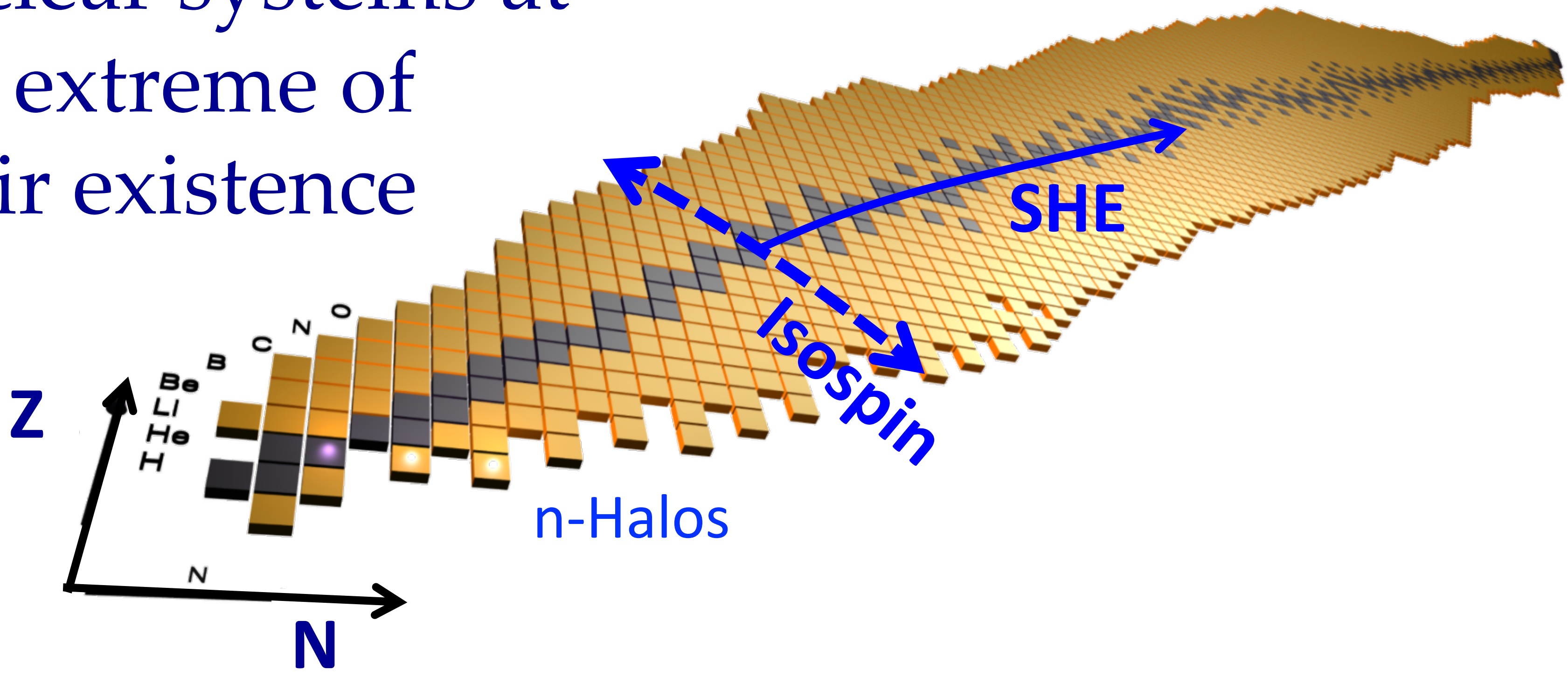
Structure of nuclear systems at the extreme of their existence

G. Verde, INFN Catania



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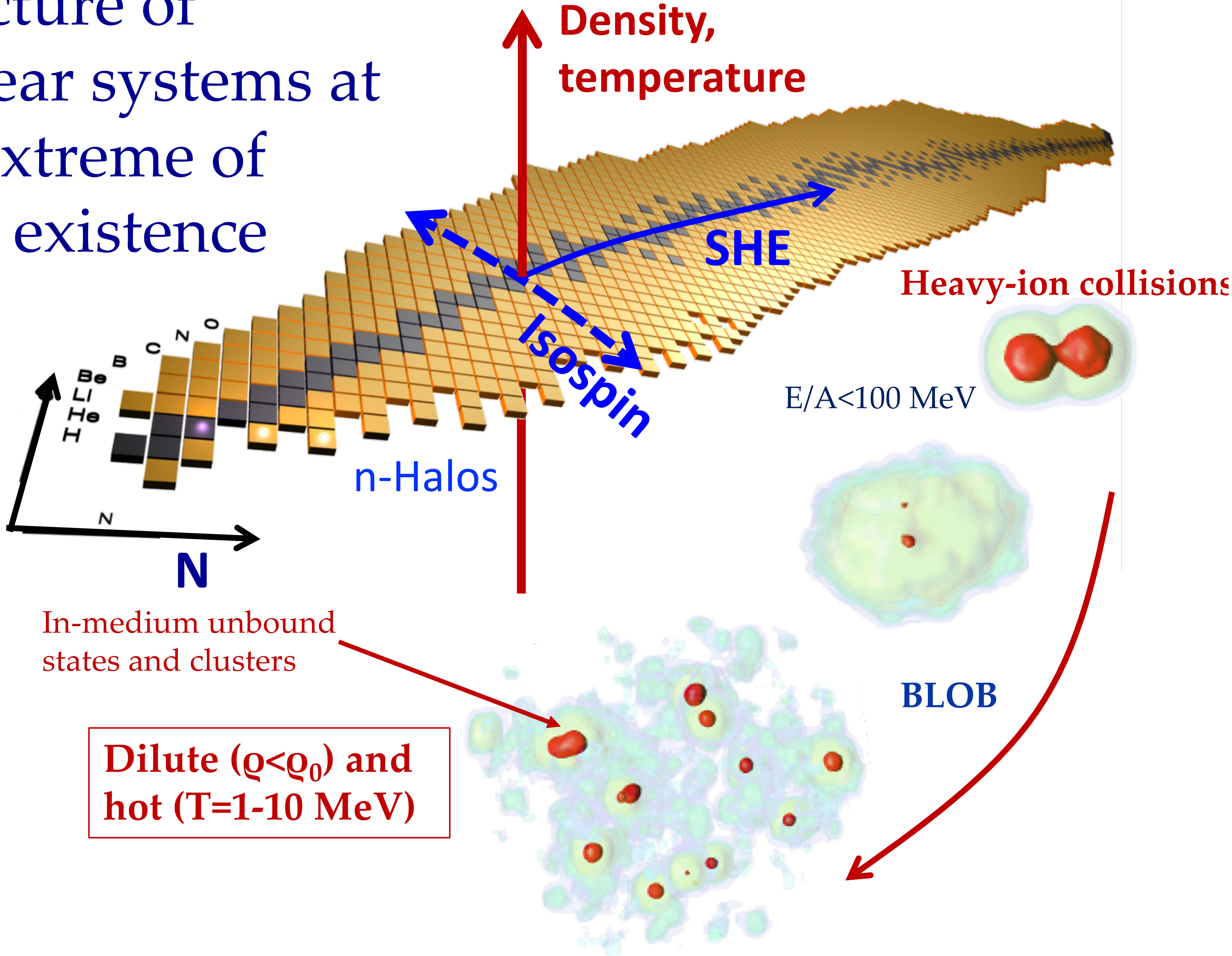
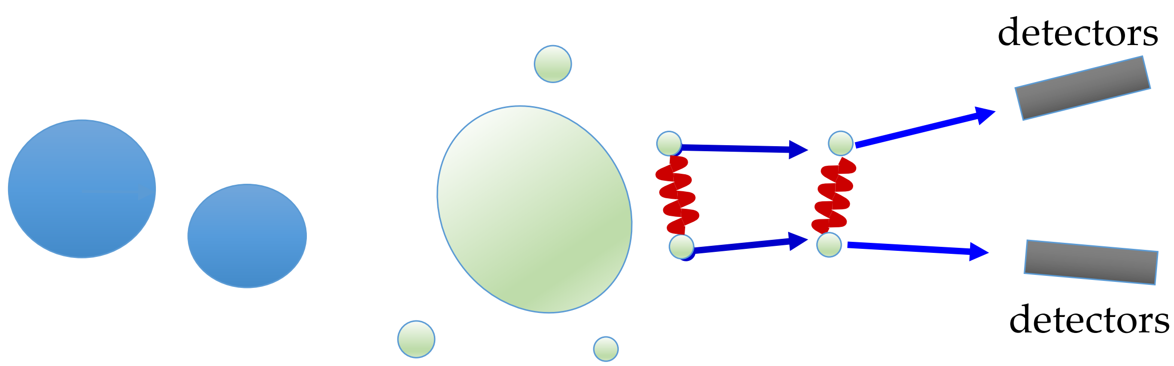


In-medium correlations and structure

- Structure of diluted and hot nuclear matter
  - Structure interplays with EoS and dynamics

- Tools: particle-particle correlations, **femtoscopy** and **resonance decays**
  - **Imaging emitting sources** and transport models
  - **IMF-IMF correlations**: time-scales and charge splitting
  - **In-medium structure and clustering** with complex light particle correlations
  - Data from MSU and GANIL experiments on Xe+Au and Ar+Ni central collisions

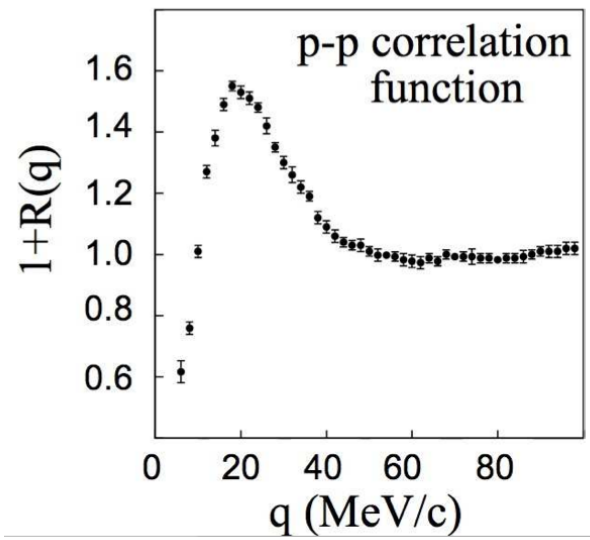
Femtoscopy in nuclear reactions



Final State Interactions + Quantum statistics (if identical)

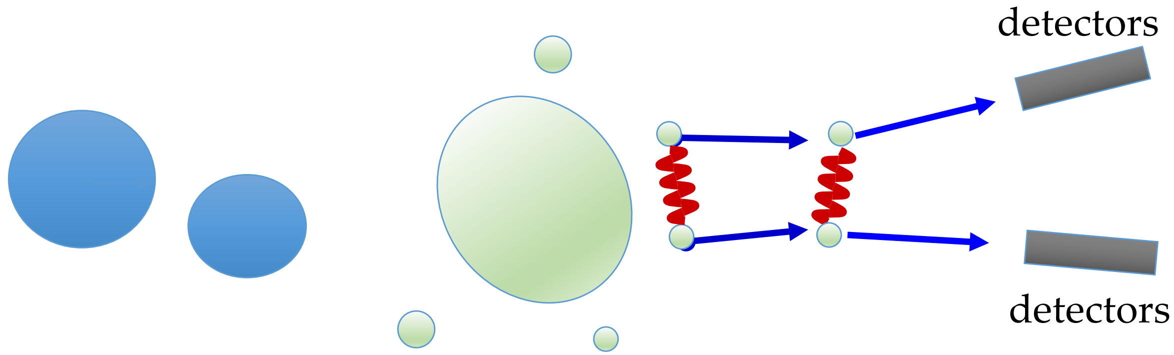
Intensity interferometry / Femtoscopy

q = mom. of relative motion



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

Femtoscopy in nuclear reactions



G. Verde et al. Phys. Rev. C65, 054609 (2002)
G. Verde et al. Phys. Rev. C67, 034606 (2002)
G. Verde et al., Phys. Lett. B653, 12 (2007)
G. Verde, A. Chbihi et al., Eur. Phys. J. A30, 81 (2008)
D.A. Brown, P. Danielewicz, Phys. Lett. B470, 33 (1999)
D.A. Brown, P. Danielewcz, Phys. Rev. C64, 014902 (2001)

