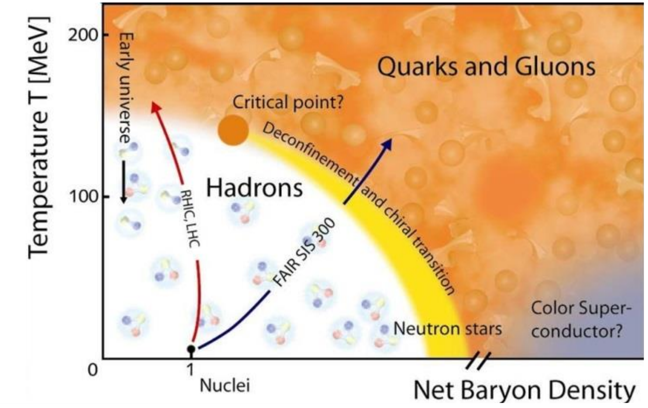



Probing high density EOS of neutron rich matter in heavy ion collisions

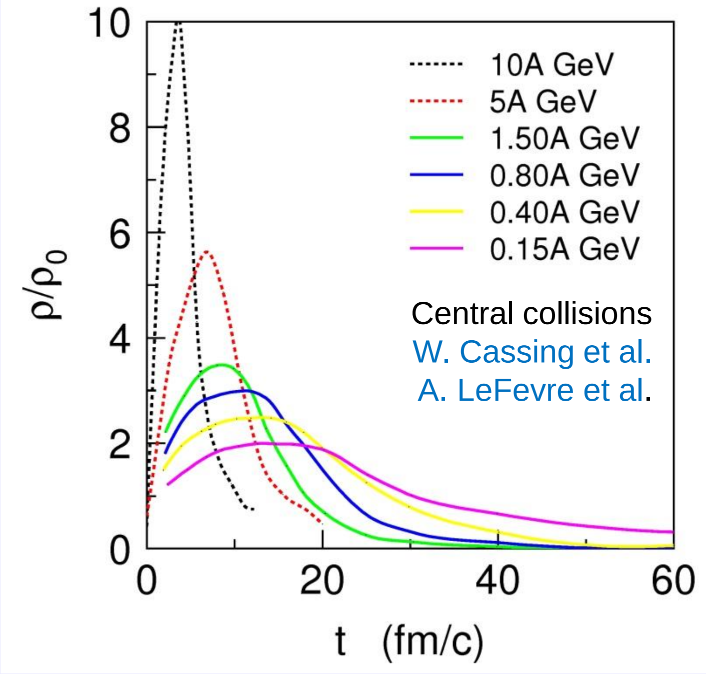
Y. Leifels for the FOPI and ASY-EOS collaborations

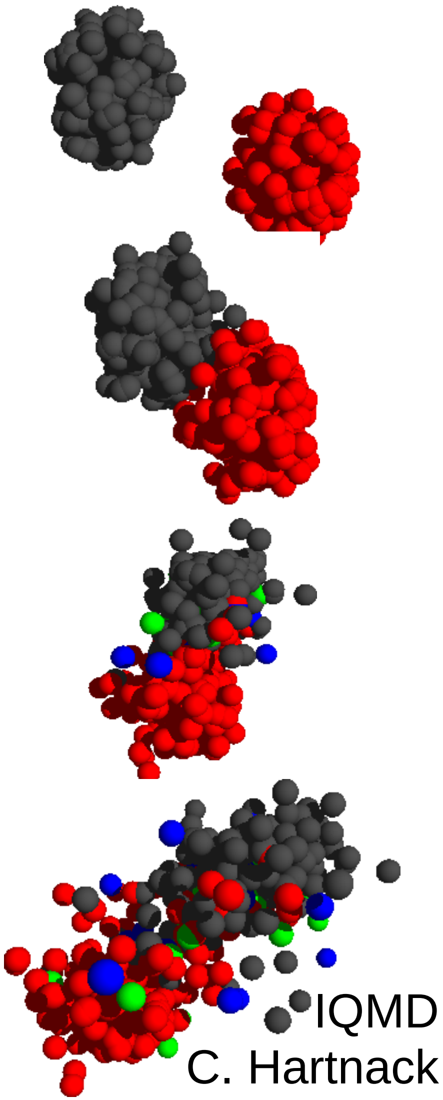
GSI Helmholtzzentrum für Schwerionenforschung GmbH Darmstadt

XXVII Texas Symposium on Relativistic Astrophysics
Dallas, December 8-13, 2013

GSI

Heavy ion collisions are unique tool to create states of high density in the laboratory



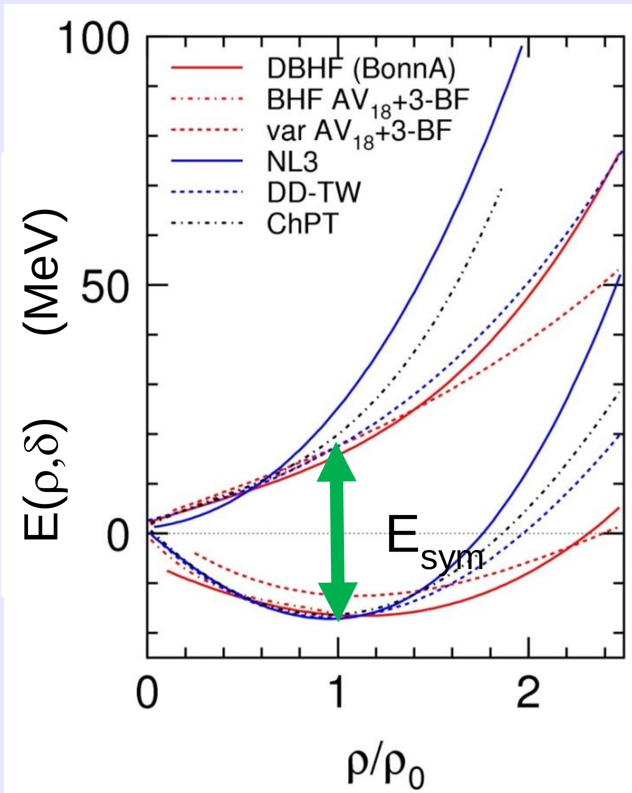


- transient state
- non-equilibrium, dynamical system
- thermal pressure, temperature and creation of particles
- access to properties
  - microscopic transport models

Equation of state of nuclear/neutron matter

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

$\delta = (\rho_n - \rho_p)/\rho$ asymmetry parameter

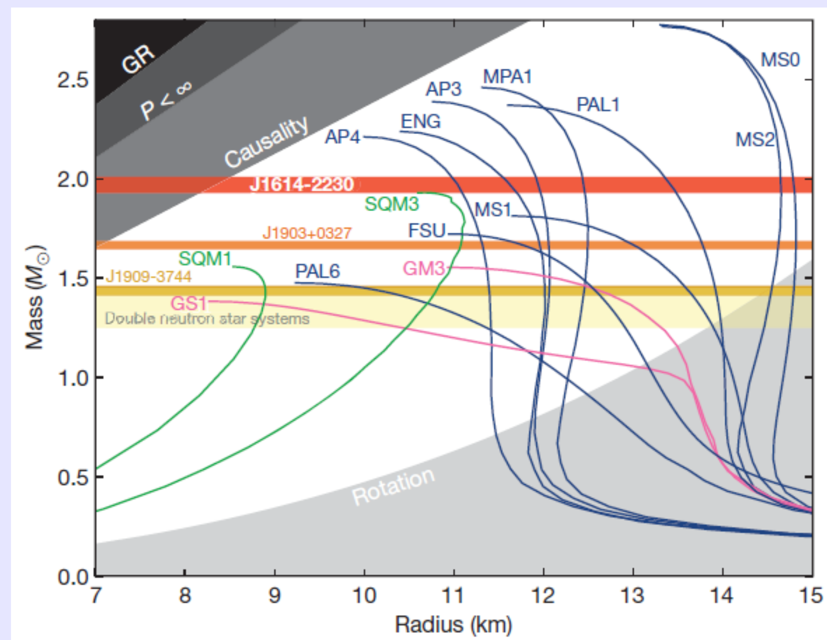


Fuchs and Wolter, EPJA 30 (2006)
nuclear-many-body theory

Compression modulus of $E(\rho,0)$

$$\kappa = 9\rho^2 \left(\frac{\partial^2 E/A(\rho, T=0)}{\partial \rho^2} \right)_{\rho=\rho_0}$$

