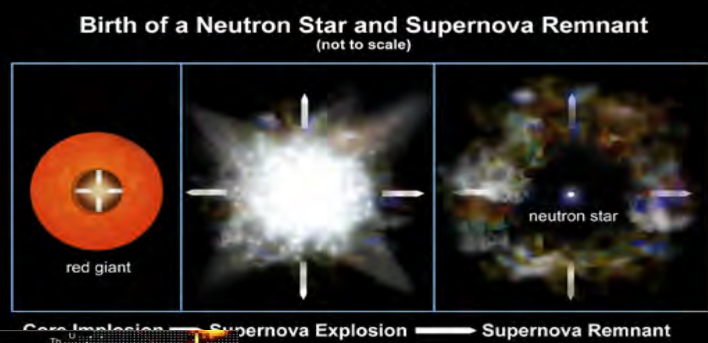
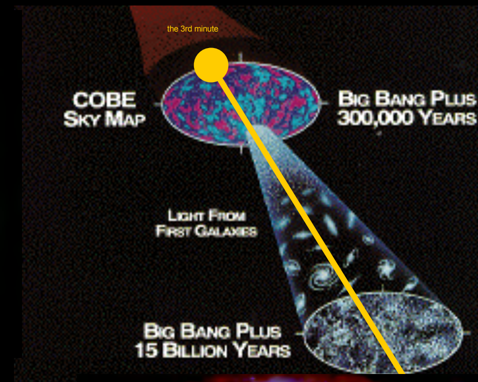
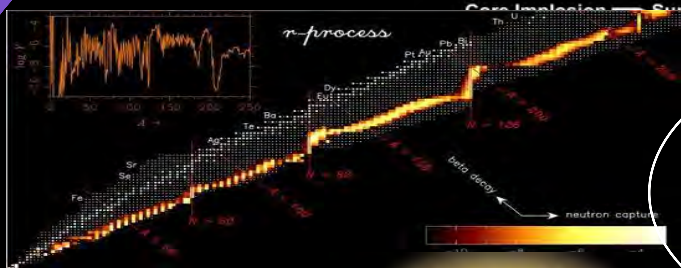
Isotopic effects in nuclear reactions and the symmetry energy at sub-saturation densities

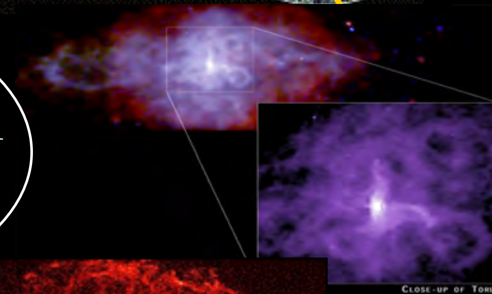
S. Yennello
Texas A&M University

from Atomic Nuclei to Neutron Stars

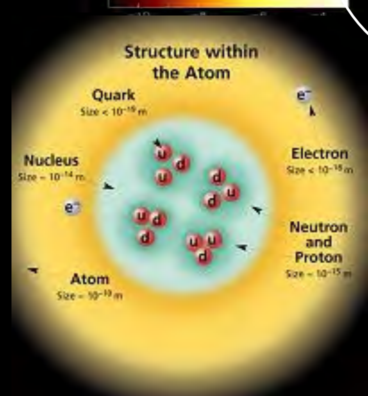


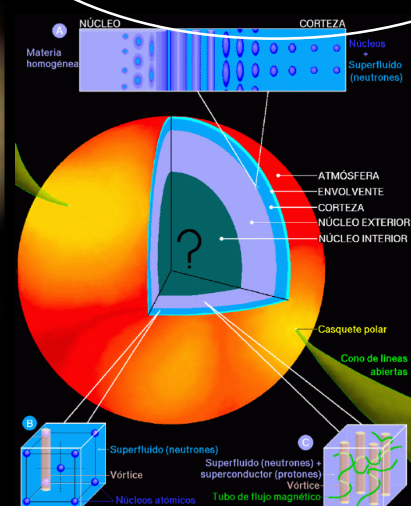


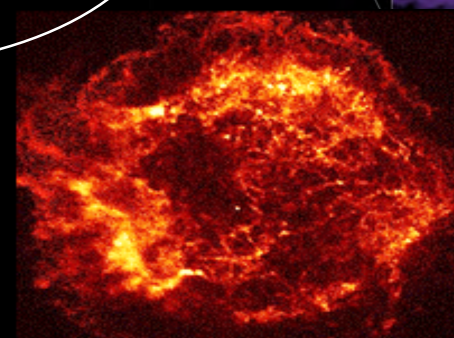




Nuclear Equation of State



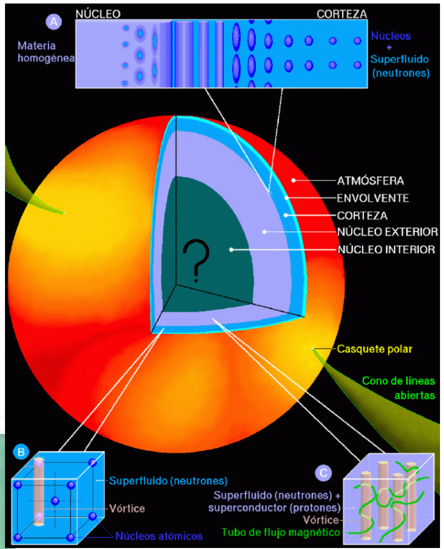


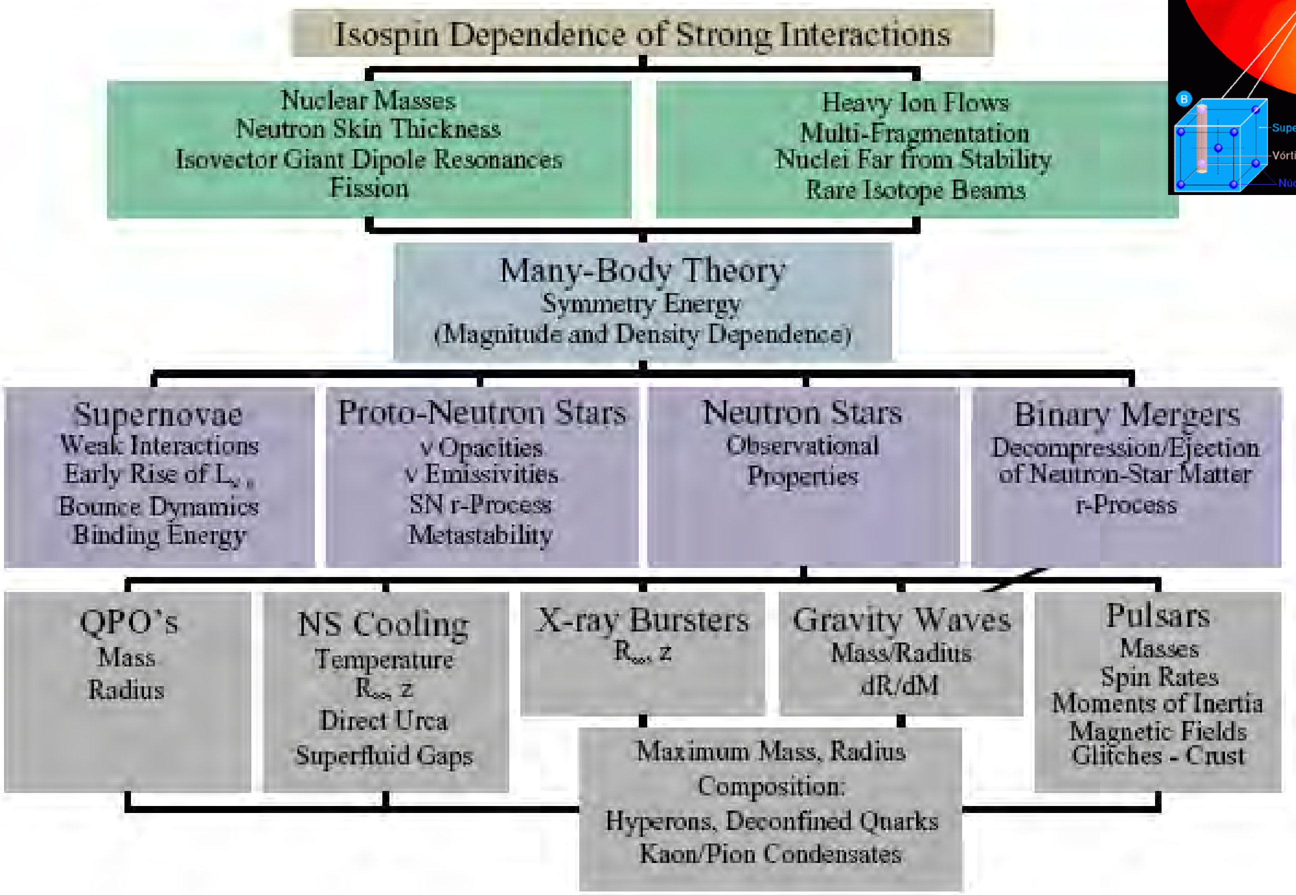


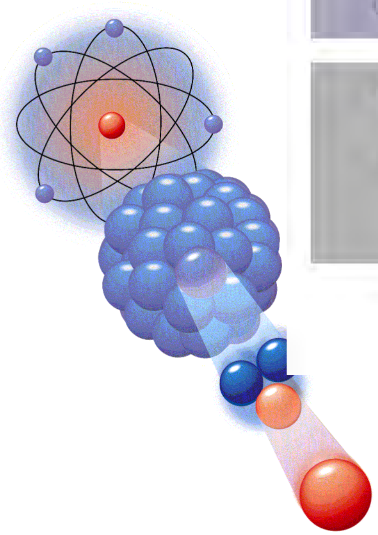
How elements are formed ?
How stars explode into supernova ?

What kind of matter exists inside a neutron star ?

Nuclear Equation of State







A. Steiner et al, Phys. Rept. 411 (2005) 325

Nuclear Equation of State (EoS)

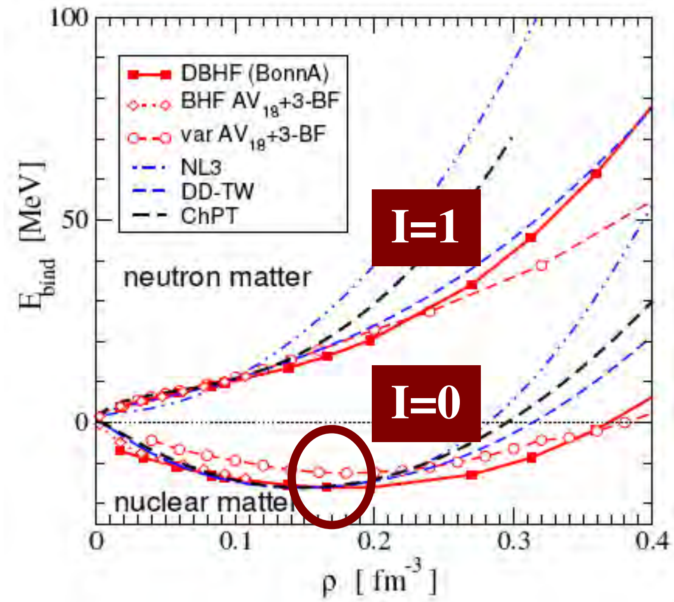
$$E(\rho, I) = E(\rho) + E_{sym}(\rho) I^2$$

$$with \quad I = \frac{\rho_n - \rho_p}{\rho_{Total}} \approx \frac{N - Z}{A}$$

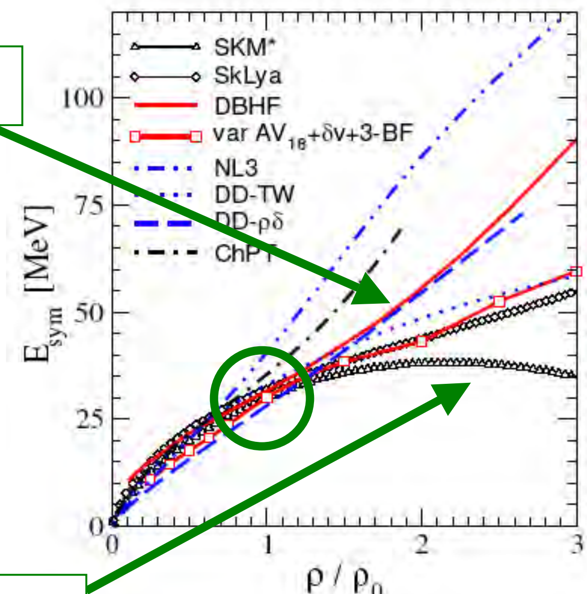
Binding Energy of Symmetric Nuclear Matter

Symmetry Energy Term for Asymmetric Matter

$$E_{sym}(\rho) = E(\rho,1) - E(\rho,0)$$



“Stiff”



“Soft”

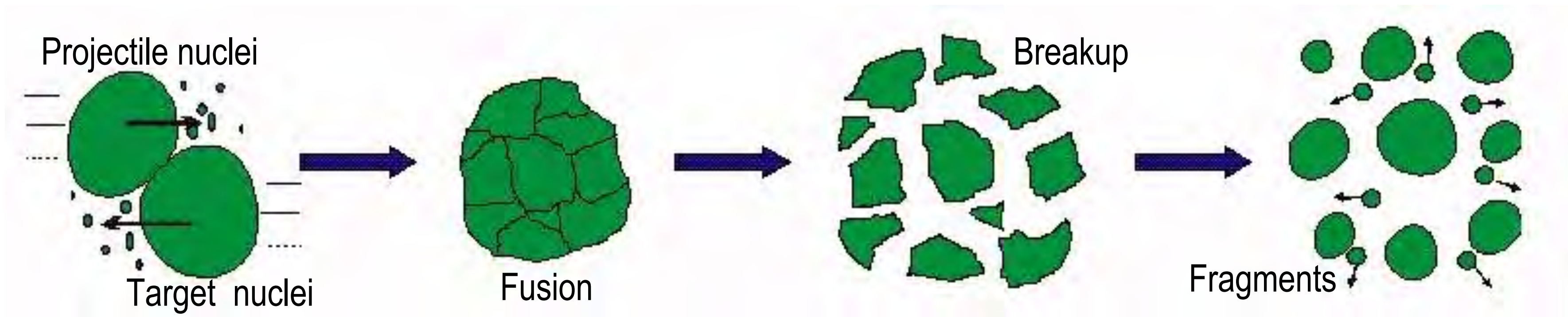
C. Fuchs and H.H. Wolter, Eur. Phys. J. A **30,** 5 (2006).
V. Baran *et al.*, Phys. Rep. **410,** 335 (2005).

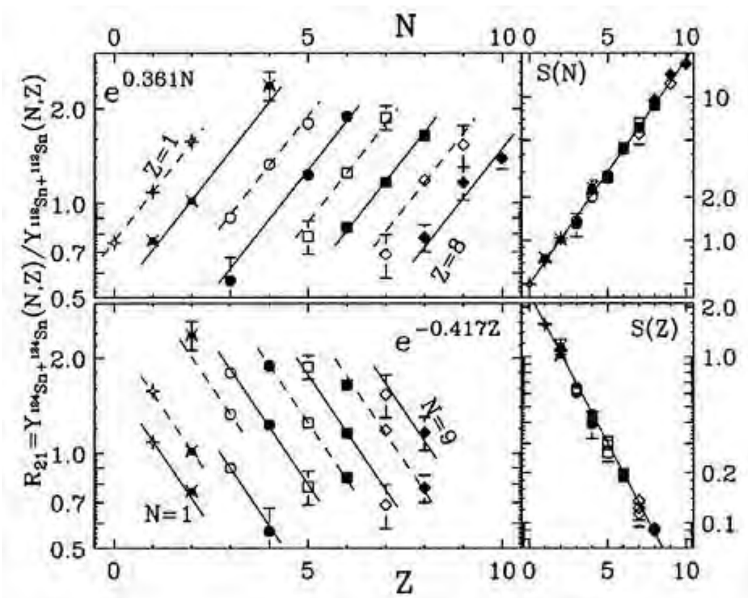
Observables sensitive to the asymmetry term in the EOS ?

Moderate density ($\rho < 1.5\ \rho_o$) :

Neutron-skin thicknesses
Pygmy resonances
Fragment isotope distribution, isotopic & isobaric yield ratios
Isospin distillation/fractionation, relative n & p densities
Isospin transport / diffusion / migration
Nuclear stopping & N/Z equilibration
Pre-equilibrium emission
Particle - particle correlation
Light cluster production
Flow
Neck emission
Fusion vs Deep Inelastic reactions

Studying density dependence of symmetry energy : Multifragmentation





$$\alpha = \frac{4C_{sym}}{T}\left(\frac{Z_1^2}{A_1^2} - \frac{Z_2^2}{A_2^2}\right)$$

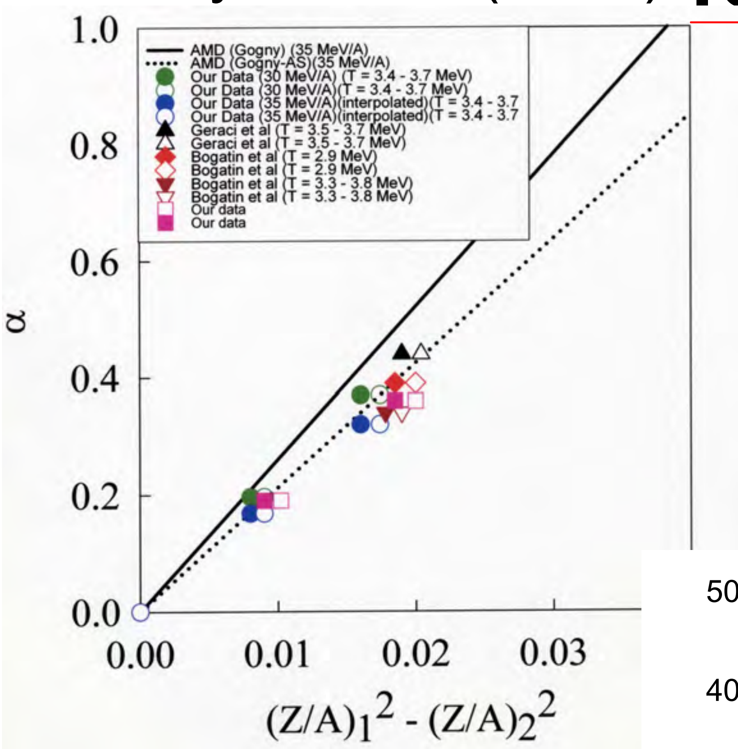
α – Scaling parameter

C_{sym} – Symmetry energy

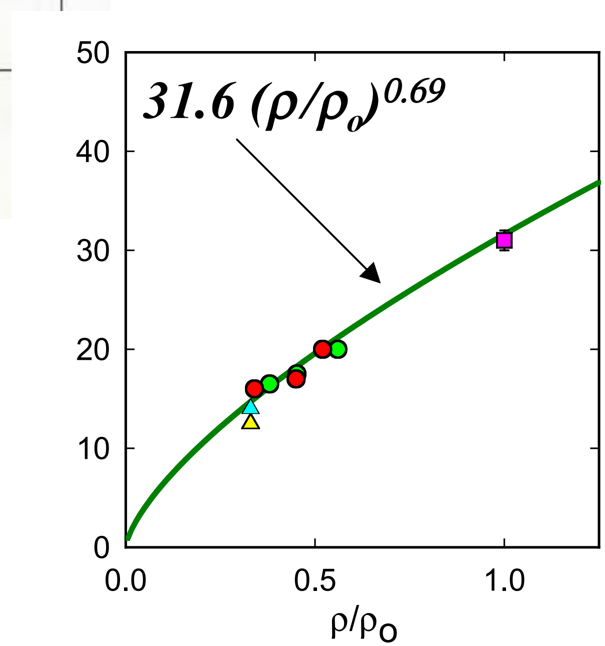
M.B. Tsang et al, Phys. Rev. Lett 68 (2001) 5023

Isoscaling

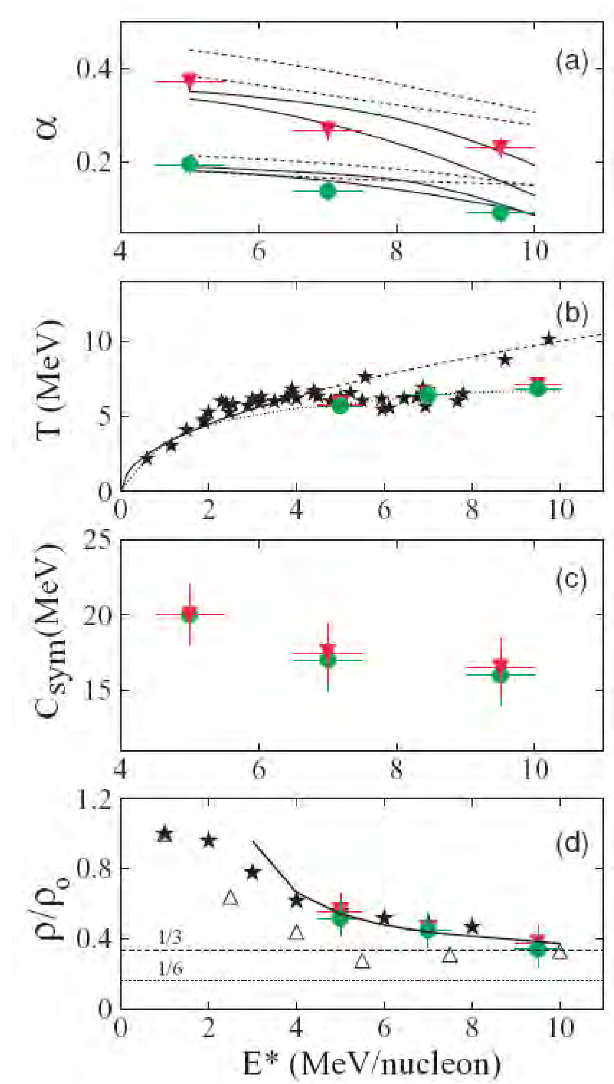
Dynamical (AMD)



