# Effects of Short-Range Correlation on Symmetry Energy and Their Manifestation in Heavy-Ion Collisions


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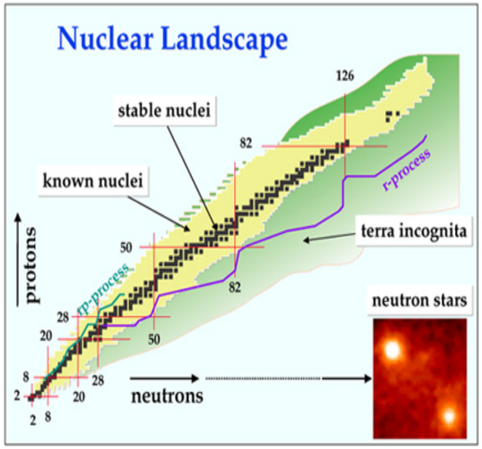
# Outline

- Brief introduction on symmetry energy
- Isospin dependence of short-range correlation
- Effects of SRC on kinetic symmetry energy
- Evidence of negative kinetic symmetry energy from heavy-ion collisions

# What is the Equation of State of neutron-rich nuclear matter?

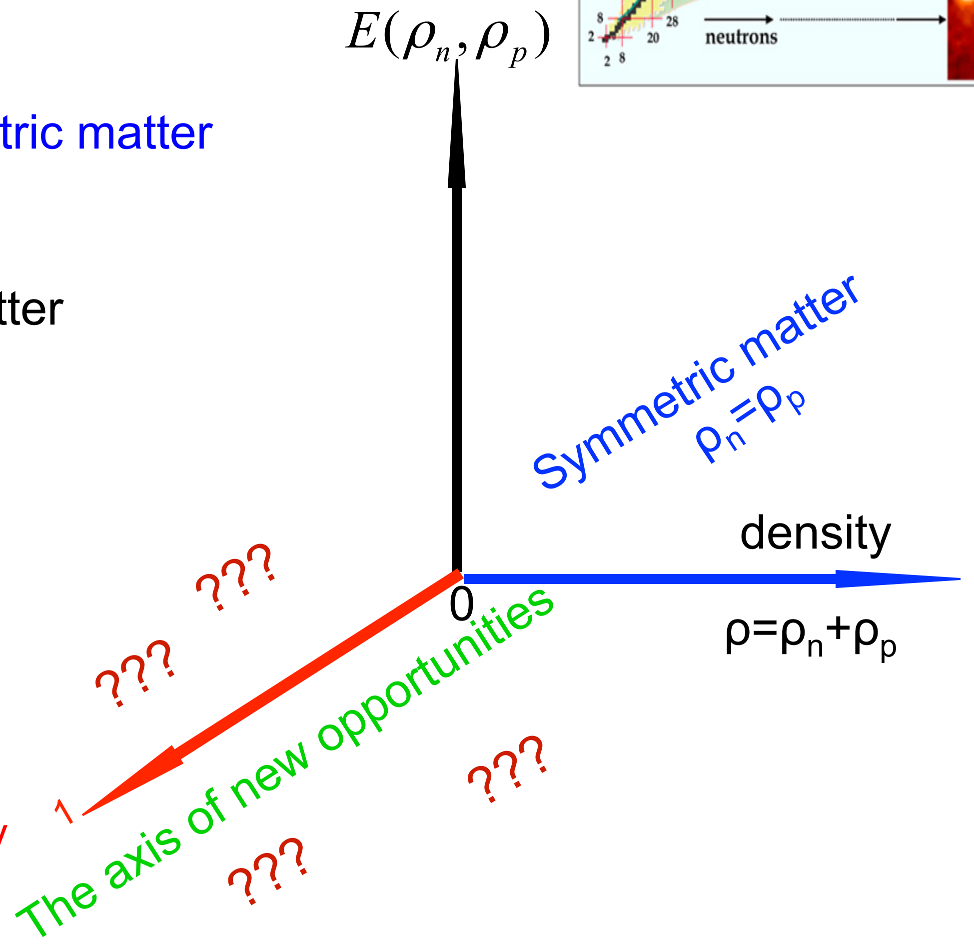



symmetry energy — Isospin asymmetry δ

$$E(\rho_n,\rho_p) = E_0(\rho_n = \rho_p) + E_{sym}(\rho)\left(\frac{\rho_n - \rho_p}{\rho}\right)^2 + o(\delta^4)$$

Energy per nucleon in symmetric matter

Energy per nucleon in asymmetric matter



# Characterization of symmetry energy near normal density

$$E_{sym}(\rho) = E_{sym}(\rho_0) + \frac{L(\rho_0)}{3}(\frac{\rho-\rho_0}{\rho_0}) + O((\frac{\rho-\rho_0}{\rho_0})^2)$$

$$L(\rho) = 3\rho\frac{dE_{\mathrm{sym}}(\rho)}{d\rho}.$$

# The physical importance of L

In npe matter in the simplest model of neutron stars at ß-equilibrium

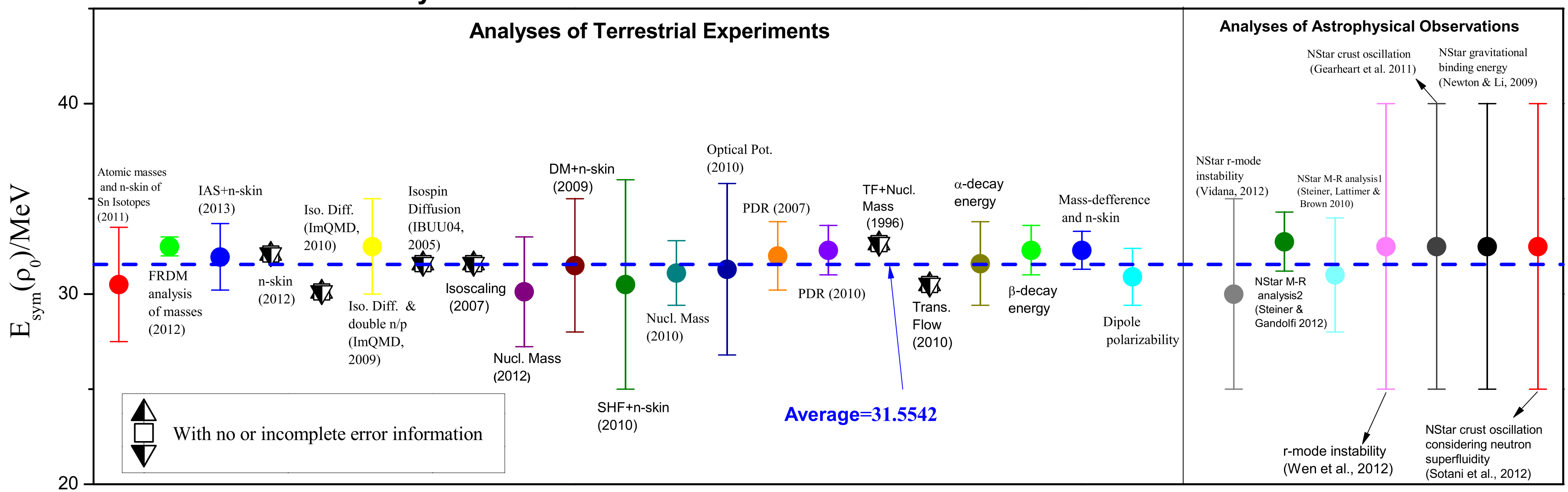
$$P(\rho,\delta) = P_0(\rho) + P_{\mathrm{asy}}(\rho,\delta) = \rho^2\left(\frac{\partial E}{\partial\rho}\right)_\delta + \frac{1}{4}\rho_e\mu_e$$

$$= \rho^2\left[E'(\rho,\delta=0) + E'_{\mathrm{sym}}(\rho)\delta^2\right] + \frac{1}{2}\delta(1-\delta)\rho E_{\mathrm{sym}}(\rho),$$

In pure neutron matter at saturation density of nuclear matter

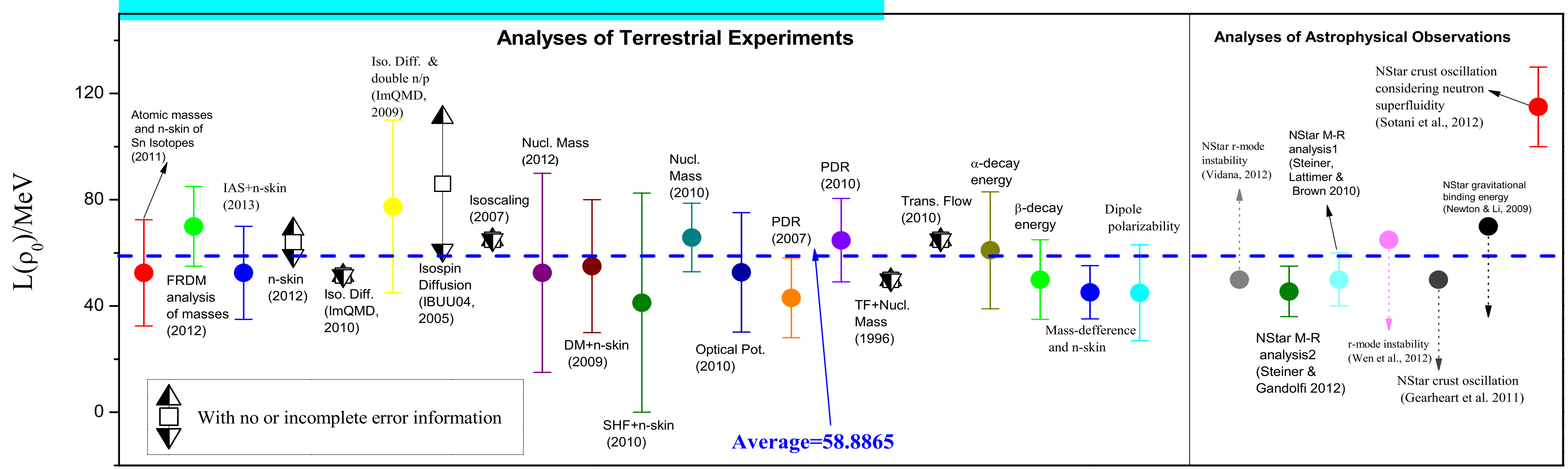
$$P_{PNM}(\rho_0) = \rho_0^2 E'_{\mathrm{sym}}(\rho_0) = \frac{1}{3}\rho_0 L,$$

# Constraints on $E_{sym}(\rho_0)$ and L based on 29 analyses of some data, Aug. 2013




| | $E_{sym}(\rho_0)$ | Slope L |
|---|---|---|
| 2013 average of the means | 31.55415 | 58.88646 |
| 2013 "standard deviation" | 2.66 | 16.52645 |

Bao-An Li and Xiao Han, Phys. Lett. B727, 276 (2013).



