Exploring strangeness production and the phase diagram of nuclear matter

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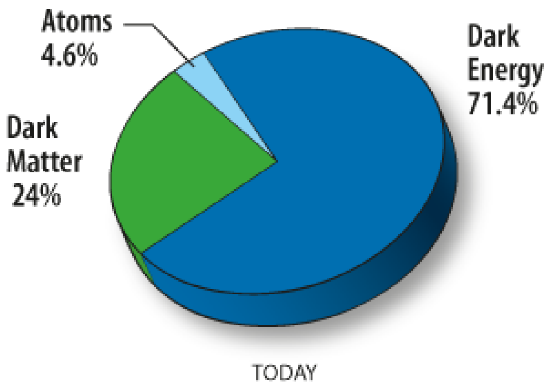
First DMLab Meeting: Scientific Kickoff

9.-10.12. 2021
DESY

Why strangeness is interesting?



- Ordinary matter (Standard Model) < 5%
- Strange matter:

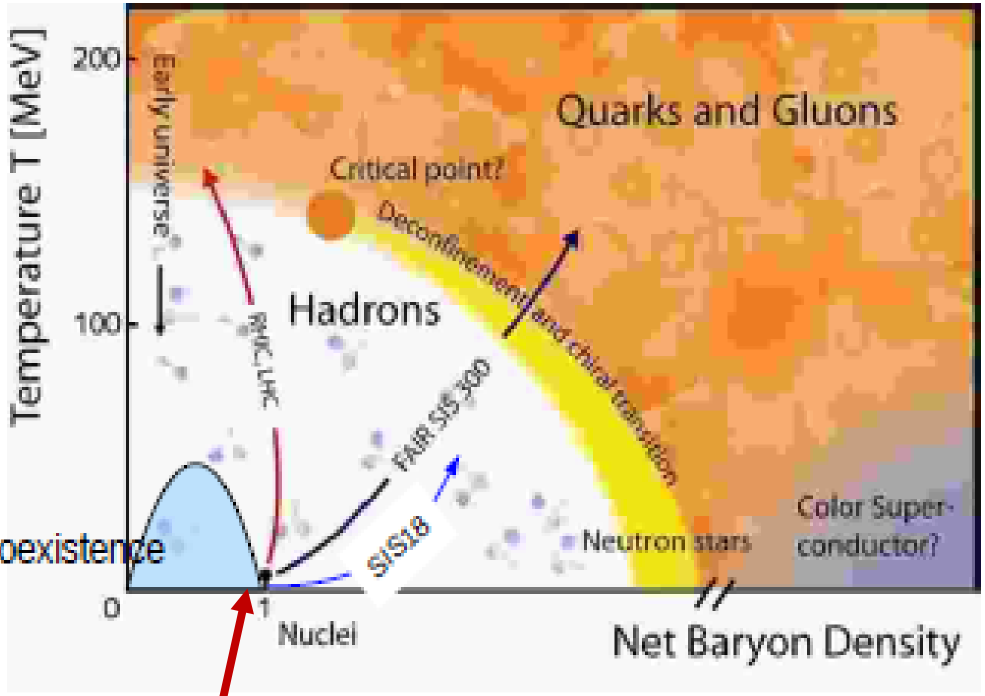
  In nature: in the core of neutron stars (?), strange stars(??)

  In laboratory: can be produced in heavy-ion collision experiments

- Strange particle can be used as a probe for nonstrange matter → Equation of State
- Properties of strange particles are changed in nuclear medium (at hight densities) → impact on understanding of neutron stars
- At high temperatures and densities in HICs → QGP creation
  → enhancement of production of strange quarks
  → useful probe for Quark Gluon Plasma (QGP) studies

Strange particles and the nuclear equation of state

Nuclear matter phase diagram (schematic)



Liquid gas coexistence

Only known point
(Nucleons of our world)

One searches for the Equation of State (EoS)

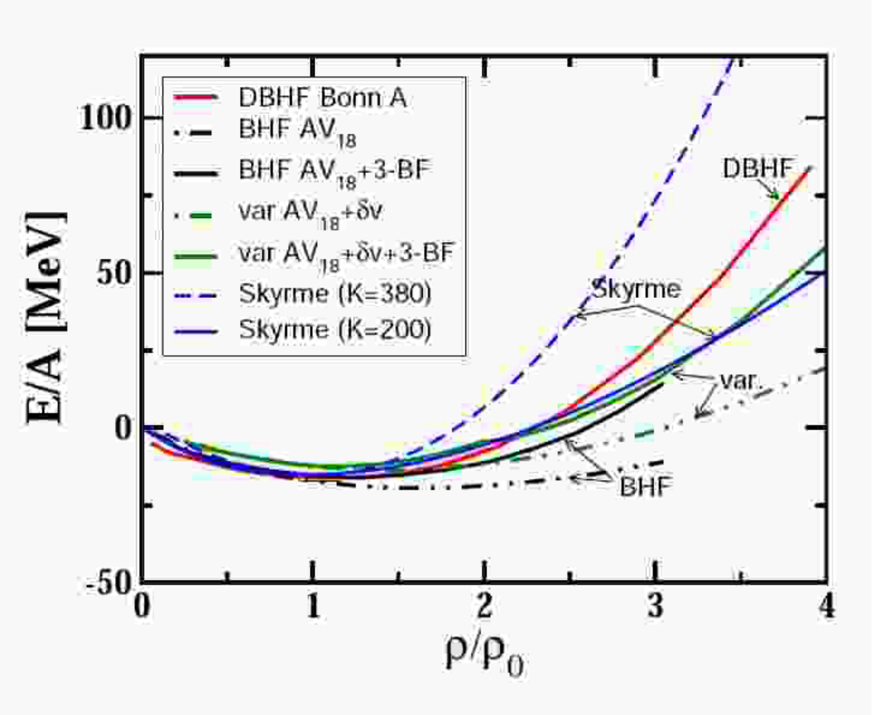
P(T,ρ(μ)) or ε(T,ρ(μ))

