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Constraints on symmetry energy and n/p effective mass splitting with HICs

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Outline

1, Symmetry energy and n/p effective mass splitting

2, constraints on symmetry energy and n/p effective mass splitting with new version of ImQMD

A, new version of ImQMD (ImQMD-Sky)
B, Ri and Ri(y)
C, DR(n/p)
D, DR(n/p) at higher beam energy

3, Conclusions

Theoretical predictions on the EOS

1, Phenomenological density functional (Based on Gogny or Skyrme force or RMF)

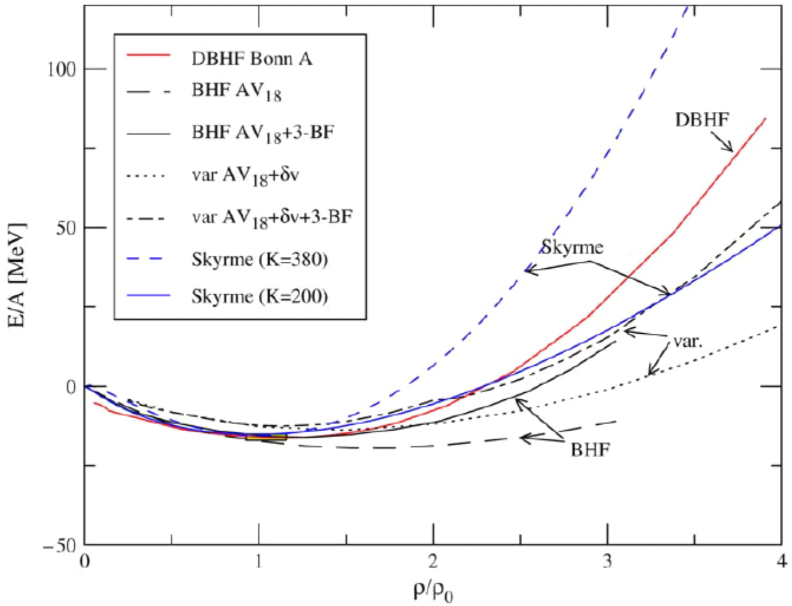
2, Effective field theory approaches (Based on Chiral perturbation theory, ……)

3, Ab initio approaches (Based on the high precision free space nucleon-nucleon interaction)

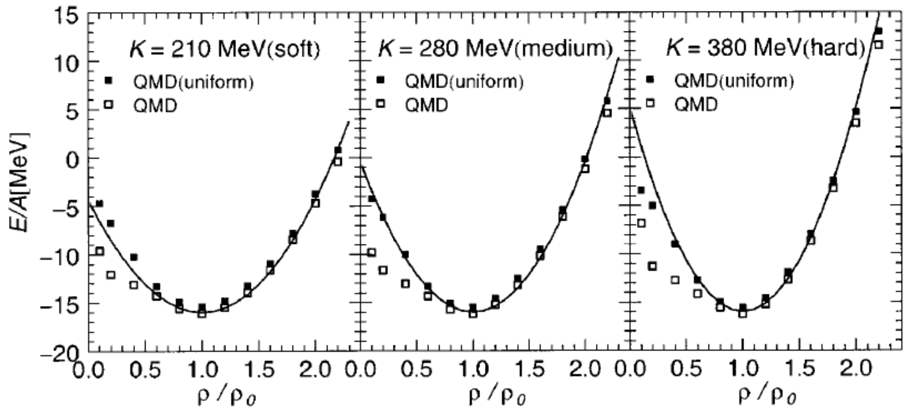
4, Molecular dynamics approaches (Many-body correlation, beyond mean field)

G.Peiler,. et.al. PLB260,271(1991),
T.Maruyam, et.al, PRC57,665(1998)
M.Papa, et.al.PRC87,014001(2013)

C. Fuchs / Progress in Particle and Nuclear Physics 56 (2006) 1–103



T.Maruyama, et.al, PRC57,665(1998



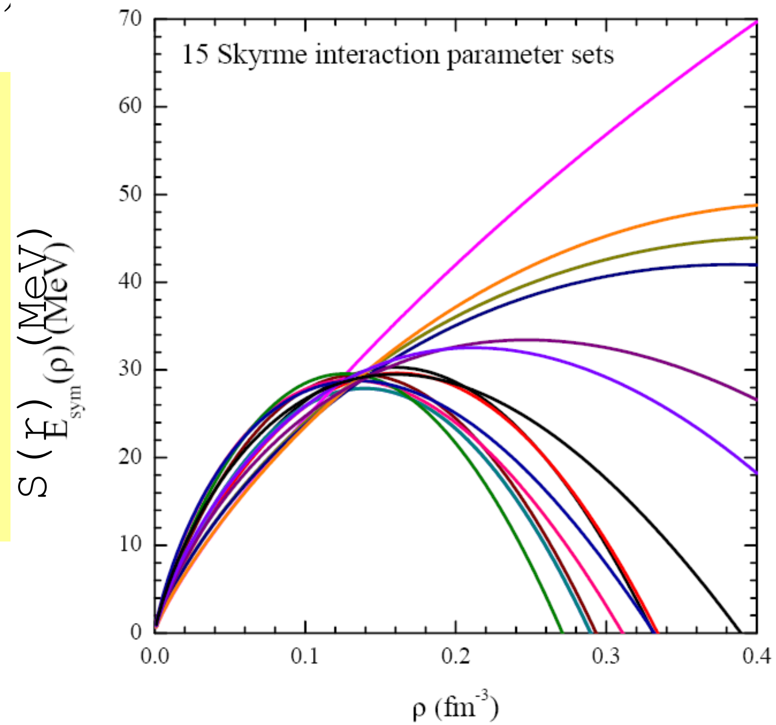
Periodic boundary condition

Isospin asymmetric Equation of State

$$E(\rho,\delta) = E(\rho,\delta=0) + S(\rho)\delta^2 + O(\delta^4)$$

It is a fundamental properties of nuclear matter, and is very important for understanding