# Where does the $S_0=E_{sym}(\rho_0)\approx 31$ MeV come from?

In the literatures in both astrophysics and nuclear physics

$S=E_{sym}=E_{sym}^{Kin}+E_{sym}^{pot}$

$$E_{sym}^{kin}(\rho)=\frac{1}{3}E_F(\rho_0)(\rho/\rho_0)^{2/3}\approx 12.5\text{MeV at }\rho_0$$

At abnormal densities, it is customary to parameterize

Kinetic

Potential

The only term goes into the reaction dynamics

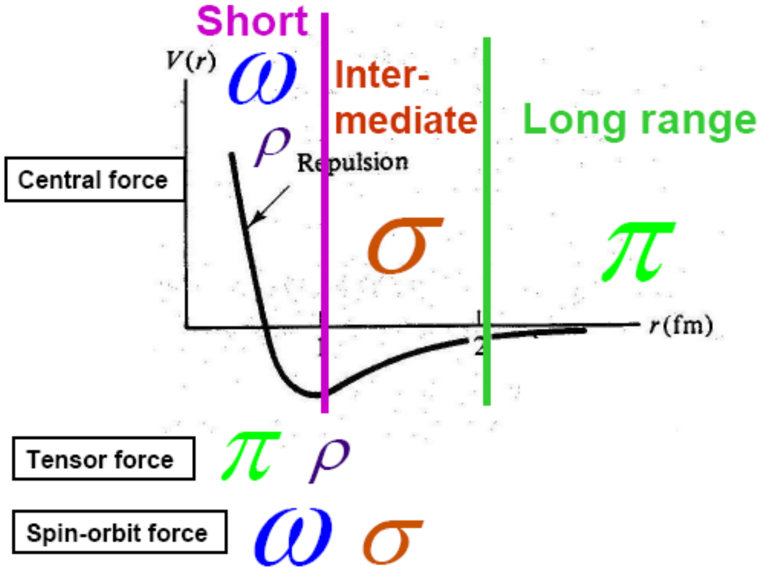
$$S(\rho)=\frac{C_{s,k}}{2}(\frac{\rho}{\rho_0})^{2/3}+\frac{C_{s,p}}{2}(\frac{\rho}{\rho_0})^{\gamma_i}$$

