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Hanwha Resort, Haeundae, Busan

Relevant studies on isospin splitting of nucleon effective mass

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Based on:

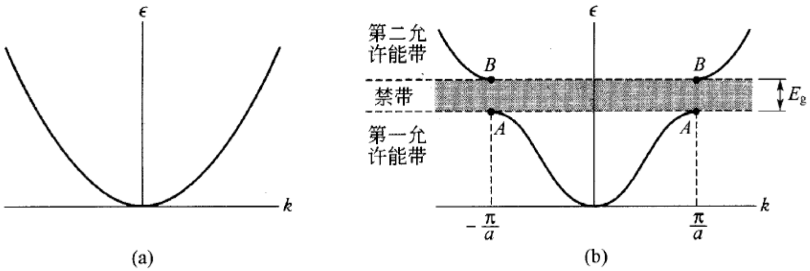
Phys. Rev. C 91, 014611 (2015);
Phys. Rev. C 91, 037601 (2015);
Phys. Rev. C 91, 047601 (2015);
Phys. Rev. C 95, 034324 (2017);
Prog. Part. Nucl. Phys. 99, 29 (2018);
arXiv: 1807.01849 [nucl-th]

Nucleon effective mass

Electron effective mass:

dispersion relation different from free electrons near the energy gap

$$\frac{1}{m^*} = \frac{1}{\hbar^2}\frac{d^2\epsilon}{dk^2}$$



Nucleon effective mass:

in-medium interaction lowers the nucleon mass

P-mass: $$\frac{\tilde{m}_\tau^*}{m} = \left[1 + \frac{m}{p}\frac{\partial U_\tau(p, \varepsilon_\tau(p))}{\partial p}\right]^{-1}$$

$\tau = n, p$

E-mass: $$\frac{\overline{m}_\tau^*}{m} = 1 - \frac{\partial U_\tau(p, \varepsilon_\tau(p))}{\partial \varepsilon_\tau}$$

Dirac mass: $m^*_{Dirac,\tau} = m + \Sigma^s_\tau$ $\qquad \Sigma^s_\tau$: scalar self-energy

Skyrme-Hartree-Fock: **non-relativistic, momentum-dependent potential**

Relativistic mean-field: **relativistic, meson exchange**

Comparison between non-relativistic mass with relativistic mass

Lorentz effective mass:

$$m^*_{Lorentz,\tau} = m\left(1 - \frac{dU_{SEP,\tau}}{dE_\tau}\right) = (E_\tau - \Sigma^0_\tau)\left(1 - \frac{d\Sigma^0_\tau}{dE_\tau}\right) - (m + \Sigma^s_\tau)\frac{d\Sigma^s_\tau}{dE_\tau} + m - E_\tau$$

M. Jaminon and C. Mahaux, PRC (1989); B.A. Li, L.W. Chen, and C.M. Ko, Phys. Rep. (2008); Z.X. Li, Nucl. Phys. Rev. (2014)

Neutron-proton effective mass splitting

Isospin dynamics in nuclear reactions

$$\frac{d\vec{p}}{dt} = -\nabla U_\tau$$

$$\frac{d\vec{r}}{dt} = \frac{\vec{p}}{m} + \nabla_p U_\tau = \frac{\vec{p}}{m_\tau^*}$$

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

Symmetry energy/potential

Effective mass $\frac{m_\tau^*}{m} = \left[1 + \frac{m}{p}\frac{dU_\tau(p)}{dp}\right]^{-1}, \tau = n, p$

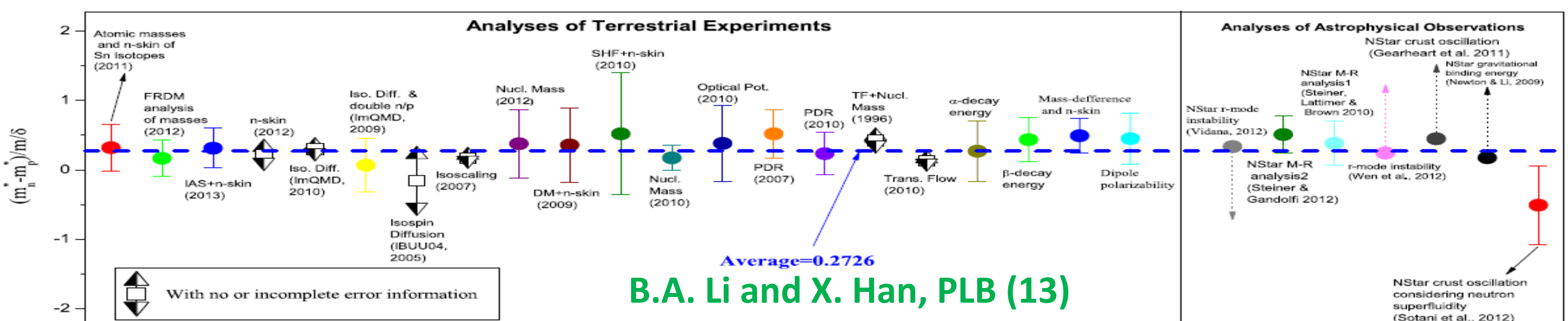
(non-relativistic p-mass)

Isoscalar effective mass: $m_s^* \approx m_{n(p)}^*(\delta = 0)$ **Isovector effective mass:** $m_n^* - m_p^* \approx \frac{2m_s^*}{m_v^*}(m_s^* - m_v^*)\delta$

Hugenholtz–Van Hove theorem

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

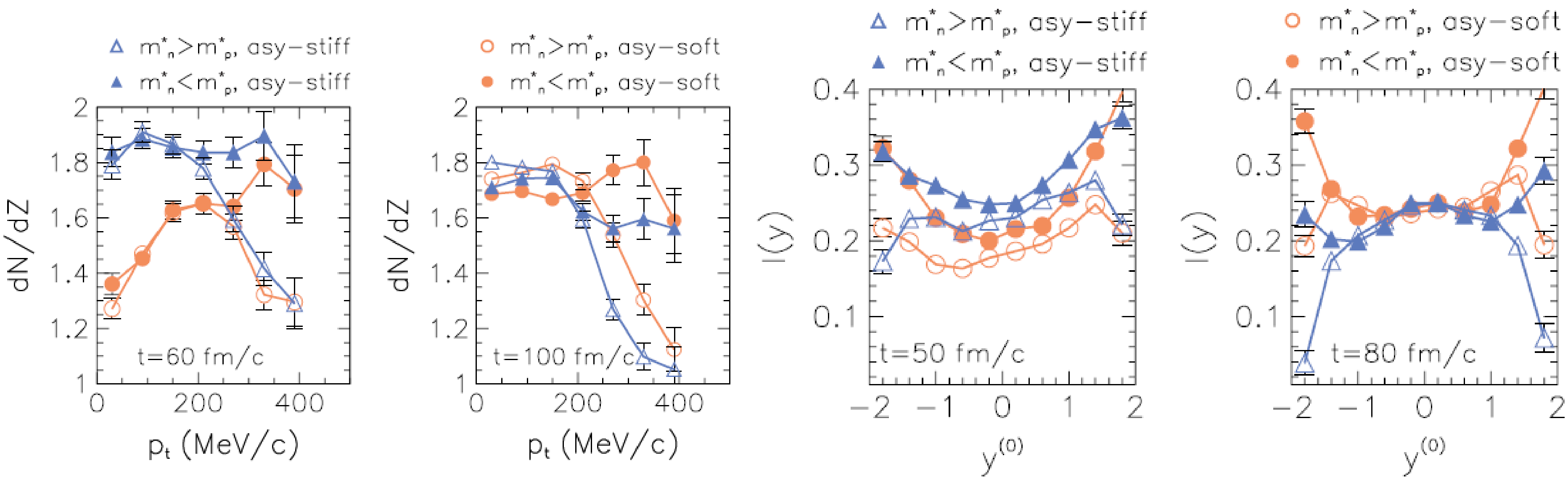
C. Xu, B.A. Li, and L.W. Chen, PRC (10); R. Chen, B.J. Cai, L.W. Chen, B.A. Li, X.H. Li, and C. Xu, PRC (12)



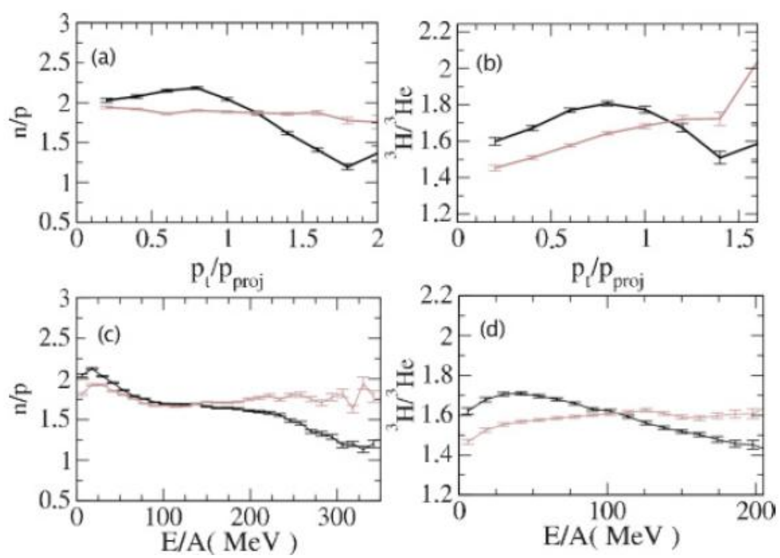
B.A. Li and X. Han, PLB (13)

np effective mass and HIC dynamics I

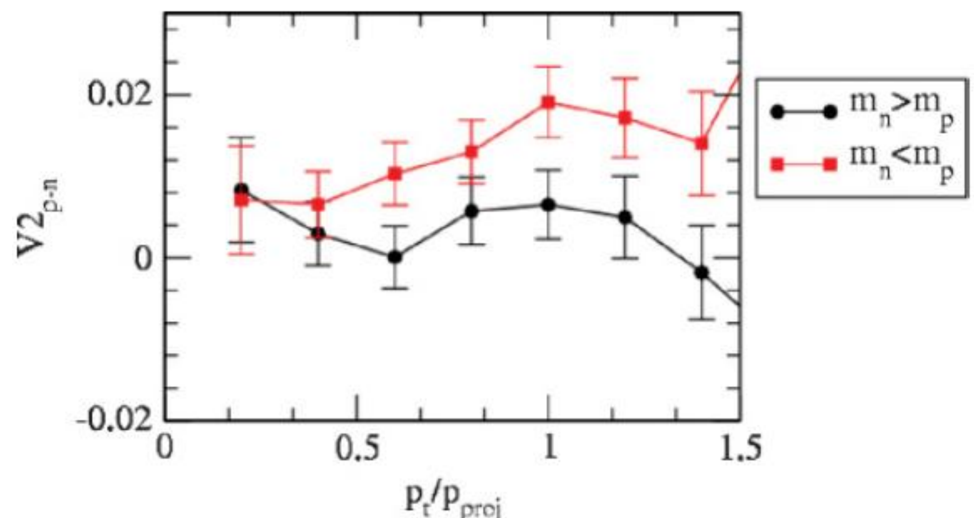
Fast emitted particles (BNV) (Rizzo, Colonna, Di Toro, PRC (05)) $^{132}Sn+^{124}Sn$@100AMeV



np ratio and v_2 splitting (SMF) (Giorando, Colonna, Di Toro, Greco, and Rizzo, PRC (10))

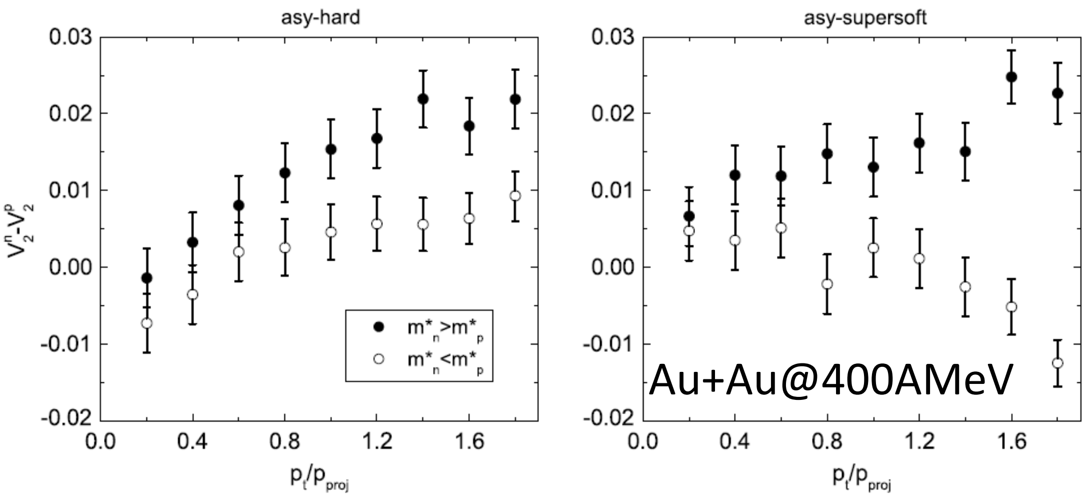


Au+Au@400AMeV



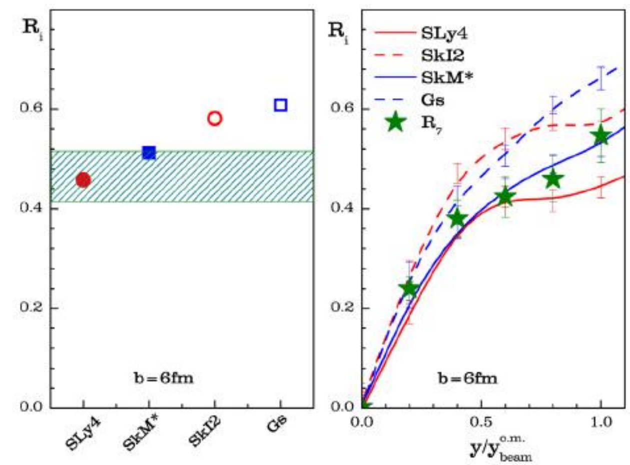
np effective mass and HIC dynamics II

np flow splitting (LQMD) (Z.Q. Feng, NPA (11))