Mass – Radius relation of neutron stars



Demorest et al. doi:10.1038/nature09466

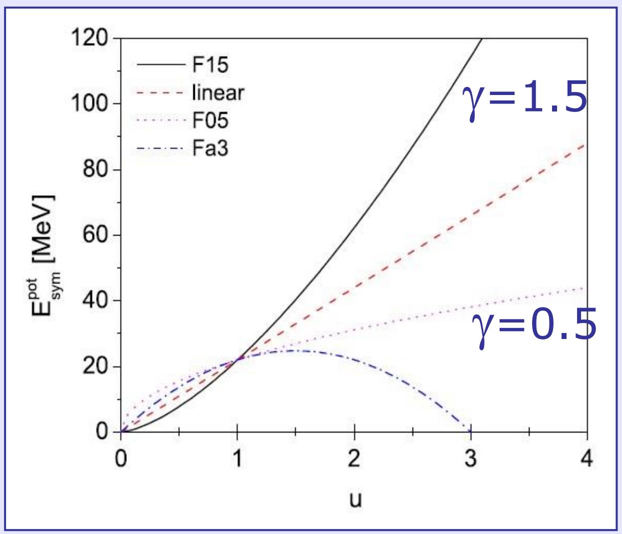
Symmetry energy

slope parameter

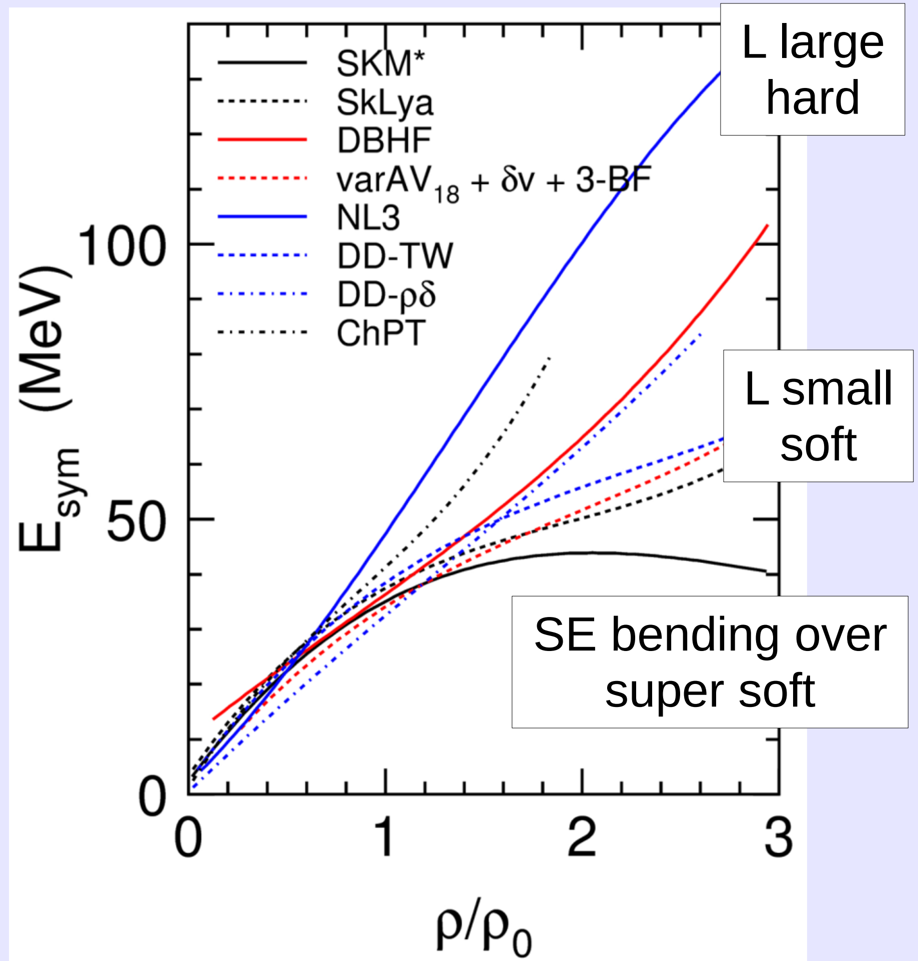
$$L = 3\rho_0 \left| \frac{dE_{sym}(\rho)}{d\rho} \right|_{\rho_0}$$

used as:

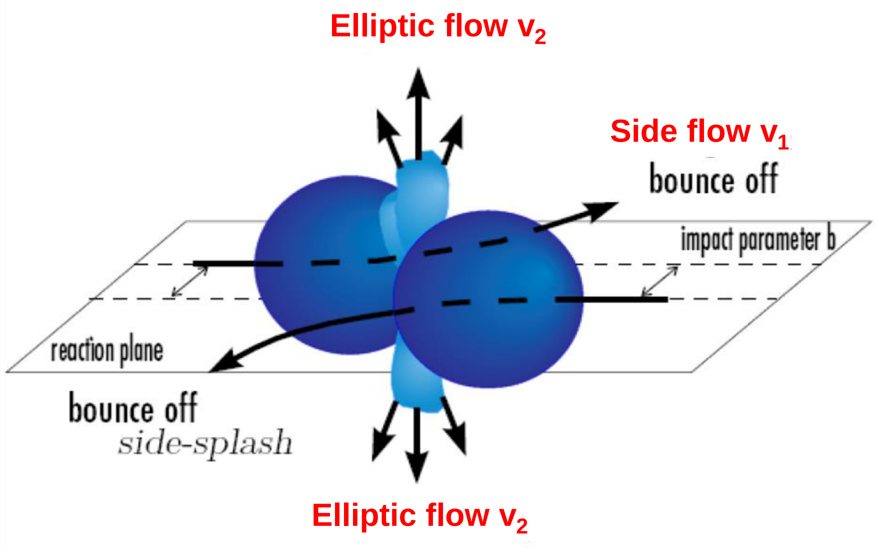
E_{sym}
$= E_{sym}^{pot} + E_{sym}^{kin}$
$= 22\ \text{MeV}\cdot(\rho/\rho_0)^{\gamma} + 12\ \text{MeV}\cdot(\rho/\rho_0)^{2/3}$



Fuchs and Wolter, EPJA 30 (2006)

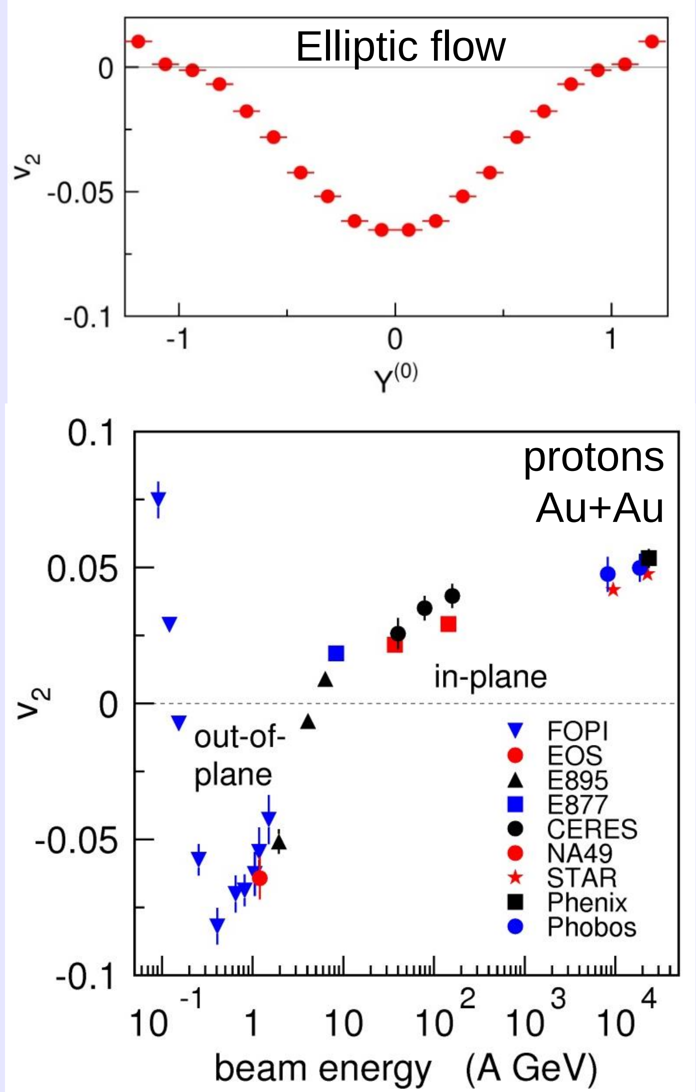


Testing pressure differences – Collective flow



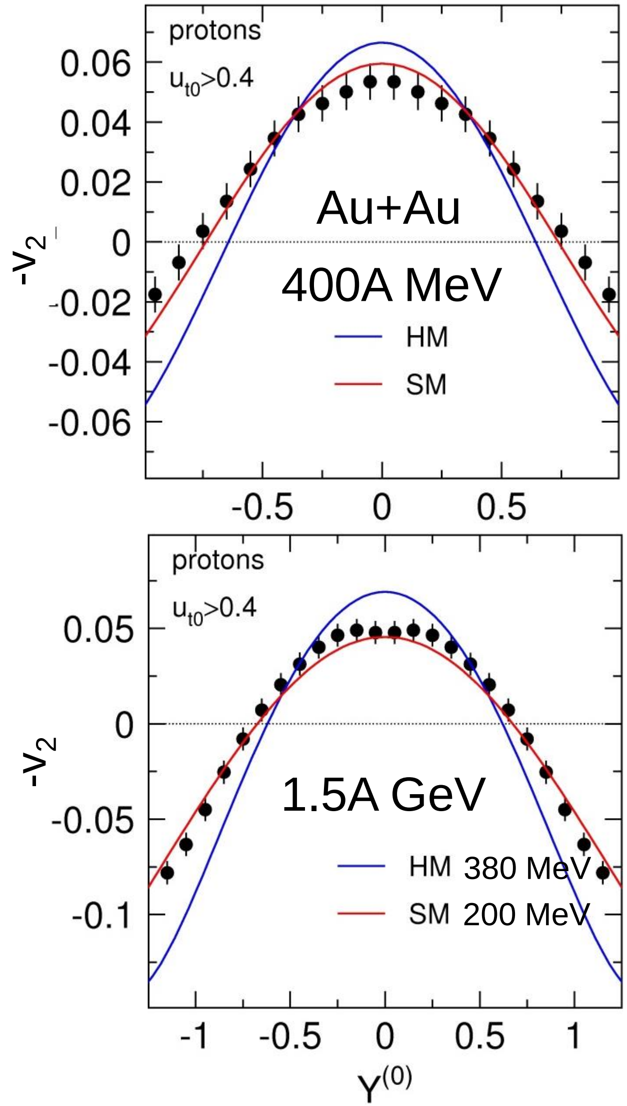
Fourier expansion of azimuthal distribution

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



P. Danielewicz et al. Science 298, 1592 (2002)

Elliptic flow at intermediate energies

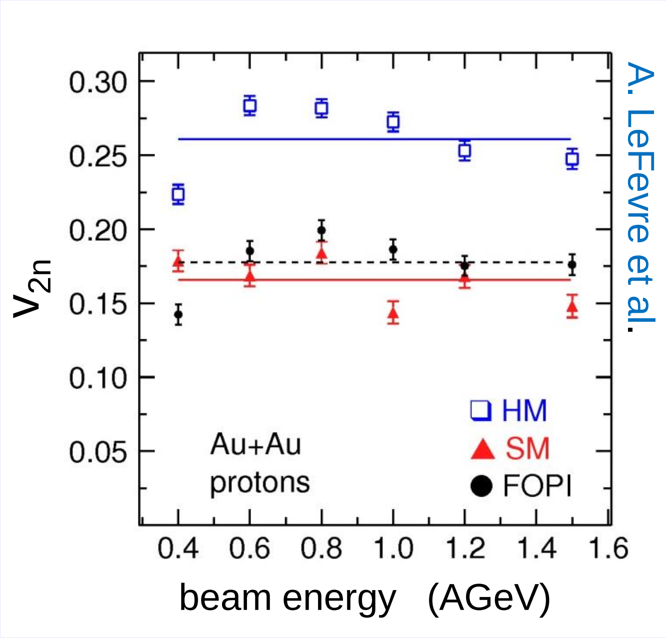


W. Reisdorf et al, Nucl. Phys. A 876 (2012) 1

parameterization of shape:

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

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



A. LeFevre et al.

- sensitive to EOS over a large energy range
- protons and light clusters

Constraining E_{sym} - Elliptic flow of isospin pairs

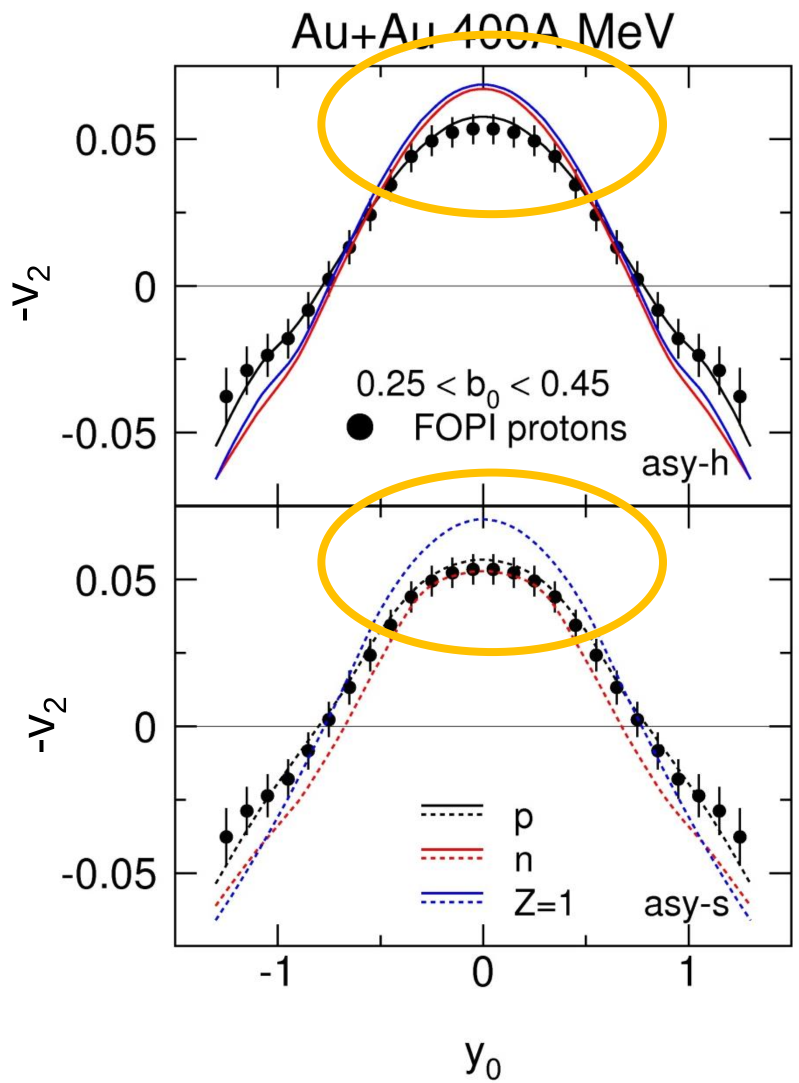
Experimental approach:

- vary N/Z of collision system (radioactive beams)
- look at isospin pairs as probes

  n/p $^3He/^3H$ $\pi^-\pi^+$ K^0/K^+
- observables: production ratios, differences/ratios of spectra and flows

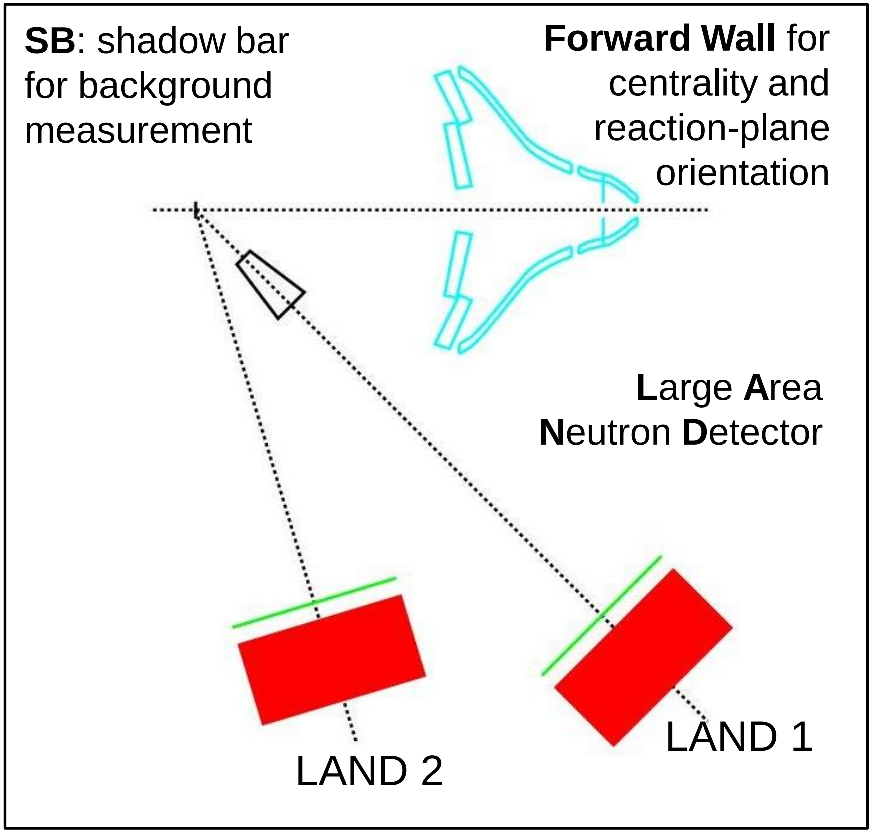
neutron elliptic flow larger with a 'hard' density dependence of SE

→ investigate $v_{2,n}/v_{2,p}$ or $(v_{2,n}-v_{2,p})$

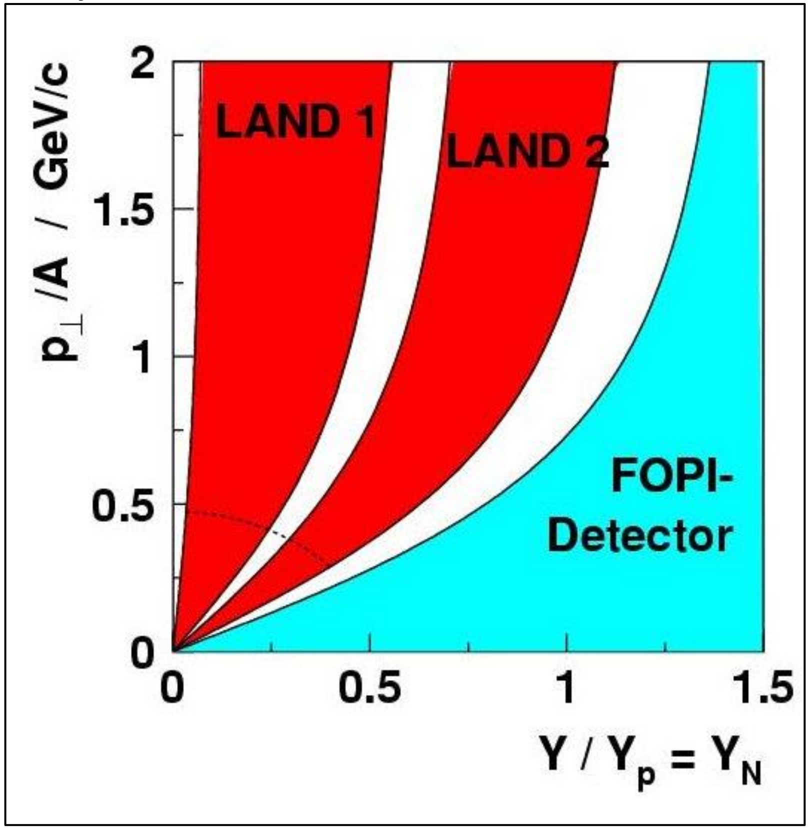


UrQMD: Qingfeng Li et al. / Y. Leifels
Data. W. Reisdorf et al.

Neutron/hydrogen elliptic flow in Au+Au collisions

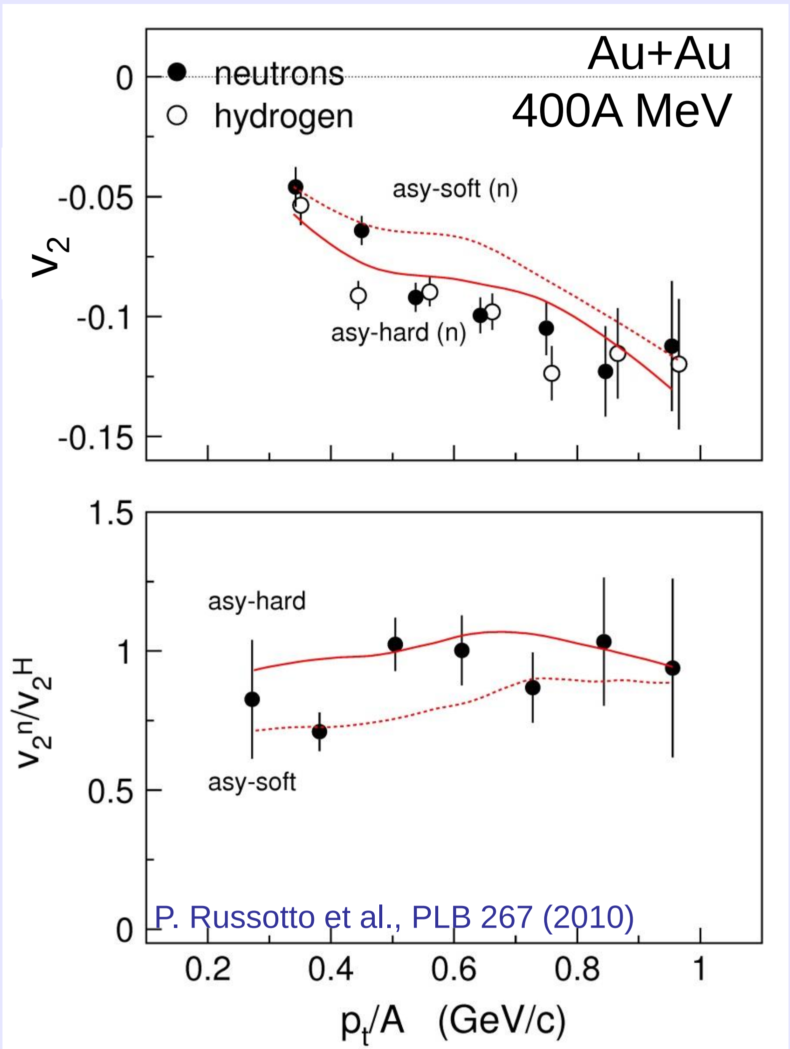


acceptance:
in p_t vs rapidity



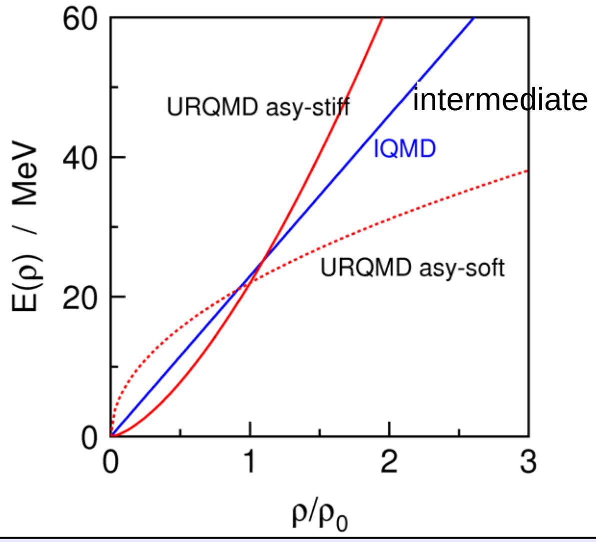
neutron squeeze-out in Au+Au collisions:
Y. Leifels et al., PRL 71, 963 (1993)

