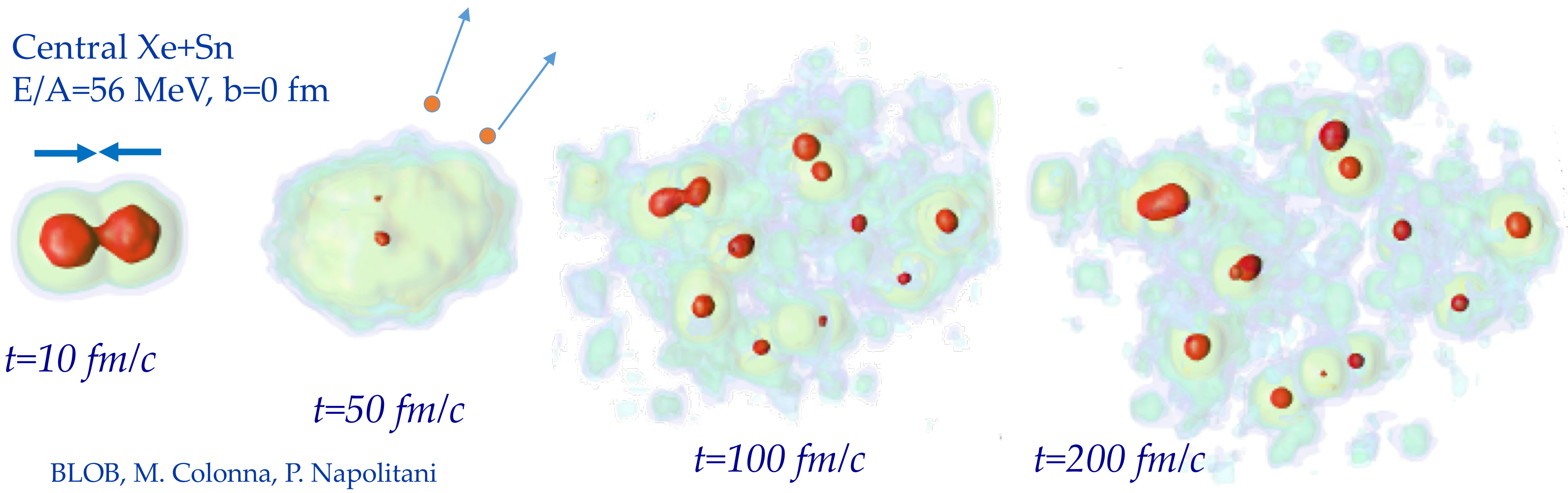
Correlation and resonance decays at low energies for clustering and dynamics

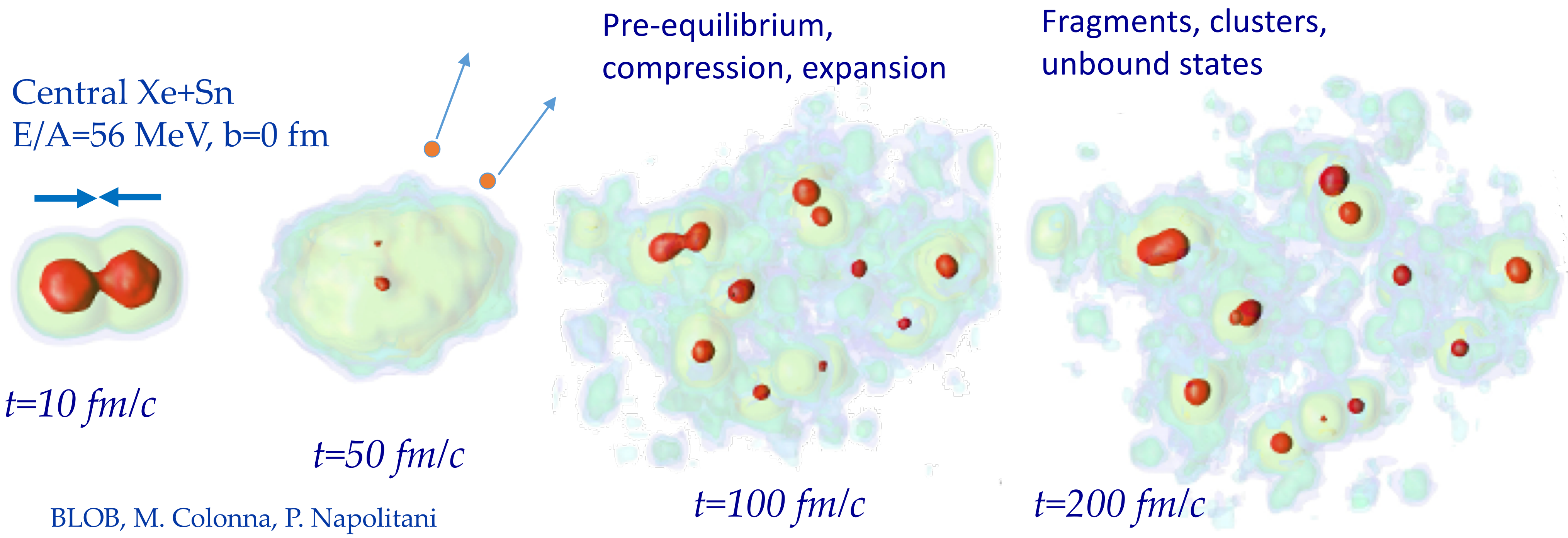


G. Verde, INFN Catania/GANIL

FAZIA & INDRA collaborations

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

Intermediate energy dynamics



Collective properties

EoS, Symmetry Energy

→ *Clusters at low densities*

→ *Neutrinosphere physics*

(See talks by P. Danielewicz and Z. Chajecki)

Resonance decays

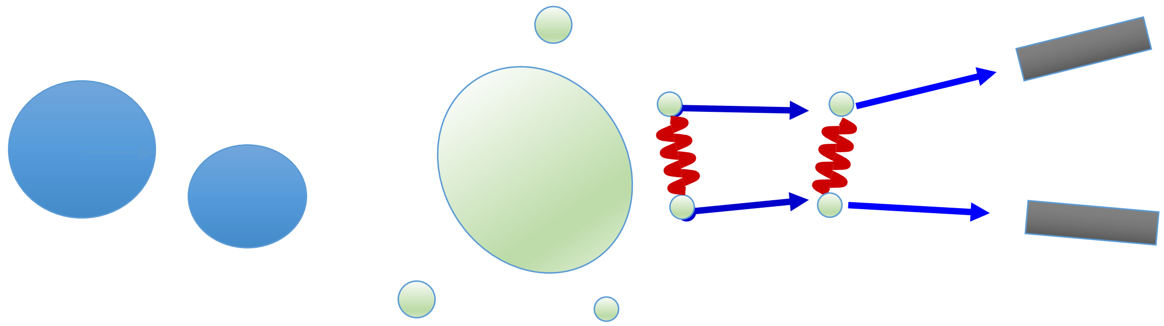
In the medium invariant mass spectroscopy: branching ratios, …

→ *in-medium structure and clusters*

Dynamics and structure

- Nuclear structure properties in low density matter:
  - Study the properties of the "medium": density, temperature, EoS → Femtoscopy
  - Resonance decays: in-medium vs out-of-medium

Proton-proton femtoscopy

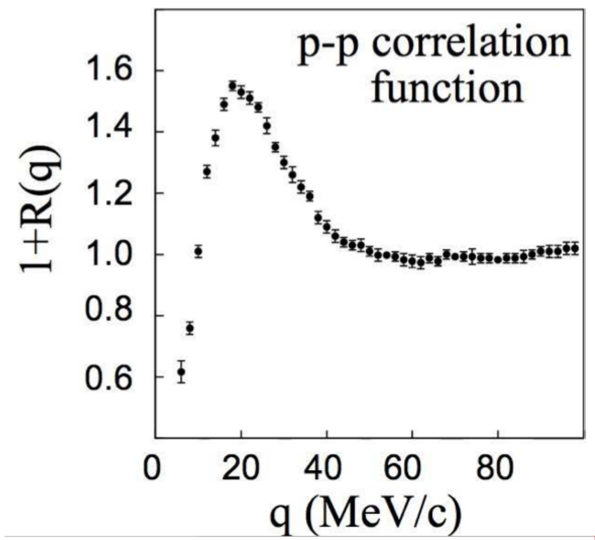


Physical correlations

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

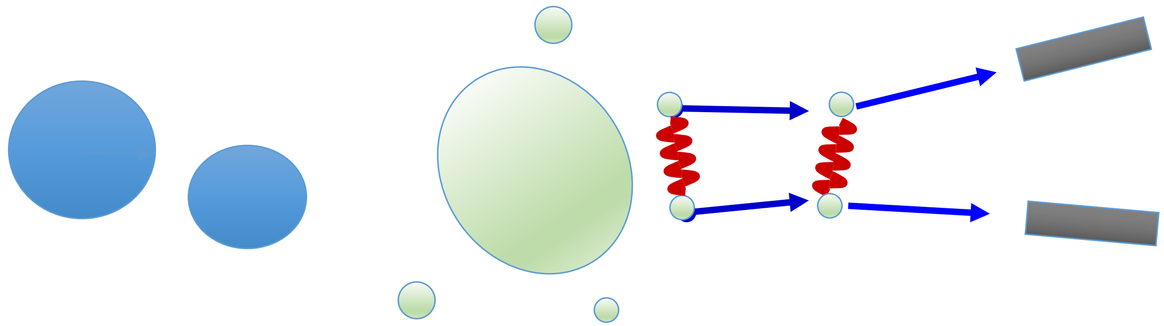
Intensity interferometry / Femtoscopy

q = mom. of relative motion



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

Proton-proton femtoscopy



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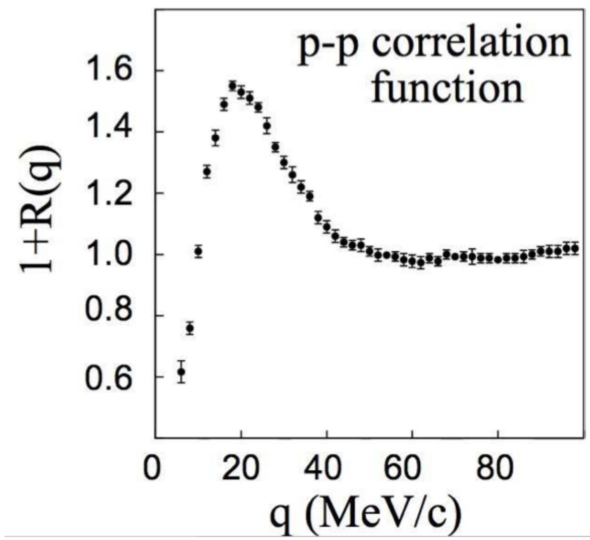
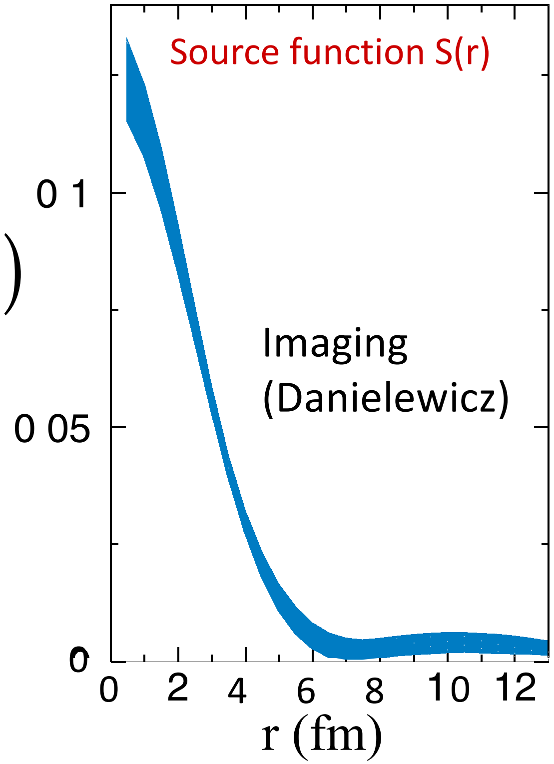


Koonin-Pratt

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

- Space-time image and size of early dynamical source



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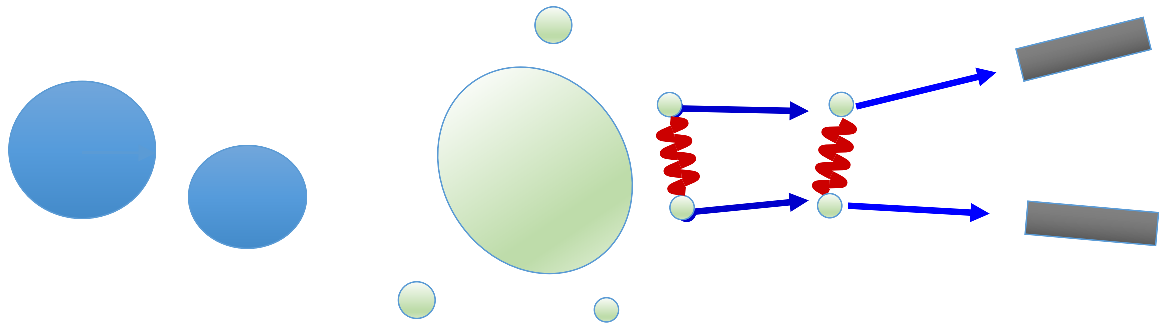
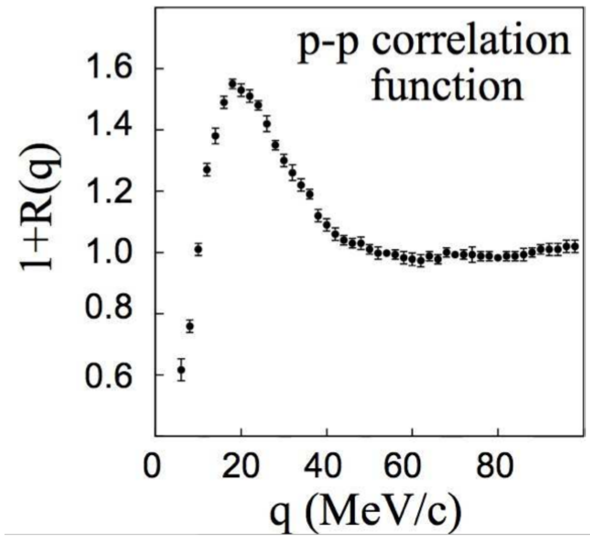
Proton-proton femtoscopy



- **Radii, λ values, etc.**
- **Directional studies, shapes, elongations, …**

Intensity interferometry / Femtoscopy

q = mom. of relative motion



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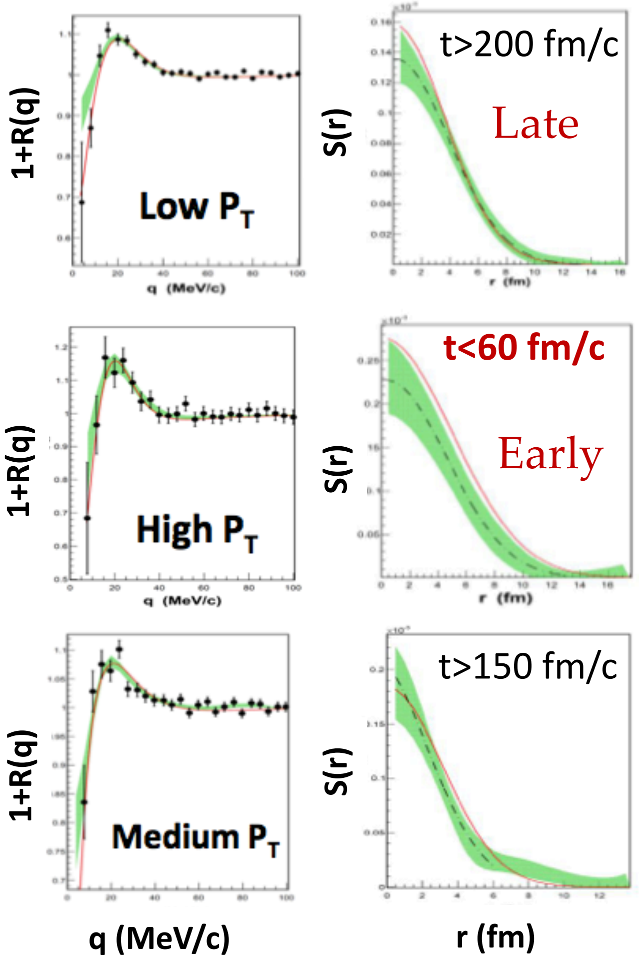
- Space-time image and size of early dynamical source

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

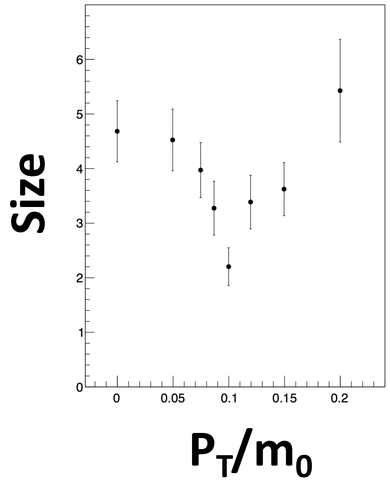
Source radii and λ Vs. p_T

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

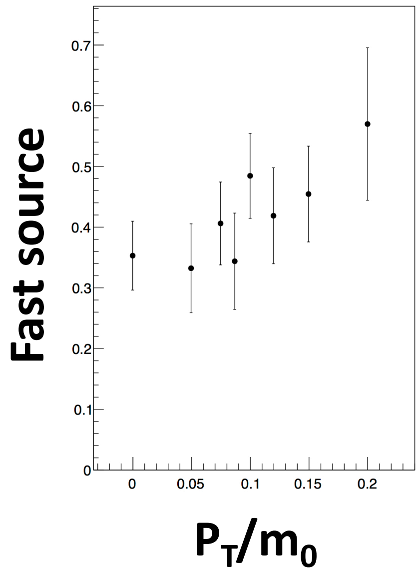
Experimental data (LASSA @ MSU)



