ZIMÁNYI SCHOOL 2025

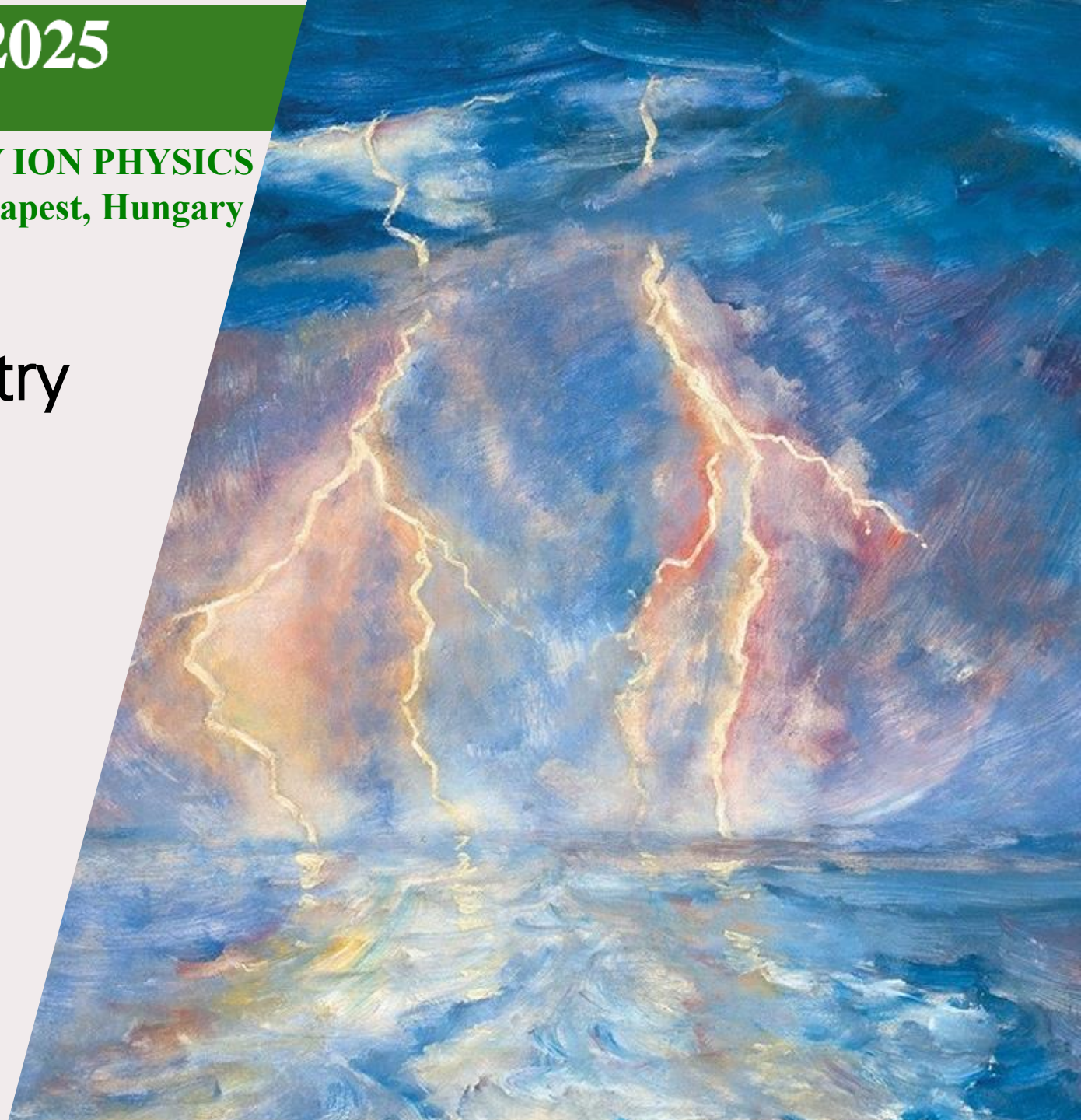
WINTER WORKSHOP ON HEAVY ION PHYSICS
December 1-5, 2025, Budapest, Hungary

Heavy-ion collisions dynamics and the symmetry energy at Intermediate Energies

Elena Geraci

Department of Physics and Astronomy, University of Catania

Istituto Nazionale di Fisica Nucleare, sez. Catania, Italy



Heavy ion collisions at Fermi Energies (15-150 MeV/A)

- The incident kinetic energies (per nucleon) are comparable with the Fermi energy of the nucleons of interacting nuclei (E_F=30-40 MeV).

- Unlike the low-energy regime, where the interaction between the nucleons of interacting nuclei can be described by a mean potential (nuclear mean field: generated by the interaction of projectile nucleons with target nucleons) acting on nucleons, the nucleus-nucleus interaction in the Fermi energy regime is characterized by the competition of the **medium field effects** and the **nucleon-nucleon interaction**, the latter predominant at higher energies (E/A>200 MeV/A).

Heavy ion collisions at Fermi energies (15-150 MeV/A)

- The dissipation process is governed by several ingredients including the relative speed between the initial partners of the reaction $v_{AA.}$
- The relative wavelength associated with collision (m nucleon mass)

$\lambda/2\pi=h/(2\pi m v_{AA})$

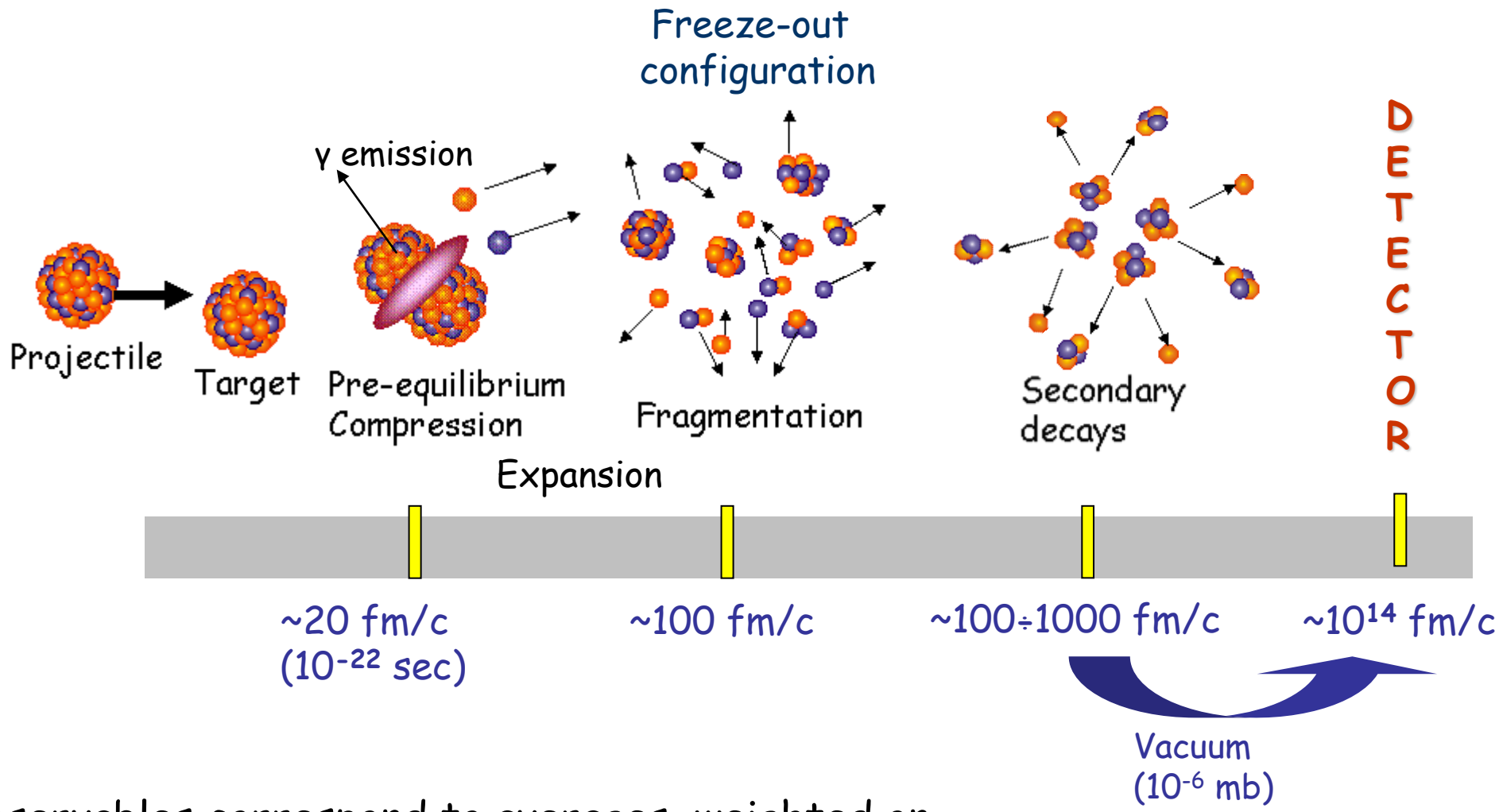
	E/A=	1,	10,	100,	1000 AMeV
➔	$\lambda/2\pi$=.	6.5,	2.1,	0.67,	0.24 fm

Mean Nucleon-Nucleon Distance in a Nucleus≈ 2 fm

For E/A<10-20 AMeV, a collective behavior of nucleons during collision prevails, i.e. the mean field effects (one-body dissipation) prevail over the nucleon-nucleon collision effects (two-body dissipation).

