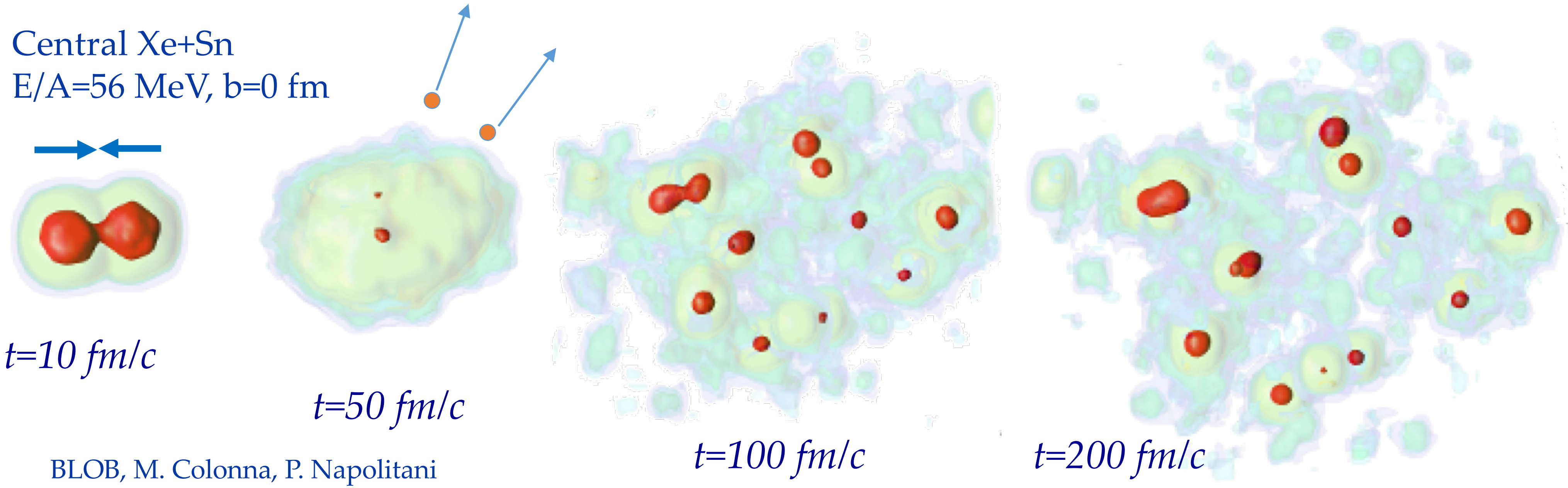
Dynamics and correlations in heavy-ion collisions at intermediate energies



G. Verde, INFN Catania/GANIL

FAZIA & INDRA collaborations

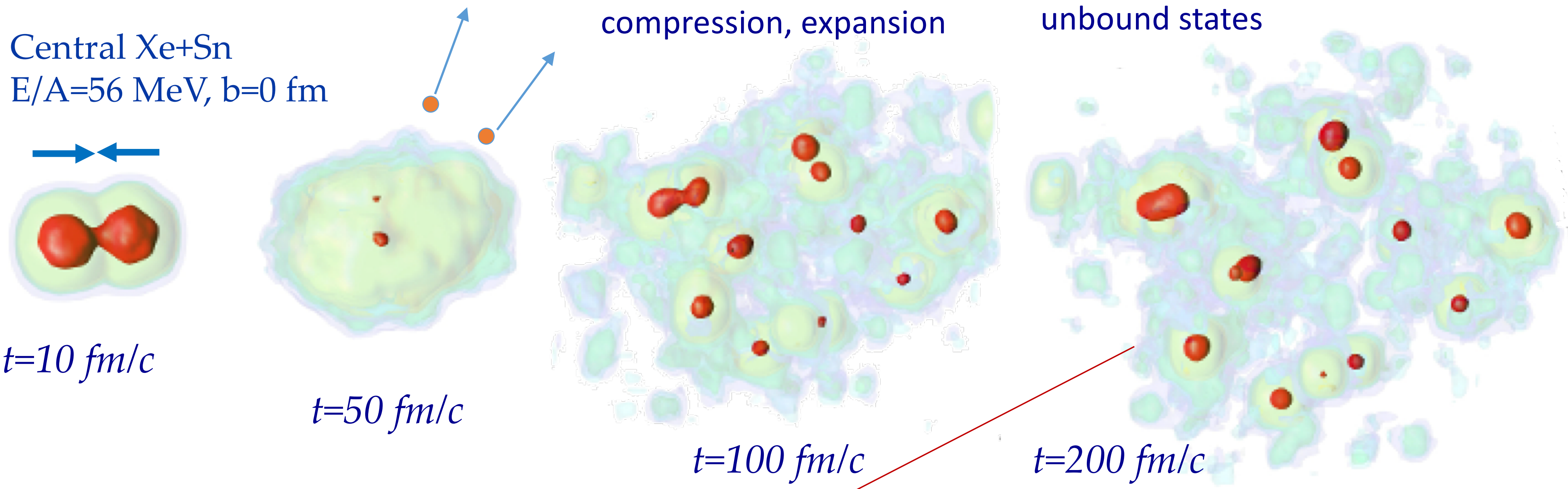
Special acknowledgements:
D. Dell'Aquila (NSCL-MSU)
D. Gruyer (LPC Caen)

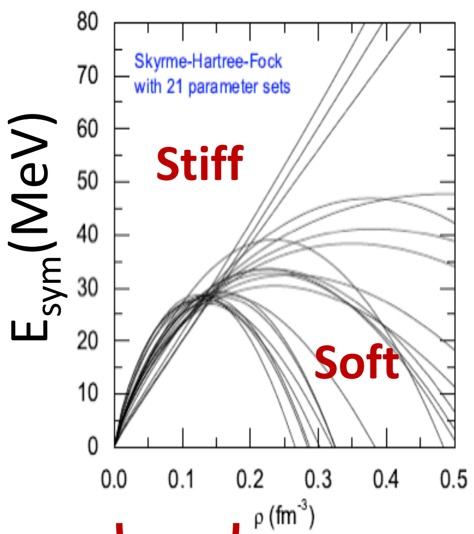
Intermediate energies and symmetry E

Central Xe+Sn
E/A=56 MeV, b=0 fm

Pre-equilibrium,
compression, expansion

Fragments, clusters,
unbound states



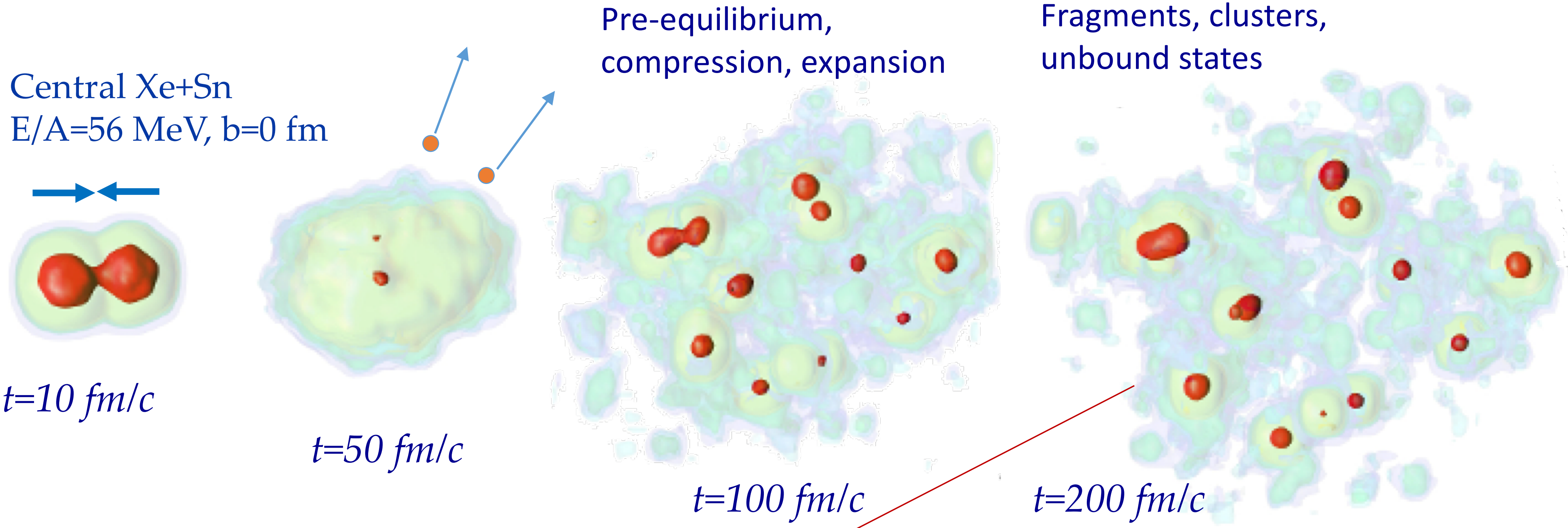


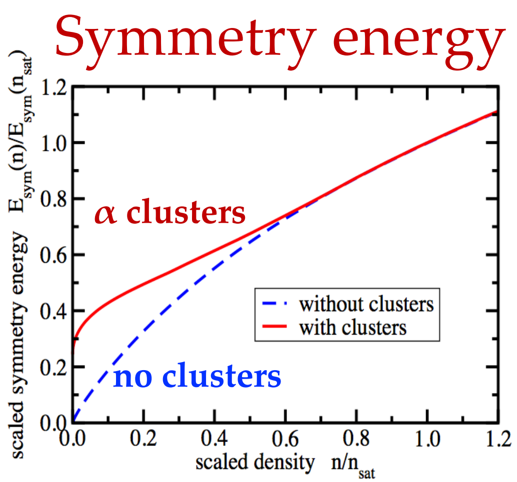
Intermediate energies

Observables at intermediate E:

- Peripheral: isospin diffusion and drift
- Central: isotopic effects on IMF emission, neutron/proton spectra and yields
- Important role of n-p m* splitting

Interplays $E_{sym} \leftrightarrow$ Nuclear structure

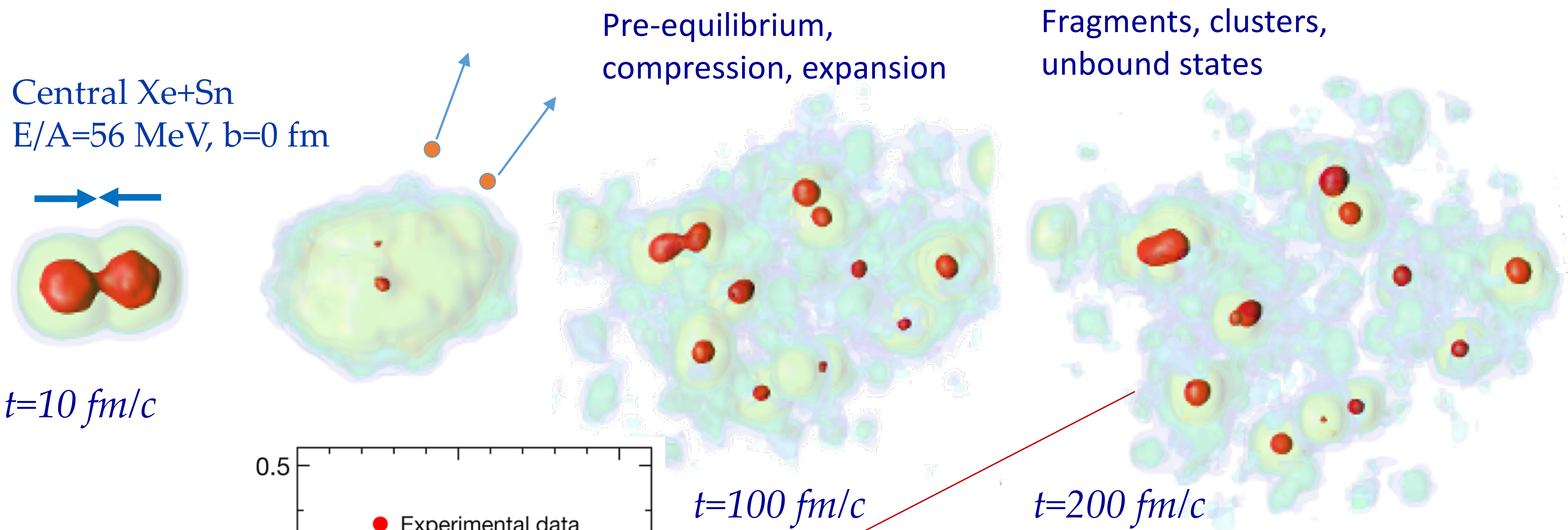


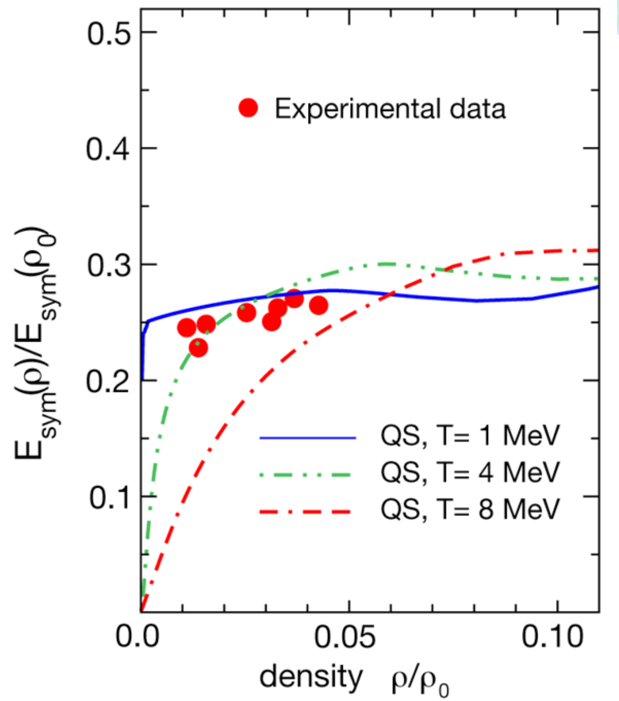


- Clusters and structure in low density matter affect EoS properties
- Relevant in modeling neutrino winds in core collapse supernovae explosions

S. Typel et al., Journal of Physics: Conf. Ser. 420 (2013) 012078

Interplays E_{sym} ↔ Nuclear structure





- Important role of clusters at low density and finite temperatures

J. Natowitz et al., Phys. Rev. Lett. 104, 202501 (2010)

Dynamics and structure

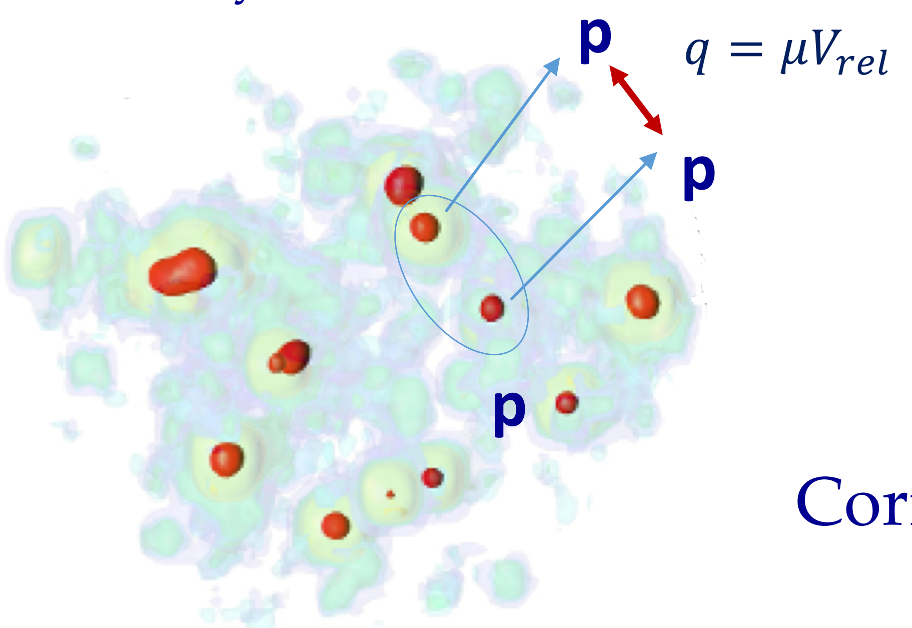
- Nuclear structure properties in low density matter: HIC as a perfect site
  - Study the properties of the medium: density, temperature, EoS → HBT, Femtoscopy
  - Unbound states decays

Dynamics and structure

- Nuclear structure properties in low density matter: HIC as a perfect site
  - **Study the properties of the medium: density, temperature, EoS → HBT, Femtoscopy**
  - Unbound states decays

Two-particle correlations: final state interaction probes of density of the medium

$\vec{v}_p, \vec{v}_{7Be}$ velocity vectors in two-body CM



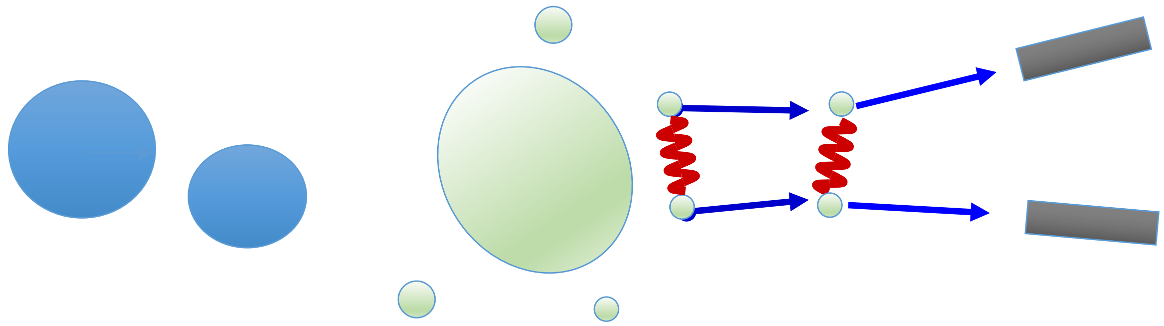
Particle emitting sources extended in phase-space

→ Sizes, space-time extent of source
→ Relative contributions from early pre-equilibrium emissions and late evaporative decays
→ Space-time profiles: probes for transport models