Source size



% of dynamical early emissions

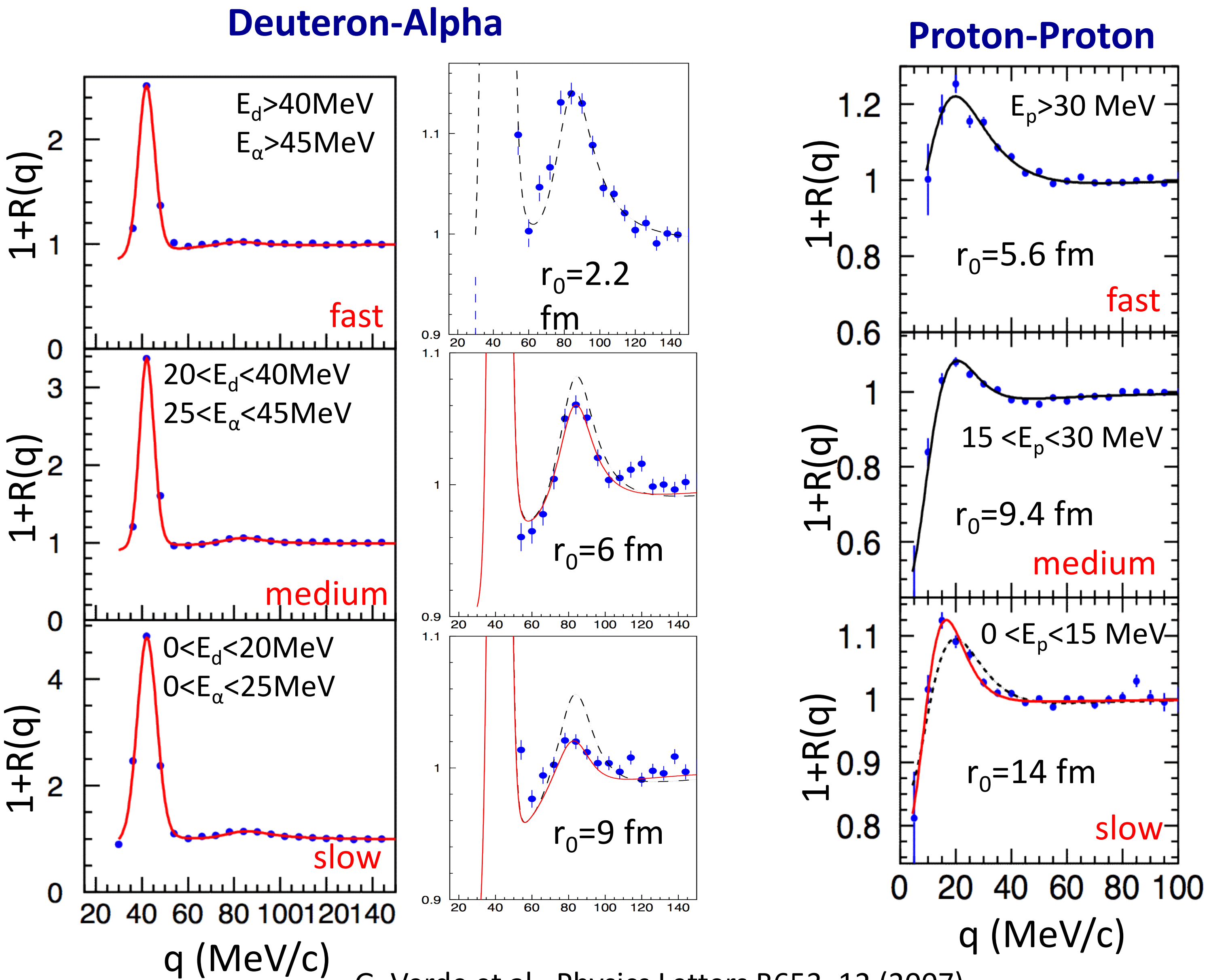


T. Minniti, GV, B. Barker, P. Danielewicz

Femtoscopy with different particles

Xe+Au E/A=50 MeV b_{red}<0.3

LASSA Data @ MSU



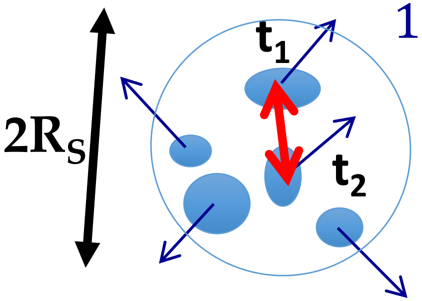
Radii, λ values, etc.
Directional studies, shapes, elongations, …

G. Verde et al., Physics Letters B653, 12 (2007)

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

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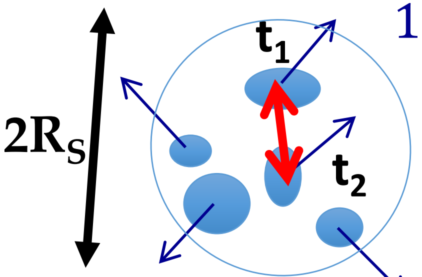

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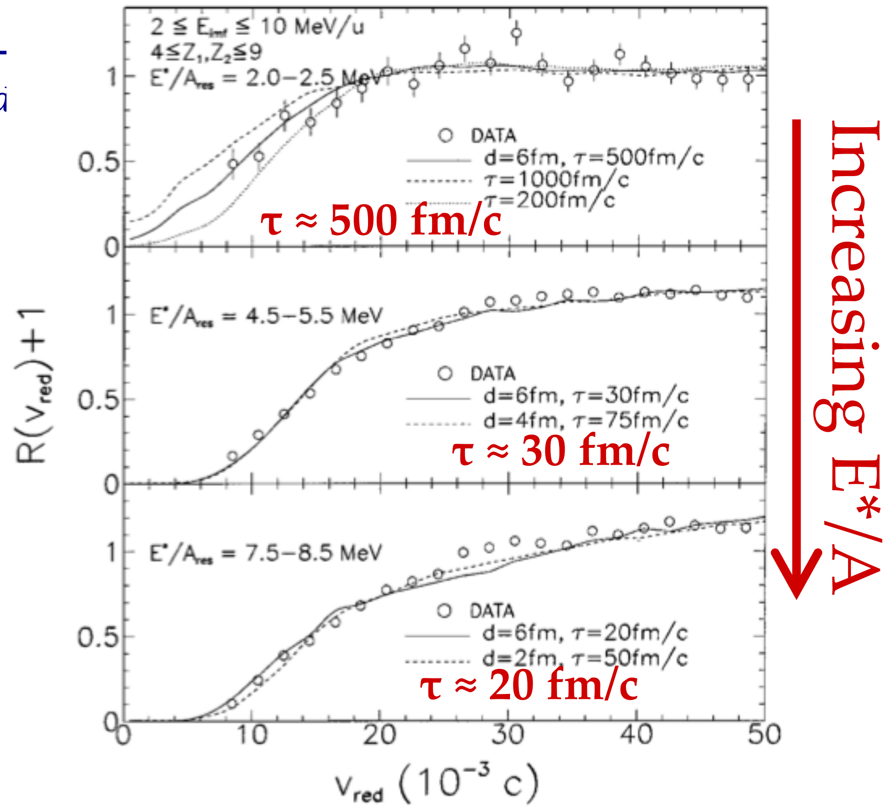
$$v_{red} = \frac{|\vec{v}_1 - \vec{v}_2|}{\sqrt{Z_1 + Z_2}}$$

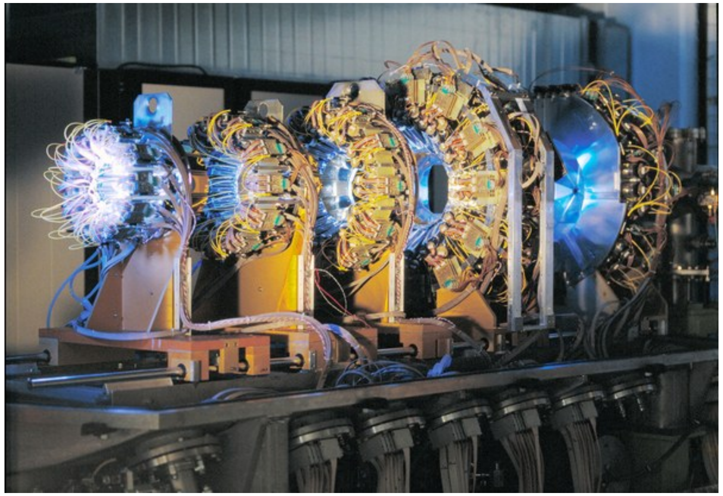
Compact thermal source (T, β_{coll}, …)

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



In-medium alpha-alpha correlations



INDRA *4p multi-detector*

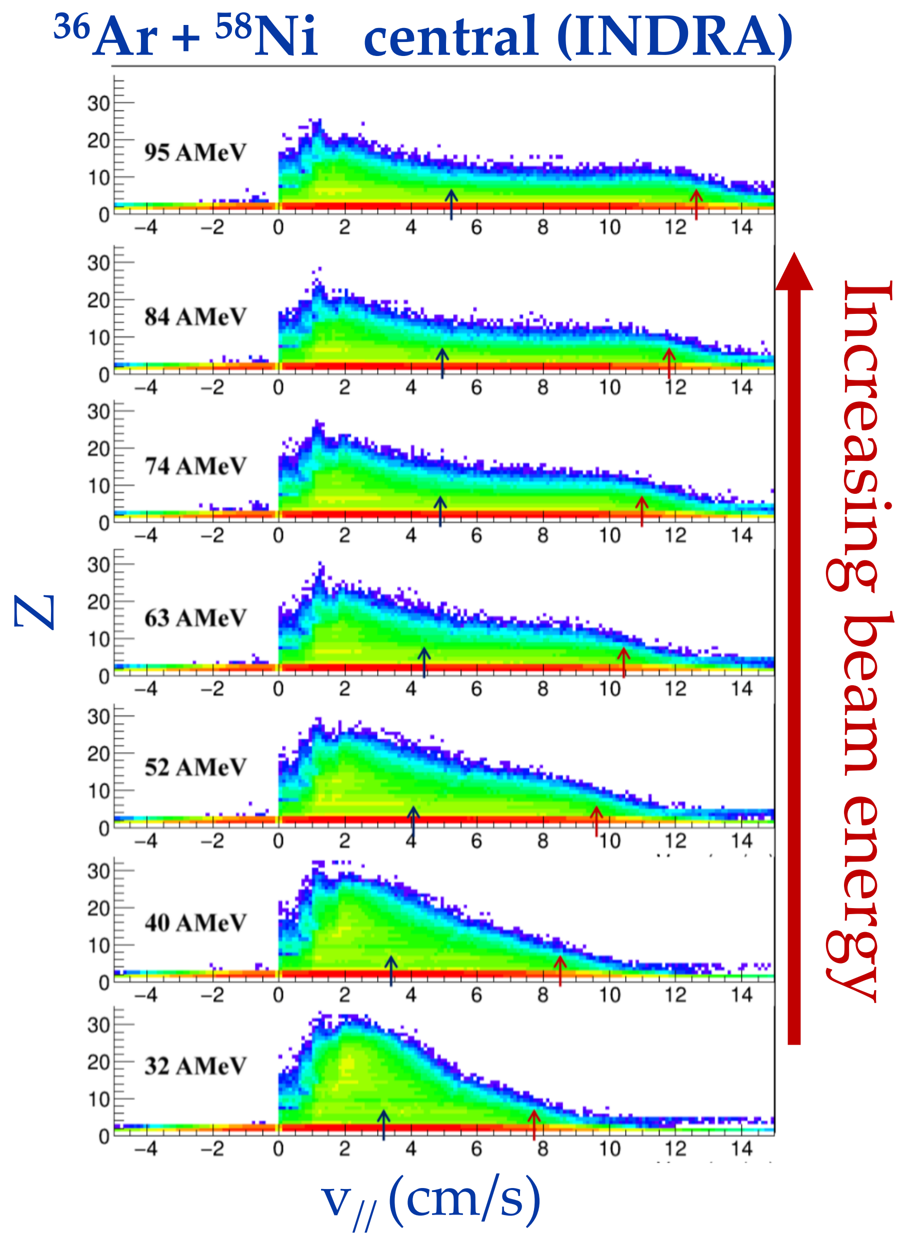
angular coverage ≈ 90% (4π)
336 *independent cells*
telecopes C_3F_8 gas chamber – Si (300 mm) – CsI (5-14cm)

^{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: time-scales



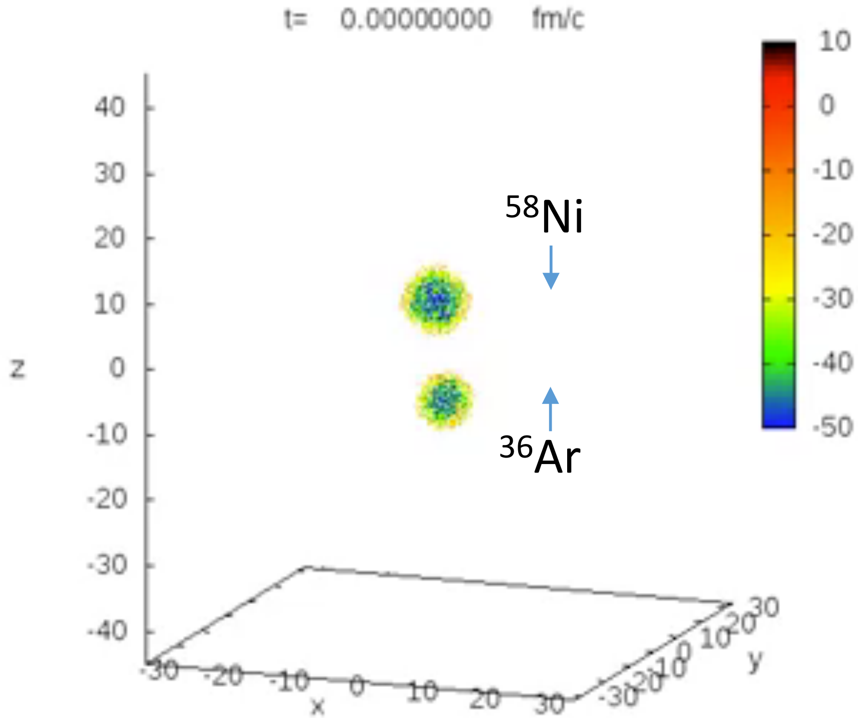
- Signals of no global equilibrium
- Forward/Backward asymmetry in CMS

L. Francalanza, G. V. et al.

"In-medium jet" fragmentation: time-scales

BLOB (P. Napolitani, M. Colonna)

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



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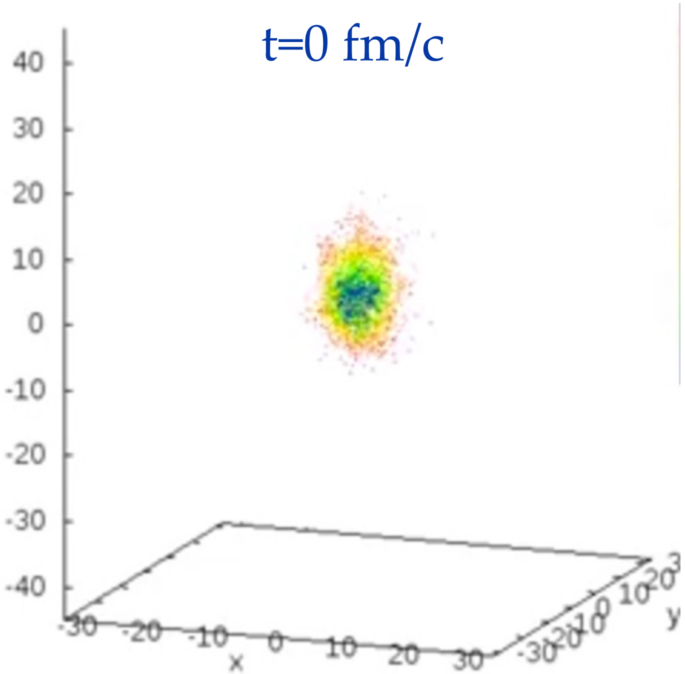

"In-medium jet" fragmentation: time-scales

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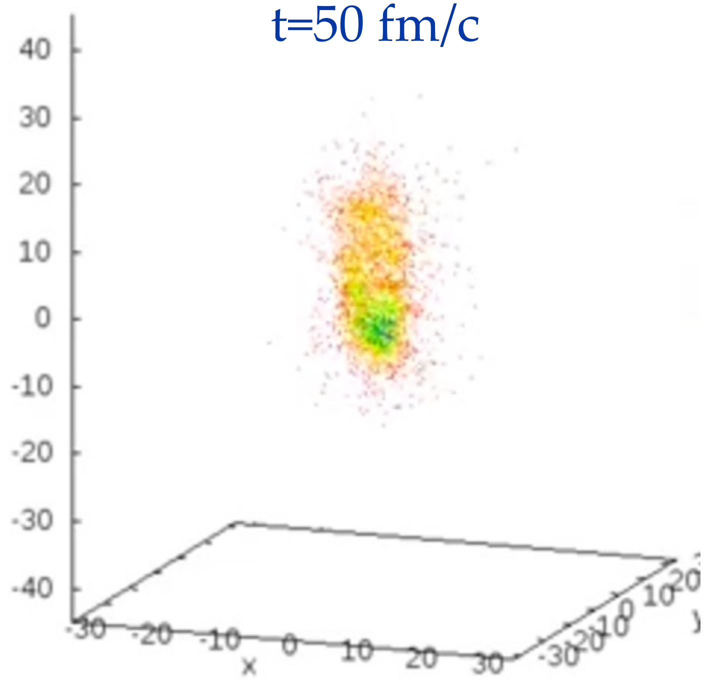
$^{36}Ar + ^{58}Ni$ E/A=40 MeV

t=50 fm/c



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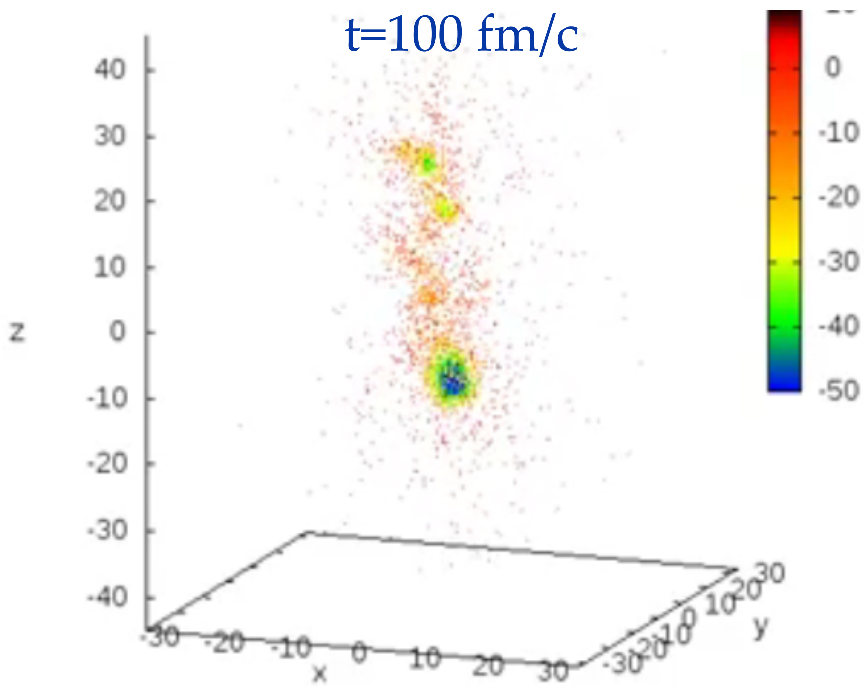

L. Francalanza, G. V. et al.

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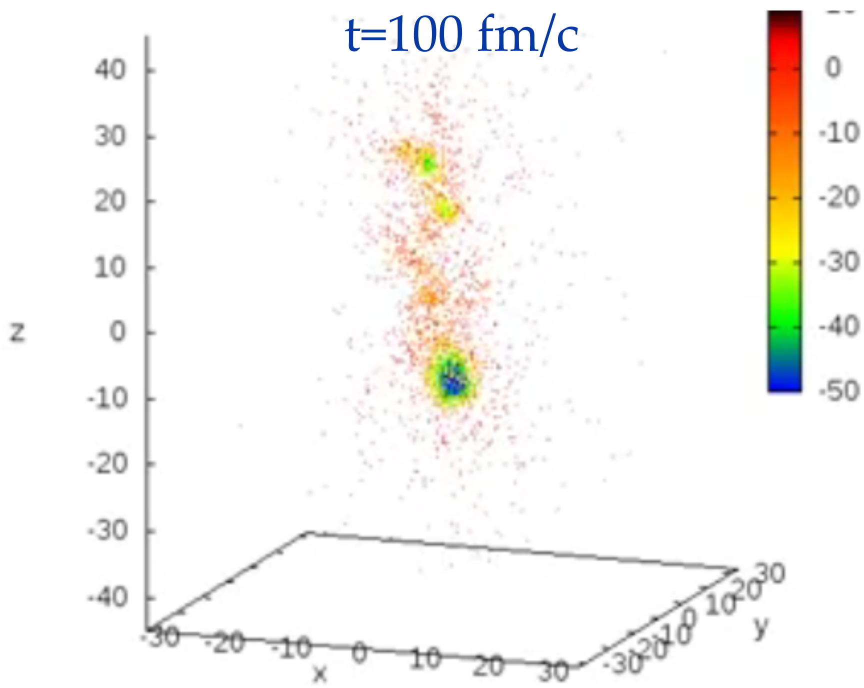
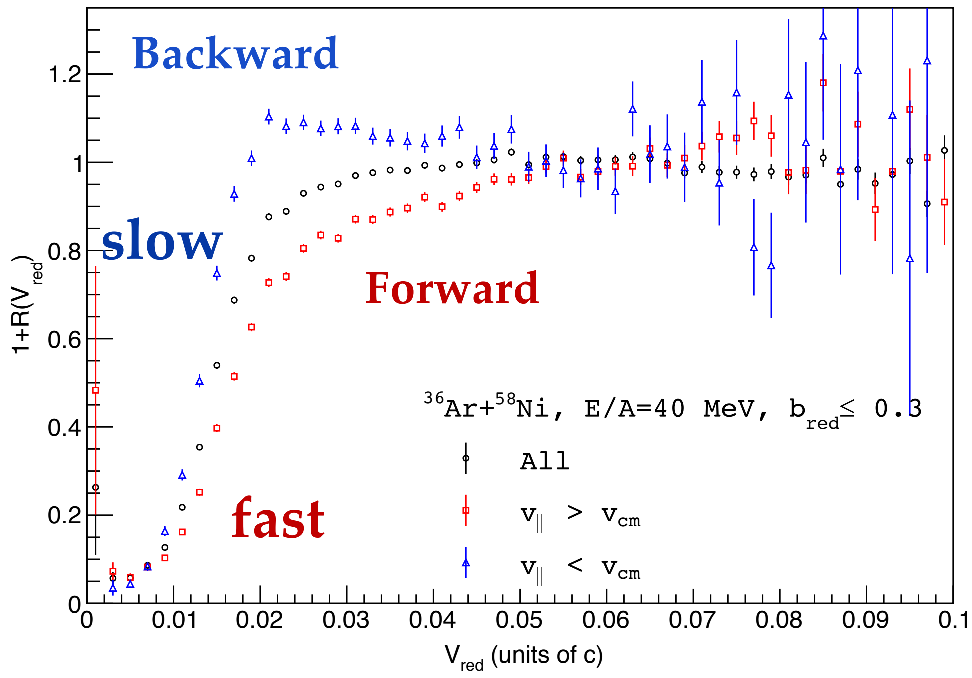


