Workshop on Challenges to Transport Theory for Heavy-Ion Collisions, ECT*, May 20-24, 2019

Medium Energy Heavy-Ion Collisions Encounter Short-Range Correlations

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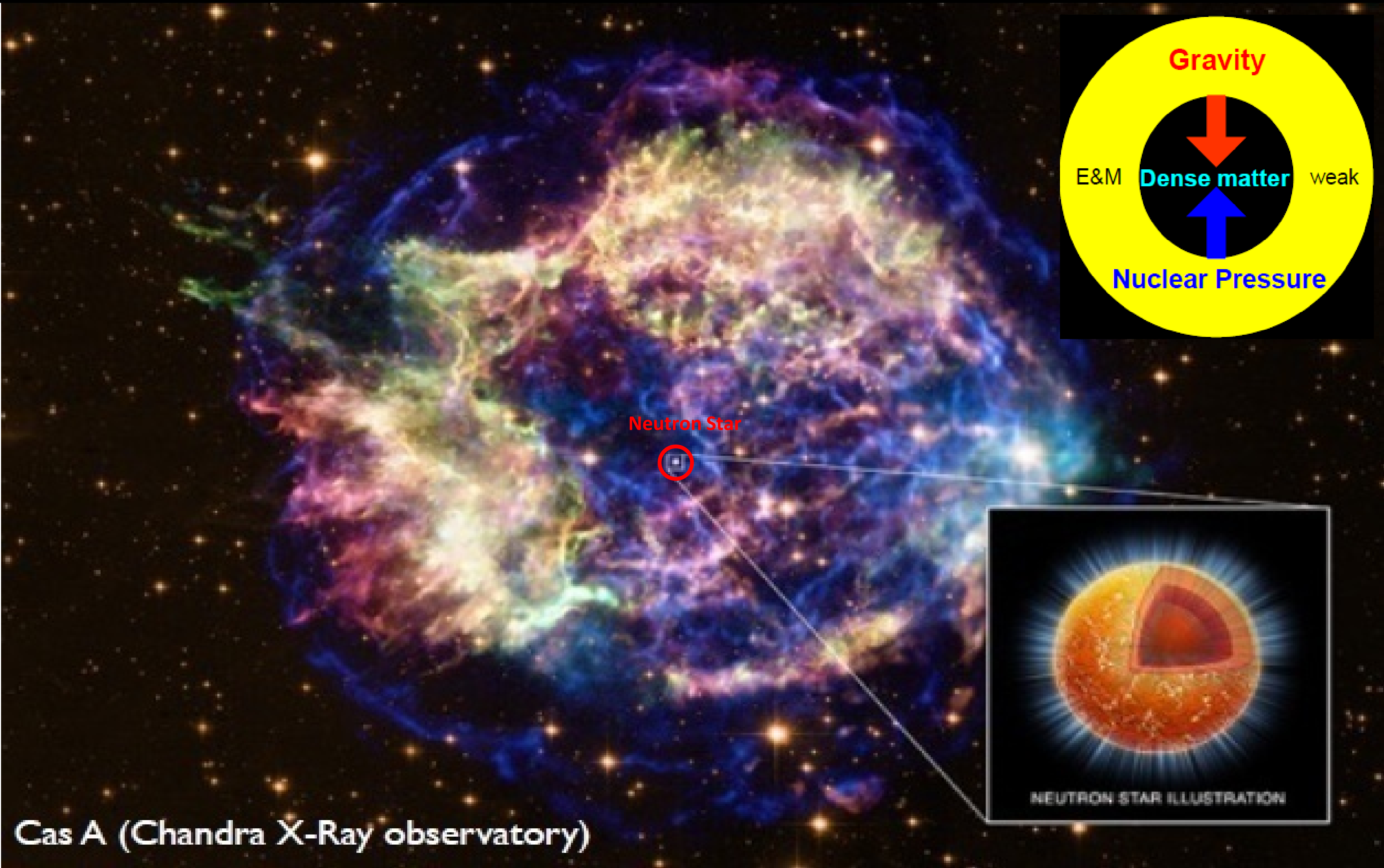
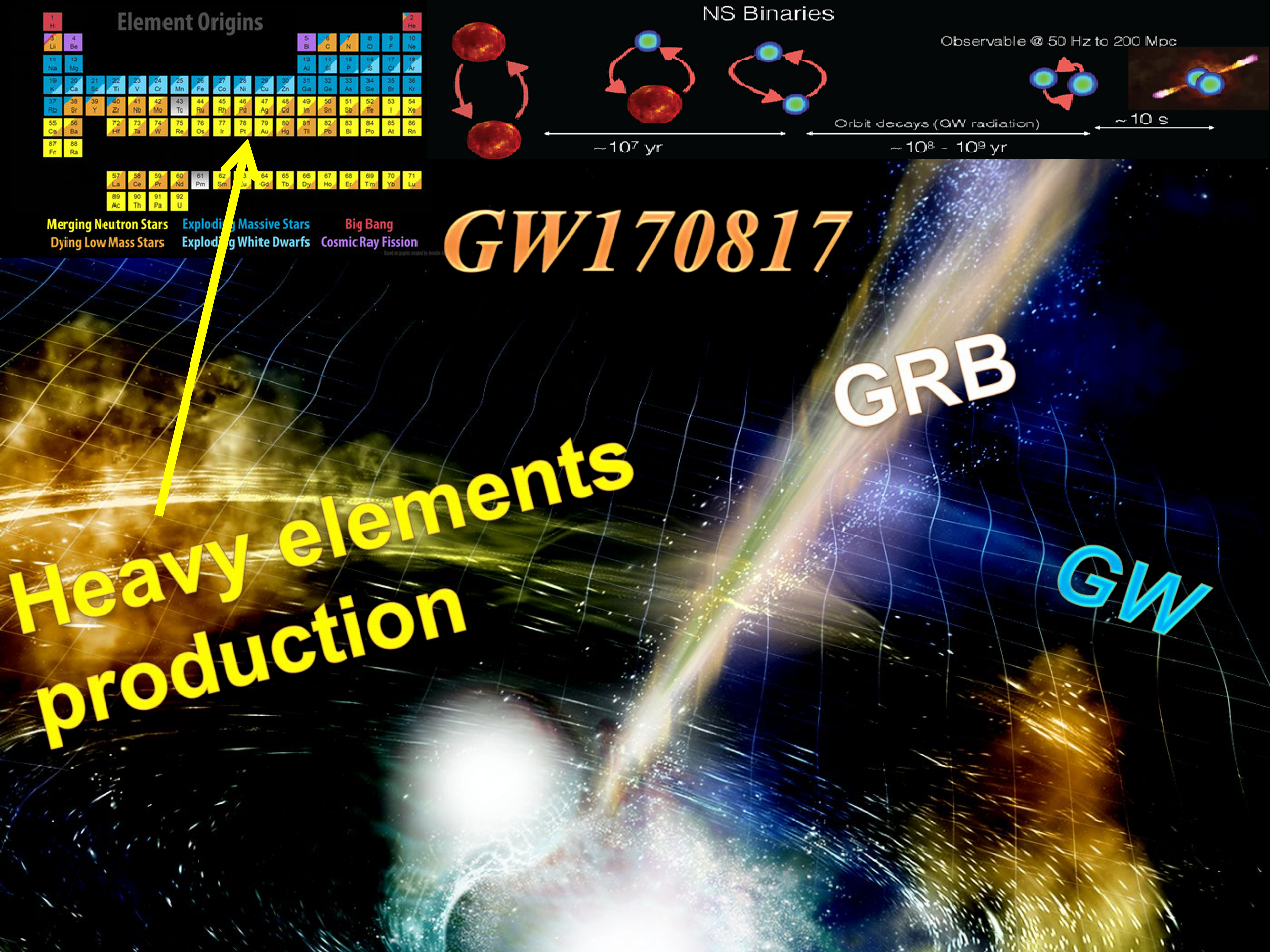
2019/5/21/15:00

Supernova explosion

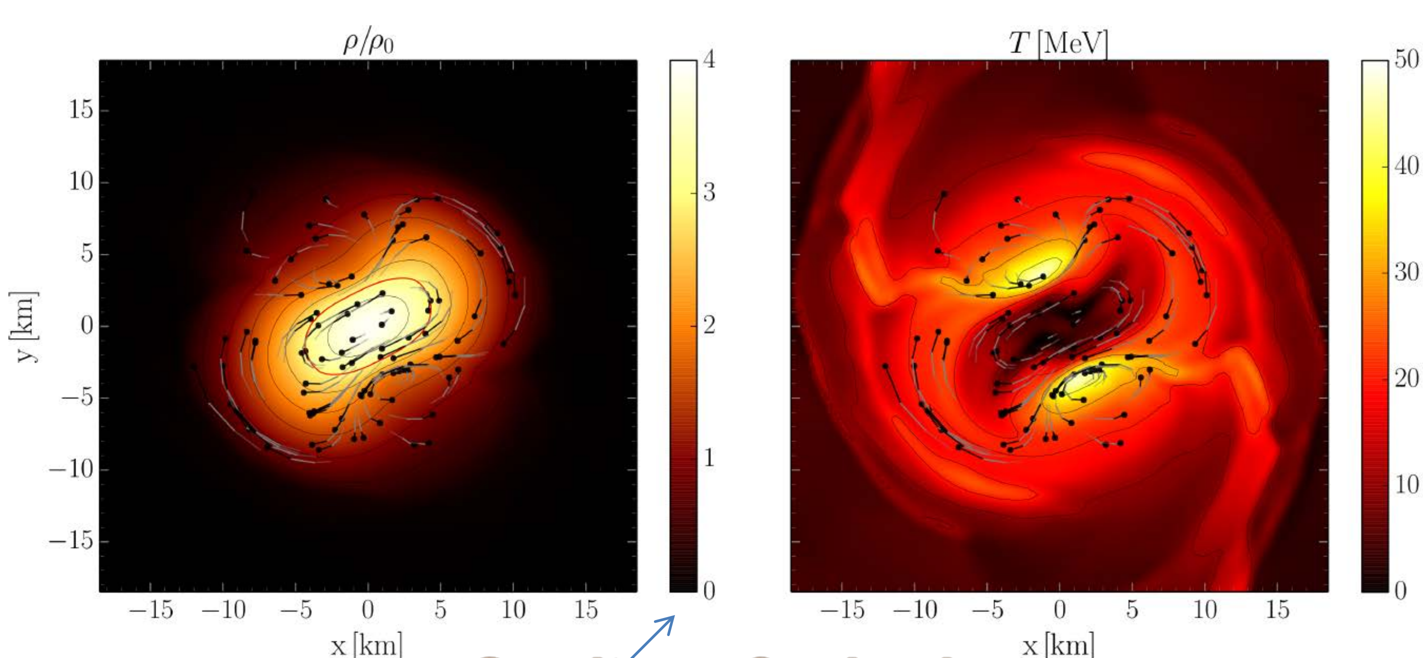




Element Origins
Merging Neutron Stars
Exploding Massive Stars
Big Bang
Dying Low Mass Stars
Exploding White Dwarfs
Cosmic Ray Fission
NS Binaries
Observable @ 50 Hz to 200 Mpc
~10⁷ yr
Orbit decays (GW radiation)
~10⁸ - 10⁹ yr
~10 s
GW170817
GRB
GW
Heavy elements production

Neutron star mergers and heavy-ion collisions

density temperature

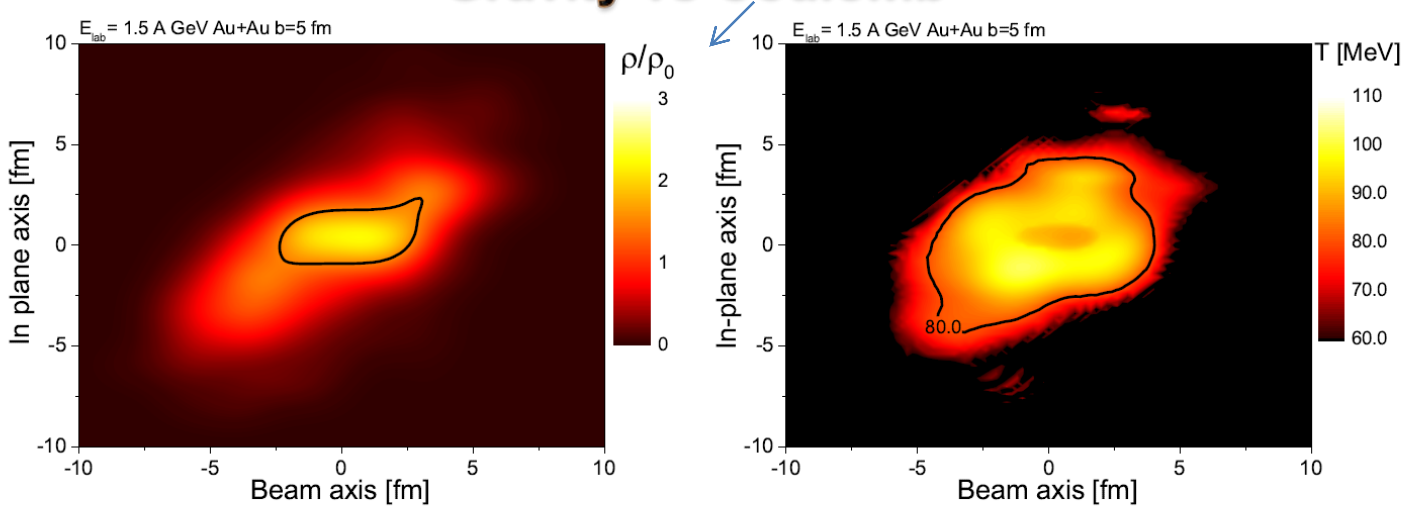


M. Hanauske et al., J. Phys.: Conf. Ser. 878 012031

n-star merger

EOS

Gravity vs Coulomb



Au +Au

1.5A GeV

Equation of Sate of nuclear matter

N=Z

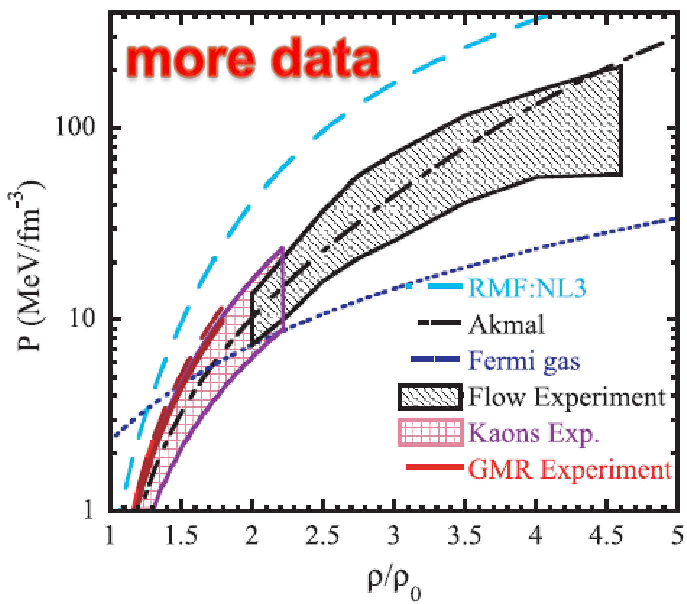
N-rich

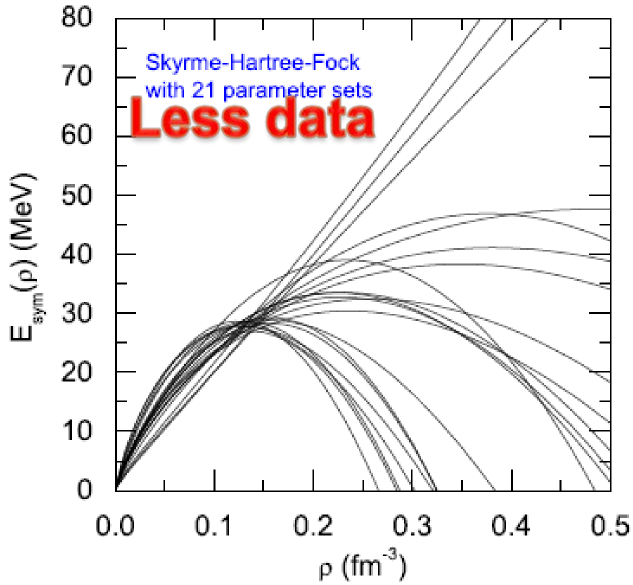
$$E(\rho,\delta) \approx E(\rho,\delta=0) + E_{sym}(\rho)\delta^2, \quad \delta = \frac{\rho_n - \rho_p}{\rho_n + \rho_p}$$