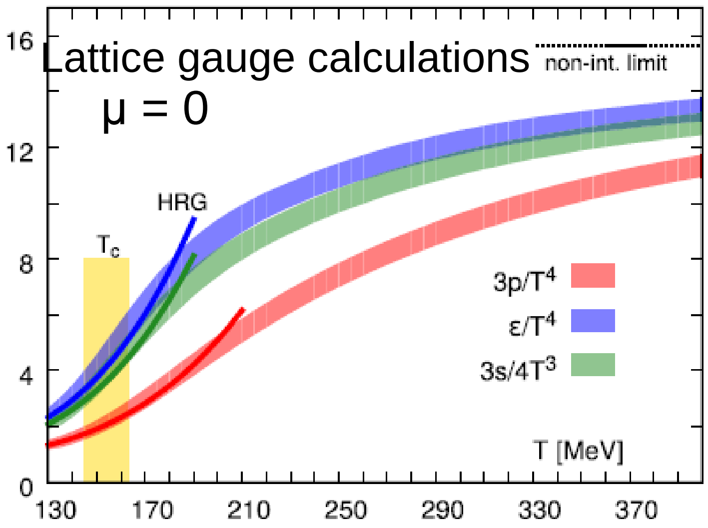
Nuclear equation of state (theory)

theory is limited to

to low temperature and $\rho < 1.5 - 2\rho_0$
Brückner G –matrix
(hole line expansion)

high temperatures and μ=0
lattice gauge calculations



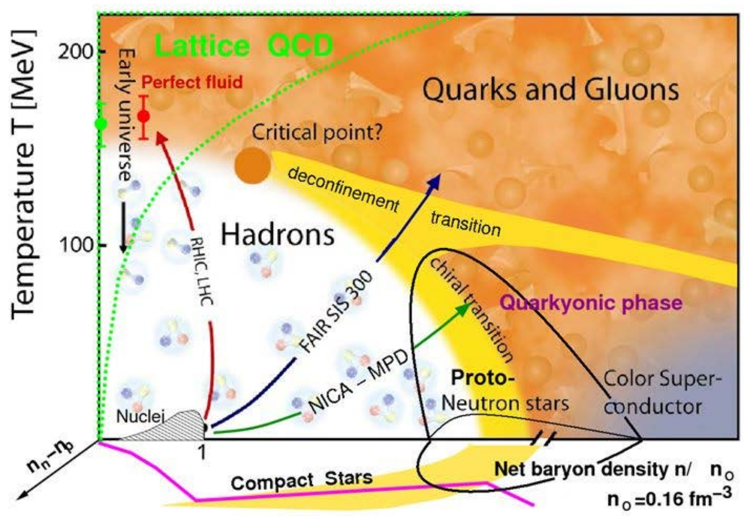


Nuclear equation of state

- Experimentally one can explore
  the region of large (T,μ)

  but the EoS is not an observable

The Phase Diagram of Strongly Interacting Matter



Equation of State (EOS): relationship between Energy, Pressure, Temperature, Density and Isospin Asymmetry of Nuclear Matter

Strategy:

- develop transport approaches
  which simulate the heavy ion collisions
- vary EoS in the simulation
- identify observables which are sensitive to the EOS
- compare experimental measurements with theory

Quantum Molecular Dynamics

Extended (time dependent) Ritz variational principle (Koonin, TDHF)

Take trial wavefct with time dependent parameters and solve

$$\delta \int_{t_1}^{t_2} dt < \psi(t)| i\frac{d}{dt} - H|\psi(t) >= 0. \qquad (1)$$

QMD: trial wavefct for particle i with p_{oi} (t) and q_{oi} (t)

$$\psi_i(q_i, q_{0i}, p_{0i}) = Cexp[-(q_i - q_{0i} - \frac{p_{0i}}{m}t)^2/4L] \cdot exp[ip_{0i}(q_i - q_{0i}) - i\frac{p_{oi}^2}{2m}t]$$

For N particles: $\psi_N = \prod_{i=1}^{N} \psi_i(q_i, q_{0i}, p_{0i})$

For the QMD trial wavefct eq. (1) yields

$$\frac{dq}{dt} = \frac{\partial < H >}{\partial p} \quad ; \quad \frac{dp}{dt} = -\frac{\partial < H >}{\partial q}$$

For Gaussian wavefct eq. of motion very similar to Hamilton's eqs. (but only for Gaussians !!)

Quantum Molecular Dynamics (QMD)

- nucleon-nucleon density dependent two body potential potential:

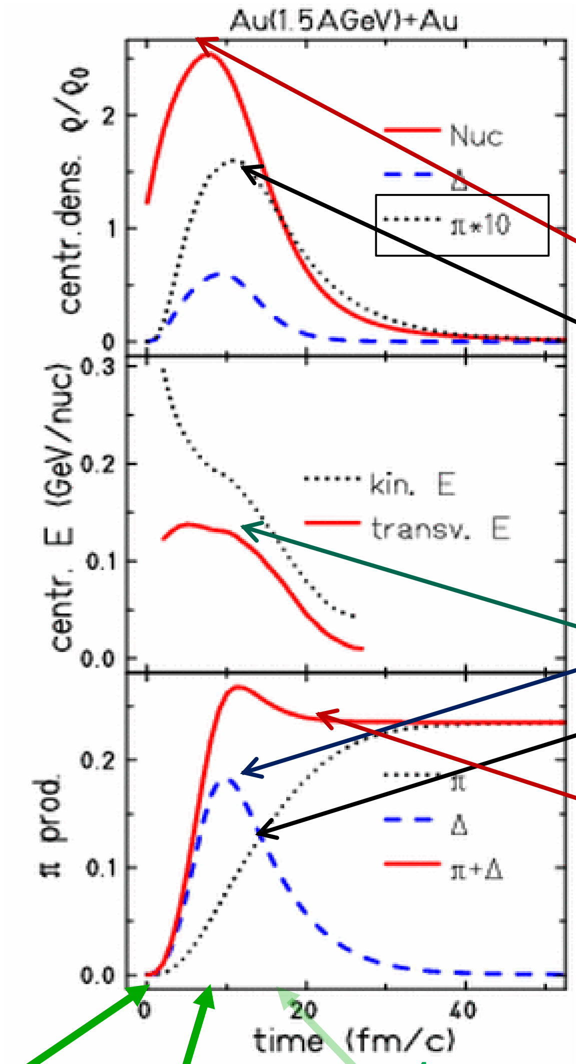
$$
\begin{aligned}
V^{ij} &= G^{ij} + V^{ij}_{\mathrm{Coul}} \\
&= V^{ij}_{\mathrm{Skyrme}} + V^{ij}_{\mathrm{Yuk}} + V^{ij}_{\mathrm{mdi}} + V^{ij}_{\mathrm{Coul}} + V^{ij}_{sym} \\
&= t_1 \delta(\vec{x}_i - \vec{x}_j) + t_2 \delta(\vec{x}_i - \vec{x}_j) \rho^{\gamma-1}(\vec{x}_i) + t_3 \frac{\exp\{-|\vec{x}_i - \vec{x}_j|/\mu\}}{|\vec{x}_i - \vec{x}_j|/\mu} + \\
& t_4 \ln^2(1 + t_5(\vec{p}_i - \vec{p}_j)^2)\delta(\vec{x}_i - \vec{x}_j) + \frac{Z_i Z_j e^2}{|\vec{x}_i - \vec{x}_j|} + \\
& t_6 \frac{1}{\varrho_0} T_3^i T_3^j \delta(\vec{r}_i - \vec{r}_j)
\end{aligned}
$$

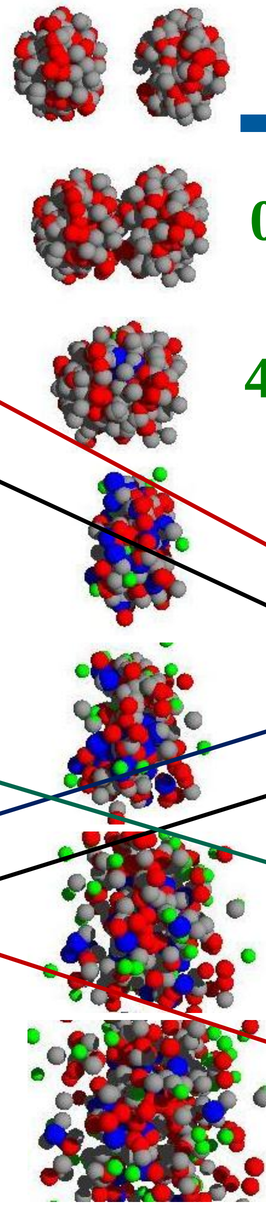
t_1 - t_4 depend on the EoS

t_4 contains the momentum dependence of the potential

- In addition cross sections: NN elastic, NN←→NΔ, Δ→Nπ

Time evolution





0 fm/c : start of the reaction

4 fm/c : raise of resonance prod.

8 fm/c: max. central ρ(nuc.)

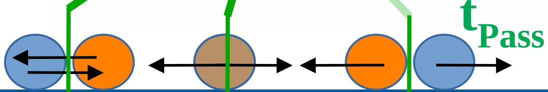
10 fm/c max central ρ(π)

12 fm/c: max number of Δ

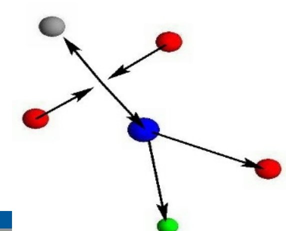
14 fm/c: π dominate over Δ

16-20 fm/c: nucleon spectra become `thermal'

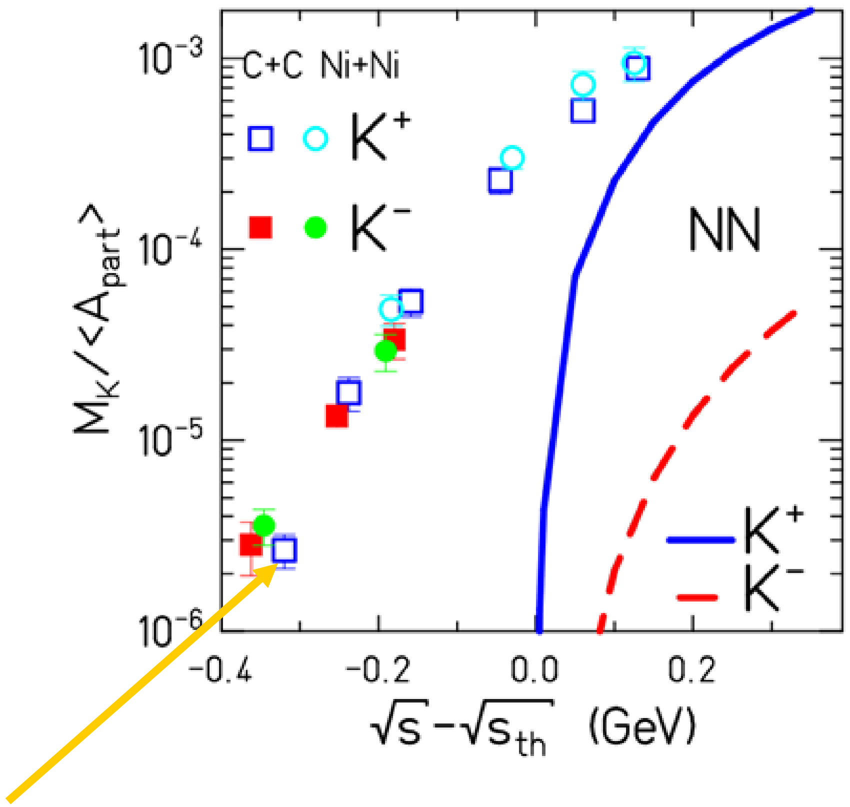
20 fm/c: π number stabilizes



Proton
Neutron
Delta
Pion



Strangeness and the nuclear equation of state



- AA collisions:
  experimental observation of K^+,K^- production below the NN-threshold