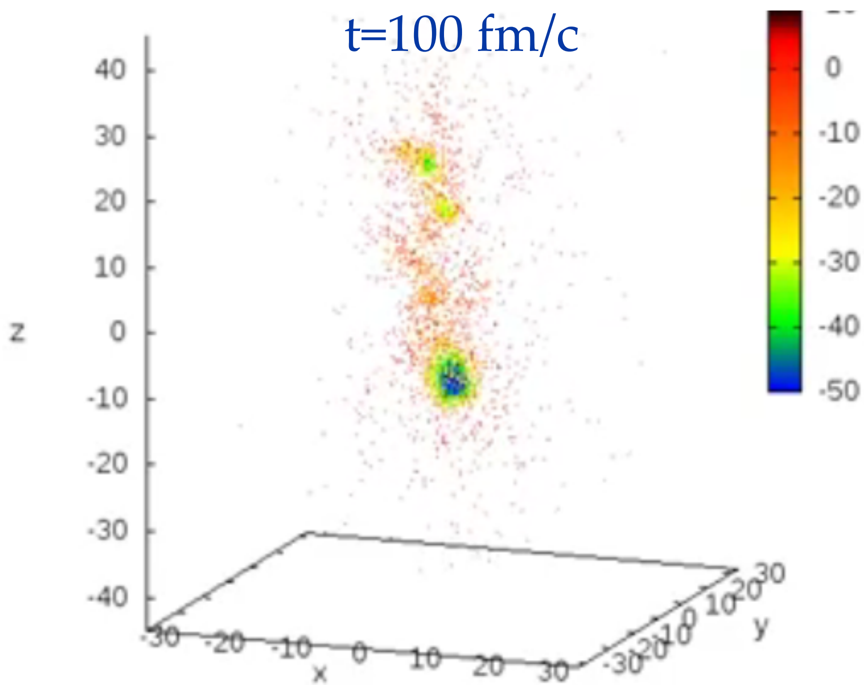


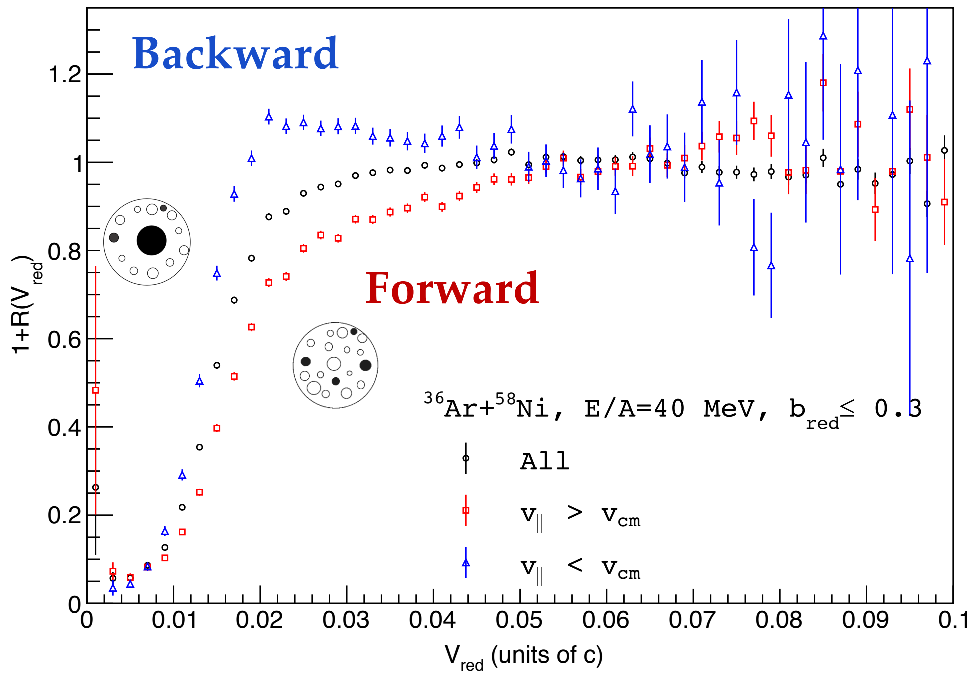
L. Francalanza, G. V. et al.

"In-medium jet" fragmentation: "tomography"

BLOB (P. Napolitani, M. Colonna)

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





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

No globally equilibrated system produced

Dynamics and structure

- Nuclear structure properties in low density matter:
  - Study the properties of the medium: density, temperature, EoS → Femtoscopy
  - Resonance decays: in-medium vs out-of-medium

^{8}Be resonance decays: thermal model

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

INDRA @ GANIL

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

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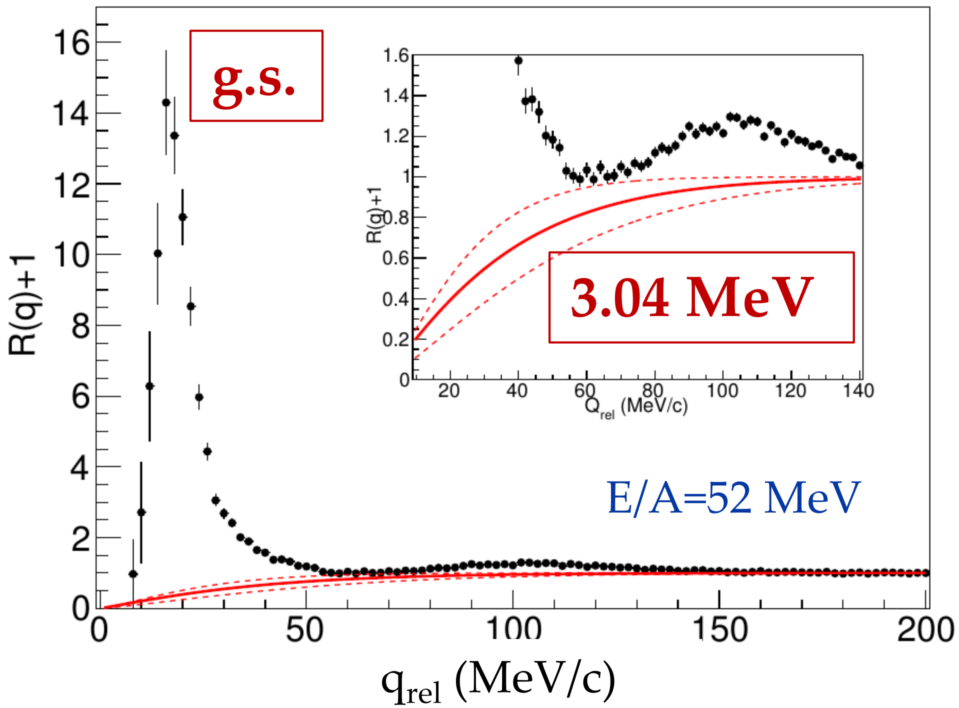

$$Y_{nucl}(E^*) =$$

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

In-medium temperature

Nuclear structure: spin, branching ratios, resonance position

^{8}Be resonance decays: thermal model

Ar+Ni, E/A=32-95 MeV – central

INDRA @ GANIL

→ **^{8}Be → $\alpha + \alpha$**

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

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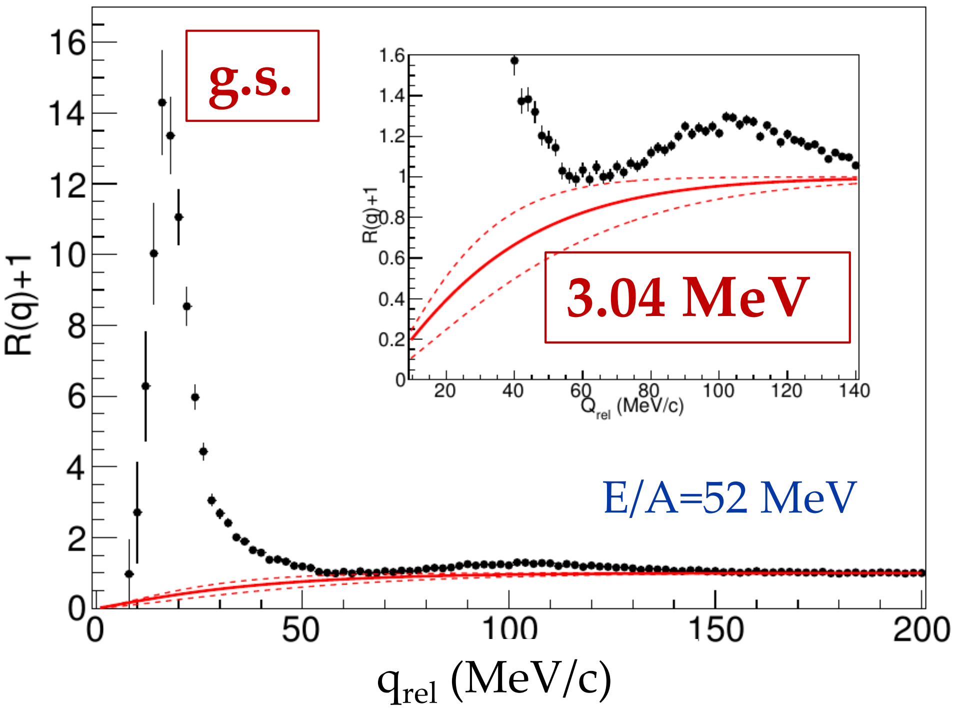
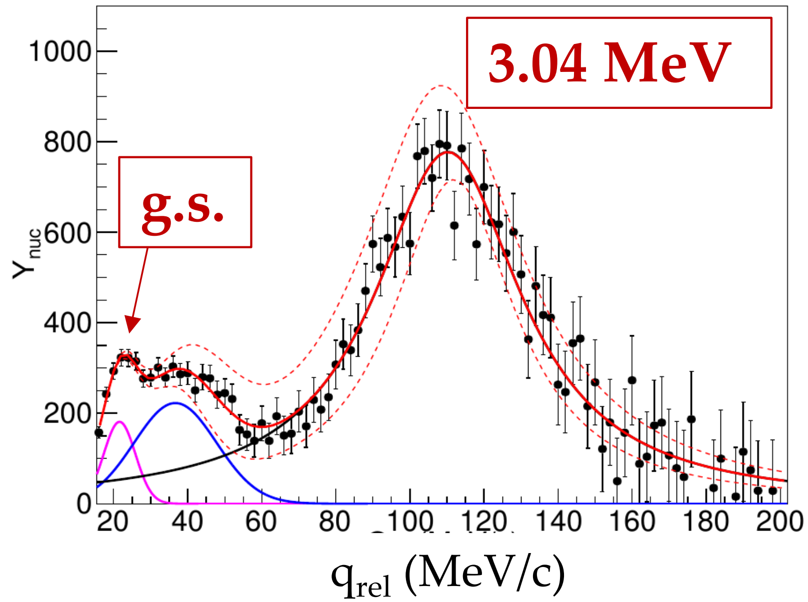


Experimental Y_{nucl}



^{8}Be resonance decays: thermal model

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INDRA @ GANIL

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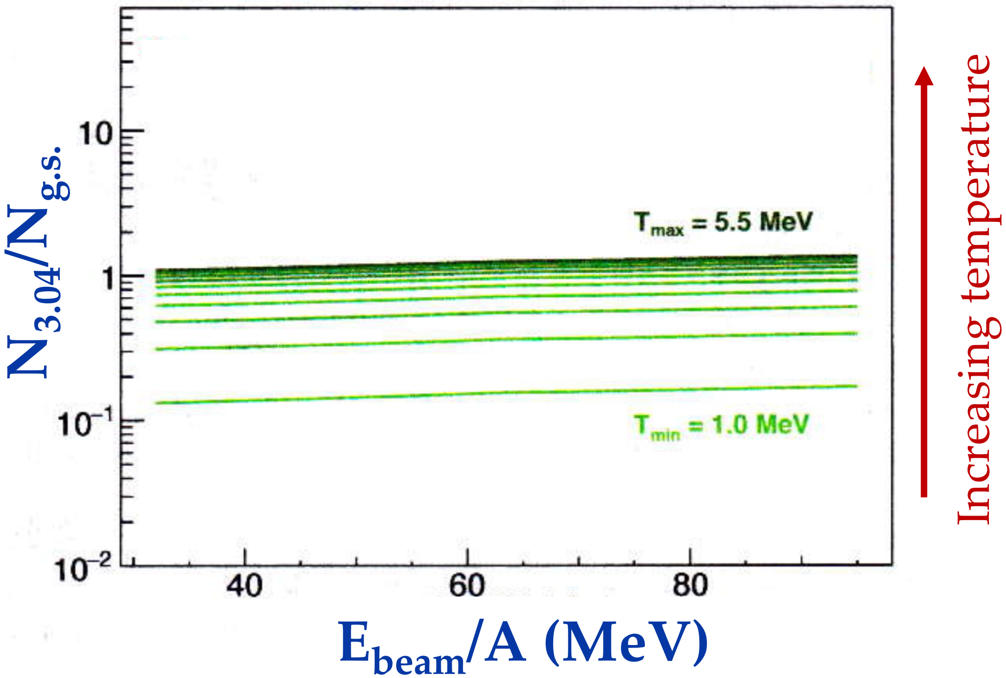

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INDRA @ GANIL

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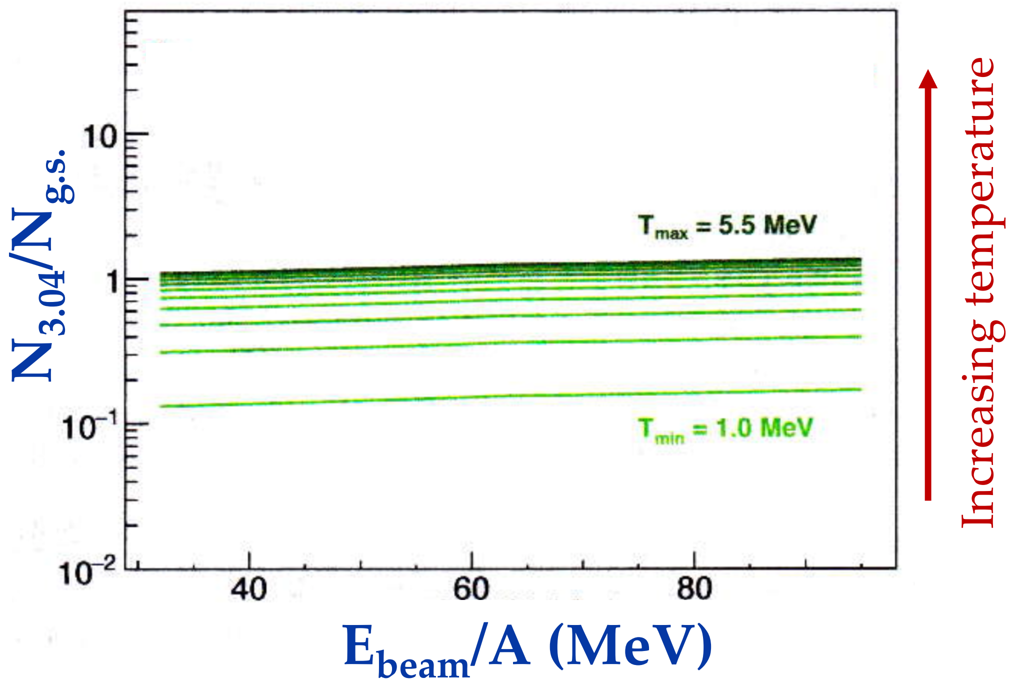


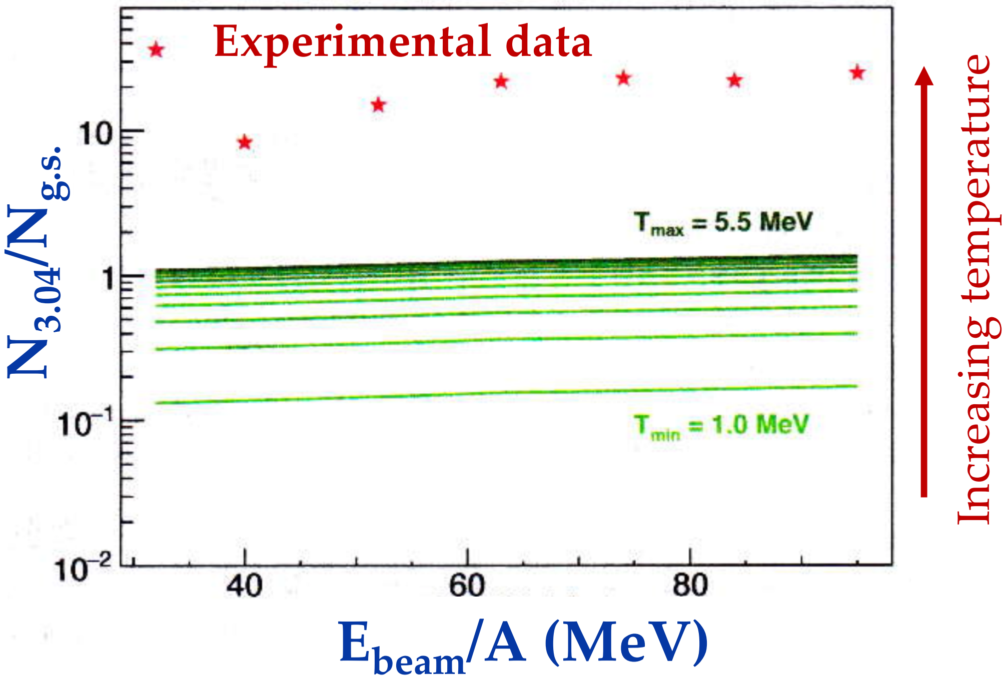
Which temperature T is consistent with a measured relative population of state?

