Probing the EOS of Neutron-Rich Matter with Heavy-Ion Reactions at RIA

Bao-An Li
Arkansas State University

Collaborators: L.W. Chen and C.M. Ko (Texas A&M University)
G.C. Yong and W. Zuo (Chinese Academy of Science)

- **EOS of neutron-rich matter and symmetry energy**
- **An isospin- and momentum-dependent transport model for RIA**
- **Formation of neutron-rich matter at RIA**
- **Terrestrial probes of the density dependence of symmetry energy**

Two examples:

1. Near-threshold π^- / π^+ **ratio**

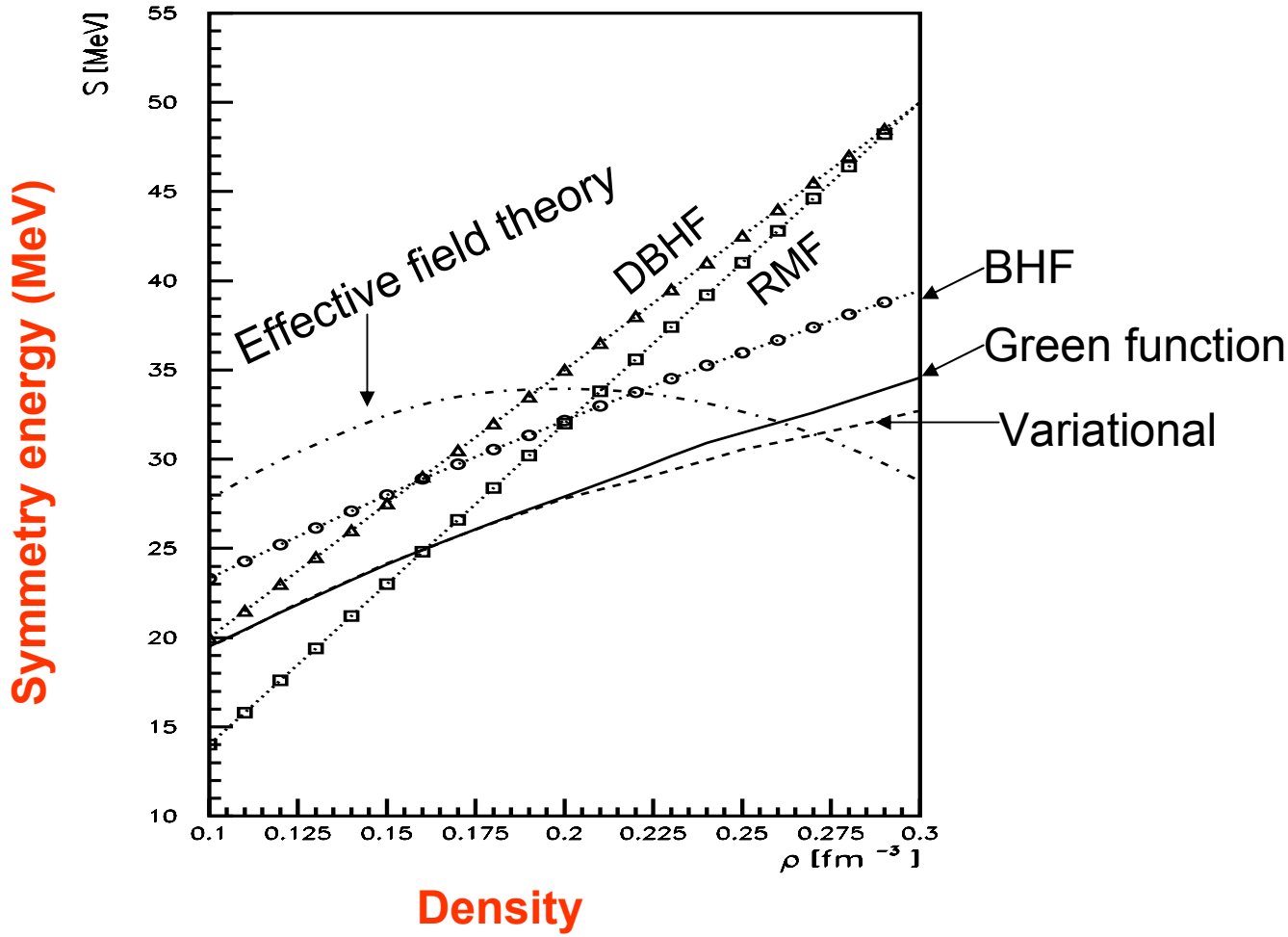
2. Neutron-proton differential transverse flow

- **Summary**

EOS of Isospin Asymmetric Nuclear Matter :

$$E(\rho,\delta) = E(\rho,0) + E_{sym}(\rho)\delta^2 + o(\delta^4)$$

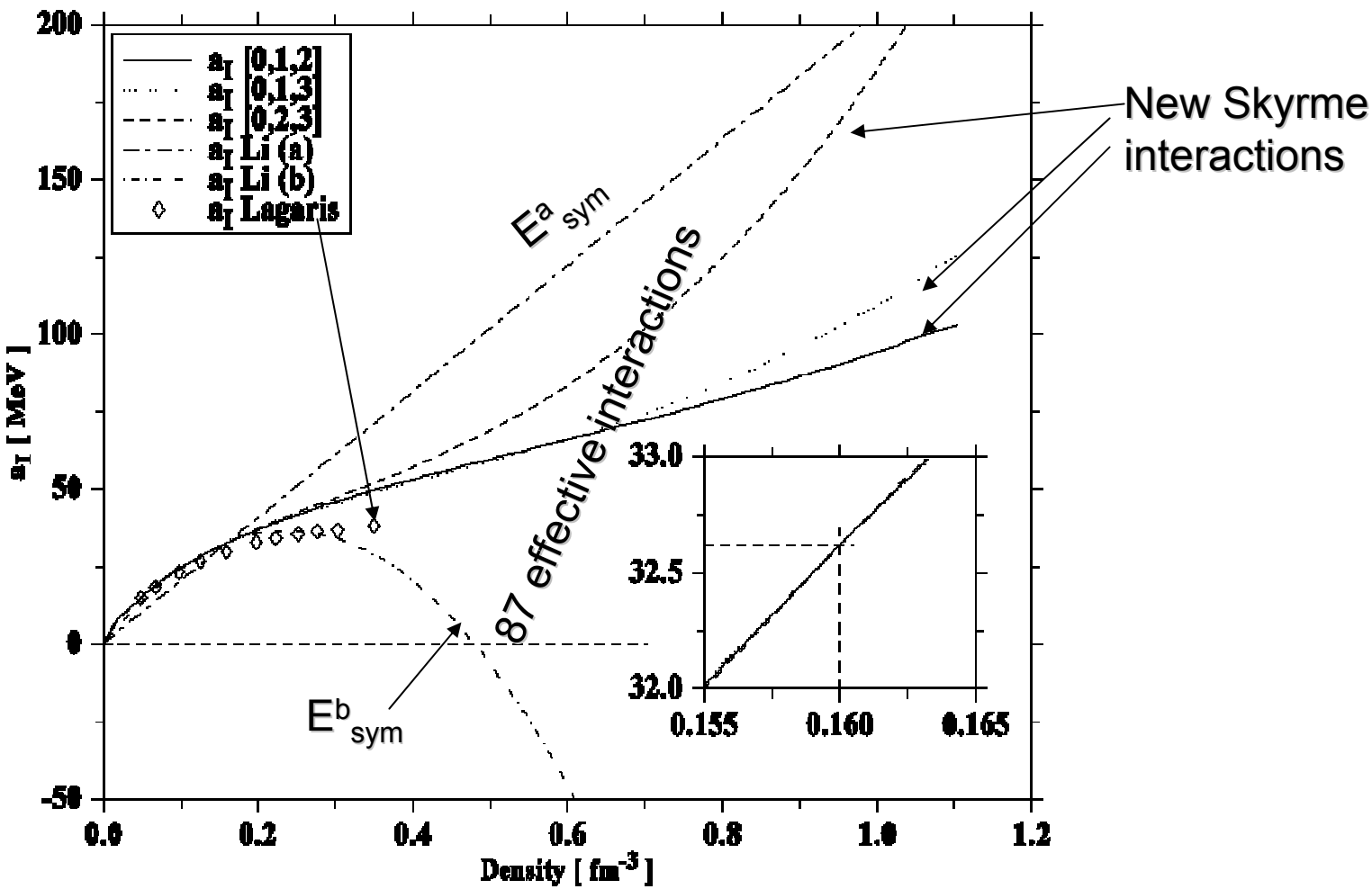
E_{sym} (ρ) predicted by microscopic many-body theories