- *properties of nuclear structure*
- *properties of neutron star*
- *properties of heavy ion reaction mechanism*



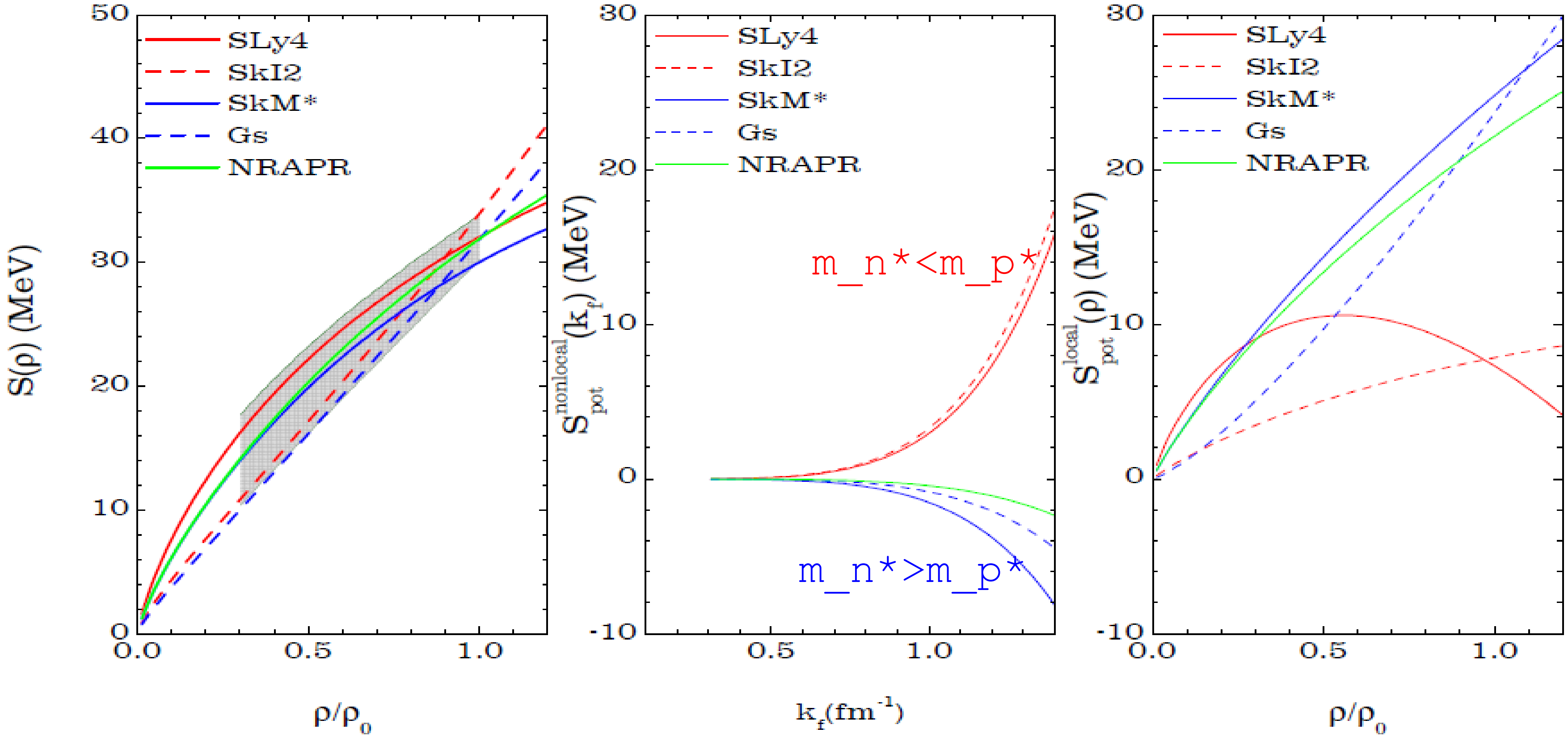
S(r) is the density dependence of symmetry energy, it is a key ingredient of the isospin asymmetric *EOS. However, S(r)* uncertainty

Symmetry energy and n/p effective mass splitting

Besides depending on the nuclear density, the symmetry potential also depends on the momentum or energy of a nucleon.

$$S(\rho) = K + S_{loc}(\rho) + S_{nlc}(\rho, k\_F)$$

For cold nuclear matter



Constraining Symmetry energy and n/p effective mass splitting with heavy ion collisions

