The symmetry energy at high density: new experimental results

W. Trautmann
GSI Helmholtzzentrum, Darmstadt, Germany

Symposium in Honour of Nikola Cindro
September 22-24, 2011, Split, Croatia

back in time with ^{14}C

1980 in Munich

14 PHYSICAL REVIEW LETTERS

Elastic and Inelastic Scattering of ^{14}C by ^{14}C

D. Konnerth, K. G. Bernhardt, K. A. Eberhard, R. Singh,[a]
A. Strzalkowski,[b] W. Trautmann, and W. Trombik
Sektion Physik, Universität München, D-8046 Garching, West Germany

(Received 14 July 1980)

1980 in Los Alamos

PHYSICS LETTERS

GROSS STRUCTURE AND RESONANT BEHAVIOR OF $^{14}C + ^{14}C$ ELASTIC SCATTERING☆

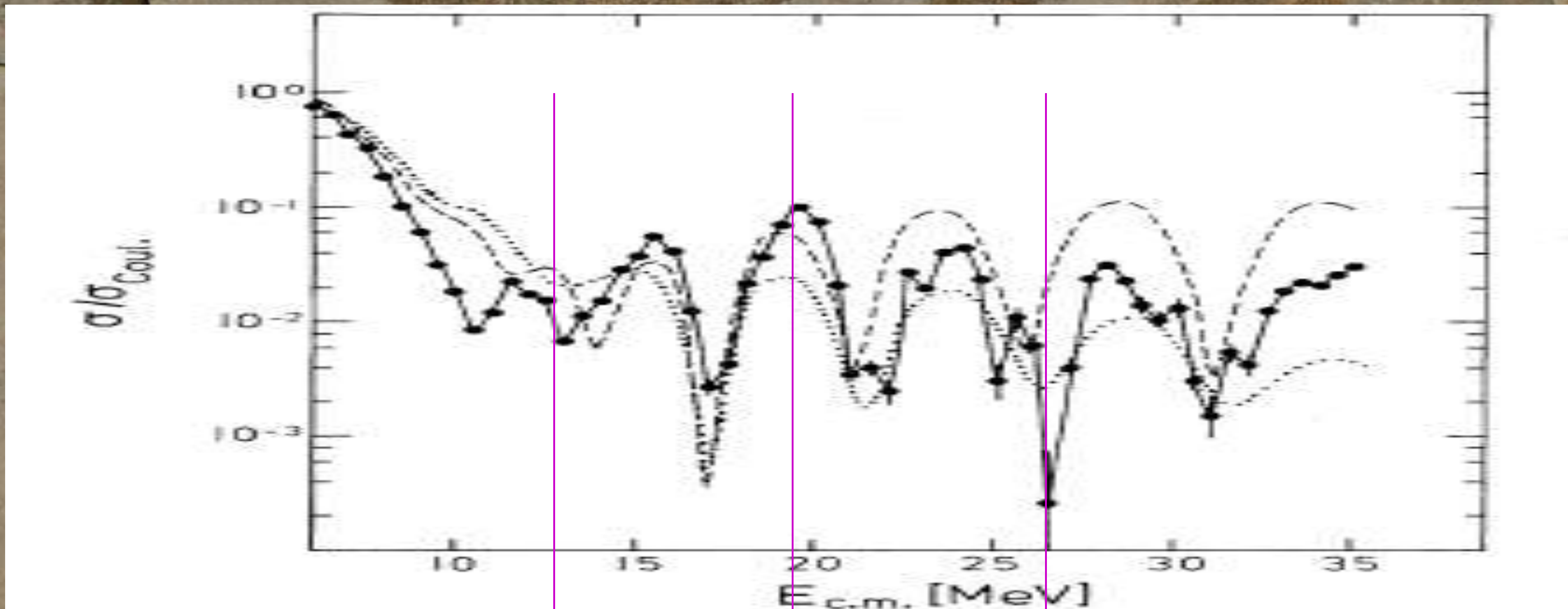
D.M. DRAKE and M. CATES
University of California, Los Alamos Scientific Laboratory, Los Alamos, NM 87545, USA

and

N. CINDRO, D. POCANIC and E. HOLUB
"Rudjer Boskovic" Institute, 41001 Zagreb, Croatia, Yugoslavia

Received 2 July 1980

back in time with 14C ...



1980 in
Los Alamos

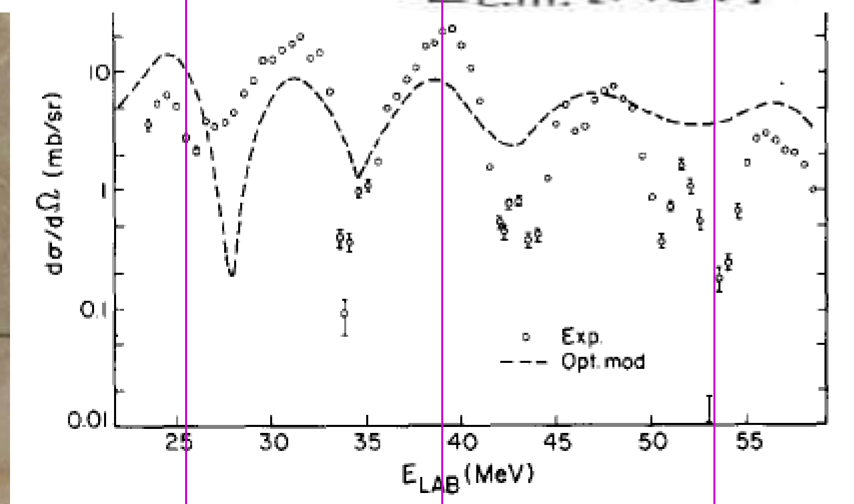


Fig. 1. Center of mass differential cross sections for ^{14}C + ^{14}C elastic scattering measured at θ_{cm} = 90° as a function

the data
agree
nicely!

Mazurian Lakes Summer School

Piaski, 1993

Acta Physica Polonica 25,645(1994)

Concert, Concert, Concert

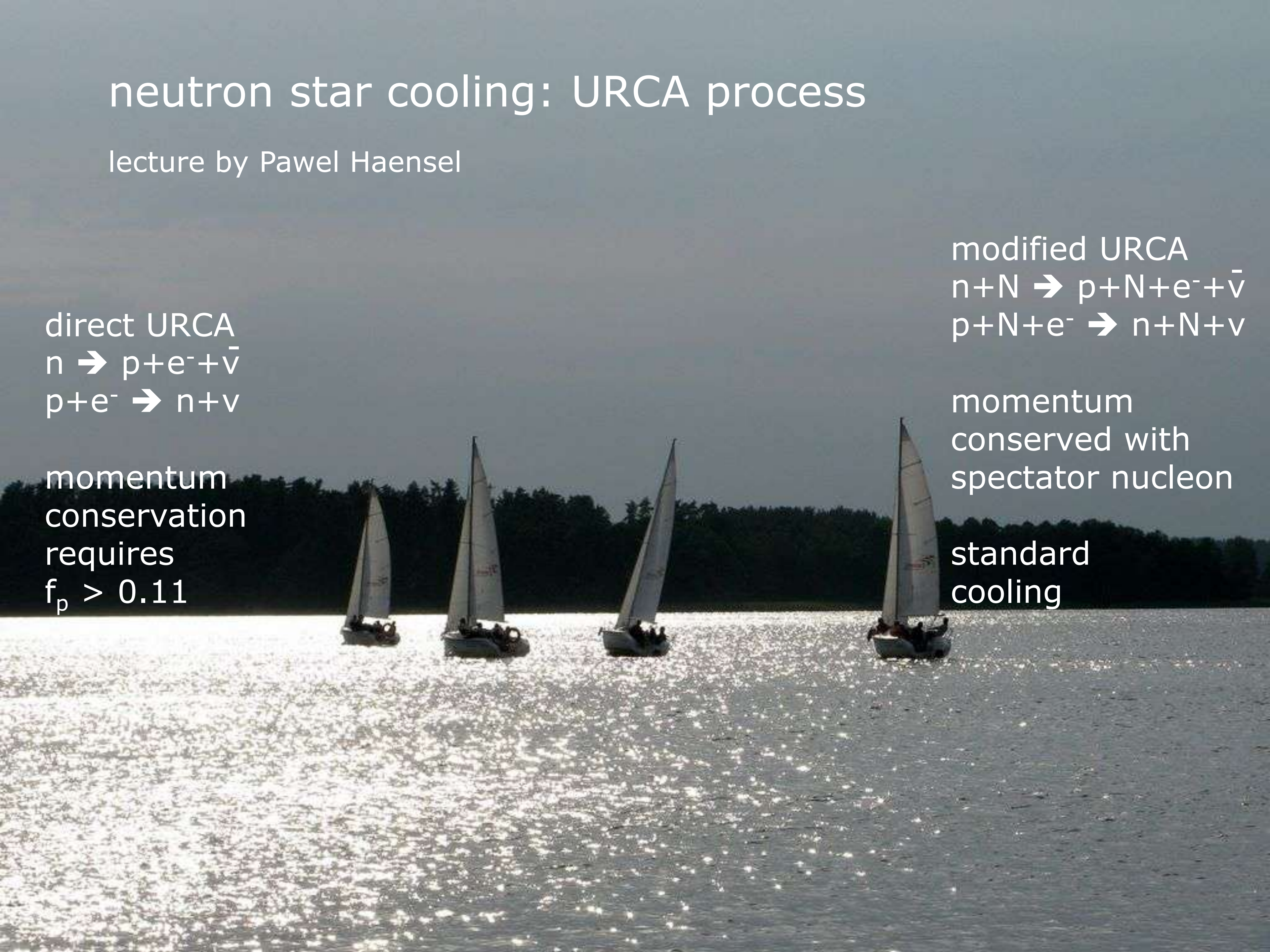
Sunday, August 22
7.30 p.m.
"I solisti di Varsavia"

