Light Fragment Production in Heavy Ion Collisions and the Symmetry Energy

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with
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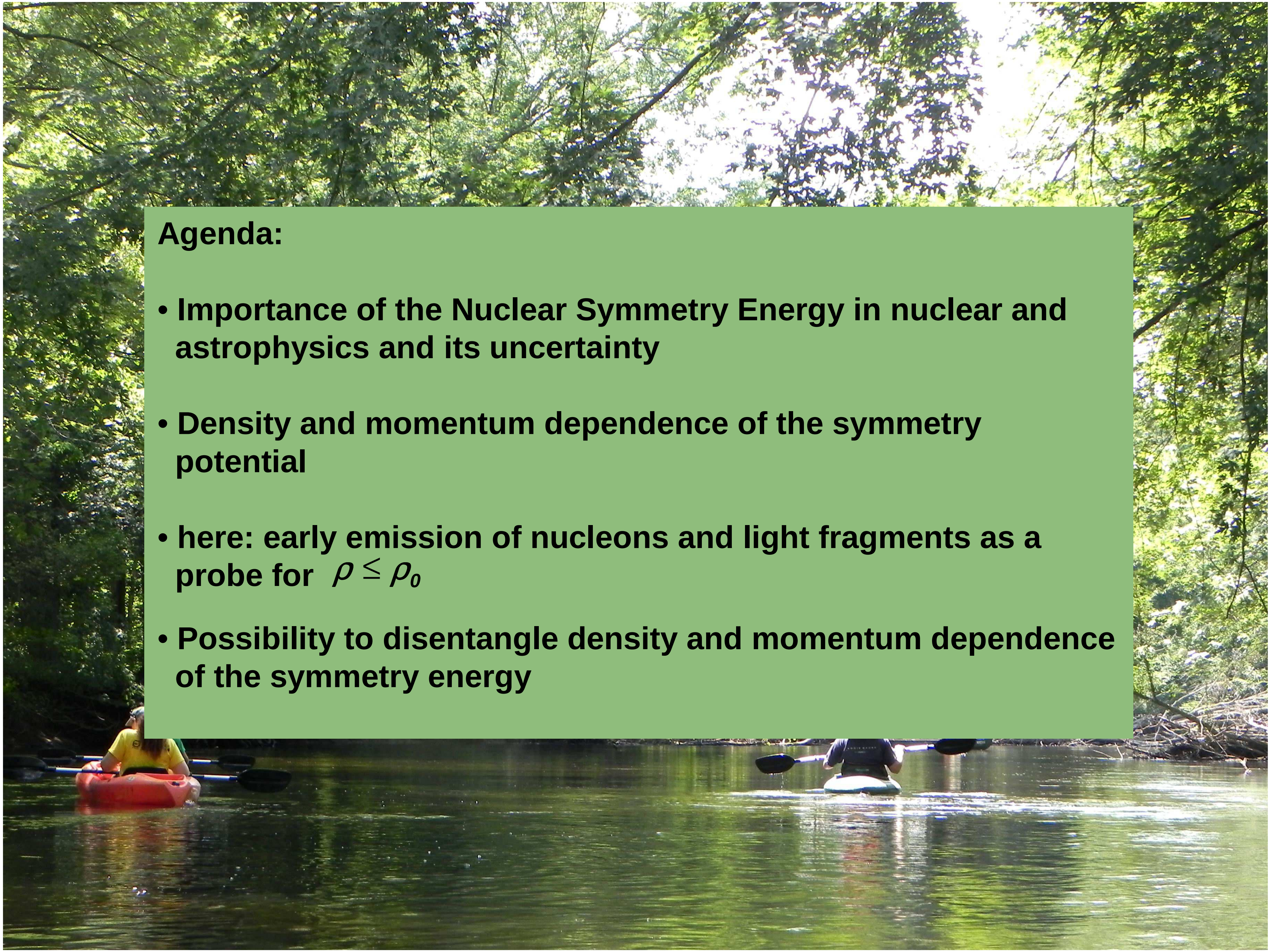
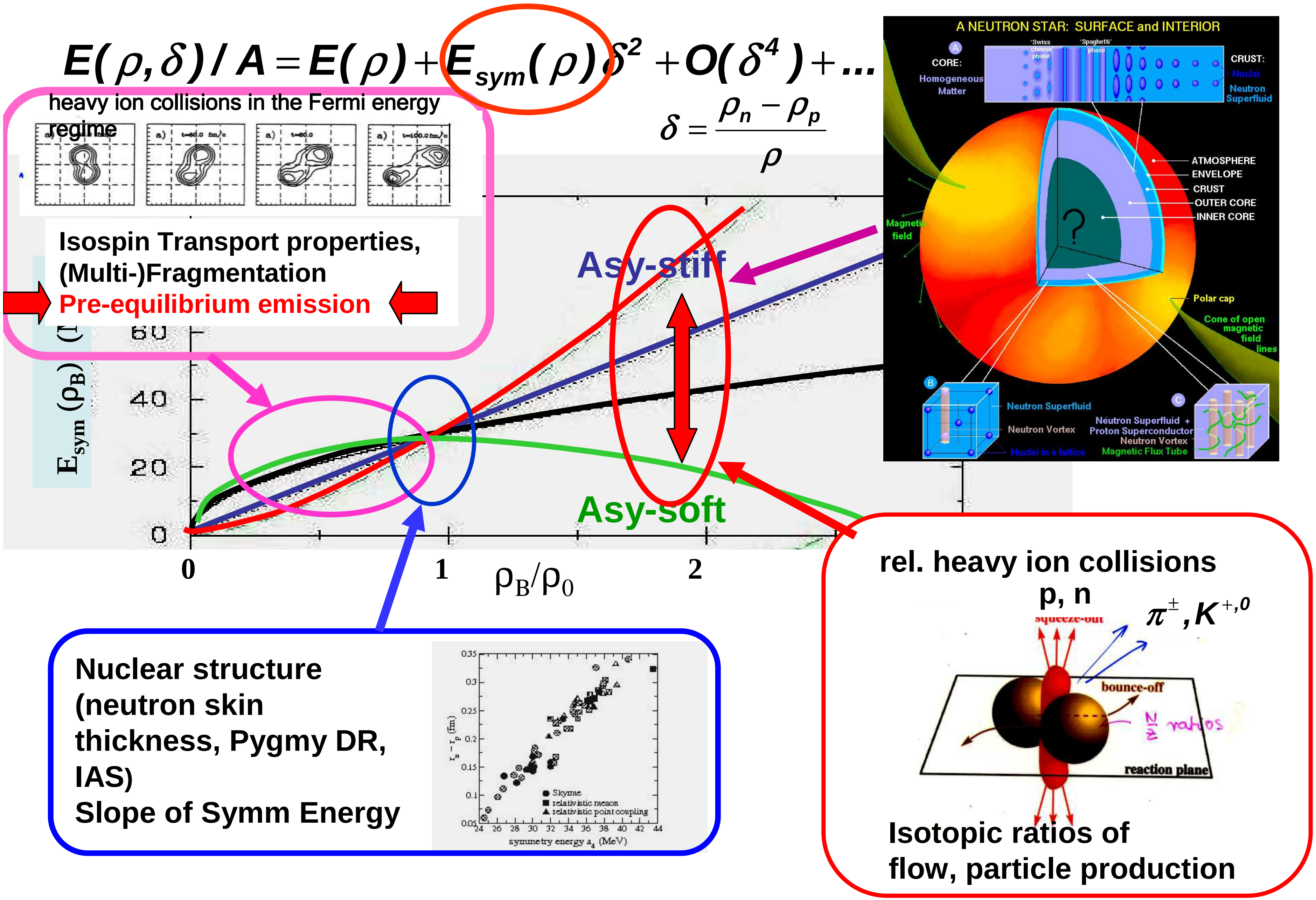
NuSym2013, FRIB/NSCL, East Lansing, USA, July 22-26, 2013



Agenda:

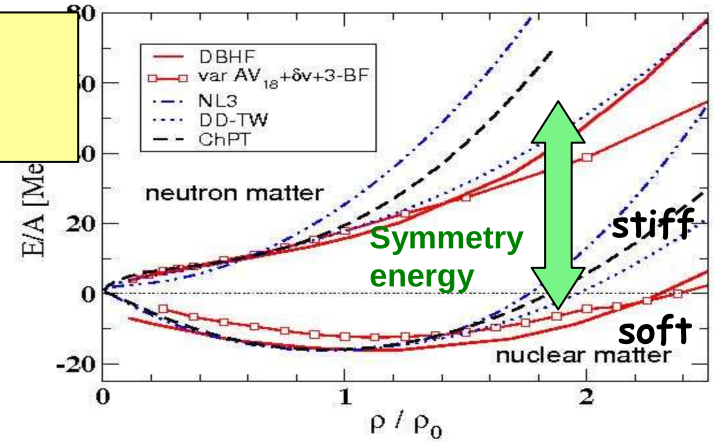
- **Importance of the Nuclear Symmetry Energy in nuclear and astrophysics and its uncertainty**
- **Density and momentum dependence of the symmetry potential**
- **here: early emission of nucleons and light fragments as a probe for** $\rho \leq \rho_0$
- **Possibility to disentangle density and momentum dependence of the symmetry energy**

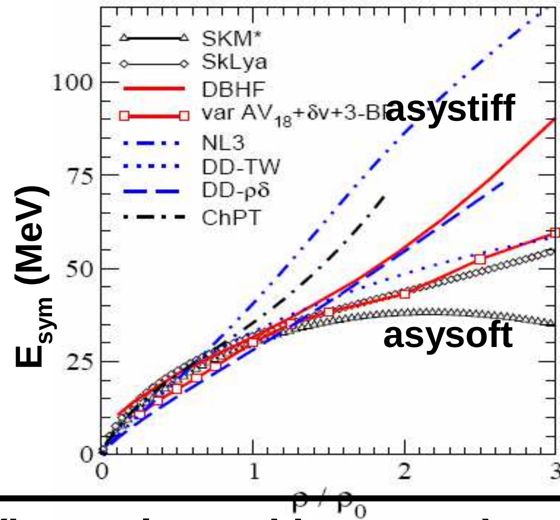
Investigations of the Nuclear Symmetry Energy in different density regions



The Nuclear Symmetry Energy in different „realistic“ models

Rel, Brueckner
Variational
Rel. Mean field
Chiral perturb.





