Symmetry Term at High Density from Heavy Ion Collisions

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for the ASY-EOS Collaboration

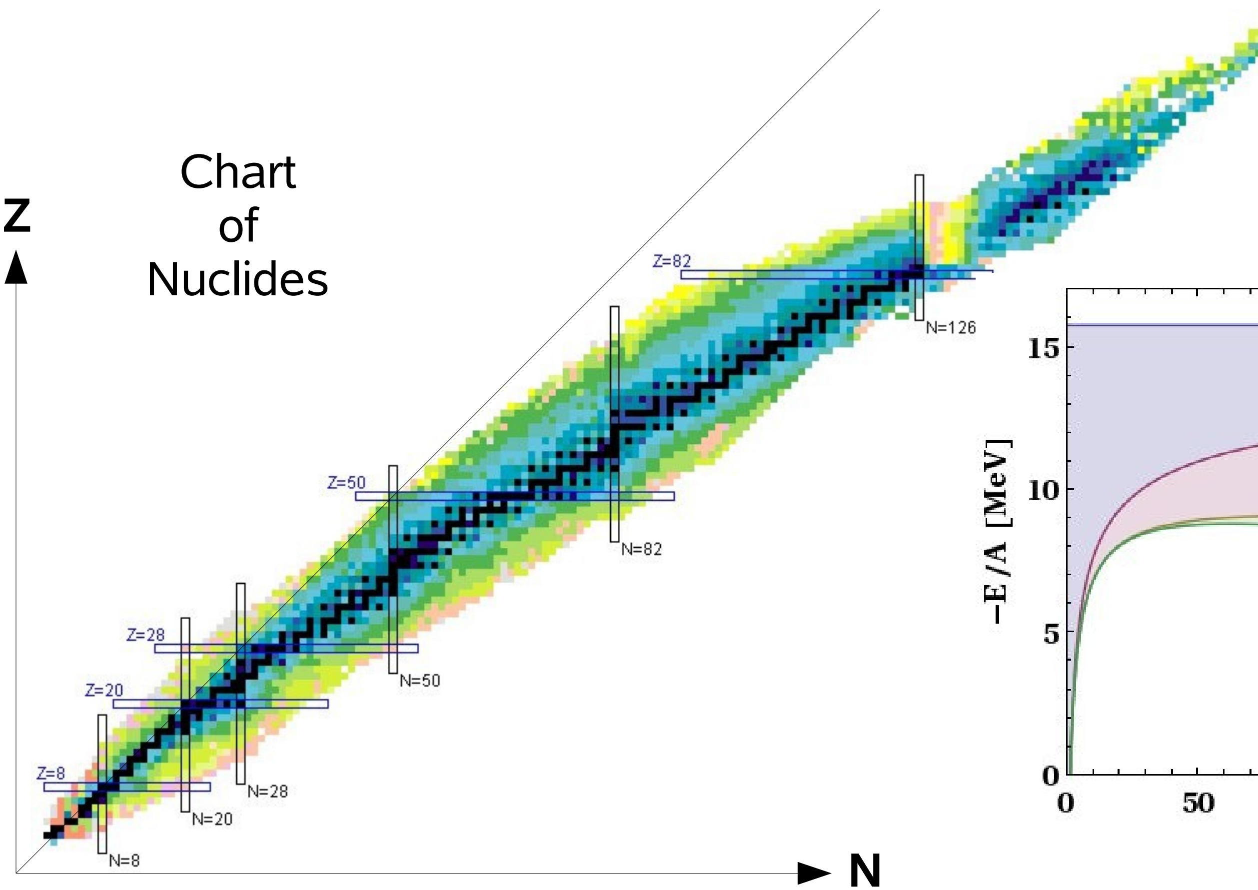
- Symmetry energy
- Reanalysis of the FOPI/LAND data
  [P. Russotto et al., PLB 697 (2011) 471]
- ASY-EOS Experiment of May 2011 (GSI)

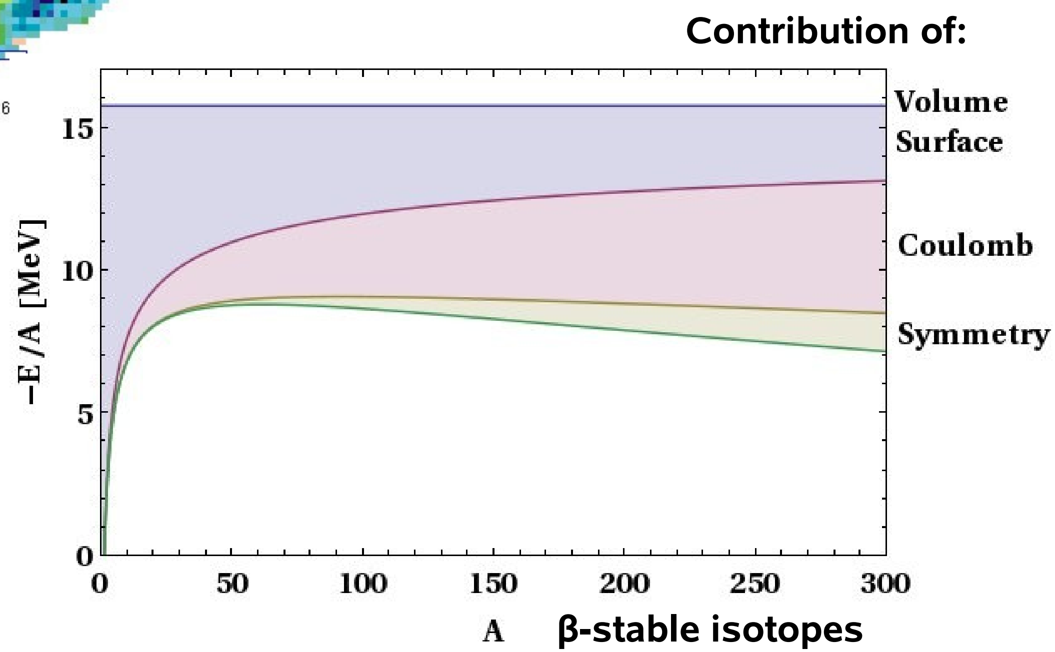
Symmetry Energy (nucleus)

$$\frac{E_B}{A} = \underbrace{-a_V}_{Volume} + \underbrace{a_S \frac{1}{A^{1/3}}}_{Surface} + \underbrace{a_C \frac{Z^2}{A^{4/3}}}_{Coulomb} \underbrace{+ a_A \left(\frac{N-Z}{A}\right)^2}_{Symmetry} \pm \underbrace{a_P \frac{1}{A^{3/2}}}_{Pairing}$$

Binding Energy/Nucleon
(Bethe-Weizsäcker)
acc. better than 1%

a_V=15.8	a_S=18.0	a_C=0.72	a_A=23.5	a_P=11.5|0	[MeV]





Symmetry Energy (nuclear matter)

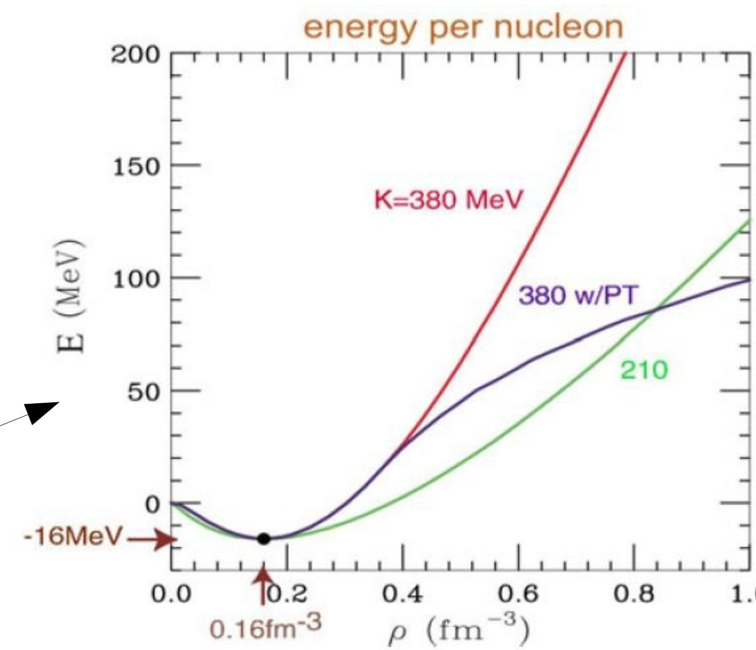
$$\frac{E_B}{A} = \underbrace{-a_V}_{Volume} + \underbrace{a_S \frac{1}{A^{1/3}}}_{Surface} + \underbrace{a_C \frac{Z^2}{A^{4/3}}}_{Coulomb} \underbrace{+ a_A \left(\frac{N-Z}{A}\right)^2}_{Symmetry} \underbrace{\pm a_P \frac{1}{A^{3/2}}}_{Pairing}$$

Energy per nucleon in nuclear matter (EoS):

$$E(\rho,\delta) = E(\rho,0) + E_{sym}(\rho)\,\delta^2 + o(\delta^4)$$

dominant symmetric matter (N=Z) term:

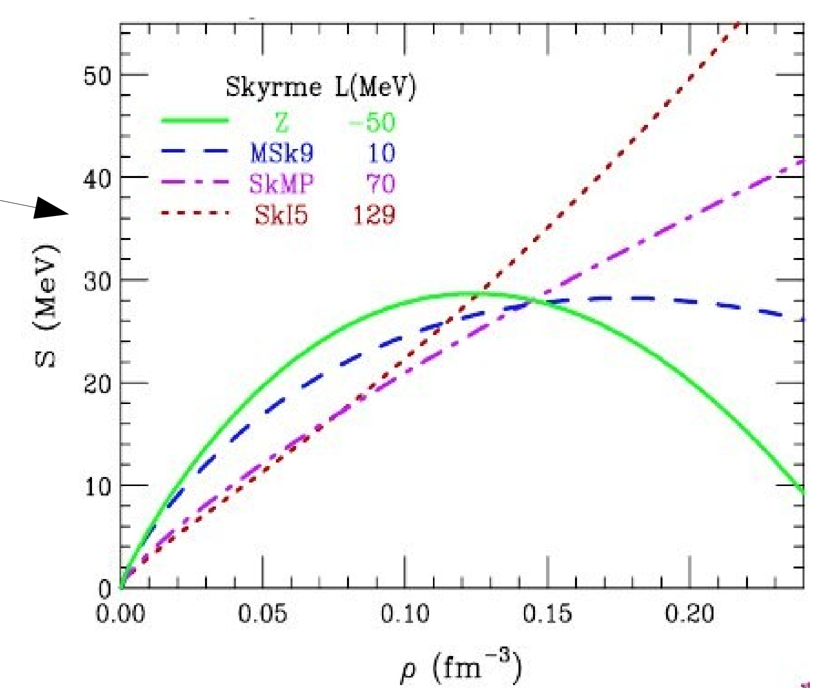
$$E(\rho,0) \approx -a_V + \frac{K}{18}\left(\frac{\rho-\rho_o}{\rho_o}\right)^2 + \cdots$$



P. Danielewicz, arXiv:nucl-th/0512009

symmetry term:

$$E_{sym}(\rho) \approx a_A^V + \frac{L}{3}\left(\frac{\rho-\rho_o}{\rho_o}\right) + \frac{K_{sym}}{18}\left(\frac{\rho-\rho_o}{\rho_o}\right)^2 + \cdots$$



(*)P. Danielewicz, J. Lee, NPA 818(2009)36

$\rho_n, \rho_p \rightarrow$ neutron, proton densities

$\rho = \rho_n + \rho_p \rightarrow$ nucleon density

$\delta = \frac{\rho_n - \rho_p}{\rho} \rightarrow$ relative neutron excess

$L = 3\rho_o \left.\frac{\partial E_{sym}}{\partial \rho}\right|_{\rho=\rho_o} \rightarrow \sim$ symmetry pressure

$K = 9\rho_o^2 \left.\frac{\partial^2 E}{\partial \rho^2}\right|_{\rho=\rho_o} \rightarrow$ compressibility

