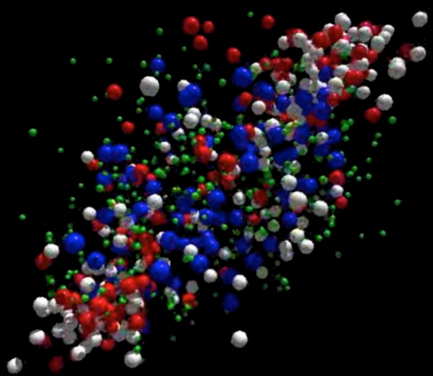
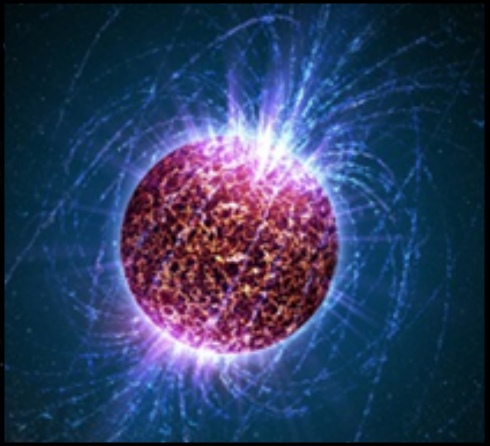
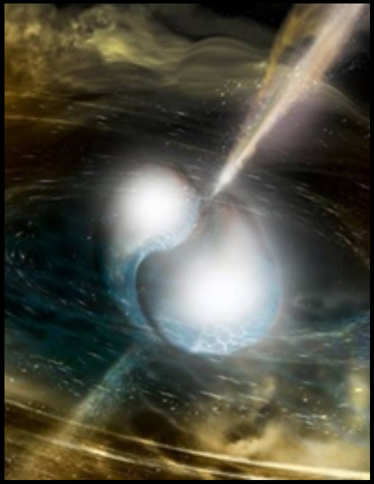


The high-density Equation of State from heavy-ion reactions

Peter Senger

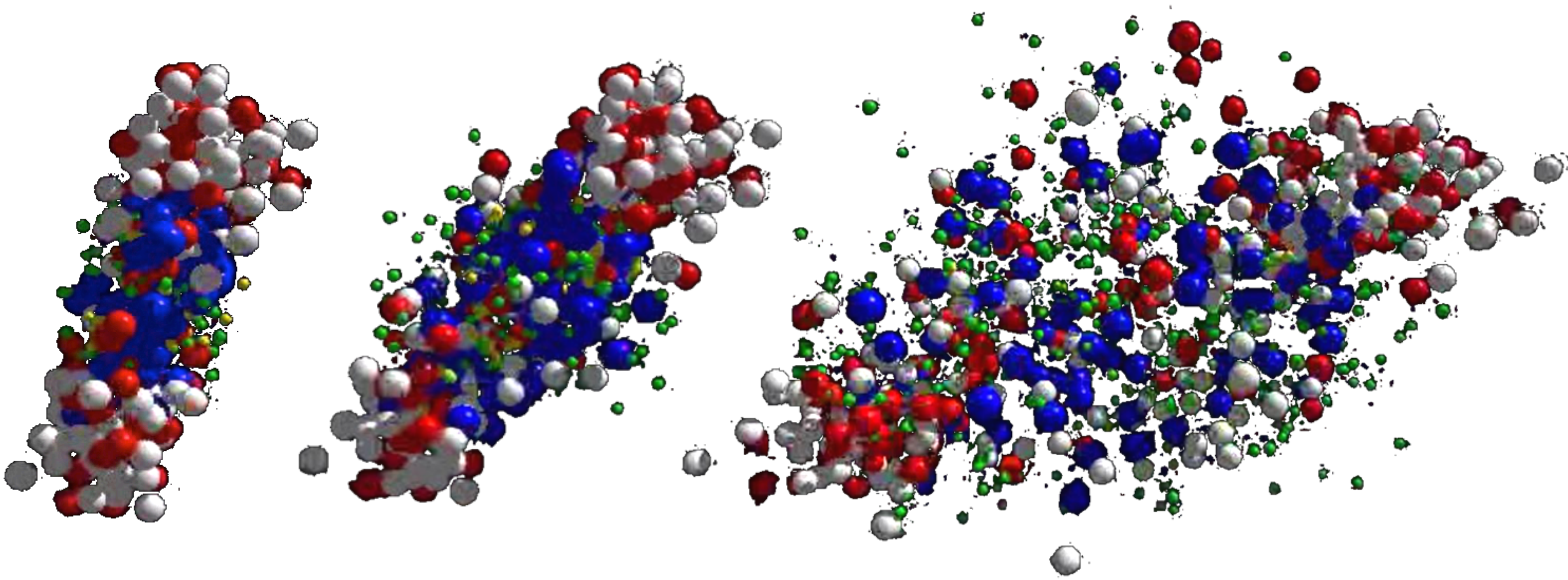
FAIR
GOETHE UNIVERSITÄT FRANKFURT AM MAIN
CENTRAL CHINA NORMAL UNIVERSITY
MEPhI

Outline:

- Exploring the high-density EoS in the laboratory
- The QCD phase diagram at large μ_B
- Future experiments: CBM at FAIR and BM@N at NICA

Nuclear equation of state and neutron stars
International Workshop XLVIII on Gross Properties of Nuclei and Nuclear Excitations
Hirschegg, Kleinwalsertal, Austria, January 12 - 18, 2020

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

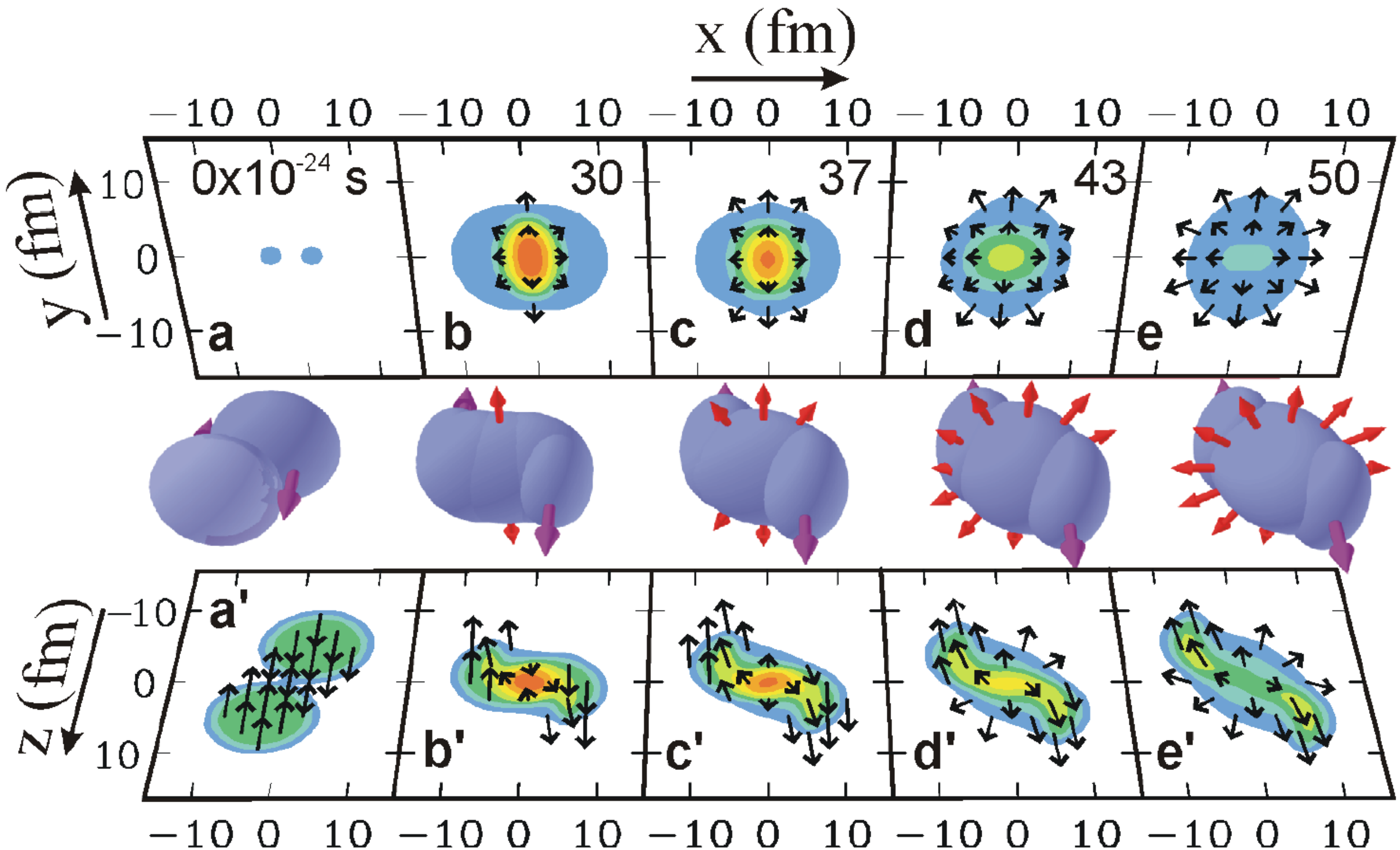


Baryon densities in the laboratory: 3 - 10 ρ_0 , but:
volume about 1000 fm^3, lifetime 10^{-22} s, T = 70 – 120 MeV,
non-equilibrated system, …

- extraction of EOS via relativistic transport calculations
- observables: collective flow, subthreshold particle production

Collective flow of nucleons

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

The nuclear matter equation-of-state

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

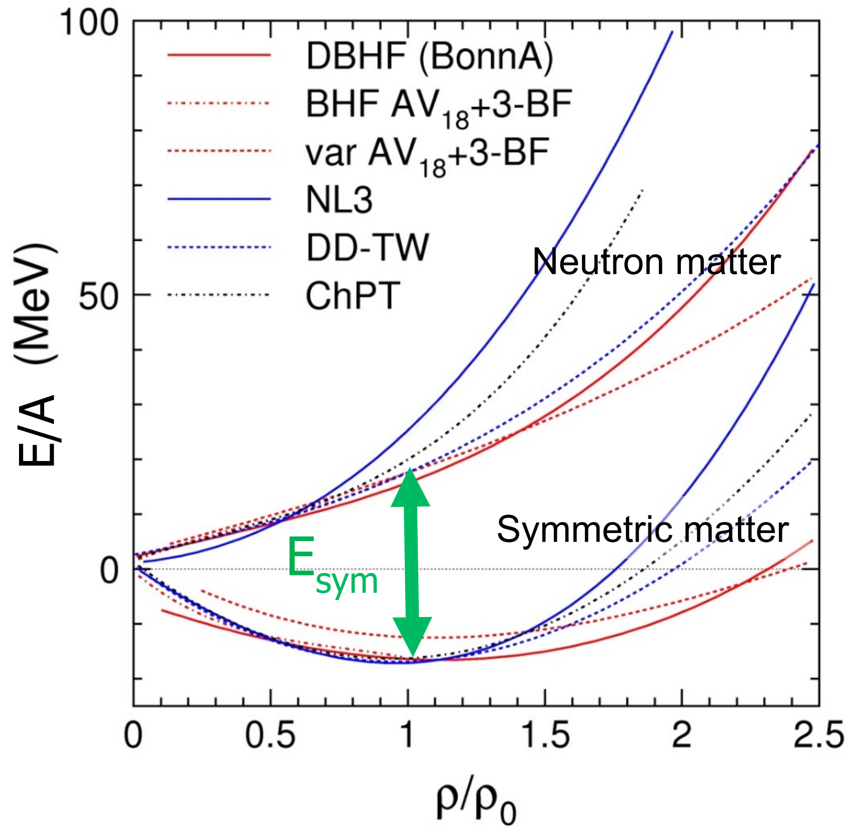
$E_A(\rho,\delta) = E_A(\rho,0)+E_{sym}(\rho)\cdot\delta^2$
with $\delta = (\rho_n - \rho_p)/\rho$

Symmetric matter (δ=0):

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

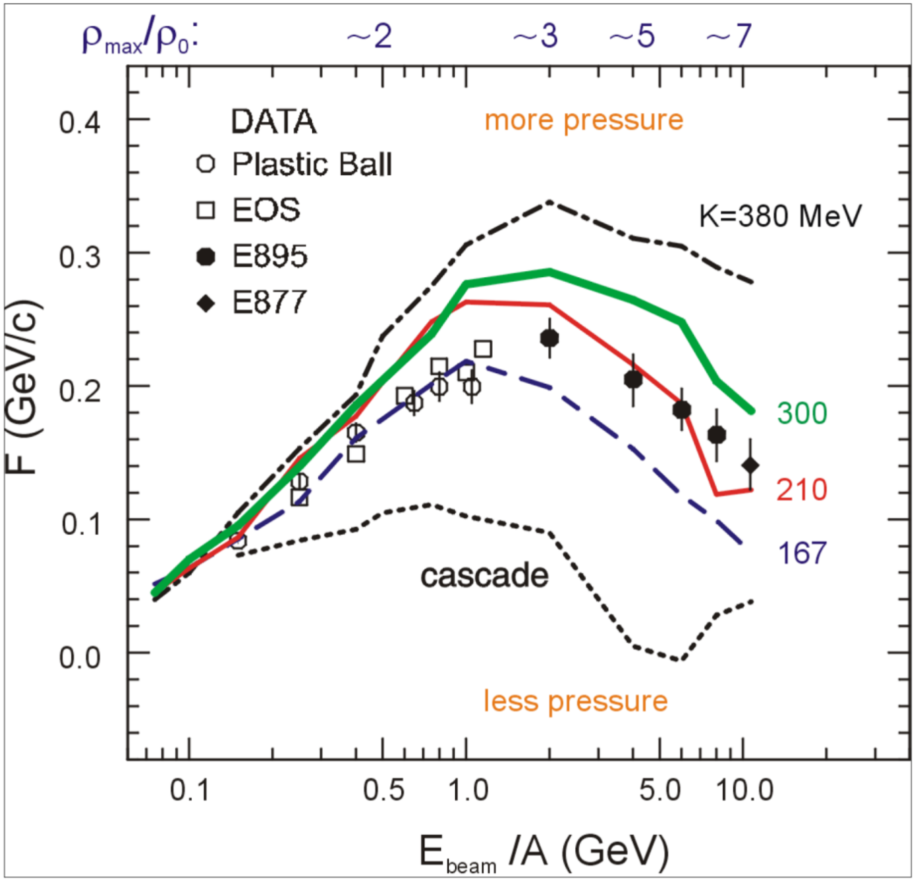
T=0: $E/A = 1/\rho \int U(\rho)d\rho$
Effective NN-potential:
$U(\rho)=\alpha\rho+\beta\rho^\gamma$

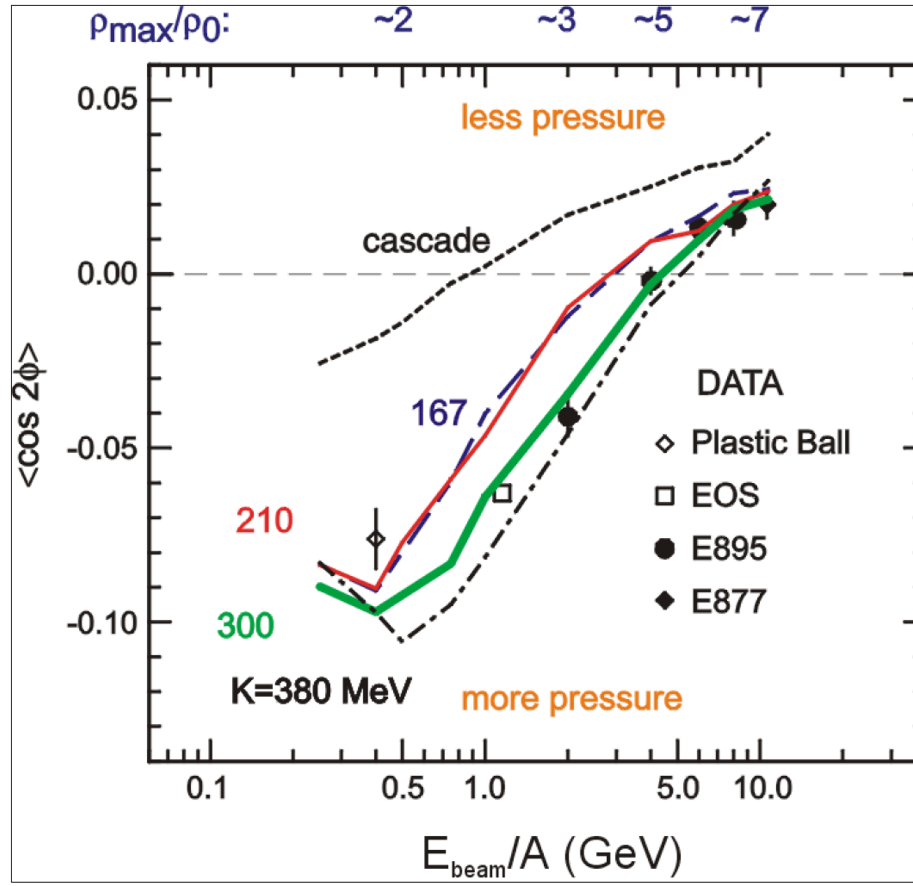
Ch. Fuchs and H.H. Wolter, EPJA 30 (2006) 5



Nuclear incompressibility from collective proton flow

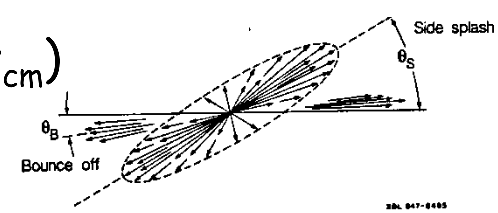
P. Danielewicz, R. Lacey, W.G. Lynch, Science 298 (2002) 1592



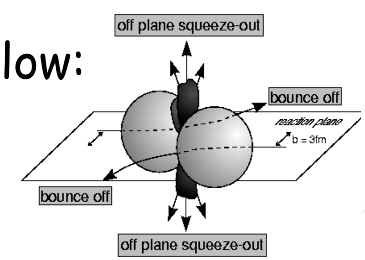


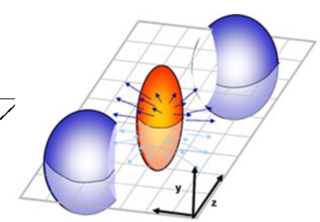
Transverse in-plane flow:

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



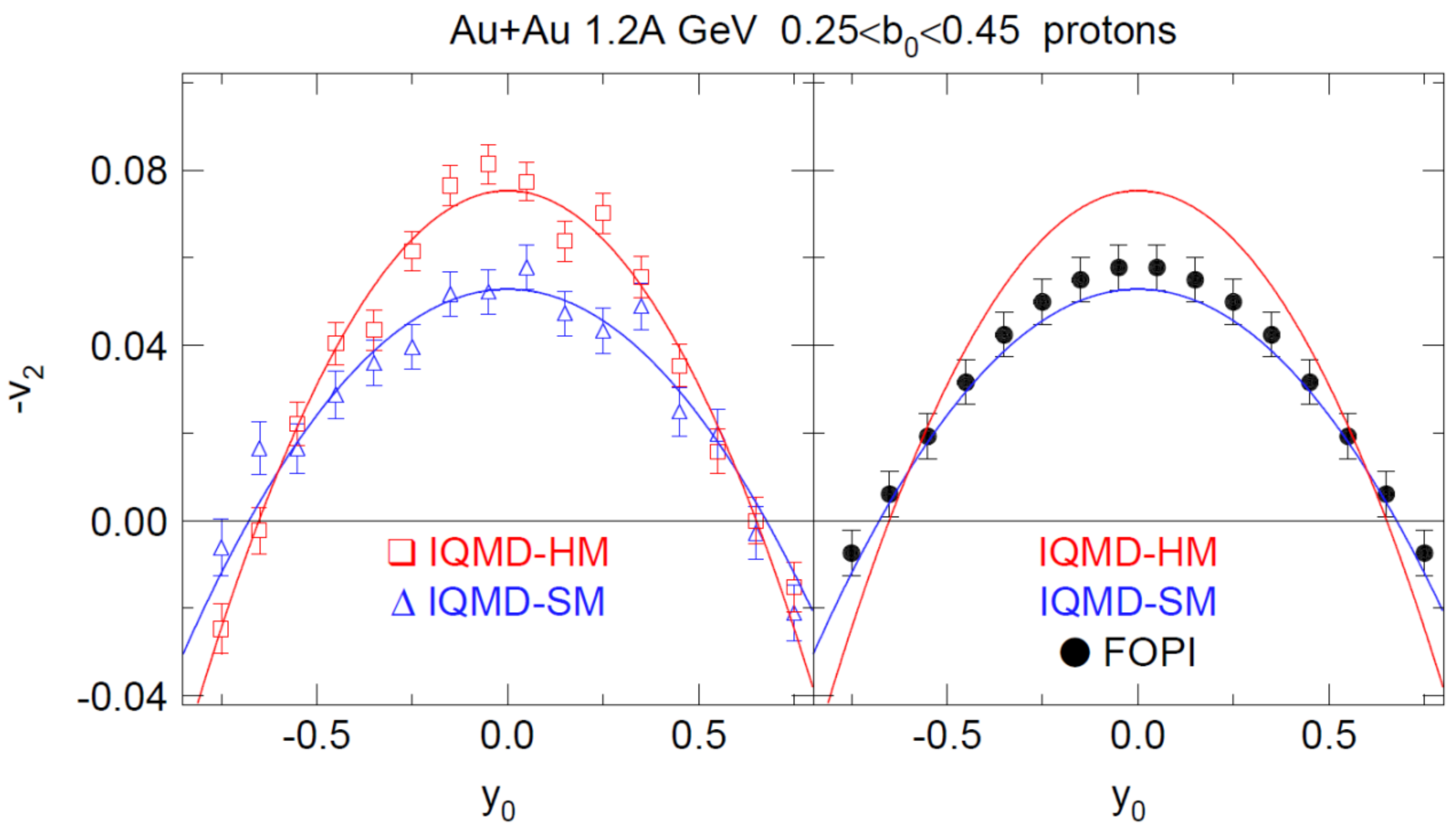
Elliptic flow:





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

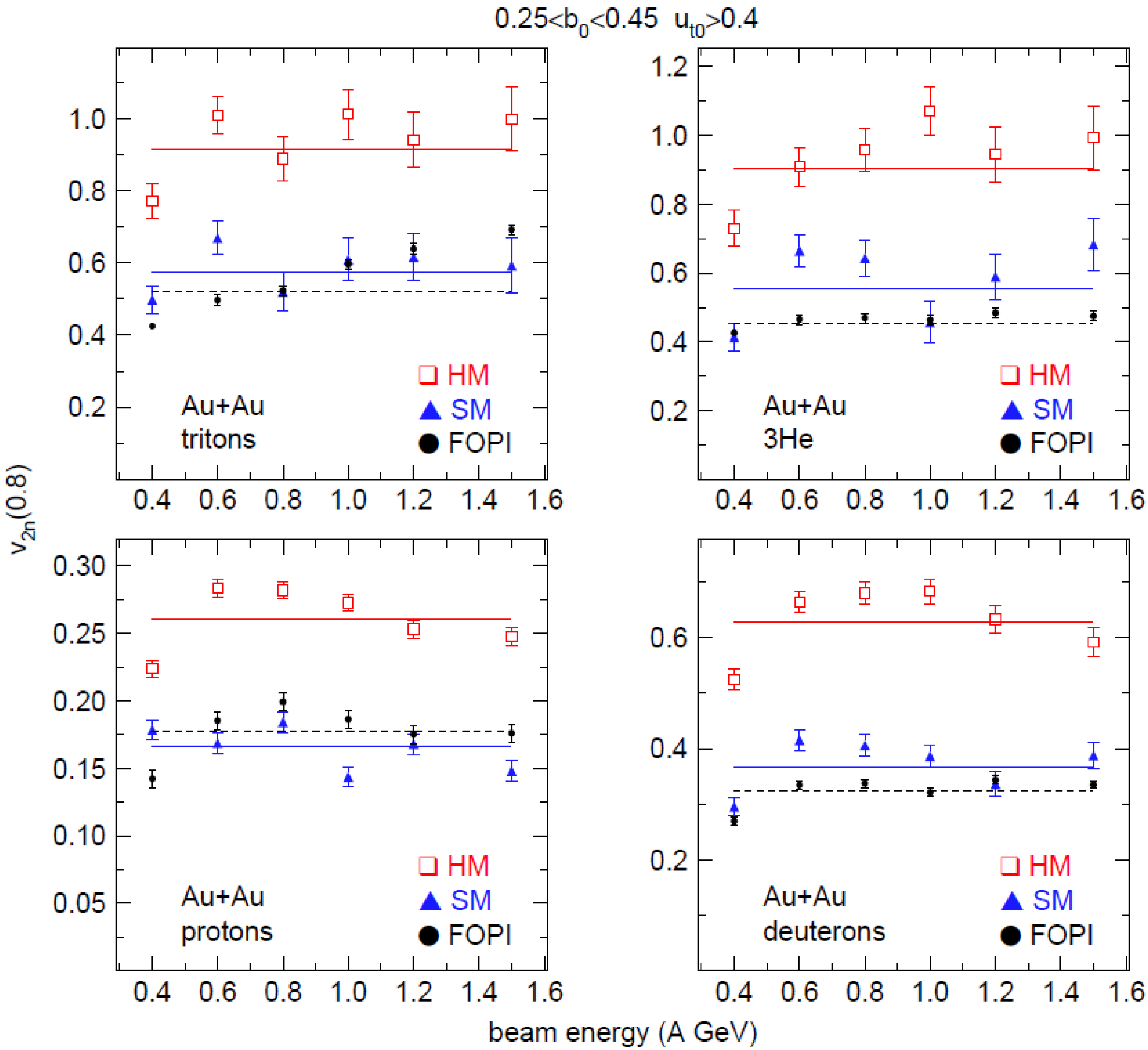
EOS from proton elliptic flow in Au+Au collisions at 1.2A GeV

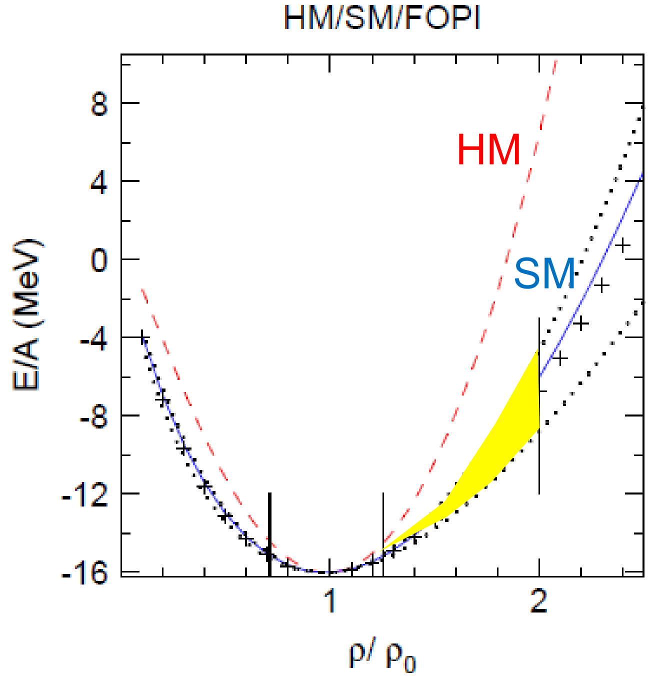


A. Le Fevre , Y Leifels, W. Reisdorf, J. Aichelin, Ch. Hartnack, Nucl. Phys. A945 (2016) 112

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, Nucl. Phys. A945 (2016) 112





HM: K = 380 ´MeV
SM: K = 200 MeV

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

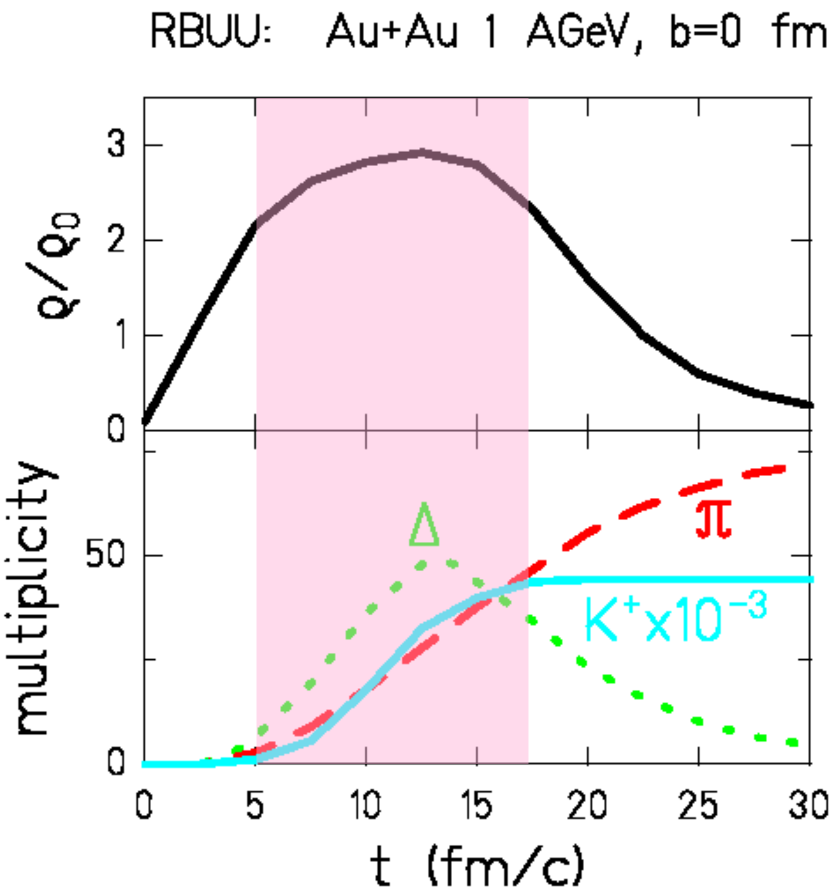
Beam energy AGeV	**central density**	**flow observable**	**incompressibility K**
0.4 – 1.5	$\rho = 1 - 3\ \rho_0$	v_2 of p, d, t, 3He	≈ 200 MeV
2 – 10	$\rho = 3 - 7\ \rho_0$	v_1 of protons	≈ 200 MeV
2 – 10	$\rho = 3 - 7\ \rho_0$	v_2 of protons	≈ 300 MeV

<u>Within microscopic transport models the collective flow is sensitive to:</u>

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

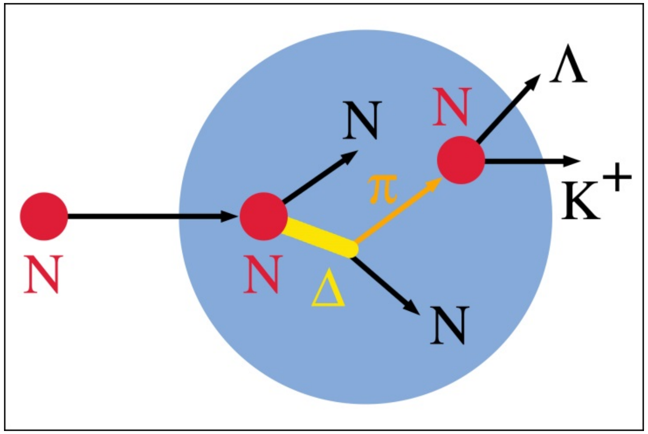
Independent observables? → particle production

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)

Threshold reached by piling up energy in sequential collisions which are enhanced with increasing density



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)

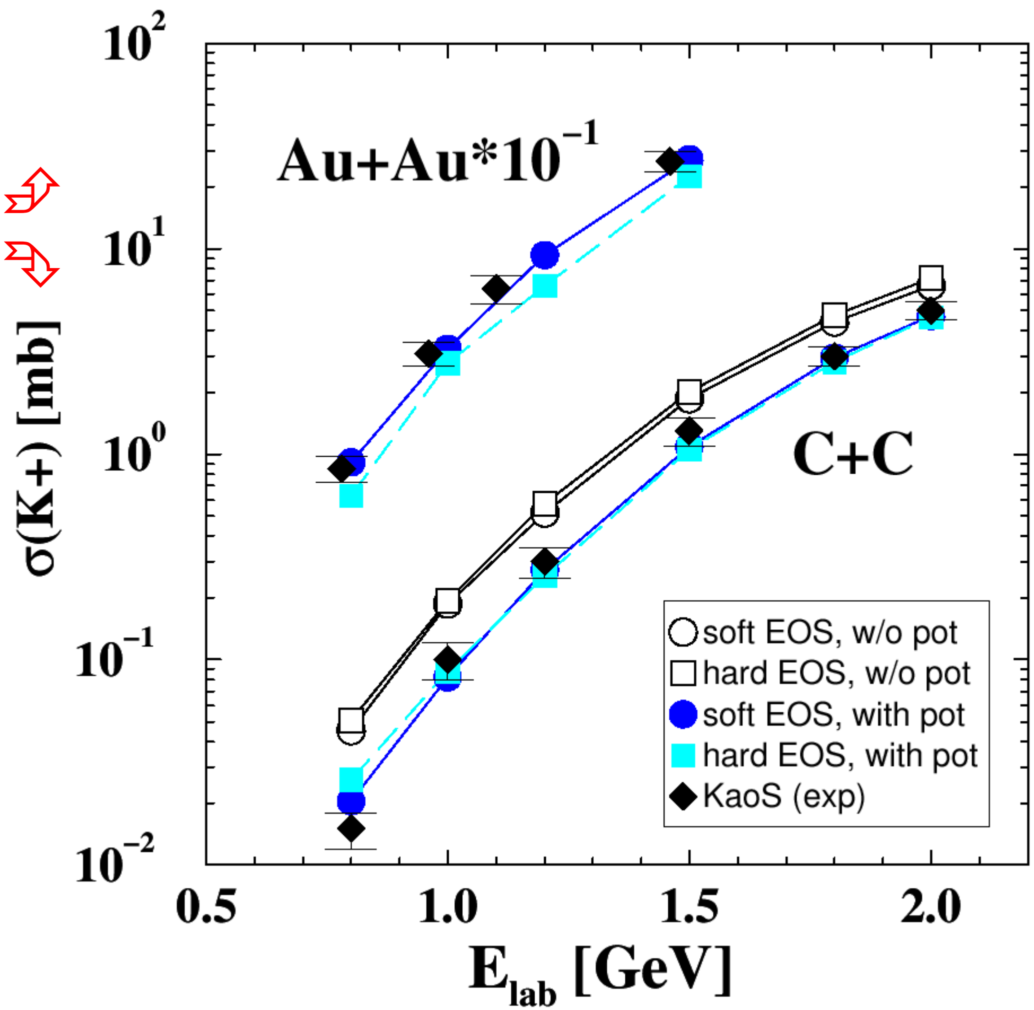
Au+Au at 1 AGeV:

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:

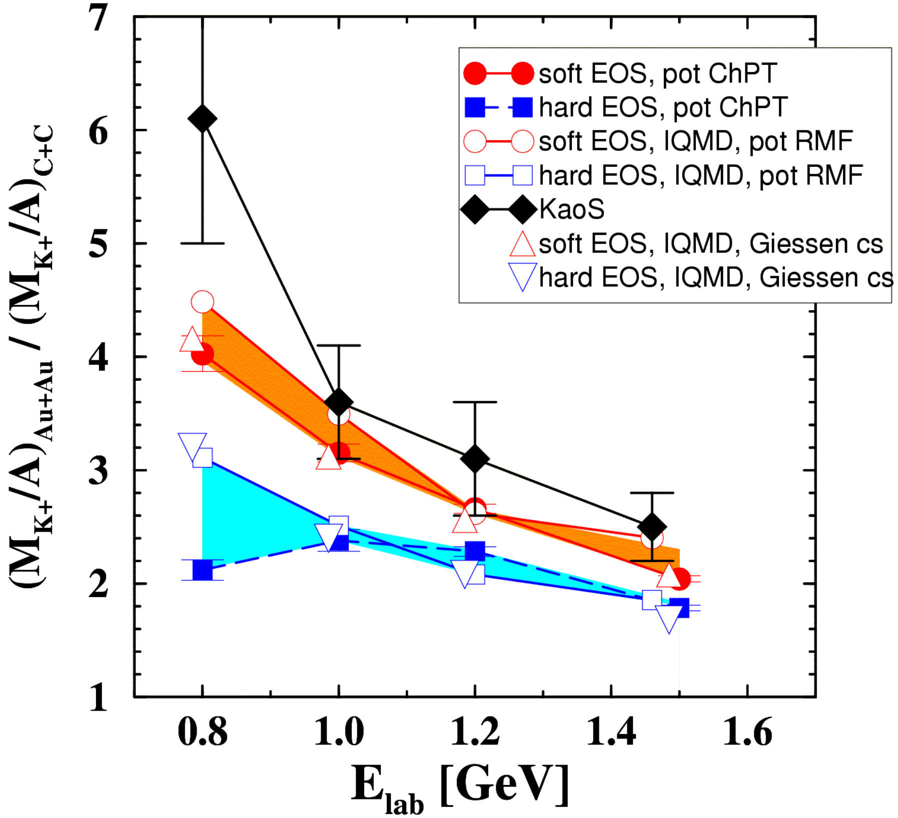
C. Sturm et al., (KaoS Collaboration), Phys. Rev. Lett. 86 (2001) 39

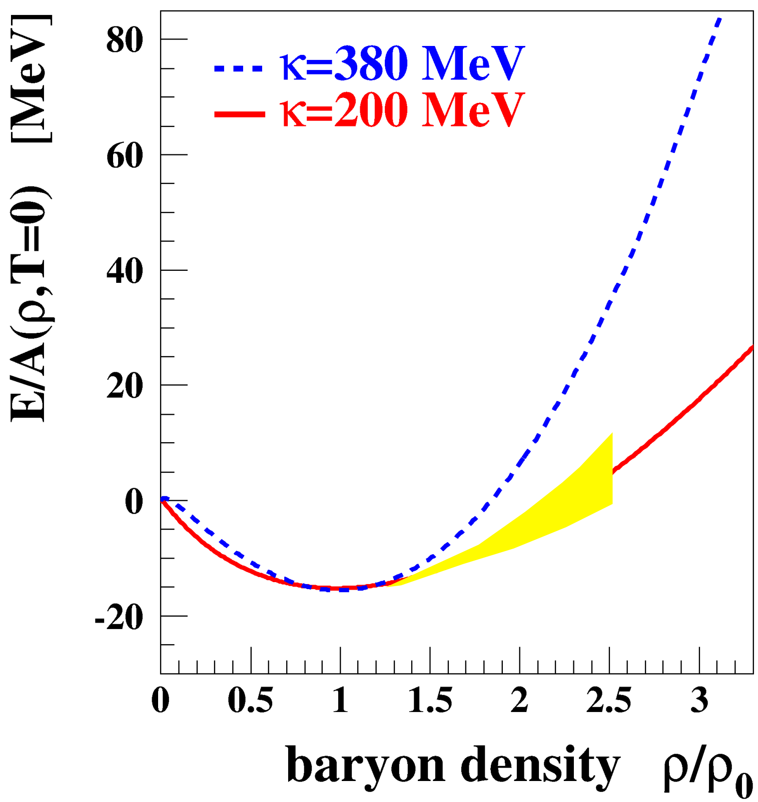
Theory:

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

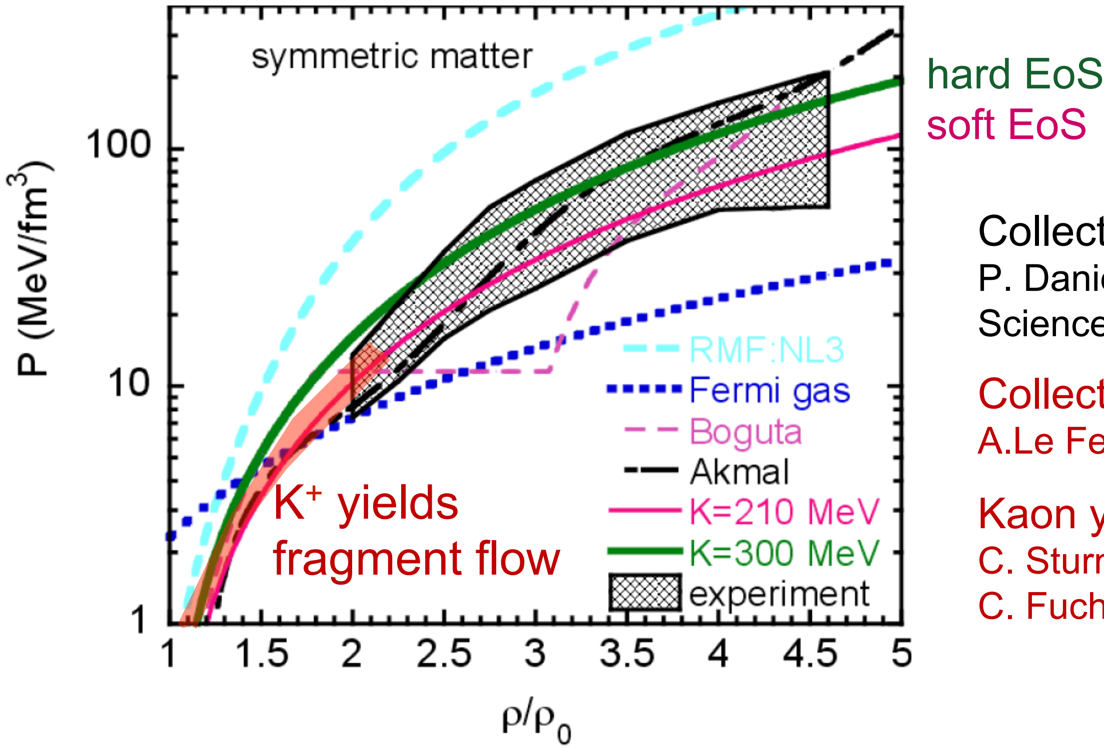




Au/C ratio: cancellation of systematic errors both in experiment and theory

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

Nuclear incompressibility from heavy-ion collisions



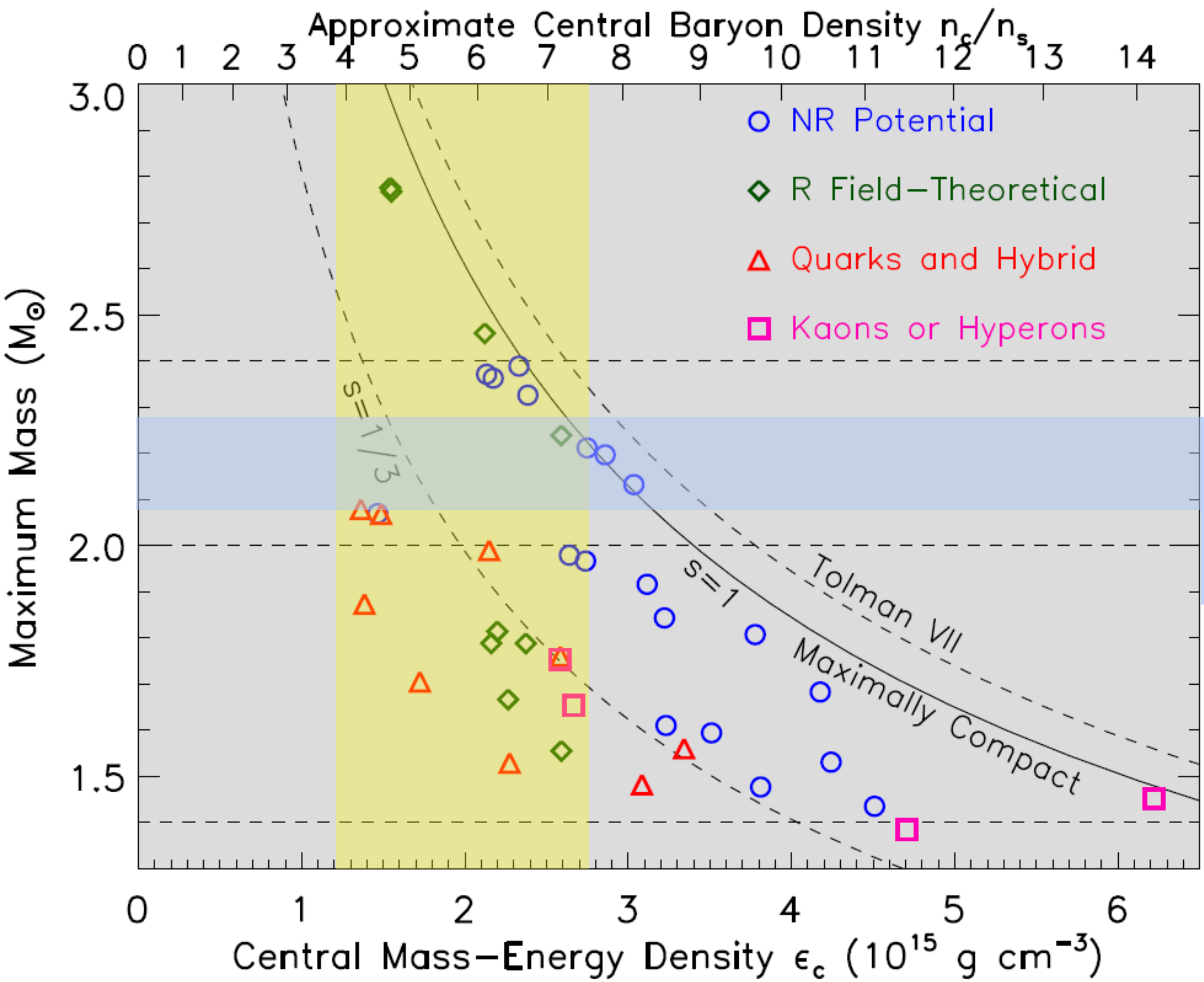
EoS at $\rho \geq 3\ \rho_0$?

Collective flow of protons:
P. Danielewicz, R. Lacey, W.G. Lynch,
Science 298 (2002) 1592

Collective flow of protons and light fragments
A.Le Fevre et. al., Nucl. Phys. A945 (2016) 112

Kaon yields
C. Sturm et al., (KaoS Collab.) PRL 86 (2001) 39
C. Fuchs PRL 86 (2001) 1974

Mass-density relation of neutron stars for different EOS



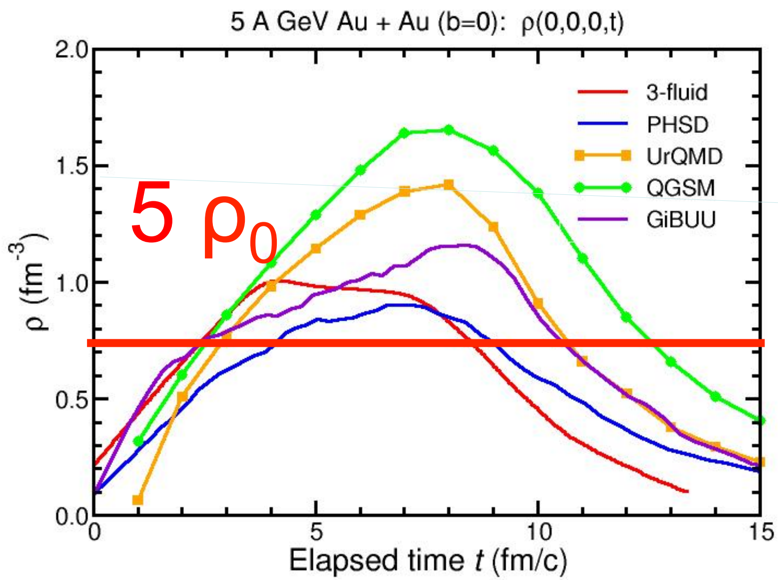
PSR J0740+6620
M = 2.17±0.11 M_{sun}
H. Cromartie et al.,
arXiv:1904.06759 (2019)

J. M. Lattimer and M. Prakash, From Nuclei to Stars, ed. S. Lee, p.275, WorldScientific. (2011) arXiv:1012.3208v1

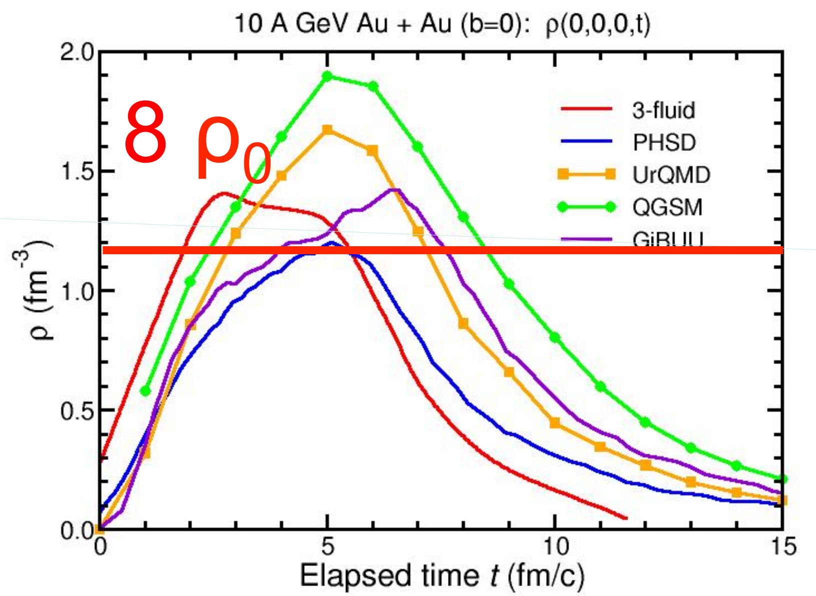
Baryon densities in central Au+Au collisions

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

5 A GeV



10 A GeV



Future attempts to study the high-density EOS

- Systematic studies of collective flow of baryons
- Threshold production of multi-strange hyperons

Idea:

Ξ and Ω yield at subthreshold energies ~ multi-step collisions ~ density → EOS

Strangeness production:

$pp \to K^+\Lambda^0 p$	(E_{thr} = 1.6 GeV)
$pp \to K^+K^- pp$	(E_{thr} = 2.5 GeV)
$pp \to \Xi^- K^+K^+ p$	(E_{thr} = 3.7 GeV)
$pp \to \Omega^- K^+K^+K^0 p$	(E_{thr} = 7.0 GeV)
$pp \to \bar{\Lambda}^0\Lambda^0 pp$	(E_{thr} = 7.1 GeV)
$pp \to \Xi^+ \Xi^- pp$	(E_{thr} = 9.0 GeV)
$pp \to \Omega^+ \Omega^- pp$	(E_{thr} = 12.7 GeV

Hyperon production via multiple collisions

$pp \to K^+ n \Sigma^+$, $pp \to K^+ p \Lambda^0$ → $\Sigma^+\Lambda^0 \to \Xi^0 p$

$pn \to K^+ p \Sigma^-$ → $\Sigma^- \Xi^0 \to \Omega^- n$

$pp \to K^+ p \Lambda^0$, $pp \to K^+ p \Lambda^0$ → $\Lambda^0\Lambda^0 \to \Xi^- p$

$pn \to nK^+ \Sigma^0$ → $\Sigma^0 \Xi^- \to \Omega^- n$

$pp \to K^+ n \Sigma^+$, $pn \to K^+ p \Sigma^-$ → $\Sigma^+\Sigma^- \to \Xi^- p$

$pp \to K^+ p \Lambda^0$ → $\Lambda^0 \Xi^- \to \Omega^- n$

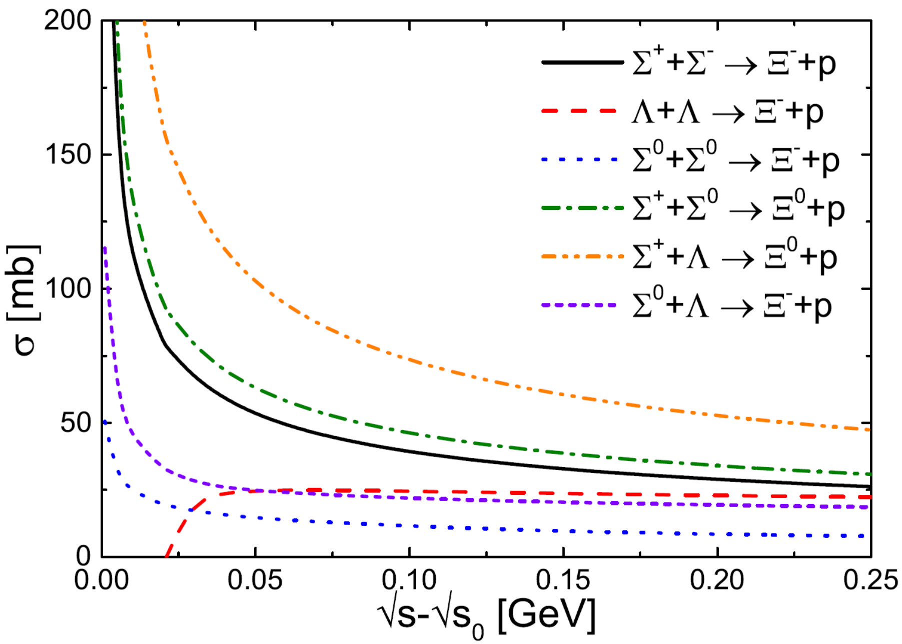
Future attempts to study the high-density EOS

- Systematic studies of collective flow of baryons
- Threshold production of multi-strange hyperons

Idea:

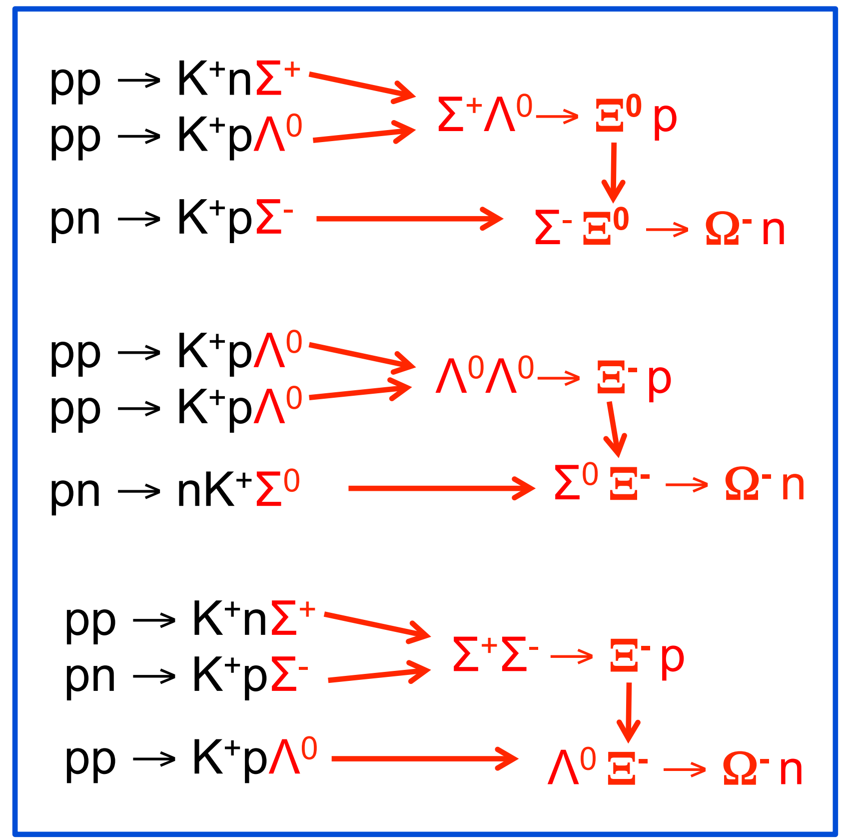
Ξ and Ω yield at subthreshold energies ~ multi-step collisions ~ density → EOS

Isospin-dependent strangeness-exchange cross sections in UrQMD



G. Graef, J. Steinheimer, F. Li, M. Bleicher, Phys. Rev. C 90, 064909 (2014)

Hyperon production via multiple collisions



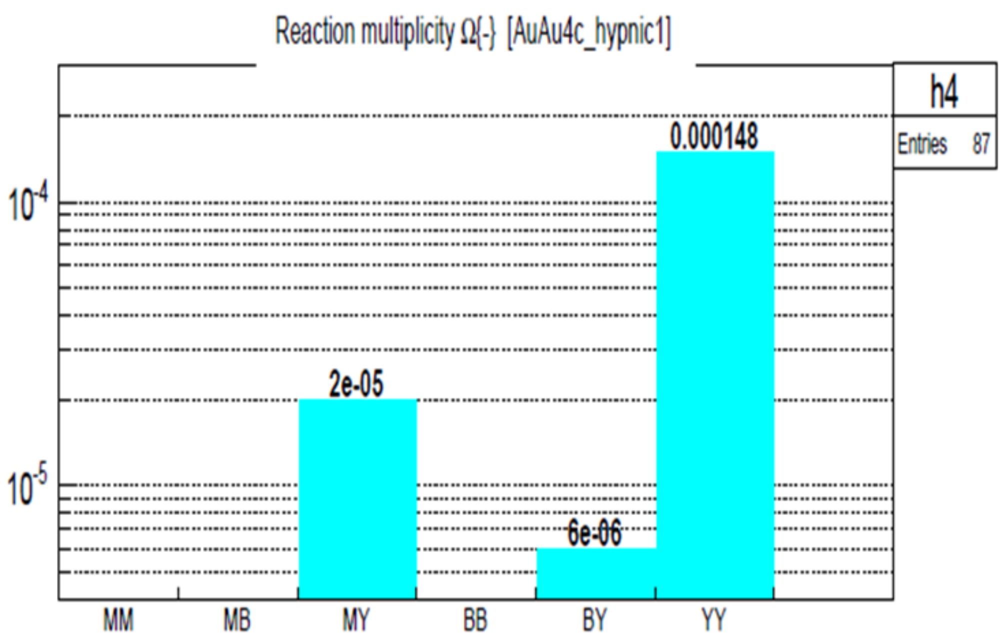
Future attempts to study the high-density EOS

- Systematic studies of collective flow of baryons
- Threshold production of multi-strange hyperons

Idea:

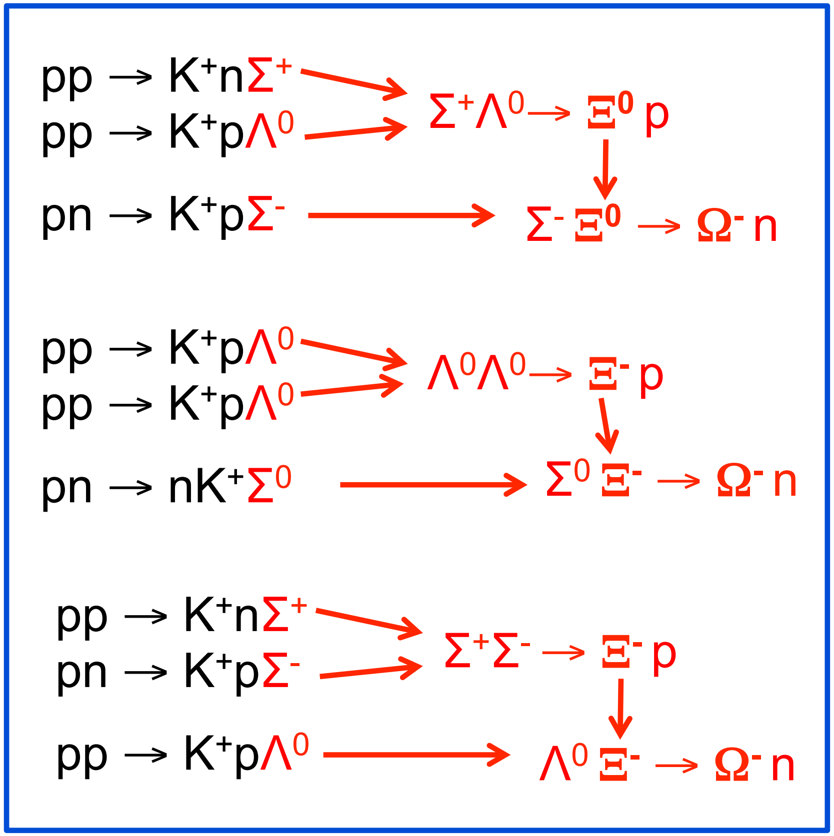
Ξ and Ω yield at subthreshold energies ~ multi-step collisions ~ density → EOS

Ω^- production in 4 A GeV Au+Au



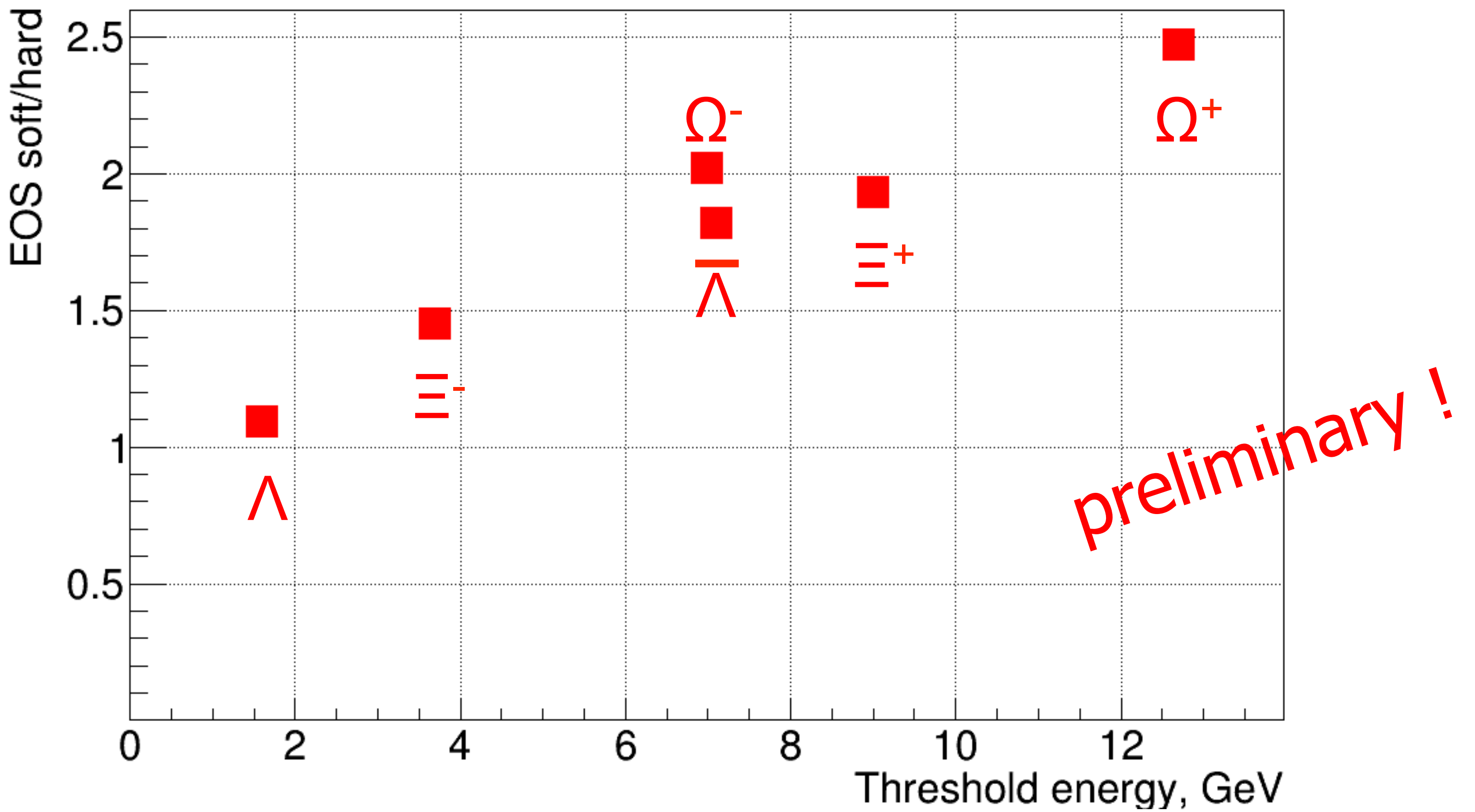
HYPQGSM calculations , K. Gudima et al.