neutron star cooling: URCA process

lecture by Pawel Haensel

neutron star cooling: URCA process

lecture by Pawel Haensel



direct URCA

$n \rightarrow p + e^- + \bar{\nu}$

$p + e^- \rightarrow n + \nu$

momentum conservation requires $f_p > 0.11$

modified URCA

$n + N \rightarrow p + N + e^- + \bar{\nu}$

$p + N + e^- \rightarrow n + N + \nu$

momentum conserved with spectator nucleon

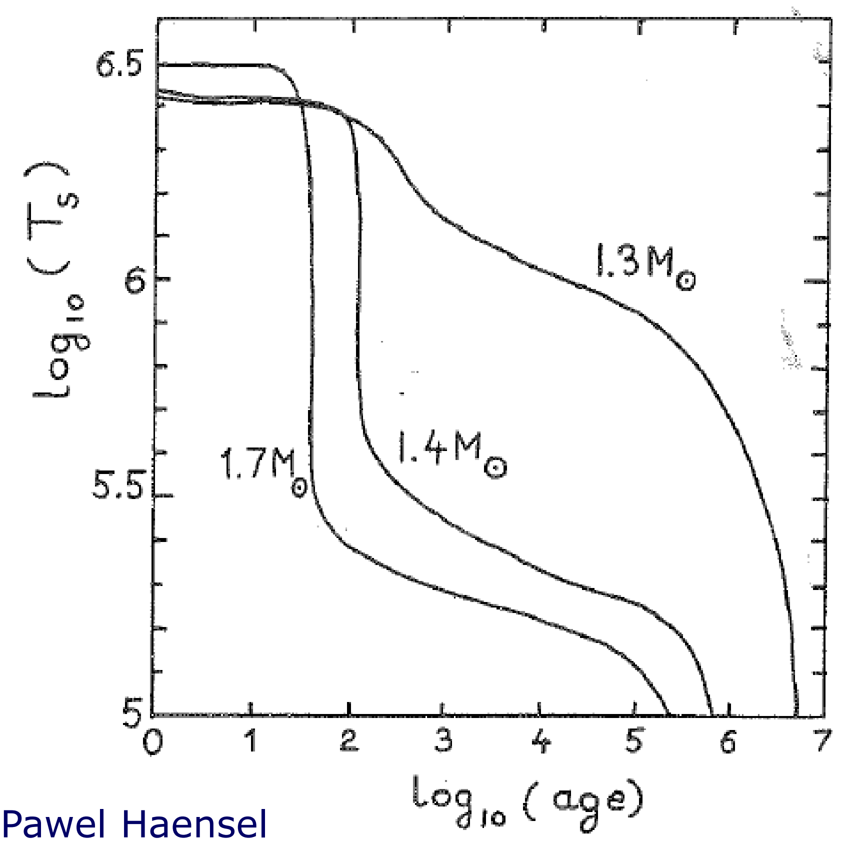
standard cooling

neutron star cooling: URCA process

direct URCA
$n \rightarrow p + e^- + \bar{\nu}$
$p + e^- \rightarrow n + \nu$

momentum conservation requires
$f_p > 0.11$

surface temperature versus age



Pawel Haensel

modified URCA
$n + N \rightarrow p + N + e^- + \bar{\nu}$
$p + N + e^- \rightarrow n + N + \nu$

momentum conserved with spectator nucleon

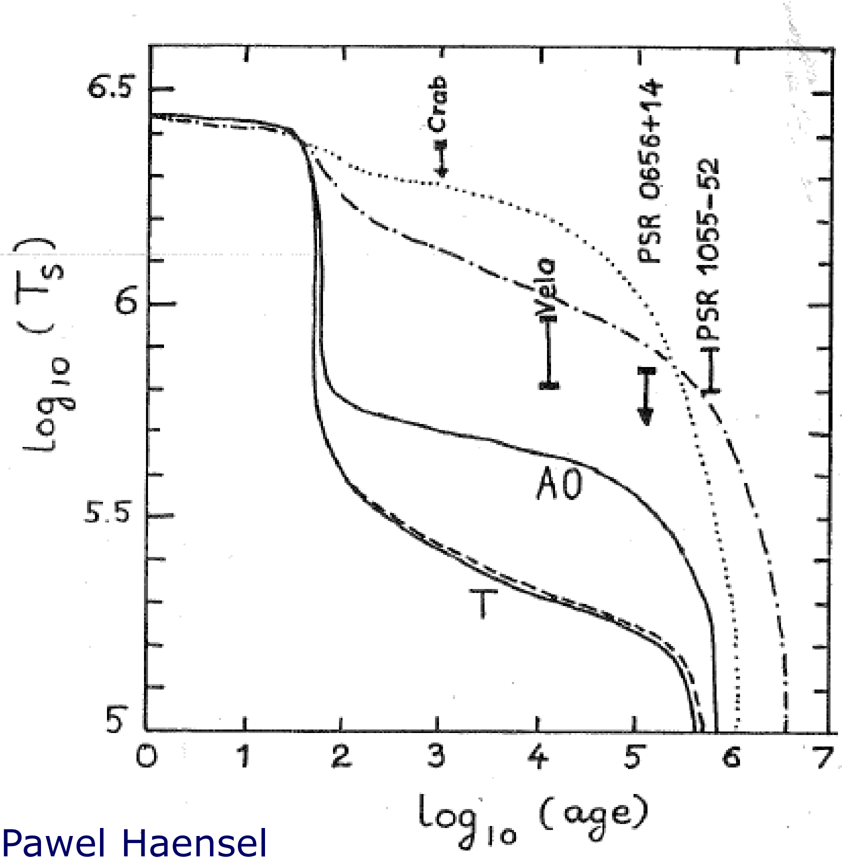
standard cooling

neutron star cooling: URCA process

direct URCA
n ➔ $p+e^-+\bar{v}$
$p+e^-$ ➔ n+v

momentum conservation requires $f_p > 0.11$

surface temperature versus age



Pawel Haensel

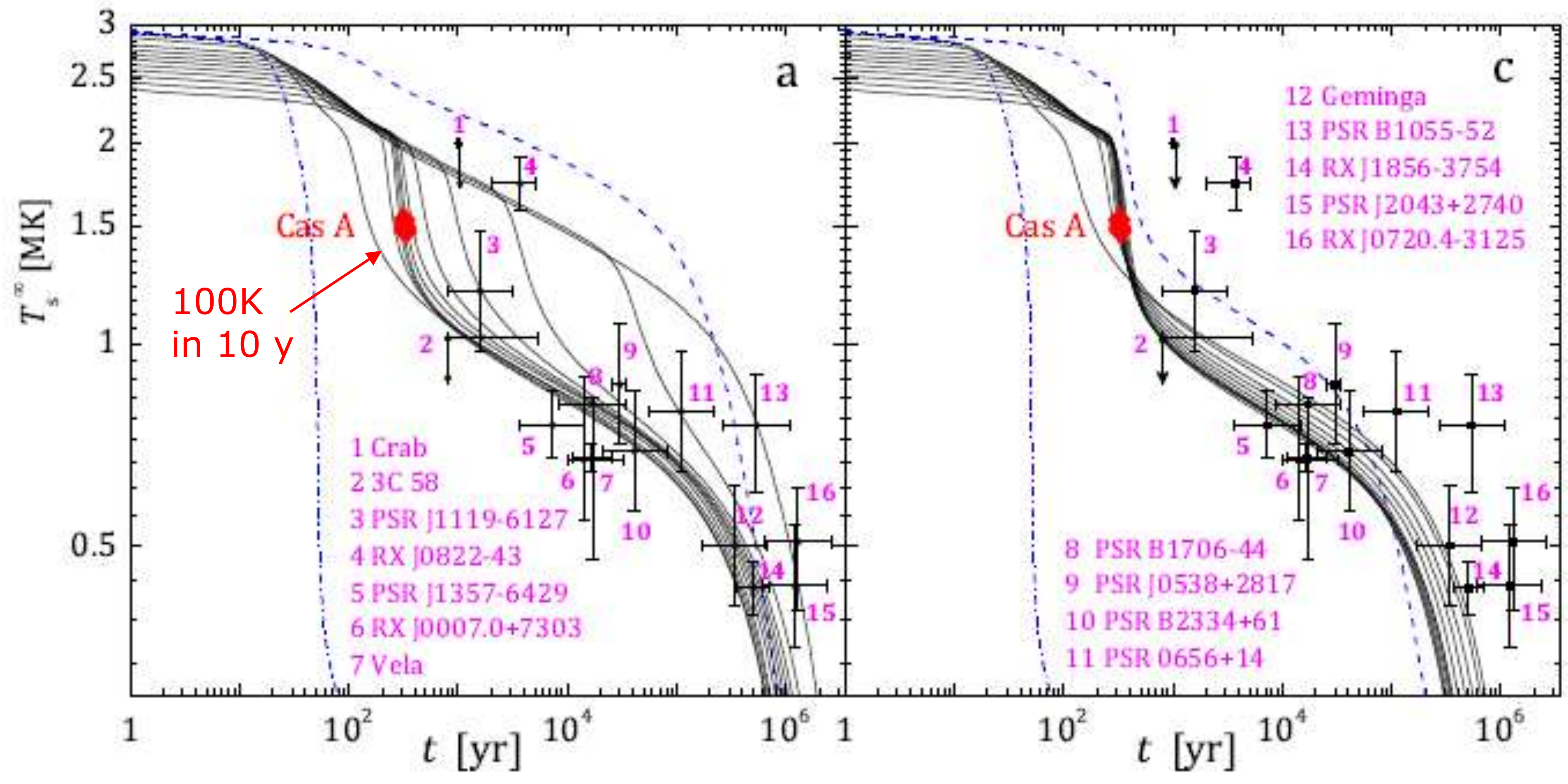
modified URCA
n+N ➔ $p+N+e^-+\bar{v}$
$p+N+e^-$ ➔ n+N+v