Symmetry energy

Constraints at high densities have been extracted

poorly known especially at high densities



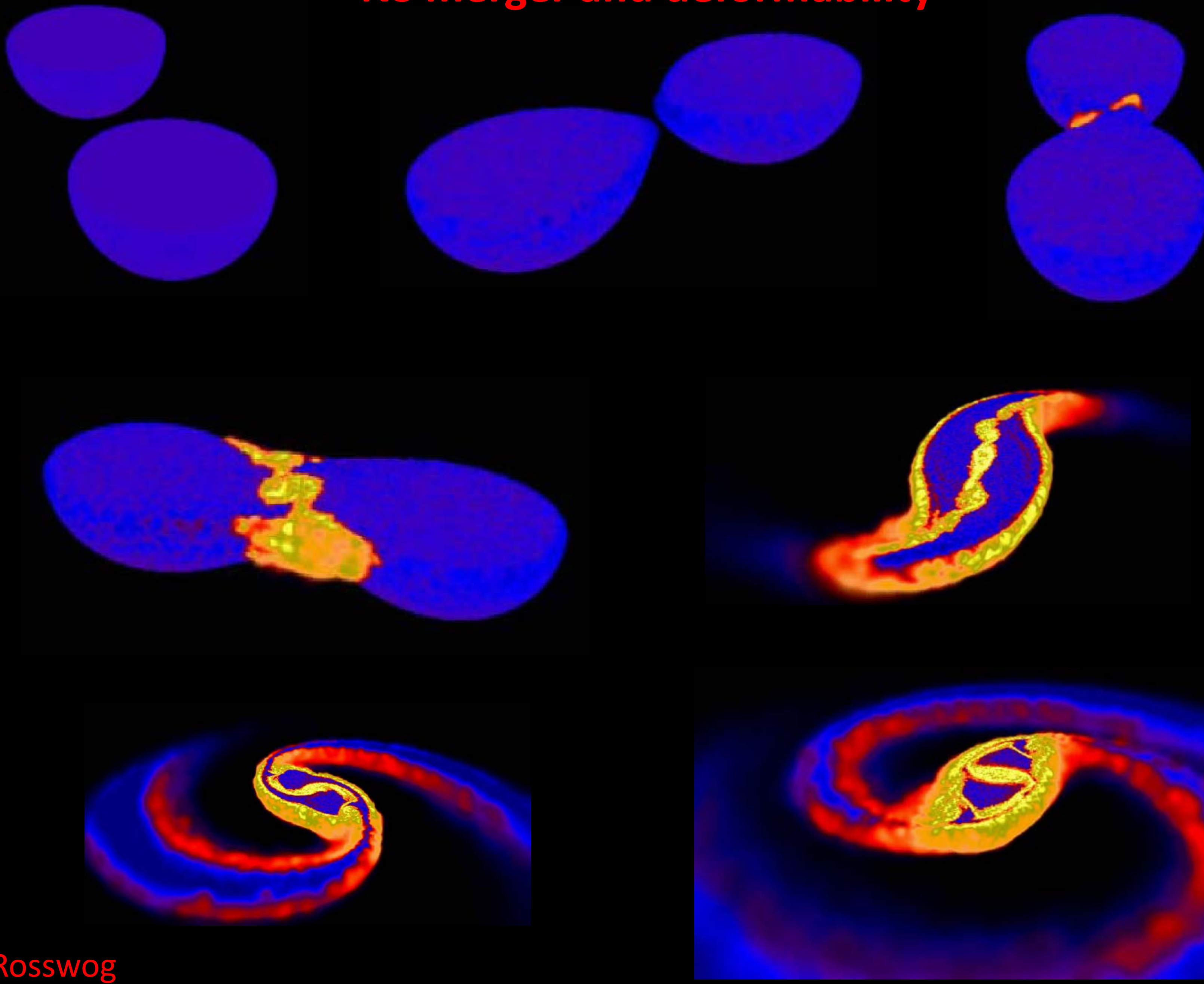


W.G. Lynch, et al., arXiv: 090.0412, [nucl-ex]

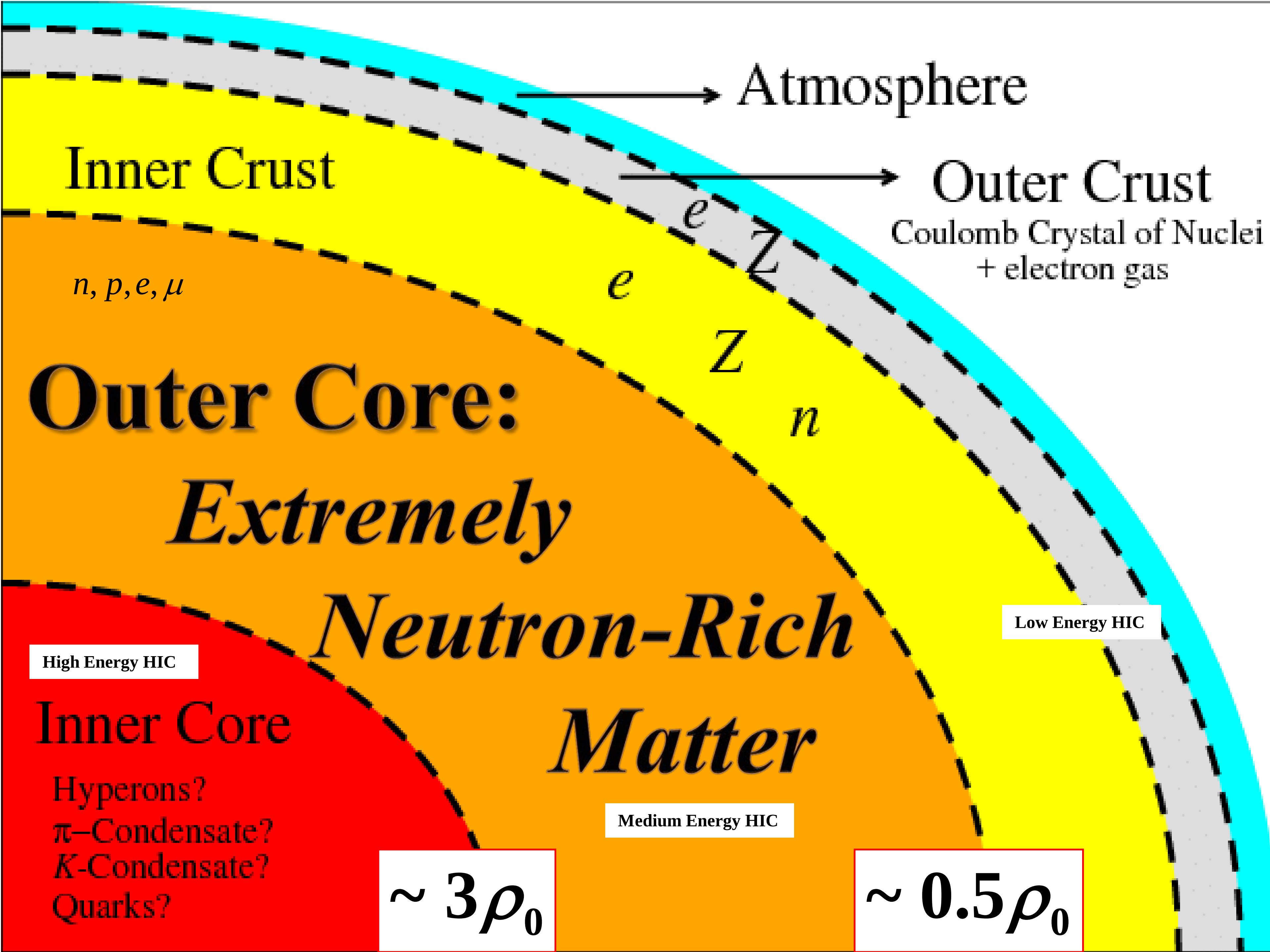
B.A. Li , L.W. Chen, Che Ming Ko, Phys. Rep. 464, 113 (2008).

P. Danielewicz, R. Lacey, W.G. Lynch, Science 298 (2002) 1592

NS merger and deformability

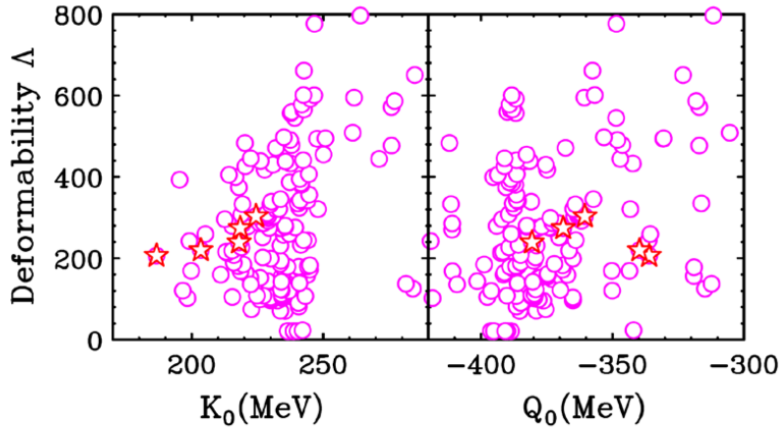


S. Rosswog
http://compact-merger.astro.su.se/index.html



Atmosphere
Inner Crust
Outer Crust
Coulomb Crystal of Nuclei
+ electron gas
e
Z
e
Z
n
n, p, e, μ
Outer Core:
Extremely
Neutron-Rich
Matter
Low Energy HIC
High Energy HIC
Inner Core
Hyperons?
π–Condensate?
K-Condensate?
Quarks?
Medium Energy HIC
~ 3ρ0
~ 0.5ρ0

Deformability and the symmetry energy



$$\varepsilon(\rho,\delta)=\varepsilon(\rho,\delta{=}0)+S(\rho)\delta^2+O(\delta^4)+\ldots$$

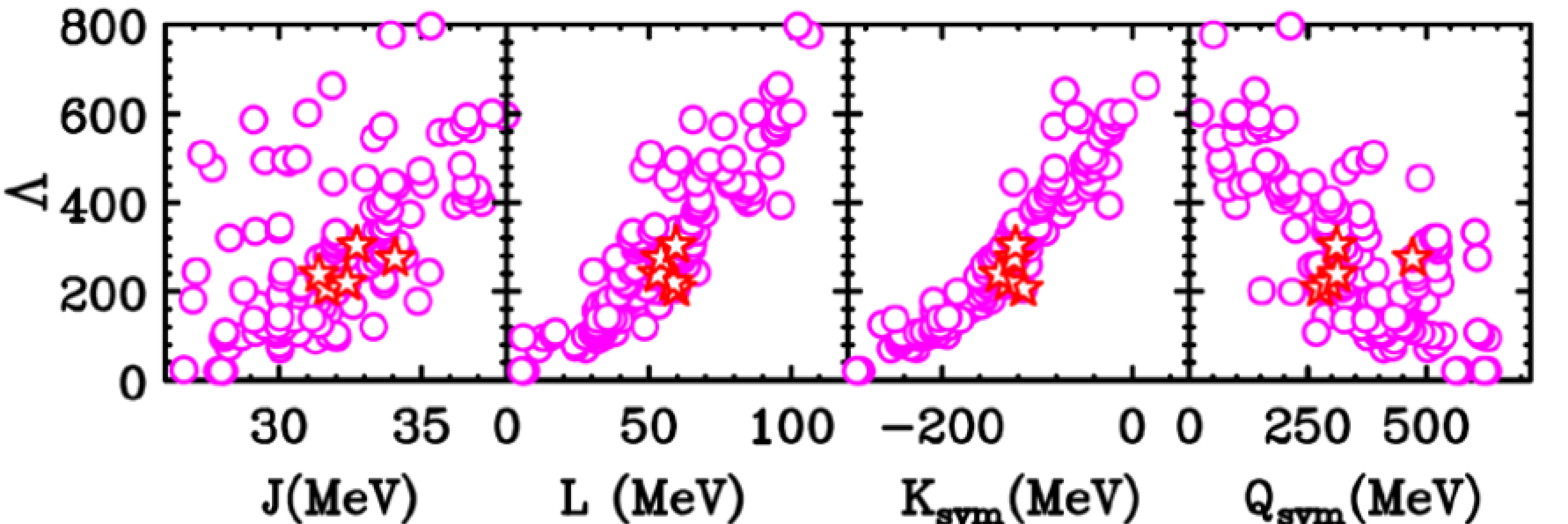
Symmetric EoS:

$$\varepsilon_{SNM}(\rho)=E_0+\frac{1}{2}K_0x^2+\frac{1}{6}Q_0x^3+O(x^4)$$

Symmetry energy:

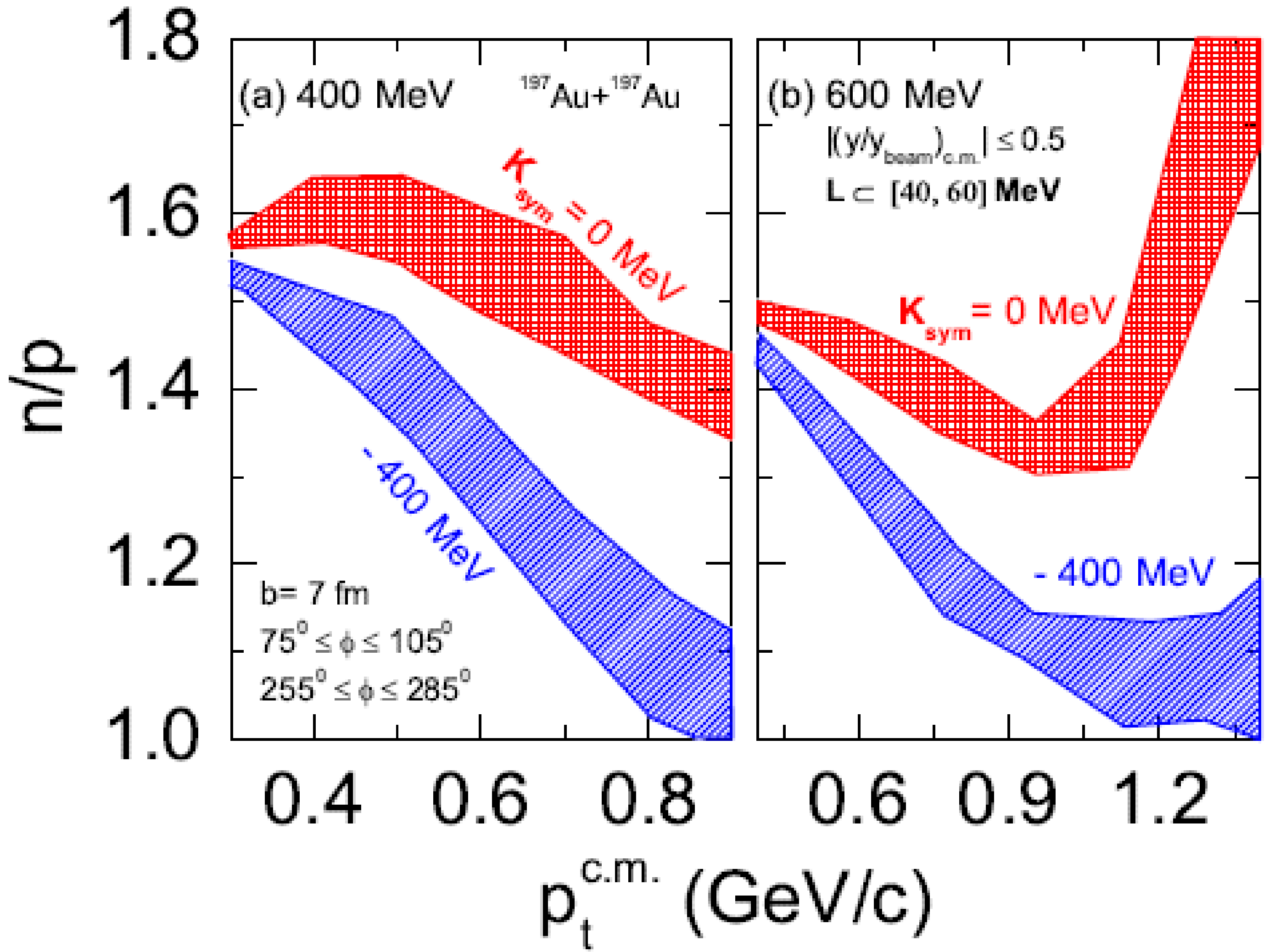
$$S(\rho)=J+Lx+\frac{1}{2}K_{sym}x^2+\frac{1}{6}Q_{sym}x^3+O(x^4)$$