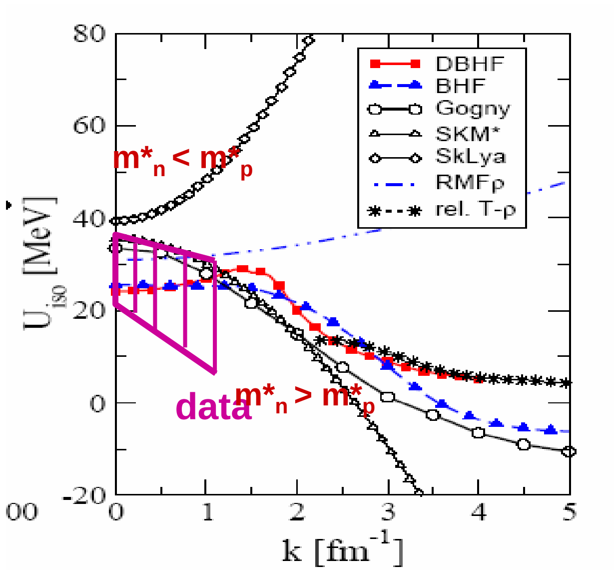
C. Fuchs, H.H. Wolter, EPJA 30(2006)5

Momentum dependence of symmetry potential (isoscalar and isovector)

$$\varepsilon(\rho[f(\rho,k)];\delta) \rightarrow U(\rho,k;\delta) = \frac{\partial \varepsilon(\rho,\delta)}{\partial f(\rho,k)} = \underbrace{U_0(\rho,k) + U_{sym}(\rho,k)(\tau\delta)}_{U_\tau(\rho,k)} + \dots$$

Effective masses and effective proton-neutron mass splitting

$$\frac{m^*_\tau}{m} = \left(1 + \frac{m}{\hbar^2 k}\frac{\partial U_\tau}{\partial k}\right)^{-1}$$

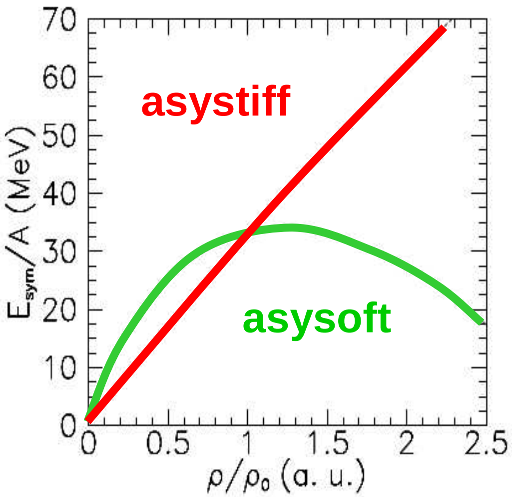


Even no agreement on ordering of n/p effective masses between Skyrme, RMF, BHF, DBHF

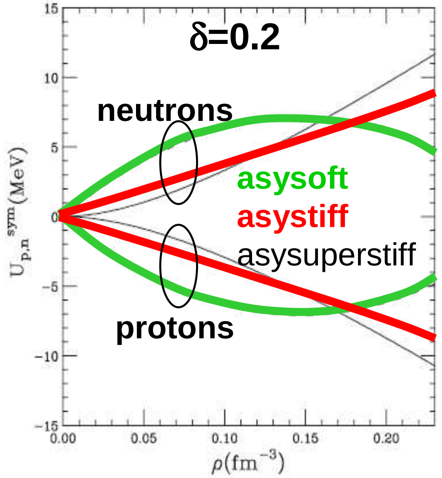
Why is symmetry energy so uncertain??
→ In-medium ρ mass, and short range isovector tensor correlations (e.g. B.A. Li, PRC81 (2010));
→ use heavy ion collisions to investigate in the laboratory

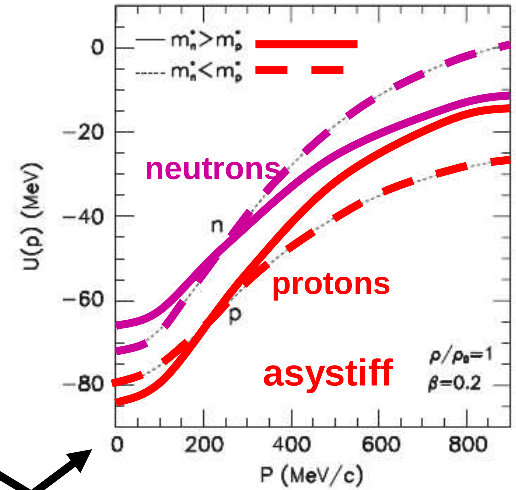
Example of the isovector dependence for a particular parametrization
(used in the following results, BGBD, Bombaci-Gale-Bertsch-DasGupta)

Symmetry energy



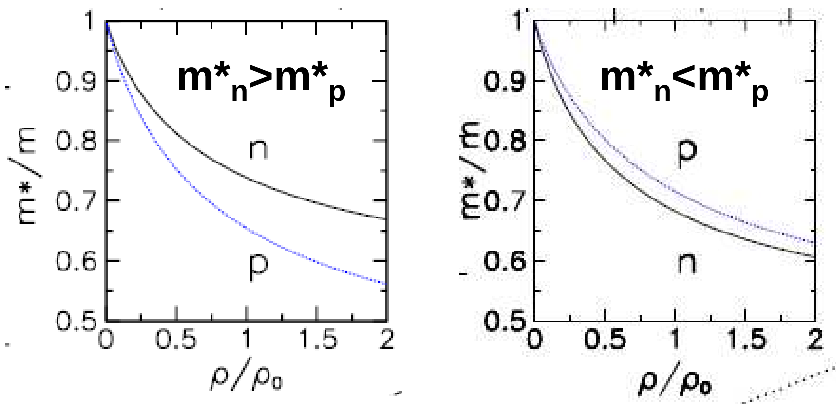
Neutron/proton potentials as a fct of density for $p=p_F$ (left) momentum for $\rho=\rho_0$ (right)





effects of the density and momentum dependence can be of the same order

Effective masses (for asystiff and $p=p_F$)



Symmetry energy and symmetry potentials (effective masses)

B.A. Li, X. Han, arXiv:1304.3368

establish a relation $\{E_{sym}, L\} \leftrightarrow \{U_{sym}, m^*_{n,p}\}$ using the Hugenholtz-Van Hove theorem

$$E_{\rm sym}(\rho) = \frac{1}{3}\frac{\hbar^2 k_F^2}{2m_0^*} + \frac{1}{2}U_{\rm sym}(\rho, k_F),$$
$$L(\rho) = \frac{2}{3}\frac{\hbar^2 k_F^2}{2m_0^*} + \frac{3}{2}U_{\rm sym}(\rho, k_F) + \frac{\partial U_{\rm sym}}{\partial k}|_{k_F} k_F,$$

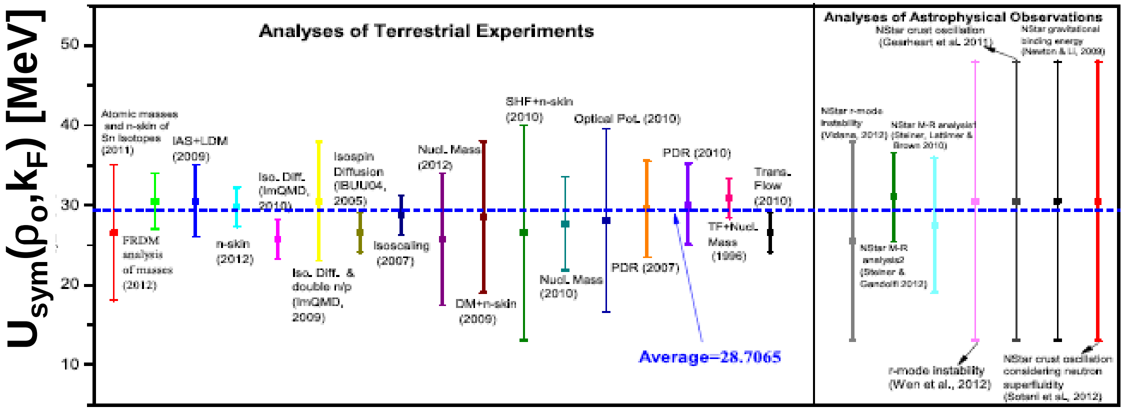
$\Leftrightarrow$

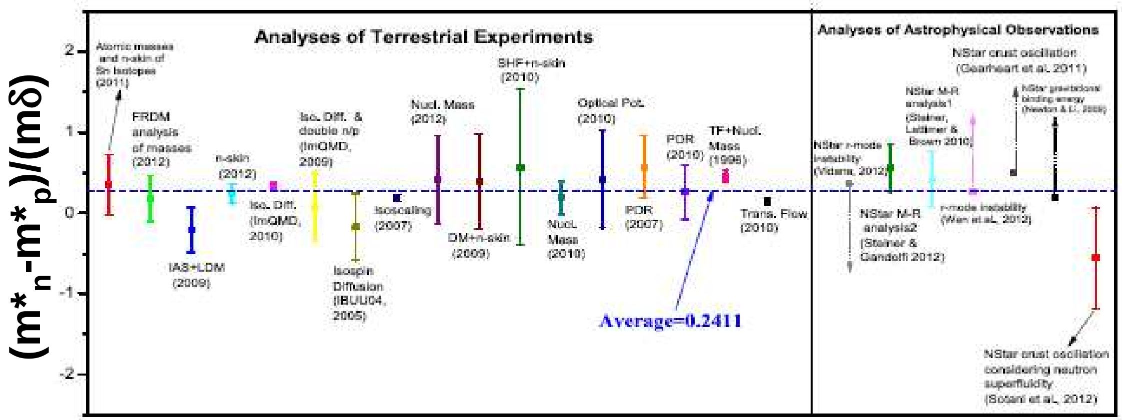
$$U_{\rm sym}(\rho_0, k_F) = 2\left[E_{\rm sym}(\rho_0) - \frac{1}{3}\frac{m}{m_0^*}E_F(\rho_0)\right],$$
$$\left.\frac{dU_{\rm sym}}{dk}\right|_{k_F}(\rho_0) = \left[L(\rho_0) - 3E_{\rm sym}(\rho_0) + \frac{1}{3}\frac{m}{m_0^*}E_F(\rho_0)\right] / k_F,$$

Use existing determinations in the literature for $\{E_{sym}, L\}$ to obtain values for $\{U_{sym}, m^*_{n,p}\}$

Without going into details, shows appearance of some consensus on the symmetry potential and the effective mass, but also the large scatter (esp. for the effective mass splitting)

