Constraints on dependence of the symmetry energy from elliptic flow data

M.D. Cozma

IFIN-HH
Magurele-Bucharest, Romania

"ASYEOS 2012" - Siracusa, Italy
4-6 September 2012

Overview

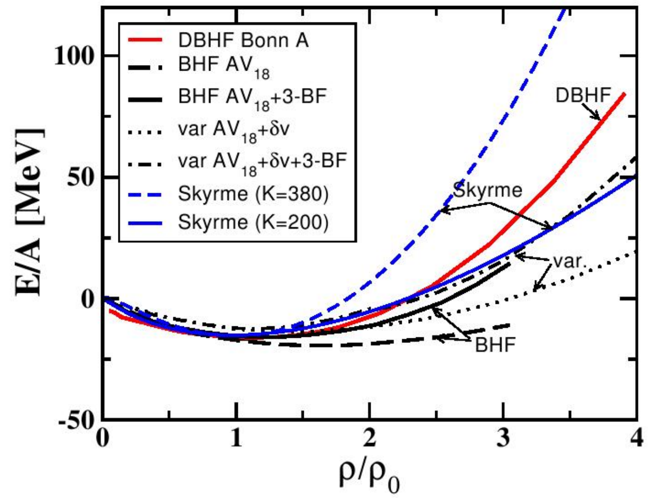
- Introduction & Motivation
- HIC Model
- In-medium effects
- Flow observables
- Summary & Outlook

Introduction

Equation of State (EoS) of Nuclear Matter:

$$E(\rho) = E(\rho_0) + \frac{K}{18}\frac{(\rho-\rho_0)^2}{\rho_0^2}$$

$$P = \rho^2 \frac{\partial E(\rho)}{\partial \rho} \qquad K = 9\frac{\partial P}{\partial \rho}$$

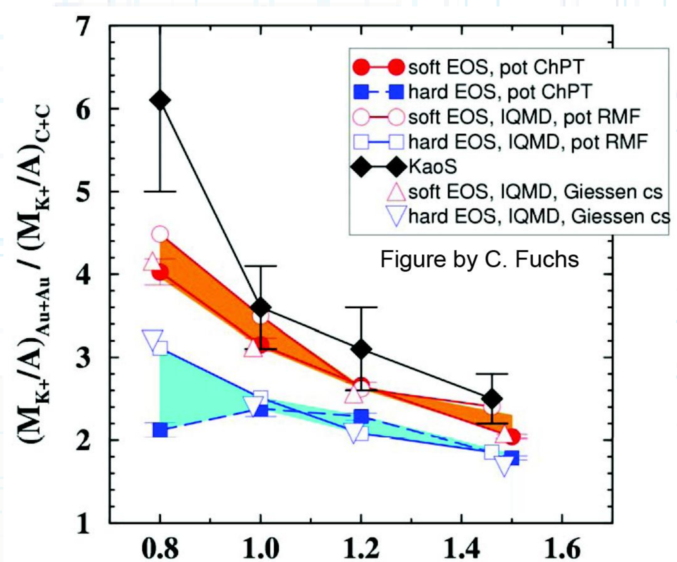


Sources

finite nuclei $\rho/\rho_0 \leq 1$

heavy − ions $\rho/\rho_0 \leq 3$

neutron stars $\rho/\rho_0 \leq 10$



Relevance:

- structure of neutron star cores
- astrophysical processes like supernova explosions

C. Fuchs *et al.* PRL 86, 1974 (2001)
C. Hartnack *et. al.* PRL 96, 012302(2006)

Symmetry Energy

EoS of Asymmetric Nuclear Matter

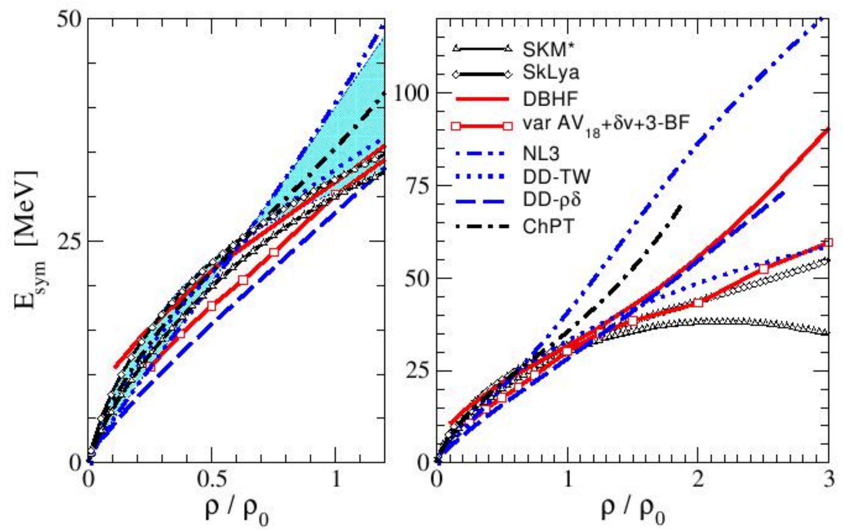
$$E(\rho,\beta)=E(\rho,\beta=0)+S(\rho)\beta^2 \quad \beta=\frac{\rho_n-\rho_p}{\rho}$$

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

Theoretical estimates of L and K

B.A. Li *et al.* Int.J.Mod.Phys. E7, 147 (1998)

Force	Paris	SKM*	SI′	SIII	DHF (b)	DHF (e)
L	68.8	45.78	35.34	9.91	132	138
K_{sym}	37.56	-155.9	-259.1	-393.7	466	276



Experimental results:

isospin diffusion/neutronskin thickness of Pb: L≃ 65 MeV B.A. Li *et al.* PRC 72,064611 (2005)

giant monopole resonances:
K_{sym} -566 +/- 1350 MeV; 34 +/- 159 MeV
S. Shlomo *et al.* PRC 47, 529 (1993)

Neutron Stars

equilibrium w.r.t. weak interactions

$$\frac{\partial E}{\partial \beta}(\rho,\beta)+\frac{\partial E_L}{\partial \beta}(\beta)=0$$

K. Saito *et al.* arXiv:1207.1554

Pure Nucleonic NS

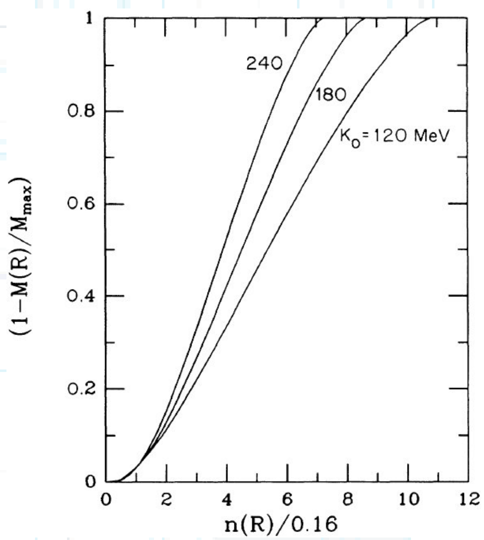
$S(\rho)$ determines how β depends on density