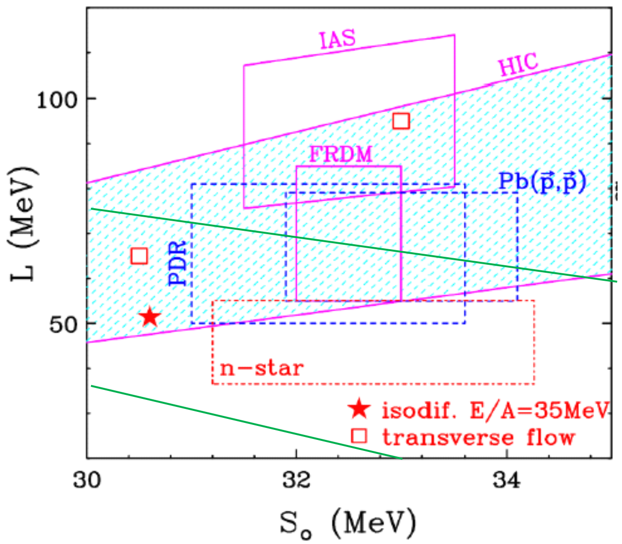
Recent progress: constraints on symmetry energy at subsaturation density

ImQMD (DR, Ri, R_7) 50MeV/A, 35Me

M.B.Tsang, Yingxun Zhang, et.al., PF

- Ri: M.B. Tsang, Yingxun Zhang, LWChen, BALi, M.Colonna, Coupland et al
- DR(n/p): Famiano, BALi, Yingxun Zhang, S.Kumar, YGMa, ZQFeng , ……

- IAS: Danielewicz, et.al.,
- PDR(Pb): A. Klimkiewicz, ….
- N-Star, A.Steiner, ….
- FRDM: P. Moller, .. ; Mass: M. Liu, FSZhang, et.al. ,
- M_12,
- alpha-



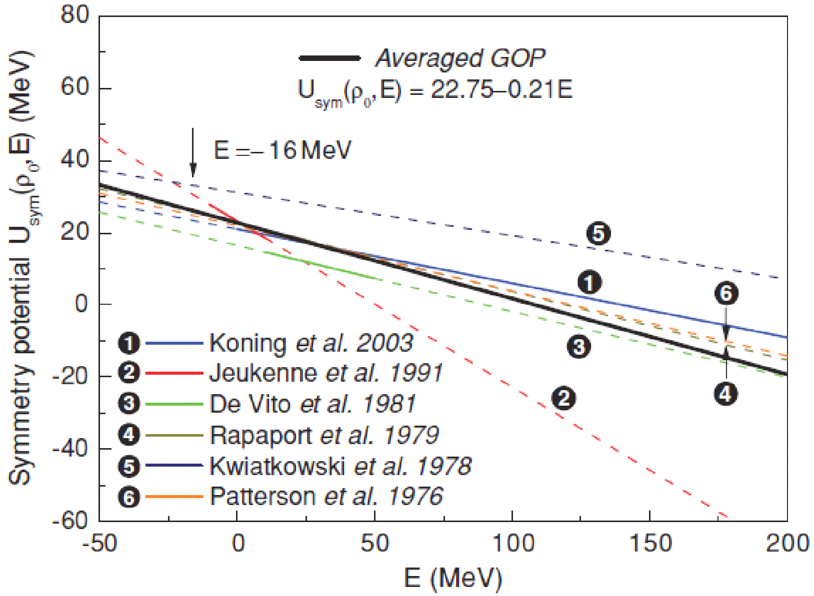
$$S(\rho) = S_0 + \frac{L}{3}\left(\frac{\rho-\rho_o}{\rho_o}\right) + \frac{K_{\rm sym}}{18}\left(\frac{\rho-\rho_o}{\rho_o}\right)^2 + \ldots,$$

Different in detail ! Depends on the model.

Challenges in the constraints on symmetry energy.

Momentum dependence of symmetry potential (n/p effective mass splitting)is ***Uncertainty! We need to constrain it as well as density dependence of symmetry energy.***

- Constraints on the n/p effective mass splitting (mn*>mp*) around normal density has been obtained by analyzing $U_{sym}(\rho_0,E)$ from nucleon-nucleus optical potential data. (B.A.Li, C. Xu, et.al., PRC2006,2010).