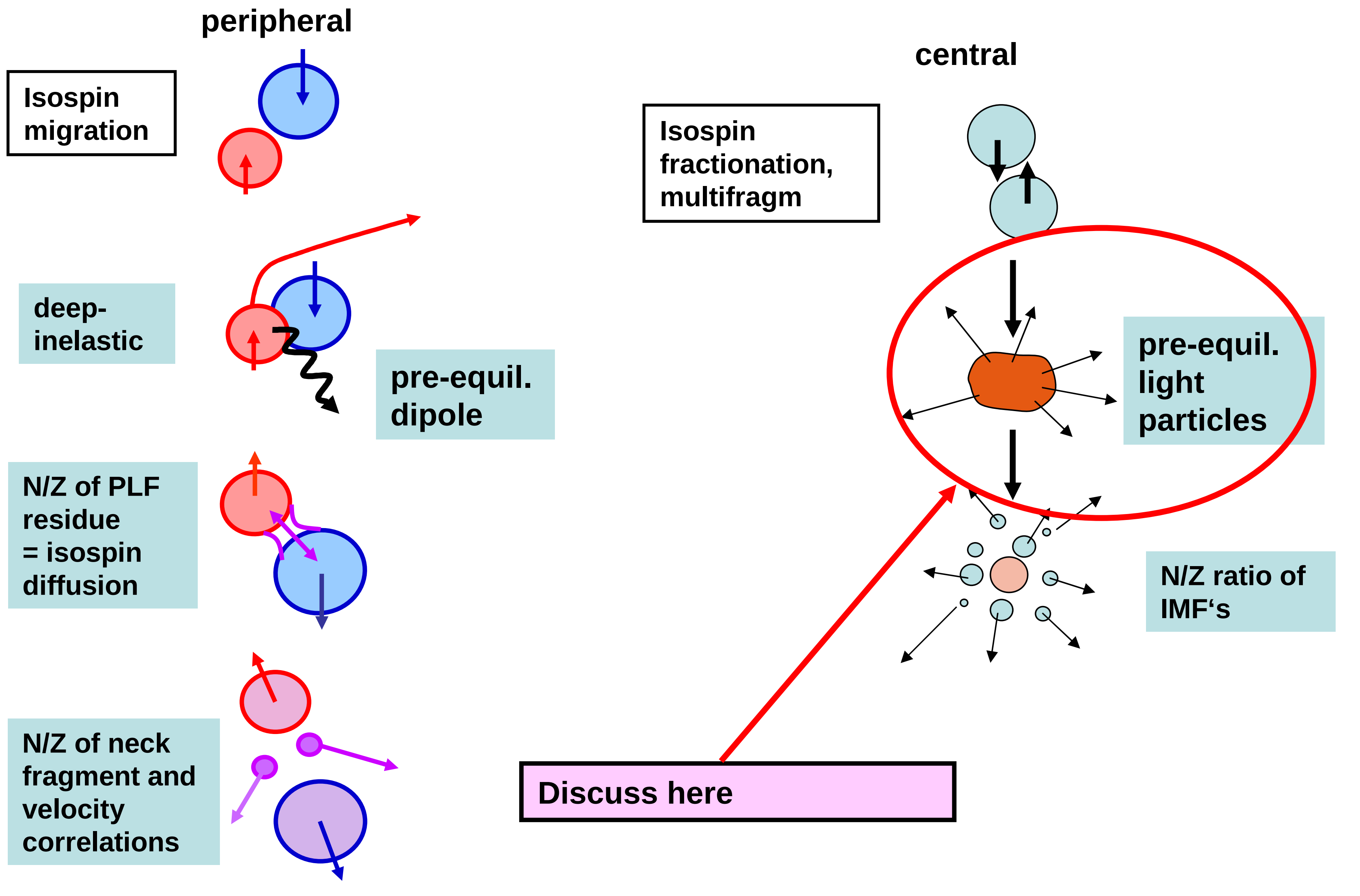
→ need to constrain this better





Isospin-related Observables in Low Energy Heavy Ion Collisions

Coulomb barrier to Fermi energies

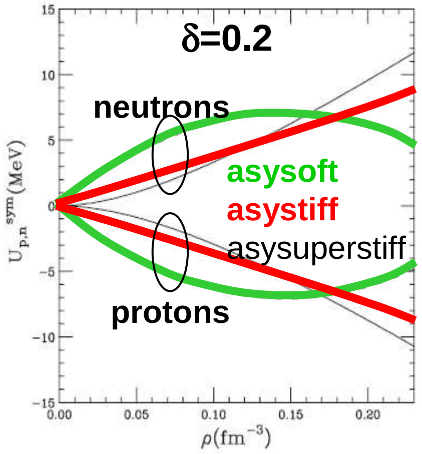


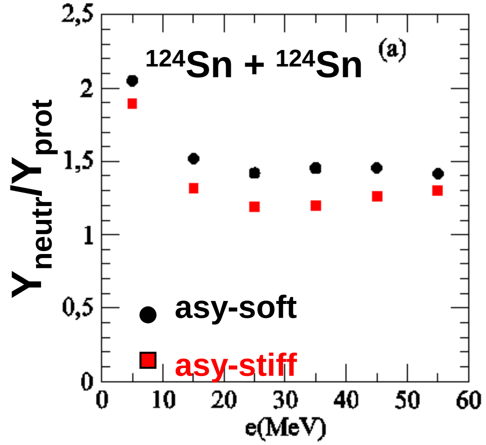
Pre-equilibrium particle emission: n/p ratio

Early emitted neutrons and protons reflect difference in potentials in expanded source, esp. ratio Y(n)/Y(p).

more emission for asy-soft, since symm potential higher

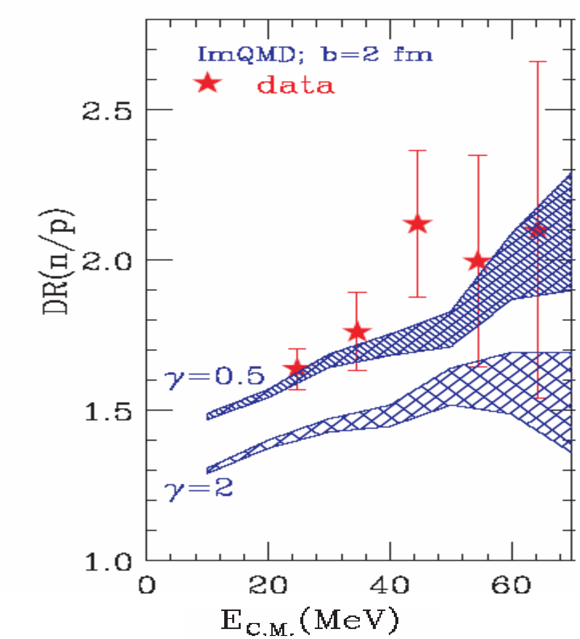
Neutrons difficult to measure, thus „Double Ratios“ $\frac{^{124}Sn + ^{124}Sn}{^{112}Sn + ^{112}Sn}$

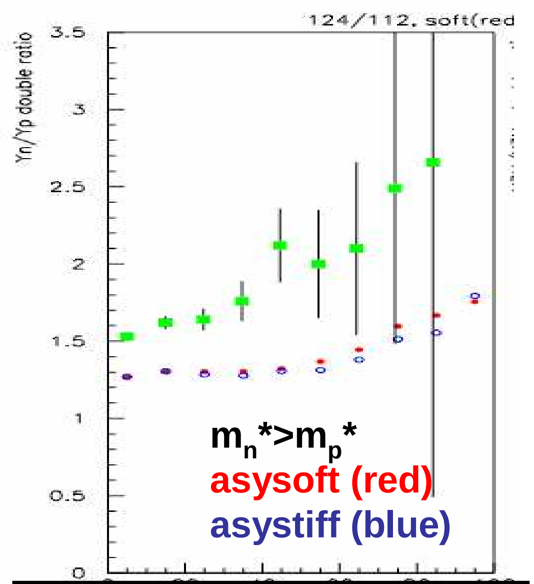




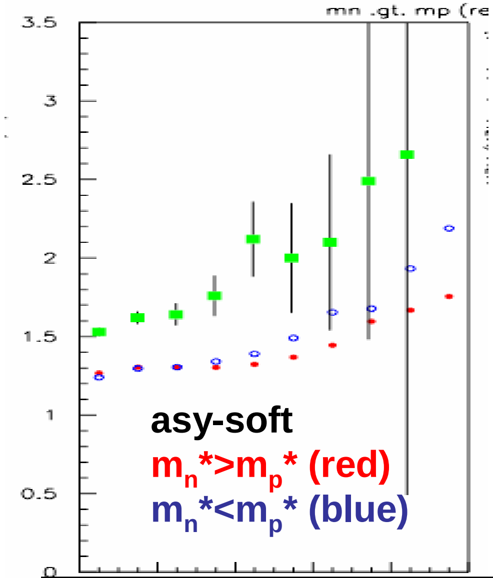
M. Zielinska-Pfabe, et al., AsyEoS-Meeting, Noto 2010

Data: Famiano et al. PRL 06
Calc.: Danielewicz, et al. 07





Similar qualitatively but smaller effect



Effect of mass splitting of same magnitude

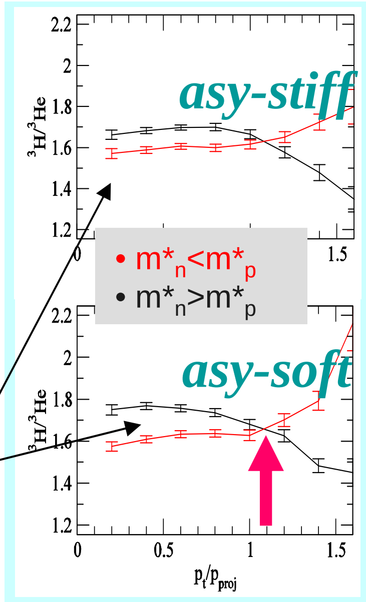
→ A sensitive observable, but perhaps double ratio not optimal. Light charged particles?

Previous studies of t/3He ratios:

Yield ratios, mainly studied at high energy

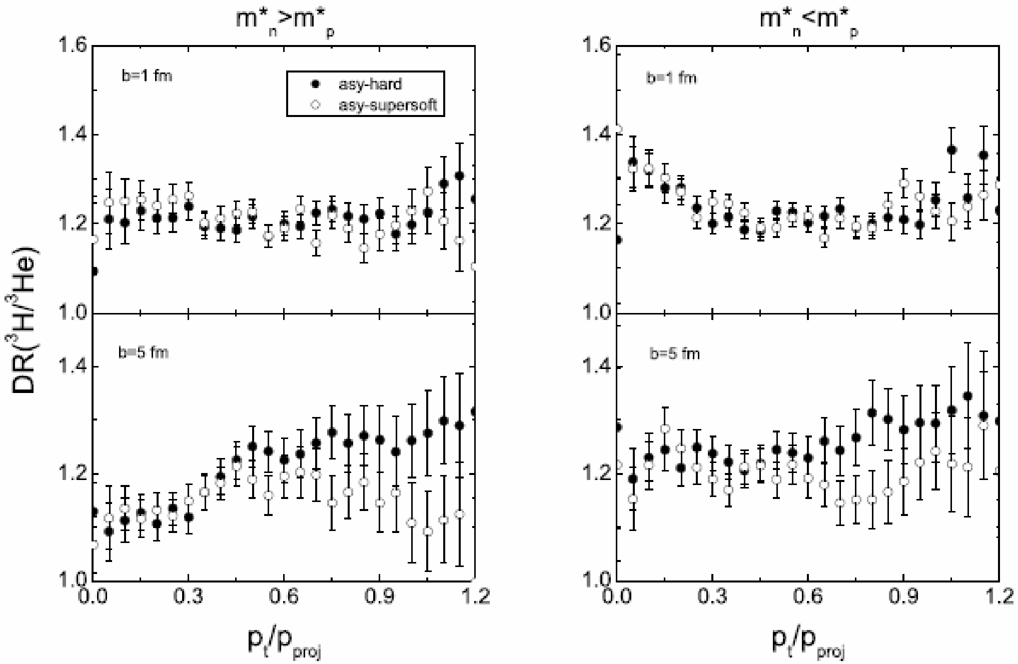
$^{197}Au+^{197}Au$
600 AMeV b=5 fm,
y(0)≤0.3

effect of effective mass more prominent than of asystiffness



(V.Giordano, et al., PRC 81(2010))

