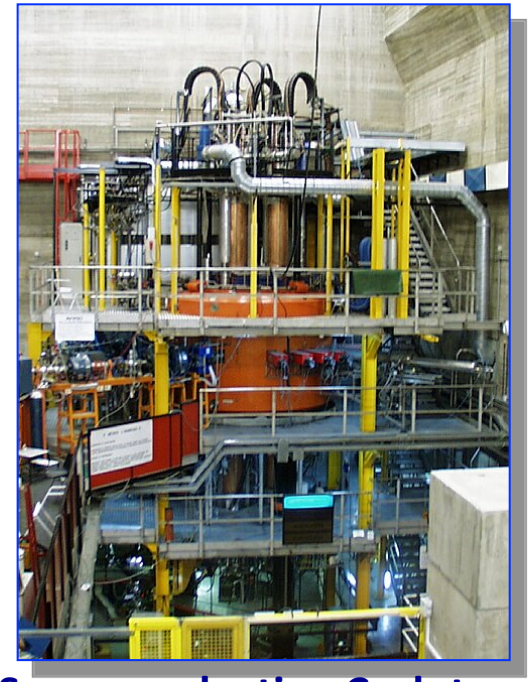
Future at intermediate and low energies (European perspective)

G. Verde, INFN-Catania

…sorry for not being there.. ☹
Thank you Abdou!

What facilities?



Superconducting Cyclotron

Intermediate energies :

LNS-Catania (2015):

A~20-150 E/A=15-50 MeV

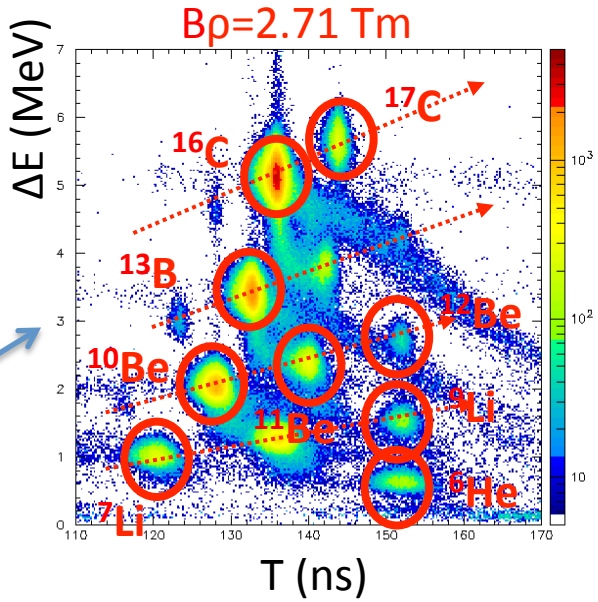
GANIL (2017):

A~20-150 E/A=25-90 MeV

Plenty of perspectives for Isospin and symmetry energy research in near future

Fragmentation exotic beams @ LNS

Example: ^{20}Ne primary beam 45 MeV/A impinging on a ^{9}Be target 500 μm.
All produced fragments are transported and tagged by ΔE-ToF correlations event-by-event



- Direct reactions with exotic light-medium mass beams (inverse kinematics)
- Reaction studies in peripheral collisions (higher σ) →isospin effects…
- Spectroscopy of unbound states with multi-particle correlations

Some intensities…

	I (kHz)	
^{16}C	40	
^{17}C	4	
^{13}B	23	
^{11}Be	6	(optimized)
^{10}Be	21	
^{8}Li	11	

