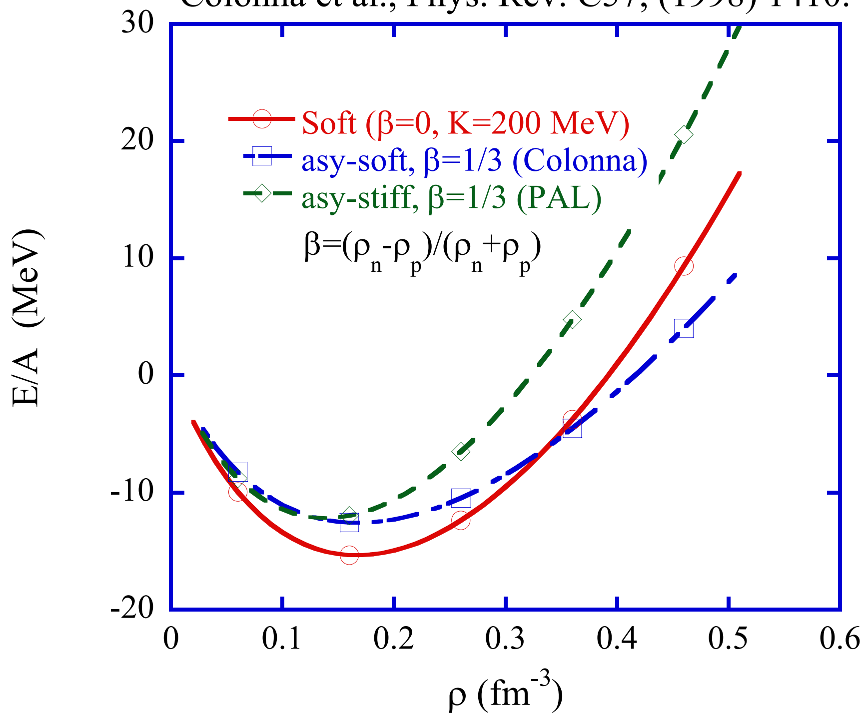
Probing Dense Asymmetric Nuclear Matter

Outline

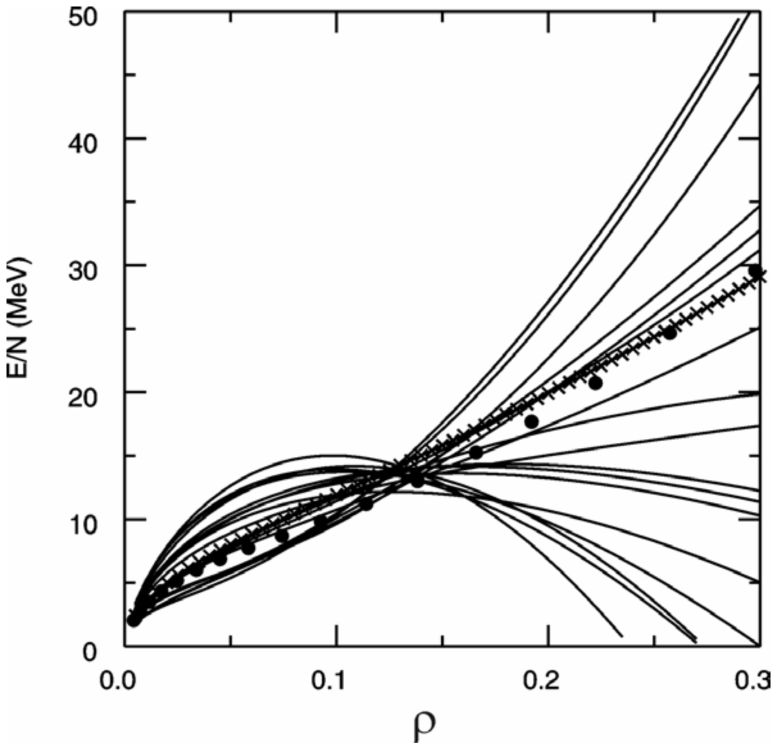
- Present constraints on the EOS.
- Relevance to dense astrophysical objects:
- Probing asymmetric matter at $\rho \leq 2\rho$.
- Prospects for probing asymmetric matter at $\rho \approx 2\rho_0$.

Isospin Dependence of the Nuclear Equation of State

PAL: Prakash et al., PRL 61, (1988) 2518.
Colonna et al., Phys. Rev. C57, (1998) 1410.



Brown, Phys. Rev. Lett. 85, 5296 (2001)



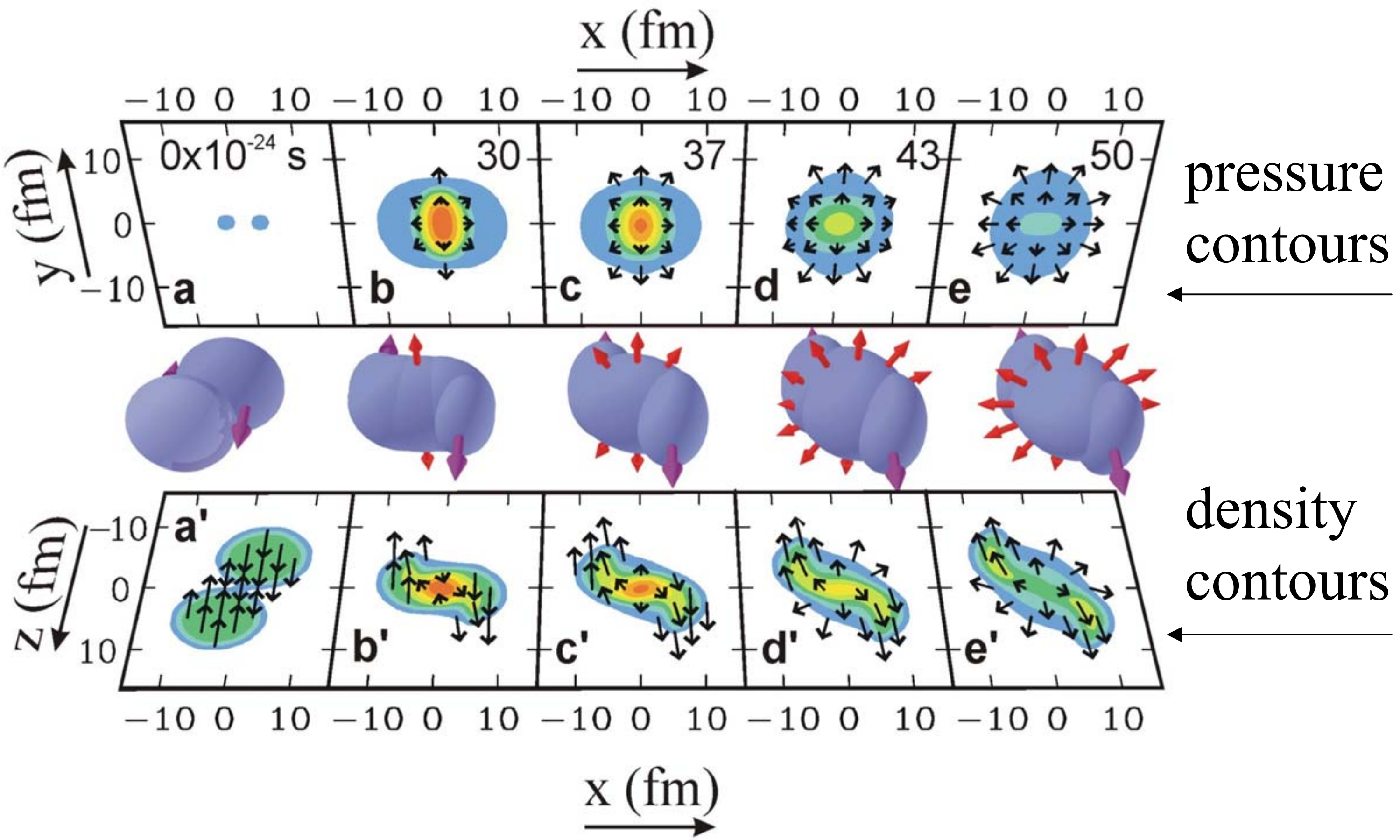
$$E/A\,(\rho,\beta) = E/A\,(\rho,0) + \delta^2\cdot S(\rho)$$

$$\delta = (\rho_n - \rho_p)/\,(\rho_n + \rho_p) = (N-Z)/A$$

- The density dependence of asymmetry term is largely unconstrained.
- Pressure, i.e. EOS is rather uncertain even at ρ_0.

