Sensitivity of Light Cluster and Nucleon Yields on Asymmetry Energy

Micha A. Kilburn

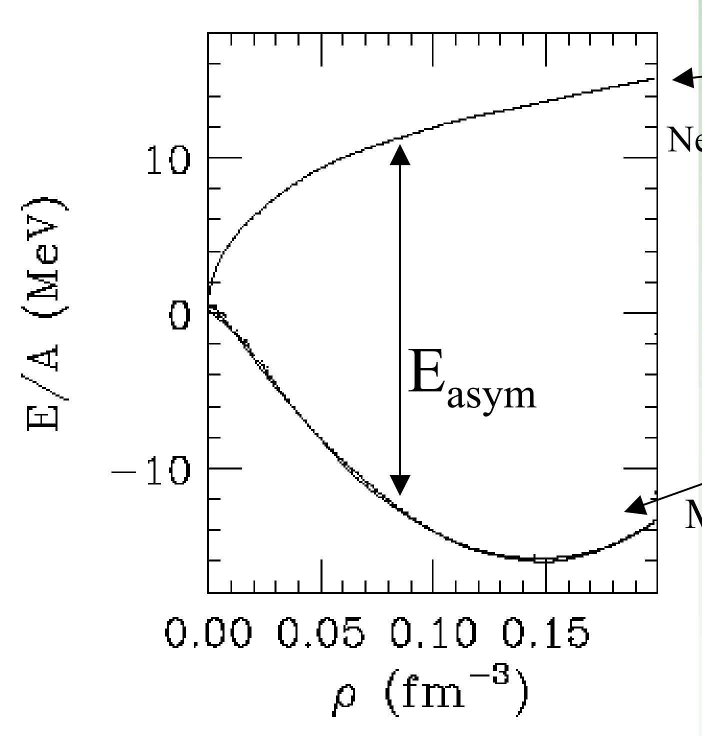
Northern Michigan University

Motivation

- The ultimate goal is to determine the Equation of State (EOS) for asymmetric nuclear matter.
- Due to availability of radioactive beams, interest is now developing in how the energy depends on asymmetry.
- Specifically, relate energy per nucleon to density of nucleons (ρ) and relative imbalance of neutrons to protons:

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

$\rho_0 = 0.16\ \mathrm{fm}^{-3}$



δ=1

Neutron matter inside neutron stars

δ=0

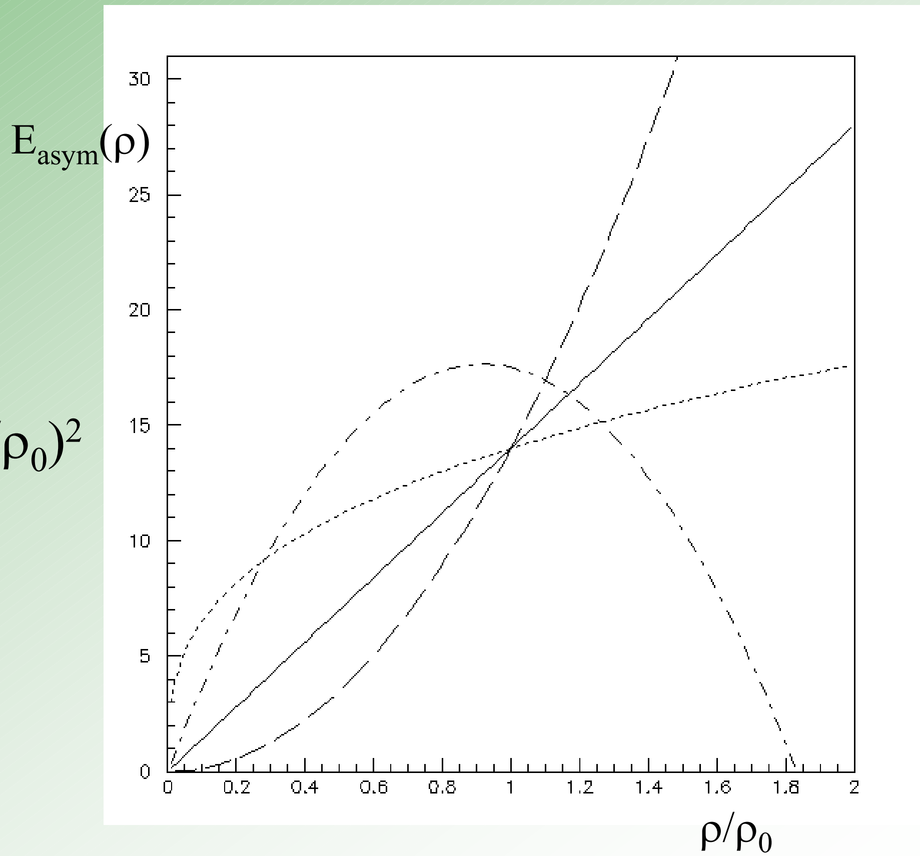
Matter inside symmetric nuclei

Asymmetry Energy

$$E_{asym}(\rho) = E_{sym}^{kin} + E_{sym}^{\text{int}}$$

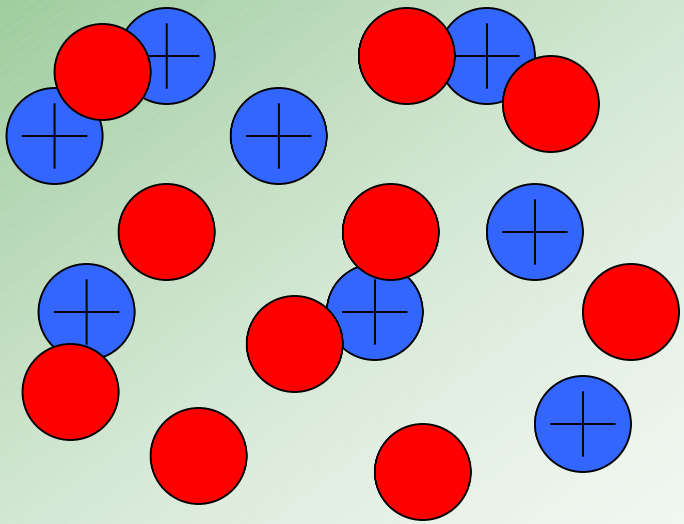
$$E_{sym}^{kin} = 12.25\,MeV\left(\rho/\rho_0\right)^{2/3}$$

Super Hard		$14MeV\ (\rho/\rho_0)^2$
Normal Hard	$E_{sym}^{\text{int}} =$	$14MeV\ (\rho/\rho_0)$
EBHF		$14MeV\ (\rho/\rho_0)^{1/3}$
SKM		$38.5(\rho/\rho_0)-21(\rho/\rho_0)^2$



Method

- One approach is to examine the ratio of free neutrons to protons in collisions between neutron-rich nuclei at intermediate energies.
- If nuclear gas and liquid phases coexist in a collision, then the n/p ratio is higher in the gas phase, and this excess reflects the nuclear asymmetry energy.
- Experimental constraints
- Relationship between the $t/^{3}He$ ratio and n/p ratio



BUU Transport Model

- The BUU Model is a relativistic hadronic transport model based on the Boltzmann equation.
- The equation describes the phase space distribution of particles. The left side collectively describes the motion due to the average mean field.

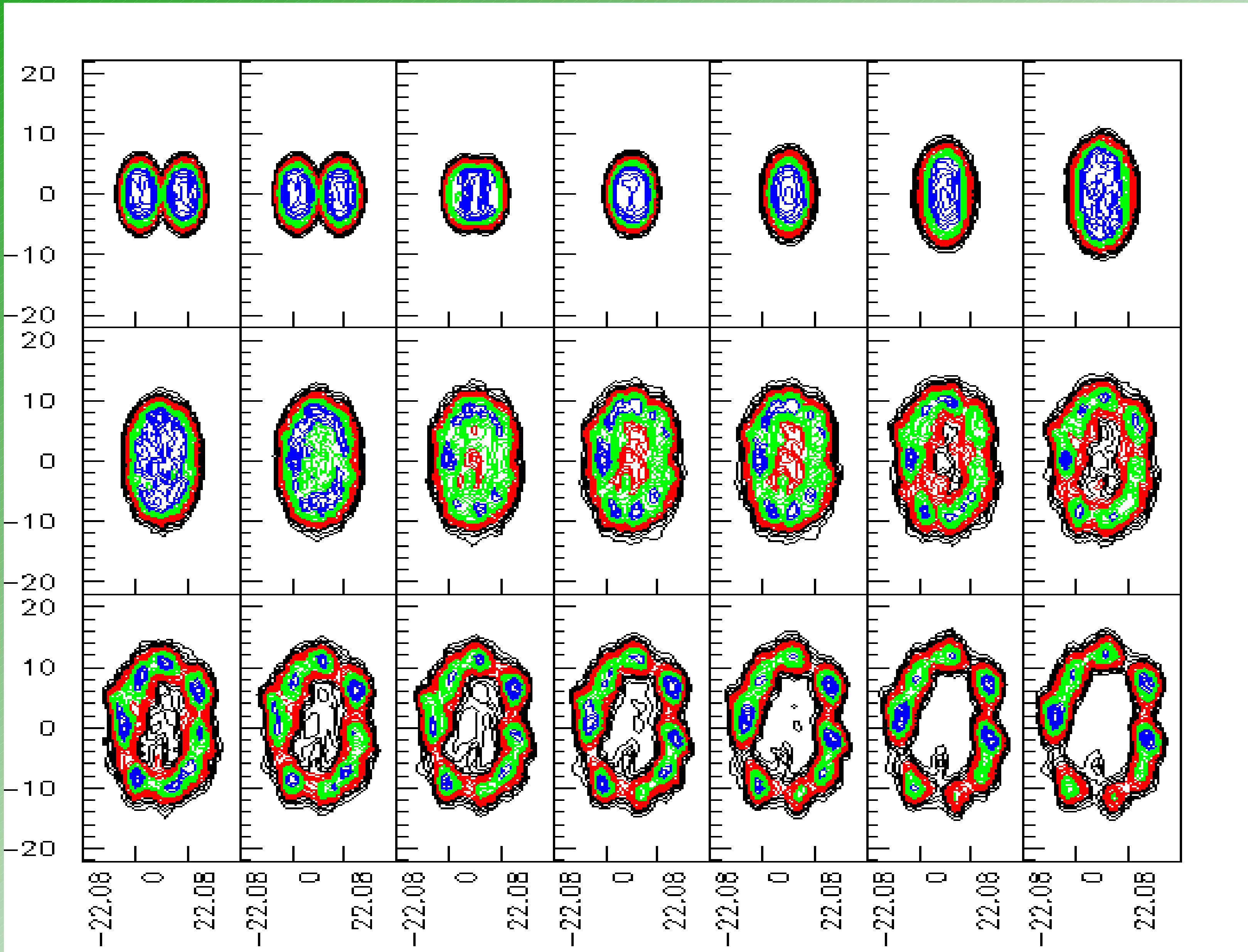
acceleration

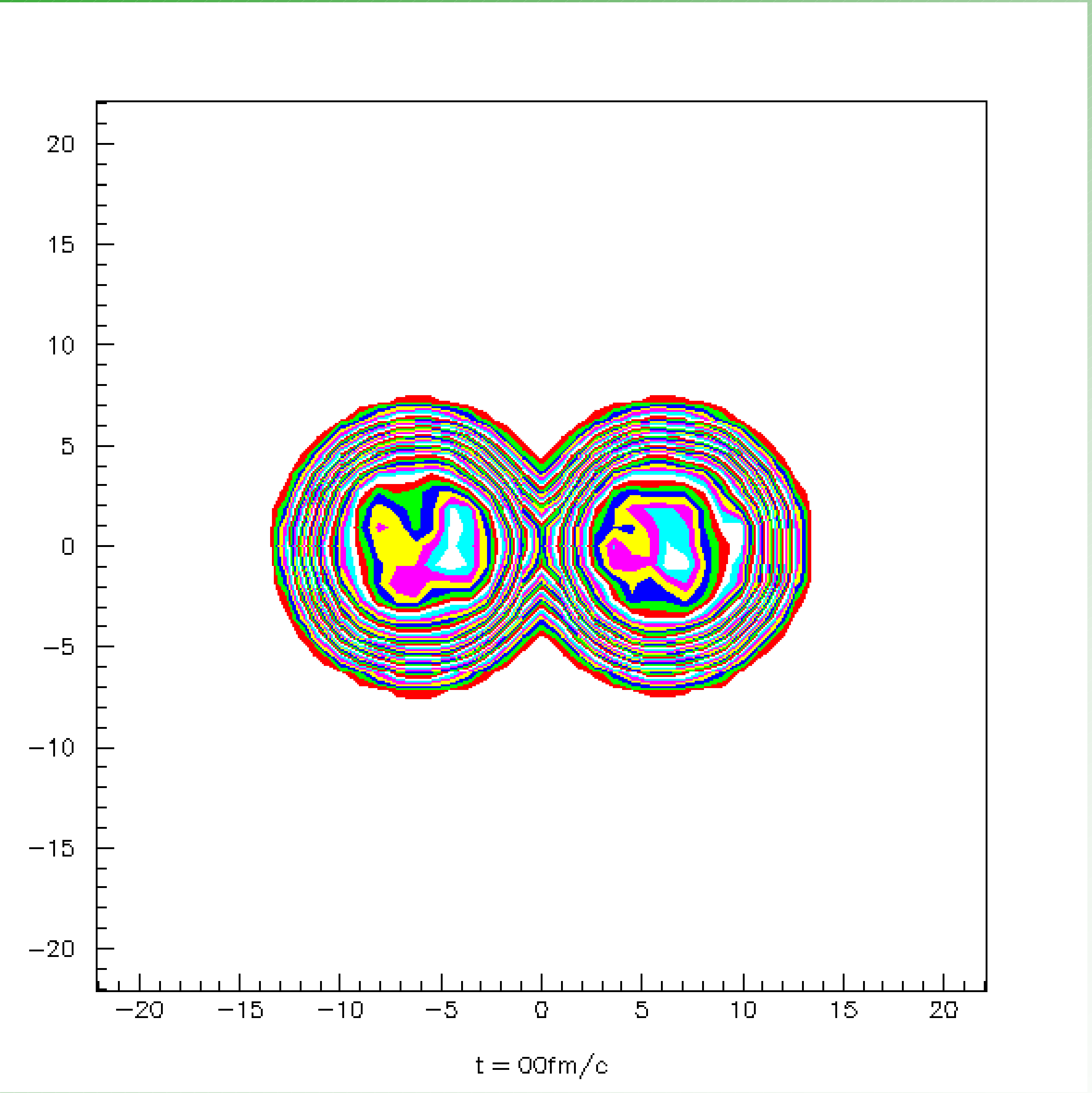
$$\frac{\partial f}{\partial t} + \frac{\partial \epsilon_{\mathbf{p}}}{\partial \mathbf{p}} \frac{\partial f}{\partial \mathbf{r}} - \frac{\partial \epsilon_{\mathbf{p}}}{\partial \mathbf{r}} \frac{\partial f}{\partial \mathbf{p}} = \int d\mathbf{p}_2 \int d\Omega' \, v_{12} \, \frac{d\sigma}{d\Omega'} \left((1 - f_1)(1 - f_2) \times f_1' \, f_2' - (1 - f_1')(1 - f_2') f_1 \, f_2\right).$$

velocity

Describes scattering events

Central Collision $^{124}Sn+^{124}Sn$





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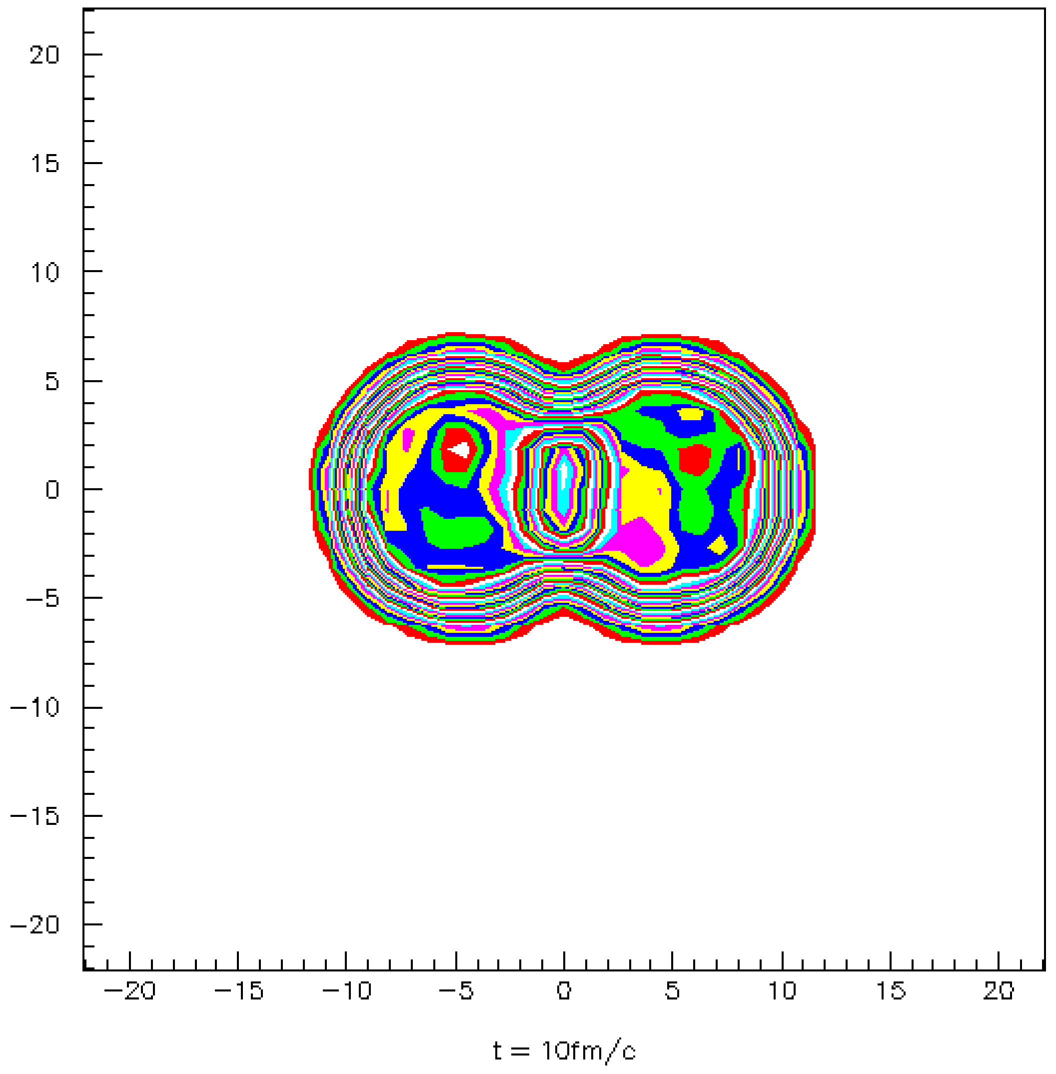
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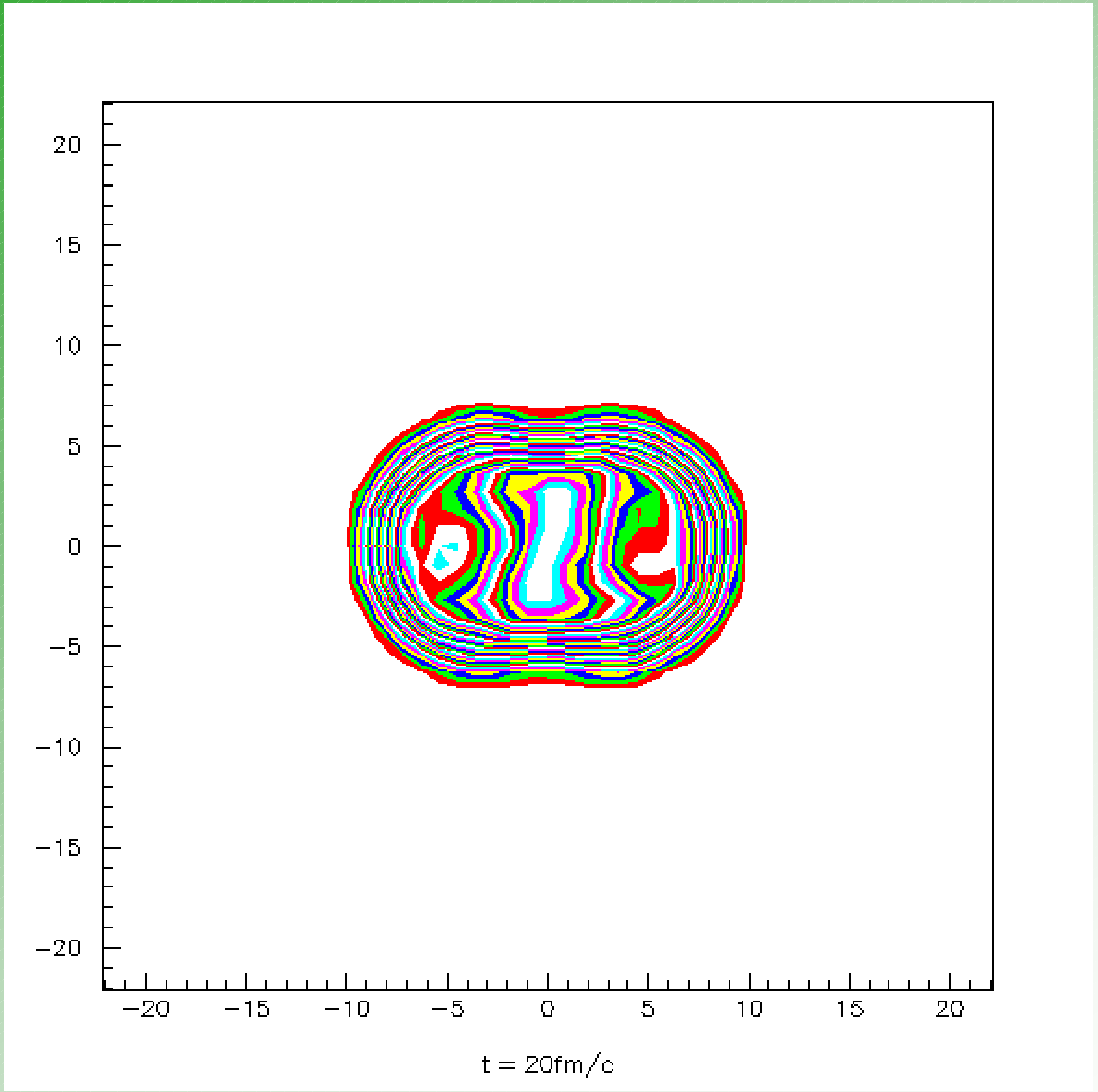