^{8}Be resonance decays: thermal model

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

INDRA @ GANIL

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



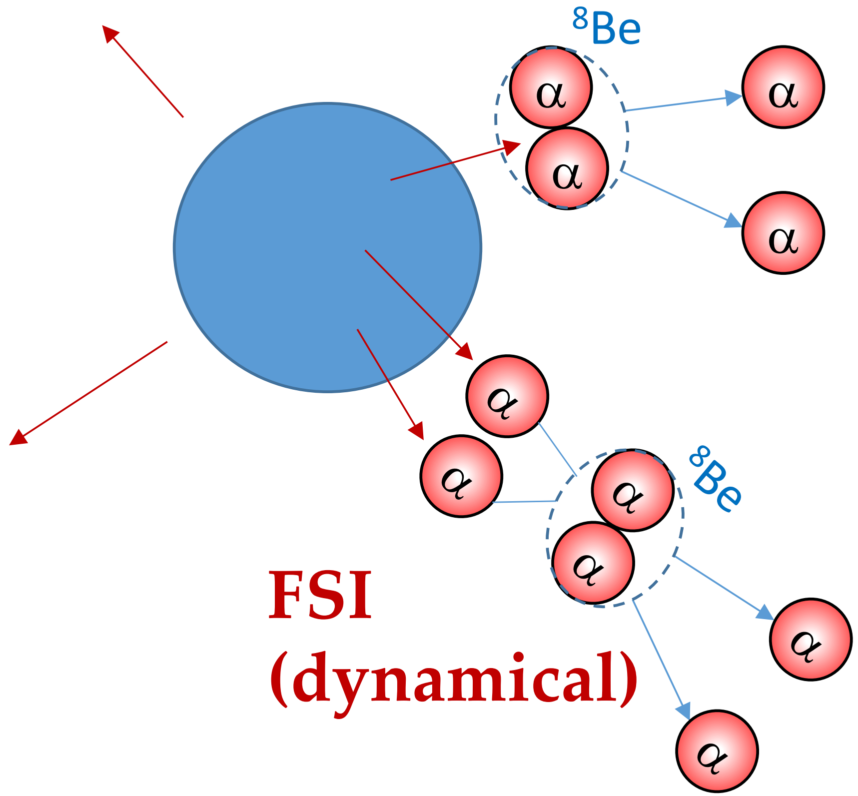
Which temperature T is consistent with a measured relative population of state?

None

overpopulation of excited states

Thermal mechanism cannot describe unbound state population for α's

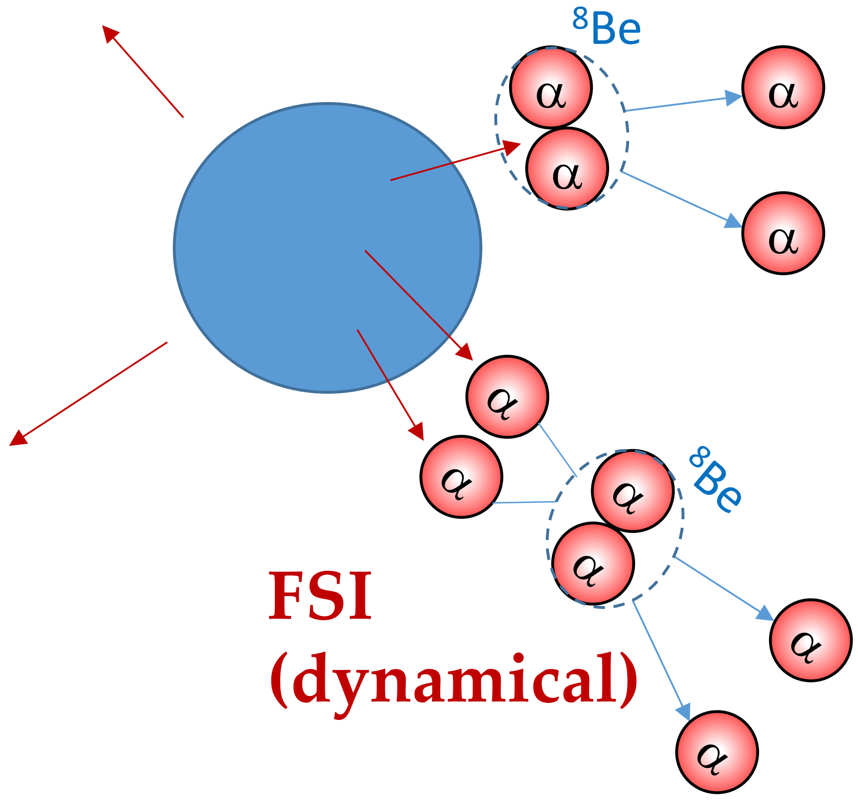
Parent decay and resonance generation by Final State Interactions

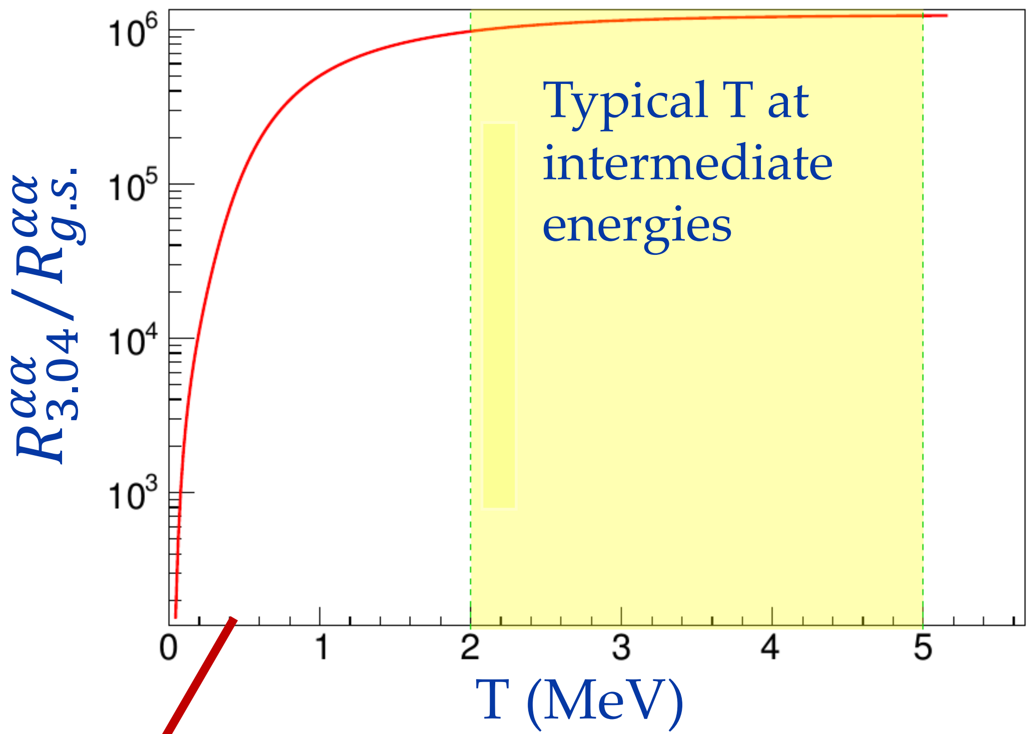


Primary parent decay (thermal)

FSI (dynamical)

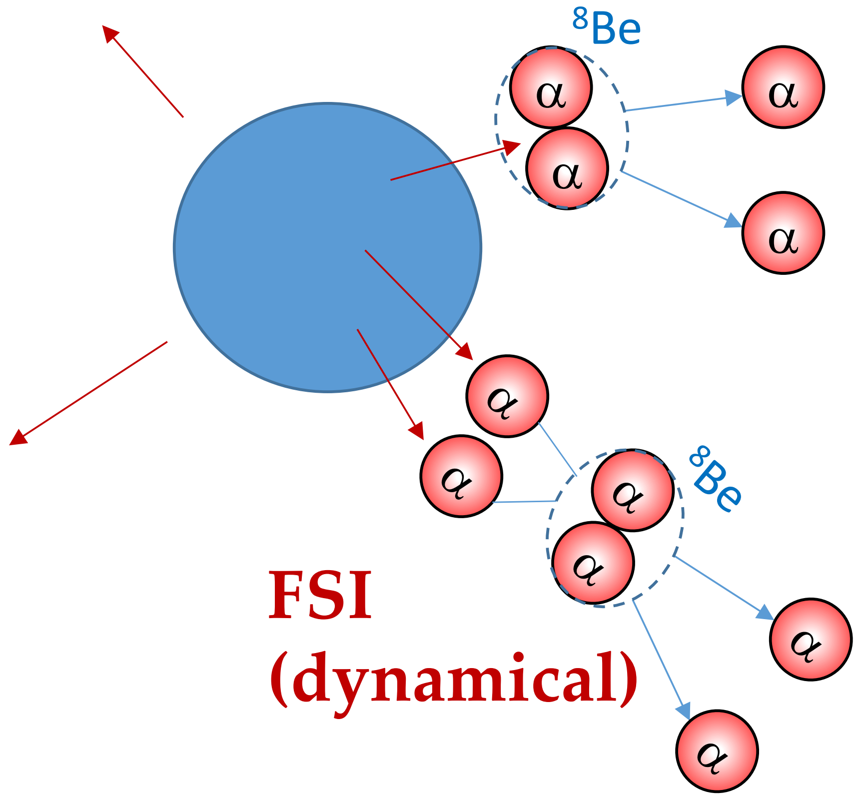
Parent decay and resonance generation by Final State Interactions





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)

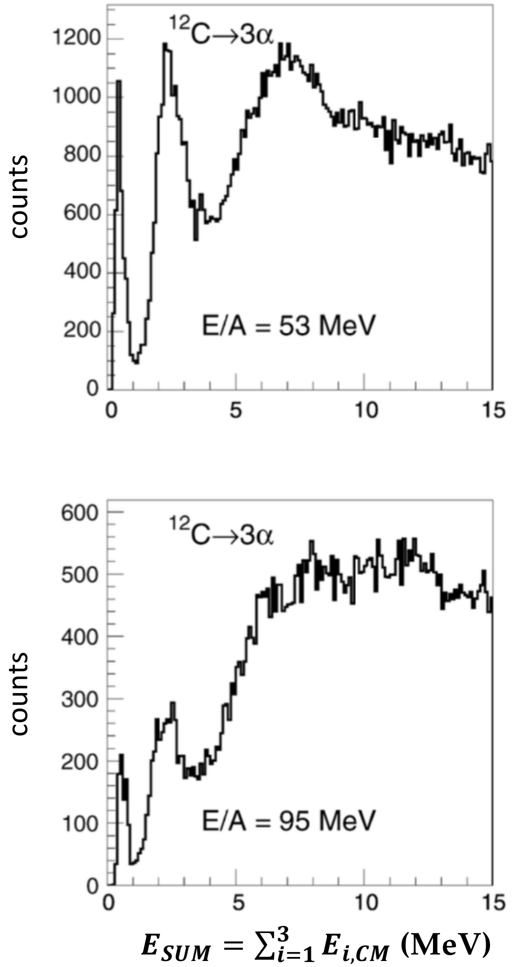
Dynamical FSI approach necessary: thermal model does not work

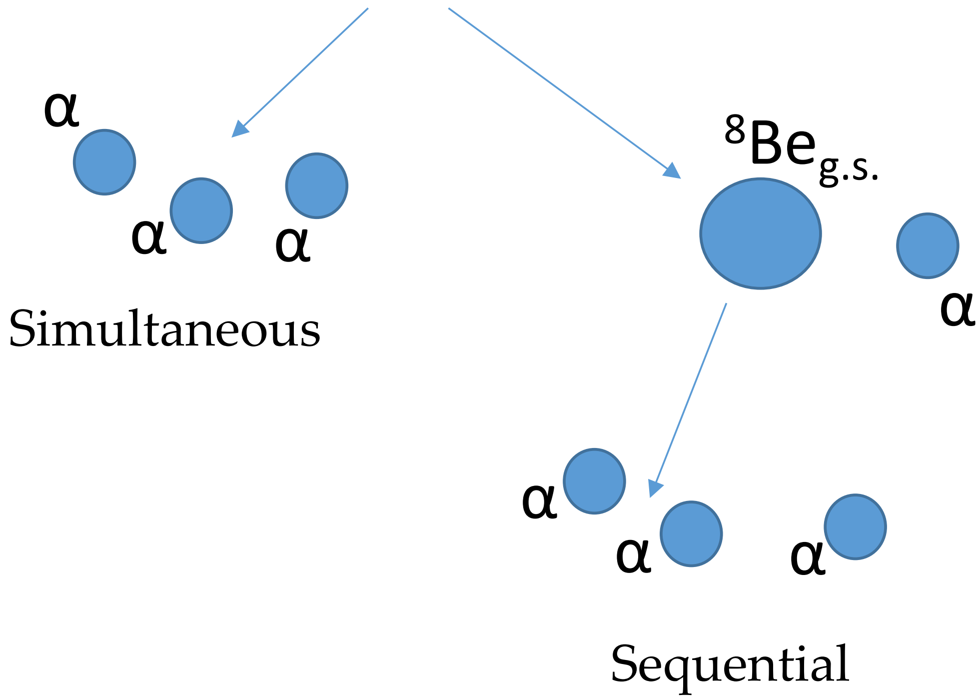
→ look forward to alpha femtoscopy

Three-alpha correlations: decay of ^{12}C Hoyle state

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

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

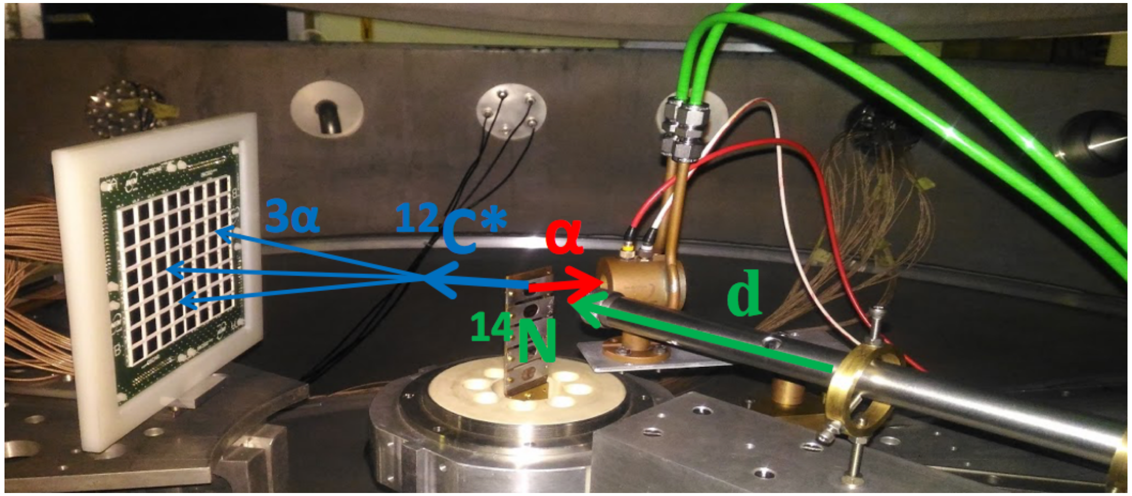




Astrophysics relevance: Which stars do host the Hoyle process?

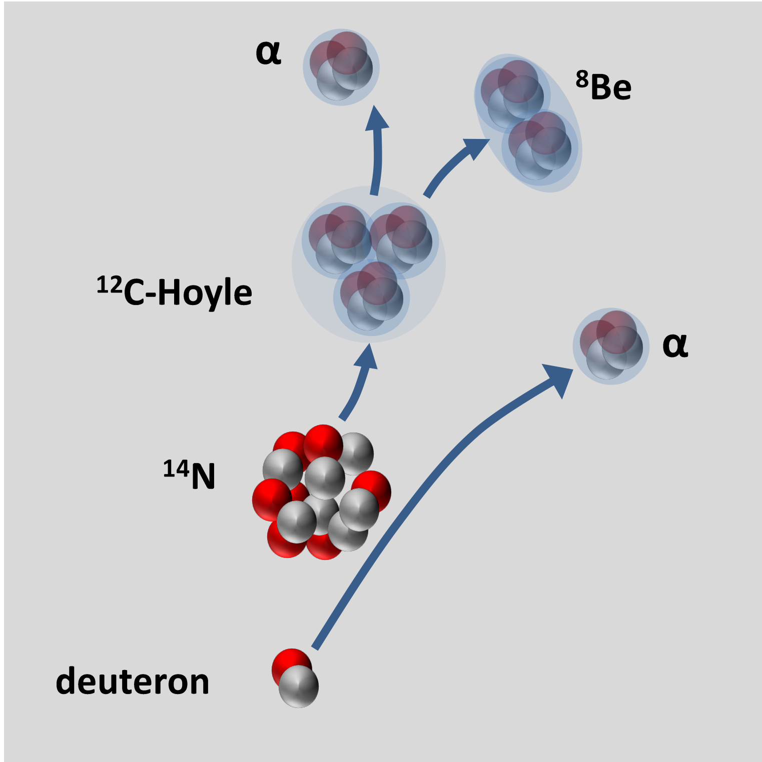
Direct reaction measurements

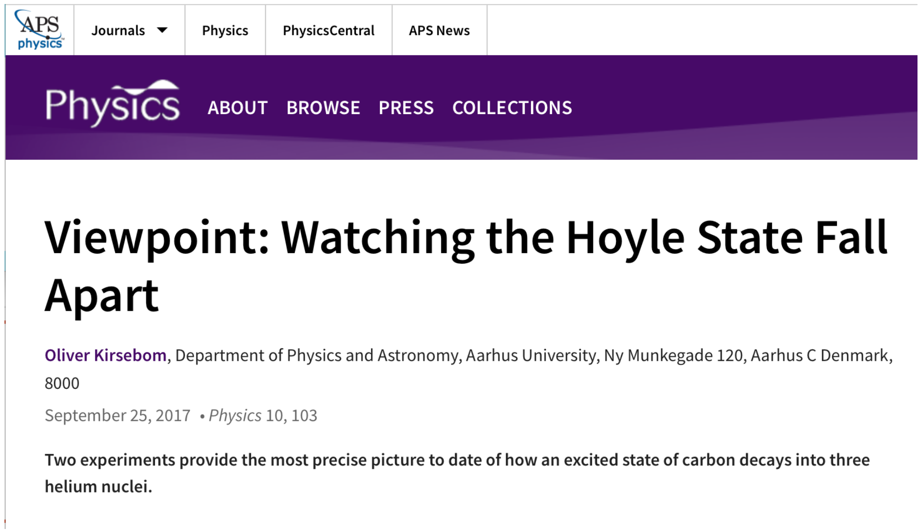
OSCAR data @ LNS



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

$^{14}N(d,\alpha)^{12}C^*$





Viewpoint: Watching the Hoyle State Fall Apart

Oliver Kirsebom, Department of Physics and Astronomy, Aarhus University, Ny Munkegade 120, Aarhus C Denmark, 8000

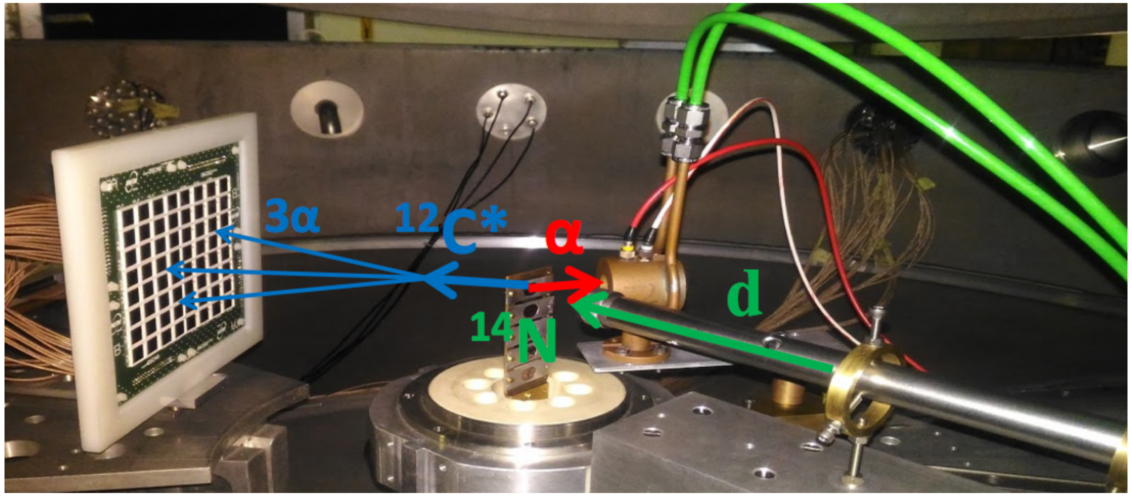
September 25, 2017 • *Physics* 10, 103

Two experiments provide the most precise picture to date of how an excited state of carbon decays into three helium nuclei.

Direct decay < 0.043% (95% C.L.)