- What is known about the EOS for symmetric matter?
  - Main information comes from heavy ion collisions.
  - Monopole, isoscaler dipole resonances only sample ~ 5% variations in density (i.e. curvature about minimum)

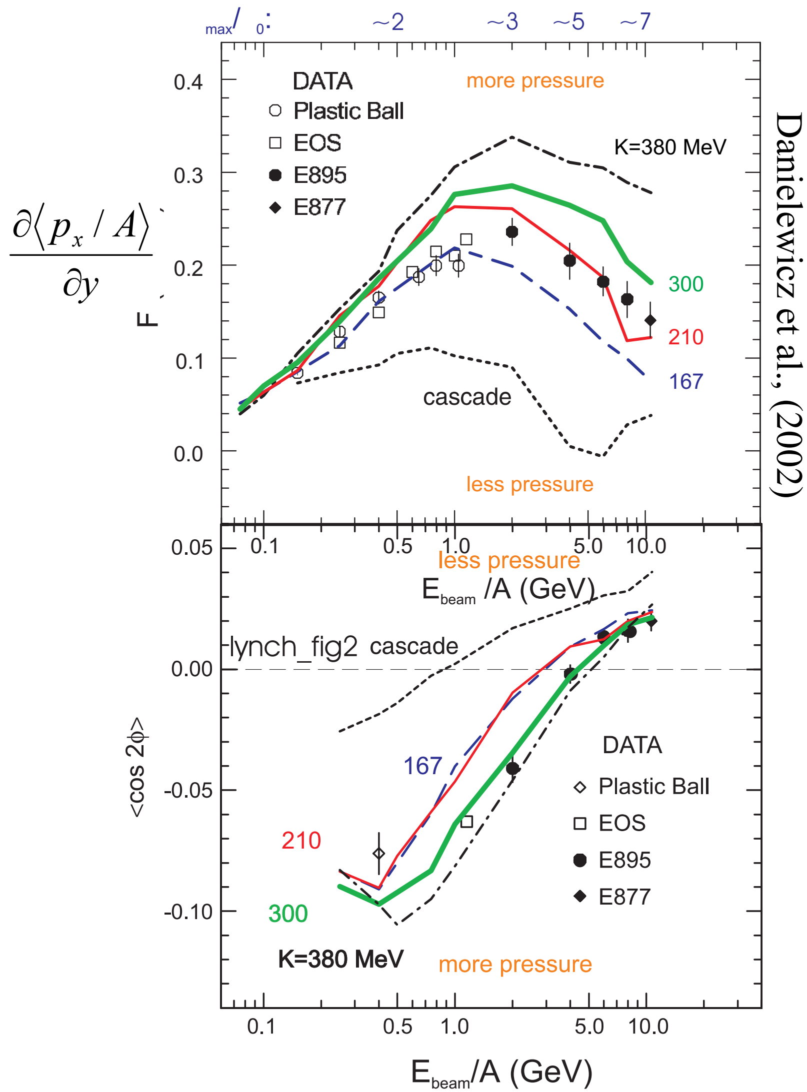
Pressure and collective flow dynamics

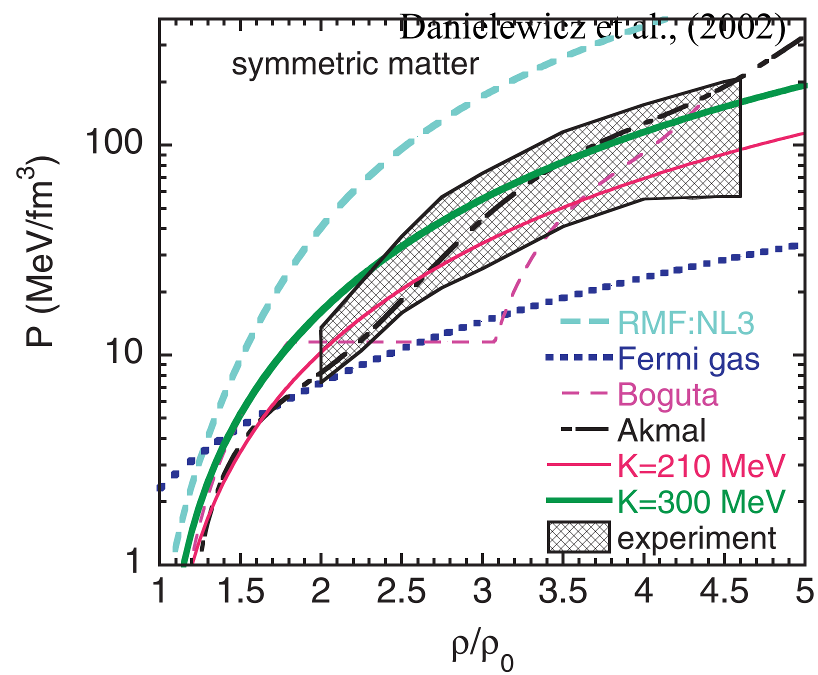


- The blocking by the spectator matter provides a clock with which to measure the expansion rate.

Constraints on symmetric matter EOS at $\rho > 2\rho_0$.

Observables: transverse, elliptical flow.



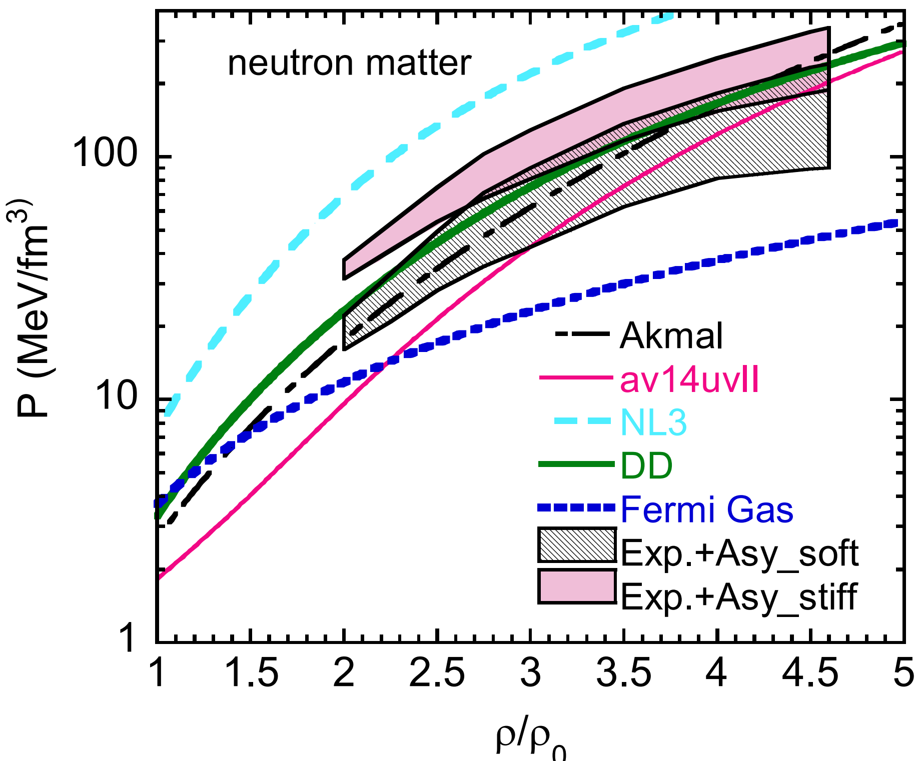


- Additional measurements needed to constrain:
  - Momentum dependence of mean fields.
  - Cross-sections due to residual interactions.

