7th ANL/INT/JINA/MSU annual FRIB workshop

Interfaces Between Nuclear Reactions and Structure

Extracting the symmetry energy with transport model

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Outline

1. Recent progress in constraining symmetry energy and their differences
2. Understanding it with QMD type model
   - ImQMD05
   - the influence of
     - symmetry potential
     - In-medium NN cross section
     - Impact parameter
     - Cluster formation

     on heavy collision observables for Sn+Sn at 50AMeV
3. Conclusions and discussion

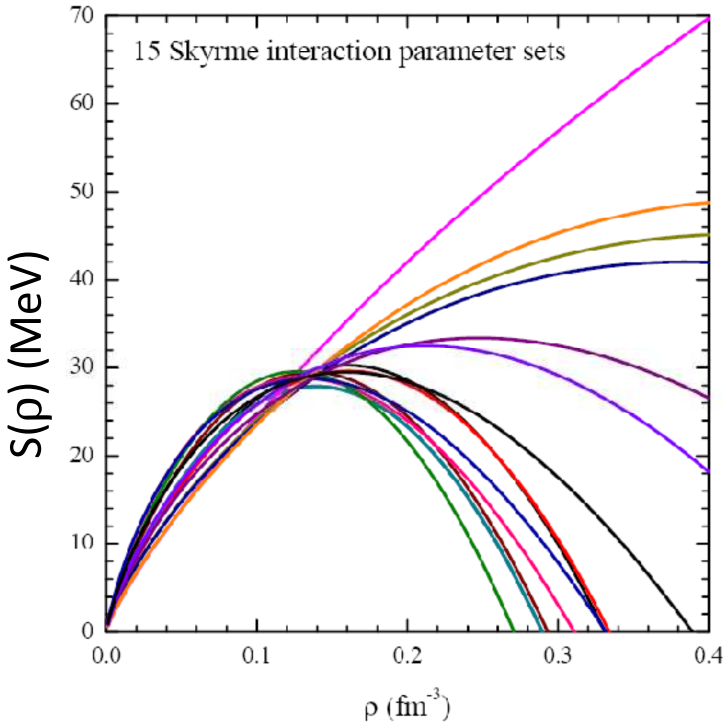
1, Recent progress in constraining symmetry energy and its difference

Isospin asymmetric nuclear Equation of State

It is a fundamental properties of nuclear matter, and is very important for understanding
masses,
fission barriers,
thickness of the neutron skins of neutron-rich nuclei.
properties of Neutron Star, ...

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

Symmetry energy



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

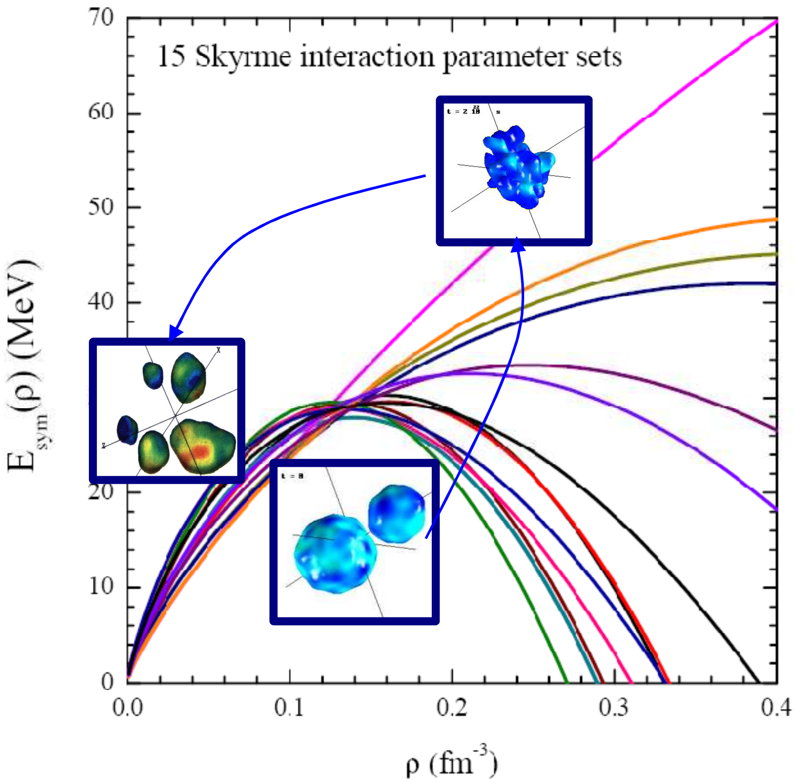
Strategies for constraining the symmetry energy

1, Astrophysical measurements
2, Nuclear structuer
3, Heavy Ion Collisions

large regions of ρ, T, δ,

measure the N/Z ratios of the emitted particles (n/p ratios, isospin diffusion, t/He3, N/Z ratios of IMFs, flow, pi-/pi+, ……)

compare with the prediction from the transport model, in which the different symmetry potential can be used.



the symmetry energy information can be extracted.
Indirectly! (depends on models)

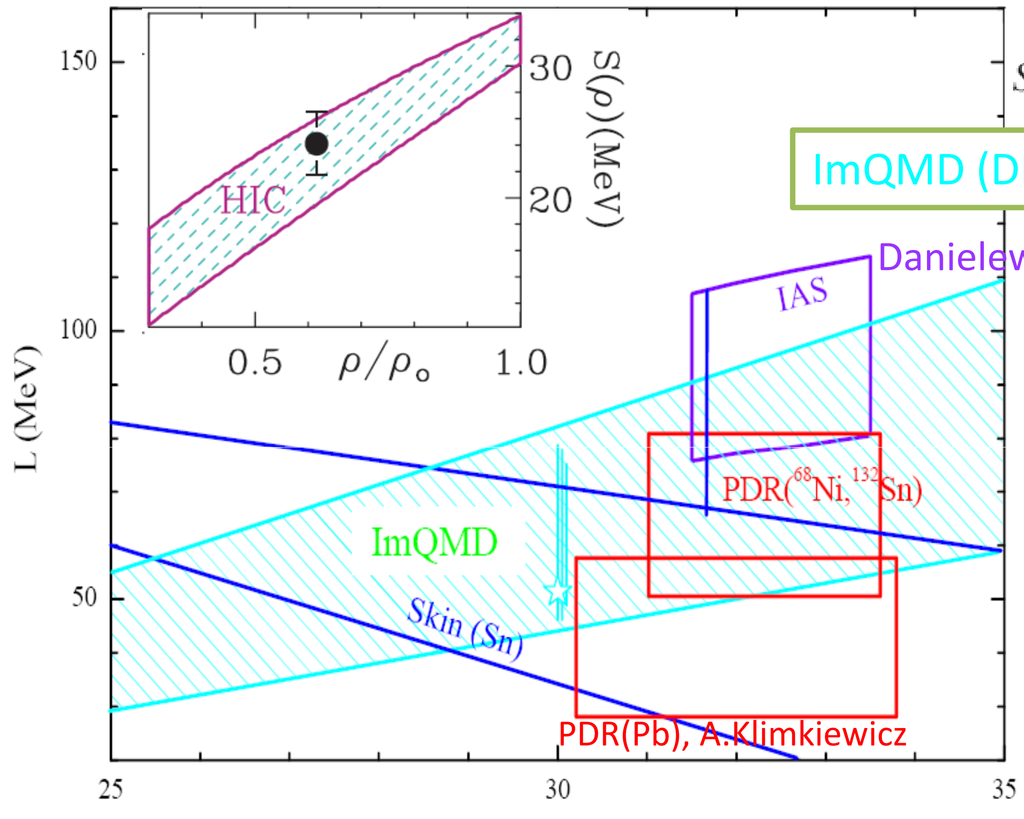
- Constraints on symmetry energy at subsaturatoin density

Tsang,Zhang, et al.,PRL102(2009)

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

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

Danielewicz, et.al



LWChen, BALi, et al,(Skin, Ri)

S_0: the values of $S(\rho)$ energy at ρ_0

L: the slope of $S(\rho)$ energy at ρ_0

K_{sym}: the curvature of $S(\rho)$ energy at ρ_0

S_0~31 ± 4 (MeV)

L~60 ± 23 (MeV)

Problem*: Although overlap, *but different in detail!

