Joint LIA COLL-AGAIN, COPIGAL and POLITA Workshop

French–Italian–Polish Collaborations on

Nuclear Structure and Reactions

April 26-29, 2016

LNS, Catania

Constraining the symmetry energy at supra-saturation densities:

the ASY-EOS experiment at GSI:

P. Russotto, INFN-Sez. di Catania, Italy

for

NewCHIM & ASY-EOS collaborations

INFN

5/17/2016 5:52 PM

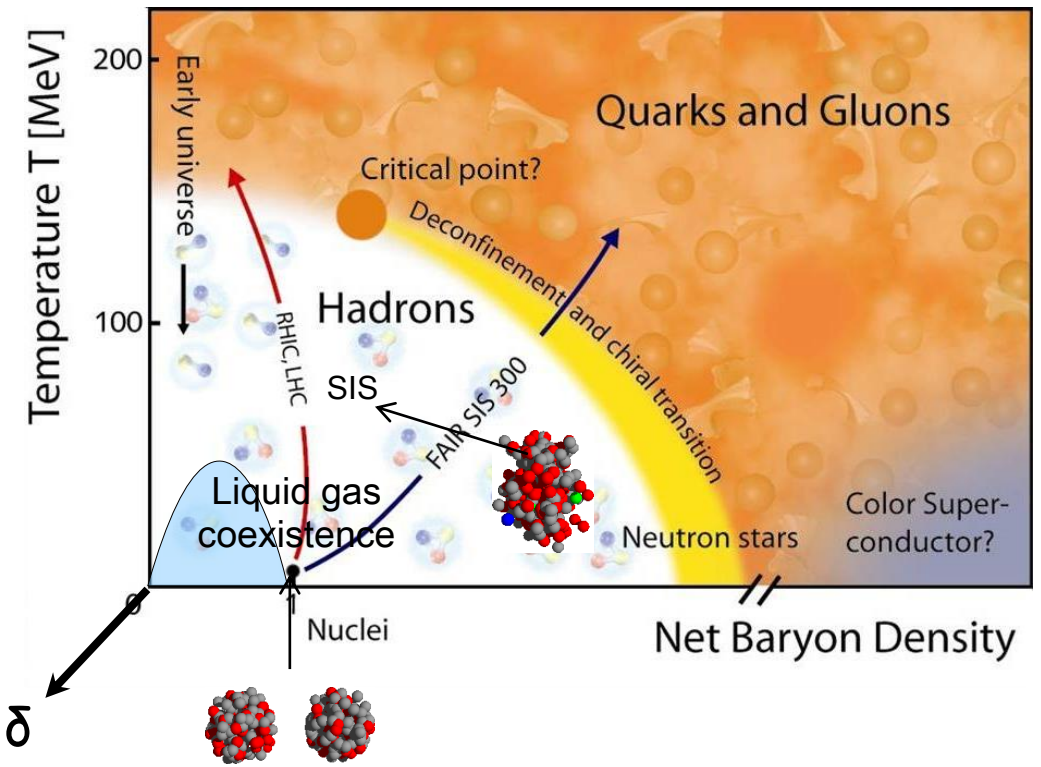
Introduction

The nuclear EOS describes the relation among energy, pressure, density, temperature and isospin asymmetry. It is a fundamental ingredient in nuclear physics and astrophysics.

Question: how E/A depends on the density ρ and isospin asymmetry

δ=(N-Z)/(N+Z) , that is, E/A(ρ, δ)=????

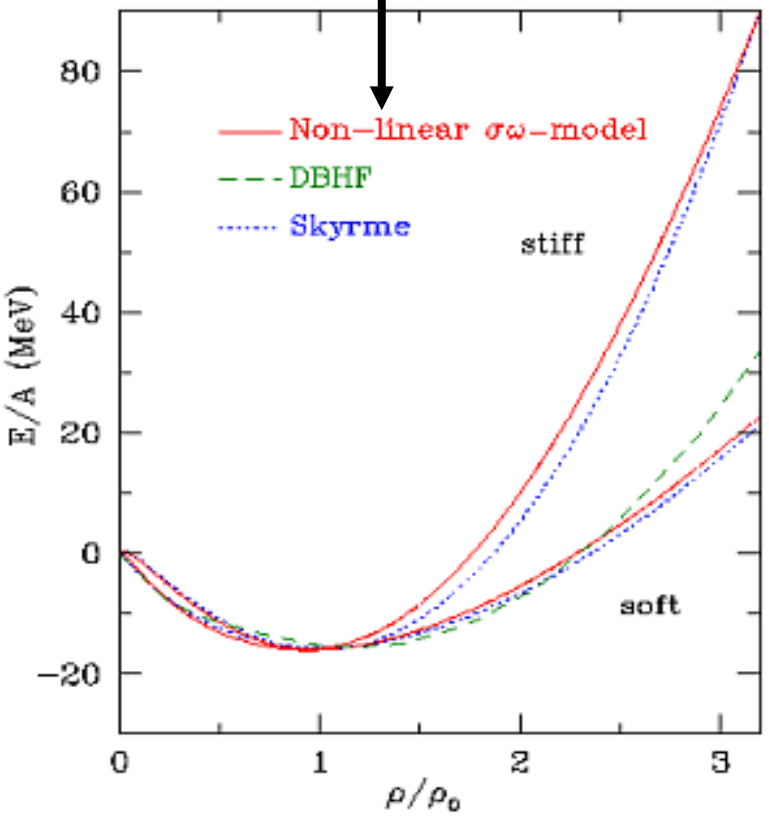
Nuclear matter phase diagram (schematic)

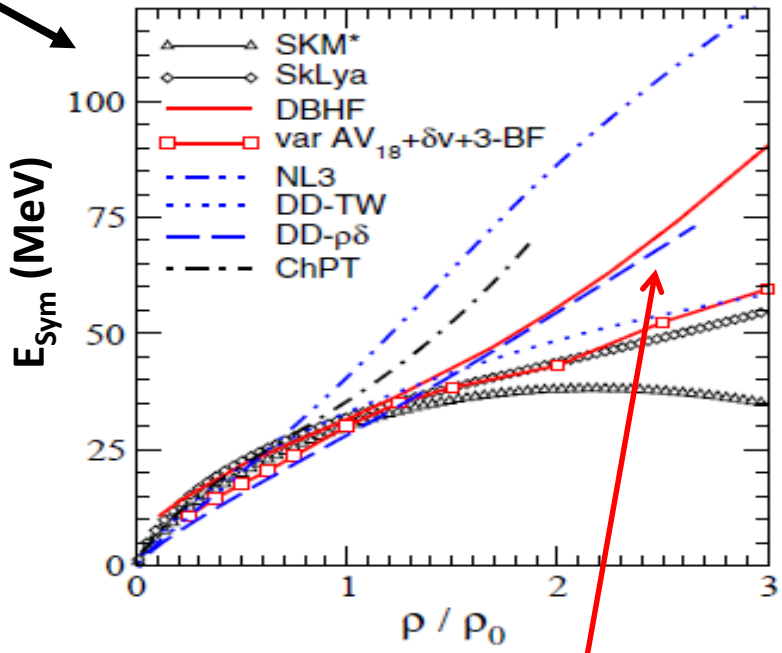


EOS for nuclear matter and Symmetry Energy

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

$$\delta = \frac{\rho_n - \rho_p}{\rho_n + \rho_p} = \frac{N-Z}{A}$$





From Ab initio calculations (red) and phenomenological approaches

Fuchs and Wolter, EPJA 30 (2006)

"How much energy is needed to compress hadronic matter?"

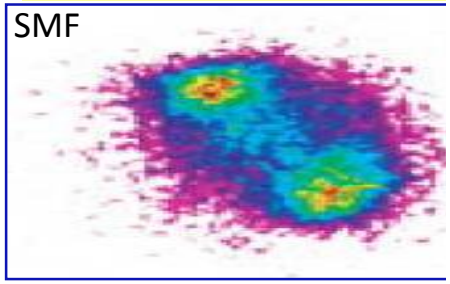
P. Danielewicz et al., Science 298 (2002)
C. Fuchs et al., PRL 86 (2001) 1974
Youngblood et al., PRL82 691 (1999)
A. Le Fevre et al., Nucl. Phys. A 945 (2016)

High density…so important!

Study of the density dependence of the symmetry energy

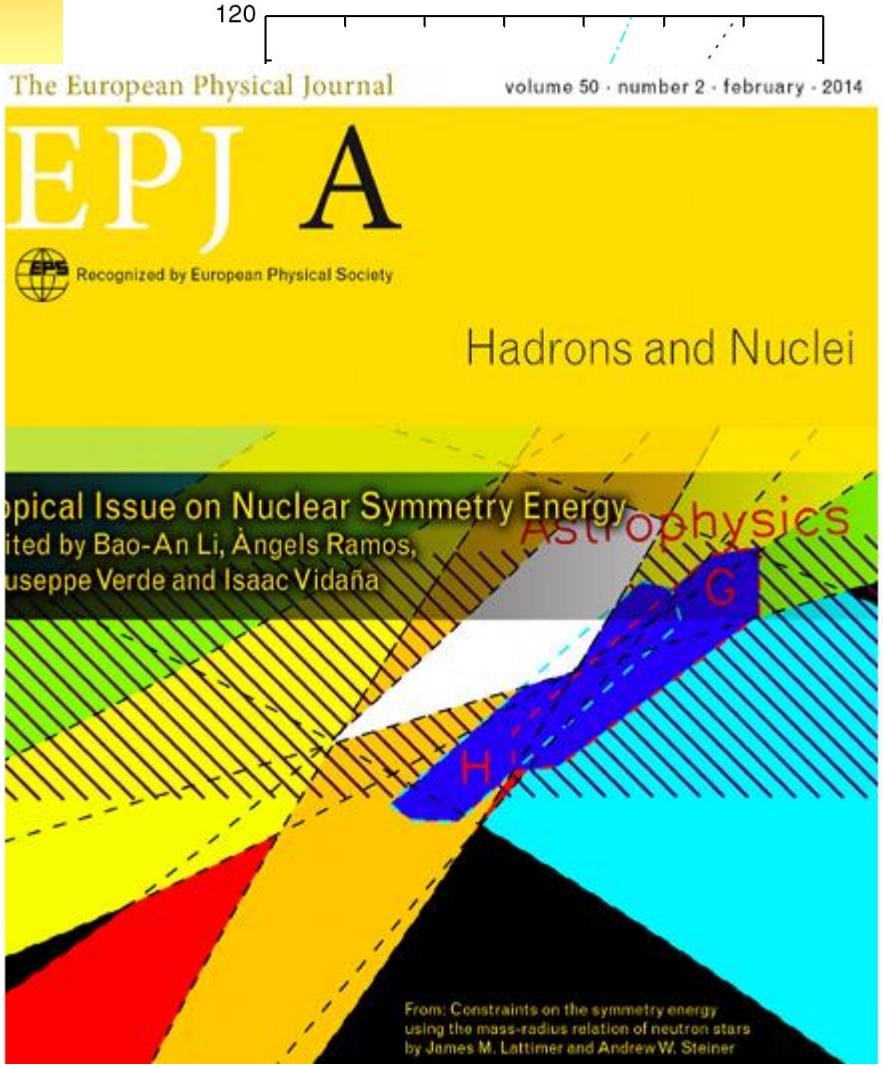
Density $\rho < \approx \rho_0$ (sub- and around saturation density, ρ_0=0.17 fm^{-3})

