The symmetry energy at high density: experimental probes

W. Trautmann
GSI Helmholtzzentrum, Darmstadt, Germany

- The present consensus that a soft EoS including momentum dependent interactions best describes the high-density behavior of symmetric nuclear matter is based on studies of **flow and kaon** production within the framework of transport theory.

- The **elliptic flow** in collisions of neutron-rich heavy-ion systems at intermediate energies emerges as an observable sensitive to the strength of the symmetry energy at supra-saturation densities.

EMMI workshop
Dense Baryonic Matter in the Cosmos and the Laboratory

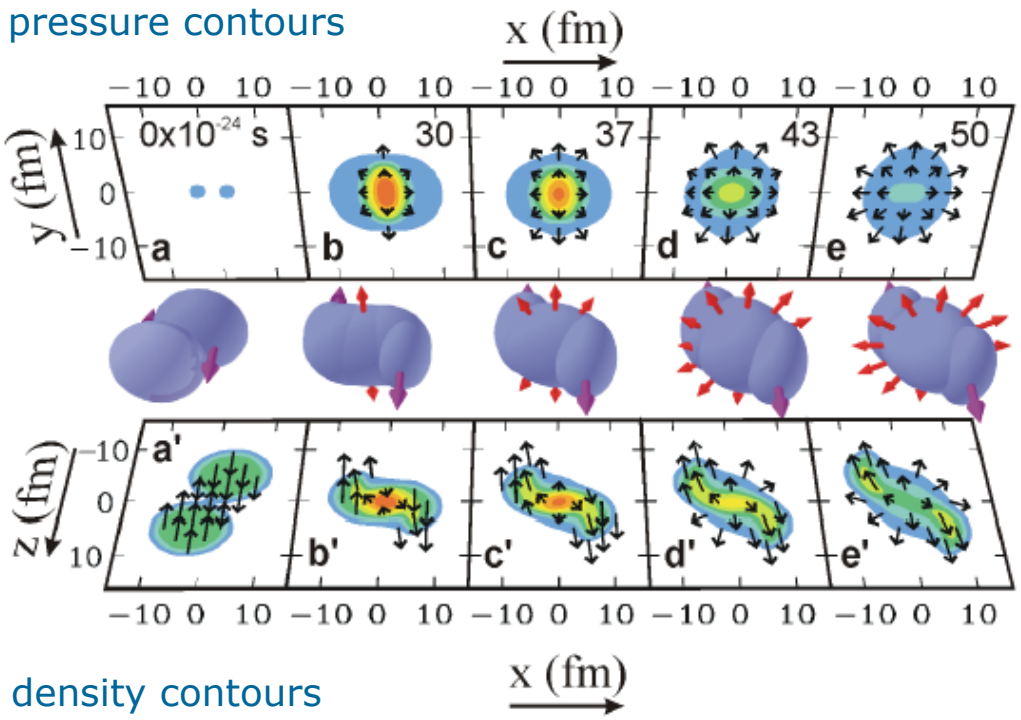
Tübingen, October 11/12, 2012

symmetric matter

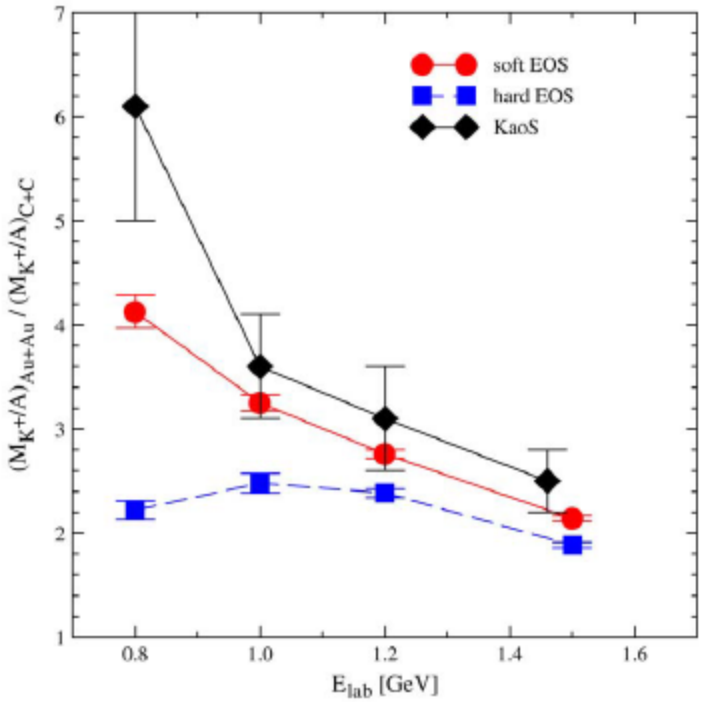
KAOS data
K^+ ratios
Au+Au vs. C+C
normalized to $<A_{part}>$ ...

1 A GeV Au+Au

pressure contours



density contours



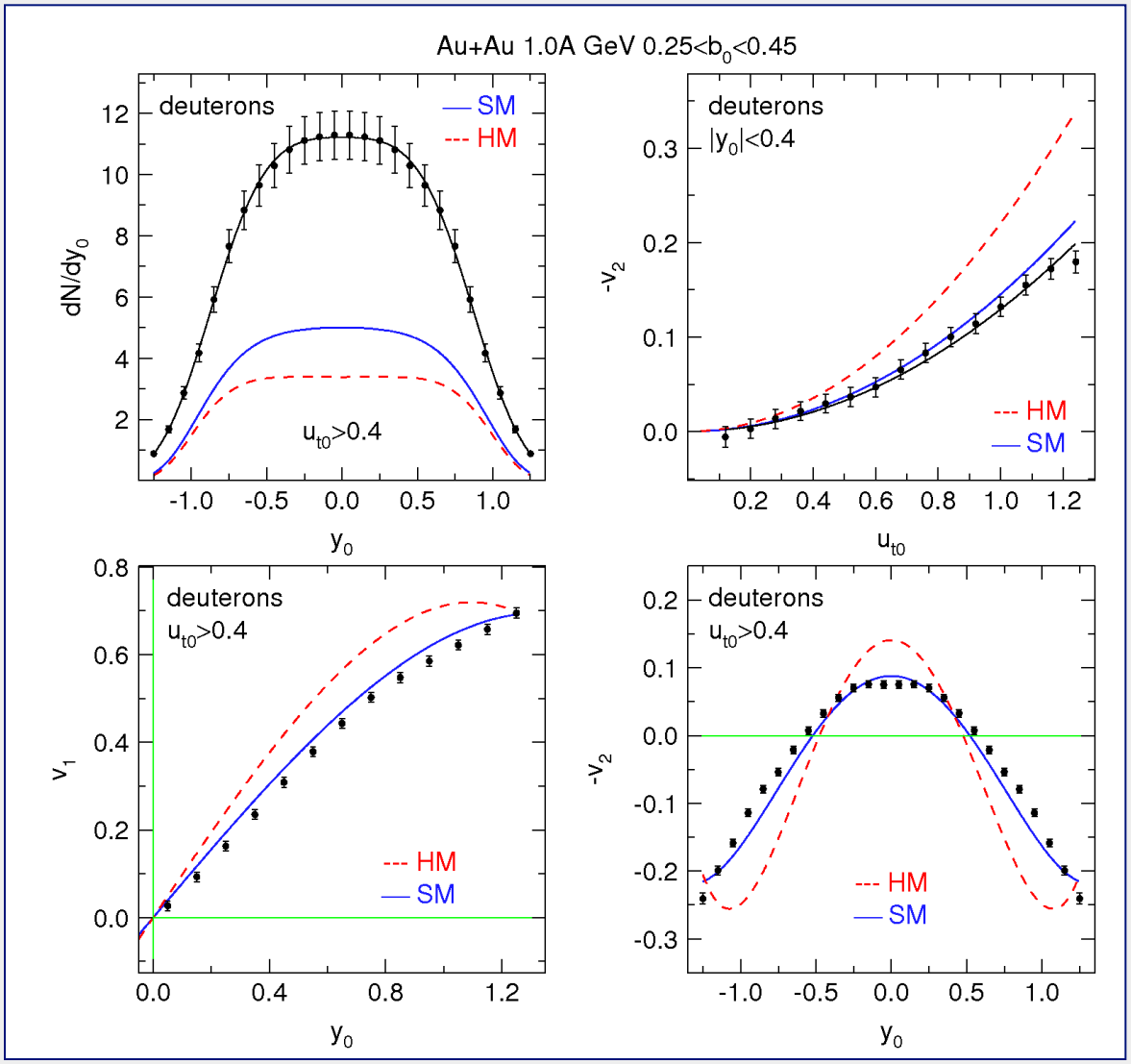
flow data rule out repulsive and super-soft EoS

... favor soft EoS

Danielewicz et al., Science 298 (2002)

