Università di Catania

Dipartimento di Fisica e Astronomia "Ettore Majorana"

INFN Istituto Nazionale di Fisica Nucleare

Women in Theoretical Physics
Premio Nazionale "Milla Baldo Ceolin" 2024

Eulalia Gambera

University of Catania & INFN Catania

eulalia.gambera@dfa.unict.it

November, 04,2025

About me

- **September 2024:** Master's Degree in Nuclear Physics at the University of Catania Thesis: **"Analysis of central events in Ni+Ca reactions at 35 MeV/A"** under the supervision of **Prof.ssa E. Geraci e Prof.ssa Colonna.**

- My thesis work combines both an **experimental** and a **theoretical analysis**, aimed at deriving information on the system, on the nature of the **nuclear fragmentation mechanism**, and on the **equation of state** by comparing experimental data with the predictions of theoretical models for a number of relevant observables.

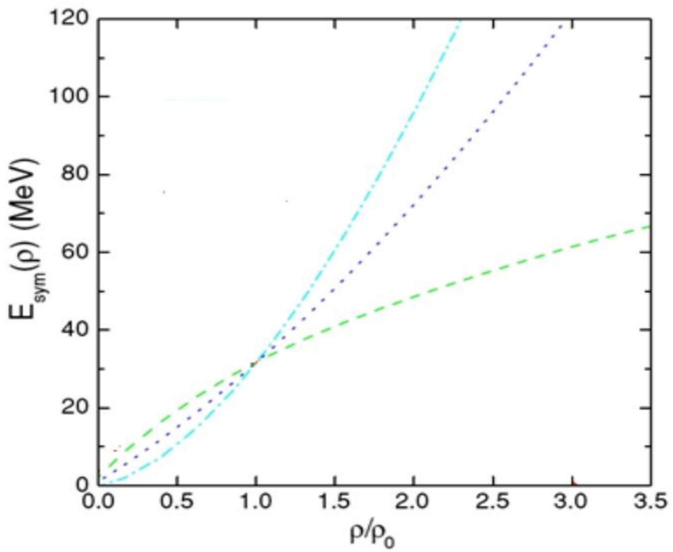
- **October 2024 – present:** PhD student at the University of Catania (INFN CATANIA), working on the equations of state of nuclear matter at low and high densities.

My supervisor is Prof. Elena Geraci, and I work within the **Chirone Group** (INFN-LNS & INFN Sezione Catania) together with **"the LNS theory group, for transport model simulations"**.

Multifragmentation and nuclear phase transition

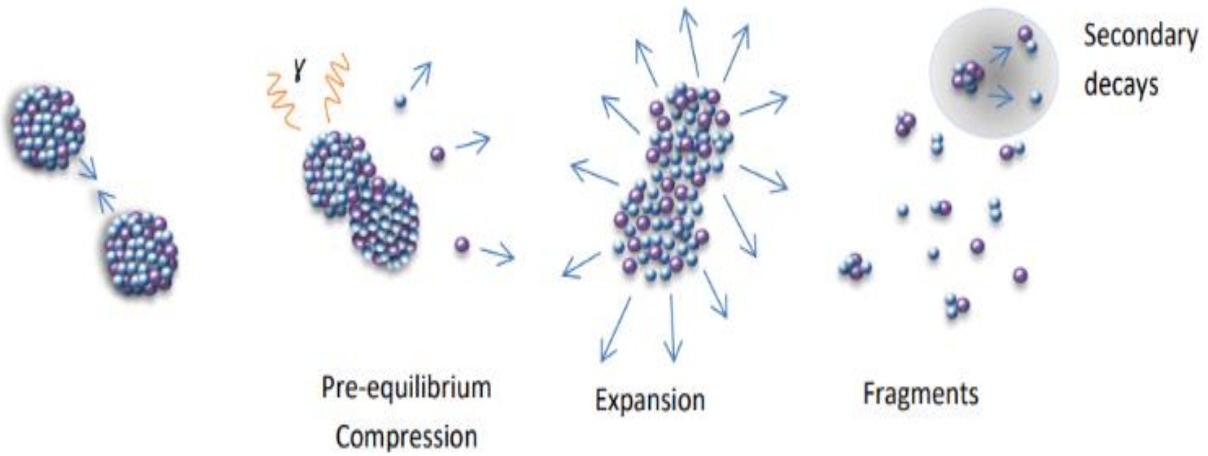
Equation of State (EoS)

