Towards a model-independent constraint of the high-density dependence of the symmetry energy

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Symmetry Energy

EoS of Asymmetric Nuclear Matter

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

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

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

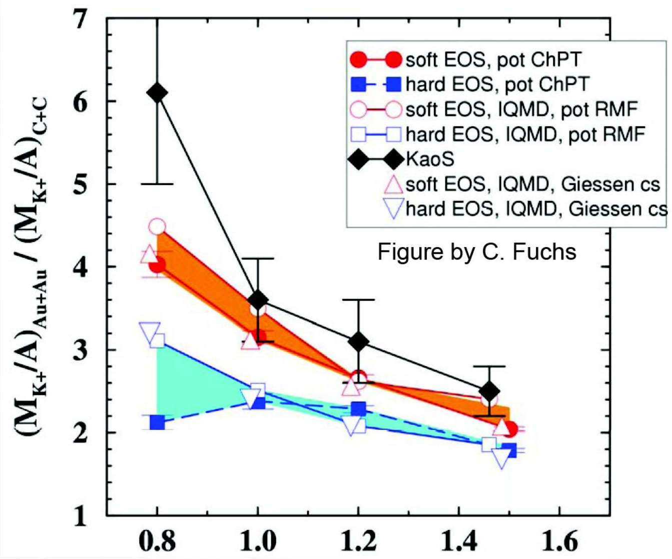
Experiment

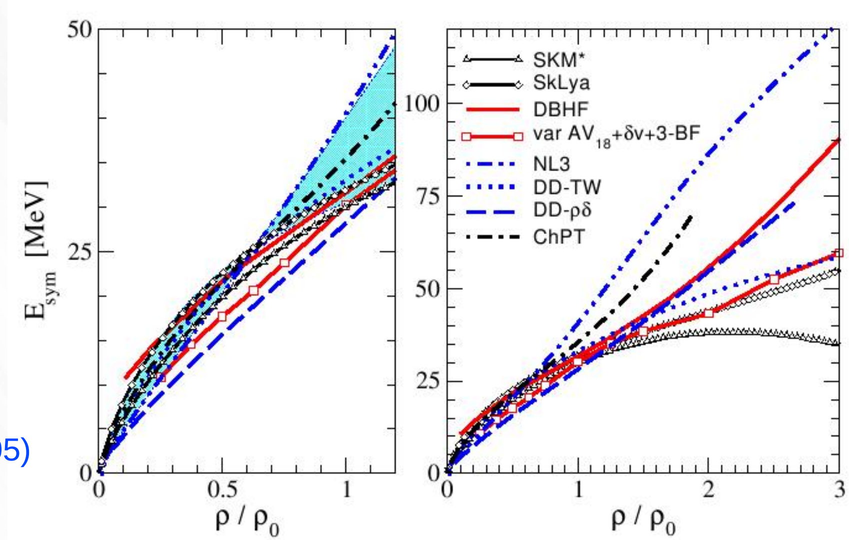
isospin diffusion/neutron skin thickness of Pb: $L_{sym} \simeq 65$ MeV B.A. Li *et al.* PRC 72,064611 (2005)

giant monopole resonances:
K_{sym} -566 +/- 1350 MeV; 34 +/- 159 MeV

S. Shlomo *et al.* PRC 47, 529 (1993)

C. Fuchs *et al.* PRL 86, 1974 (2001)





See also: M.B. Tsang *et al.* PRC86, 015803 (2012)

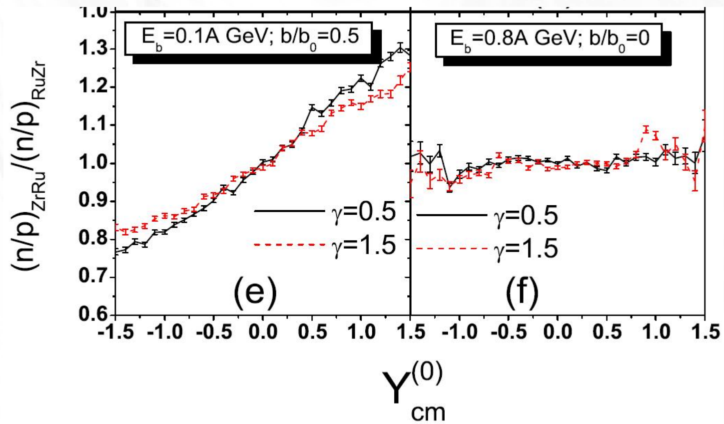
Observables

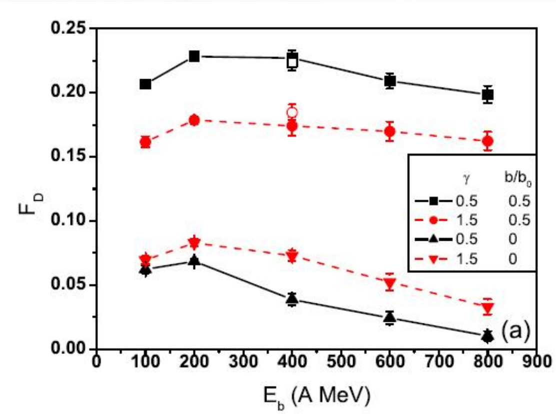
symmetry potential has opposite sign for neutrons (repulsive) and protons (attractive)

slope of double neutron to proton ratio (n/p)AB/(p/n)BA

Li,Li, Stoecker PRC 73, 051601 (2006)

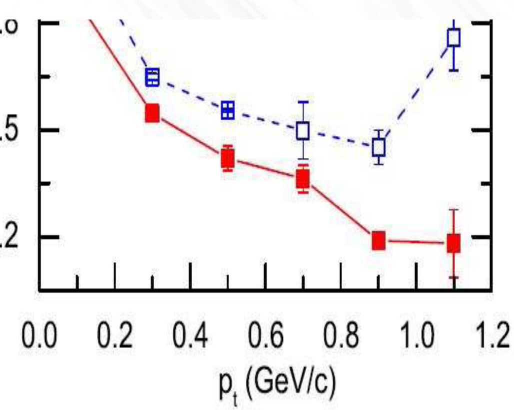
$$S(u)=S_0\,u^{\gamma}\quad u=\rho/\rho_0$$



