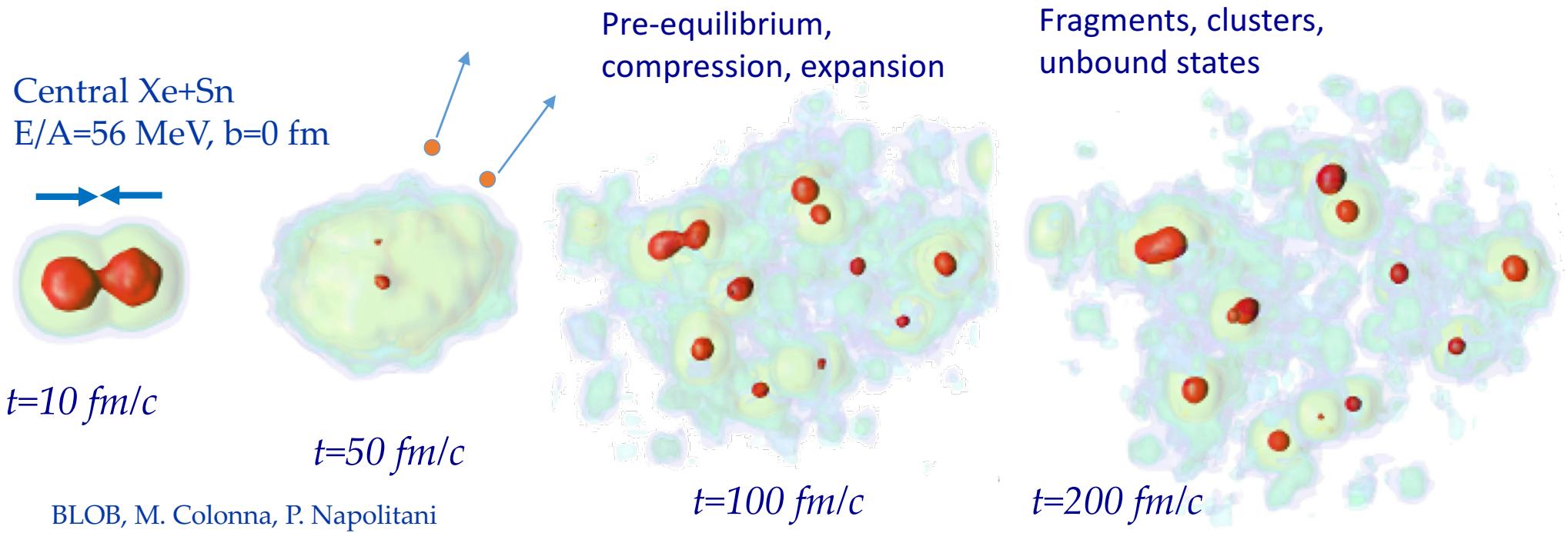


In-medium structure and dynamics in heavy-ion collisions at intermediate energies



G. Verde, INFN Catania

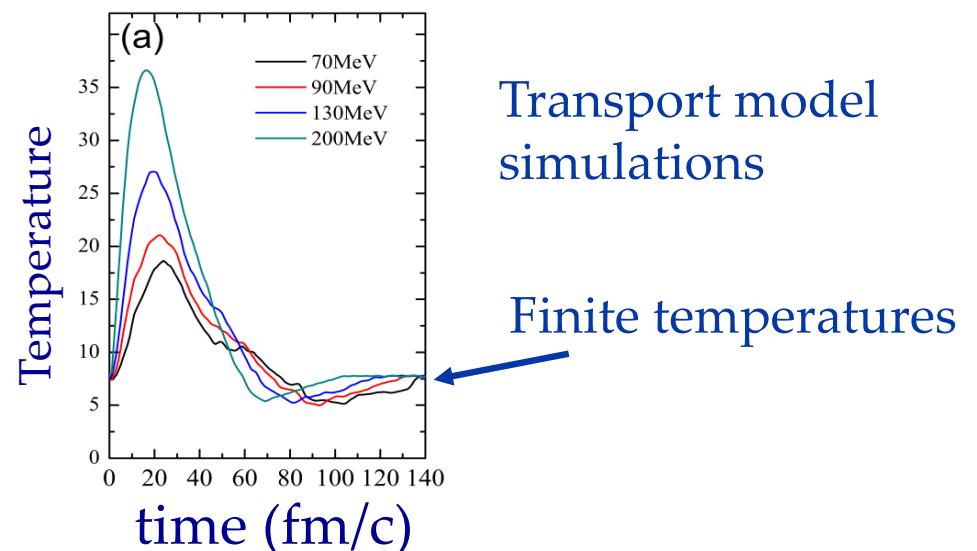
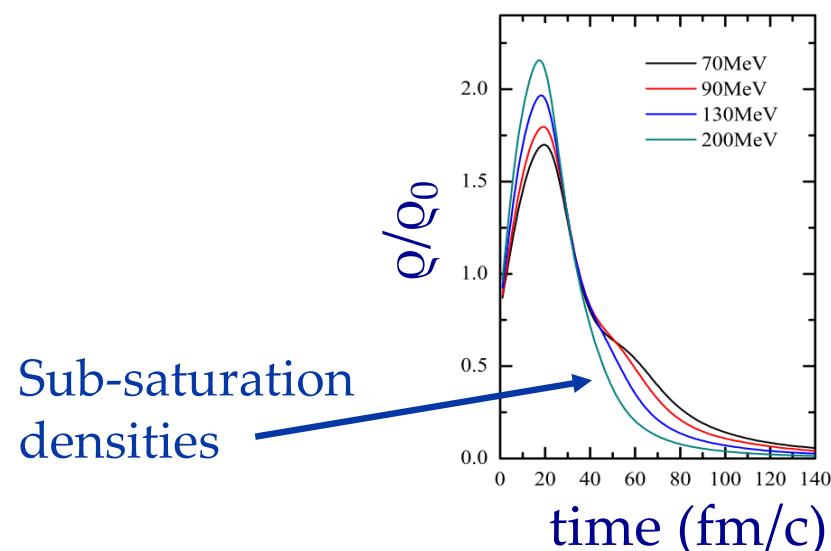
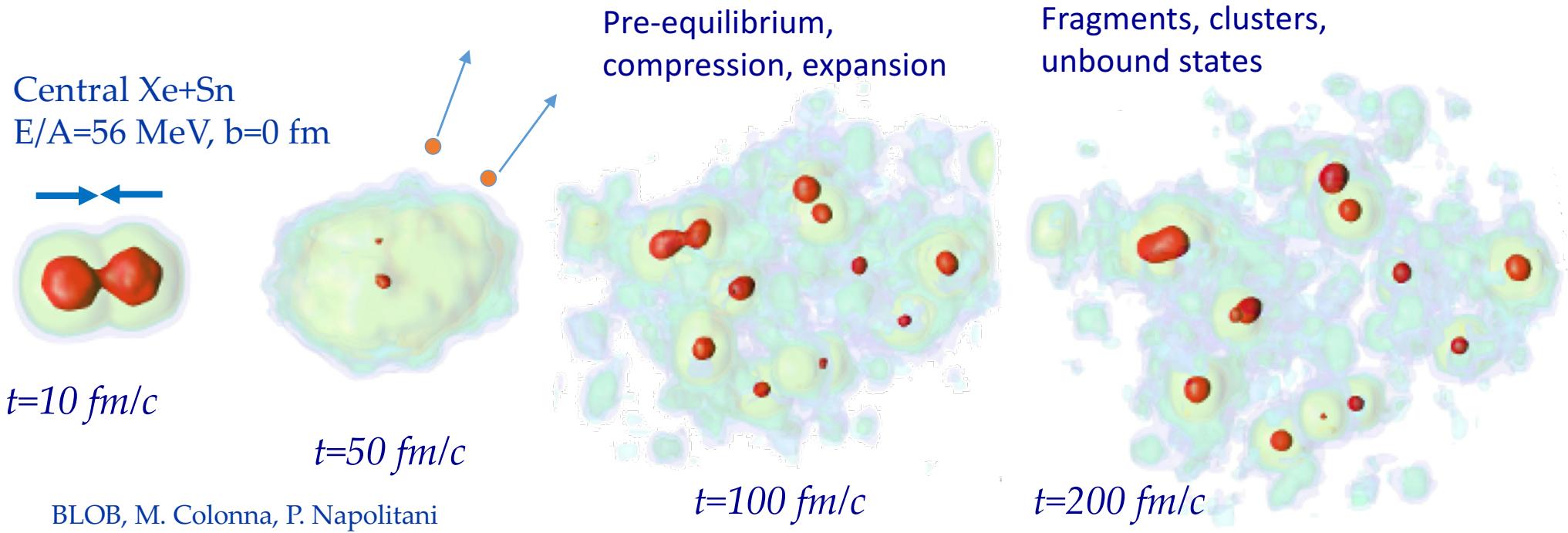
FAZIA & INDRA collaborations

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

Outline

- Introduction to HIC at intermediate energies:
densities, temperatures, EoS, Symmetry energy
- Effects of clustering → in-medium structure
- Studying in-medium dynamics and structure:
correlations and resonance decays
 - $^{36}\text{Ar}+^{58}\text{Ni}$ $E/A=32\text{-}95 \text{ MeV}$ Indra @ GANIL
- Present status and the FAZIA-INDRA program

Densities and temperatures at intermediate energies... not so bad ☺



EoS and symmetry energy

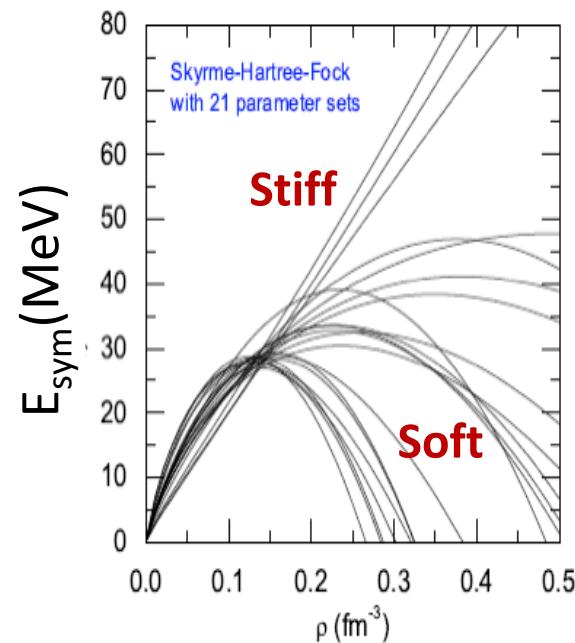
$$E(\rho, \delta) = E(\rho, \delta = 0) + [E_{\text{sym}}(\rho) \cdot \delta^2] + O(\delta^4)$$

Asymmetry term

$$\delta = \frac{\rho_n - \rho_p}{\rho_n + \rho_p} \neq 0$$

$$\rho = \rho_n + \rho_p$$

B.A. Li et al., Phys. Rep. 464, 113 (2008)



Still large uncertainties....

Quantum N-body systems,
three-body forces, ...

