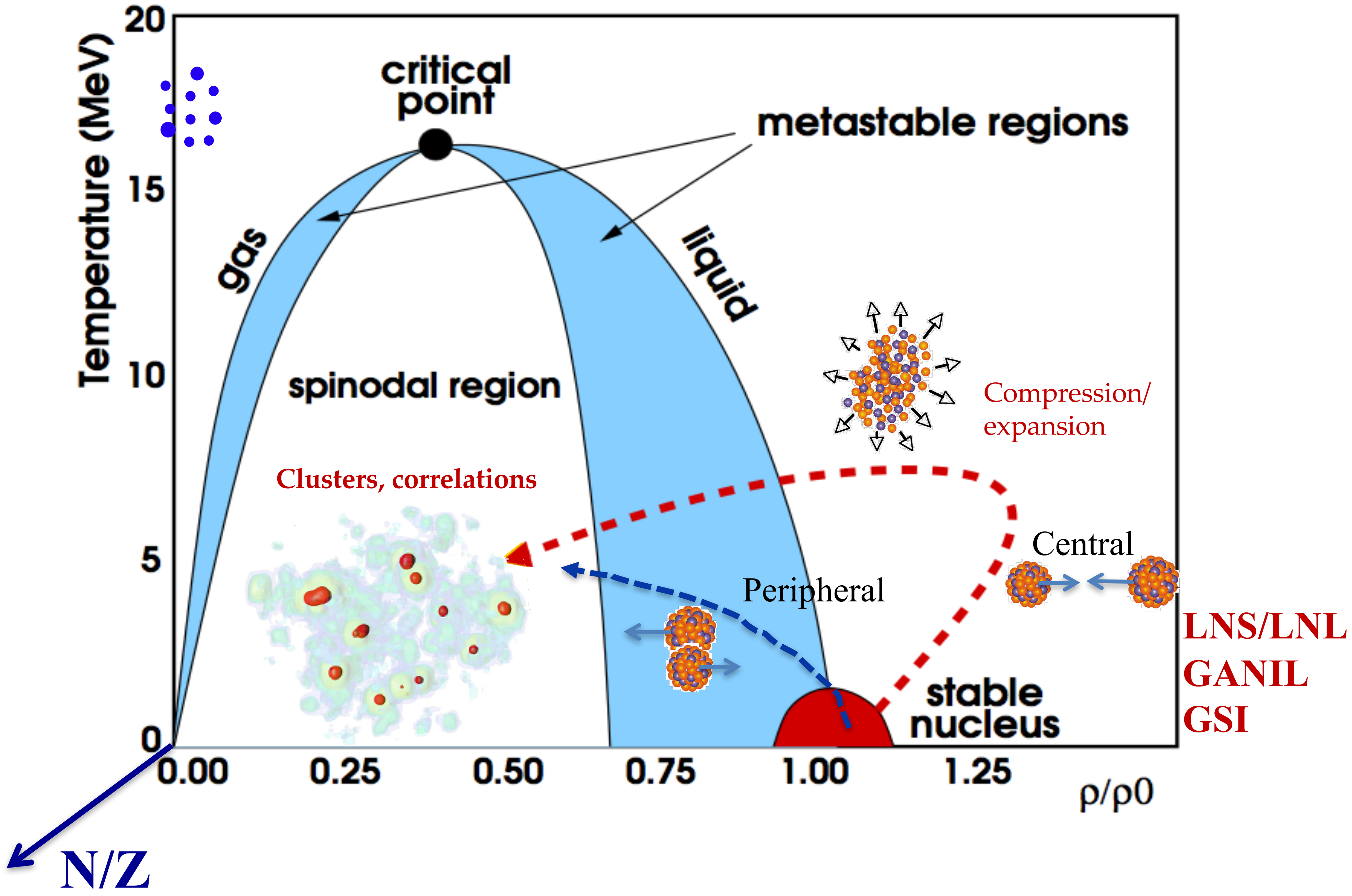
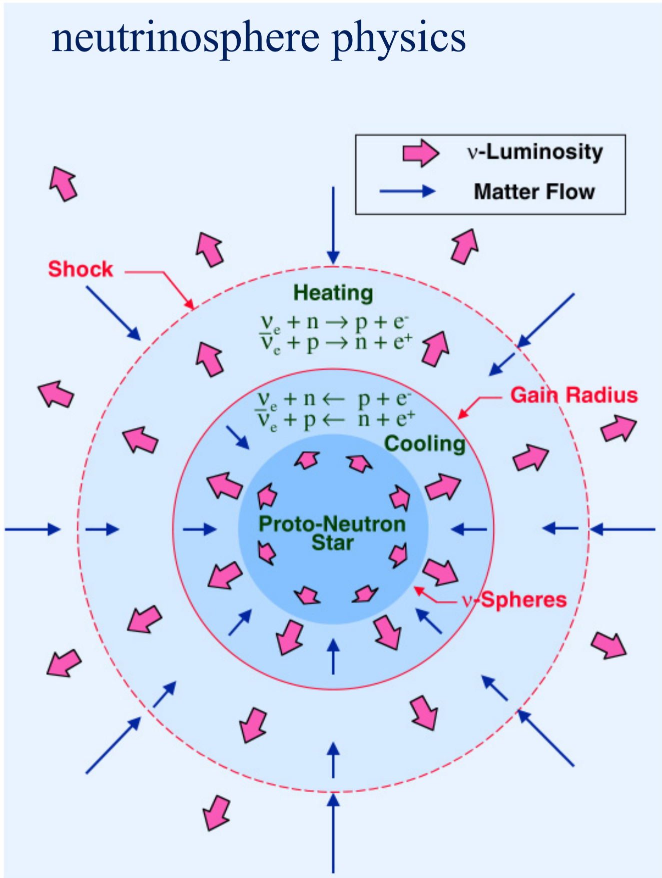
Correlations & Femtoscopy

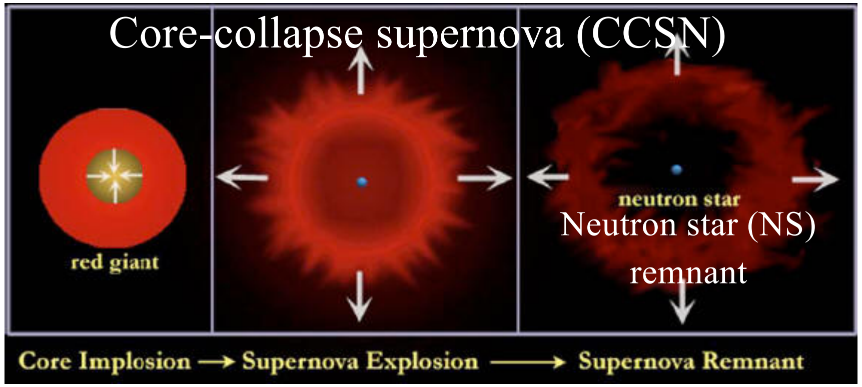
- Context: heavy-ion collisions and in-medium nuclear interaction (not only EoS)
- Femtoscopy
  - Densities, temperatures, time-scales,
  - Methodology: measuring the (space-time) size nuclear N-body systems (quantum) under the effect of nuclear forces
- Multi-particle correlations
  - Nuclear structure of hot matter at sub-saturation density
  - Methodology: resonance decays