- NN: Excitation function of K^+ and K^- quite different
- AA: Excitation function of K^+ and K^- quite similar
- Fermi motion cannot explain very subthreshold production
- Conclusion
  AA: new mechanisms for strangeness production

Near threshold strangeness production in AA

I. Strangeness production channels at low energies

- **baryon-baryon collisions:**

$$B+B \rightarrow B+Y+K$$

$$B+B \rightarrow B+B+K+\overline{K}$$

$$B+Y \rightarrow B+B+\overline{K}$$

$K = (K, K^0)$

$\overline{K} = (K^-, \overline{K}^0)$

$B = (N, \Delta, ...)$

$Y = (\Lambda, \Sigma)$

- **meson-baryon collisions:**

$$\pi+B \rightarrow Y+K$$

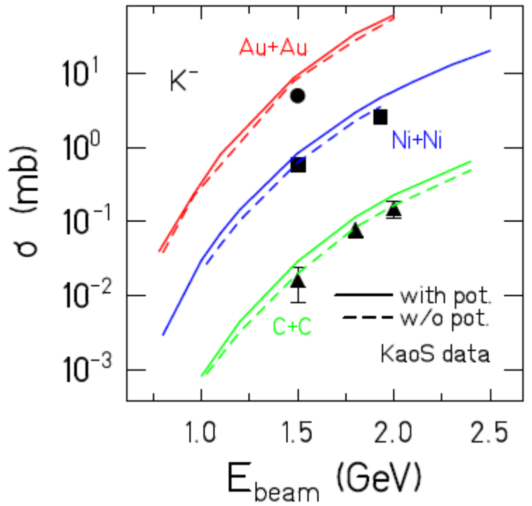
$$\pi+B \rightarrow B+K+\overline{K}$$

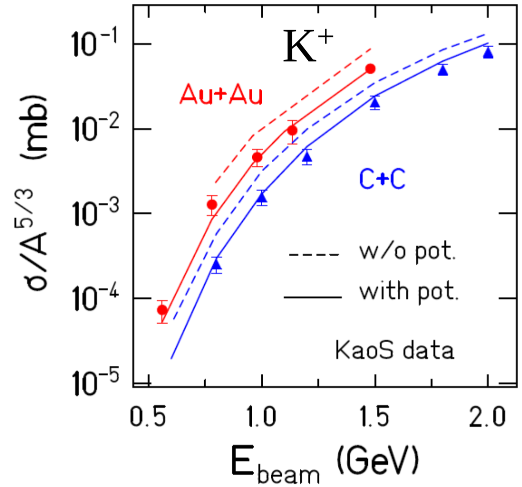
$$\pi+Y \rightarrow B+\overline{K}$$

→ dominant channel for low energy K^- production!

- **meson-meson collisions:** $\pi+\pi \rightarrow K+\overline{K}$

- **resonance decays:** $K^* \rightarrow \pi+K, ...,$ $\phi \rightarrow K+\overline{K}$ ...,





II. Strangeness rescattering

= (quasi-)elastic scattering with baryons and mesons

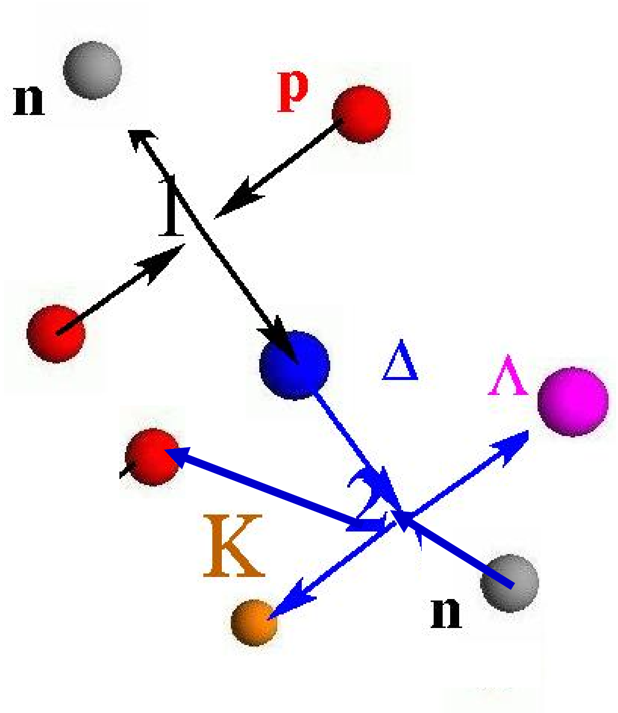
The production cross sections and self-energies of K, Kbar are modified in the nuclei medium !