Correlation function:

$$1 + R(q) = \frac{Y_{coinc}(q)}{Y_{evt\ mixing}(q)}$$

Femtoscopy: two-proton correlations

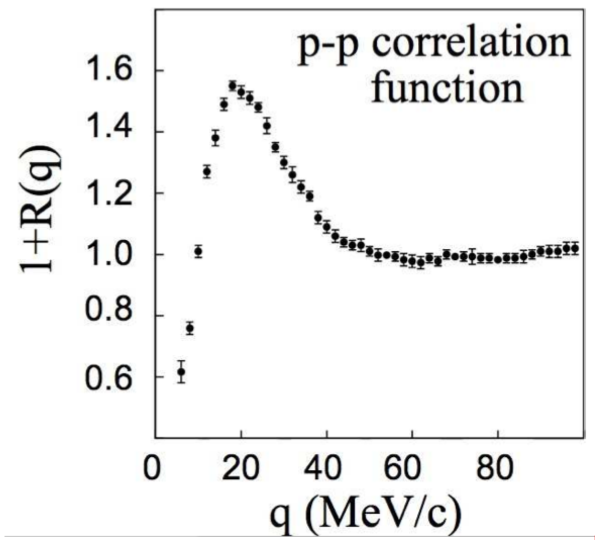


Physical correlations

- Final State Interactions: Coulomb + Nuclear
- Quantum statistics (if identical)
- Phase-space, …

Intensity interferometry / Femtoscopy

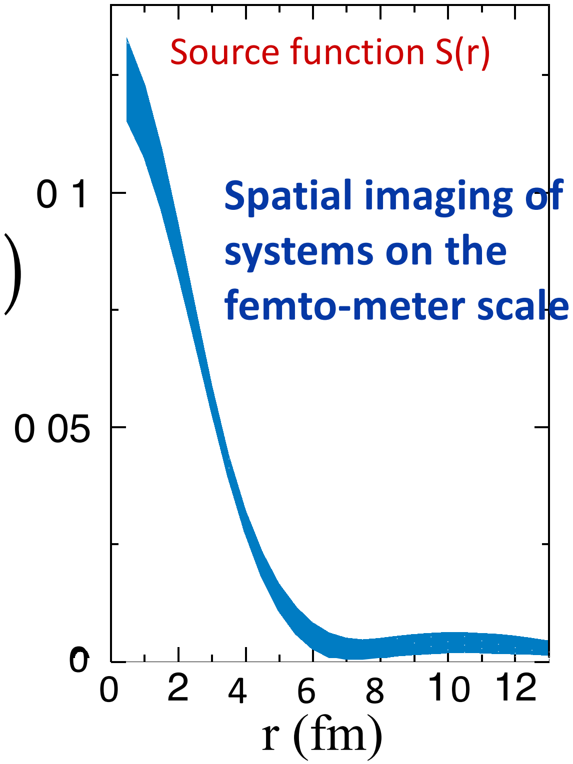
q = mom. of relative motion



Koonin-Pratt

$$R(\vec{q}) = \int d\vec{r} \cdot S(\vec{r}) \cdot K(\vec{r}, \vec{q})$$

- Space-time image and size of early dynamical source

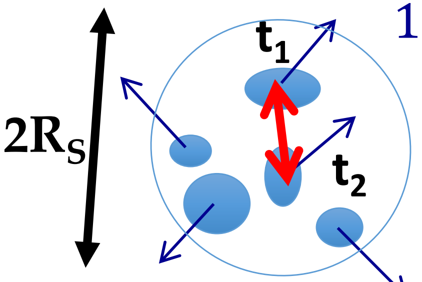


$$1 + R(q) = k \cdot \frac{Y_{coinc}(q)}{Y_{evt.mixing}(q)}$$

Fragment emission time-scales

IMF-IMF Correlation Functions

IMF: Z>2



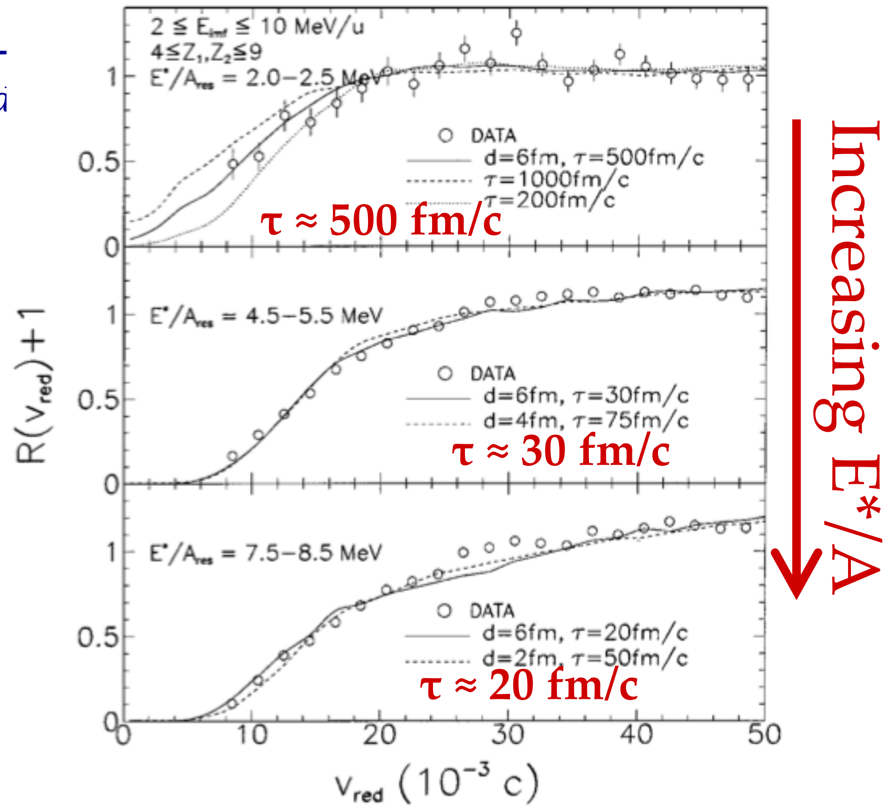
$$1 + R(v_{red}) = \frac{Y_{coinc}(v_{red})}{Y_{evt\ mixing}(v_{red})}$$

$$v_{red} = \frac{|\vec{v}_1 - \vec{v}_2|}{\sqrt{Z_1 + Z_2}}$$

Compact thermal source (T, β_{coll}, …)

N-body Coulomb trajectories
Source radius and emission times:
R_S, P(t) = (1/τ) · exp(-t/τ) → **τ**

π^-, p + Au 8.0, 8.2, 9.2, 10.2 GeV/c

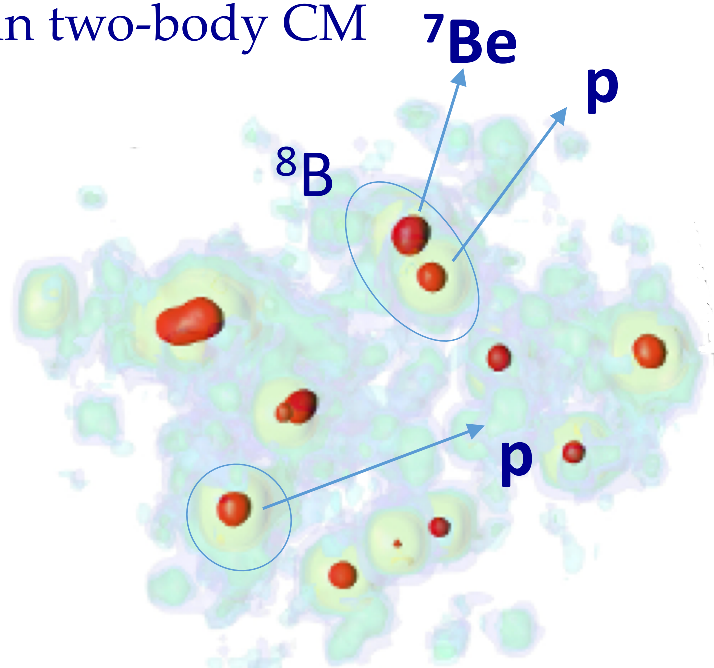


Dynamics and structure

- Nuclear structure properties in low density matter: HIC as a perfect site
  - Study the properties of the medium: density, temperature, EoS → HBT, Femtoscopy
  - **Unbound states decays**

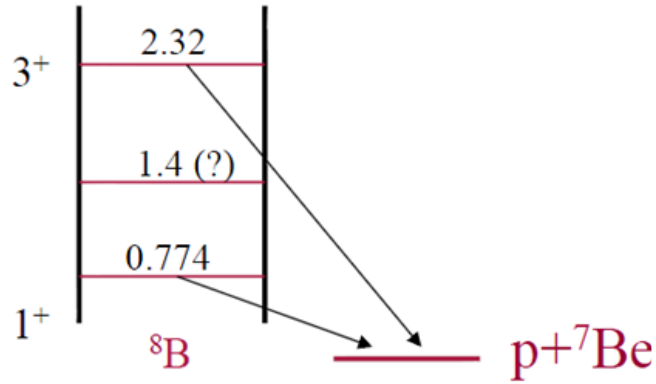
Thermal model of in-medium resonance decays