ZH Li, U. Lombardo, PRC74 047304
(2006)

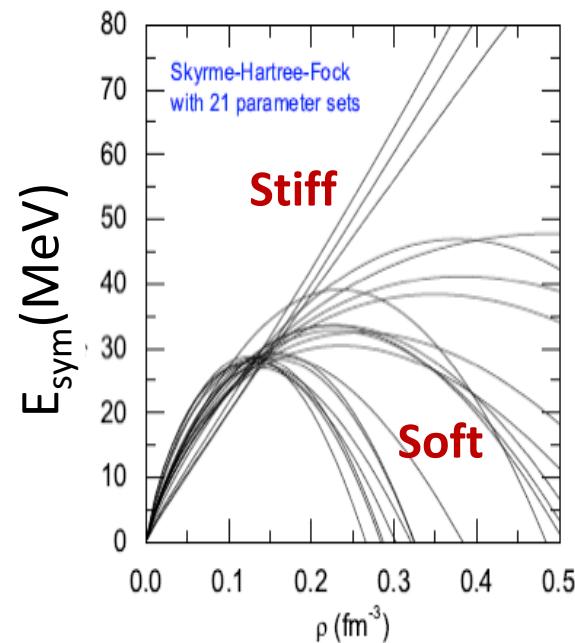
EoS and symmetry energy

$$E(\rho, \delta) = E(\rho, \delta = 0) + [E_{\text{sym}}(\rho) \cdot \delta^2] + O(\delta^4)$$

Asymmetry term

$$\delta = \frac{\rho_n - \rho_p}{\rho_n + \rho_p} \neq 0$$
$$\rho = \rho_n + \rho_p$$

B.A. Li et al., Phys. Rep. 464, 113 (2008)

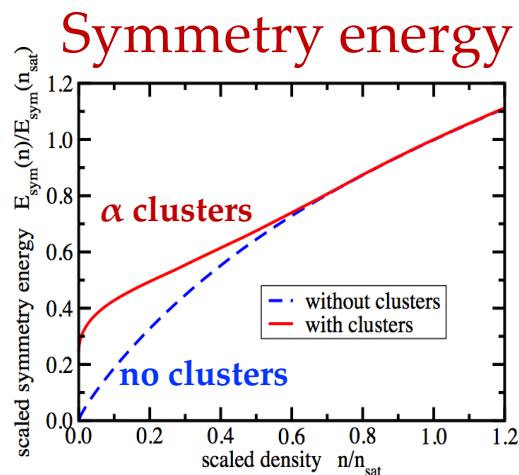
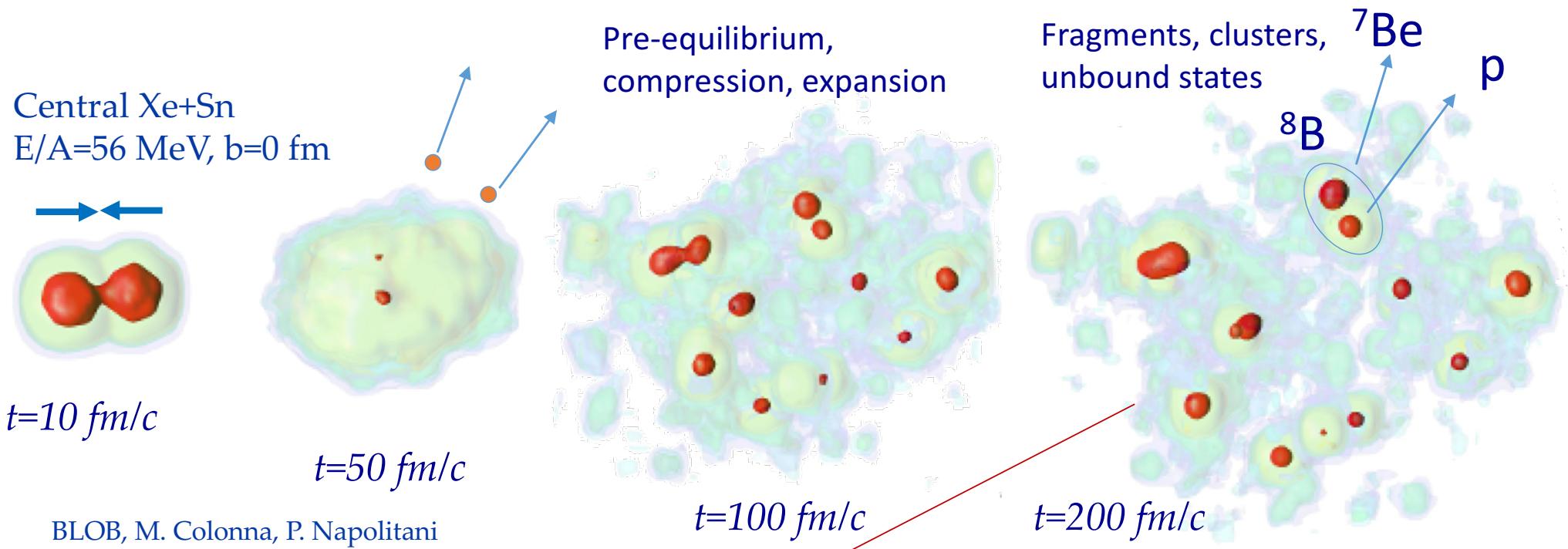


Observables in HIC:

- Peripheral collisions: isospin diffusion and drift
- Central collisions: neutron/proton emissions and effective mass splitting

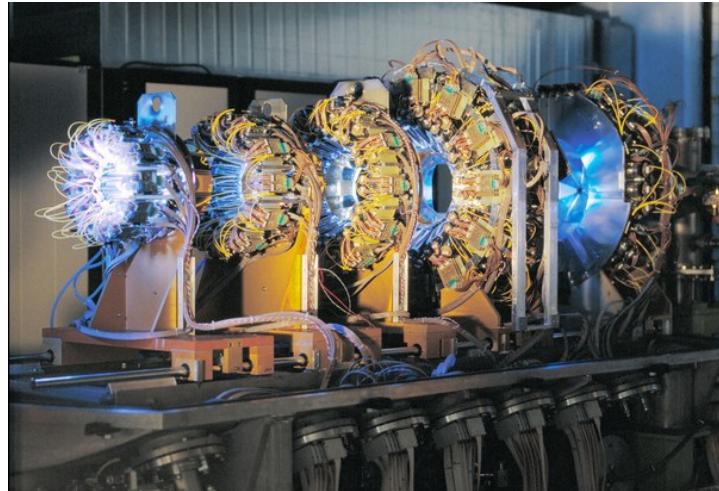
B.-A. Li, A. Ramos, G. Verde, I. Vidana
Eur. Phys. J. A50, 2014
“Nuclear Symmetry Energy”

Interplays EoS vs nuclear structure



- Clusters and structure in low density matter affect EoS properties
- Modeling neutrino wind induced nucleosynthesis in Core Collapse Supernovae explosions

In-medium fragmentation and correlations @ INDRA



INDRA *4p multi-detector*

angular coverage $\approx 90\%$ (4π)

336 *independent cells*

telecopes C_3F_8 gas chamber –
Si (300 mm) – CsI (5-14cm)

Talk by P. St-Onge



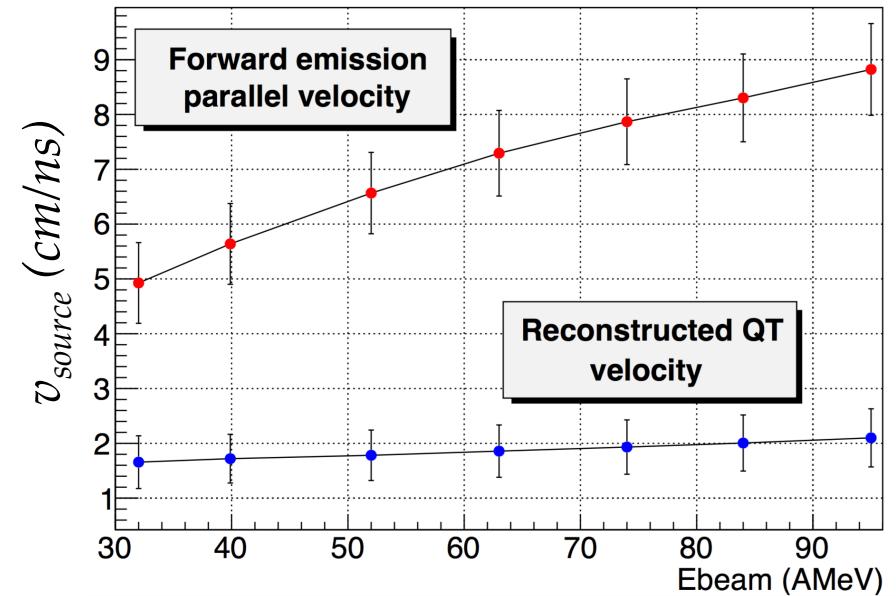
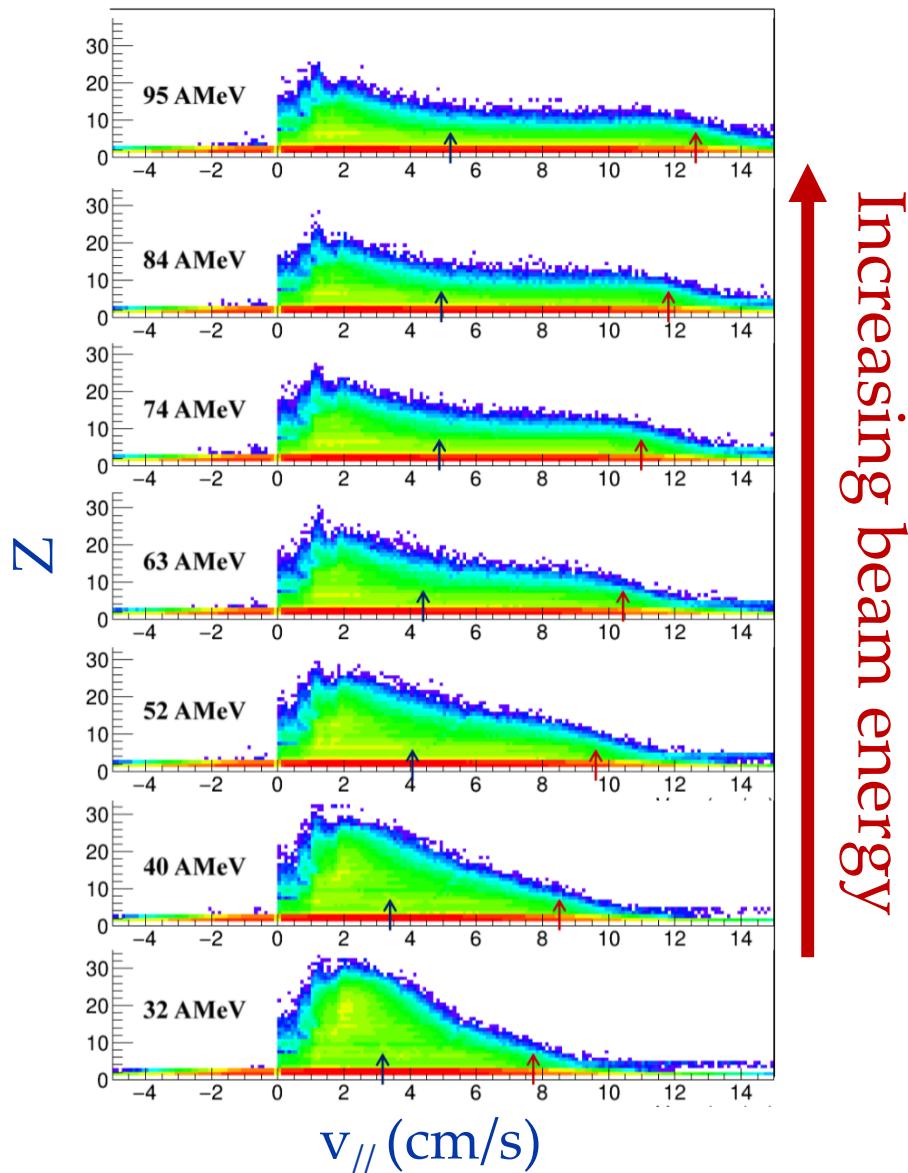
α conjugate

talk by I. Lombardo

Role of projectile structure on
dynamics \rightarrow in-medium clustering

In-medium jet fragmentation

Ar+Ni E/A=32, 40, 52, 63, 74, 85, 95 MeV - CENTRAL
INDRA @ GANIL



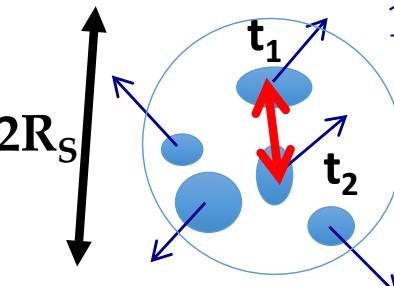
Forward dissipative transparency

L. Francalanza et al. (2016)
Zimanyi School 2016

Fragment emission time-scales

IMF-IMF Correlation Functions

IMF: Z>2

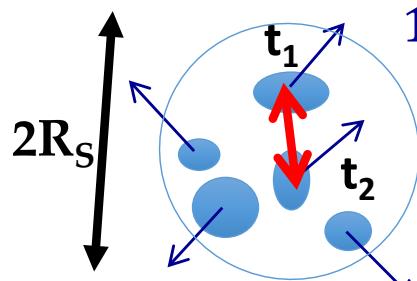

$$1 + R(v_{red}) = \frac{Y_{coinc}(v_{red})}{Y_{evt\ mixing}(v_{red})}$$
$$v_{red} = \frac{|\vec{v}_1 - \vec{v}_2|}{\sqrt{Z_1 + Z_2}}$$