Intensity interferometry / Femtoscopy

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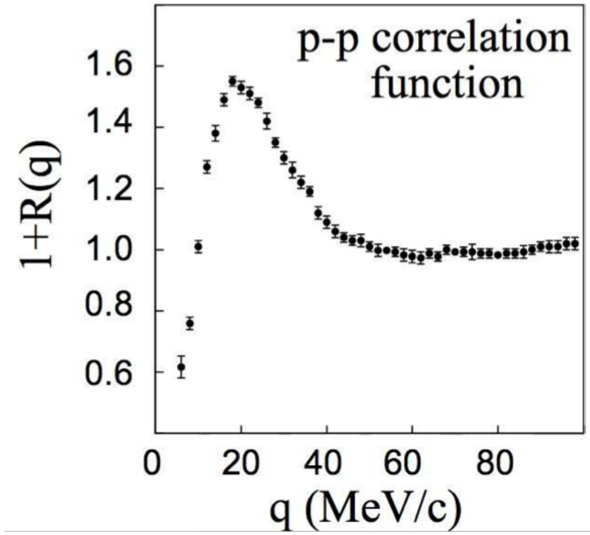
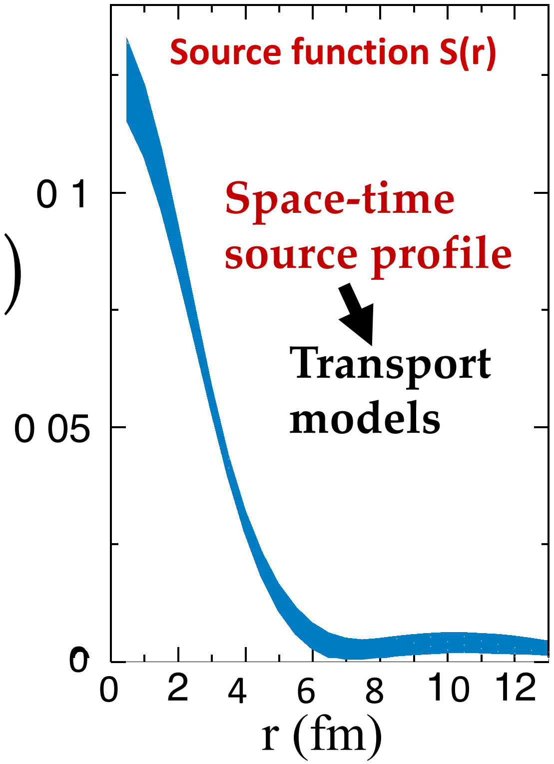


Koonin-Pratt Eq.

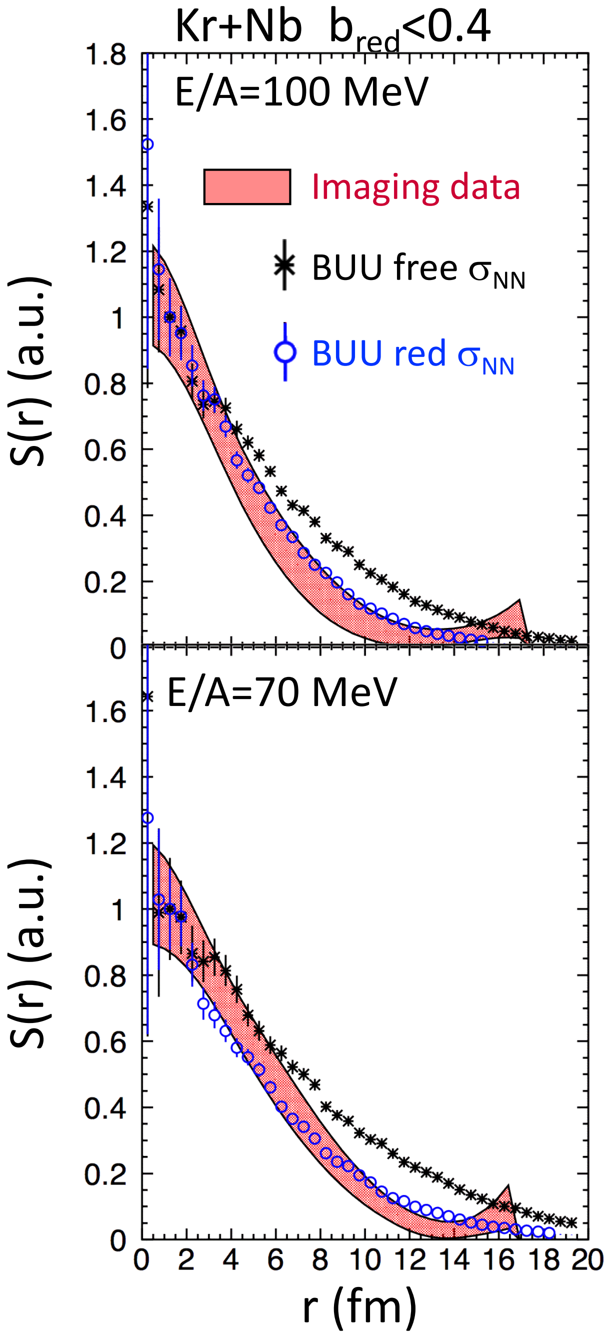
$$R(\vec{q}) = \int d\vec{r} \cdot S(\vec{r}) \cdot K(\vec{r}, \vec{q})$$

Imaging - Danielewicz

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



pp sources: pBUU vs Data



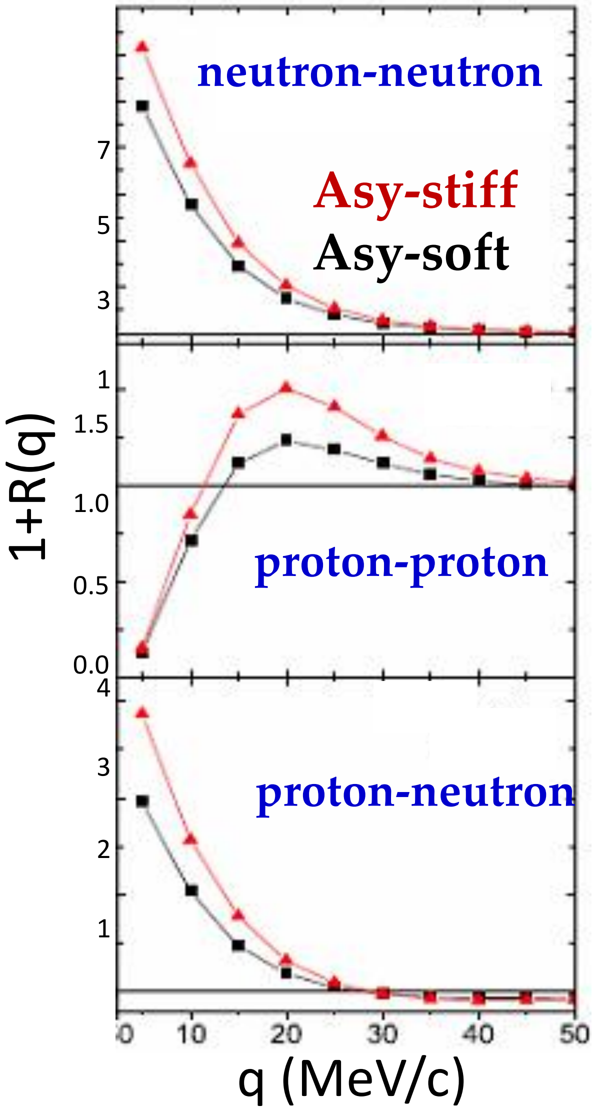
Significant sensitivity to σ_{NN}

Experimental observables sensitive to the Dynamical pre-equilibrium stage

G. Verde, P. Danielewicz et al. Phys. Rev. C67, 034606 (2002)

Symmetry energy and femtoscopy

Correlation functions

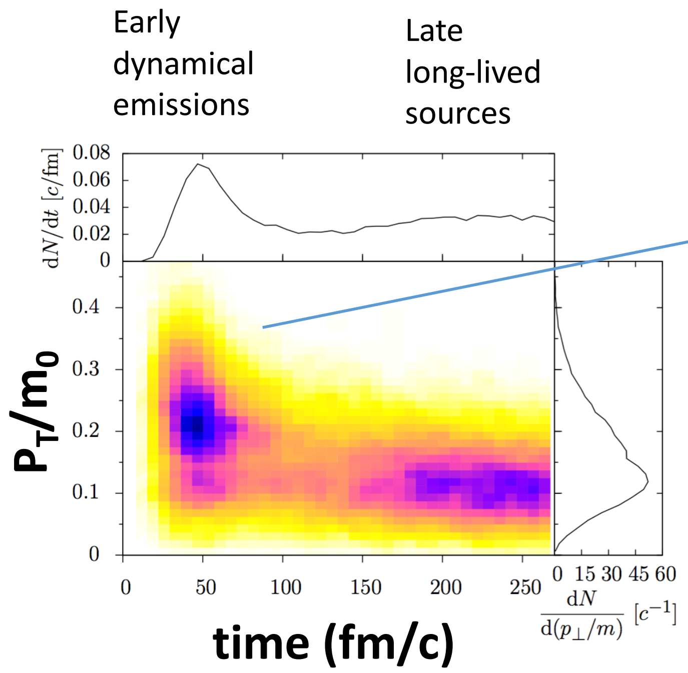


Sensitivity determined by effects of Esym on neutron/proton relative emission times at the **early stages of the collision**

IBUU (Texas A&M 2003)

Early dynamical sources: pBUU Vs. Data

Xe+Au E/A=50 MeV (Central)



High PT protons emitted at early dynamical stage

pBUU simulations

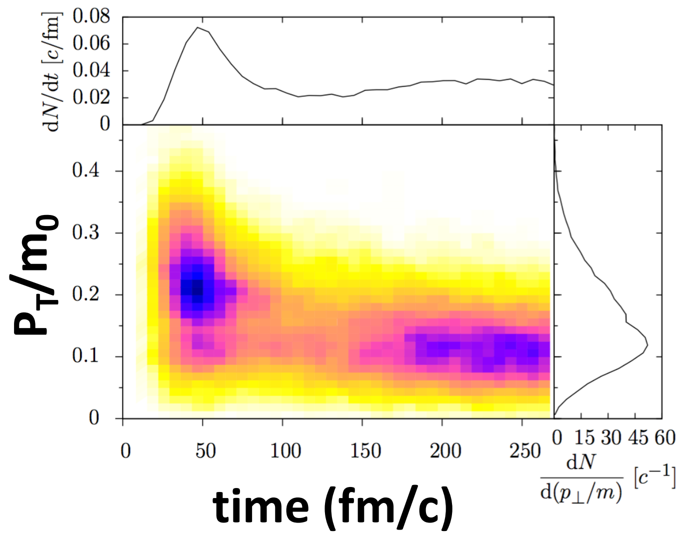
T. Minniti, B. Barker, GV, P. Danielewicz et al.
to be submitted

Early dynamical sources: pBUU Vs. Data

Xe+Au E/A=50 MeV (Central)