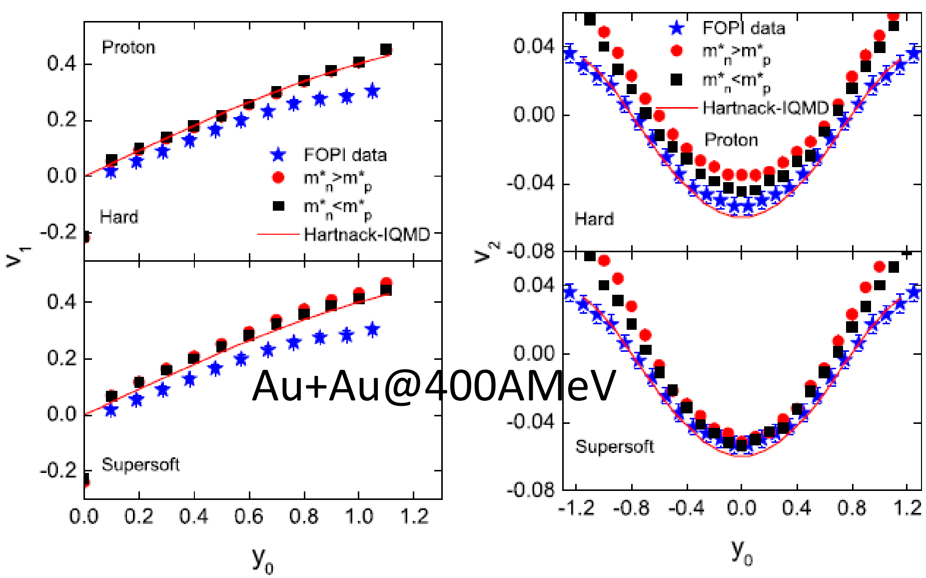
Isospin diffusion

$$R_i = \frac{2X - X_{aa} - X_{bb}}{X_{aa} - X_{bb}}$$



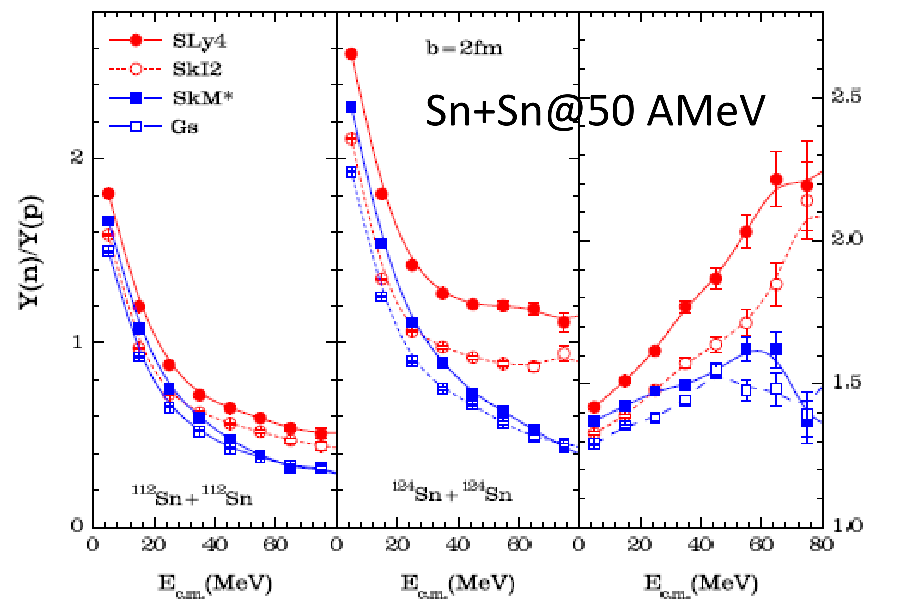
np flow splitting (IQMD-BNU)

(W.J. Xie and F.S. Zhang, PLB (14))



n/p ratio (ImQMD)

(Y.X. Zhang, M.B. Tsang, Z.X. Li, and H. Liu, PLB (14))



An improved momentum-dependent interaction (ImMDI)

Effective NN potential:

$$v(\vec{r}_1,\vec{r}_2) = \frac{1}{6}t_3(1+x_3P_\sigma)\rho^\gamma\left(\frac{\vec{r}_1+\vec{r}_2}{2}\right)\delta(\vec{r}_1-\vec{r}_2)$$
$$+(W+GP_\sigma-HP_\tau-MP_\sigma P_\tau)\frac{e^{-\mu|\vec{r}_1-\vec{r}_2|}}{|\vec{r}_1-\vec{r}_2|}$$

Potential energy density:

$$V(\rho,\delta) = \frac{A_u\rho_n\rho_p}{\rho_0}+\frac{A_l}{2\rho_0}(\rho_n^2+\rho_p^2)+\frac{B}{\sigma+1}\frac{\rho^{\sigma+1}}{\rho_0^\sigma}$$
$$\times(1-x\delta^2)+\frac{1}{\rho_0}\sum_{\tau,\tau'}C_{\tau,\tau'}$$
$$\times\iint d^3p\,d^3p'\frac{f_\tau(\vec{r},\vec{p})f_{\tau'}(\vec{r},\vec{p}\,')}{1+(\vec{p}-\vec{p}\,')^2/\Lambda^2}.$$

Mean-field potential:

$$U_\tau(\rho,\delta,\vec{p}) = A_u\frac{\rho_{-\tau}}{\rho_0}+A_l\frac{\rho_\tau}{\rho_0}$$
$$+B\left(\frac{\rho}{\rho_0}\right)^\sigma(1-x\delta^2)-4\tau x\frac{B}{\sigma+1}\frac{\rho^{\sigma-1}}{\rho_0^\sigma}\delta\rho_{-\tau}$$
$$+\frac{2C_l}{\rho_0}\int d^3p'\frac{f_\tau(\vec{r},\vec{p}\,')}{1+(\vec{p}-\vec{p}\,')^2/\Lambda^2}$$
$$+\frac{2C_u}{\rho_0}\int d^3p'\frac{f_{-\tau}(\vec{r},\vec{p}\,')}{1+(\vec{p}-\vec{p}\,')^2/\Lambda^2}.$$

$$A_l(x,y) = A_{l0}+y+x\frac{2B}{\sigma+1},$$
$$A_u(x,y) = A_{u0}-y-x\frac{2B}{\sigma+1},$$
$$C_l(y,z) = C_{l0}-2(y-2z)\frac{p_{f0}^2}{\Lambda^2\ln\left[(4p_{f0}^2+\Lambda^2)/\Lambda^2\right]},$$
$$C_u(y,z) = C_{u0}+2(y-2z)\frac{p_{f0}^2}{\Lambda^2\ln\left[(4p_{f0}^2+\Lambda^2)/\Lambda^2\right]},$$

0, we choose the following empirical values: $\rho_0 = 0.16\ \text{fm}^{-3}$, $E_0(\rho_0) = -16$ MeV, $K_0 = 230$ MeV, $m_s^\star = 0.7m$, $E_{\text{sym}}(\rho_0) = 32.5$ MeV, and $U_{0,\infty} = 75$ MeV, which lead to $A_{l0} = A_{u0} = -66.963$ MeV, $B = 141.963$ MeV, $C_{l0} = -60.4860$ MeV, $C_{u0} = -99.7017$ MeV, $\Lambda = 2.42401 p_{f0}$, and $\sigma = 1.26521$.

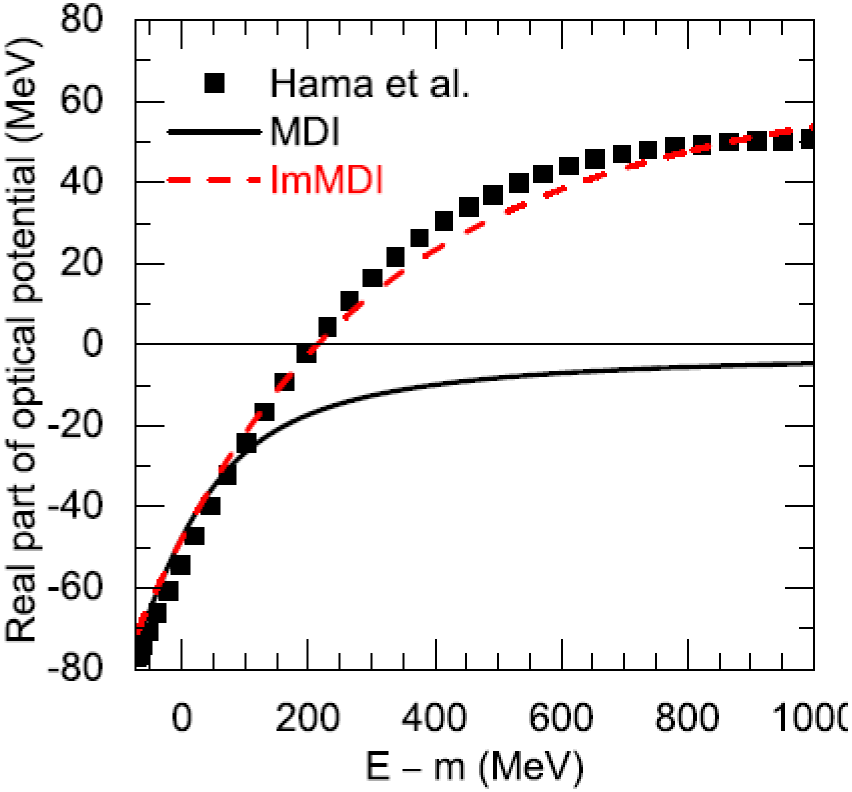
For nuclear matter

$$f_\tau(\vec{r},\vec{p}) \sim \frac{1}{\exp\left[\left(\frac{p^2}{2m}+U_\tau(\vec{p})-\mu_\tau\right)/T\right]+1}$$

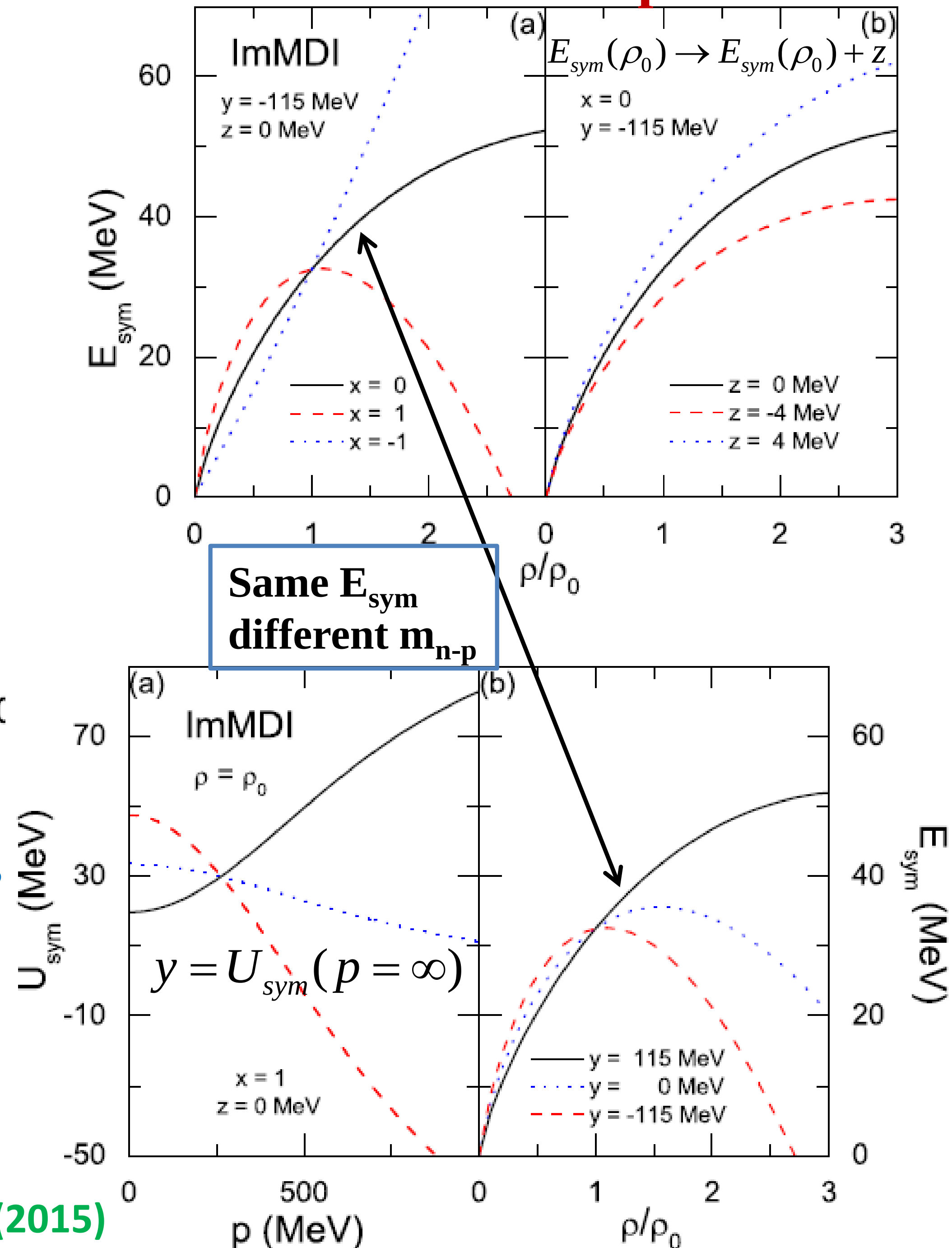
Relevant parameters: x, y, z

JX, L.W. Chen, and B.A. Li, PRC 91, 014611 (2015)

