Elliptic flow and the symmetry energy at supra-saturation density

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Astrophysics and Nuclear Structure

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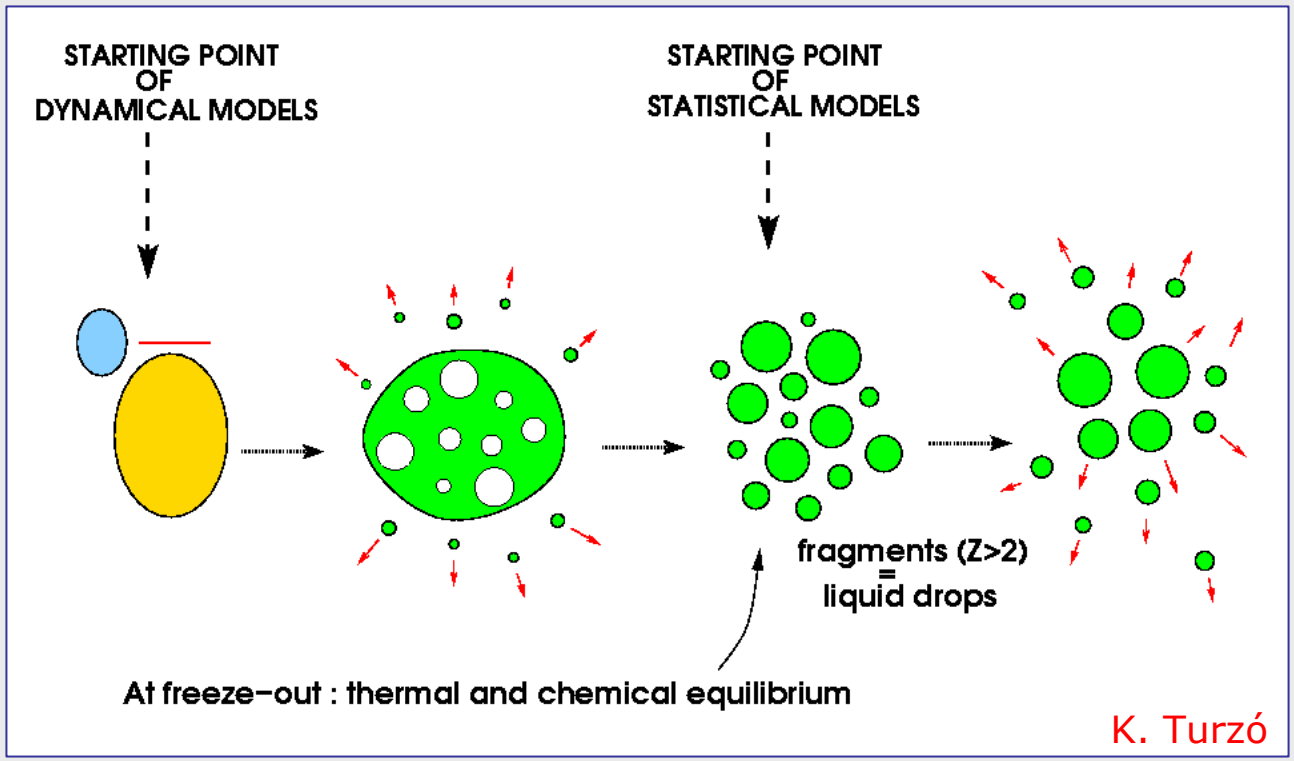
Catania: Angelo Pagano, Paolo Russotto PLB 697 (2011)
FIAS/Houchou (China): Qingfeng Li
GSI: Yvonne Leifels, Maja Zoric (Zagreb)
Kraków: Jerzy Łukasik, Piotr Pawłowski
Liverpool: Marielle Chartier, Roy Lemmon, Pete Wu
München: Hermann Wolter review in IJMPE 21 (2012)

the multifragmentation scenario



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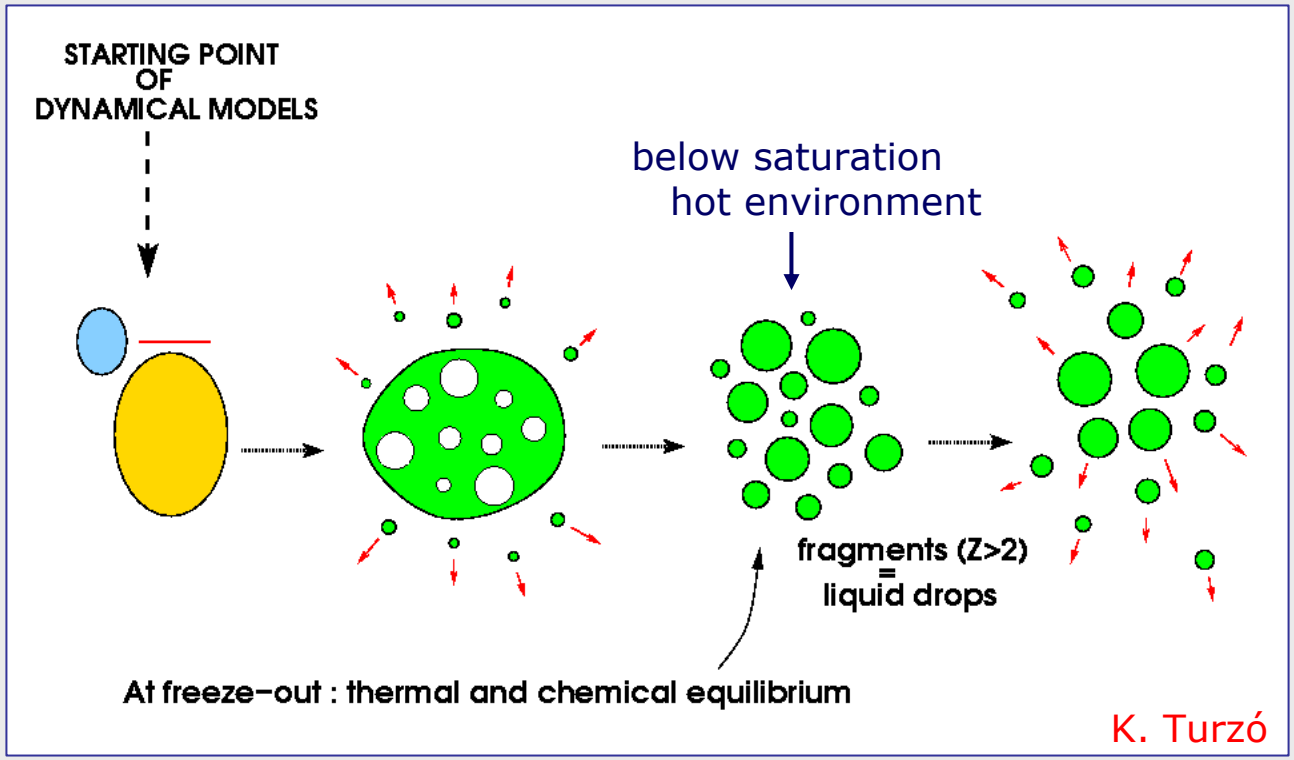
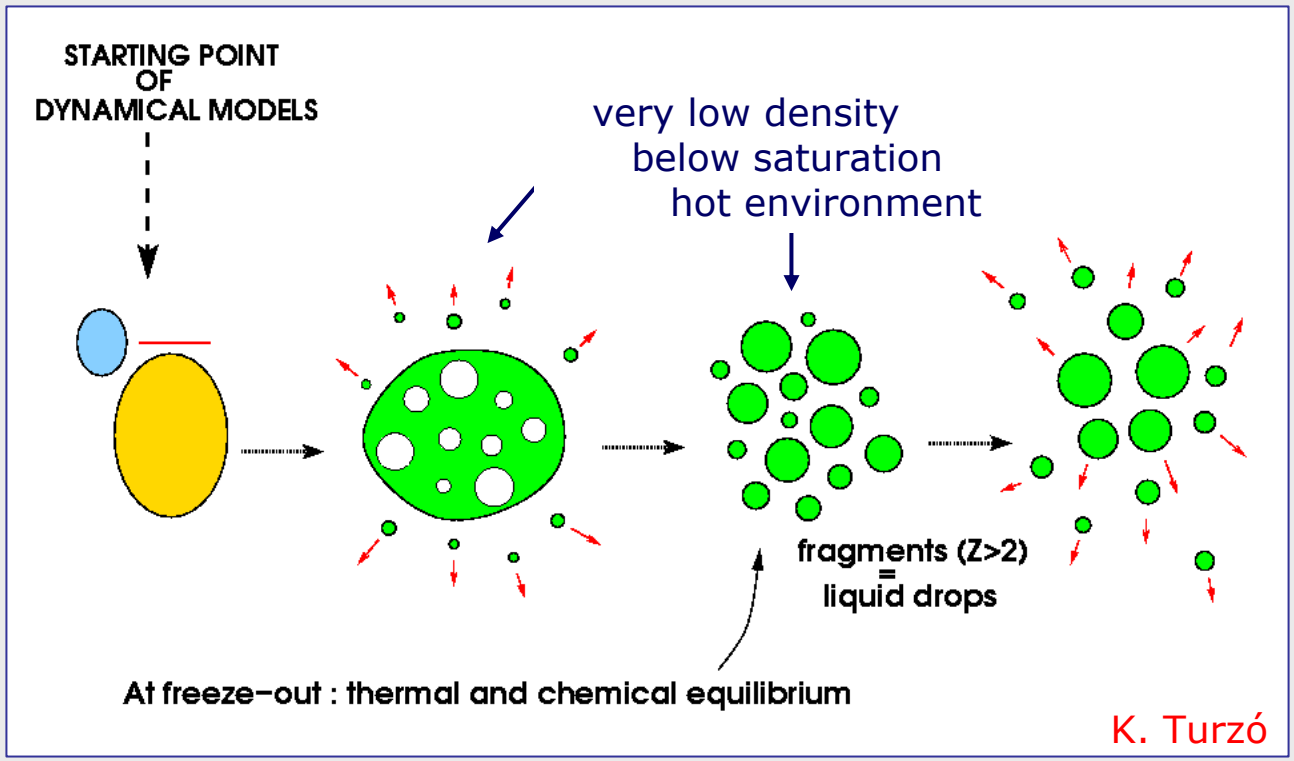


ALADIN/GSI:
modified properties;
reduced E_{sym} in liquid-drop description of fragments

the multifragmentation scenario



Texas A&M:
PRL104 (2010)
$E_{sym} \approx 8$ MeV
at $\rho \approx 0.02\ \rho_0$
theory:
Typel, Röpke et al.