Sturm et al., Fuchs et al., PRL 86 (2001)

symmetric matter



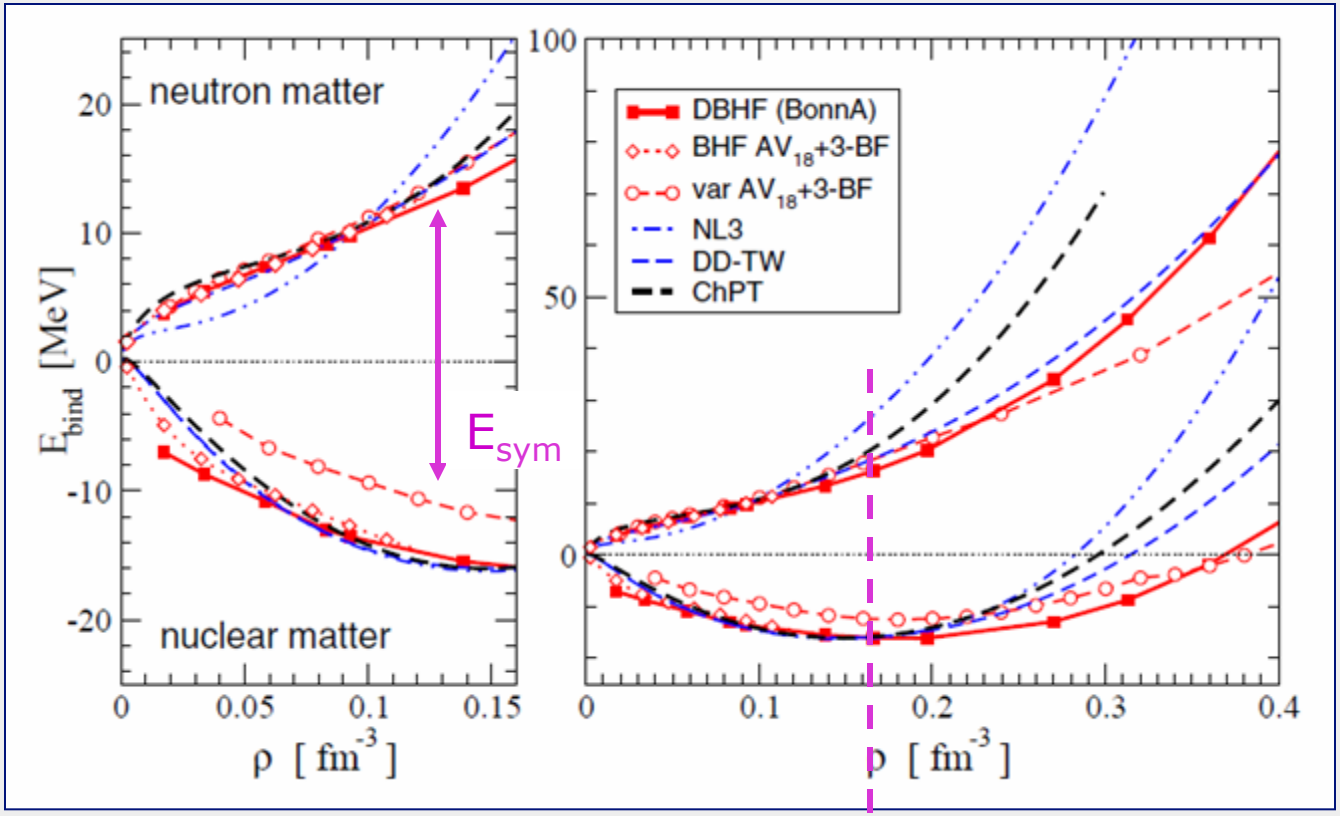
FOPI data
1 A GeV Au+Au

deuteron yields and flows

IQMD model calculations favor soft EoS

source: Reisdorf, AsyEos Siracusa (2012)

the symmetry energy



Fuchs and Wolter, EPJA 30 (2006)

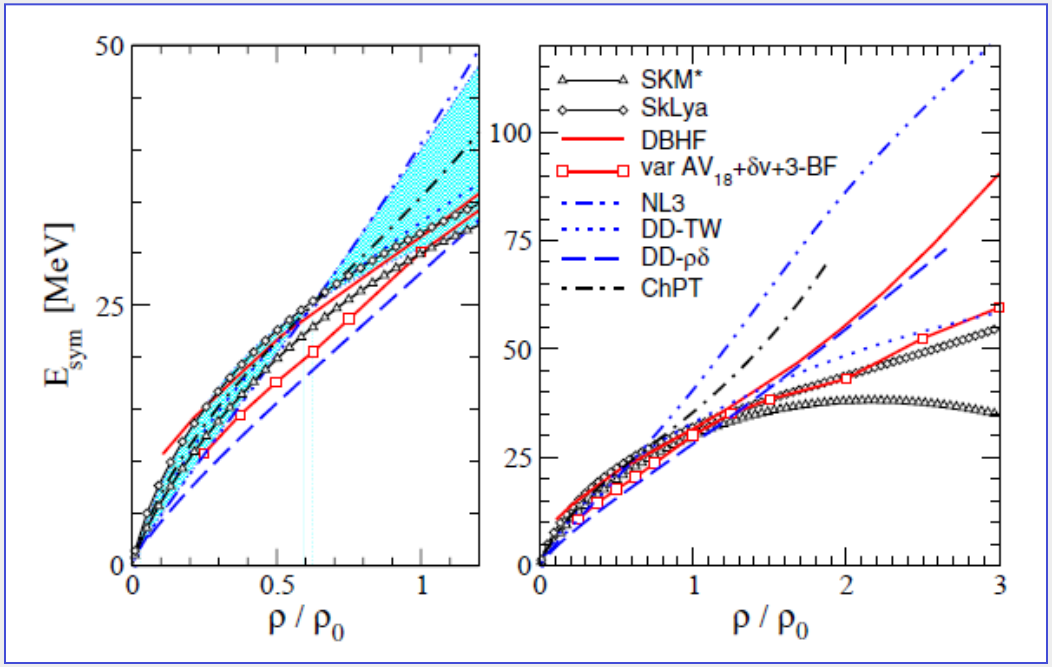
why so uncertain at high density?

related to uncertainty of three-body and tensor forces at high density

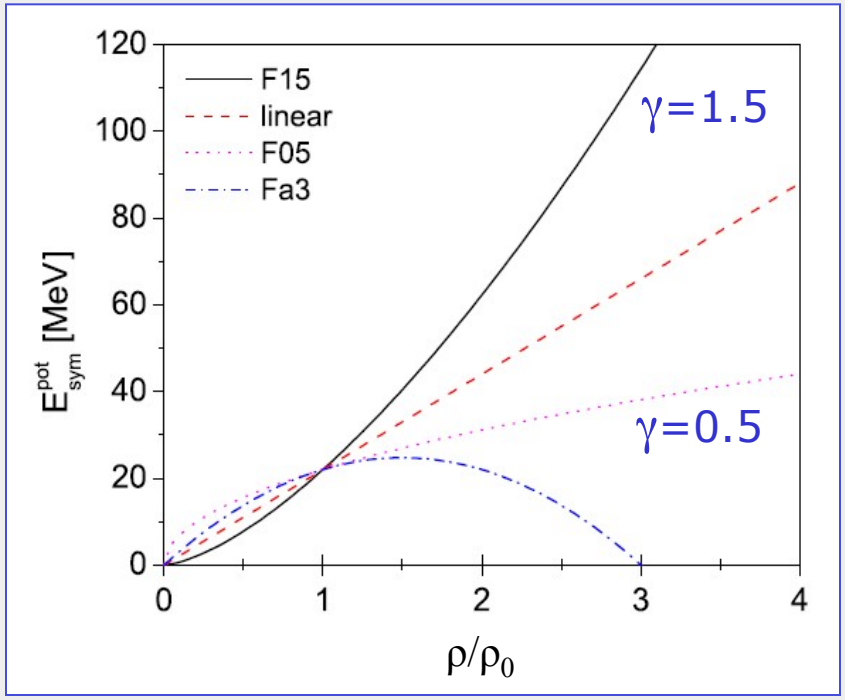
normal nuclear density

the symmetry energy

Fuchs and Wolter, EPJA 30 (2006)



param. in transport: UrQMD, Q.F. Li et al.



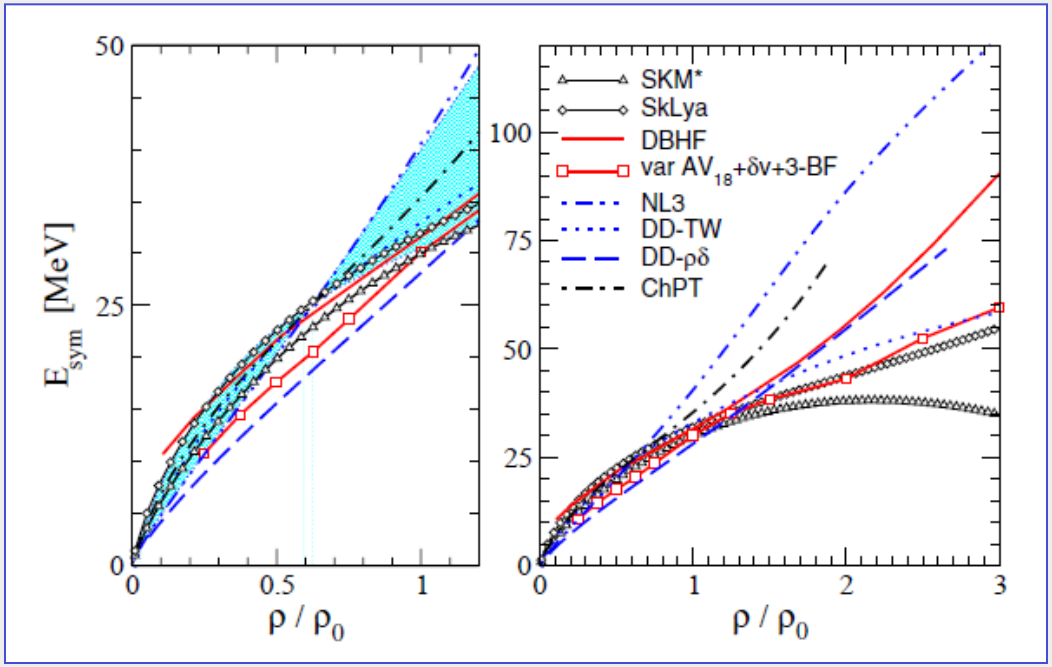
$E_{sym} = E_{sym}^{pot} + E_{sym}^{kin}$
$= 22MeV \cdot (\rho/\rho_0)^{\gamma} + 12MeV \cdot (\rho/\rho_0)^{2/3}$