Isoscalar part



Isovector part



More reliable at higher energies

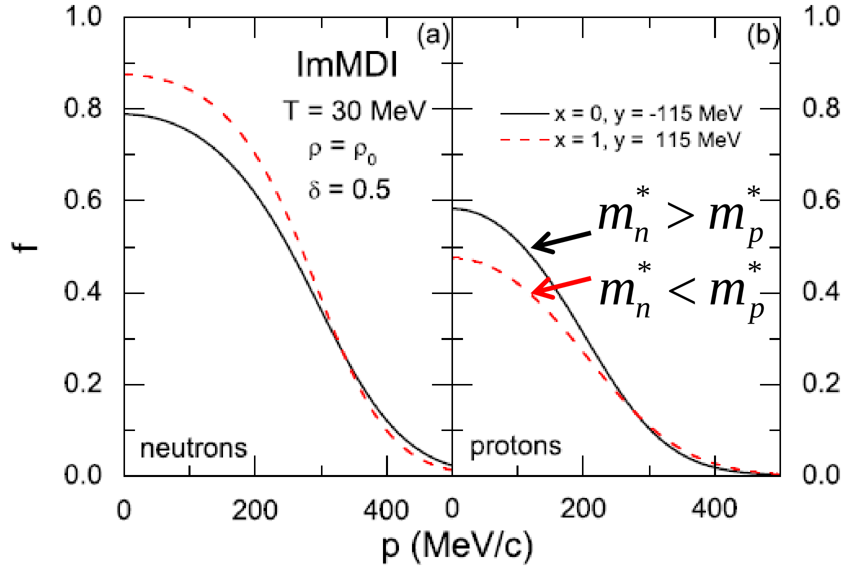
More flexible in studying isospin effects

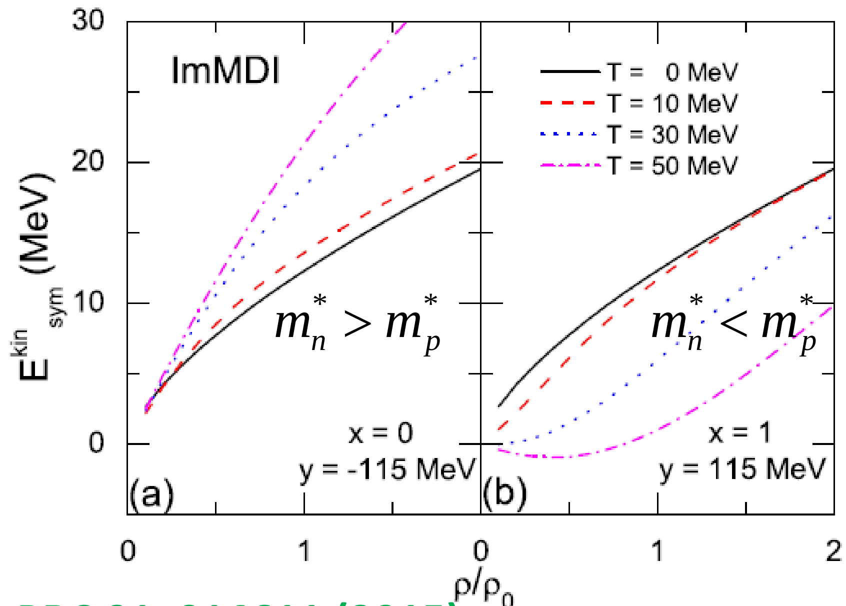
$$U_{n/p} \approx U_0 \pm U_{sym}\delta$$

$$\frac{m_\tau^*}{m} = \left(1 + \frac{m}{p}\frac{dU_\tau}{dp}\right)^{-1}$$

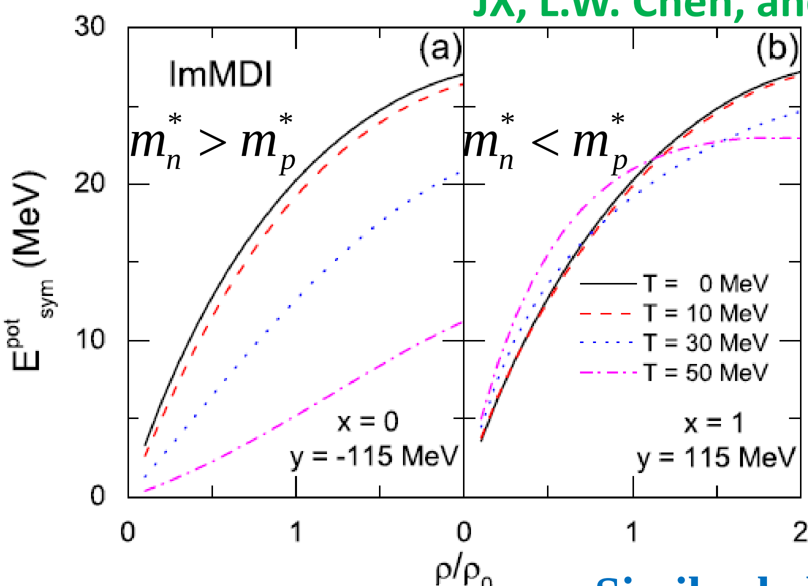
JX, L.W. Chen, and B.A. Li, PRC 91, 014611 (2015)

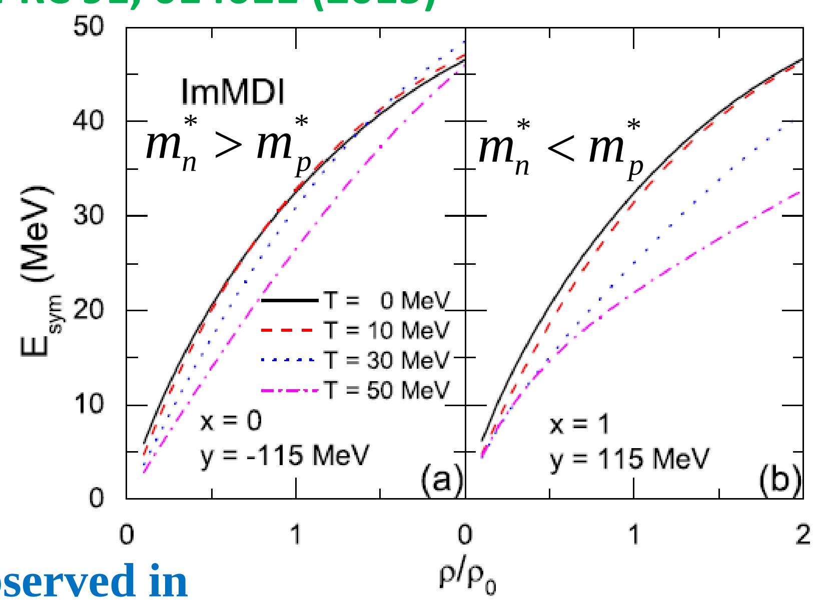
np effective mass splitting and nuclear thermodynamics I





JX, L.W. Chen, and B.A. Li, PRC 91, 014611 (2015)

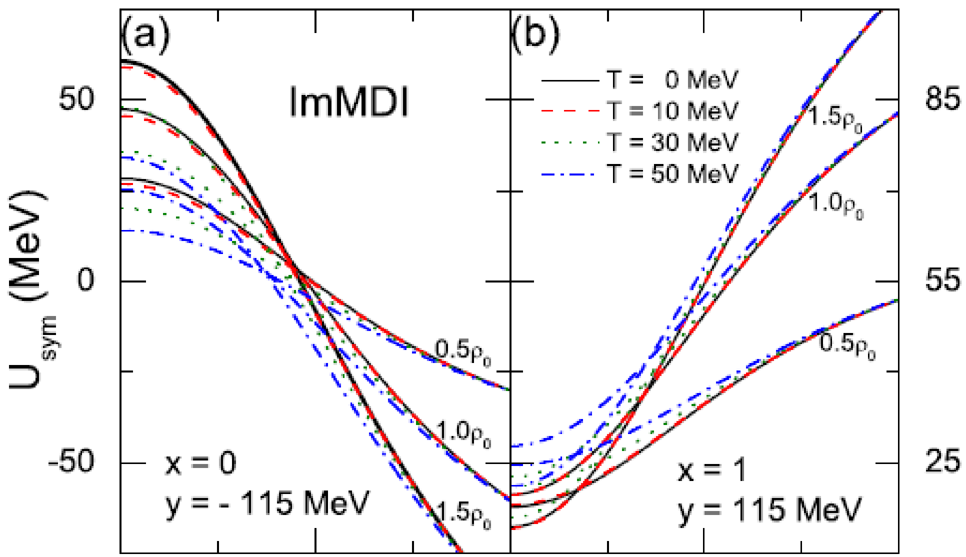


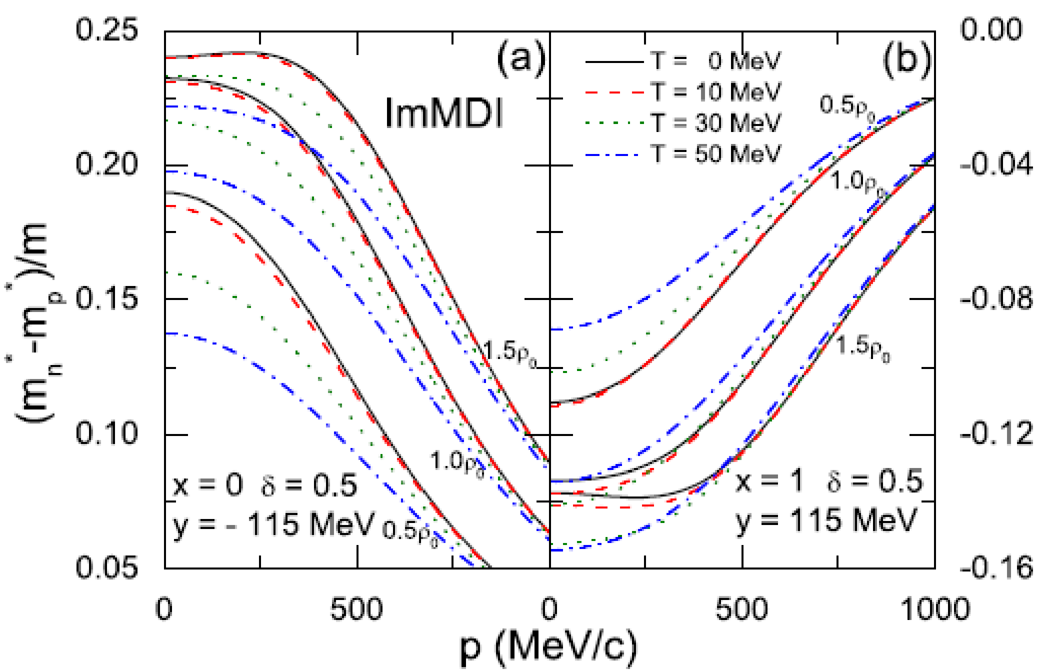


Similar behavior observed in

L. Ou, Z.X. Li, Y.X. Zhang, and H. Liu, PLB (11)

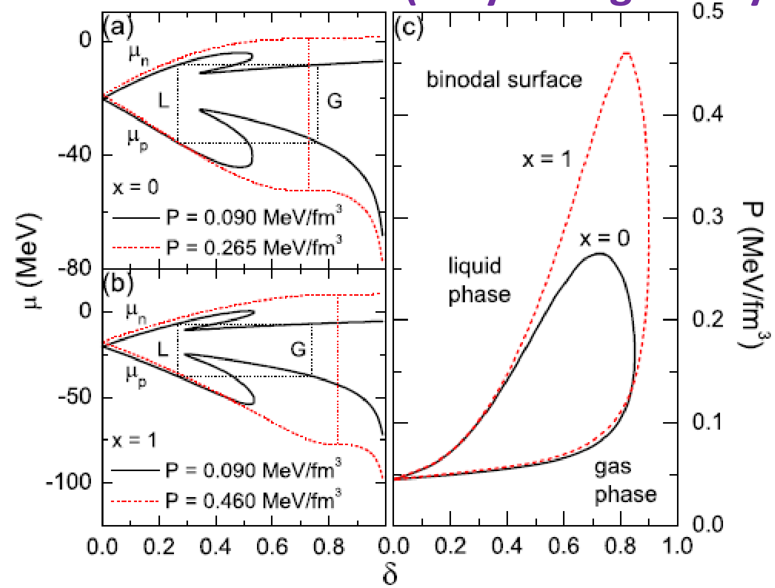
np effective mass splitting and nuclear thermodynamics II



