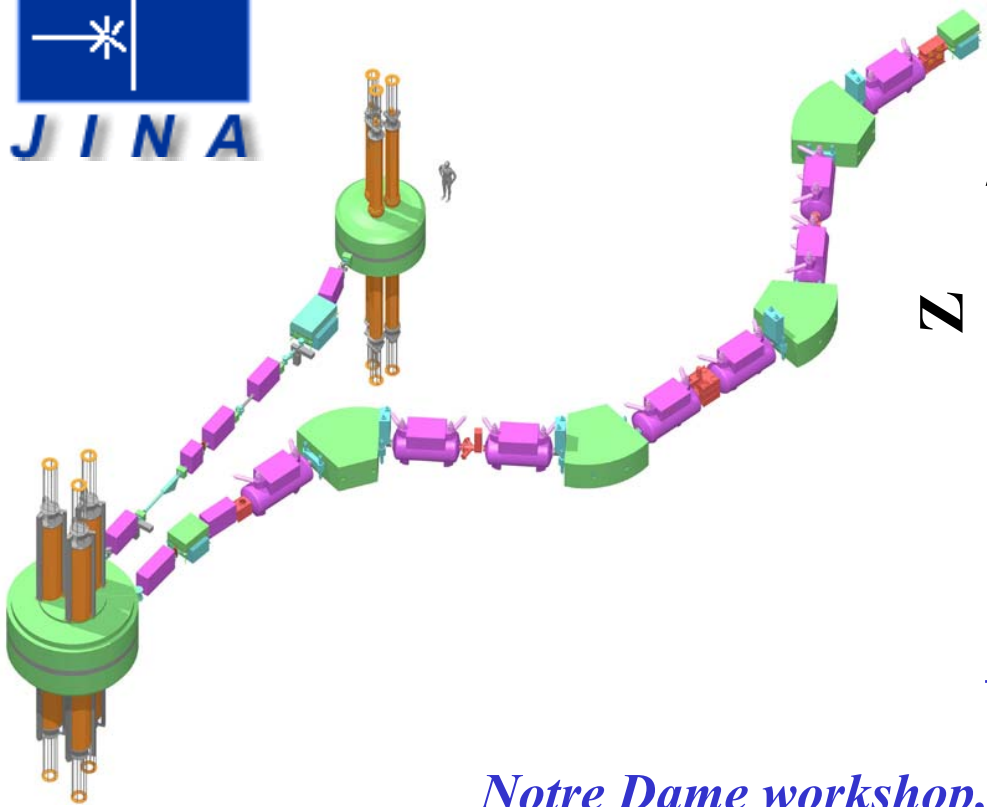
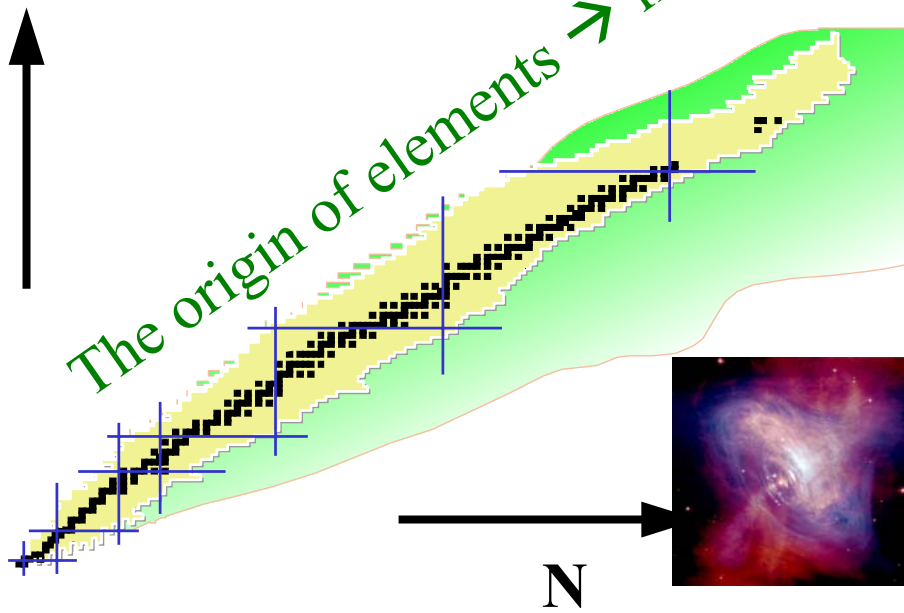
Constraining symmetry energy with isospin diffusion experiments





Notre Dame workshop, July 14-15, 2005

Betty Tsang

The National Superconducting Cyclotron Laboratory

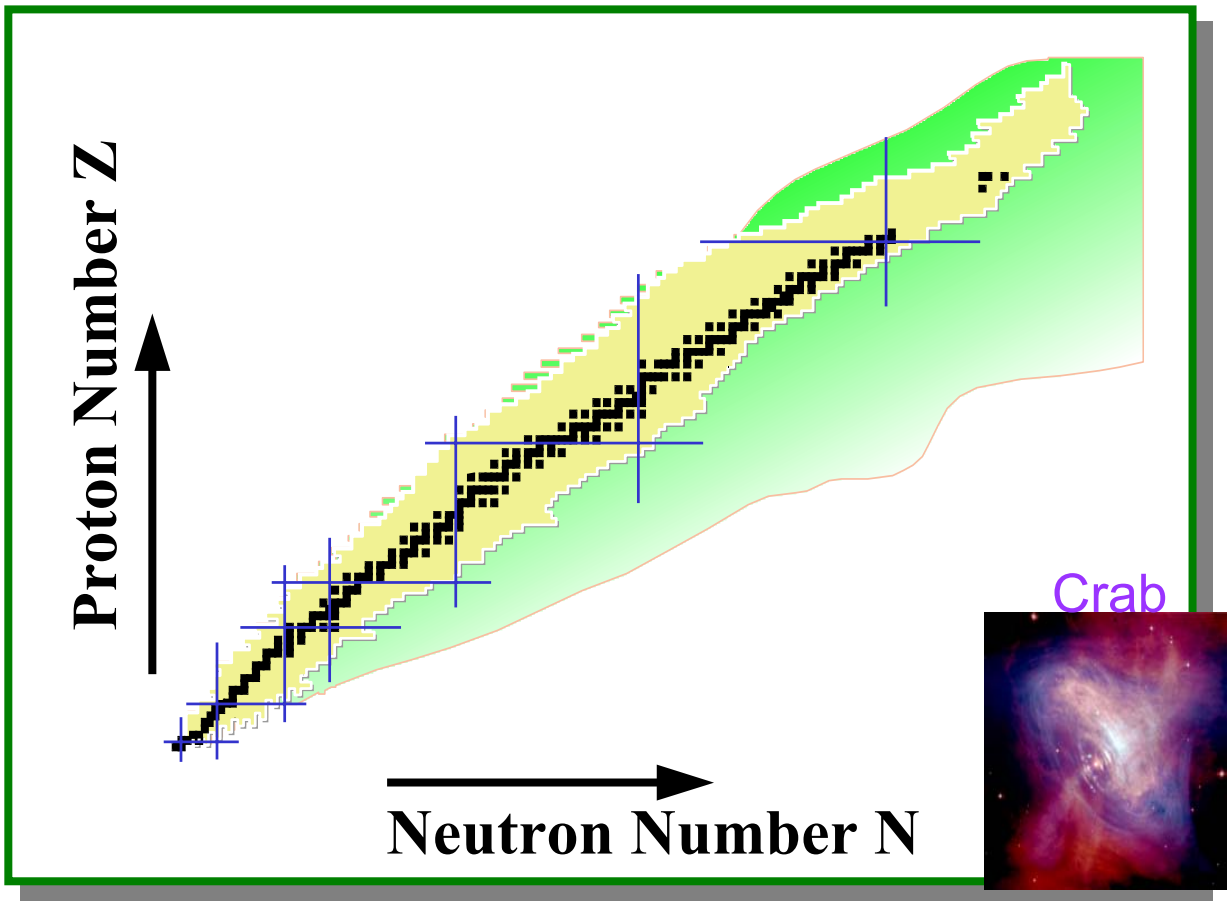
Michigan State University

Constraints from Nuclei

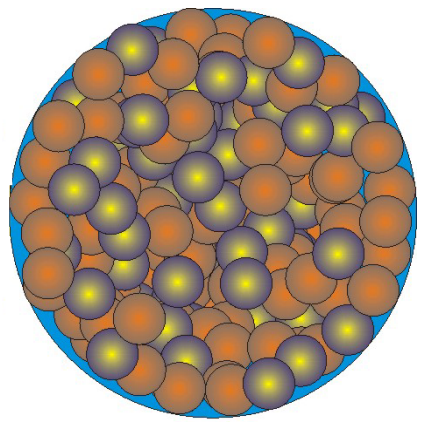
$$B = a_V A - a_S A^{2/3} + \delta - a_C \frac{Z(Z-1)}{A^{1/3}} - a_{sym} \frac{(A-2Z)^2}{A}$$

$$(a^V_{sym} A - a^S_{sym} A^{2/3}) \frac{(A-2Z)^2}{A^2}$$

Inclusion of surface terms in symmetry



Crab



^{208}Pb

Density dependence of symmetry energy influences

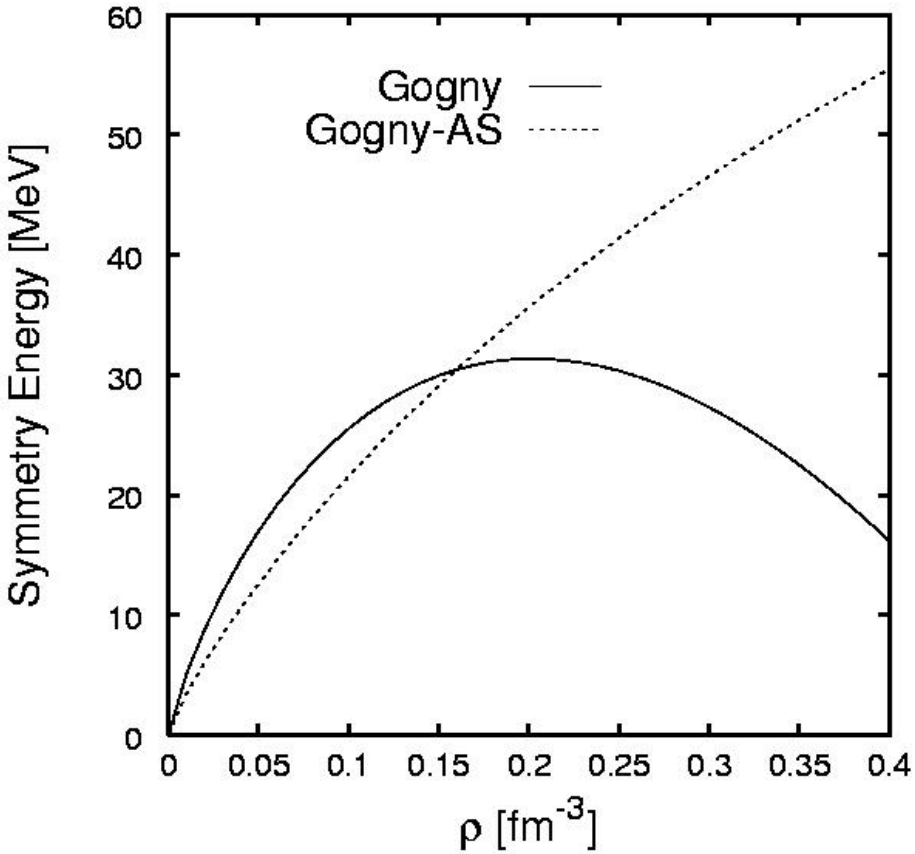
$$\left\langle r_n^2 \right\rangle^{1/2} - \left\langle r_p^2 \right\rangle^{1/2}$$

Parity violating e$^-$ scattering: $R_n(^{208}Pb)$

JLAB (2005)

Density dependence of symmetry energy

*A. Ono et al. PRC **68**,051601 (2003)*



Observable currently explored in Heavy Ion Collisions:

Central collisions (isospin fractionation)

n/p ratios; $\langle E_n \rangle$, $\langle E_p \rangle$

Isotope distributions

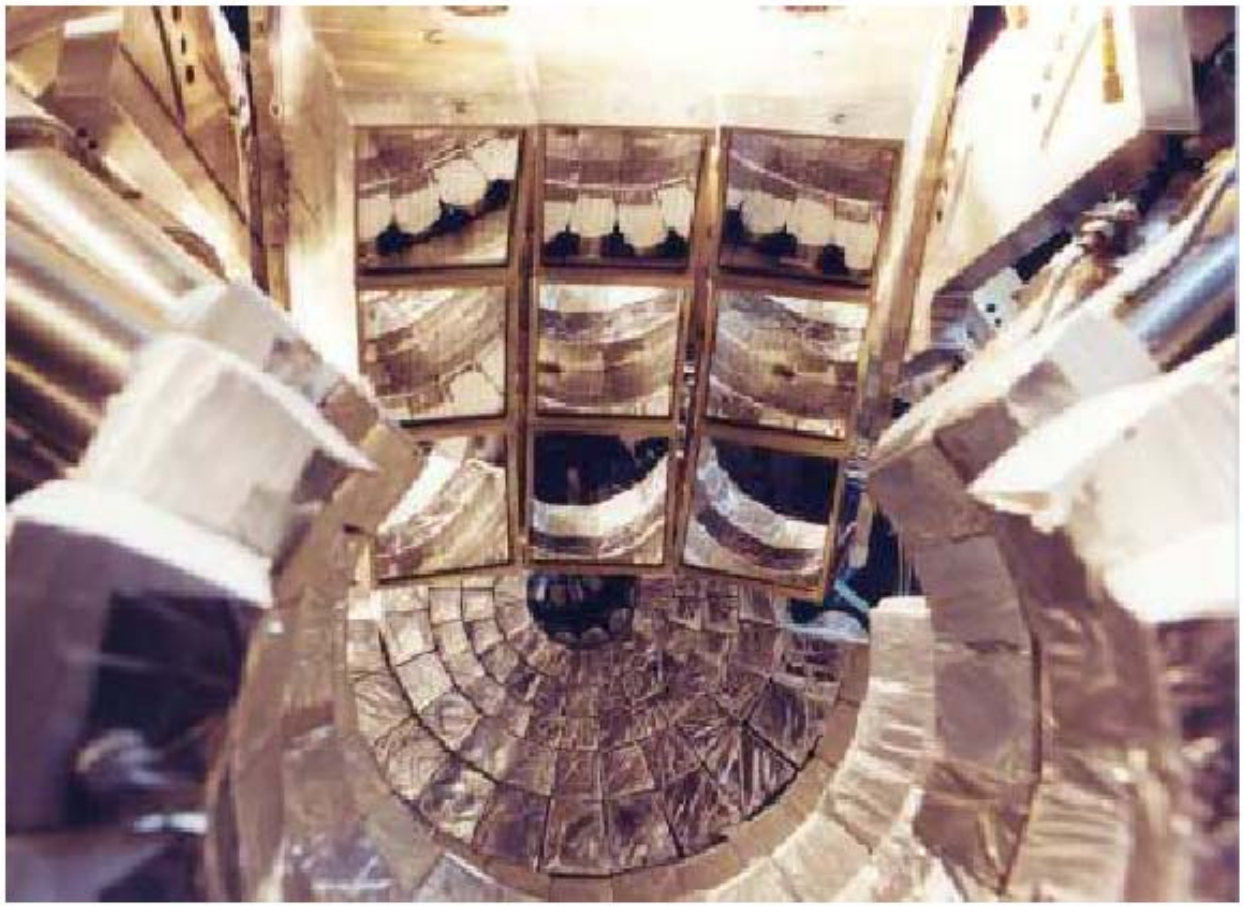
Peripheral Collisions

Isospin diffusion

Isotope Distribution Experiment

MSU, IUCF, WU collaboration

Sn+Sn collisions involving ^{124}Sn, ^{112}Sn at E/A=50 MeV



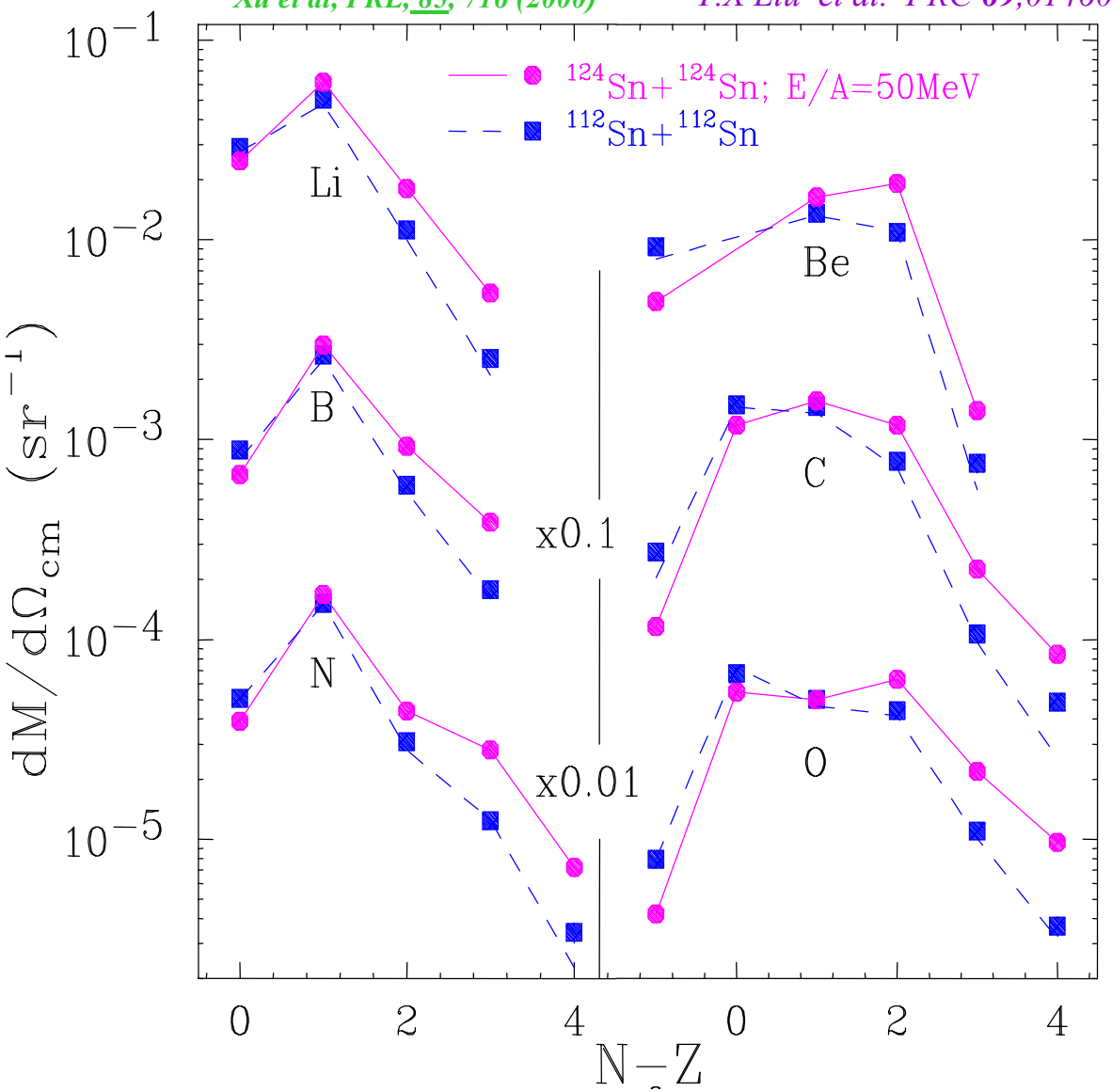
Miniball + Miniwall
4 π multiplicity array
Z identification, A<4

LASSA
Si strip +CsI array
Good E, position,
isotope resolutions

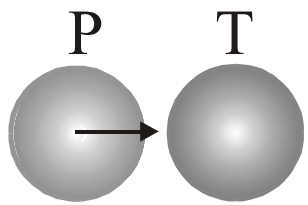
Xu et al, PRL, 85, 716 (2000)

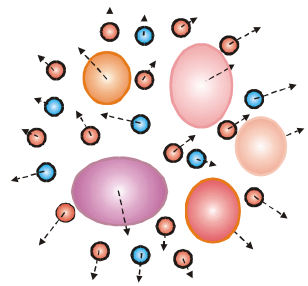
Measured Isotopic yields

Xu et al, PRL, 85, 716 (2000) *T.X Liu et al. PRC 69,014603*



Central collisions



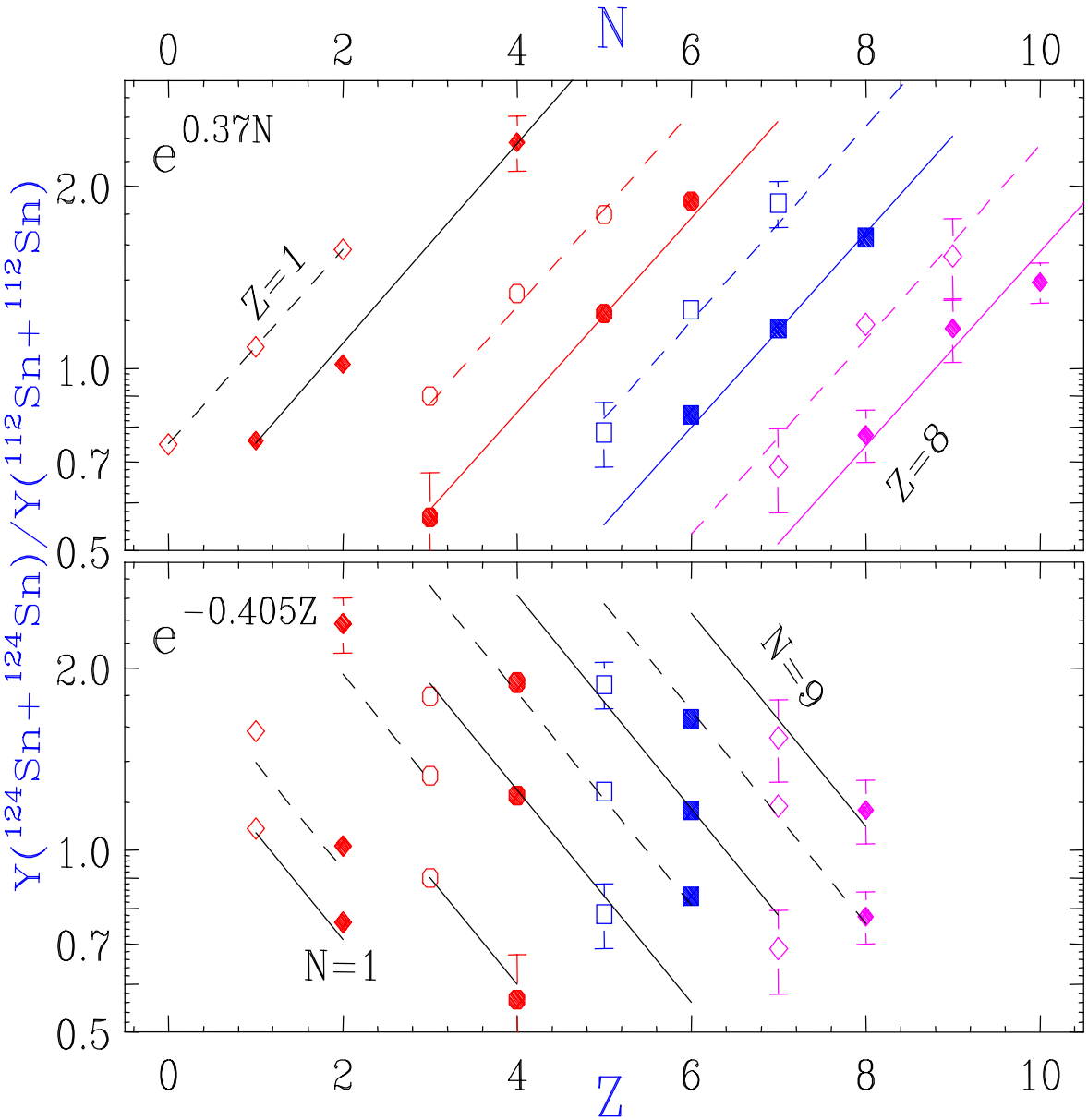


Multifragmentation

Similar distributions

$R_{21}(N,Z)=Y_2(N,Z)/\ Y_1(N,Z)$

Isoscaling from Relative Isotope Ratios



$R_{21}(N,Z) = Y_2(N,Z)/\ Y_1(N,Z)$

$$\propto e^{\alpha N+\beta Z}$$

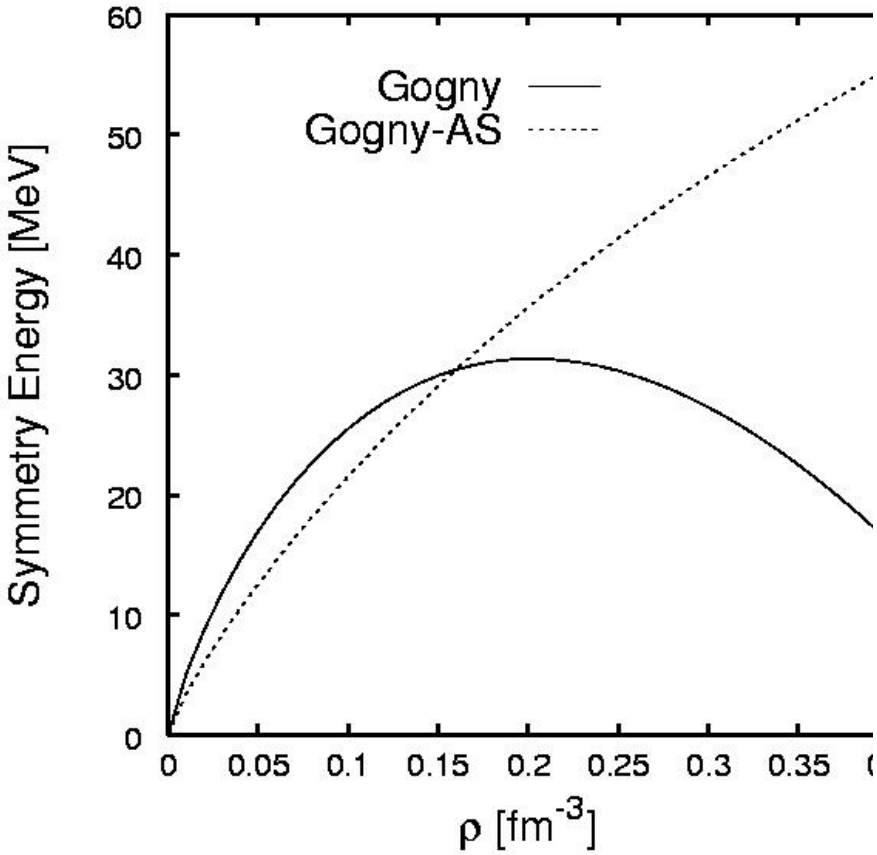
In statistical and dynamical models, α is related to the symmetry energy and asymmetry of the emitting source

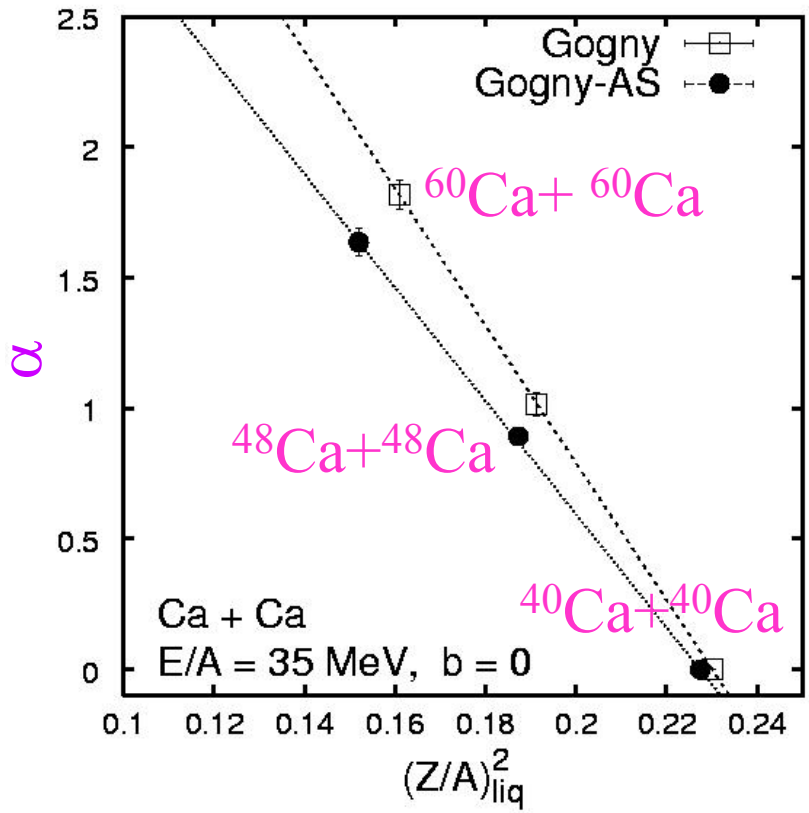
$\alpha = 2C_{sym}[\Delta\delta(1-\delta)]/T$

