Nuclear dynamics and thermodynamics with INDRA and FAZIA

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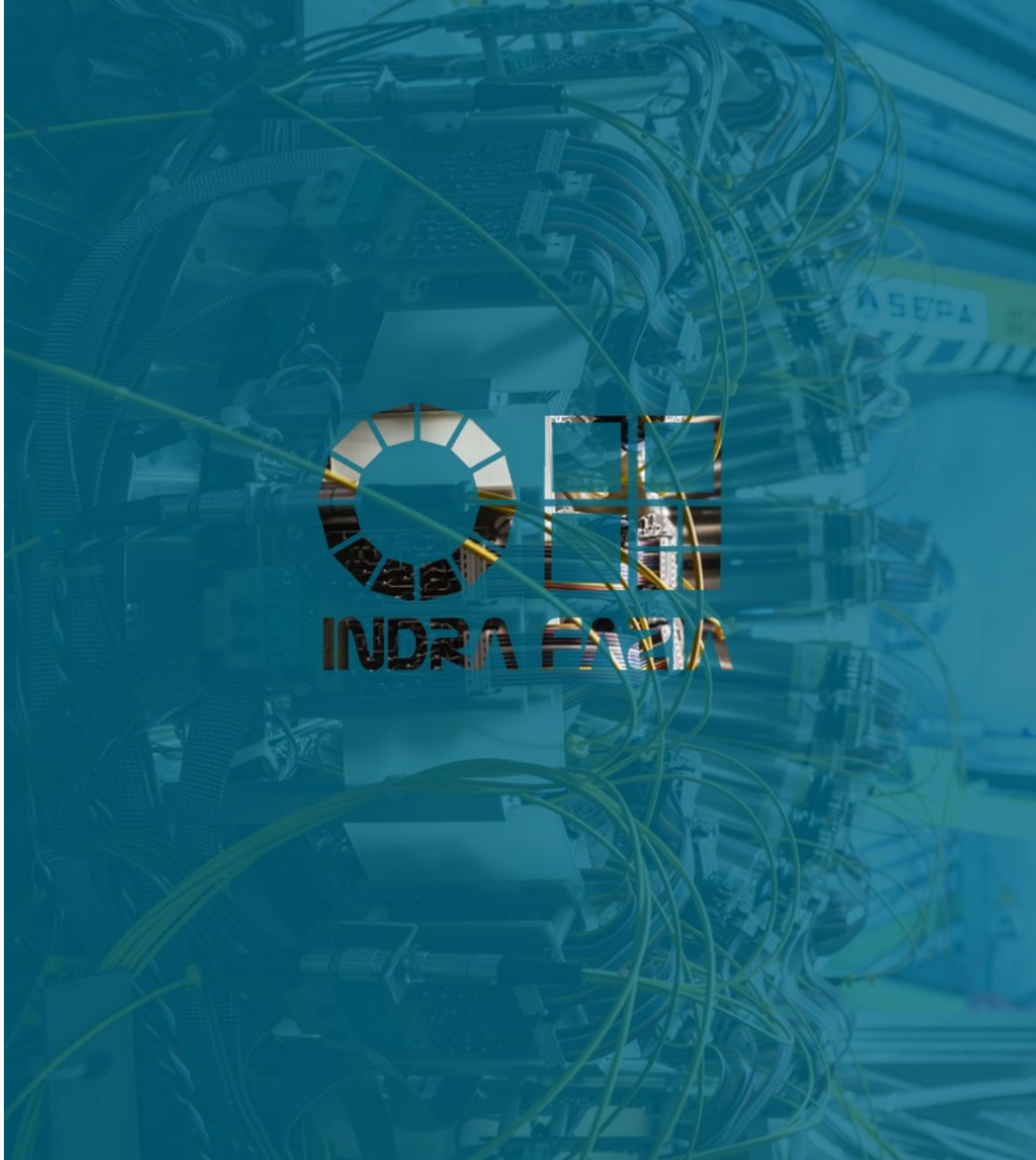
(for the INDRA and FAZIA Collaborations)

→ INDRA and FAZIA collaborations
→ EoS physics with INDRA-FAZIA
→ Short term plans @ GANIL
→ Possible implications @ FRIB



INDRA collaboration

Phase transition studies in hot nuclei using HIC at intermediate energies (E ~ 10-100 MeV/nuc.).