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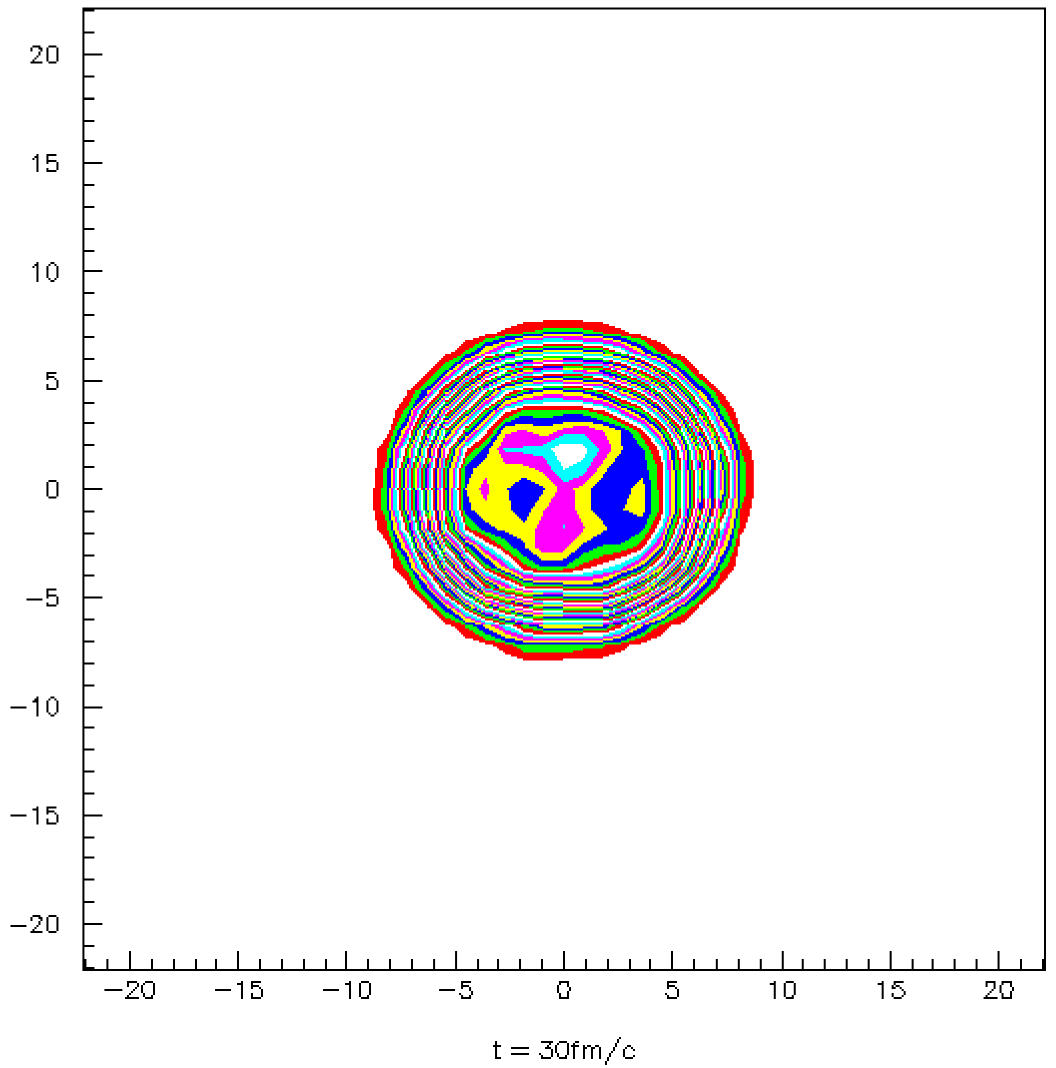
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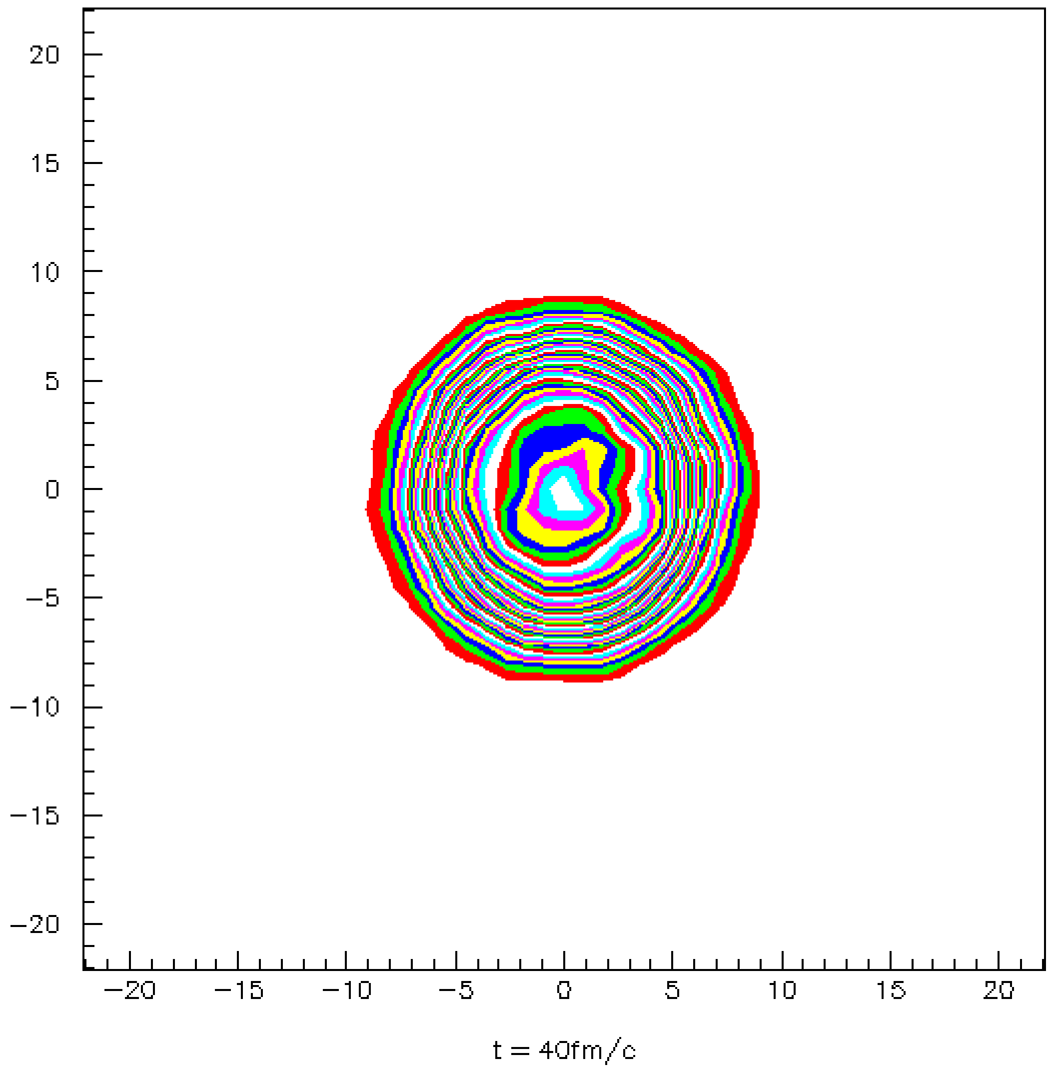
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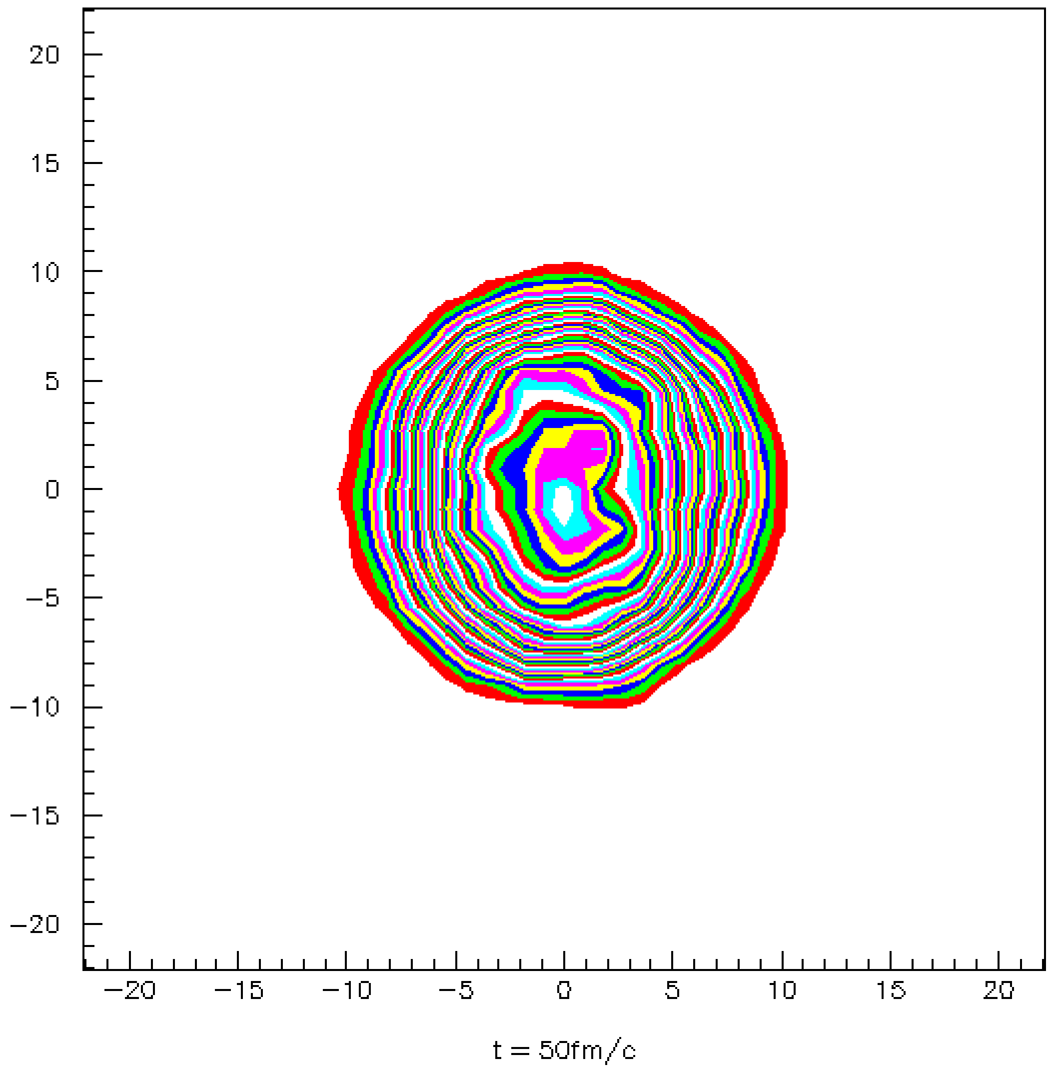
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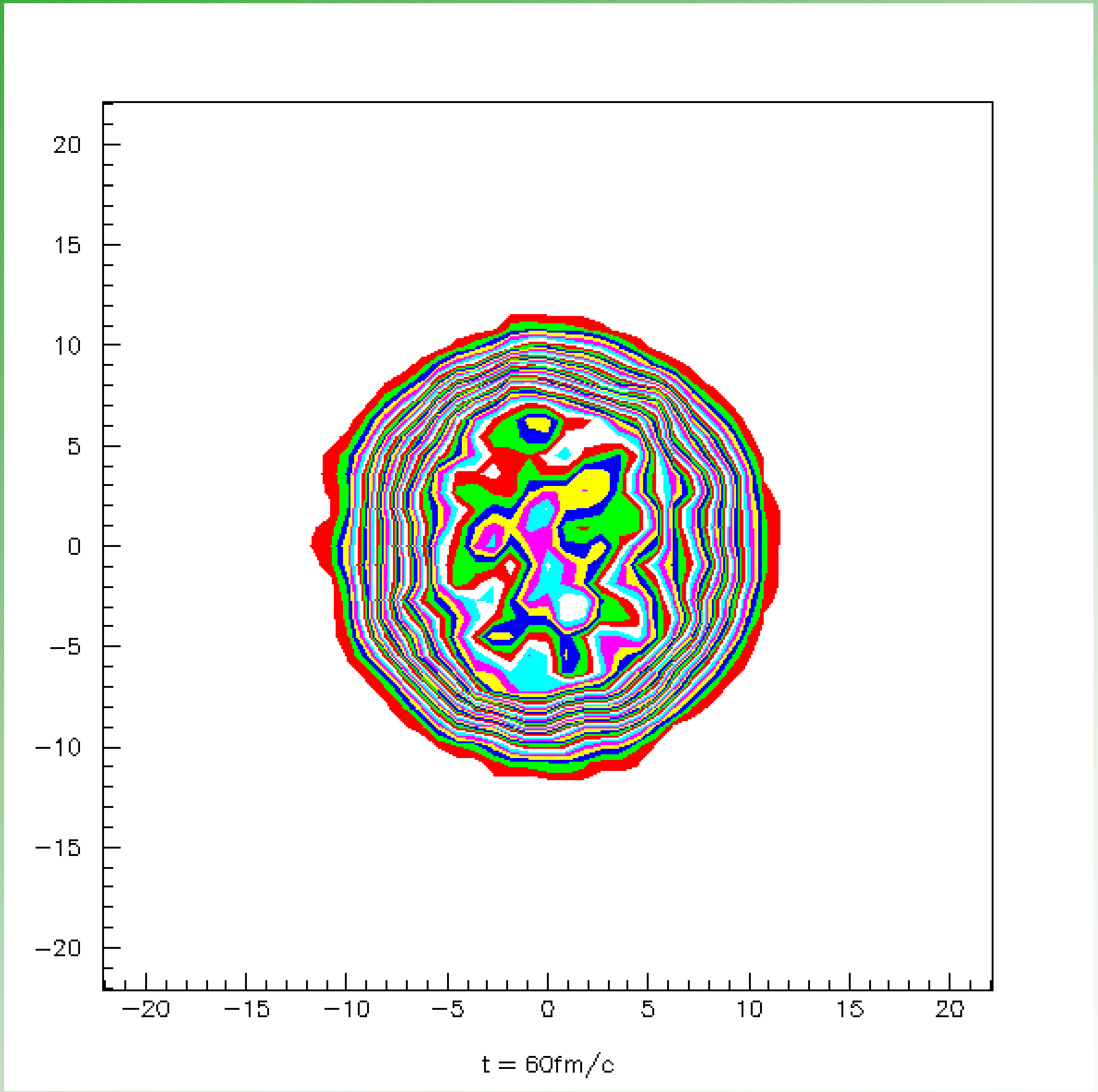
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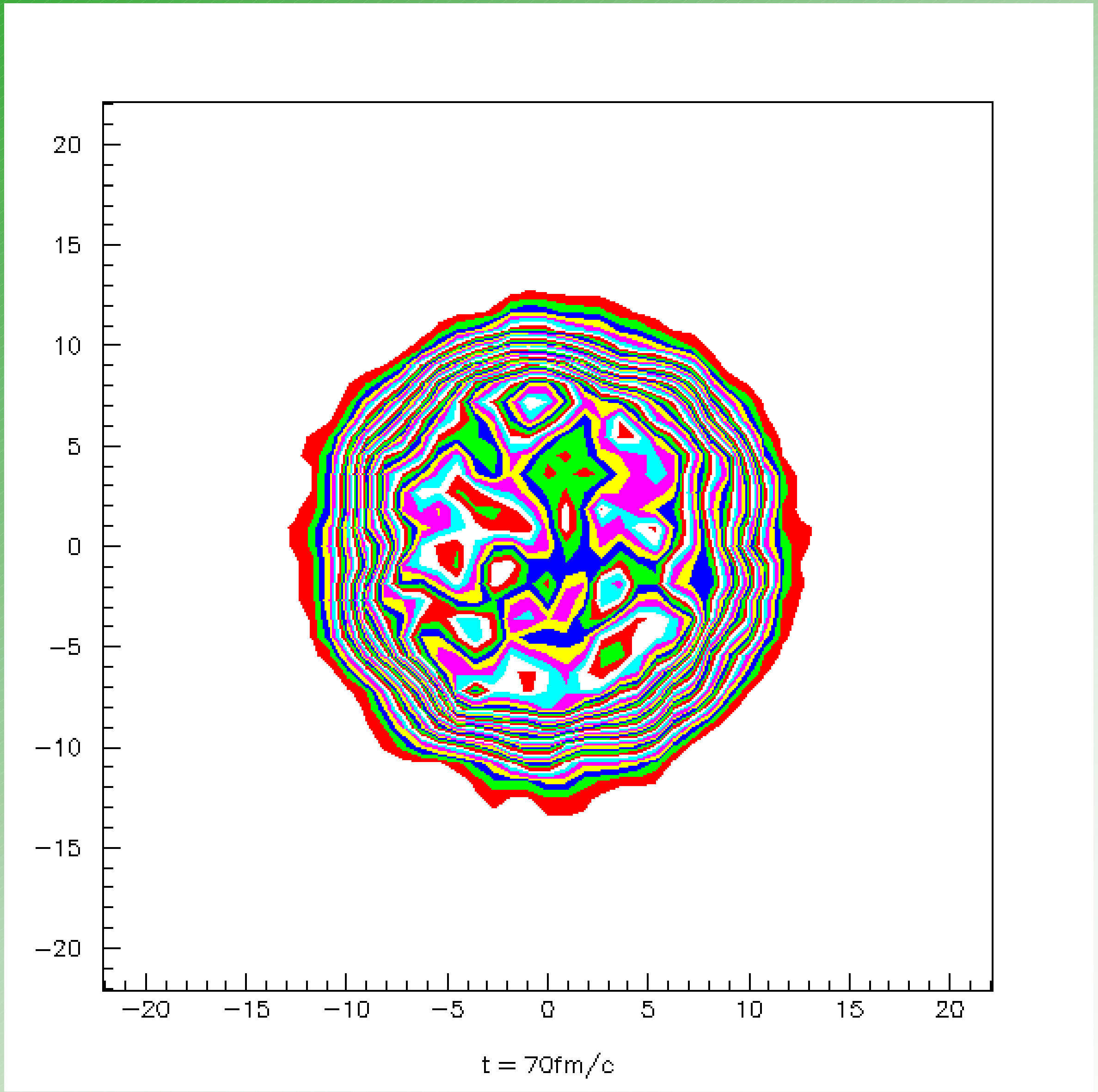