Probing all of the unknown physics

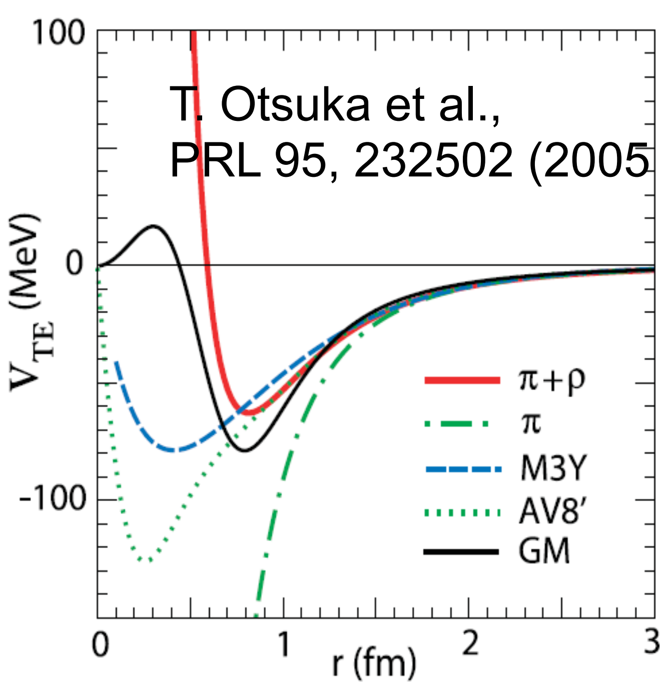
$C_{s,k}=25$ MeV

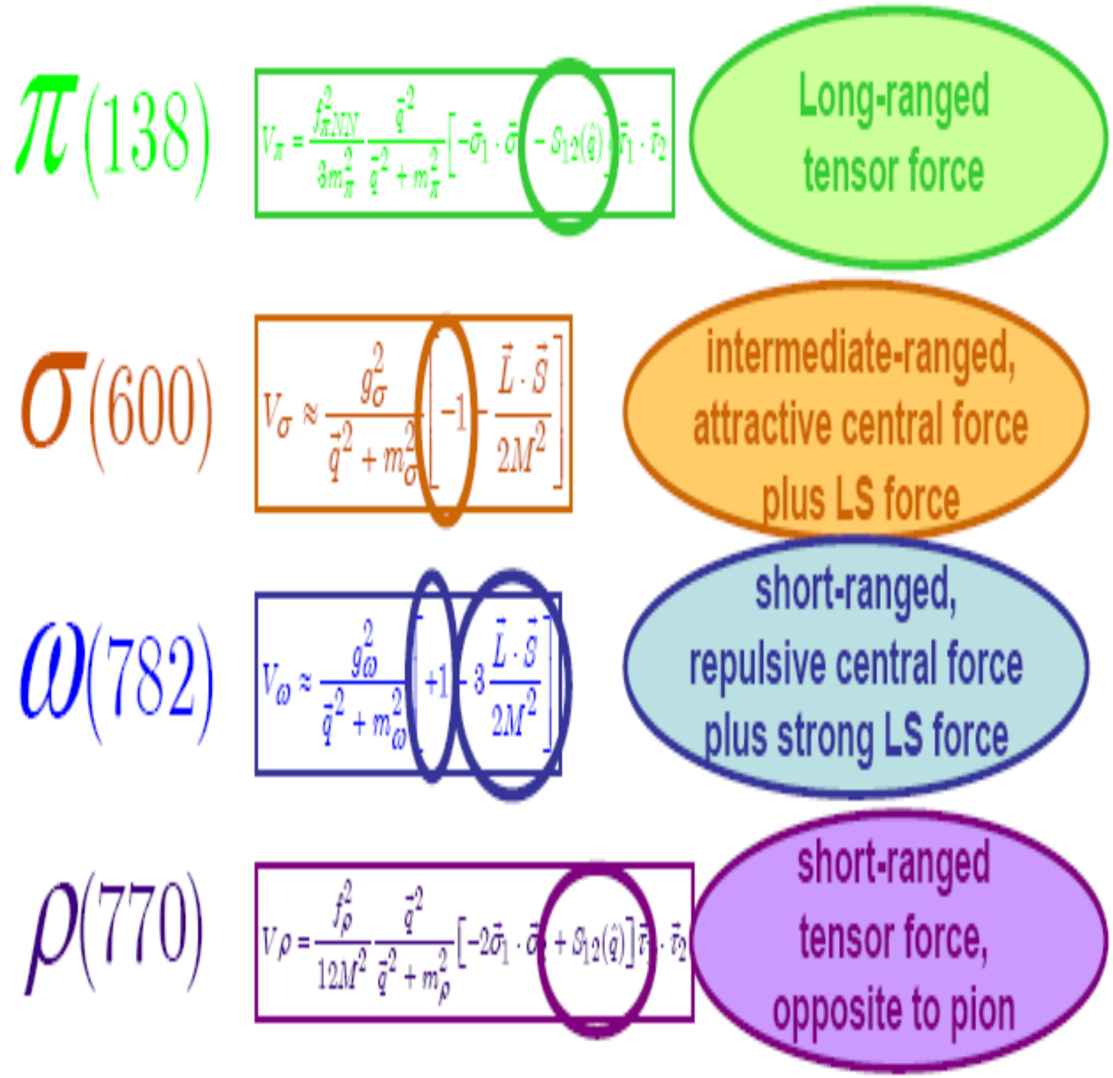
$$C_{s,p}=2S_0-C_{s,k}$$

# The short and long range tensor force



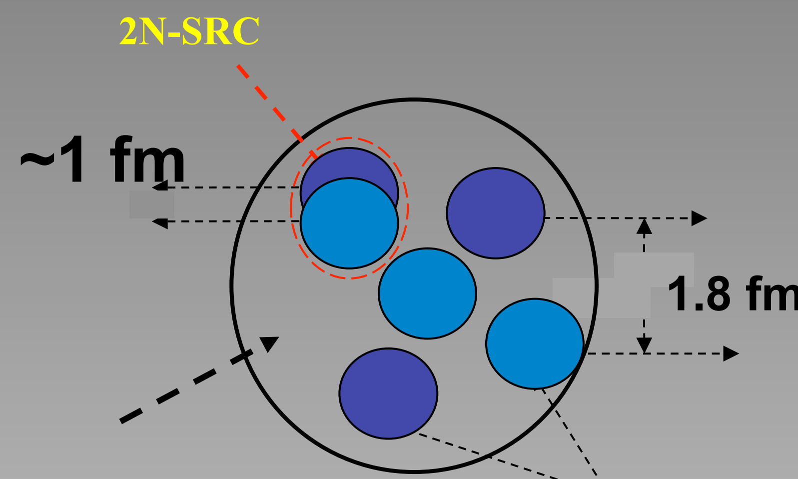

Lecture notes of R. Machleidt
CNS summer school, Univ. of Tokyo
Aug. 18-23, 2005



# What are Short Range Correlations in nuclei ? (taken from Eli Piasetzky)

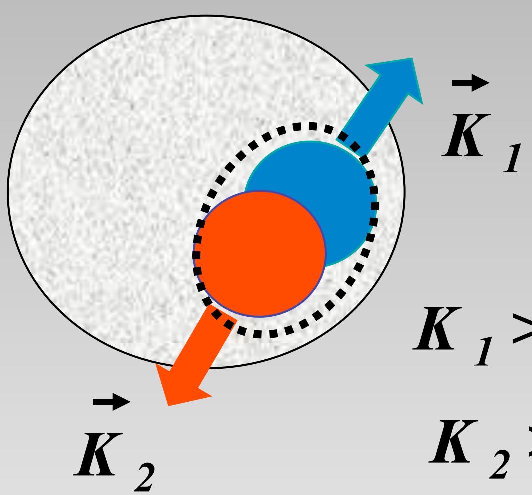
SRC ~$R_N$ LRC ~$R_A$




$\rho_o = 0.16\ \mathrm{GeV/fm}^3$

$k_F \sim 250$ MeV/c
High momentum tail:
300-600 MeV/c
1.5 $K_F$ - 3 $K_F$

**In momentum space:**




$\cong \vec{K}_1 \quad \vec{K}_2$

$K_1 > K_F$,

$K_2 > K_F$

A pair with large relative momentum between the nucleo
and small CM momentum.

# Tensor force induced (1) high-momentum tail in single-particle momentum distribution and (2) isospin dependence of NN correlation

**Theory of Nuclear matter**
**H.A. Bethe**
Ann. Rev. Nucl. Part. Sci., 21, 93-244 (1971)

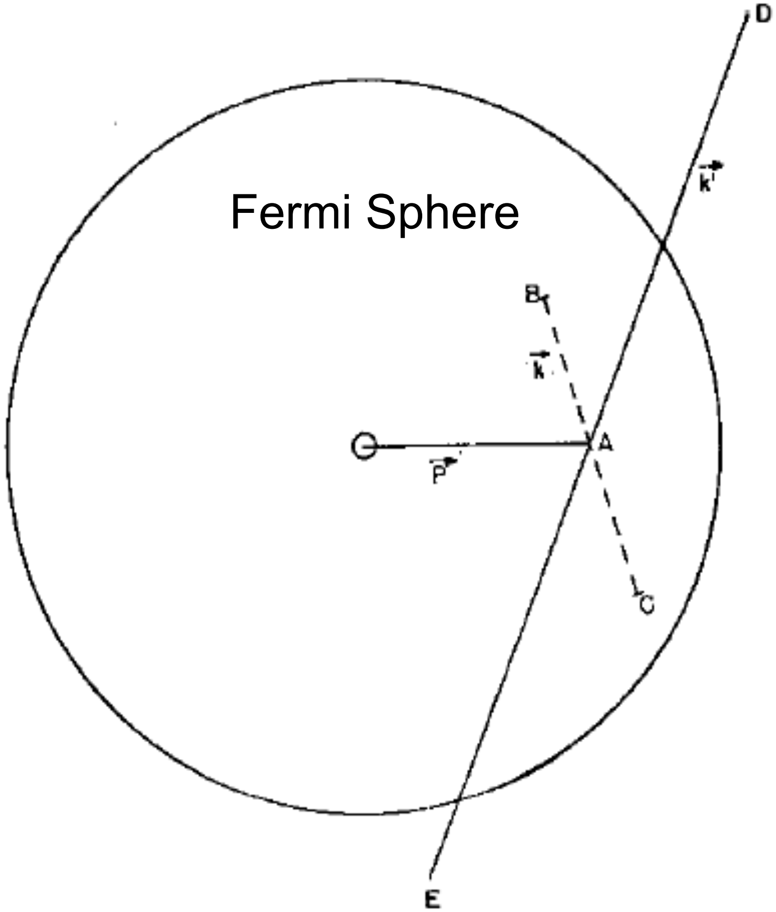
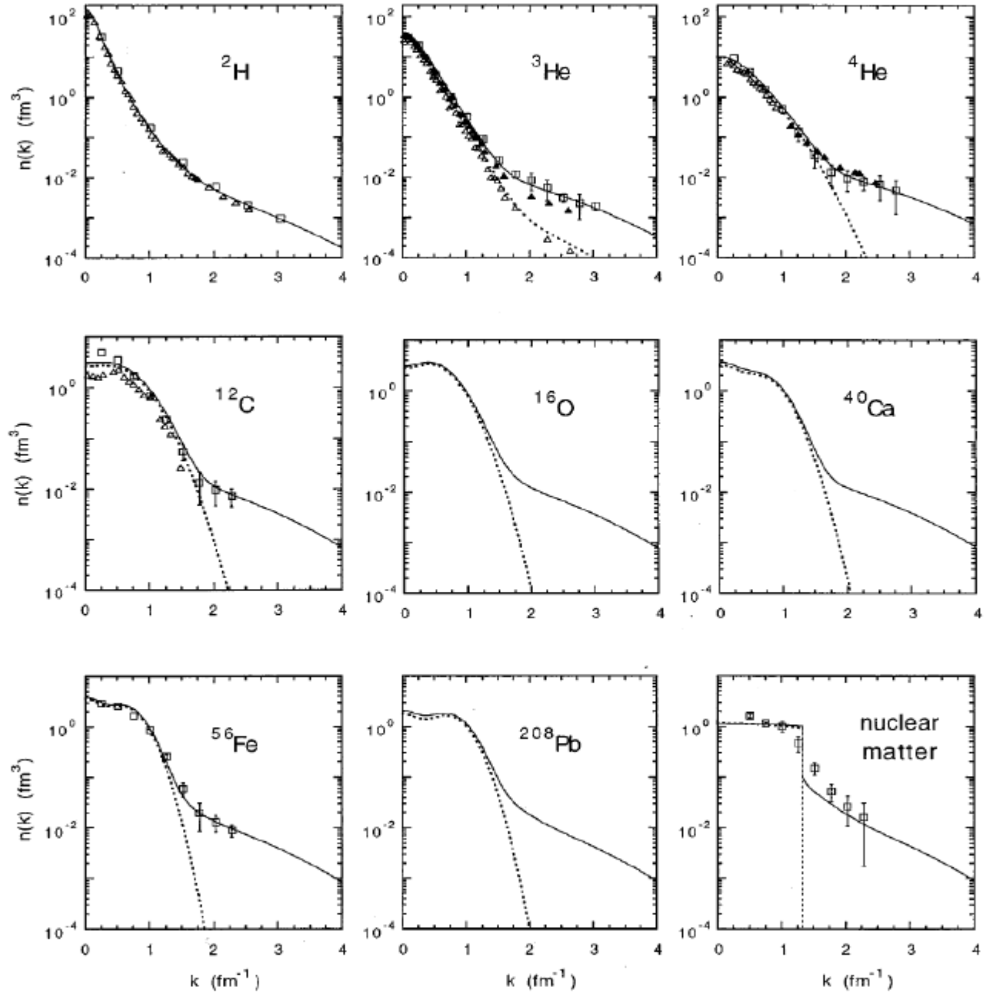
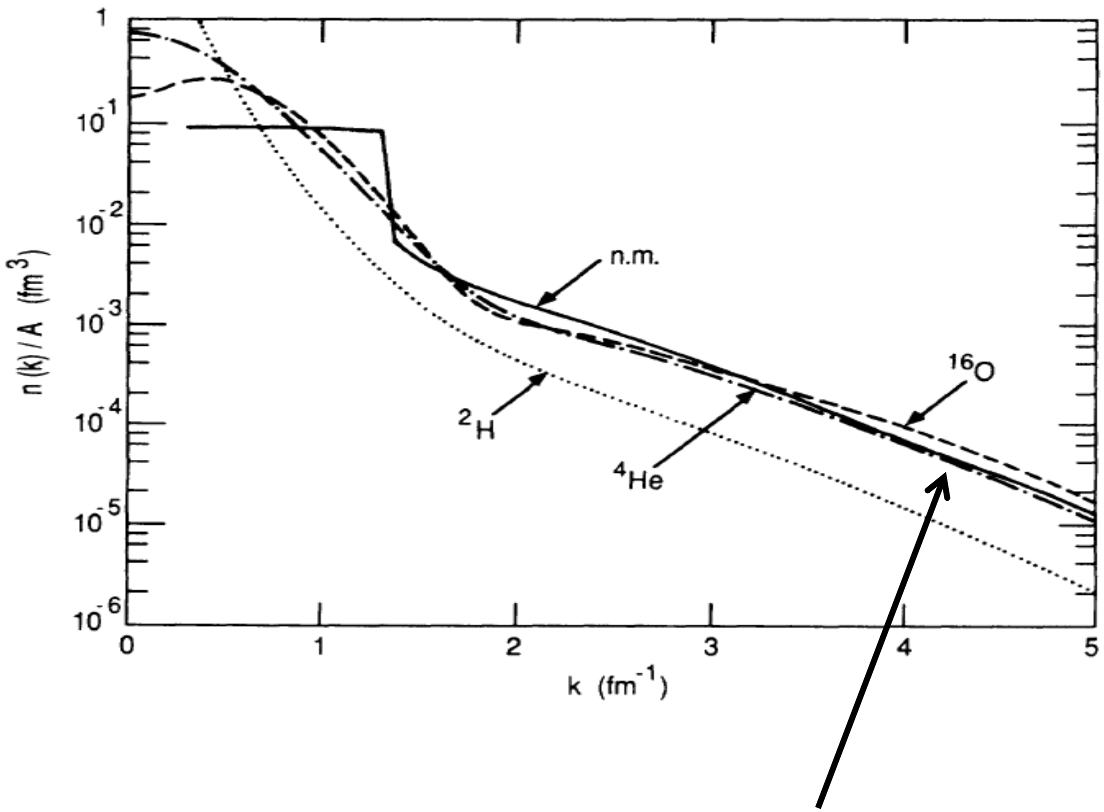



