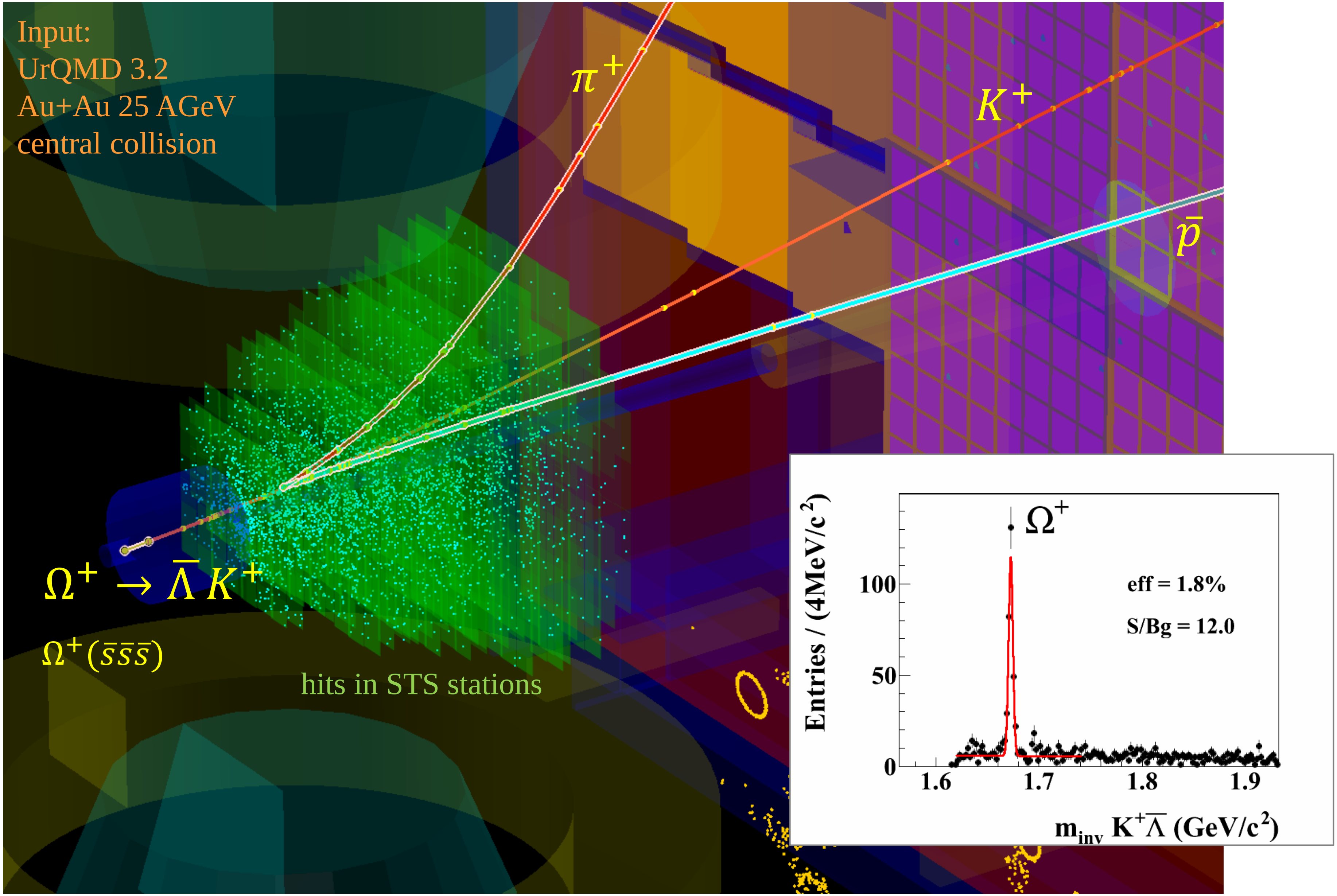
Projectile Spectator Detector

data transport to DAQ/FLES HPC cluster

CBM particle identification



Anti-hyperon reconstruction



Input:
UrQMD 3.2
Au+Au 25 AGeV
central collision

$\Omega^+ \rightarrow \bar{\Lambda} K^+$

$\Omega^+(\bar{s}\bar{s}\bar{s})$

hits in STS stations