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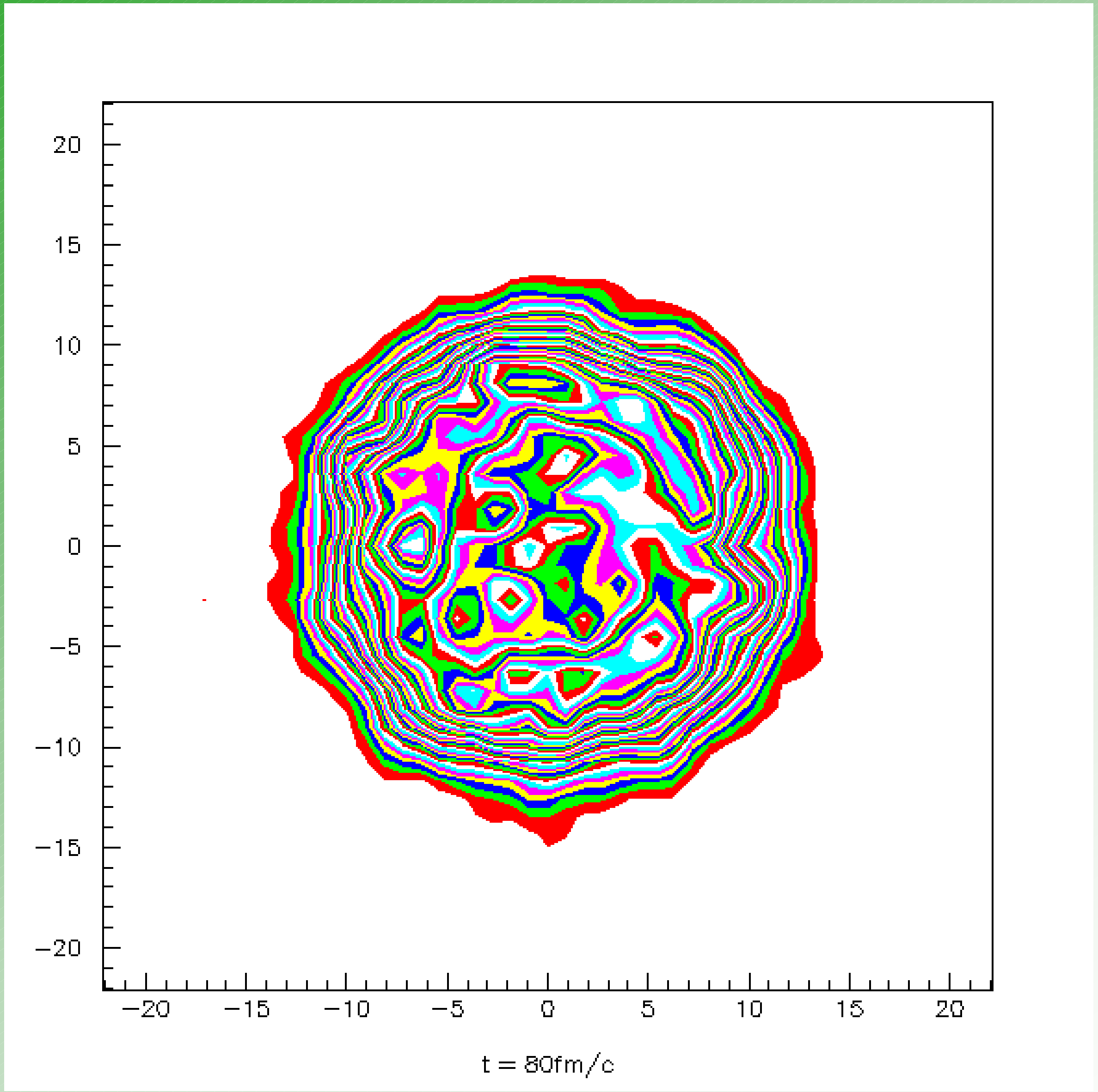

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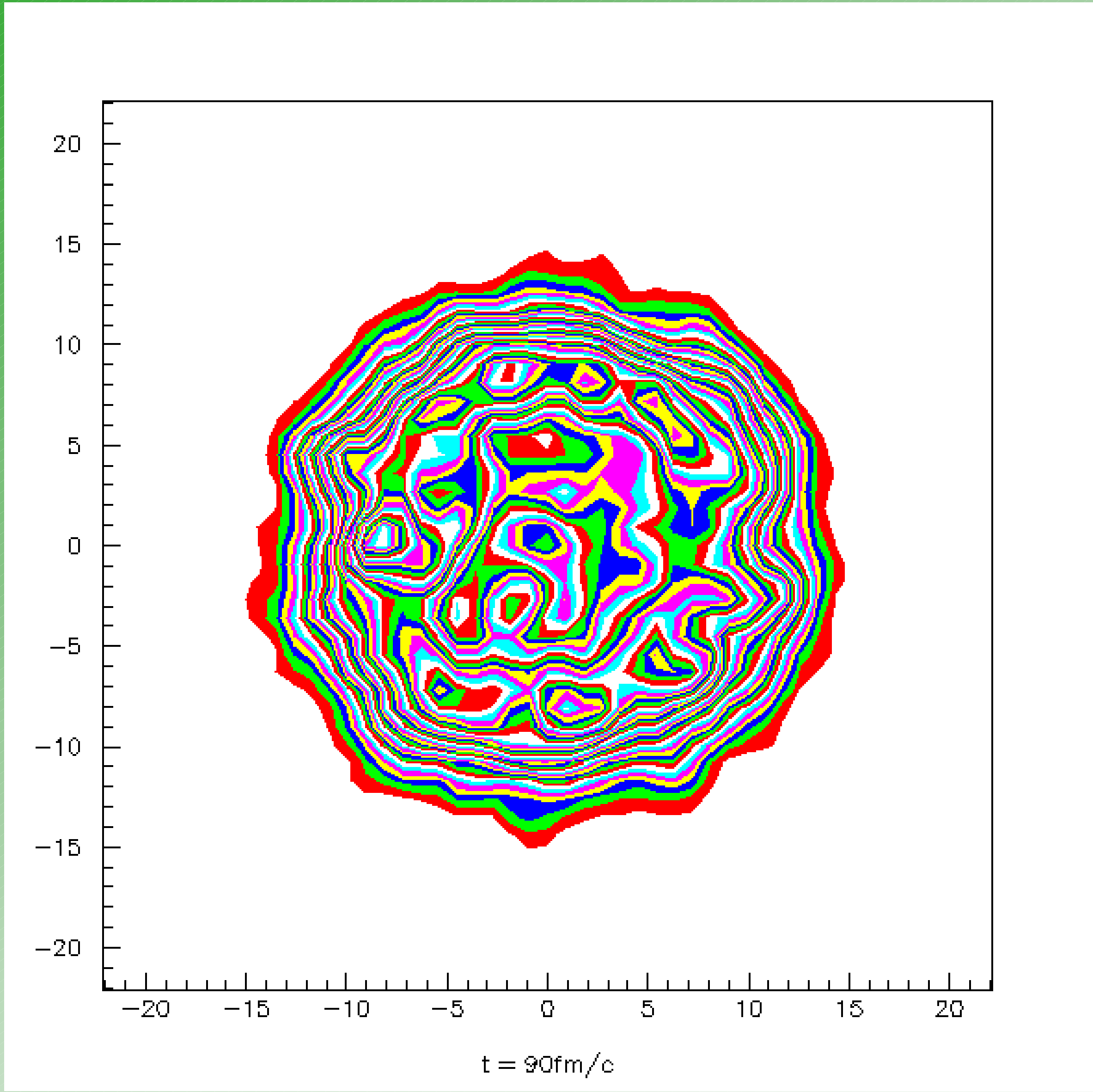

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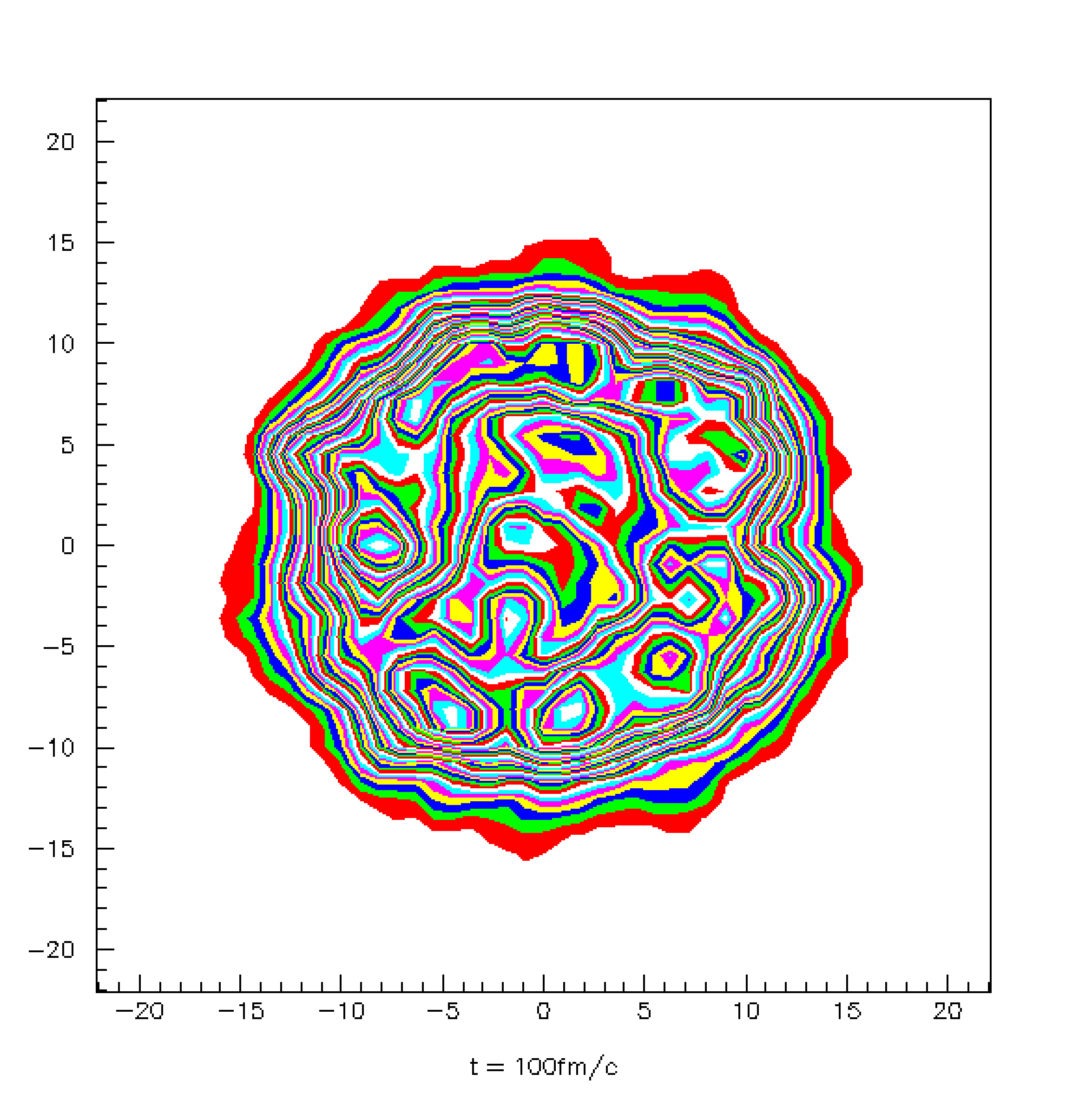

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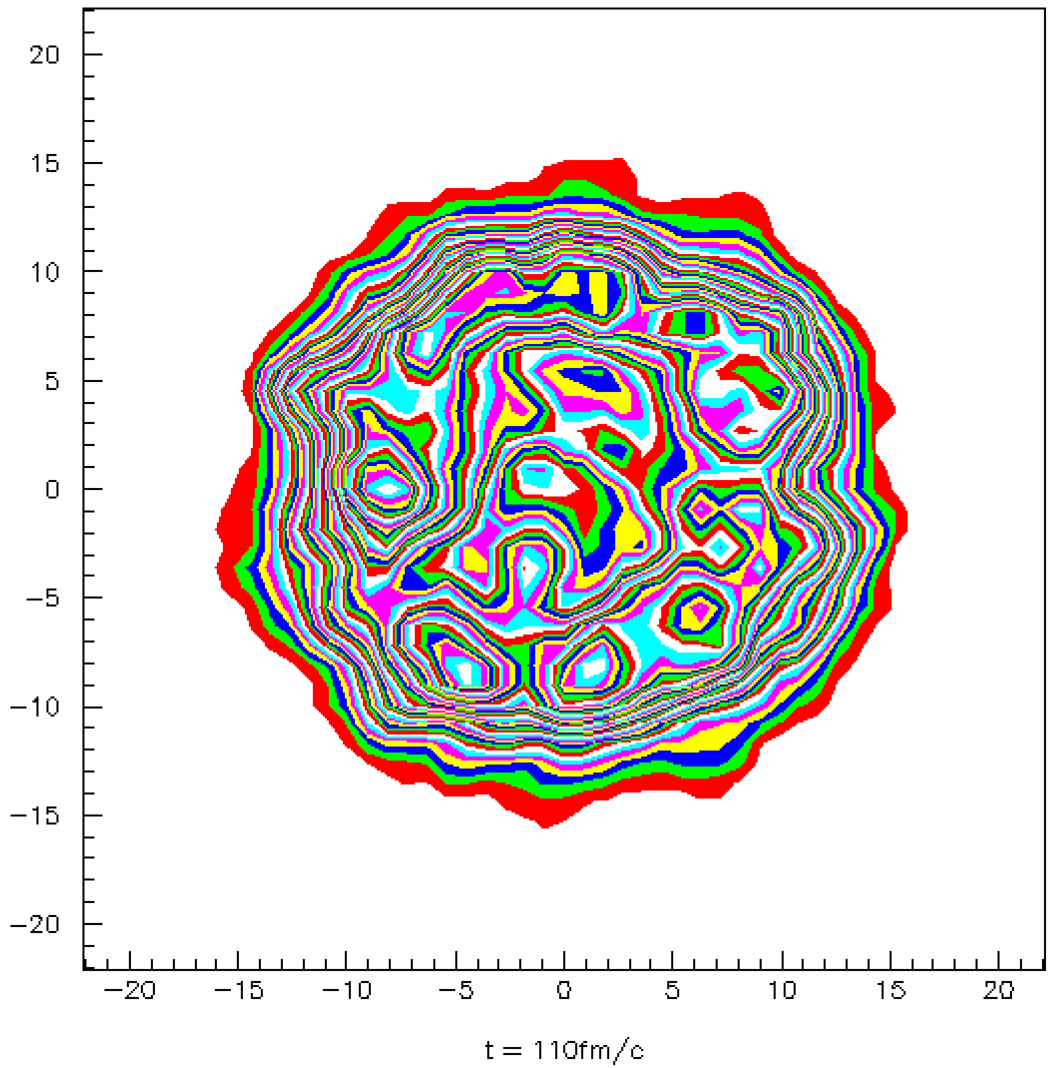

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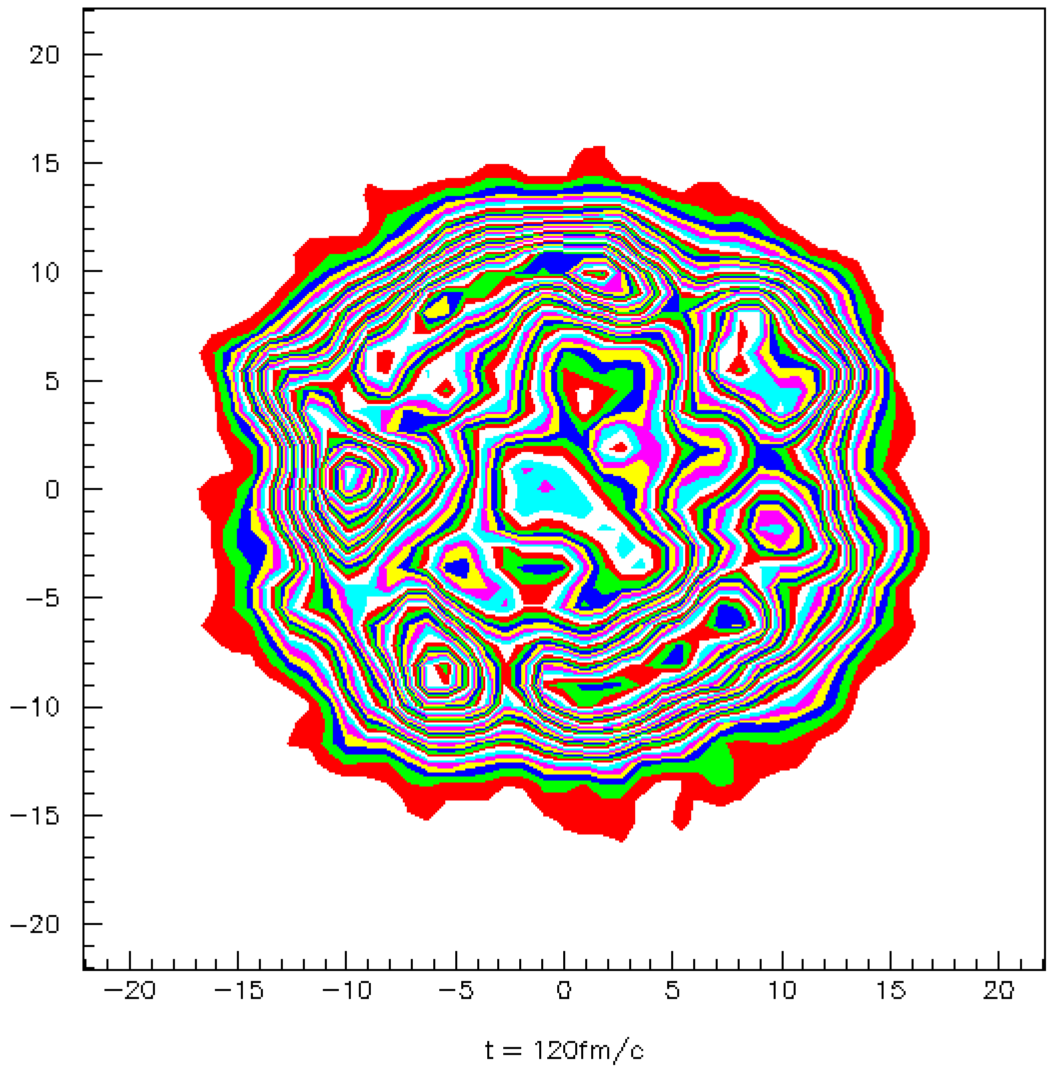