momentum conserved with spectator nucleon

standard cooling

neutron star cooling: CPF neutrinos

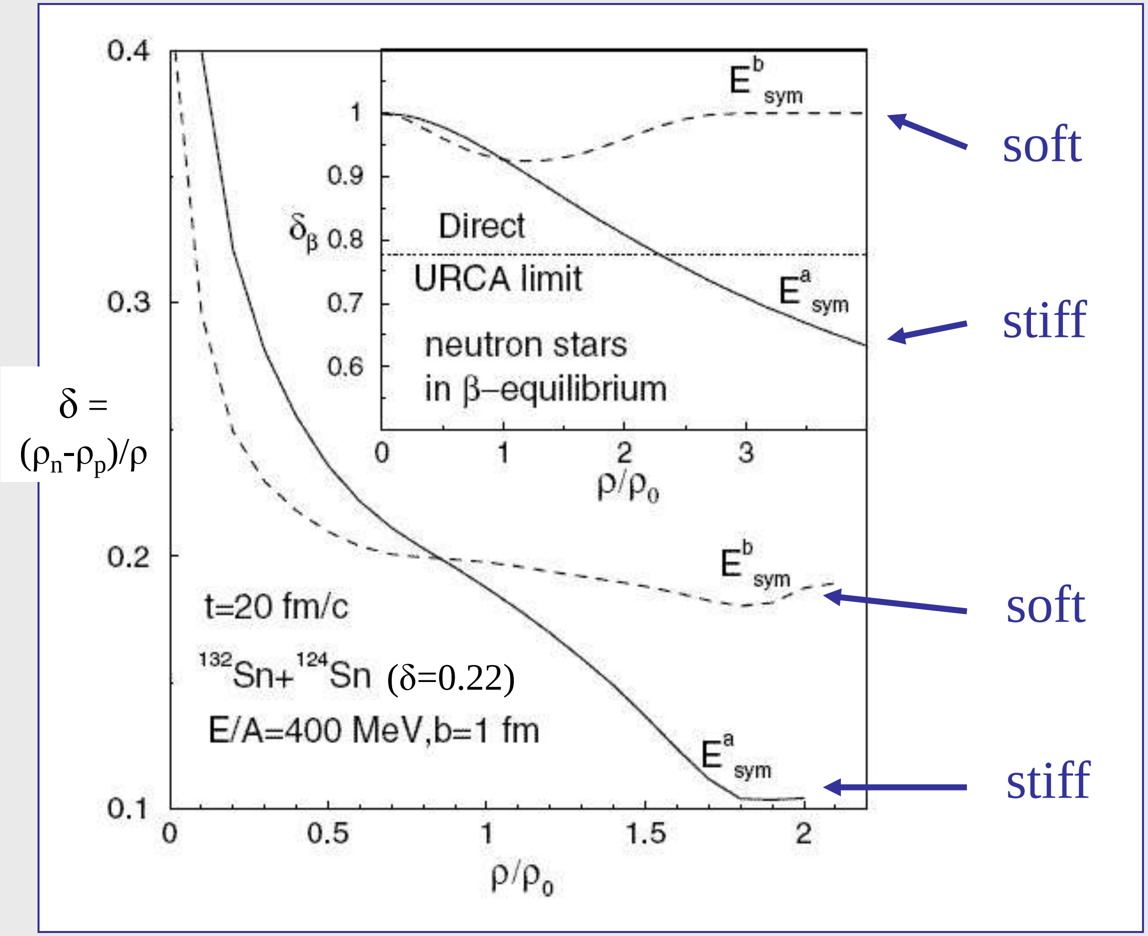
Cooper pair formation



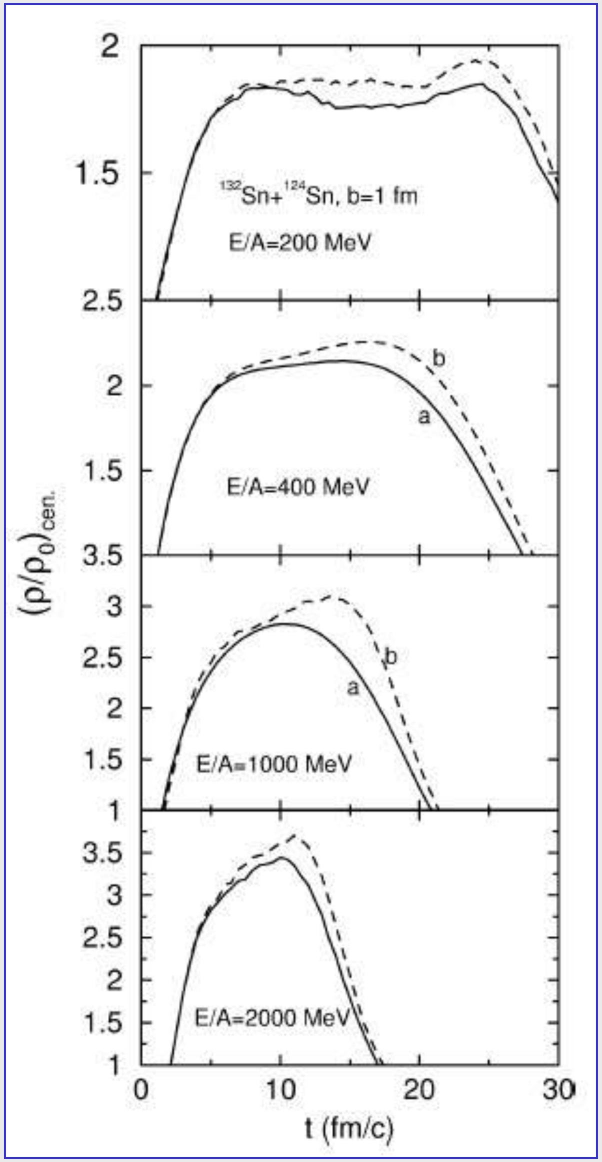
Shternin et al., arXiv:1012:0045 : direct observation of Cas A cooling with CHANDRA
a, c: different models for critical temperature of triplet-state neutron pairing in NS core.

symmetry energy in HI reactions

Bao-An Li, PRL 88, 192701 (2002)



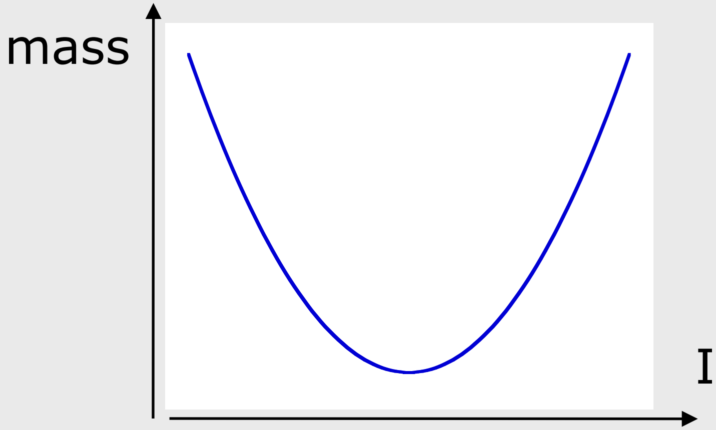
Bao-An Li, NPA 708(2002)

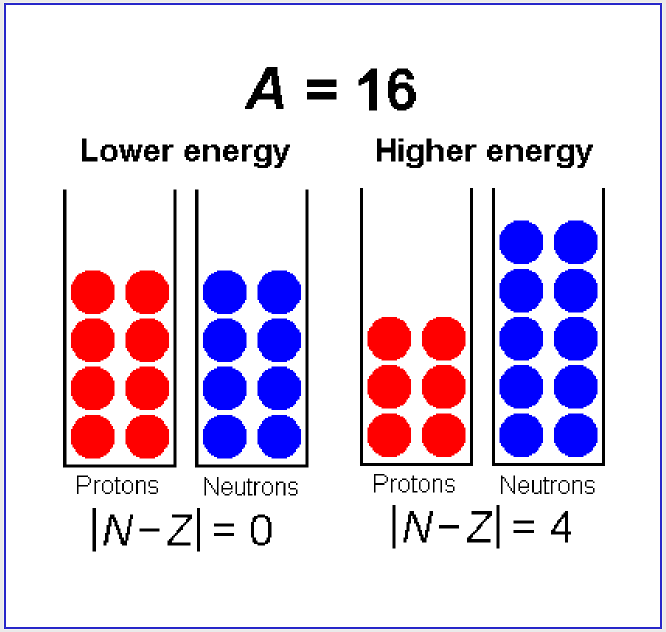


probe the early reaction phase with suitable observables like differential neutron-proton flow!

the symmetry energy

Bethe Weizsäcker





B_{sym} = -23.4 MeV · $(N-Z)^2/A$

Fermi-gas model for kinetic part:
$B_{sym} = -(\varepsilon_F/3) \cdot (N-Z)^2/A$

density dependence $(\rho/\rho_0)^{2/3}$

equivalent to ≈1/3 of strength
potential part equivalent to ≈2/3

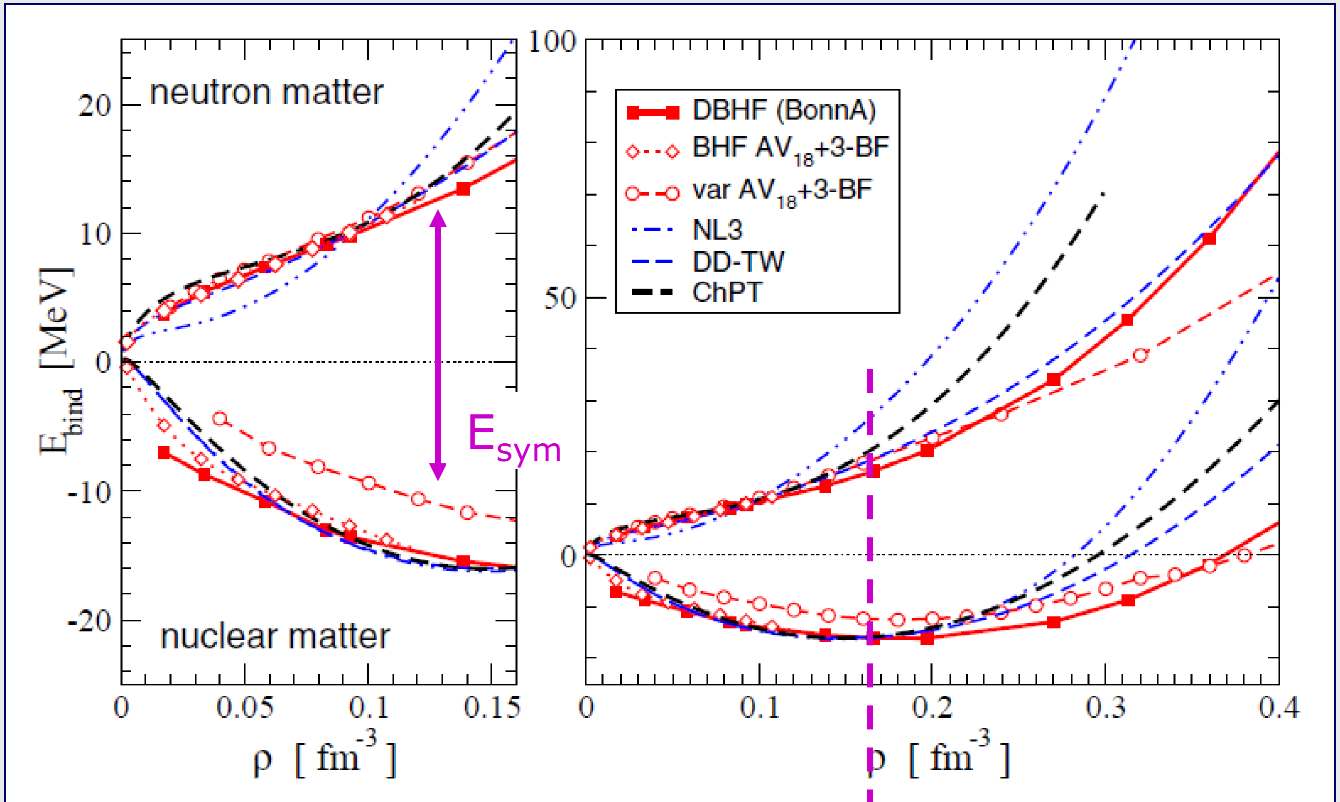
isospin asymmetry $I = (N-Z)/A$

nuclear-matter equation of state
$E_A(\rho,\delta) = E_A(\rho,0) + E_{sym}(\rho) \cdot \delta^2$

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

proton fraction $f_p = \rho_p/\rho = (1- \delta)/2$

the symmetry energy



Fuchs and Wolter, EPJA 30 (2006)

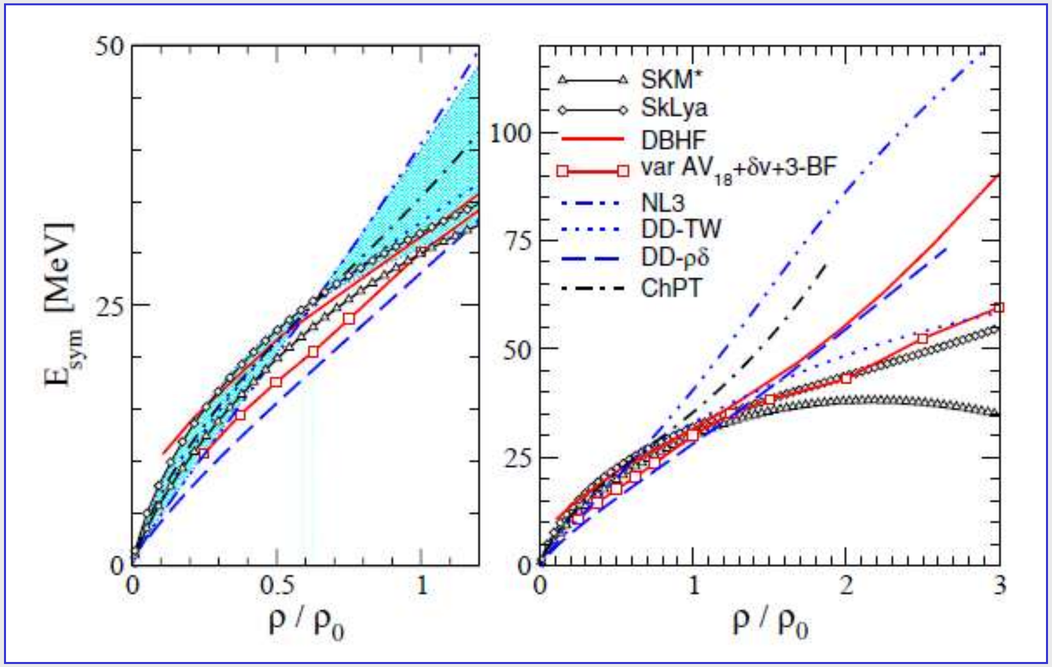
why so uncertain at high density?