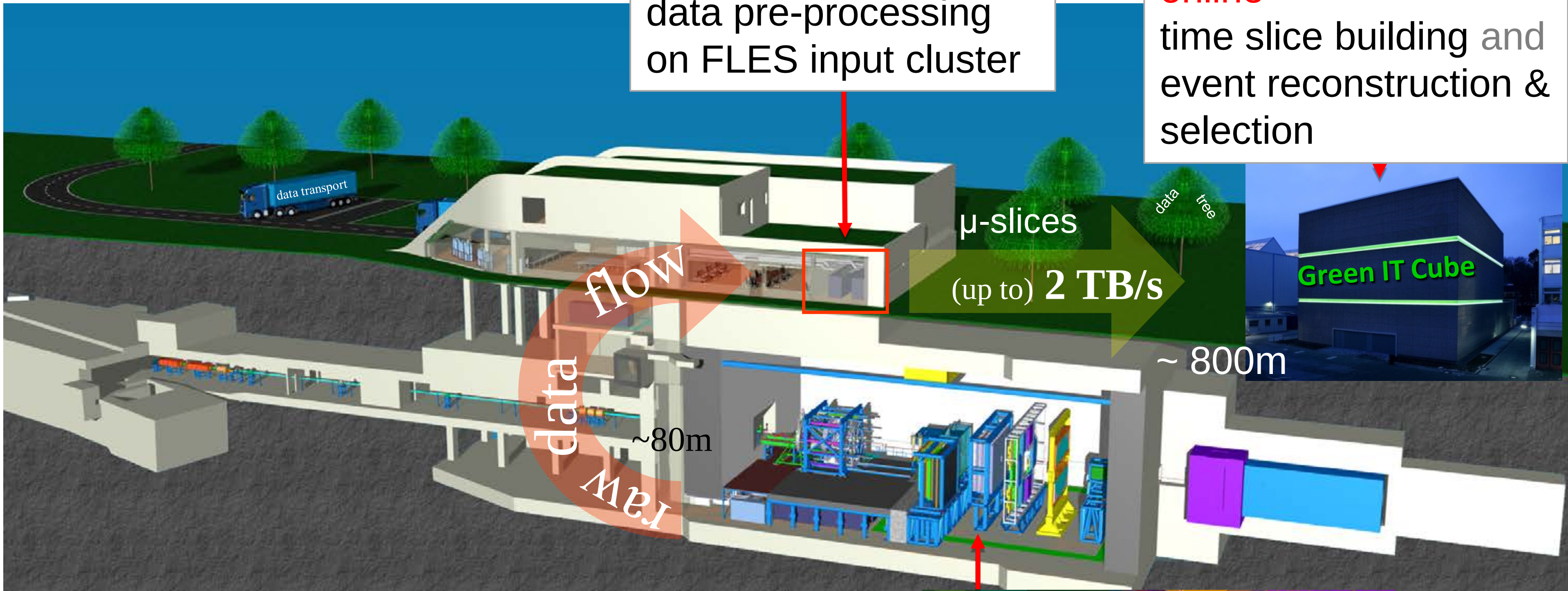
eff = 1.8%

S/Bg = 12.0

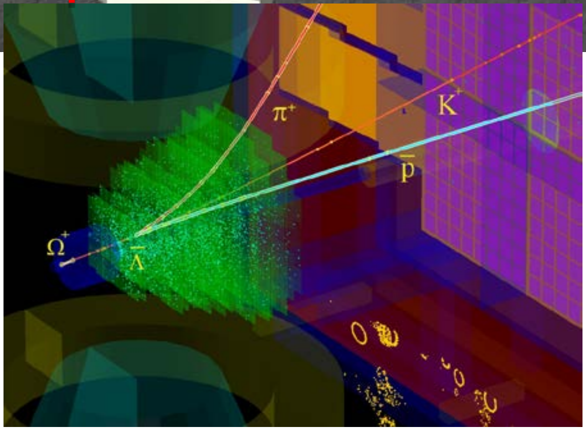
The high-performance free-streaming DAQ system of CBM

DAQ room:
data pre-processing
on FLES input cluster

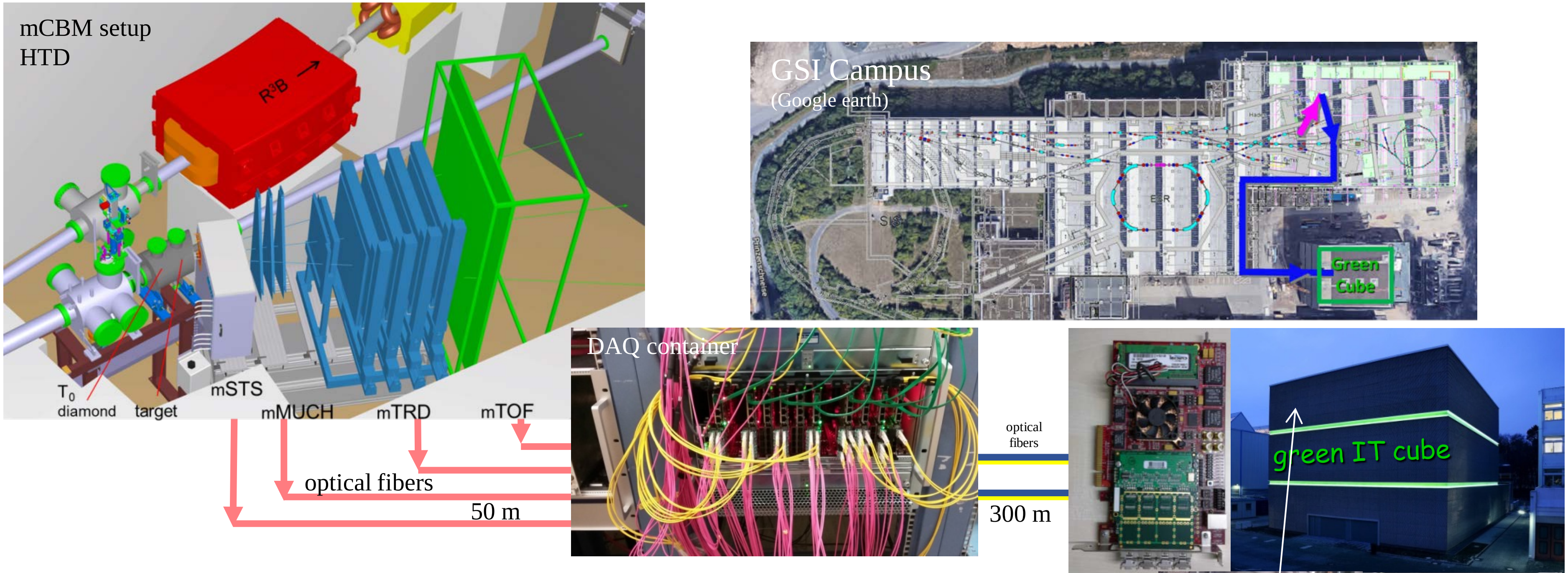
Green IT Cube:
online
time slice building and
event reconstruction &
selection