D. V. Shetty et al, PRC 70 (2004) 011601(R)

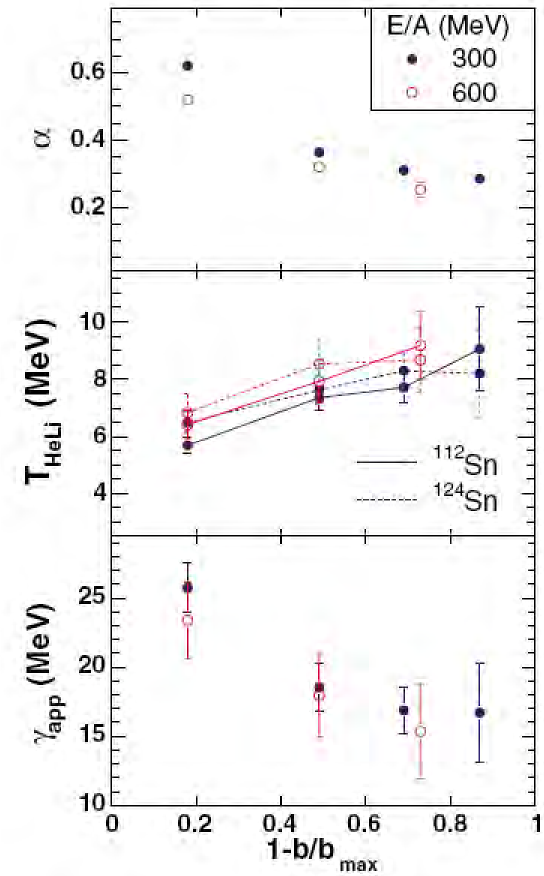


Statistical (SMM)

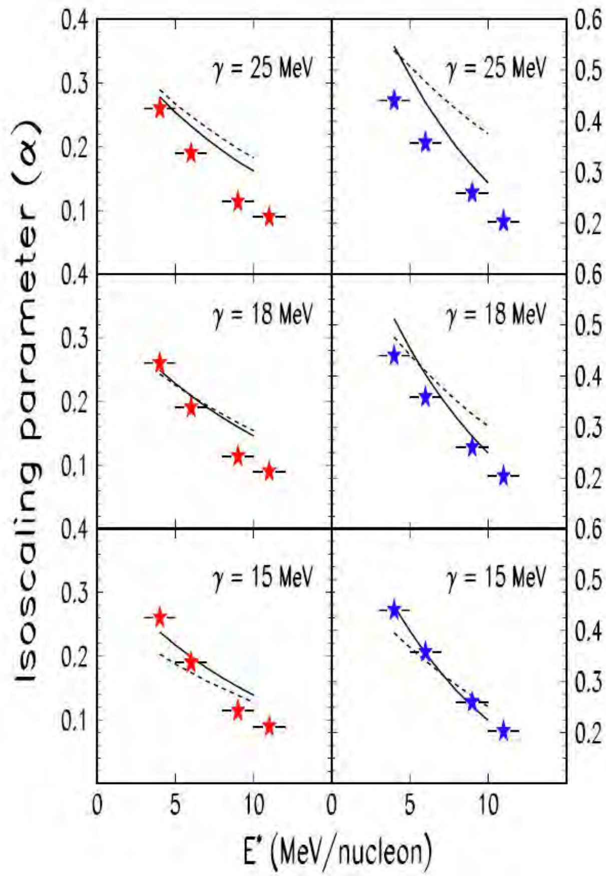


D.V. Shetty et al., PRC 76 (2007) 024606

Decrease in Symmetry energy (Expt. Observation)



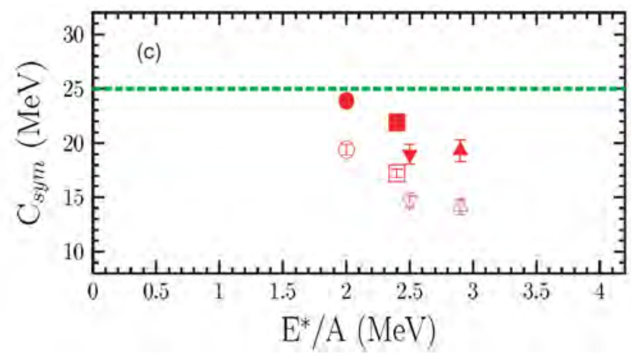
A. Le Fevre et al., PRL 94 (2005) 162701

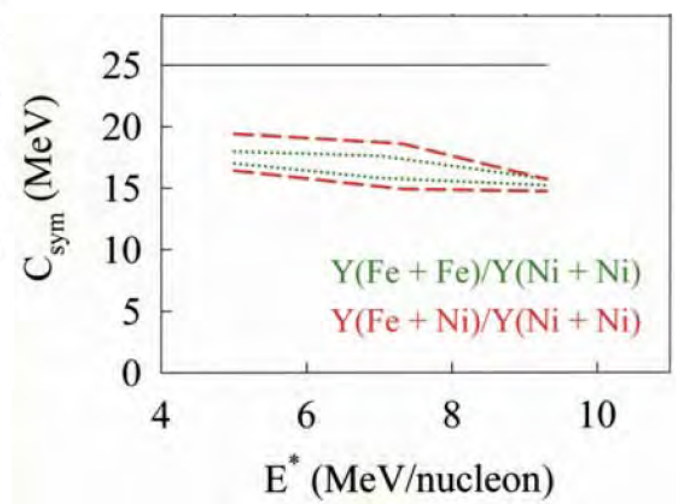


J. Iglio et al., PRC 74 (2006) 024605

G.A. Souliotis et al., PRC 73 (2006) 024606

G.A. Souliotis et al., PRC 75 (2007) 011601

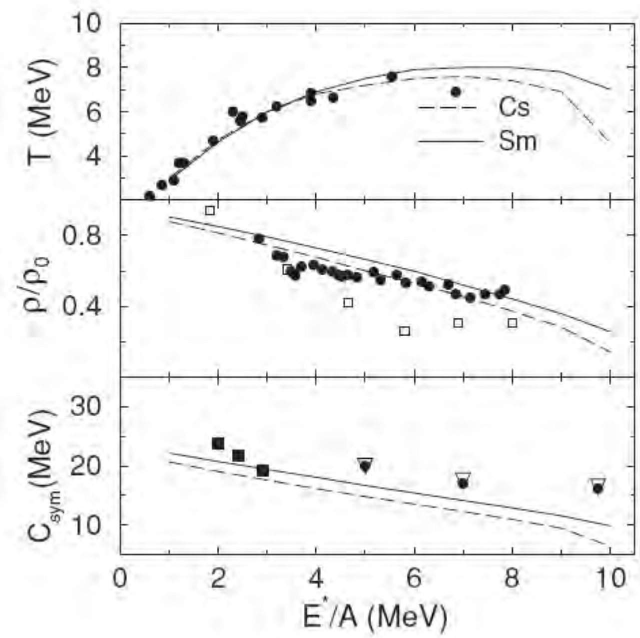




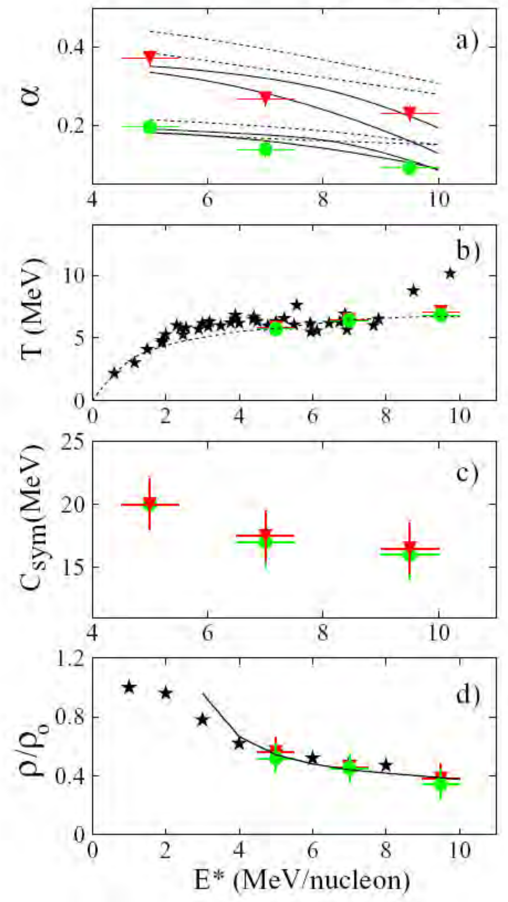
D.V. Shetty et al., PRC 74 (2005) 024602

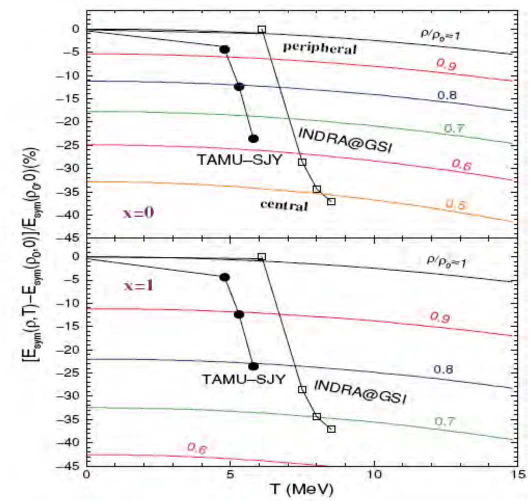
Decrease due to thermal expansion

- Finite T Thomas-Fermi
Seyler Blanchard interaction



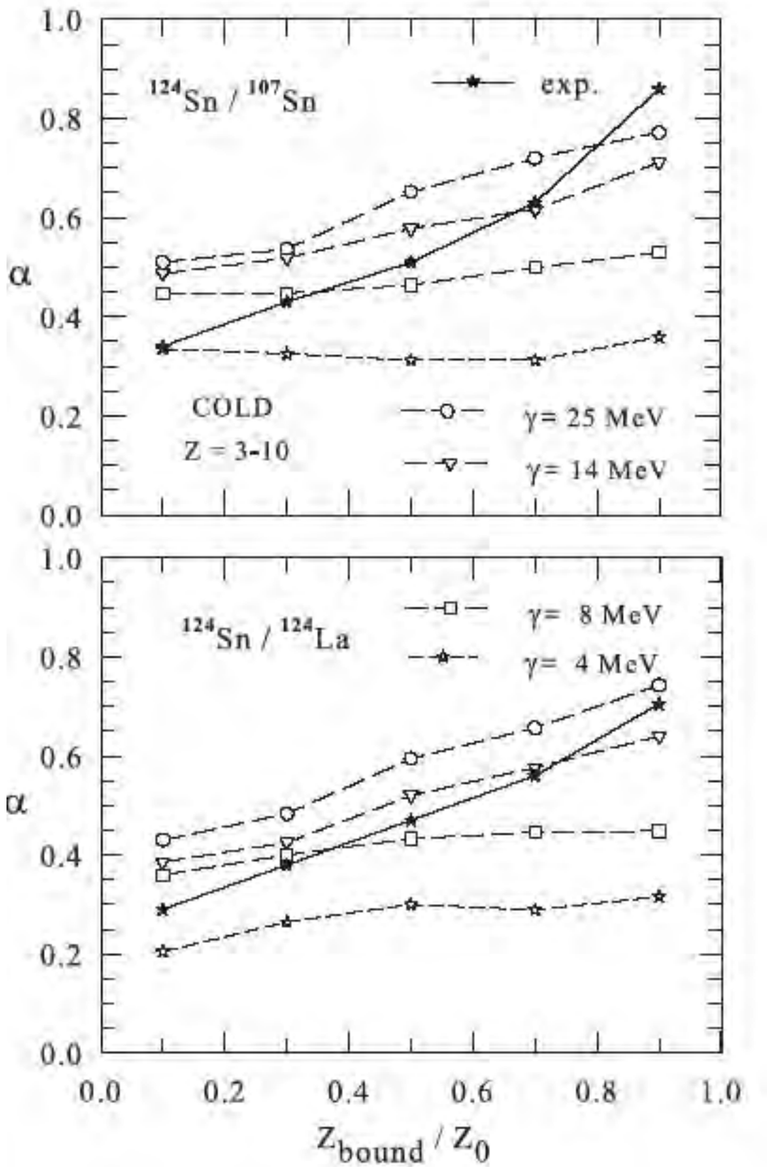
S.K. Samaddar et al., PRC 76 (2007) 041602

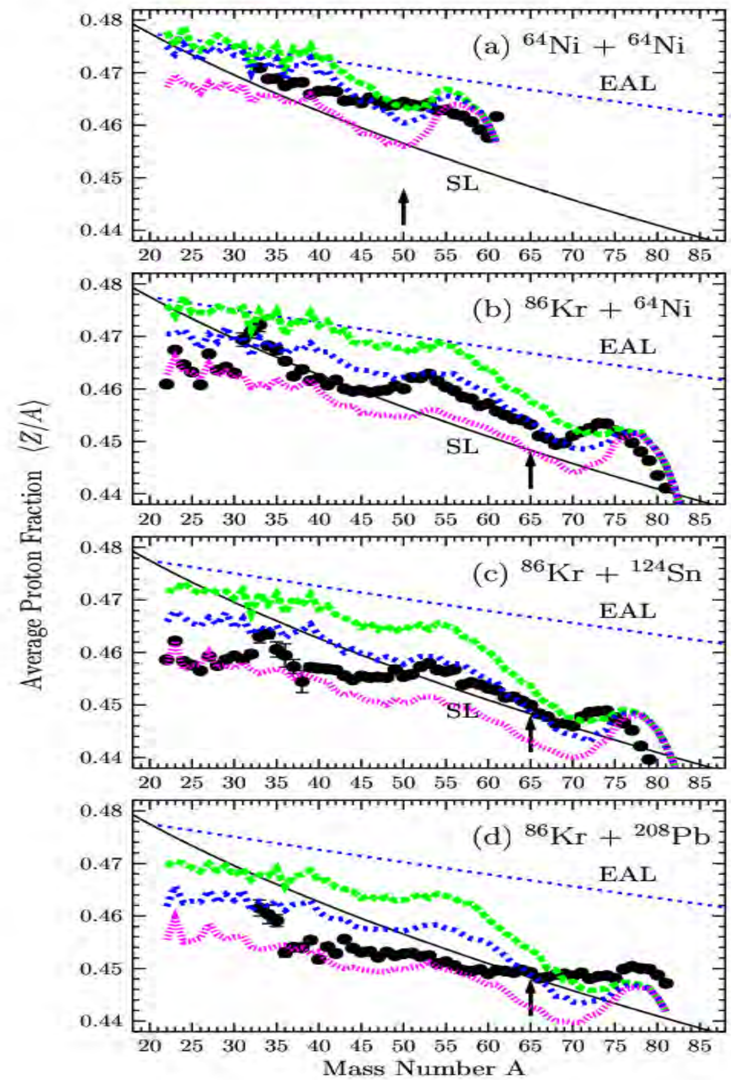




B.A. Li et al., PRC 74 (2006) 034610

Evolving Csym





DIT/SMM05 Calculations:

------ C_{sym} = 25 MeV

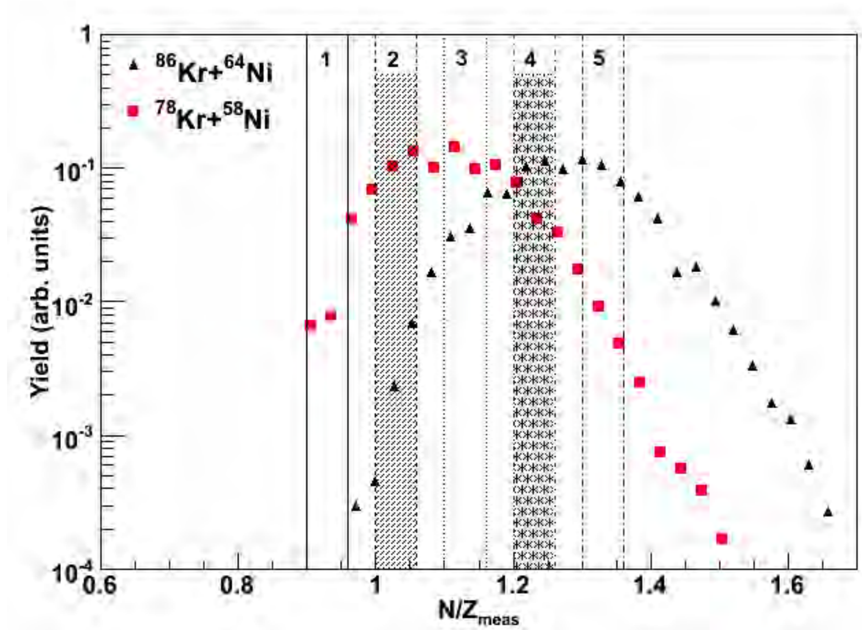
------ C_{sym} = 20 MeV

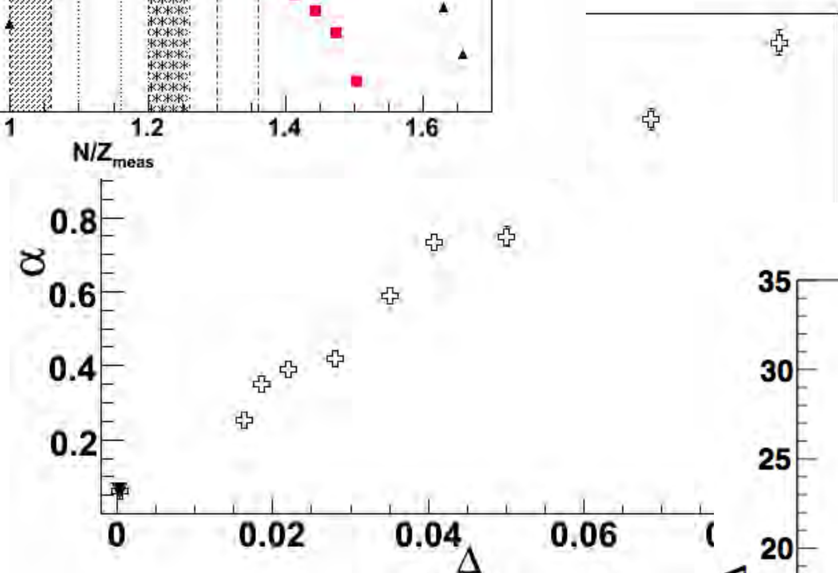
------ C_{sym} = 15 MeV

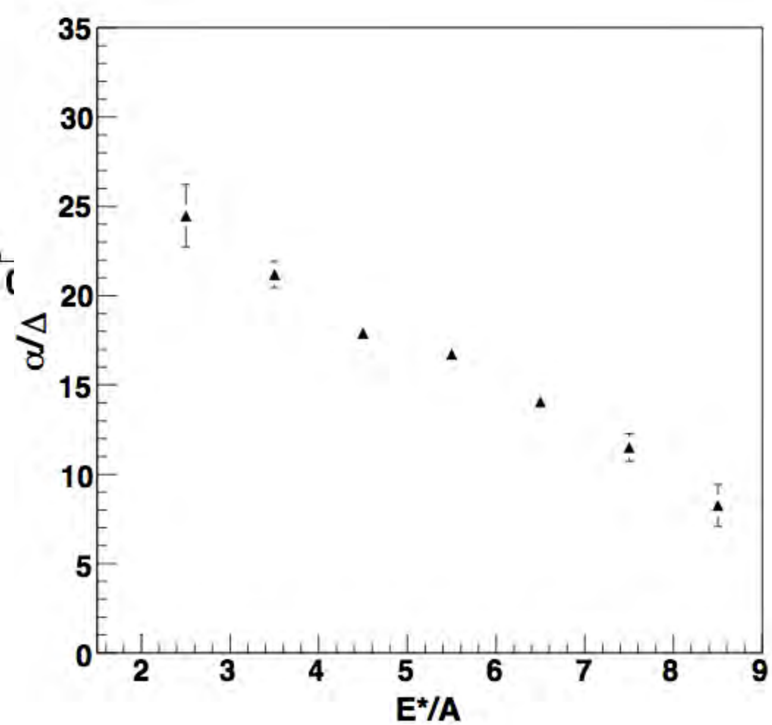
* G.A. Souliotis et al. Phys. Rev. C **75**, 011601 (2007)

