# Investigating dense matter relevant to supervovae and neutron stars

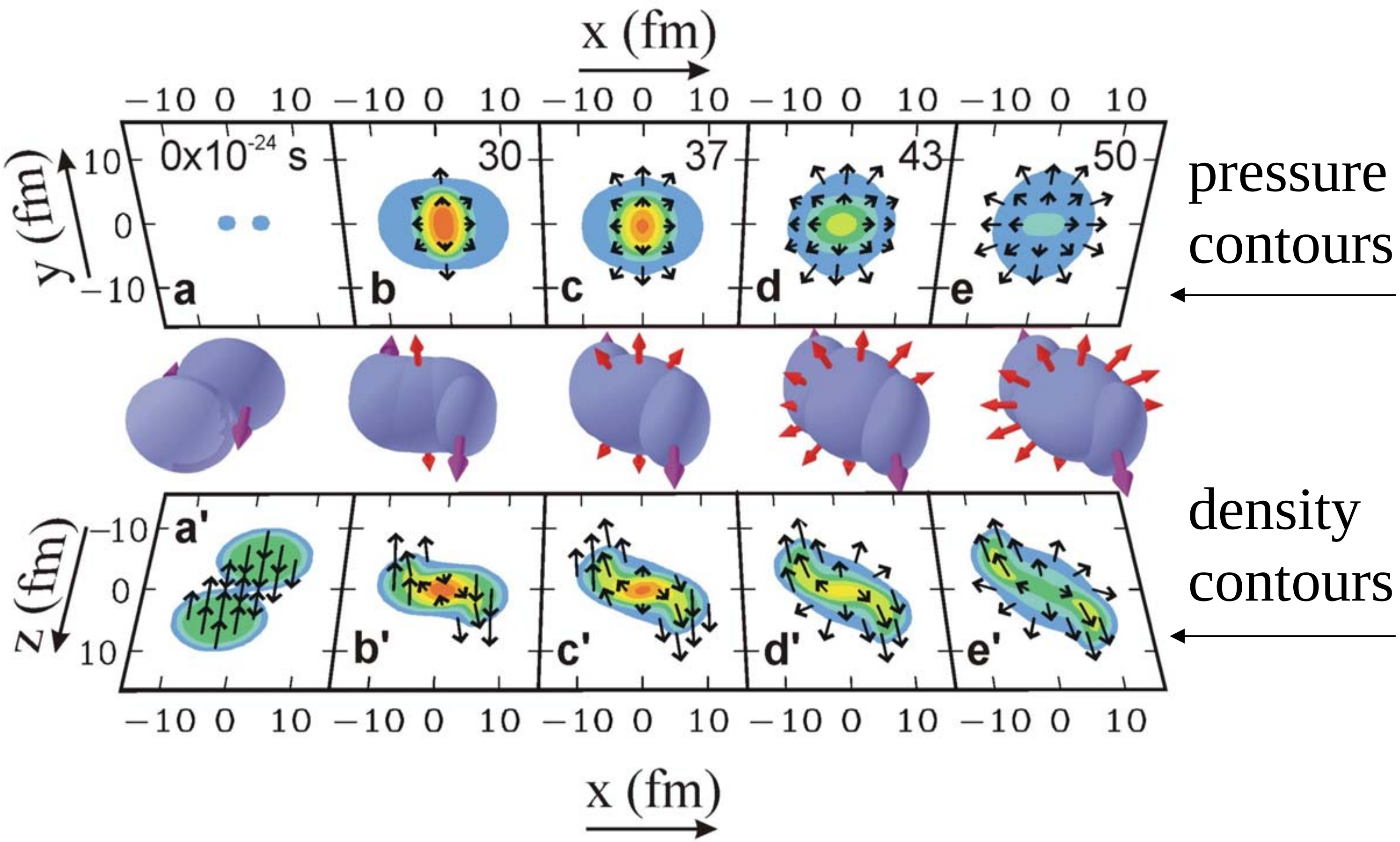
***Tianxiao Liu, Manyee Tsang, Michael Famiano, Lijun Shi, Pawel Danielewicz, Konrad Gelbke, Xiaodong Liu, William Lynch, Wanpeng Tan, Giuseppe Verde, Andreas Wagner, Hushan Xu ,Luc Beaulieu, Brian Davin, Romualdo de Souza, Yves Larochelle, Thomas Lefort, Riccardo Yanez, Victor Viola, Robert Charity, Lee Sobotka, William Friedman***

## 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)

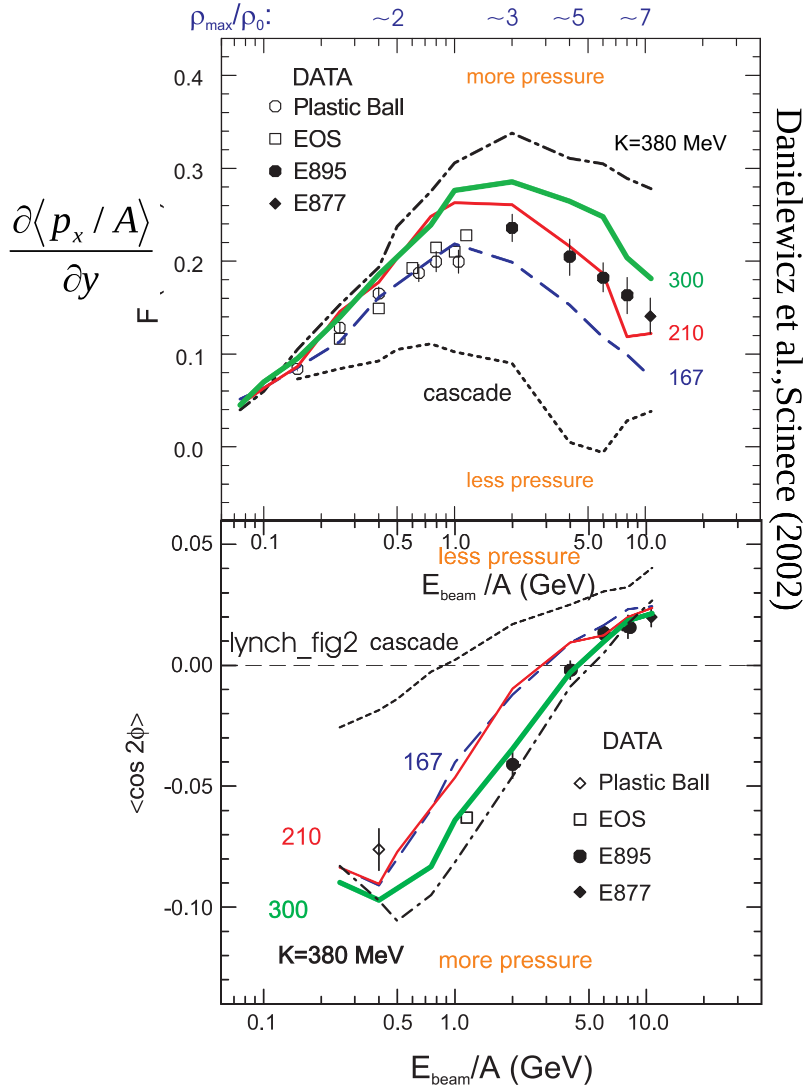
# Pressure and collective flow dynamics



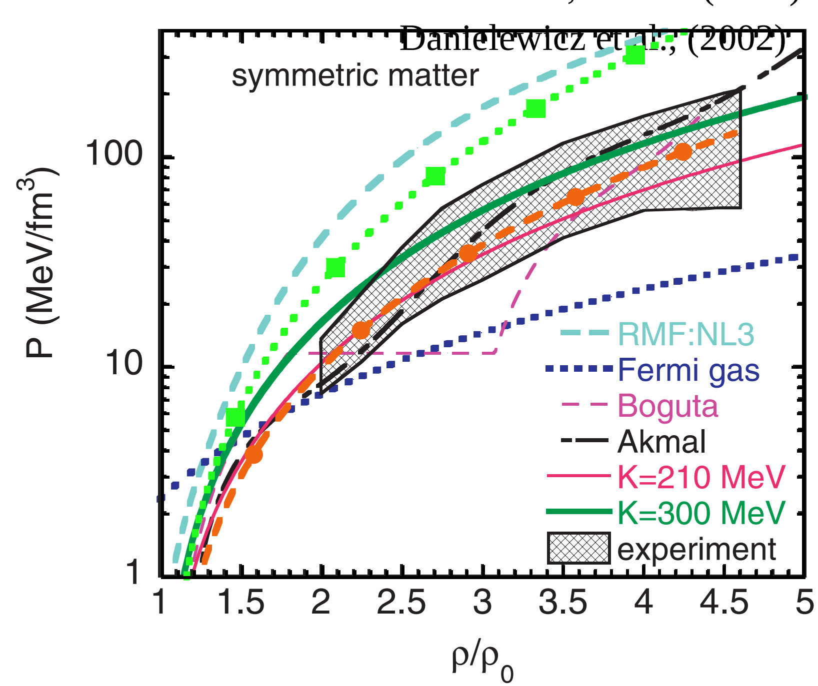

- The blocking by the spectator matter provides a clock with which to measure the expansion rate.

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

Observables: transverse, elliptical flow.




Danielewicz et al.,Scinece (2002)

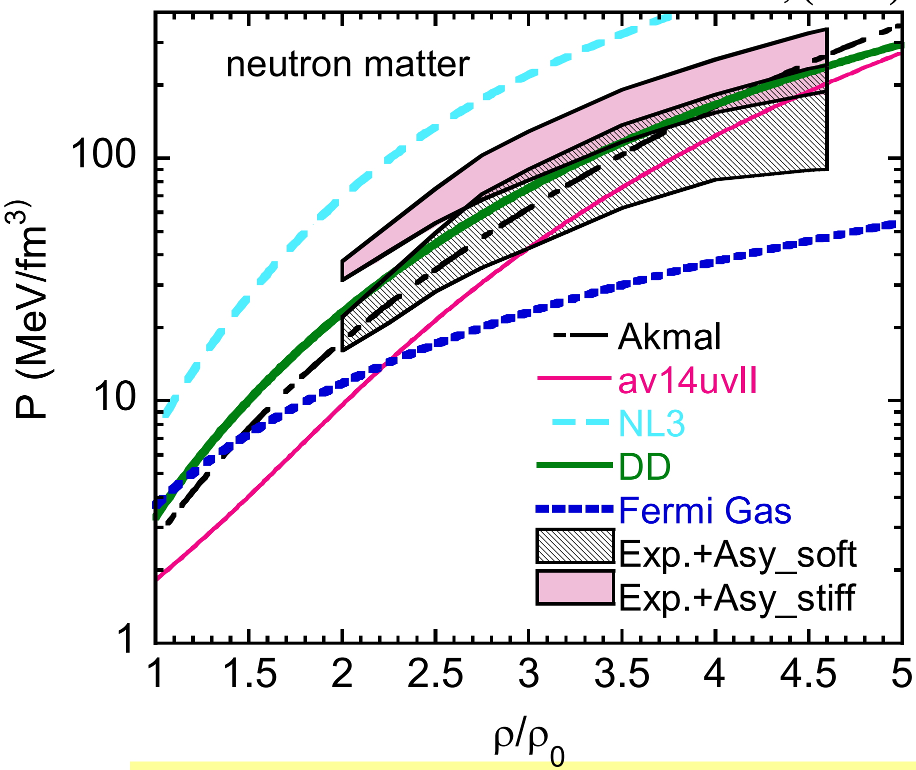



- Additional measurements were needed to constrain:
  - Momentum dependence of mean fields.
  - Cross-sections due to residual interactions.

# 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:

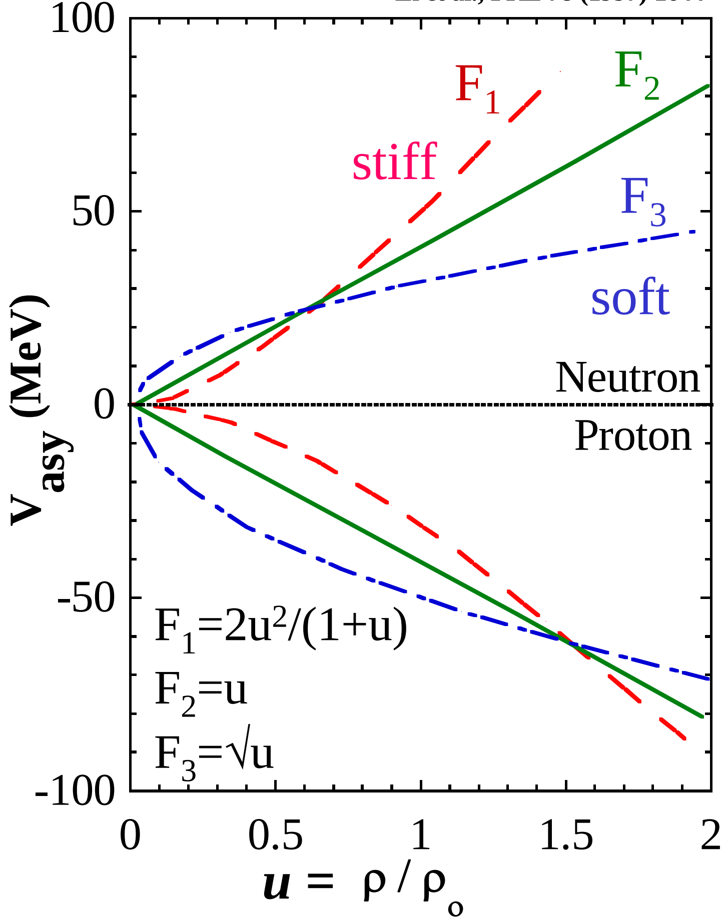
$$S(\rho) = S_{kin}(\rho) + S_{\text{int}}(\rho);$$

$$S_{kin}(\rho) \approx \frac{1}{3} E_{Fermi}(\rho) \approx 13 \cdot (\rho / \rho_0)^{2/3} MeV$$

- 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

Li et al., PRL 78 (1997) 1644



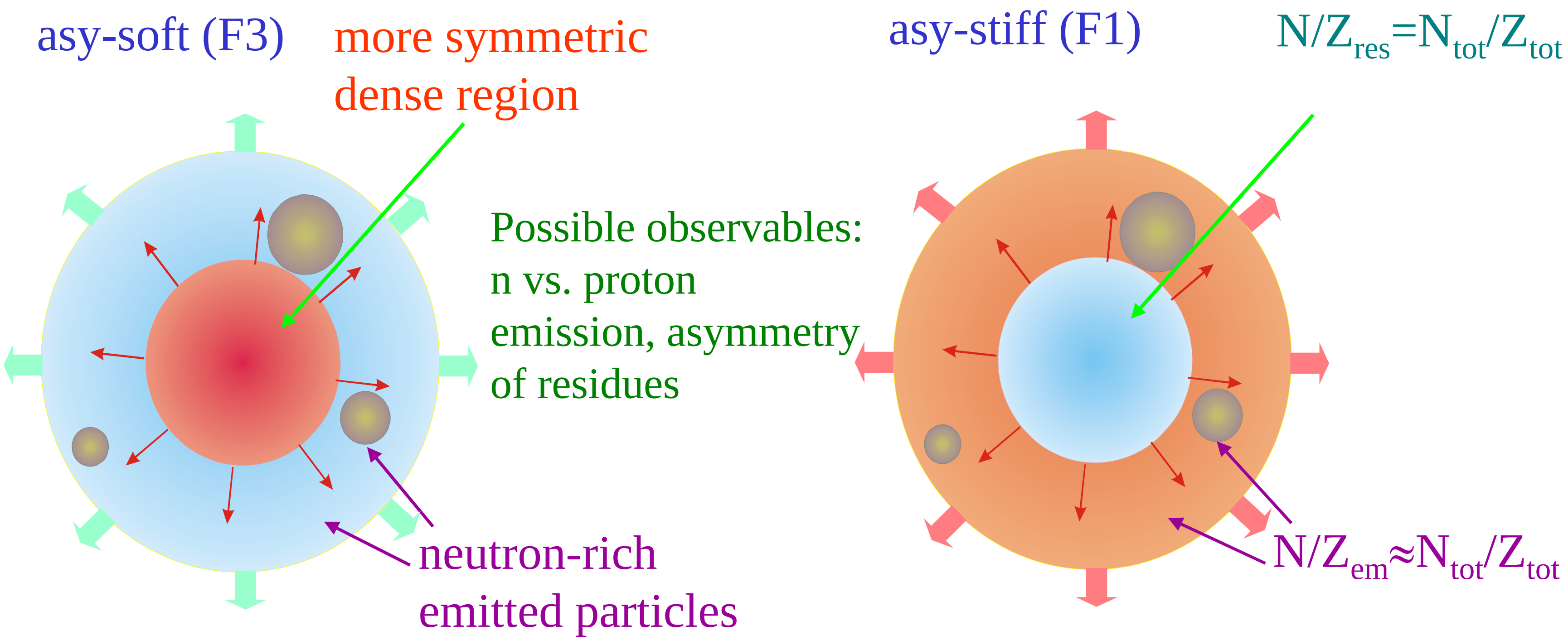

- Sign of mean field opposite for protons and neutrons.
- Shape is influenced by incompressibility.

