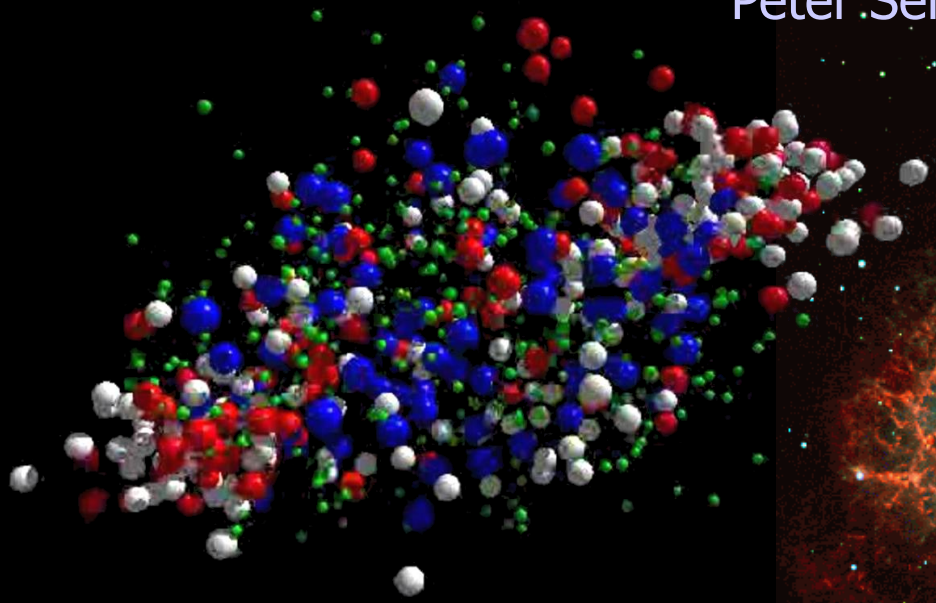
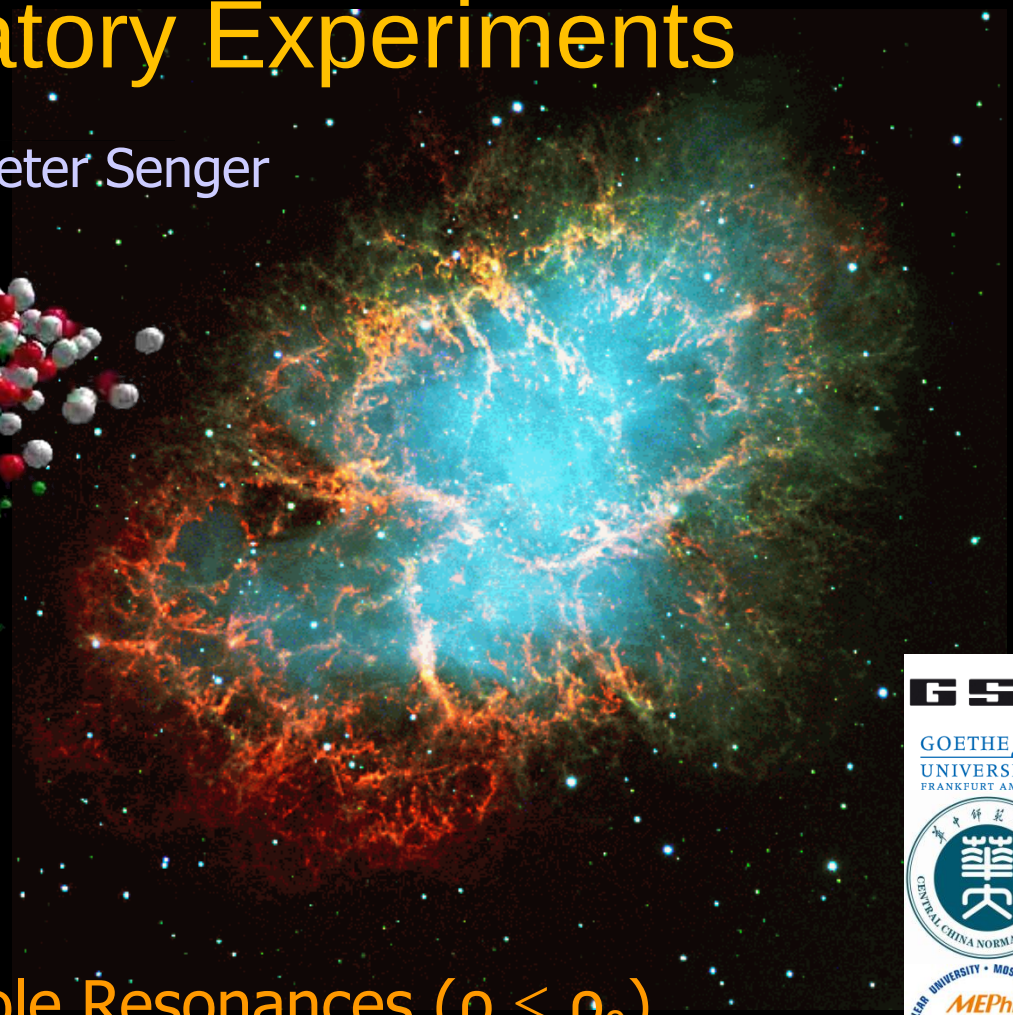
The high-density Equation of State from Laboratory Experiments

Peter Senger





Outline:

- EOS from Giant Monopole Resonances ($\rho \leq \rho_0$)
- EOS from heavy-ion collisions at $\rho < 3\ \rho_0$
- Observables sensitive to EOS at $\rho > 3\ \rho_0$?

3rd CBM China workshop, April 16 -18, 2018, Yichang, China

Even stronger push for the scientific motivation of FAIR ….

from P. Giubellino

Neutron Star Mergers

FAIR Research Pillars

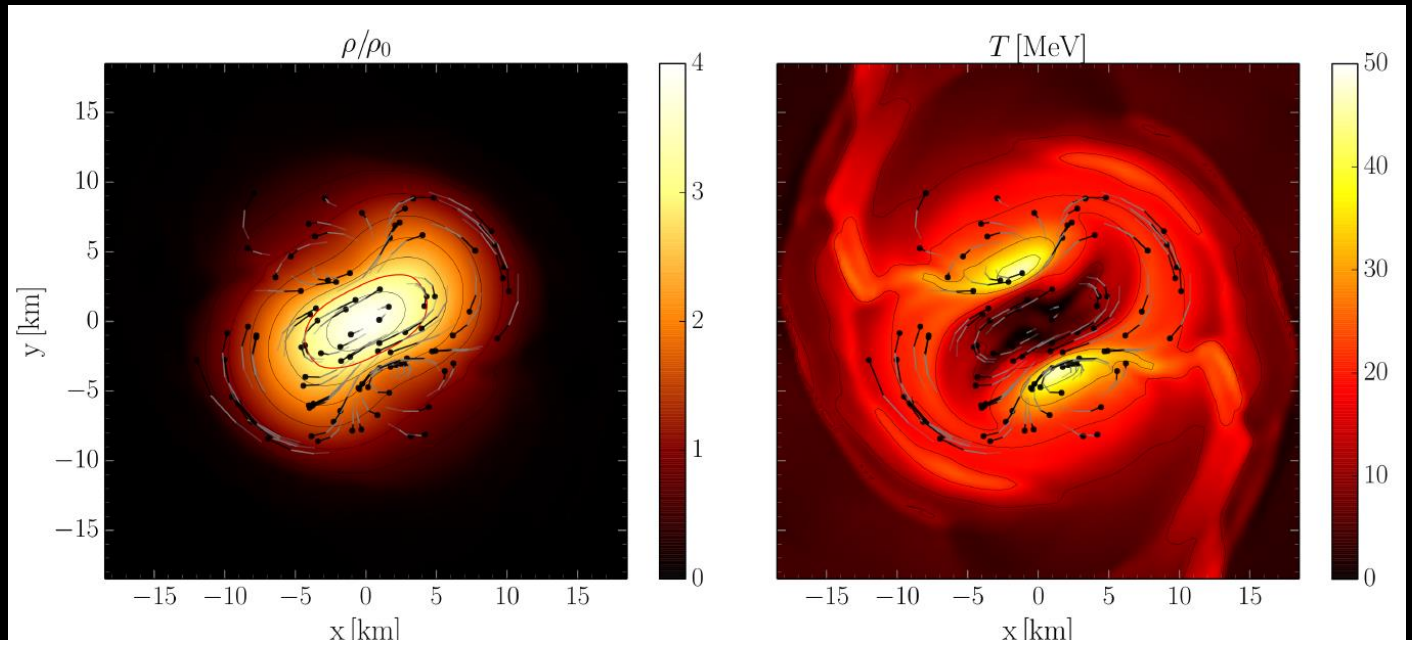
- Equation of State (**Hades, CBM**)
  - Gravitational wave signal
  - Amount of ejecta
- Baryon-Baryon interaction (**PANDA**)
- Exotic neutron-rich nuclei (**NUSTAR**)
  - r-process nucleosynthesis and abundancies of the heaviest elements gold, platinum and beyond
- Plasma and atomic opacities (**APPA**)
  - Kilonova electromagnetic transient

FAIR offers unique opportunities for studying these fundamental questions!

Neutron star mergers and heavy-ion collisions

density

temperature

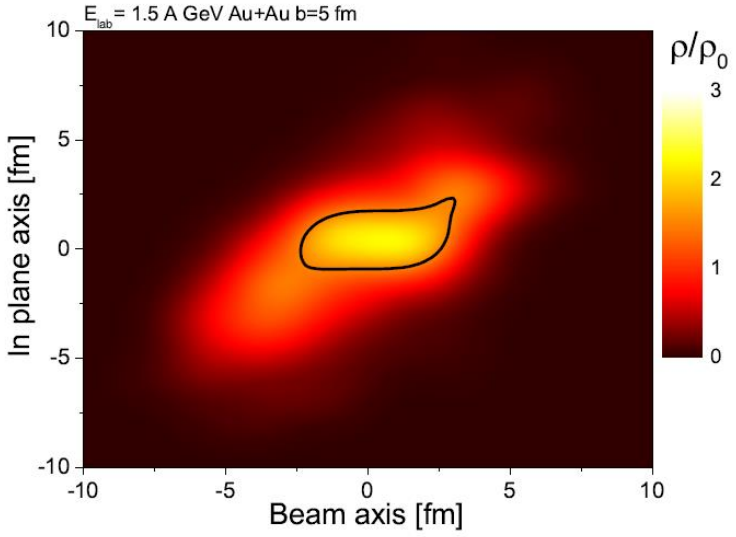


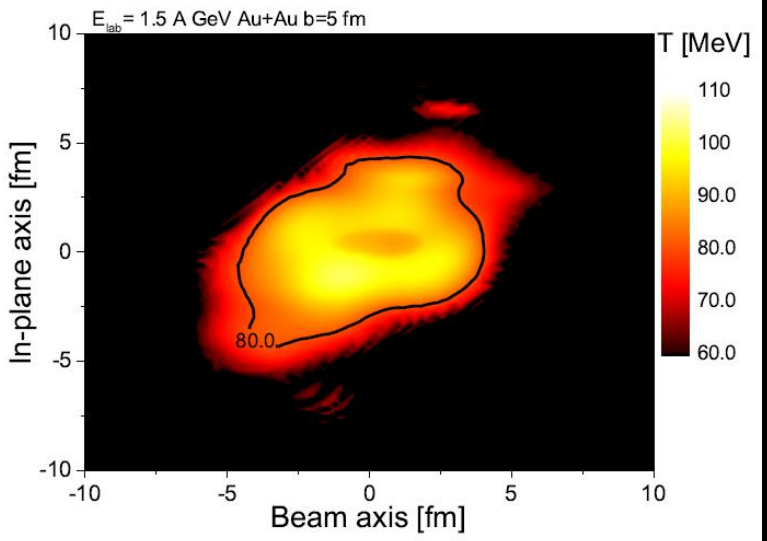
M. Hanauske et al., J. Phys.: Conf. Ser. 878 012031

n-star merger

EOS

Au +Au 1.5A GeV





The equation-of-state of nuclear matter

The nuclear matter equation of state (EOS) describes the relation between density, pressure, temperature, energy, and isospin asymmetry

$$P = \delta E/\delta V \Big|_{T=const}$$
$$V = A/\rho$$
$$\delta V/\delta\rho = -A/\rho^2$$
$$P = \rho^2\, \delta(E/A)/\delta\rho \Big|_{T=const}$$

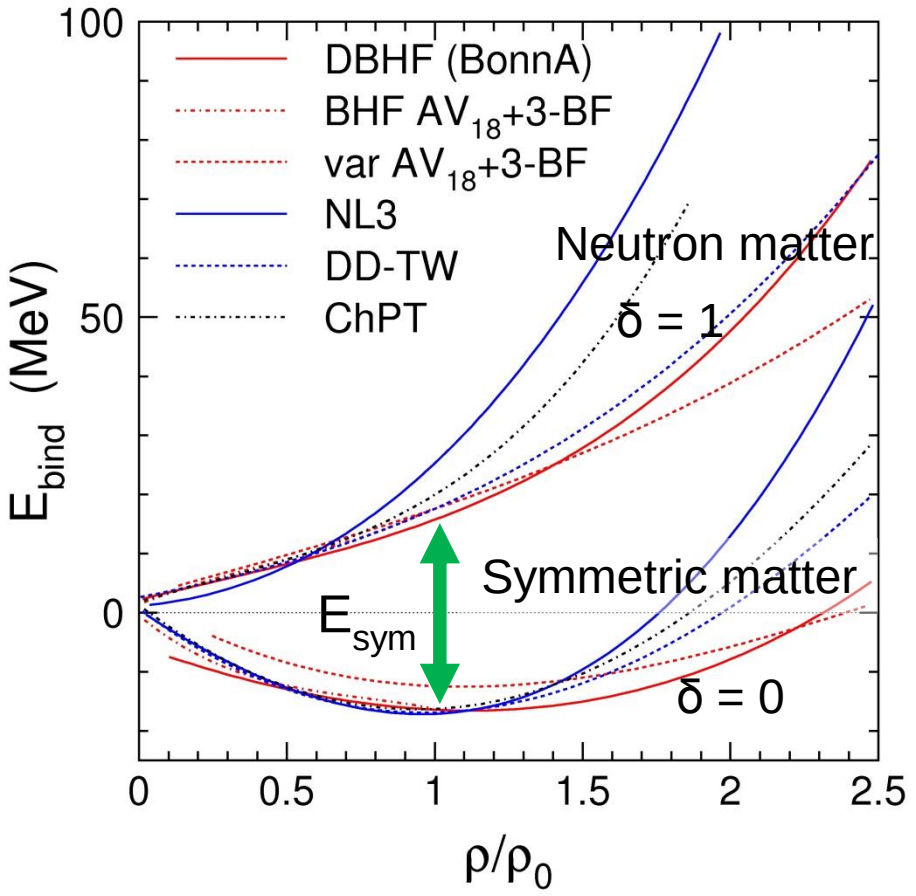
$E_A(\rho,\delta) = E_A(\rho,0) + E_{sym}(\rho)\cdot\delta^2 + O(\delta^4)$
with asymmetry parameter $\delta = (\rho_n - \rho_p)/\rho$

Finite nuclei:

$$E = -a_{vol}\,A + a_{surf}\,A^{2/3} + a_{sym}\,\frac{(N-Z)^2}{A} + a_c\,\frac{Z^2}{A^{1/3}} + E_{pair}$$

Bethe-Weizsäcker mass formula

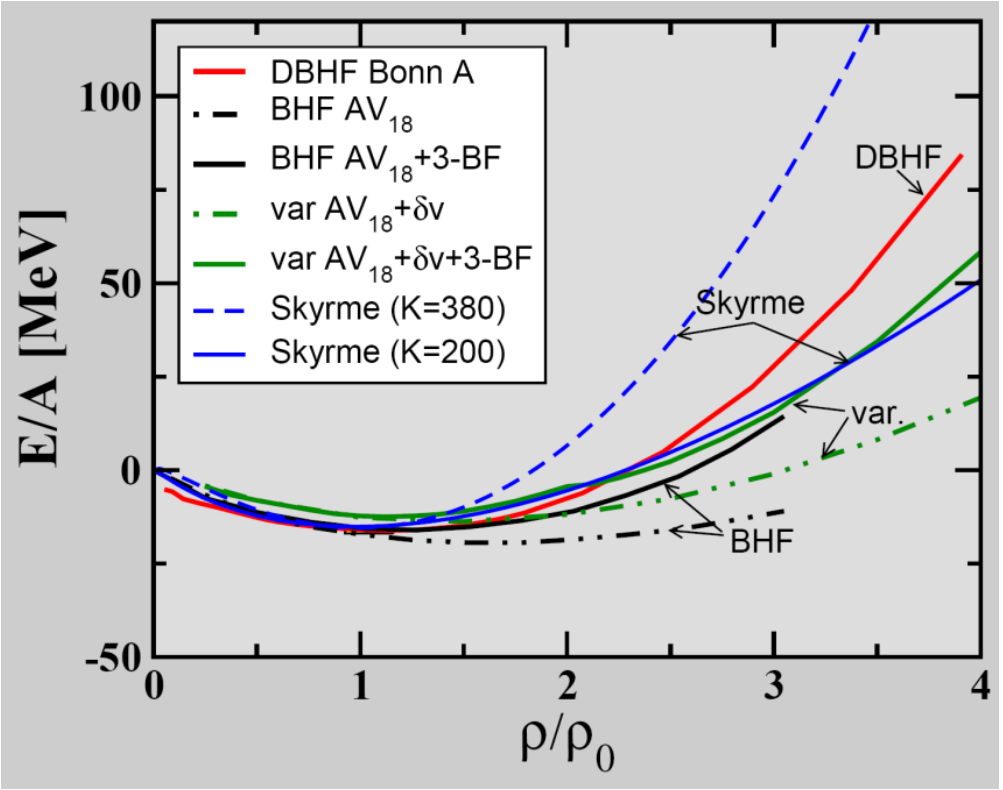
Fuchs and Wolter, EPJA 30 (2006)



The equation-of-state of (symmetric) nuclear matter

$$E_A(\rho,\delta) = E_A(\rho,0) + E_{sym}(\rho)\cdot\delta^2 + O(\delta^4)$$

C. Fuchs, Prog. Part. Nucl. Phys. 56 (2006) 1



T=0: $E/A = 1/\rho \int U(\rho)d\rho$

Effective NN-potential:

$U(\rho)=\alpha\rho+\beta\rho^{\gamma}$

- $E/A(\rho_o) = -16$ MeV
- $\delta(E/A)(\rho_o)/\delta\rho = 0$
- $K_{nm} = 9\rho^2\ \delta^2(E/A)/\delta\rho^2$

  (nuclear incompressibility)