Extrapolation to neutron stars

$E/A(\rho, \delta) = E/A(\rho,0) + \delta^2 \cdot S(\rho)$ $\delta = (\rho_n - \rho_p)/(\rho_n + \rho_p) = (N-Z)/A \approx 1$

Danielewicz et al., (2002)



- Uncertainty due to the density dependence of the asymmetry term is greater than that due to symmetric matter EOS.

Symmetry term influences:

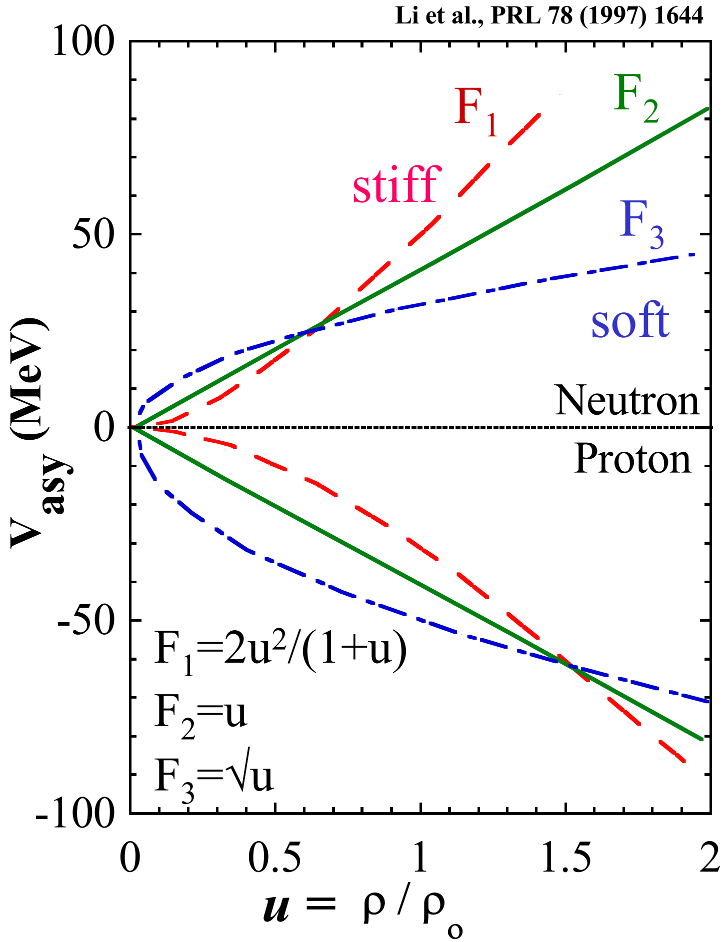
- Macroscopic properties:
  - Neutron star radii, moments of inertia and central densities.
  - Maximum neutron star masses and rotation frequencies.
- Proton and electron fractions throughout the star.
  - Cooling of proton-neutron star.
- Thickness of the inner crust.
  - Frequency change accompanying star quakes.
- Role of Kaon condensates and mixed quark-hadron phases in the stellar interior.

- How can one probe the asymmetry term?
  - Note: important factor is the interaction term:

$$S(\rho) = S_{kin}(\rho) + S_{\text{int}}(\rho);$$

$$S_{kin}(\rho) \approx \frac{1}{3} E_{Fermi}(\rho) \approx 13 \cdot (\rho / \rho_0)^{2/3} MeV$$

Probing the asymmetry term



- Sign of mean field opposite for protons and neutrons.
- Shape is influenced by incompressibility.

Observables:

- "First order": depend on isospin of detected particles.
  - Isospin dependencies of pion production.
  - Transverse flow (n.vs.p).
  - Isospin diffusion
  - Prequilibrium particle emission.
  - Asymmetry of bound vs. emitted nucleons.
  - difference between neutron and proton matter radii.
- "Second order": do not depend on isospin of detected particles.

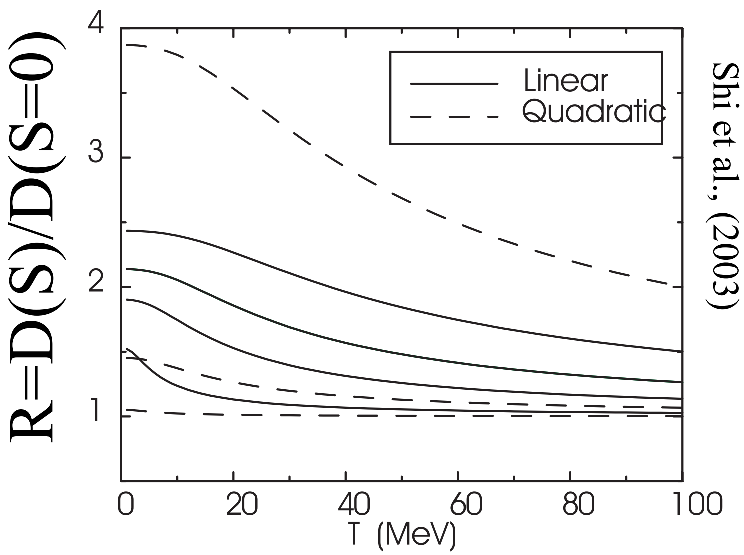
- Present investigations of asymmetry term at $\rho \leq \rho_0$.
  - Central collisions : Relative emission rates of neutron vs. protons – fragment isotopic distributions.
  - Peripheral collisions: Isospin diffusion.
- Future investigations of asymmetry term at $\rho \approx 2\rho_0$.

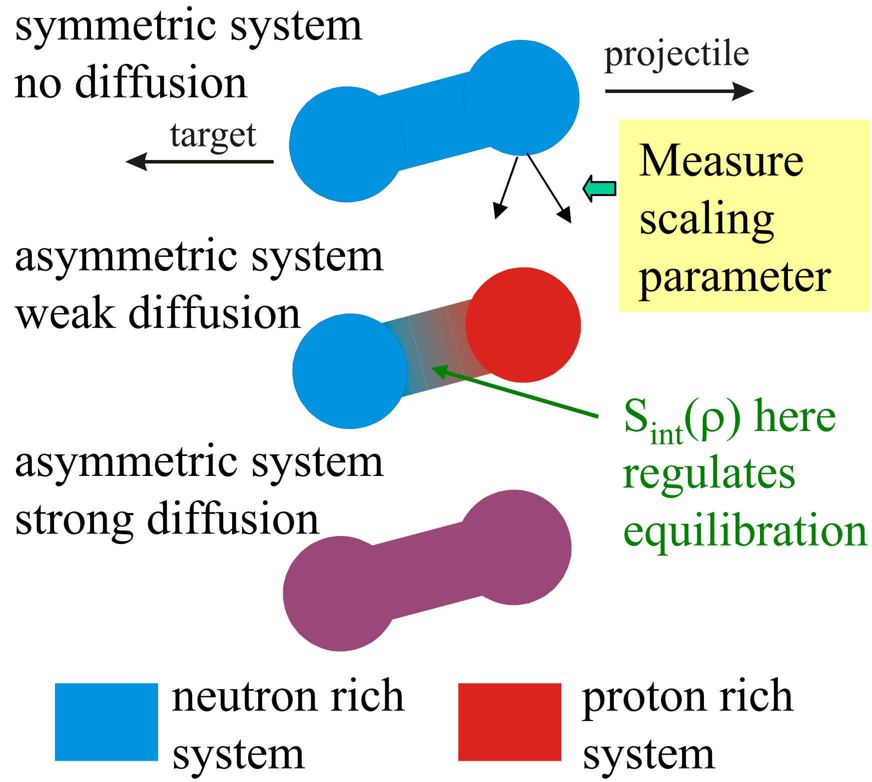
Isospin diffusion in peripheral collisions

- In a frame where the matter is stationary:

  $$\vec{\Gamma}_\delta \equiv \left(\rho_n \vec{v}_n - \rho_p \vec{v}_p\right) = -\rho D_\delta \vec{\nabla}\delta$$

  – D_δ the isospin diffusion coef.
- D_δ governs the relative flow of neutrons and protons
  – D_δ decreases with σ_{np}
  – D_δ increases with $S_{int}(\rho)$