$$\Lambda=(2/3)k_2[(c^2/G)(R/m)]^5$$



C. Y. Tsang, M. B. Tsang, Pawel Danielewicz, W. G. Lynch, F. J. Fattoyev, arXiv:1905.02601

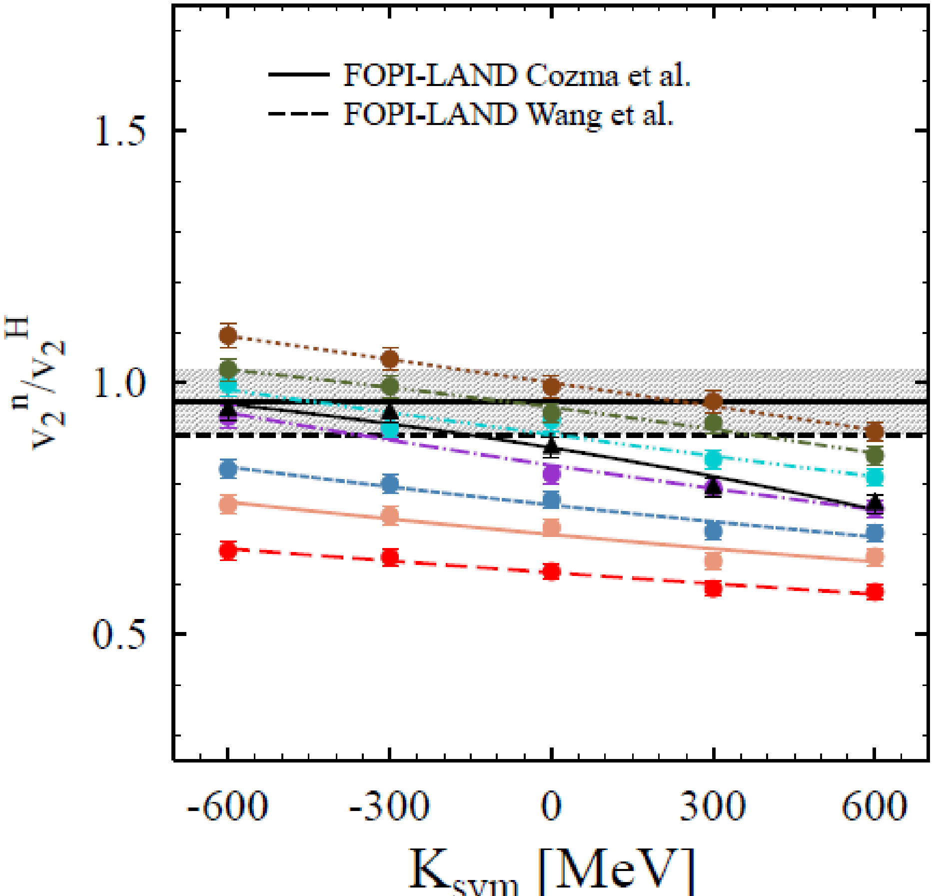
Probing Ksym by HIC

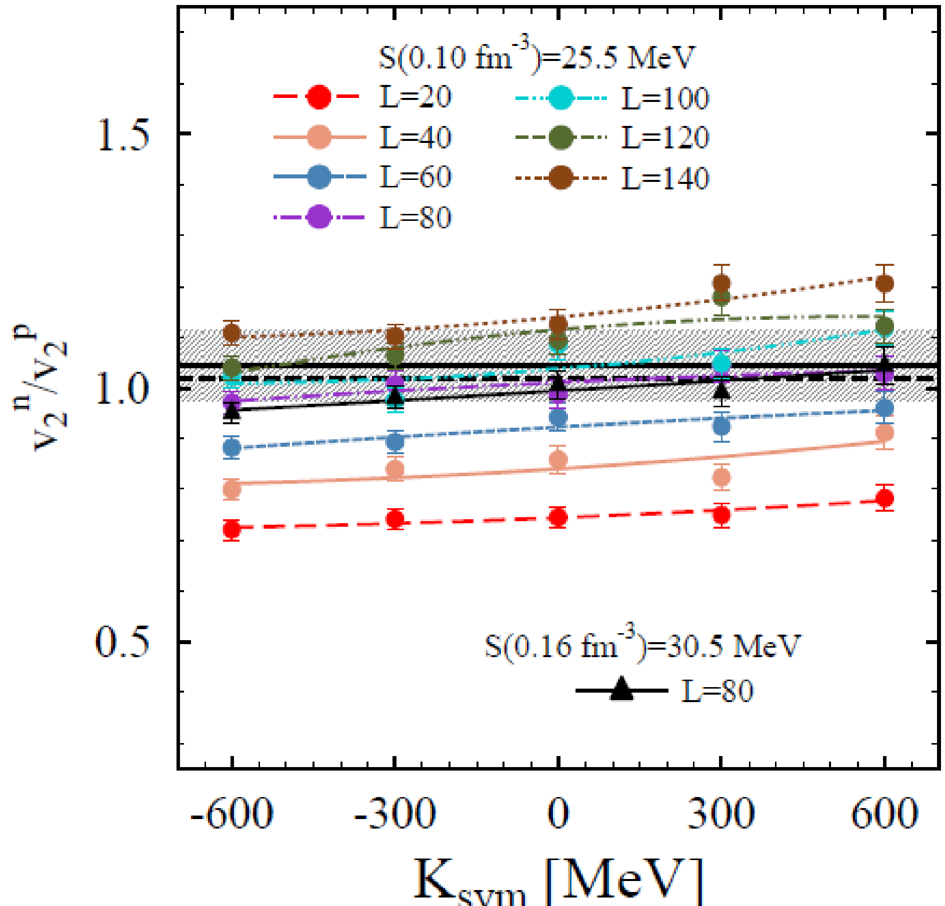


Y. Guo, G. C. Yong, submitted

Probing Ksym by HIC

Cozma, M.D. Eur. Phys. J. A (2018) 54: 40





More detailed data are needed.

Challenges of transport model

old days:

- In-medium effects of transport cannot be experimentally well determined
- Non-equilibrium quantum many-body system in finite volume is troublesome

nowadays:

- Pursuing more details/tiny effects
- Nucleon-nucleon Short-range interactions is not well understood

Short-Range-Correlation by Jlab

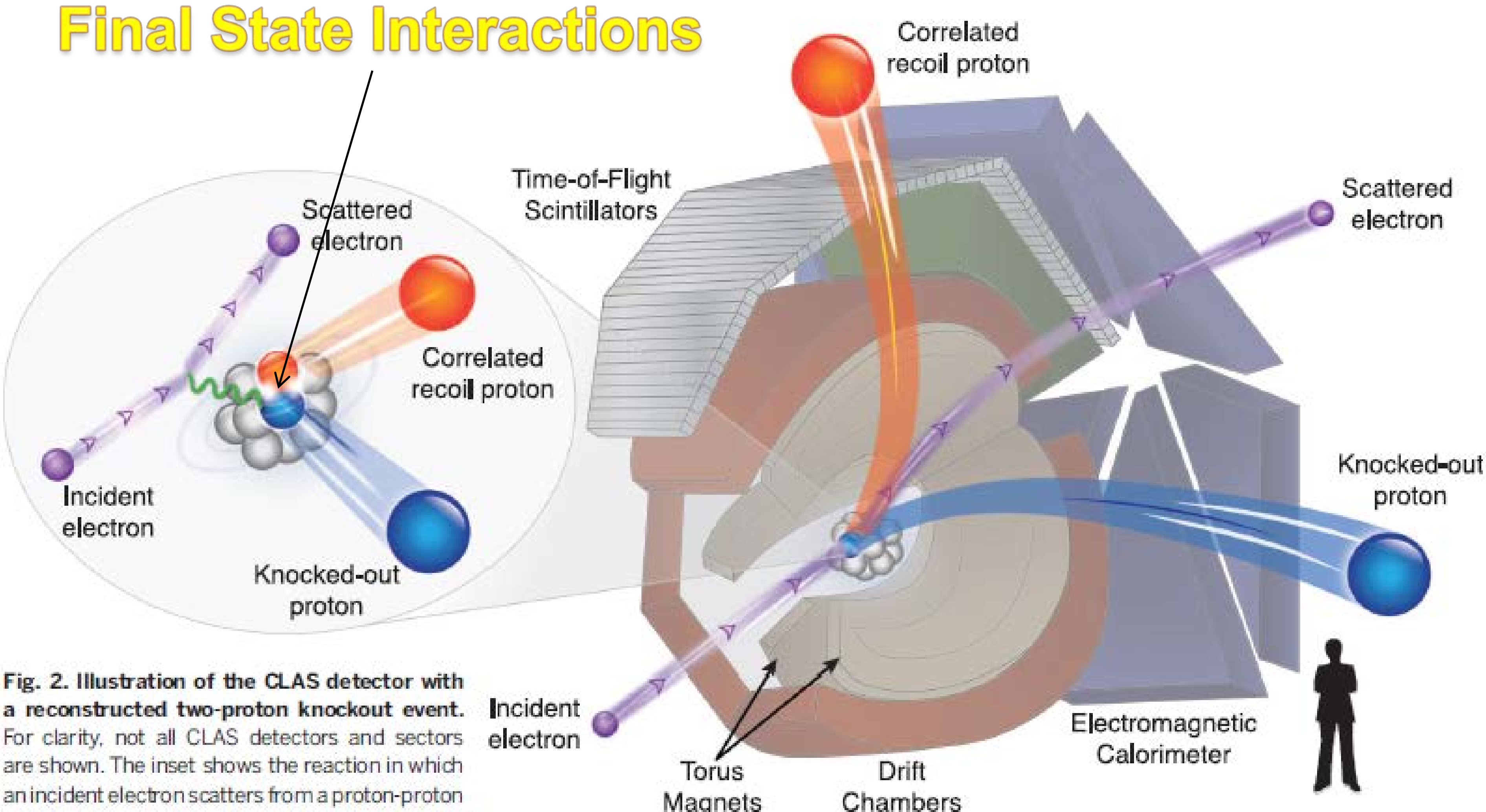


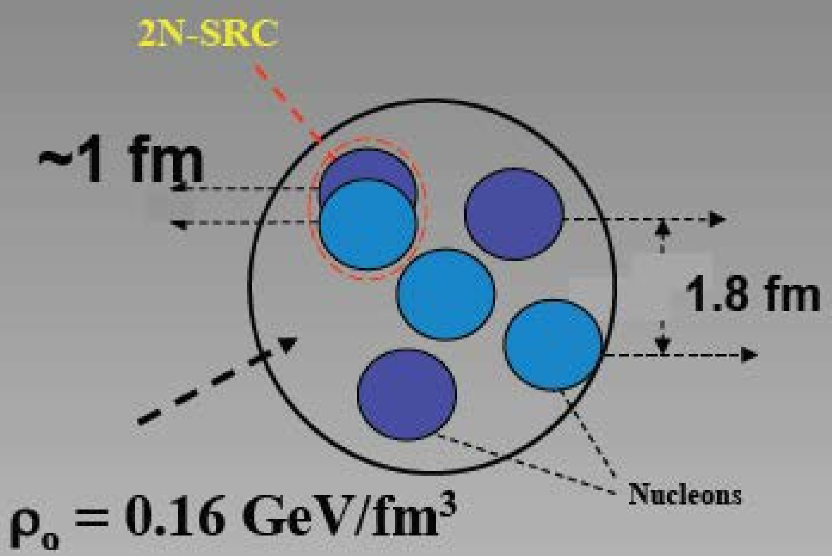
Fig. 2. Illustration of the CLAS detector with a reconstructed two-proton knockout event. For clarity, not all CLAS detectors and sectors are shown. The inset shows the reaction in which an incident electron scatters from a proton-proton pair via the exchange of a virtual photon. The human figure is shown for scale.

O. Hen et al., Science 346, 614 (2014).

What are Short Range Correlations (SRC) in nuclei ?

(Eli Piasetzky)

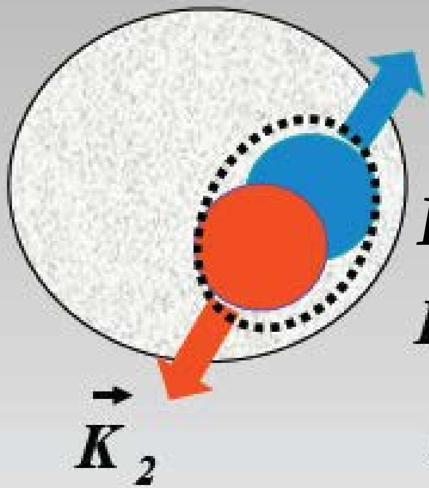
SRC ~R_N LRC ~R_A



k_F ~ 250 MeV/c

High momentum tail:
300-600 MeV/c
1.5 K_F - 3 K_F

In momentum space:



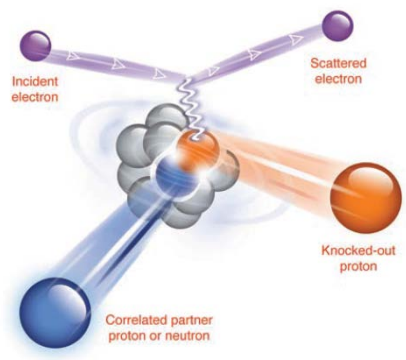
$K_{CM} < K_F$

$K_1 > K_F$,

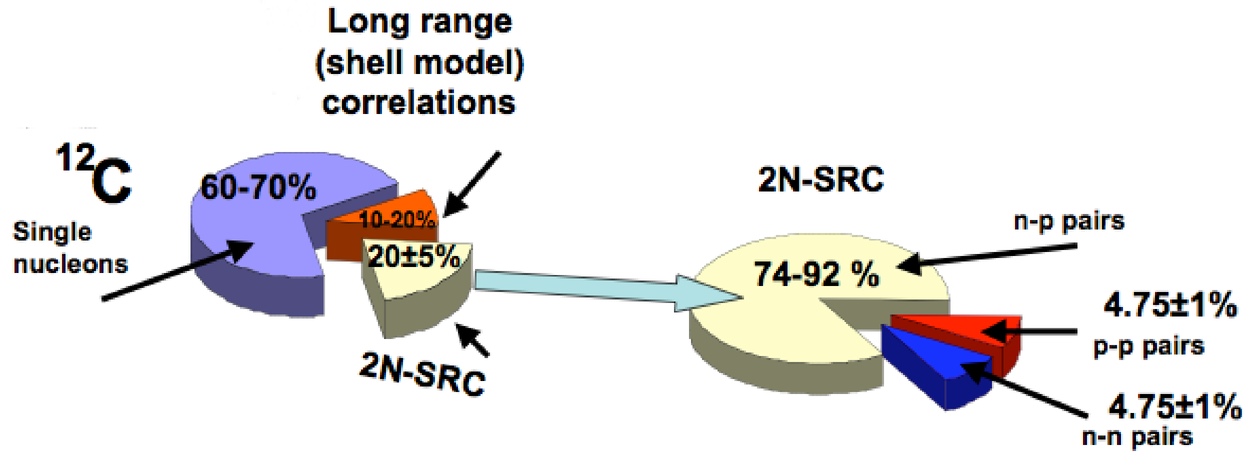
$K_2 > K_F$

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

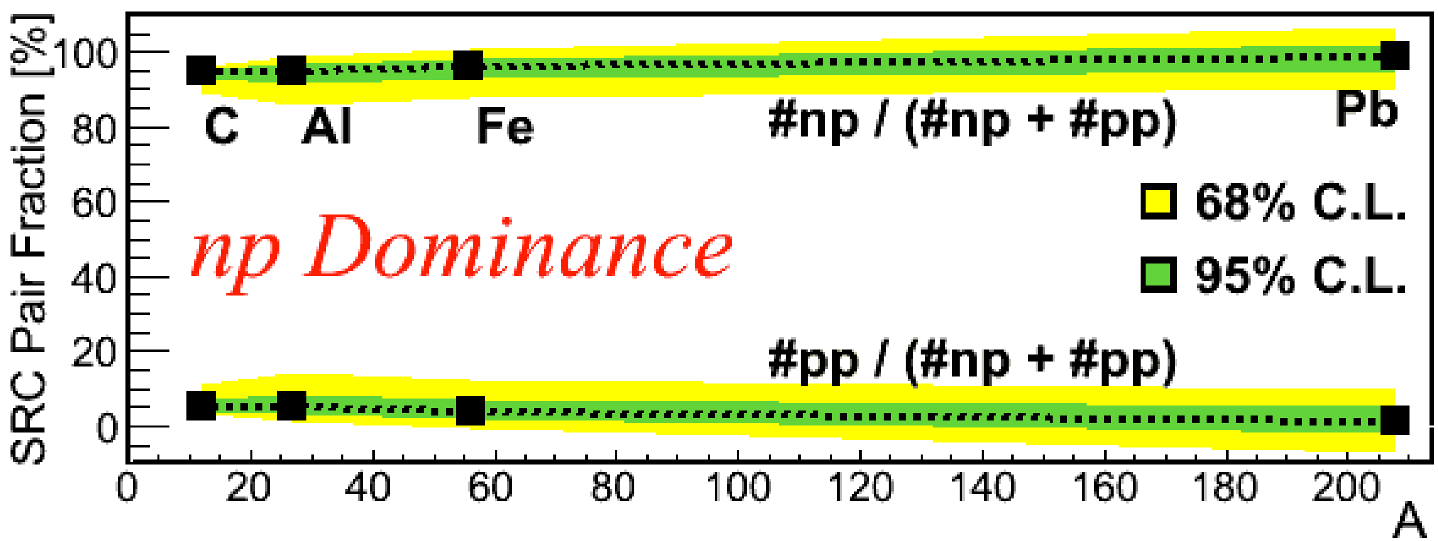
Nucleon-nucleon Short-range-Correlations