FIGURE 10. Two nucleons are initially in states $B$ and $C$, having average momentum $\boldsymbol{P}$ and relative momentum $\boldsymbol{k}$. When they interact they are shifted to states $D$ and $E$ outside the Fermi sphere, with relative momentum $\boldsymbol{k}'$. If they are initially in a $^3S$ state and interact by tensor force, then they are in a $^3D_1$ state in $DE$.




S. Fantoni and V. R. Pandharipande, Nucl. Phys. A **427**, 473 (1984).
C. Ciofi degli Atti and S. Simula, Phys. Rev. C **53**, 1689 (1996).

# Scaling of the high-momentum tail due to tensor force




Universal shape of high-momentum tail

→due to short-range interaction of two nearby nucleons

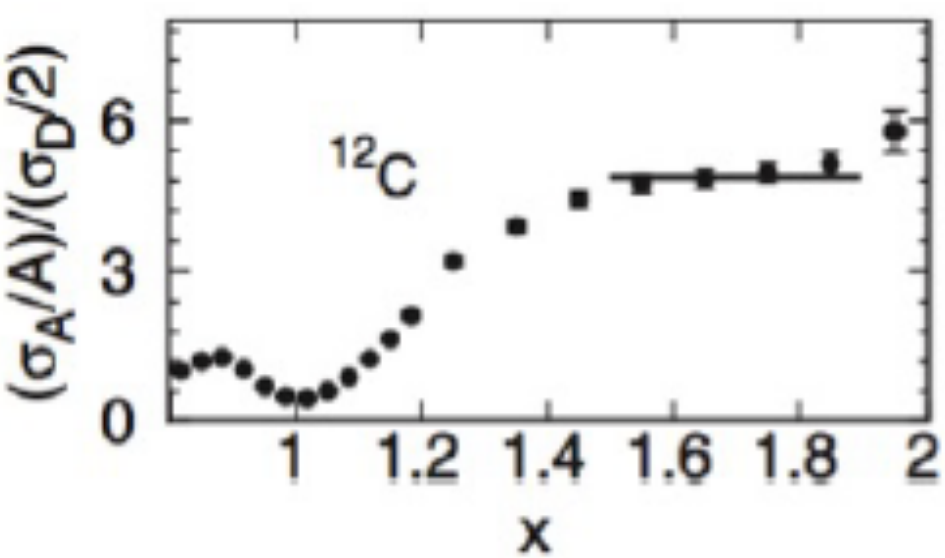
→ scaling of weighted (e,e’) inclusive xsections from light to heavy nuclei: the ratio of weighted xsection should be independent of the scattering variables

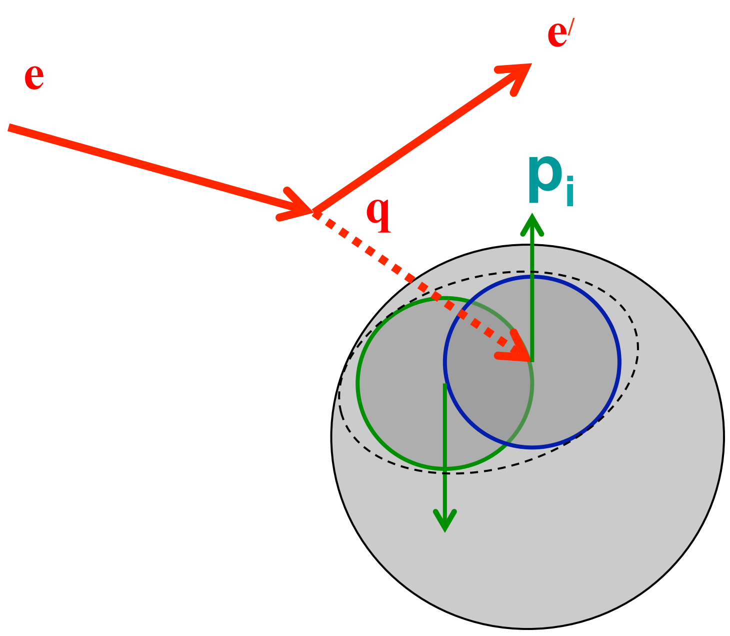
# The inclusive A(e,e') measurements

K. Sh. Egiyan et al. PRC 68, 014313 (2003)

K. Sh. Egiyan et al. PRL. 96, 082501 (2006)

N. Fomin et al. PRL 108, 092502 ( 2012)

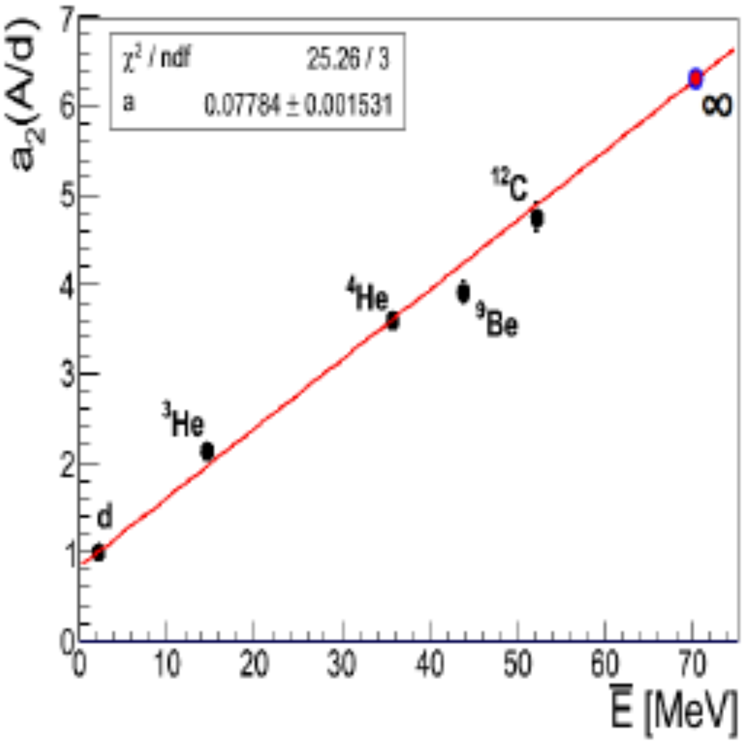



$$x_B = \frac{Q^2}{2m\omega} \qquad Q^2 = \vec{q}^{\,2} - \omega^2$$

# Relative probability of SRC in nucleus A with respect to that in deuteron

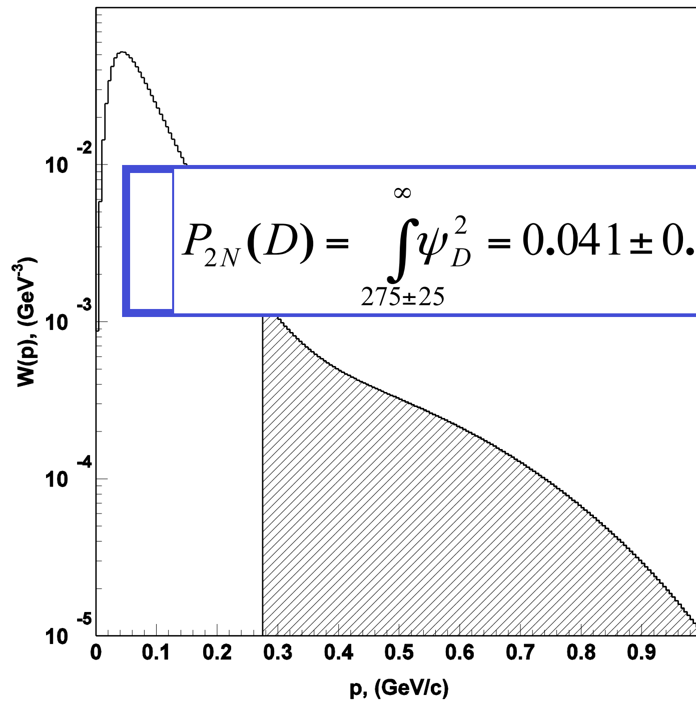
## $a_2(A/d)$ extrapolated to infinite SNM