"low-energy" nuclear phase diagram



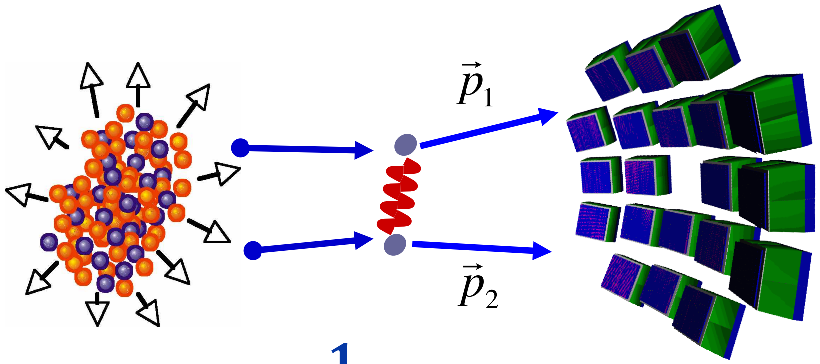
Supernovae neutrinos and the structure of dilute nuclear matter





- Role of weak processes on neutrino-wind nucleosynthesis
- Opacity of nuclear matter at T>0 and $\rho < \rho_0$ to neutrinos

Correlation functions and Final State Interactions (FSI)



$$\vec{q} = \frac{1}{2}(\vec{p}_1 - \vec{p}_2)$$

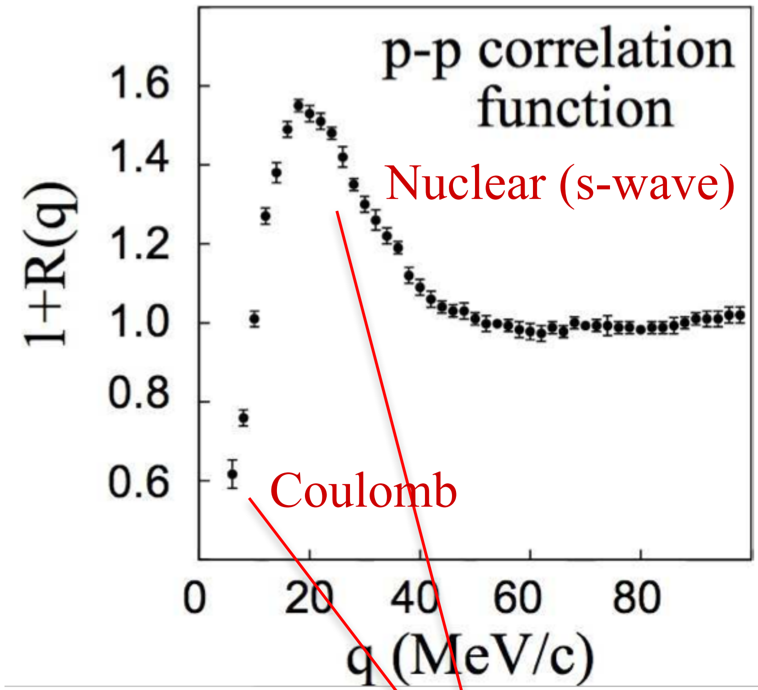
Two-proton coincidence yields

$$Y_{coinc}(q)$$

Two-proton uncorrelated yields (event-mixing)

$$Y_{evt.mix}(q)$$

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



1. Final state interactions FSI (nuclear, Coulomb)

2. Quantum statistics QS

Anti-symmetrization of wf (fermions)

Space-time extent of the source

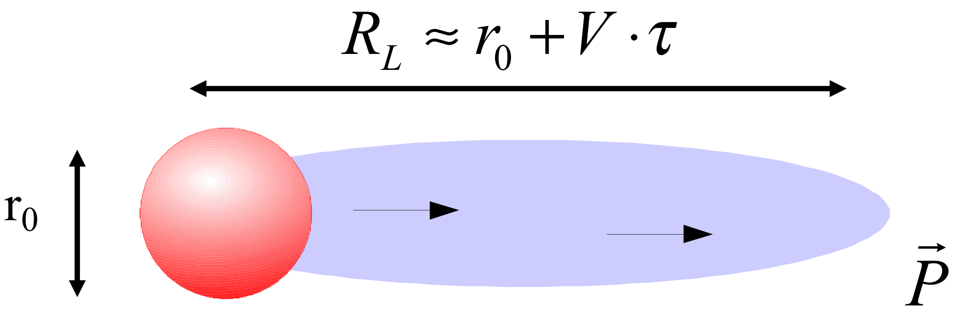
$$R(\vec{q},\vec{P}) = \int d\vec{r} \cdot S_{\vec{P}}(\vec{r}) \cdot K(\vec{r},\vec{q})$$

Koonin-Pratt Equation

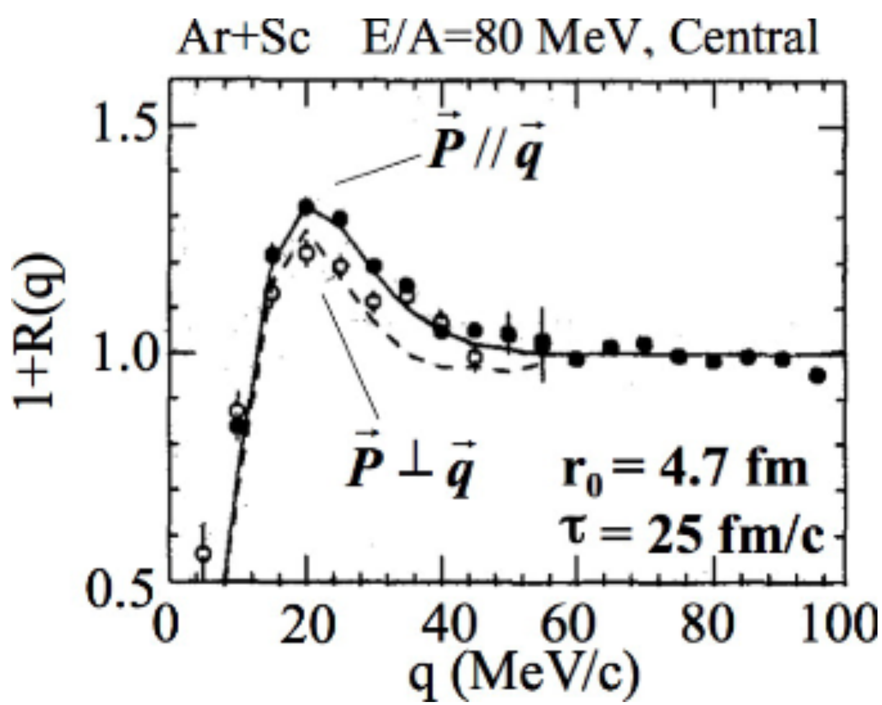
Correlation function

Source function: probability of emitting a pair of particles separated by r (at at the time the second one is emitted)

- If $t_1 \neq t_2$ (no simultaneous emission)

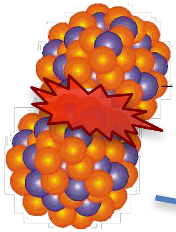


see also G.F. Bertsch, NPA 498, 173 (1989)



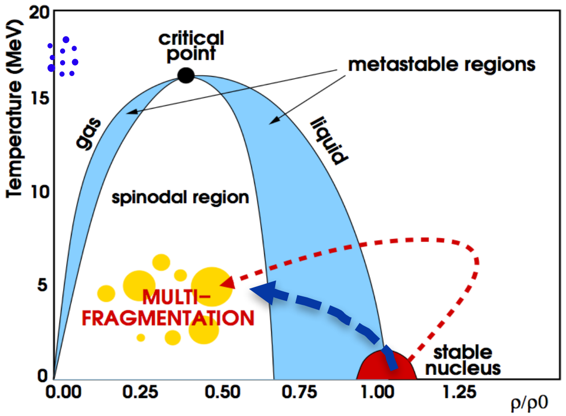
M.A. Lisa et al., Phys.Rev.Lett. 71, 2863 (1993)