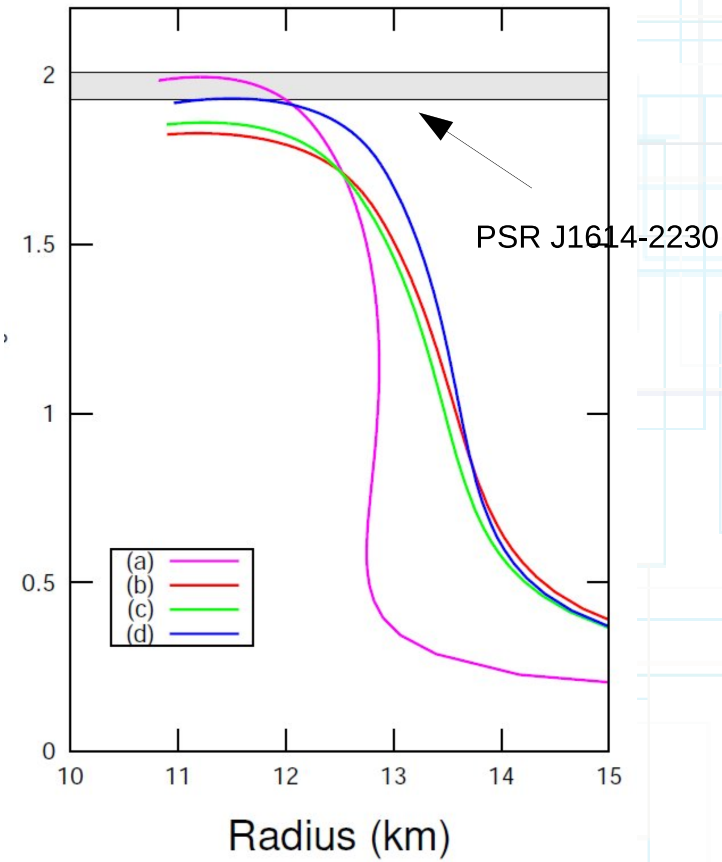
maximum mass scales like $K^{1/2}$

$S(\rho)$ bigger impact for softer K

M. Prakash *et al.* PRL 61, 2518 (1988)

$F(u)$	K_0 (MeV)	$M_{max}/M_\odot$	R (km)
u	120	1.458 (1.70)	9.114
	180	1.722 (1.90)	9.879
	240	1.935 (2.07)	10.57
$\frac{2u^2}{1+u}$	120	1.470 (1.95)	9.895
	180	1.738 (2.10)	10.318
	240	1.952 (2.24)	10.933
$\sqrt{u}$	120	1.404 (1.45)	8.435
	180	1.679 (1.71)	9.324
	240	1.895 (1.92)	10.112

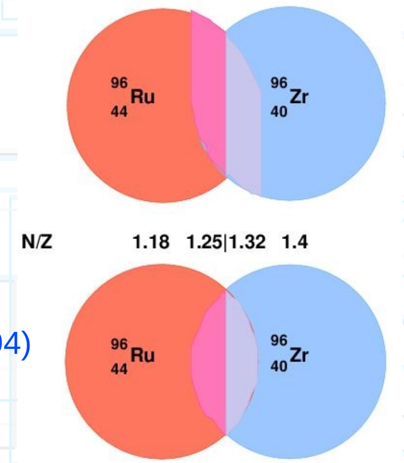




Motivation: FOPI/FOPI-LAND Experiments

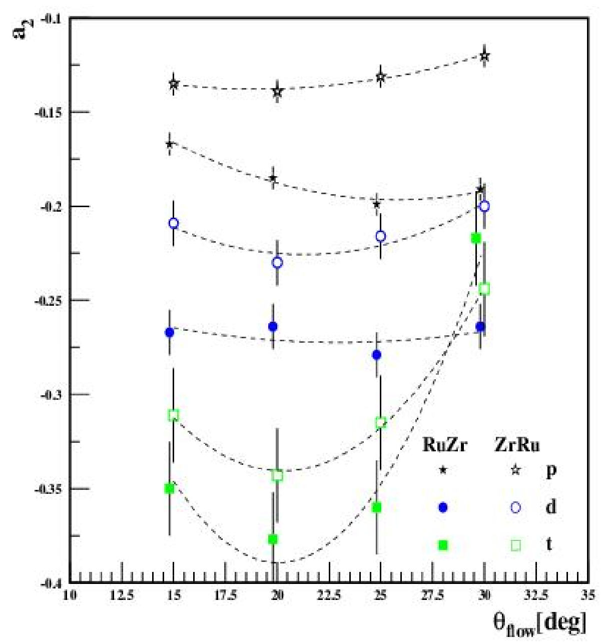
FOPI Collaboration: p and charged mass fragments in the 0.150 – 1.5 AGeV energy range

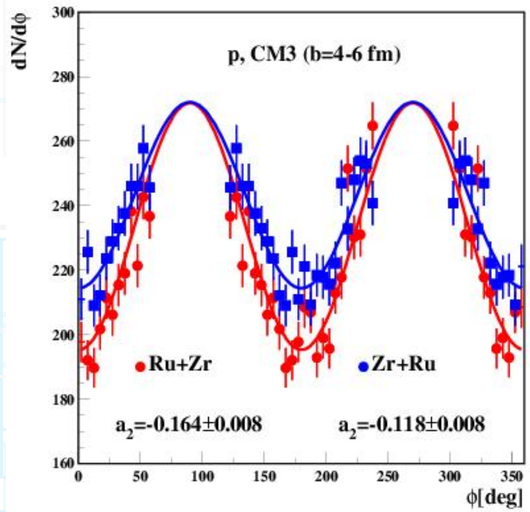
Rami et al., PRL 84,1120;
Hong et al., PRC 66, 034901; A. Andronic et al. NPA 679,765 (2001)



FOPI LAND: n, p and light mass fragments

Y. Leifels et al. PRL 71, 963 (1993); D. Lambrecht Z.Phys. 350,115 (1994)





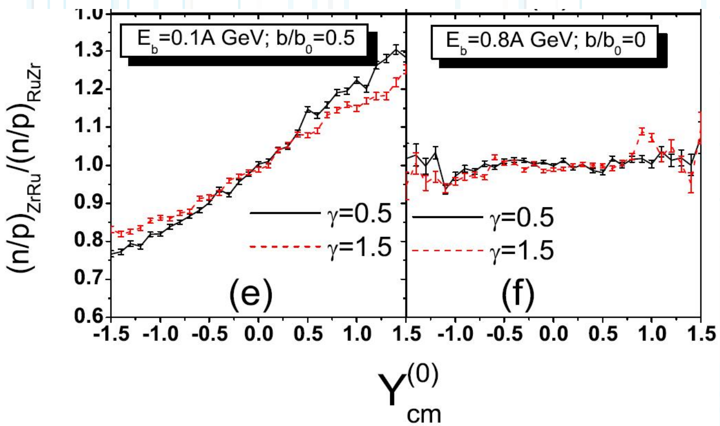
M. Petrovici et al. (FOPI) preliminary/ unpublished

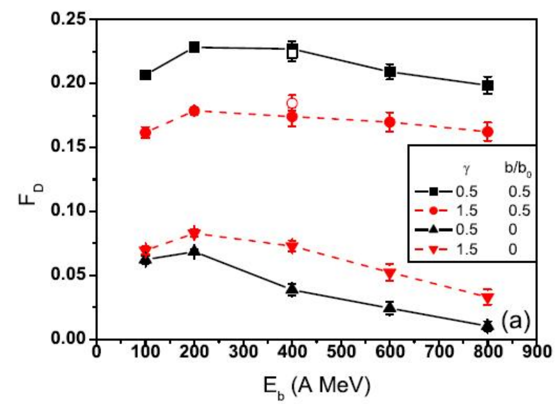
Observables

symmetry potential has opposite sign for neutrons (repulsive) and protons (attractive)

