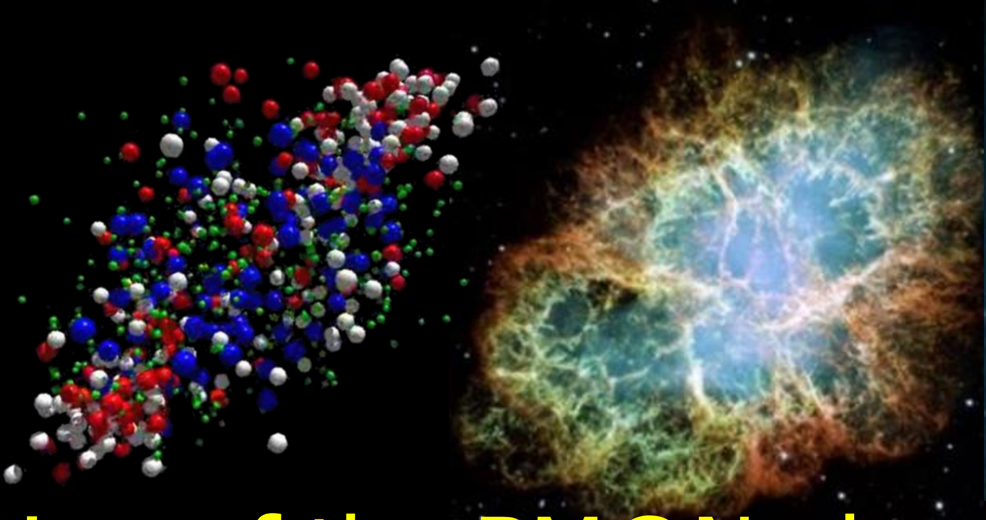
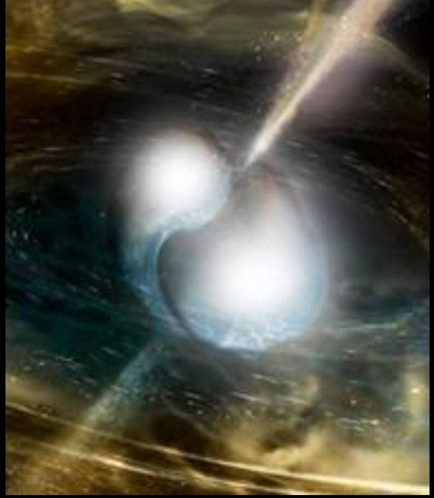




Review of the BM@N physics and upgrade program

Peter Senger

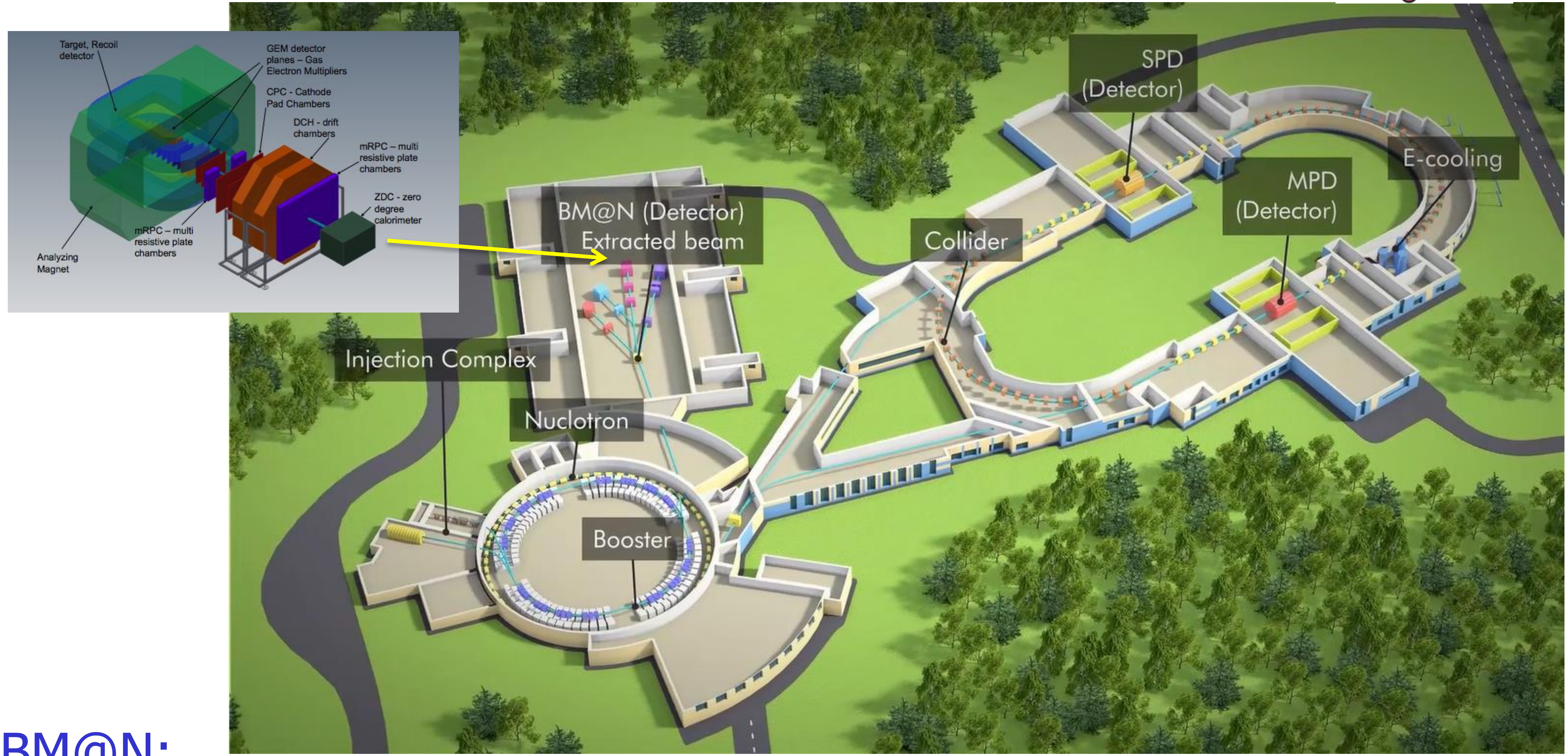
Outline:
- BM@N status quo
- The future heavy-ion research program:
  Investigating nuclear matter at neutron star core densities
- Upgrading the BM@N detector system

Conference on RFBR Grants for NICA, 20 – 23 October 2020, JINR, Dubna, Russia

FAIR GSI | GOETHE UNIVERSITÄT FRANKFURT AM MAIN | MEPhI | CENTRAL CHINA NORMAL UNIVERSITY | CREMLIN PLUS Connecting Russian and European Measures for Large-scale Research Infrastructures

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 871072

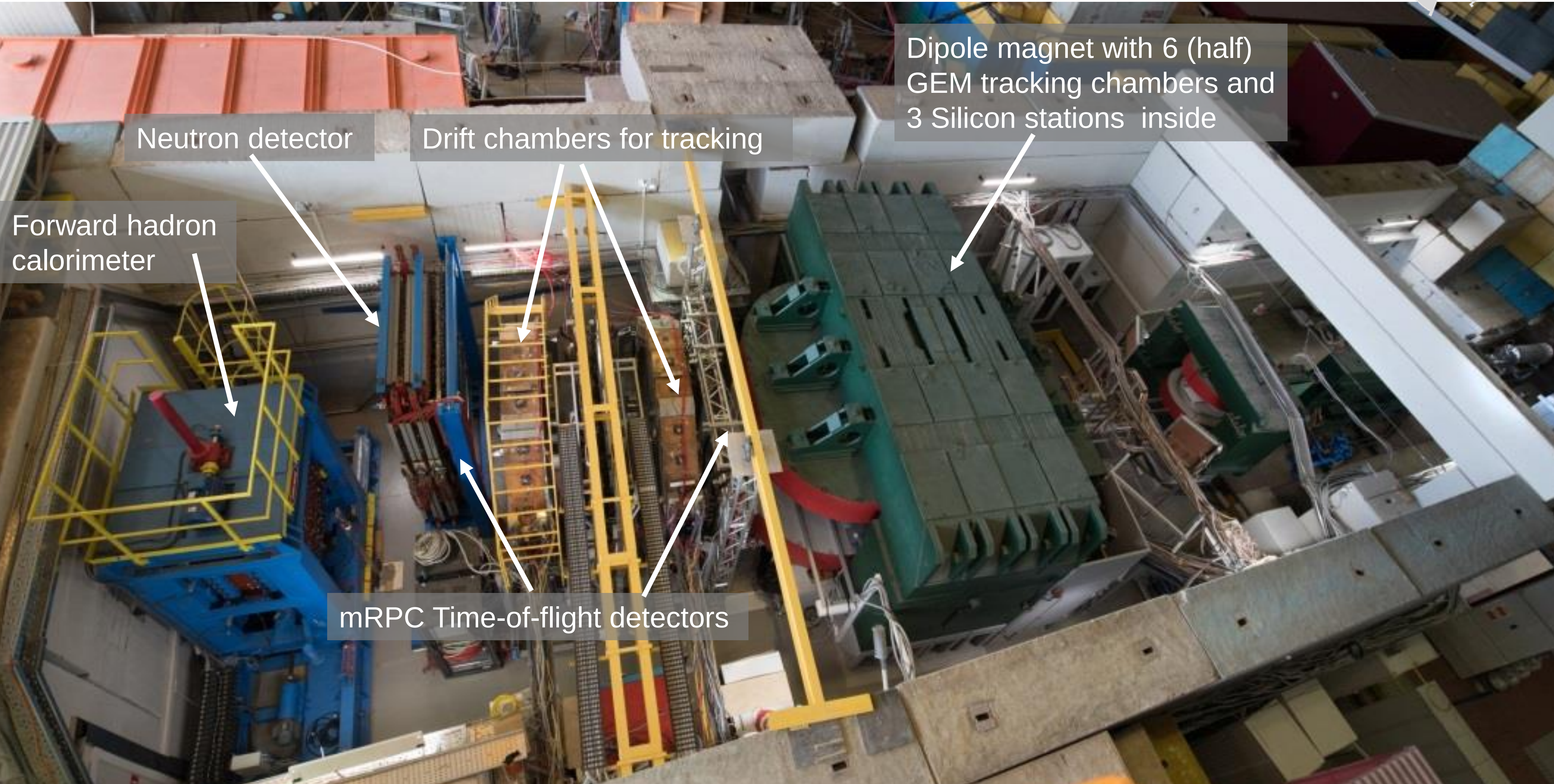
NICA Heavy Ion Complex



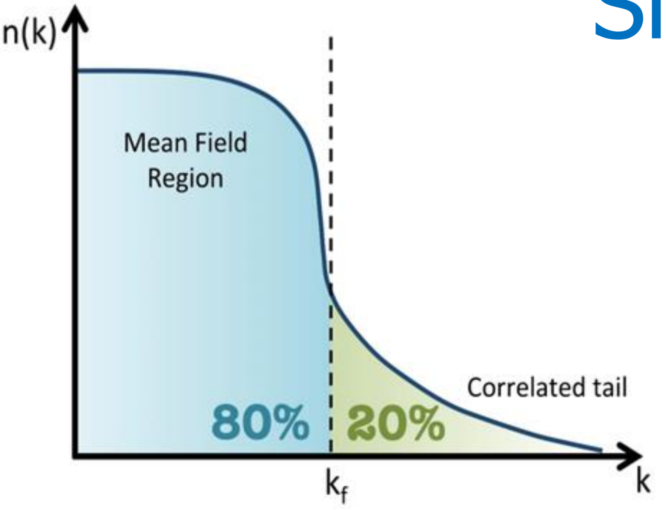
BM@N:

beams from p to Au, heavy ion energy 1- 3.8 GeV/n (17 kG Nuclotron magnets), Au intensity ~ few 10^6 Hz

Baryonic Matter at Nuclotron (BM@N) Experiment



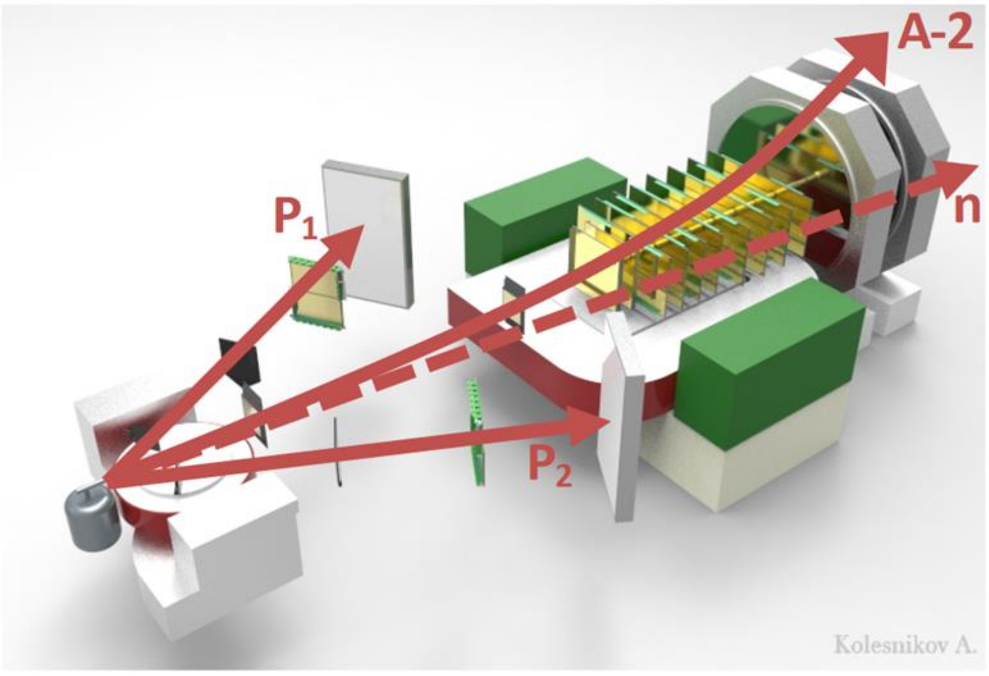
Experiments performed at BM@N: Short-Range Correlations (SRC)



$k<k_F$ Mean field region: Single nucleons

$k>k_F$ High momentum region: Correlated pairs of nucleons, which are close together in spa relative momentum, but a low c.m. mome to the Fermi momentum k_F. SRC probe nu partonic degrees-of-freedom in nuclear sy

See talk by Maria Patsyuk on Wednesday 21.Oct.2020 and talks by Sergei Merts, Valeri Panin, and Yuri Uzikov on Thursday, 22. Oct. 2020



Experiment at BM@N with a 4A GeV C-beam:

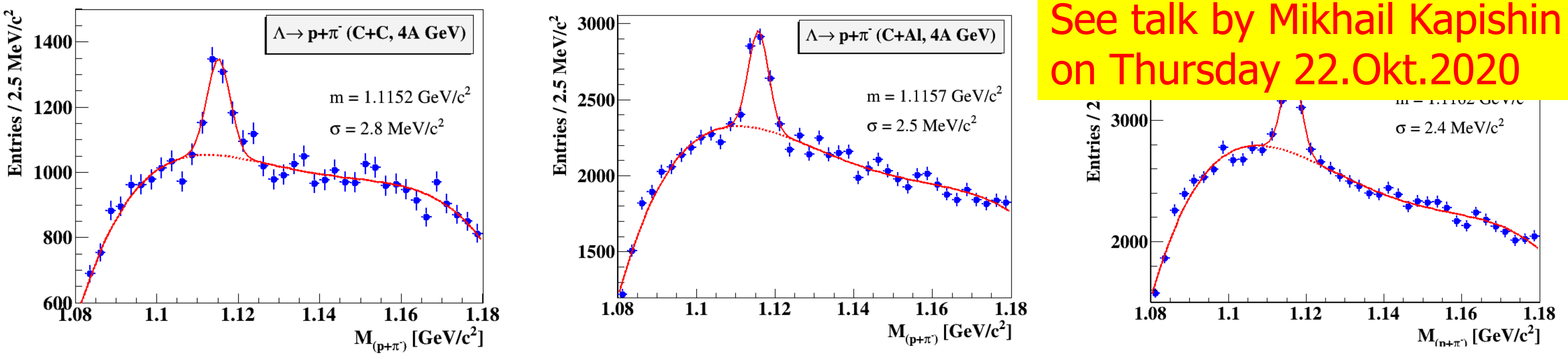
$^{12}C + p \rightarrow 2p + {}^{10}_{5}B + n$ (np SRC)

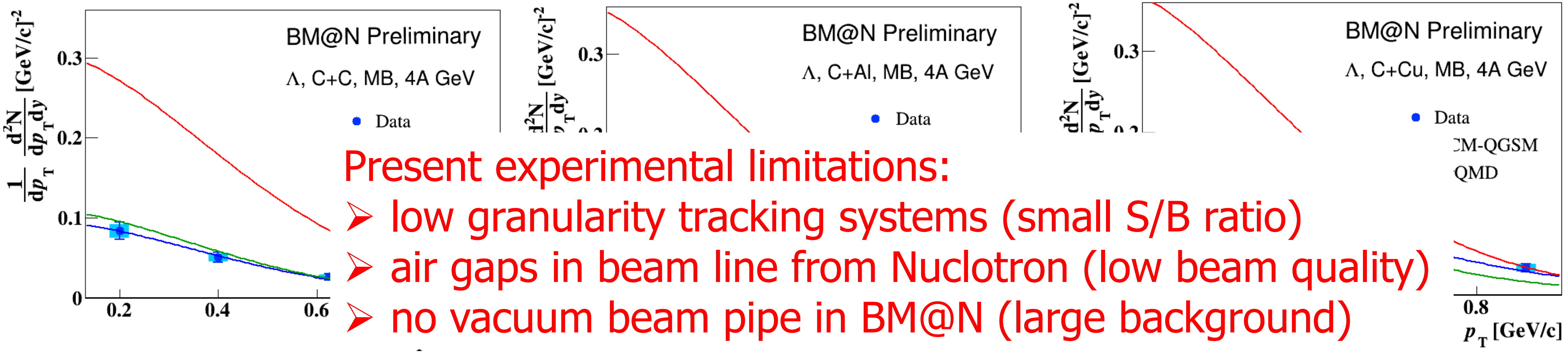
$^{12}C + p \rightarrow 2p + {}^{10}_{4}Be + p$ (pp SRC)

First fully exclusive measurement in inverse kinematics probing the residual A-2 nuclear system!

Experiments performed at BM@N: Lambda production in C + C, Al, Cu collisions at 4A GeV

See talk by Mikhail Kapishin on Thursday 22.Okt.2020

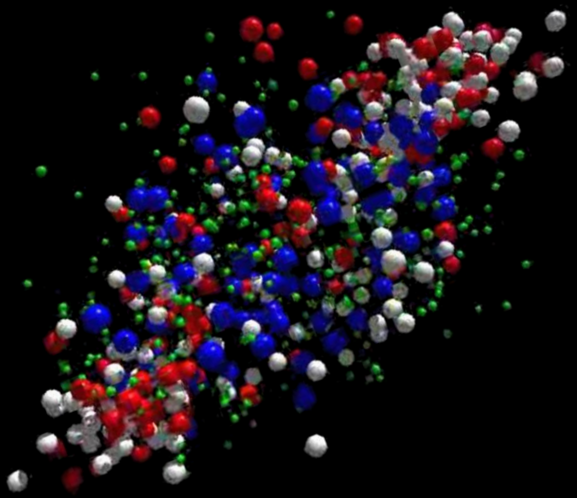


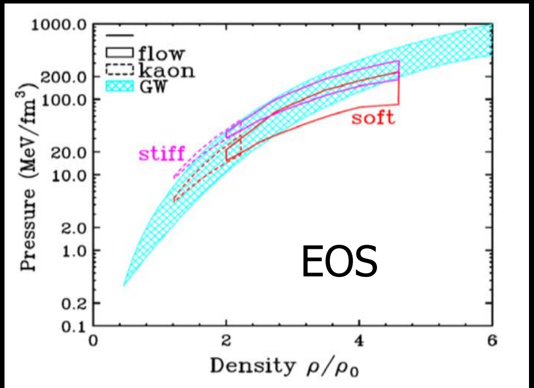


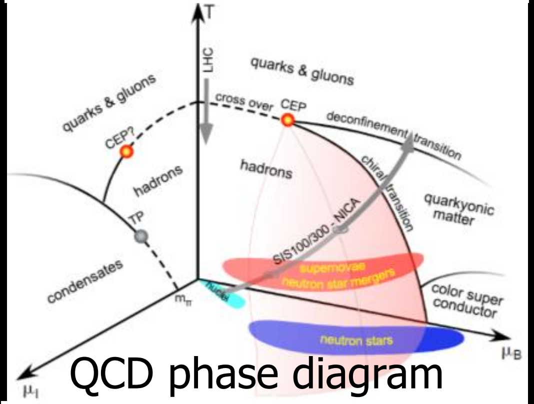
Present experimental limitations:

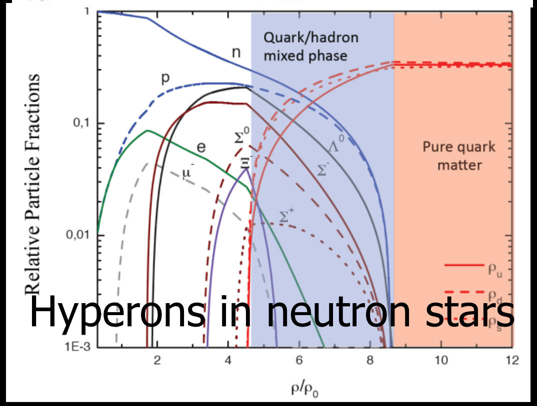
- ➢ low granularity tracking systems (small S/B ratio)
- ➢ air gaps in beam line from Nuclotron (low beam quality)
- ➢ no vacuum beam pipe in BM@N (large background)

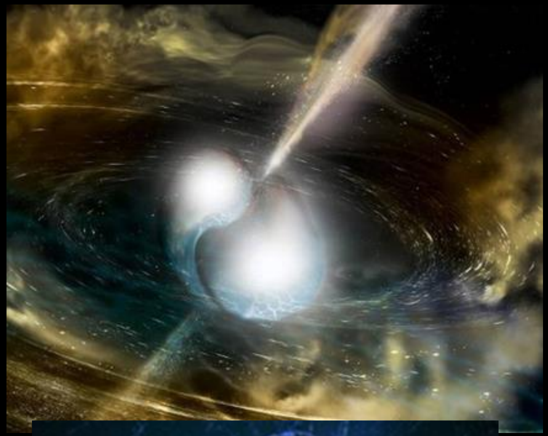
Upgrading the BM@N experiment:
Exploring nuclear matter at neutron star core densities