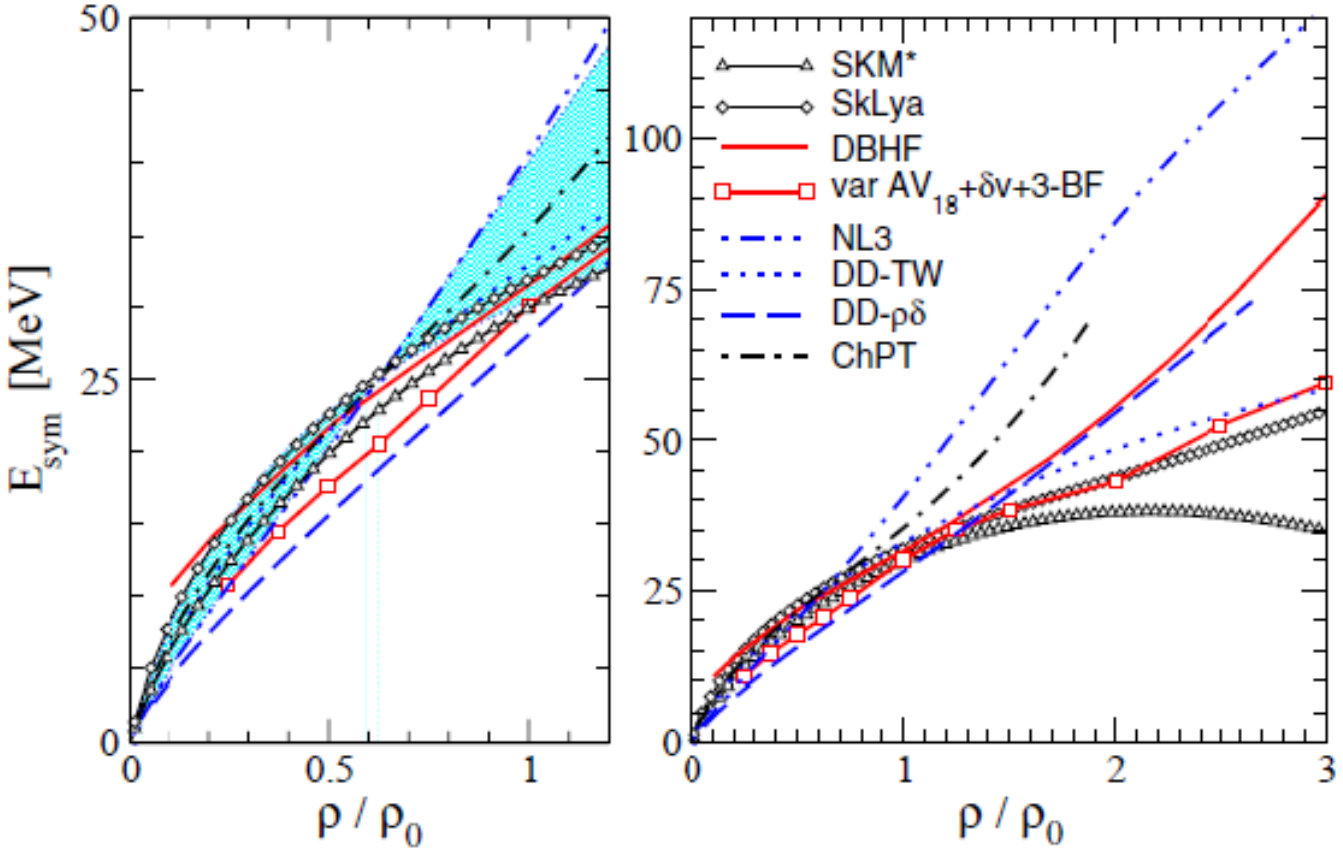
K_{nm} = 200 MeV: "soft" EOS

K_{nm} = 380 MeV: "stiff" EOS

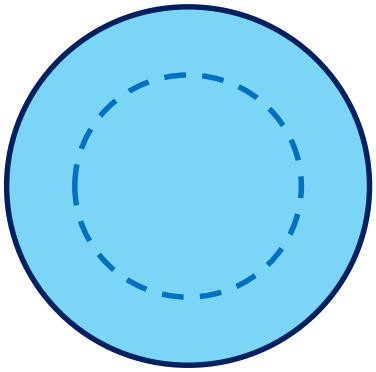
The symmetry energy

$E_A(\rho,\delta) = E_A(\rho,0) + E_{sym}(\rho)\cdot\delta^2 + O(\delta^4)$

with asymmetry parameter $\delta = (\rho_n - \rho_p)/\rho$



Nuclear Incompressibility from Giant Monopole Resonances ($\rho \leq \rho_0$)



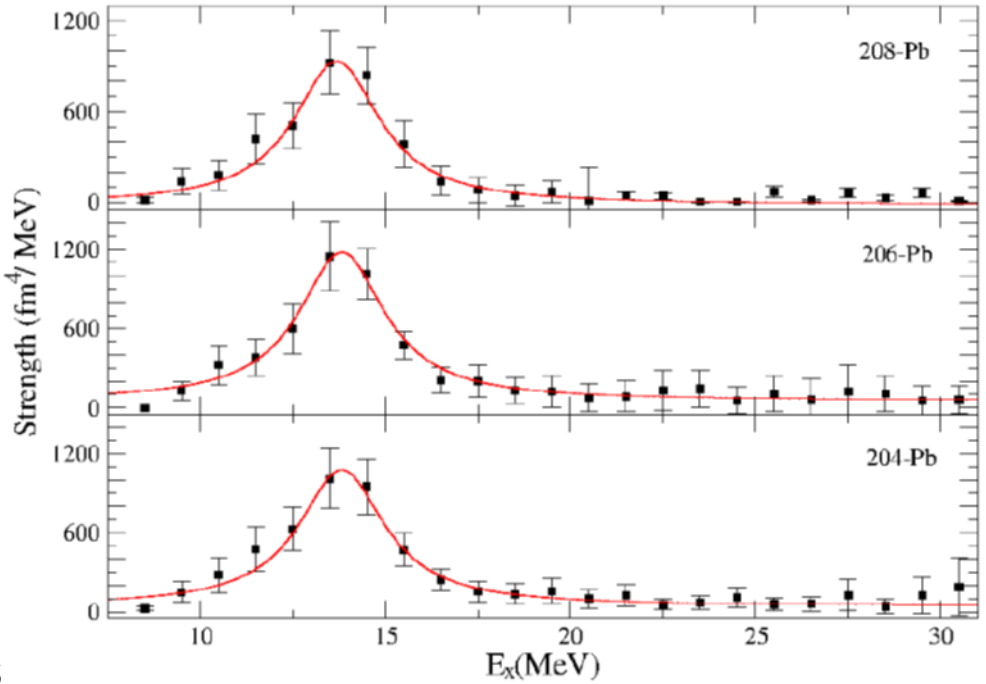
GMR

Energy of the GMR

$$E_{GMR} = \sqrt{\frac{\hbar^2 K_A}{m \langle r^2 \rangle_0}}$$

K_A: incompressibility of the nucleus

inelastic scattering 400 MeV α + Pb
at very forward angles

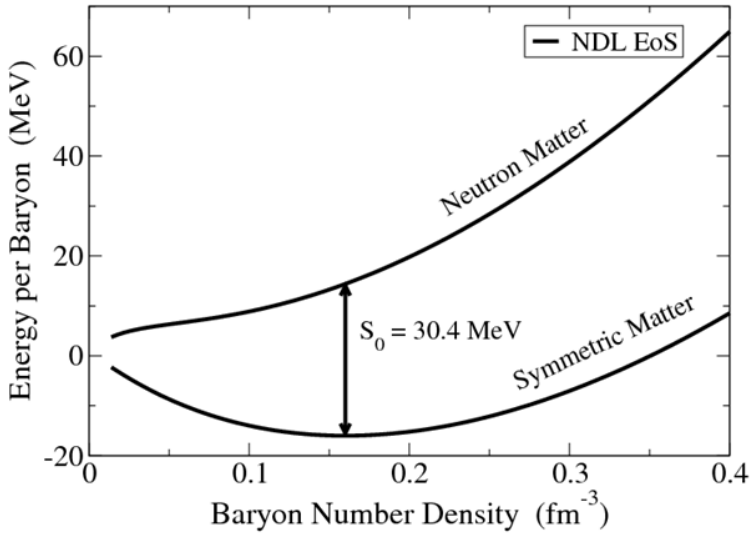


U. Garg, Progress of Theoretical Physics Supplement No. 196, 2012

Nuclear Incompressibility from Giant Monopole Resonances ($\rho \leq \rho_0$)

Nuclear incompressibility:

$$K_{nm} = 9\rho^2 \frac{d^2(E/A)}{d\rho^2} \quad \text{at } \rho=\rho_0$$



Energy of the GMR

$$E_{GMR} = \sqrt{\frac{\hbar^2 K_A}{m \langle r^2 \rangle_0}}$$

K_A: inkompressibility of the nucleus

$$K_A = K_{vol} + K_{surf} A^{-1/3} + K_{sym}(N-Z)^2/A^2 + K_{Coul} Z^2/A^{4/3} + \ldots \text{ (liquid drop model)}$$

$$K_{nm} = \lim_{A\to\infty} K_A = K_{vol}$$

400 MeV α + ^{206}Pb:

K_{nm} = 220 – 240 MeV

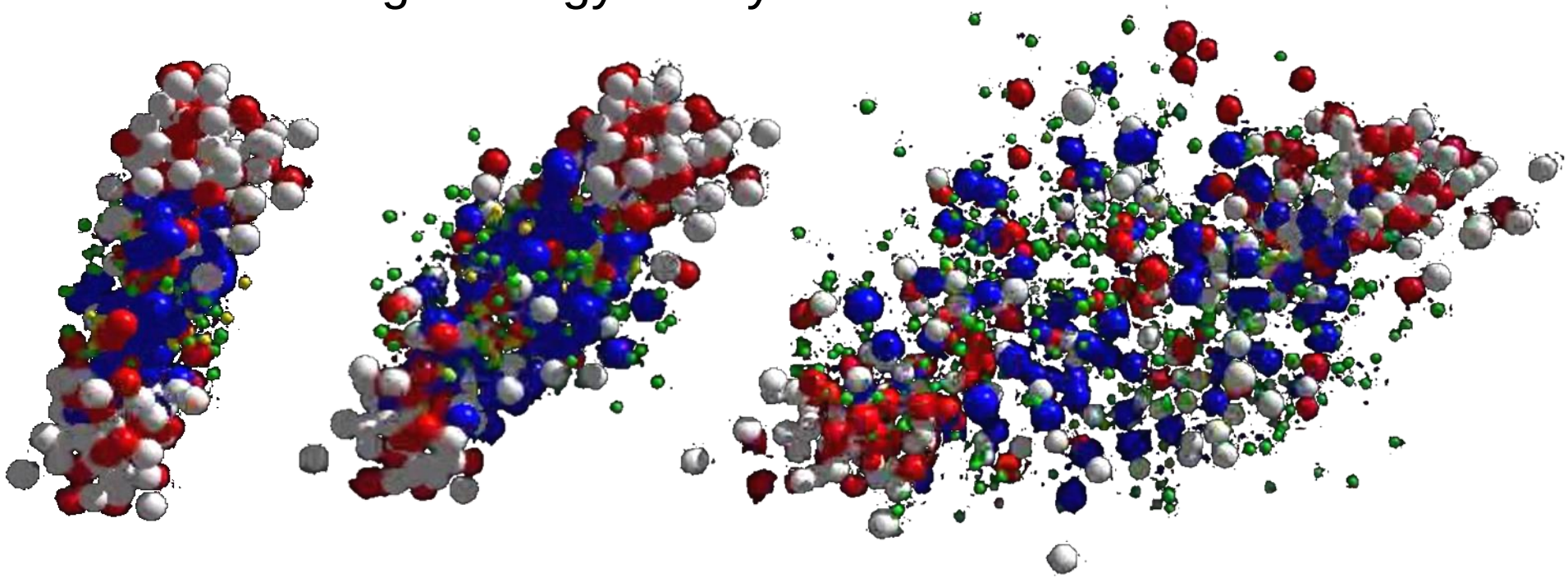
400 MeV α + $^{112\text{-}124}$Sn:

K_{sym} = 400 – 600 MeV

J.P. Blaisot et al., Nuclear Physics A 591 (1995) 435-457

The EOS of nuclear matter at $\rho > \rho_0$

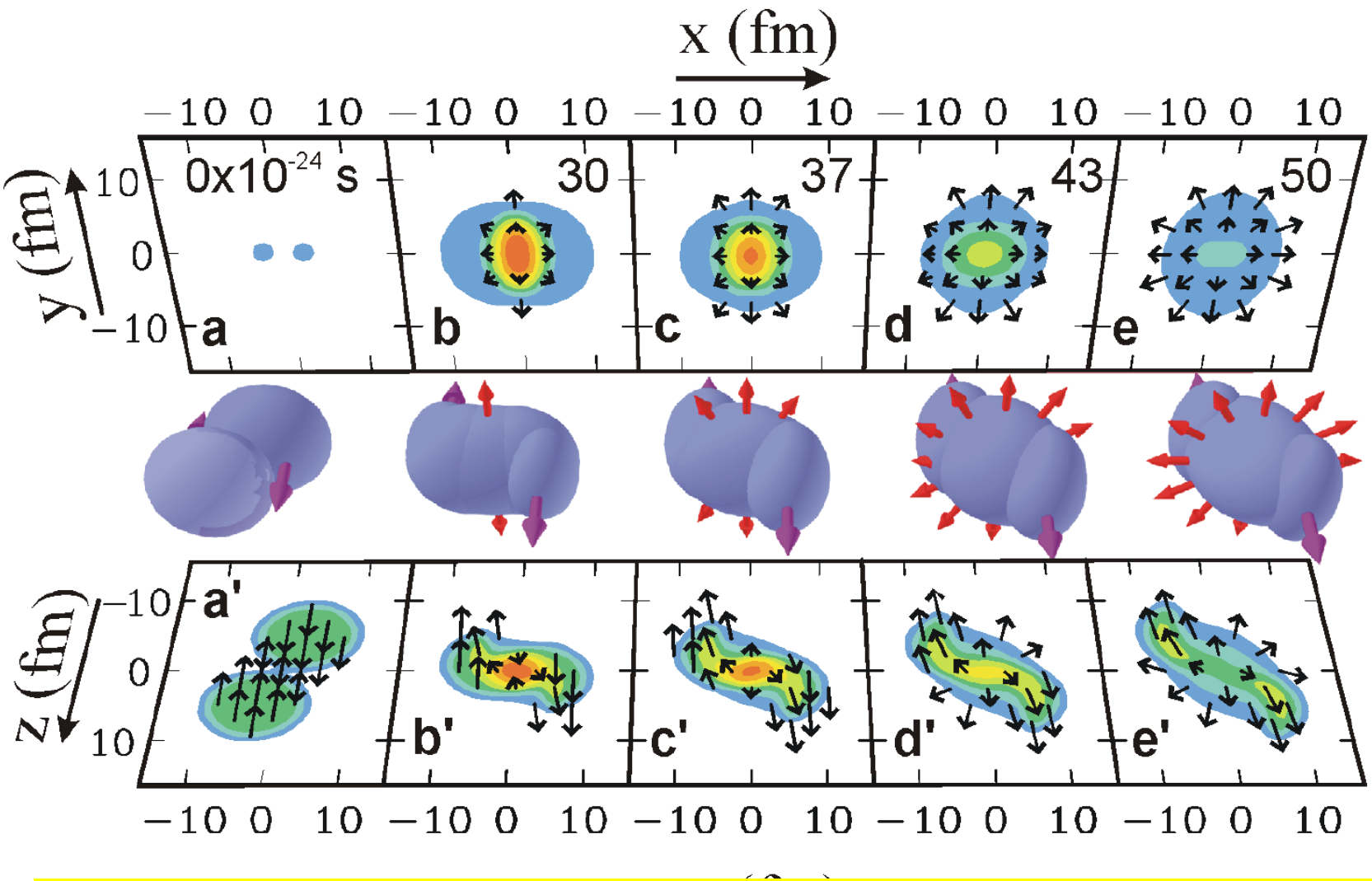
Production of dense nuclear matter in high-energy heavy-ion collisions



Volume about 1000 fm^3, lifetime 10^{-22} s

- Finite size, finite lifetime effects?
- Observables:
  - Collective flow
  - Subthreshold particle production

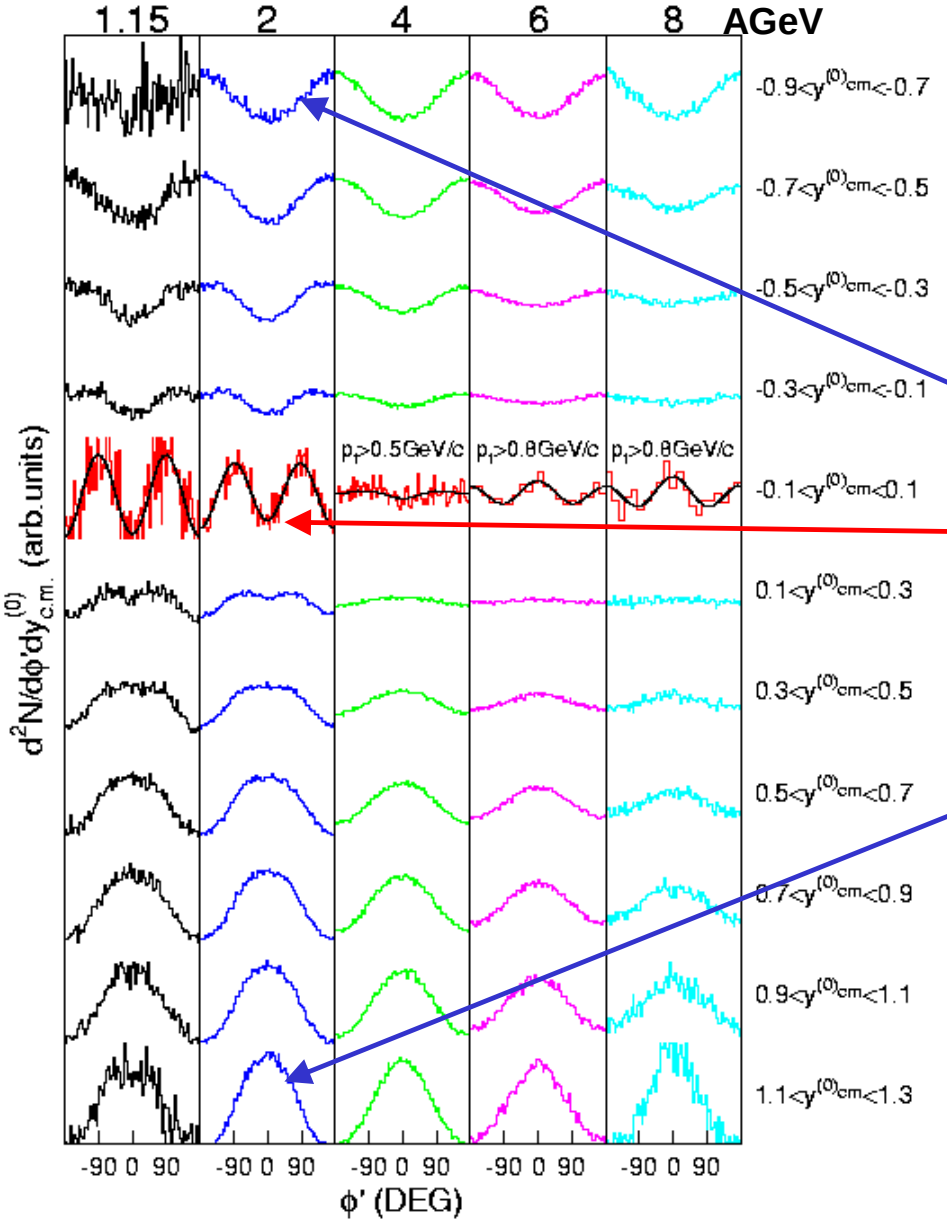
Dynamics of a semi-central Au+Au collision at 2 AGeV



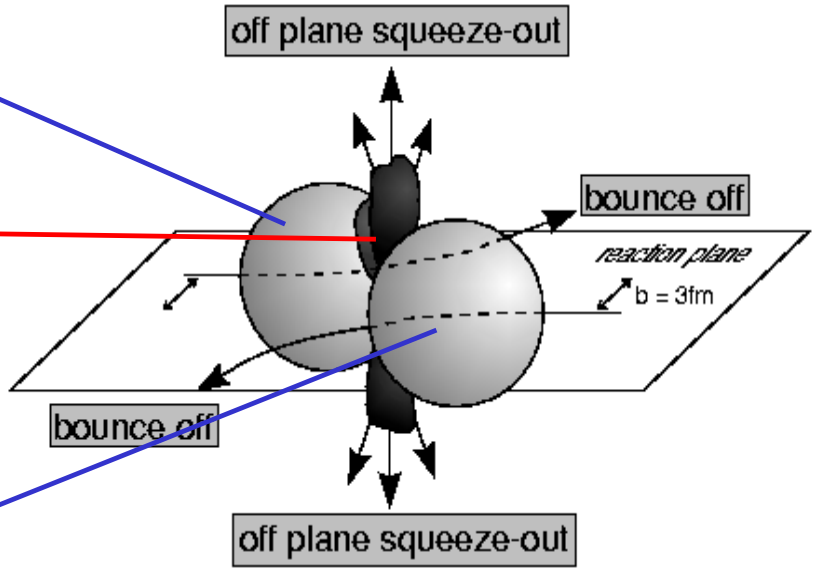
Collective flow of nucleons: driven by pressure gradient