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modified properties;
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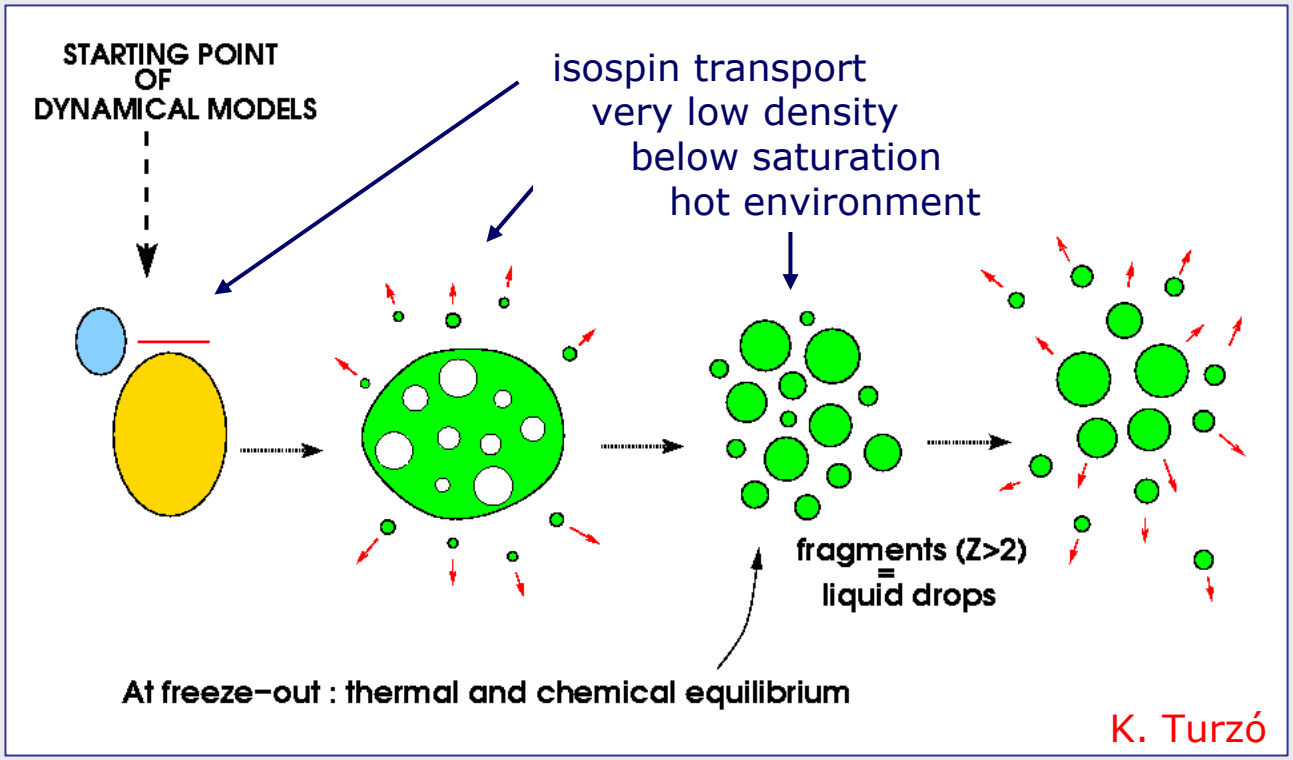

MSU/Catania:
$\gamma \approx 0.7$
$L \approx 70$ MeV
continued at Riken with higher incident energies

Texas A&M:
PRL104 (2010)
$E_{sym} \approx 8$ MeV
at $\rho \approx 0.02\ \rho_0$
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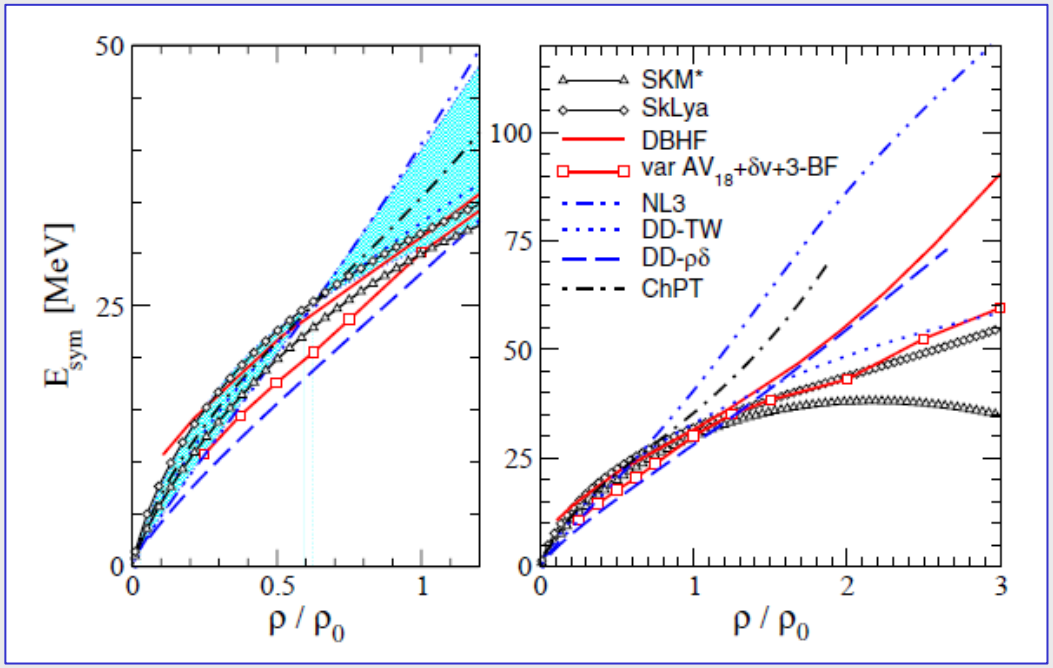
the symmetry energy

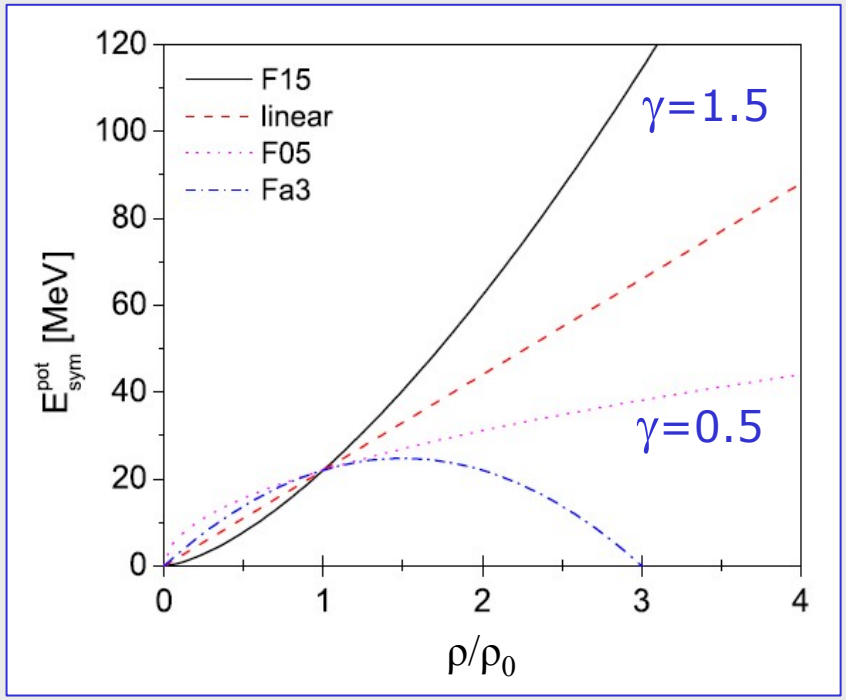
$E_A(\rho,\delta) = E_A(\rho,0) + \mathbf{E_{sym}(\rho)} \cdot \delta^2 + O(\delta^4)$

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

parameterization
in transport theory: UrQMD, Q.F. Li et al.



Fuchs and Wolter, EPJA 30 (2006)



γ	L (MeV)
0.5	57
1.0	90
1.5	123

$E_{sym} = E_{sym}^{pot} + E_{sym}^{kin}$

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

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

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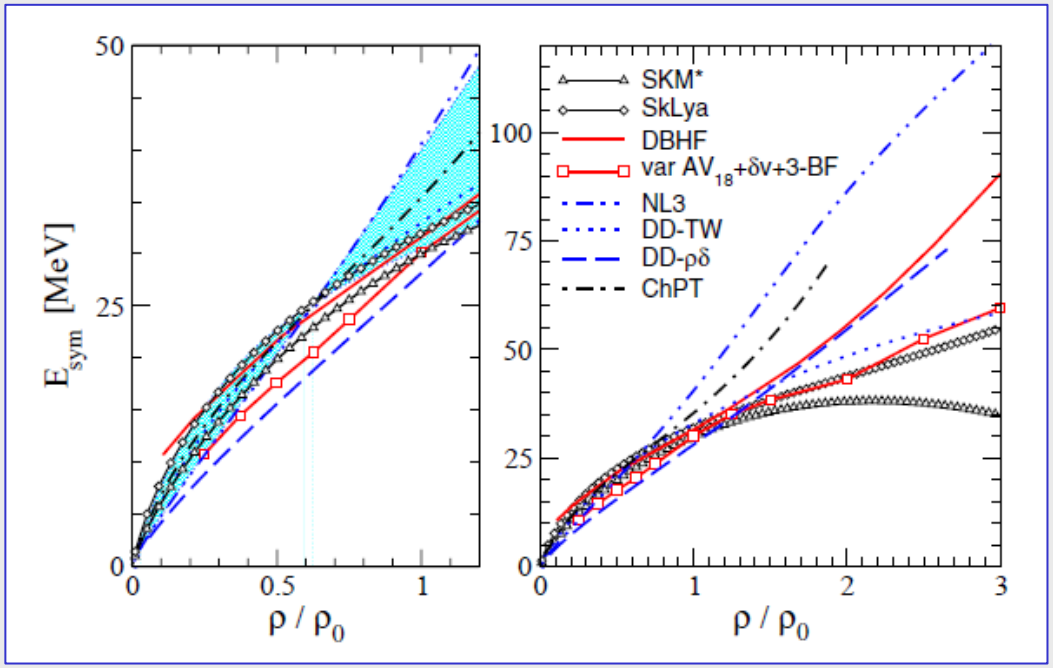