Neutron/hydrogen elliptic flow



SE used in UrQMD model calculations

P. Russotto et al. PLB 267 (2010)



Conclusion out of all available data:

- n/p and n/H

by varying input parameters to the model:

- elastic NN cross sections

L = 85±40 MeV

Neutron/hydrogen elliptic flow

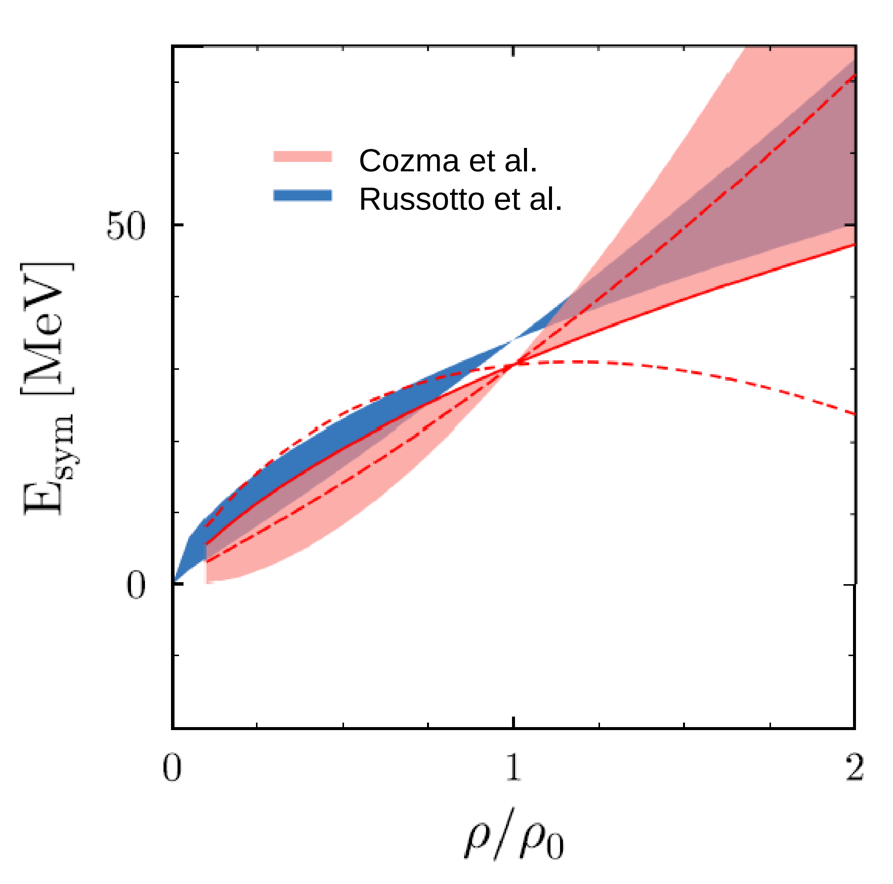
Towards model independence
Tested stability of results:

- soft vs. hard **190<K<280 MeV**
- density dependence of $\sigma_{NN,elastic}$
- asymmetry dependence of $\sigma_{NN,elastic}$
- optical potential
- momentum dependence of isovector potential

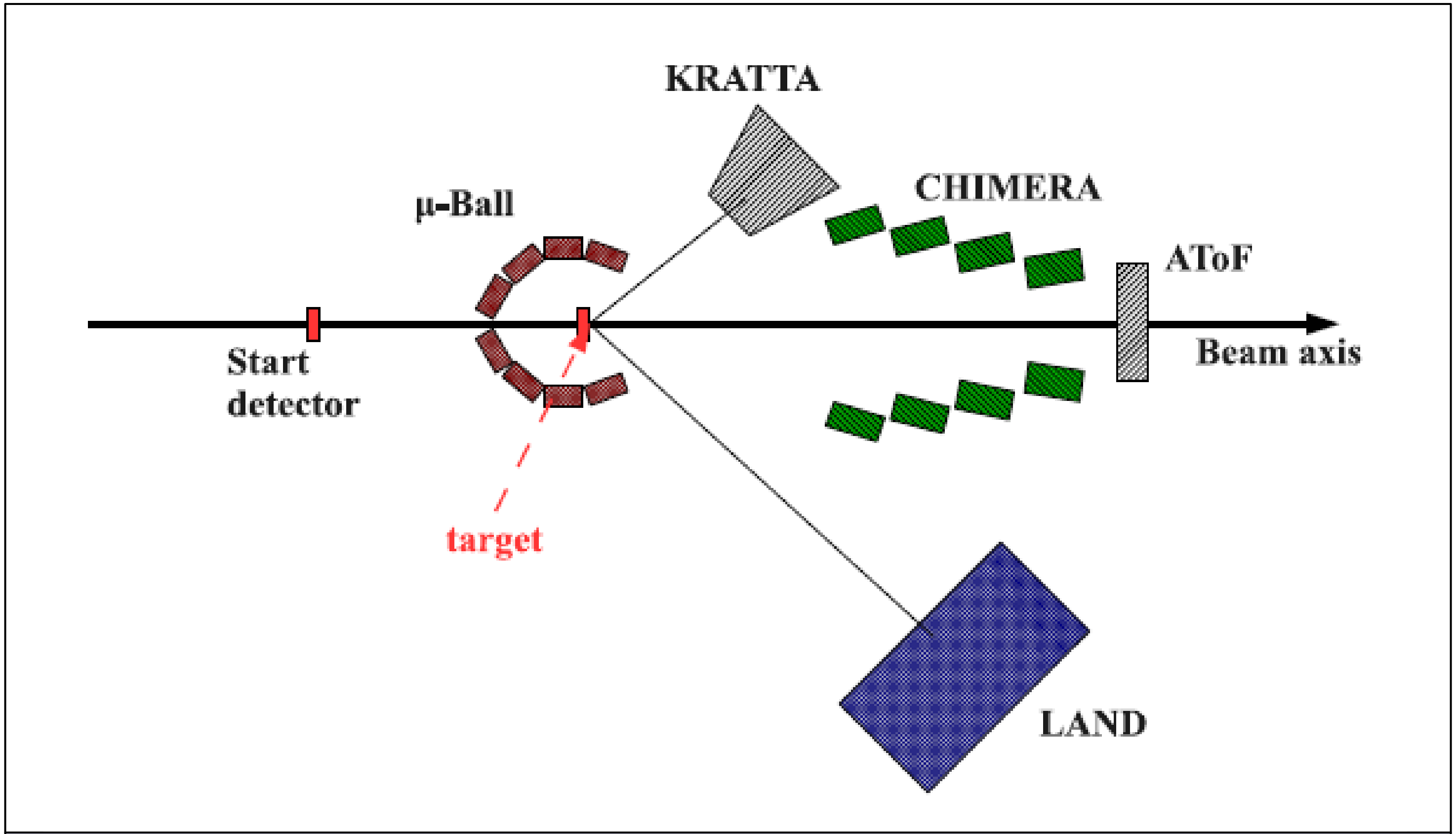
Cozma et al. (Tübingen-QMD) :
L = 106±46 MeV
Russotto et al. (UrQMD):
L = 85±40 MeV

- ruling out particular hard or soft E_{sym}
- statistics unsatisfactory
- other observables?

M.D. Cozma et al., arXiv:1305.5417
P. Russotto et al., PLB 267 (2010)



The ASY-EOS experiment at GSI



studied reactions:

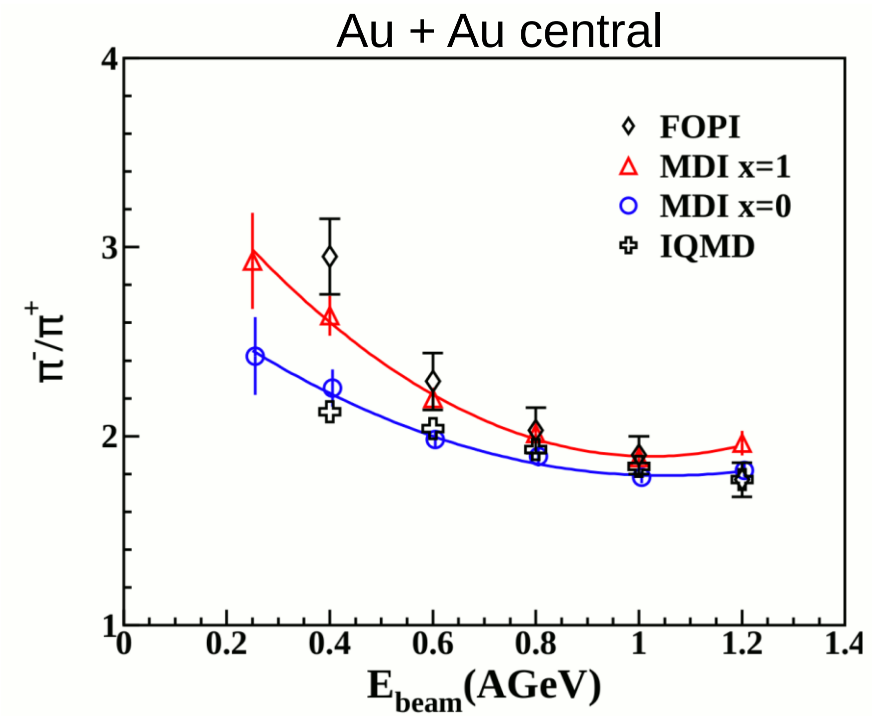
^{197}Au + ^{197}Au @ 400 A MeV

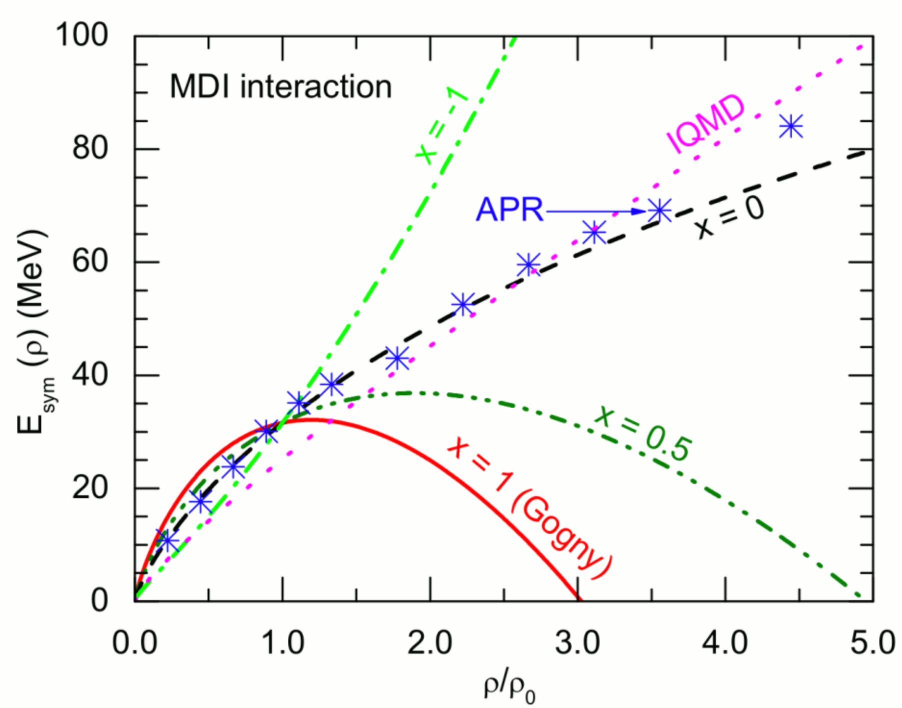
^{96}Ru + ^{96}Ru @ 400 A MeV

^{96}Zr + ^{96}Zr @ 400 A MeV

CHIMERA, ALADIN Tof-wall, µ-ball, for impact parameter orientation and modulus

Testing density differences - The π^-/π^+ ratio





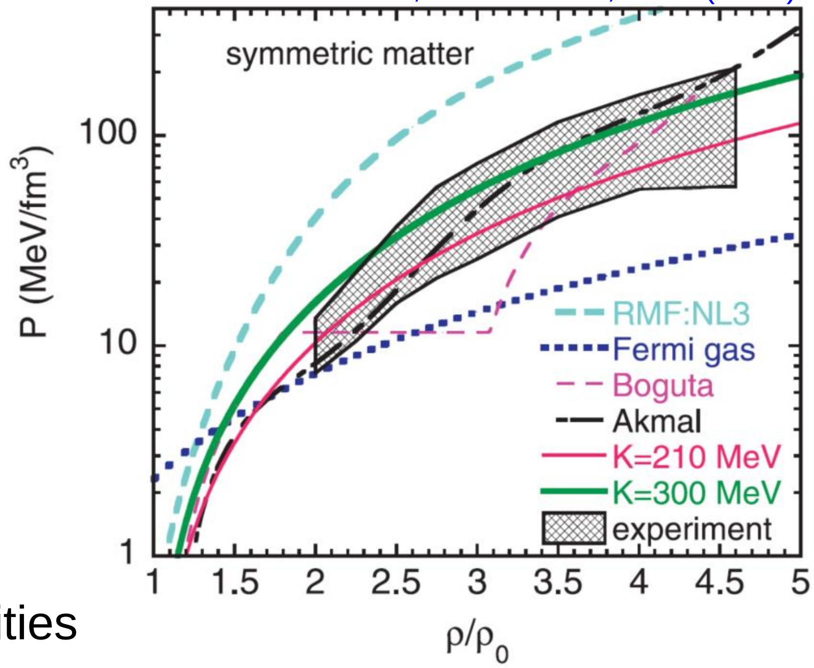
Data described by various models with stiff (or soft) density dependences of the symmetry energy

Ferini et al.	RMF	stiffer	for ratio up
Xiao et al.	IBUU	softer	"
Feng & Jin	ImIQMD	stiffer	"
Xie et al.	ImIBL	softer	"

Data: W. Reisdorf et al., NPA 781 (2007)
Calculations: Z. Xiao et al, Phys. Rev. Lett. 102, 062502 (2009)

Summary and conclusions

P. Danielewicz et al., Science 298, 1592 (2002)



At ~ (2-3)ρ_0 , E_{beam}=0.2 – 2 AGeV

- multitude of experimental data help to constrain the various input parameters to the microscopic transport models
  - EOS of symmetric matter, in-medium cross sections...
  - data support a soft Skyrme type EOS

Symmetry energy at supra-saturation densities

- very few data points at supra saturation densities
- elliptic flow data
  - ratios or differences reduces influence of uncertainties in model parameters
  - available data consistent with L~100+/- 45 MeV – new results soon
  - slightly harder than experiments at lower densities/astrophysical observations
- promising pion observables, but no consistent description
- more data WITH radioactive beam will be available soon

New projects at radioactive beam facilities

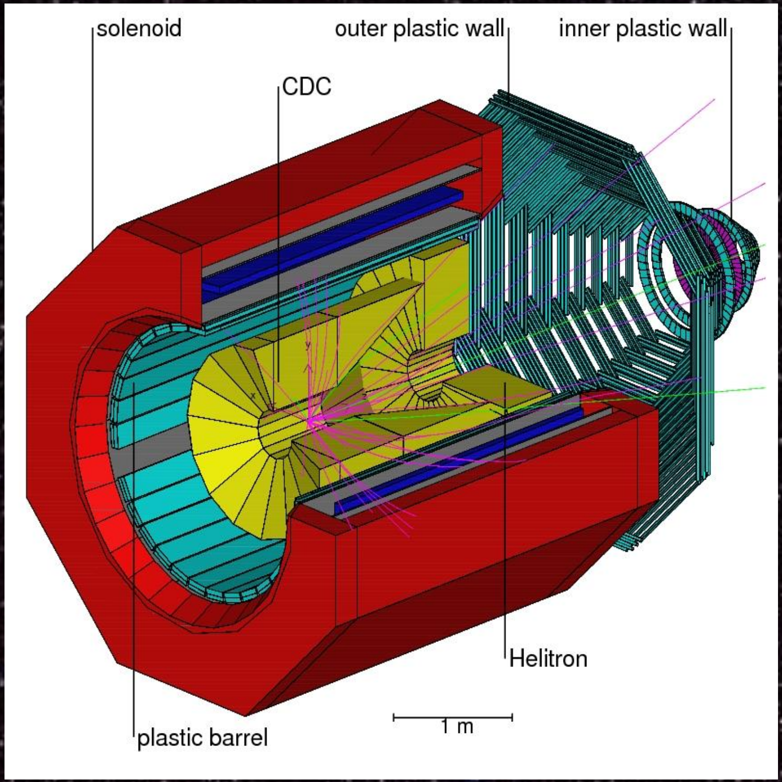
The FOPI collaboration

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, B. Sikora, K.S. Sim, V. Simion, 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

J. Aichelin, E. Bratkovskaya, W. Cassing, C. Hartnack, T.Gaitanos, Q. Li, D. Cozma

IPNE Bucharest, Romania, ITEP Moscow, Russia 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)



The Asy-Eos Collaboration

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

[1]INFN-Sezione di Catania, Catania, Italy
[2]University of Liverpool, Liverpool, UK
[3]GSI Helmholtzzentrum, Darmstadt, Germany
[4]Ruder Boškoviè Institute, Zagreb, Croatia
[5]Technische Universität, Darmstadt, Germany
[6]Jagiellonian University, Krakòw, Poland
[7]STFC Laboratory, Daresbury, UK
[8]IFJ-PAN, Krakow, Poland
[9]Texas A&M University, College Station, USA
[10]GANIL, Caen, France
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[13]Institute of Physics, Slovak Academy of Sciences, Bratislava, Slovakia
[14]INFN-Laboratori Nazionali del Sud, Catania, Italy
[15]KACST Riyadh, Riyadh, Saudi Arabia
[16]King Saud University, Riyadh, Saudi Arabia
[17]University of Santiago de Compostela, Santiago de Compostela, Spain
[18]University of Bucharest, Bucharest, Romania
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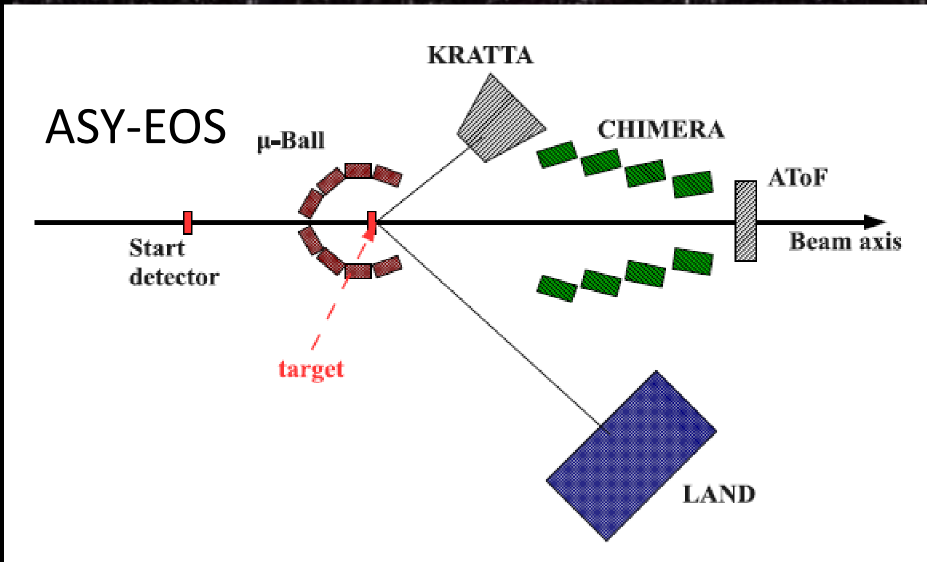
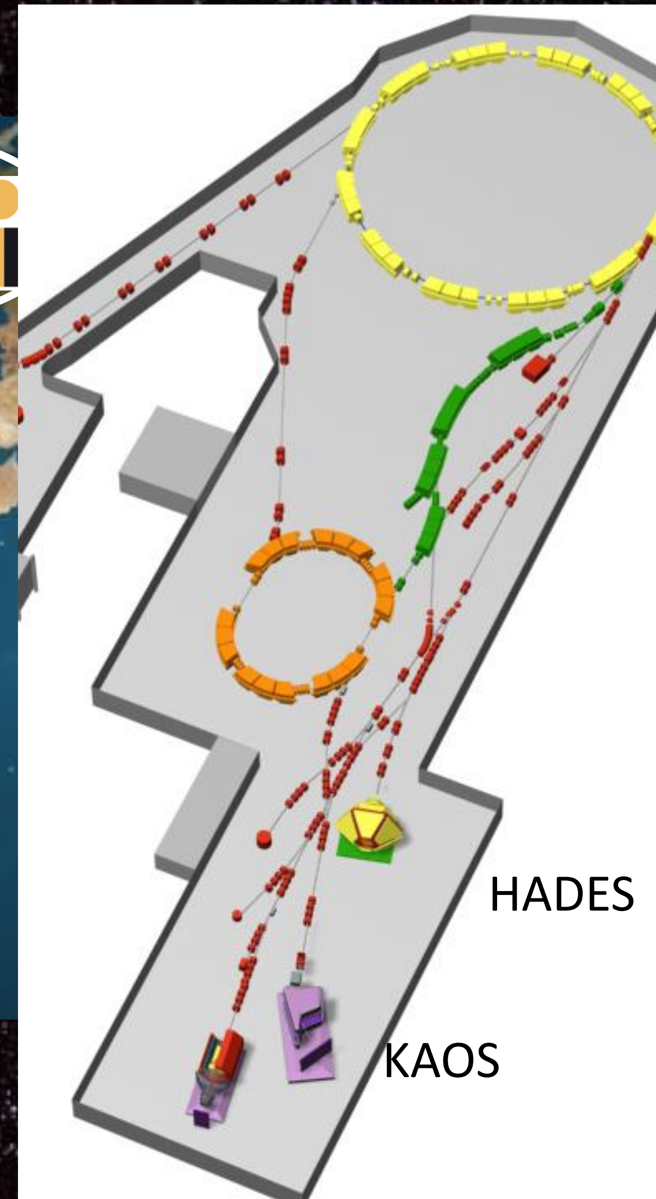
[22]Università di Catania, Catania, Italy