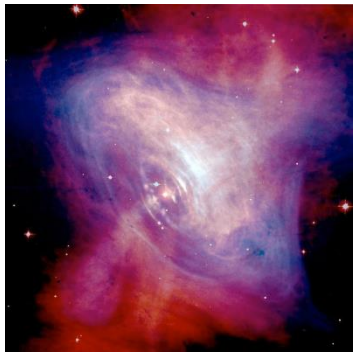
Z. Xiao, Bao-An Li et al., PRL 102, 062502 (2009)



Isospin Transport properties in HI collisi at Fermi Energies, (diffusion, fractionatic migration), flows, n/p emission , clusterizati

Nuclear structure (IAS Resonances (PDR,GDR n skin thickness …





Density $\rho > \rho_0$ (supra-saturation): connected with *neutron stars, supernovae expl.*

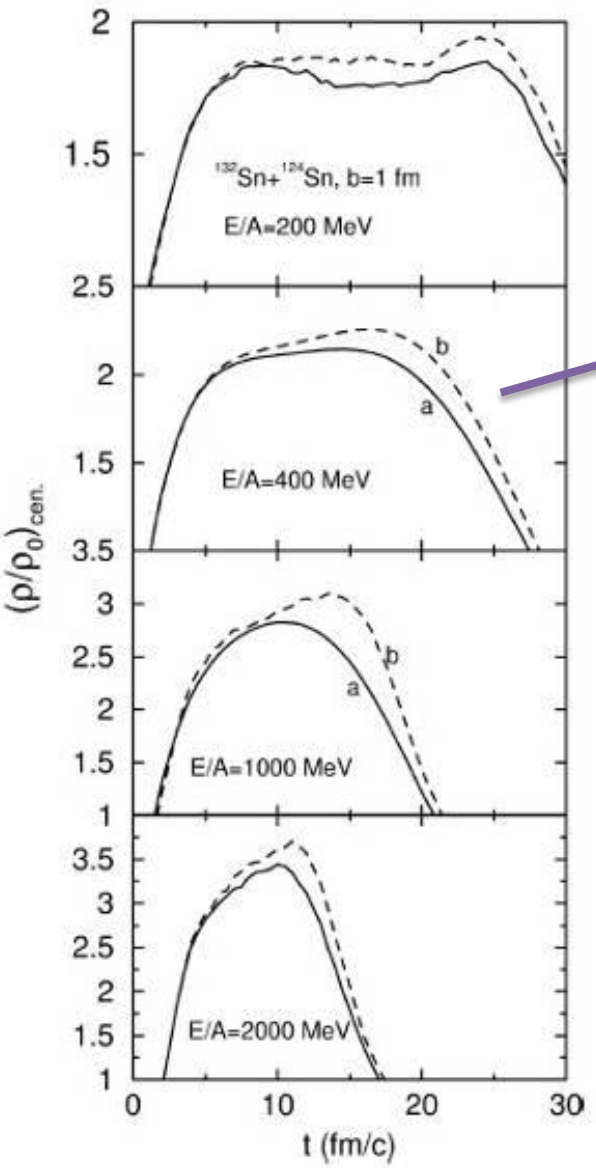
Observable: coming soon !

•**Several constrai** …**und and below** ρ_0

See Eur. Phys. J. A, 50 2 (2014) topical issue on Symmetry Energy

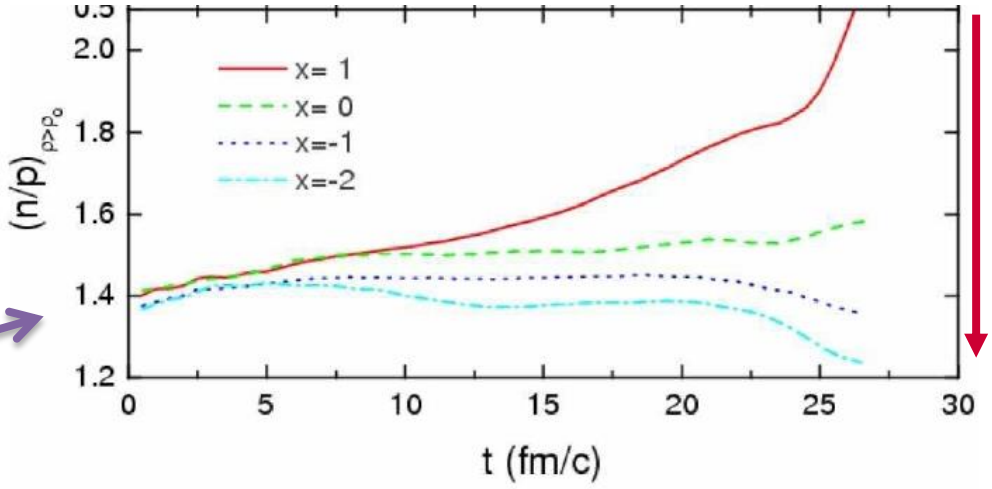
High density symmetry energy in relativistic heavy ion collisions

Which densities can be explored in the early stage of the reaction ?

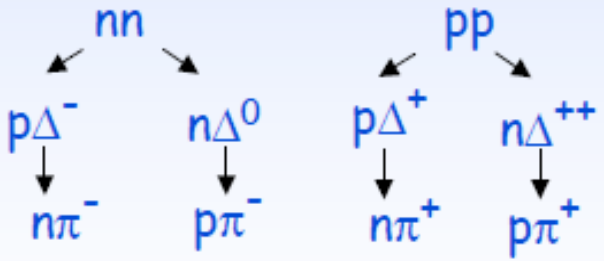


Bao-An Li, NPA 708 (2002)

B.A. Li et al., PRC71 (2005)



- N/Z of high density regions sensitive to $E_{sym}(\rho)$
- High $\rho>\rho_0$: asy-stiff more repulsive on neutrons



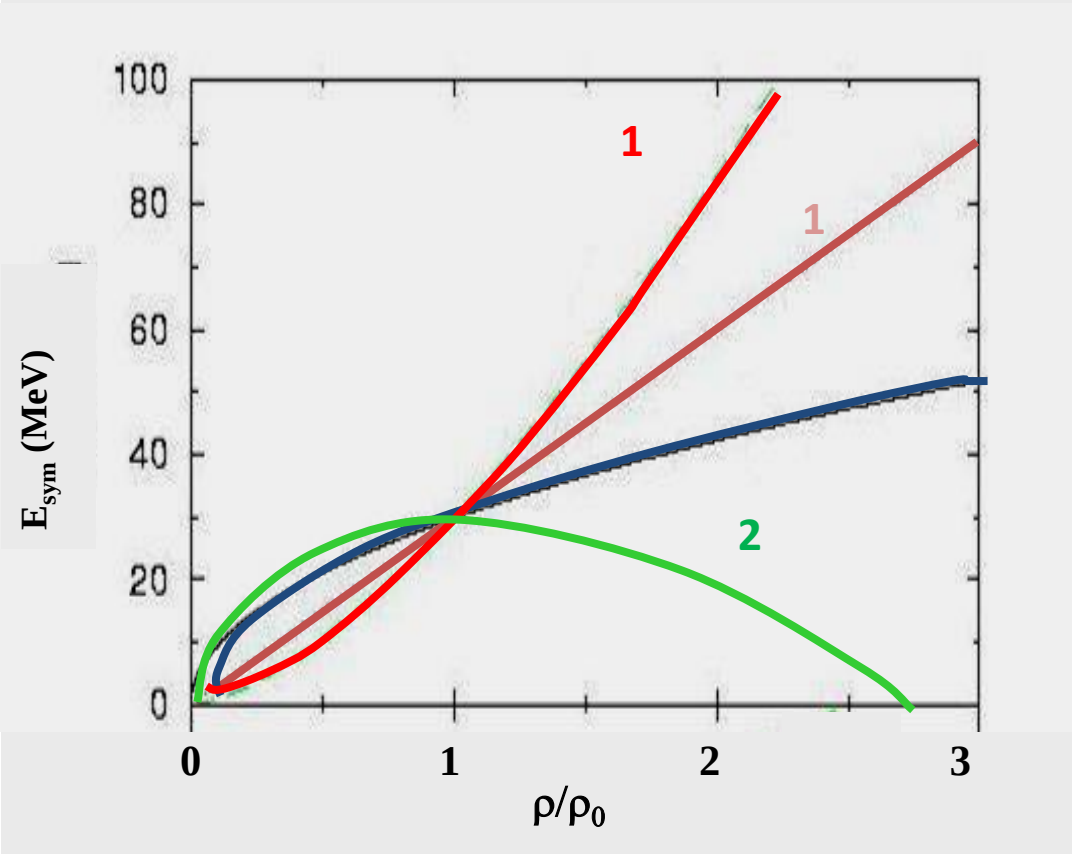
NN collisions in high density regions

π^-/π^+ reflecting the $(N/Z)_{dense}$

π^-/π^+ sensitive to $E_{sym}(\rho)$ at high ρ

But results are strongly model dependent (up to now) !