197Au+197Au, 400 AMeV



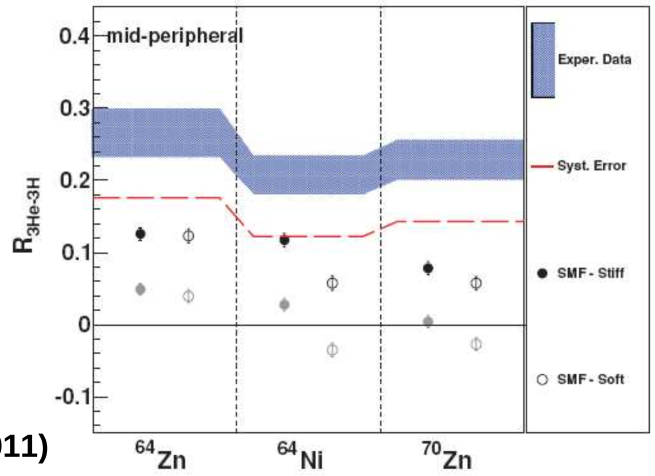
Z.Q. Feng, NPA878, 3 (2012)

Flow ratios At low energy

$$R_{^3He\text{-}^3H} = \frac{F^{^3He} - F^{^3H}}{F^{^3He} + F^{^3H}},$$

Effect of symm energy seen, but far away from data

Z.Kohley, et al., PRC83, 044601 (2011)



symmetric collisions, 35 AMeV

Also studies at higher energy, e.g. G.C,Yong, et al., PRC80, 044608 (2009)

Situation not so clear,

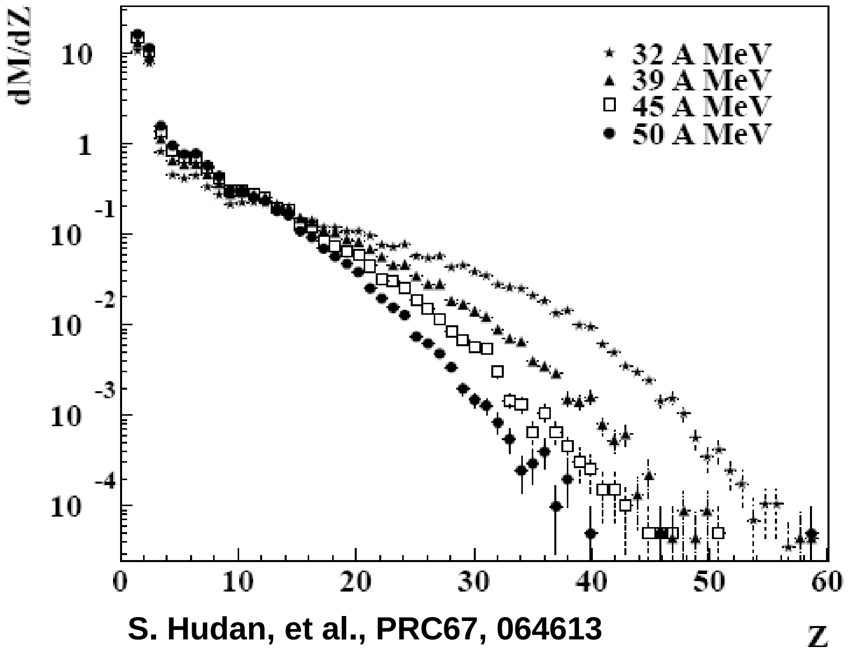
More data desirable

Systematic study useful

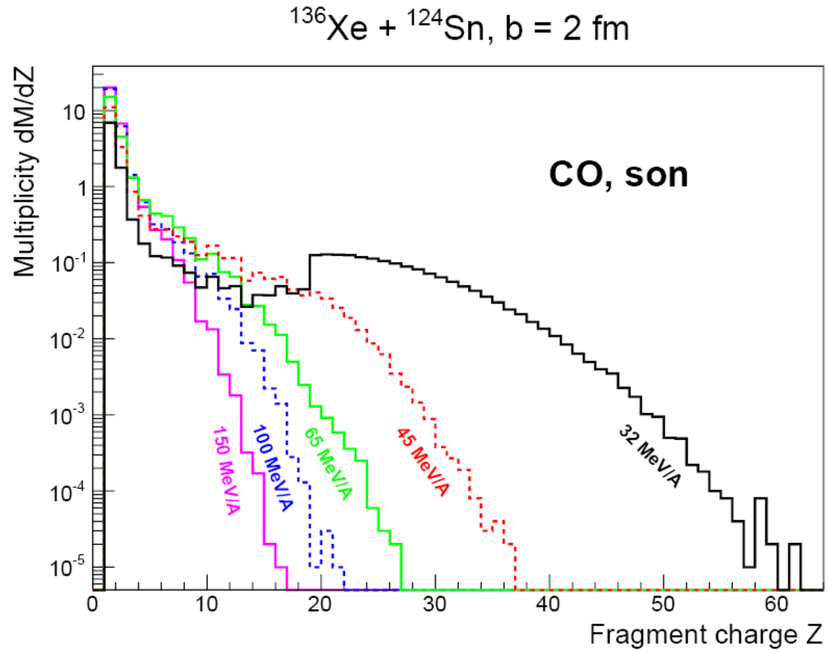
Study of Light Fragment Emission: $^{136,124}Xe+^{124,112}Sn$, E = 32,..,150 AMeV ,

Prelim. data from R. Bougault, et al.,GANIL

Cluster recognition by two methods: Coalescence (CO) in phase space
Density cut (DC, „gas“ (p.n) and „liquid“)
Global charge distributions agree resonably



S. Hudan, et al., PRC67, 064613



Calculations with variation of symmetry energy and effective mass splitting

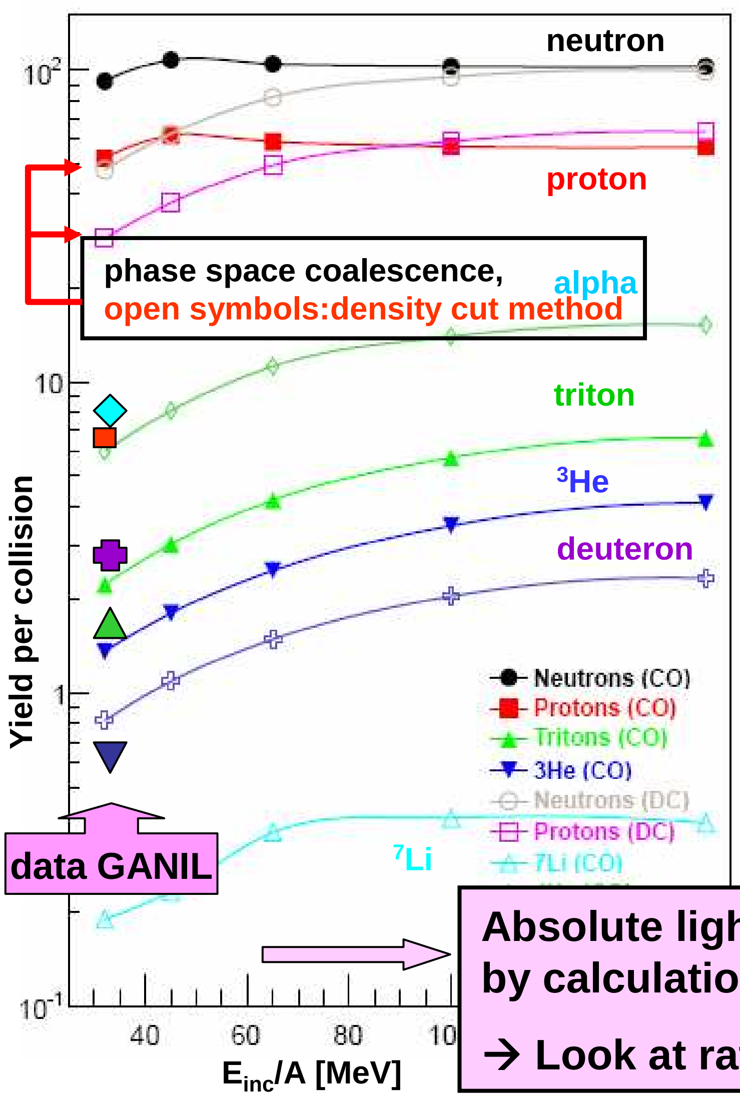
asy-soft	so	n	$m_n^* > m_p^*$
asy-stiff	st	p	$m_p^* > m_n^*$

→ son, stn, sop, stp

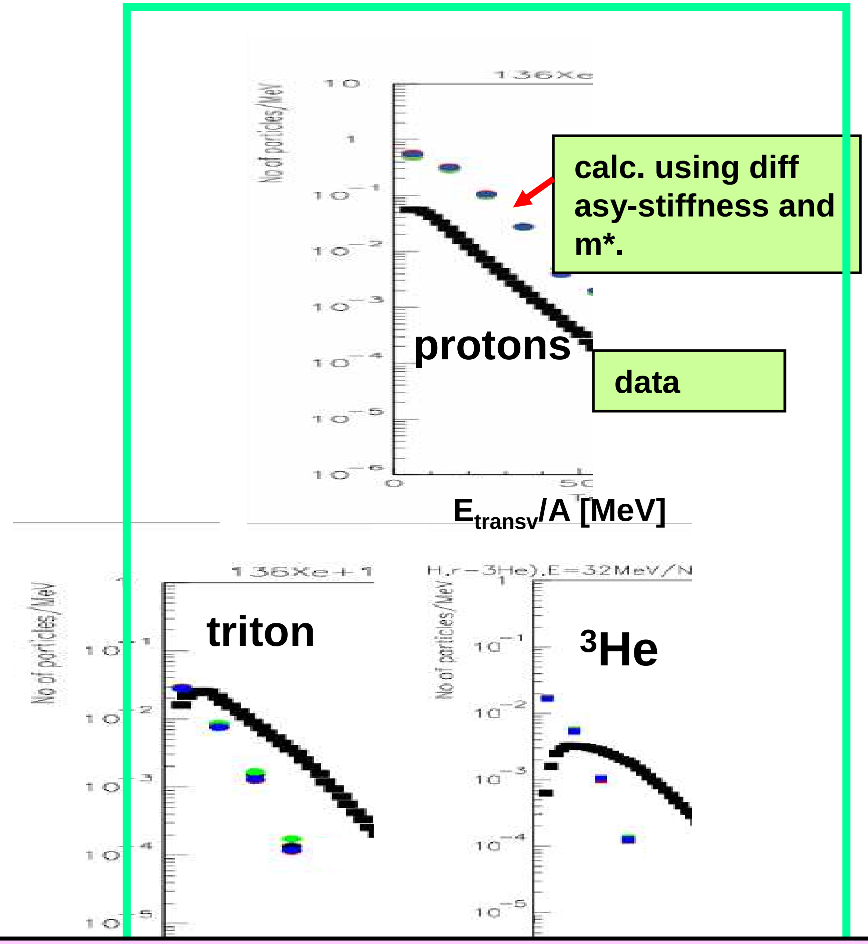
Study of Light Fragment Emission: $^{136,124}Xe+^{124,112}Sn$, E = 32,.,150 AMeV ,
Yields and spectra in comp. to experiment

136Xe+124Sn (n-rich)

Total yields



Transverse energy spectra



Absolute light fragment yields and spectra not well reproduced by calculations – important to improve!