E/A ~ 40-50 MeV
ΔP/P <1%

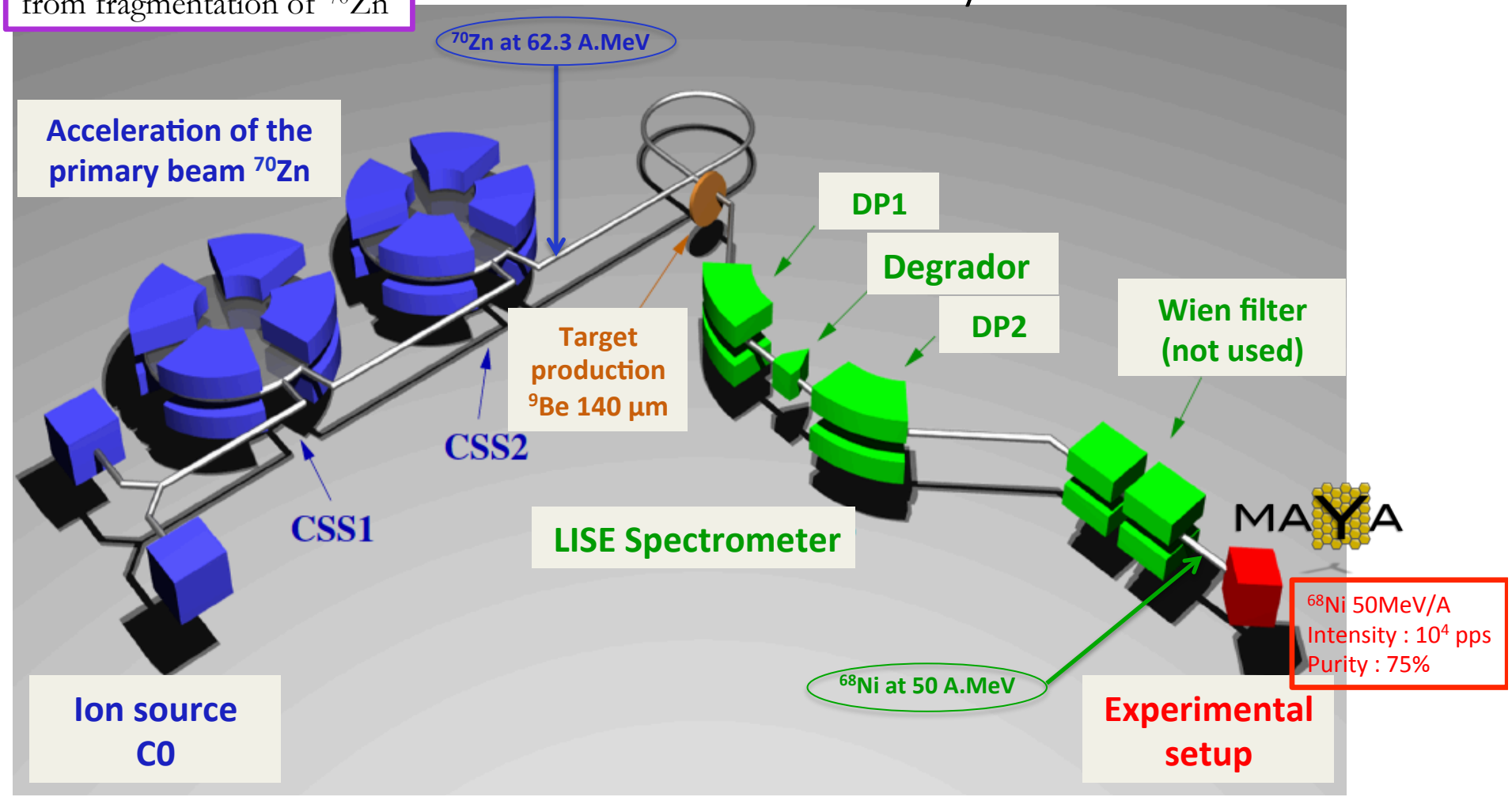
Setup : the active target MAYA

Production of the ^{68}Ni at GANIL

Similar fragmentation exotic beams can be produced at GANIL and selected by LISE

Production of ^{68}Ni beam from fragmentation of ^{70}Zn

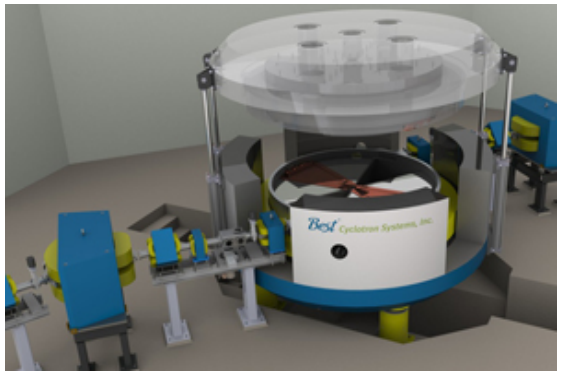
Courtesy of Marine Vandebrouck



What facilities ahead? **SPES**

SPES@Legnaro: Selective Production (and reacceleration) of Exotic Species

Production neutron-rich isotopes and reacceleration



Cyclotron: E=70 MeV at I 200μA

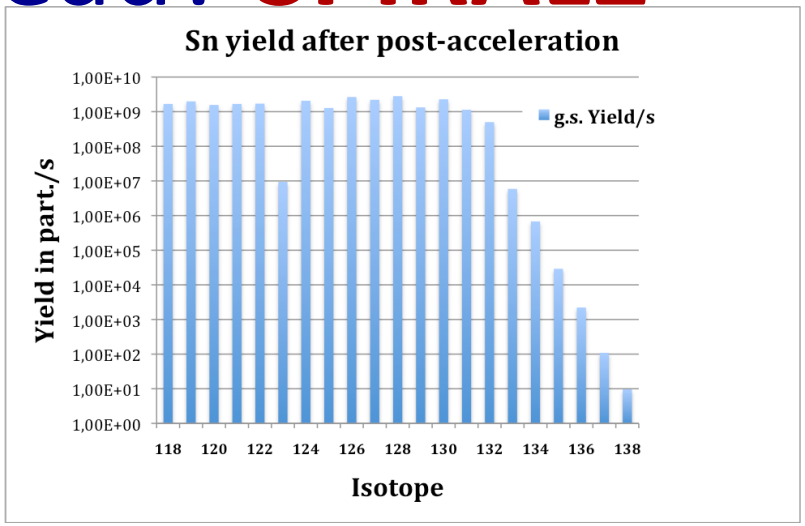
Production process:
Proton induced reactions on UCx target: ~10^{13} fission/s

Primary beam: 2 exit ports Cyclotron
protons at 70 MeV and I~200μA

Re-acceleration stage: ALPI Superconductive Linac
→ E/A=10 MeV (A=132)

Fundamental research & Applications
(medical, material science, etc.)

What facilities ahead? **SPIRAL2**



SPIRAL2@GANIL: Système de Production d'Ions RAdioactifs en Ligne de 2ème génération)

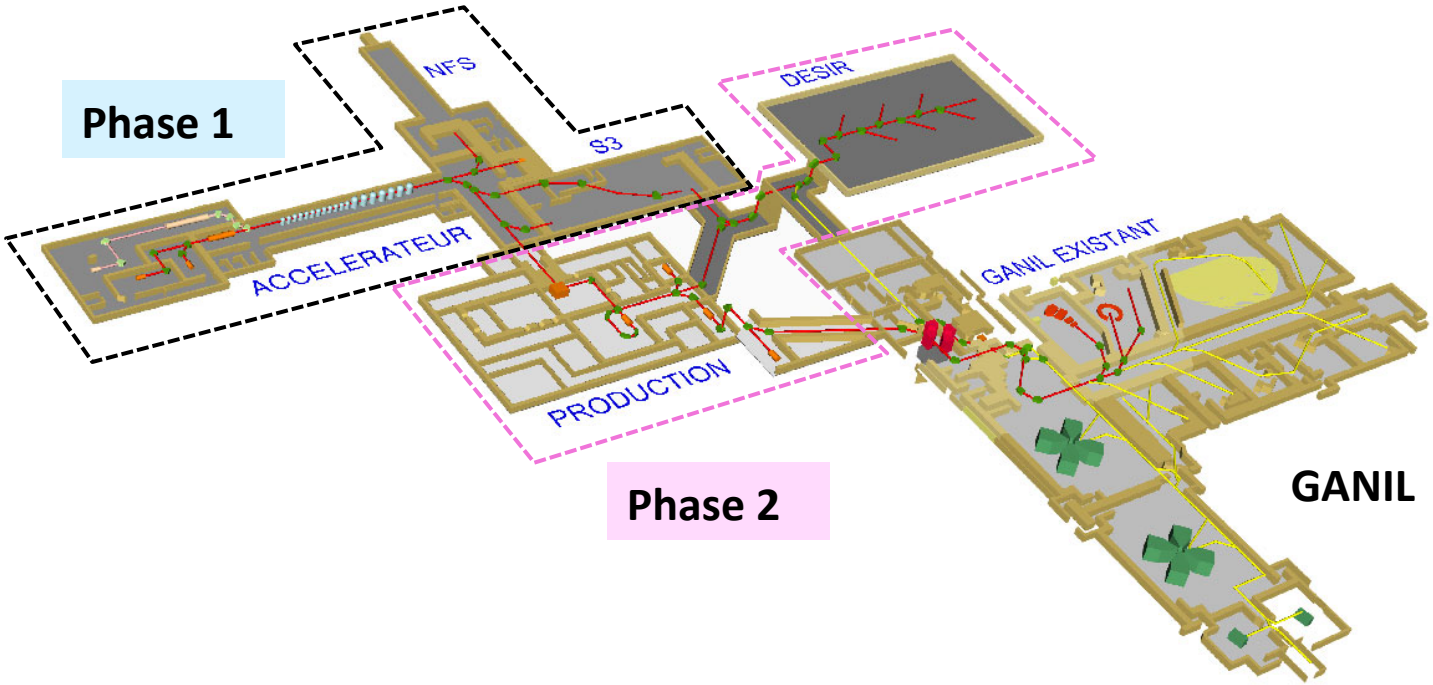
Production process:
Light-ion and neutron induced reactions on thick and thin targets
Ucx targets bombarded with secondary neutrons
(from d+graphite) or direct LCP

Primary beam: Superconducting LINAC
d (40 MeV), p (33 MeV) @ I~5mA; HI (14.5 MeV/u) @ I~1mA

Re-acceleration stage: CIME cyclotron
→ E/A=3 to 10 MeV for A~100-150 (fission fragments 10^9 pps)