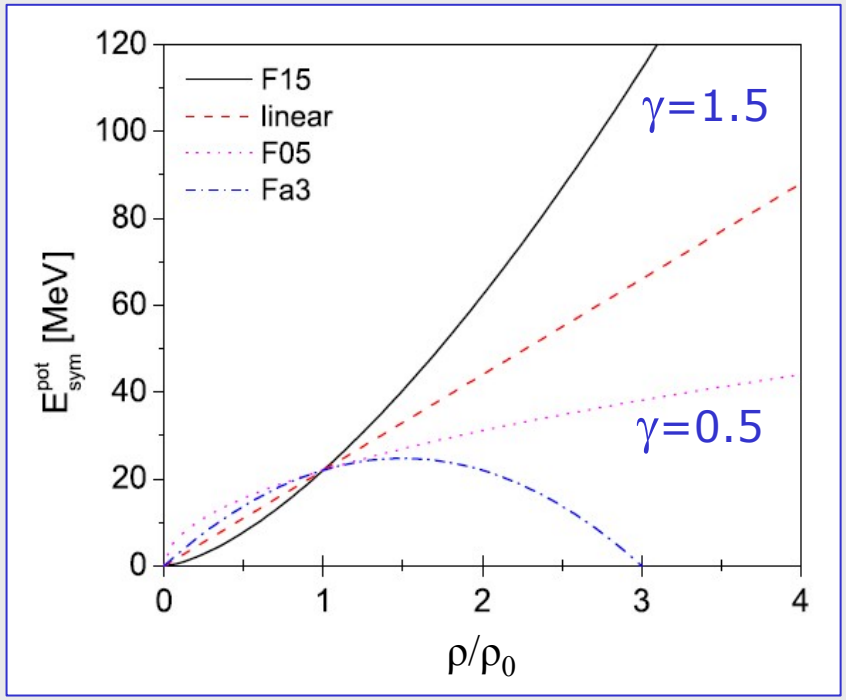

Fuchs and Wolter, EPJA 30 (2006)

γ	L (MeV)
0.5	57
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L = 66.5 MeV, I. Vidaña et al. PRC80 (2009)
BHF with Argonne V18 plus Urbana phenom. 3BF

L = 45±10 MeV, Hebeler & Schwenk, PRC82 (2010)
EFT with chiral three-nucleon forces ($\rho \le \rho_0$)

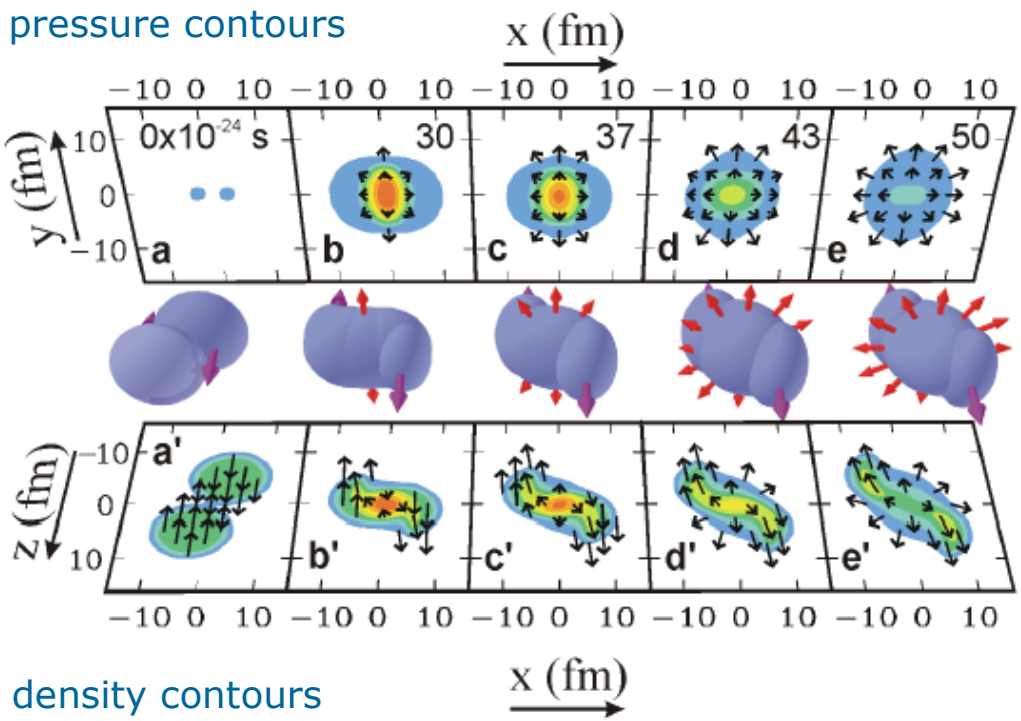
supra-saturation density

remember: symmetric matter

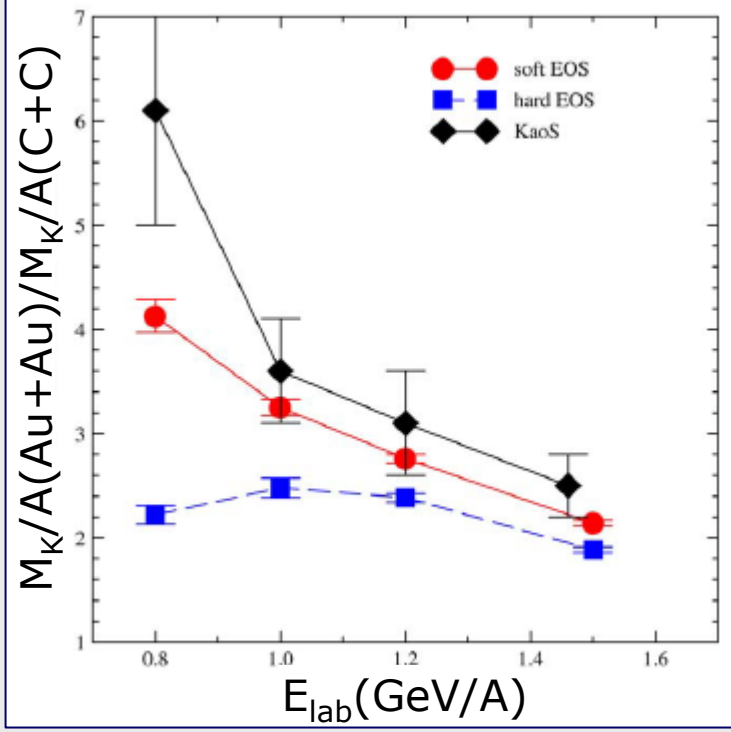
KAOS data (GSI)
K^+ double ratios
Au+Au vs. C+C
normalized to $\langle A_{part} \rangle$ ...

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)

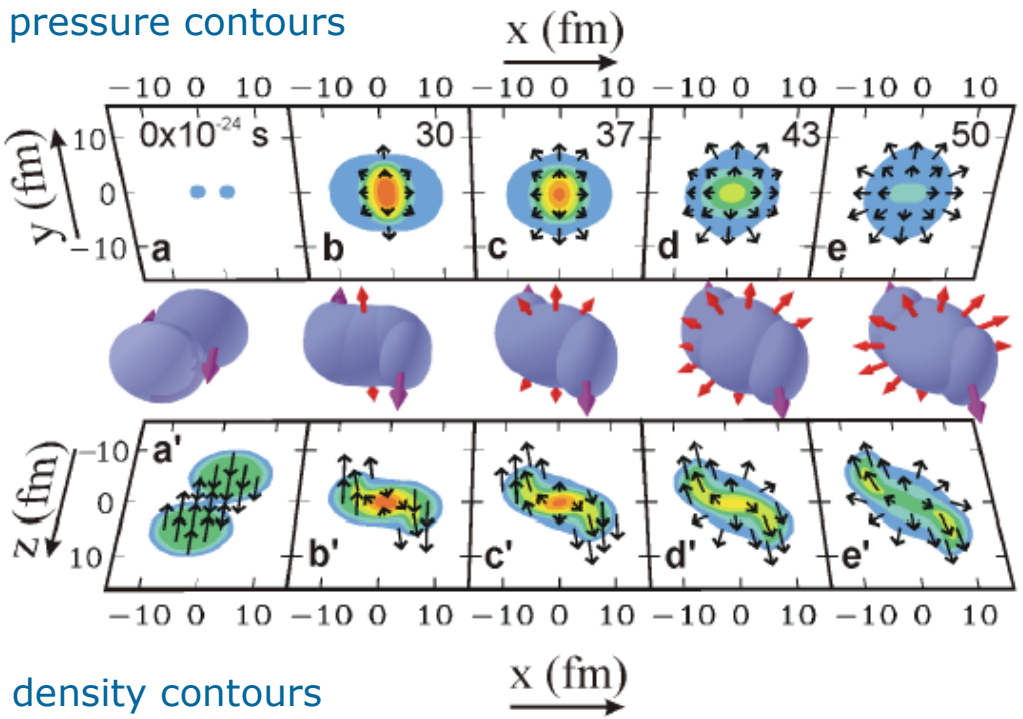
Sturm et al., Fuchs et al., PRL 86 (2001)

supra-saturation density

remember: symmetric matter

1 A GeV Au+Au

pressure contours



density contours

asymmetric matter
(need differential observables)