P. Danielewicz, R. Lacey, W.G. Lynch, Science 298 (2002) 1592

Azimuthal angular distribution of protons in Au+Au collisions at 1.15 - 8 AGeV



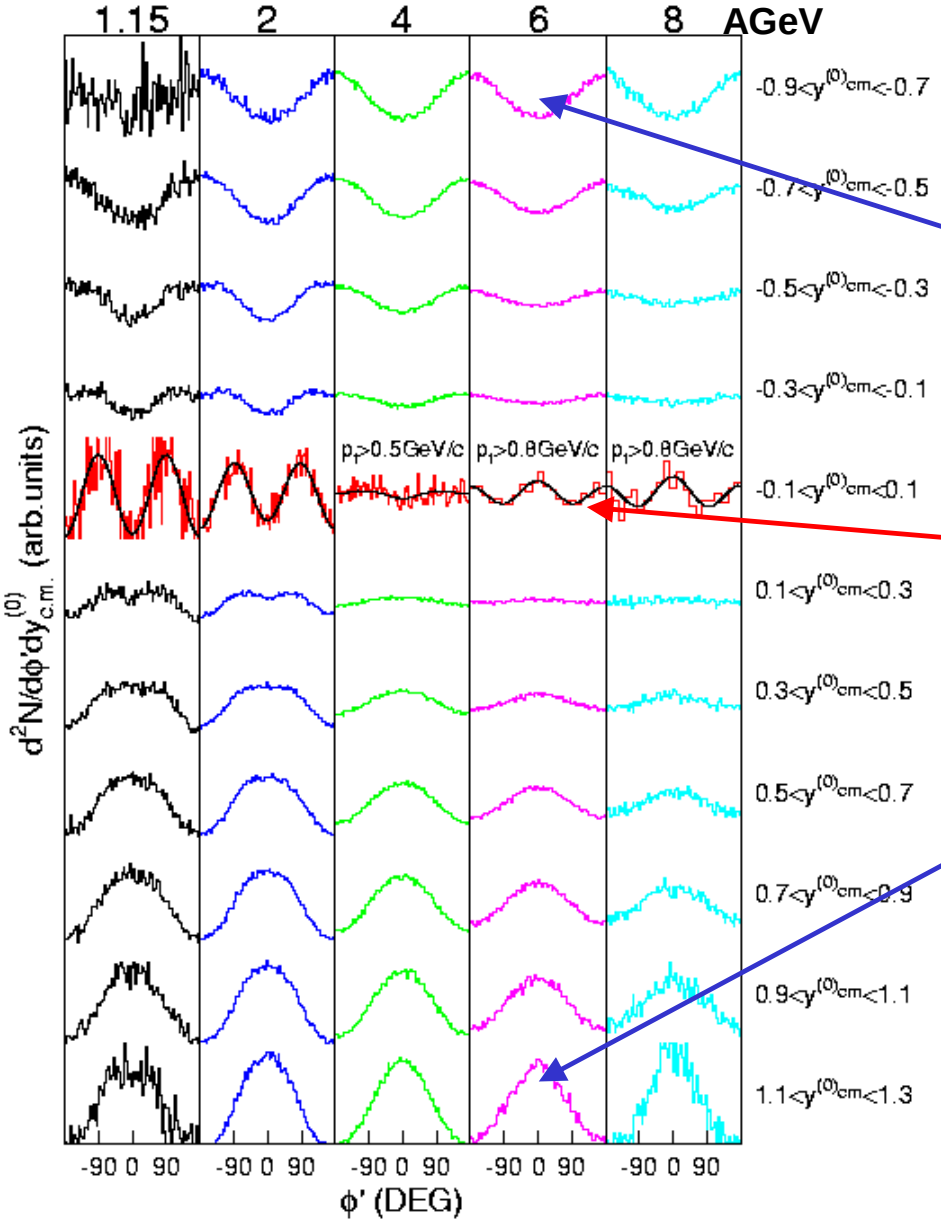
C.Pinkenburg et al., (E895),
Phys. Rev. Lett. 83 (1999) 1295



Azimuthal angle distribution:
$dN/d\Phi \propto (1 + 2v_1 \cos\Phi + 2v_2 \cos 2\Phi)$

Rapidity: $y^{(0)} = y - y_m$
with $y = 0.5 \ln [(E+p_z)/(E-p_z)]$

Azimuthal angular distribution of protons measured in Au+Au collisions at 1.15, 2, 4, 6, 8 AGeV



C.Pinkenburg et al., (E895),
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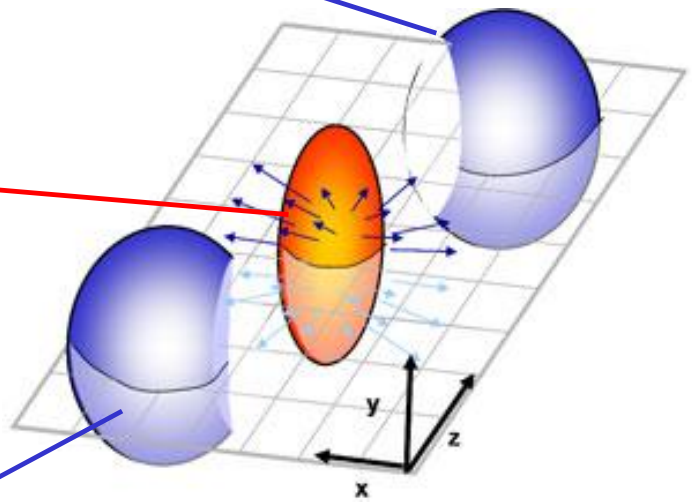

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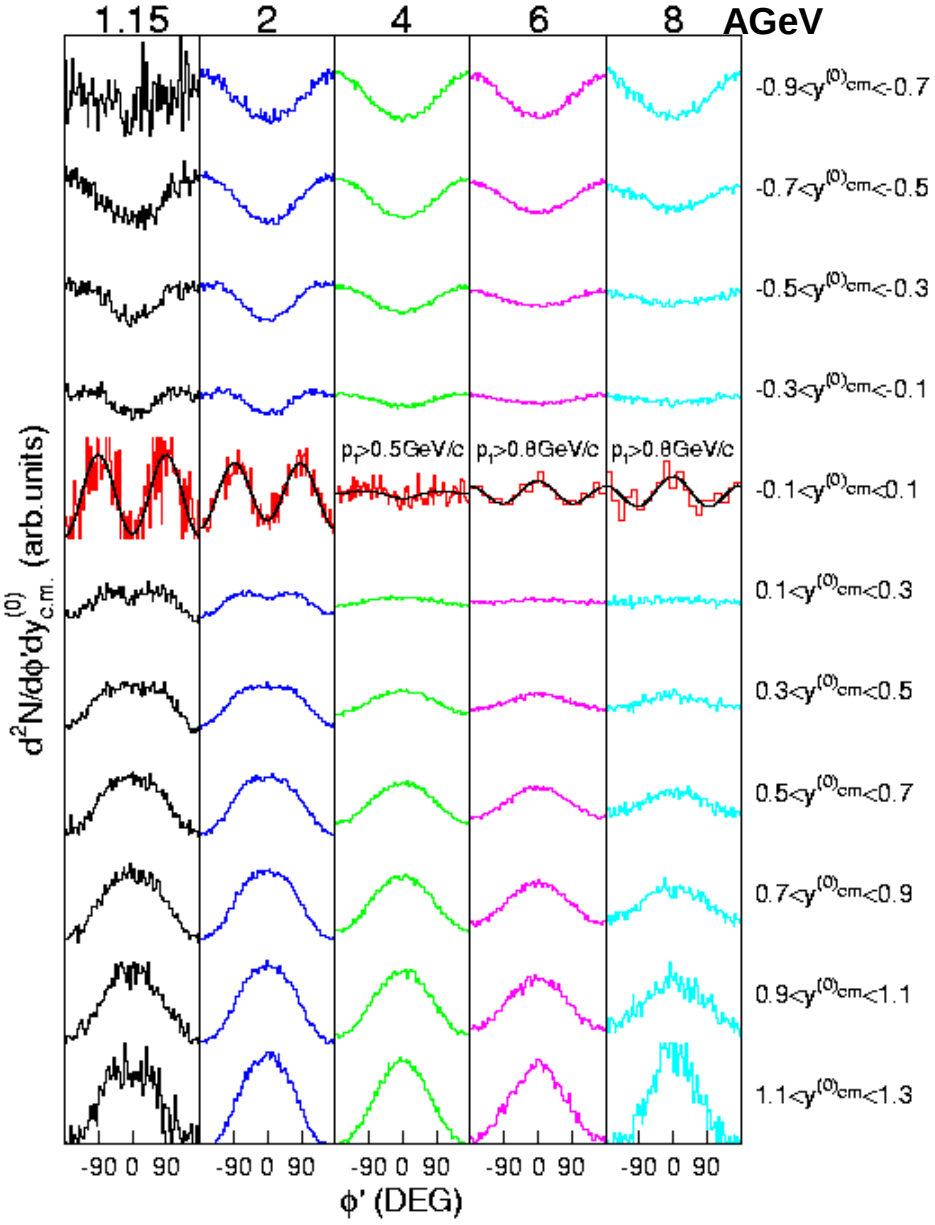
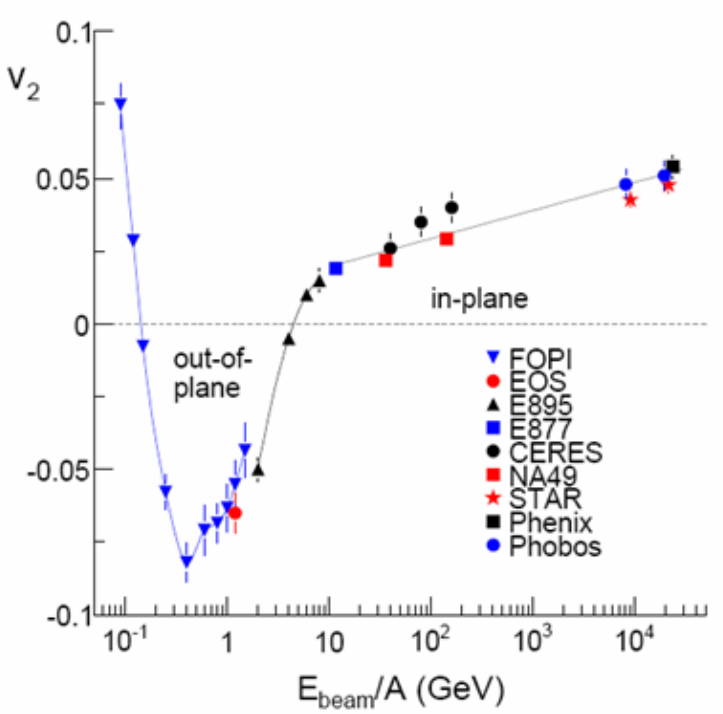


C.Pinkenburg et al., (E895),
Phys. Rev. Lett. 83 (1999) 1295



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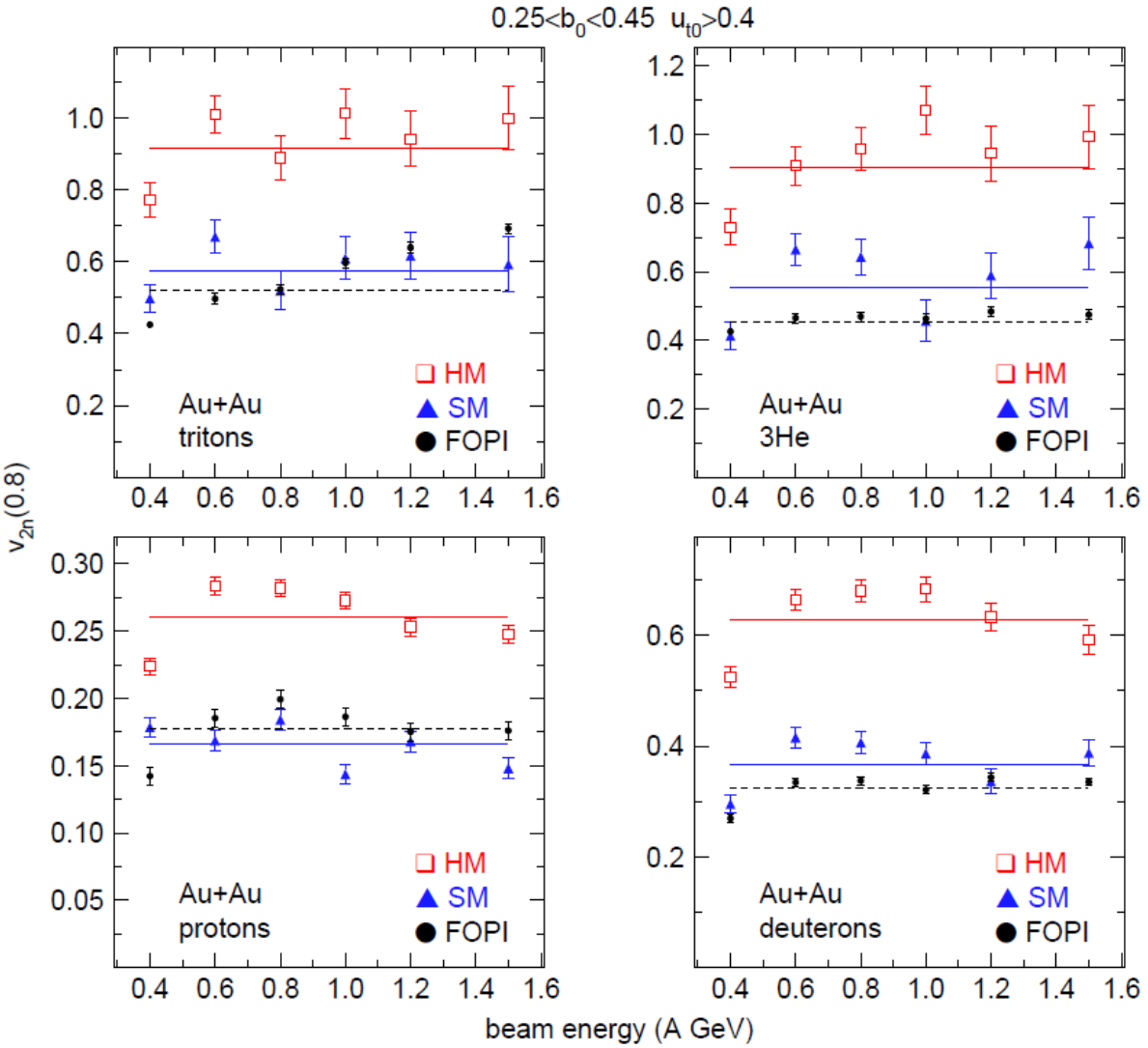
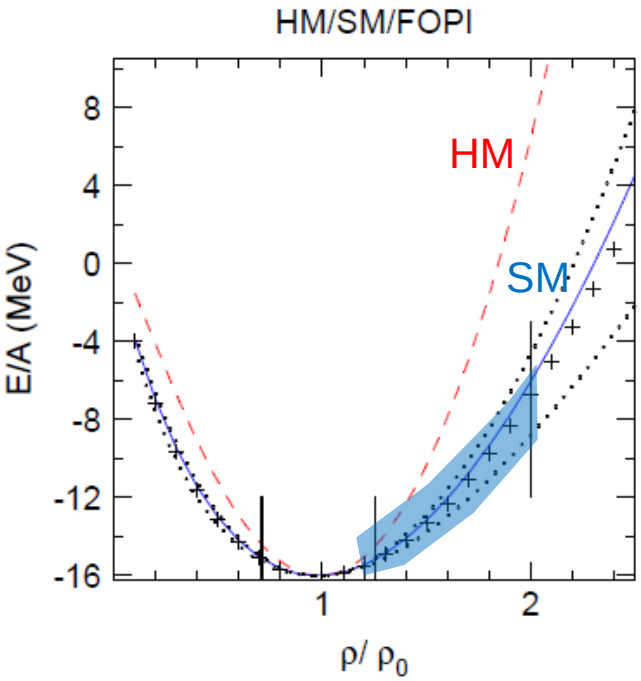
Rapidity: $y^{(0)} = y - y_m$
with $y = 0.5 \ln [(E+p_z)/(E-p_z)]$

EOS from the elliptic flow of fragments in Au+Au collisions at SIS18 energies ($\rho < 3\rho_0$)

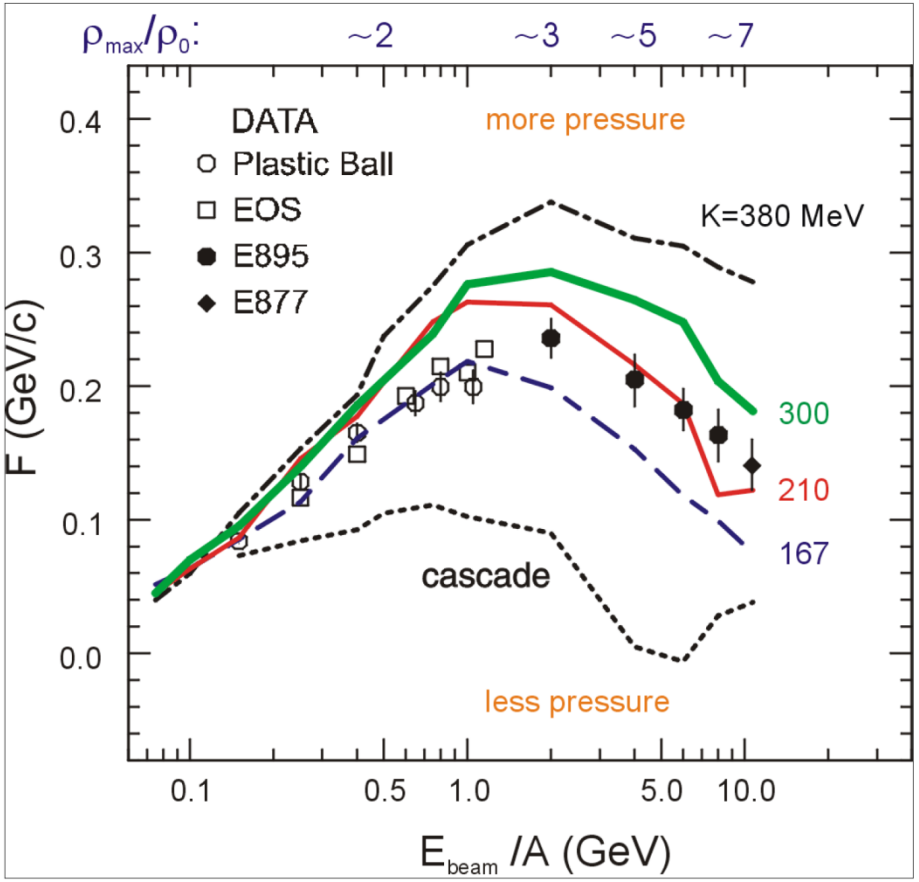
A. Le Fevre , Y Leifels, W. Reisdorf, J. Aichelin, Ch. Hartnack, arXiv:1501.02546

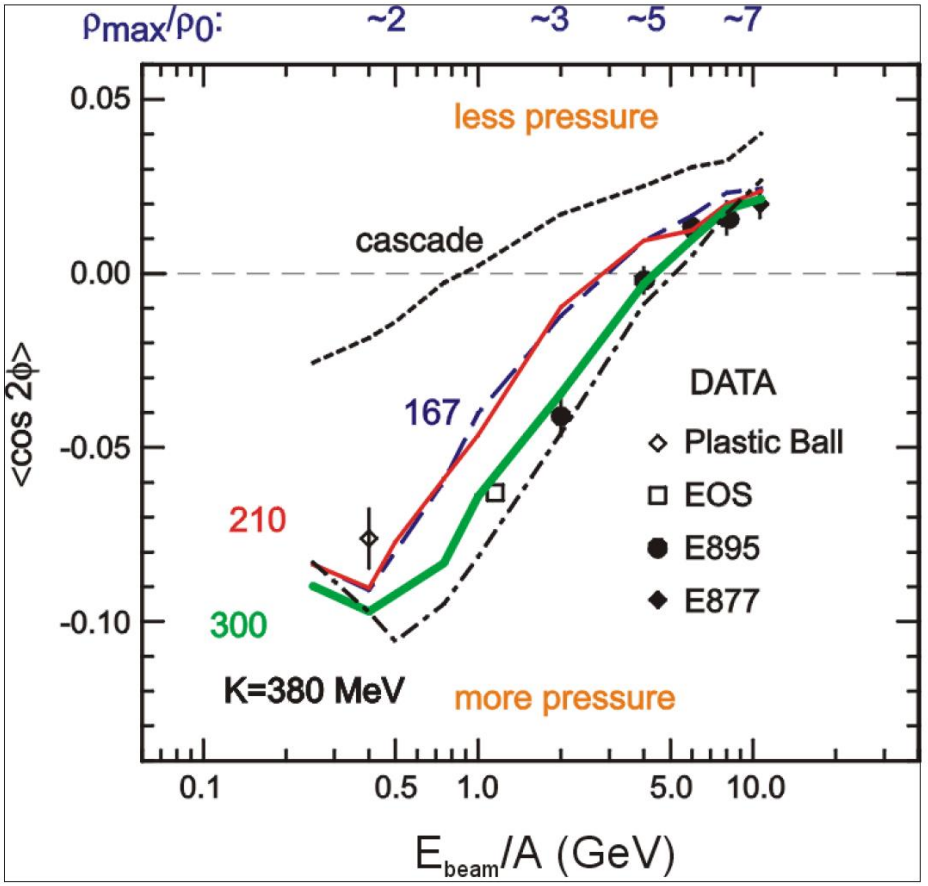




Nuclear incompressibility from collective proton flow

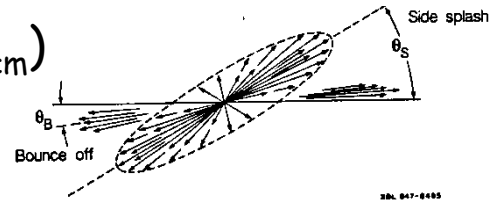
P. Danielewicz, R. Lacey, W.G. Lynch, Science 298 (2002) 1592