Tsang et al, PRL, 86, 5023 (2001) *MB Tsang et al. PRC 64,054615*

Symmetry energy from AMD

*A. Ono et al. PRC **68**,051601 (2003)*



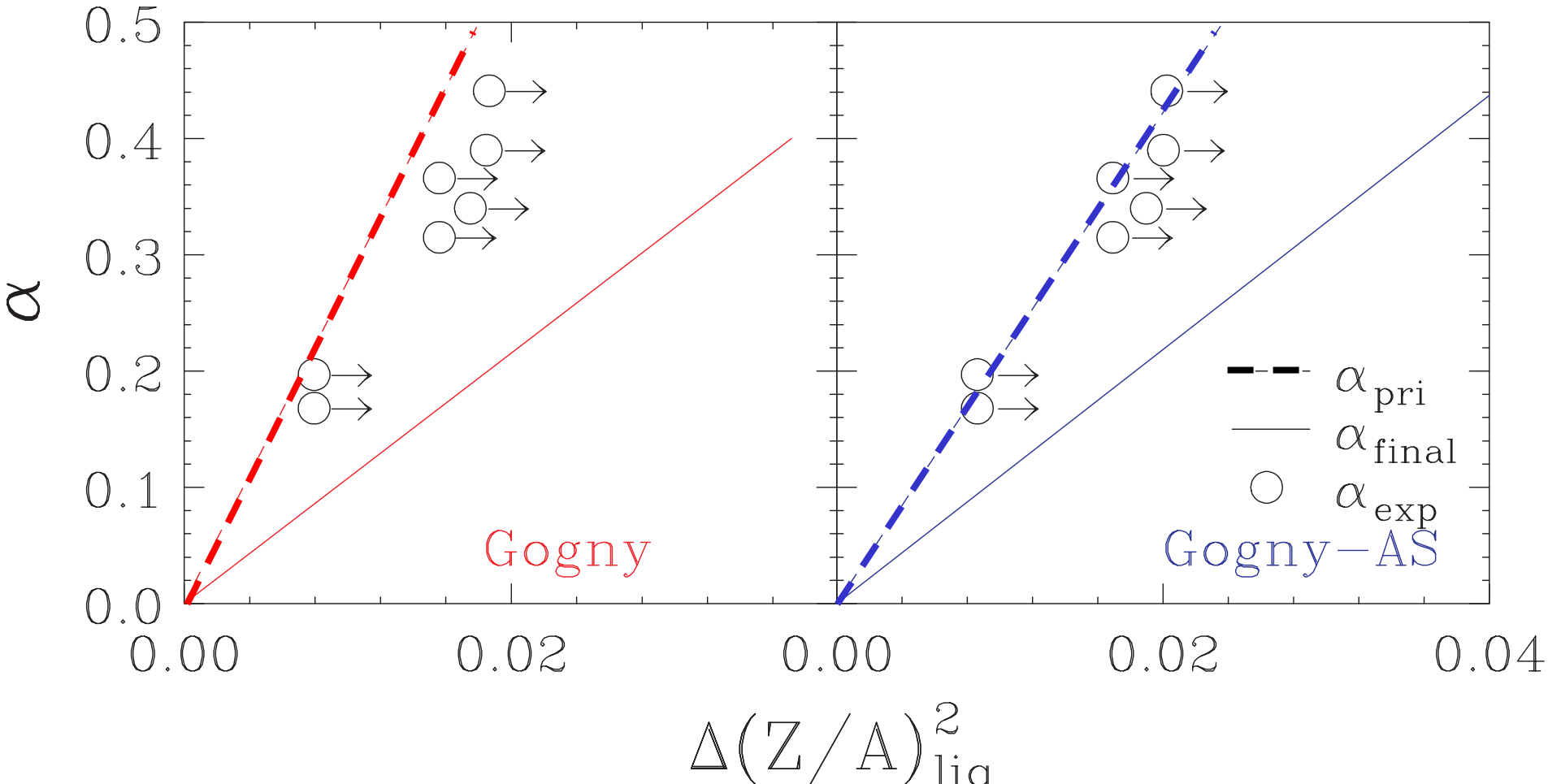


α depends on symmetry term interactions

Problems with Central Collisions

AMD Calculations : Ca+Ca; b=0 fm
Data: Ni, Ca, Fe, Sn, p, He collisions; b>>0 fm

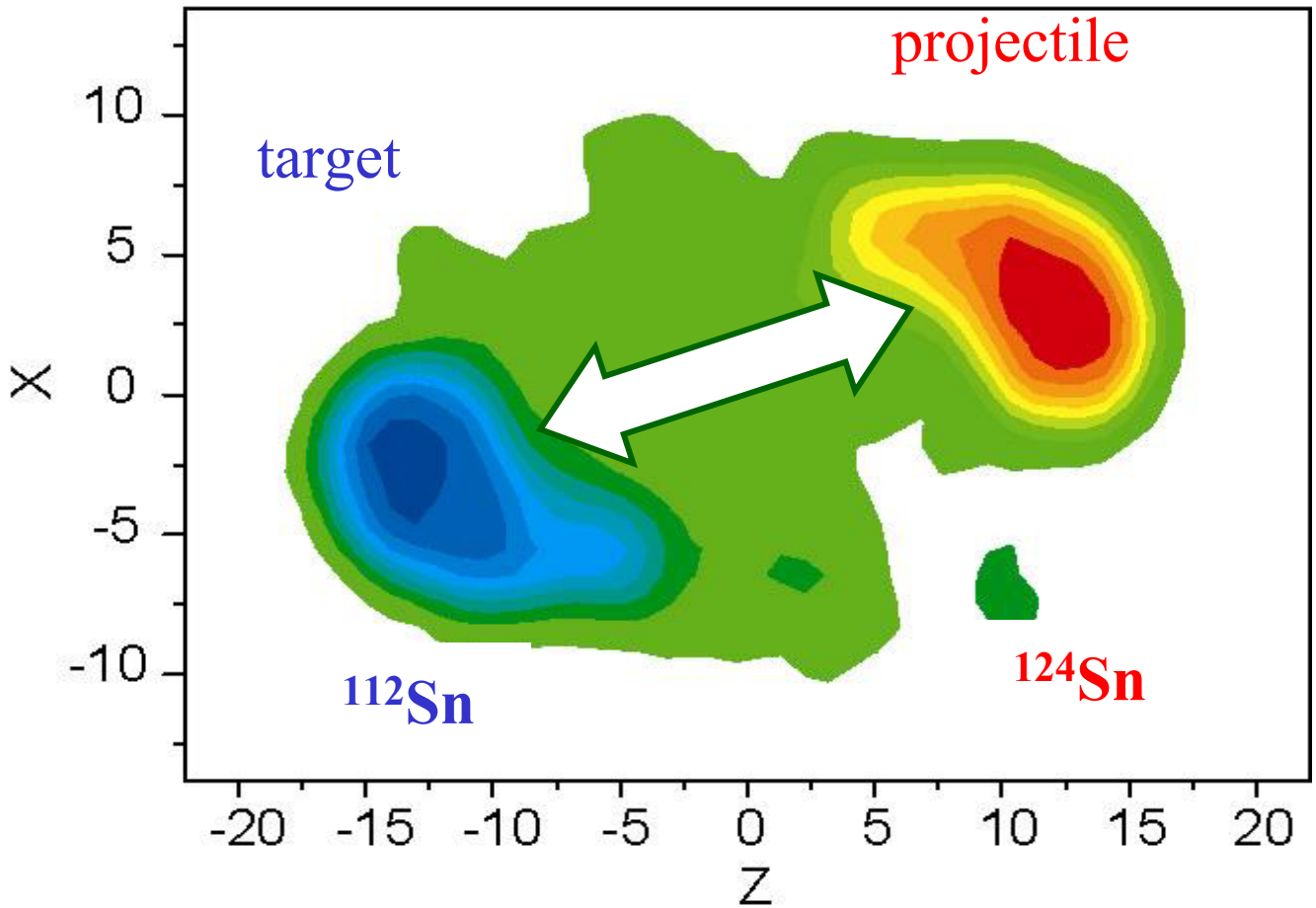
- Effects of sequential decays – y axis?
- Determination of asymmetry of fragmenting system – x axis

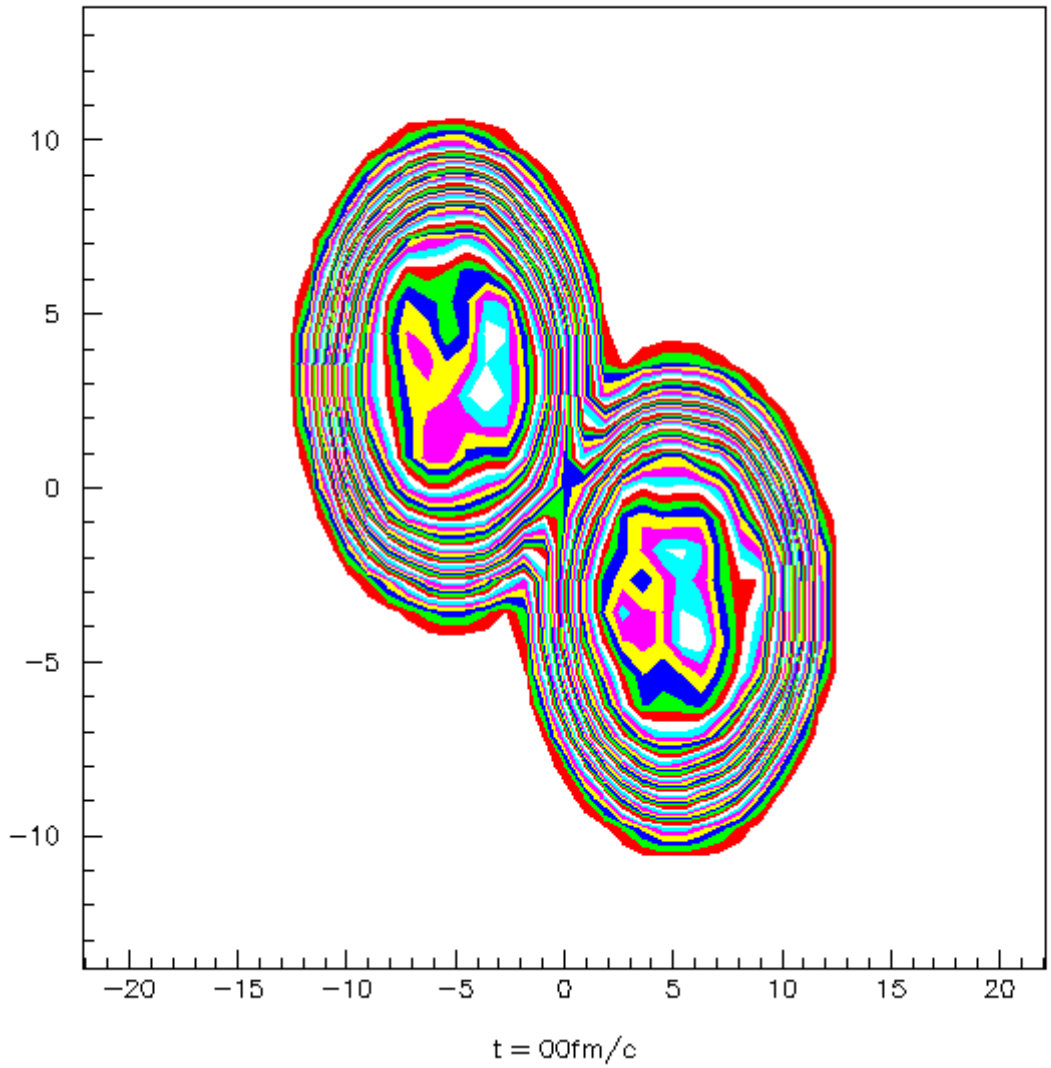


Observables in Peripheral HI collisions

Isospin diffusion in asymmetry collisions ^{124}Sn+ ^{112}Sn

Symmetry energy will act as a driving force to transport the n or p from projectile to target or vice versa via the neck region.