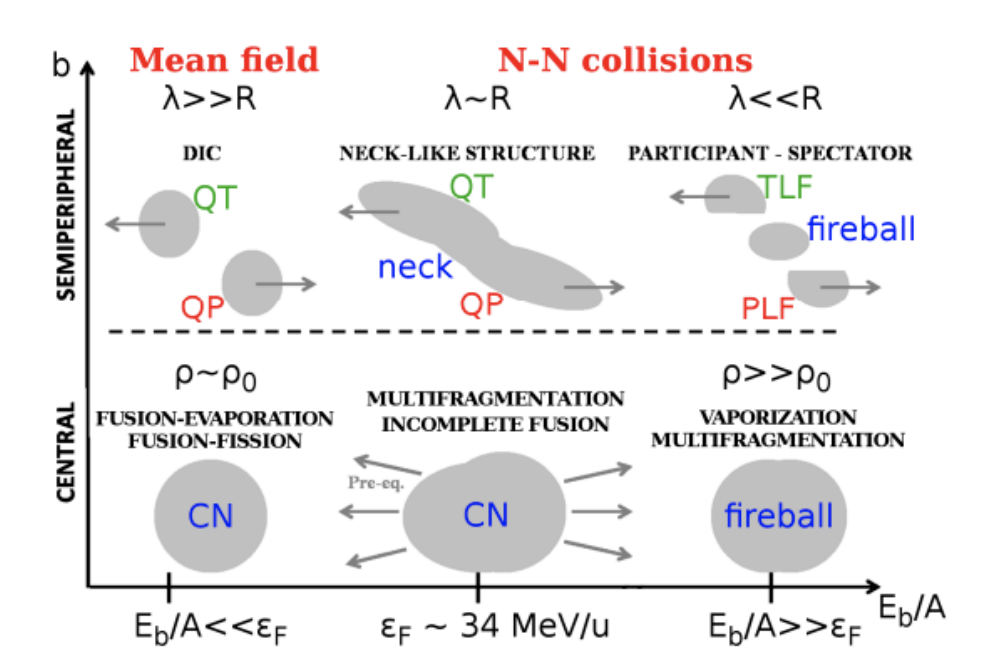
At Fermi Energies, incident energies are below pion production threshold ($E \approx 290\ MEV/A$), implying that nucleon excited stated will have a negligible influence.

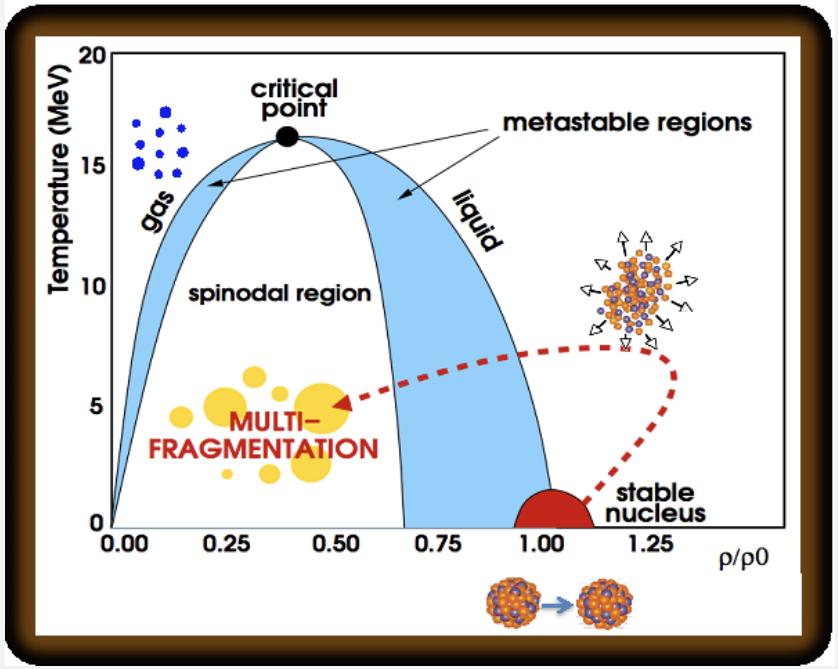
HEAVY ION COLLISIONS AT INTERMEDIATE ENERGIES



Inclusive observables correspond to averages, weighted on the impact parameter

Multifragmentation at Fermi Energies

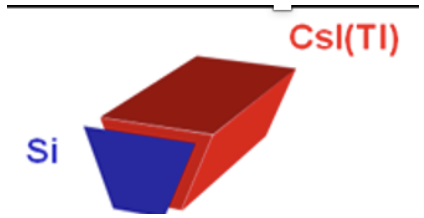


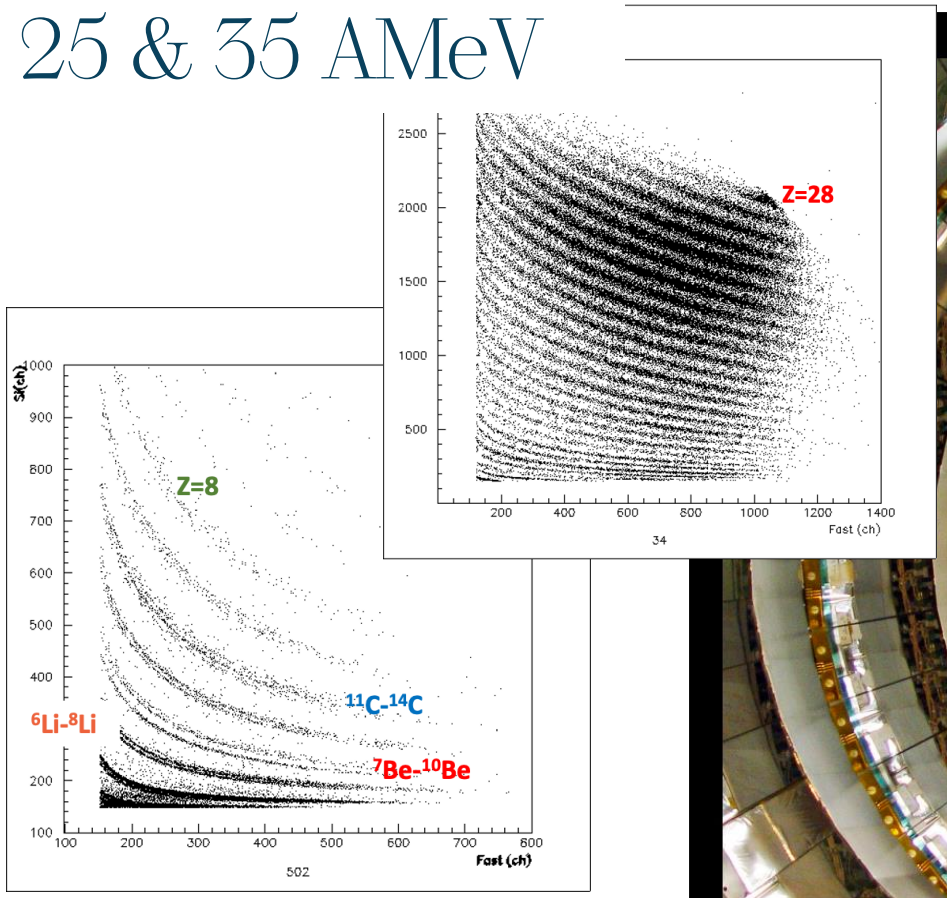


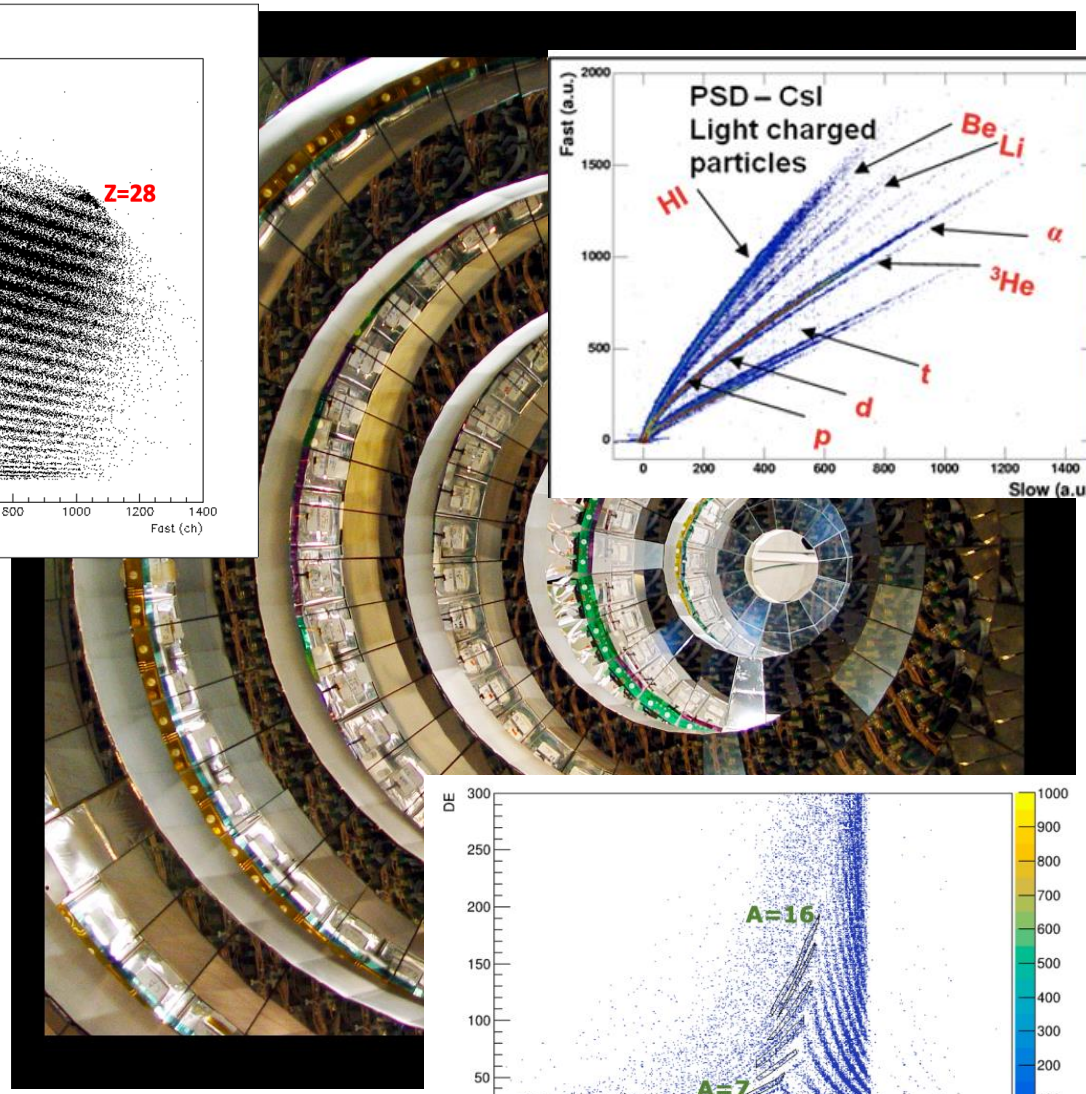
- Multifragmentation (MF) is a one step process, occurring in 100 fm/c
- Theoretical models predict that the emitting source reaches densities significantly lower than the saturation density ($\rho \approx (1/3 \div 1/5)\rho_0$)
- Fragments are formed simultaneously and are distributed over the entire volume of the source.
- The source that emits the fragments has reached equilibrium.