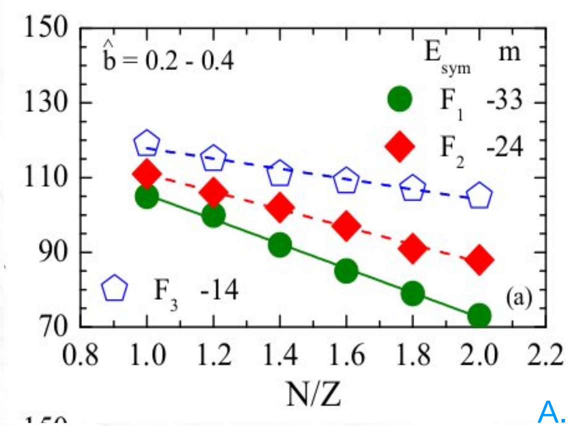


neutron/proton ratio at midrapidity

balance energy of transverse flow



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



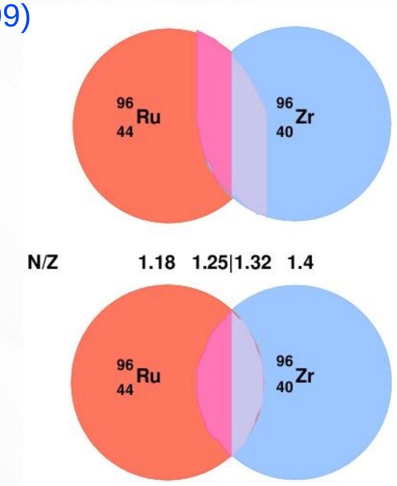
$$\langle p_x^{dir}\rangle=\frac{1}{N}\sum_{1}^{N} sign(y_i)\;p_x(i)$$

A. Sood, PRC84, 014611 (2011)

Motivation: FOPI/FOPI-LAND

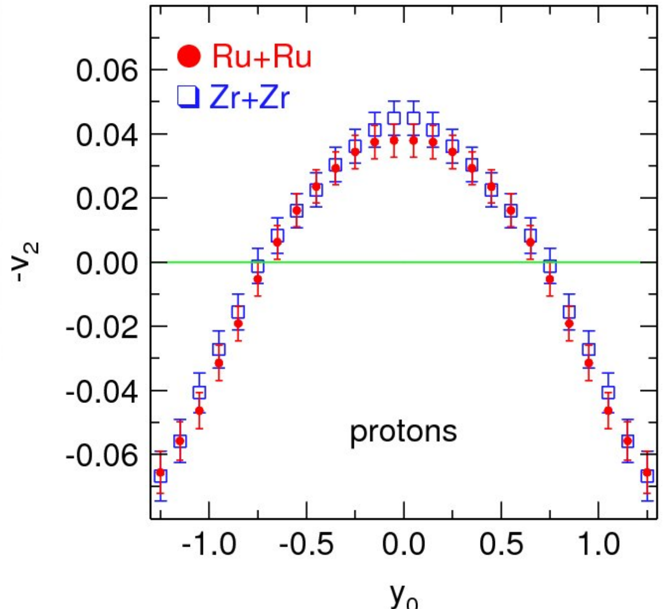
FOPI Collaboration: p and charged mass fragments (0.15-1.5 AGeV)

- isospin tracing — Rami et al., PRL 84,1120 (2000); Rami et al., NPA 646, 367 (1999)
- stopping — Hong et al., PRC 66, 034901 (2002);
- elliptic flow — A. Andronic et al. NPA 679,765 (2001)

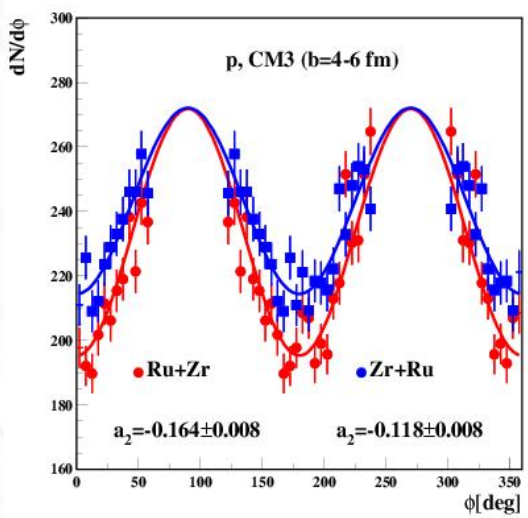


FOPI LAND: n, p and light mass fragments – elliptic flow

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



W. Reisdorf, et al. NPA 876, 1 (2012)



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

Transport Model

Quantum Molecular Dynamics (QMD):

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

all 4∗ resonances below 2 GeV - 10 Δ^* and 11 N^*

baryon-baryon collisions:

all elastic channels

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

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 (2003);D. Cozma, PLB640,170 (2006); E.Santini PRC78,03410 (2008)
-EoS of symmetric nuclear matter: C. Fuchs, PRL 86, 1974 (2001); Z.Wang NPA 645, 177 (1999)
-In-medium effects and HIC dynamics: C. Fuchs, NPA 626,987 (1997); U. Maheswari NPA 628,669 (1998)

Isospin dependence of EoS

a) momentum dependent – generalization of the Gogny interaction:

Das, Das Gupta, Gale, Li PRC67, 034611 (2003)