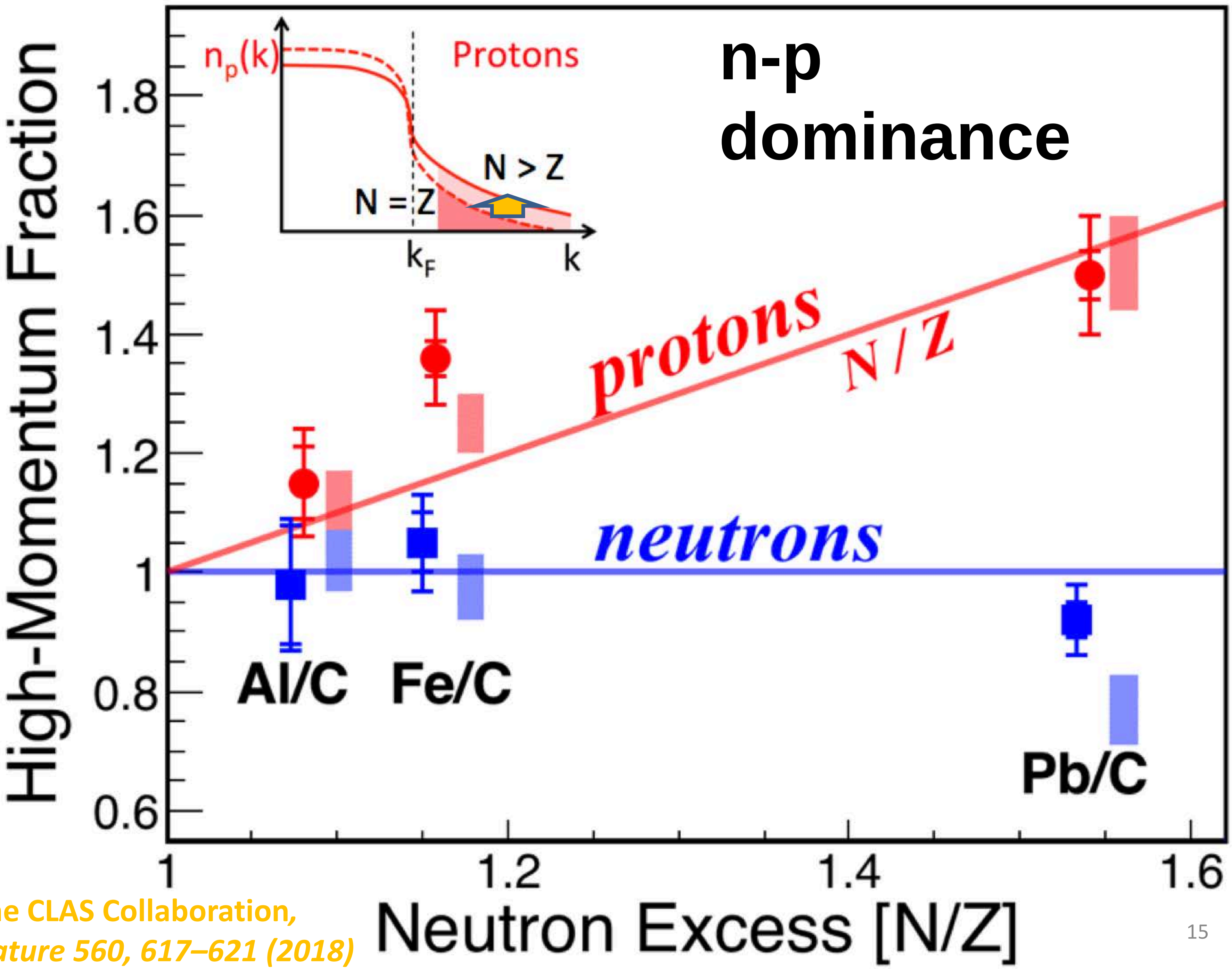
Jlab



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

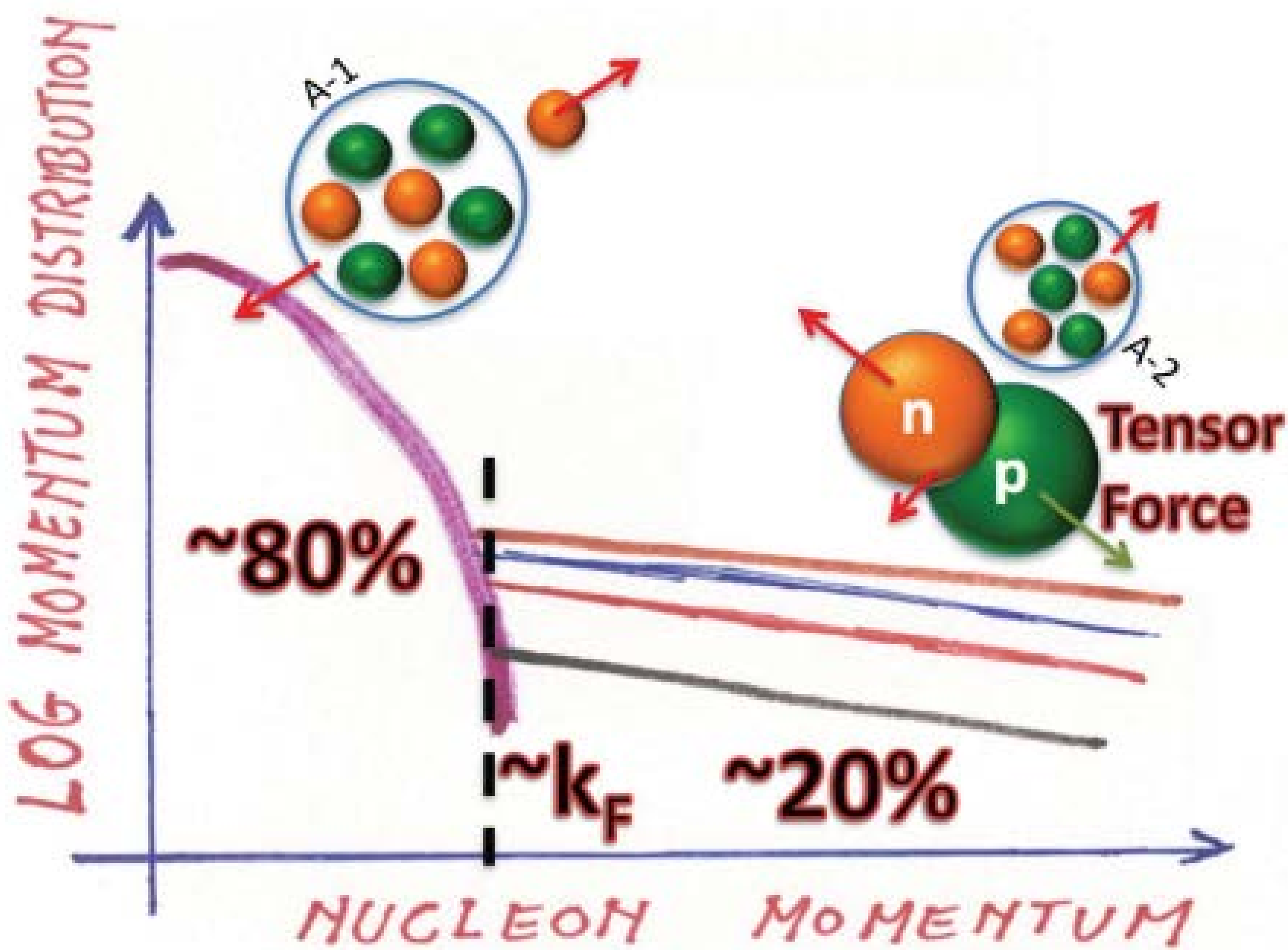


O. Hen et al., Science 346, 614 (2014).



The CLAS Collaboration, Nature 560, 617–621 (2018)

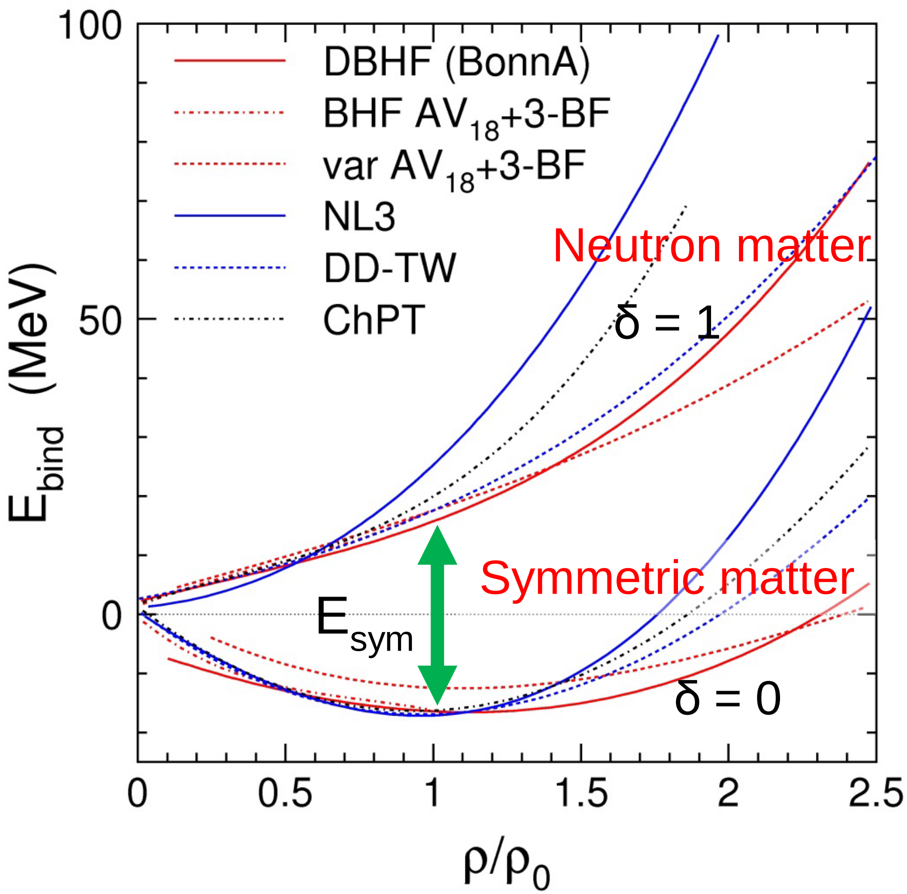
Dominant features of nucleon mom. Dis.



Or Hen et al., Rev. Mod. Phys. 89, 045002 (2017)

How SRC affect symmetry energy

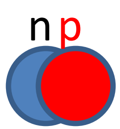
Fuchs and Wolter, EPJA 30 (2006)



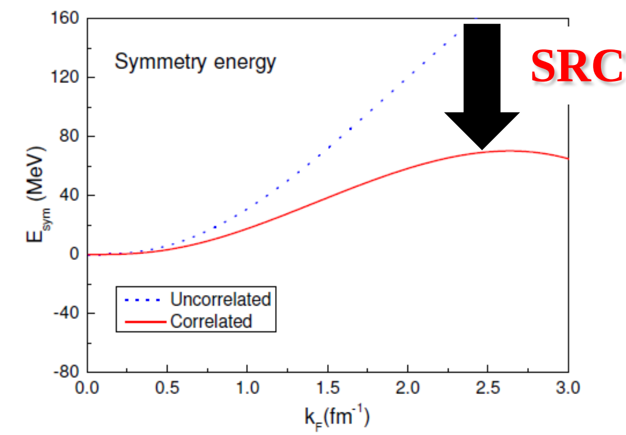
$$E(\rho,\delta) \approx E(\rho,\delta=0) + E_{sym}(\rho)\delta^2, \quad \delta = \frac{\rho_n - \rho_p}{\rho_n + \rho_p}$$

$$E_{sym} \propto E_{nentron} - E_{proton}$$

n-p SRC:



En-Ep↓ Esym↓

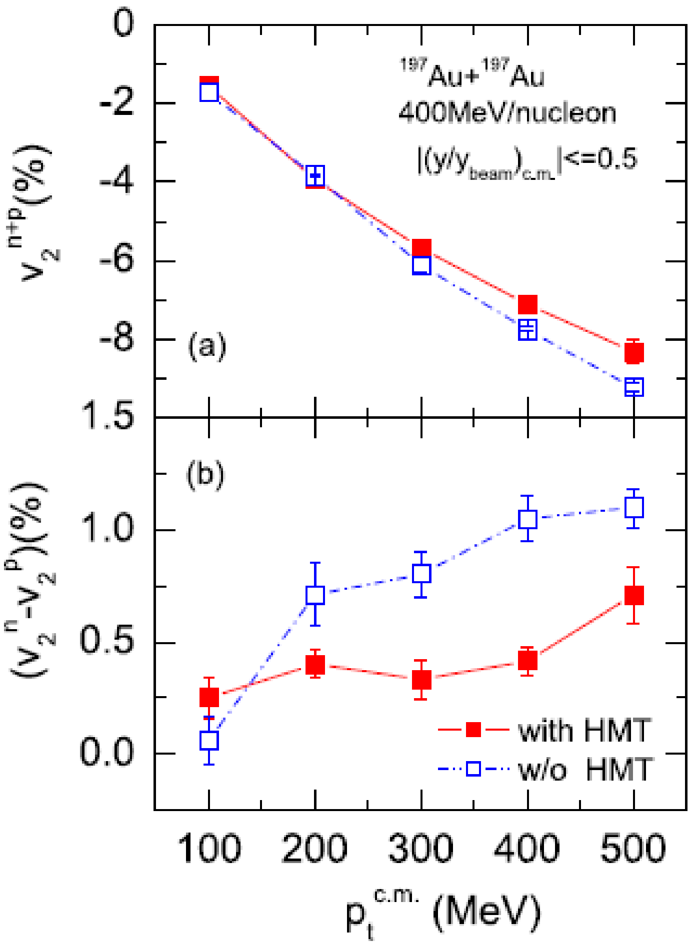


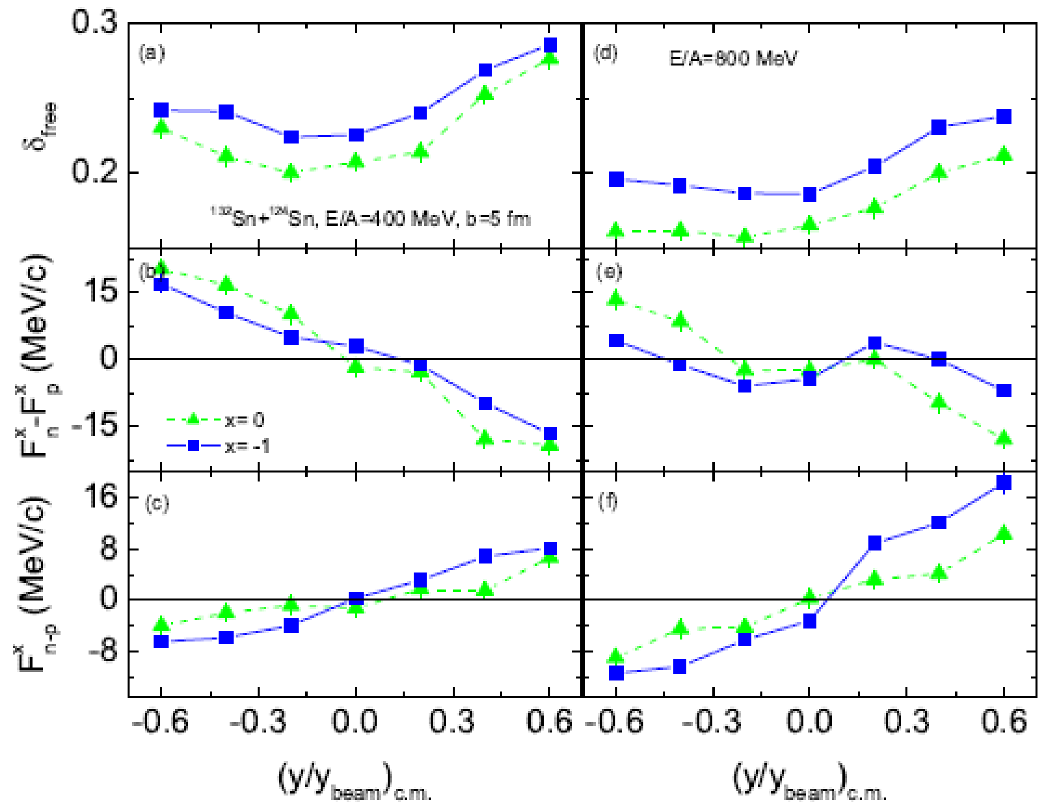
Xu and Li, arXiv:1104.2075

The Esym is decided by the difference of En and Ep

On HIC-hadron probe

SRC ← Both effects are at the same level → Esym



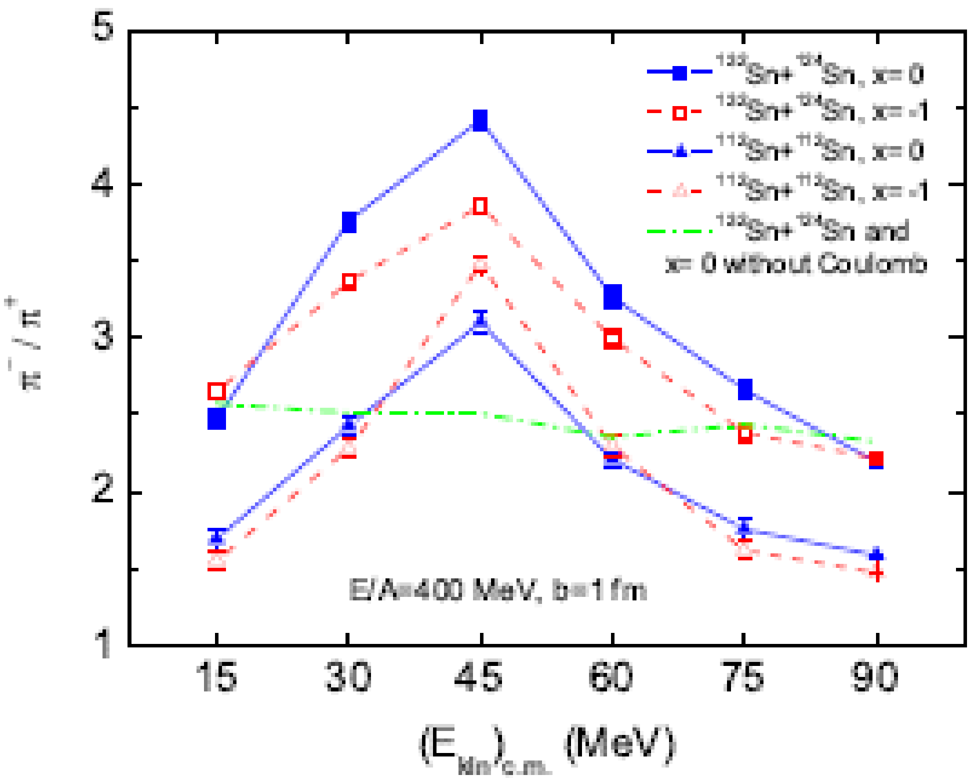


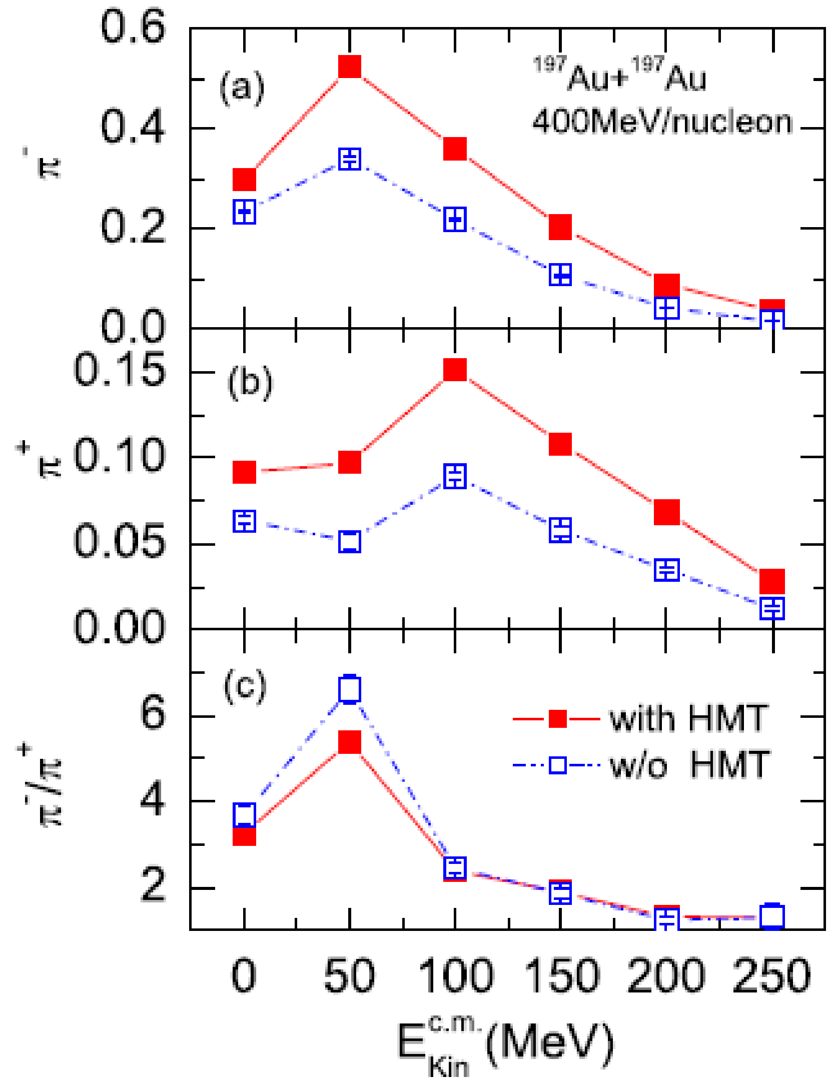
F. Zhang and G.C. Yong, Eur. Phys. J. A (2016) 52

G.C. Yong, B.A. Li, L.W. Chen, Phys.Rev.C74 (2006) 064617

On HIC-hadron probe

Esym ← Both effects are at the same level → SRC





F. Zhang and G.C. Yong, Eur. Phys. J. A (2016) 52

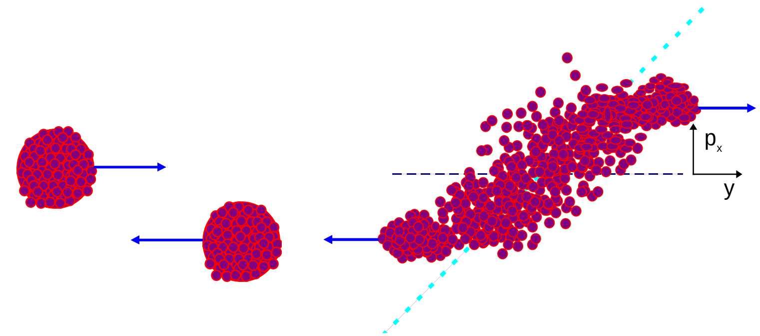
G.C. Yong, B.A. Li, L.W. Chen, W. Zuo, Phys.Rev.C73 (2006) 034603

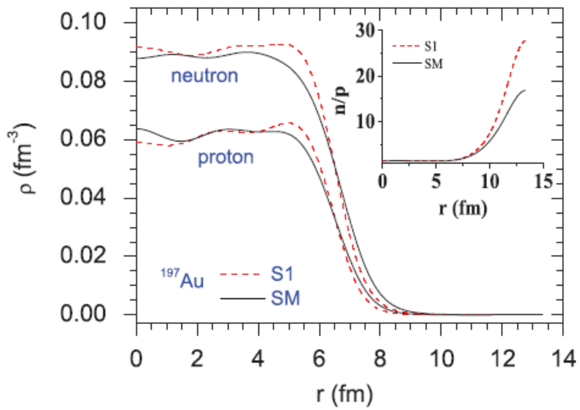
(1) Initialization:

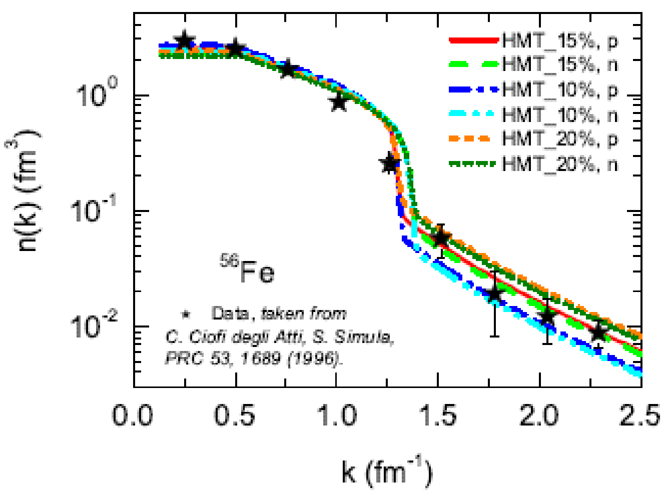
(1) Nucleons in coordinates, RMF, SHF

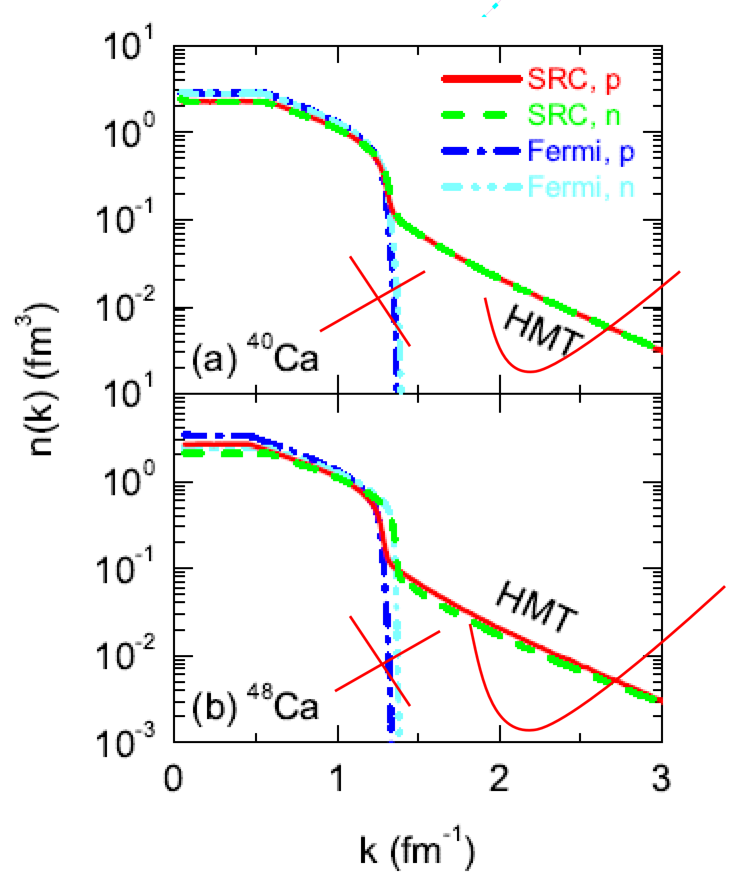
(2) Momentum-space: localThomas-Fermi

Reproduce HMT with equal Numbers of n and p







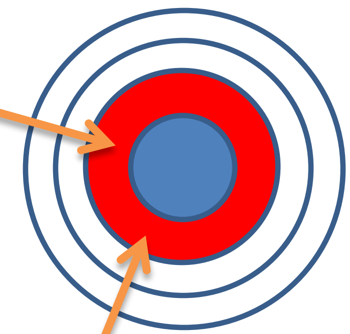


Yong and Li, PRC96, 064614(2017).

Formula used to reproduce SRC/HMT

$$n(k) = \begin{cases} C_1, k \le k_F \\ C_2 / k^4, k_F < k \le \lambda k_F \end{cases}$$

Nucleus = many Spherical shells



$$K_{F_{n,p}}(r) = [3\pi^2 \rho(r)_{n,p}]^{1/3}$$

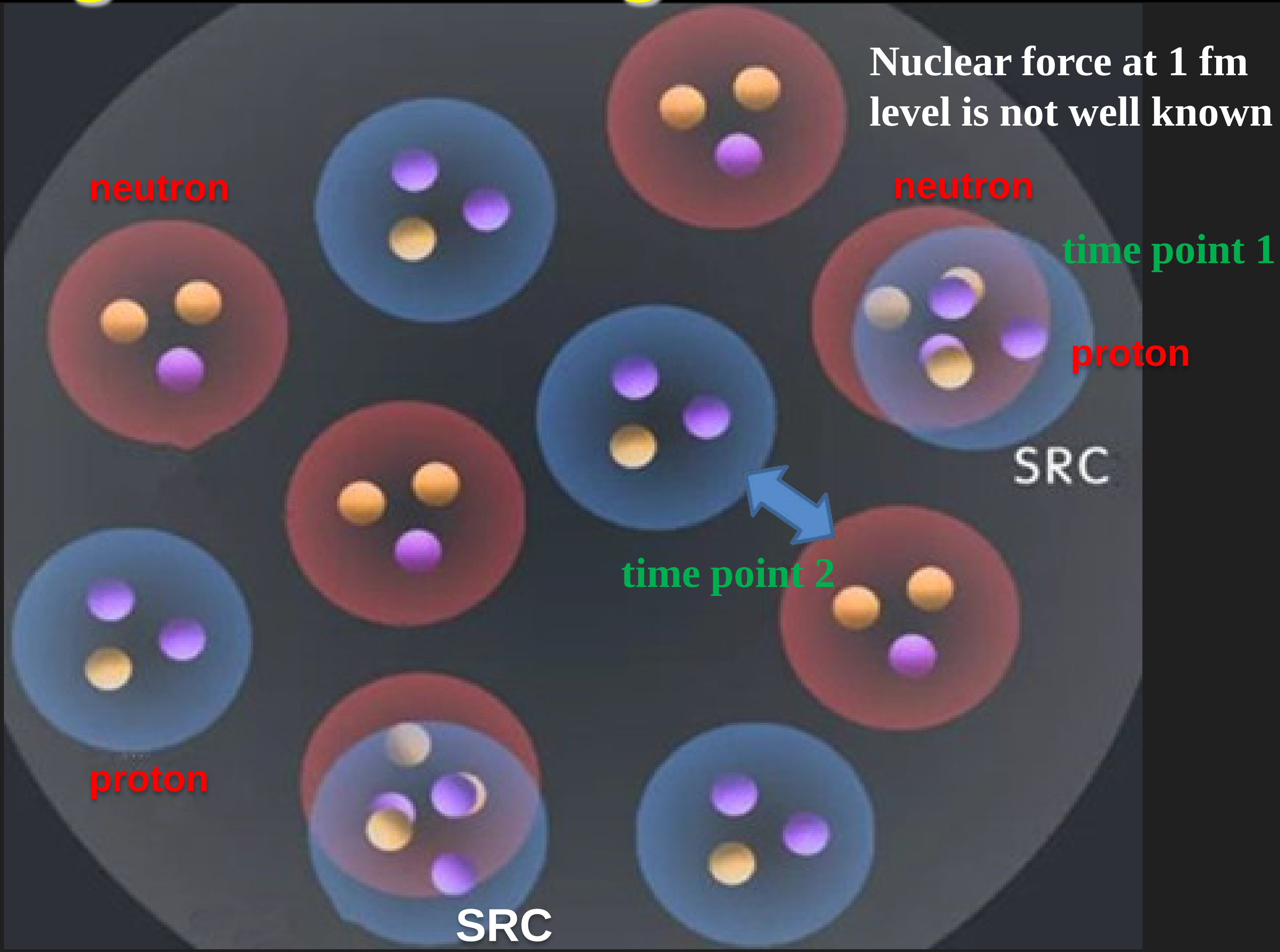
$$\int_0^{\lambda k_F} n(k) k^2 dk = 1$$

$$n(k) = \frac{1}{N, Z} \int_0^{r_{\max}} d^3 r \rho(r)_{n,p} n[k, K_{F_{n,p}}(r)]$$

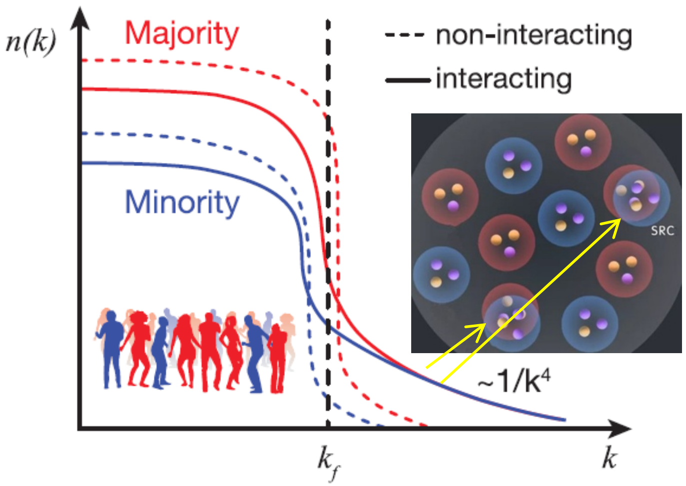
nucleus

Nuclear spherical shell

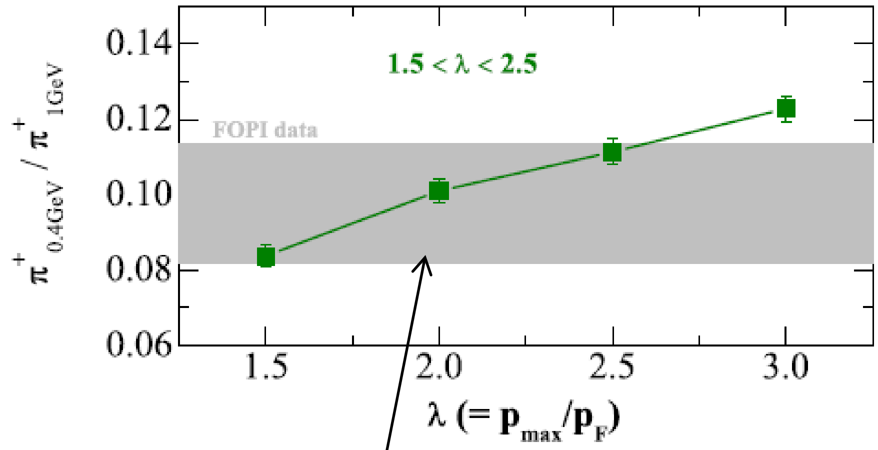
Imagined SRC-image of nucleus

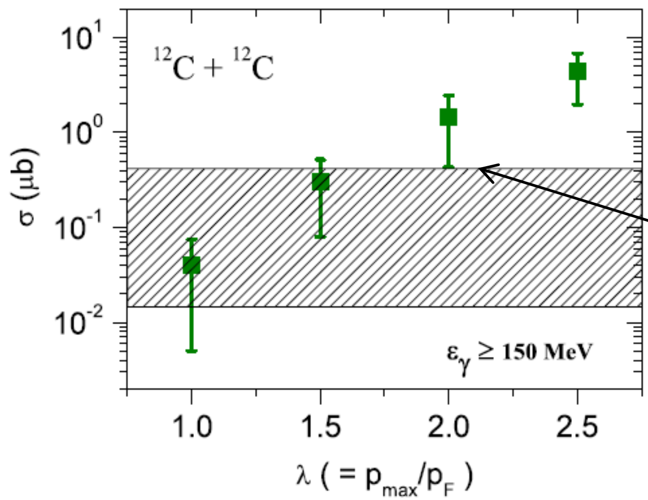


Constrain nucleon motion from HIC



O. Hen et al., Science 346, 614 (2014).





In nuclei:

There is a HMT cutoff

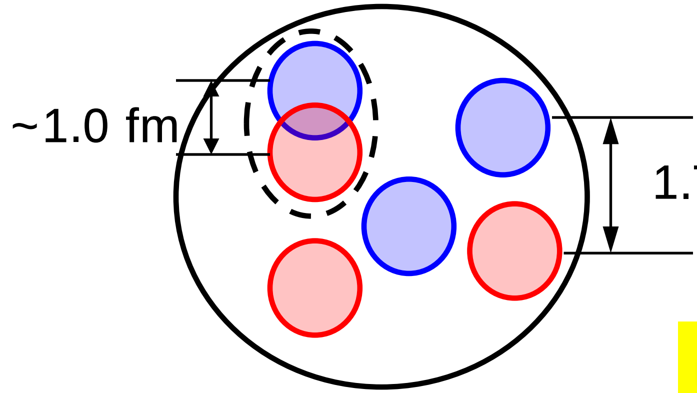
$$p_{\max} \leq 2 p_F$$

$$p_{\max} \leq 2.75 p_F \Leftarrow Exp. \leftarrow deutron$$

Yong, Physics Letters B 765 (2017) 104

(2) Mean-field:

Yong, PRC93, 044610（2016）



ρ_0 = 0.16 fm^{-3}

modify isovector while isoscalar unchanged

$$U(\rho,\delta,\vec{p},\tau) = A_u(x)\frac{\rho_{\tau'}}{\rho_0} + A_l(x)\frac{\rho_\tau}{\rho_0}$$

$$+B(\frac{\rho}{\rho_0})^\sigma(1-x\delta^2) - 8x\tau\frac{B}{\sigma+1}\frac{\rho^{\sigma-1}}{\rho_0^\sigma}\delta\rho_{\tau'}$$

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

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

Considering n-p correlations:

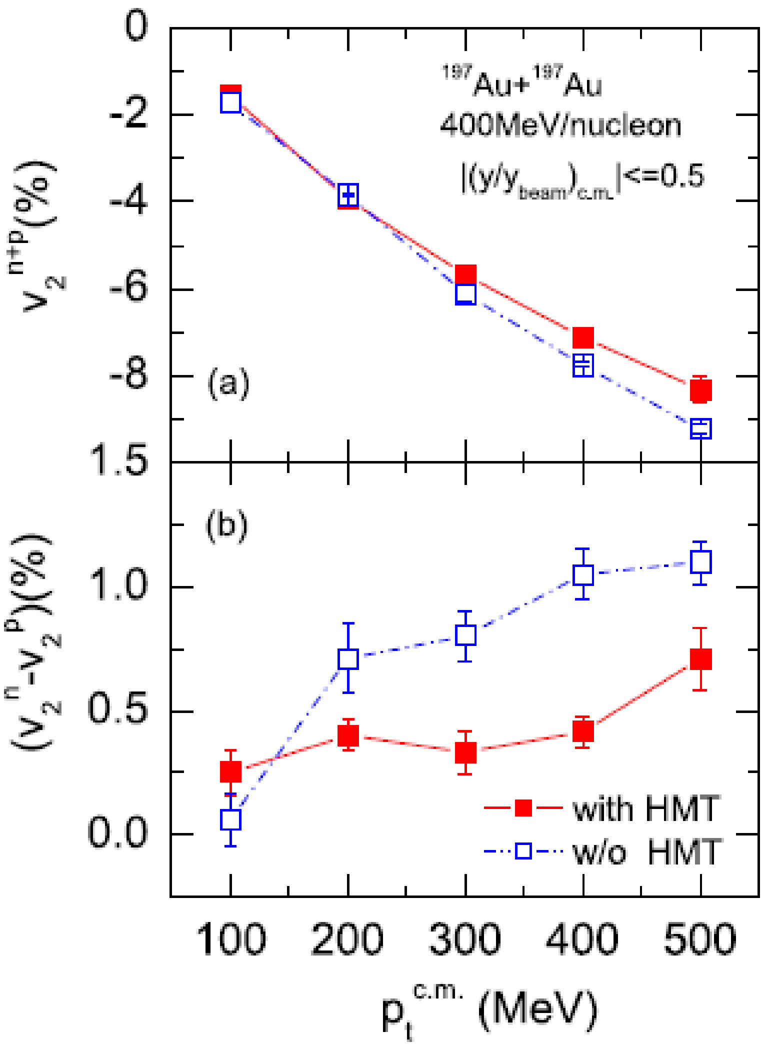
The parameters A, B, C, et al., are readjusted

$U = U_0 + Usym$

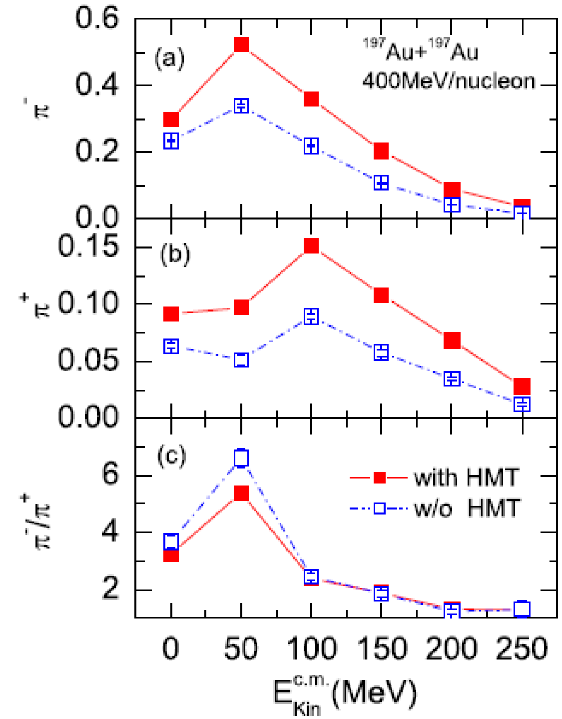
$Esym^{kin} \approx 0$

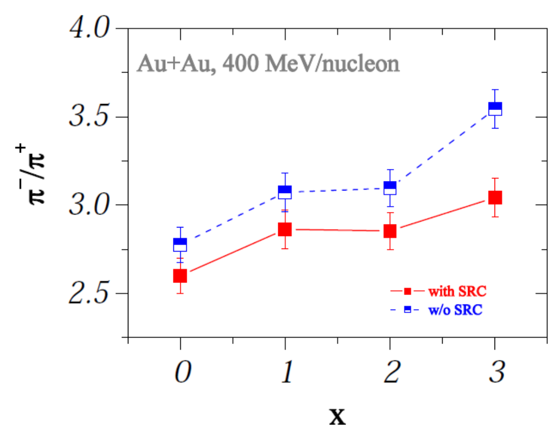
$Esym^{pot} \approx 31.6(MeV)$

SRC effects in HIC



F. Zhang, Gao-Chan Yong, Eur. Phys. J. A (2016) 52: 350





Yong, Phys. Rev. C 93, 044610 (2016)

Transition momentum:

$$n_p^{\mathrm{HMT}}(k)/n_n^{\mathrm{HMT}}(k) \simeq \rho_n/\rho_p$$

$$\int_{k_F}^{\lambda k_F} n^{HMT}(k)k^2dk / \int_0^{\lambda k_F} n(k)k^2dk \simeq 20\%$$

$$\int_0^{\lambda k_F} n(k)k^2dk = 1$$

$$respective-transition-momentum$$

A)

$$n(k)\_n = \begin{cases} C_1, k \le k_{F_n} \\ \downarrow \\ C_2/k^4, k_{F_n} < k \le \lambda k_{F_n} \end{cases}$$

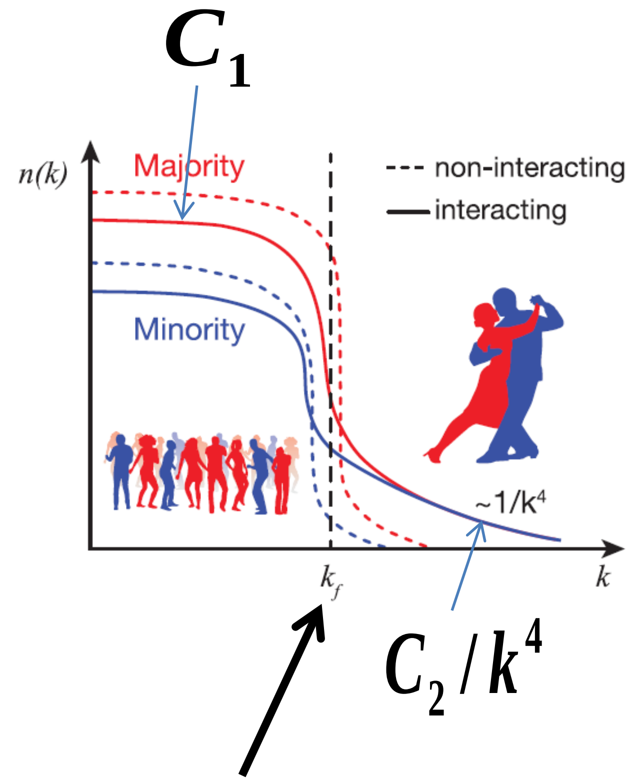
$$n(k)\_p = \begin{cases} C_1, k \le k_{F_p} \\ \downarrow \\ C_2/k^4, k_{F_p} < k \le \lambda k_{F_p} \end{cases}$$

$$majority-transition-momentum$$

B)

$$n(k)\_n = \begin{cases} C_1, k \le k_{F_n} \\ \downarrow \\ C_2/k^4, k_{F_n} < k \le \lambda k_{F_n} \end{cases}$$

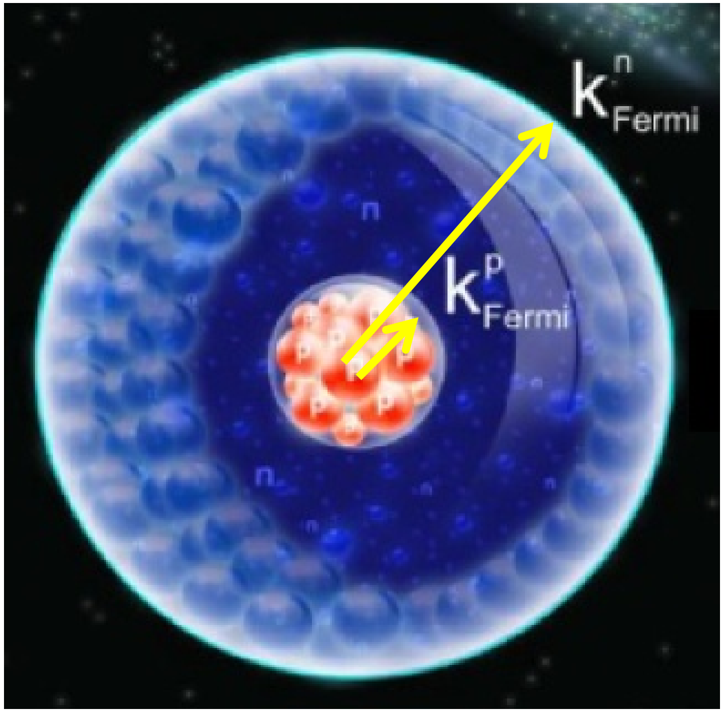
$$n(k)\_p = \begin{cases} C_1, k \le k_{F_p} \\ \downarrow \\ C_2/k^4, k_{F_n} < k \le \lambda k_{F_n} \end{cases}$$

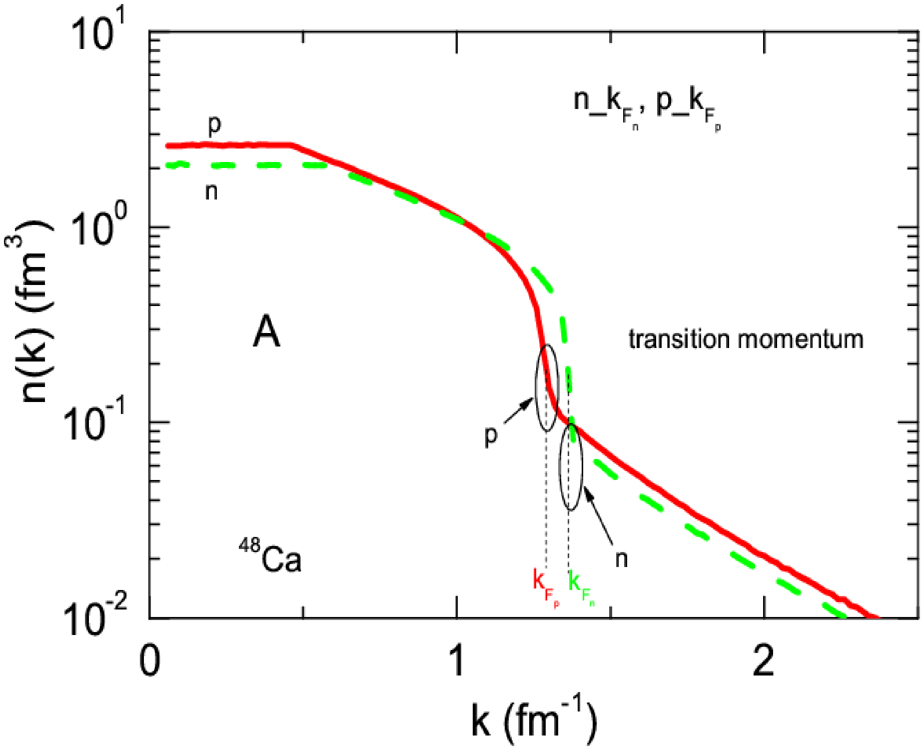


Transition momentum

Neutron-star matter

$$k_{F_{n,p}}(r) = [3\pi^2\hbar^3\rho(r)_{n,p}]^{\frac{1}{3}}$$

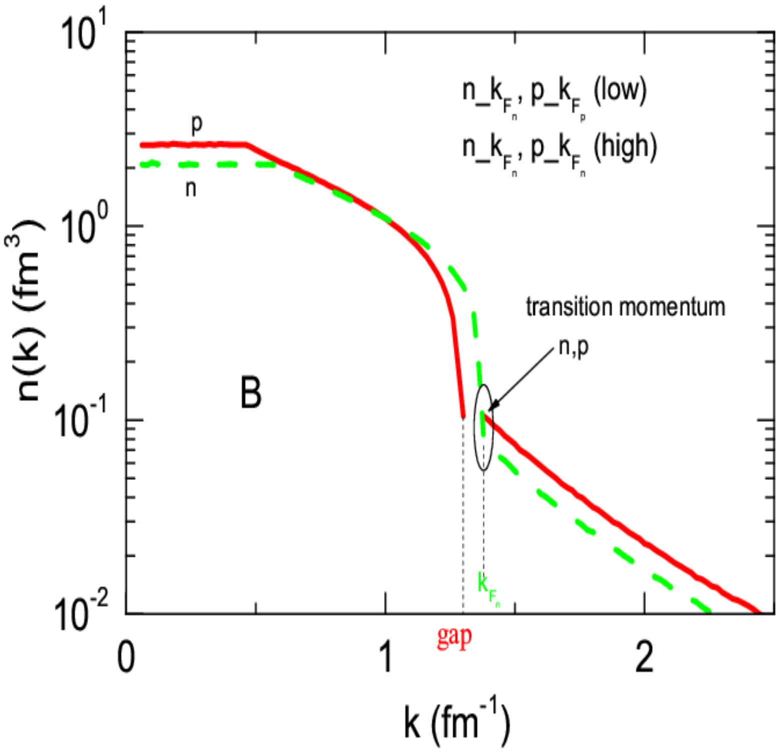


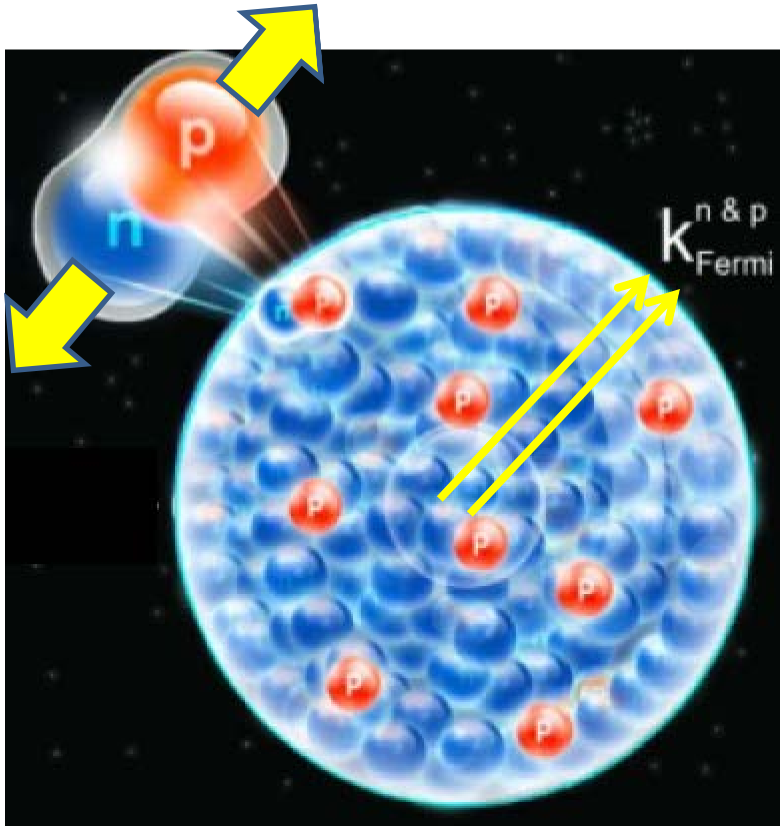


k_proton: not matched

Transition mom. = Respective Fermi mom.