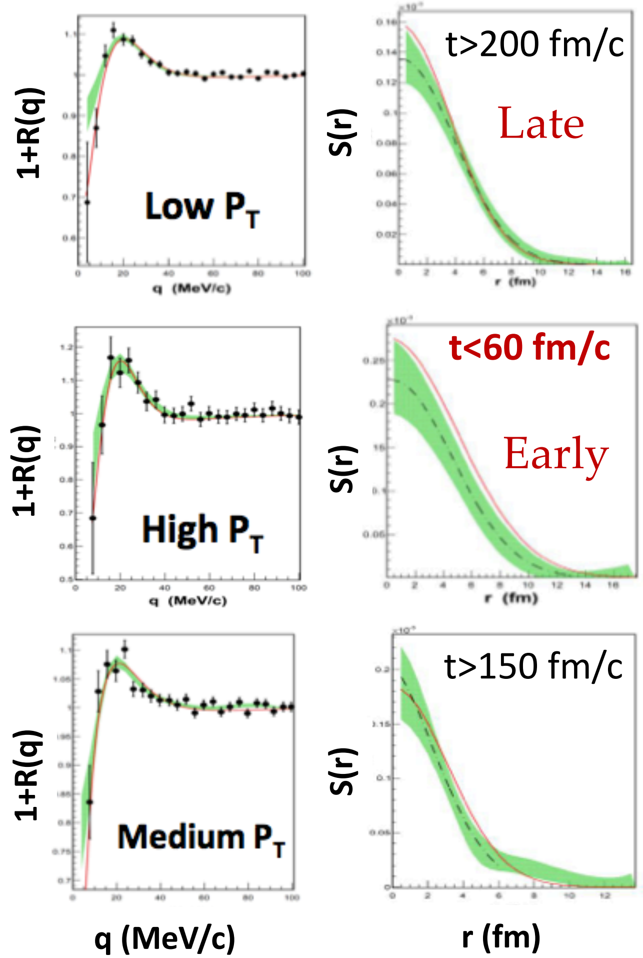
Early dynamical emissions

Late long-lived sources



BUU simulations

Experimental data (LASSA @ MSU)



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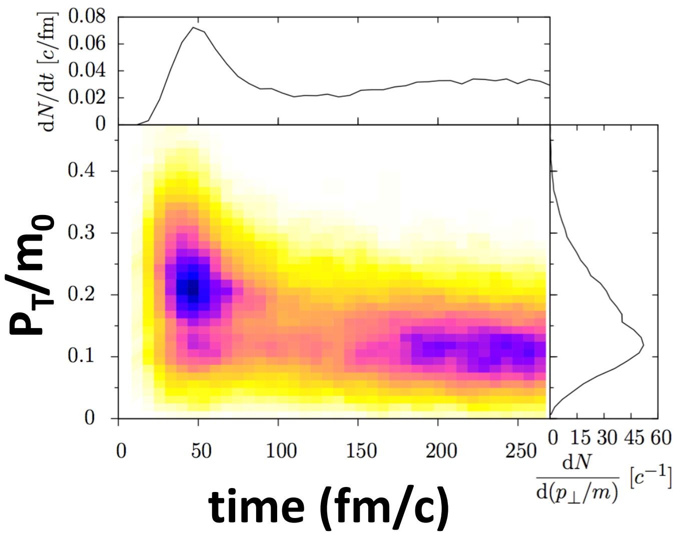

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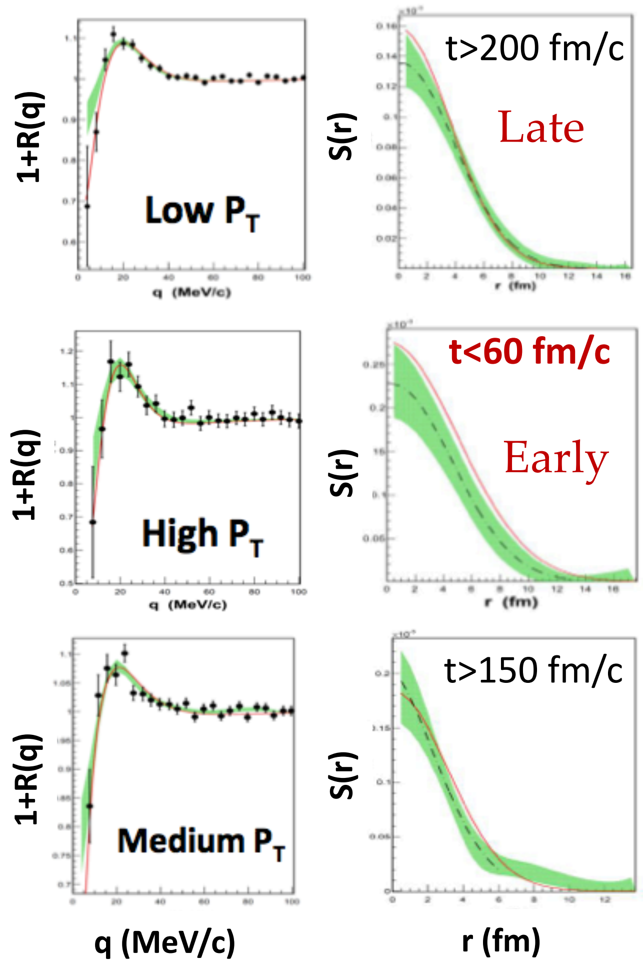
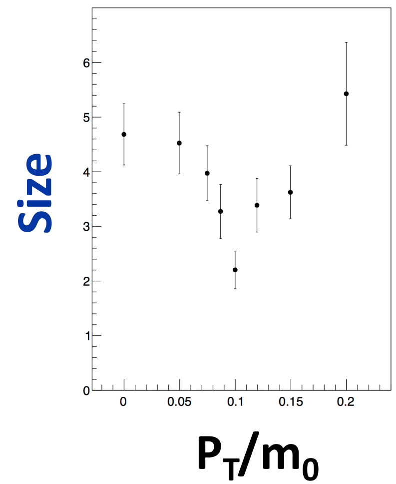
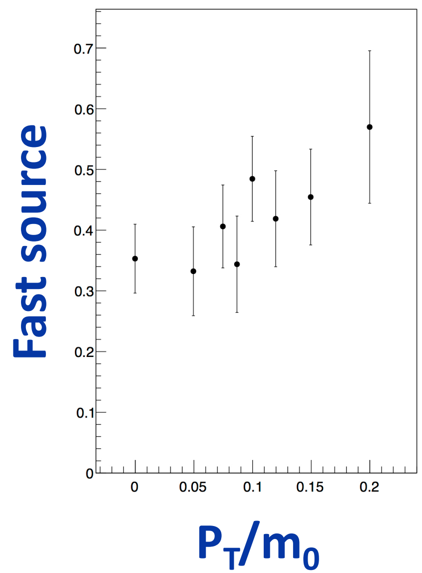


Source size

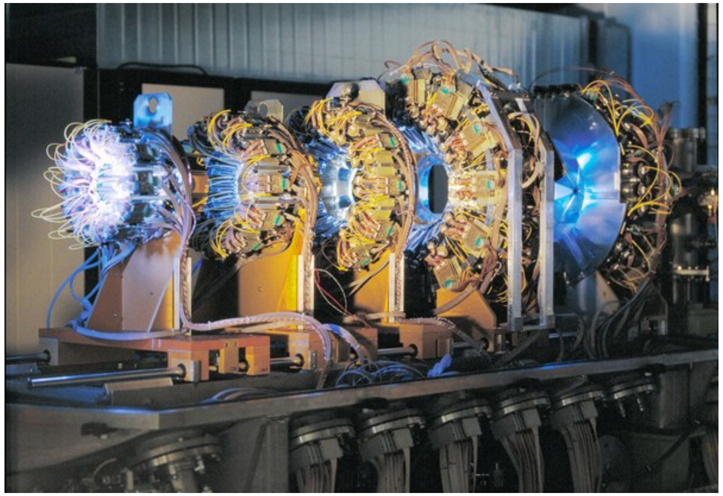


% of dynamical early emissions



T. Minniti, B. Barker, GV, P. Danielewicz et al.
to be submitted

Energy scan of central collisions



INDRA *4p multi-detector*

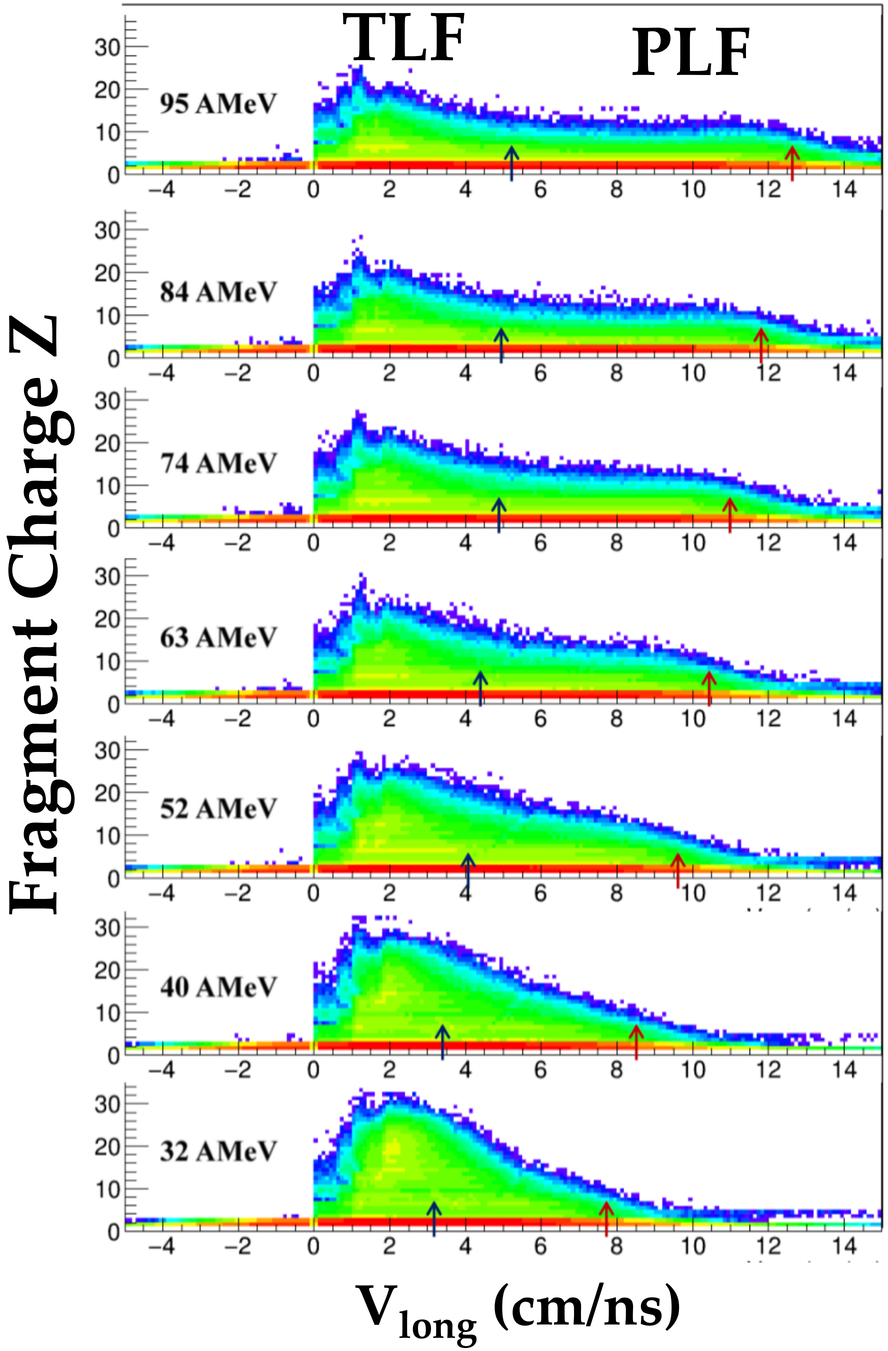
angular coverage ≈ 90% (4π)
336 *independent cells*
telecopes C_3F_8 gas chamber – Si (300 mm) – CsI (5-14cm)