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

Fragment emission time-scales

IMF-IMF Correlation Functions

IMF: Z>2



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

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

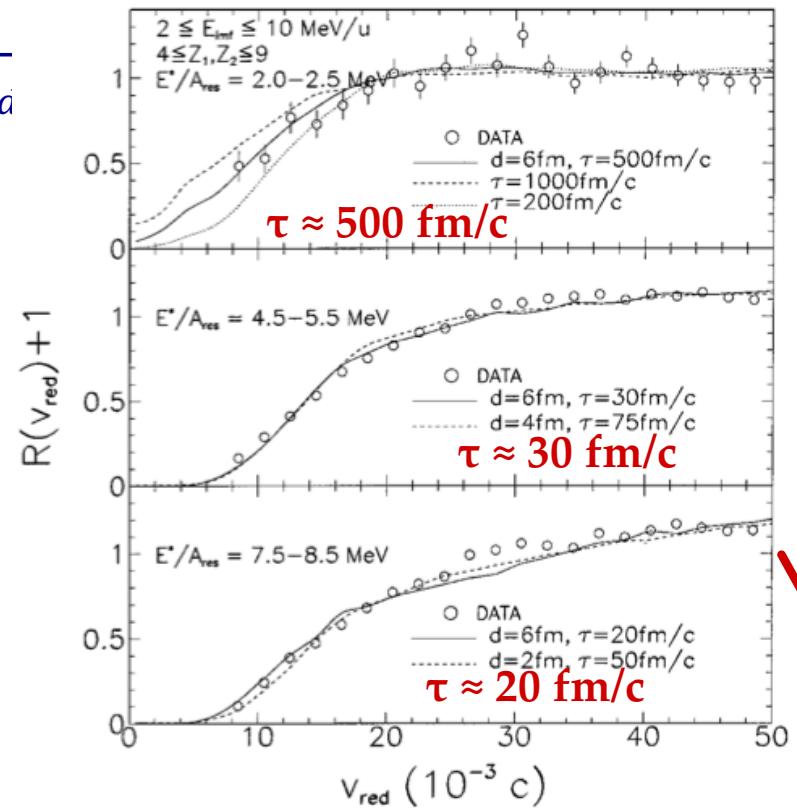
Compact thermal source (T, β_{coll}, \dots)

N-body Coulomb trajectories

Source radius and emission times:

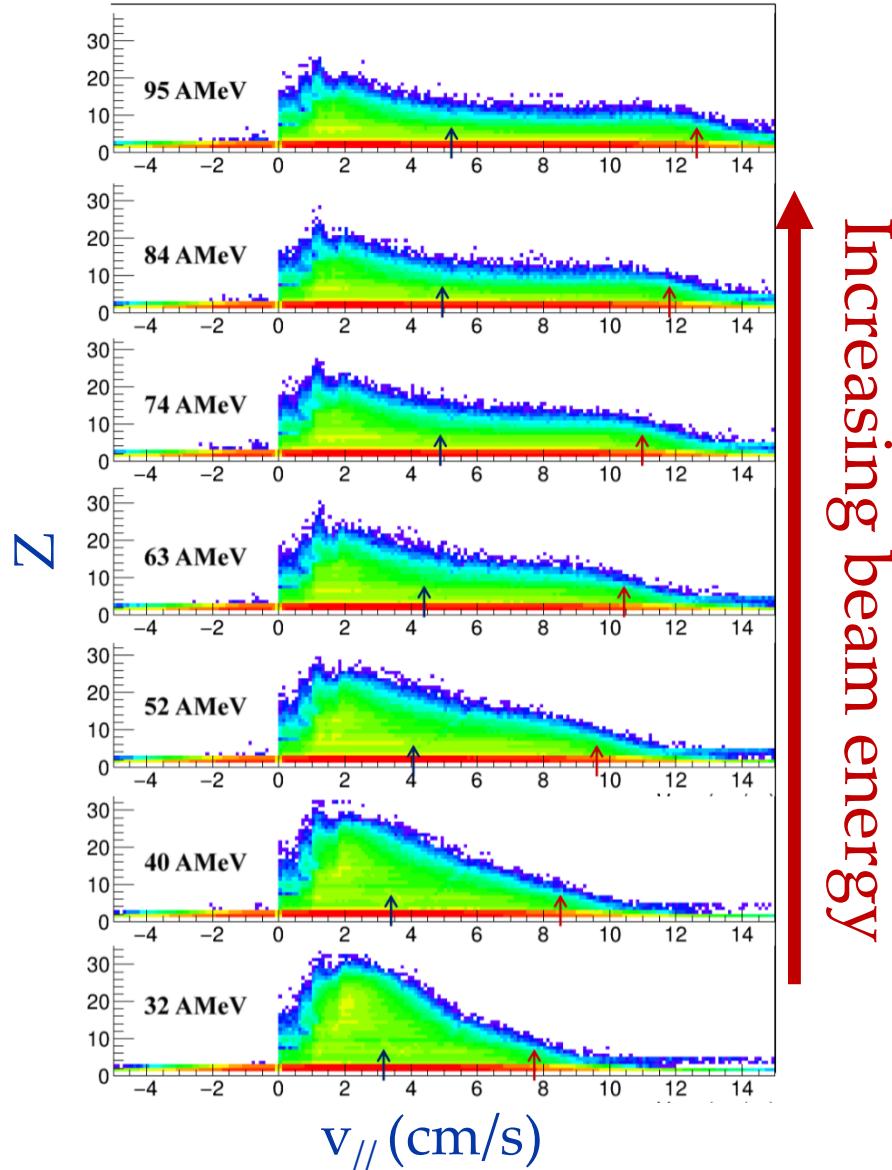
$$R_s, P(t) = (1/\tau) \cdot \exp(-t/\tau) \rightarrow \tau$$

$\pi^-, p + Au \quad 8.0, 8.2, 9.2, 10.2 \text{ GeV}/c$

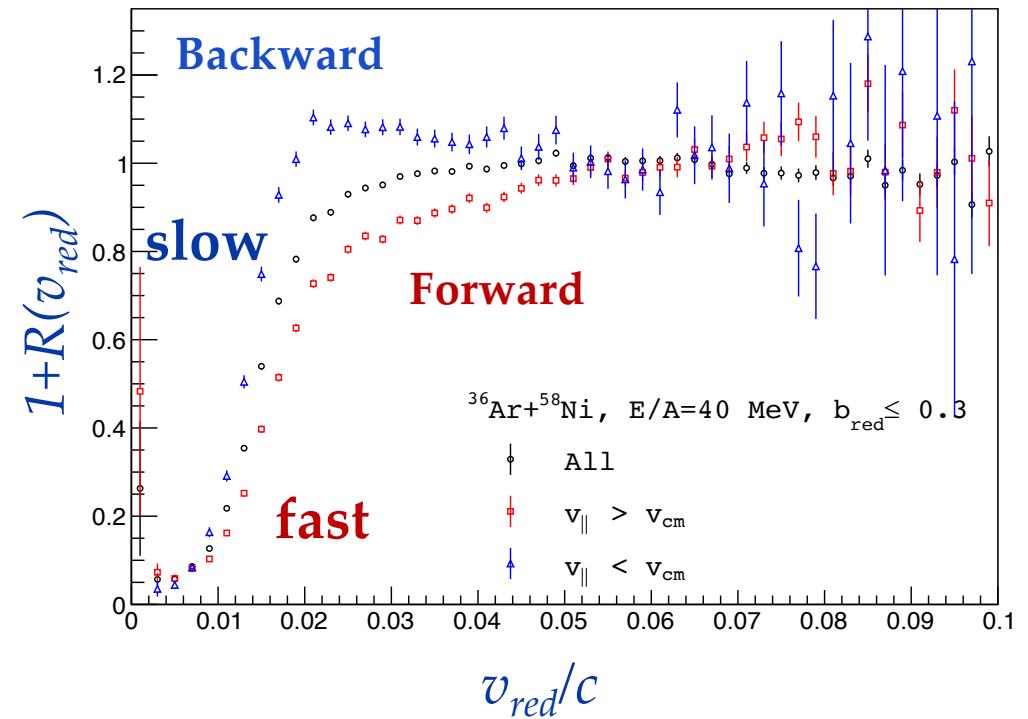


“In-medium jet” fragmentation: time-scales

$^{36}\text{Ar} + ^{58}\text{Ni}$ central (INDRA)



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

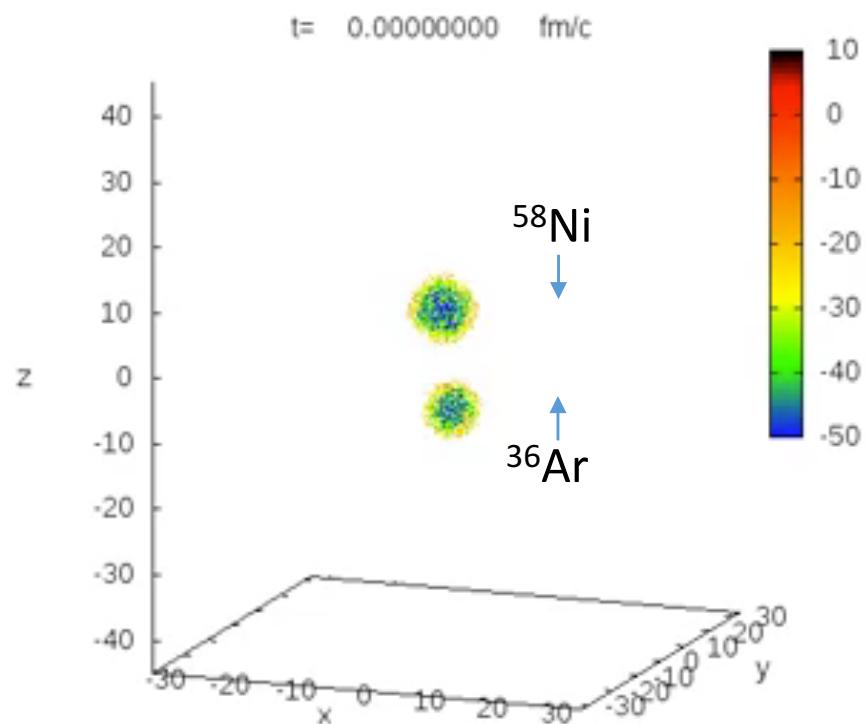


“In-medium jet” fragmentation: time-scales

BLOB (P. Napolitani, M. Colonna)

$^{36}\text{Ar} + ^{58}\text{Ni}$

E/A=40 MeV

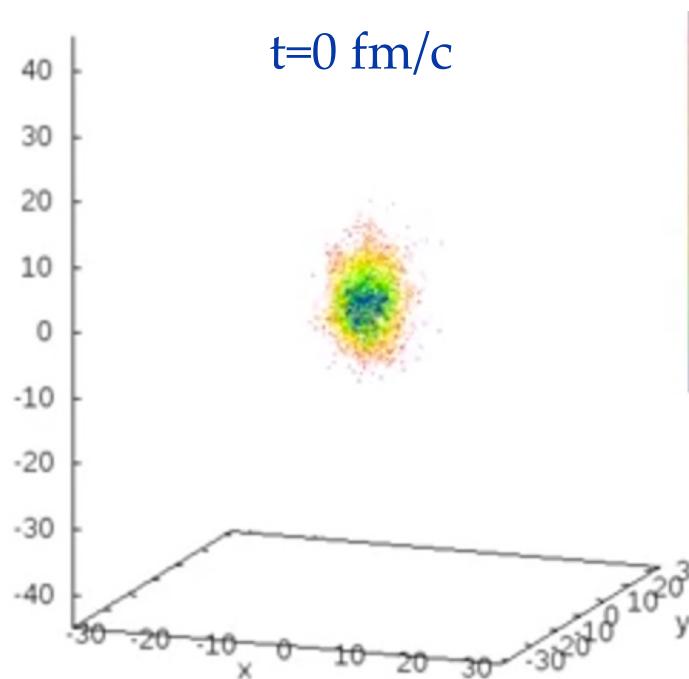


“In-medium jet” fragmentation: time-scales

BLOB (P. Napolitani, M. Colonna)