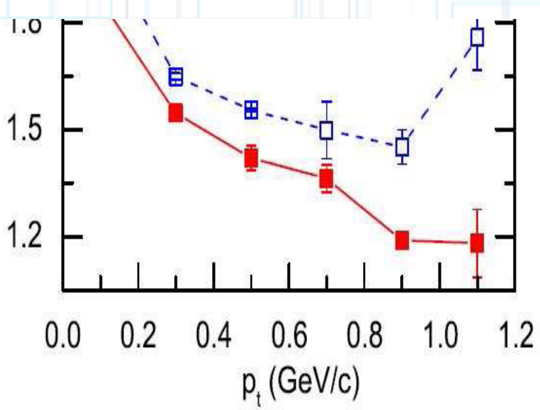
slope of double neutron to proton ratio (n/p)AB/(p/n)BA   Li,Li, Stoecker PRC 73, 051601(2006)

$$S(u)=S_0\,u^{\gamma} \quad u=\rho/\rho_0$$

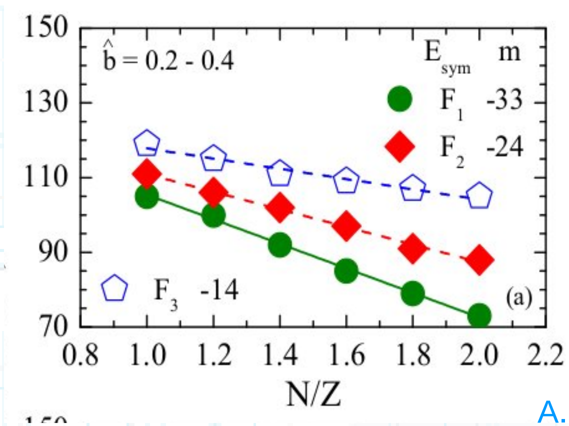




neutron/proton ratio at midrapidity



balance energy of transverse flow



$$\langle p_x^{dir}\rangle=\frac{1}{N}\sum_{1}^{N} sign(y_i)\; p_x(i)$$

Yong, Li, Chen PLB 650, 344 (2007)

A. Sood, PRC 84, 014611 (2011)

Transport Model

Quantum Molecular Dynamics (QMD):

Monte Carlo cascade + Mean field + Pauli-blocking+ in medium cross section

all 4$\ast$ resonances below 2 GeV - 10 Δ^* and 11 N^*

baryon-baryon collisions:

all elastic channels

inelastic channels $NN \to NN^*$, $NN \to N\Delta$, $NN \to \Delta N^*$, $NN \to \Delta\Delta^*$, $NR \to NR'$

pion-absorption ⇋ resonance-decay channels: $\Delta \leftrightarrow N\pi$, $\Delta^* \leftrightarrow \Delta\pi$, $N^* \leftrightarrow N\pi$

meson production/absorption: η(547), ρ(770), ω(782), η'(958), f_0(980), a_0(980), Φ(1020)

applied to study:

-dilepton emission in HIC: K.Shekter, PRC 68, 014904 (2004);D. Cozma, PLB640,170 (2006); E.Santini PRC78,03410 (2008)

-EoS of symmetric nuclear matter: C. Fuchs, PRL86, 1974; Z.Wang NPA645,177

-In-medium effects and HIC dynamics: C. Fuchs, NPA 626,987; U. Maheswari NPA 628,669

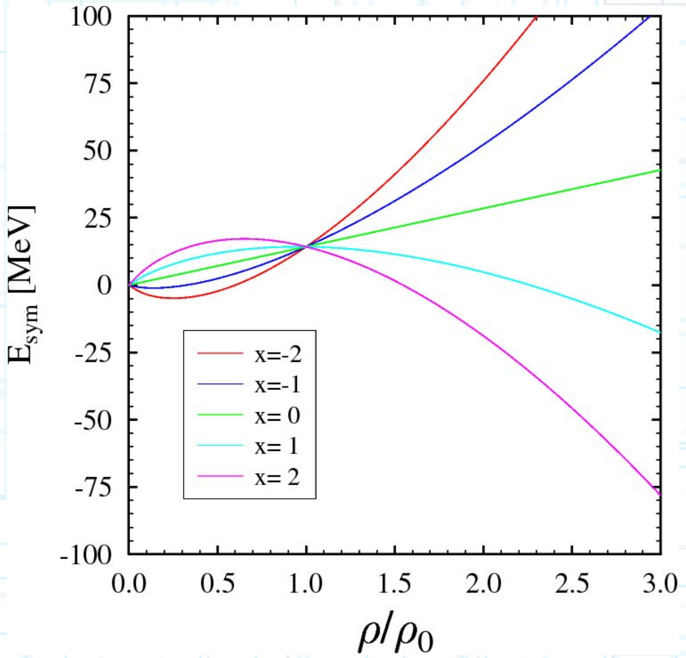
Isospin dependence of EoS

EoS of isospin asymmetric nuclear mater: Das, Das Gupta, Gale, Li PRC67, 034611 (2003)

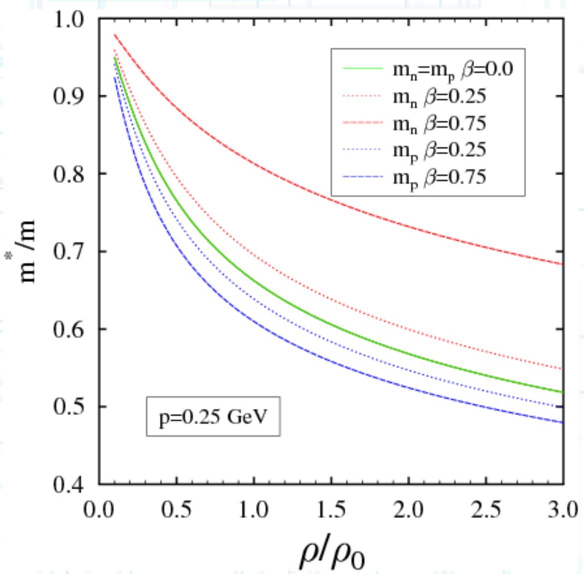
$$U(\rho,\beta,p,\tau,x) = A_u(x)\frac{\rho_{\tau'}}{\rho_0} + A_l(x)\frac{\rho_\tau}{\rho_0} + B(\rho/\rho_0)^\sigma(1-x\beta^2) - 8\tau x\frac{B}{\sigma+1}\frac{\rho^{\sigma-1}}{\rho_0^\sigma}\beta\rho_{\tau'}$$
$$+\frac{2C_{\tau\tau}}{\rho_0}\int d^3p'\,\frac{f_\tau(\vec{r},\vec{p'})}{1+(\vec{p}-\vec{p'})^2/\Lambda^2} + \frac{2C_{\tau\tau'}}{\rho_0}\int d^3p'\,\frac{f_{\tau'}(\vec{r},\vec{p'})}{1+(\vec{p}-\vec{p'})^2/\Lambda^2}$$