**Nucleon removal energy**

$$\bar{E} = \bar{T}\frac{A-2}{A-1} - \frac{E_0}{A}$$

Greens Function Monte-Carlo (GFMC)



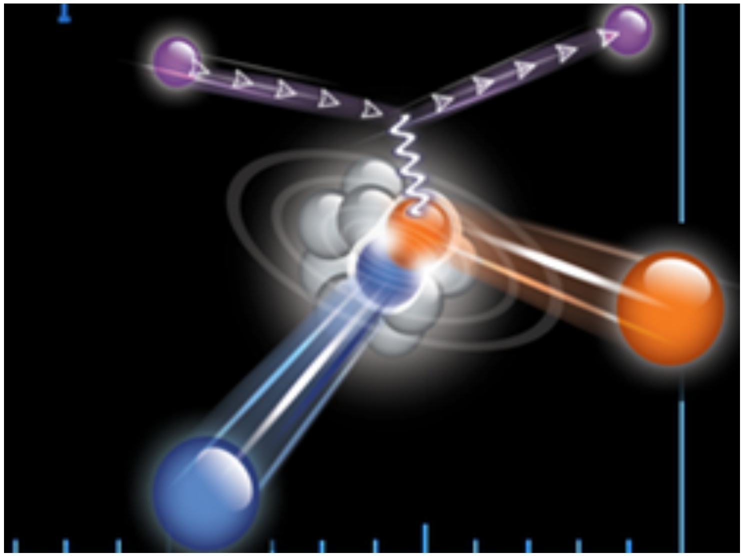

$$P_{2N}(D) = \int_{275\pm 25}^{\infty} \psi_D^2 = 0.041 \pm 0.008$$

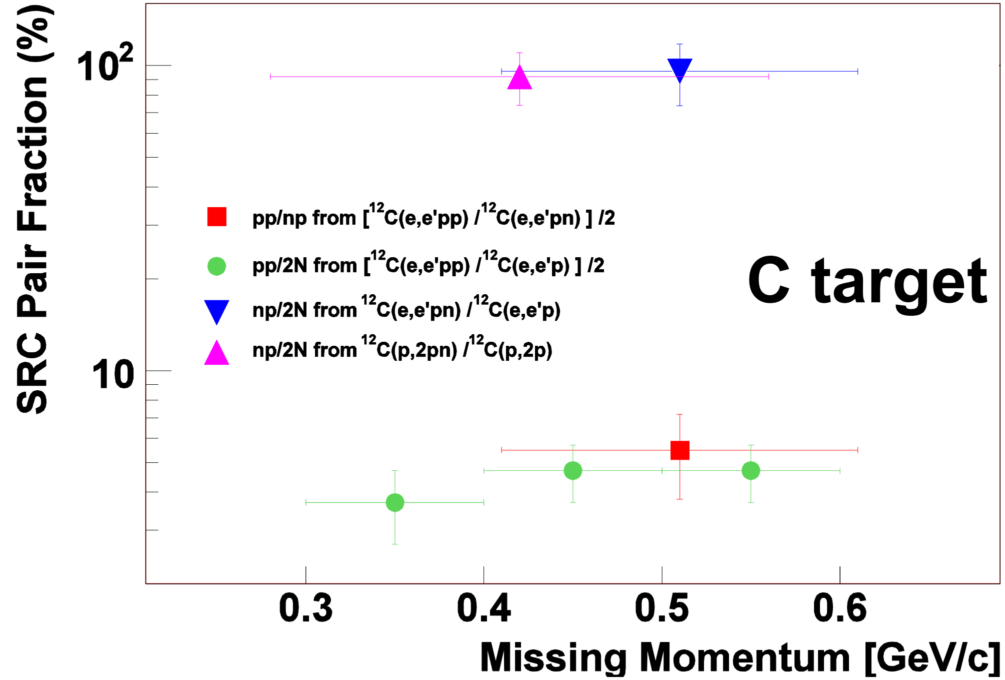
$$P_{2N}(A) = a_{2N}(A/d) \cdot P_{2N}(D)$$

$P_{2N}(\infty) \approx 20\text{-}30\%$

E. Piasetzky, O. Hen, L. B. Weinstein
Proceedings of plenary talk at CIPANP 2012

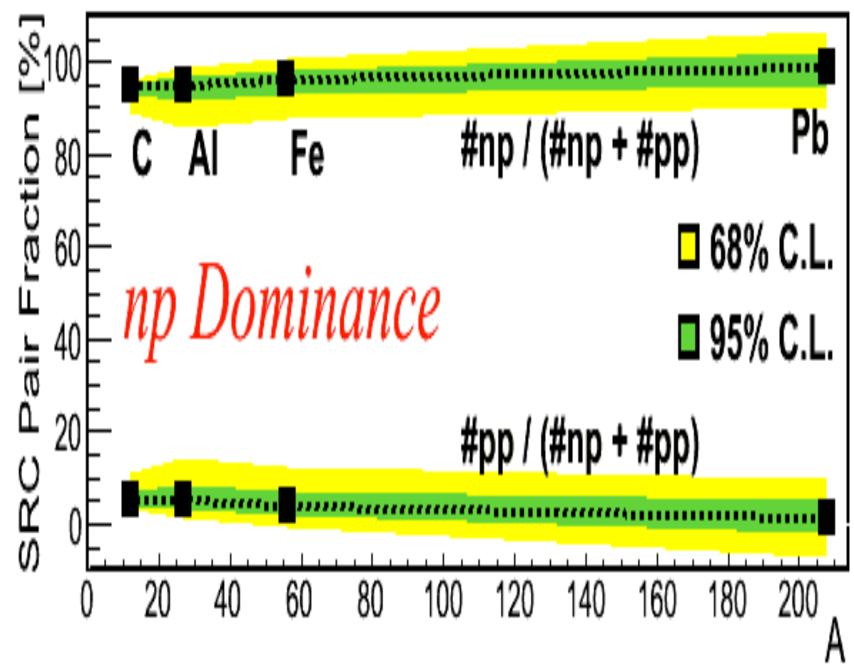
# Triple coincidence measurement df the isospin dependence of SRC






R. Subedi et al., Science 320, 1476 (2008

Or Hen et al., sub. to Science (2014)




1. np/pp≈18

2. High momentum tail in pure neutron matter is about 1-2%

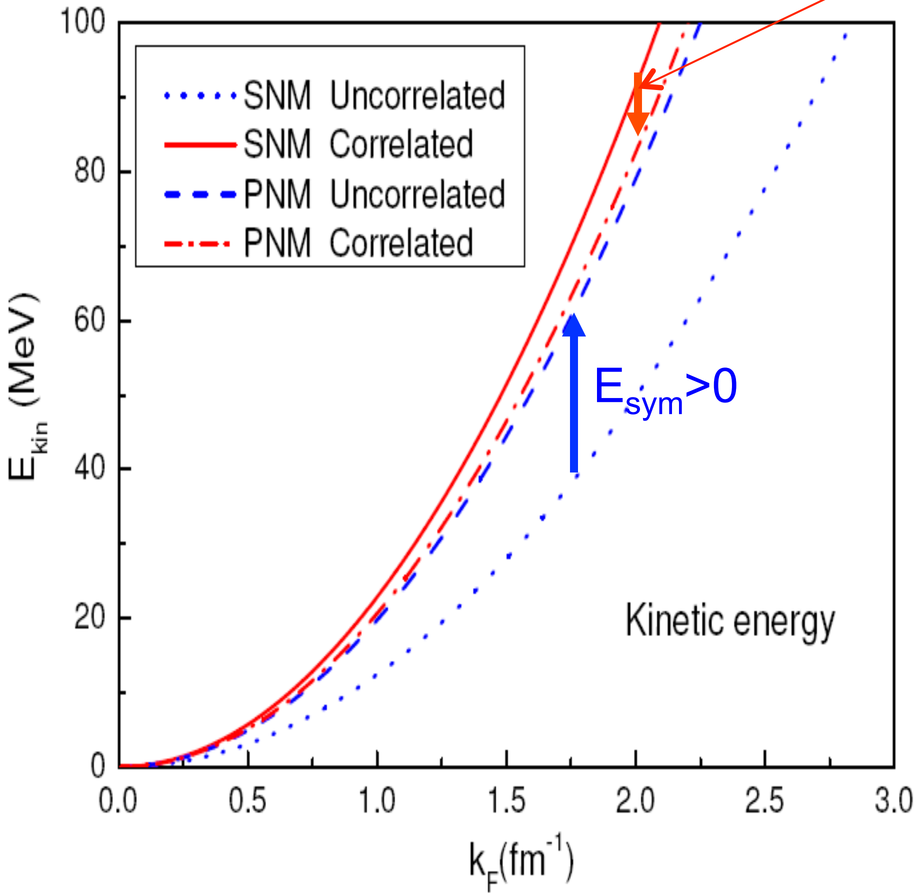
# How does the tensor force affect the kinetic symmetry energy?