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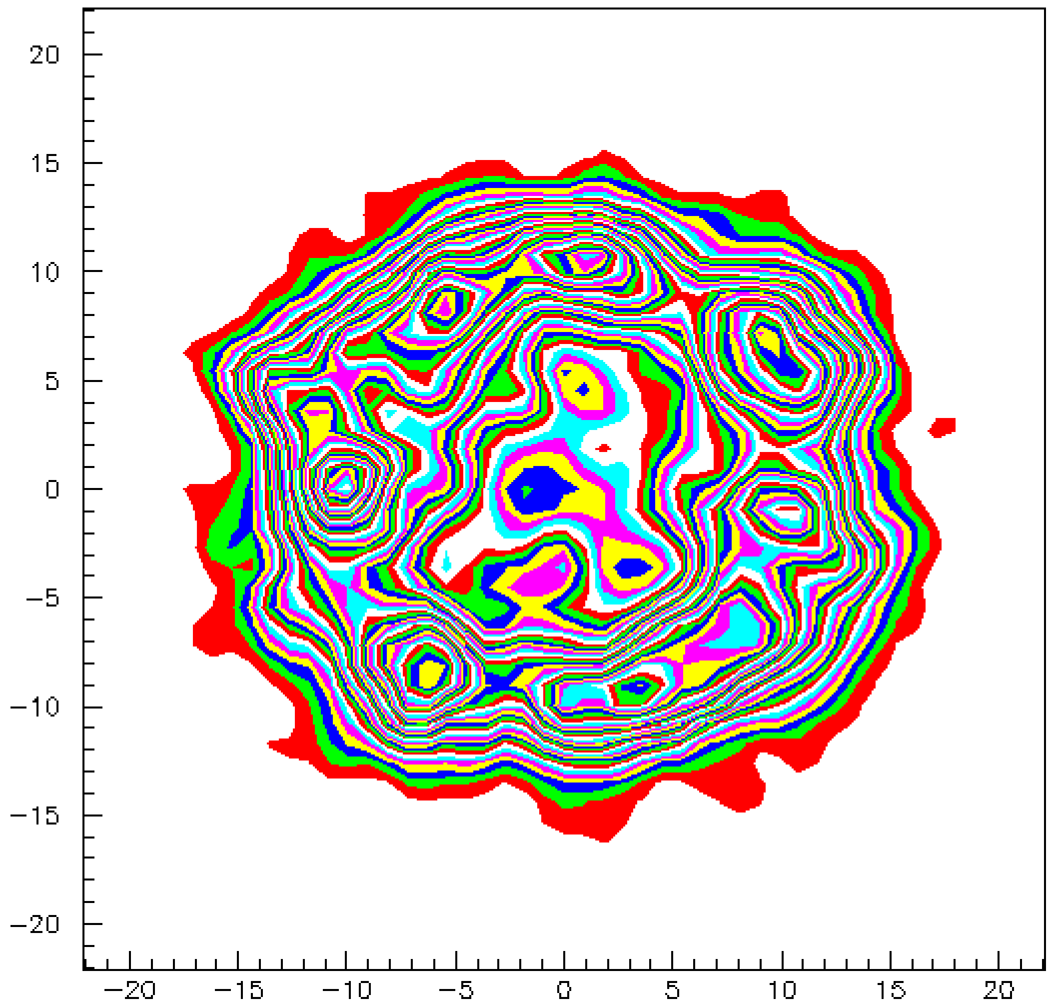
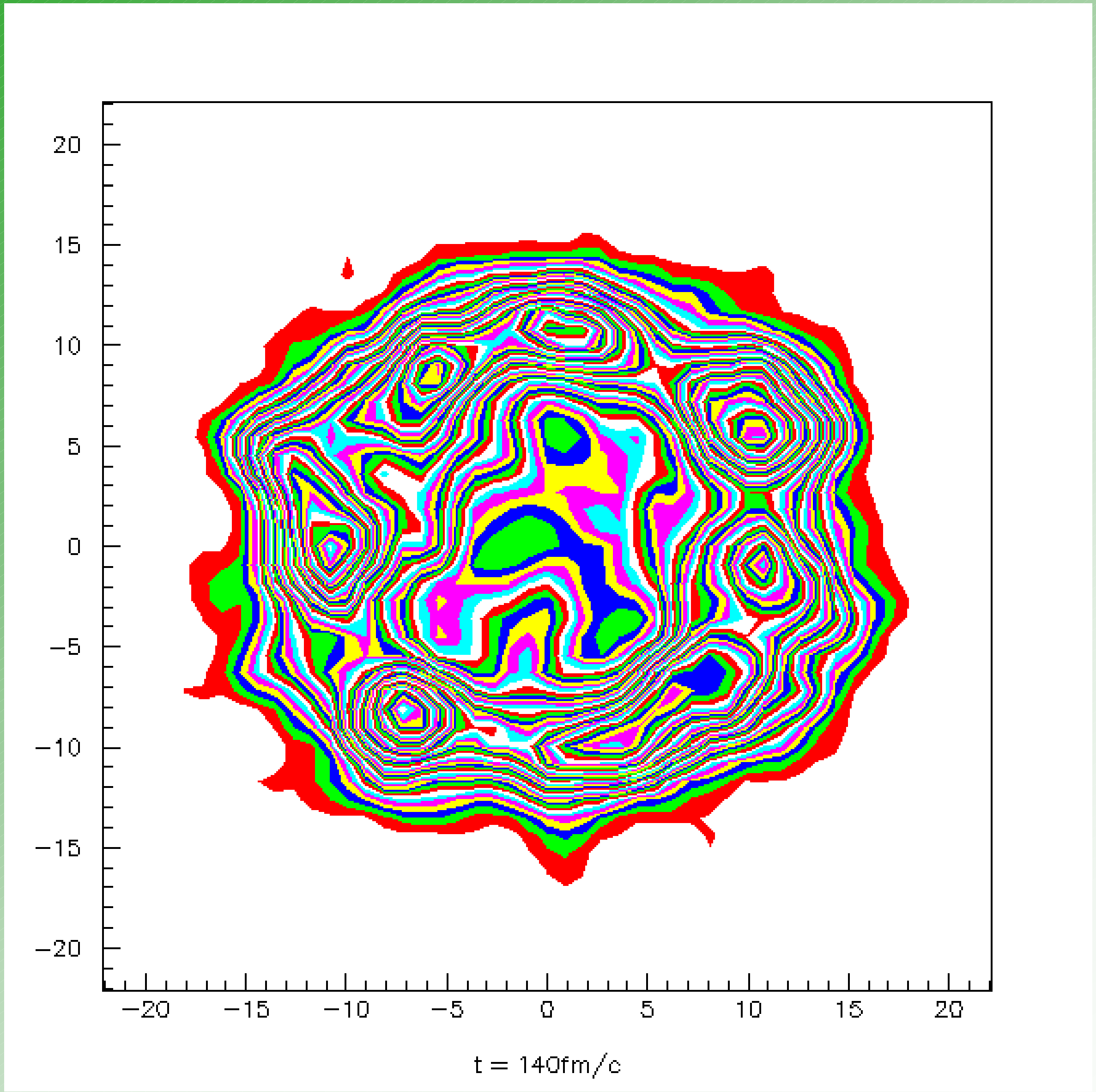


t = 130fm/c



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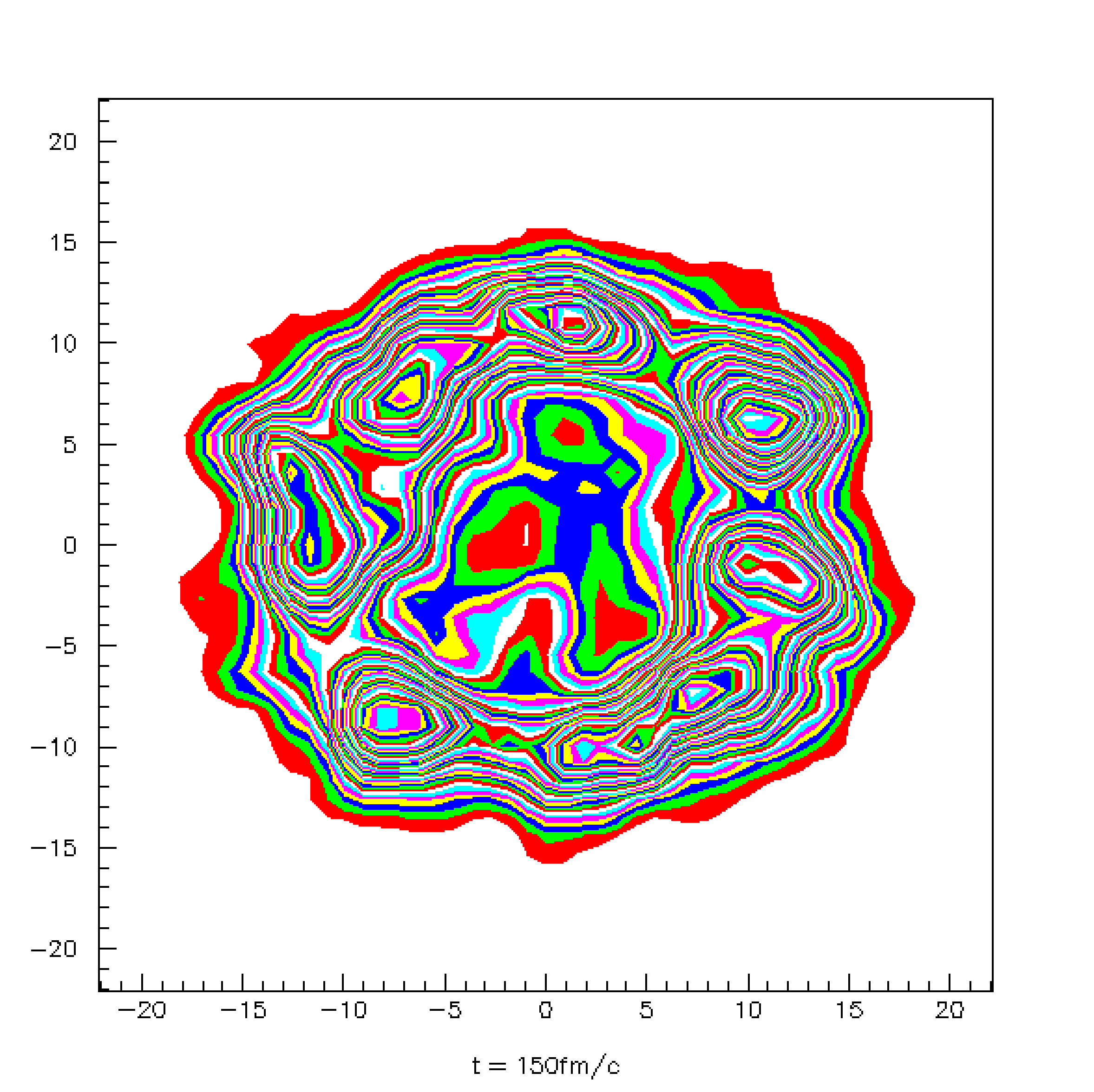
t = 140fm/c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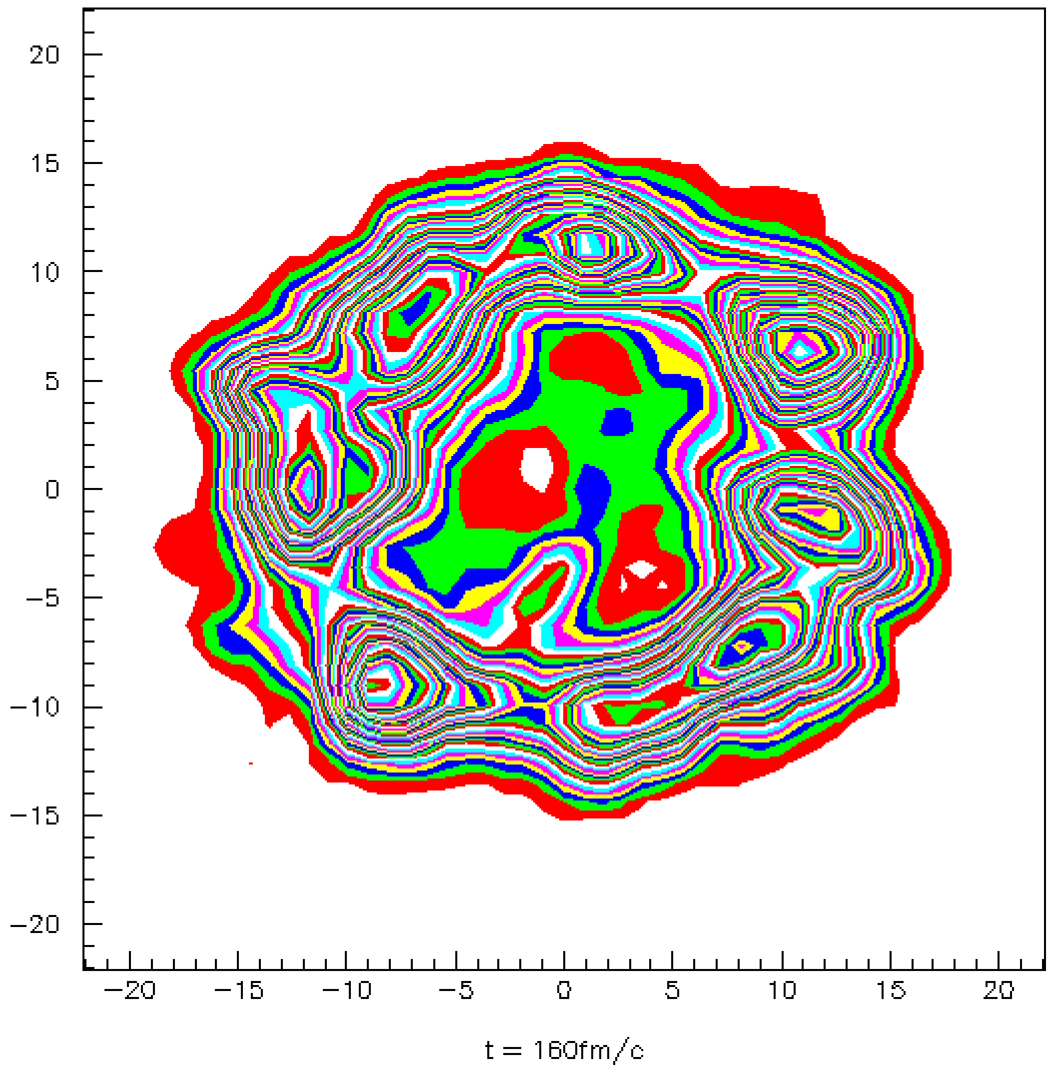

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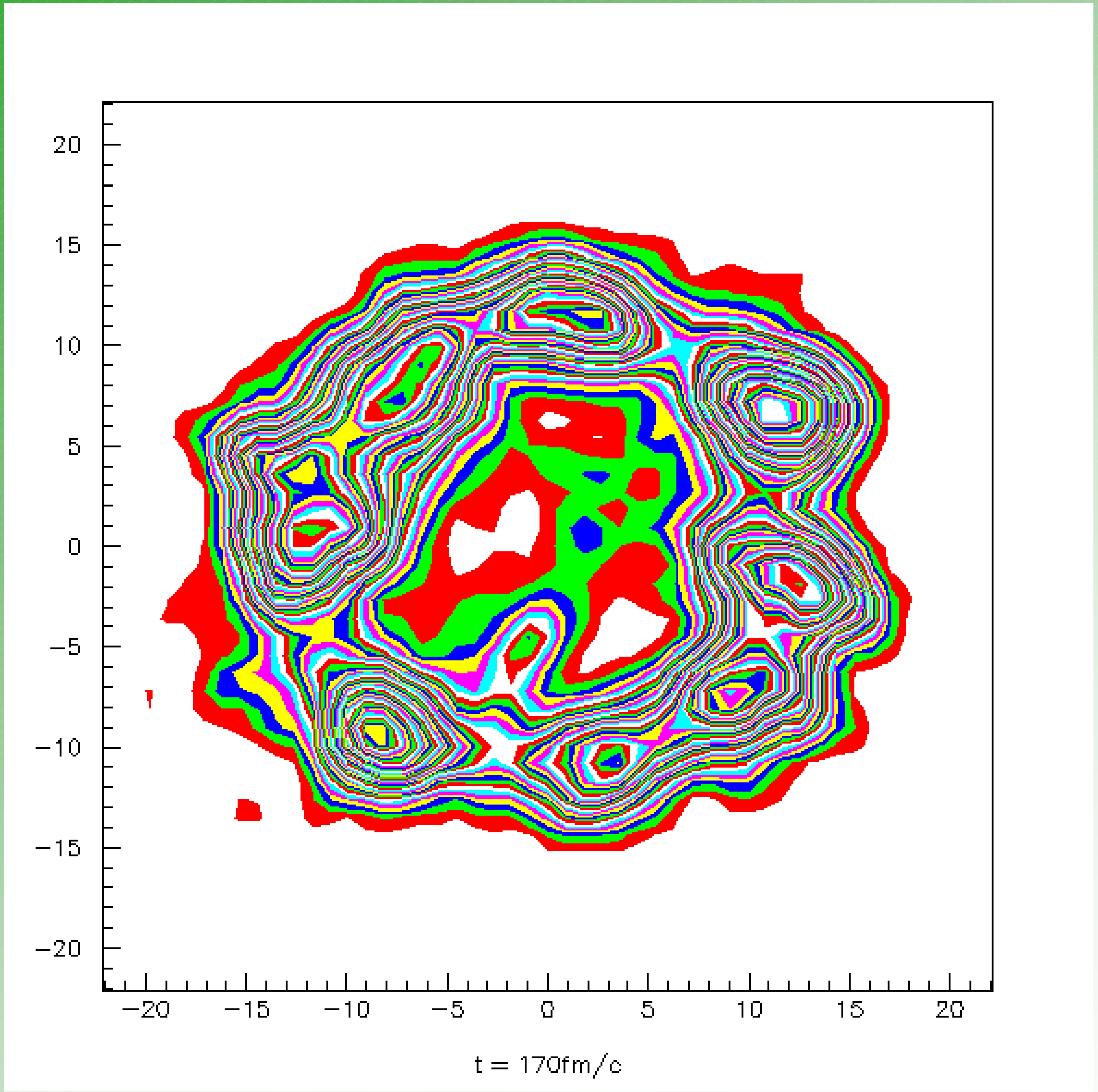
t = 160fm/c



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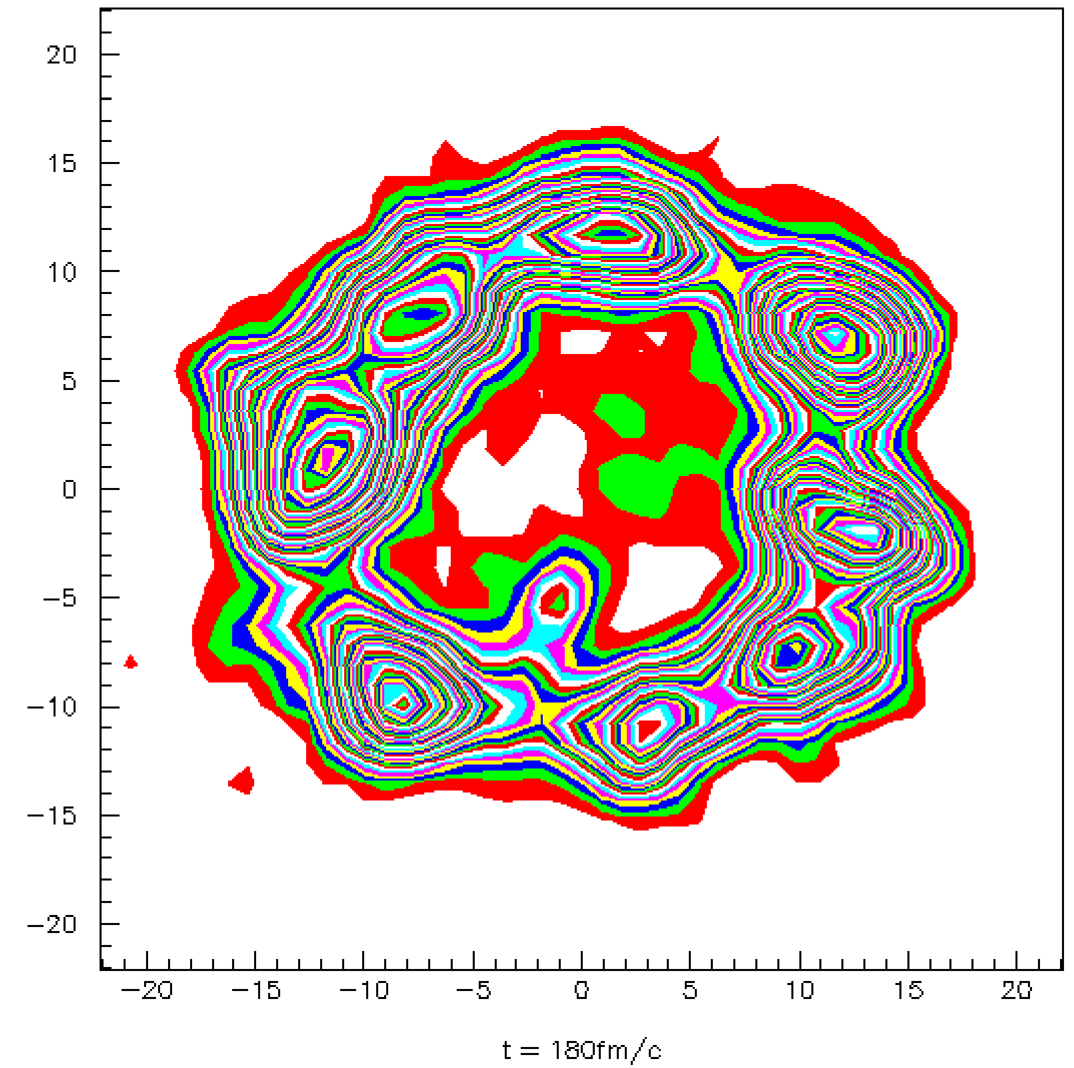