A.E. L. Dieperink et al., Phys. Rev. C68 (2003) 064307

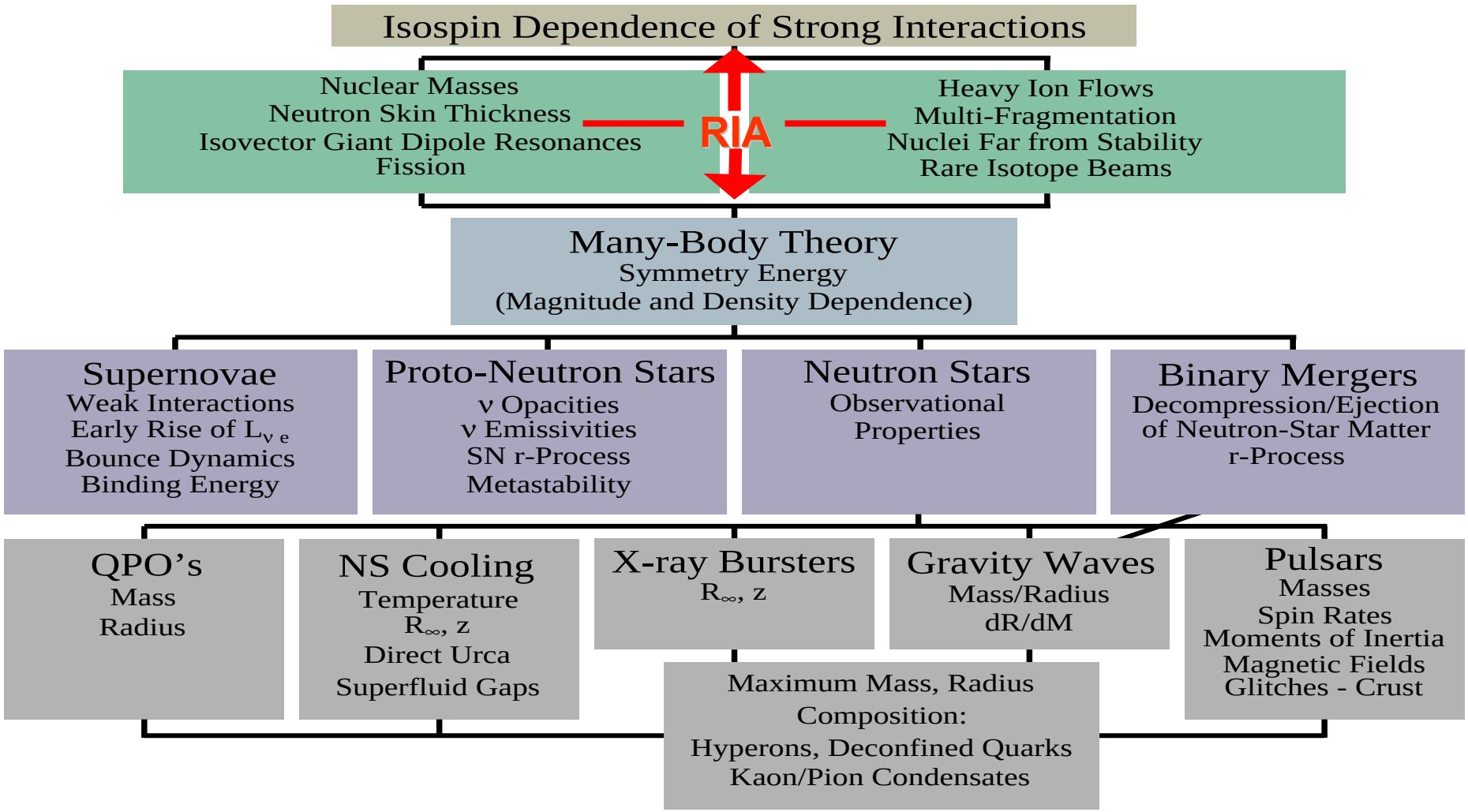
$E_{sym}(\rho)$ from *phenomenological approaches*

B. Cochet, K. Bennaceur, P. Bonche, T. Duguet and J. Meyer, nucl-th/0309012
J. Stone, J.C. Miller, R. Koncewicz, P.D. Stevenson and M.R. Strayer, PRC **68**, 034324 (2003)



The multifaceted influence of symmetry energy in astrophysics and nuclear physics

J.M. Lattimer and M. Prakash, *Science Vol. 304 (2004) 536-542.*
A.W. Steiner, M. Prakash, J.M. Lattimer and P.J. Ellis, *Phys. Rep. (2004), nucl-th/0410066*



The proton fraction x at ß-equilibrium in proto-neutron stars is determined by

$$x \simeq 0.048[E_{sym}(\rho)/E_{sym}(\rho_0)]^3(\rho/\rho_0)(1-2x)^3$$

The critical proton fraction for direct URCA **process** to happen is X_c=1/9 from energy-momentum conservation on the proton Fermi surface

Slow cooling: modified URCA:

$$n+(n,p)\rightarrow p+(n,p)+e^- +\overline{\nu}_e$$

$$p+(n,p)\rightarrow n+(n,p)+e^+ +\nu_e$$

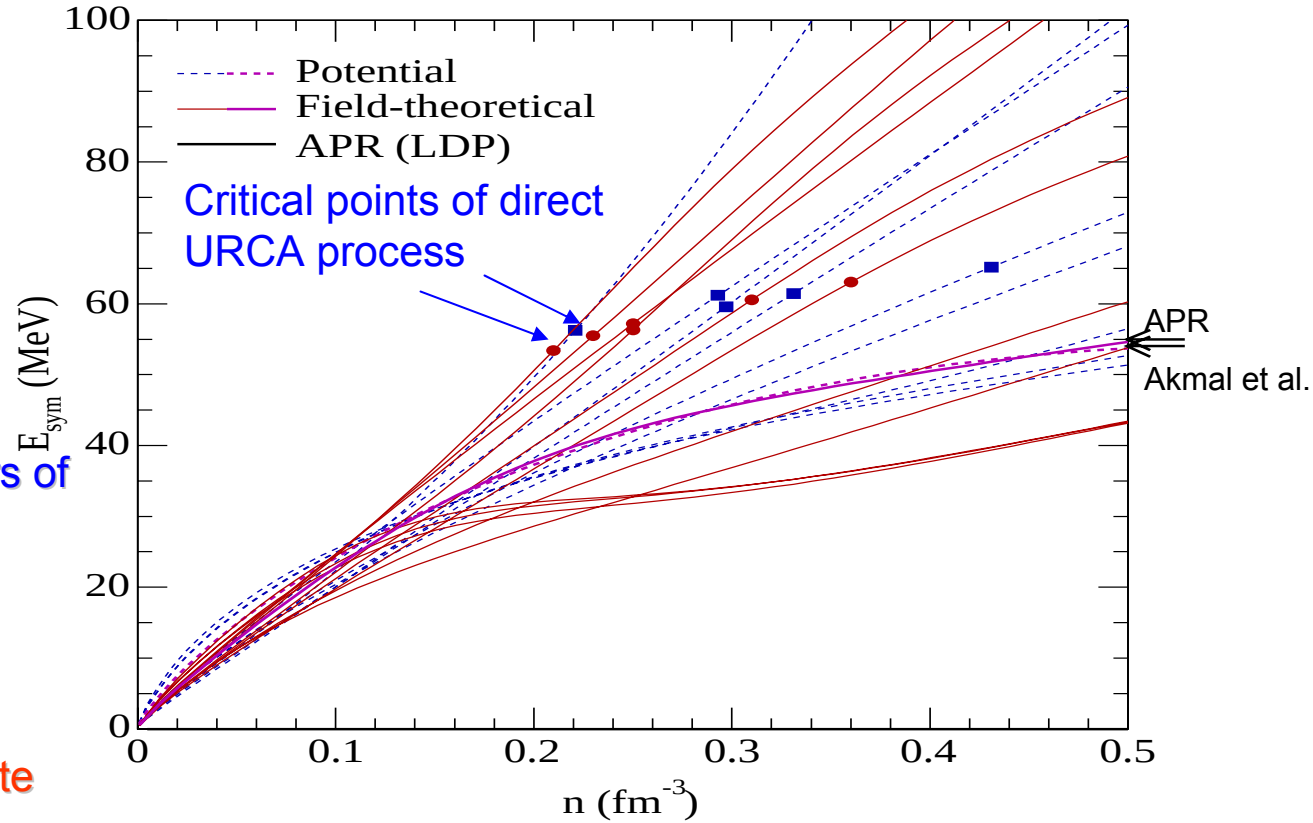
Consequence: long surface thermal emission up to a few million years

Faster cooling by 4 to 5 orders of magnitude: direct URCA

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

$$p \rightarrow n + e^+ + \nu_e$$

PSR J0205+6449 in 3C58 was suggested as a candidate



A.W. Steiner, M. Prakash, J.M. Lattimer and P.J. Ellis, Phys. Rep. (2004), nucl-th/0410066

Promising Probes of the $E_{sym}(\rho)$ in Nuclear Reactions (an incomplete list !)