Origin of the different excitation functions

Dominant for K^+ in AA: Two step process NN→NΔ NΔ→K^+Λ N

lowers the effective threshold

enhances K^+ below NN threshold



two step process more probable in central collision

Theory and simulations:

soft EoS: system gets to higher densities

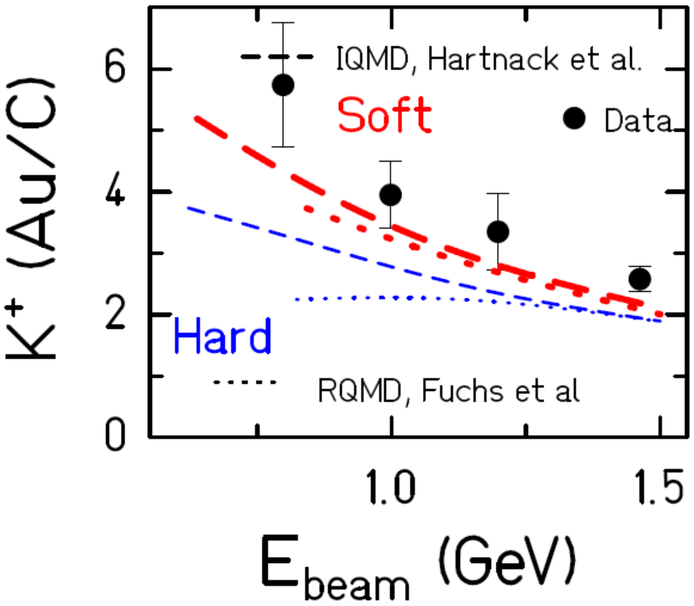
→ mean free path for NΔ→K^+Λ N shorter

K^+Λ N competes with Δ decay

→ for a soft EOS we expect more NΔ→K^+Λ N collisions

and hence more K^+

Strangeness production and the nuclear EoS



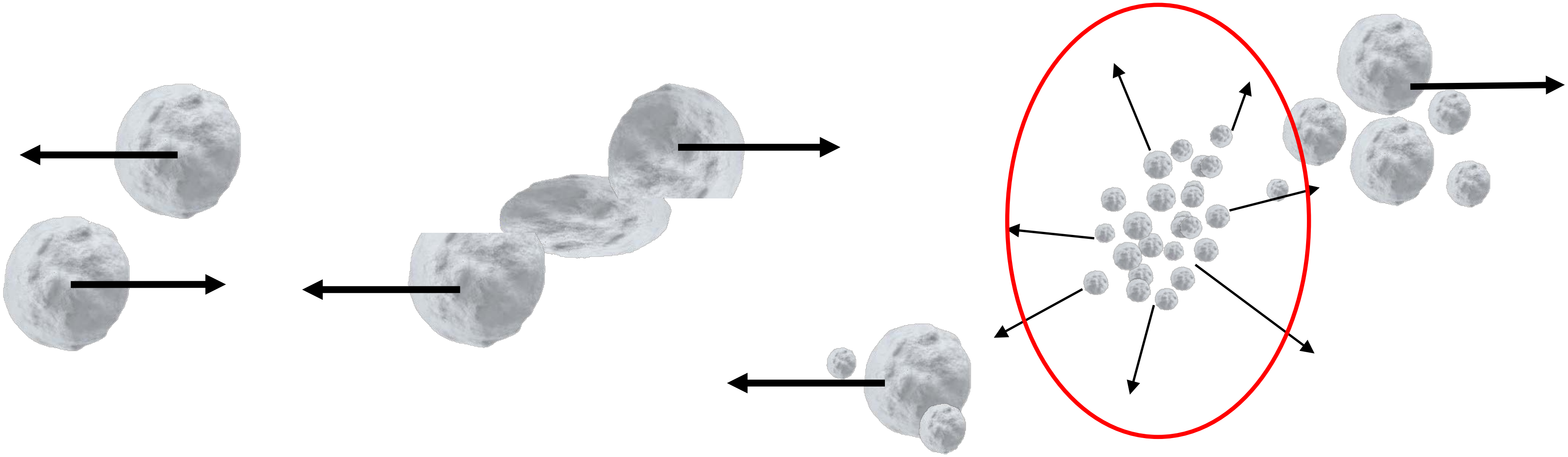
Comparison with experiment

- confirmes the EoS dependence of K^+ yield
- soft EoS: best agreement with data

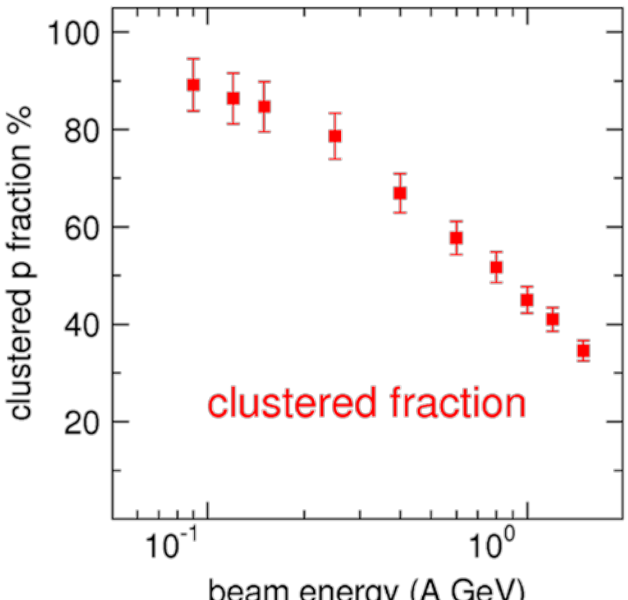
Up to today the observable
which shows the strongest EoS dependence

- Perspectives: FAIR and NICA (Russia) have higher beam energies
  excitation functions of Ξ and Ω become available
  sensitive probes for studying the reaction mechanism