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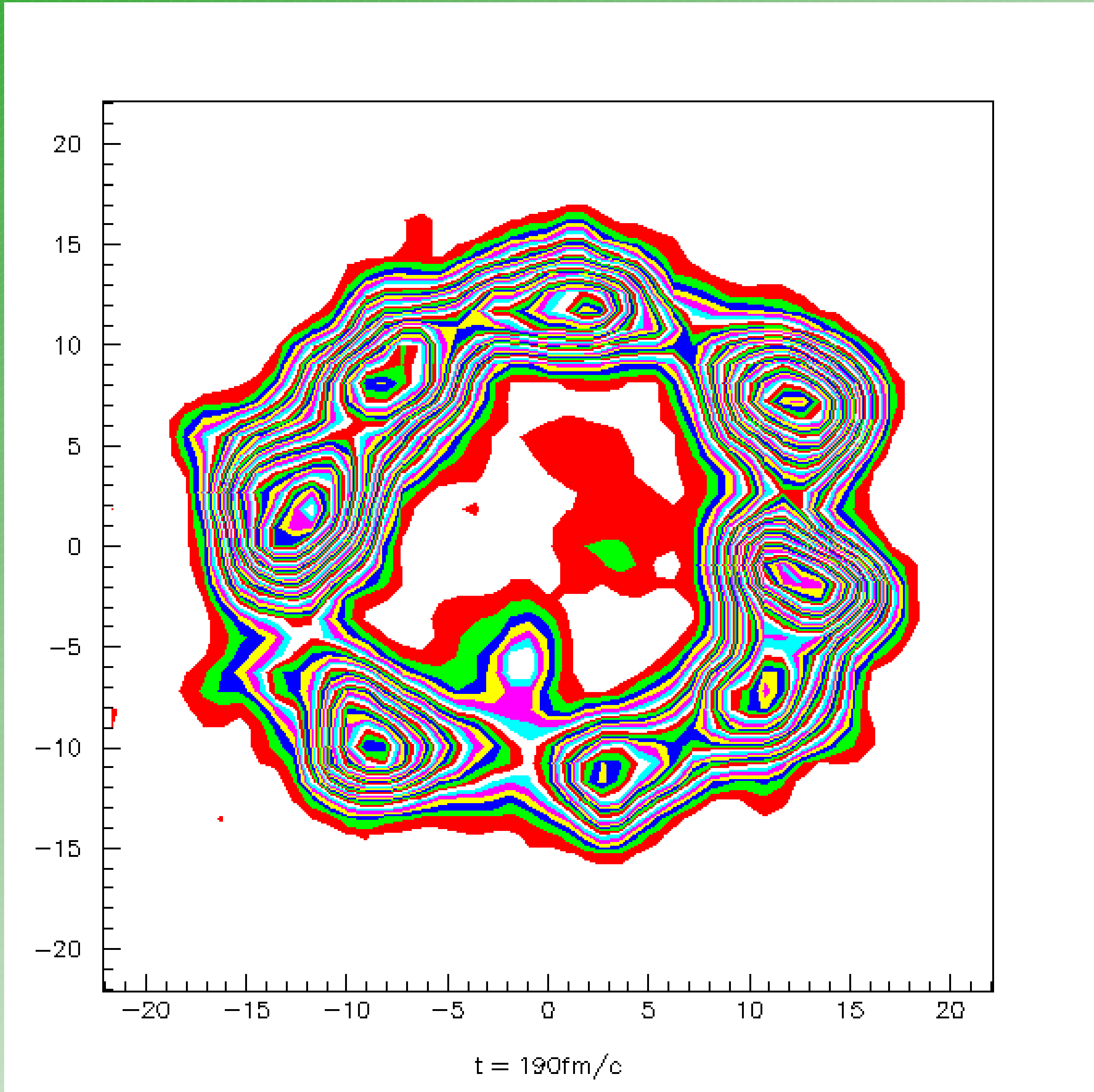
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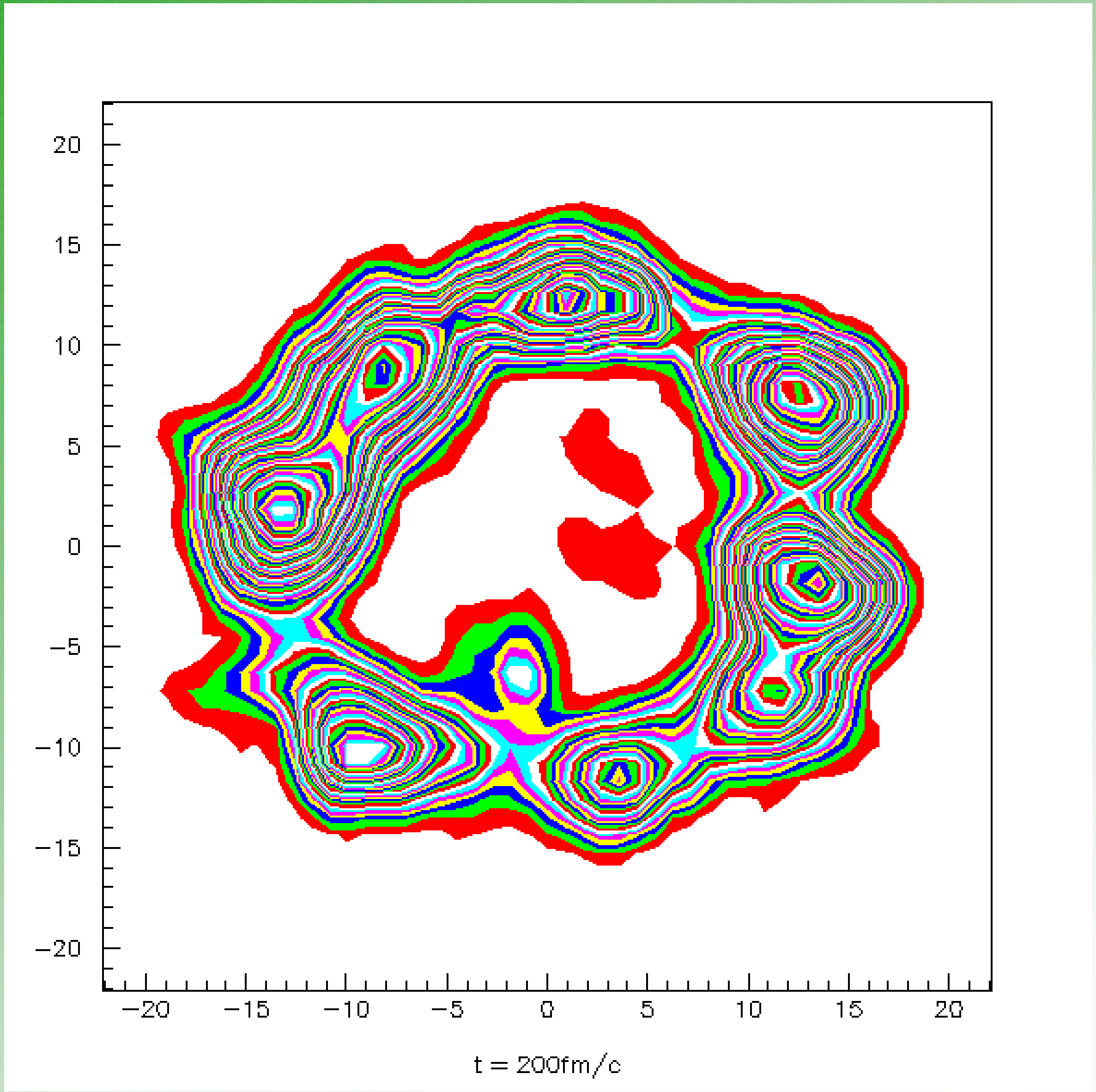

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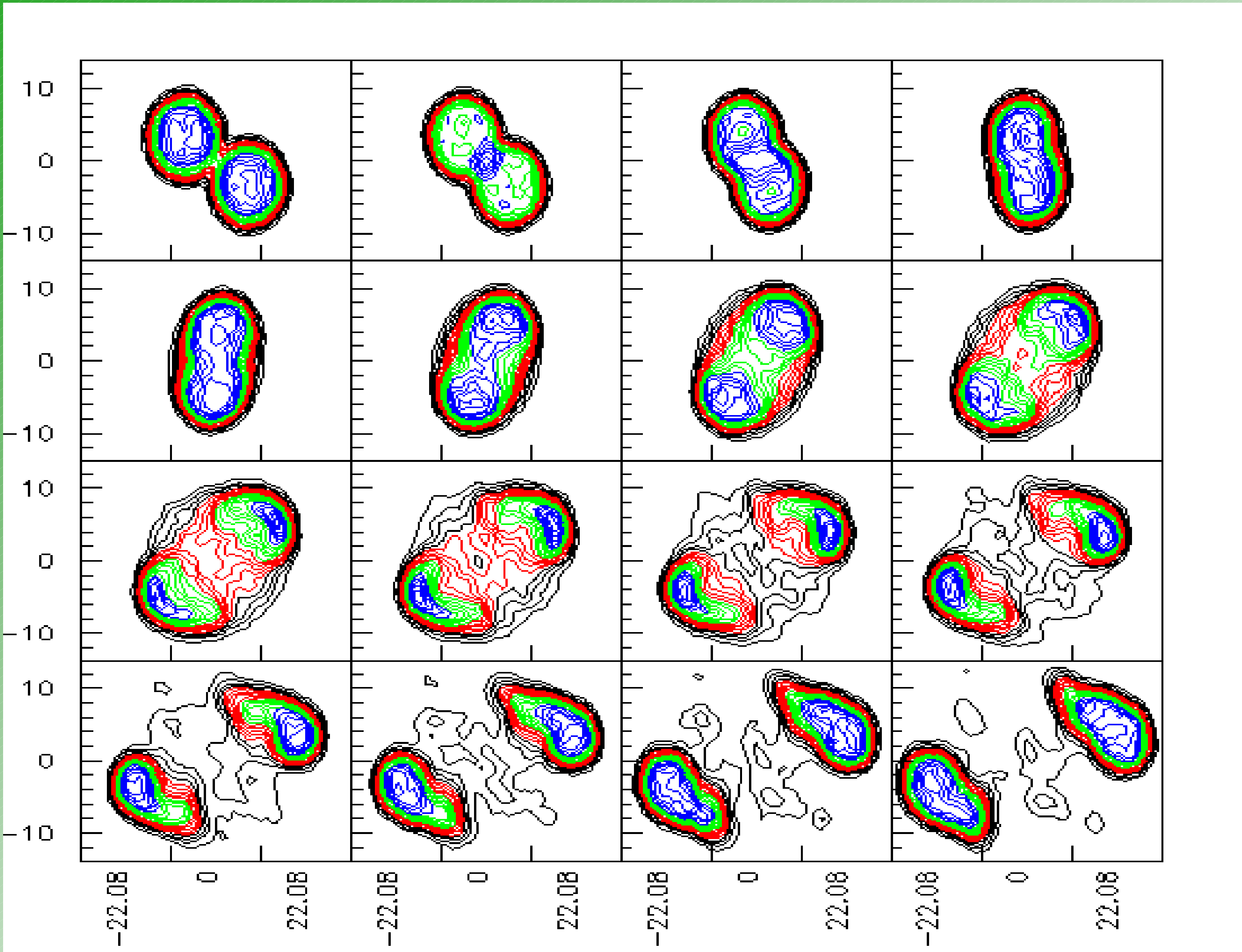
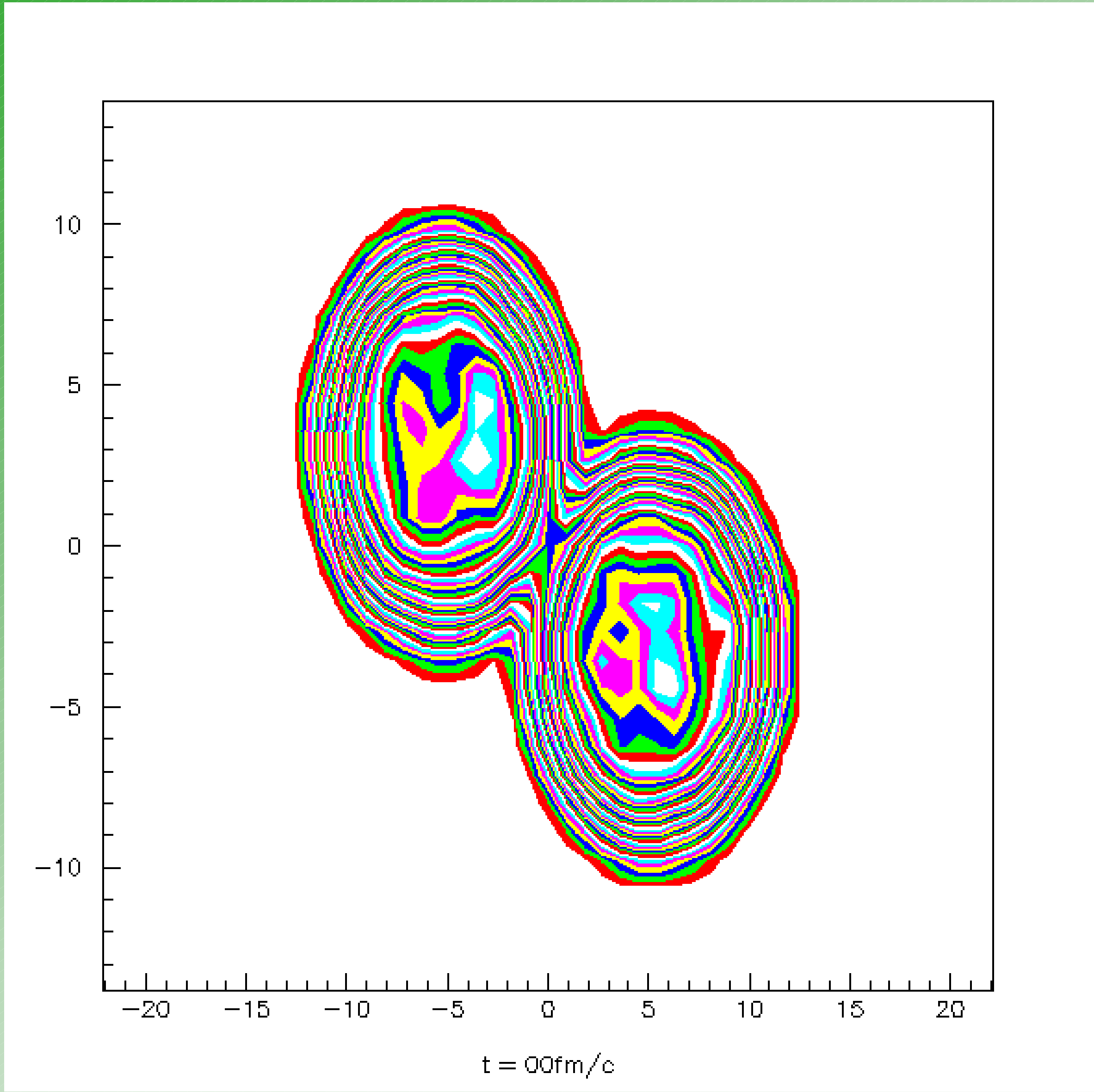
t = 200fm/c

Peripheral Collision $^{124}Sn+^{124}Sn$





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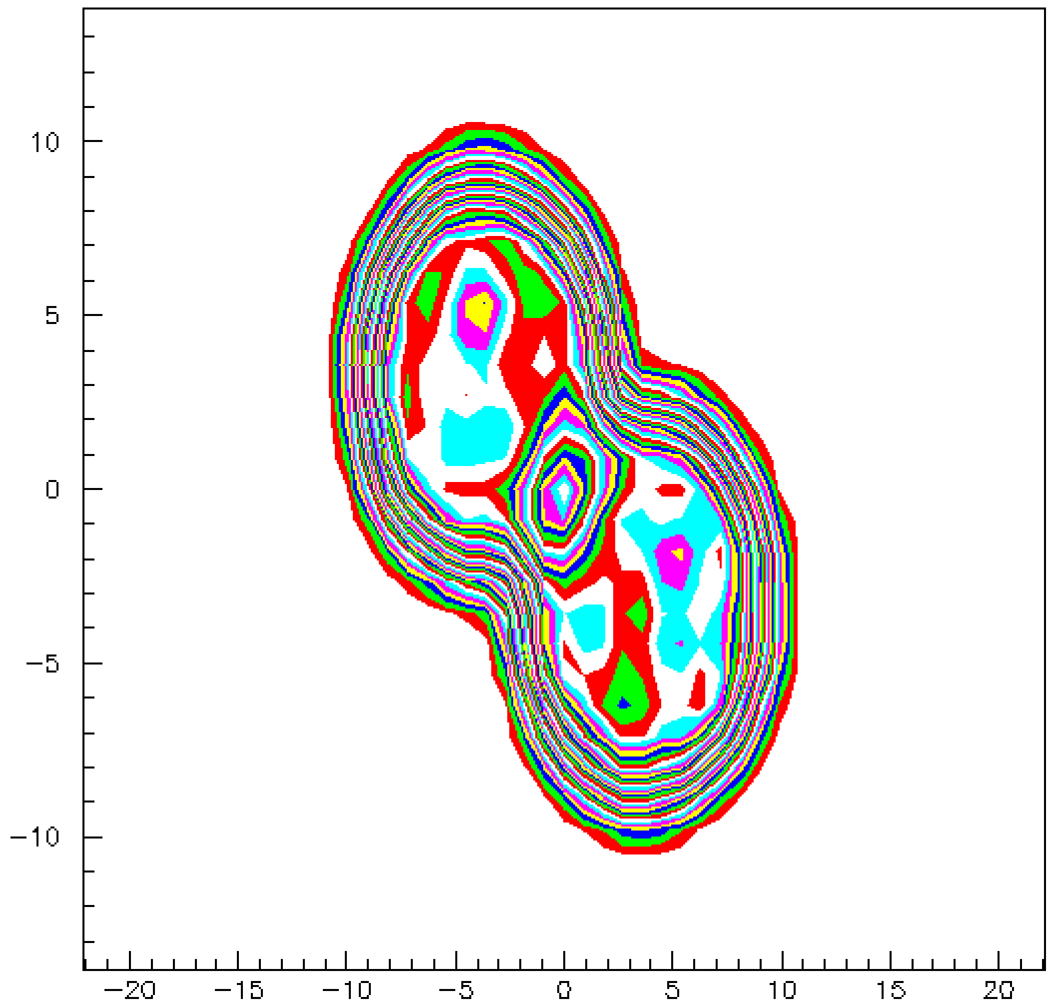

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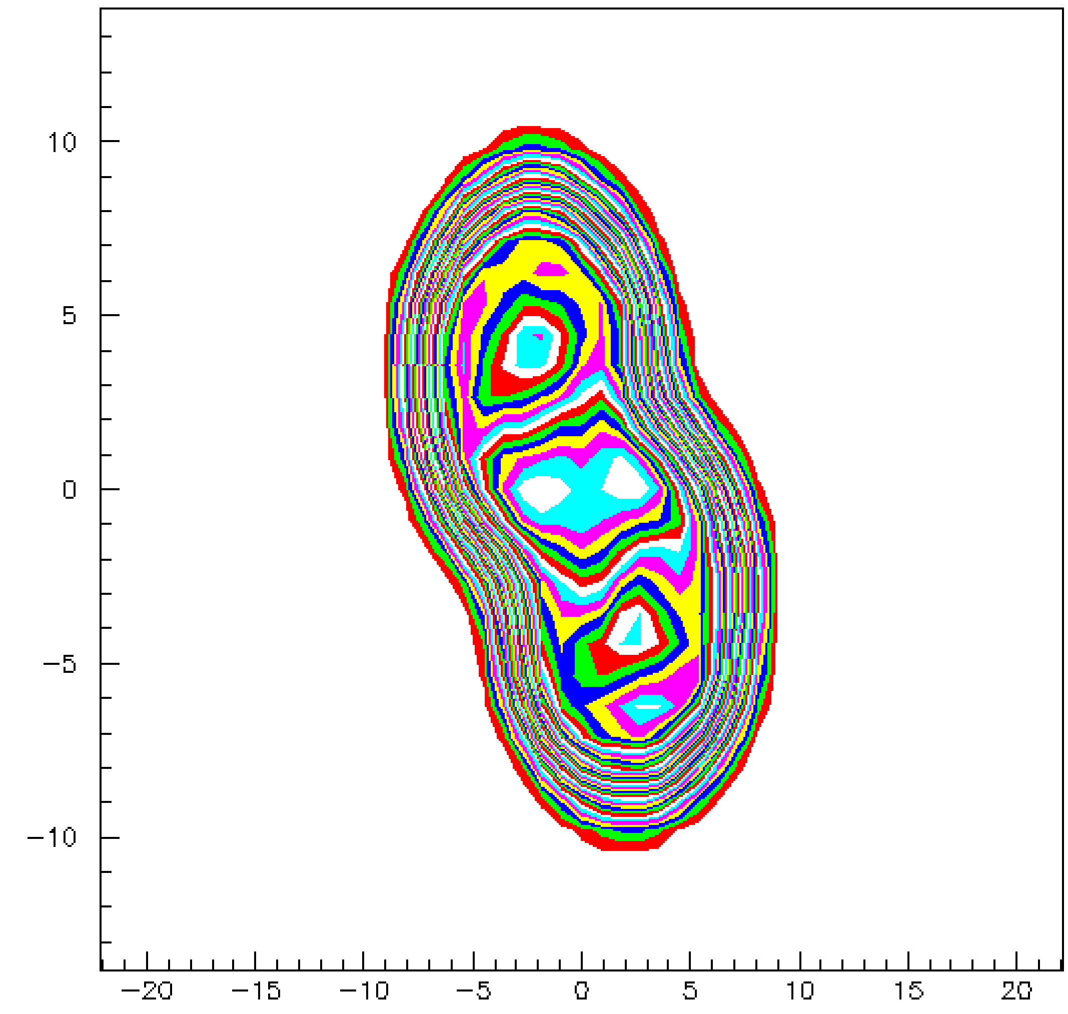