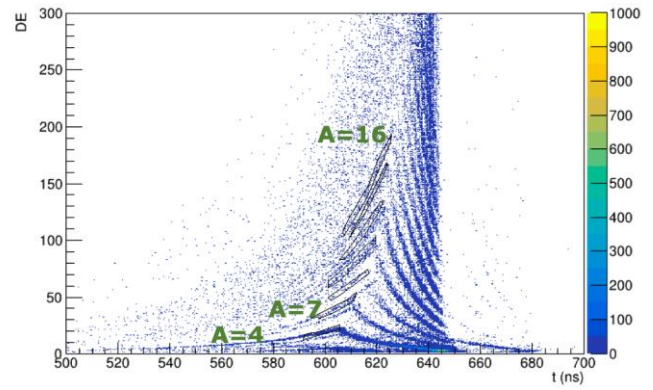
$^{58,62}Ni+^{40,48}Ca$ @ 25 & 35 AMeV

THERMO EXPERIMENT







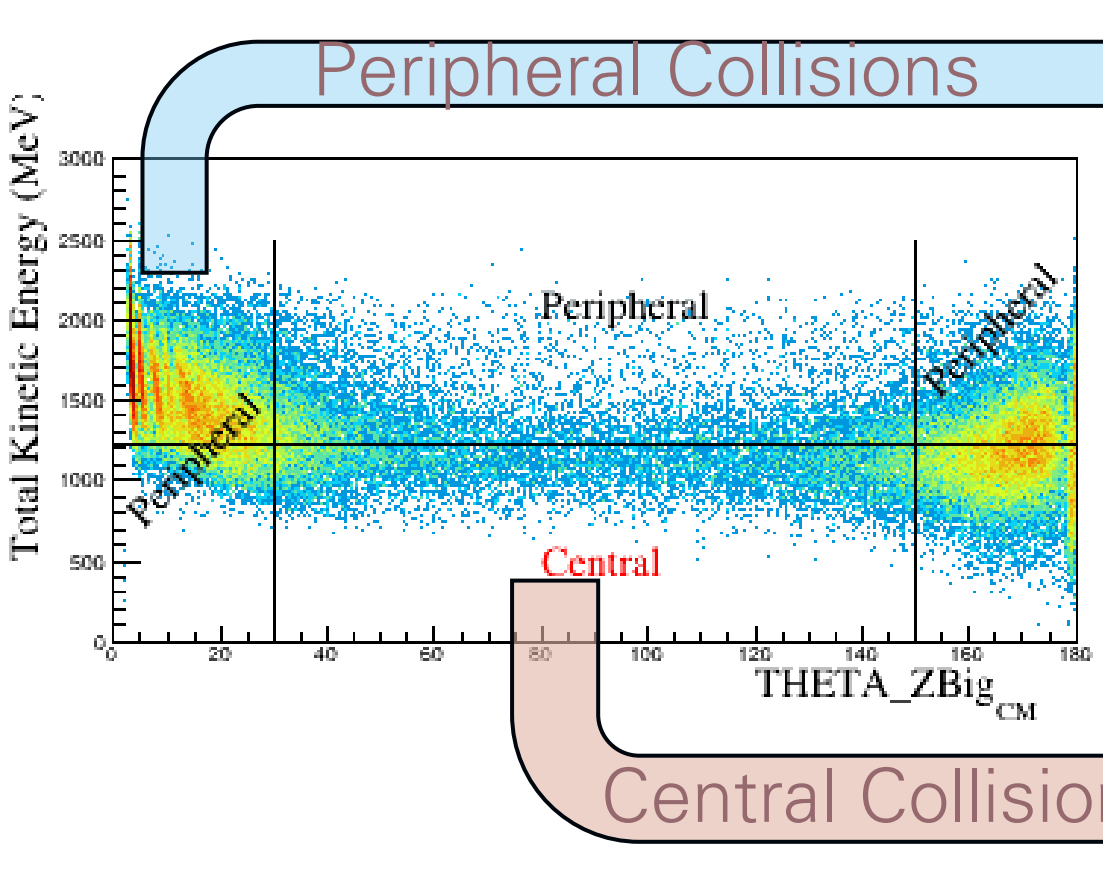


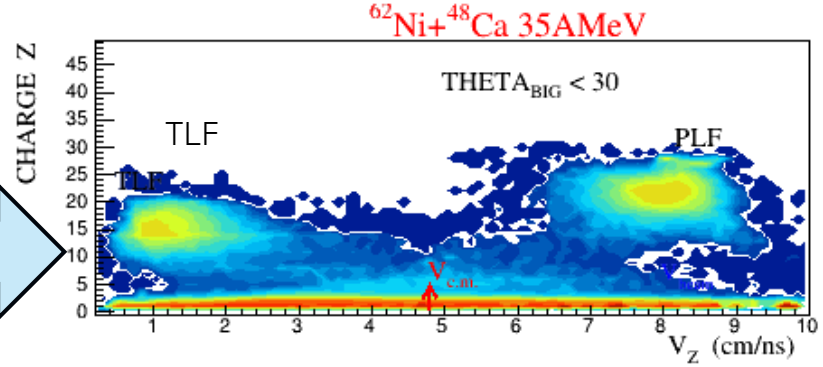
Chimera Apparatus @ LNS-INFN (Italy):

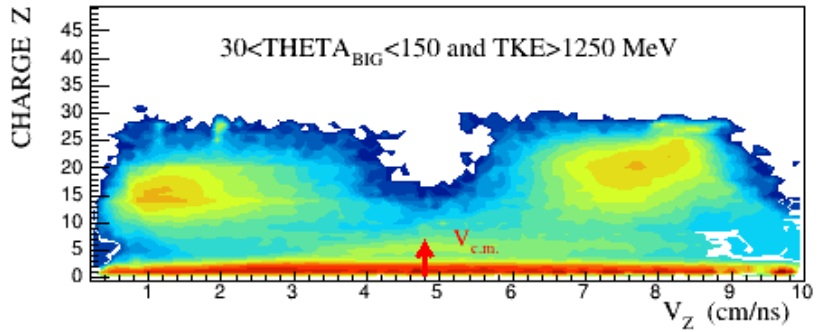
- 94% of total solid angle
- low detection thresholds
- systematic TOF measurements
- identification in mass for fragments with the E-TOF technique
- identification in charge of all fragments and in mass for fragments Z<=8 in $13<\theta_{lab}<176$ with ΔE-E technique