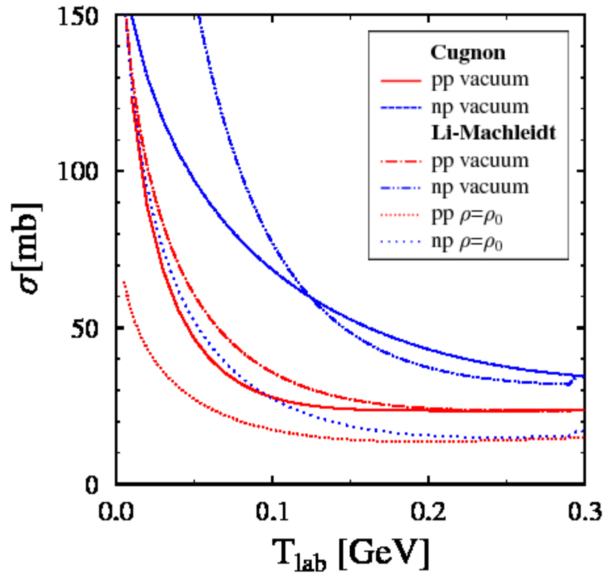
nucleons and resonances propagate in an isospin dependent mean field

$$U_{asym}(n^*) = U_{asym}(\Delta^0) = U^n_{asym}$$
$$U_{asym}(p^*) = U_{asym}(\Delta^+) = U^p_{asym}$$
$$U_{asym}(\Delta^{++}) = 2U^p_{asym} - U^n_{asym}$$
$$U_{asym}(\Delta^-) = 2U^n_{asym} - U^p_{asym}$$



Isospin/Density Dep. Cross-Sections





Isospin asymmetry dependence of NN cross-sections

Li, Machleidt PRC 48, 1702 (1993)
Li, Machleidt PRC 49, 566 (1994)

$$\sigma_{NN}(\rho,\beta) = \sigma_{NN}(\rho,\beta=0)\,\frac{m_1(\rho,\beta)\,m_2(\rho,\beta)}{m_1(\rho,\beta=0)\,m_2(\rho,\beta=0)}$$

Density/Isospin asymmetry dependence of NN cross-sections above pion production threshold

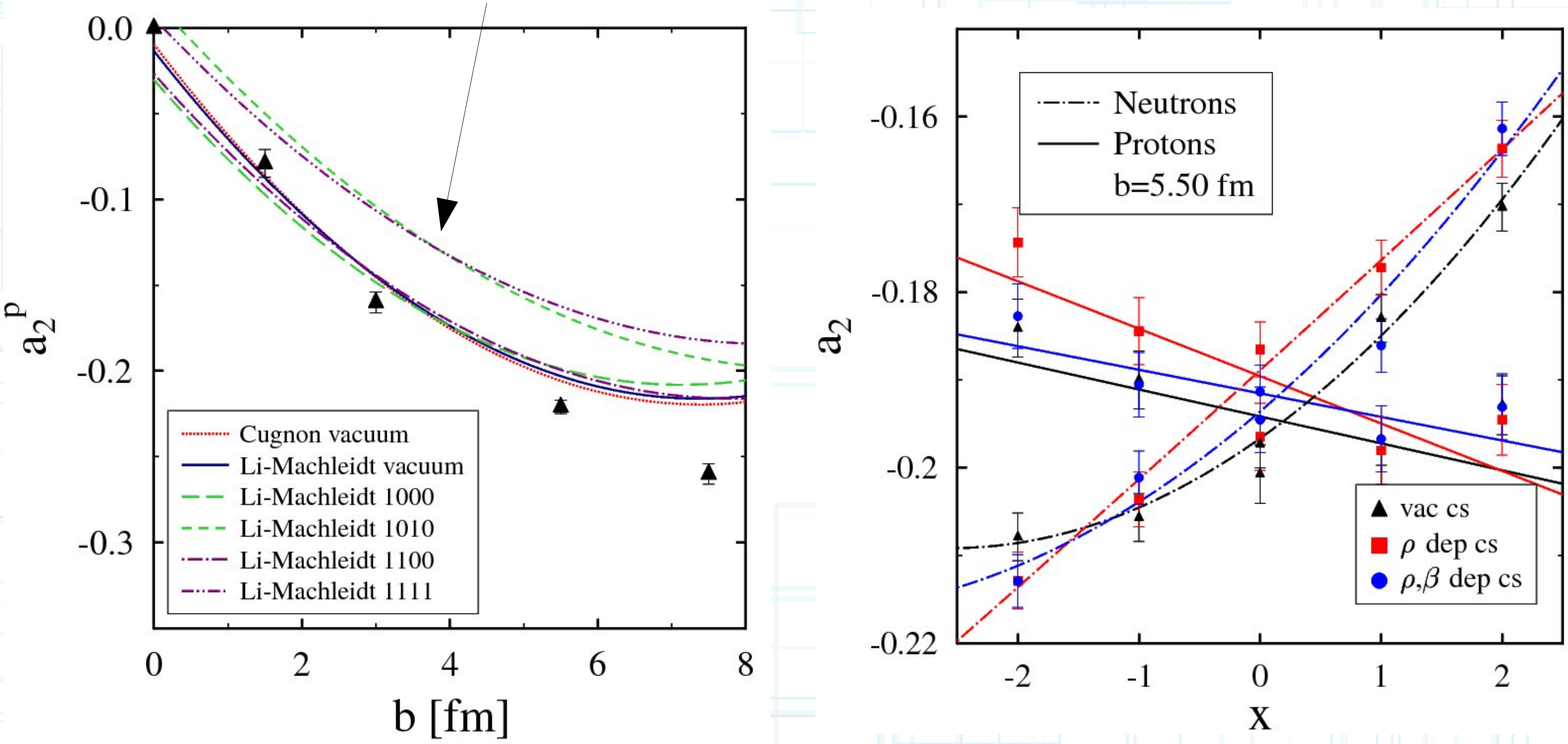
$$\sigma_{NN}(\rho,\beta) = \sigma_{NN}(\rho=0,\beta=0)\,\frac{m_1(\rho,\beta)\,m_2(\rho,\beta)}{m_N^2}$$

Elliptic Flow

$$\frac{dN}{d\phi} \sim 1 + a_1 \cos\phi + a_2 \cos 2\phi$$

$$a_2 = 2 v_2$$

ρ,β dependence of cross-sections
above pion production threshold important !!!