$$\frac{E}{A}(\rho, I) = \frac{E}{A}(\rho) + \frac{E_{sym}}{A}(\rho) I^2$$



$$I = \frac{\rho_n - \rho_p}{\rho} = \frac{N-Z}{A}$$

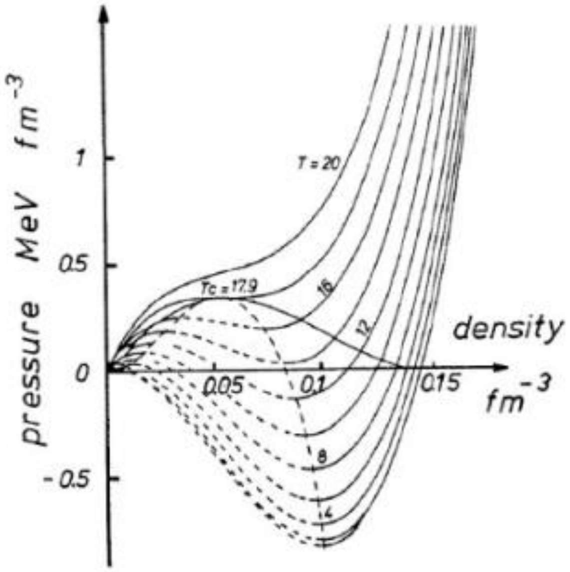
$$E_{sym}(\rho) = E_0 + \frac{L}{3}\left(\frac{\rho-\rho_0}{\rho_0}\right) + \frac{K_{sym}}{18}\left(\frac{\rho-\rho_0}{\rho_0}\right)^2 + \cdots .$$



- Central;
- At Fermi energy;

- **Spinodal zone**

$$\frac{\partial P}{\partial \rho} < 0 \quad \wedge \quad \frac{\partial P}{\partial V} > 0$$



THERMO Experiment: $^{58}Ni + ^{40}Ca$ @ 35 AMeV LNS INFN CATANIA

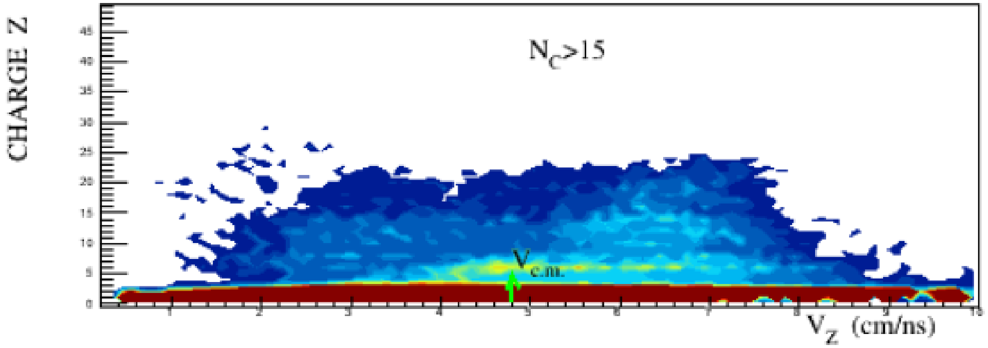
Multi-detector CHIMERA

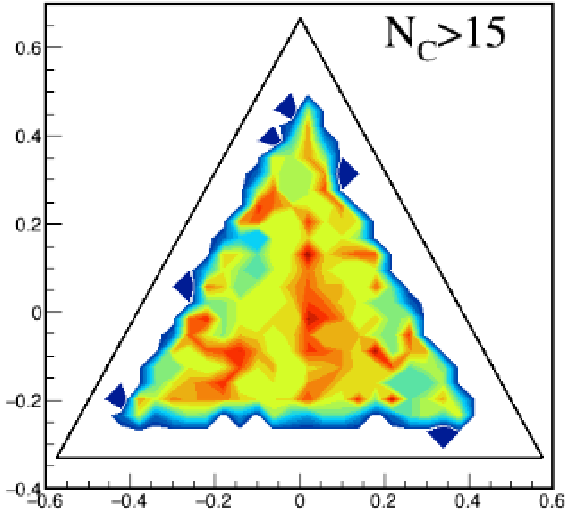
- Wide angular coverage;
- Good spatial resolution;
- Low energy detection thresholds;
- High granularity;

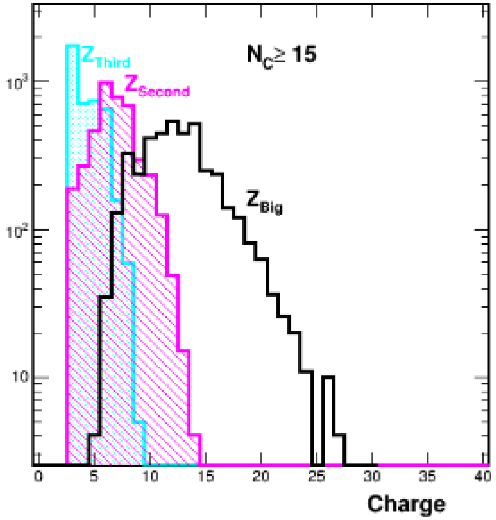
- Complete event selection;
- The global variables determine which reaction mechanisms are selected.