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

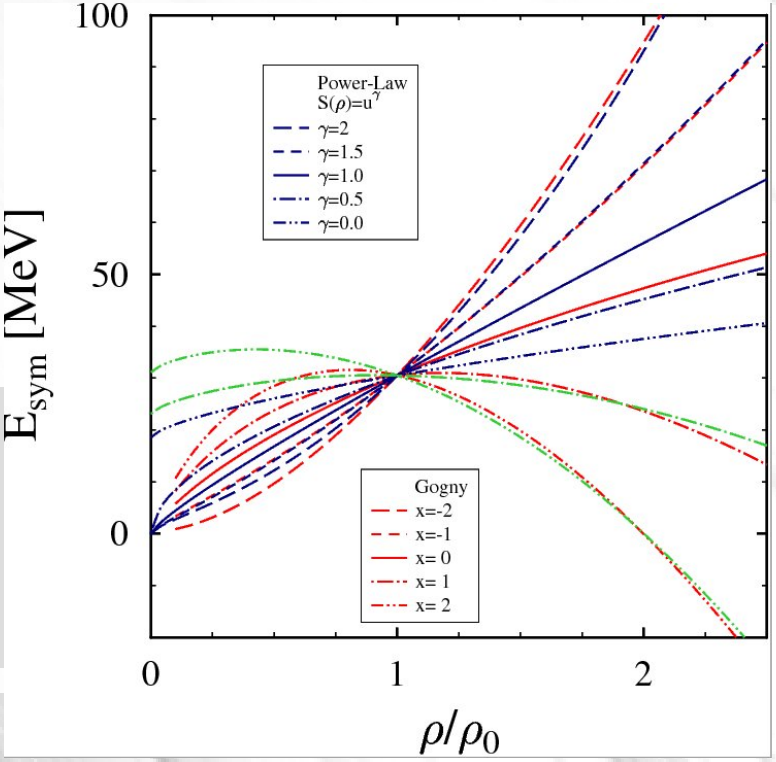
b) momentum dependent – power law

add references:

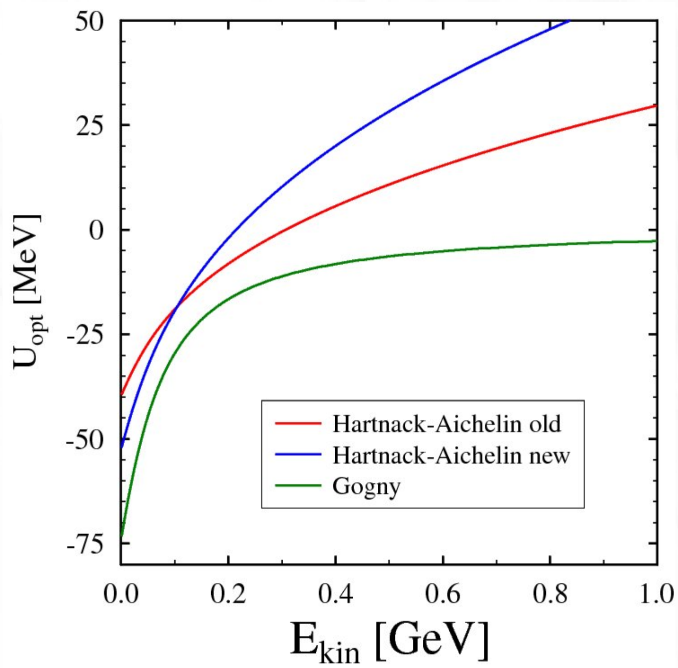
$$U_{sym}(\rho,\beta)=\begin{cases} S_0(\rho/\rho_0)^\gamma - linear, stiff \\ a+(18.5-a)(\rho/\rho_0)^\gamma - soft, supersoft \end{cases}$$

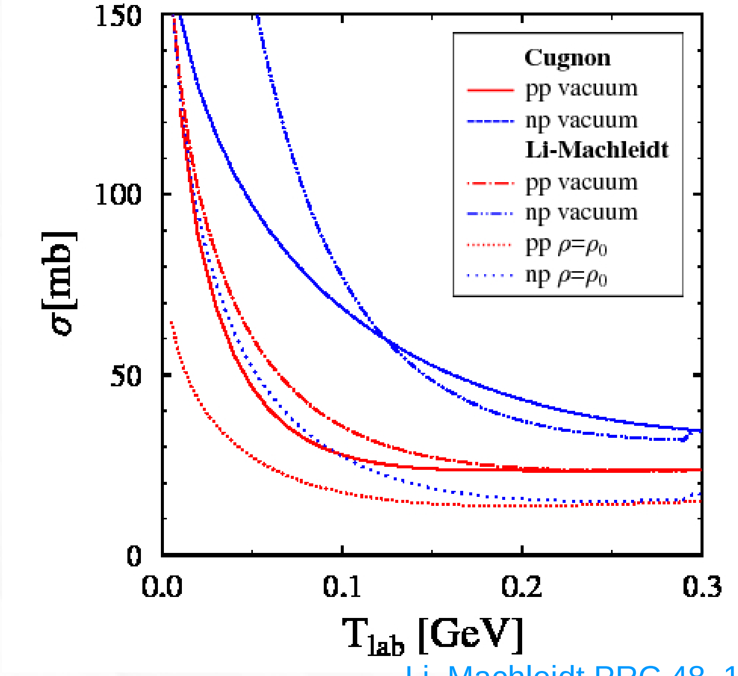
nucleons and resonances propagate in an isospin dependent mean field

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



Optical potential/NN Cross-Sections





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

Das, Das Gupta, Gale, Li PRC 67, 034611 (2003)
Hartnack and Aichelin, PRC 49, 2801 (1994)

$$V_{opt}^{(HA)}(p-p')=V_0+\delta\ln^2[(p-p')^2\epsilon+1]$$
$$V_0=-54\,MeV\,;\,\delta=1.58\,MeV\,;\,\epsilon=500\,GeV^{-2}$$