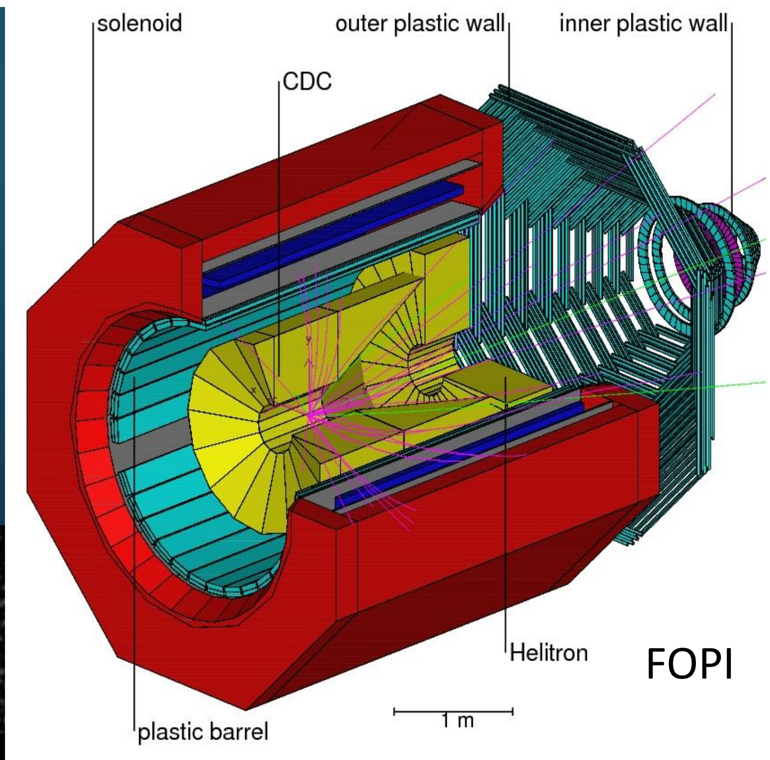
[21]Western Michigan University, USA
[24]Politecnico di Milano, Milano, Italy
[25]Università degli Studi di Milano, Milano, Italy
[26]INFN, Politecnico di Torino, Torino, Italy
[27]RIKEN, Wako, Japan
[28]Institute of Nuclear Research, Debrecen, Hungary
[29]Università Kore, Enna, Italy
[30]Huzhou Teachers College, China
[30]INFN-Sezione di Napoli, Napoli, Italy
[31]Università di Napoli, Napoli, Italy
[32]LMU, München, Germany

Thank you

Star clusters young and old
Chris Hetlage
APOD 2006, September 10


ASY-EOS
KRATTA
μ-Ball
CHIMERA
AToF
Start detector
target
Beam axis
LAND


HADES
KAOS


solenoid
outer plastic wall
inner plastic wall
CDC
Helitron
FOPI
plastic barrel
1 m

Inside IQMD

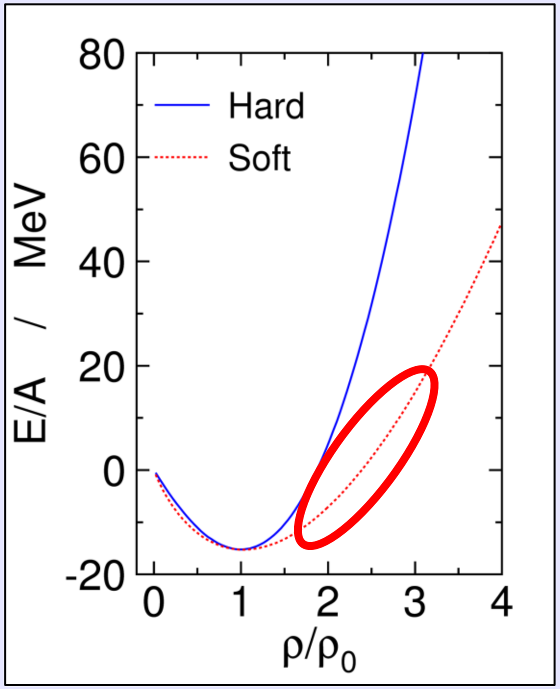
after the convolution of the Skyrme type potentials supplemented by momentum dependent interactions (mdi) for infinite saturated nuclear matter at equilibrium

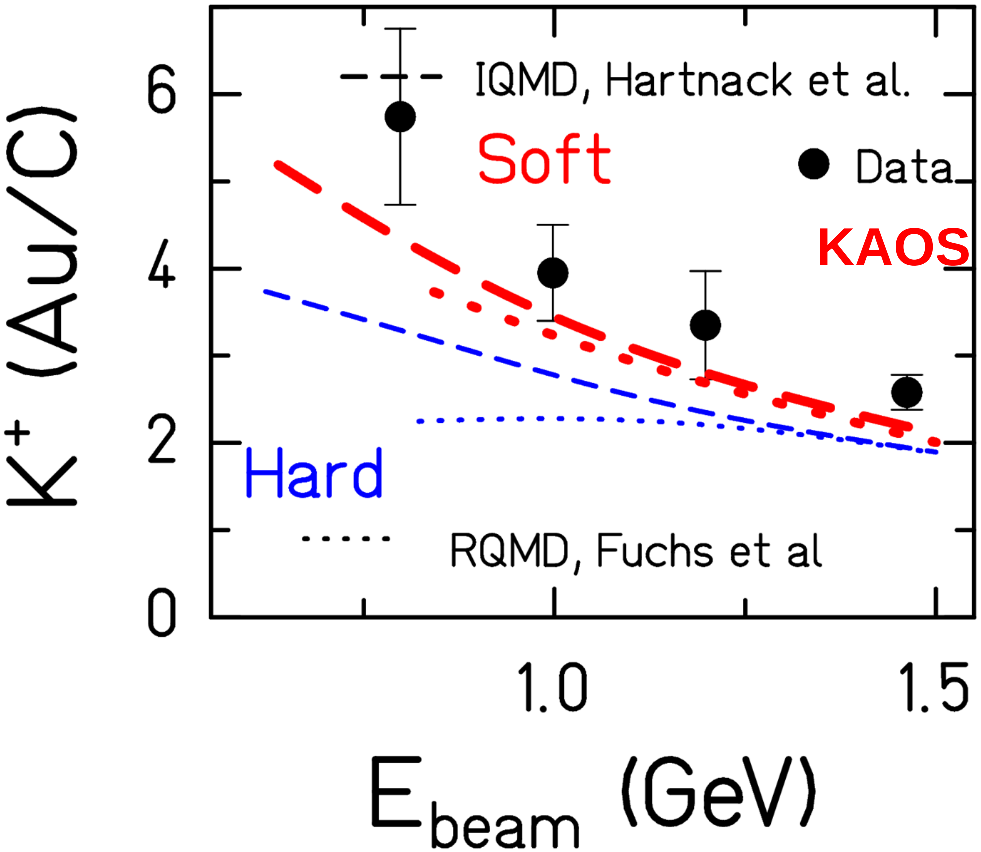
$$U = \alpha \cdot \left(\frac{\rho_{int}}{\rho_0}\right) + \beta \cdot \left(\frac{\rho_{int}}{\rho_0}\right)^{\gamma} + \delta \cdot \ln^2\left(\varepsilon \cdot (\Delta\vec{p})^2 + 1\right) \cdot \left(\frac{\rho_{int}}{\rho_0}\right)$$

	α (MeV)	β (MeV)	γ	δ (MeV)	ε $\left(\frac{c^2}{\mathrm{GeV}^2}\right)$	κ (MeV)
S	-356	303	1.17	—	—	200
SM	-390	320	1.14	1.57	500	200
H	-124	71	2.00	—	—	376
HM	-130	59	2.09	1.57	500	376
INT	-157	103	1.58	—	—	284
VH	-110	56	2.40	—	—	456

Testing density – Kaon production below threshold

Independent on models and details of the input (cross sections, in medium potentials etc.)
Testing densities at 2-3 ρ_0