10
5
0
−5
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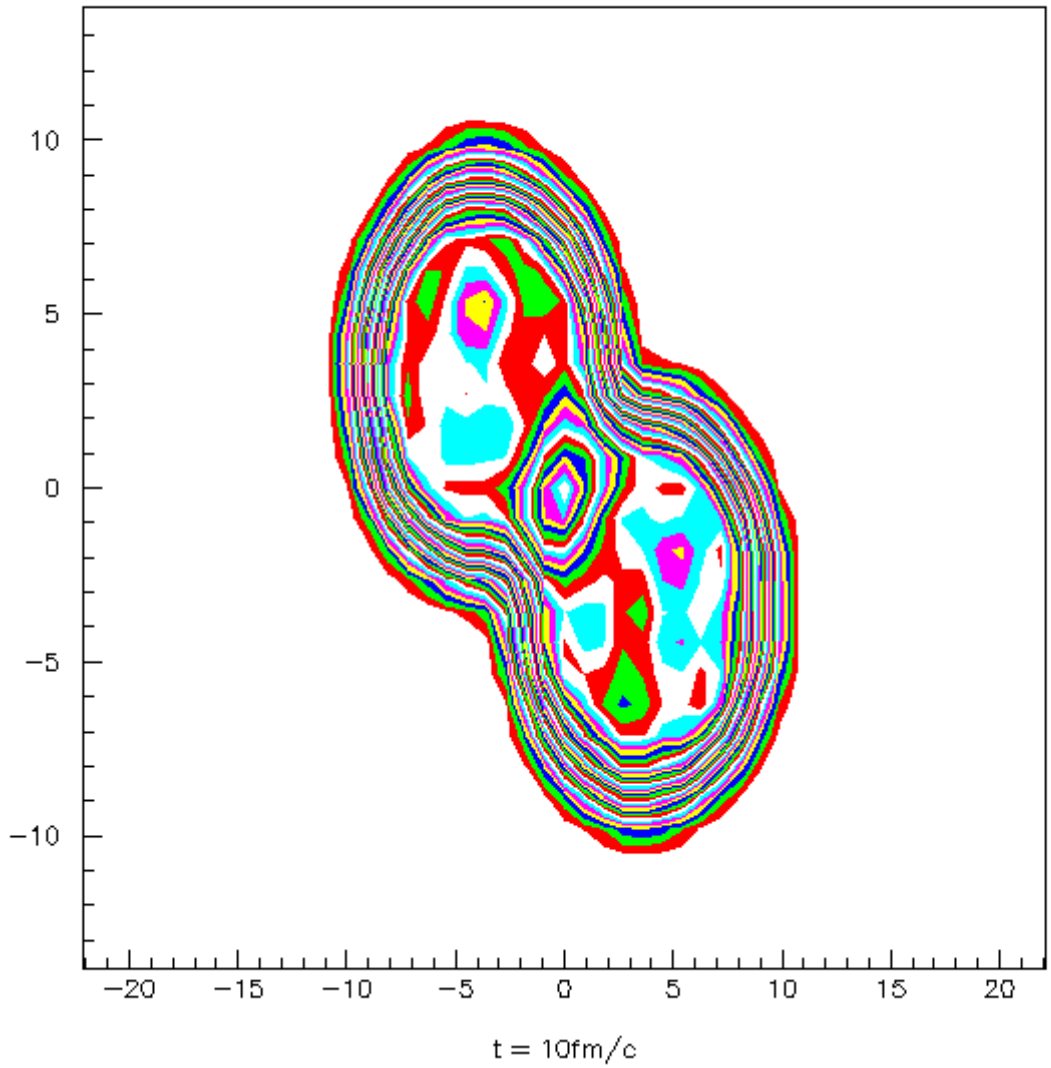
0
5
10
15
20
t = 00fm/c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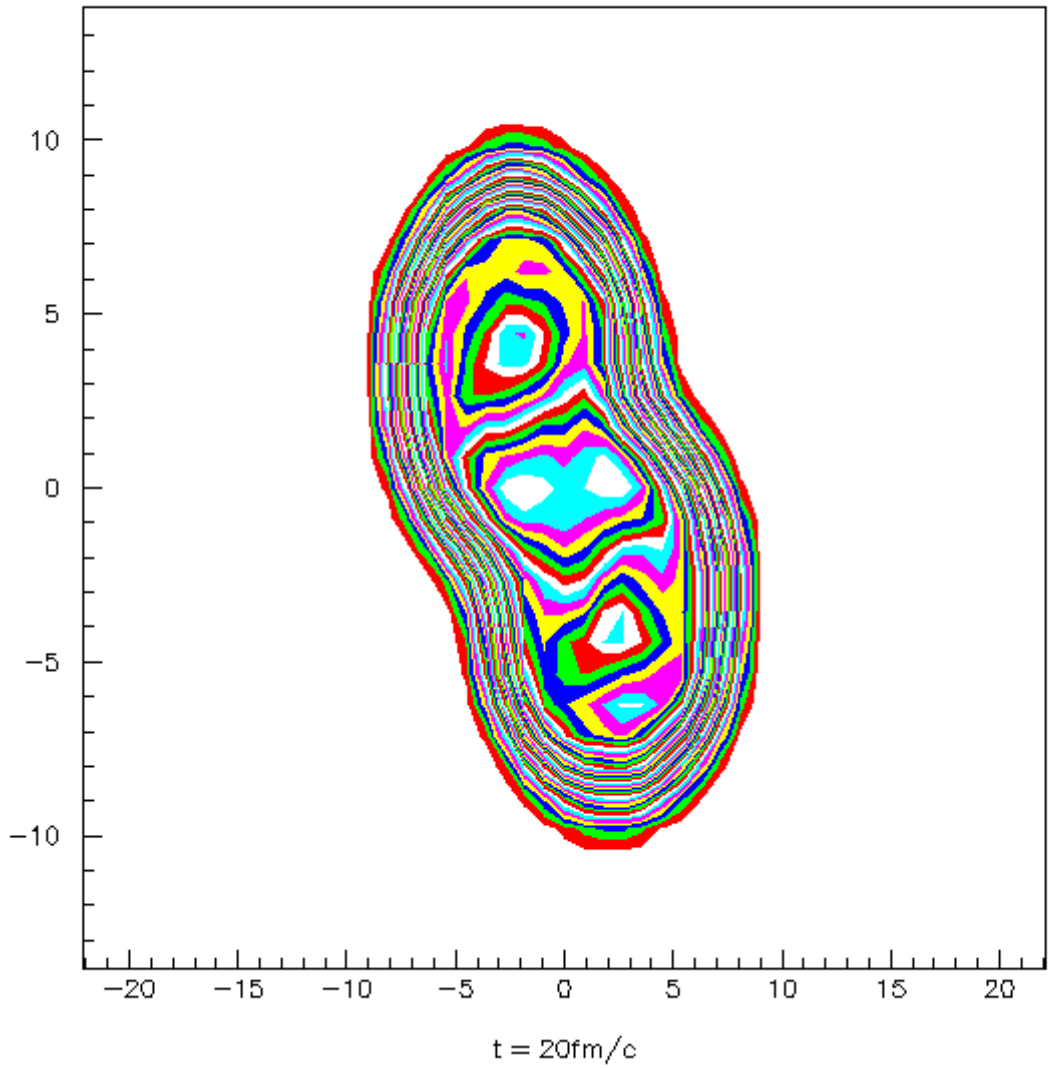
t = 10fm/c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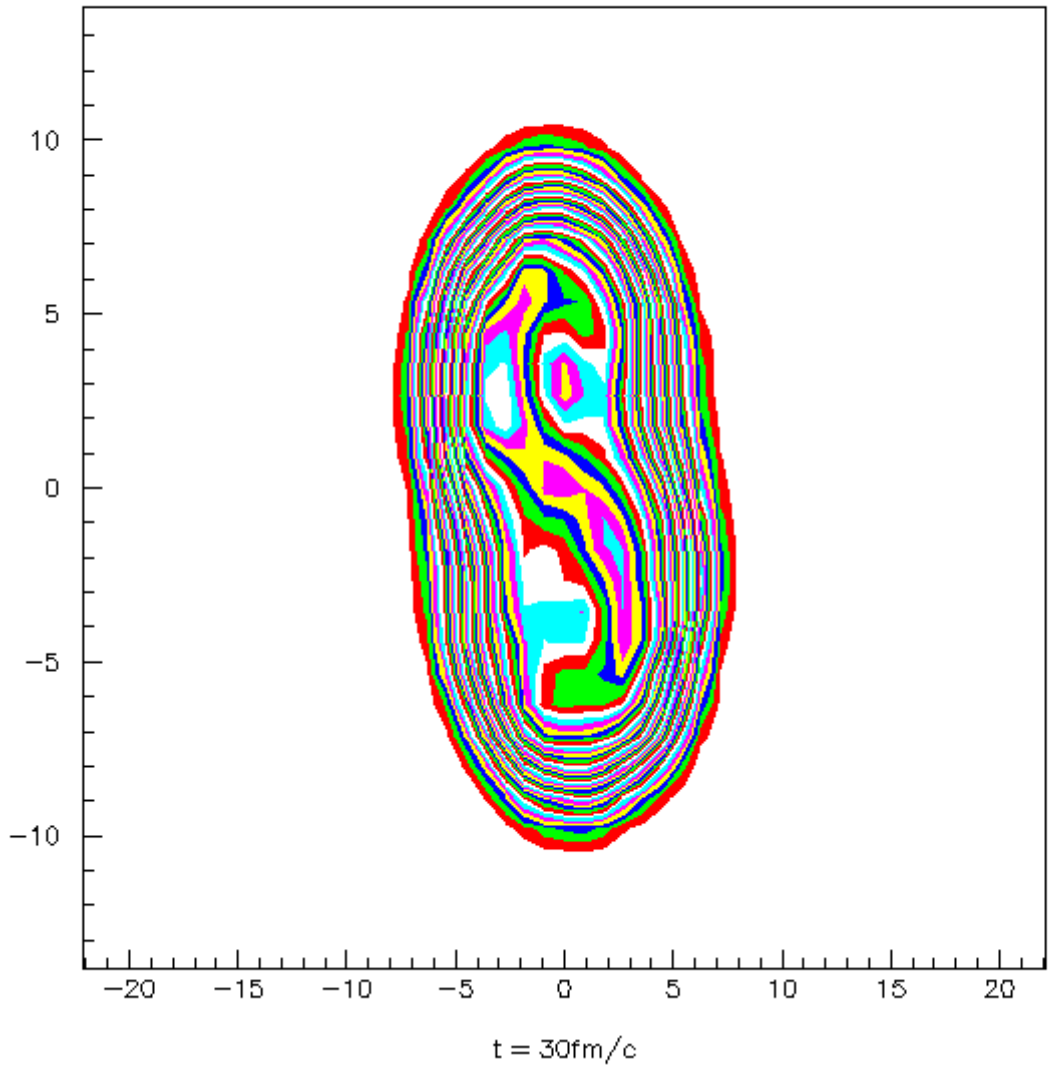
t = 20fm/c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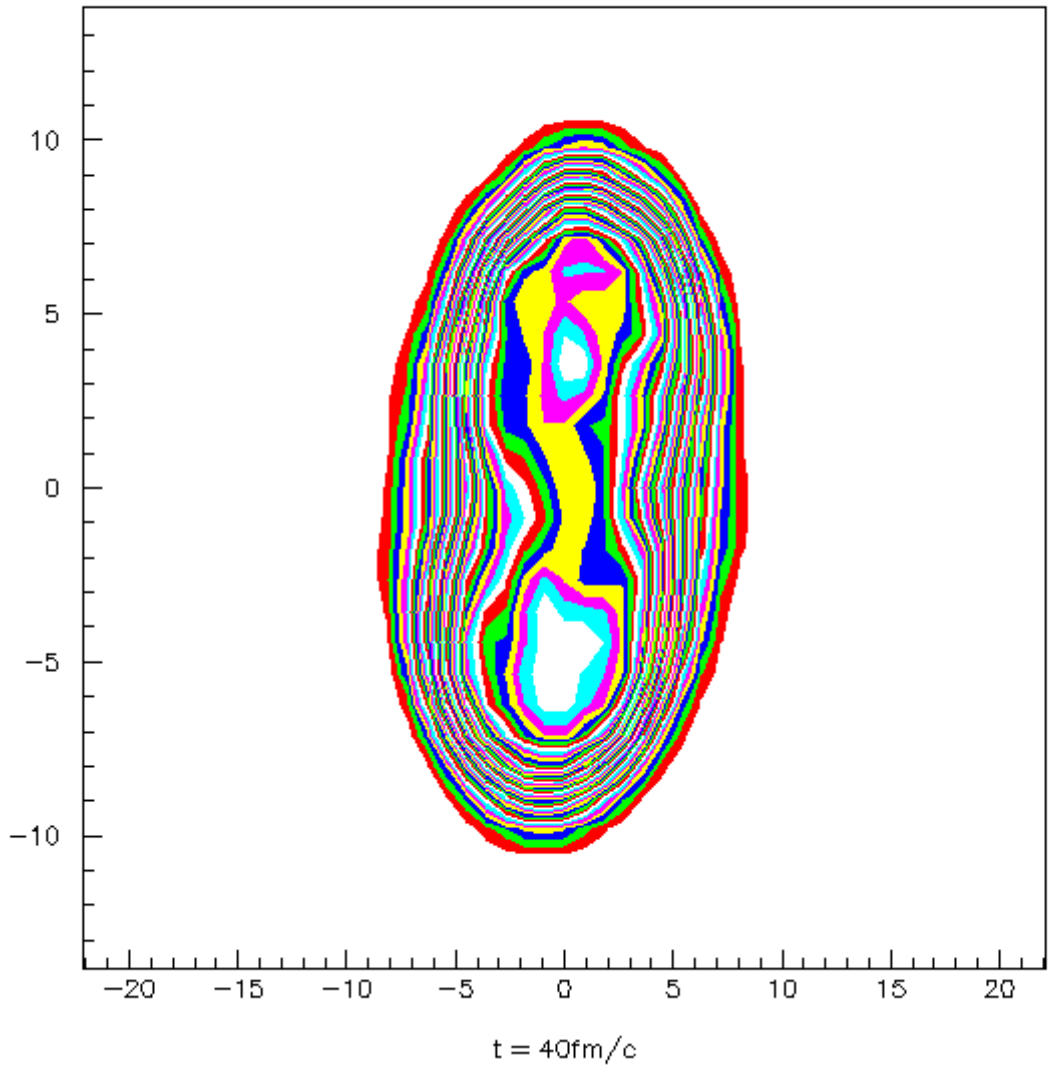
t = 30fm/c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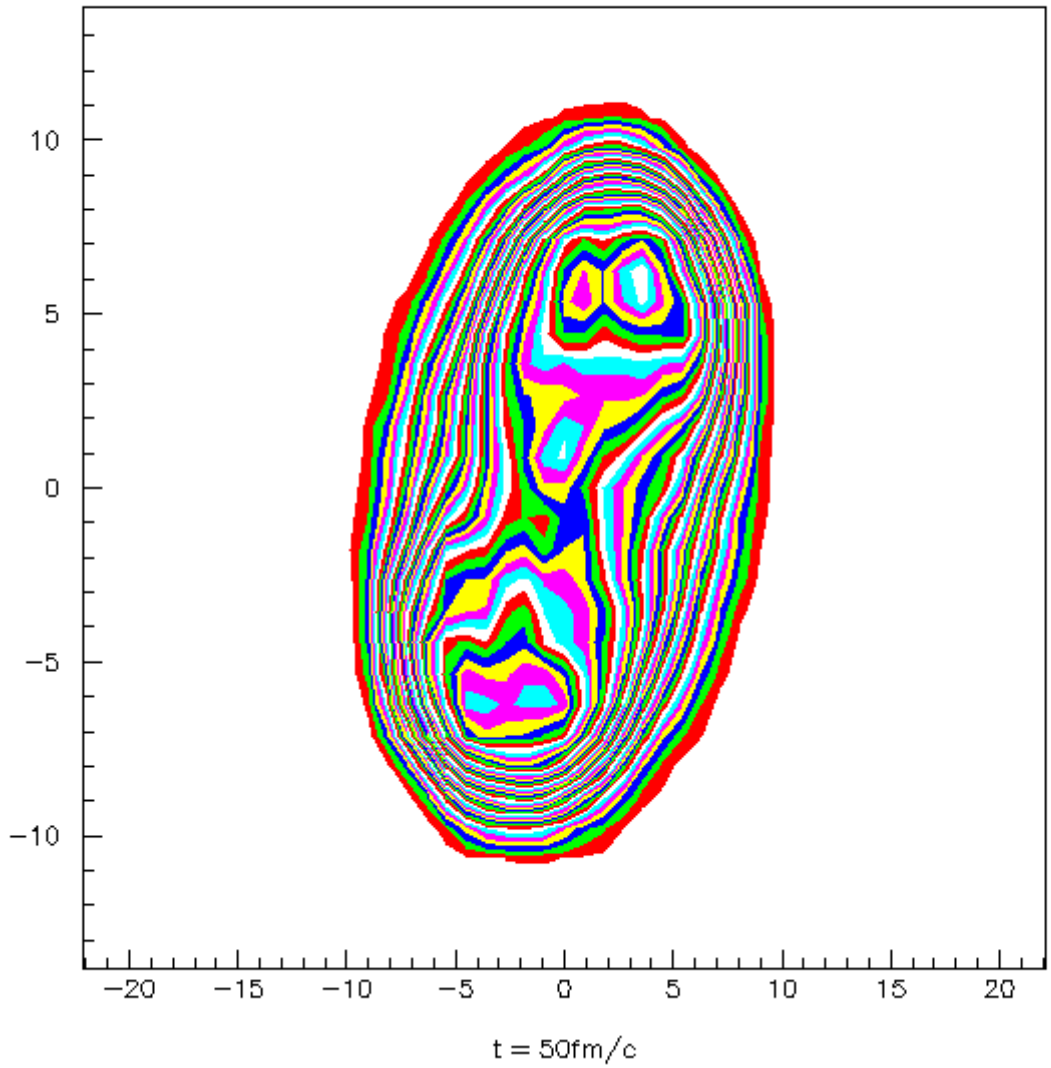
t = 40fm/c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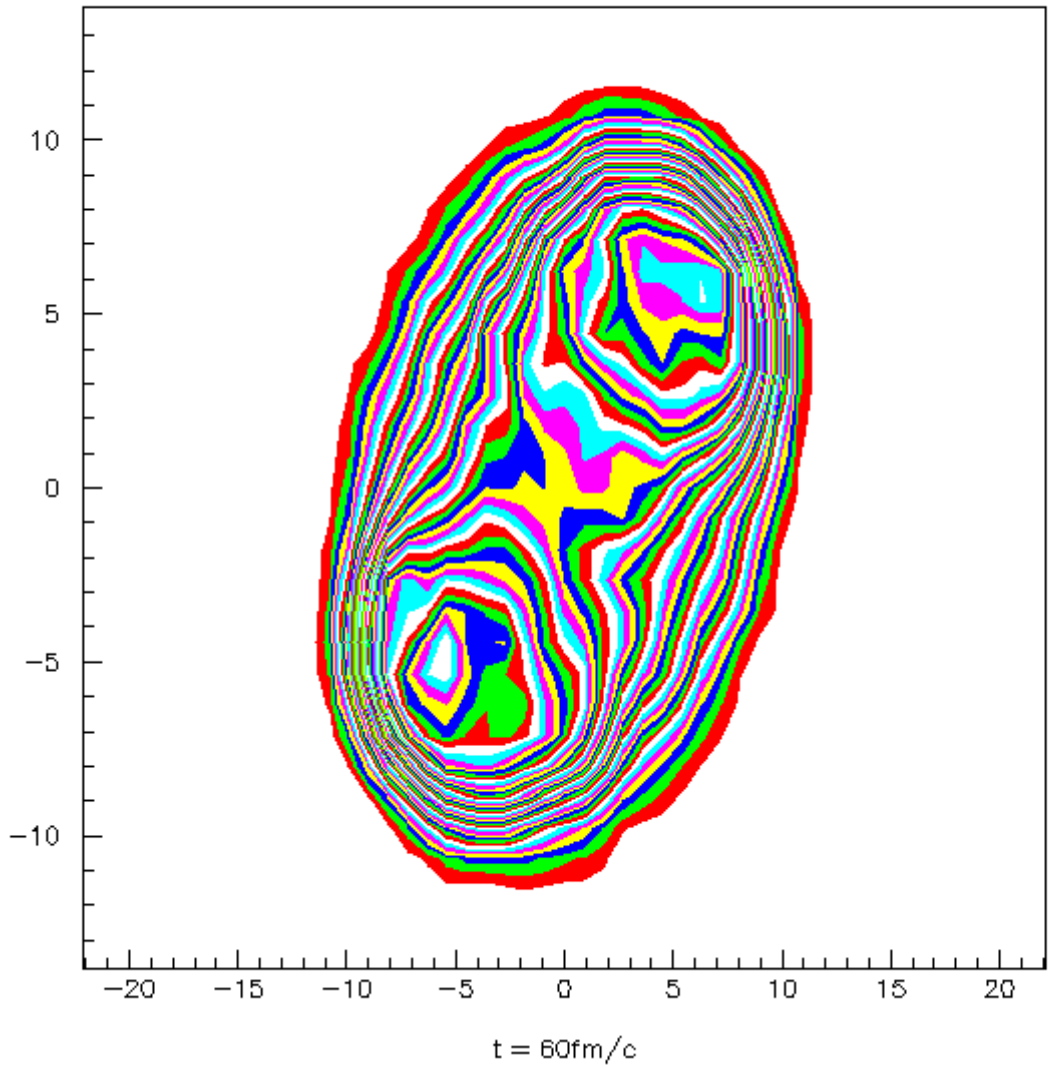
20
t = 50fm/c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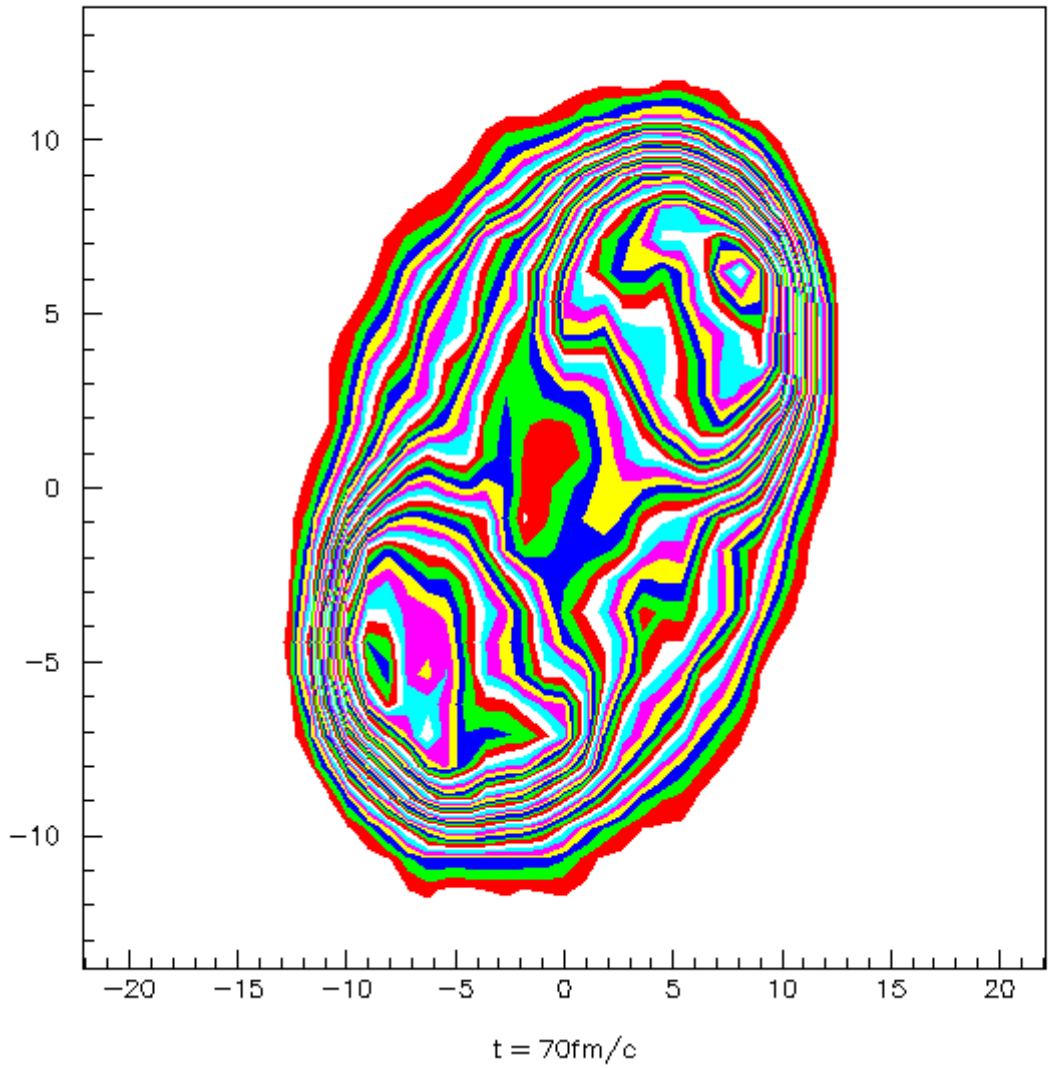
t = 60fm/c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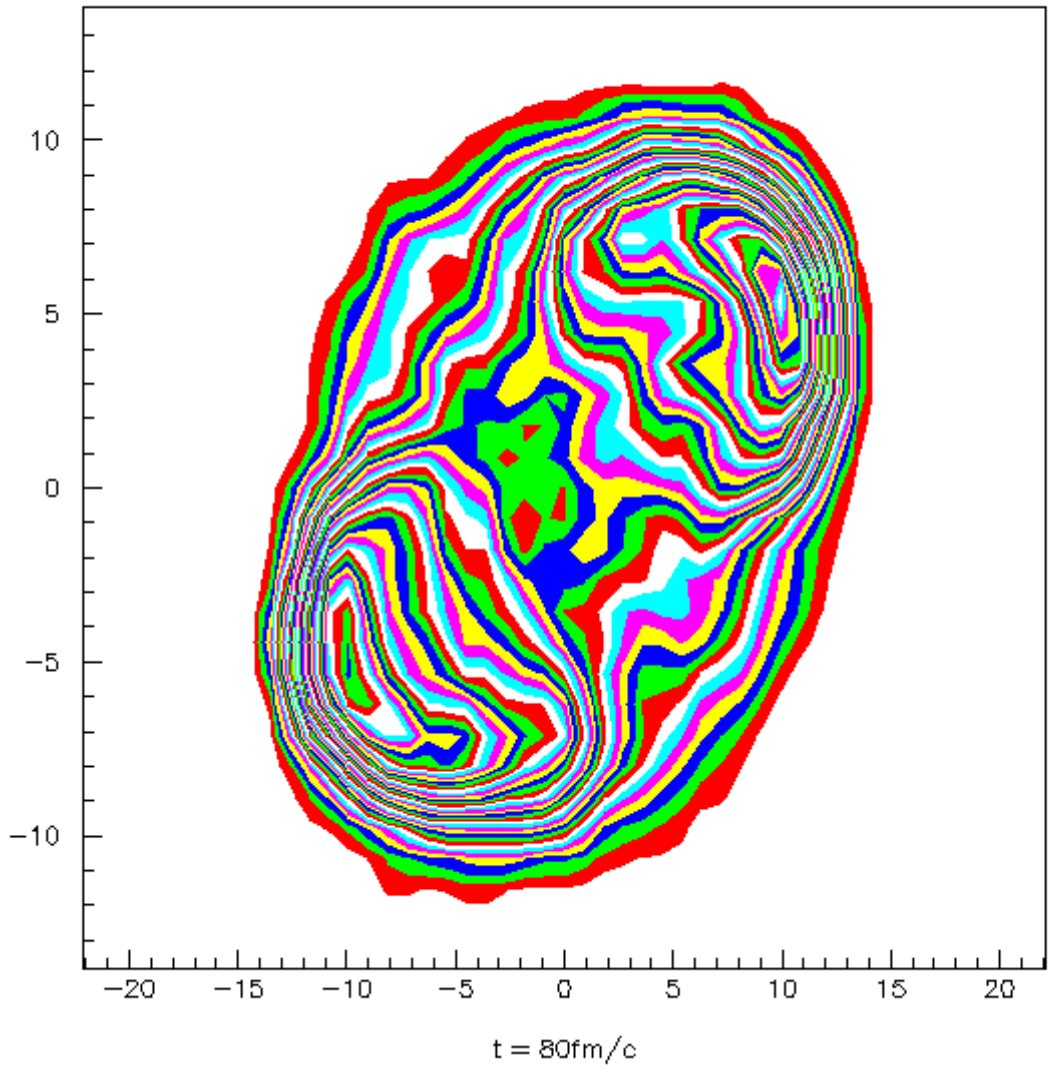
t = 70fm/c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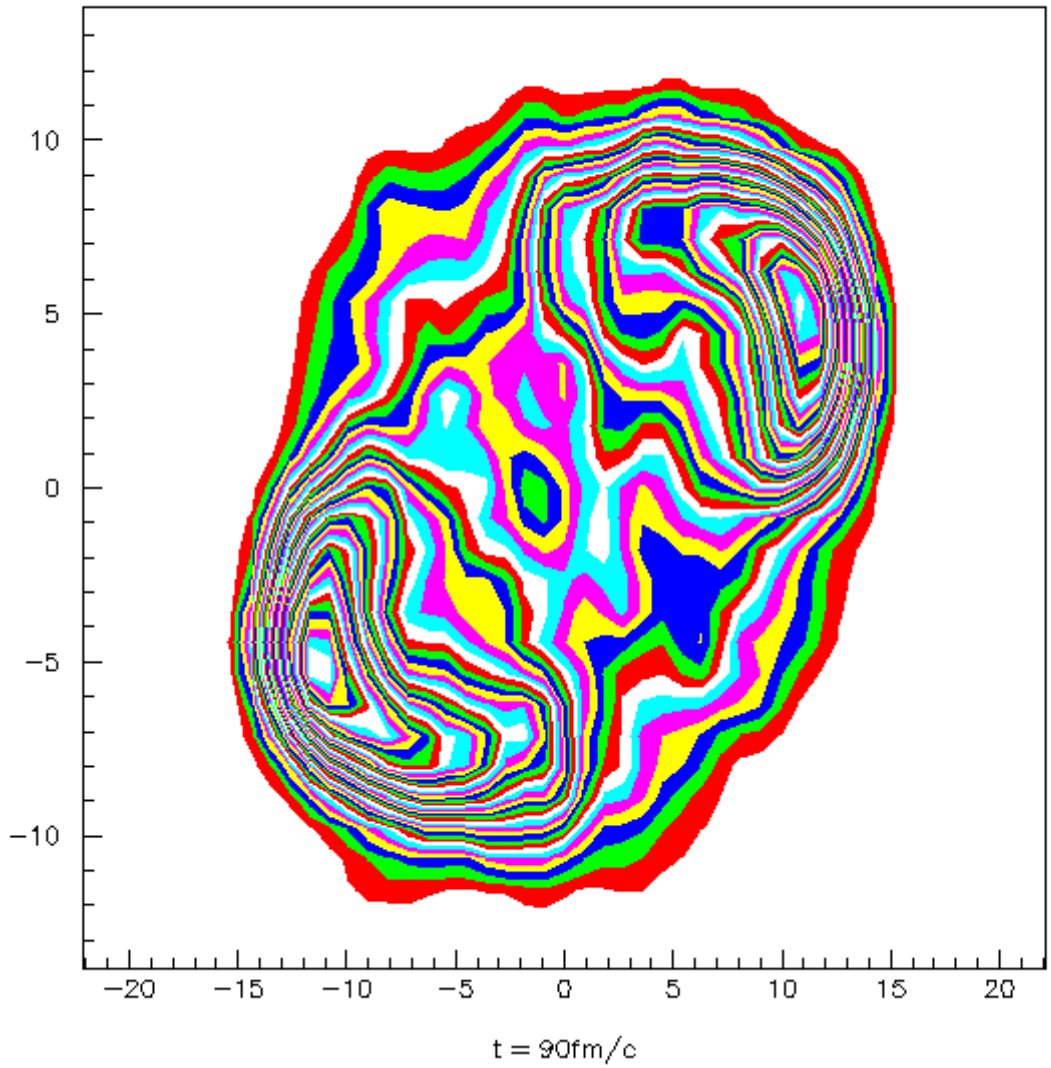
t = 80fm/c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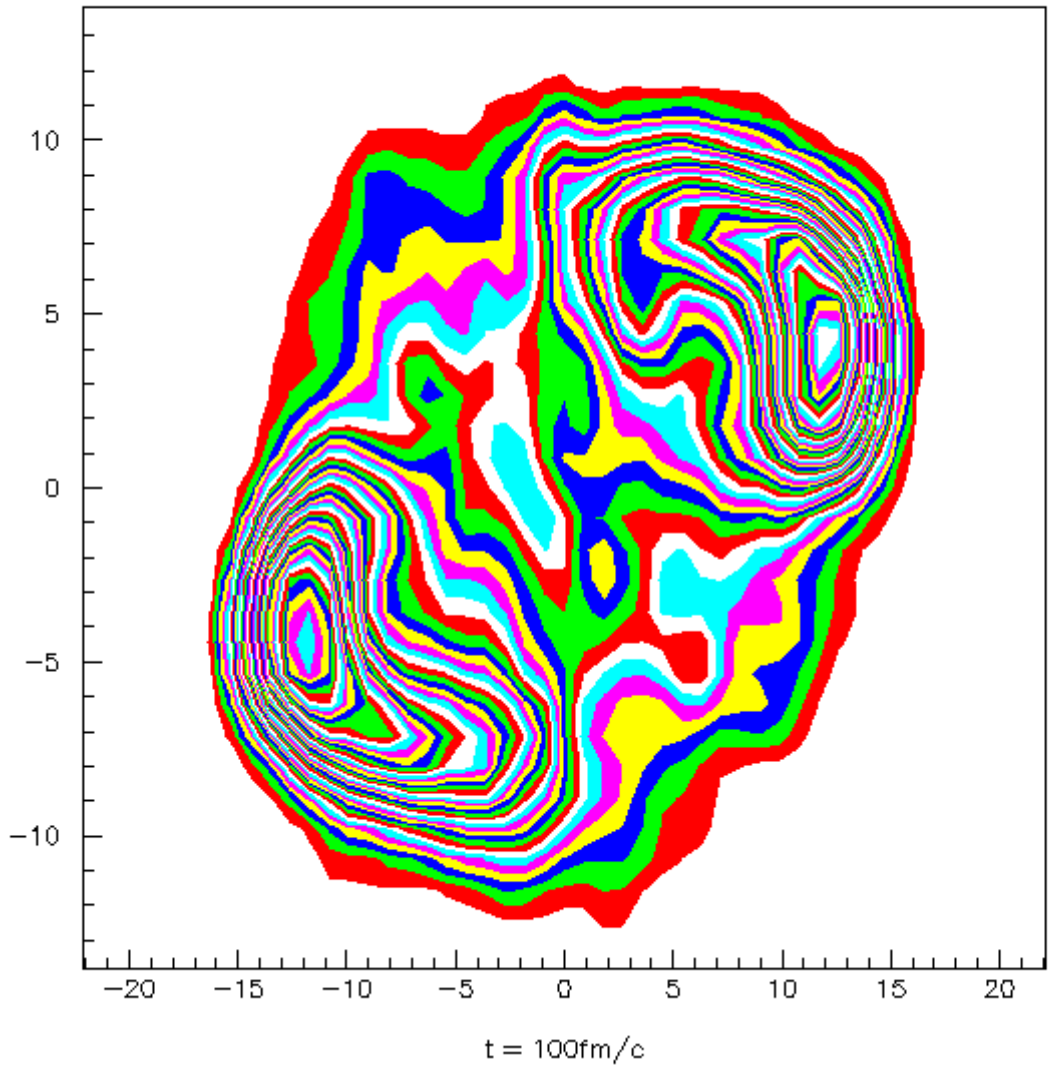
20
t = 90fm/c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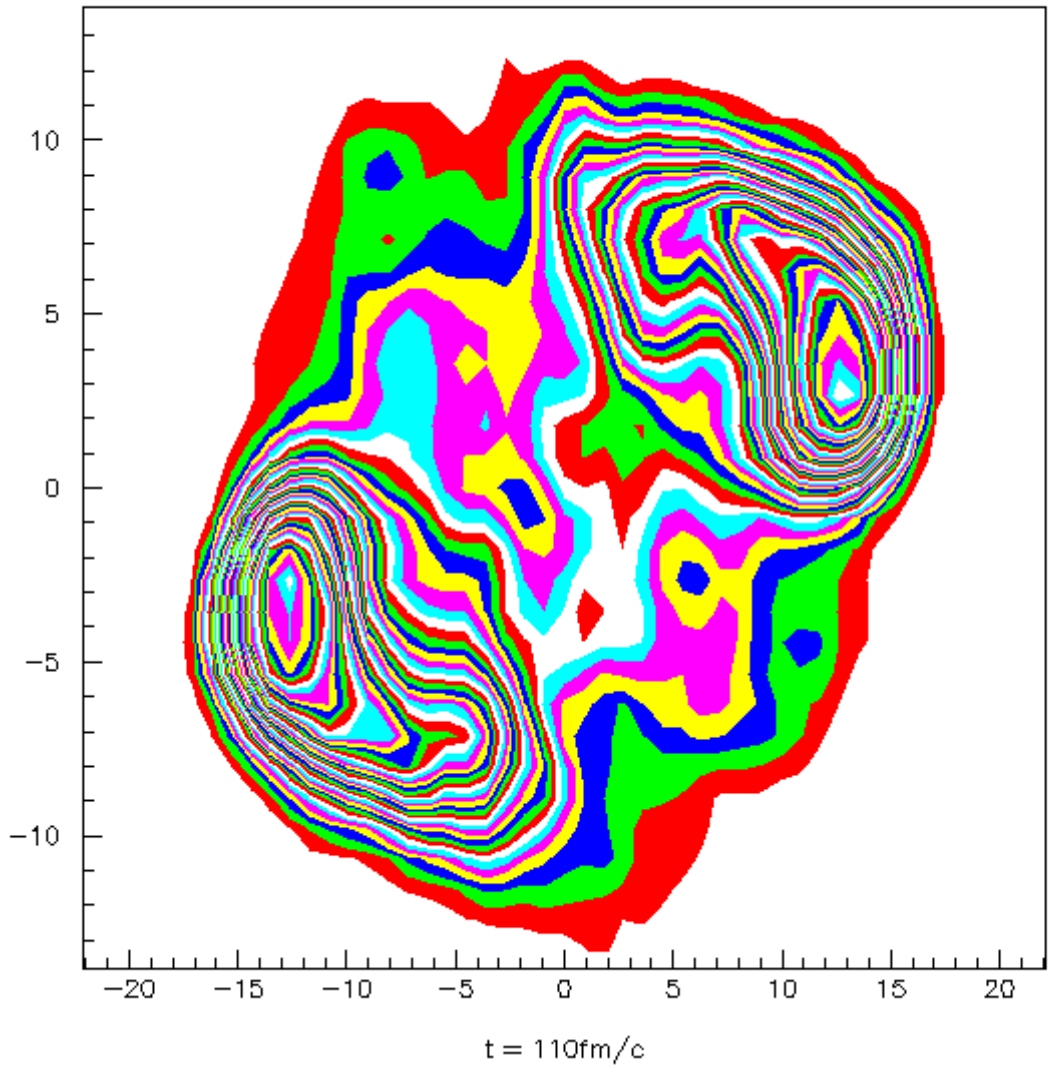
20
t = 100fm/c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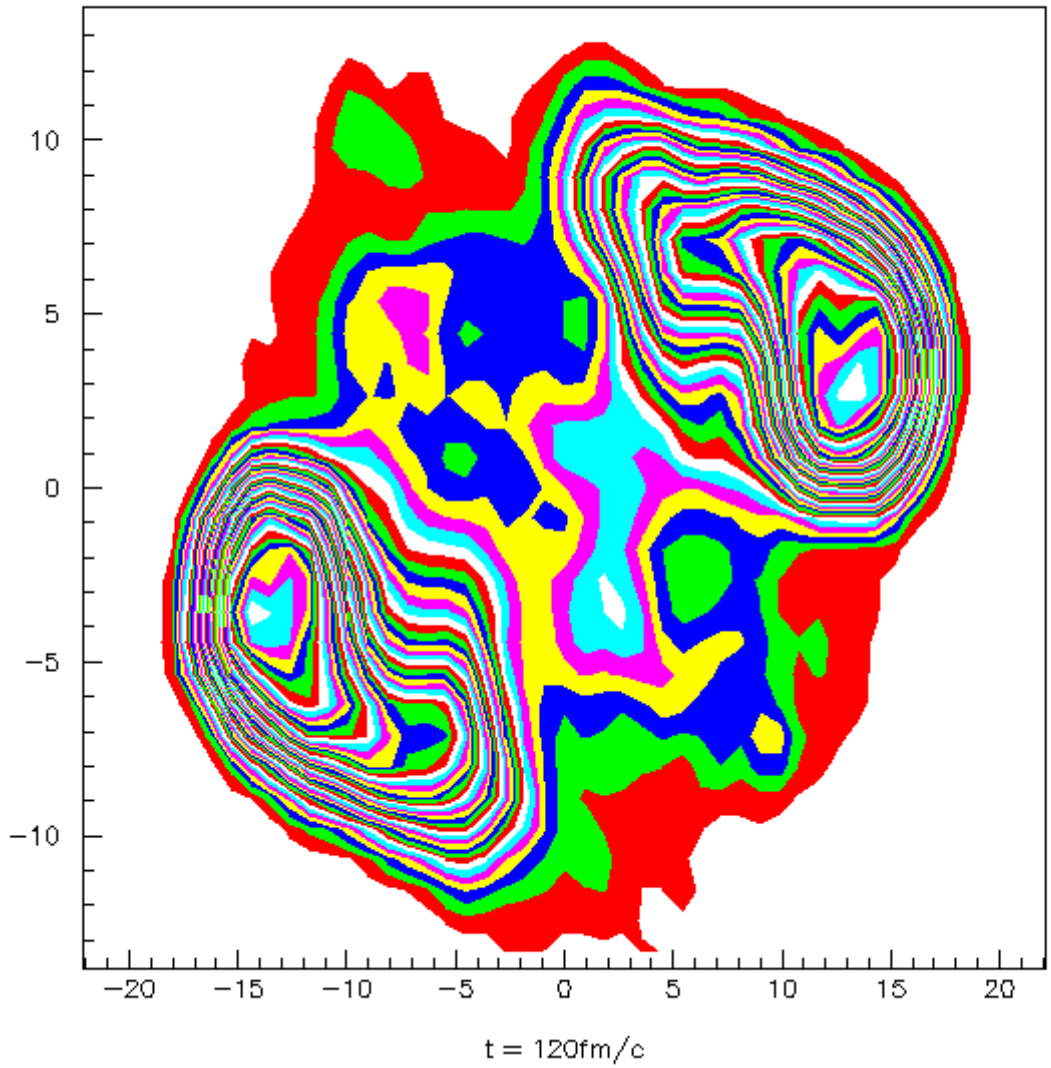
t = 110fm/c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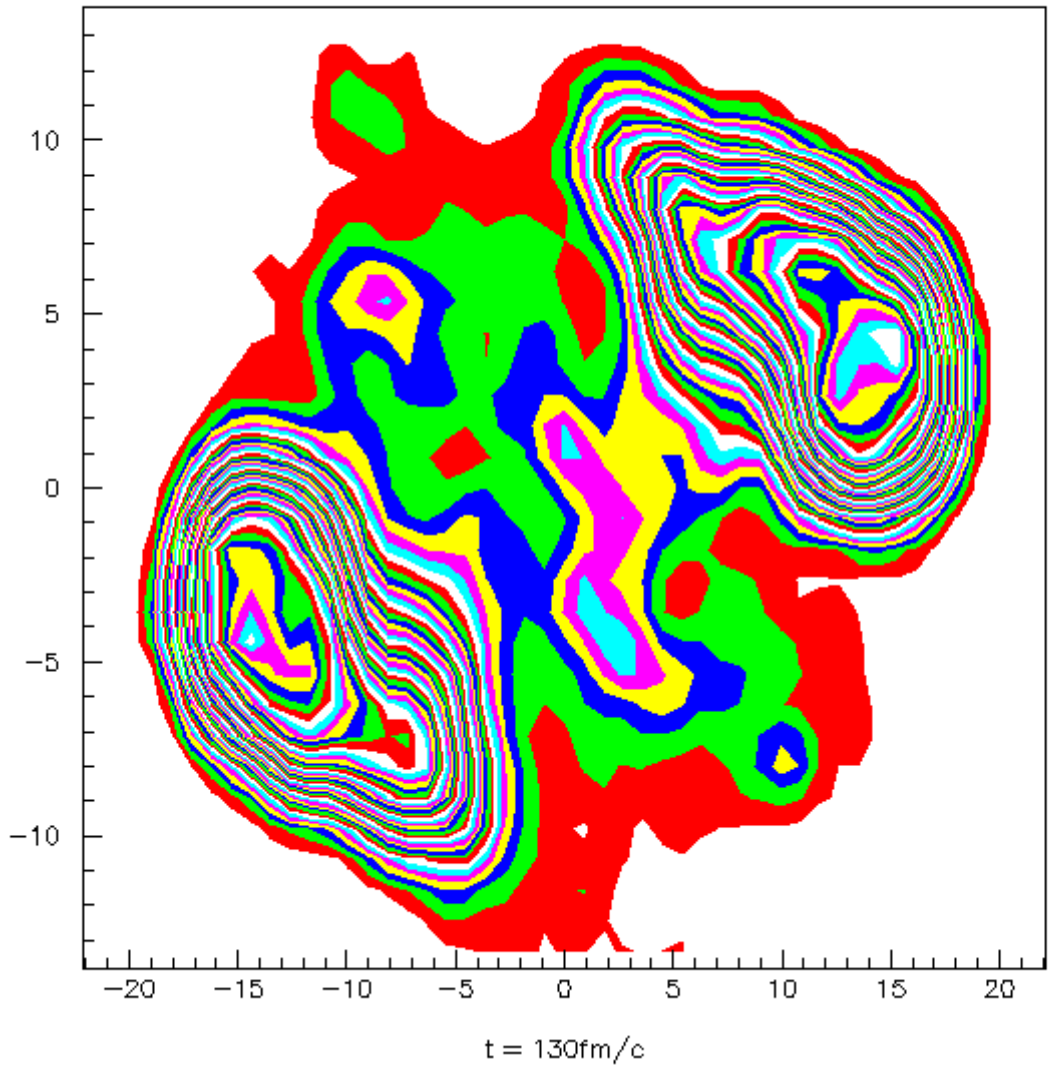
15
20
t = 120fm/c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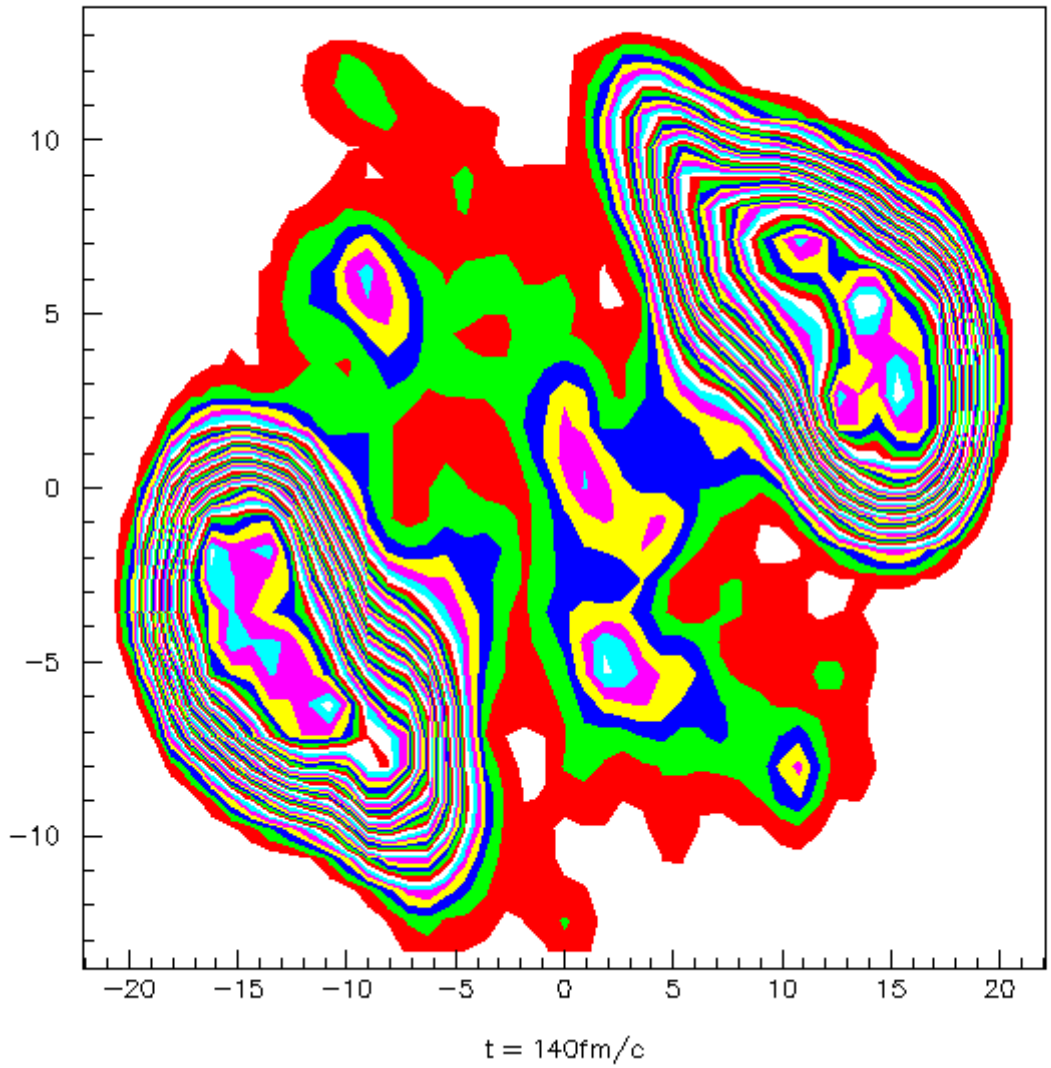
t = 130fm/c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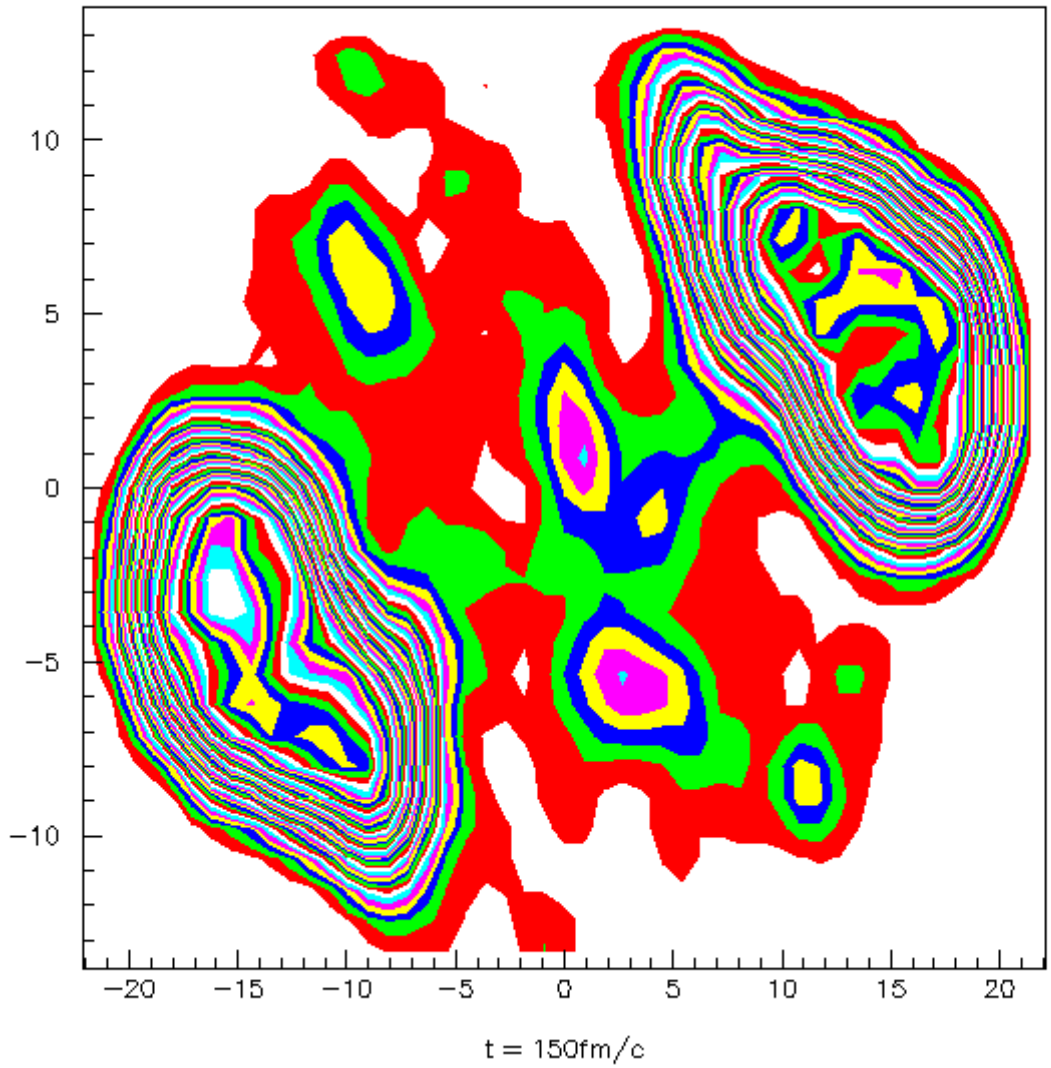
20
t = 140fm/c