INDRA detector

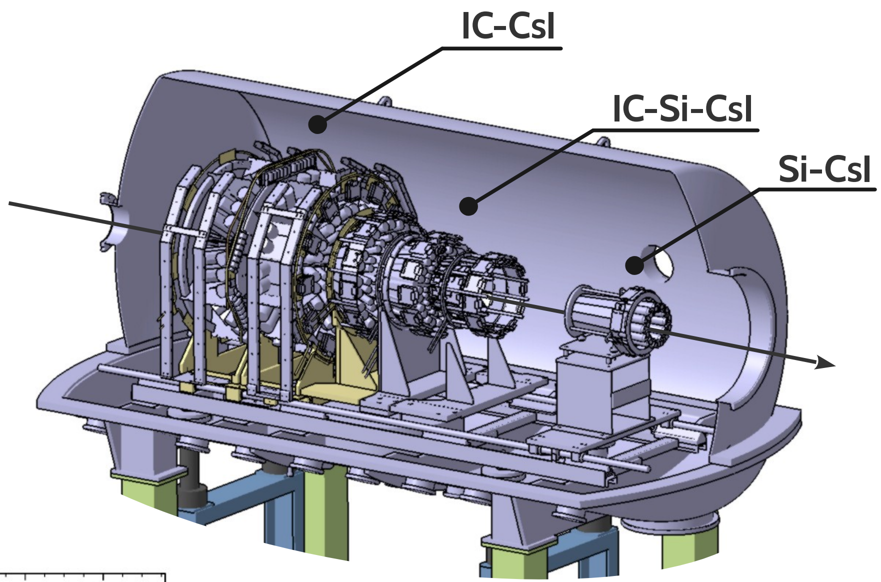
4π charged particle multidetector optimized for detecting ~50 particles. 17 rings with 12 to 24 telescopes : IC-Si-CsI (<45°), IC-CsI (>45°). Covers 90% of solid angle (336 modules). Full charge identification, masses resolved up to Z~5.

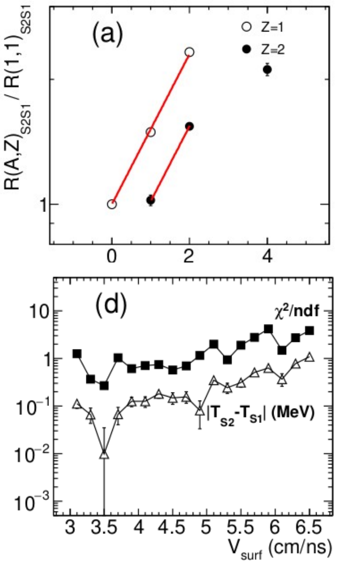
Scientific highlights

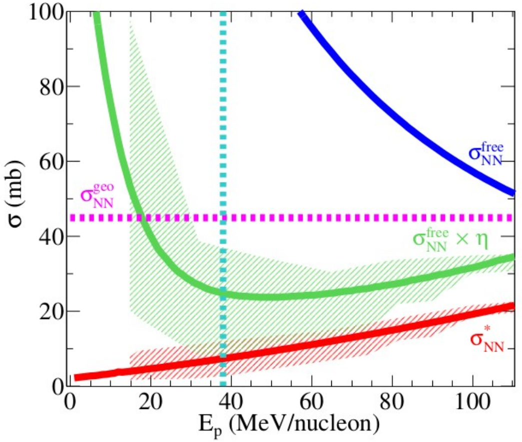
Experimental campaigns at GANIL (1993) and GSI (1998). Signals of phase transition, reaction mechanism, isoscaling [1], stopping and σ_{NN} [2]...

→ Complete renewal of the electronics in 2020.

[1] Rebillard-Soulié, accepted in JoPG (2023)
[2] Henry, PRC **101** (2020) 064622

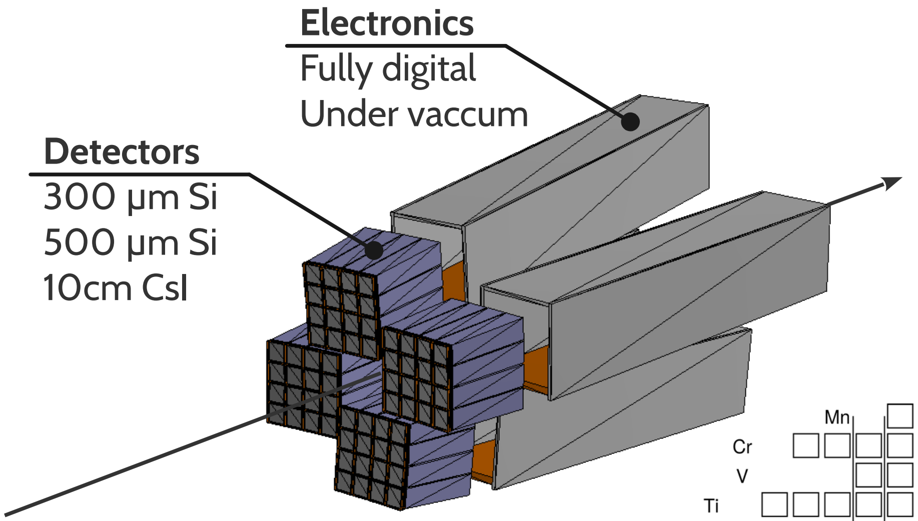






FAZIA collaboration

European initiative to build a charged particle multidetector with isotopic resolution (Z and A) : optimization detectors and digital electronics.
→ Korean colleagues joined the collaboration in 2018