Quantities sensitive to asymmetry term: $S(\rho) \approx C_{sym}(\rho / \rho_0)^\gamma$

- At sub-saturation densities
  - Isospin diffusion
    - Tsang, PRL **92**, 062701 (2004)
    - B.Li, JINA (2005) 0.7<γ<1.1
  - Asymmetry of bound residues.
  - Prequilibrium n vs. p emission.
  - Transverse flow (n.vs.p).
  - Difference between neutron and proton matter radii (TJLab future experiment).
- At supra-saturation densities
  - Isospin dependencies of pion production.
  - Transverse flow (n.vs.p).

# Central collisions: isospin fractionation

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

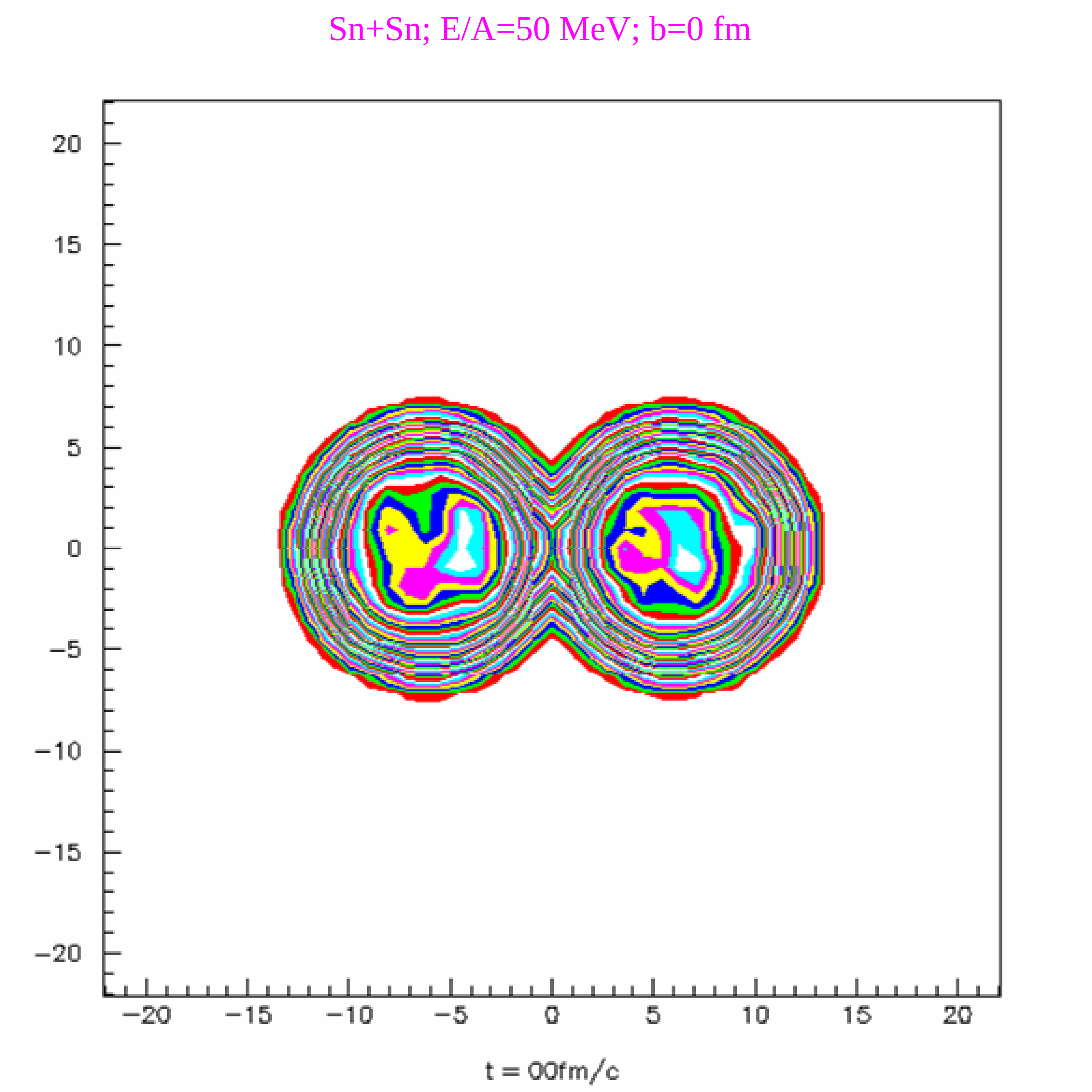



BUU predictions for central $^{124}Sn+\,^{124}Sn$ ($N_0/Z_0=1.48$) collisions at E/A=50 MeV

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

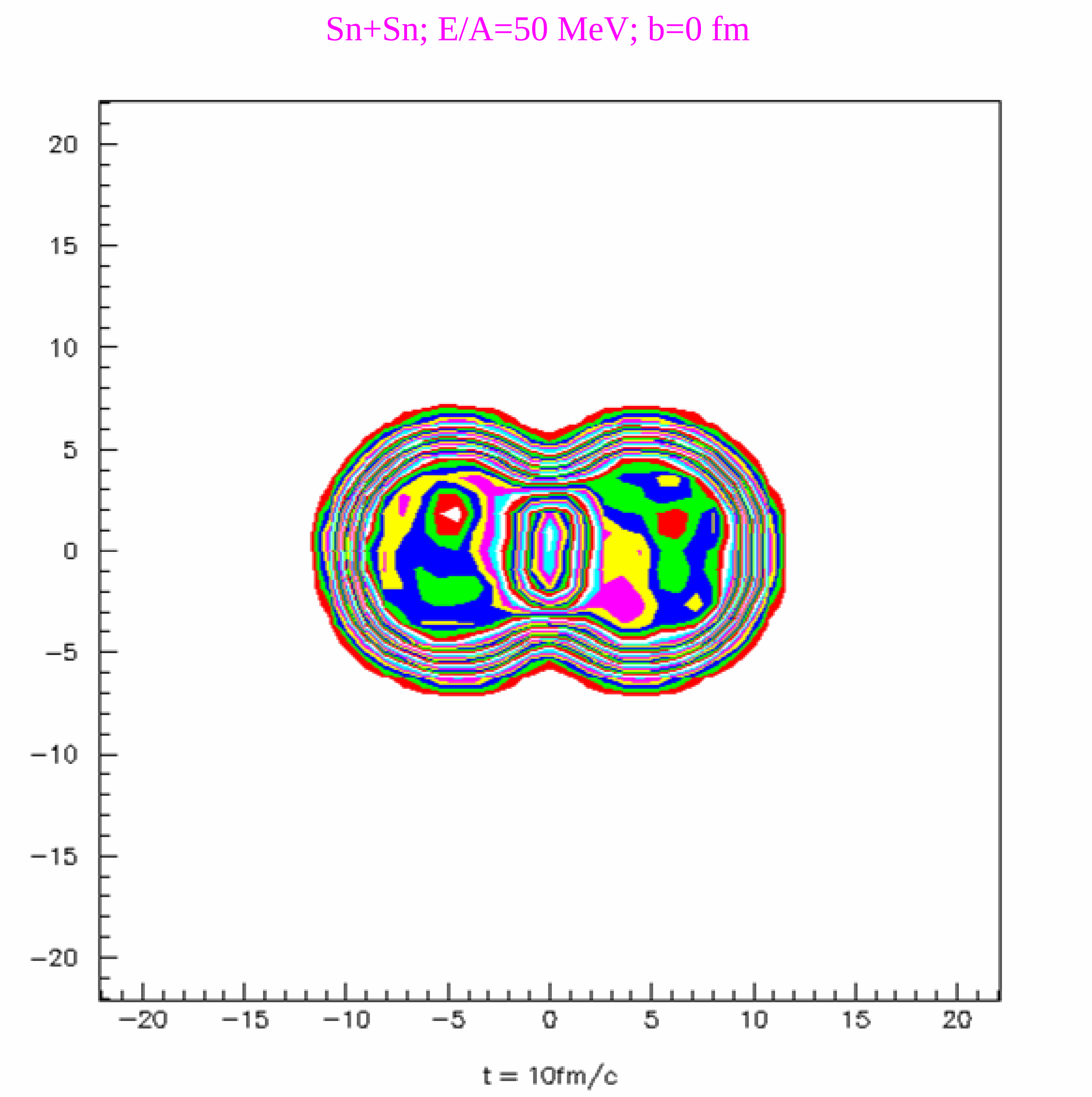
| EOS | Residue N/Z |
|---|---|
| F_1 (asy-stiff) | 102/71=1.44 |