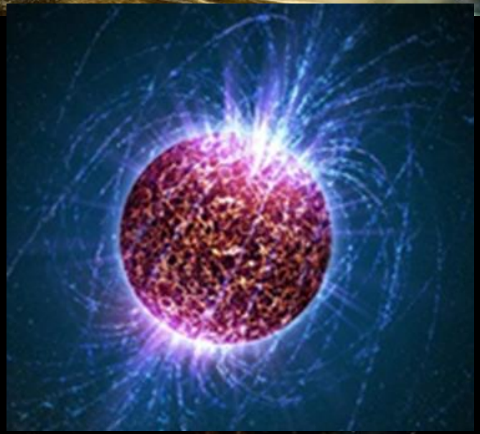




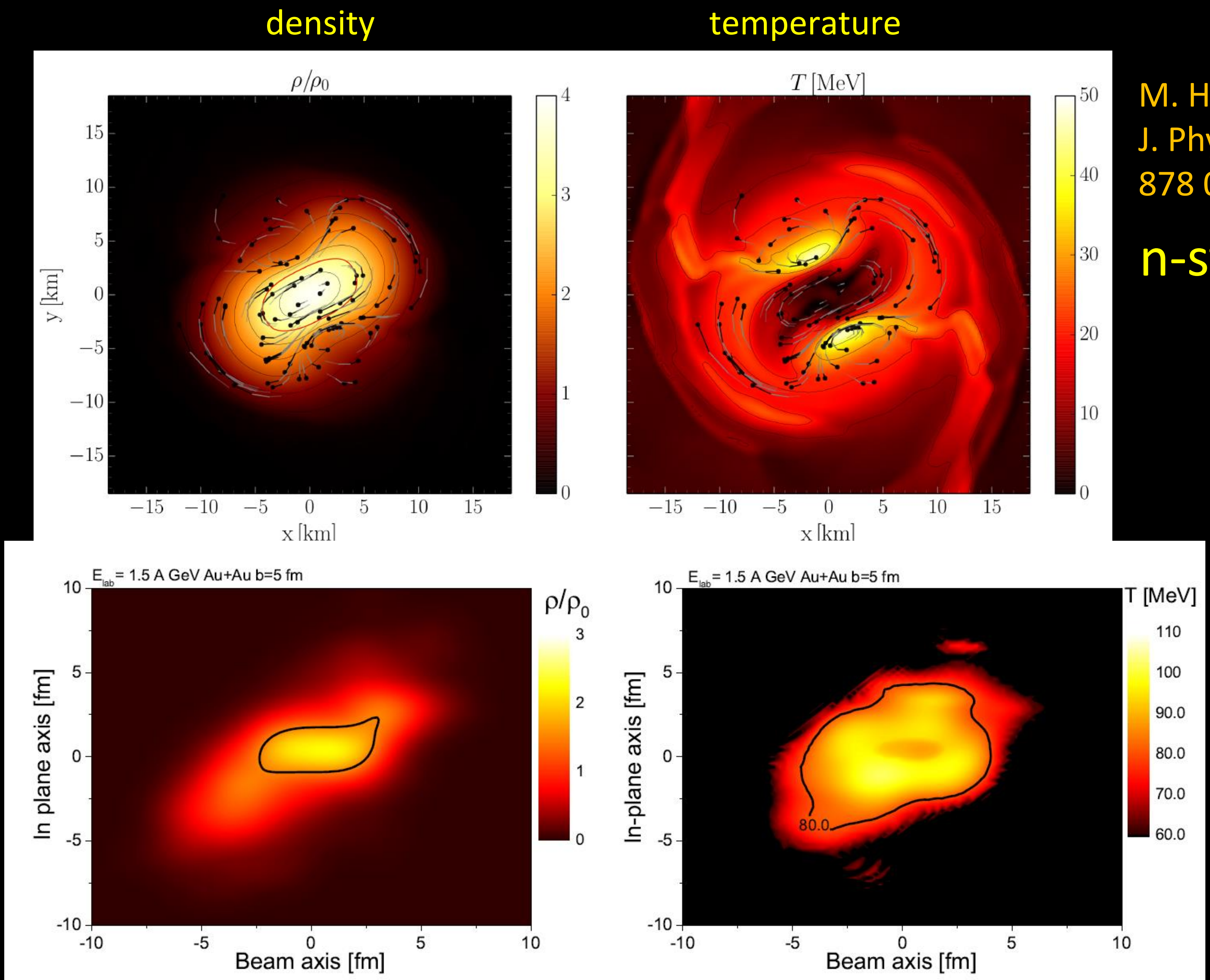






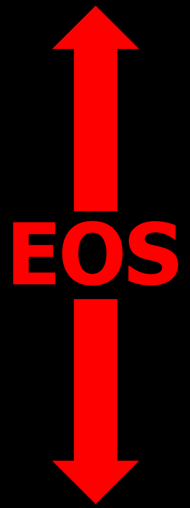


Neutron star mergers and heavy-ion collisions



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

n-star merger



Au +Au
1.5A GeV

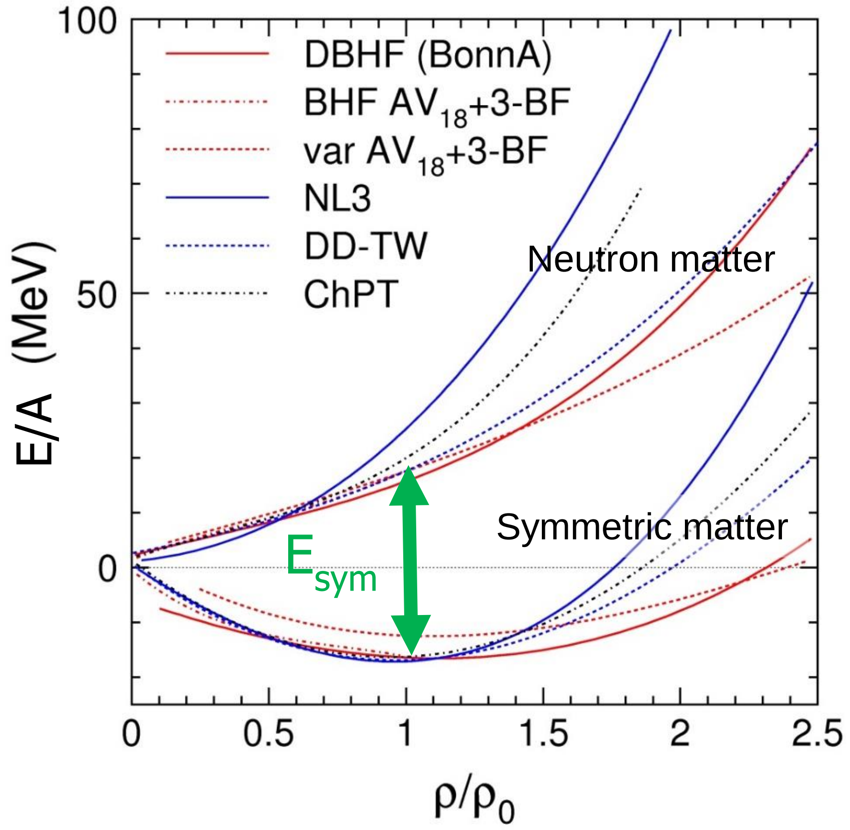
The nuclear matter equation-of-state

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

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

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

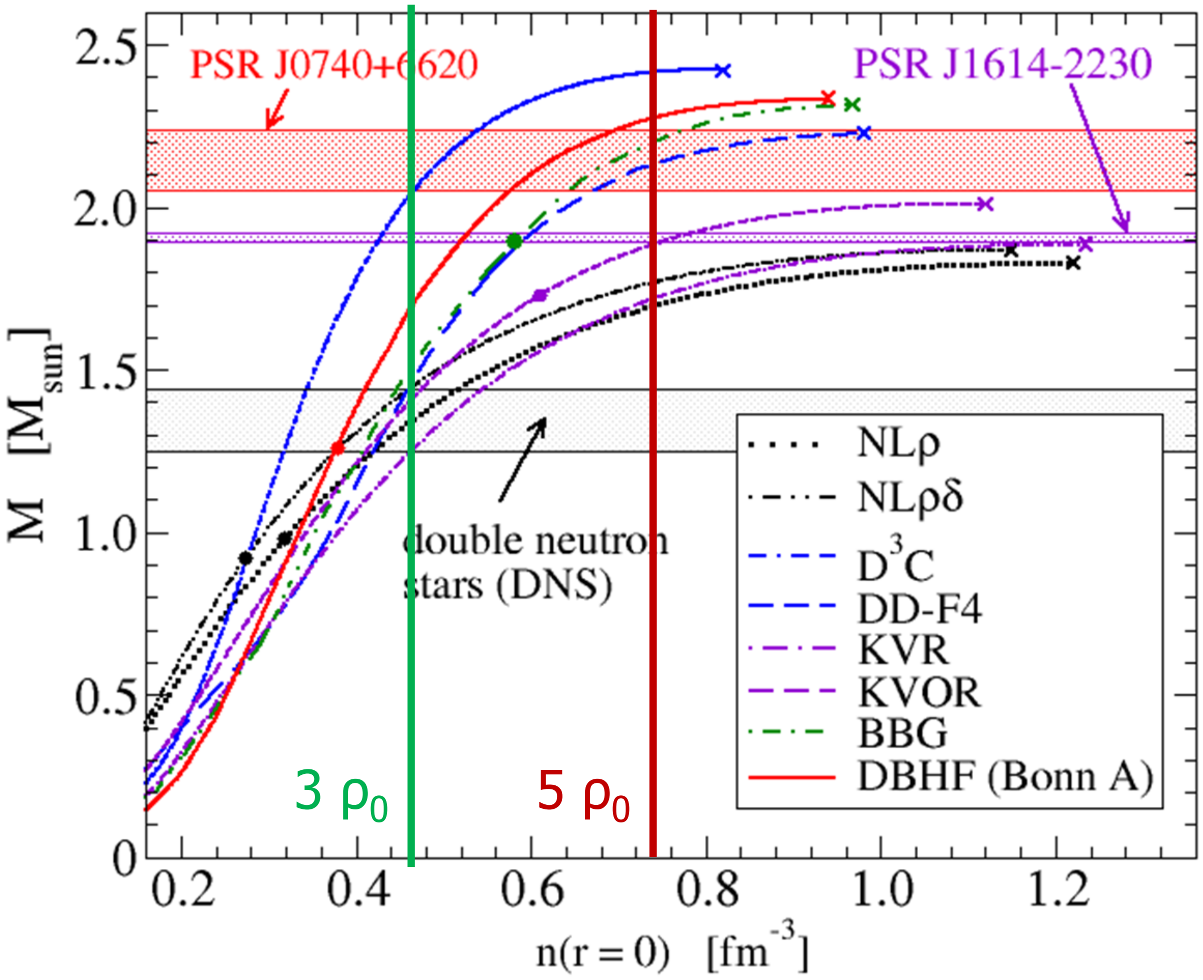
Ch. Fuchs and H.H. Wolter, EPJA 30 (2006) 5



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)

Mass-density relation of neutron stars for different EOS



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

PSR J0348+0432
$M = 2.01 \pm 0.04\ M_{sun}$
J. Antoniadis et al.,
Science ***340***, *6131 (2013)*

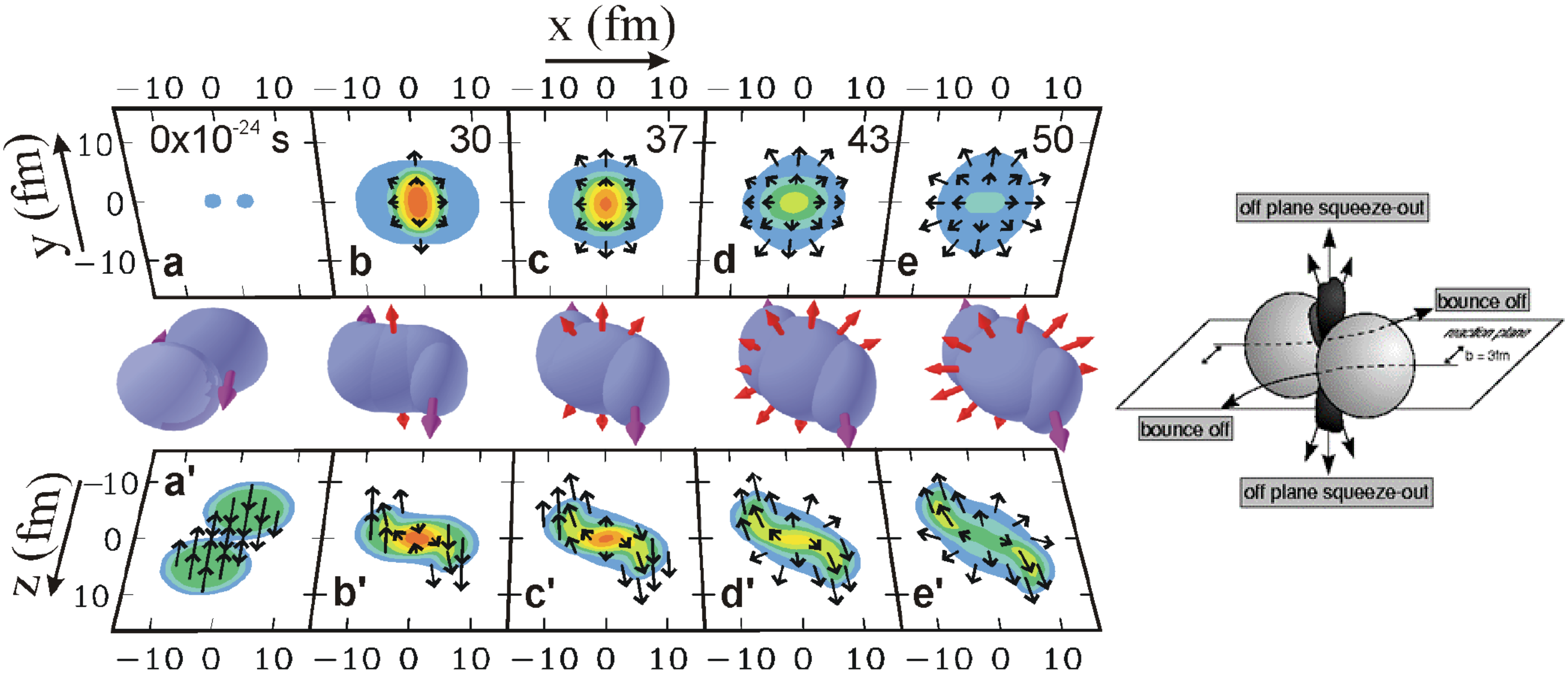
PSR J1614-2230
$M = 1.97 \pm 0.04\ M_{sun}$
P. Demorest et al.,
Nature 467, 1081 (2010)

EOS for $\rho > 3\text{-}4\ \rho_0$!

T. Klaehn et al., Phys. Rev. C74: 035802, 2006. Update by D. Blaschke, priv. comm.

Observable in heavy-ion collisions: Collective flow of nucleons

semi-central Au+Au collision at 2 AGeV

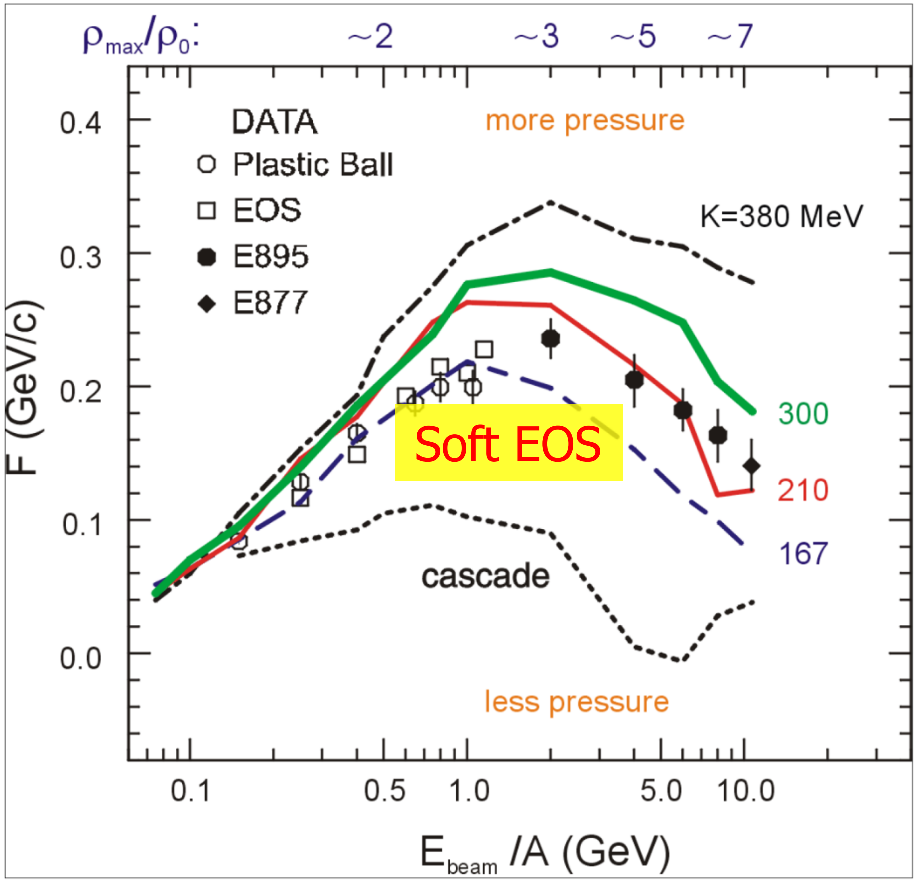


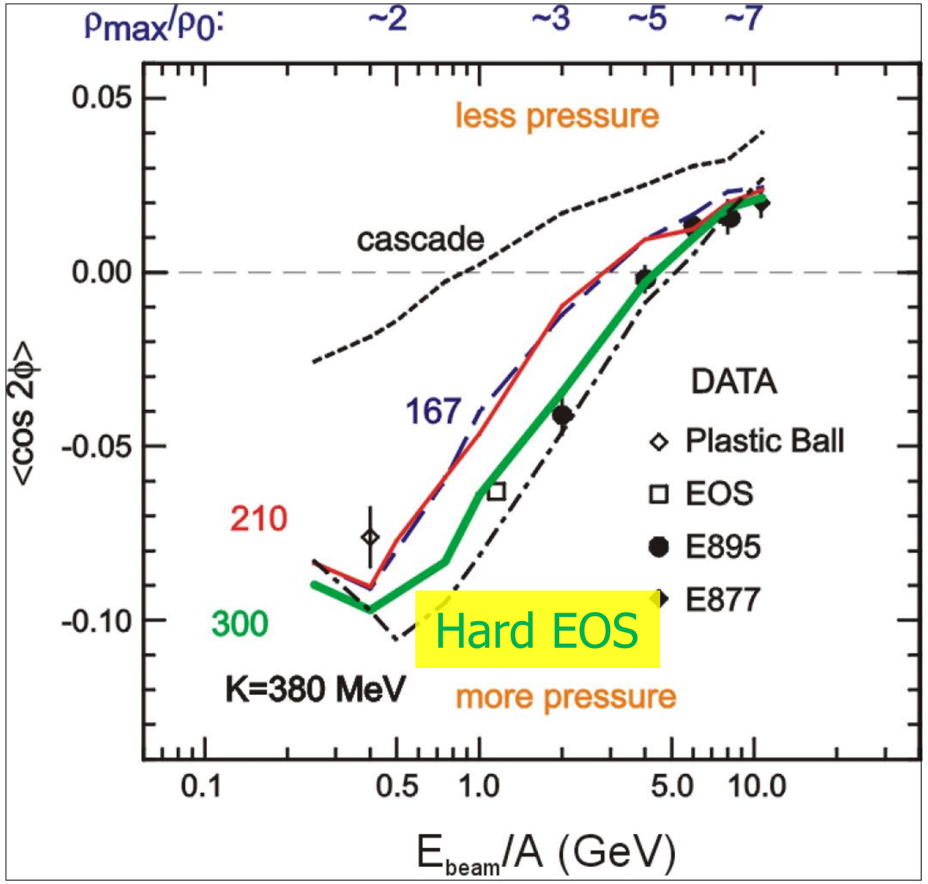
Collective flow of nucleons: driven by pressure gradient in the fireball

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

Nuclear incompressibility from collective proton flow

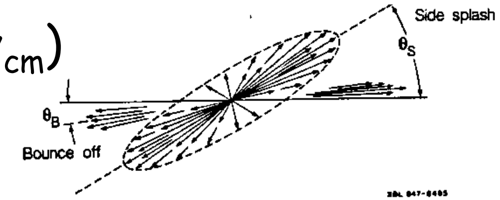
P. Danielewicz, R. Lacey, W.G. Lynch, Science 298 (2002) 1592



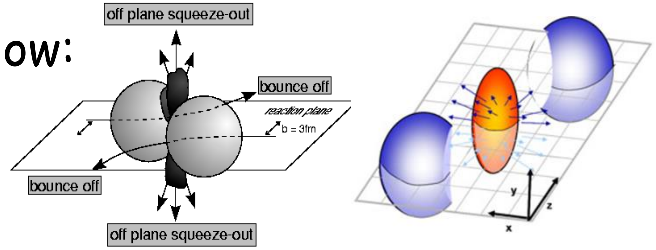


Transverse in-plane flow:

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

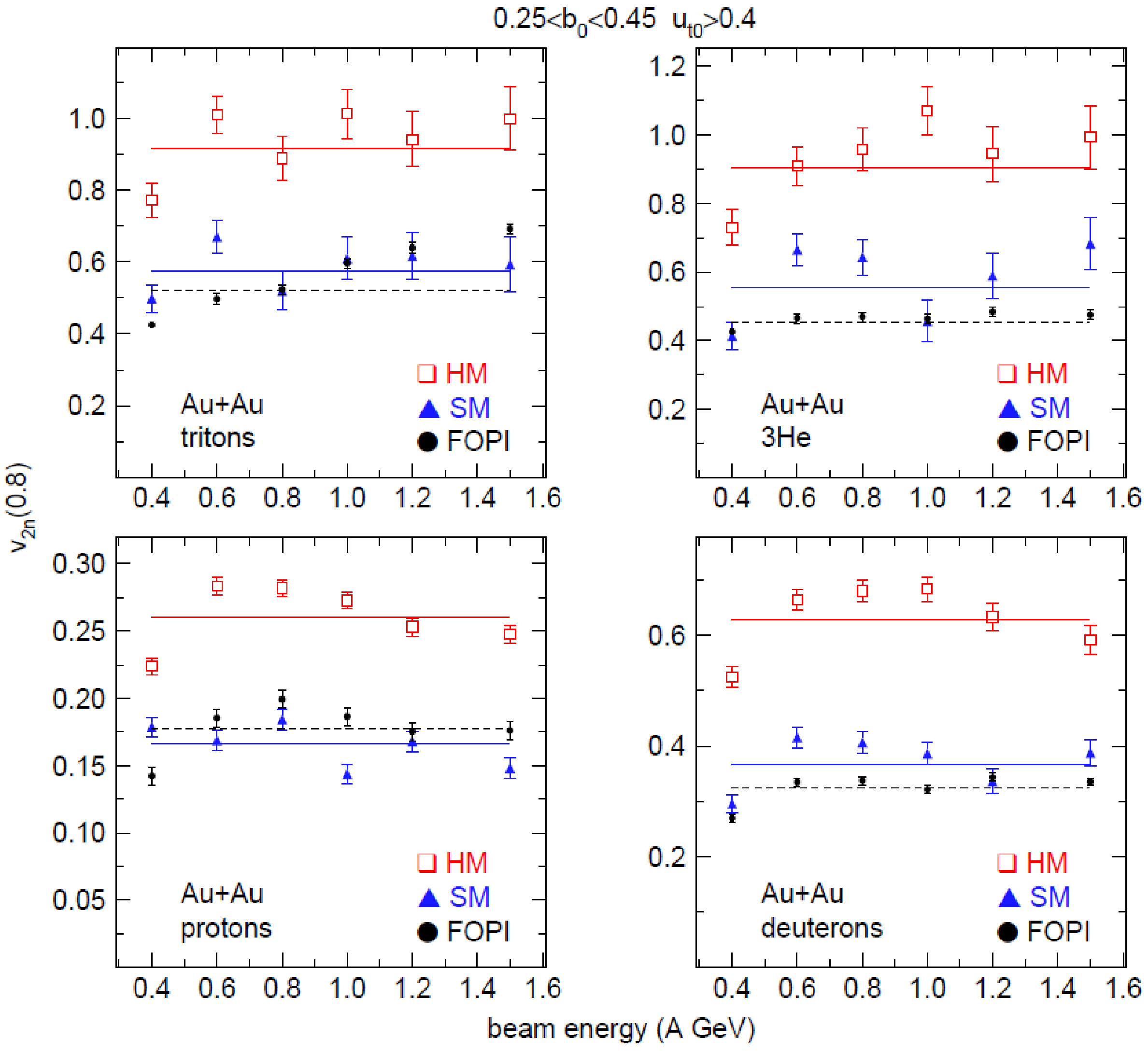


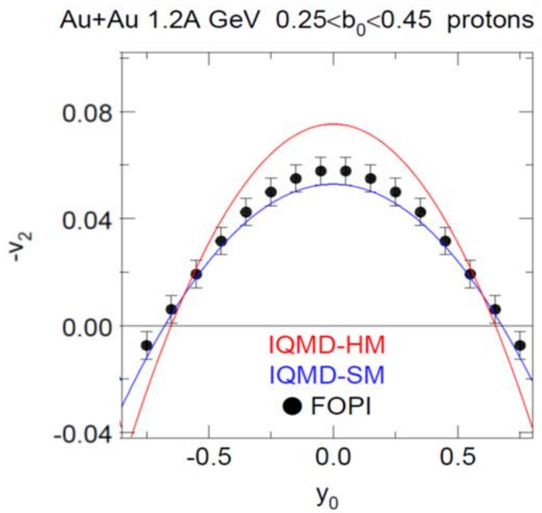
Elliptic flow:

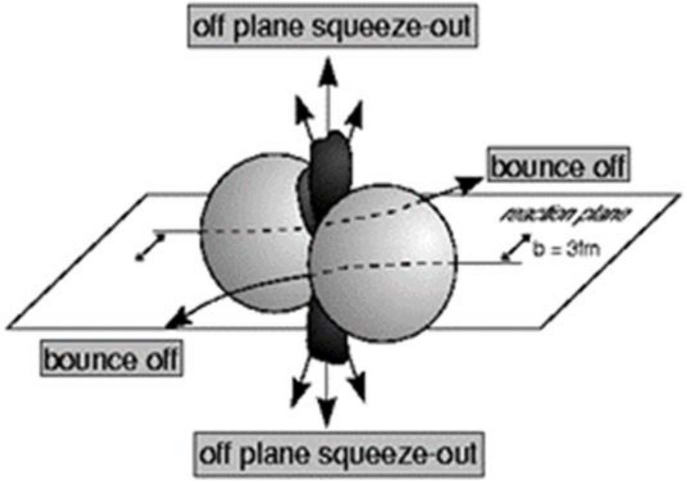


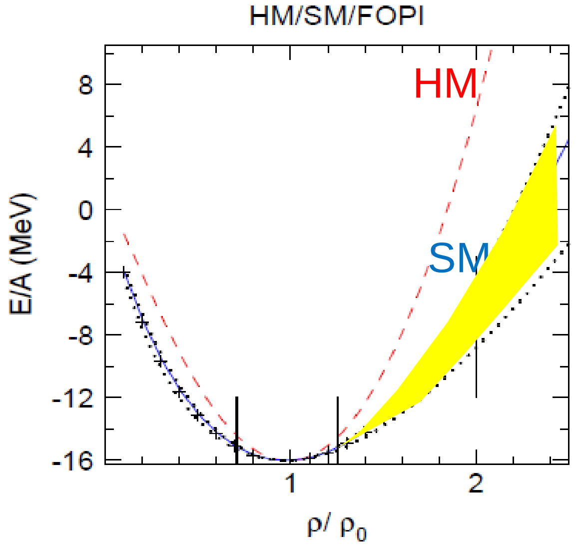
$dN/d\Phi \propto (1 + 2v_1 \cos\Phi + 2v_2 \cos 2\Phi)$

FOPI at GSI: EOS from the elliptic flow of fragments in Au+Au collisions at SIS18 energies ($\rho < 2.5\rho_0$)









Hard Momentum-dependent
HM: K_{nm} = 380 MeV

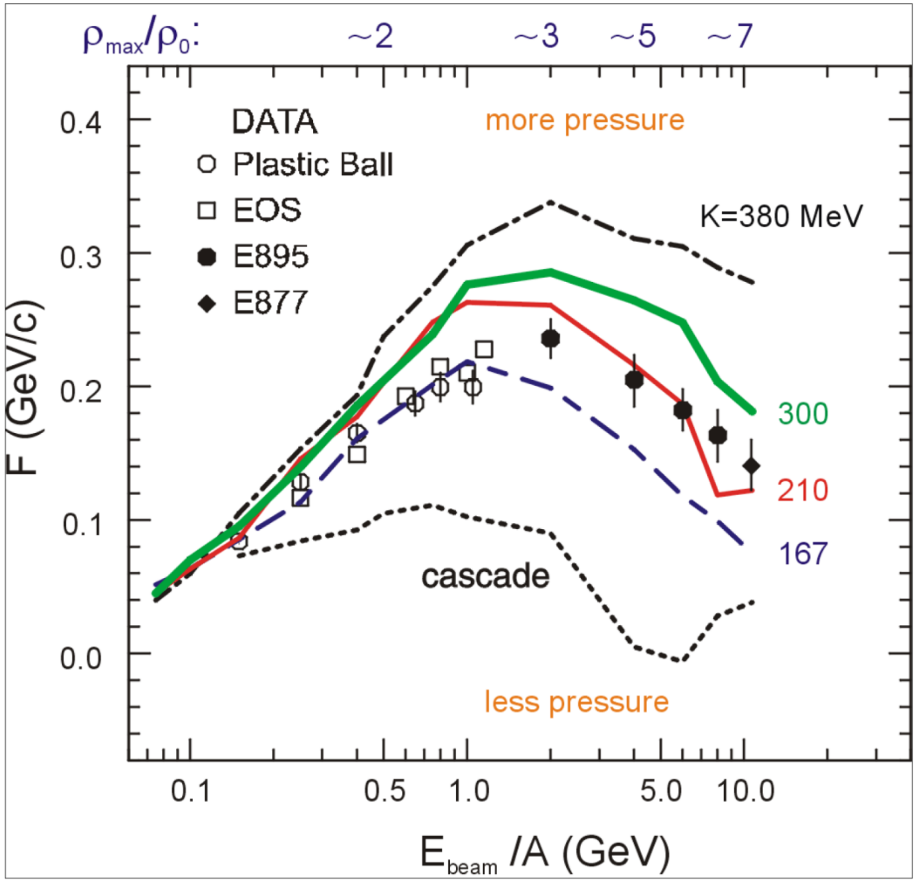
Soft Momentum dependent
SM: K_{nm} = 200 MeV

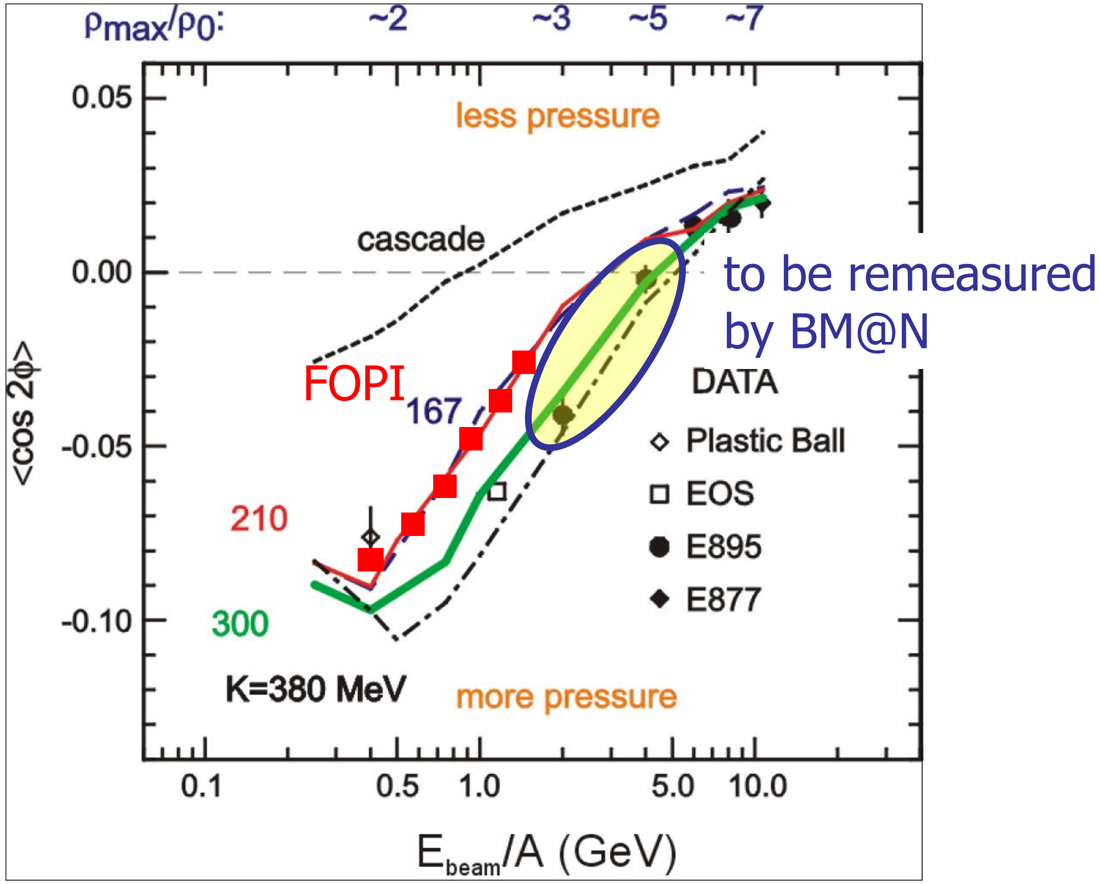
Nuclear incompressibility
K_{nm}=190 ±30 MeV

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

Nuclear incompressibility from collective proton flow

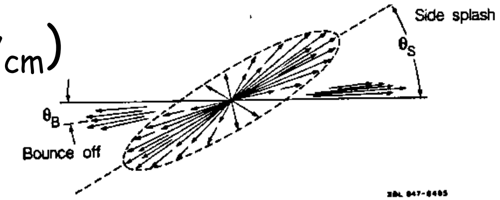
P. Danielewicz, R. Lacey, W.G. Lynch, Science 298 (2002) 1592



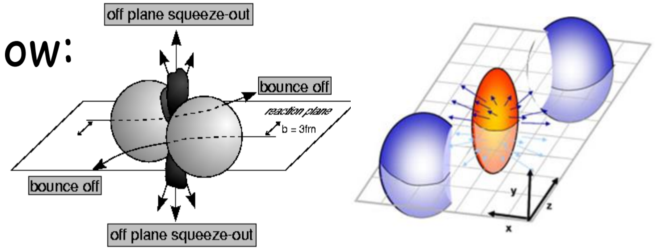


Transverse in-plane flow:

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



Elliptic flow:

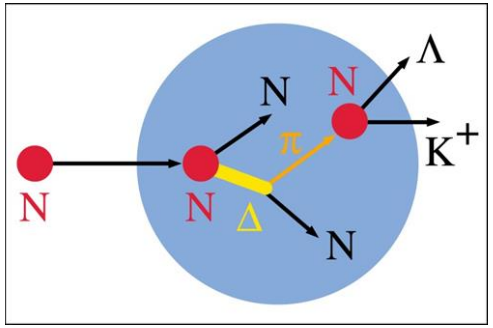


$dN/d\Phi \propto (1 + 2v_1 \cos\Phi + 2v_2 \cos 2\Phi)$

Alternative probe of the high-density EOS: Subthreshold production of strange particles

Poineering experiments at GSI SIS18 ($\rho \leq 2.5\rho_0$):
Subthreshold production of K^+ mesons in Au+Au and C+C collisions $\rightarrow K_{nm} \approx 200$ MeV
KaoS –Experiment: C. Sturm et al., Phys. Rev. Lett. 86 (2001) 39, Theory: Ch. Fuchs et al., Phys. Rev. Lett. 86 (2001) 1974

$pp \rightarrow K^+\Lambda^0 p$
(E_{thr} = 1.6 GeV)



Future experiments with BM@N ($\rho \leq 4\rho_0$):
Ξ (ssd) and Ω (sss) yield at subthreshold energies
via multi-step collisions → density → EOS

$pp \rightarrow \Xi^- K^+K^+p$ (E_{thr} = 3.7 GeV)
$pp \rightarrow \Omega^- K^+K^+K^0p$ (E_{thr} = 7.0 GeV)
$pp \rightarrow \Lambda\bar{\Lambda} pp$ (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 collisions

$pp \rightarrow K^+n\Sigma^+$, $pp \rightarrow K^+p\Lambda^0$ → $\Sigma^+\Lambda^0 \rightarrow \Xi^0 p$
$pn \rightarrow K^+p\Sigma^-$ → $\Sigma^- \Xi^0 \rightarrow \Omega^- n$

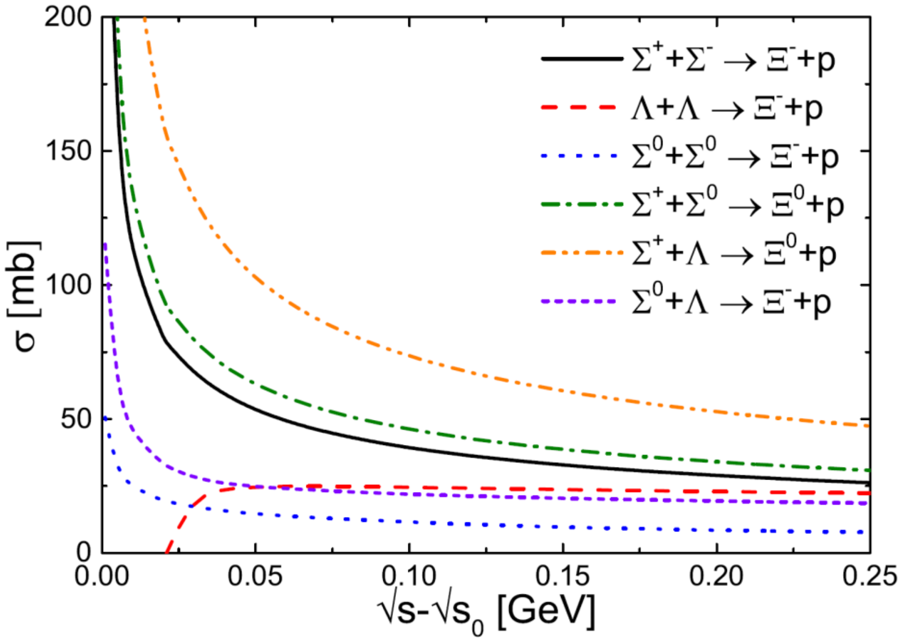
$pp \rightarrow K^+p\Lambda^0$, $pp \rightarrow K^+p\Lambda^0$ → $\Lambda^0\Lambda^0 \rightarrow \Xi^- p$
$pn \rightarrow nK^+\Sigma^0$ → $\Sigma^0 \Xi^- \rightarrow \Omega^- n$

$pp \rightarrow K^+n\Sigma^+$, $pn \rightarrow K^+p\Sigma^-$ → $\Sigma^+\Sigma^- \rightarrow \Xi^- p$
$pp \rightarrow K^+p\Lambda^0$ → $\Lambda^0 \Xi^- \rightarrow \Omega^- n$

New probe of the high-density EOS: subthreshold production of multi-strange hyperons

Idea: Ξ and Ω yield at subthreshold energies ~ multi-step collisions ~ density $\rightarrow$ EOS

Isospin-dependent strangeness-exchange cross sections in UrQMD



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

<u>Hyperon production via multiple collisions</u>

$pp \rightarrow K^+ n \Sigma^+$

$pp \rightarrow K^+ p \Lambda^0$ $\;\rightarrow\;$ $\Sigma^+\Lambda^0 \rightarrow \Xi^0\, p$

$pn \rightarrow K^+ p \Sigma^-$ $\;\rightarrow\;$ $\Sigma^-\Xi^0 \rightarrow \Omega^-\, n$

$pp \rightarrow K^+ p \Lambda^0$

$pp \rightarrow K^+ p \Lambda^0$ $\;\rightarrow\;$ $\Lambda^0\Lambda^0 \rightarrow \Xi^-\, p$

$pn \rightarrow n K^+ \Sigma^0$ $\;\rightarrow\;$ $\Sigma^0\Xi^- \rightarrow \Omega^-\, n$

$pp \rightarrow K^+ n \Sigma^+$

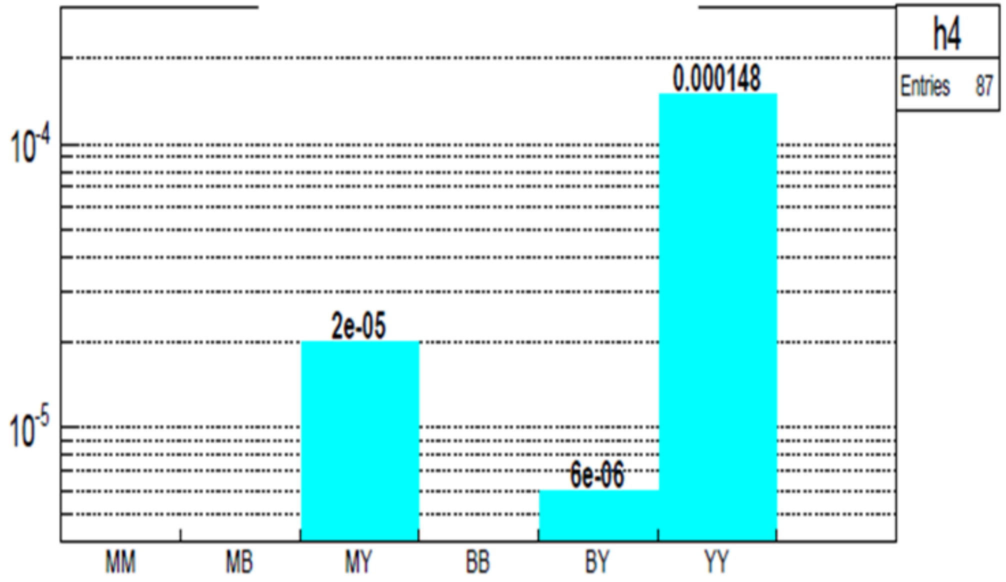
$pn \rightarrow K^+ p \Sigma^-$ $\;\rightarrow\;$ $\Sigma^+\Sigma^- \rightarrow \Xi^-\, p$

$pp \rightarrow K^+ p \Lambda^0$ $\;\rightarrow\;$ $\Lambda^0\Xi^- \rightarrow \Omega^-\, n$

New probe of the high-density EOS: subthreshold 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 (BM@N energies!)



HYPQGSM calculations , K. Gudima et al.

Hyperon production via multiple collisions

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

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

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

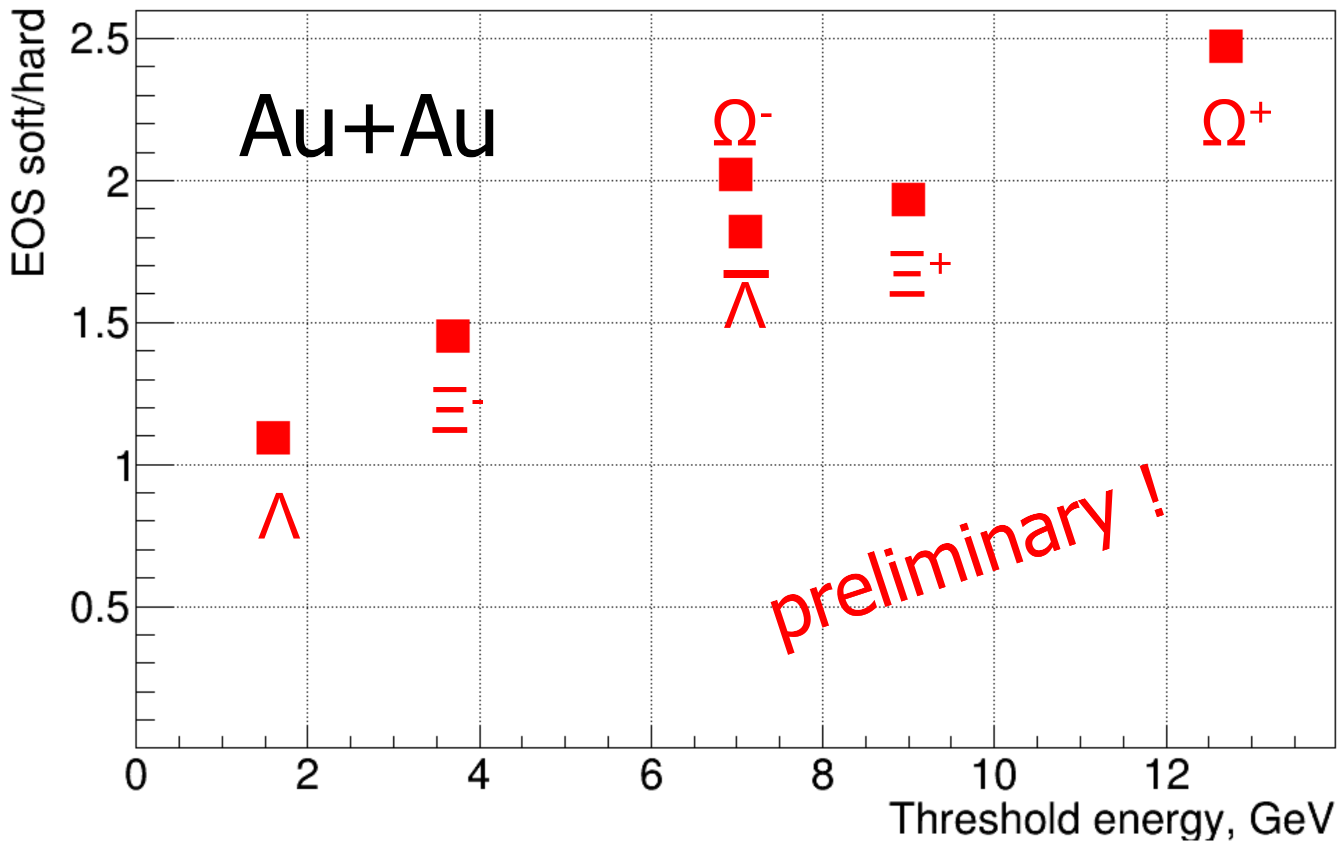
$pn \to n K^+ \Sigma^0$ → $\Sigma^0 \Xi^- \to \Omega^- n$

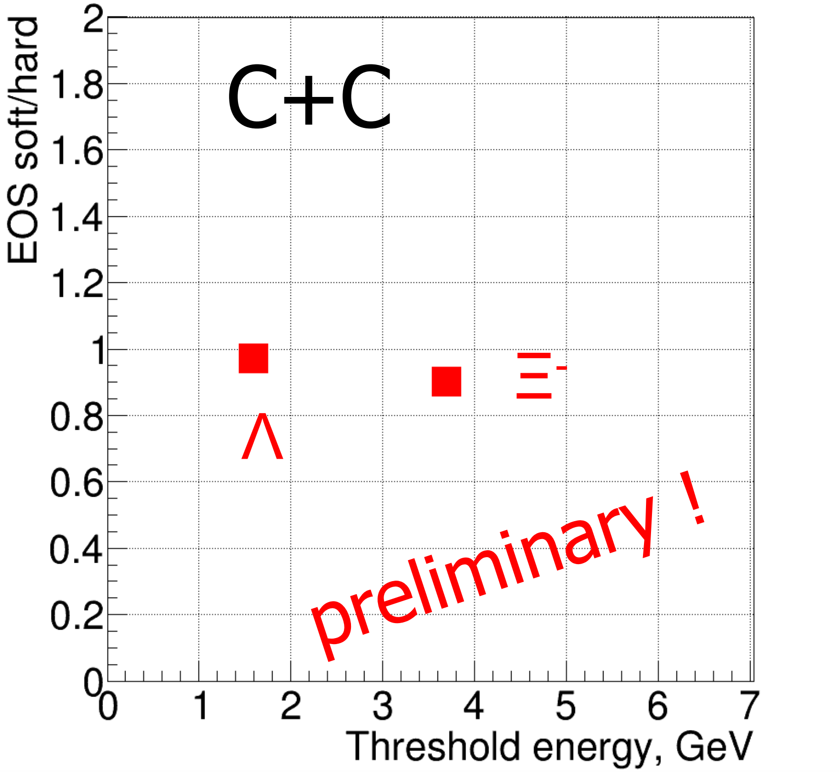
$pp \to K^+ n \Sigma^+$, $pn \to K^+ p \Sigma^-$ → $\Sigma^+\Sigma^- \to \Xi^- p$

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

Multi-strange hyperons: promising observables for the EOS of symmetric matter at Nuclotron beam energies

Hyperon yield in heavy ion collisions at 4A GeV (BM@N energies):
soft EOS (K=240 MeV) / hard EOS (K=350) MeV

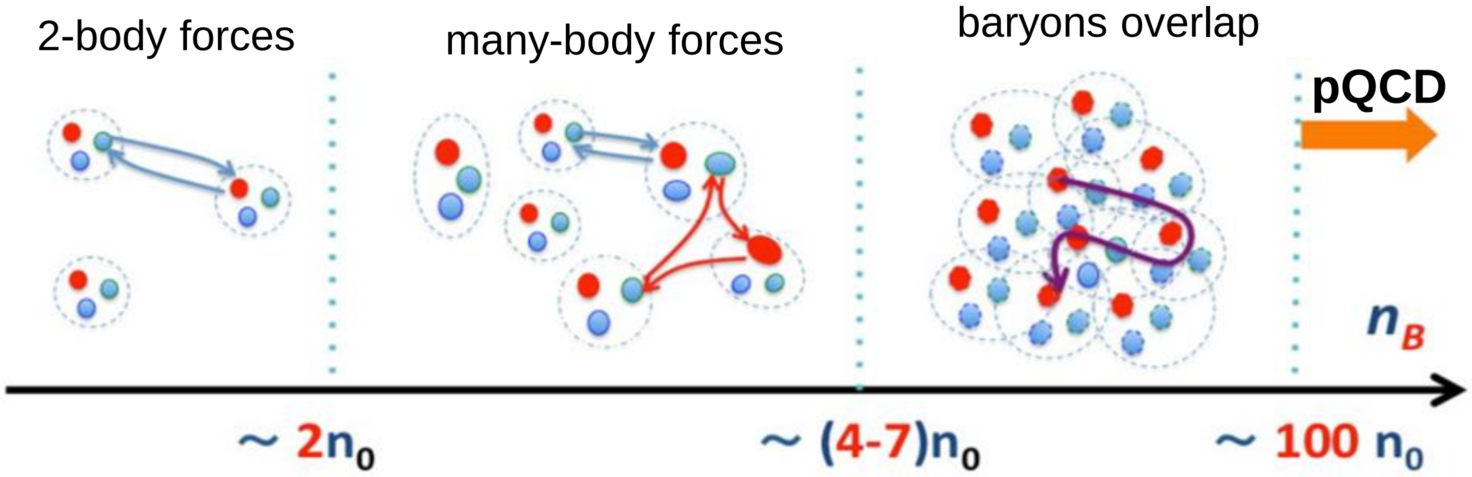




PHQMD calculations , J. Aichelin, E. Bratkovskaya, V. Kireyeu et al., priv. comm.