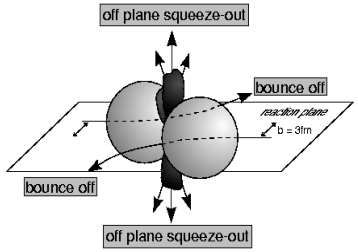


Transverse in-plane flow:

$F = d(p_x/A)/d(y/y_{cm})$

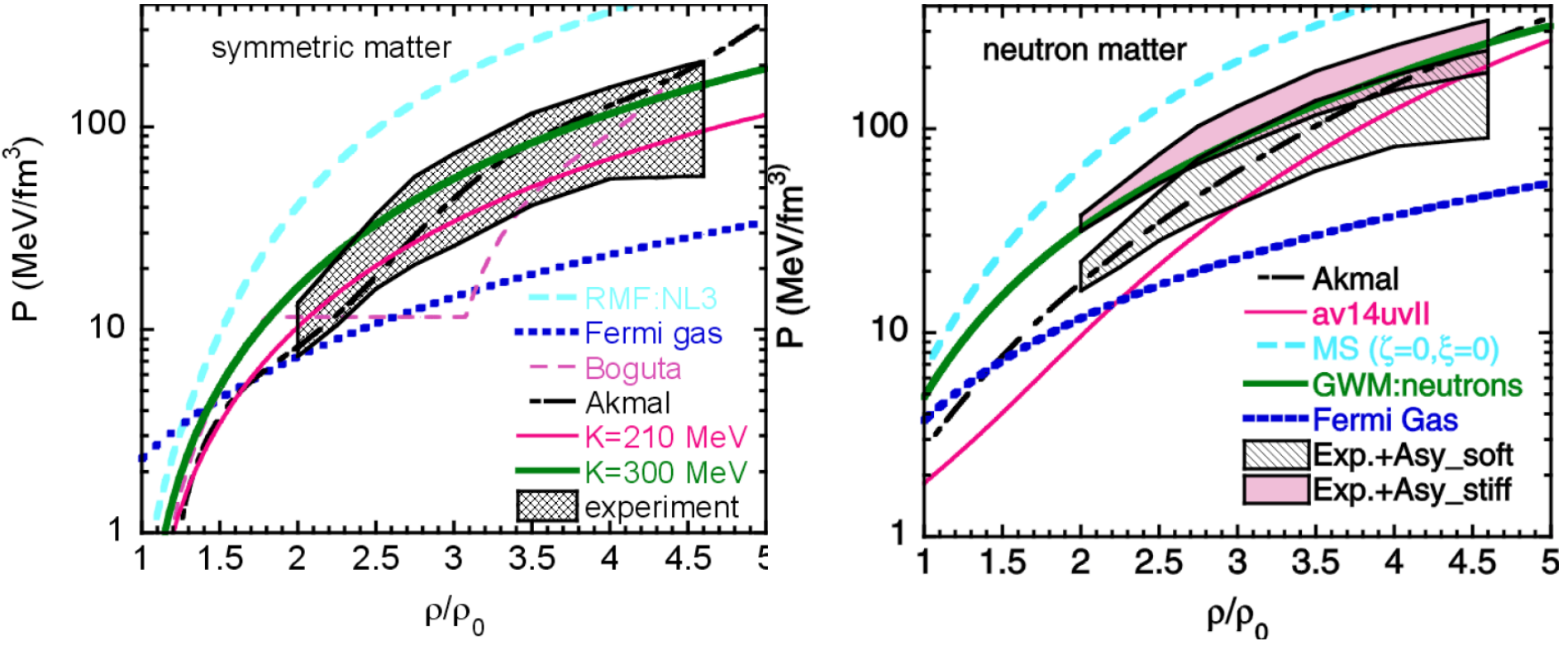


Elliptic flow:



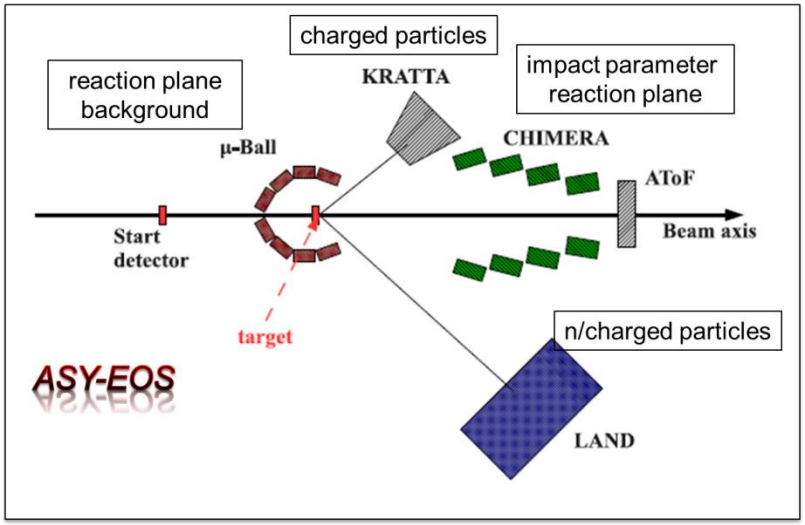
$dN/d\Phi \propto (1 + 2v_1 \cos\Phi + 2v_2 \cos 2\Phi)$

Nuclear equation-of-state from collective proton flow



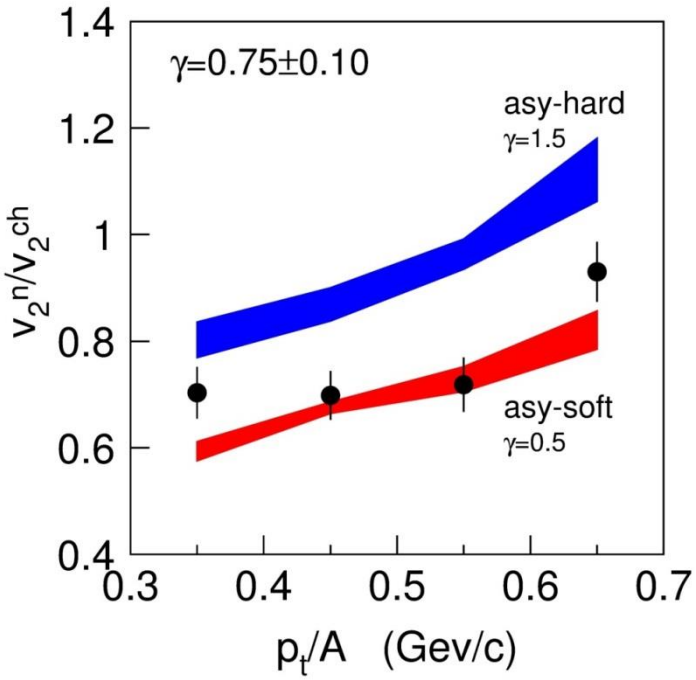
P. Danielewicz, R. Lacey, W.G. Lynch, Science 298 (2002) 1592

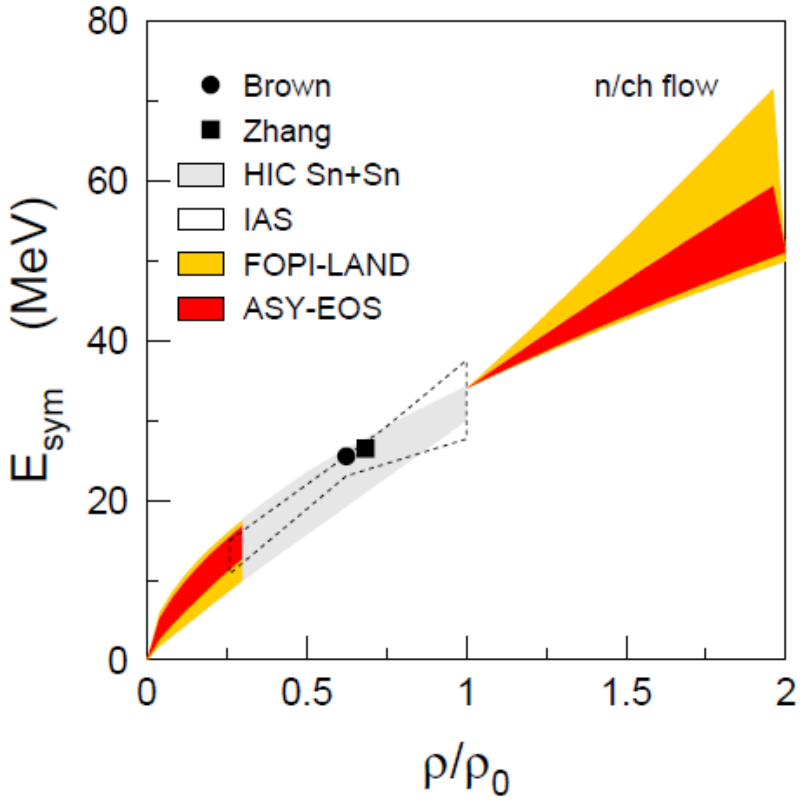
The ASY-EOS experiment at GSI: The symmetry energy at supra-saturation density



P. Russotto et al.,
Phys. Rev. C 94, 034608 (2016)

Measuring the elliptic flow of charged particles and neutrons in Au+Au collisions at 400A MeV



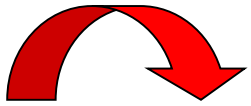


Collective flow in Au+Au collisions and the nuclear matter EOS

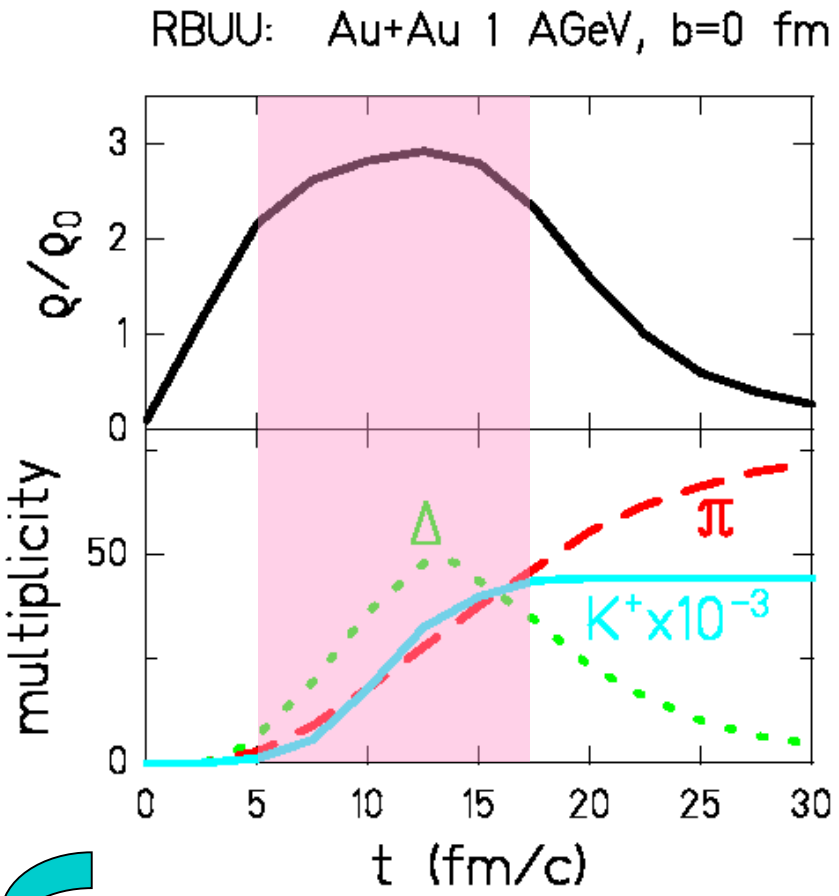
Beam energy AGeV	central density	flow observable	incompressibility K
0.4 – 1.5	$\rho = 1 - 3\ \rho_0$	v_2 of p, d, t, 3He	≈ 200 MeV
2 – 10	$\rho = 3 - 7\ \rho_0$	v_1 of p,	≈ 200 MeV
2 – 10	$\rho = 3 - 7\ \rho_0$	v_2 of p,	≈ 300 MeV

Within microscopic transport models the collective flow is sensitive to:

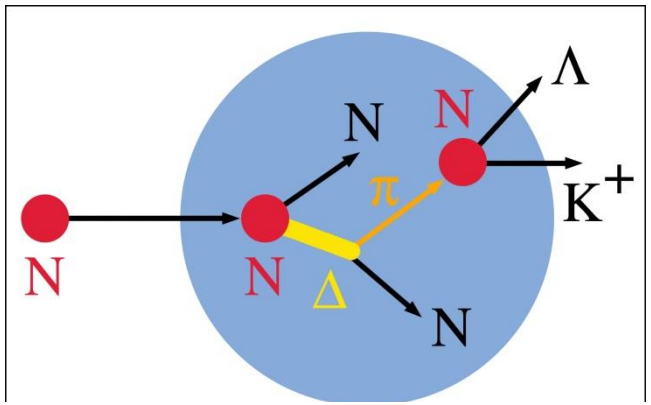
- The nuclear matter equation of state
- In-medium nucleon-nucleon cross sections
- Momentum dependent interactions

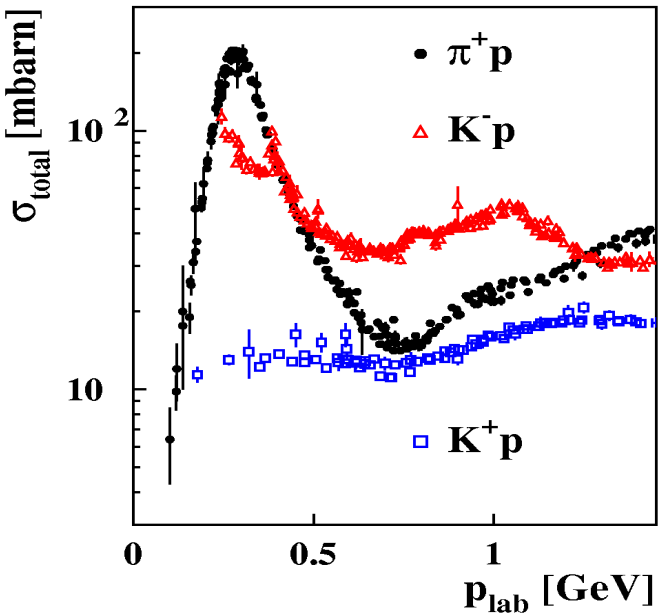
Independent observables?  particle production

Probing the nuclear equation-of-state ($\rho = 1 - 3\ \rho_0$) by K^+ meson subthreshold production in HI collisions



$pp \rightarrow K^+\Lambda p$ (E_{thres}= 1.6 GeV)





K^+ mesons probe high densities

K^+ mesons scatter elastically only

Probing the nuclear equation-of-state ($\rho = 1 - 3\ \rho_0$) by K^+ meson production in C+C and Au+Au collisions

Idea: K^+ yield $\propto$ baryon density $\propto$ compressibility

Transport model (RBUU)

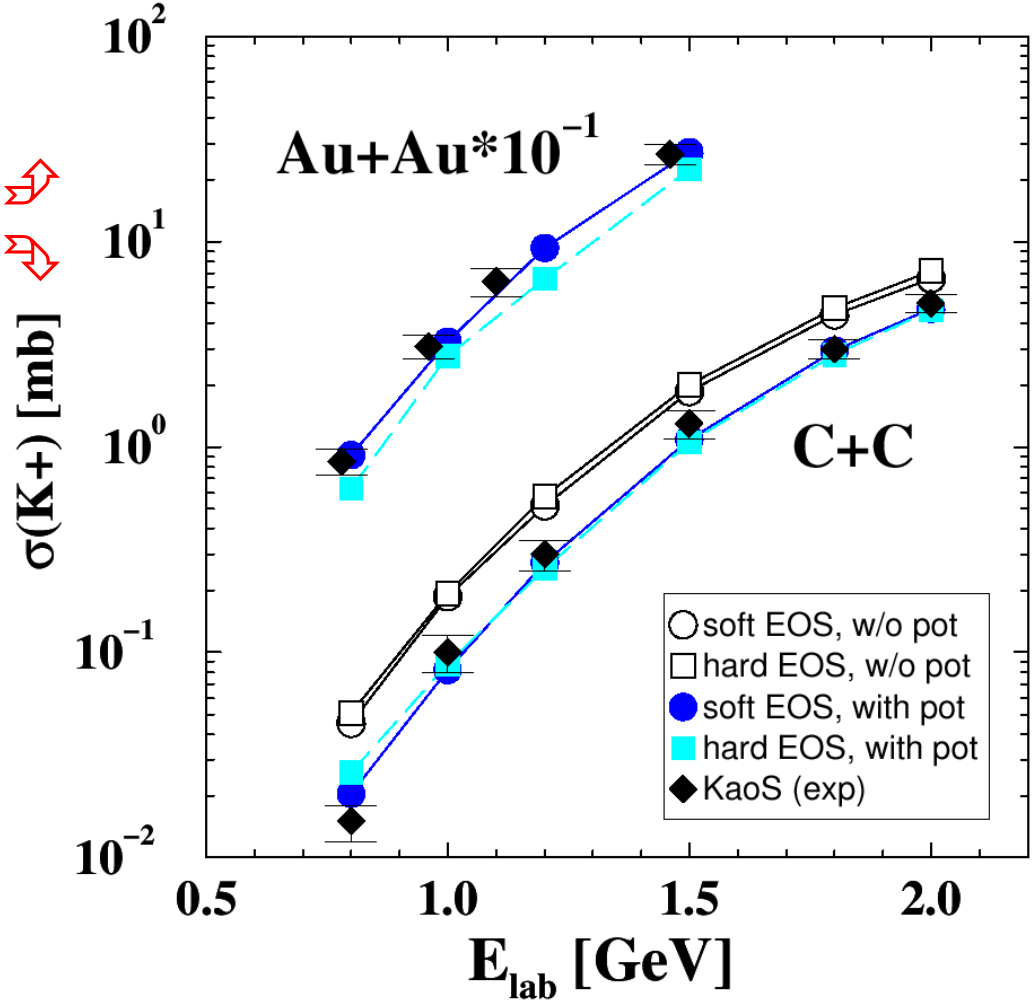
Au+Au at 1 AGeV:

κ = 200 MeV ⇨ $\rho_{max} \approx 2.9\ \rho_0$ ⇨ K^+ ⇧

κ = 380 MeV ⇨ $\rho_{max} \approx 2.4\ \rho_0$ ⇨ K^+ ⇩

Reference system C+C:

K^+ yield not sensitive to EOS



Experiment:

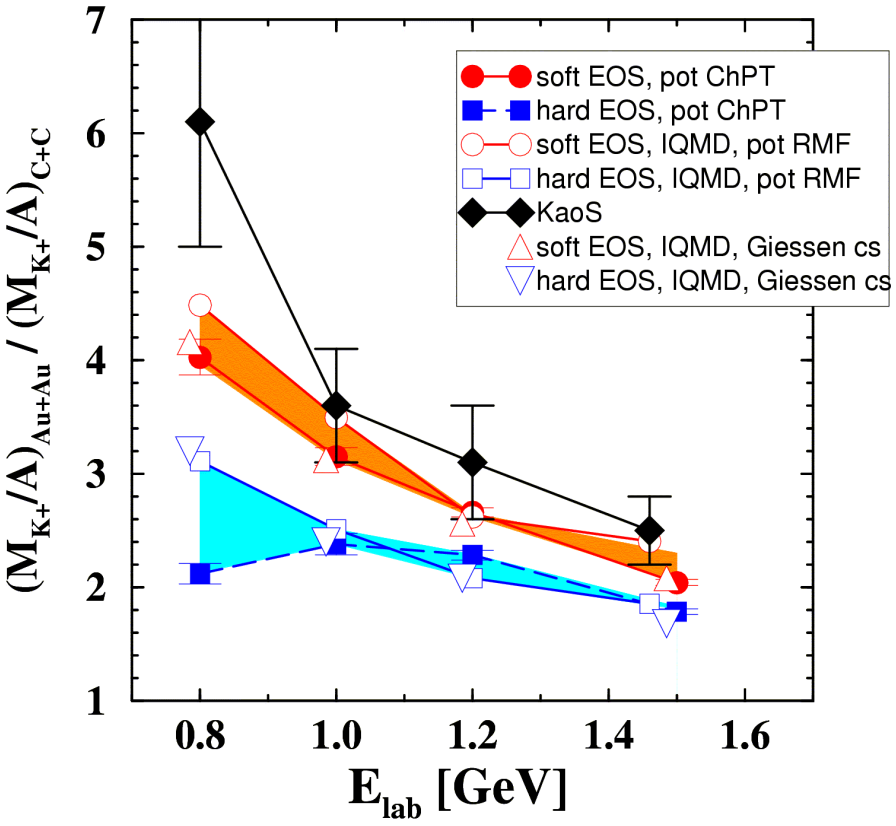
C. Sturm et al., (KaoS Collaboration), Phys. Rev. Lett. 86 (2001) 39