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

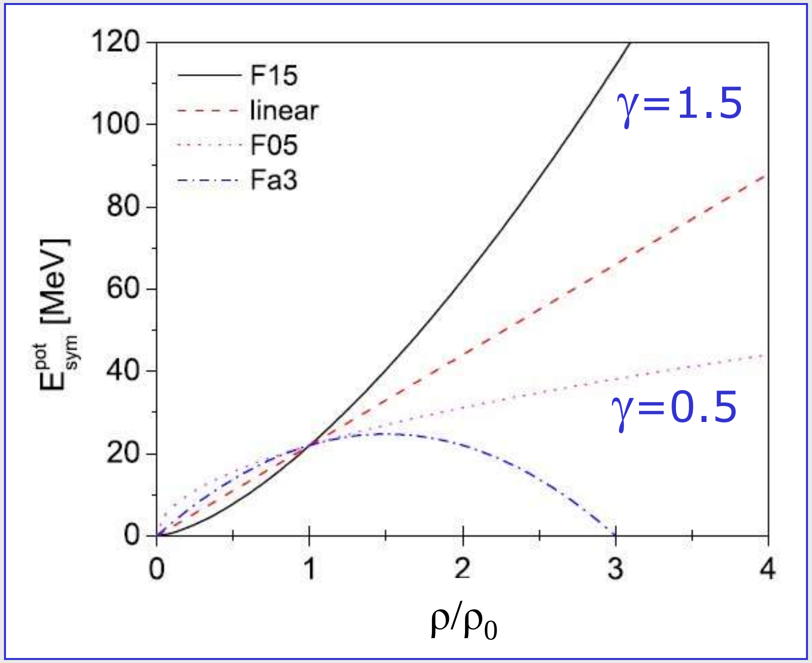
normal nuclear density

the symmetry energy

Fuchs and Wolter, EPJA 30 (2006)



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



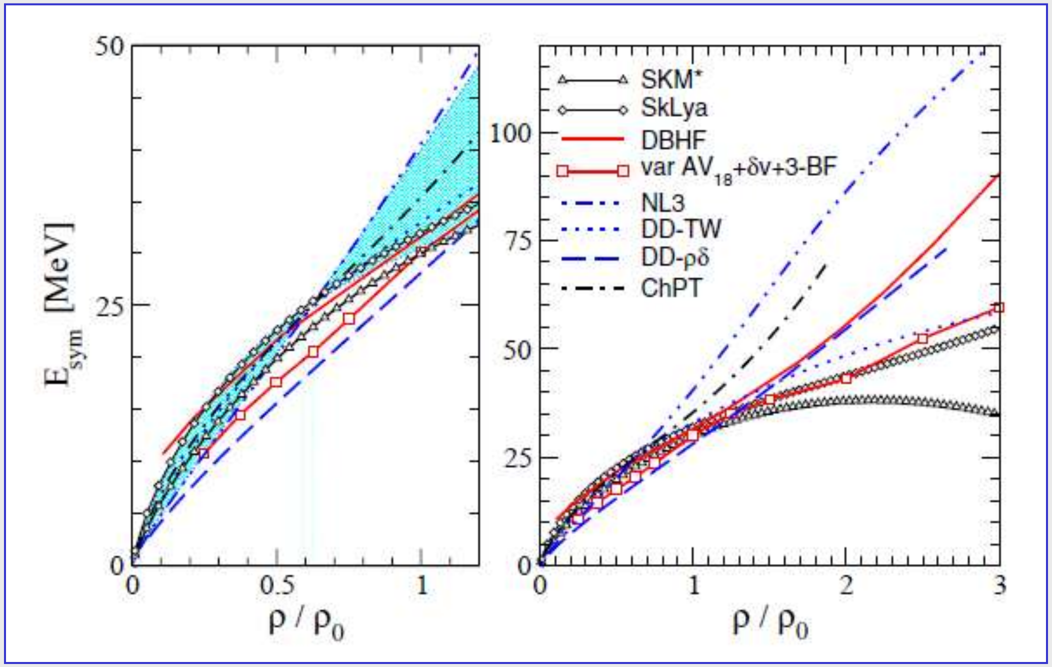
$$E_{sym} = E_{sym}^{pot} + E_{sym}^{kin}$$
$$= 22\text{MeV}\cdot(\rho/\rho_0)^{\gamma} + 12\text{MeV}\cdot(\rho/\rho_0)^{2/3}$$

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

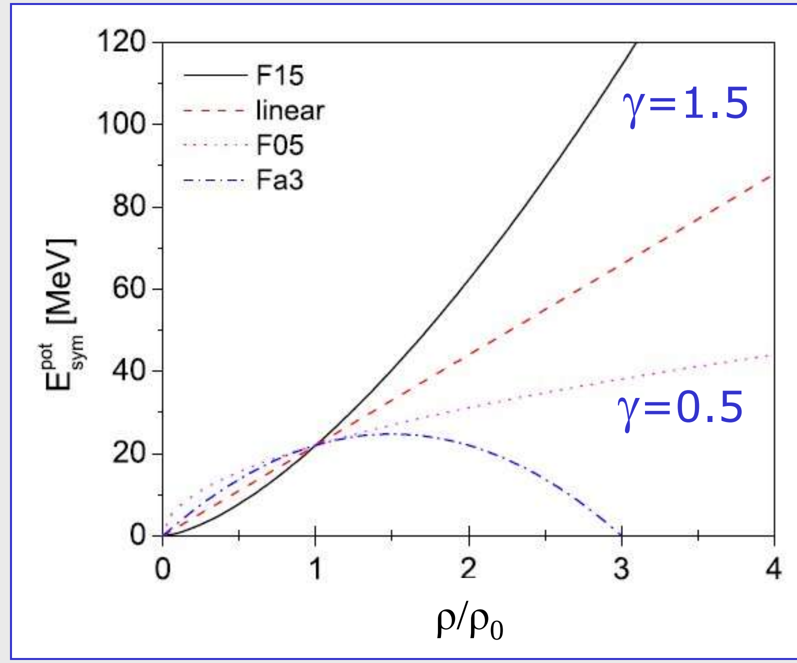
γ =	0.5	1.0	1.5
L =	57	90	123 MeV

the symmetry energy

Fuchs and Wolter, EPJA 30 (2006)



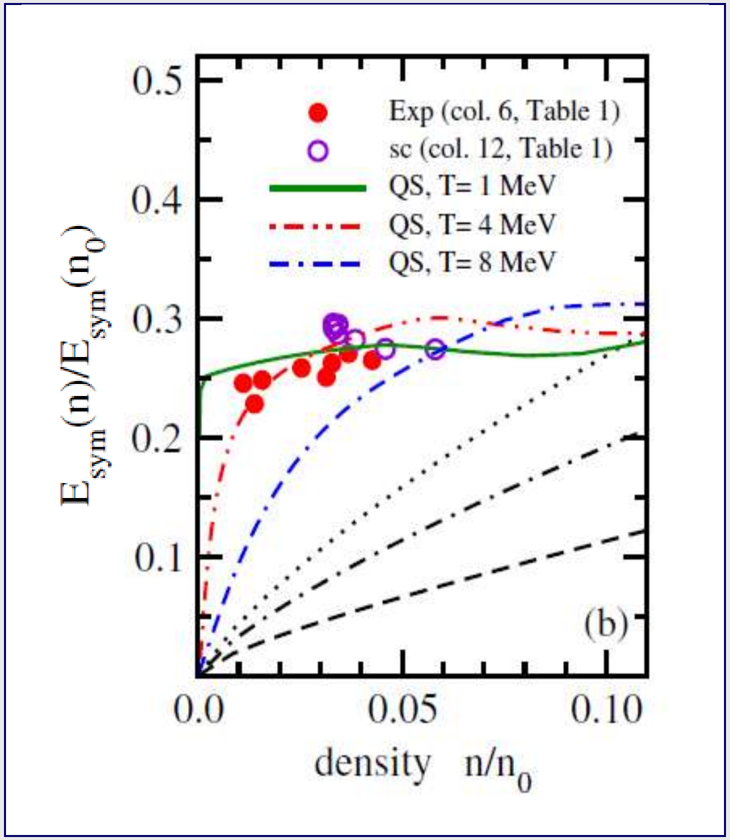
param. in transport: UrQMD, Q.F. Li et al.

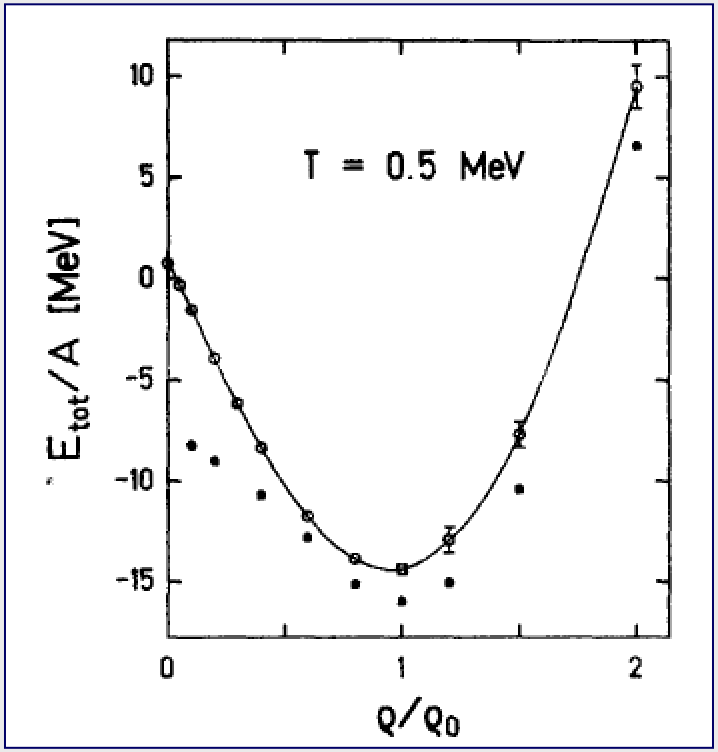


- at very low densities: E_{sym} finite because of clustering
- near normal density: E_{sym} constrained by g.s. masses, nuclear structure and reactions; can we extrapolate?
- probes for high density

the symmetry energy at very low density

C.J. Horowitz, A. Schwenk, NPA 776 (2006)
S. Typel et al., PRC **81,** 015803 (2010)
J.B. Natowitz et al., PRL **104**, 202501 (2010)