We must understand the differences between the transport models in order to improve this constraints through HICs.

transport models and their differences

A, BUU type: *f(r,p,t)* one body phase space density

$$\frac{\partial f}{\partial t}+v\cdot\nabla_{\mathbf{r}}f-\nabla_{\mathbf{r}}U\cdot\nabla_{\mathbf{p}}f$$

Mean field

$$=-\frac{1}{(2\pi)^6}\int d^3p_2d^3p_{2'}d\Omega\frac{d\sigma}{d\Omega}v_{12}$$
$$\times\{[ff_2(1-f_{1'})(1-f_{2'})]-[f_{1'}f_{2'}(1-f)(1-f_2)]$$
$$\times(2\pi)^3\delta^3(\mathbf{p}+\mathbf{p}_2-\mathbf{p}_{1'}-\mathbf{p}_{2'})\}$$

Two-body collision: occurs between test part.

$$f(\mathbf{r},\mathbf{p})\cong\frac{1}{\tilde{N}}\sum_{i=1}^{N\tilde{N}}\delta(\mathbf{r}-\mathbf{r}_i)\delta(\mathbf{p}-\mathbf{p}_i)$$

Solved with test particle methods

Many version: IBUU04, pBUU, SMF, BNV, RBUU, ……

B, QMD type: solve N-body equation of motion

$$\phi_i(\mathbf{r}_i,t)=\frac{1}{(2\pi\sigma_r^2)^{3/4}}\exp[-\frac{(\mathbf{r}-\mathbf{r}_i)^2}{4\sigma_r^2}+\frac{i\mathbf{p}_i\cdot\mathbf{r}}{\hbar}]$$

nucleon

$$\dot{\mathbf{r}}_i=\frac{\mathbf{p}_i}{m}+\nabla_{\mathbf{p}_i}\sum_j\langle V_{ij}\rangle=\nabla_{\mathbf{p}_i}\sum_j\langle H\rangle$$
$$\dot{\mathbf{p}}_i=-\nabla_{\mathbf{r}_i}\sum_j\langle V_{ij}\rangle=-\nabla_{\mathbf{r}_i}\sum_j\langle H\rangle$$

Two body collision: occurs between nucleons

Rearrange whole nucleon-> large flucturation

Many version: ImQMD, QMD, IQMD, UrQMD, AMD ……

Further differences between transport models:

1. ***the mean field (local, MDI,)***
2. ***in-medium NN cross sections,***
3. ***Pauli blocking***
4. ***Cluster formation***
5. ***width of Wavepacket, number of test part.***

→ Lead to different constraints on symmetry energy!

Completely understanding the impacts of those differences on HIC observables are highly requested!

And understanding their differences on conclusion need the codes comparison in this community. There is an efforts in Trento meeting (2009,ECT*), but no conclusion from it till now.

2, Understanding its impacts with QMD type model (ImQMD05)

- ImQMD05

- The influence of
  - symmetry potential
  - In-medium NN cross section
  - Impact parameter
  - Cluster formation

on heavy collision observables (DR(n/p), Ri) for Sn+Sn at50AMeV by ImQMD05.

- ImQMD05 (Improved QMD model developed at CIAE)

Detail of code: Zhang, et alPR **C71** (05) 024604, PR **C74** (06) 014602, PRC75,034615(07)., PL **B664** (08) 145,

➢ ***the mean fields acting on nucleon wavepackets are derived from Skyrme potential energy density functional***

$$\dot{\mathbf{r}}_i = \frac{\partial H}{\partial \mathbf{p}_i}, \quad \dot{\mathbf{p}}_i = -\frac{\partial H}{\partial \mathbf{r}_i}.$$

H=T+U+U_coul

EOS

$$U = \int u_{loc} + u_{md} + u_{coul} d^3 r$$

potential energy density functional:

$$\begin{aligned} u_{loc} &= \frac{\alpha}{2}\frac{\rho^2}{\rho_0} + \frac{\beta}{\gamma+1}\frac{\rho^{\gamma+1}}{\rho_0^{\gamma}} + \frac{g_{sur}}{2\rho_0}(\nabla\rho)^2 \\ &+ \frac{g_{sur,iso}}{\rho_0}[\nabla(\rho_n - \rho_p)]^2 \\ &+ (A_{sym}\rho^2 + B_{sym}\rho^{\gamma+1} + C_{sym}\rho^{8/3})\delta^2 \\ &+ g_{\rho\tau}\frac{\rho^{8/3}}{\rho_0^{5/3}} \end{aligned}$$

Surface symmetry energy term

$$\delta = (\rho_n - \rho_p)/(\rho_n + \rho_p)$$

Parameters in U_{loc} are obtained from standard Skyrme interactions parameters

$$\begin{aligned}
\frac{\alpha}{2} &= \frac{3}{8}t_0\rho_0, \quad \frac{\beta}{\gamma+1} = \frac{1}{16}t_3\rho_0^{\gamma}, \\
\frac{g_{sur}}{2} &= \frac{1}{64}(9t_1-5t_2-4x_2t_2)\rho_0, \\
\frac{g_{sur,iso}}{2} &= -\frac{1}{64}(3t_1(2x_1+1)+t_2(2x_2+1))\rho_0 \\
A_{sym} &= -\frac{t_0}{4}(x_0+1/2), \\
B_{sym} &= -\frac{t_3}{24}(x_3+1/2), \\
C_{sym} &= -\frac{1}{24}(\frac{3\pi^2}{2})^{2/3}\Theta_{sym} \\
g_{\rho\tau} &= \frac{3}{80}(3t_1+(5+4x_2)t_2)(\frac{3\pi}{2})^{2/3}\rho_0^{5/3}
\end{aligned}$$

$$\Theta_{sym} = 3t_1x_1 - t_2(4+5x_2)$$

$$\alpha = -356MeV \quad \beta = 303MeV, \ \eta = 7/6, \ g_{sur} = 19.47MeV\,fm^2$$

$$C_s = 35.19MeV \qquad g_{\rho\tau} = 0.$$

- Isospin dependent nucleon-nucleon cross sections are adopted, the medium corrections are

$$\sigma_{np}^{med} = (1 - \eta\, \rho / \rho_0)\sigma_{np}^{free}$$
$$\sigma_{nn,pp}^{med} = (1 - \eta\, \rho / \rho_0)\sigma_{nn,pp}^{free}$$

$$\sigma_{np,nn(pp)}^{free}, d\sigma / d\Omega$$

Cugnon, et al., Nucl.Instr.Meth.Phys. B111, 215(1996)

η depend on the beam energy

$$\sigma^{*}_{nn/np} = (1 - \eta(E_{beam})\rho/\rho_0) * \sigma^{free}_{nn/np}, \eta(E_{beam}) = \begin{cases} 0.2, & E_{beam} < 150MeV; \\ 0.0, & 150\mathrm{MeV} \leq E_{beam} < 200\mathrm{MeV}; \\ -0.2, & 200\mathrm{MeV} \leq E_{beam} < 400\mathrm{MeV}; \\ -0.4, & 400\mathrm{MeV} \leq E_{beam}\ . \end{cases}$$

- isospin independent Momentum dependence interaction

$$u_{md} = \frac{1}{2\rho_0} \sum_{N_1, N_2 = n,p} \frac{1}{16\pi^6} \int d^3 p_1 d^3 p_2 f_{N_1}(\vec{p}_1) f_{N_2}(\vec{p}_2) 1.57 \left[\ln\left(1 + 5\times10^{-4} (\Delta p)^2\right) \right]^2$$

Aichelin, et al., PRL58,1926(1987)