*Micha Kilburn*
*2003*



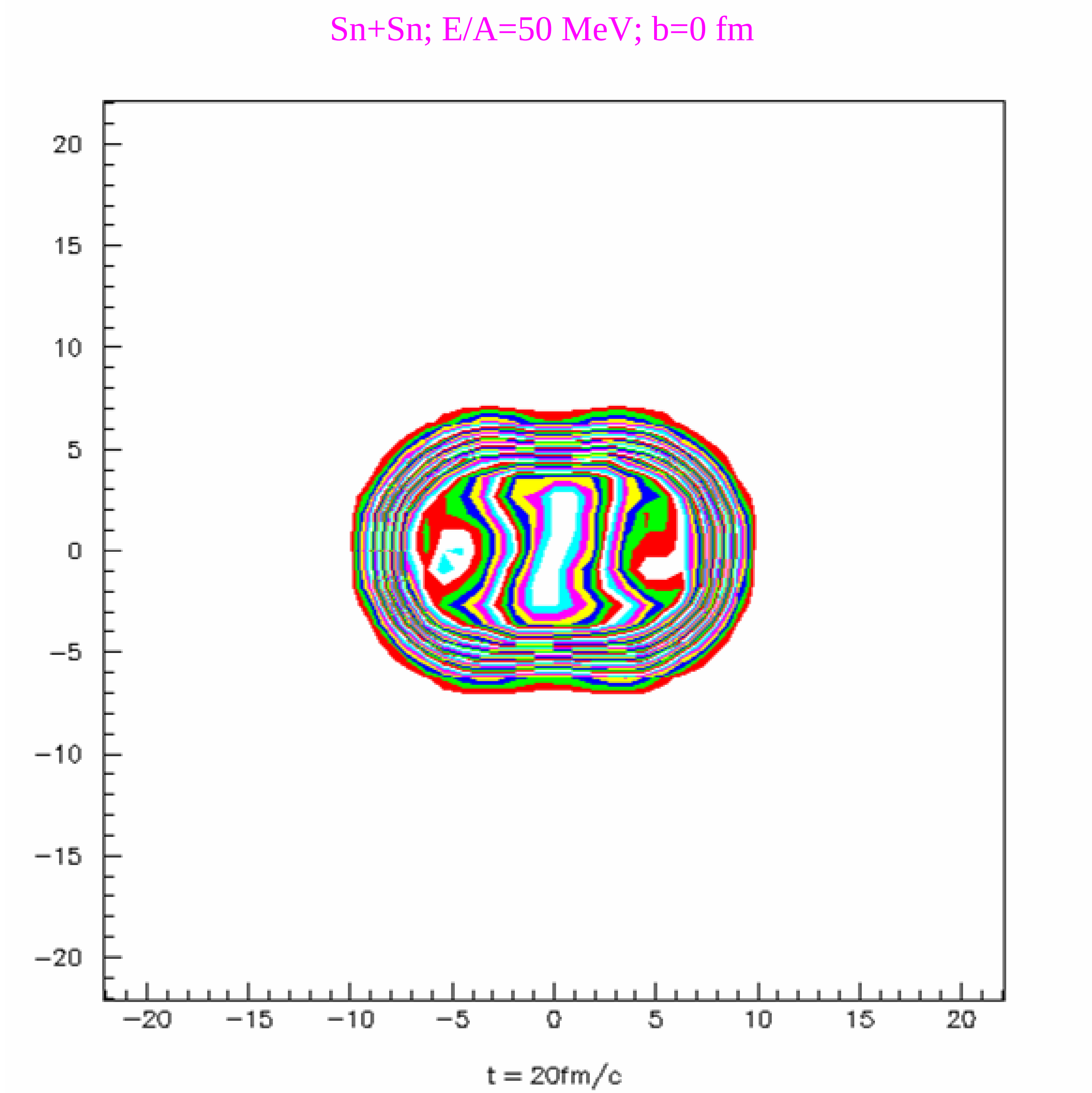

# *BUU: Transport theory simulations*

*Micha Kilburn*
*2003*




# *BUU: Transport theory simulations*

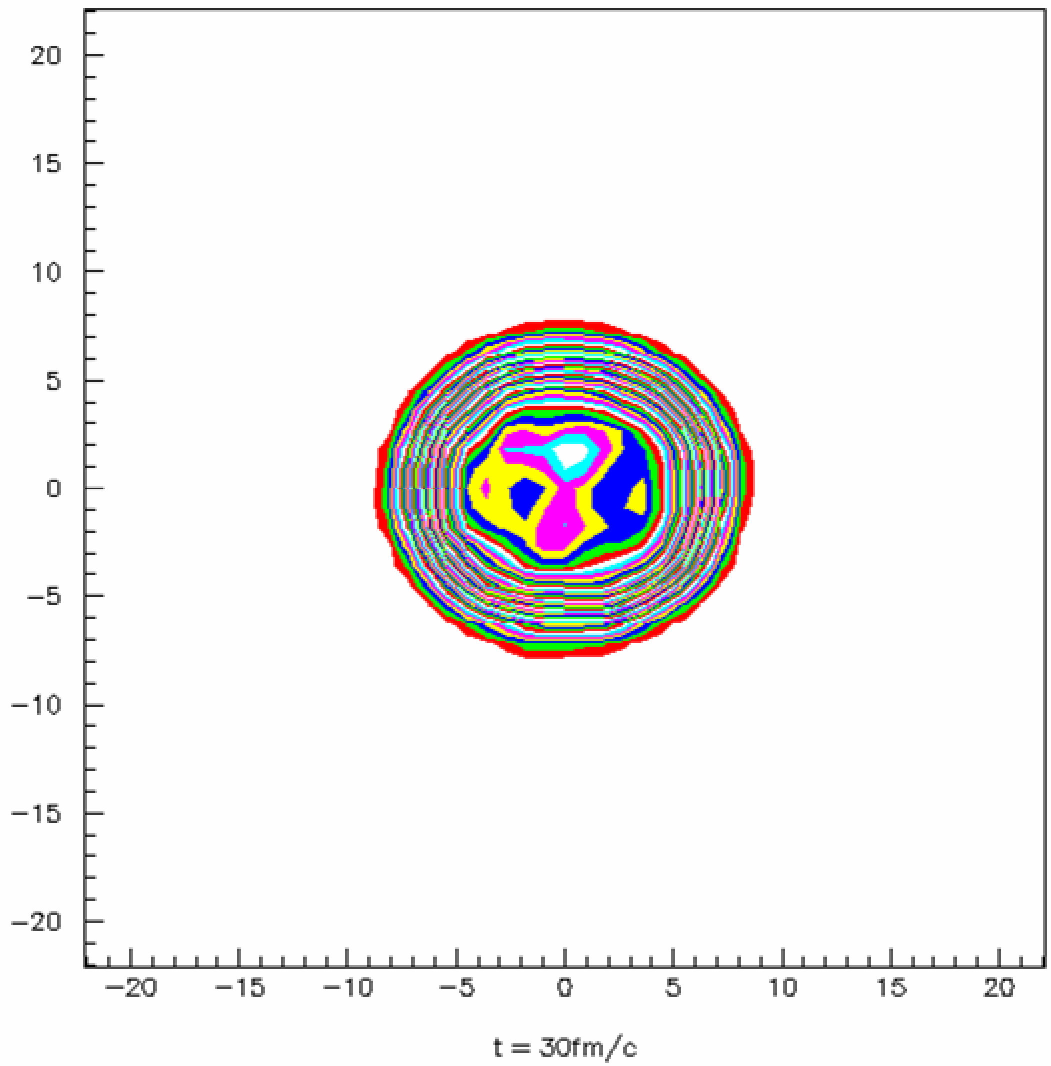
*Micha Kilburn*
*2003*




# *BUU: Transport theory simulations*

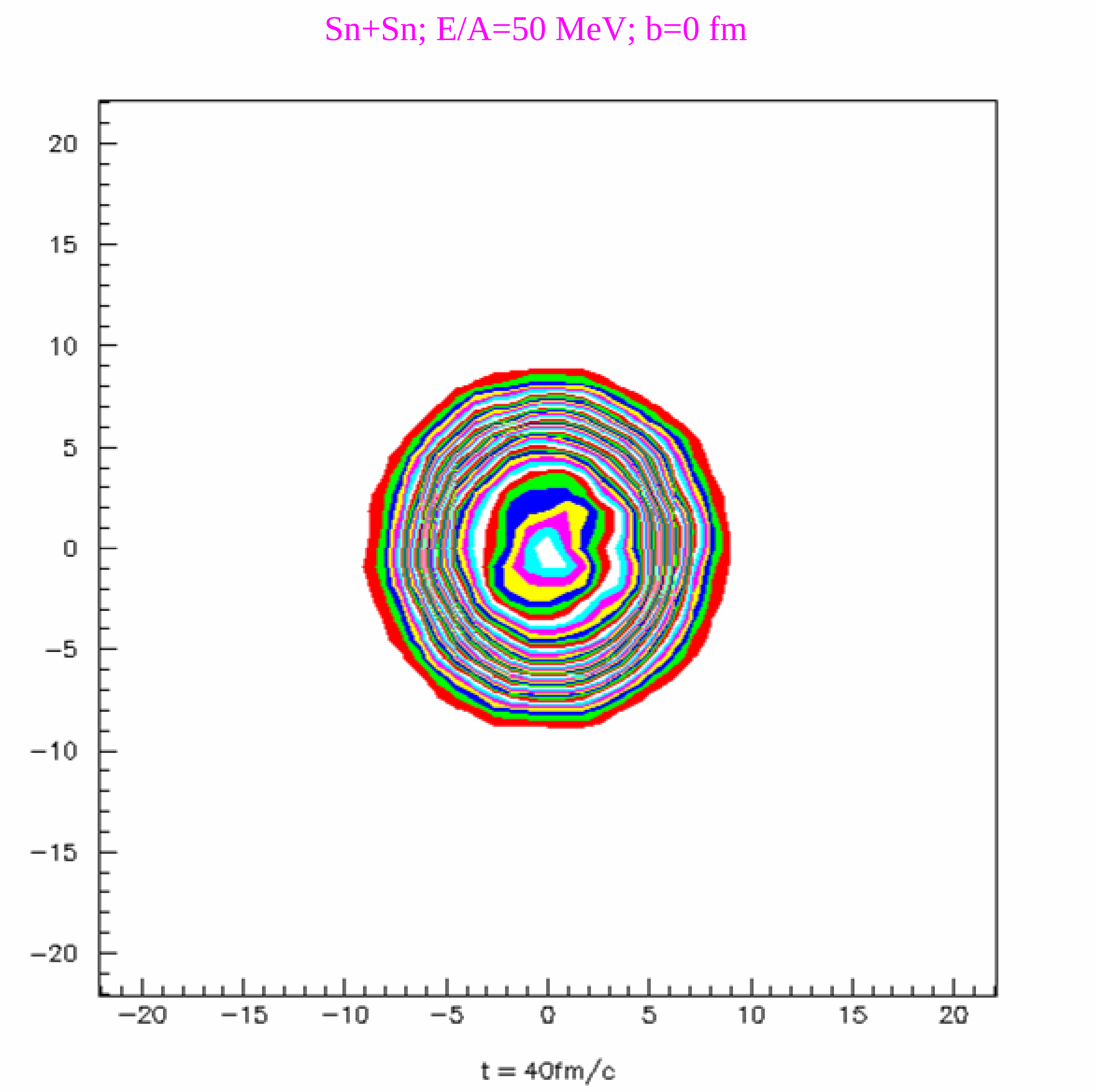
***Micha Kilburn***
***2003***

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



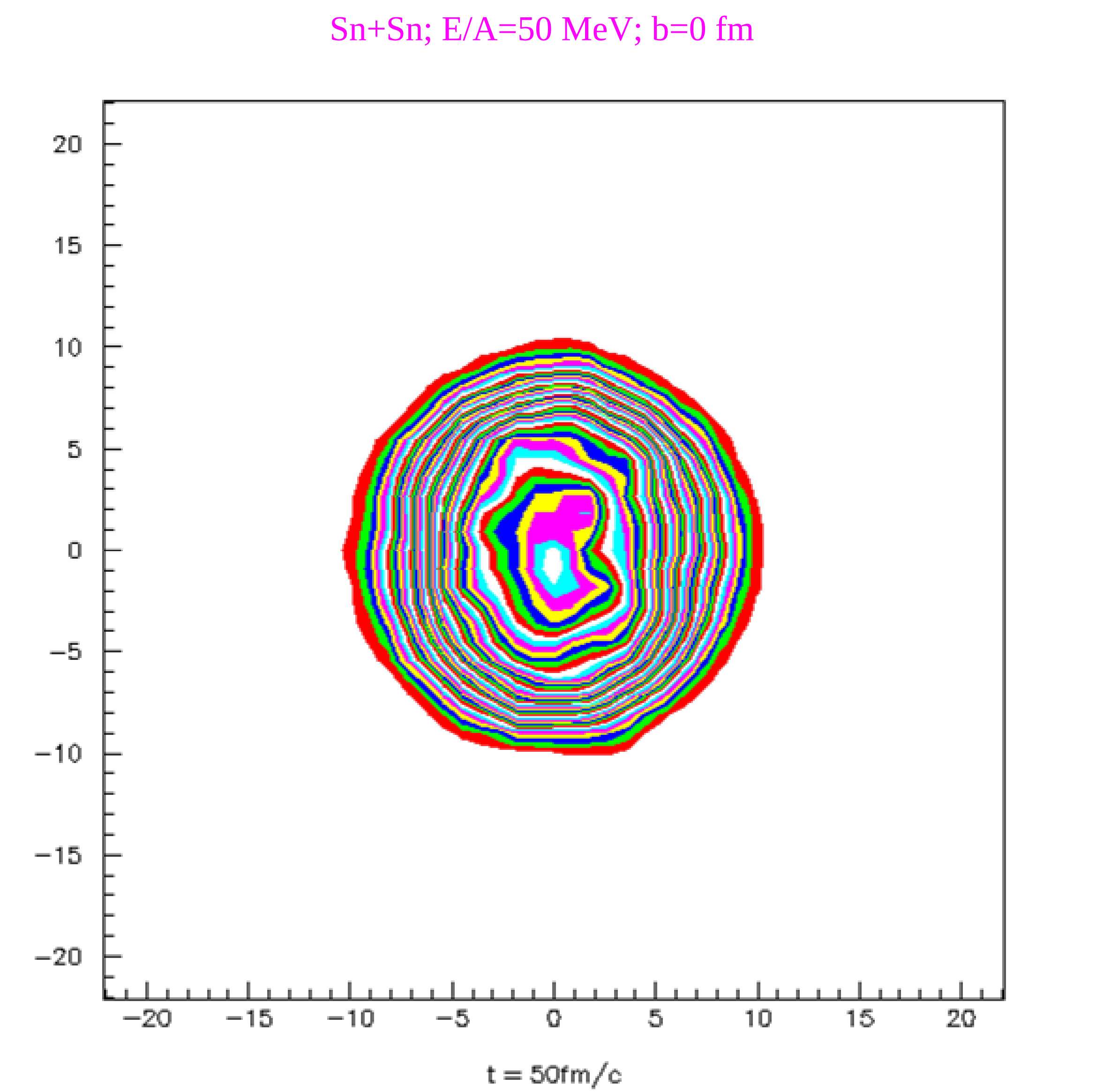

*BUU: Transport theory simulations*

*Micha Kilburn*
*2003*



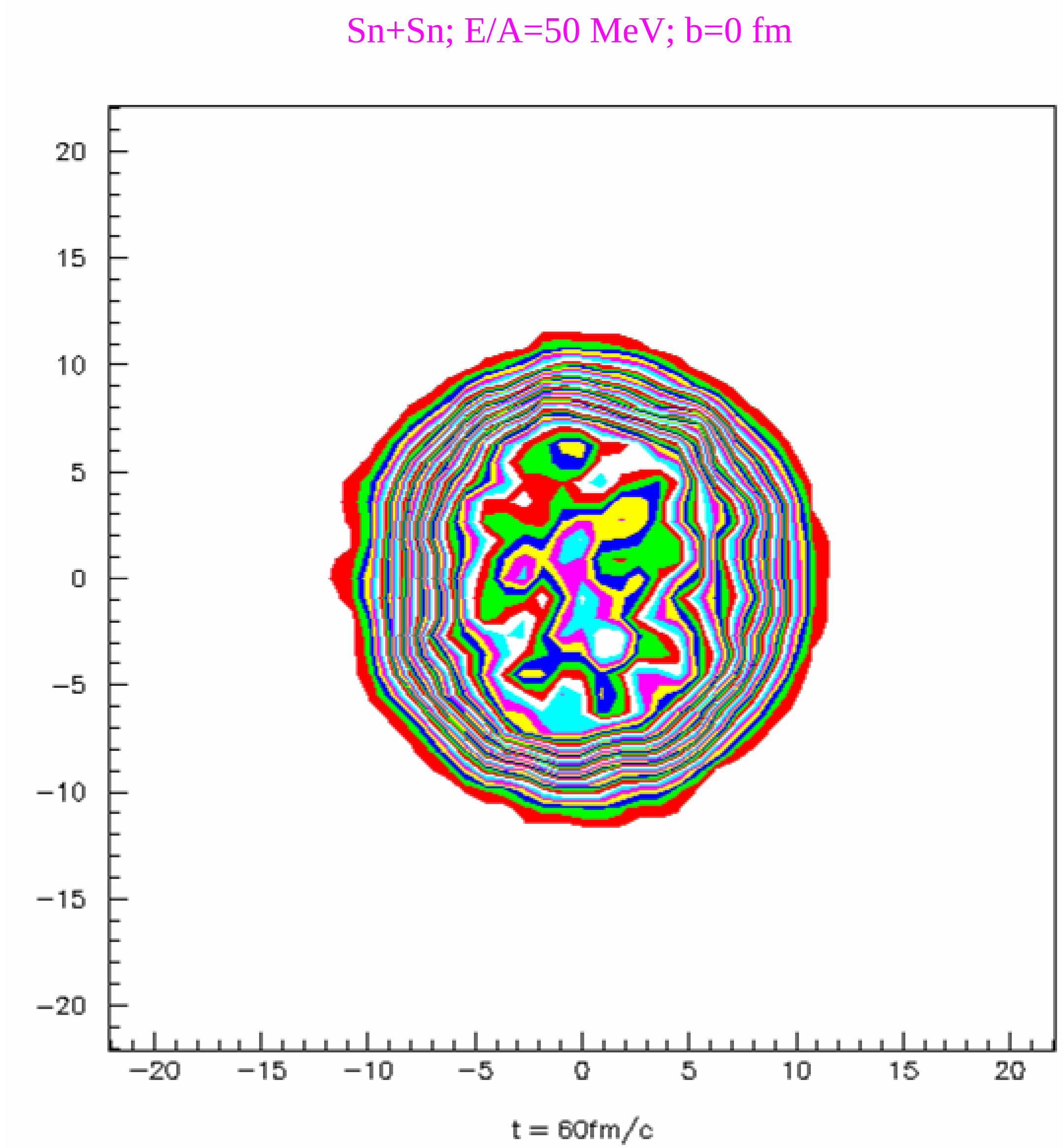

*BUU: Transport theory simulations*

Micha Kilburn
2003



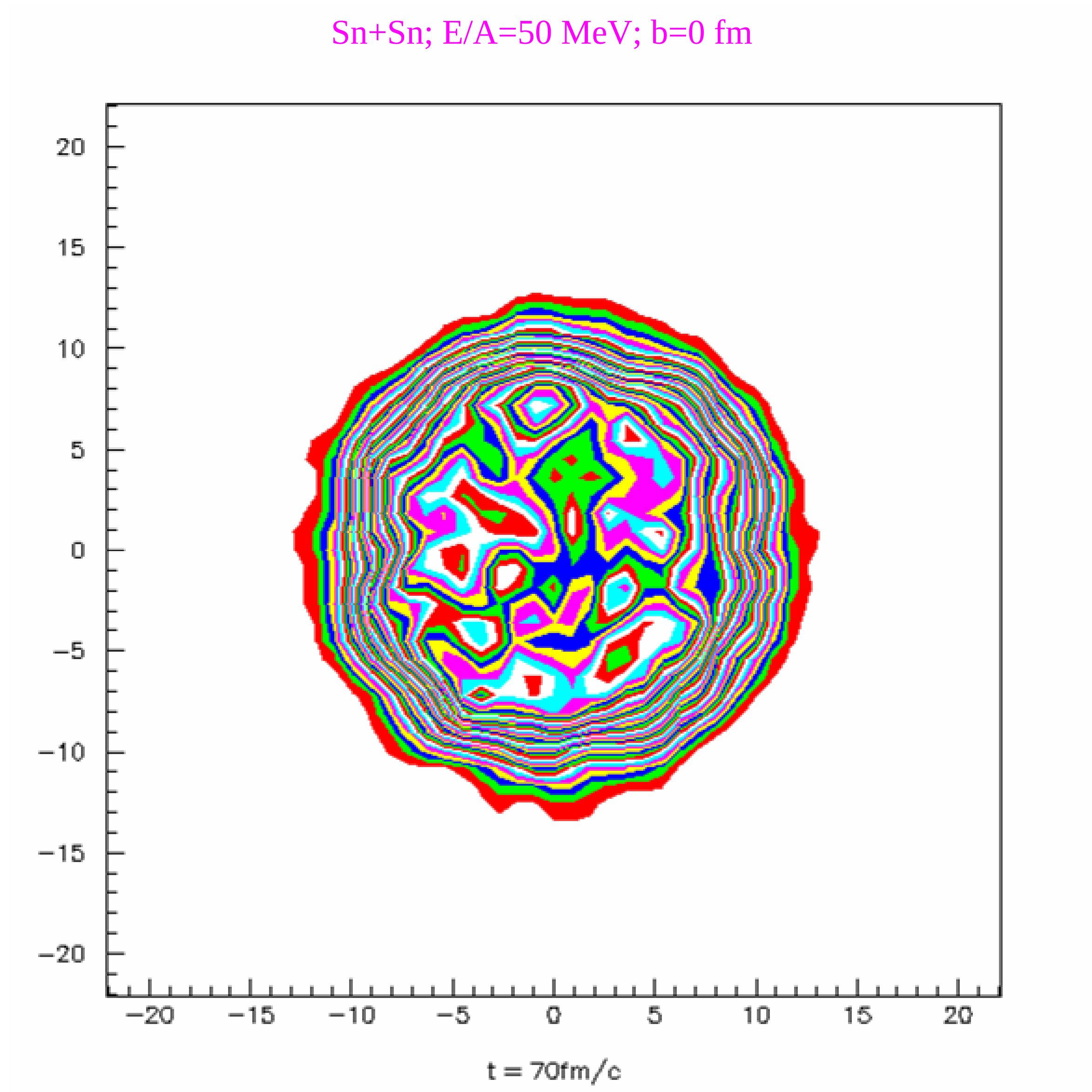