$L = 3\rho_o \cdot dE_{sym}/d\rho$ at $\rho=\rho_0$

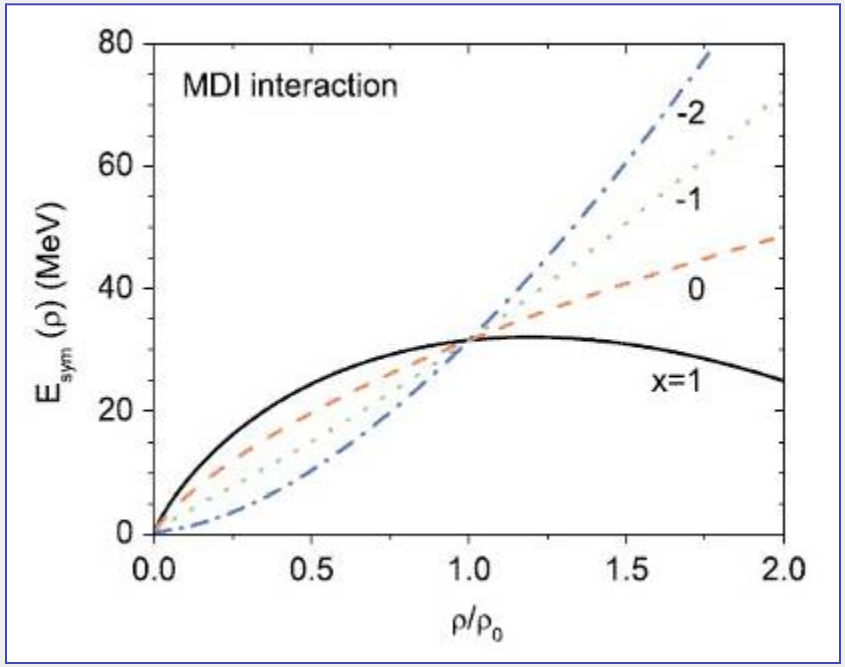
γ	L (MeV)
0.5	57
1.0	90
1.5	123

the symmetry energy

Fuchs and Wolter, EPJA 30 (2006)



param. in transport: MDI, Bao-An Li et al.



force developed by
Das, Das Gupta, Gale, and Bao-An Li,
Phys. Rev. C 67 (2003) 034611.

with explicit momentum dependence in the isovector part

differential flow in heavy-ion collisions

minimizes role of isoscalar part of the EoS
see Bao-An Li PRL (2000) and subsequent work

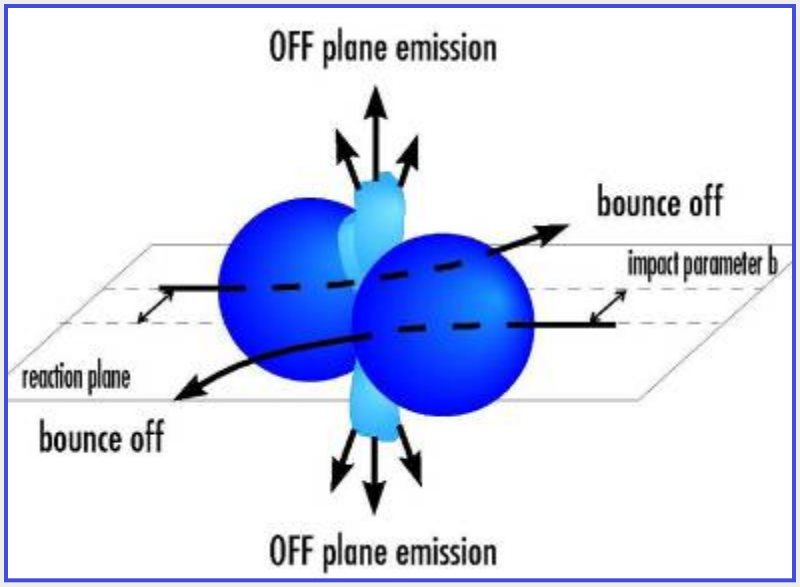
differential: neutrons vs. protons
t vs. ^{3}He, ^{7}Li vs ^{7}Be, ...

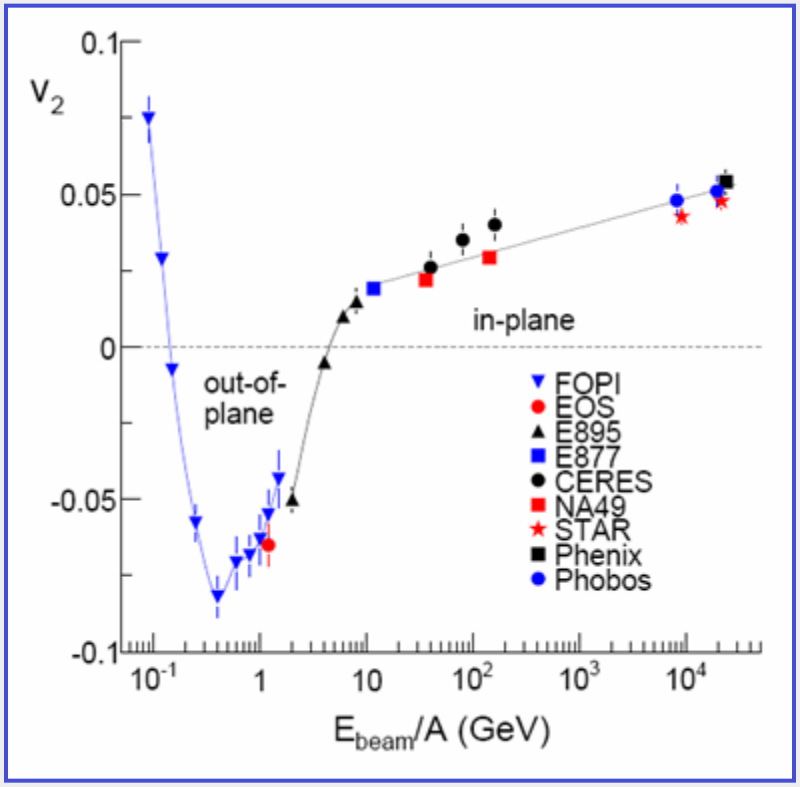
UrQMD: significant sensitivity predicted for differential elliptic flow
(Qingfeng Li and Paolo Russotto)

reanalysis of FOPI-LAND data:

$$\gamma_{pot} = 0.9 \pm 0.4$$

Russotto, Wu, Zoric, Chartier, Leifels, Lemmon, Li, Lukasik, Pagano, Pawlowski, Trautmann, PLB 697 (2011) 471
Trautmann & Wolter, IJMPE 21 (2012) 1230003