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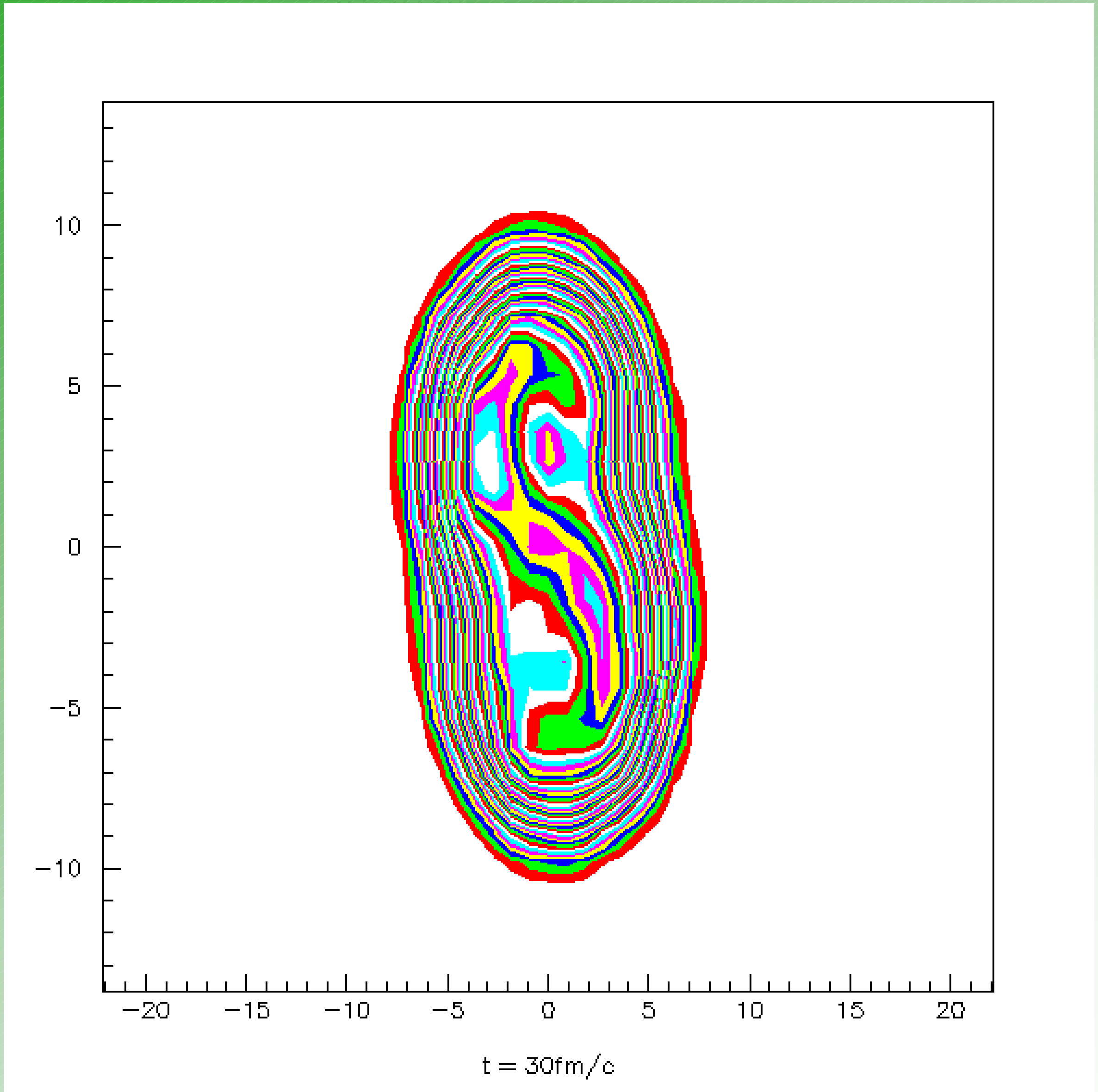

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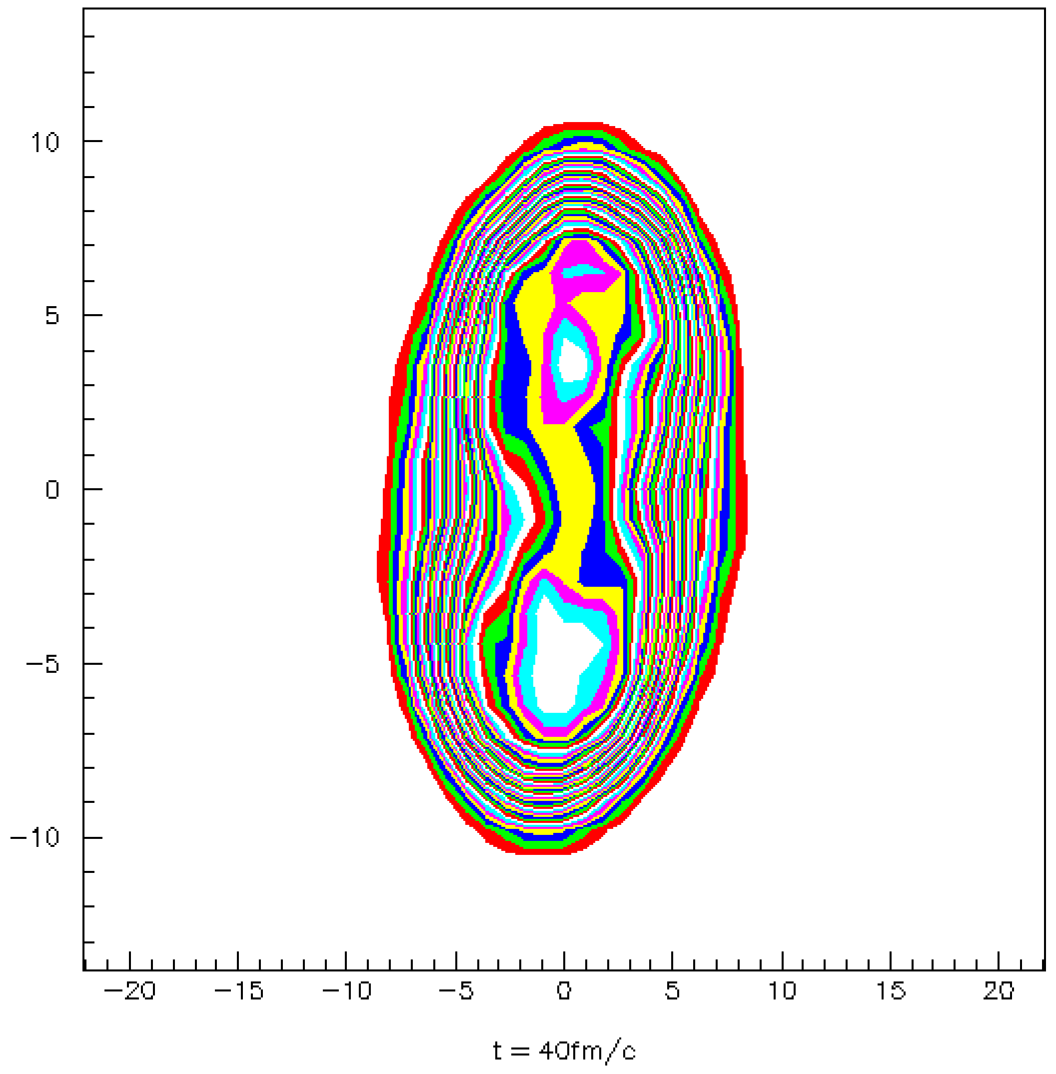
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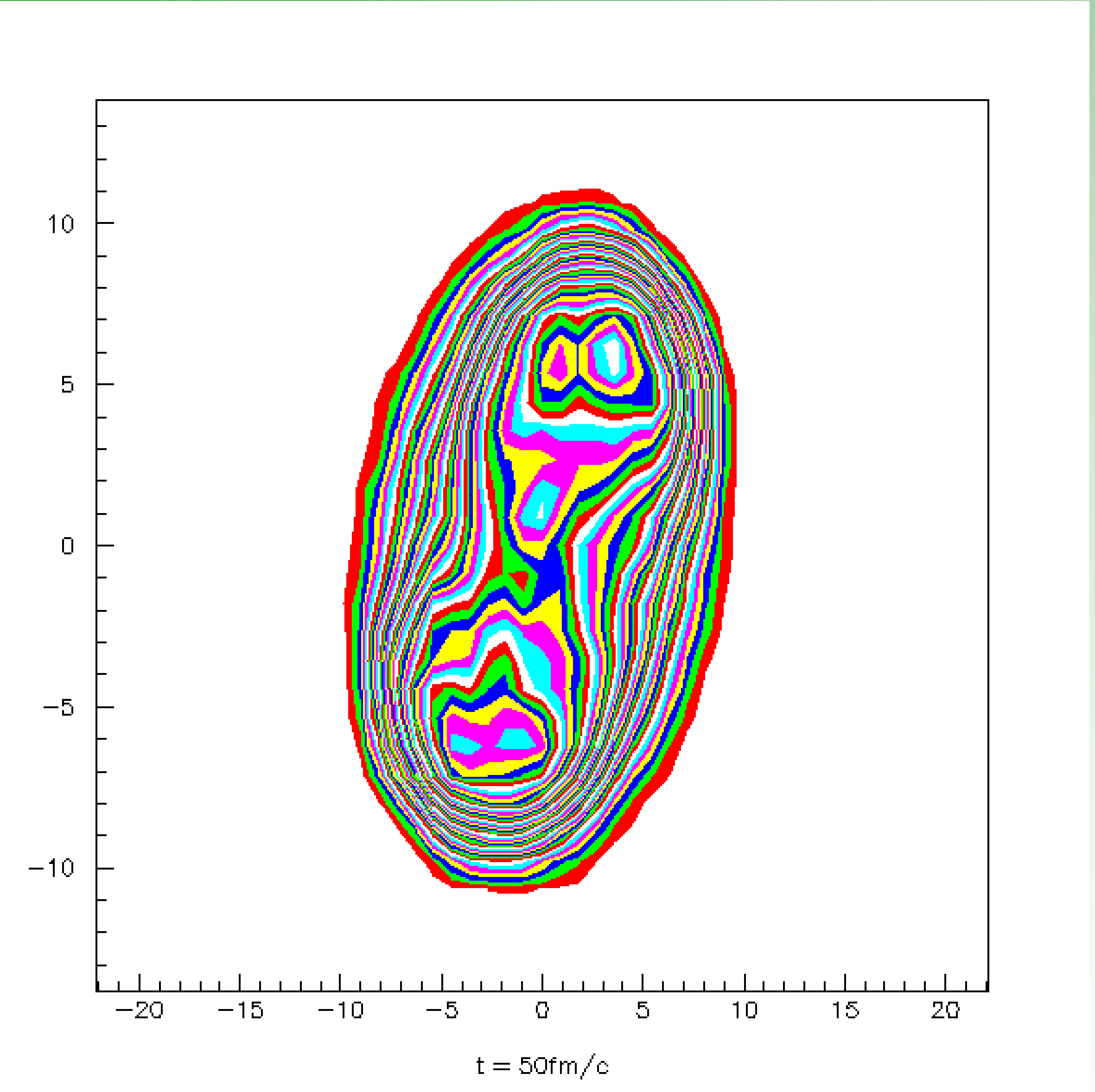

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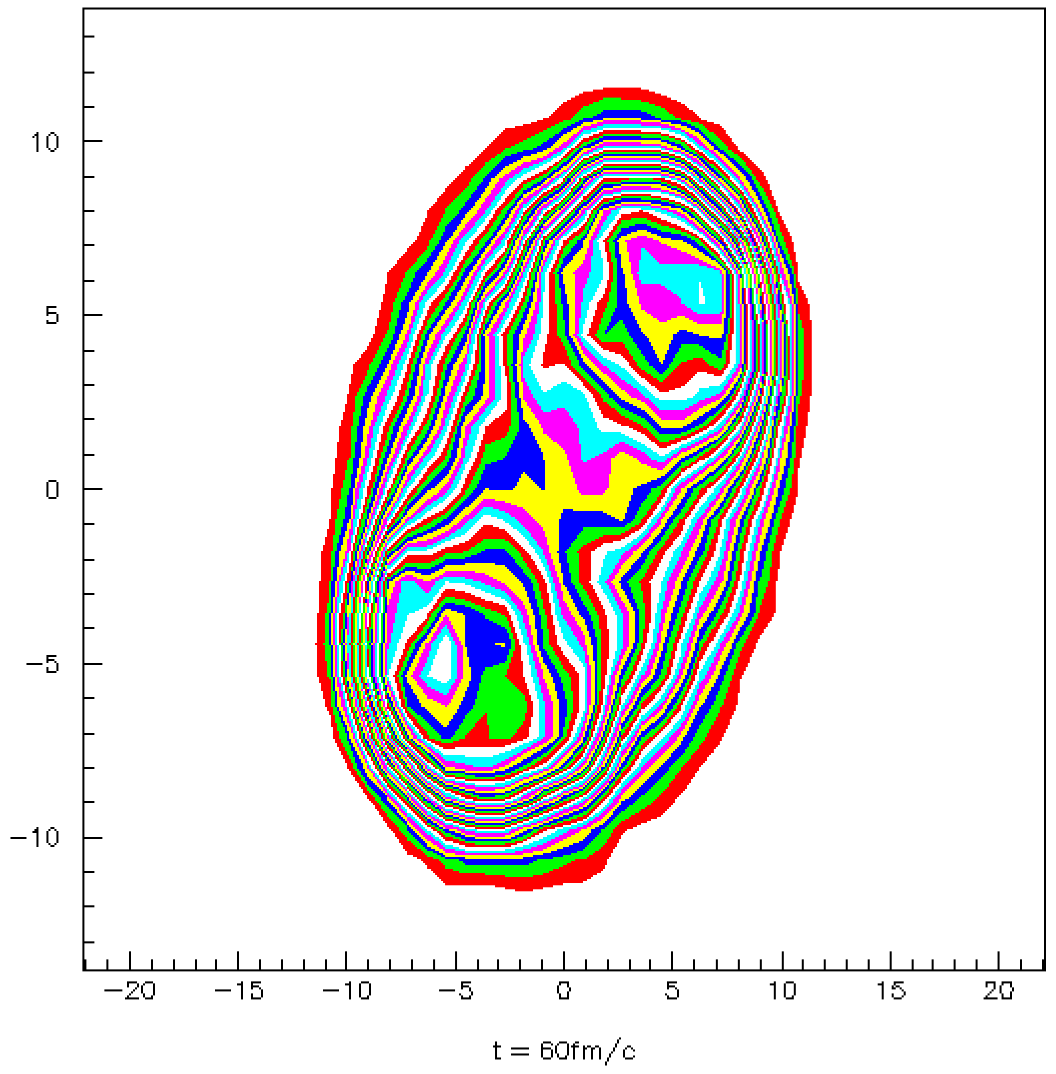

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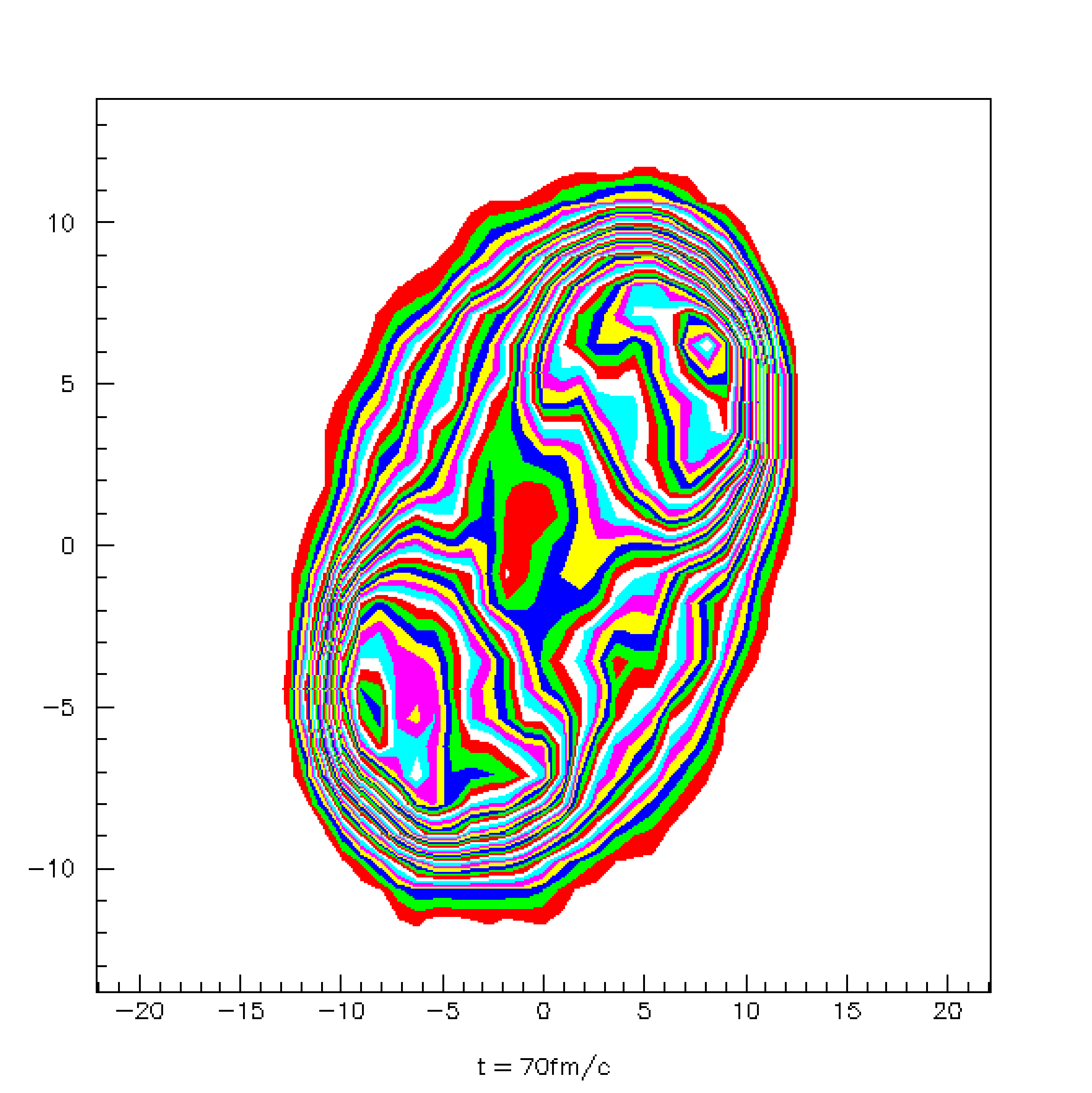