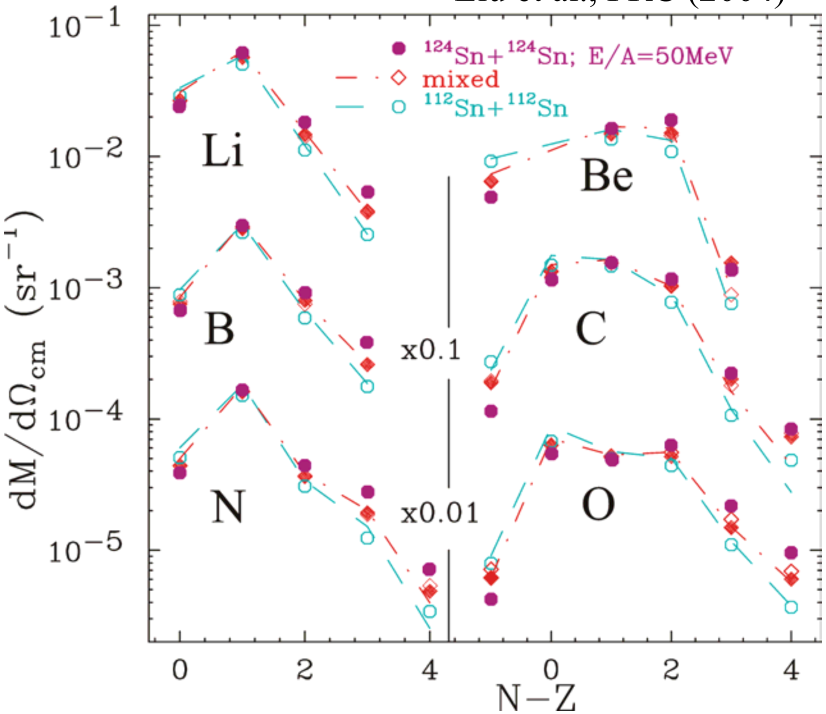


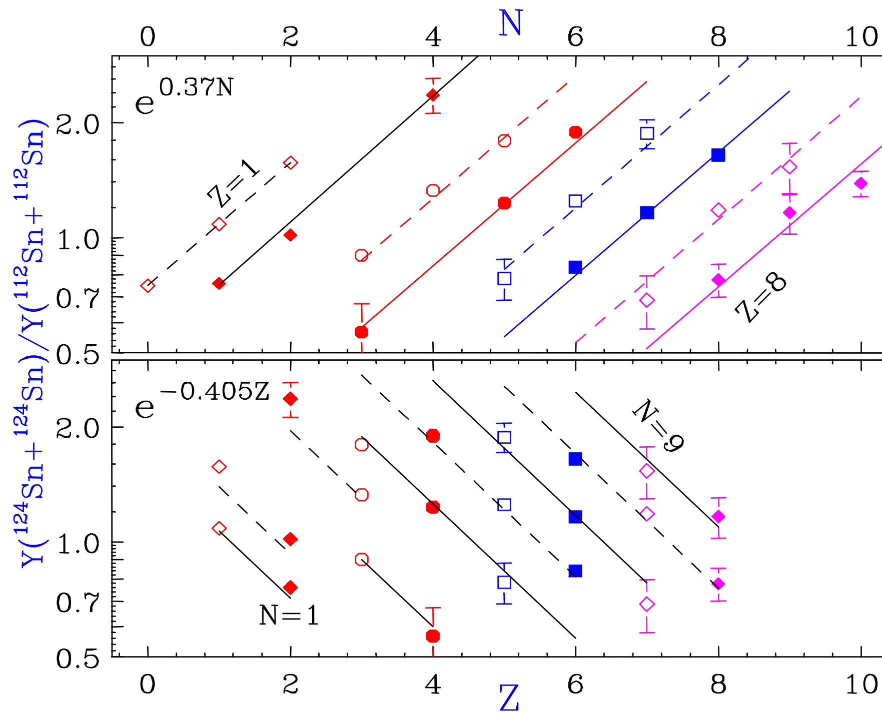


- Vary isospin driving forces by changing the isospin of projectile and target.
- measure the scaling parameter for projectile decay.

1^{st} Observable: Isoscaling parameters of isotopic distributions

Liu et al., PRC (2004)





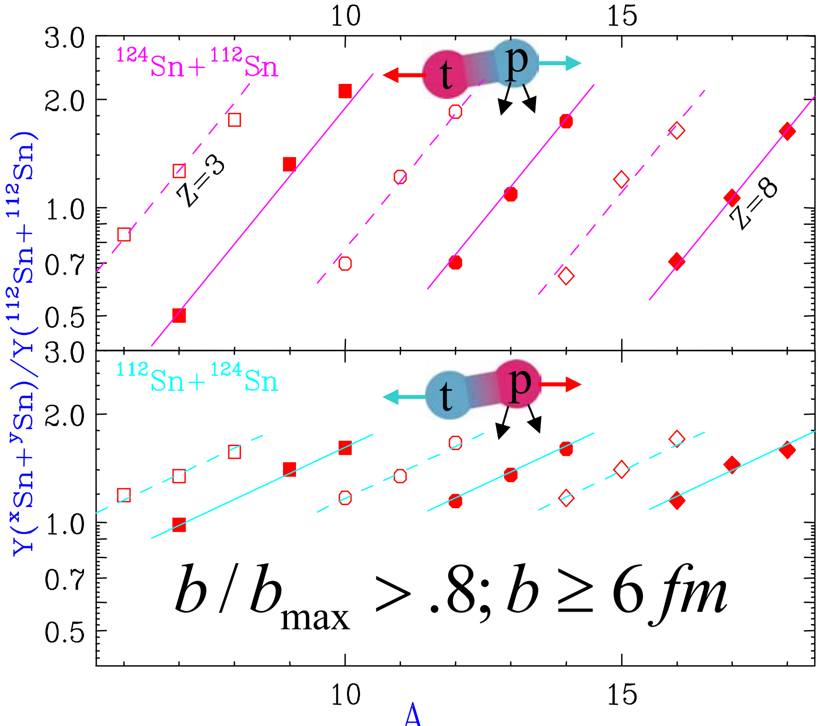
- Shape of isotopic distributions depends on overall isospin asymmetry.
  - Dependence on overall isospin asymmetry is described by isoscaling laws.

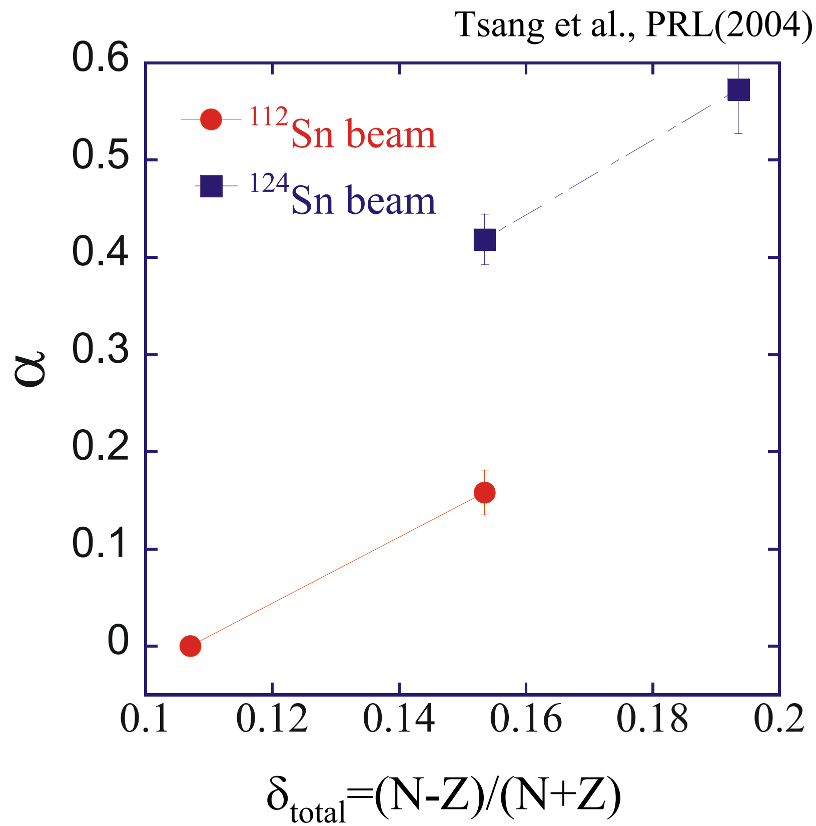
- Ratios of isotopic yields of two reactions at same "temperature" are related exponentially.

$$R_{21} = Y_2(N,Z)/Y_1(N,Z) \propto e^{(\alpha N+\beta Z)}$$

- Relationship can be derived from a variety of statistical theories and is also obtained in AMD calculations: $\alpha \propto \delta_{source}$.