Reconstructed sources

^{78}Kr, ^{86}Kr + ^{58}Ni, ^{64}Ni
35 MeV/nucleon
NIMROD-ISiS
(includes free neutrons)







$$\frac{\alpha}{\Delta} = \frac{4C_{sym}}{T}$$

S. Wuenschel, Phys. Rev. C 79, 061602(R) (2009)

Mirror nuclei ratios in well defined systems

Landau expansion of free energy near the critical point

$$\frac{F}{T} = \frac{1}{2}am^2 + \frac{1}{4}bm^4 + \frac{1}{6}cm^6 - \frac{H}{T}m$$

m (=N-Z)/A: Order parameter
H : External field

$$\frac{H}{T} = am_S\left(1 + Higher\ order\ terms\ in\ 'm'\ and\ 'm_s'\right)$$

For mirror nuclei yield ratio (ignoring the higher order terms)

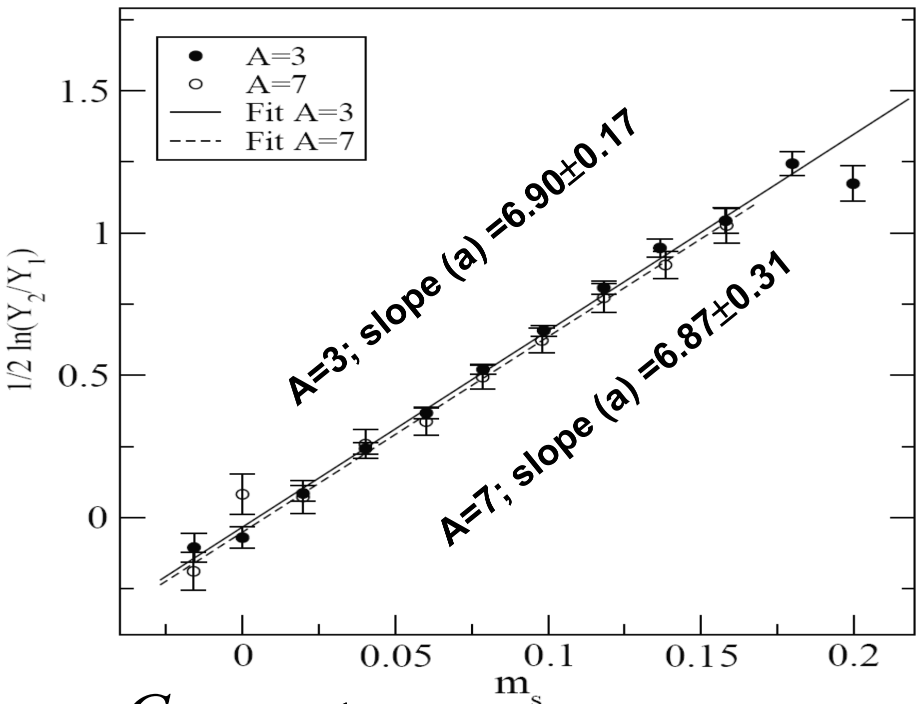
$$\frac{1}{2}\ln\left(\frac{Y_2}{Y_1}\right) = am_S$$

Source Isospin

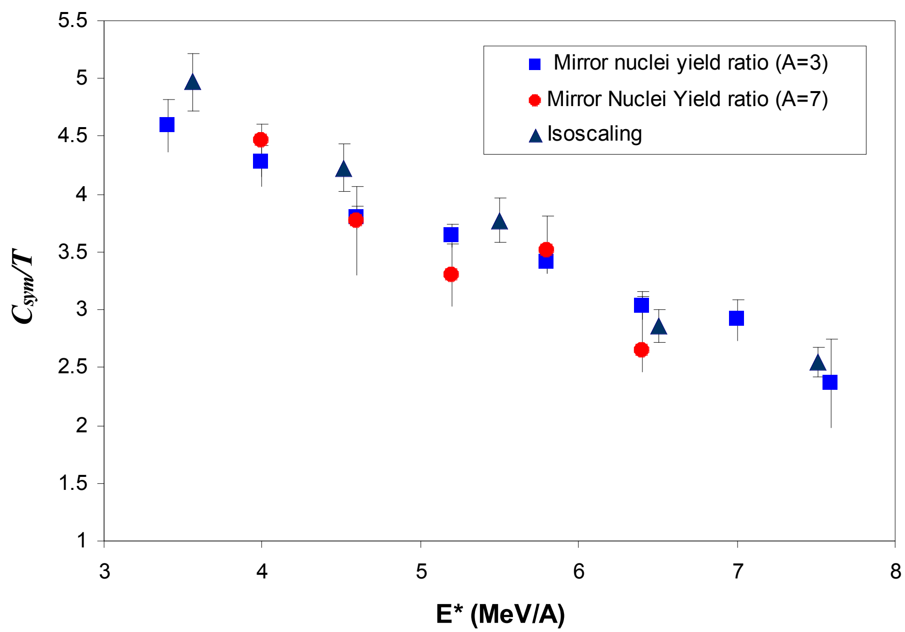
$$\frac{C_{Sym}}{T} \approx \frac{1}{2}a$$

Average ratios (A=3 and A=7) from four different reaction systems

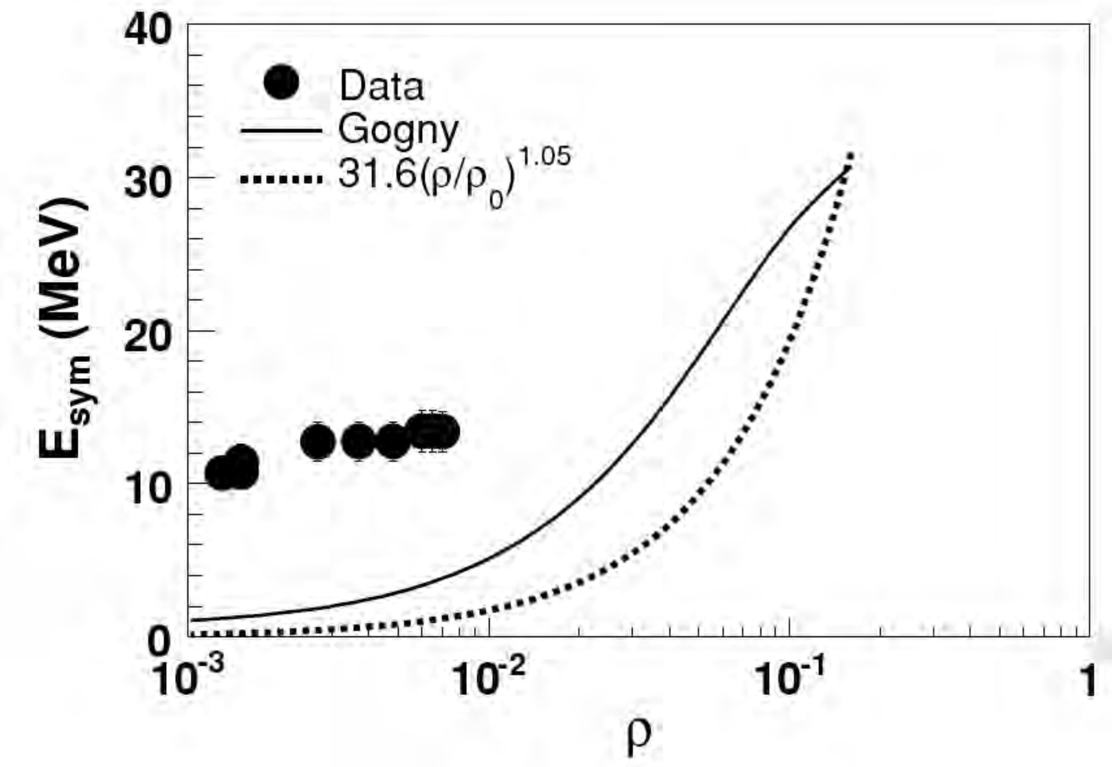
^{78,86}Kr+^{58,64}Ni (E_{lab}=35 MeV/A)



$$\frac{C_{Sym}}{T} \approx \frac{1}{2}a$$



Low density

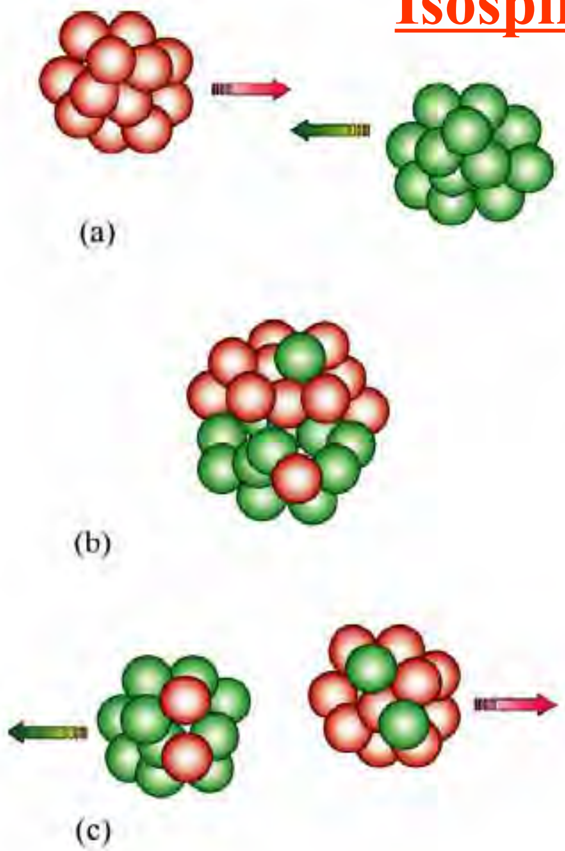


clusters matter
Entropy

Kowalski, C 75, 014601 (2007)

Isospin Equilibration / Diffusion

Isospin Diffusion/Transport



Particle Flux:

$$\Gamma_i = n_i \left(\underline{\mathbf{v}}_i - \underline{\mathbf{v}} \right),$$

Isospin Flow:

$$\Gamma_I = \Gamma_n - \Gamma_p = -n D_I \frac{\partial \delta}{\partial \mathbf{r}}.$$

Isospin diffusion coefficient D_I depends on the symmetry potential

*L. Shi and P. Danielewicz, Phys. Rev. C**68**, 017601 (2003).*

How to measure Isospin Diffusion?

F. Rami et al. (FOPI/GSI) **PRL84, 1120 (2000)**

A measure of isospin transport in the reaction A+B using any isospin tracer X

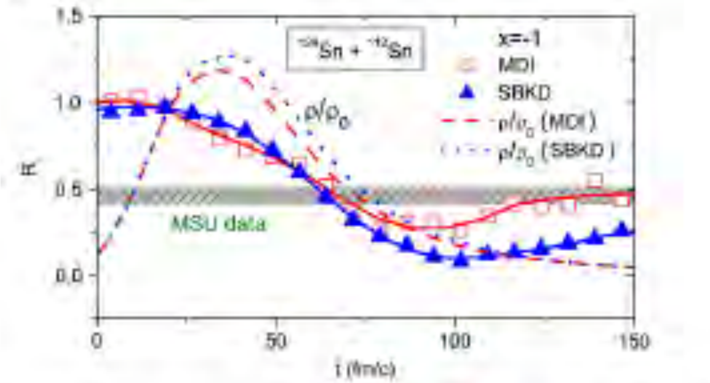
$$R_X = \frac{2X^{A+B} - X^{A+A} - X^{B+B}}{X^{A+A} - X^{B+B}}$$

A+A,B+B,A+B

X: isospin tracer

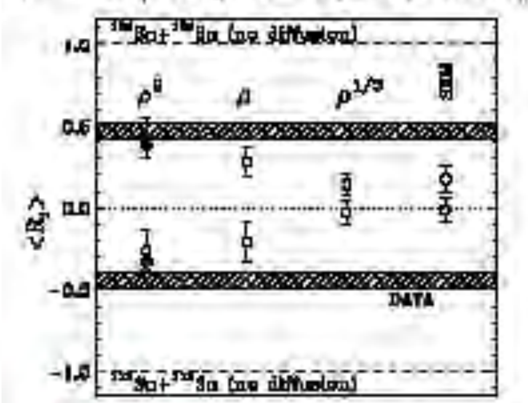
MSU data

$x = \alpha$



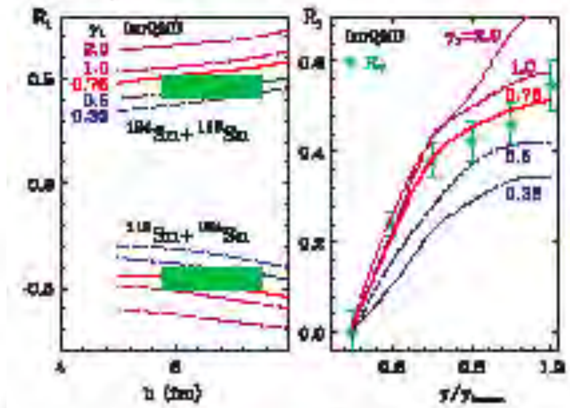
Comparison to IBUU04, b=6 fm (B.A. Li)
Best agreement for asy-stiff: x=-1 $\equiv \gamma$=1

$x = \alpha$ (Tsang PRL 92 (2004) 062701)

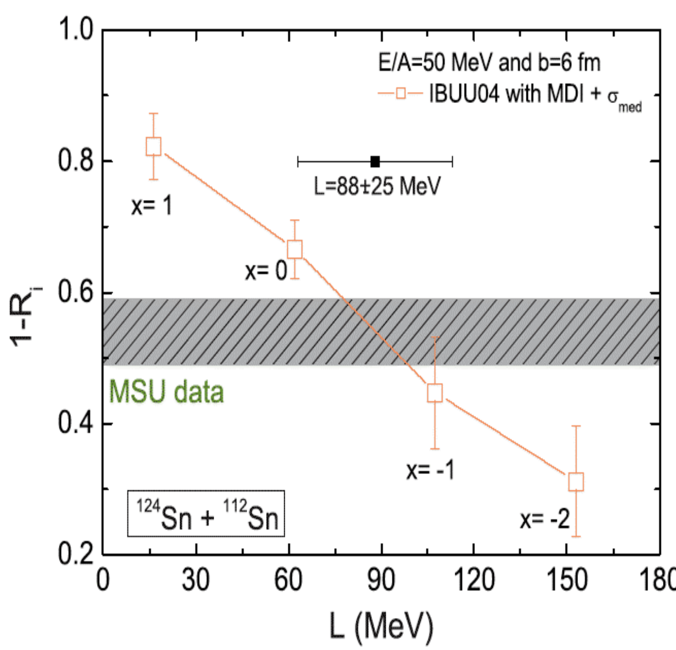


Comparison to BUU97 (B. A. Li
asy-stiff $\gamma \sim 2$

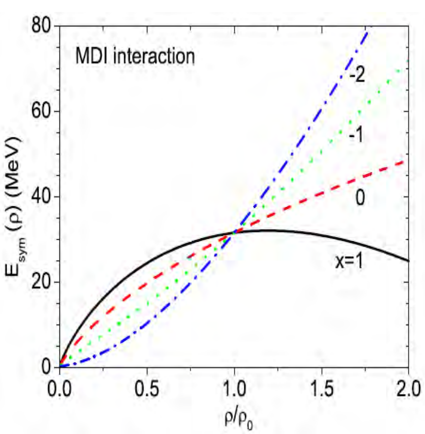
$x = \alpha$ (left) and R_7 (right)
both agree in QP region
$y/y_{beam} > 0.7$ (*Tsang PRL 102 (2004) 122701*)

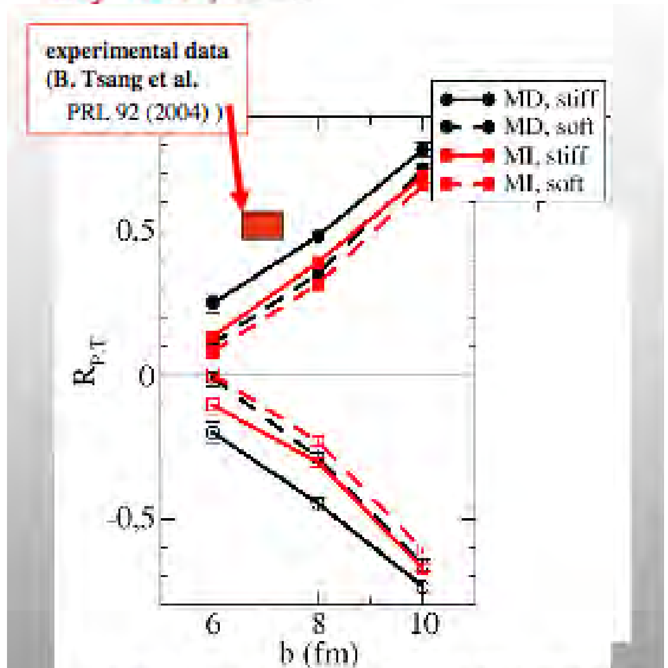


Comparison ImQMD (Z. Li):
asy-soft $\gamma \sim 0.7$



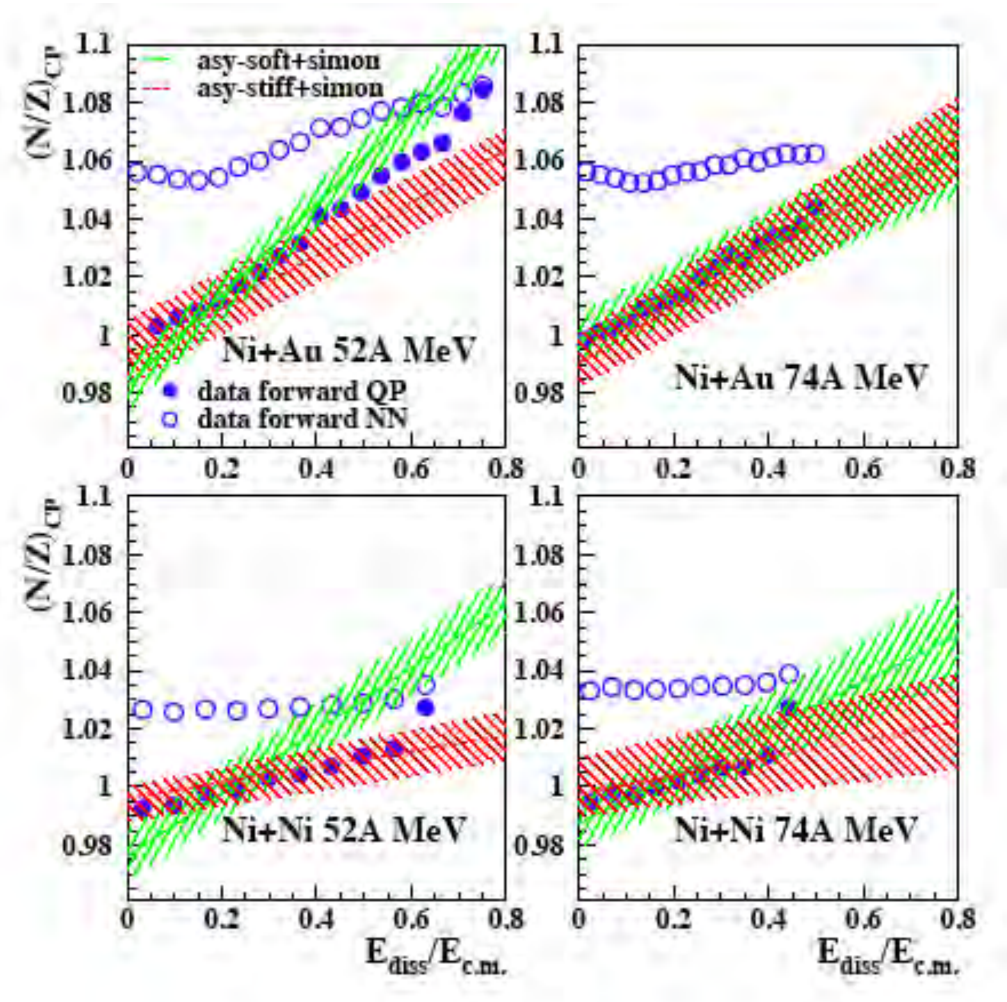
Chen/Ko/Li, PRC72,064309 (2005)





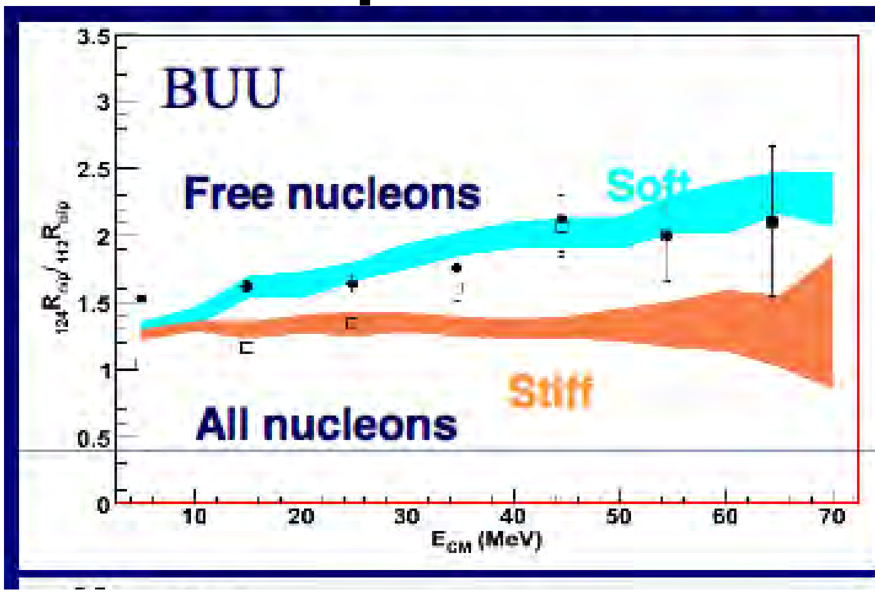
J.Rizzo, et al., Nucl. Phys. A806 (2008) 79

