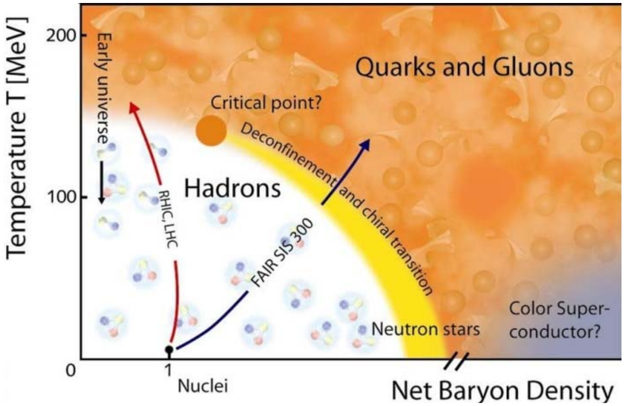


From FOPI to FAIR – Constraining the Nuclear Matter Equation of State at Supra Normal Densities

Y. Leifels
GSI Helmholtzzentrum für Schwerionenforschung GmbH Darmstadt

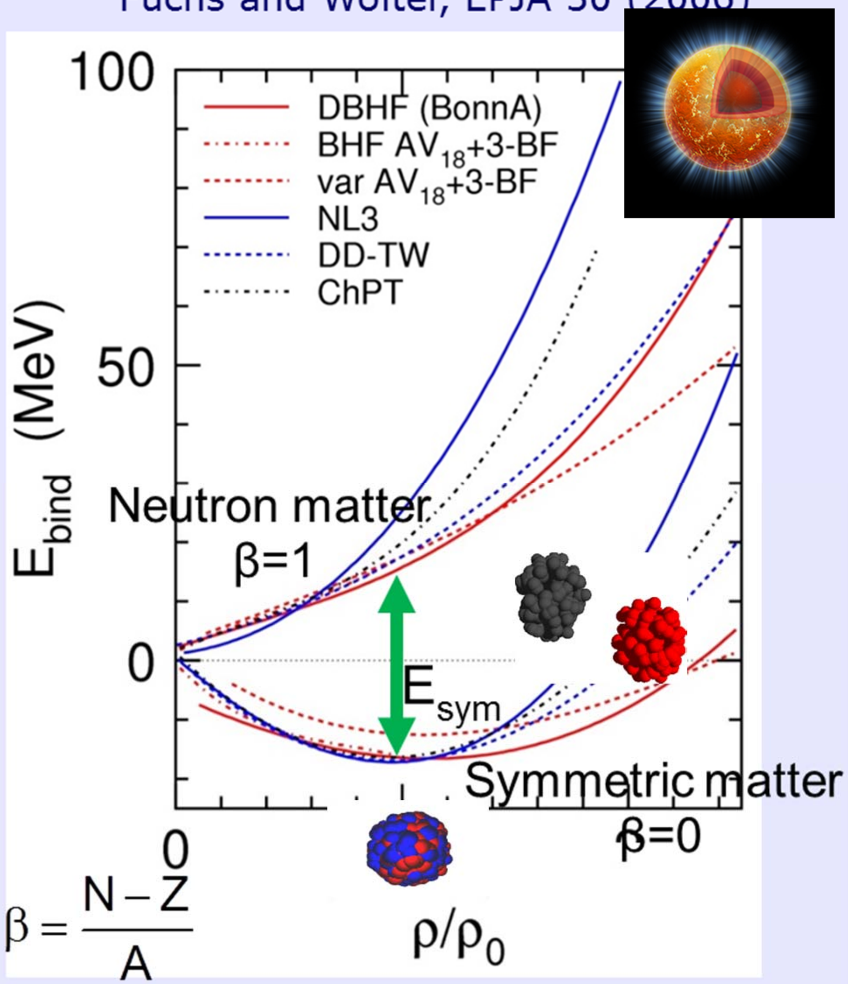
NUSYM 2015
Krakow, June 29 – July 2, 2015

GSI

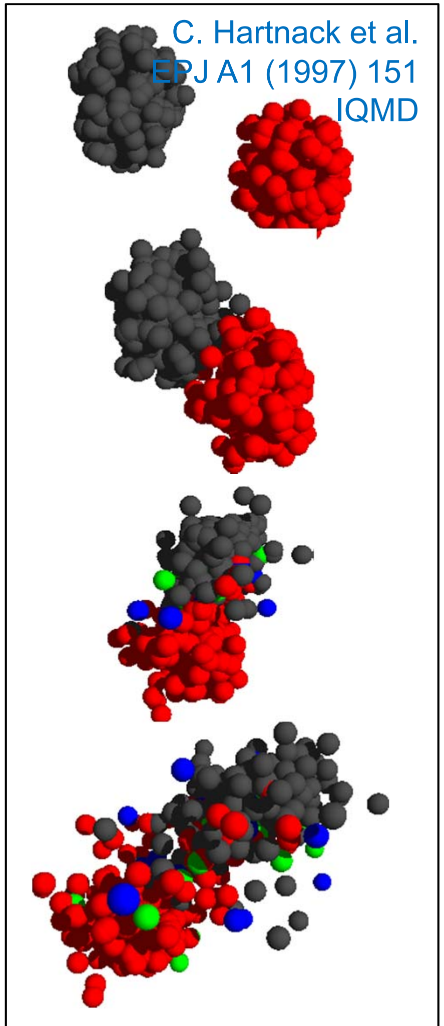
Outline

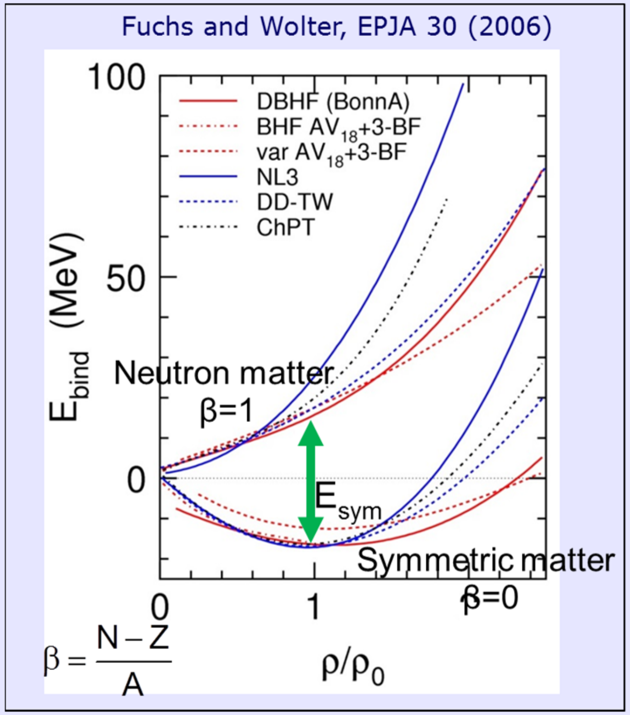
- ✓ Introduction
- ✓ FOPI Detector
- ✓ Experimental data
  - stopping
  - clusterization
  - flow
  - isospin pairs
- ✓ Conclusions
- ✓ Outlook and future perspectives

Fuchs and Wolter, EPJA 30 (2006)



Heavy ion collisions at intermediate energies

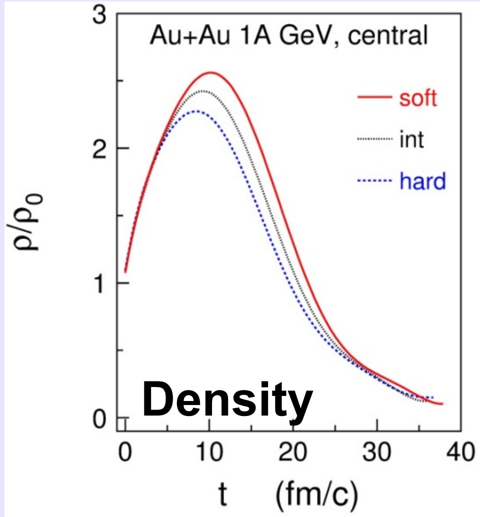


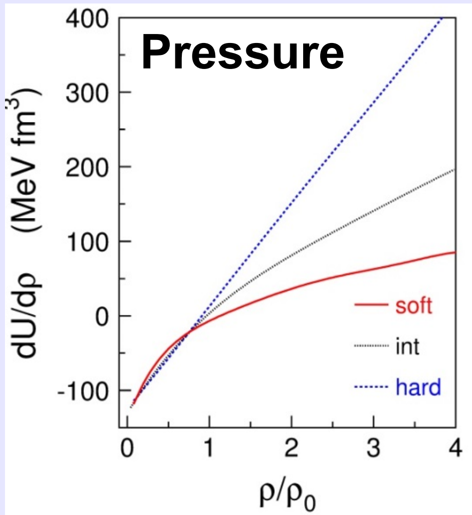


But also

- momentum dependence
- Pauli blocking
- effective masses
- in-medium cross sections
- ...

access via microscopic transport models

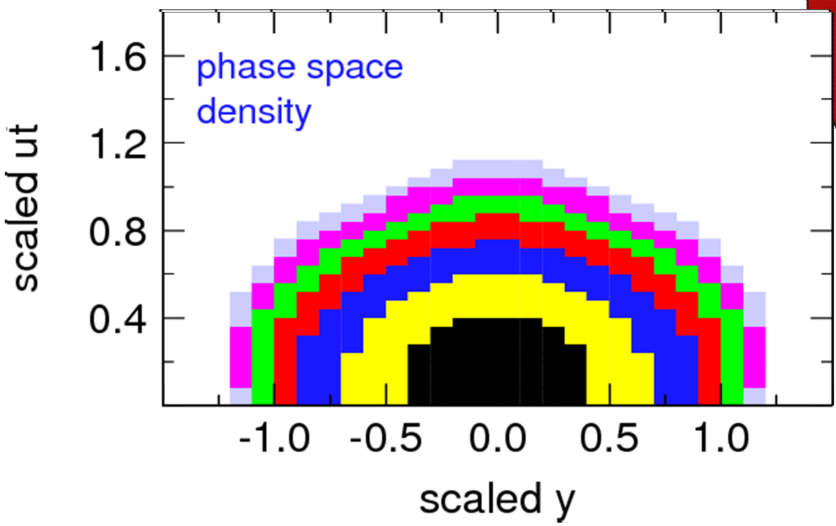


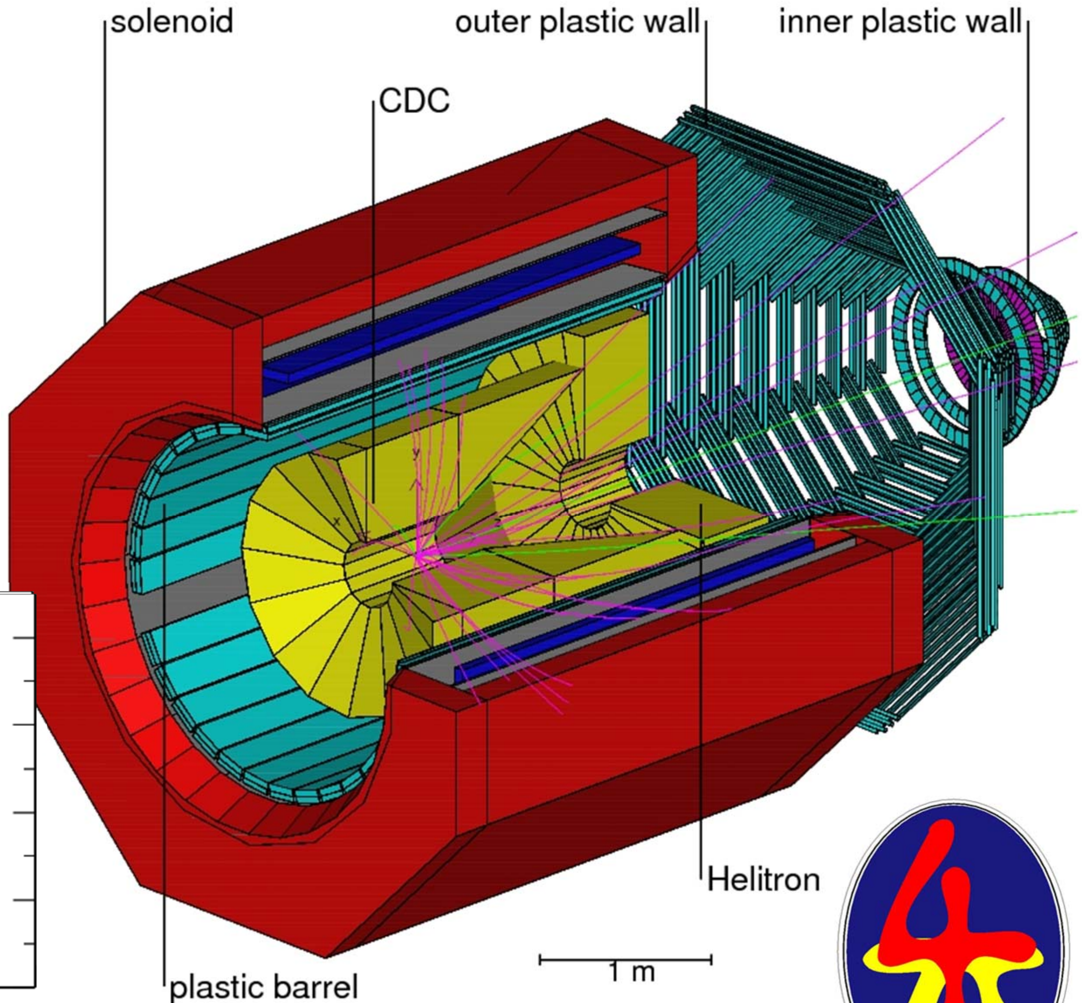


The FOPI Experiment

Characteristics:

- homogeneous field 0.6 T
- charged particle tracking
- time-of-flight RPCs
- close to symmetric acceptance in azimuth
- (π^-, π^+) (t, ^{3}He) (n/p) (K^0/K^+) measured with **stable** beams





FOPI collaboration

A. Andronic, R. Averbeck, Z. Basrak, N. Bastid,
M.L. Benabderramahne, M. Berger, P. Bühler,
R. Caplar, M. Cargnelli, M. Ciobanu, P. Crochet,
I. Deppner, P. Dupieux, M. Dzelalija, L. Fabbietti,
J. Frühauf, F. Fu, P. Gasik, O. Hartmann,
N. Herrmann, K.D. Hildenbrand, B. Hong,
T.I. Kang, J. Keskemeti, Y.J. Kim, M. Kis,
M. Kirejczyk, R. Münzer, P. Koczon, M. Korolija,
R. Kotte, A. Lebedev, K.S. Lee, Y. Leifels,
A. LeFevre, P. Loizeau, X. Lopez, M. Marquardt,
J. Marton, M. Merschmeyer, M. Petrovici,
K. Piasecki, F. Rami, V. Ramillien, A. Reischl,
W. Reisdorf, M.S. Ryu, A. Schüttauf, Z. Seres,
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K. Siwek-Wilczynska, K. Suzuki, Z. Tyminski,
J. Weinert, K. Wisniewski, Z. Xiao, H.S. Xu,
J.T. Yang, I. Yushmanov, V. Zimnyuk, A. Zhilin,
Y. Zhang, J. Zmeskal
and
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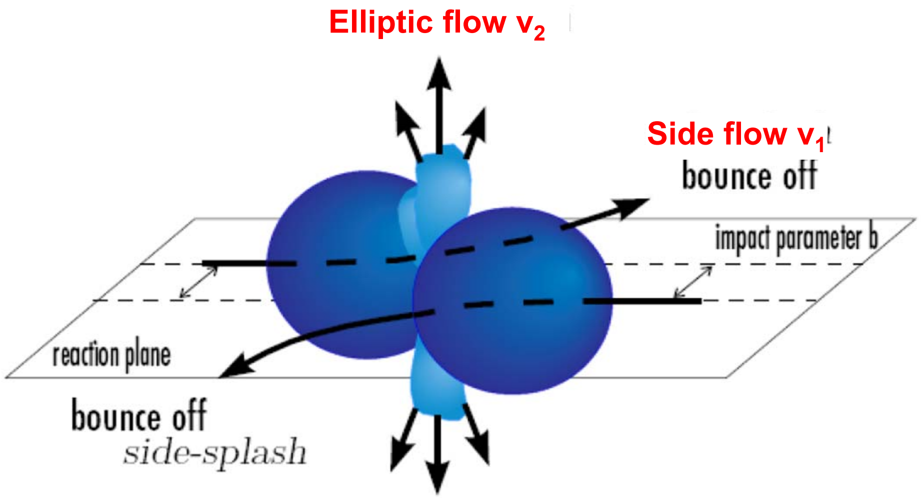
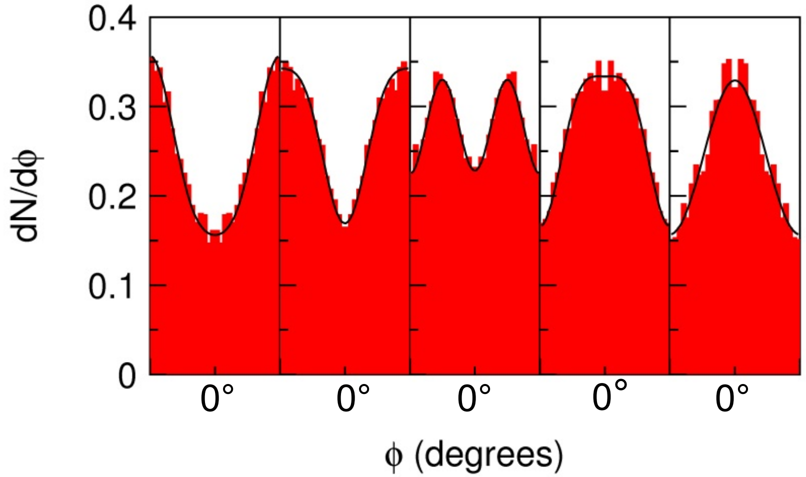
CRIP/KFKI Budapest, Hungary
Kurchatov Institute Moscow, Russia
LPC Clermont-Ferrand, France
Korea University, Seoul, Korea
GSI Darmstadt, Germany
IReS Strasbourg, France
FZ Rossendorf, Germany
Univ. of Heidelberg, Germany
Univ. of Warsaw, Poland
RBI Zagreb, Croatia
IMP Lanzhou, China
SMI Vienna, Austria
TUM, Munich, Germany
+ P. Kienle (TUM), T.Yamazaki (RIKEN)

Collective flow





Discovery at Bevalac

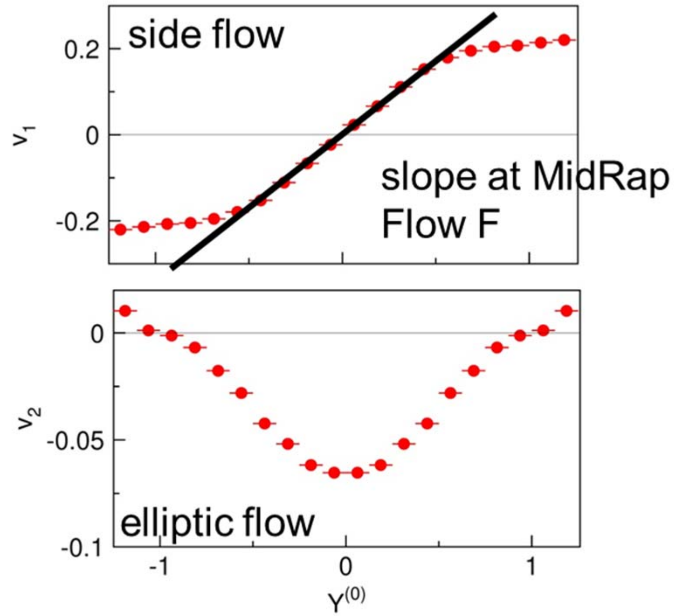
H.A. Gustafsson, et al., Phys. Rev. Lett. 52 (1984) 1590.
R.E. Renfordt, et al., Phys. Rev. Lett. 53 (1984) 763.

Phase space distribution with respect to reaction plane

$$\frac{dN}{d\phi} \sim 1 + 2v_1 \cos(\phi) + 2v_2 \cos(2\phi)$$

$$\phi = \phi_R - \varphi$$

S. Voloshin, Y. Zhang, *hep-ph/9407082*
J.Y. Ollitrault, *nucl-ex/9711003*



Collisions of heavy ions between 0.1 – 2AGeV

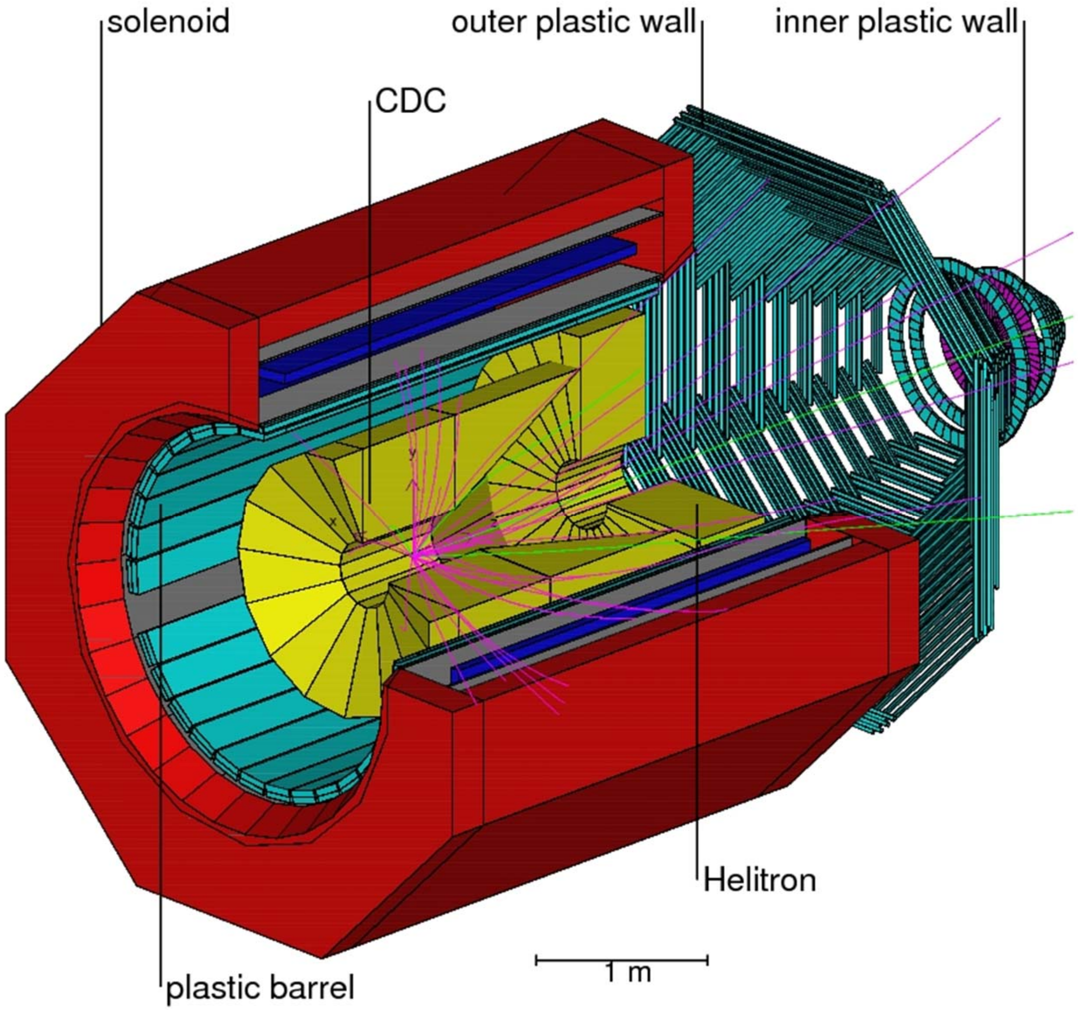
At intermediate energies

- stopping
- expansion
- clusterization
- flow
- particle production
    - pions, kaons

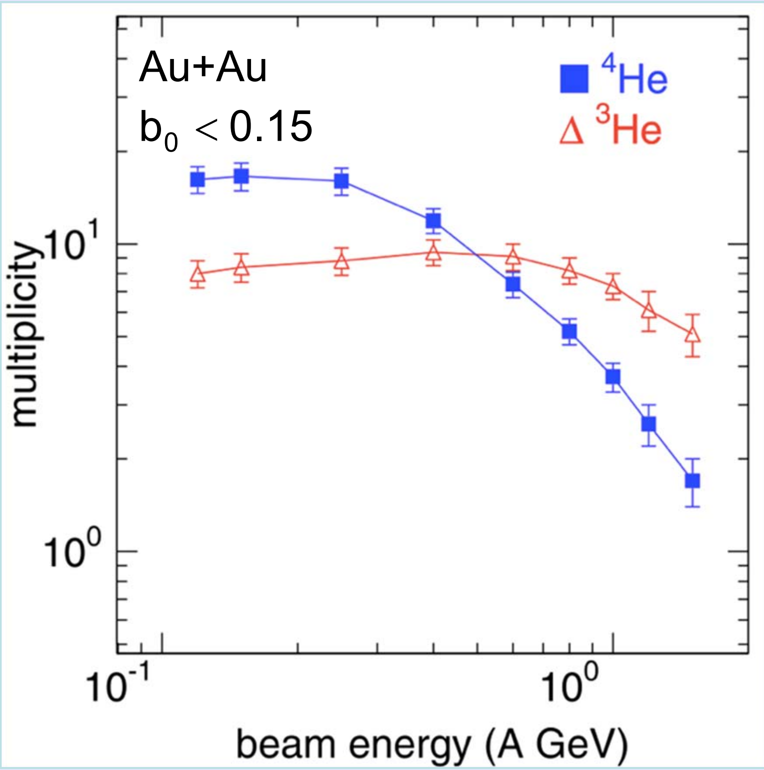
What did we learn?