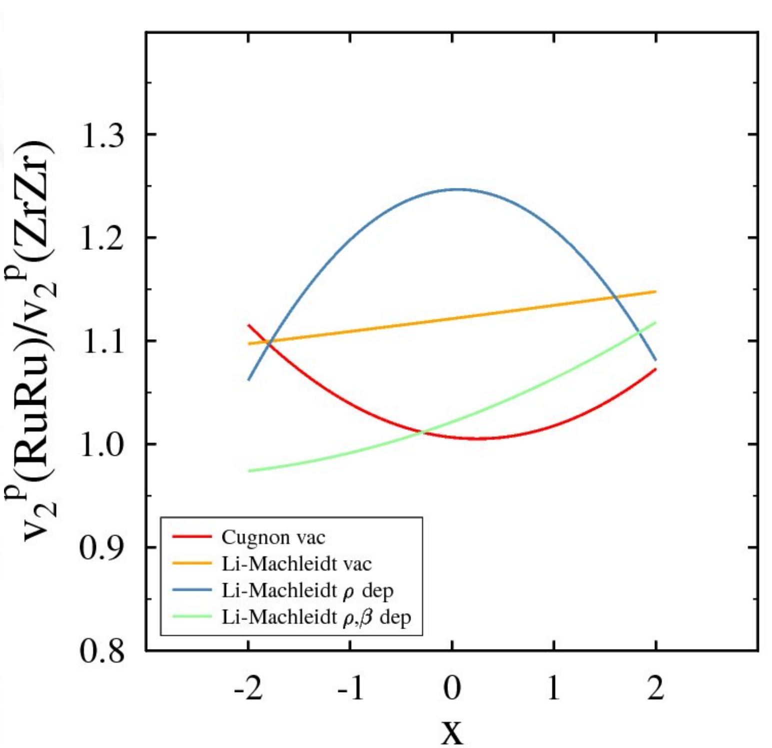
isospin asymmetry dependence of NNCS

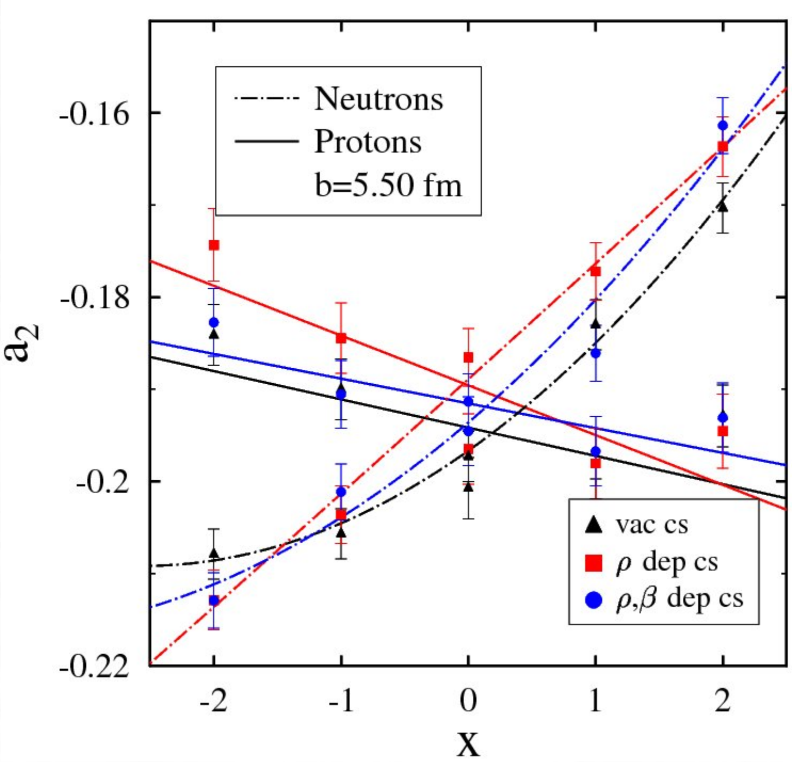
$$\sigma_{NN}(\rho,\beta) \quad = \quad \sigma_{NN}(\rho,\beta=0)\,\frac{m_1(\rho,\beta)\,m_2(\rho,\beta)}{m_1(\rho,\beta=0)\,m_2(\rho,\beta=0)}$$