# BUU: Transport theory simulations

*Micha Kilburn*
*2003*



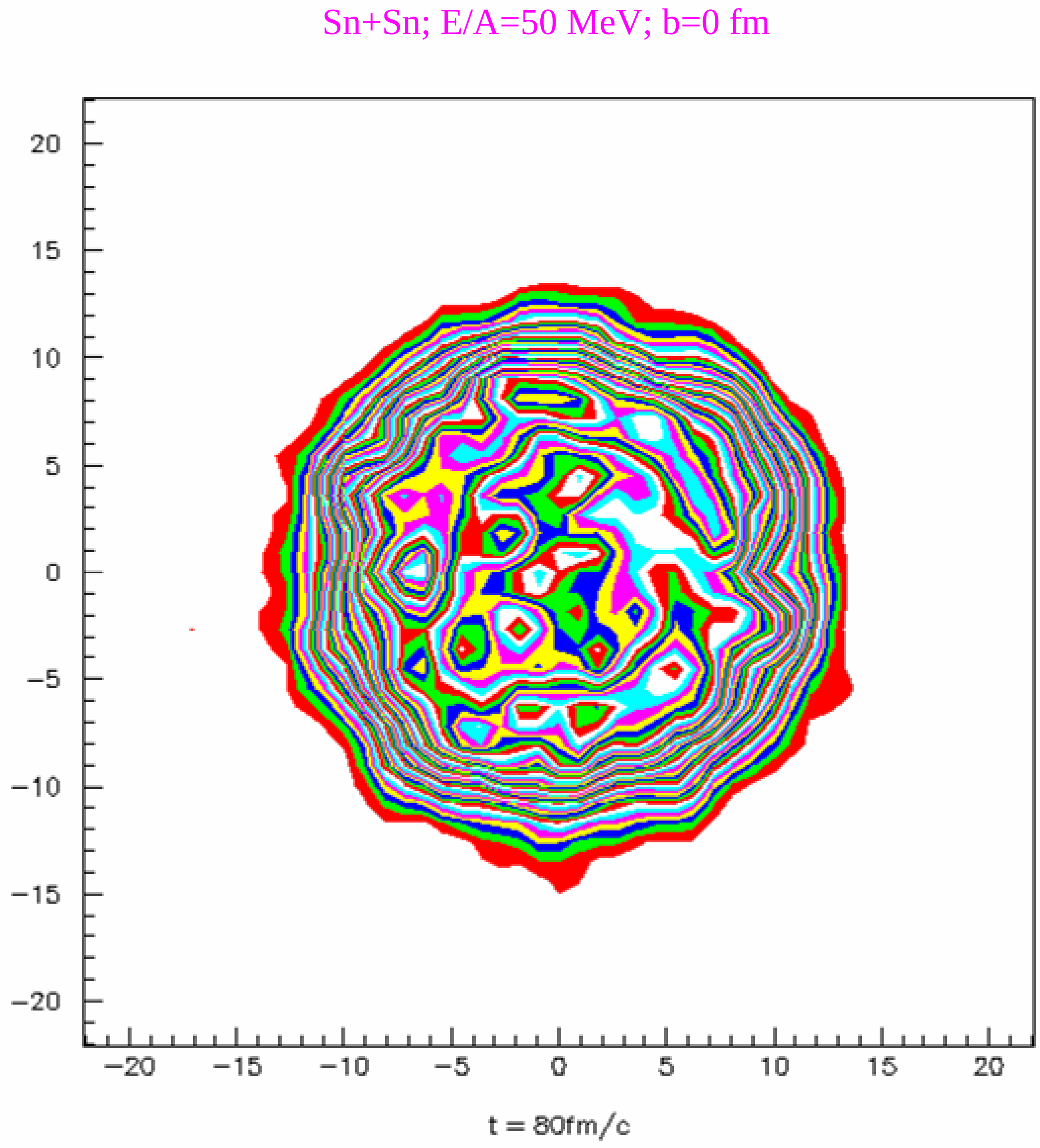

# *BUU: Transport theory simulations*

*Micha Kilburn*
*2003*



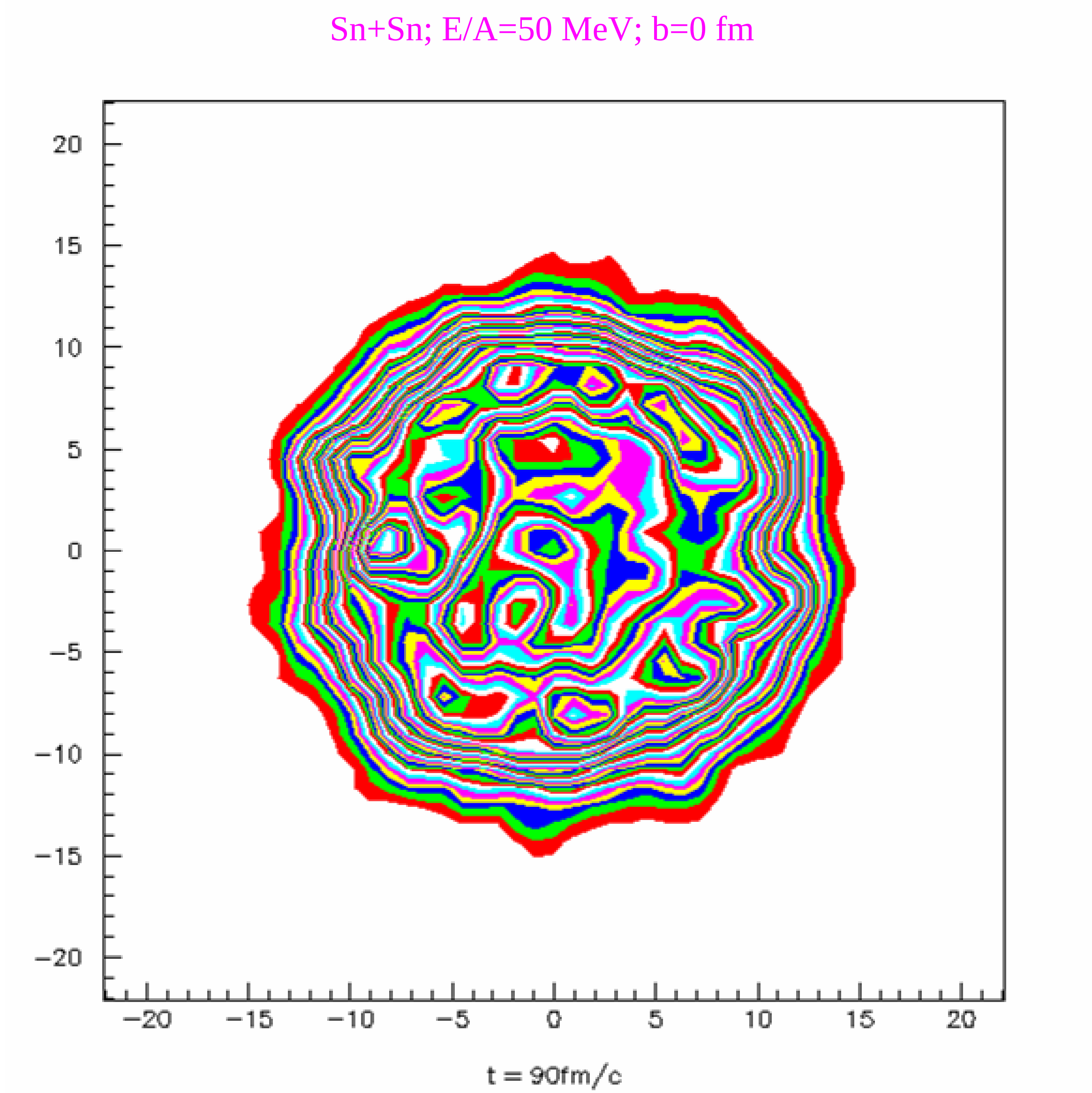

# *BUU: Transport theory simulations*

*Micha Kilburn 2003*



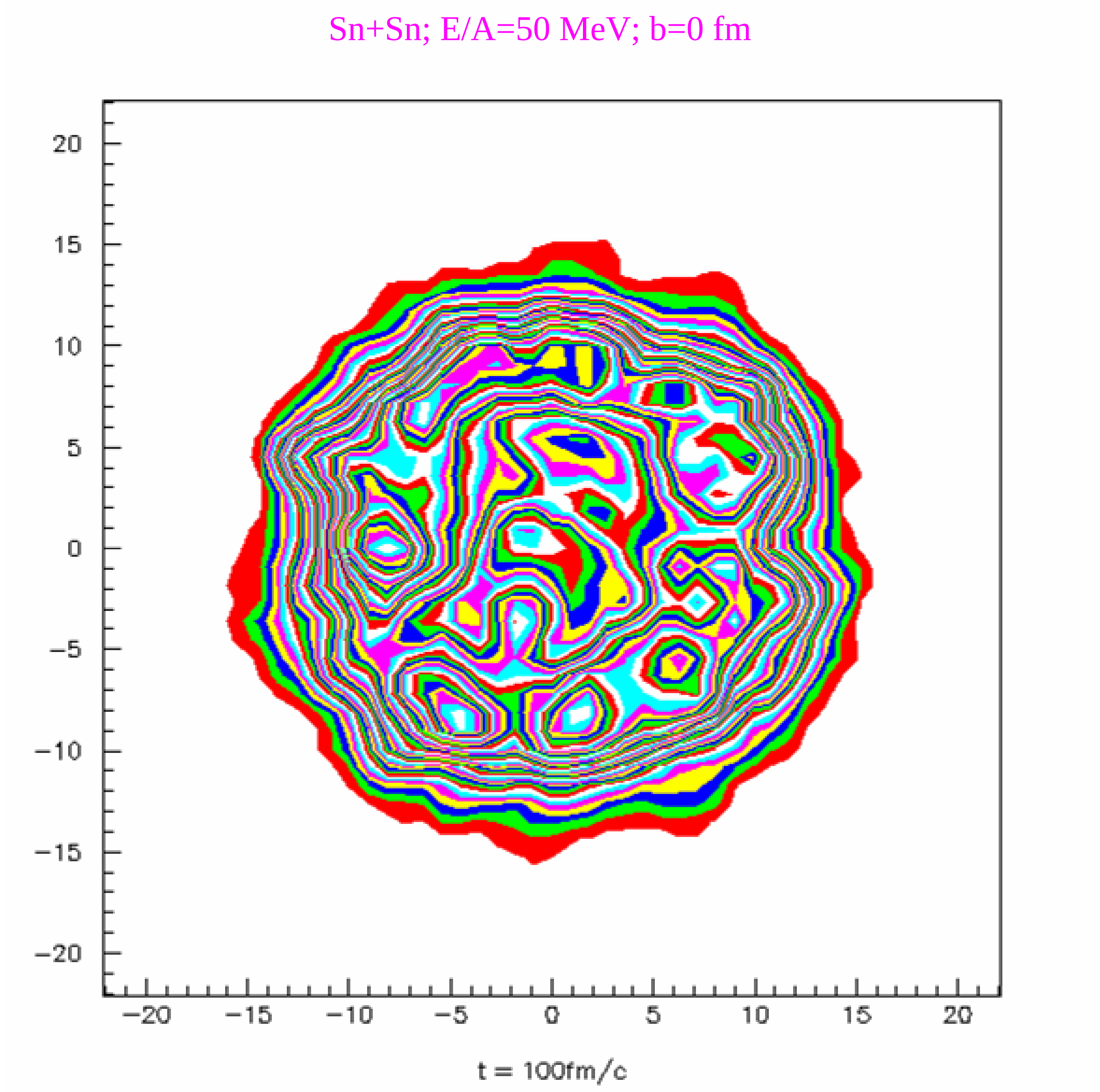

# *BUU: Transport theory simulations*

*Micha Kilburn*
*2003*



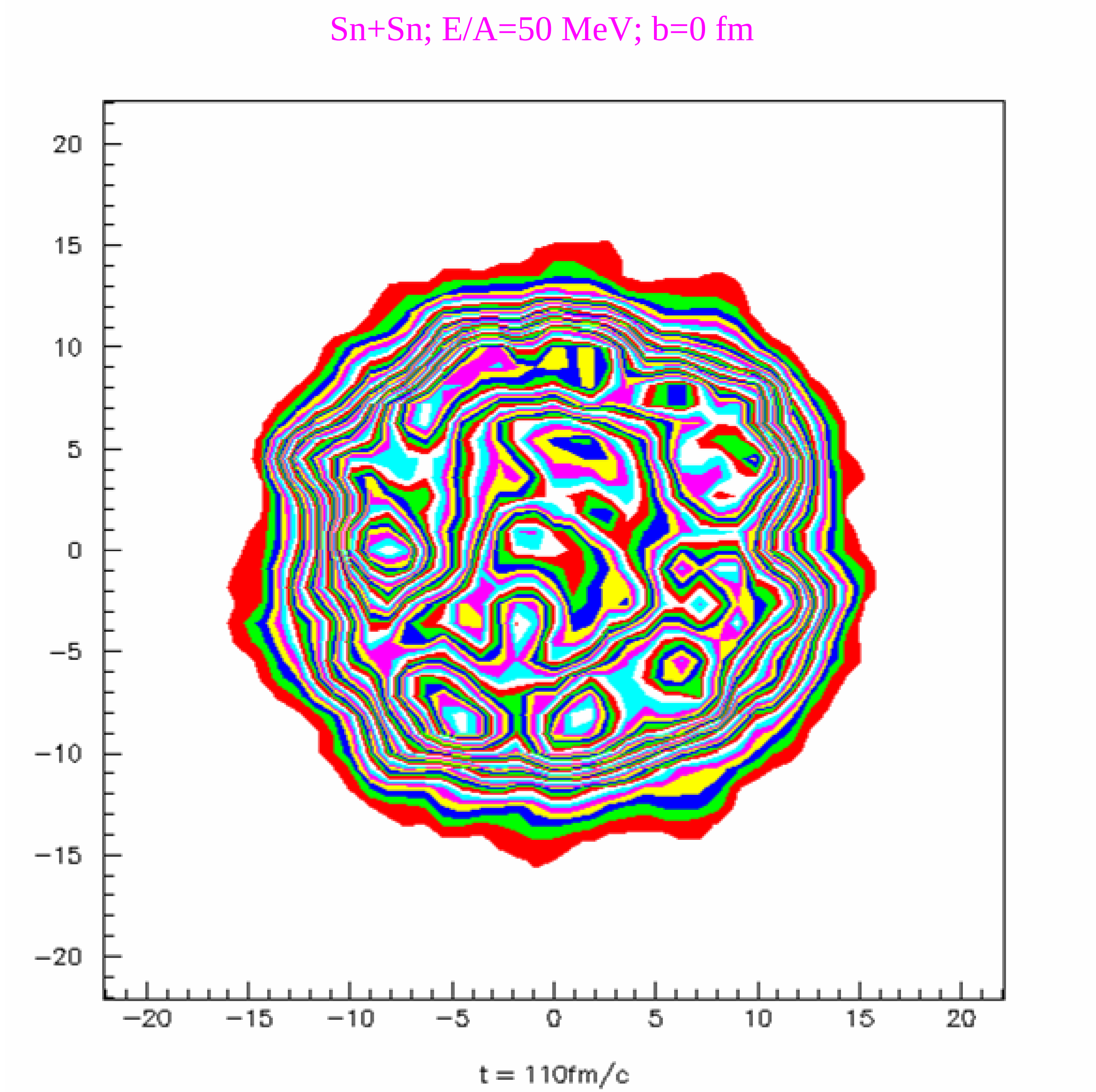

# *BUU: Transport theory simulations*

*Micha Kilburn*
*2003*



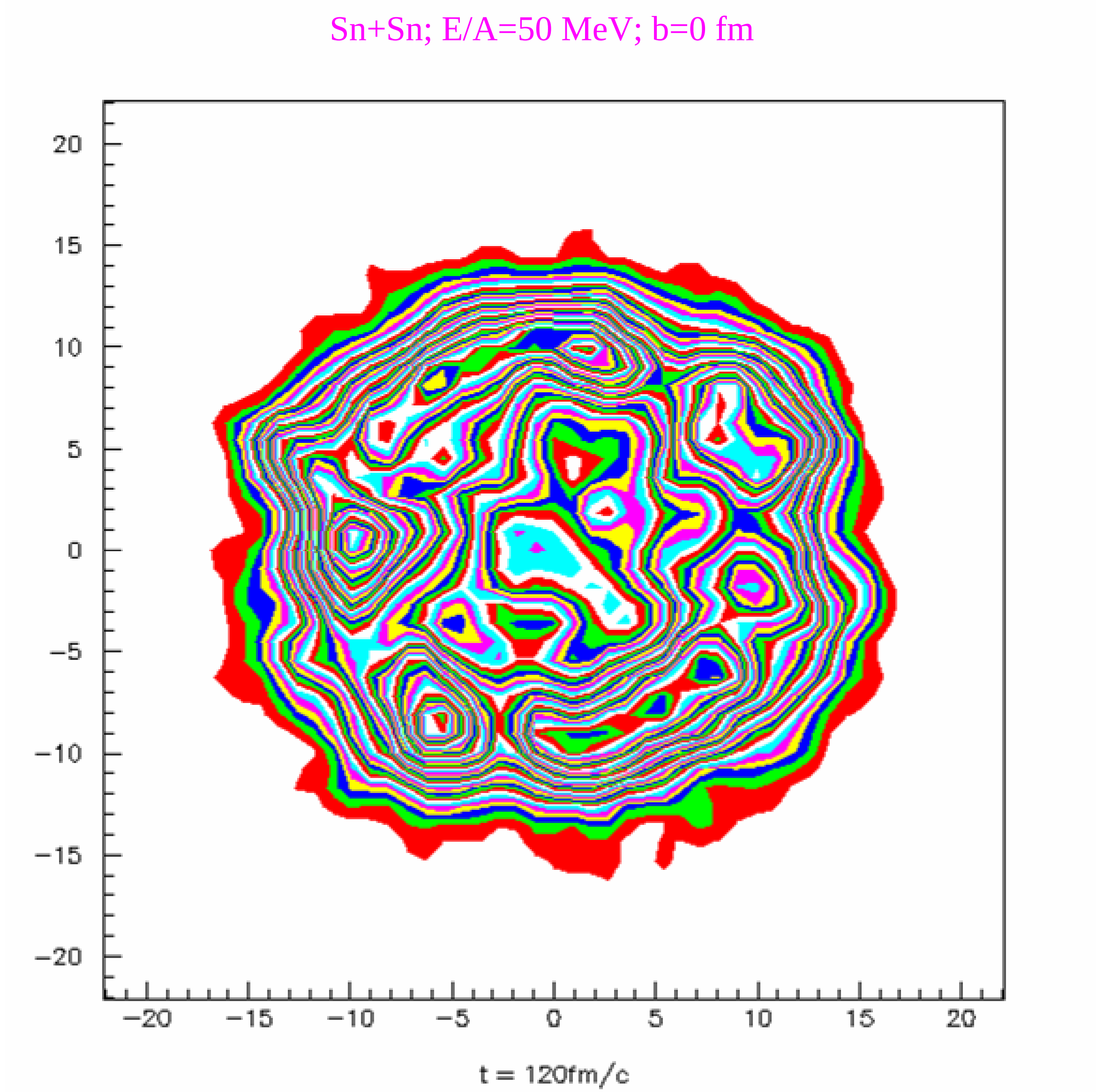

# *BUU: Transport theory simulations*

*Micha Kilburn*
*2003*



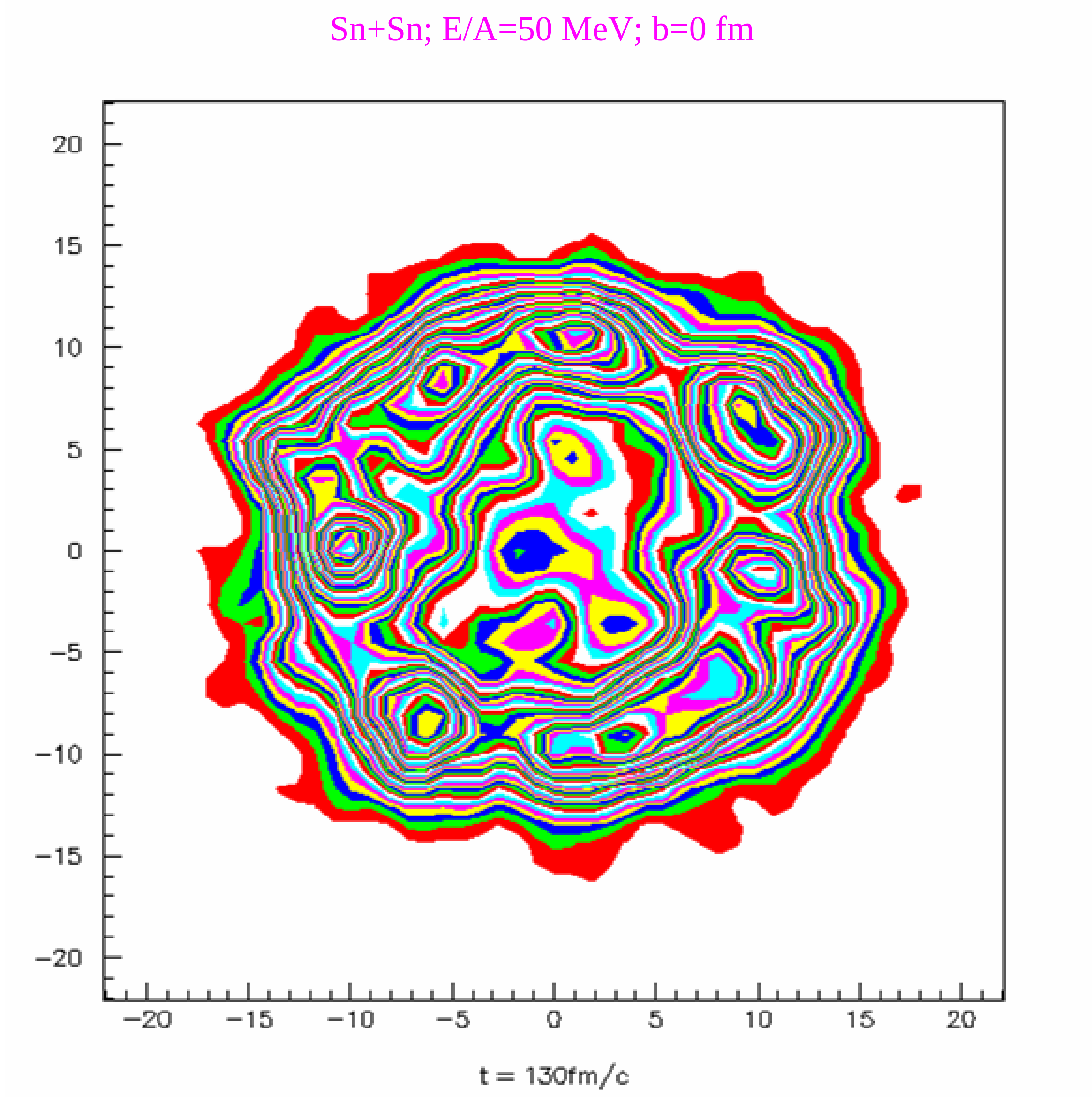

# *BUU: Transport theory simulations*

*Micha Kilburn*
