Central Collisions and the EOS of Dense Asymmetric Nuclear Matter

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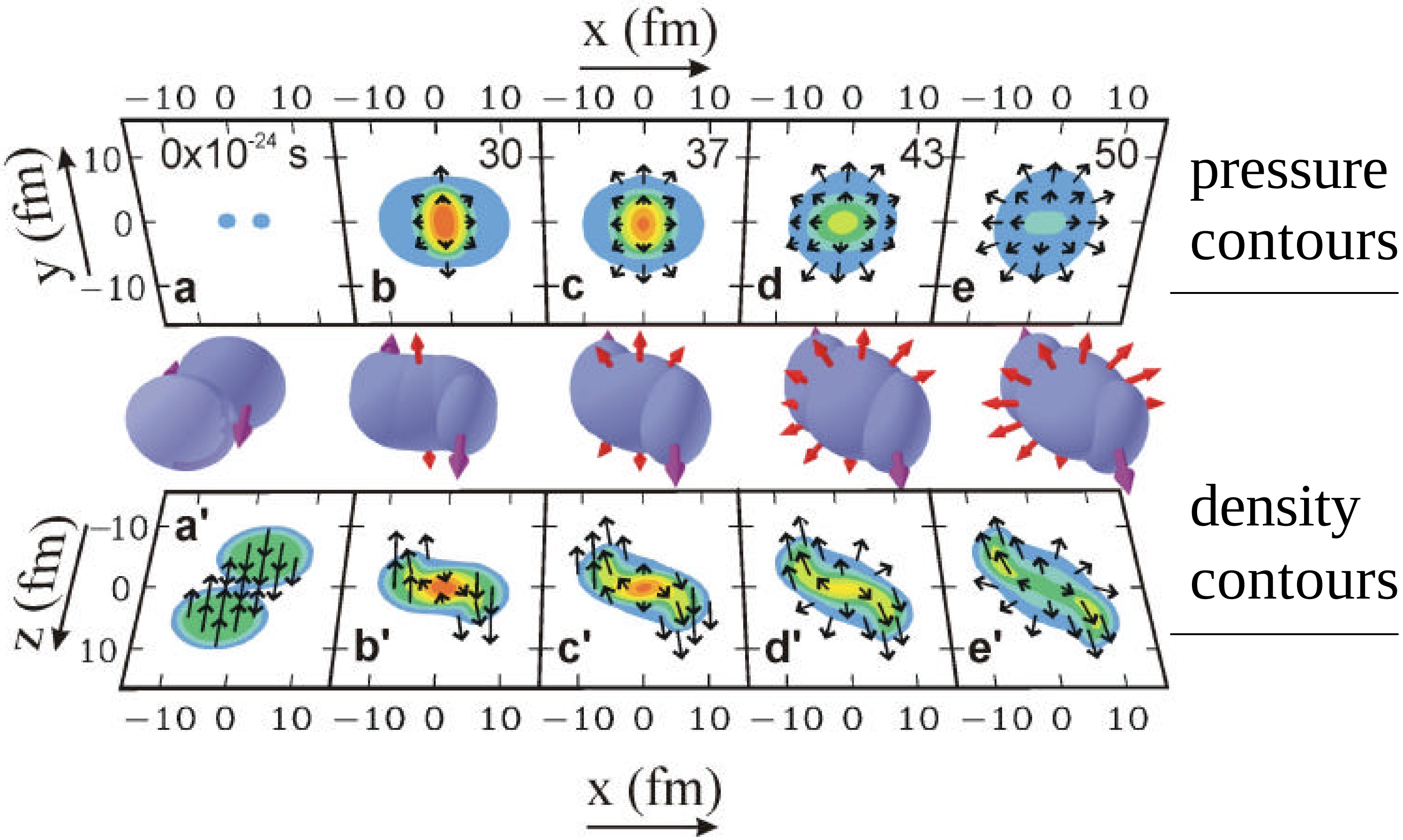
Outline

- Present constraints on the EOS.
- Relevance to dense astrophysical objects:
- Probing asymmetric matter at $\rho \leq 2\rho_0$.

- What is known about the EOS for symmetric matter?
  - Main information comes from heavy ion collisions.
  - Monopole, isoscaler dipole resonances sample ~ 5% variations in density (i.e. curvature about minimum)

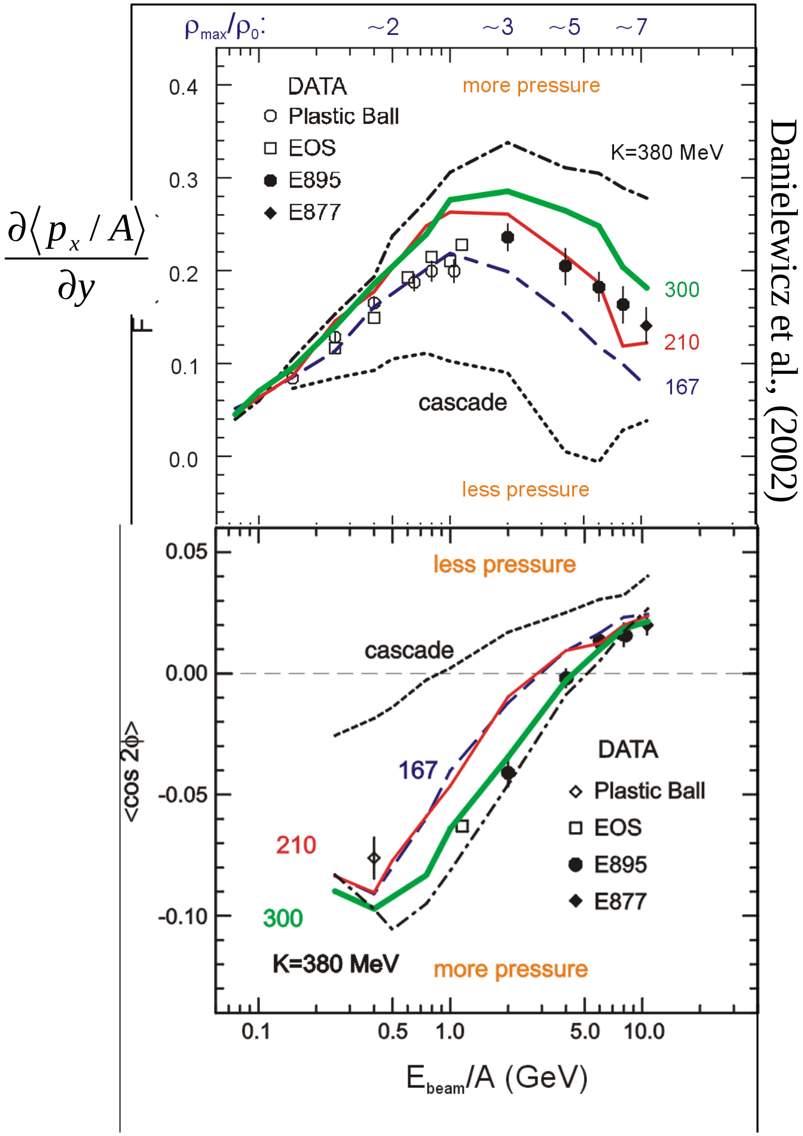
Pressure and collective flow dynamics

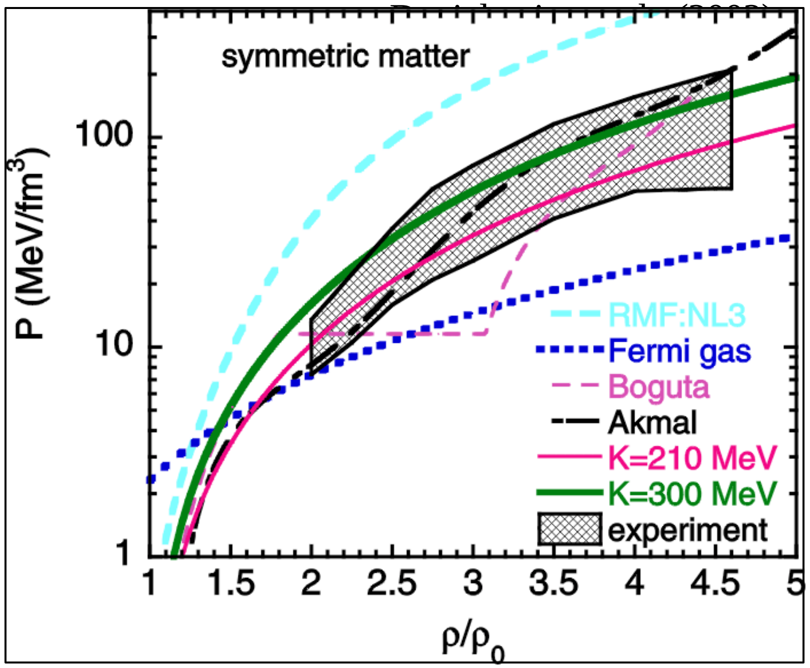


- The blocking by the spectator matter provides a clock with which to measure the expansion rate.

Constraints on symmetric matter EOS at $\rho > 2\rho_0$.

Observables: transverse, elliptical flow.



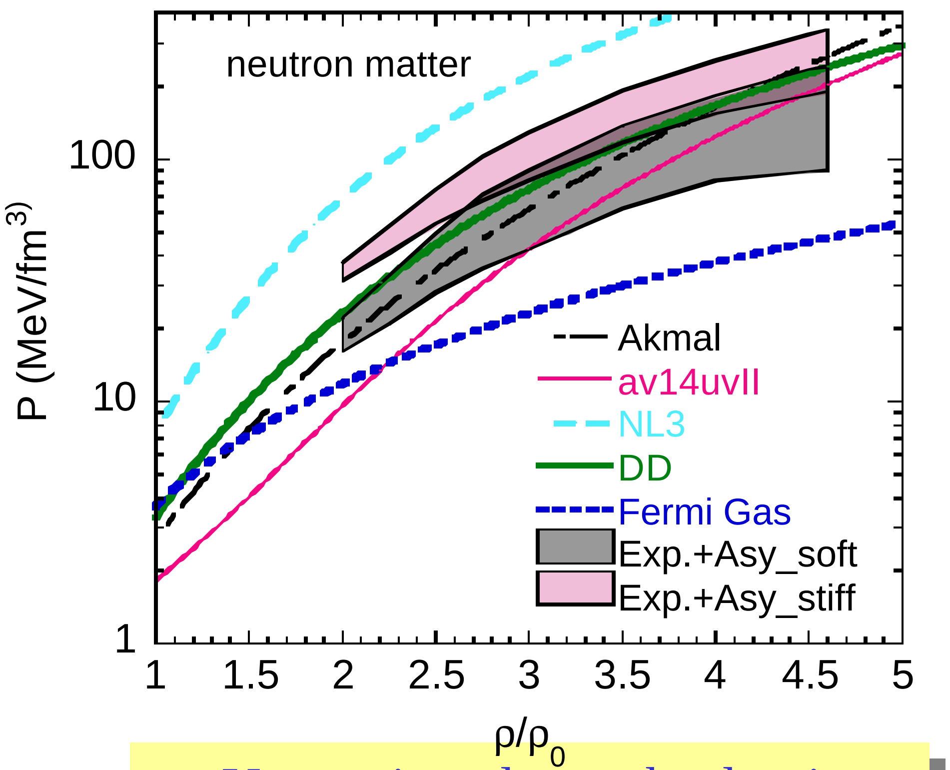


- Additional measurements were needed to constrain:
  - Momentum dependence of mean fields.
  - Cross-sections due to residual interactions.

Extrapolation to neutron stars

$E/A(\rho, \delta) = E/A(\rho,0) + \delta^2 \cdot S(\rho)$ $\delta = (\rho_n - \rho_p)/(\rho_n + \rho_p) = (N-Z)/A \approx 1$

Danielewicz et al., (2002)



- Uncertainty due to the density dependence of the asymmetry term is greater than that due to symmetric matter EOS.

Symmetry term influences:

- Macroscopic properties:
  - Neutron star radii, moments of inertia and central densities.
  - Maximum neutron star masses and rotation frequencies.
- Proton and electron fractions throughout the star.
  - Cooling of proton-neutron star.
- Thickness of the inner crust.
  - Frequency change accompanying star quakes.
- Role of Kaon condensates and mixed quark-hadron phases in the stellar interior.

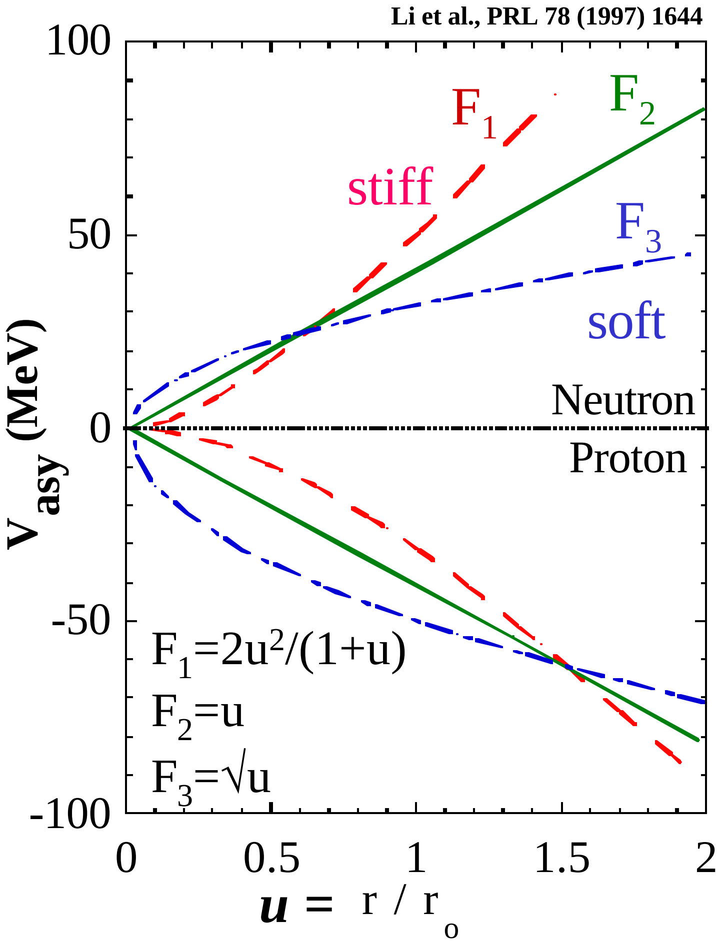
- How can one probe the asymmetry term?
  - Note: observables are needed mainly to constrain the interaction term:

$$S(r) = S_{kin}(r) + S_{\text{int}}(r);$$

$$S_{kin}(r) \approx \frac{1}{3} E_{Fermi}(r) \approx 13 \cdot (r/r_0)^{2/3} MeV$$

  - Other observables will also be needed to constrain isospin dependent in-medium NN cross sections and neutron and neutron and proton effective masses

Probing the asymmetry term



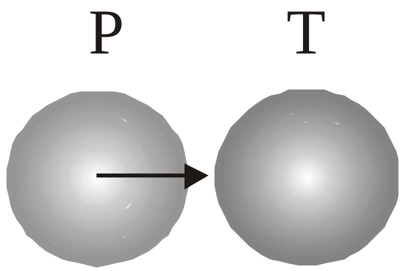
- Sign of mean field opposite for protons and neutrons.
- Shape is influenced by incompressibility.

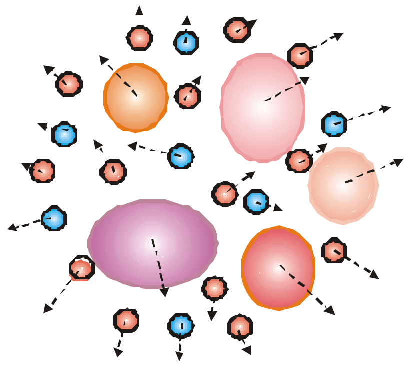
Quantities sensitive to asymmetry term:

- At sub-saturation densities
  - Difference between neutron and proton matter radii.
  - Isospin diffusion
  - Asymmetry of bound residues.
  - Prequilibrium n vs. p emission.
  - Transverse flow (n.vs.p).
- At supra-saturation densities
  - Isospin dependencies of pion production.
  - Transverse flow (n.vs.p).