At low densities

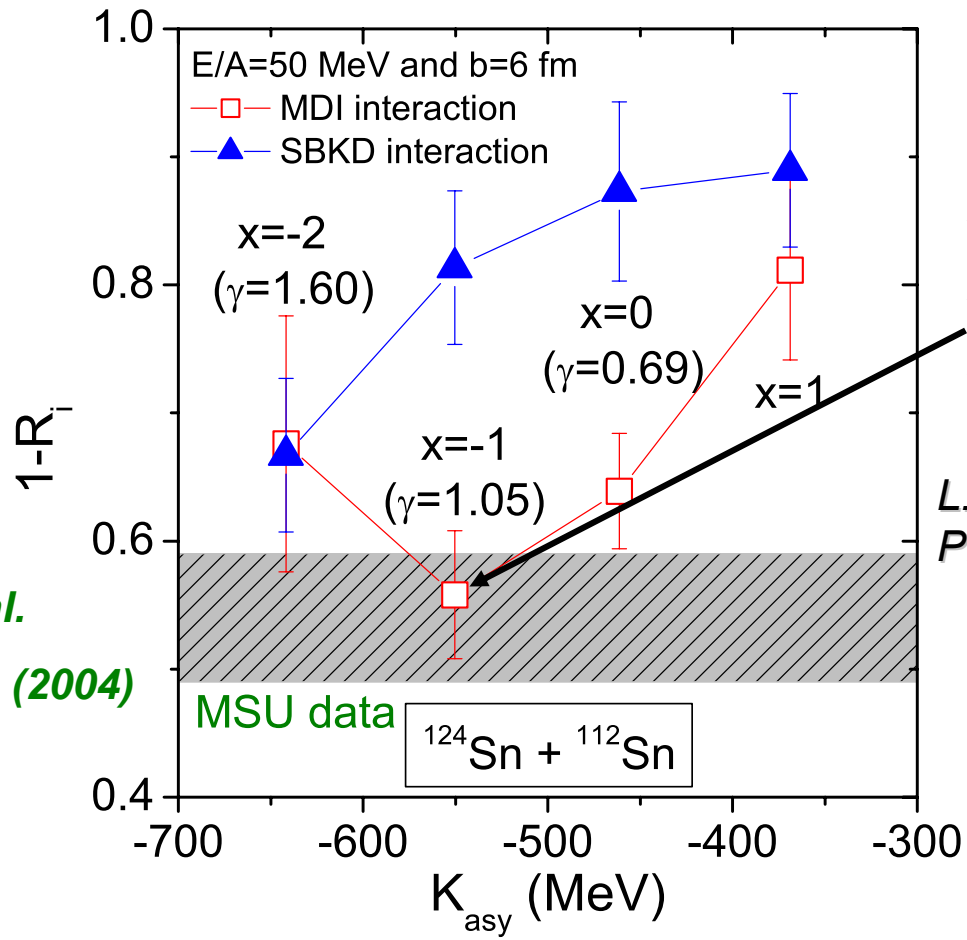
- **Sizes of n-skins of unstable nuclei from total reaction cross sections**
- **Proton-nucleus elastic scattering in inverse kinematics**
- **Parity violating electron scattering studies of the n-skin in ^{208}Pb (C.J. Horowitz)**
- **n/p ratio of fast, pre-equilibrium nucleons**
- **Isospin fractionation and isoscaling in nuclear multifragmentation**
- **Isospin diffusion**
- **Neutron-proton differential flow**
- **Neutron-proton correlation functions at low relative momenta**
- **t/^{3}He ratio**

The latest conclusion: $E_{sym}(\rho)=32(\rho/\rho_0)^{1.1}$ for $\rho < 1.2\ \rho_0$ from isospin diffusion studies
*L.W. Chen, C.M. Ko and B.A. Li, PRL **94** (2005) 32701.*

Towards high densities reachable at RIA and GSI

- **π^- yields and π^-/π^+ ratio**
- **Neutron-proton differential transverse flow**
- **n/p ratio at mid-rapidity**
- **K^+/K^0 ratio ??**

Comparing momentum-dependent IBUU predictions with data on isospin diffusion from MSU



Experiments favors:

$E_{sym}(\rho)=32\,(\rho/\rho_0)^{1.1}$ *for* $\rho<1.2\rho_0$

$K_{asy}(\rho_0)\sim-550$ *MeV*

L.W. Chen, C.M. Ko and B.A. Li, PRL 94, 32701 (2005).

M.B. Tsang et al.

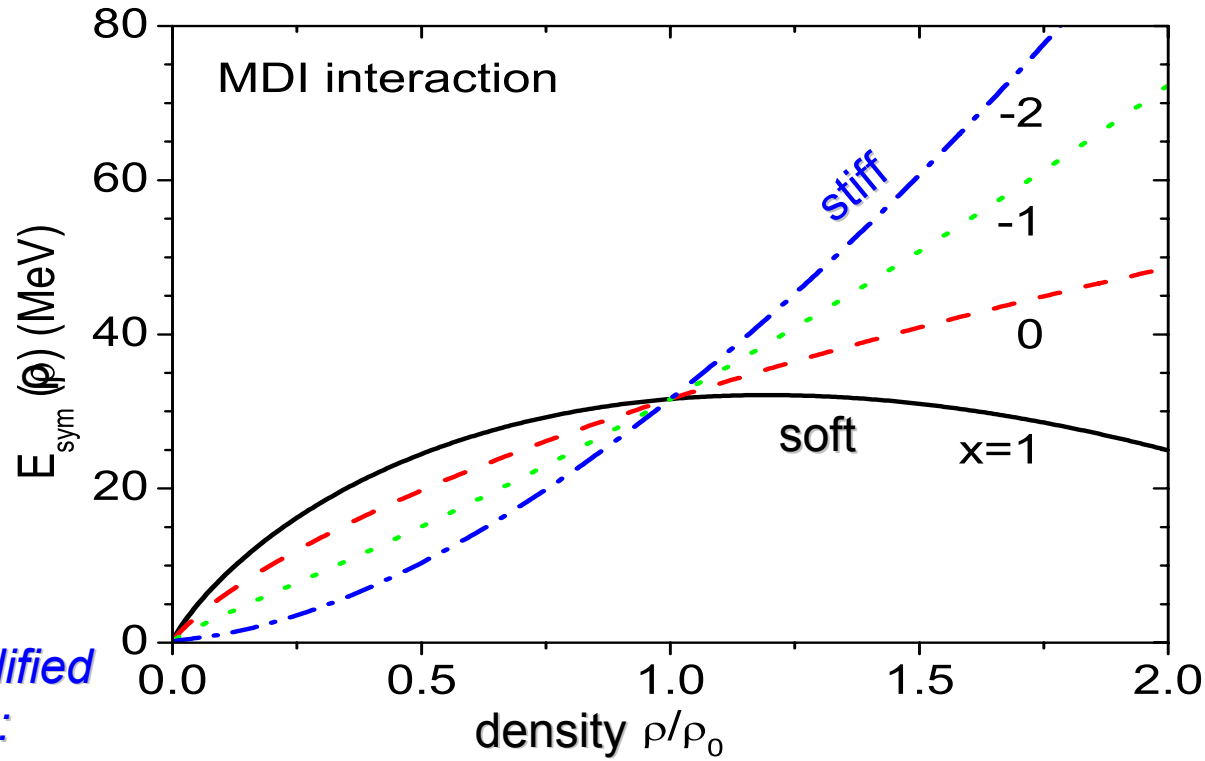
PRL 92, 062701 (2004)

Isobaric incompressibility of asymmetric nuclear matter

$$K(\rho,\delta)=K_0(\rho)+K_{asy}(\rho)\delta^2$$

$$K_{asy}(\rho_0)\equiv 9\rho_0^2(d^2E_{sym}/d\rho^2)_{\rho_0}-18\rho_0(dE_{sym}/d\rho)_{\rho_0}$$

Symmetry energy and single nucleon potential used in an isospin- and momentum-dependent transport model



Using a modified Gogny force:

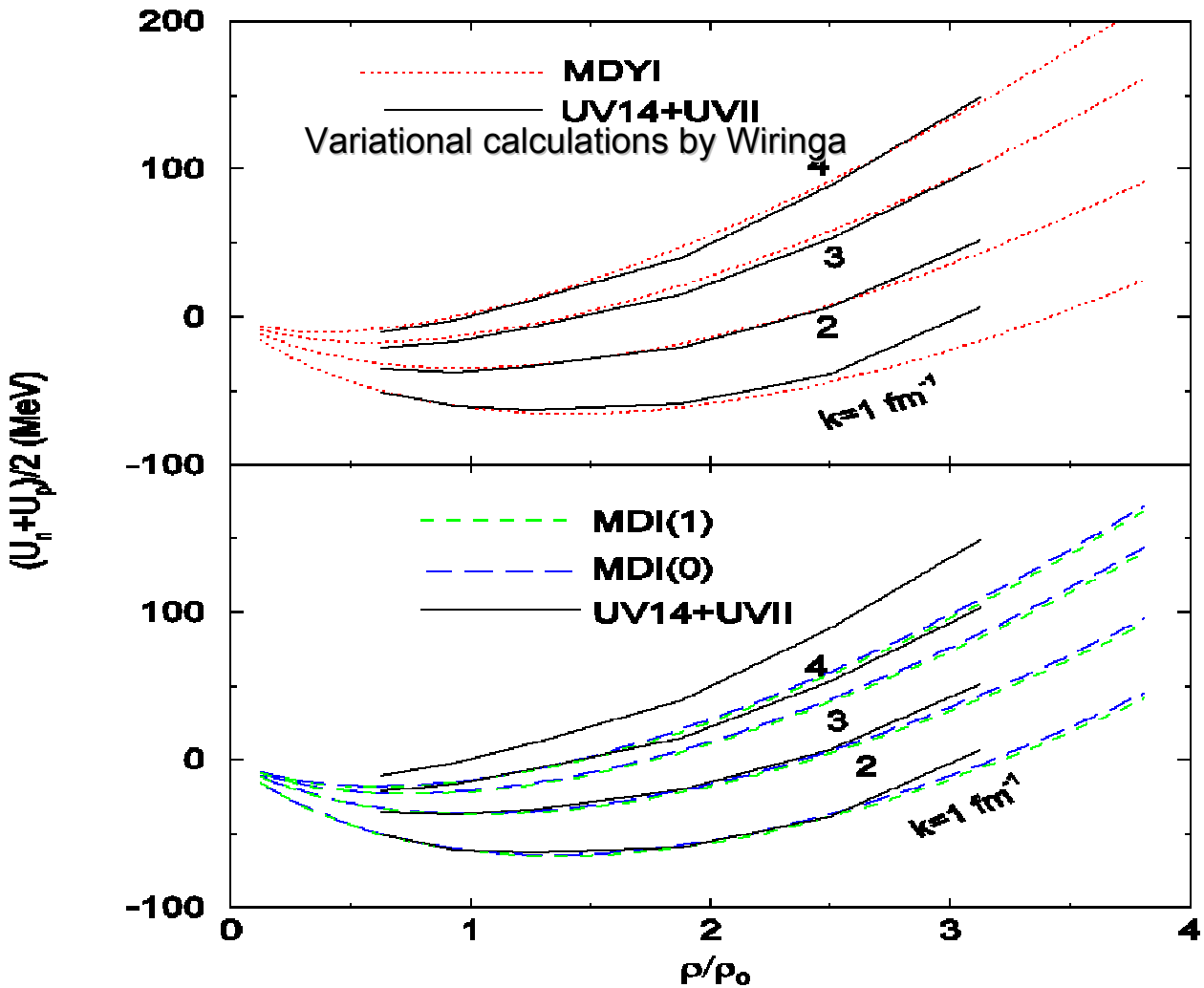
$$U(\rho,\delta,\vec{p},\tau,x) = A_u(x)\frac{\rho_{\tau'}}{\rho_0} + A_l(x)\frac{\rho_\tau}{\rho_0} + B(\frac{\rho}{\rho_0})^\sigma(1-x\delta^2) - 8\tau x\frac{B}{\sigma+1}\frac{\rho^{\sigma-1}}{\rho_0^\sigma}\delta\rho_{\tau'}$$

$$+\frac{2C_{\tau,\tau}}{\rho_0}\int d^3p'\frac{f_\tau(r,p')}{1+(p-p')^2/\Lambda^2} + \frac{2C_{\tau,\tau'}}{\rho_0}\int d^3p'\frac{f_{\tau'}(r,p')}{1+(p-p')^2/\Lambda^2}$$