Elliptic Flow

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

$$a_2 = 2v_2$$



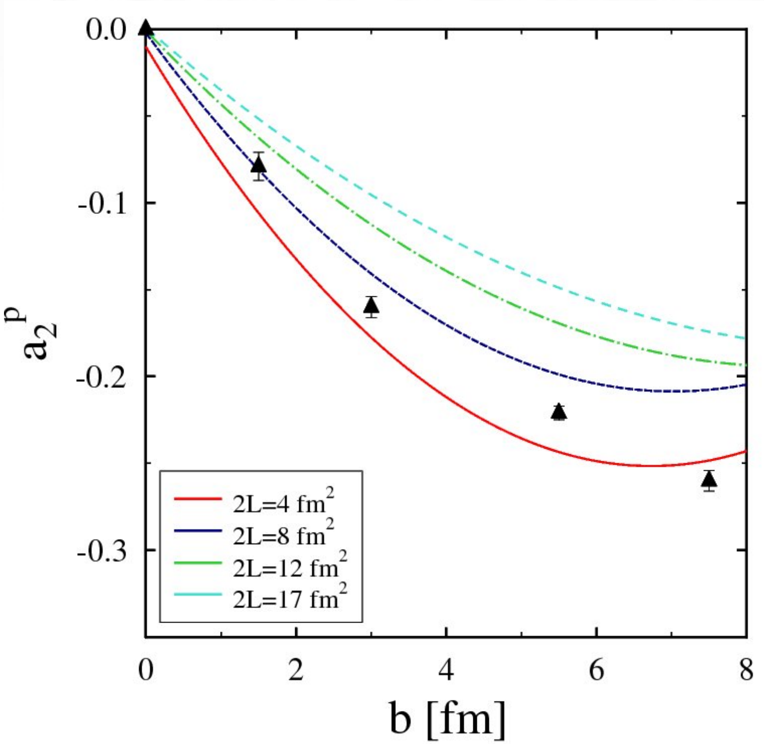


Extra model parameters

Width of the wave packet: *L*

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

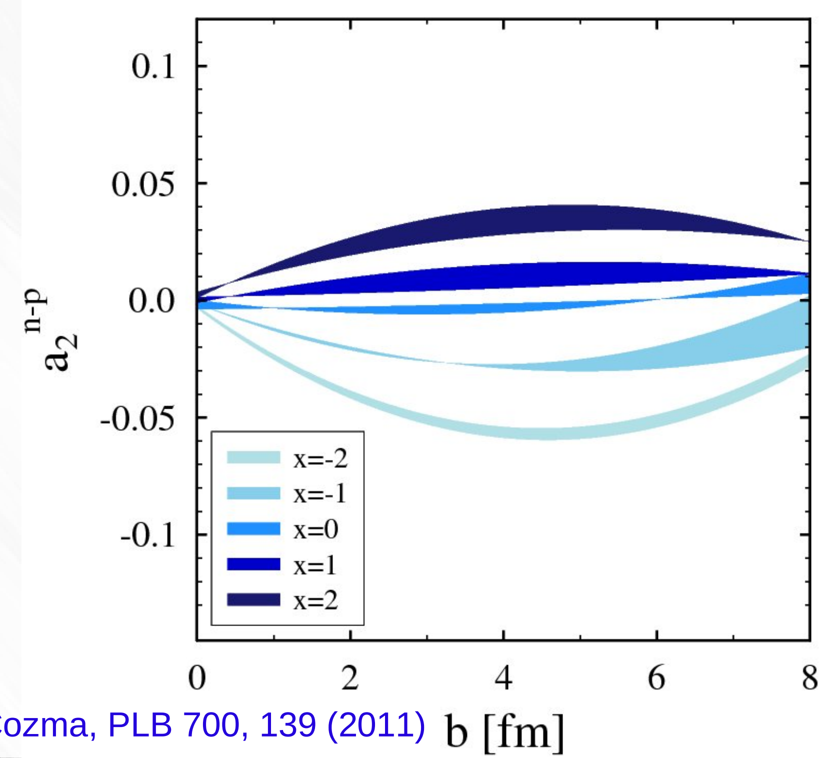
stability of heavy nuclei: L=8 fm^2
C. Hartnack et al. Eur.Phys.J.A1,151 (1998)



Compressibility modulus: *K*

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

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



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

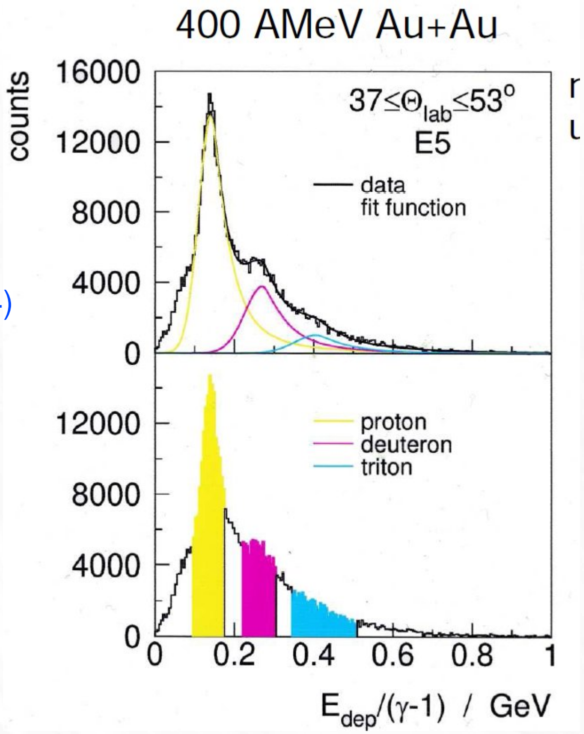
Experimental data (FOPI): A. Andronic et al. Nucl. Phys. A 679, 765 (2001)