Experimental data (FOPI): A. Andronic et al. Nucl. Phys. A 679, 765 (2001)

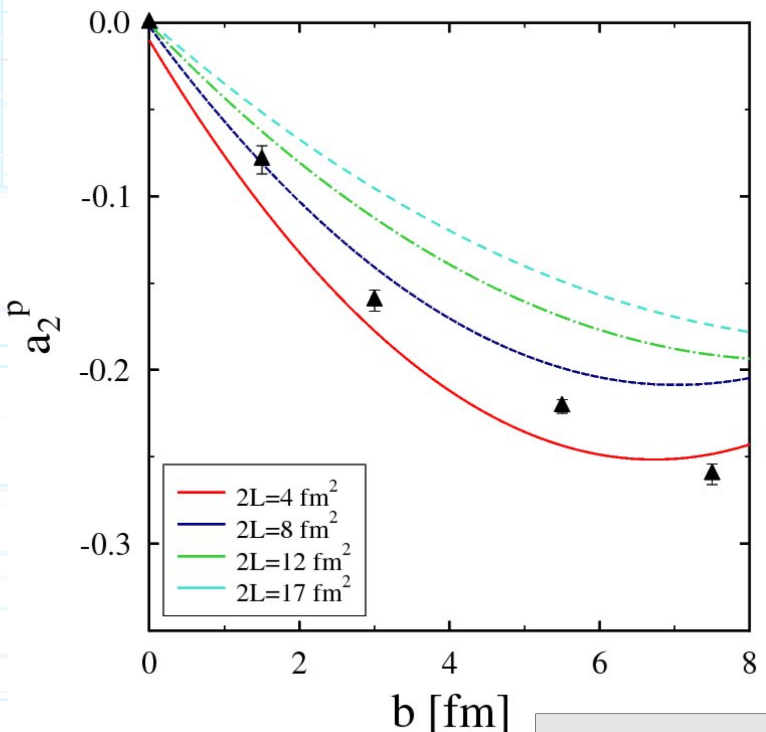
Model dependence of a_2

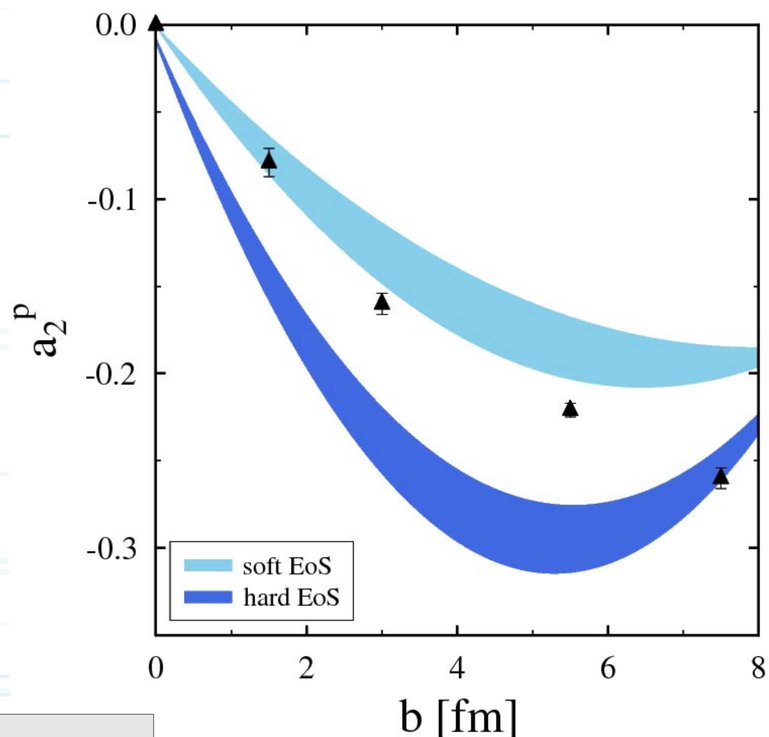
spread of the wave packet: *L*

$$\Psi(\vec{r},\vec{p},t) \sim \exp(-(\vec{x}-\vec{r})^2/L)\,\exp(i\vec{x}\vec{p})$$
$$f_i(\vec{r},\vec{p},t) \sim \exp(-(\vec{r}-\vec{r}_i)^2 2/L)\exp(-(\vec{p}-\vec{p}_i)^2 L/2)$$

stability of heavy nuclei: $2L=8\ \mathrm{fm}^2$

C. Hartnack et al. Eur.Phys.J.A1,151 (1998)





stiffness of EoS

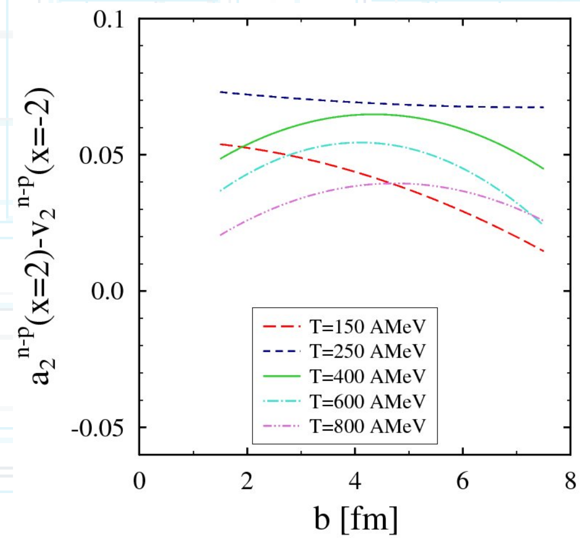
$$E(\rho)=E(\rho_0)+\frac{K}{18}\,\frac{(\rho-\rho_0)^2}{\rho_0^2}$$

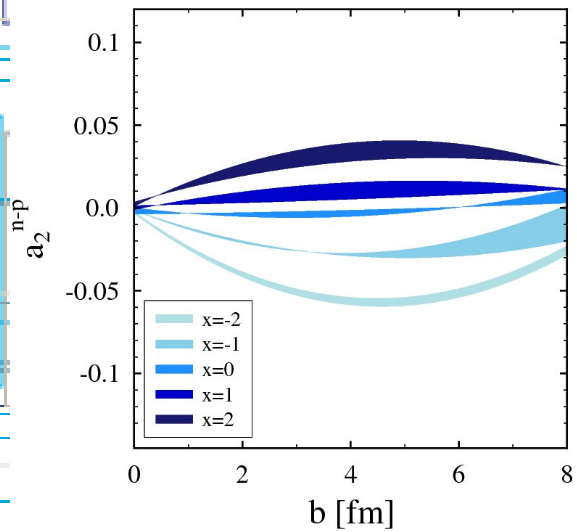
K=210 MeV (soft) / 380 MeV (stiff)

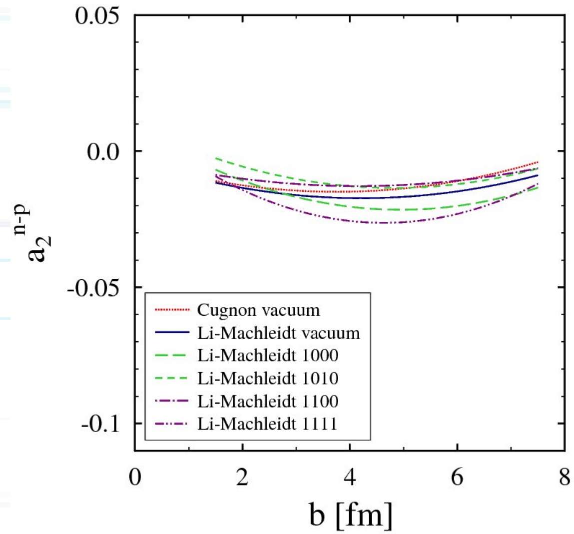
Neutron-Proton EF difference

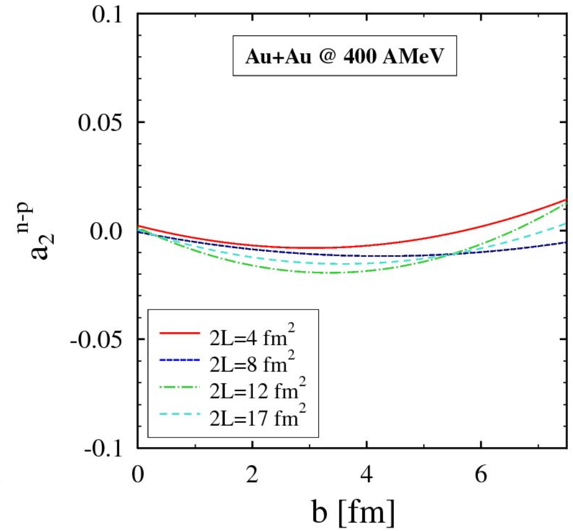
Mean field potential:
- 2,3 - body contact Skyrme
+ empiric momentum dependent part
(Hartnack & Aichelin, Phys. Rev. C 49, 2801 (1994))