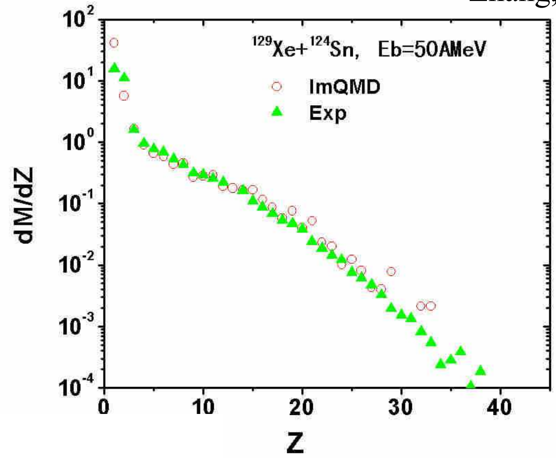
- Clusters are recognized by means of the coalescence model widely used in QMD calculations, DR<=3.5fm, DP<=250MeV/c

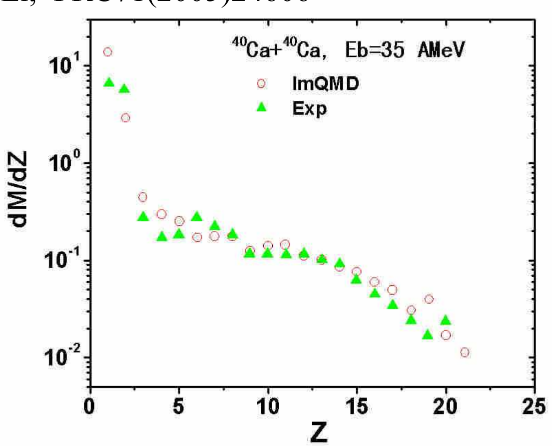
The isoscalar part of mean field and in-medium NN cross section are determined through charge distribution, collective flow and stopping power!

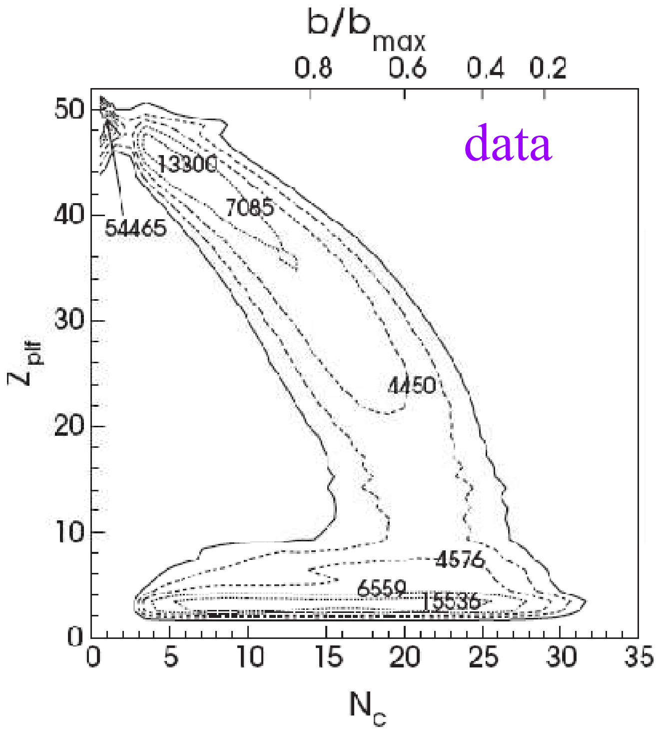
It describe the charge distribution, flow and stopping power well for the heavy ion collisions for Ebeam=30-400MeV,

