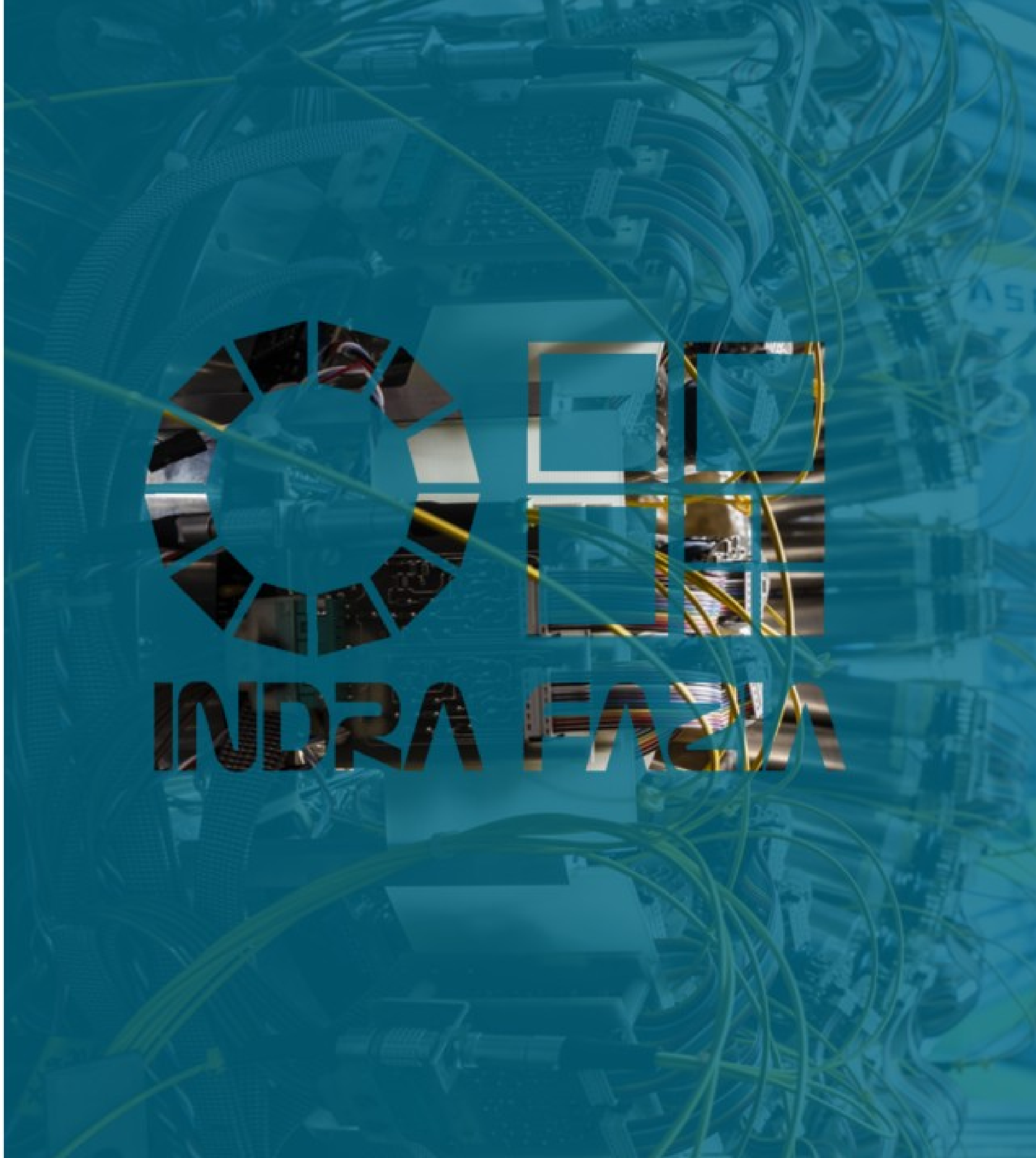
# La matière nucléaire : contraintes expérimentales avec le couplage INDRA-FAZIA au GANIL.

Diego Gruyer, LPC Caen

(for the INDRA and FAZIA collaborations)



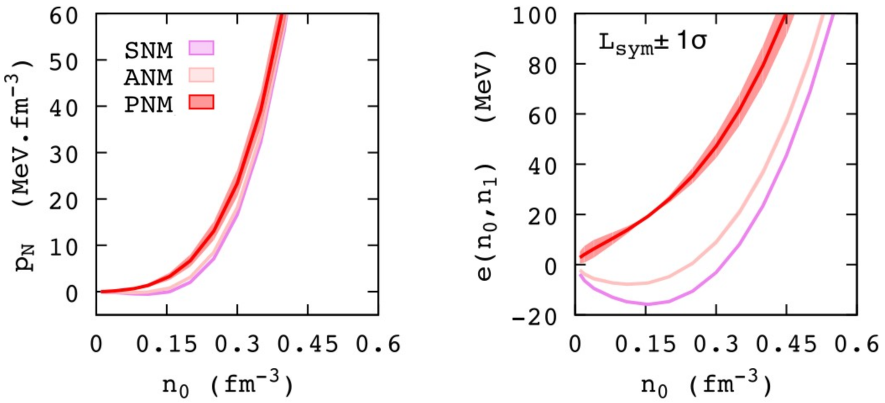

RÉGION NORMANDIE INFN cnrs GANIL spiral2 laboratoire commun CEA/DRF CNRS/IN2P3 INDRA FAZIA

**The nuclear equation of state**

Fundamental properties of nuclear matter.

Macroscopic counterpart of nuclear interaction.

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




Margueron PRC **97** (2018) 025805

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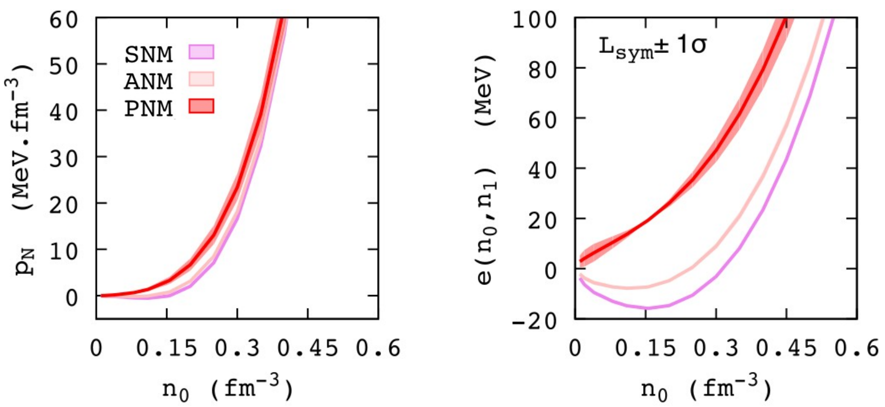
Mandatory ingredient to compute neutron star mass-radius or tidal polarizability, supernovae explosion dynamics...

## Implication in nuclear physics

Governs the dynamics of heavy-ion collisions, nuclear masses and radii, dipole polarizability...