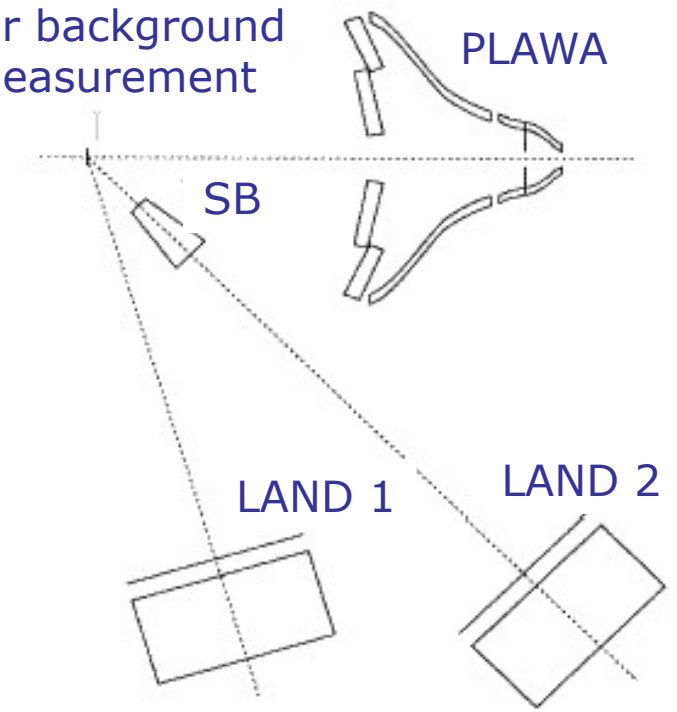




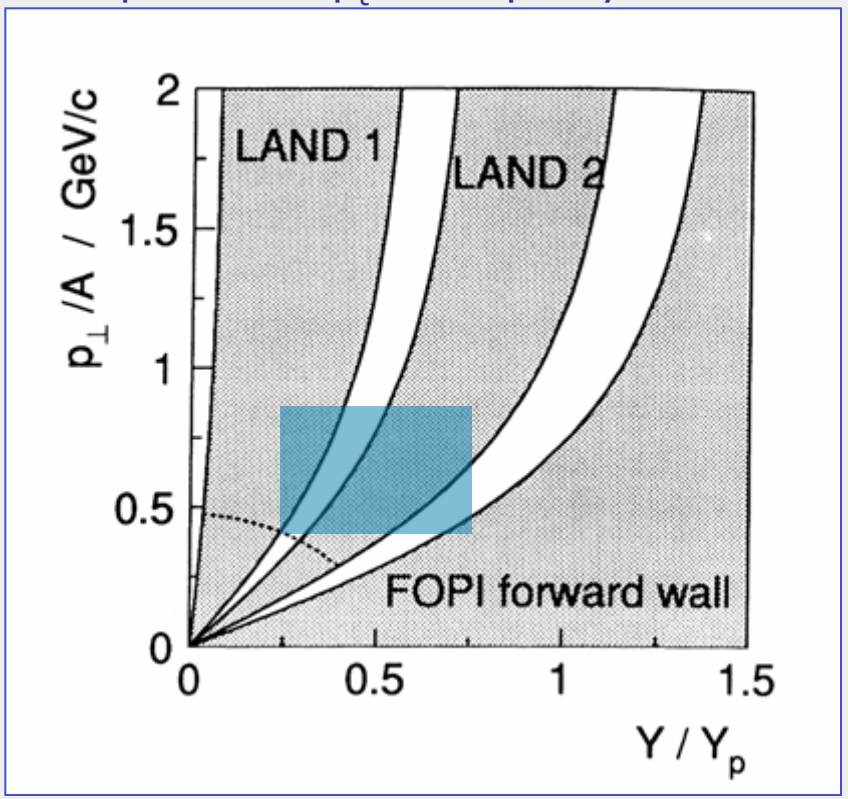
results from FOPI/LAND experiment

reanalysis of Au+Au 400 A MeV data

SB: shadow bar for background measurement



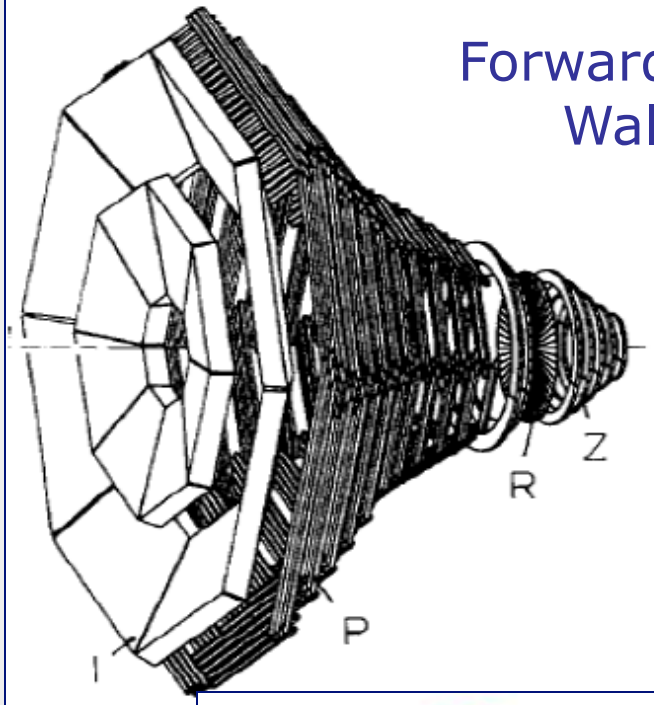
acceptance in p_t vs. rapidity



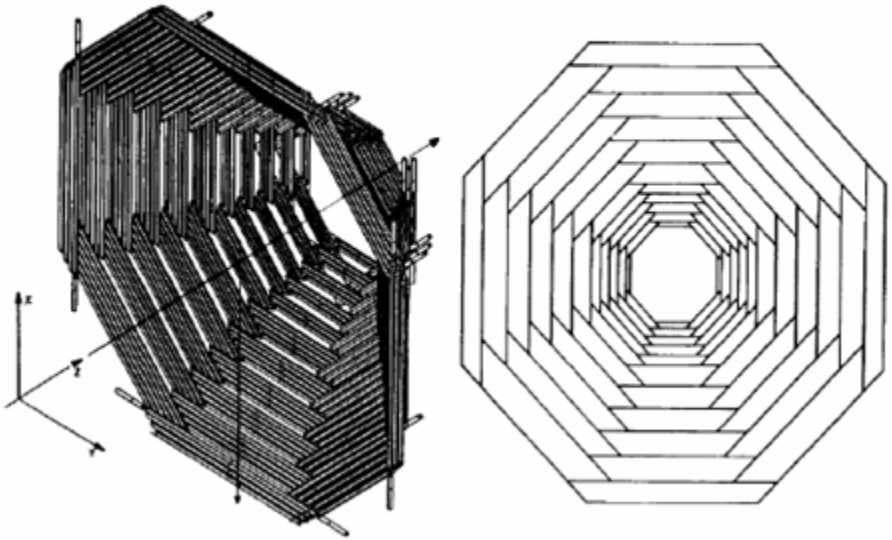
neutron squeeze-out:
Y. Leifels et al., PRL 71, 963 (1993)