Searching for the onset of deconfinement

3-stage schematic model
(point-like nucleons)



Courtesy of T. Kojo

nucleons with
hard core and pion cloud

K. Fukushima, T. Kojo, W. Weise,
arXiv:2008.08436

BM@N density range

Searching the onset of deconfinement with multistrange hyperons

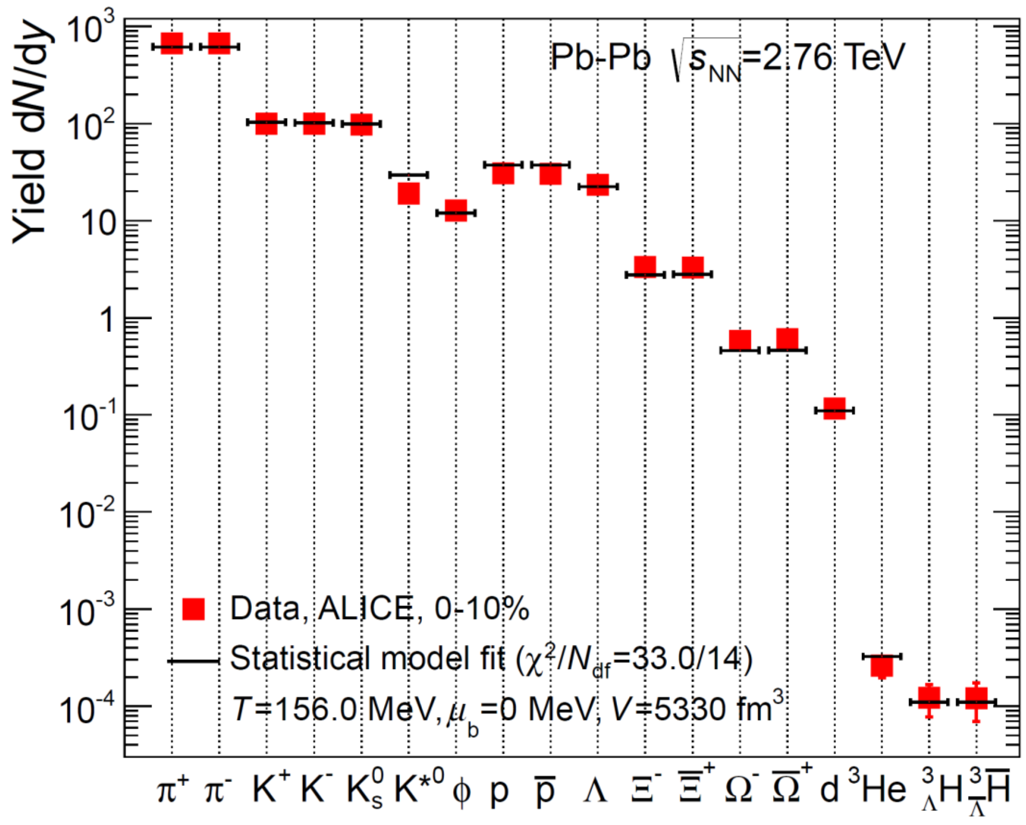
Observation at high energies: Multi-strange hyperons Ξ^-, Ξ^+, Ω^-, Ω^+ in chemical equilibrium! Why?

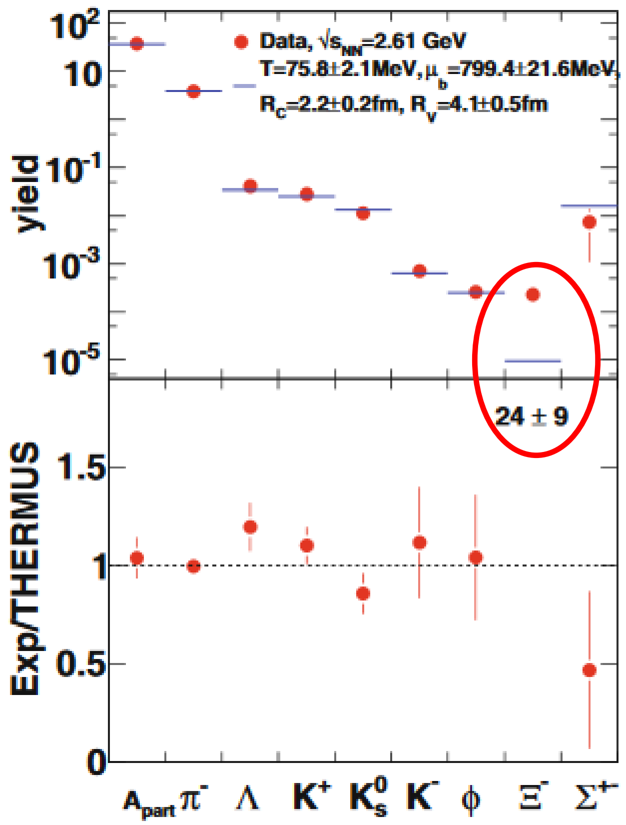
Hyperon-nucleon cross section too small to reach equilibrium in hadronic phase

Explanation: Equilibrium reached by multiple collisions in high density at phase transition

(P. Braun-Munzinger, J. Stachel, C. Wetterich, Phys. Lett. B 2004, 596, 61)

A. Andronic et al., Jour. Phys. G38 (2011)





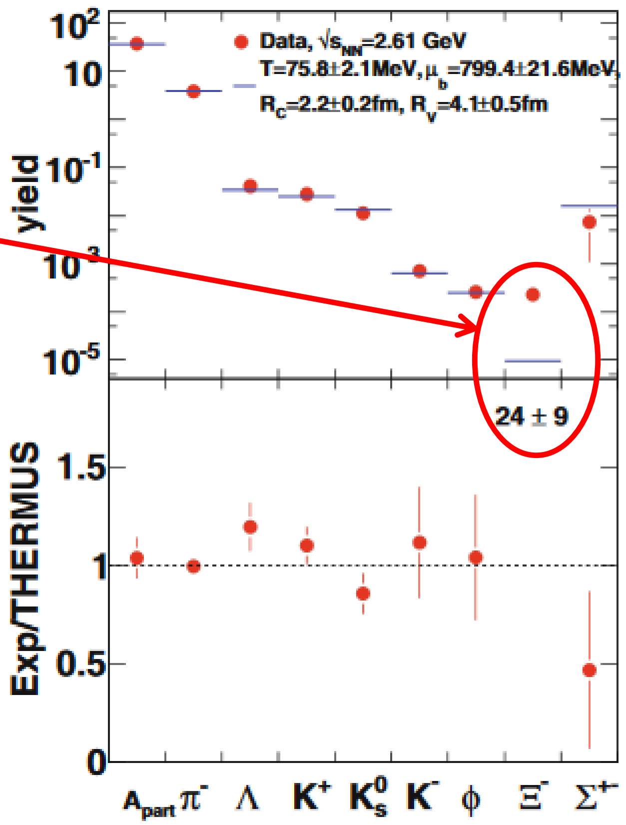
HADES:
Ar + KCl 1.76 A GeV
G. Agakishiev et al.,
Eur. Phys. J. A 47 (2011) 21

Searching the onset of deconfinement with multistrange hyperons

Excitation function of strangeness: $\Xi^-(dss)$, $\Xi^+(\overline{dss})$, $\Omega^-(sss)$, $\Omega^+(\overline{sss})$
→ chemical equilibration at the phase boundary ?

Particle yields and thermal model fits $$n_i = N_i/V = -\frac{T}{V}\frac{\partial \ln Z_i}{\partial \mu} = \frac{g_i}{2\pi^2}\int_0^\infty \frac{p^2 dp}{\exp[(E_i-\mu_i)/T] \pm 1}$$

- Ξ^- production by multiple collisions including strangeness exchange
- No thermal equilibration in hadronic environment because of small hyperon-nucleon cross sections



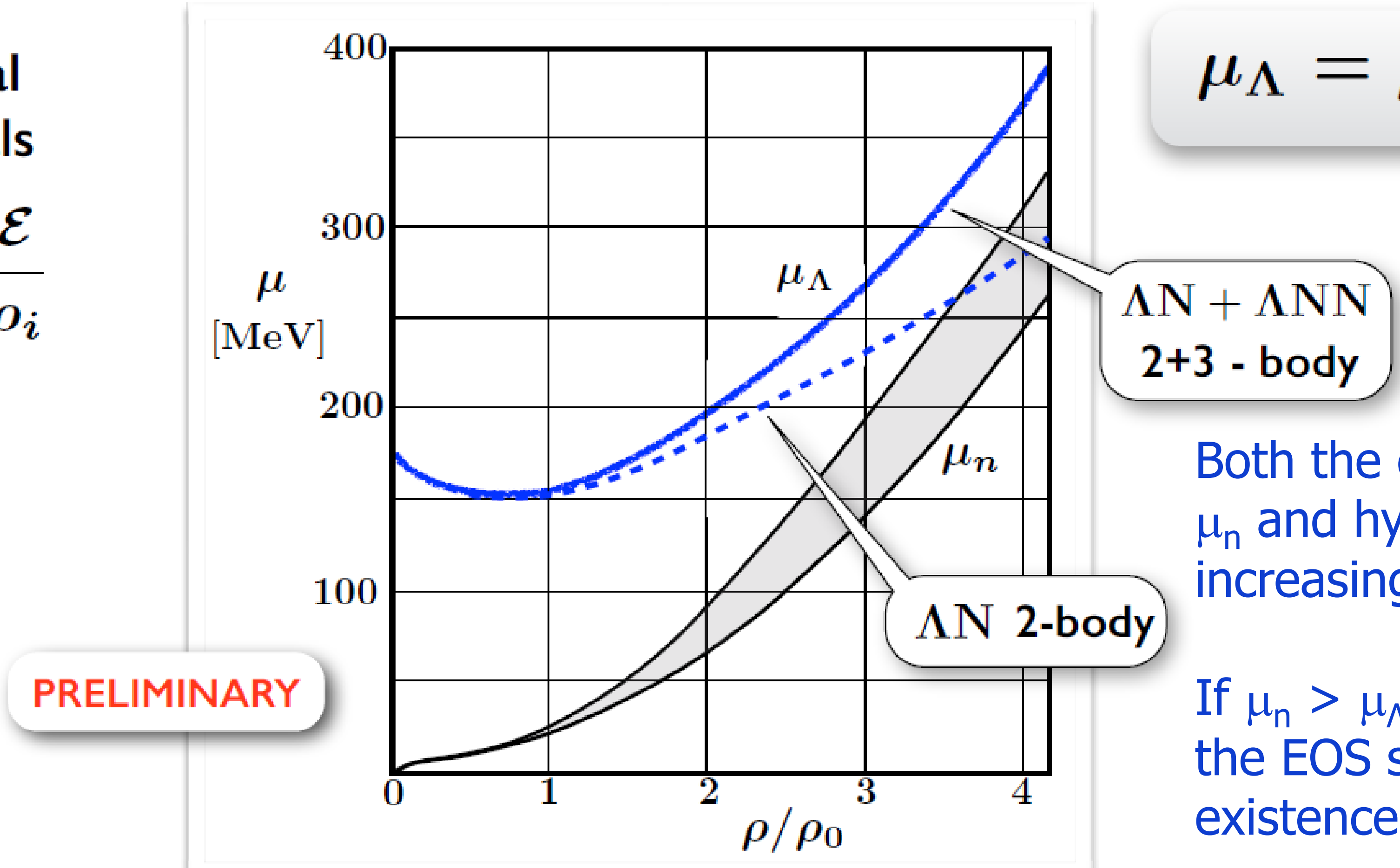
HADES:
Ar + KCl 1.76 A GeV
G. Agakishiev et al.,
Eur. Phys. J. A 47 (2011) 21

Strategy:
measure excitation function of Ξ and Ω production.
The beam energy, where thermal equilibration is reach
(or disappears), indicates onset of deconfinement

Hyperons in massive neutron stars?