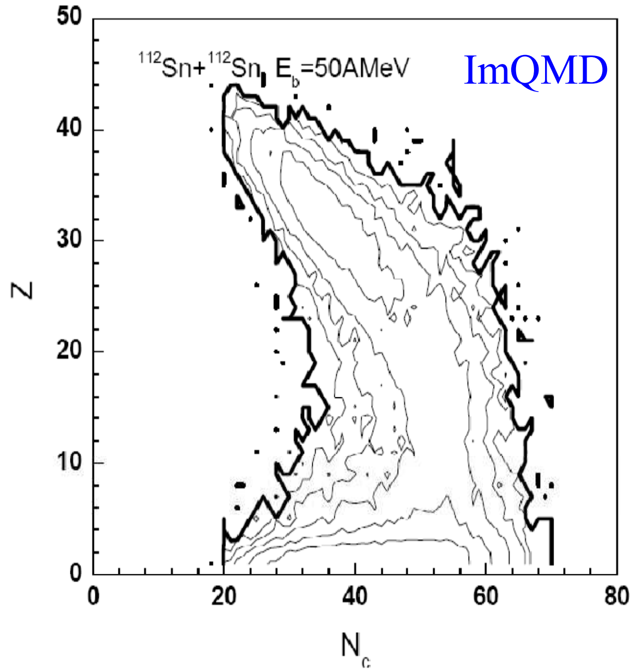
Charge distribution

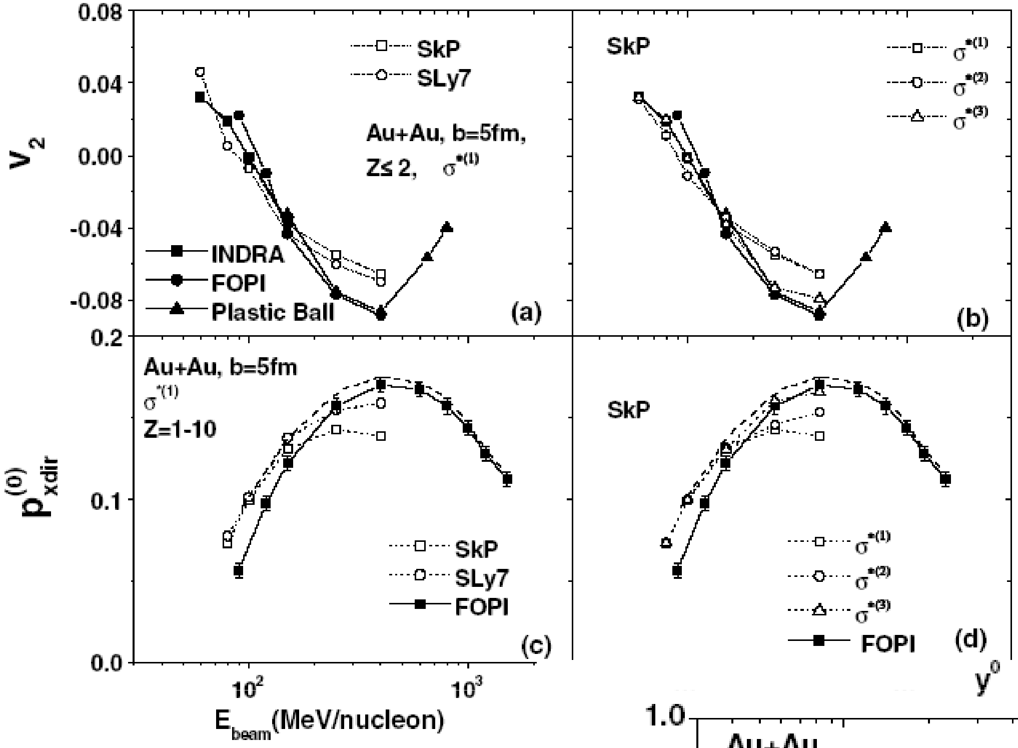
Zhang, Li, PRC71(2005)24606







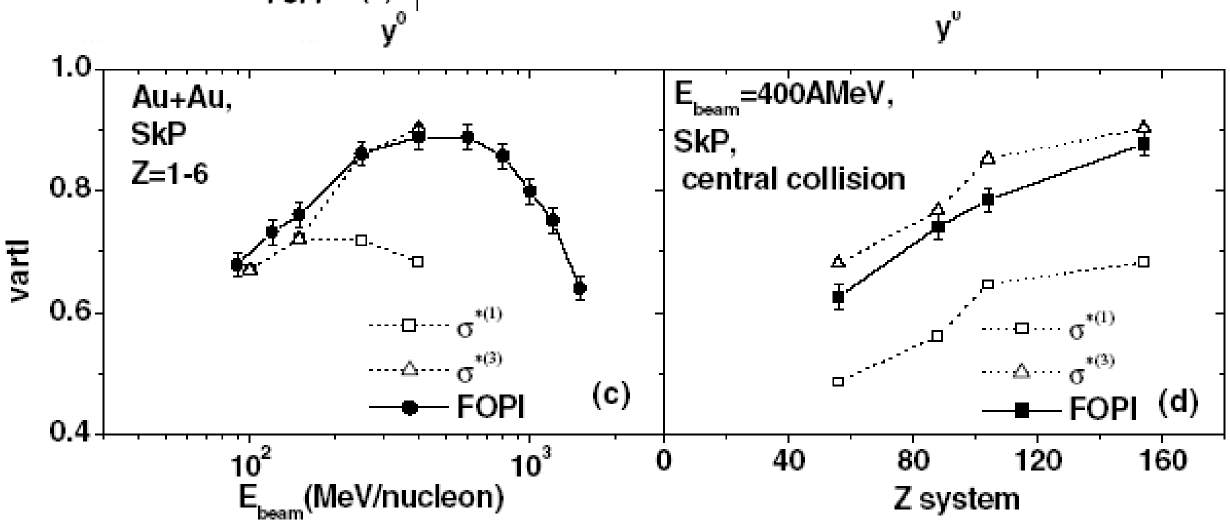




Zhang, Li, PRC74,014602

flow

stopping



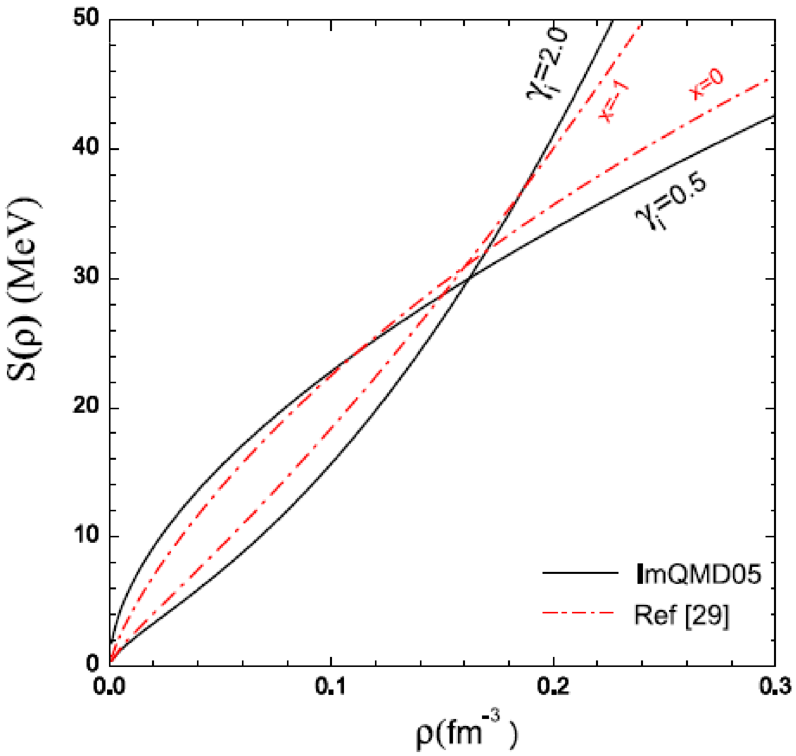
Zhang, Li, PRC74,014602 Data: Residorf, PRL 92(2004)232301

Give our confidence to study the isospin effects from different symmetry energy case.

• The influence of different aspects on isospin sensitive observables (DR(n/p), Isospin diffusion) at E_beam=50AMeV

➢ Symmetry potential

$$w_{asy}^{pot} = \frac{C_s}{2}\left(\frac{\rho}{\rho_0}\right)^{\gamma}\delta^2\rho \quad \Rightarrow \quad v_{asy}^{pot}(\rho_i) = \frac{\partial w_{asy}^{pot}}{\partial \rho_i}, i = n, p$$



➢ in-medium NN cross section

$$\sigma_{nn/np}^{*} = \sigma_{nn/np}^{free}$$

The influence of medium correction

$$\sigma_{nn/np}^{*} = (1 - 0.2\rho/\rho_0)\sigma_{nn/np}^{free}$$

The influence of $\sigma_{np}^{*} / \sigma_{nn}^{*}$

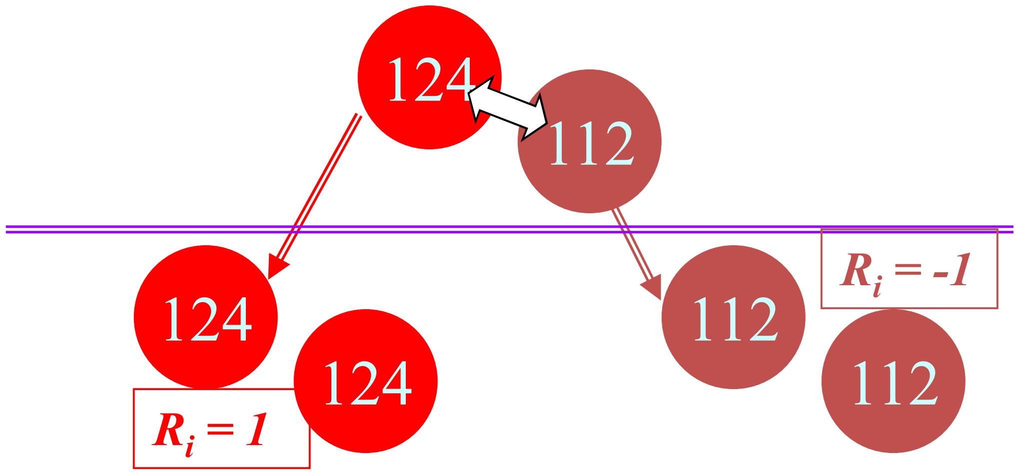
$$\sigma_{nn}^{*} = \sigma_{pp}^{*} = \sigma_{np}^{*}$$

DR(n/p) ratio

$R_{n/p}=Y(n)/Y(p)$ The yield ratio of emitted neutron to proton

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

isospin diffusion



No isospin diffusion between symmetric systems

Isospin diffusion occurs only in asymmetric systems A+B, and diffusion ability depends on the symmetry energy.

Isospin transport ratio

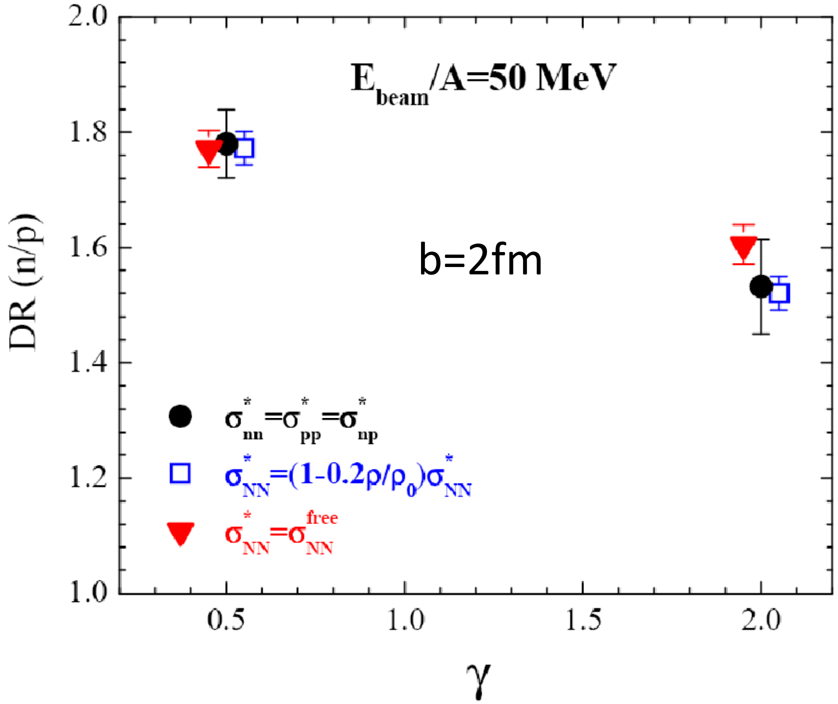
$$R_i=(2X-X_{AA}-X_{BB})/(X_{AA}-X_{BB})$$