*2003*



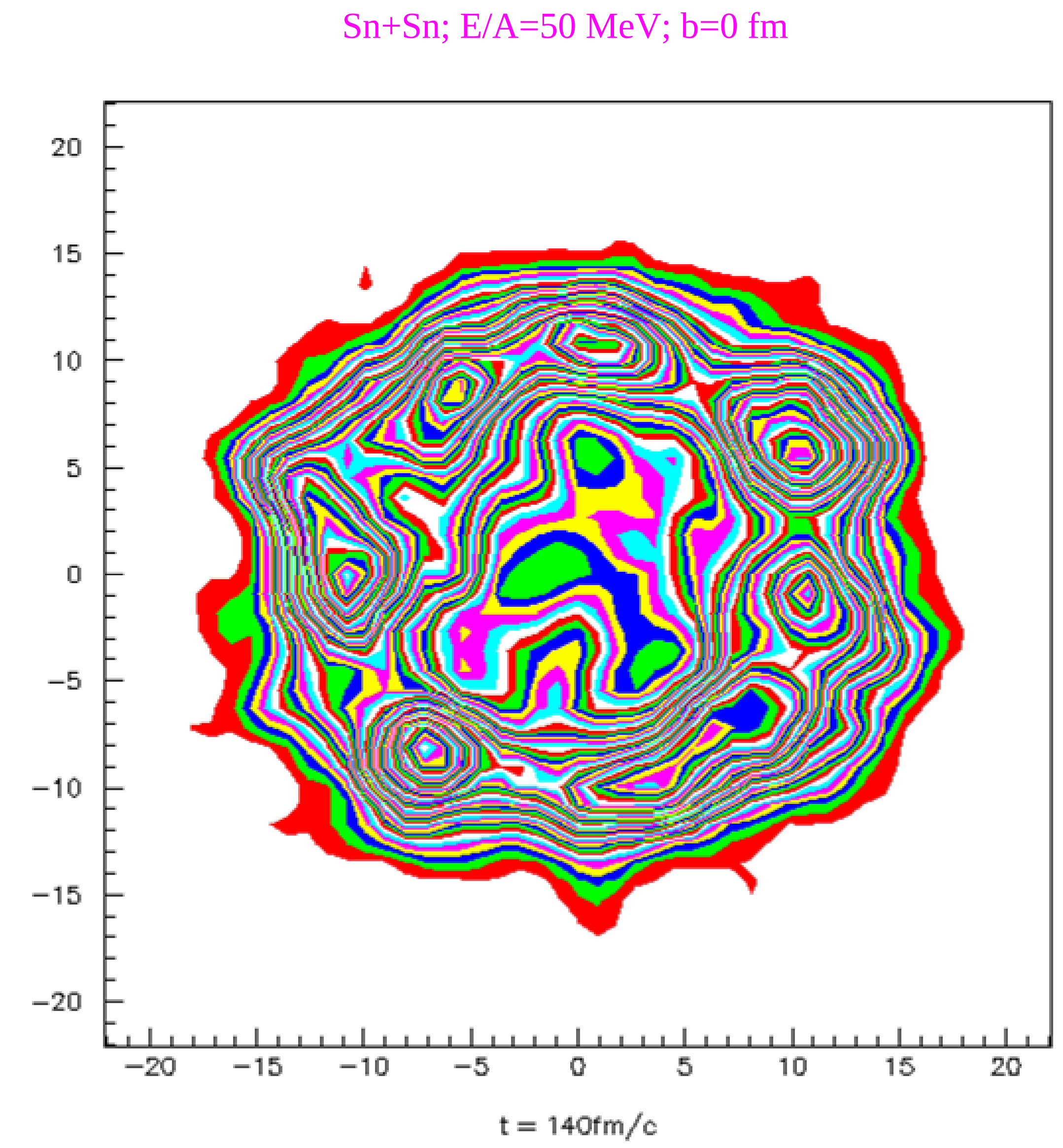

# *BUU: Transport theory simulations*

*Micha Kilburn*
*2003*



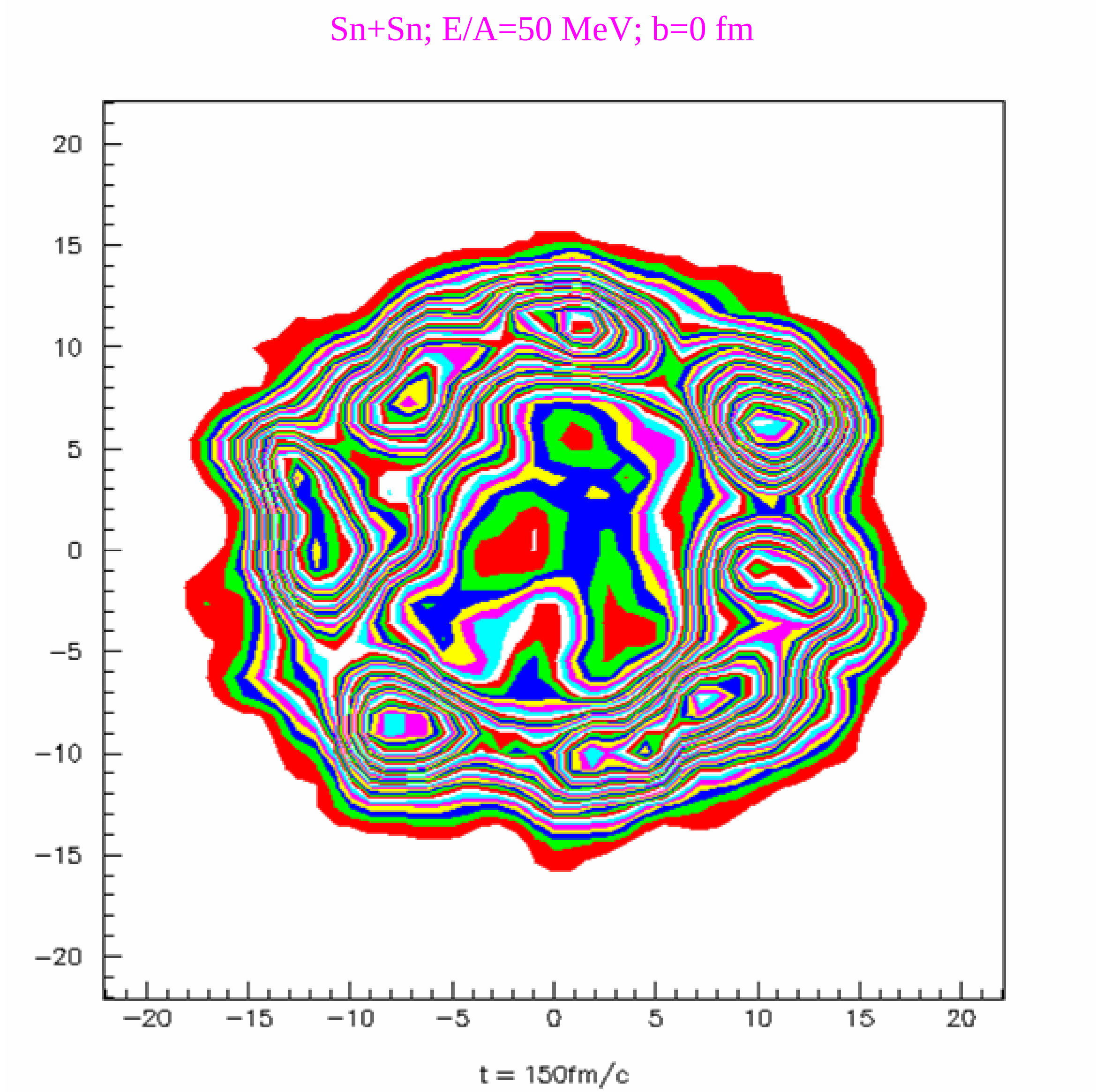

*BUU: Transport theory simulations*

*Micha Kilburn*
*2003*



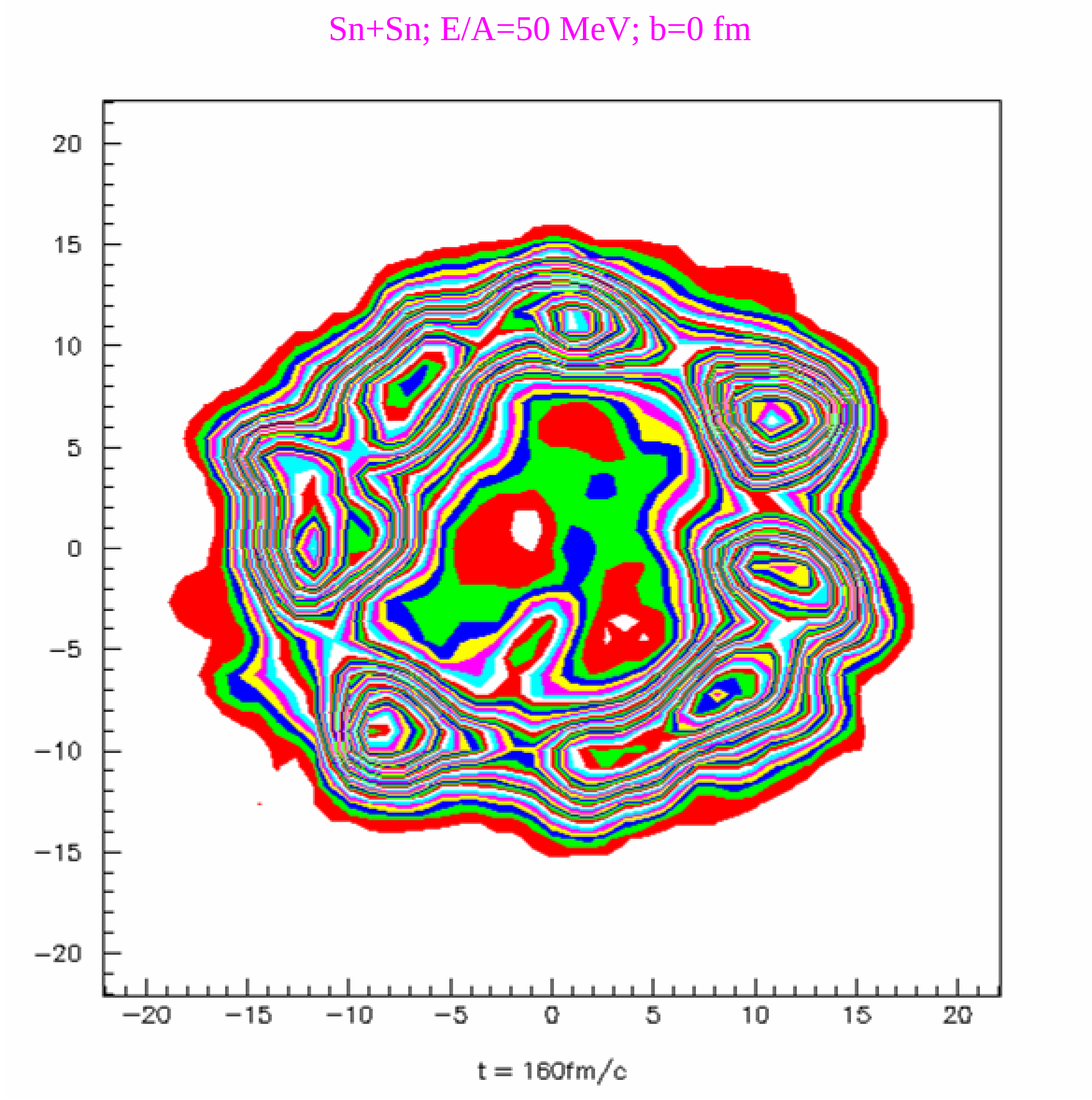

# *BUU: Transport theory simulations*

*Micha Kilburn*
*2003*



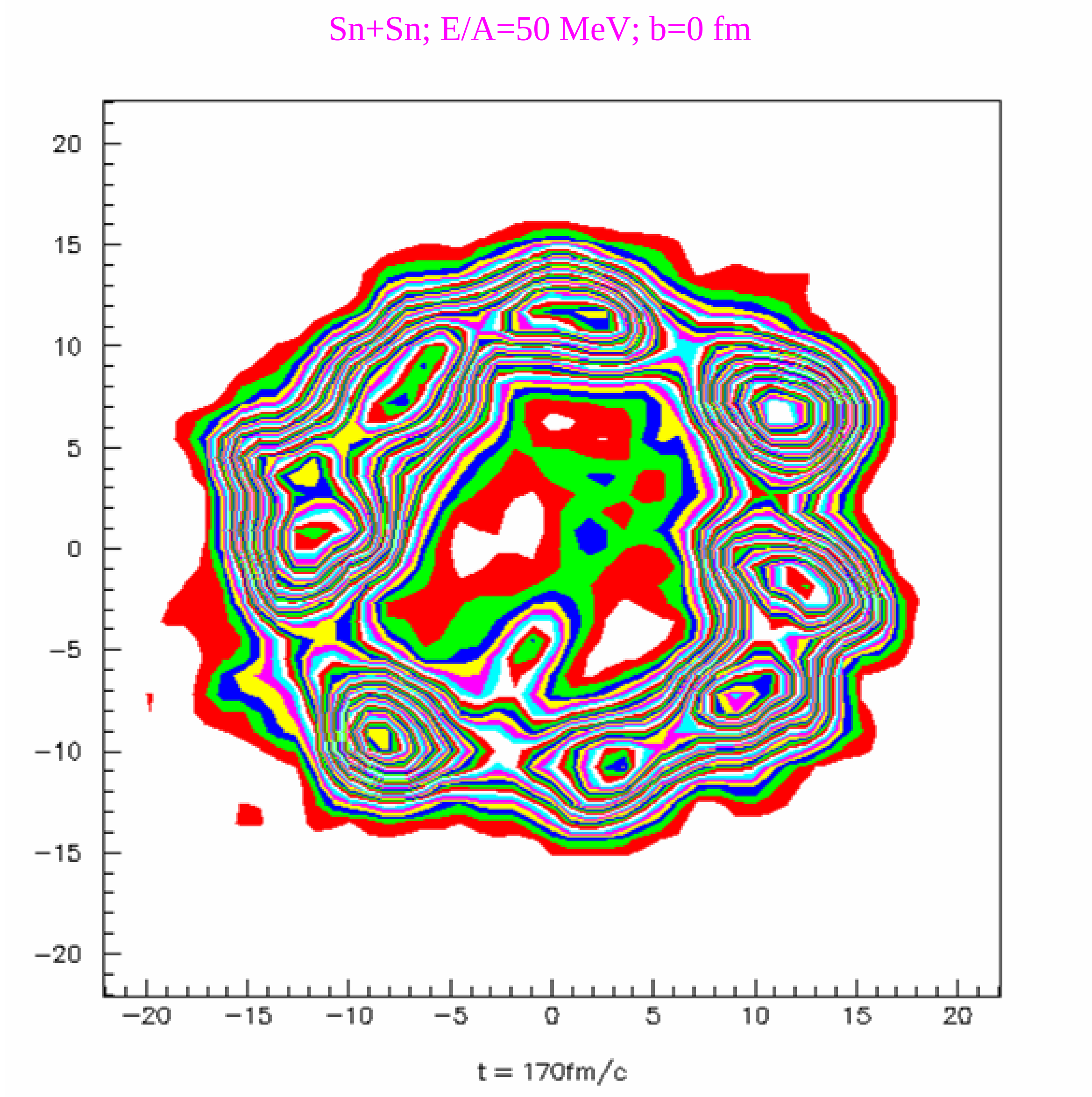

*BUU: Transport theory simulations*

*Micha Kilburn 2003*



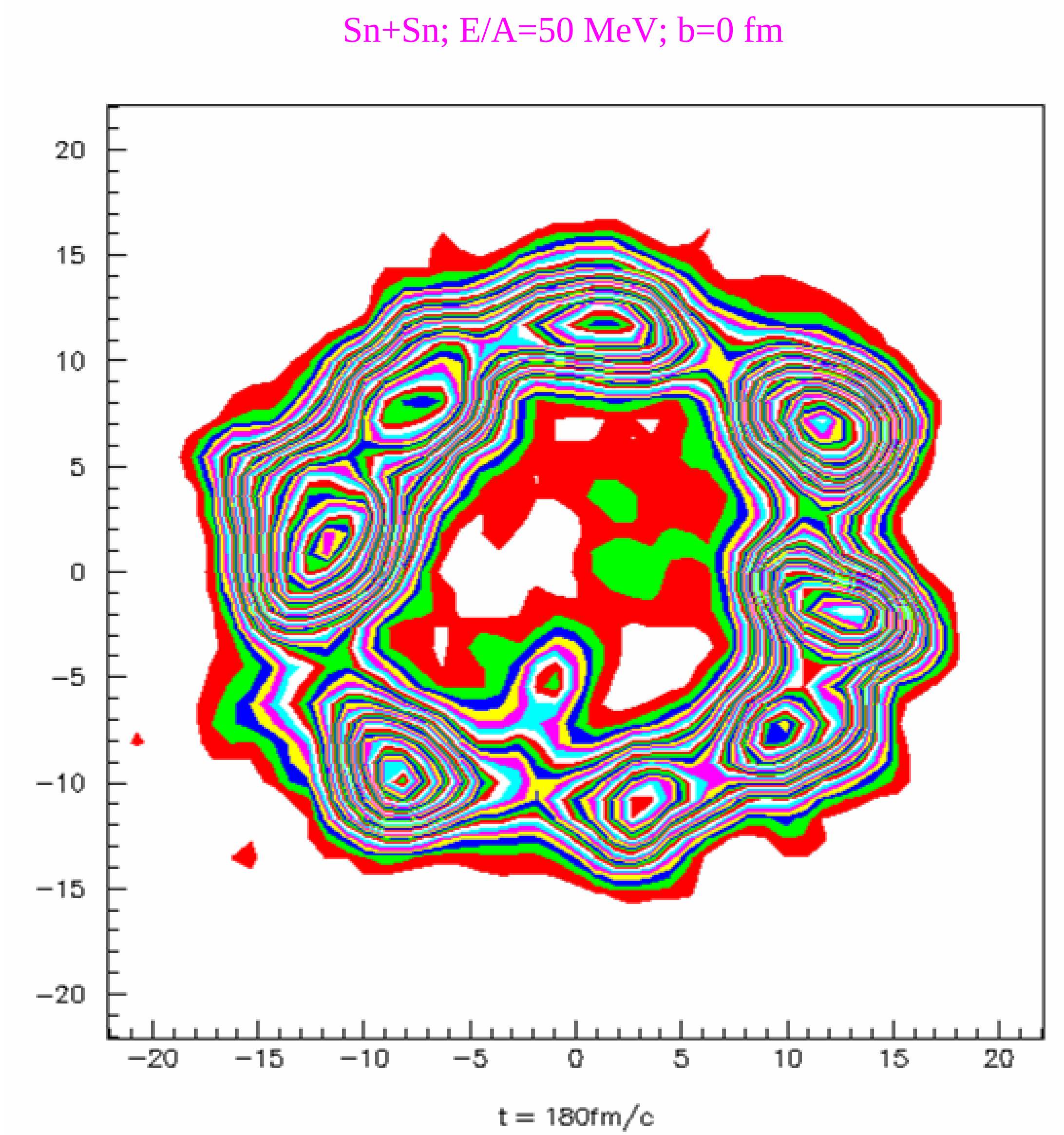

# *BUU: Transport theory simulations*

*Micha Kilburn*
*2003*



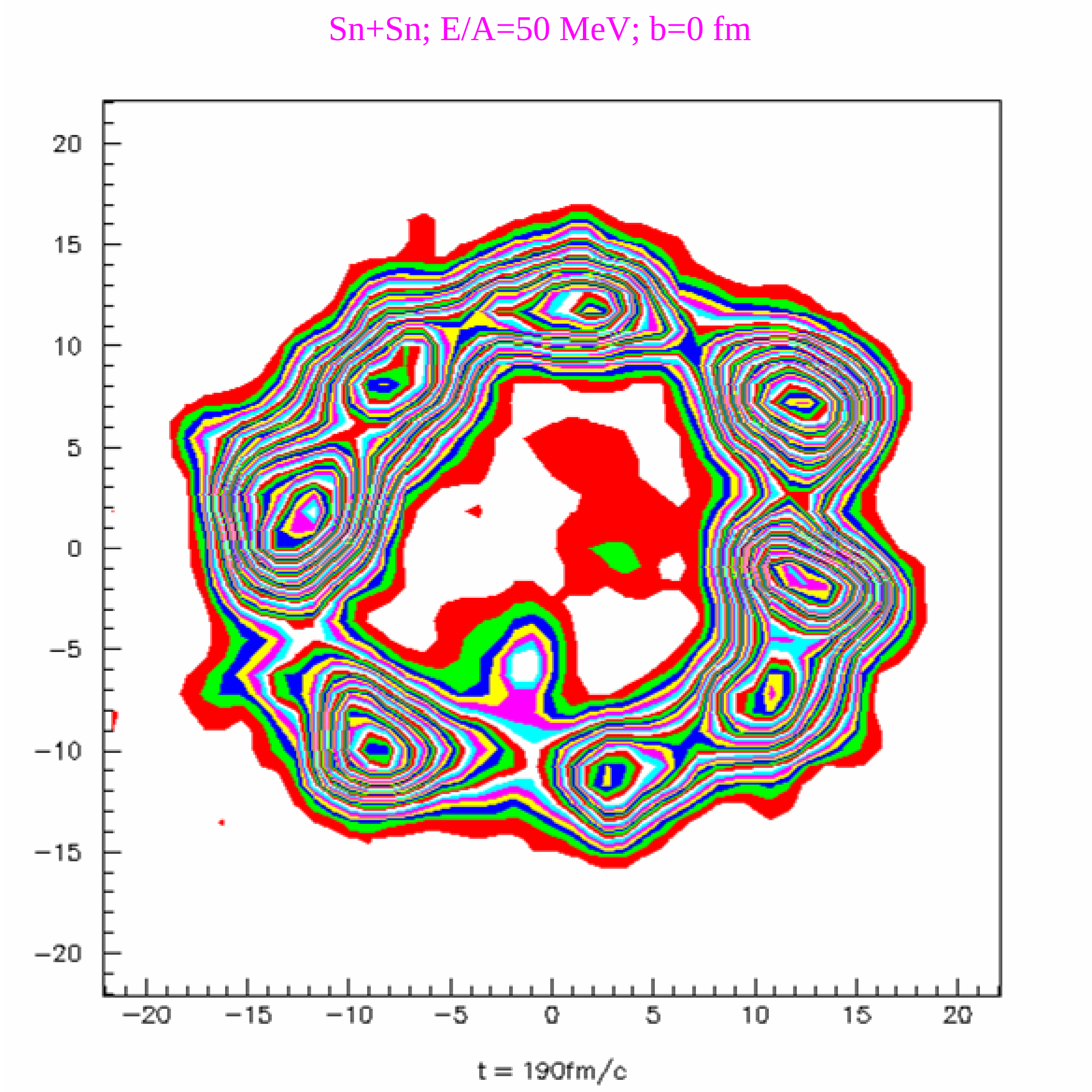

# *BUU: Transport theory simulations*

*Micha Kilburn*
*2003*