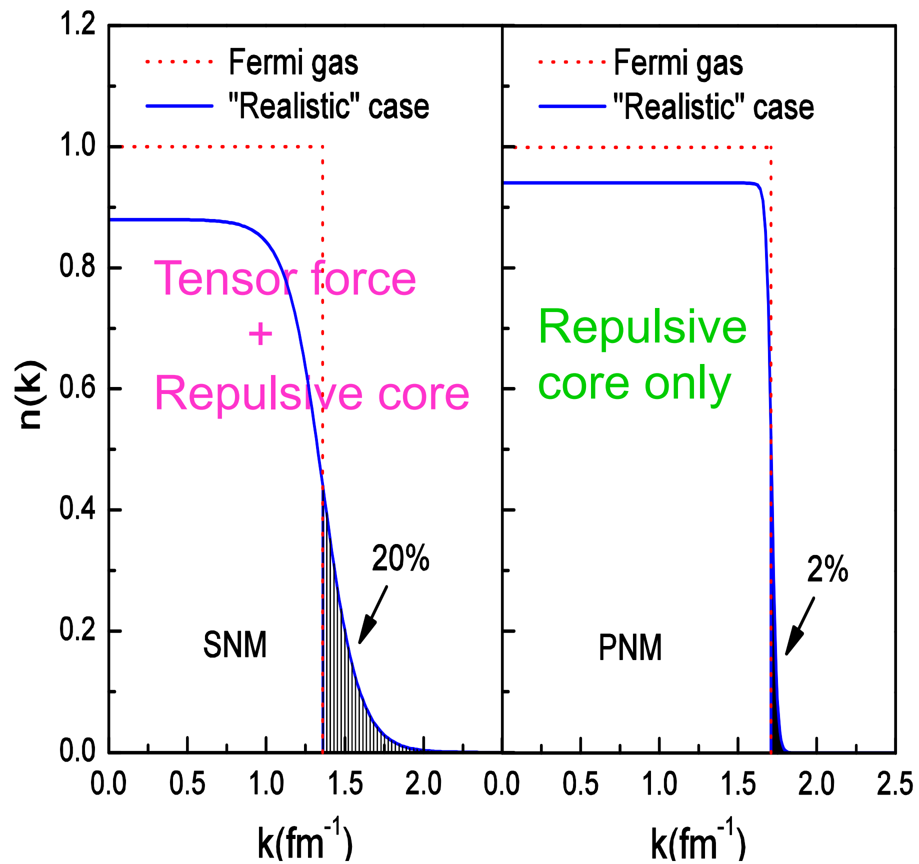
Chang Xu and Bao-An Li, arXiv:1104.2075

Chang Xu, Ang Li and Bao-An Li, JPCS 420, 012190 (2013).

$$E_{kin} = \alpha \int_0^\infty \frac{\hbar^2 k^2}{2m} n(k) k^2 dk,$$

$$E_{sym}^{kin} = E_{PNM}^{kin} - E_{SNM}^{kin} < 0$$



# Confirmation by Microscopic Many-Body Theories

**1.** Isaac Vidana, Artur Polls, Constanca Providencia

*PRC84, 062801(R) (2011)*

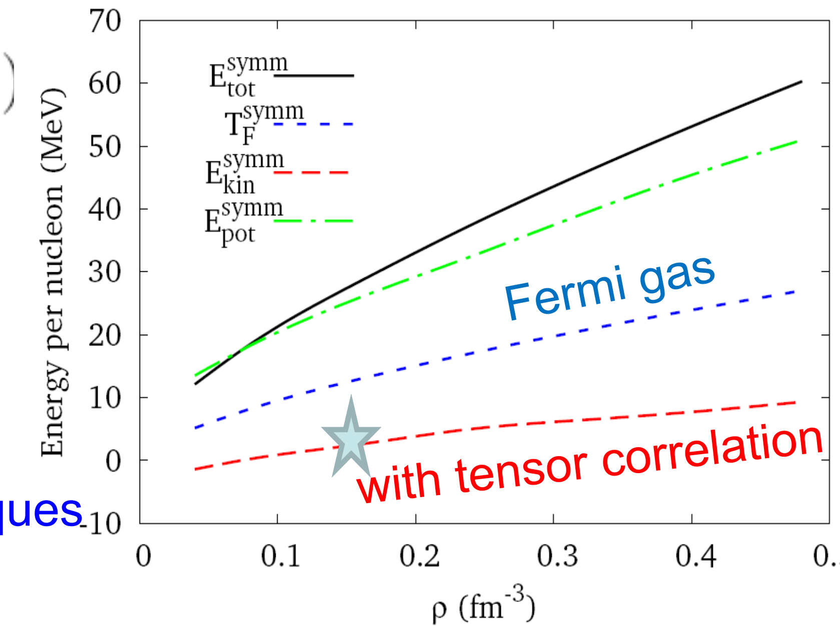
Brueckner--Hartree--Fock approach using the Argonne V18 potential plus the Urbana IX three-body force

**2.** Arianna Carbone, Artur Polls, Arnau Rios, EPL 97, 22001 (2012)
Self-Consistent Green's Function Approach with Argonne Av18, CDBonn, Nij1, N3LO interactions

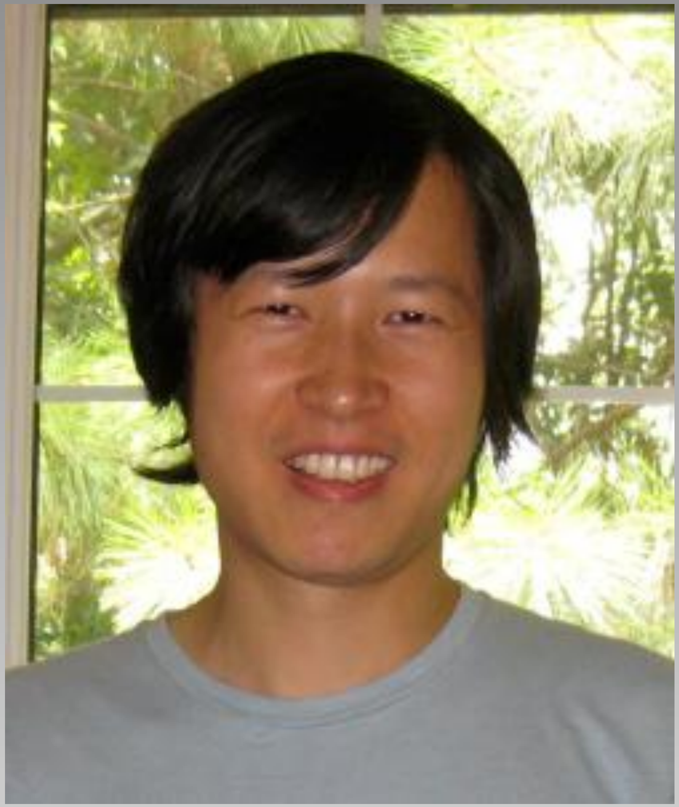
**3.** Alessandro Lovato, Omar Benhar et al.,
extracted from results already published in
*Phys. Rev. C83:054003,2011*
Using Argonne $V'_6$ interaction
Fermi-Hyper-Netted-Chain (FHNC)
Single Operator Chains (SOC)

4. A. Rios, A. Polls, W. H. Dickhoff
PRC 89, 044303 (2014).
Ladder Self-Consistent Green Function

They all included the tensor force and many-body correlations using different techniques



The universal shape of the high-momentum tail in all symmetric 2-component fermion systems with strong contact/interaction between unlike particles if $a >> d >> r_{eff}$