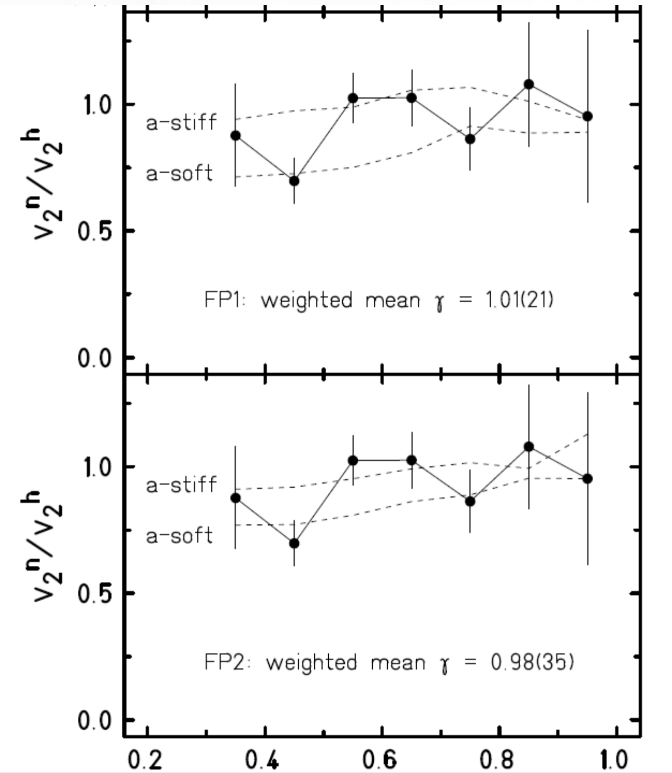
FOPI-LAND

first detection of neutron squeeze-out

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

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





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

γ=0.9±0.4

v_2^n/v_2^h γ=1.01±0.21 / 0.98±0.35

5.5<b<7.5 γ=0.58±0.27 / 0.35±0.44

v_2^n/v_2^p γ=0.99±0.28 / 0.85±0.47

clustering algorithm – good Z=1 reproduction

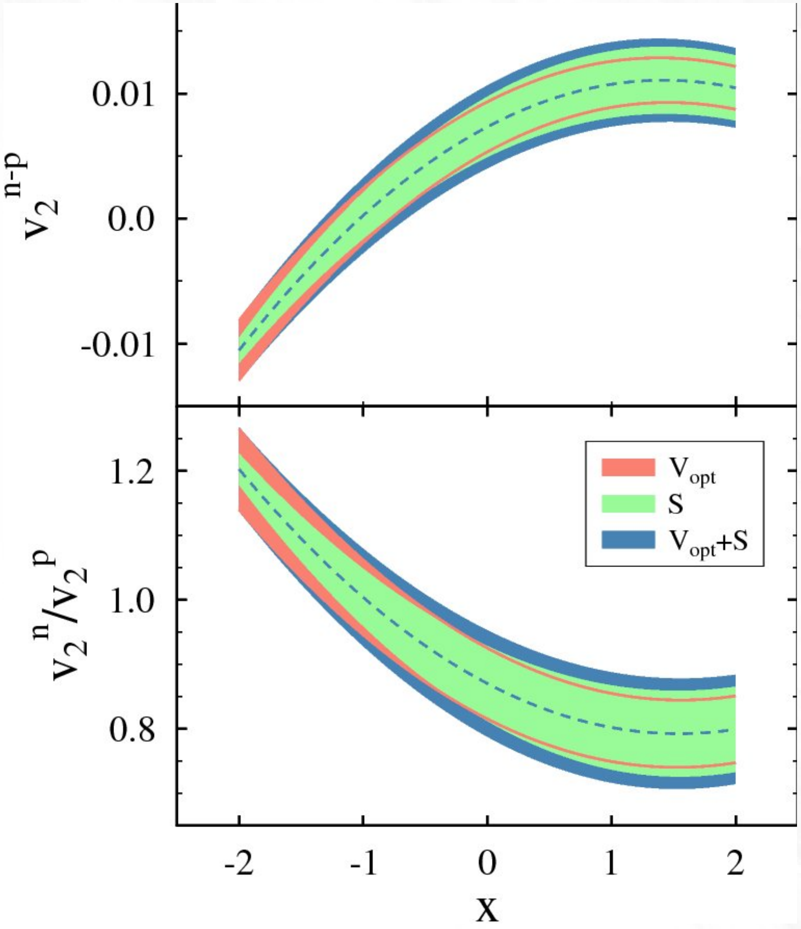
P. Russotto et al. PLB 697, 471 (2011)

UrQMD model (upgrades):

Q. Li et al. PRC 83, 044617 (2011)
Y.Wang et al., nucl-th 1305.4730 (2013)

Model dependence & FOPI-LAND

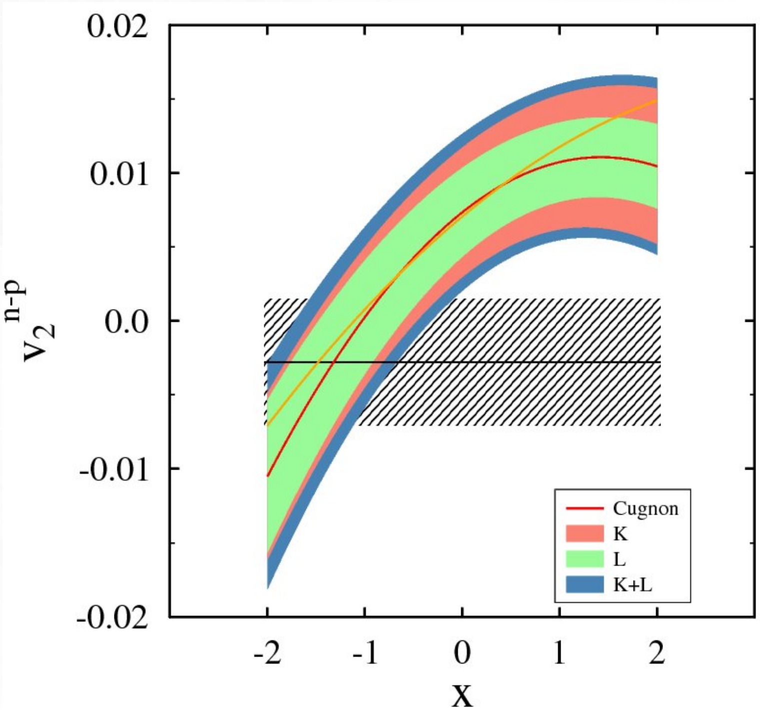
optical potential & symmetry energy



see also L.Zhang et.al Eur.Phys.J. A48, 30 (2012)

wave function width (L) and
compressibility modulus (K)