CXu,BALi,LWChen, PRC82,054607

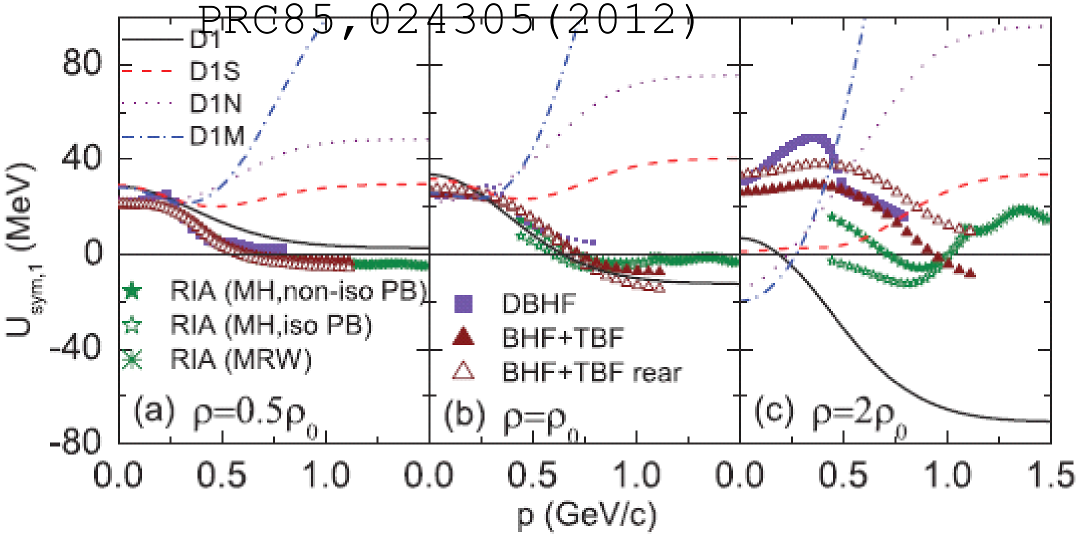
$U_{sym}(\rho_0,E)=22.75-0.21E$

$m_n^*>m_p^*$

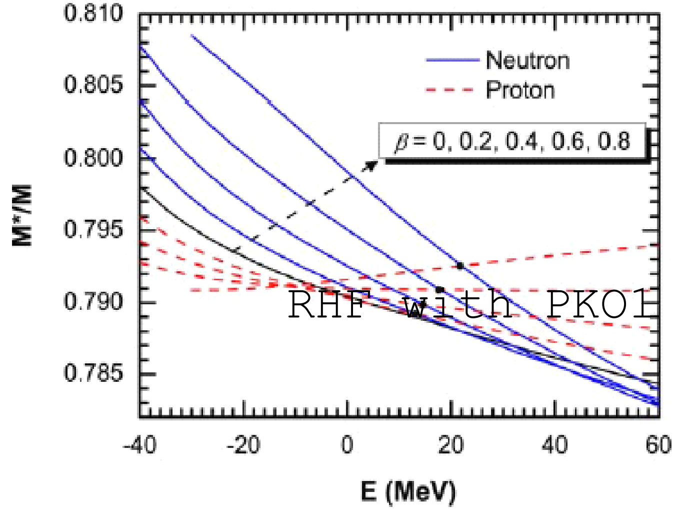
$(m_n^*-m_p^*)/m=0.32\delta$

- Need more information on symmetry potential (n/p effective mass splitting away from normal density and Fermi momentum)
  - Sign of effective mass splitting can be changed with energy?
  - behaviors of symmetry potential ?
- HICs (away from normal density and Fermi momentum)

R Chen, BJ Cai, LWChen, BALi, XHLi, CXu, PRC85,024305(2012)



WHLong, N Van Giai, J.Meng, PLB64



- Several works has been done for proposing the HIC observables which are sensitive to the momentum dependence of symmetry potential(or n/p effective mass splitting).
    - J.Rizzo, et.al., Phys.Rev.C (2005), n/p (p_
    - H.H.Wolter, et.al.,; t/He3 (p_t) ;
    - Z.Q Feng, et.al. PLB2012, DR(n/p) (pt), DR(
    - …… .

Here, we would like to constrain the symmetry energy and n/p effective mass splitting simultaneously by comparing HIC data with the transport model calculations.

2, constraints on the symmetry energy and n/p ef

One of best choices in transport models is to use full Skyrme EDF

1. The Skyrme parameter sets have been adjusted for fitting the properties of nuclear matter, binding energy, actinide fission barrier, masses, …… Thus, E_0, K_0, S_0, L, K_{sym}, m*_s, m*_v, ……. are correlated.

2. In Skyrme EDF, one can easily choose different values L, m*_v for similar K_0 and S_0, m*_s.

If one use the Skyrme interaction in transport models, one could get the constraints on Skyrme parameters, also on symmetry energy and n/p effective mass splitting from reaction data simultaneously.

New version of ImQMD

In the new version of ImQMD code, nucleons are represented by Gaussian wavepackets and the mean fields acting on these wavepackets are derived from an energy functional with the potential energy U that includes the full Skyrme potential energy without the spin-orbit term:

$$U = U_\rho + U_{md} + U_{coul} \tag{2}$$

and U_{coul} is the Coulomb energy. The nuclear contributions are represented in a local form with

$$U_{\rho,md} = \int u_{\rho,md} d^3 r \tag{3}$$

and

$$\begin{aligned} u_\rho = & \frac{\alpha}{2}\frac{\rho^2}{\rho_0} + \frac{\beta}{\eta+1}\frac{\rho^{\eta+1}}{\rho_0^\eta} + \frac{g_{sur}}{2\rho_0}(\nabla\rho)^2 \\ & + \frac{g_{sur,iso}}{\rho_0}[\nabla(\rho_n - \rho_p)]^2 \\ & + A_{sym}\rho^2\delta^2 + B_{sym}\rho^{\eta+1}\delta^2 \end{aligned}$$

$$\begin{aligned} u_{md} &= u_{md}(\rho\tau) + u_{md}(\rho_n\tau_n) + u_{md}(\rho_p\tau_p) \\ &= C_0 \int d\vec{p}\, d\vec{p}'\, f(\vec{r},\vec{p}) f(\vec{r},\vec{p}')(\vec{p}-\vec{p}')^2 \\ &\quad + D_0\left[\int d\vec{p}\, d\vec{p}'\, f_n(\vec{r},\vec{p}) f_n(\vec{r},\vec{p}')(\vec{p}-\vec{p}')^2 + \int d\vec{p}\, d\vec{p}'\, f_p(\vec{r},\vec{p}) f_p(\vec{r},\vec{p}')(\vec{p}-\vec{p}')^2\right] \end{aligned} \tag{5}$$