pre-summary

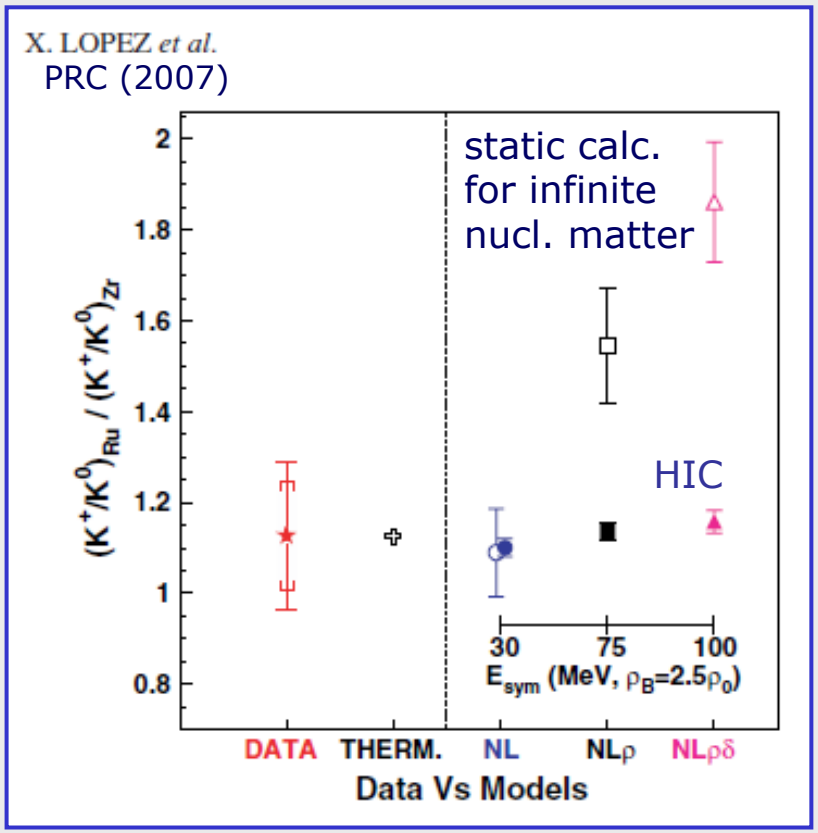
- the **differential elliptic flow** in neutron-rich systems emerges as an observable sensitive to the strength of the symmetry energy at supra-saturation densities.
- kaon and pion ratios interesting probes but results presently inconclusive.

Danielewicz et al., Science 298 (2002)

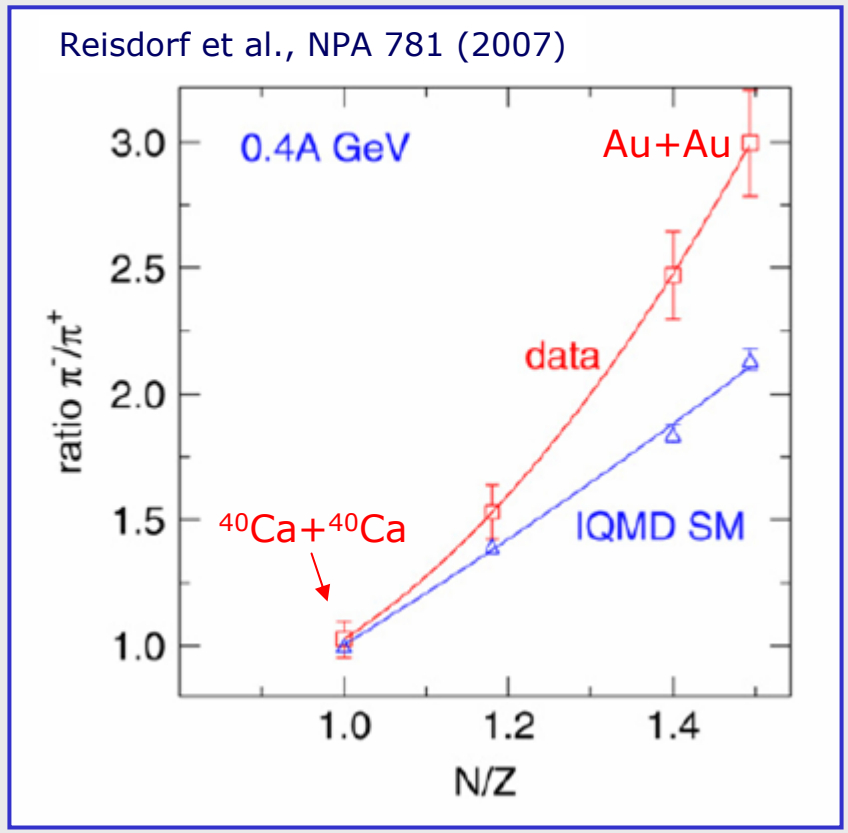
isotopic particle (double) ratios

FOPI data

K^+/K^0 ratio



π^-/π^+ ratio



HIC scenario:
- fast neutron emission (mean field)
- NN=>NΔ threshold effects
  no chemical equilibrium

see, e,g, di Toro et al., J.Phys.G (2010)

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

consequence: extremely stiff (soft) solutions

elliptic flow

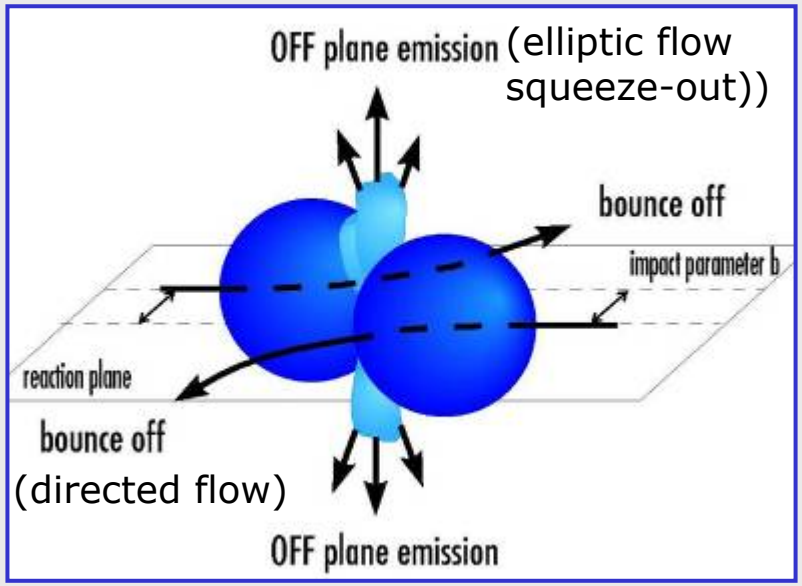
differential: neutrons vs. protons
t vs. ^{3}He, ^{7}Li vs ^{7}Be, ...
(Bao-An Li PRL (2000) and subsequent work)

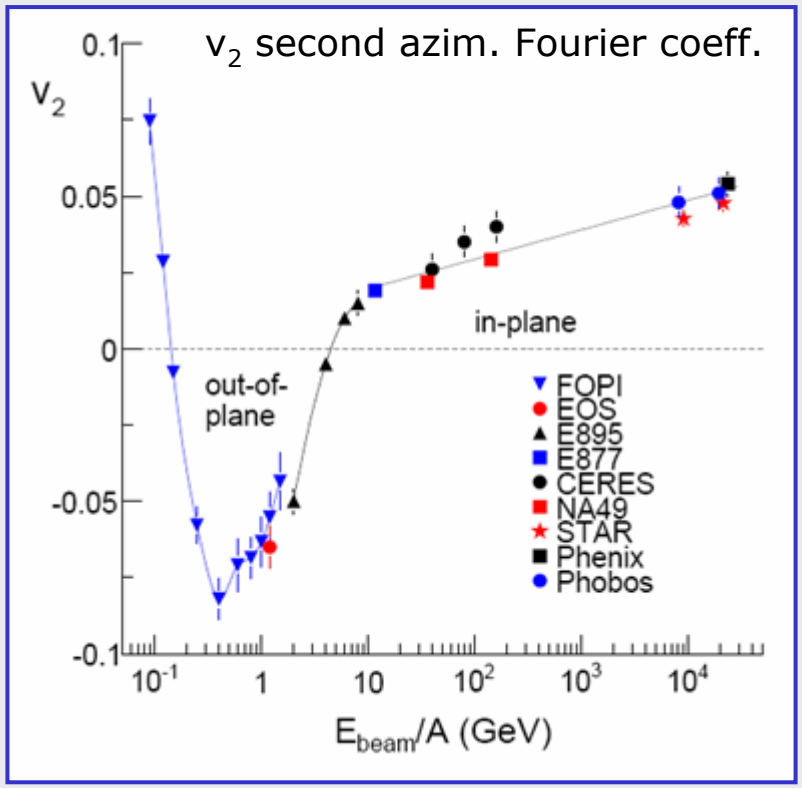
UrQMD: significant sensitivity predicted;
neutron vs. proton elliptic flows inverted
(Qingfeng Li and Paolo Russotto)

reanalysis of FOPI-LAND data
Au+Au @ 400 MeV per nucleon:
$\gamma_{pot} = 0.9 \pm 0.4$

Russotto, Wu, Zoric, Chartier, Leifels, Lemmon, Li, Łukasik, Pagano, Pawłowski, Trautmann, PLB 697 (2011) 471