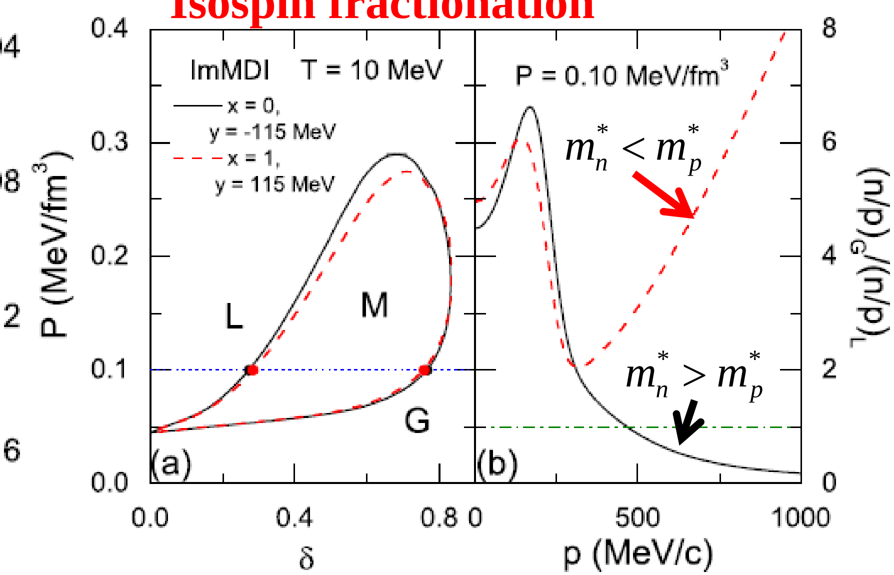


Nuclear liquid-gas phase transition

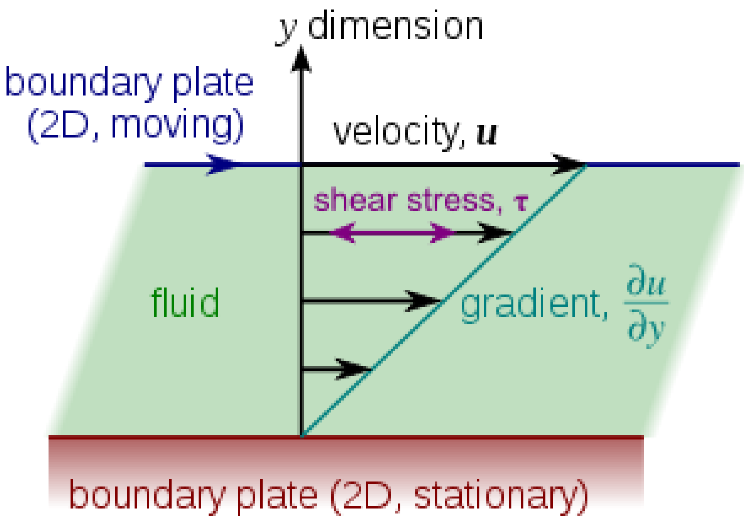
Gibbs construction (only change x-Esym)



Isospin fractionation



Shear viscosity



$$\tau = \frac{F}{A} = \eta \frac{\partial u}{\partial y} \qquad \eta \propto \frac{\langle p \rangle}{\sigma}$$

Strong interaction ⇒ **Small η**

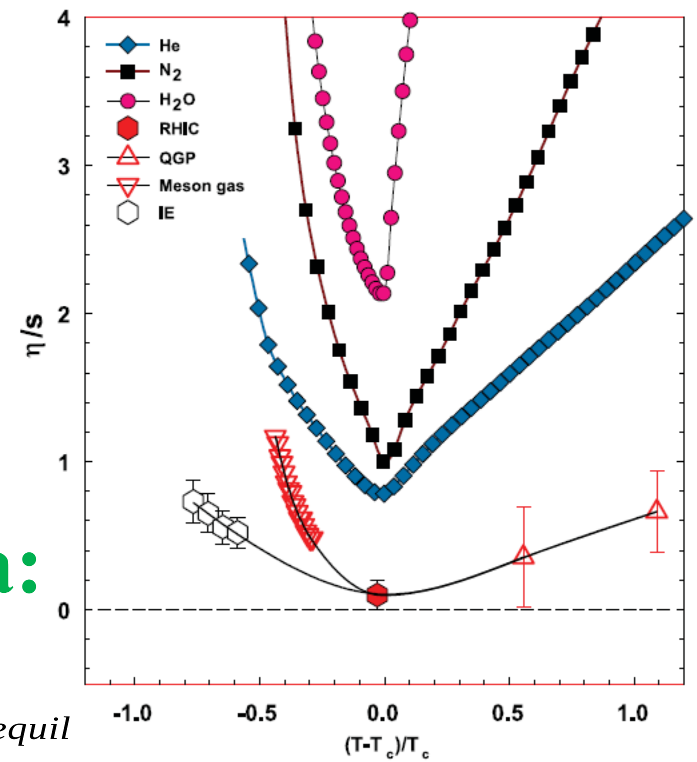
Viscous hydrodynamics: $\frac{\eta}{s}$

Ideal fluid: $\eta = 0$

Ads/CFT: $\frac{\eta}{s} \geq \frac{1}{4\pi}$

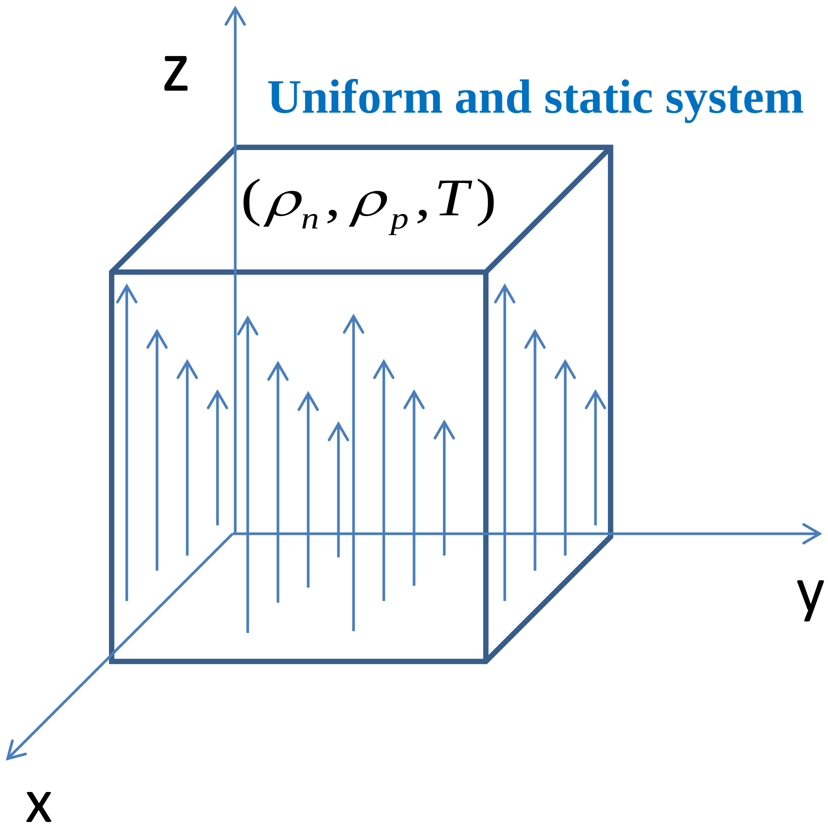
Green-Kubo's formula:

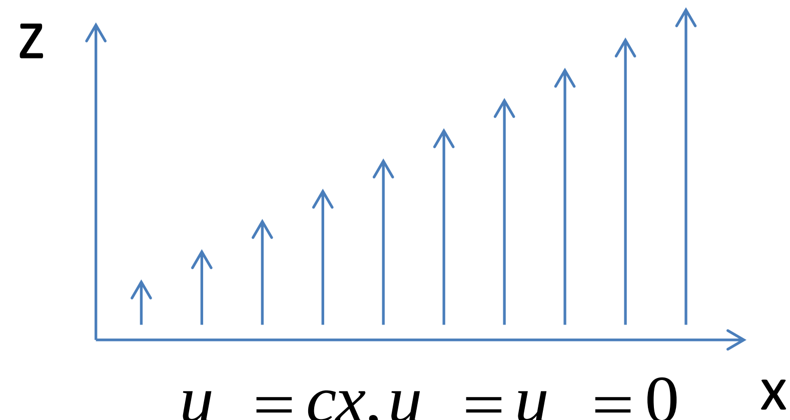
$$\eta = \frac{1}{T}\int d^3r \int_0^\infty dt \left\langle \pi^{ij}\left(\vec{0},0\right)\pi^{ij}\left(\vec{r},t\right)\right\rangle_{equil}$$



R. Lacey *et al.*, PRL, 2007

Shear viscosity from a relaxation time approach





$$u_z = cx, u_x = u_y = 0$$

Shear viscosity:

$$\eta = \sum_{\tau} -\frac{d}{(2\pi)^3} \int \tau_\tau(p) \frac{p_z^2 p_x^2}{p m_\tau^\star} \frac{dn_\tau}{dp} dp_x dp_y dp_z$$

$$\tau = n, p$$

$$n_\tau^*(\vec{p}) = \left\{ \exp\left[\left(\frac{p^2}{2m} + U_\tau(\vec{p}) - \mu_\tau \right) \Big/ T \right] + 1 \right\}^{-1}$$

Relaxation time: $$\frac{1}{\tau_\tau(p)} = \frac{1}{\tau_\tau^{\text{same}}(p)} + \frac{1}{\tau_\tau^{\text{diff}}(p)}$$

near Fermi surface

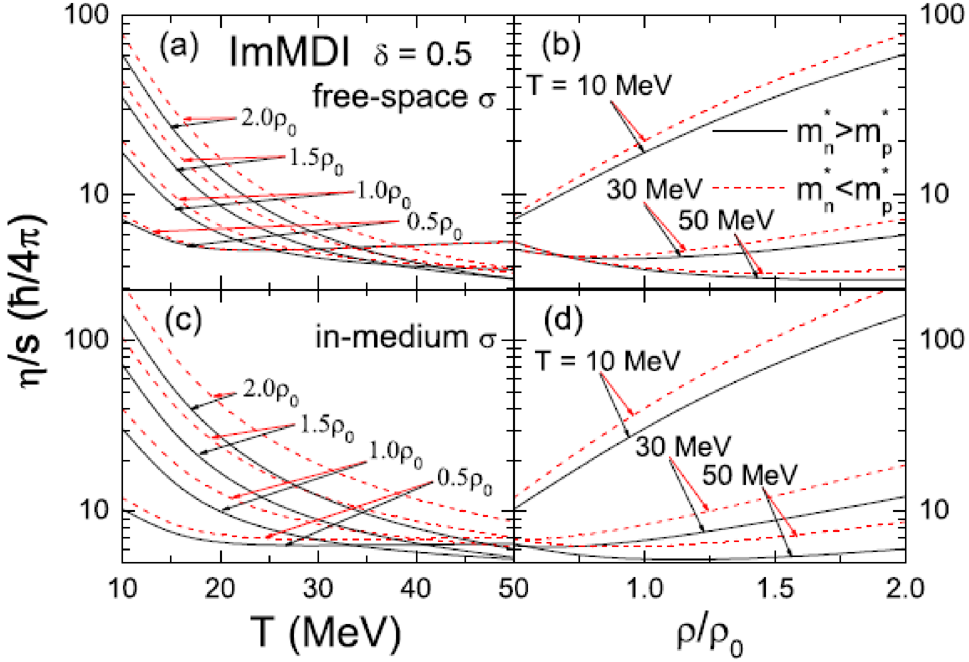
From linearizing isospin-dependent BUU equation

$$\sigma_{NN}^{\text{medium}} = \sigma_{NN} \left(\frac{\mu_{NN}^\star}{\mu_{NN}} \right)^2$$

JX, PRC 84, 064603 (2011)

np effective mass splitting and nuclear transport properties

Effects are robust even with free-space NN scattering cross section

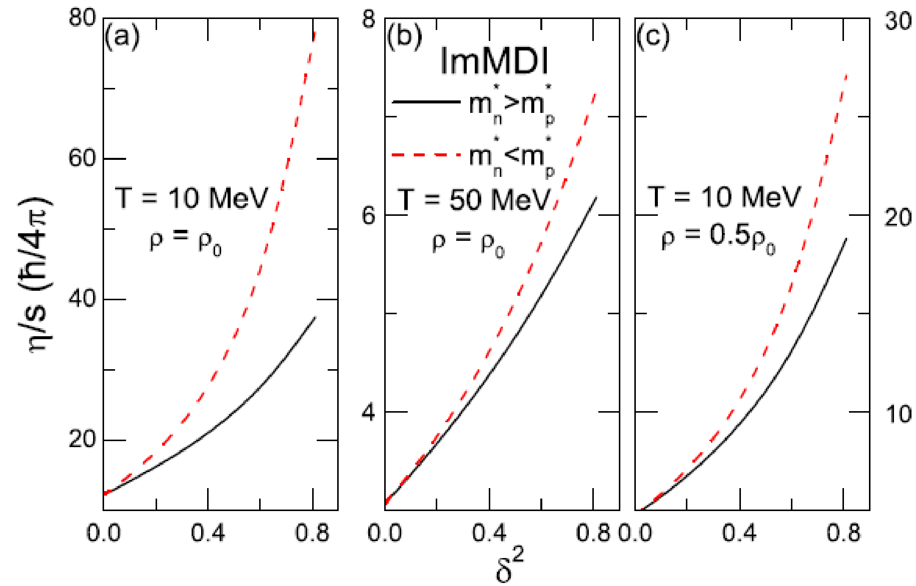


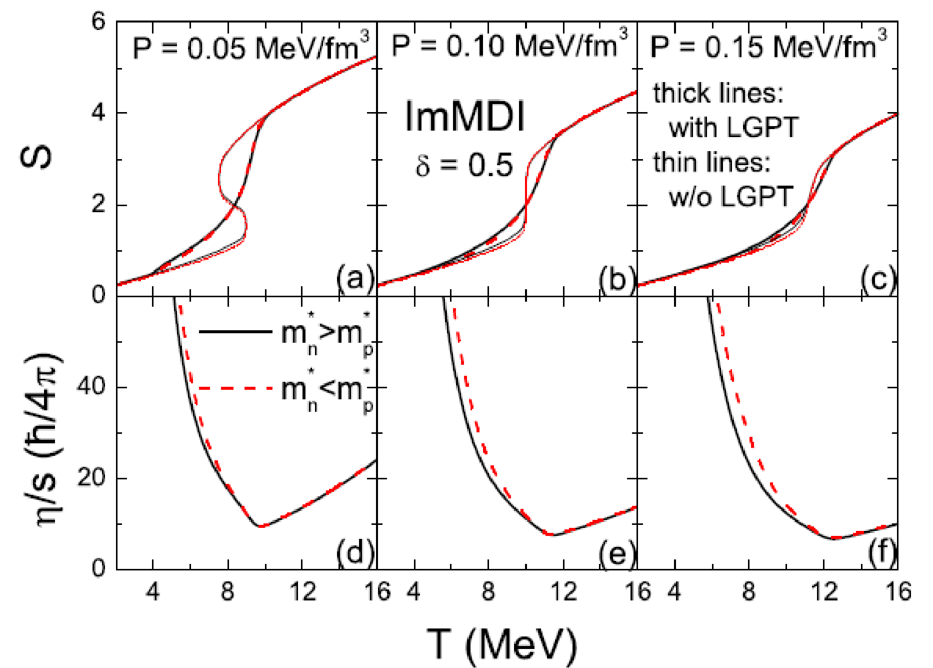
1) **Flux between flow layers;**
2) **Effective mass scaling on σ**