Central collisions

E/A<100 MeV; Multifragmentation Scenario





- Initial compression and energy deposition
- Expansion – emission of light particles.
- Cooling – formation of fragments
- Disassembly

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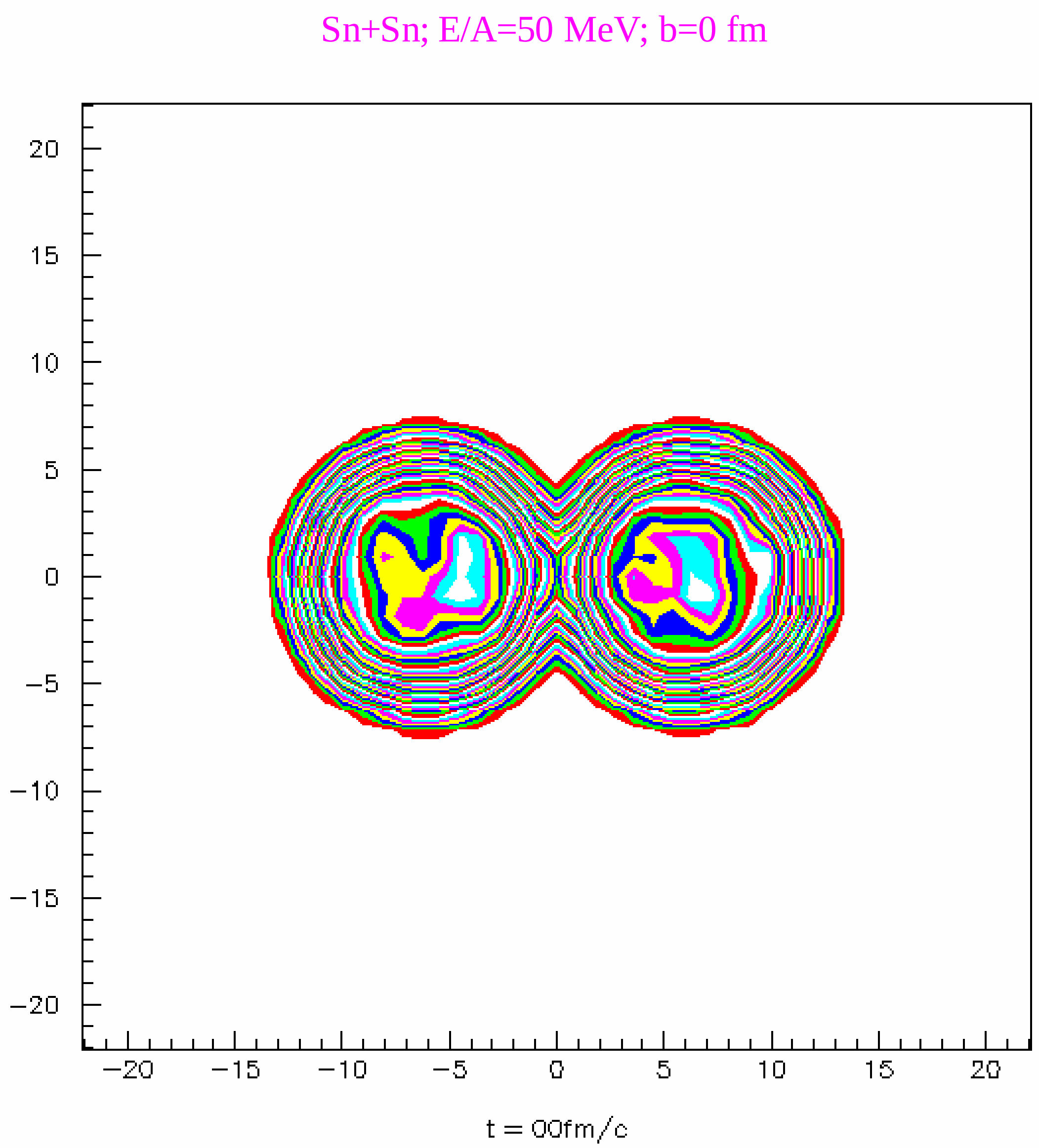

BUU: Transport theory simulations

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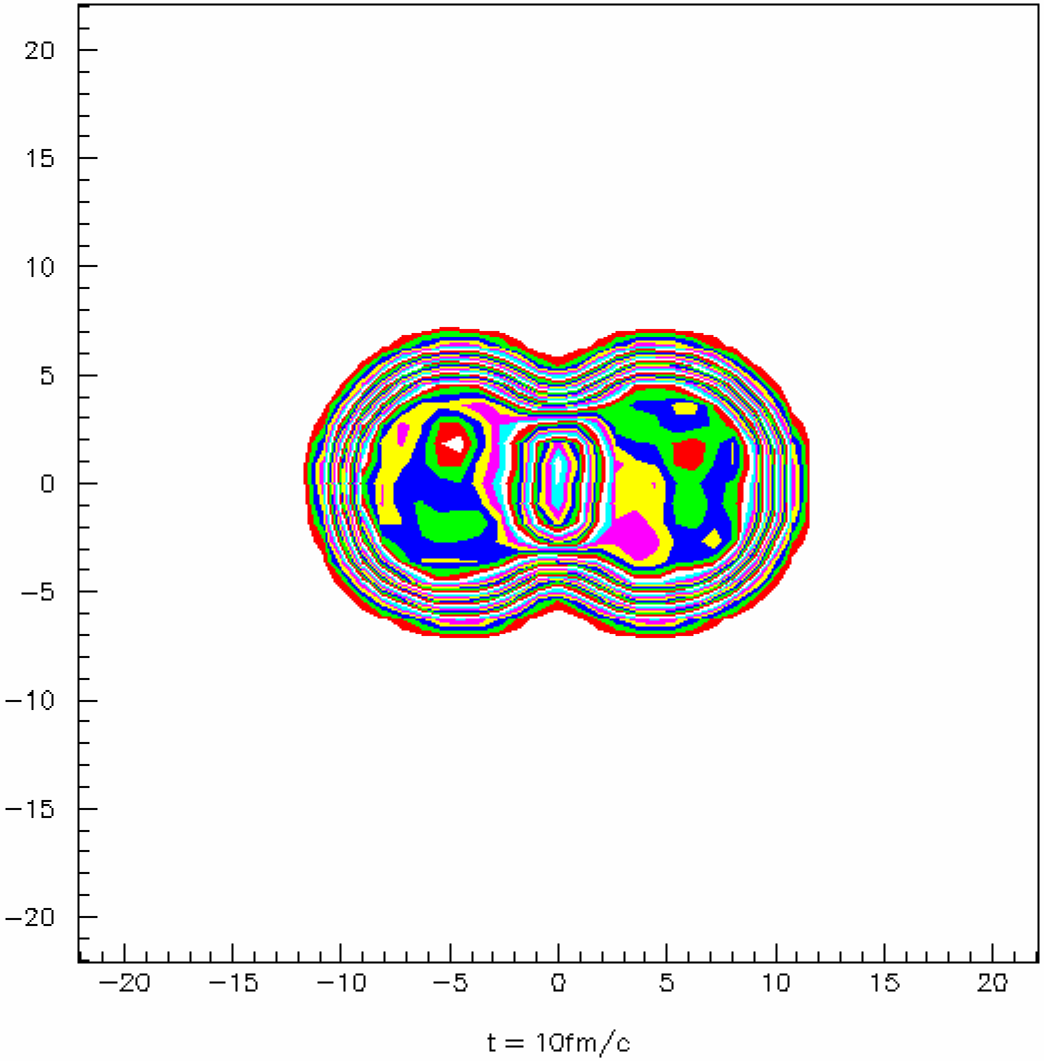
Sn+Sn; E/A=50 MeV; b=0 fm



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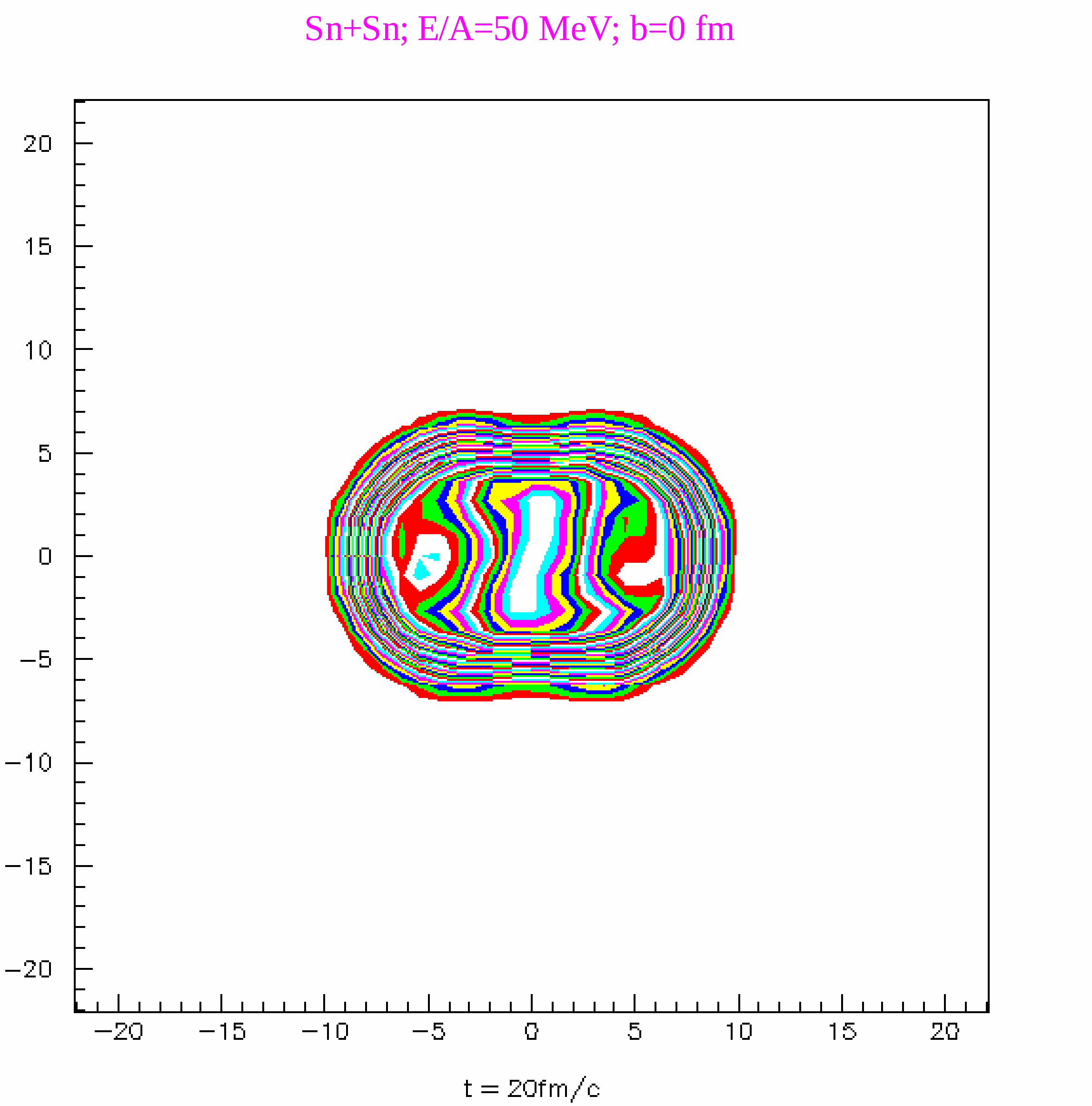

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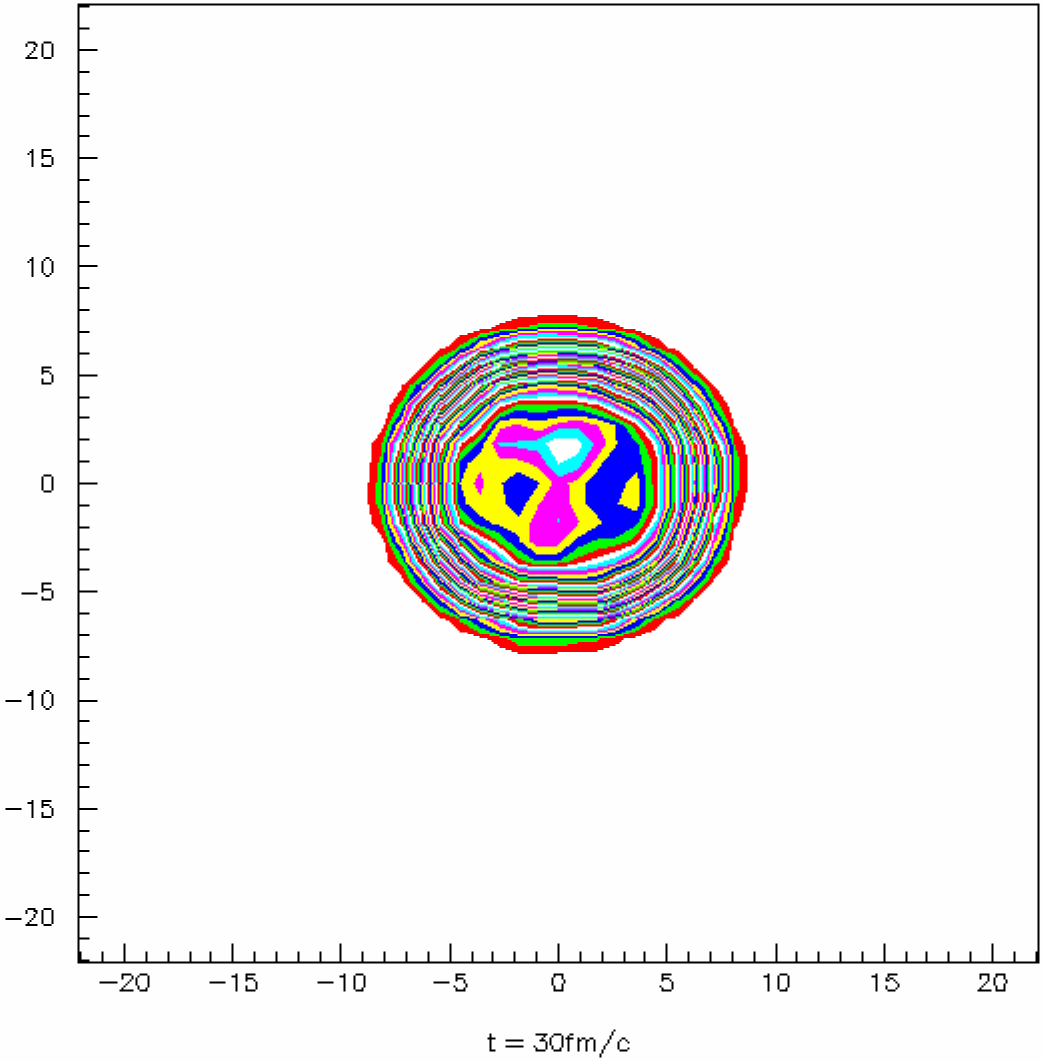

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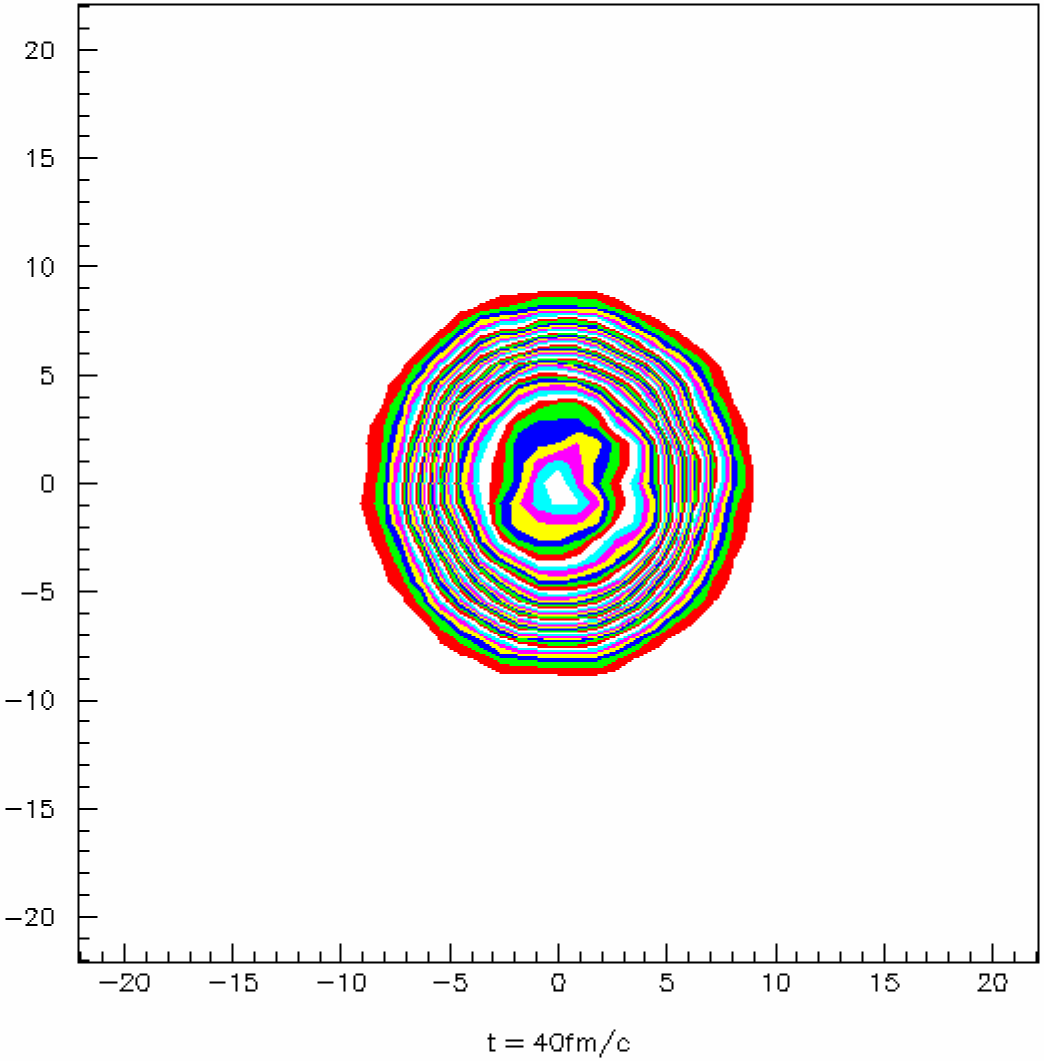