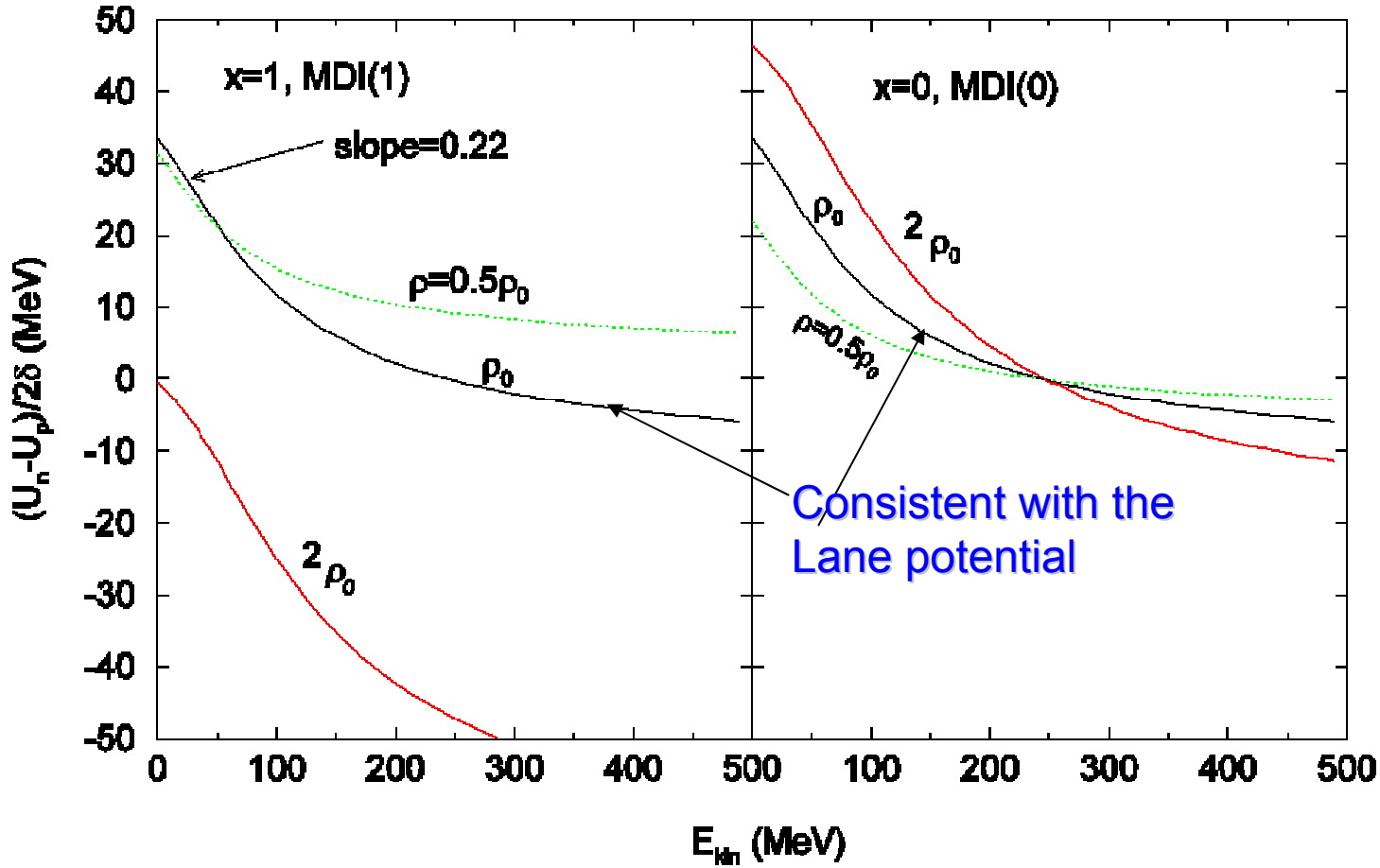
$$\tau,\tau' = \pm\frac{1}{2}, A_l(x) = -121 + \frac{2Bx}{\sigma+1}, A_u(x) = -96 - \frac{2Bx}{\sigma+1}, K_0 = 211MeV$$

B.A. Li, C.B. Das, S. Das Gupta and C. Gale, PRC **69**, 034614, NPA **735**, 563 (2004).

Momentum dependence of the isoscalar potential



Momentum dependence of the symmetry potential



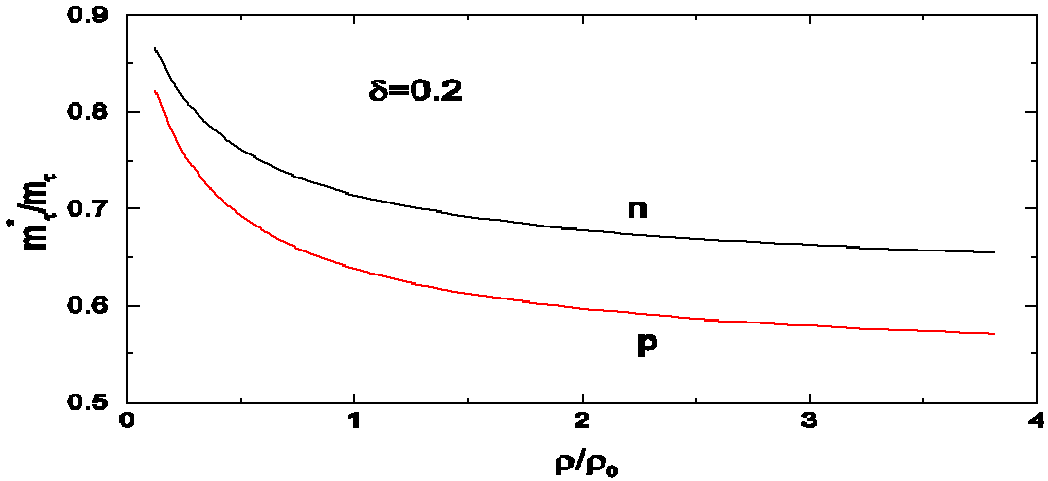
Lane potential extracted from n/p-nucleus scattering data indicates:

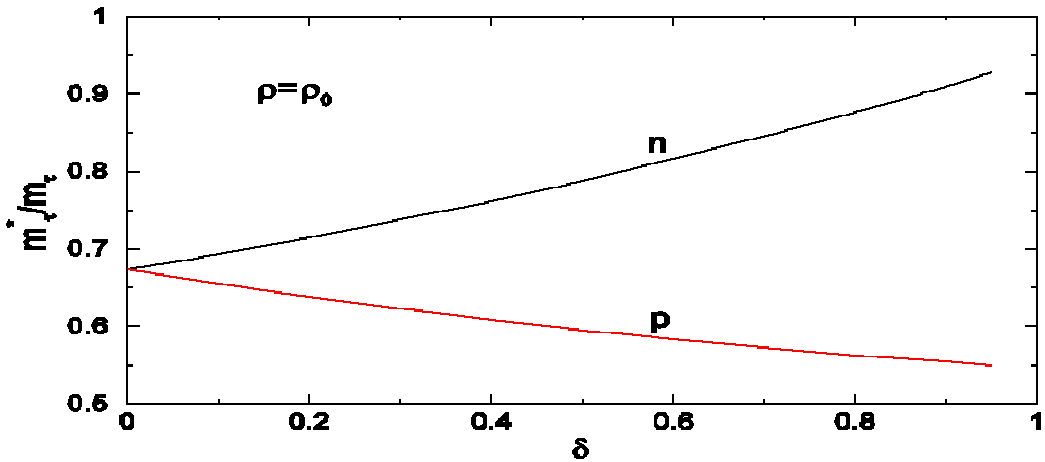
$$U_{Lane} \equiv (U_n - U_p)/2\delta \approx V_1 - \varepsilon_R \cdot E_{kin},$$

$$V_1 \simeq 28 \pm 6\,MeV, \varepsilon_R \approx 0.1 - 0.2$$ for E_{kin} < 100 MeV