Esym at high density: pions



Results model dependent: density dependence of symmetry energy unambiguously soft or hard

- symmetry energy → n/p ratio, number of nn, np, pp collisions

$$\text{asystiff}\,\frac{n}{p}\downarrow \Rightarrow \frac{Y(\Delta^{0,-})}{Y(\Delta^{+,++})}\downarrow \Rightarrow \frac{\pi^-}{\pi^+}\downarrow$$

- medium → effective masses (N, π, Δ), cross sections → thresholds

$$\text{asystiff} \Rightarrow \frac{\pi^-}{\pi^+}\uparrow$$

- Pions absorption and rescattering destroy high-density signal, pion in-medium effects

Interpretation of pion data not straight forward

See:

Z. Xiao et al., PRL 102 (2009) **IBUU04**

Z.Q. Feng, PLB 683 (2010) **ImIQMD**

W.J. Xie , et al., PLB 718 (2013) **ImIBL**

G. Ferini, et al., NPA 762 (2005) **RMF**

From IWM 2011 – Y. Leifels

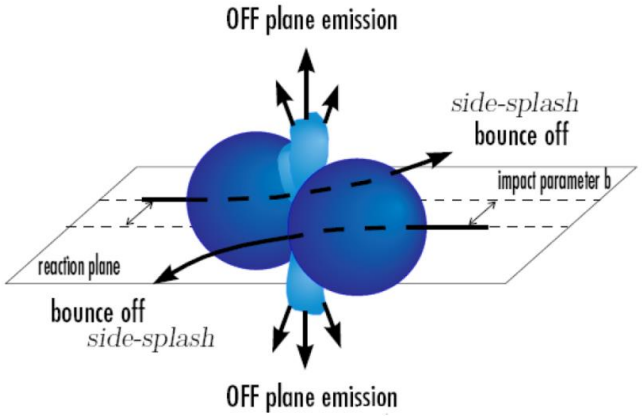
High densities: flows

$$\frac{dN}{d(\phi-\phi_R)}(y,p_t)=\frac{N_0}{2\pi}\left(1+2\sum_{n\geq 1}v_n\cos n(\phi-\phi_R)\right)$$

y = rapidity
pt = transverse momentum

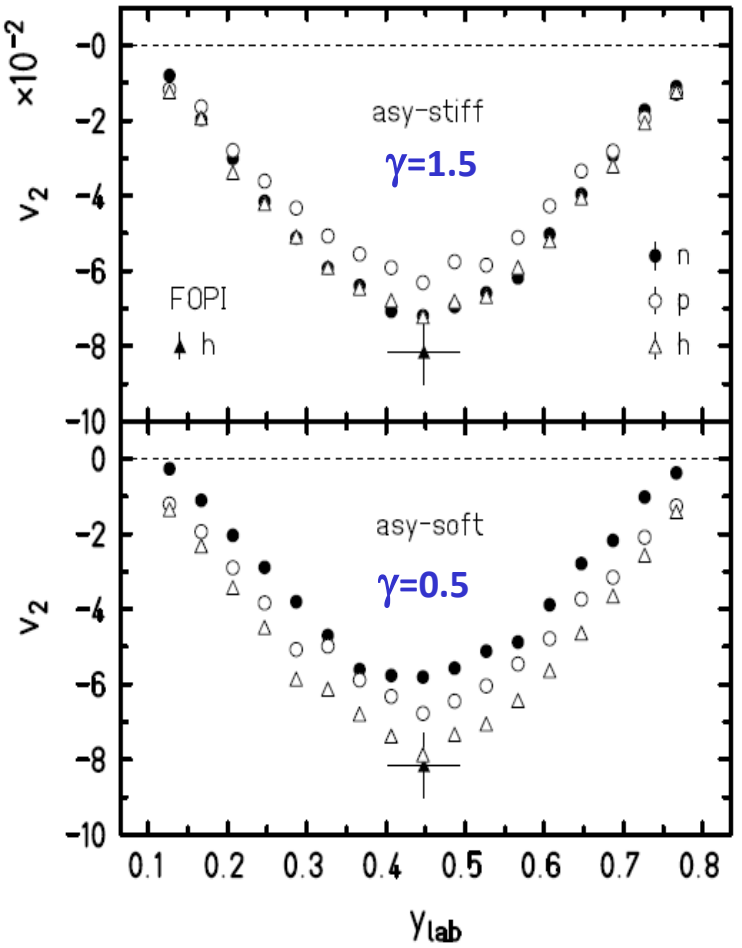
$$V_2(y,p_t)=\left\langle\frac{p_x^2-p_y^2}{p_t^2}\right\rangle$$

Elliptic flow: competition between in plane (v_2>0) and out-of-plane ejection (v_2<0)



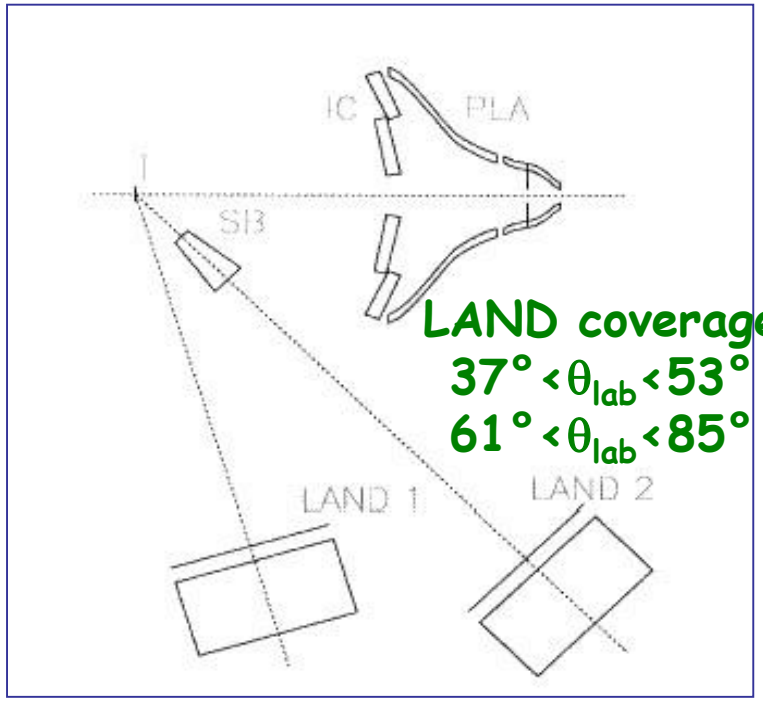
$$E_{sym}=E_{sym}^{pot}+E_{sym}^{kin}$$
$$=22\ \text{MeV}\cdot(\rho/\rho_0)^{\gamma}+12\ \text{MeV}\cdot(\rho/\rho_0)^{2/3}$$

UrQMD :Au+Au @ 400 AMeV
5.5<b<7.5 fm



Qingfeng Li, J. Phys. G31 1359-1374 (2005)
P.Russotto et al., Phys. Lett. B 697 (2011)

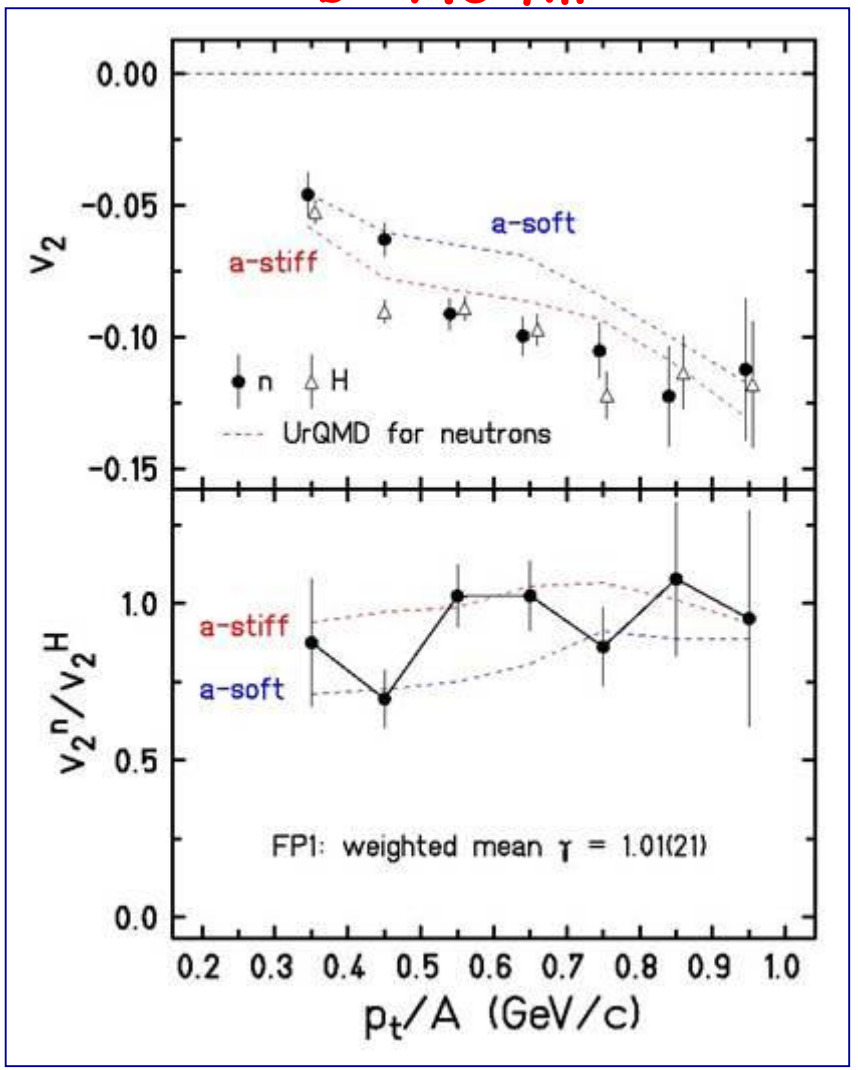
FOPI/LAND experiment on neutron squeeze out (1991)