- The total charge multiplicity : N_c
- $N_c \leq 5$;
- $5 < N_c < 15$
- $N_c \geq 15$

$N_c \geq 15$







A. Pagano and all, (Nuclear Physics A, 734 , 504-5 ,11, 2004

BOLTZMANN-LANGEVIN ONE-BODY (BLOB)

The **Vlasov equation**:

$$\frac{\partial f(r,p,t)}{\partial t} + \{\hat{H}, f(r,p,t)\} = 0$$

$f(r,p,t)$ is the semi-classical analog of the Wigner transform, $H = T + V$

$$\lambda \frac{\partial V}{\partial x} \ll \frac{p^2}{m}$$

The **Landau-Vlasov equation**:

$$\frac{\partial f(r,p,t)}{\partial t} + \{\hat{H}, f(r,p,t)\} = I_{Coll}$$

$$I_{coll} = -\int \frac{d\vec{p_2}\, d\Omega}{\frac{h^3}{4}} f(\vec{r},\vec{p},t) f(\vec{r},\vec{p_2},t) v_{rel} \frac{d\sigma}{d\Omega} f_{34}^{PB} + \\ + \int \frac{d\vec{p_2}\, d\Omega}{\frac{h^3}{4}} f(\vec{r},\vec{p_3},t) f(\vec{r},\vec{p_4},t) v_{rel} \frac{d\sigma}{d\Omega} f_{12}^{PB}$$

$$f_{12}^{PB} = [1 - f(\vec{p})][1 - f(\vec{p_2})]$$

$$f_{34}^{PB} = [1 - f(\vec{p_3})][1 - f(\vec{p_4})]$$

The average effect of the residual two-body direct collisions → deterministic;

The Boltzmann-Langevin equation:

$$\frac{\partial f^{(n)}}{\partial t} + \left\{H^{(n)}, f^{(n)}\right\} = \bar{I}[f^{(n)}] + \delta I^{(n)}[f^{(n)}]$$

$\bar{I}\,[f^{(n)}]$ accounts for the average effect, while $\delta I^{(n)}\,[f^{(n)}]$ represents the fluctuating part.

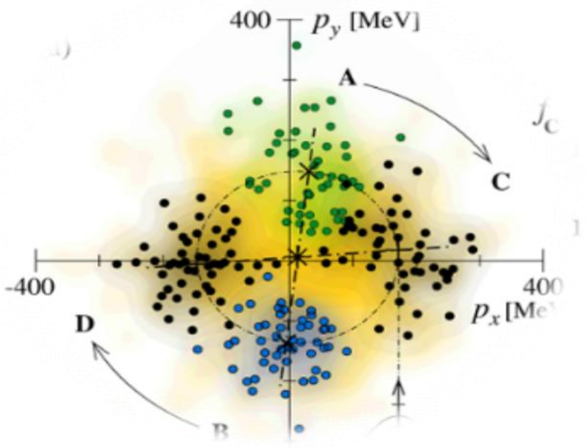
To numerically solve the Boltzmann-Langevin equation and simulate the phenomenon of multifragmentation, the **BLOB model** was employed.

M. Colonna, P. Napolitani, PHYSICAL REVIEW C, 96, 054609, 2017

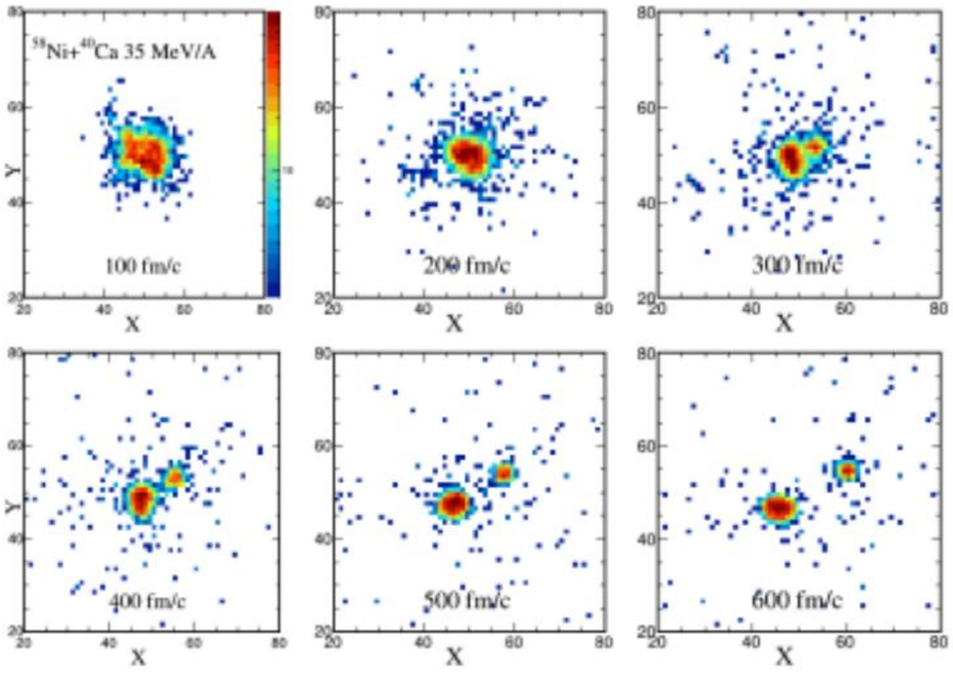
Test Particle method

$$f(\vec{r},\vec{p},t) = C \sum_{i=1}^{N \cdot N_{\text{test}}} g_r(\vec{r}-\vec{r}_i)\, g_p(\vec{p}-\vec{p}_i)$$

This code provides a solution to the BL equations, allowing for more efficient nucleon identification and more accurate control of **Pauli blocking factors** compared to other stochastic codes.