# *BUU: Transport theory simulations*

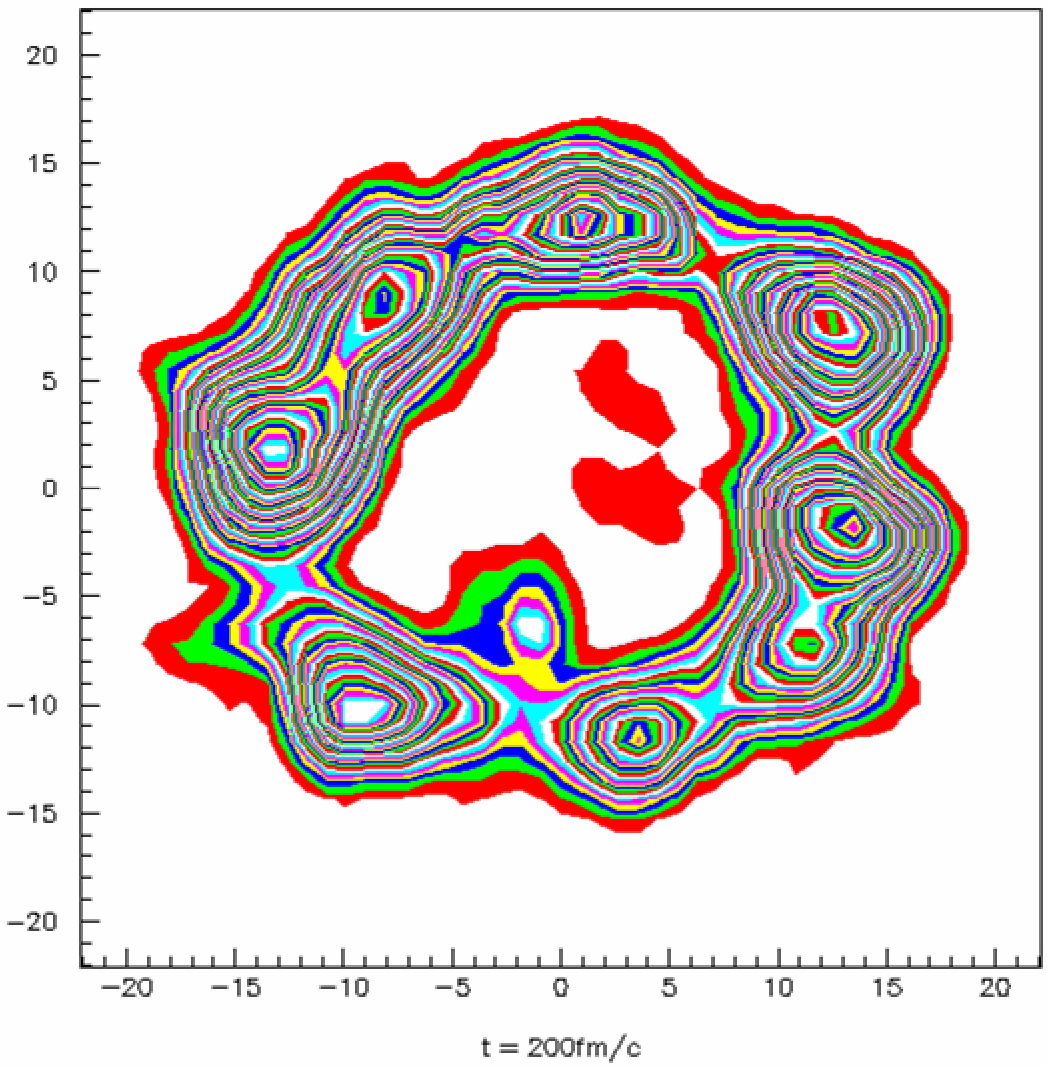
*Micha Kilburn*
*2003*




# *BUU: Transport theory simulations*

*Micha Kilburn 2003*

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



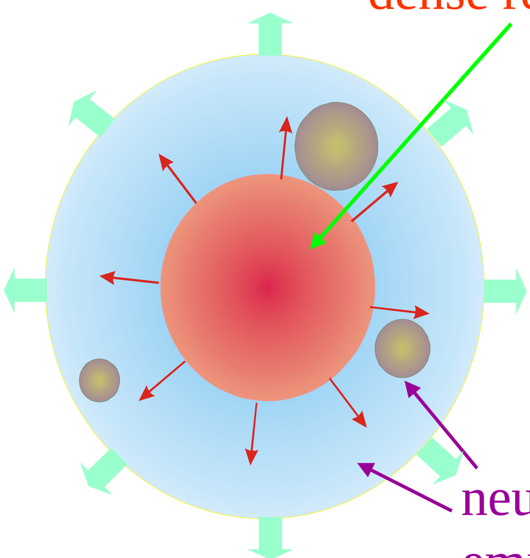

# *BUU: Transport theory simulations*

# Central collisions: isospin fractionation

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

asy-soft (F3)

more symmetric dense region

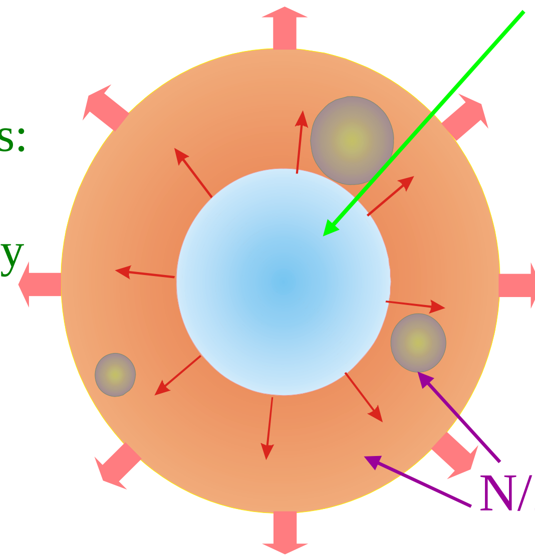


neutron-rich emitted particles

Possible observables:
n vs. proton emission, asymmetry of residues

asy-stiff (F1)

$N/Z_{res}=N_{tot}/Z_{tot}$



$N/Z_{em}\approx N_{tot}/Z_{tot}$