All observables are interrelated

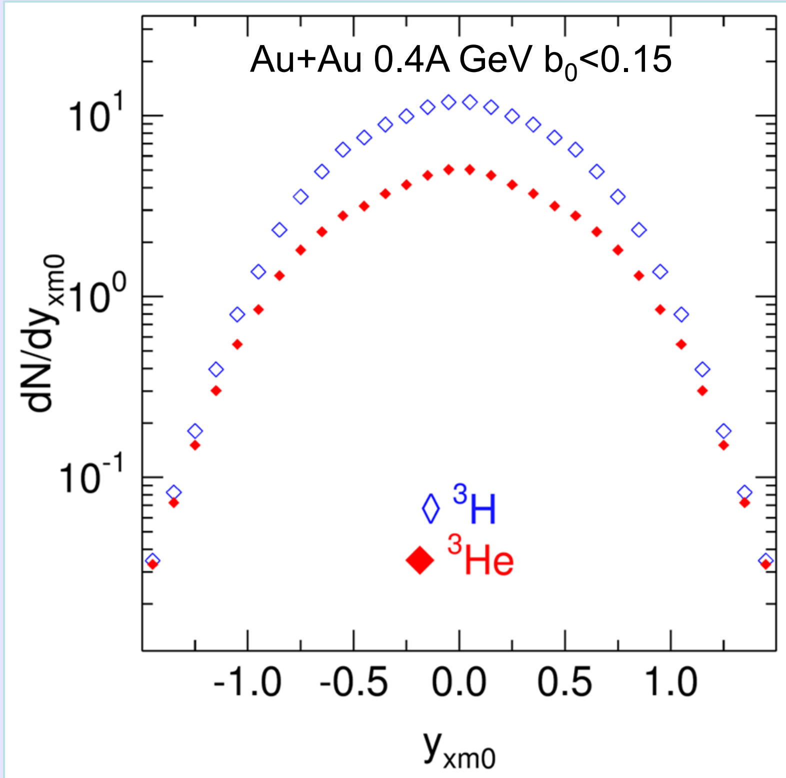
- ✓ flow – stopping
- ✓ expansion – clusterization
- ✓ clusterization - spectra



t, ^{3}He, ^{4}He production linked together

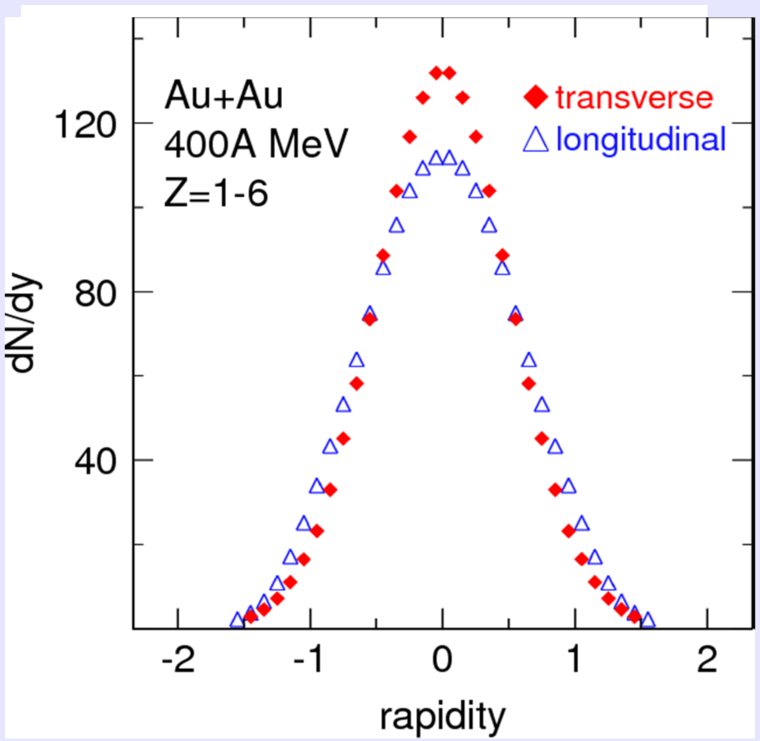


- ^{3}He yield reduced by neutron capture to form ^{4}He?
- t yield less affected



- transverse rapidity spectra of t and ^{3}He match at high rapidities
- clusterization influences spectra/ apparent “temperatures”

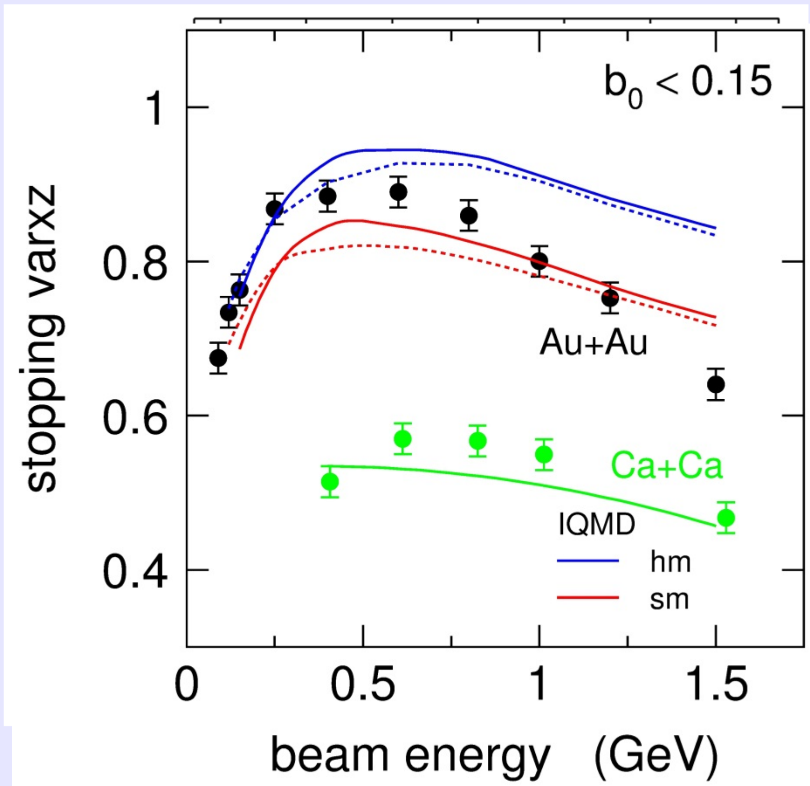
Stopping and flow are interrelated



W. Reisdorf et al., NPA 848(2010)366

Define stopping:

$$\mathrm{var}\,xz = \frac{\sigma^2_{y_t}}{\sigma^2_{y_l}}$$

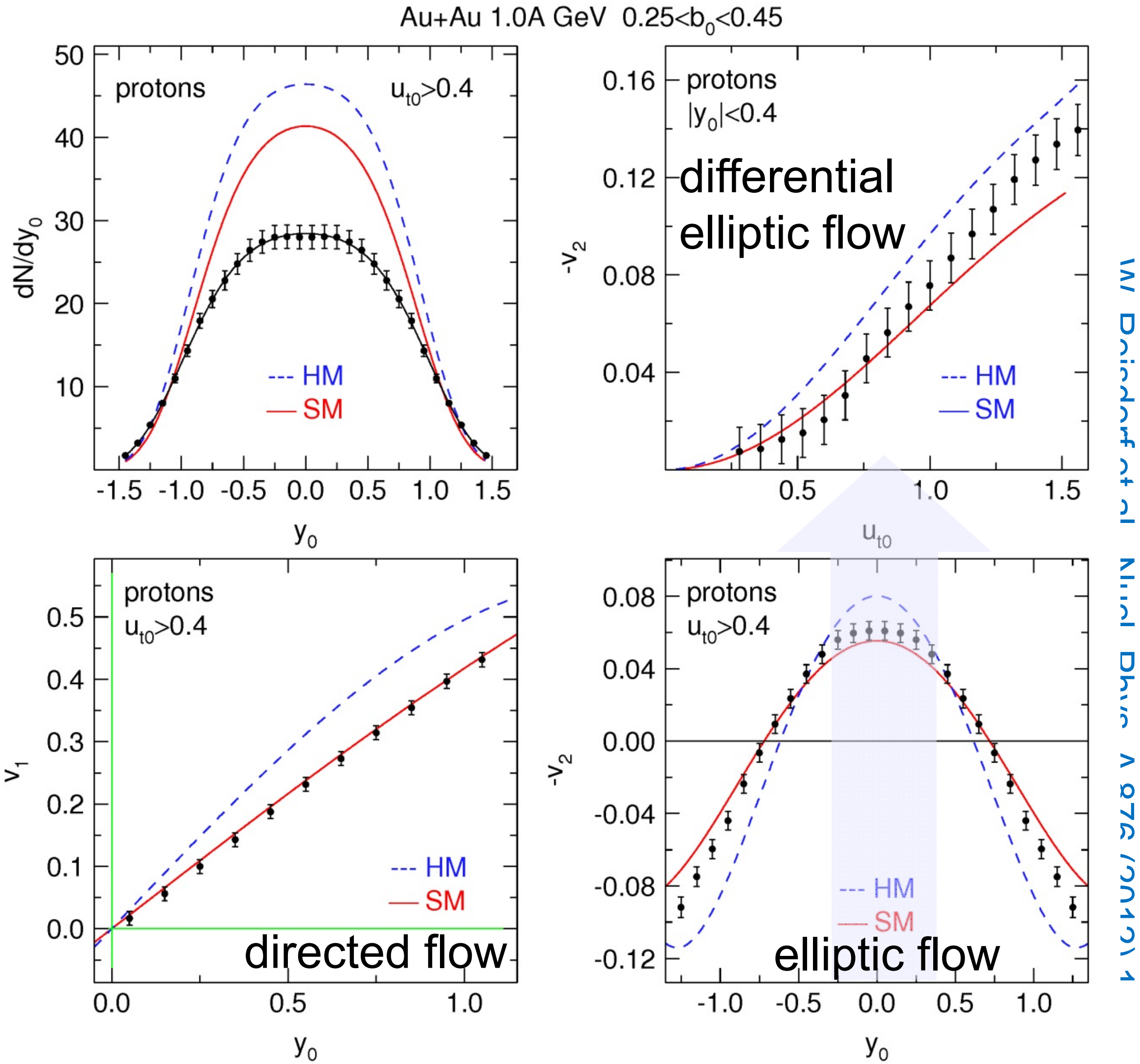


Stopping and flow are correlated

- ➢ constraining σ_{NN}, EOS...

IQMD, C. Hartnack et al. EPJ A1 (1997) 151

Collective flows in Au+Au at 1.0 AGeV



All flow results

- Au+Au 0.4 – 1.5AGeV Ru+Ru/Zr+Zr
- directed flow
- elliptic flow
- protons
- d, t, ^{3}He, α

reasonably well described by IQMD transport code employing **a soft EOS for symmetric matter**

➢ **talk by A. Le Fevre**

IQMD, C. Hartnack et al. EPJ A1 (1997) 151

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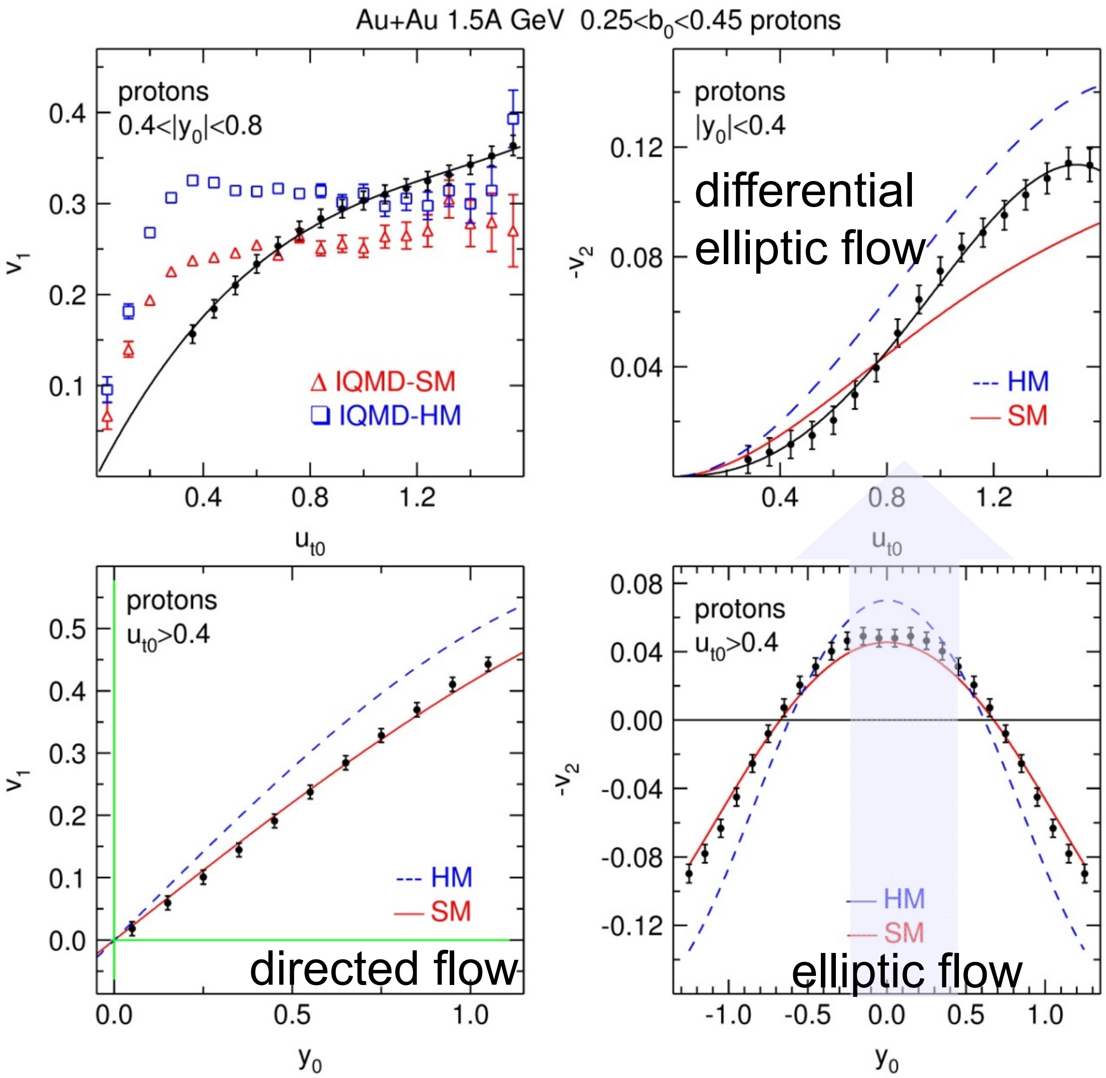