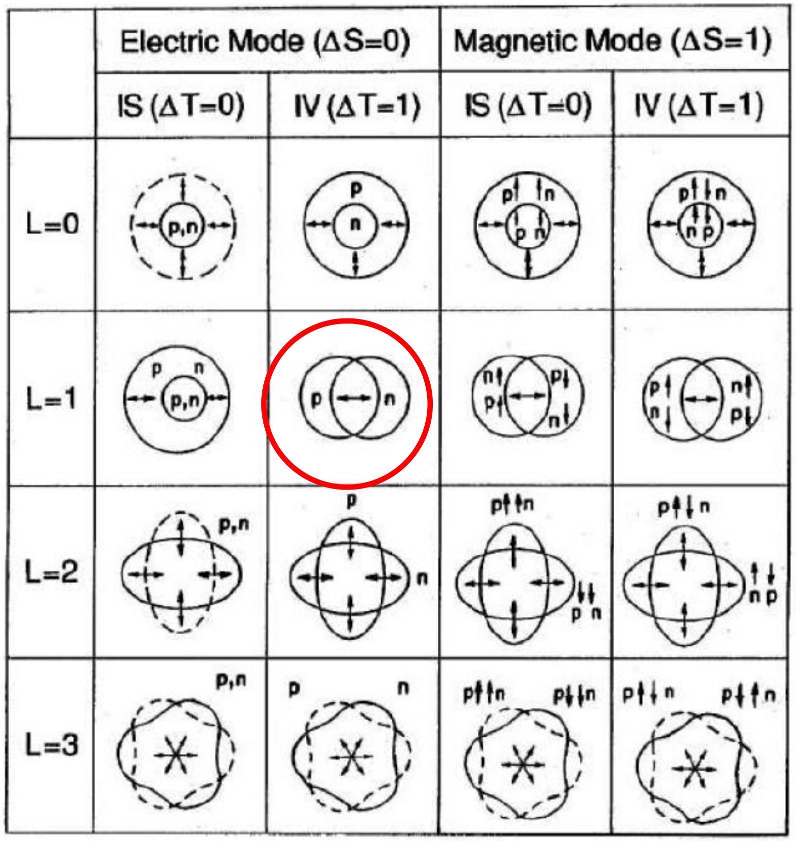
Effects remain even with naive MFP method

$$\tau_\tau^{same}(p_1) = \frac{1}{\langle \sigma_{\tau,\tau}^{tr} \rho_\tau v_{rel} \rangle} \qquad \tau_\tau^{diff}(p_1) = \frac{1}{\langle \sigma_{\tau,-\tau}^{tr} \rho_{-\tau} v_{rel} \rangle}$$

JX, PRC 91, 037601 (2015)







Isovector giant dipole resonance

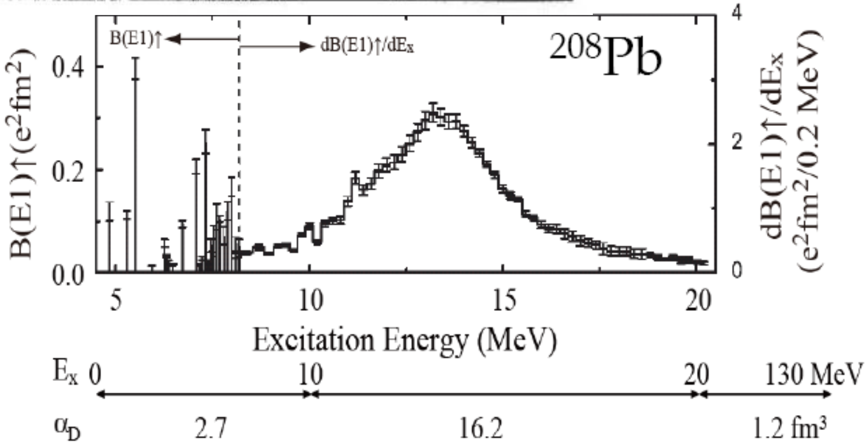
Symmetry energy as a restoring force

Harmonic oscillator $\omega \propto \sqrt{\frac{k}{m}}$

Constrain the symmetry energy and the np effective mass splitting using the exp data of ^{208}Pb giant resonance

With random-phase approximation:

Z. Zhang and L.W. Chen, PRC (2017)



With IBUU transport model:

Hai-Yun Kong, JX*, et al., Phys. Rev. C 95, 034324 (2017)

Electric dipole polarizability Total: $\alpha_D = 20.1 \pm 0.6\ \text{fm}^3$

Subtract quasideuteron excitation

$\alpha_D = 19.6 \pm 0.6\ \text{fm}^3$

Photon absorption measurement $E_{-1} = 13.46$ MeV

Extract m_s^* from ISGQR

Operator of isoscalar giant quadrupole resonance (ISGQR) :

$$\hat{Q} = \sum_{i=1}^{A} r_i^2 Y_{20}(\hat{r_i}) = \sum_{i=1}^{A} \sqrt{\frac{5}{16\pi}} \left(3z_i^2 - r_i^2\right)$$

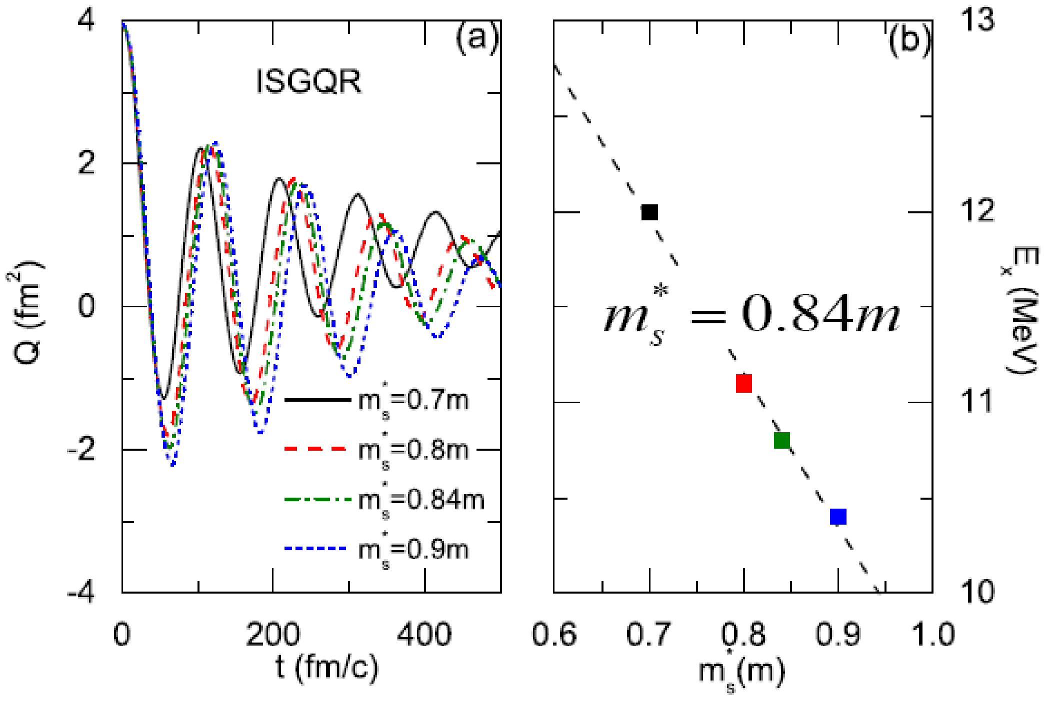
From $\alpha - ^{208}Pb$ scattering data

$$E_x = 10.9 \pm 0.1 \text{ MeV}$$

Initial excitation of ISGQR (based on scaling relation):

$$\begin{cases} x \to x/\lambda \\ y \to y/\lambda \\ z \to \lambda^2 z \end{cases} \begin{cases} p_x \to \lambda p_x \\ p_y \to \lambda p_y \\ p_z \to p_z/\lambda^2 \end{cases}$$

$$\lambda = 1.1$$



Hai-Yun Kong, JX*, et al.,
Phys. Rev. C 95, 034324 (2017)

Extract L and m_v^* from IVGDR

Operator of isovector giant dipole resonance (IVGDR):

$$\hat{D} = \frac{NZ}{A}\hat{X},$$

Initial excitation of IVGDR:

$$p_i \rightarrow \begin{cases} p_i - \eta\frac{N}{A} & \text{(protons)} \\ p_i + \eta\frac{N}{A} & \text{(neutrons)} \end{cases}$$

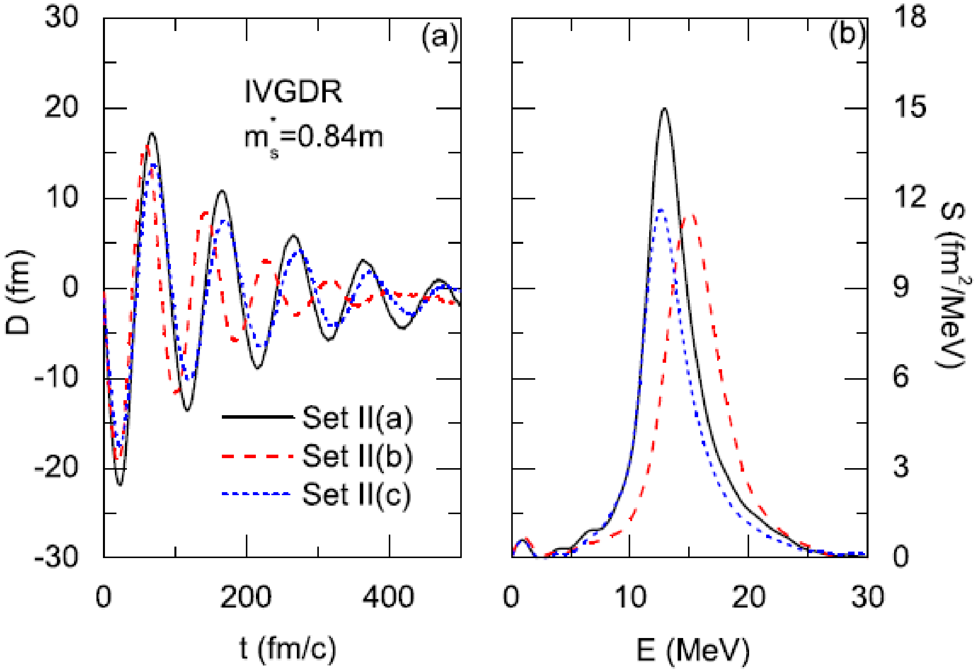
Strength function:

$$S(E) = \frac{-Im\left[\tilde{D}(\omega)\right]}{\pi\eta}$$

$$\tilde{D}(\omega) = \int_{t_0}^{t_{max}} D(t)\, e^{i\omega t} dt$$

Electronic dipole polarizability:

$$\alpha_D = \frac{\hbar c}{2\pi^2}\int\frac{\sigma_f}{\omega^2}d\omega = \int_0^\infty E^{-1}S(E)dE$$



(a), (b), and (c) correspond to different values of L, m_v^*

Extracted slope parameter of symmetry energy:

$$L = 53.85 \pm 10.29 \text{ (MeV)}$$

Extracted np effective mass splitting:

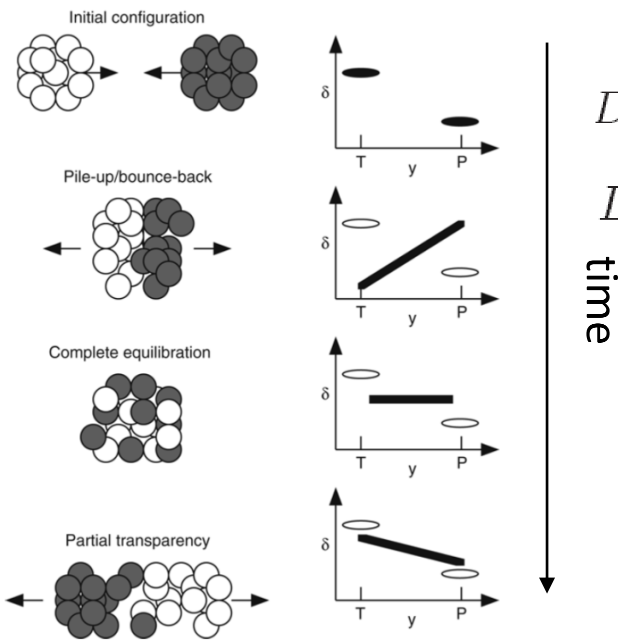
$$(m_n^* - m_p^*)/m = (0.216 \pm 0.114)\delta$$

Hai-Yun Kong, JX*, et al., Phys. Rev. C 95, 034324 (2017)

Isospin transport in HIC

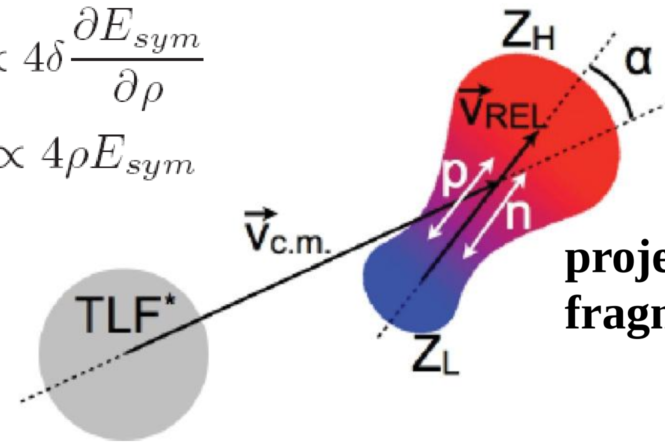
The isovector current: $\vec{j}_n - \vec{j}_p = (D_n^\rho - D_p^\rho)\nabla\rho - (D_n^I - D_p^I)\nabla\delta$