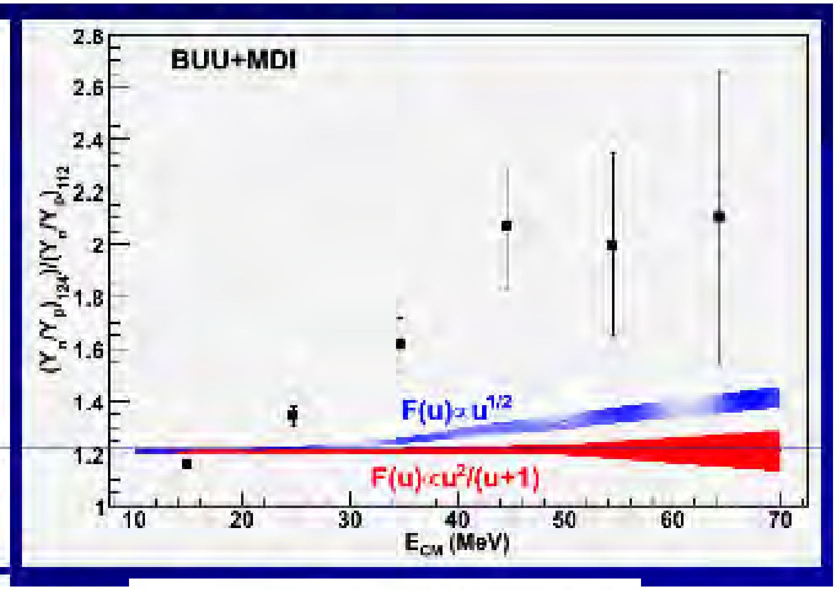
INDRA Data



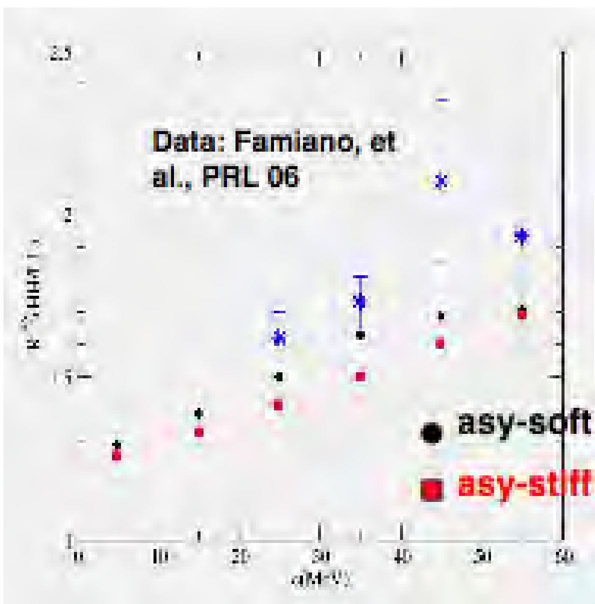
Colonna, IWM09; INDRA data E. Galichet et al. PRC 79 (2009) 064614/15

n/p ratios $^{124}Sn + ^{124}Sn$, $^{112}Sn + ^{112}Sn$

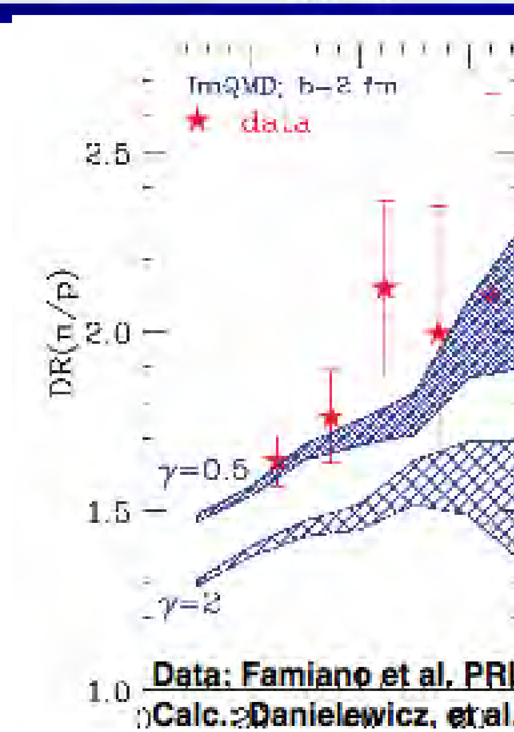




Famiano, 2006 (Li, 1997)



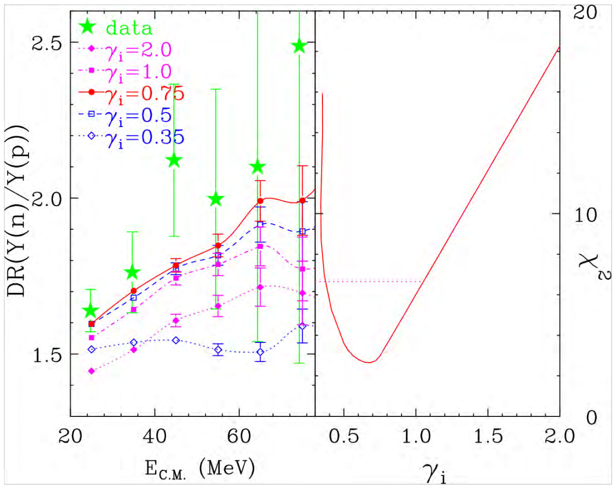
SMF simulations V. Baran 07

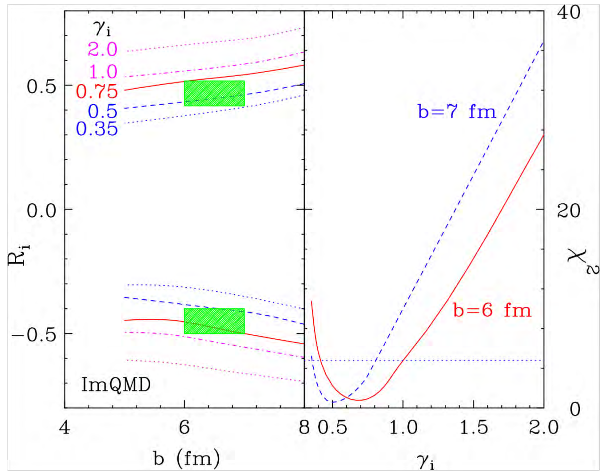


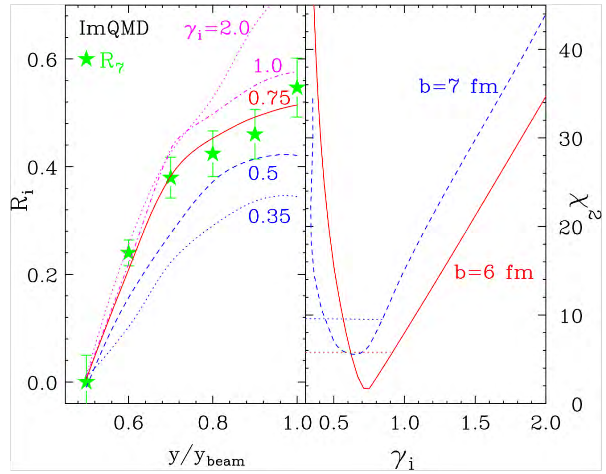
Isospin diffusion and double n/p ratio

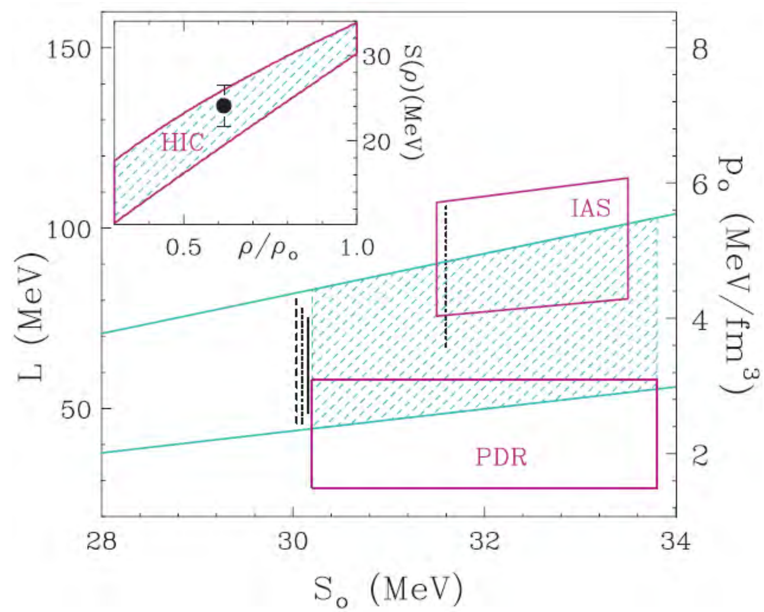
ImQMD: n/p ratios and two isospin diffusion measurements

Tsang/Zhang/Danielewicz/Famiano/Li/Lynch/Steiner, PRL 102, 122701 (2009)







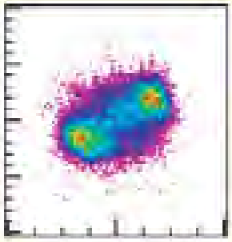


ImQMD: Isospin Diffusion and double n/p ratio ➔

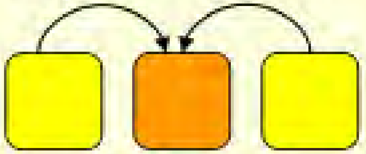
$E_{sym}(\rho_0)$=28 - 34 MeV

L=38 - 103 MeV

Isospin migration in neck fragmentation



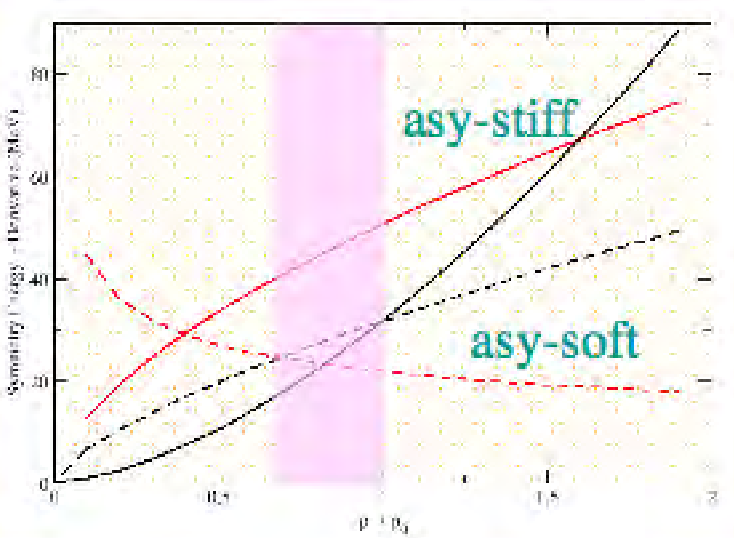
Asymmetry flux



$\rho_{IMF} < \rho_{PLF(TLF)}$

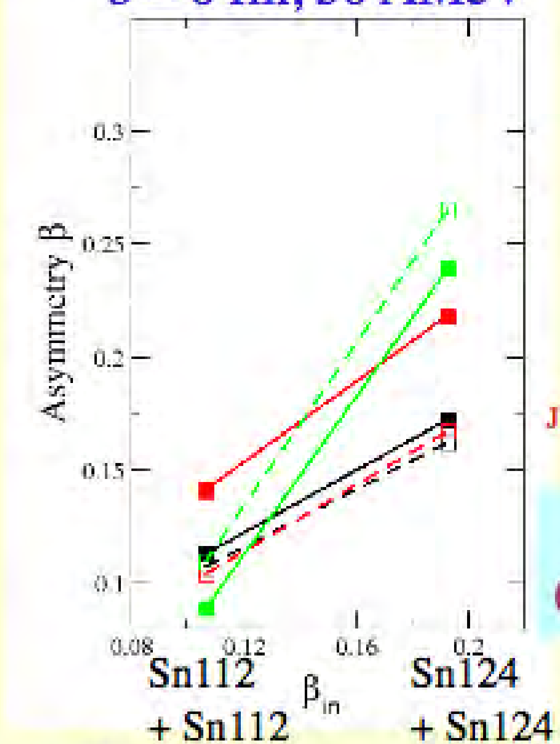
- Transfer of asymmetry from PLF and TLF to the low density neck region: **neutron enrichment of the neck region**
- Effect related to the derivative of the symmetry energy with respect to density

Density gradients ⟶ derivative of E_{sym}



Larger derivative with asy-stiff ⟶ larger isospin migration effects

b = 6 fm, 50 AMeV



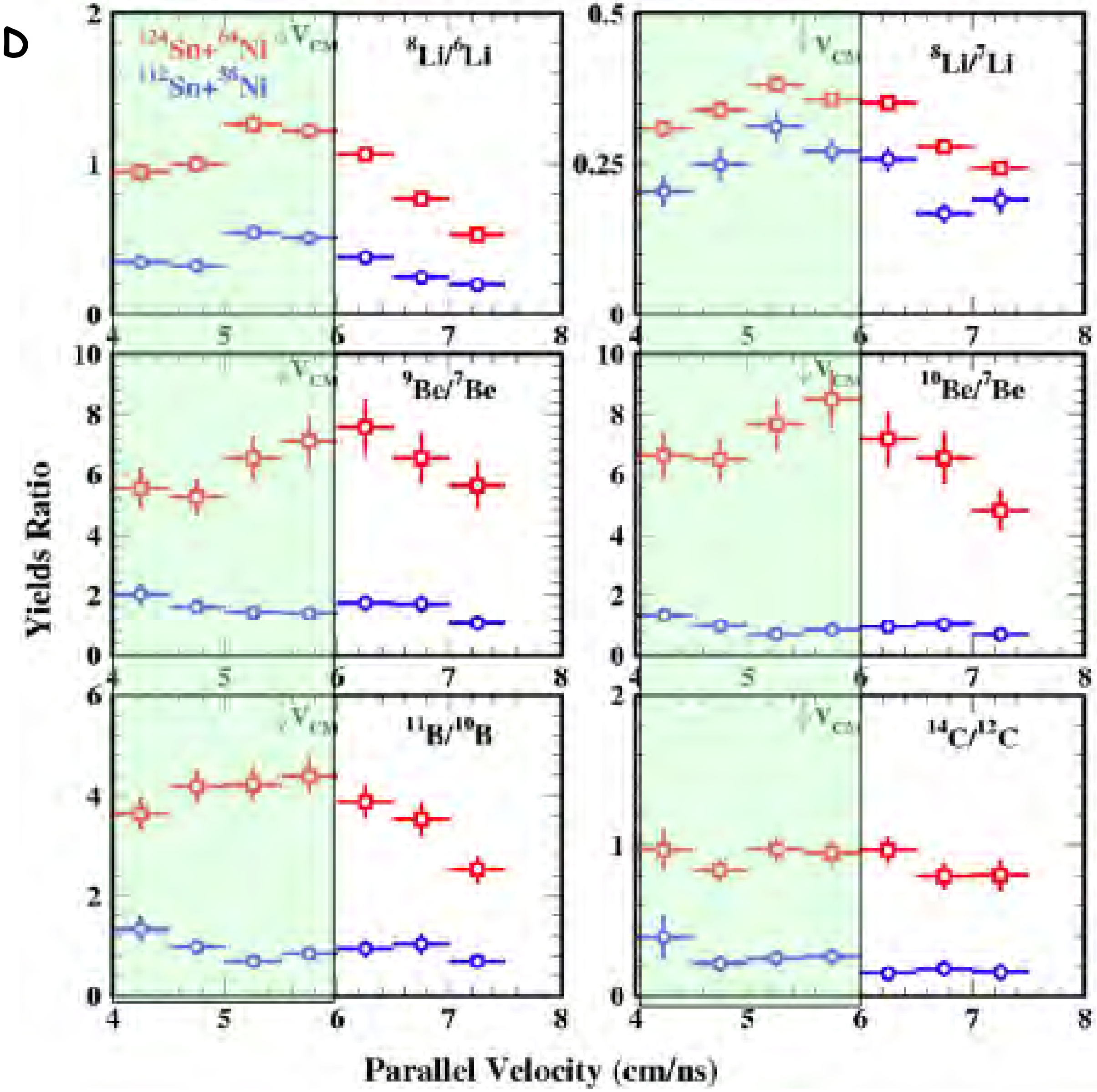
PLF, TLF
neck
emitted nucleons

J.Rizzo et al. NPA806 (2008) 79

⟶ see **CHIMERA data**

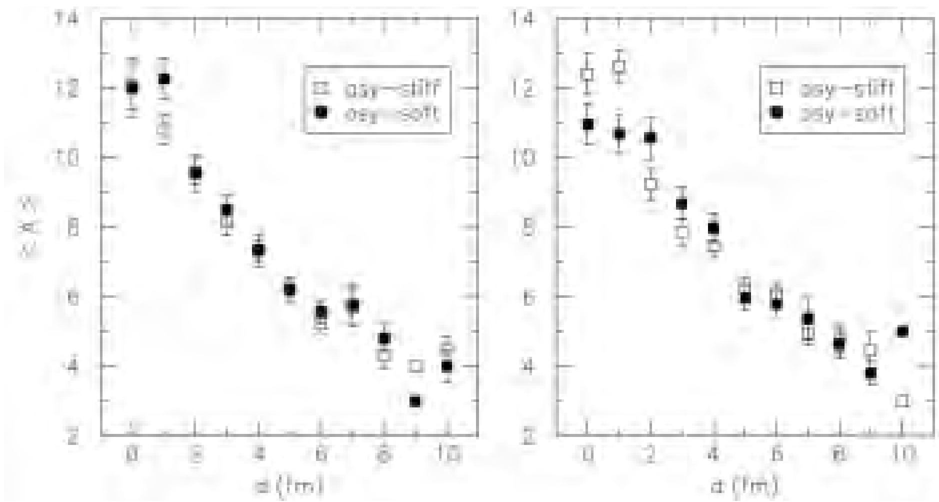
The asymmetry of the neck is larger than the asymmetry of PLF (TLF) in the stiff case

ISOTOPIC RATIOS FOR LIGHT FRAGMENTS (Z=3-6) IN THE 35/A.MeV
NEUTRON RICH $^{124}Sn+^{64}Ni$ AND
NEUTRON POOR $^{112}Sn + ^{58}Ni$
REACTIONS