- Gogny inspired isovector part
(C.B. Das et al., Phys. Rev. C 67, 034611-1 (2003))





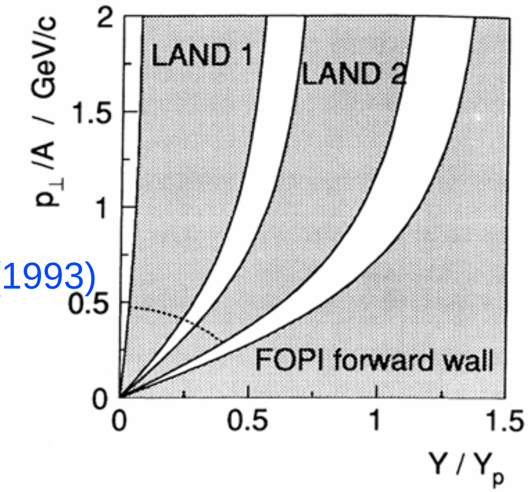




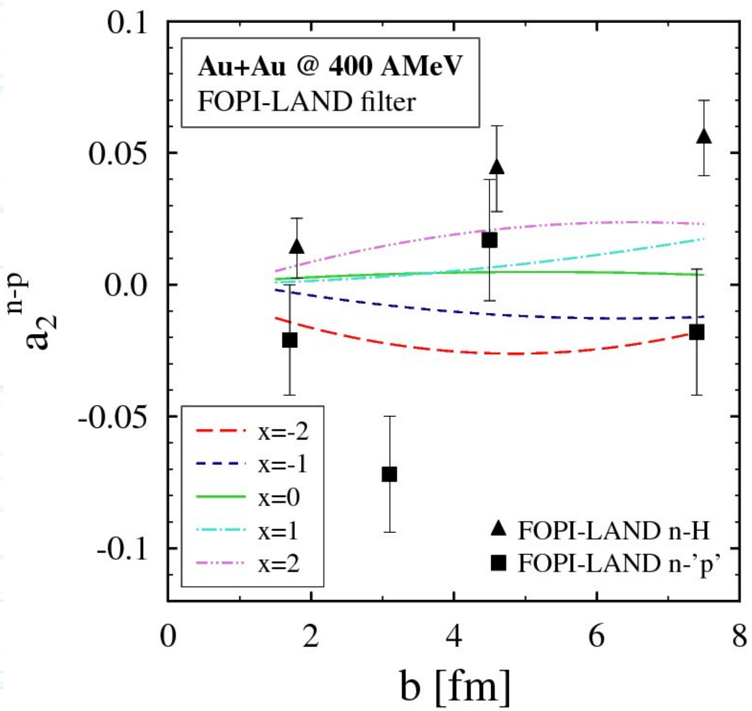
FOPI-LAND

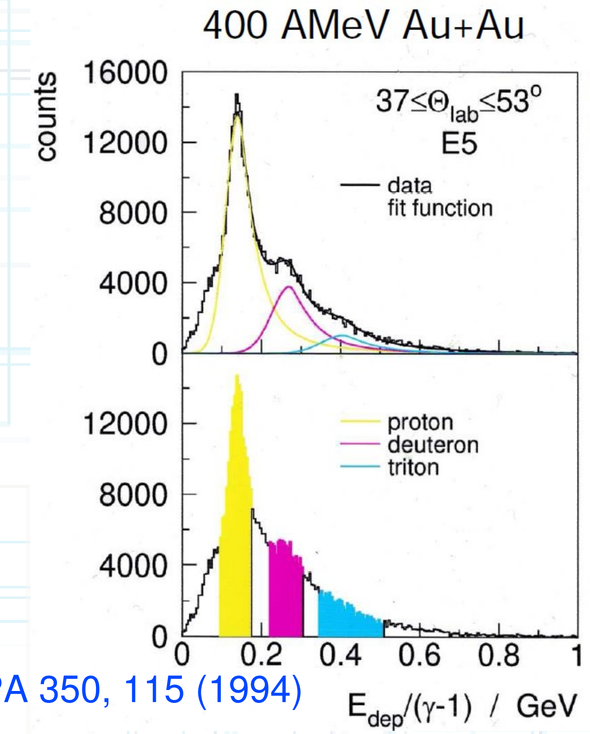
first detection of neutron squeeze-out

Y. Leifels et al. PRL 71, 963 (1993)



M.D. Cozma, PLB 700, 139 (2011)





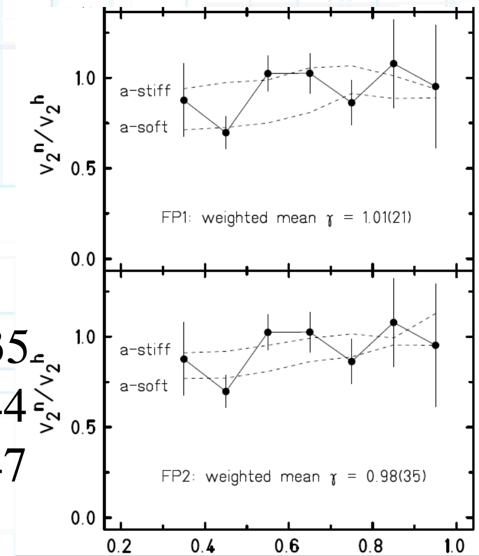
D. Lambrecht et al., ZPA 350, 115 (1994)

New FOPI-LAND data

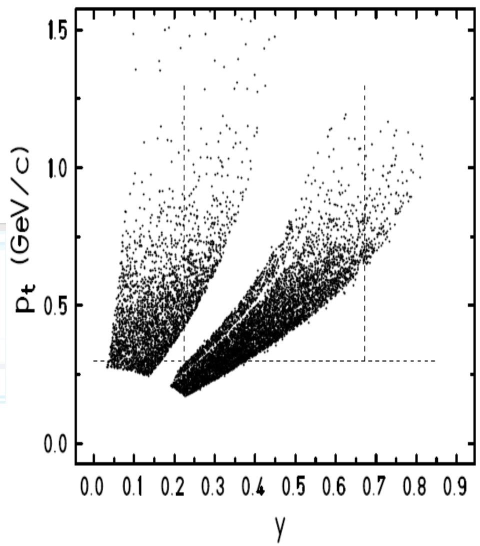
P. Russotto et al. PLB 697, 471 (2011)