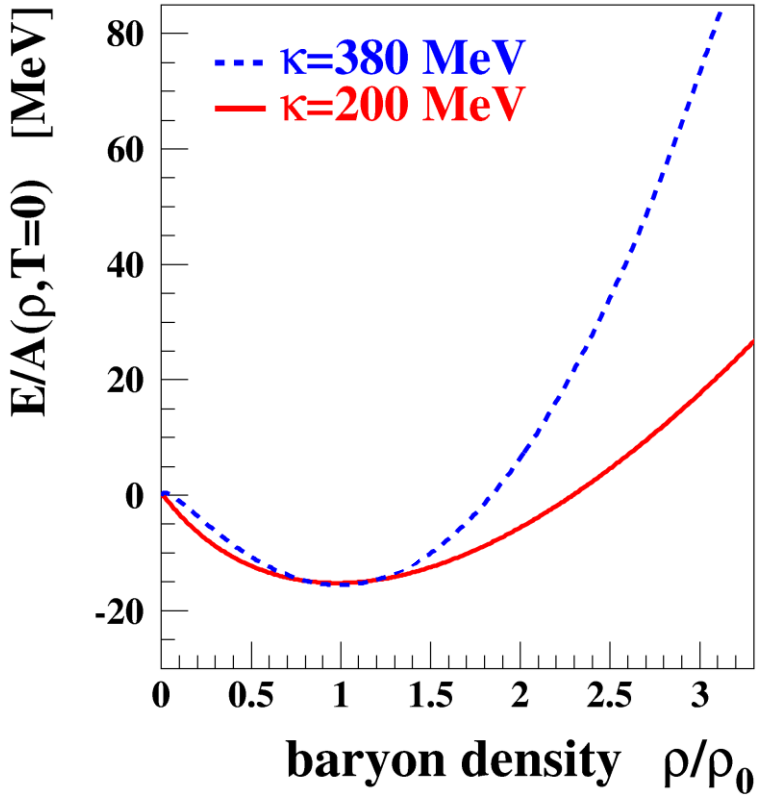
Theory:

Ch. Fuchs et al., Phys. Rev. Lett. 86 (2001) 1974

The compressibility of (symmetric) nuclear matter

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

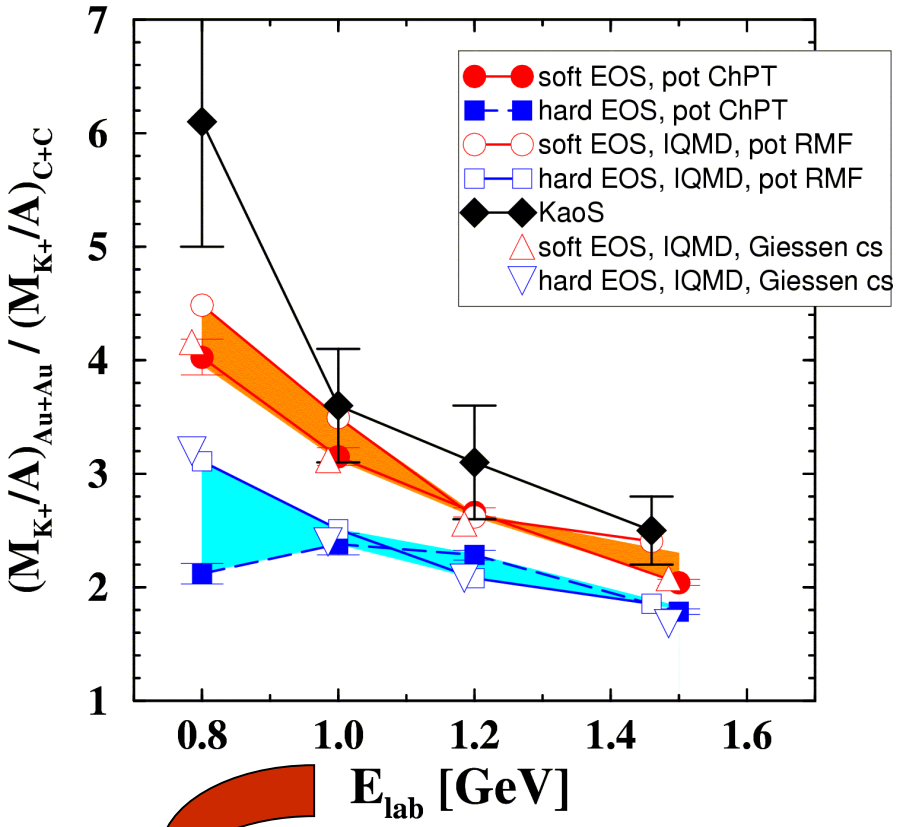


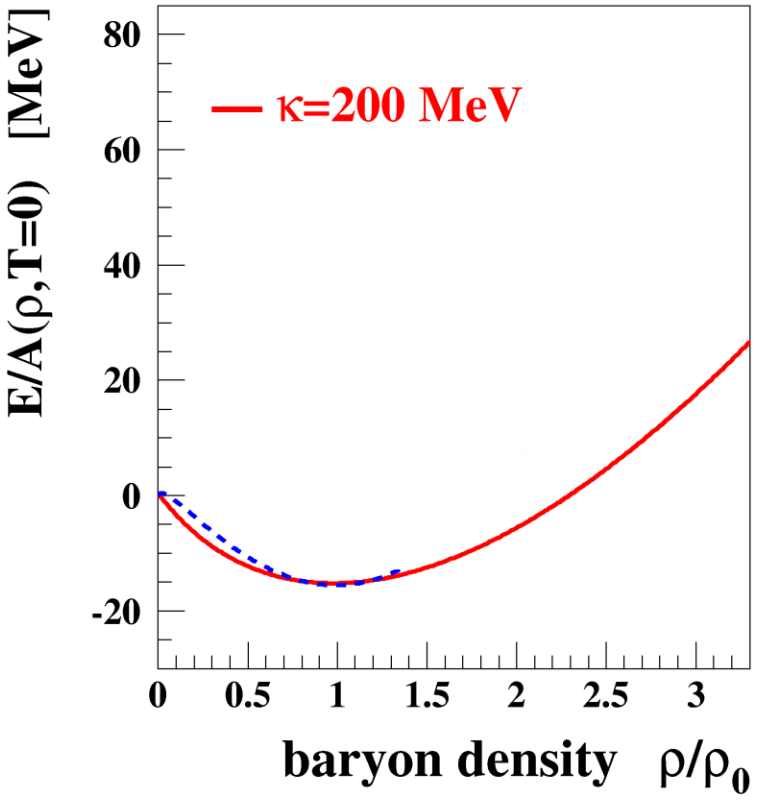


Au/C ratio: cancellation of systematic errors both in experiment and theory

The compressibility of (symmetric) nuclear matter

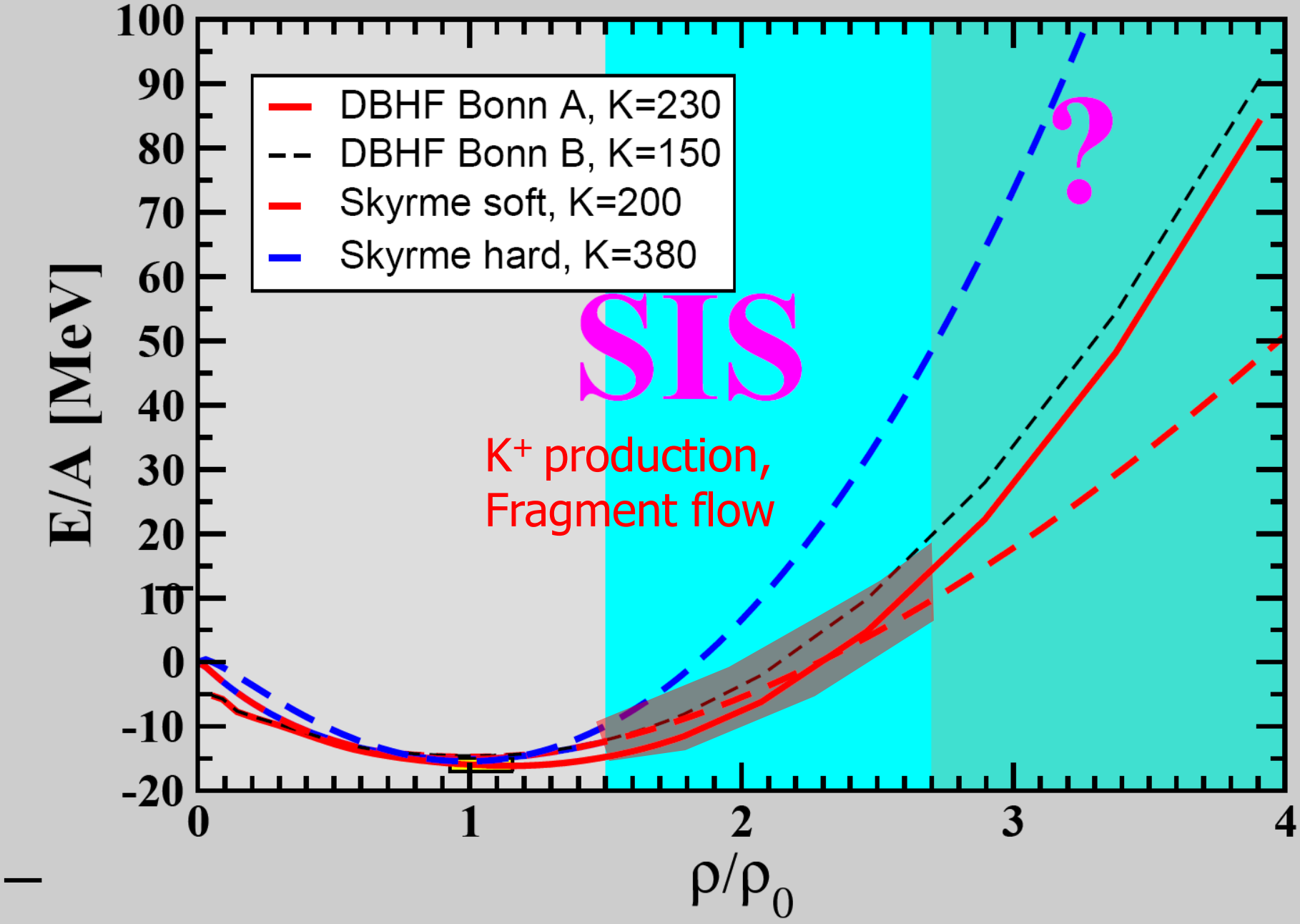
Experiment: C. Sturm et al., (KaoS Collaboration) Phys. Rev. Lett. 86 (2001) 39
Theory: QMD Ch. Fuchs et al., Phys. Rev. Lett. 86 (2001) 1974
IQMD Ch. Hartnack, J. Aichelin, J. Phys. G 28 (2002) 1649



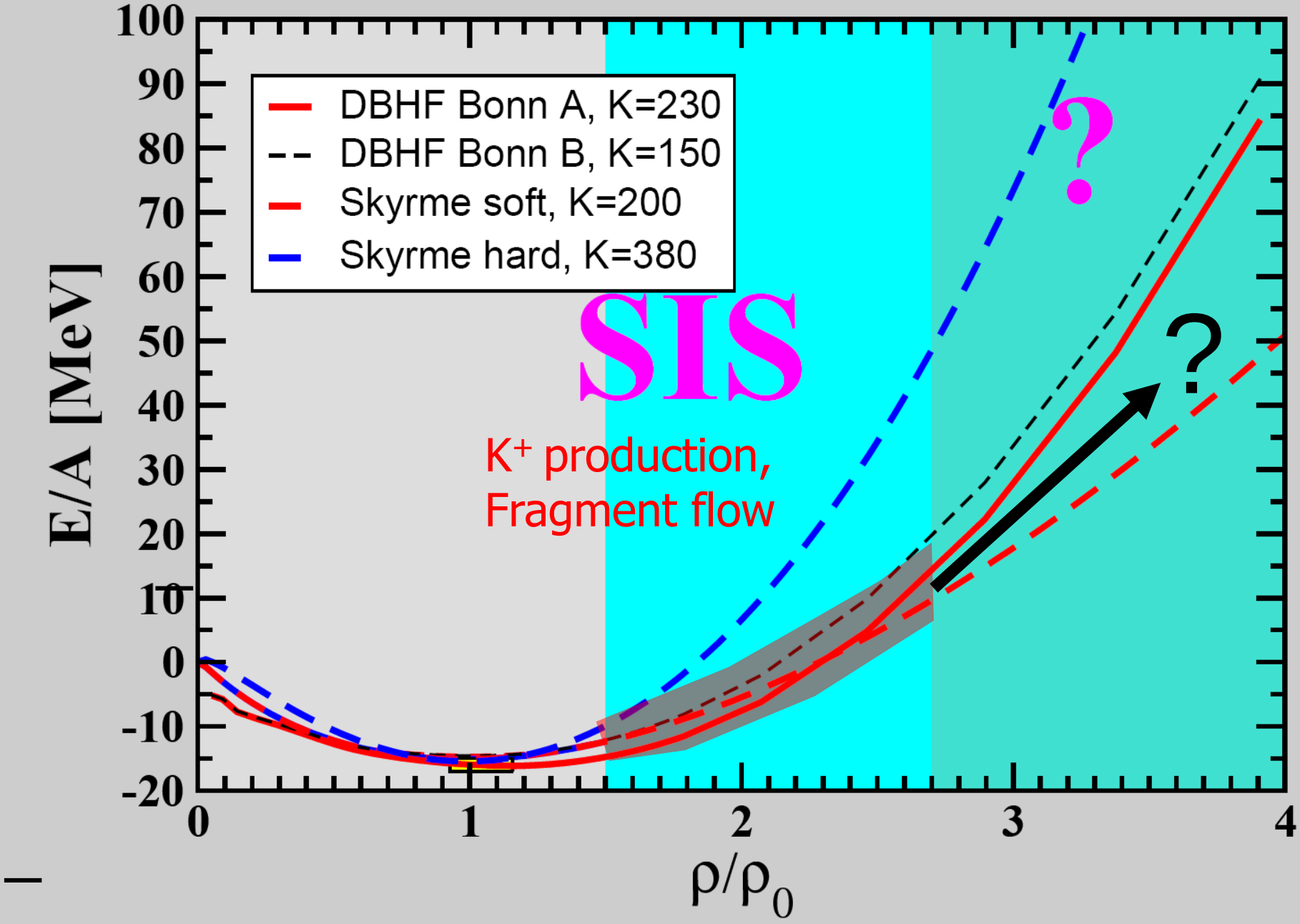


Soft equation-of-state: κ ≤ 200 MeV
Confirmation of flow measurements

nuclear matter EOS



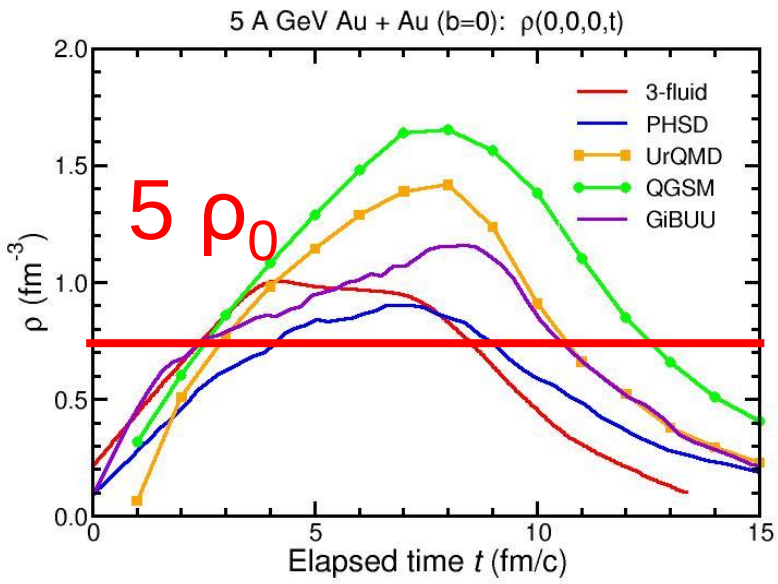
nuclear matter EOS



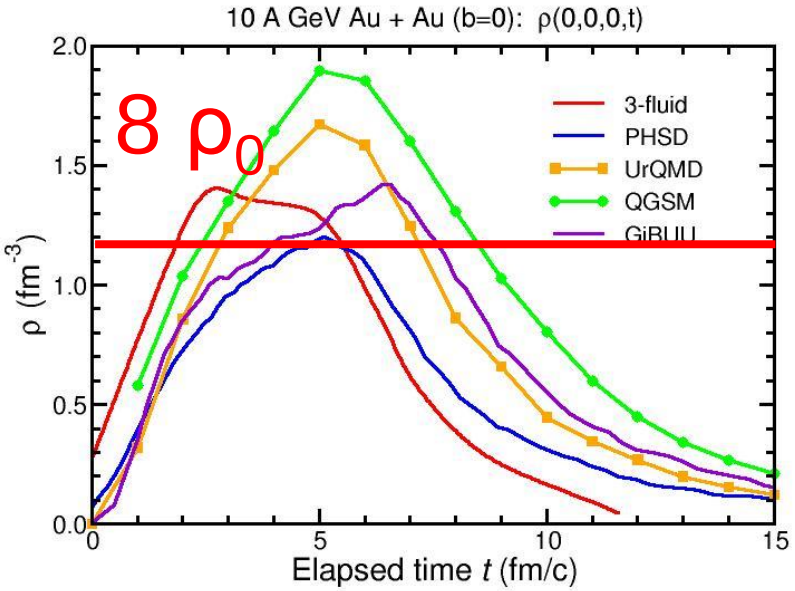
Baryon densities in central Au+Au collisions

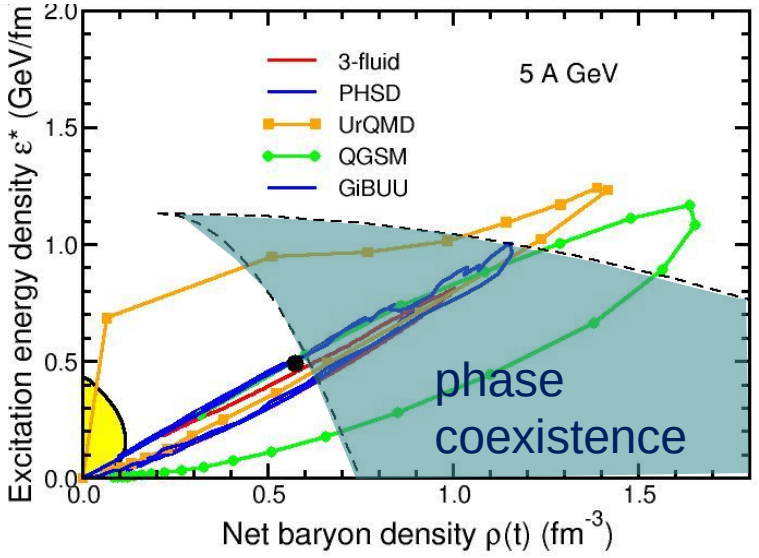
I.C. Arsene et al., Phys. Rev. C 75, 24902 (2007)