Simulation Results



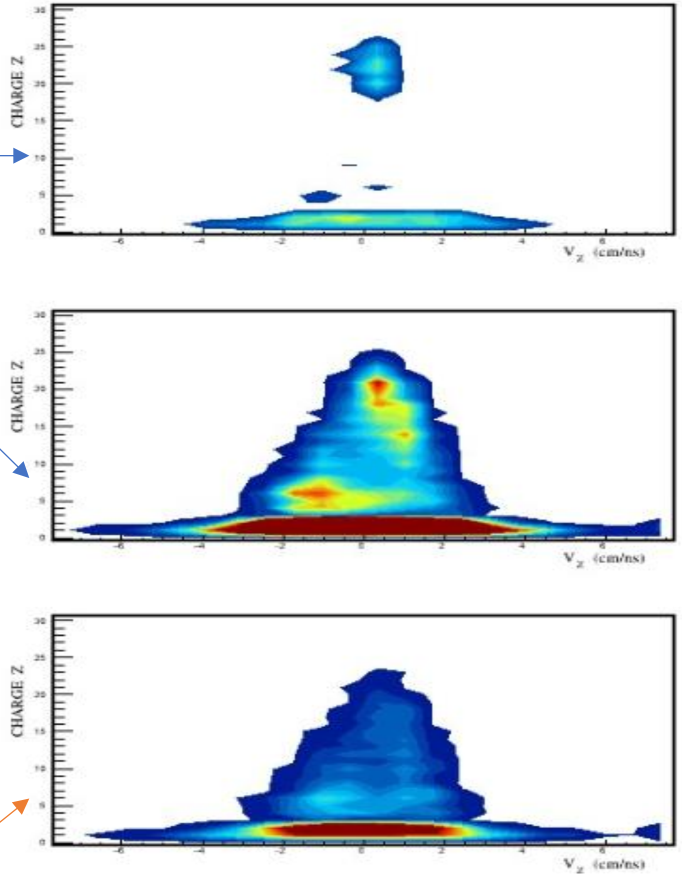
b = 0 – 3fm;

- A = 60 amu;
- An atomic number Z = 26 – 28;
- An excitation energy of 2 AMeV ;