Target spectators at GSI (ALADiN)



Au+Au   E/A=1 GeV

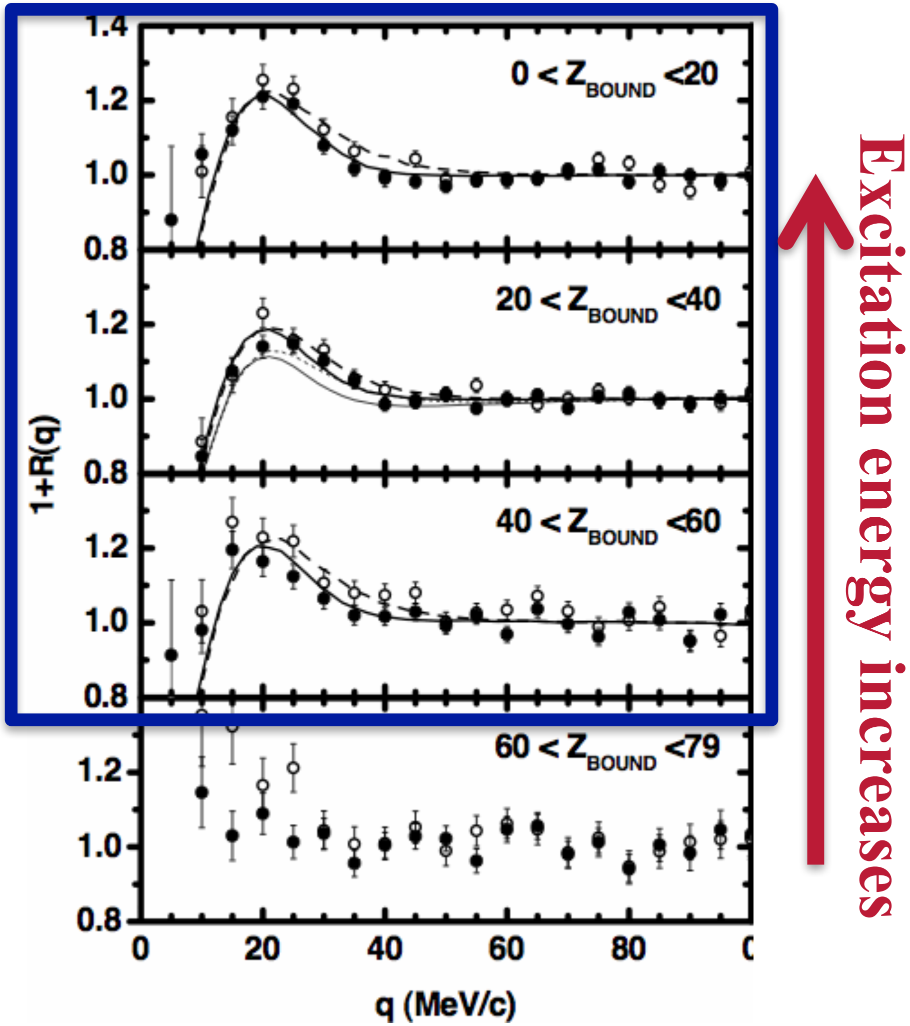
Target spectators decay



- Emission times: τ_{pp} **~ 20-30 fm/c**

→ Densities $\varrho/\varrho_0 \sim 0.15\text{-}0.4$

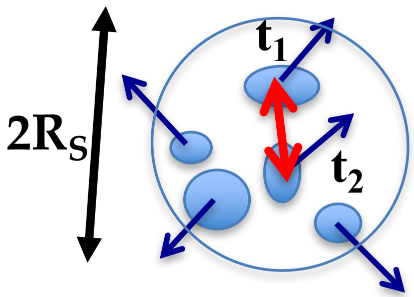
HodoCT (INFN): Si+CsI(Tl)



V. Serfling et al., Phys. Rev. Lett. 80, 3928 (1998)
S. Fritz et al., Phys. Lett. B461, 315 (1999)

Time-scales with IMF-IMF correlations

IMF: Z>2



Correlations dominated by Coulomb (spinodal region at sub-saturation densities)

$$V_{red} = V_{12} / \sqrt{Z_1 + Z_2}$$

N-body Coulomb trajectories

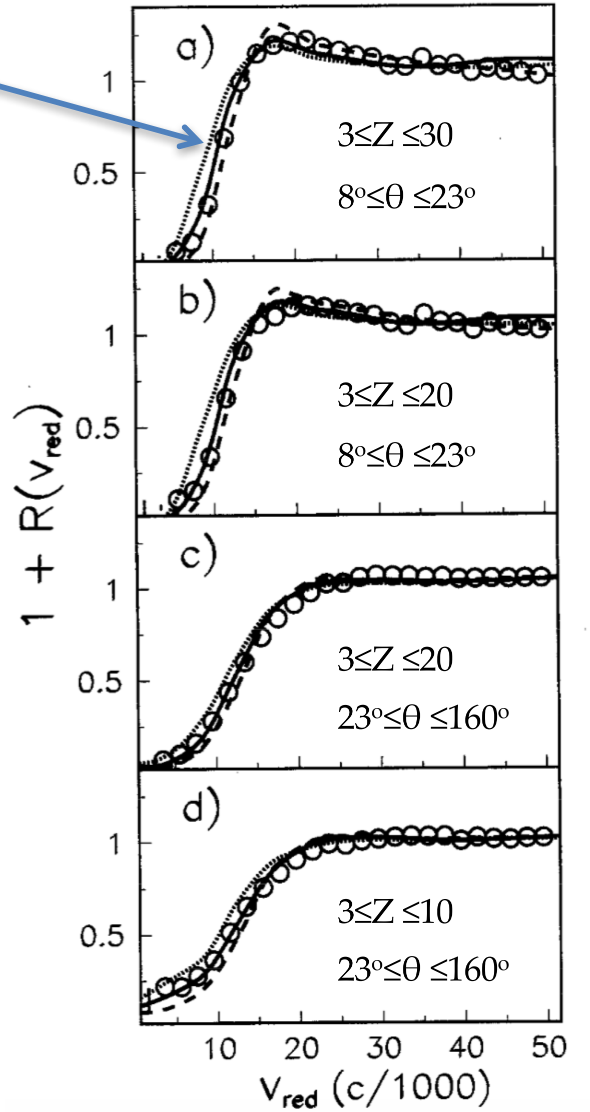
Source radius and emission times:

R_S, $P(t) = (1/\tau) \cdot \exp(-t/\tau)$ → **τ**

$\tau \approx$ **85** fm/c

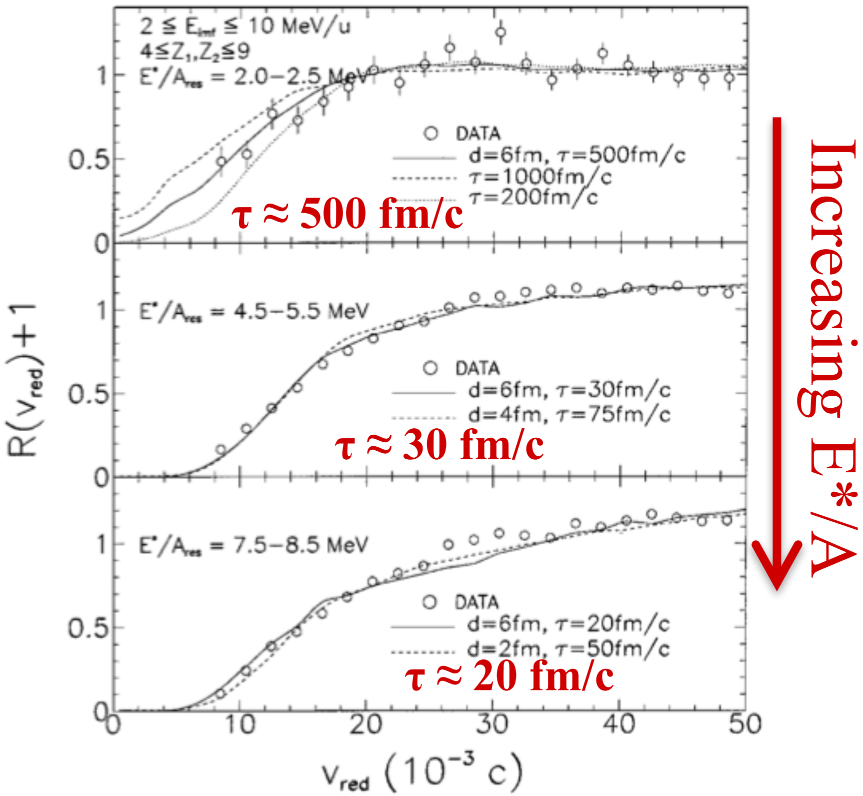
MULTICS (INFN) + Miniball

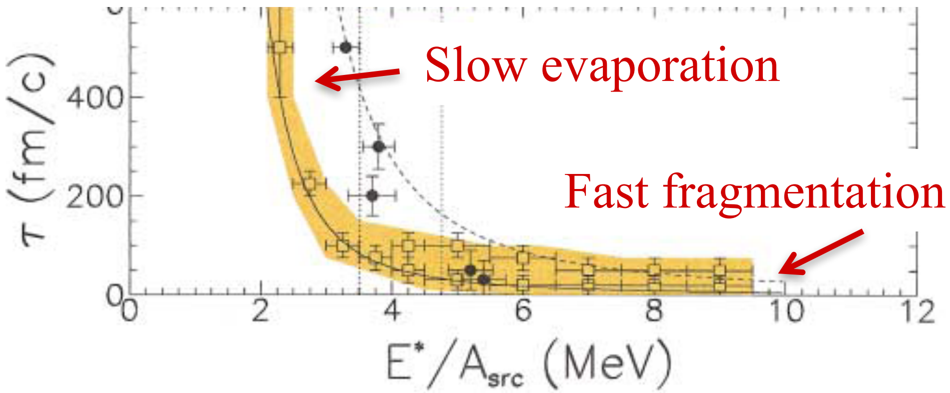
Au+Au E/A=35 MeV

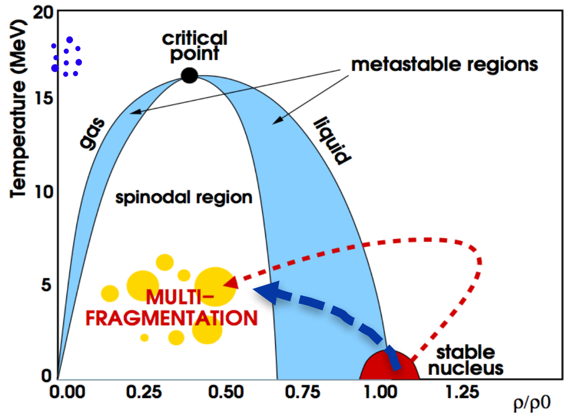


Time-scales in hadron-induced fragmentation

π^-, p + Au   8.0, 8.2, 9.2, 10.2 GeV/c







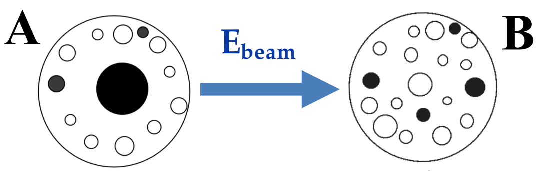
ISiS data @ Brookhaven

L. Beaulieu et al., PRL84 (2000) 5971

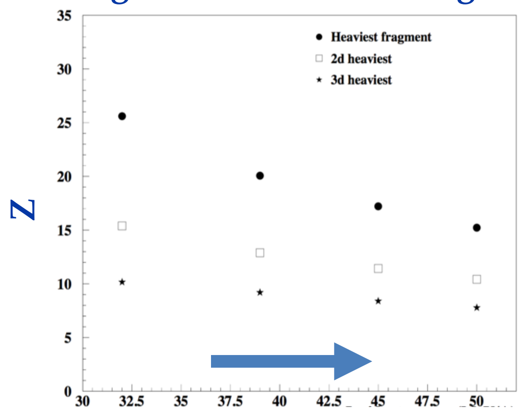
Transition from Surface (**slow**) to Bulk (**fast**) fragment emission

Central collisions: fragment-fragment correlations

Xe+Sn (central) – Indra data
E/A=32, 39, 45, 50 MeV

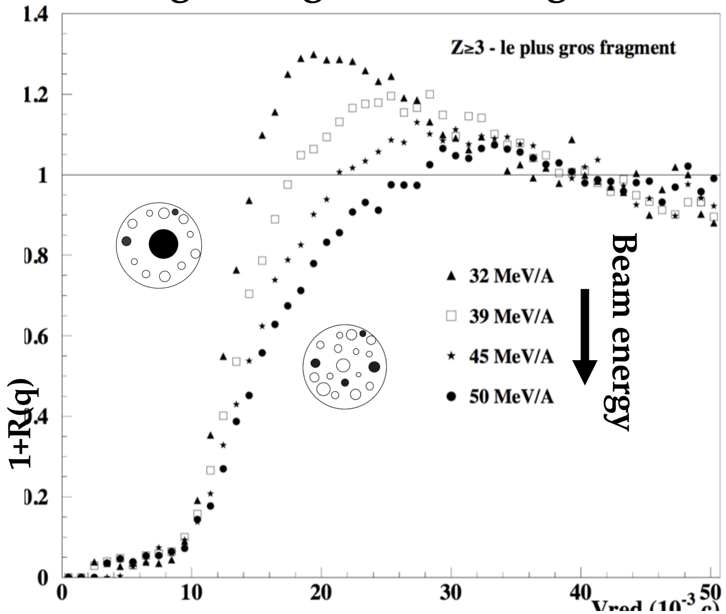


Charge of the 3 heaviest fragments



Beam energy (MeV)

Largest fragment-All fragments



$V_{red}(10^{-3}c)$

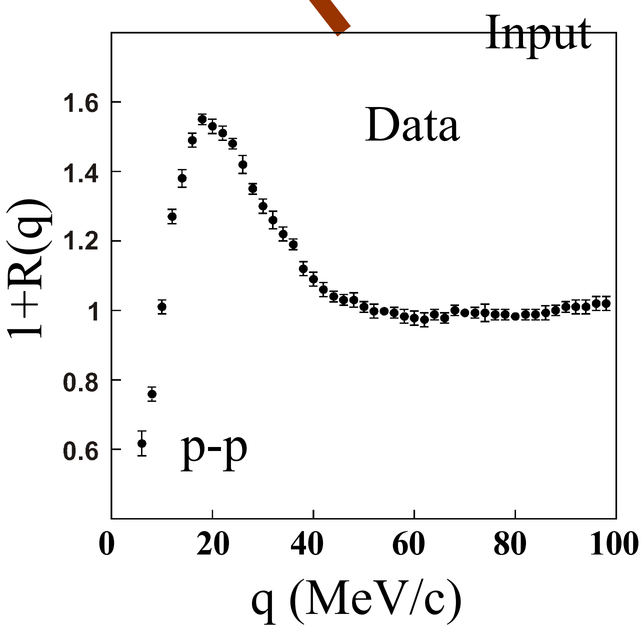
Emission times decrease with beam energy