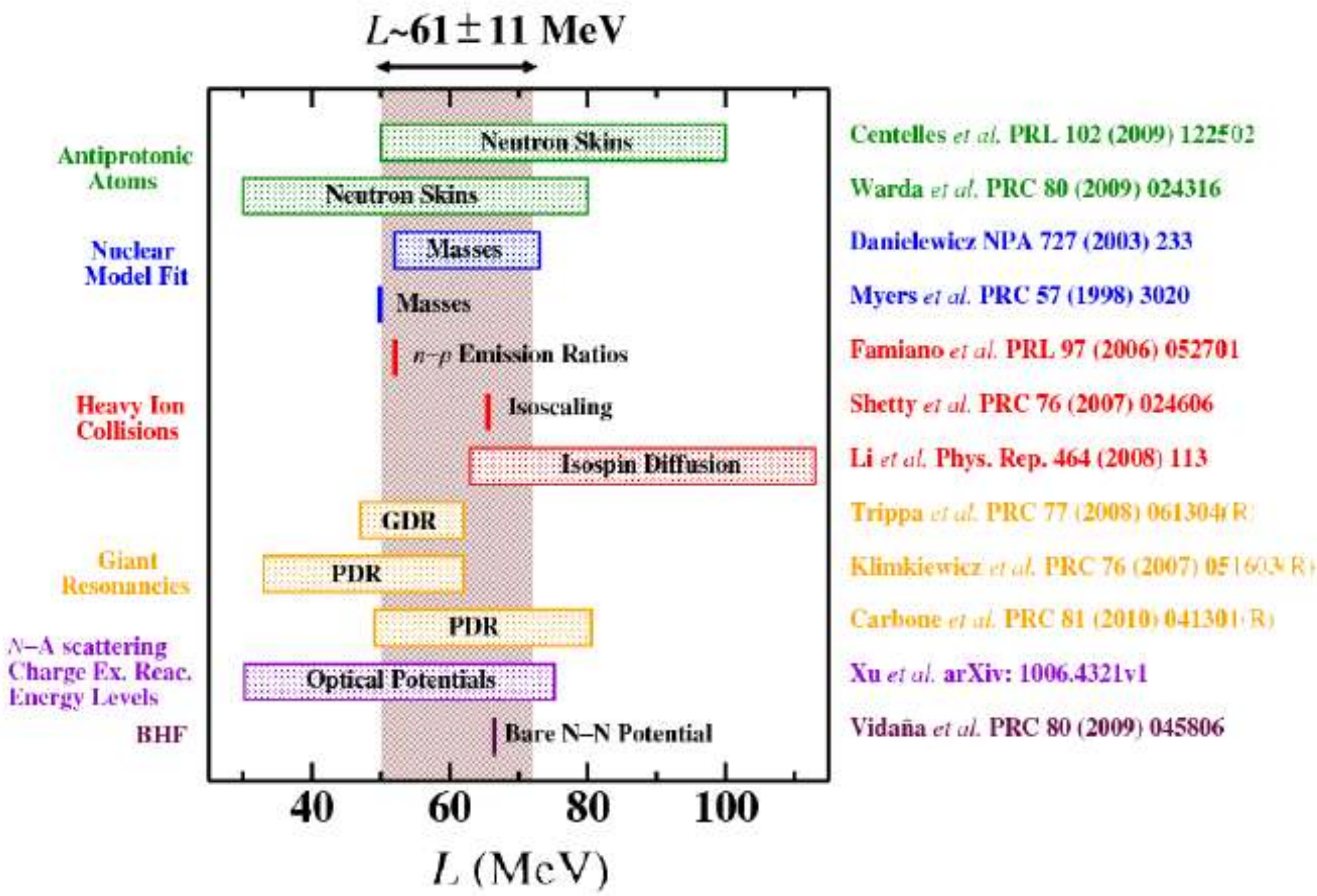
Clustering at subsaturation densities
G. Peilert, J. Randrup, H. Stöcker and W. Greiner, PLB 260 (1992)

„... for ρ~0 the binding energy approaches that characteristic of finite nuclei, namely E/A=6-8 MeV.

ECT* Workshop, June 2011
"Clusters in Nuclei and Nuclear Matter"

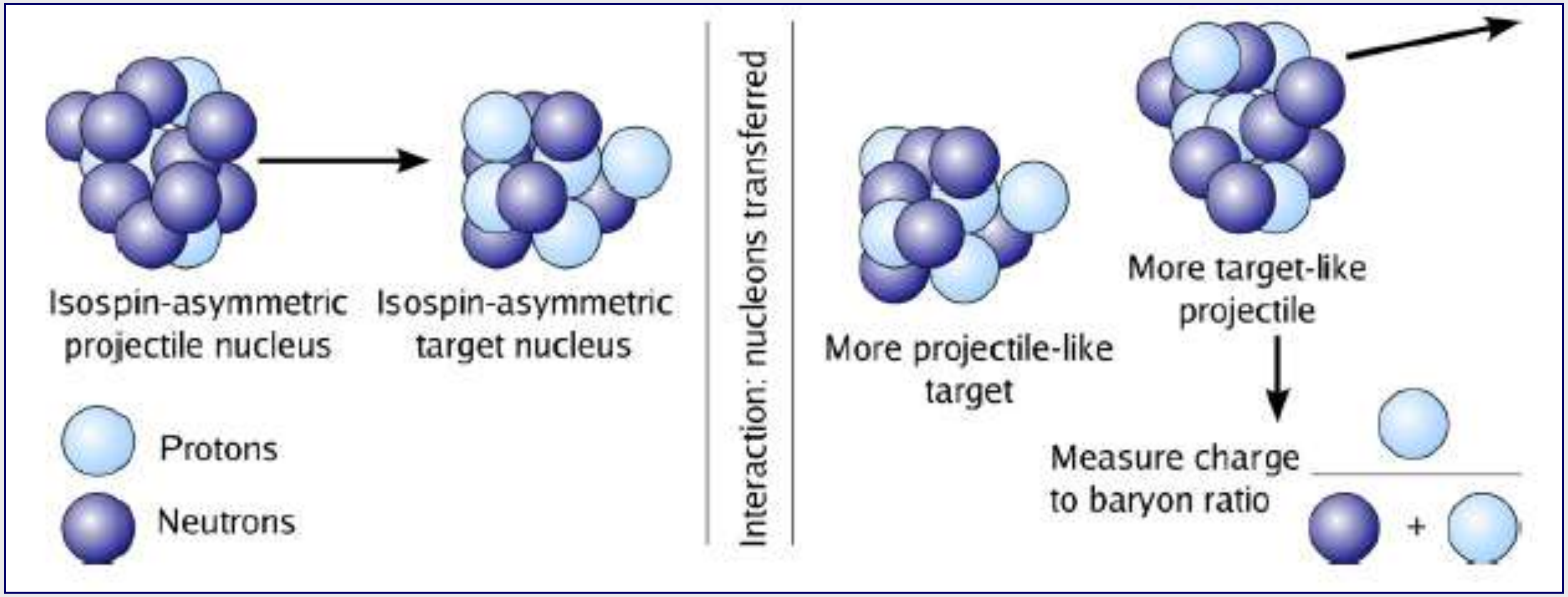
slide from talk of X. Viñas, ECT*, Trento, June 2011

Constraints on the slope of the symmetry energy



isospin diffusion

figure from Lattimer and Prakash, Phys. Rep. (2007)



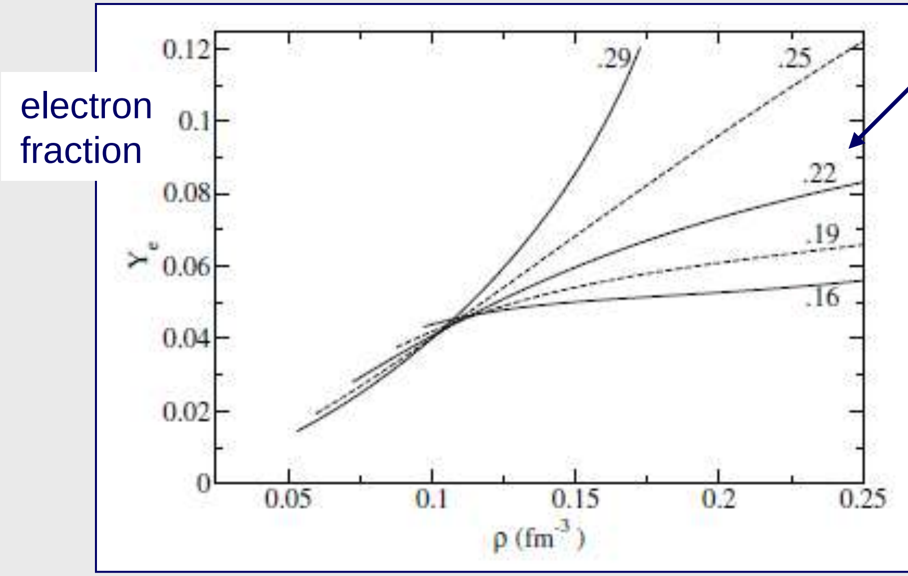
Tsang et al., PRL 102, 122701 (2009): $0.4 \leq \gamma \leq 1.0$
45 MeV $\leq L \leq$ 100 MeV

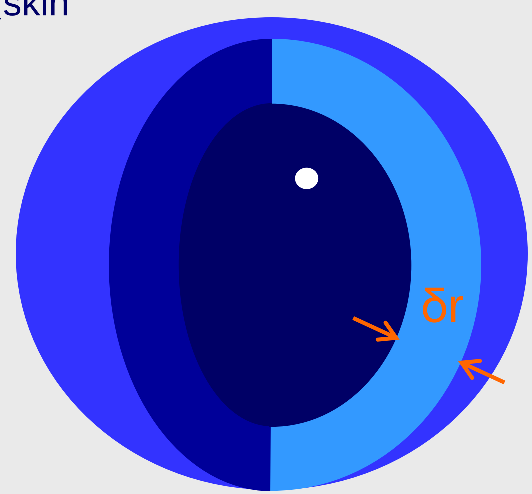
from isospin diffusion and neutron-proton double ratios
interpreted with ImQMD calculations by Y. Zhang et al.

previously: $E_{sym}(\rho) \approx 31.6 \cdot (\rho/\rho_0)^{0.69}$ with IBUU04, Li and Chen, PRC72(2005)

data

neutron skin and the symmetry energy





neutron stars $3x10^{+30}$ kg

^{208}Pb nucleus $3x10^{-25}$ kg

Horowitz & Piekarewicz, PRL 86 (2001): a data-to-data relation between the neutron skin of a heavy nucleus and the crust of a neutron star