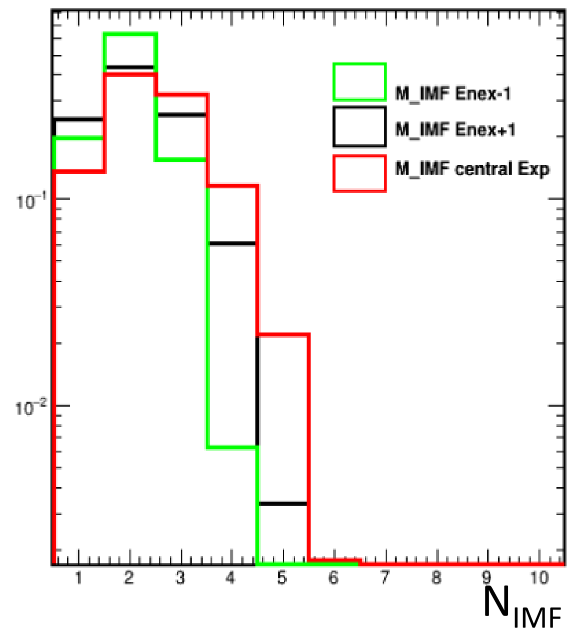
MIMF = 1

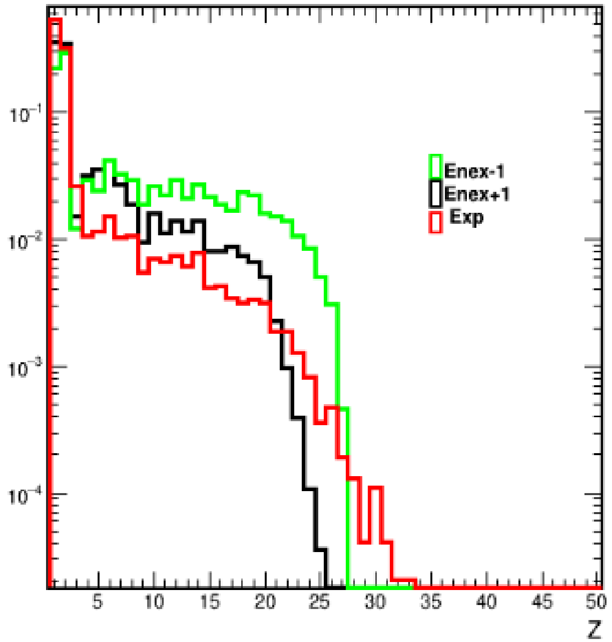
MIMF = 2

MIMF ≥ 3



Comparison between experimental data and theoretical predictions





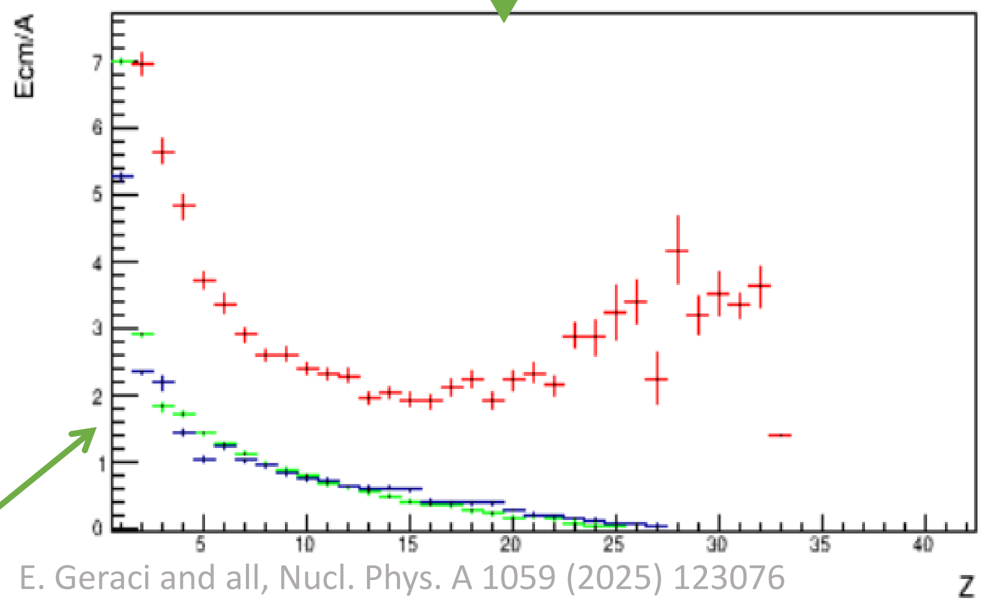
GEMINI++ is a statistical de-excitation code;

- Intrinsic uncertainty of excitation energy per nucleon: ±1MeV ;

- The kinetic energy in the center of mass depends not only on the thermal component but also on the one associated with radial collective flow.

Comparison of multiplicity of IMF (plot on the left) and charge distribution (on the right) using the BLOB+GEMINI++ model with varying excitation energy (green -1Mev/A and black +1Mev/A) and experimental data (red).

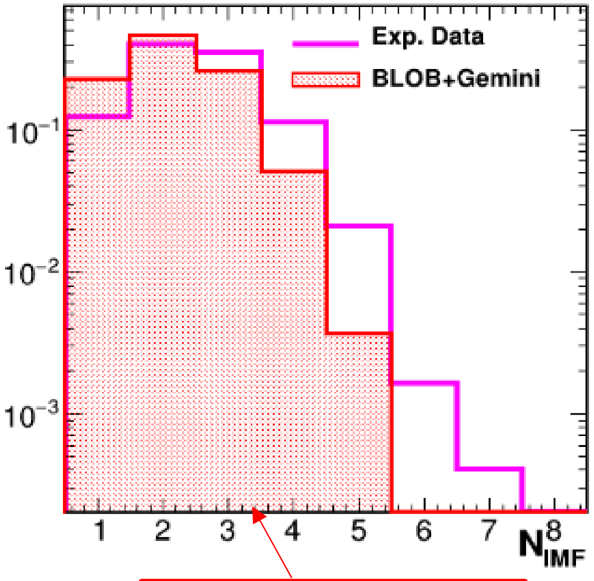
The radial flow plateau, is clearly visible in the experimental data around 2 MeV/A but is underestimated in the BLOB+GEMINI++ simulations, approximately by 1 MeV/A.



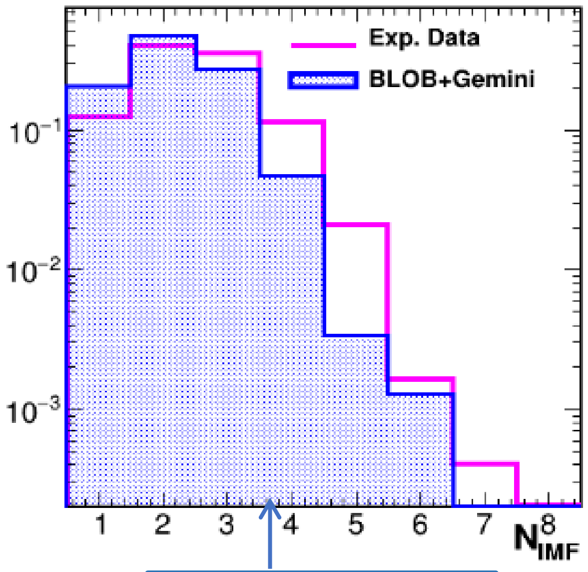
E. Geraci and all, Nucl. Phys. A 1059 (2025) 123076

Asy-stiffness

The first set of simulations was produced with the asy-stiffness parameter of 1, corresponding to a linear behavior, while the second was produced with the parameter of **asy-stiffness of 2**, which refers to a soft behavior.