LAND coverage
$37° < \theta_{lab} < 53°$
$61° < \theta_{lab} < 85°$

$\gamma = 0.9 \pm 0.4$
$L = 83 \pm 26$

Au+Au 400 A MeV
b< 7.5 fm



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

Y. Leifels et al., PRL 71, 963 (1993)
P.Russotto et al., PLB 697 (2011)

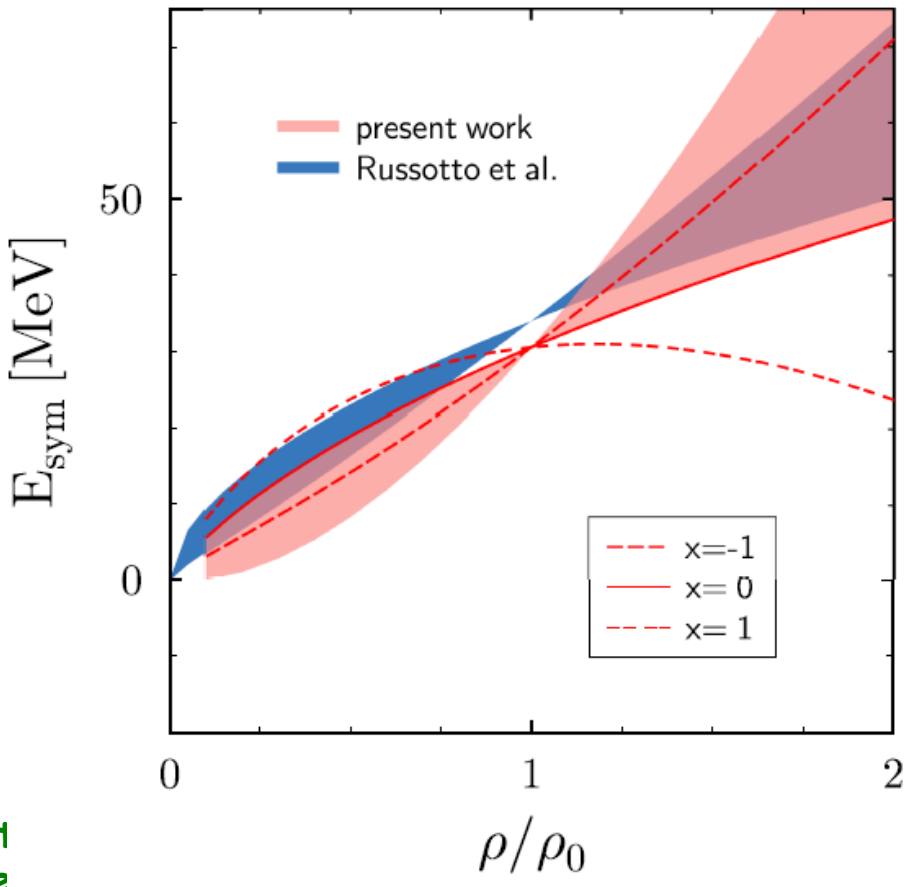
Results with Tübingen QMD

UrQMD:
momentum dep. of isoscalar field
momentum dep. of NNECS
momentum independent power-law
parameterization of the symmetry energy

Tübingen-QMD:
density dep. of NNECS
asymmetry dep. of NNECS
soft vs. hard EoS
width of wave packets
momentum dependent (Gogny inspired)
parameterization of the symmetry energy

M.D. Cozma, PLB 700, 139 (2011);
arXiv:1102.2728

Au+Au 400 A MeV b< 7.5 fm



M.D. Cozma et al., Towards a model-independent constraint of the high-density dependence of the symmetry energy

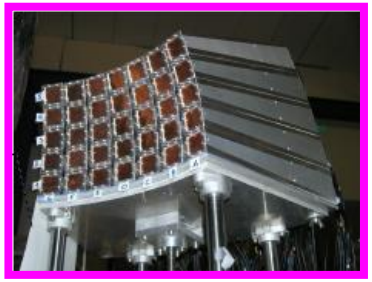
arXiv:1305.5417 [nucl-th] PRC88 044912 (2013)

x = -1.0±1.0

ASY-EOS S394 experiment @ GSI Darmstadt (May 2011)

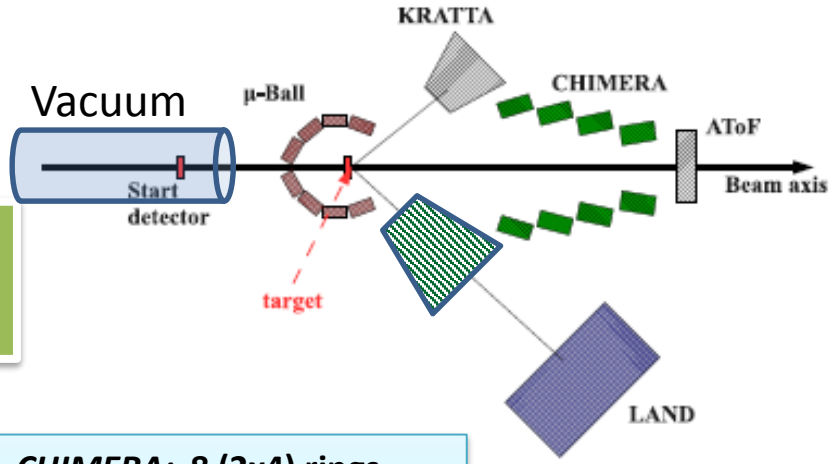
Au+Au, ^{96}Zr+^{96}Zr , ^{96}Ru+^{96}Ru @ 400 AMev

μBall: 4 rings 50 CsI(Tl), Θ>60°. Discriminate target vs. reactions with air. Multiplicity and reaction plane measurements.

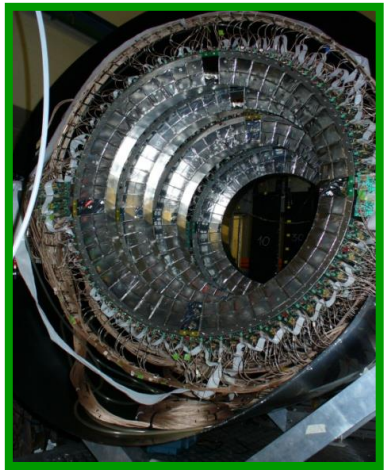


KraTTA: 35 (5x7) triple telescopes (Si-CsI-CsI) placed at 21°<Θ<60° with digital readout . Light particles and IMFs emitted at midrapidity

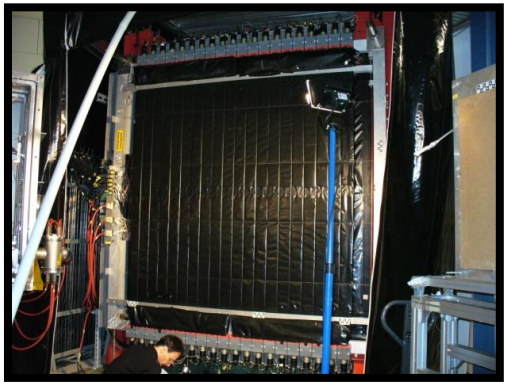
Shadow bar: evaluation of background neutrons in LAND



TOFWALL: 96 plastic bars; ToF, ΔE, X-Y position. Trigger, impact parameter and reaction plane determination