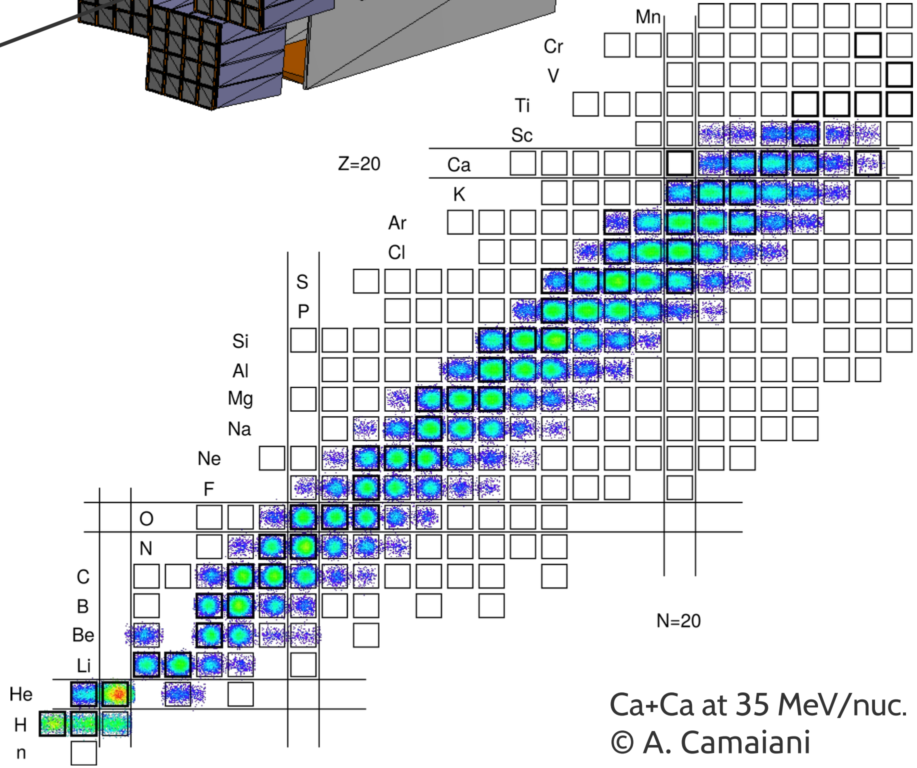


FAZIA detector

Blocks of 4x4 Si-Si-CsI telescopes with modular geometry. Identification with ΔE-E and PSA : full charge identification, masses resolved up to Z~25.

Scientific highlights

Campaign at LNS Catania (2015-2018) with 4 to 7 blocks: isospin diffusion and drift [1], first imbalance ratio with FAZIA [2], cluster production and decay [3], QP break-up channel [4].



Ca+Ca at 35 MeV/nuc.
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[1] Piantelli, PRC **101** (2020) 034613, **103** (2021) 014603
[2] Camaiani, PRC **102** (2020) 044607, **103** (2021) 014605
[3] Frosin, PRC **107** (2023) 044614
[4] Piantelli, PRC **107** (2023) 044607

The nuclear equation of state

Fundamental properties of nuclear matter.
Macroscopic counterpart of nuclear interaction.