Isospin equilibrium or not?





neutron rich system

proton rich system

- Projectile and target residues do not come to isospin equilibrium at E/A=50 MeV.

- Very useful to rescale the data:

$$R(\alpha) = \frac{2\alpha - \alpha_{124+124} - \alpha_{112+112}}{\alpha_{124+124} - \alpha_{112+112}}$$

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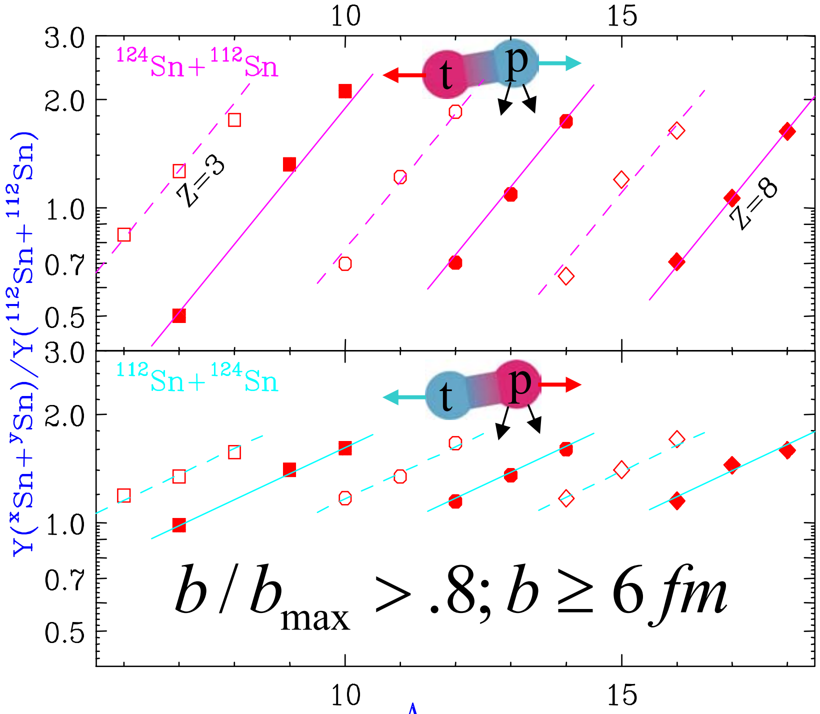

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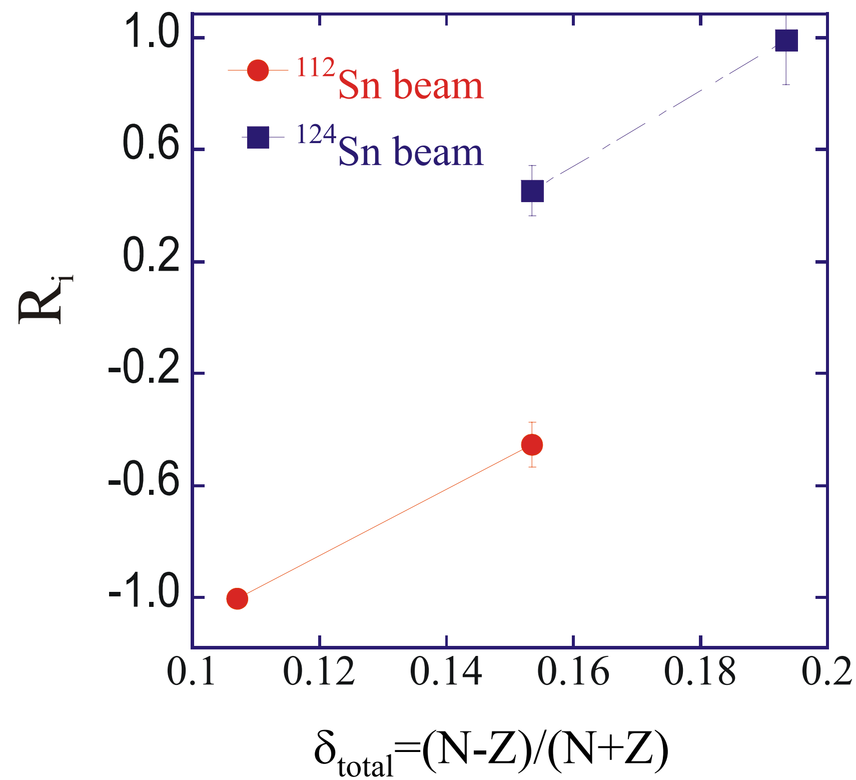
Tsang et al., PRL(2004)



- Very useful to rescale the data:

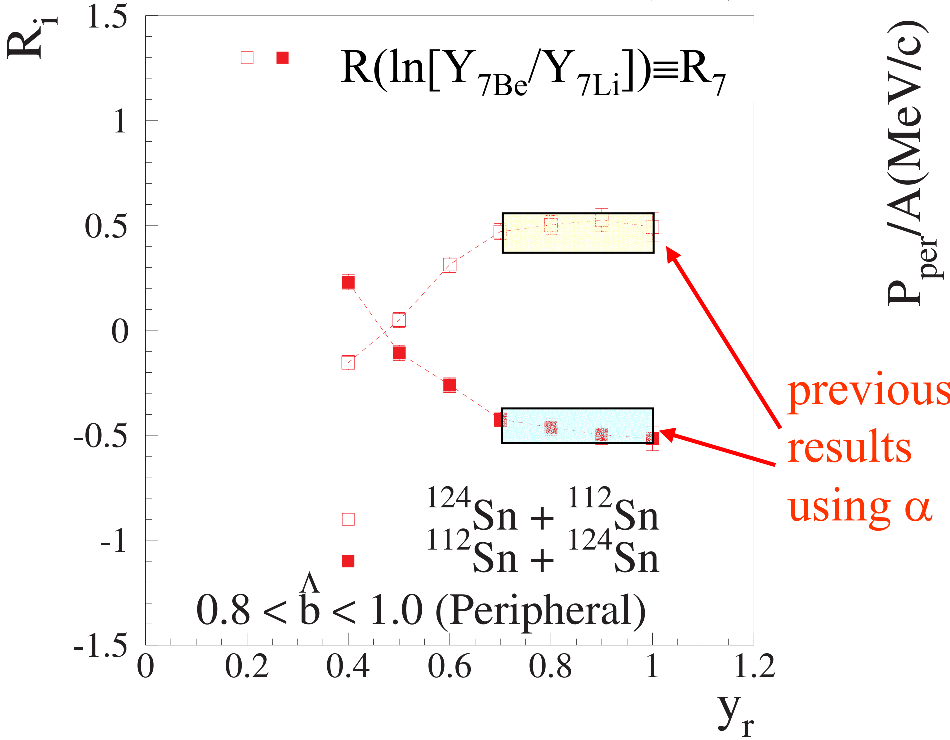
$$R(\alpha) = \frac{2\alpha - \alpha_{124+124} - \alpha_{112+112}}{\alpha_{124+124} - \alpha_{112+112}} \approx R(\delta_{PLF})$$