K=190÷280 MeV
L=2.5÷7.0 fm^2

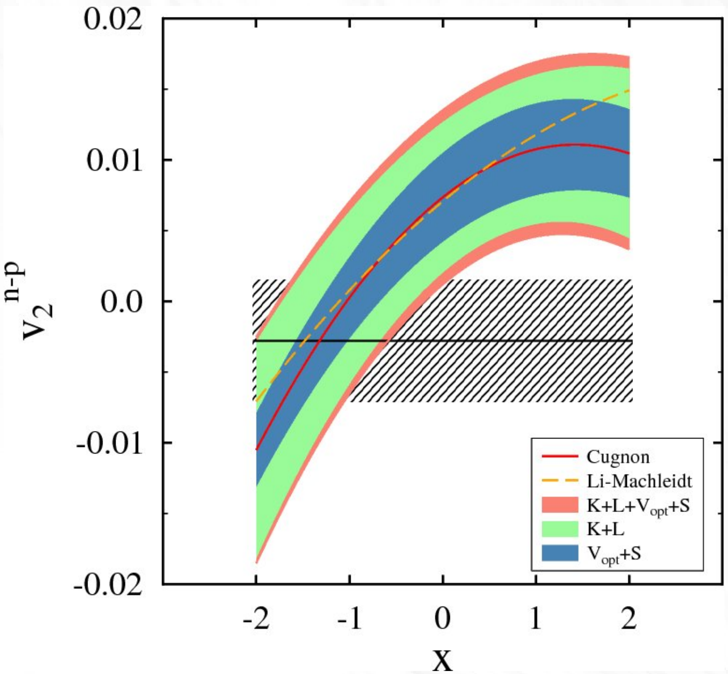


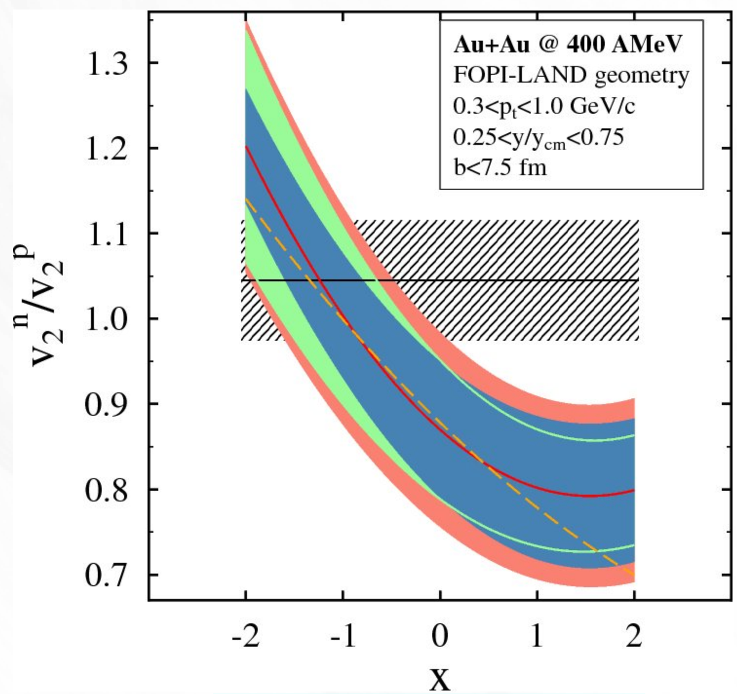
M.D. Cozma et al. ArXiv:1305.5417 [nucl-th]

Constraints on Asy-EoS

flow difference: $x = -1.50^{+1.75}_{-1.00}$

flow ratio: $x = -1.25^{+1.25}_{-1.00}$





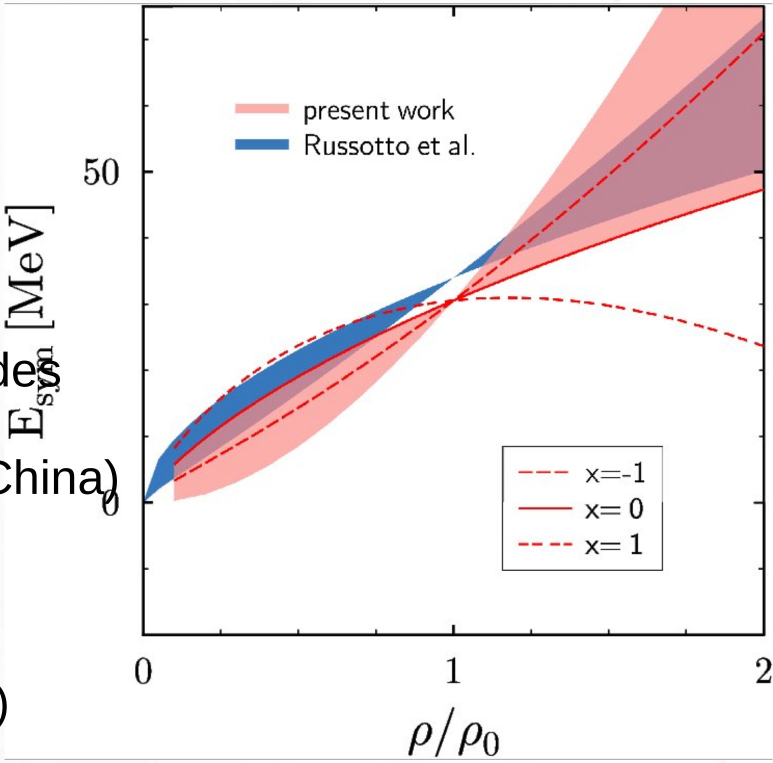
$L_{sym} = 129^{+46}_{-80}$ MeV
$K_{sym} = 272^{+291}_{-508}$ MeV

$L_{sym} = 118^{+45}_{-57}$ MeV
$K_{sym} = 199^{+291}_{-362}$ MeV

M.D. Cozma et al. ArXiv:1305.5417 [nucl-th]

Density dependence of SE

studies presented in
M.D. Cozma PLB 700, 139 (2011)
P. Russotto et al. PLB 697, 471 (2011)
M.D. Cozma et al. ArXiv:1305.5417 [nucl-th]



-**Independently developed** transport codes and upgrades
QMD – Tuebingen/ upgraded in Bucharest
UrQMD – Frankfurt/ upgraded Q.Li et al. Huzhou (China)

-**different parametrizations** of the symmetry energy
- momentum dependent (QMD) /
momentum independent (UrQMD)

-inclusion of **in-medium effects**
-in medium NN cross-section (both QMD and UrQMD)

-**thorough study** of various model parameters:
- width of nucleon wave-function (L)
- compressibility modulus of nuclear matter (K)
- impact of optical potential