main yield here

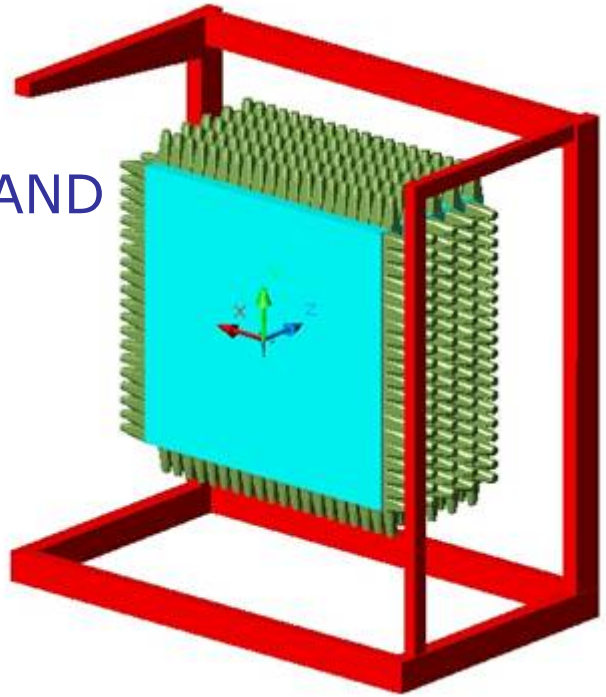
Forward Wall



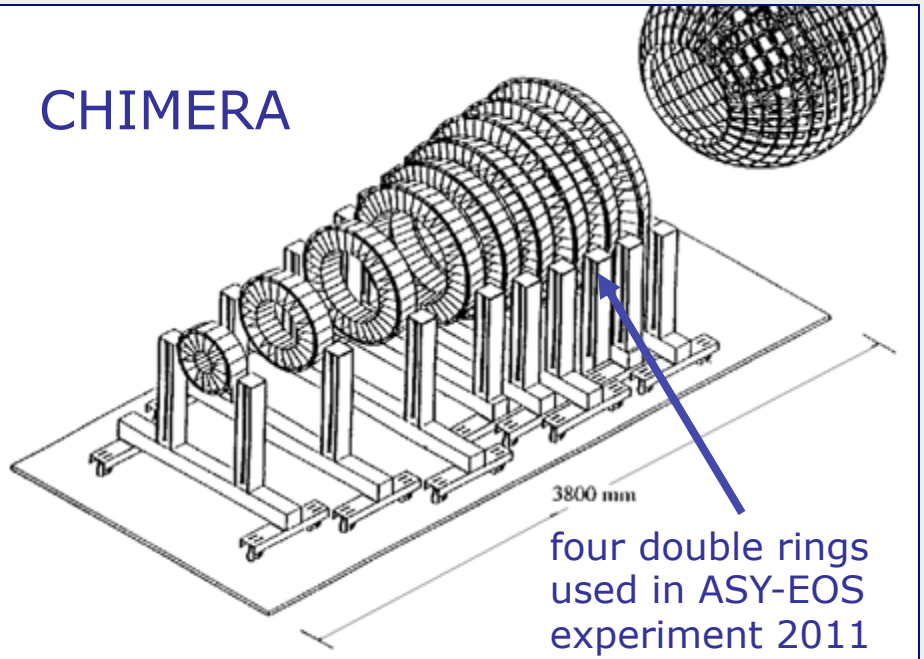
FOPI Outer Wall



LAND



CHIMERA



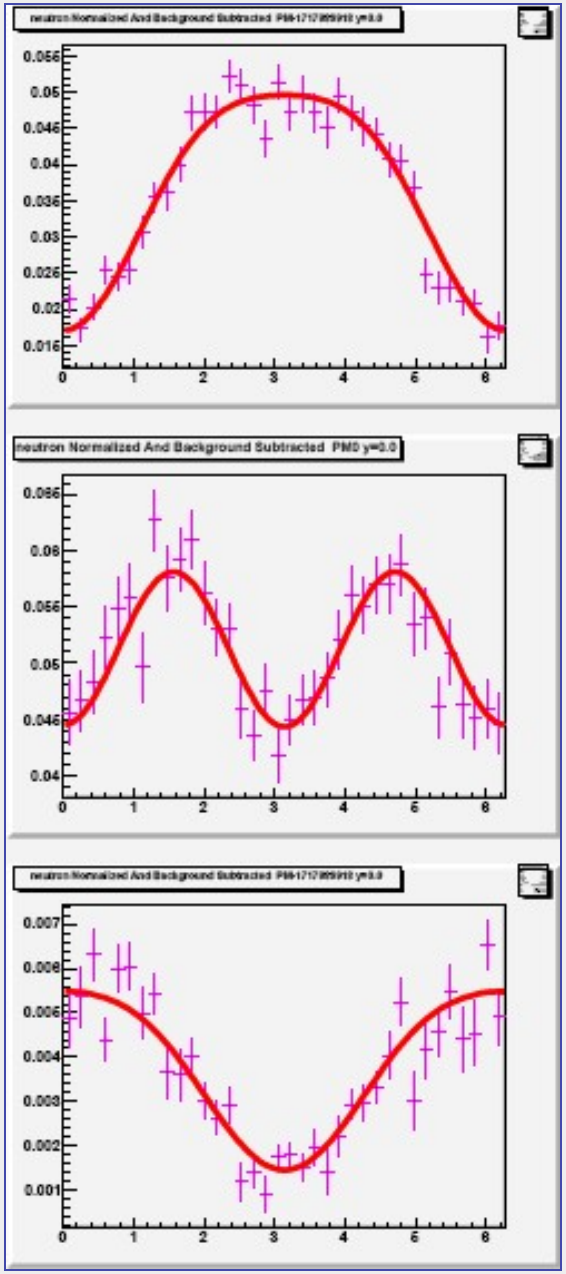
azimuthal angular distributions

relative to the reaction plane
for neutrons, background subtracted

near **target rapidity**
mostly directed flow

at **mid-rapidity**
strong squeeze-out

near **projectile rapidity**
mostly directed flow

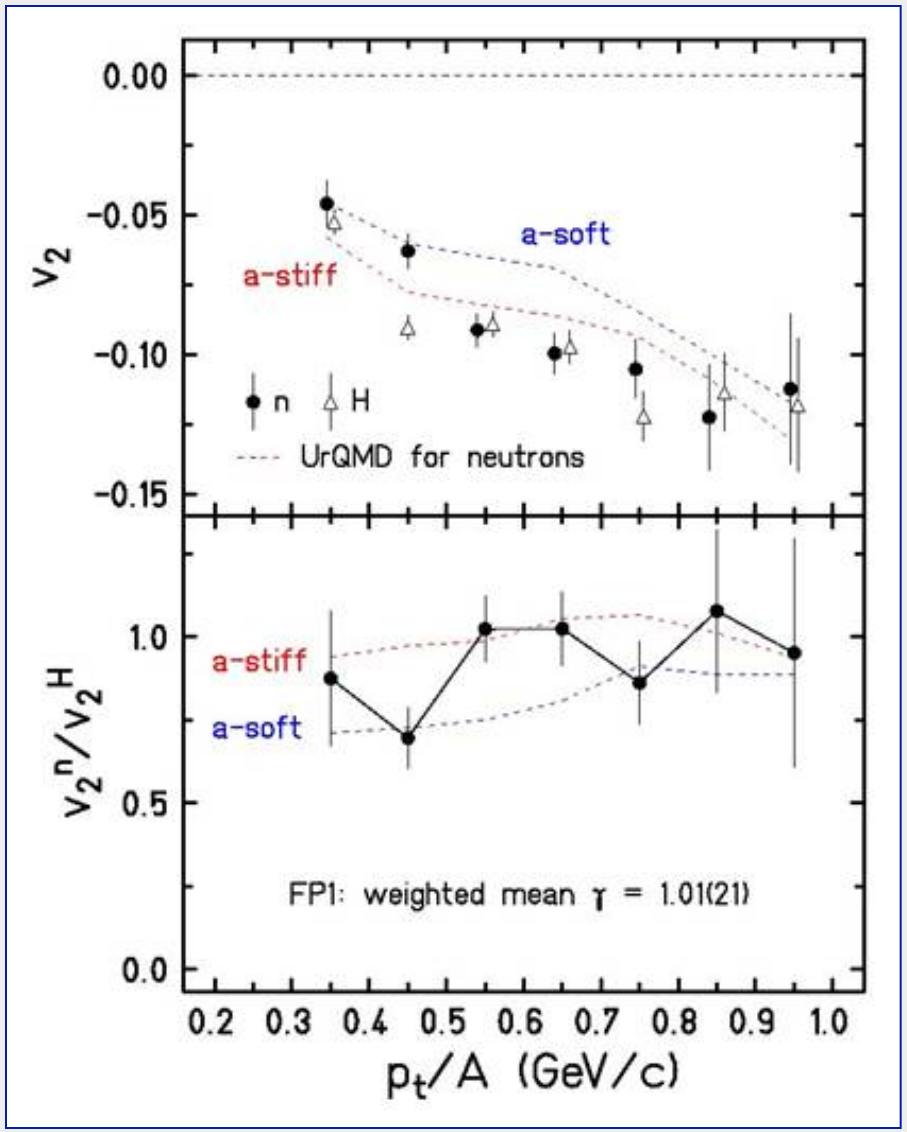


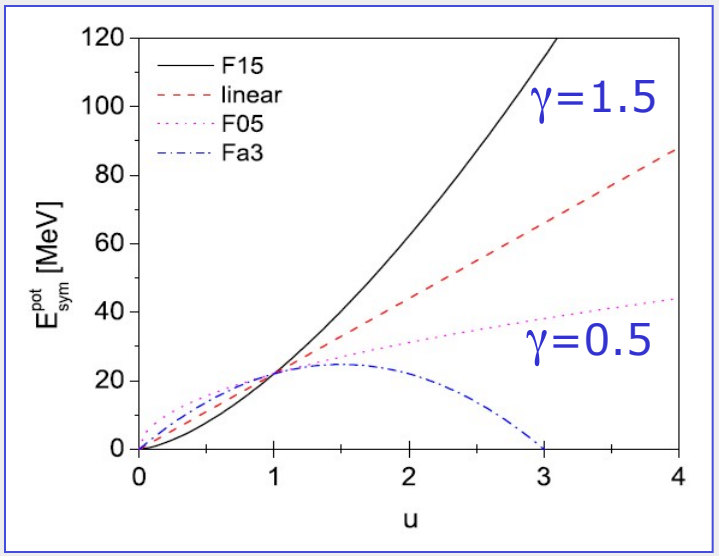
fitted with:
$f(\Delta\varphi)=a_0*(1.0+2\mathbf{v_1}*\cos(\Delta\varphi)+2\mathbf{v_2}*\cos(2\Delta\varphi))$
$\Delta\varphi = \varphi_{particle} - \varphi_{reaction\ plane}$

and compared to **UrQMD** model predictions
UrQMD: Q. Li et al., J. Phys. G 31(2005); 32 (2006)

results from FOPI/LAND experiment

parameters in UrQMD





neutron/hydrogen

FP1: $\gamma = 1.01 \pm 0.21$

FP2: $\gamma = 0.98 \pm 0.35$

neutron/proton

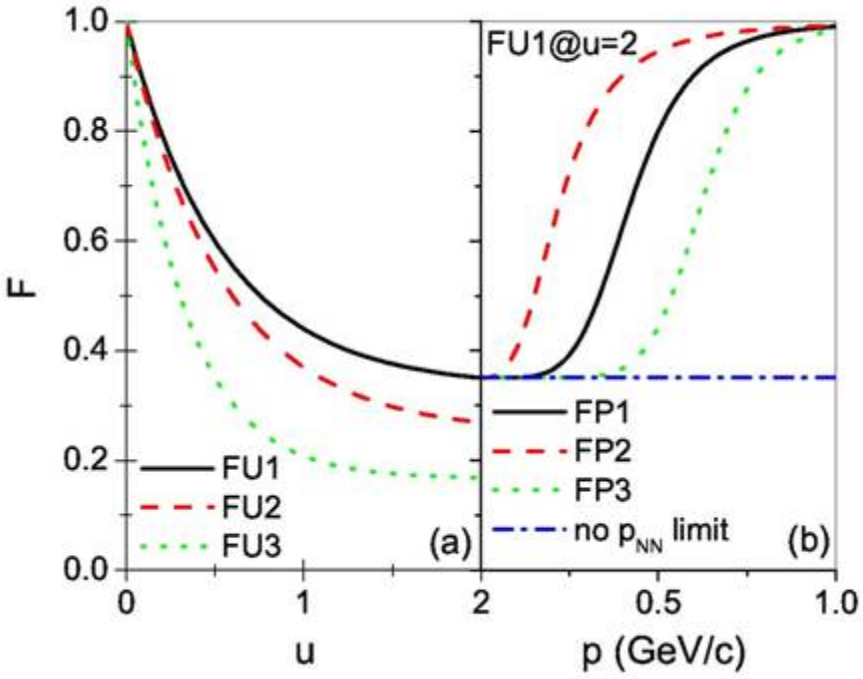
FP1: $\gamma = 0.99 \pm 0.28$

FP2: $\gamma = 0.85 \pm 0.47$

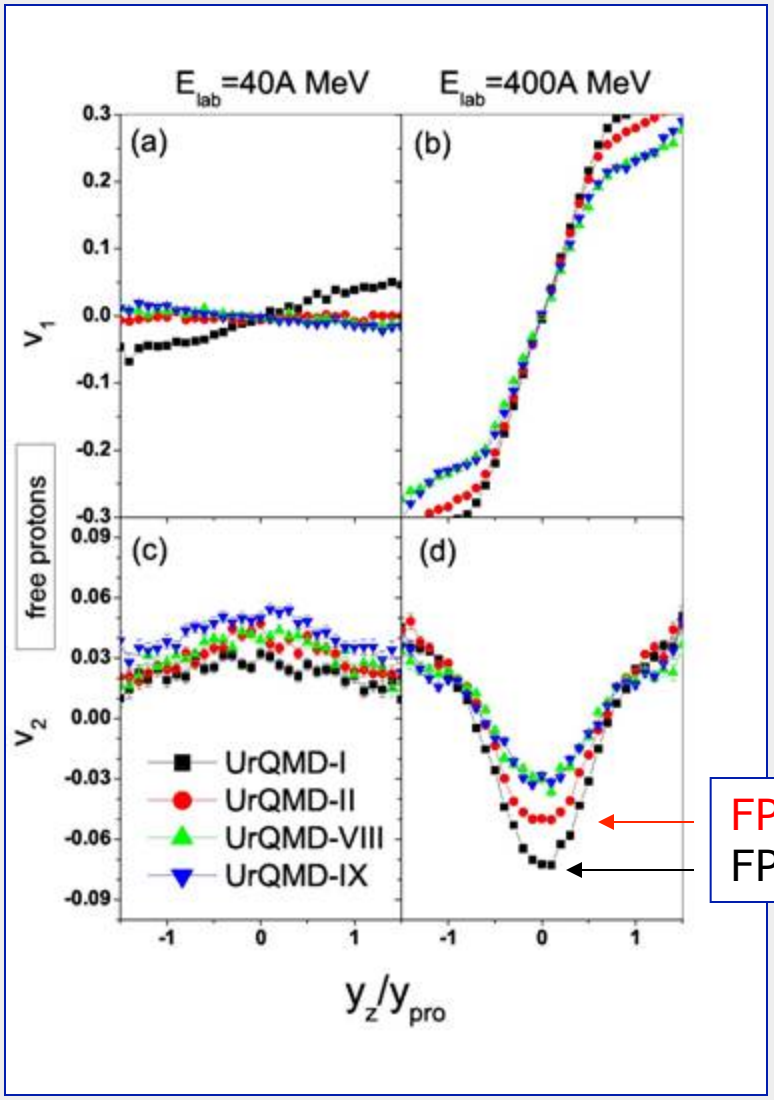
adopted: $\gamma = 0.9 \pm 0.4$

parameterizations in UrQMD

Medium modifications (FU1, …) and momentum dependence (FP1, …) of **nucleon-nucleon elastic Xsects**