10
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−5
0
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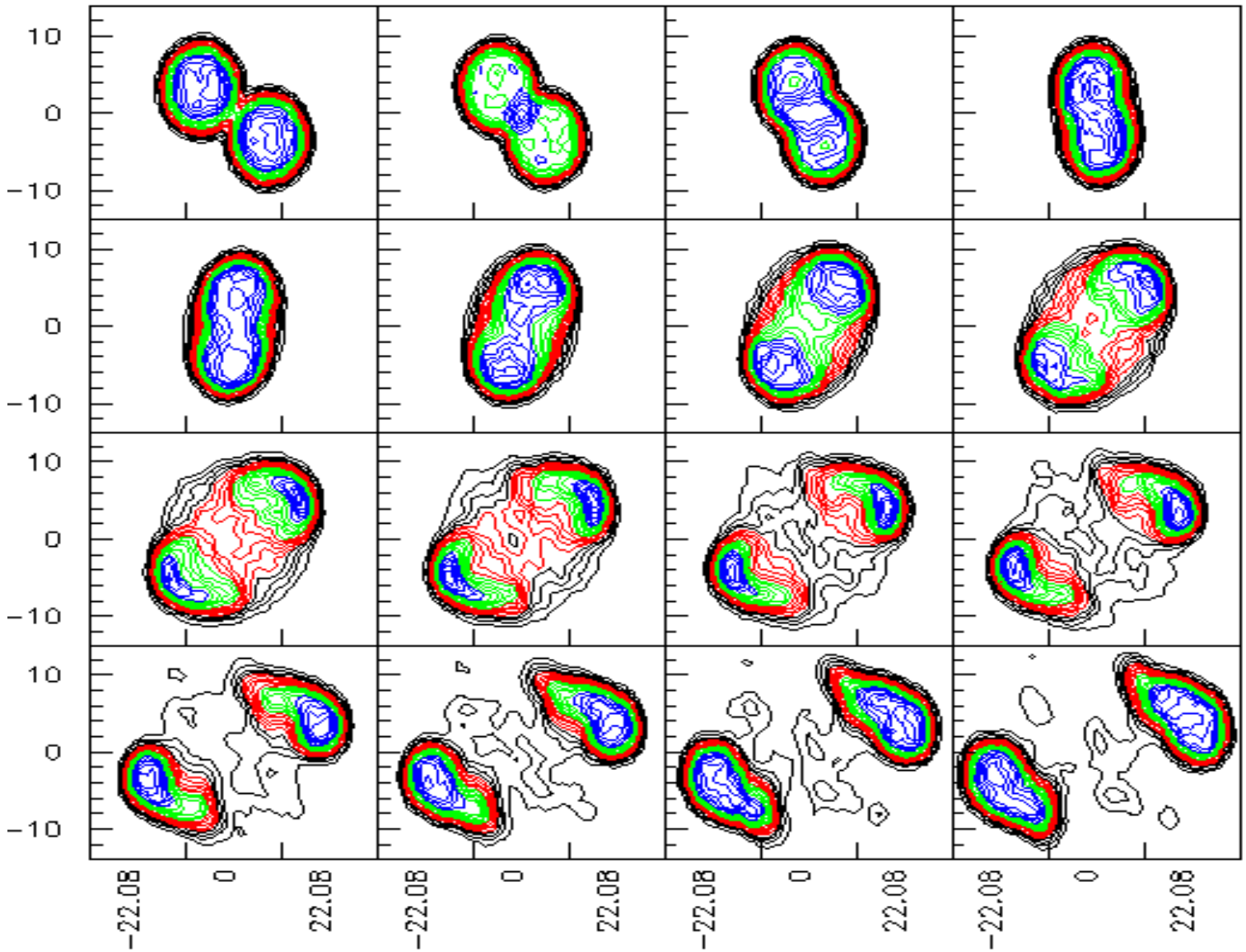
10
15
20
t = 150fm/c

Density for $(\rho/\rho_0)^2$ and 6.6 fm Impact Parameter



Observables in HI collisions

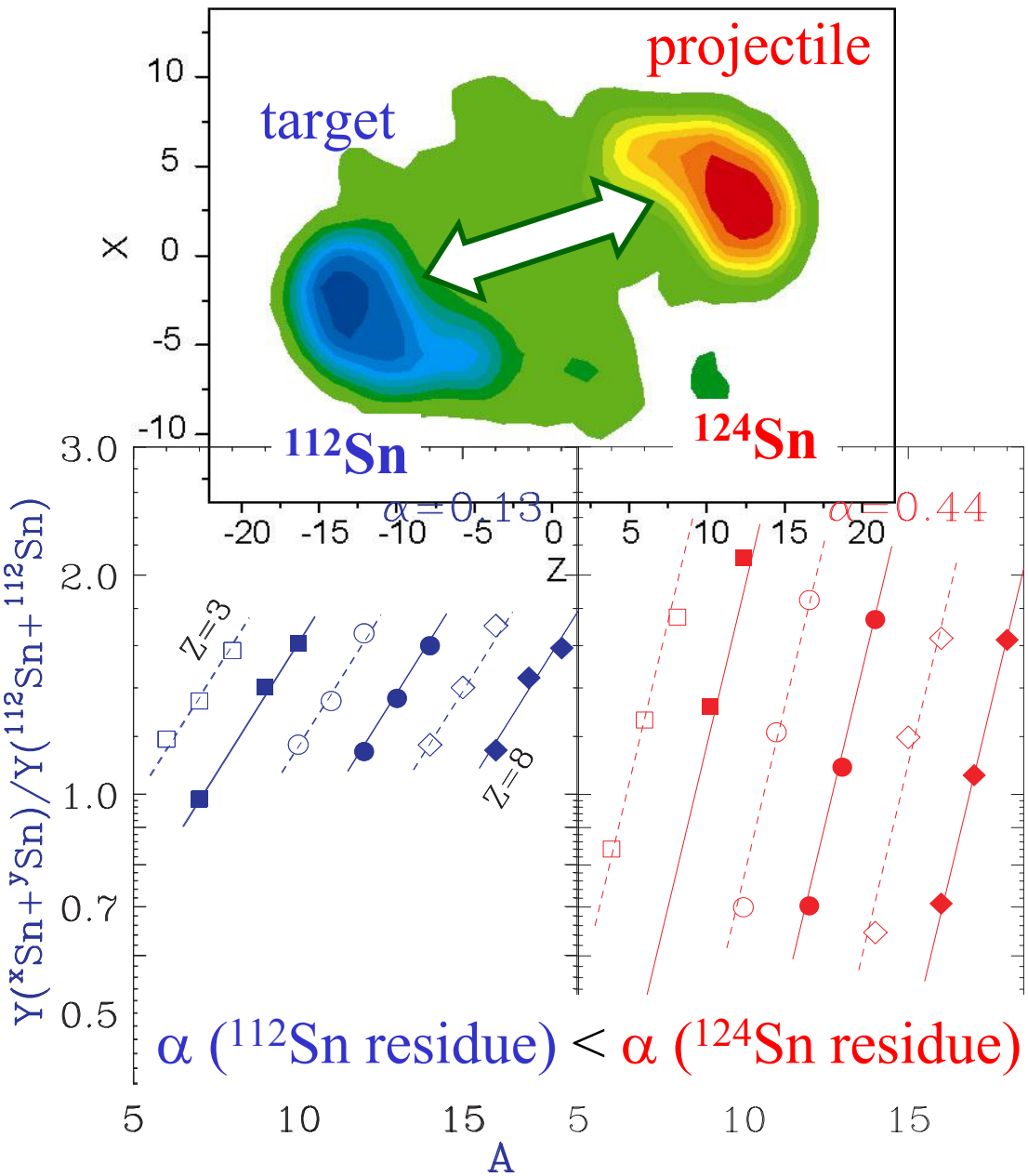
Peripheral Collisions

→ Isospin diffusion

^{124}Sn+ ^{112}Sn

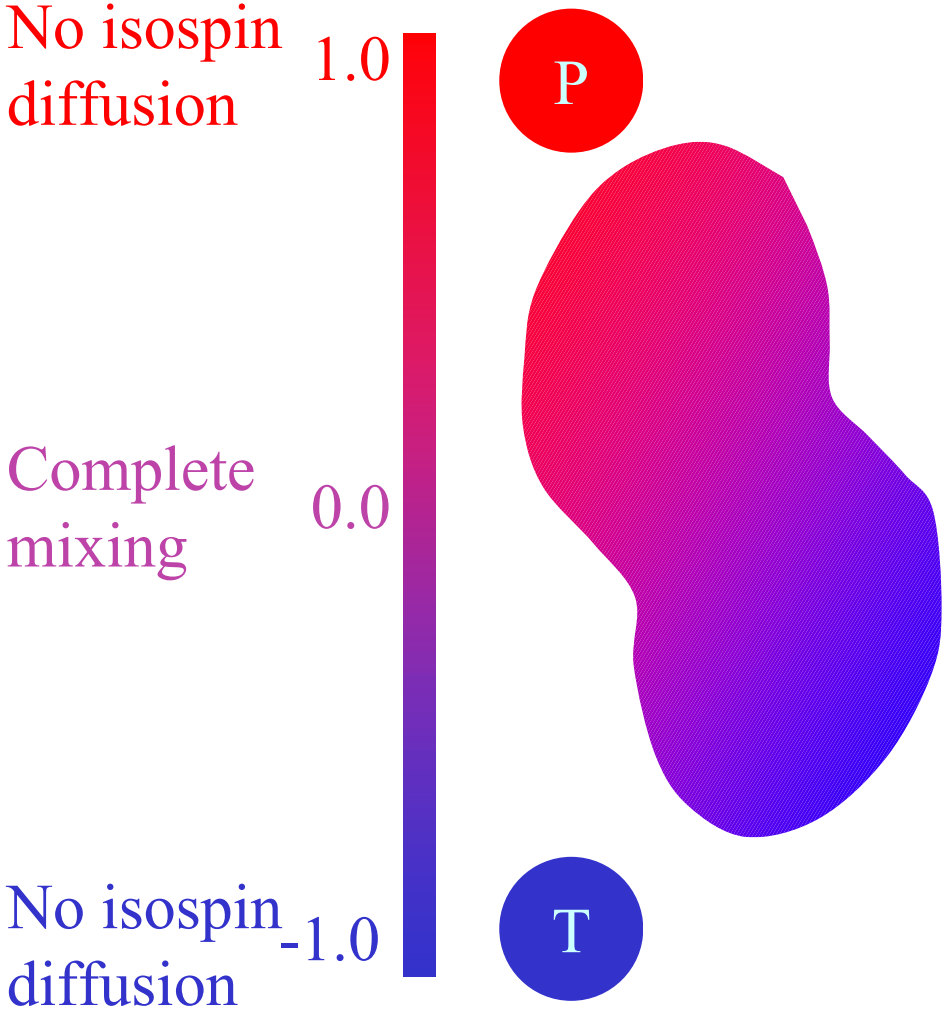
Symmetry energy will act as a driving force to transport the n or p from projectile to target or vice versa via the neck region.

N/Z diffusion?
Coulomb?
Pre-equilibrium?
Theoretical observable?



Isospin Diffusion

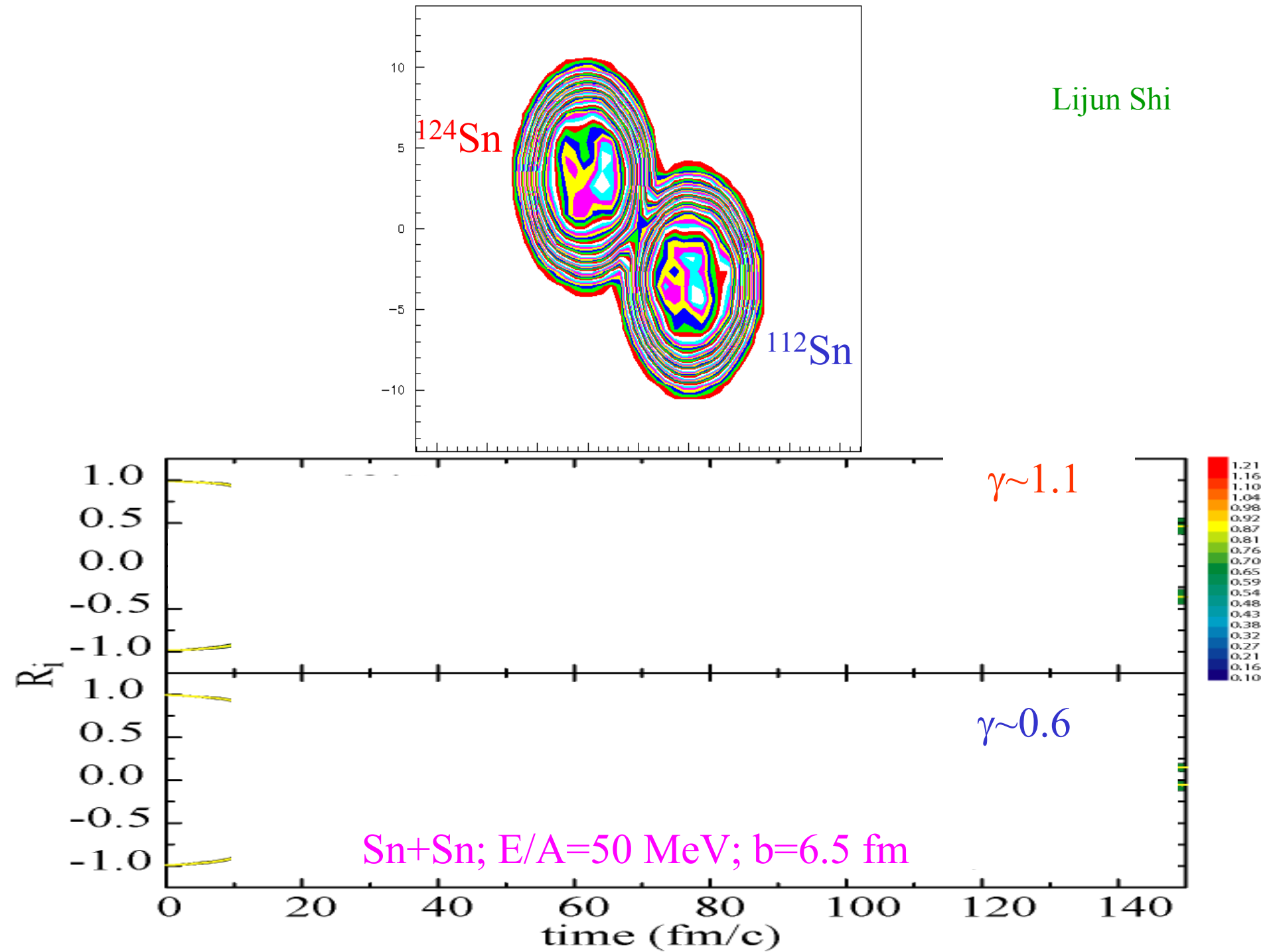
$$R_i = \frac{2\delta - \delta_{PP} - \delta_{TT}}{\delta_{PP} - \delta_{TT}}$$

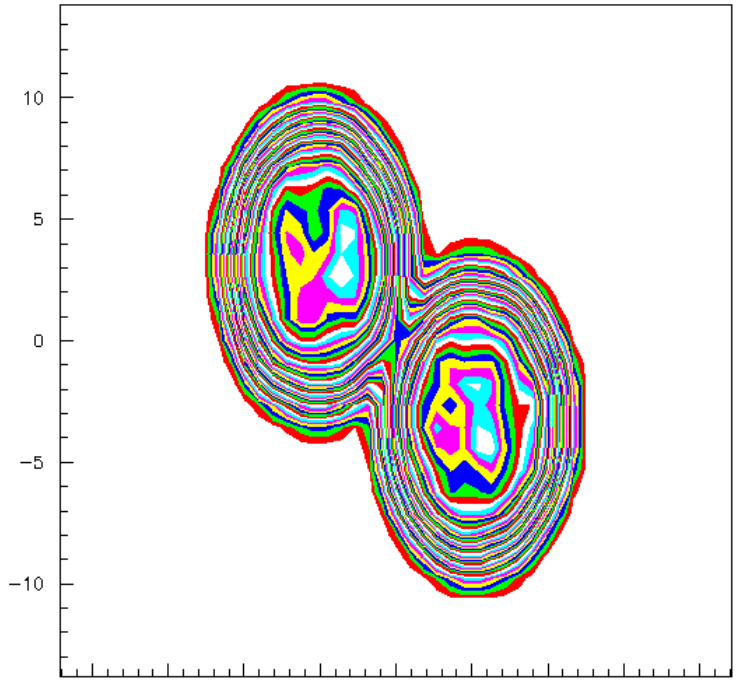


Difference between projectile and target spectator asymmetry, $\delta=(N-Z)/(N+Z)$, measures the isospin diffusion which can be used to extract information about symmetry energy.