$$P(\rho,T) \leftrightarrow e(\rho_n,\rho_p,T)$$

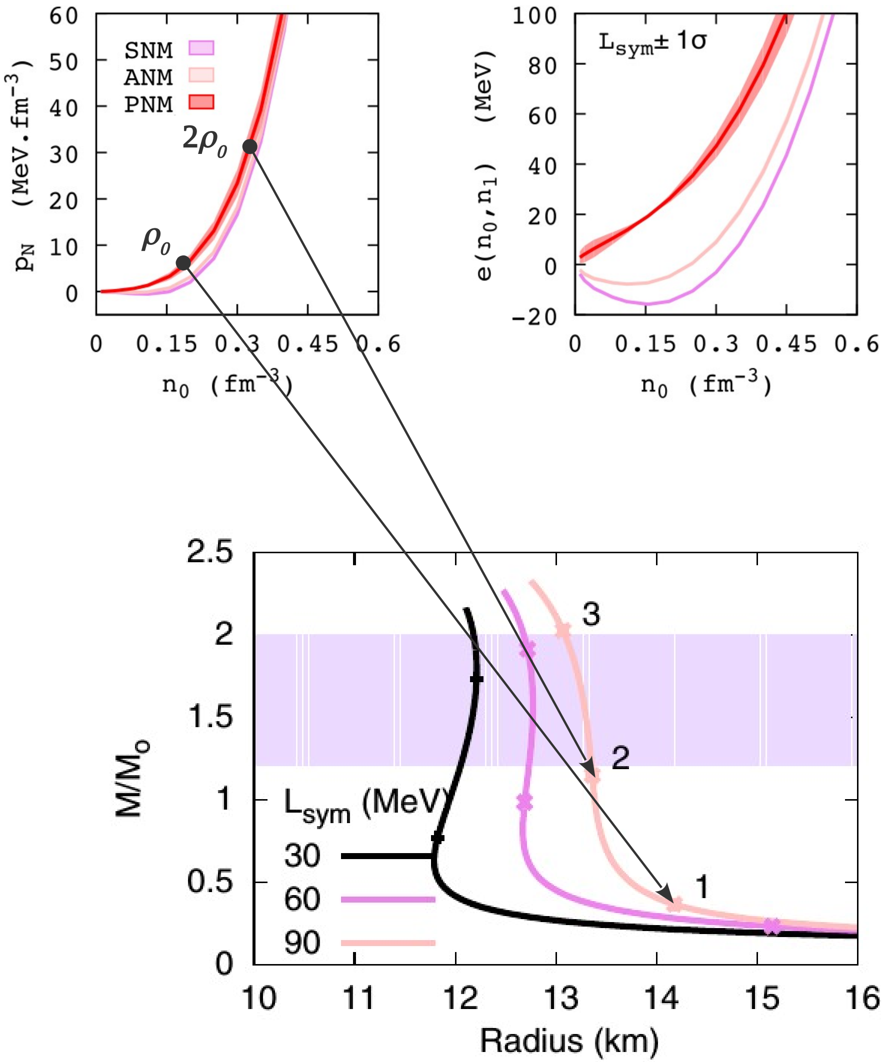
Implication in astrophysics

Mandatory ingredient to compute neutron star mass-radius : solve the relativistic hydrostatic equation (TOV) starting from the core density down to the surface of the star.
→ Very sensitive to the equation of state !

Observational constraints

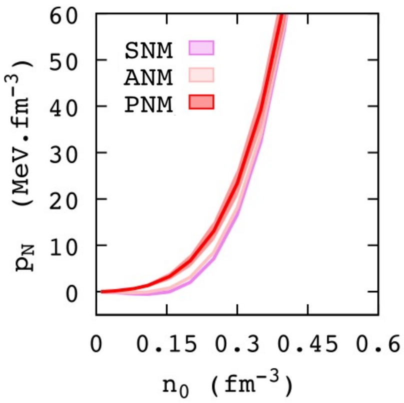
Any valid equation of state should be able to produce a neutron star as heavy as the heaviest observed one. Precise measurement of both mass and radius would drastically constrain the EoS !

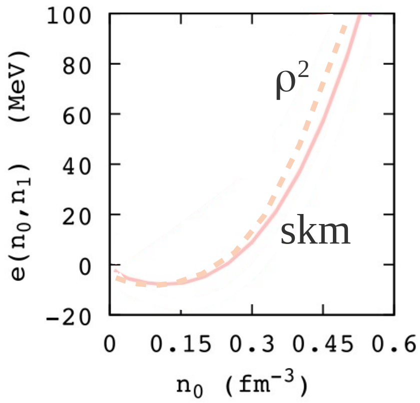
[1] Margueron, PRC **97** (2018) 025805, **97** (2018) 025806

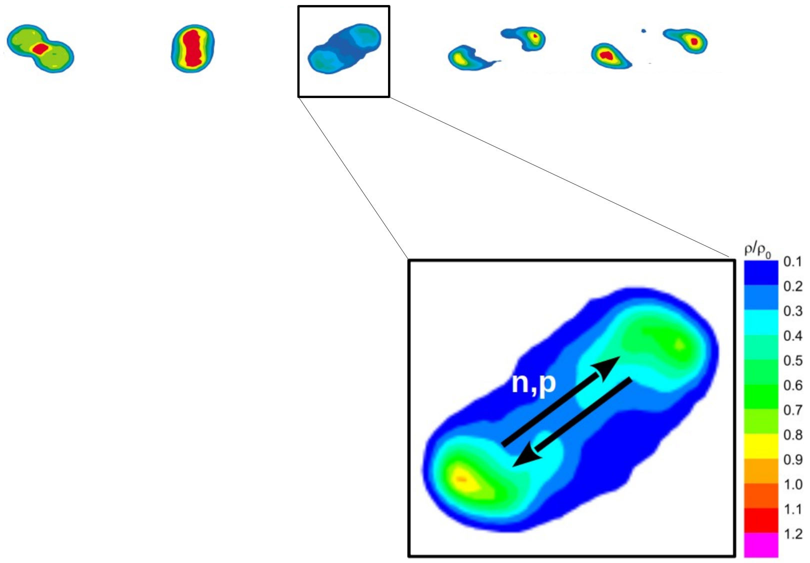


Heavy ion collisions

During peripheral collisions, projectile and target interact and exchange some nucleons.







[1] Margueron PRC **97** (2018) 025805
[2] Tsang PRL **92** (2004) 062701

Heavy ion collisions

During peripheral collisions, projectile and target interact and exchange some nucleons.