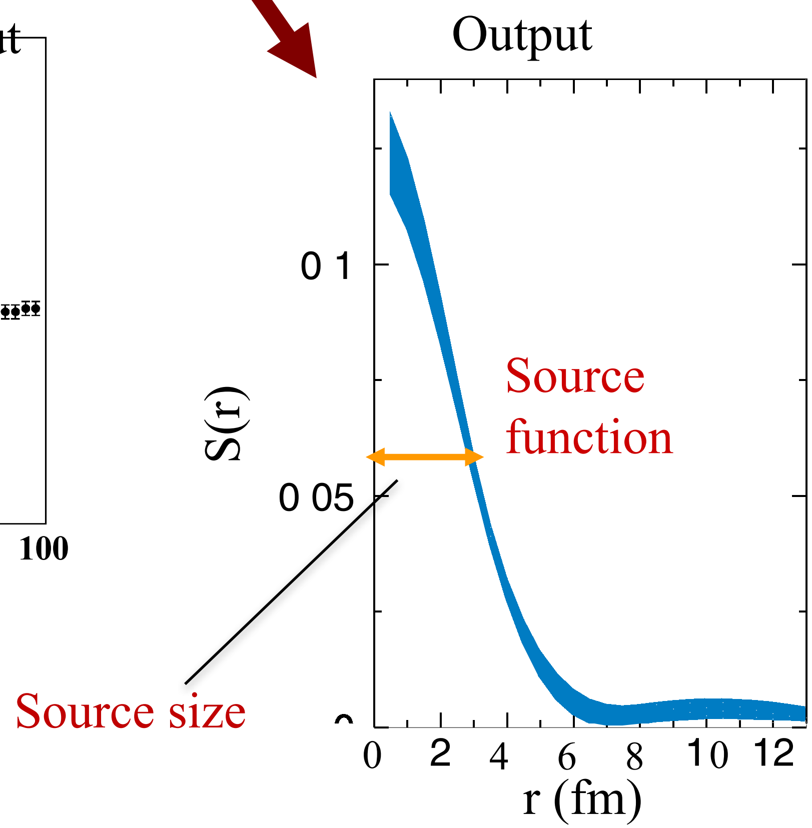
- **from asymmetric splitting** (sequential/evaporation-like) **to homogeneous and simultaneous** in-medium fragmentation
- Tests of cluster emission in transport models (D. Dell'Aquila, GV)

S. Salou, PhD thesis, GANIL
G. Verde, A. Chbihi, Int. J. Mod. Phys. E, Special-Topics Issue on Nuclear Particle Correlations and Cluster Physics

Imaging femtoscopy

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





- Relative contributions: pre-equilibrium/late evaporative emissions
- Probes of transport models

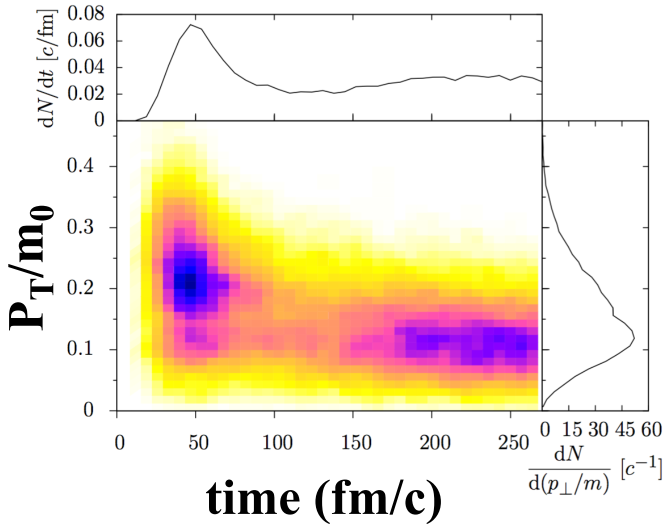
G. Verde et al., PRC65, 069604 (2002)
G. Verde et al., PRC67, 034606 (2003)

Imaging sources at different emission stages

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

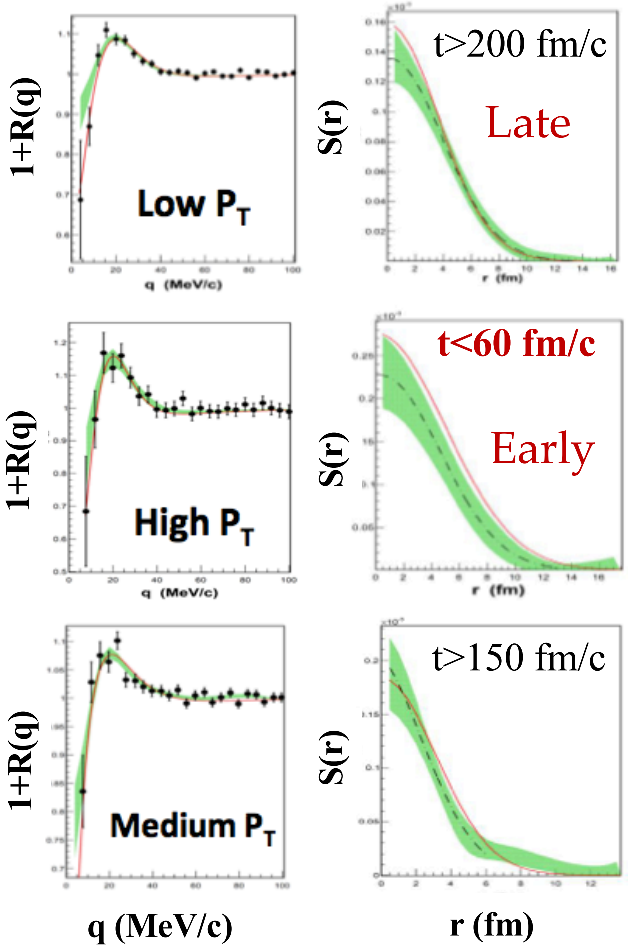
Early dynamical emissions

Late long-lived sources

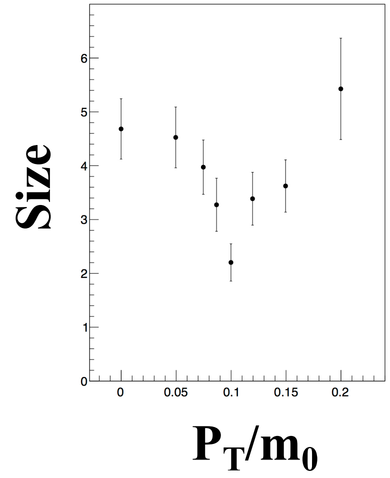


BUU simualtions

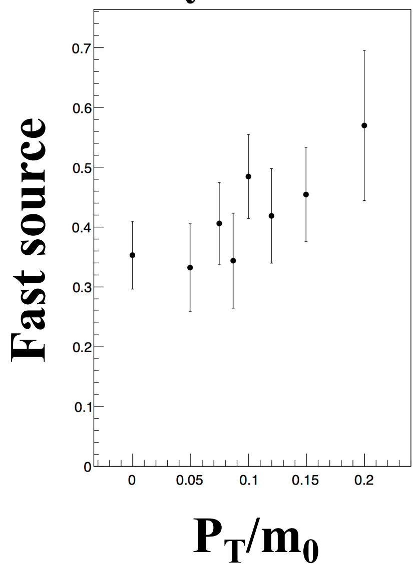
Experimental data (LASSA @ MSU)