→ Look at ratios: p/n, t/3He single ratios and double ratios

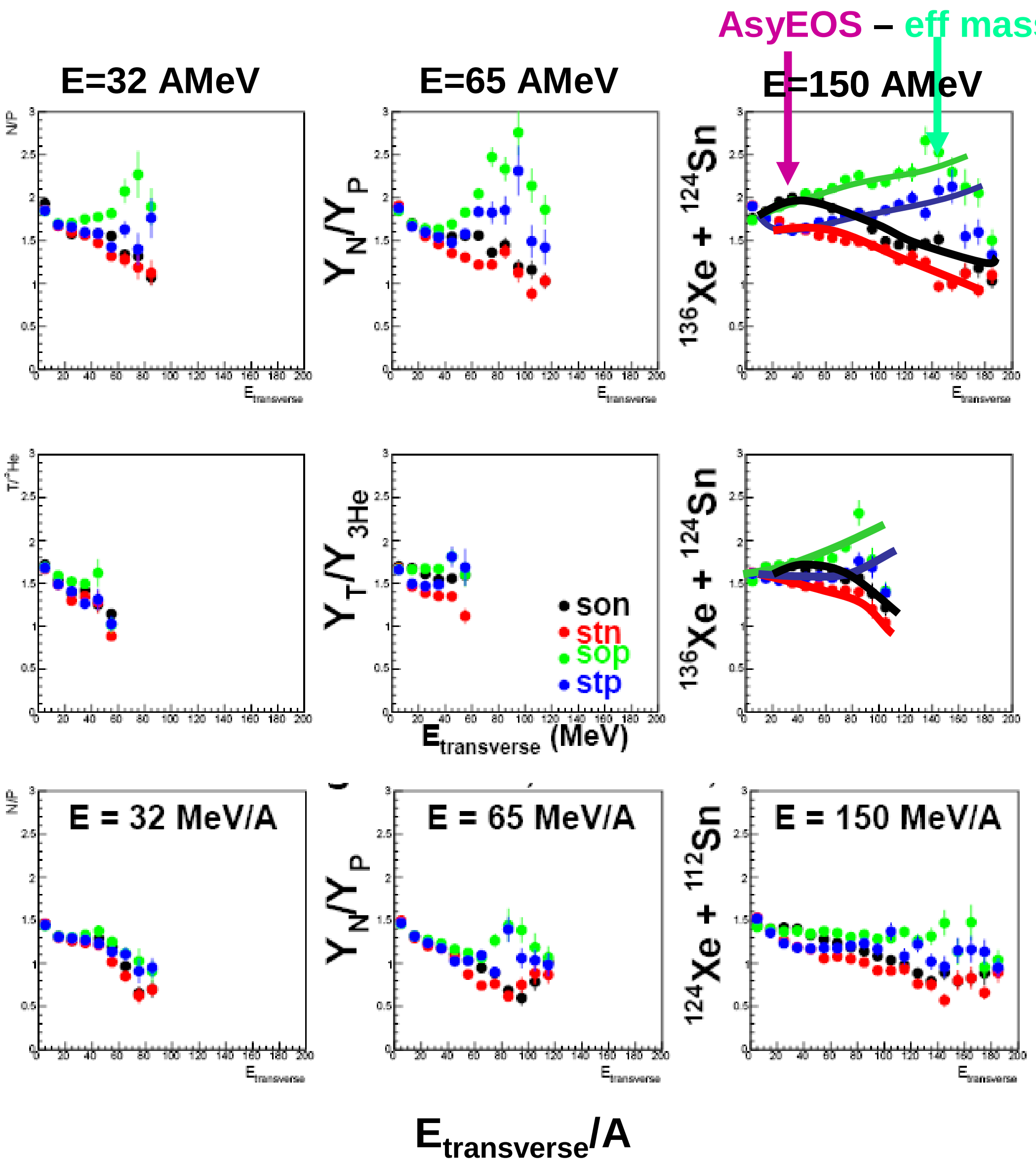
Study of Light Fragment Emission: $^{136,124}Xe+^{124,112}Sn$, E = 32,.,150 AMeV ,

Single ratios

Single ratio n/p
neutron rich
$^{136}Xe+^{124}Sn$

Single ratio t/3He
neutron rich
$^{136}Xe+^{124}Sn$

Single ratio n/p
neutron poor
$^{124}Xe+^{112}Sn$



Possibility to separate density and momentum dependence of symmetry energy

Effects smaller for light clusters $t/^{3}He$ improve statistics!

Smaller neutron excess: effects smaller

son: asysoft, $m_n^*>m_p^*$
stn: asystiff, $m_n^*>m_p^*$
sop: asysoft, $m_n^*<m_p^*$
stp: asystiff, $m_n^*<m_p^*$

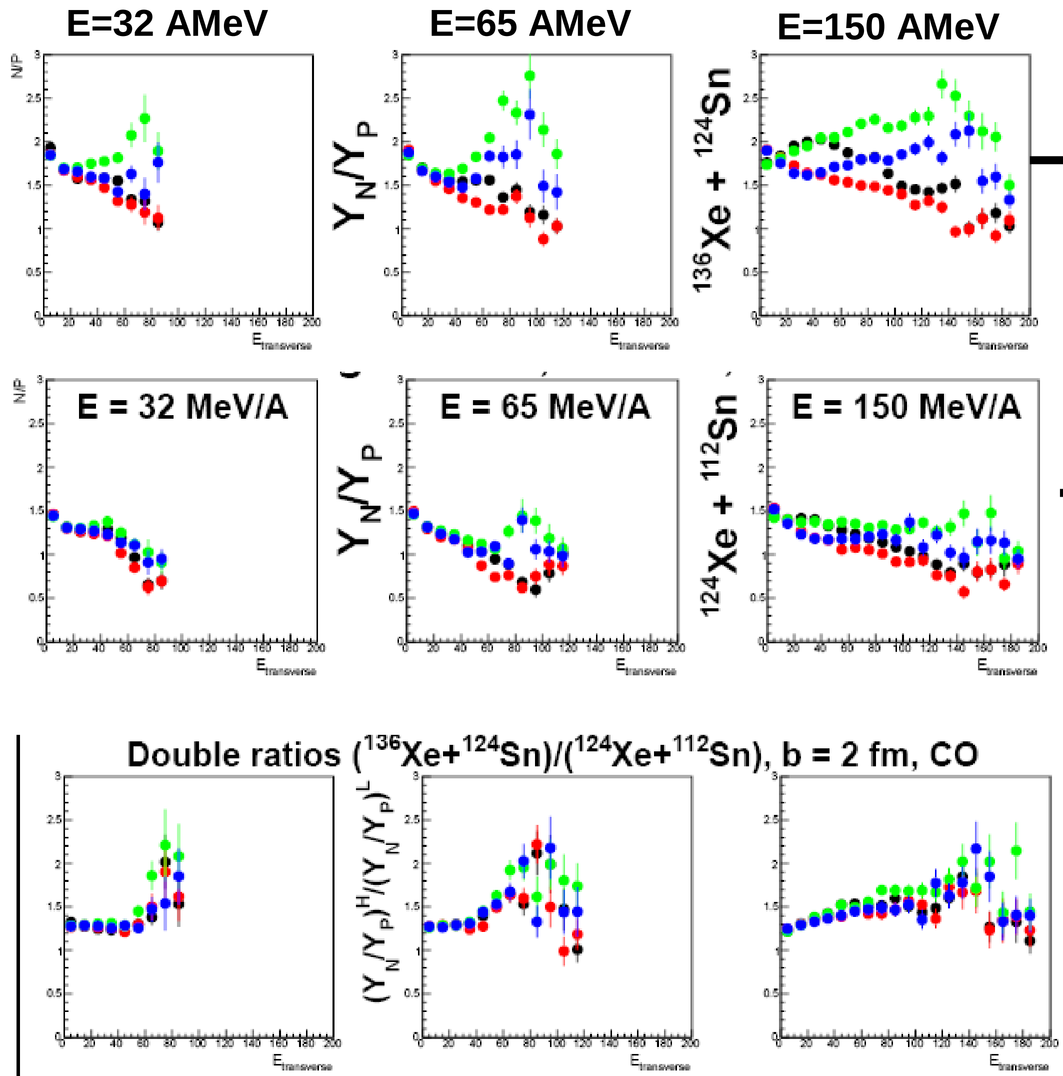
Study of Light Fragment Emission: $^{136,124}Xe+^{124,112}Sn$, E = 32,.,150 AMeV ,

Double ratios

Single ratio n/p
neutron rich
$^{136}Xe+^{124}Sn$

Single ratio n/p
neutron poor
$^{124}Xe+^{112}Sn$

Double ratio n/p
neutron rich / neutron poor



Ratio

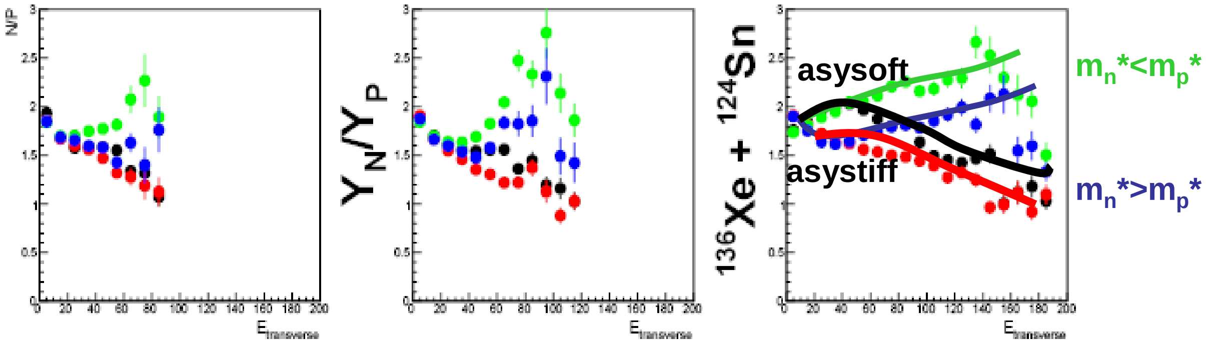
Double ratio also shows effect but less sensitive to symmetry energy

son: asysoft, $m_n^*>m_p^*$
stn: asystiff, $m_n^*>m_p^*$
sop: asysoft, $m_n^*<m_p^*$
stp: asystiff, $m_n^*<m_p^*$