W. Reisdorf et al, Nucl. Phys. A 876 (2012) 1

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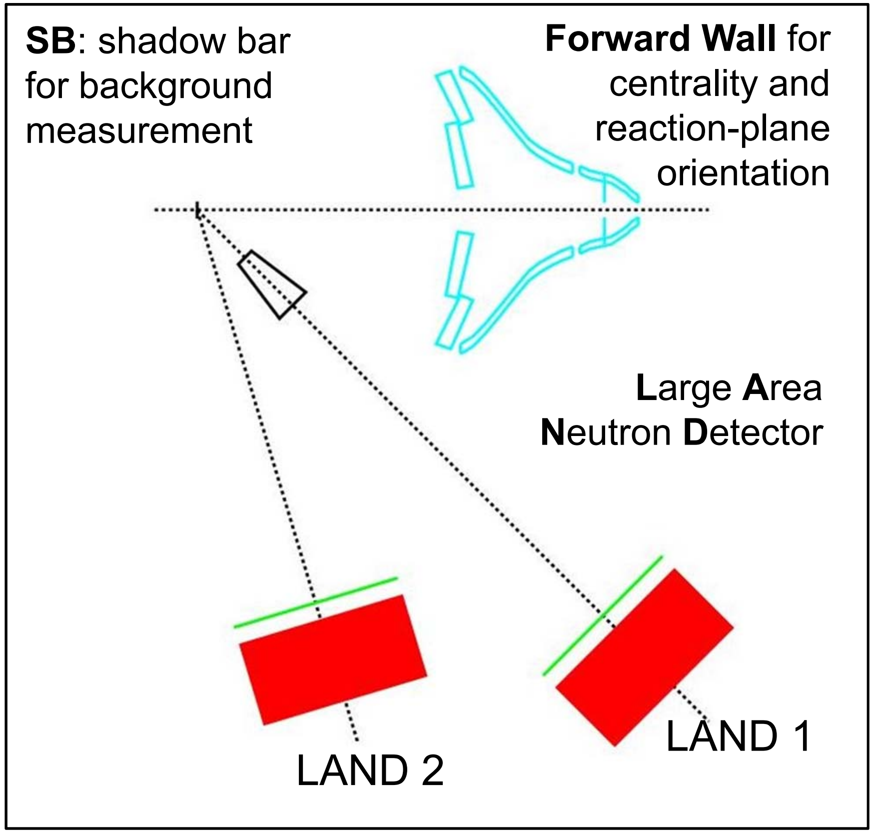
IQMD, C. Hartnack et al. EPJ A1 (1997) 151

Elliptic flow of neutrons and charged particles
From LAND + FOPI to ASY-EOS + LAND

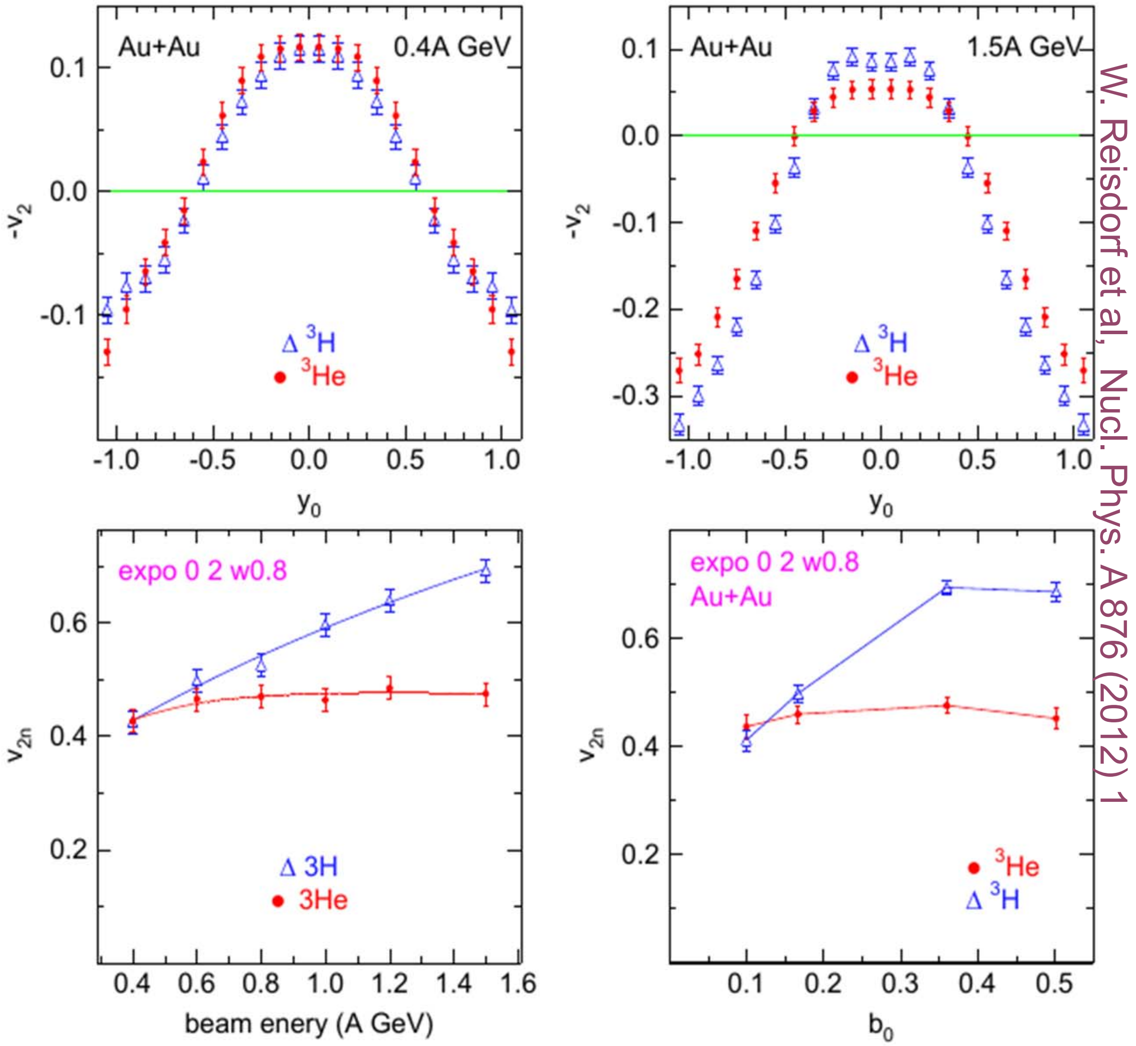


Neutron squeeze-out:
Y. Leifels et al., PRL 71, 963 (1993)

→ **Talk by P. Russotto**

Symmetry energy at high densities? – Elliptic flow of t and ^{3}He

Au+Au 0.25 < b_0 < 0.45



Same system

- difference of t and ^{3}He elliptic flow rising with energy
- and larger for peripheral events
- momentum vs density effect
- creation of t and ^{3}He

Parameterization of shape

$$v_{2n} = |v_{20}| + |v_{22}|$$

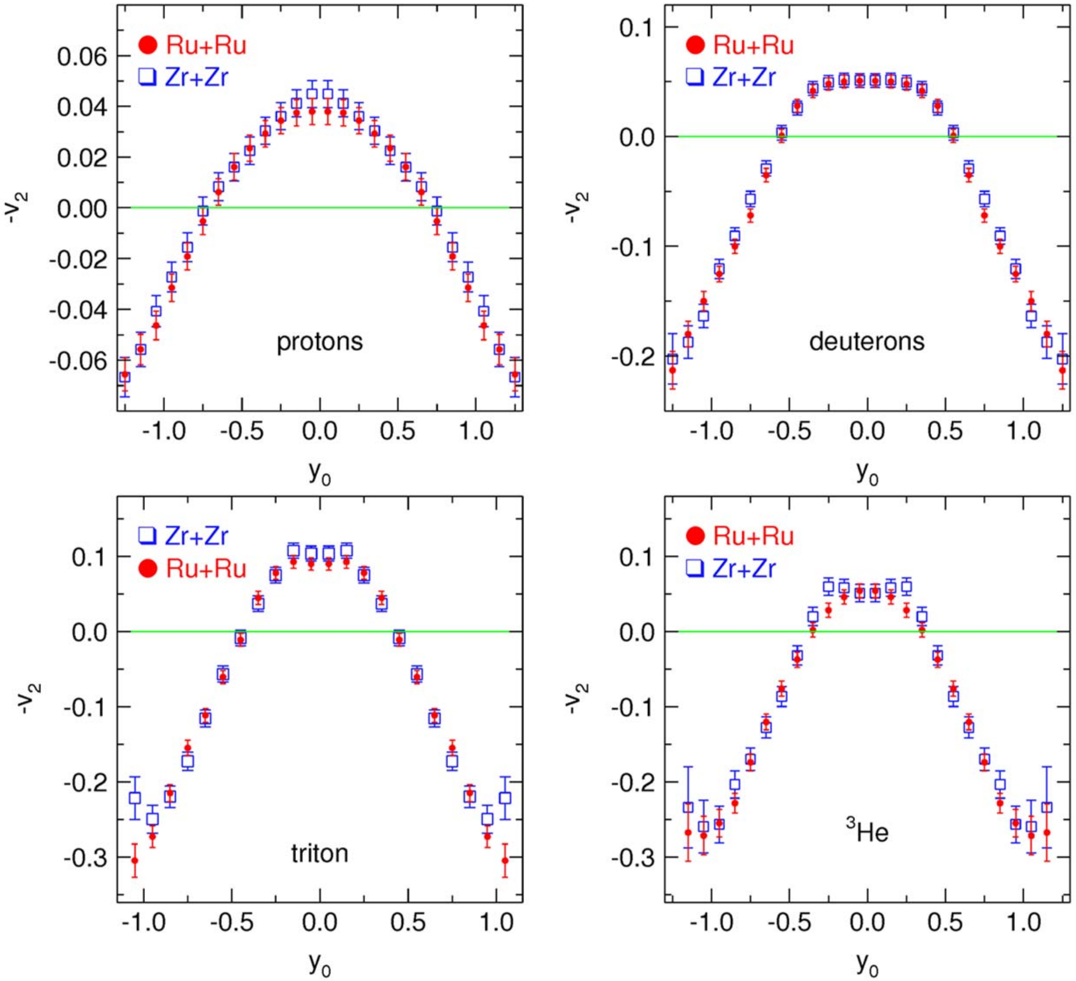
$$v_2(Y^{(0)}) = v_{20} + v_{22} \cdot Y^{(0)2}$$

beam energy vs

impact parameter

Elliptic flow
Changing isospin of system

Ru+Ru/Zr+Zr 1.5AGeV $0.25<b_0<0.45$ $u_{t0}>0.4$

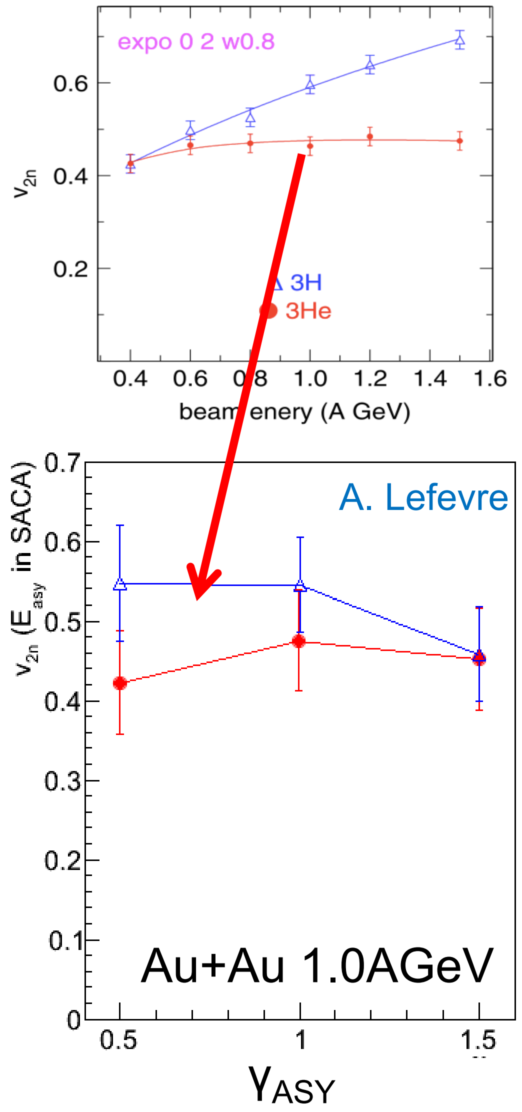


W. Reisdorf et al, Nucl. Phys. A 876 (2012) 1

Systems with same mass but with different isospin content

- $^{96}_{44}Ru + Ru, ^{96}_{40}Zr + Zr$
- no significant difference between neutron rich and proton rich system
- difference between t and ^{3}He persistent