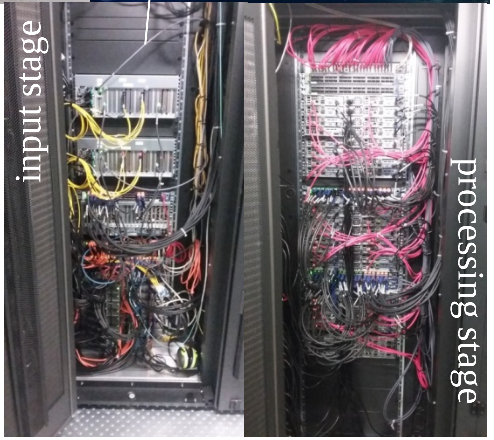


Free-streaming DAQ system
- all detector hits with time stamps
- software based
  event reconstruction & selection



The mCBM experiment at SIS18





mCBM@SIS18 - a CBM full system test-setup
for high-rate nucleus-nucleus collisions at GSI/FAIR

- CBM prototype detector systems
- free-streaming read-out and data transport to the mFLES inside the GreenITCube
- online event reconstruction and selection
- up to 10 MHz collision rate
- first successful commissioning with beam in Dec. 2018 and March 2019

mCBM commissioning

Diamond T0:
GSI

mSTS:
GSI &
Univ. of
Tübingen

mRICH:
Univ. of
Gießen &
Wuppertal

mTOF:
Univ. of
Heidelberg

mTRD:
Univ. of
Münster &
Frankfurt

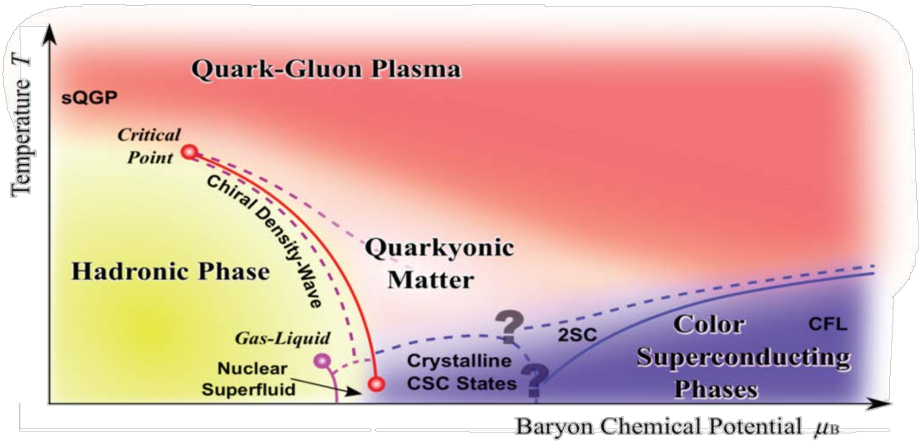
mMUCH:
VECC
Kolkata

mFLES:
FIAS &
Univ. of
Frankfurt

Summary – CBM Program

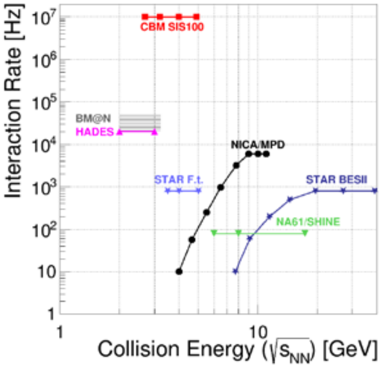
Open questions at high net baryon densities

- ➢ 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 with CBM at FAIR**

Extremely rare probes
→ CBM high-tec developments
to achieve unprecedented collision rates (10 MHz)



Commissioning of a precursor experiment, full-system test mCBM@SIS18 (“mini-CBM”) has started → planned program until 2023, potential physics results