Isospin drift **Isospin diffusion**



$$D_n^\rho - D_p^\rho \propto 4\delta \frac{\partial E_{sym}}{\partial \rho}$$

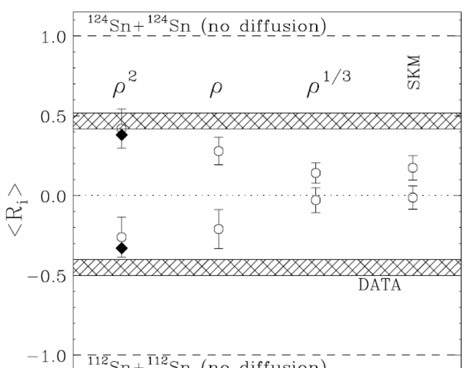
$$D_n^I - D_p^I \propto 4\rho E_{sym}$$



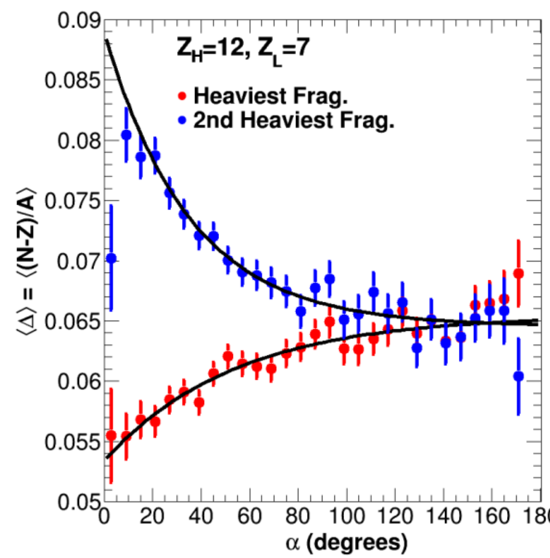
projectile-like fragment

Hudan et al., Phys. Rev. C. 86, 921603(R) (2012)

B.A. Li, L.W. Chen, and C.M. Ko, Phys. Rep. 464, 113 (2008)



M. B. Tsang et al., Phys. Rev. Lett. 92, 062701 (2004)



Jedele et al., Phys. Rev. Lett. 118, 062501 (2017).

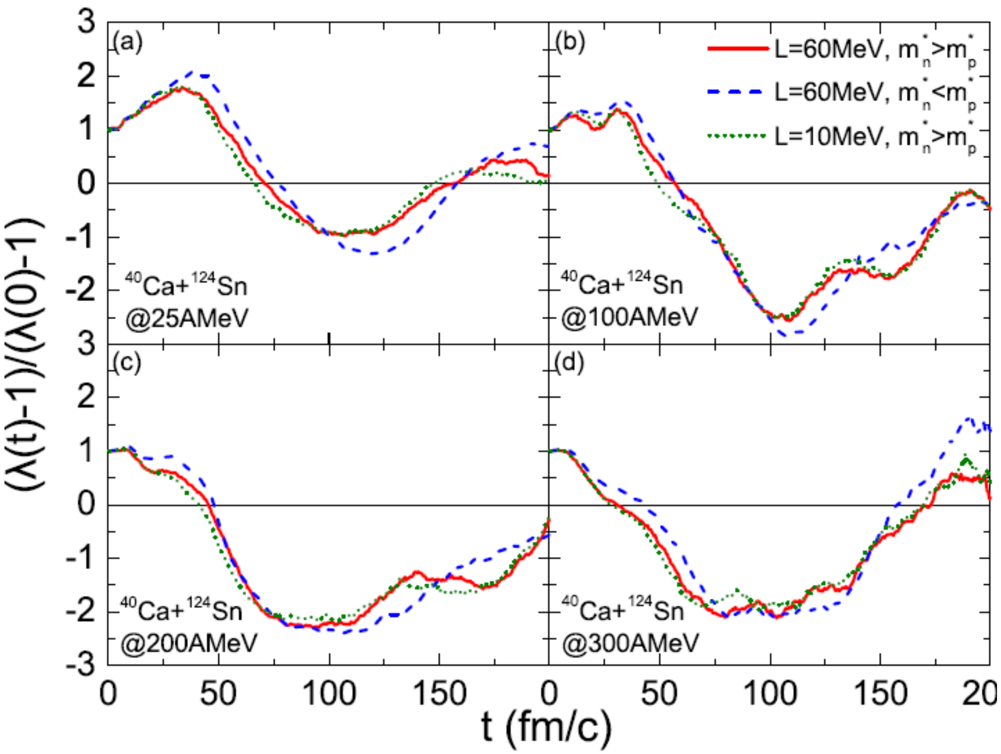
Isospin transport between projectile and target

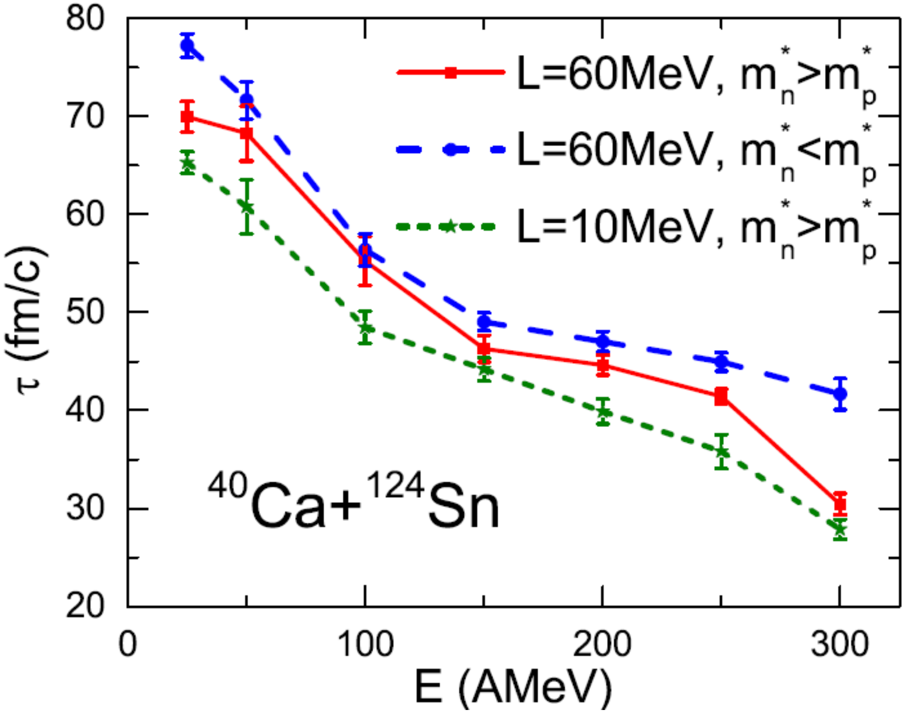
$^{40}Ca+^{124}Sn$@b=1fm

$$\lambda(t) \equiv \frac{(n/p)_{y>0}}{(n/p)_{y<0}}$$

characterizing isospin stopping/equilibrium

Isospin relaxation time τ is defined when the isospin equlibration meter [λ(t)-1]/[λ(0)-1] first crosses 0.

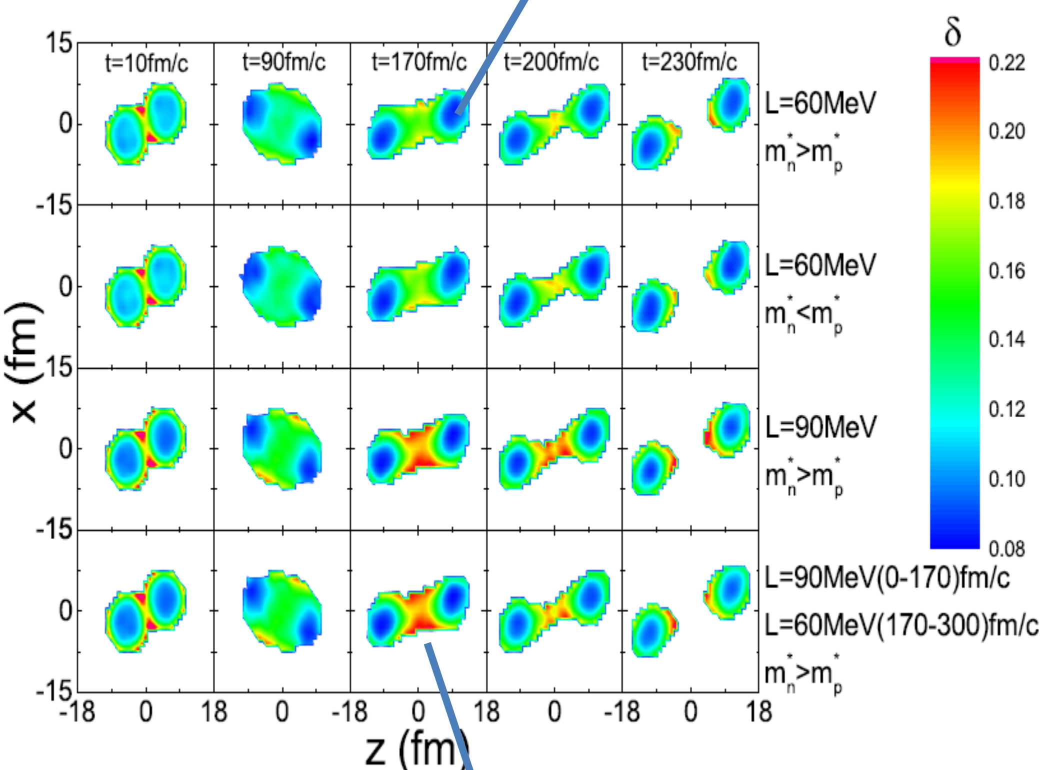




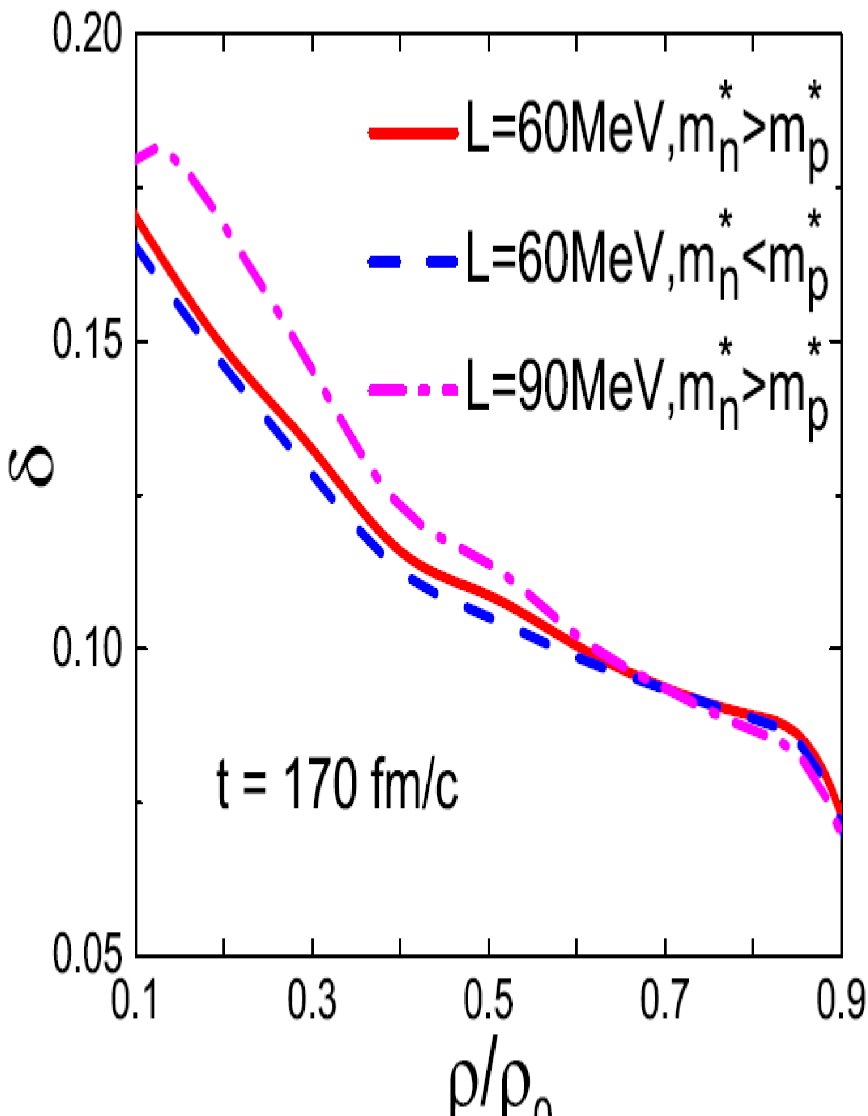
H.S. Wang, JX*, et al., arXiv: 1807.01849 [nucl-th]

Isospin transport between neck and spectator

Normal-density
less neutron-rich spectator



Low-density
neutron-rich neck



H.S. Wang, JX*, et al., arXiv: 1807.01849 [nucl-th]