$E_{transverse}/A$

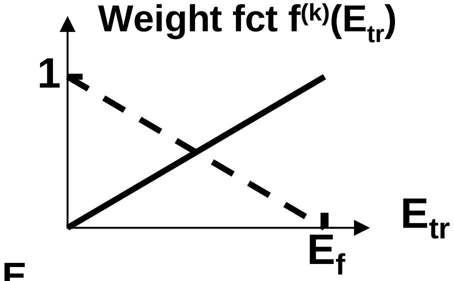
Moments of single ratios: characterize behavior on asy-EoS and m*

son: asysoft, $m_n^*>m_p^*$
stn: asystiff, $m_n^*>m_p^*$
sop: asysoft, $m_n^*<m_p^*$
stp: asystiff, $m_n^*<m_p^*$

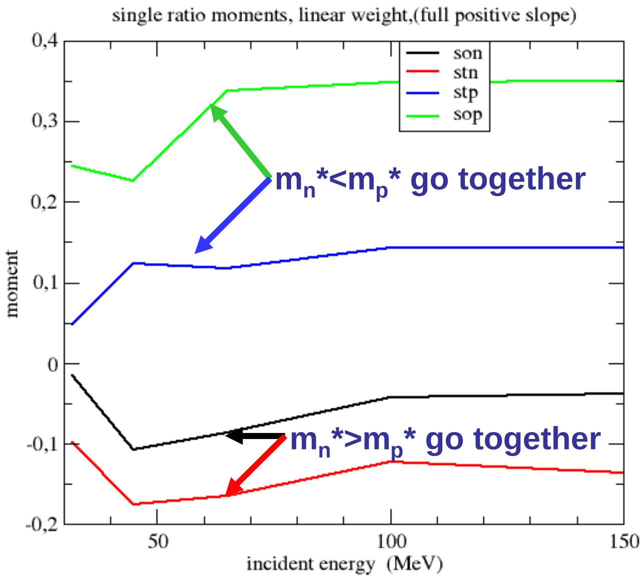


Calculate moments of the single ratios, e.g. for n/p ratio

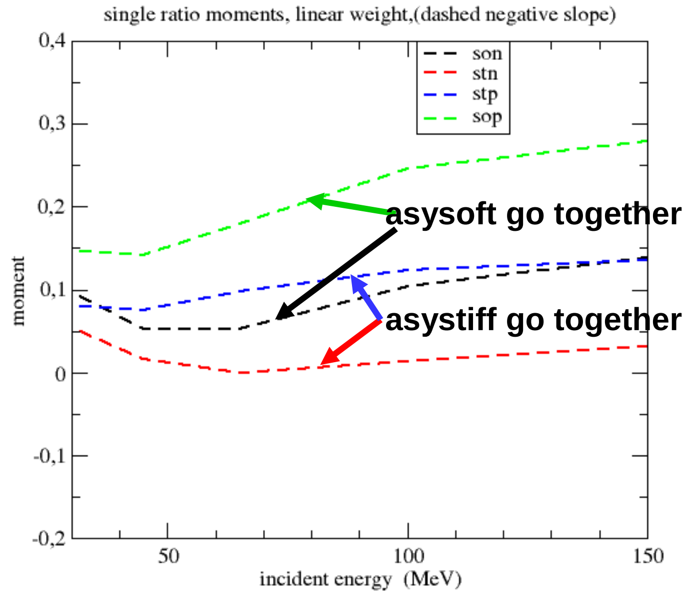
$$R_\alpha^{(k)}(E_{inc}) = \frac{1}{E_f}\int_0^{E_f} dE_{tr} f^{(k)}\left(\frac{E_{tr}}{E_f}\right)\left(R_\alpha(E_{tr},E_{inc}) - N/Z\right)$$



emphasize high E_{tr}



emphasize low E_{tr}



Characteristic patterns depending on asy-EoS and m*: perhaps an observable?

Comparison to data $^{136,124}Xe+^{124,112}Sn$, E = 32,…,150 AMeV

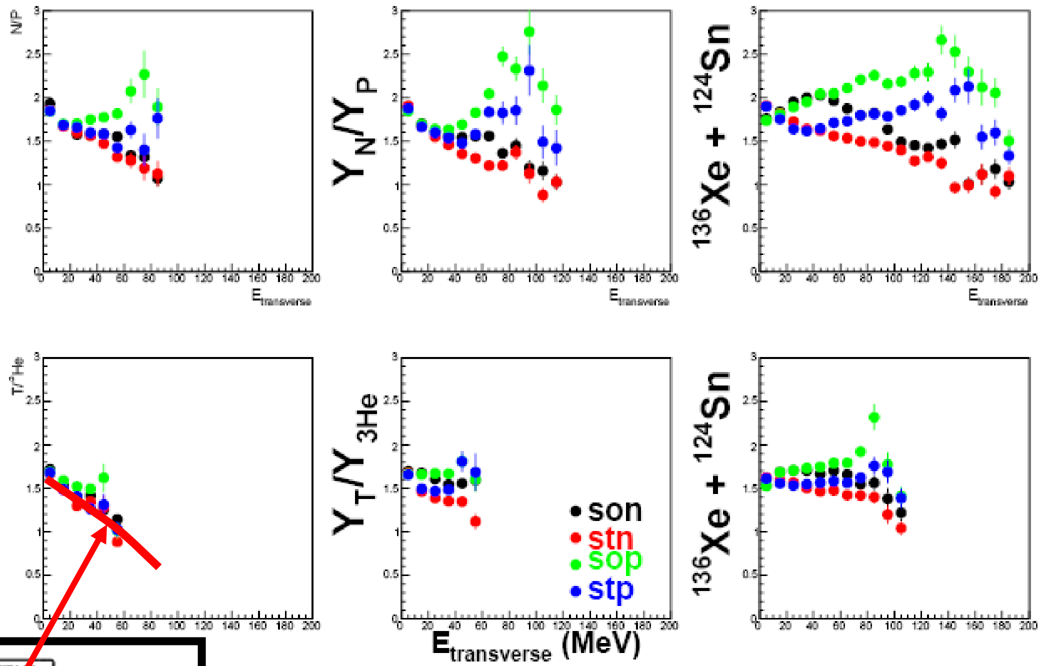
data R. Bougault, A. Chbihi (Ganil, prelim, IWM11)

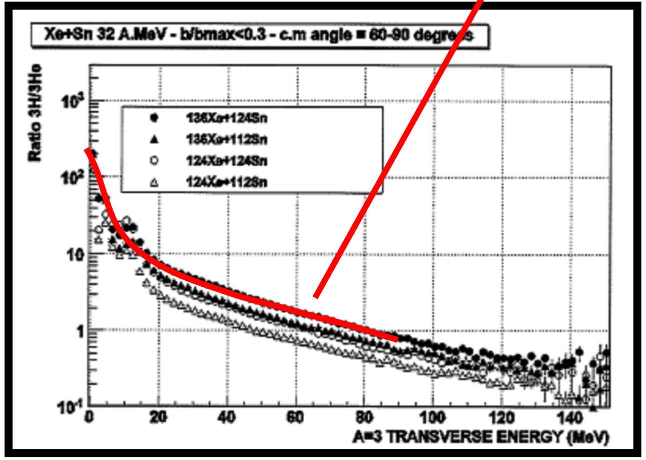
son: asysoft, $m_n^*>m_p^*$
stn: asystiff, $m_n^*>m_p^*$
sop: asysoft, $m_n^*<m_p^*$
stp: asystiff, $m_n^*<m_p^*$