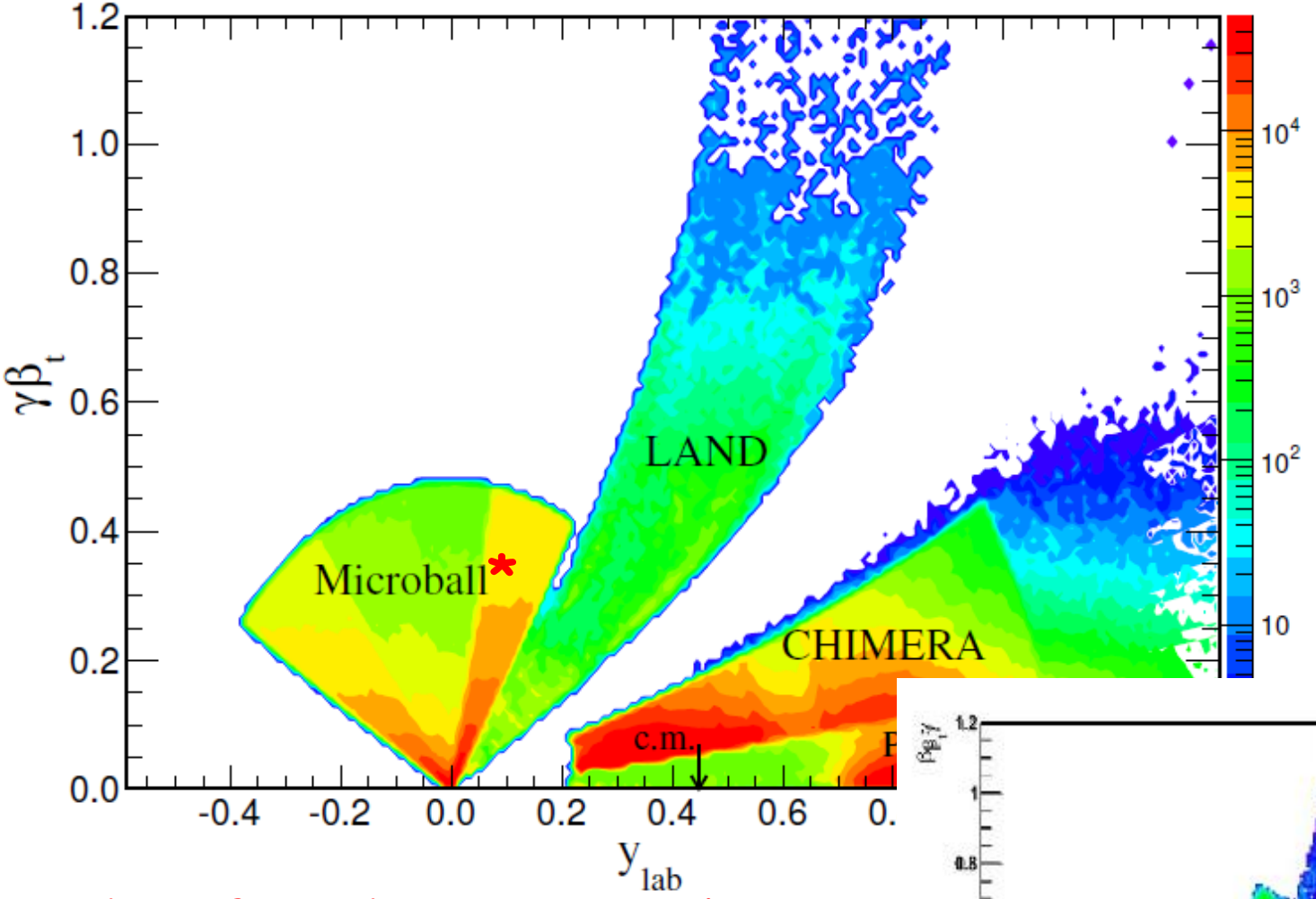


CHIMERA: 8 (2x4) rings, high granularity CsI(Tl), 352 detectors 7°<θ<20° + 16x2 pads silicon detectors. Light charged particle identification by PSD. Multiplicity, Z, A, Energy: impact parameter and reaction plane determination

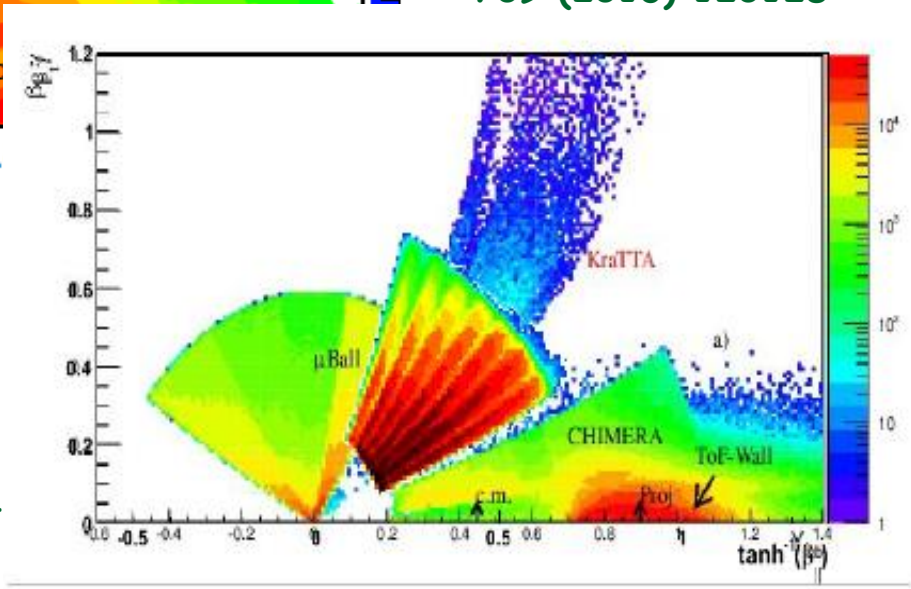


LAND: Large Area Neutron Detector . Plastic scintillators sandwiched with Fe 2x2x1 m^3 plus plastic veto wall. New Taquila front-end electronics. Neutrons and Hydrogen detection. Flow measurements

Au+Au @ 400 A.MeV: Some kinematics



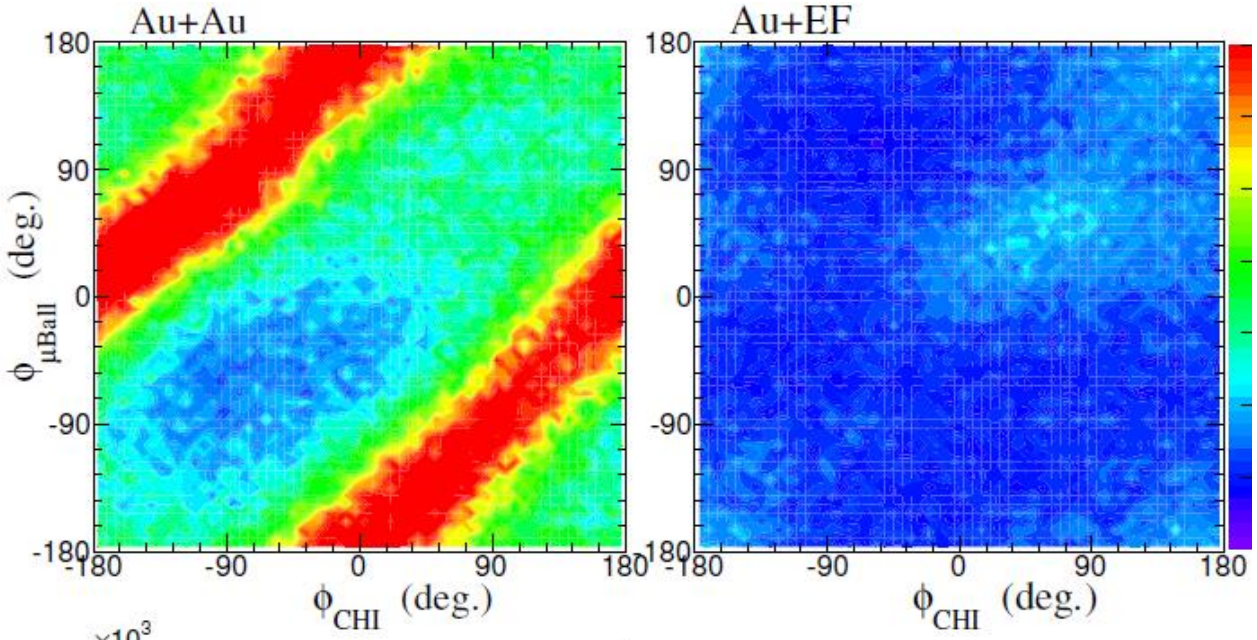
KRATTA:
J. Lukasik et al.,
Nucl. Instr. Meth.
709 (2013) 120128

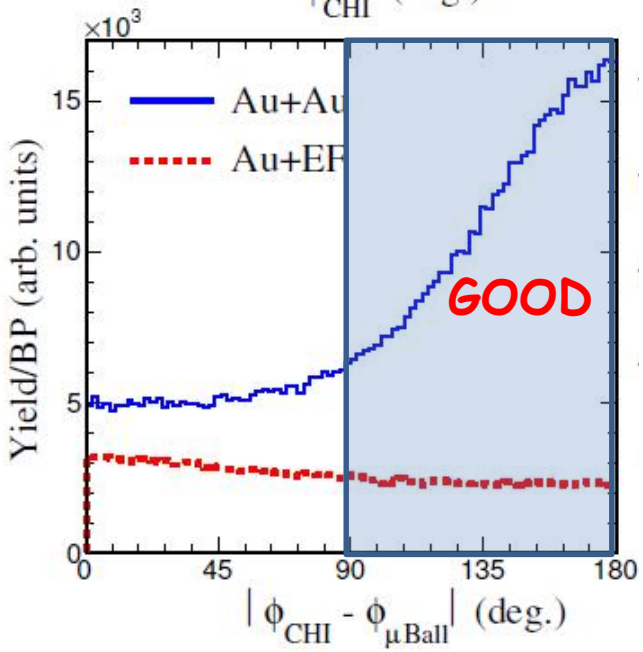


*** Uniform distribution with EKin<100 Mev**

P. Russotto et al., EPJA 50, 38 (2014).
P. Russotto et al., Procs. of INPC2013, EPJ Web of Conf.
P. Russotto et al., Journal of Phys. Conf. Series 420, 012092, (201
P. Russotto et al., Procs of NN2015, to be published
P. Russotto et al. to be submitted

Au+Au @ 400 A.MeV: Background rejection





CHIMERA $M(Y_{cm}>0.1) \geq 4$

$$\vec{Q} = \sum_{i=1}^{M} w_i Z_i \gamma \vec{\beta}_t^{\,i} \qquad w_i = \begin{cases} 1 & \text{for } Y_{cm}>0.1 \\ 0 & \text{for } Y_{cm}<0.1 \end{cases}$$