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 |

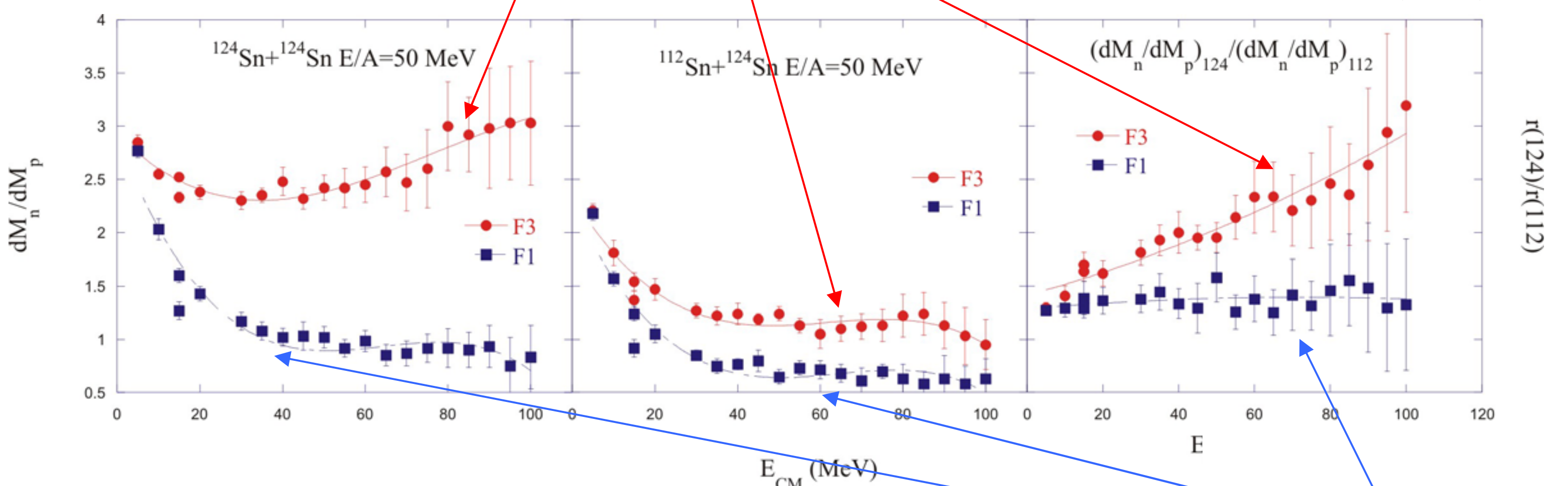
| EOS | Residue N/Z |
|---|---|
| F_1 (asy-stiff) | 102/71=1.44 |

# Comparison of n and p spectra

- Probes the pressure from asymmetry term at saturation density and below.
  - Some of the primordial nucleons emerge as clusters; this can be addressed within coalescence invariant analyses

soft asymmetry term

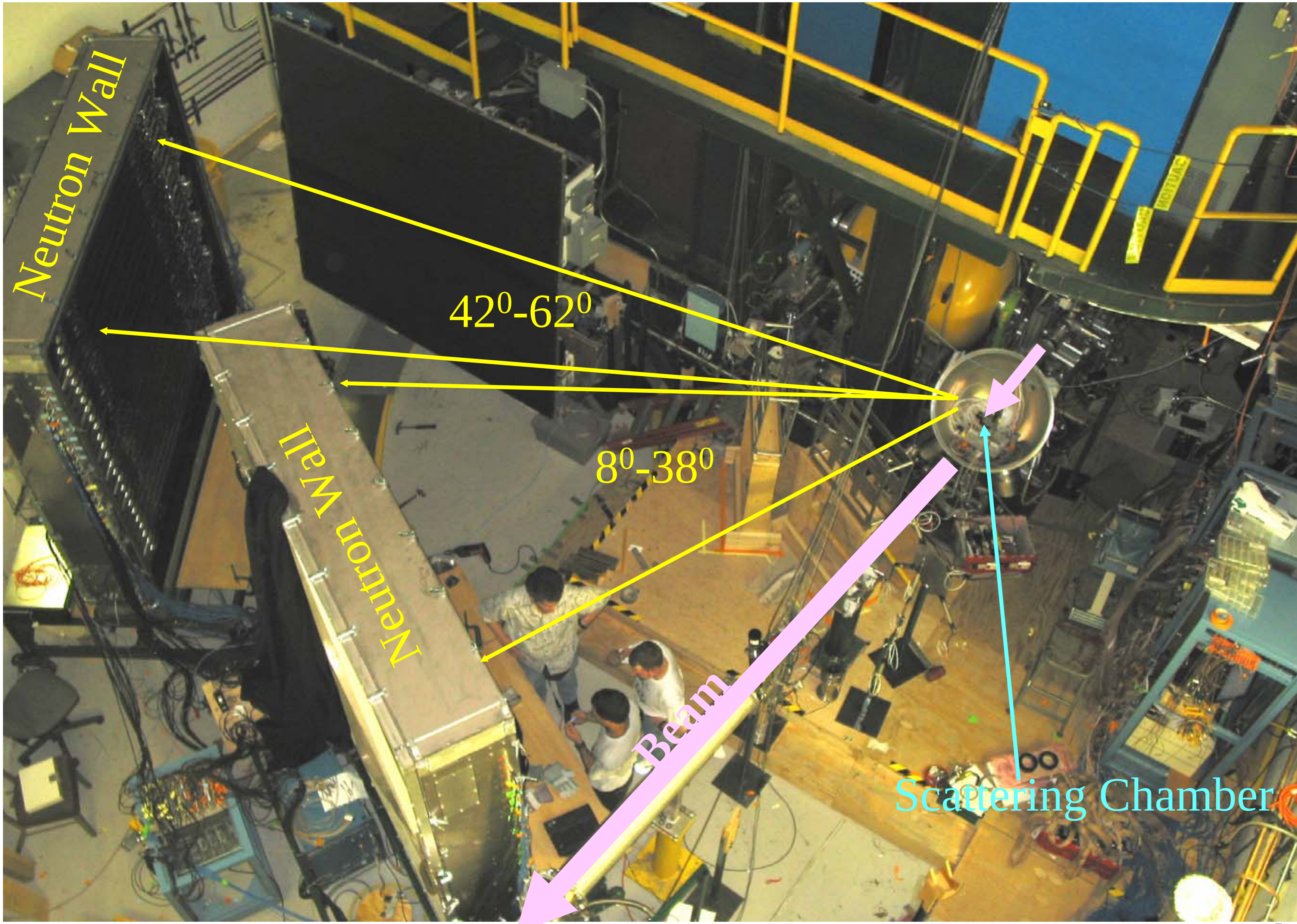
Bao-An Li et al., PRL 78, 1644 (1997)




stiff asymmetry term

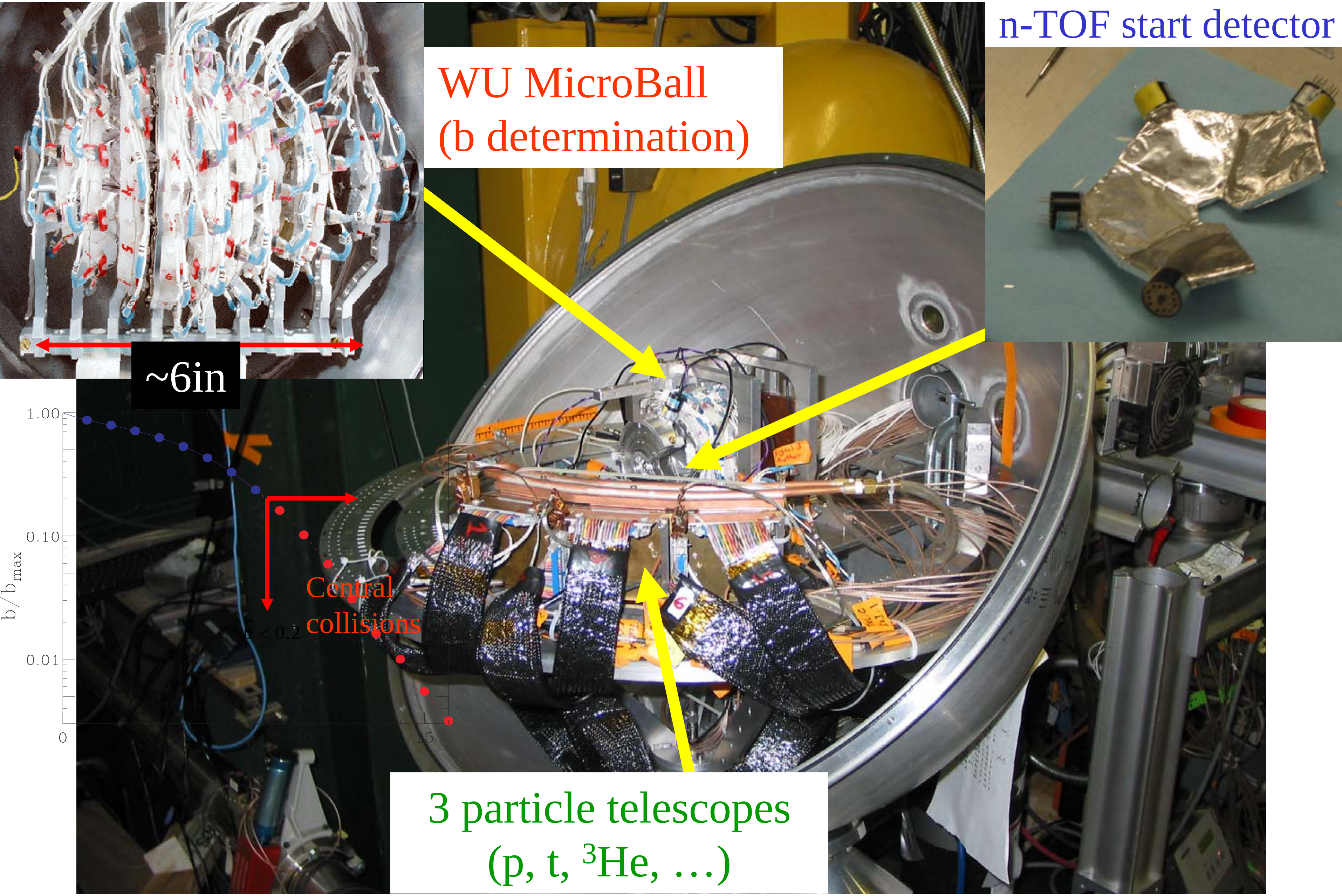
- Double ratio is less sensitive to energy calibration and neutron efficiency uncertainties.