Isospin equilibration

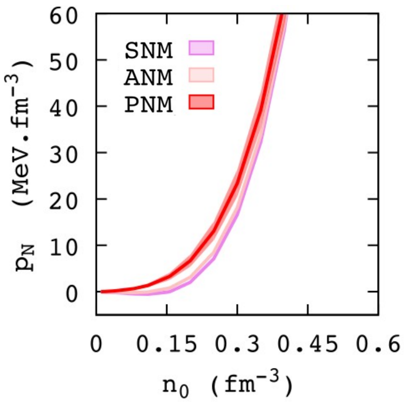
Projectile and target with different neutron to proton ratio equilibrate their N/Z over time. Two different interactions, leading to different equations of state, produce different equilibration path.

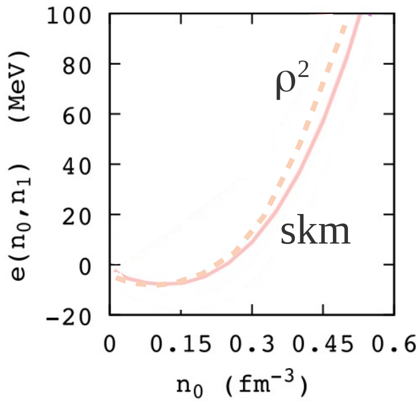
Experimental constraints

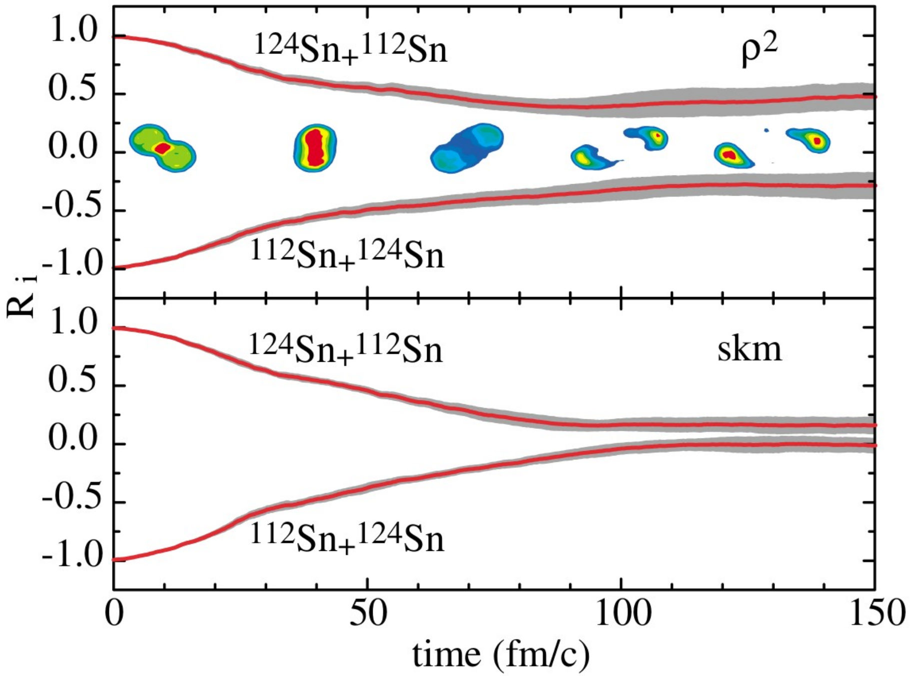
Any experimental measurement of the isospin equilibration rate would constrain the EoS !

→ Mesure the quasi-projectile charge and mass
→ Characterize the collision geometry (b)