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

Energy scan of central collisions

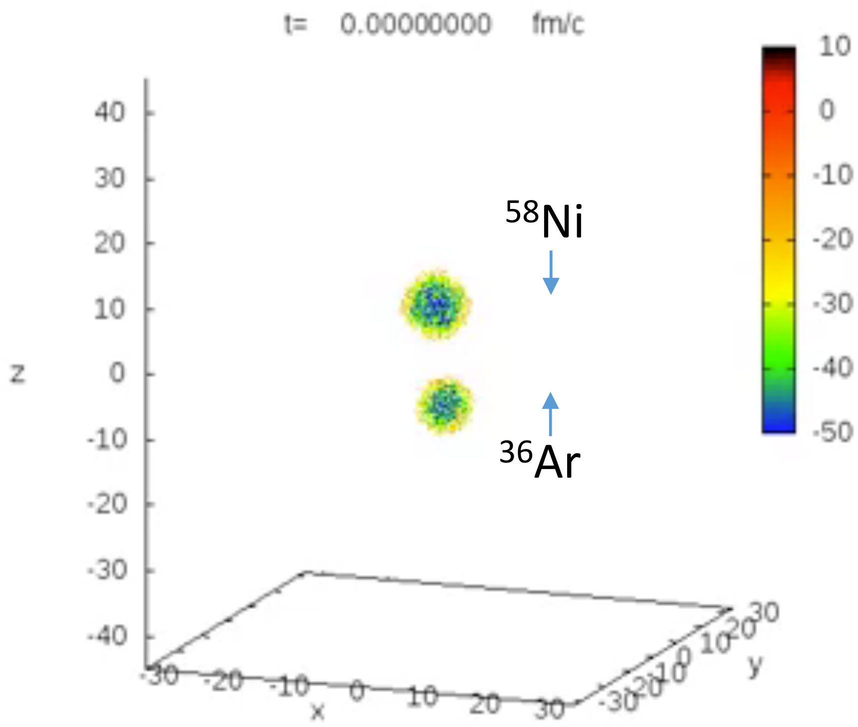
$^{36}Ar + ^{58}Ni$
E/A=32, 40, 52, 63, 74, 84, 95 MeV

- Breakup asymmetry in CM-Forward Vs. CM-Backward Emissions
- Granular projectile fragmentation mechanism (jet) (talk by P. Napolitani)



Transport BLOB sims

BLOB (P. Napolitani, M. Colonna)



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

Transport BLOB sims

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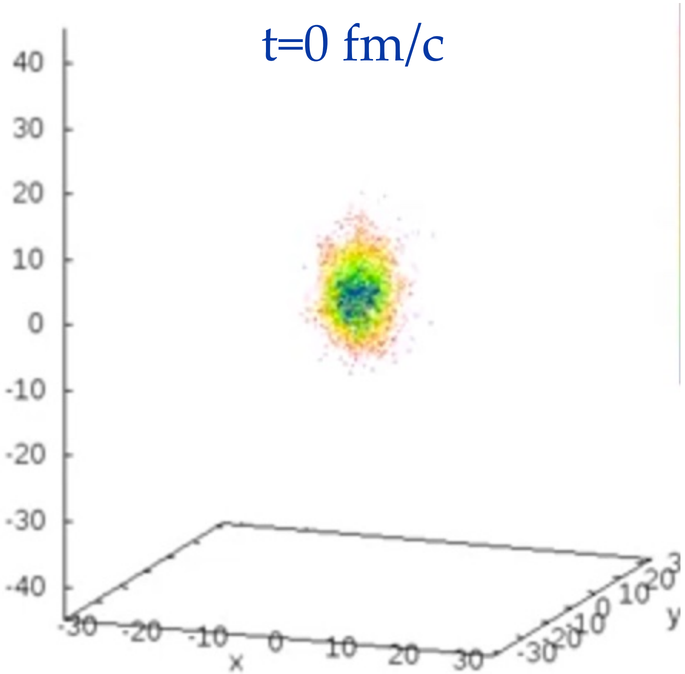
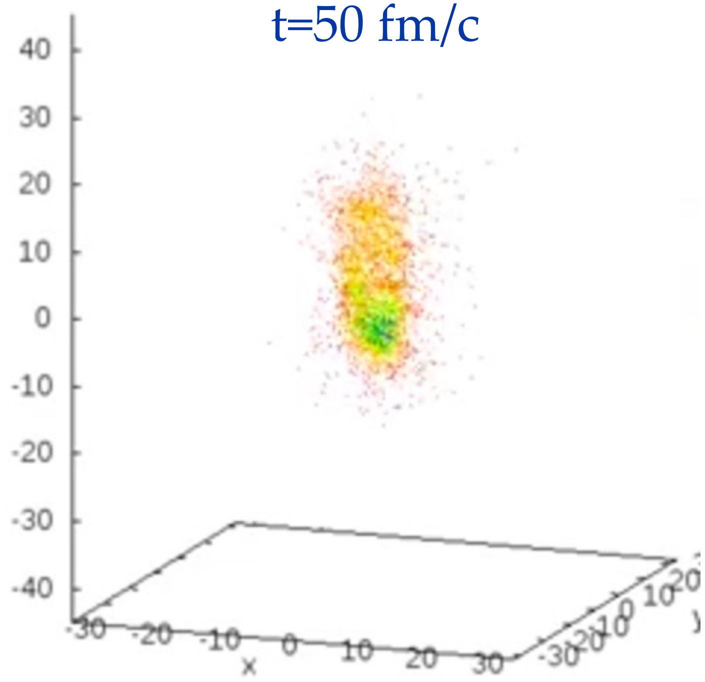


$^{36}Ar + ^{58}Ni$ E/A=40 MeV

Transport BLOB sims

BLOB (P. Napolitani, M. Colonna)

t=50 fm/c



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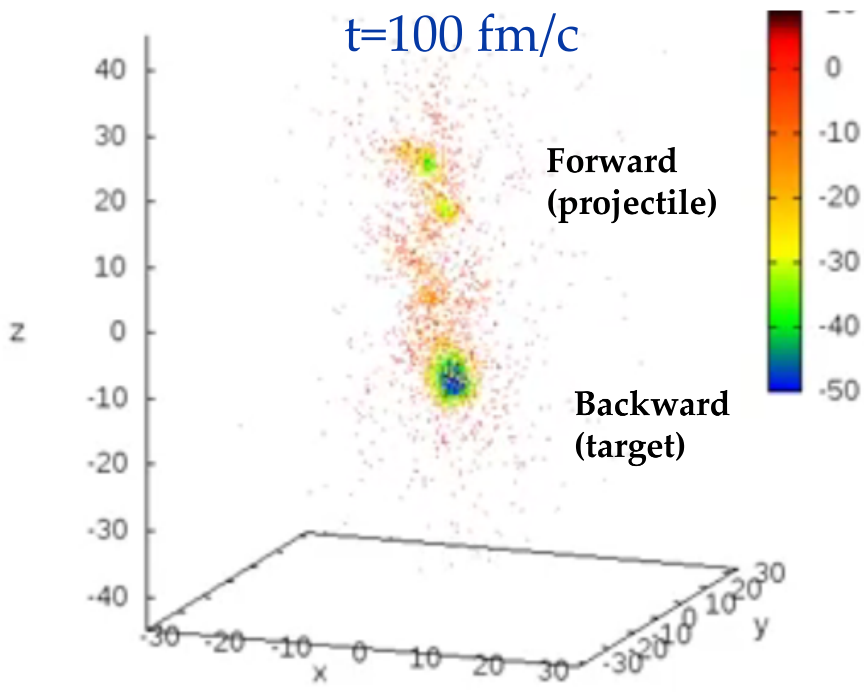

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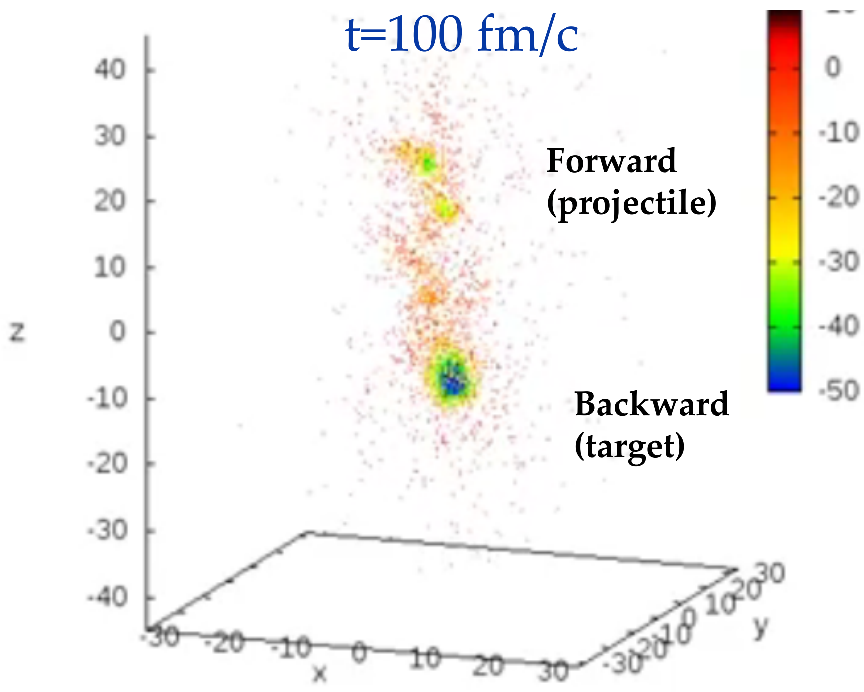

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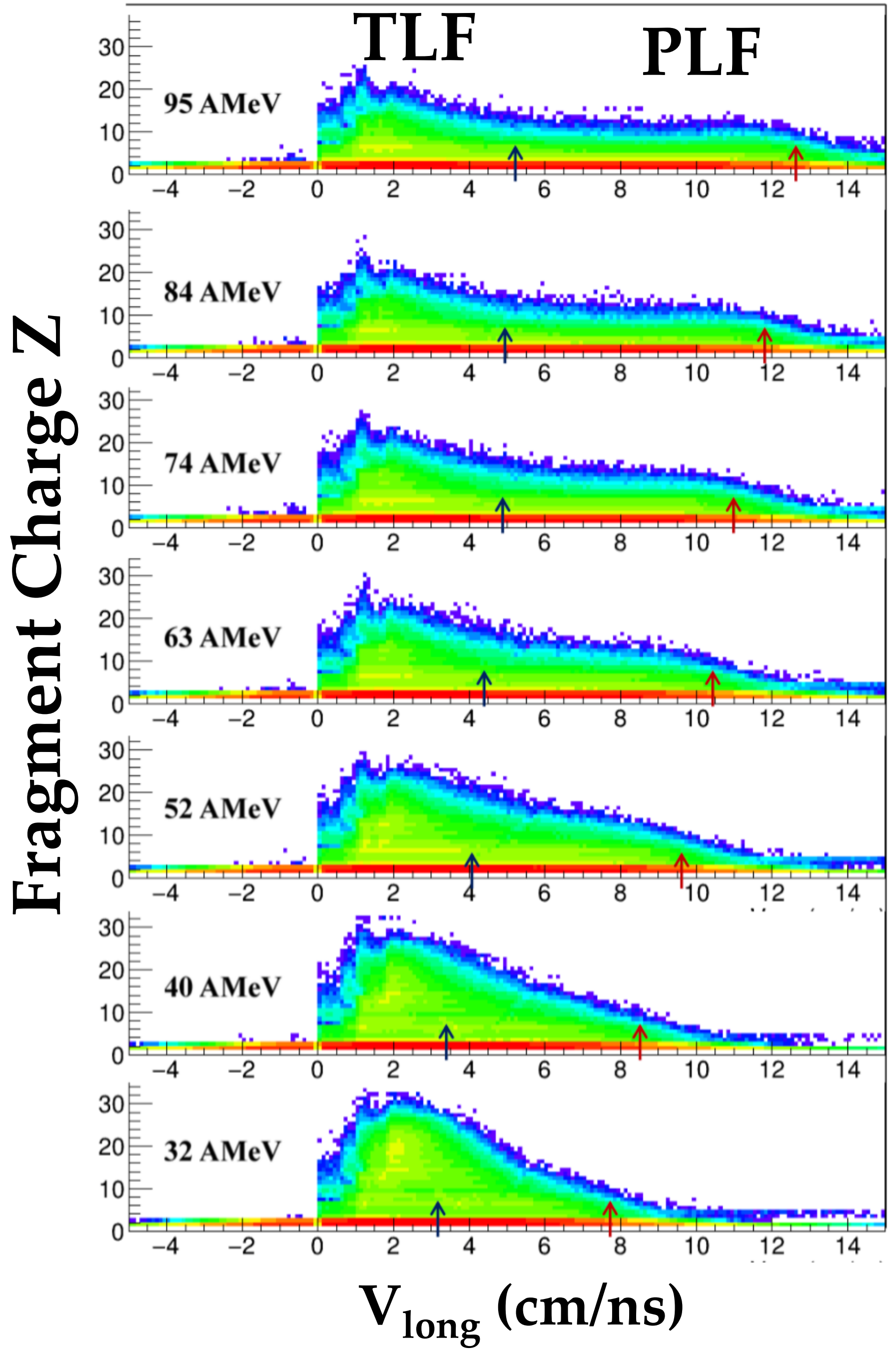
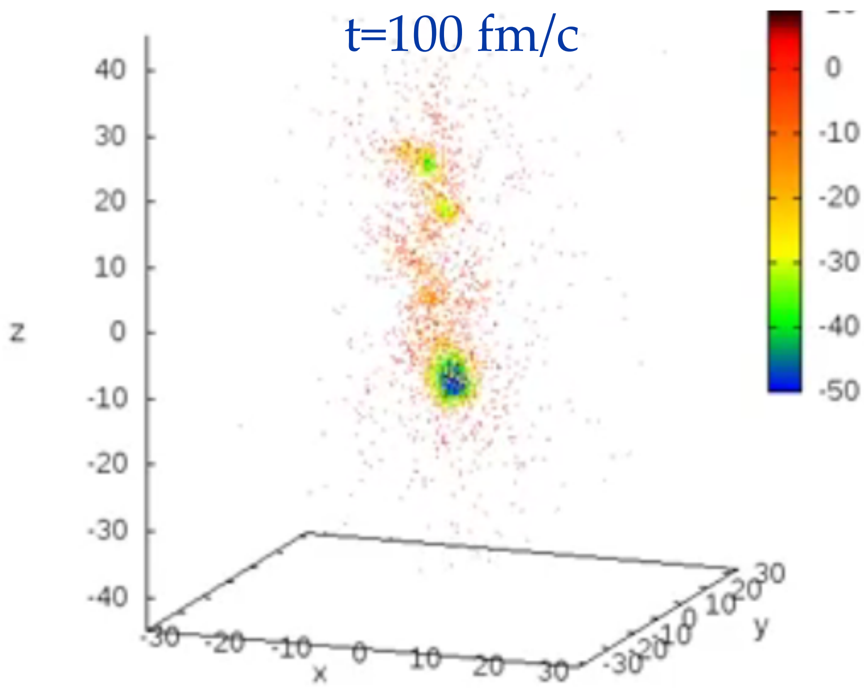