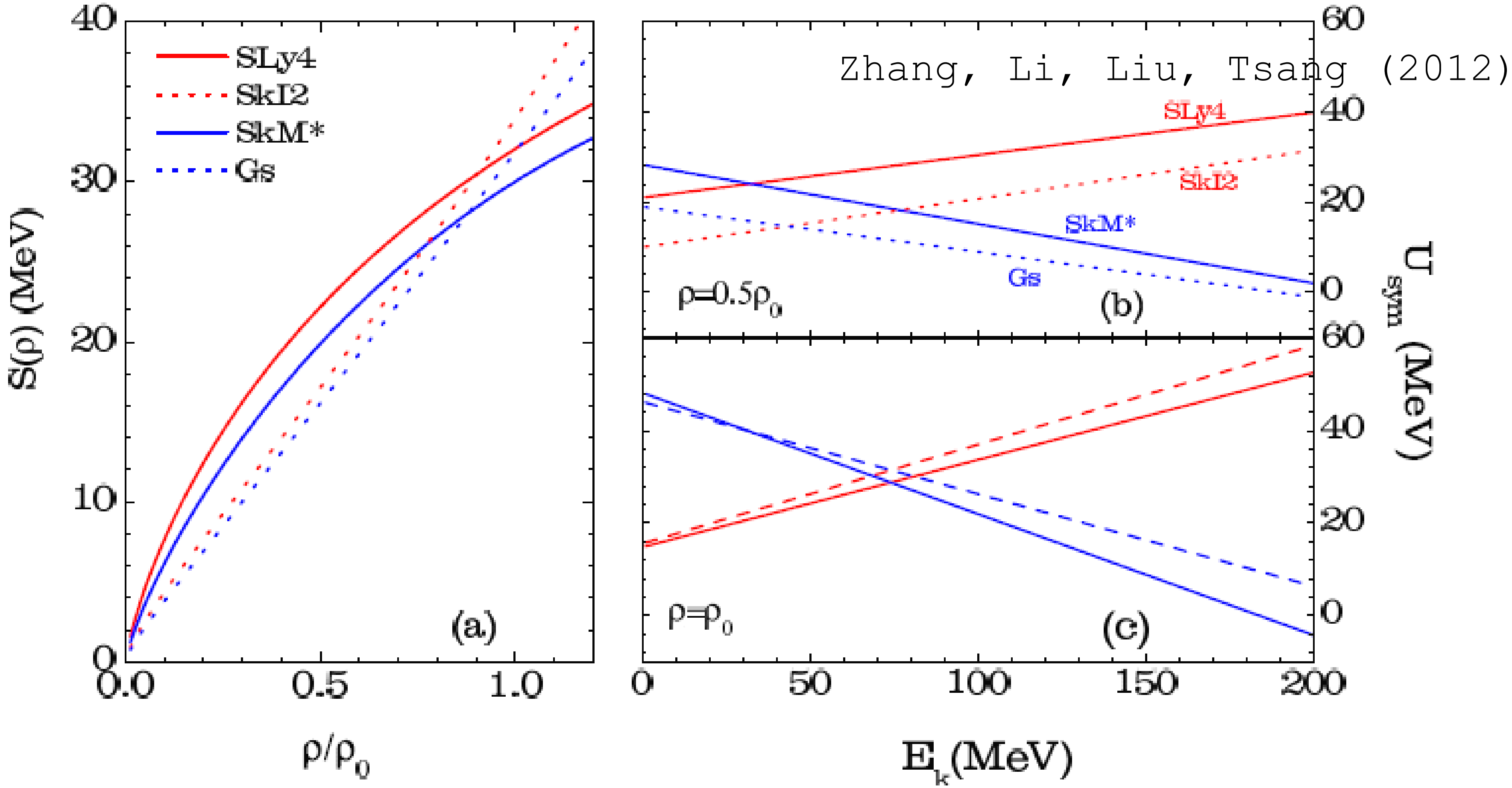
Select four parameter sets

$K_0 = 230 \pm 20MeV$, $S_0 = 32 \pm 2MeV$, m*_s=0.
different *L* and *n/p effective mass splitt*

Para.	Rho_0	E_0	K_0	Q_0	*J*	*L*	K_{sym}	m*_s	m*_n/m*_p
SLy4	0.16	-15.97	229.91	363.11	32	46	-120	0.69	<1
SkI2	0.158	-15.78	240.93	339.70	33	104	71	0.68	<1
SkM*	0.16	-15.77	216.61	386.09	30	46	-156	0.79	>1
Gs	0.158	-15.59	237.29	348.79	31	93	14	0.78	>1

	Small L	Large L
m_n*<m_p*	SLy4 (L=46MeV)	SkI2 (L=104MeV)
m_n*>m_p*	SkM* (L=46MeV)	Gs (L=93MeV)

Corresponding density dependence of symmetry energy , and the symmetry potential as a function of nucleon energy



- The Larger the L is, the smaller the symmetry
- The larger the U_{sym} is, the larger the n/p rat