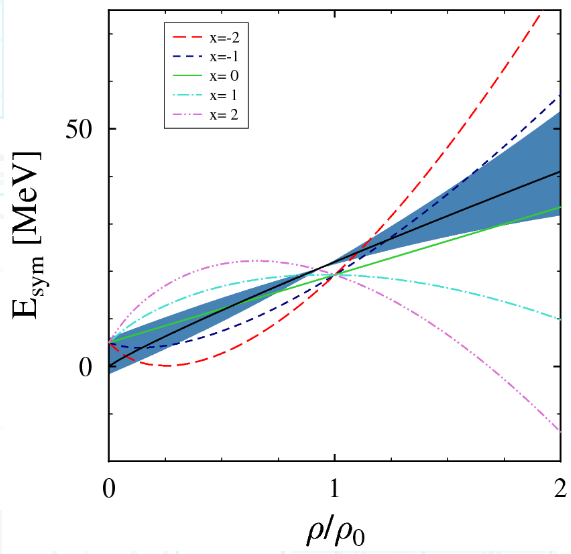
$$E_{sym} = 22(\rho/\rho_0)^{\gamma} + 12(\rho/\rho_0)^{2/3}\,\text{MeV}$$

clustering algorithm – good
Z=1 reproduction



v_2^n/v_2^h	$\gamma=1.01\pm0.21$ / 0.98 ± 0.35
5.5<b<7.5	$\gamma=0.58\pm0.27$ / 0.35 ± 0.44
v_2^n/v_2^p	$\gamma=0.99\pm0.28$ / 0.85 ± 0.47

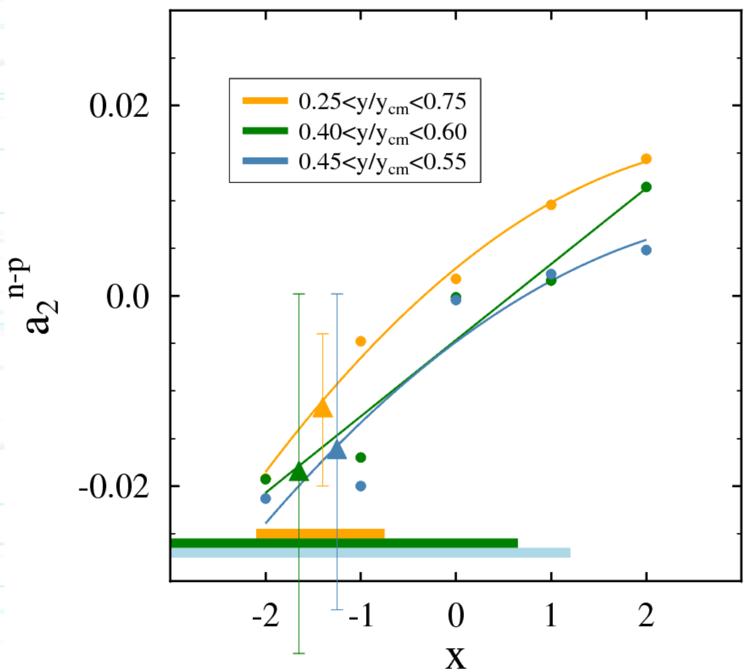


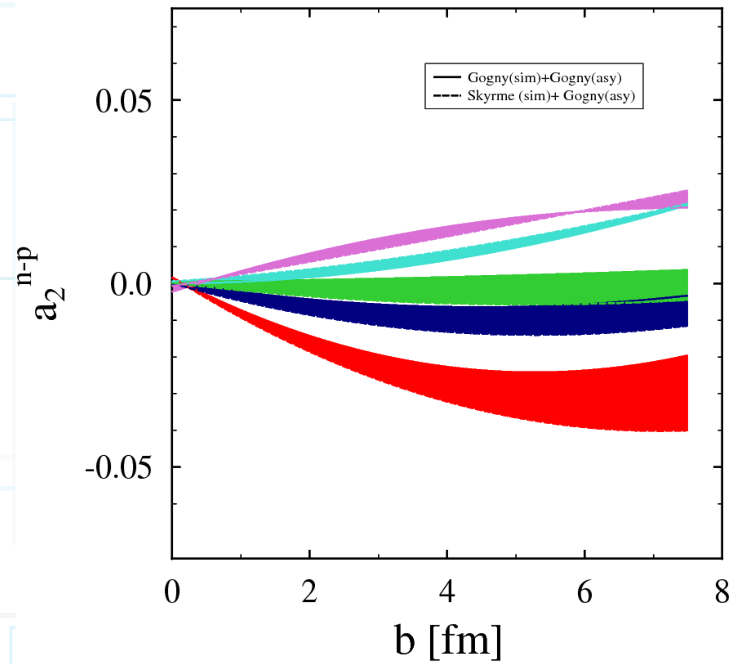


$\gamma=0.9\pm0.4$

New FOPI-LAND data

experimental data: FOPI-LAND preliminary (W. Trautmann et al.)





see also L.Zhang et.al nucl-th 12031724

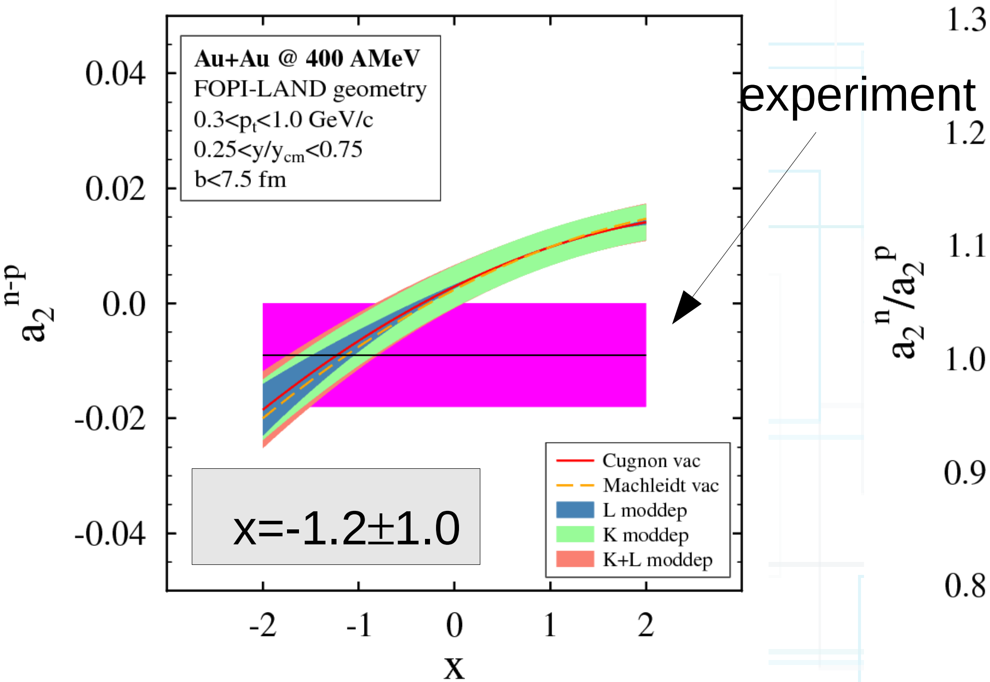
rather poor reproduction of new FOPI-LAND a_2^n and a_2^p values