$^{36}\text{Ar} + ^{58}\text{Ni}$

E/A=40 MeV

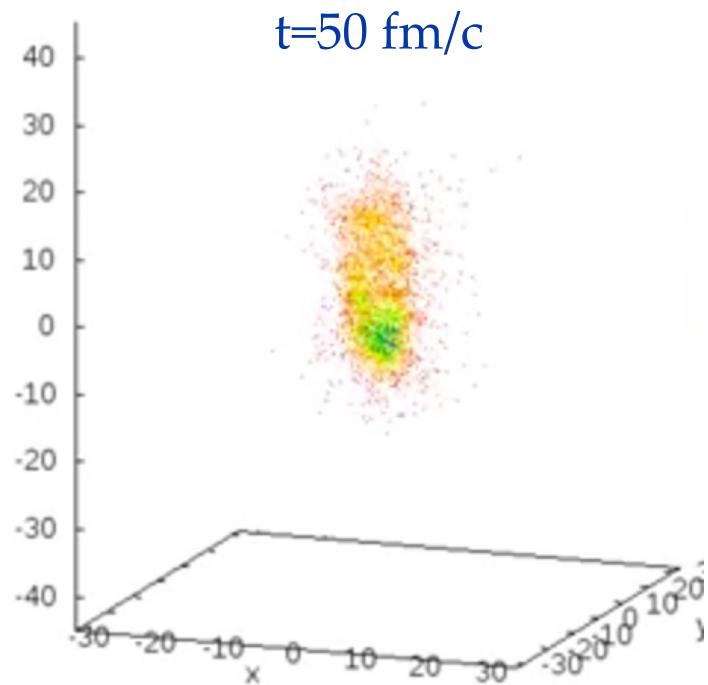


“In-medium jet” fragmentation: time-scales

BLOB (P. Napolitani, M. Colonna)

$^{36}\text{Ar} + ^{58}\text{Ni}$

E/A=40 MeV

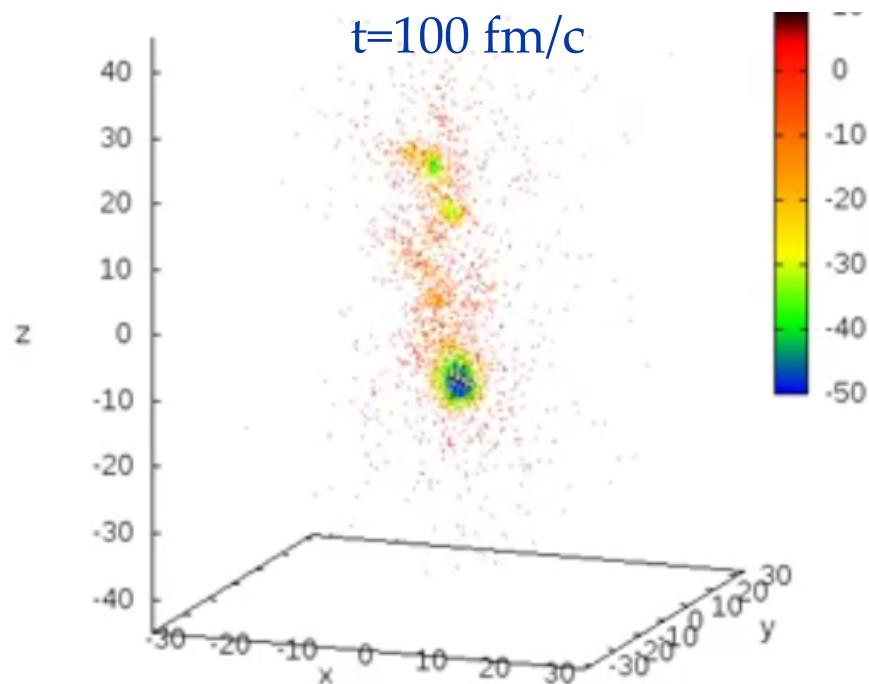


“In-medium jet” fragmentation: time-scales

BLOB (P. Napolitani, M. Colonna)

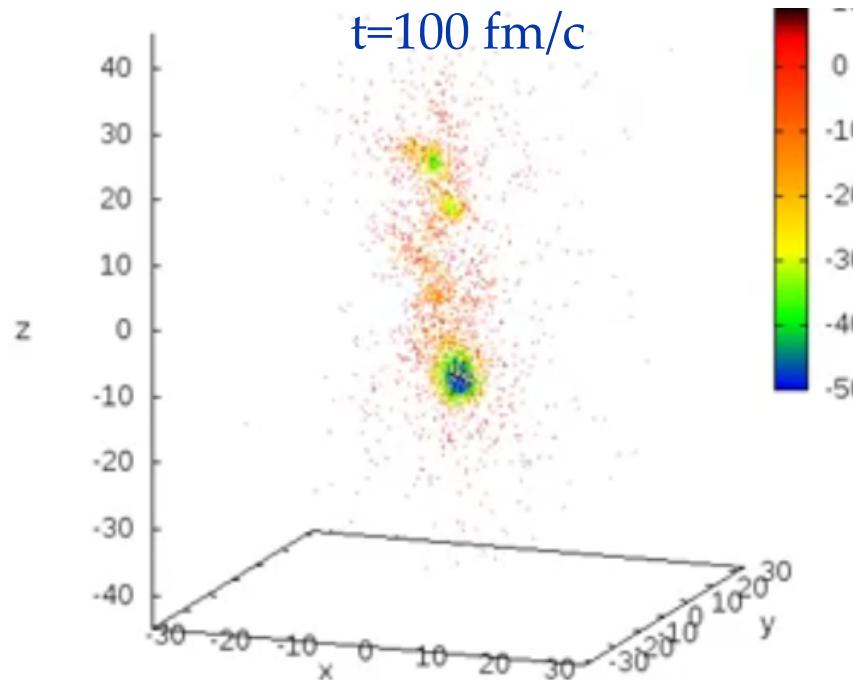
$^{36}\text{Ar} + ^{58}\text{Ni}$

E/A=40 MeV



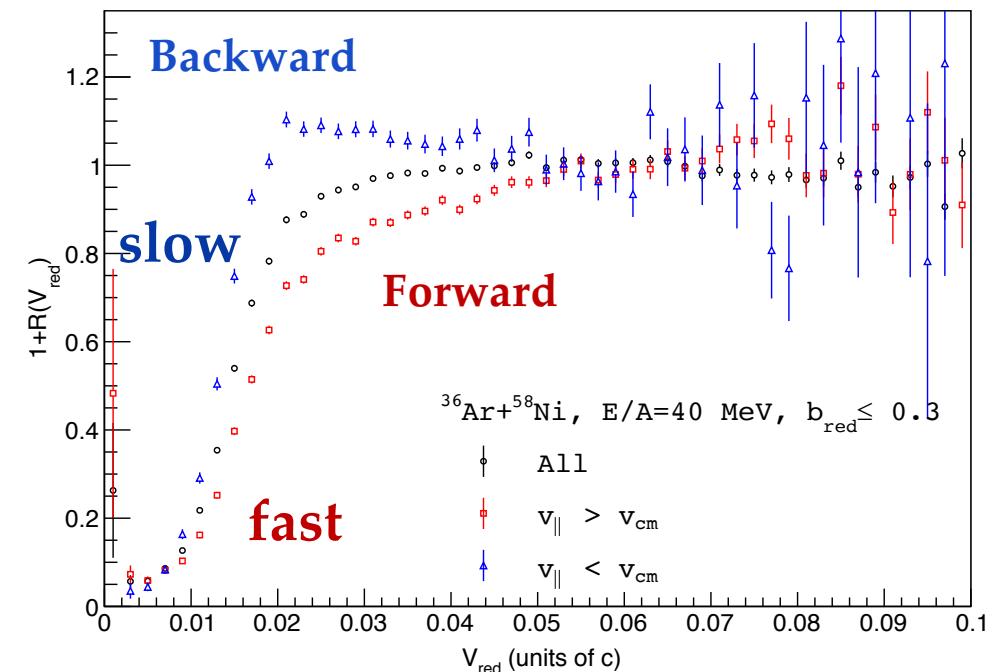
“In-medium jet” fragmentation: time-scales

BLOB (P. Napolitani, M. Colonna)



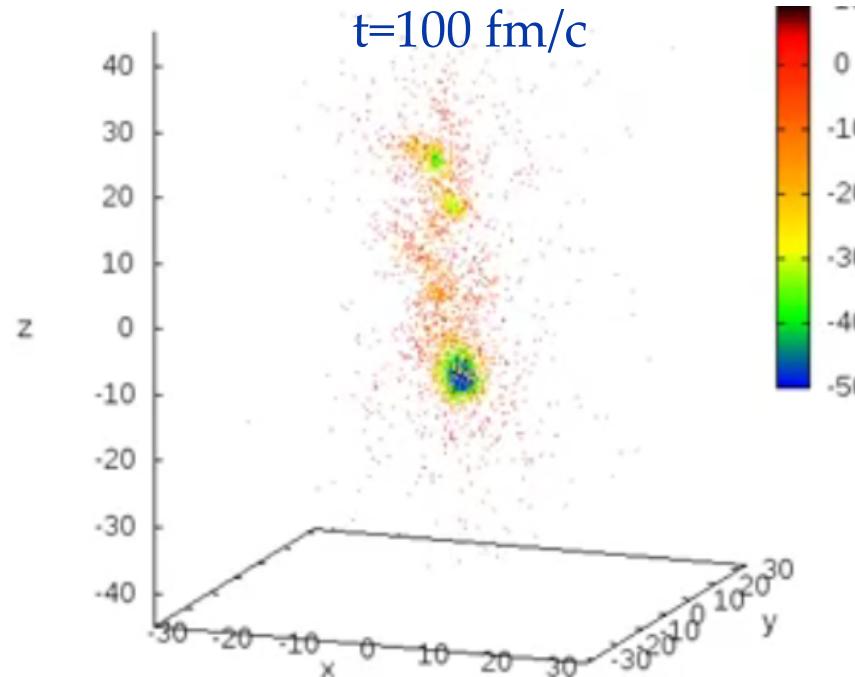
$^{36}\text{Ar} + ^{58}\text{Ni}$

$E/A=40 \text{ MeV}$



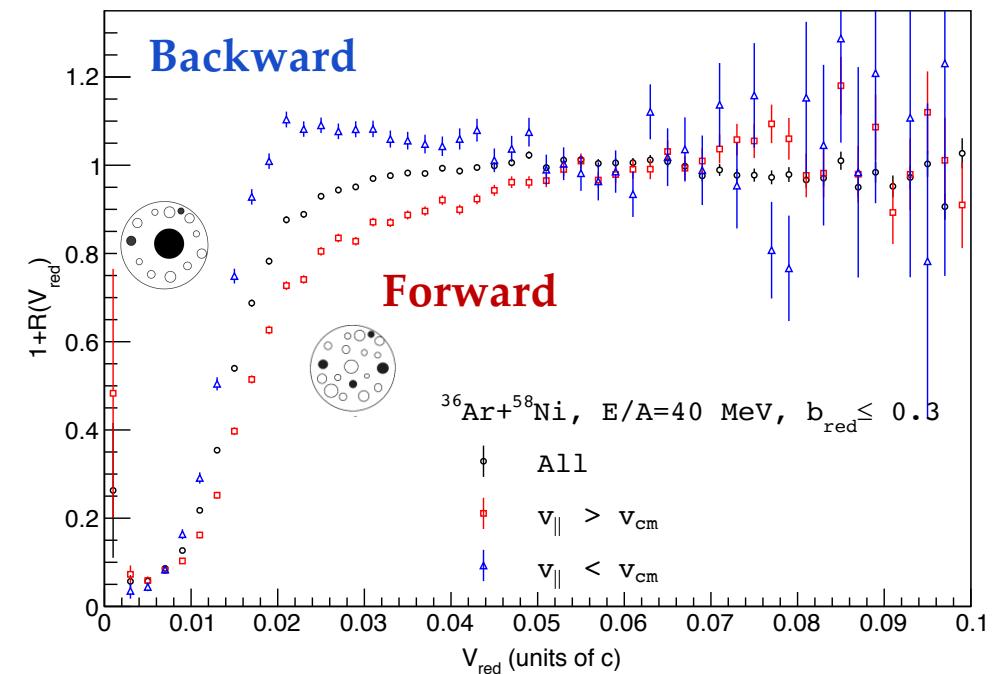
“In-medium jet” fragmentation: “tomography”