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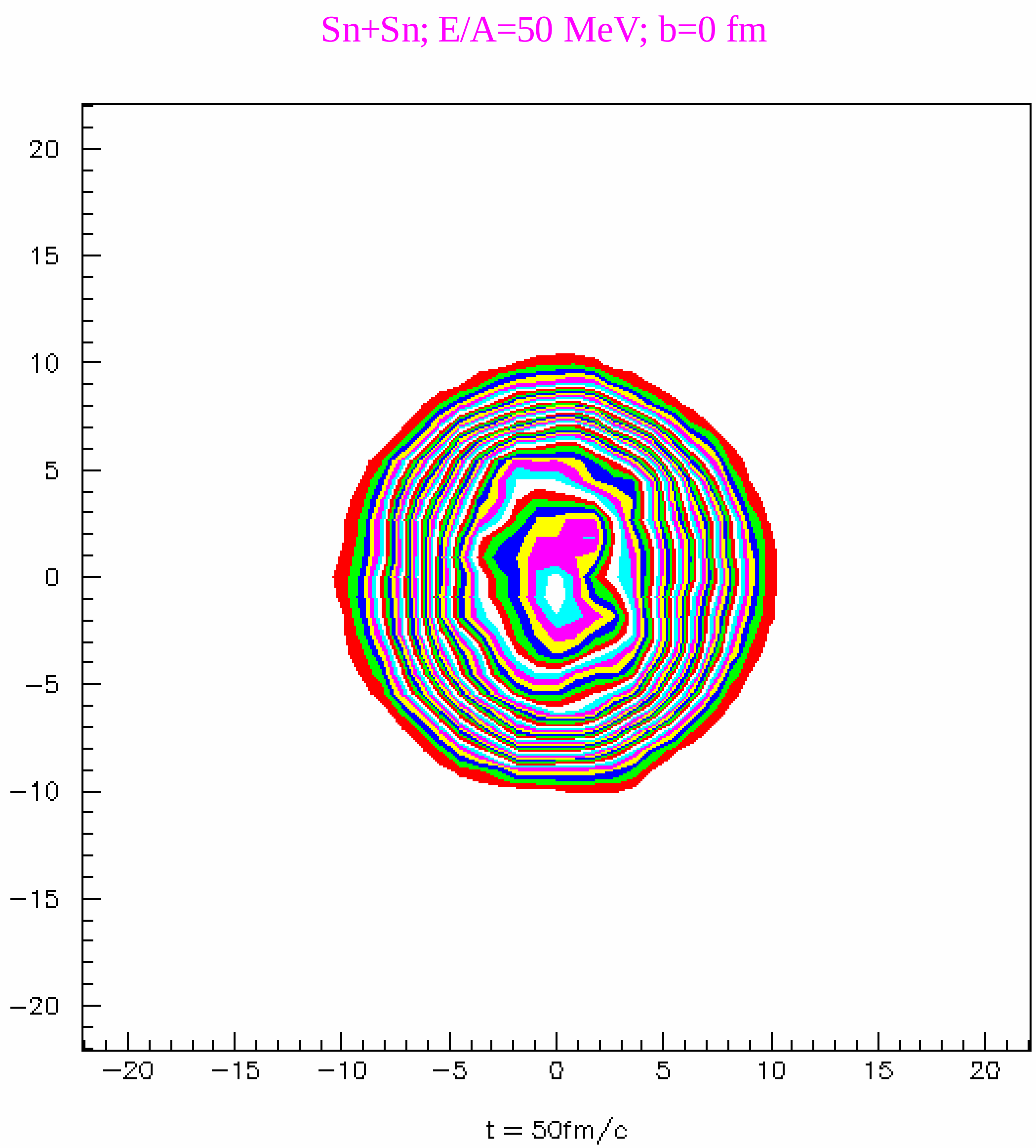

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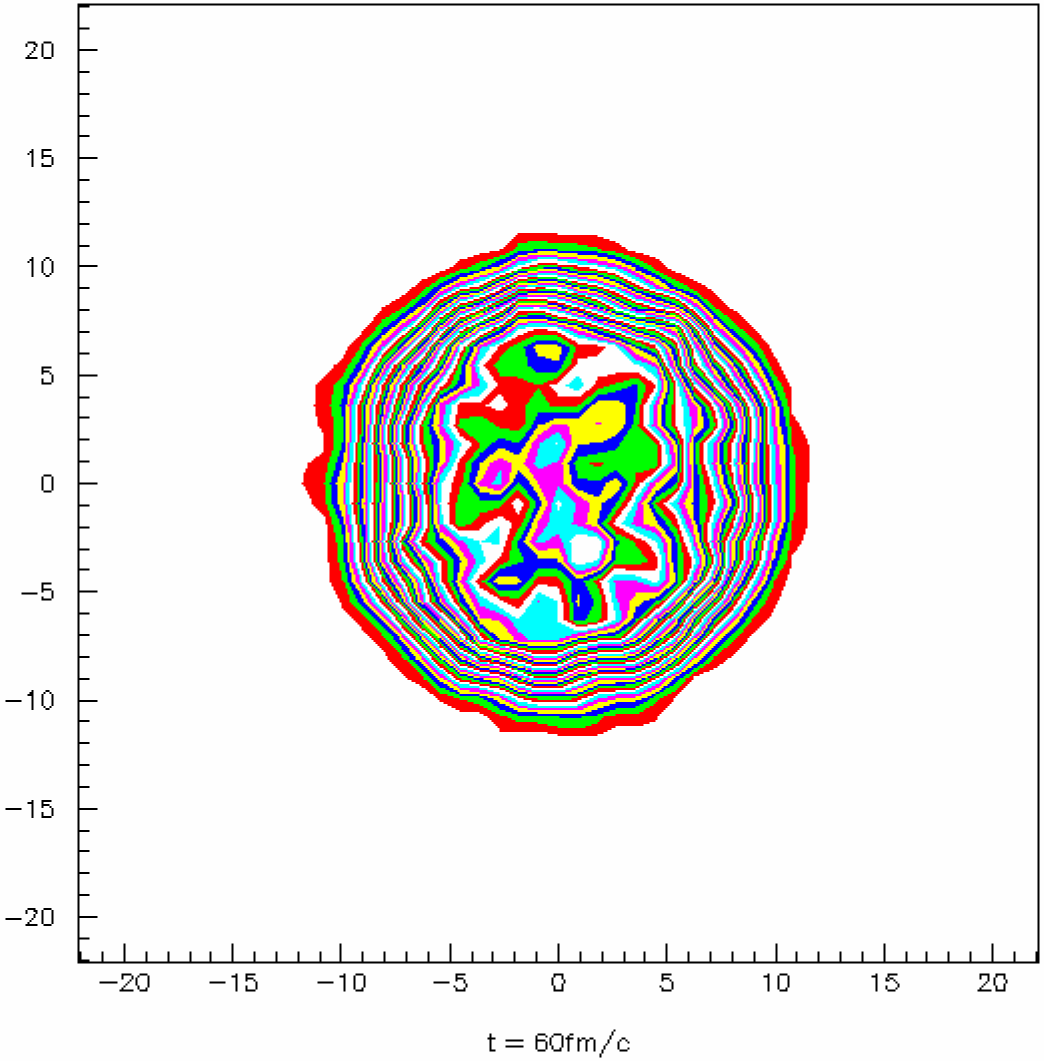

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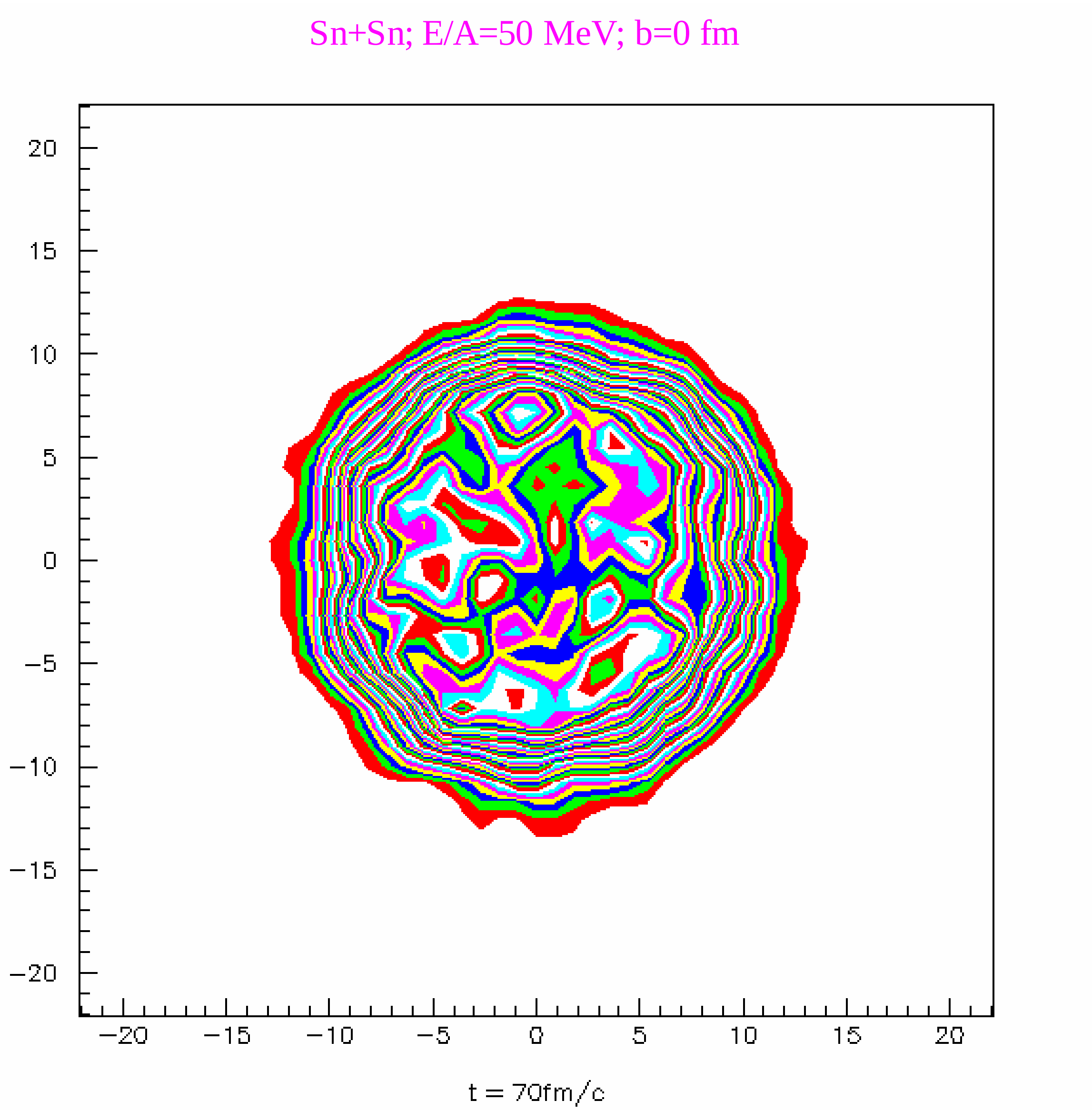

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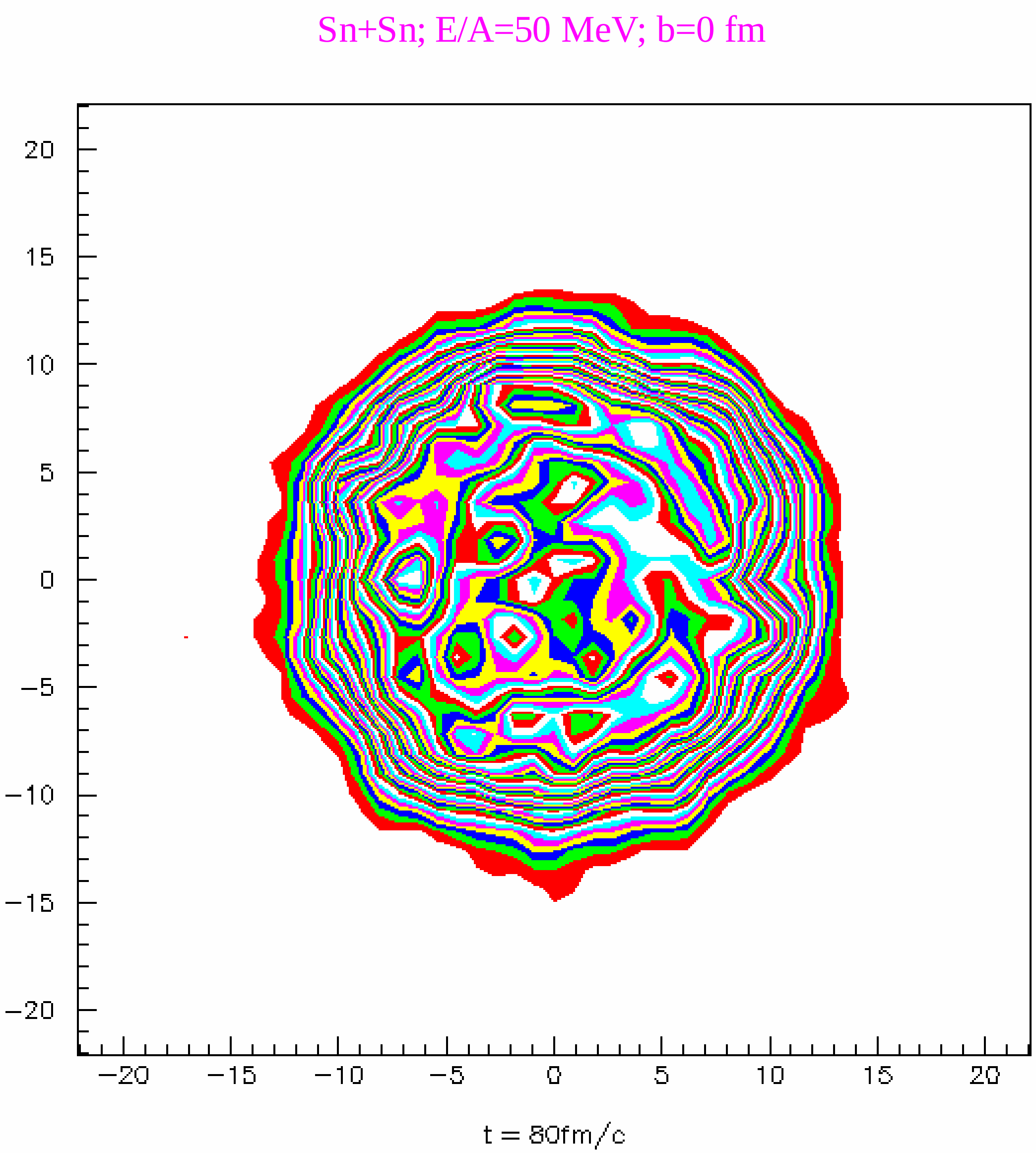