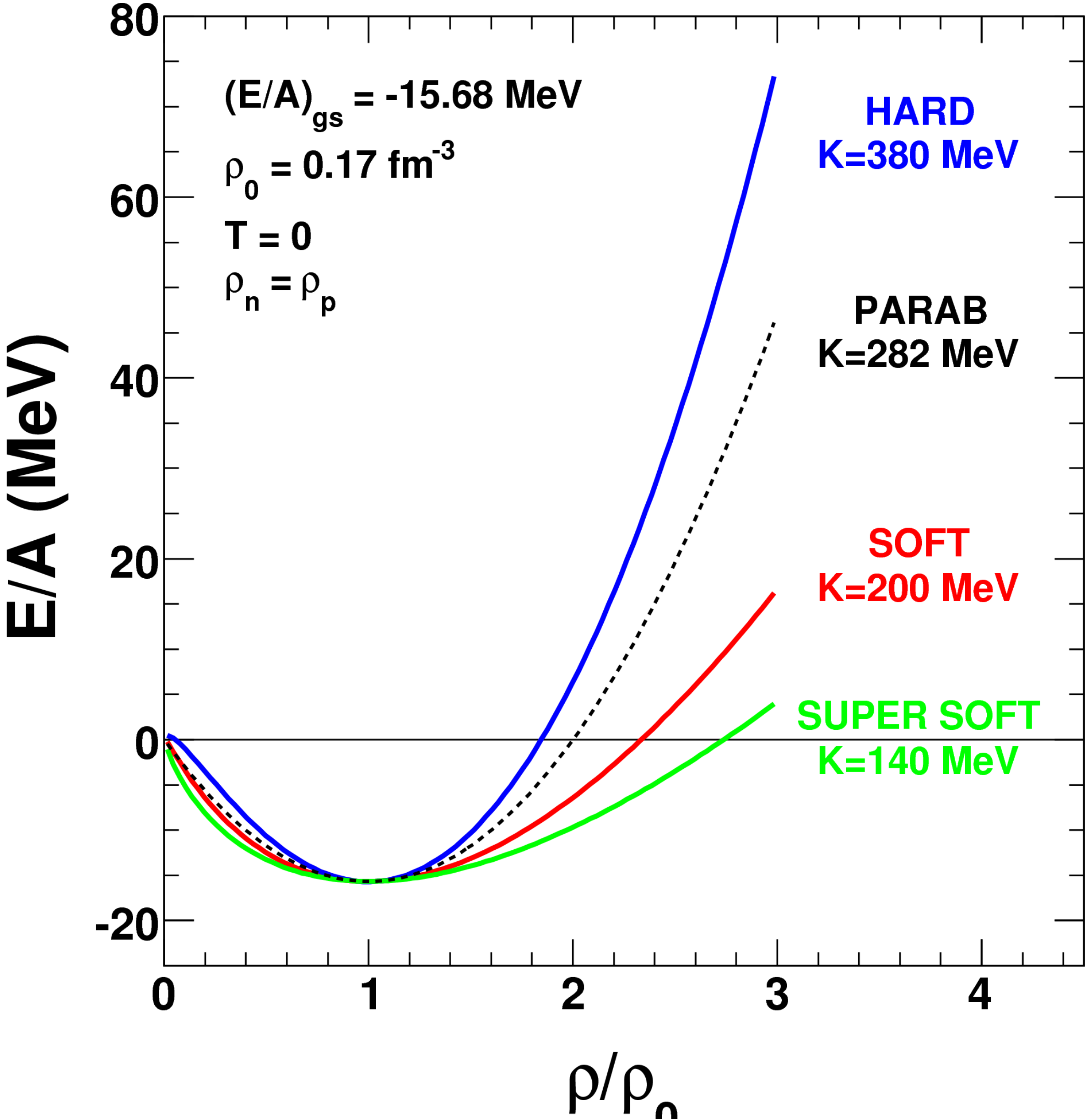
$a_V \approx 15.8\ MeV$

$a_A^V \approx 32.5^{(*)}\ MeV$

$\delta^2({}^{208}\mathrm{Pb}) \simeq 0.04$

$\delta^2({}^{271}\mathrm{Pb}) \simeq 0.16$

Symmetric matter (δ=0)



Simple Skyrme parametrization

$$\frac{E}{A}(\rho) = \frac{3\, p_F^2(\rho)}{10\, m} + \frac{\alpha}{2}\frac{\rho}{\rho_0} + \frac{\beta}{1+\gamma}\left(\frac{\rho}{\rho_0}\right)^{\gamma}$$

Compressibility parameter

$$K \equiv 9\,\rho^2 \left.\frac{\partial^2 E/A}{\partial \rho^2}\right|_{\rho=\rho_0}$$

Danielewicz, Lacey, Lynch: Science 298(2002)1592

Directed flow

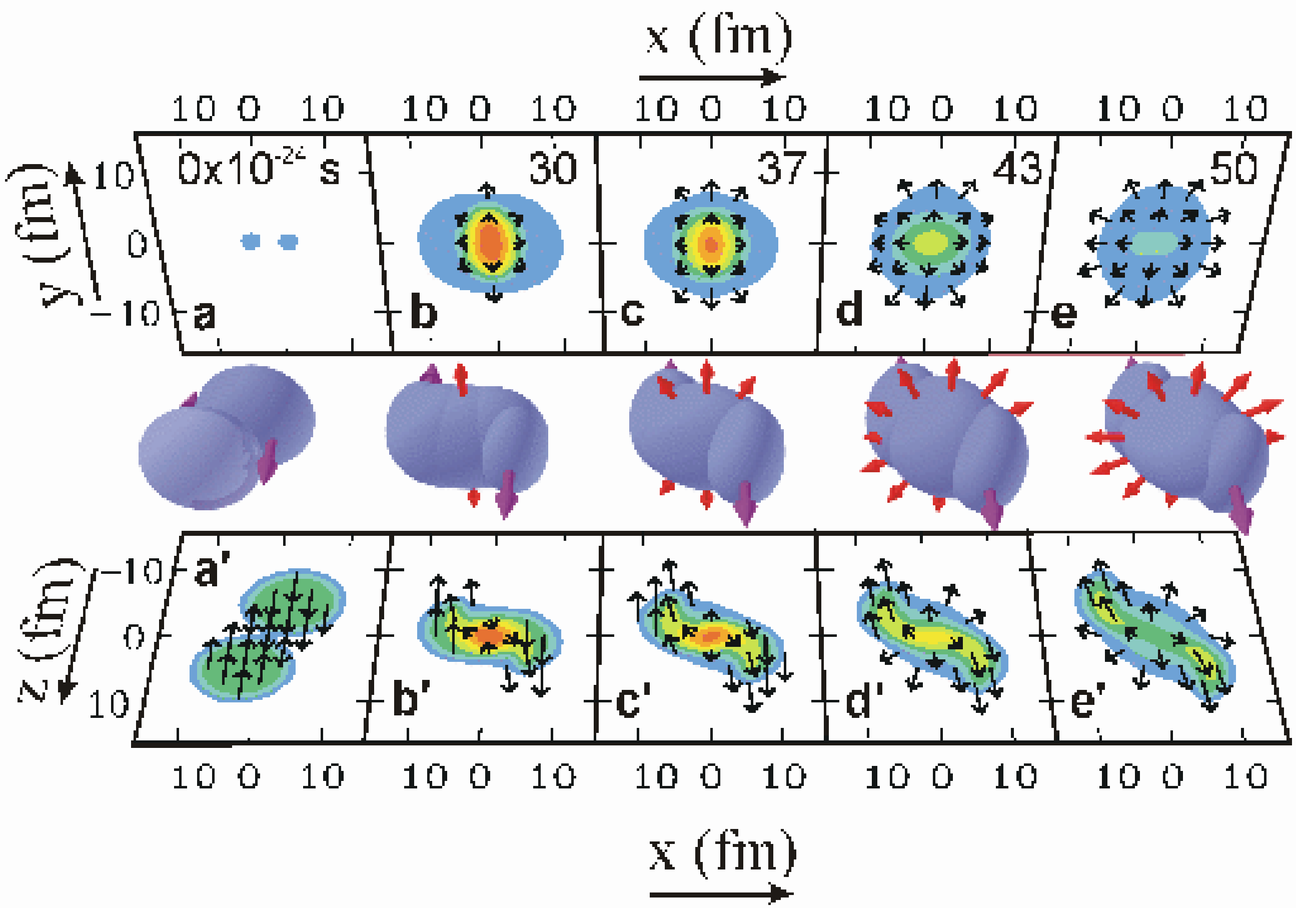
Flow -> a density sensitive observable

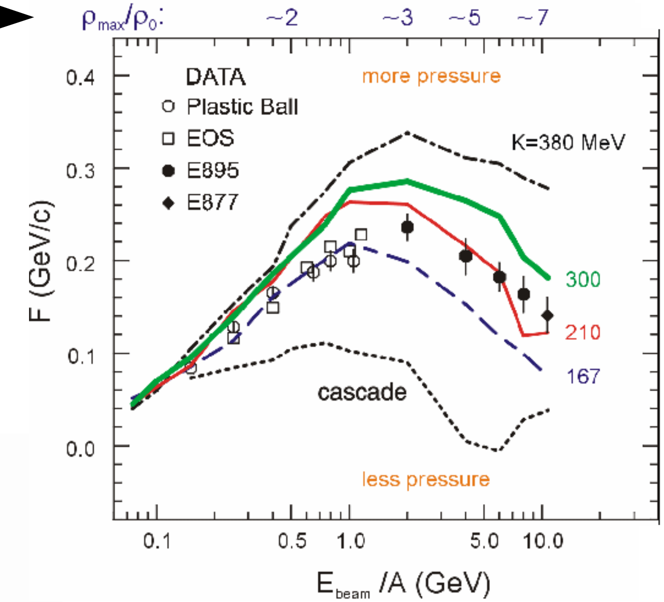
$$F = \left.\frac{d\langle p_x/A\rangle}{d(y/y_{cm})}\right|_{y/y_{cm}=1} \rightarrow \text{slope at midrapidity of the mean transverse in-plane momentum per nucleon}$$

$$E\frac{d^3N}{dp^3} = \frac{1}{2\pi}\frac{d^2N}{p_T dp_T dy}\left(1+\sum_{n=1}^{\infty} 2v_n \cos(n(\phi-\phi_{RP}))\right)$$

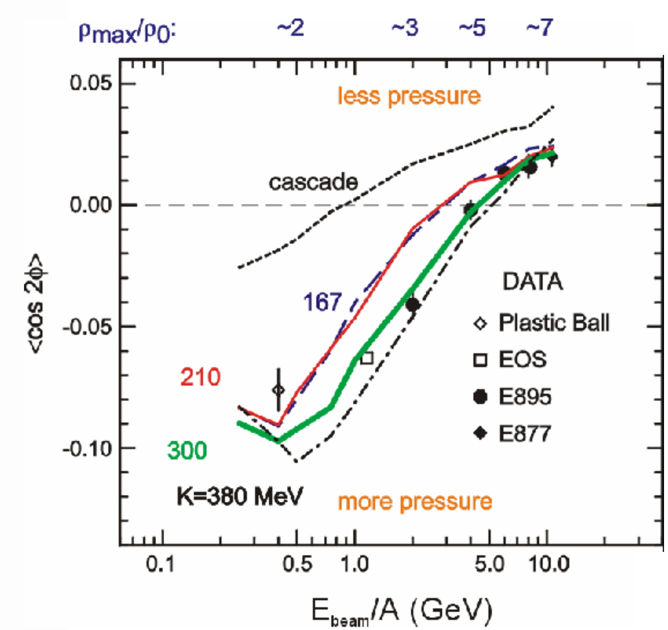
with: $v_1 = \langle\cos\Delta\phi\rangle, v_2 = \langle\cos 2\Delta\phi\rangle, \ldots, v_n = v_n(b, Z, A, y, p_T)$

Au+Au @ 2 AGeV, b=6 fm (BEM)



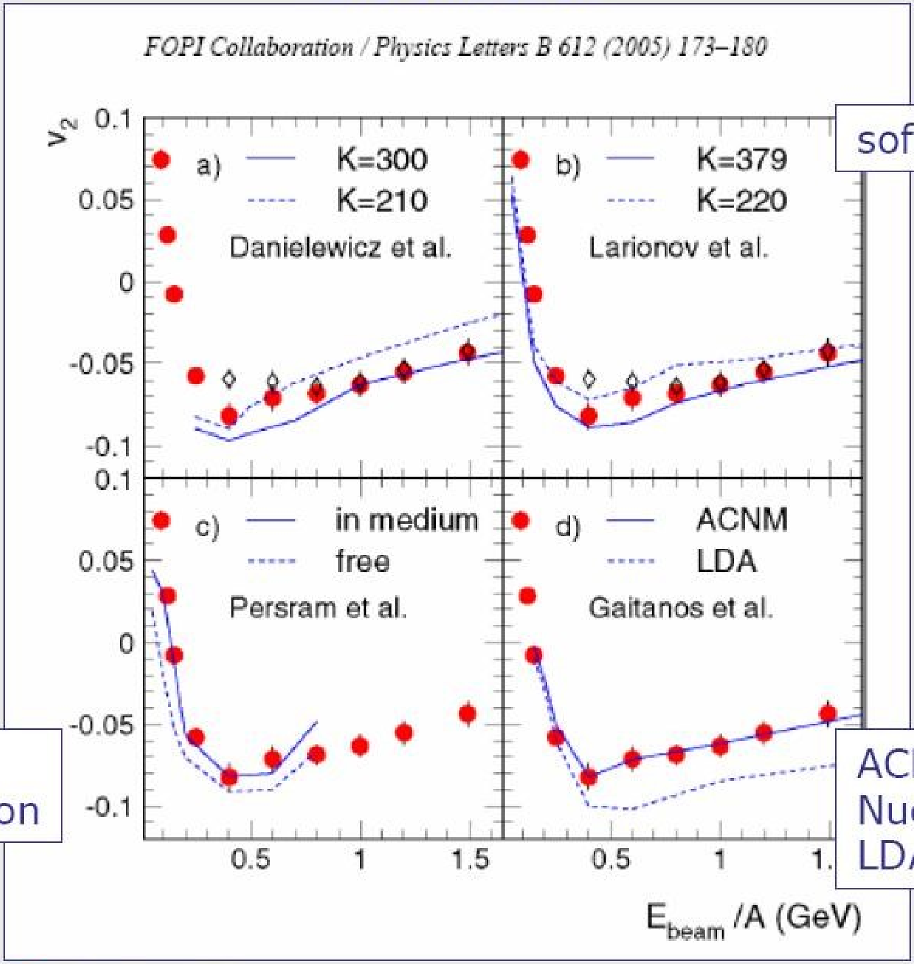


Elliptic flow



parameter dependence of elliptic flow

Andronic et al.