BLOB (P. Napolitani, M. Colonna)



$^{36}\text{Ar} + ^{58}\text{Ni}$

$E/A=40 \text{ MeV}$

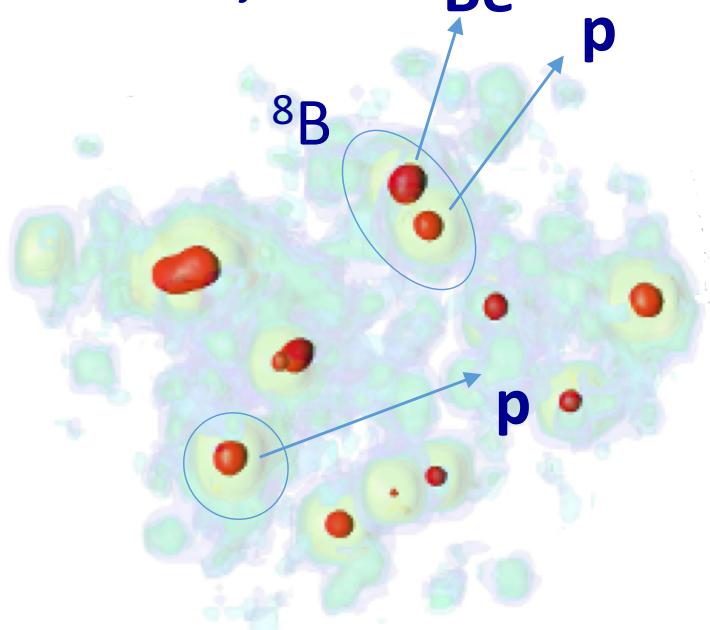


- **Projectile region:** fast emission (explosive) + homogeneous fragmentation
- **Target region:** long time-scales (evaporative)+ inhomogeneous fragmentation

No globally equilibrated system produced

Multi-particle correlations and resonances in dilute nuclear medium

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



Particle emitting sources
extended in phase-space

$$Q_{decay} = M_{8B} \cdot c^2 - (M_p \cdot c^2 + M_{7Be} \cdot c^2)$$

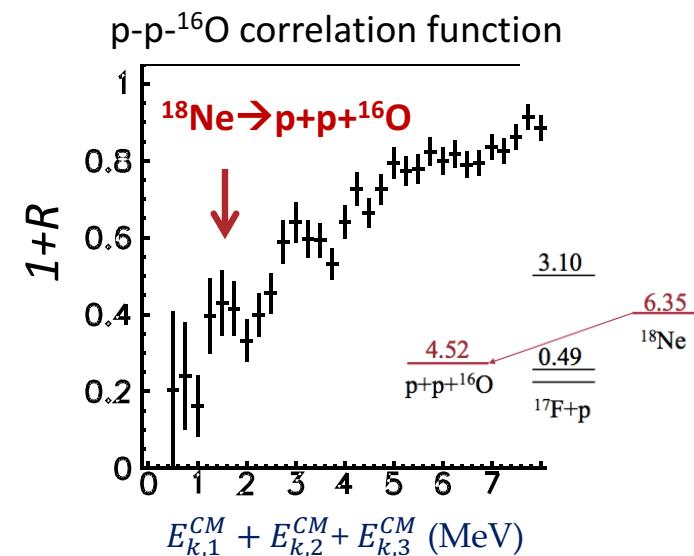
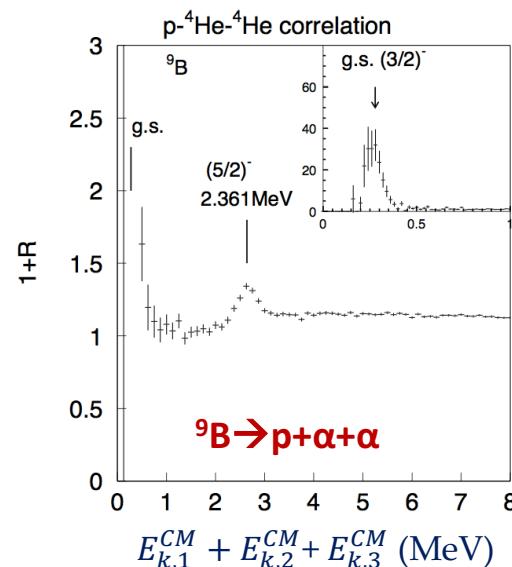
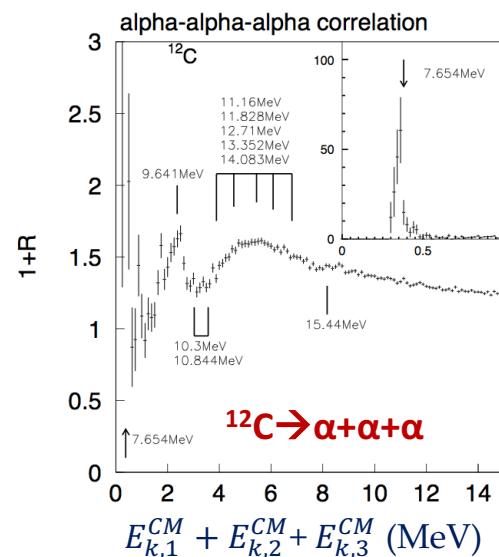
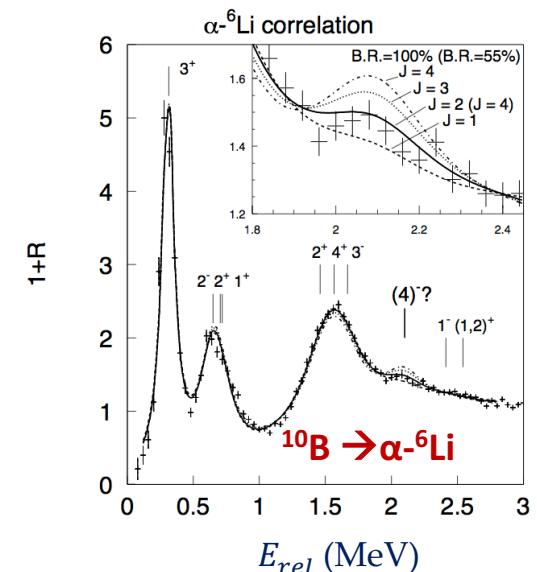
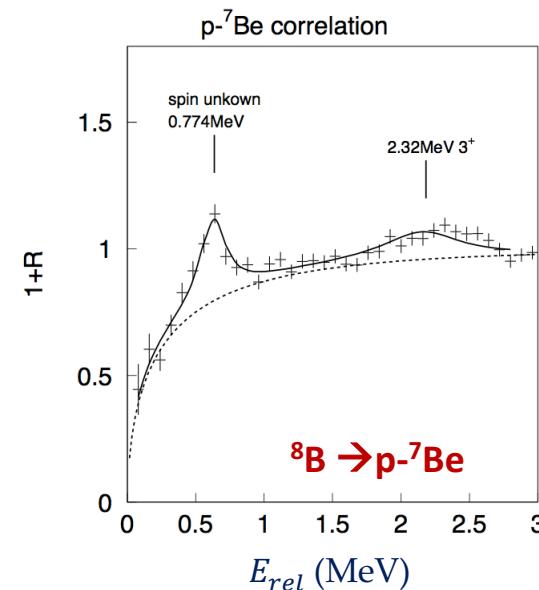
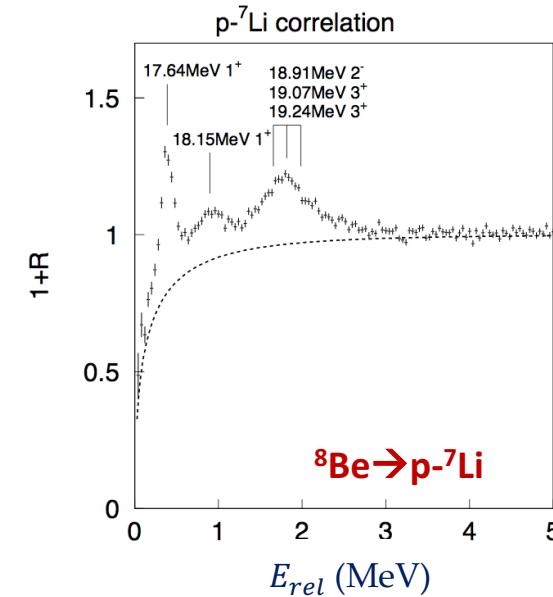
$$\begin{aligned} E^*({}^8B) &= -Q_{decay} + \frac{1}{2} M_p v_p^2 + \frac{1}{2} M_{7Be} \\ &= -Q_{decay} + \frac{1}{2} \cdot \mu v_{rel}^2 = -Q_{decay} + E_{rel} \end{aligned}$$

Correlation function:

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

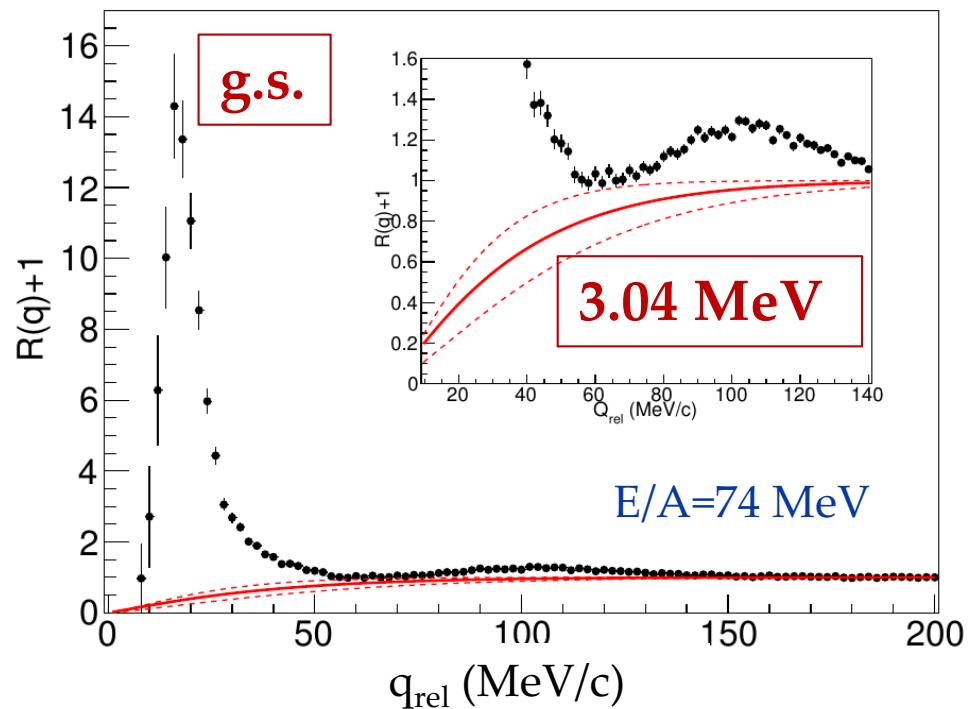
Multi-particle correlations and resonances in dilute nuclear medium

$^{112}\text{Sn} + ^{112}\text{Sn}$ E/A=50 MeV



Two-alpha thermal model

Ar+Ni, E/A=32-95 MeV – central $\rightarrow {}^8\text{Be} \rightarrow \alpha + \alpha$
INDRA @ GANIL