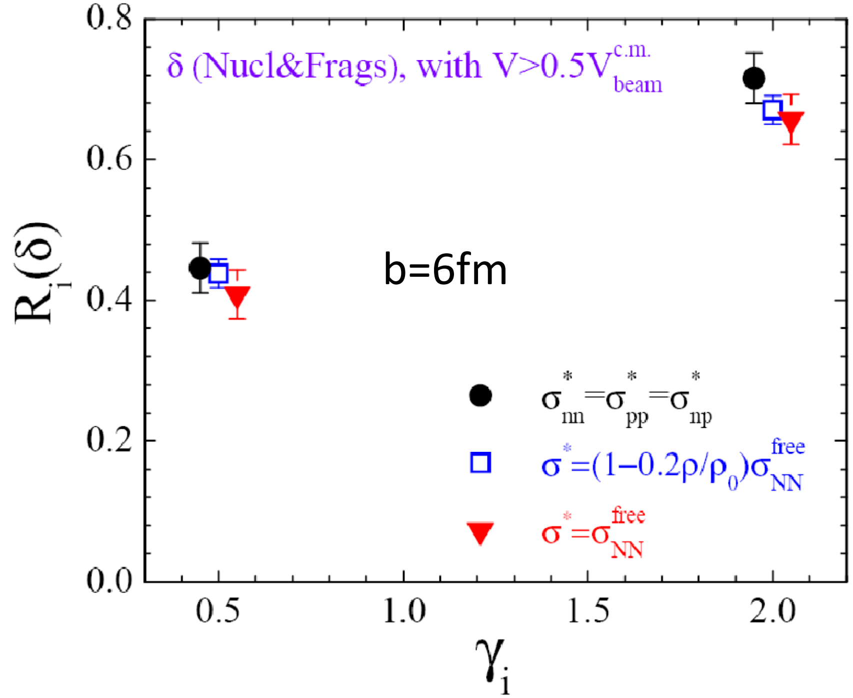
In absence of isospin diffusion R=1 or R=-1, R~0 for isospin equilibrium

Theory: X is the δ, the isospin asymmetry of projectile residues
Exp: X is the isoscaling parameter α (Tsang, PRL)
There is linear relationship between δ and α, So, $Ri(\delta)=Ri(\alpha)$

The influence of the symmetry potential, in-medium NN cs on DR and Ri

DR(n/p) with Ek>40MeV



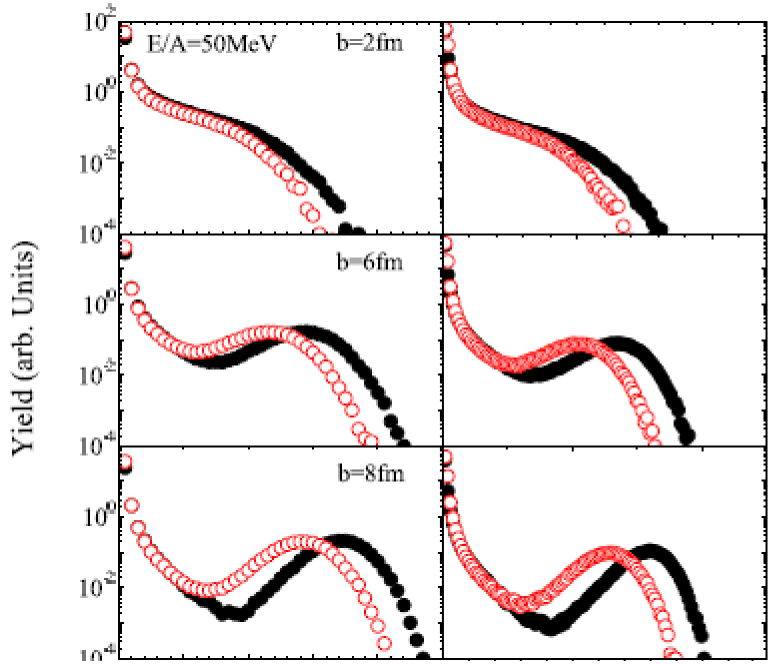


- *larger symmetry energy at subsaturation density leads to larger DR and smaller Ri*

- *DR(n/p) and Ri sensitive to the density dependence of symmetry energy rather than in-medium NN cs for Sn+Sn at E/A=50MeV*

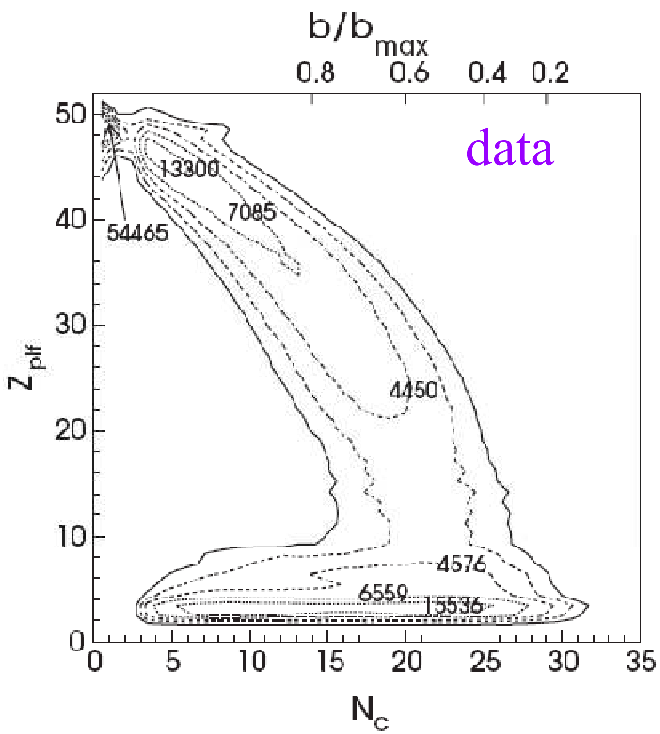
➢ Cluster emission

Low intermediate energy HICs-> Multifragmentation



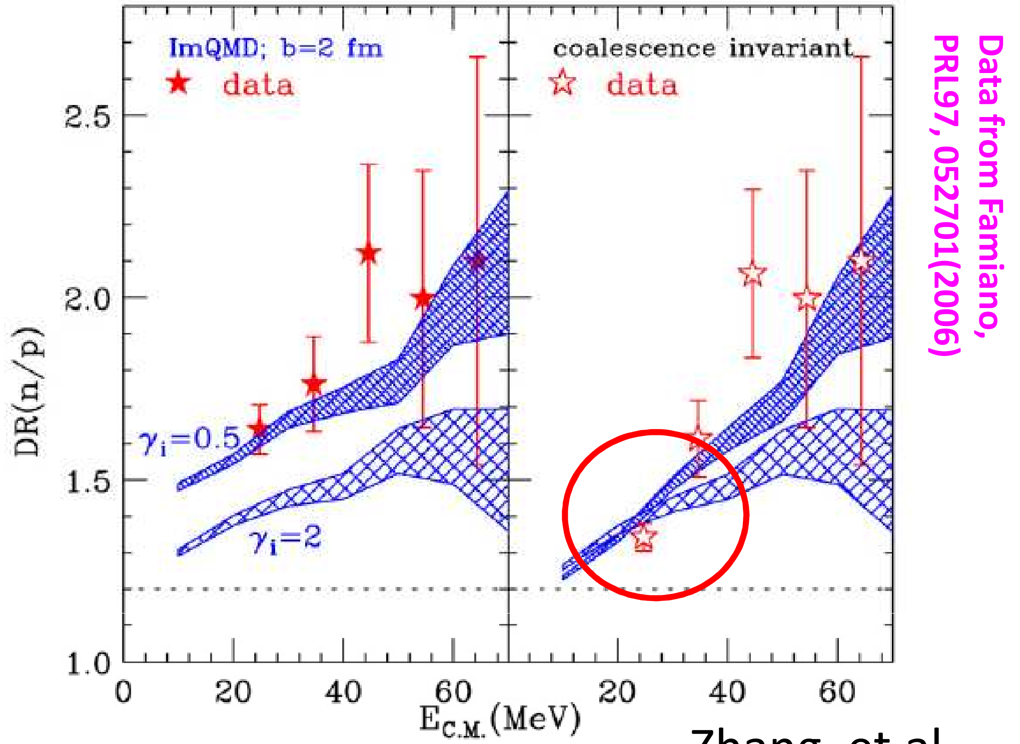
➢ Impact parameters

Experiment-> centrality, impact parameter smearing effect in exp.