Direct reaction measurements

OSCAR data @ LNS



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

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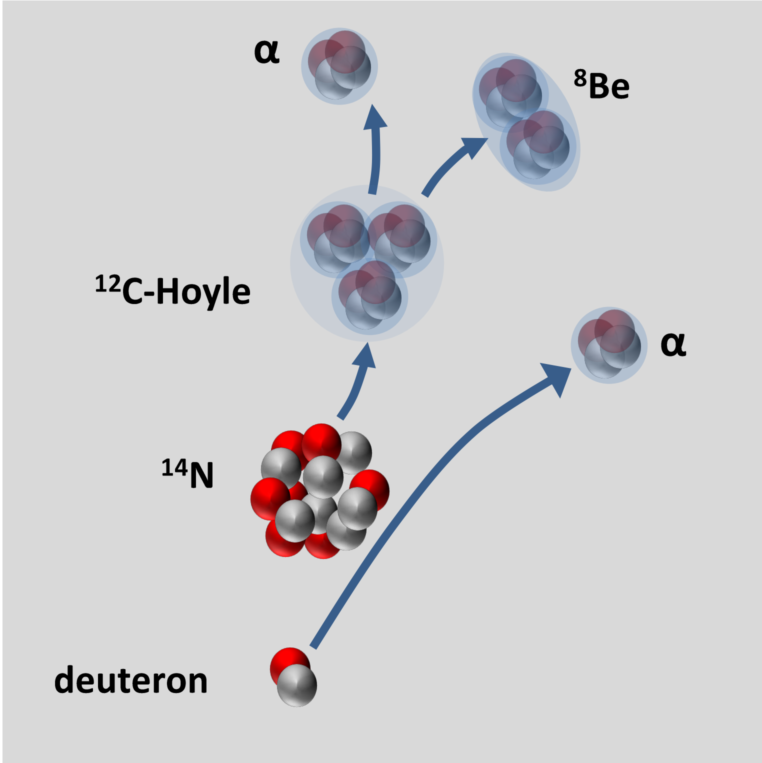
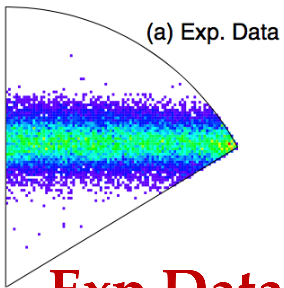
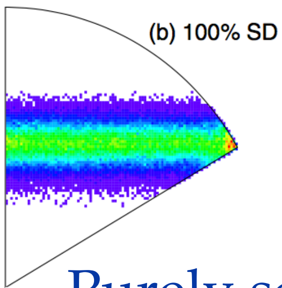
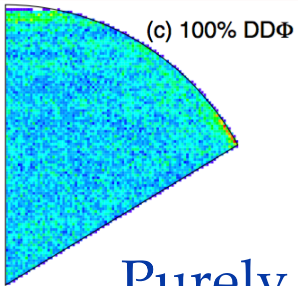




Exp Data



Purely sequential



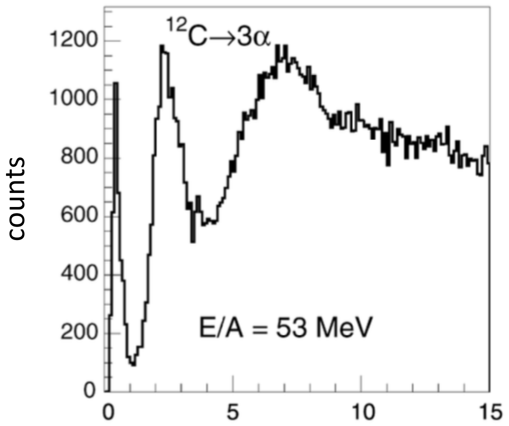
Purely direct

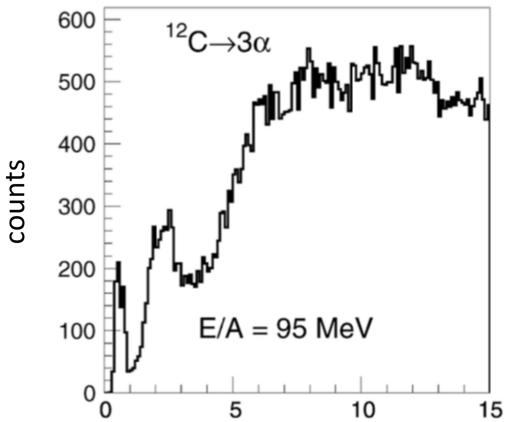
No direct decay
DD < 0.043% (95% C.L.)

In-medium heavy-ion collision experiments

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

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





$E_{SUM} = \sum_{i=1}^{3} E_{i,CM}$ (MeV)

^{12}C (Chimera and INDRA data)

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

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

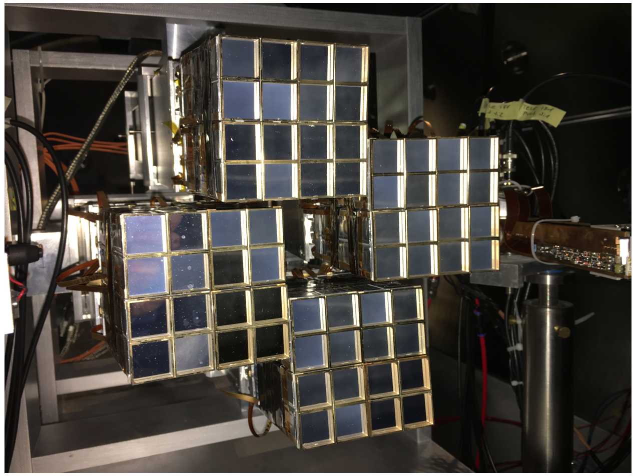
A. Raduta et al., Phys. Lett. B 705, 65 (2011)
F. Grenier et al., Nucl. Phys. A811, 233 (2008)

Strong contributions from 3α direct decay mode?

….17% in Phys. Lett. B 705, 65 (2011)!

Dedicated in-medium studies

FAZIA

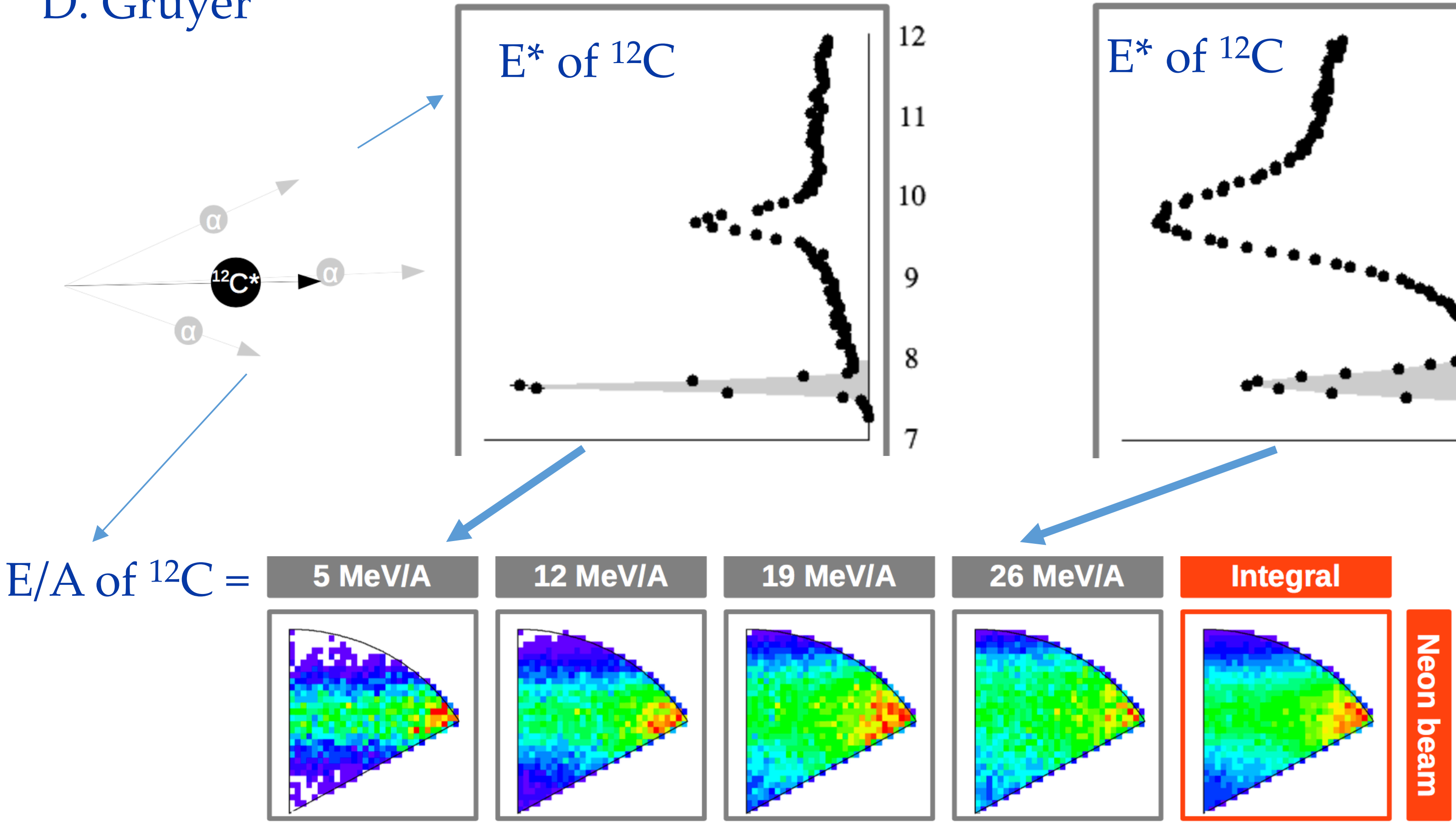


FAZIACOR @ LNS
G. Verde, D. Gruyer, FAZIA Collaboration

^{32}S + ^{12}C E/A=25, 50 MeV
^{36}S + ^{12}C E/A=25, 50 MeV … → ^{20}Ne+^{12}C

Preliminary data on the Hoyle state

D. Gruyer



Slow ^{12}C

→ Only direct decay

→ Negligible background

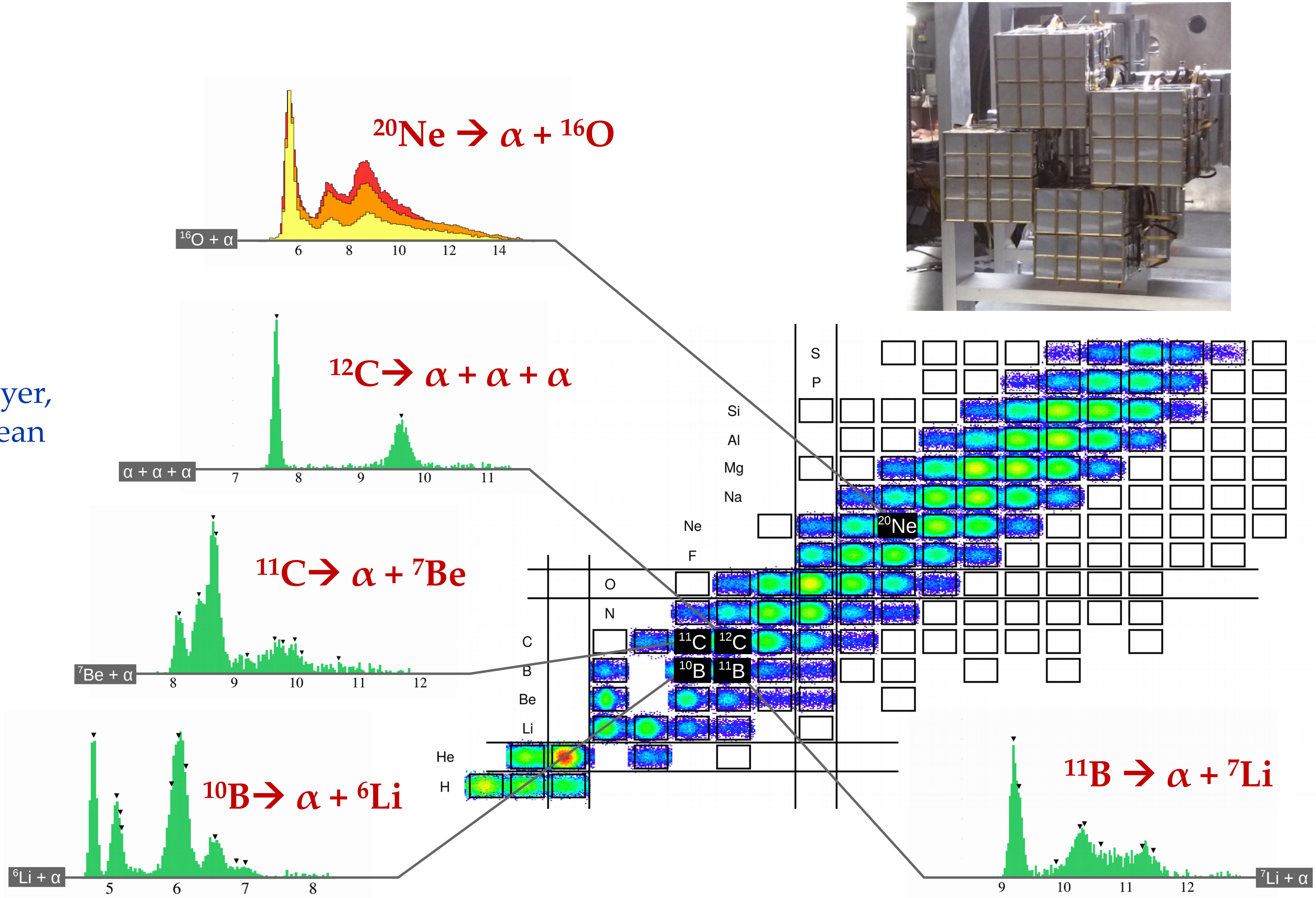
→ Agreement with out-of-medium results

Fast ^{12}C

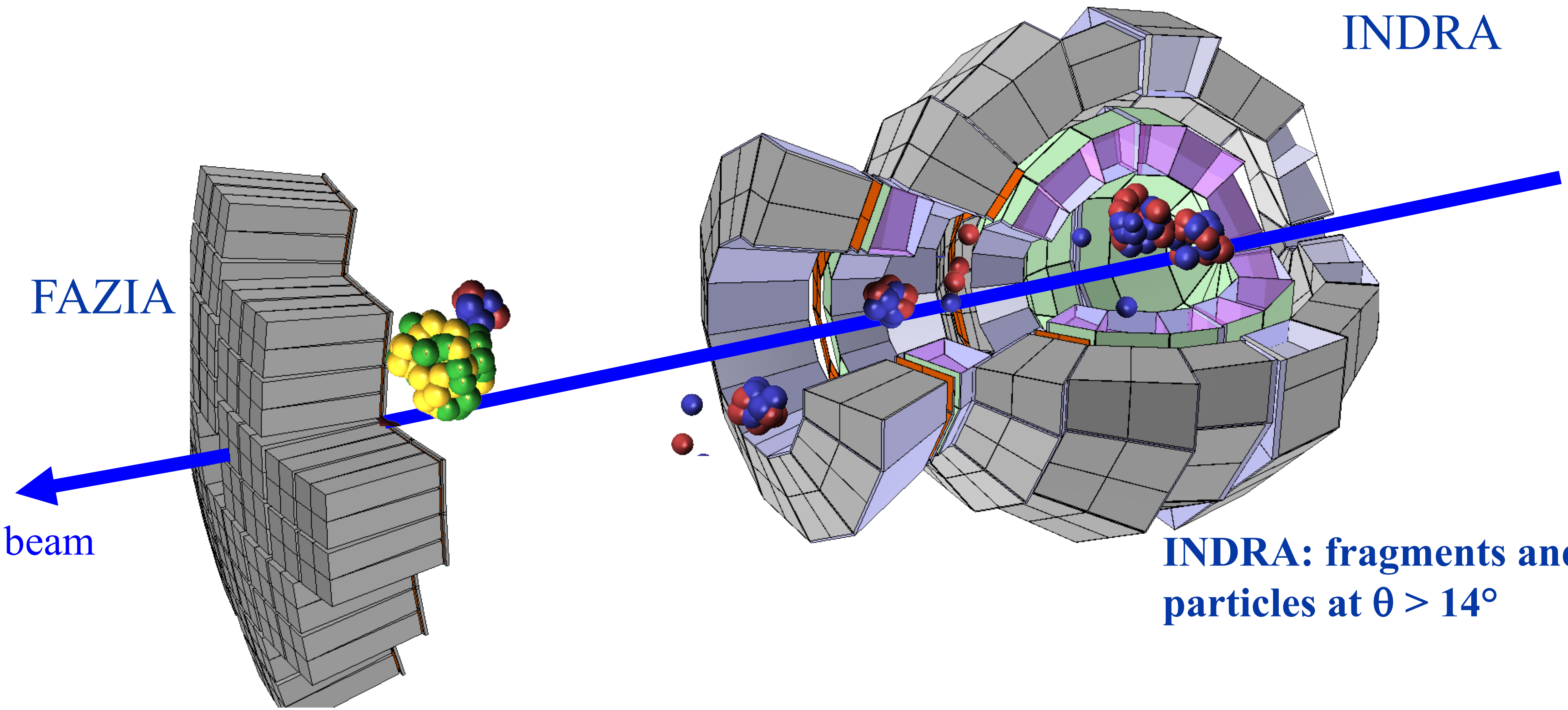
→ direct decay: Effects of medium on nuclear structure? Links to alpha density estimates… BES?

Some preliminary Nα-X correlations

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°**

Ca+Ca
Ni+Ni
Xe+Sn

E/A=30-90 MeV

…energy, mass and N/Z scan!

In-medium investigations

- HIC: warm and dilute medium with plenty of unbound states
  - Femtoscopic probes to characterize medium
  - Study structure properties: spins, branching ratios (sequential vs direct), etc…. *in-medium structure*
  - Complimentary to structure studies with exotic beams
- Modification of structure properties in resonance decays?
  - Future perspectives: INDRA-FAZIA campaigns at GANIL

    Welcome to collaborate (experiment, analysis techniques, theory)

Thank you for the organization of this WPCF: second time in the beautiful Krakow!

…how about having a second-time WPCF in Catania?
for example 2020 or 2021? Eventually joint organization?