μBall $M \geq 2$

$$\vec{Q} = \sum_{i=1}^{M} \hat{r}_t^{\,i}$$

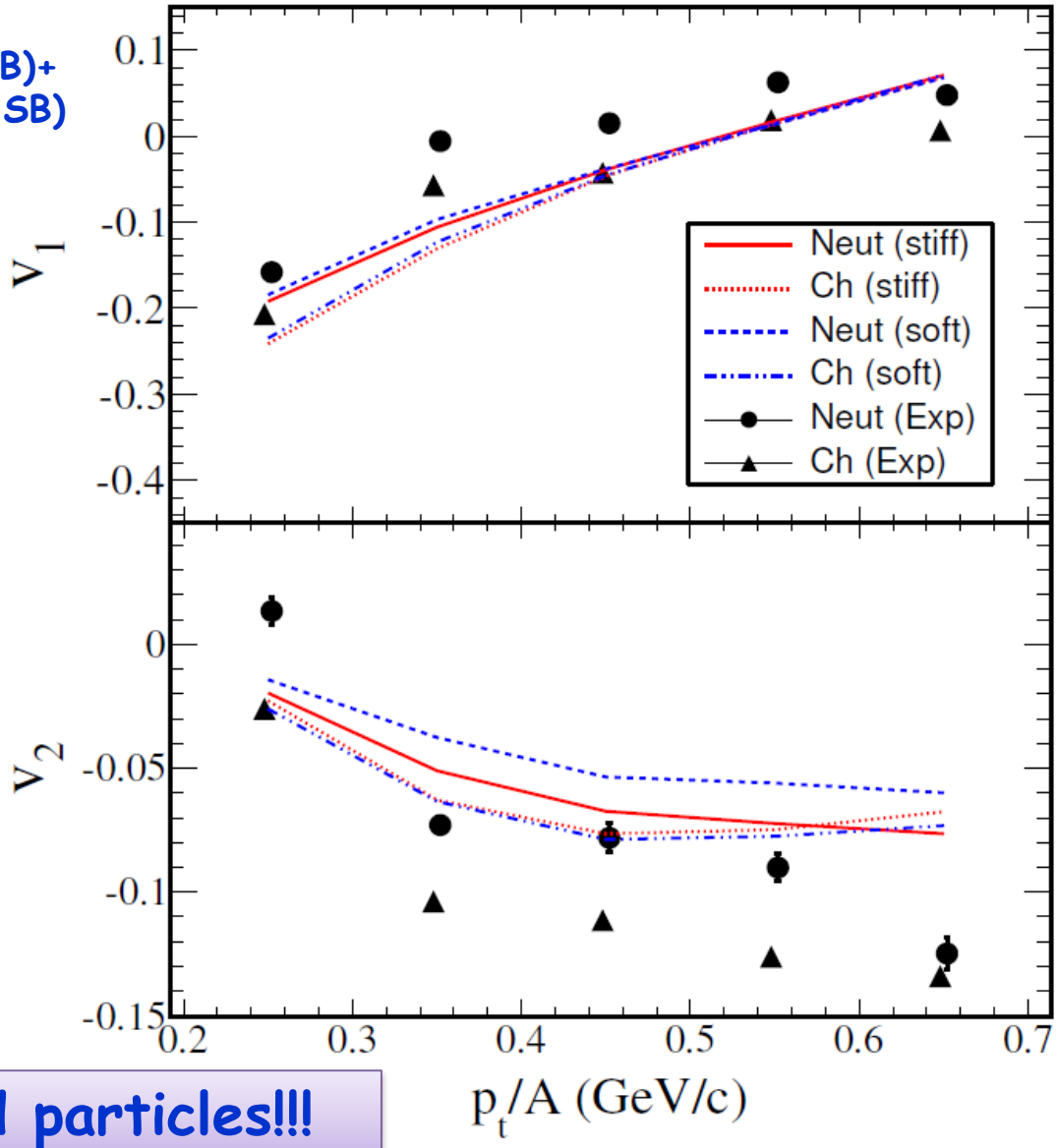
ad. from P. Danielewicz et al., PLB 1985

Comparison with UrQMD

Au+Au @ 400 AMeV b<7.5 fm

Neutrons:
(Au+Au)-(Au+Au with SB)+
-(Au+EF)+(Au+EF with SB)

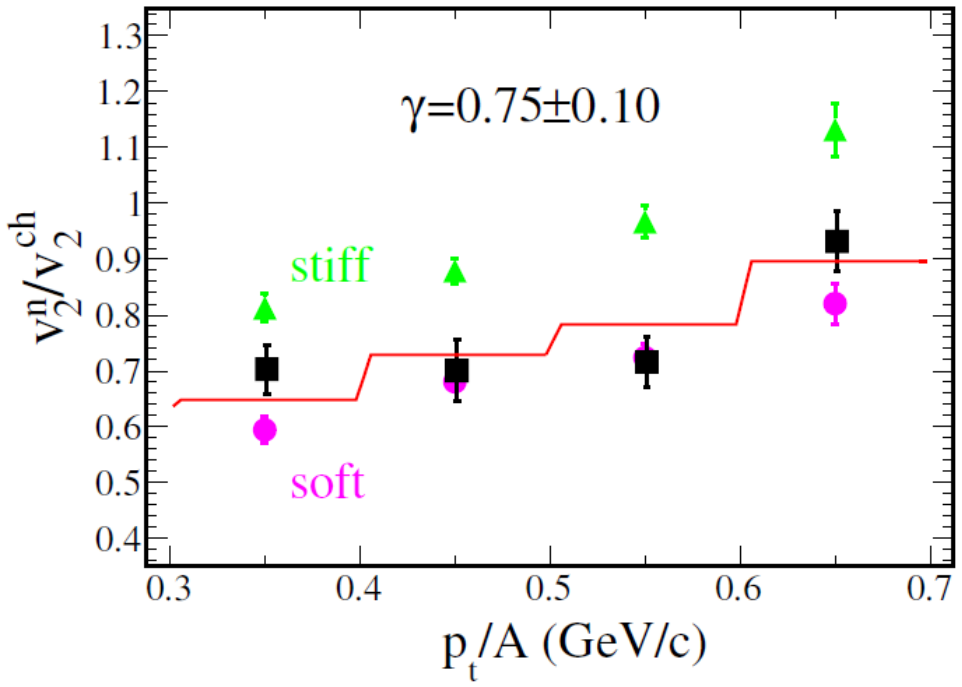
Charged Particles:
(Au+Au)-(Au+EF)

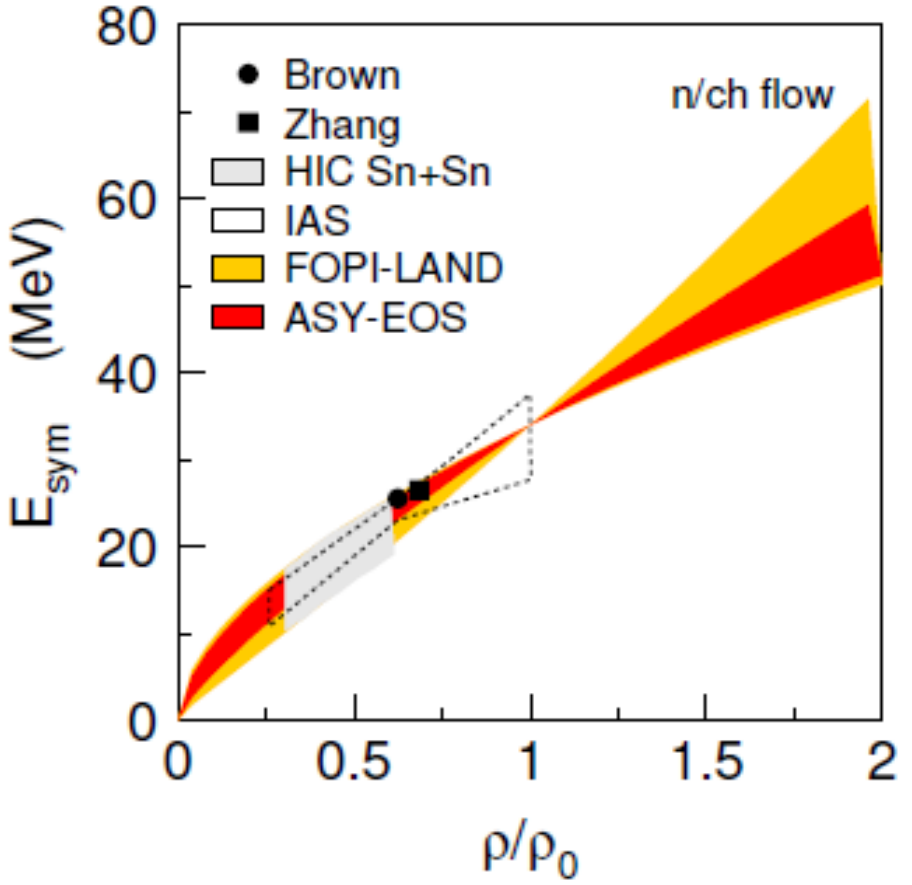


Only charged particles!!!

Results…

Au+Au @ 400 AMeV b<7.5 fm





FOPI DATA : P.Russotto et al., Phys. Lett. B 697 (2011)

γ = 0.9 ± 0.4 ; L=83±26

ASY-EOS DATA: P. Russotto et al., to be submitted

γ = 0.72± 0.19 ; L=72±13

P. Russotto et al., to be submitted

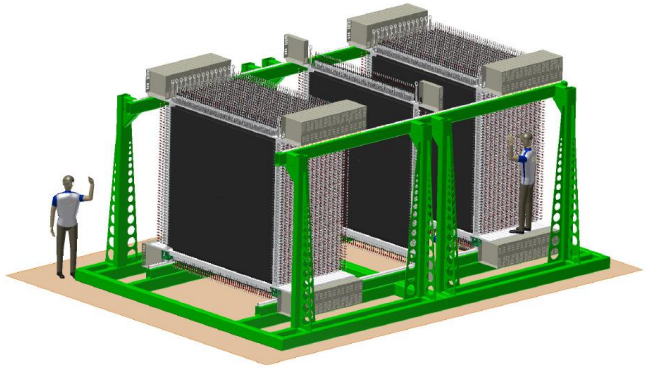
HIC: (mainly Isospin diffusion for Sn+Sn) M.B. Tsang et al., PRC 86, 015803 (2012)

neutron skin thickness, binding energies,….: Brown, PRL 111, 232502 (2013); Zhang & Chen, Phys. Lett. B 726 (2013), Danielewicz & Lee, NPA922 (2014).