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

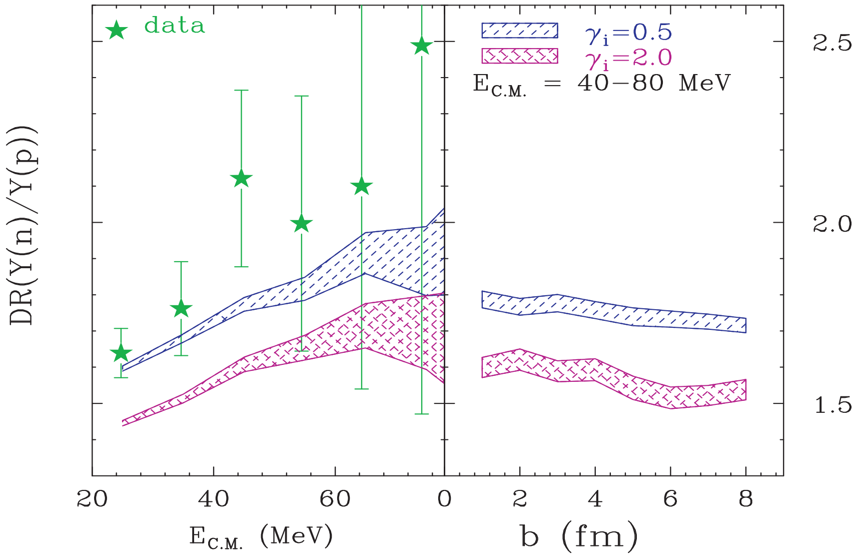
Y.Zhang, P.Danielewicz, et al, PLB664,145(2008)



Over the whole energy range for both free and coalescence-invariant DR(n/p) the data seem closer to the g_i=0.5 calculation

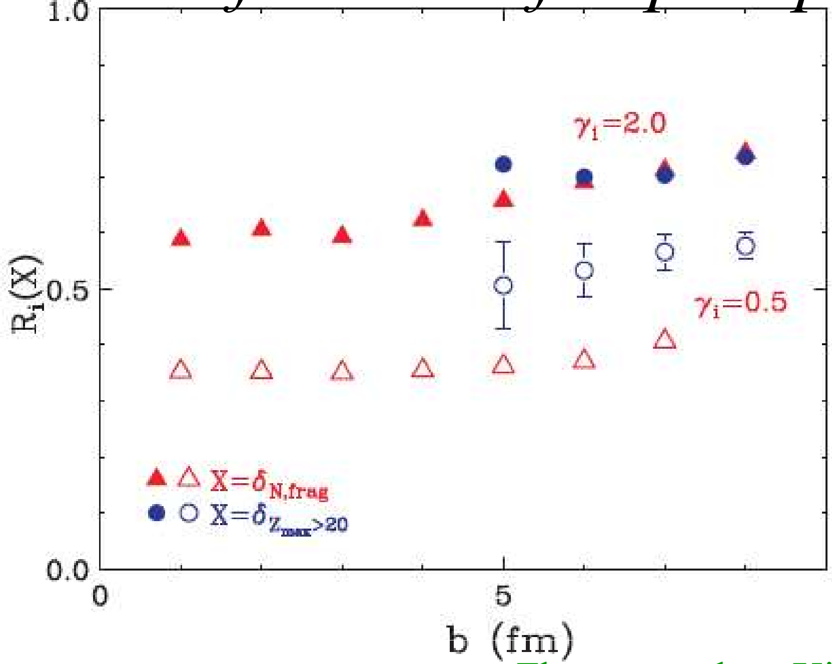
Significant cluster and sequential decay effects are at low energy!

Zhang, et.al



DR(n/p) with higher kinetic energy weakly depend on the impact parameters

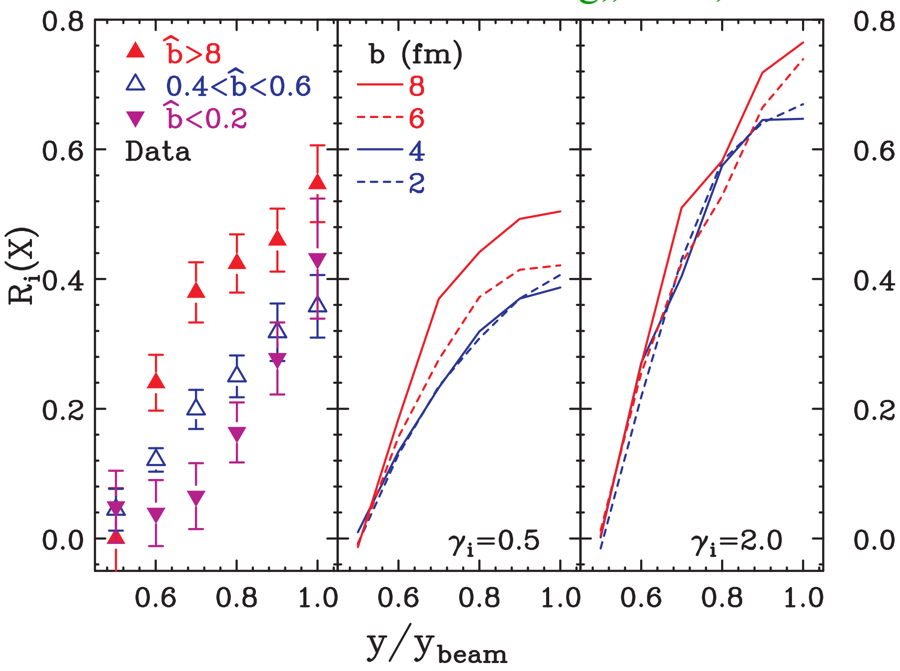
Ri as a function of impact parameters



1, Ri weakly depend on the impact parameters for b<5fm; increase with b for b>5fm.

2, cluster emission from neck region increase the values of Ri with heavy fragments.

Zhang,, et.al., arXiv.



3, the rapidity dependence of *Ri* also sensitive to the density dependence of symmetry energy

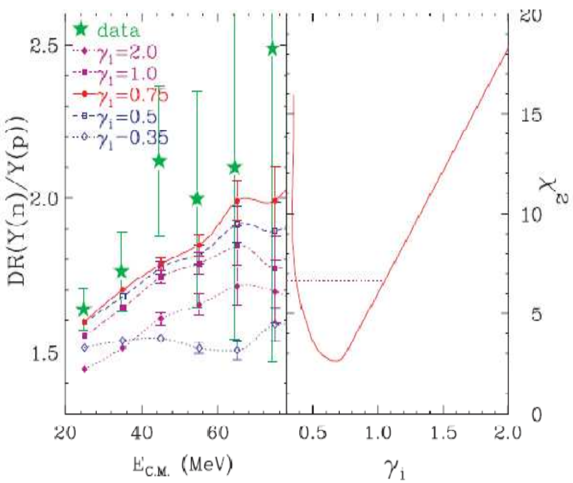
3, Conclusions and discussion

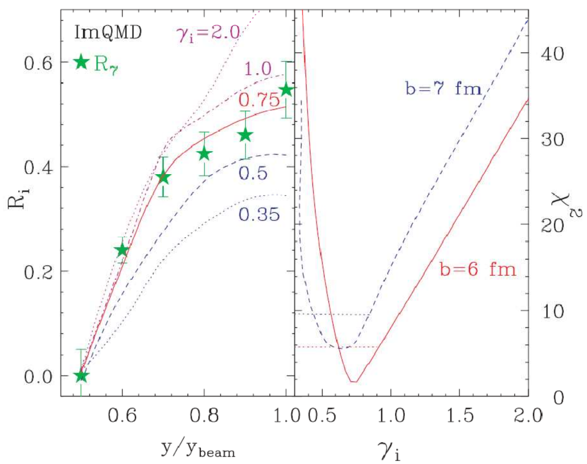
1) Around Fermi energy, the Ri and DR are strongly sensitive to the density dependence of symmetry energy rather than the in-medium cross section.