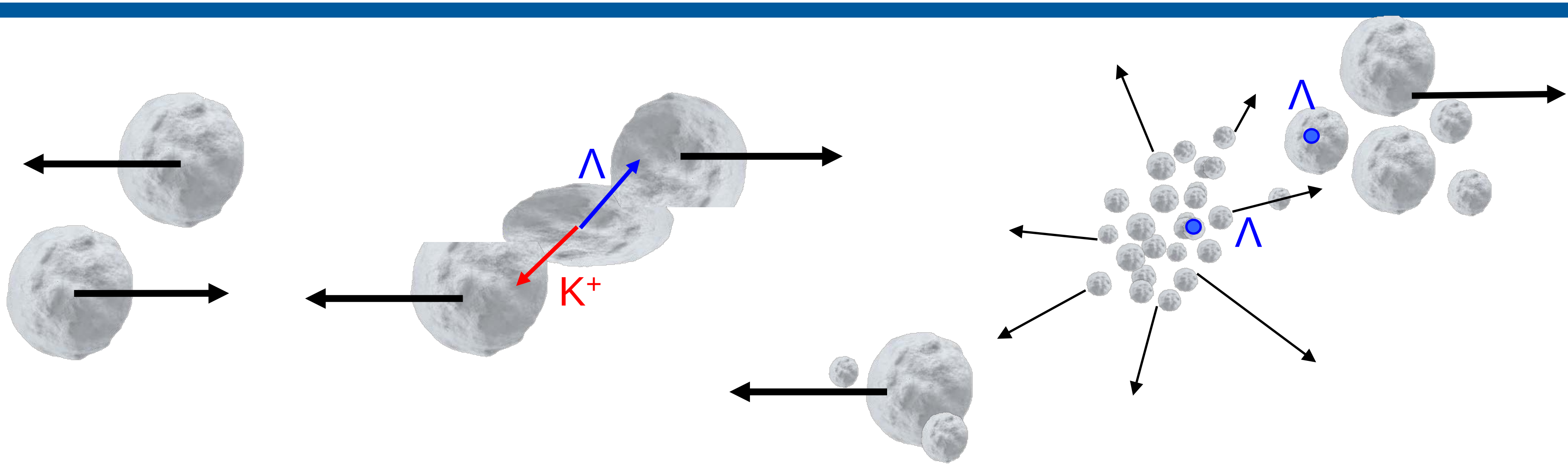
Cluster formation in heavy ion collisions



- cluster production influences phase space distributions of all baryons
- clusters are less disturbed by „thermal noise“
  - stronger flow patterns than protons
  - more sensitive tool to study potential effects
- complete dynamical description needed

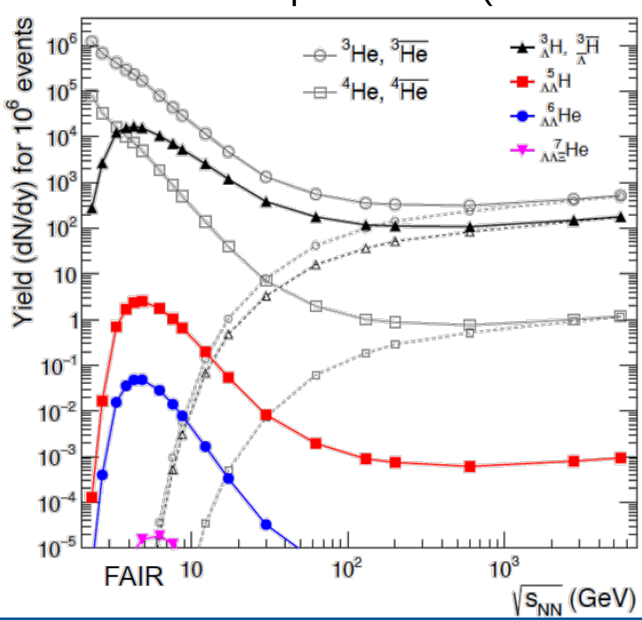


Hyper nuclei formation in heavy ion collisions



- access to the third dimension of the nuclear chart (strangeness)
- information on hyperon-nucleon and hyperon-hyperon interactions
- important e.g. for neutron stars (production of hypermatter at high density and low temperature)
- new field of hyperon spectroscopy
- Study of the interface between spectators and participants

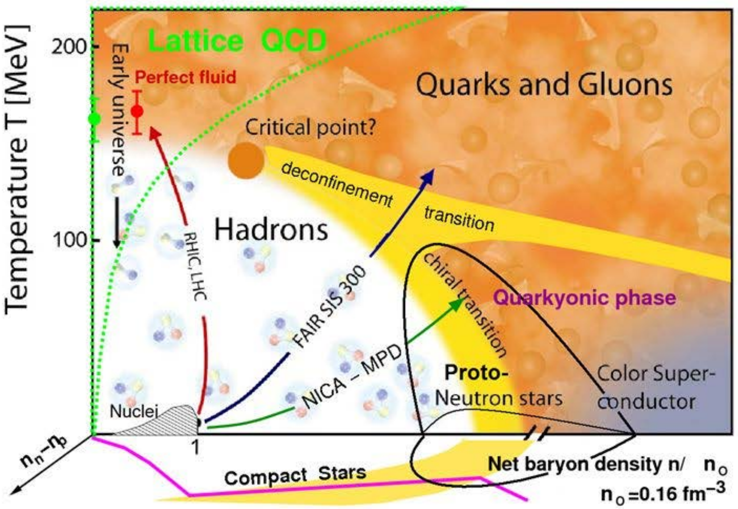
Thermal model predictions (A. Andronic)



Work in Progress

- Extension of production of strangeness and hyper-nuclei at higher beam energies

The Phase Diagram of Strongly Interacting Matter



Equation of State (EOS): relationship between Energy, Pressure, Temperature, Density and Isospin Asymmetry of Nuclear Matter

- Higher energies require a more sophisticated transport approach which includes the transition to a Quark Gluon Plasma during the reaction

Parton Hadron Quantum Molecular Dynamics (PHQMD)

PHQMD: Parton Hadron Quantum Molecular Dynamics

PHQMD

PHQMD: a **unified n-body microscopic transport approach** for the description of heavy-ion collisions and **dynamical cluster formation** from low to ultra-relativistic energies