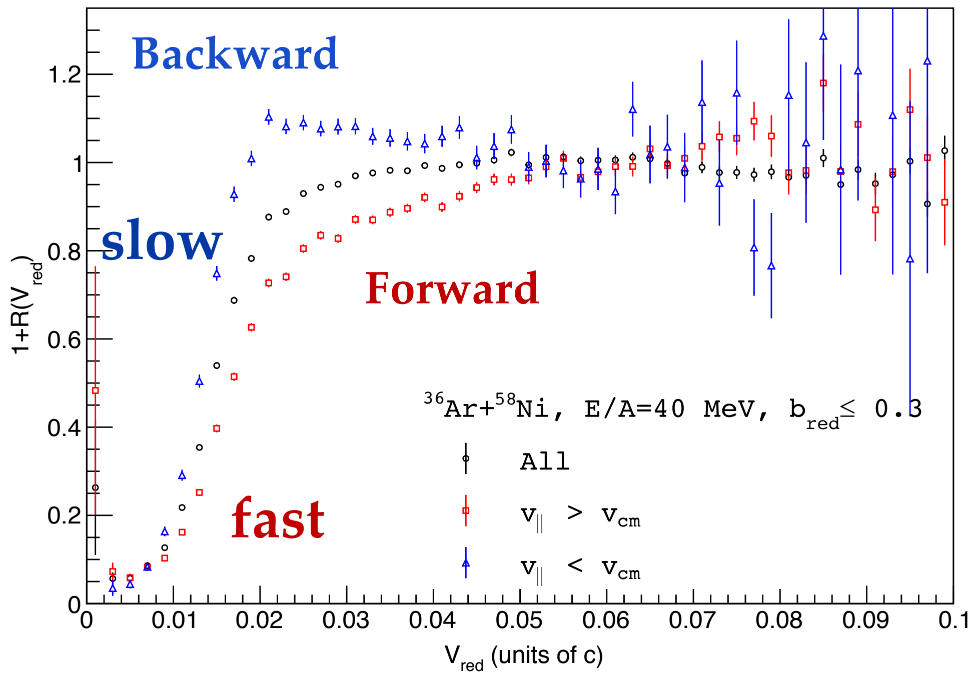
Time-scales

BLOB (P. Napolitani, M. Colonna)



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

INDRA data



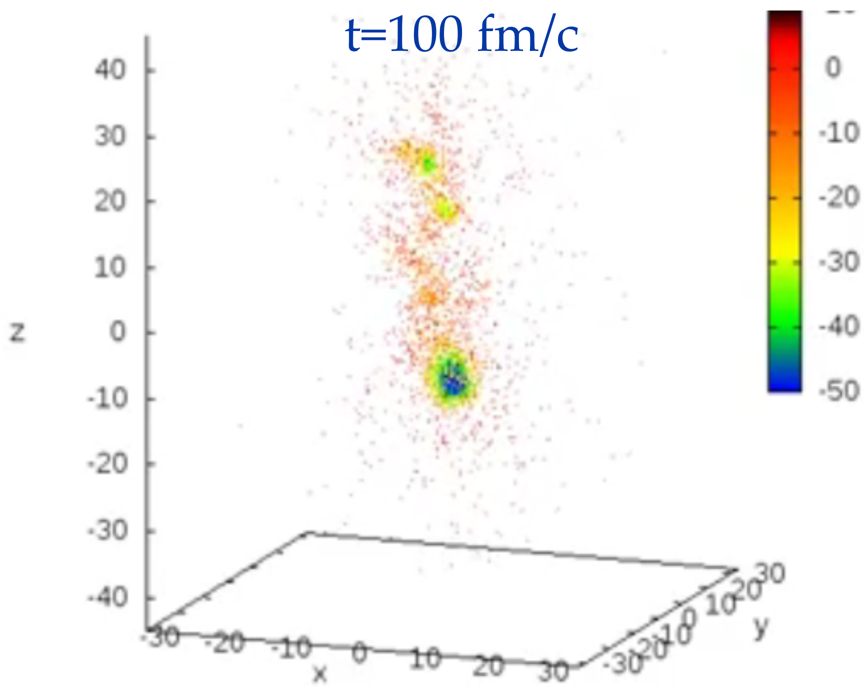
IMF-IMF correlation functions: Coulomb FSI dominates

→ Emission times (low V_{red})

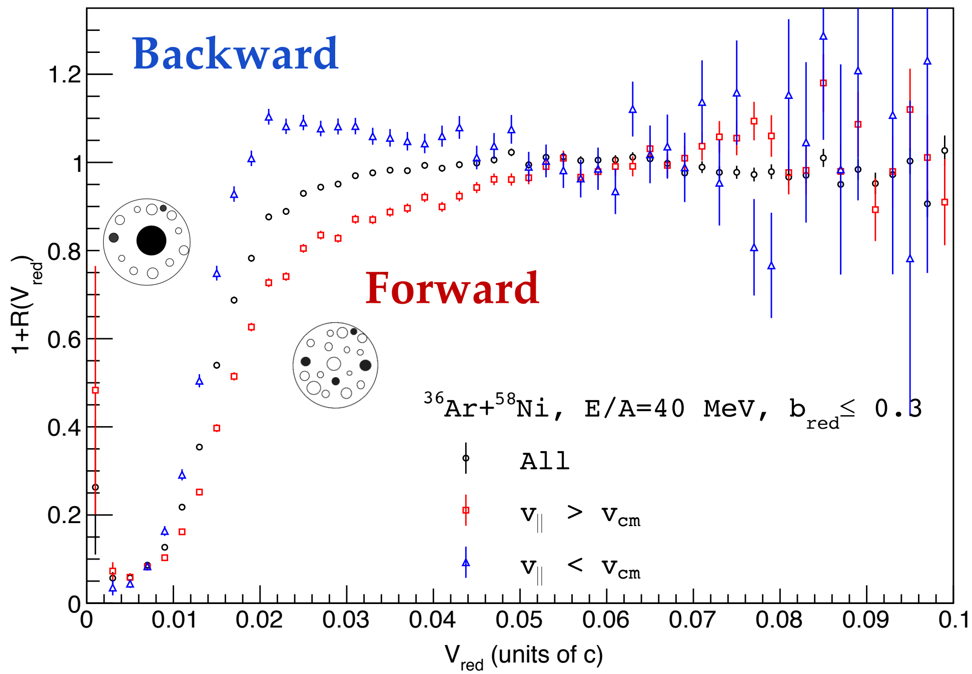
→ Charge splitting topology

Fragmentation "tomography"

BLOB (P. Napolitani, M. Colonna)



INDRA data

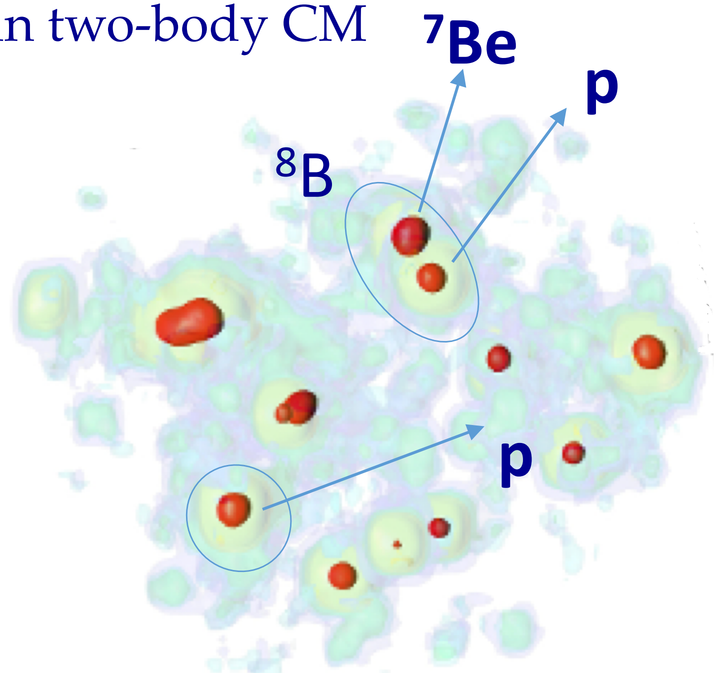


- **Projectile region**: fast emission (explosive) + homogeneous fragmentation
- **Target region**: long time-scales (evaporative)+ inhomogeneous fragmentation

No globally equilibrated mechanism (talk by P. Napolitani)