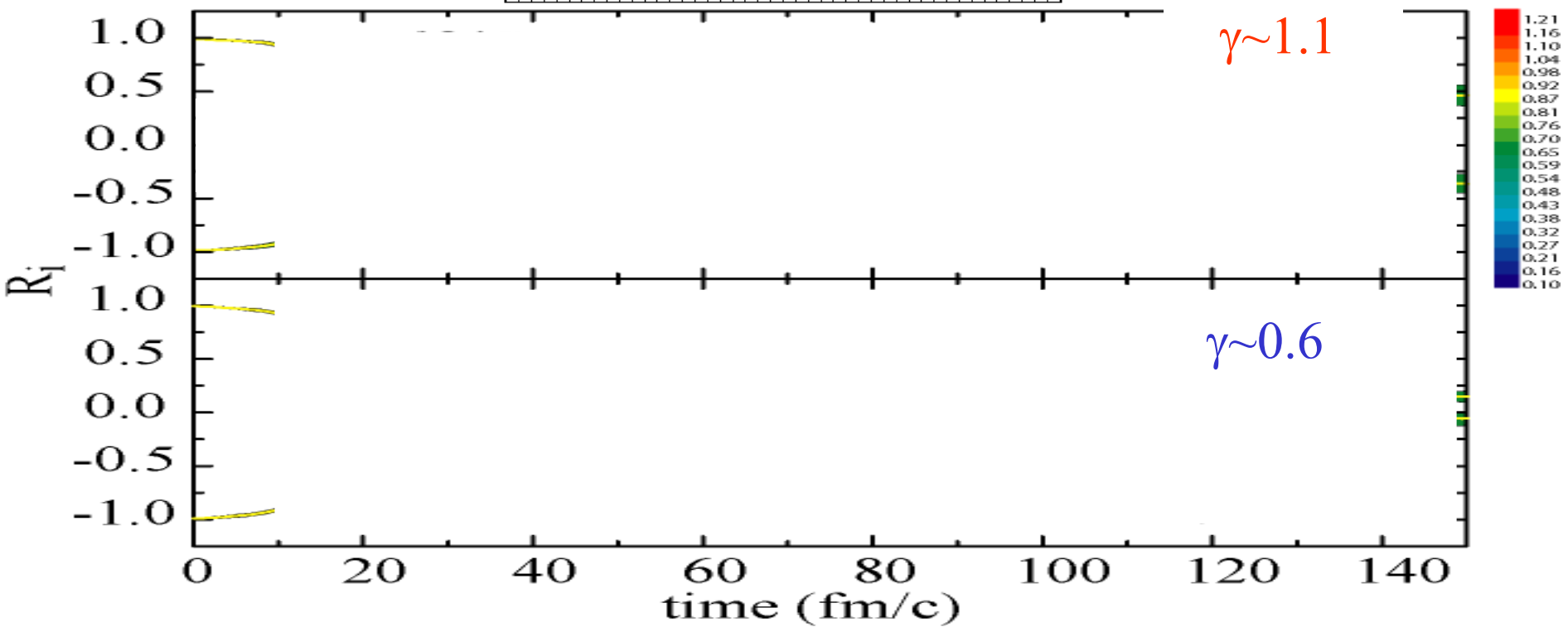
$$E(\rho, \delta) = E(\rho, \delta=0) + E_{sym}(\rho,\delta)\,\delta^2$$

Assume $E_{sym}(\rho) \propto (\rho/\rho_0)^{\gamma}$

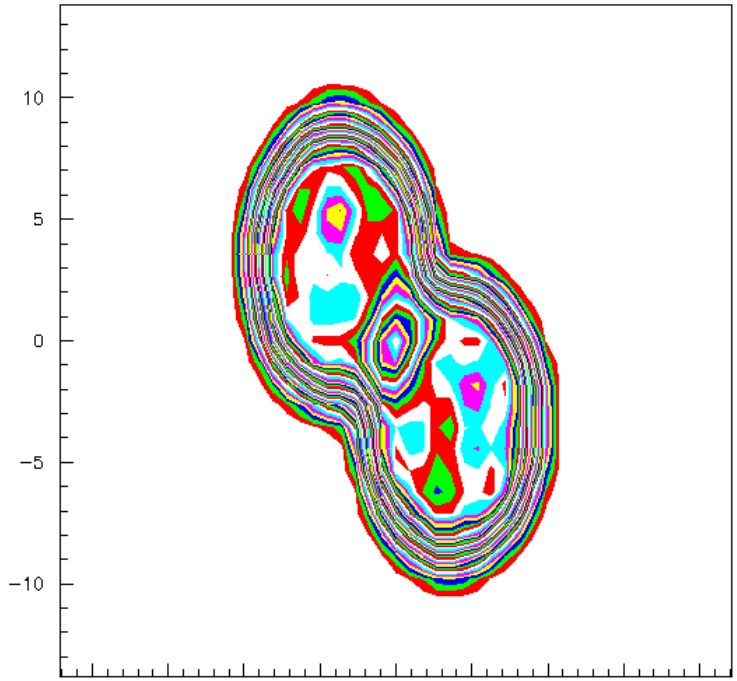

Lijun Shi
124Sn
112Sn
γ~1.1
γ~0.6
Sn+Sn; E/A=50 MeV; b=6.5 fm
Ri
time (fm/c)

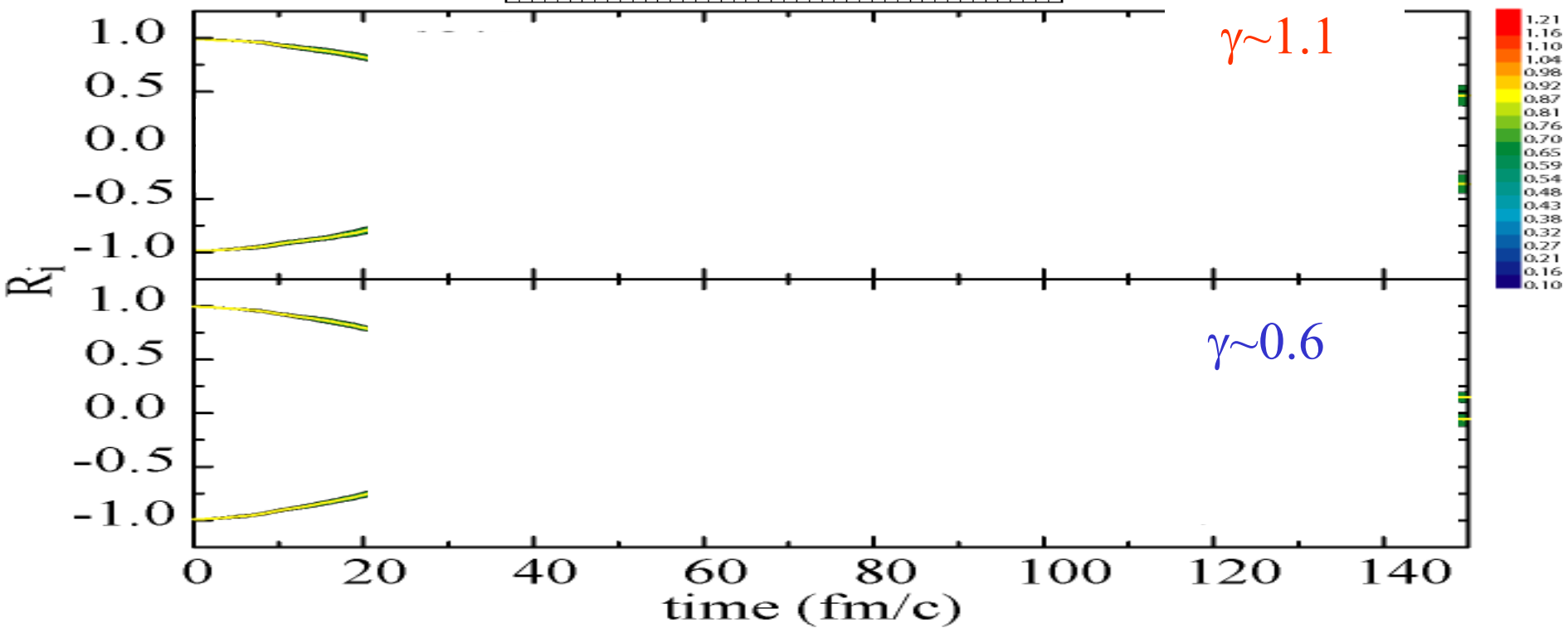

10
5
0
-5
-10

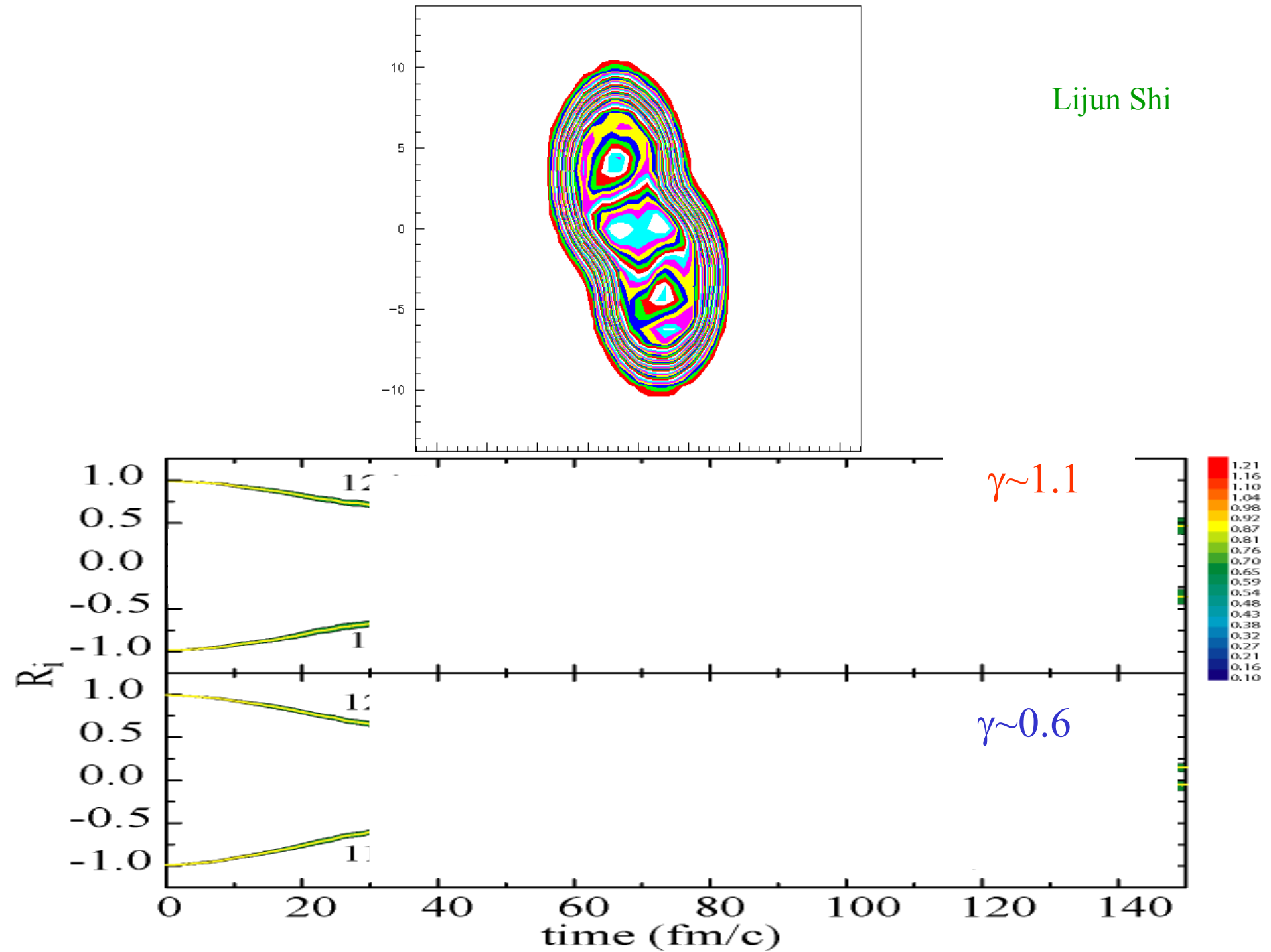
Lijun Shi

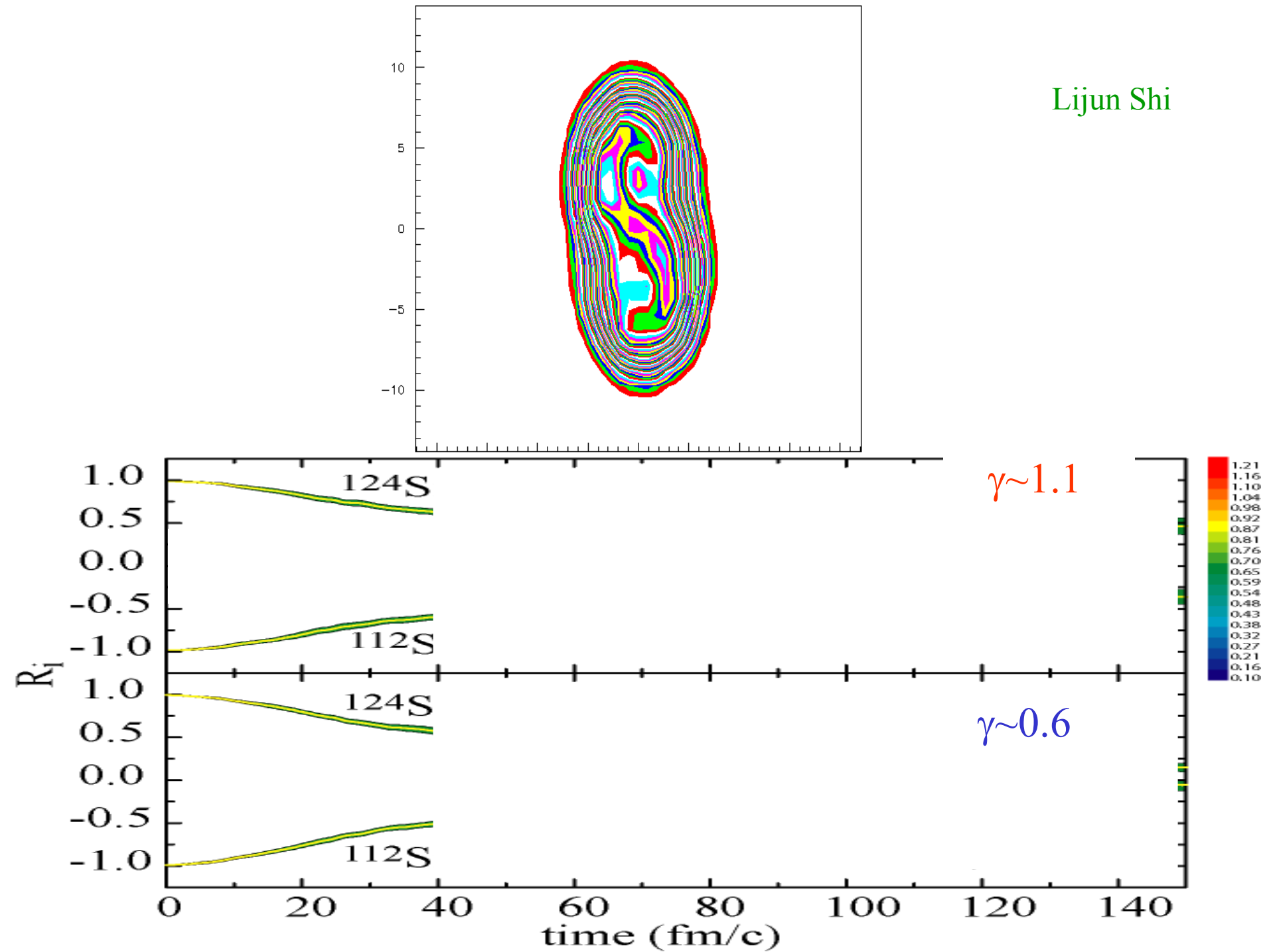

γ~1.1
γ~0.6
R_i
1.0
0.5
0.0
-0.5
-1.0
0
20
40
60
80
100
120
140
time (fm/c)
1.21
1.16
1.10
1.04
0.98
0.92
0.87
0.81
0.76
0.70
0.65
0.59
0.54
0.48
0.43
0.38
0.32
0.27
0.21
0.16
0.10

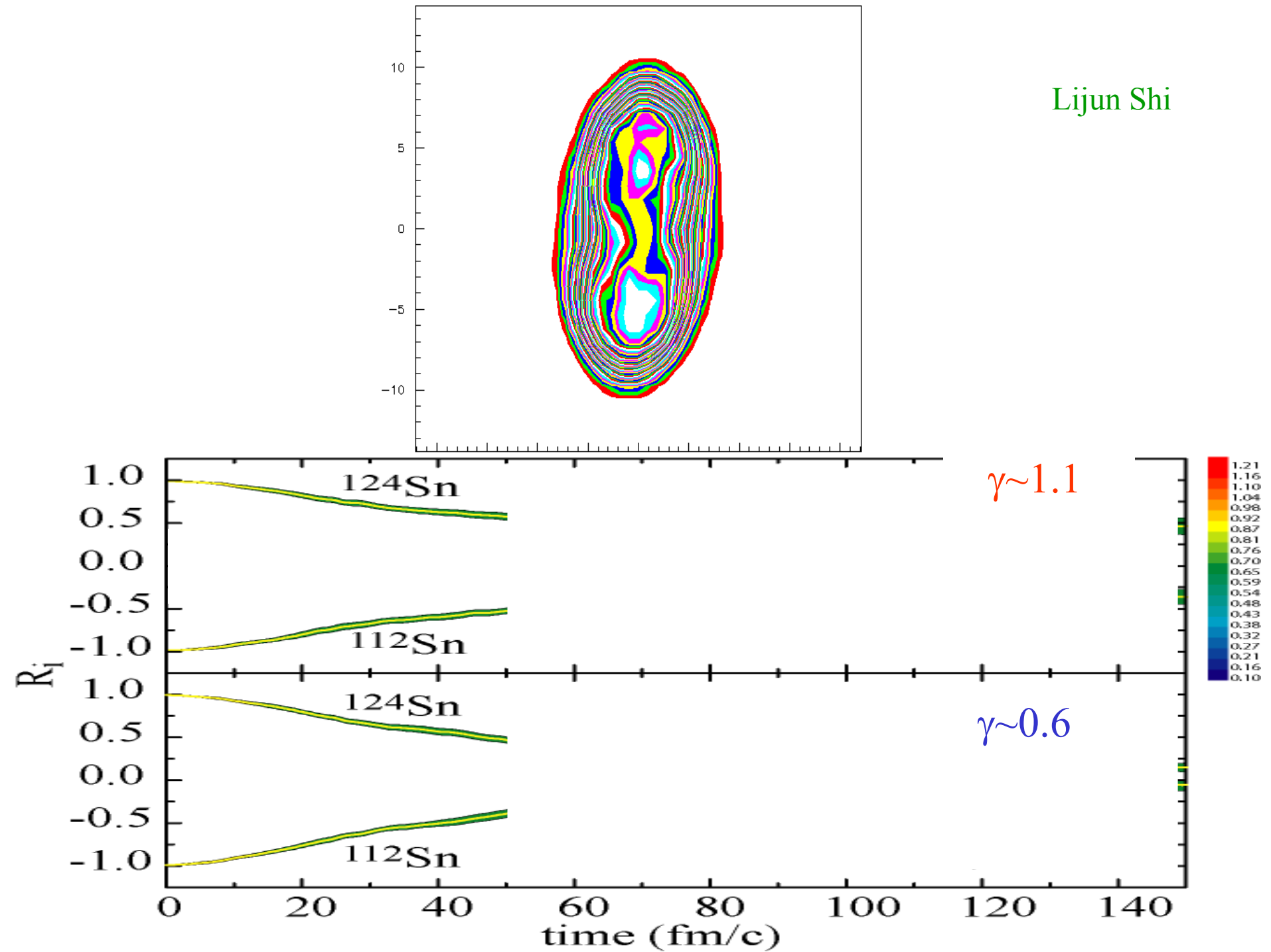
Lijun Shi


10
5
0
-5
-10

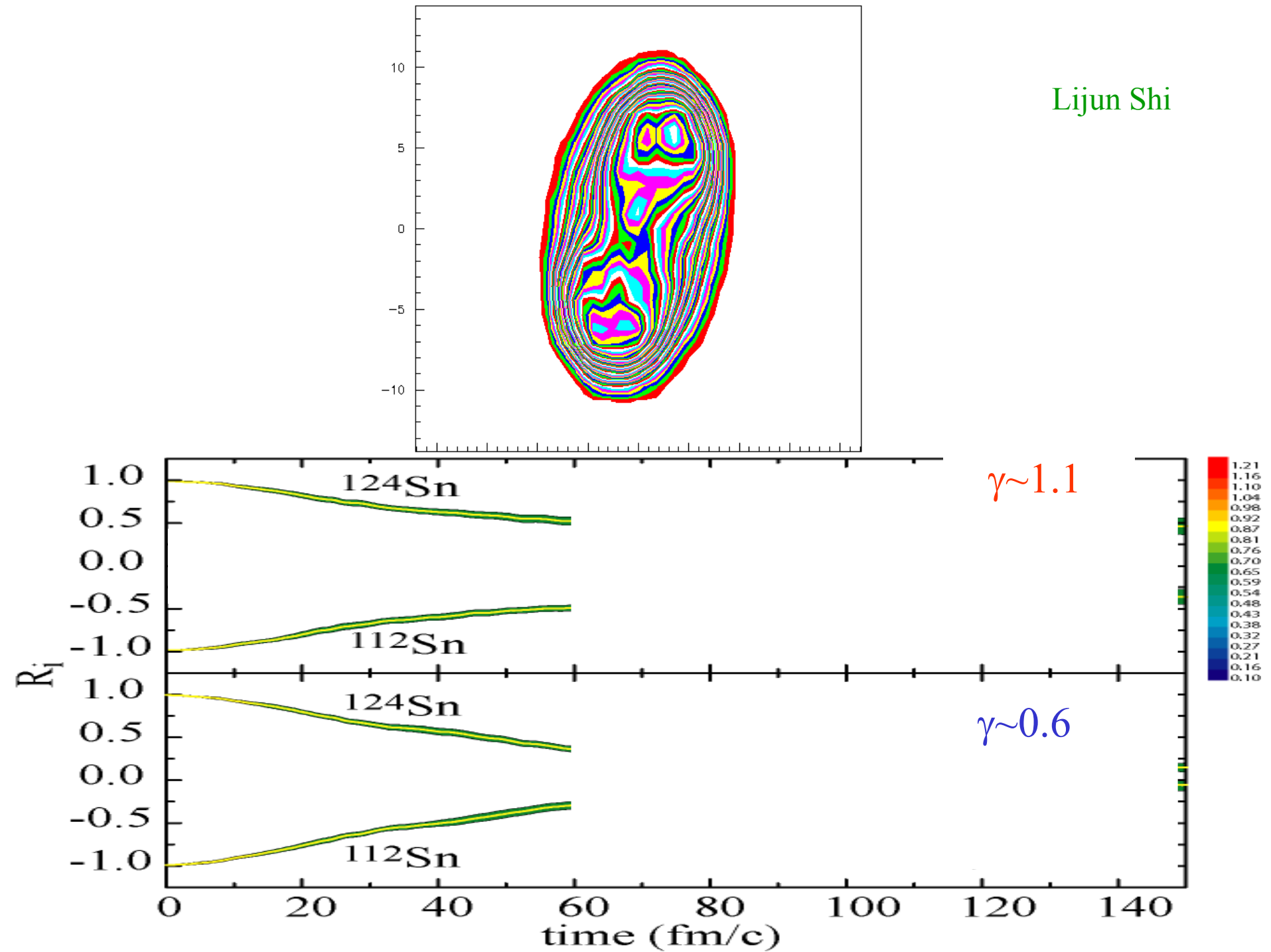

γ~1.1
γ~0.6
R_j
1.0
0.5
0.0
-0.5
-1.0
0
20
40
60
80
100
120
140
time (fm/c)
1.21
1.16
1.10
1.04
0.98
0.92
0.87
0.81
0.76
0.70
0.65
0.59
0.54
0.48
0.43
0.38
0.32
0.27
0.21
0.16
0.10

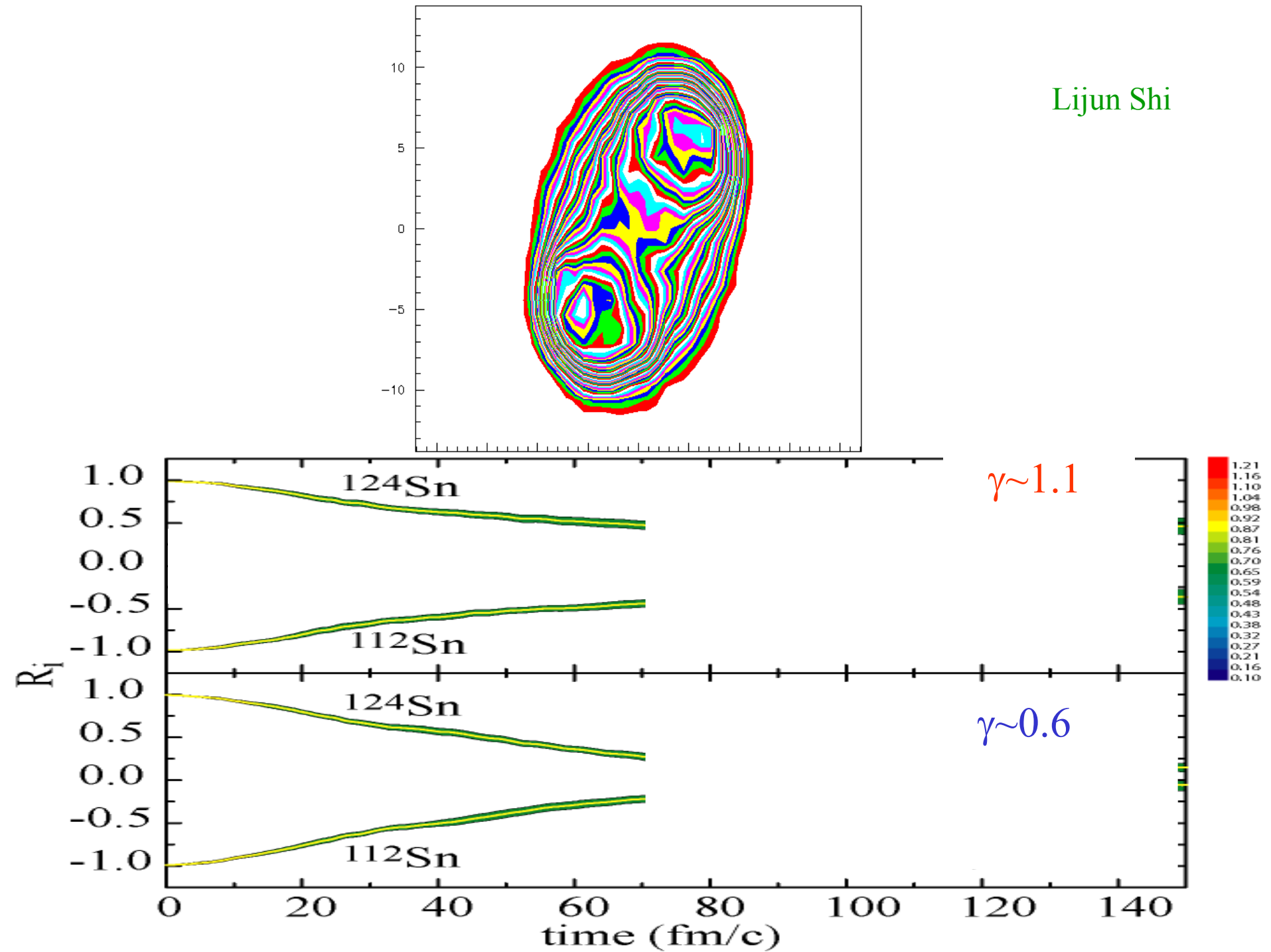

Lijun Shi
γ~1.1
γ~0.6
R_i
time (fm/c)


Lijun Shi
γ~1.1
γ~0.6
124S
112S
124S
112S
R_i
time (fm/c)