soft vs. hard EoS

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

D. Persram, C. Gale, PRC 65 (2002) 064611

A.B. Larionov, W. Cassing, C. Greiner, U. Mosel, PRC 62 (2000) 064611

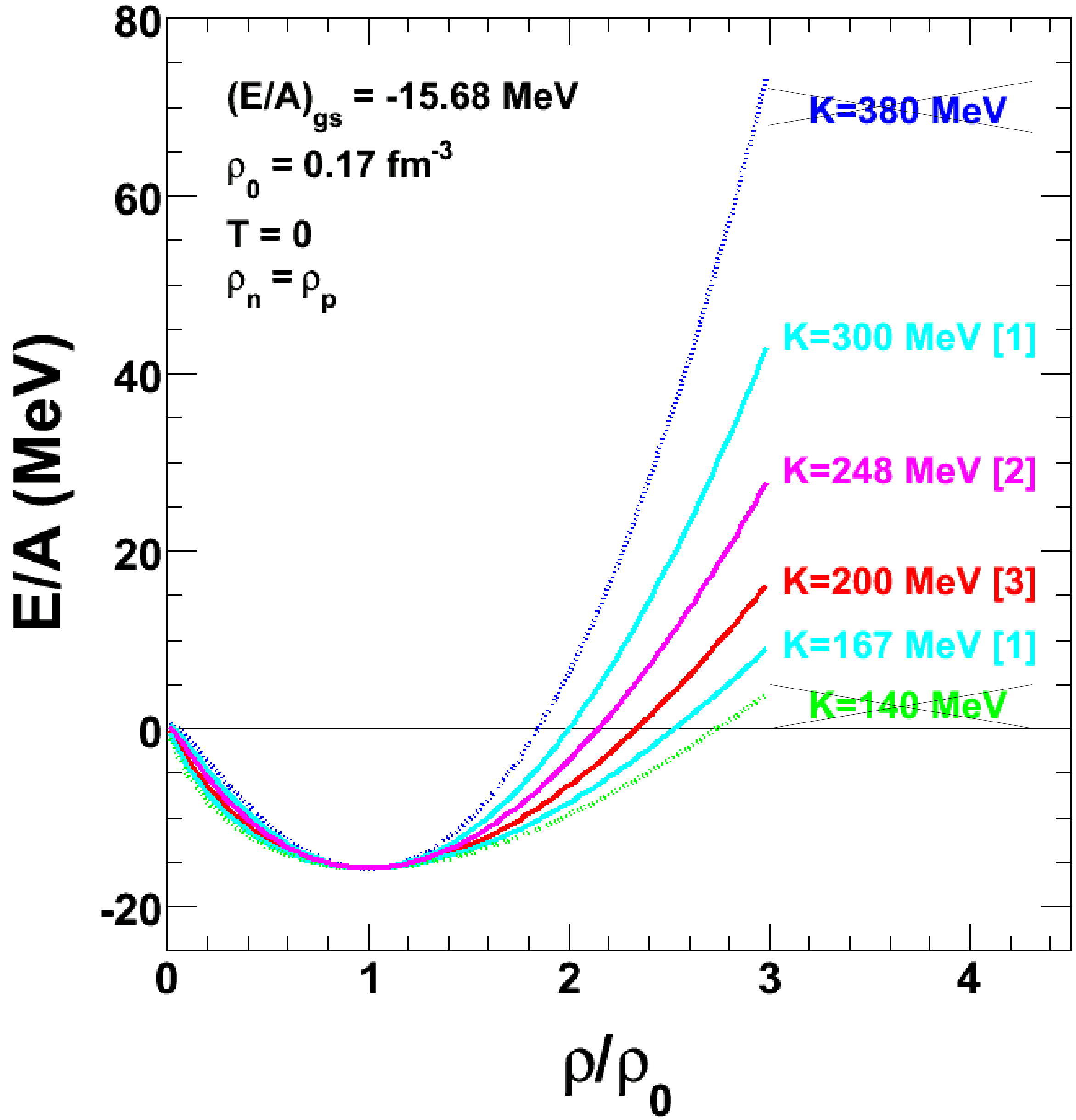
T. Gaitanos, C. Fuchs, H.H. Wolter, NPA 741 (2004) 287

in-medium nucleon–nucleon Xsection

ACNM: Asymmetric Colliding Nuclear Matter Approx.
LDA: Local Density Approx.

● Z=1 ◇ protons

Symmetric matter (δ=0)



[1] Flow:
P. Danielewicz et al., Science 298 (02) 1592
K = 167-300 MeV

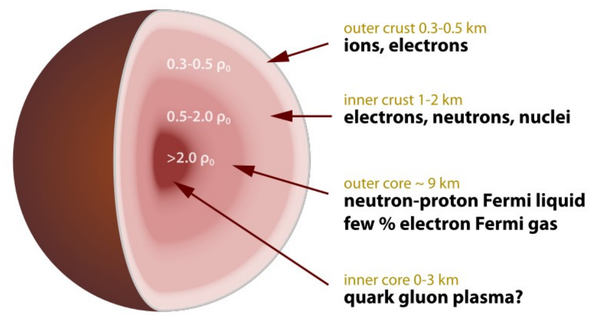
[2] ISGMR:
J. Piekarewicz, PRC 69 (04) 041301
RMF: K=248 MeV
G. Colò et al.,PRC 70 (04) 024307
Skyrme HF: K=230 MeV

[3] Subtreshold K^+:
C. Sturm et al., PRL 86 (01) 39
Ch. Hartnack et al., PRL 96 (06) 012302
K=200 MeV

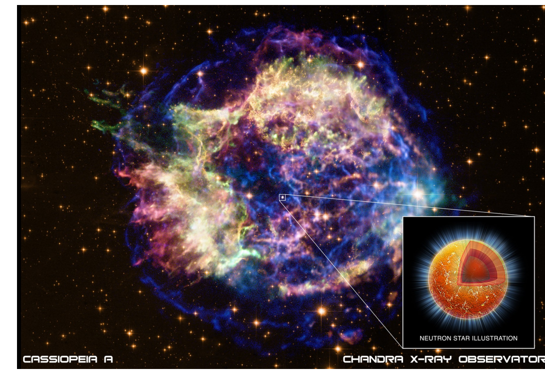
Model and data dependent values of K
Still ~20-30% uncertainty

Symmetry energy affects:

- Neutron star structure, composition, size, mass and cooling
- Supernova explosions

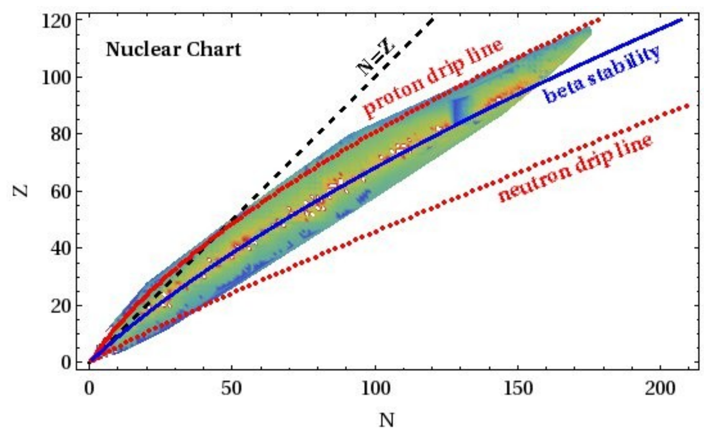


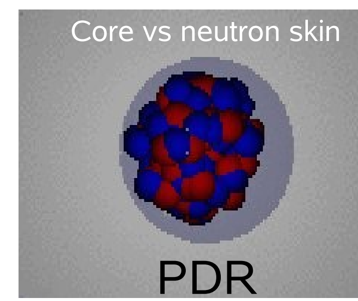
Robert Schulze (Wikipedia)



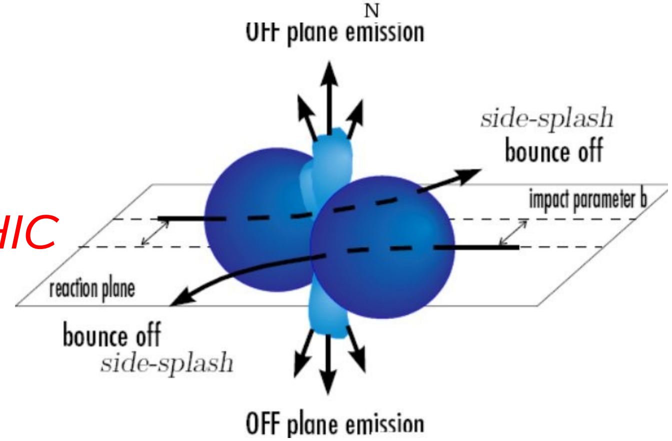
Cassiopeia A Supernova Remnant (http://chandra.harvard.edu/photo/printgallery/2004/)

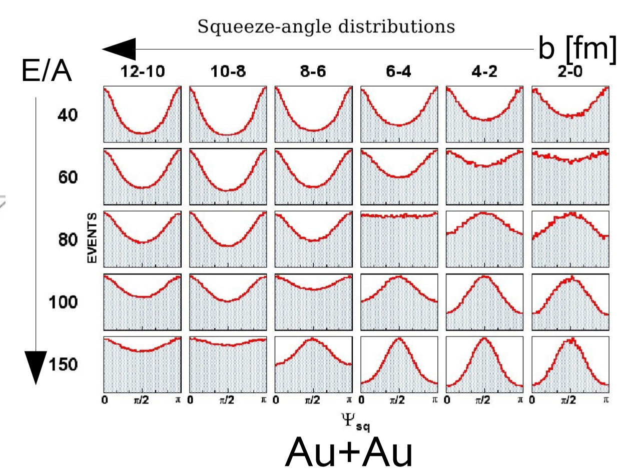
- Structure of the nucleus (masses, drip lines)
- Neutron skin thickness
- IvGDR
- Pygmy resonances
- Differences between IAS



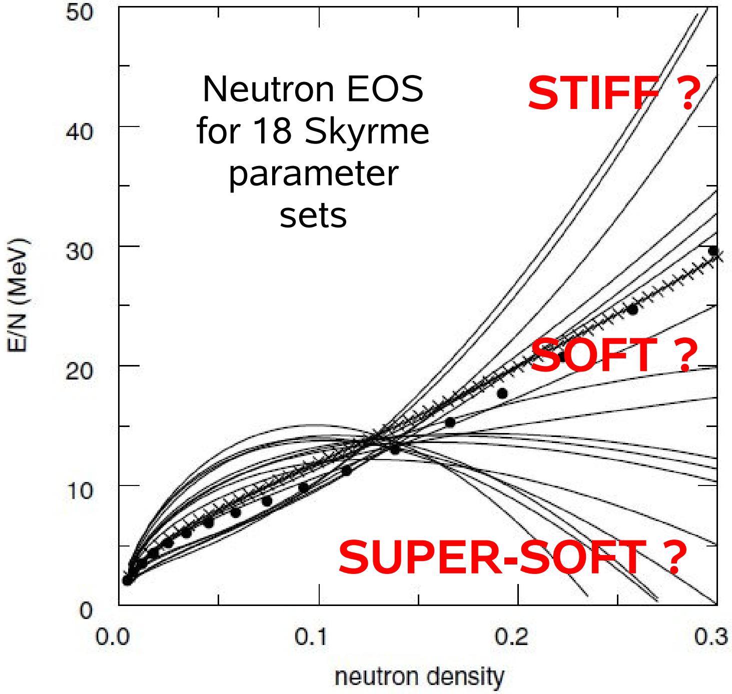


- *Flow patterns in HIC*
- *n/p, t/^{3}He, π^-/π^+, K^+/K^0 ratios in HIC*

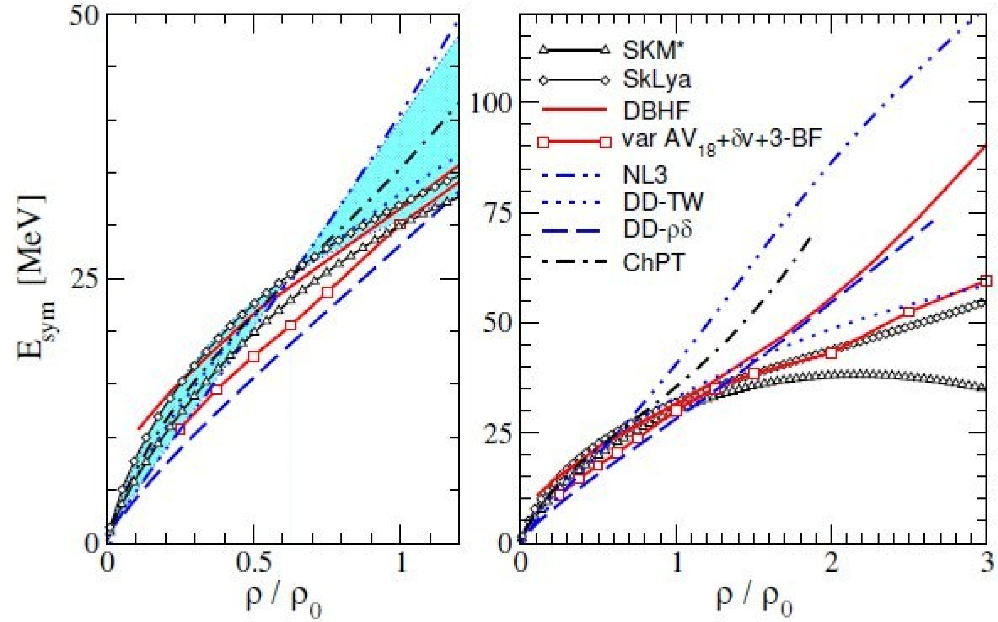




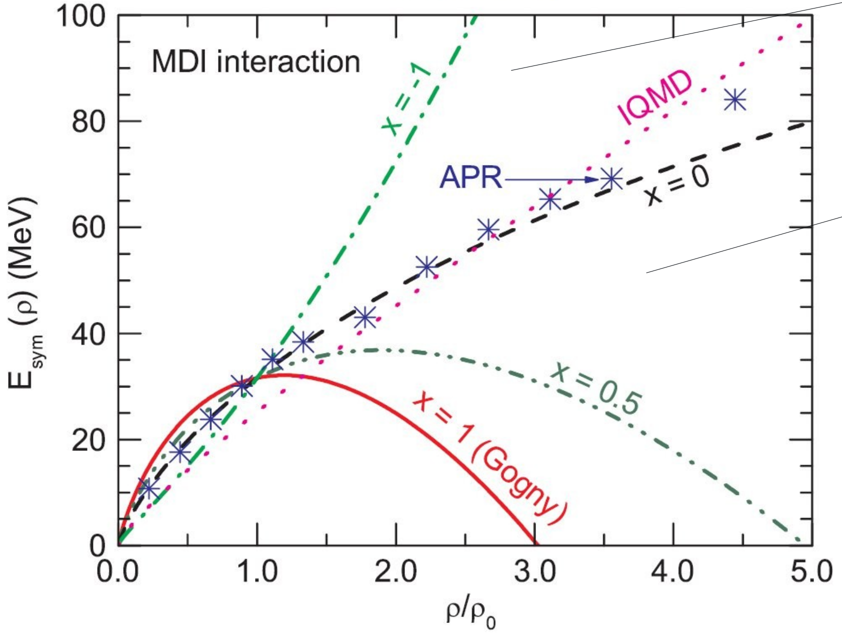
Symmetry term. Why so uncertain?