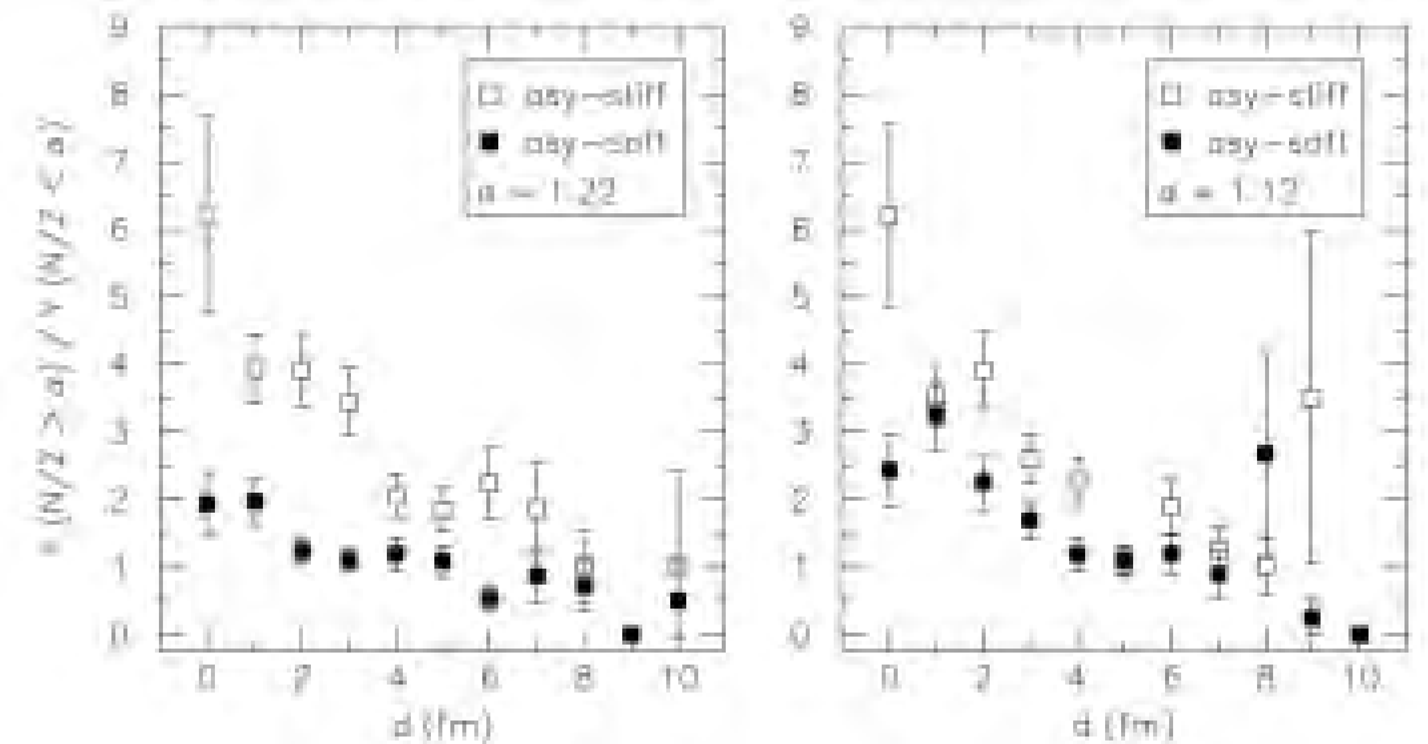


Enhancement
In n-rich fragments
for mid velocity

E. De Filippo et al., Acta Physica Polonica B37, 199, 2006;
P. Russotto, Procs of IWM 05, pp. 13, ed. SIF, 2006.

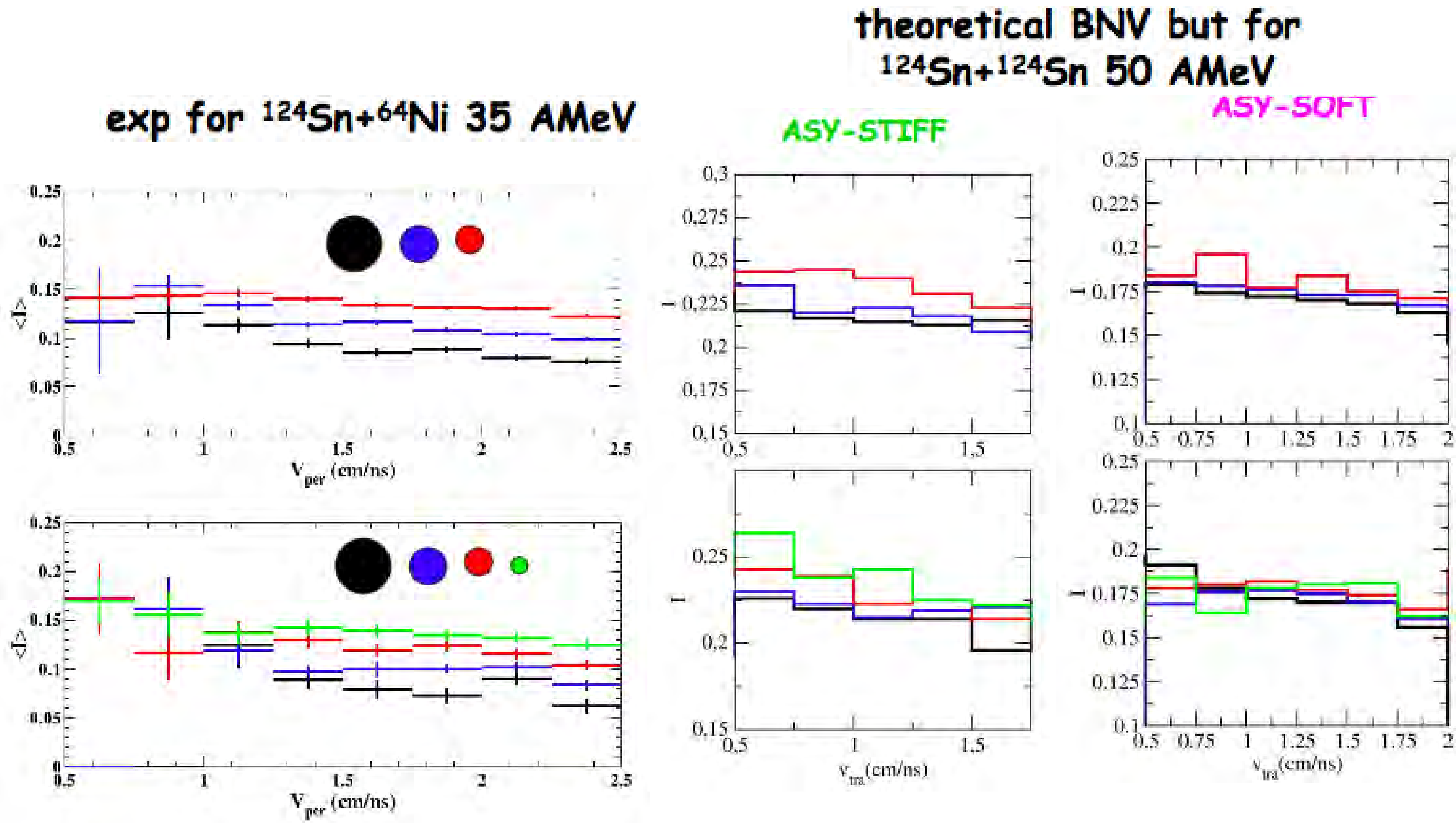


58 Fe + 58 Fe (N/Z = 1.23) and
58Ni + 58Ni (N/Z = 1.07), at 47A MeV



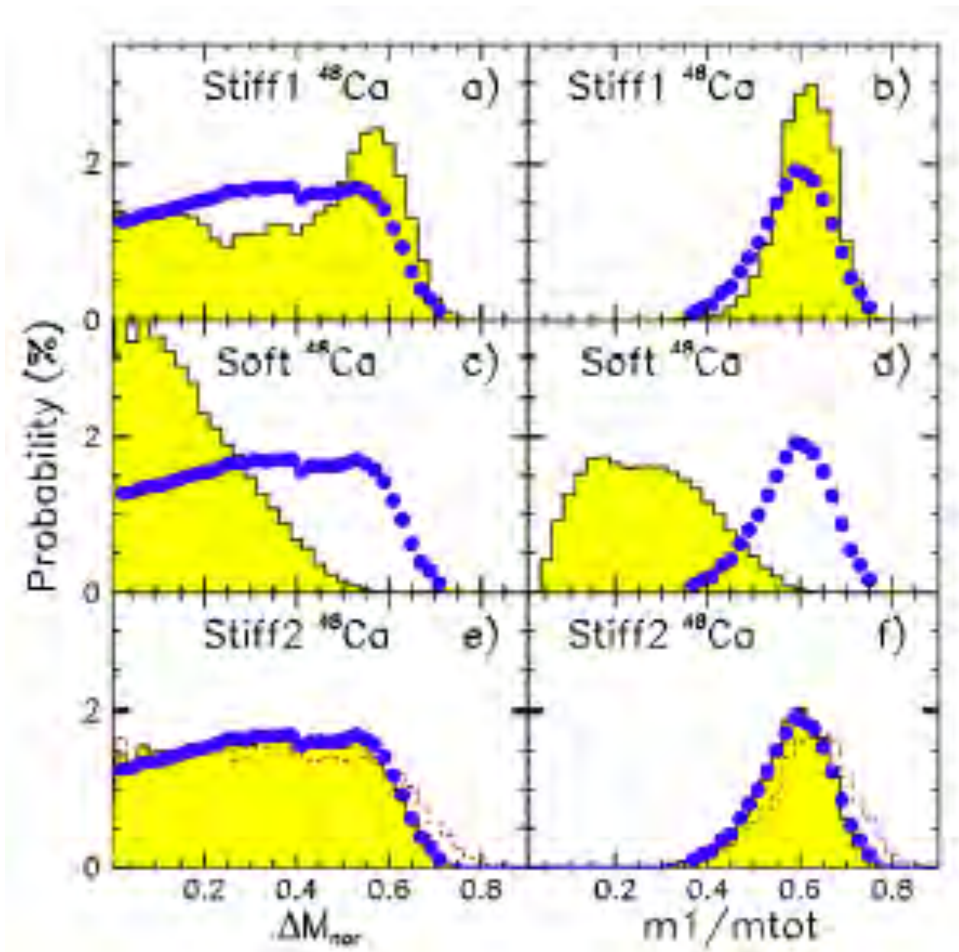
R. Lionti et al. / Physics Letters B 625 (2005) 33–40

Isospin and fragment hierarchy

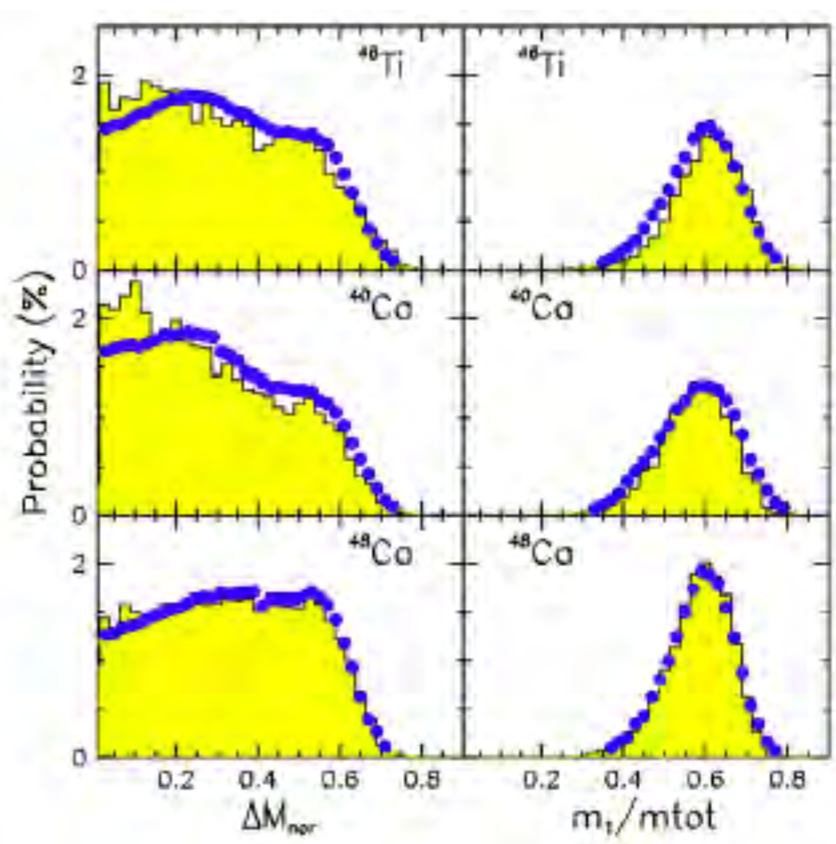


Russsotto_nufra2009

Fusion vs Deep Inelastic in Central collisions

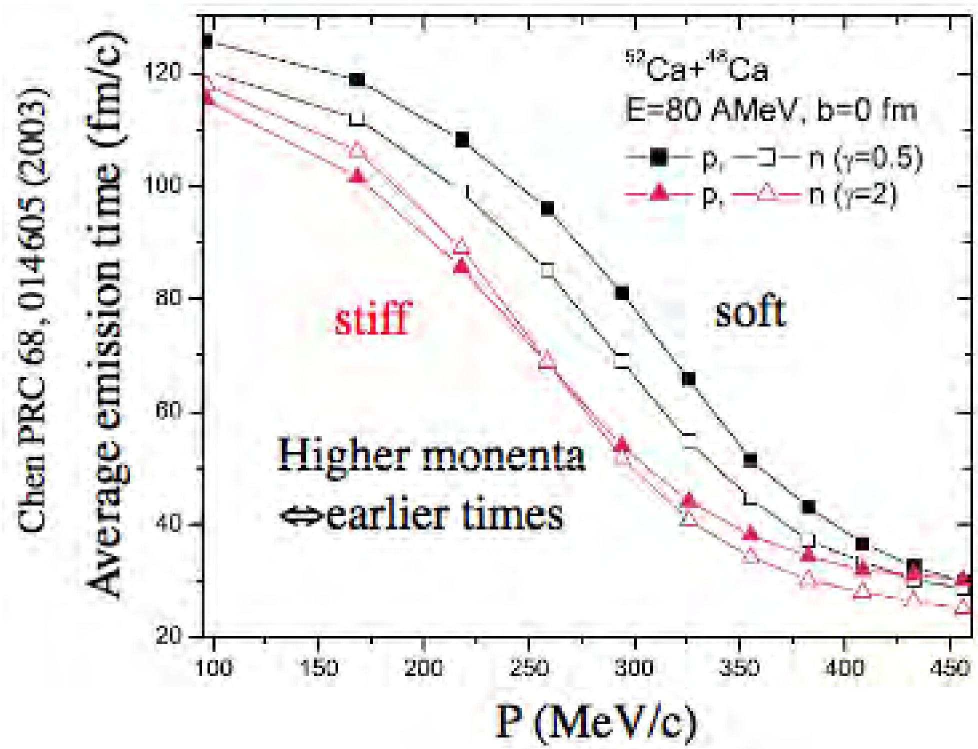


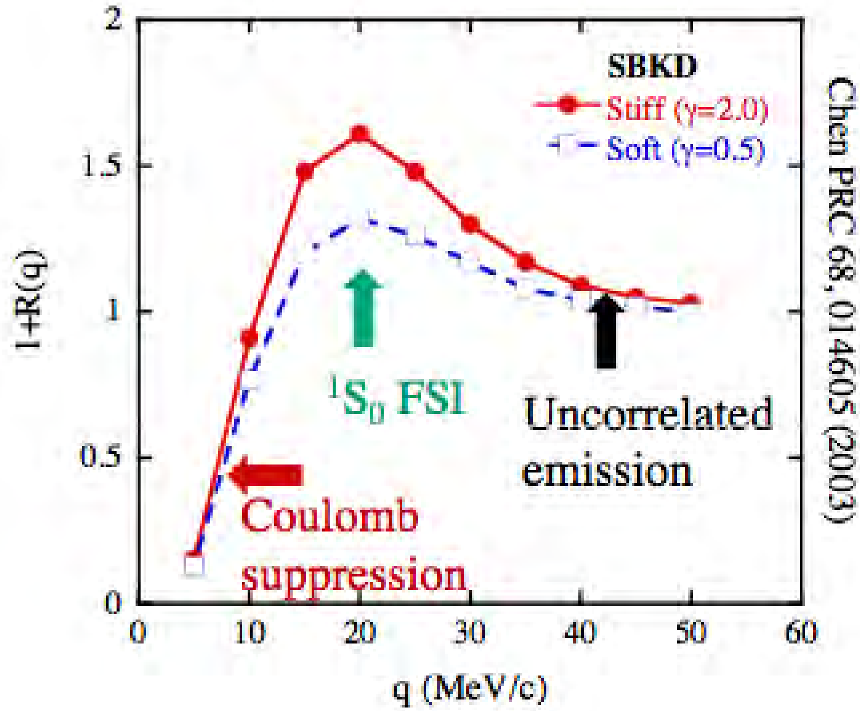
^{40}Ca + ^{40}Ca, ^{48}Ca, ^{46}Ti at 25 MeV/A

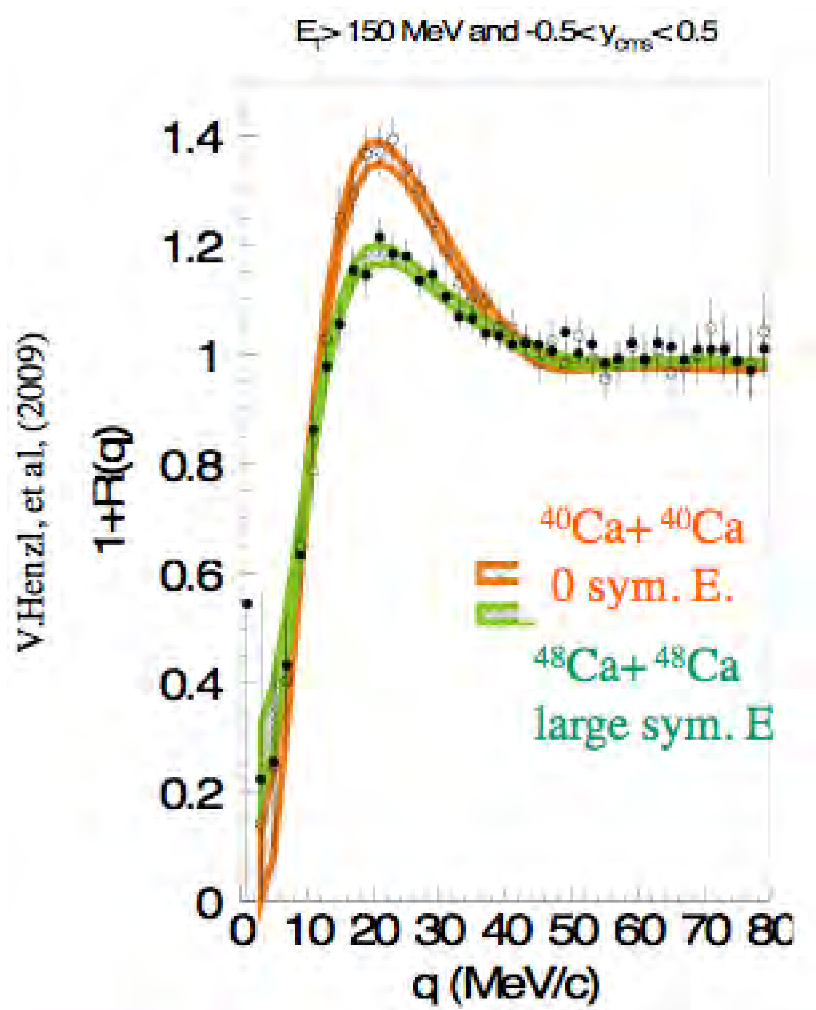


Amorini et al. PRL 102 (2009) 112701

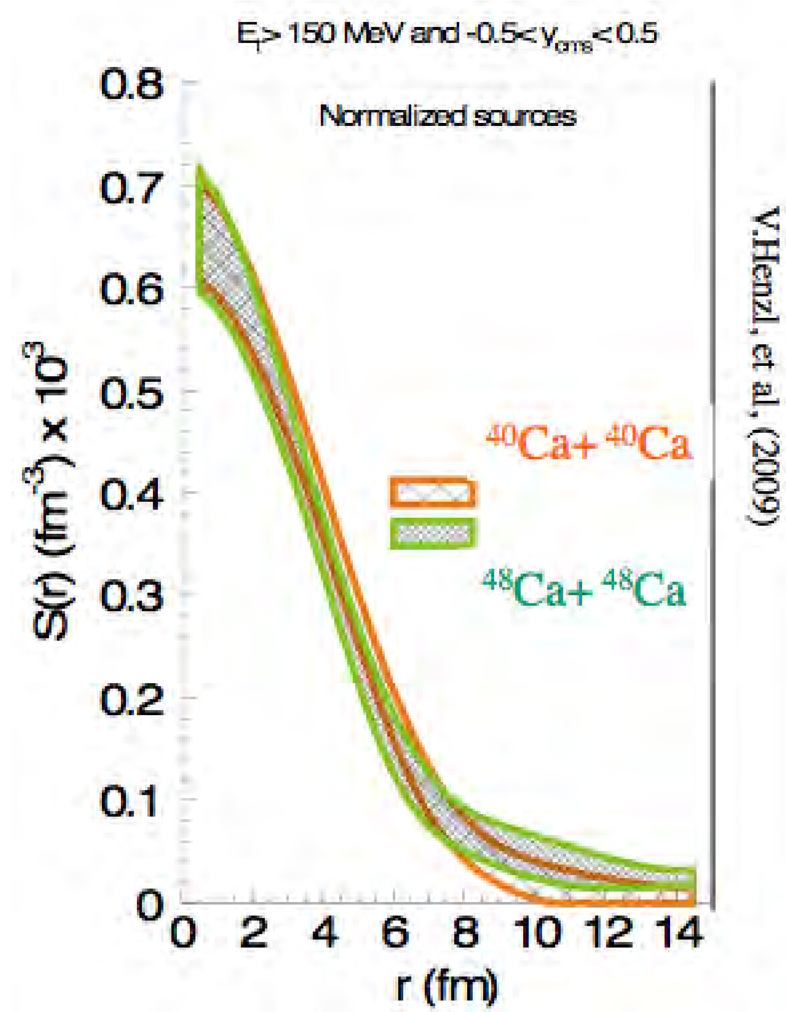
Correlation functions







E_t> 150 MeV and -0.5< y_{cms}< 0.5
V.Henzl, et al, (2009)
1+R(q)
q (MeV/c)
^{40}Ca+ ^{40}Ca
0 sym. E.
^{48}Ca+ ^{48}Ca
large sym. E



E_t> 150 MeV and -0.5< y_{cms}< 0.5
Normalized sources
S(r) (fm^{-3}) x 10^{3}
r (fm)
^{40}Ca+ ^{40}Ca
^{48}Ca+ ^{48}Ca
V.Henzl, et al, (2009)

Nuclear Mass in Thomas-Fermi Model

Myers/Swiatecki, NPA 601, 141 (1996)

Thomas-Fermi Model analysis of 1654 ground state mass of nuclei with N,Z≥8

- Four Liquid Drop Properties

Radius constant of nuclear matter	$r_0 = 1.14$ fm
Volume binding coefficient	$a_1 = 16.24$ MeV
Symmetry energy coefficient	$J = 32.65$ MeV
Surface energy coefficient	$a_2 = 18.63$ MeV

- Five Droplet Model Properties [26]

Compressibility coefficient	$K = 234$ MeV
Curvature energy coefficient	$a_3 = 12.1$ MeV
Neutron skin stiffness coefficient	$Q = 35.4$ MeV
Density-symmetry coefficient	$L = 49.9$ MeV
Symmetry anharmonicity coefficient	$M = 7.2$ MeV.