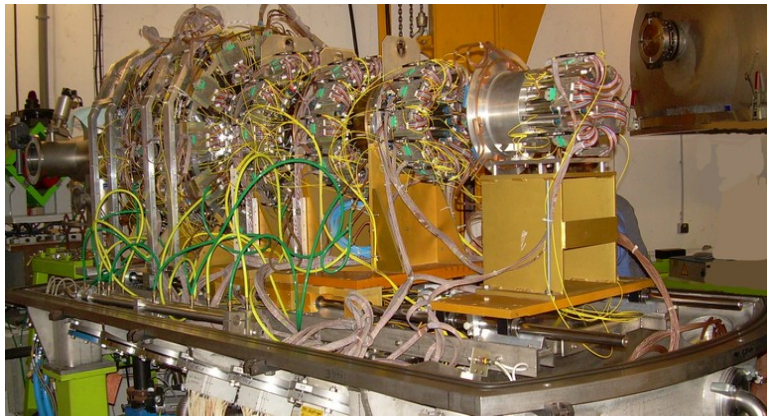
Fundamental research & Applications

SPIRAL 2

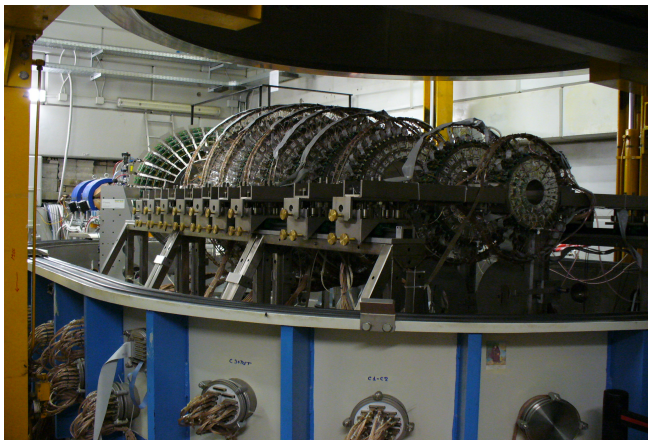

Phase 1
NFS
S3
DESIR
ACCELERATEUR
GANIL EXISTANT
PRODUCTION
Phase 2
GANIL

Availability of 4π detectors

Indra @ GANIL, GSI



Chimera @ LNS



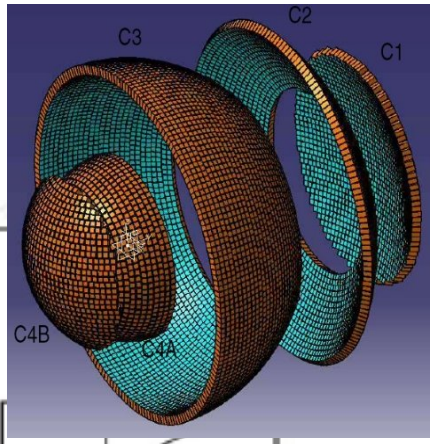
Nuclear dynamics and thermodynamics studies at low and intermediate energies

→ great progress achieved in the last 15 years!

→ new challenges:

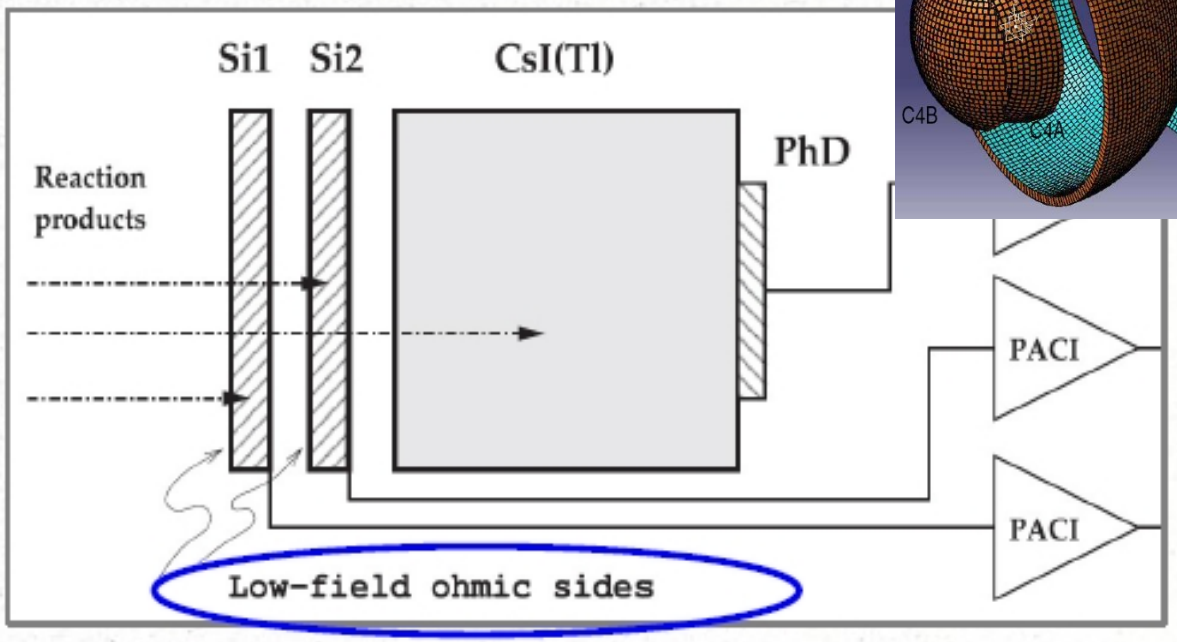
- upgrades (digital electronics, detectors, …)
- coupling to new arrays and Spectrometers

On going projects: FAZIA



Silicons
20x20mm2
nTD type
ρ~3-4000 ohm*cm
300 and 500 μm
7deg cut off <100>

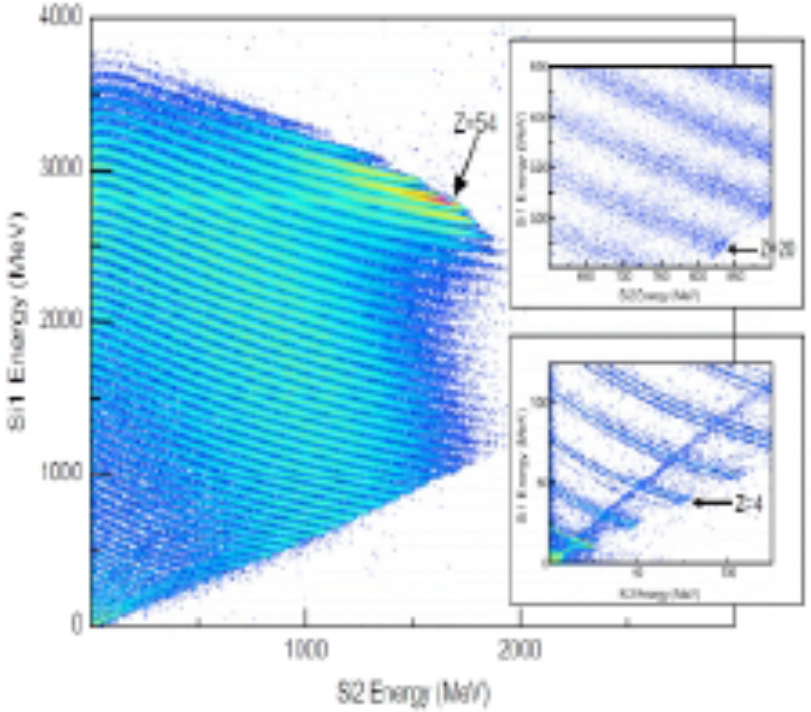
CsI(Tl)
20x20mm2
tapered
1500-2000ppm Tl-doping
Uniform doping
10 cm thick