Trautmann and Wolter, review in IJMPE 21 (2012)





the symmetry energy

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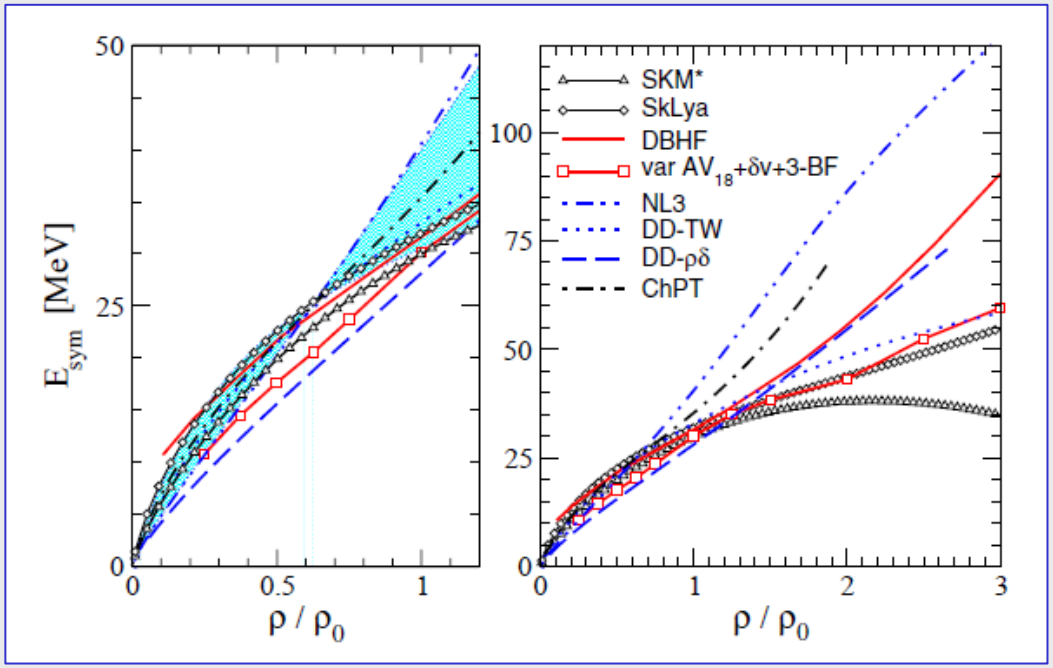
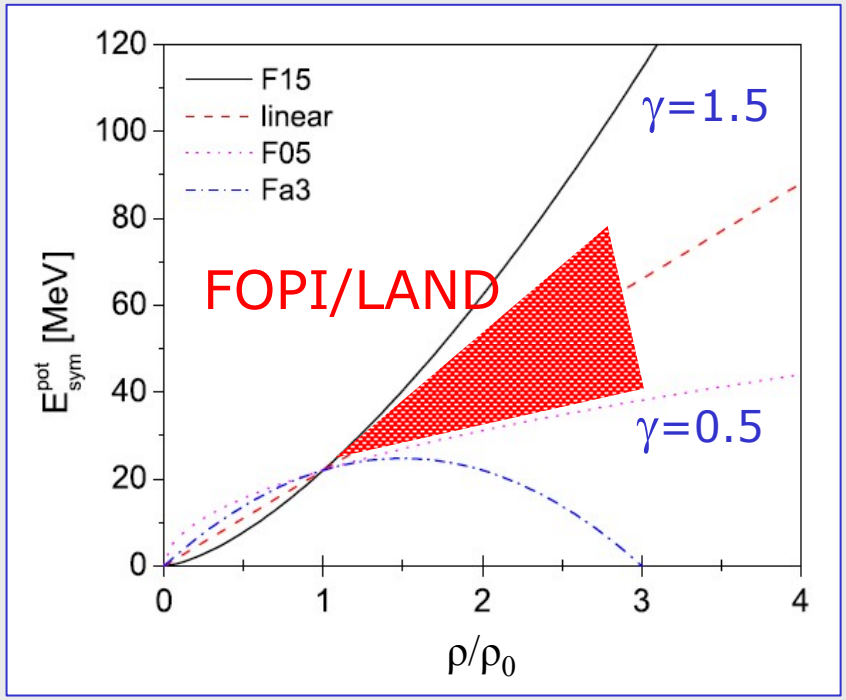


Fuchs and Wolter, EPJA 30 (2006)

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



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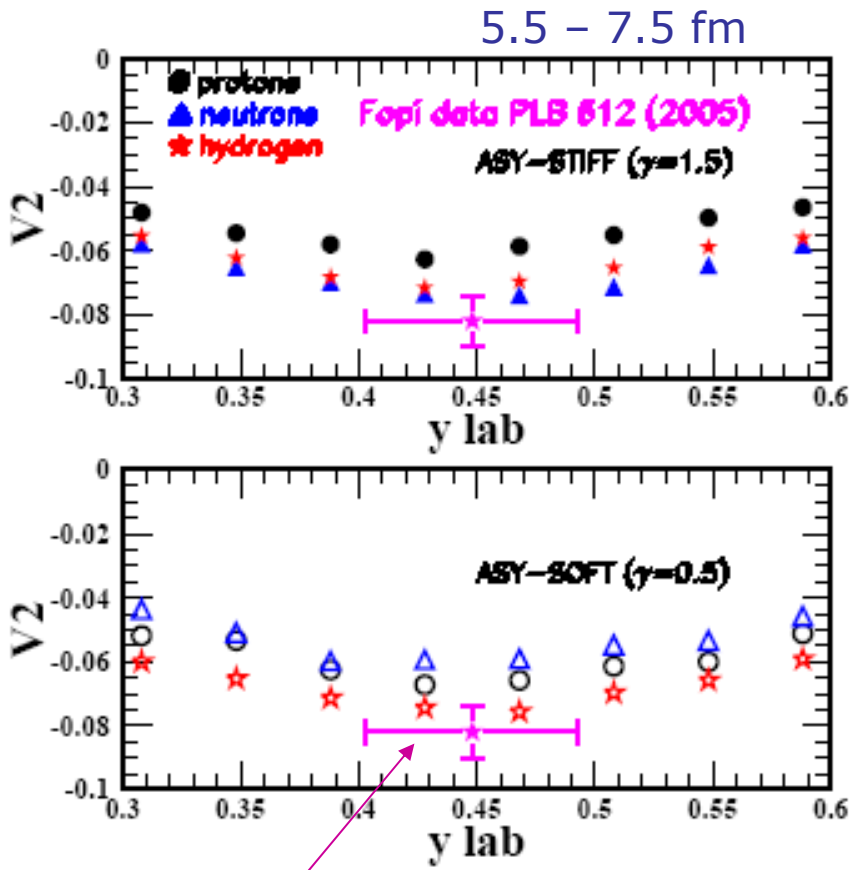
$L = 3\rho_o \cdot dE_{sym}/d\rho$ at $\rho = \rho_0$

$L \approx 80$ MeV

sensitivity of elliptic flow: UrQMD predictions

(Qingfeng Li and Paolo Russotto)



stiff

soft

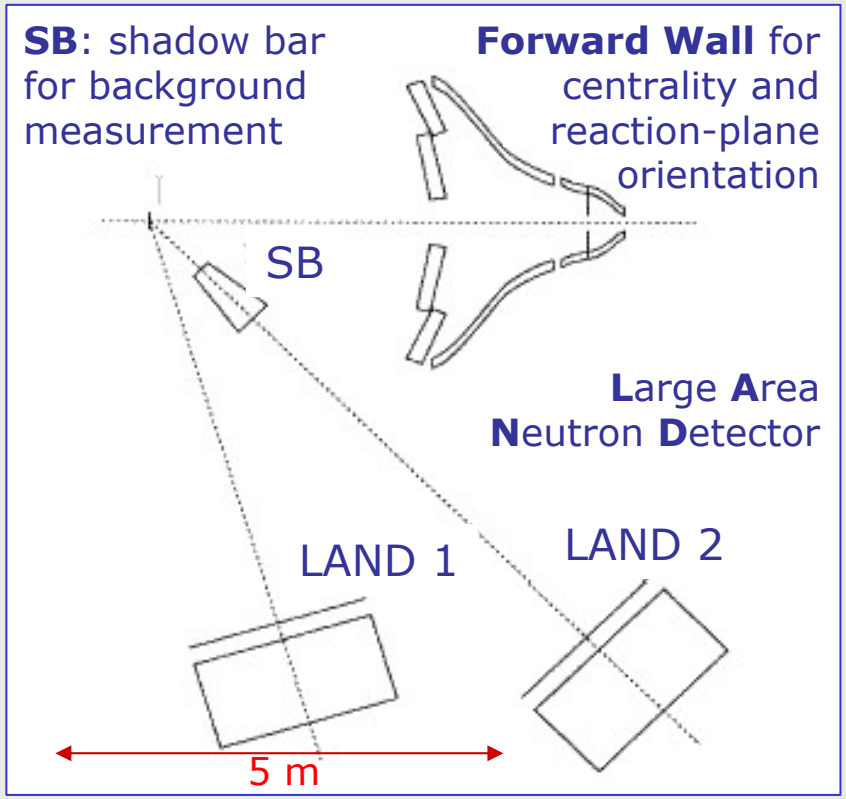
Au+Au @ 400 A MeV

inversion of neutron and hydrogen flows

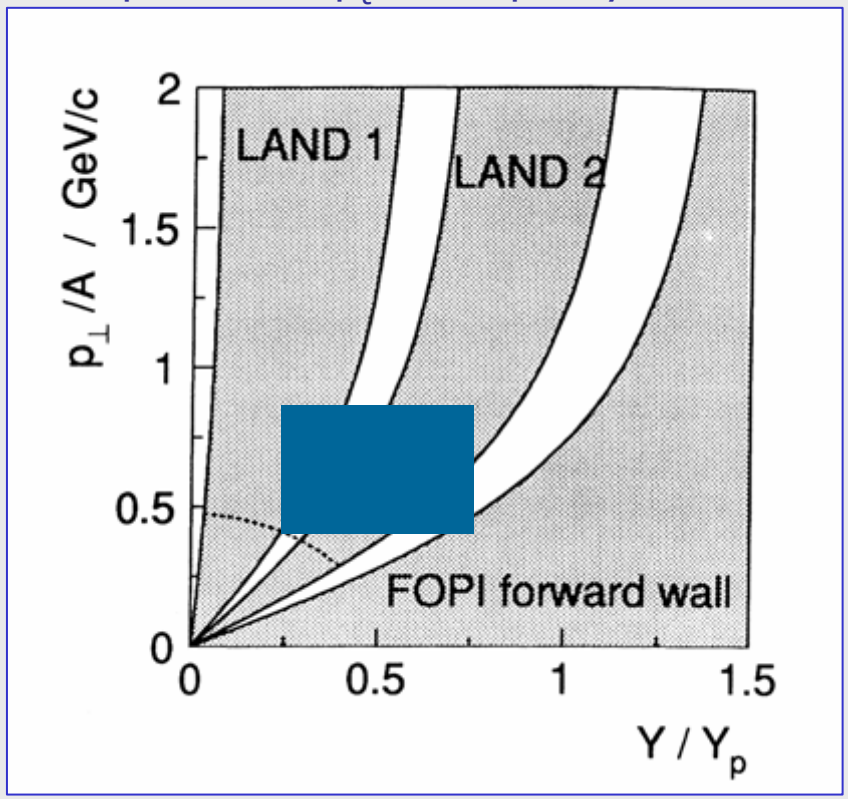
neutron |v2| is larger in the stiff case