Neutron-star matter



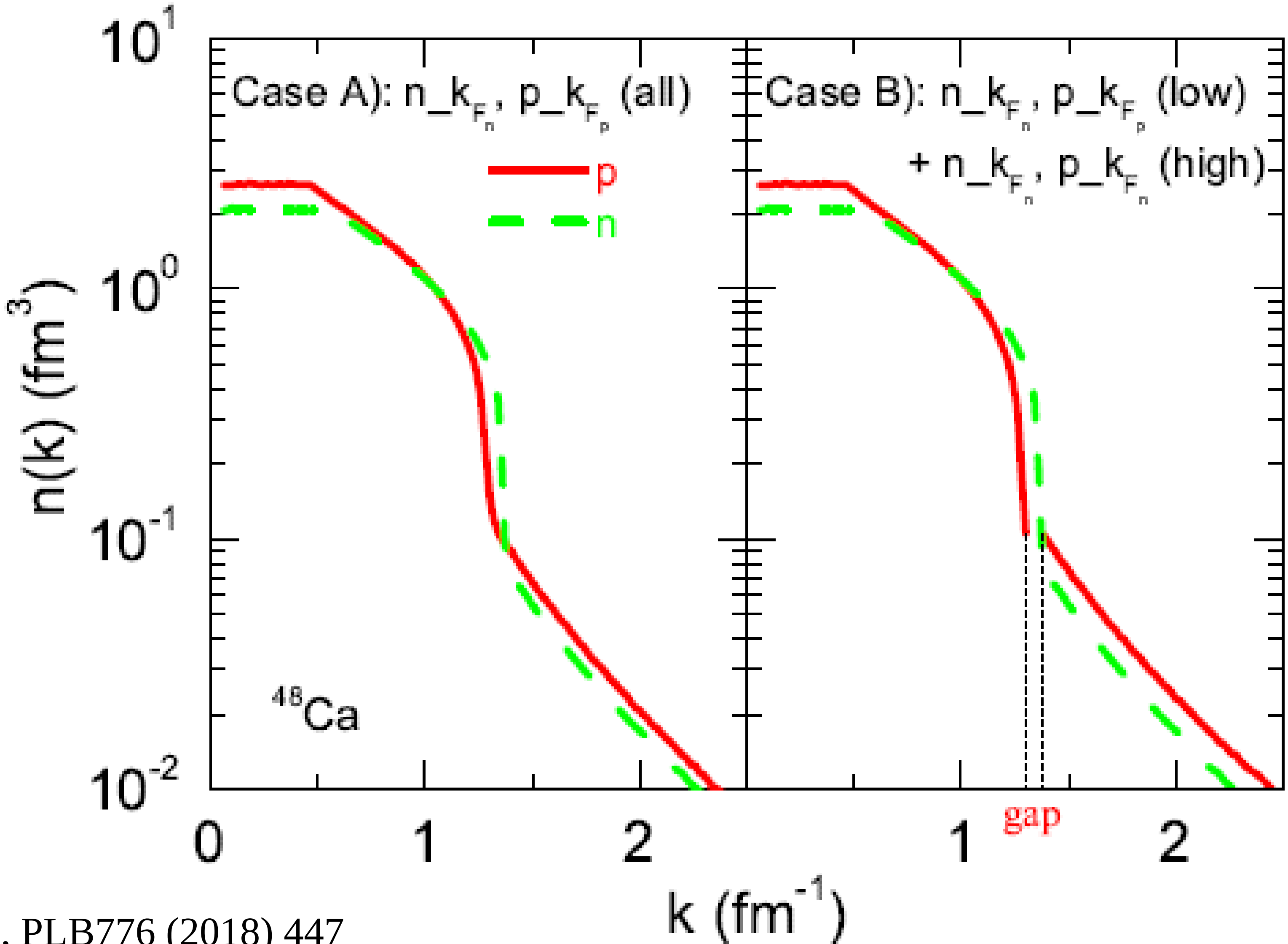


k_proton: matched

Minority transition mom.
= majority transition mom.

Which one is correct?

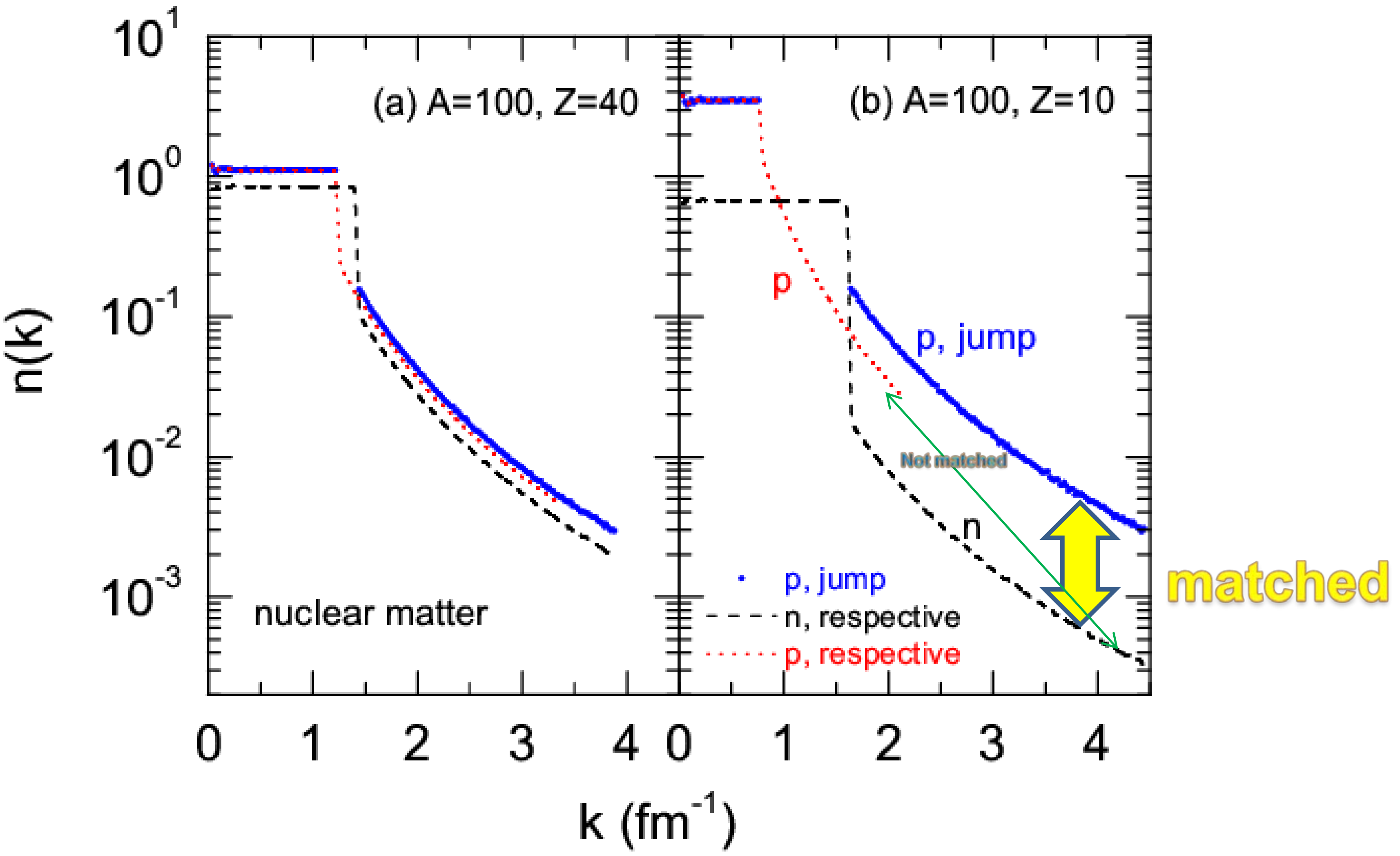
$$\boldsymbol{nucleus : 20\% \times (1 - \delta^2)}$$



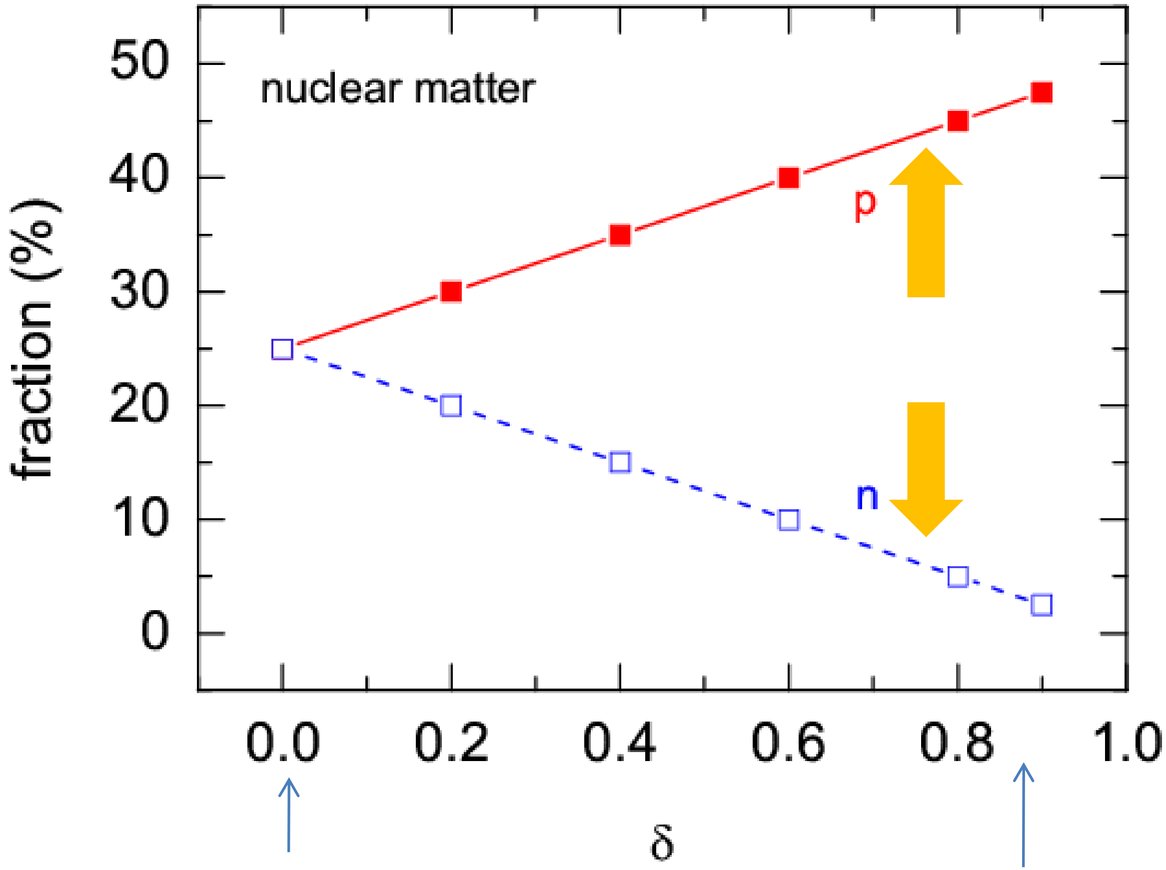
Yong, PLB776 (2018) 447

Which one is correct?