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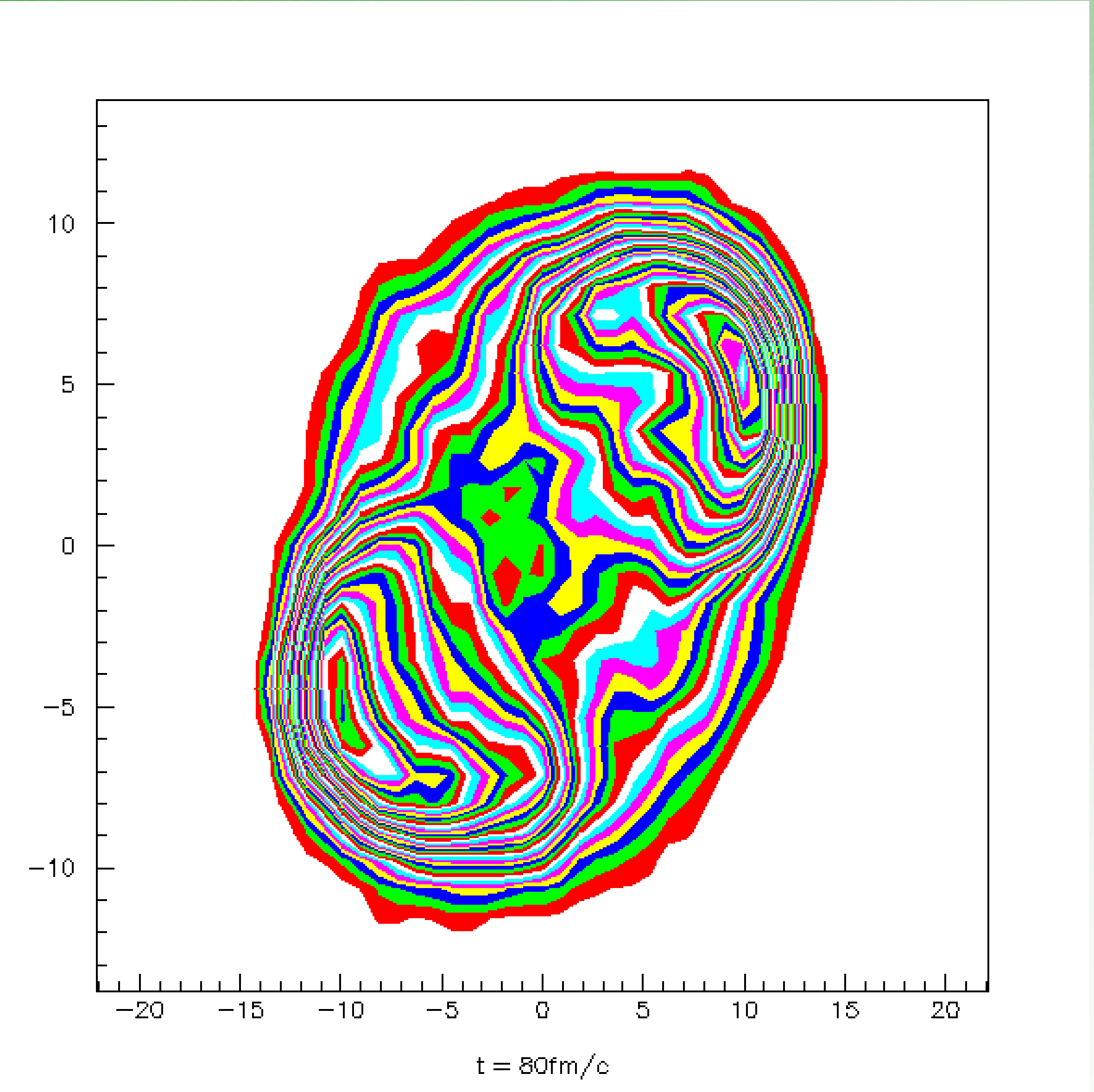
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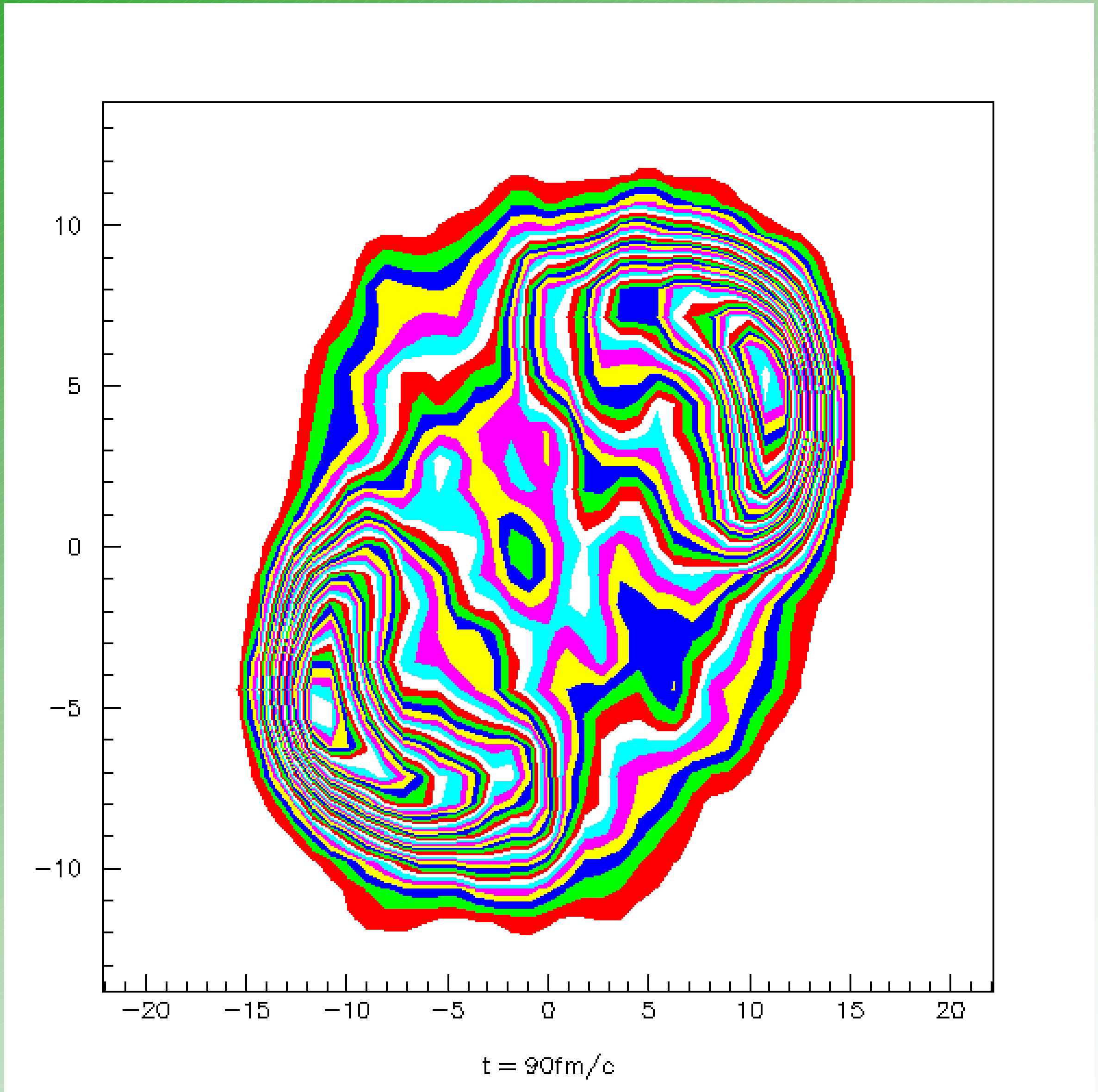
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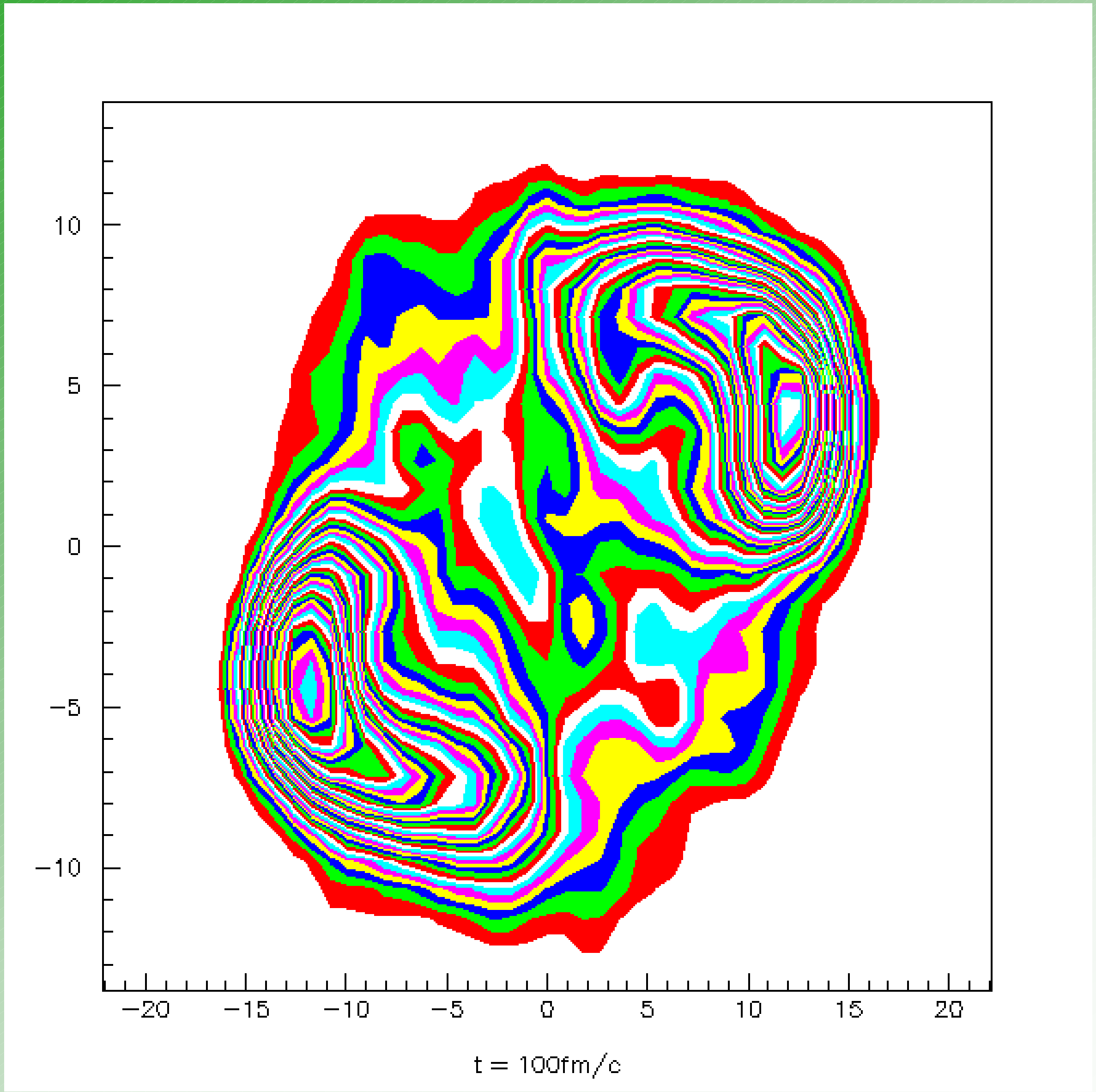
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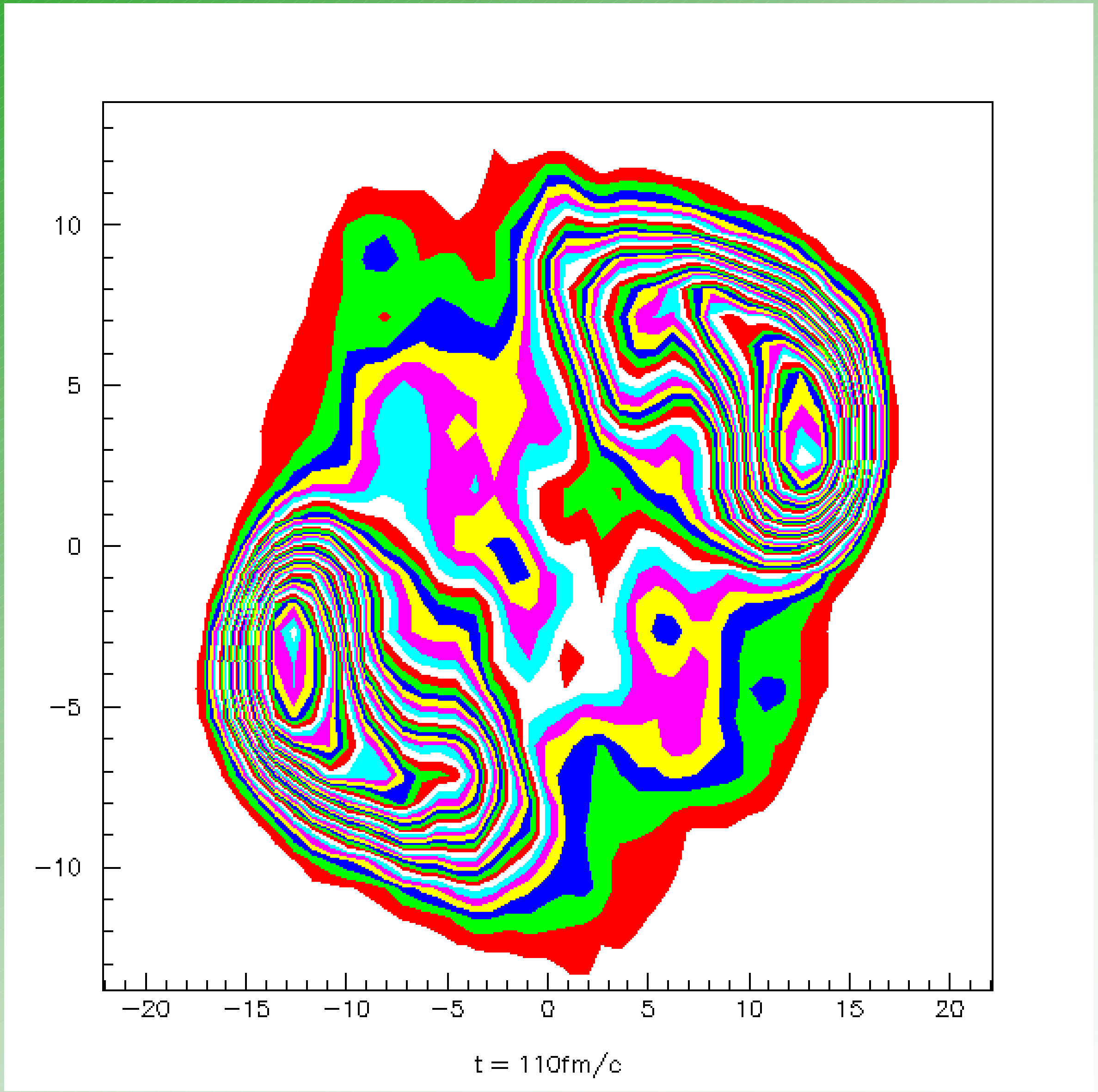

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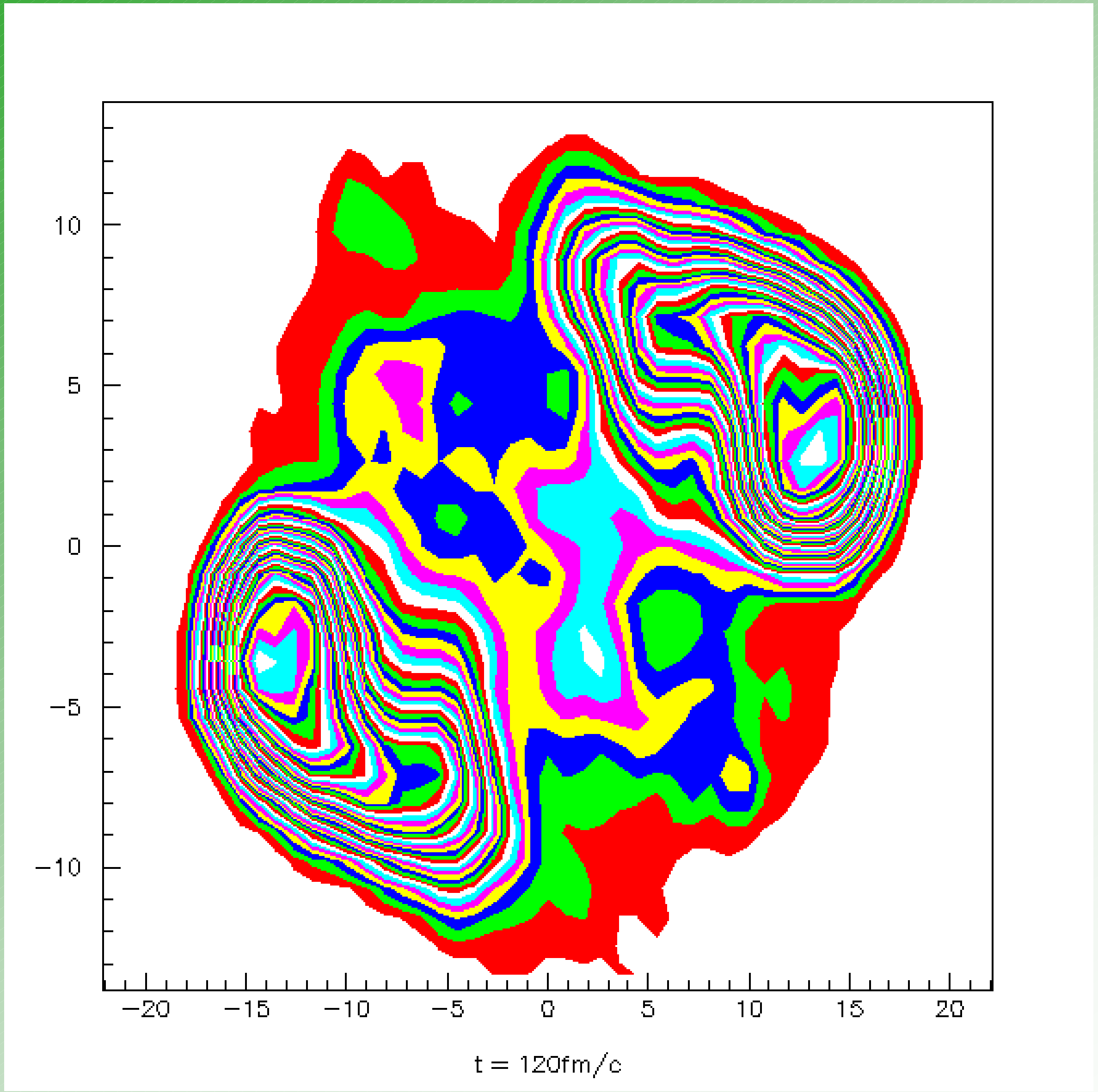
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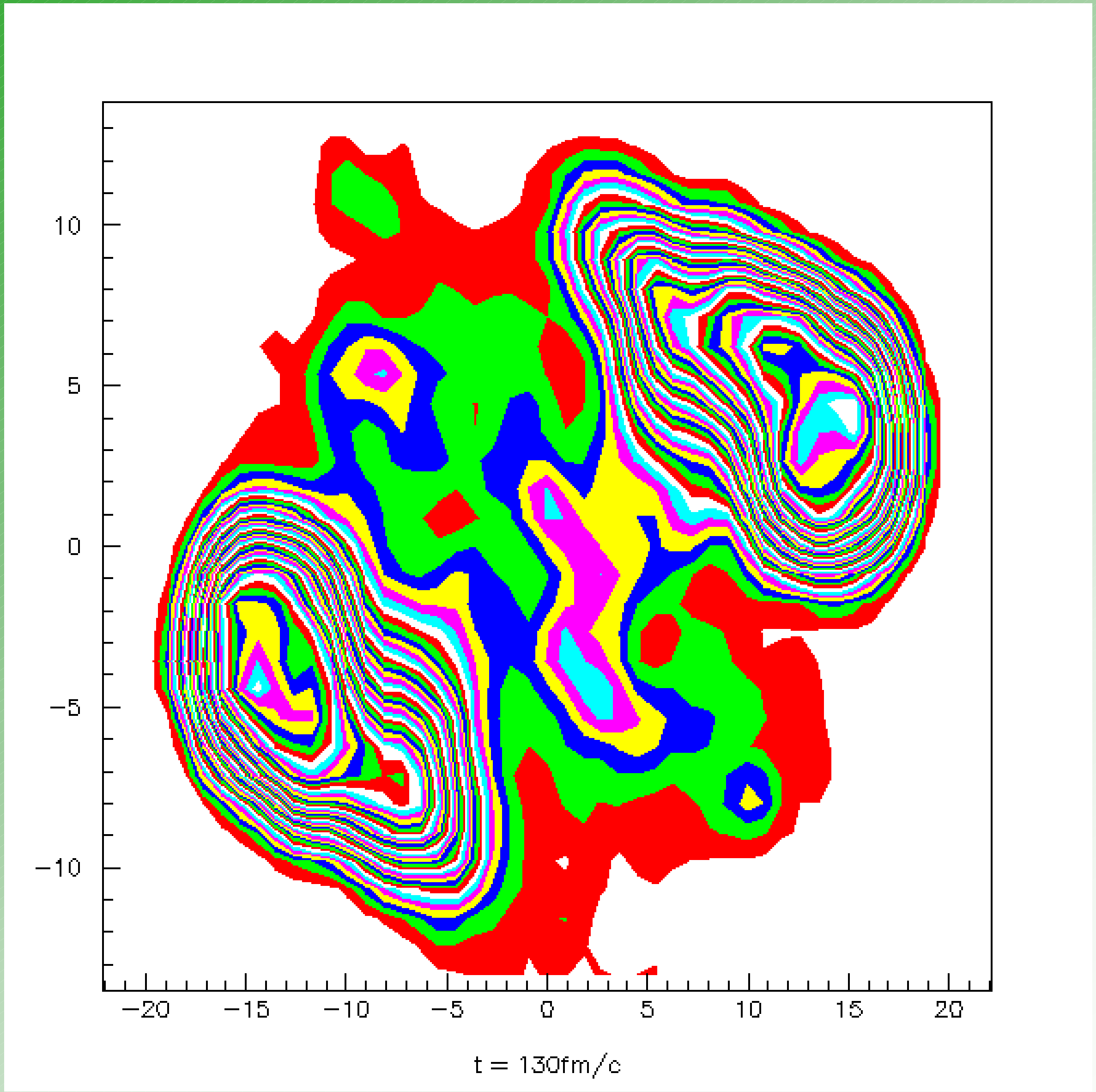
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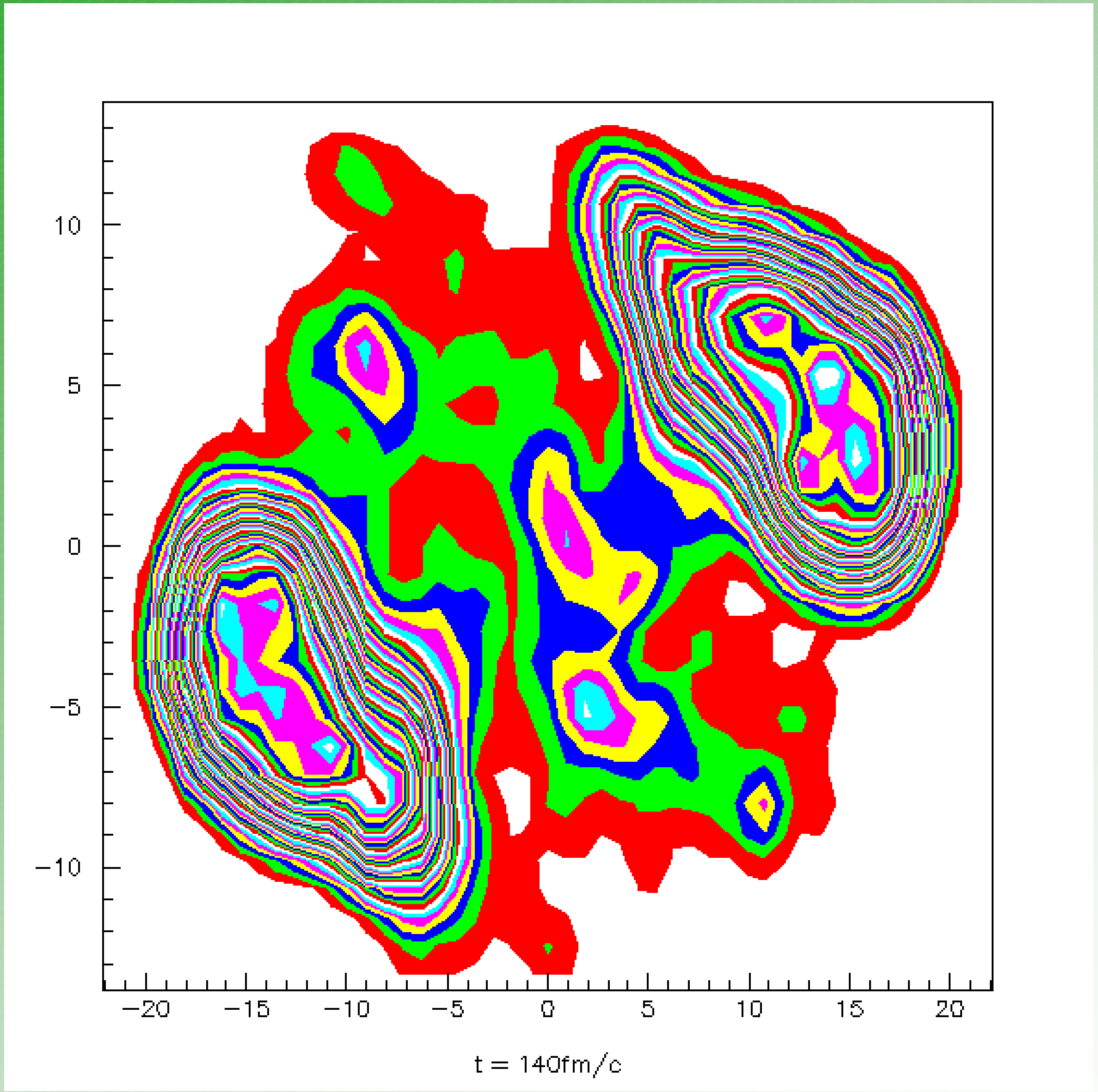