$\vec{v}_p, \vec{v}_{7Be}$ velocity vectors in two-body CM



Particle emitting sources extended in phase-space

States of ^8B → $p+^7Be$



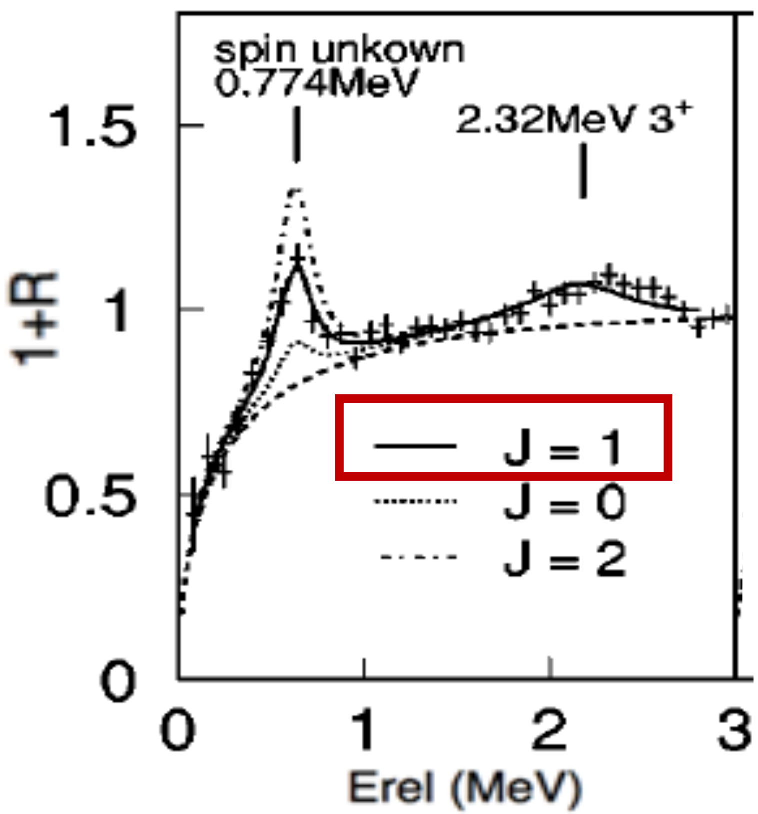
Correlation function:

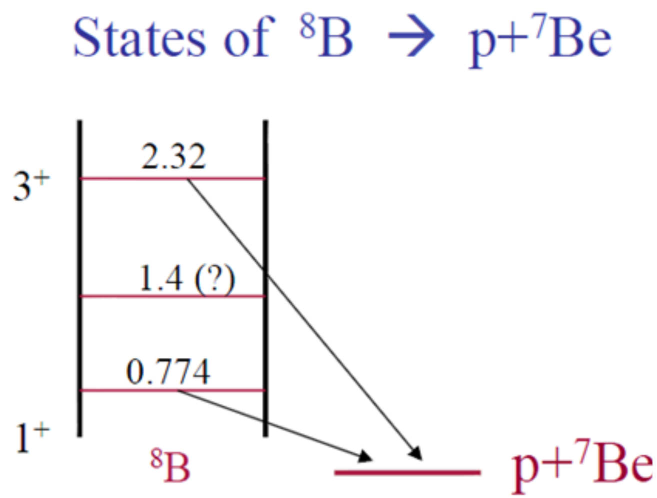
$$1 + R(E_{rel}) = \frac{Y_{coinc}(^7Be, p)}{Y_{evt\ mixing}(^7Be, p)}$$

Structure properties: spin

p-^{7}Be correlation function

$$1 + R(E_{rel}) = \frac{Y_{coinc}(^7Be,p)}{Y_{evt\ mixing}(^7Be,p)} \propto \sum_i (2J_i + 1)\left[\frac{\Gamma_i/2}{(E^* - E_i)^2 + \Gamma_i^2/4}\right]$$





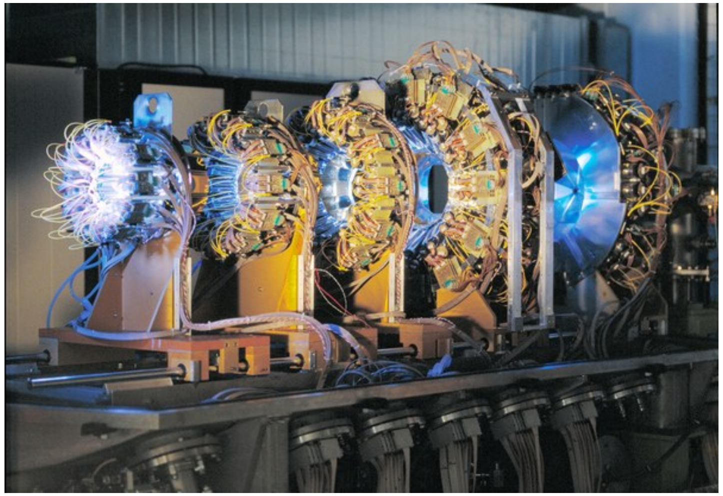
Xe+Au E/A=50 MeV central collisions
(LASSA data)

W.P. Tan et al. Phys. Rev. C69, 061304 (2004)

Recent results from INDRA/FAZIA experiments

- Nuclear structure properties in low density matter: HIC as a perfect site
  - **Study the properties of the medium: density, temperature, EoS → dynamics of HIC**
  - Unbound states decays

In-medium fragmentation and correlations



INDRA *4p multi-detector*

angular coverage ≈ 90% (4π)
336 *independent cells*
telecopes C_3F_8 gas chamber – Si (300 mm) – CsI (5-14cm)