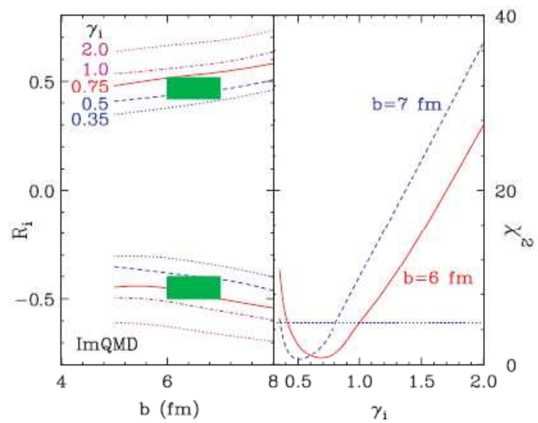
2) Cluster emission also play import roles on the HICs observables DR, Ri and its dependence on rapidity.

3) The data of Ri and DR consistently support the results of ImQMD predictions with soft symmetry energy form.

Tsang, Zhang, et.al., PRL102(2009)

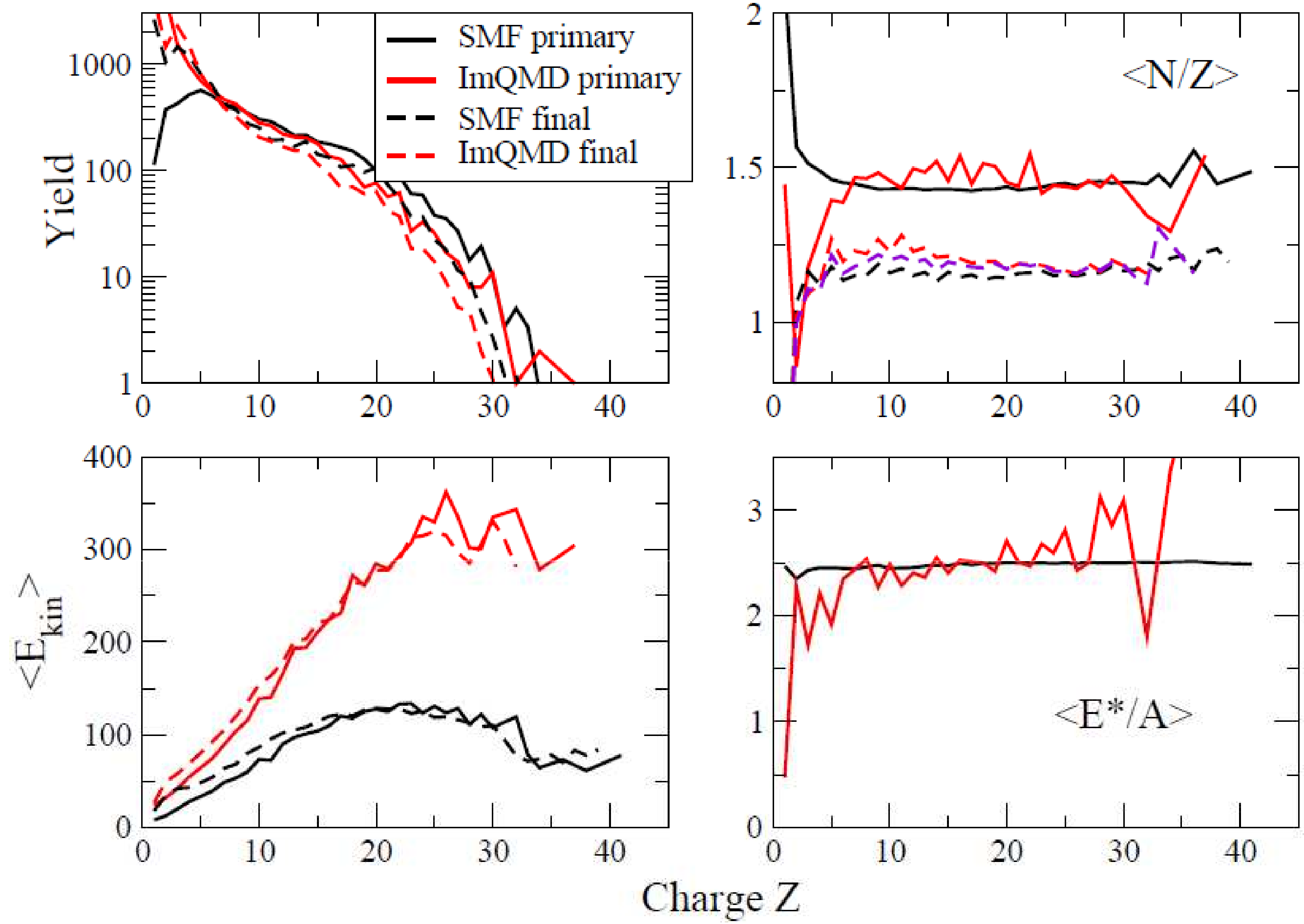




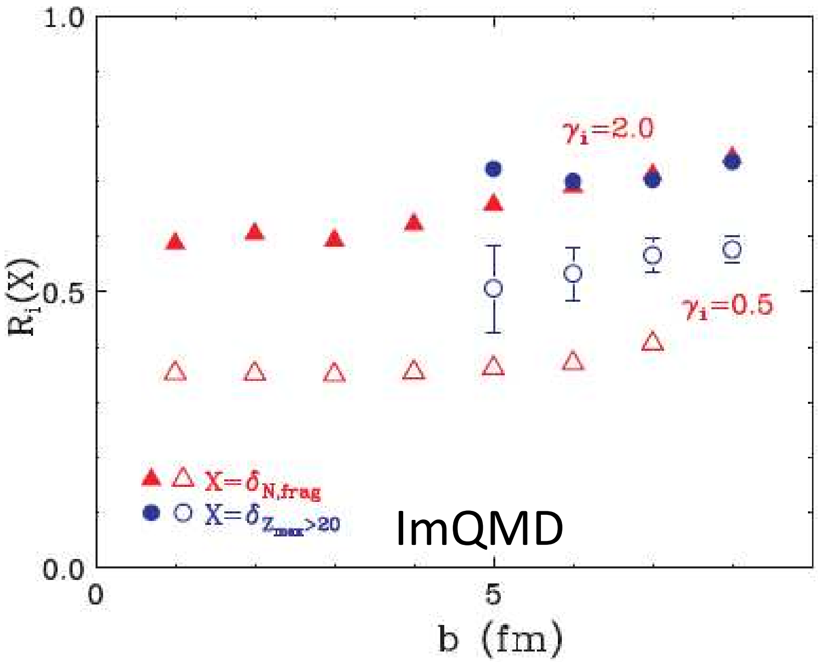


4), Why different codes draw different conclusion? (code comparison)

ImQMD and SMF comparison(with Maria Colonna)

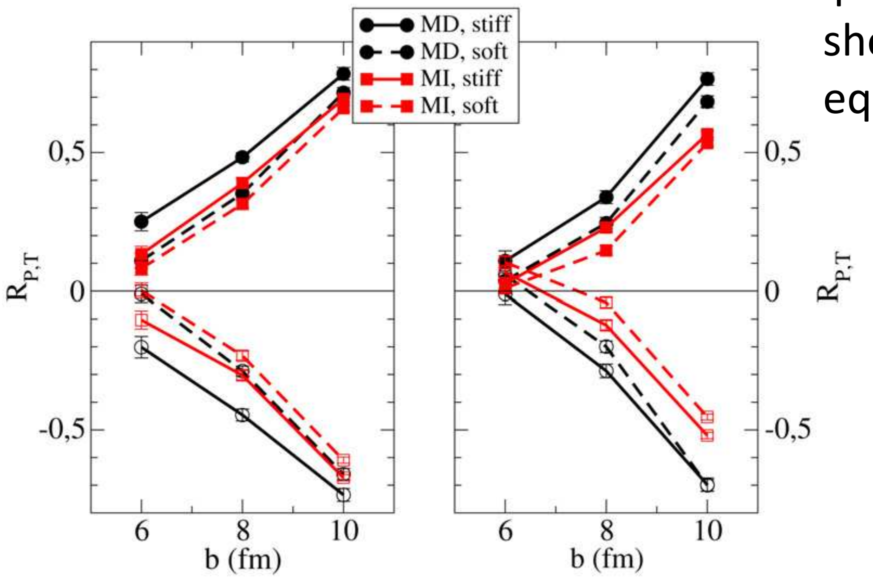


1) The charge distribution and <N/Z> for products -> There is large difference for Z<9
2) <Ek> and <E*/A>as a funciton of Z : ImQMD, more transparence, SMF, more equilibrium