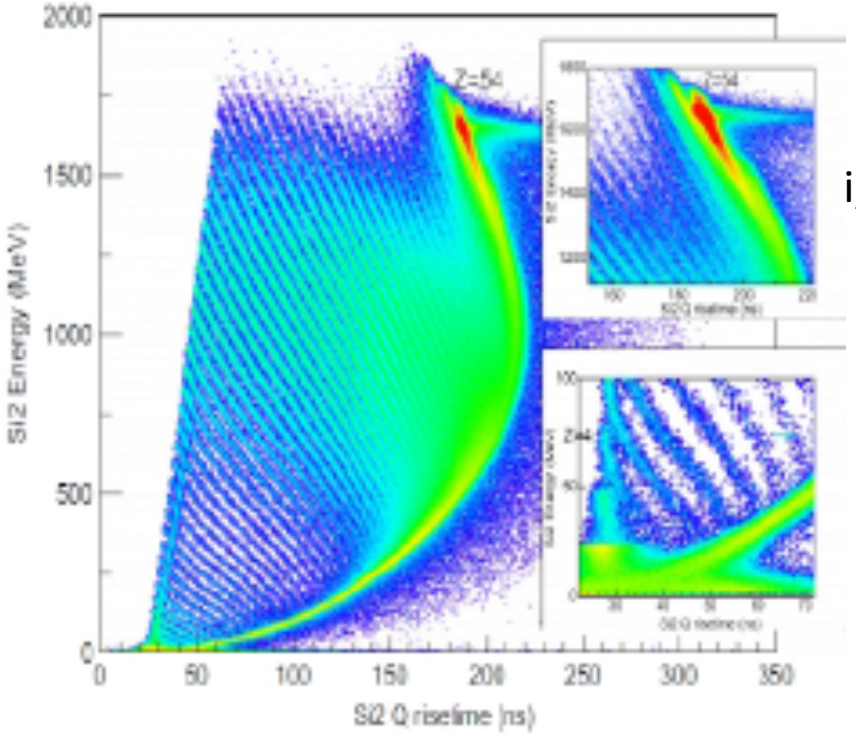


G. Casini, INFN-FI

- **Digitalization of signals (Silicon and CsI(Tl) with high dynamic range**
- **Low identification thresholds (PSA) → Low energy HIC…**
- **Geometric flexibility → Coupling to 4π, Spectrometers, … + Stand Alone experiments**

Capability of FAZIA

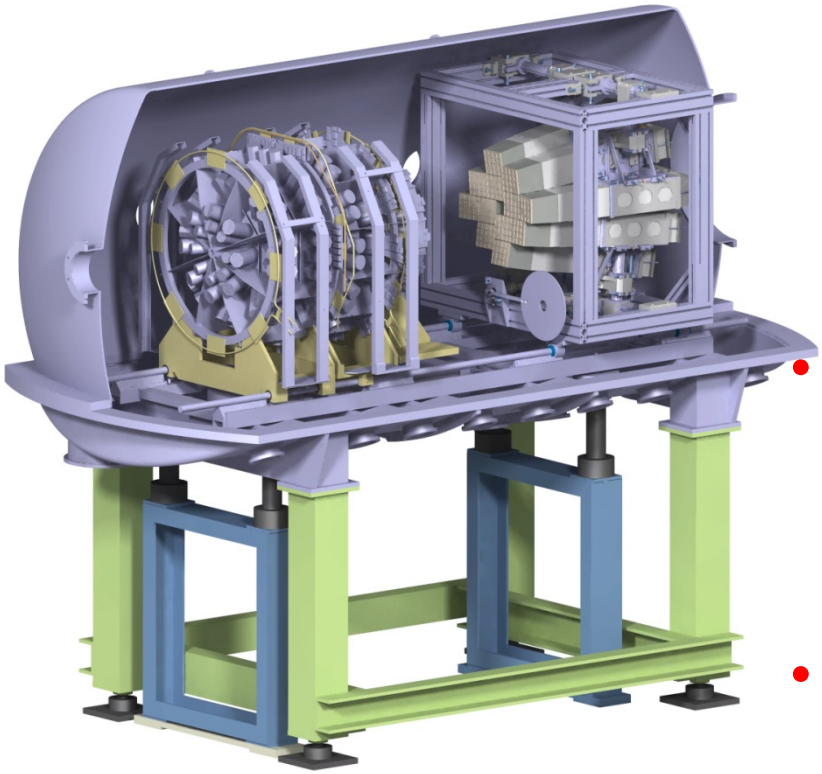




i, INFN-FI

High A- & Z-resolution achieved with existing demonstrator. Isotopic resolution up to Z = 20