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

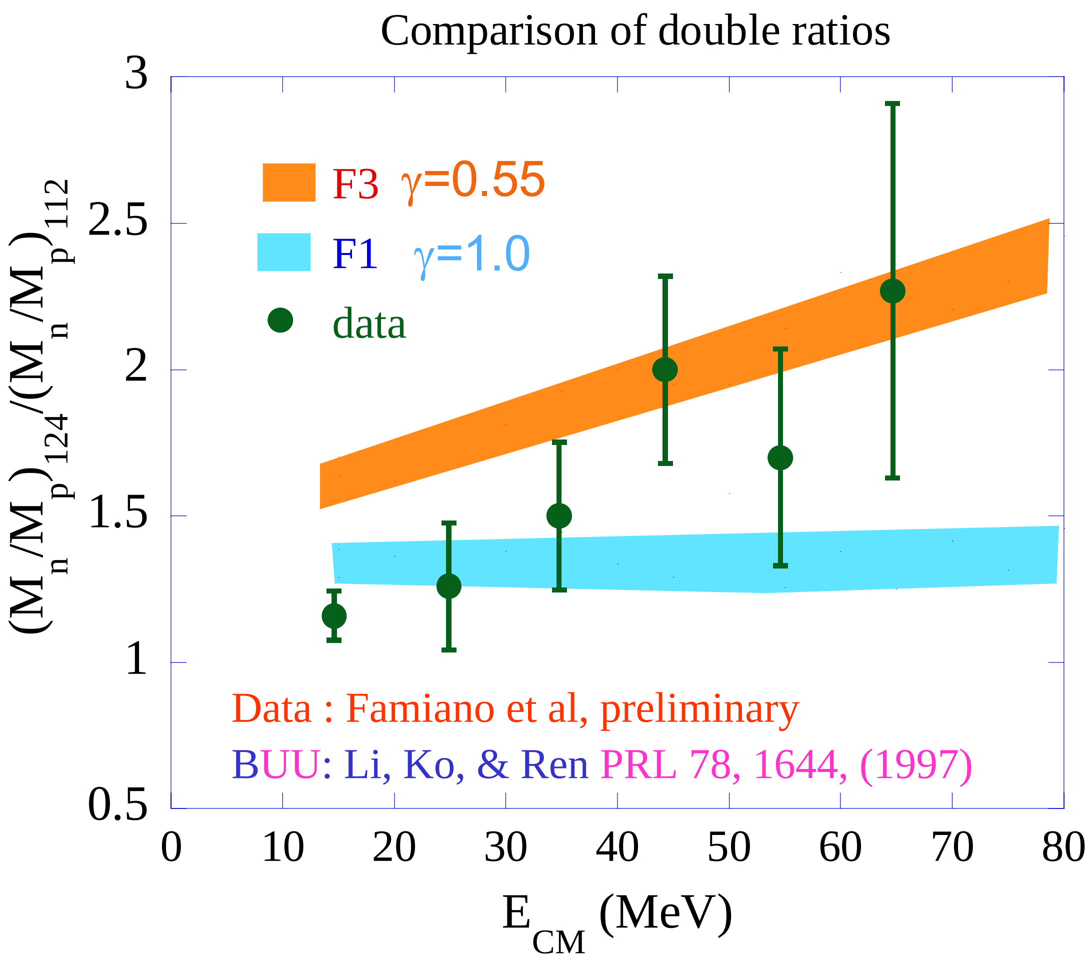



Famiano et al

# P-detection: Scattering Chamber



# Coalescence invariant spectra




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

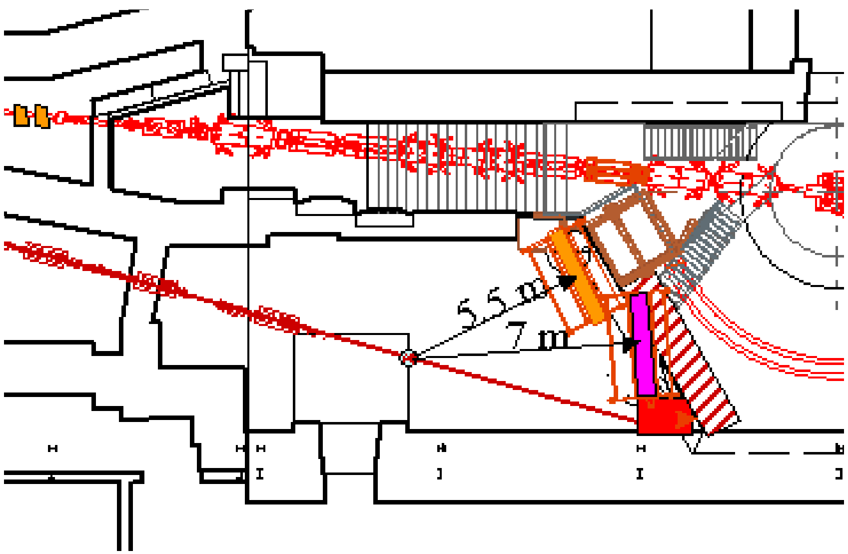
- Coalescence invariant analysis decreases sensitivity to cluster production model uncertainties:
  - Approach consistent with successful flow analyses.
  - Permits accurate comparisons to theory at E/A>30 MeV

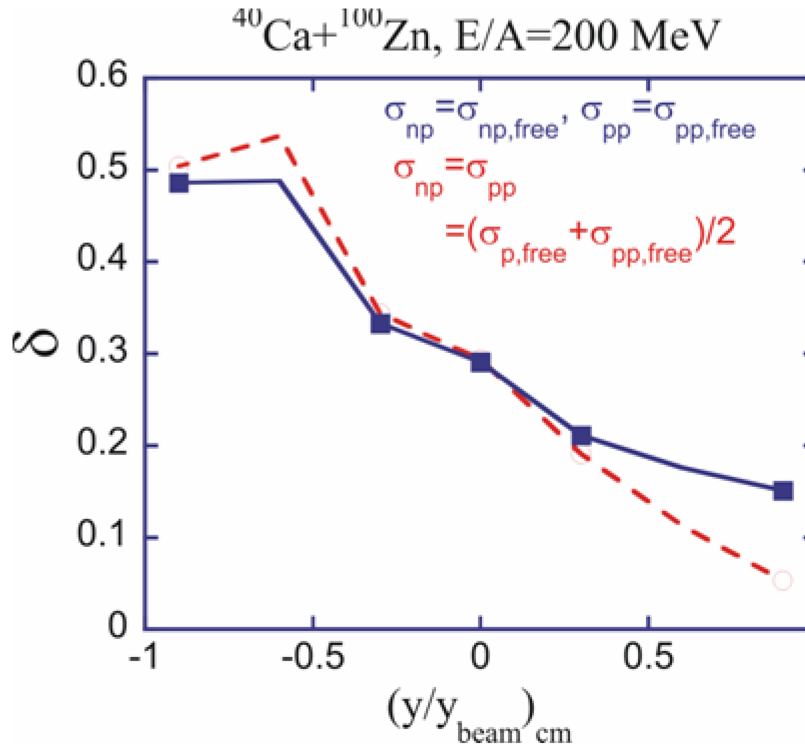
# Summary

- We have two promising observables to probe the asymmetry term:
  - Isospin diffusion
  - Comparisons of neutron and proton emission rates and flow.
- 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 other observables to constrain these quantities:
  - New neutron area in N2 vault at the CCF.
- Other factors:
  - uncertainty in the impact parameter.
  - role of fluctuations.

# 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), $m^*_{n,}$, $m^*_p$, $\sigma_{pp}$ and $\sigma_{np}$.




•Li, et al., PRC 71, 054603 (2005)

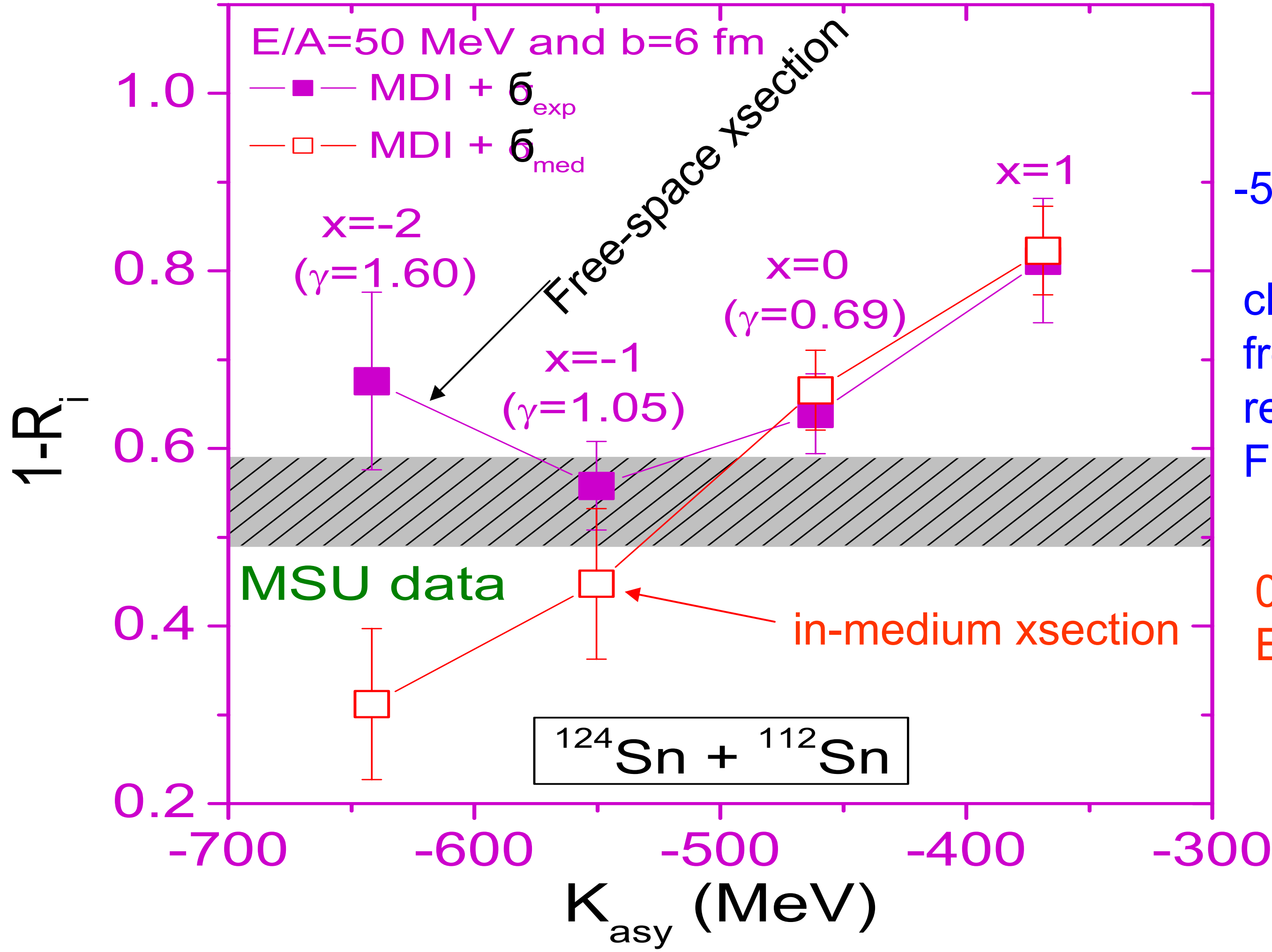
# Coalescence invariant analyses

$$\left.\frac{dM_n}{dv^3}\right|_{eff} = \sum_i \frac{dM_n}{dv^3} N_i$$

$$\left.\frac{dM_p}{dv^3}\right|_{eff} = \sum_i \frac{dM_p}{dv^3} Z_i$$

- Assumptions: The modification of nucleon momenta by the cluster production is small compared to the nucleon momenta themselves.

Effects of the in-medium nucleon-nucleon cross sections



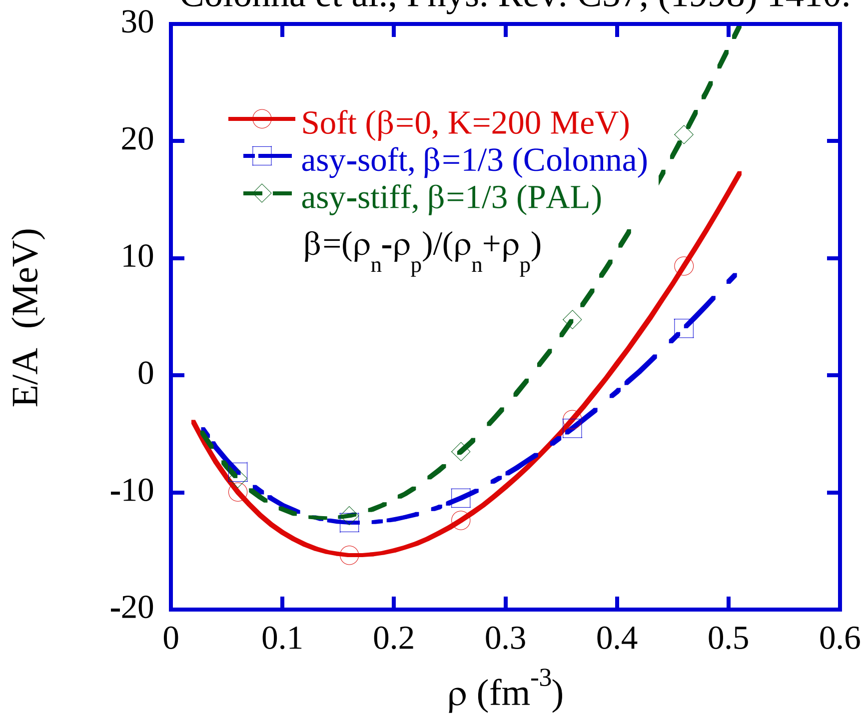

$-550 < K_{asy} < -450$ MeV

close to that extracted from Osaka giant resonsnces data by Fujiwara et al.

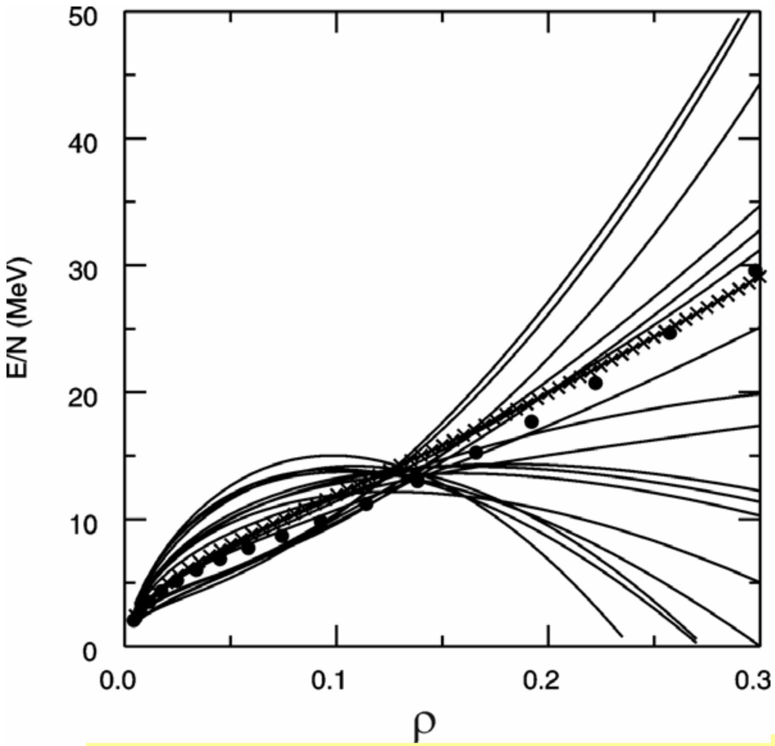
$0.7 < \gamma < 1.1$ in fitting $E_{sym}=32(\rho/\rho_0)^{\gamma}$

# 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 $\rho_0$.