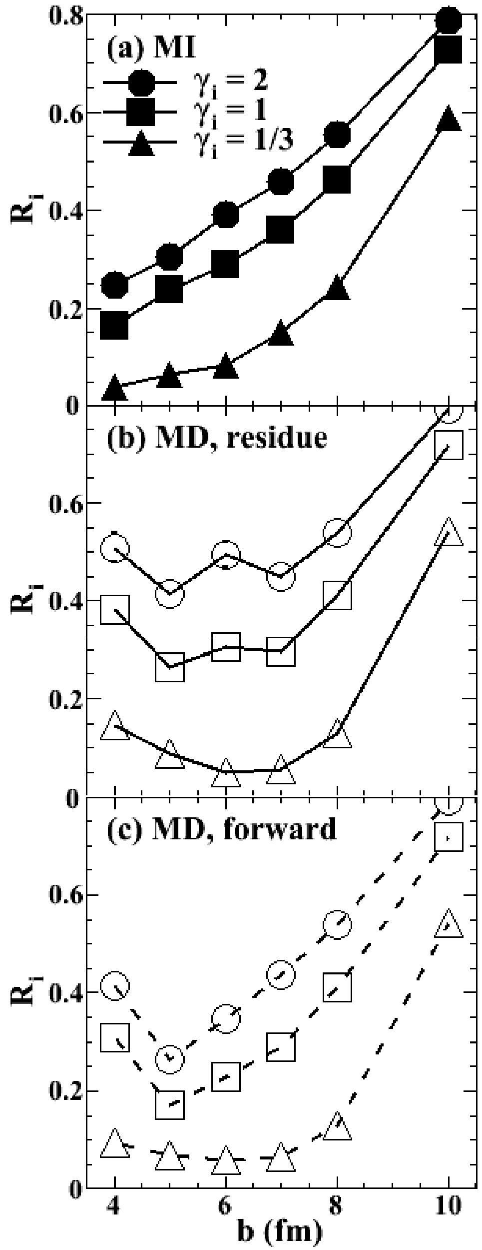


ImQMD shows more transparence

pBUU and SMF show more equilibration

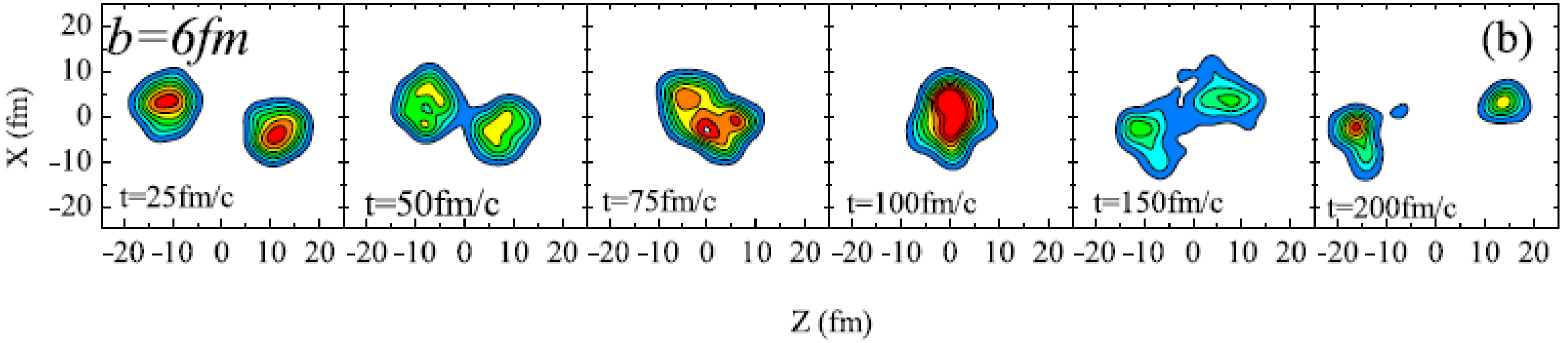


SMF

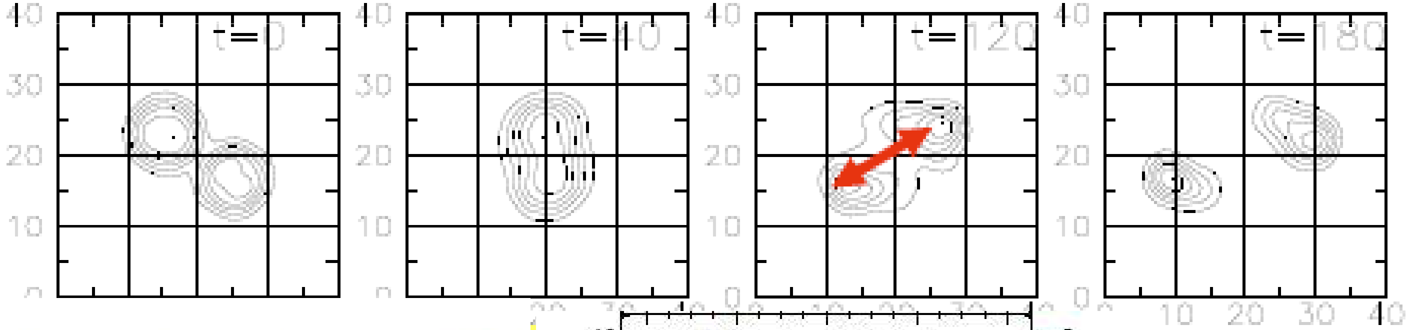


pBUU, D.Coupland

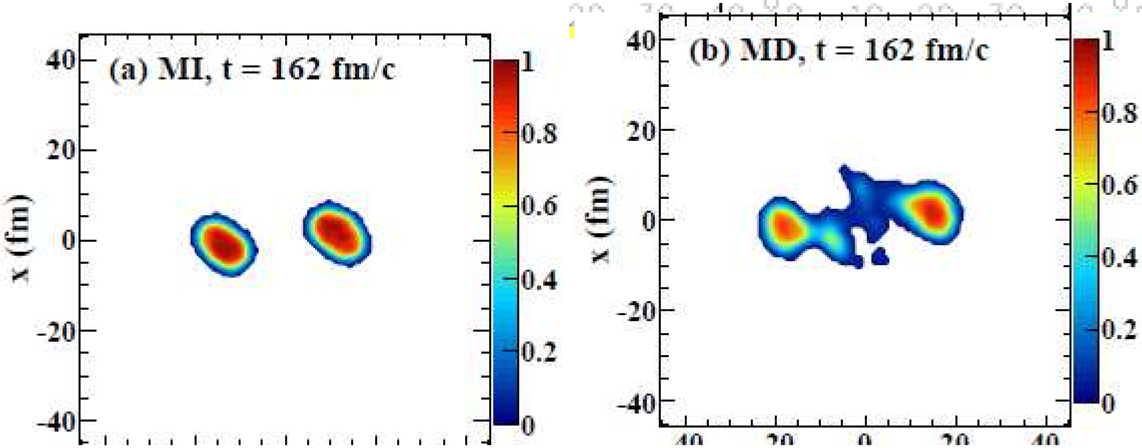
- ImQMD produce more light charged particles than that with SMF



ImQMD



SMF



pBUU

D.Coupland

Possible reasons:

1) Fragmentation mechanism, production of light and IMF.

2) Pauli blocking (QMD: more restrictive)

3) Momentum dependent interaction

Not solved yet! We still need further work.

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