Neutron-proton effective mass splitting in neutron-rich matter

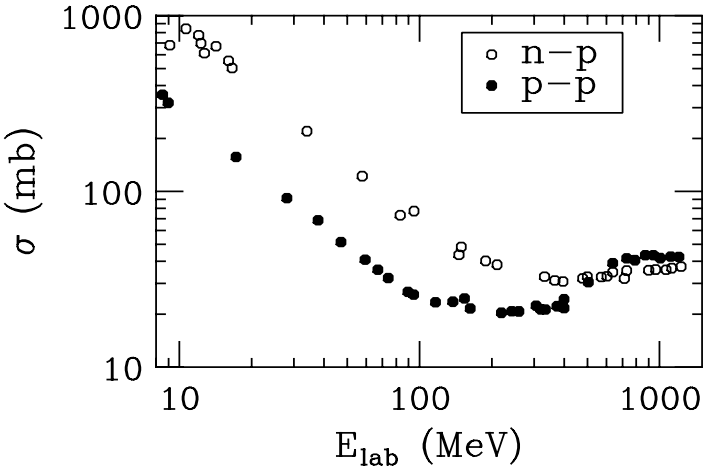
$$\frac{m_\tau^*}{m_\tau} = [1 + \frac{m_\tau}{p}\frac{\partial U}{\partial p}]^{-1}_{p_F^\tau}$$



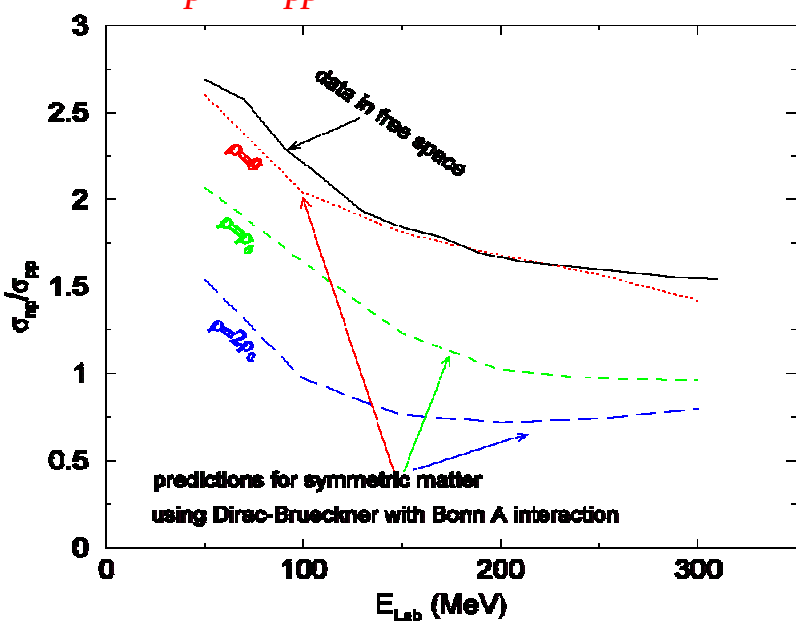


Isospin-dependent in-medium nucleon-nucleon cross sections

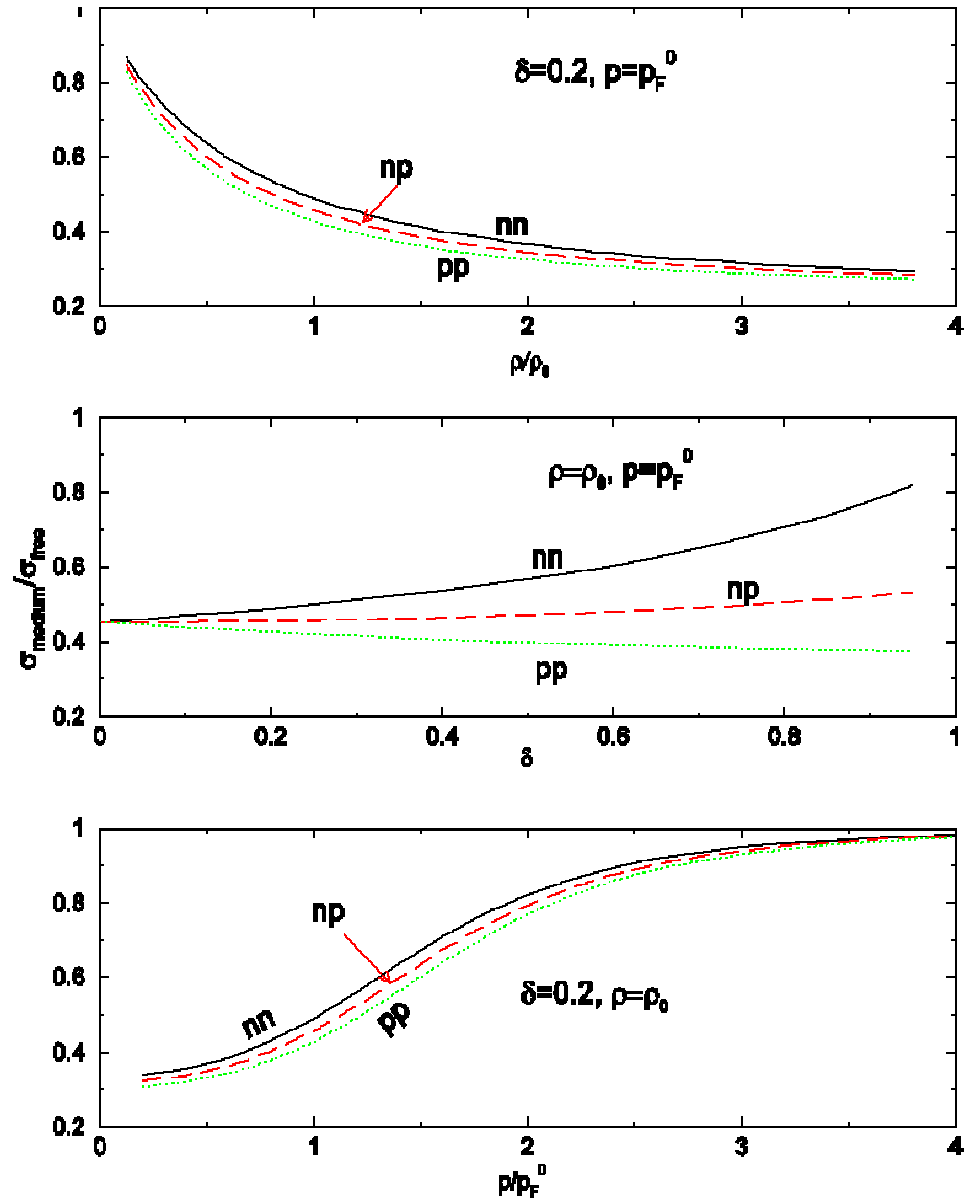
NN cross sections in free-space



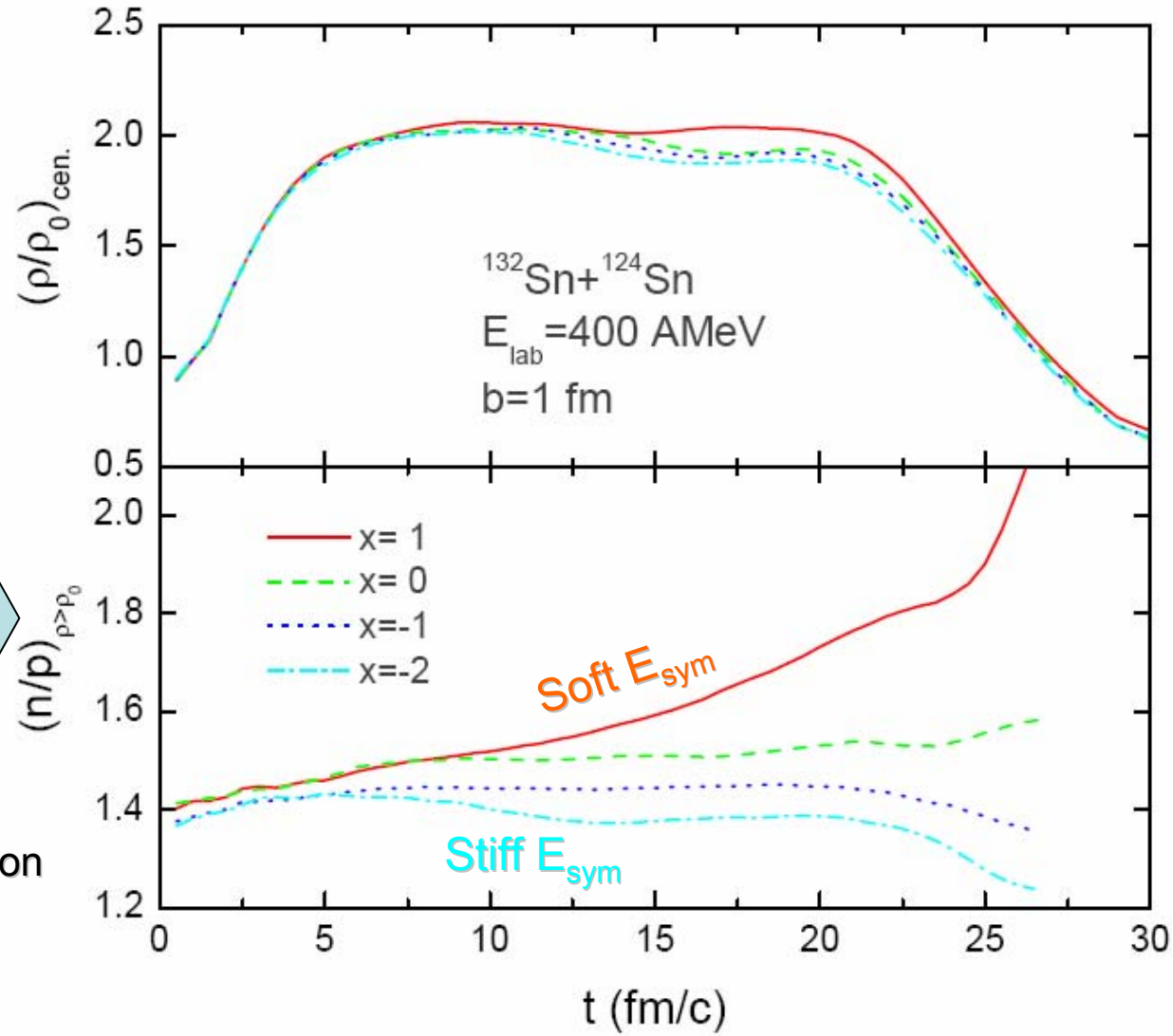
$\sigma_{np} / \sigma_{pp}$ in symmetric matter