Source size

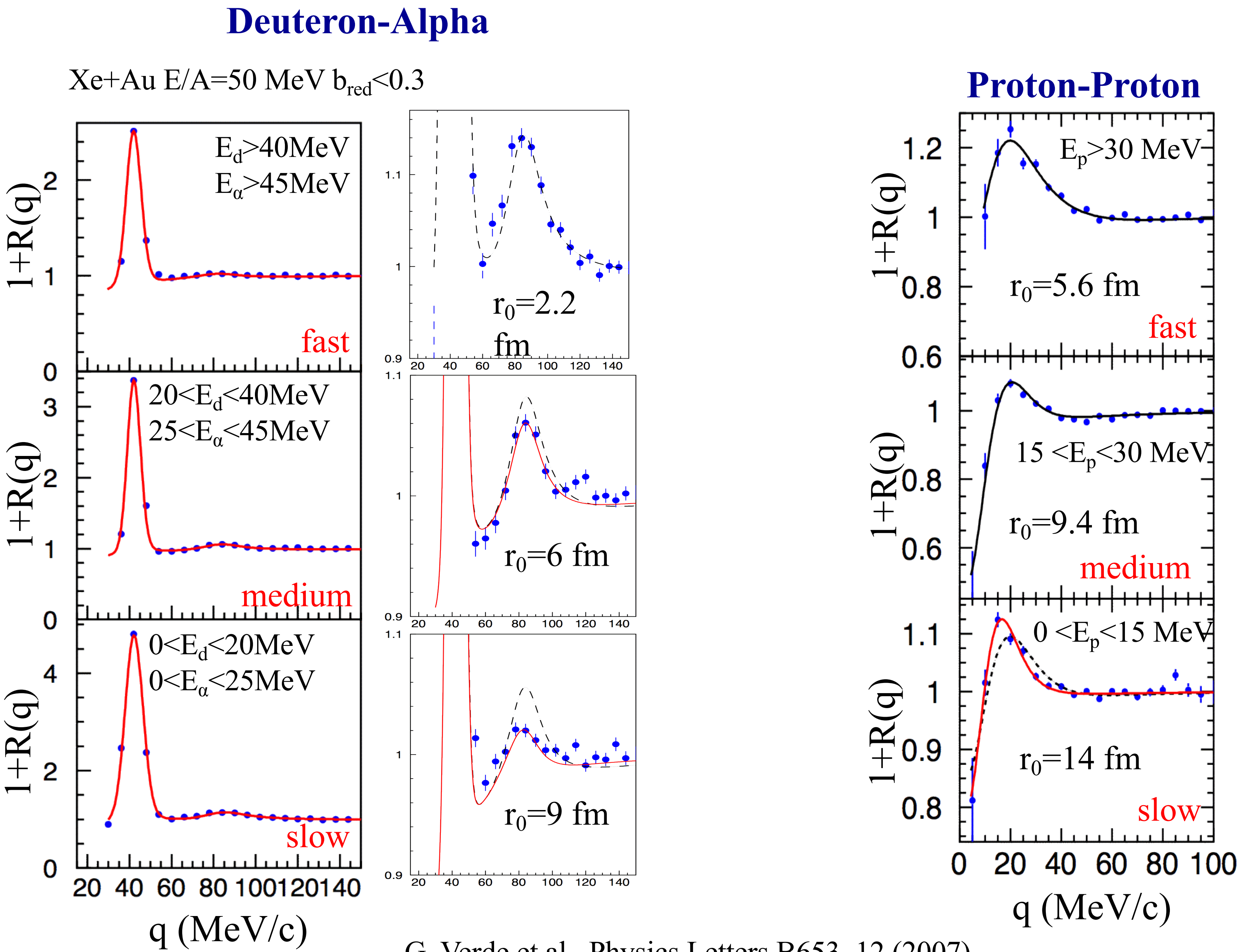


% of dynamical early emissions



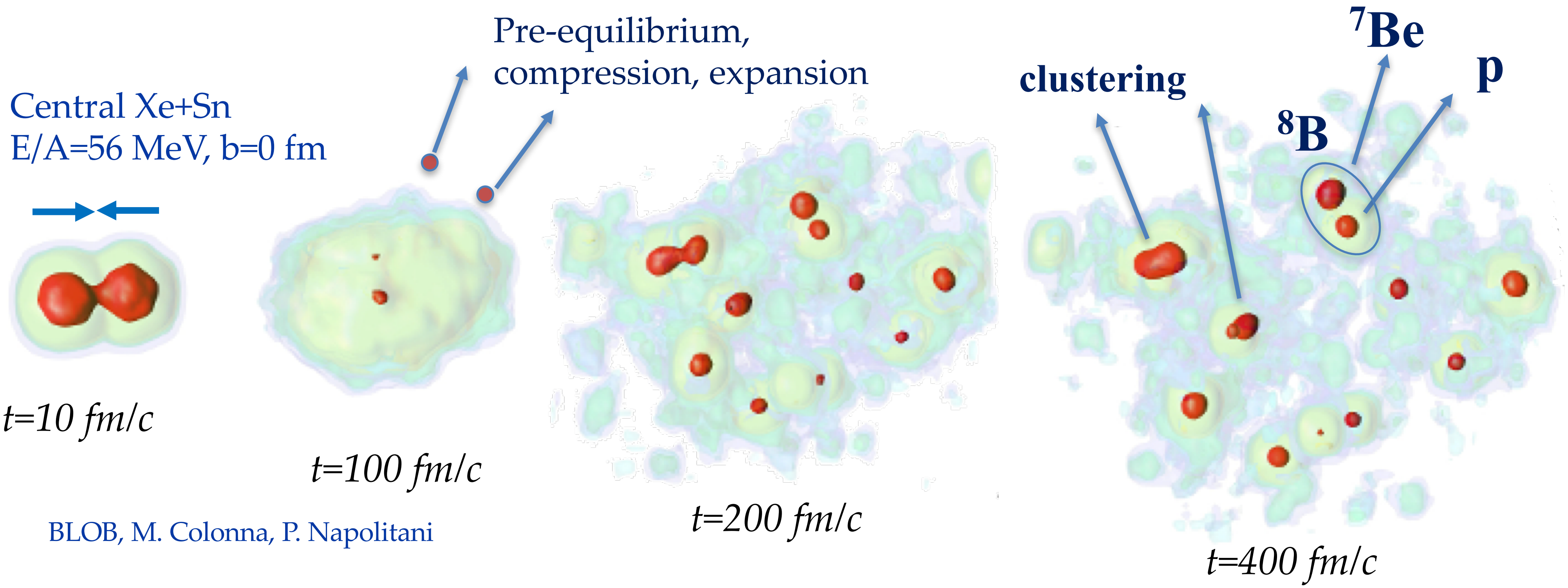
T. Minniti, F. Miano, GV, B. Barker, P. Danielewicz

Different particles → different sources



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

Structure of hot nuclear matter at sub-saturation densities



"Femtonova" (C. Horowitz)