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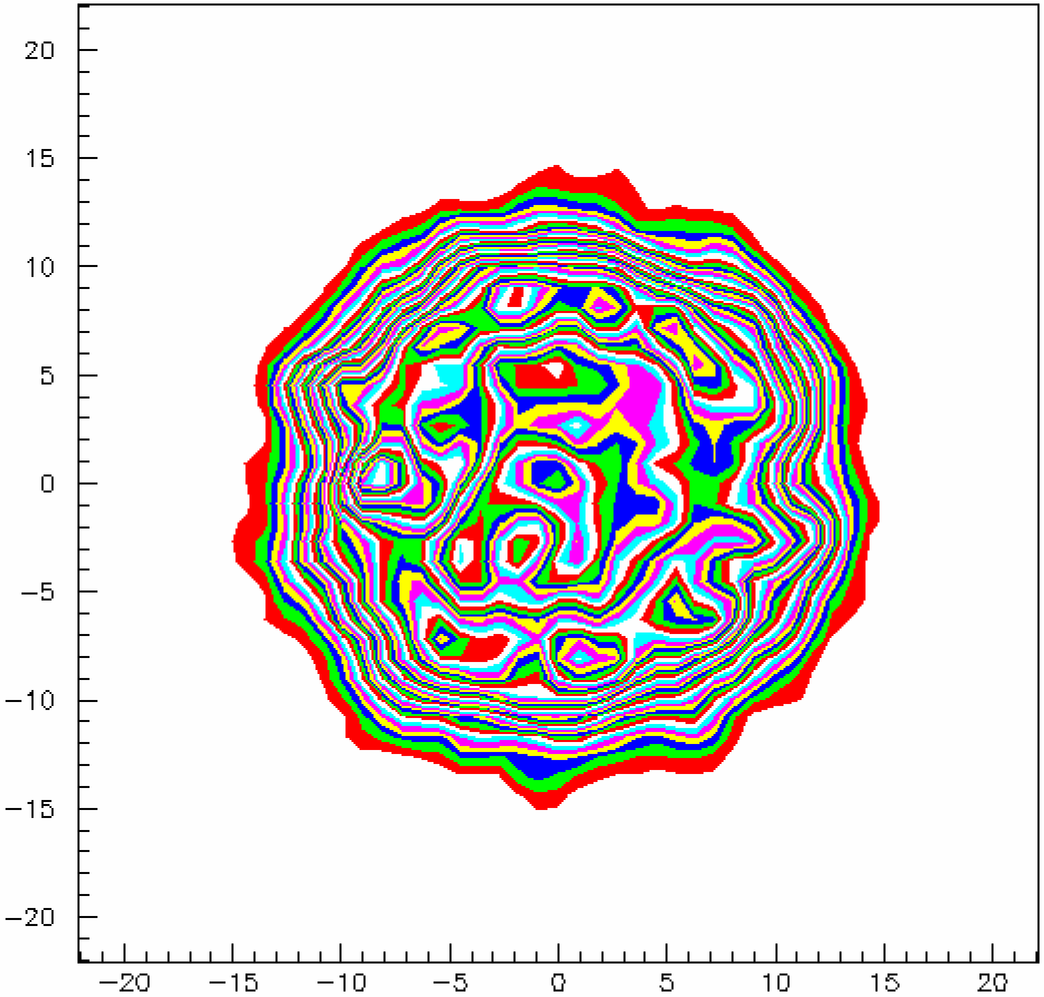

t = 90fm/c

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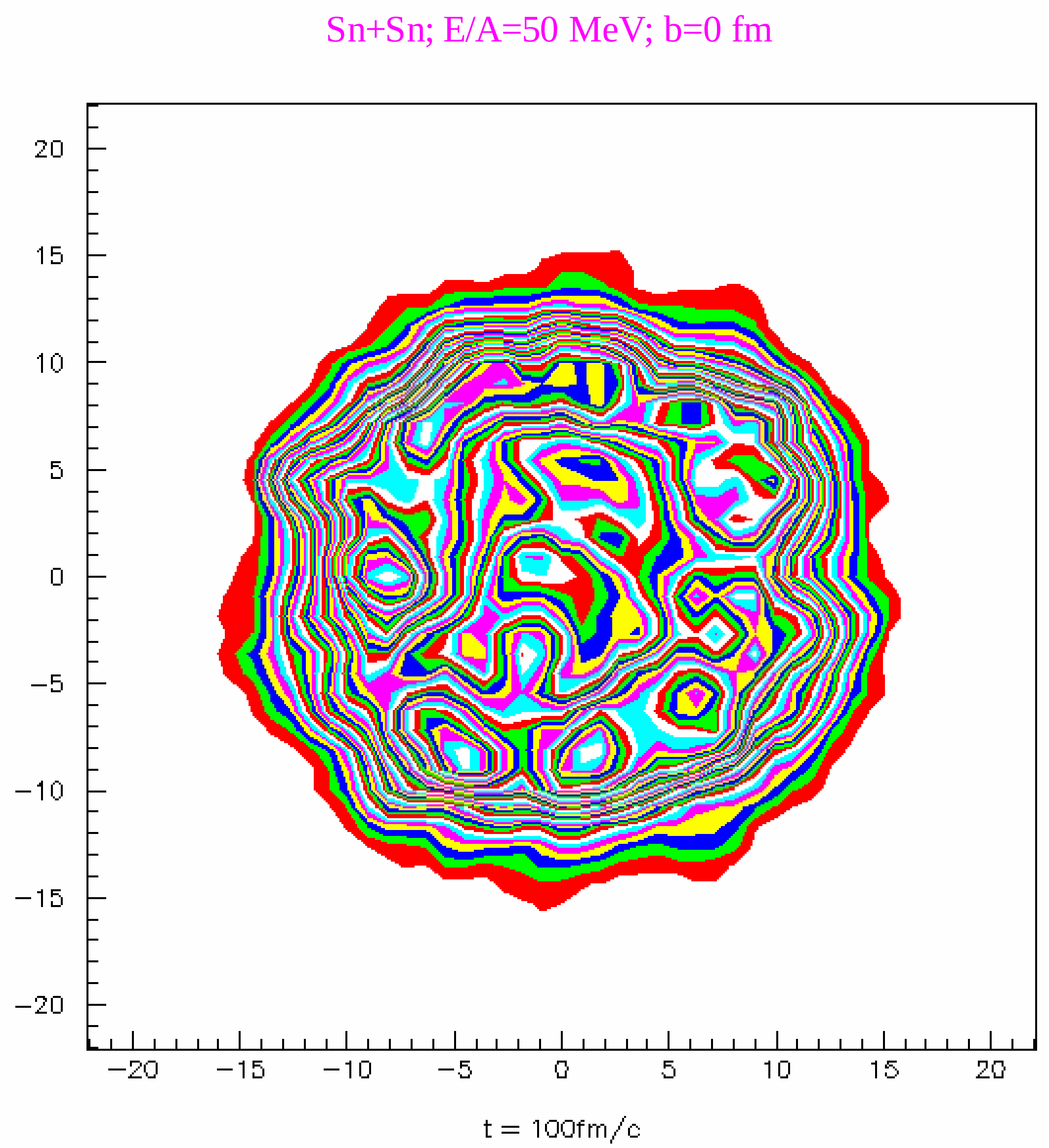

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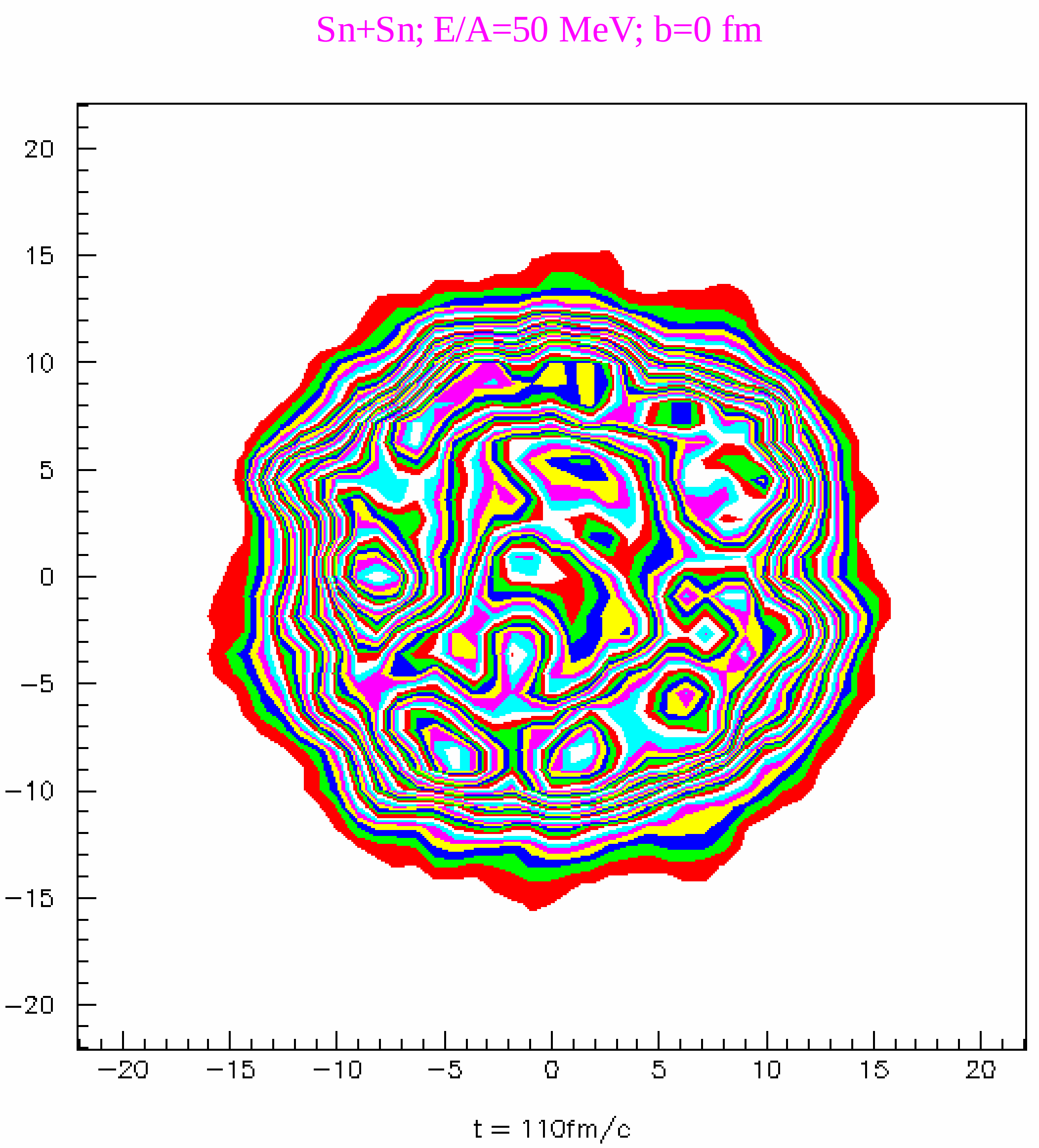

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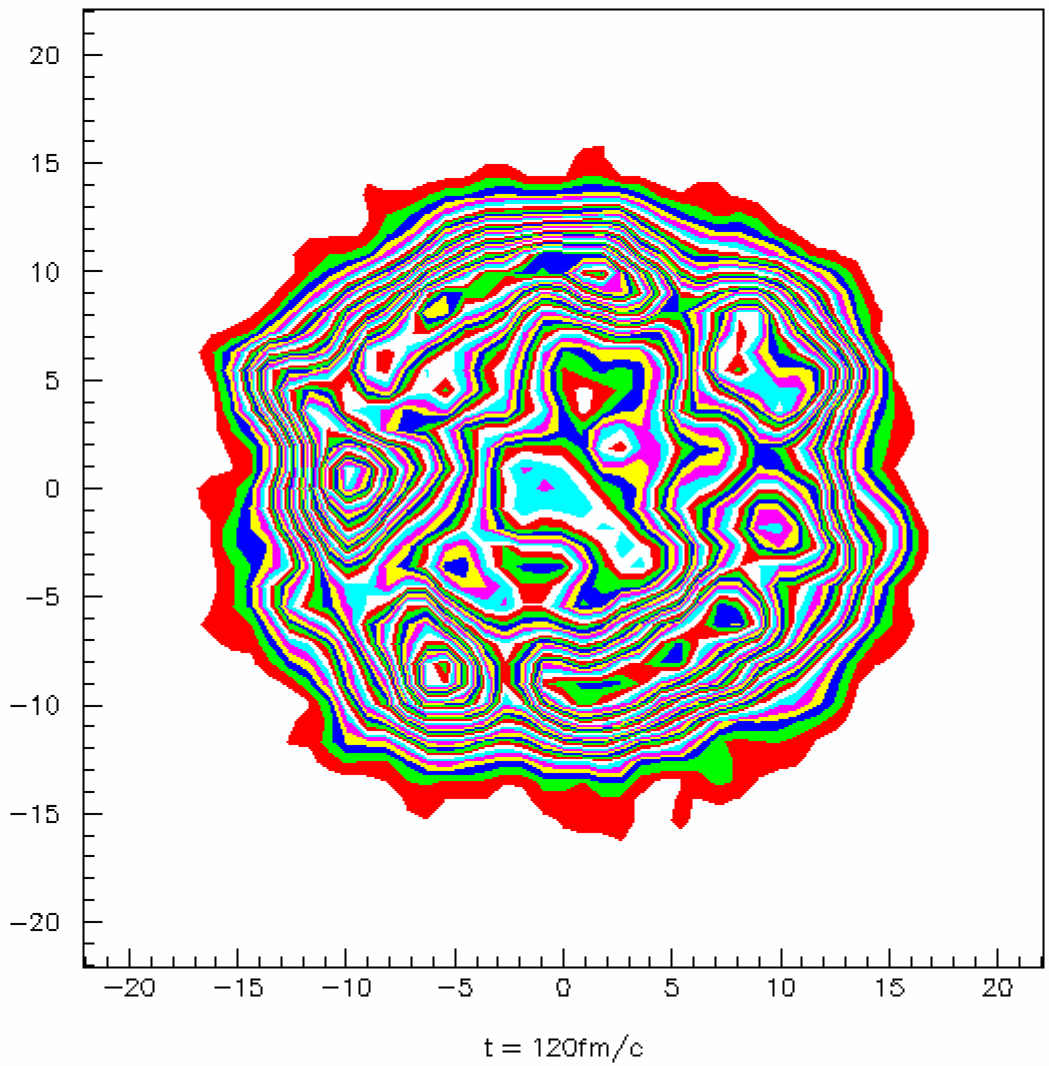

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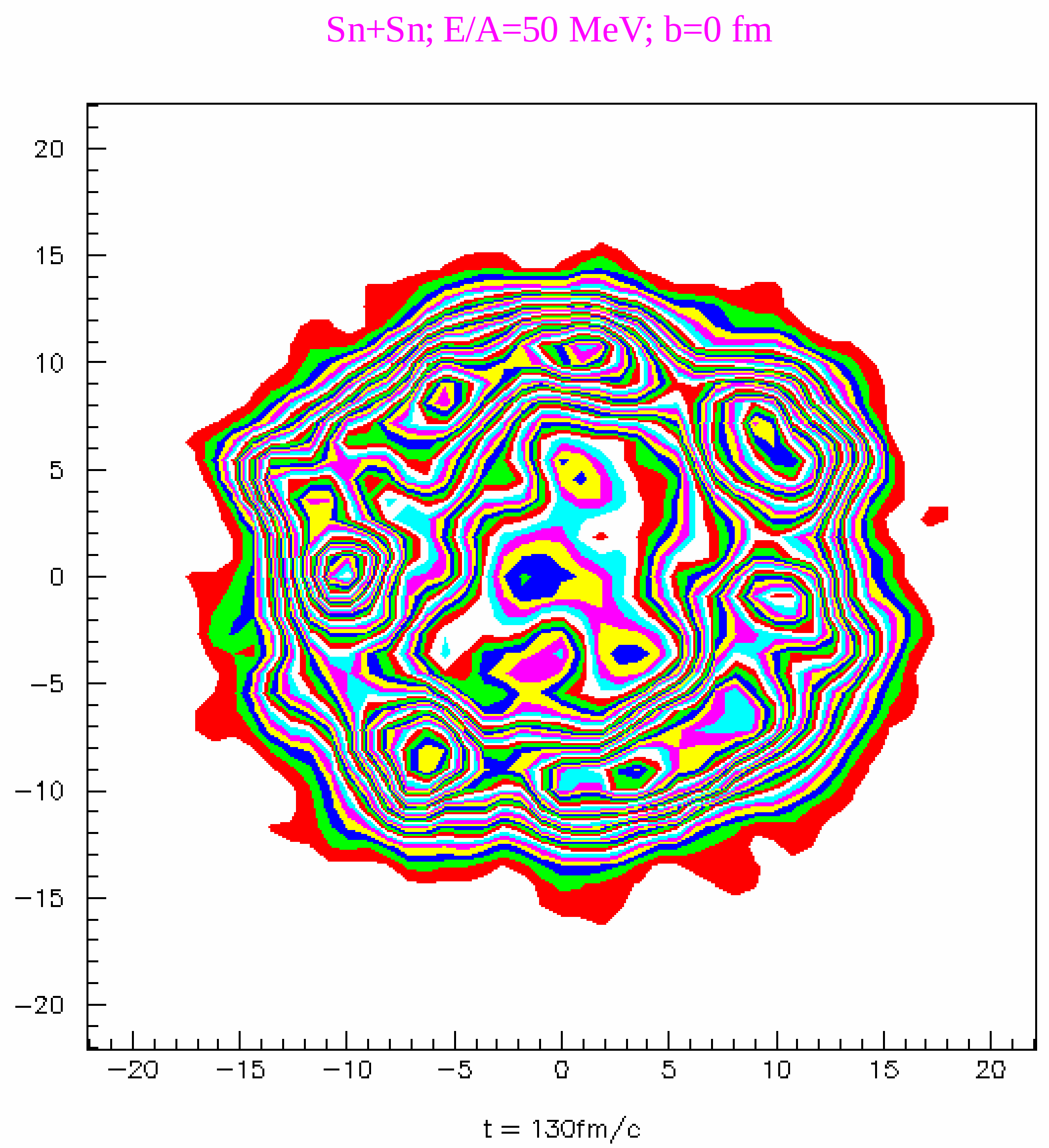