Single ratio n/p
neutron rich
$^{136}Xe+^{124}Sn$

Single ratio t/3He
neutron rich
$^{136}Xe+^{124}Sn$

E=32 AMeV | E=65 AMeV | E=150 AMeV

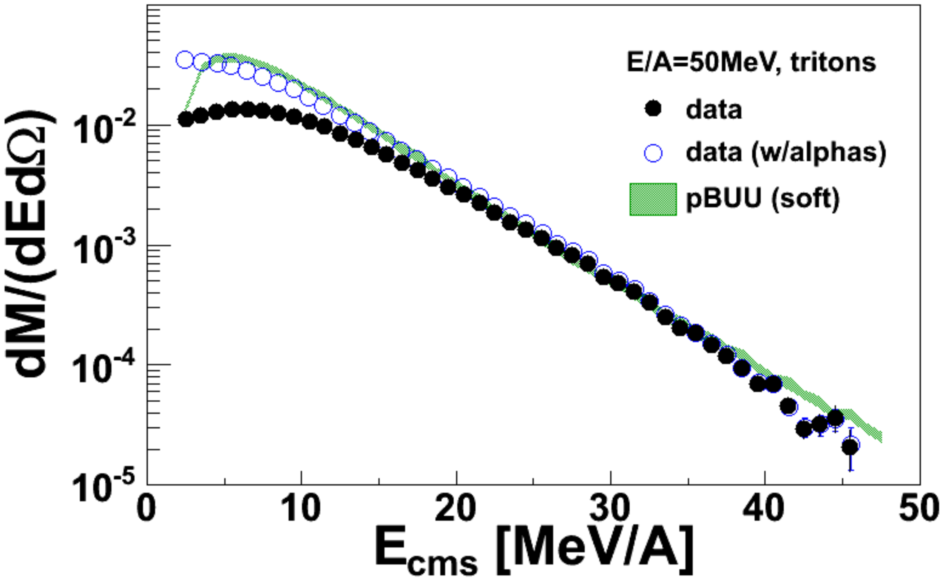


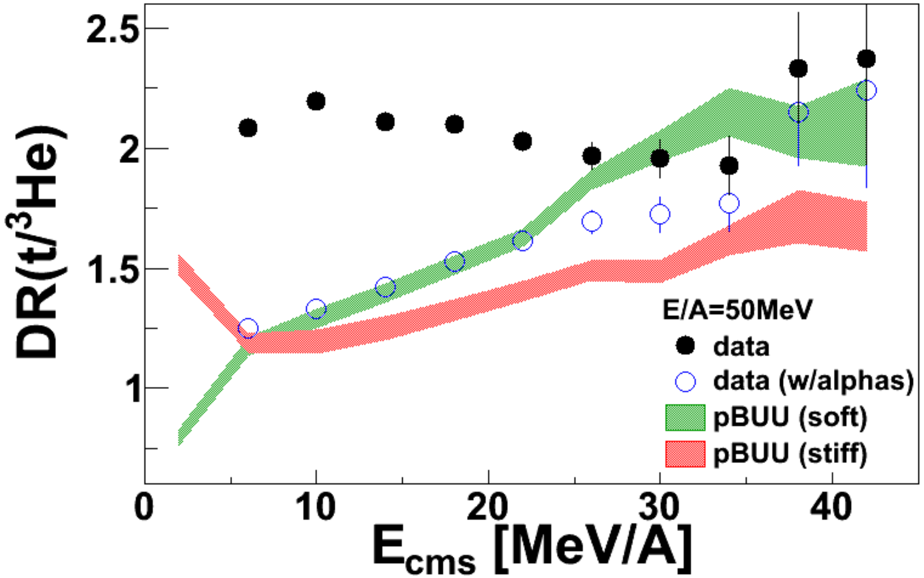


Prelim. data
136+124, 32 AMeV,
INDRA
favors asy-stiff with
$m_n^*>m_p^*$

The single t/3He ratio seems to be a promising observable

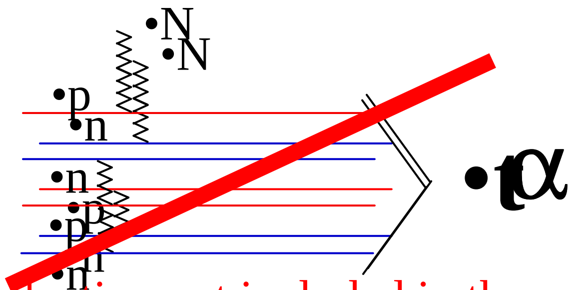
Similar work at MSU: W.Lynch, INPC, Florence, 2013: $^{124,112}Sn+^{124,112}Sn$, 50 AMeV
Calculations using P. Danielewicz code with clusters





- Illustrate with Danielewicz BUU with cluster production.
- Approx. QM description of cluster production up to A=3 (but not beyond)
- $m^*=0.7m_0$, $m^*_p= m^*_n$
- Calculations underpredict the double-ratio

Figure courtesy of Z. Chajecki.



•Alpha production not included in the model => alphas end up being t or ^{3}He

•**Check**: combine experimental alpha spectra with tritons and helium-3 and compare to the model predictions.

•Need to extend cluster production past A=4.

Conclusions:

- The nuclear symmetry potential is density and momentum dependent; both behaviors are not well known from nuclear matter theories

- both are important for isospin sensitive observables in HIC; one should study many observables simultaneously to constrain the symmetry energy

- the ratios of p/n and light fragment spectra are promising to disentangle the density and momentum behaviour.
  new observable: moments of ratios?

- more experimental data desirable (FRIB!)
- but also improved treatment of cluster production in transport calc.

Thank you

backup

Effective masses:

Non-relativistic mass

$$m_{NR}^* = \left[m + \frac{1}{k}\frac{dU_{sp}}{dk} \right]^{-1} = |k| \left[\frac{dE}{d|k|} \right]^{-1}$$

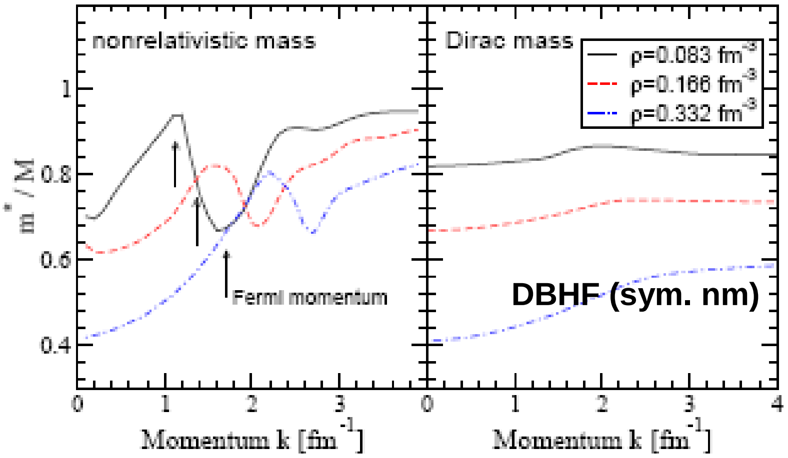
Parametrizes non-locality in space (k-mass) and time (E-mass)

Dirac mass $m_D^* = m + \Sigma_s$

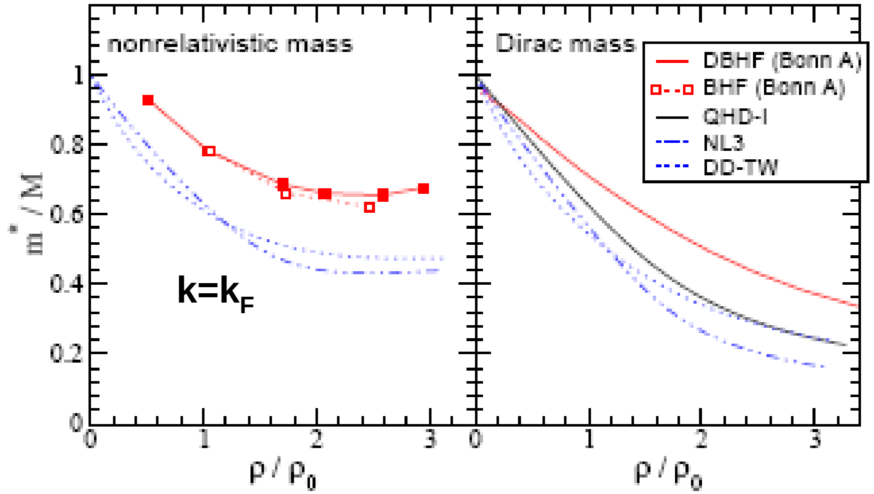
Includes part of the interaction;

relativistically $U_{sp} \approx \frac{m_D^*}{E^*}\Sigma_s + \Sigma_0$

k-dependence



ρ-dependence



C. Fuchs, H.H. Wolter, EPJA 30(2006)5

Effective mass splitting

$$m^*_{NR,n} \Leftrightarrow m^*_{NR,p} \qquad m^*_{D,n} \Leftrightarrow m^*_{D,p}$$

	$m^*_{NR,n} \Leftrightarrow m^*_{NR,p}$	$m^*_{D,n} \Leftrightarrow m^*_{D,p}$	
BHF:	>		
RMF (ρ+δ)	<	<	**Baran, PhysRep 410**
DBHF (fit S)	>	>	**Sammarucca, PRC67**
DBHF (project)	>	<	**v. Dalen, Fuchs, PRL95**

No agreement on ordering of n/p effective masses!

Example of the isovector dependence for a particular partametrization
(used in the following results, BGBD, Bombaci-Gale-Bertsch-DasGupta)

Energy density: kinetic + potential terms

$$\varepsilon_{kin}(\rho) = \frac{3}{10}\rho E_F\left[(1+\beta)^{5/3} + (1-\beta)^{5/3}\right] = \frac{3}{5}E_F + \frac{1}{3}\rho E_F \beta^2 \qquad \beta = \frac{N-Z}{A}$$

Bombaci-Gale-Bertsch-Das Gupta (BGBD) interaction

isoscalar | **isovector**

$$\varepsilon_A = \frac{A}{2}\frac{\rho^2}{\rho_0} - \frac{A}{3}\left(\frac{1}{2}+x_0\right)\frac{\rho^2}{\rho_0}\beta^2$$

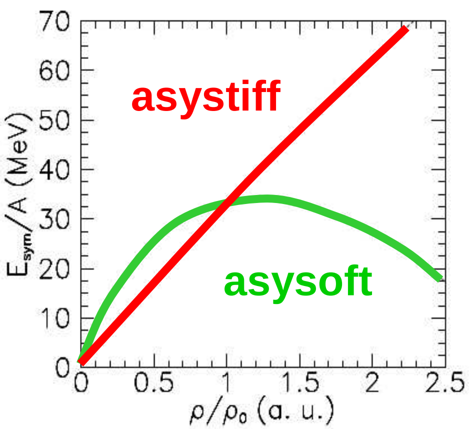
$$\varepsilon_B = \frac{B}{\sigma+1}\frac{\rho^{\sigma+1}}{\rho_0^{\sigma}} - \frac{2}{3}\frac{B}{\sigma+1}\left(\frac{1}{2}+x_3\right)\frac{\rho^{\sigma+1}}{\rho_0^{\sigma}}\beta^2$$

Momentum Dependence (MD): isoscalar + isovector

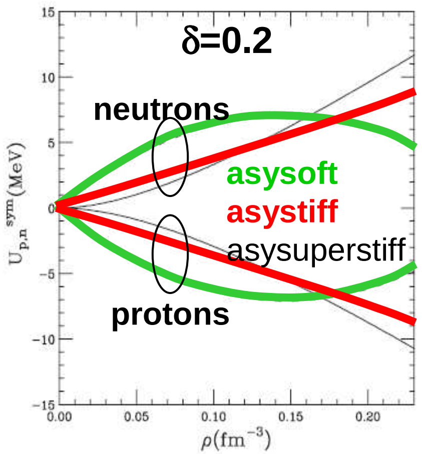
$$\varepsilon_{C,z} = \frac{8}{5\rho_0}(C+2z)I_{np} + \frac{2}{5\rho_0}(3C-4z)(I_{nn}+I_{pp})$$

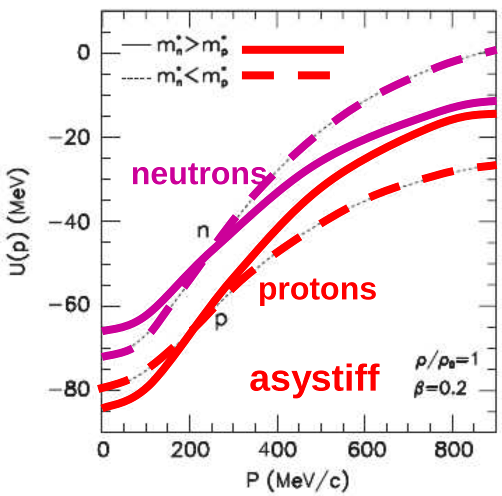
$$I_{tt'} = \left[\frac{2}{(2\pi)^3}\right]^2 \int d^3k\, d^3k'\, f_t(\vec{r},\vec{k})\, f_{t'}(\vec{r},\vec{k}')\, g(\vec{k},\vec{k}')$$