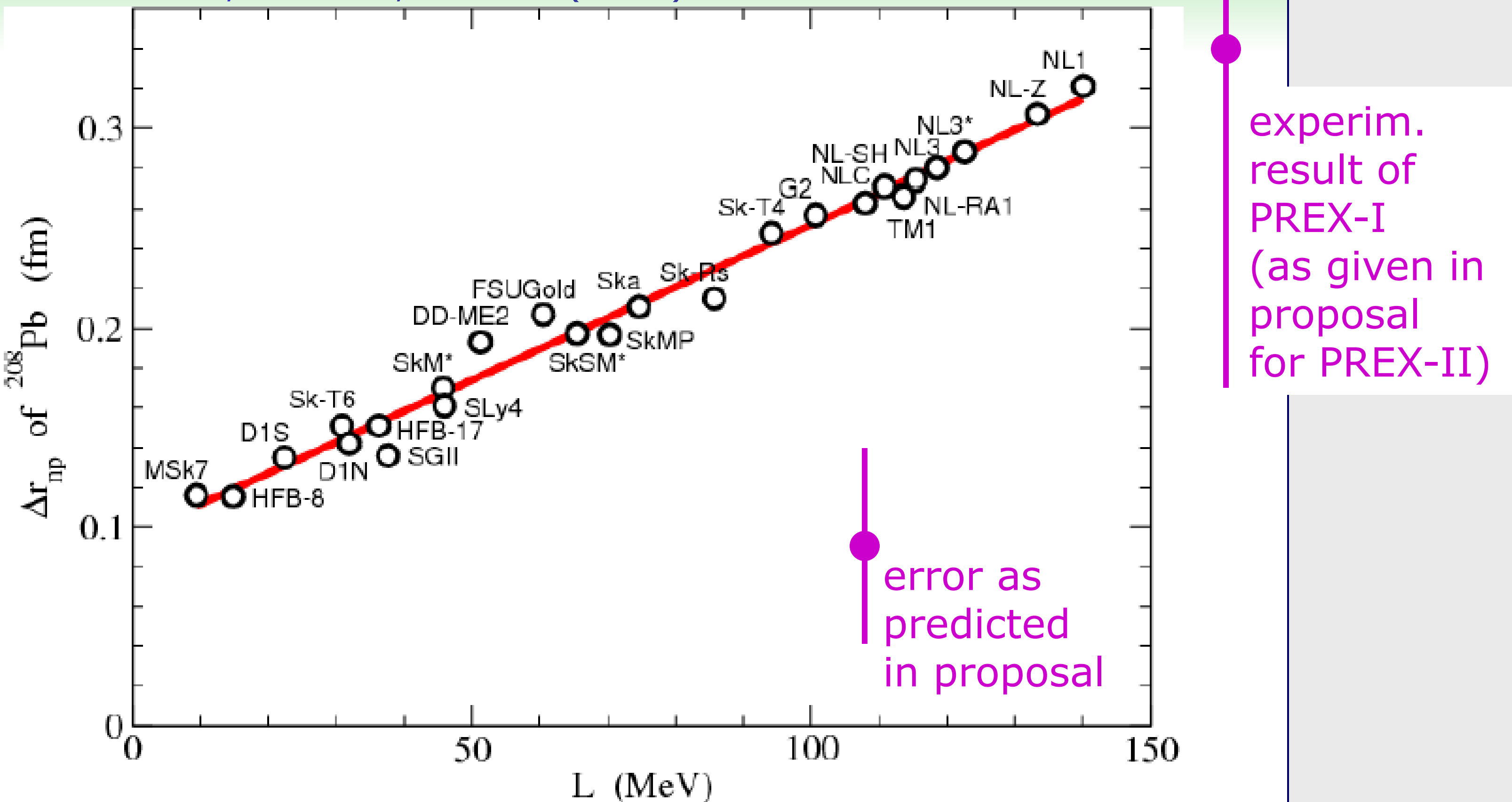
JLAB E-003

A CLEAN MEASUREMENT OF THE NEUTRON SKIN OF 208 Pb THROUGH PARITY VIOLATING ELECTRON SCATTERING

The Lead Radius Experiment (PREX) measures the parity violating asymmetry A_{pv} for 1.063 GeV electrons scattering from ^{208}Pb at 5 degrees.
This measurement should be sensitive to the neutron r.m.s radius of 208Pb to 1%.

neutron skin and the symmetry energy

Roca-Maza et al., PRL 106, 252501 (2011)

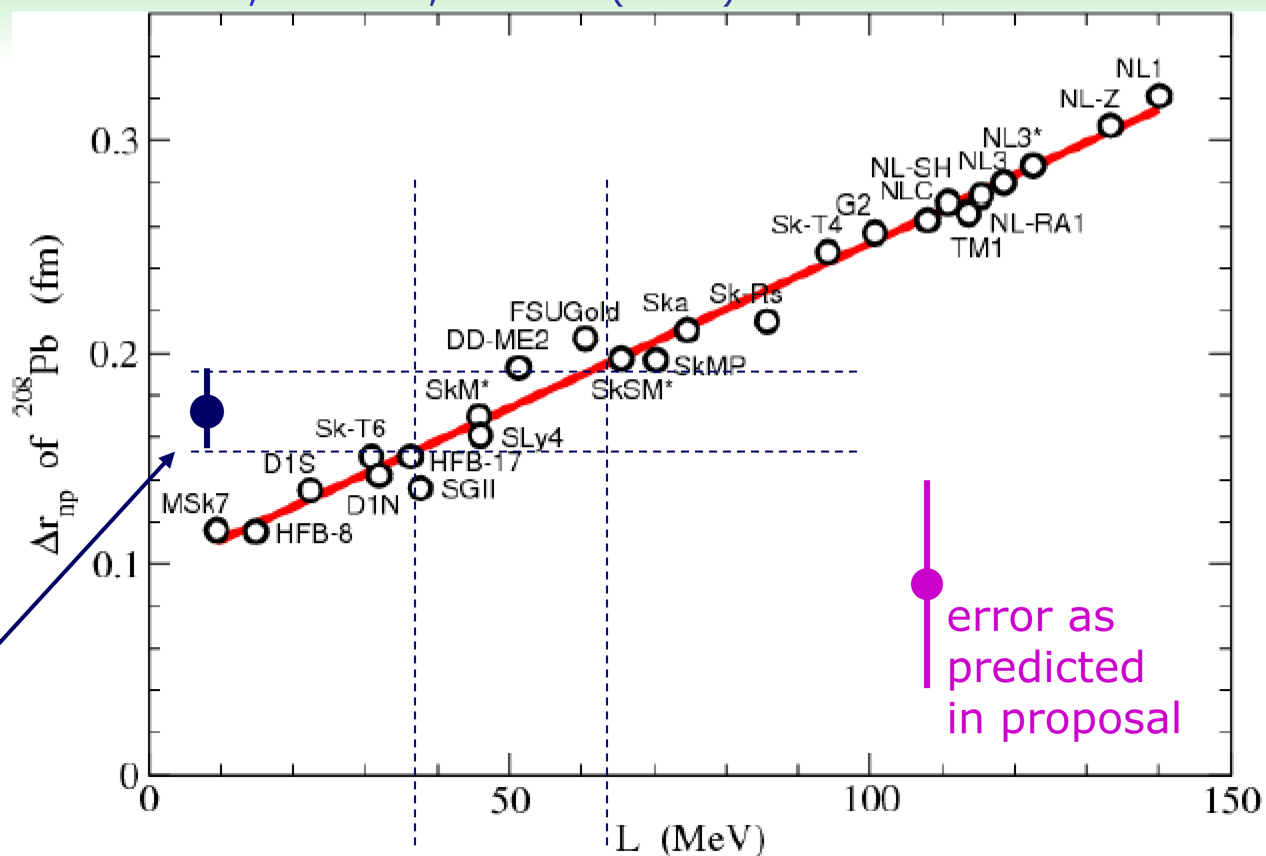


$$\Delta r_{np} = \langle r^2 \rangle_n^{1/2} - \langle r^2 \rangle_p^{1/2}$$

slide from talk of X. Viñas, ECT*, Trento, June 2011

neutron skin and the symmetry energy

Roca-Maza et al., PRL 106, 252501 (2011)



experim. result of PREX-I (as given in proposal for PREX-II)

LAND/GSI
$\delta_{np} = 0.17 \pm 0.02$
A. Klimkiewicz, PRL (2007)
RQRPA calculations by N. Paar

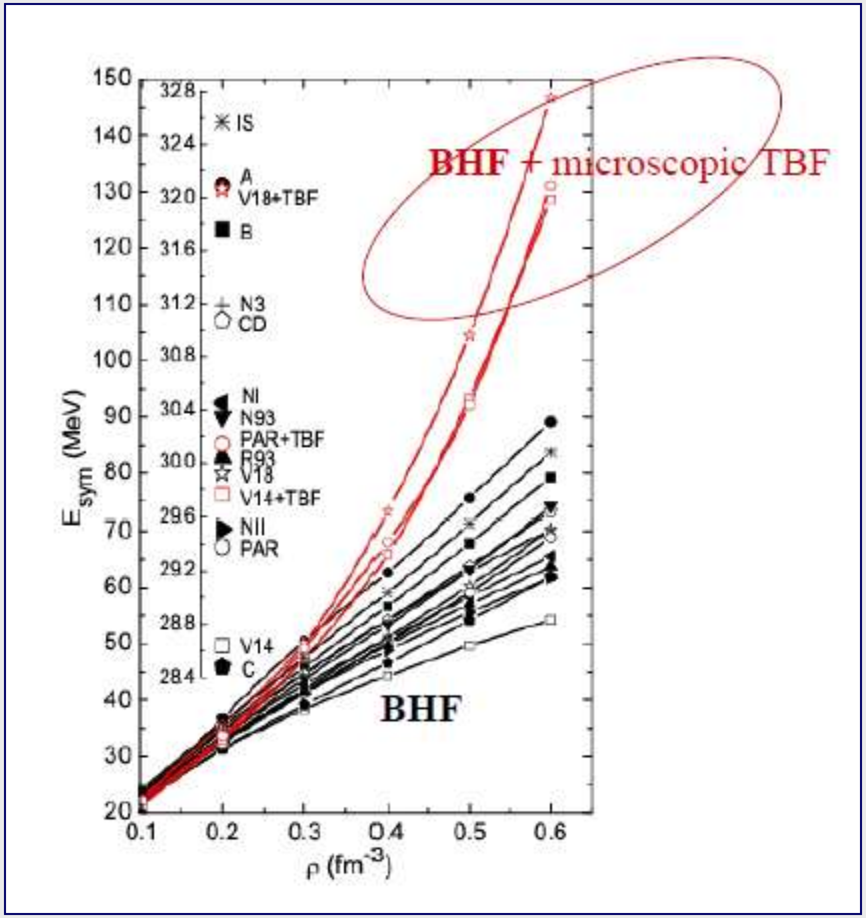
$$\Delta r_{np} = \langle r^2 \rangle_n^{1/2} - \langle r^2 \rangle_p^{1/2}$$

slide from talk of X. Viñas, ECT*, Trento, June 2011

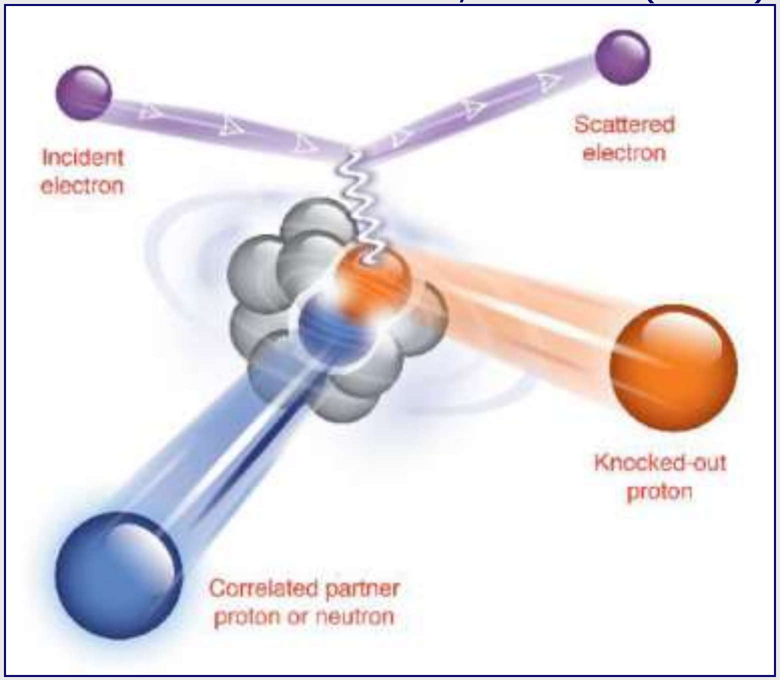
the symmetry energy at high density

why is is so uncertain ?