Realization: combined model **PHQMD = (PHSD & QMD) & (MST/SACA)**

Parton-Hadron-Quantum-Molecular Dynamics

↓

Initialization → propagation of baryons:
QMD (Quantum-Molecular Dynamics)

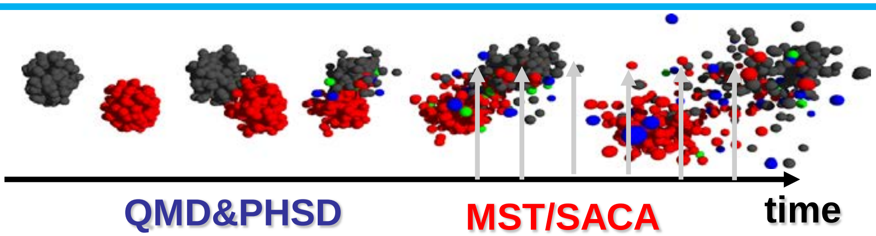
↓

Propagation of partons (quarks, gluons) and mesons
+ collision integral = interactions of hadrons and partons (sQGP)
from PHSD (Parton-Hadron-String Dynamics)

↓

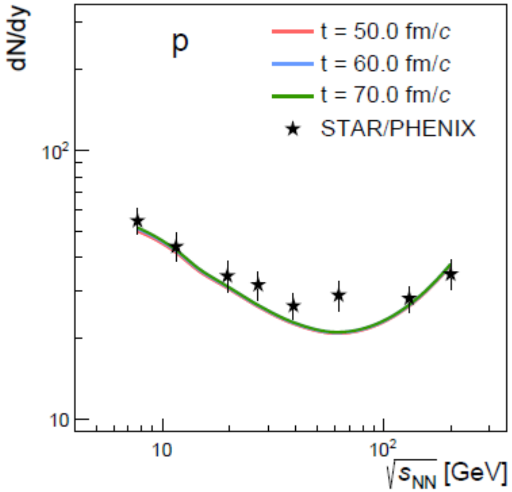
Clusters recognition:
SACA (Simulated Annealing Clusterization Algorithm)
or MST (Minimum Spanning Tree)

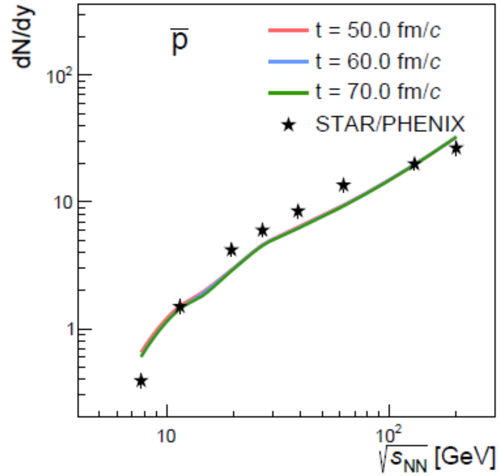
PHSD:
W. Cassing,
E. Bratkovskaya,
PRC 78 (2008) 034919;
NPA831 (2009) 215;
W. Cassing,
EPJ ST 168 (2009) 3
P. Moreau et al.,
PRC100 (2019) 014911

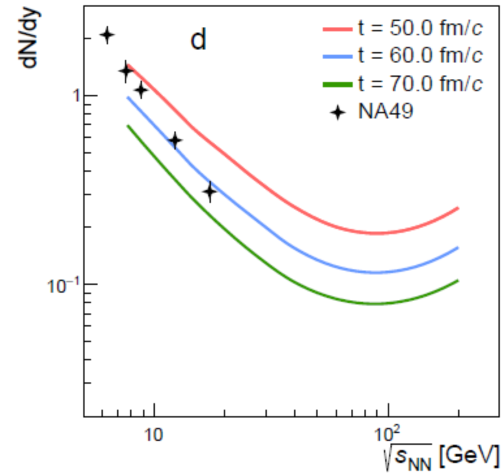


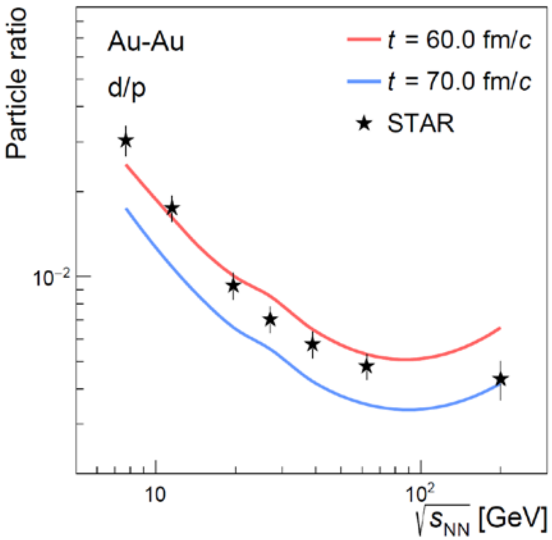
PHQMD: J. Aichelin et al.,
PRC 101 (2020) 044905
& arXiv:1907.03860

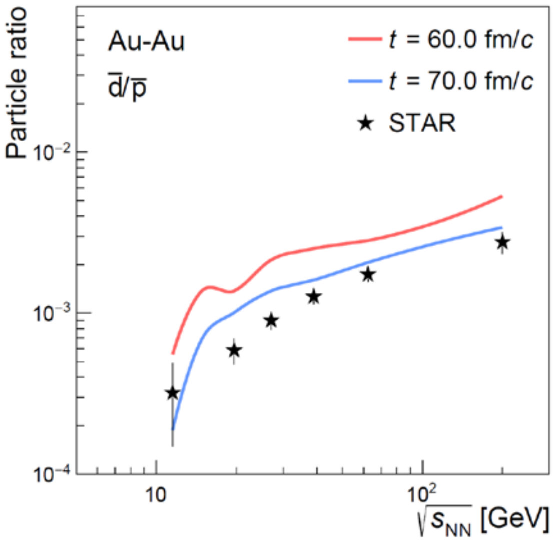
Excitation function of multiplicity of $p, \bar{p}, d, \bar{d}$