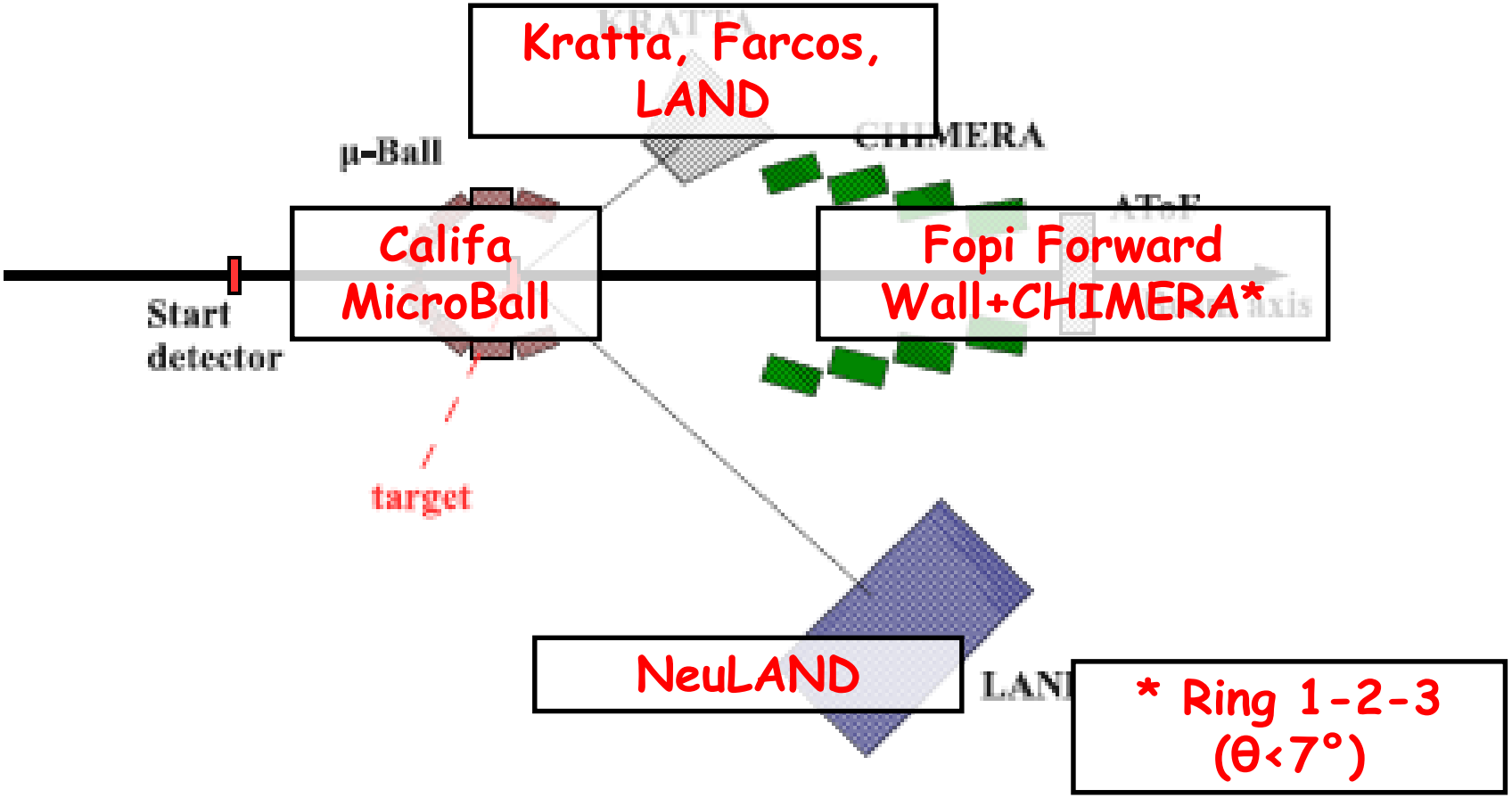
FUTURE Possibilities

NeuLAND @ FAIR/GSI

- TDR finalized in Oct 2011 and submitted
- total volume 2.5x2.5x3 m^3
- each bar readout by two PMT
- 3000 modules (plastic scintillator bars) 250x5x5 cm^3
- 30 double planes with 100 bars each, bars in neighboring planes
- mutually perpendicular
- $\sigma_t \leq 150$ ps and $\sigma_{x,y,z} \leq 1.5$ cm
- one-neutron efficiency ~95% for energies 200-1000 MeV
- multi-neutron detection capability



I. Gasparic AsyEOS2012 workshop, 6.9.2012, Siracusa, Italy



FUTURE Possibilities

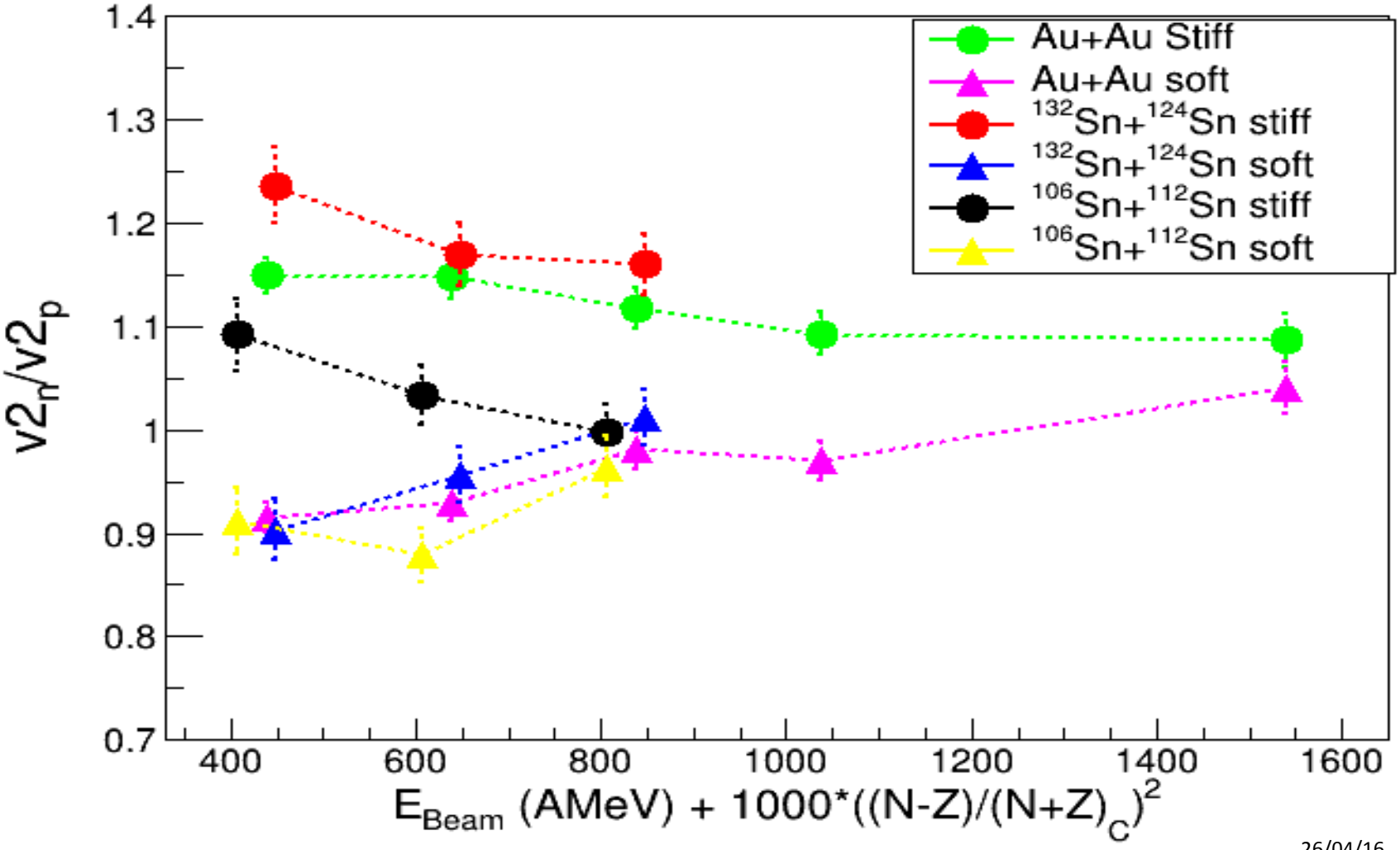
UrQMD prediction for some interesting beams (and δ^2)

$^{197}Au+^{197}Au$ @ 400, 600, 800, 1000,1500 AMeV (0.039+0.039)

$^{132}Sn+^{124}Sn$ @ 400, 600, 800 AMeV (0.059+0.037)

$^{106}Sn+^{112}Sn$ @ 400, 600, 800 AMeV (0.003+0.011)