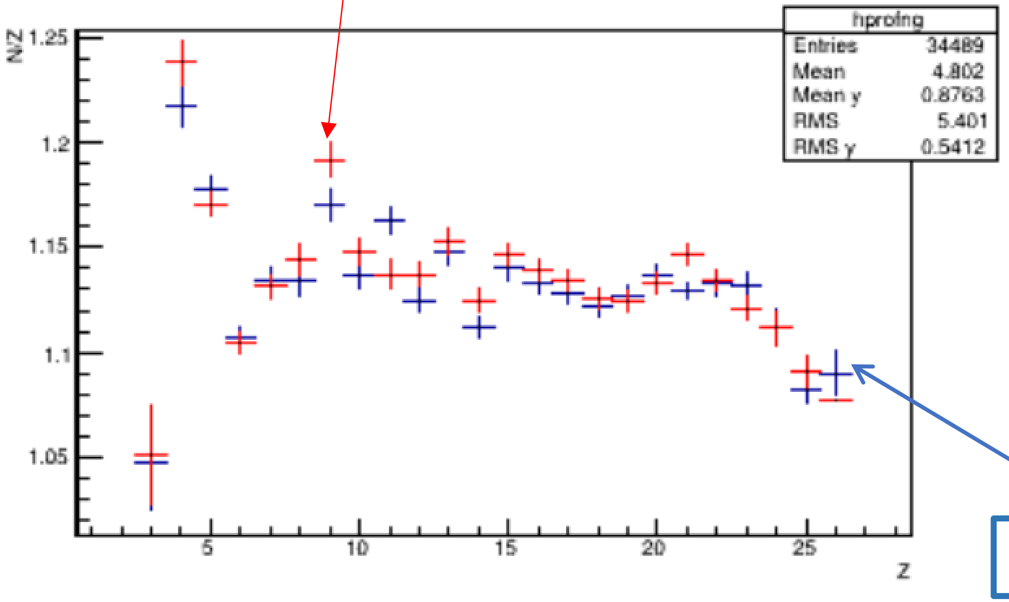


asy-stiffness=1



asy-stiffness=2

soft

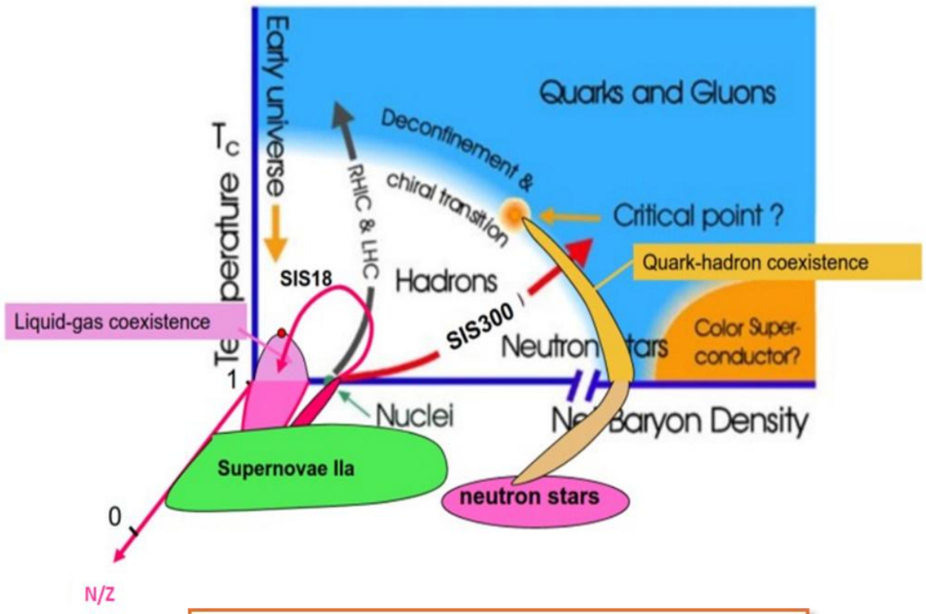


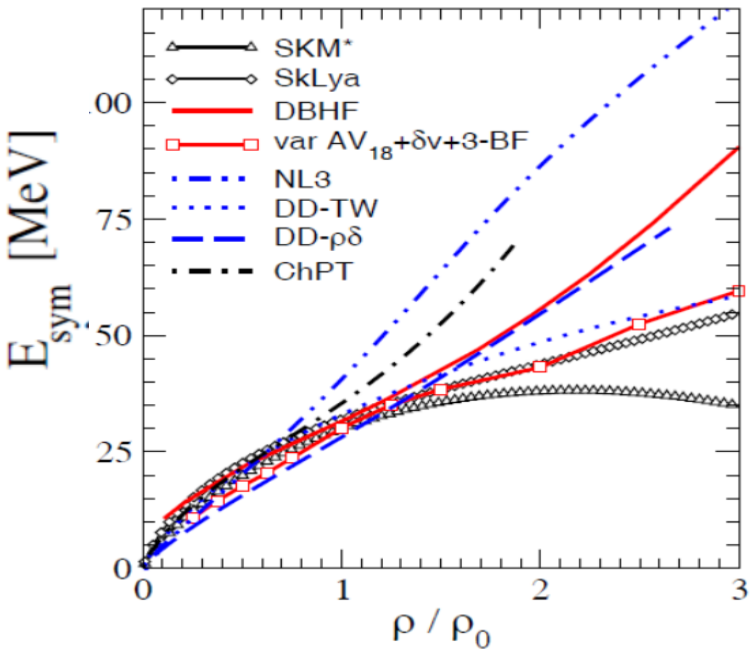
stiff

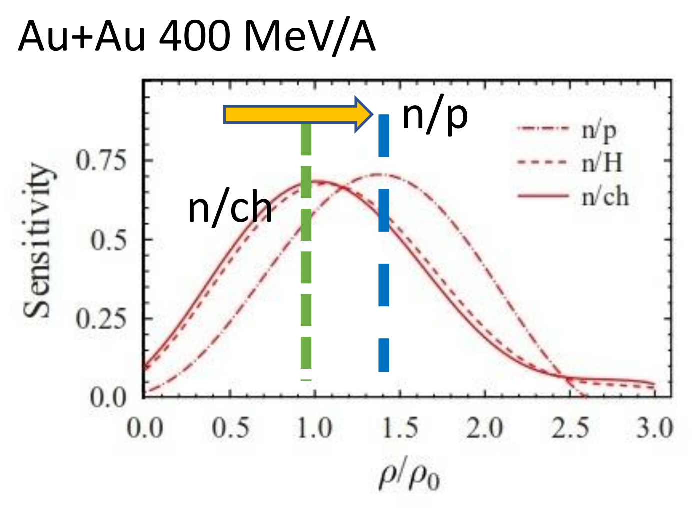
Comparison of IMF fragment multiplicity between the GEMINI+BLOB model and the experimental data.

In the soft case, nuclear matter tends to retain more neutrons and release a greater number of protons and clusters.