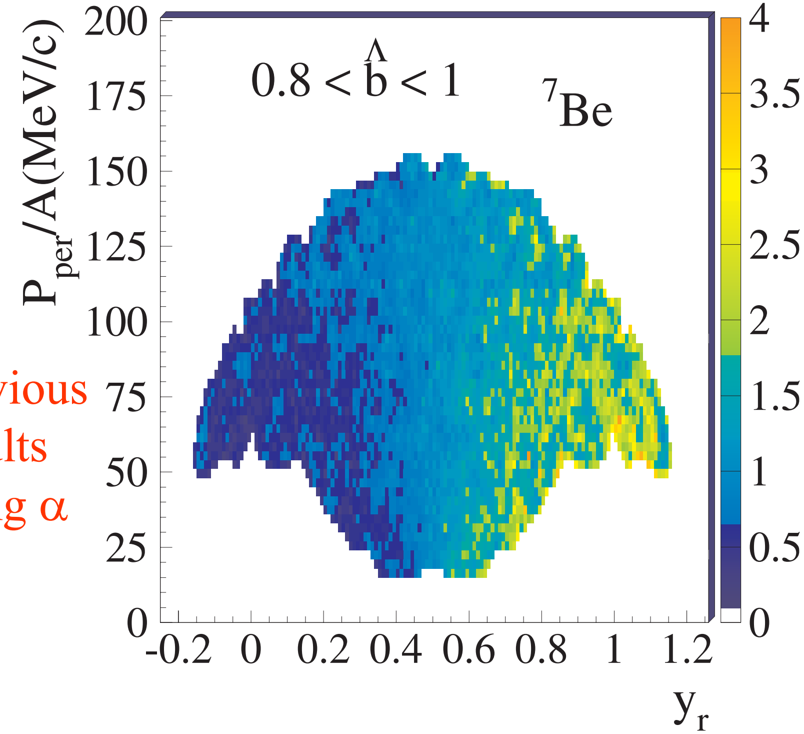
- Since $\alpha \propto \delta_{PLF}$, $R(\alpha)=R(\delta_{PLF})$.

How Robust is the Observable?

Dependence on rapidity and transverse momentum:

Liu, et al., (2004)





- Mirror nuclei ratios is another observable:

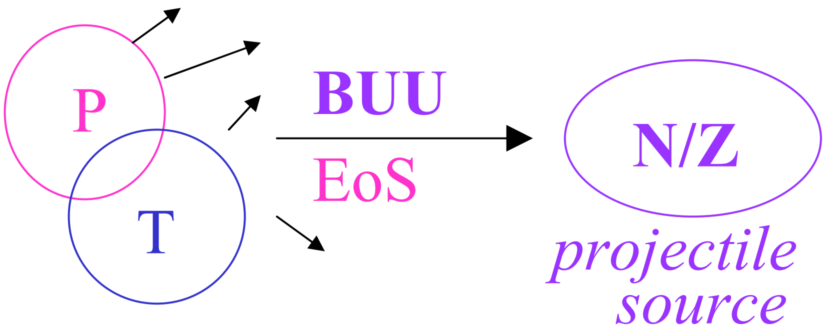
$$R_7 = Ln(Y_{7Be}/Y_{7Li}) \propto \mu_p - \mu_n$$

- Rapidity dependence is weak except at mid rapidity

- Quantity shown is $Y(^7Be, 112+124) / Y(^7Be, 124+112) \propto \exp(\kappa R_7)$
- No strong p_t dependence seen. Overall trends are smooth.

Transport model predictions

Asymmetry of PLF:



$$R_i = \frac{2x - x_{124+124} - x_{112+112}}{x_{124+124} - x_{112+112}}$$

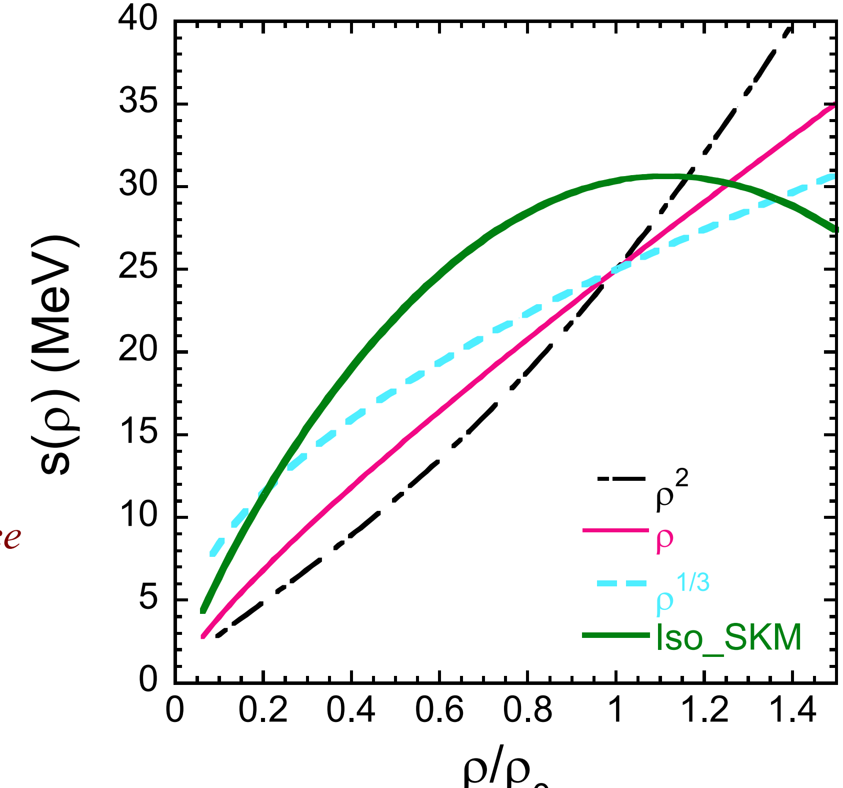
$$x = \delta_{source} = (N - Z)/(N + Z)_{source}$$

Asymmetry terms:

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

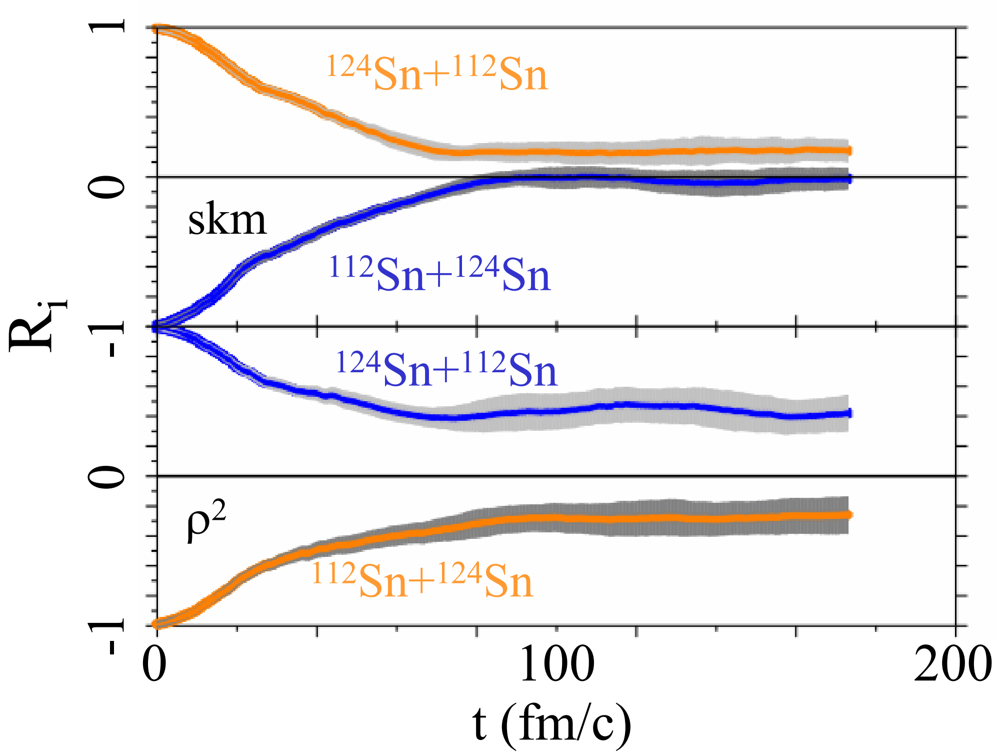
$$S_{sym}(\rho) \propto (\rho)^{\gamma};\ \gamma = 2,\ 1,\ 0.5,$$