B. Alex Brown, PRL 85(2000)5296



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



Z. Xiao et al., PRL 102(2009)062502

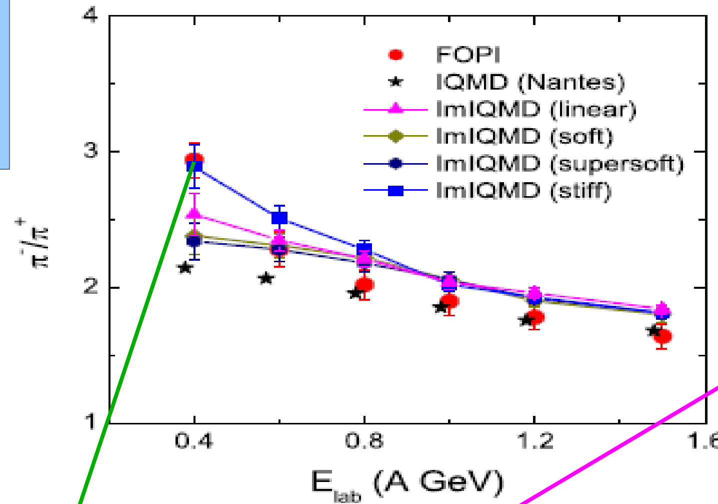
Thicker neutron skins,
larger proton fraction in NS

Thinner neutron skins,
smaller proton fraction in NS

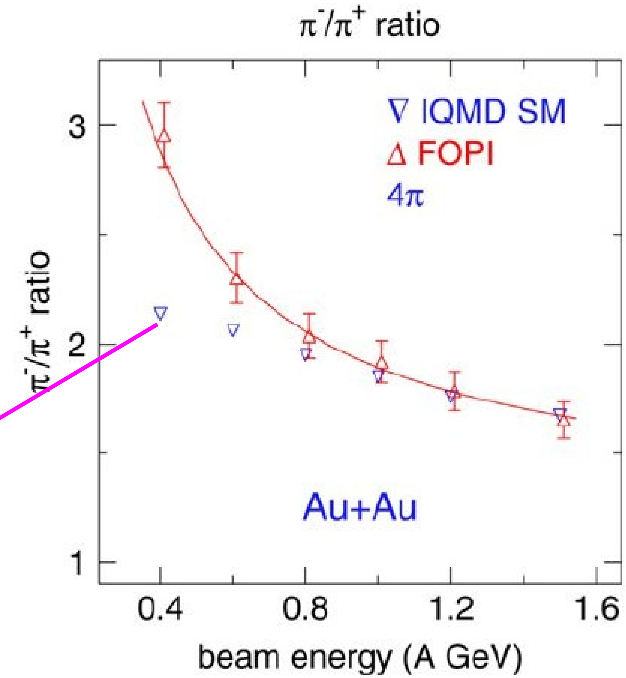
Symmetry energy uncertain at high density
and modified by clustering at low density

Pion ratios (FOPI, Au+Au)

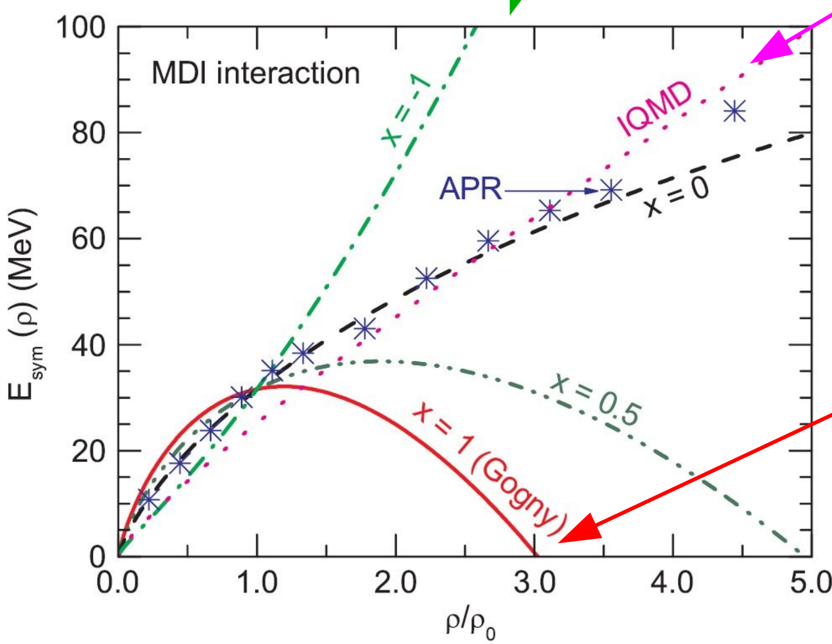
$$\frac{\pi^-}{\pi^+} = \frac{5n^2 + np}{5p^2 + np} \approx \left(\frac{n}{p}\right)^2$$

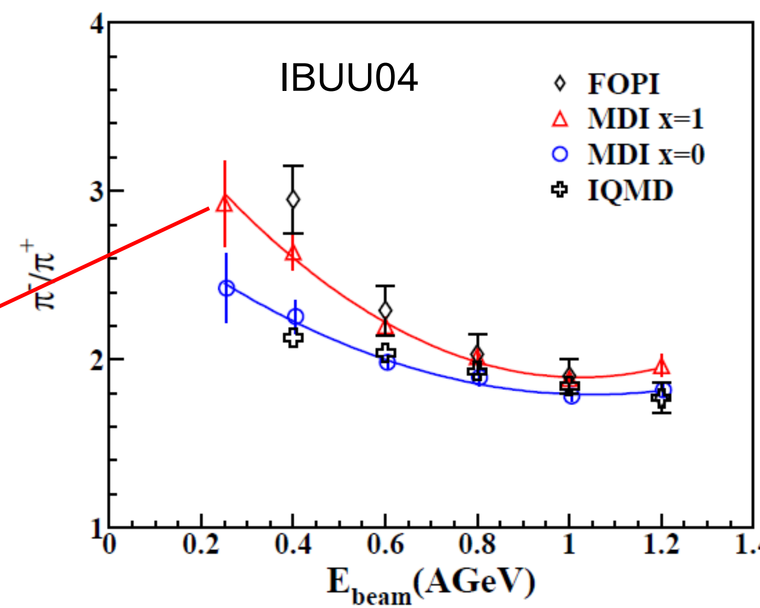


Feng, Jin, PLB 683 (2010) 140



^{197}Au+^{197}Au, FOPI data, W.Reisdorf et al. NPA 781 (2007) 459





Z. Xiao et al., PRL 102 (2009) 062502

Reanalysis of FOPI/LAND Au+Au @ 400, 600, 800 AMeV

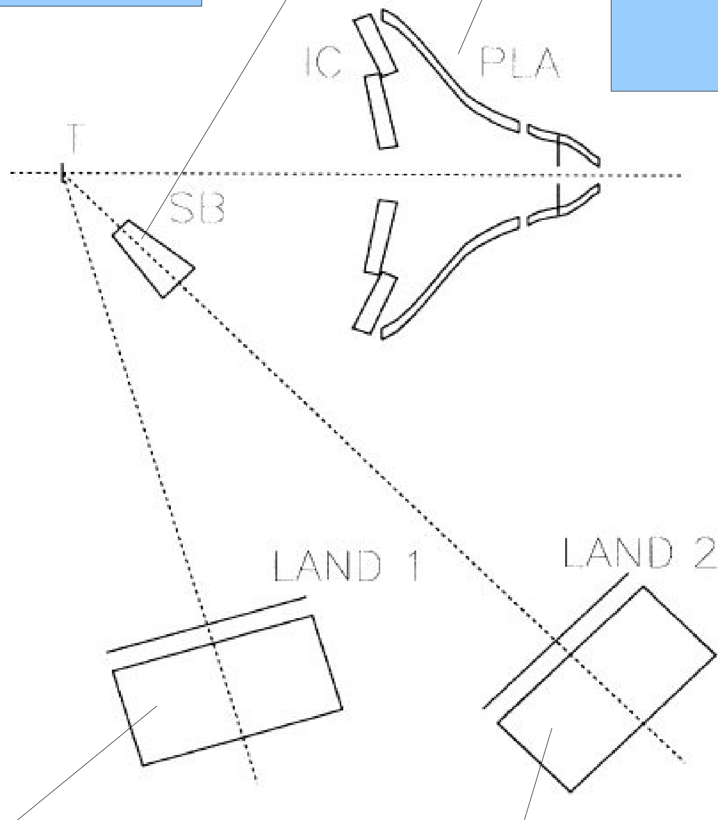
[Y. Leifels et al. PRL 71 (1993) 963]

Setup'93

„shadow bar”

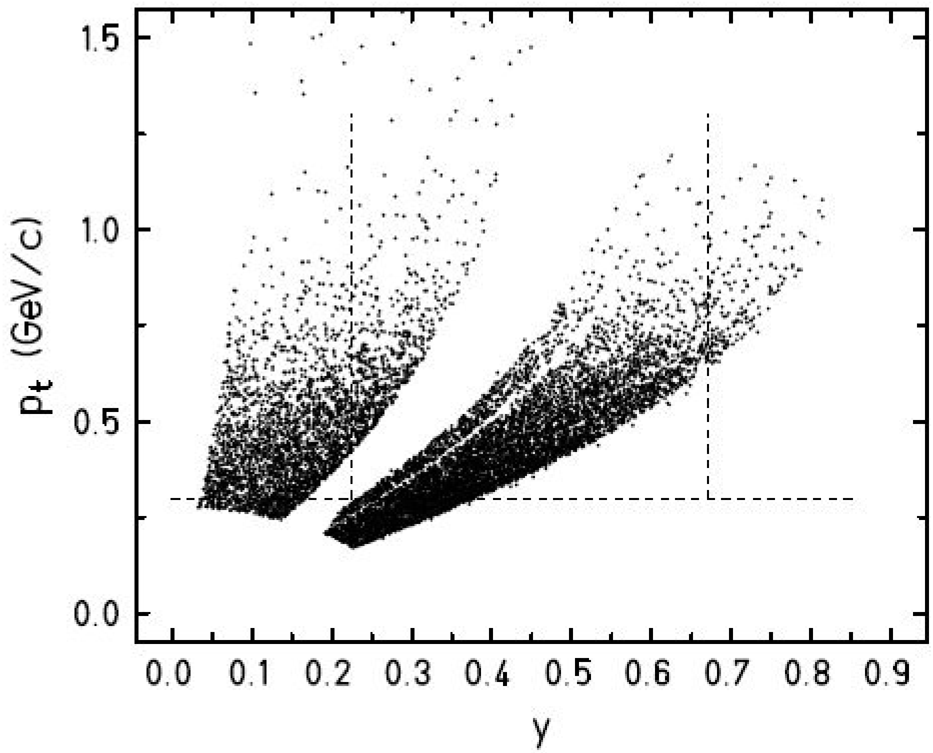
Plastic wall (1°<θ<30°)
Centrality &
Reaction plane

beam



LAND1 (61°<θ<85°)
Neutrons, Z=1

LAND2 (37°<θ<53°)
Neutrons, Z=1



Acceptance for neutrons
and cuts for analysis (dashed)