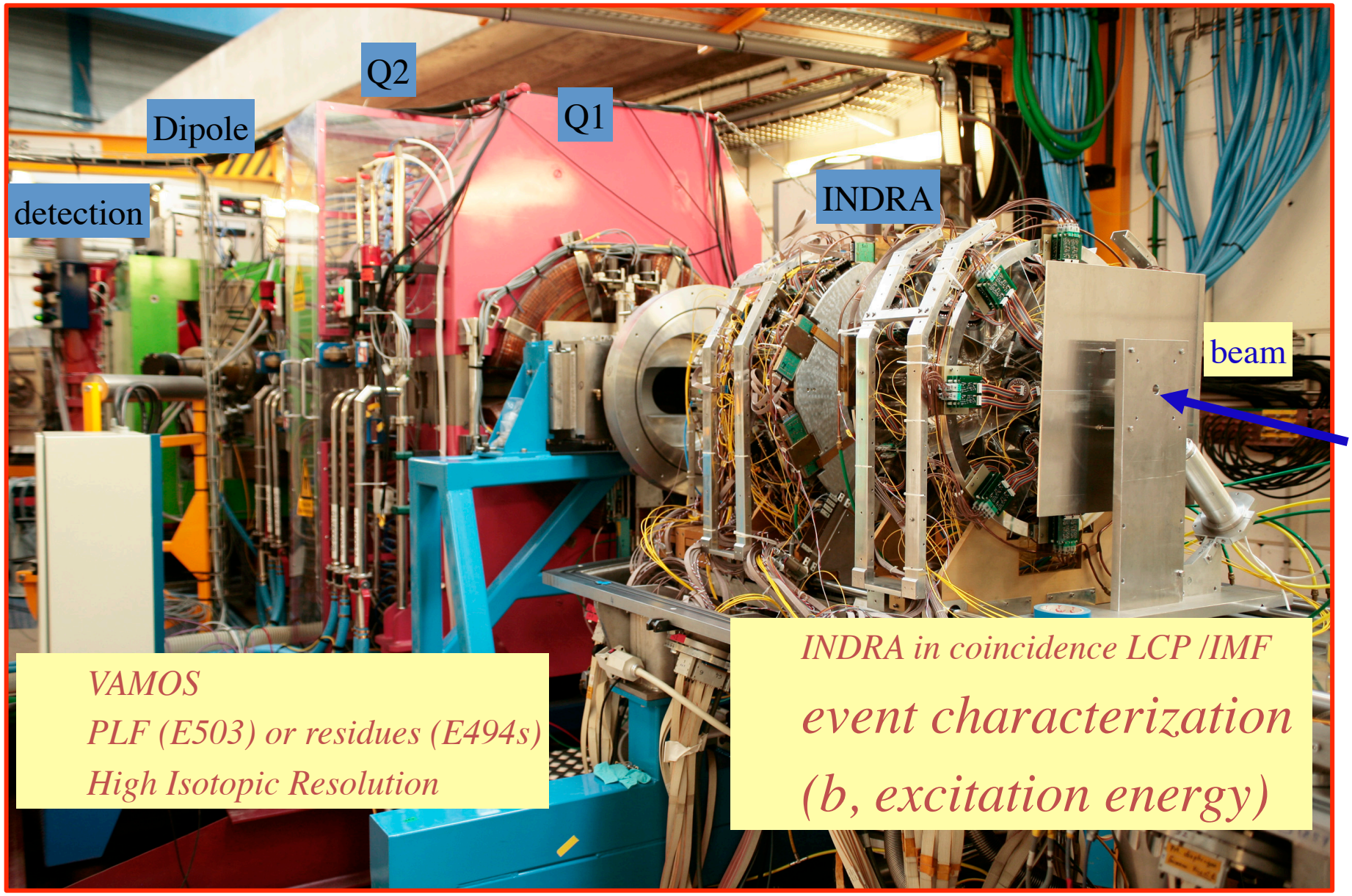
Future for Fazia….



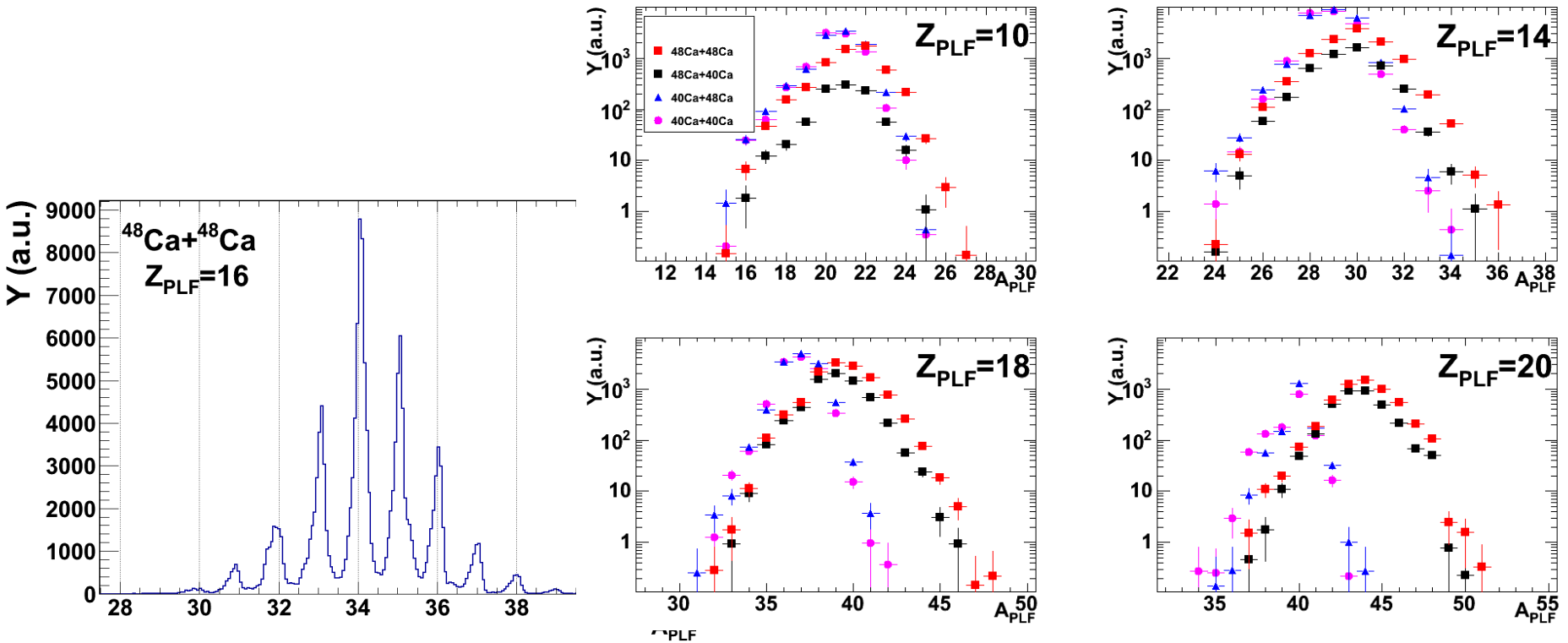
Indra+Fazia @ GANIL
Demonstrator : 192 telescopes

- **Coupling to 4π detectors**
  - **Study of isospin effects in mid-peripheral reactions (neck and QP physics)**
- **Coupling to Spectrometers: increase acceptance of regions with high A- and Z-resolution**
  - **Deep-inelastic studies SPES/ Spiral2: Spectroscopy+Dynamics**

Coupling 4π+Vamos: important future direction

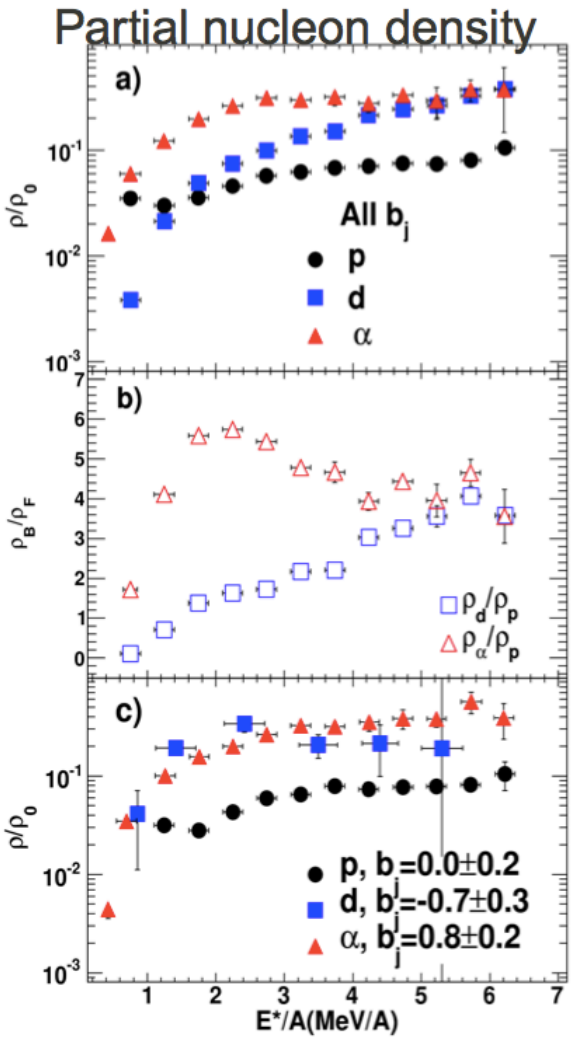


Projectile-like isotopic resolution…



INDRA – VAMOS Experiment

…and light particles in coincidence



Very nice results from coupling:

- Spectrometer to select QP + telescopes to reconstruct its identity and excitation energy
- Determine Excitation energy, density, temperature event-by-event
- Study thermodynamical properties (caloric curves, critical exponents, Zmax distributions, etc.)