$$\propto (a\rho - b\rho^2)\ skm$$

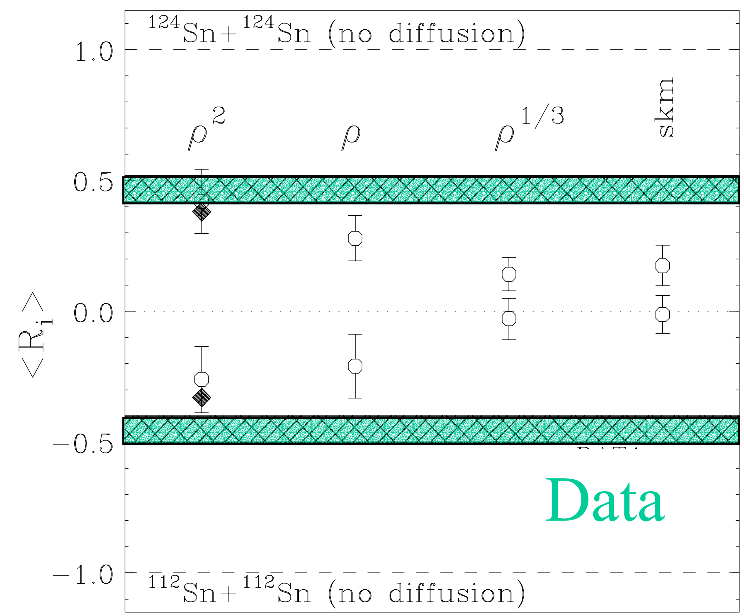


Comparisons to data

L. Shi et al. (2004)



Tsang et al., PRL (2004).

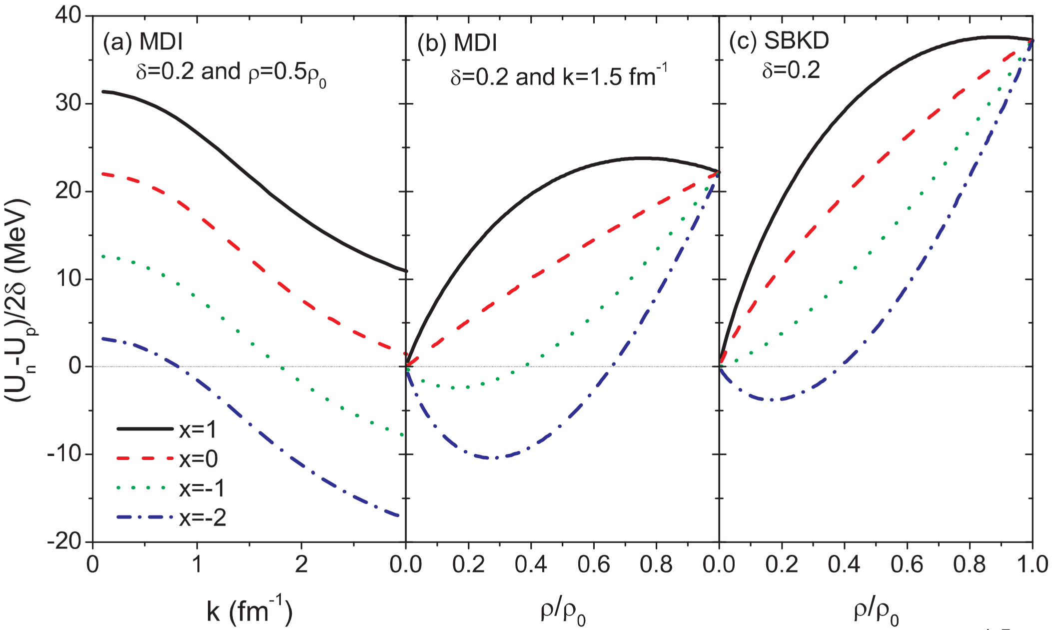


Diffusion occurs within ≈120 fm/c.

- More mixing with soft S(ρ)
  - consistent with large E_{sym} at $\rho<\rho_0$.
- Less mixing with stiff S(ρ).

- Explicit secondary decay correction gives same result.
- Stiff S(ρ) favored.
- What about isospin dep. of mom. dependence, cross sections?

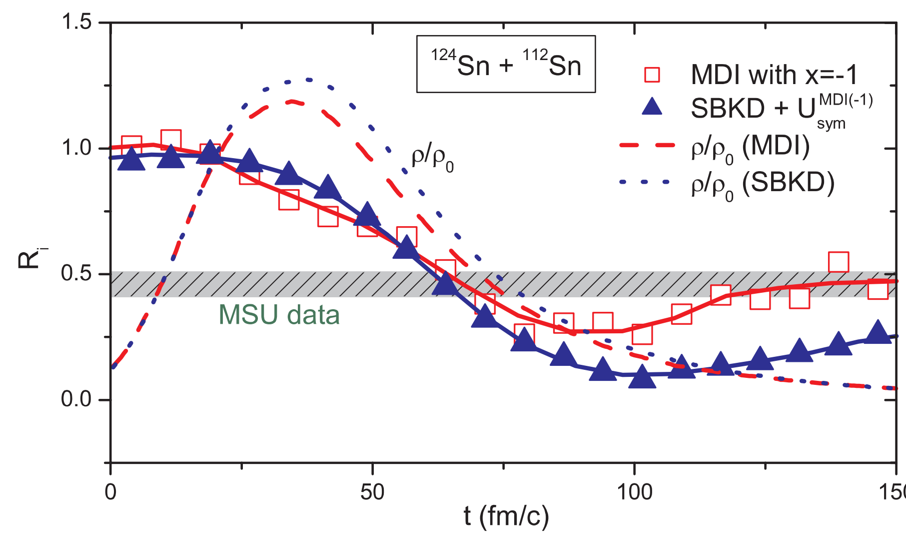
Results with momentum dependent mean field



- Momentum dependence of isovector potential also potentially important.
  - Parameterize and test sensitivity.
  - x value governs the density dpendence of isovector potential.

Chen et al., (2004).

- Including momentum dependence of isovector potential changes the degree of equilibration and conclusions about the density dependence.

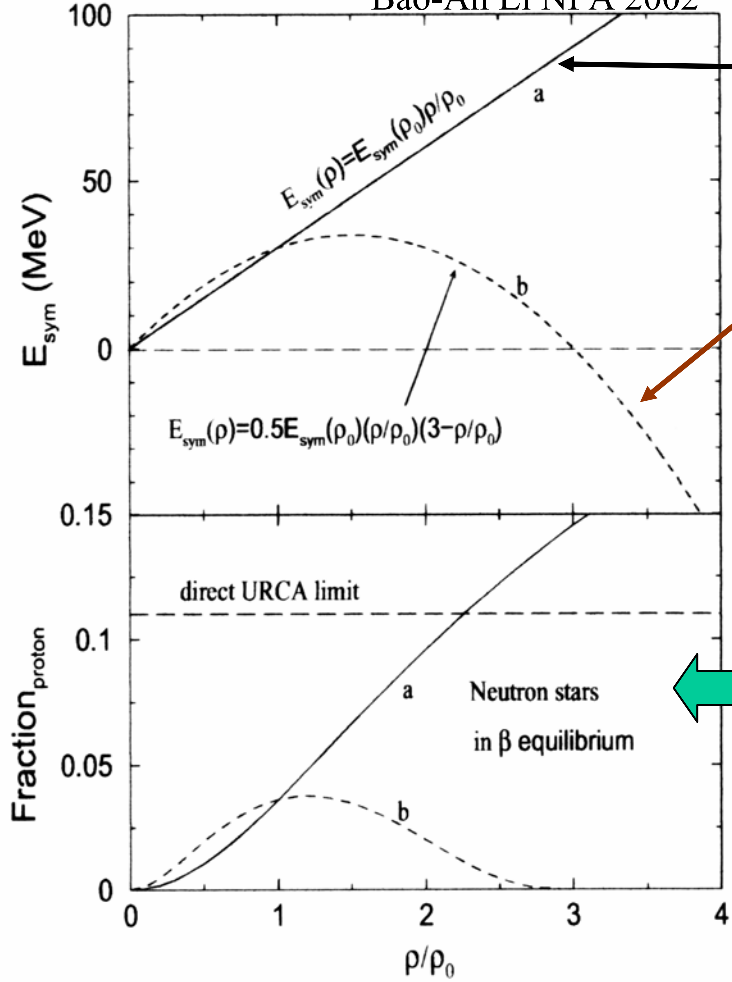


- How can one probe the asymmetry term at higher densities?
  - New projectile fragmentation facilities offer new opportunities.