FOPI result for Z=1

FOPI/LAND experiment



acceptance in p_t vs. rapidity



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

main yield here

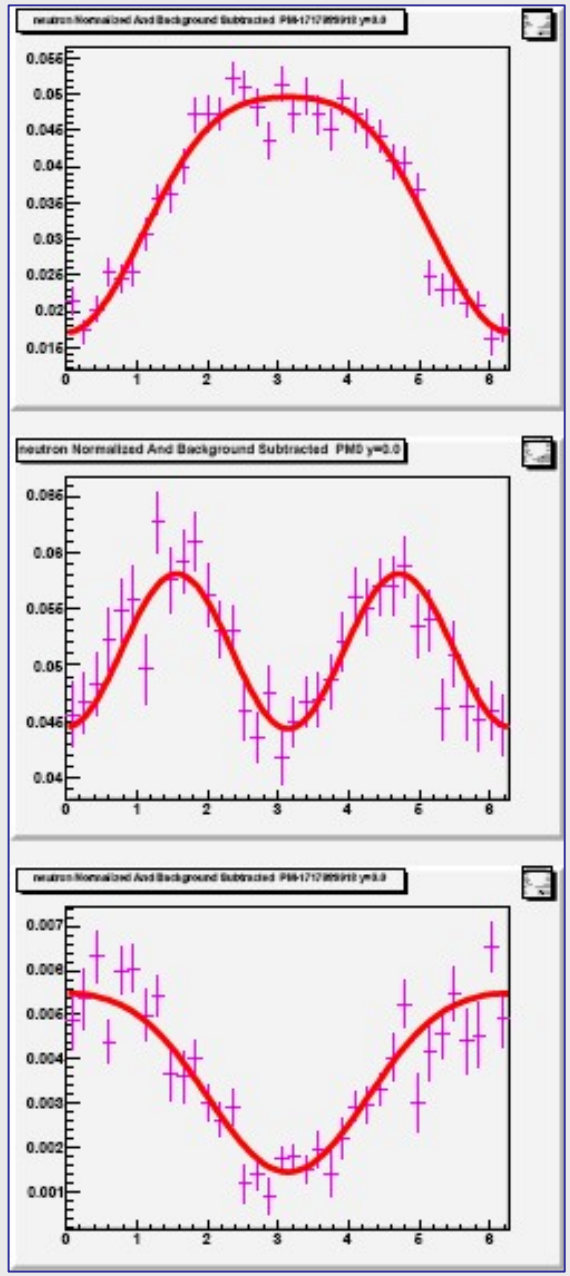
azimuthal angular distributions

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

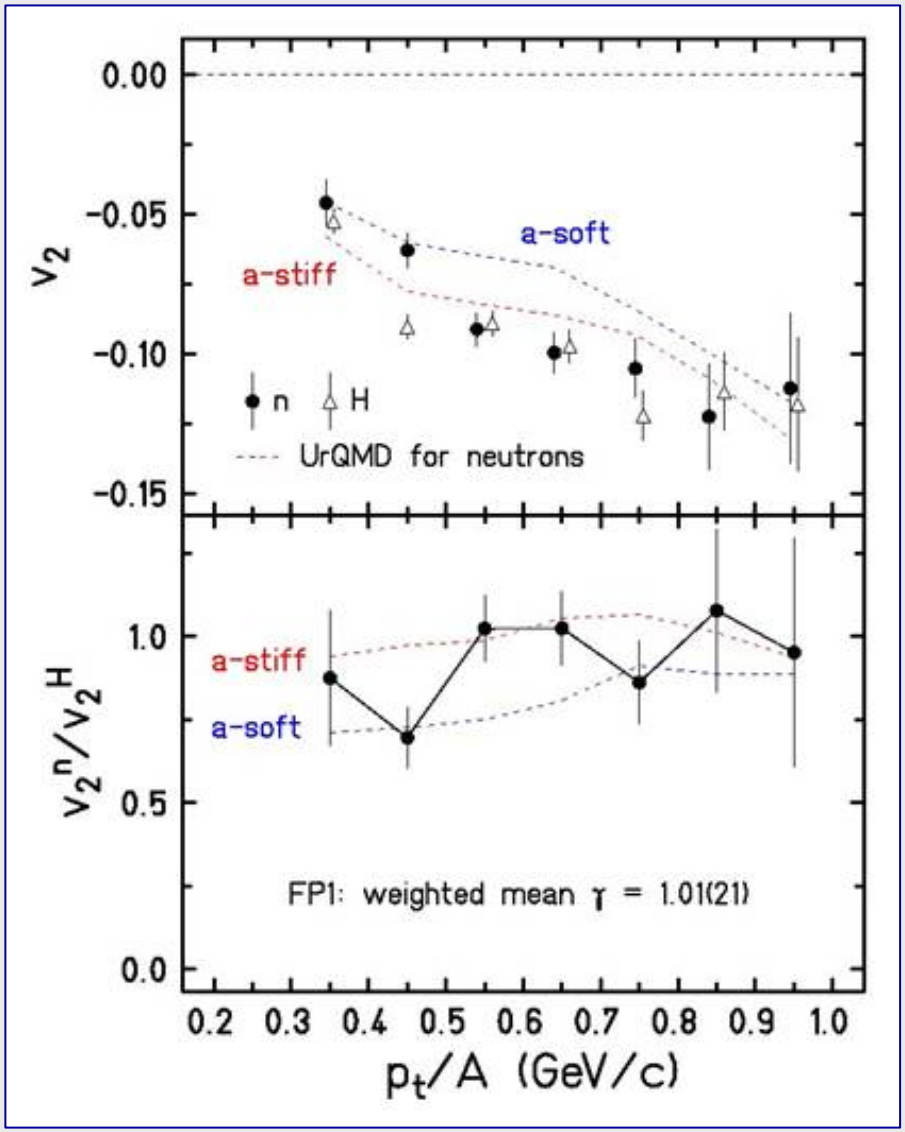


0 Δφ 2π

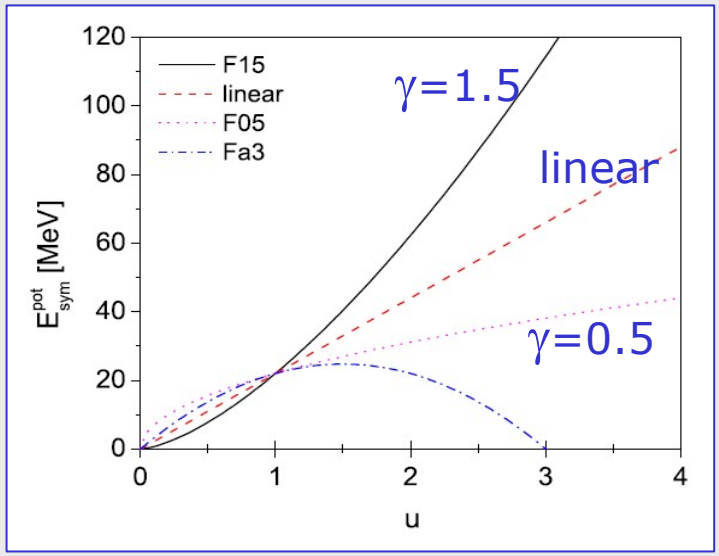
fitted with:
$f(\Delta\varphi)=a_0*(1.0+2\mathbf{v_1}*\cos(\Delta\varphi)+2\mathbf{v_2}*\cos(2\Delta\varphi))$
$\Delta\varphi = \varphi_{particle} - \varphi_{reaction\ plane}$

and compared to **UrQMD** model predictions
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