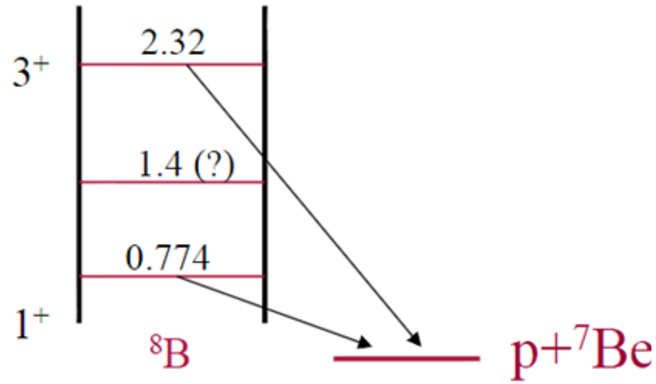
In-medium resonance decay spectroscopy

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



Final stage of HIC events

States of $^8B \rightarrow p+^7Be$

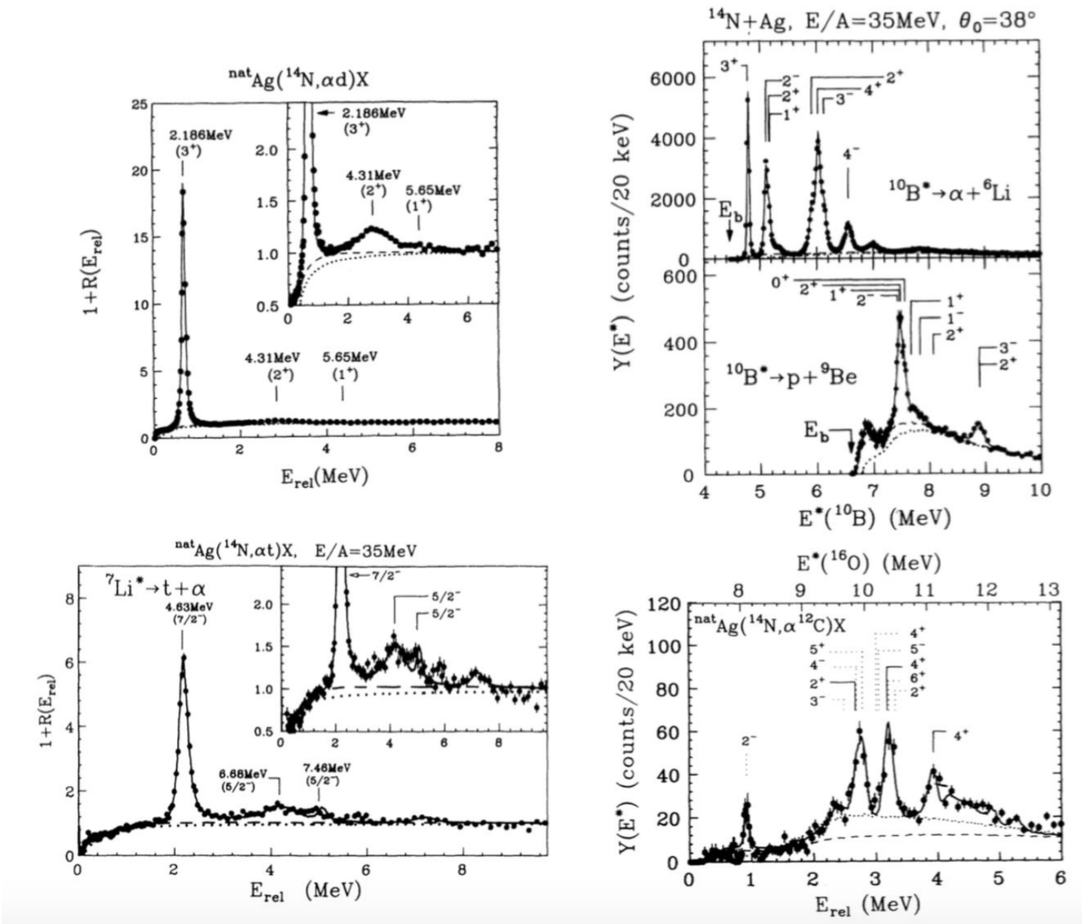


Correlation function:

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

In-medium resonance decay spectroscopy

N + Ag   E/A=35 MeV
MSU data



^{5}Li	→ α + p
^{8}Be	→ α + α
^{12}N	→ ^{11}C + p
^{10}B	→ ^{6}Li+α, ^{8}Be+d, ^{9}Be+p
^{12}C	→ ^{8}Be+ α, α+α+α

...other many cases...

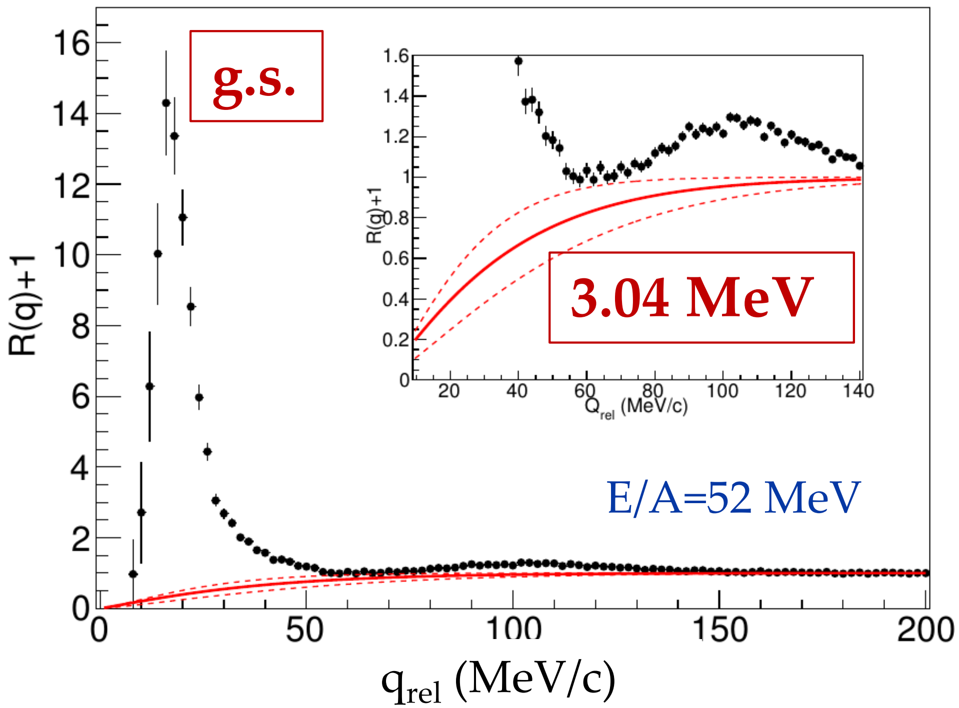
- Plenty of resonances → probes of structure properties
- Lifetimes of resonances important (dynamics)

In-medium ^{8}Be unbound states

Ar+Ni, E/A=32-95 MeV – central

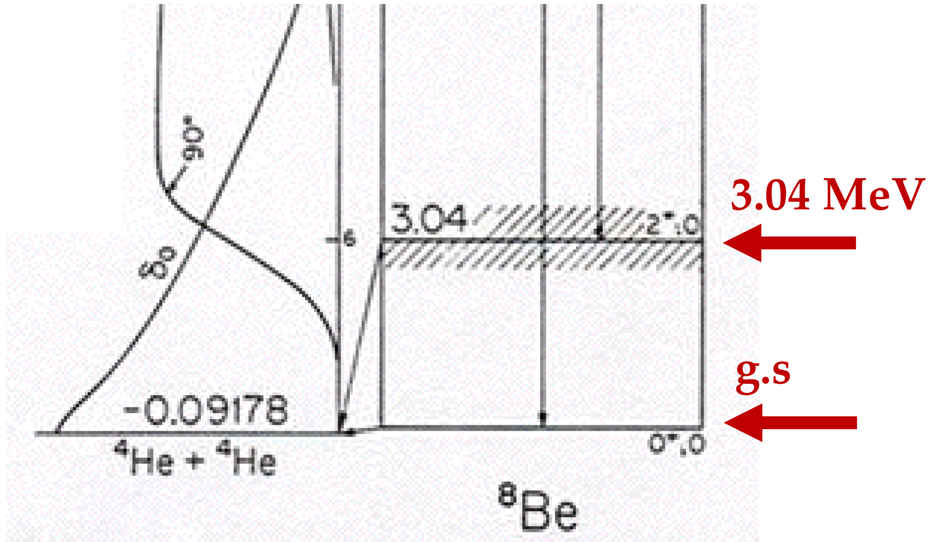
INDRA @ GANIL data

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



$\alpha - \alpha$ correlations

^{8}Be → $\alpha + \alpha$



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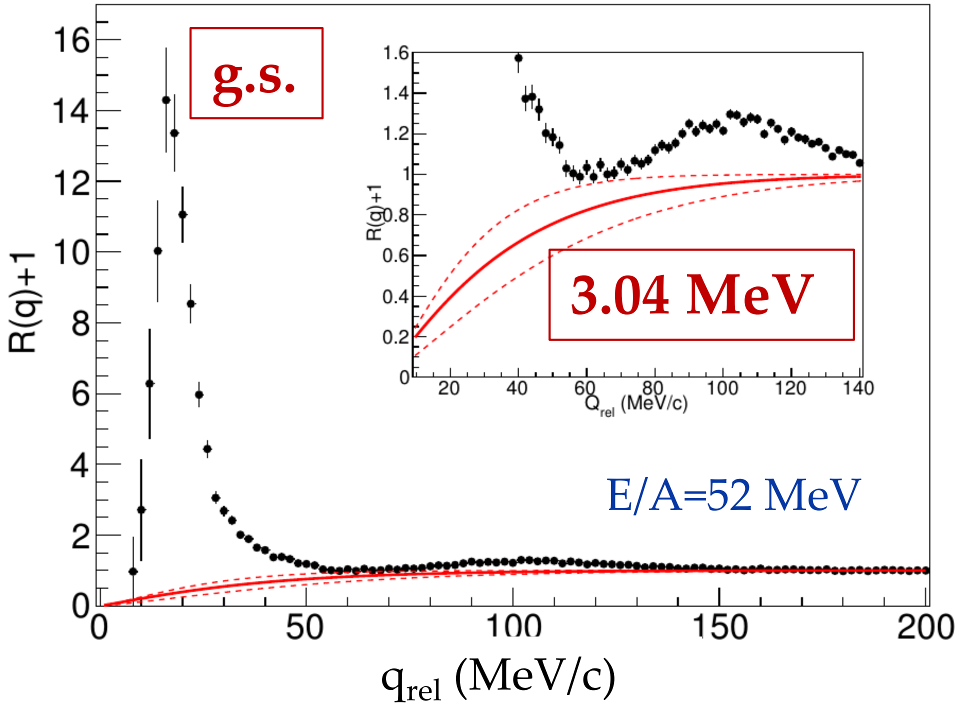

$\alpha - \alpha$ correlations

Thermal model approach

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

Shape of correlation peaks depend on properties of the corresponding unbound states (spin, branching ratios, etc.)

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

In-medium ^{8}Be unbound states

Ar+Ni, E/A=32-95 MeV – central

INDRA @ GANIL data

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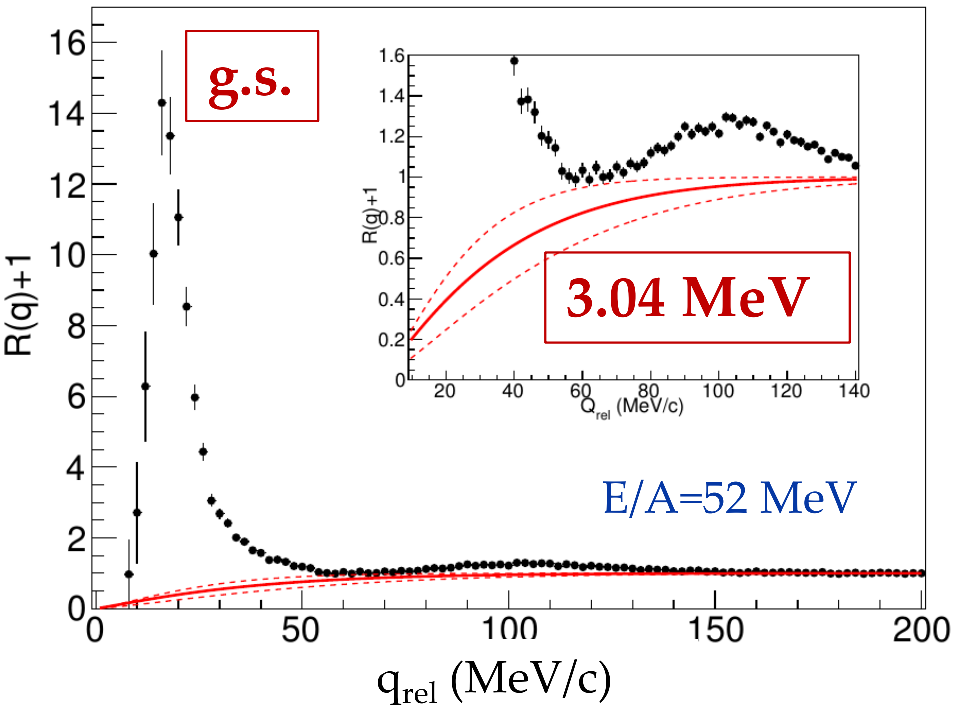