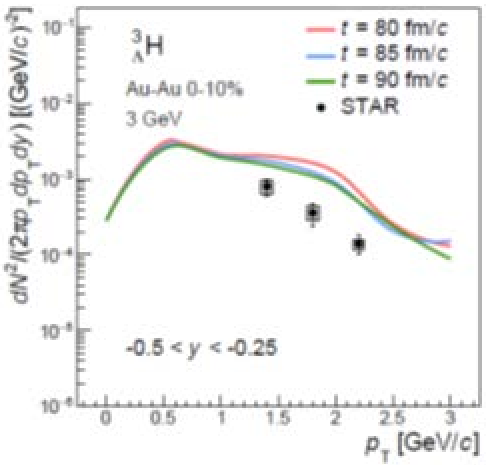


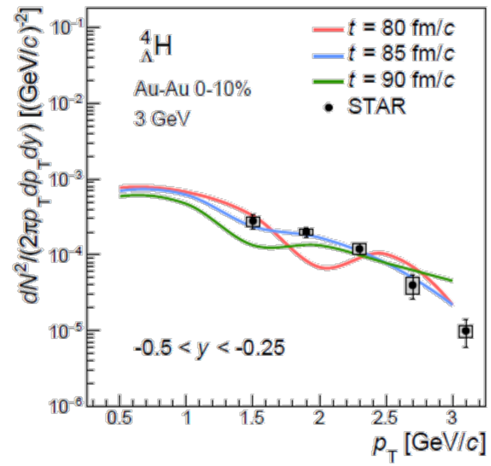
The p, $\bar{p}$ yields at y~0 are stable, the d, $\bar{d}$ yields are best described at *t= 60-70* fm/c

Hypernuclei from PHQMD

The PHQMD comparison with most recent STAR fixed target p_T distribution of $^3H_\Lambda$, $^4H_\Lambda$ from Au+Au central collisions at $\sqrt{s}$ =3 GeV

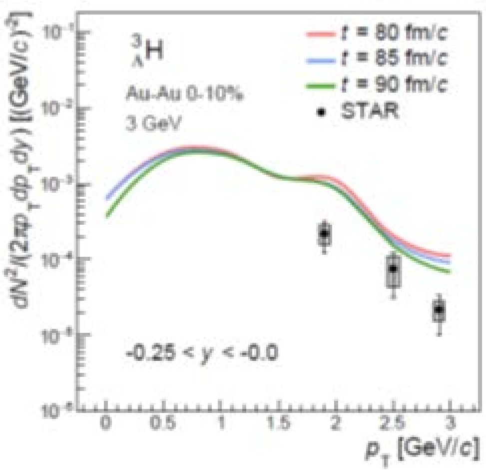
- Assumption on nucleon-hyperon potential: $V_{N\Lambda} = 2/3\ V_{NN}$

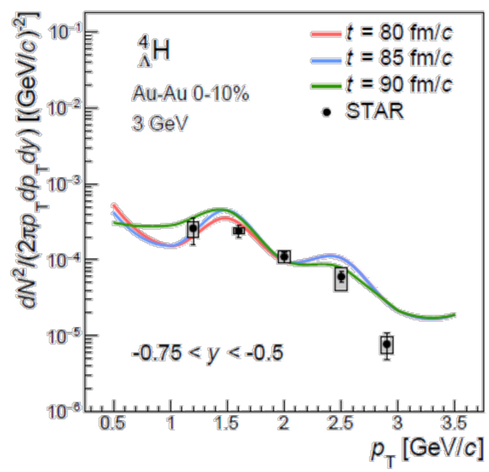


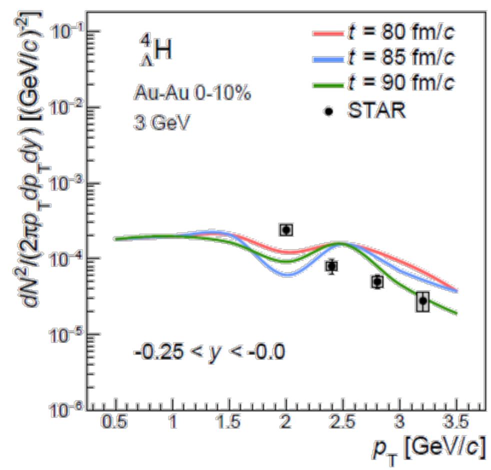


Star data preliminary

Good description in view of these very complex hypernuclei







Present challenges

Extension of the EoS to finite μ,T (→ gravitational wave studies)

effective field theory   Polyakov Nambu Jona Lasinio

Dynamical Quasi Particle Model

Simulate a first order phase transition in a finite system

Λ-N Potential depends strongly on the nuclear density

G-matrix calculations

has to be considered for predictions of hypernuclei

Heavy mesons (with c and b quarks) and jets

How the DMLab can help

Strangeness in HIC is a common project between 3 labs:
SUBATECH (Nantes), GSI (Darmstadt), JINR (Dubna)

What would help:

- medium term visits (1 month) of postdocs and PhD students
- short term visits (1 week) of senior, PhD students, postdocs
- eventually 6 month stay for senior scientist at GSI

We started the new project - **search of dark matter in heavy ion collisions**:
to study how dark matter can be produced in heavy ion collisions and
detected in HIC experiments (dark photons - PRD104,2021,015008)

➔ an exchange with other theoretical and experimental groups working
on dark matter studies would be very useful

Thank you