similar result

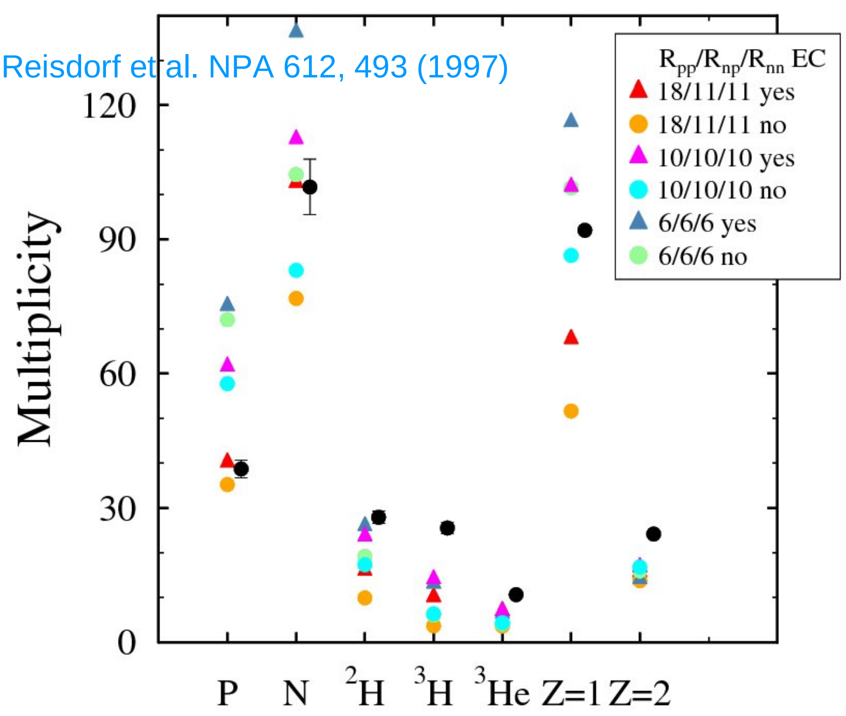
$\boxed{x=-1.0\pm1.0}$

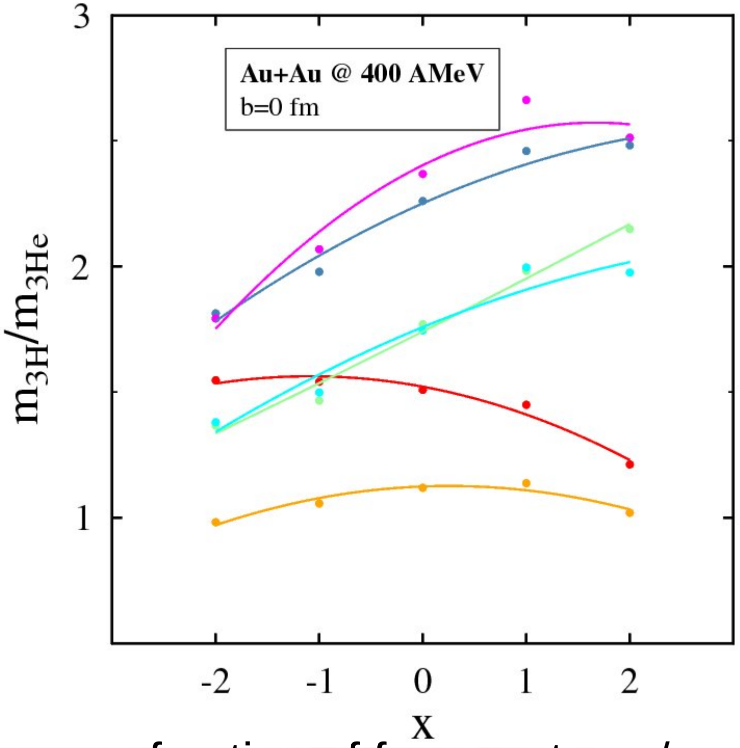
$L_{sym}=106\pm46$ MeV
$K_{sym}=127\pm290$ MeV

A note on light mass fragments

- phase space coalescence model: Y.Zhang et al. PRC 85, 051602R (2012)
- modest goal: describe FOPI neutron, proton, deuteron, Z=1 multiplicities

W. Reisdorf et al. NPA 612, 493 (1997)





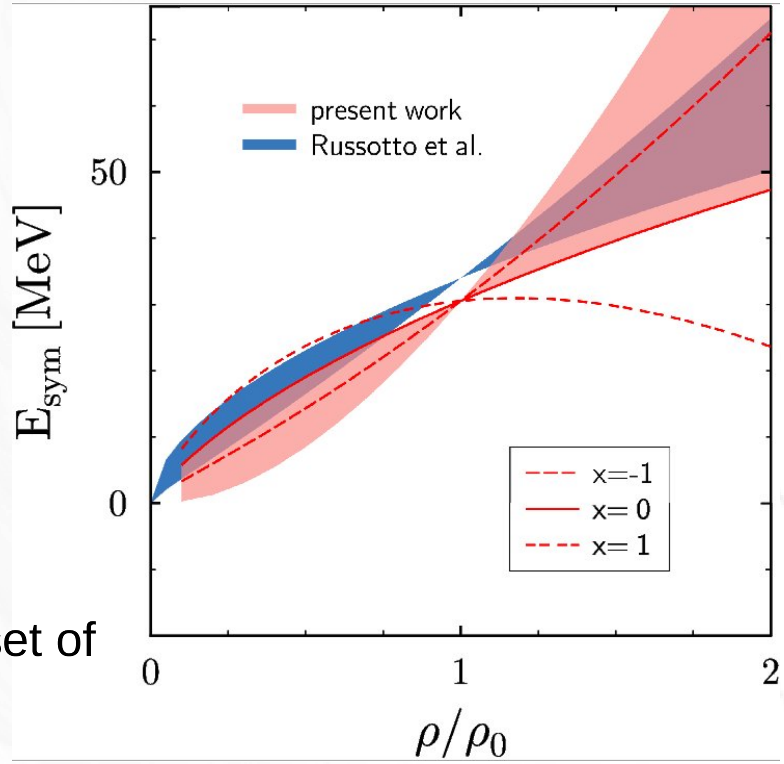
-prescription for spurious clusters (guided by exp. fraction of free neutrons/protons)

2n → n + n	4n → n + ^{3}H	5He → n + ^{4}He
2p → ^{2}H + π^+	4p → p + ^{3}He	5Li → p + ^{4}He
3n → ^{3}H + π^-	3np → n + ^{3}H	5Be → 2p + ^{3}He
3p → ^{3}He + π^+	3pn → p + ^{3}He	6Be → 2p + ^{4}He

on the topic see also
A. Le Fevre et al., talk at ASYEOS 2012
G-C. Yong et al. PRC 80, 044608 (2009)

Summary & Outlook

x=-1.0±1.0



-Elliptic flow observables – sensitive to the density dependence of symmetry energy

-**Thorough study** of model dependence

-**Similar extracted constraints** of the density dependence of symmetry energy

OUTLOOK:

• reduce model dependence by describing a larger set of observables

• more accurate experimental data (ASYEOS, NEULAND) will also help push the constraints towards higher density regions

• extend the analysis to light mass fragments

• pion ratios – a test of our understanding of hadronic interactions: constraints from elliptic flow observables may serve as a benchmark