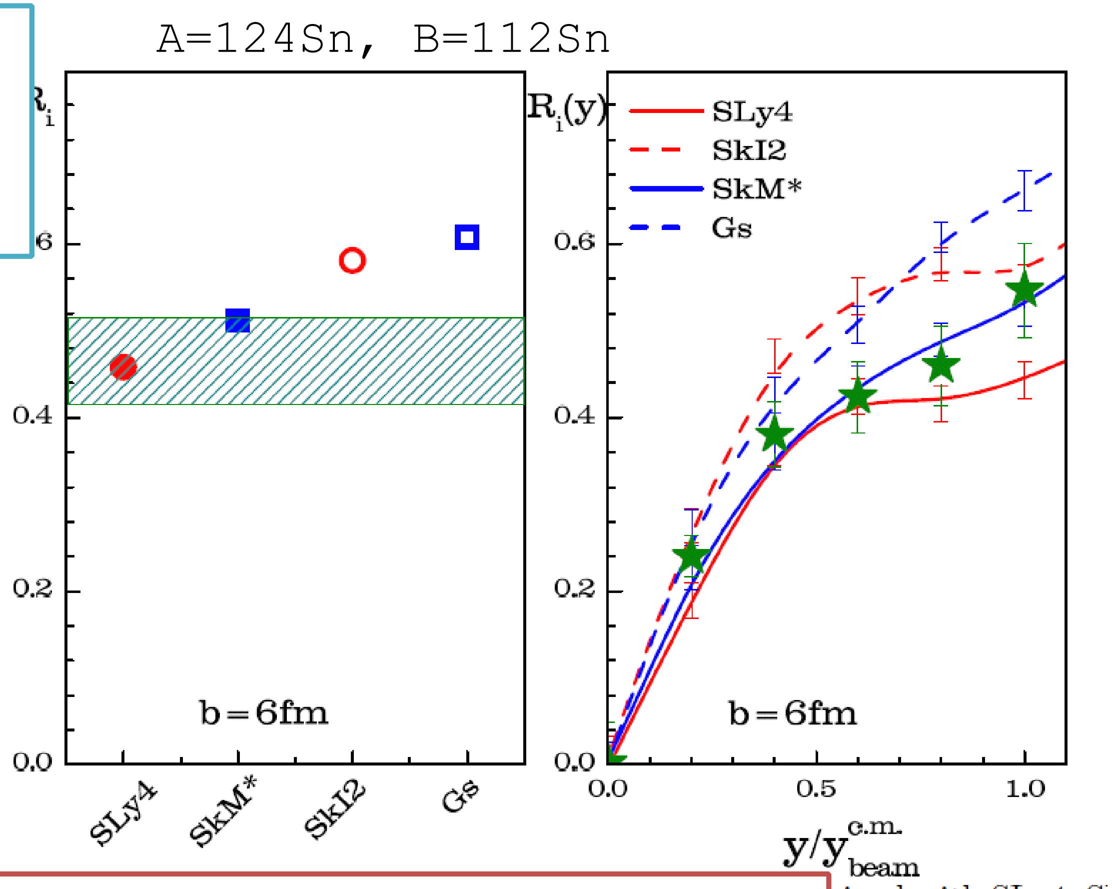
Isospin diffusion and isospin transport ratios as a function of rapidity

Isospin diffusion occurs only in asymmetric systems A+B, and diffusion ability depends on the symmetry energy and n/p effective mass splitting.

For $m^*_n < m^*_p$, the isospin diffusion process is accelerated due to larger Lane potential at subsaturation density.

$R_i=(2X-X_{AA}-X_{BB})/(X_{AA}-X_{BB})$

In absence of isospin diffusion R=1 or R=-1,
R~0 for isospin equilibrium



Ri(SLy4, L=46MeV, m*_n<m*_p)<Ri(SkM*, L=46MeV, m*_n>m*_p) < Ri(SkI2, L=104MeV, m*_n<m*_p)<Ri(Gs, L=93MeV, m*_n>m*_p)

R_i is more sensitive to L than n/p effective mass splitting.

The calculated results of Ri from SLy4 and SkM* can fall in the data range

For SLy4 and SkM*, they have S_0=30-32M

Chi-square analysis on Ri(y)

	Chi-Square
SLy4	9.41
SkM*	1.62
SkI2	22.64

The Ri(y) data fit the results from SkM* among four parameter sets.

SkM*:

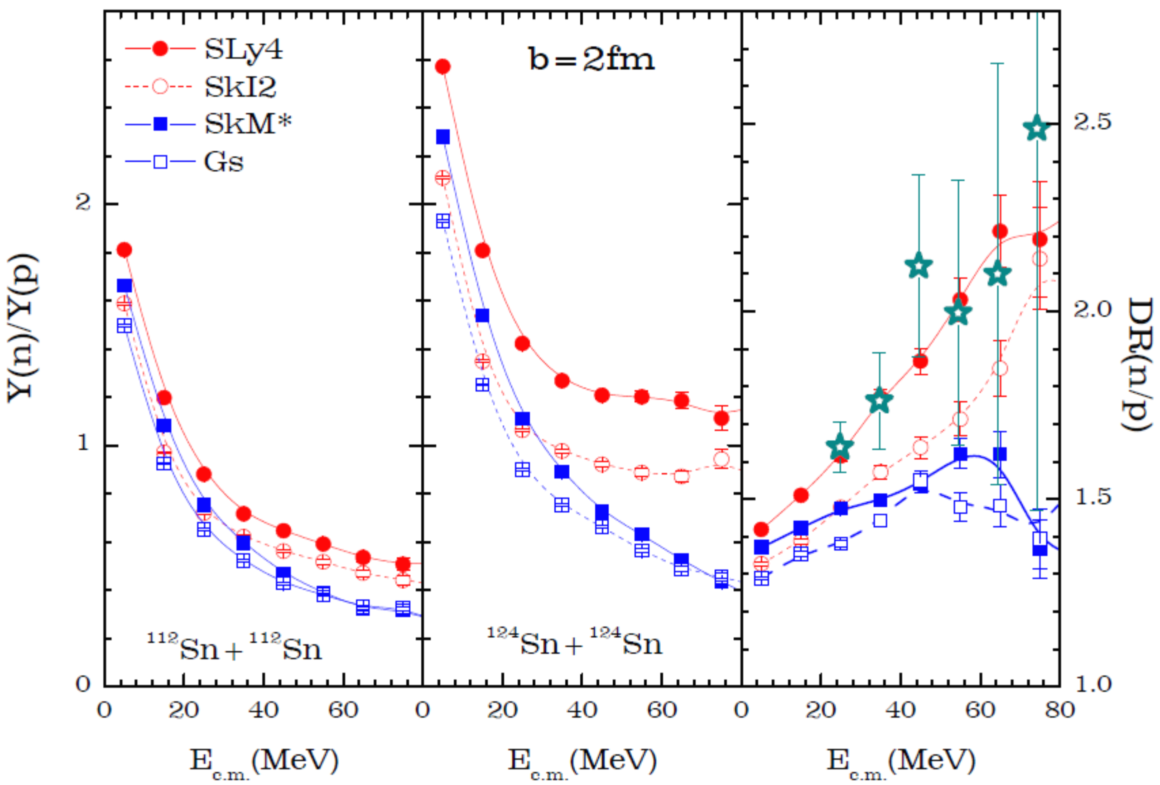
S_0=30MeV, L=46Mev, K_{sym}=-156MeV, m*=0.79 and $m^*_n > m^*_p$

n/p and DR(n/p) ratios as a function of kinetic energy

$$R_{n/p} = Y(n)/Y(p) = \frac{dM_n / dE_k}{dM_p / dE_k}$$

DR(n/p)=$R_{n/p}$(124)/$R_{n/p}$(112)

50AMeV, b=2fm



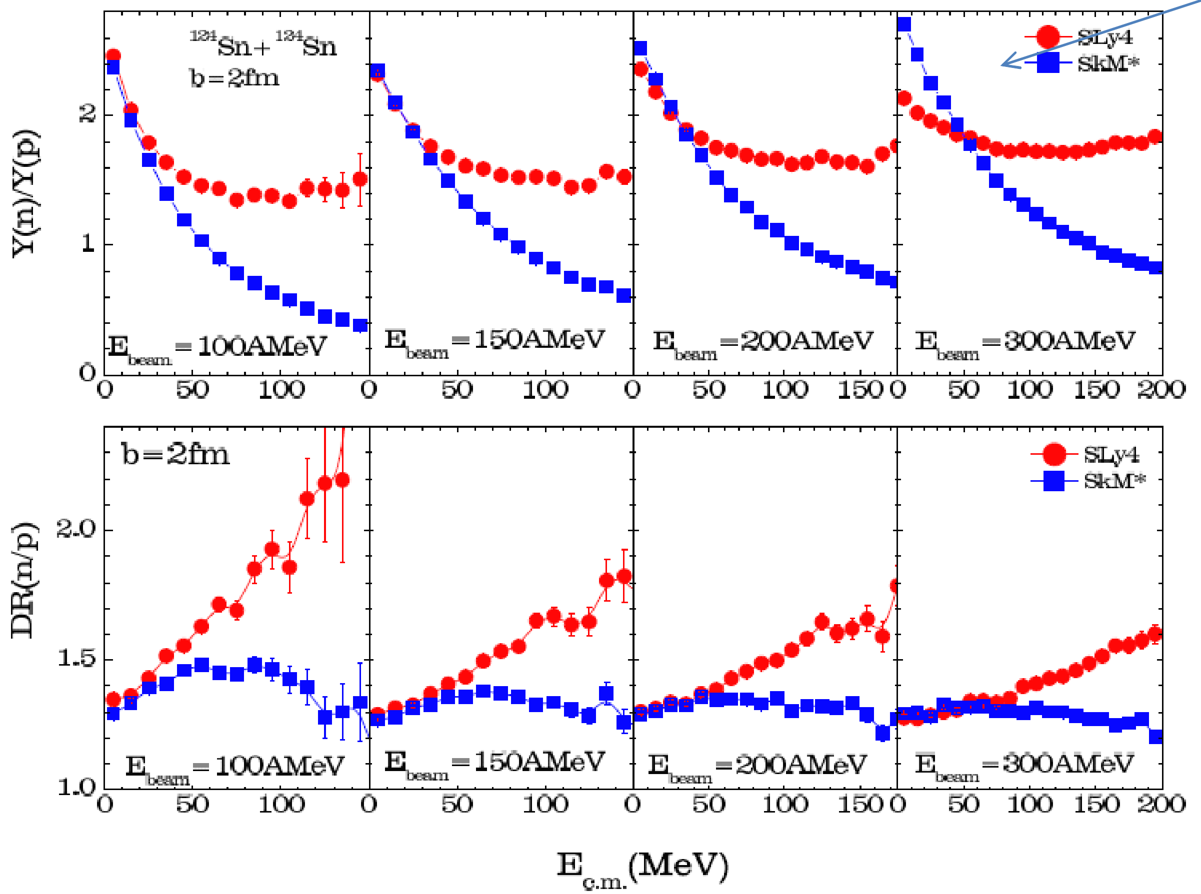
- The Larger the L is, the smaller the n/p ratio is.
- $m^*_n < m^*_p$ enhance the Y(n)/Y(p) ratios at higher kinetic energy region.
- DR(n/p) ratios are sensitive to the n/p effective mass splitting.