Towards an understanding of the t/^{3}He elliptic flow

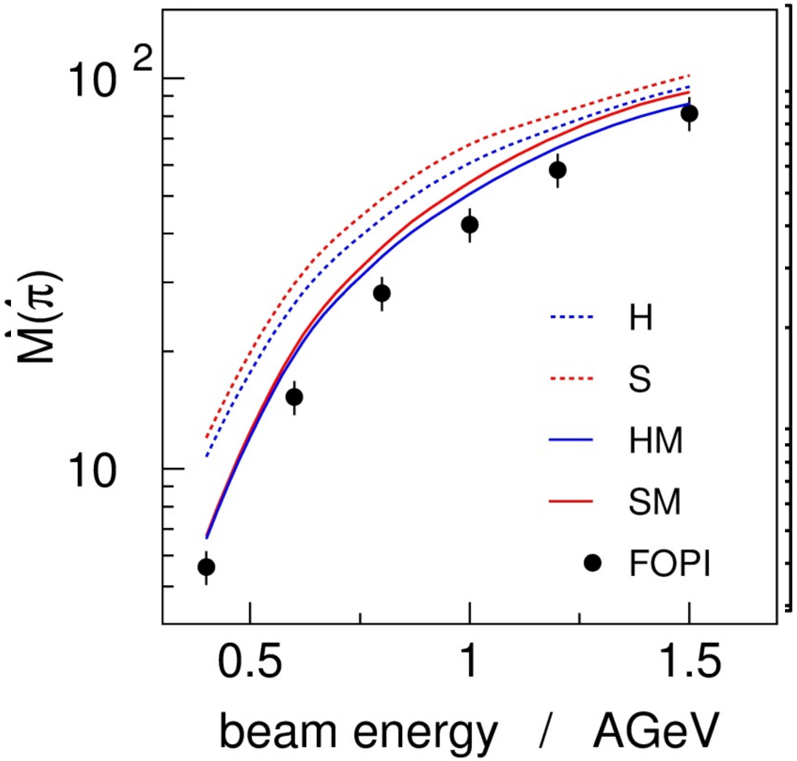


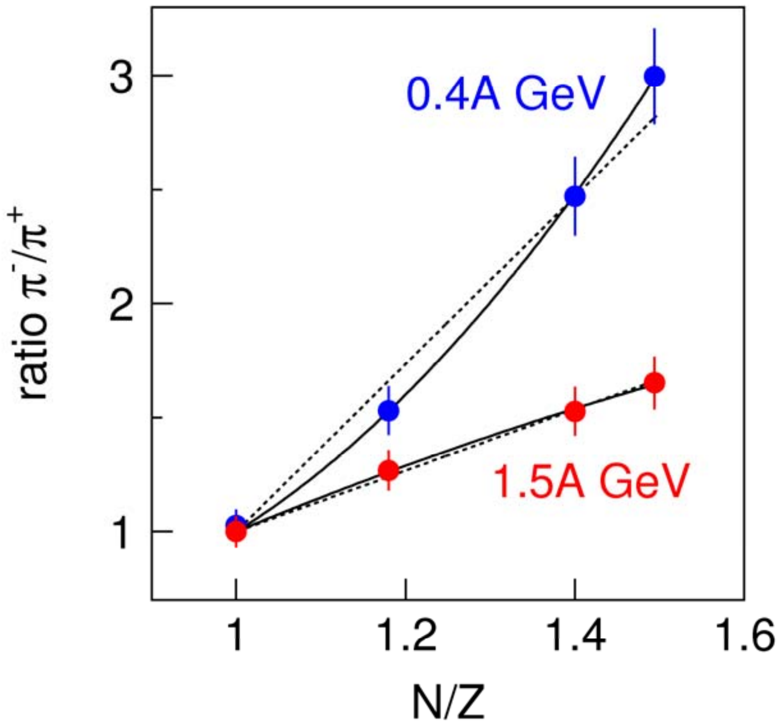
IQMD SM + SACA - simulated annealing mechanism

Ingredients to the binding energy of the clusters:

- Volume component: mean field (Skyrme, dominant), for NN, NΛ (Hypernuclei)
- Surface effect correction: Yukawa term.
- Asymmetry energy : 23.3MeV $(\langle\rho'_B\rangle)^{(\gamma_{ASY})}.(\langle\rho'_n\rangle-\langle\rho'_p\rangle)^2/\langle\rho'_B\rangle)$
- Extra « structure » energy (N,Z,ρ) = $B_{MF}(\rho).((B_{exp}-B_{BW})/(B_{BW}-B_{Coul}-B_{asy}))(\rho_0)$
- ^{3}He+n recombination.
- Secondary decay: GEMINI.

Particle production
Pion multiplicities





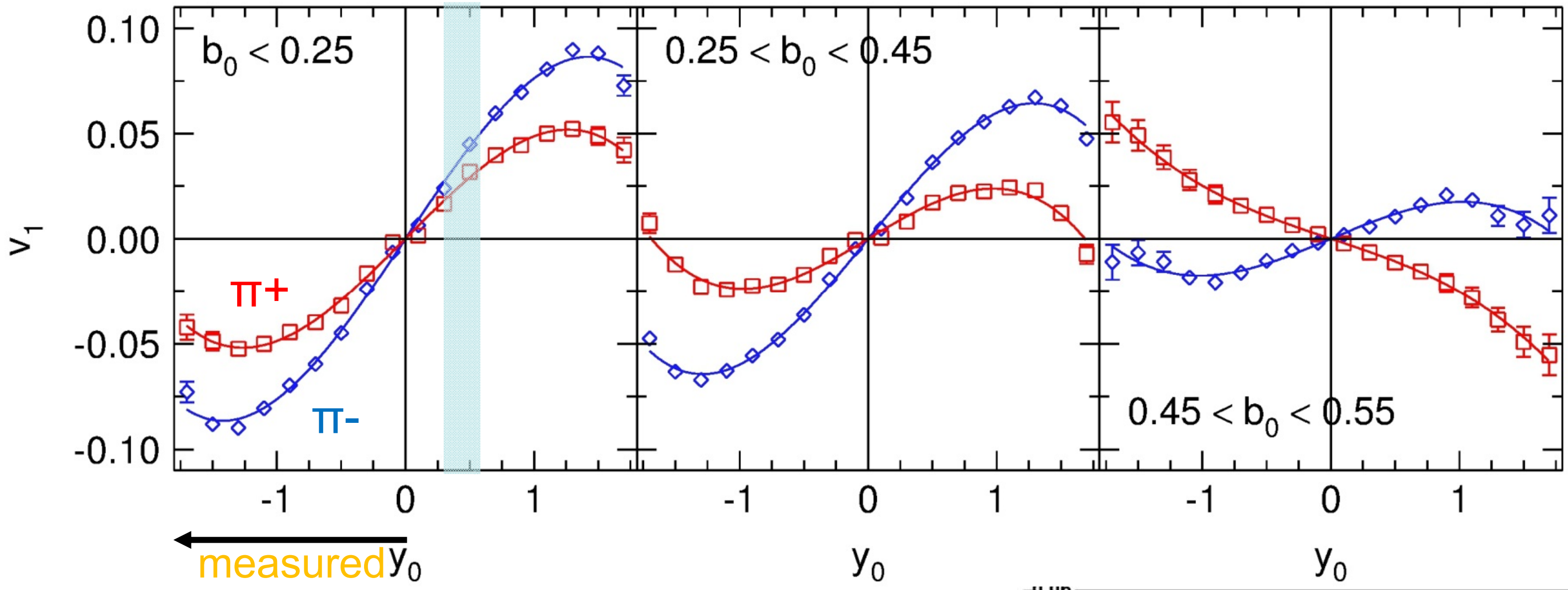
- in detail complicated (lifetime and shape of Δ), but reasonably well reproduced (~10 %)
- NO sensitivity to the symmetric EOS
- BUT to momentum dependence

π^-/π^+ ratio sensitive to (N/Z) of system

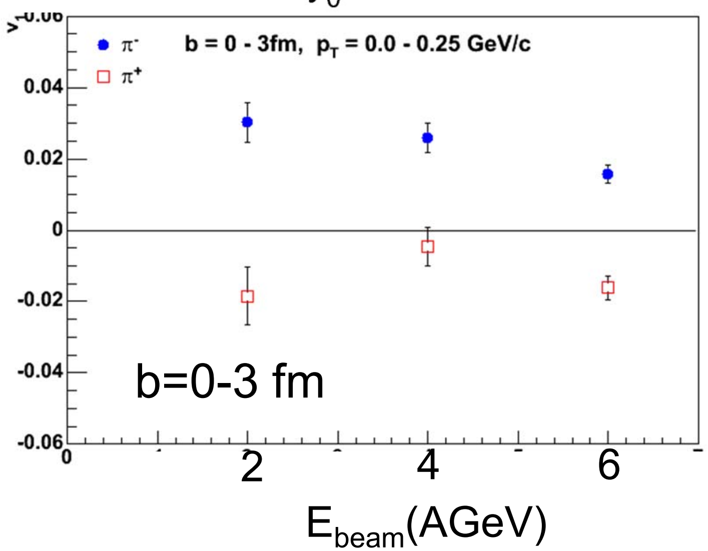
Isobar model $NN \rightarrow N\Delta \rightarrow NN\pi$

$$\frac{\pi^-}{\pi^+} = \frac{5N^2 + NZ}{5Z^2 + NZ} \approx \left(\frac{N}{Z}\right)^2$$

Pion directed flow in Au+Au collisions at 1.5A GeV



- clockwise rotation of directed flow signal when b is increased
- at all centralities difference between π^+ and π^-
  - similar observations have been made at higher (AGS) energies
- Quantitatively not reproduced by IQMD-SM

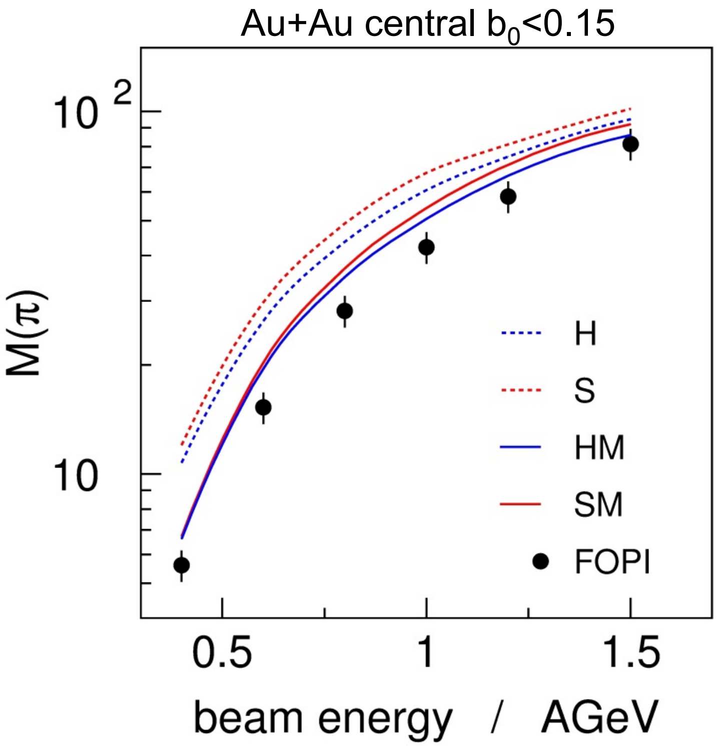


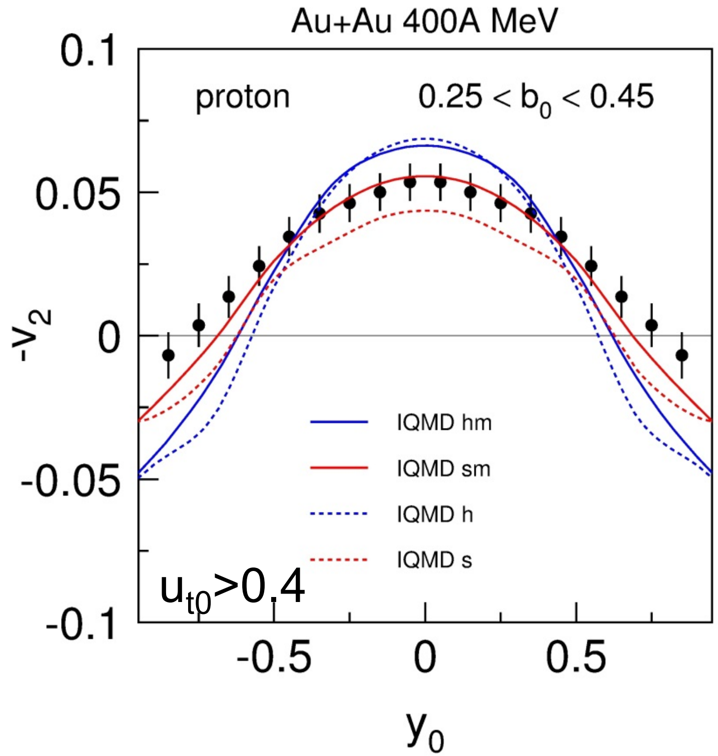
E895 Issah et al. SQM 2004

Conclusions

- FOPI collected vast amount of data on HICs between 0.1 and 1A GeV
- convincing conclusions on basic nuclear properties imply a successful simulation:
  - of the full set of experimental observables
  - with the same code
  - using the same physical and technical parameters
- reached for a number of observables using the SM option

Are there other solutions?