$^{36}Ar + ^{58}Ni$ E/A=32, 40, 52, 63, 74, 84, 95 MeV

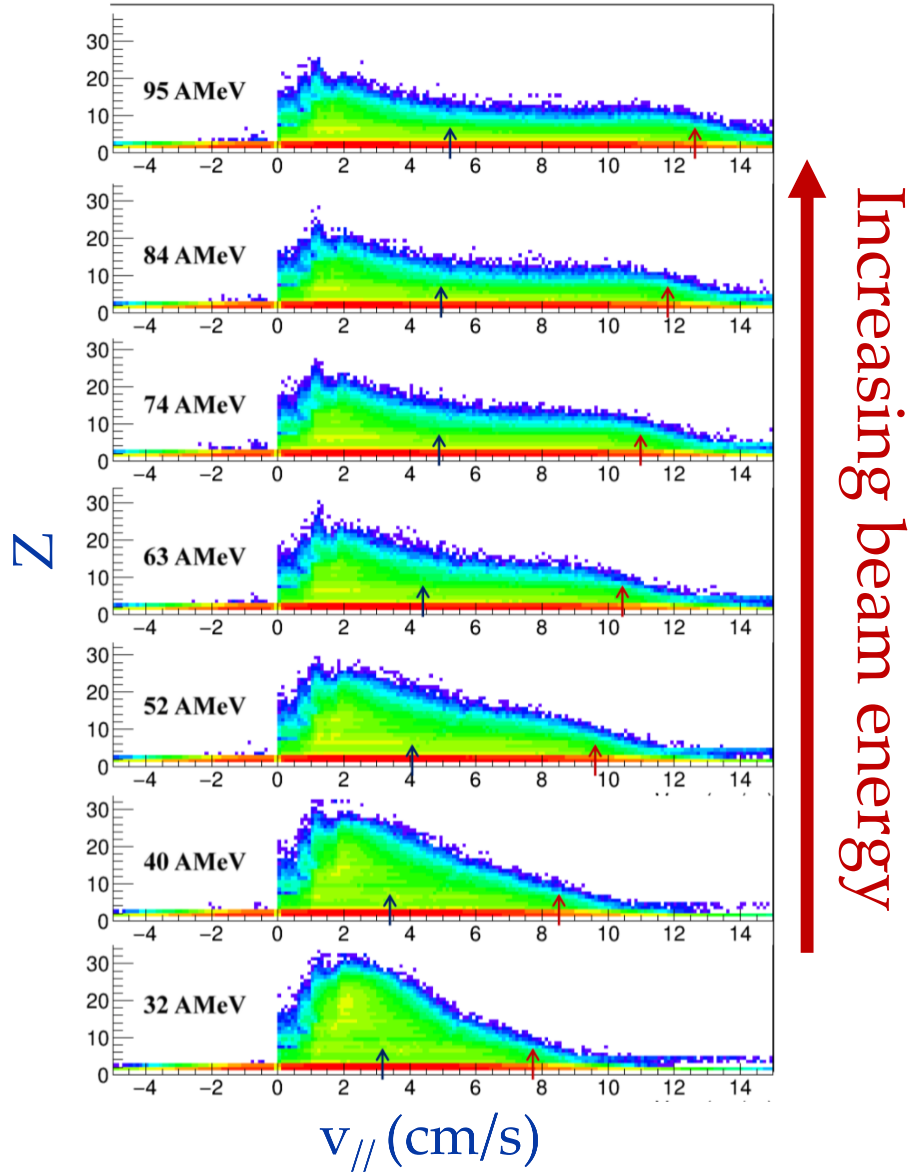
α conjugate

Role of projectile structure on dynamics → in-medium clustering

In-medium jet fragmentation

Ar+Ni E/A=32, 40, 52, 63, 74, 85, 95 MeV - Central

INDRA @ GANIL

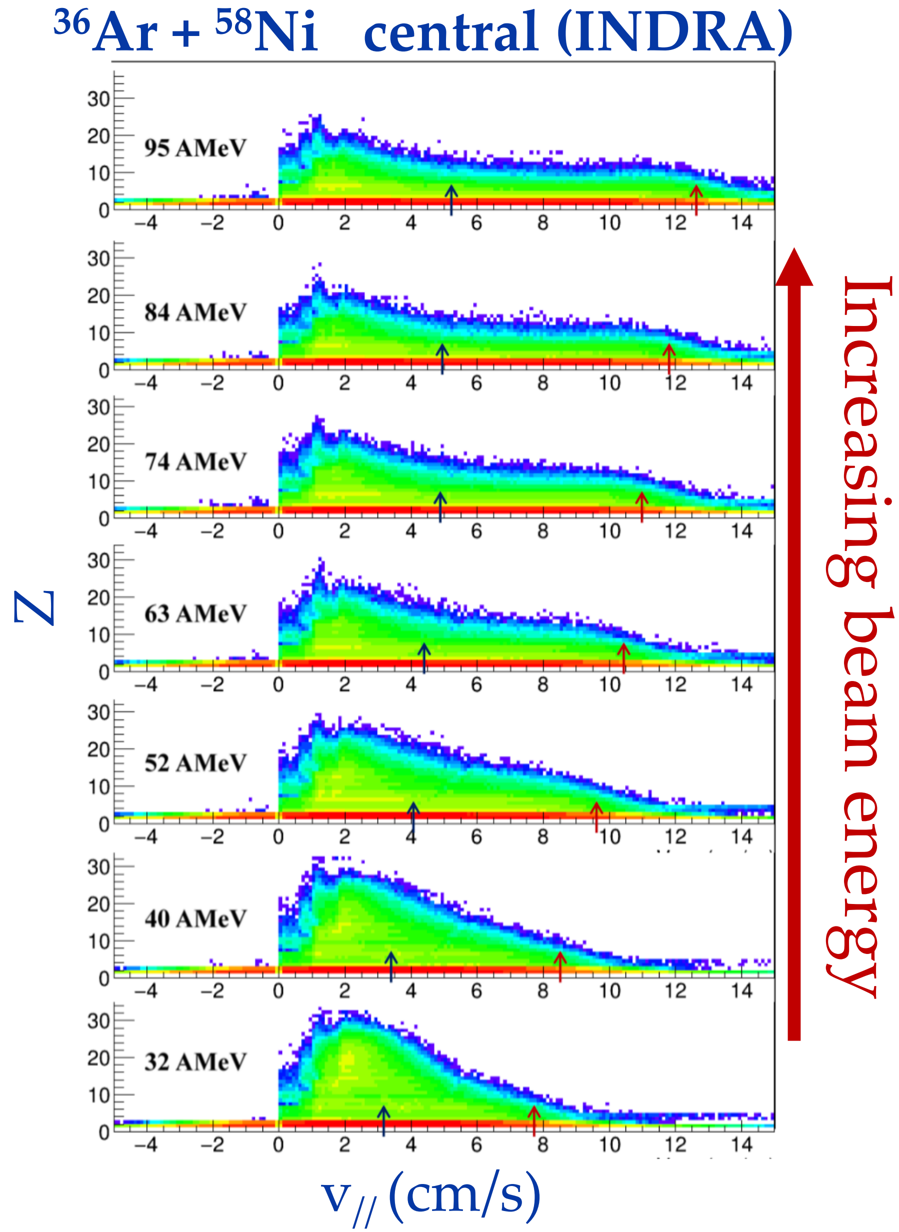


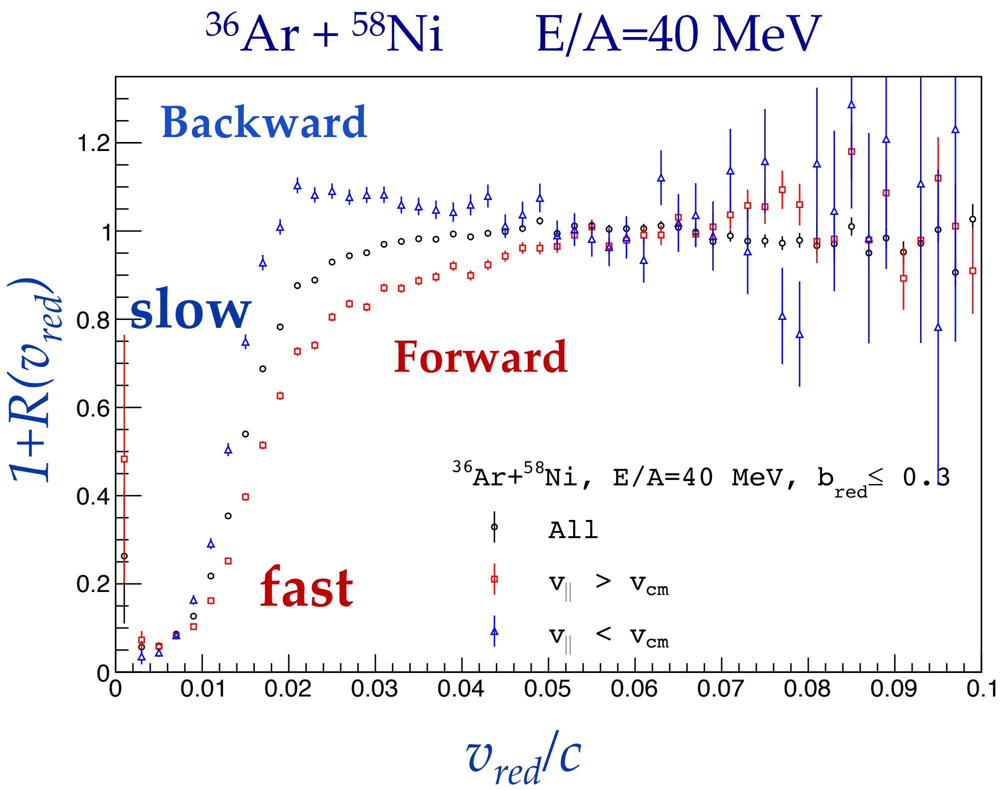
Forward dissipative transparency

L. Francalanza et al. (2016)

Zimanyi School 2016

"In-medium jet" fragmentation: time-scales



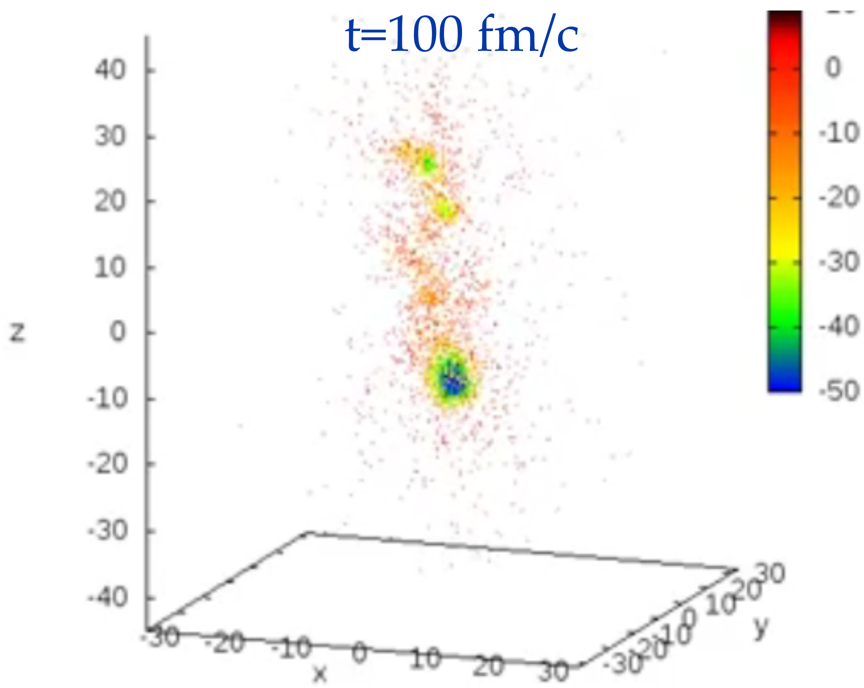


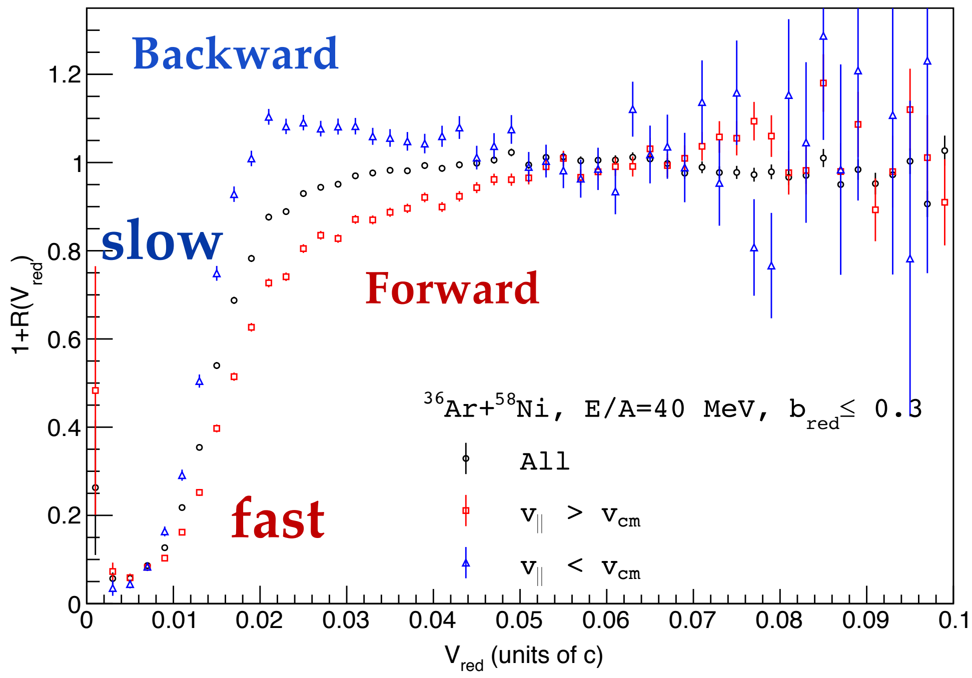
L. Francalanza, G. V. et al.