Reanalysis of FOPI/LAND Au+Au @ 400, 600, 800 AMeV

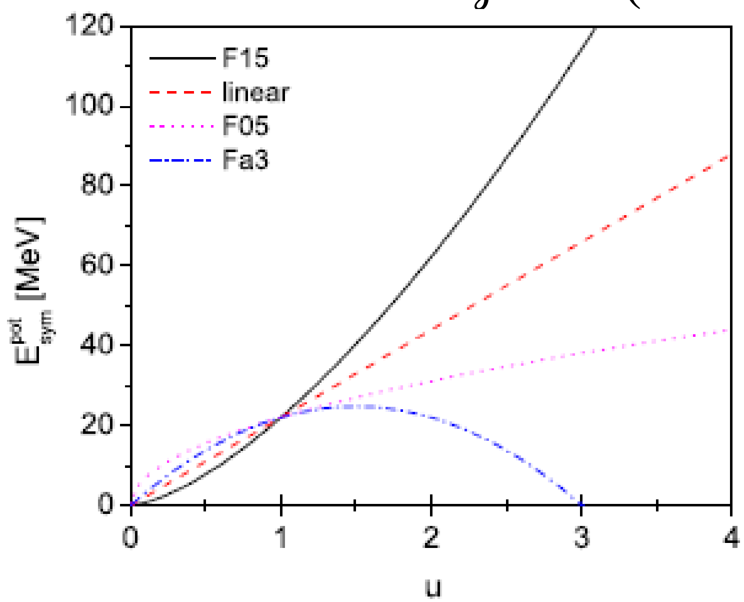
[Y. Leifels et al. PRL 71 (1993) 963] -> [P. Russotto et al. PLB 697 (2011) 471]

UrQMD, Q. Li, J.Phys. G 31(2005)1359

„Fermi-gas" parametrization of the symmetry term:

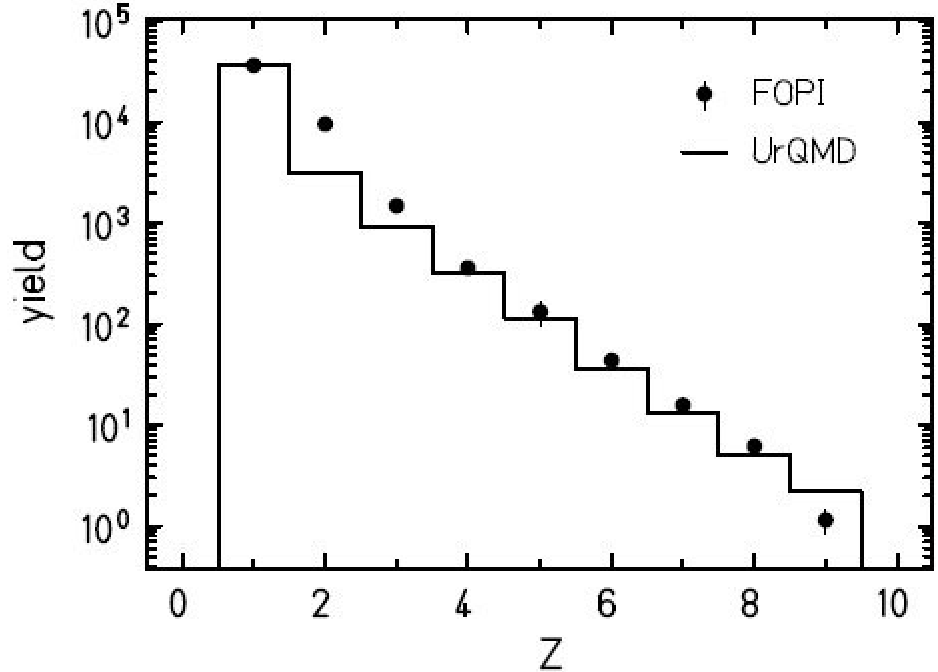
$$E_{sym} = E_{sym}^{pot} + E_{sym}^{kin} = 22\ \text{MeV}\left(\frac{\rho}{\rho_o}\right)^{\gamma} + 12\ \text{MeV}\left(\frac{\rho}{\rho_o}\right)^{2/3}$$

$\gamma = 1.5\,(\text{STIFF})$



$\gamma = 0.5\,(\text{SOFT})$

P. Russotto et al. PLB 697 (2011) 471
Data: W. Reisdorf, et al., NPA 612 (1997) 493
Central collisions, Au+Au @ 400 AMeV



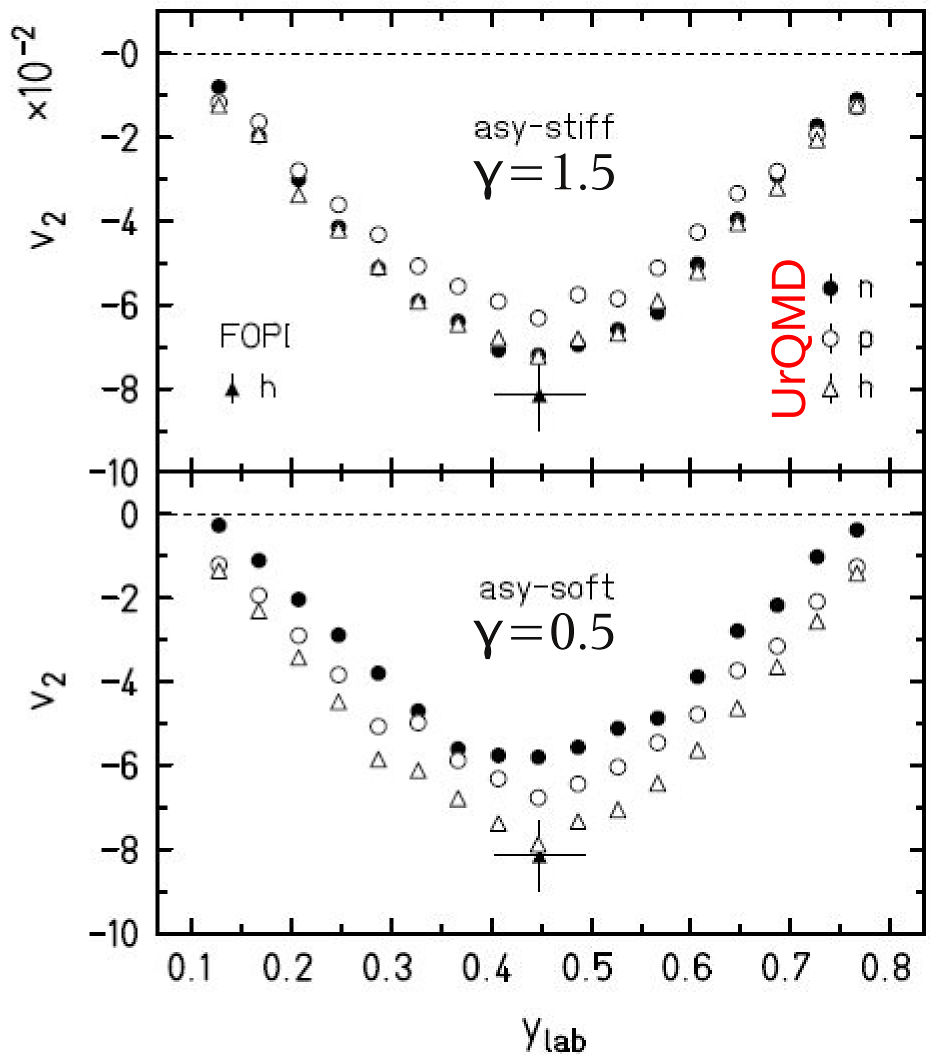
Fragment yields
(test of clustering procedure
with Δr=3 fm and Δp=275 MeV/c)
Normalization at Z=1

d,t,α underpredicted (x 2-3)

Reanalysis of FOPI/LAND Au+Au @ 400, 600, 800 AMeV

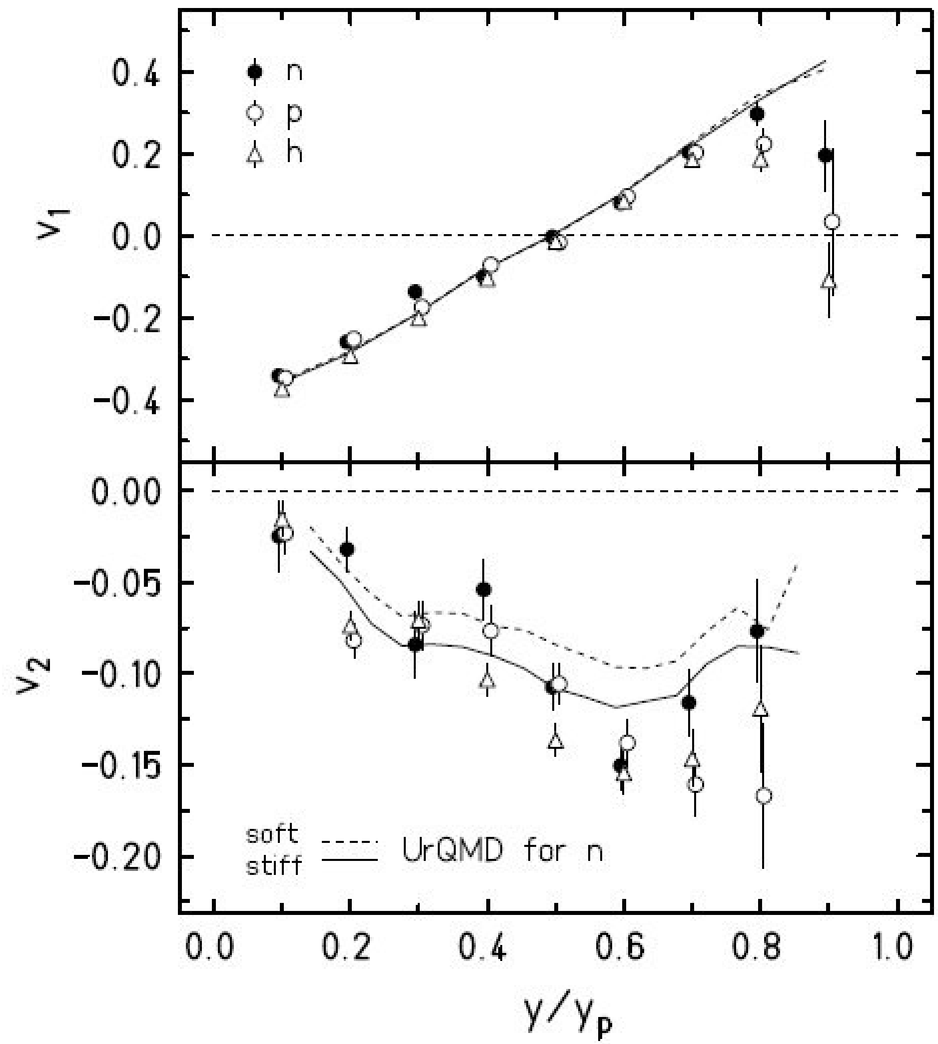
[P. Russotto et al. PLB 697 (2011) 471]

Elliptic flow (v_2)
400 AMeV, 5.5<b<7.5 fm



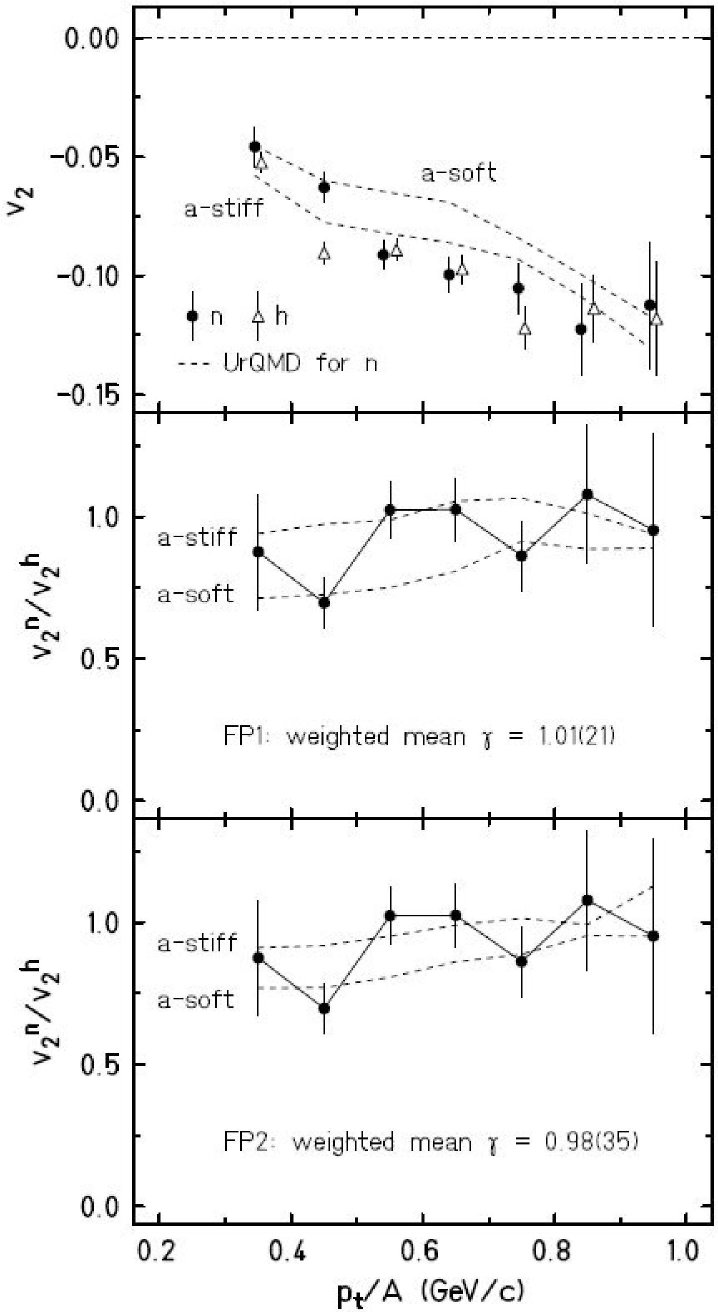
Inversion of neutron and hydrogen flows

v_2 more sensitive than v_1



Reanalysis of FOPI/LAND Au+Au @ 400, 600, 800 AMeV

[P. Russotto et al. PLB 697 (2011) 471]