R. Subedi et al., Science (2008)



three body forces enhance the symmetry energy at high density (Fiorella Burgio, ASY-EOS Workshop, Noto, 2010)



test of short range correlations in $^{12}C(e,e')$ at J-Lab show that the neutron-proton pairs are nearly twenty times as prevalent as proton-proton pairs;
modifies momentum distributions in asymmetric matter and confirms the role of the tensor force acting in neutron-proton isosinglet pairs .

ESF Exploratory Workshop on

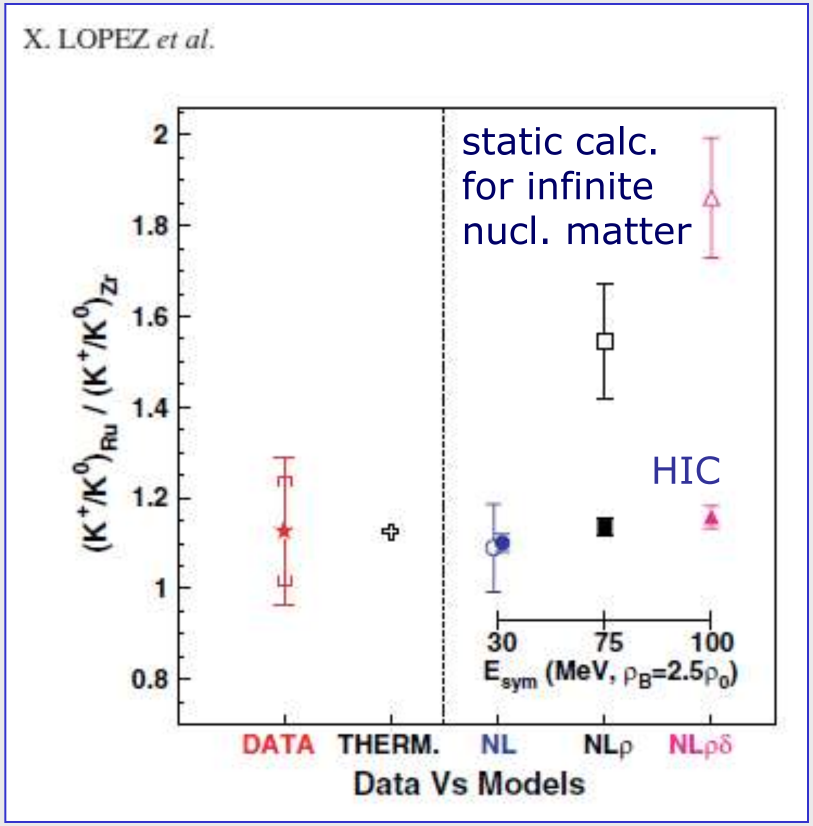
How to Constrain the High Density Symmetry Energy - HiDeSymEne

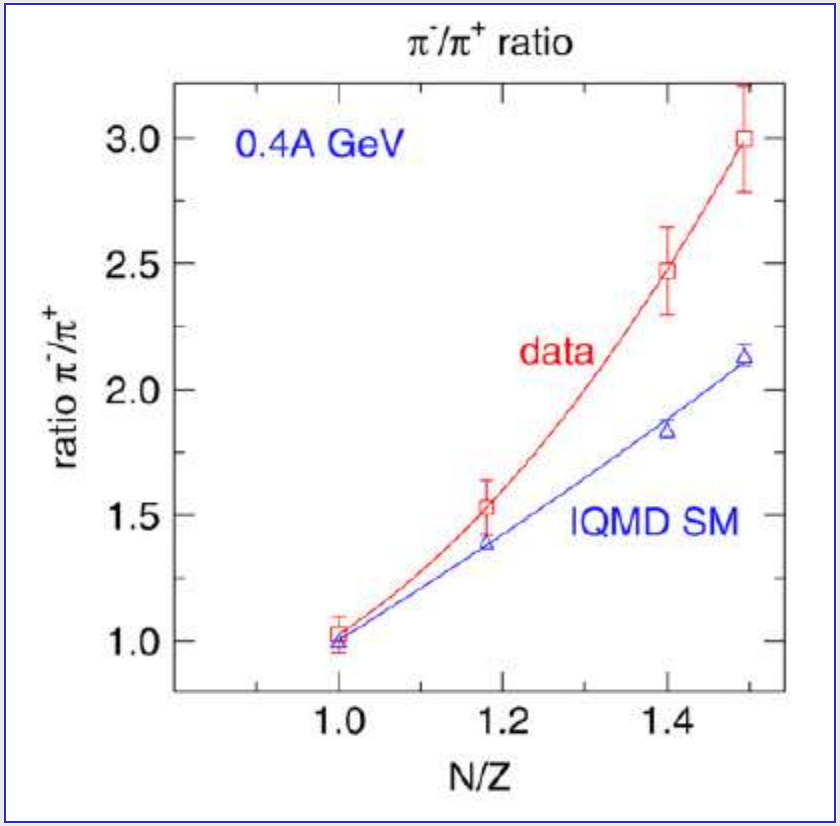
16-18 October 2009, Zagreb, Croatia

Convened by: Zoran Basrak, RBI

isotopic particle (double) ratios

FOPI data





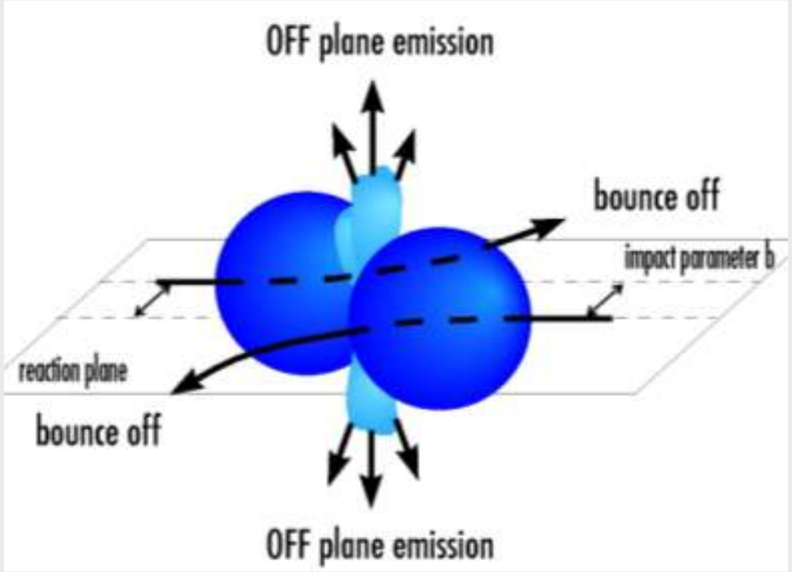
HIC scenario:
fast neutron emission (mean field effect) and transformation of neutron into proton in inelastic channels (no-chemical equilibrium)

Ferini et al.	stiffer for ratio up
Xiao et al.	softer "
Feng and Jin	stiffer "

consequence: extremely stiff (soft) solutions

differential flow in heavy-ion collisions

minimizes role of isoscalar part of the EoS



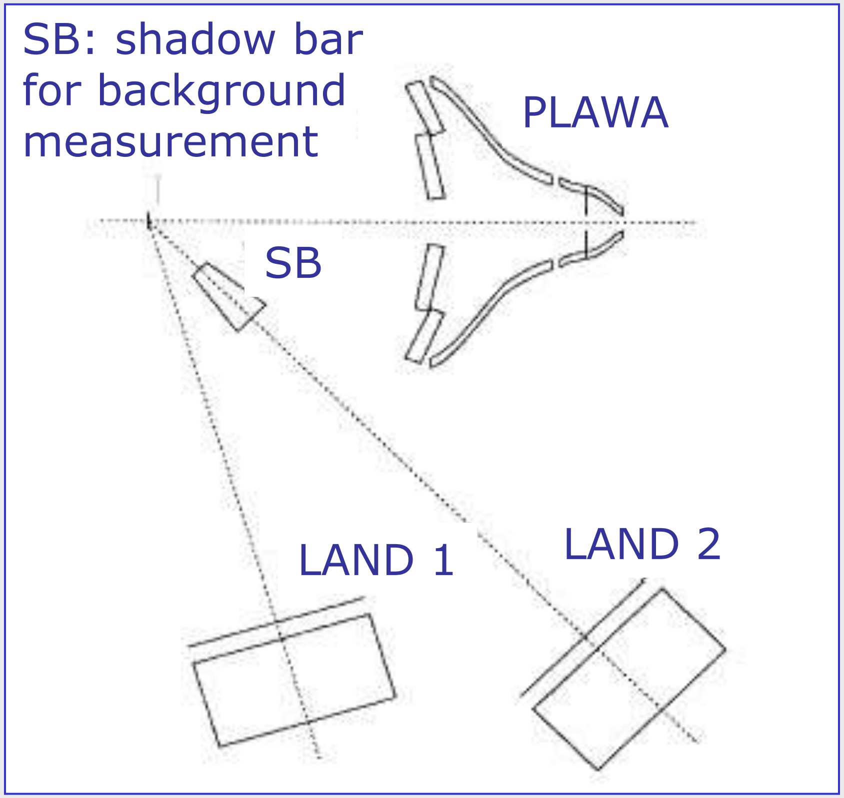
differential: neutrons vs. protons
t vs. ^{3}He, ^{7}Li vs ^{7}Be, ...