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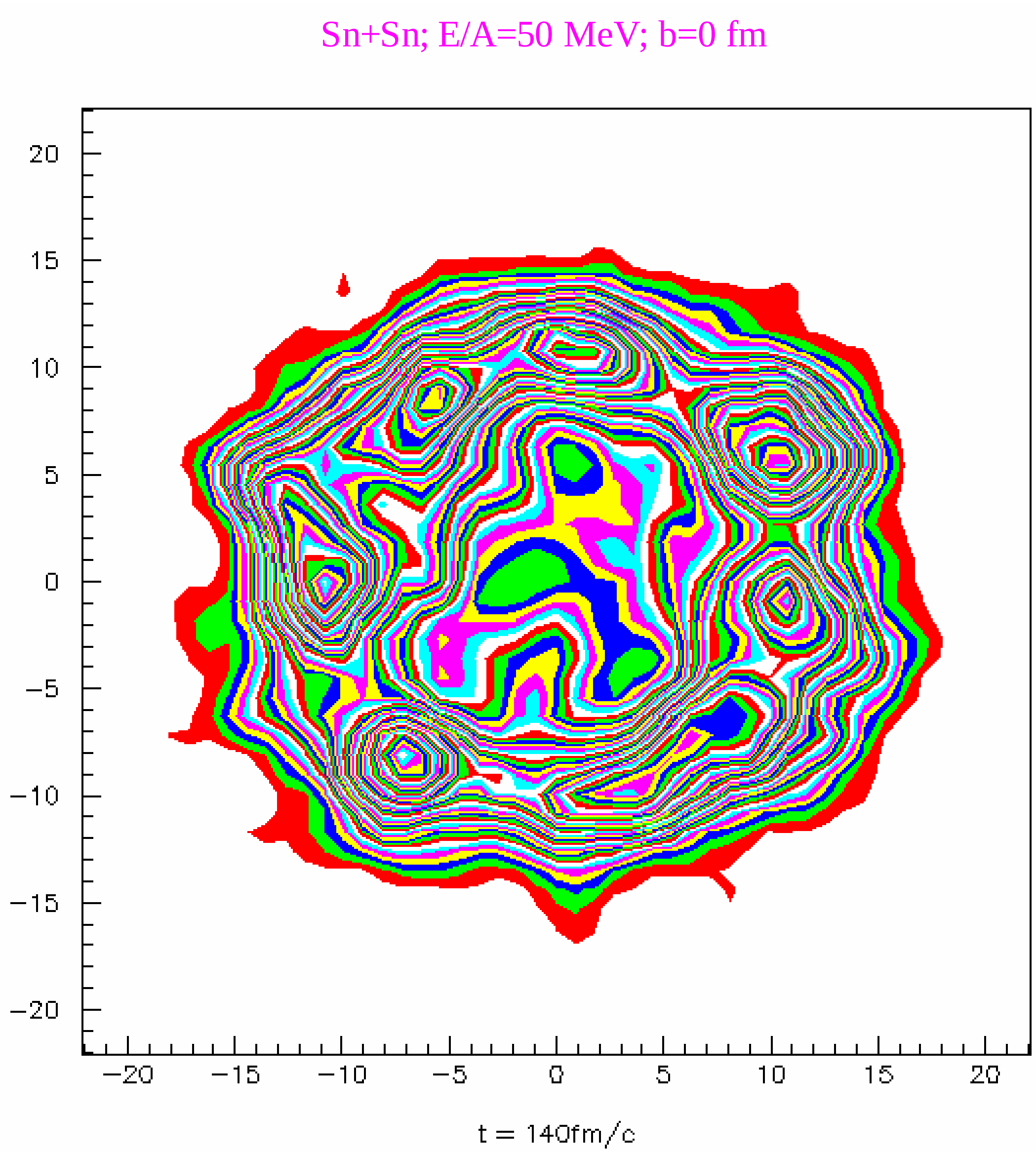

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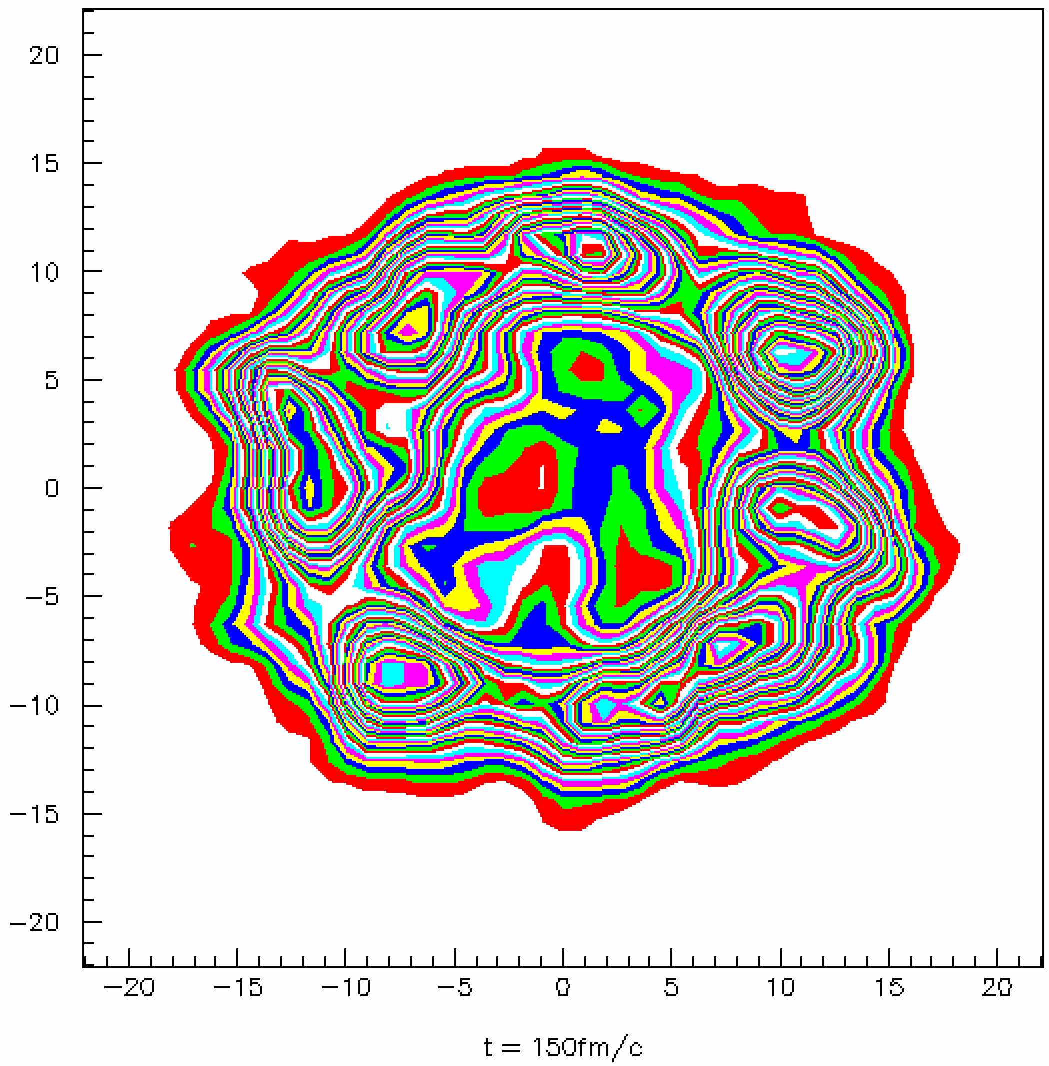

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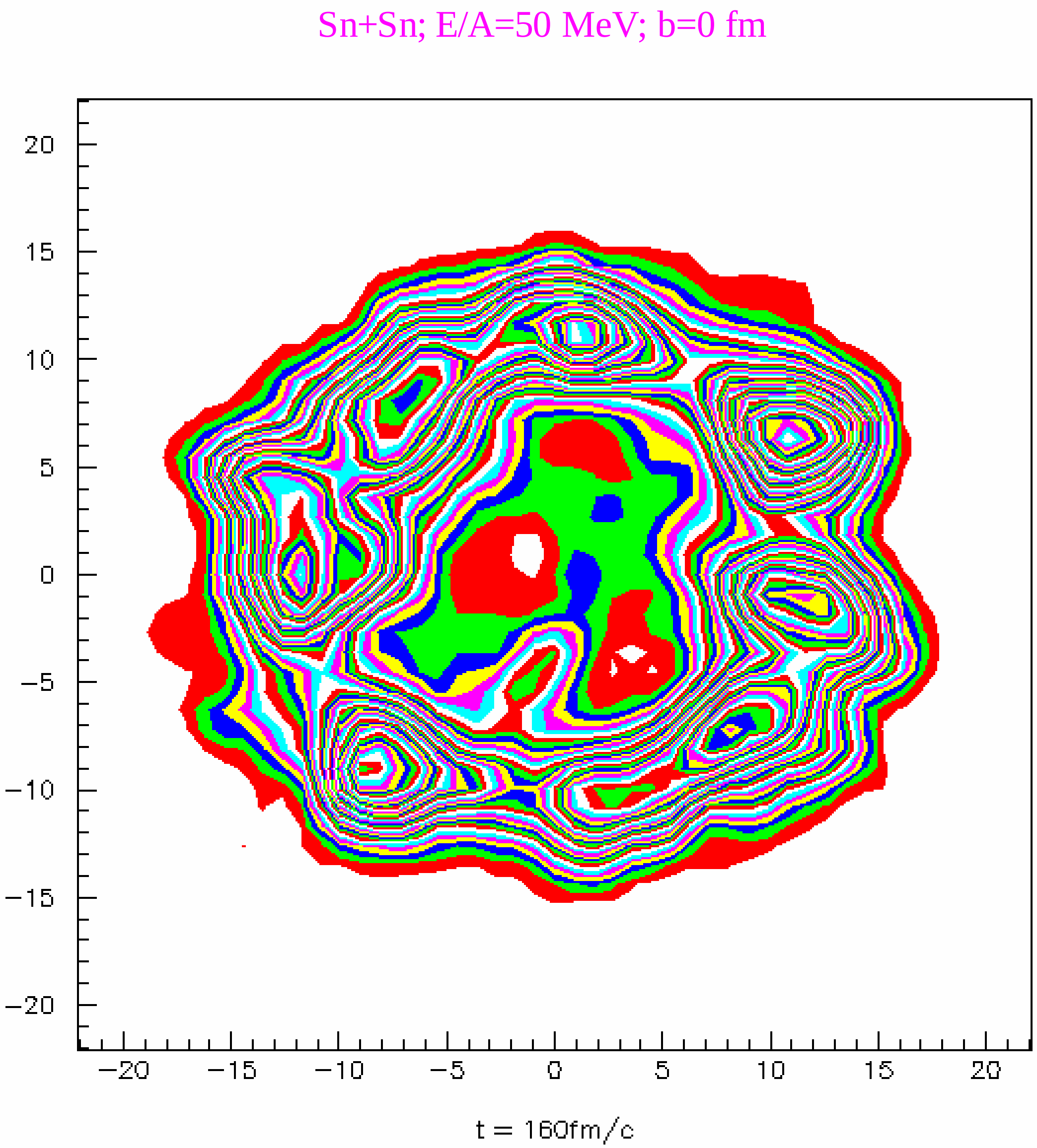

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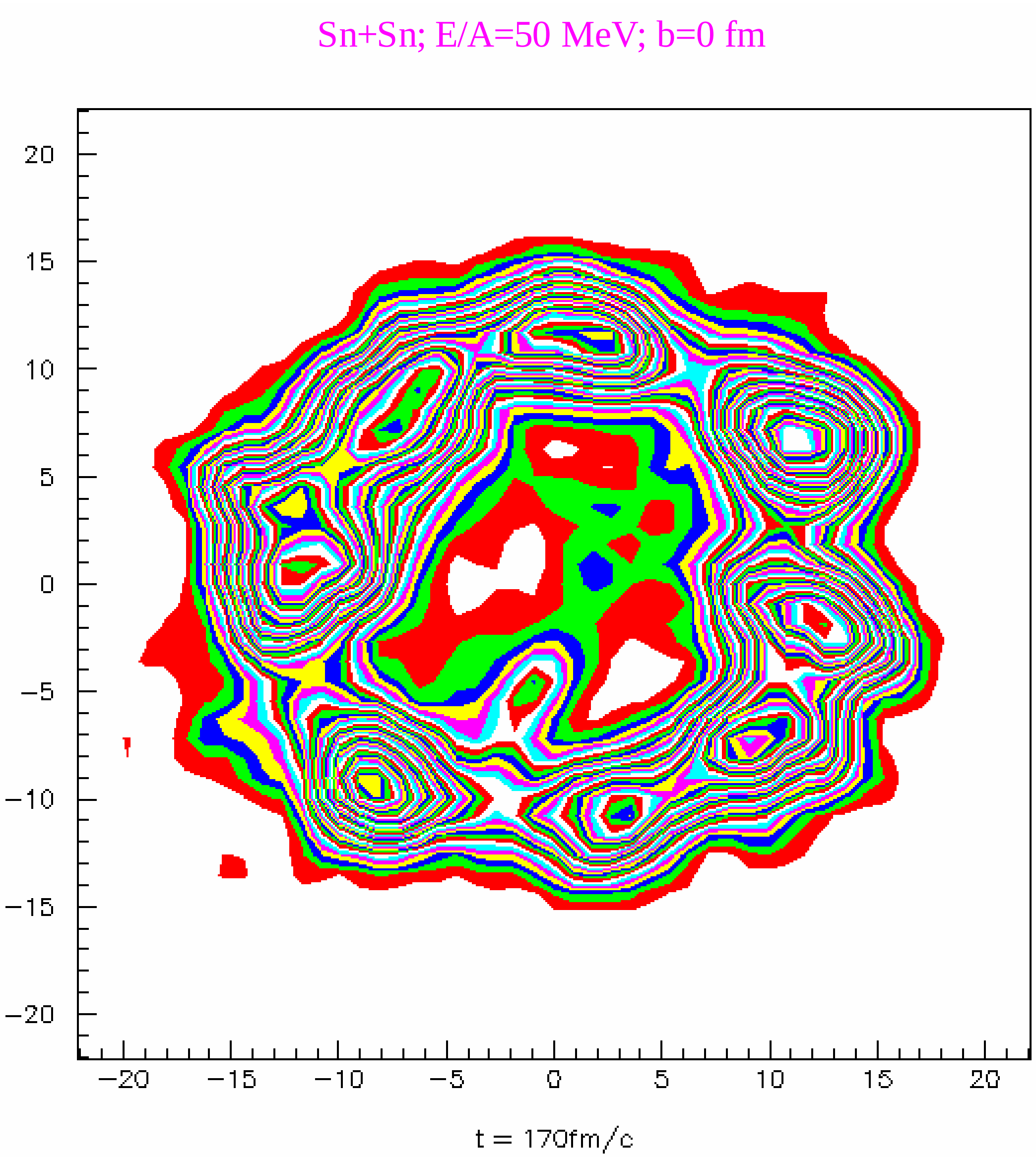

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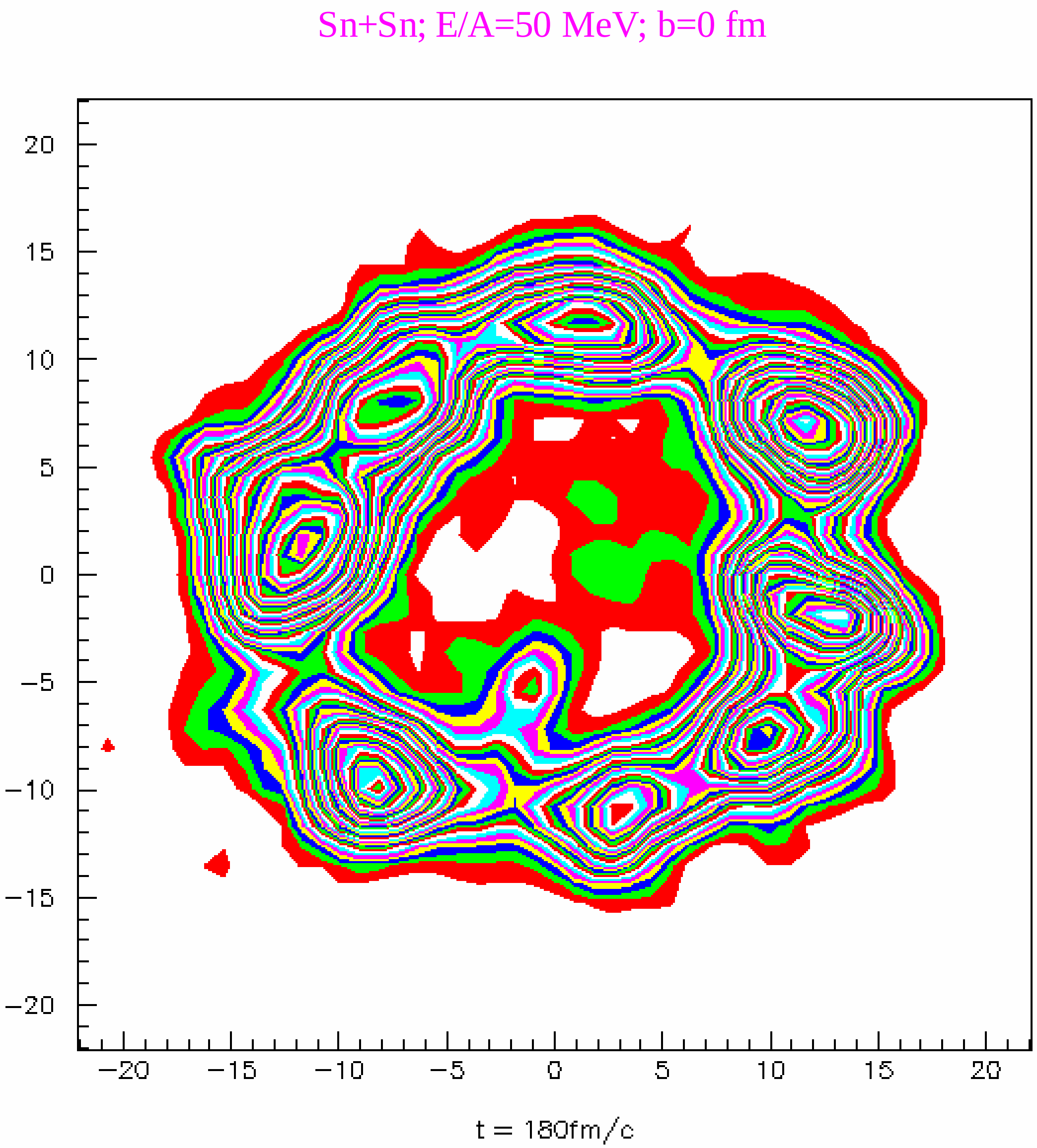