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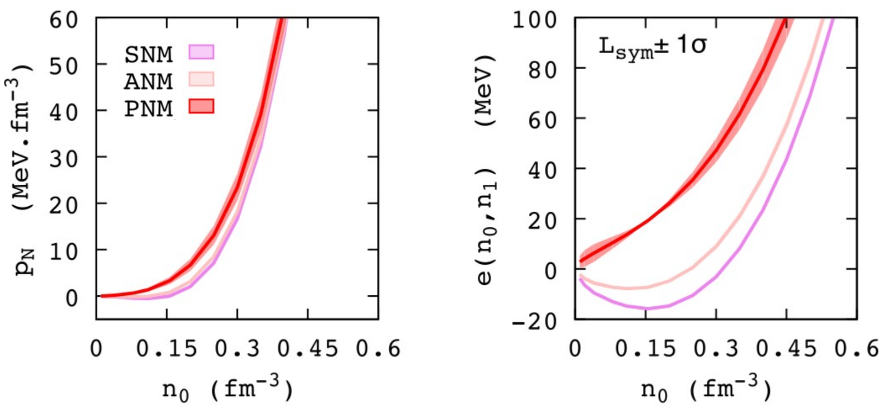
## Jumping accros the scales

Nuclear experiment → astrophysic ingredients
Observation → test for nuclear interaction

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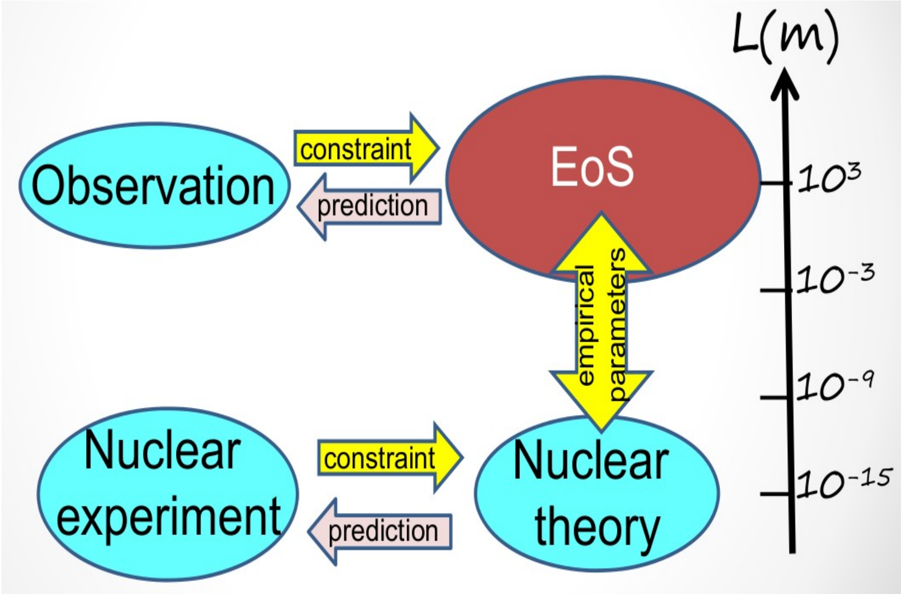


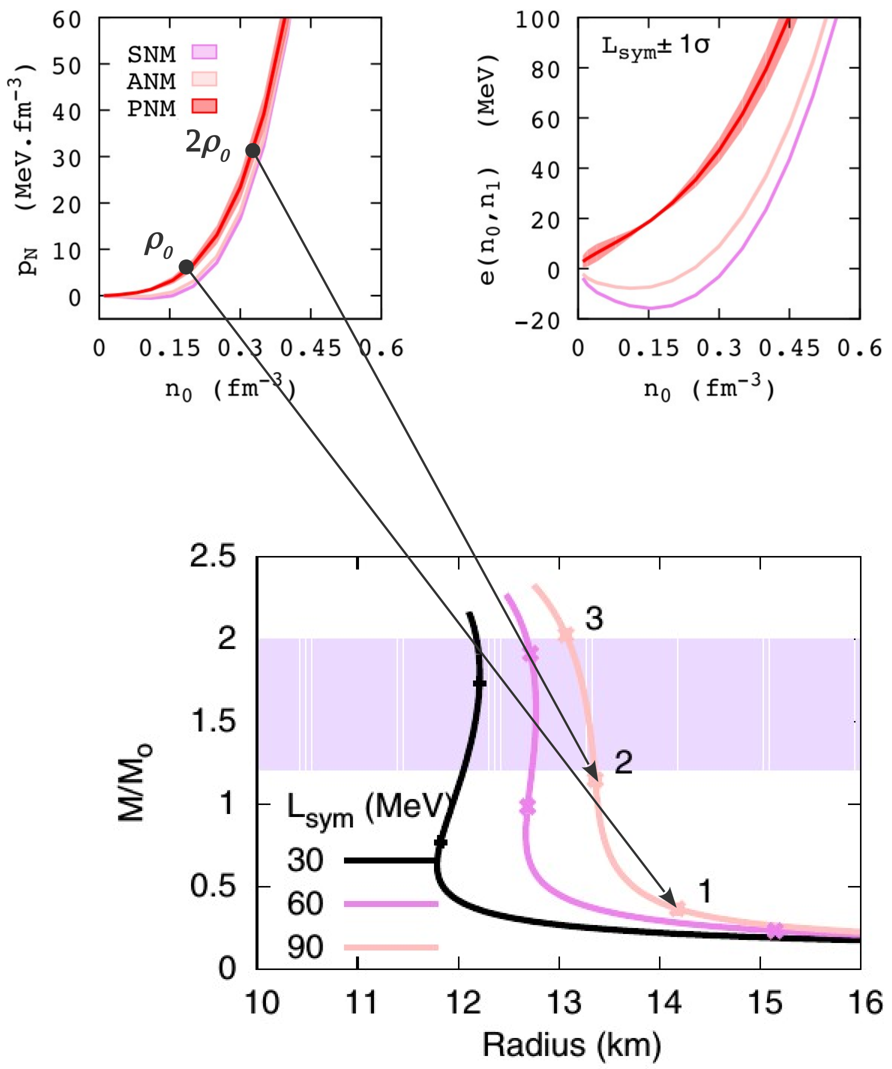

Courtesy F. Gulminelli

## Neutron star ingredients

Equation of state, isospin content (neutron-proton proportion) from beta-equilibrium and general relativity.

## Mass and radius

Relativistic hydrostatic equation (Tolman-Oppenheimer-Volkoff) starting from the core density down to the surface of the star. Very sensitive to the equation of state !

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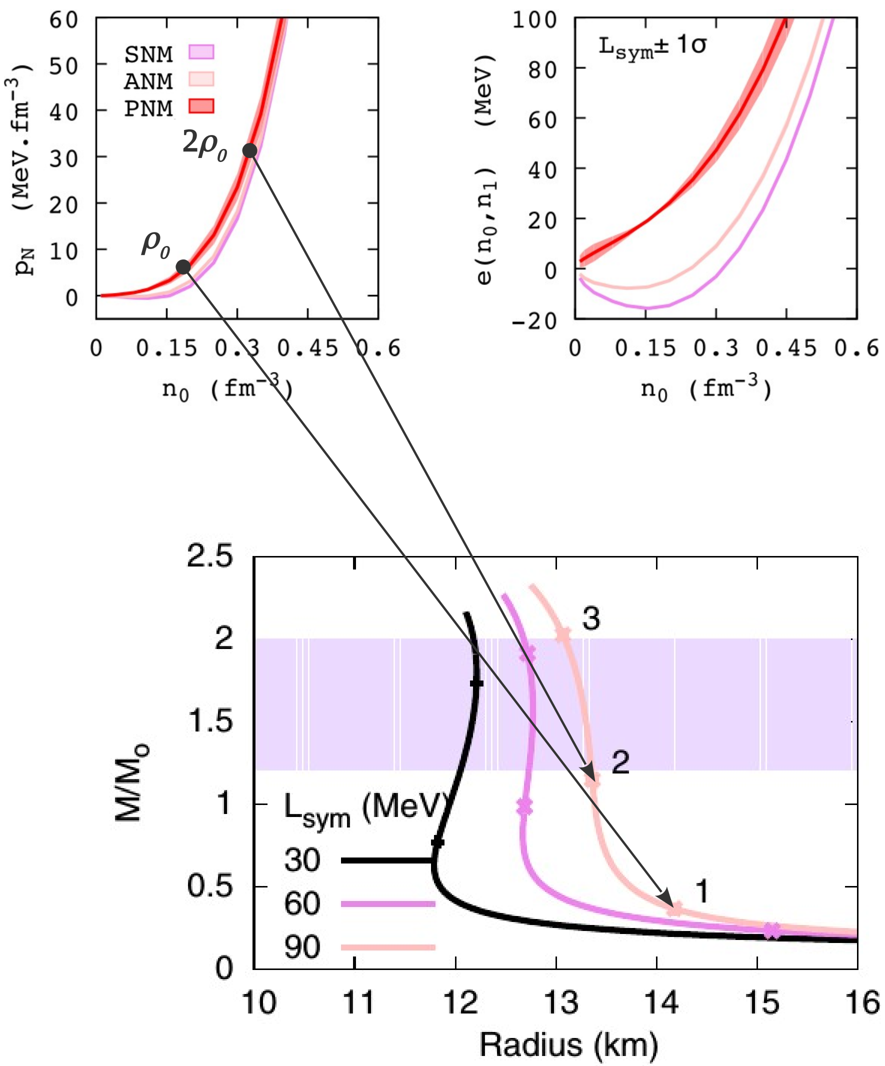
**Observational constraints**
Any valid equation of state should be able to produce a neutron star as heavy as the heaviest observed one. Precise measurement of both mass and radius will drastically constrain the EoS !