Hyperon production via multiple collisions



Multi-strange hyperons: promising observables for the EOS of symmetric matter

6 M central Au+Au collisions at 4A GeV
soft EOS (K=240 MeV) / hard EOS (K=350) MeV



PHQMD calculations , J. Aichelin, E. Bratkovskaya, V. Kireyeu et al., priv. comm.

The nuclear symmetry energy

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

$$E_{sym}(\rho) = E_{sym}(\rho_0) + \frac{L}{3}\left(\frac{\rho-\rho_0}{\rho_0}\right) + \frac{K_{sym}}{18}\left(\frac{\rho-\rho_0}{\rho_0}\right)^2$$

Empirical value $E_{sym}(\rho_0) \approx 30$ MeV

slope $$L = 3\rho_0 \left.\frac{\partial E_{sym}(\rho)}{\partial\rho}\right|_{\rho=\rho_0}$$

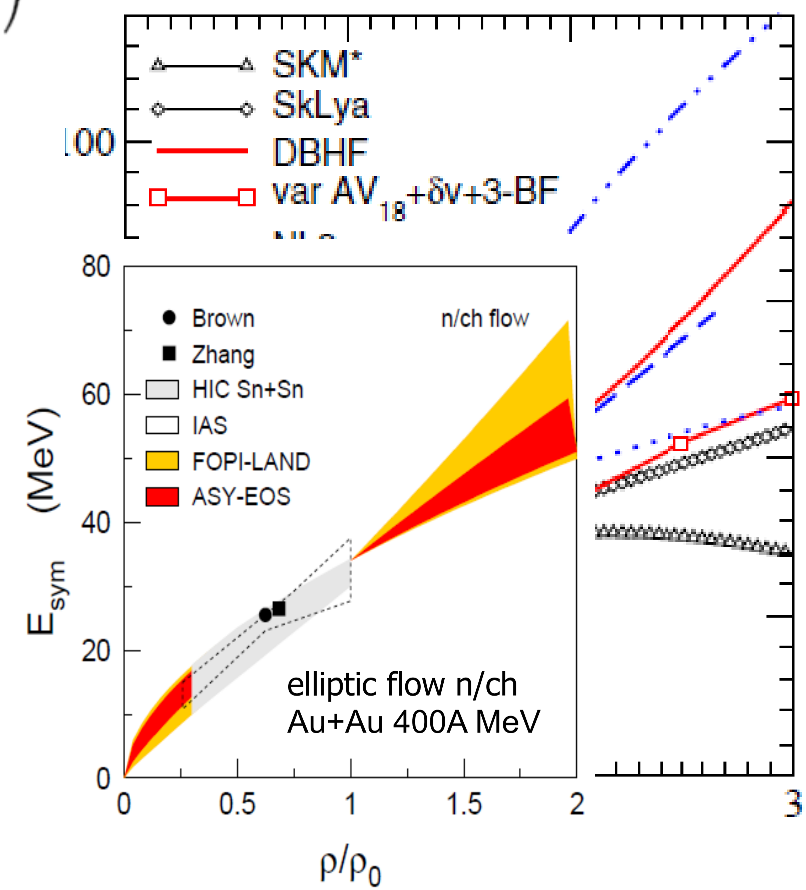
theoretical value $L(\rho_0) \approx 60$ MeV

B.A. Li and X. Han, Phys. Lett. B 727 (2013) 276

curvature $$K_{sym} = 9\rho_0^2 \left.\frac{\partial^2 E_{sym}(\rho)}{\partial^2\rho}\right|_{\rho=\rho_0}$$

theoretical value K_{sym} = -700 to 470 MeV

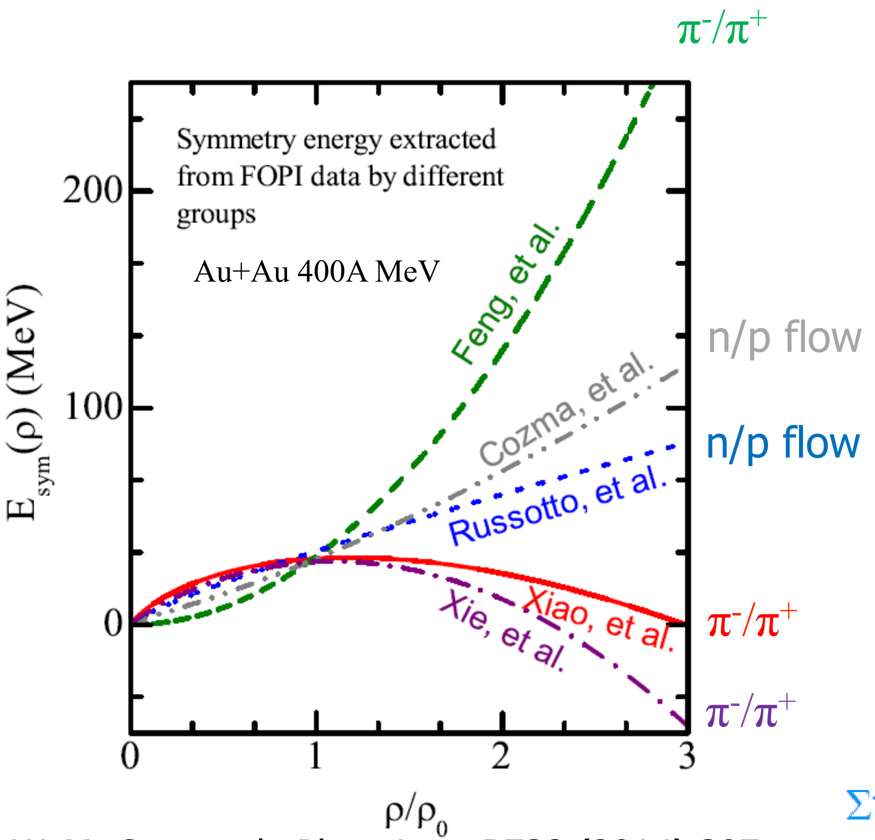
Ch. Fuchs and H.H. Wolter, EPJA30 (2006) 5



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

The symmetry energy E_{sym} at high density

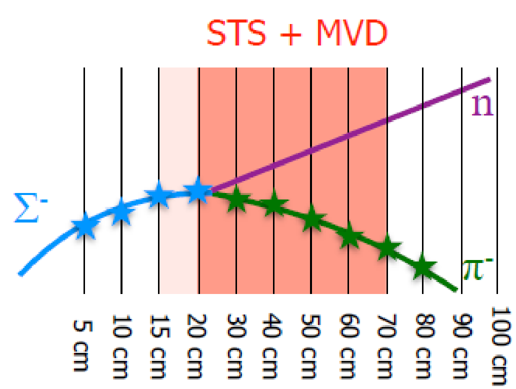
- Elliptic flow neutrons/protons
- Particles with opposite isospin ?
- Flow of Σ^+ and Σ^- ?

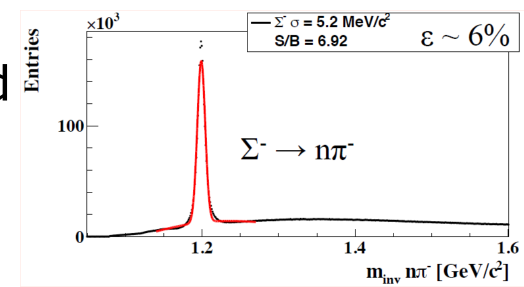


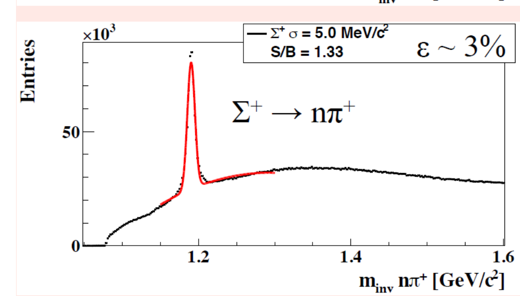
W.-M. Guo et al., Phys. Lett. B738 (2014) 397

I_3	particle	production	E_{thr} GeV	decay
+1	Σ^+(uus)	$pp \to \Sigma^+K^+n$ $pp \to \Sigma^+K^0p$ $pn \to \Sigma^+K^0n$	1.8	$\Sigma^+ \to p\pi^0$ $\Sigma^+ \to n\pi^+$
-1	Σ^-(dds)	$pn \to \Sigma^-K^+p$ $nn \to \Sigma^-K^+n$	1.8	$\Sigma^- \to n\pi^-$

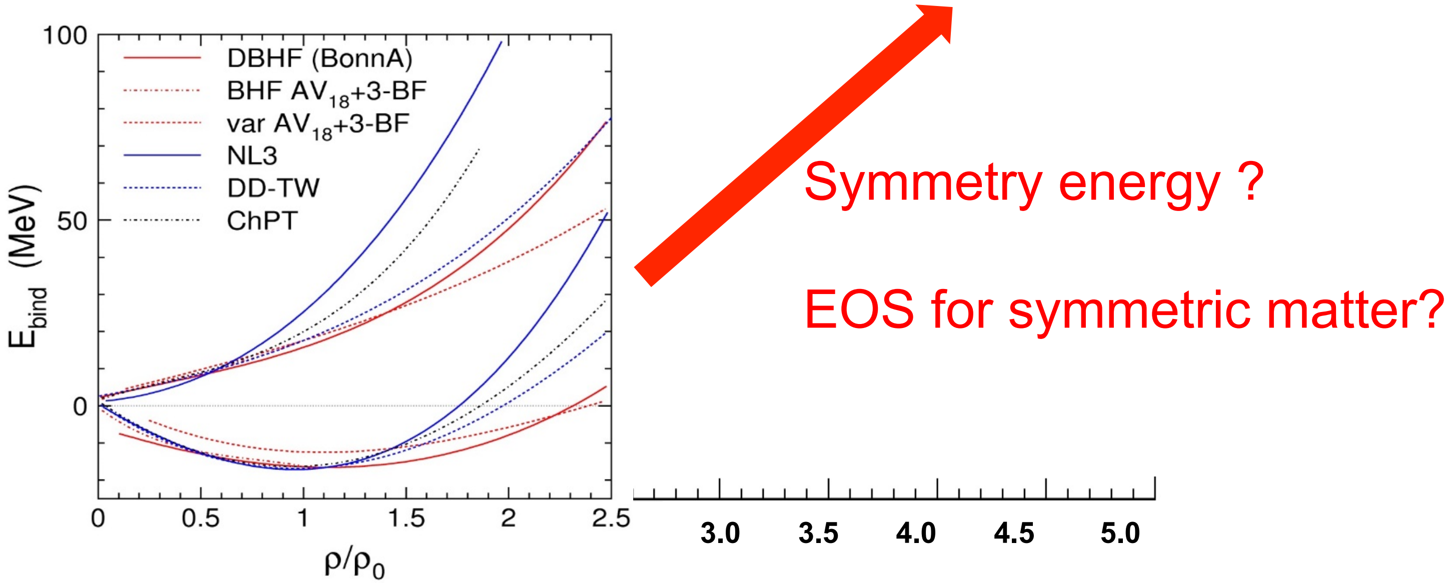
Missing mass method

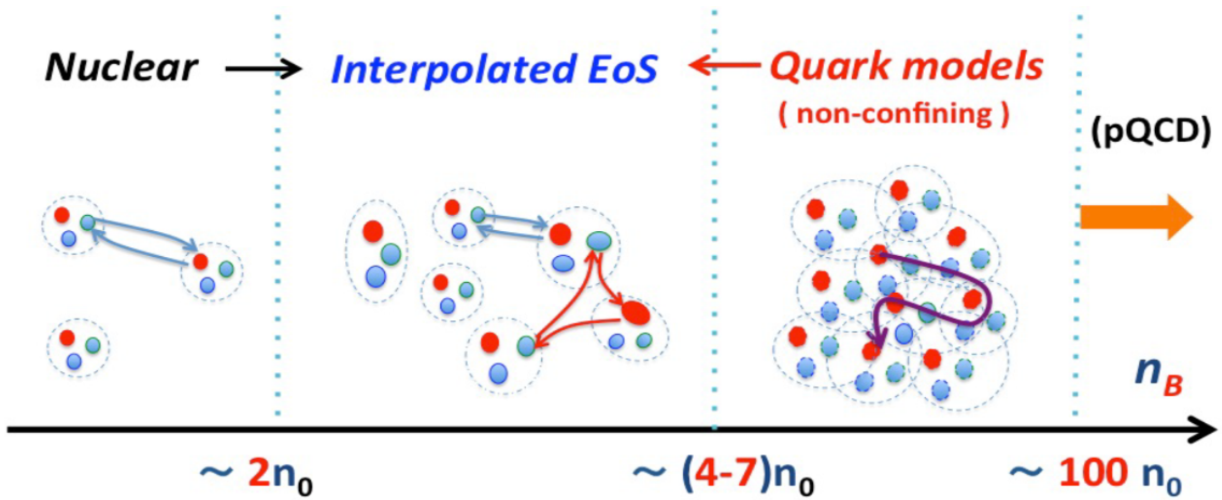






Properties of nuclear matter at neutron star core densities

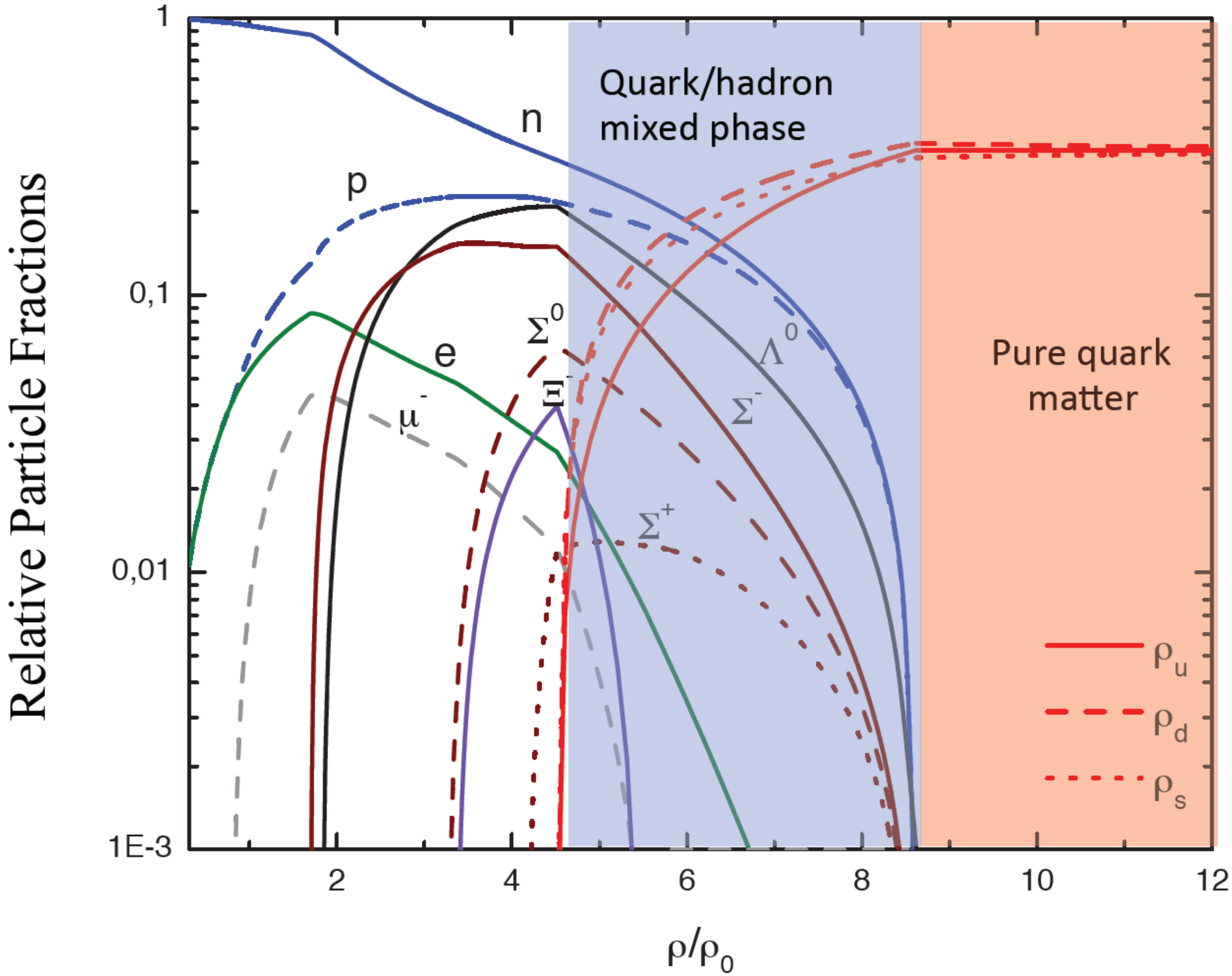




Courtesy of T. Kojo

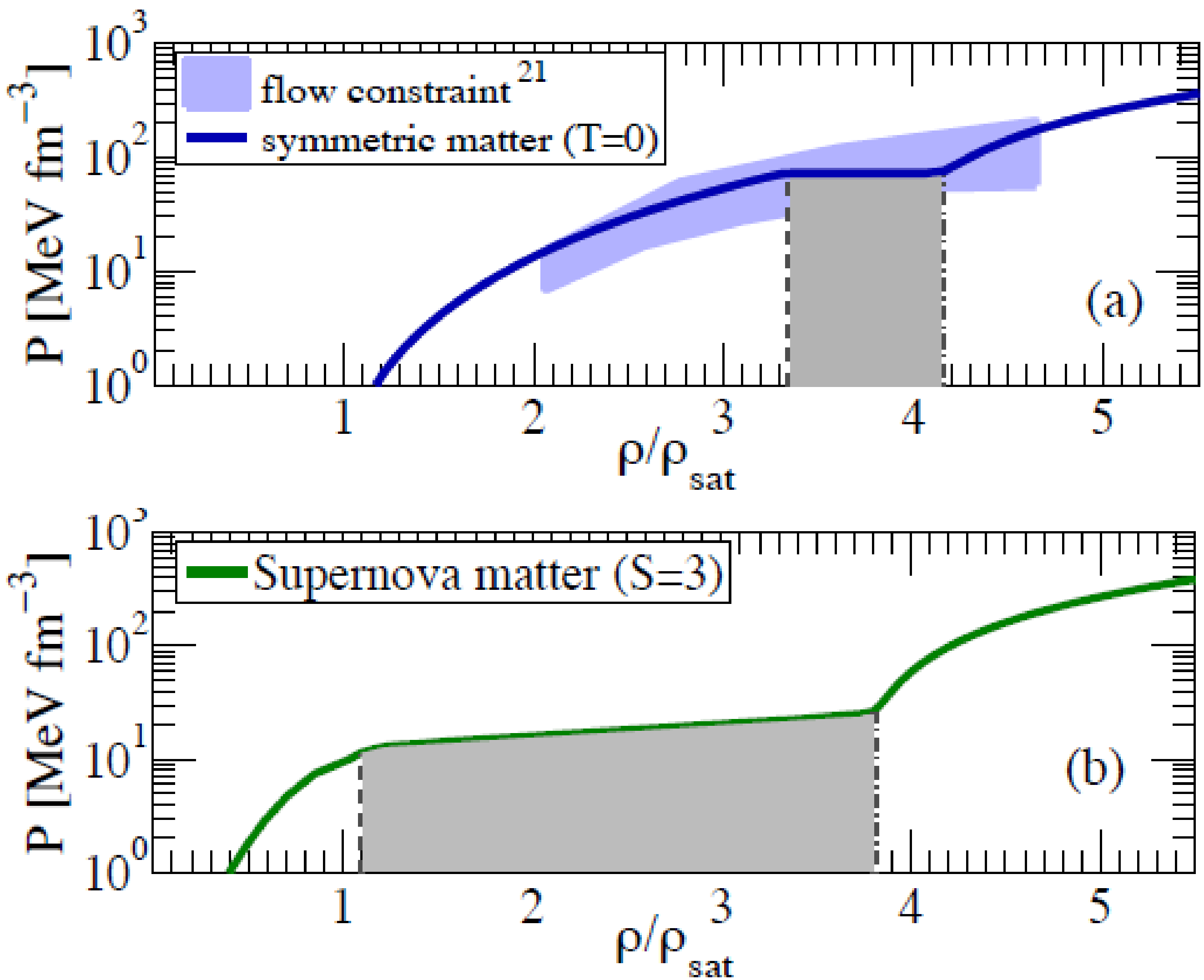
Degrees-of-freedom at high density?