Interplays:
Clustering ↔ Equation of State

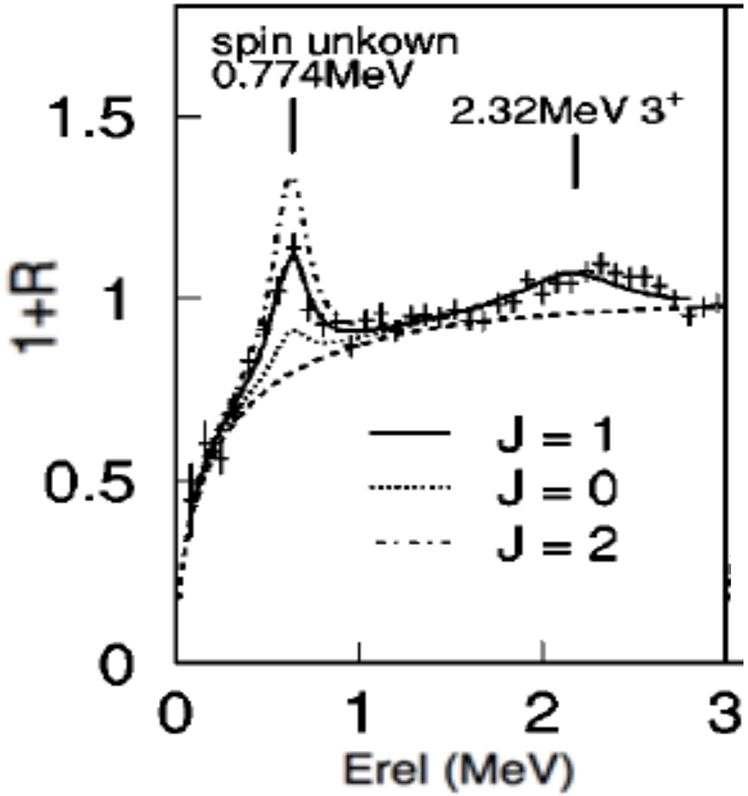
Invariant mass spectroscopy

In-medium structure: spin

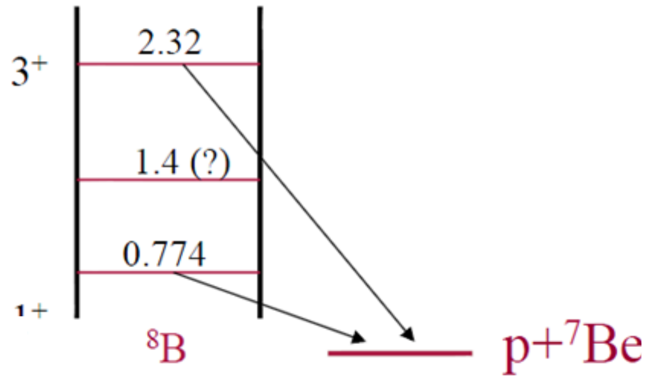
Xe+Au E/A=50 MeV
central collisions

Decay
$^{8}B^{*} \rightarrow p + {}^{7}Be$

p-^{7}Be correlation function



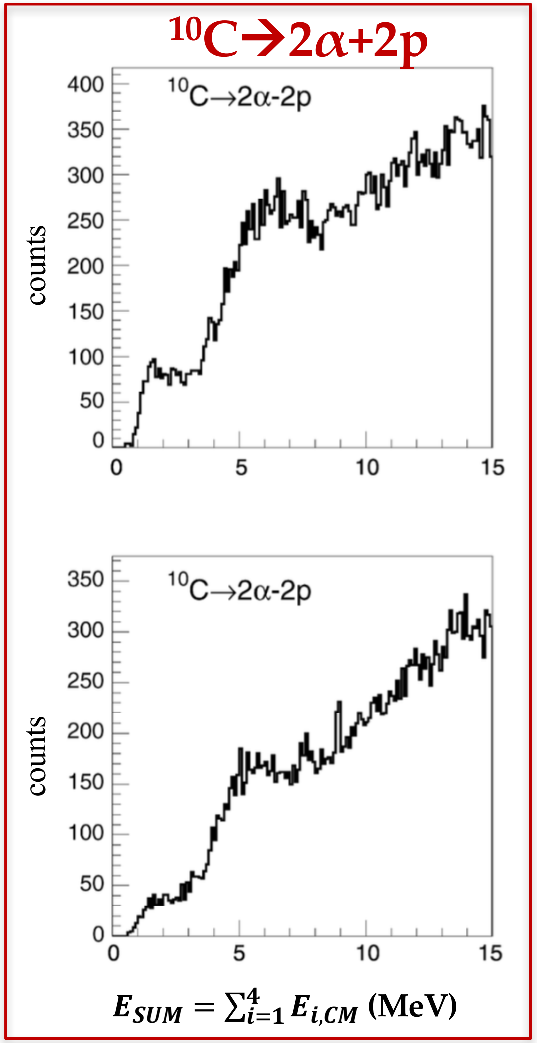
States of $^{8}B \rightarrow p+{}^{7}Be$

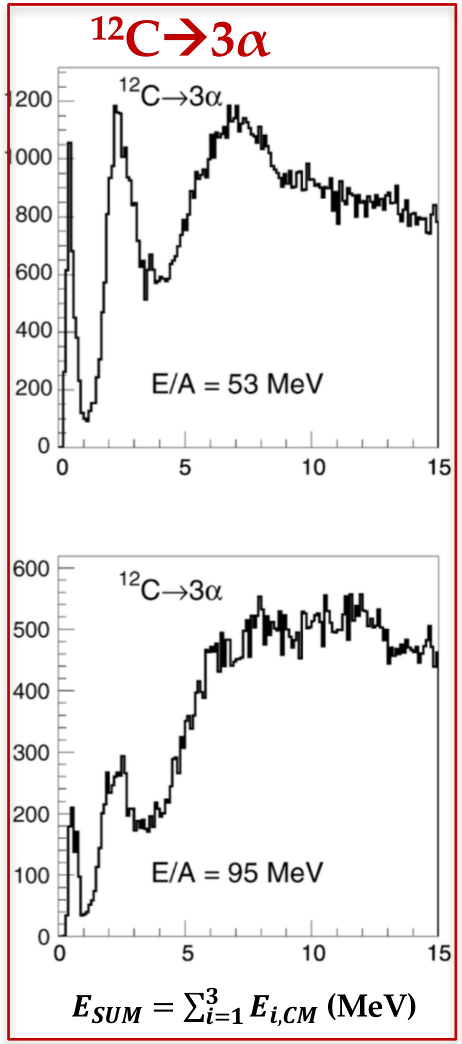


W.P. Tan et al. Phys. Rev. C69, 061304 (2004)

Resonance decays in dilute and hot expanding nuclear systems

In-medium structure: decay modes and branching ratios





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

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

^{10}C (Indra data)

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

$^{10}C^* \rightarrow {}^{8}Be + p + p \rightarrow (\alpha + \alpha) + p + p$

$^{10}C^* \rightarrow {}^{9}B + p \rightarrow (p + \alpha + \alpha) + p$

^{12}C (Chimera and INDRA data)