In-medium
temperature

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

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

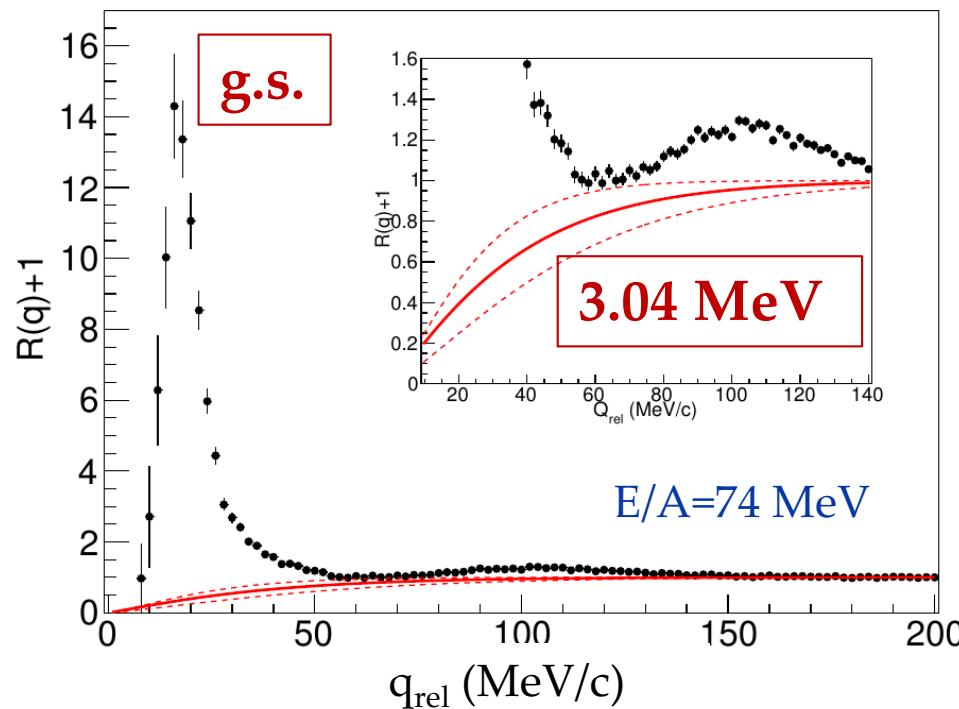
$$Y_{nucl}(E^*) =$$

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

Nuclear structure:
spin, branching ratios,
resonance position

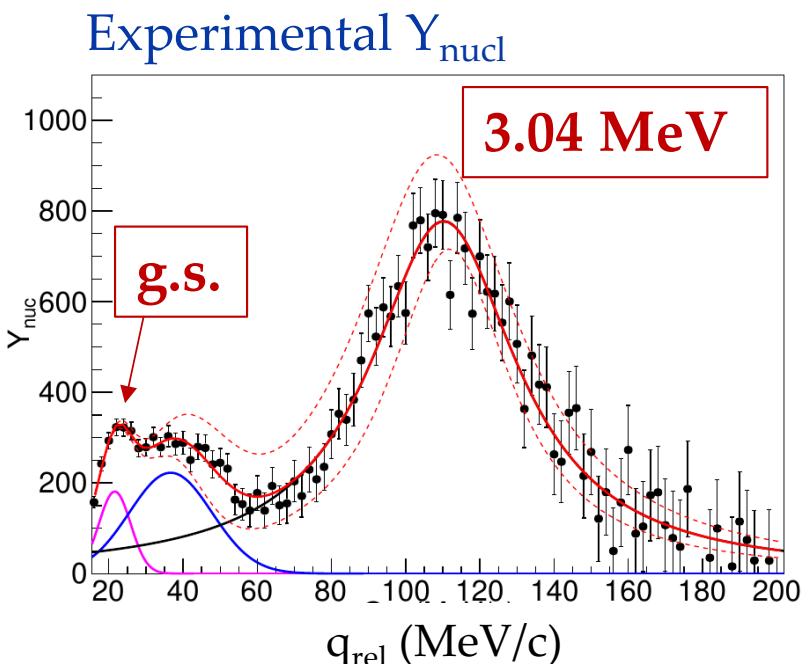
Two-alpha thermal model

Ar+Ni, E/A=32-95 MeV – central $\rightarrow {}^8\text{Be} \rightarrow \alpha + \alpha$
INDRA @ GANIL



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

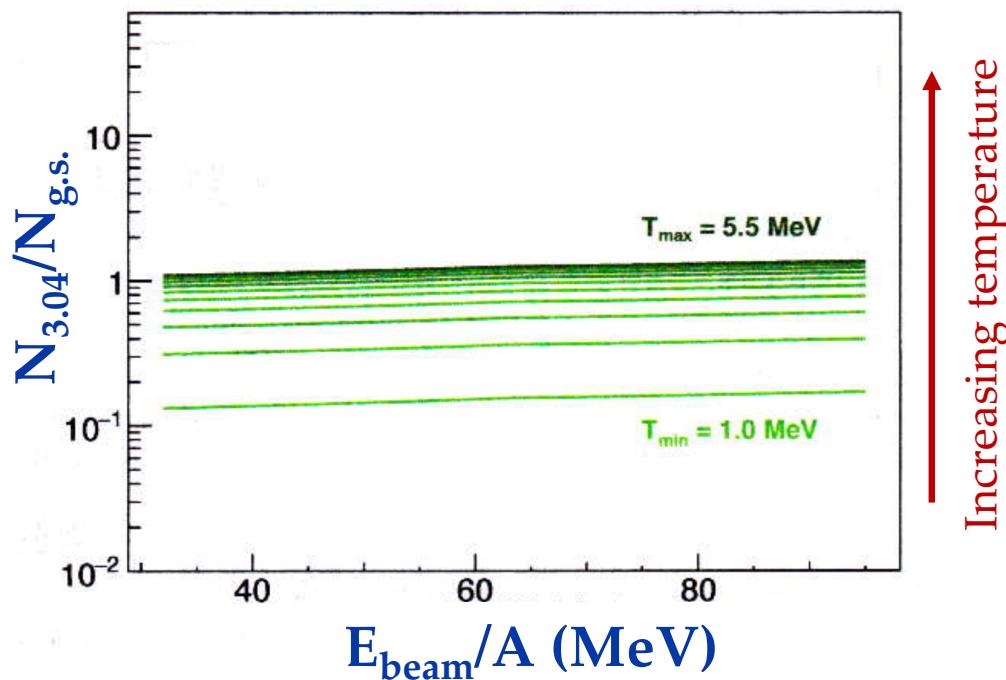
$$Y_{\text{nucl}}(E^*) = \frac{N}{\pi} e^{-E^*/T} \sum_i (2J_i + 1) \left[\frac{\Gamma_i/2}{(E^* - E_i)^2 + \Gamma_i^2/4} \right]$$



Two-alpha thermometer

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

INDRA @ GANIL



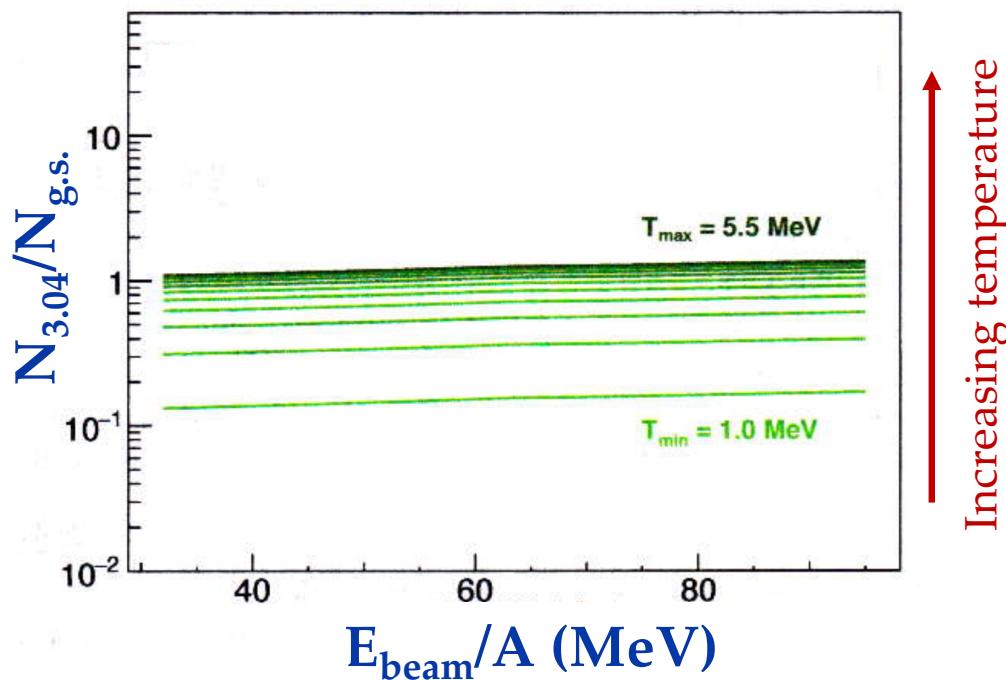
$$Y_{nucl}(E^*) =$$

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

Two-alpha thermometer

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

INDRA @ GANIL



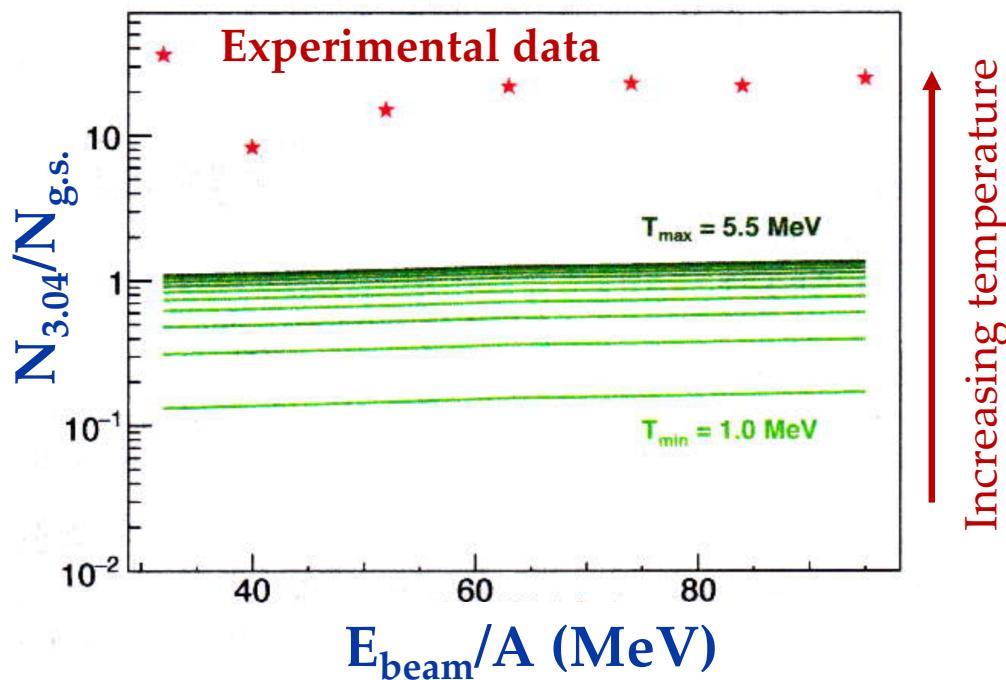
$$Y_{nucl}(E^*) =$$

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

Which temperature T is consistent with a measured relative population of state?