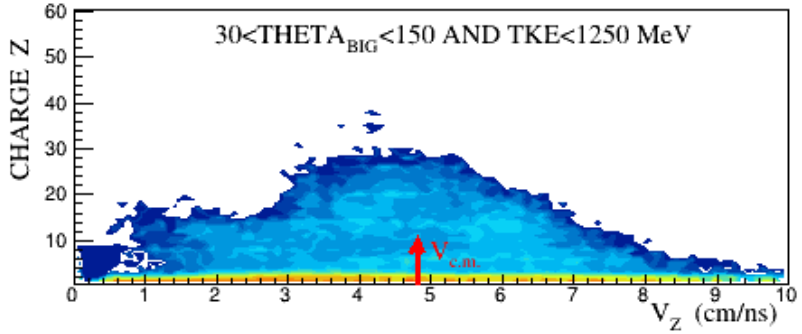
CENTRALITY SELECTION

$^{62}Ni+^{48}Ca$ 35 AMeV

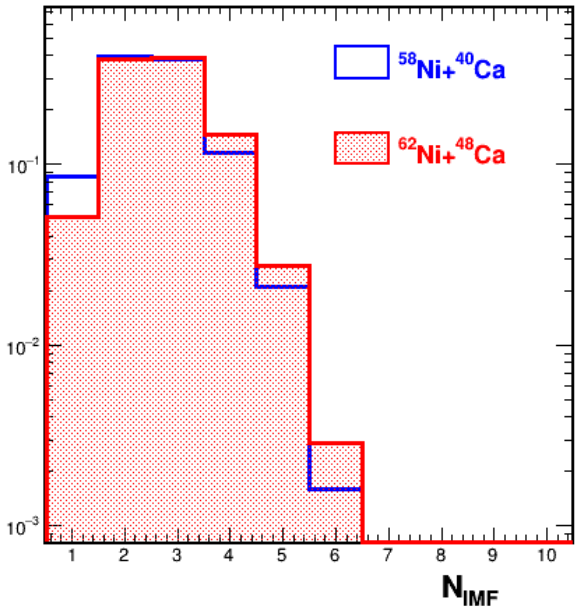


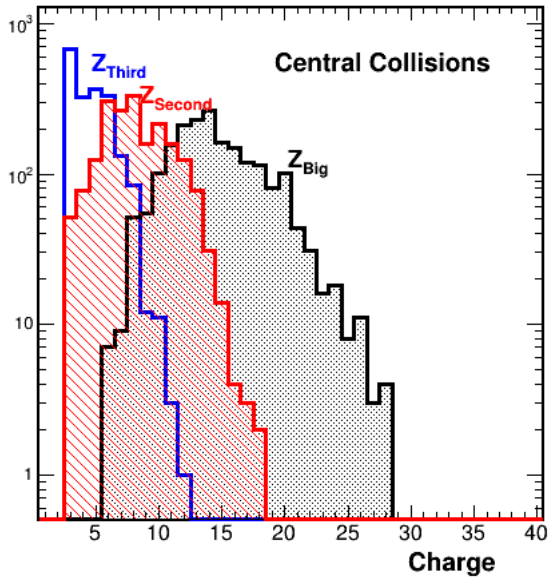


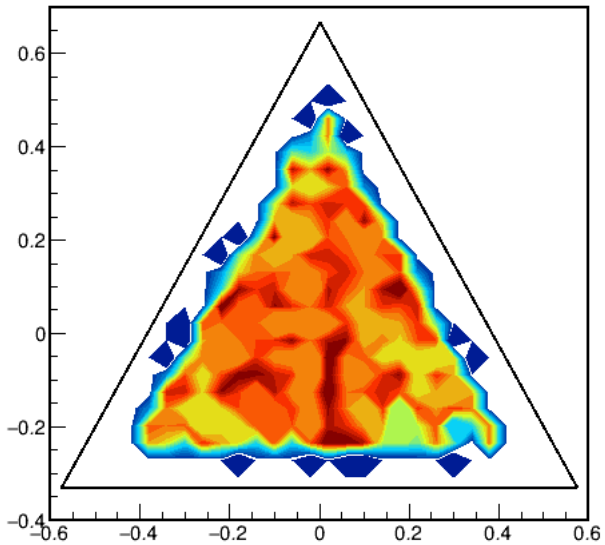


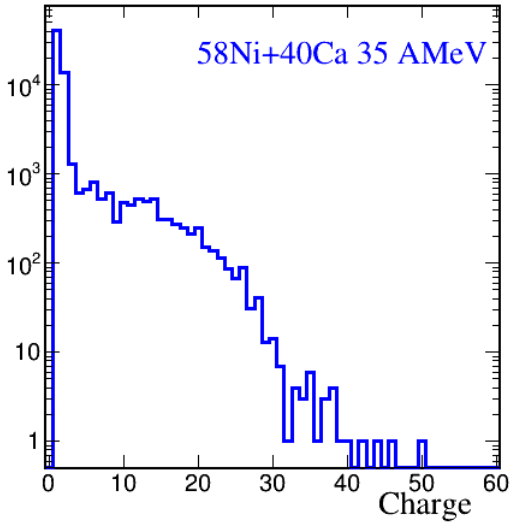


FEATURES OF CENTRAL COLLISIONS

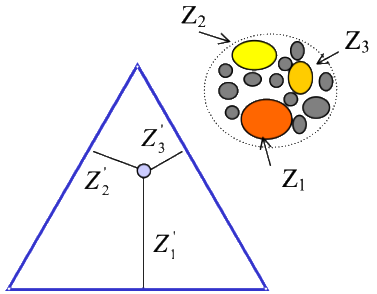








8% of Total Events for 58Ni+40Ca
10% of Total Events for 62Ni+48Ca

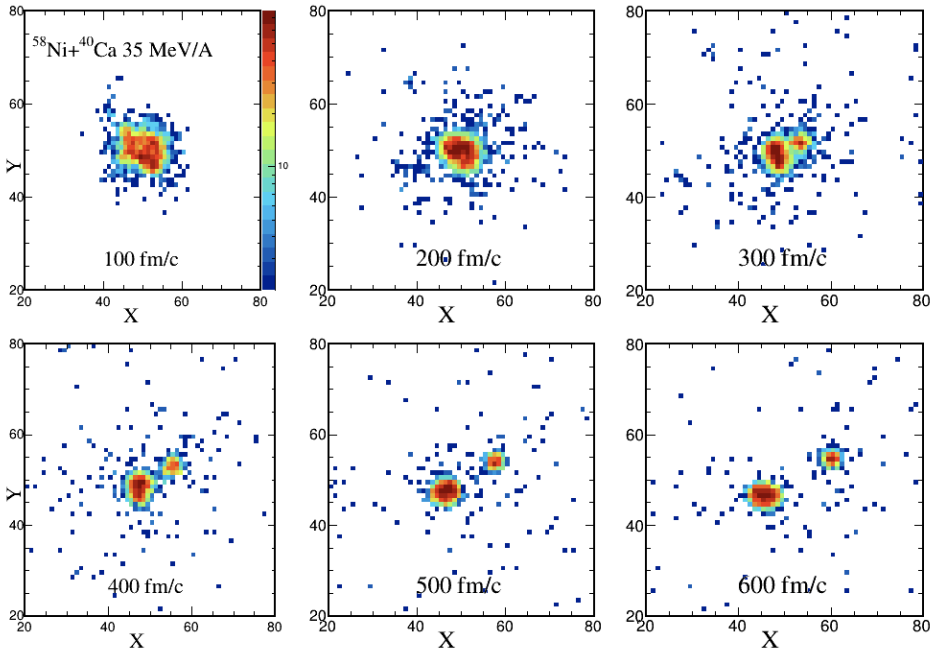


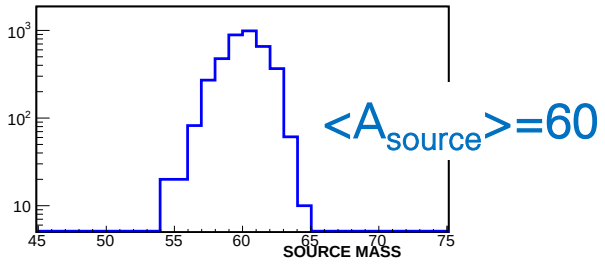
MODEL PREDICTIONS $^{58}NI+^{40}CA$ @ 35 AMEV

Boltzman Langevin One Body (**BLOB**) Model

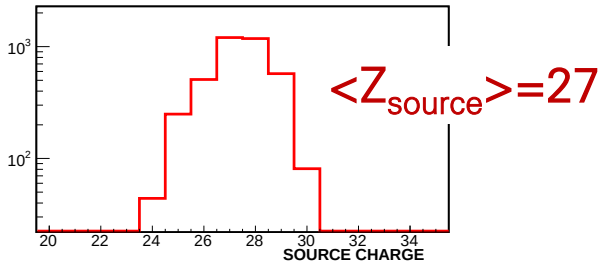
M. Colonna and P. Napolitani, Phys. Rev. C 96 (2017) 054609