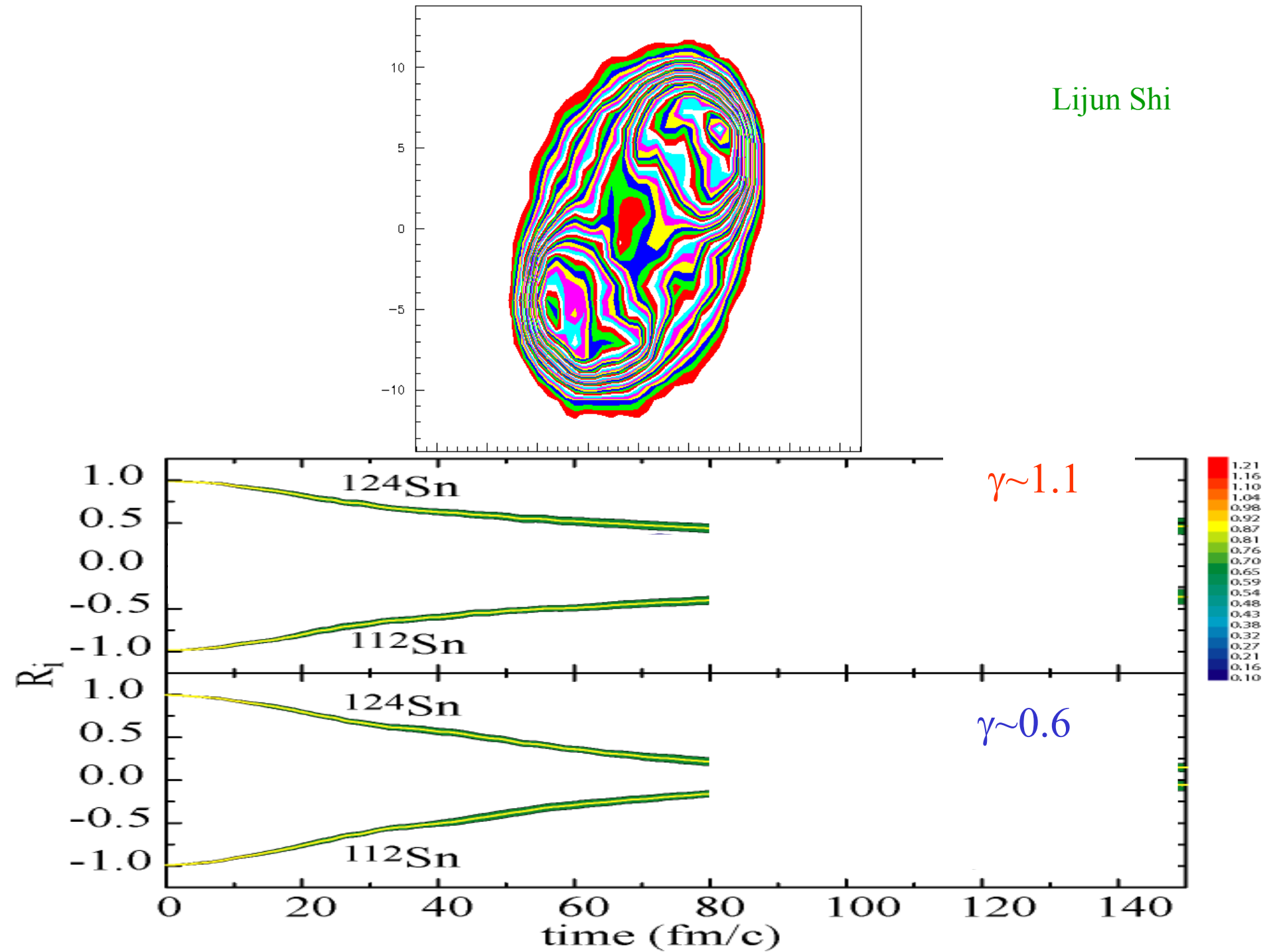

Lijun Shi
γ~1.1
γ~0.6
124Sn
112Sn
124Sn
112Sn
R_i
time (fm/c)

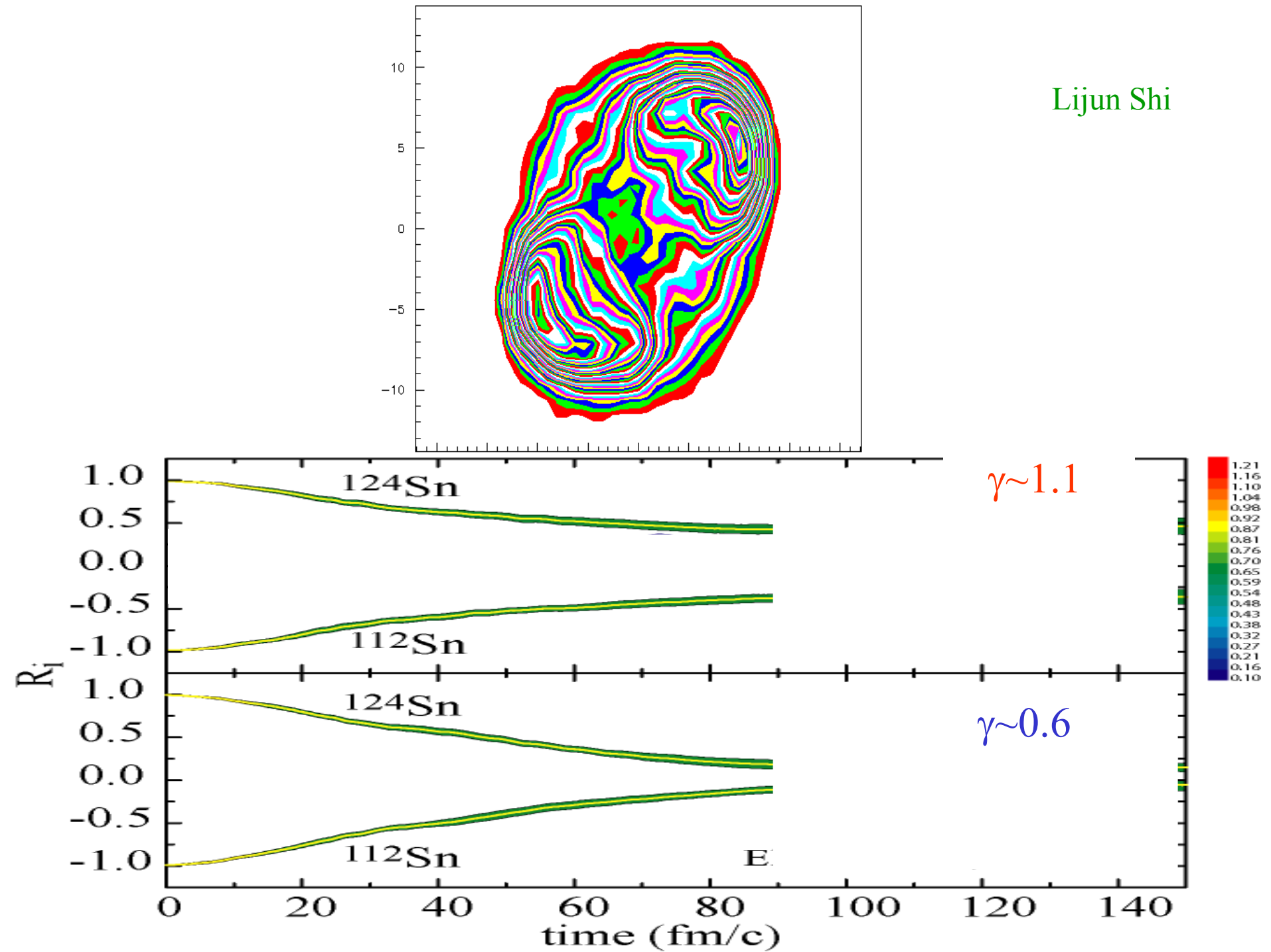
Lijun Shi

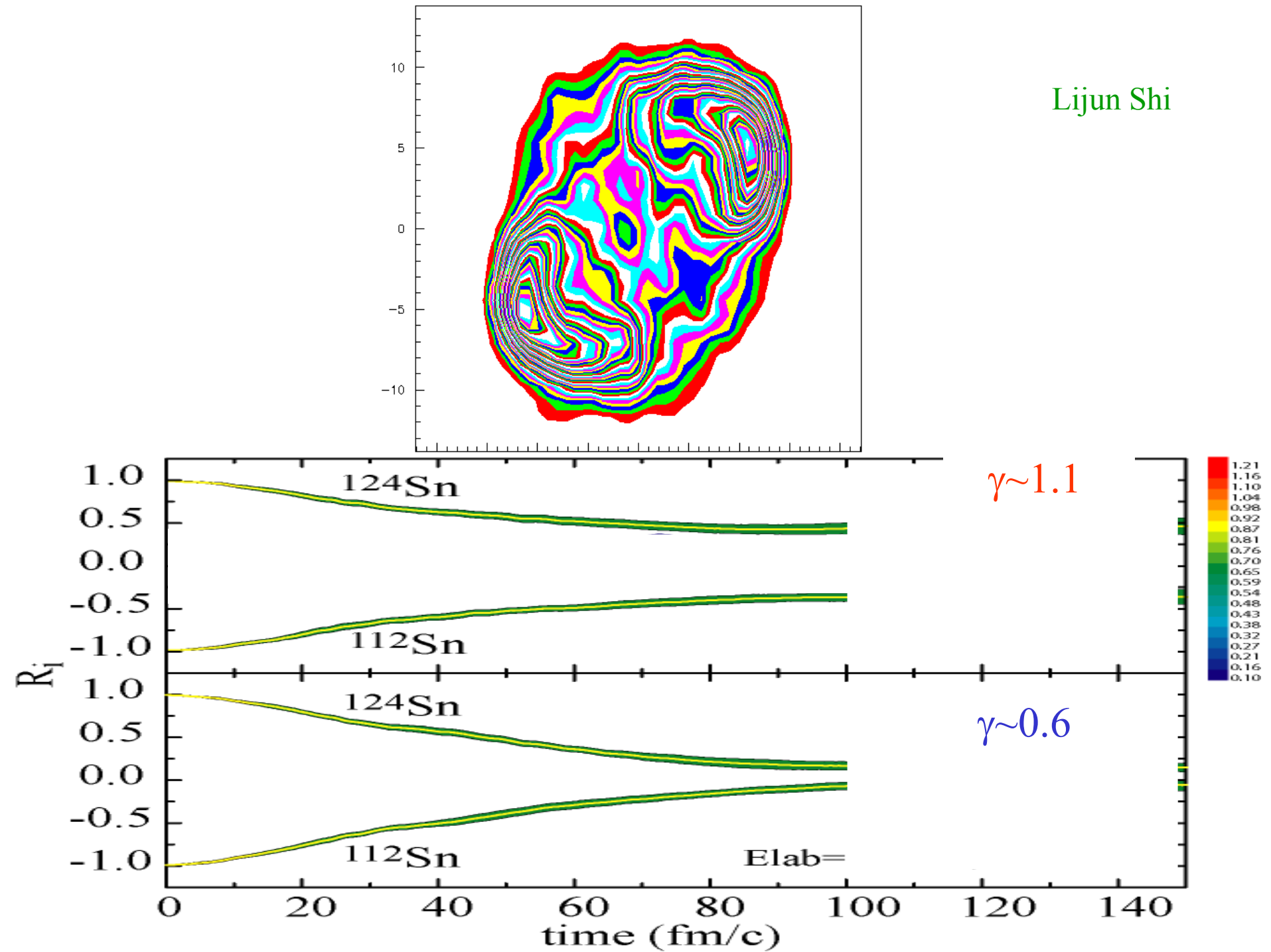

10
5
0
-5
-10
γ~1.1
124Sn
112Sn
γ~0.6
124Sn
112Sn
1.0
0.5
0.0
-0.5
-1.0
R_i
0
20
40
60
80
100
120
140
time (fm/c)
1.21
1.16
1.10
1.04
0.98
0.92
0.87
0.81
0.76
0.70
0.65
0.59
0.54
0.48
0.43
0.38
0.32
0.27
0.21
0.16
0.10

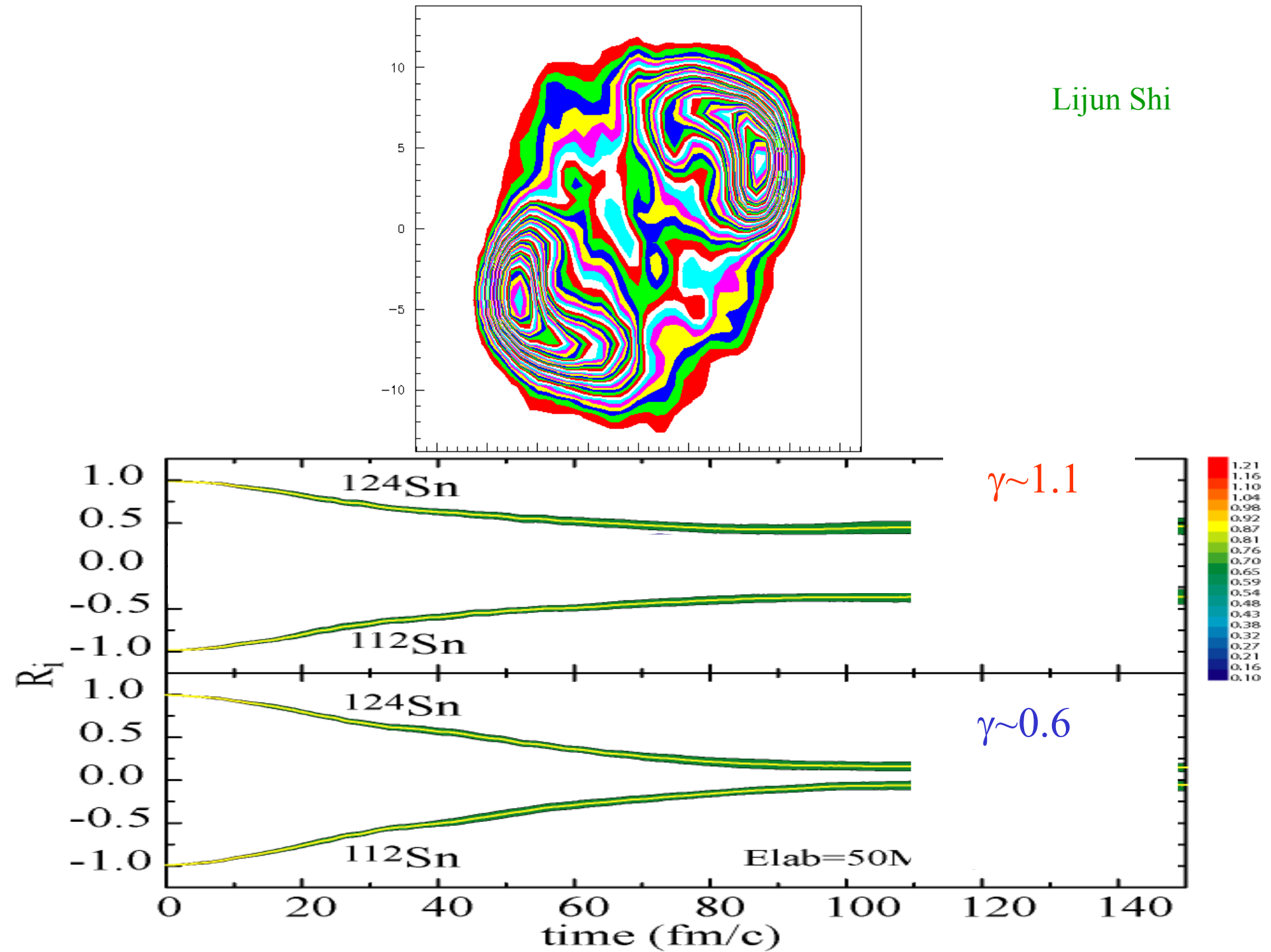

Lijun Shi
γ~1.1
γ~0.6
124Sn
112Sn
124Sn
112Sn
R_i
time (fm/c)

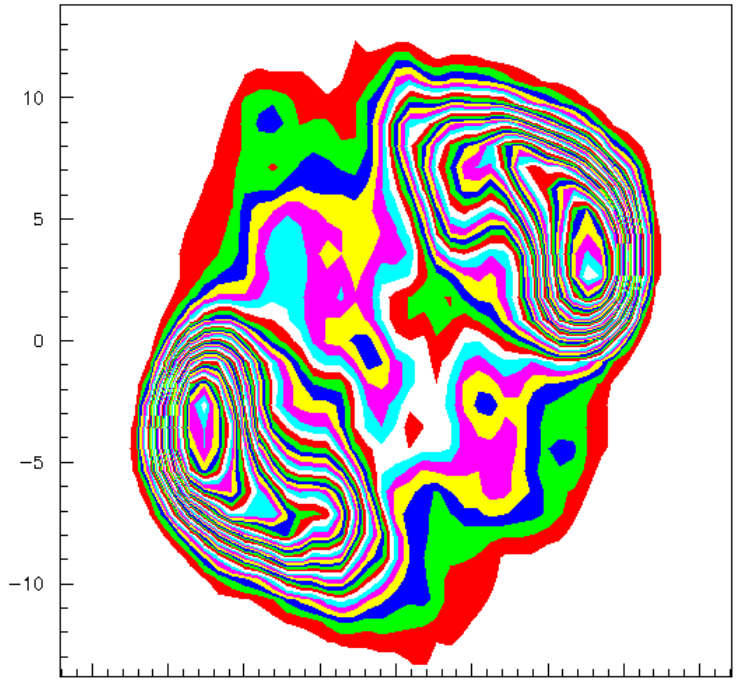
Lijun Shi


10
5
0
-5
-10
γ~1.1
124Sn
112Sn
γ~0.6
124Sn
112Sn
1.0
0.5
0.0
-0.5
-1.0
Ri
0
20
40
60
80
100
120
140
time (fm/c)
1.21
1.16
1.10
1.04
0.98
0.92
0.87
0.81
0.76
0.70
0.65
0.59
0.54
0.48
0.43
0.38
0.32
0.27
0.21
0.16
0.10

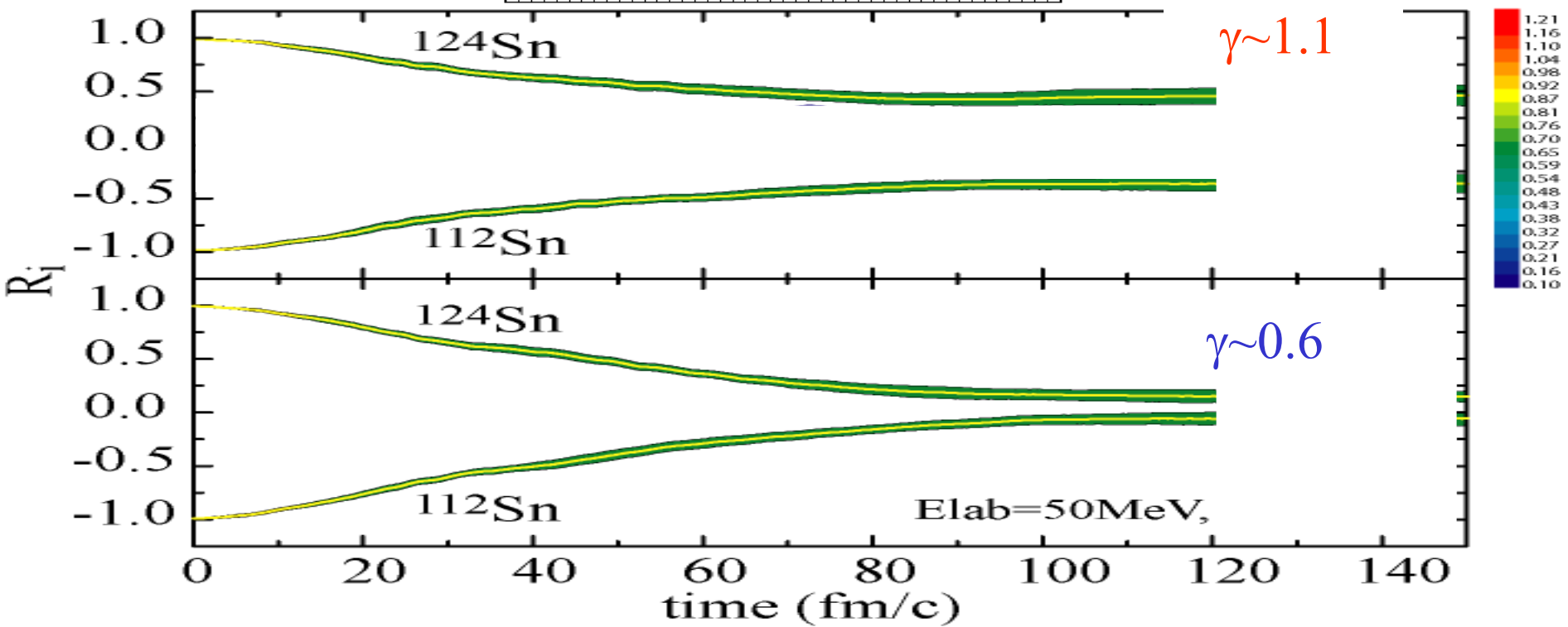

Lijun Shi
γ~1.1
γ~0.6
124Sn
112Sn
124Sn
112Sn
R_i
time (fm/c)

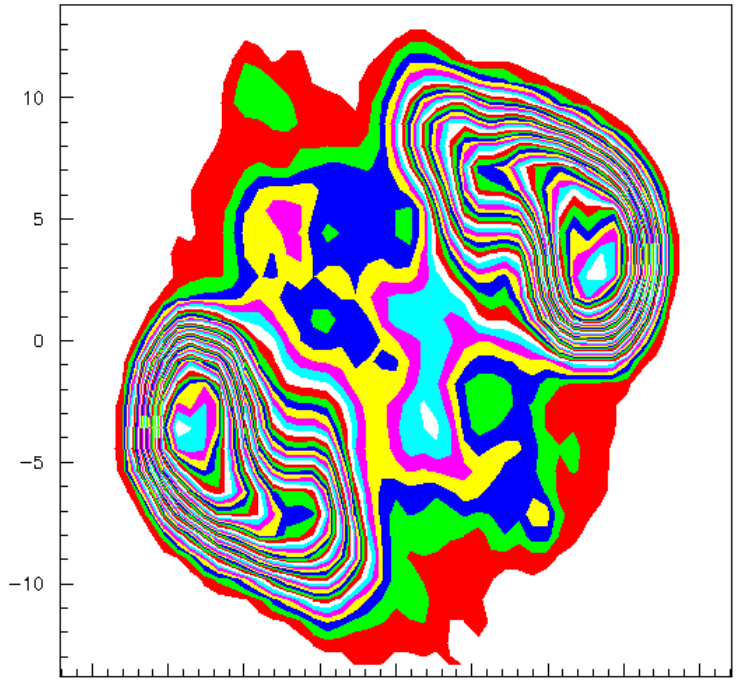

Lijun Shi
γ~1.1
γ~0.6
124Sn
112Sn
124Sn
112Sn
Elab=
Ri
time (fm/c)


Lijun Shi
γ~1.1
γ~0.6
124Sn
112Sn
124Sn
112Sn
Elab=50M
Ri
time (fm/c)

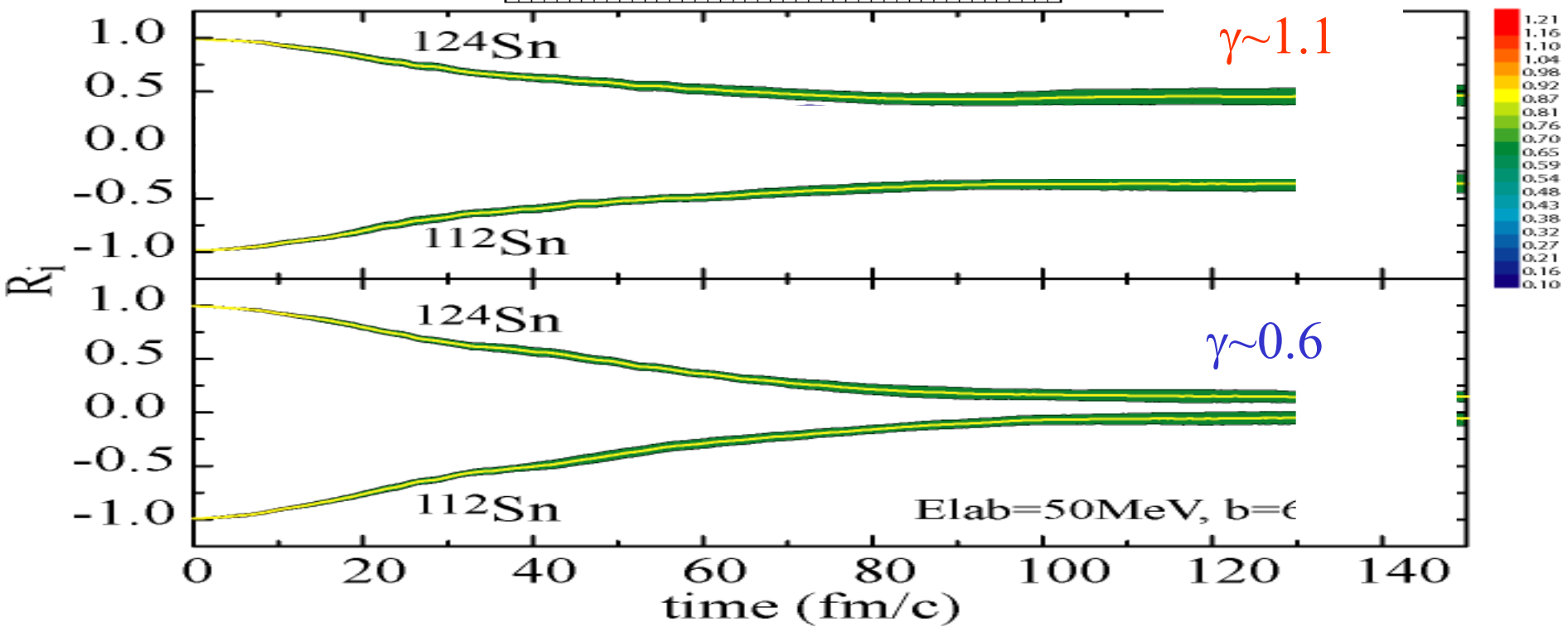

10
5
0
-5
-10

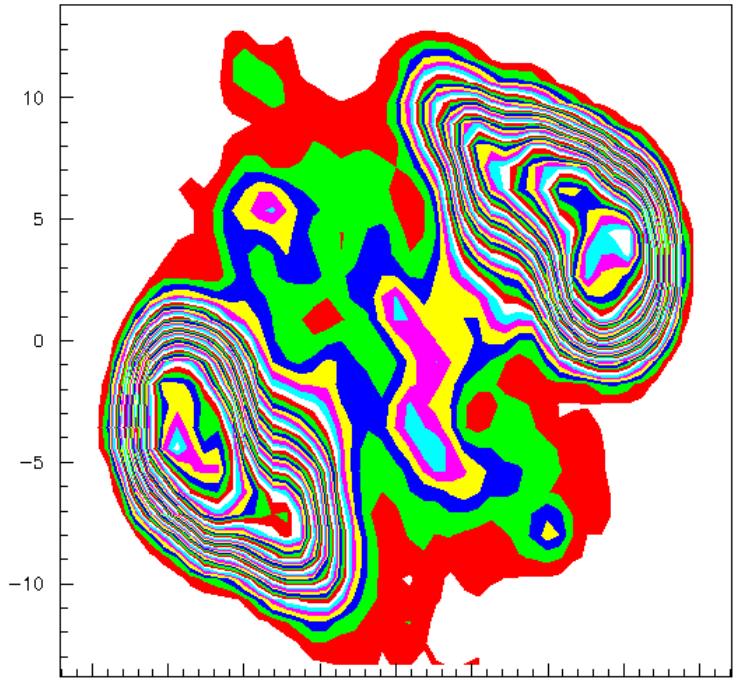
Lijun Shi


γ~1.1
124Sn
112Sn
γ~0.6
124Sn
112Sn
Elab=50MeV,
R_i
time (fm/c)
1.0
0.5
0.0
-0.5
-1.0
0
20
40
60
80
100
120
140
1.21
1.16
1.10
1.04
0.98
0.92
0.87
0.81
0.76
0.70
0.65
0.59
0.54
0.48
0.43
0.38
0.32
0.27
0.21
0.16
0.10