M. Orsaria, H. Rodrigues, F. Weber, G.A. Contrera, arXiv:1308.1657
Phys. Rev. C 89, 015806, 2014 (SU(3)-NJL model calculations)

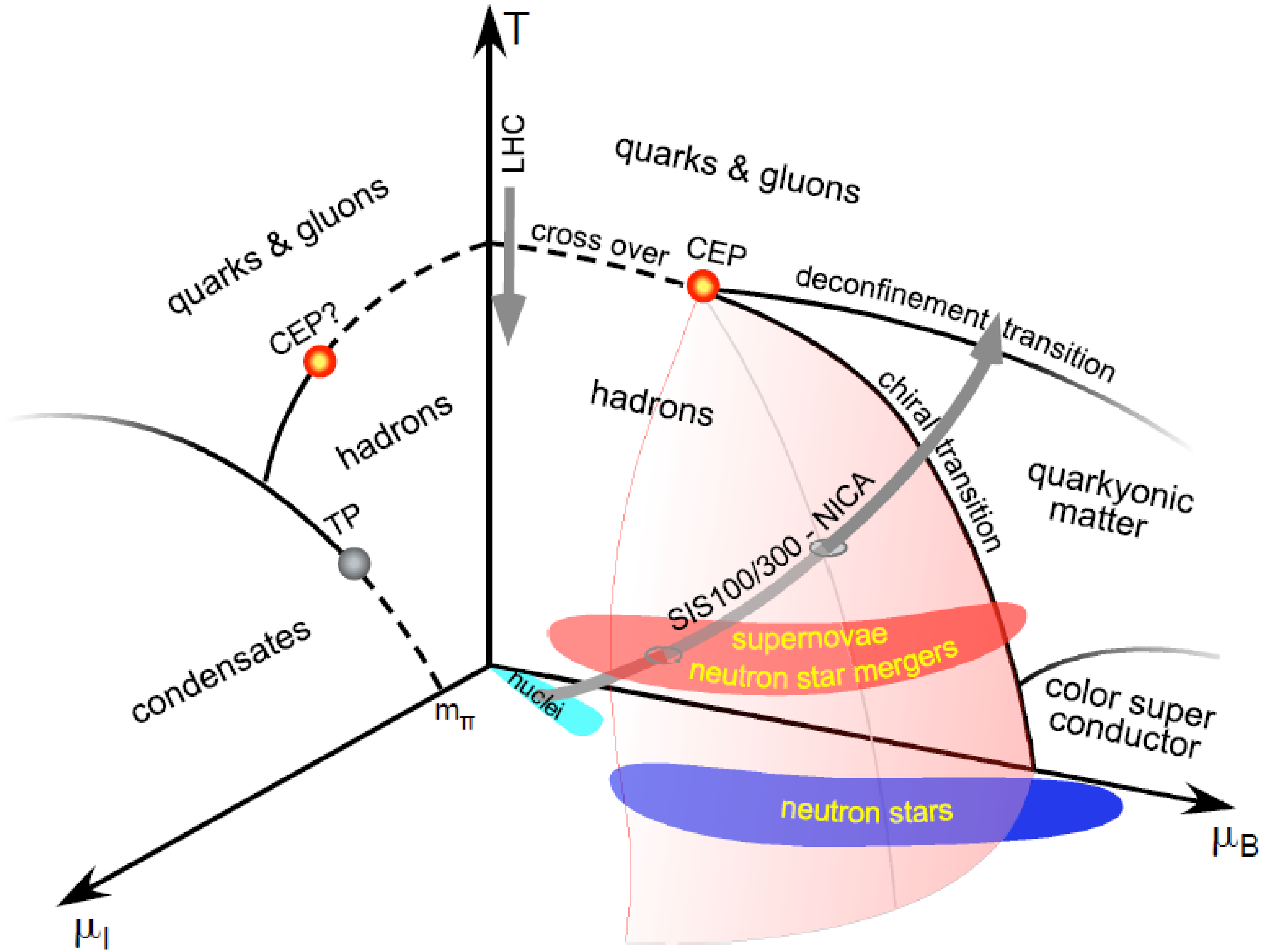


EOS with phase transition

T. Fischer, N. Bastian, M. Wu, S. Typel, T. Klähn, D. Blaschke,
Nature Astronomy (2018), DOI: 10.1038/s41550-018-0583-0, arXiv:1712.08788v2
Quark deconfinement as supernova explosion engine for massive blue-supergiant stars

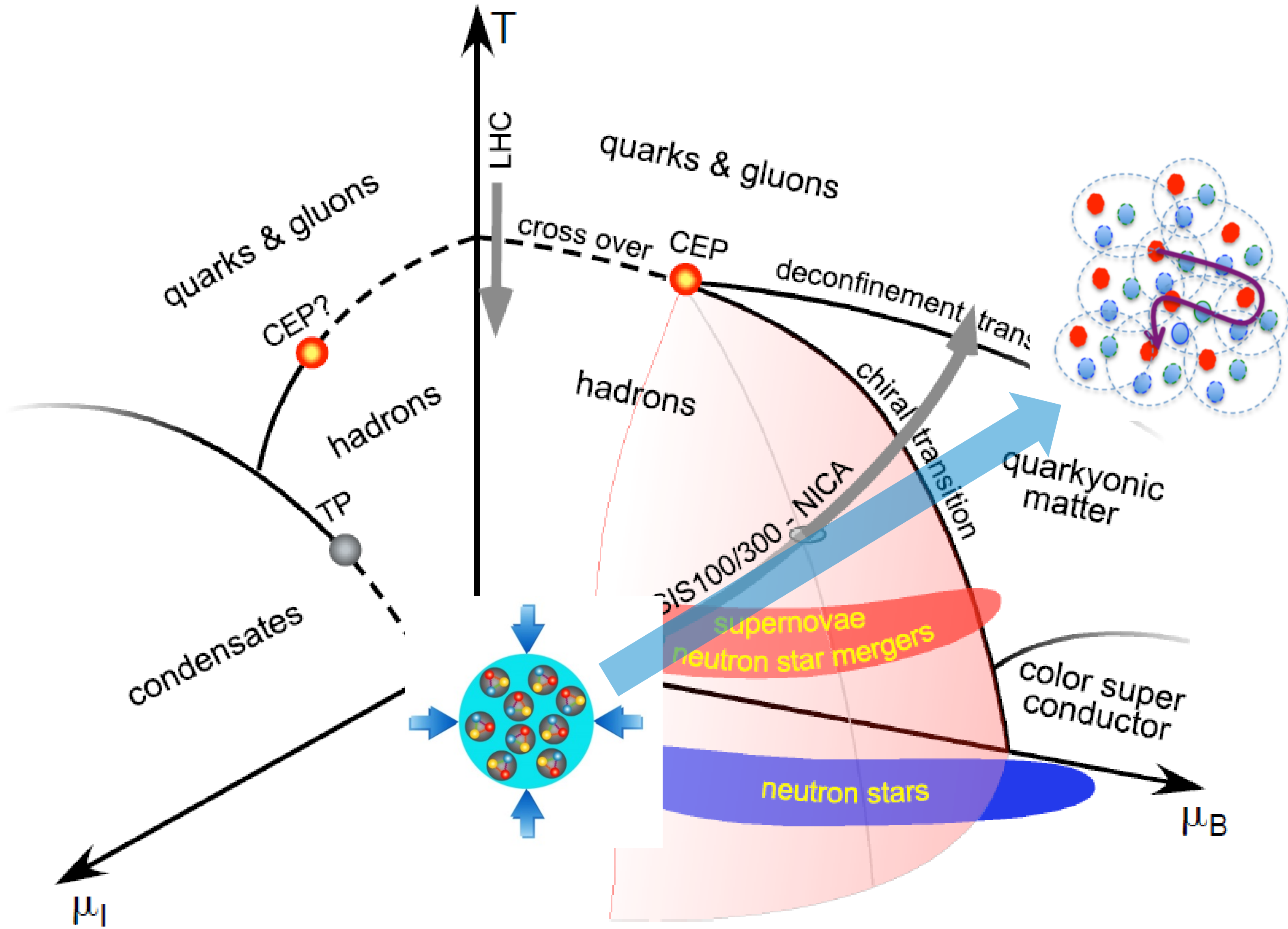


Exploring the QCD phase diagram

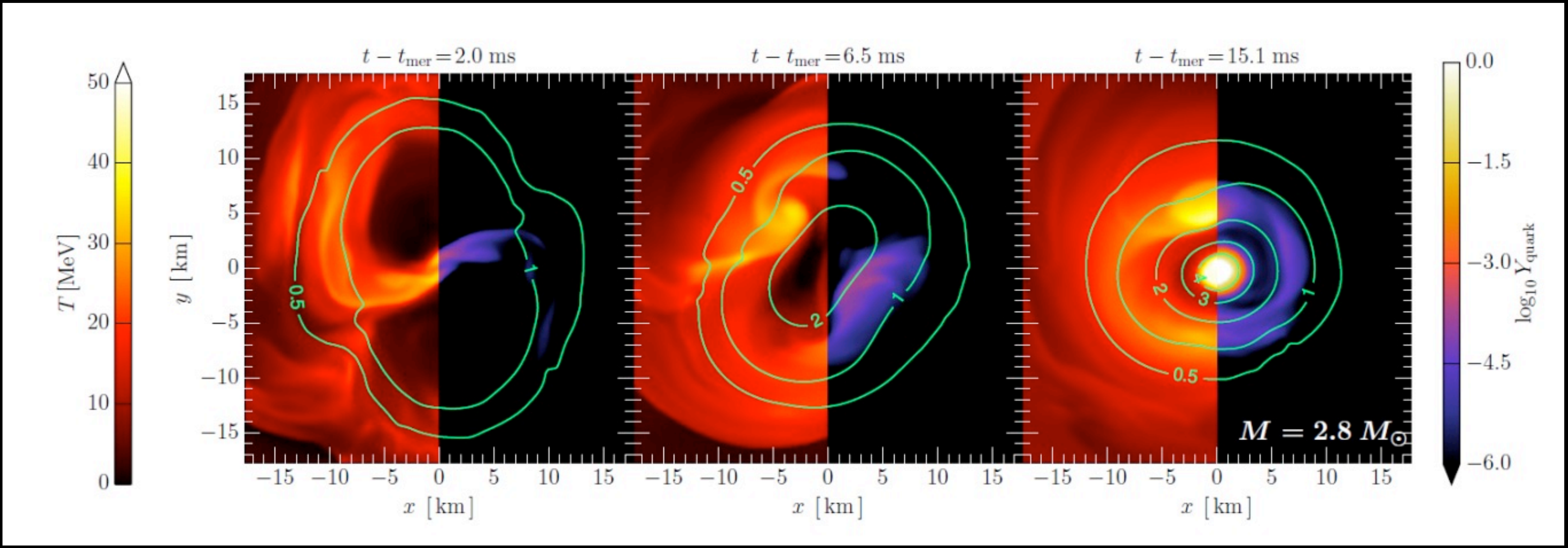


NUPECC Long Range Plan 2017

Exploring the QCD phase diagram



Quark-hadron phase transitions in general-relativistic neutron-star mergers ?



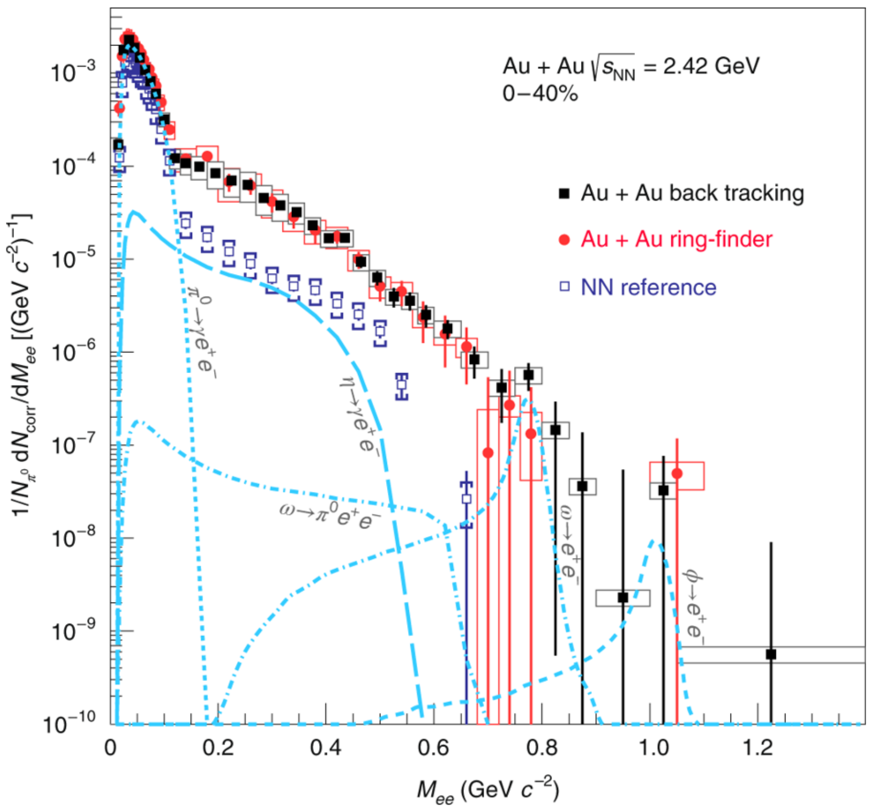
E. Most et al., (… M Hanauske, L. Rezzola), Phys. Rev. Lett. 122, 061101 (2019)

Transition from hadronic matter to quark matter at $\rho > 4\, \rho_0$ and $T > 50$ MeV ?

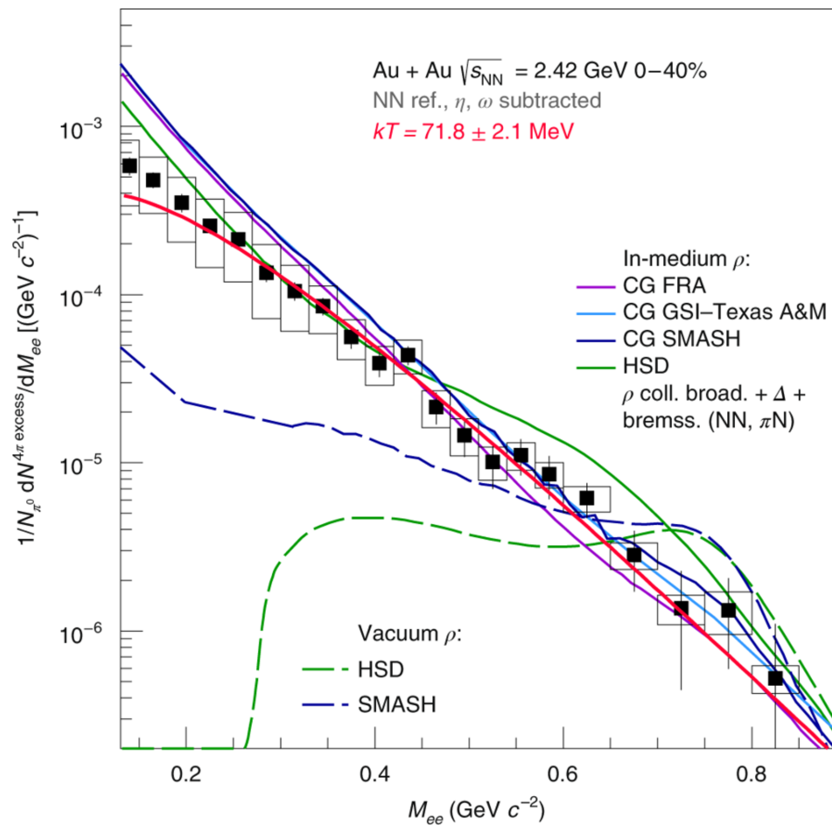
Thermal radiation from dense QCD matter

Au+Au collisions at 1.25 A GeV: $\rho \leq 2.5\ \rho_0$, $T \approx 72$ MeV

Di-electron yield



Di-electron excess yield
after subtraction of vector mesons

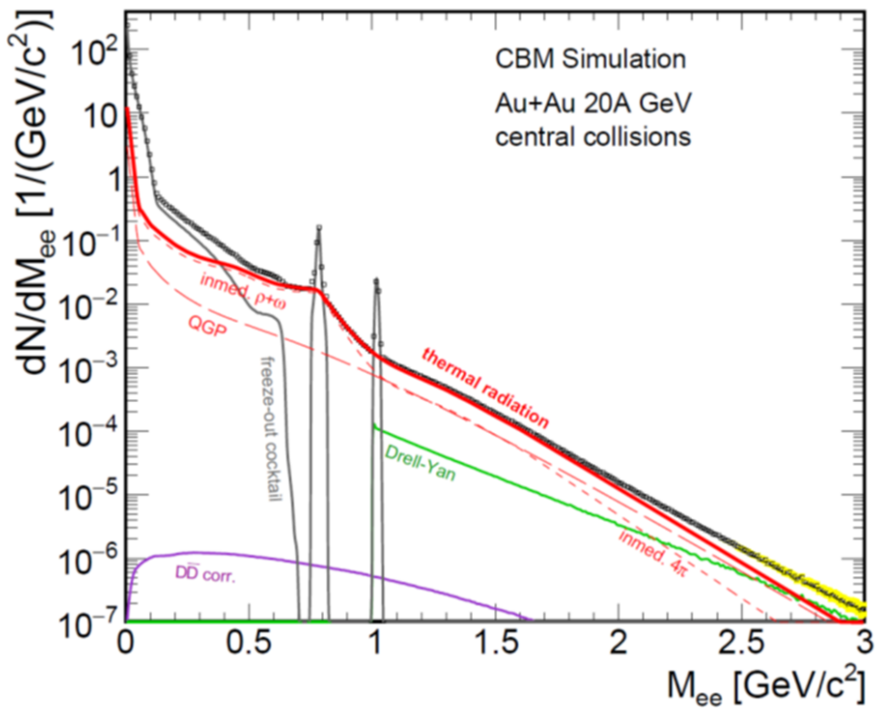


J. Adamczewski-Musch et al., The HADES Collaboration, Nature Physics 2019,
https://doi.org/10.1038/s41567-019-0583-8

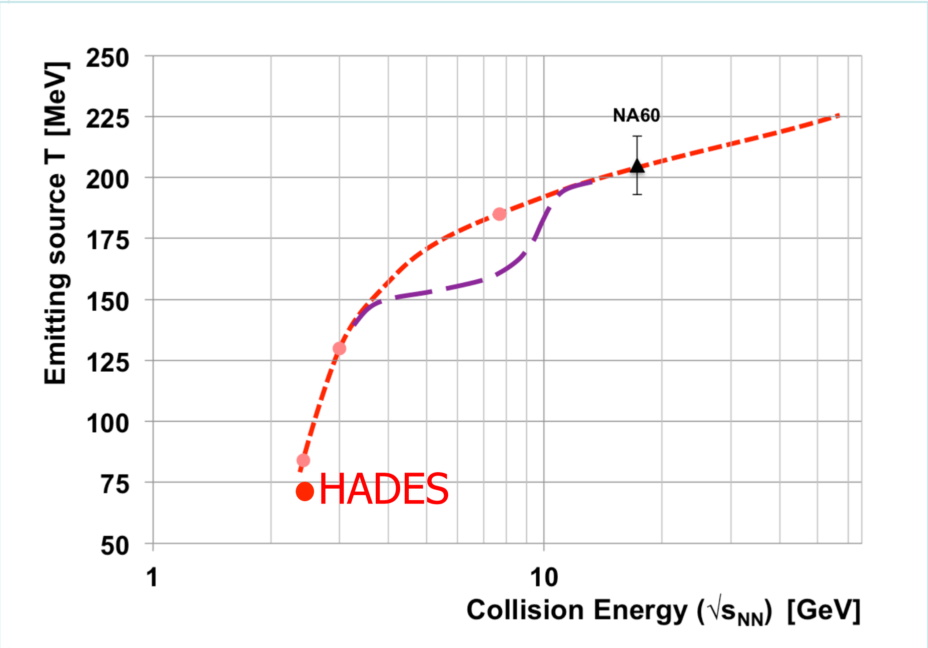
Experimental indication for a phase transition at large μ_B?

Invariant mass (M_{inv} > 1 GeV/c^2) of lepton pairs as function of beam energy → thermal radiation from fireball → caloric curve → phase coexistence (1st order transition)

Invariant mass distribution of lepton pairs



Slope of dilepton invariant mass spectrum
1 GeV/c^2 < M_{inv} < 2.5 GeV/c^2



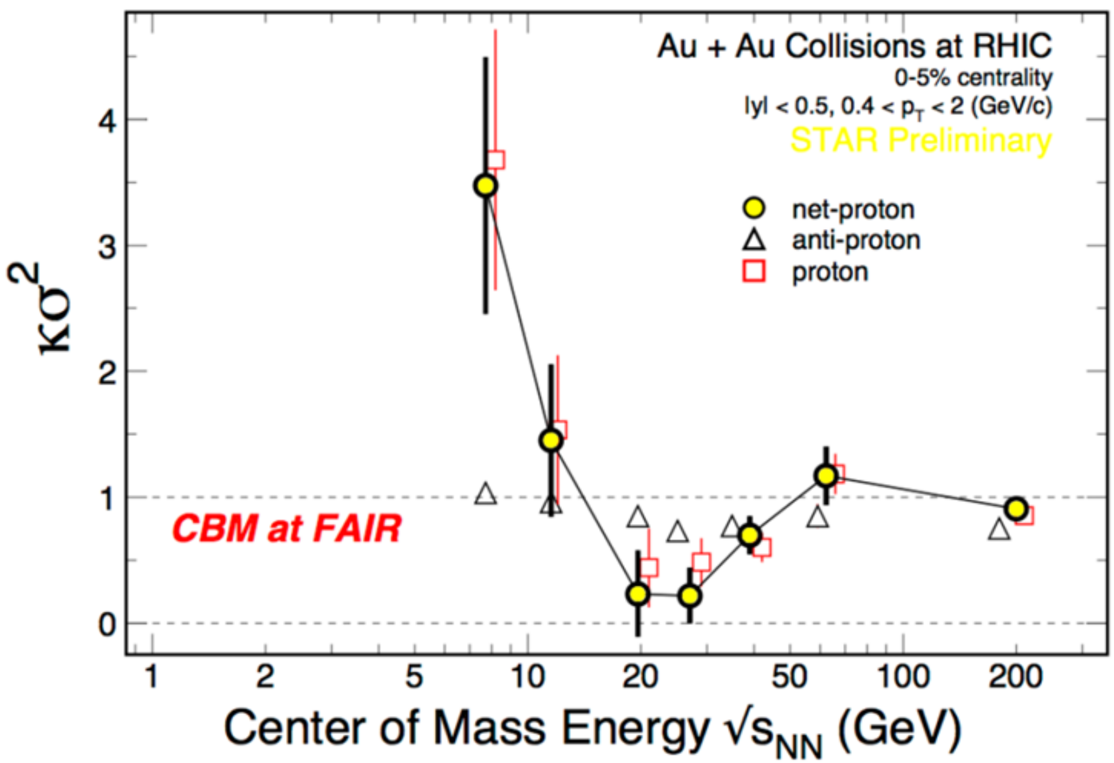
T. Ablyasimov et al., (CBM Collaboration)
Eur. Phys. J. A 53 (2017) 60

Searching for the critical endpoint of the 1st order phase transition at SIS100 energies ?