b=0-3 fm

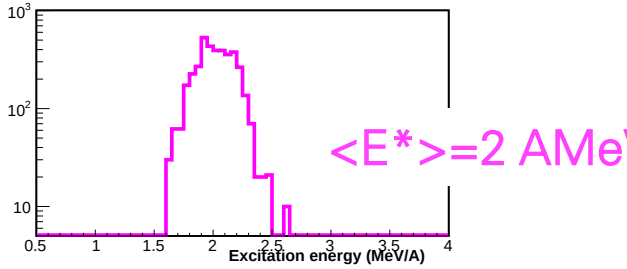




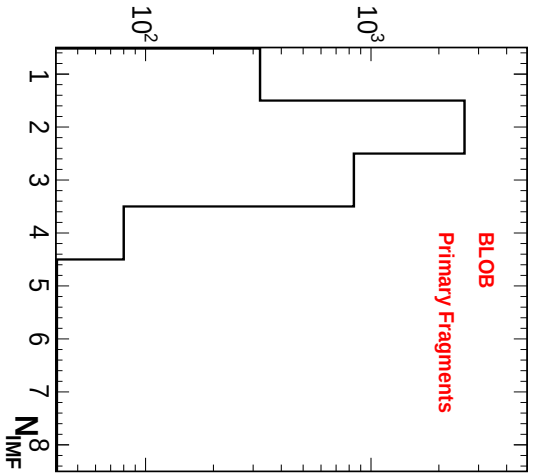
$<A_{source}>=60$



$<Z_{source}>=27$

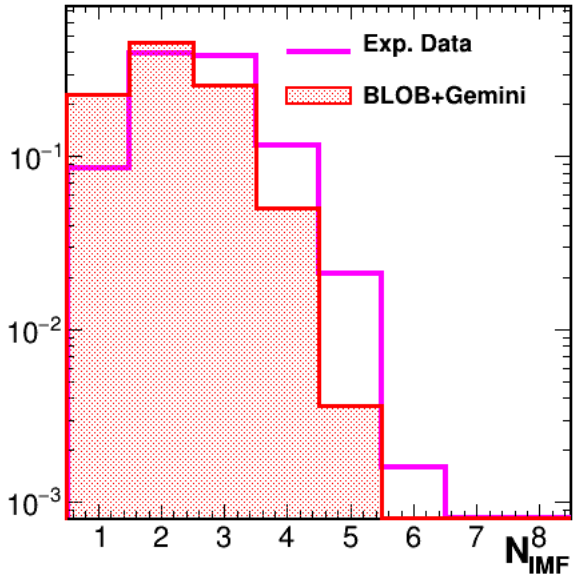


$<E^*>=2$ AMeV

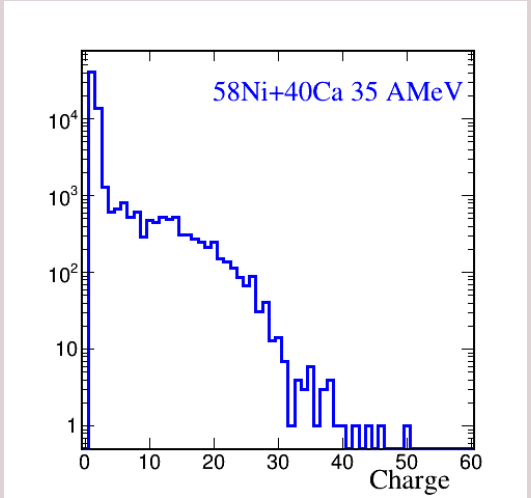


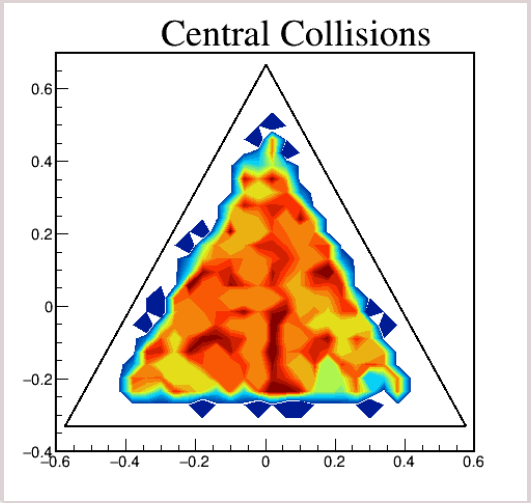
MODEL AND DATA COMPARISON

BLOB +Gemini Predictions and $^{58}Ni+^{40}Ca$ data @ 35 AMeV

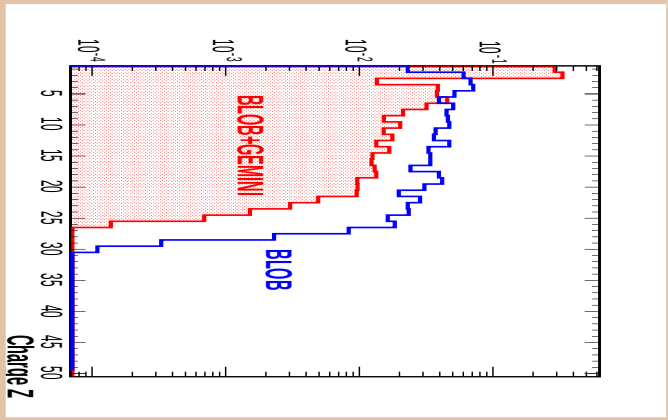


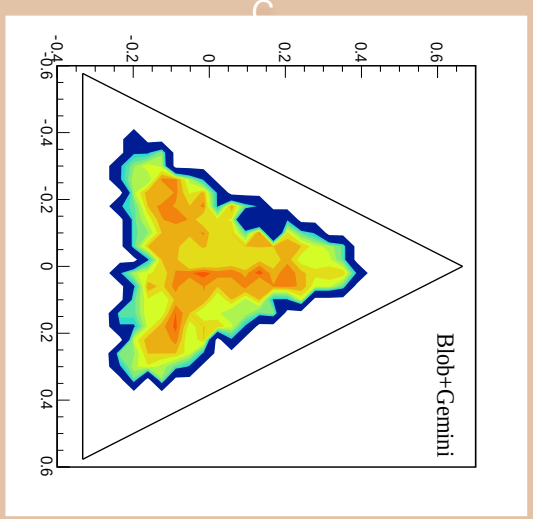
Experimental Data





Model Prediction



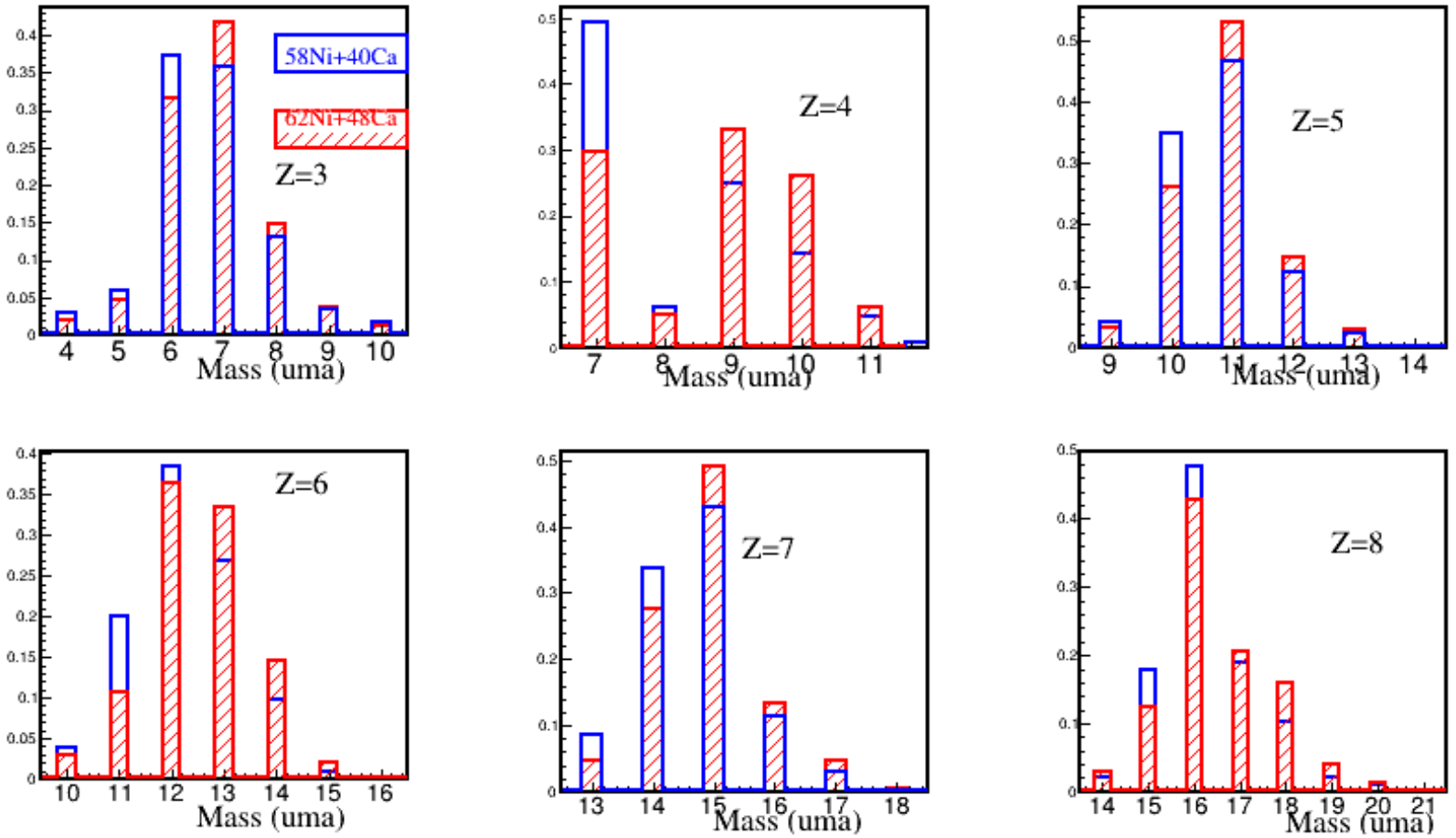


E Geraci et al., J. Phys. Conf. Ser. 2586 (2023) 012067

ISOSPIN DEPENDENCE

$^{58}Ni+^{40}Ca$
35 AMeV

$^{62}Ni+^{48}Ca$
35 AMeV



E Geraci et al., Nucl. Phys. A 1059 (2025) 123076

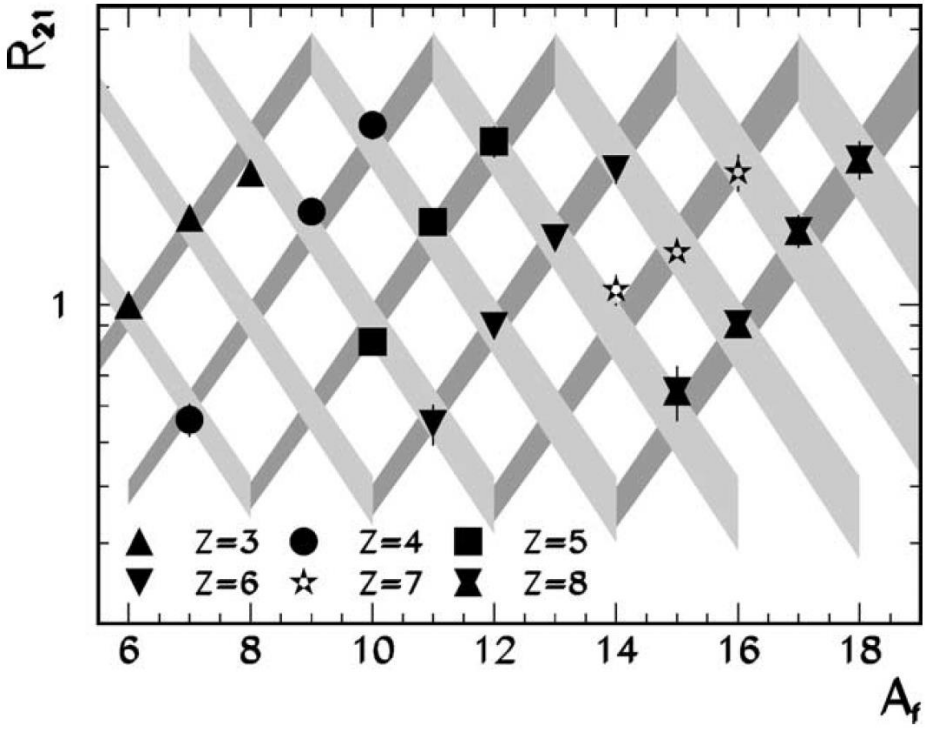
ISOSCALING

$^{112}Sn + {}^{58}Ni$ and $^{124}Sn + {}^{64}Ni$ 35 MeV/A

$$R_{21} = \frac{Y_2(N,Z)}{Y_1(N,Z)} = Ce^{\alpha N + \beta Z}$$

$$\alpha = 0.44 \pm 0.01 \quad \beta = -0.46 \pm 0.02$$

$$R_{21}(N,Z) = \frac{Y_2(N,Z)}{Y_1(N,Z)} = Ce^{N\Delta\mu_n/T} e^{Z\Delta\mu_p/T}$$
$$= C\left(\frac{\rho_{n,2}}{\rho_{n,1}}\right)^N \left(\frac{\rho_{p,2}}{\rho_{p,1}}\right)^Z = C\hat{\rho}_n^N \hat{\rho}_p^Z.$$