$\sigma_{medium} / \sigma_{free}$ in neutron-rich matter



Formation of dense, asymmetric nuclear matter at RIA



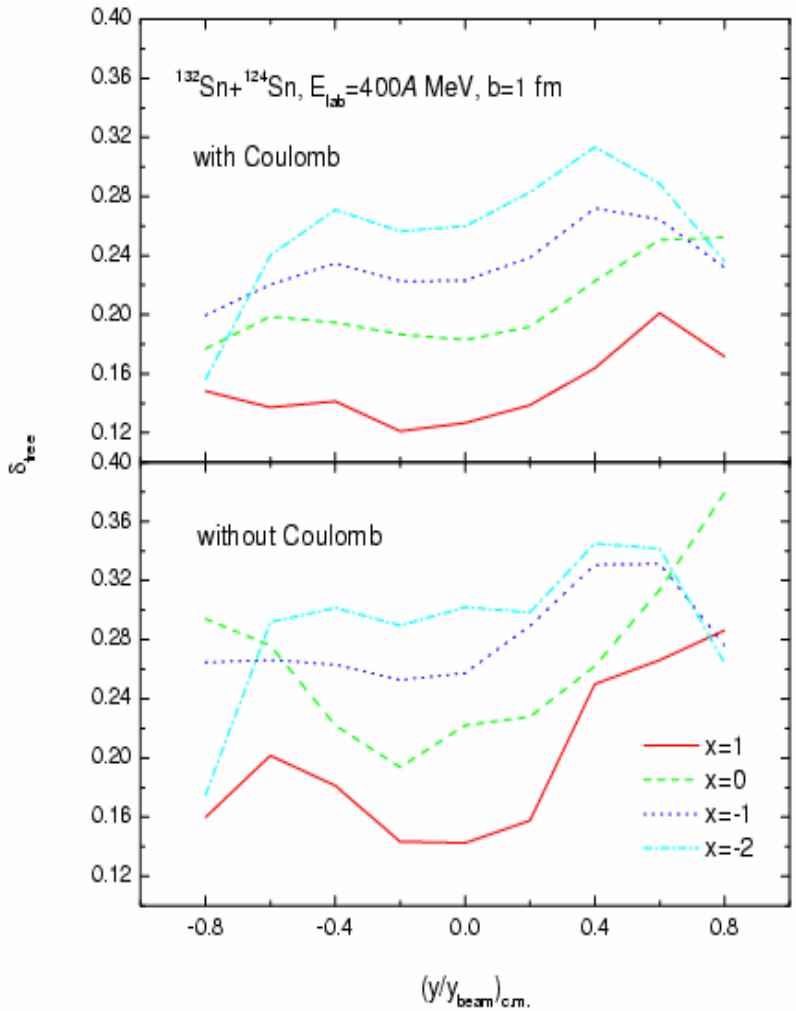
n/p ratio of the high density region

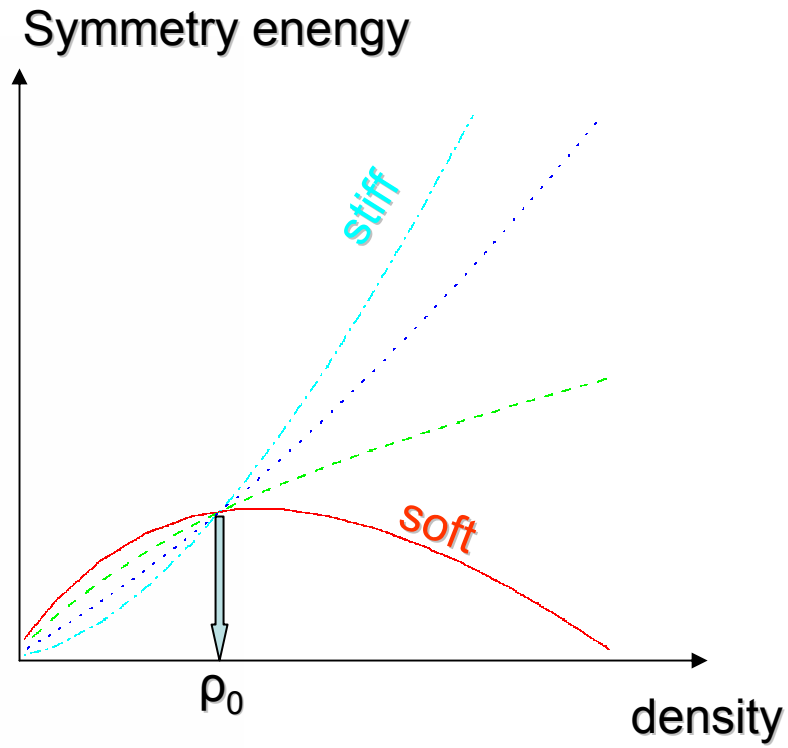
Isospin fractionation (distillation): at isospin equilibrium $E_{sym}(\rho_1)\bullet\delta_1 = E_{sym}(\rho_2)\bullet\delta_2$

EOS requirement: $E(\rho,\delta) = E(\rho,0) + E_{sym}(\rho)\delta^2$

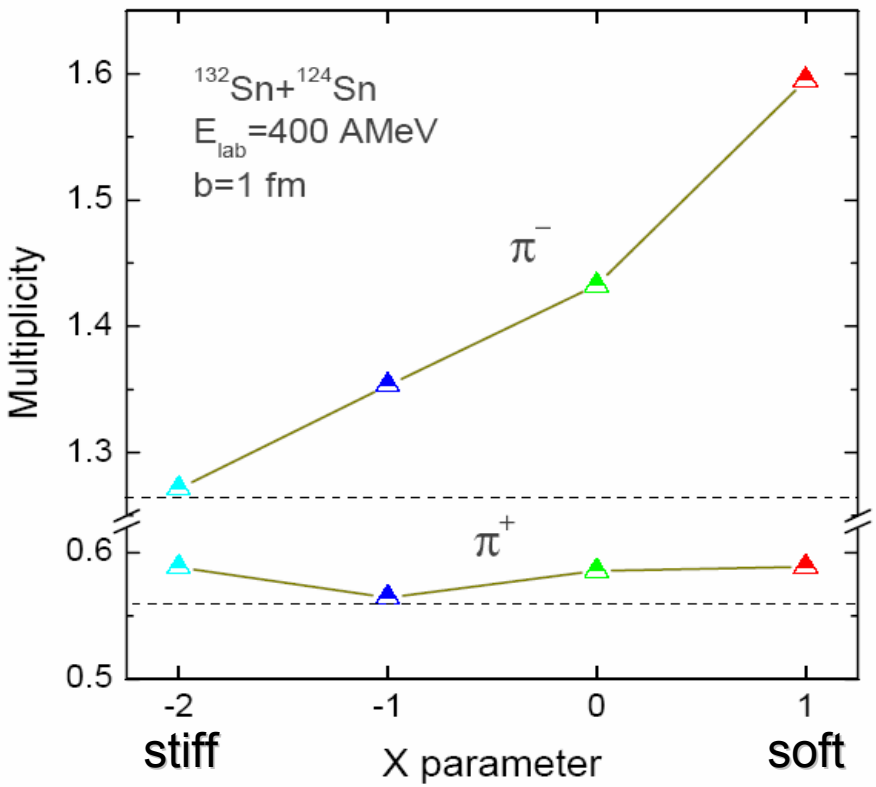
low (high) density region is more neutron-rich with stiff (soft) symmetry energy

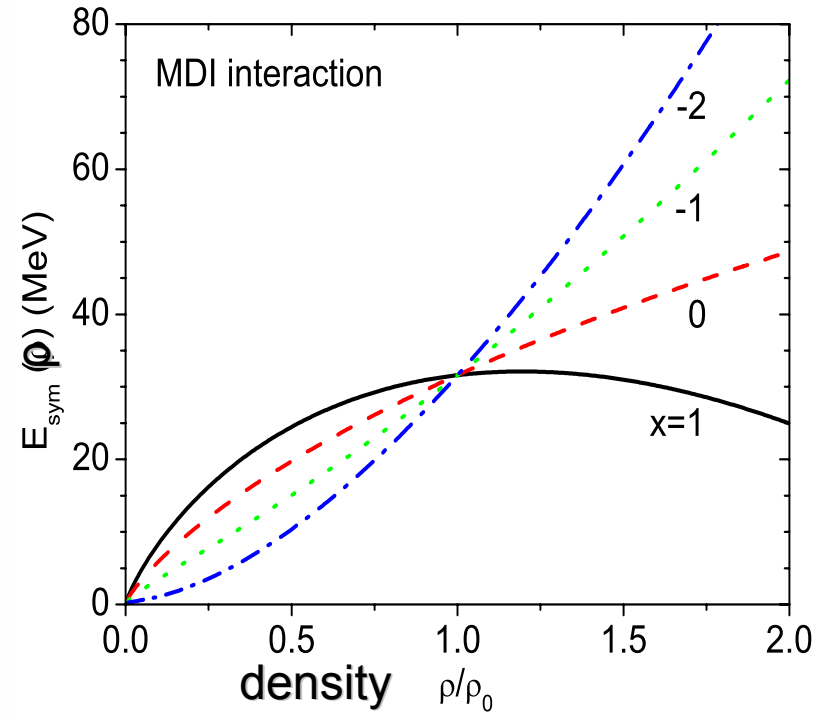
Isospin asymmetry of free nucleons





Near-threshold pion production with radioactive beams at RIA





π^- yields are more sensitive to the symmetry energy $E_{sym}(\rho)$ since they are mostly produced in the neutron-rich region

However, pion yields are also sensitive to the symmetric part of the EOS

$$E(\rho,\delta) = E(\rho,0) + E_{sym}(\rho)\delta^2 + o(\delta^4)$$

Pion ratio probe of symmetry energy

	π^+	π^0	π^-
nn	**0**	**1**	**5**
pp	**5**	**1**	**0**
np	**1**	**4**	**1**

a) Δ(1232) resonance model
in first chance nucleon-nucleon scatterings:
(negelect rescattering and reabsorption)

$$\frac{\pi^-}{\pi^+} = \frac{5N^2 + NZ}{5Z^2 + NZ} \approx \left(\frac{N}{Z}\right)^2$$

R. Stock, Phys. Rep. 135 (1986) 259.

b) Thermal model: (*G.F. Bertsch, Nature 283 (1980) 281*.)