v_2^n / v_2^H ratio vs p_T sensitive to the symmetry term

neutron/hydrogen

FP1: γ = 1.01 ± 0.21

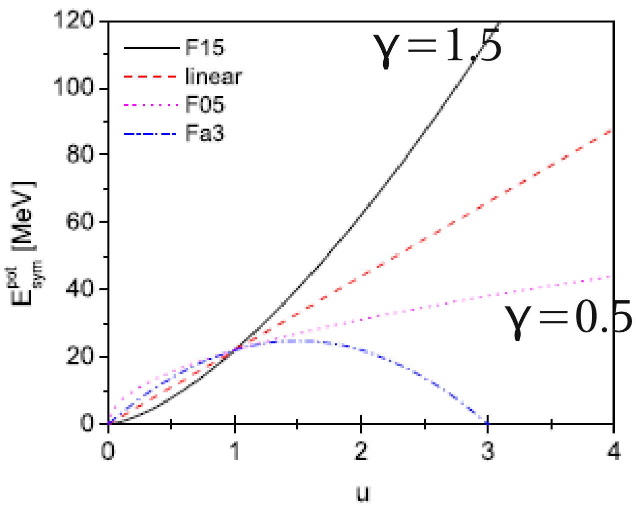
FP2: γ = 0.98 ± 0.35

neutron/proton

FP1: γ = 0.99 ± 0.28

FP2: γ = 0.85 ± 0.47

adopted: γ = 0.9 ± 0.4

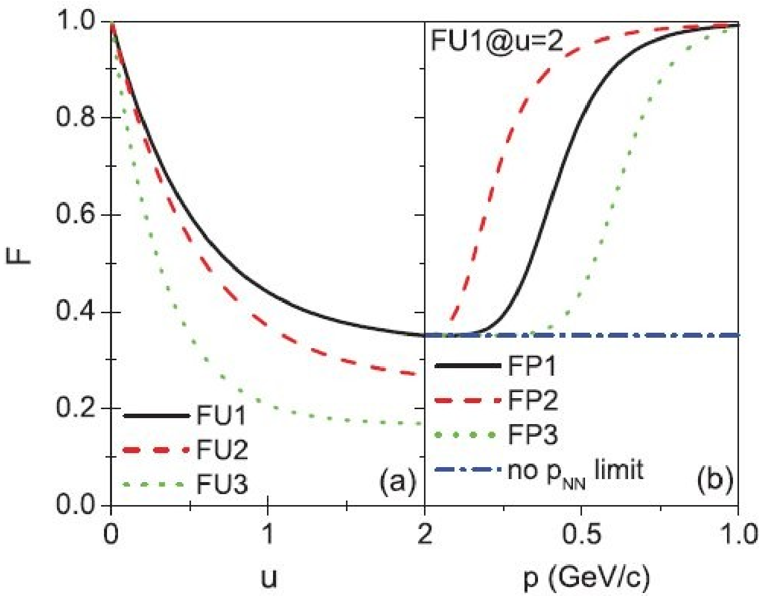


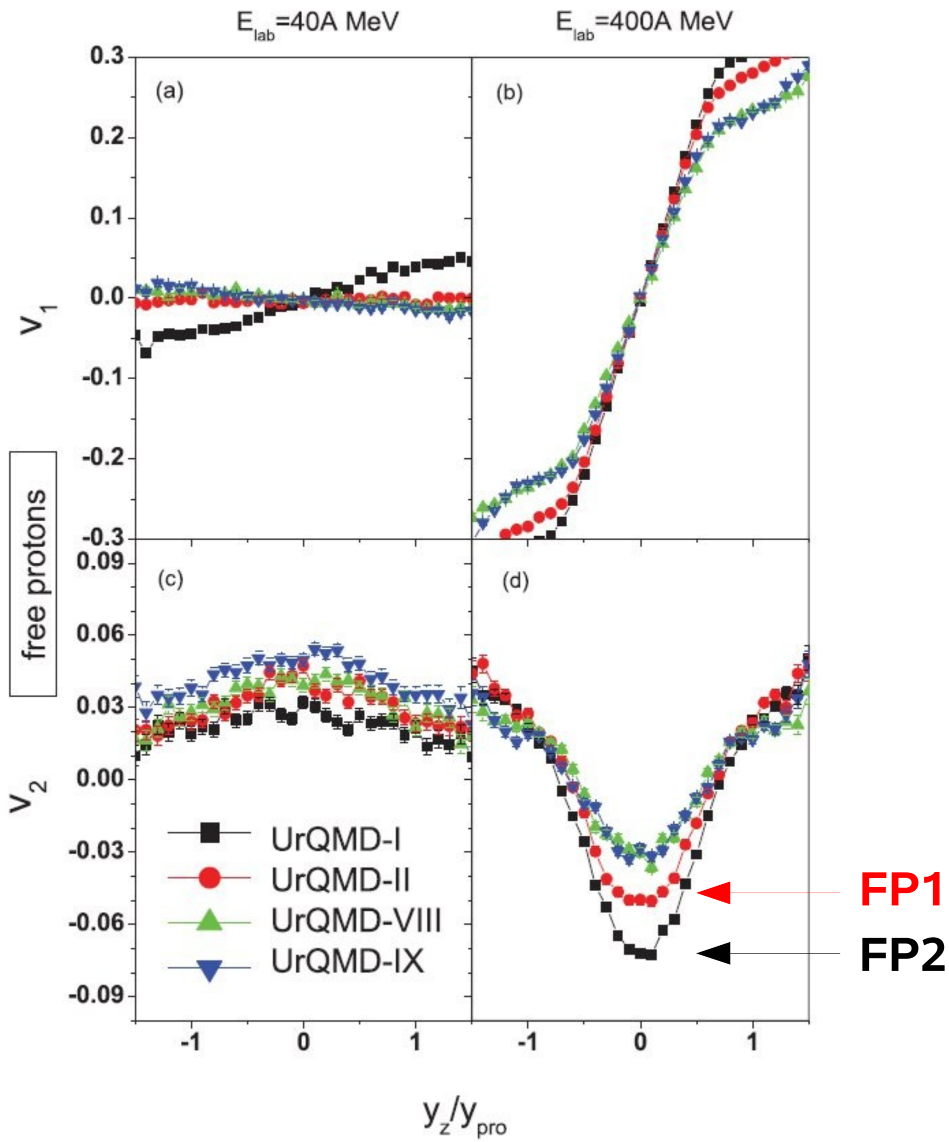
FP1, FP2: different parametrizations of the Momentum dependnce of the elastic nucleon-nucleon cross section
[Q. Li et al. PRC 83(2011)044617]

Medium correction factors to the elastic σ_{NN}

[UrQMD, Q. Li et al., PRC 83(2011)044616]

$$\sigma^*_{tot} = \sigma_{in} + \sigma^*_{el} = \sigma^{free}_{in} + F(\rho, p)\,\sigma^{free}_{el}$$

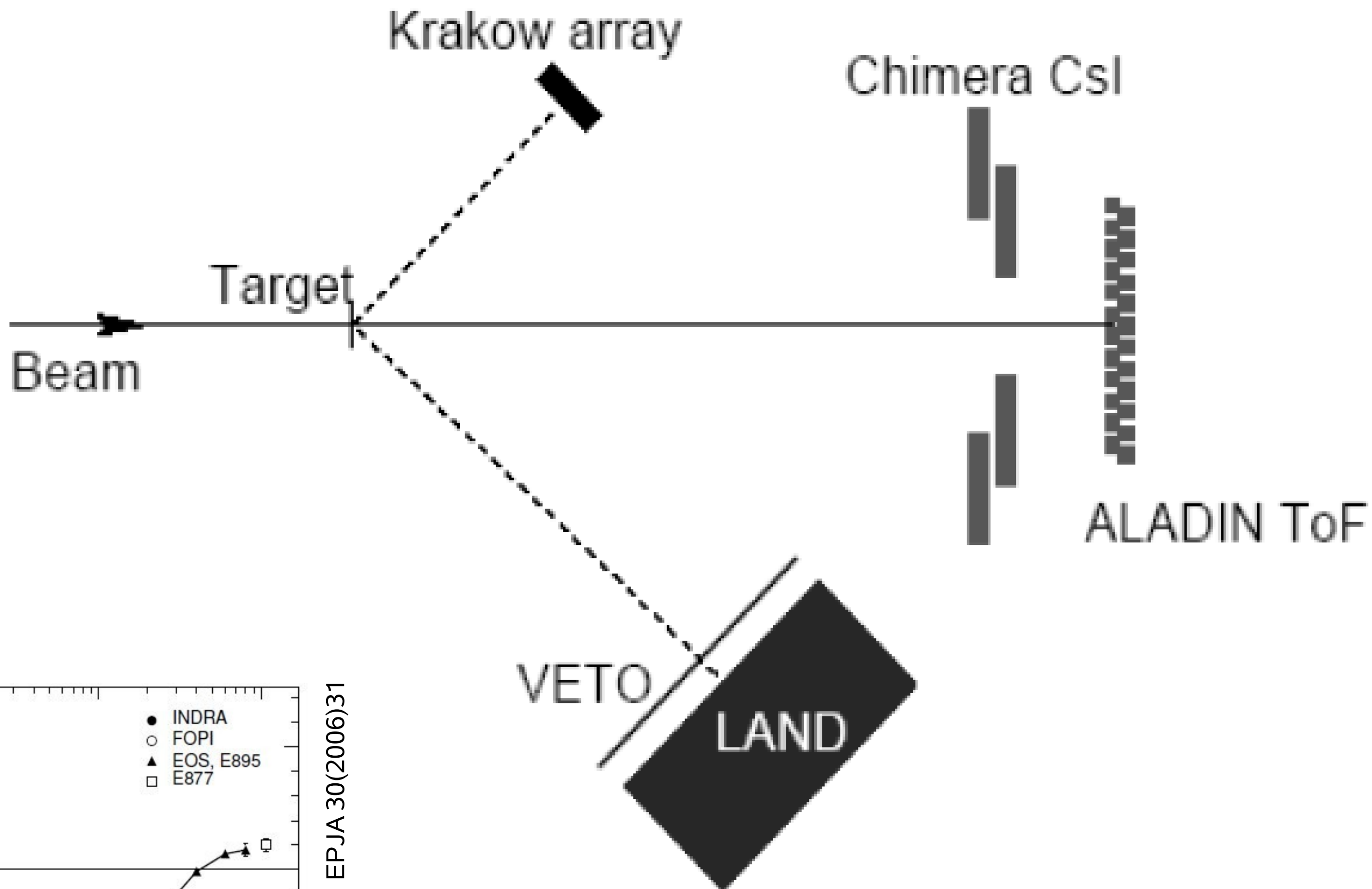


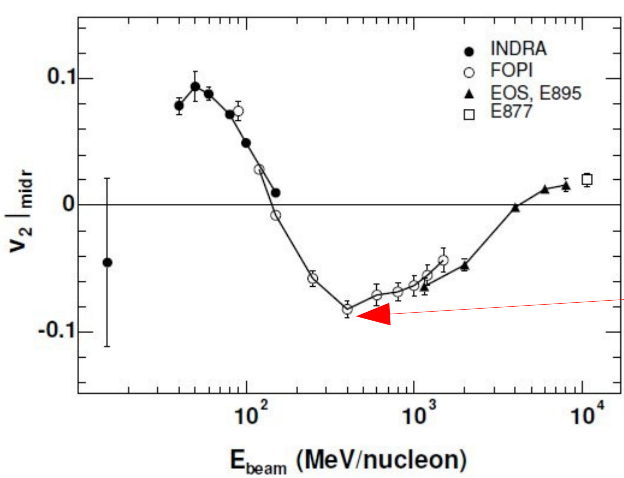


ASY-EOS experimental setup

May 2011

Setup from the proposal of 2009

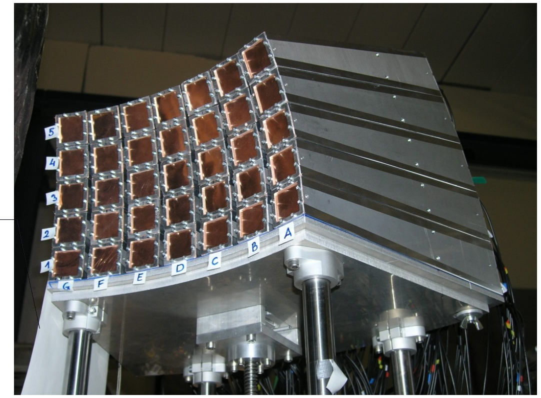




A. Andronic et al. EPJA 30(2006)31

^{197}**Au**	**+**	^{197}**Au**	**@ 400 AMeV**	$\delta^2 = 0.039$
^{96}**Zr**	**+**	^{96}**Zr**	**@ 400 AMeV**	$\delta^2 = 0.028$
^{96}**Ru**	**+**	^{96}**Ru**	**@ 400 AMeV**	$\delta^2 = 0.007$