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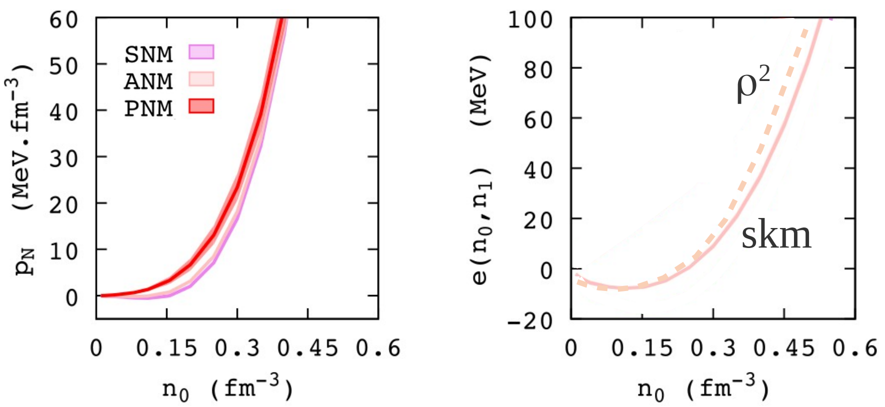
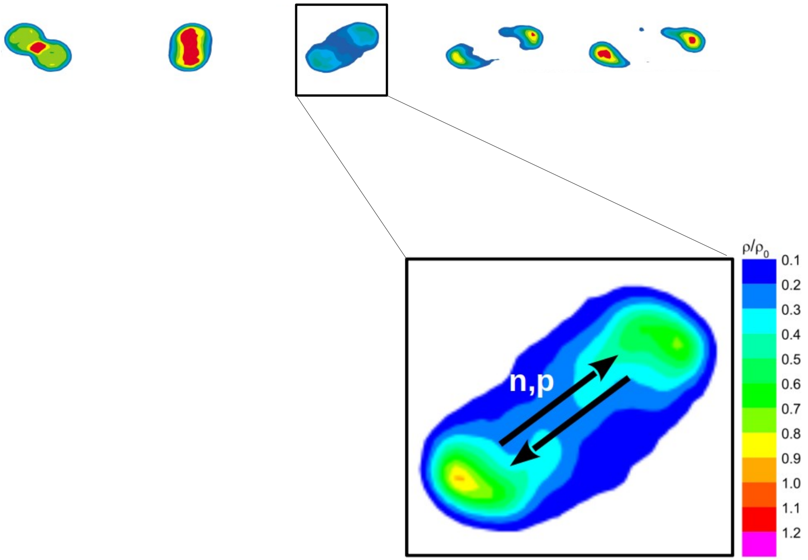
**Heavy ion collisions**

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

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**Heavy ion collisions**

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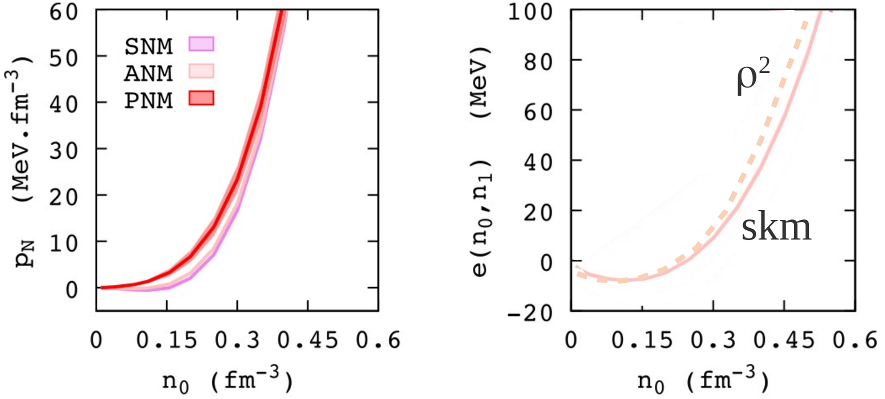
**Isospin equilibration**

Projectile and target with different neutron to proton ratio equilibrate their N/Z during a collision. Two different interactions, leading to different equation of state, produce different equilibration path.

**Experimental constraints**

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

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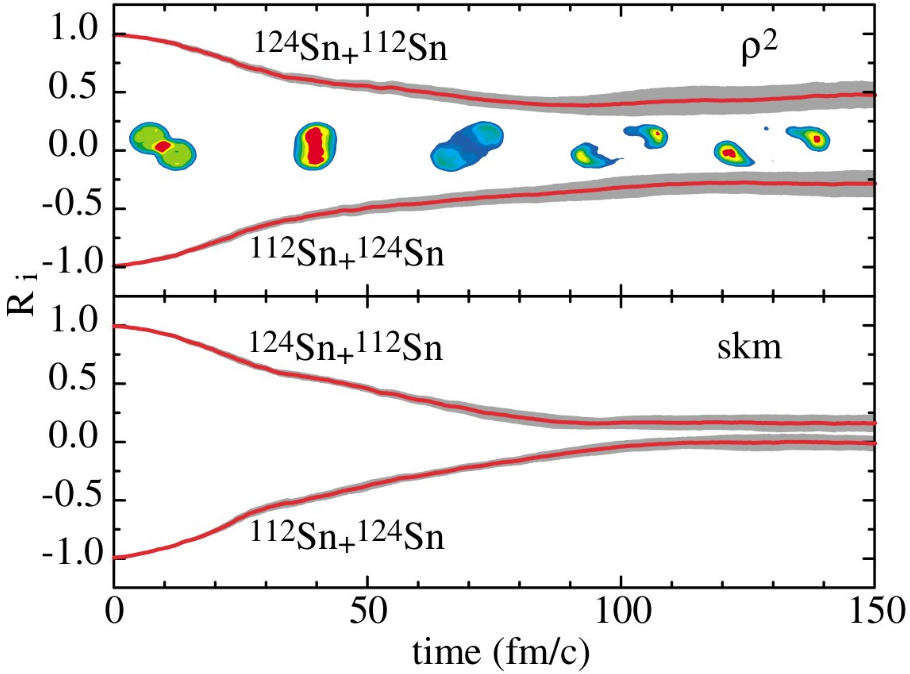