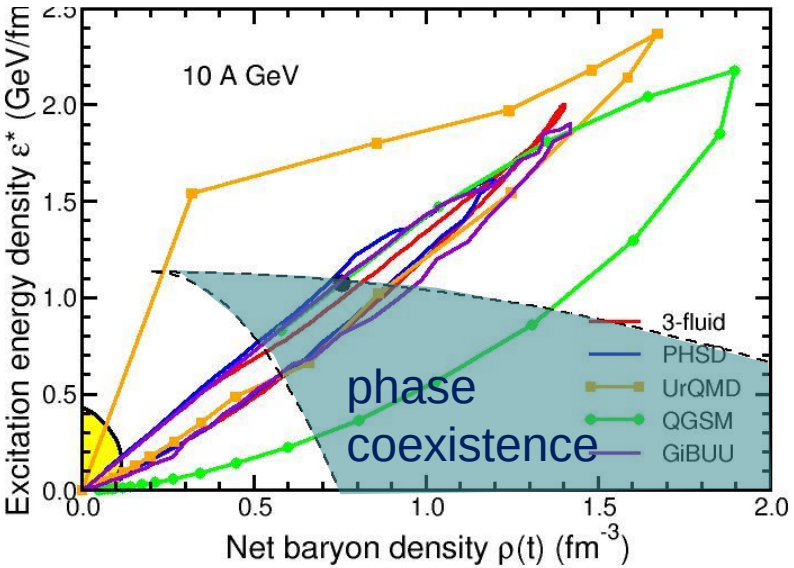
5 A GeV



10 A GeV

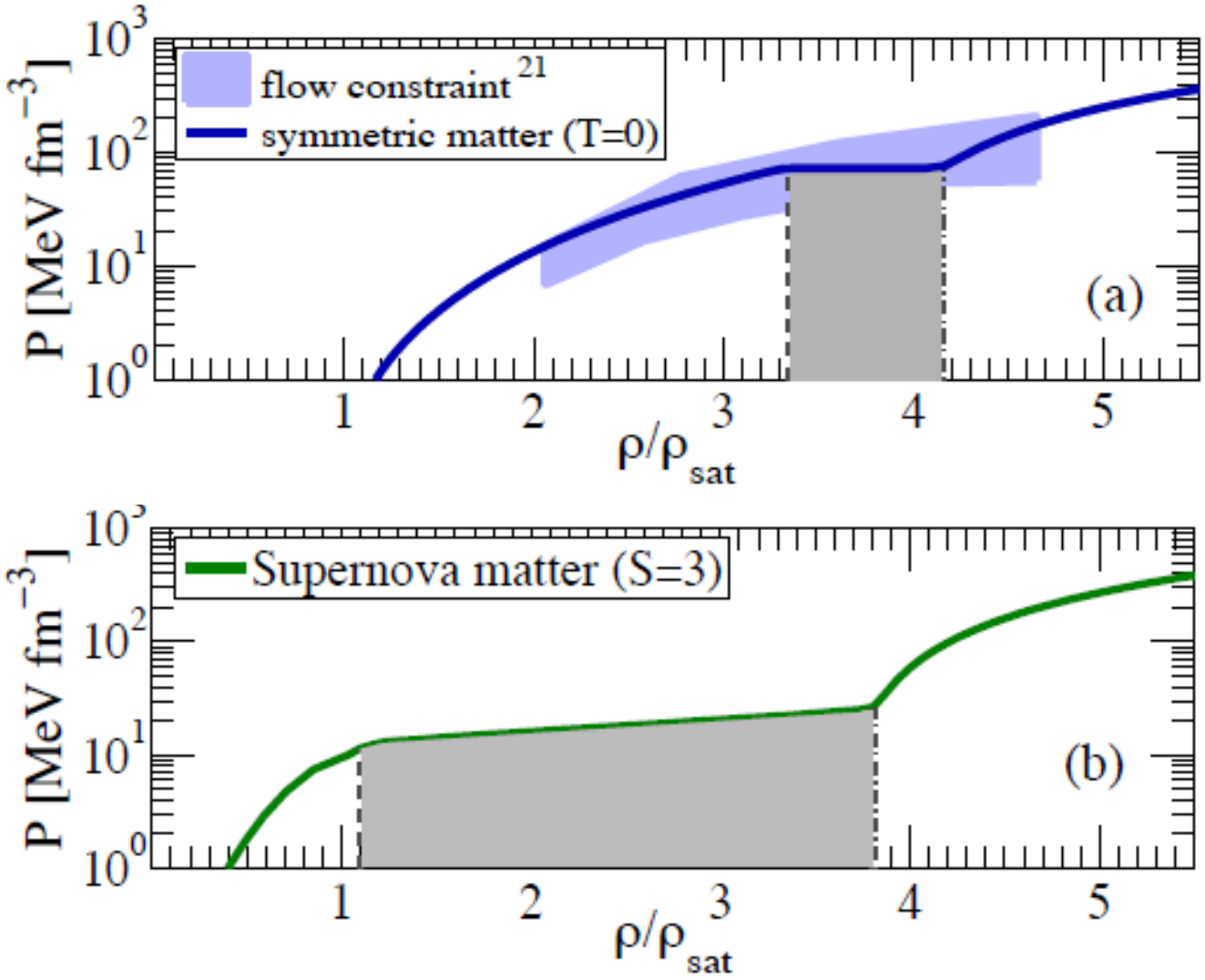






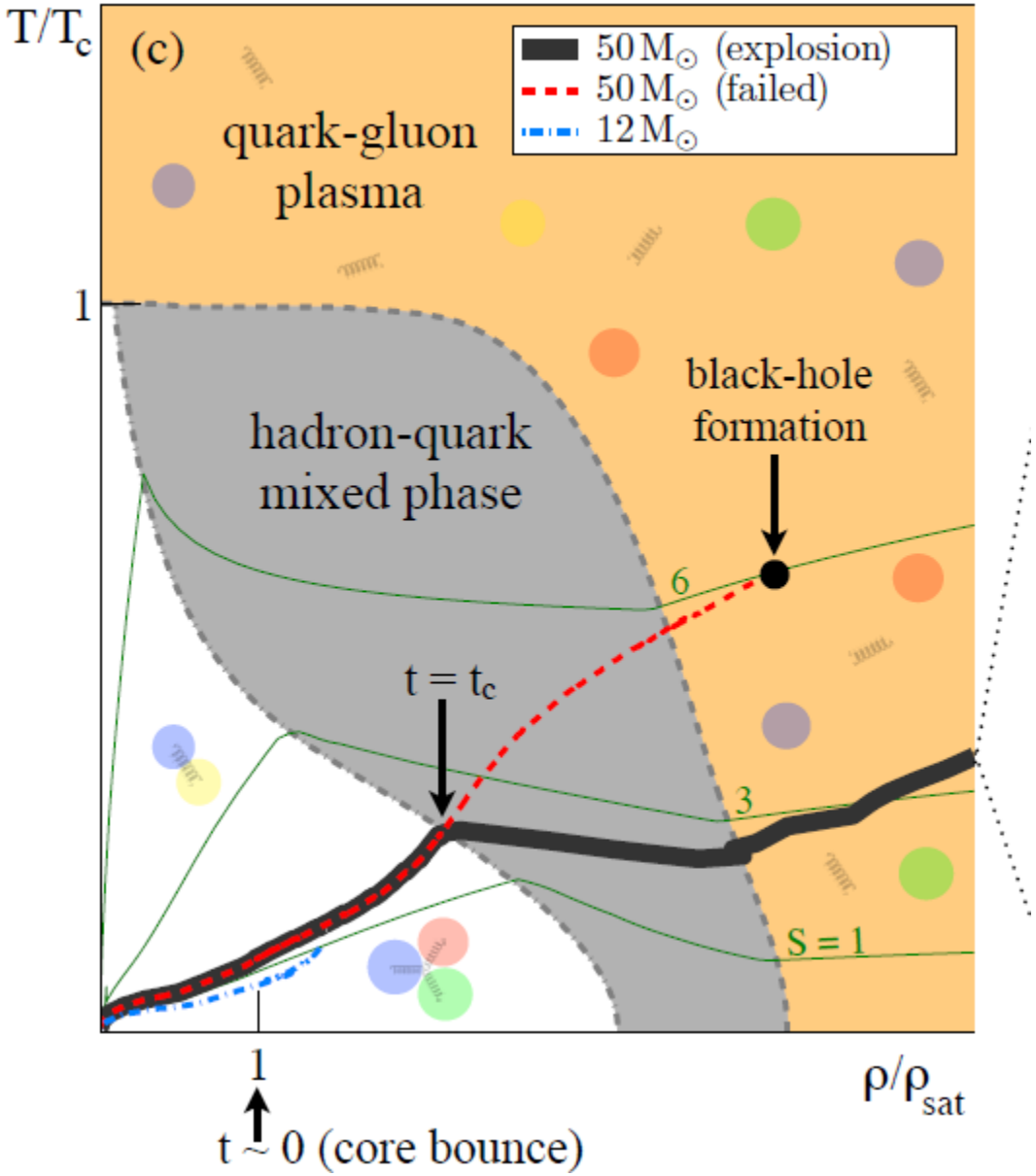
EOS with phase transition

T. Fischer, N. Bastian, M. Wu, S. Typel, T. Klähn, D. Blaschke, arXiv:1712.08788



Supernova explosion of a supermassive star

T. Fischer, N. Bastian, M. Wu, S. Typel, T. Klähn, D. Blaschke, arXiv:1712.08788



The equation-of-state of symmetric nuclear matter at neutron star core densities

Observable: multistrange hyperon production at (sub)threshold energies

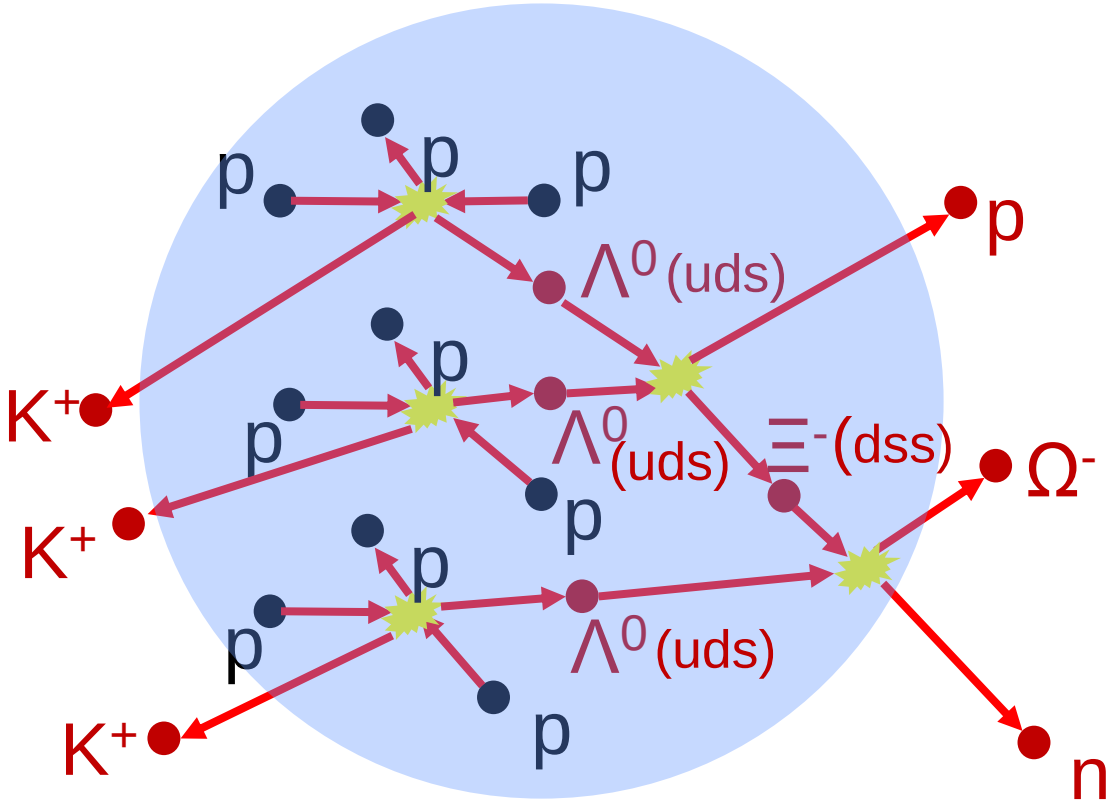
Direct multi-strange hyperon production:

$pp \rightarrow \Xi^- K^+K^+p$ (E_{thr} = 3.7 GeV)
$pp \rightarrow \Omega^- K^+K^+K^0p$ (E_{thr} = 7.0 GeV)
$pp \rightarrow \overline{\Lambda}^0\Lambda^0 pp$ (E_{thr} = 7.1 GeV)
$pp \rightarrow \Xi^+ \Xi^- pp$ (E_{thr} = 9.0 GeV)
$pp \rightarrow \Omega^+ \Omega^- pp$ (E_{thr} = 12.7 GeV

Hyperon production via multiple strangeness exchange reactions:

Hyperons (s quarks):
1. $pp \rightarrow K^+\Lambda^0p$, $pp \rightarrow K^+K^-pp$,
2. $p\Lambda^0 \rightarrow K^+ \Xi^- p$, $\pi\Lambda^0 \rightarrow K^+ \Xi^- \pi$,
3. $\Lambda^0\Lambda^0 \rightarrow \Xi^- p$, $\Lambda^0K^- \rightarrow \Xi^- \pi^0$
4. $\Lambda^0 \Xi^- \rightarrow \Omega^- n$, $\Xi^-K^- \rightarrow \Omega^- \pi^-$

Antihyperons (anti-s quarks):
1. $\overline{\Lambda}^0 K^+ \rightarrow \Xi^+\pi^0$,
2. $\Xi^+ K^+ \rightarrow \Omega^+ \pi^+$.

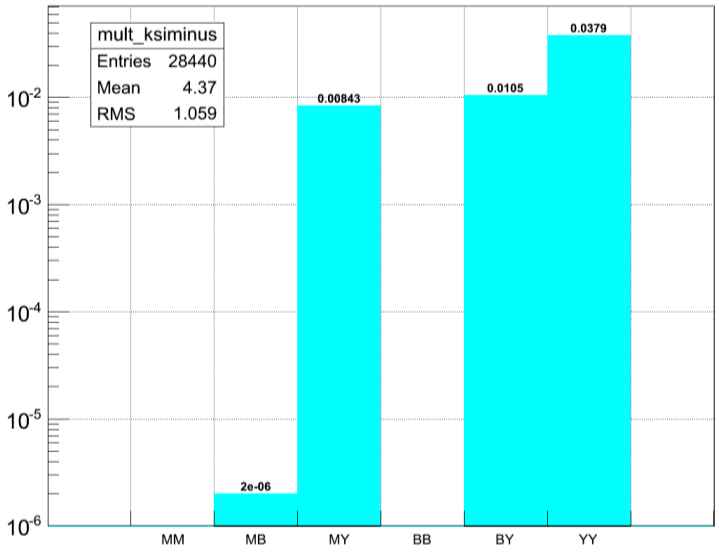


The equation-of-state of symmetric nuclear matter at neutron star core densities

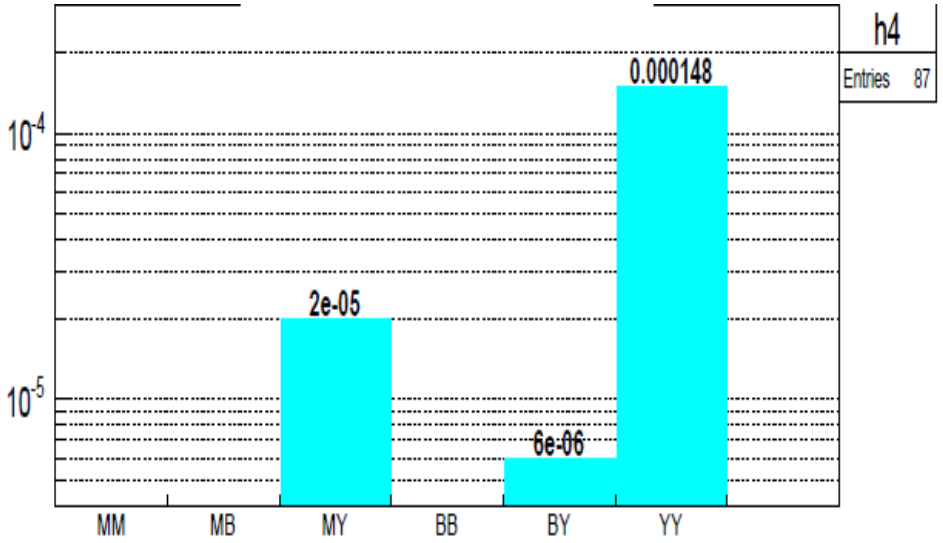
Observable: multistrange hyperon production at (sub)threshold energies

HYPQGSM calculations for 4 A GeV Au+Au

$\Xi^- \rightarrow \Lambda\pi^-$



$\Omega^- \rightarrow \Lambda K^-$

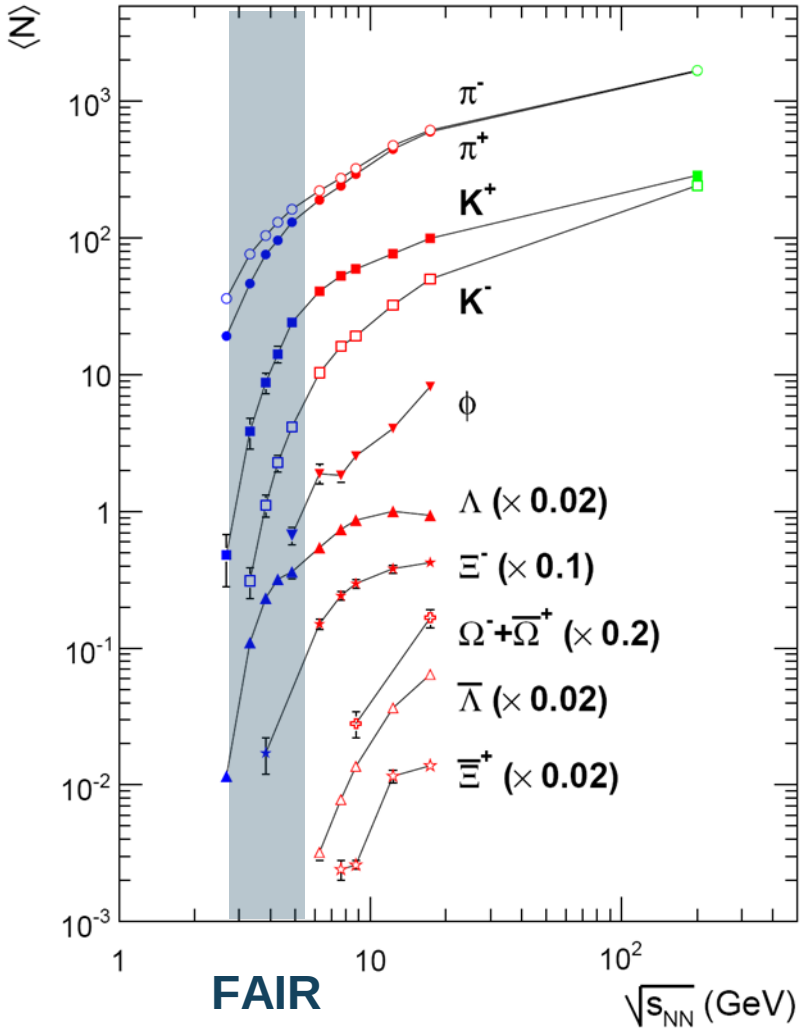


Yu.A. Murin[† 1], *K.K. Gudima*[1,2], *E.I. Litvinenko*[1], *V.A. Vasendina*[1], *and A.I. Zinchenko*[1]

[1]Joint Institute for Nuclear Research (JINR), Dubna, Russia; [2]Institute of Applied Physics of Academy of Sciences of Moldova, Chisinau, Moldova

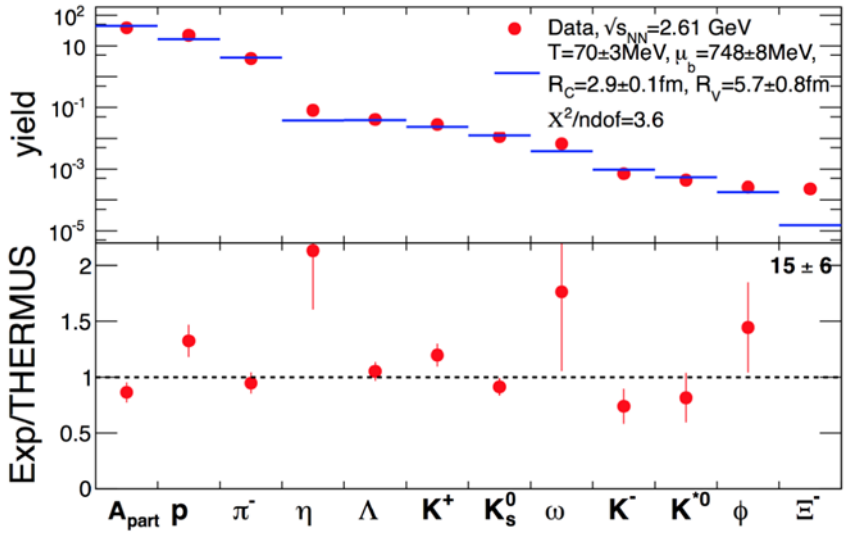
Strangeness
Data situation

Pb+Pb, Au+Au (central)