$\alpha - \alpha$ correlations

Thermal model approach

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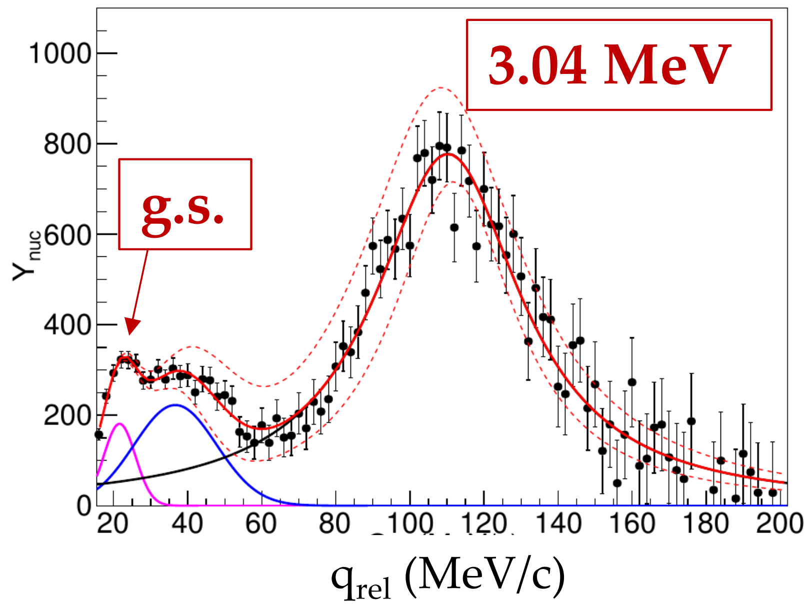
$$= \frac{N}{\pi} e^{-E^*/T} \sum_i (2J_i + 1) \left[\frac{\Gamma_i/2}{(E^* - E_i)^2 + \Gamma_i^2/4} \right]$$

Experimental Y_{nucl}

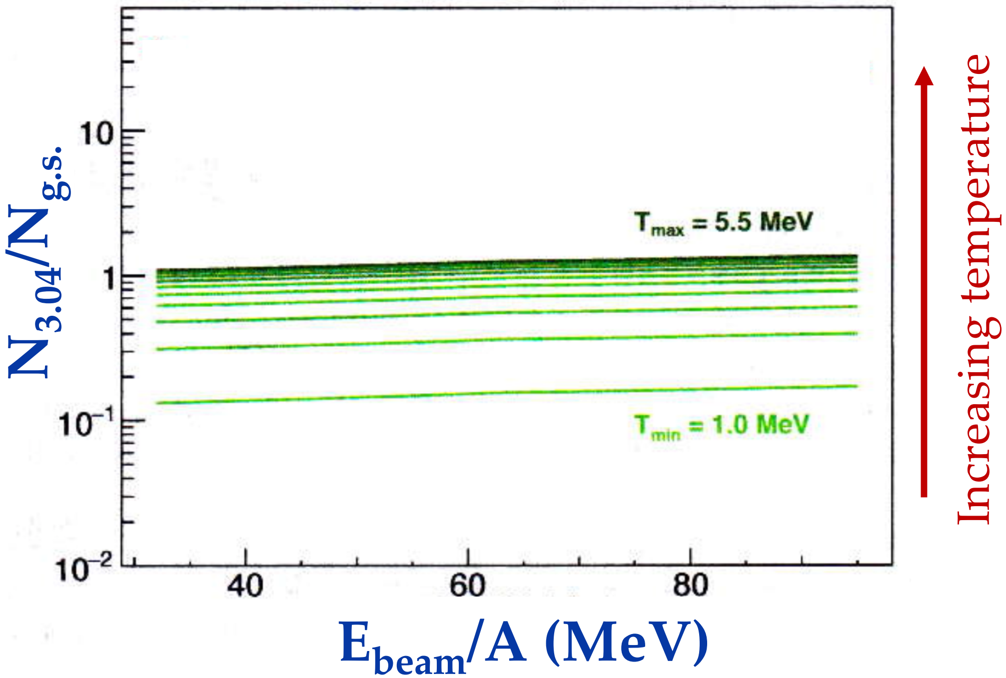


In-medium ^{8}Be unbound states: thermal approach?

Ar+Ni, E/A=32-95 MeV – central

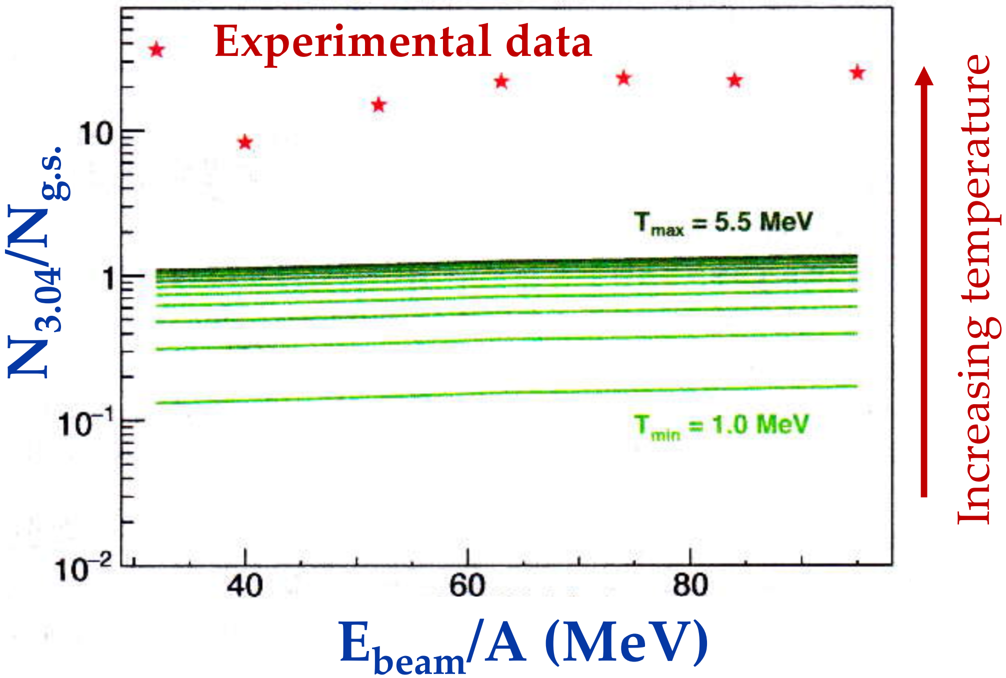
INDRA @ GANIL data

$$\frac{3.04\ Population}{g.s.\ Population} = \frac{N_{3.04}}{N_{g.s.}} \propto e^{-\Delta E/T}$$



In-medium ^{8}Be unbound states: thermal approach?

Ar+Ni, E/A=32-95 MeV – central
INDRA @ GANIL data



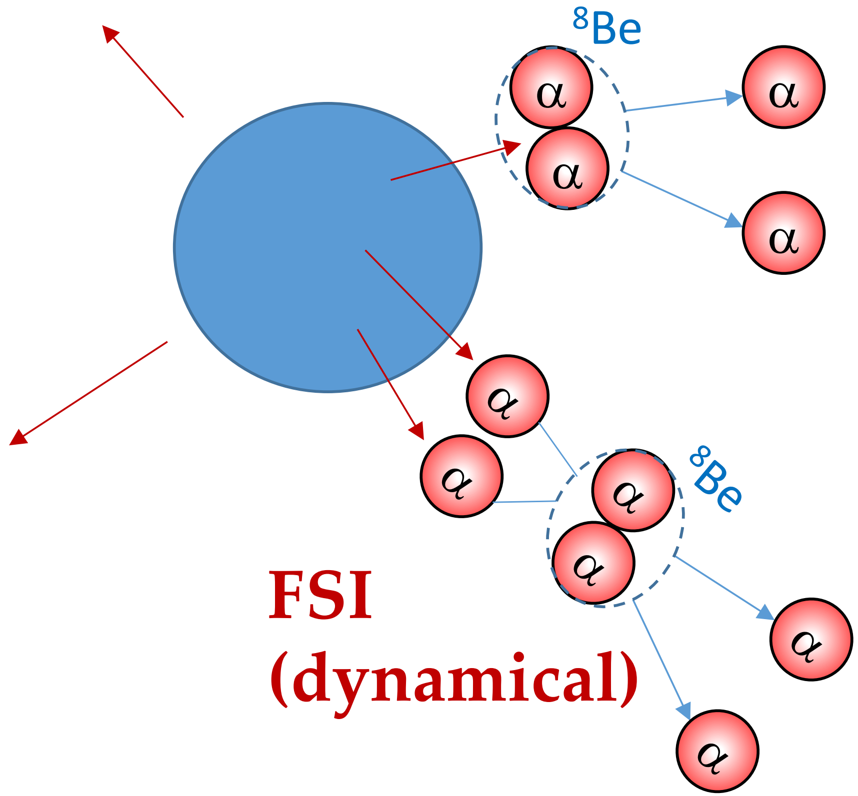
$$\frac{3.04\ Population}{g.s.\ Population} = \frac{N_{3.04}}{N_{g.s.}} \propto e^{-\Delta E/T}$$

Thermal model does not reproduce data:

overpopulation of excited states

No globally equilibrated system

Parent decay and resonance regeneration by FSI



Primary parent decay (thermal)

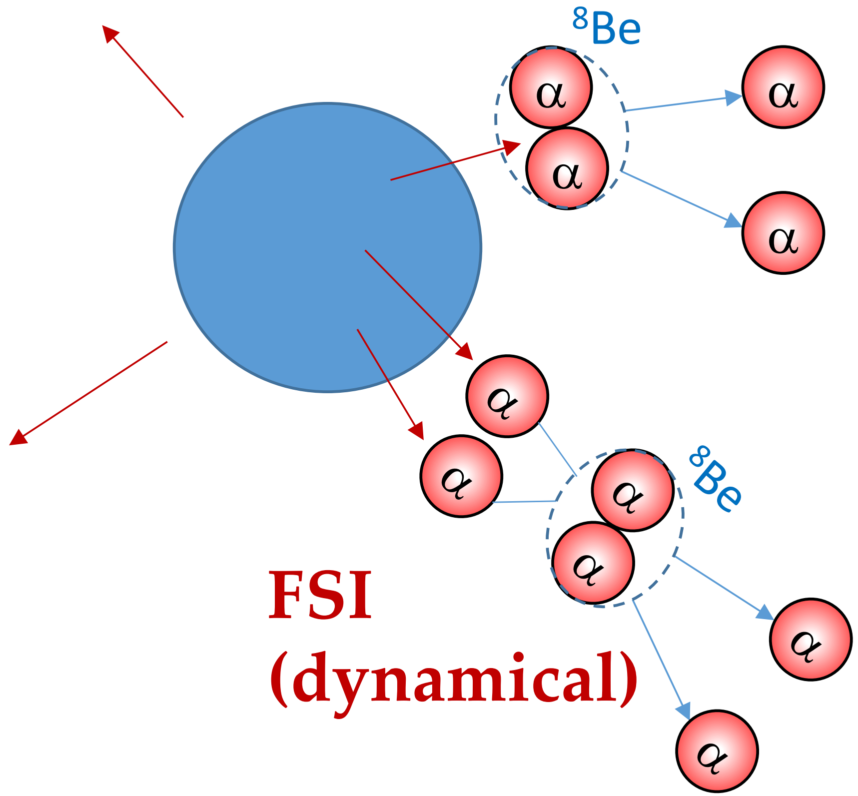
FSI (dynamical)