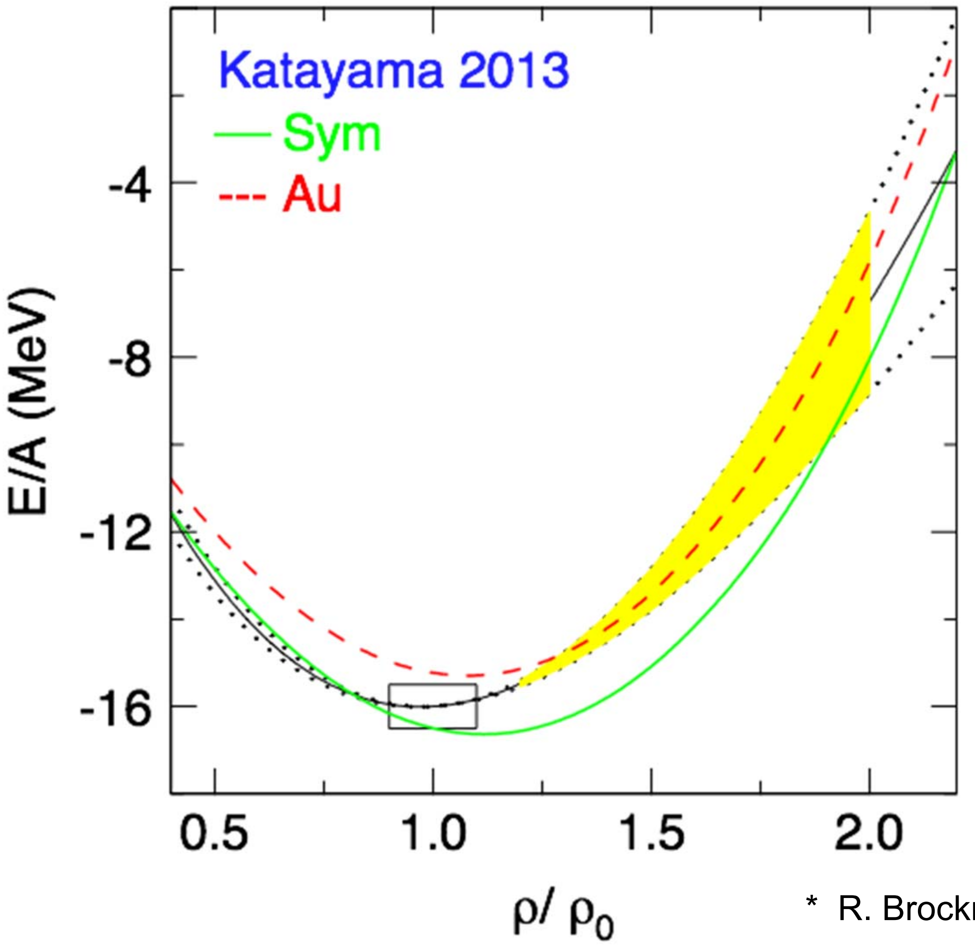




Choice in IQMD for
- σ_{NN}, momentum dependence of optical potentials, prescription of Pauli blocking and detailed balance etc.

describes most of the data

Comparison of FOPI "constrained" EOS to recent microscopic model calculations



Dirac-Brueckner-Hatree-Fock (DBHF) calculation* using the Bonn A nucleon-nucleon potential **

* R. Brockmann, R. Machleidt, Phys. Rev. C 42 (1990) 1965.

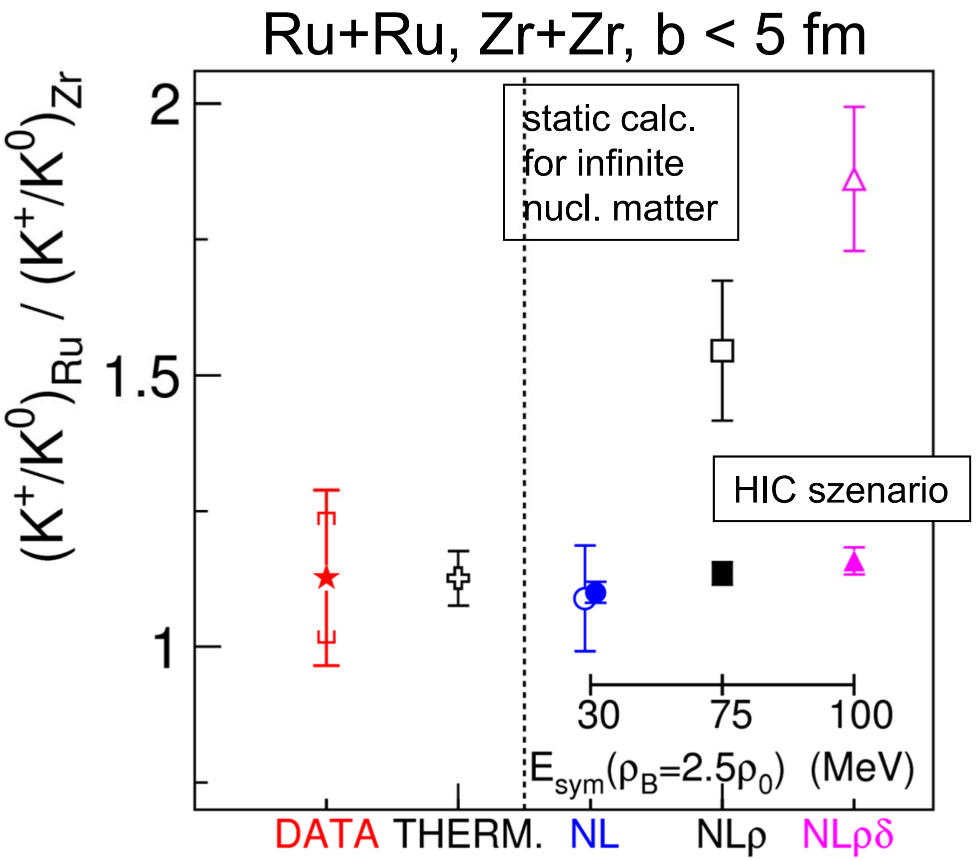
** T. Katayama, K. Saito, Phys. Rev. C 88 (2013) 035805.

Conclusions

- FOPI collected vast amount of data on HICs between 0.1 and 1A GeV
- convincing conclusions on basic nuclear properties imply a successful simulation:
  - of the full set of experimental observables
  - with the same code
  - using the same physical and technical parameters
- reached for a number of observables using the SM option
- for some other data not yet the case
  - pion yields: differ only by about 10% between HM and SM options, imply high experimental accuracy and better transport model predictions (elementary pion cross sections not precisely known).
- a single parameter v_{2n}, characterising the elliptic flow over a large rapidity interval, for protons and other light isotopes -> clear discrimination for soft EOS.
- stiffness of the asymmetry energy can be discriminated by the shape (v_{2n}) the elliptic flow over a large range of rapidity (not only mid-rapidity) of ^{3}He and tritons. Preliminary indication of $0.5 \le \gamma_{asy} < 1$ by confronting IQMD-SACA to FOPI data.

Outlook
Kaon production ratio as a probe for symmetry energy

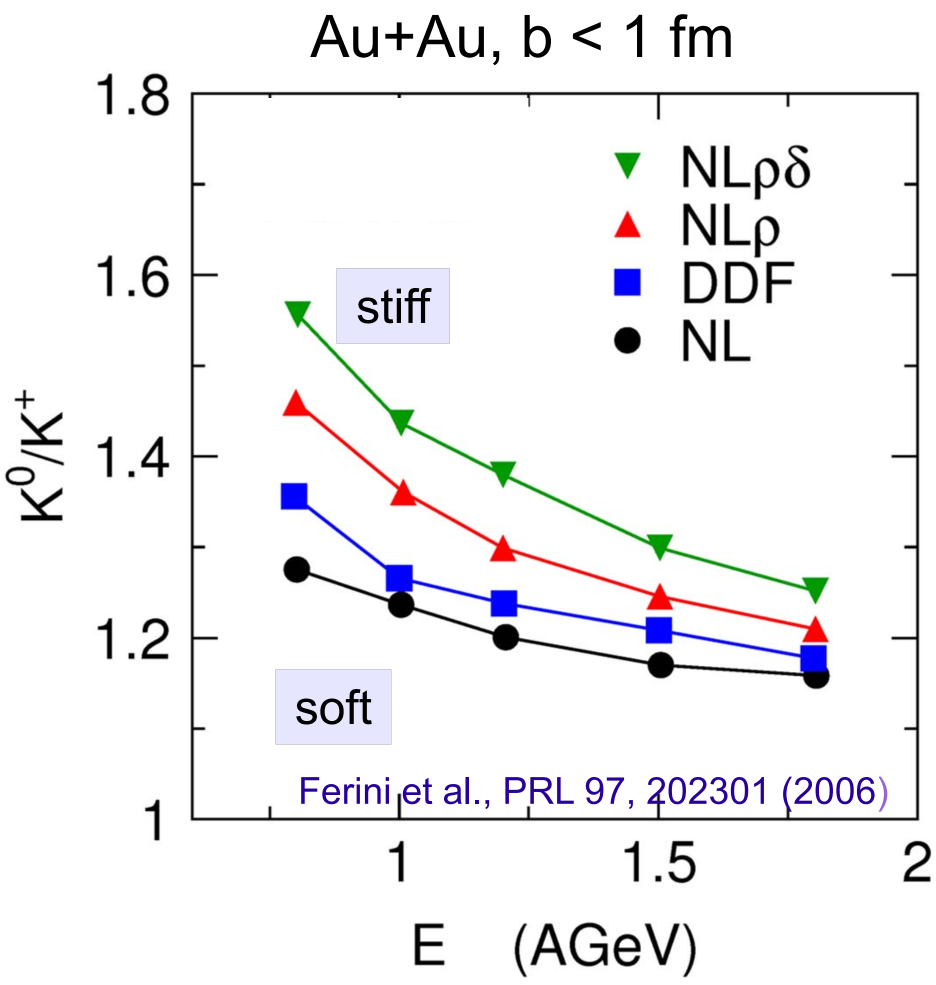
X.Lopez, PRC (2007)



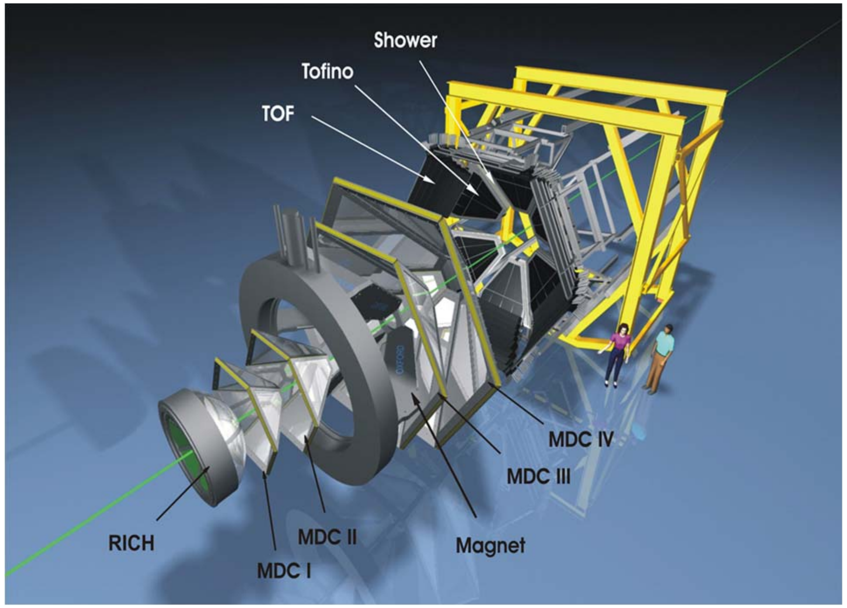
HIC scenario:
- fast neutron emission (mean field)
- NN=>NΔ threshold effects

see, e.g., di Toro et al., J.Phys.G (2010)