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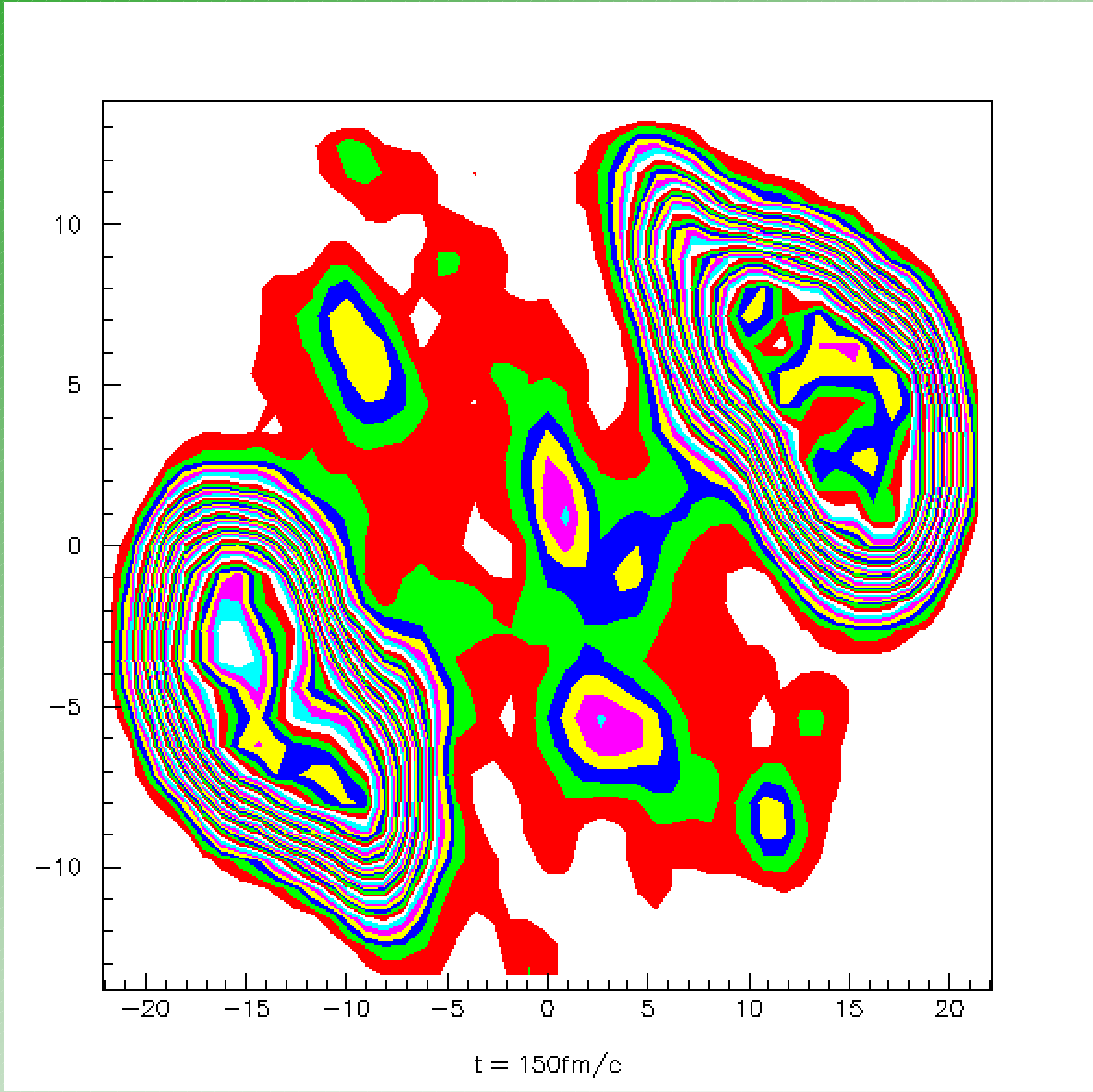
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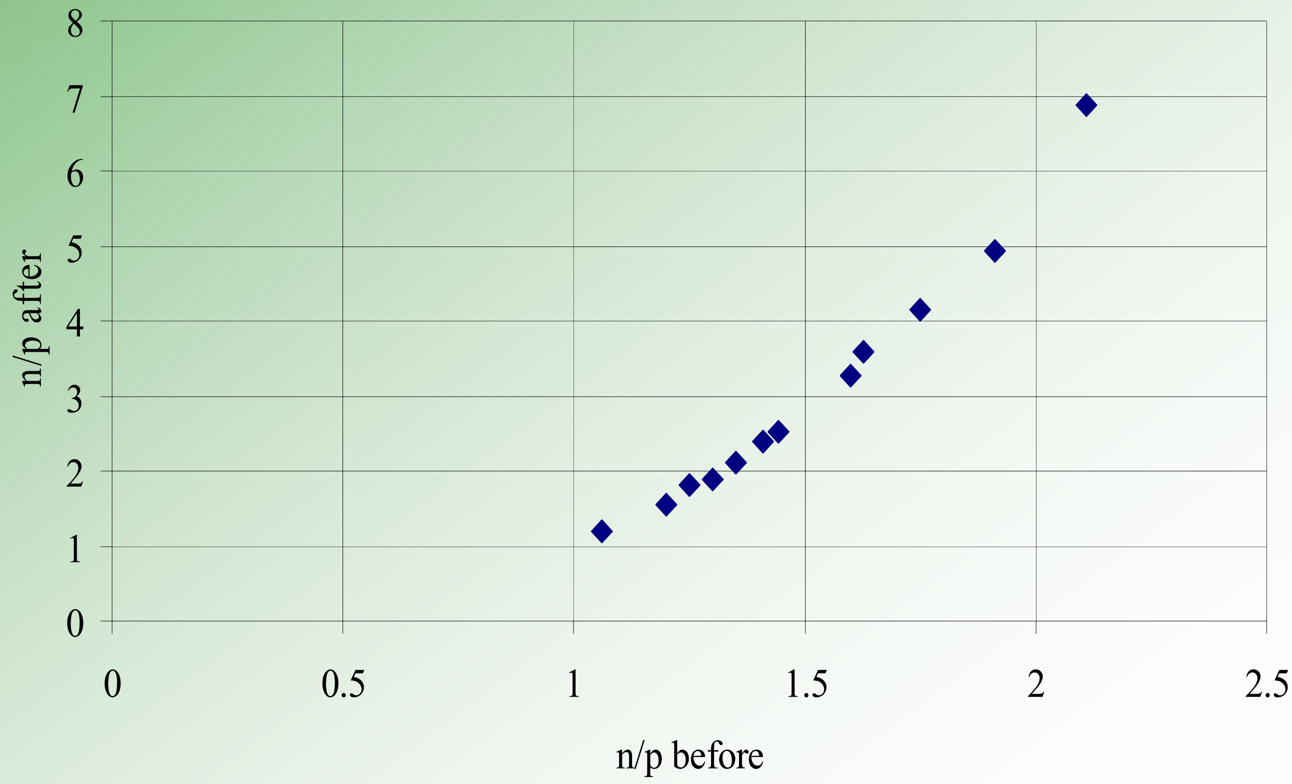
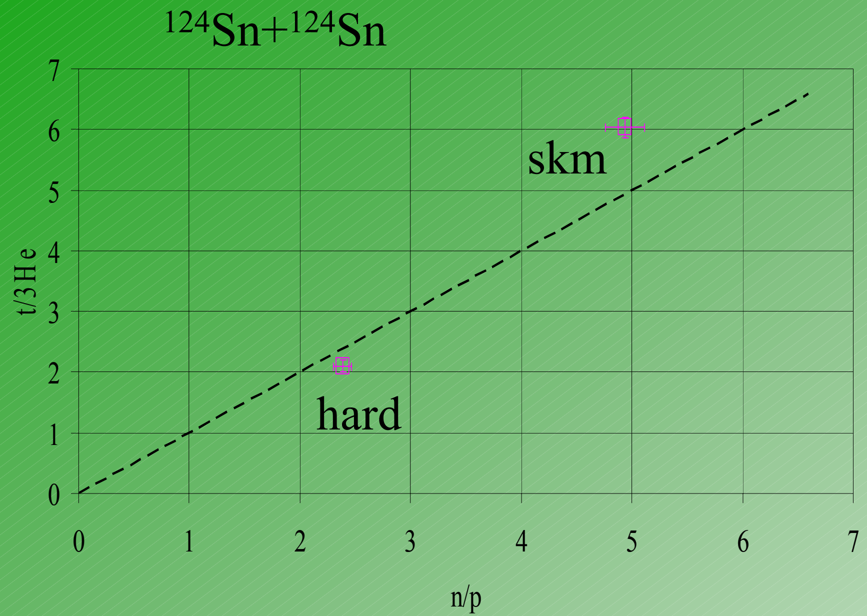
t = 150fm/c

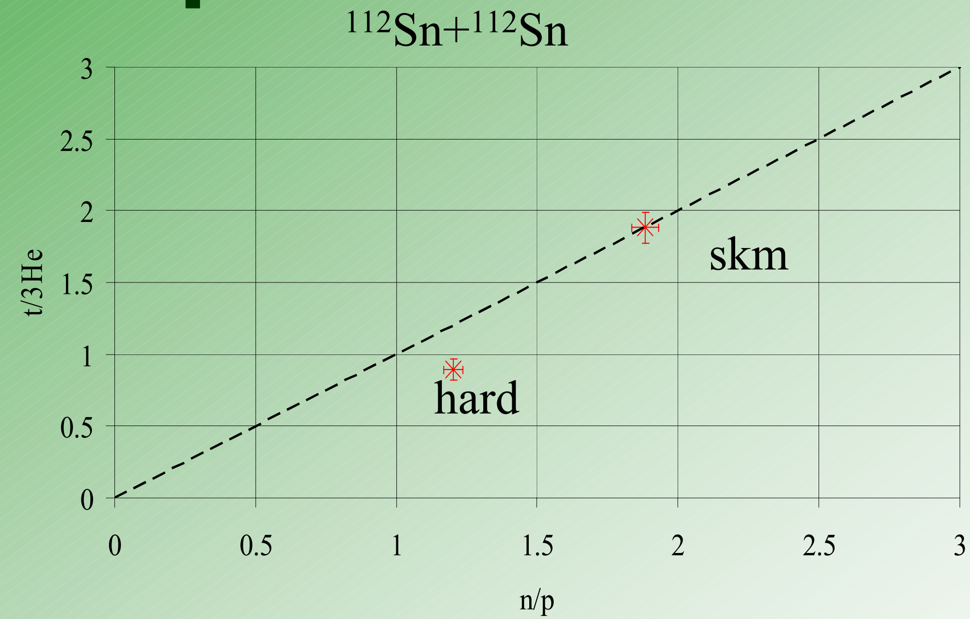
Coalescence

- Nucleons are considered to be part of a cluster if the difference between velocity and position is small.
- As clusters are formed, the n/p ratio increases, consistent with neutron enrichment seen in experiment



t/^{3}He vs n/p


124Sn+124Sn
skm
hard
t/3He
n/p


112Sn+112Sn
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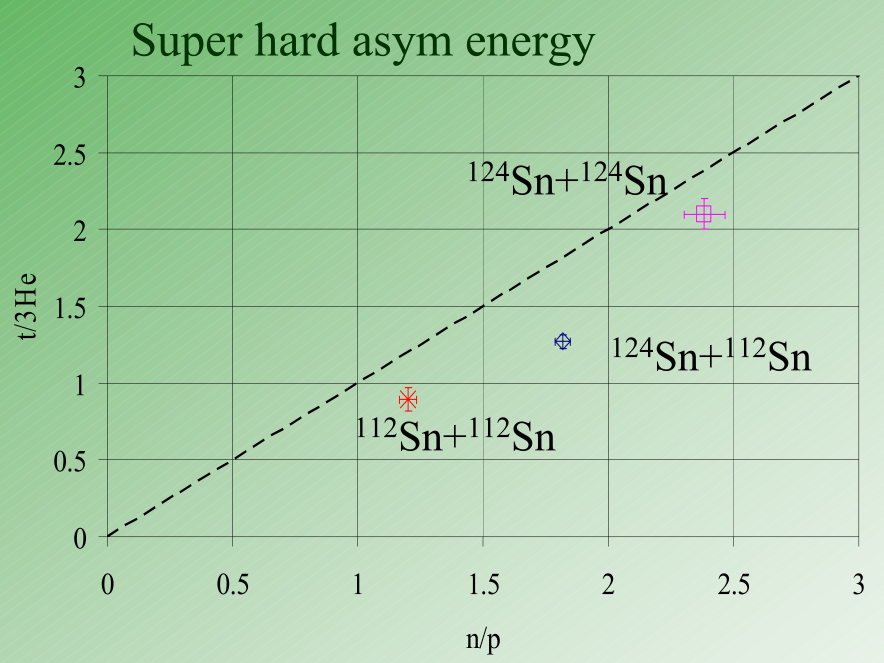
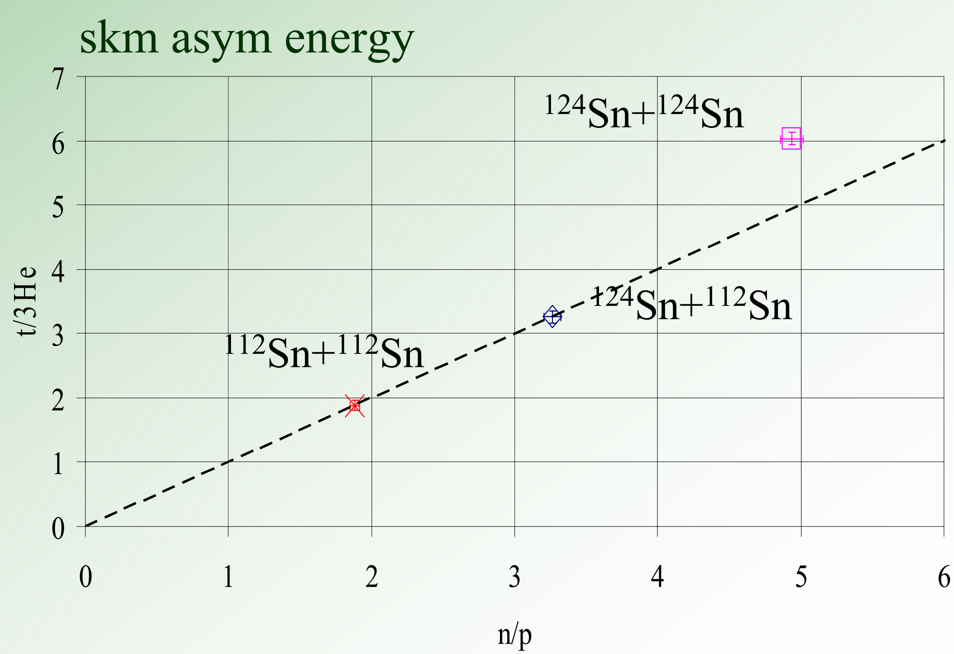
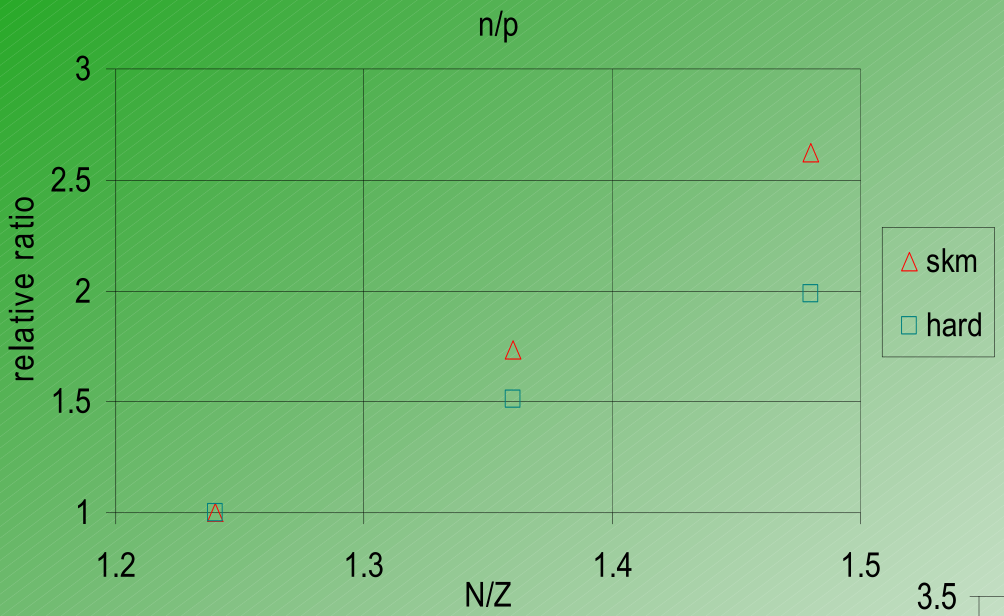
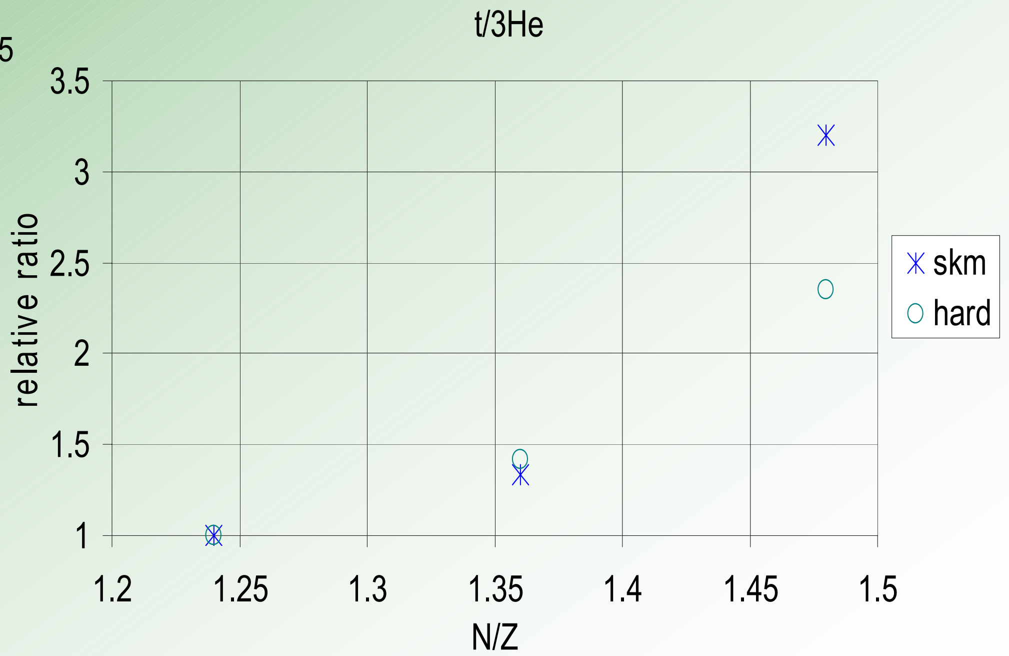

Super hard asym energy
124Sn+124Sn
124Sn+112Sn
112Sn+112Sn
t/3He
n/p


skm asym energy
124Sn+124Sn
124Sn+112Sn
112Sn+112Sn
t/3He
n/p

Comparison of ratios between different systems





Conclusions

- Coalescence underestimates the $t/^3He$ ratio and number of alpha particles produced when compared to experiment.
  - Doesn't take binding energy into account.
- Shows a correlation between $t/^3He$ and n/p ratios
  - sensitive to the asymmetry energy
- A better understanding of nuclear asymmetry energy can lead to advances in knowledge about:
  - Radioactive nuclei
  - Neutron stars
  - Supernovae