Signals of boson condensation and fermion quenching in the dilute phase?

(P. Marini et al., in preparation)

4π detectors + Correlators

- Correlations as probes for spectroscopy and dynamics

[dynamics, thermodynamics] ←→ [spectroscopy]

Nuclear equation of state; Symmetry energy

+

Primary fragment reconstruction

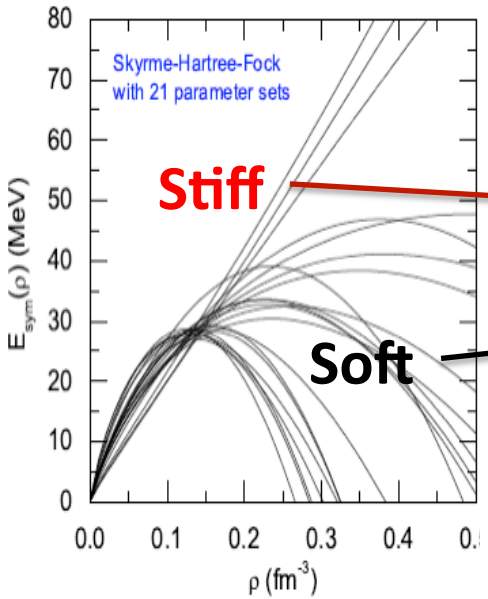
Spectroscopic properties of unbound states (spins, branching ratios, …)

Symmetry energy and correlation functions

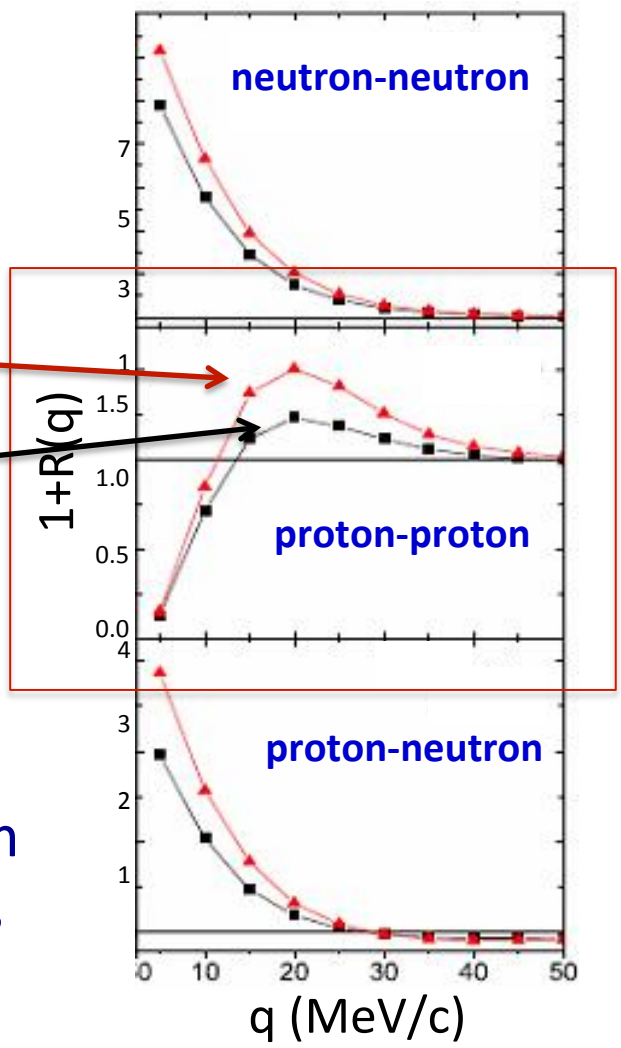
IBUU simulations

$^{52}Ca+^{48}Ca$ E/A=80 MeV Central collisions

Lie-Wen Chen et al., PRL (2003), PRC(2005)



Correlation functions

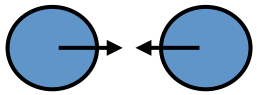


- Proton-proton correlation sensitive to Esym
- nn and np →real challenge for future expts

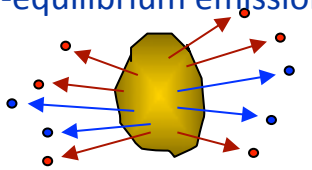
→ …but also **t-^{3}He, t-t and ^{3}He-^{3}He, …**

Symmetry energy at very low densities? (TAMU)

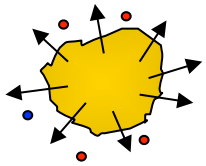
Central



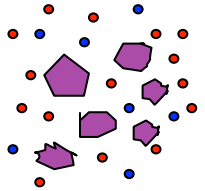
Pre-equilibrium emission



Flow



Multifragmentation



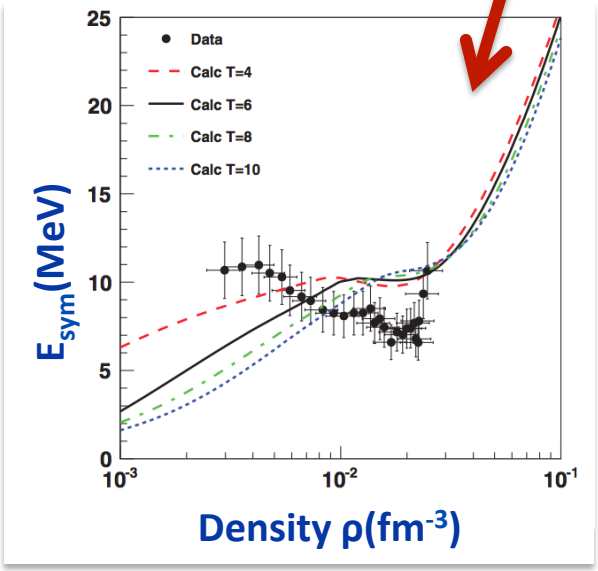
→ $\rho \approx 0.01 \cdot \rho_0$

Clustering (~alphas) at small densities affects E_{sym}

C.J. Horowitz et al., NPA776, 55 (2006),
G. Wanatabe et al., PRL103, 121101 (2009)

$E_{sym}(\rho)$ not vanishing at very low ρ

NIMROD @ TAMU



$^{64}Zn+^{92}Mo, ^{197}Au$
$^{40}Ar, ^{64}Zn+^{112,124}Sn$
E/A=35 MeV

Emission volumes and densities from coalescence analyses of energy spectra!