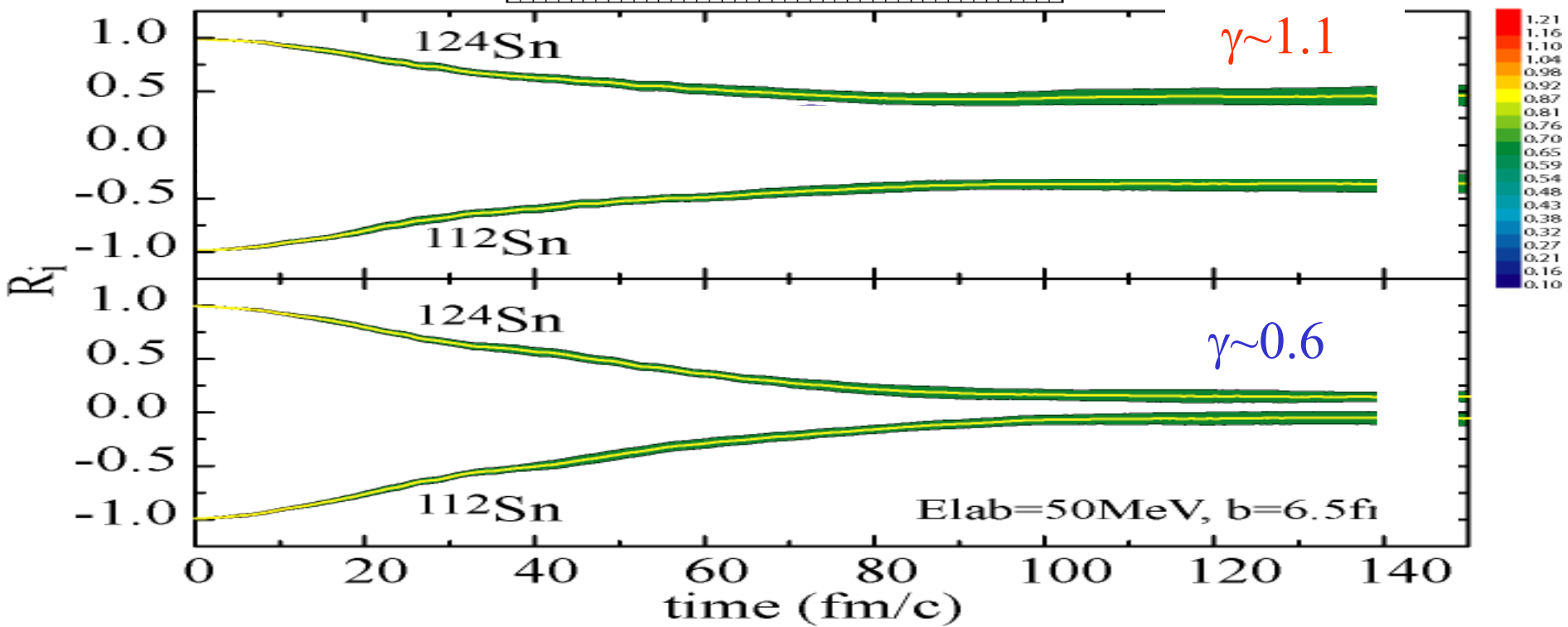

10
5
0
-5
-10

Lijun Shi

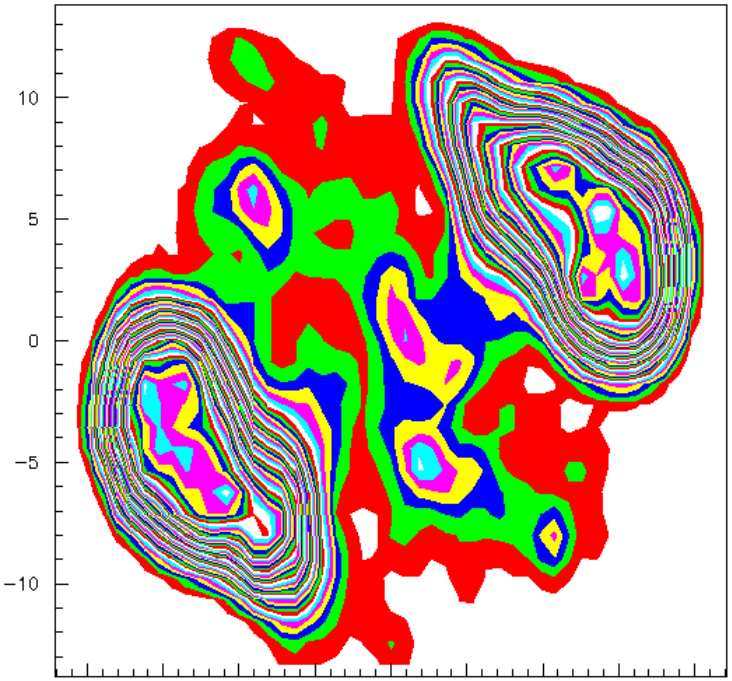

γ~1.1
124Sn
112Sn
γ~0.6
124Sn
112Sn
Elab=50MeV, b=6
R_i
1.0
0.5
0.0
-0.5
-1.0
0
20
40
60
80
100
120
140
time (fm/c)
1.21
1.16
1.10
1.04
0.98
0.92
0.87
0.81
0.76
0.70
0.65
0.59
0.54
0.48
0.43
0.38
0.32
0.27
0.21
0.16
0.10


10
5
0
-5
-10

Lijun Shi


γ~1.1
124Sn
112Sn
γ~0.6
124Sn
112Sn
Elab=50MeV, b=6.5fi
Ri
1.0
0.5
0.0
-0.5
-1.0
0
20
40
60
80
100
120
140
time (fm/c)
1.21
1.16
1.10
1.04
0.98
0.92
0.87
0.81
0.76
0.70
0.65
0.59
0.54
0.48
0.43
0.38
0.32
0.27
0.21
0.16
0.10

Lijun Shi


10
5
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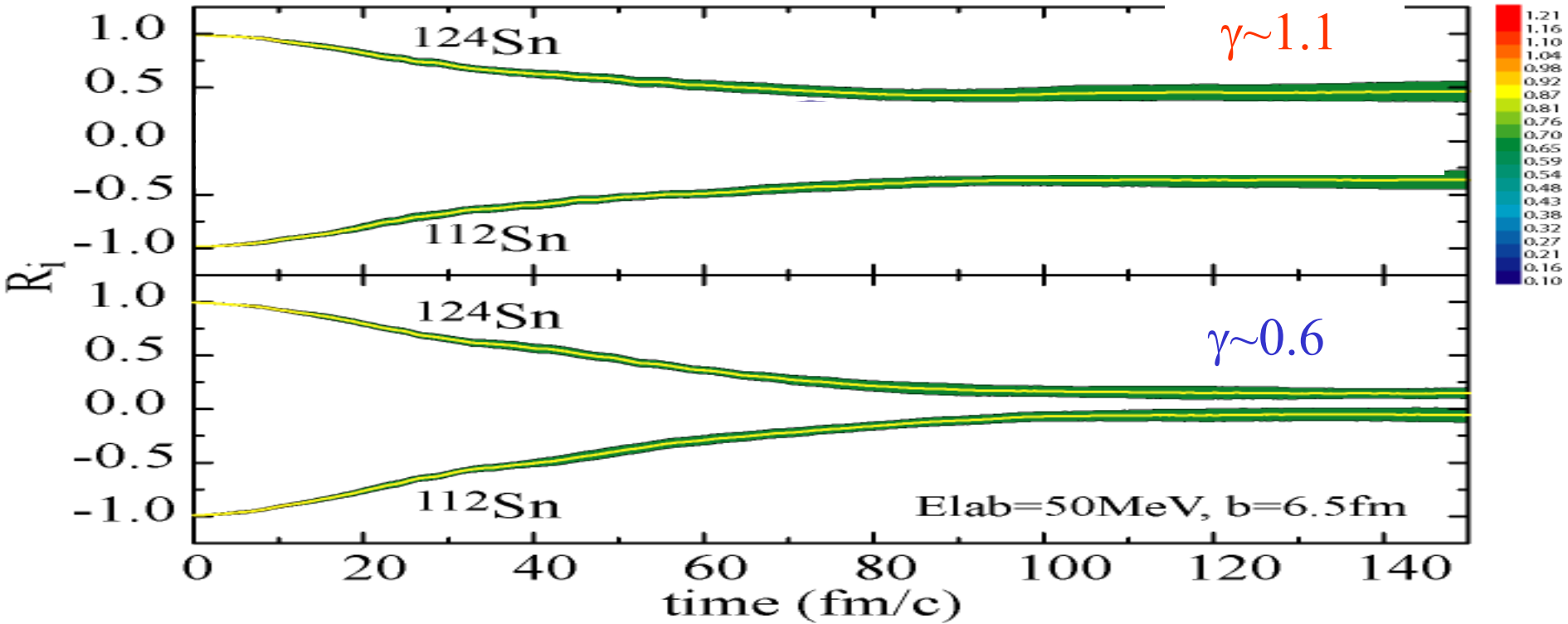
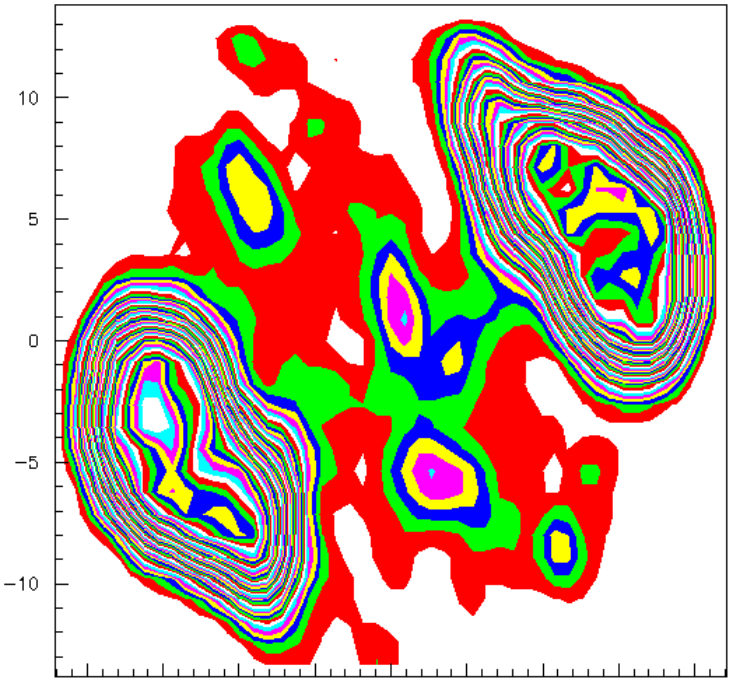
-5
-10


γ~1.1
124Sn
112Sn
γ~0.6
124Sn
112Sn
Elab=50MeV, b=6.5fm
R_i
time (fm/c)
1.0
0.5
0.0
-0.5
-1.0
0
20
40
60
80
100
120
140
1.21
1.16
1.10
1.04
0.98
0.92
0.87
0.81
0.76
0.70
0.65
0.59
0.54
0.48
0.43
0.38
0.32
0.27
0.21
0.16
0.10

Lijun Shi


10
5
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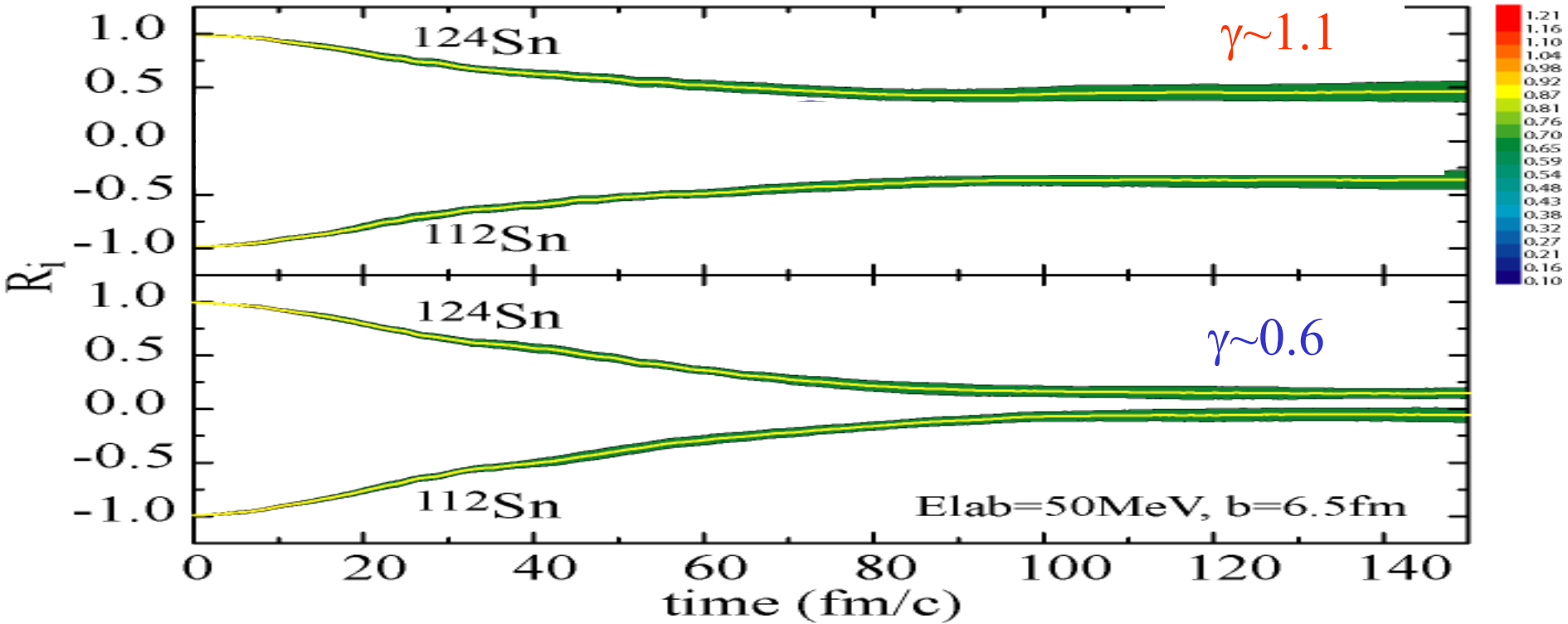
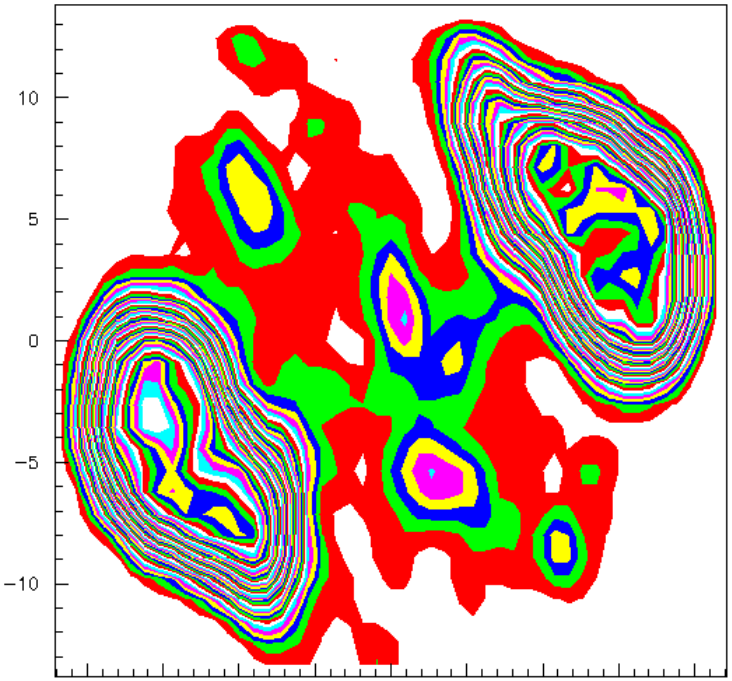
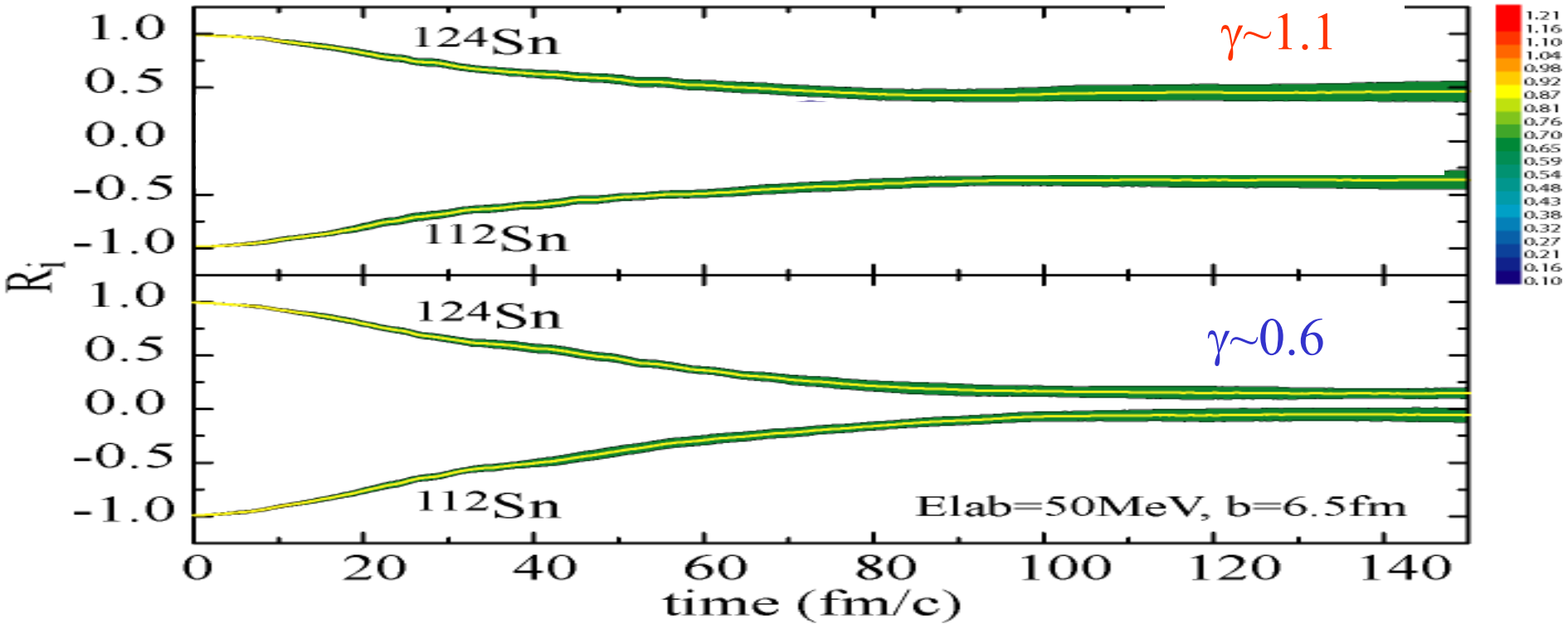
-5
-10


γ~1.1
124Sn
112Sn
γ~0.6
124Sn
112Sn
Elab=50MeV, b=6.5fm
R_i
time (fm/c)
1.0
0.5
0.0
-0.5
-1.0
0
20
40
60
80
100
120
140
1.21
1.16
1.10
1.04
0.98
0.92
0.87
0.81
0.76
0.70
0.65
0.59
0.54
0.48
0.43
0.38
0.32
0.27
0.21
0.16
0.10

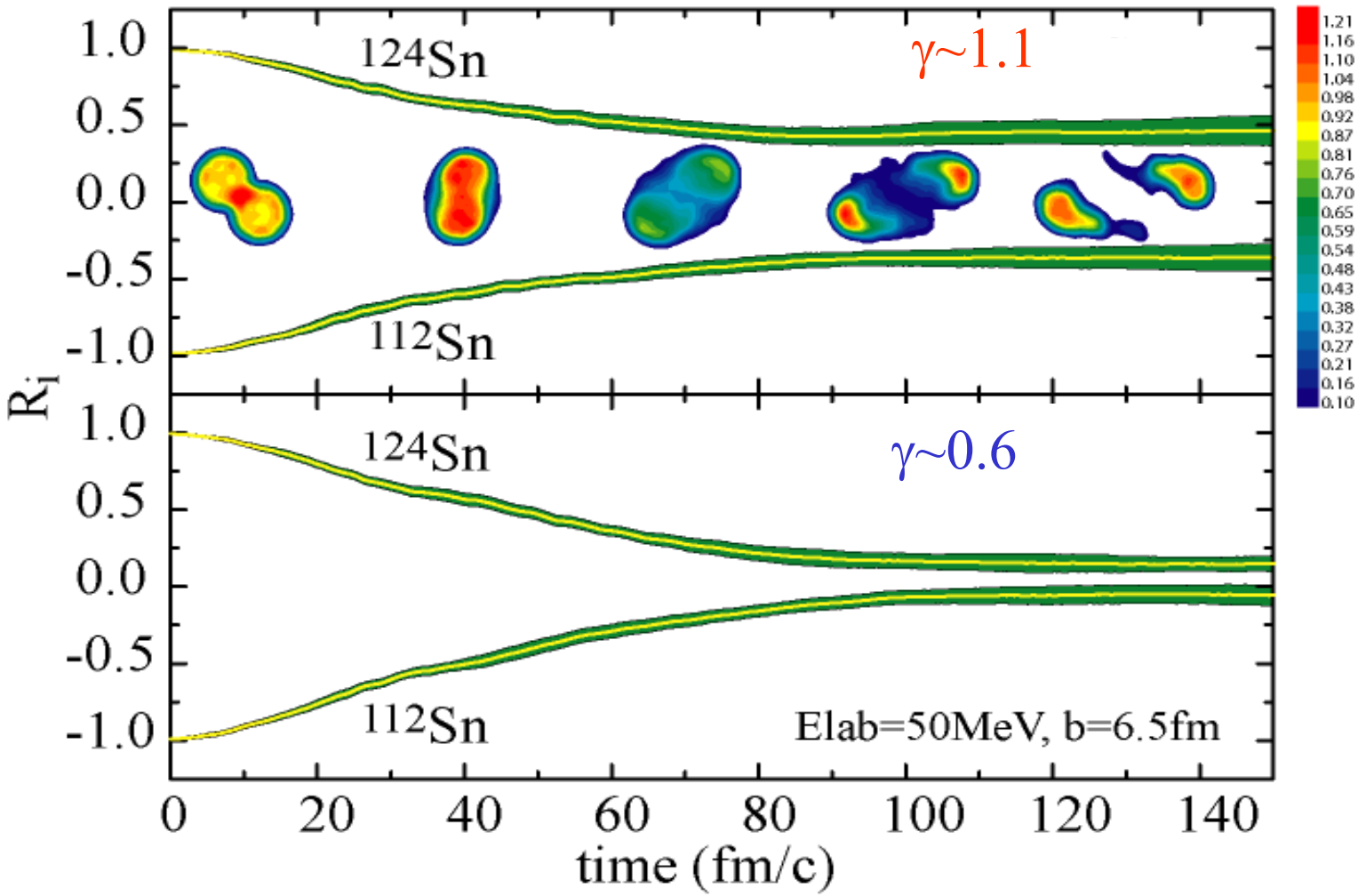
Lijun Shi


10
5
0
-5
-10


γ~1.1
124Sn
112Sn
γ~0.6
124Sn
112Sn
Elab=50MeV, b=6.5fm
R_i
time (fm/c)
1.0
0.5
0.0
-0.5
-1.0
0
20
40
60
80
100
120
140
1.21
1.16
1.10
1.04
0.98
0.92
0.87
0.81
0.76
0.70
0.65
0.59
0.54
0.48
0.43
0.38
0.32
0.27
0.21
0.16
0.10

Effect of symmetry terms on isospin diffusion

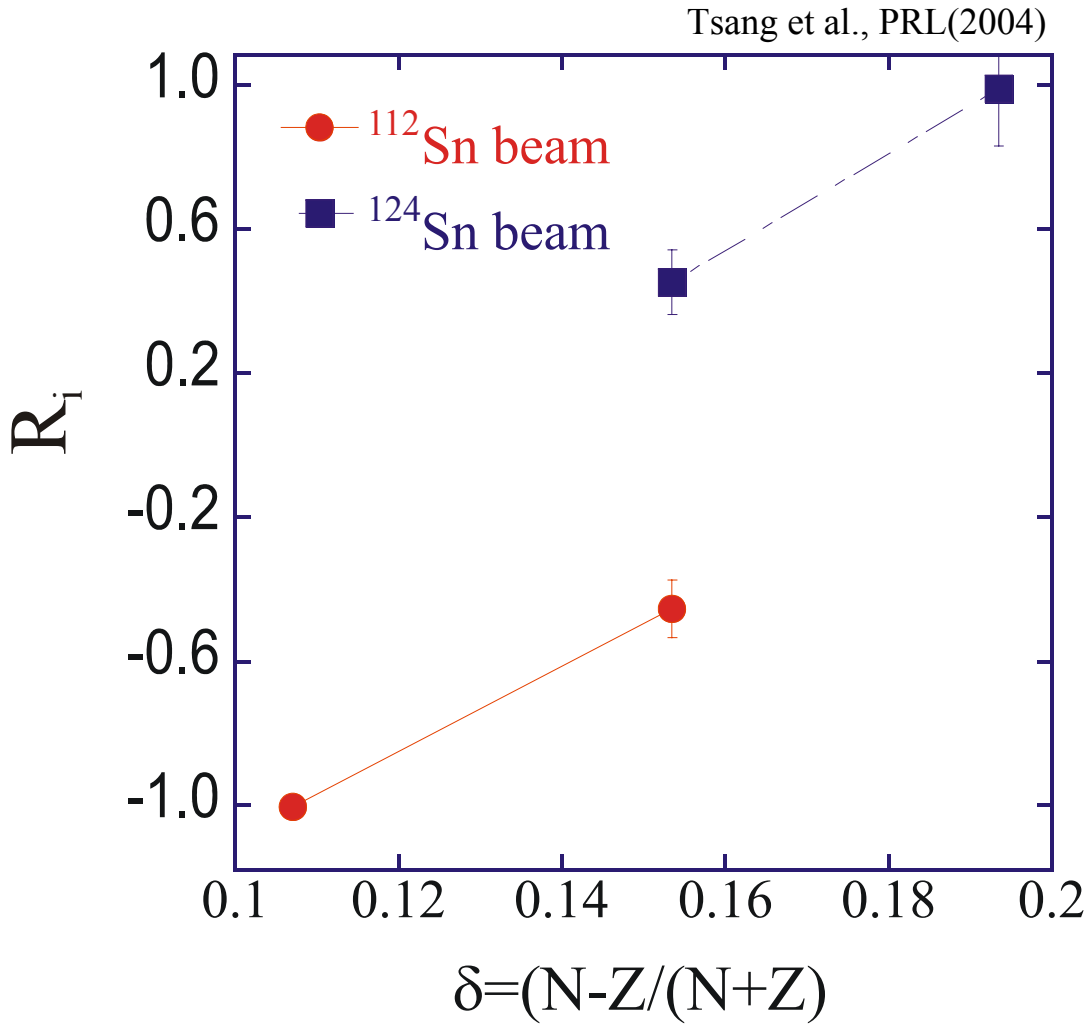
LiJun Shi ((2004)



- *Diffusion occurs within ≈120 fm/c.*

Tsang et al. PRL 92, 062701(2004)

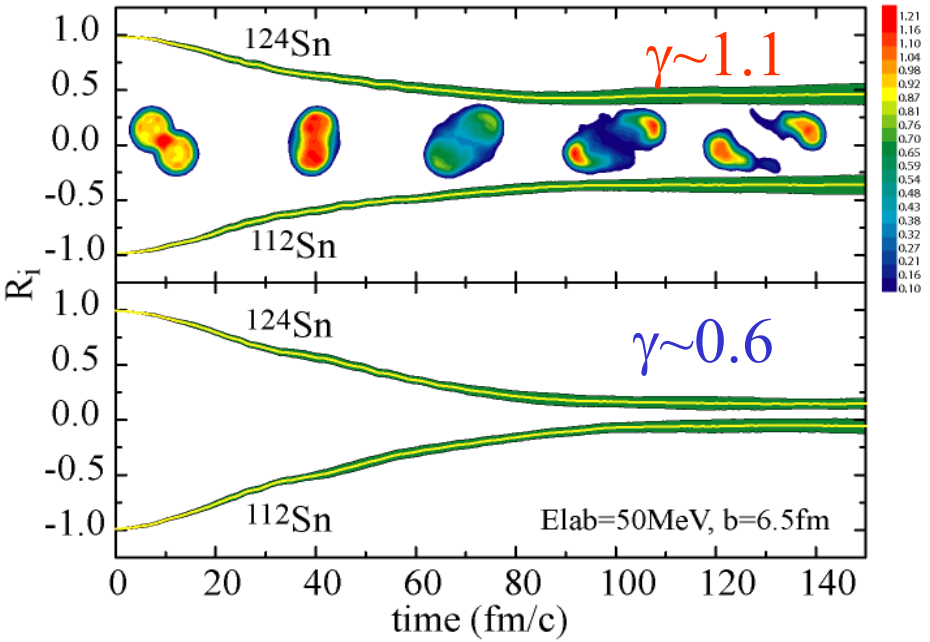
Isospin equilibrium or not?