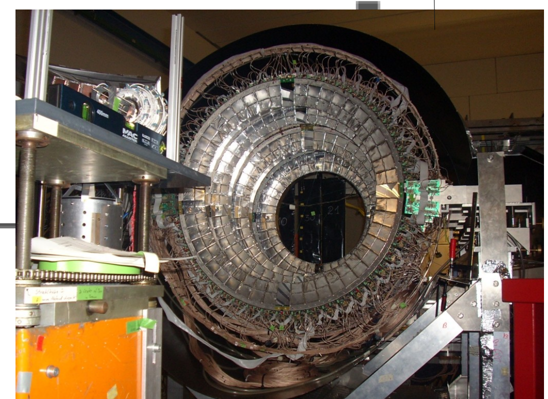
ASY-EOS setup



Krakow array

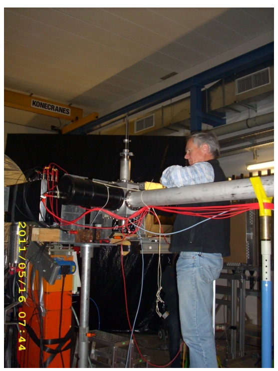
5x7 triple telescopes, 20°<θ<60°
Si-CsI-CsI
Midrapidity pdt +
Isotopes of Z<9

Chimera CsI



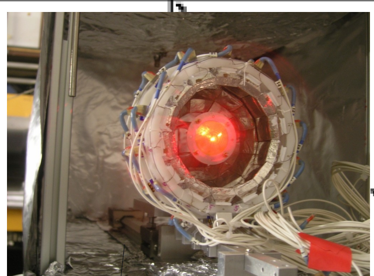
4 rings, 352 CsI(Tl), 7°<θ<20°
Centrality
&
Reaction plane

Start + ROLU



Target

Beam



μ-Ball + Halo

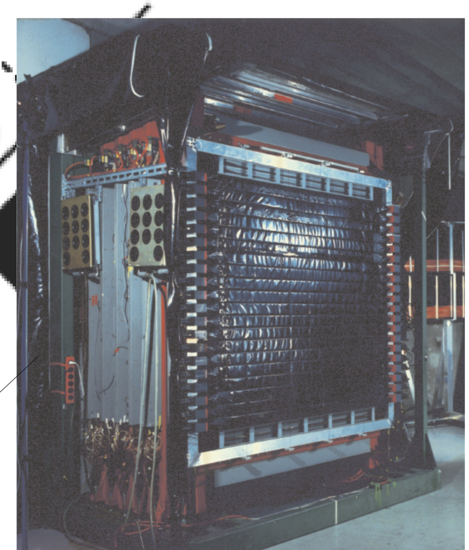
4 rings, θ>60°, CsI(Tl)
Discriminate target vs air interactions, remove halo, possibly centrality + rpl

ALADIN ToF

96 plastic bars
x-y positions, centrality, reaction plane, trigger

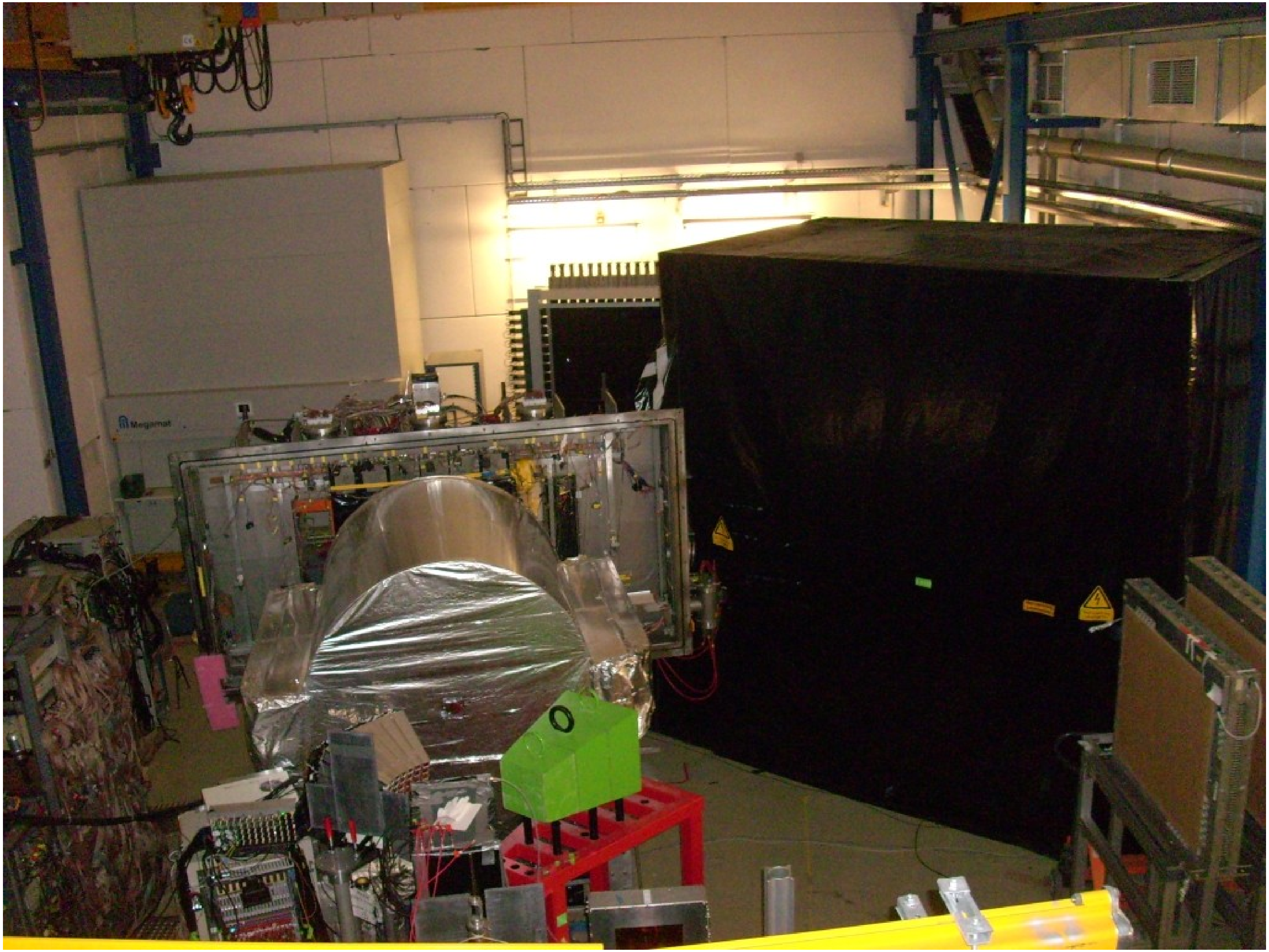
SHADOW BAR

LAND+VETO



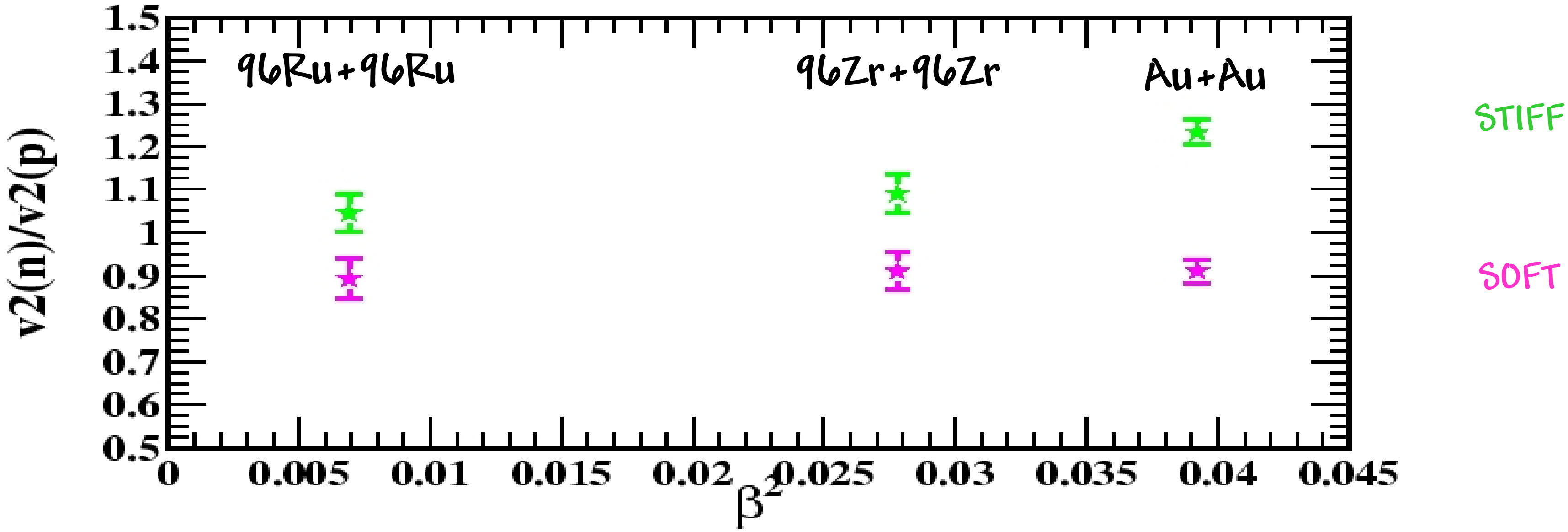
$2 \times 2 \times 1\ m^3$ plastic/Fe sandwich
+ plastic veto wall
Midrapidity neutrons & Z=1

ASY-EOS experimental setup



URQMD simulations: @ 400 AMeV

V2 for |(y/yp)c.m.|<0.1



β=(N-Z)/(N+Z)

Au+Au b=5.5-7.5 fm

96Zr+96Zr b=4-6 fm

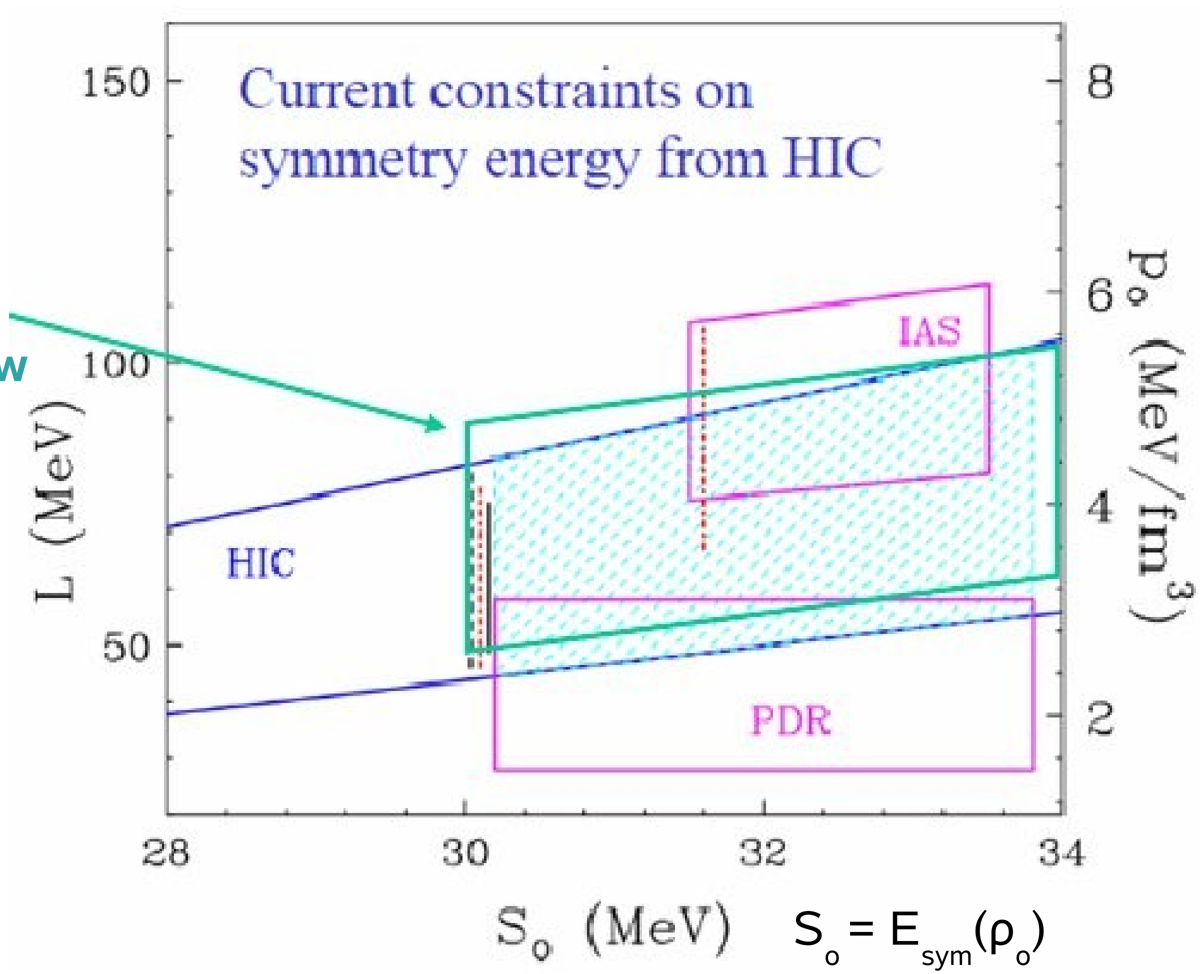
96Ru+96Ru b=4-6 fm

From Paolo Russotto

summary

$$L = 3\rho_o \left.\frac{\partial E_{sym}}{\partial \rho}\right|_{\rho=\rho_o}$$

from elliptic n/p flow



IAS -
isobaric analog states
Danielewicz/Lee 2008

HIC -
heavy-ion collisions
isospin diffusion, n/p ratios
Tsang et al., 2009

PDR -
pygmy dipole resonance
Klimkiewicz et al. 2007

$P_o = (L/3)\,\rho_o$
symmetry pressure

[M.B. Tsang et al., PRL 102(2009)122701]