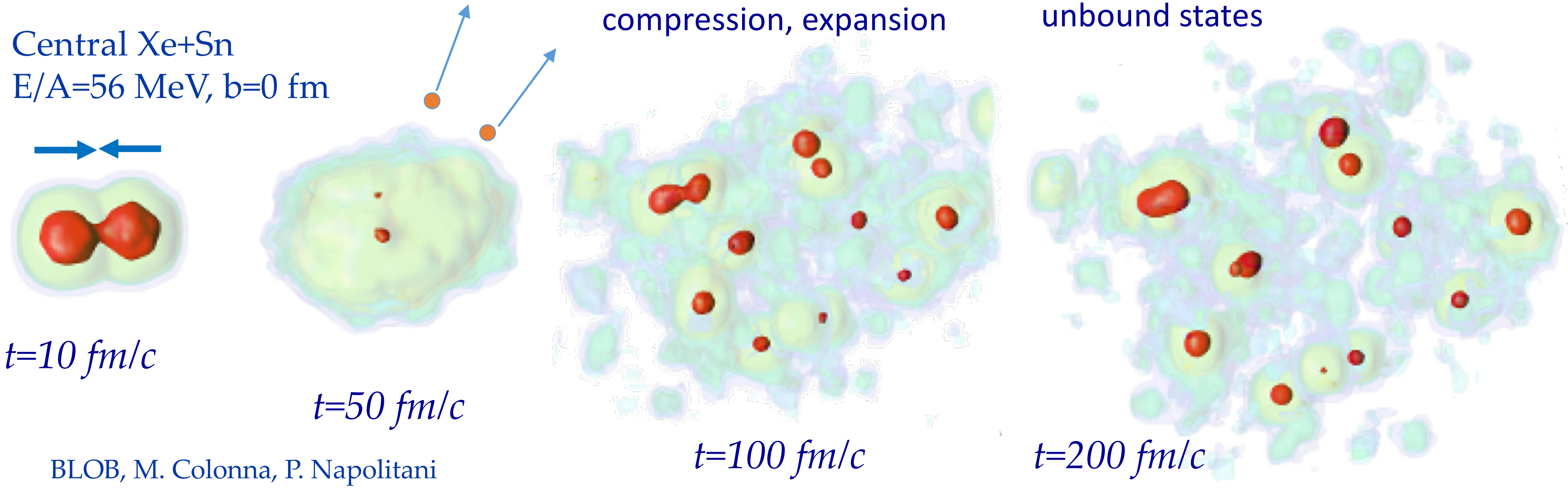
Backup slides

Intermediate energy dynamics

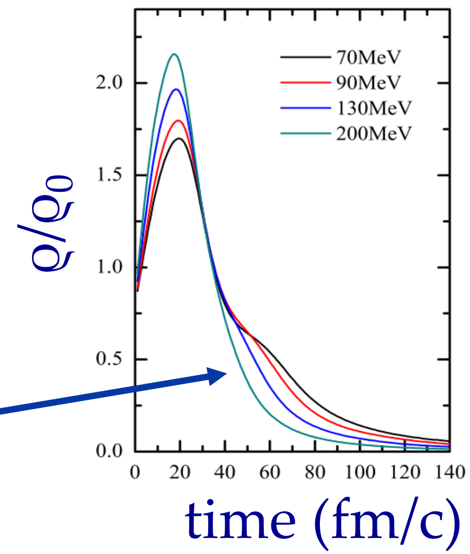
Central Xe+Sn
E/A=56 MeV, b=0 fm

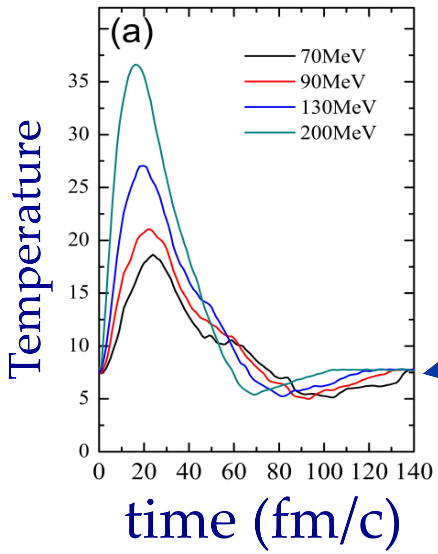
Pre-equilibrium,
compression, expansion

Fragments, clusters,
unbound states



BLOB, M. Colonna, P. Napolitani





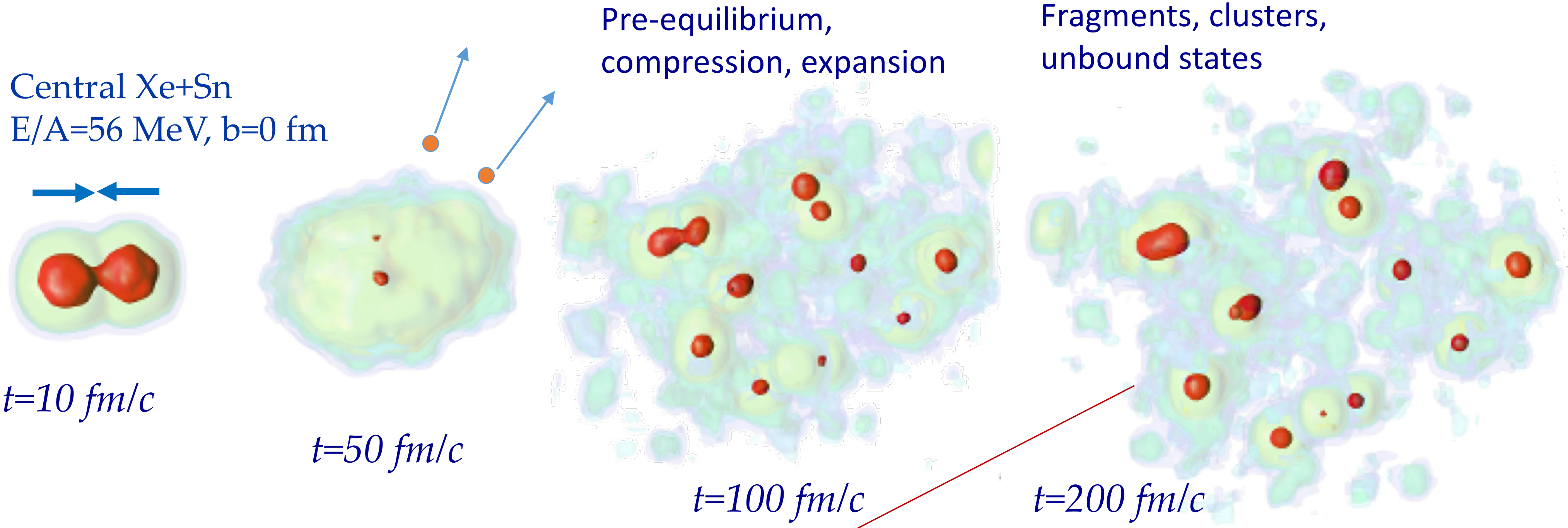
Transport model simulations

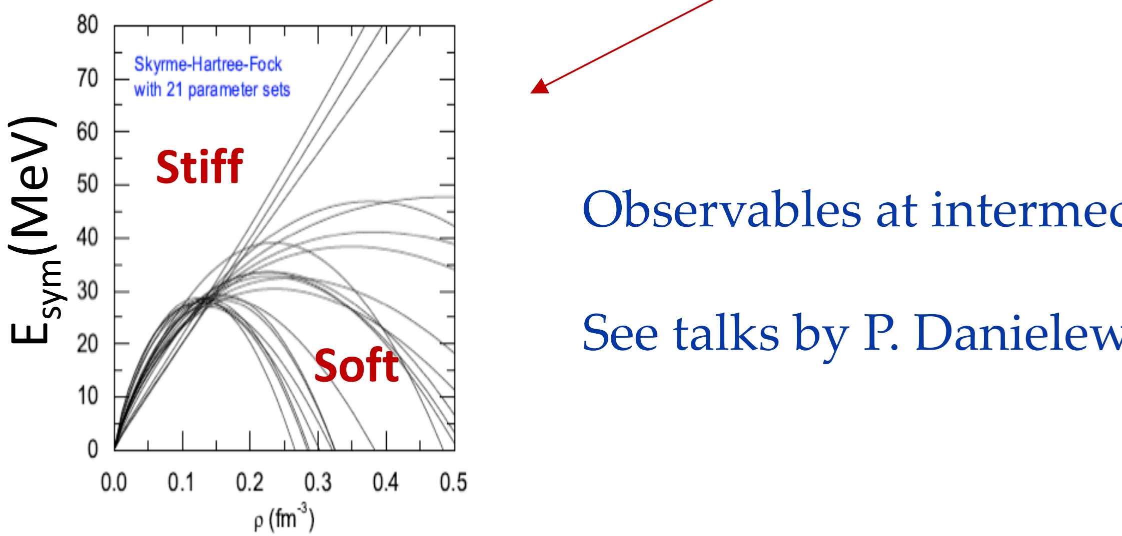
Finite temperatures

Sub-saturation densities

Intermediate energy dynamics

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

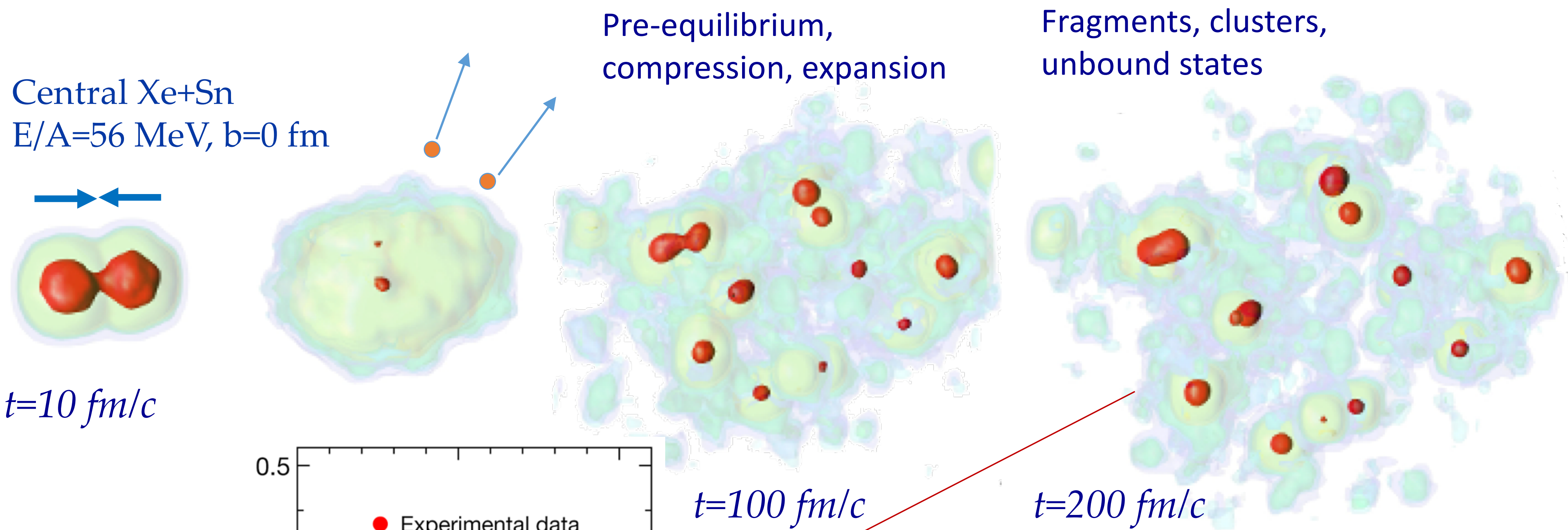


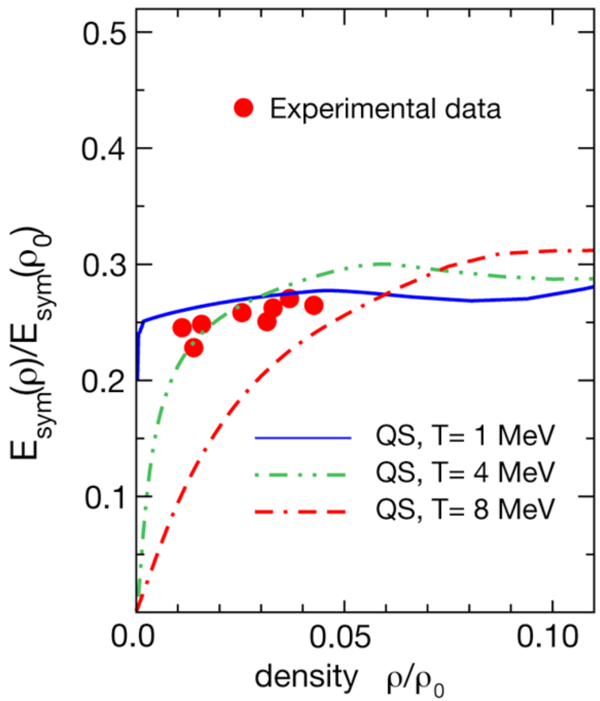


Observables at intermediate Energies:

See talks by P. Danielewicz and Z. Chajecki

Interplays dynamics ↔ structure





- Important role of clusters at low density and finite temperatures
  Femtonova (talk by K. Hagel)

→ **in-medium effects on structure**

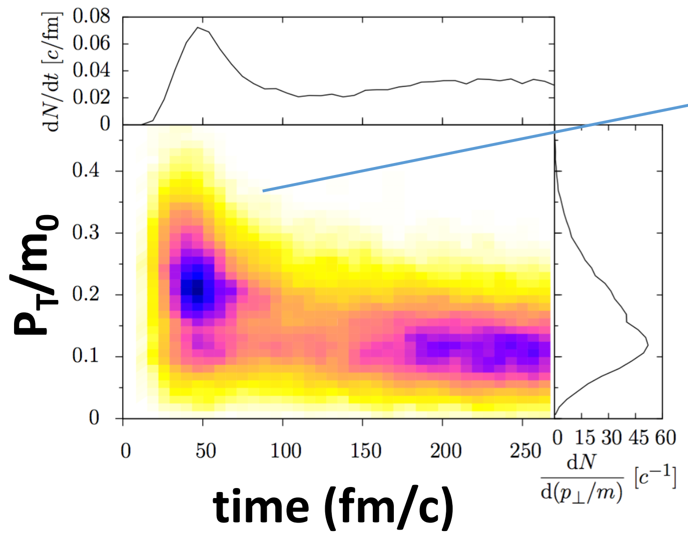
J. Natowitz et al., Phys. Rev. Lett. 104, 202501 (2010)

Imaging sources at different emission stages

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

Early dynamical emissions

Late long-lived sources



High PT protons emitted at early dynamical stage

BUU simualtions

T. Minniti, F. Miano, GV, B. Barker, P. Danielewicz

Imaging sources at different emission stages

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

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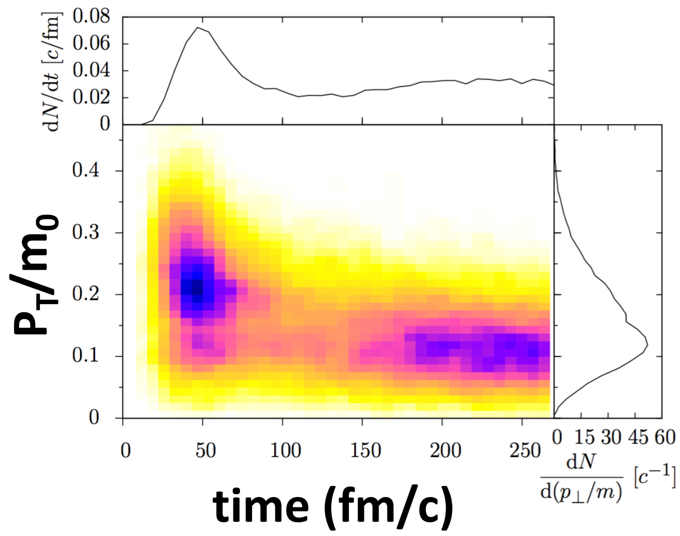
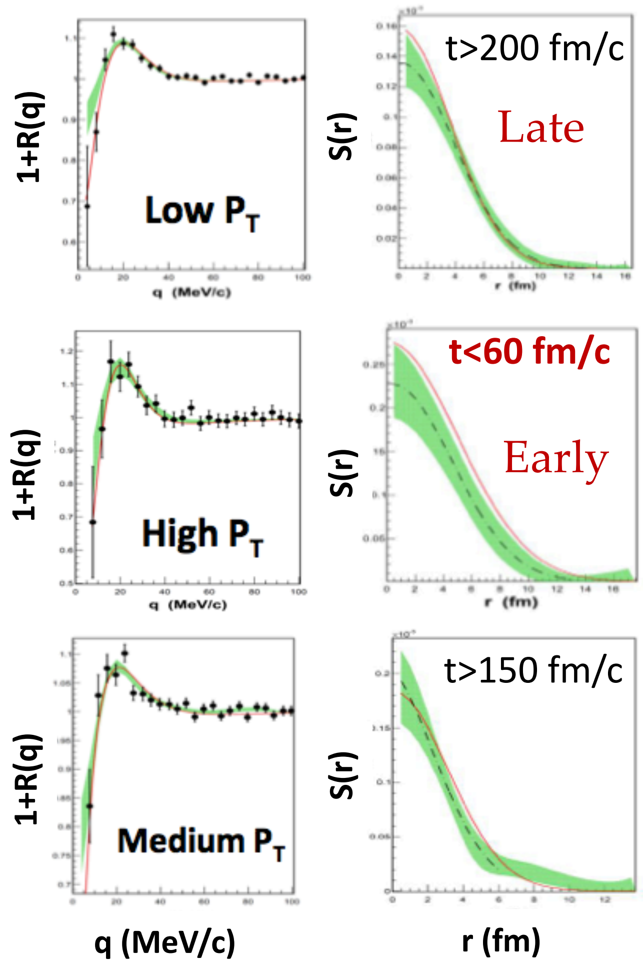


BUU simualtions

Experimental data (LASSA @ MSU)



T. Minniti, F. Miano, GV, B. Barker, P. Danielewicz

Imaging sources at different emission stages

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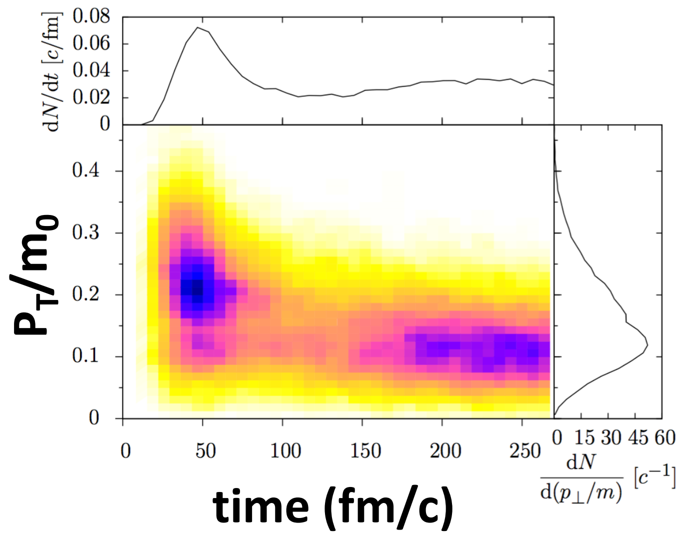

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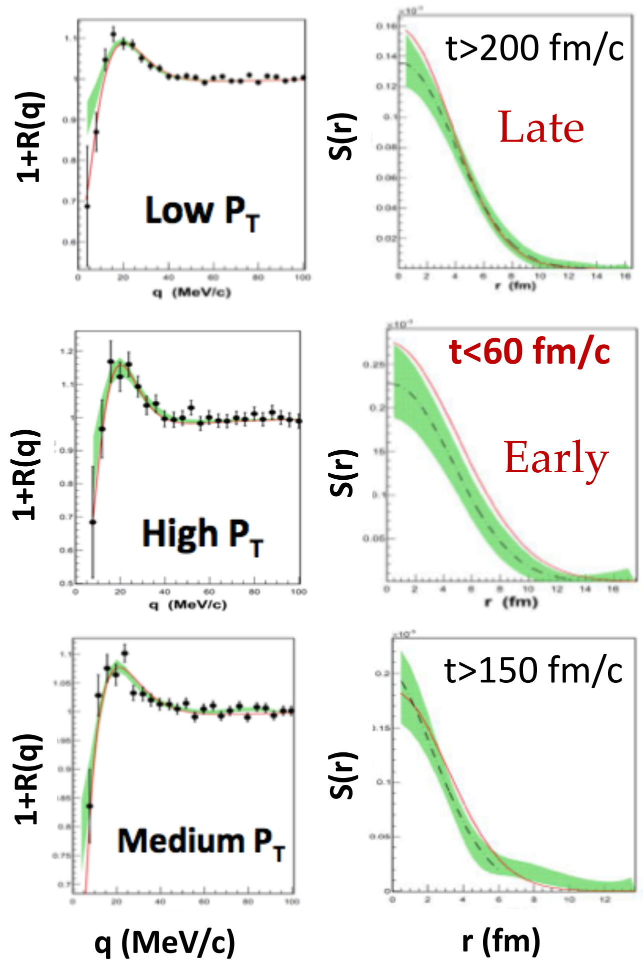
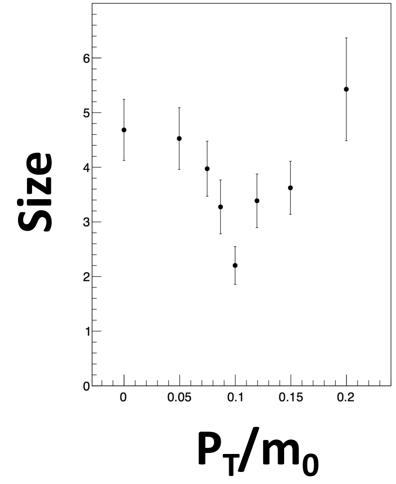
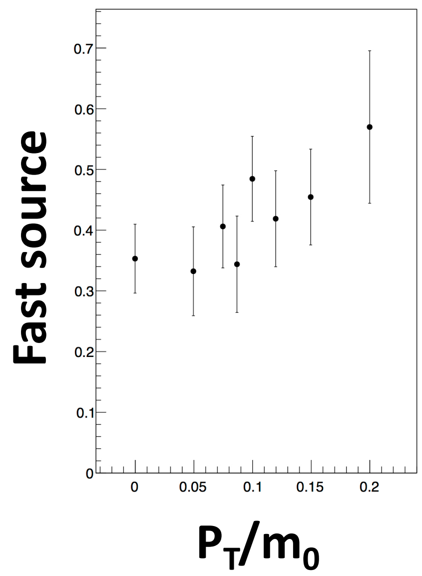