Studies of asymmetry term at $\rho>\rho_0$.

- High density behavior of asymmetry terms can be group into two classes: i.e. increasing or decreasing with density.

Bao-An Li NPA 2002



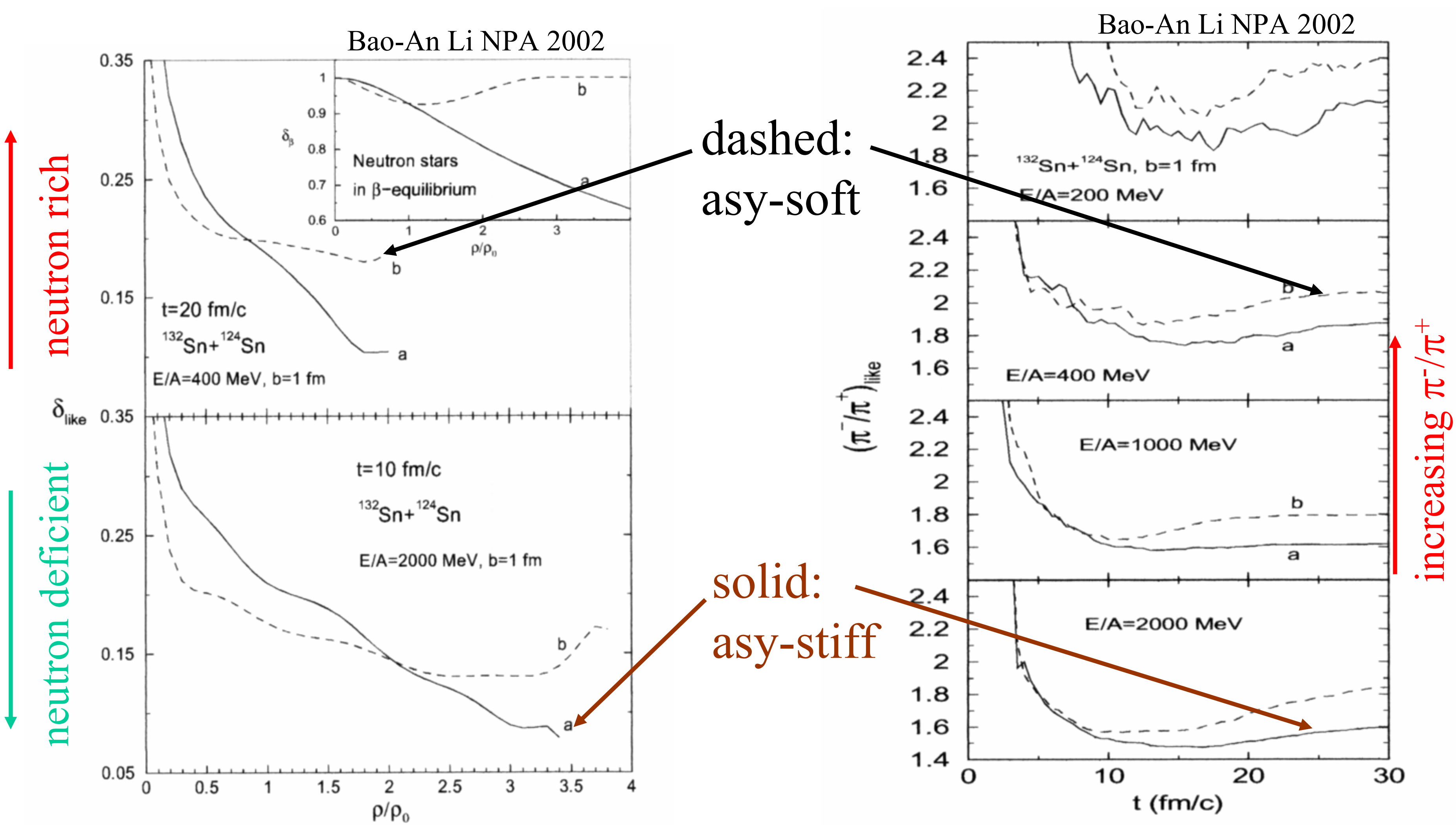
stronger density dependence (asy-stiff)

weaker density dependence (asy-soft) typical of many Skyrme EOS's or some variational calculations (UV14+UV11)

Influences significantly the inner structure of neutron star and the cooling of proto-neutron stars by URCA processes.

Observables relevant to high density behavior: Observable 1: pion yields

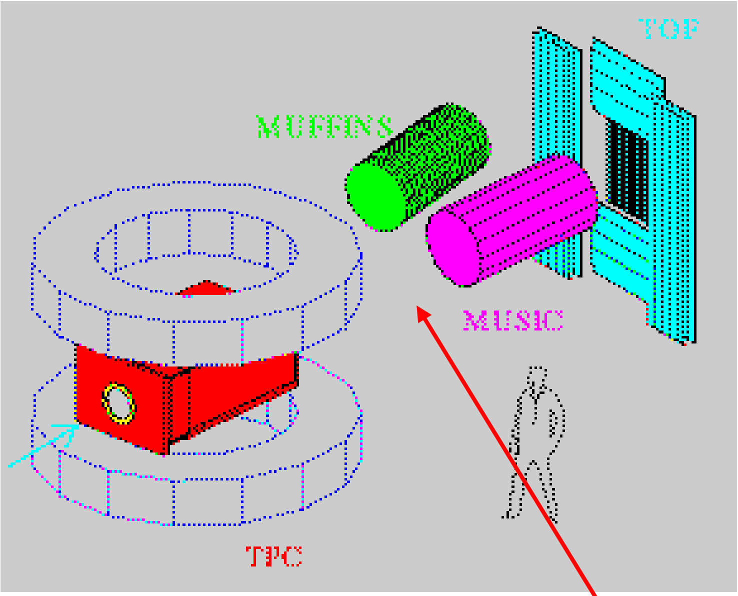
- Softer asymmetry term favors neutron rich dense regions and larger relative π^-/π^+ yield ratios:



Applications of TPC to such collisions

Example: EOS at LBL

- Rectangular TPC.
- Open forward geometry providing access for TOF wall, neutron detector and MUSIC.



- Advantages:
  - Good momentum resolution at forward angles.
  - Possibly lower detection thresholds at forward angles.
- Disadvantages:
  - Beam is perpendicular to magnetic field making beam line problematic.
  - acceptances of π^+, π^- differ.

Probably can’t have long flight to MUSIC at RIKEN, RIA or CCF energies –thresholds would be too high.

Conclusion

- Significant constraints on symmetric matter EOS have been obtained.
- Density dependence of symmetry energy can be examined experimentally.
- Observed isoscaling laws
- Conclusions from fragmentation

  work are model dependent:
  - BUU-SMM favors ρ^2 dependence of $S(\rho)$.
  - SMF favors ρ^2 dependence but isotope distributions are poorly reproduced
  - EES favors $\rho^{2/3}$ dependence of $S(\rho)$.
- Signals have been identified for measurements of asymmetry term at higher densities $\rho \approx \rho_0 - 3.5\rho_0$:
  - Isospin dependence of n vs. p flow, pion yields.