"In-medium jet" fragmentation: time-scales

$^{36}Ar + ^{58}Ni$ E/A=40 MeV

BLOB (P. Napolitani, M. Colonna)





L. Francalanza, G. V. et al.

Recent results from INDRA/FAZIA experiments

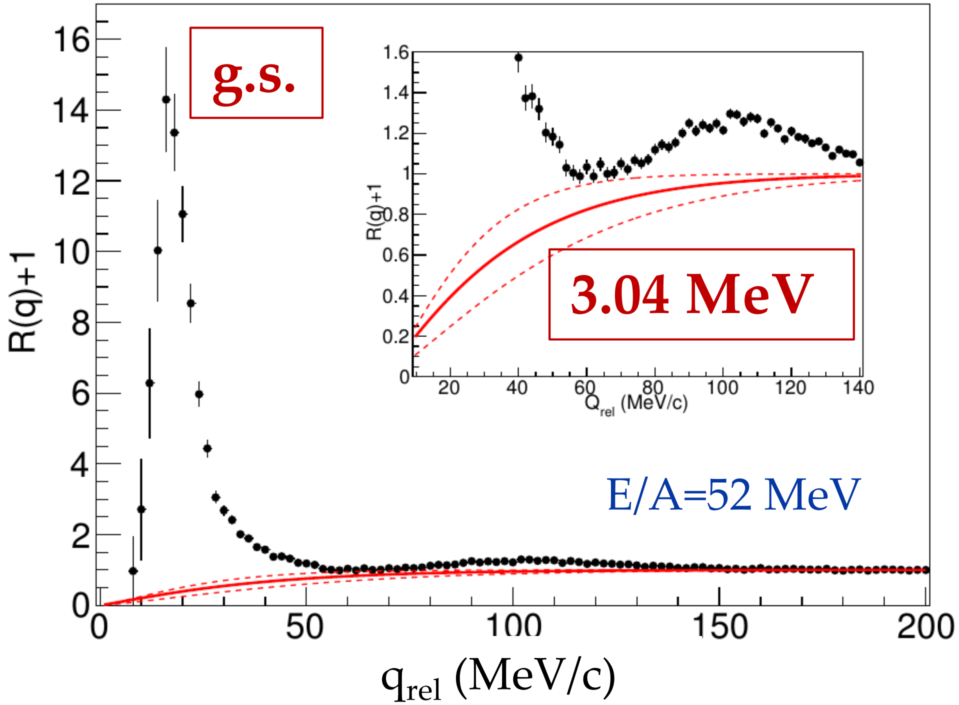
- Nuclear structure properties in low density matter: HIC as a perfect site
  - Study the properties of the medium: density, temperature, EoS → dynamics of HIC
  - **Unbound states decays**

Two-alpha thermal model?

Ar+Ni, E/A=32-95 MeV – central → ^{8}Be → $\alpha + \alpha$

INDRA @ GANIL

$$1 + R(q_{rel}) = \frac{Y_{coinc}(\alpha,\alpha)}{Y_{evt\ mixing}(\alpha,\alpha)}$$



$$1 + R(q_{rel}) = \frac{Y_{coinc}(\alpha,\alpha)}{Y_{evt\ mixing}(\alpha,\alpha)}$$

$$R(q_{rel}) = R_{coul}(q_{rel}) + R_{nucl}(q_{rel})$$

$$\boldsymbol{Y_{nucl}(E^*) = \frac{N}{\pi} e^{-E^*/T} \sum_i (2J_i + 1)\left[\frac{\Gamma_i/2}{(E^* - E_i)^2 + \Gamma_i^2/4}\right]}$$

In-medium temperature

Nuclear structure: spin, branching ratios, resonance position

D. Dell'Aquila, PhD thesis

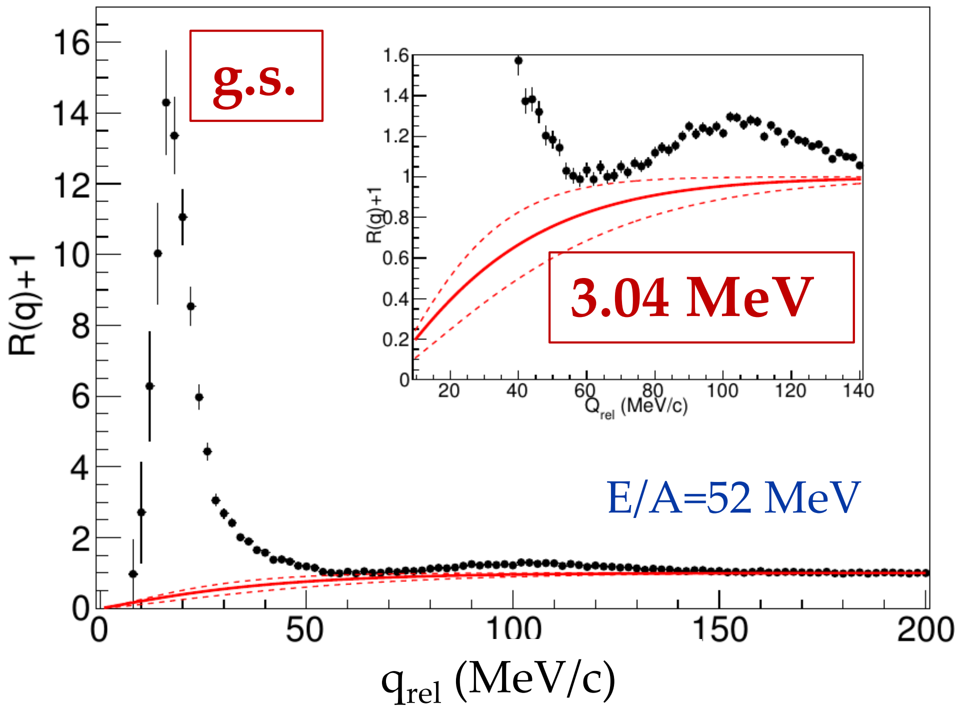
Two-alpha thermal model

Ar+Ni, E/A=32-95 MeV – central → ^{8}**Be → α + α**

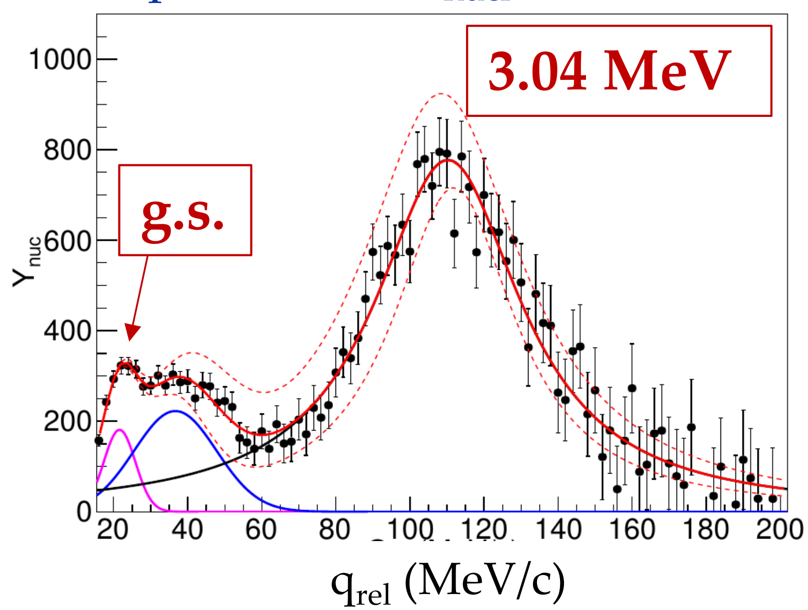
INDRA @ GANIL

$$Y_{nucl}(E^*) = \frac{N}{\pi} e^{-E^*/T} \sum_i (2J_i + 1) \left[\frac{\Gamma_i/2}{(E^* - E_i)^2 + \Gamma_i^2/4} \right]$$

$$1 + R(q_{rel}) = \frac{Y_{coinc}(\alpha,\alpha)}{Y_{evt\ mixing}(\alpha,\alpha)}$$