$$\hat{\rho}_p = 0.63 \pm 0.01 \qquad \hat{\rho}_n = 1.55 \pm 0.02,$$

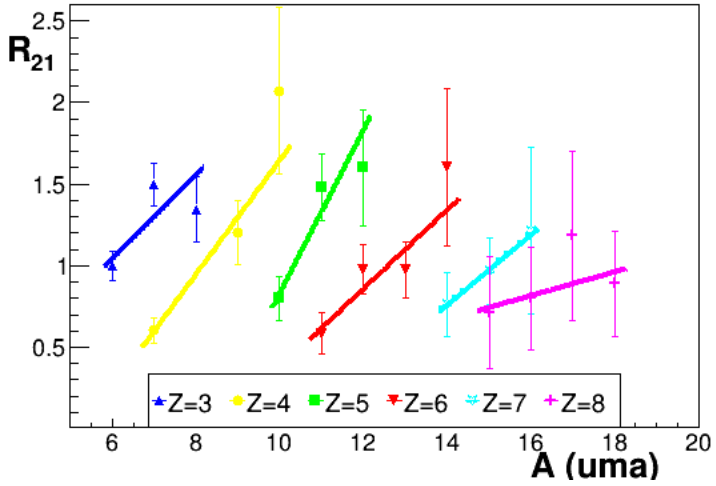
$$C = 1.02 \pm 0.05.$$

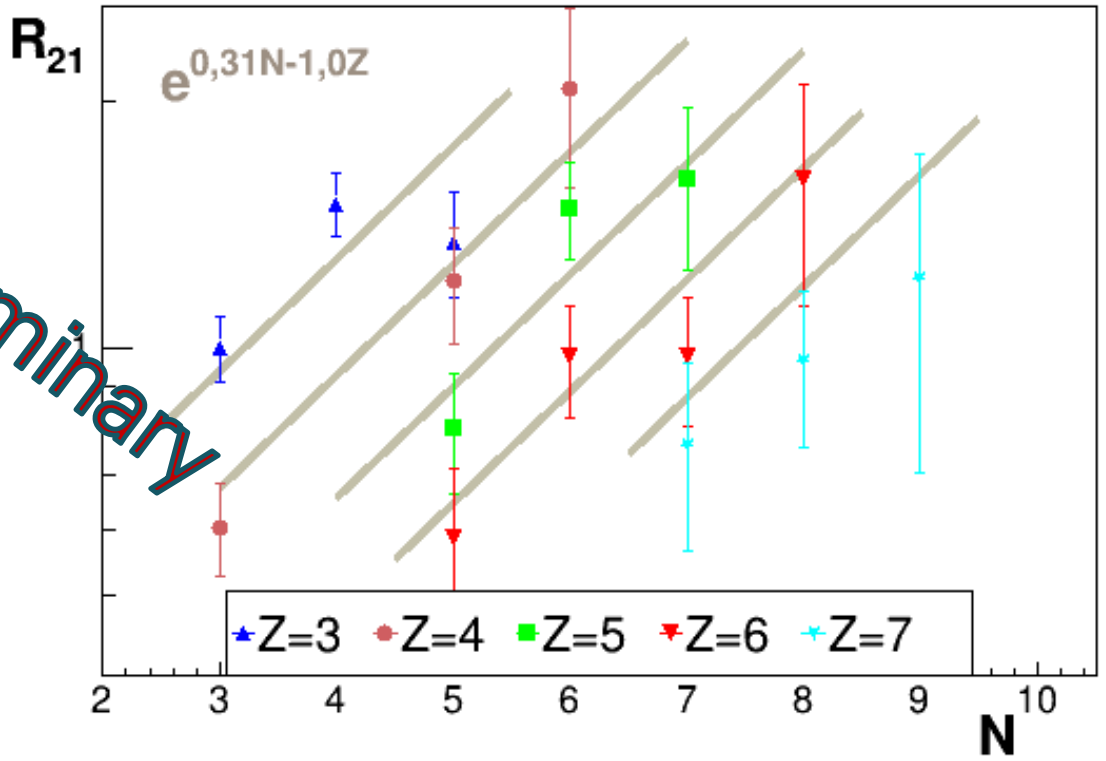
H. S. Xu, M. B. Tsang et al., Phys. Rev. Lett. 85 (2000) 716
M. B. Tsang et al., Phys. Rev. C 64 (2001) 054615
A. Hannaman , A. B. McIntosh, et al., Phys. Rev C 101, 034605 (2020)
A. Rebillard-Soulie et al.,J. Phys. G, Nucl. Part. Phys. 51 (2024) 015104

Reverse experiment
E. Geraci et al., Nuclear Physics A 732 (2004) 173

ISOSCALING THERMO EXP

$^{58}Ni+^{40}Ca$ and $^{62}Ni+^{48}Ca$ 35 AMeV





Preliminary

$$R_{21} = \frac{Y_2(N.Z)}{Y_1(N.Z)} = C\hat{\rho}_n^N \hat{\rho}_p^Z = C' e^{\alpha N + \beta Z}$$

$$\alpha = 0{,}31 \quad \beta = -1$$

WHAT CAN WE LEARN FROM ISOSCALING?

- Isoscaling was claimed as a signature of liquid-gas phase transition

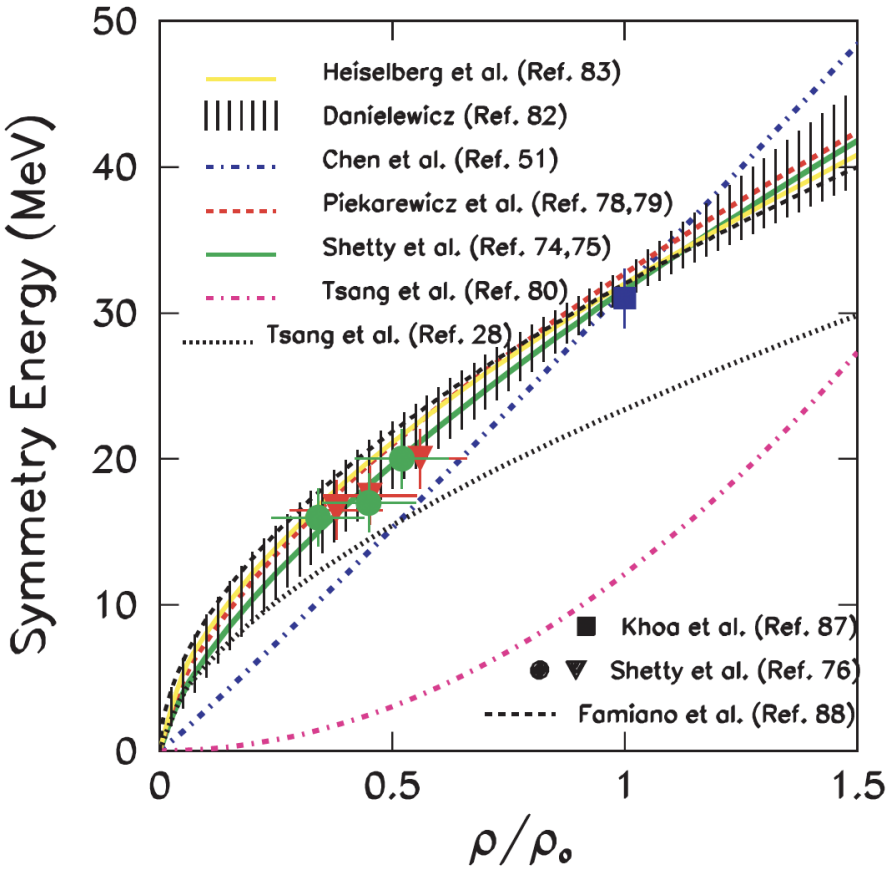
It was shown that also fragments produced in regions different from the coexistence zone exhibited isoscaling

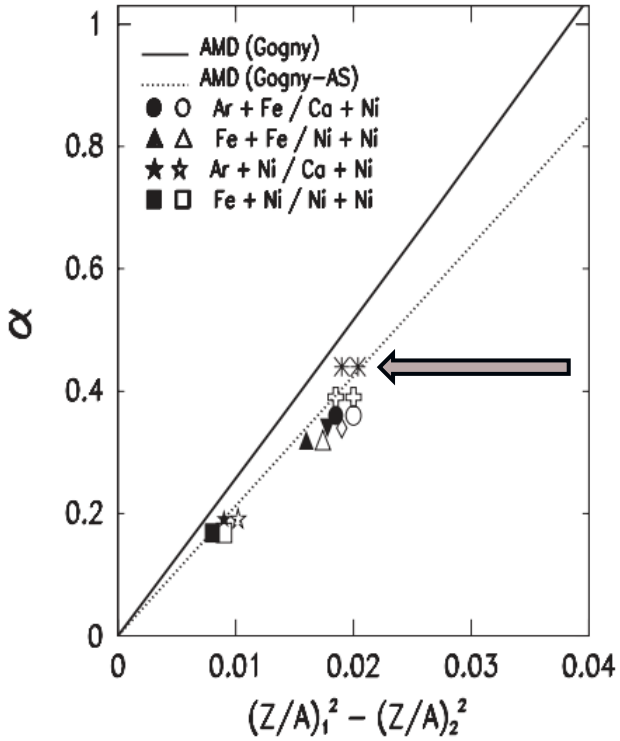
- It has been observed in multifragmentation, deep inelastic collisions, evaporation, and fission
- It was underlined that it is a signature of statistical equilibrium reached by the emitting sources

Isoscaling can be interpreted as a signature of emitting sources that reached similar conditions (Temperature, Volume, …)

PROBING THE SYMMETRY ENERGY FROM THE NUCLEAR ISOSCALING

$$\alpha = \frac{4C_{\mathrm{sym}}}{T}\left(\frac{Z_1^2}{A_1^2} - \frac{Z_2^2}{A_2^2}\right),$$