Source size

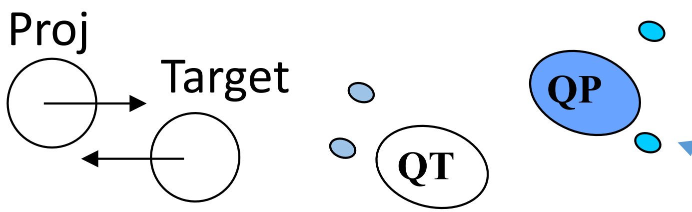


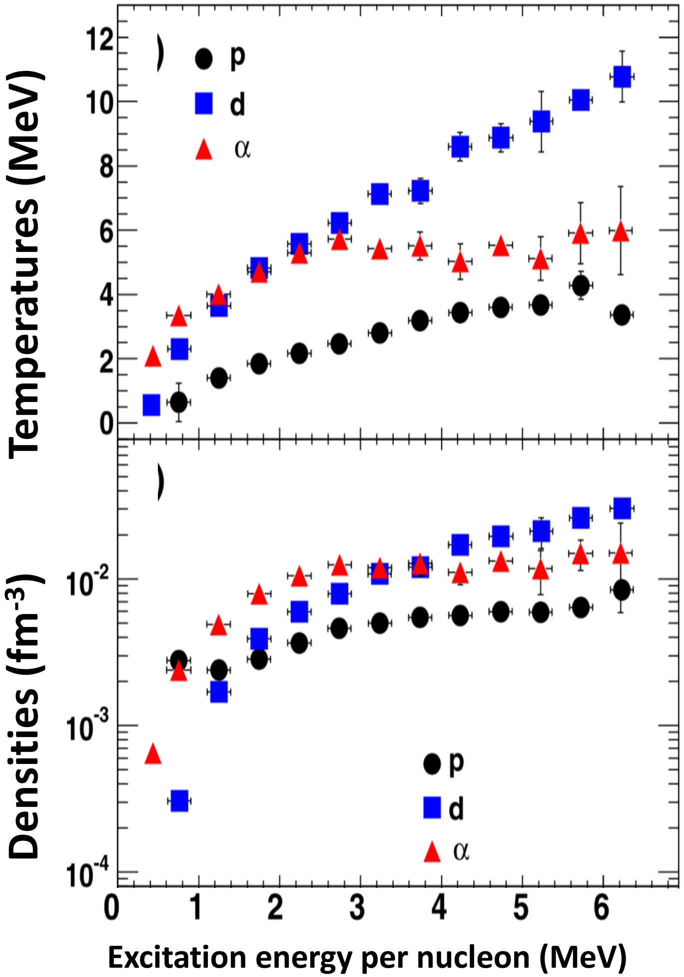
% of dynamical early emissions



T. Minniti, F. Miano, GV, B. Barker, P. Danielewicz

Densities "as seen" by bosons and fermions





INDRA-VAMOS experiment

^{40}Ca + ^{40}Ca @ E/A = 35 MeV

Decay of excited quasi-projectile

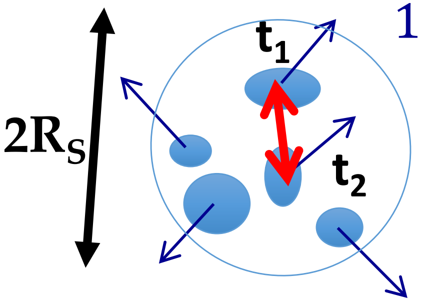
- Different particle species probe different densities and temperatures
- Mixtures of bosonic and fermionic hot matter at sub-saturation density

P. Marini, H. Zheng, M. Boisjoli, G. Verde, A. Chbihi et al.
Phys. Lett. B 756, 194 (2016)

Fragment emission time-scales

IMF-IMF Correlation Functions

IMF: Z>2



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

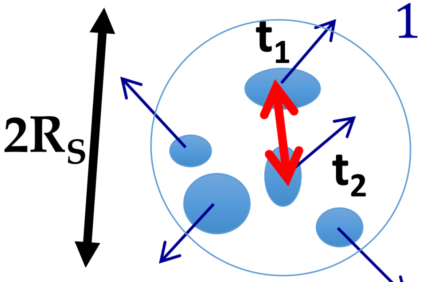
$$v_{red} = \frac{|\vec{v}_1 - \vec{v}_2|}{\sqrt{Z_1 + Z_2}}$$

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

Fragment emission time-scales

IMF-IMF Correlation Functions

IMF: Z>2



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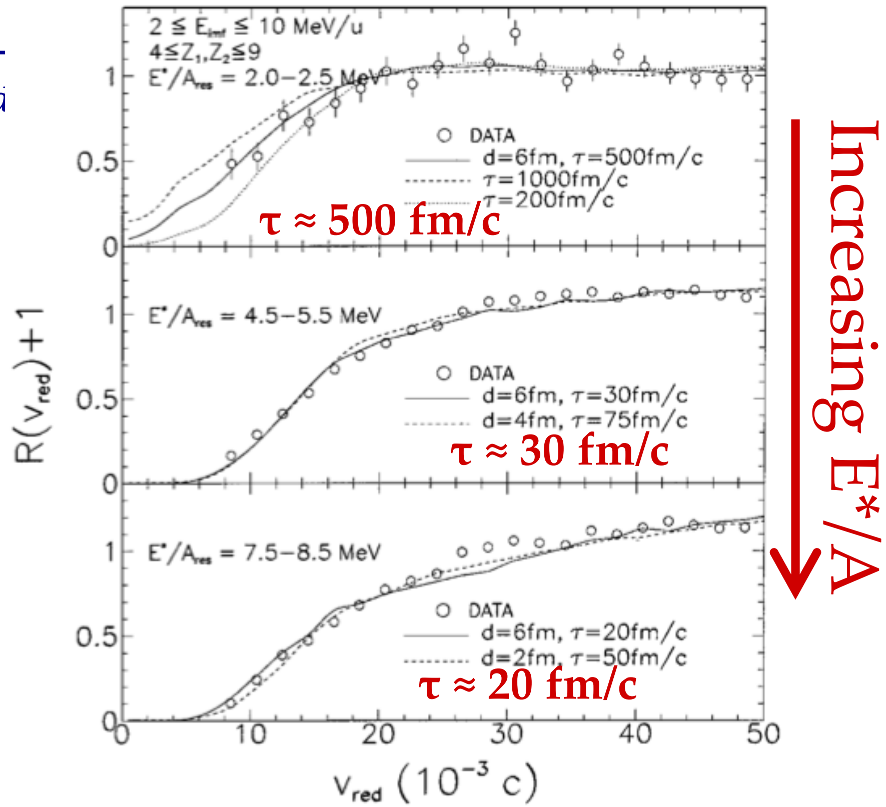
Compact thermal
source (T, β_{coll}, …)

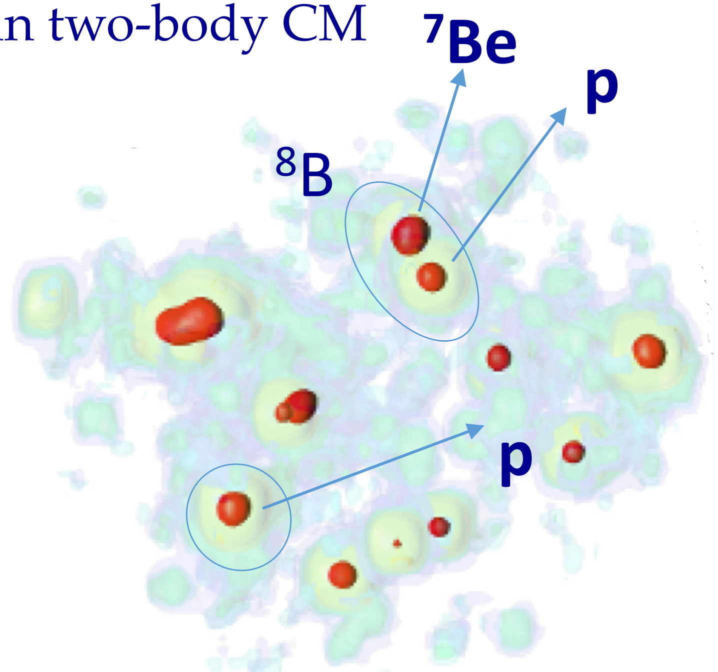
N-body Coulomb trajectories
Source radius and emission times:
R_S, $P(t) = (1/\tau) \cdot \exp(-t/\tau)$ → **τ**

π^-, p + Au 8.0, 8.2, 9.2, 10.2 GeV/c



Two-particle correlations: resonances in dilute nuclear medium

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



Particle emitting sources extended in phase-space

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

$$E^*(^8B) = -Q_{decay} + \frac{1}{2} M_p v_p^2 + \frac{1}{2} M_{7Be}$$

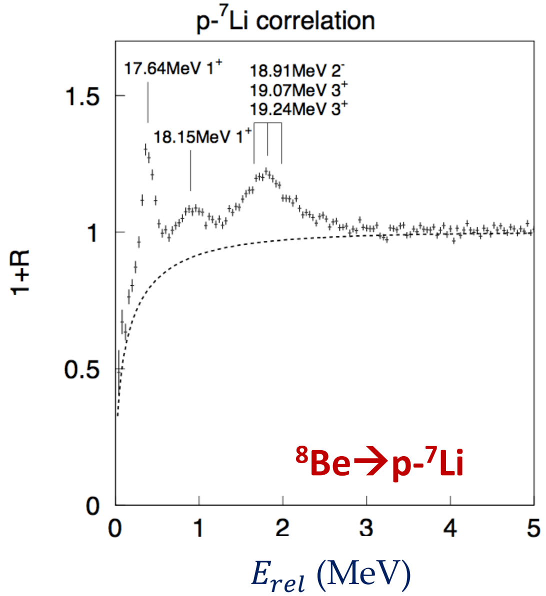
$$= -Q_{decay} + \frac{1}{2} \cdot \mu v_{rel}^2 = -Q_{decay} + E_{rel}$$

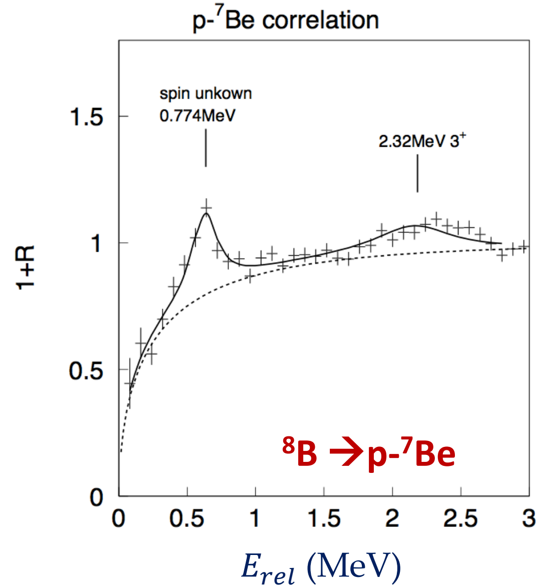
Correlation function:

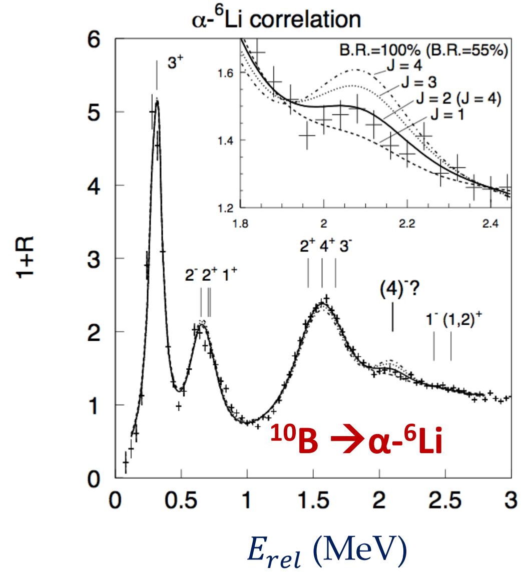
$$1 + R(E_{rel}) = \frac{Y_{coinc}(^7Be, p)}{Y_{evt\ mixing}(^7Be, p)}$$

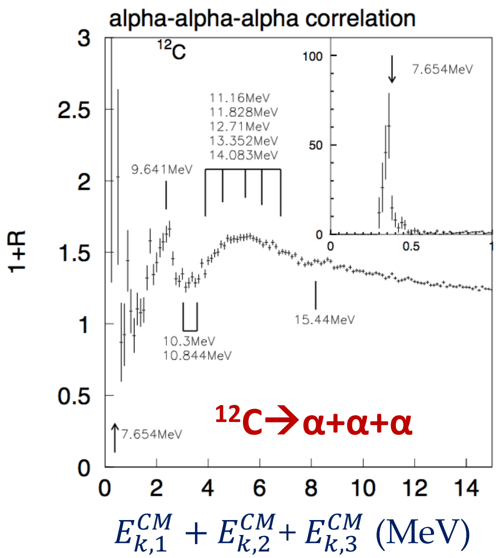
Resonance decays in dilute and warm nuclear medium

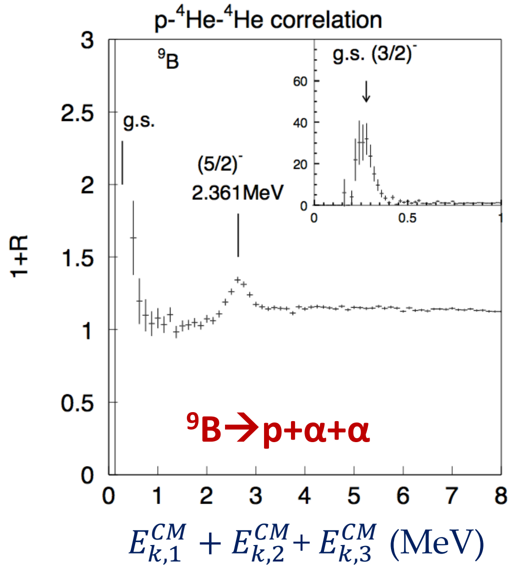
^{112}Sn+^{112}Sn E/A=50 MeV

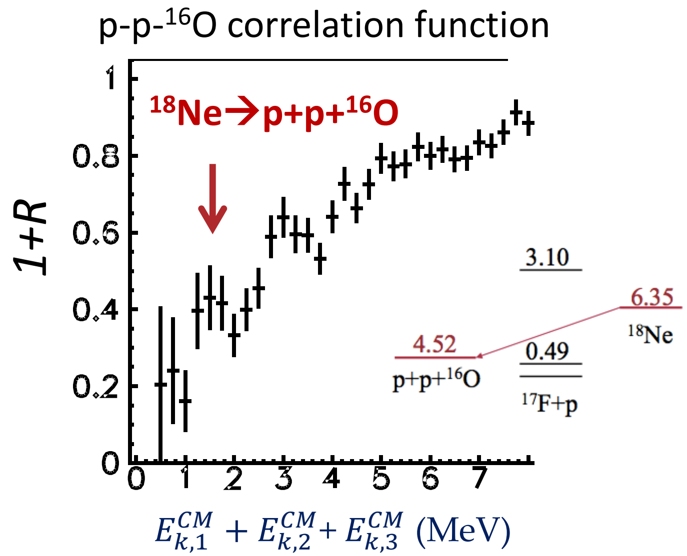






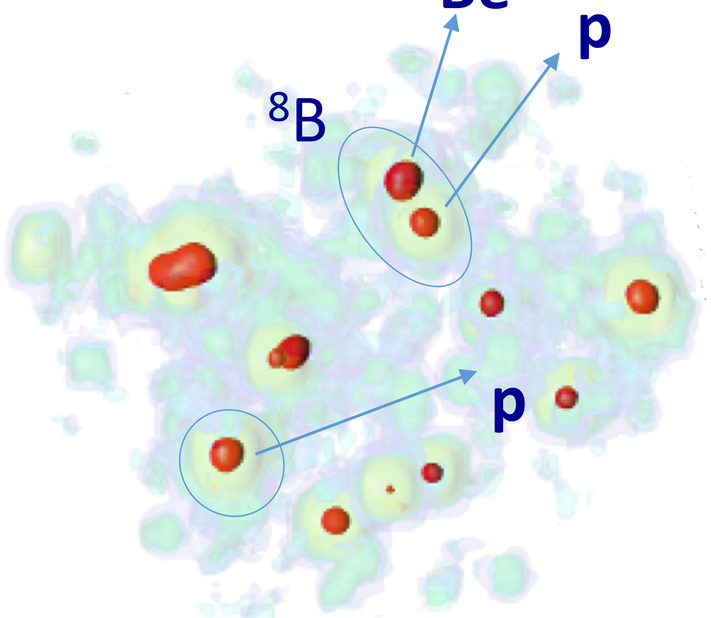






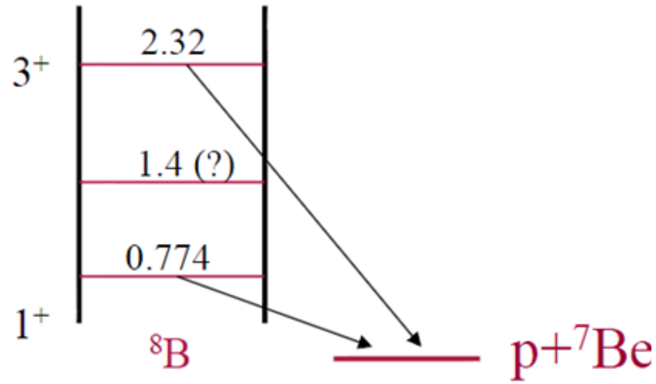
Thermal model of in-medium resonance decays

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



Particle emitting sources extended in phase-space

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

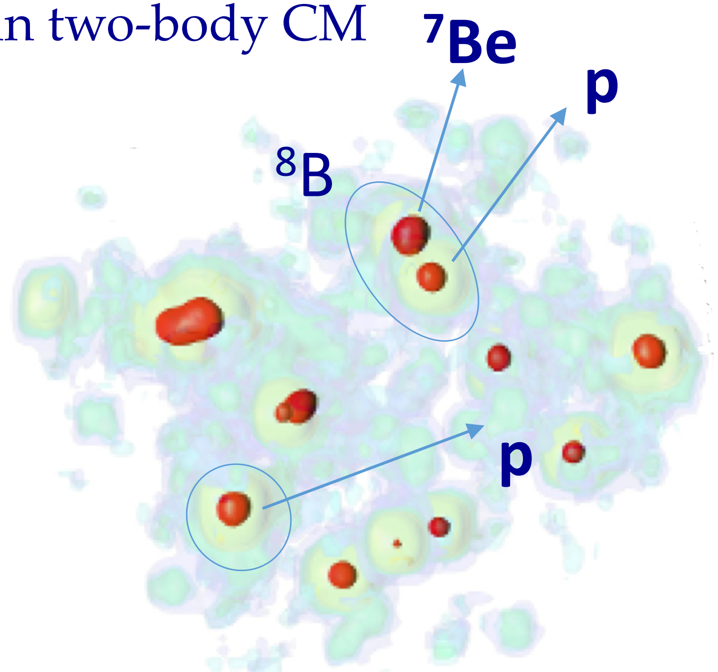


Correlation function:

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

Thermal model of in-medium resonance decays

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



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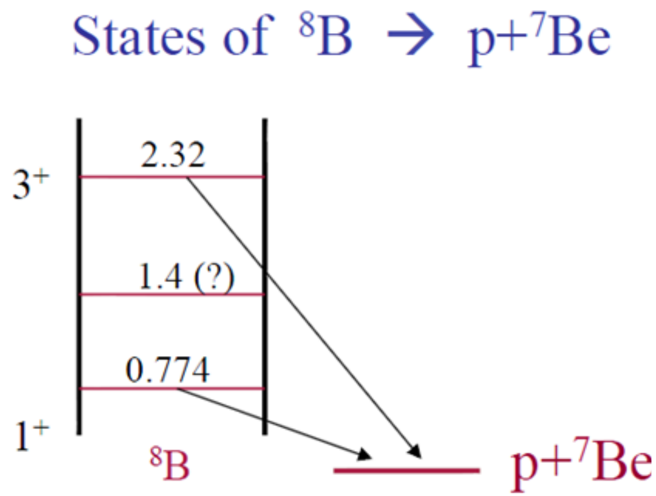


$$Y_{nucl}(E^*) = \frac{N}{\pi} e^{-E^*/T} \sum_i (2J_i + 1) \left[\frac{\Gamma_i/2}{(E^* - E_i)^2 + \Gamma_i^2/4} \right]$$

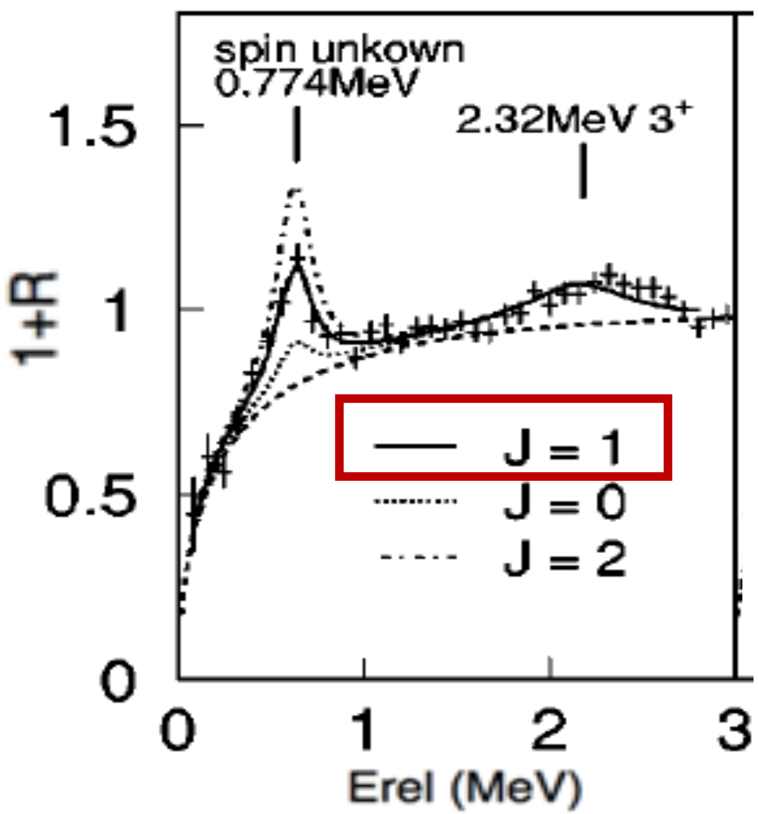
In-medium temperature

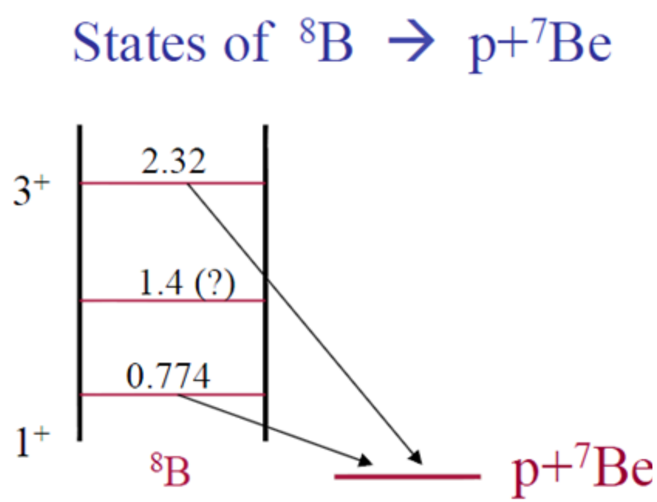
Nuclear structure: spin, branching ratios, resonance position

In-medium structure: spin

p-^{7}Be correlation function

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





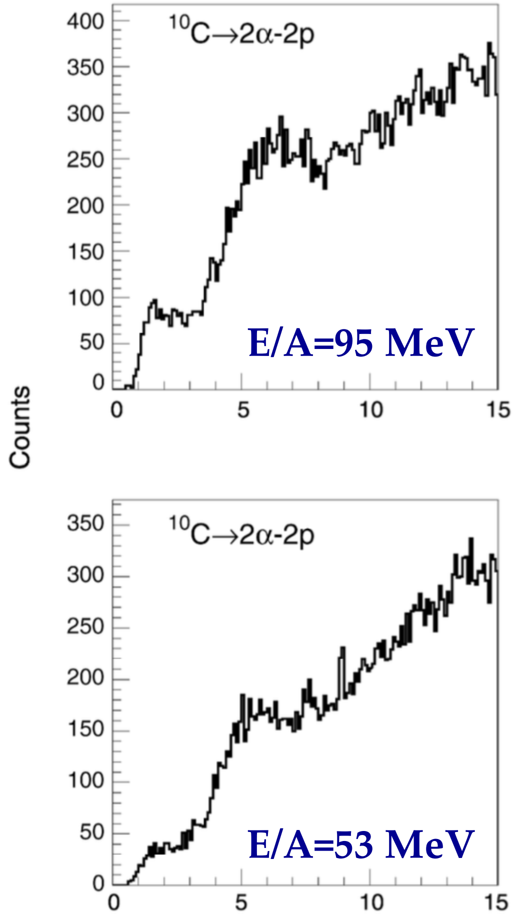
Xe+Au E/A=50 MeV central collisions (LASSA data)

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

Other cluster correlations: N>2

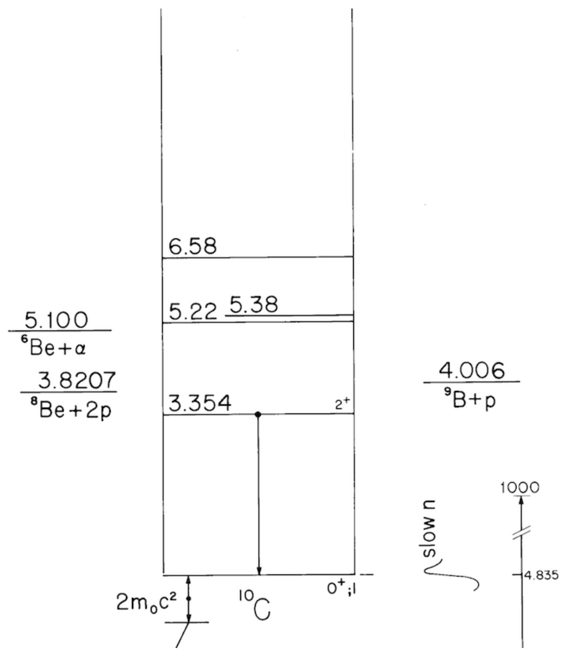
$\alpha + \alpha + \mathrm{p} + \mathrm{p}$

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



E_{sum} (MeV)

^{10}C



$Q_{decay} = -3.7\ MeV$

$E_{sum} = \sum_{i=1}^{4} E_{k,i}$ (MeV)

Doubly Borromean (Brunnian) nuclear system

F. Grenier et al., Nucl. Phys. A811, 233 (2008)

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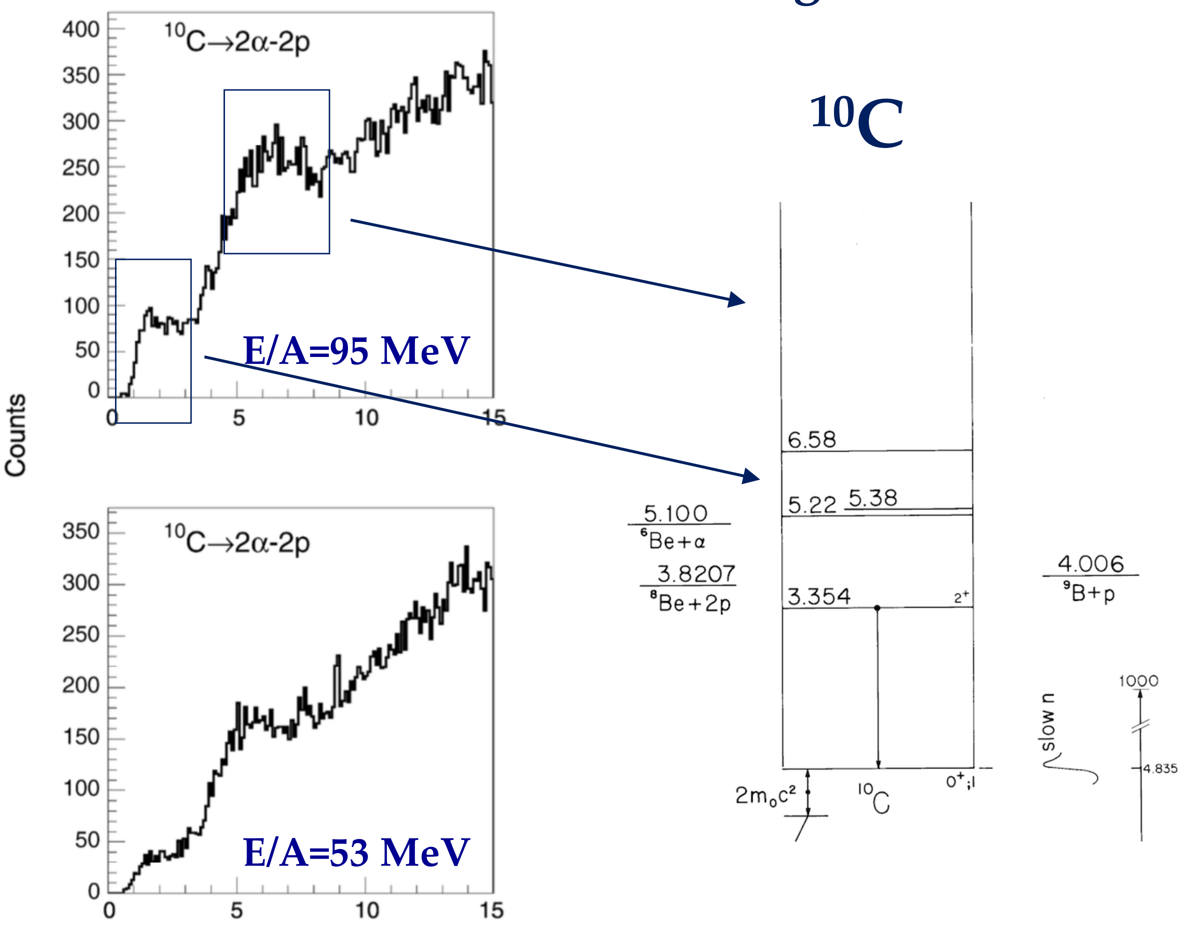

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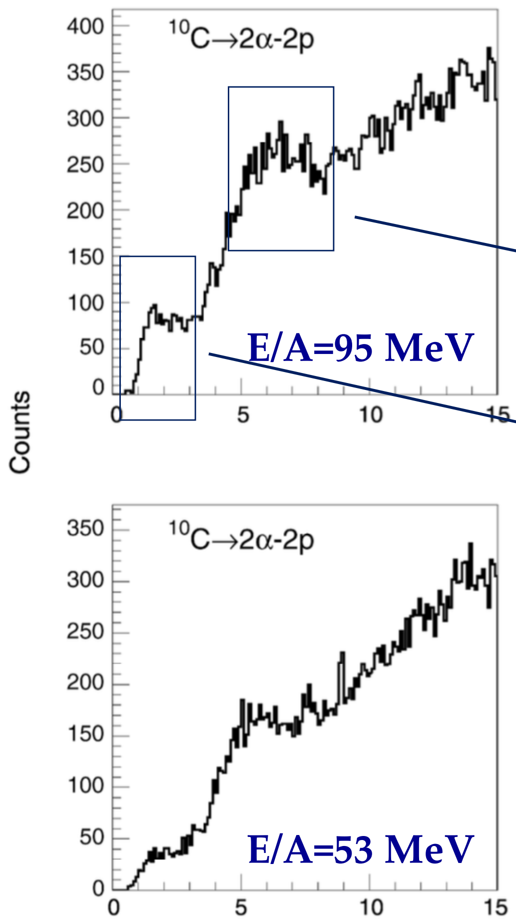
Doubly Borromean (Brunnian) nuclear system

F. Grenier et al., Nucl. Phys. A811, 233 (2008)

In-medium structure: branching ratios

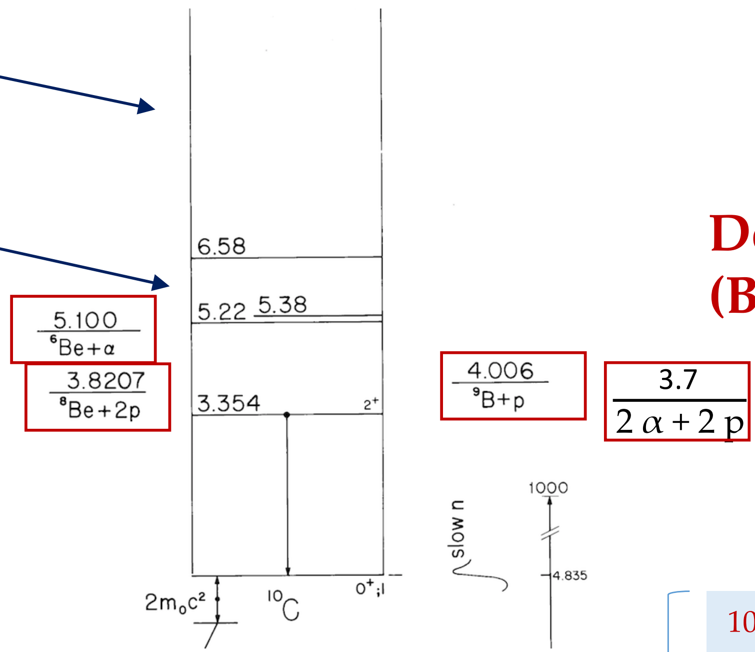
$\alpha + \alpha + p + p$

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



E_{sum} (MeV)

^{10}C



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Doubly Borromean (Brunnian) nuclear system

Sequential

- $^{10}C^* \rightarrow {}^{6}Be+\alpha \rightarrow (2p+\alpha)+\alpha$
- $^{10}C^* \rightarrow {}^{8}Be+p+p \rightarrow (\alpha+\alpha)+p+p$
- $^{10}C^* \rightarrow {}^{9}B+p \rightarrow (p+\alpha+\alpha)+p$

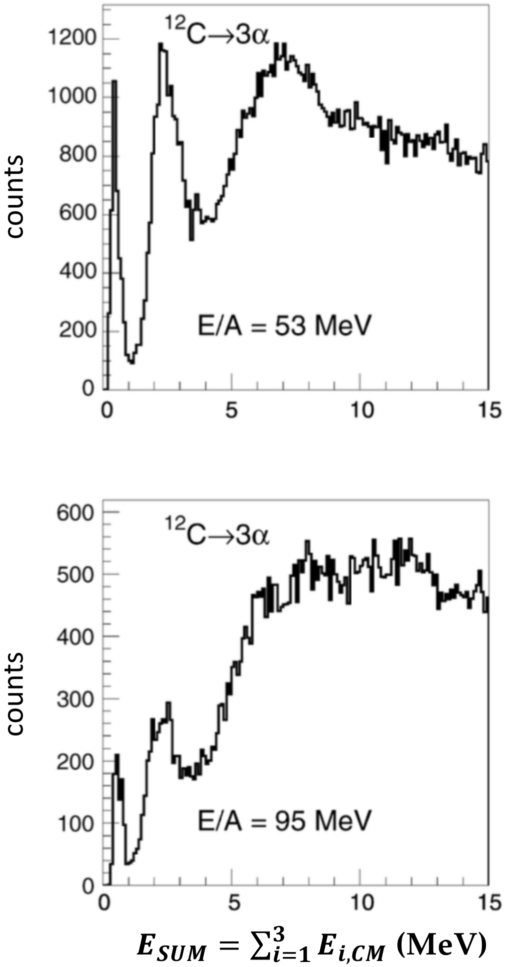
Direct

- $^{10}C^* \rightarrow \alpha+\alpha+p+p$

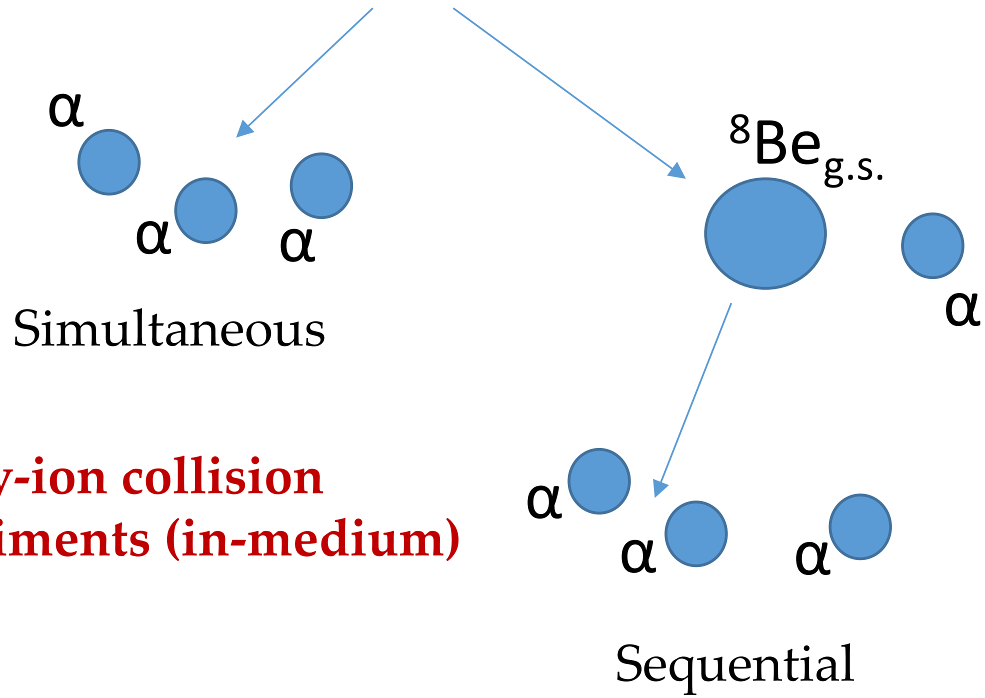
In-medium vs out-of-medium?

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

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



^{12}C E*=7.65 MeV (Hoyle state)

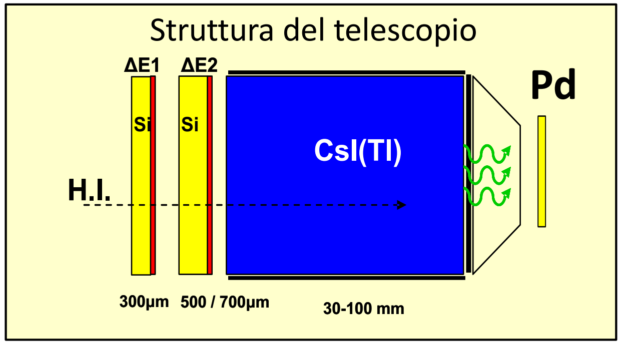


Heavy-ion collision experiments (in-medium)

Direct transfer reaction experiments (out-of-medium, "vacuum")

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)

FAZIACOR experiment (March 2017)

G. Verde, D. Gruyer, FAZIA Coll.

^{20}Ne, ^{32}S + ^{12}C

E/A=25 and 50 MeV