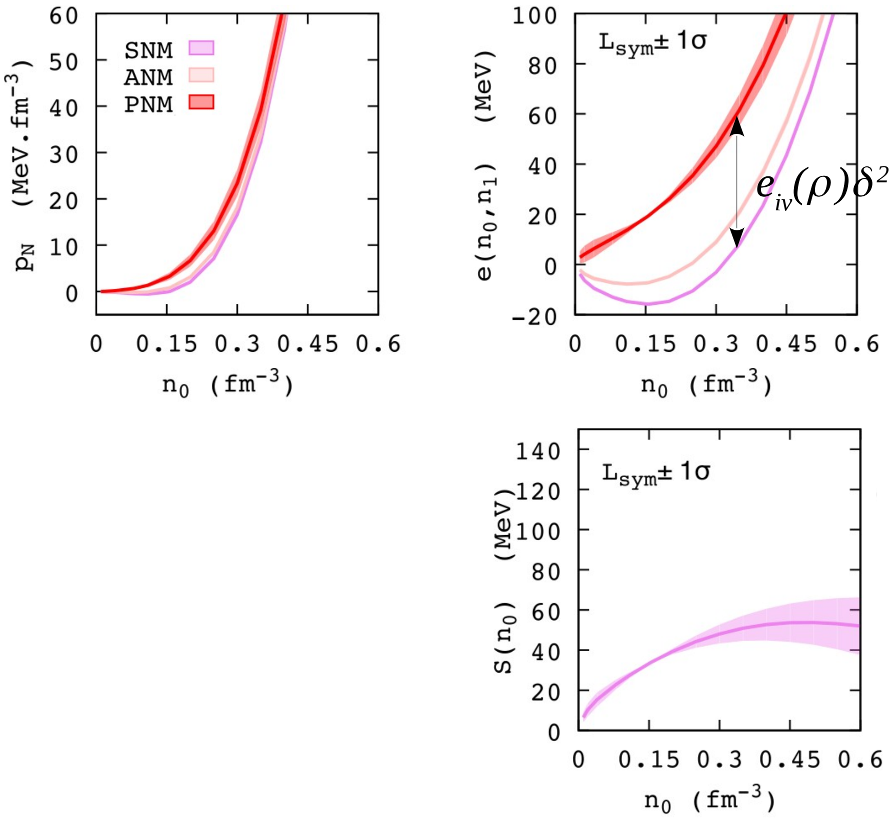

Tsang PRL **92** (2004) 062701

**Symmetry energy**

Isovector part of the equation of state (difference between symmetric and pure neutron matter)

$$e(\rho,\delta) = e_{is}(\rho) + e_{iv}(\rho)\delta^2 + O(\delta^4)$$

$$\delta = (\rho_n - \rho_p)/\rho$$

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Drischle PRL **125** (2020) 172503
Reed PRL **126** (2021) 172503

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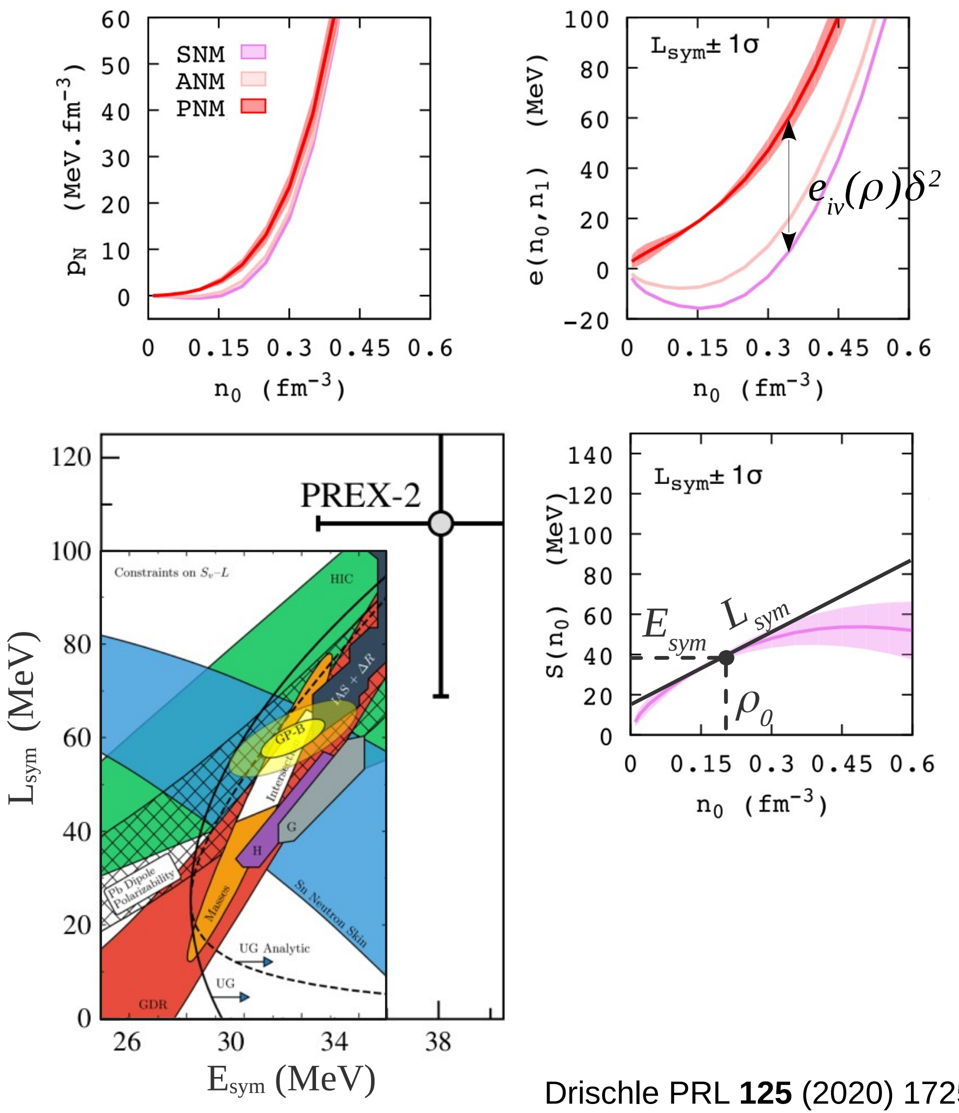
## World wide multi-scale effort

International effort to constrain this term from nuclear experiment, observation and theory. A recent compilation using many experimental probes gives $E_{sym}$ ~ 33MeV and $L_{sym}$ ~ 60MeV. Then, PREX-2 results were published….

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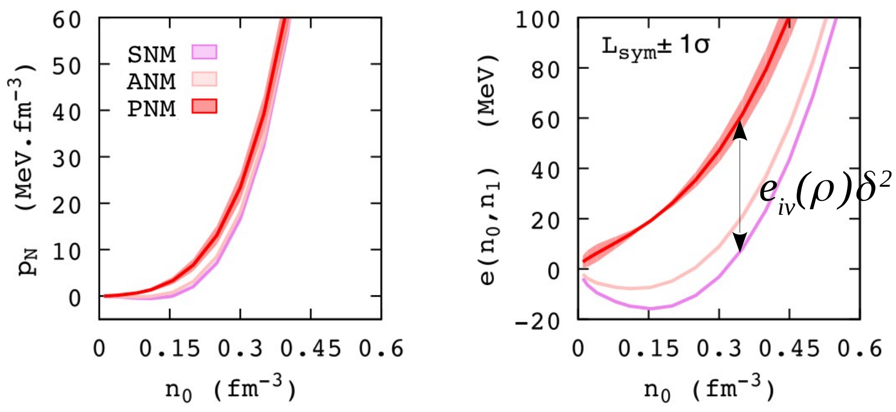
## Challenges for heavy-ion collisions

→ $\rho \ll \rho_0$ : cluster population and properties (intermediate energy, see R. Bougault's talk)

→ $\rho \sim \rho_0$ : low order parameters (this talk)

→ $\rho > \rho_0$ : high order parameters (high energy)