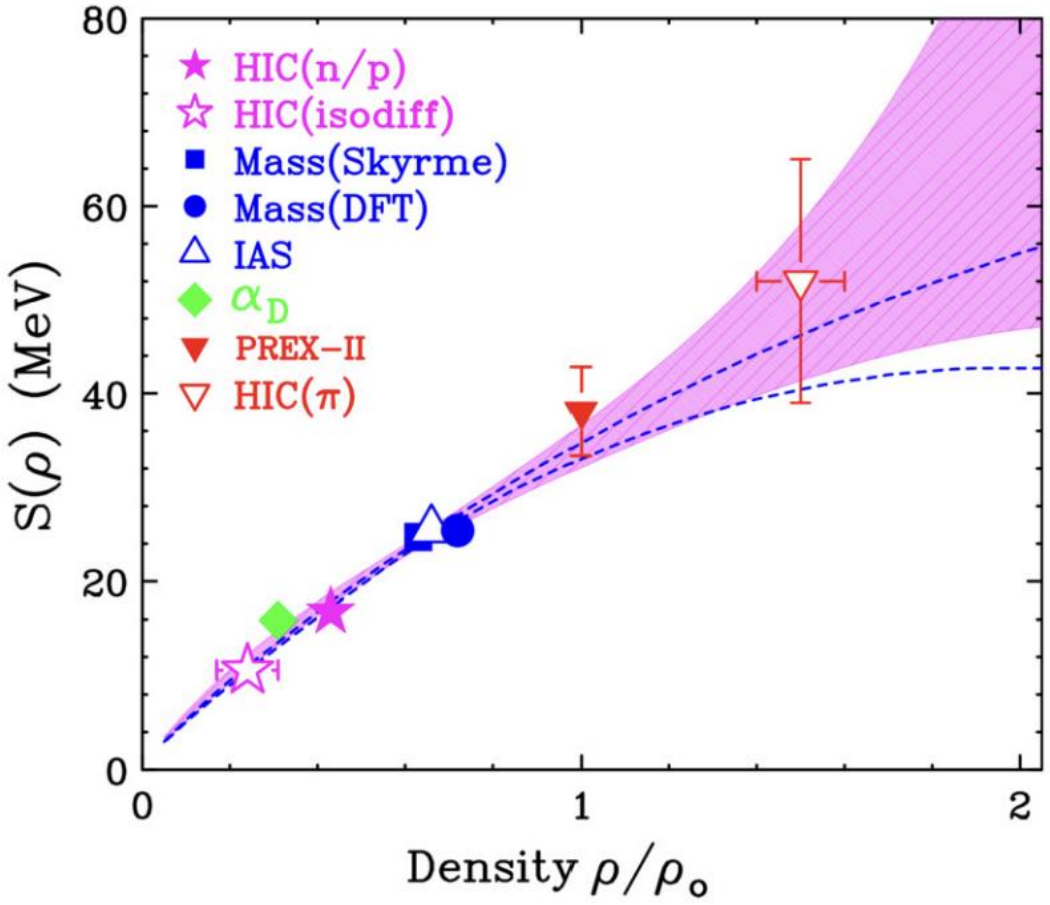


D. V. Shetty, S. J. Yennello, and G. A. Souliotis, Phys. Rev. C 75, 034602 (2007)

DENSITY DEPENDENCE OF THE SYMMETRY ENERGY

In the low density region, several experimental observables were used to constraint the symmetry energy :

- isospin diffusion and migration
- properties of isobaric analog states
- thickness of neutron skins in neutron rich nuclei
- electric dipole polarizability in giant dipole resonances
- isoscalar monopole resonances



W. Lynch and M.B. Tsang,
PLB 830, 137098 (2022)

Symmetry energy at Supra-saturation density

Heavy-ion collisions at relativistic energy can be used to explore the symmetry energy at densities above the saturation density.

Usually used observables are related to the production of isospin pairs:

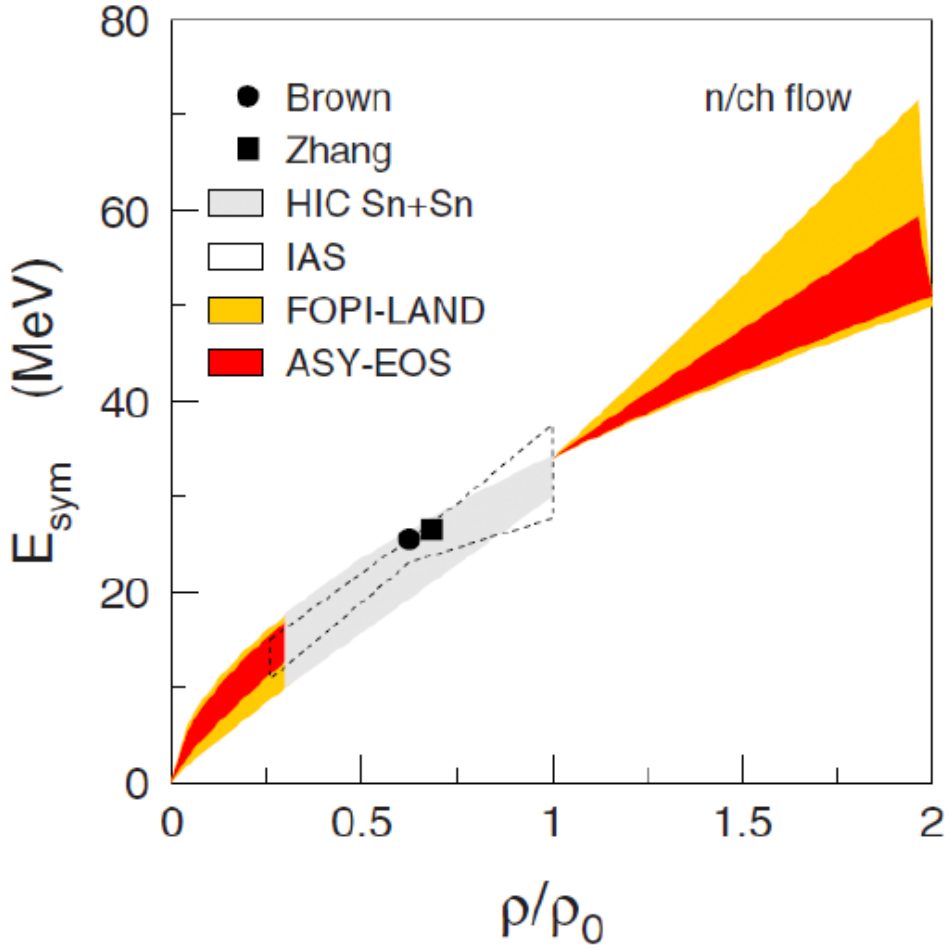
-ratio of negative to positive pions (π^-/π^+),

-kaon multiplicity ratio (K^+/K^0)

- yields and flows of neutrons and protons or light clusters

FROM ASY-EOS I TO ASY-EOS II

Au+Au 400 MeV/A



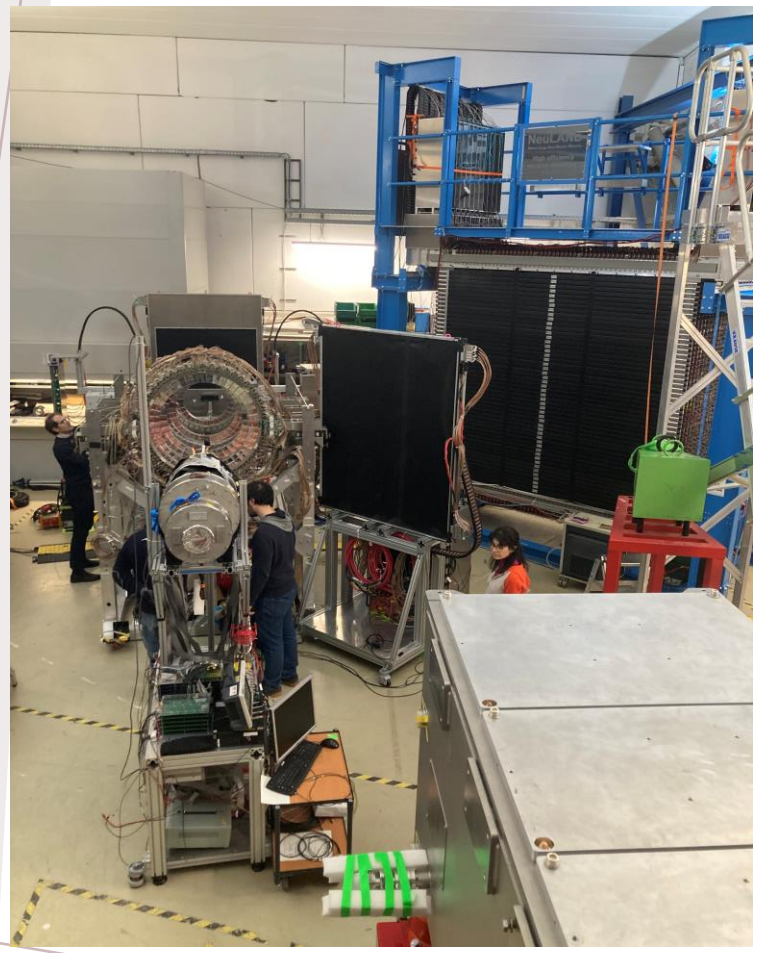
P. Russotto et al., PRC 94, 034608 (2016)