At midvelocity b/bred <0.53



FUTURE Possibilities

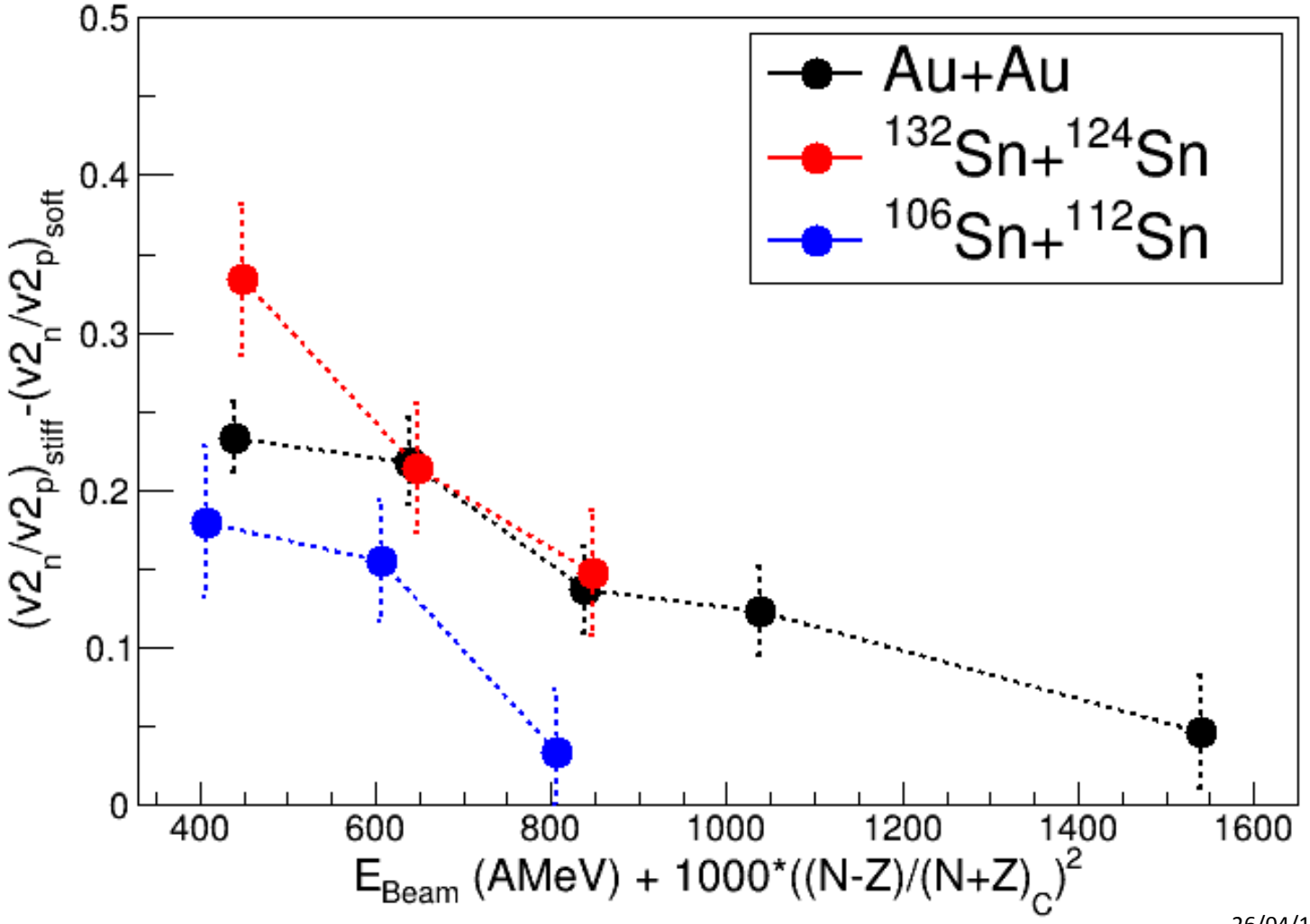
UrQMD prediction for some interesting beams (and δ^2)

$^{197}Au+^{197}Au$ @ 400, 600, 800, 1000,1500 AMeV (0.039+0.039)

$^{132}Sn+^{124}Sn$ @ 400, 600, 800 AMeV (0.059+0.037)

$^{106}Sn+^{112}Sn$ @ 400, 600, 800 AMeV (0.003+0.011)

At midvelocity b/bred <0.53

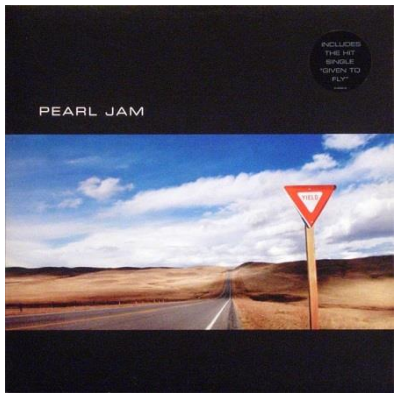


Conclusions

Symmetry Energy:

- Low densities: several constraints quite consistent
- High density:
  - pion constraints not consistent
  - n/p flows suggests…a route "Towards a model-independent constraint of the high-density dependence of the symmetry energy"
  - ASY-EOS data analysis is done, new constraint obtained
- Work on code consistency needed…everywhere
- New and better experiments on n,p flows and ratio, pions and kaons, also with high asymmetric beams (e.g. ^{132}Sn) and new detectors (Riken TPC, NeuLand@R3B)
- International collaborations and efforts

On the road…..



The Asy-Eos Collaboration

P. Russotto,[1] S. Gannon,[2] S. Kupny,[3] P. Lasko,[3] L. Acosta,[4,5] M. Adamczyk,[3] A. Al-Ajlan,[6] M. Al-Garawi,[7] S. Al-Homaidhi,[6] F. Amorini,[4] L. Auditore,[8,9] T. Aumann,[10,11] Y. Ayyad,[12] Z. Basrak,[13] J. Benlliure,[12] M. Boisjoli,[14] K. Boretzky,[11] J. Brzychczyk,[3] A. Budzanowski,[15,*] C. Caesar,[10] G. Cardella,[1] P. Cammarata,[16] Z. Chajecki,[17] M. Chartier,[2] A. Chbihi,[14] M. Colonna,[4] M. D. Cozma,[18] B. Czech,[15] E. De Filippo,[1] M. Di Toro,[4,19] M. Famiano,[20] I. Gašparić,[10,13] L. Grassi,[13] C. Guazzoni,[21,22] P. Guazzoni,[21,23] M. Heil,[11] L. Heilborn,[16] R. Introzzi,[24] T. Isobe,[25] K. Kezzar,[7] M. Kiš,[11] A. Krasznahorkay,[26] N. Kurz,[11] E. La Guidara,[1] G. Lanzalone,[4,27] A. Le Fèvre,[11] Y. Leifels,[11] R. C. Lemmon,[28] Q. F. Li,[29] I. Lombardo,[30,31] J. Łukasik,[15] W. G. Lynch,[17] P. Marini,[14,16,32] Z. Matthews,[2] L. May,[16] T. Minniti,[1] M. Mostazo,[12] A. Pagano,[1] E. V. Pagano,[1,19] M. Papa,[1] P. Pawłowski,[15] S. Pirrone,[1] G. Politi,[1,19] F. Porto,[4,19] W. Reviol,[33] F. Riccio,[21,22] F. Rizzo,[4,19] E. Rosato,[30,31,*] D. Rossi,[10,11] S. Santoro,[8,9] D. G. Sarantites,[33] H. Simon,[11] I. Skwirczynska,[15] Z. Sosin,[3,*] L. Stuhl,[26] W. Trautmann,[11] A. Trifirò,[8,9] M. Trimarchi,[8,9] M. B. Tsang,[17] G. Verde,[1,34] M. Veselsky,[35] M. Vigilante,[30,31] Yongjia Wang,[29] A. Wieloch,[3] P. Wigg,[2] J. Winkelbauer,[17] H. H. Wolter,[36] P. Wu,[2] S. Yennello,[16] P. Zambon,[21,22] L. Zetta,[21,23] and M. Zoric[13]

[1] *INFN-Sezione di Catania, I-95123 Catania, Italy*

[2] *University of Liverpool, Physics Department, Liverpool L69 7ZE, United Kingdom*

[3] *M. Smoluchowski Institute of Physics, Jagiellonian University, Pl-30-348 Kraków, Poland*

[4] *INFN-Laboratori Nazionali del Sud, I-95123 Catania, Italy*

[5] *Instituto de Física, Universidad Nacional Autónoma de México, A.P. 20-364, México 01000 D.F., Mexico*

[6] *KACST, Riyadh, Saudi Arabia*

[7] *Physics Department, King Saud University, Riyadh, Saudi Arabia*

[8] *INFN-Gruppo Collegato di Messina, I-98166 Messina, Italy*

[9] *Dipartimento di Scienze Matematiche e Informatiche, Scienze Fisiche e Scienze della Terra, University of Messina, I-98166 Messina, Italy*

[10] *Technische Universität Darmstadt, D-64289 Darmstadt, Germany*

[11] *GSI Helmholtzzentrum für Schwerionenforschung GmbH, D-64291 Darmstadt, Germany*

[12] *Universidade de Santiago de Compostela, 15782 Santiago de Compostela, Spain*

[13] *Ruđer Bošković Institute, HR-10002 Zagreb, Croatia*

[14] *GANIL, CEA et IN2P3-CNRS, F-14076 Caen, France*

[15] *H. Niewodniczański Institute of Nuclear Physics, Pl-31342 Kraków, Poland*

[16] *Department of Chemistry and Cyclotron Institute, Texas A&M University, College Station, TX-77843, USA*

[17] *Department of Physics and Astronomy and NSCL, Michigan State University, East Lansing, MI-48824, USA*

[18] *IFIN-HH, Reactorului 30, 077125 Măgurele-Bucharest, Romania*

[19] *Dipartimento di Fisica e Astronomia-Università, I-95123 Catania, Italy*

[20] *Western Michigan University, Kalamazoo, MI-49008, USA*

[21] *INFN-Sezione di Milano, I-20133 Milano, Italy*

[22] *Dipartimento di Elettronica, Informazione e Bioingegneria, Politecnico di Milano, I-20133 Milano, Italy*

[23] *Dipartimento di Fisica, Università degli Studi di Milano, I-20133 Milano, Italy*

[24] *INFN and DISAT, Politecnico di Torino, I-10129 Torino, Italy*

[25] *RIKEN, Wako, Saitama 351-0198, Japan*

[26] *Institute for Nuclear Research (MTA Atomki), P.O. Box 51, H-4001 Debrecen, Hungary*

[27] *Università degli Studi di Enna "Kore", I-94100 Enna, Italy*

[28] *STFC Daresbury Laboratory, Warrington WA4 4AD, United Kingdom*

[29] *School of Science, Huzhou University, Huzhou 313000, P.R. China*

[30] *INFN-Sezione di Napoli, I-80126 Napoli, Italy*

[31] *Dipartimento di Fisica "Ettore Pancini", Università di Napoli Federico II, I-80126 Napoli, Italy*

[32] *CENBGn Université de Bordeaux, CNRS/IN2P3, F-33175 Gradignan, France*

[33] *Chemistry Department, Washington University, St. Louis, MO-63130, USA*

[34] *Institut de Physique Nucléaire, IN2P3-CNRS et Université Paris-Sud, F-91406 Orsay, France*

[35] *Institute of Physics, Slovak Academy of Sciences, Bratislava, Slovakia*

[36] *Fakultät für Physik, Universität München, D-85748 Garching, Germany*