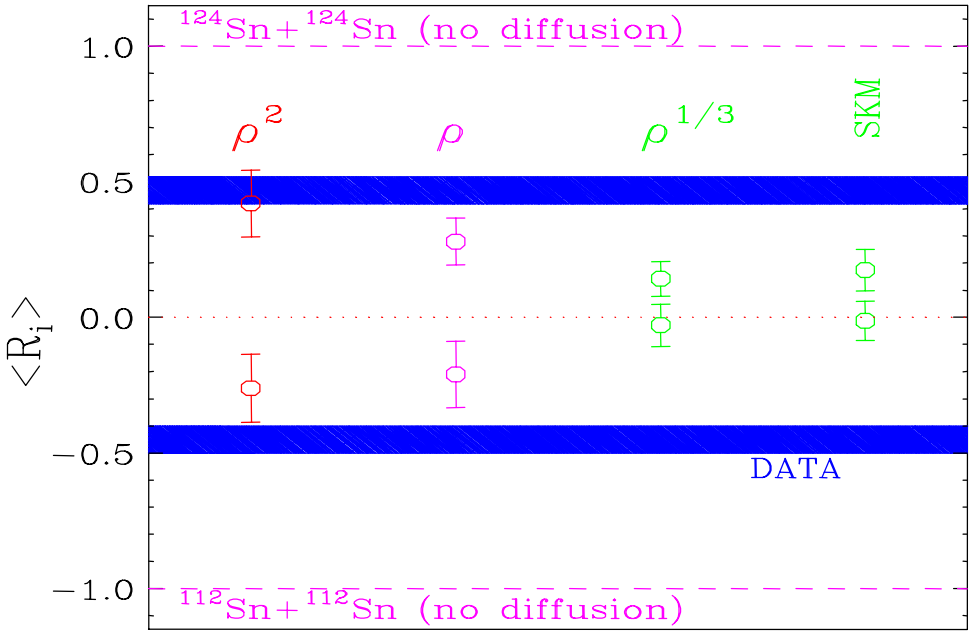


- Projectile and target residues do not come to isospin equlibrium at E/A=50 MeV.

Comparisons to data

Tsang et al. PRL 92, 062701(2004)



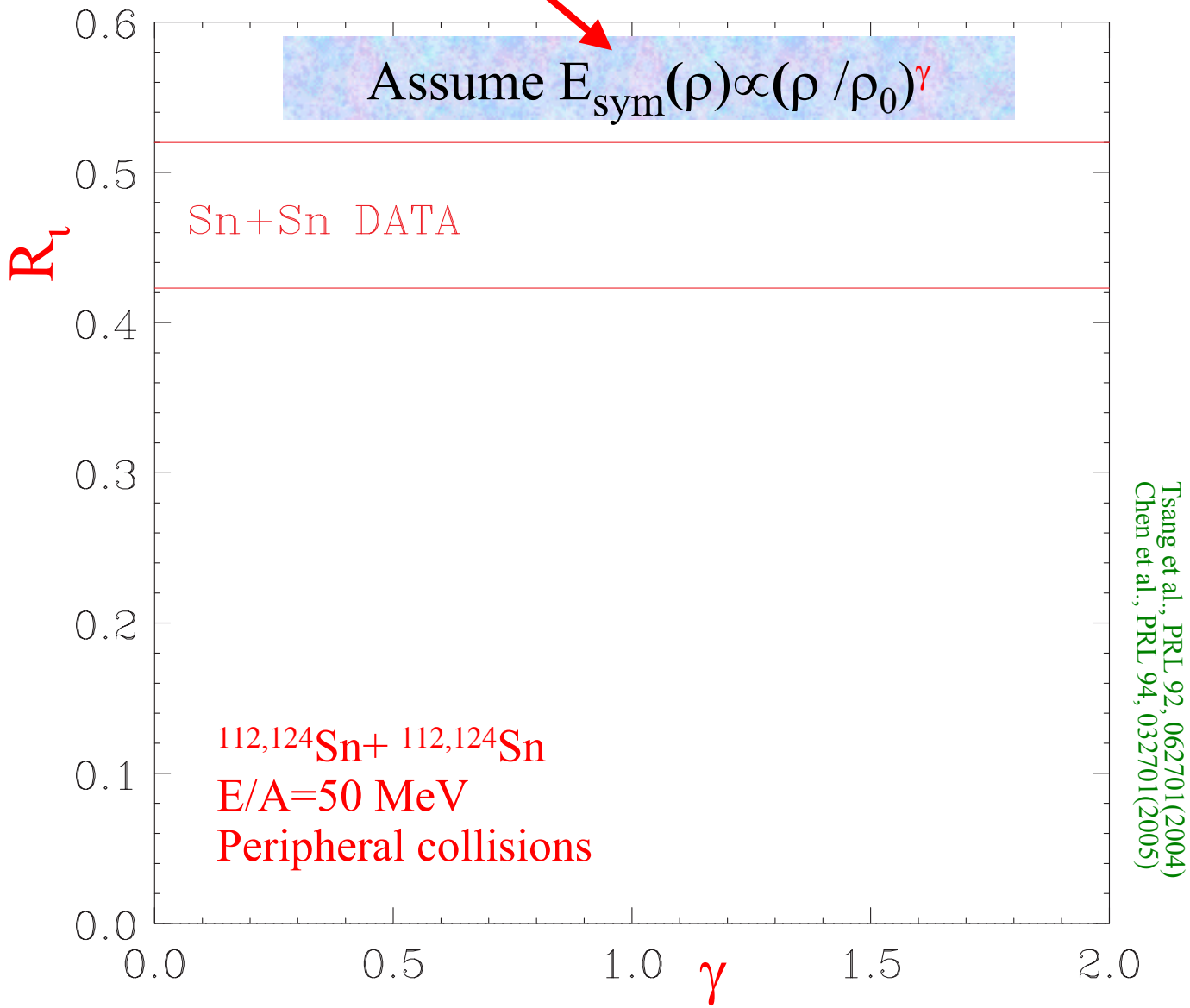


- *Diffusion occurs within ≈120 fm/c.*
- *More mixing with soft S(ρ)*
  - *consistent with large E_{sym} at $\rho<\rho_0$.*
- *Less mixing with stiff S(ρ).*

- *Explicit secondary decay correction gives same result.*
- *Stiff S(ρ) favored.*
- *Momentum-isospin dependence?*

Constraints on symmetry term in EOS from isospin diffusion

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

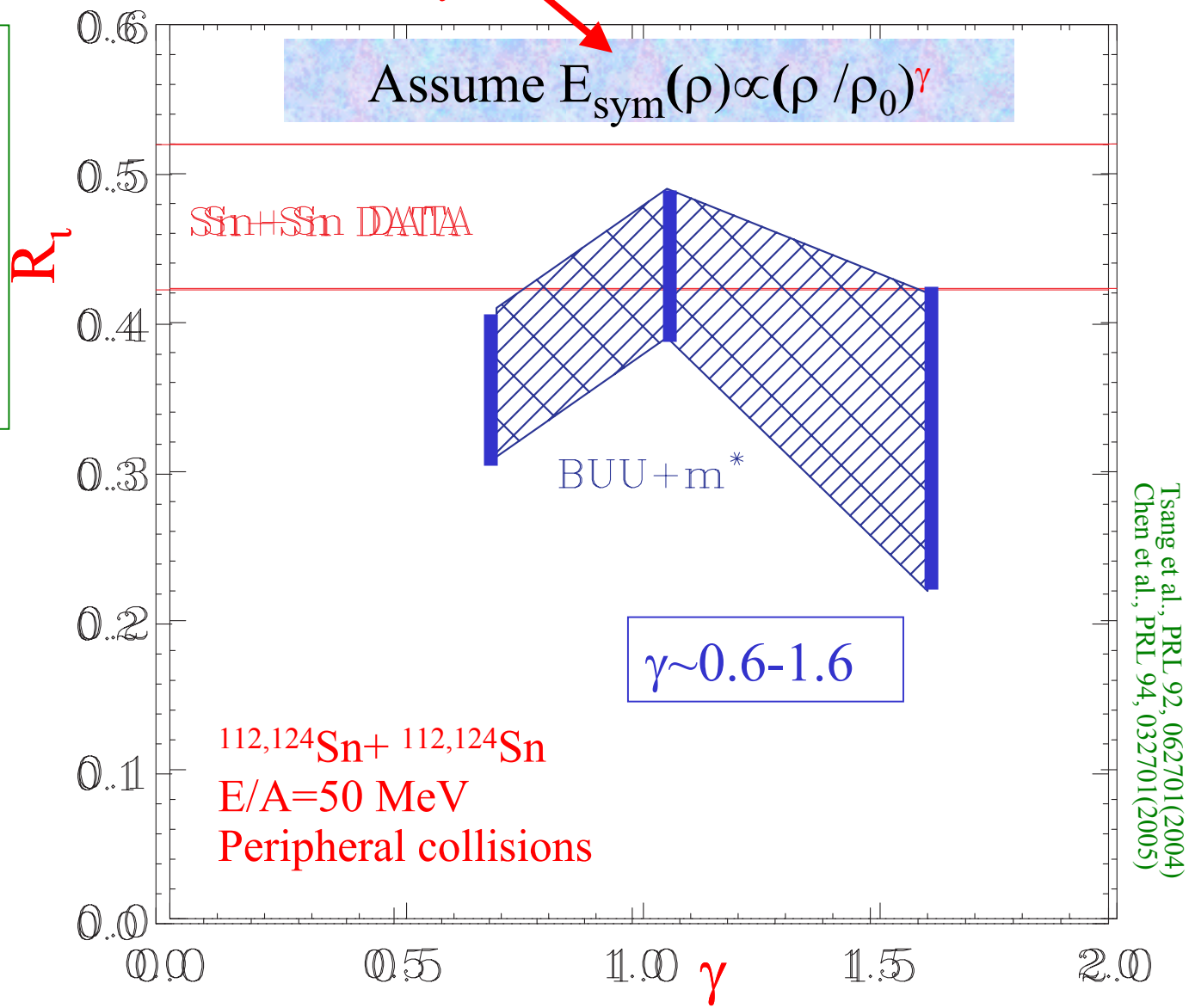


Constraints on symmetry term in EOS from isospin diffusion

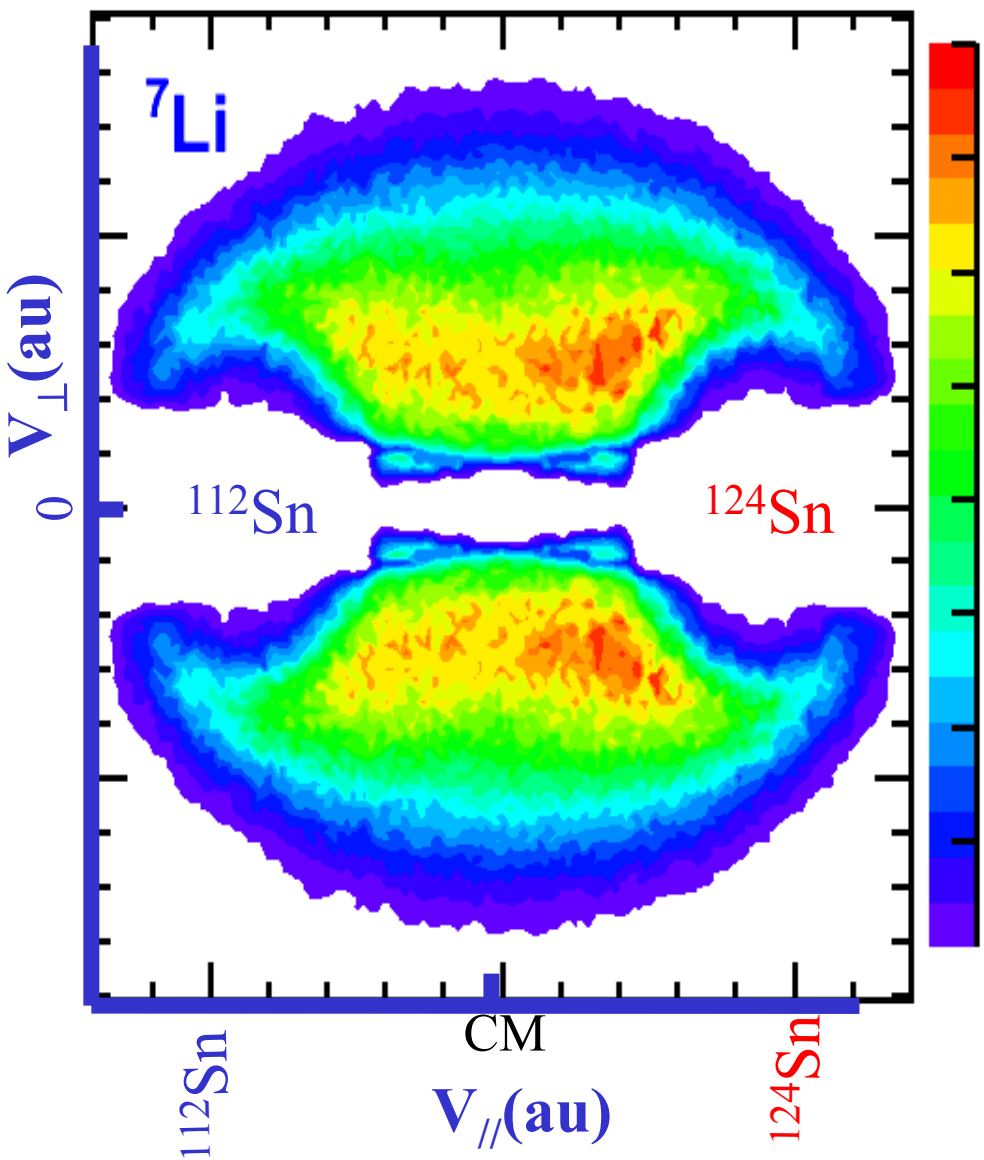
$$E(\rho, \delta) = E(\rho, 0) + E_{sym}(\rho)\delta^2; \quad \delta=(\rho_n-\rho_p)/(\rho_n+\rho_p)$$

BUU+m:*
Transport theory based on Boltzmann Equations & include momentum dependence in mean field.

Need better calculations as well as further constraints from experiments (n/p ratios and correlation experiments)



^{112}Sn+^{124}Sn; E/A=50 MeV



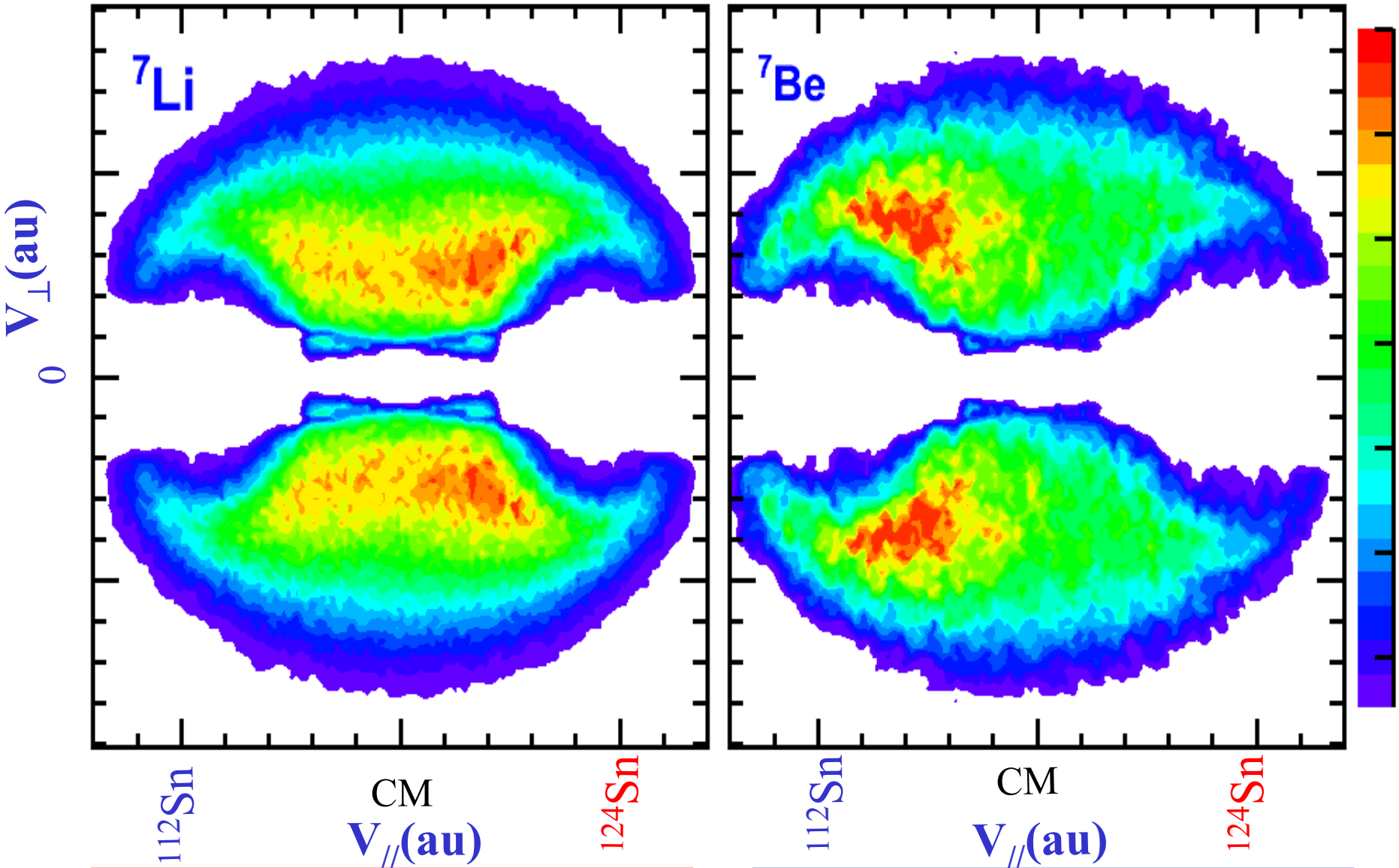
Emission patterns of charged particles e.g. ^{7}Li

Observable: $V_{//}$ vs. $V_\perp$

Acceptance: No detector coverage around beam & detector energy thresholds

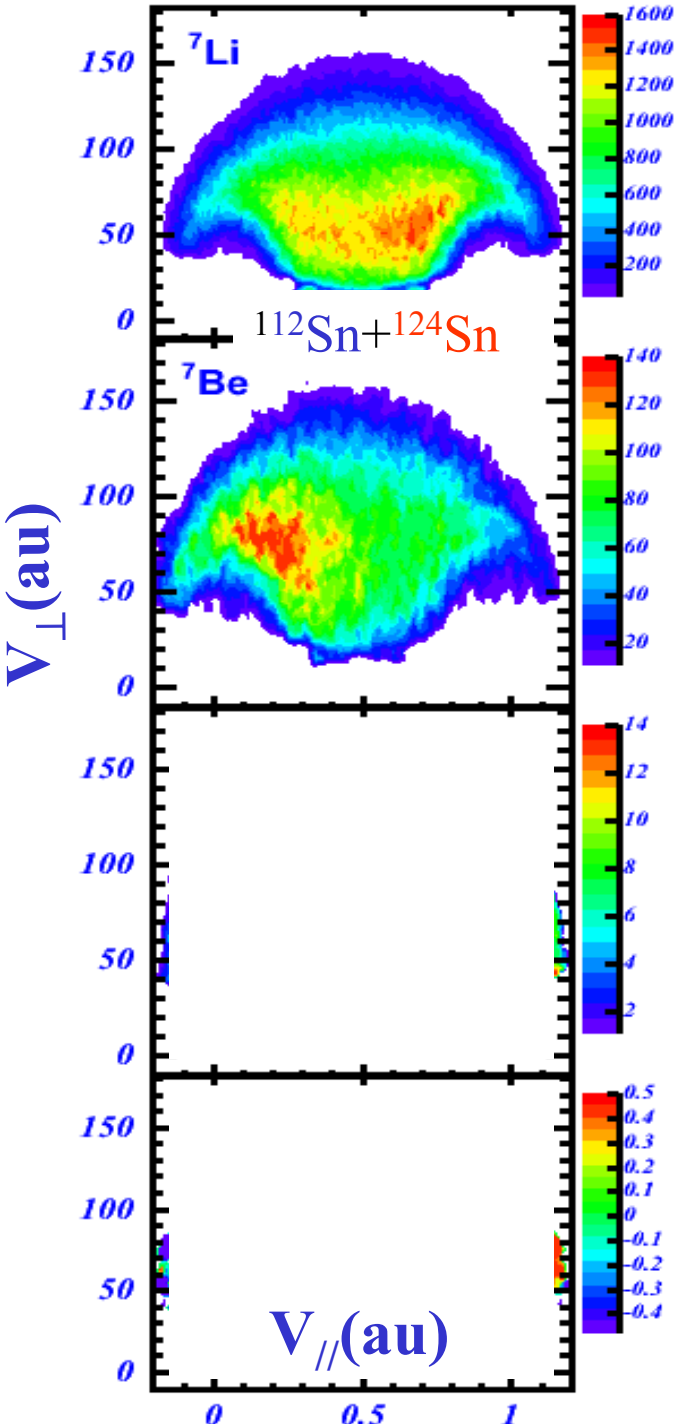
Emission from projectile and target residues would create ridges from Coulomb repulsions.

Emission patterns of ^{7}Li & ^{7}Be from ^{124}Sn+^{112}Sn; E/A=50 MeV



Y(^{7}Li) enhanced from ^{124}Sn

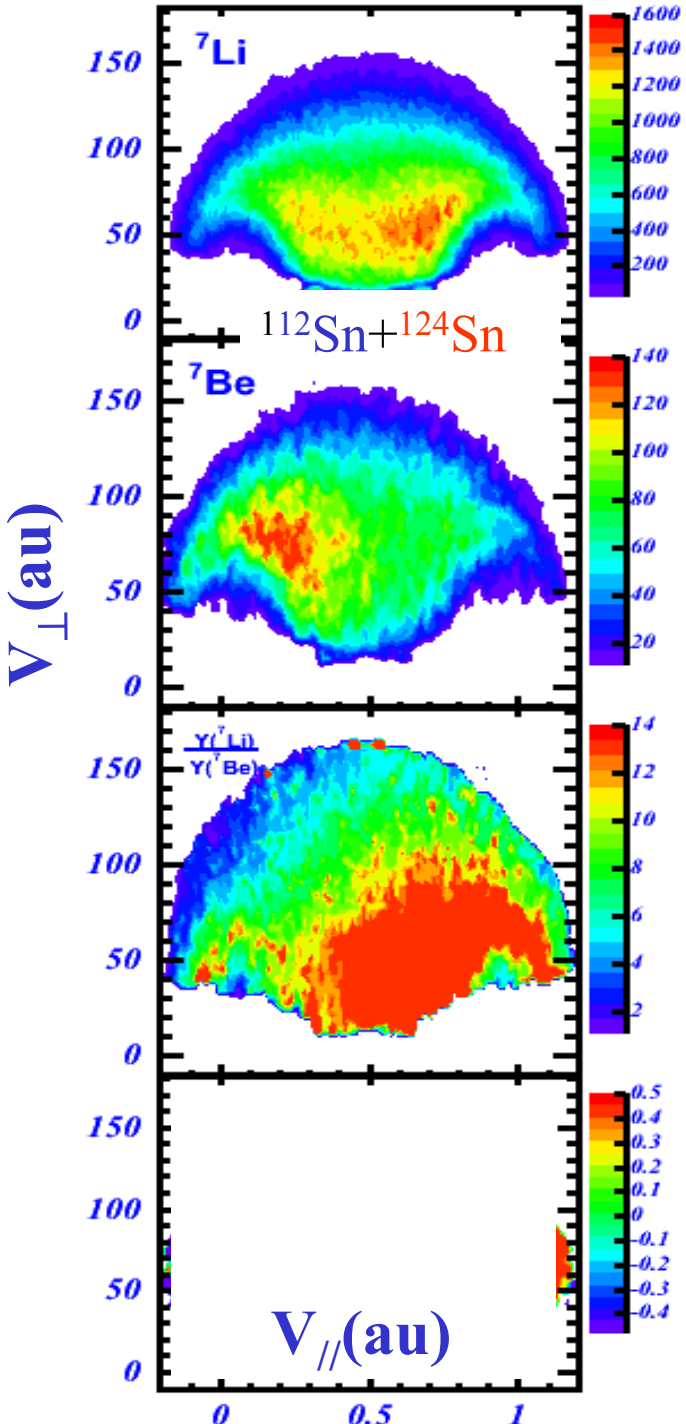
Y(^{7}Be) enhanced from ^{112}Sn



Isospin transport observable

Y(^{7}Li) enhanced from ^{124}Sn

Y(^{7}Be) enhanced from ^{112}Sn



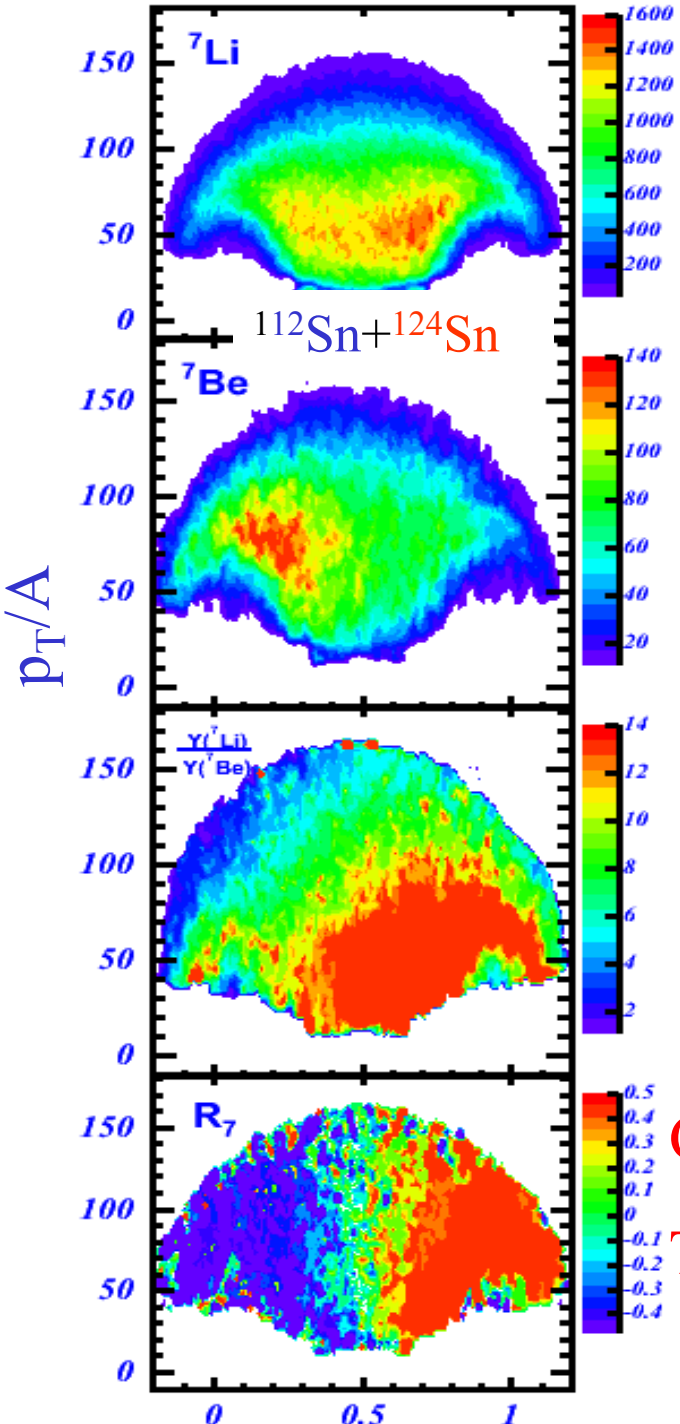
Isospin transport observable

Y(^{7}Li) enhanced from ^{124}Sn

Y(^{7}Be) enhanced from ^{112}Sn

Ratio Y(^{7}Li)/Y(^{7}Be)
Mainly dominated by Coulomb

What about isospin transport ?



Isospin Transport Ratio

$$R_i = \frac{2x_{AB} - x_{AA} - x_{BB}}{x_{AA} - x_{BB}}$$

Rami et al., PRL, 84, 1120 (2000)

x_{AB}=experimental or theoretical isospin observable for system AB

$x_{AB}=x_{AA} \rightarrow R_i = 1.$

$x_{AB}=x_{AB} \rightarrow R_i = -1.$

Coulomb & other effects are "cancelled"

The P_T dependence is weak. R_i varies with y

Summary

- Isospin diffusion provides a robust sensitivity to the density dependence of the asymmetry term.
  - impact parameter and rapidity dependence.
- Need other observables such as n/p ratios, n/p differential flow – see BaoAn Li's list.
- quantities to be constrained in calculations:
  - density dependence:
  - momentum-isospin dependence:
  - isospin dependent in-medium cross sections:
- Other factors:
  - role of fluctuations.