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

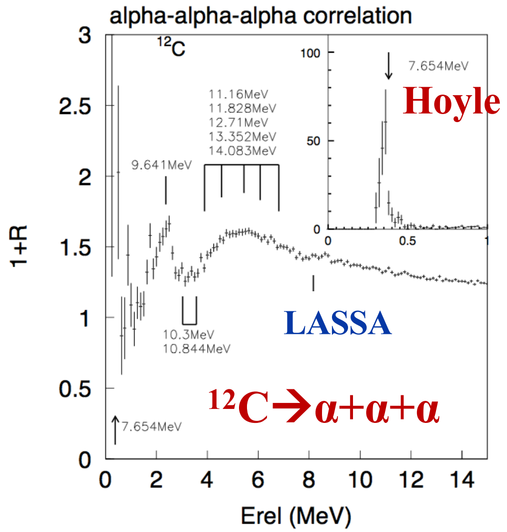
^{12}C (Hoyle) $\rightarrow \alpha + \alpha + \alpha$

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

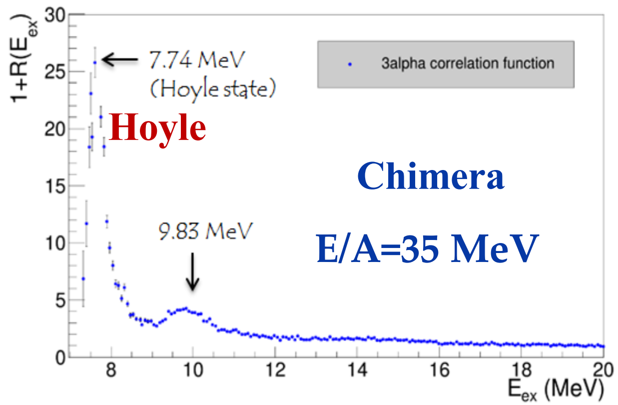
3α decay of the Hoyle state

Xe+Au   E/A=50 MeV



T. Wanpeng, PHD Thesis @ MSU

^{12}C+^{24}Mg E/A=50 MeV

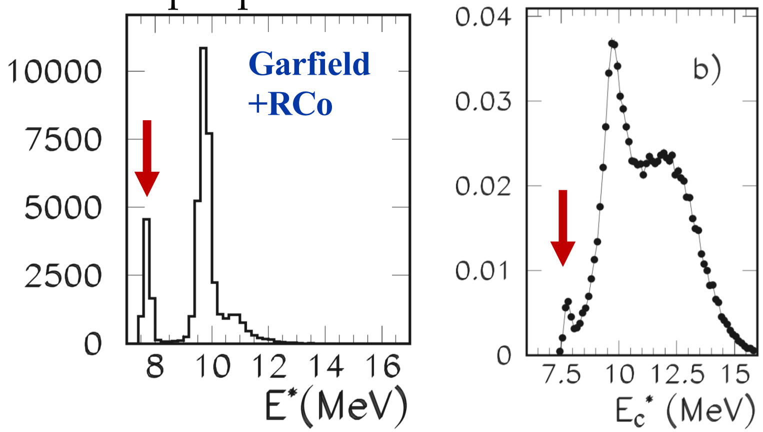


L. Quattrocchi, PHD Thesis @ Univ. Messina

Strong contribution from 3-body direct decay > 20%

^{12}C+^{12}C   E=95 MeV → **Hoyle state**

peripheral   central



L. Morelli et al., J.Phys.G43, 045110 (2016)

Branching ratios

^{12}C(Hoyle) ➔ ^{8}Be+α➔ (α +α)+α

^{12}C (Hoyle) ➔ α+α+α

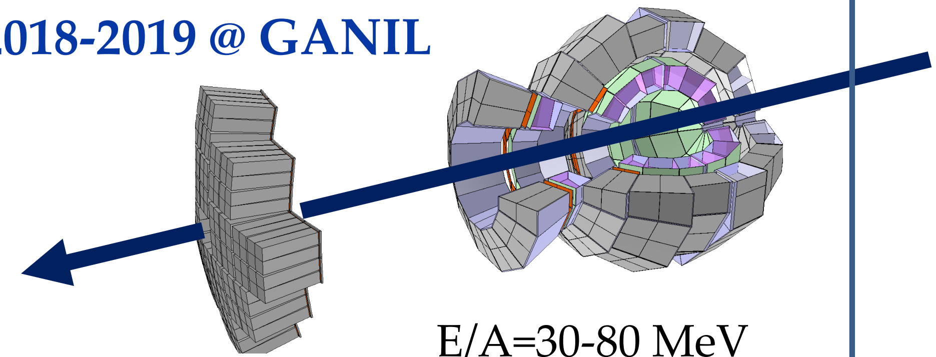
Discrepancies?

Almost no contribution from 3-body direct decay < 1%

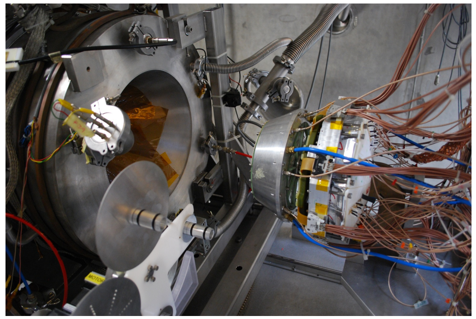
→ Confirmed by direct reaction and inelastic scattering experiments

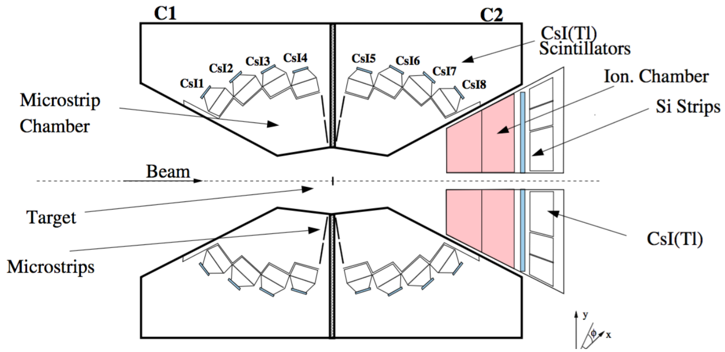
Present/future perspectives

INDRA-FAZIA
2018-2019 @ GANIL

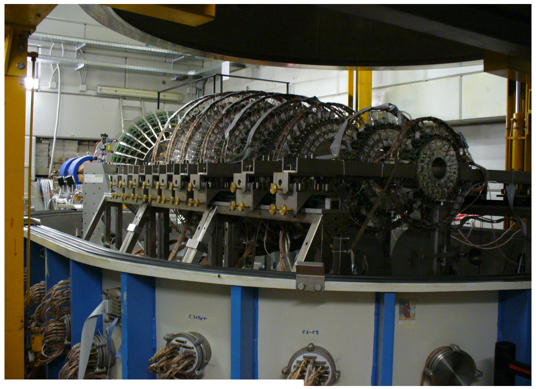


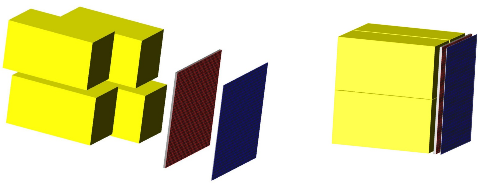
E/A=30-80 MeV





Garfield-RCo @ LNL





Chimera-Farcos @ LNS

Conclusions

- **Femtoscopy**: size of nuclear dynamical systems
- Probing **time-scales and densities** in HIC:
  - **Imaging** pp correlations
  - **IMF-IMF correlations**: tomography and time-scales
  - Multiple sources → models
- **In-medium structure**
  - Examples: ^{10}C, ^{12}C sequential decay branching ratios; ^{8}B spin of 0.74 MeV state
- Implications in **neutrinosphere** of SN explosions and perspectives

"Kind of makes you feel large and significant, doesn't it?"