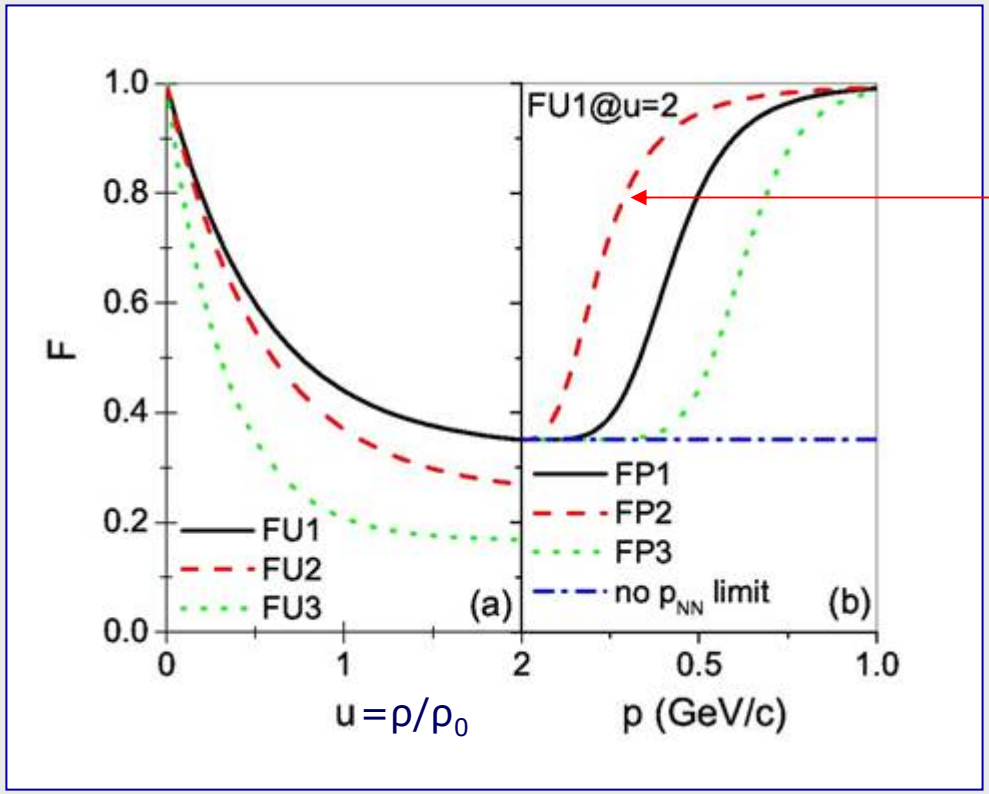
FP1: $\gamma = 0.99 \pm 0.28$

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 Xsections**



v_2 40% larger with FP2

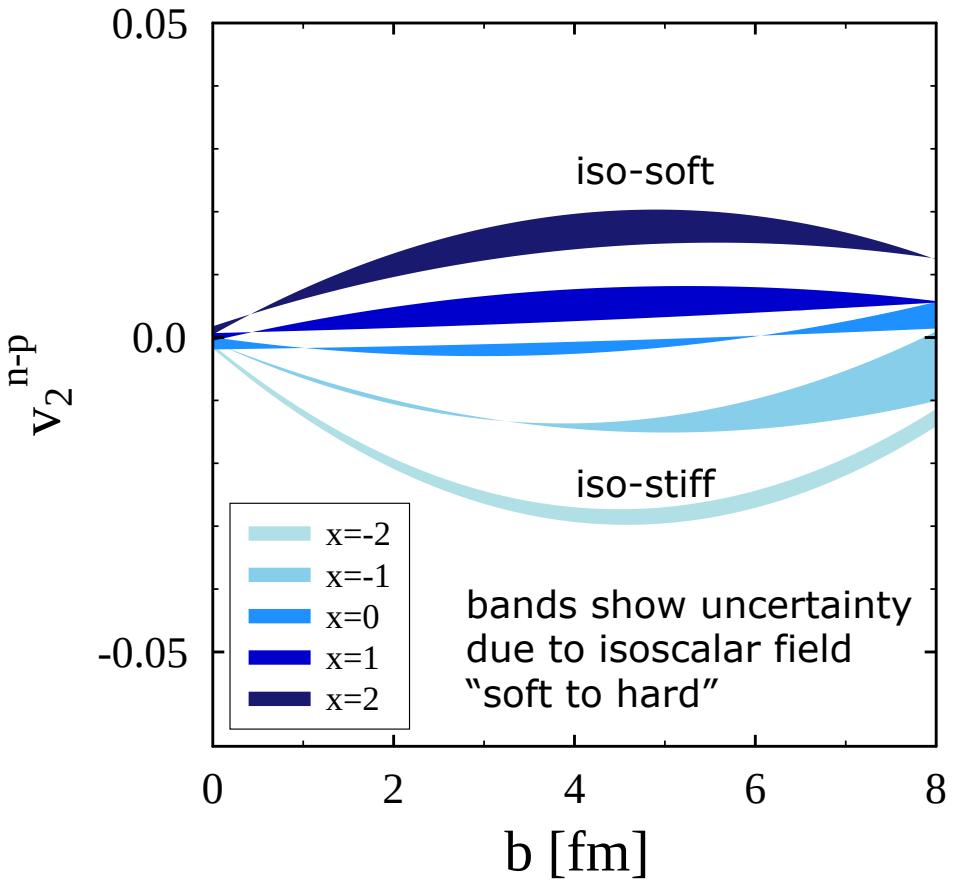
small effect on ratios

Qingfeng Li et al., Mod. Phys. Lett. A 9 (2010)

parameter test with Tübingen QMD*)

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

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



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

first steps towards
model invariance:

tested in UrQMD:
FP1 vs. FP2,
i.e. momentum dep. of NNECS

tested in T-QMD:
soft vs. hard EoS
density dep. of NNECS
asymmetry dep. of NNECS
width of single-nucleon distribution

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

the symmetry energy

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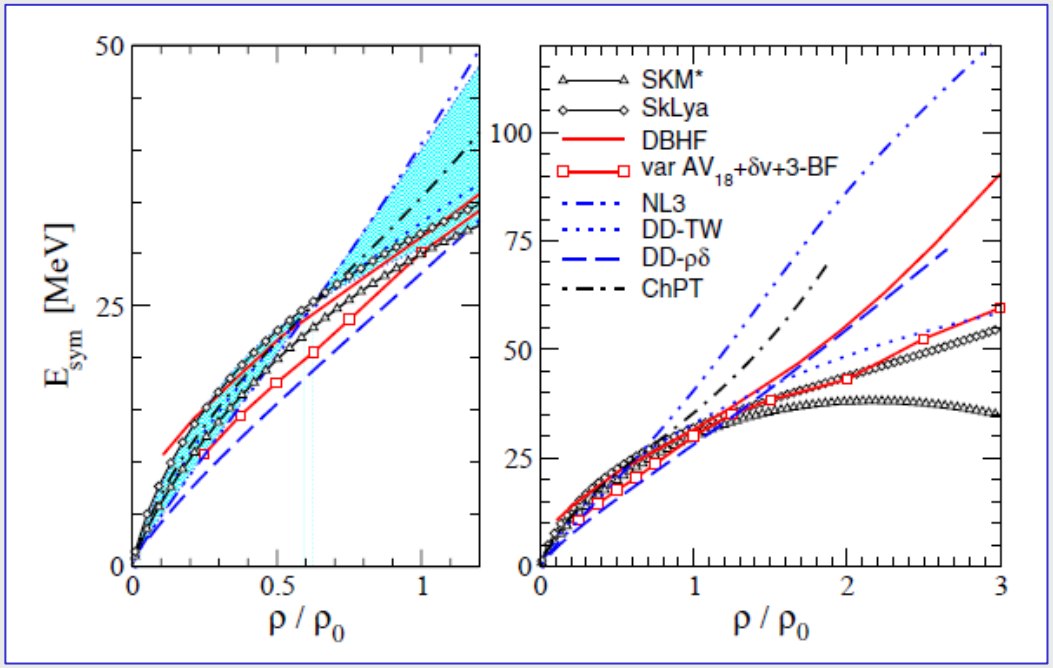
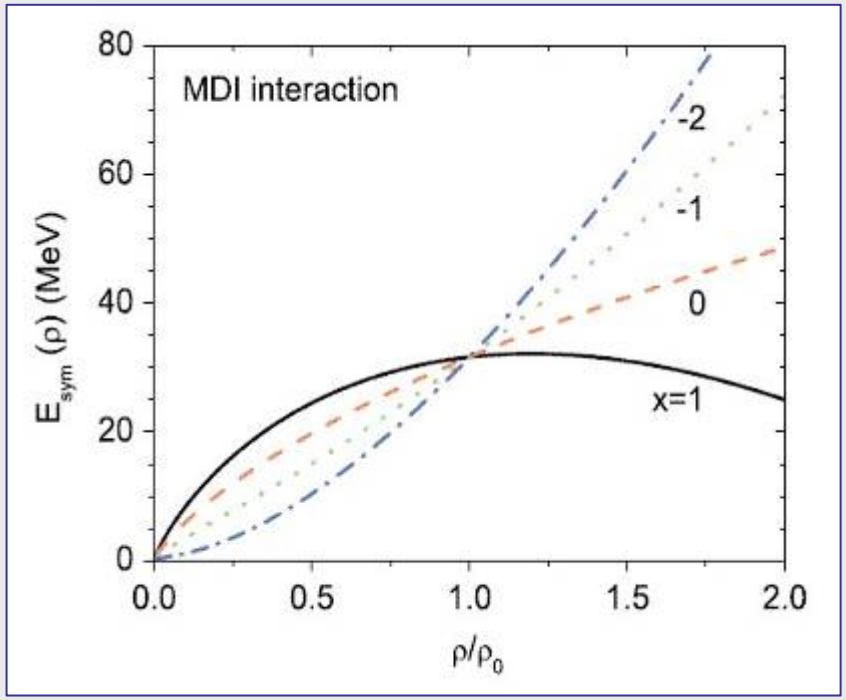


Fuchs and Wolter, EPJA 30 (2006)

parameterization
in transport theory: 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

summary and outlook

- L ≈ 60 MeV ($\gamma \approx 0.6$) from nuclear structure and reactions probing densities of ≈ 2/3 ρ_0; **big expectations** on PREXII

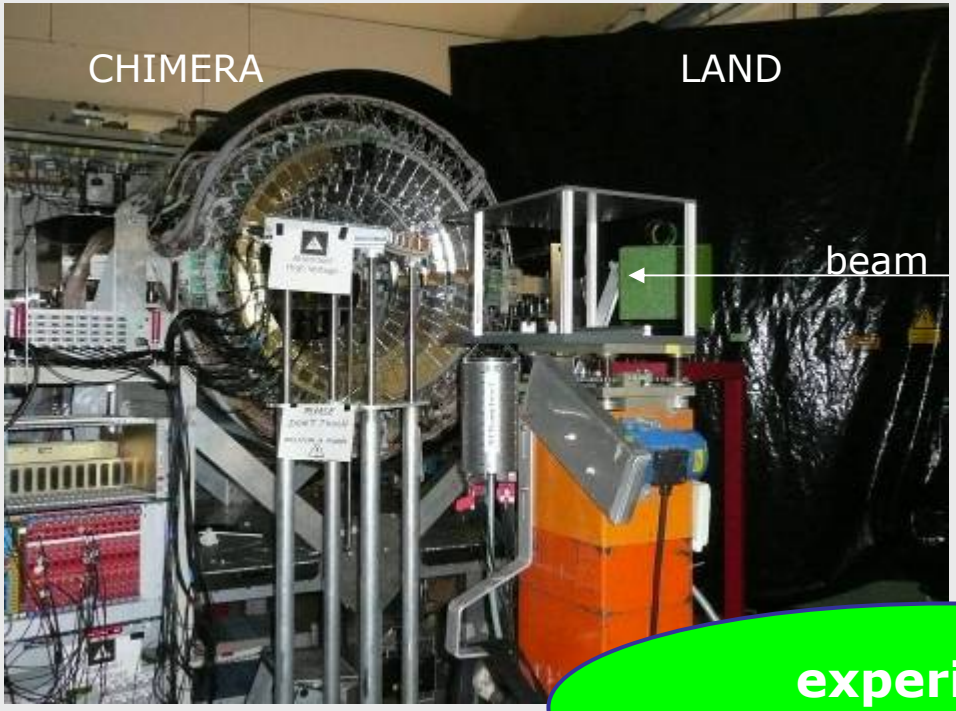
- increasingly more precise data from **neutron-star** observations, typically L ≈ 40 MeV; e.g. Steiner, Lattimer and Brown, ApJ (2010)