Qingfeng Li et al., PRC 83 (2011)

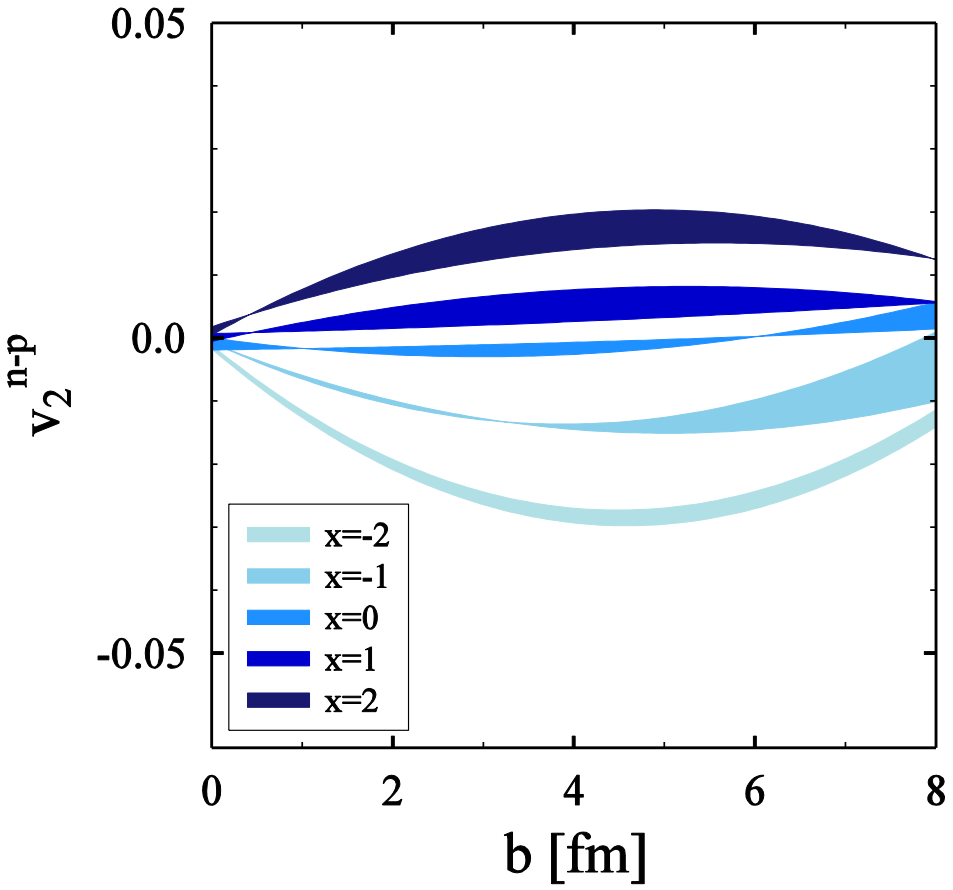


▲ ▼ w/o momentum dep.

new: result obtained with Tübingen QMD*)

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

difference of neutron and proton squeeze-outs
Au + Au @ 400 A MeV



- with FOPI filter
- bands show uncertainty due to isoscalar field "soft to hard"

conclusion in paper:
super-soft not compatible with FOPI-LAND data

tested in UrQMD:
momentum dep. of isoscalar field
momentum dep. of NNECS

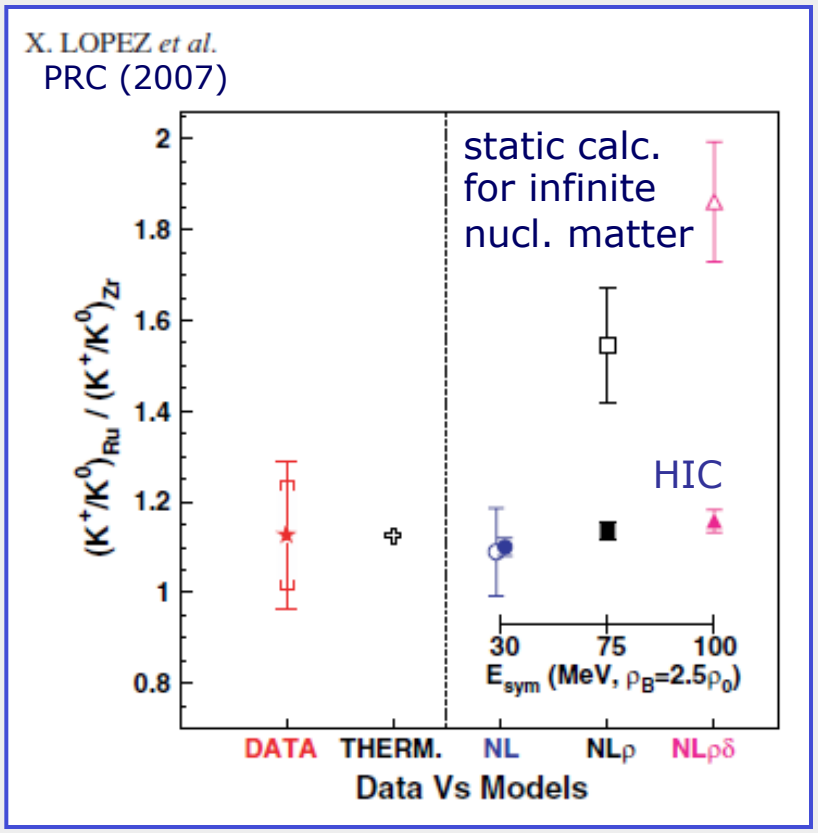
tested in T-QMD:
density dep. of NNECS
asymmetry dep. of NNECS
soft vs. hard EoS
width of wave packets

*) V.S. Uma Maheswari, C. Fuchs, Amand Faessler, L. Sehn, D.S. Kosov, Z. Wang, NPA 628 (1998)

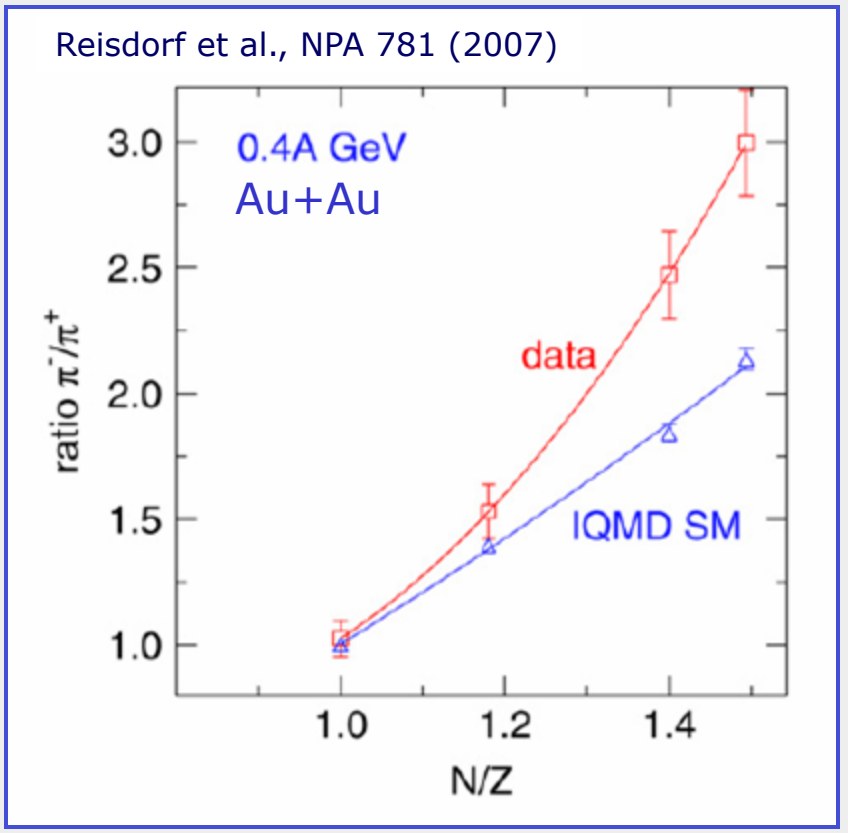
isotopic particle (double) ratios

FOPI data

K^+/K^0 ratio



π^-/π^+ ratio



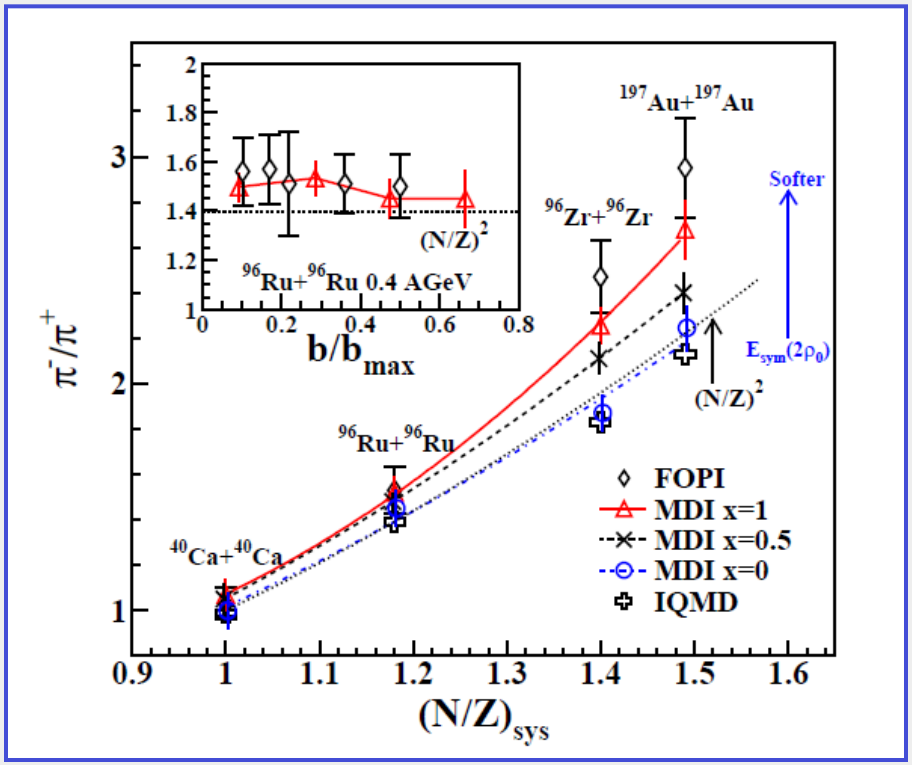
HIC scenario:
fast neutron emission (mean field effect), transformation of neutron into proton in inelastic channels, and NN>NΔ threshold effects (no-chemical equilibrium)