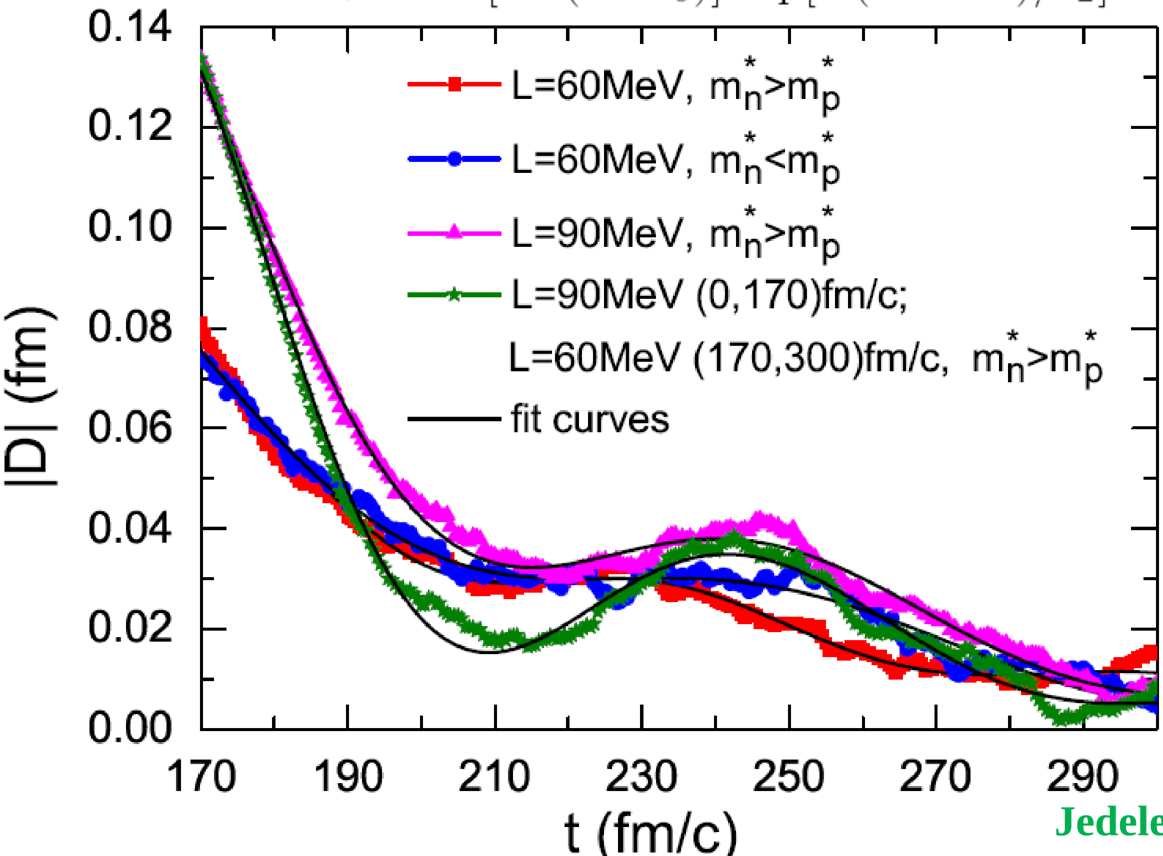
Isospin transport between neck and spectator

Isovector dipole moment for neck-spectator matter

$$\vec{D}(t) \equiv \vec{R}_Z(t) - \vec{R}_N(t)$$

Fit with

$$\left|\vec{D}(t)\right| = a\exp[-(t-170)/\tau_1] + b\cos[\omega\cdot(t-t_0)]\exp[-(t-170)/\tau_2]$$



Isospin relaxation time: Upper envelope of |D| drops to 1/e of its initial value

$$\vec{j}_n - \vec{j}_p = (D_n^\rho - D_p^\rho)\nabla\rho - (D_n^I - D_p^I)\nabla\delta$$

Different initial $\nabla\delta$ from different L

$L(MeV)$	$m_n^* - m_p^*(m)$	$\tau(fm/c)$
60	0.426δ	68.00±1.22
60	-0.251δ	73.52±3.45
90	0.426δ	60.02±1.05
(90,60)	0.426δ	56.30±0.15

TAMU's experiment:

$$\tau = 100 \pm^{233.3}_{66.7}\ fm/c$$

Jedele et al., Phys. Rev. Lett. 118, 062501 (2017)

H.S. Wang, JX*, et al., arXiv: 1807.01849 [nucl-th]

Final remarks

- **The effect of np effective mass splitting is as important as Esym in isospin dynamics of HIC and non-negligible for properties of asymmetric nuclear matter.**

The neutron–proton effective mass splitting $m_{\text{n-p}}(\rho_0)$ in neutron-rich matter of isospin asymmetry δ at saturation density.

Approach	$m_{\text{n-p}}(\rho_0)$	Reference
Optical model Analyses of nucleon–nucleus scattering data	$(0.41 \pm 0.15)\delta$	[41] X.H. Li et al.
Universal nuclear energy density functional	0.637δ	[92] M. Kortelainen et al.
ISGQR, IVGDR & dipole polarizability of ^{208}Pb using SHF+RPA	$(0.27 \pm 0.15)\delta$	[42] Z. Zhang and L.W. Chen
ISGQR, IVGDR & dipole polarizability of ^{208}Pb using IBUU	$(0.216 \pm 0.114)\delta$	[106] K.Y. Kong et al.
General analyses of symmetry energy using HVH theorem	$(0.27 \pm 0.25)\delta$	[67] B.A. Li and X. Han
Chiral effective field theory	$(0.309 \pm 0.227)\delta$	[128,135] Jeremy Holt et al.
BCPM energy functional	0.2δ	[141] M. Baldo et al.
General analyses of energy density functional	$(0.17 \pm 0.24)\delta$	[143] C. Mondal et al.

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Collaborators:

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Lie-Wen Chen (SJTU)

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Han-Sheng Wang

Thank you!

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Backup 1

MDI: from NN interaction to energy density

Effective two-body NN interaction:

$$v(\vec{r}_1, \vec{r}_2) = \frac{1}{6} t_3 (1 + x_3 P_\sigma) \rho^\alpha \left(\frac{\vec{r}_1 + \vec{r}_2}{2} \right) \delta(\vec{r}_1 - \vec{r}_2)$$

$$+ (W + B P_\sigma - H P_\tau - M P_\sigma P_\tau) \frac{e^{-\mu|\vec{r}_1 - \vec{r}_2|}}{|\vec{r}_1 - \vec{r}_2|}$$

Hartree-Fock framework

Potential energy density:

$$H(\rho, \delta) = \frac{A_1}{2\rho_0}\rho^2 + \frac{A_2}{2\rho_0}\rho^2\delta^2 + \frac{B}{\sigma + 1}\frac{\rho^{\sigma+1}}{\rho_0^\sigma}(1 - x\delta^2)$$

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

$$t_3 = \frac{16B}{(\sigma + 1)\rho_0^\sigma},$$

$$x_3 = \frac{3x - 1}{2},$$

$$\alpha = \sigma - 1,$$

$$\mu = \Lambda,$$

$$W = \frac{\Lambda^2}{3\pi\rho_0}(A_1 - A_2 + C_l - C_u),$$

$$B = \frac{\Lambda^2}{6\pi\rho_0}(-A_1 + A_2 - 4C_l + 4C_u)$$

$$H = \frac{\Lambda^2}{3\pi\rho_0}(-2A_2 - C_u),$$

$$M = \frac{\Lambda^2}{3\pi\rho_0}(A_2 + 2C_u).$$

JX and C.M. Ko, PRC 82, 044311 (2010)

Backup 2

The cross section for the scattering of two nucleons in vacuum, from momentum states $\mathbf{k}_1$ and $\mathbf{k}_2$ to states $\mathbf{k}_3$ and $\mathbf{k}_4$ is given by

$$\frac{d\sigma}{d\Omega}=\frac{L^3}{v_{\rm rel}}\frac{2\pi}{\hbar}|t|^2 D_f \ , \qquad (2.1)$$

where L^3 is the normalization volume, $v_{\rm rel}$ the relative velocity,

$$v_{\rm rel}=\hbar|\mathbf{k}_1-\mathbf{k}_2|/m \ ,$$

and the density of final states

$$D_f=L^3 m|\mathbf{k}_3-\mathbf{k}_4|/32\pi^3\hbar^2 \ .$$

Effective mass scaling of NN cross section

$$\frac{1}{\hbar}\frac{de(k,\rho)}{dk}=\frac{\hbar k}{m}+\frac{1}{\hbar}\frac{d}{dk}U(k,\rho)\equiv\frac{\hbar k}{m^*(k,\rho)}$$

$$D_f'=D_f\frac{m^*[\sqrt{\frac{1}{2}(k_3^2+k_4^2)},\rho]}{m}$$

the present context. Using $t'\approx t$ we obtain

$$\frac{d\sigma'}{d\Omega}=\frac{v_{\rm rel}}{v'_{\rm rel}}\frac{D_f'}{D_f}\frac{d\sigma}{d\Omega} \qquad (2.8)$$

$$=\frac{|\mathbf{k}_1-\mathbf{k}_2|}{m}\left[\left|\frac{\mathbf{k}_1}{m^*(k_1,\rho)}-\frac{\mathbf{k}_2}{m^*(k_2,\rho)}\right|\right]^{-1}$$

$$\times\frac{m^*[\sqrt{(k_3^2+k_4^2)/2},\rho]}{m}\frac{d\sigma}{d\Omega} \ . \qquad (2.9)$$

Pandharipande and Peiper PRC (1992)

PHYSICAL REVIEW C, VOLUME 65, 045201

Asymmetric nuclear matter: The role of the isovector scalar channel

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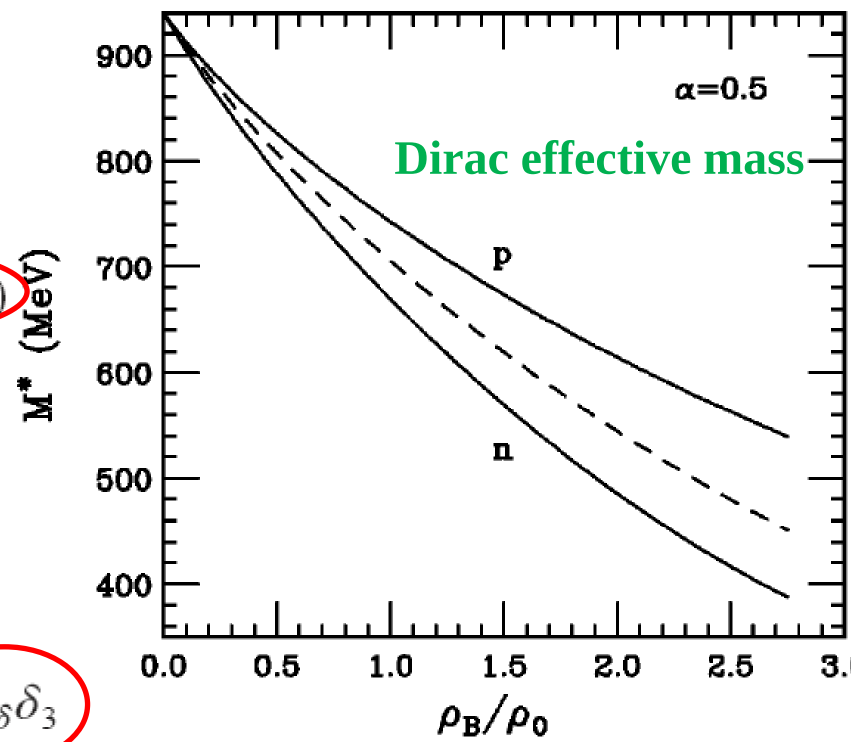
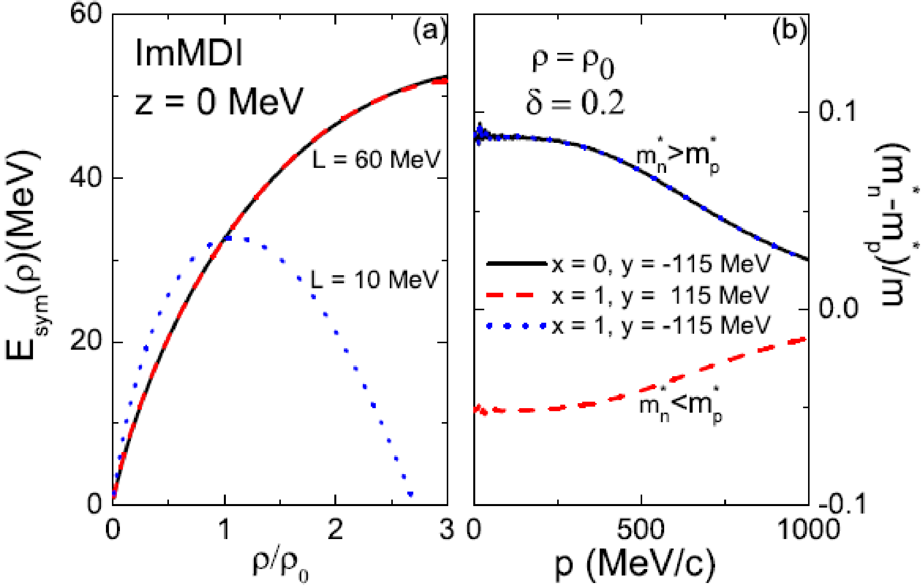
Langrangian $\sigma, \omega, \rho, \delta$

$$\mathcal{L}=\bar{\psi}[i\gamma_\mu\partial^\mu-(M_N-g_\sigma\phi-g_\delta\vec{\tau}\cdot\vec{\delta})-g_\omega\gamma_\mu\omega^\mu-g_\rho\gamma^\mu\vec{\tau}\cdot\vec{b}_\mu]\psi+\tfrac{1}{2}(\partial_\mu\phi\partial^\mu\phi-m_\sigma^2\phi^2)-U(\phi)+\tfrac{1}{2}m_\omega^2\omega_\mu\omega^\mu+\tfrac{1}{2}m_\rho^2\vec{b}_\mu\cdot\vec{b}^\mu+\tfrac{1}{2}(\partial_\mu\vec{\delta}\cdot\partial^\mu\vec{\delta}-m_\delta^2\vec{\delta}^2)-\tfrac{1}{4}F_{\mu\nu}F^{\mu\nu}-\tfrac{1}{4}\vec{G}_{\mu\nu}\vec{G}^{\mu\nu}.$$

Field equation $m_\delta^2\delta_3=g_\delta\bar{\psi}\tau_3\psi=g_\delta\rho_{S3}$