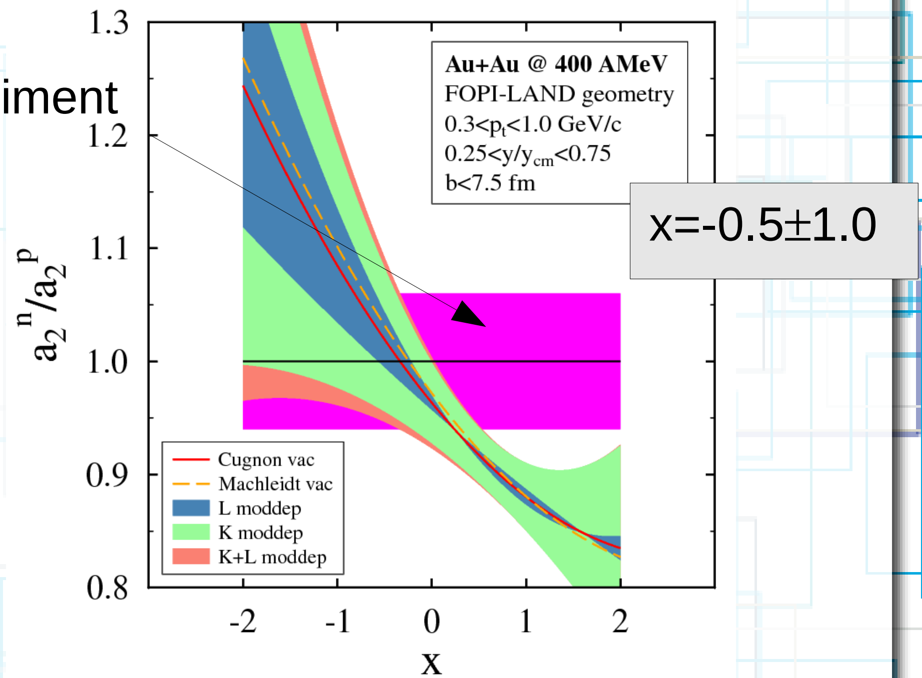
extra model dependece ? (momentum dependent part of symmetric EoS)

some differences between old/new FOPI LAND data sets

EF ratios vs. differences

flow difference | **flow ratio**



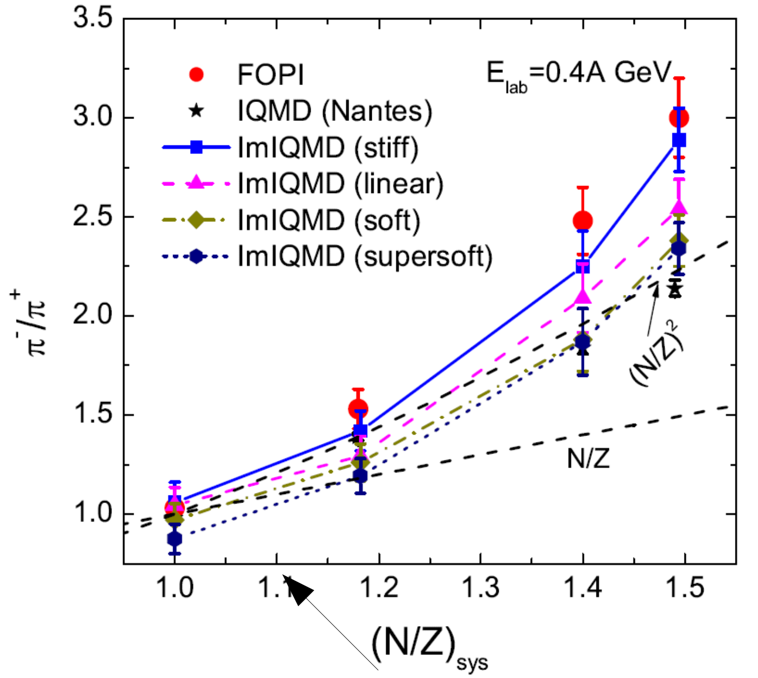


experimental data: FOPI-LAND preliminary (W. Trautmann et al.)

Constraints from other observables

$\pi^-/\pi^+=(5N^2+NZ)/(5Z^2+NZ)$

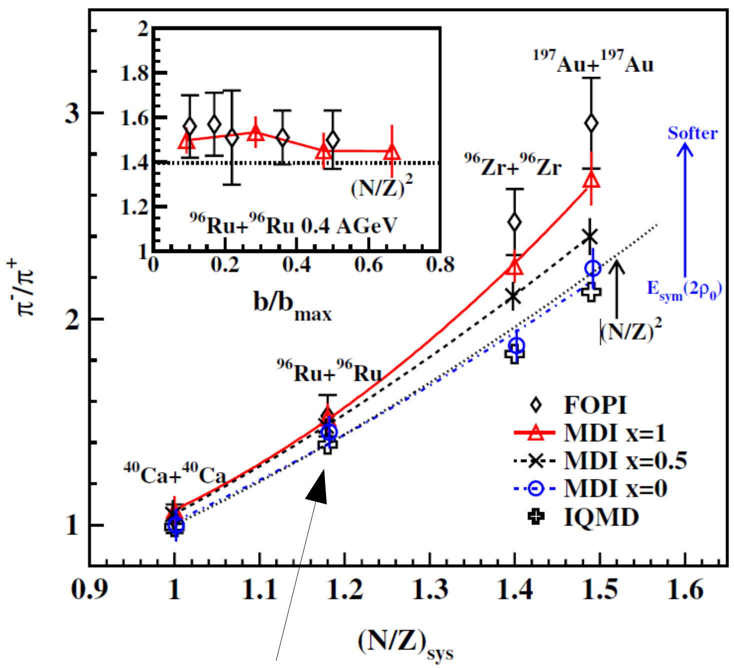
Z.-Q. Feng et al., PLB 683, 140, (2010)



IQMD

$S(u)=S_0\,u^{\gamma}$

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



IBUU

Gogny force

Summary & Outlook

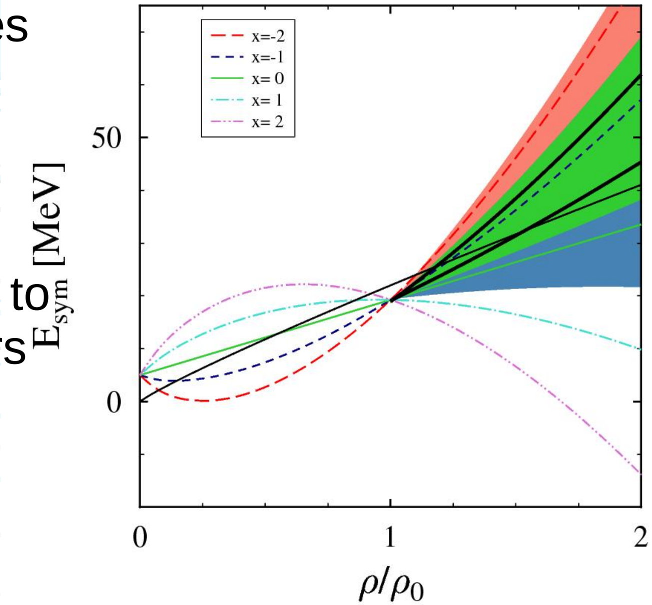
symmetry energy – important for describing
astrophysical related phenomena/quantities

CAN be constrained at suprasaturation densities -
heavy-ion related observables

elliptic flow observables – suppressed dependence to
certain model parameters
(K,L, cs)

some model dependence still present –
differences vs ratios

x=-0.8±0.5



OUTLOOK:

- study left over model dependence
- mitigate differences w.r.t other observables (pion ratios)
- how about light mass fragments?