[1] Margueron PRC **97** (2018) 025805
[2] Tsang PRL **92** (2004) 062701







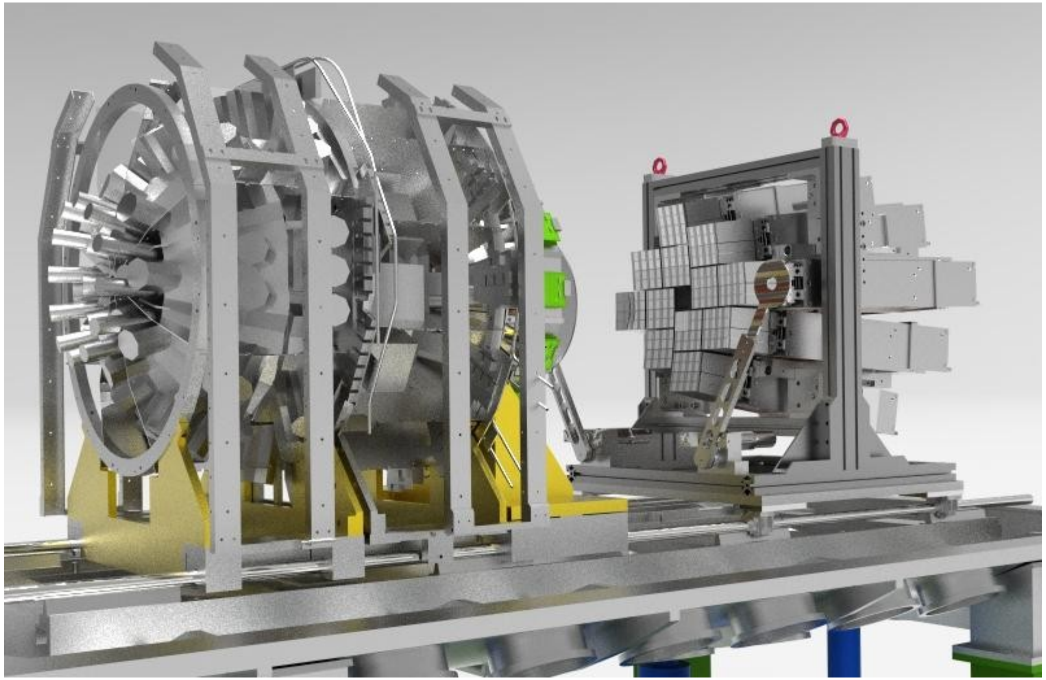
INDRA-FAZIA @ GANIL

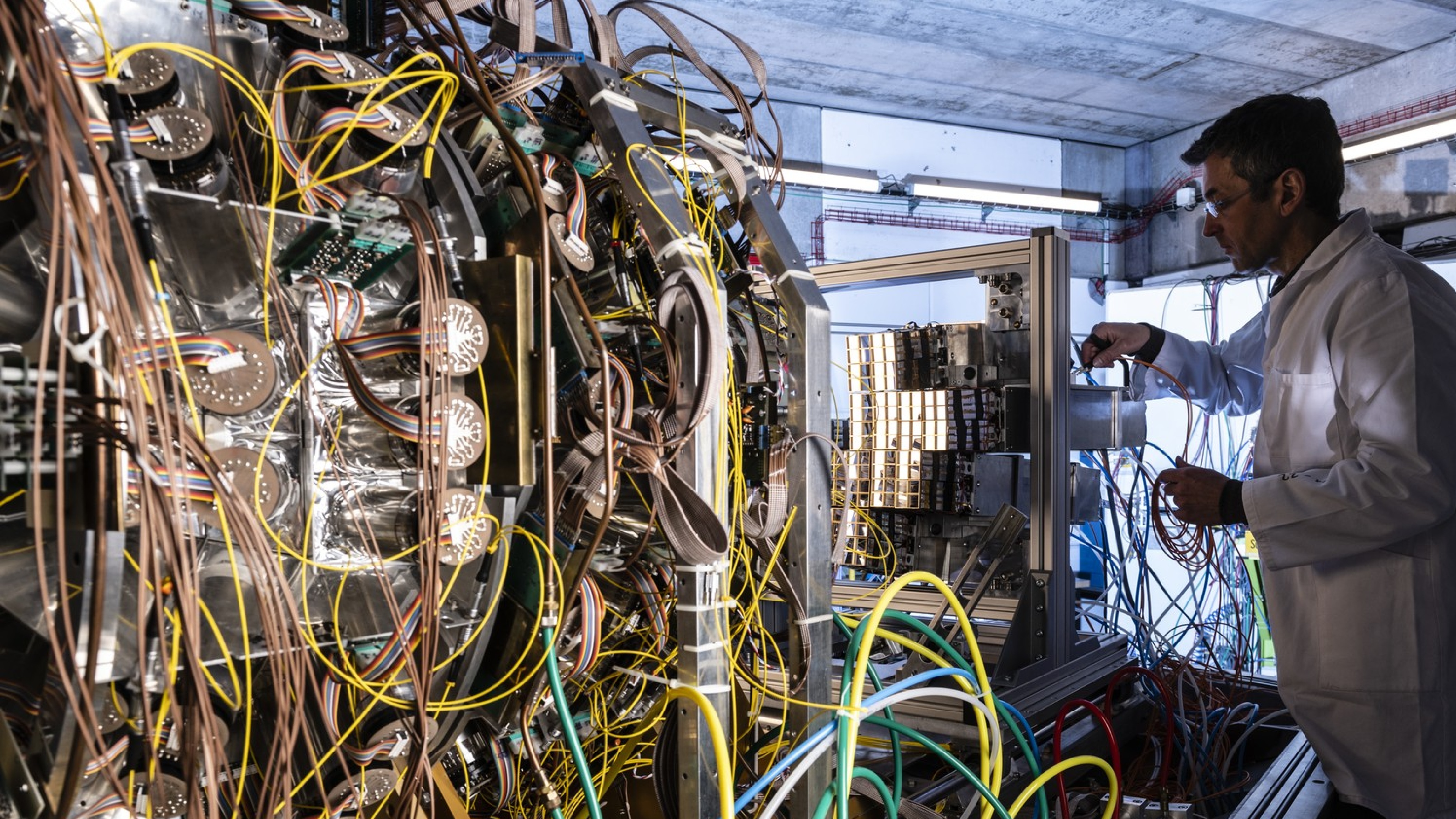
Replace the rings 1-5 of INDRA with 12 FAZIA blocks in wall configuration (1.5° - 13°).