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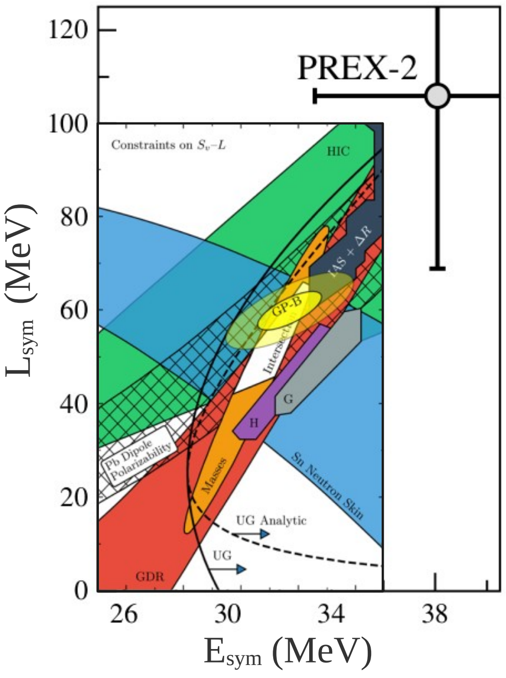


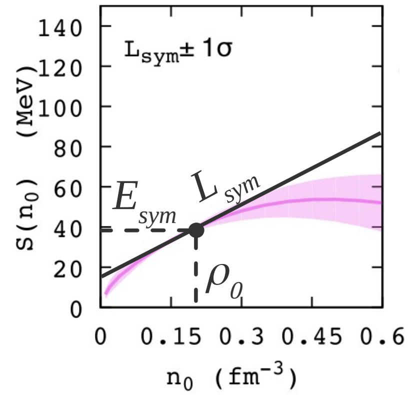


B.An Li et al, Univ. 2021, 7(6), 182

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**End of the introduction** (check the timing)

**Isospin equilibration**

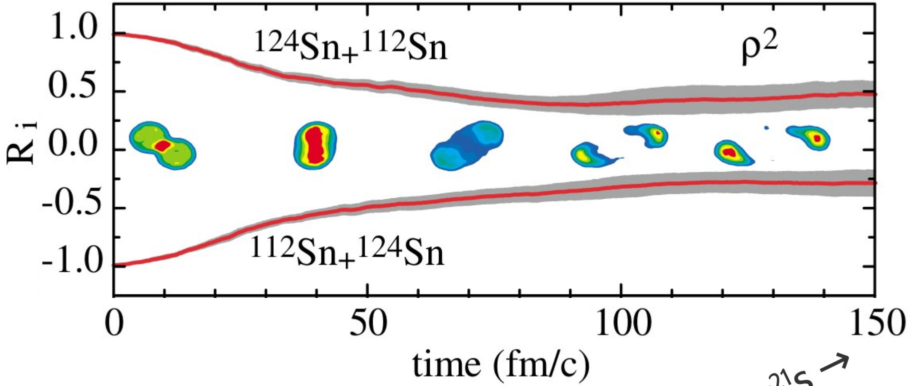
Projectile and target N/Z equilibrate with time
Equilibration rate sensitive to the EoS parameters
It would require to follow the evolution of the N/Z ratio of the quasiprojectile as a function of time…
→ None of these quatity were measurable (2004)

$R_i = (2X_i - X_1 - X_2)/(X_1 - X_2)$, with $X_i = f(Z,N) = N/Z$

$R_i = +1\ (-1)$ : no isospin equilibration

$R_i = 0$ : full isospin equilibration

detection →




0.5 zs = 0.5 $10^{-21}$s →

Tsang PRL **92** (2004) 062701

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## Experimental approach

Really measure the N/Z ratio of quasi-projectile
Interaction time and window size depend both on the impact parameter and the beam energy
→ Replace time by impact parameter and run the same systems at 2 beam energies

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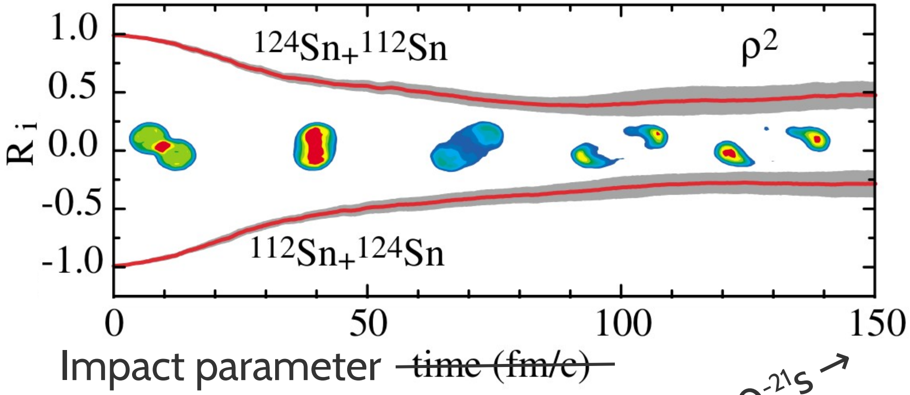


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## E789 INDRA-FAZIA experiment

$^{64}Ni+^{64}Ni$ collisions at 32 and 52 MeV/nuc
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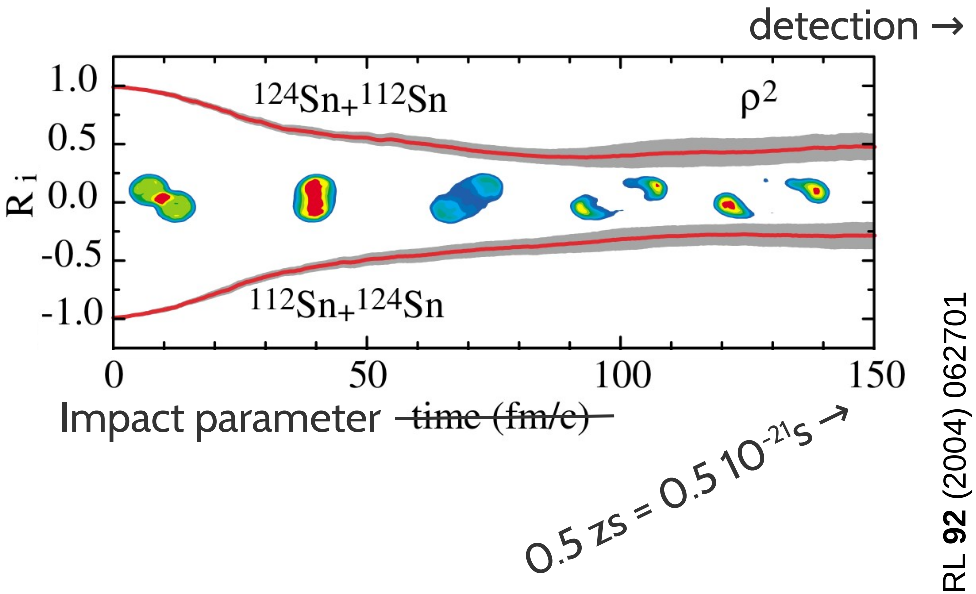



Tsang PRL **92** (2004) 062701

## INDRA-FAZIA coupling in GANIL

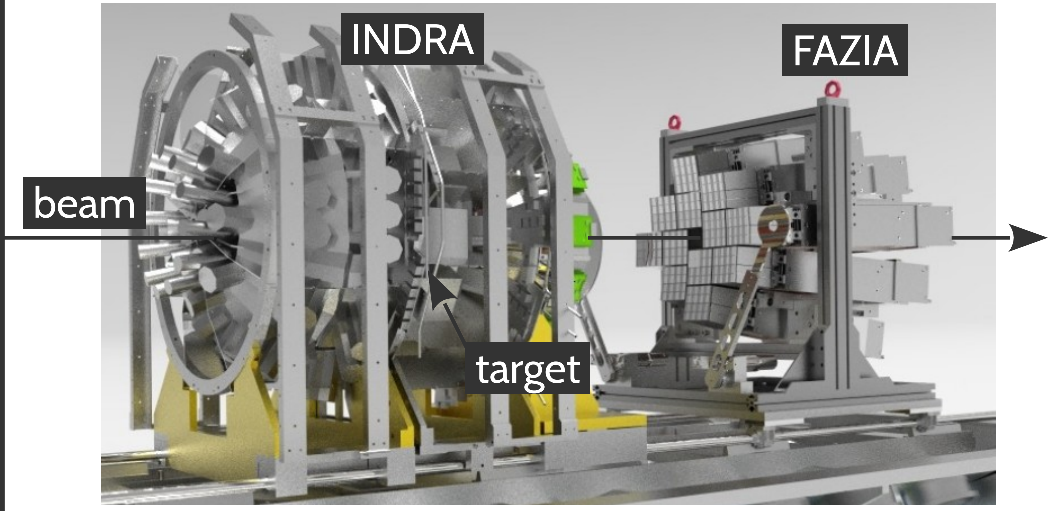
INDRA in GANIL since 1993. 12 FAZIA blocks replaced the forward part of INDRA in 2018.