**With large scattering length a between different Fermions of separation d And short-range ($r_{eff}$) interaction**

$$n(k) = C / k^4$$

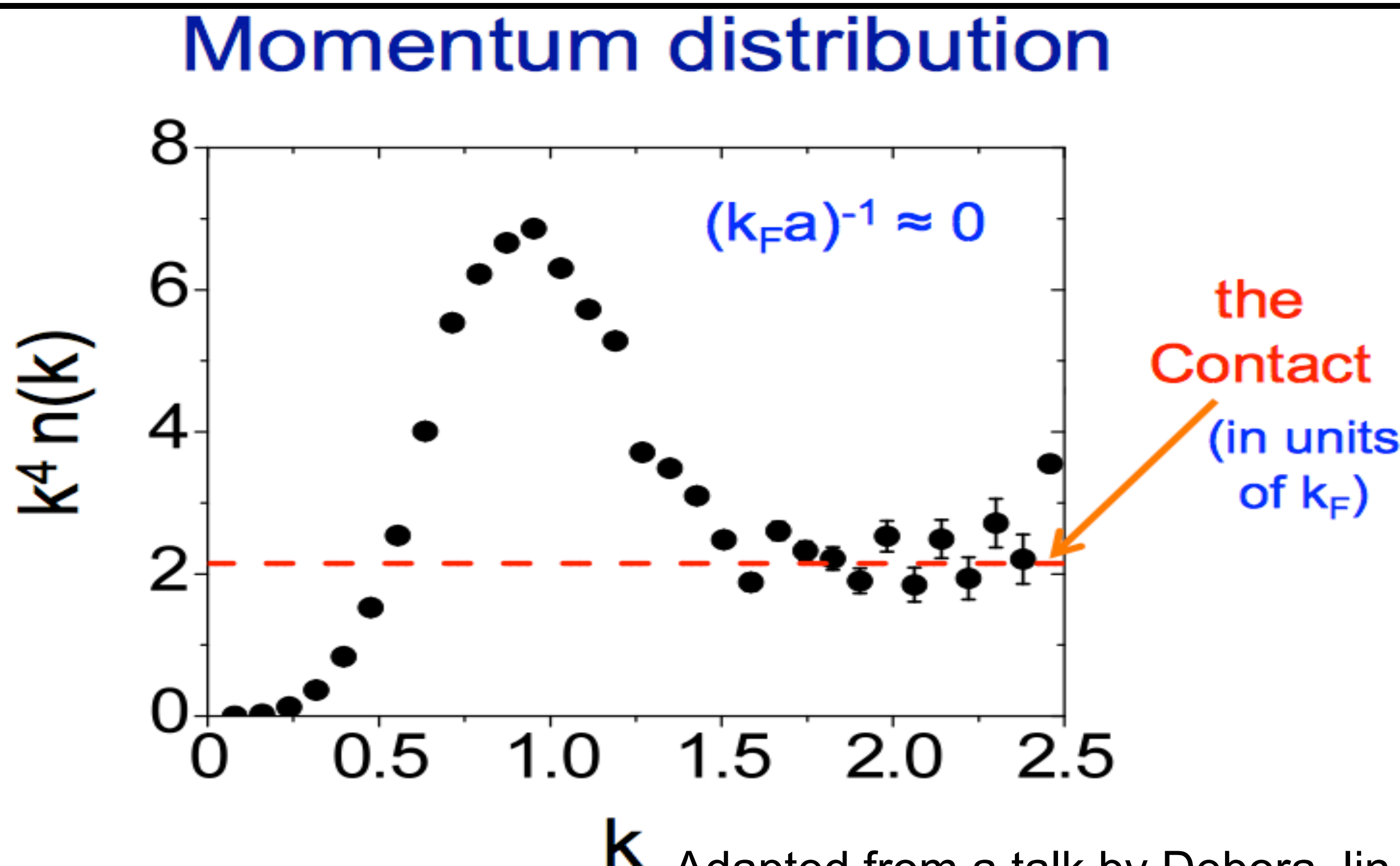
C is the Tan's contact term

B.S. Tsinghua, 1997, Ph.D. U. of Chicago 2006

Thermodynamics can be describe by thr single parameter C

Shina Tan, Annals of Physics 323 (2008) 2952, ibid 2971, ibid 2987
(*George E. Valley Prize, American Physical Society 2010* )

# Experiments with two spin-state mixtures of ulta-cold $^{40}K$ and $^{6}Li$ atomic gas systems extracted the contact term and verified the universal relations




Adapted from a talk by Debora Jin (JILA).

Stewart et al. PRL **104**, 235301 (210)

Kuhnle et al. PRL **105**, 070402 (2010)

# What about nuclear contact ?

## (Eli Piasetzky)

$a >> d >> r_{eff}$ ?

$$d = \rho^{-1/3} \approx 1.8\, fm$$

$$r_{eff} \approx \frac{\hbar}{2 \cdot m_{\pi} \cdot c} \approx 0.7\, fm$$ Tensor force

The high- momentum tail is predominantly:

J=1 S and D pairs :

T=0 S=1 L=0 $^3S_1$

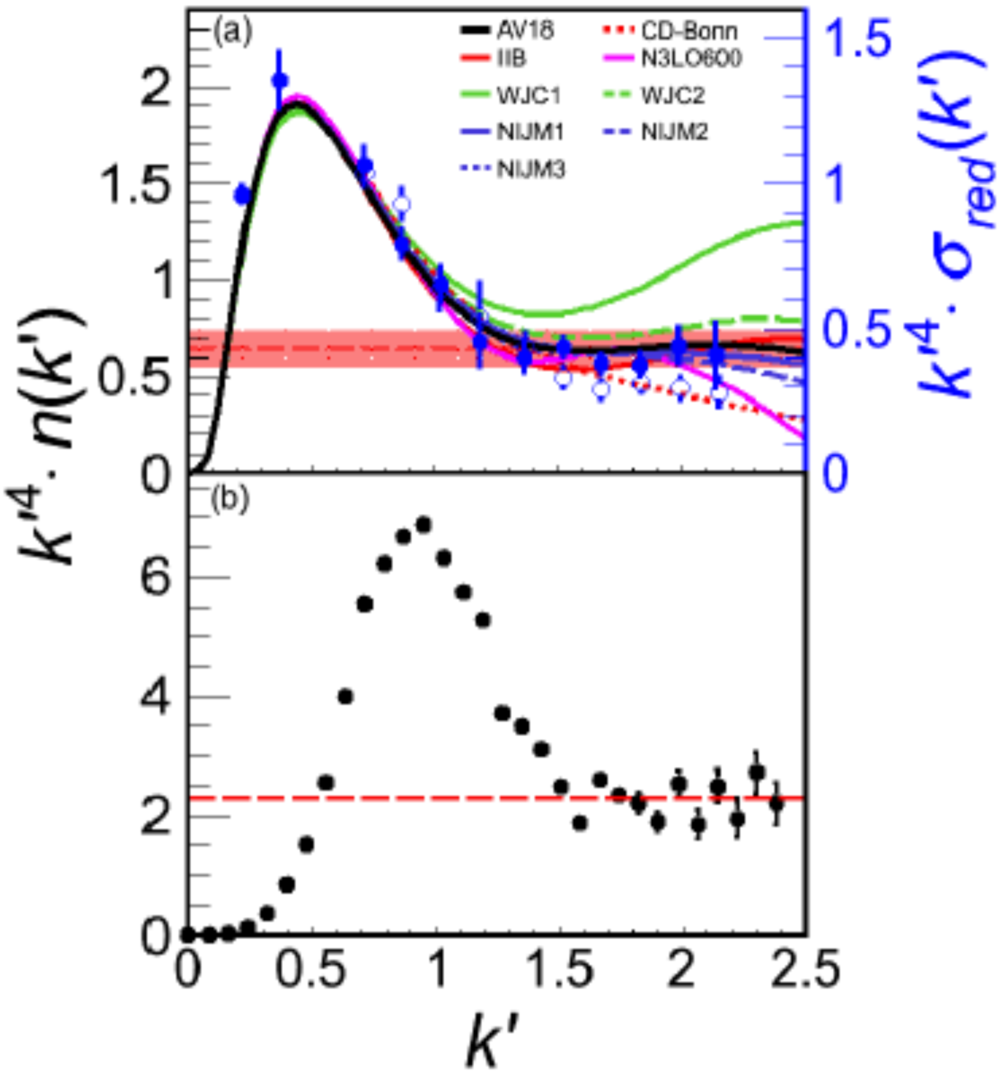
T=0 S=1 L=2 $^3D_1$

$a(^3S_1)=5.424\pm0.003$ fm.

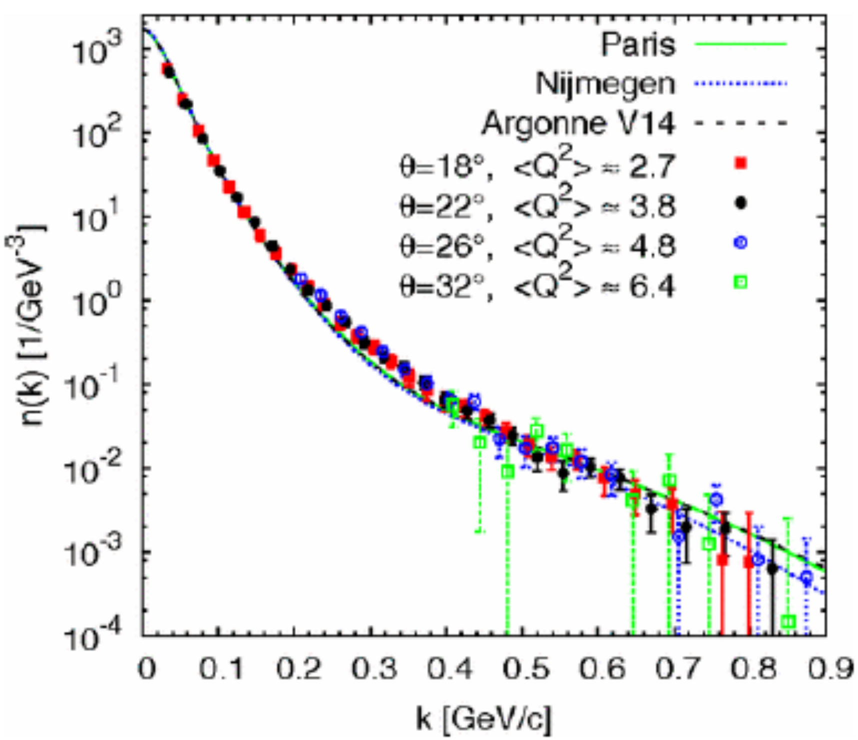
$$a(\approx 5.4\, fm) > d(1.8\, fm) > r_{eff}(0.7\, fm)$$

# The high-momentum tail in deuteron scales as $1/K^4$

O. Hen, L. B. Weinstein, E. Piasetzky, G. A. Miller, M. M. Sargsian, **arXiv:1407.8175**




$R_d$=0.64±0.10



# Kinetic symmetry energy of correlated fermions

$$n_{SNM}^{SRC}(k) = \begin{cases} A_0 & k < k_F \\ C_\infty / k^4 & k_F < k < \lambda k_F^0 \\ 0 & k > \lambda k_F^0 \end{cases}$$

$$R_d = (k/k_F)^4 \cdot n_d(k/k_F) \qquad 1.3 \leq k/k_F \leq 2.5$$

$$E_{\rm sym}^{kin}(\rho) = E_{sym}^{kin}(\rho)|_{\rm FG} - \Delta E_{sym}^{kin}(\rho) \qquad (7)$$