Experimental Y_{nucl}



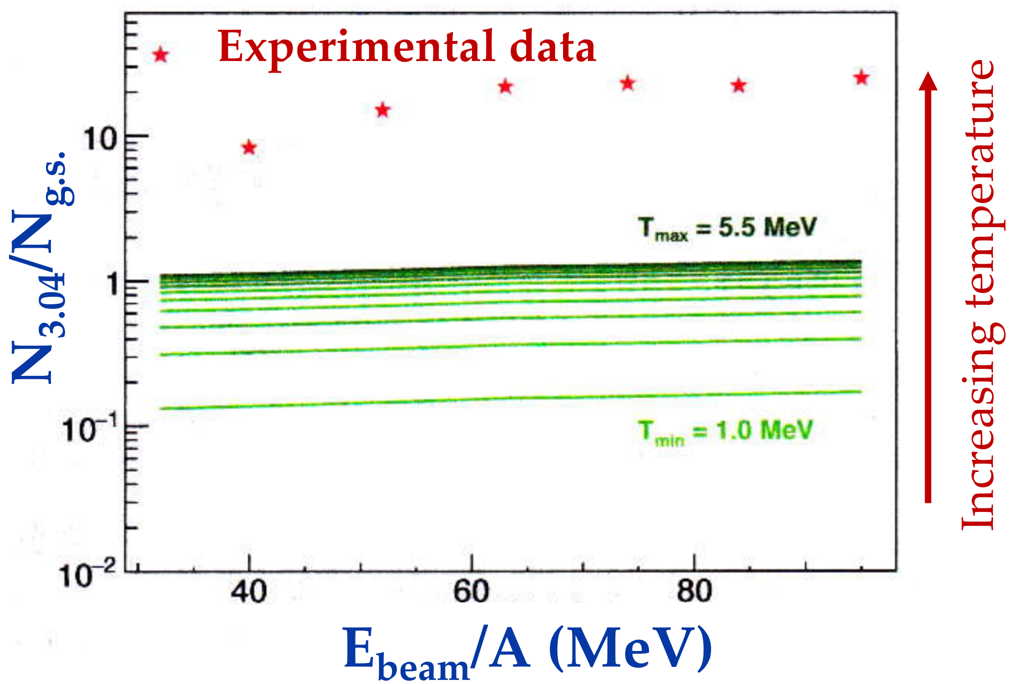
D. Dell'Aquila, PhD thesis

Two-alpha thermometer

Ar+Ni, E/A=32-95 MeV – central → ^{8}**Be → α + α**

INDRA @ GANIL

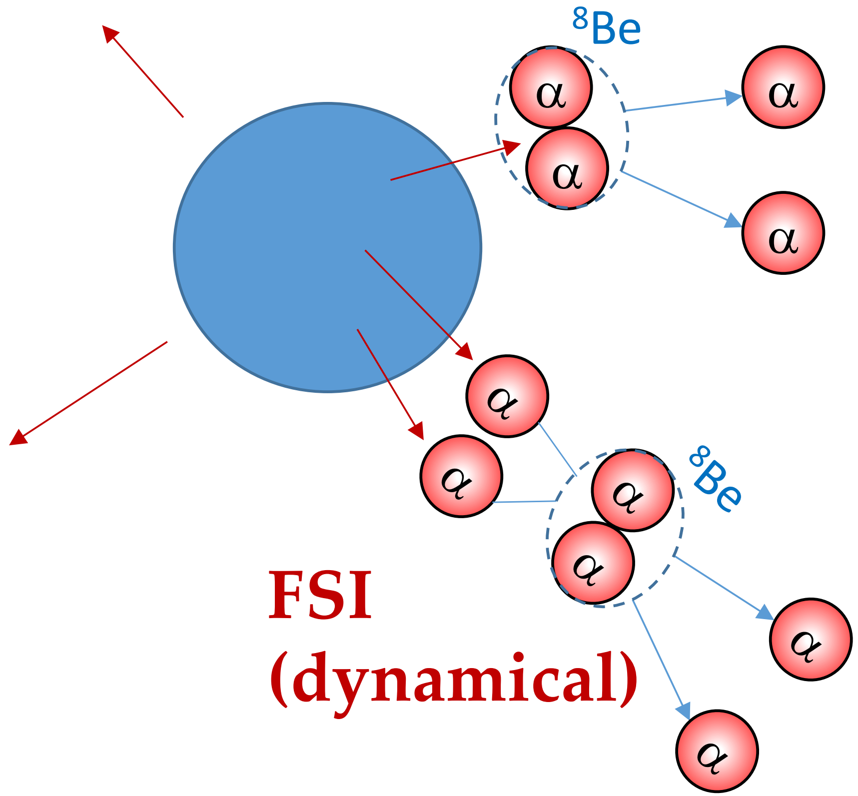
$$Y_{nucl}(E^*) =$$
$$= \frac{N}{\pi} e^{-E^*/T} \sum_i (2J_i + 1) \left[\frac{\Gamma_i/2}{(E^* - E_i)^2 + \Gamma_i^2/4} \right]$$



Thermal mechanism cannot describe unbound state population for α's

D. Dell'Aquila, PhD thesis

Parent decay and resonance generation by Final State Interactions



Primary parent decay (thermal)

Quantitative estimate of dynamical FSI vs Thermal decay yields **in progress**

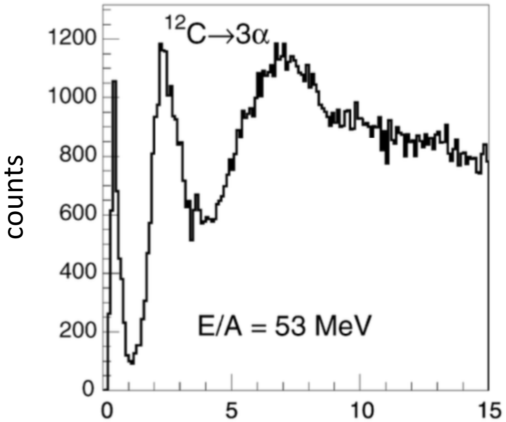
- Providing alpha density estimates in dilute medium

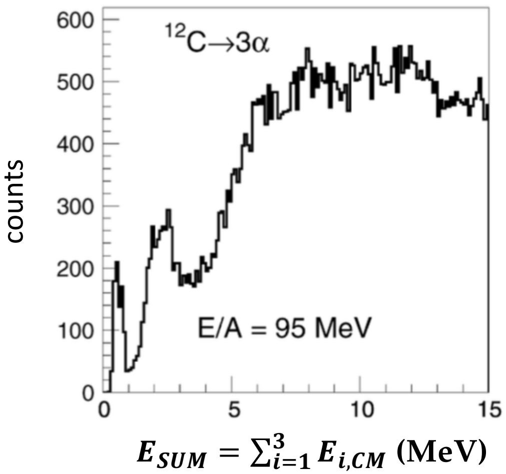
D. Dell'Aquila, PhD thesis

In-medium three-alpha correlations: decay of ^{12}C states

$^{12}C+^{24}Mg$ E/A=53 and 95 MeV
INDRA data

$^{12}C \rightarrow 3\alpha$





^{12}C (Chimera and INDRA data)

^{12}C(Hoyle) ➔ $^{8}Be+\alpha$ ➔ $(\alpha+\alpha)+\alpha$

^{12}C (Hoyle) ➔ $\alpha+\alpha+\alpha$

A. Raduta et al., Phys. Lett. B 705, 65 (2011)
F. Grenier et al., Nucl. Phys. A811, 233 (2008)

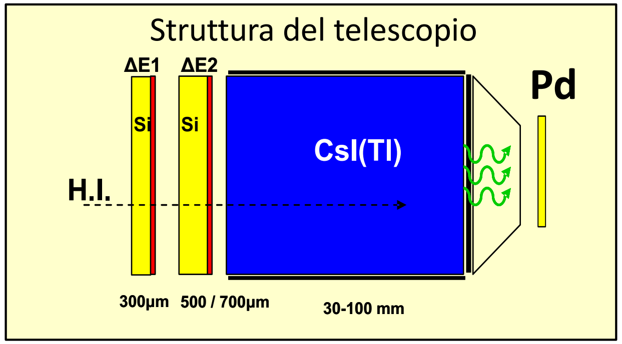
Strong contributions from 3α direct decay mode?

≠ all studies with direct reactions (no medium) on isolated 12C states: 100% sequential decay mode of the Hoyle state

D. Dell'Aquila, I. Lombardo, G. Verde et al., Physical Review Letters 119, 132501 (2017)

In-medium resonance decays in HIC

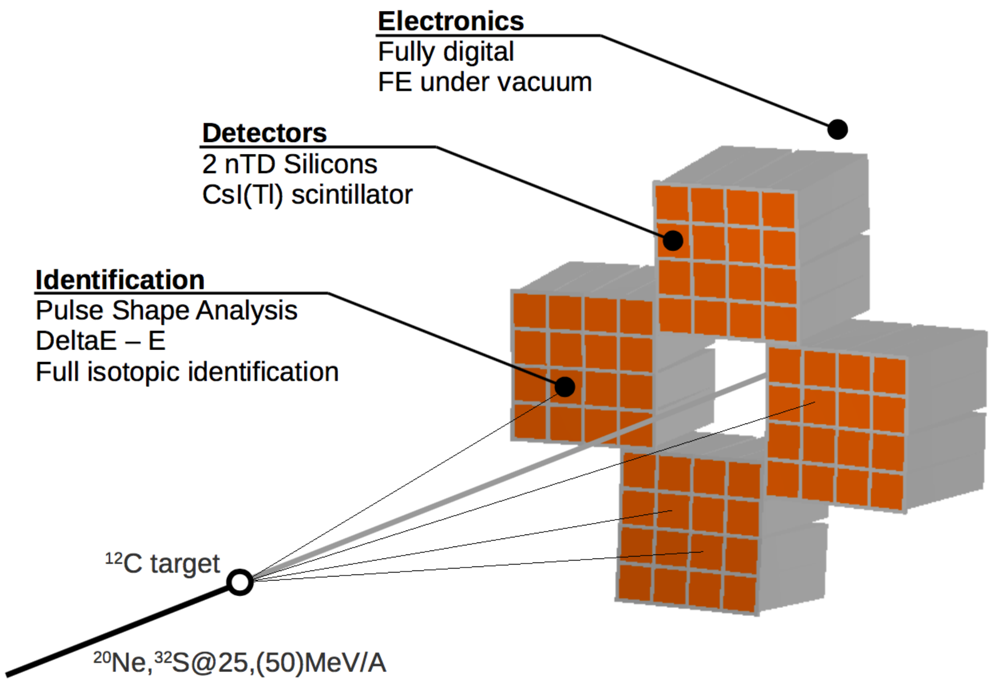
FAZIA (Four-pi A- and Z-Identification Array)



Fully digital electronics: particle identification directly from digitalization of Si and CsI(Tl) signals