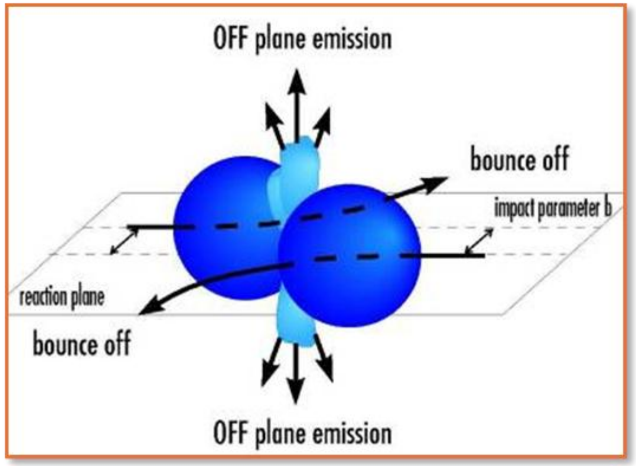
Current work and perspectives



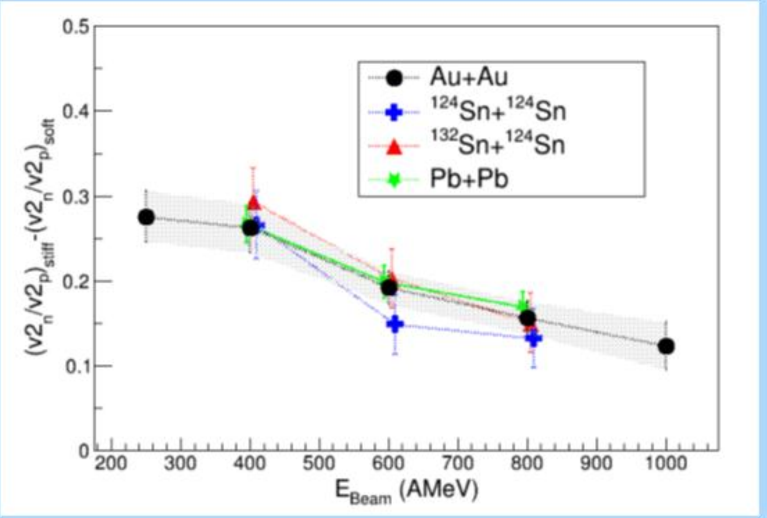




n/p observable (Z=1 isotopic resolution): greater sensitivity to higher densities.



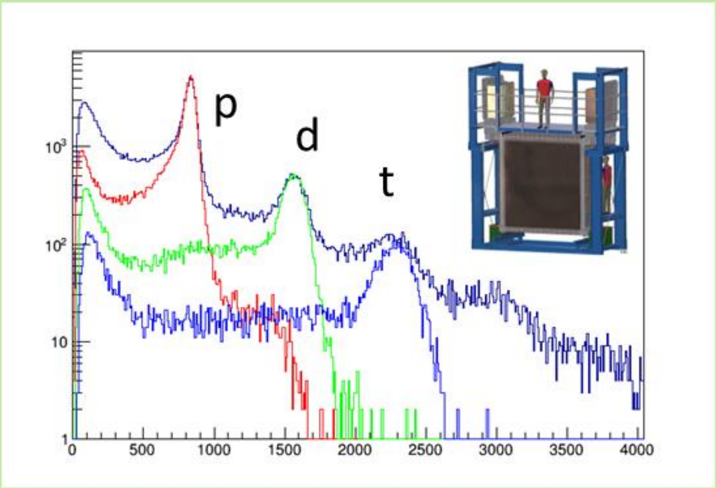
$$\frac{dN}{d(\phi-\phi_R)}(y,p_t)=\frac{N_0}{2\pi}\left(1+2\sum_{n\geq 1}v_n\cos n(\phi-\phi_R)\right)$$