HADES: Ar + KCl 1.76 A GeV

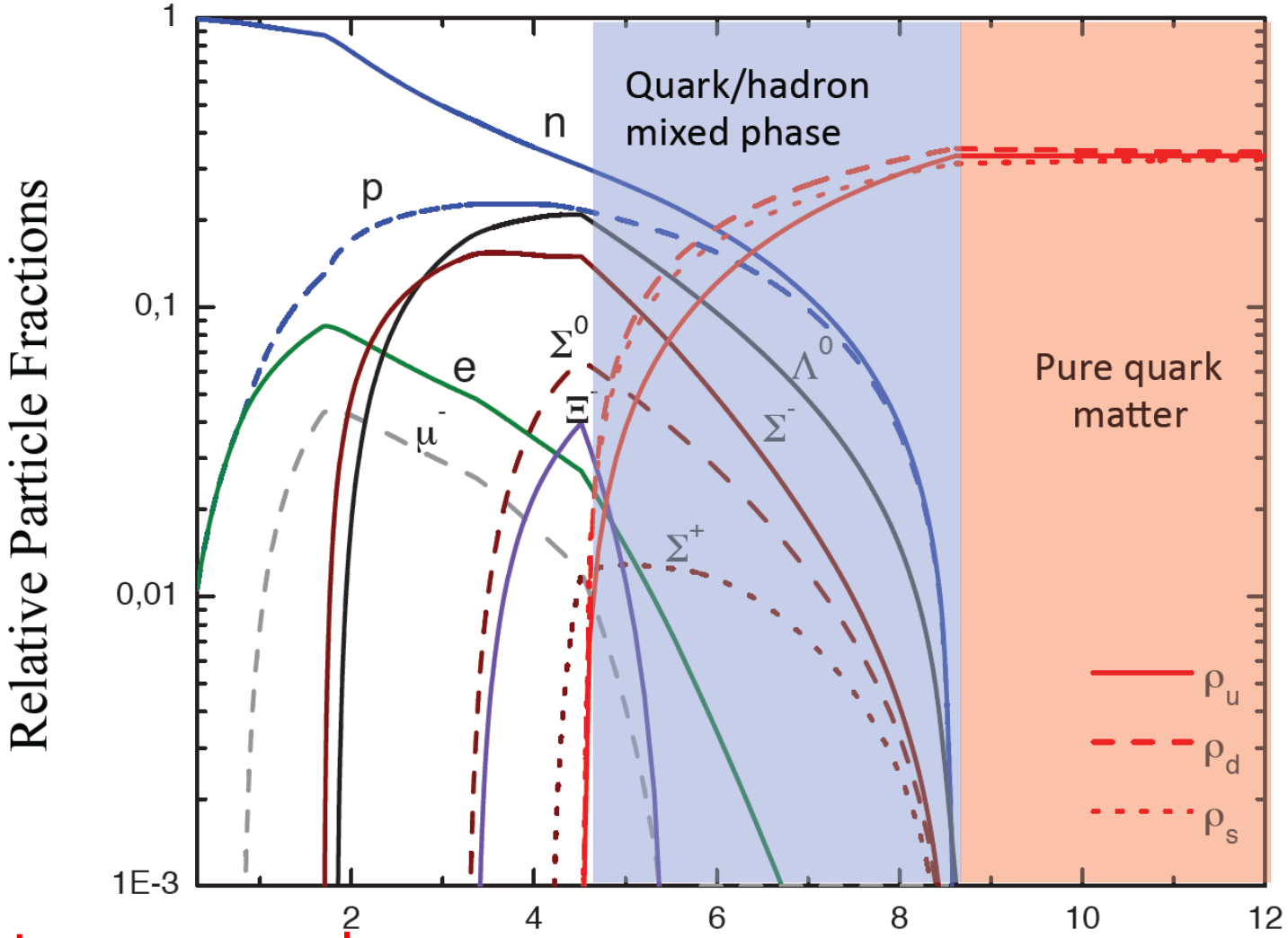
G. Agakishiev et al., arXiv:1512.07070



Degrees of freedom in massive neutron stars?

Equation-of-state: Non-local SU(3) NJL with vector coupling

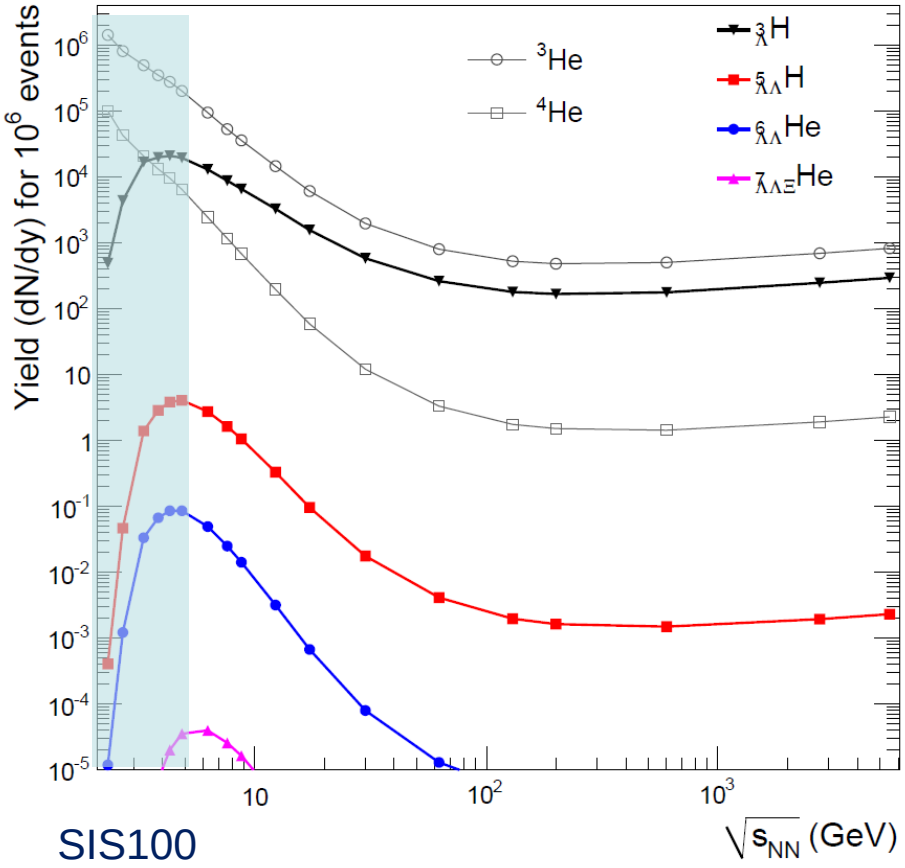
M. Orsaria, H. Rodrigues, F. Weber, G.A. Contrera, arXiv:1308.1657



Hyperon puzzle in neutron stars → N-Λ, Λ-Λ interaction ?

Hyperon production in A+A collisions

N-Λ, Λ-Λ interaction ➢ (double-) lambda hypernuclei



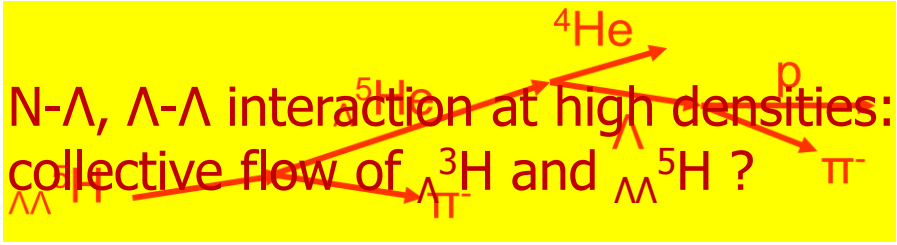
A. Andronic et al., Phys. Lett. B697 (2011) 203

Double lambda hypernuclei production in central Au+Au collisions at 10 A GeV:

	Multiplicity	Yield in 1 week
$_{\Lambda\Lambda}{}^5$H	$5 \cdot 10^{-6}$	3000
$_{\Lambda\Lambda}{}^6$He	$1 \cdot 10^{-7}$	60

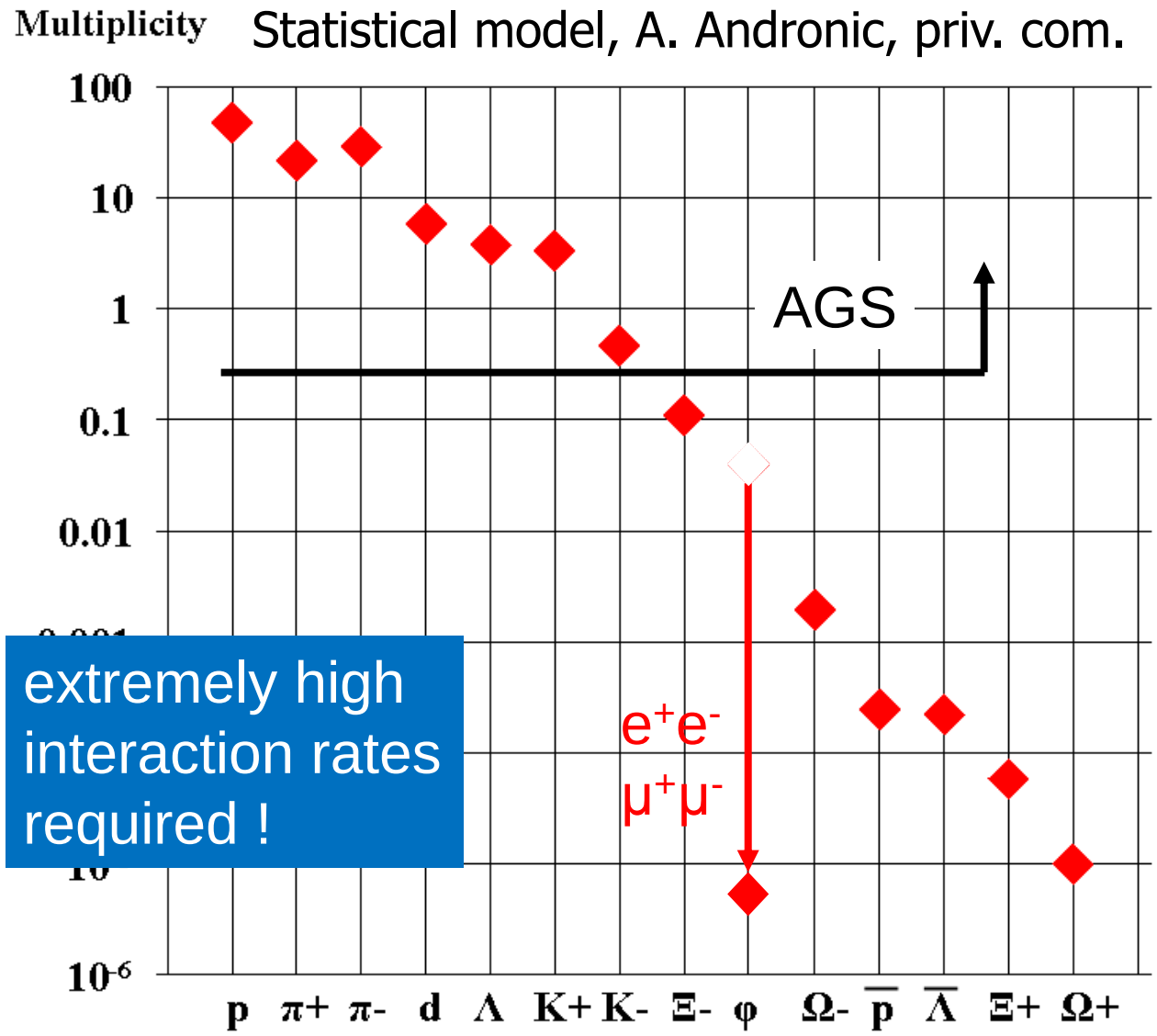
Assumption for yield calculation:
Reaction Rate 1 MHz
BR 10% (2 sequential weak decays)
Efficiency 1%

N-Λ, Λ-Λ interaction at high densities: collective flow of $_\Lambda{}^3$H and $_{\Lambda\Lambda}{}^5$H ?



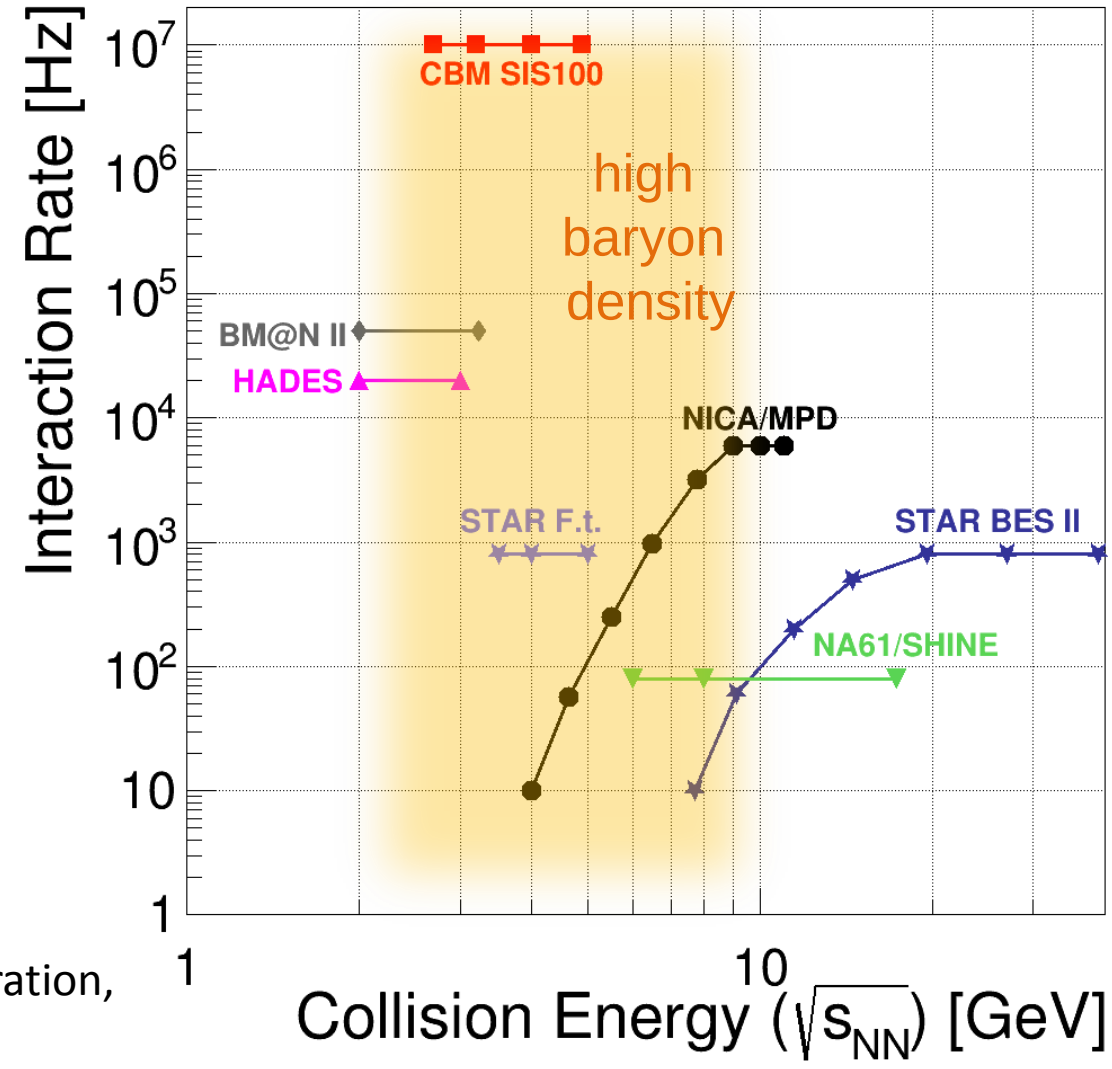
Experimental challenges

Particle yields in central Au+Au 4 A GeV



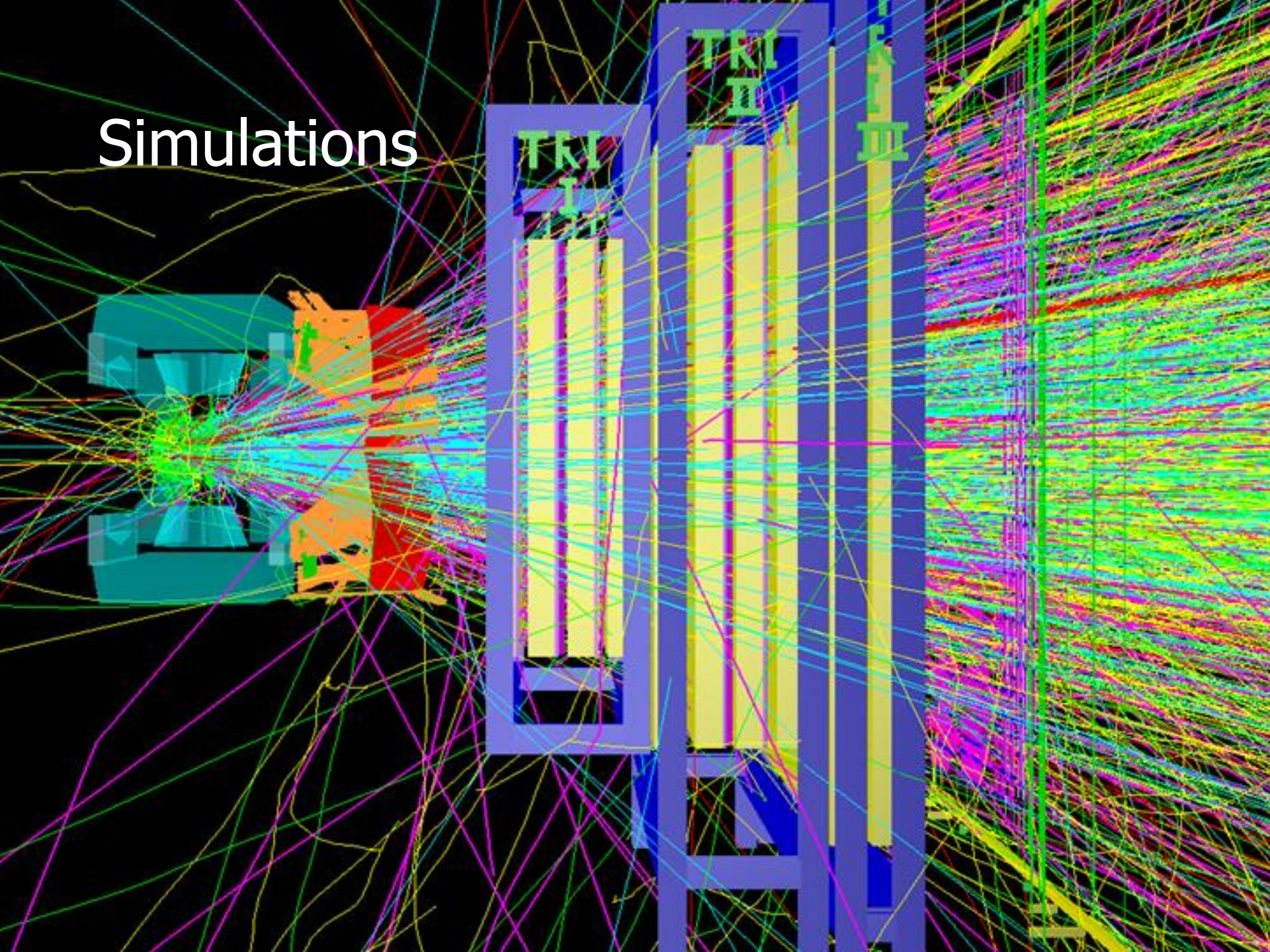
extremely high interaction rates required !