Difficulties in measuring the $E_{sym}(\rho)$

Experiment

- Mixture of density, temperature and time dependent processes
- Detection of neutrons and protons simultaneously
- Tiny effects – high precision and statistics needed
- Observables minimizing the influence of the isoscalar part
- Correlations of many observables needed
- Exotic beams (larger δ) would help

Model

- In-medium cross sections (ρ and p dependent)
- Realistic inelastic cross sections, particle production (π, K)
- Momentum dependence of the mean-field
- Control the competition between the mean-field and collisions
- Realistic description of cluster formation (at least t/^{3}He)
- Ability to describe „hot” and „cold” observables

The ASY-EOS Collaboration

Co-Spokespersons: R.C. Lemmon[1]and P. Russotto[2]

Collaboration

F. Amorini[2], A. Anzalone[17], T. Aumann[3], V. Avdeichikov[12], V. Baran[23], Z. Basrak[4], J. Benlliure[13], I. Berceanu[11], A. Bickley[14], E. Bonnet[6], K. Boretzky[3], R. Bougault[30], J. Brzychczyk[8], B. Bubak[22], G. Cardella[7], S. Cavallaro[2], J. Cederkall[12], M. Chartier[5], M.B. Chatterjee[16], A. Chbihi[6], M. Colonna[17], D. Cozma[11], B. Czech[10], E. De Filippo[7], K. Fissum[12], D. Di Julio[12], M. Di Toro[2], M. Famiano[27], J.D. Frankland[6], E. Galichet[18], I. Gasparic[4], E. Geraci[15], V. Giordano[2], P. Golubev[12], L. Grassi[15], A. Grzeszczuk[22], P. Guazzoni[21], M. Heil[3], J. Helgesson[31], L. Isaksson[12], B. Jacobsson[12], A. Kelic[3], M. Kis[4], S. Kowalski[22], E. La Guidara[20], G. Lanzalone[29], N. Le Neindre[30], Y. Leifels[3], Q. Li[9], I. Lombardo[2], O. Lopez[30], J. Lukasik[10], W. Lynch[14], P. Napolitani[30], N.G. Nicolis[24], A. Pagano[7], M. Papa[7], M. Parlog[30], P. Pawlowski[10], M. Petrovici[11], S. Pirrone[7], G. Politi[15], A. Pop[11], F. Porto[2], R. Reifarth[3], W. Reisdorf[3], E. Rosato[19], M.V. Ricciardi[3], F. Rizzo[2], W.U. Schroder[28], H. Simon[3], K. Siwek-Wilczynska[26], I. Skwira-Chalot[26], I. Skwirczynska[10], W. Trautmann[3], M.B. Tsang[14], G. Verde[7], E. Vient[30], M. Vigilante[19], J.P. Wieleczko[6], J. Wilczynski[25], P.Z. Wu[5], L.Zetta[21], W. Zipper[22]

Symmetry energy from elliptic flow in $^{197}Au + ^{197}Au$

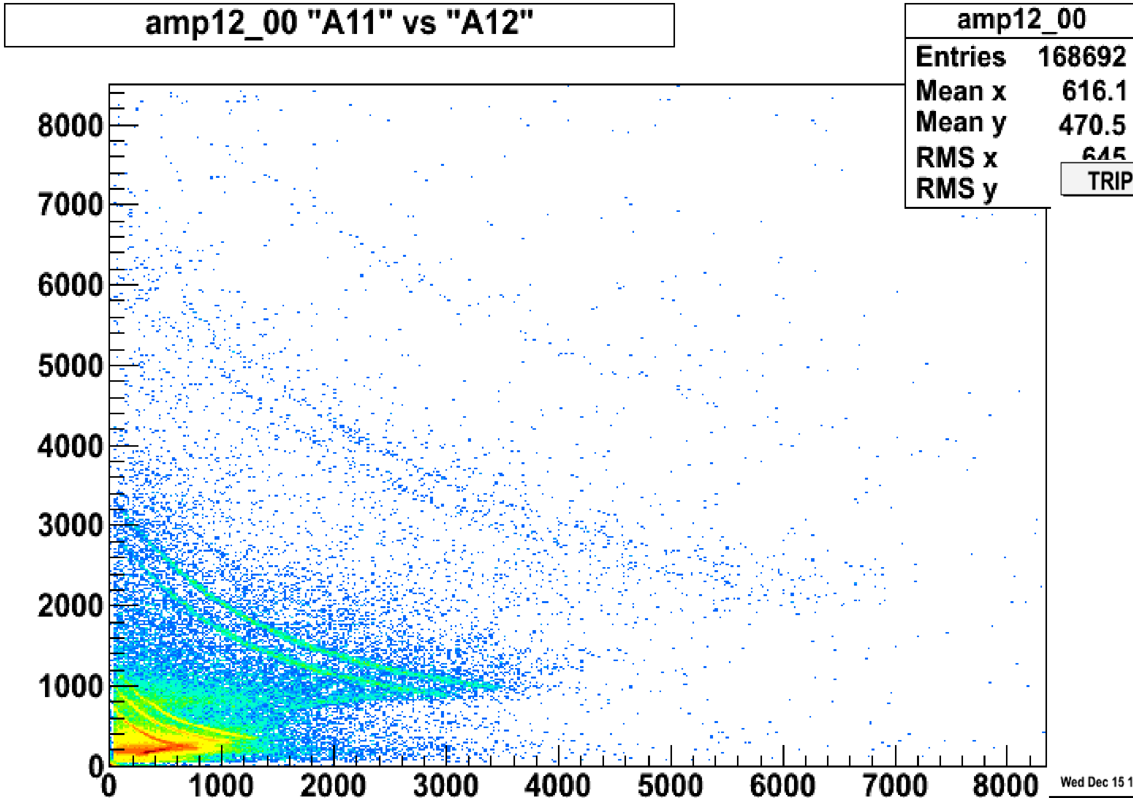
[PLB 697 (2011) 471]

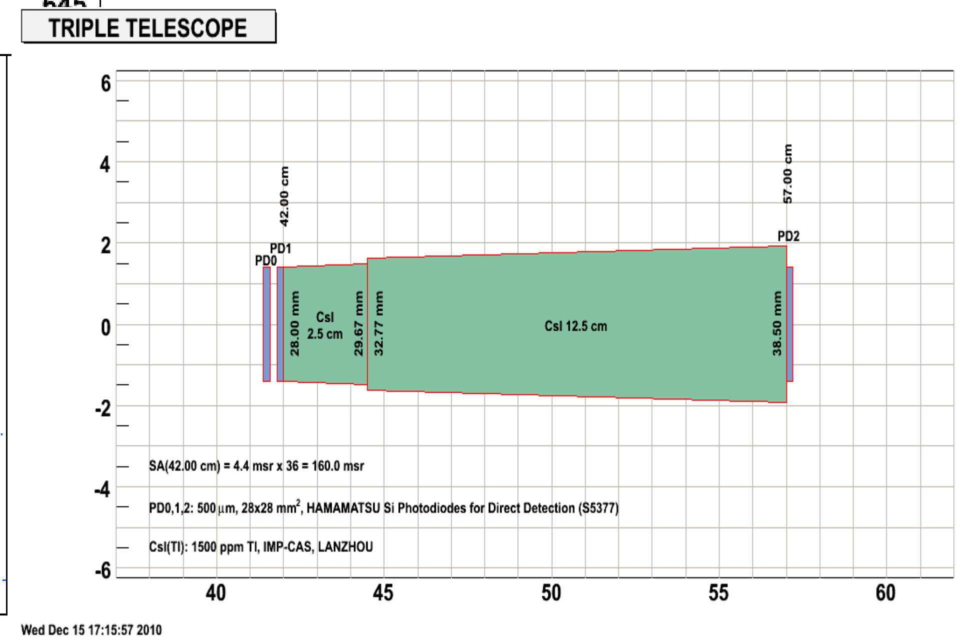
P. Russotto, P.Z. Wu, M. Zoric, M. Chartier, Y. Leifels,

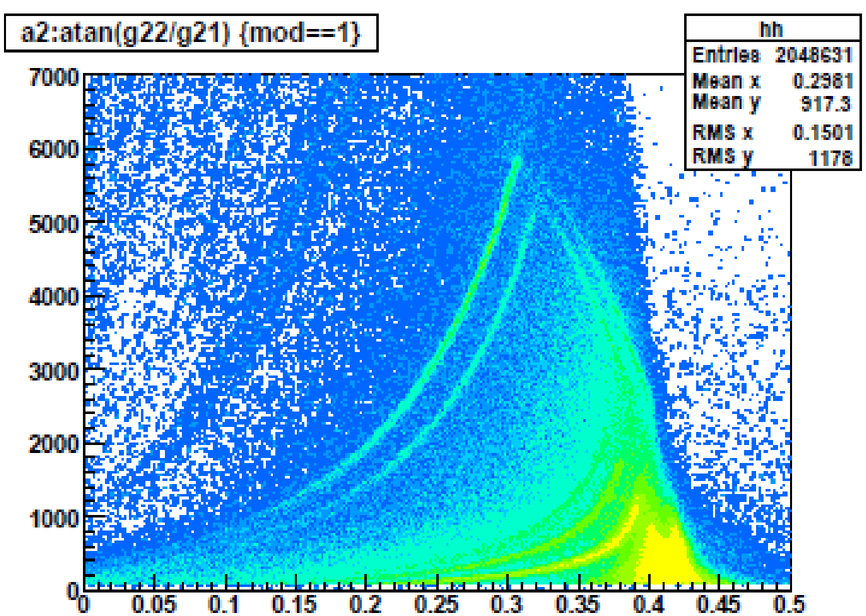
R.C. Lemmon, Q. Li, J. Łukasik, A. Pagano, P. Pawłowski,

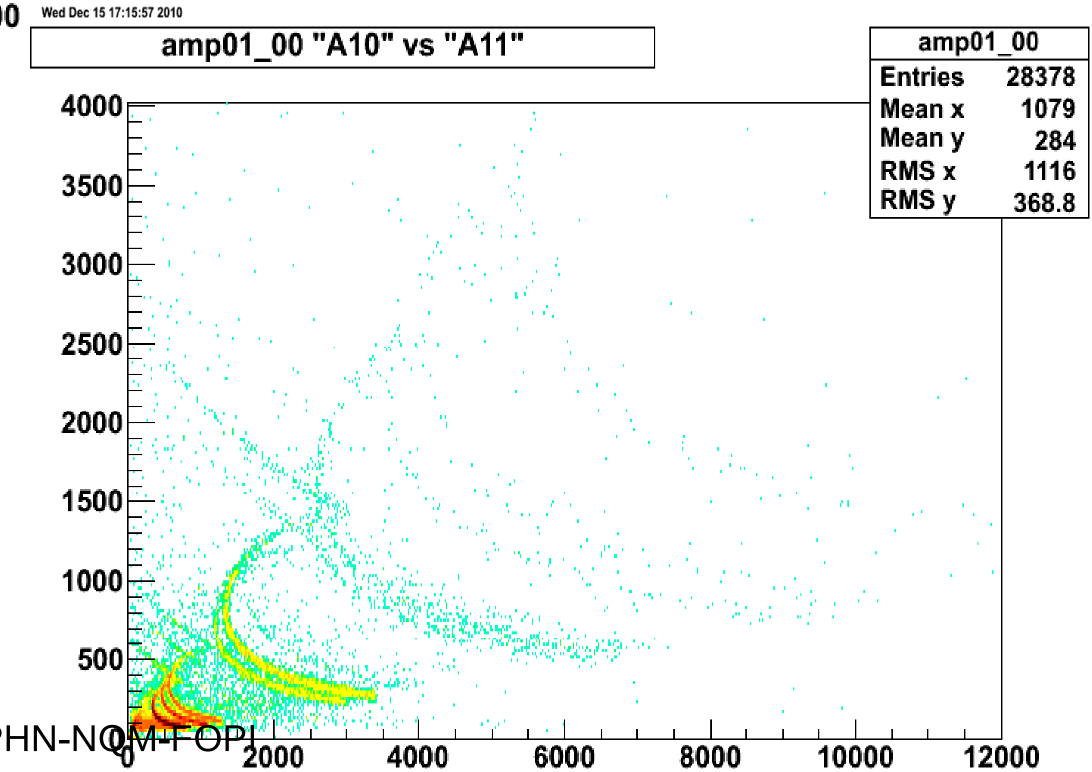
W. Trautmann

Krakow array









i.de/informationen/wti/library/scientificreport2010/index.html#PHN-NQM-FOPI

Differential flow

(minimizes the influence of the isoscalar part of the EOS)

Bao-An Li, PRL 85 (2000) 4221

$$F^{x}_{n-p}(y) \equiv \frac{1}{N(y)} \sum_{i=1}^{N(y)} p^{x}_{i}(y)\,\tau_{i} \;=\; \frac{N_n(y)}{N(y)} \langle p^{x}_{n}(y) \rangle - \frac{N_p(y)}{N(y)} \langle p^{x}_{p}(y) \rangle$$

where $N_n(y)$ is the total number of free nucleons at rapidity y, $p^x_i(y)$ is the transverse in-plane momentum of particle i and $\tau_i = 1 \;(-1)$ for neutrons (protons).