Symmetry energy

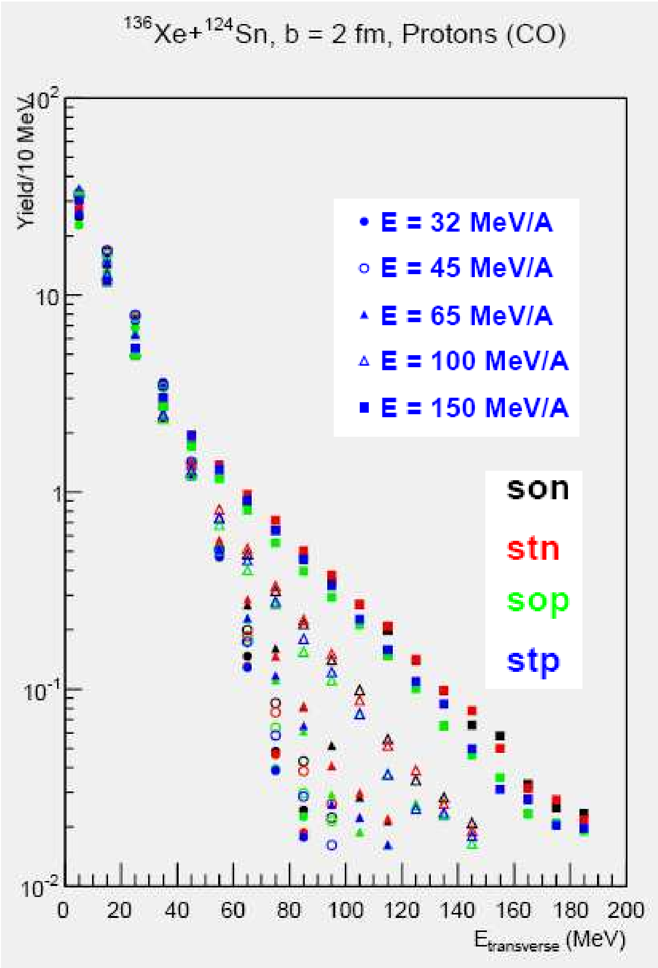


Neutron/proton potentials
as fct as fct of density for $p=p_F$ (left)
and of momentum for $\rho=\rho_0$ (right)

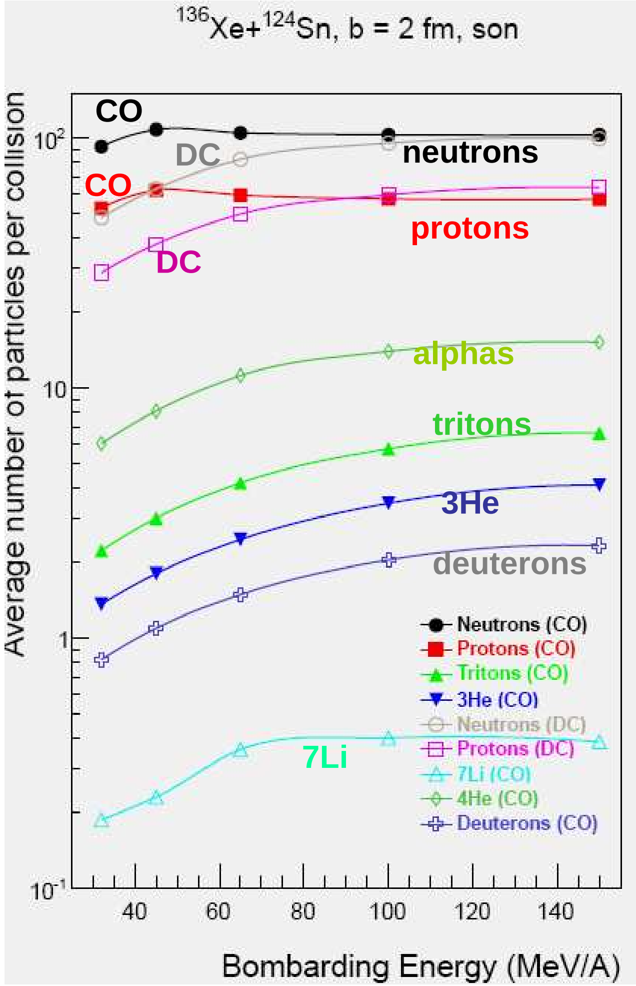




Study of Light Fragment Emission: $^{136,124}Xe+^{124,112}Sn$, E = 32,..,150 AMeV ,
Spectra and multiplicities



Steeper with increasing incident energy effect of AsyEoS amd m_{eff} seen

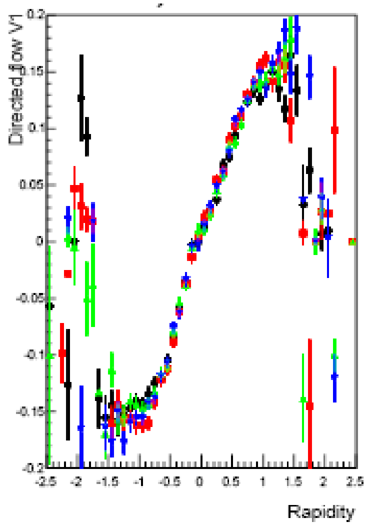


BE effects seen in particle yields Coalescence (CO) has too many free nucleons

Study of Light Fragment Emission: $^{136,124}Xe+^{124,112}Sn$, E = 32,.,150 AMeV , Proton flows

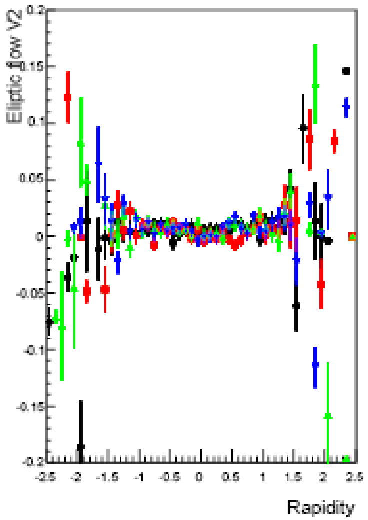
Flows: protons, $^{136}Xe + ^{124}Sn$, b = 2 fm, CO

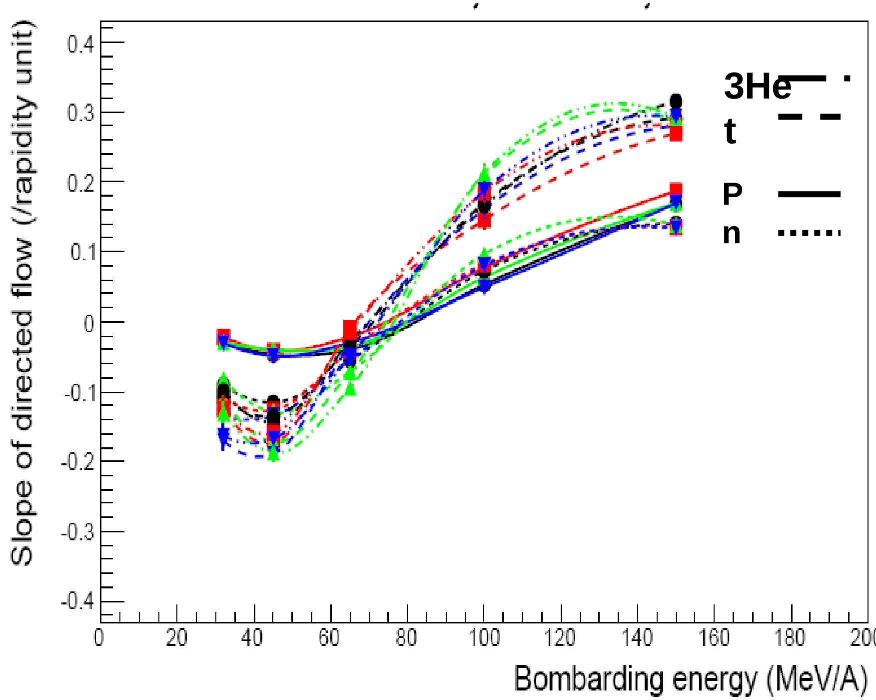
Directed flow



E = 150 MeV/A

Elliptic flow

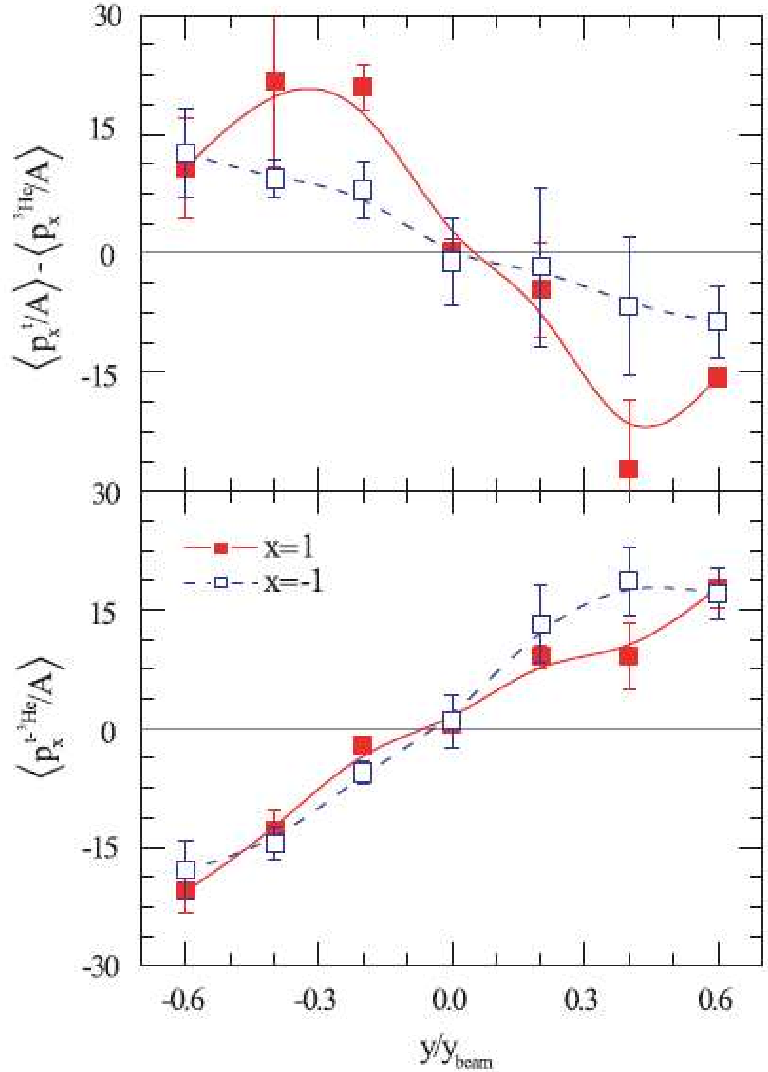




- Heavier particles have larger flow (known)
- AsyEoS differences small

→ Look at differences or differential flow

Differential flow



G.C,Yong, et al., PRC80, 044608 (2009)

$^{132}Sn+^{124}Sn$, 400 AMeV