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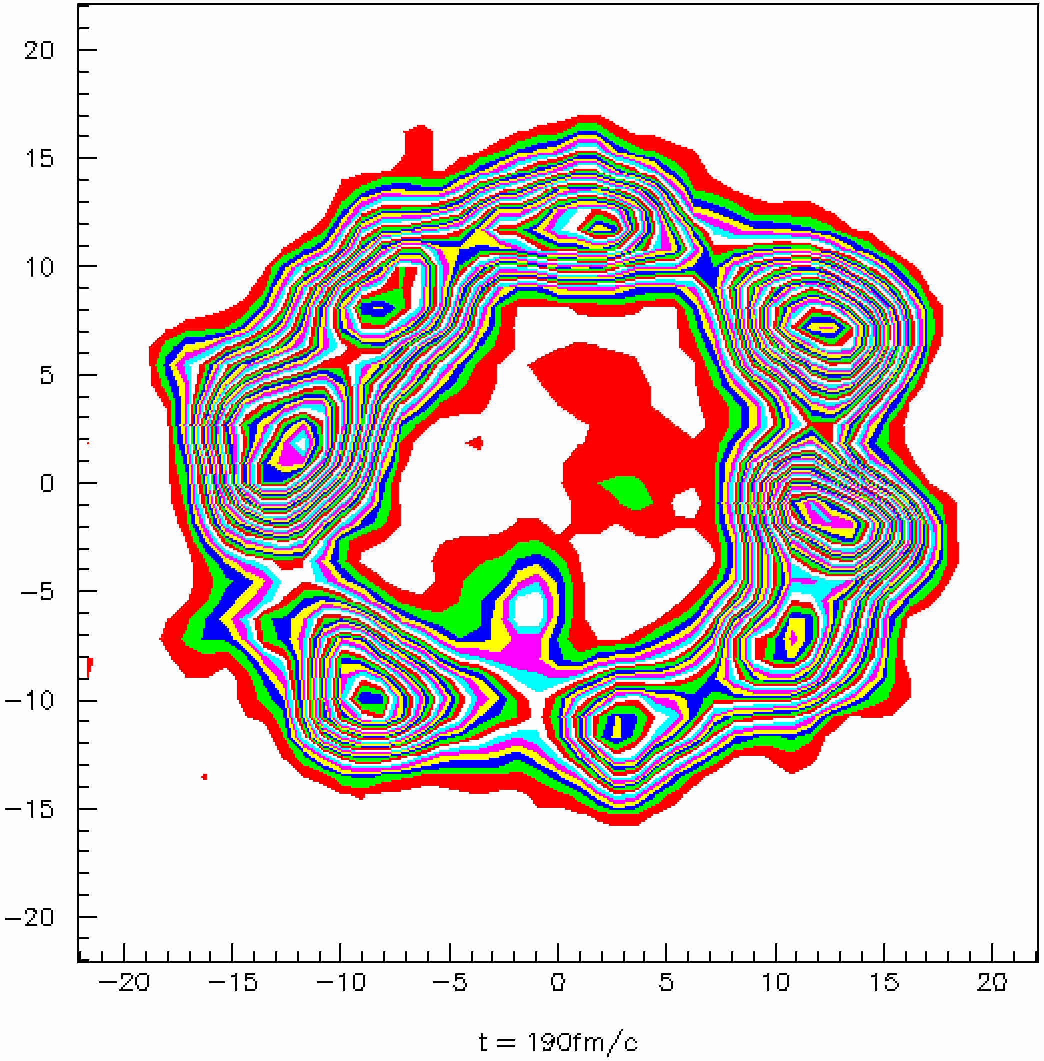

BUU: Transport theory simulations

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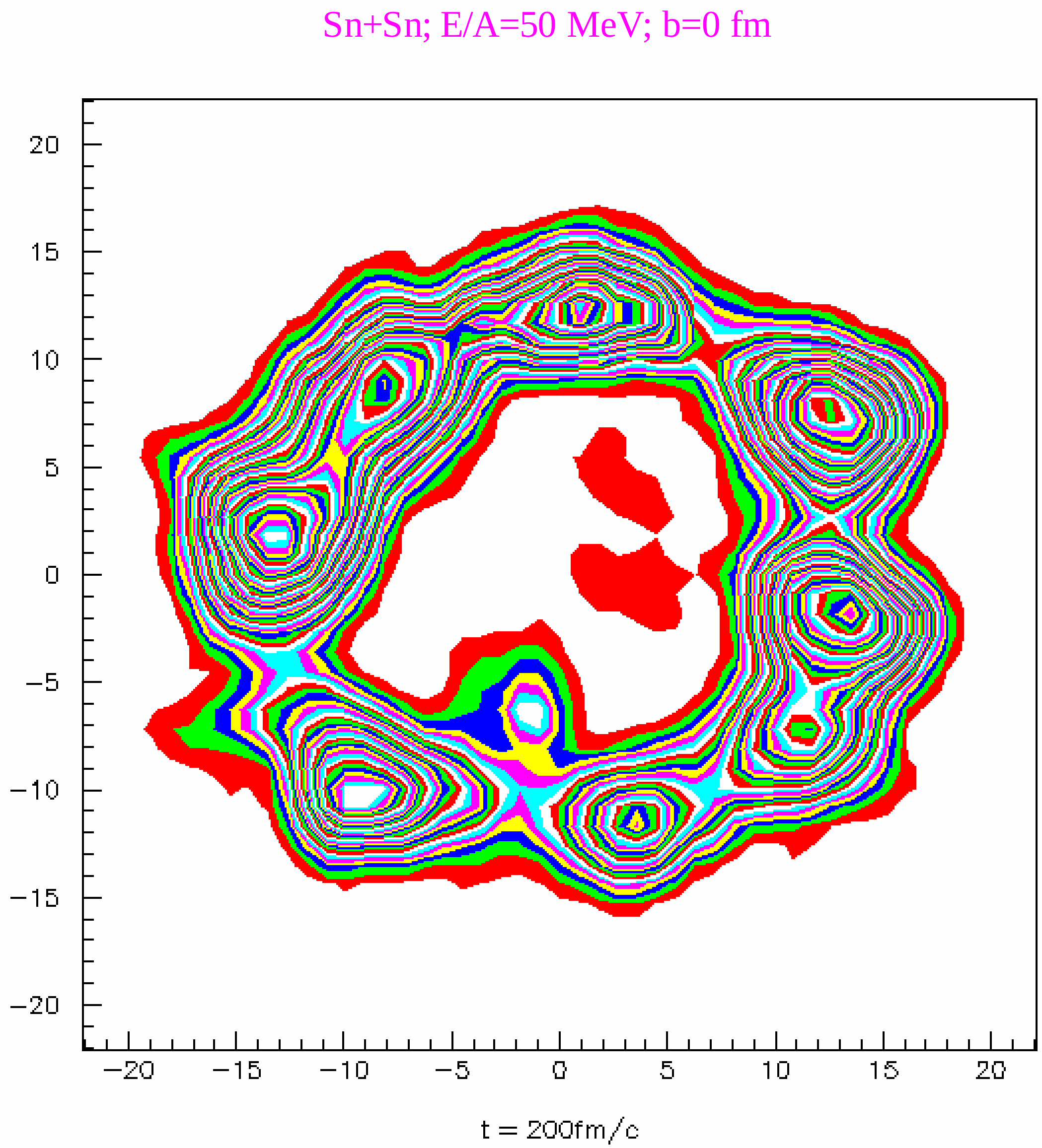
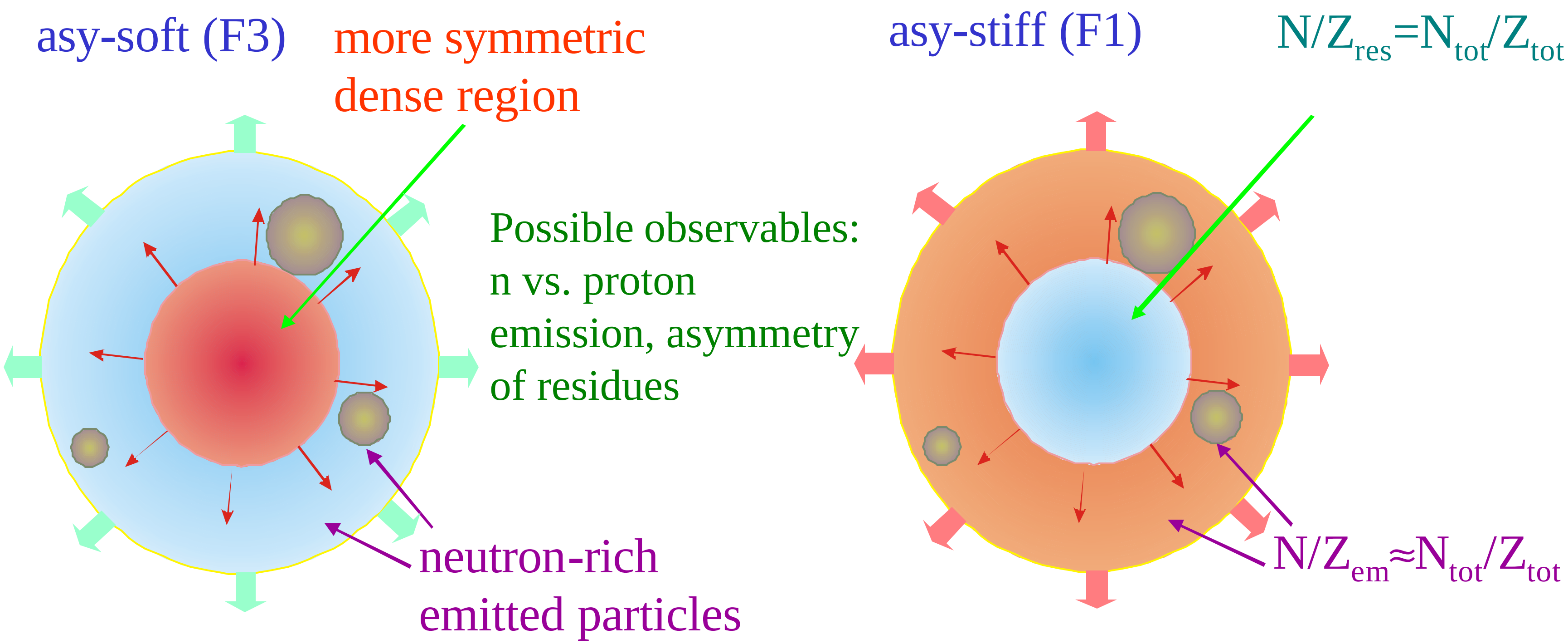


BUU: Transport theory simulations

Central collisions: isospin fractionation

For a neutron rich system at $\rho<\rho_0$:



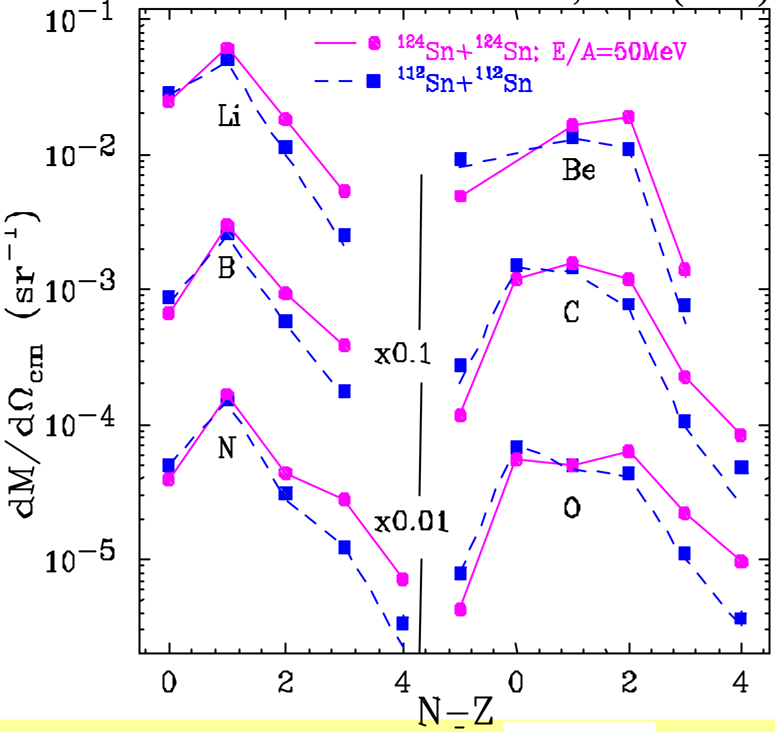
BUU predictions for central $^{124}Sn+{}^{124}Sn$ ($N_0/Z_0=1.48$) collisions at E/A=50 MeV

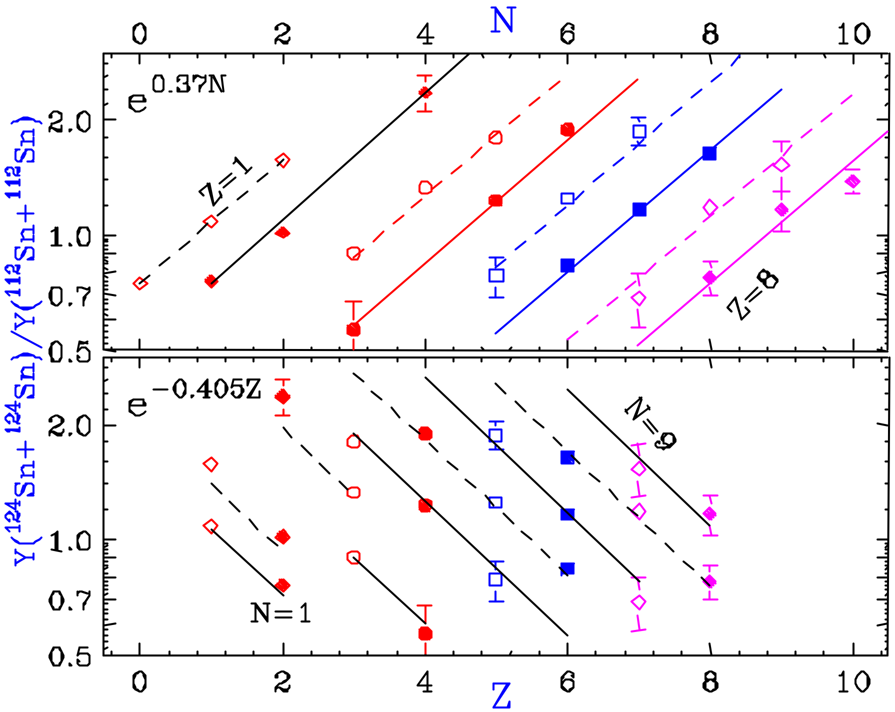
EOS	Residue N/Z
F_3 (asy-soft)	95/77=1.23

EOS	Residue N/Z
F_1 (asy-stiff)	102/71=1.44

1st Observable: Isoscaling parameters of fragments

Liu et al., PRC (2004)





- Shape of isotopic distributions depends on overall isospin asymmetry of source (PLF).
  - Dependence on overall isospin asymmetry is described by isoscaling laws.

- Ratios of isotopic yields of two reactions at same “temperature” are related exponentially.