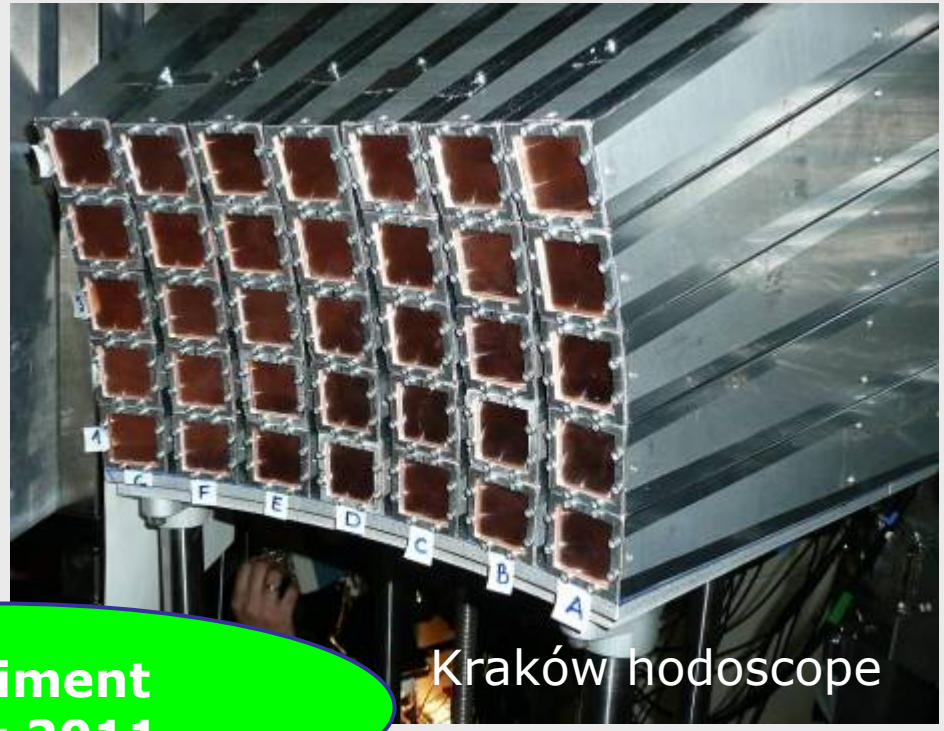
- high-densities probed in reactions at SIS energies;
  γ_{pot} = 0.9 ± 0.4 from FOPI/LAND elliptic flow;
  super-soft ruled out; study of **model invariance** under way;
  analysis of **ASY-EOS** experiment in progress!

- kaon and pion ratios interesting probes but results presently inconclusive: **new activity** at RIKEN (Samurai) and MSU;
  HADES kaon data for Ar+KCl and Au+Au potentially useful

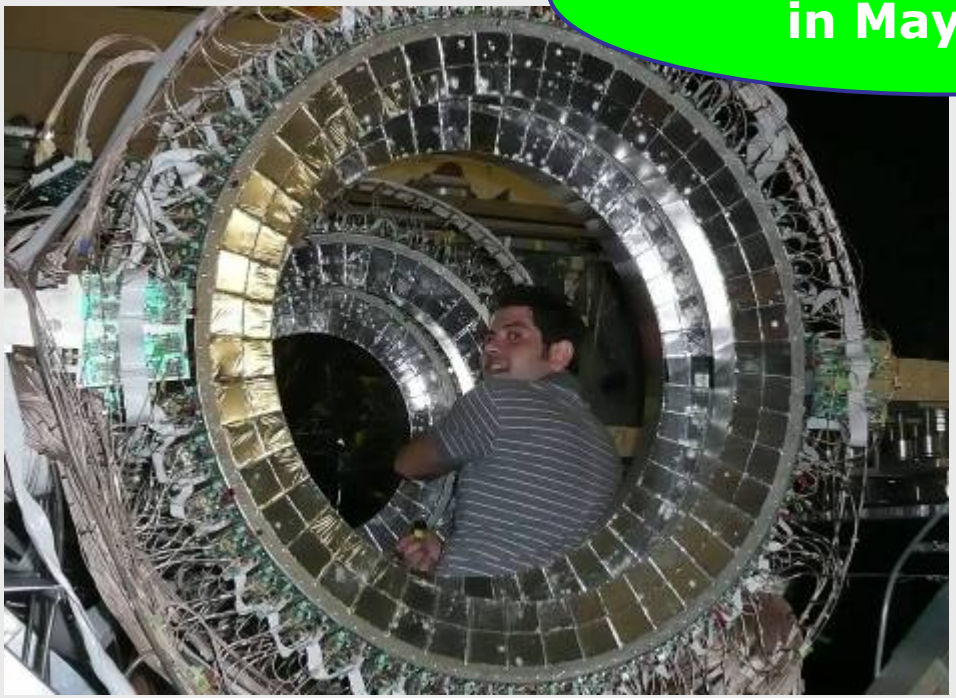
- interesting new results from effective field theory

- new facilities under construction worldwide

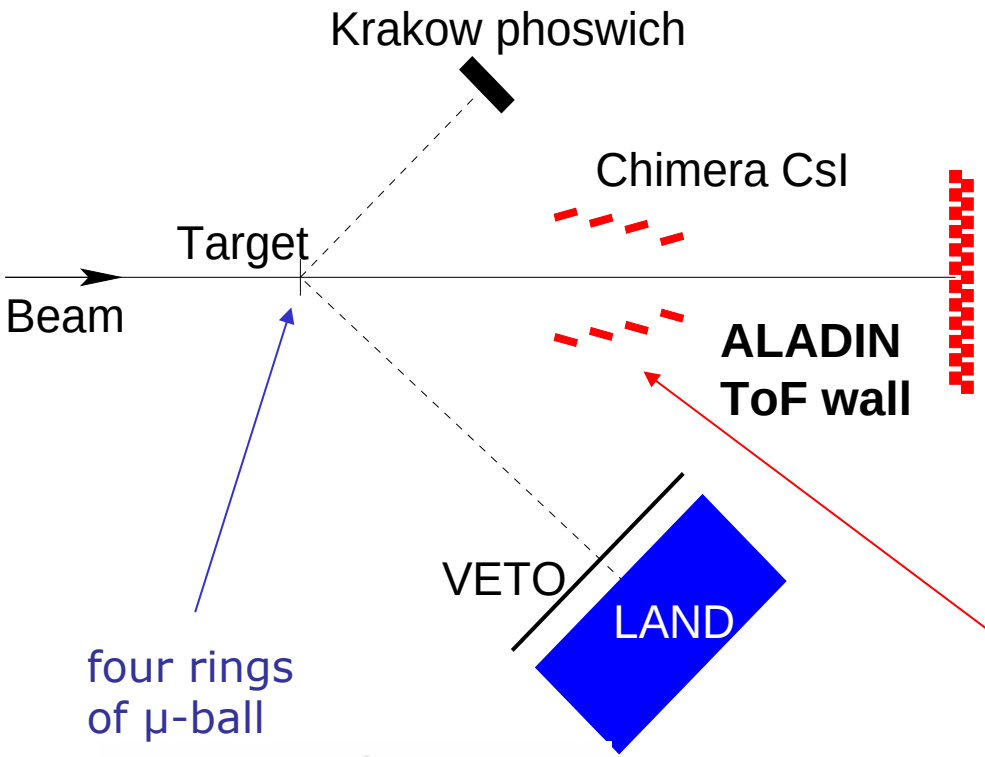




experiment in May 2011



AsyEos experiment S394 in May 2011



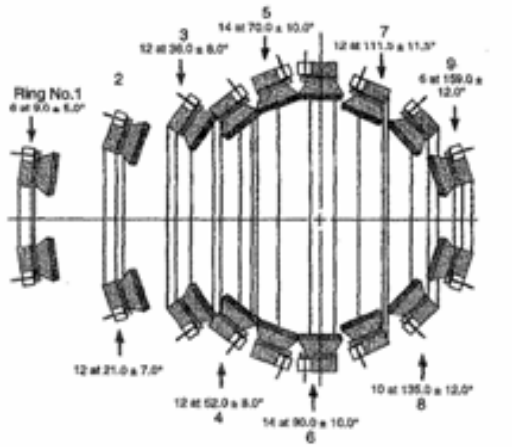
studied reactions:

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

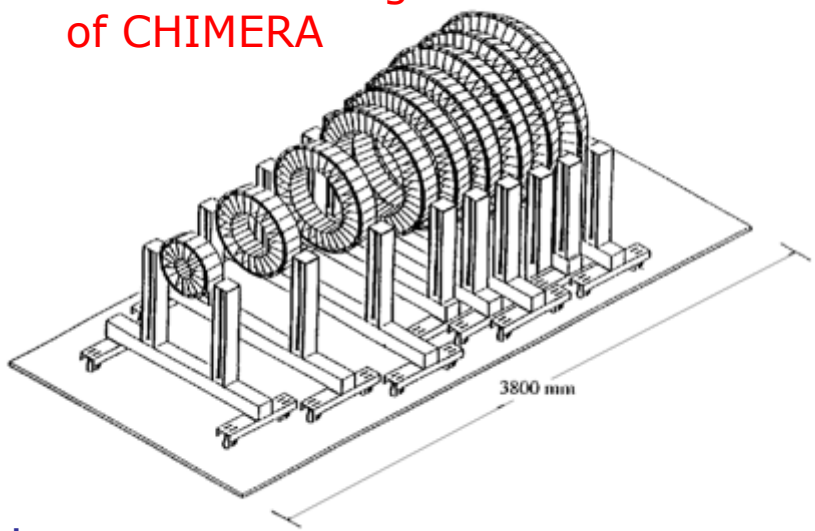
$^{96}Ru + ^{96}Ru$ @ 400 A MeV

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

four rings of μ-ball



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]

SAMURAI dipole magnet at RIKEN

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

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

RIKEN NISHINA CENTER
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