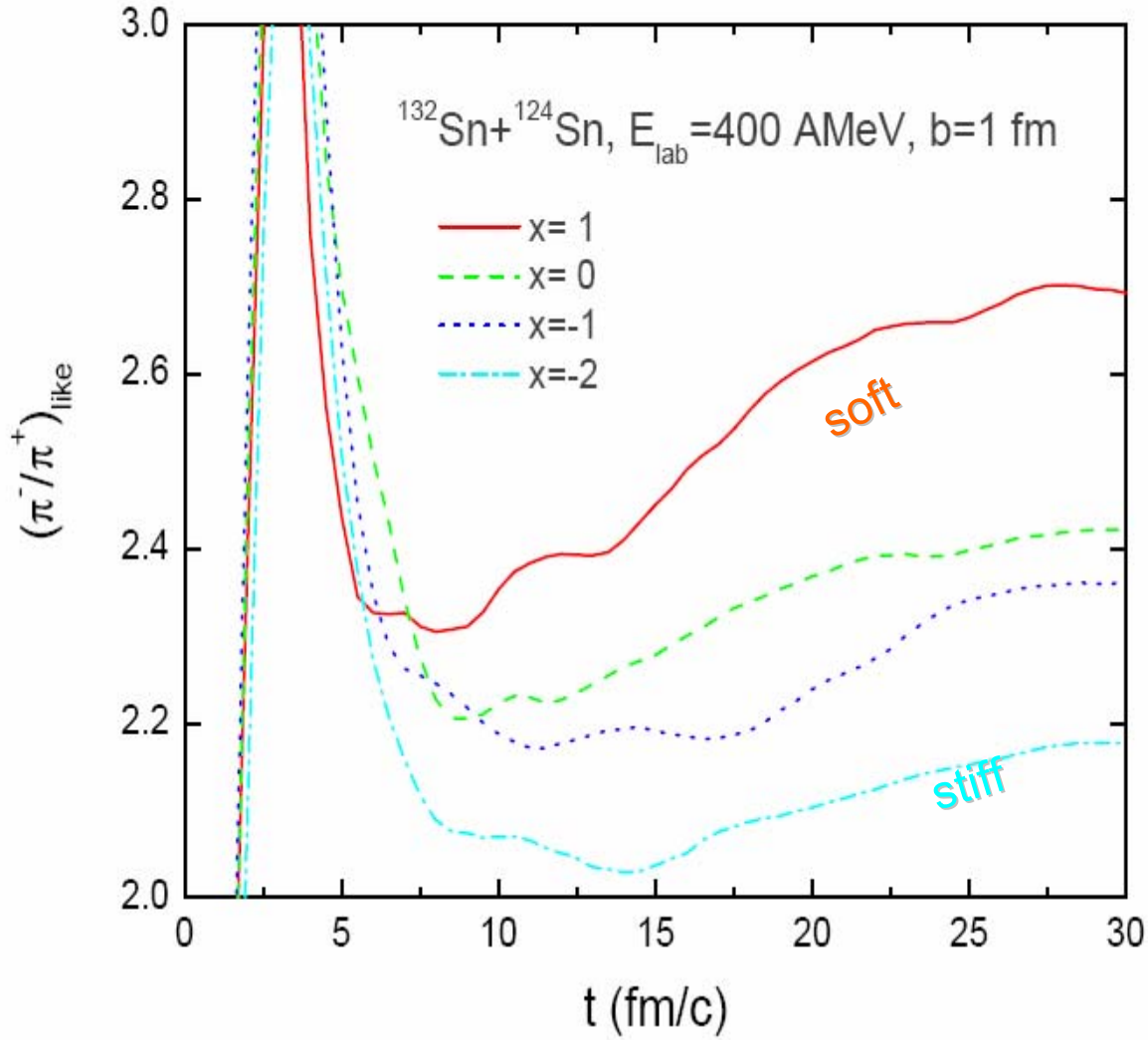
$$\frac{\pi^-}{\pi^+} \propto \exp[(\mu_n - \mu_p)/kT]$$

$$\mu_n - \mu_p = 2V_{sym}(\rho)\delta - V_{Coul} + kT\{\ln\frac{\rho_n}{\rho_p} + \sum_m \frac{m+1}{m} b_m (\frac{1}{2}\lambda_T^3)^m (\rho_n^m - \rho_p^m)\}$$

H.R. Jaqaman, A.Z. Mekjian and L. Zamick, PRC (1983) 2782.

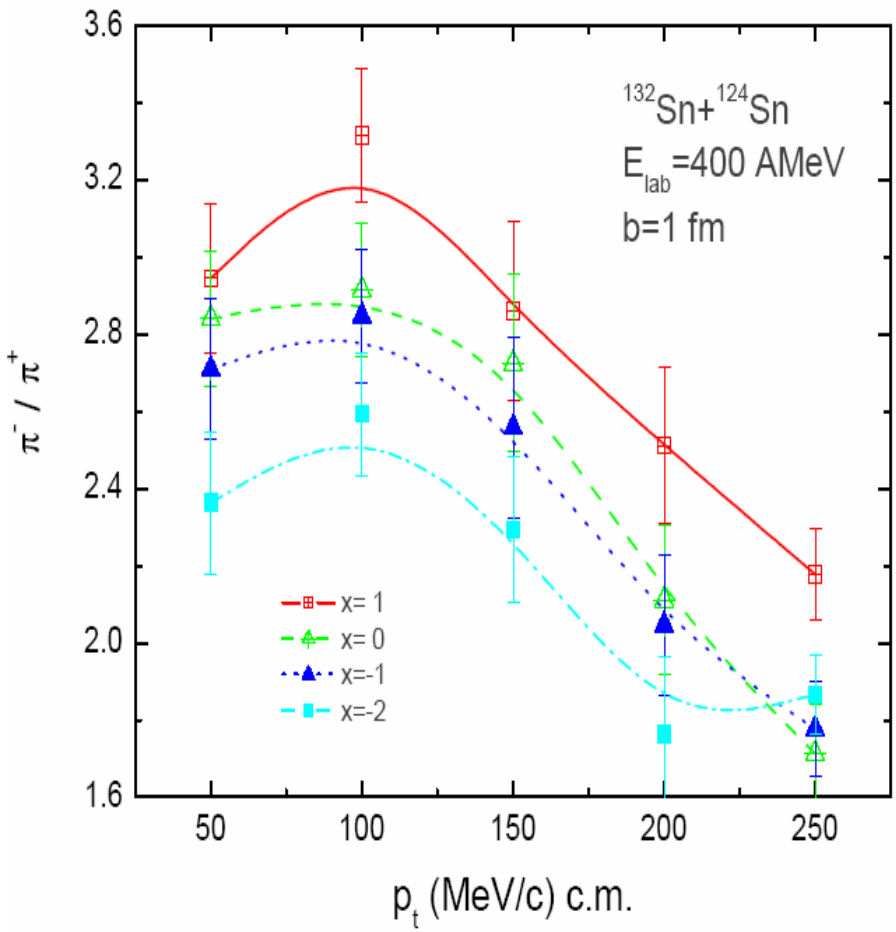
c) Transport models: (the more realistic tool)
see, e.g., *Bao-An Li, Phys. Rev. Lett. 88 (2002) 192701*.