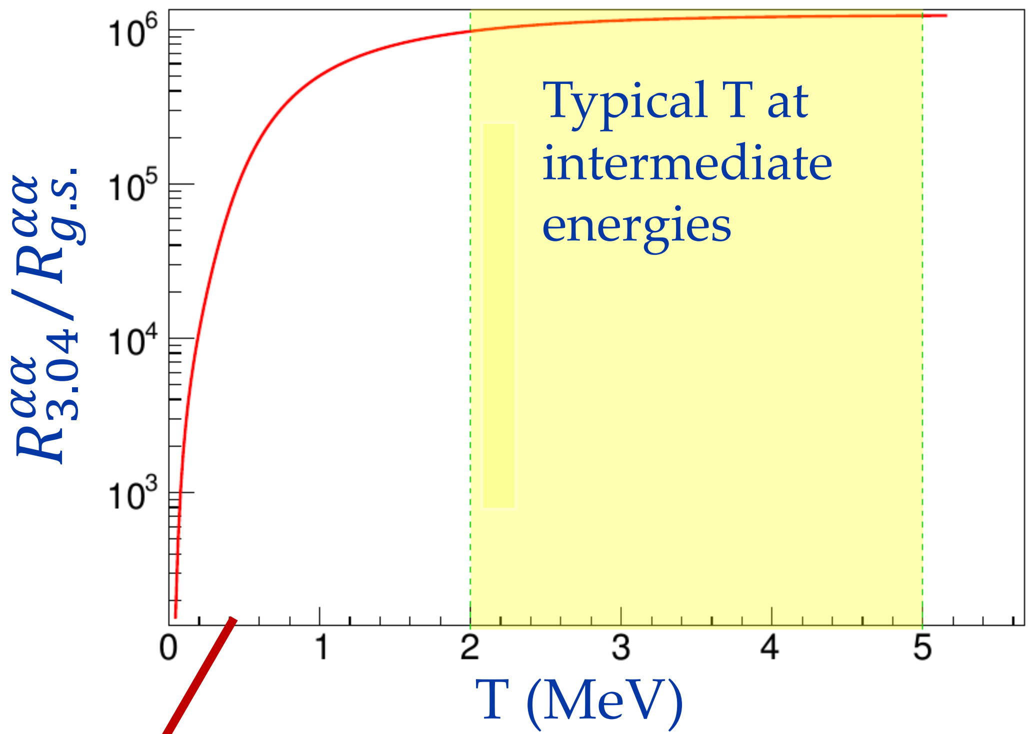
Regeneration of resonance depending on unbound state lifetime and reaction dynamics

D. Dell'Aquila, PhD thesis
PRC, in preparation

Parent decay and resonance regeneration by FSI

Primary parent decay (thermal)





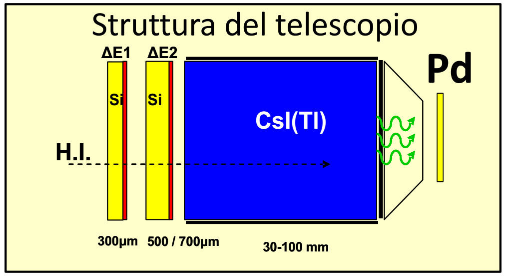
Generation of g.s. suppressed with respect to state at 3.04 MeV

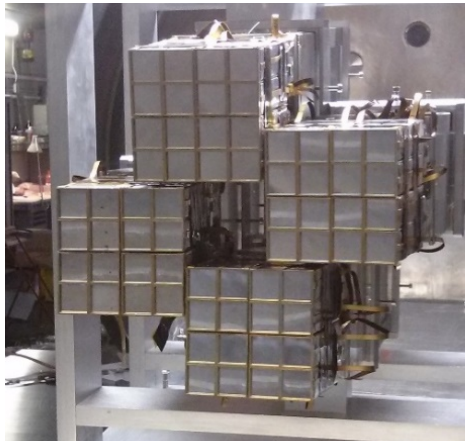
D. Dell'Aquila, PhD thesis

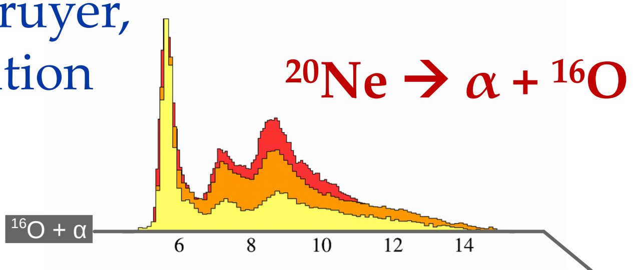
Multiparticle correlation measurements

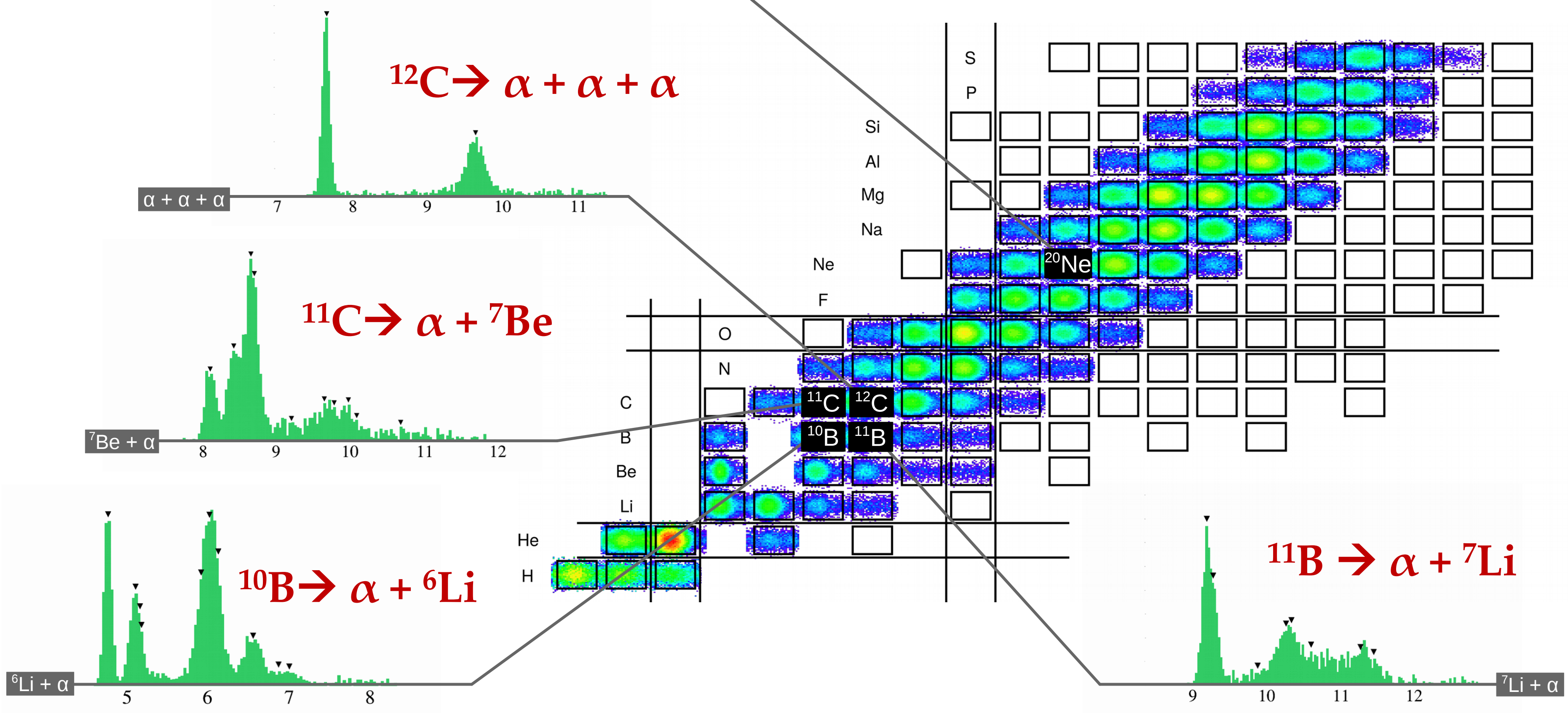
FAZIACOR @ LNS

G. Verde & D. Gruyer,
FAZIA collaboration

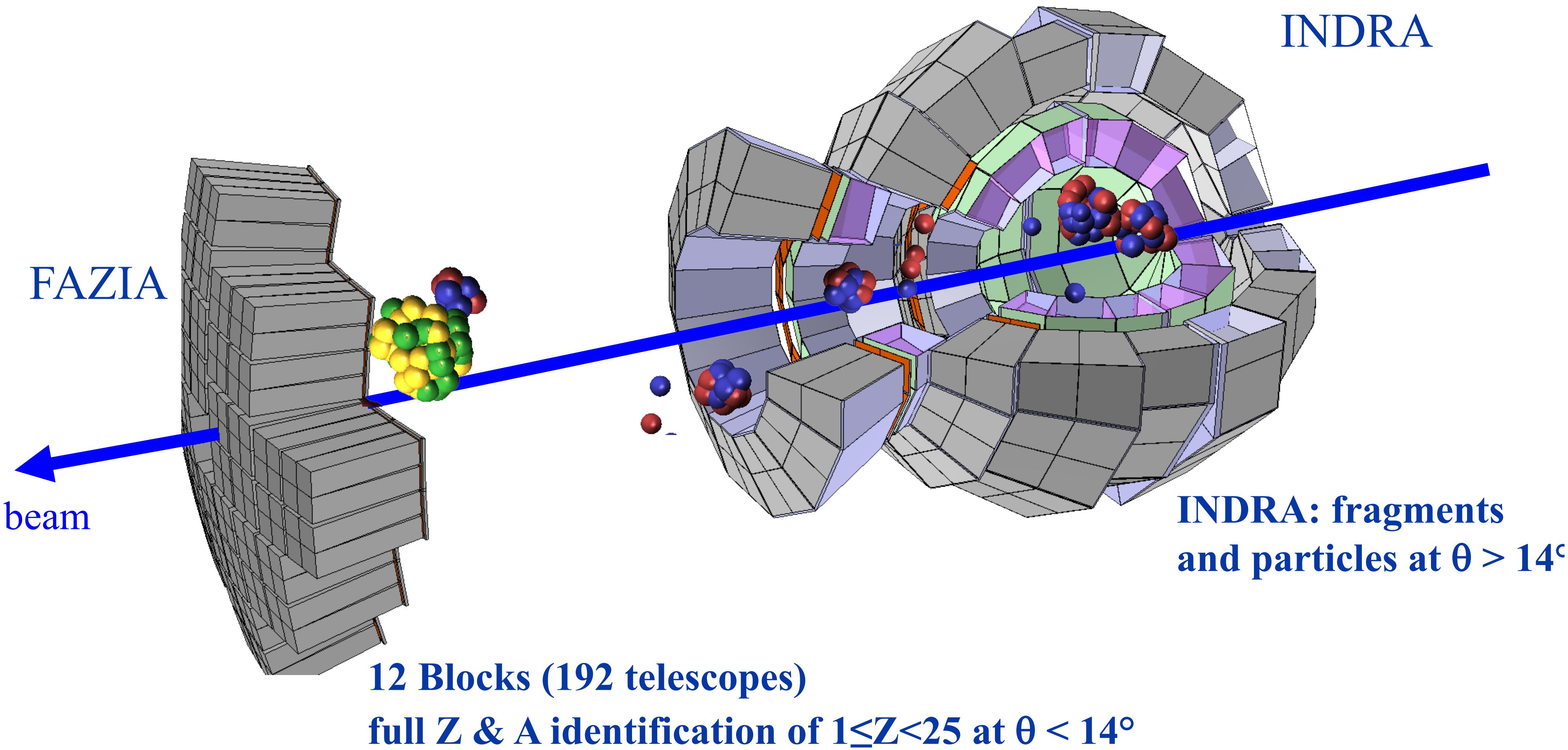








FAZIA-INDRA @ GANIL (≈ 2019-2021)



- Isospin and symmetry energy
- In-medium clustering and correlations

You're welcome to collaborate

conclusions

- HIC to explore structure and dynamics of hot and dilute nuclear matter
- Femtoscopic imaging and IMF-IMF correlations
  - space-time probes for transport model simulations: beyond single particle observables
    - p-p in Xe+Au at 50 MeV/nucleon Vs. pBUU sims (Danielewicz)
    - IMF-IMF in Ar+Ni at 32-95 MeV/nucleon Vs. BLOB sims (Napolitani)
- Cluster structure: resonance decays
  - useful tool for nuclear structure & interplays Structure/Dynamics/EoS (spin, branching ratios)
  - higher order probes for transport models… (?)
    - Ex: elpha-alpha correlations in Ar+Ni at 32-95 MeV/nucleon: FSI Vs. Parent decay dynamics
- Look forward to INDRA-FAZIA campaigns @ GANIL