"Critical opalescence":

Event-by-event fluctuations of conserved quantities (B,S,Q)

4th moment of net-proton multiplicity distribution



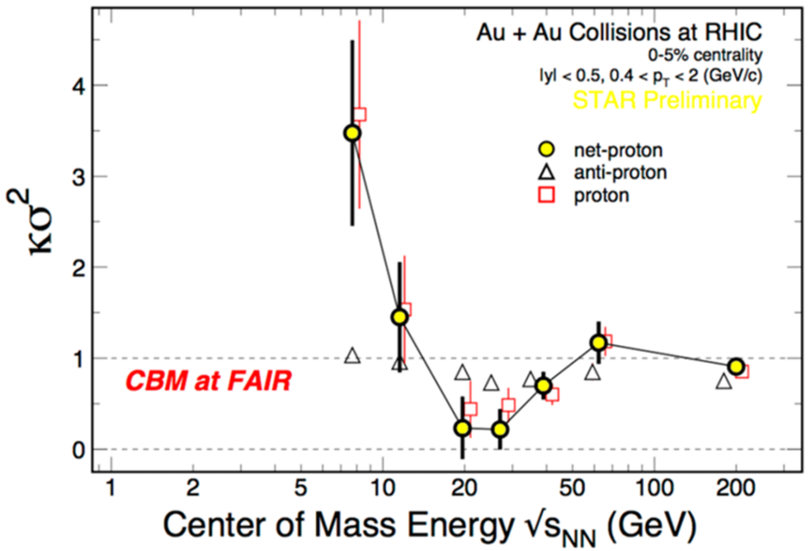
Data:
STAR at RHIC
beam energy scan

Experimental indication for a phase transition at large μ_B?

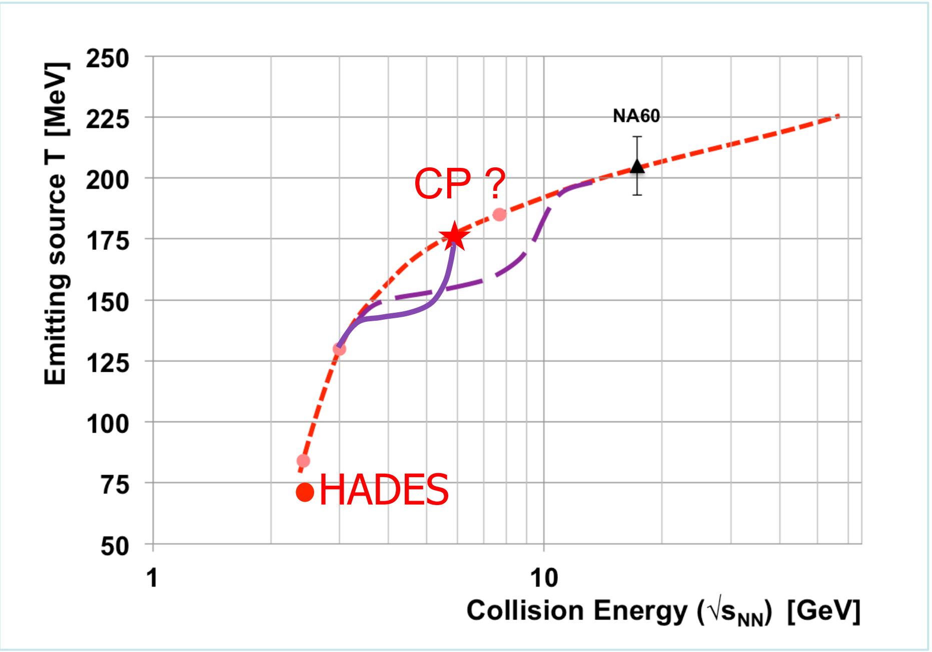
Required: consistent signatures from different observables

For example:

Critical opalescence

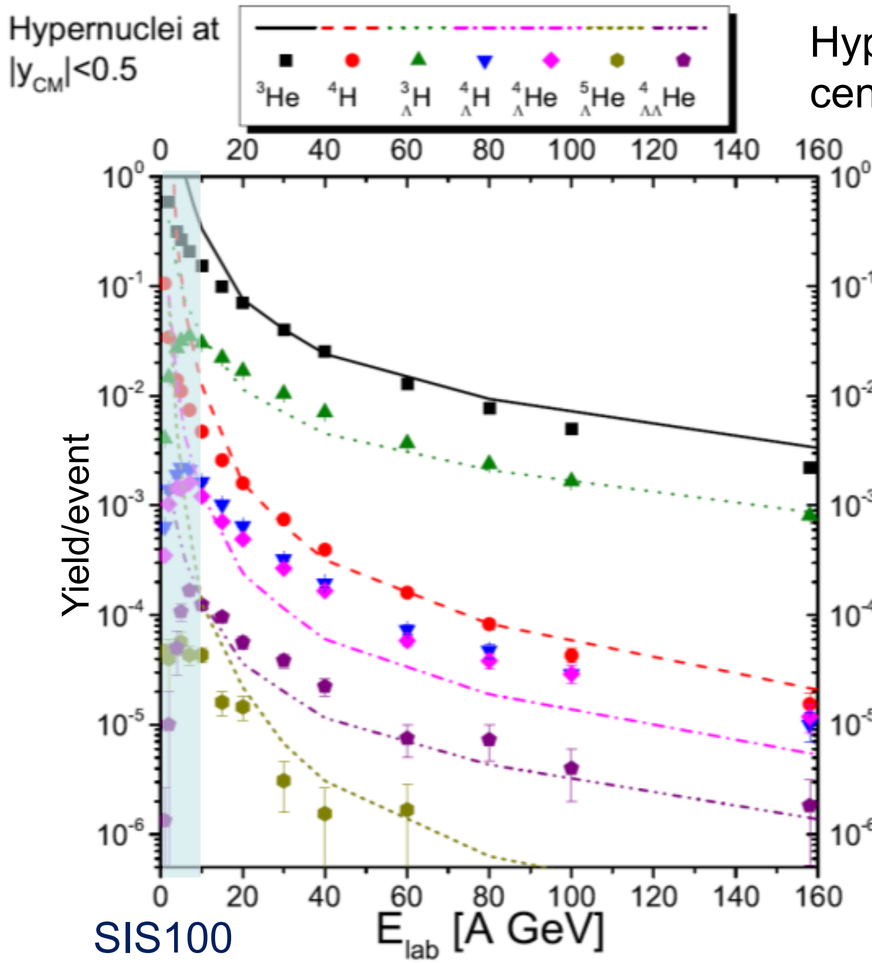


Caloric curve



Hyperons in neutron stars

Study of ΛN, ΛNN, and ΛΛN interactions



Hypernuclei production in central Pb+Pb/Au+Au collisions

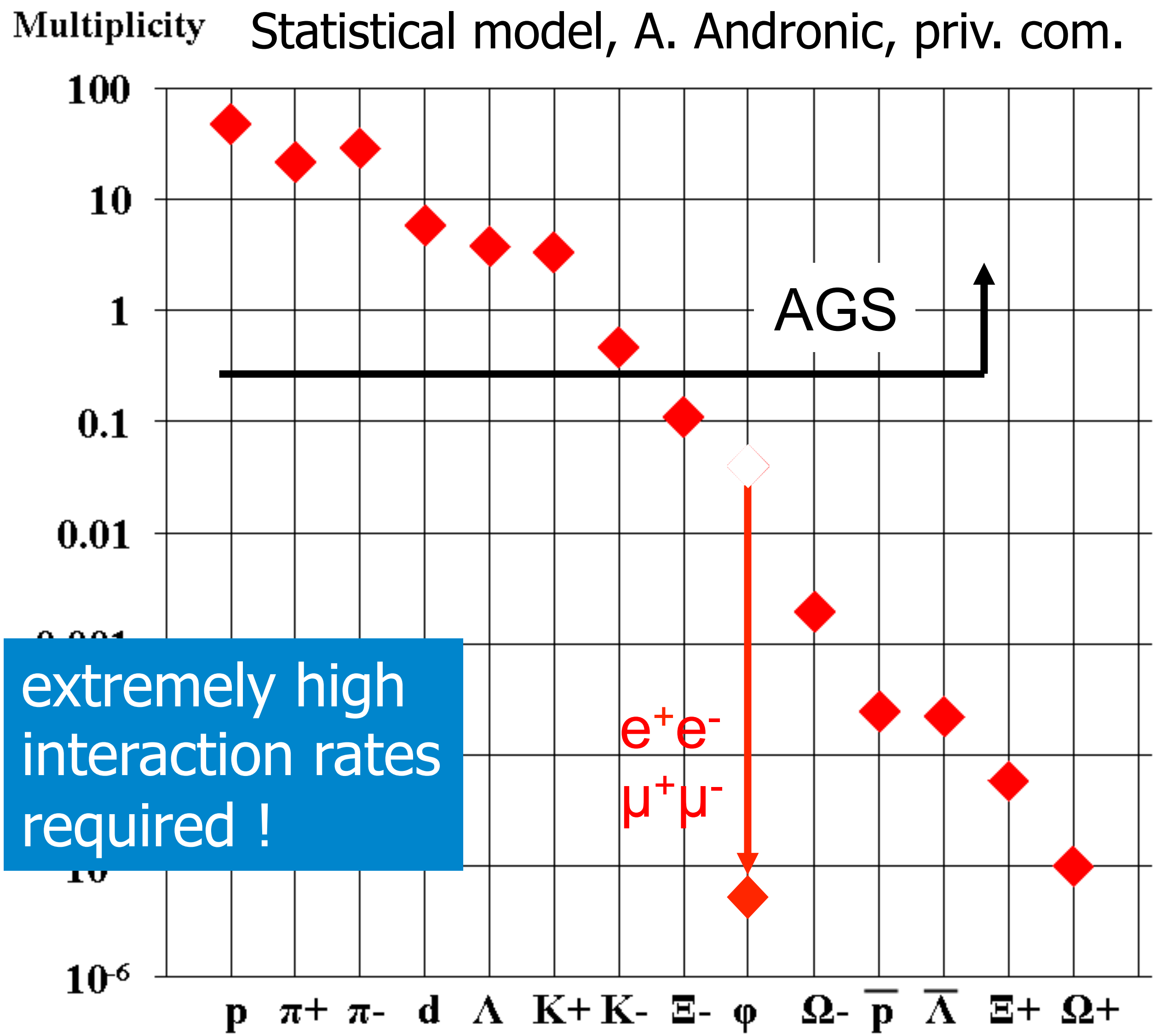
Lines:
Thermal production
(UrQMD-hydro hybrid model)

Symbols:
Coalescence results
(Dubna Cascade Model, DCM-QGSM)

J. Steinheimer et al., Phys. Lett. B 714 (2012) 85

Experimental challenges

Particle yields in central Au+Au 4 A GeV

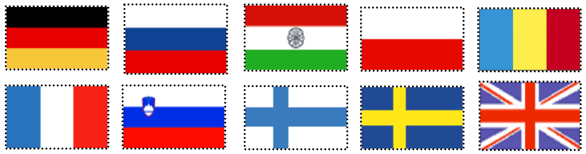


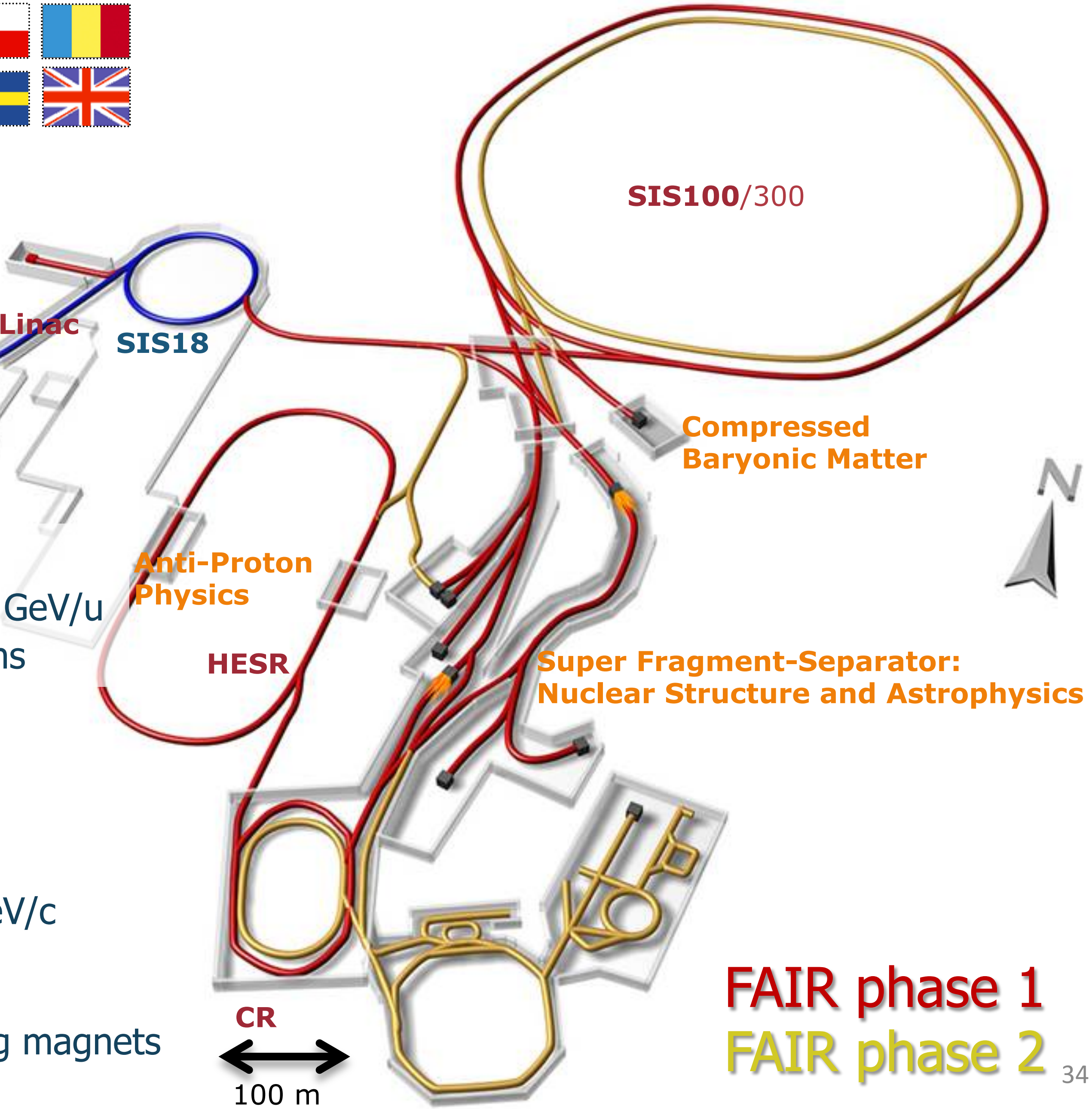
extremely high interaction rates required !

Experimental requirements

- 10^5 - 10^7 Au+Au reactions/sec
- identification of leptons and hadrons
- fast and radiation hard detectors and FEE
- free-streaming readout electronics
- high speed data acquisition and high performance computer farm for online event selection
- 4-D event reconstruction

Facility for Antiproton & Ion Research





Primary Beams

- 10^{12}/s; 1.5 GeV/u; $^{238}U^{28+}$
- 10^{10}/s $^{238}U^{92+}$ up to 11 (35) GeV/u
- 3×10^{13}/s 30 (90) GeV protons

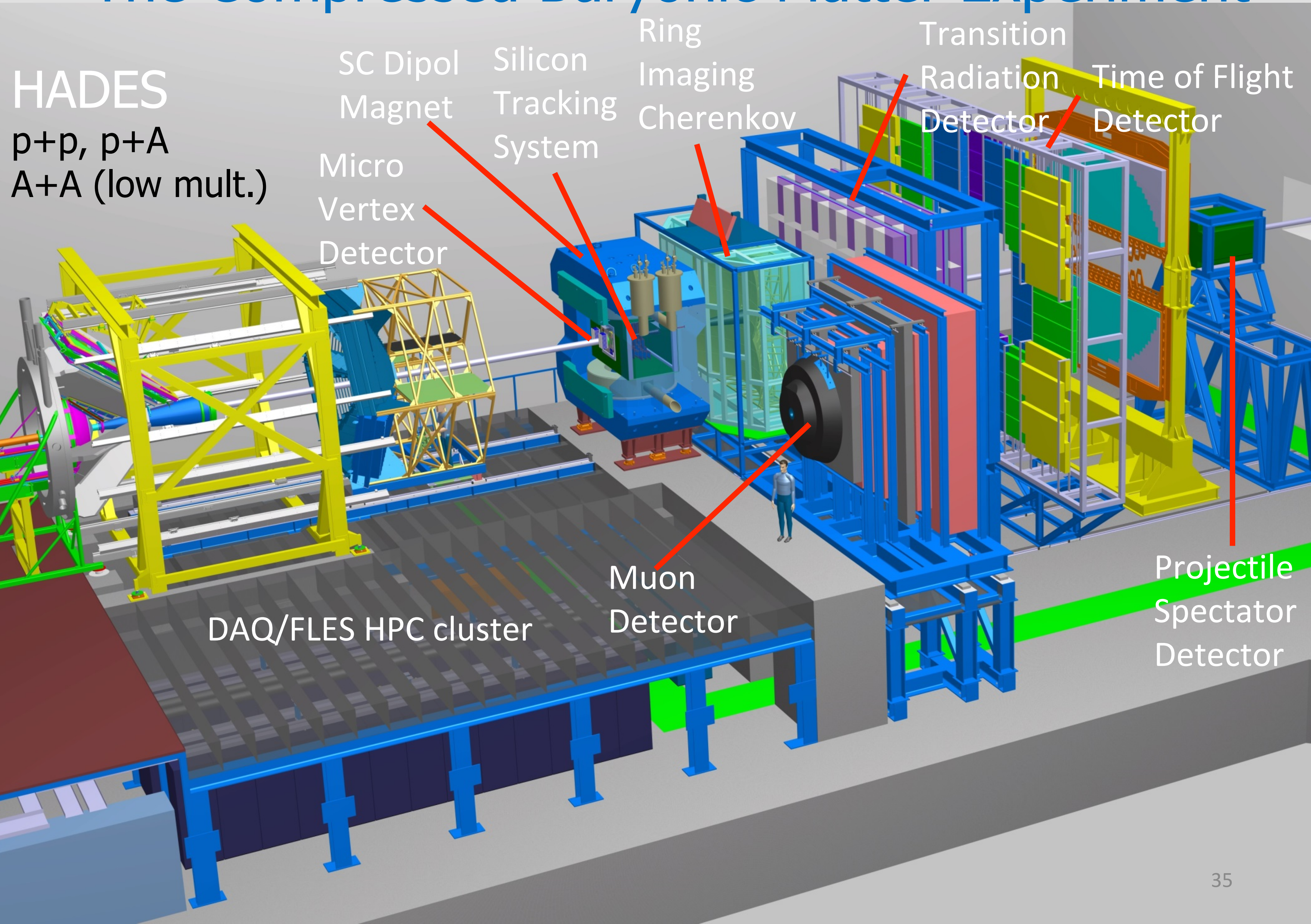
Secondary Beams

- radioactive beams up to 1.5 - 2 GeV/u;
- 10^{11} antiprotons 1.5 - 15 GeV/c

Technical Challenges

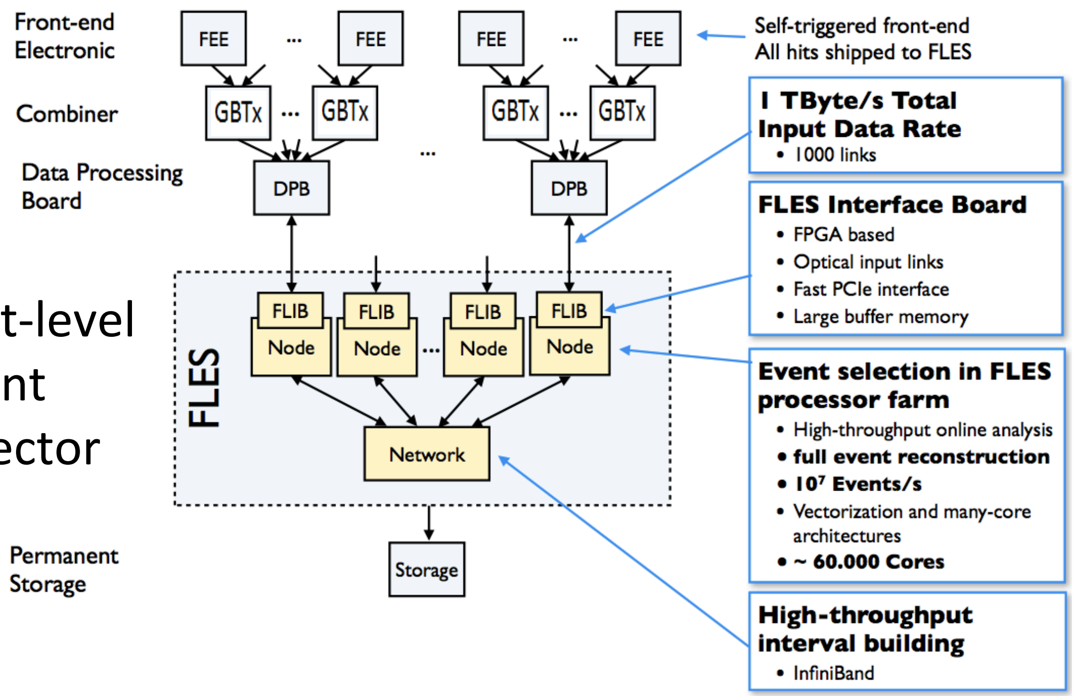
- rapid cycling superconducting magnets
- dynamical vacuum