chemical potentials

$$\mu_i = \frac{\partial \mathcal{E}}{\partial \rho_i}$$



$$\mu_\Lambda = \mu_n$$

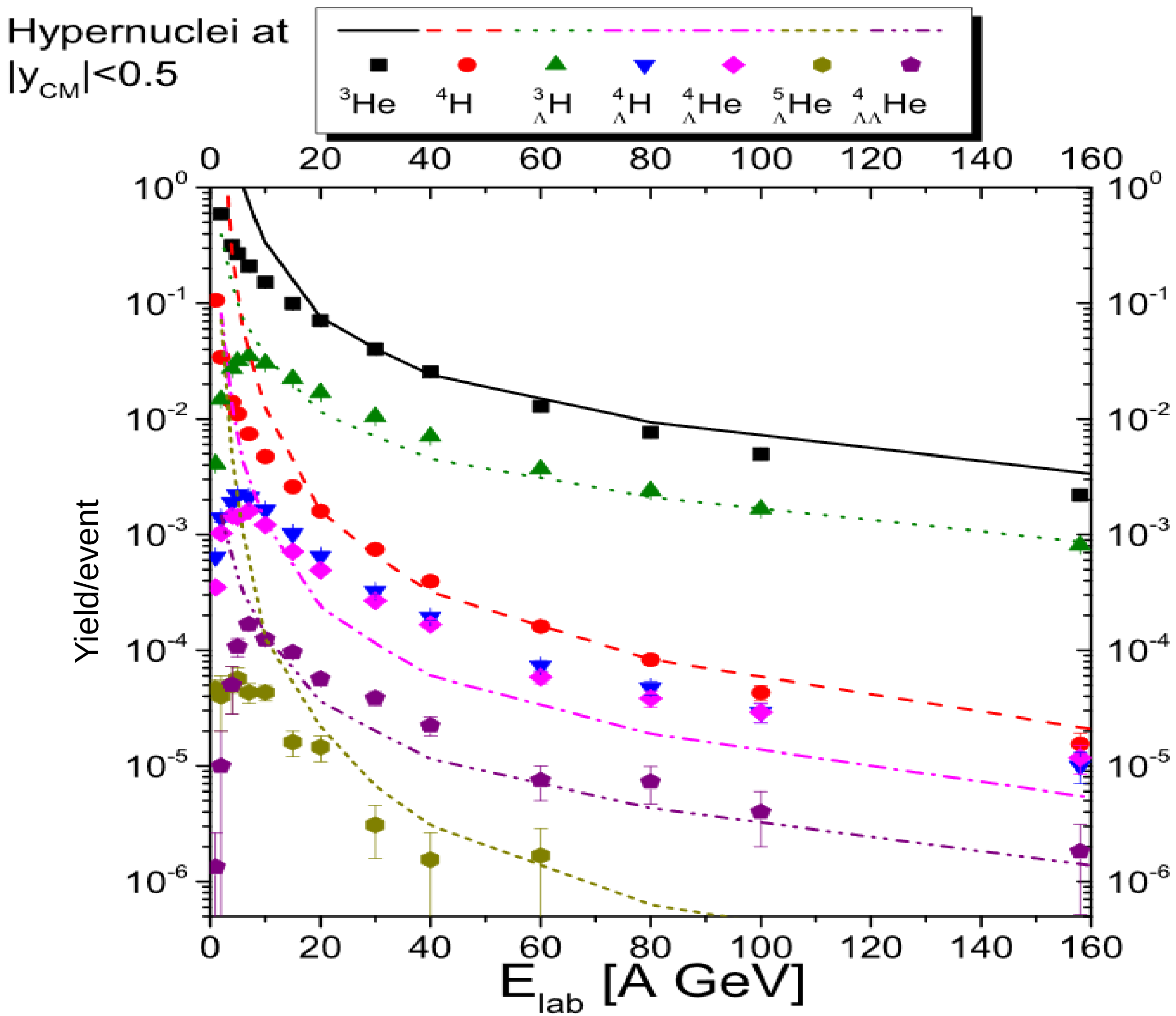
Both the chemical potentials of nucleons μ_n and hyperons μ_Λ increase with increasing baryon density.

If $\mu_n > \mu_\Lambda$, neutrons decay into hyperons, the EOS softens, and prevents the existence of massive neutron stars.

Measure ΛN, ΛNN, and ΛΛN interactions !

W. Weise, arXiv:1905.03955v1, to appear in JPS Conf. Proc
(Lambda single particle potential in neutron star matter from Chiral SU(3) EFT interactions)

Hypernuclei production in heavy-ion collisions



central Pb+Pb/Au+Au collisions

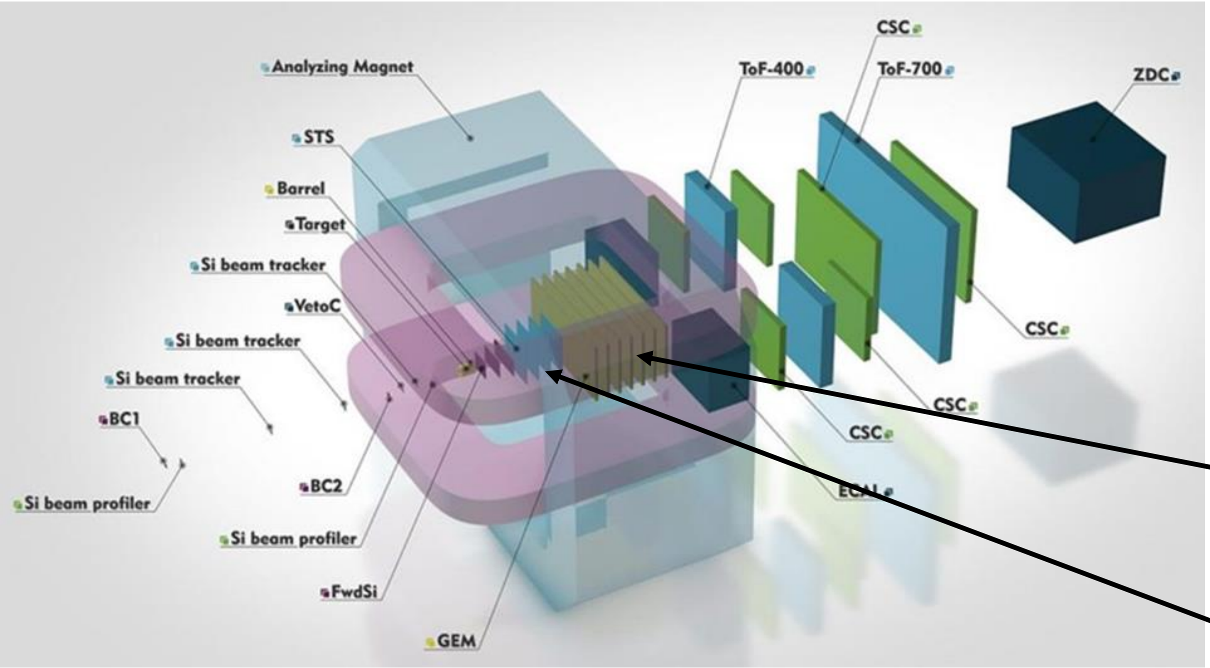
<u>Lines:</u>
Thermal production
(UrQMD-hydro hybrid model)

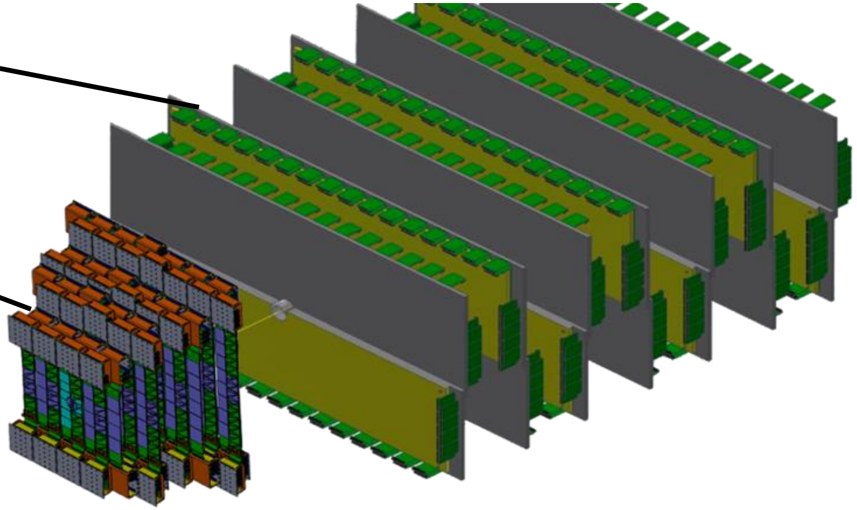
<u>Symbols:</u>
Coalescence results
(Dubna Cascade Model, DCM-QGSM)

The discovery of new hypernuclei and the precise measurement of their life times will shed light on the ΛN, ΛNN, and ΛΛN interactions

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

BM@N upgrade for Au+Au collisions up to 4.0A GeV

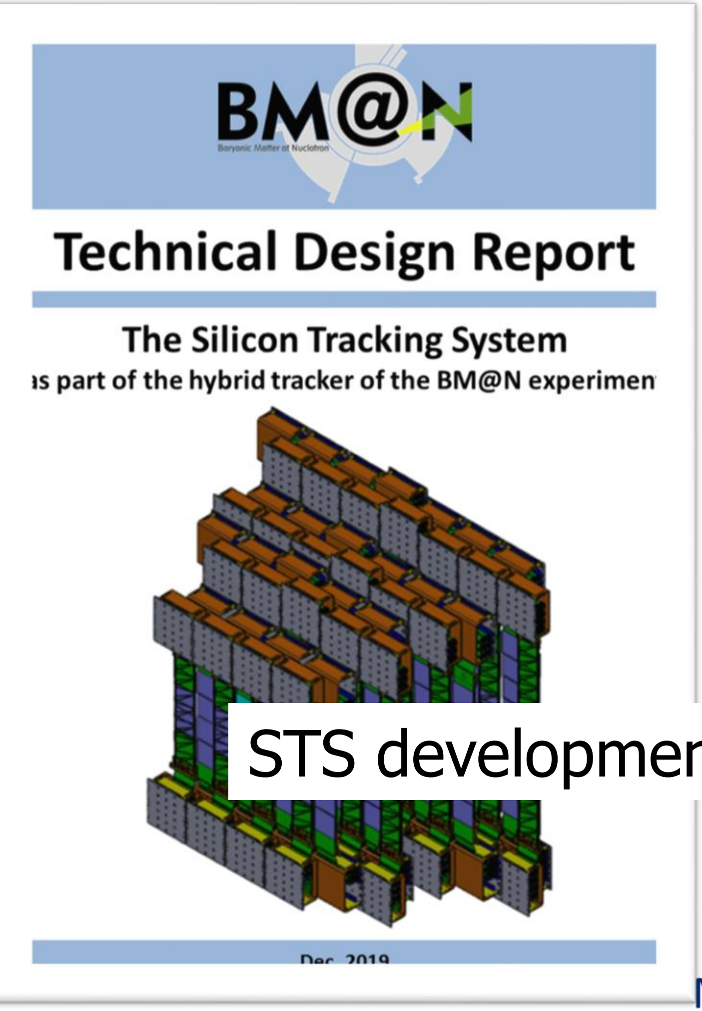




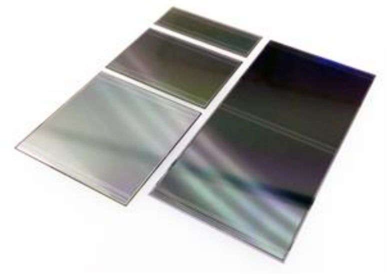
Upgrade:

- 4 stations double-sided micro-strip silicon sensors
- 7 full stations Gas-Electron-Multiplier (GEM) chambers
- Forward Hadron Calorimeter
- vacuum beam pipe from Nuclotron to BM@N
- vacuum target chamber and downstream beam pipe with low material budget

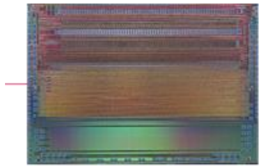
The BM@N Silicon tracking system:
Based on double-sided micro-strip sensors


BM@N
Baryonic Matter at Nuclotron
Technical Design Report
The Silicon Tracking System
as part of the hybrid tracker of the BM@N experiment
Dec. 2019

sensors



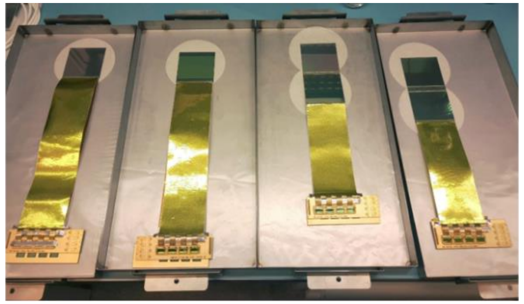
ASIC

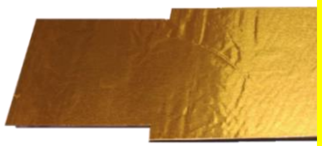


STS XYTER v.2.1

Front-end B

sensors + micro cables + FEBs



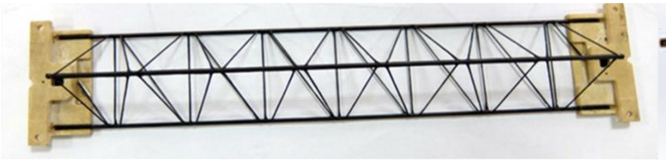


Assembled modu
with aluminu

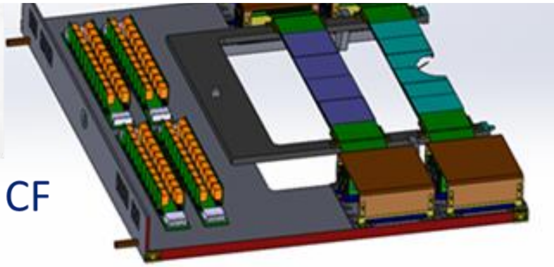
See talks by
Mikhail Merkin,
Dmitrii Dementev,
Mikhail Shitenkov,
Anatoly Kolozhvari,
Nikita Sukhov,
Vladimir Elsha,
Petr Kharlamov
on Friday 23.Oct.2020

half-station

STS development in close collaboration with CBM collaboration at FAIR

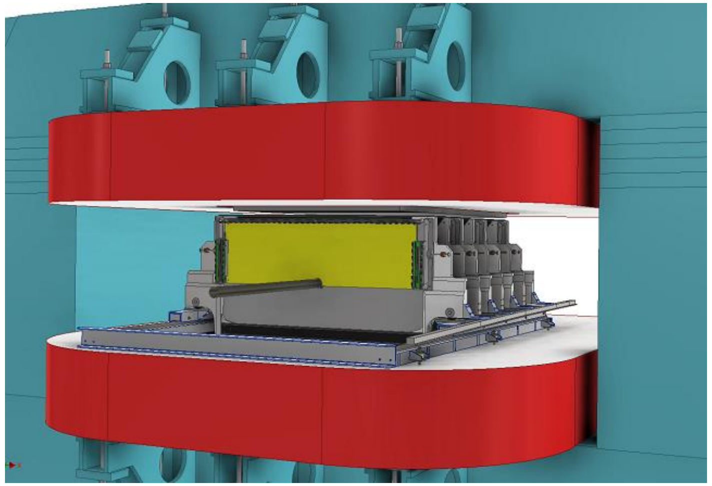


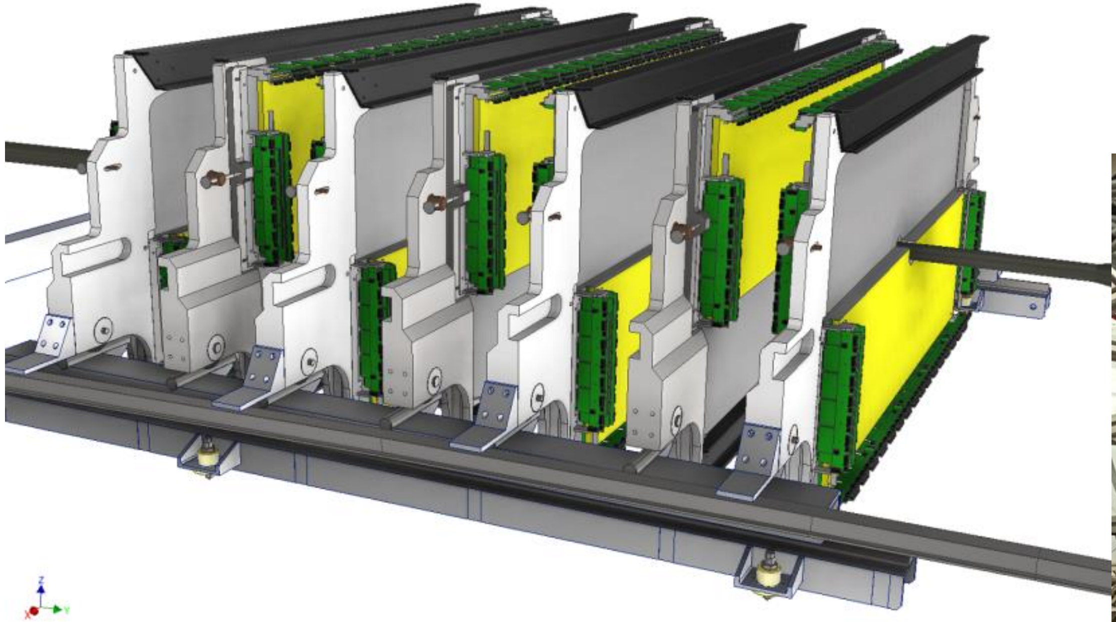
Modules are in groups installed on CF
trusses with mounting blocks