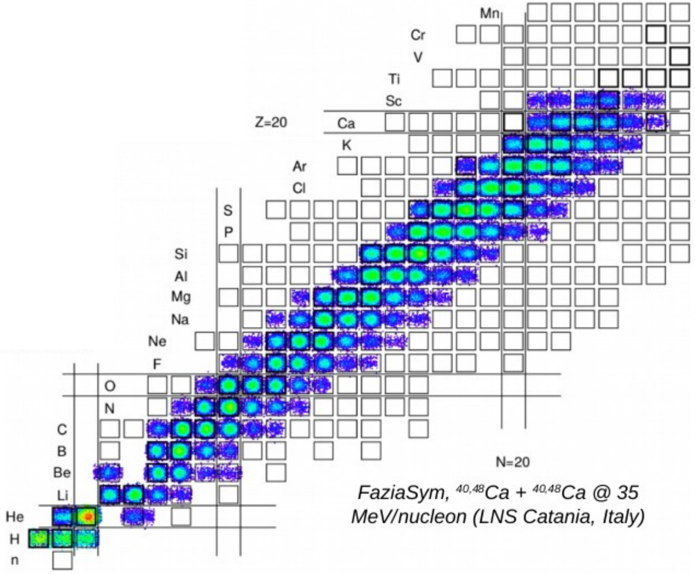
## INDRA

240 detection modules (~14° to ~180°)
Si-CsI or CsI telescopes (ΔE-E and PSA in CsI)
Fully analogic electronics (digital upgrade in 2020)
→ full Z-identification, A-identification up to Z=5
→ impact parameter selector (multiplicity)

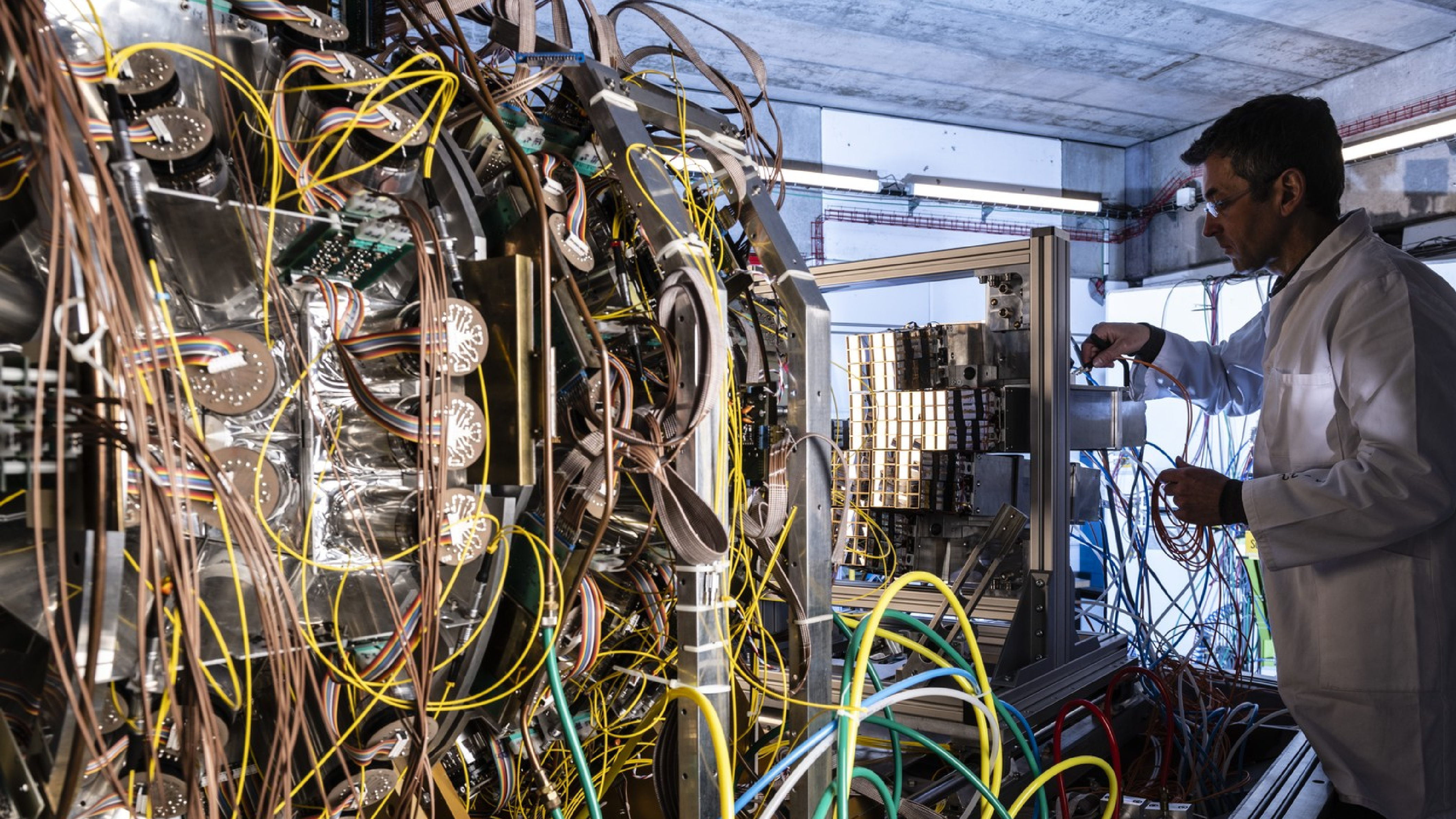
## FAZIA

12 blocks for 192 detection modules (~1.5° to ~13°)
Si-Si-CsI telescopes (ΔE-ΔE-E and PSA in Si/CsI)
Fully digital and custom electronics
→ full Z-identification, A-identification up to **Z~25**
→ isospin sensitive observable (quasi-proj. N/Z)



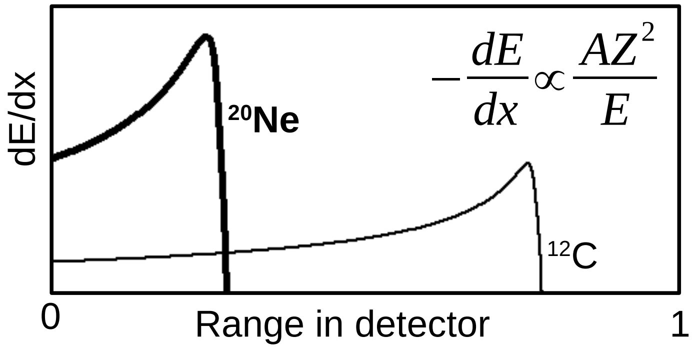




Pouthas NIMA 357 (1995) 418-442
Valdre NIMA 930 (2019) 27-36



**Particle identification**

The energy loss of a particle in the detector depends on its charge (Z), mass (A), and energy (E)