- ***Coalescence radii Vs. Femtoscopy radii ?***
- ***Femtoscopy (FSI) and cluster production***

J.B. Natowitz et al, PRL 104 (2010) 202501
R. Wada et al., PRC85, 064618 (2012)

Future experiments @ LNS (Coll LNS, GANIL, TAMU)

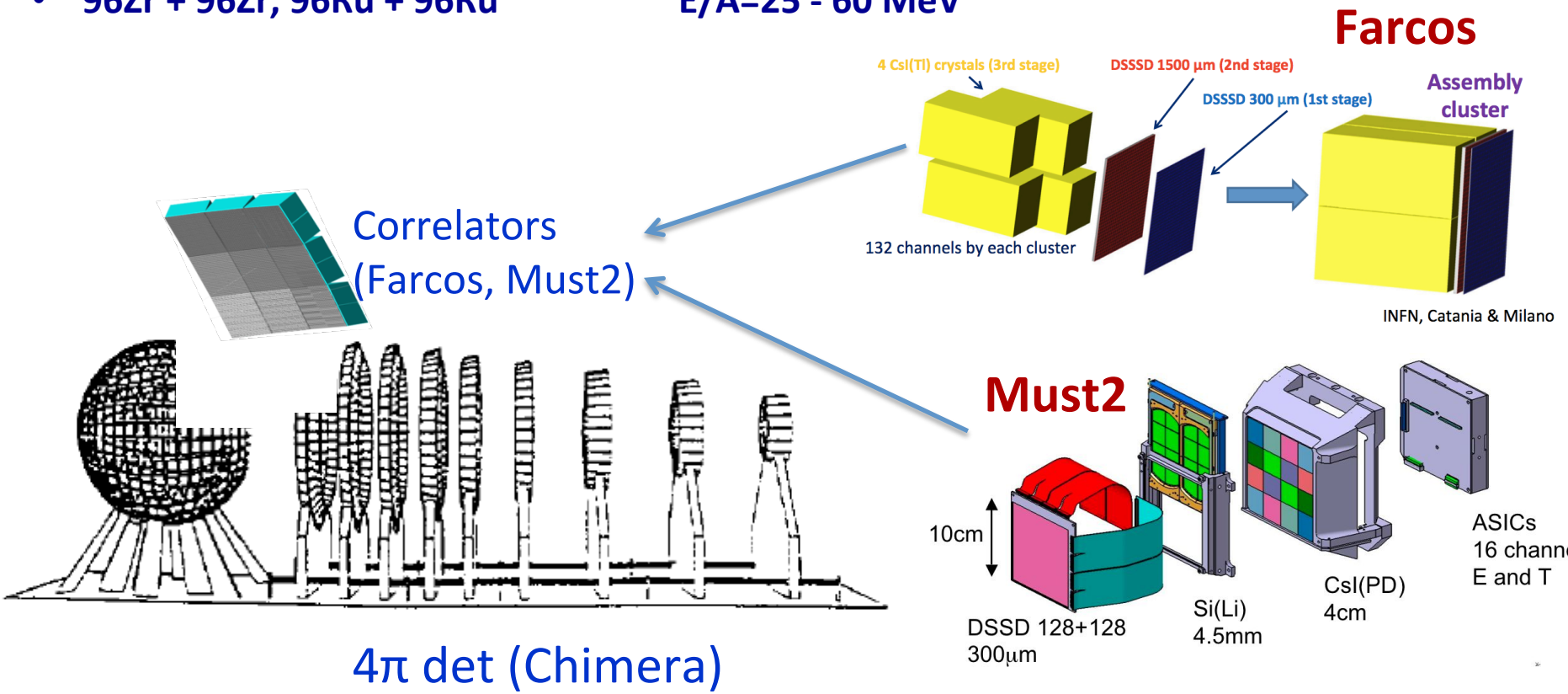
Correlation campaigns (2015-2018)

N/Z-scan, Mass (A)-scan, Energy-scan:

- 40Ca + 40Ca, 48Ca + 48Ca
- 58Ni + 58NiCa, 64Ni + 64Ni E/A=25 - 80 MeV
- 112Sn+112Sn, 124Sn+124Sn

N/Z-scan and Energy-scan (disentangling mass and N/Z effects):

- 48Ca + 48Ca, 48Ti + 48Ti E/A=40 – 80MeV
- 96Zr + 96Zr, 96Ru + 96Ru E/A=25 - 60 MeV



Low energies: Isospin effects on CN decay

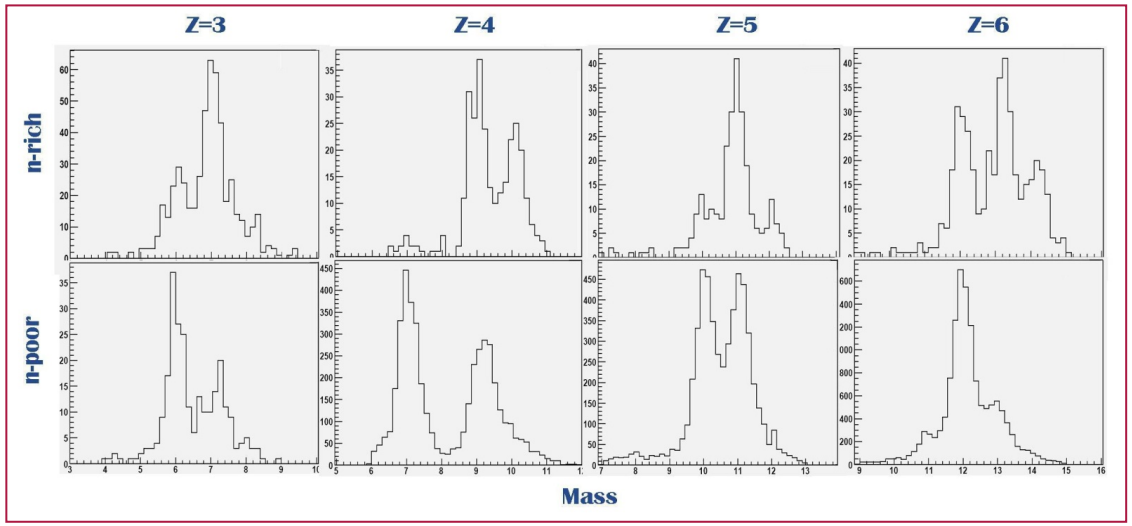
Isodec @ Chimera and Indra:

$^{78}Kr + ^{40}Ca$ ^{118}Ba

$^{86}Kr + ^{48}Ca$ ^{134}Ba

E/A=5.5 & 10 MeV

Detection of isotopically resolved fragments from CN decay and fission



- **Effects of Isospin (N/Z) → pairing force, structure effects on dynamics, links to Esym**

Perspective for SPES:

New systems with higher N/Z would bring new insights

$^{94}Kr + ^{40,48}Ca$ 10 AMeV ^{132,140} Ba* E* ~ 320 MeV

Low energies: clustering effects on dynamics

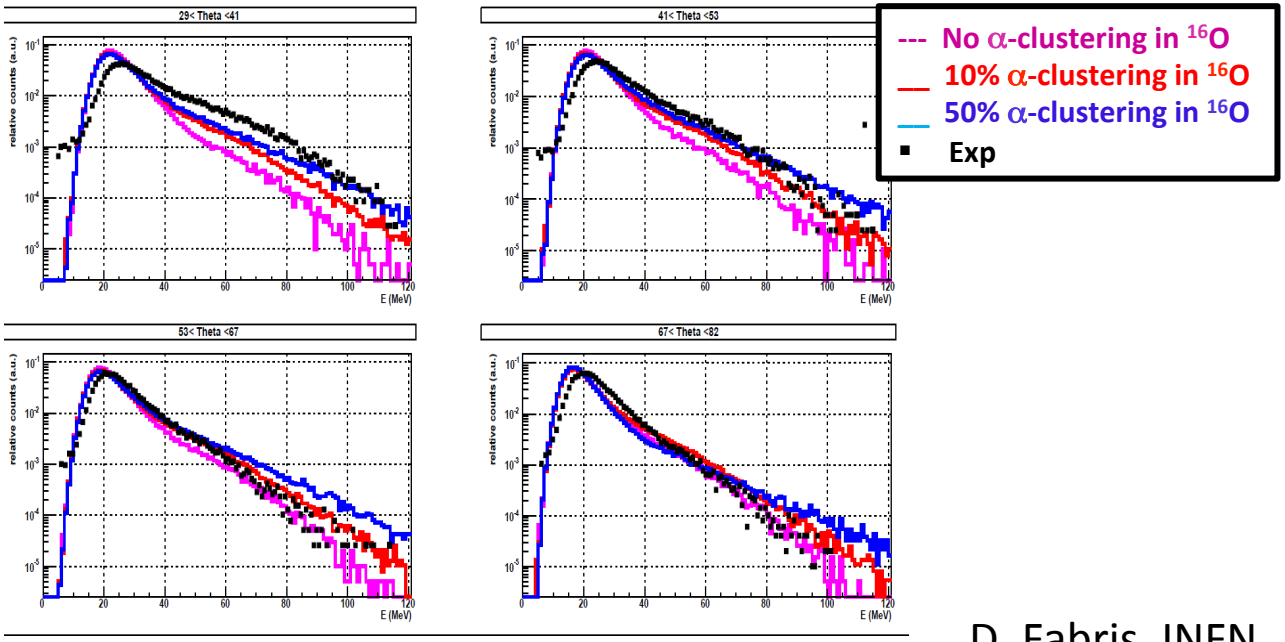
Hybrid Exciton Model

Garfield @ LNL-Legnaro:

$^{16}O + ^{116}Sn$

E/A = 8 ÷ 16 MeV

Shape of energy spectra strongly affected by cluster structure in projectile



D. Fabris, INFN

- **Competition to other decay probes (protons, etc.)**
- **Investigate in final state clusters by means of multi-particle correlations**
- **Good physics cases for Fazia and correlators**

Conclusions

- Good perspectives to continue studies on isospin effects in nuclear dynamics
- Isospin diffusion: profit from FAZIA and encourage coupling to spectrometers (VAMOS@GANIL and Magnex@LNS)
- Two-particle correlations to be further explored with campaigns:

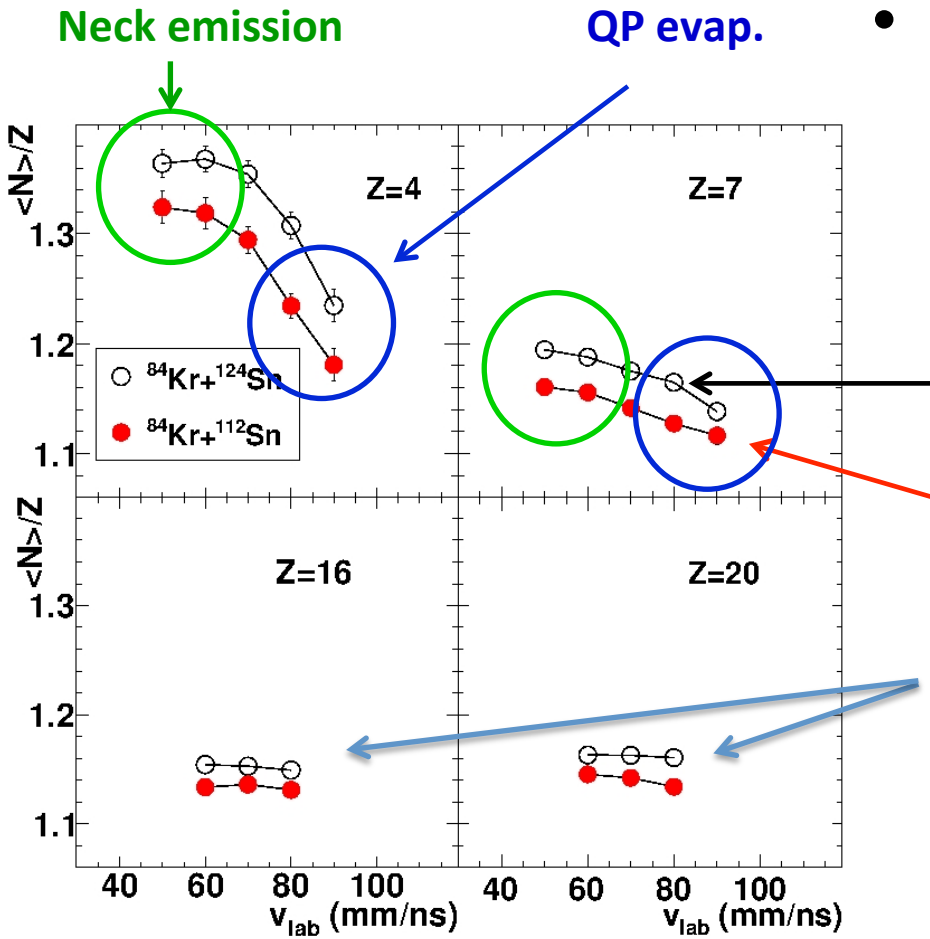
  energy-scan, mass-scan and isospin-scan → Esym, clusters at low density, in-medium spectroscopy
- Low energy reactions at SPES and Spiral2: interplays of dynamics and spectroscopy
  - ✓ isospin physics with CN and DIC studies
  - ✓ Cluster structure effects on energy spectra

Fazia physics: isospin transport phenomena

Isospin effects in different rapidity region

^{84}**Kr** + ^{112,124}**Sn** E/A=35AMeV

→ effects of N/Z of target on QP and Neck fragments



- **Light fragments**

  neck emission (with higher <N>/Z)

  QP evaporation (smaller <N>/Z)

  Isospin drift effect

  <N>/Z of QP fragments depends on N/Z of target:

  Isospin diffusion effect

- **Heavy fragments:**

  no dependence on v_{lab} (produced by QP fission)

S.Barlini et al., PRC87(2013)054607