The landscape of experiments exploring dense QCD matter

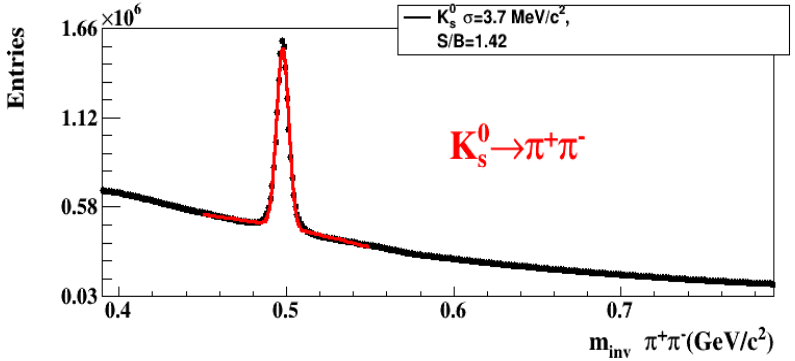


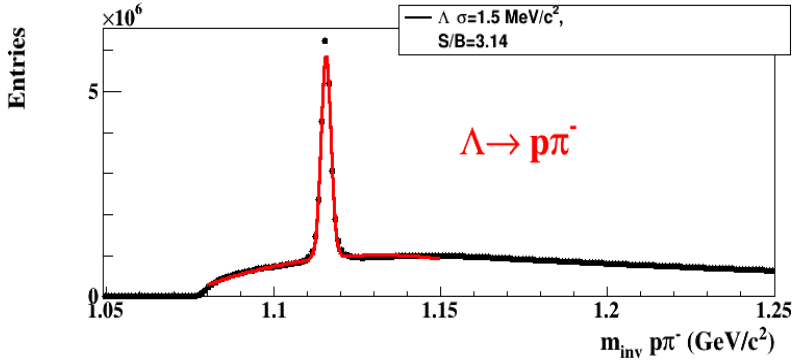
The CBM Collaboration, arXiv:1607.01487

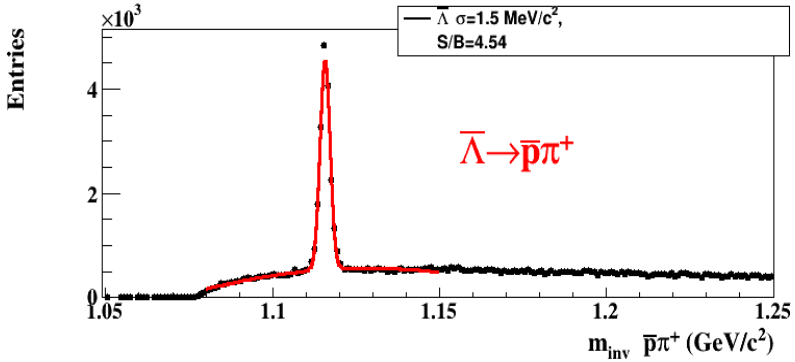
Simulations

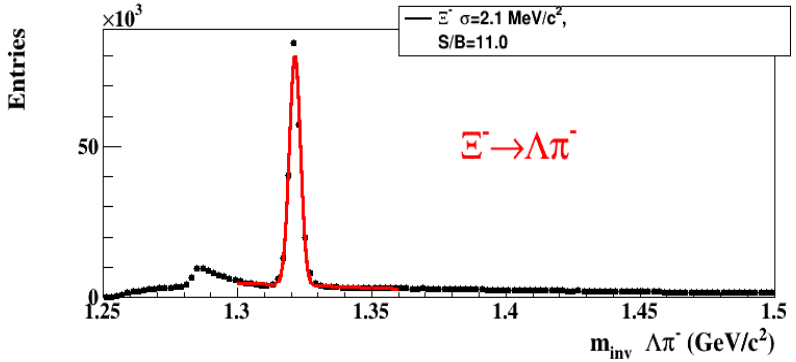


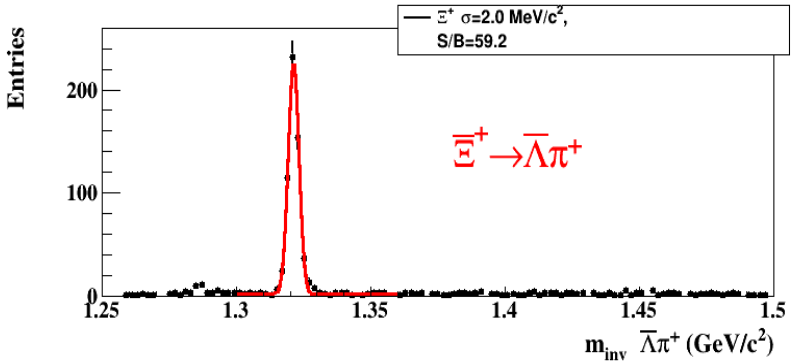
Simulations using CBM KF Particle Finder
5M central AuAu collisions 10A GeV (Lab)

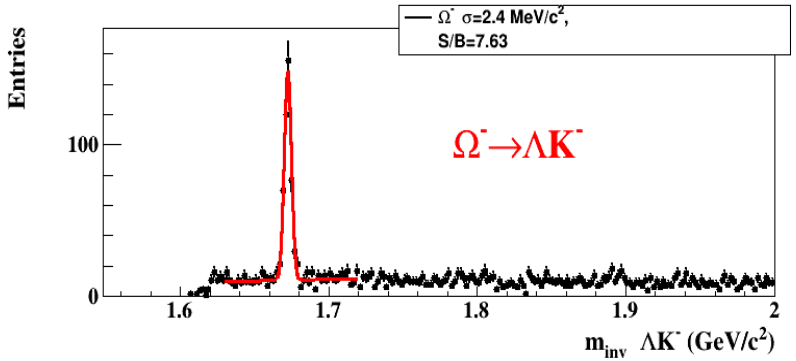




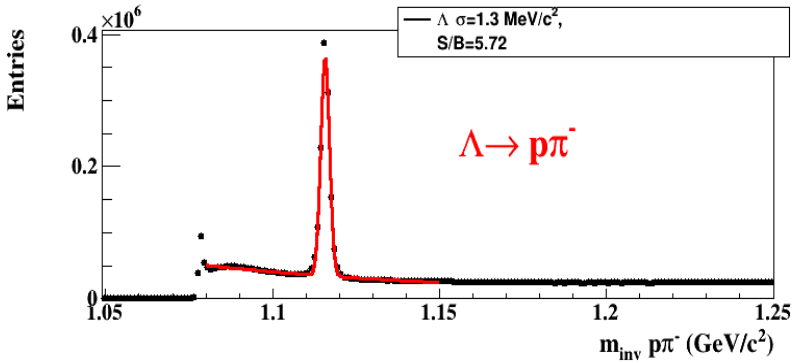


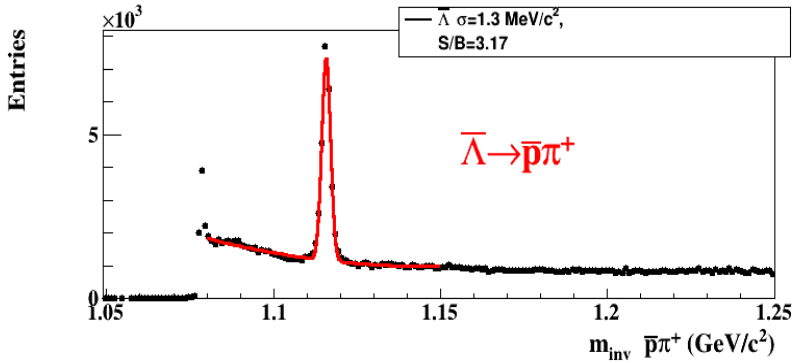


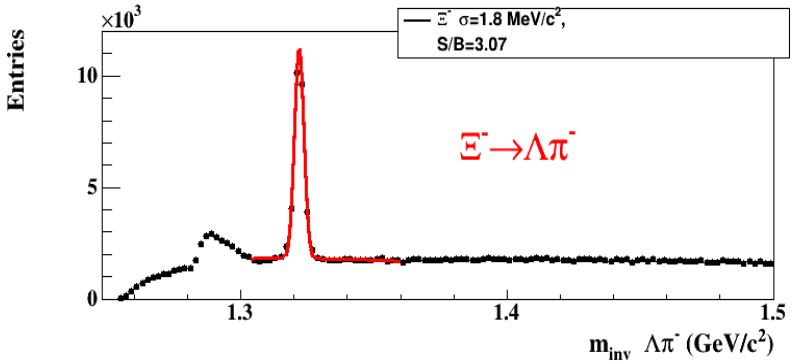


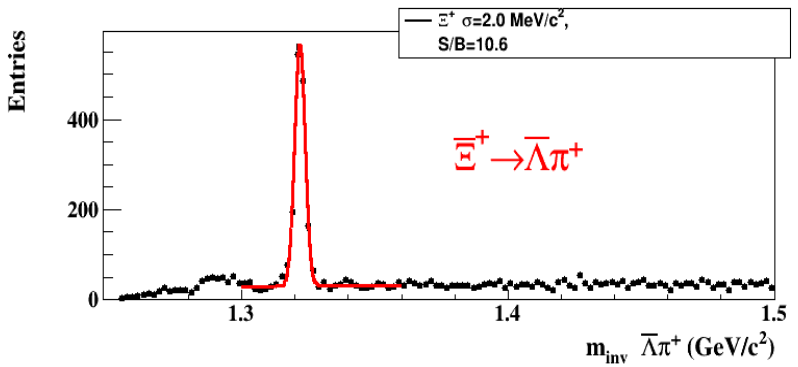


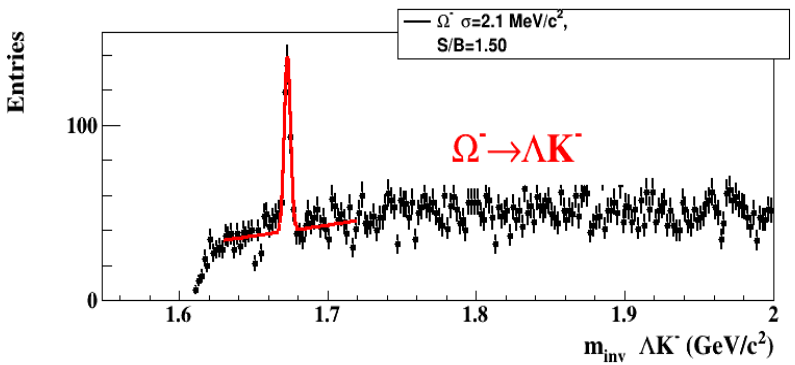
Real data analyzed with CBM KF Particle Finder
STAR 4.4 M mbias AuAu collisions, $\sqrt{s_{NN}}$=7.7 GeV

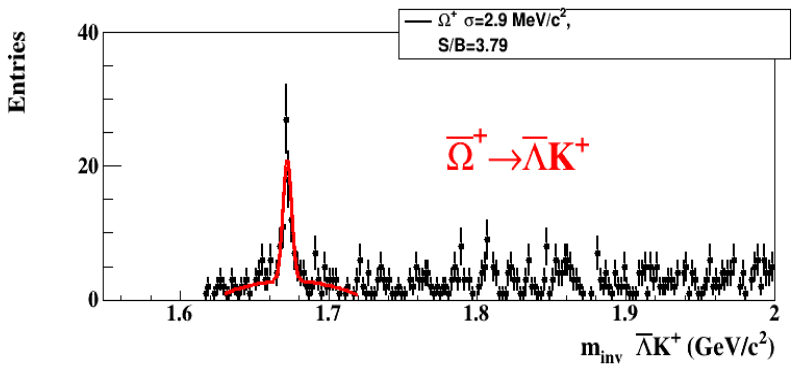












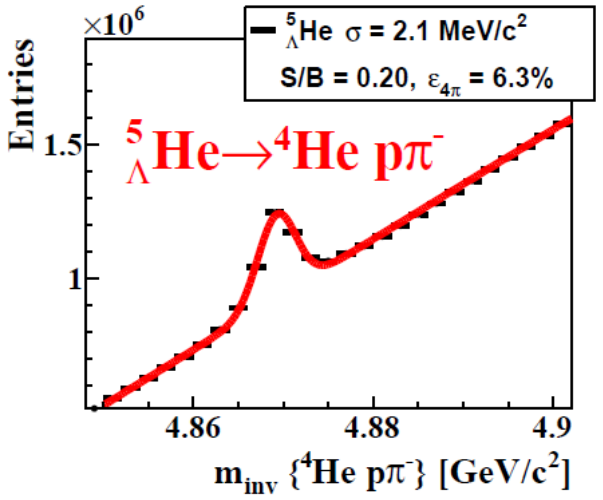
Hyperon yields at CBM

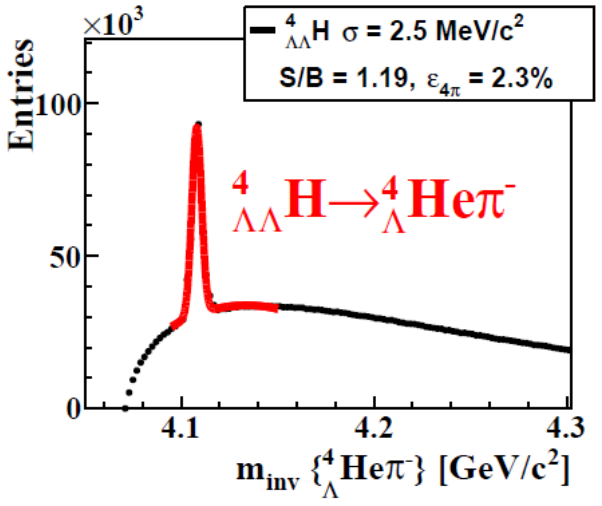
4 A GeV min. bias Au+Au collisions,
multiplicities from statistical model,
Reaction rate 10^6/s

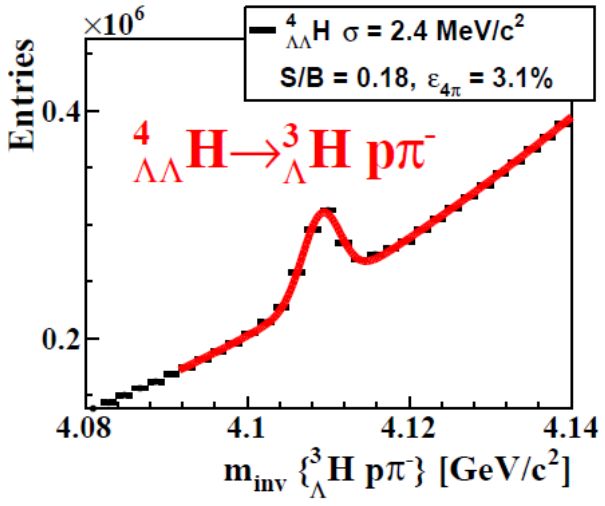
Particle	E_{thr}NN GeV	Multiplicity min.bias	ε %	Yield/week min. bias
Ξ^-	3.7	$2.5 \cdot 10^{-2}$	3	$4.5 \cdot 10^8$
Ω^-	6.9	$5 \cdot 10^{-4}$	3	$9 \cdot 10^6$
Anti-Λ	7.1	$5 \cdot 10^{-5}$	15	$9 \cdot 10^5$
Ξ^+	9.0	$1.5 \cdot 10^{-5}$	3	$2.7 \cdot 10^5$
Ω^+	12.7	$2.5 \cdot 10^{-6}$	3	$4.5 \cdot 10^4$

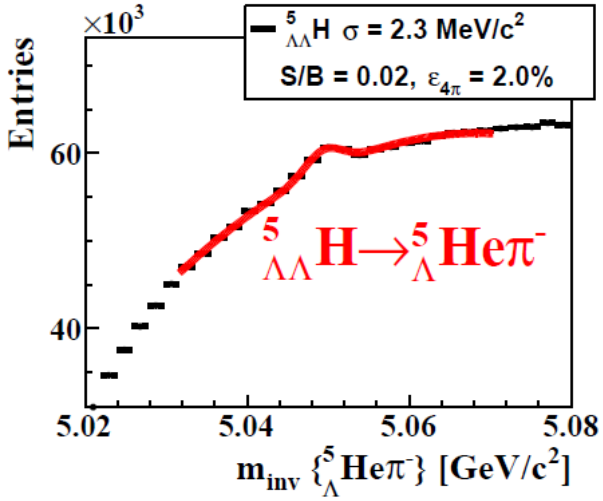
Simulation and reconstruction

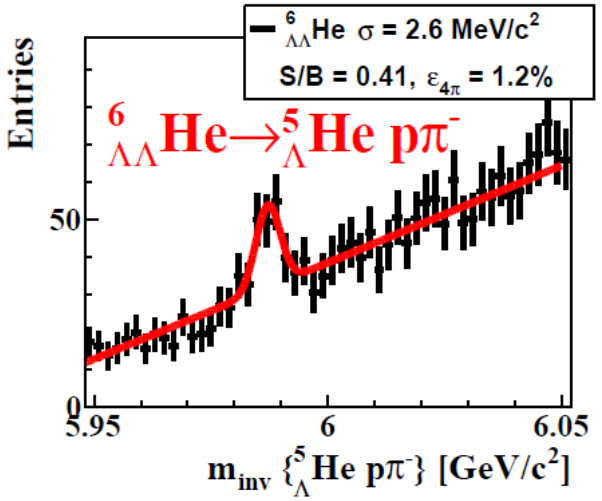
Hypernuclei in central Au+Au 10 AGeV











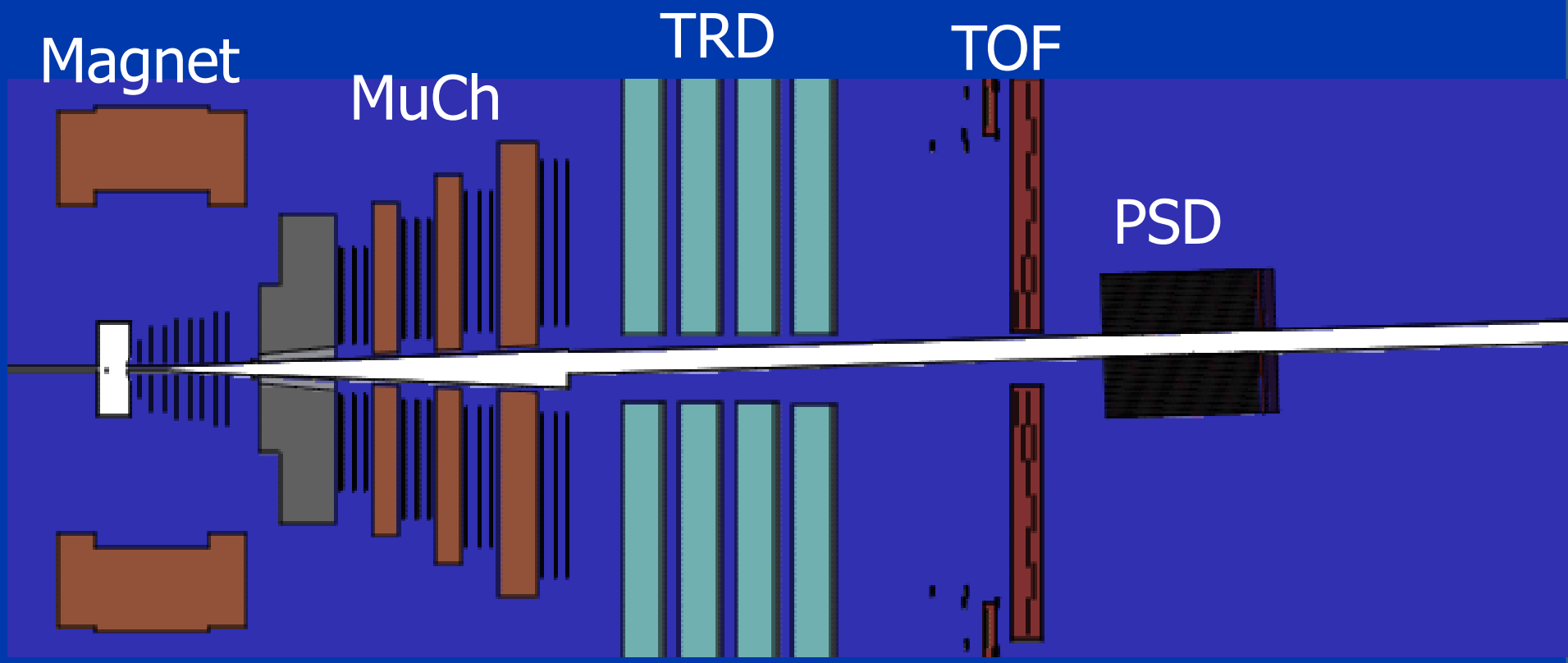
Conclusions

The CBM physics program includes:

- The exploration of the high density nuclear matter EOS by measuring excitation functions of:
  - the collective flow of identified particles
  - multi-strange hyperon production
- The study of ΛΛ and ΛN interactions by measuring yields, livetime, and collective flow of (double) Λ hypernuclei

The goal is to produce multi-differential data with unprecedented statistics in heavy-ion collisions at beam energies from 2 - 14 A GeV (Au beam up to 11 A GeV)

Measurement of E_{sym} with CBM ?



Measurement of E_{sym} with CBM ?