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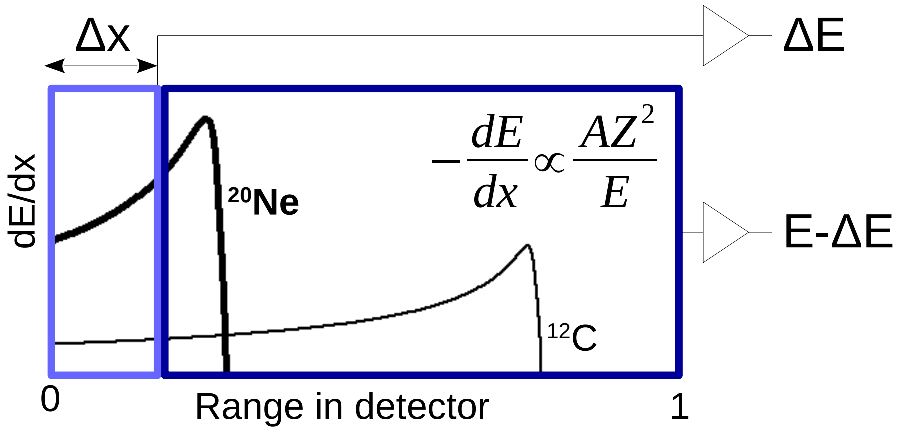
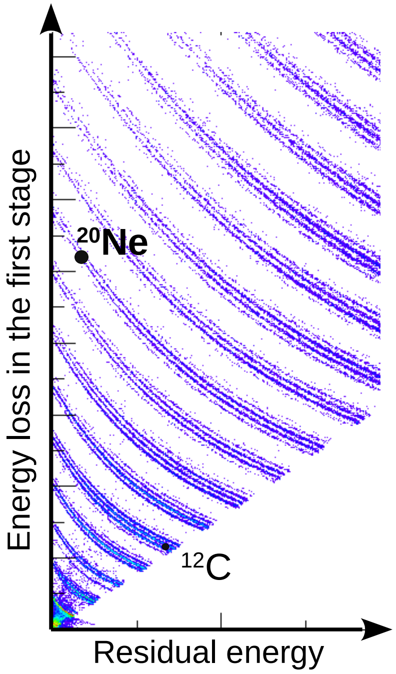
Divide the material in ΔE and E layers
In the ΔE-E plot, particles populate lines charact-eristic of their charge (Z) and mass (A)
→ old method pushed to its limit with FAZIA



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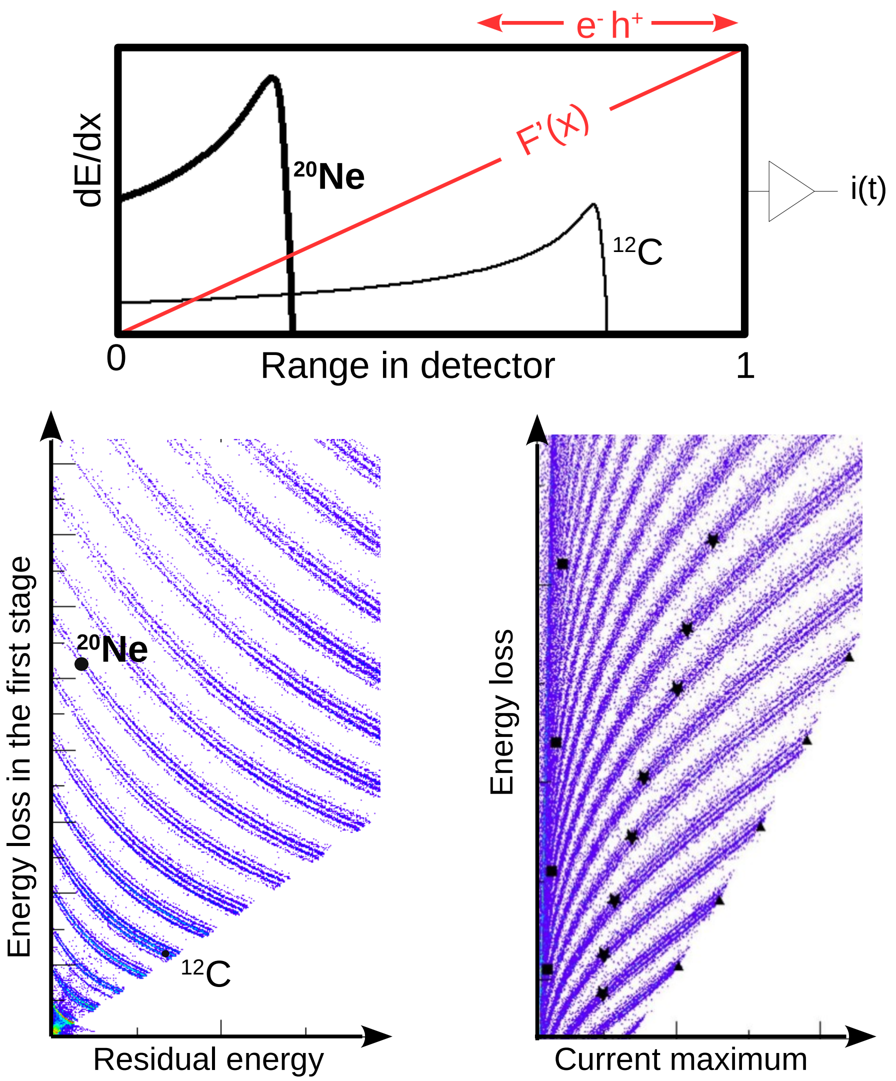
**Pulse shape analysis**
Use the shape of the signal induced by charge collection to measure the charge (Z) and the mass (A). Requires to sample the signal.
→ specificity of FAZIA silicon detectors




Pastore NIMA **860** (2017) 42

## E789 data reduction

Experiment performed at GANIL in 2019
First experiment with INDRA and FAZIA coupled
Long and tedious identification and calibration phase : tasks shared between France, Italy and South Korea (~10 people involved, 4 PhD thesis)

Ciampi PRC 106 (2022) 024603
Fable PRC 107 (2023) 014604

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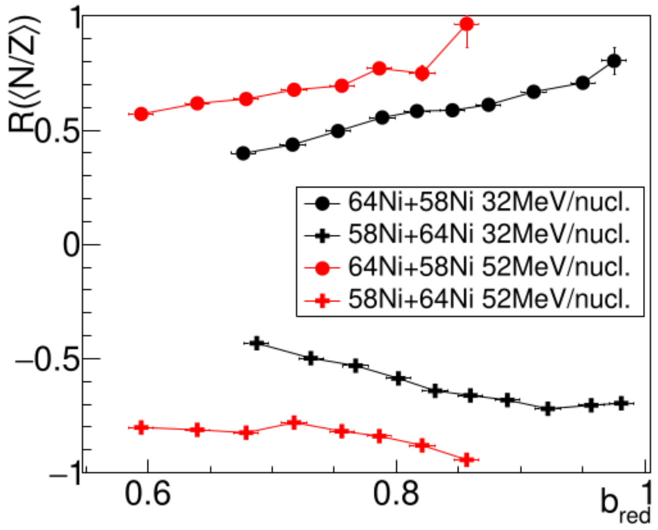
First « true » measurement of the equilibration as a function of the impact parameter at two beam energies. First publication by Caterina Ciampi in 2022 and two more articles ready for submission.