•Reproducing the data at high E_k requires larger symmetry potential, and thus **$m^*_n < m^*_p$ at high momentum**

n/p and DR(n/p) at different beam energy

SLy4 (S_0=32MeV, L=46MeV, $m^*_n<m^*_p$)
SkM* (S_0=30MeV, L=46MeV, $m^*_n>m^*_p$)

Cross over



- For higher beam energy, the Y(n)/Y(p) obtained with $m^*_n>m^*_p$ are greater than that with $m^*_n<m^*_p$ cases at lower kinetic energy for Skyrme type symmetry potential

3, Conclusion

1, Developed a new version of ImQMD which can accommodate the Standard Skyrme interaction in parameters. It can bridge the reaction and structure study by using same EDF.

2, The Ri, Ri(y) support the SLy4 and SkM* interactions, they have L=46MeV.

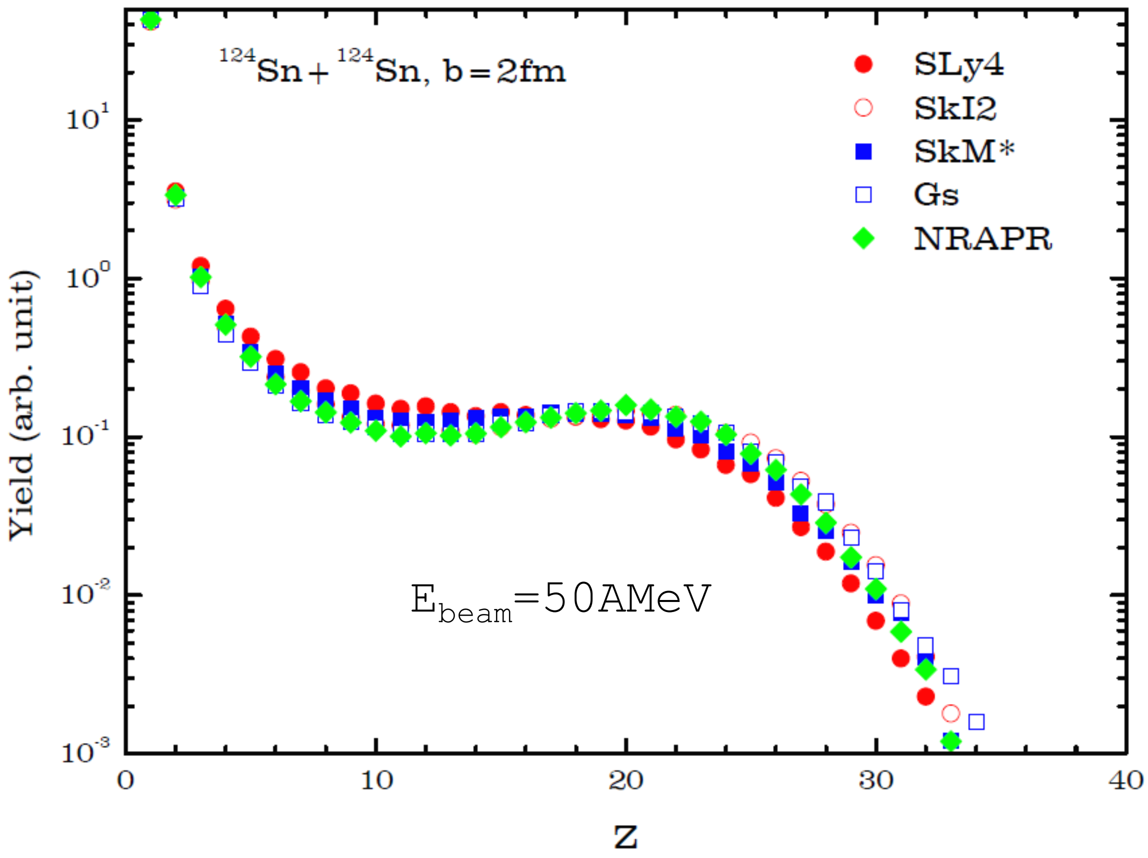
3, **Isospin diffusion data Ri(y) support the neutron effective mass is greater than proton effective mass (mn*>mp*) around k_f. Reproducing the DR(n/p) ratios at high kinetic energy require larger symmetry potential at high k, and thus mn*<mp* at high momentum.**

4, We still needs further experiments at higher incident energies, and more theoretical collaborations.

Thanks a lot for Prof. Bao-An Li, Lie-Wen Chen helpful communications and comments!

Thanks for your attention

Charge distribution



Weak dependence on the parameters we selected

E_{beam}=50AMeV, ^{124}Sn+^{124}Sn, ^{112}Sn+^{112}Sn