Thomas-Fermi Model + Nuclear Mass ➔ $E_{sym}(\rho_0)$=32 .65 MeV L=49.9 MeV

E_{sym}: Pygmy Dipole Resonances

RAPID COMMUNICATIONS

PHYSICAL REVIEW C **76**, 051603(R) (2007)

Nuclear symmetry energy and neutron skins derived from pygmy dipole resonances

A. Klimkiewicz,[1,2] N. Paar,[3] P. Adrich,[1,2] M. Fallot,[1] K. Boretzky,[1] T. Aumann,[1] D. Cortina-Gil,[4] U. Datta Pramanik,[1]
Th. W. Elze,[5] H. Emling,[1] H. Geissel,[1] M. Hellström,[1] K. L. Jones,[1] J. V. Kratz,[6] R. Kulessa,[2] C. Nociforo,[6] R. Palit,[5]
H. Simon,[1] G. Surówka,[2] K. Sümmerer,[1] D. Vretenar,[3] and W. Waluś[2]
(LAND Collaboration)

using the experimental pygmy strength, parameters of the nuclear symmetry energy ($a_4 = 32.0 \pm 1.8$ MeV and $p_0 = 2.3 \pm 0.8$ MeV/fm^3) are deduced as well as neutron-skin thicknesses $R_n - R_p$ of 0.24 ± 0.04 fm for ^{132}Sn

Pygmy Dipole Resonances of ^{130,132}Sn ➔ $E_{sym}(\rho_0)$=32 ± 1.8 MeV L=43.125 ± 15 MeV

RAPID COMMUNICATIONS

PHYSICAL REVIEW C **81**, 041301(R) (2010)

Constraints on the symmetry energy and neutron skins from pygmy resonances in ^{68}Ni and ^{132}Sn

Andrea Carbone,[1] Gianluca Colò,[1,2] Angela Bracco,[1,2] Li-Gang Cao,[1,2,3,4] Pier Francesco Bortignon,[1,2]
Franco Camera,[1,2] and Oliver Wieland[2]

Pygmy Dipole Resonances of ^{68}Ni and ^{132}Sn ➔
$E_{sym}(\rho_0)$=32.3 ± 1.3 MeV, L=64.8 ± 15.7 MeV

E_{sym}: IAS+LDM

E_{sym} from Isobaric Analog States + Liquid Drop model with surface symmetry energy

tions, especially for the slope scaled with a_a^V. Thus, e.g. the analysis of excitation energies of isobaric analog states [97,98] yields independent values of a_a^V and a_a^S. While the volume symmetry coefficient from this type of analysis, $a_a^V \simeq (31.5\text{–}33.5)$ MeV, comes out quite in the middle of values found for the Skyrme interactions, the surface symmetry coefficient, $a_a^S \simeq (9.5\text{–}12)$ MeV, comes out right at the lower end of the values encountered for the Skyrme interactions. The coefficient ratio from that analysis is in the range $a_a^V/a_a^S \simeq (2.8\text{–}3.3)$. That ratio produces the effective surface displacement in the range of $\Delta_e R = (r_0/3)(a_a^V/a_a^S) \simeq (1.06\text{–}1.26)$ fm. Moreover, Figs. 14 and 15 yield the respective ranges of $\Delta R^0 \simeq (0.85\text{–}1.05)$ fm and $L/a_a^V \simeq (2.4\text{–}3.4)$ or $L \simeq (78\text{–}111)$ MeV. The analysis [97,98] is relatively model-independent, provided the curvature effects play little role for heavier nuclei. If the latter were not the case, though, a bit softer symmetry energy would need to be deduced.

IAS+Liquid Drop Model with Surface Esym ➔
$E_{sym}(\rho_0)$=32.5 ± 1 MeV L=94.5 ± 16.5 MeV

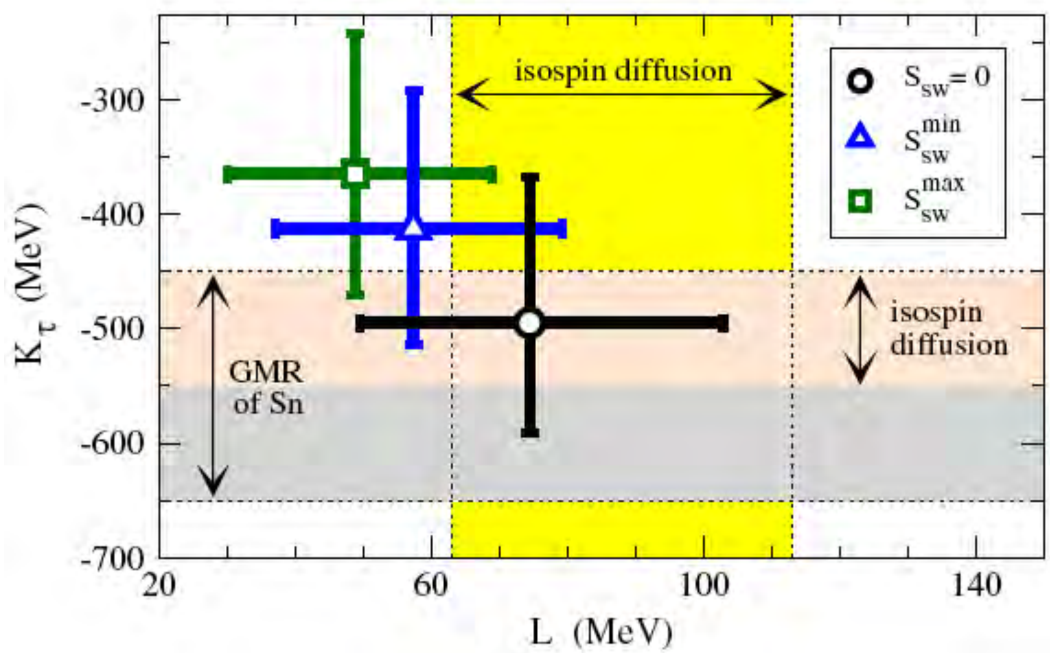
Danielewicz/Lee, NPA 818, 36 (2009)

Droplet Model Analysis on Neutron Skin

PRL 102, 122502 (2009) PHYSICAL REVIEW LETTERS week ending 27 MARCH 2009

Nuclear Symmetry Energy Probed by Neutron Skin Thickness of Nuclei

M. Centelles,[1] X. Roca-Maza,[1] X. Viñas,[1] and M. Warda[1,2]



meaningful [26]. We first set $b_n = b_p$ (i.e., $S_{sw} = 0$) as done in the DM [12,23,26] and in the analysis of data in Ref. [19]. Following the above, we find $L = 75 \pm 25$ MeV

extremes of S_{sw} according to mean field models. The results are shown in Fig. 3. Our above estimates of L and K_τ could be shifted by up to -25 and $+125$ MeV, respec-

Droplet Model + N-skin ➔ $E_{sym}(\rho_0)$=31.6 MeV, L=66.5 ± 36.5 MeV

Droplet Model Analysis on Neutron Skin

PHYSICAL REVIEW C **80**, 024316 (2009)

Neutron skin thickness in the droplet model with surface width dependence: Indications of softness of the nuclear symmetry energy

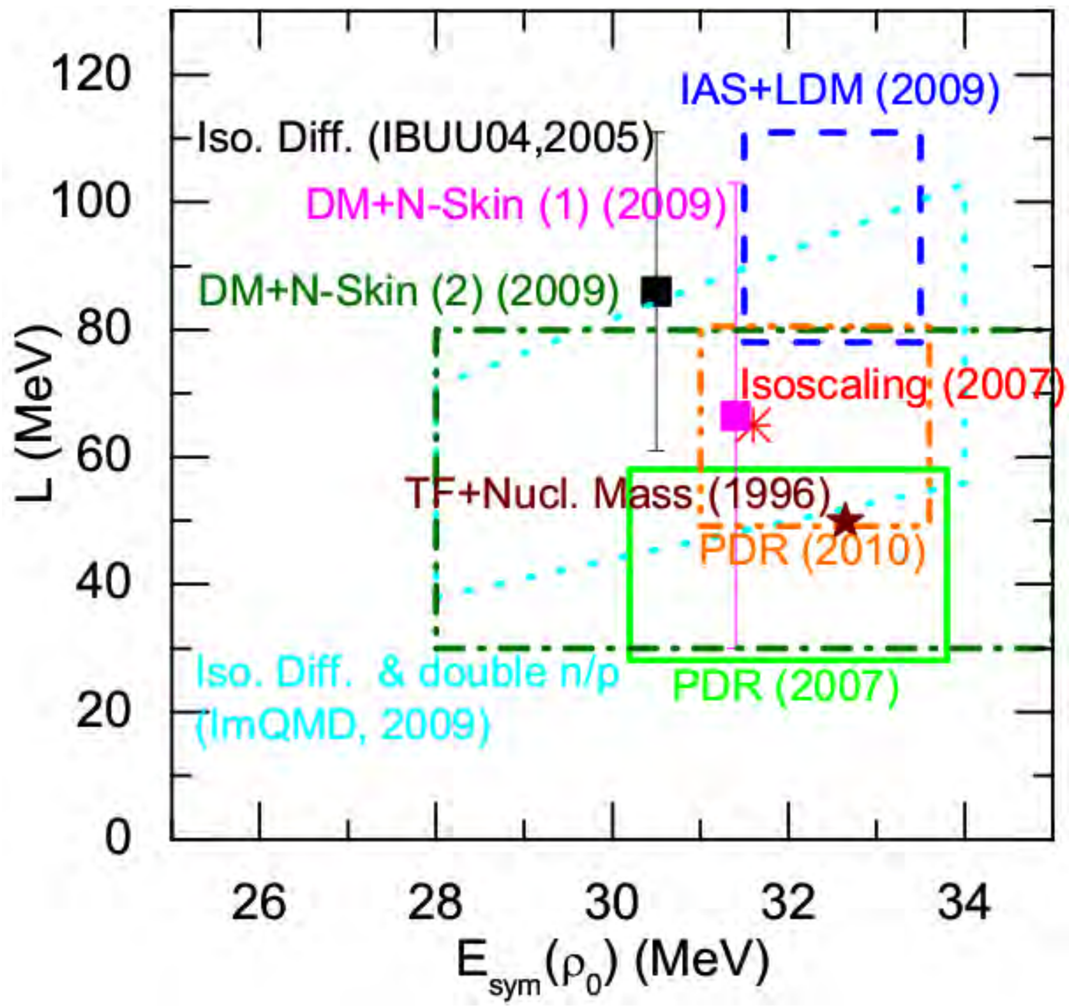
M. Warda,[1,2,*] X. Viñas,[1,†] X. Roca-Maza,[1,‡] and M. Centelles[1,§]

of J/Q values is known, the compatible range of values of the parameter L can be estimated from the linear correlation between L and J/Q shown in Fig. 1. From our analysis we find the constraints $30 \lesssim L \lesssim 80$ MeV.

Droplet Model + N-skin ➔ $E_{sym}(\rho_0)$=28 - 35 MeV, L=55 ± 25 MeV

E_{sym} around normal density

9 constraints on E_{sym} (ρ_0) and L from nuclear reactions and structures



$E_{sym}(\rho_0)$=28 - 35 MeV
L=28 - 111 MeV

Still within large uncertain region !!

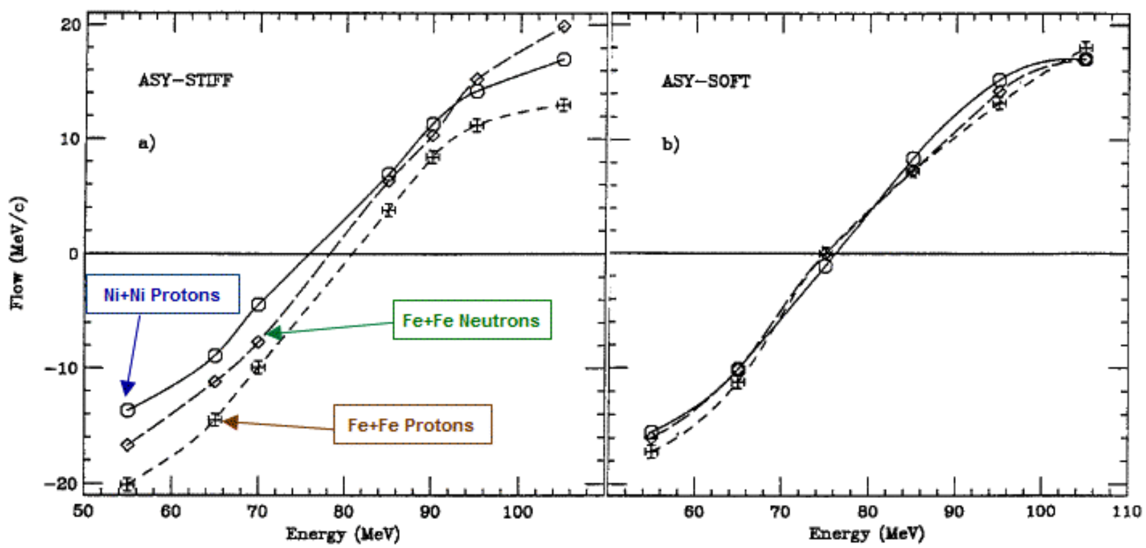
Transverse Collective Flow

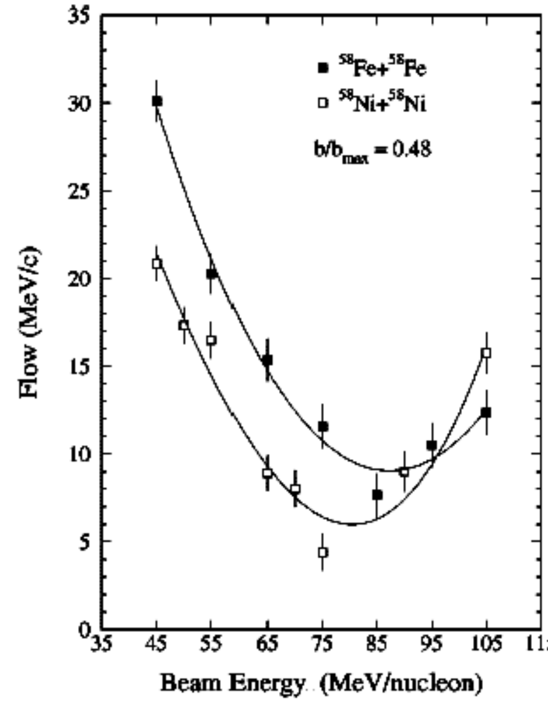
Isospin Effects observed in transverse flow of Z =1, 2, & 3 fragments

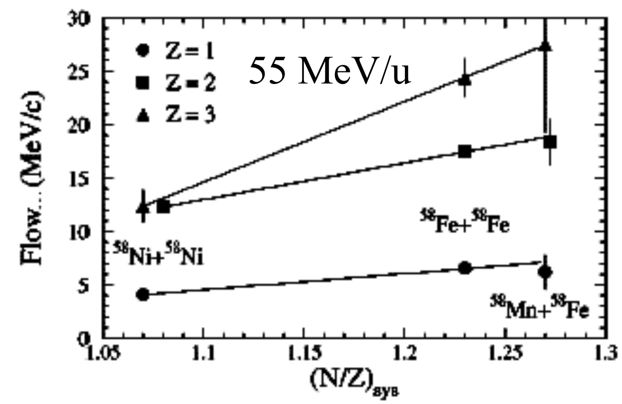
BNV Calculation: 55 MeV/u $^{58}Fe+^{58}Fe$

-Asy-Stiff Esym(ρ) shows 20% increased ^{3}He flow in comparison to ^{3}H flow.

-Asy-Soft Esym(ρ) shows ^{3}He and ^{3}H flow are equal.







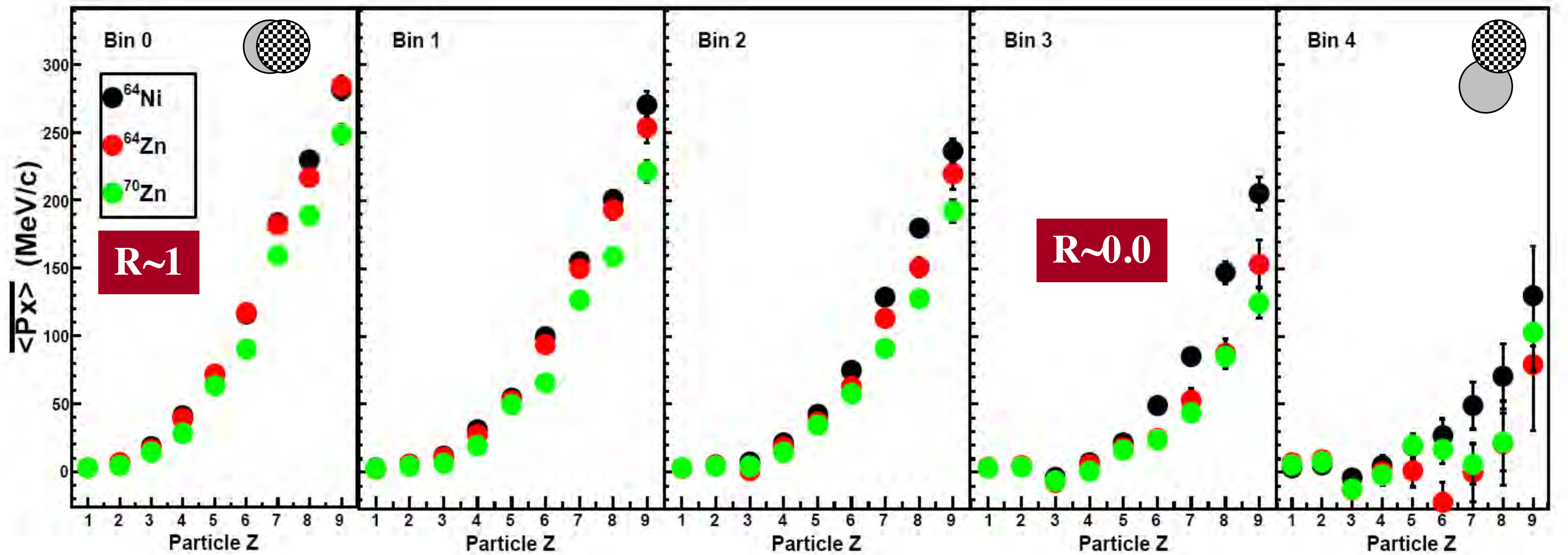
M. Di Toro *et al.,* Prog. Part. Nucl. Phys. **42,** 125 (1999).

L. Scalone *et al.,* Phys. Lett. B **461,** 9 (1999).

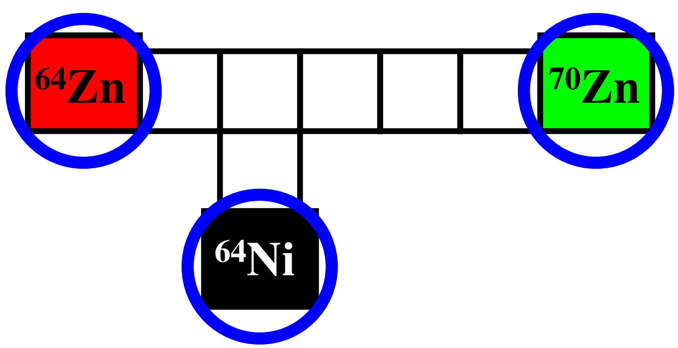
R. Pak *et al.,* Phys. Rev. Lett. **78,** 1026 (1997).