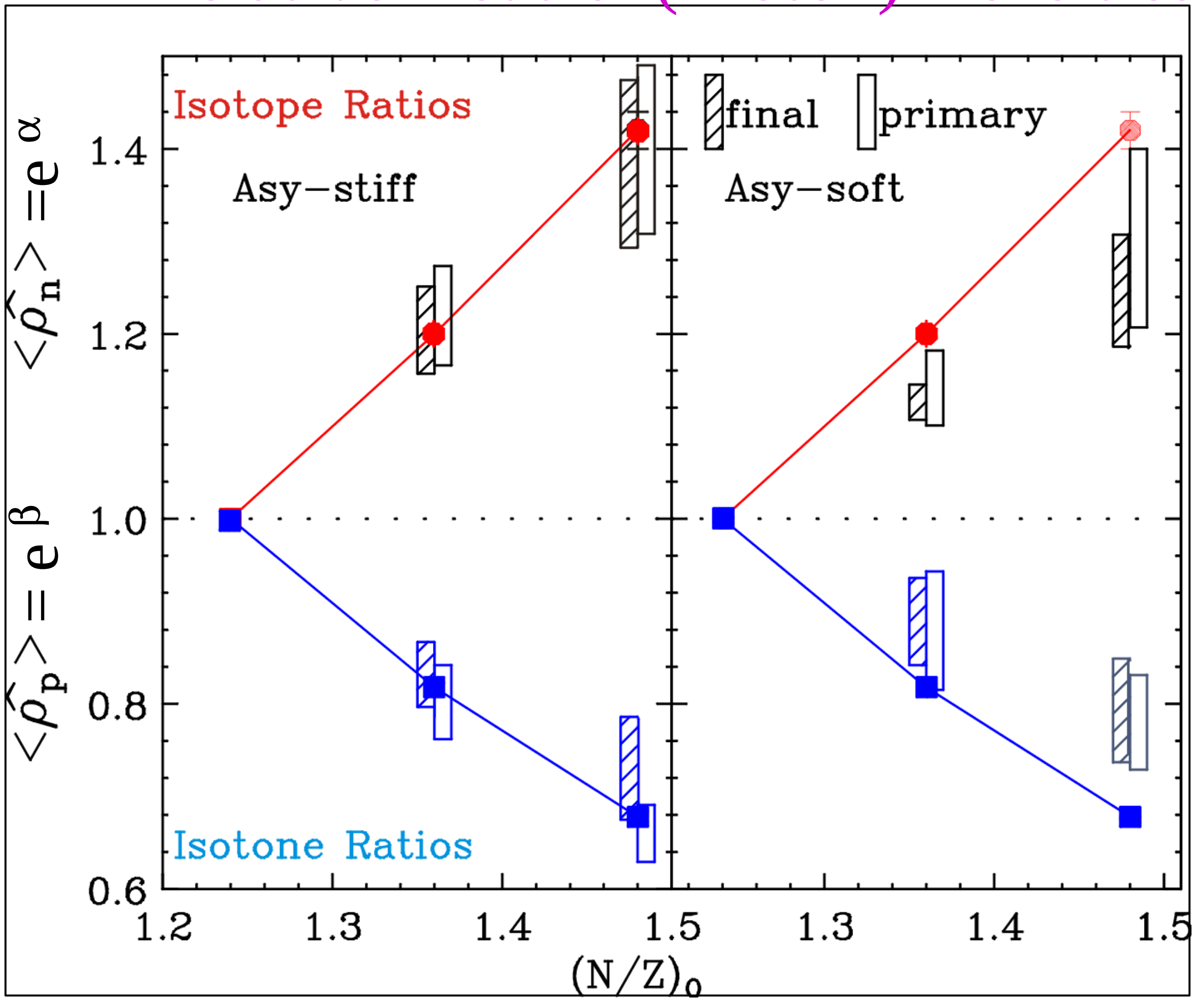
$$R_{21} = Y_2(N,Z)/Y_1(N,Z) \propto e^{(aN+bZ)}$$

- Relationship can be derived from a variety of statistical theories and is also obtained in AMD calculations: $\alpha \propto \delta_{source}$.

Model dependence of fragment isoscaling parameters.

- Few precise calculations:
  - BUU-ISMM, EES, AMD and SMF.
- Existing calculations break into two groups:
  - Dynamical SMF and hybrid BUU-ISMM models predict that the asy-soft EOS leads to smaller isoscaling parameters for central collisions than does the asy-stiff EOS .
  - Dynamical AMD and statistical surface emission model (EES), however, predict that the asy-soft EOS leads to larger isoscaling parameters for central collisions than does the asy-stiff EOS.
  - ⇒Connection between fragment isoscaling parameters and the EOS is model dependent.

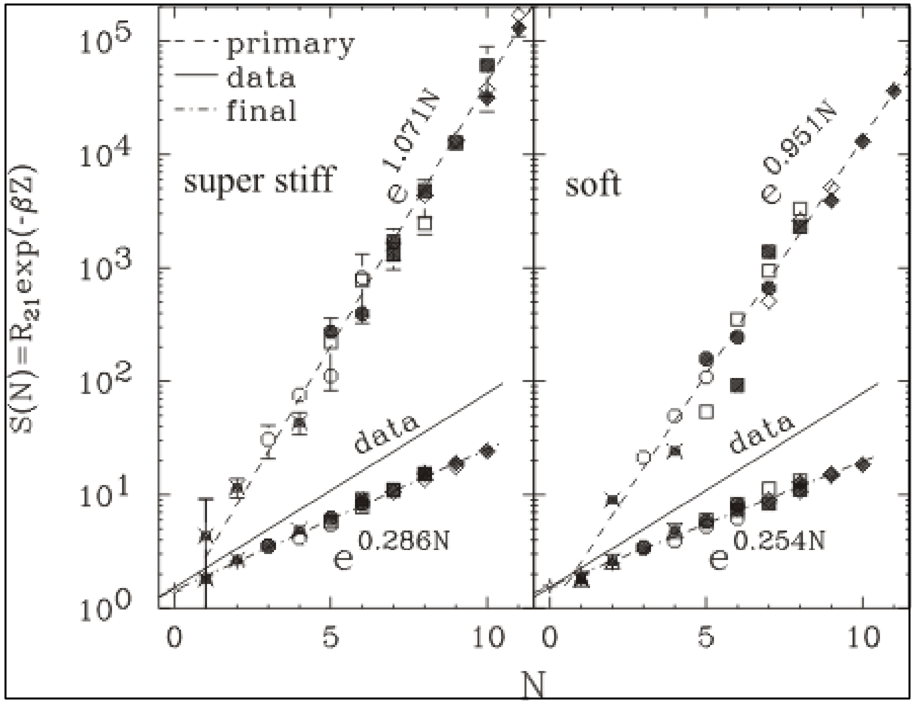
Relative Neutron(Proton) Densities

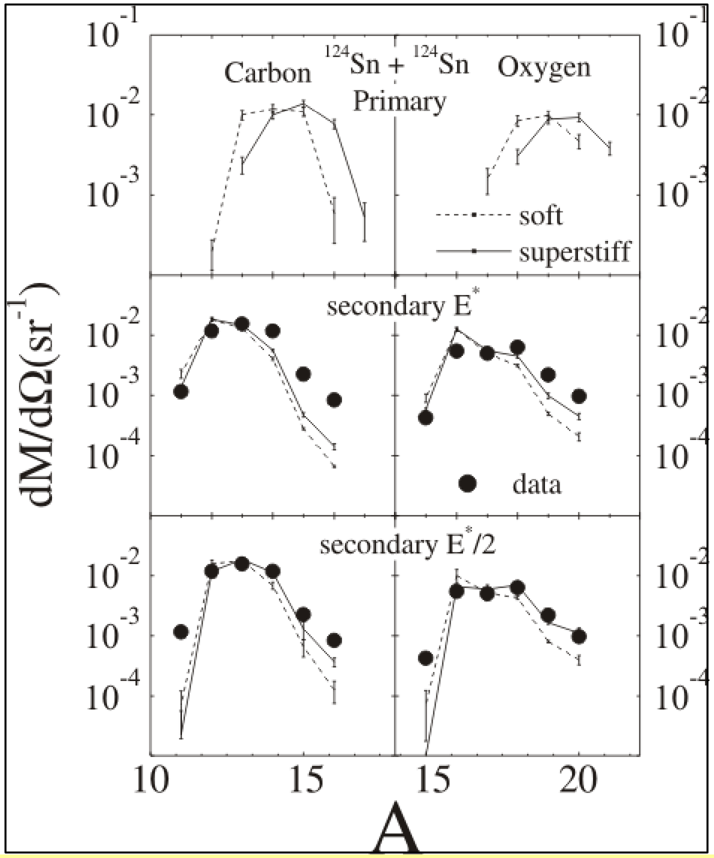


Tan et al. PRC (2001)

- $<\hat{r}_n>$ and $<\hat{r}_p>$ are not sensitive to secondary decays.
- $<\hat{r}_n>/<\hat{r}_p>$ increases more rapidly than $(N/Z)_0$ ⇒ fractionation.
- Comparison favors the stiffer asymmetry term.
- Similar conclusions obtained from comparisons of mirror nuclei.

SMF calculations





- Significant difference between the scaling parameters for primary and secondary distributions
- Similar though smaller effect observed for AMD calculation

- SMF theory assumes bulk decomposition within adiabatic spinodal.
- Calculations favor stiff asymmetry term.

Surface emission EES model

- Theoretically:

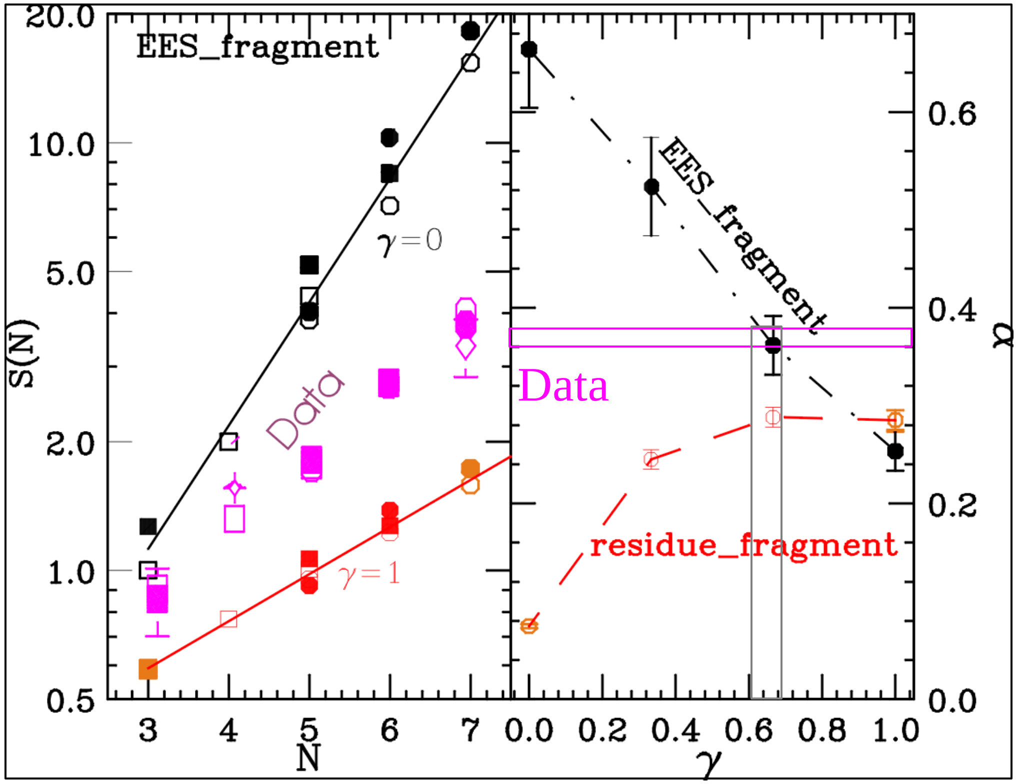
$$R_{21}(N,Z) \approx C\exp([-N\cdot\Delta s_n(\rho) - Z\cdot\Delta s_p(\rho) + e\Delta\Phi(Z_{tot} - Z)]/T)$$

- Separation energies depend on density dependence asymmetry term: $S(\rho) = 23.4\text{MeV} \bullet \left(\rho/\rho_0\right)^{\gamma}$
- Strong influence of symmetry term on fragment isotopic ratios.
  - trend is opposite to SMF and BUU-SMM results.

Use scaling to simplify representation:

$$S(N) = R_{21}(N,Z)/(\hat{\rho}_p)^Z$$

Tsang et al., PRL (2001)



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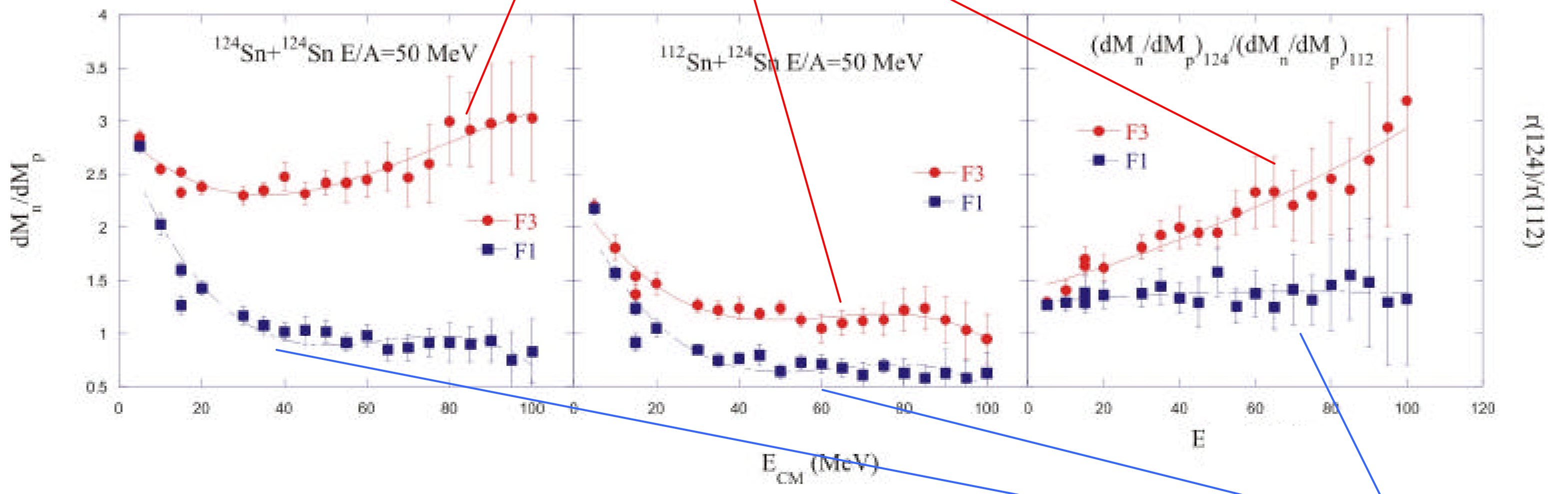
  - Dynamical AMD and statistical surface emission model (EES), however, predict that the asy-soft EOS leads to larger isoscaling parameters for central collisions than does the asy-stiff EOS.
  - ⇒Connection between fragment isoscaling parameters and the EOS is model dependent.
- All models agree that the asy-soft EOS leads to a larger preequilibrium neutron emission than does the asy-stiff EOS.

2^{nd} Observable n and p spectra

- Direct measurements of n vs. proton emission rates and transverse flows - Probes the pressure from asymmetry term at saturation density and below.
  - Clusters can be addressed within coalescence invariant analyses

soft asymmetry term

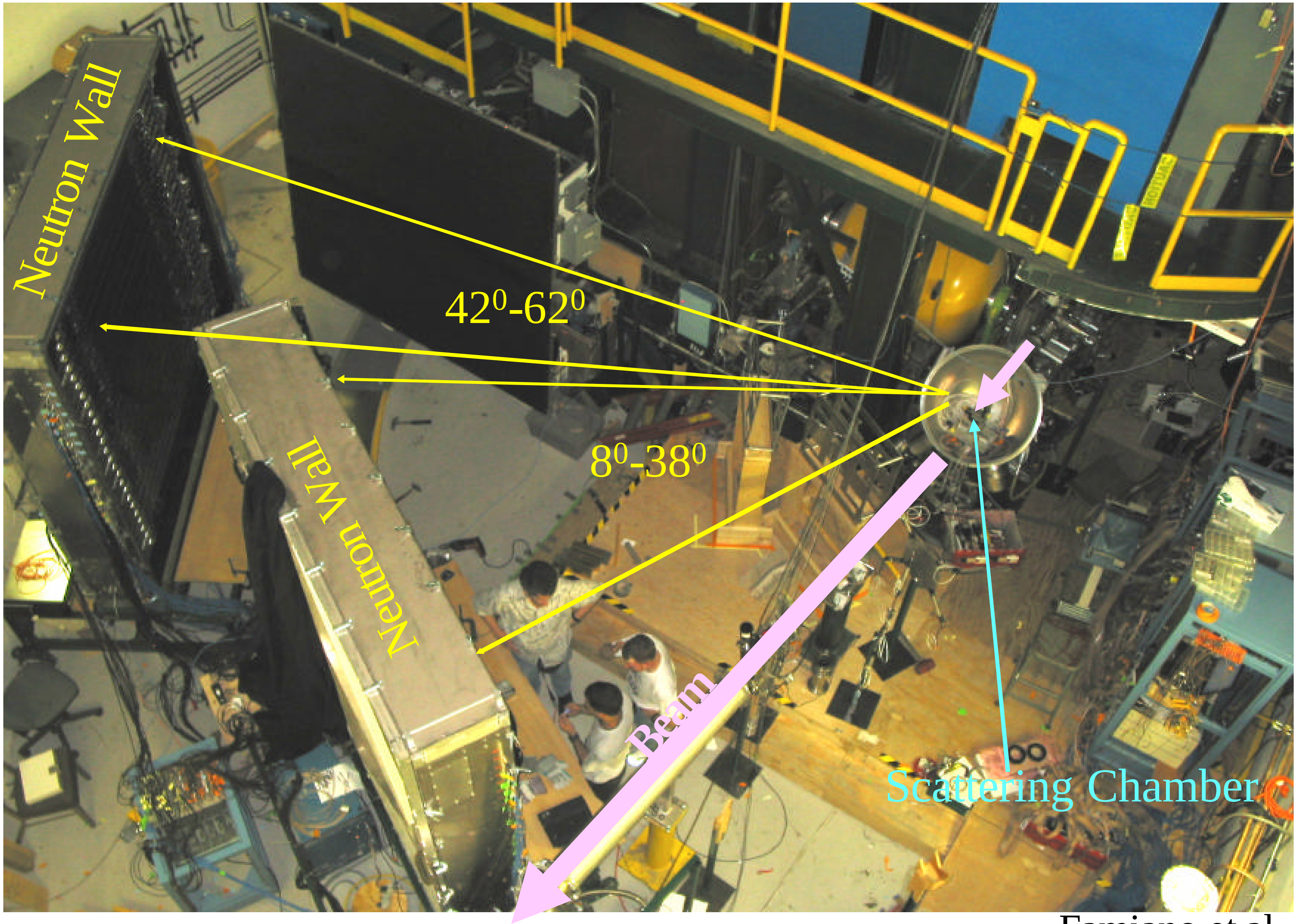
Bao-An Li et al., PRL 78, 1644 (1997)