L = 72 ± 13 MeV

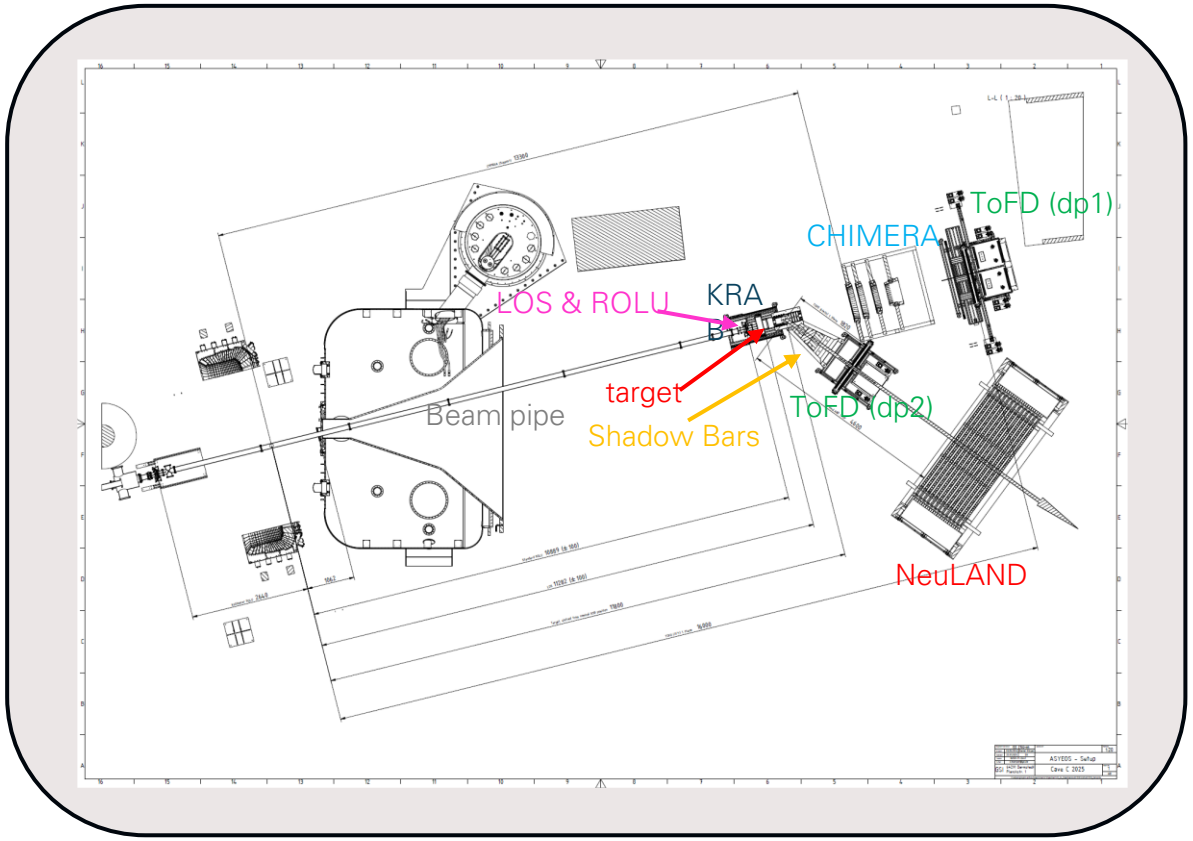
with $E_{sym}(\rho_0)$ = 34 MeV

- Higher incident energies → higher probed densities
- n/p observable: Z=1 isotopic resolution
  → greater sensitivity to higher densities
- R3B NeuLAND: resolving p,d,t
- New KRAB detector:
  Multiplicity trigger, reaction plane and centrality detector
- Enforcement of tight constraints on nuclear transport theories

S122 (ASY-EOS II) - SYMMETRY ENERGY AT HIGH DENSITIES FROM N/P FLOW EXCITATION FUNCTIONS

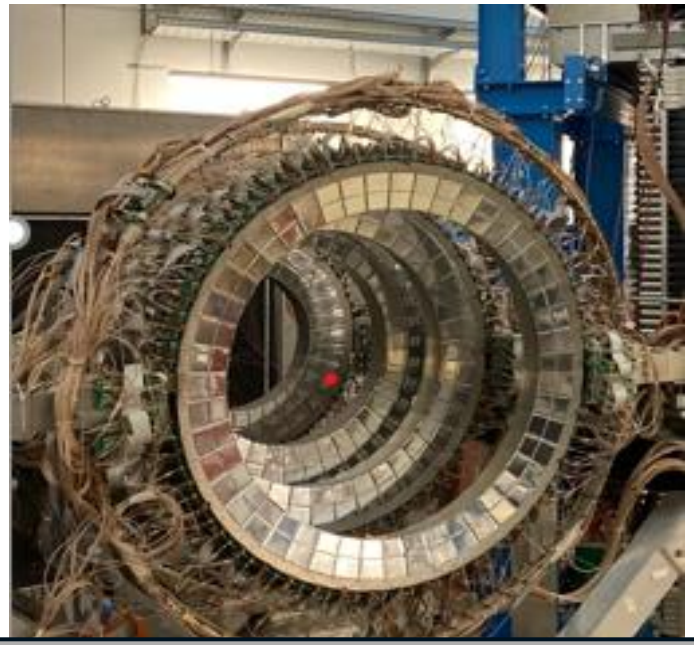


March 2025, Cave C, GSI

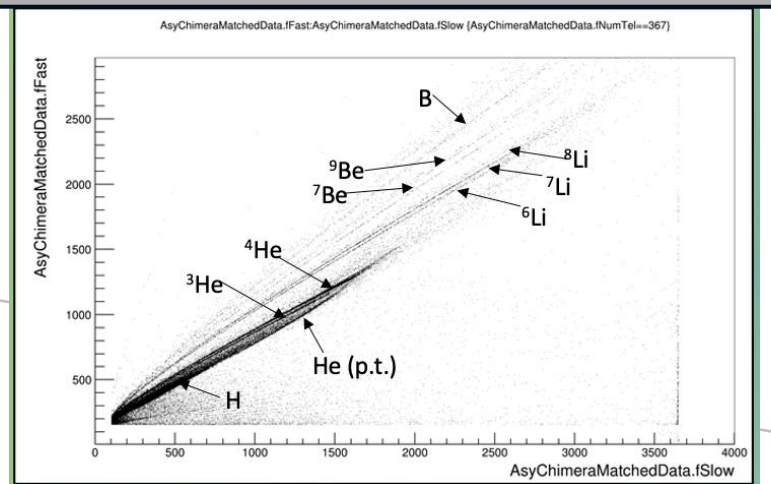


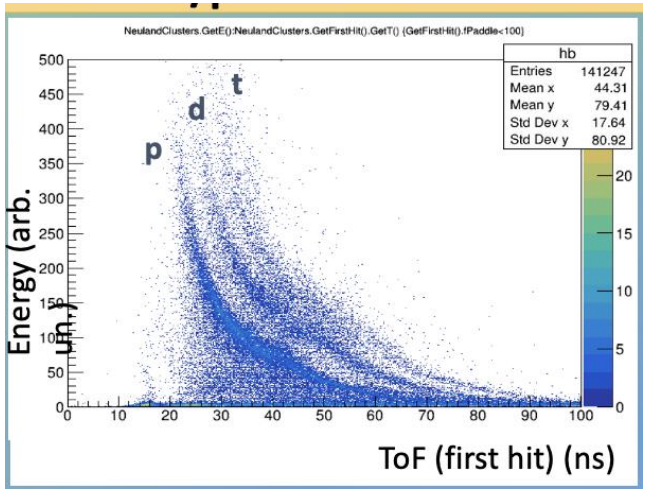
Energy [AMeV]	Purpose
280	highest sensitivity on K_{sym}
400	reference to ASY-EOS I, n/p tests higher densities than before
600	highest sensitivity on L, high-density tested
1000	Maximum energy (≈ density) where models agree on v2 sensitivity

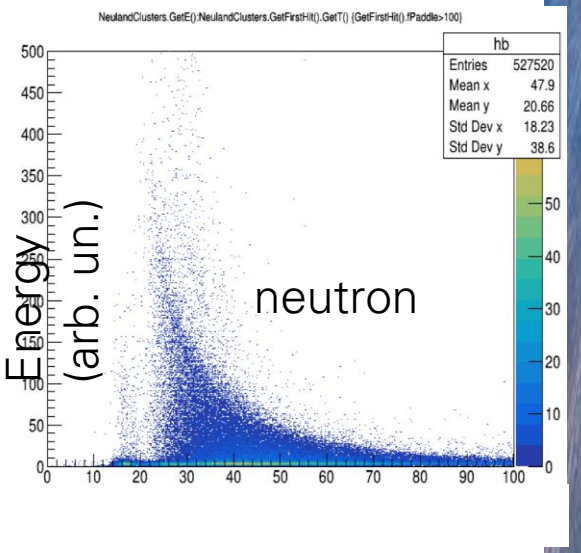
ASY-EOS 2



Chimera and Krab used to determine the reaction plane







Neuland used to extract the neutron/proton flow

CONCLUSIONS

- Heavy Ion collisions at Fermi energies can be a powerful tool to explore the EOS of nuclear matter
- Challenging experimental Apparata are needed to investigate isospin degree of freedom
- Advanced Laboratories are needed to deliver beams with wide N/Z
- Theorethical Models are needed to reconstruct the dynamical phase of the reactions and support the use of experimental observables

THANK YOU

THANKS TO CHIMERA COLLABORATION

L. Acosta(3)(8), A. Barbon(4)(1), G. Cardella(1), A. Castoldi(5)(6), G. D'Agata(4)(1), E. De Filippo(1)(∗), E. Geraci(4)(1), B. Gnoffo(4)(1), C. Guazzoni(5)(6), C. Maiolino(2), N. S. Martorana(1), A. Pagano(1), E. V. Pagano(2), M. Papa(1), S. Pirrone(1), G. Politi(4)(1), L. Quattrocchi(7), F. Risitano(7)(1), F. Rizzo(4)(2), P. Russotto(2), G. Sacca`(1), G. Santagati(1), M. Trimarchi(7)(1) and C. Zagami(4)(2)

(1) INFN, Sezione di Catania - Catania, Italy
(2) INFN, Laboratori Nazionali del Sud - Catania, Italy
(3) Instituto de Fisica, Universidad Nacional Auton´oma de Mexico - Mexico City, Mexico
(4) Dip. Fisica e Astronomia, University of Catania - Catania, Italy
(5) Dip. di Elettronica, Informazione e Bioingegneria, Politecnico di Milano - Milano, Italy
(6) INFN, Sezione di Milano - Milano, Italy
(7) Dipartimento di Scienze MITF, University of Messina - Messina, Italy
(8) Instituto de Estructura de la Materia, CSIC - Madrid, Spain

and R3B Collaboration