→ Isotopic identifiation of forward emitted fragments
→ Event topology thanks to 80 % angular coverage

Experiments

→ **Isospin transport and EoS (2019)**
→ Vaporisation and clusters in medium (2022)
→ Size asymmetry and isospin transport (2025)
→ **Measurement of the ^{12}C Hoyle state radius (2025)**





E789 experiment @ GANIL

Ni +Ni collisions with various combinations of stable Ni isotopes (^{58}Ni and ^{64}Ni) at 32 and 52 MeV/nuc [1].
→ N/Z equilibration ratio versus impact parameter[2]

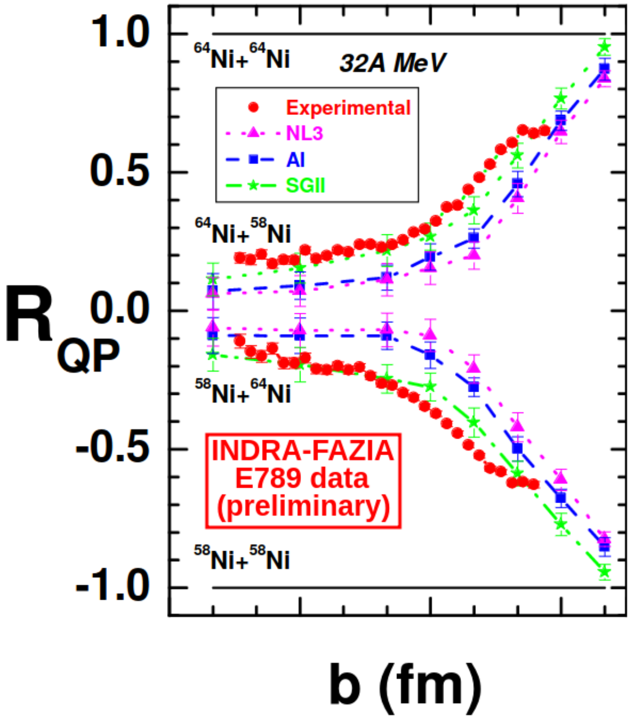
Constraints on EoS

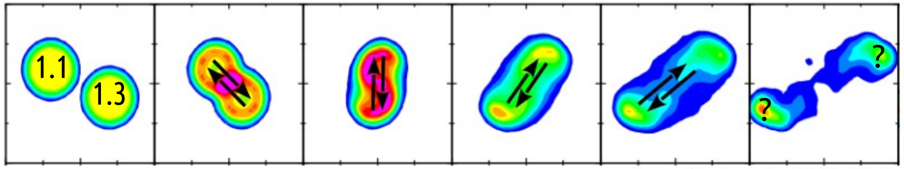
Comparison of equilibration ratio versus impact parameters with transport model calculations using various EoS (BUU).

Future prospects

New experiment at GANIL in 2025 to understand the effect of size asymmetry on isospin transport.
→ Higher the N/Z difference, higher the sensitivity
→ Need to find other mechanism at FRIB energies
→ Synergy with FRIB on transport models

[1] Ciampi, PRC **106** (2022) 024603, PRC **108** (2023) 054611
[2] Frankland, PRC **104** (2021) 034609