$$matter: 25\% \times (1-\delta^2)$$

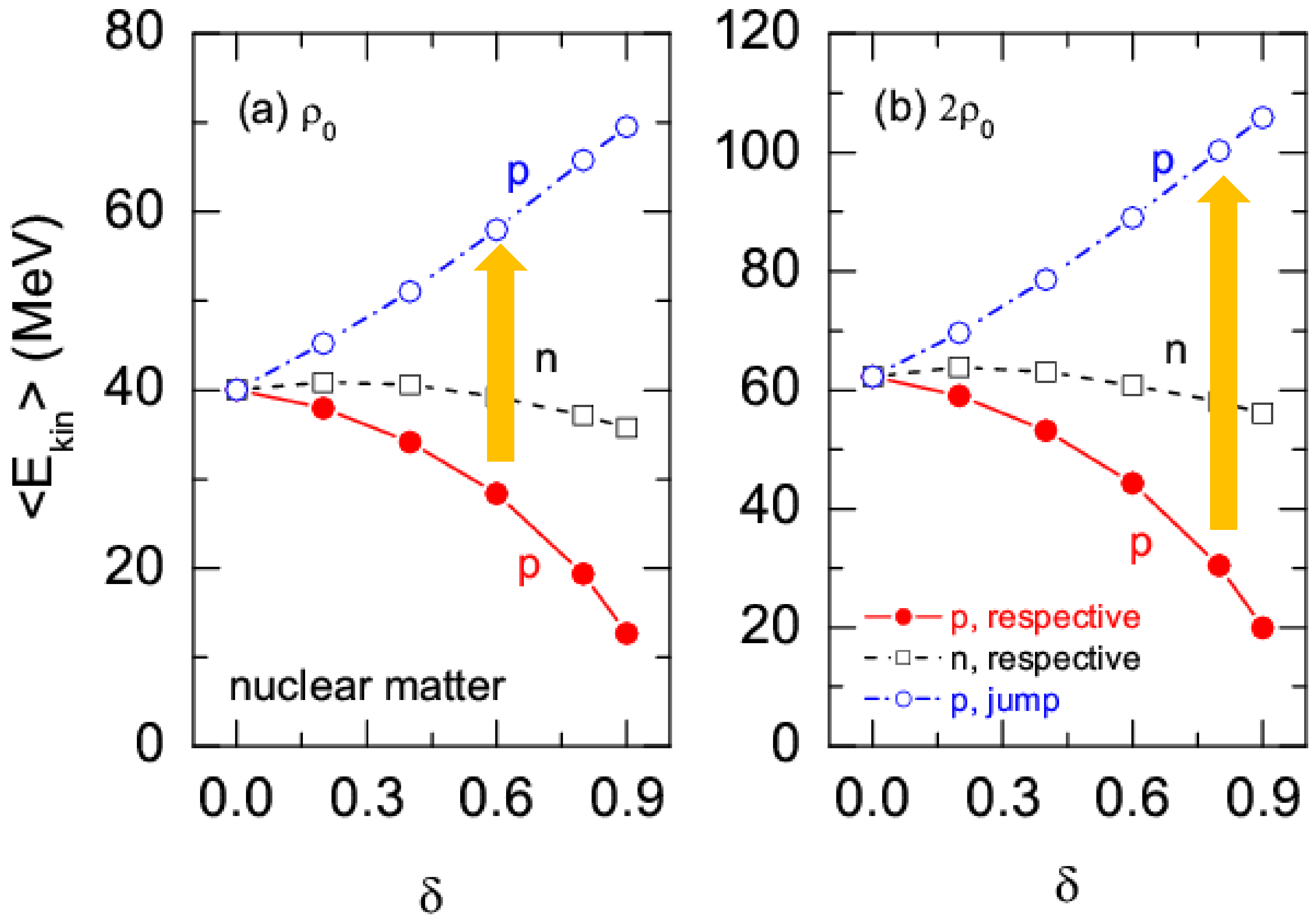


Fraction of SRC-nucleon



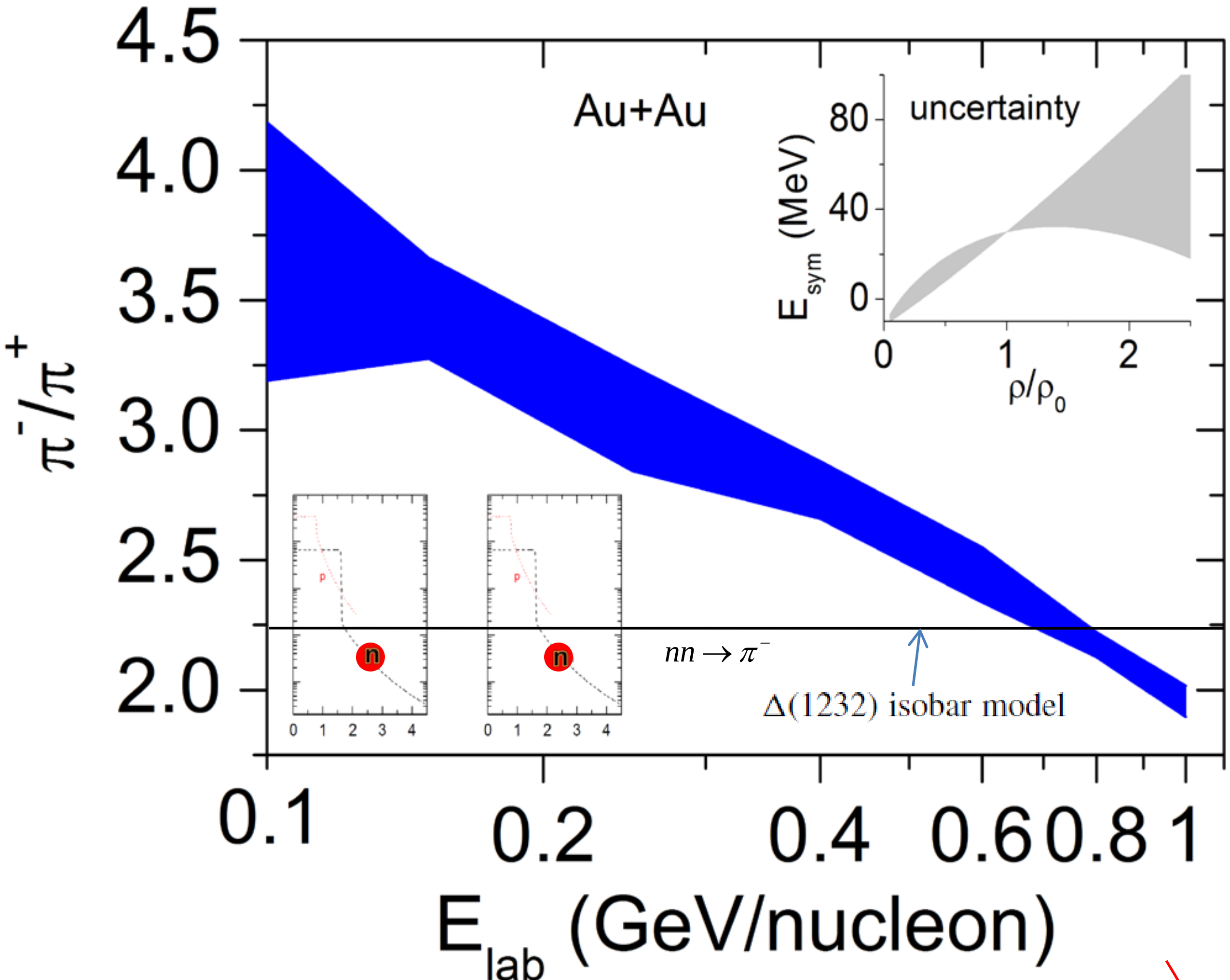
Symmetric matter **Neutron star matter**

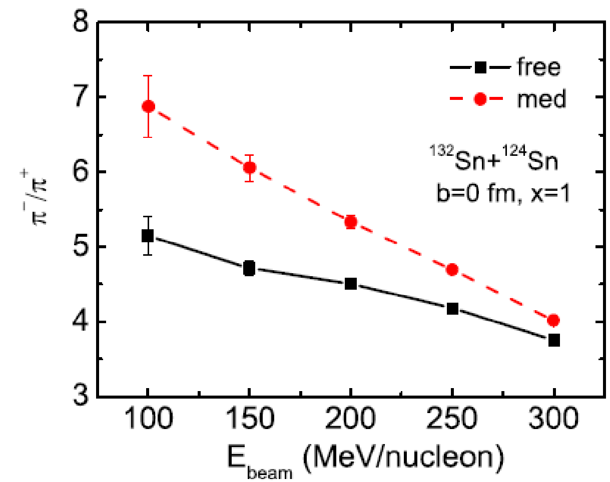
On Nucleon kinetic energy



Proton ekin is enhanced significantly

SRC effects on pion ratio in HIC





Without SRC

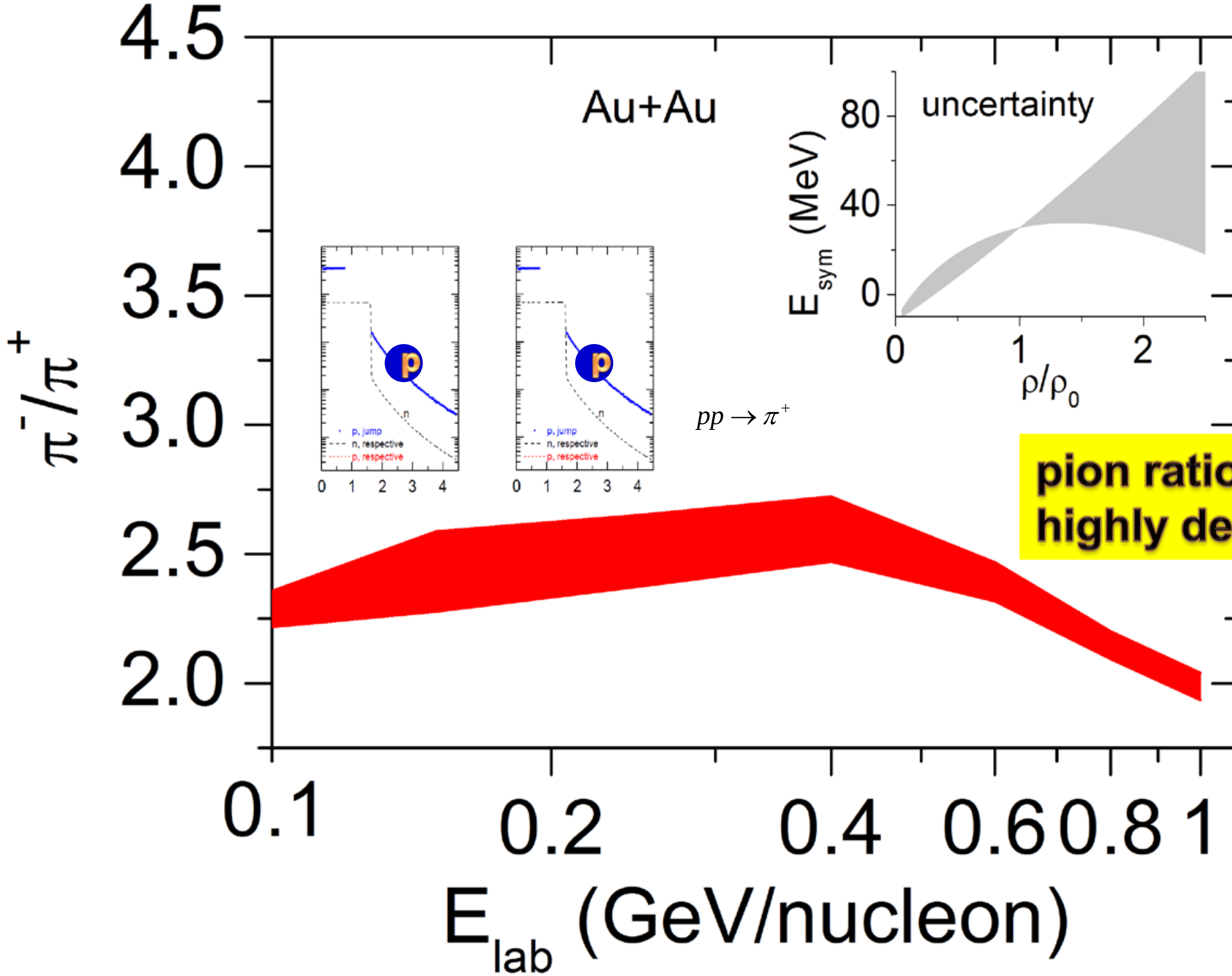
Guo, Yong, Zuo, PRC90, 044605(2014)

Isobar model is always wrong

Δ(1232) isobar model R. Stock, Phys. Rep. **135**, 259 (1986)

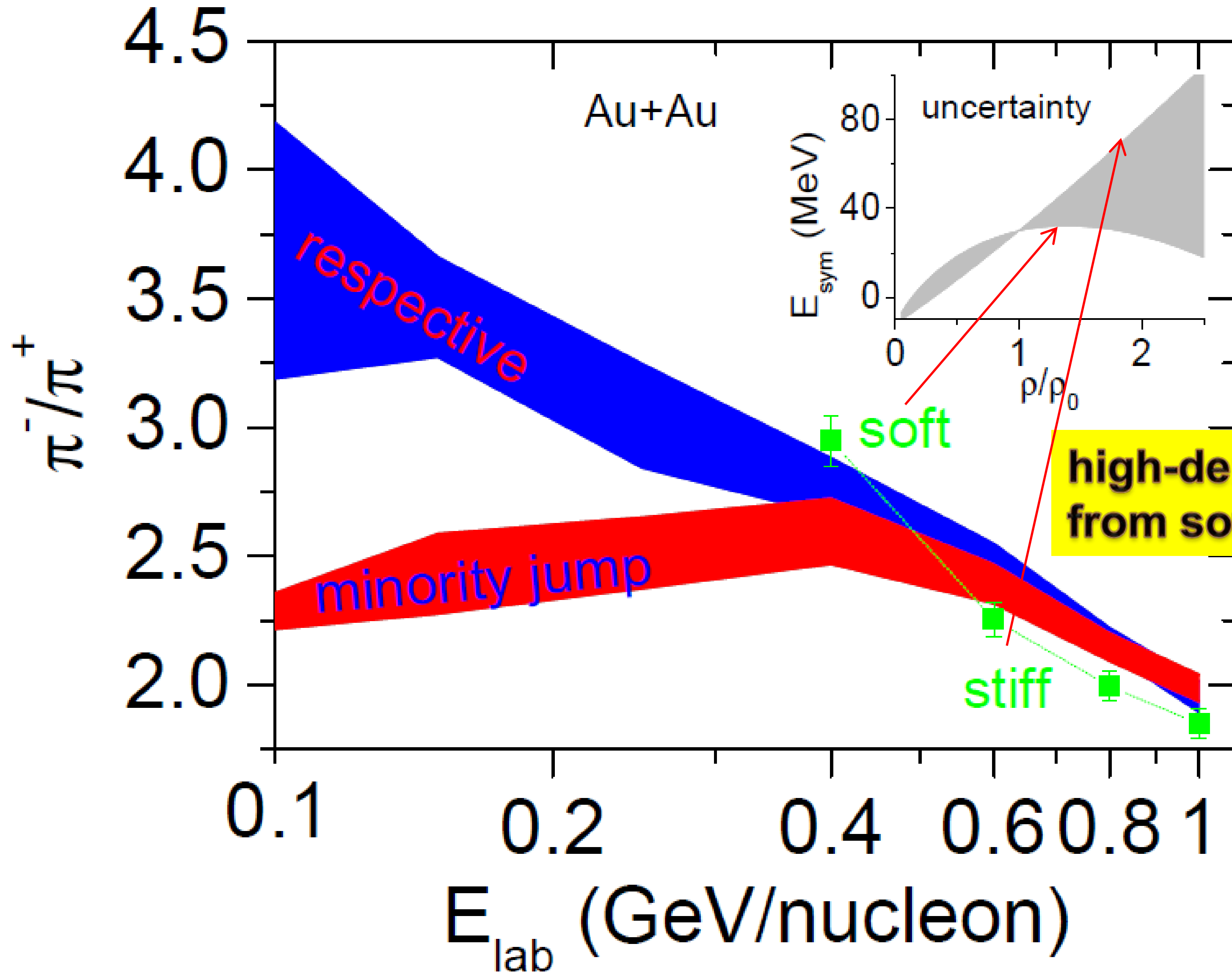
$$R_{\rm isob} \equiv (\pi^-/\pi^+)_{\rm res} \equiv (5N^2 + NZ)/(5Z^2 + NZ) \approx (N/Z)^2_{\rm dense}$$

SRC effects on pion ratio in HIC



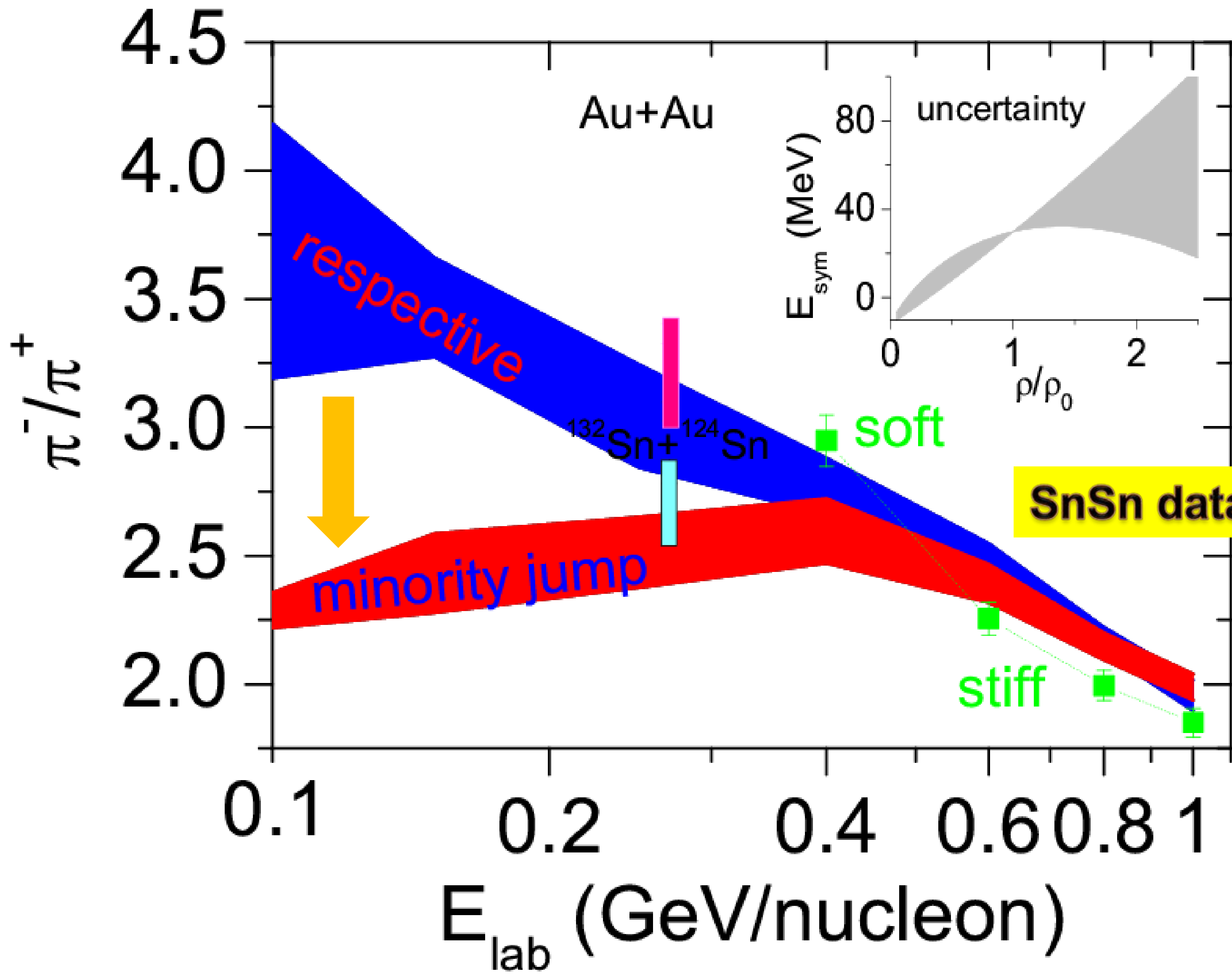
pion ratio is highly depressed

SRC effects on pion ratio in HIC



high-density Esym from soft to stiff?

SRC effects on pion ratio in HIC



SnSn data is useful

Summary&Comments

- It is not possible that SRC does not affect Esym sensitive probes.
- The picture of SRC is not clear (most many-body approaches fails to fit experimental SRC data) although there are some solid data.
- To check the SRC effects, 100-400 MeV beam energy HICs are favored.
- A perfect SRC consideration in the transport model seems hard to do, but we can first consider the main factors.
- Beam energy scans from 100-600 MeV beam energy n-rich HIC, more data information (such as pion-,pion+, their mom. Distribution, etc.) are welcomed (everyone can fit well if the experimental information is less).

Welcome your comments or suggestions！