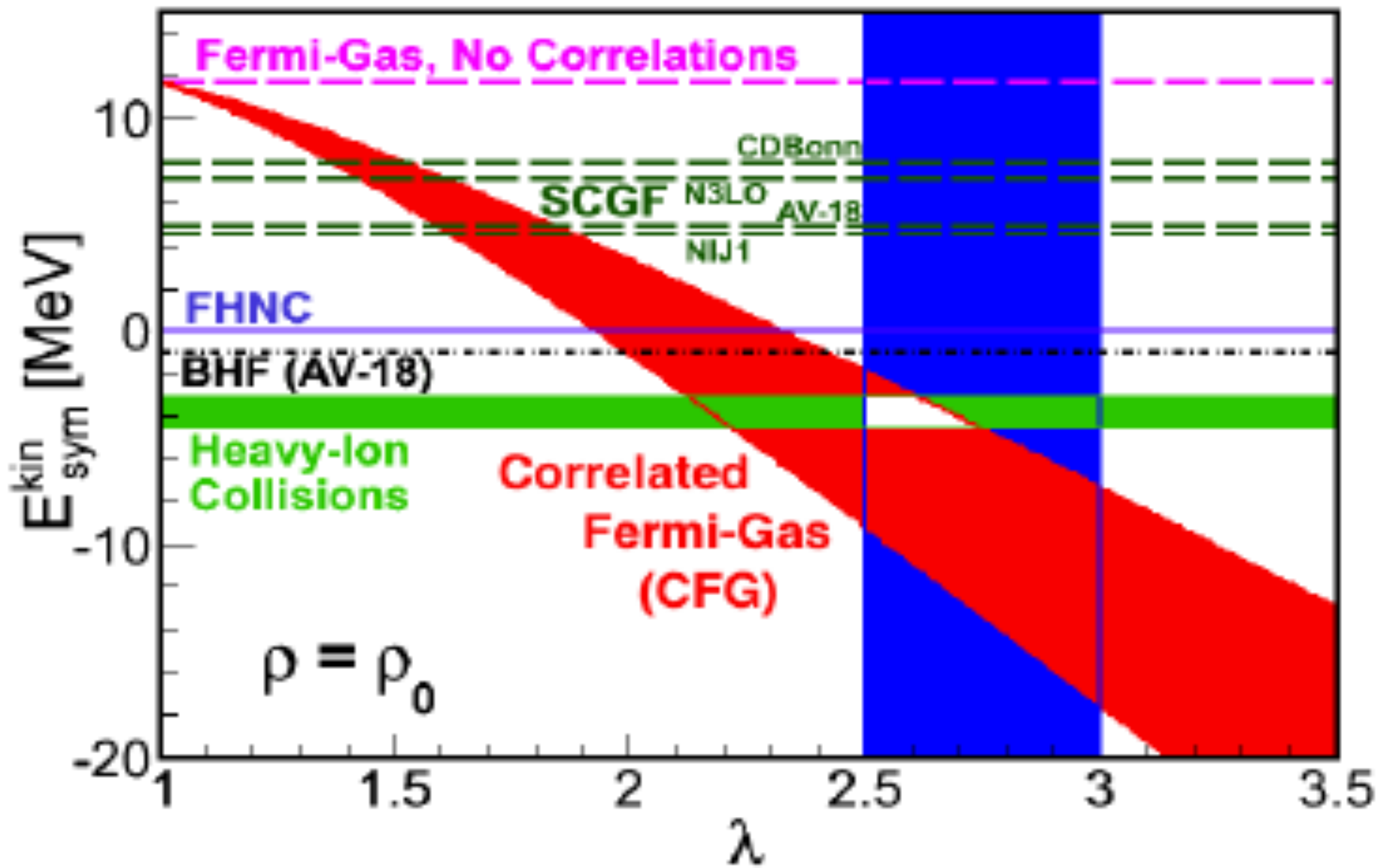
where the SRC correction term is:

$$\Delta E_{sym}^{kin} \equiv \frac{E_F^0}{\pi^2} c_0 \left[ \lambda (\frac{\rho}{\rho_0})^{1/3} - \frac{8}{5} (\frac{\rho}{\rho_0})^{2/3} + \frac{3}{5} \frac{1}{\lambda} (\frac{\rho}{\rho_0}) \right]. \qquad (8)$$

$C_0 = R_d * a_2(\infty)$

# Kinetic symmetry energy of correlated fermions

Or Hen, Bao-An Li, Wen-Jun Guo, L.B. Weinstein, Eli Piasetzky, **arXiv:1408.0772**

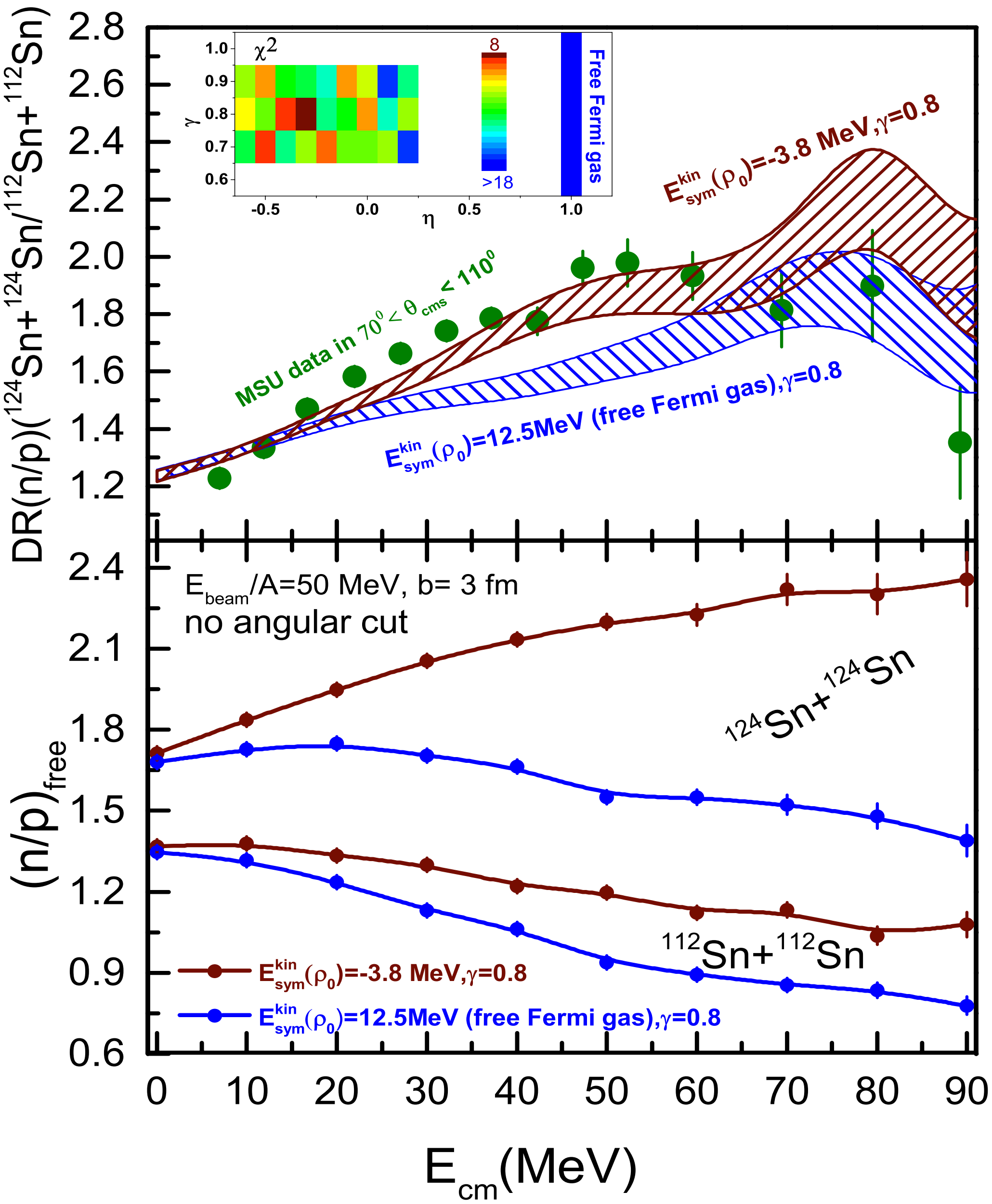



Width of the high momentum tail above the Fermi momentum

# Effects of reduced kinetic symmetry energy on heavy-ion collisions

$$E^{pot}_{sym}(\rho) = [E_{sym}(\rho_0) - \eta \cdot E^{kin}_{sym}(\rho_0)|_{\rm FG}] \cdot (\rho/\rho_0)^{\gamma}.$$

$$V^{n/p}_{\rm sym}(\rho,\delta) = [E_{sym}(\rho_0) - \eta \cdot E^{kin}_{sym}(\rho_0)|_{\rm FG}](\rho/\rho_0)^{\gamma} \times [\pm 2\delta + (\gamma-1)\delta^2]. \quad (10)$$



# Summary

## Where does the $S_0 = E_{sym}(\rho_0) \approx 31$ MeV come from?

**It is probably all coming from the potential contribution due to the NN SRC-induced reduction of the kinetic symmetry energy**

$$E_{sym}^{kin}(\rho) = \frac{1}{3} E_F(\rho_0)(\rho/\rho_0)^{2/3} \approx 12.5 \text{MeV at } \rho_0$$

Kinetic     Potential

$$S(\rho) = \frac{C_{s,k}}{2}\left(\frac{\rho}{\rho_0}\right)^{2/3} + \frac{C_{s,p}}{2}\left(\frac{\rho}{\rho_0}\right)^{\gamma_i}$$

$C_{s,k} = 25$ MeV

$$C_{s,p} = 2S_0 - C_{s,k}$$

**The MSU double n/p ratio data strongly indicate the need of a SRC-reduced kinetic symmetry energy**