Two-alpha thermometer

Ar+Ni, E/A=32-95 MeV – central $\rightarrow {}^8\text{Be} \rightarrow \alpha + \alpha$
INDRA @ GANIL



$$Y_{nucl}(E^*) =$$

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

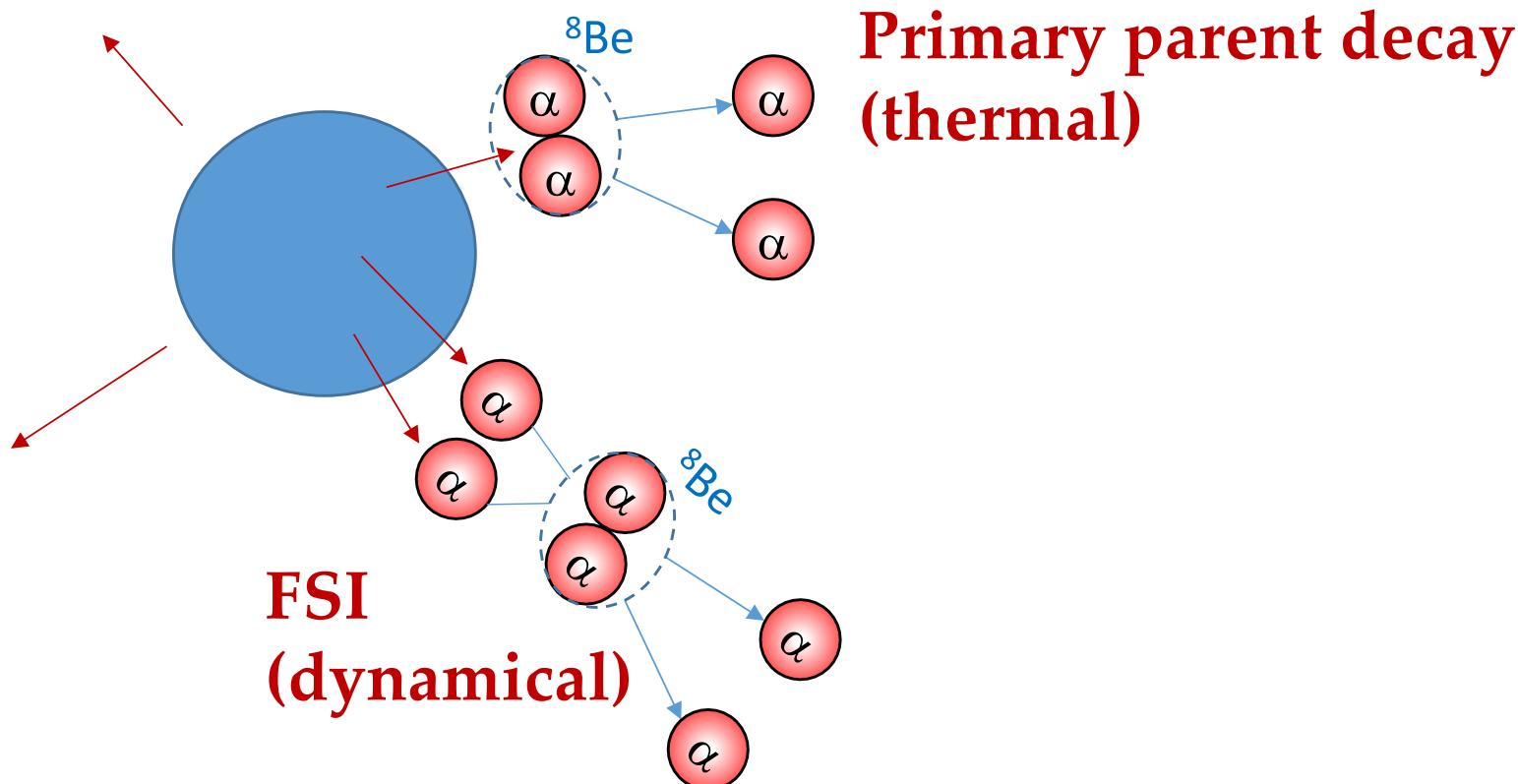
Which temperature T is consistent with a measured relative population of state?

None
overpopulation of excited states

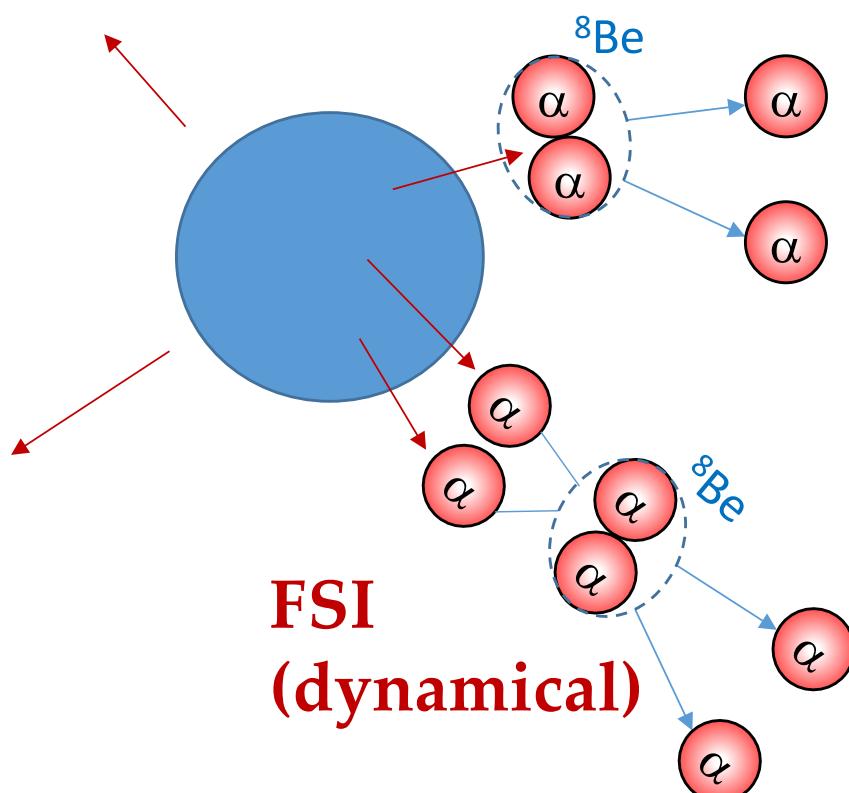
Thermal mechanism cannot describe unbound state population for α 's

D. Dell'Aquila, PhD thesis

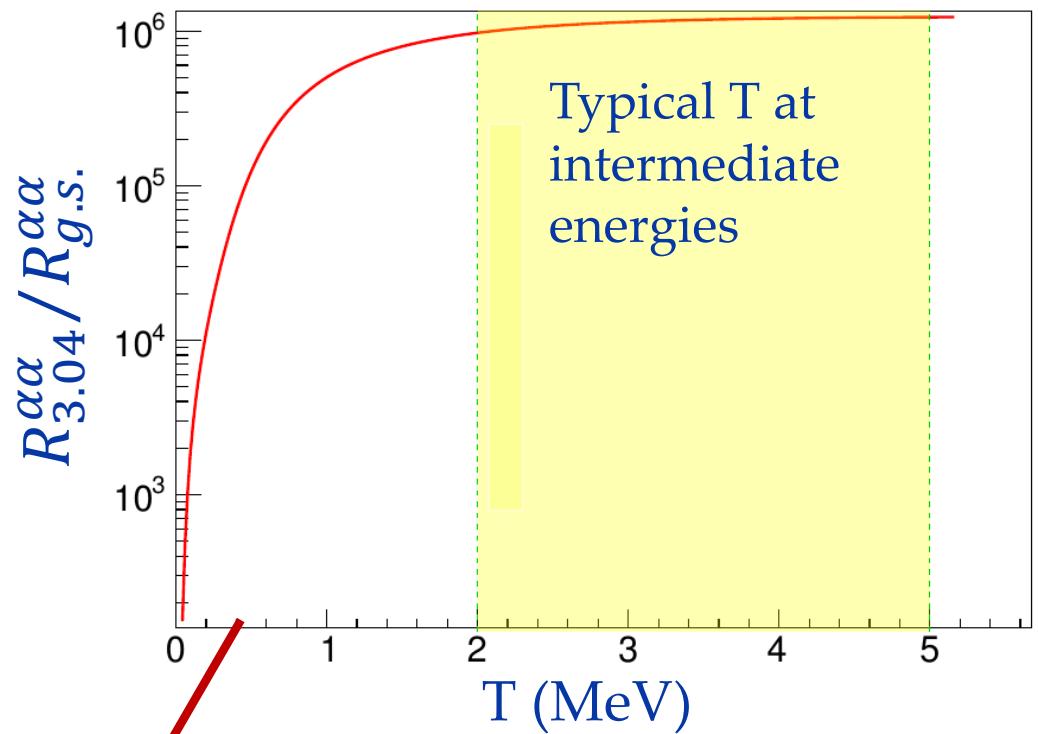
Parent decay and resonance generation by Final State Interactions



Parent decay and resonance generation by Final State Interactions

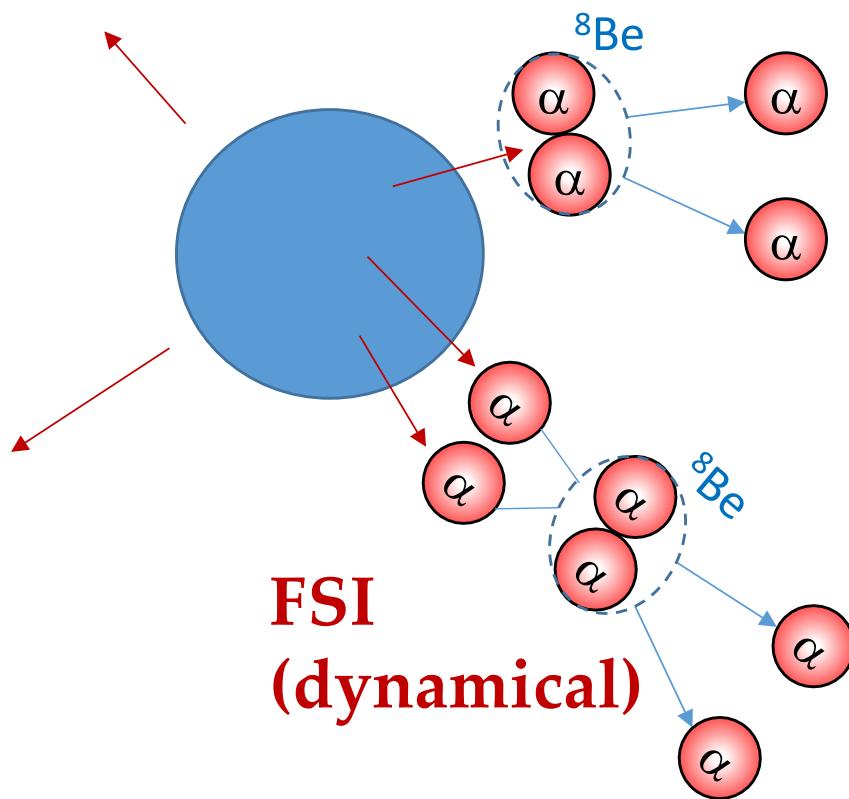


Primary parent decay
(thermal)



Generation of g.s. suppressed with respect to state at 3.04 MeV

Parent decay and resonance generation by Final State Interactions



Primary parent decay
(thermal)

FSI
(dynamical)

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

- Relevant to symmetry energy
and EoS predictions
- Relevant to understand in-
medium α -clustering

In-medium vs Pure structure

Heavy-ion collisions

- Thermal models
- FSI effects
- Femtoscopy
- Interplays mechanism/structure

FAZIA+INDRA
@ LNS and GANIL

Direct reactions

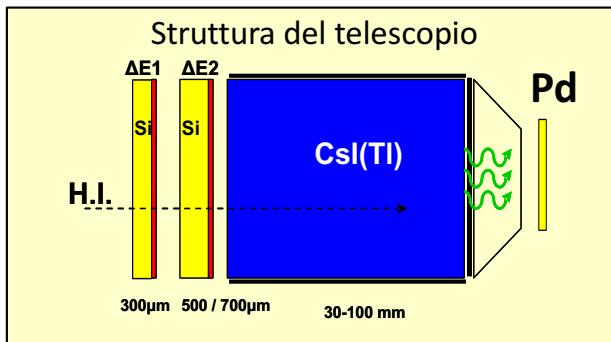
- Transfer, Knockout, ...
- Pure state produced and studied with high resolution
- α clustering in stable and exotic nuclei

OSCAR

Talk by Ivano Lombardo



In-medium structure in HIC: FAZIA

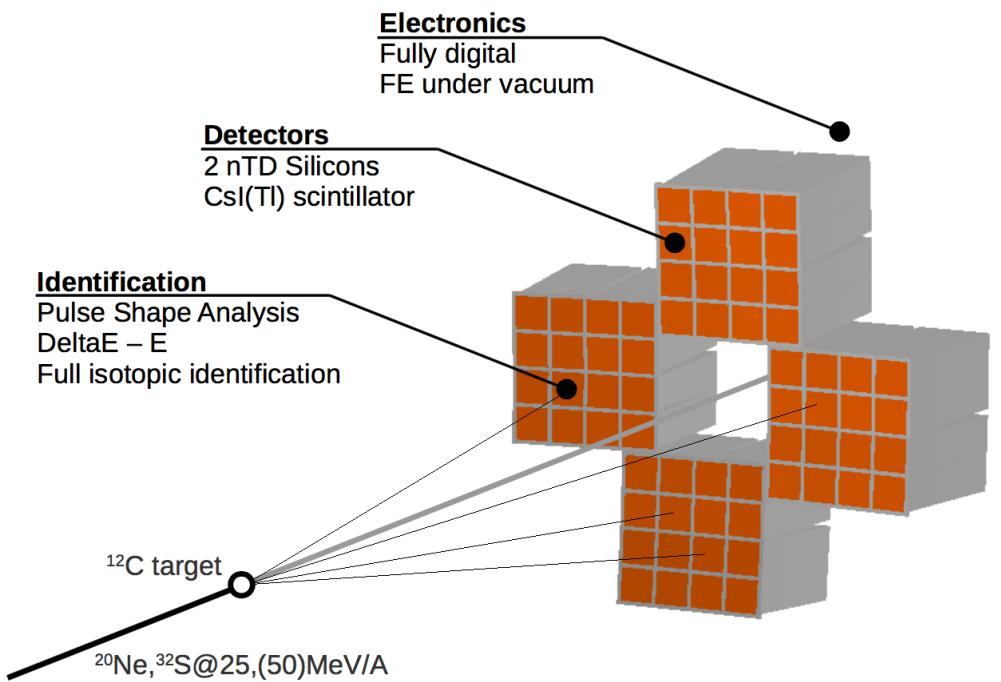


Fully digital electronics: particle identification directly from digitalization of Si and CsI(Tl) signals
→ almost online available
→ Wide dynamic range (100 keV- GeV)