stiff asymmetry term

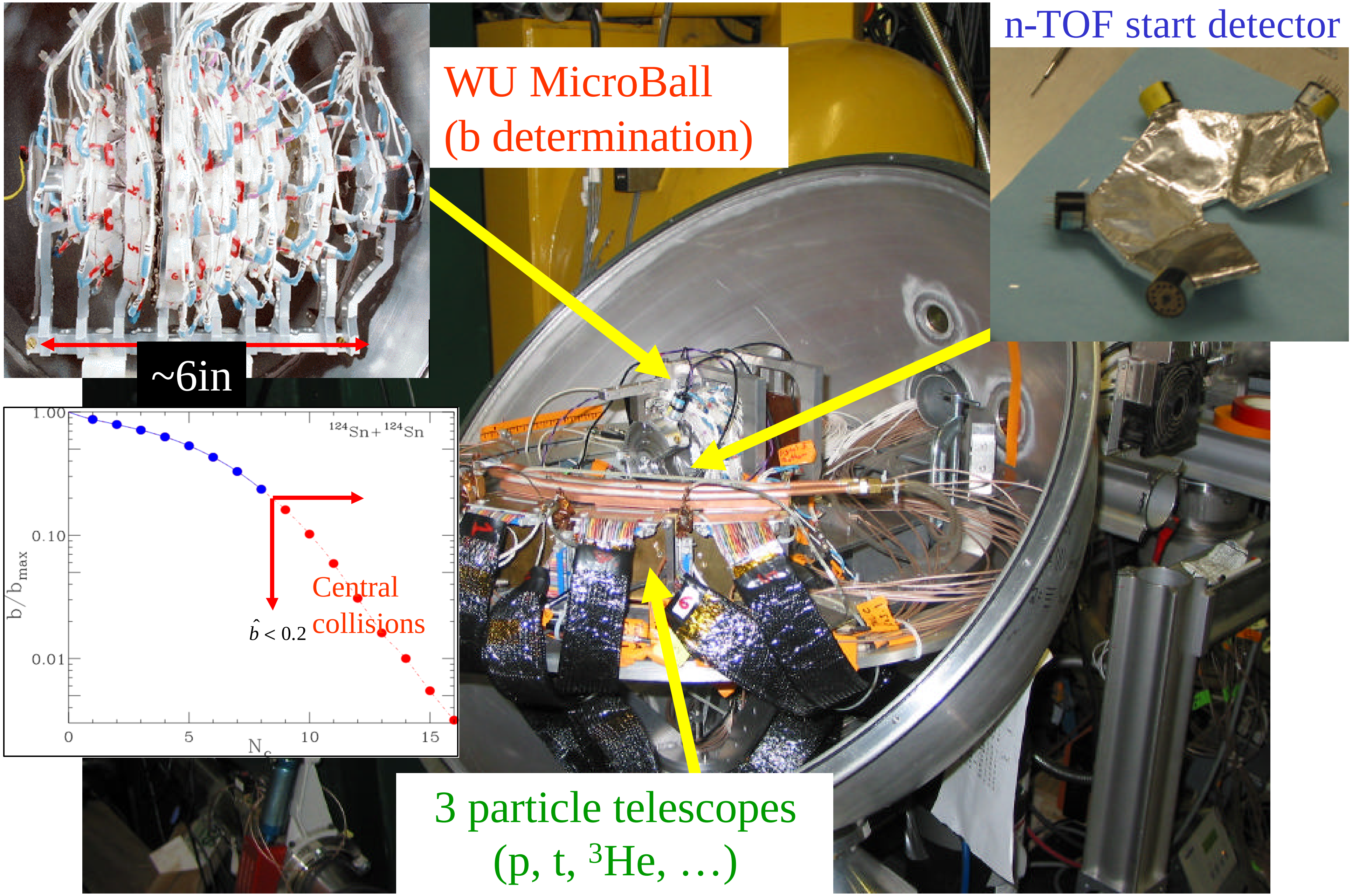
- Double ratio is less sensitive to energy calibration and neutron efficiency uncertainties.

n/p Experiment $^{124}Sn+^{124}Sn$; $^{112}Sn+^{112}Sn$; E/A=50 MeV

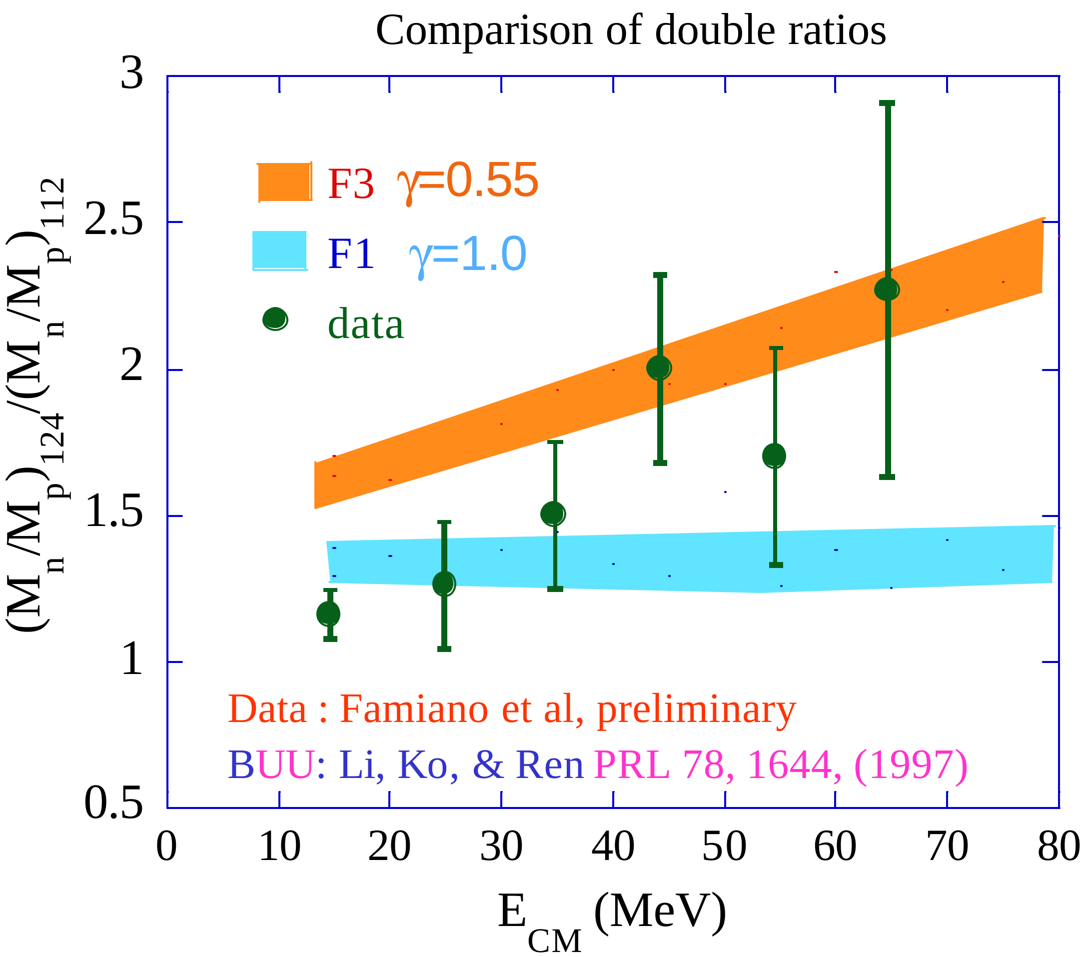


Famiano et al

P-detection: Scattering Chamber



Coalescence invariant spectra

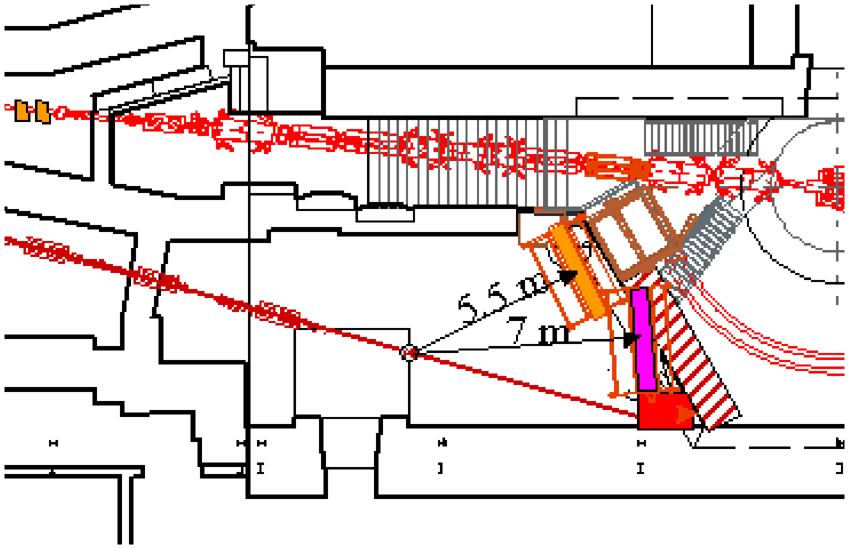


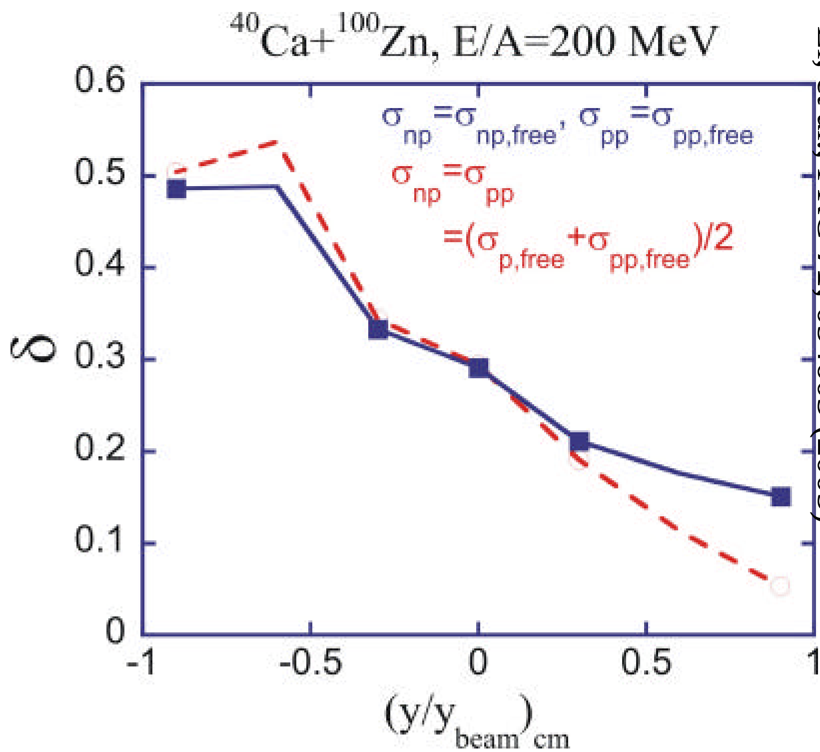
- Comparisons neglect
  - momentum dependence of mean field potential.
  - Uncertainties due to isospin dependent NN cross sections

- Coalescence invariant analysis decreases sensitivity to cluster production model uncertainties:
  - Approach consistent with successful flow analyses.
  - Permits accurate comparisons to theory at E/A>30 MeV

Future plans: S2 reconfiguration

- A program of neutron measurements in the S2 vault was favorably reviewed by the program advisory committee at its latest meeting.
- Collaboration WMU (Famiano), MSU (Lynch, Tsang) and WU (Sobotka, Charity).
- Objectives are to constrain S(ρ), $m^*_{n,}$, m^*_p, σ_{pp} and σ_{np}.





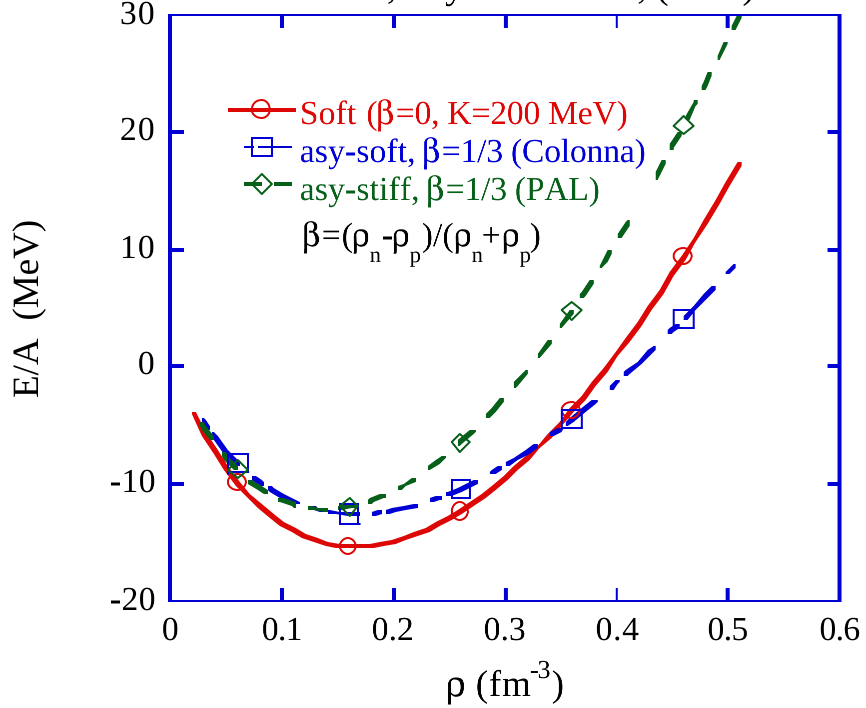
•Li, et al., PRC **71**, 054603 (2005)

Summary

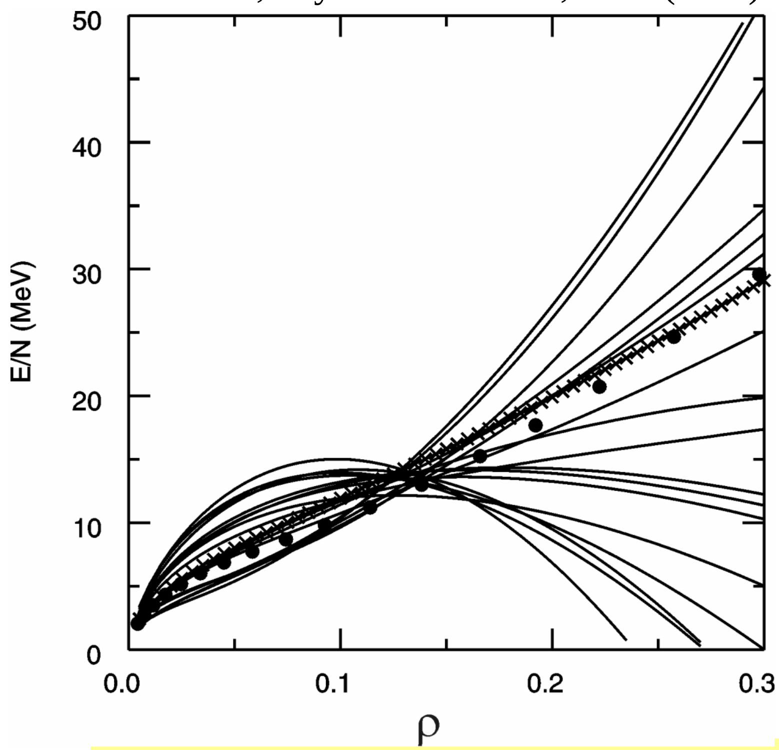
- Dependence of fragment isoscaling parameters on asymmetry term is model dependent.
- Comparisons of neutron and proton observables appear to be very promising.
- We expect that three quantities need to be constrained:
  - density dependence: started
  - momentum-isospin dependence: started
  - isospin dependent in-medium cross sections: next
- We have promising observables to constrain these.
- Other factors:
  - uncertainty in the impact parameter.
  - role of fluctuations.

Isospin Dependence of the Nuclear Equation of State

PAL: Prakash et al., PRL 61, (1988) 2518.
Colonna et al., Phys. Rev. C57, (1998) 1410.



Brown, Phys. Rev. Lett. 85, 5296 (2001)



$$E/A\,(\rho,\beta) = E/A\,(\rho,0) + \delta^2\cdot S(\rho)$$

$$\delta = (\rho_n - \rho_p)/(\rho_n + \rho_p) = (N-Z)/A$$

- The density dependence of asymmetry term is largely unconstrained.
- Pressure, i.e. EOS is rather uncertain even at ρ_0.