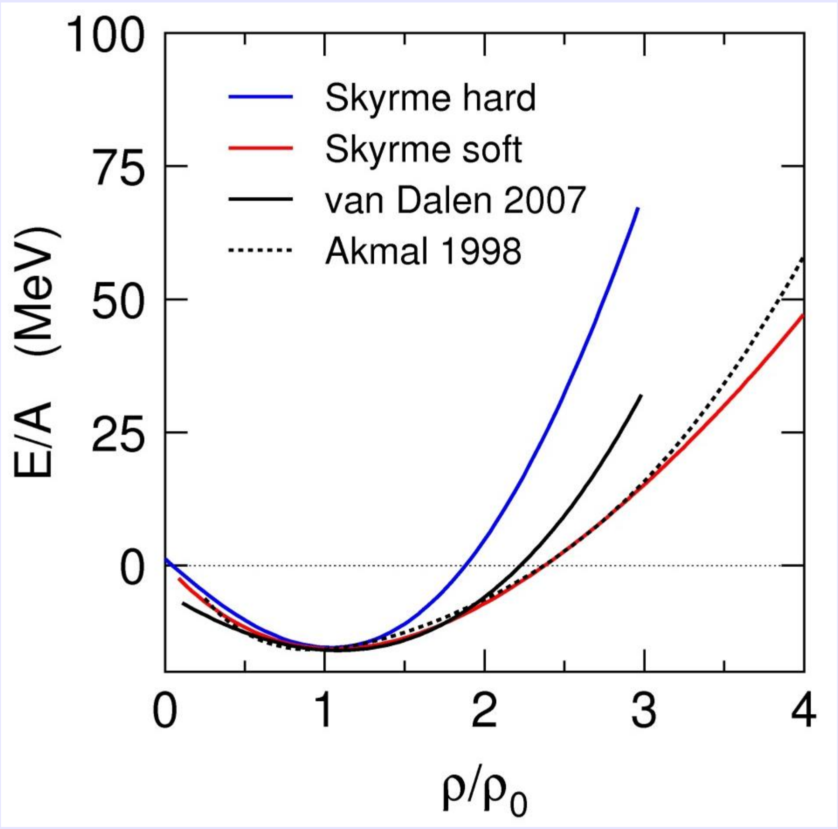


Data: C. Sturm et al., PRL 86 (2001) 39
IQMD: C. Hartnack et al., PRL96:012302,2006
RQMD: C. Fuchs et al., PRL 86 (2001) 1974

Summary and conclusions

At ~ (2-3)ρ_0 data is consistent with a soft Skyrme type EOS for symmetric matter

- ➢ confirmed for two different observables within the same model, which is describing reasonably well all reaction data in this energy regime
- ➢ absolute value may still model dependent
- ➢ more data will available at higher densities with CBM@FAIR or NICA



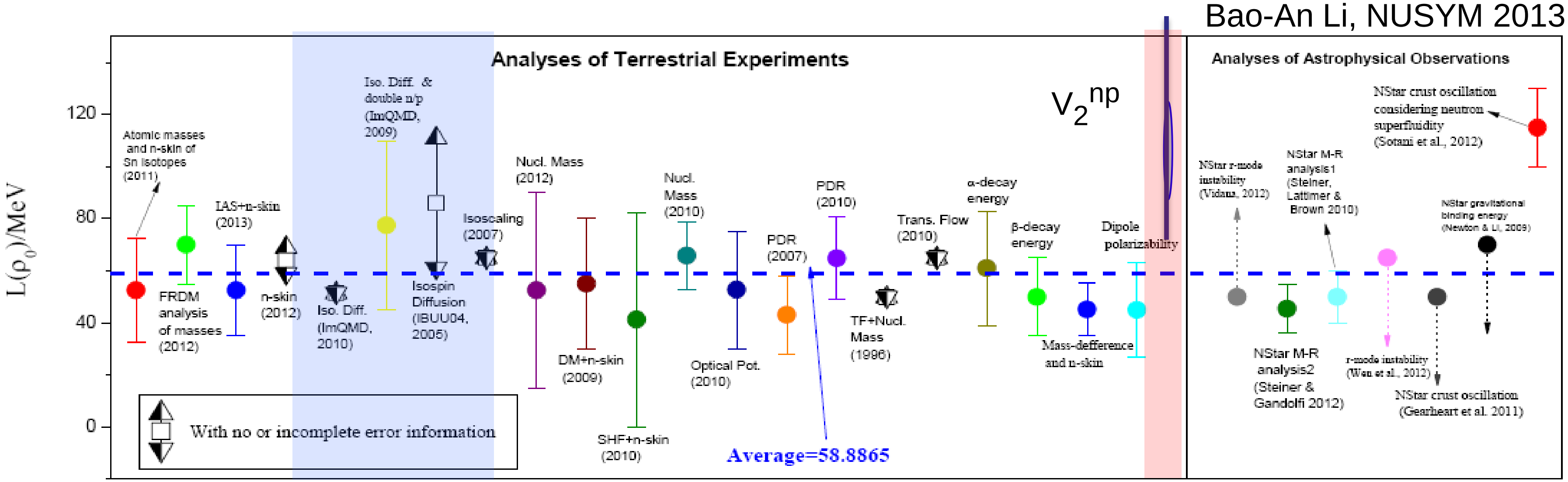
In the relevant density regime soft Skyrme type EOS follows closely the A18+UIX+δv EOS of Akmal, Pandharipande, Ravenhall
Phys. Rev. C, 58 (1998) 1804

Summary and conclusions

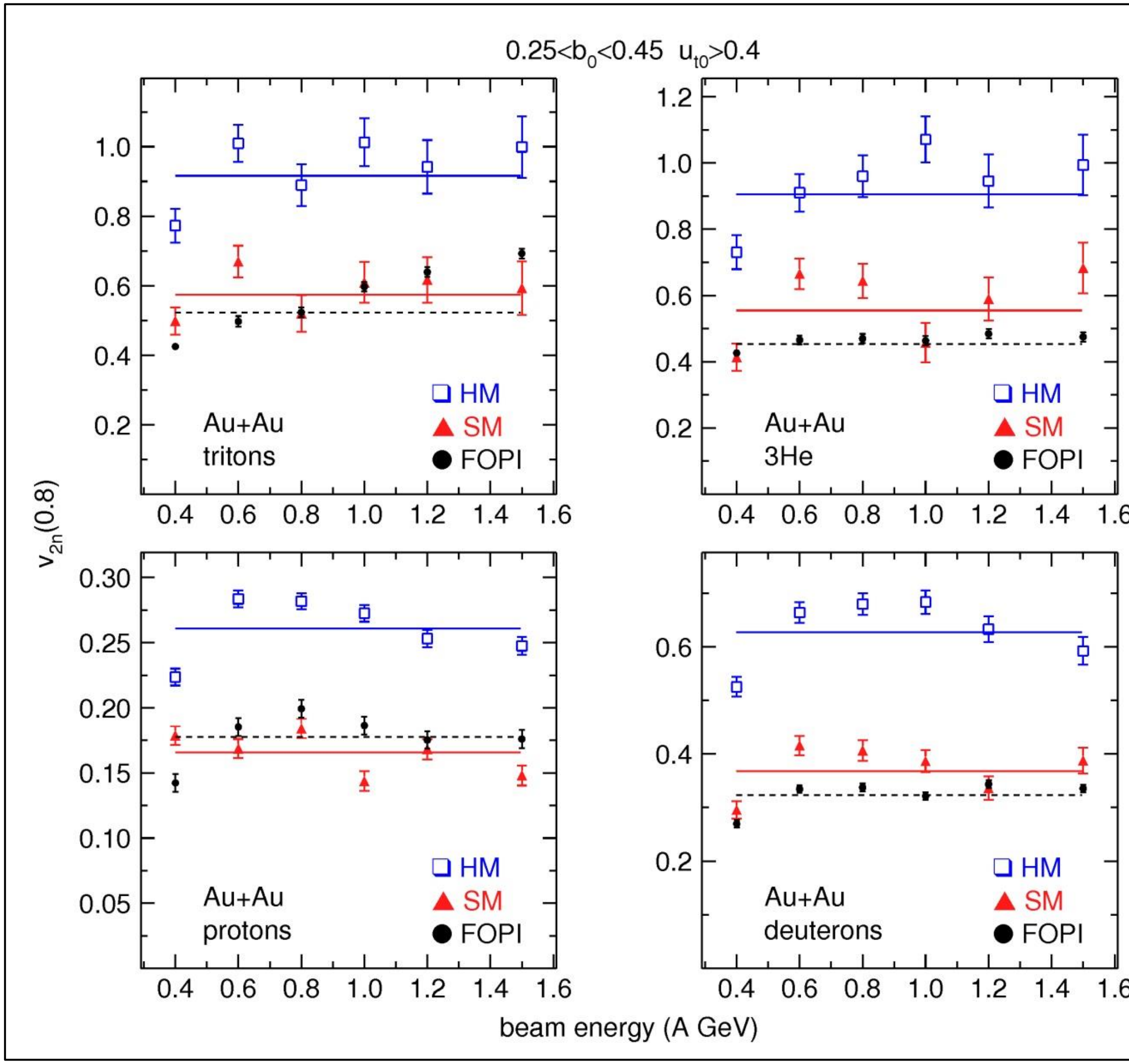
Symmetry energy at supra-saturation densities

- very few data points at supra saturation densities (experiments at GSI)
- elliptic flow data
  - consistent with L~100+/- 45 MeV
  - slightly harder than experiments at lower densities/astrophysical observations
- pion ratio, but no consistent description, new experimental efforts at the radioactive beam facility at RIKEN
- more data WITH radioactive beams will be available soon

Bao-An Li, NUSYM 2013



Elliptic flow of light clustered



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

Parameterization of shape:

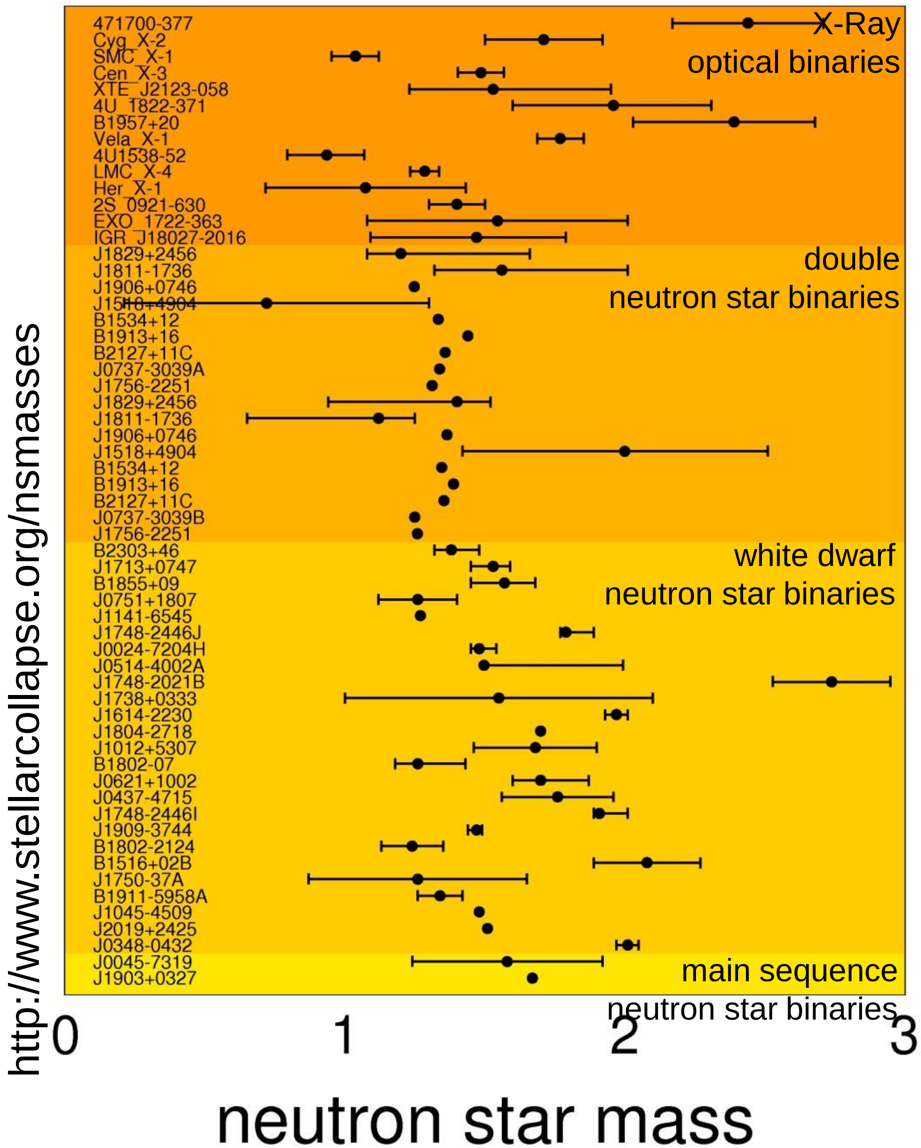
$$v_{2n} = |v_{20}| + |v_{22}|$$

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

- observable sensitive to EOS over a large energy range
- protons and light clustered

Soft EOS favored

Masses of neutron stars



Heaviest Neutron Stars

Name: J1614-2230

Mass: $(1.976 \pm 0.04)\ M_{\odot}$

P. Demorest et al. 2010

Shapiro delay

Name: J0348+0432

Mass: $(2.01 \pm 0.04)\ M_{\odot}$

J. Antoniadis et al. 2013

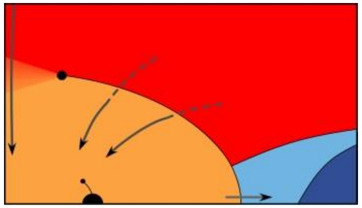
White dwarf spectroscopy

What else?

- Hyperon production and propagation
- YN and YY interaction in dense medium
- Hypernuclei production

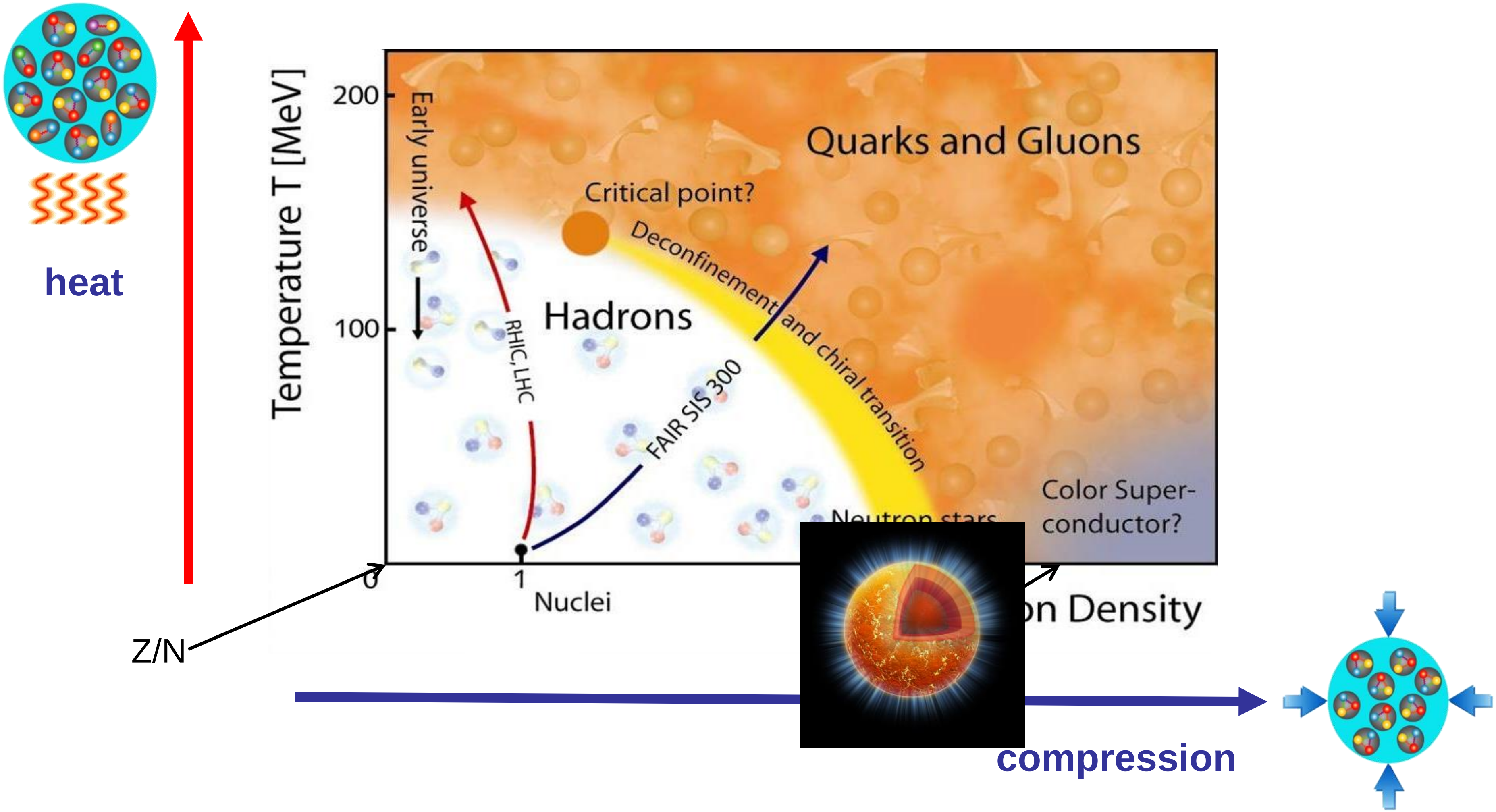
- $K^{-}N$ interaction in dense medium
- In-medium effects as a function of momentum and density

- “Hot” cluster formation

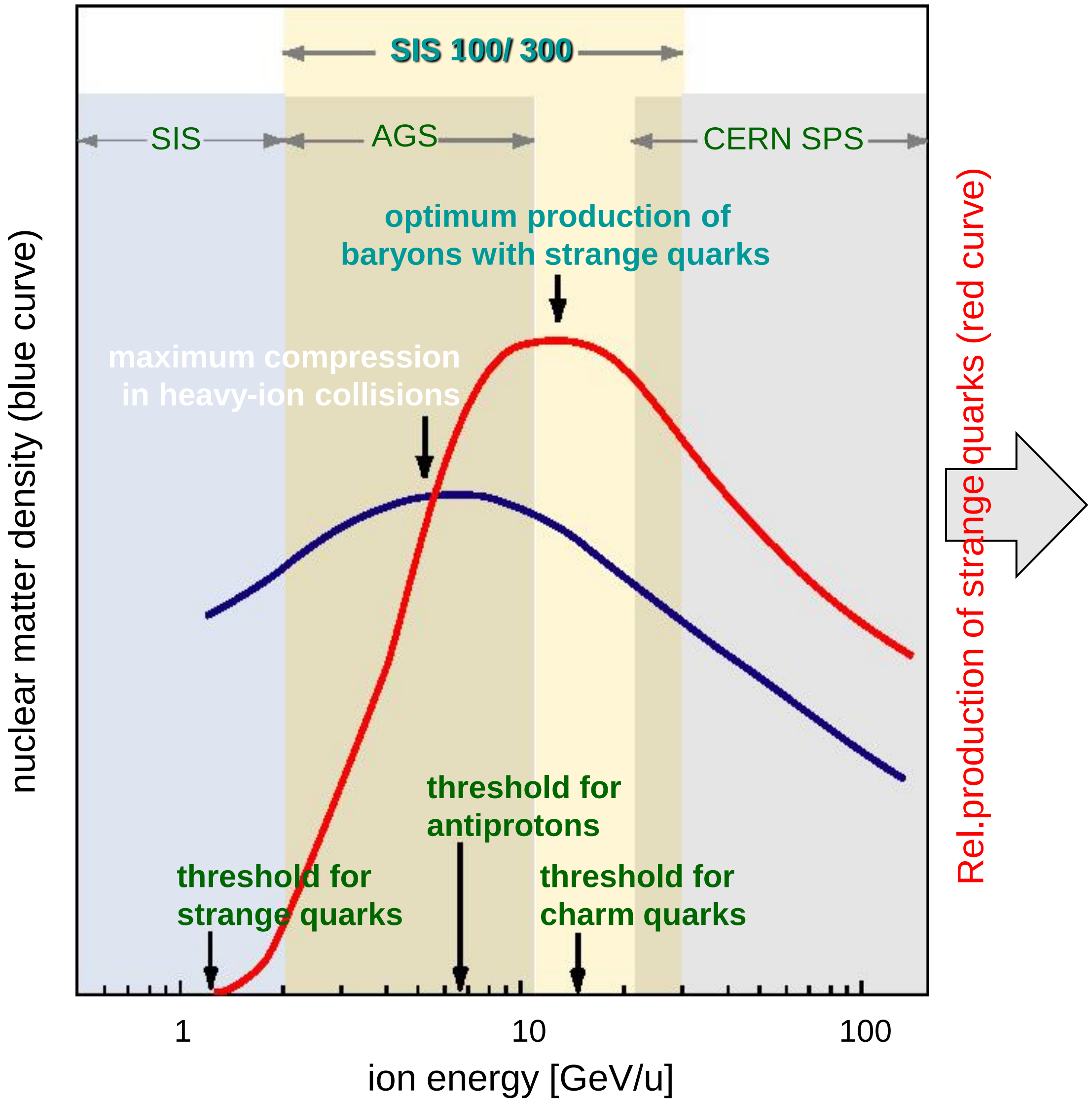


- Phase transitions (QGP), new phases (SCC...)

Phase diagram of nuclear matter



Maximum compression reached at FAIR energies



To be determined:
Temperature
Pressure
Density

Observables:
Particle production
Flow of bulk matter
Production of D^0, $D^{\pm}$
ρ, ω, $\phi \rightarrow$ e^+e^- or $\mu^+\mu^-$