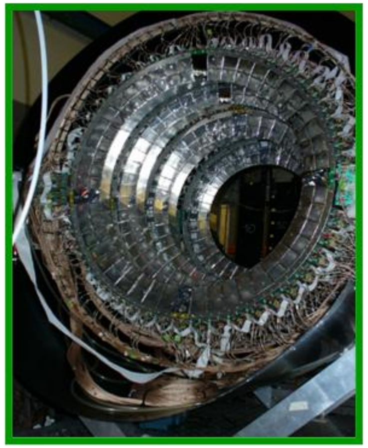
UrQMD simulations:
good sensitivity to EOS parametrization up to 1 GeV/A.

ASY-EOS II

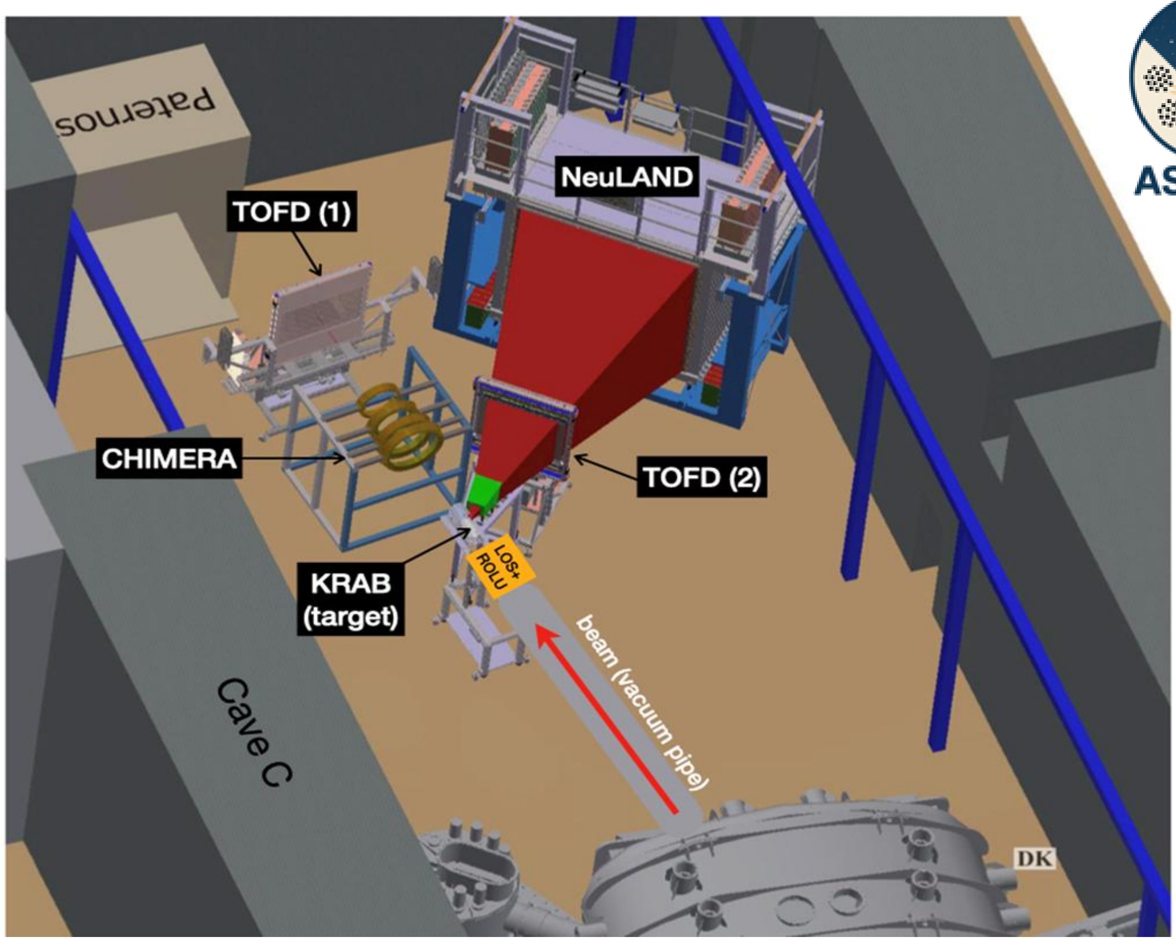
March 2025 at GSI: Au + Au collision



R3B NeuLAND: resolving p,d,t



***CHIMERA*: 8 (2x4) rings, high granularity CsI(Tl), 352 detectors 7°<θ<20° + 16x2 pads silicon detectors. Light charged particle identification by PSD. Multiplicity, Z, A, Energy: impact parameter and reaction plane determination**



Energy [AMeV]	Justification
280	highest sensitivity on K_{sym}
400	reference to ASY-EOS I, n/p tests higher densities than before
600	highest sensitivity on L, high-density tested
1000	Maximum energy (≈ density) where models agree on v2 sensitivity

Thank you for your attention!