UrQMD: significant sensitivity predicted for differential elliptic flow
(Q.F. Li and P. Russotto)

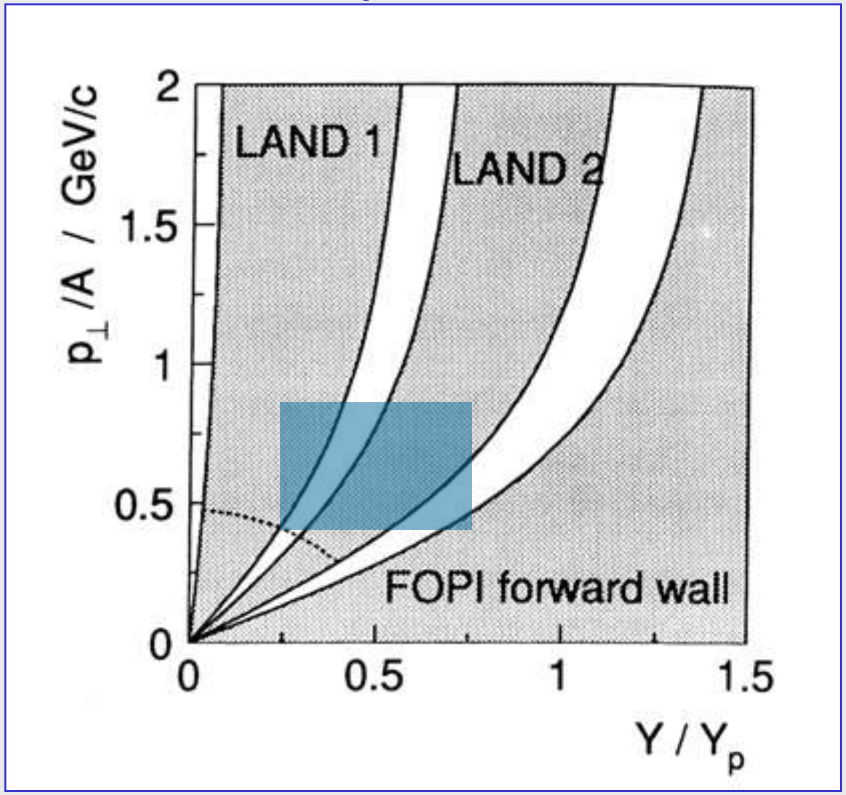
promising results from reanalysis of FOPI-LAND data:
$\gamma = 0.9 \pm 0.4$
Russotto, Wu, Zoric, Chartier, Leifels, Lemmon, Li, Lukasik, Pagano, Pawlowski, Trautmann, PLB 697, 471 (2011)

results from FOPI/LAND experiment

reanalysis of Au+Au 400 A MeV data



acceptance in p_t vs. rapidity



main yield here

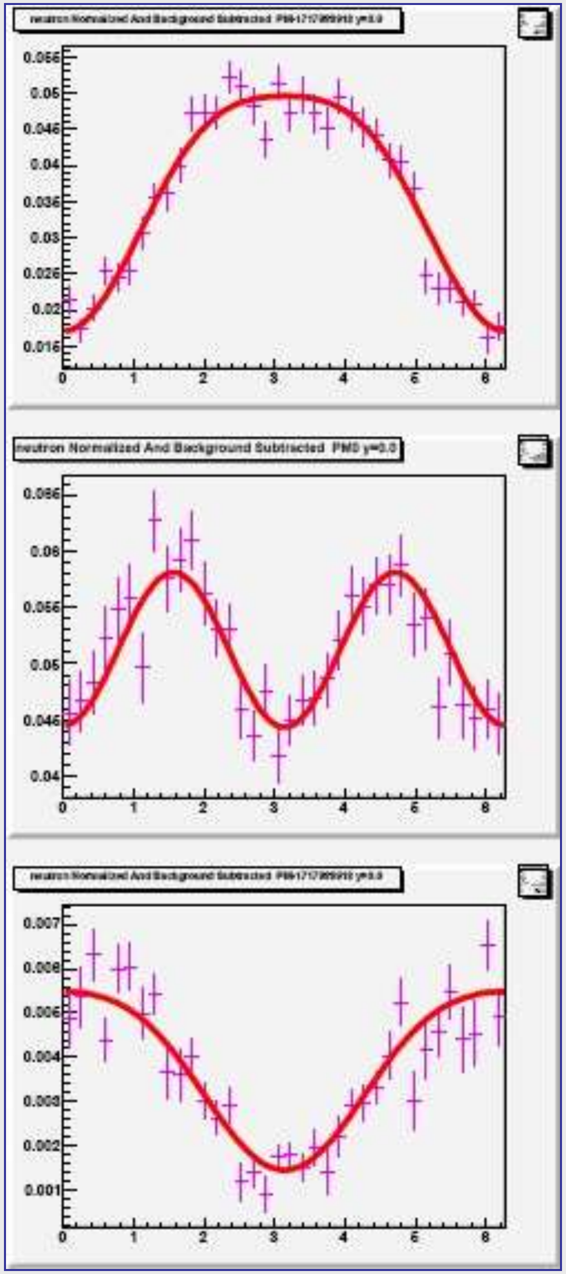
azimuthal angular distributions

for neutrons, background subtracted

near **target rapidity**
mostly directed flow

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

near **projectile rapidity**
mostly directed flow



fitted with:

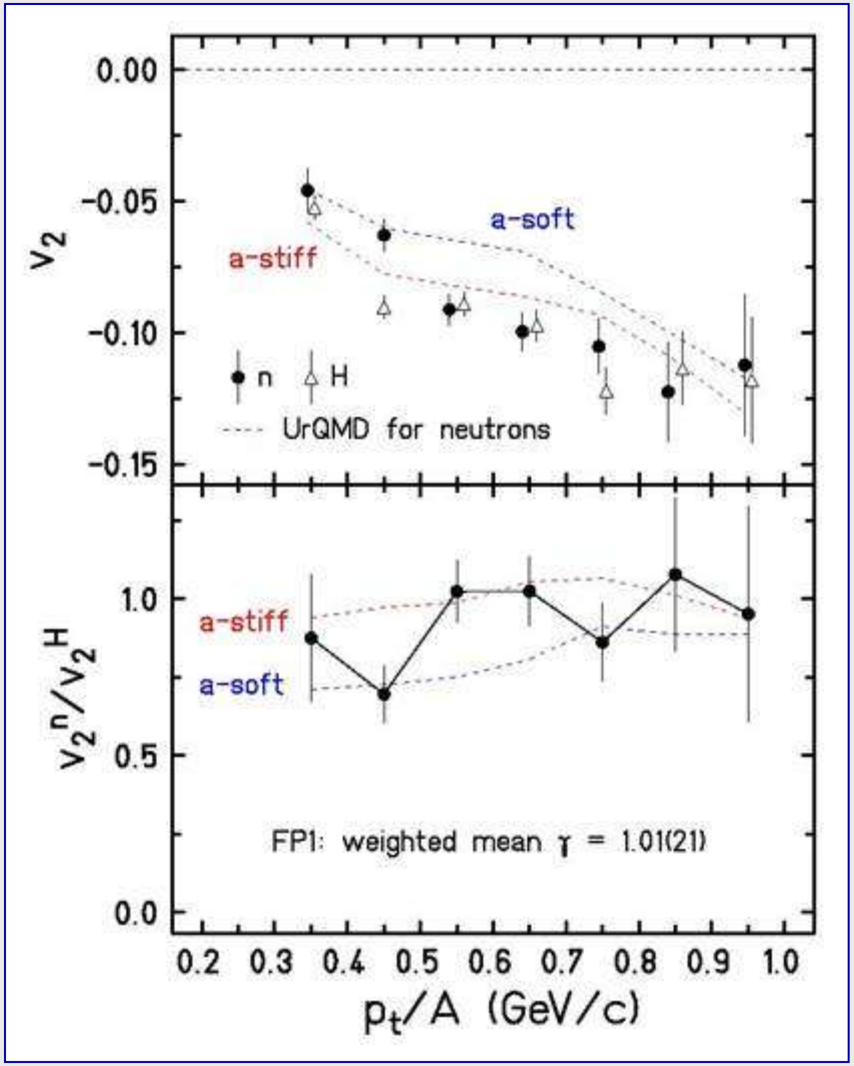
$f(\Delta\varphi)=a_0*(1.0+2\mathbf{v_1}*\cos(\Delta\varphi)+2\mathbf{v_2}*\cos(2\Delta\varphi))$

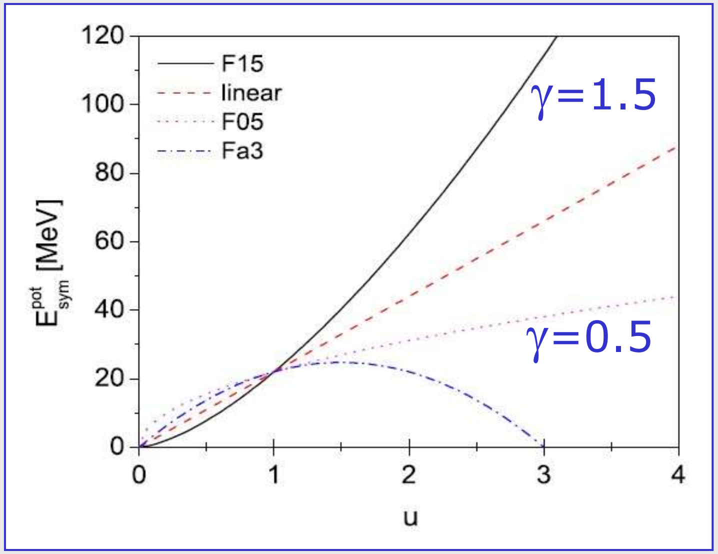
$\Delta\varphi = \varphi_{particle} - \varphi_{reaction\ plane}$

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

results from FOPI/LAND experiment

parameters in UrQMD, Q.F. Li et al.





neutron/hydrogen
FP1: γ = 1.01 ± 0.21
FP2: γ = 0.98 ± 0.35
neutron/proton
FP1: γ = 0.99 ± 0.28
FP2: γ = 0.85 ± 0.47
adopted: γ = 0.9 ± 0.4

neutron/hydrogen squeeze-out ratio, UrQMD: P. Russotto et al., PLB 697, 471 (2011)

summary

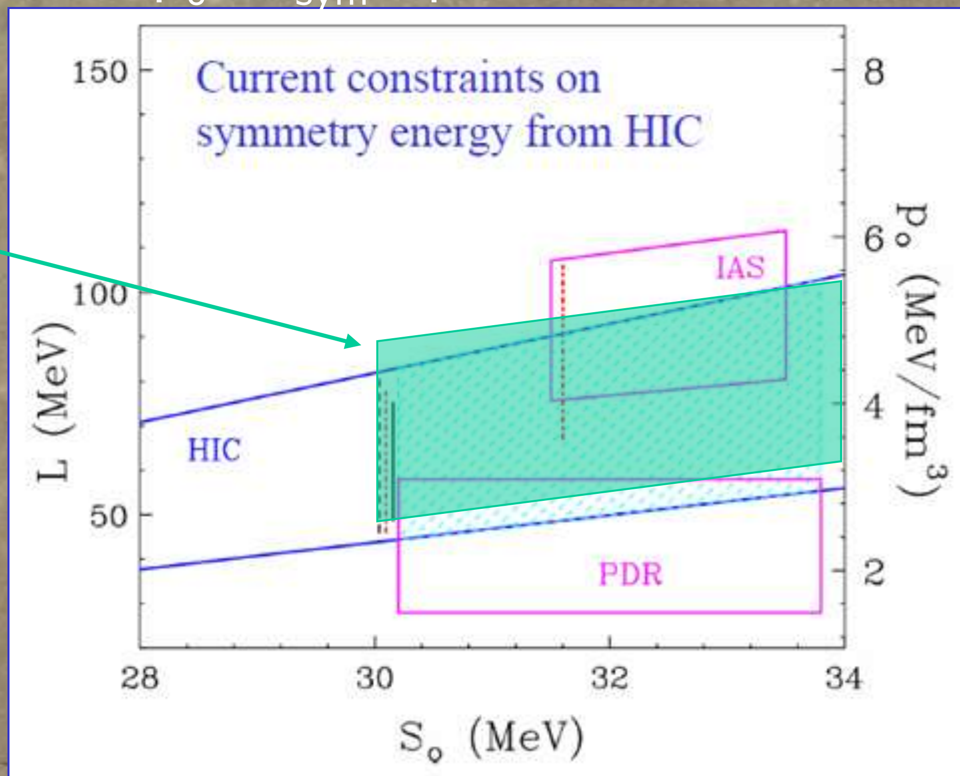
IAS isobaric analog states
Danielewicz/Lee 2008

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



see also "Complete Electric Dipole Response in ^{208}Pb"
Tamii et al.,
arXiv:1104.5431

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)