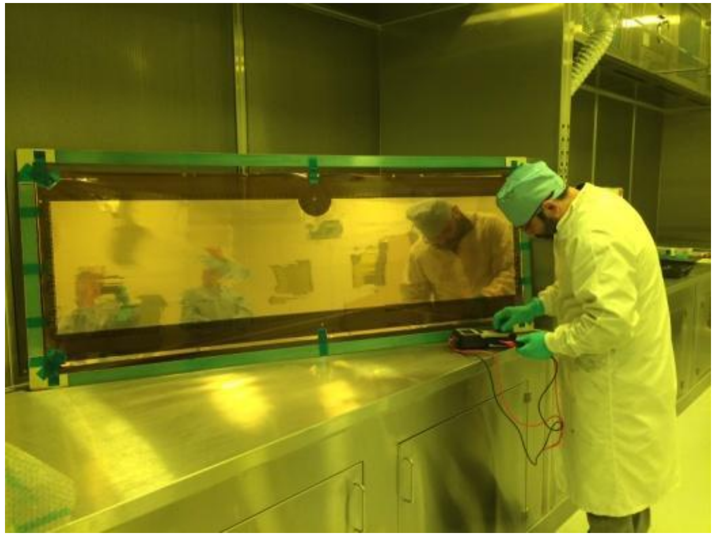


GEM central tracker for heavy ion runs

- 7 upper GEM 163x45 cm^2 chambers produced at CERN were integrated into BM@N
- 7 lower GEM 163x39 cm^2 chambers were assembled, delivered to BM@N and tested







GEM 163x39 cm^2 chamber assembly at CERN

Setup of GEM detectors for cosmic tests

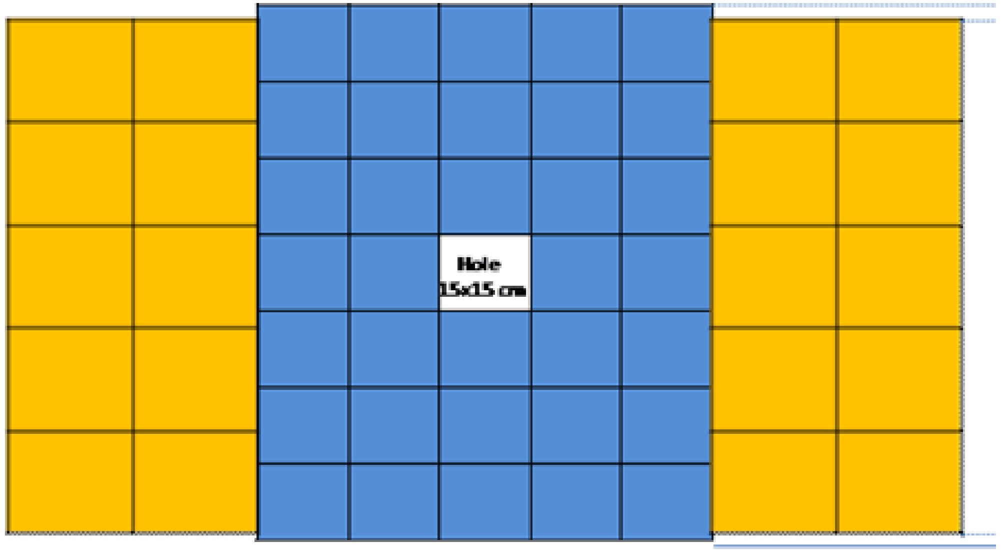
Forward Hadron Calorimeter

Determination of:
- Orientation of the reaction plane
- Collision centrality

See talks by Fedor Guber on Wednesday 21.Oct.2020, and by Nikolay Karpushkin on Thursday 22. Oct. 2020

- FHCAL assembled and installed into BM@N setup
- Cosmic tests are under way

CBM modules MPD modules



Team of INR RAS, Troitsk

Physics performance simulations for the hybrid tracking system

Ξ^- and $_\Lambda H^3$ reconstruction in central Au+Au at 4A GeV (A. Zinchenko)

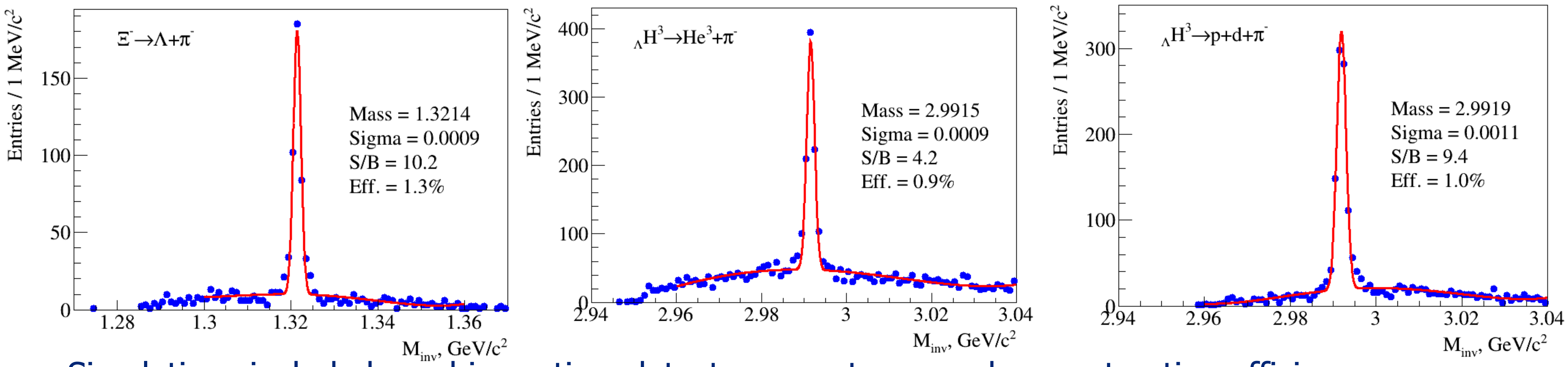
Generator: PHQMD (V. Kireyeu), 500k events, Au+Au at 4A GeV, b = 0-5 fm

Statistics: $\approx 2{\cdot}10^6\ \Lambda$, $\approx 2{\cdot}10^4\ \Xi^-$, $\approx 8.4{\cdot}10^4\ {}_\Lambda H^3$

Detectors: STS + GEMs + TOF

PID: m^2 in TOF

See talk by Alexander Zinchenko on Thursday 22.Oct.2020

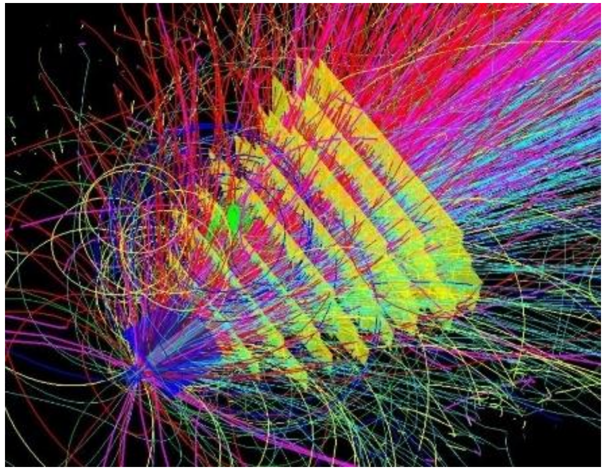


Simulations include branching ratios, detector acceptance and reconstruction efficiency

Beam parameters and setup at different stages of the BM@N experiment

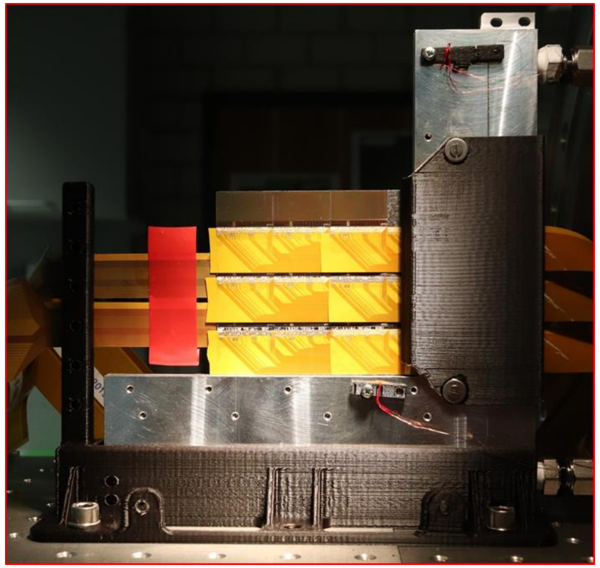
Year	2016	2017 spring	2018 spring	fall 2021	2022	2023
Beam	d(↑)	C	Ar,Kr, C(SRC)	Kr,Xe	up to Au	up to Au
Max.intensity, Hz	0.5M	0.5M	0.5M	0.5M	0.5M	0.5M
Trigger rate, Hz	5k	5k	10k	10k	10k	50k
Central tracker status	6 GEM half planes	6 GEM half planes	6 GEM half planes + 3 forward Si planes	7 GEM full planes + forward Si planes	7 GEM full planes + forward Si + 2 large STS planes	7 GEM full planes + 4 large STS planes
Experimental status	technical run	technical run	technical run+physics	physics run	stage1 physics	stage2 physics

Budget 25 M€ over 4 years: 2020 - 2023
GSI/FAIR and JINR involvement in two Working Packages



WP2: Collaboration with NICA
Develop the instrumentation for NICA/BM@N and FAIR/CBM
Engineering and construction of fast detectors, and development of high rate data acquisition chain and software packages for simulation and data analysis
Total budget 4.6 M€

Participants: JINR (9 FTE), FAIR (8.5 FTE), U Tübingen (1 FTE), WUT Warsaw (2 FTE), Wigner Budapest (2 FTE), MEPhI (4 FTE) INR Moscow (1 FTE), NPI Prague (2 FTE)

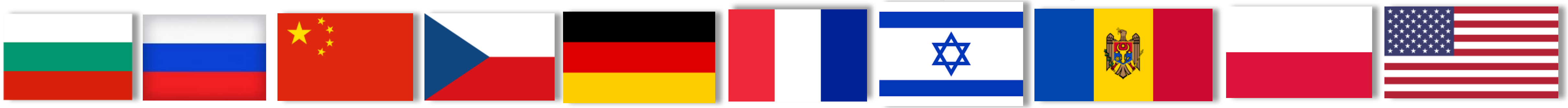


WP7: **Joint development of detector technologies**
Develop a beyond state of the art CMOS pixel sensors (MAPS) for high-rate Silicon trackers for several particle physics and heavy-ion research communities in Europe and Russia for the potential upgrade of many experimental setups (e.g. at SCT, at NICA, at CERN-colliders), development of neutron detectors, detector school at BINP
Total budget 1.75 M€

Participants: JINR (1 FTE), FAIR (1 FTE), DESY (1 FTE), U Frankfurt (1 FTE), IPHC Strasbourg (1 FTE), KINR Kiev (1 FTE), BINP (1 FTE)

Baryonic Matter at Nuclotron (BM@N) Collaboration

10 Countries, 20 Institutions, 246 participants



- University of Plovdiv, Bulgaria;
- Shanghai Institute of Nuclear and Applied Physics, CFS, China;
- Tsinghua University, Beijing, China;
- Nuclear Physics Institute CAS, Czech Republic;
- CEA, Saclay, France;
- TU Darmstadt & GSI Darmstadt, Germany;
- Tübingen University, Germany;
- Tel Aviv University, Israel;
- Joint Institute for Nuclear Research;
- Institute of Applied Physics, Chisinev, Moldova;
- Warsaw University of Technology, Poland;
- St Petersburg University, Russia;
- University of Wroclaw, Poland;
- Institute of Nuclear Research RAS, Moscow, Russia
- NRC Kurchatov Institute, Moscow;
- Institute of Theoretical & Experimental Physics, NRC KI, Moscow, Russia;
- Moscow Engineer and Physics Institute, Russia;
- Skobeltsin Institute of Nuclear Physics, MSU, Russia;
- Moscow Institute of Physics and Technics, Moscow, Russia;
- Massachusetts Institute of Technology, Cambridge, USA.

Summary

- The upgraded BM@N experiment offers the opportunity to explore nuclear matter at neutron star core densities in heavy-ion collisions at energies of up to 3.8A GeV.
- The research program includes:
  - the high-density equation-of-state
  - the onset of deconfinement
  - the role of hyperons in neutron stars
- Sensitive observables:
  - elliptic flow of charged particles
  - excitation function of multi-strange hyperons
  - hypernuclei
- First measurements with Au beams are expected in 2023.

- The new Silicon Tracking System at BM@N will be realized in closed collaboration with groups from the CBM collaboration as a prototype detector for the CBM experiment at FAIR, which is expected to take first beams in 2025.