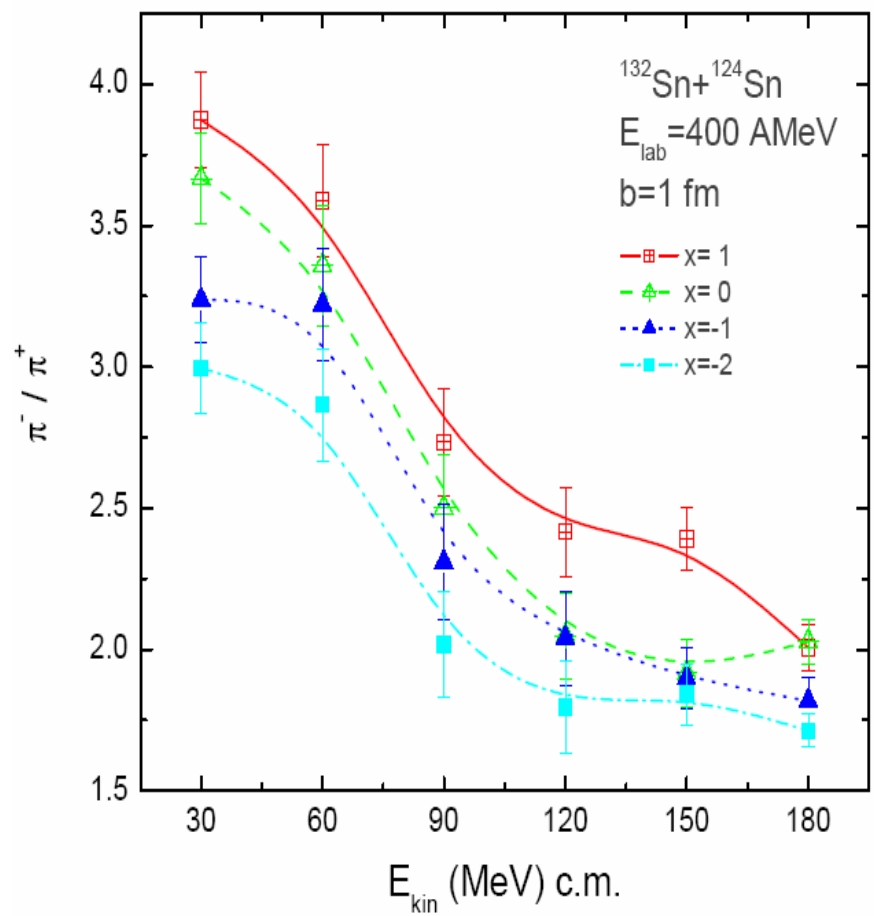
Time evolution of π^-/π^+ ratio in central reactions at RIA



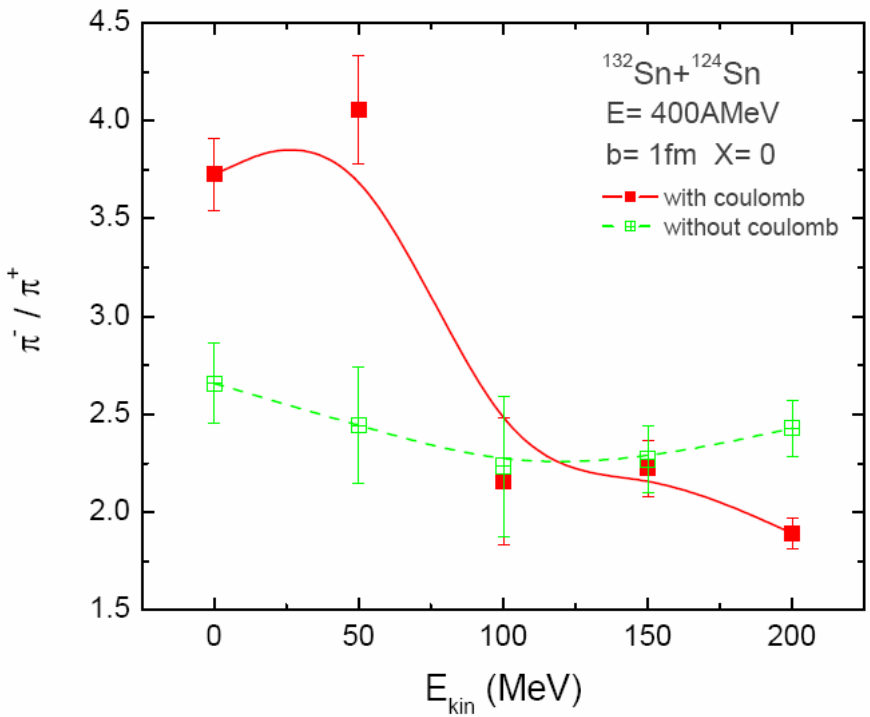
$$\left(\frac{\pi^-}{\pi^+}\right)_{like} \equiv \frac{\pi^- + \Delta^- + \frac{1}{3}\Delta^0 + \frac{2}{3}N^{*0}}{\pi^+ + \Delta^{++} + \frac{1}{3}\Delta^+ + \frac{2}{3}N^{*+}} \xrightarrow[t\to\infty]{} \frac{\pi^-}{\pi^+}$$

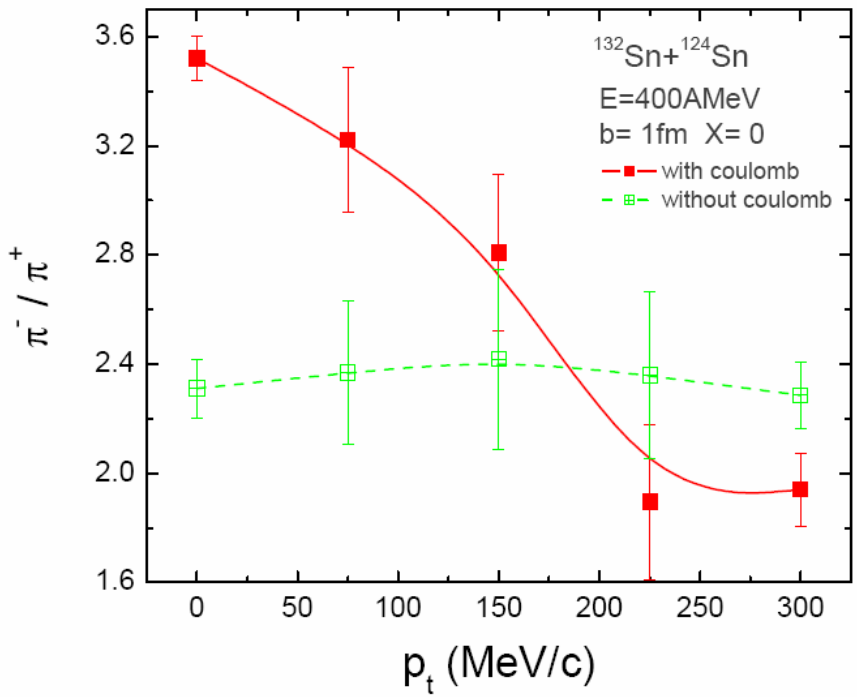
Differential π^- / π^+ ratios





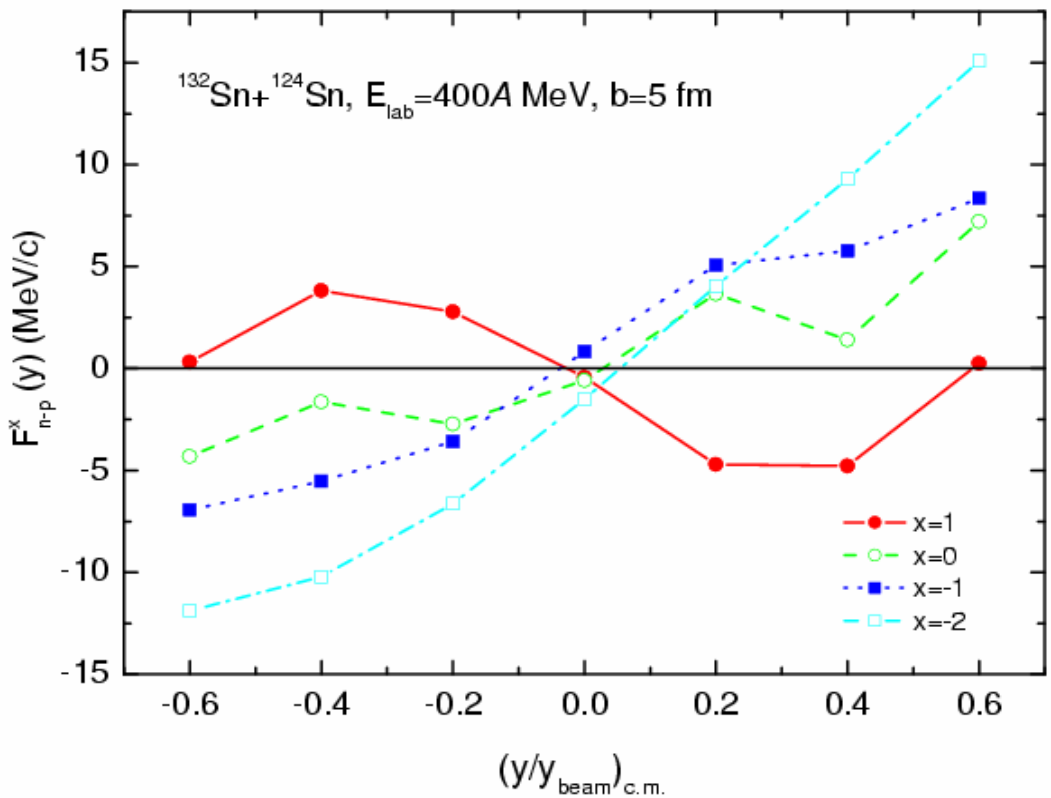
Coulomb effects on π-/π+ ratio is well known





Bao-An Li, G-C. Yong and W. Zuo, Phys. Rev. C71, 014608 (2005).

Neutron-proton differential transverse flow: $F^{x}_{n-p}(y) \equiv \frac{1}{N(y)} \sum_{i=1}^{i=N(y)} p_i^x \cdot \tau_i$



Summary

- $E_{sym}(\rho)$ is very important for both astrophysics and nuclear physics

- *Isospin diffusion experiments favors:*
  $E_{sym}(\rho)=32\ (\rho/\rho_0)^{1.1}$ *for* $\rho<1.2\rho_0$
  $K_{asy}(\rho_0)\sim-550$ *MeV*

- Several sensitive probes for $E_{sym}(\rho)$ at high densities are found. Such as, the π^-/π^+ ratio, in particular at low transverse momentum, is promising for determining the $E_{sym}(\rho)$ up to $2\rho_0$

- Need a powerful Time Projection Chamber (TPC) at RIA