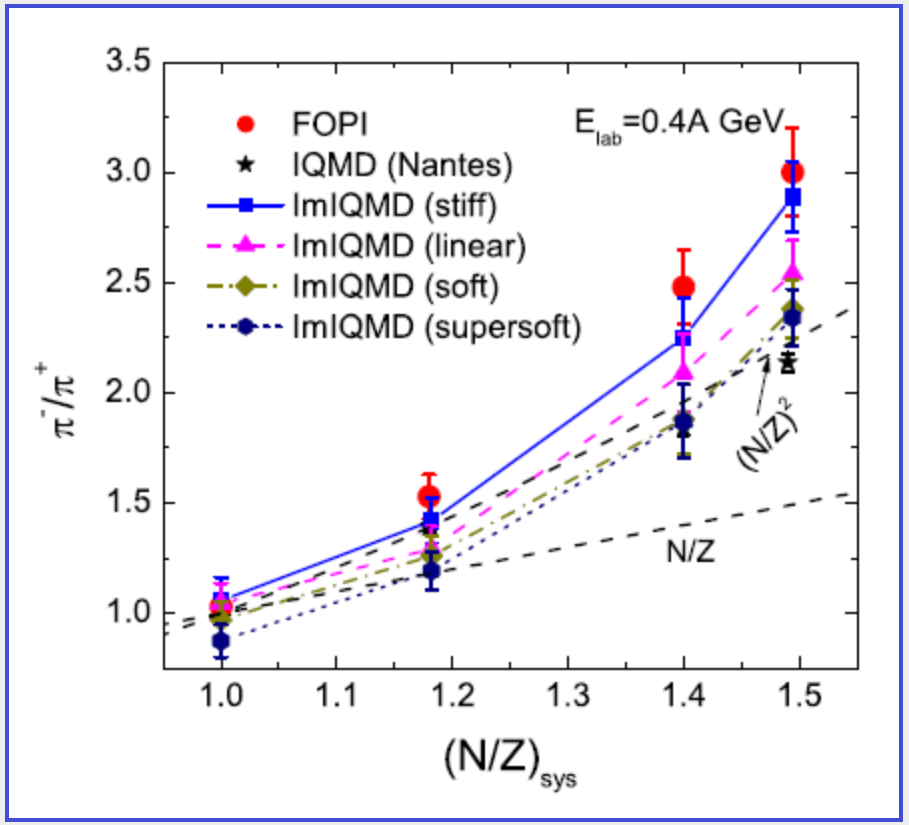
Ferini et al. (RMF)	stiffer for ratio up
Xiao et al. (IBUU)	softer "
Feng & Jin (ImIQMD)	stiffer "

consequence: extremely stiff (soft) solutions

inconsistent results from pion ratios

analysis of π^-/π^+ ratios in Au+Au at 400 A MeV
FOPI data, Reisdorf et al., NPA (2007)





π ratios + IBUU04:
x=1 super soft

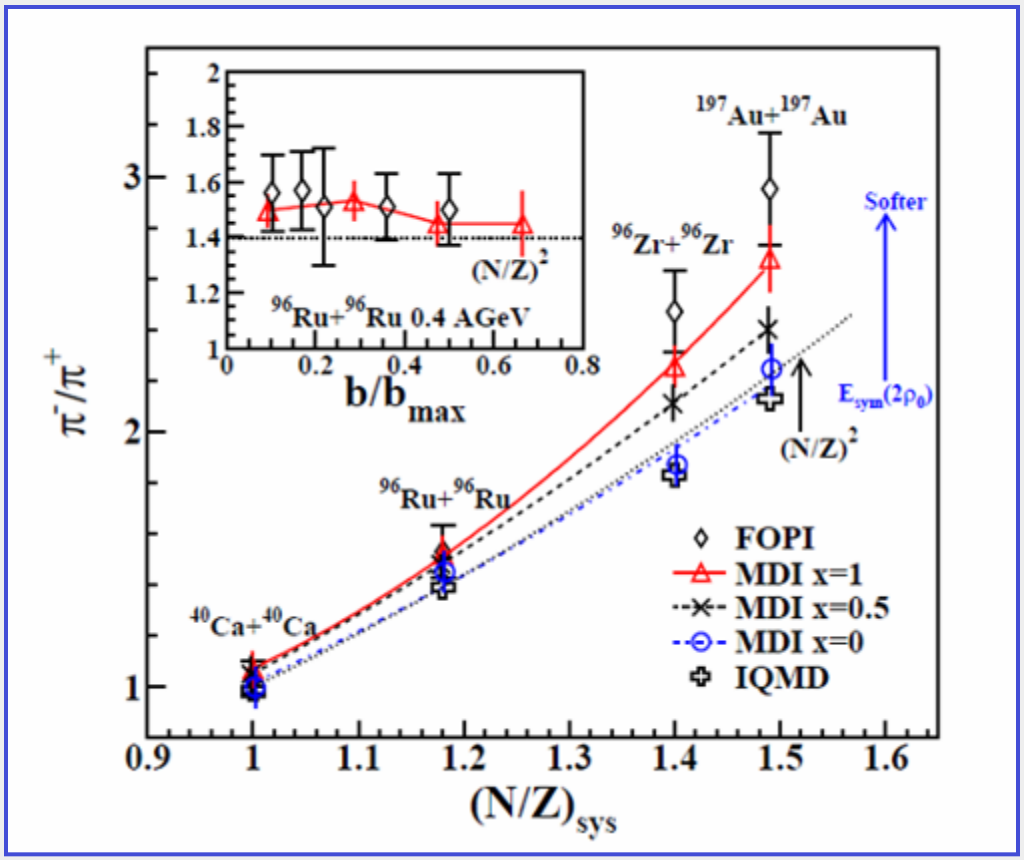
Xiao et al., PRL 102 (2009)

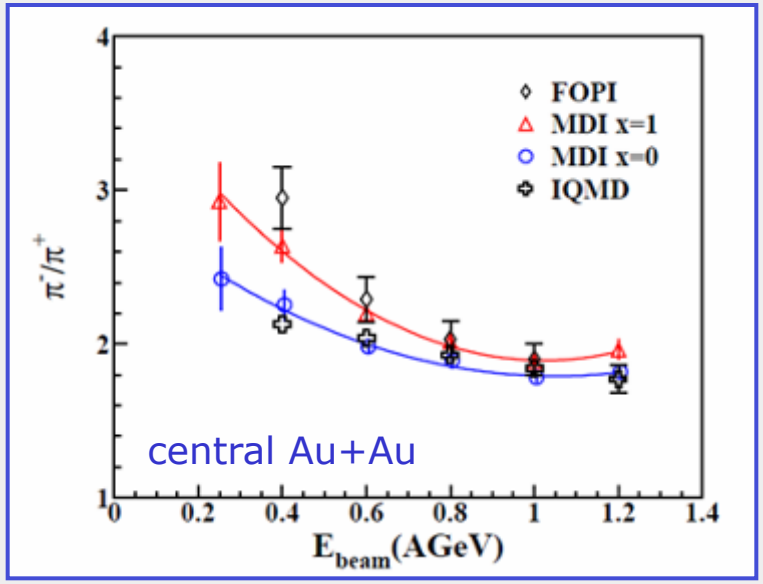
π ratios + ImIQMD:
SLy6 with γ=2 very stiff

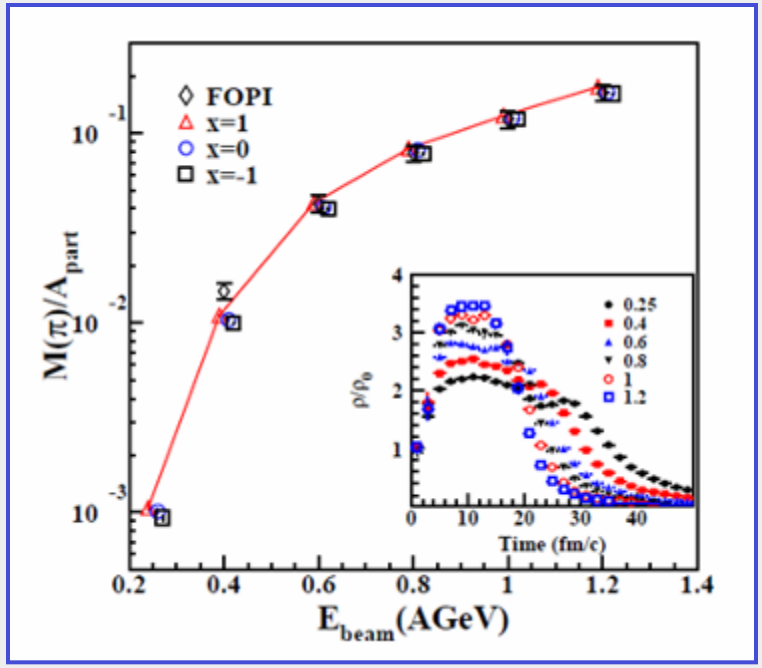
Feng and Jin, PLB 683 (2010)

analysis of π^-/π^+ ratios in Au+Au

Zhigang Xiao et al.
PRL 102, 062502 (2009)
FOPI data of Reisdorf et al.