^{12}C Hoyle state

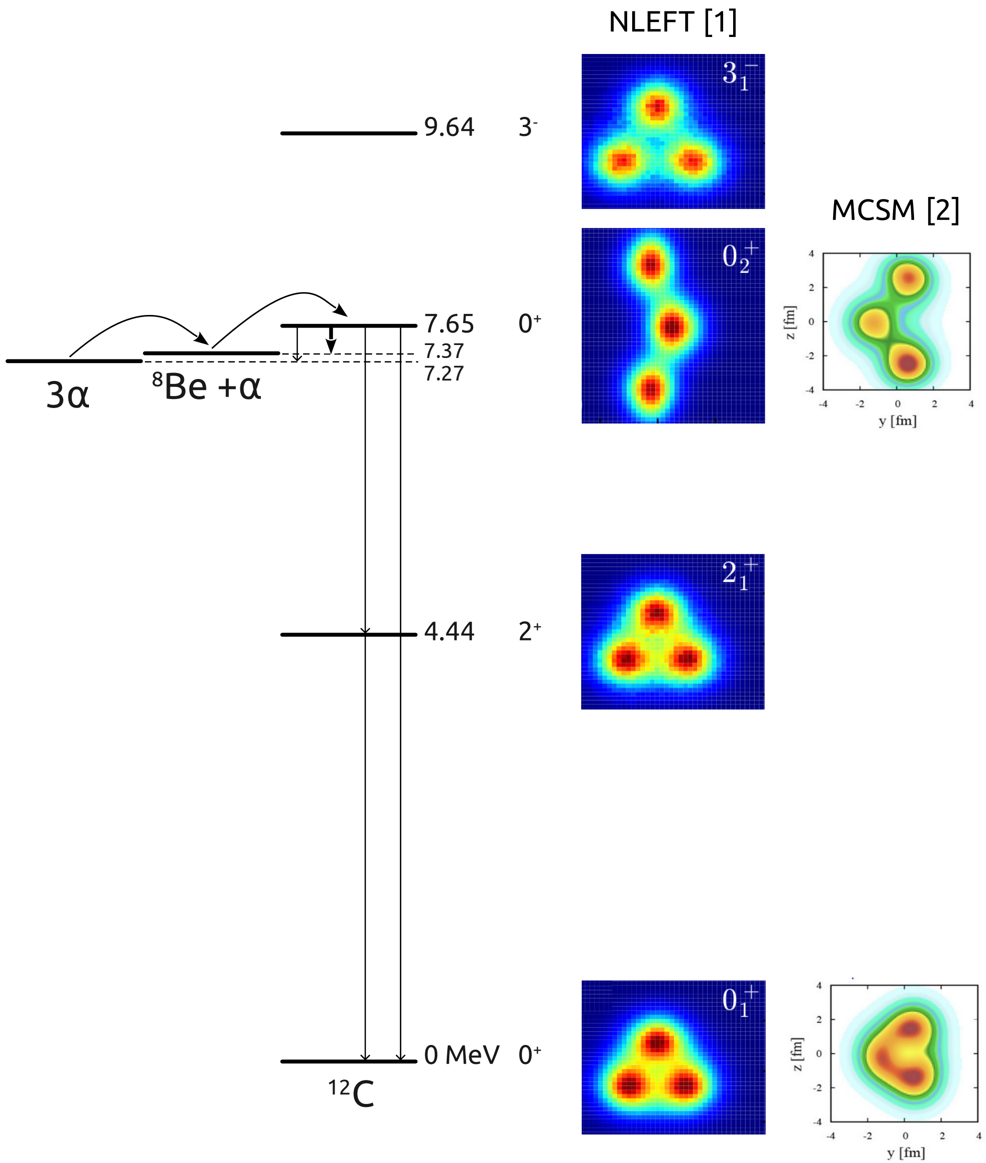
Second 0^+ state, above ^{8}Be + α and 3α thresholds. Still a challenge for nuclear theory : strong difference in Hoyle state radius predictions.
→ NLEFT : obtuse 3α triangle (r = **3.45 fm**)
→ MCSM : compact 3α triangle (r = **2.81 fm**)

Experimental probe

^{12}C + ^{12}C inelastic scattering at 105 MeV. Measure the angular distributions for all combinations of projectile-like and target-like excitation. Radius by comparing single and double Hoyle excitation.

→ Experiment using FAZIA at GANIL in 2025
→ Synergy with structure and reaction theorists ?

[1] S. Shen et al., Nature Com. 14 (2023) 2777
[2] T. Otsuka et al., Nature Com. 13 (2022) 2234



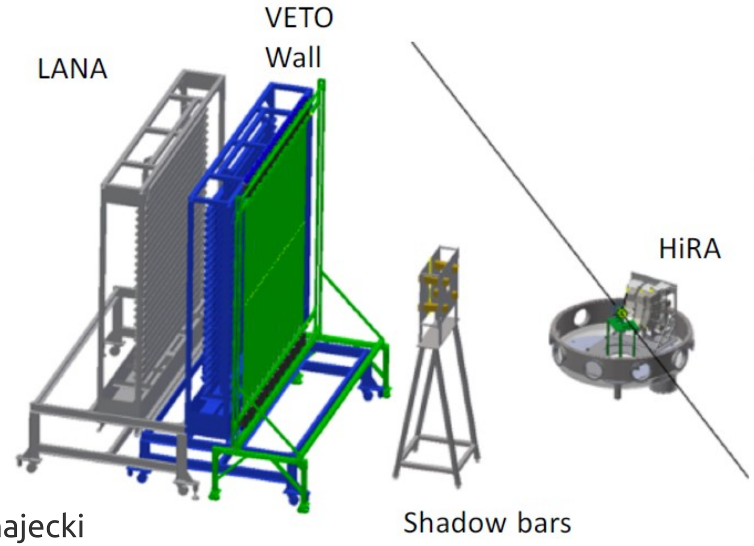
Discussions with FRIB

→ K. Brown and Z. Chajecki proposed us to participate in the 23058 experiment at FRIB
→ Z. Chajecki gave a seminar on EoS physics at FRIB
→ FAZIA collaboration started a working group on FRIB
→ Visit of FAZIA physicists to discuss technical feasability

→ Sub-groups on different physics topics (EoS, transport, correlations, direct reactions…)
→ Internal restitution meeting in spring 2024 to build a LoI and/or experiment proposals

Synergies

Evident synergies on comparison with transport models
Collaboration about detectors in discussion
Theory on structure and direct reactions for ^{12}C ?



23058 @ PAC2 FRIB
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