The Compressed Baryonic Matter Experiment



CBM DAQ and online event selection

First-level Event Selector

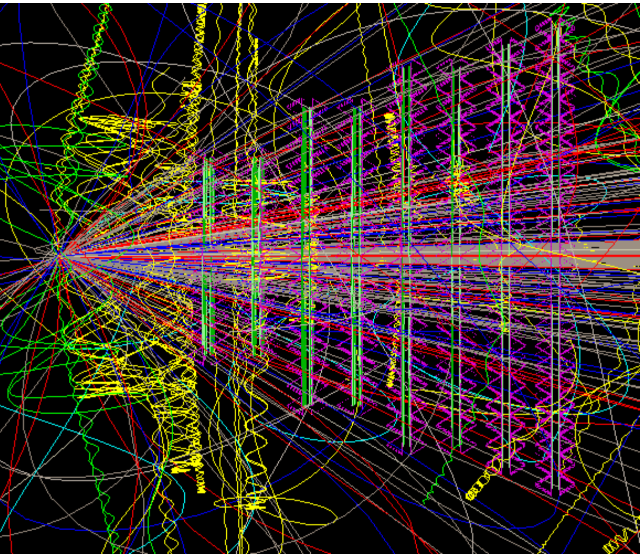


Novel readout and data acquisition system:

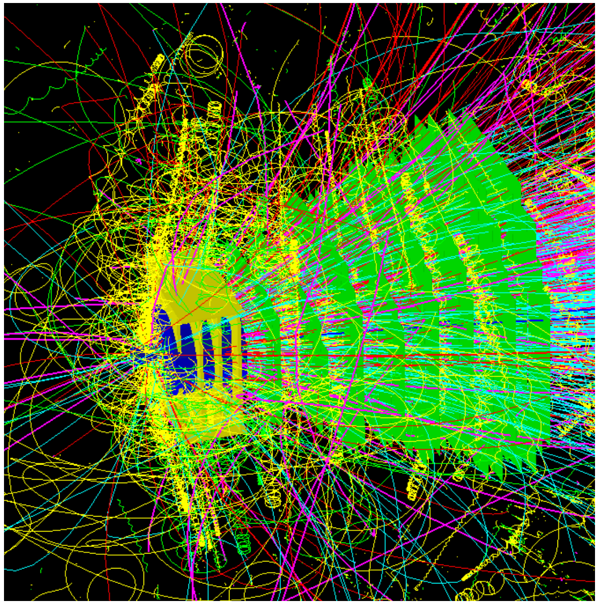
- no hardware trigger on events, free-streaming data read-out
- each detector hit provided with a time stamp
- full online „4-D“ track reconstruction, event definition and data selection by high-speed algorithms running on the GSI GreenIT cube

4D track and event reconstruction

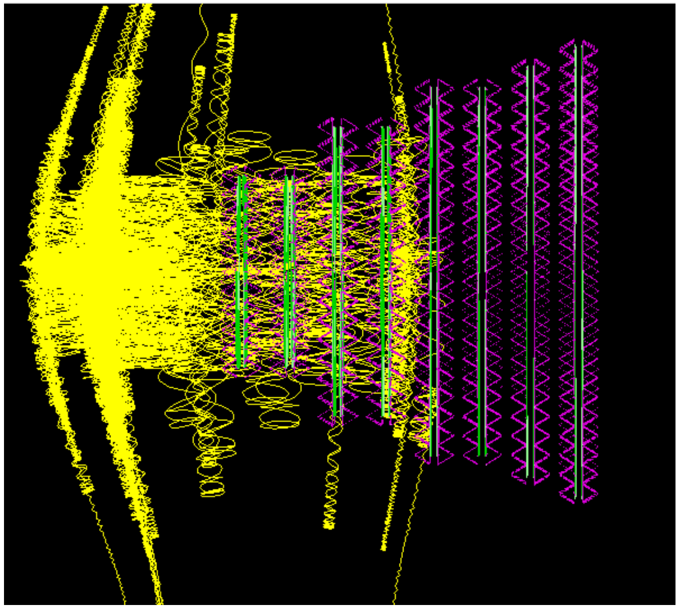
Au+Au 8 A GeV
peripheral collision
UrQMD + GEANT3



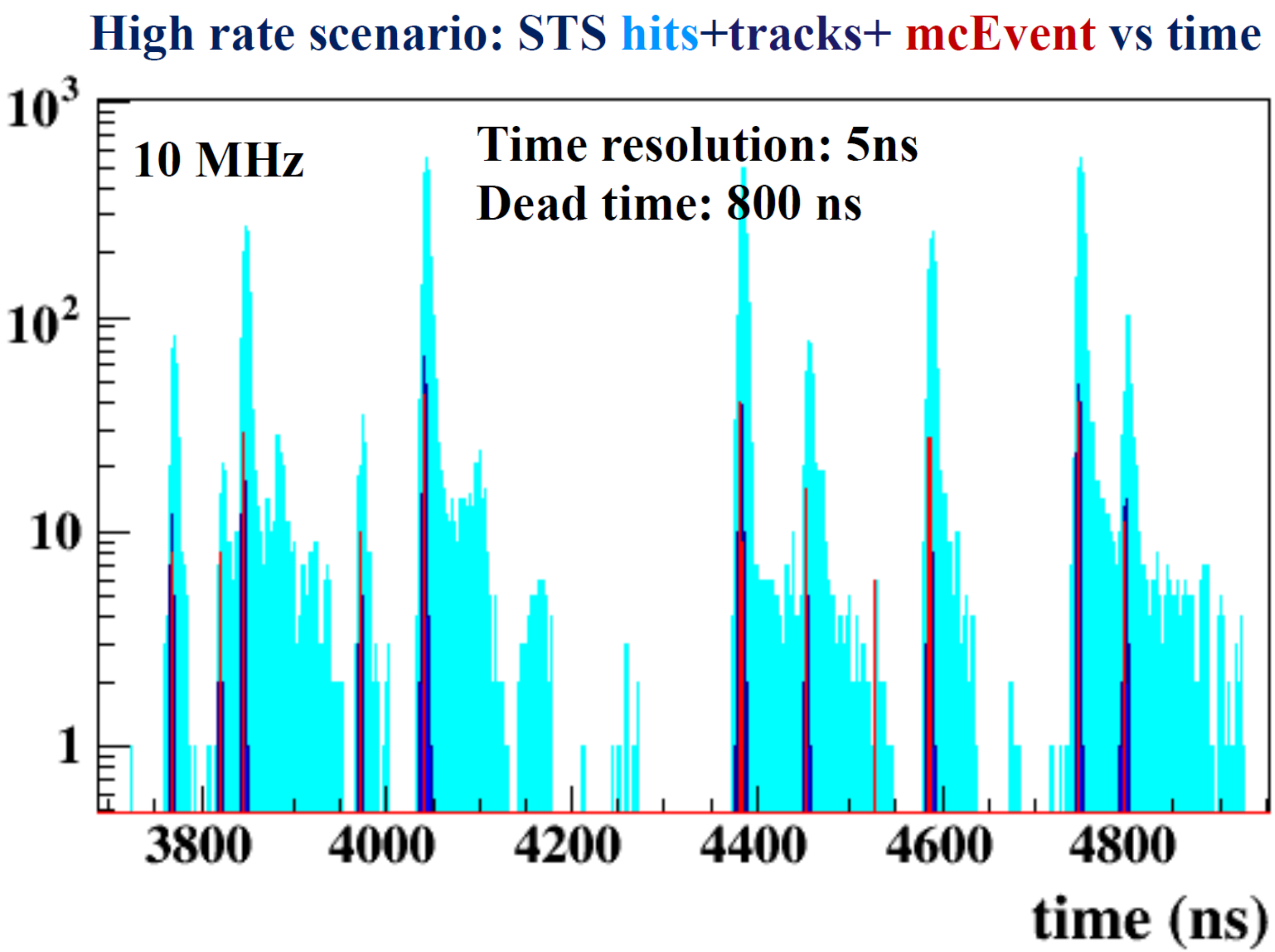
Au+Au 8 A GeV
central collision
UrQMD + GEANT3



Au beam 8 A GeV
one single ion
passing the target
FairIon + GEANT3

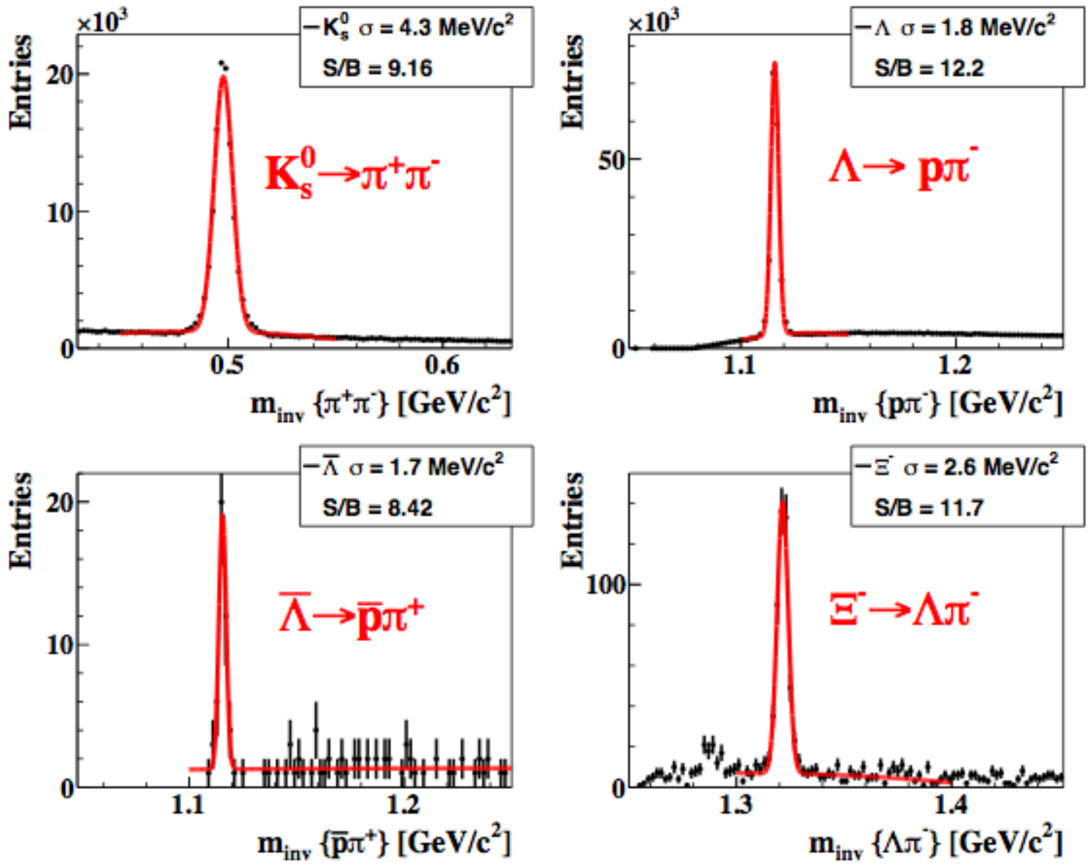


4D track and event reconstruction



4D track and event reconstruction

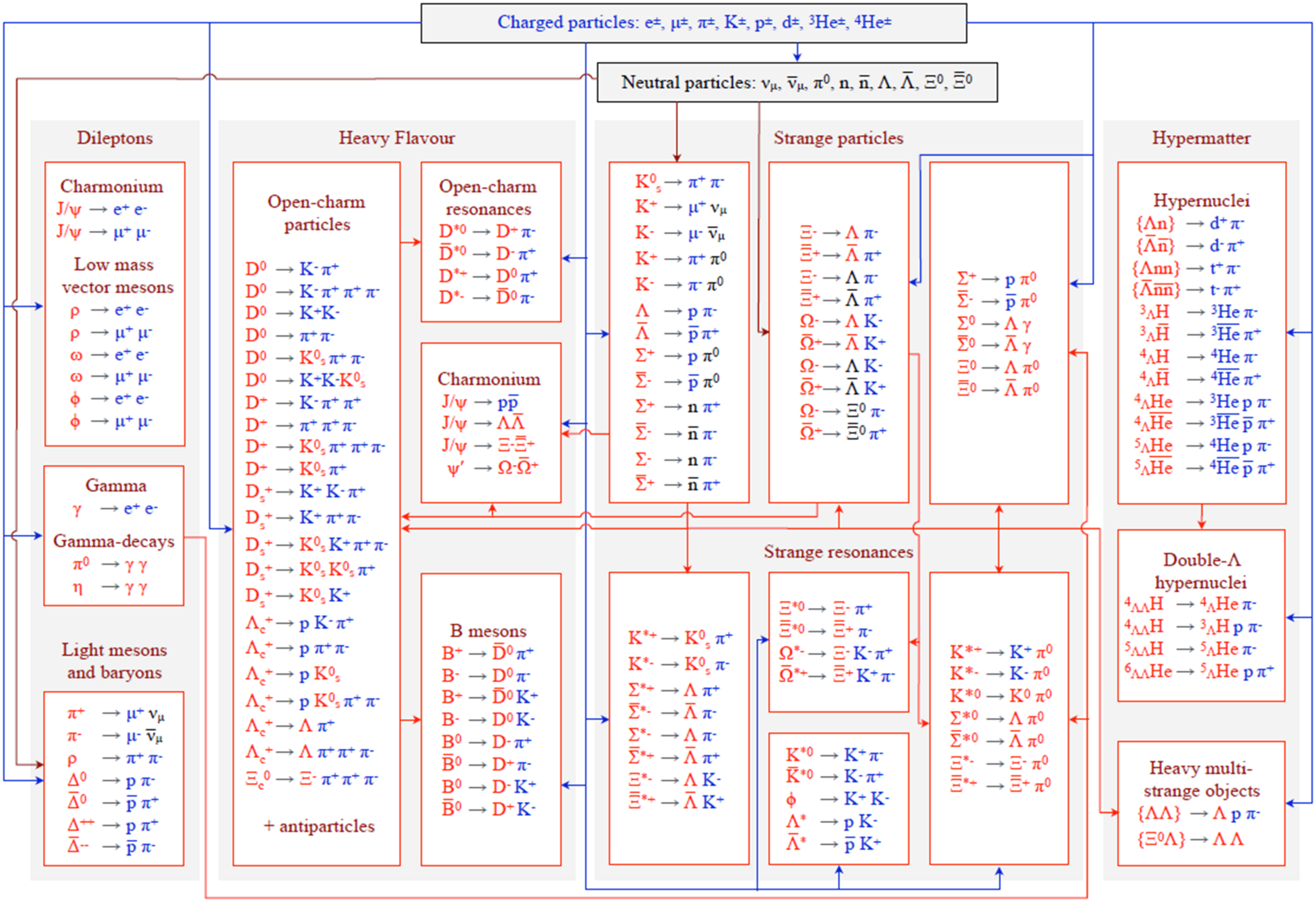
10 MHz Au+Au, 10 AGeV,
300k mbias UrQMD events, ideal PID



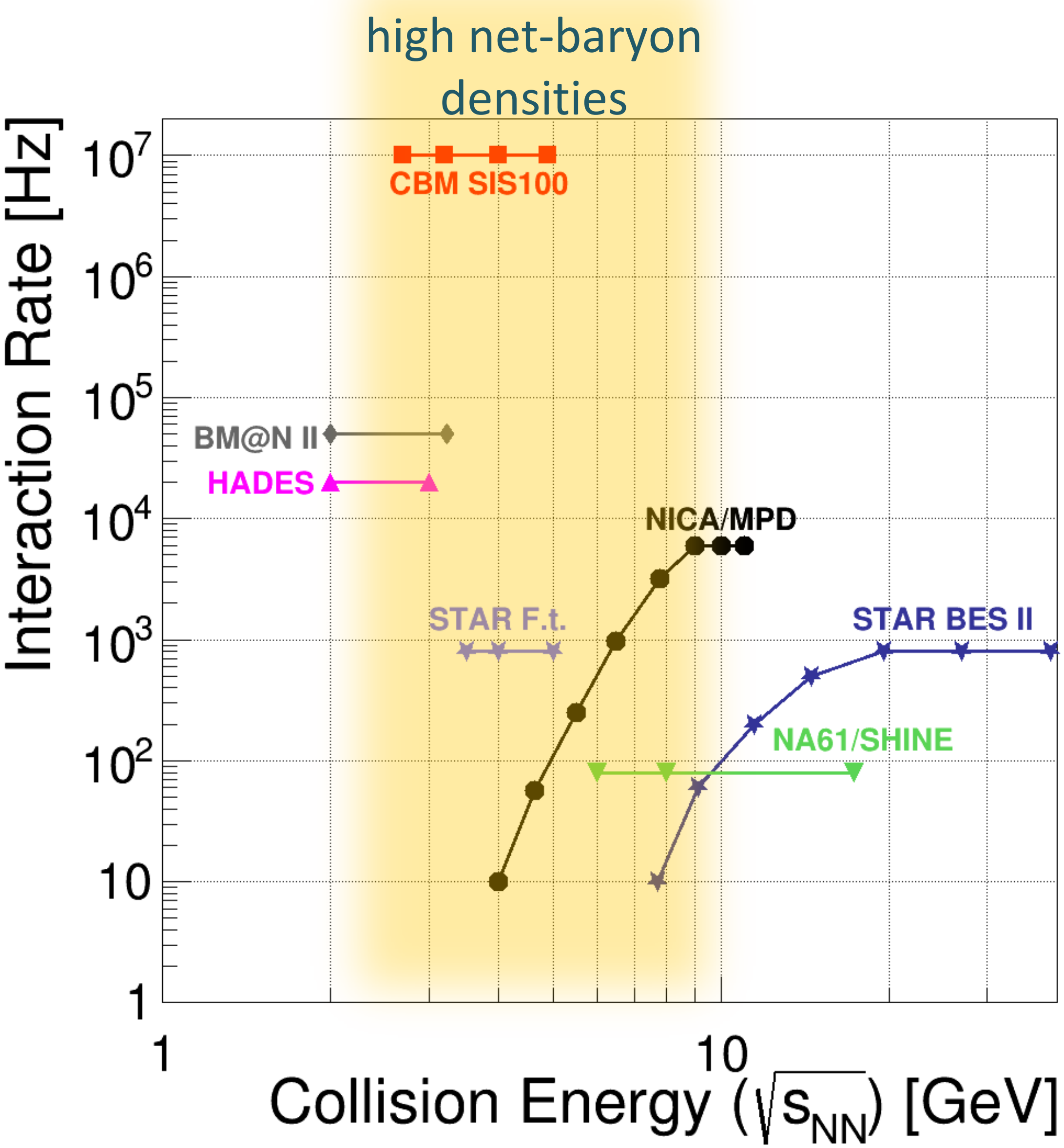
		K^0s	Λ	$\bar{\Lambda}$	Ξ^-
3 D	ε_{method}, %	68.6	61.2	67	46.7
	$\varepsilon_{4\pi}$, %	20.7	19.4	28	10.5
	S/B	10.6	23.7	12.7	21.8
0.1 MHz	ε_{method}, %	68.5	62.0	62	45.2
	$\varepsilon_{4\pi}$, %	21.1	20.6	32	11.7
	S/B	9.8	12.9	10	14.2
1 MHz	ε_{method}, %	67.5	60.9	59	46.0
	$\varepsilon_{4\pi}$, %	19.4	18.7	26	10.6
	S/B	9.3	12.5	10	12.3
10 MHz	ε_{method}, %	66.8	60.0	64	41.8
	$\varepsilon_{4\pi}$, %	17.6	16.7	28	8.2
	S/B	9.2	12.2	8	11.7

all mother particles emitted from one primary vertex

Online particle identification in CBM: The KF Particle Finder



Experiments exploring dense QCD matter



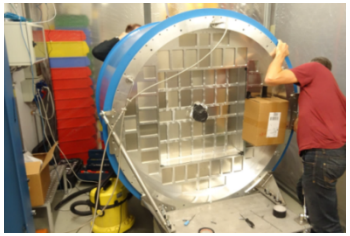
Complementary approaches towards the study of dense baryonic matter, but joint technical developments:

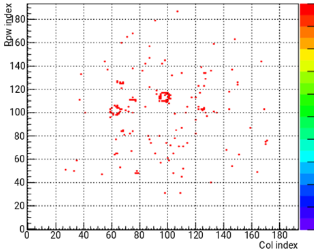
- CBM photon detector used in HADES
- CBM TOF detector and reconstruction software used in STAR
- Foreward calorimeters for CBM and NA61/SHINE
- Silicon detector and software developments for NICA

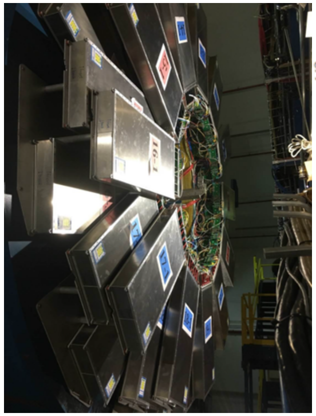
T. Ablyasimov et al., (CBM Collaboration) Eur. Phys. J. A 53 (2017) 60

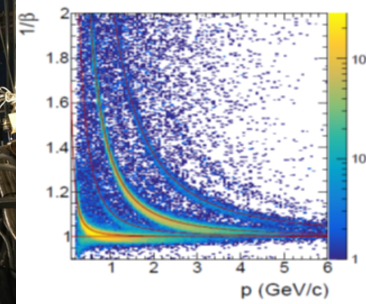
CBM „phase 0“ experiments on dense QCD matter

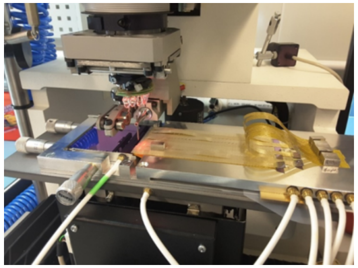
1. CBM RICH photon detector: 430 out of 1100 multi-anode photo-multipliers (MAPMT) installed in HADES experiment and used for physics runs
2. CBM TOF detector: 10% of the CBM TOF modules including read-out chain installed and used at STAR/RHIC (BES II 2019/2020)
3. Four Silicon Tracking Stations and a Projectile Spectator Detector will be installed in the BM@N experiment at the Nuclotron in JINR/Dubna (start 2022 with Au-beams up to 4.5A GeV)
4. miniCBM experiment installed at GSI/SIS18 and commissioned with beam for a full system test with high-rate nucleus-nucleus collisions from 2020 - 2023





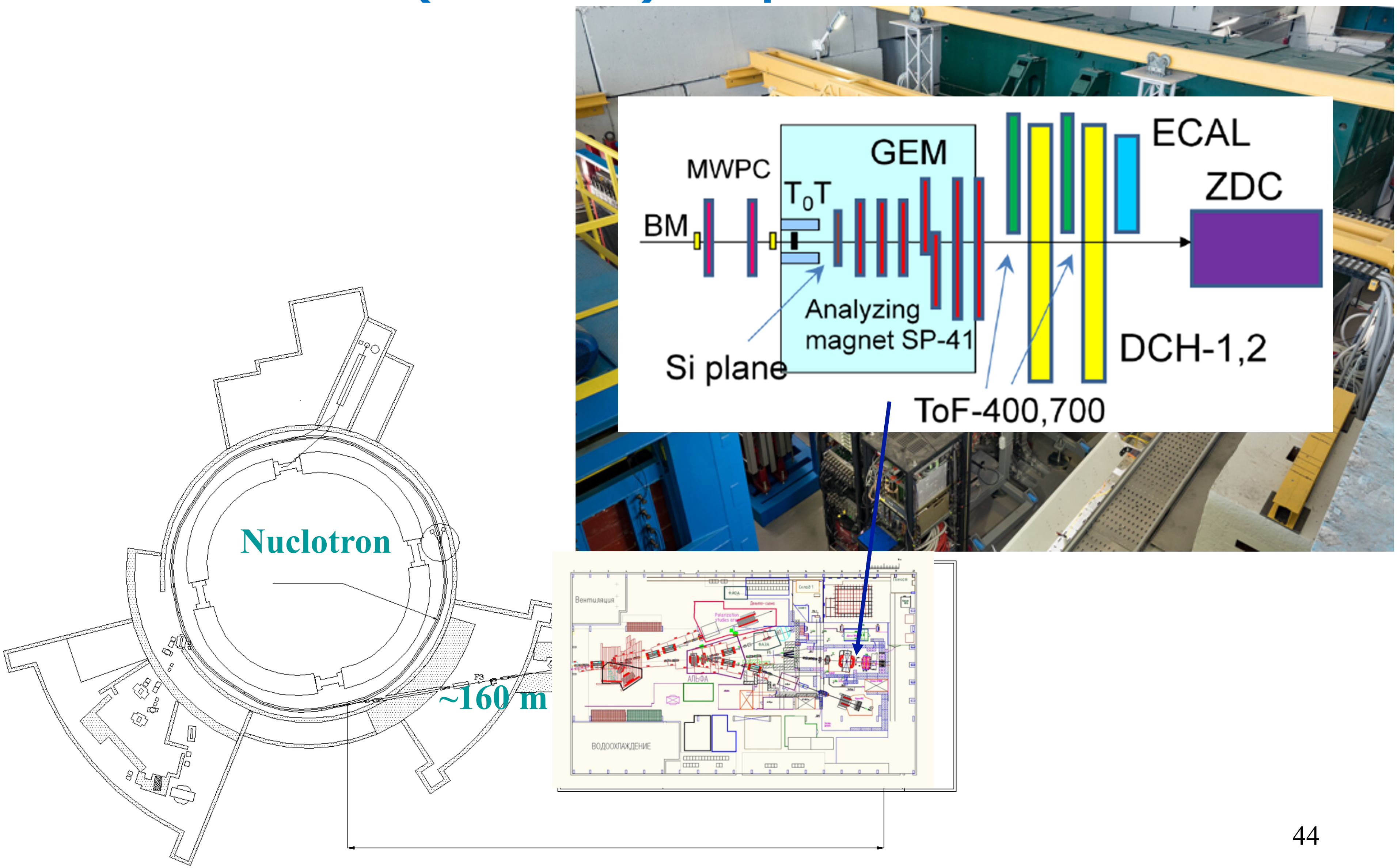




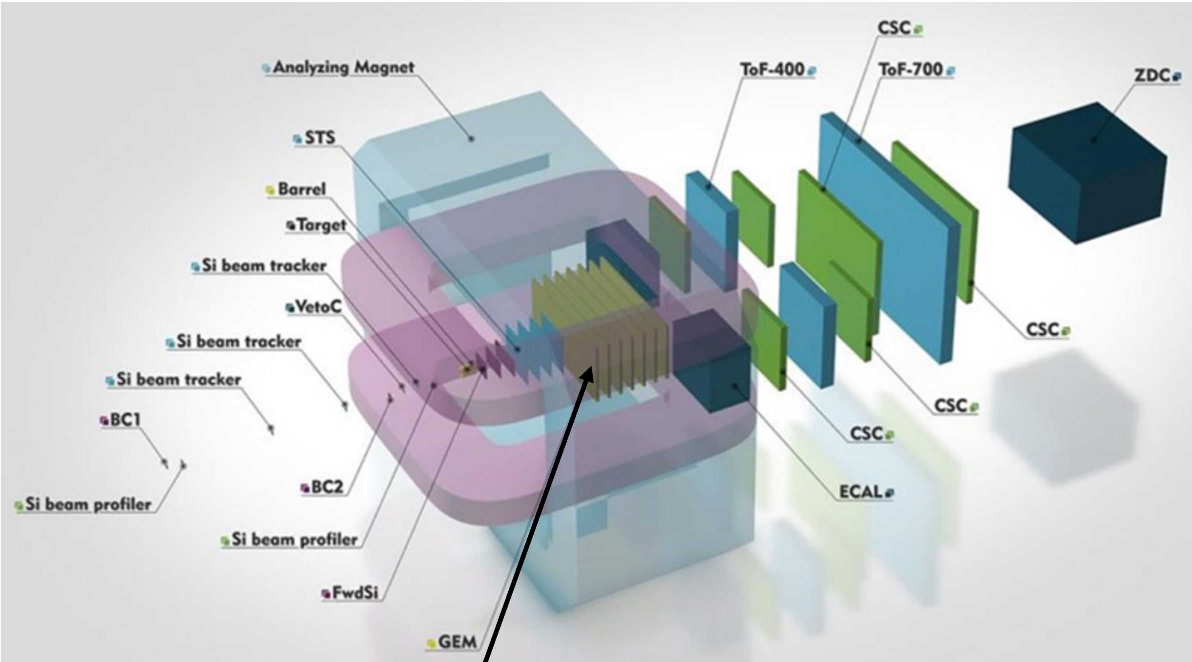


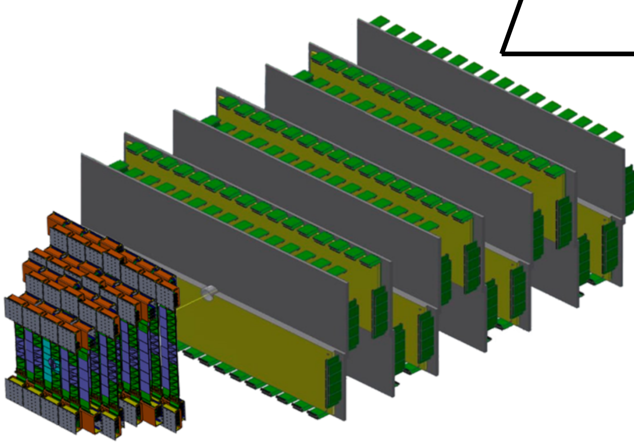
FAIR and NICA

The Baryonic Matter at Nuclotron (BM@N) experiment



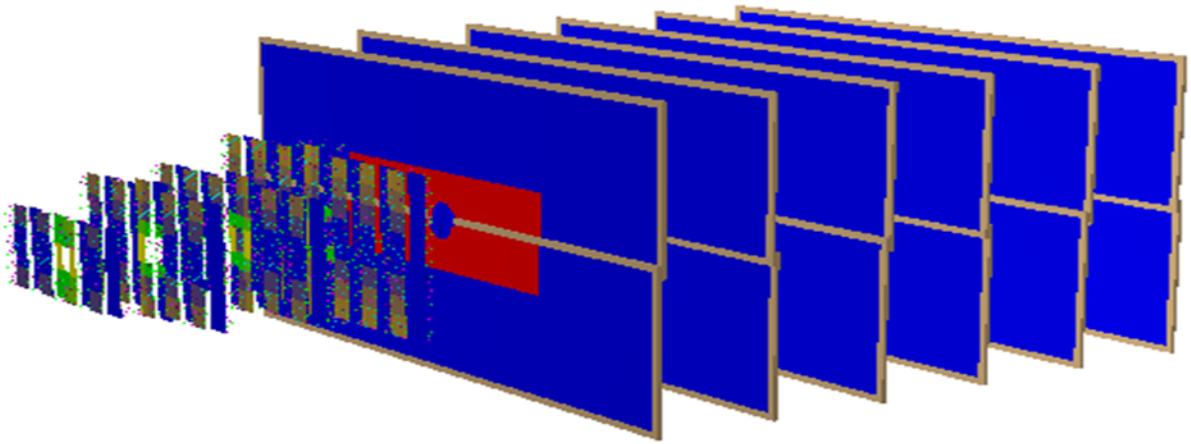
BM@N upgrade for Au+Au collisions up to 4.5A GeV





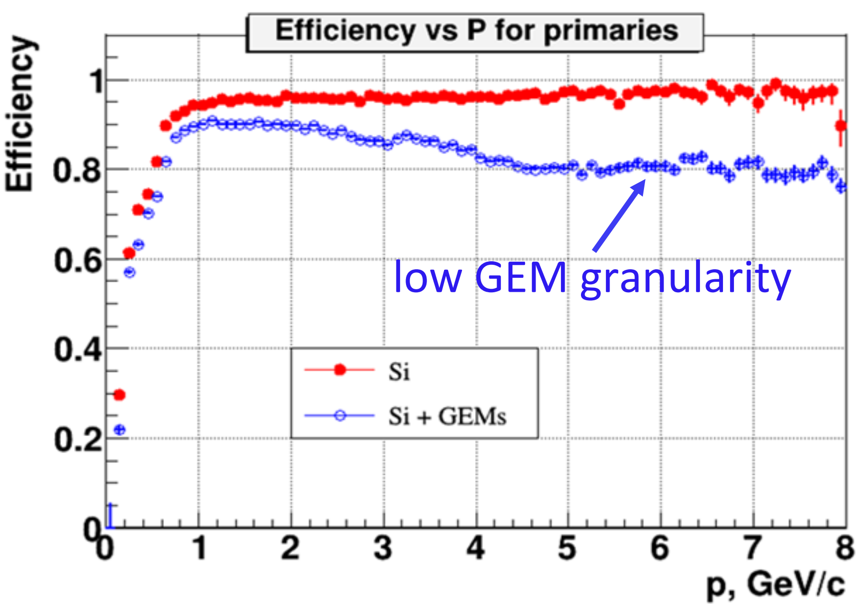
The hybrid tracking system:
4 stations double-sided micro-strip silicon sensors
7 stations Gas-Electron-Multiplier (GEM) chambers

BM@N upgrade for Au+Au collisions

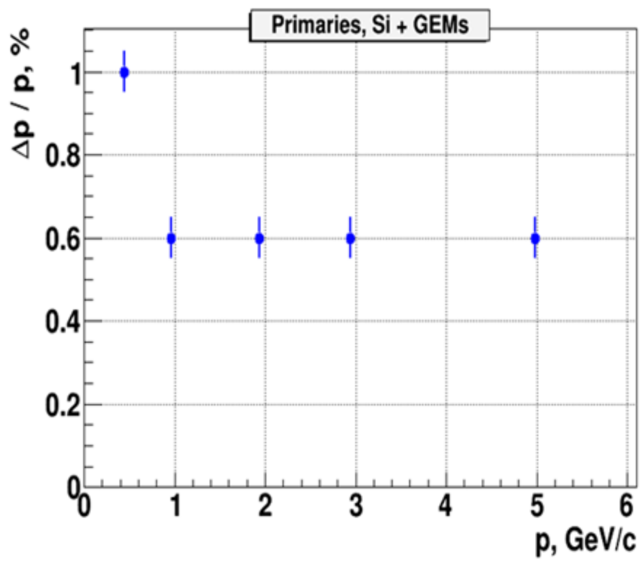


central Au+Au collisions at 4A GeV (QGSM generator)

track reconstruction efficiency



momentum resolution



Joint development of instrumentation for NICA and FAIR/CBM

Grant 5.6 M€ over 4 years for manpower (starting 2020)

Task	Partners
Integration, installation, and test of Silicon Trackers for NICA and CBM	JINR Dubna, FAIR/GSI, Univ. Tübingen
Developments for the data acquisition chain, for data preprocessing and computing procedures	JINR Dubna, FAIR/GSI, WUT Warsaw
Development of common software packages for simulation and data analysis, participation in physics performance studies	JINR Dubna, FAIR/GSI, MEPhI, Wigner Inst. Budapest
Development and construction of beam monitors, target chamber, beam pipe for NICA and CBM	JINR Dubna, FAIR/GSI
Development and construction of Zero Degree Calorimeters for NICA and CBM	INR Moscow, NRI-CAS Prague
Develop a beyond state of the art CMOS pixel sensors (MAPS) for high-rate Silicon trackers	JINR Dubna, FAIR/GSI, Univ. Frankfurt, KINR Kiev, IPHC Strasbourg,


October 2019

The CBM Collaboration: 58 institutions, > 460 members

China:
CCNU Wuhan
Tsinghua Univ.
USTC Hefei
CTGU Yichang
Chongqing Univ.
IMP Lanzhou

Czech Republic:
CAS, Rez
Techn. Univ. Prague

France:
IPHC Strasbourg

Hungary:
KFKI Budapest
Eötvös Univ.

Germany:
Darmstadt TU
FAIR
Frankfurt Univ. IKF
Frankfurt Univ. FIAS
Frankfurt Univ. ICS
GSI Darmstadt
Giessen Univ.
Heidelberg Univ. P.I.
Heidelberg Univ. ZITI
HZ Dresden-Rossendorf
KIT Karlsruhe
Münster Univ.
München TU
Tübingen Univ.
Wuppertal Univ.
ZIB Berlin

India:
Aligarh Muslim Univ.
Bose Inst. Kolkata
Panjab Univ.
Rajasthan Univ.
Univ. of Jammu
Univ. of Kashmir
Univ. of Calcutta
B.H. Univ. Varanasi
VECC Kolkata
IOP Bhubaneswar
IIT Kharagpur
IIT Indore
Gauhati Univ.

Japan:
KEK Tsukuba

Korea:
Pusan Nat. Univ.

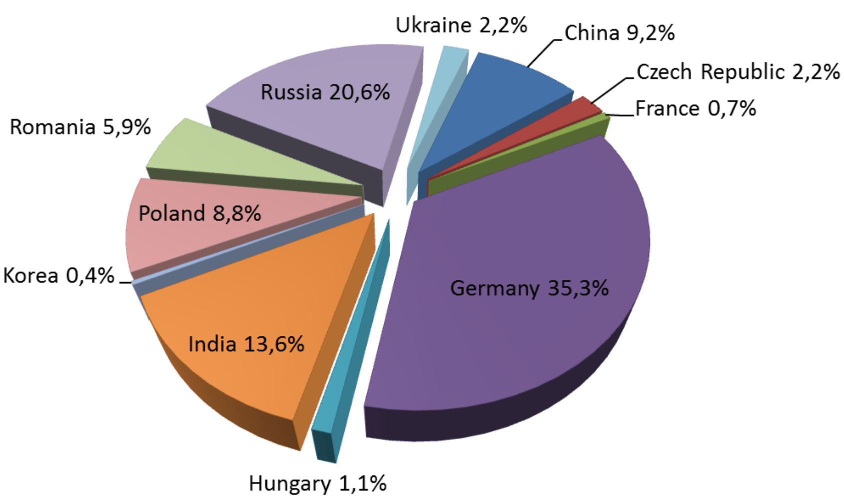
Poland:
AGH Krakow
Jag. Univ. Krakow
Warsaw Univ.
Warsaw Univ. Tech.

Romania:
NIPNE Bucharest
Univ. Bucharest

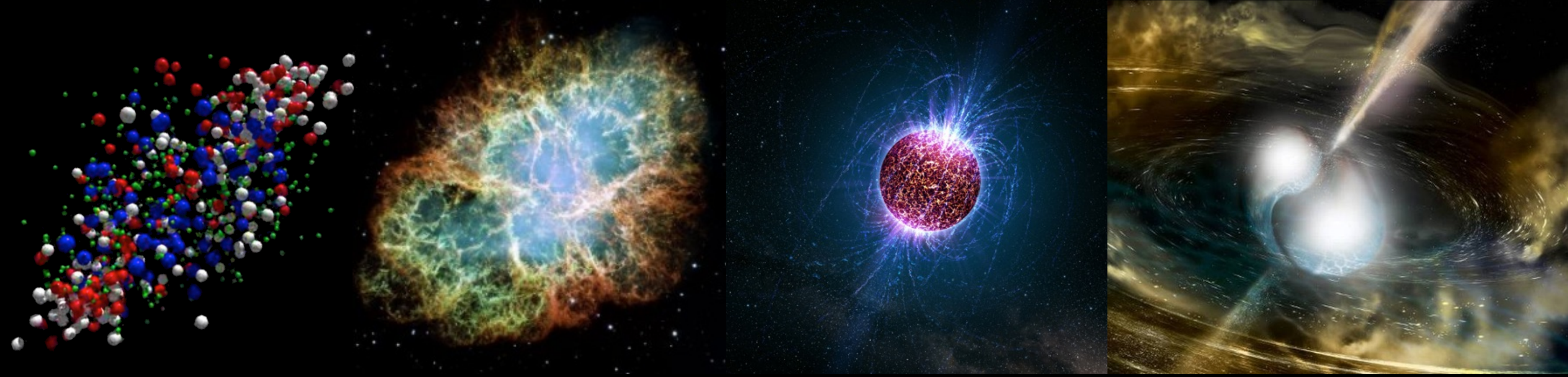
Russia:
IHEP Protvino
INR Troitzk
ITEP Moscow
Kurchatov Inst., Moscow
VBLHEP, JINR Dubna
LIT, JINR Dubna
MEPHI Moscow
PNPI Gatchina
SINP MSU, Moscow

Ukraine:
T. Shevchenko Univ. Kiev
Kiev Inst. Nucl. Research

CBM Scientists



30th CBM Collaboration meeting Sept. 2017, CCNU, Wuhan, China



Summary

- The goal of the CBM experiment at FAIR is to explore fundamental properties of dense QCD matter by measuring multi-differential observables (hadrons and leptons) with unprecedented precision. First beams of Au ions up to 11A GeV are expected in 2025.

- The BMN experiment at NICA offers the opportunity to prototype the CBM silicon tracking system, and to start the investigation of dense nuclear matter produced in Au+Au collisions at beam energies of up to 4.5A GeV in 2023.