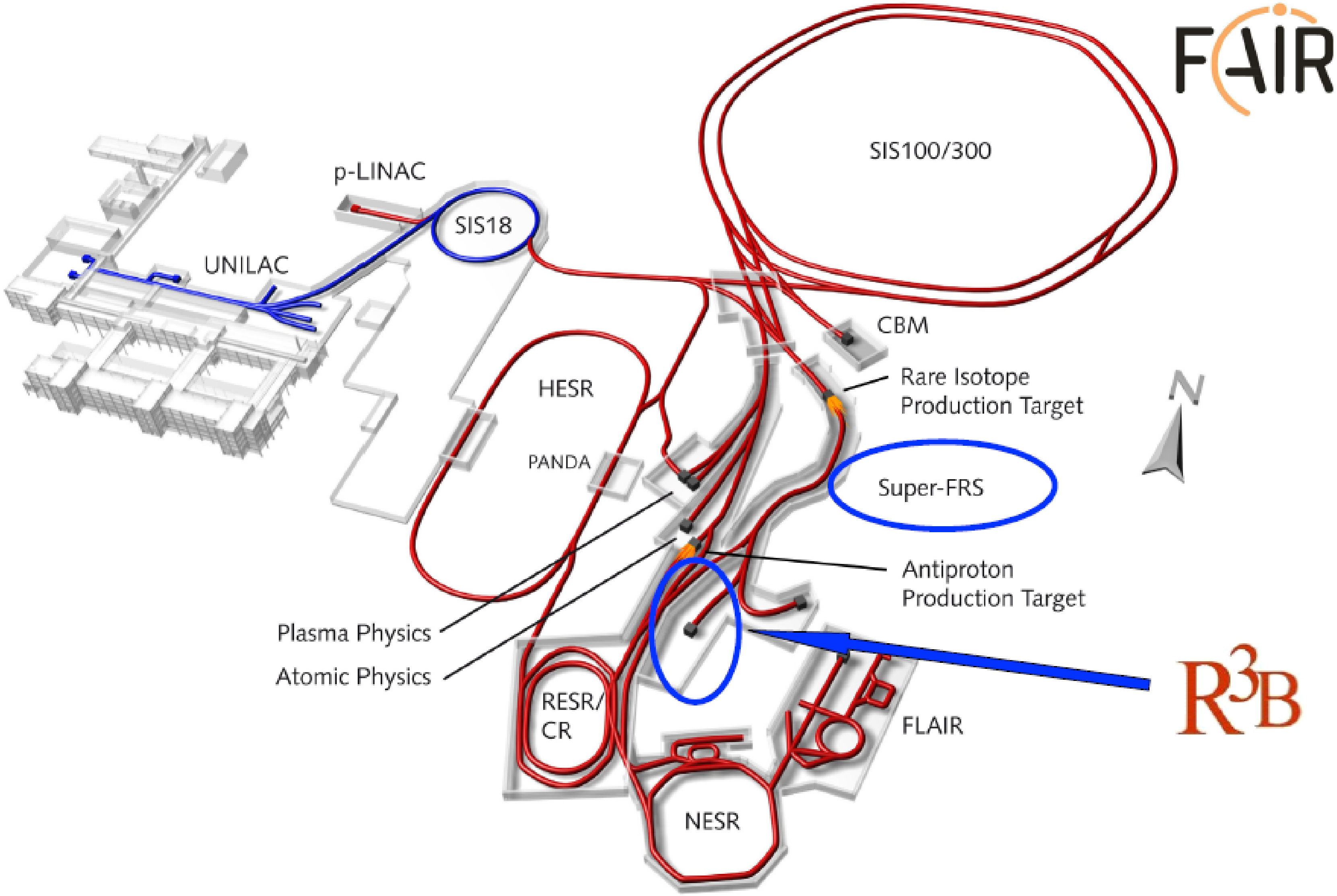
Perspective at SIS18 with HADES



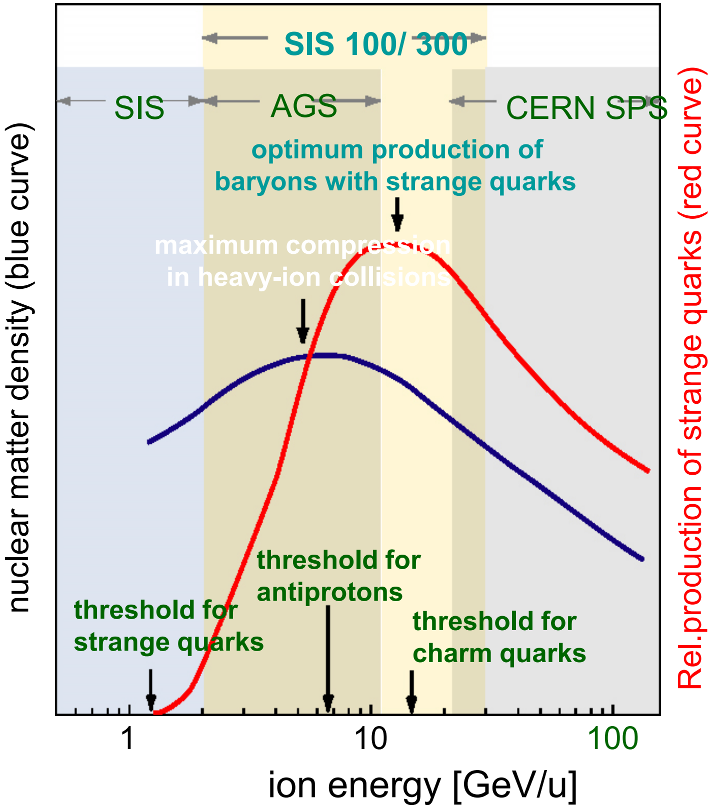
- higher sensitivity at lower energies
- requires excellent kaon identification and long beam times (~3-4 weeks)
- HADES



FAIR – Facility



Nuclear EOS of dense matter – Maximum compression reached at FAIR energies



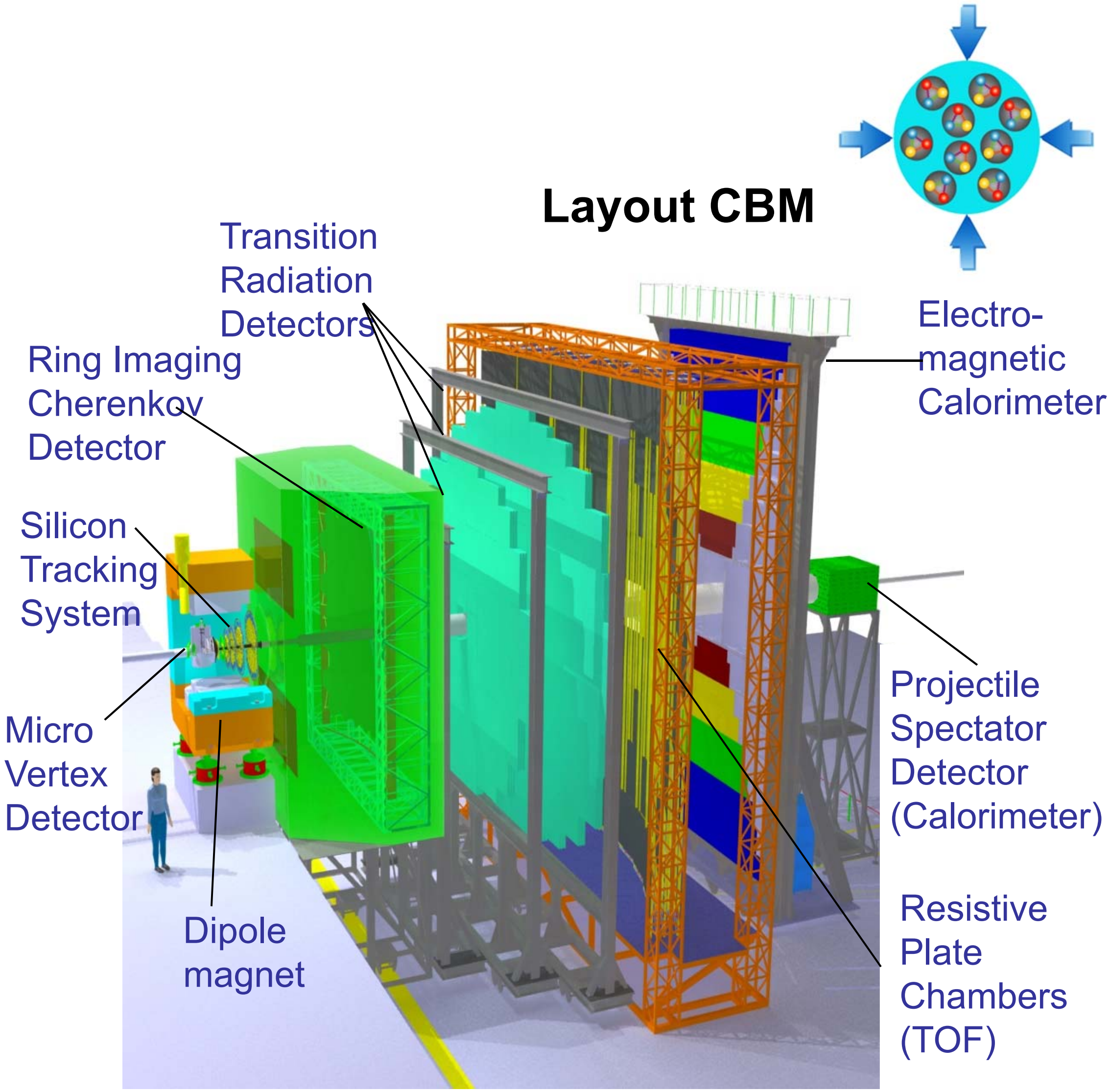
Observables:

Particle production

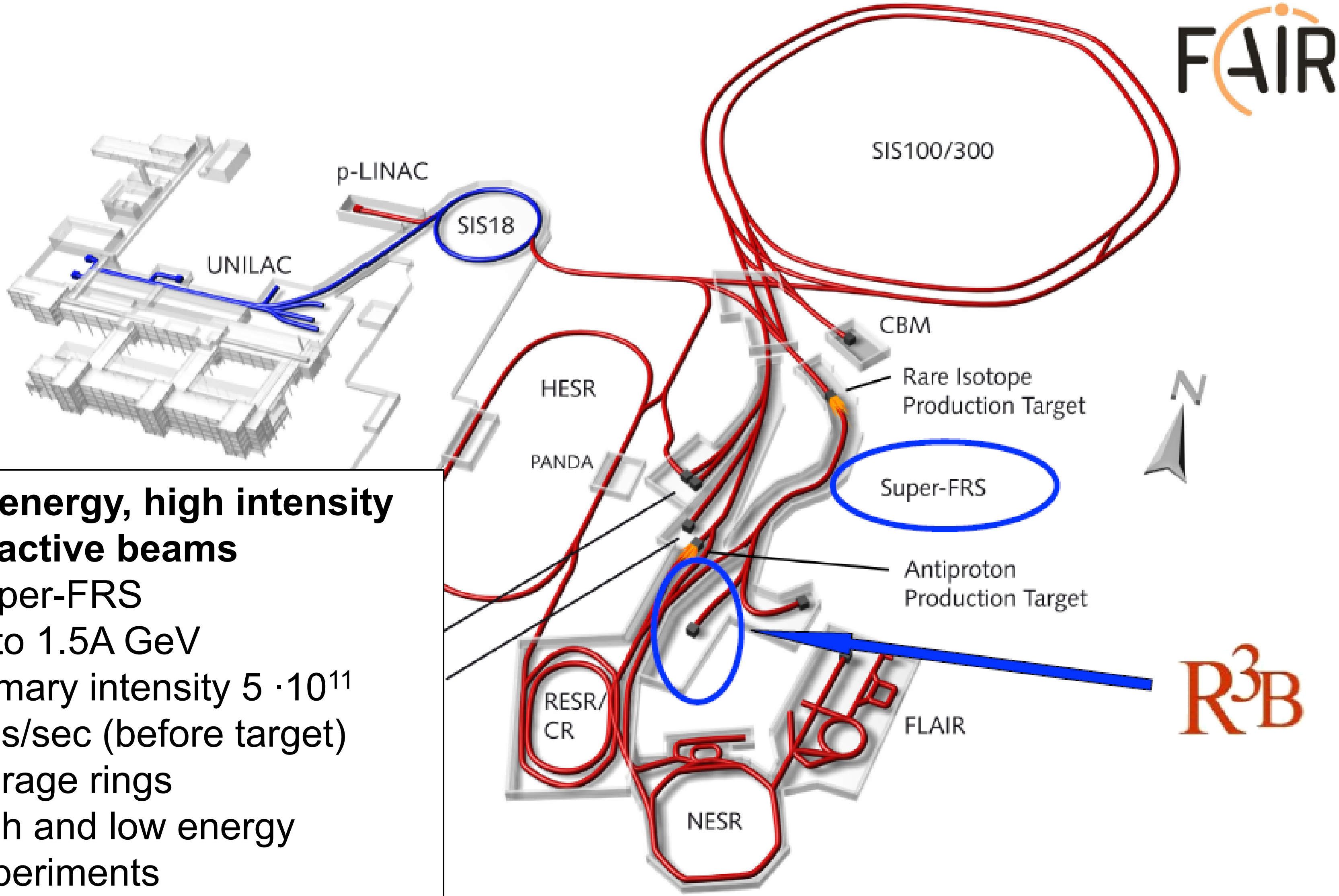
Flow of bulk matter

Production of D^0, $D^{\pm}$

ρ, ω, $\phi \rightarrow e^+e^-$ or $\mu^+\mu^-$



Radioactive beams at FAIR



High energy, high intensity radioactive beams

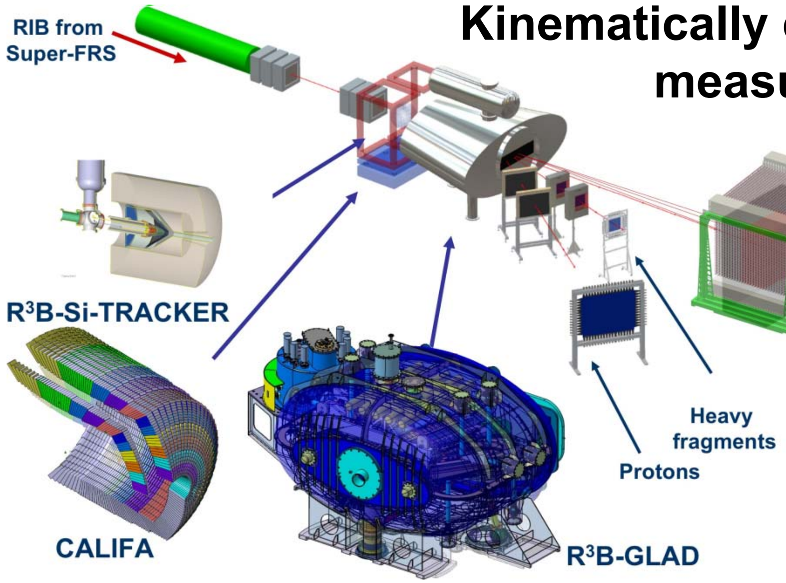
- Super-FRS
- upto 1.5A GeV
- primary intensity 5 $\cdot 10^{11}$ ions/sec (before target)
- storage rings
- high and low energy experiments

Studies of neutron rich matter with R^3B

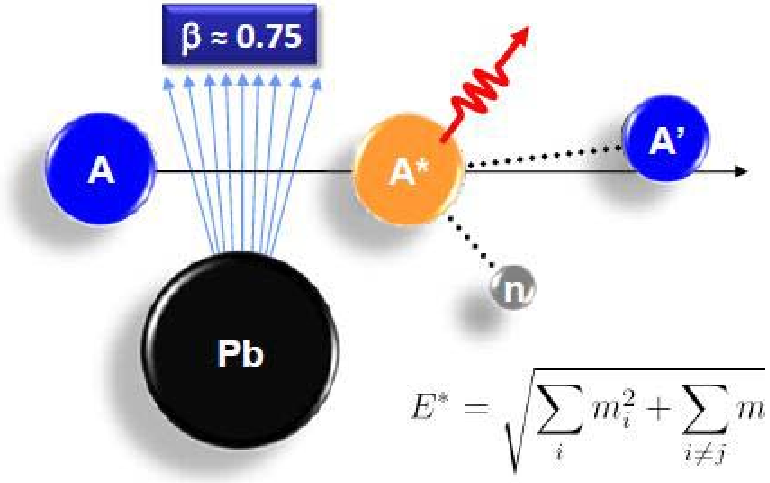
Neutron skins
- dipole response of nuclei
  - Pygmy resonances
  - dipole polarizability
- matter radii

Correlations in nuclei
- hadronic quasi free scattering

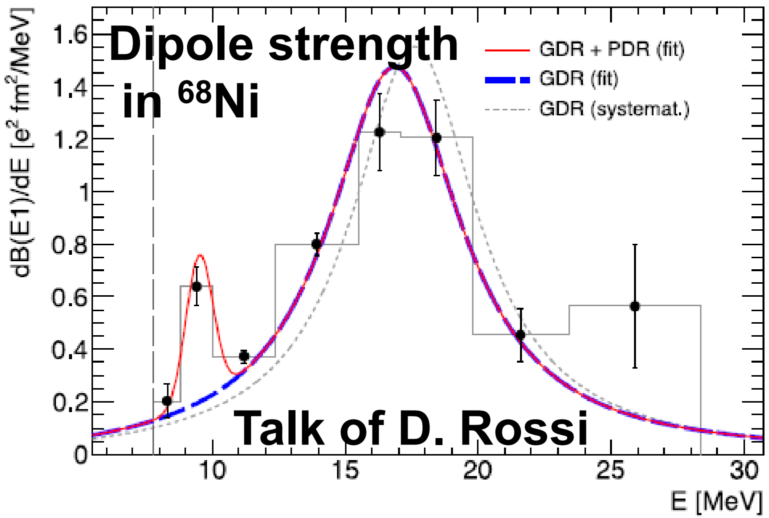
Kinematically complete measurements



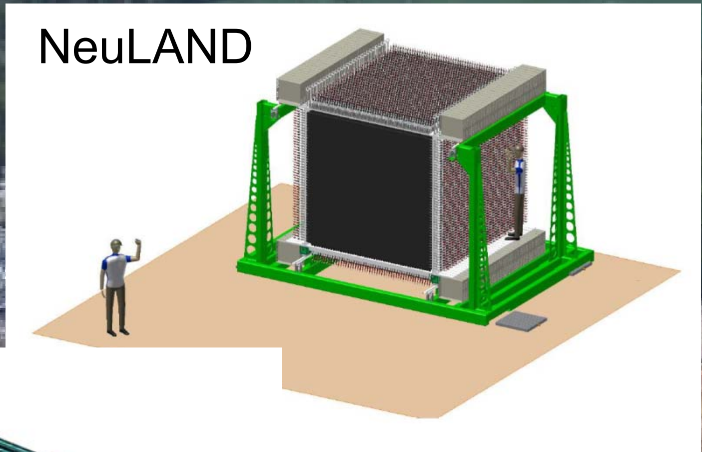
Heavy ion induced electromagnetic Excitation

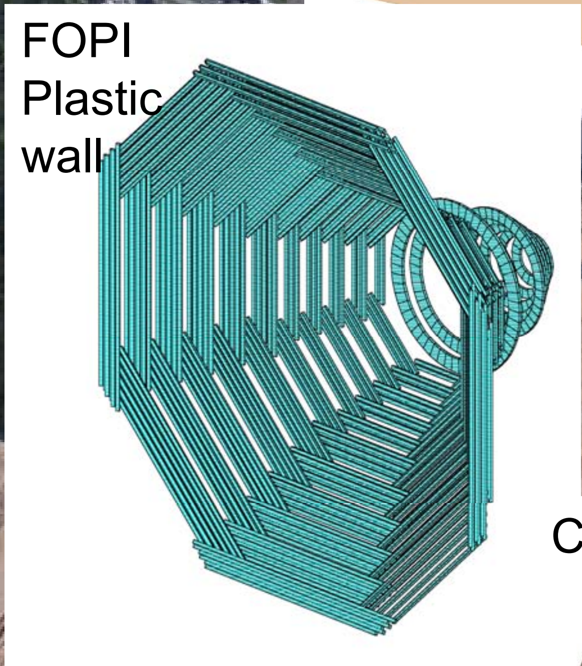


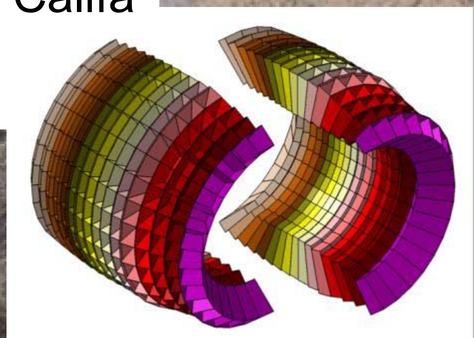
$$E^* = \sqrt{\sum_i m_i^2 + \sum_{i \neq j} m$$



Symmetry energy at supra normal densities
Prospects at SIS18 and later at FAIR







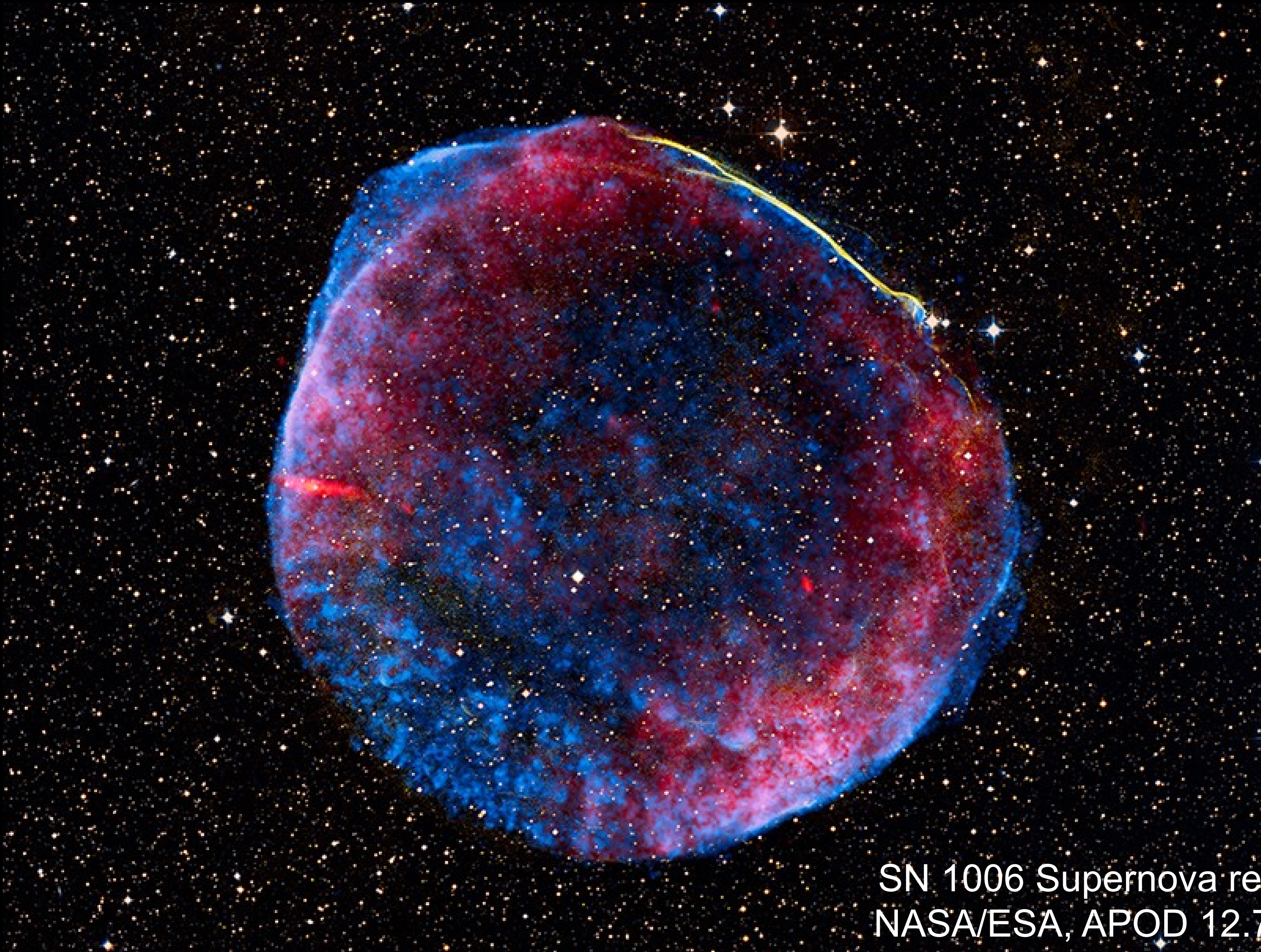
Symmetry energy at supra-normal densities

- Radioactive beams at the highest rigidities
- Study of momentum dependence of isovector part
- Extend studies to higher densities
- n/p and t/^{3}He ratio and flow
  - detectors for reaction plane and impact parameter determination
  - neutron + charged particle detectors

Other observables:

- Pions sensitive at 250-400A MeV
- Kaon ratio requires dedicated setup (magnet + tracking + ToF)
  - feasibility needs still to be proven -> HADES@SIS18

Thank you for your attention!



SN 1006 Supernova remnant
NASA/ESA, APOD 12.7.2014