R. Pak *et al.,* Phys. Rev. Lett. **78,** 1022 (1997).

IMF Transverse Flow

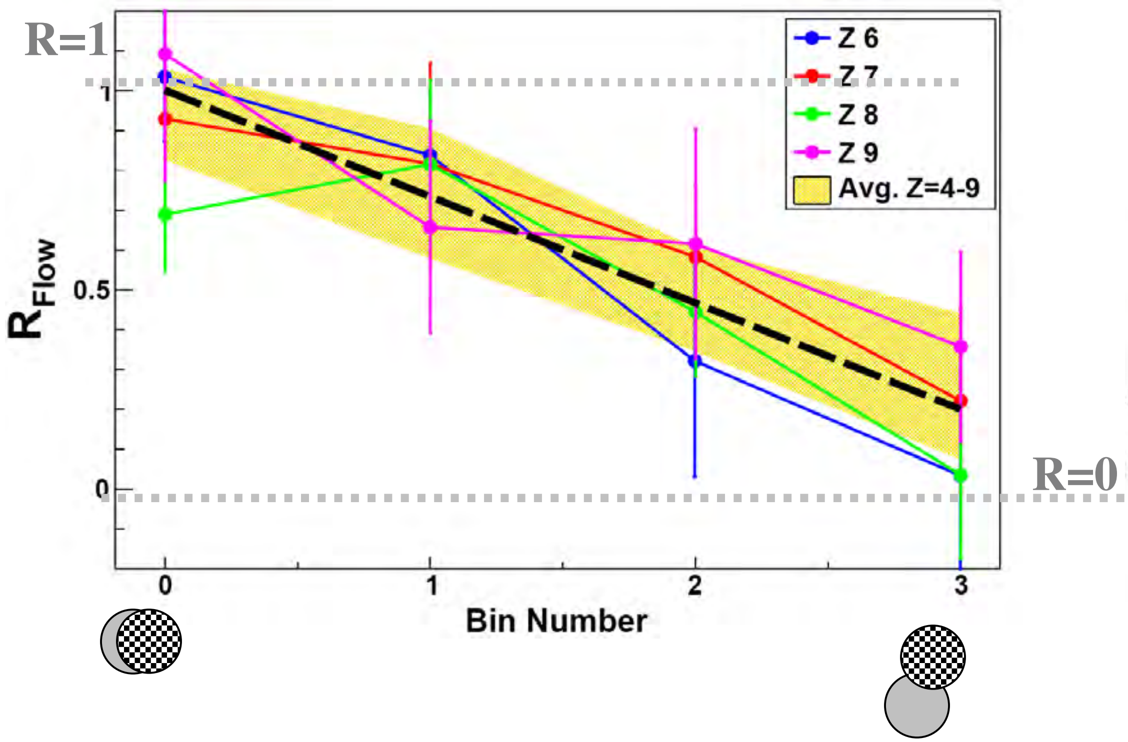


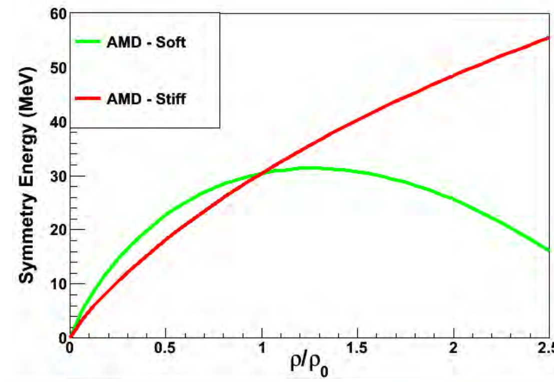
Mass Dependence → *Coulomb Dependence*

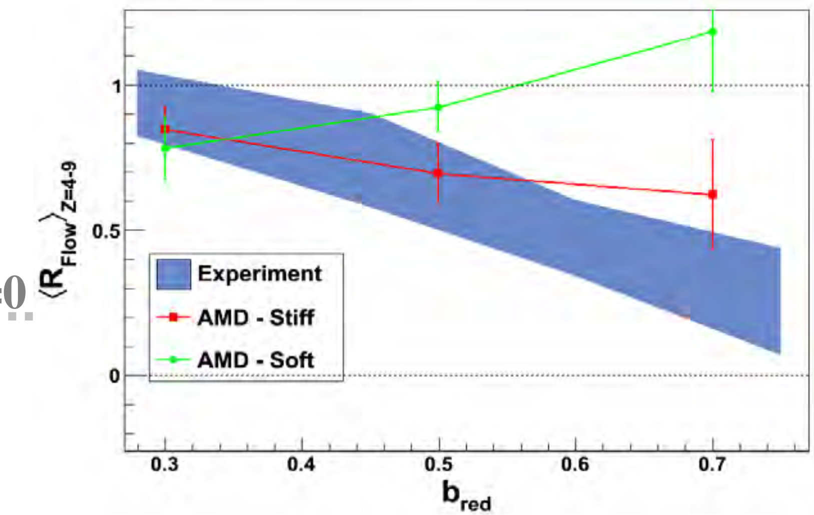


$$R_{Flow} = \frac{\overline{\langle Px/A \rangle}_{^{64}Zn} - \overline{\langle Px/A \rangle}_{^{70}Zn}}{\overline{\langle Px/A \rangle}_{^{64}Ni} - \overline{\langle Px/A \rangle}_{^{70}Zn}}$$

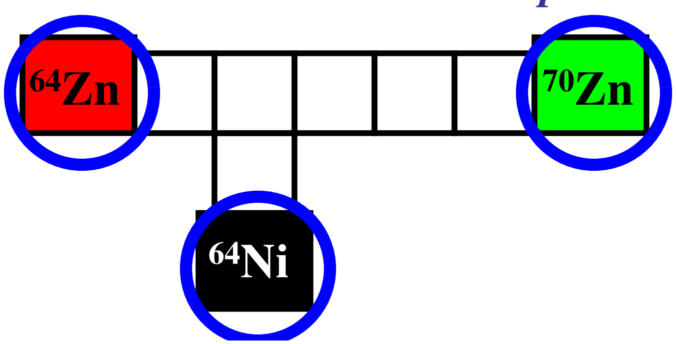
IMF Transverse Flow







Mass Dependence → *Coulomb Dependence*

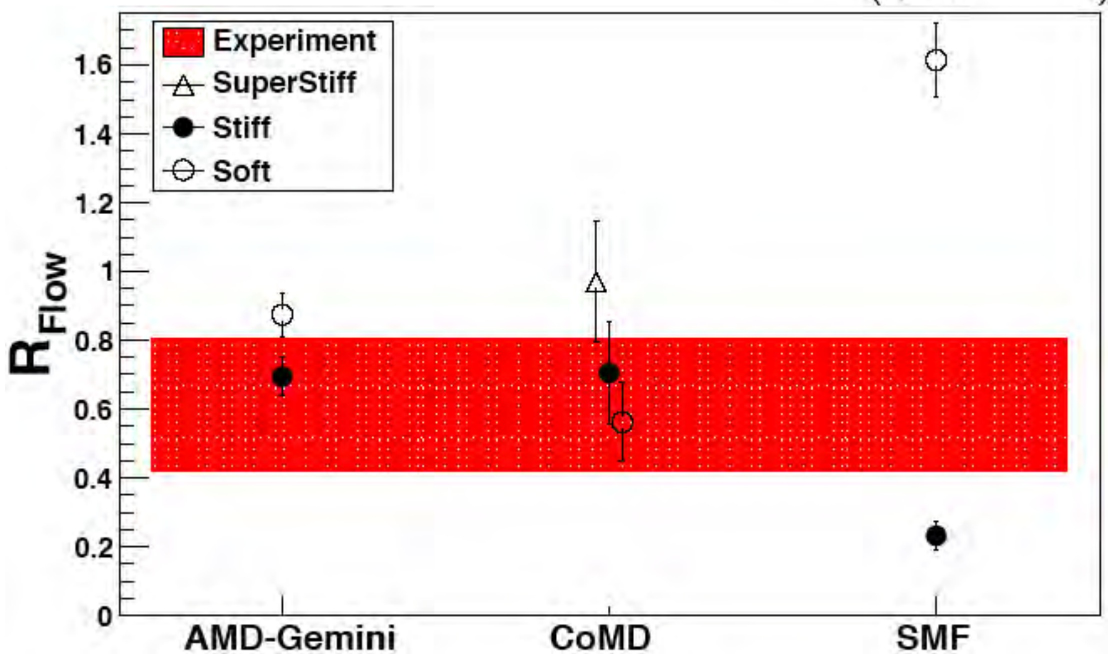


$$R_{Flow} = \frac{\overline{\langle Px/A \rangle_{^{64}Zn}} - \overline{\langle Px/A \rangle_{^{70}Zn}}}{\overline{\langle Px/A \rangle_{^{64}Ni}} - \overline{\langle Px/A \rangle_{^{70}Zn}}}$$

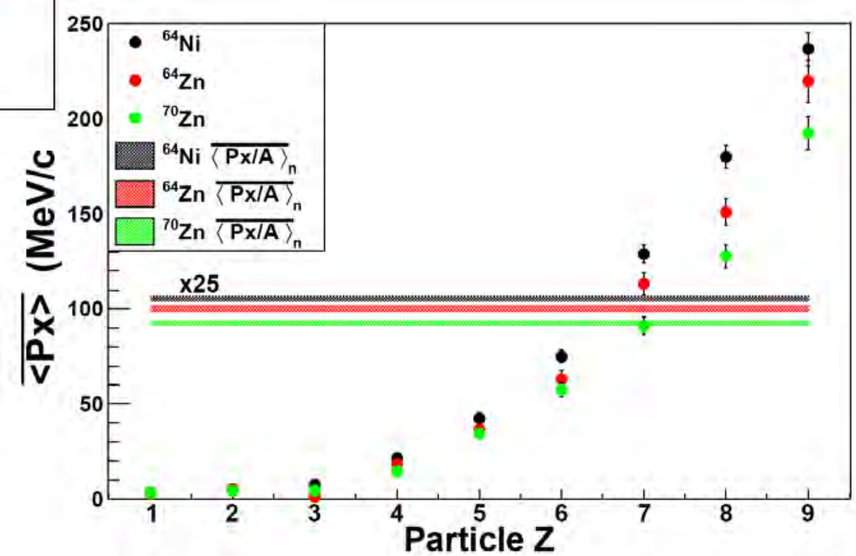
Average Z=4-9

Nucleon weighted flow

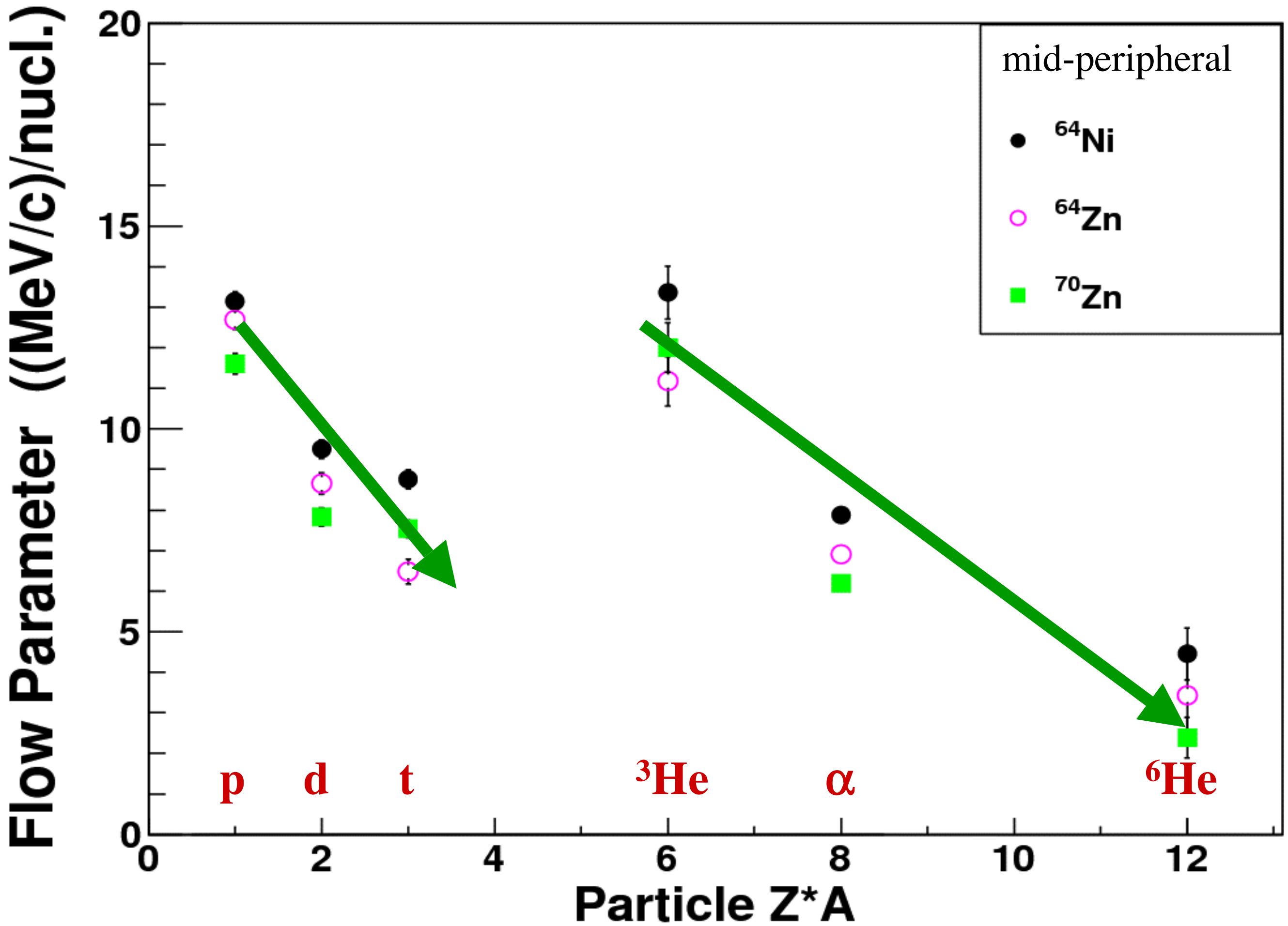
$$\langle Px/A \rangle_{Nucleon} = \left(\sum_{f=0}^{N_{frag}} (Px)_f \right) \div N_{Nucleons}$$ .....for Z=3-9



Note: SMF nucleon flow calculated for Z>3



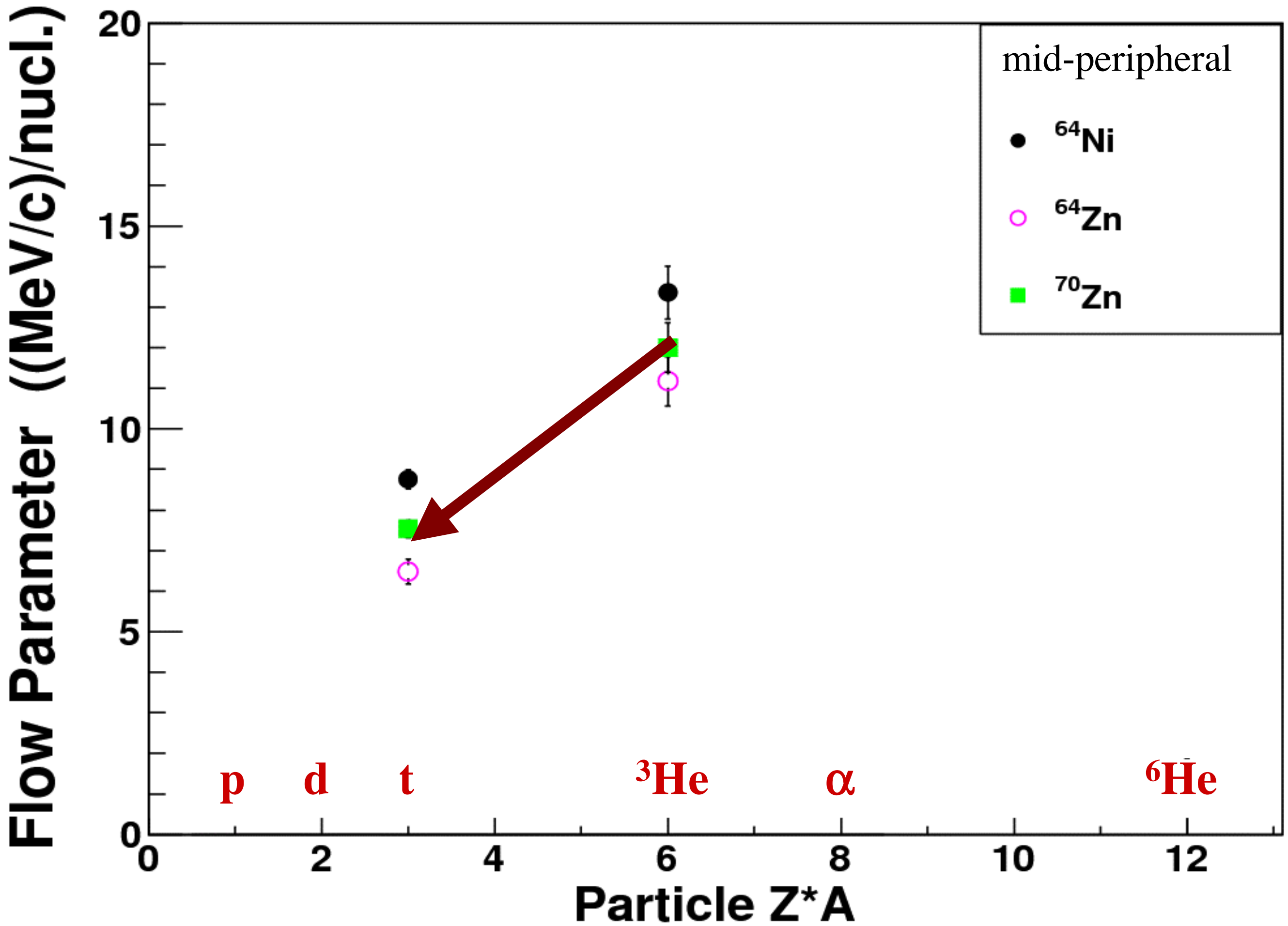
LCP Flow



- Dependence on $(N/Z)_{sys}$
- Expands on Pak *et al*.

- Strong Isotopic Trends
- ↓Flow with ↑n-rich

LCP Flow

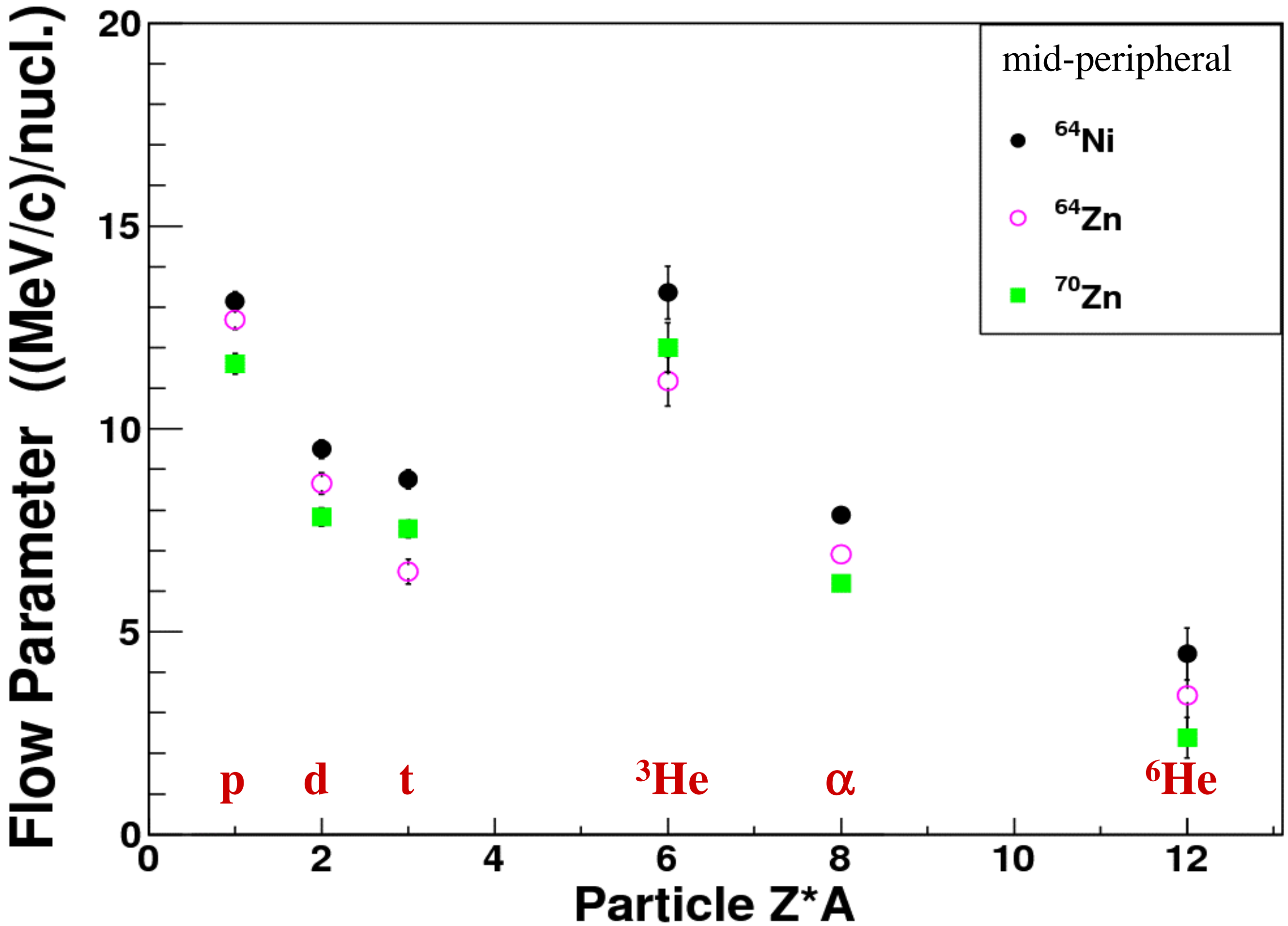


- Dependence on $(N/Z)_{sys}$
- Expands on Pak *et al*.