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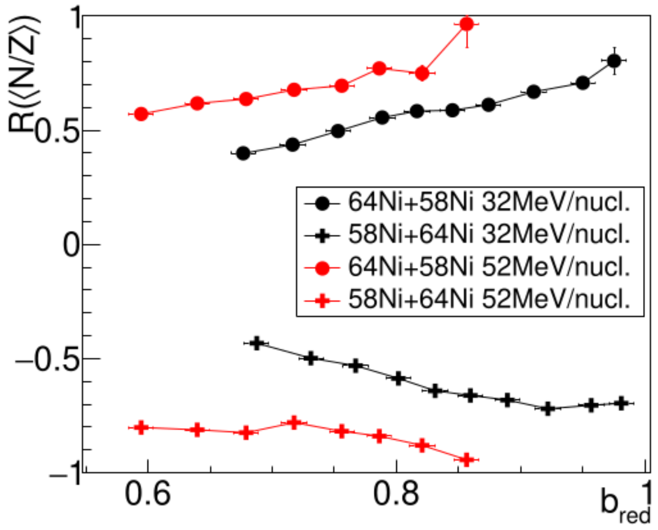
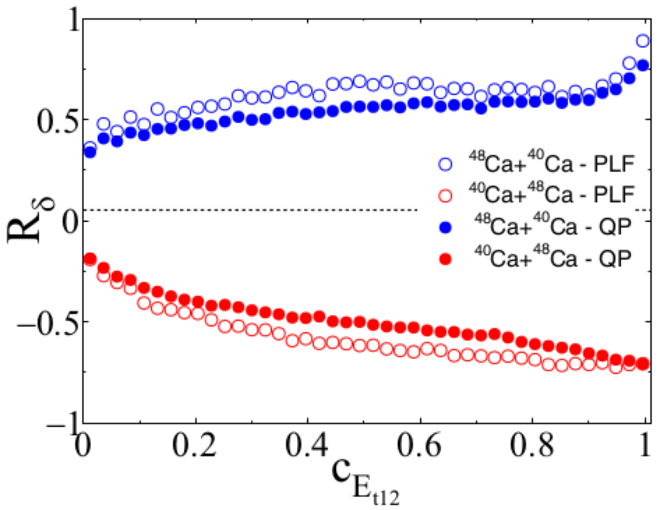
## Previous INDRA-VAMOS experiment

Also measured with INDRA coupled to the VAMOS spectrometer years ago but published at the same time (see poster by Quentin Fable)




Ciampi PRC 106 (2022) 024603
Fable PRC 107 (2023) 014604

## Transport model calculations

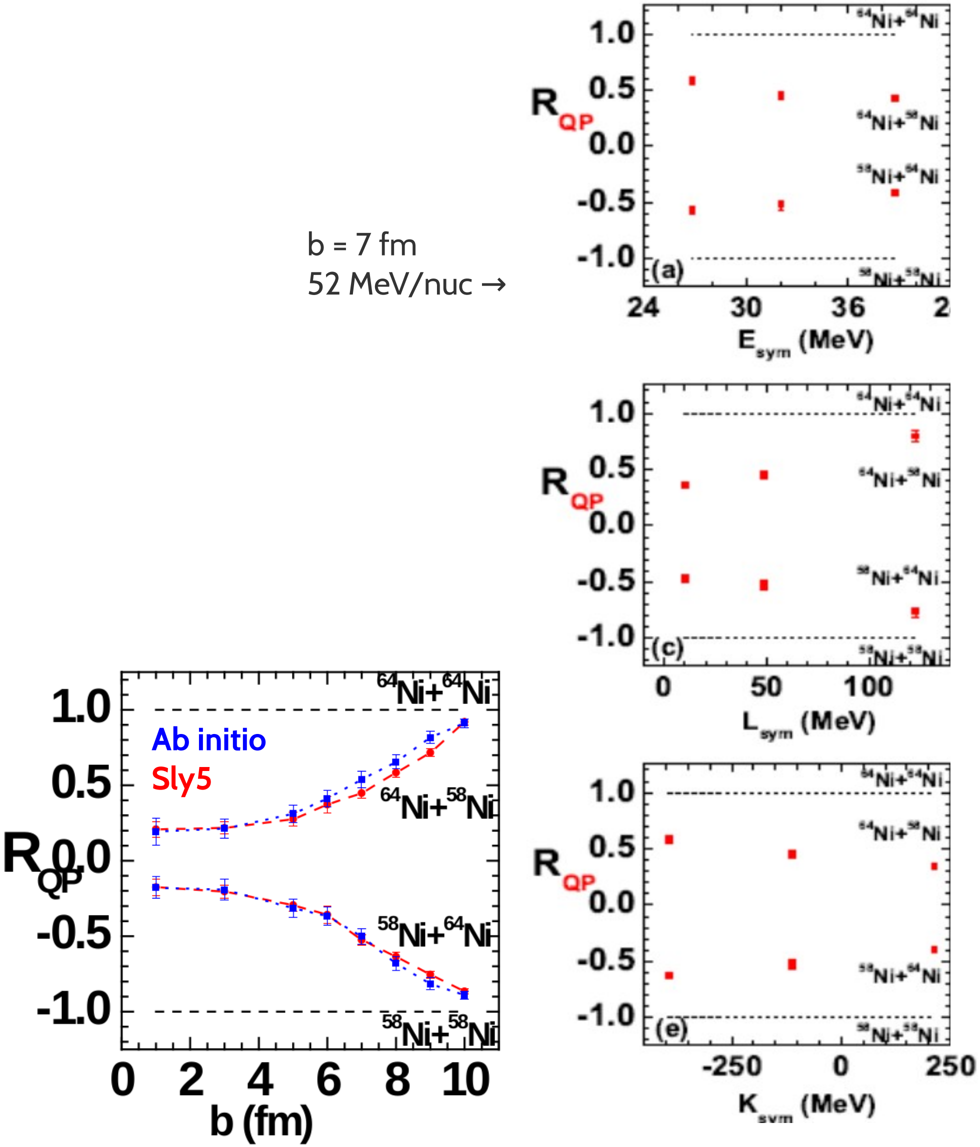
BUU transport model by Swagato Mallik. All equation of state empirical parameters can be modified + momentum dependance of the EoS.

## Strategy

1. Explore the full EoS parameter space
2. Run the model for all experimental impact parameters (very time consuming)
3. Compare with data and extract the EoS parameter probability distribution

## Workplan

Show the sensitivity to low order parameters
Run the full bayesian analysis (in progress)
Swagato Mallik inviting scientist at GANIL in september to complete this analysis




Mallik JoP G **49** (2021) 015102

D. Gruyer[1], R. Bougault[1], **N. Le Neindre**[1], O. Lopez[1], L. Manduci[1], M. Parlog[1], J. Quicray[1], E. Vient[1], A. Rebillard-Soulié[1],A. Valente[1], A. Chbihi[2], J.D. Frankland[2], M. Henri[2], L. Morelli[2], C. Ciampi[2], E. Bonnet[3], B. Borderie[4], E. Galichet[4], Q. Fable[18], P. Napolitani[4], S. Barlini[5], M. Bini[5], A. Camaiani[5], **G. Casini**[5], P. Ottanelli[5], G. Pasqualli[5], S . Piantelli[5], G. Poggi[5], S. Valdré[5], L. Baldesi[5], I. Lombardo[6], G. Verde[6], R. Alba[7], C. Maiolino[7], D. Santonocito[7], M . Vigilante[8], M. La Commara[8], F. Gramegna[9], M. Cicerchia[9], G. Mantovani[9], T. Marchi[9], M. Cinausero[10], D. Fabris[10], M. Bruno[11], T. Kozick[12], S. Upadhyaya[12], A. Kordyasz[13], A.A. Benitez[14], F.P. Bernal[14], J. Duenas[14], J.E. Garcia Ramos[14], B. Hong[15], S.H. Nam[15], S. Kim[15,16], K.I. Hahn[16], M. Kweon[17], H. Lee[17].

INDRA FAZIA

[1]LPC Caen, France. [2]GANIL, France. [3]Subatech Nantes, France. [4]IPN Orsay, France. [5]Univ./INFN Florence, Italy. [6]INFN Sezione di Catania, Italy. [7]INFN LNS Catania, Italy. [8]INFN/University Naples, Italy. [9]INFN LNL Legnaro, Italy. [10]INFN/University Padova, Italy. [11]INFN / University Bologna, Italy. [12]Jagellionian University, Cracow, Poland. [13]University Varsaw, Poland. [14]University of Huelva, Spain. [15] Korea University, Seoul, Korea. [16]Ewha womans University, Seoul, Korea. [17]Inha University, Nam-gu, Korea. [18]L2I Toulouse, France