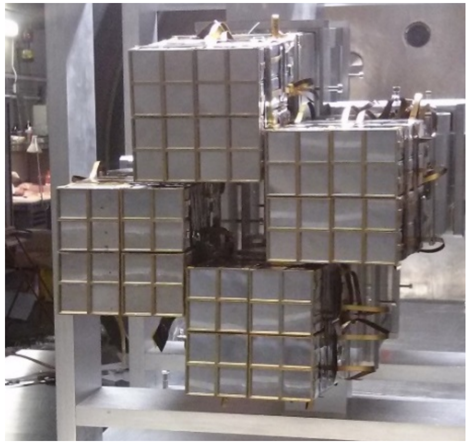
→ almost online available

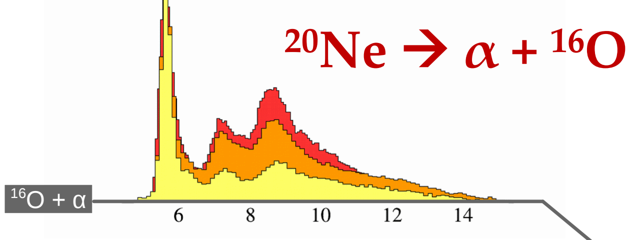
→ Wide dynamic range (100 keV- GeV)

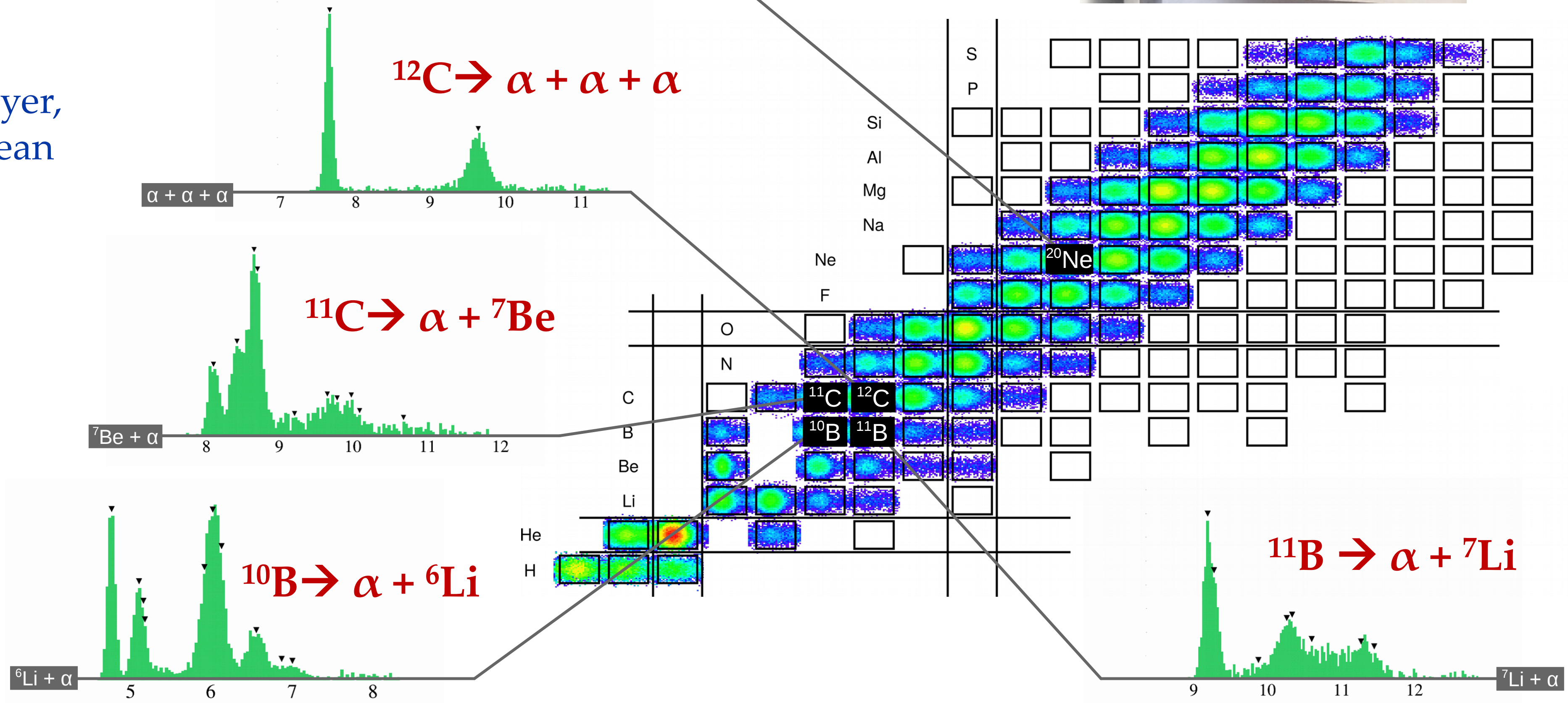


Some preliminary Nα-X correlations

Projects for students available

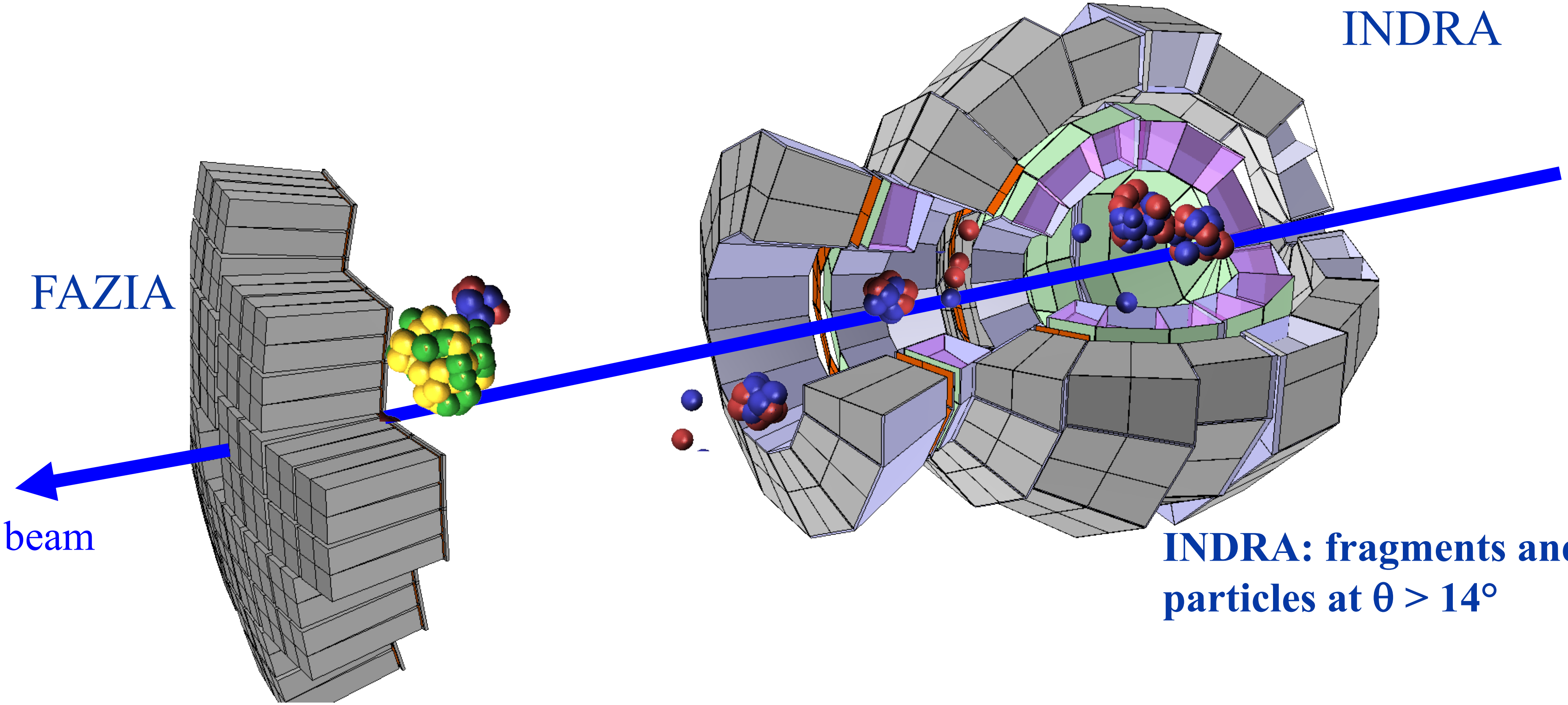






D. Gruyer,
LPC Cean

FAZIA-INDRA @ GANIL (2019-2020)



INDRA: fragments and particles at θ > 14°

- **12 Blocks (192 telescopes)**
- **full Z & A identification of 1≤Z<25 at θ < 14°**

$^{40,48}Ca+^{40,48}Ca$

$^{58,64}Ni+^{58,64}Ni$ E/A=30-90 MeV

… other systems

In-medium investigations

- HIC provide hot and dilute medium with plenty of unbound states (free in just one single experiment)
  - Study dynamics and EoS
  - Study structure properties: spins, branching ratios (sequential vs direct), etc…. *in-medium structure*
- Modification of structure properties? Difficult to probe
  - Study medium properties (ex. Thermal model, IMF-IMF correlations, …): T, ϱ, Esym, …
  - Multi-particle correlations to isolate resonance decays: thermal models Vs. FSI approaches → density and temperature effects?
- Future perspectives
  - INDRA-FAZIA campaigns at GANIL

    Welcome to submit proposals and collaborate (experiment and theory)