FAZIACOR experiment (March 2017)

G. Verde, D. Gruyer, FAZIA Coll.

$^{20}\text{Ne}, ^{32}\text{S} + ^{12}\text{C}$
E/A=25 and 50 MeV



In-medium structure in HIC: FAZIA

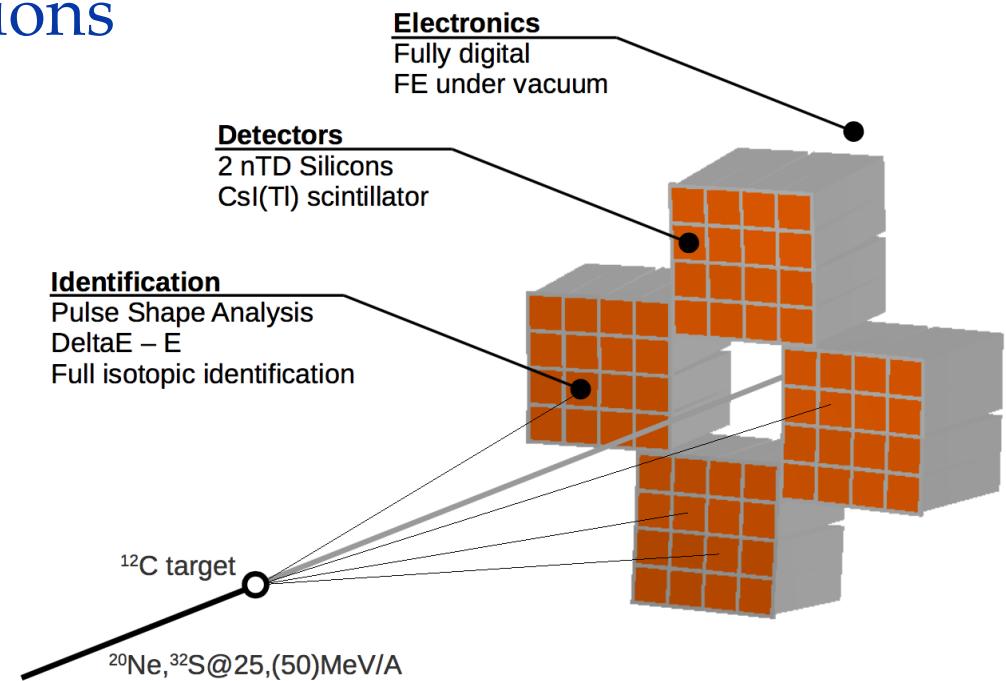
In-medium effects on resonance decays and FSI correlations

Two- and three-particle correlations with very high statistics and for Z=1-15 with full isotopic identification

FAZIACOR experiment (March 2017)

G. Verde, D. Gruyer, FAZIA Coll.

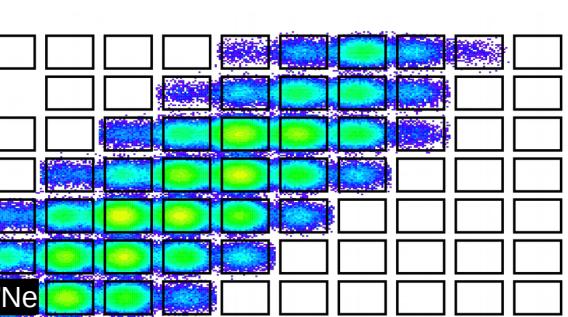
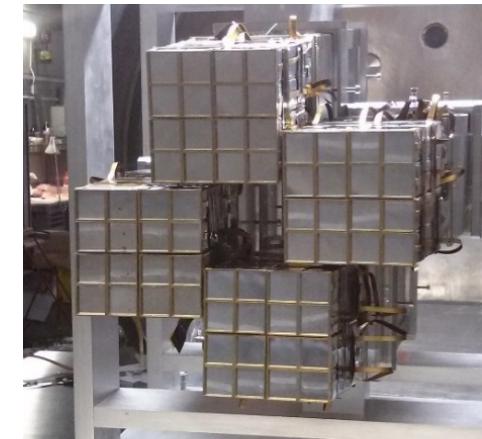
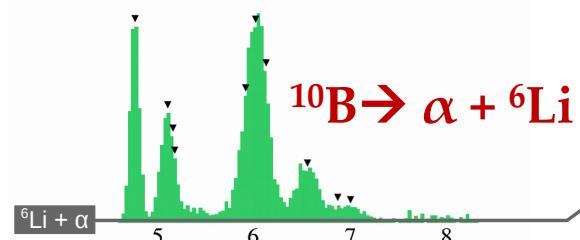
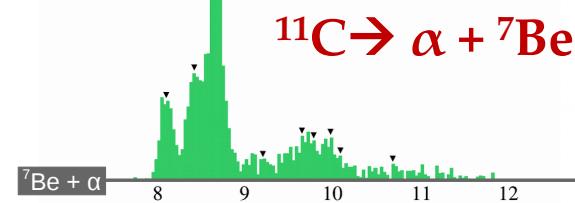
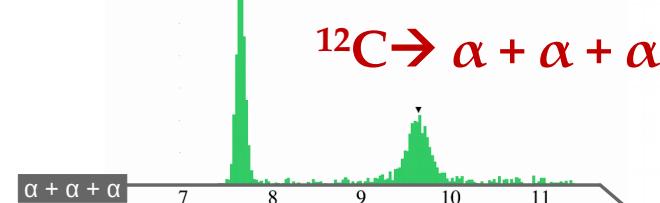
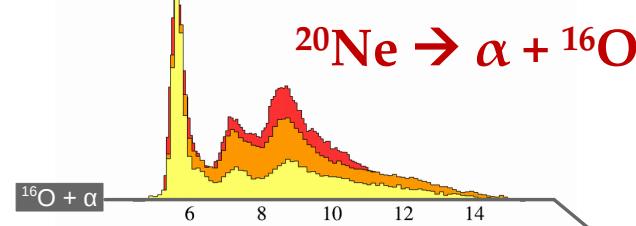
^{20}Ne , $^{32}\text{S} + ^{12}\text{C}$
E/A=25 and 50 MeV



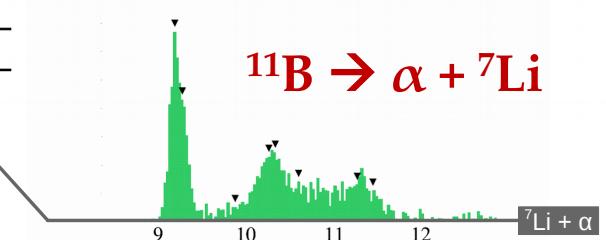
Some preliminary $\text{Na}-\text{X}$ correlations

Projects for
students available

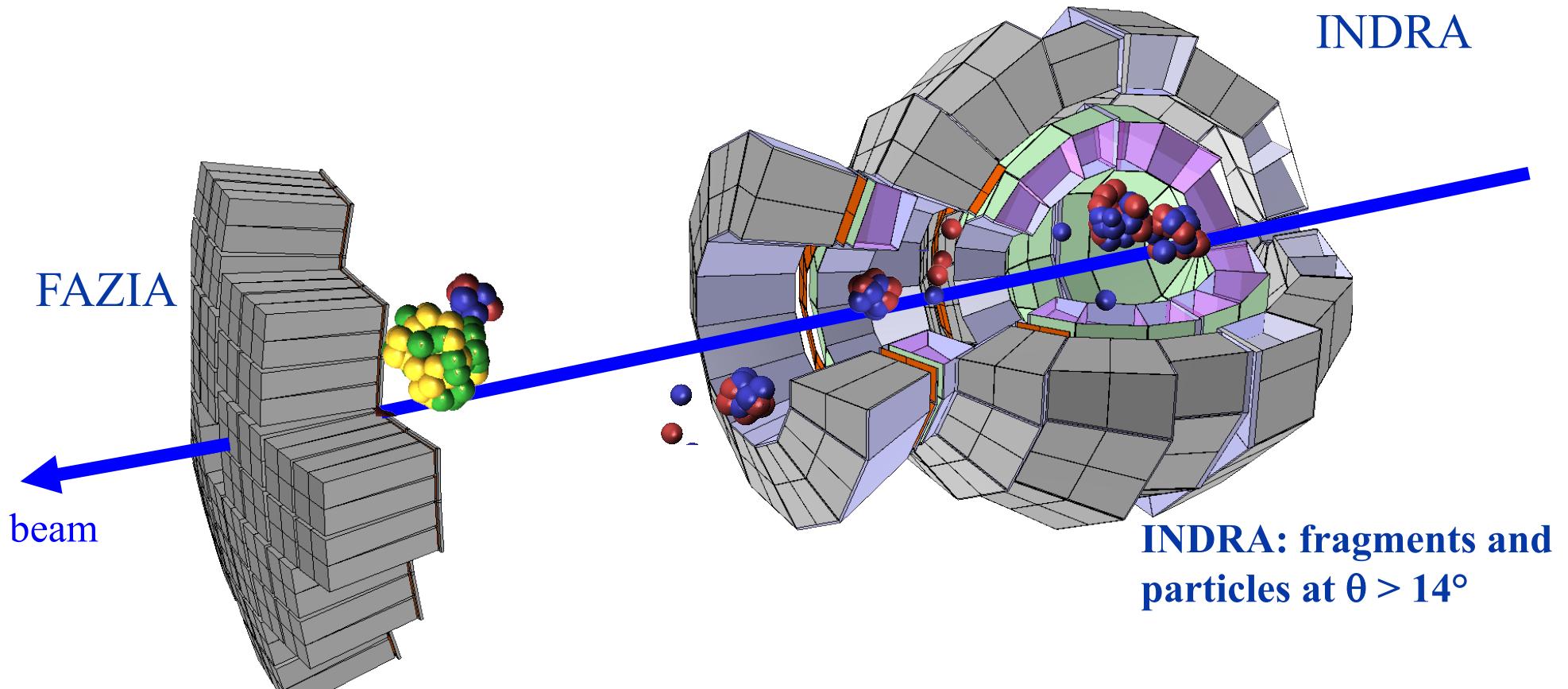
D. Gruyer,
LPC Cean



$^{11}\text{B} \rightarrow \alpha + ^7\text{Li}$



FAZIA-INDRA @ GANIL (2018-2020)



- **12 Blocks (192 telescopes)**
- **full Z & A identification of $1 \leq Z < 25$ at $\theta < 14^\circ$**



Energy scan: E/A=30-90 MeV

Summary

- HIC at intermediate energies: access to structure of dilute and hot (warm!) nuclear matter
 - Interplays between thermodynamics (EoS) and Femtoscopic properties (resonance decays and clustering)
- Time-scales and fragmentation patterns: IMF-IMF correlations
 - Ar+Ni E/A=32-95 MeV → no isotropy/no global equilibrium
 - Jet fragmentation with forward dissipative transparency
- Resonance decays: in-medium structure properties
 - Spin in ${}^8\text{Be}$ → 2α : parent decay + FSI effects
 - Dynamical effects distortions on thermal model picture
 - Implications on EoS and symmetry energy modeling
- FAZIA program @ LNS and @ GANIL (w INDRA)
- Students and collaborations welcome