Nucleon effective mass $M_i^\star=M_N-g_\sigma\phi\mp g_\delta\delta_3$

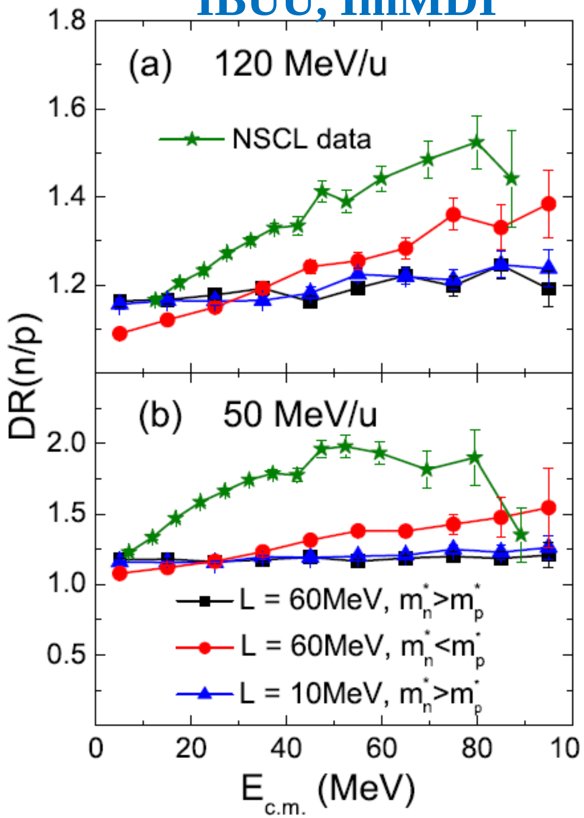




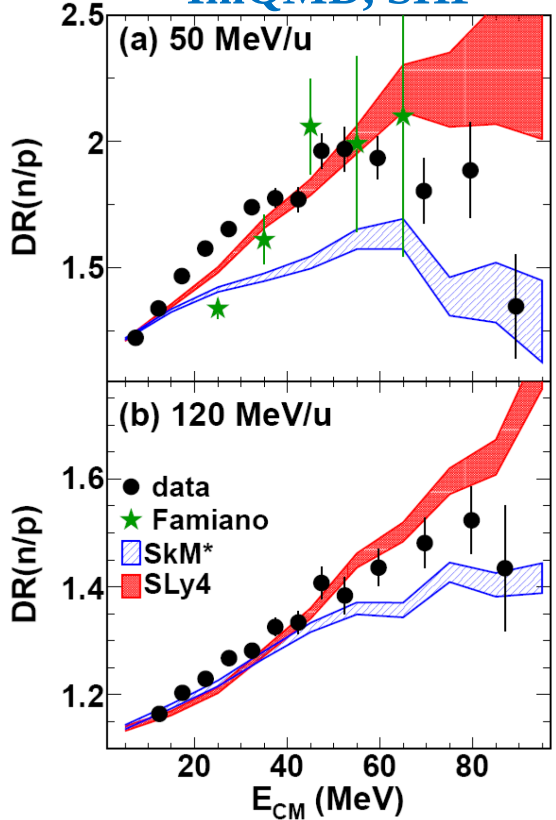
Skyrme	S_0(MeV)	L (MeV)	m_n^*/m_n	m_p^*/m_p
SLy4	32	46	0.68	0.71
SkM*	30	46	0.82	0.76

D.D.S. Coupland et al., arXiv:1406.4546

IBUU, ImMDI



ImQMD, SHF

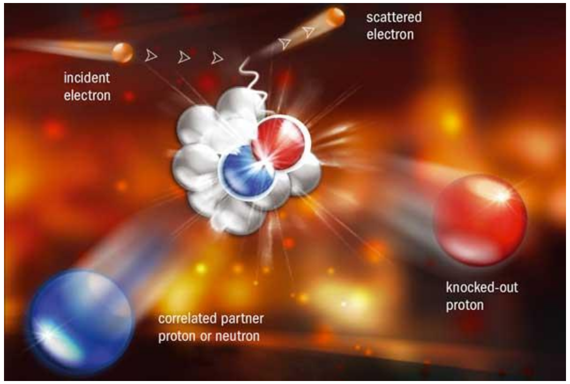


$$\mathrm{DR(n/p)} = \frac{[Y(n)/Y(p)]_{^{124}\mathrm{Sn}+^{124}\mathrm{Sn}}}{[Y(n)/Y(p)]_{^{112}\mathrm{Sn}+^{112}\mathrm{Sn}}}$$

Still below the NSCL/MSU data no matter how the symmetry energy and effective mass splitting is adjusted.

H.Y. Kong, Y. Xia, JX*,
L.W. Chen, B.A. Li, and Y.G. Ma
PRC 91, 047601 (2015)

How to explain DR(n/p) data?



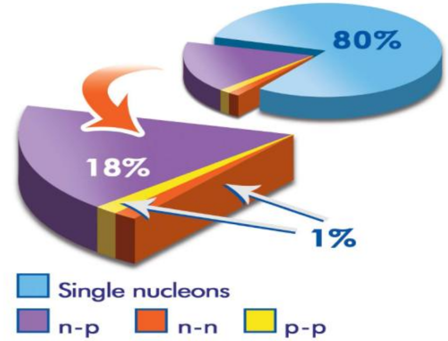


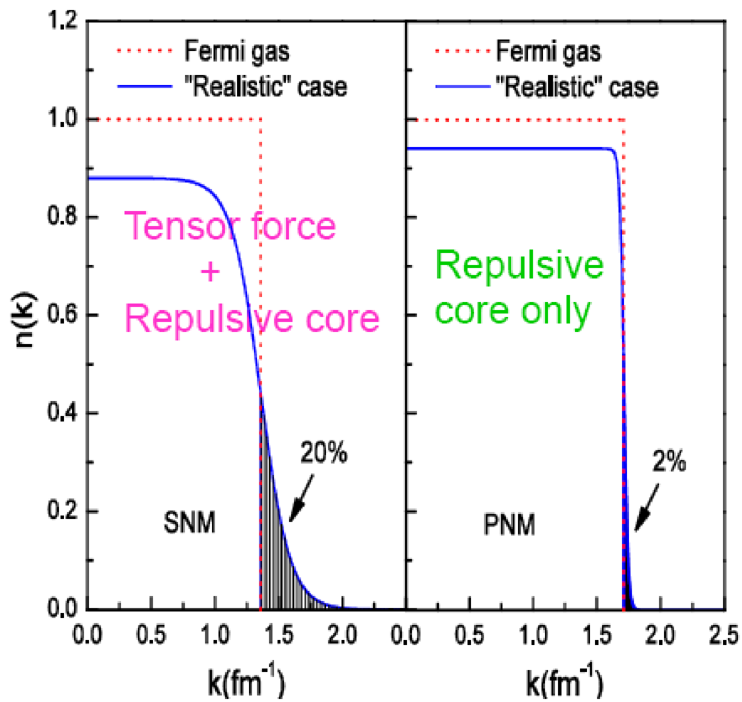
Figure 3: The average fraction of nucleons in the various initial state configurations of ^{12}C.

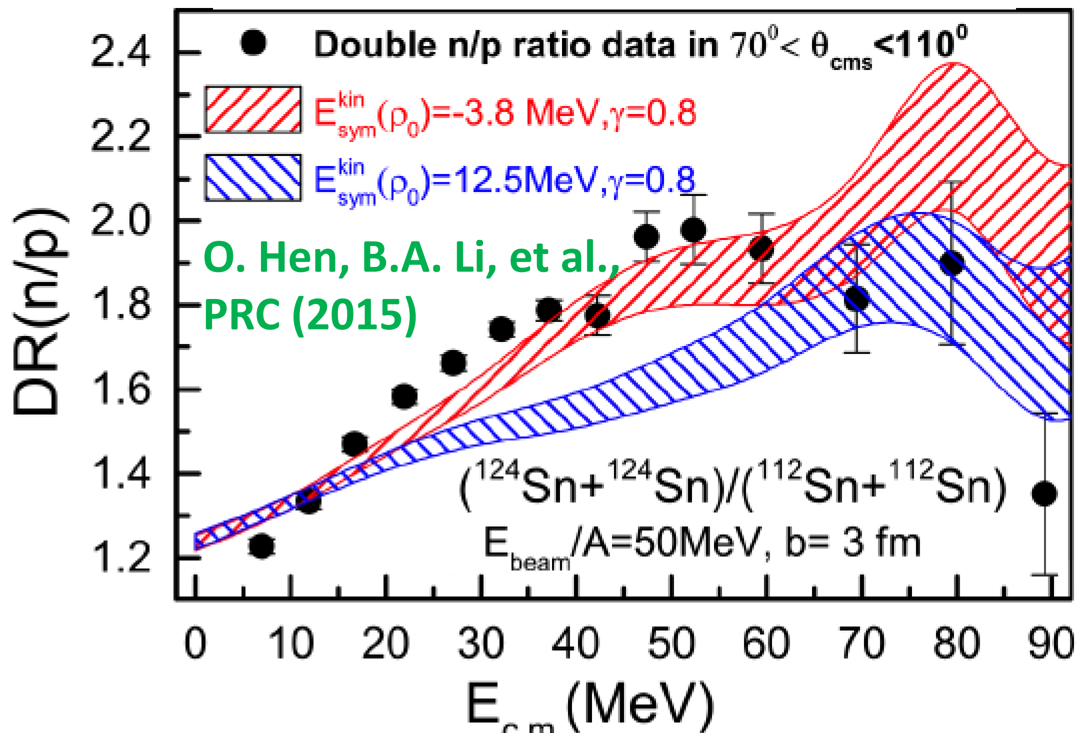
$$E_{kin} = \alpha \int_0^\infty \frac{\hbar^2 k^2}{2m} n(k) k^2 dk$$

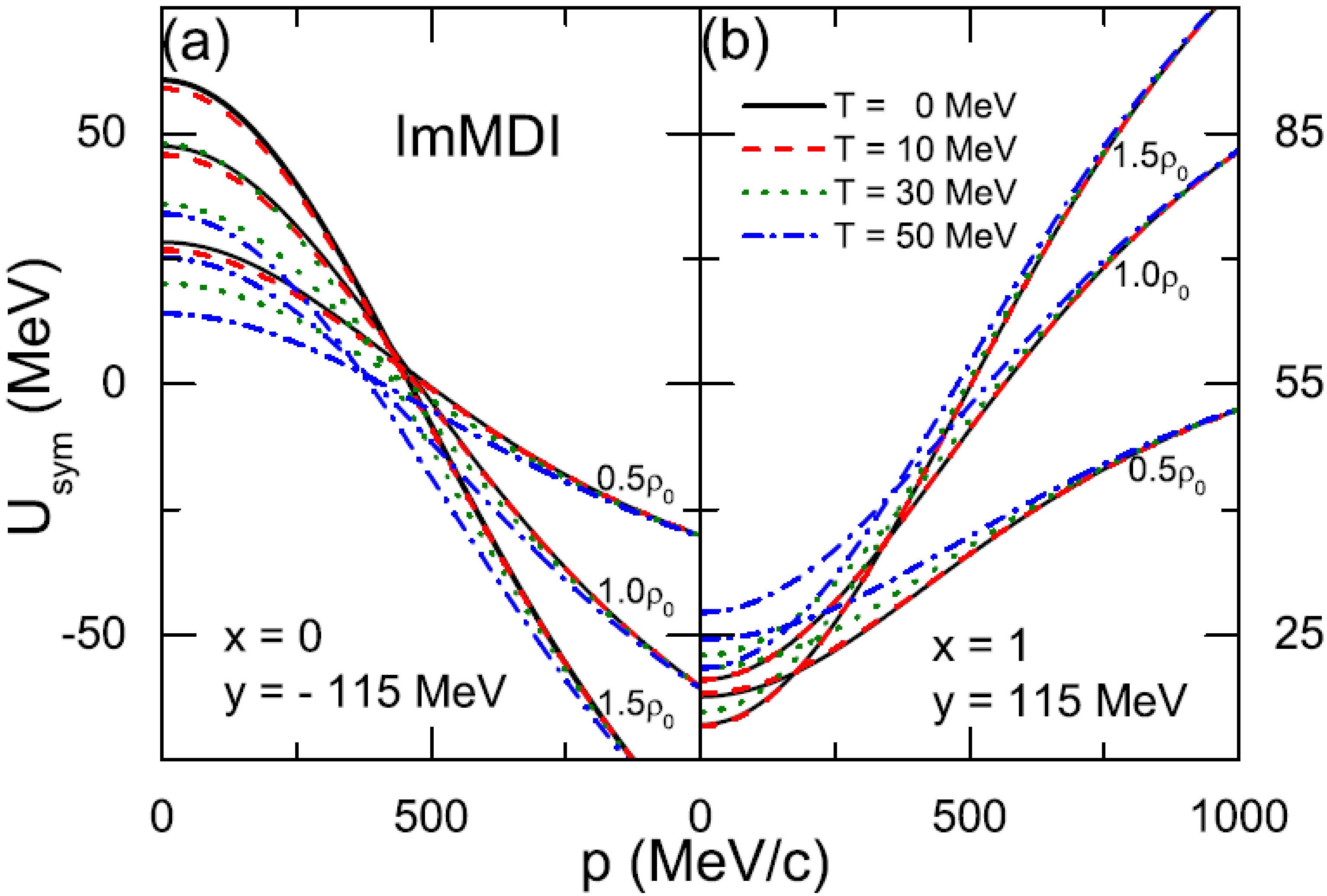
$$E^{kin}_{sym} = E^{kin}_{PNM} - E^{kin}_{SNM} < 0$$

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

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







(x=0, y=-115 Mev) and (x=1,y=115 MeV) have almost the same density dependence of Esym, but Usym at lower momenta is different, and the difference increases with increasing density.

JX, L.W. Chen, and B.A. Li, PRC 91, 014611 (2015)