- Strong Isotopic Trends
- ↓Flow with ↑n-rich

- Isobaric Effects (A=3)
- Same A, different N/Z
- $E_{sym}(\rho)$ prediction

LCP Flow



- Dependence on $(N/Z)_{sys}$
- Expands on Pak *et al*.

- Strong Isotopic Trends
- ↓Flow with ↑n-rich

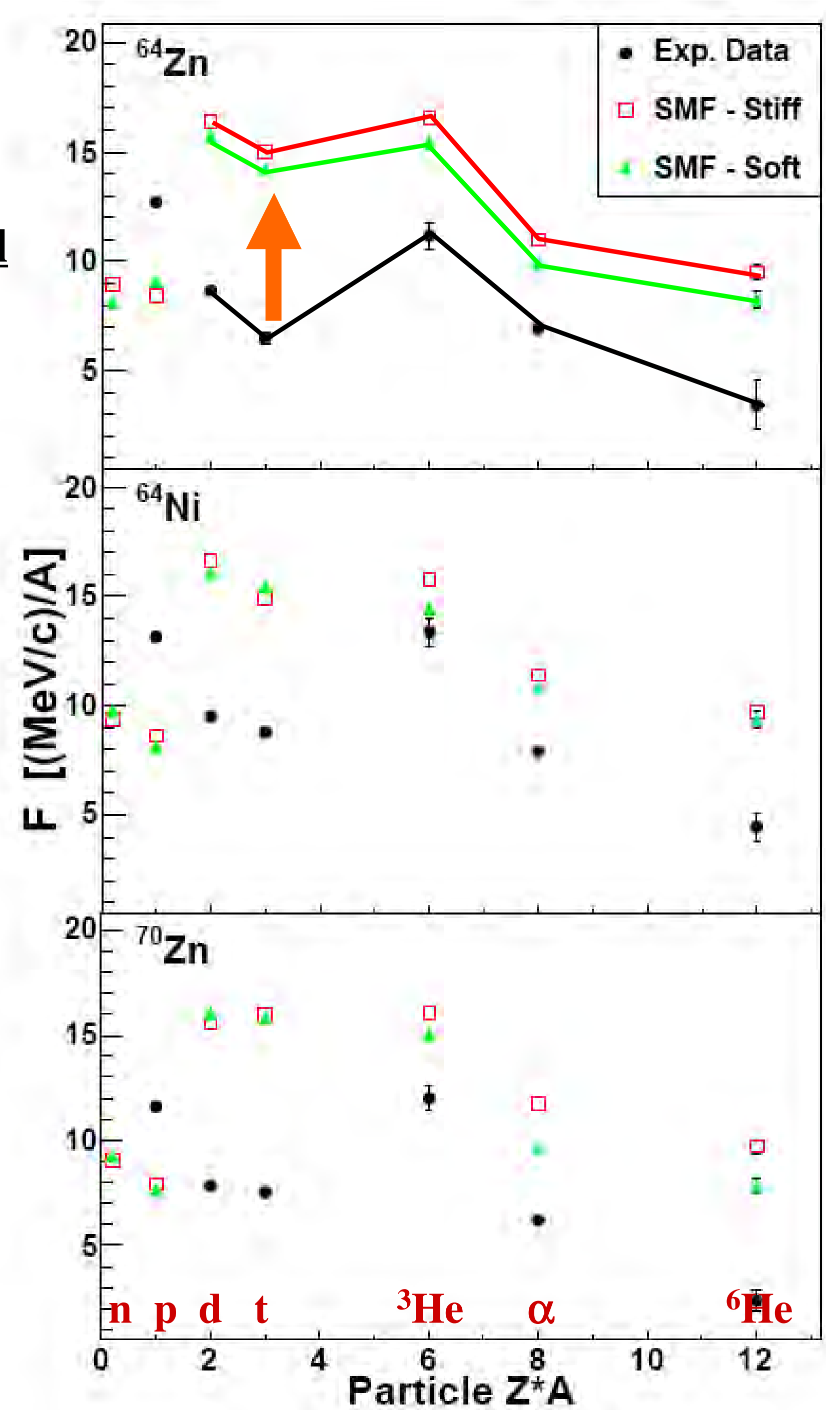
- Isobaric Effects (A=3)
- Same A, different N/Z
- $E_{sym}(\rho)$ prediction

Decreasing flow with increasing N/Z with both const. Z and A for LCPs.

LCP Flow

<u>Comparison with the Stochastic Mean-Field Model</u>

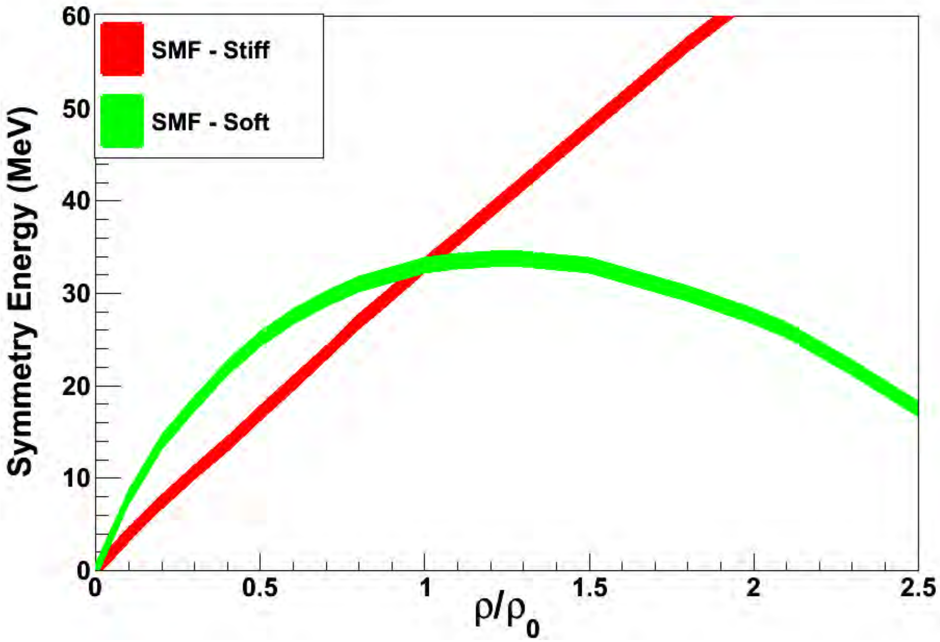
- Overall isotopic flow trend is reproduced, except protons.
- Differential movement of neutrons and protons
- Phase-space coalescence and early emission time.

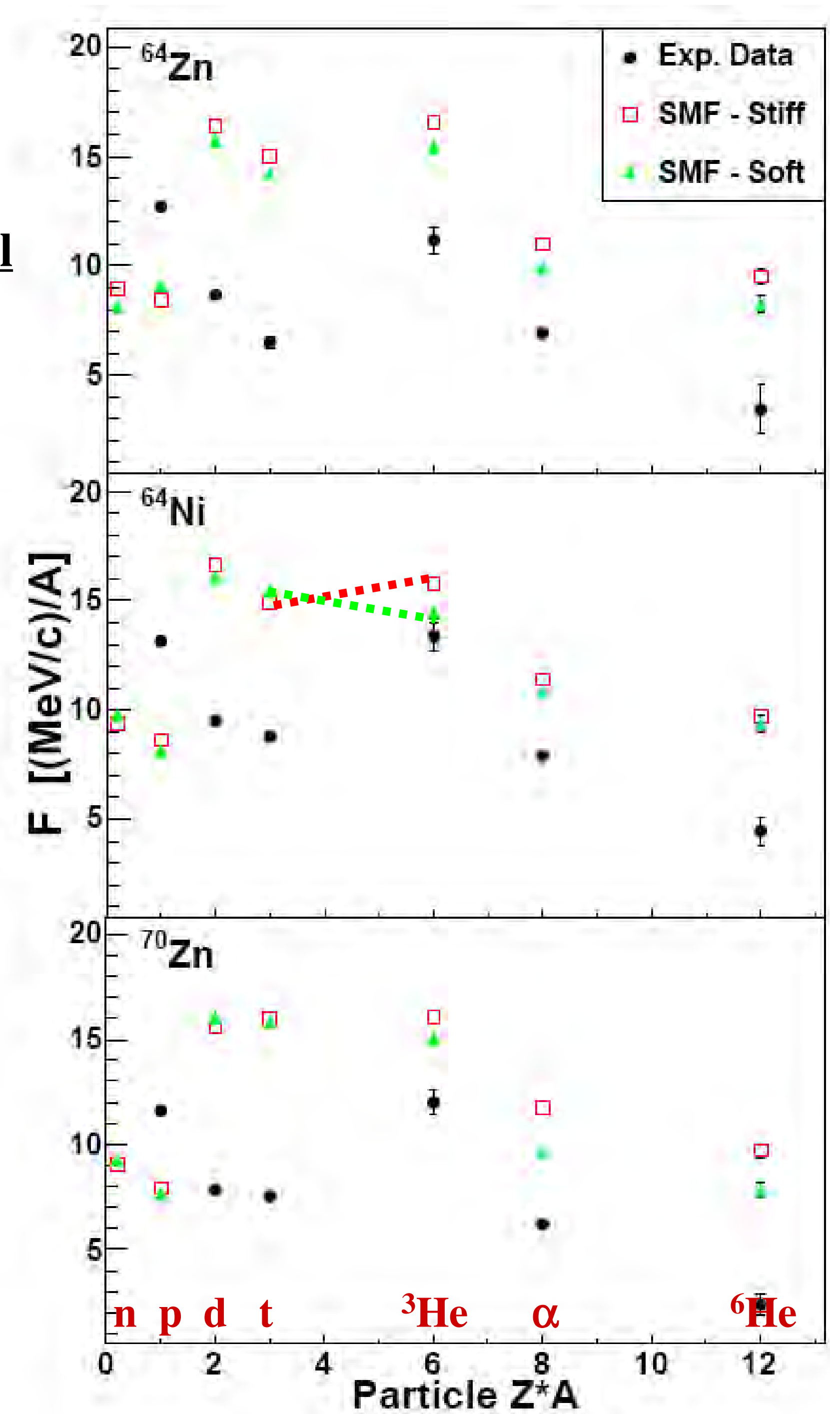


LCP Flow

Comparison with the Stochastic Mean-Field Model

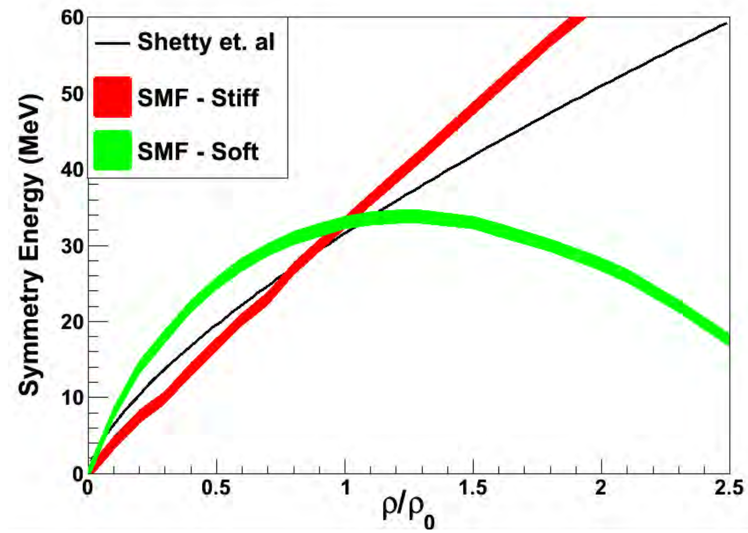
- Overall isotopic flow trend is reproduced, except protons.
- Phase-space coalescence and early emission time.
- Differential movement of neutrons and protons.
- Sensitivity to symmetry energy.



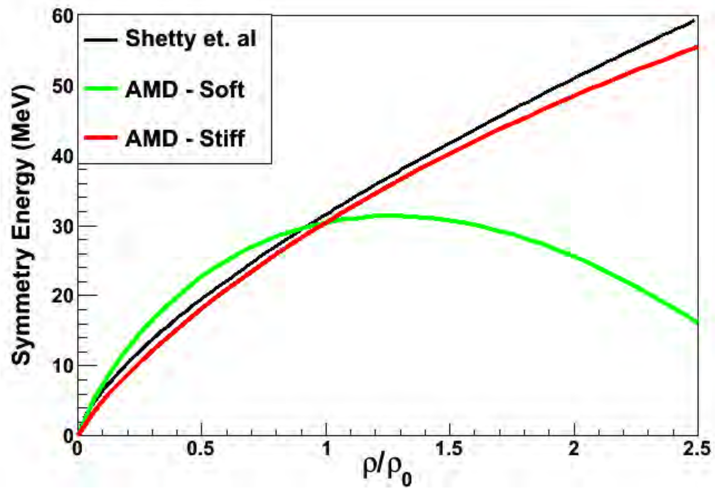


Flow Summary

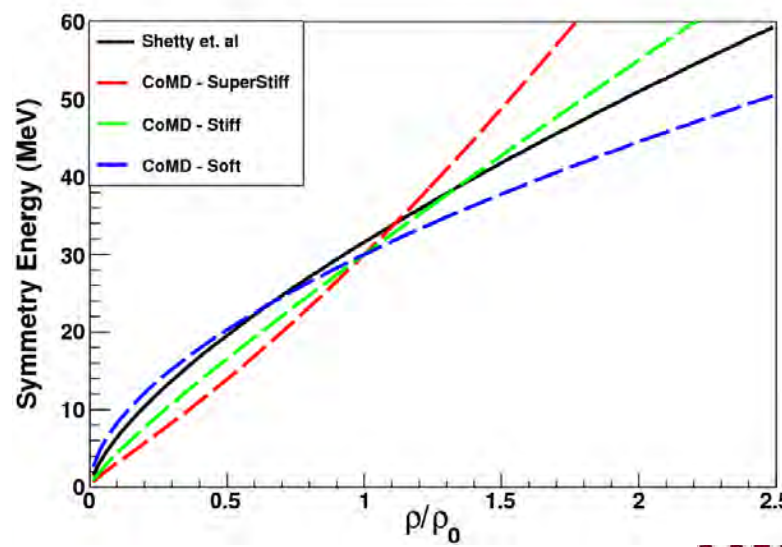
SMF Model
- triton/^{3}He Flow
- $(N/Z)_{sys}$ Dependence
- R_{Flow} (mid-peripheral)



AMD Model
- Mass-Coulomb Dependence
- R_{Flow} (mid-peripheral)



CoMD Model
- R_{Flow} (mid-peripheral)



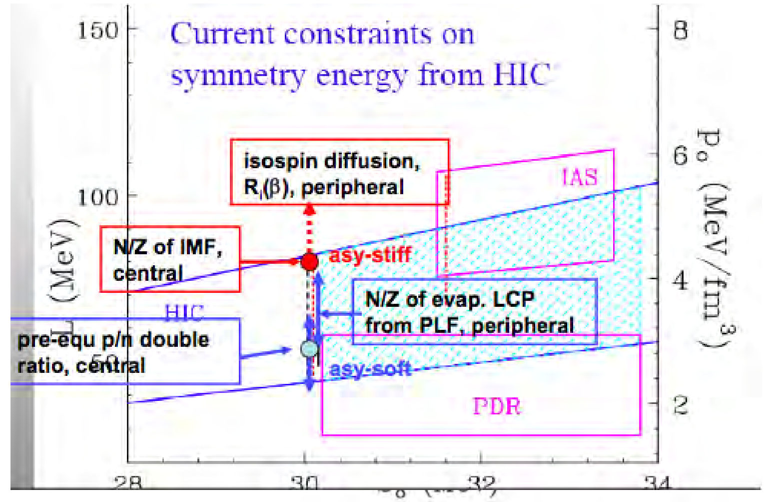
M.B. Tsang *et al*. Phys. Rev. Lett. **102,** 122701 (2009).
B.A. Li, L.W. Chen and C.M. Ko. Phys. Rep. **464,**113 (2008).
D.V. Shetty, S.J. Yennello, and G.A. Souliotis. PRC **76**, 24606 (2007).

Summary $E_{sym}(\rho)$

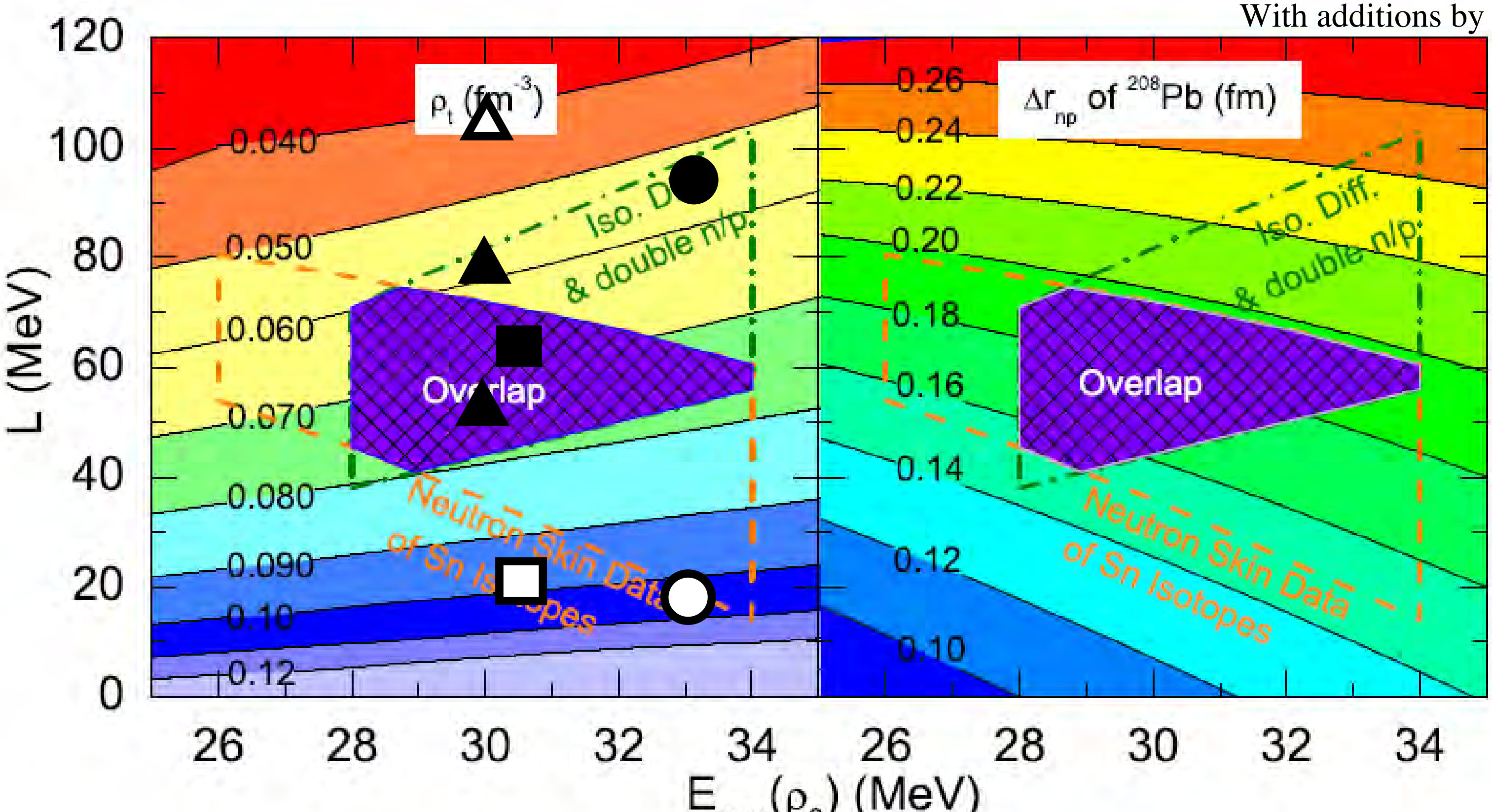
AMD ■
CoMD ▲
SMF ●

some agreement ●
did not agree ○

$$E_{sym} = S_o + \frac{L}{3}\left(\frac{\rho_B - \rho_0}{\rho_0}\right) + \frac{K_{sym}}{18}\left(\frac{\rho_B - \rho_0}{\rho_0}\right)^2 + \dots$$



M.B. Tsang *et al*. PRL. **102,** 122701 (2009).
With additions by H. Wolter, NUFRA209



L.W. Chen *et al*., *arXiv: [nucl-th]*

Summary

- Many proposed observables
- Various data sets

(apologies to that which I didn't have time to show)

- Some overlap - plenty of room for improvement
- Need to understand differences in model predictions
- New observables with increased power to discriminate welcome

Many Thanks

Z. Kohley, L. W. May, S. Wuenschel, R. Tripathi, R. Wada, K. Hagel, G. A. Souliotis, D. V. Shetty, S. Galanopoulos, M. Mehlman, W. B. Smith, S. N. Soisson, B. C. Stein, R. Dienhoffer

M. Di Toro, M. Colonna, M. Zielinska-Pfabe,
A. Bonasera
A. Botvina

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