normalized π multiplicity

outlook

- L ≈ 60 MeV (γ ≈ 0.6) from nuclear structure and reactions probing densities of ≈ 2/3 ρ_0; **big expectations** on PREXII
- increasingly more precise data from **neutron-star** observations, typically L ≈ 40 MeV
- high-densities probed in reactions at SIS energies; analysis of **ASY-EOS** experiment in progress!
- kaon and pion ratios interesting probes but results presently inconclusive: **new activity** at RIKEN (Samurai) and MSU; analysis of HADES kaon data for Ar+KCl and Au+Au
- remarkable progress in theory (3N force in ChEFT)

SAMURAI dipole magnet at RIKEN

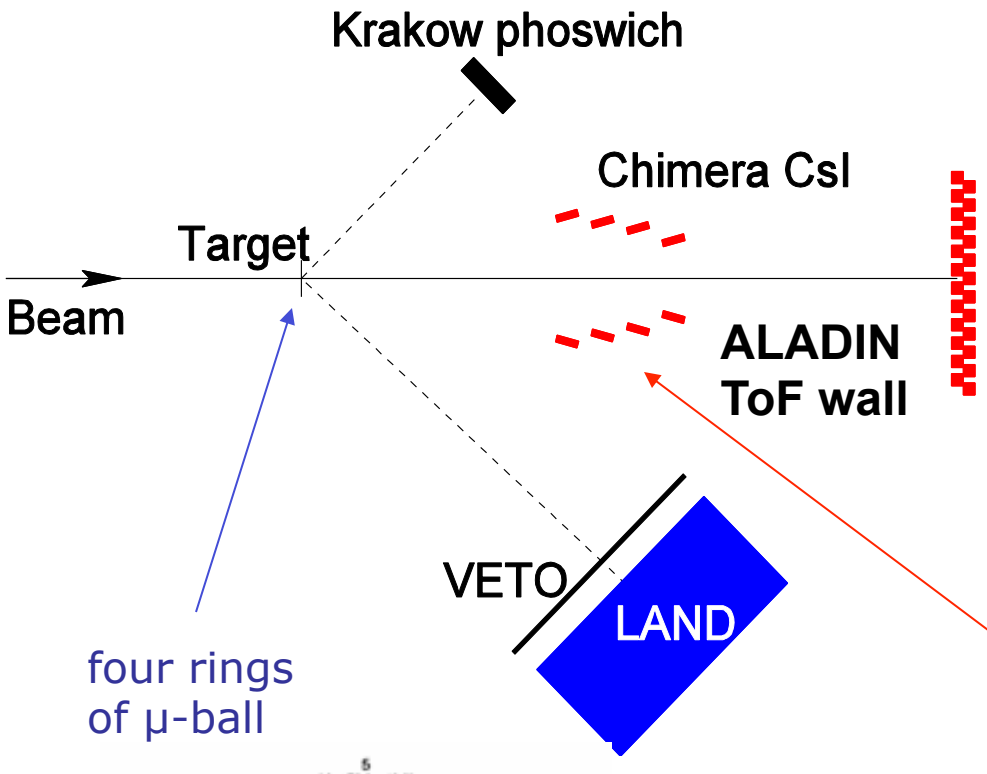
TPC project for SAMURAI
Tsang, Isobe, McIntosh, Murakami et al.

Superconducting **A**nalyzer for **MU**lti-particle from **RA**dio **I**sotope Beam with 7Tm of bending power

RIKEN NISHINA CENTER
RIKEN Nishina Center for Accelerator-Based Science
NSCL
KYOTO UNIVERSITY FOUNDED 1897 KYOTO JAPAN
WESTERN MICHIGAN UNIVERSITY
TEXAS A&M UNIVERSITY

Piotr Pawłowski

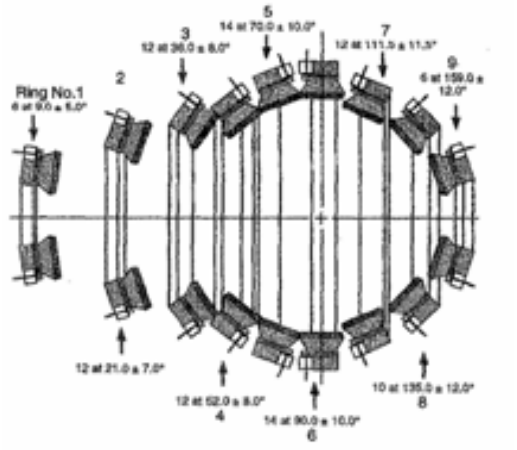
AsyEos experiment S394 in May 2011

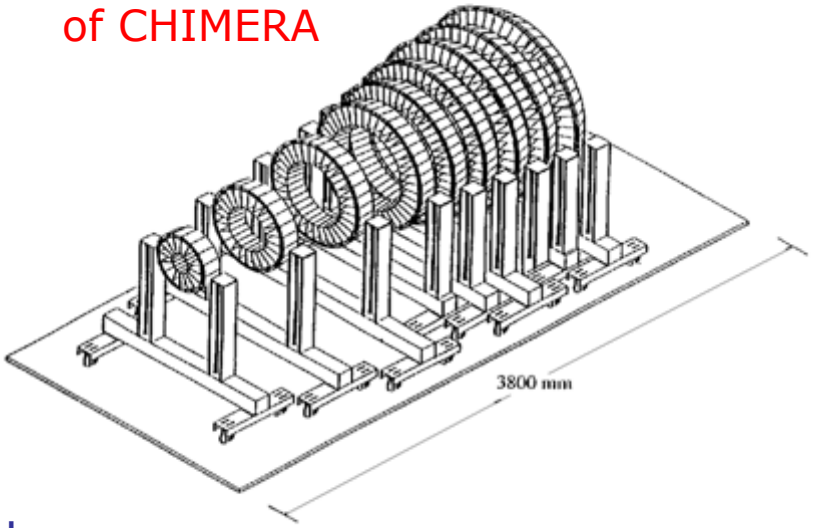


four rings
of μ-ball

studied reactions:
^{197}Au + ^{197}Au @ 400 A MeV
^{96}Ru + ^{96}Ru @ 400 A MeV
^{96}Zr + ^{96}Zr @ 400 A MeV

four double rings
of CHIMERA





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

The Asy-Eos Collaboration

authors of proposal 2009

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]

L vs. S_0

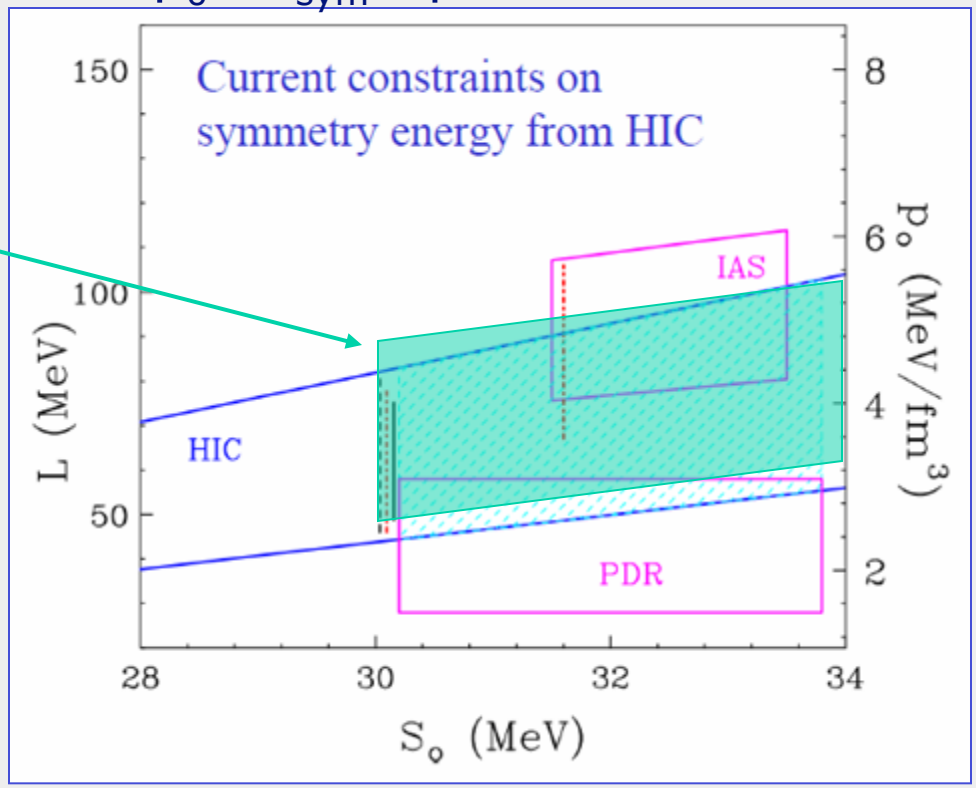
IAS isobaric analog states
Danielewicz/Lee 2008

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

PDR pygmy dipole resonance
Klimkiewicz et al. 2007

$L=3\rho_0 \cdot \partial E_{sym}/\partial \rho$

from elliptic n/p flow



symmetry pressure $P_0=(L/3)\rho_0$

$S_0=E_{sym}(\rho_0)$

from M.B. Tsang et al., PRL 102, 122701 (2009)
vertical lines: analyses with ImQMD (Zhang et al.)
and IBUU04 (Li and Chen)