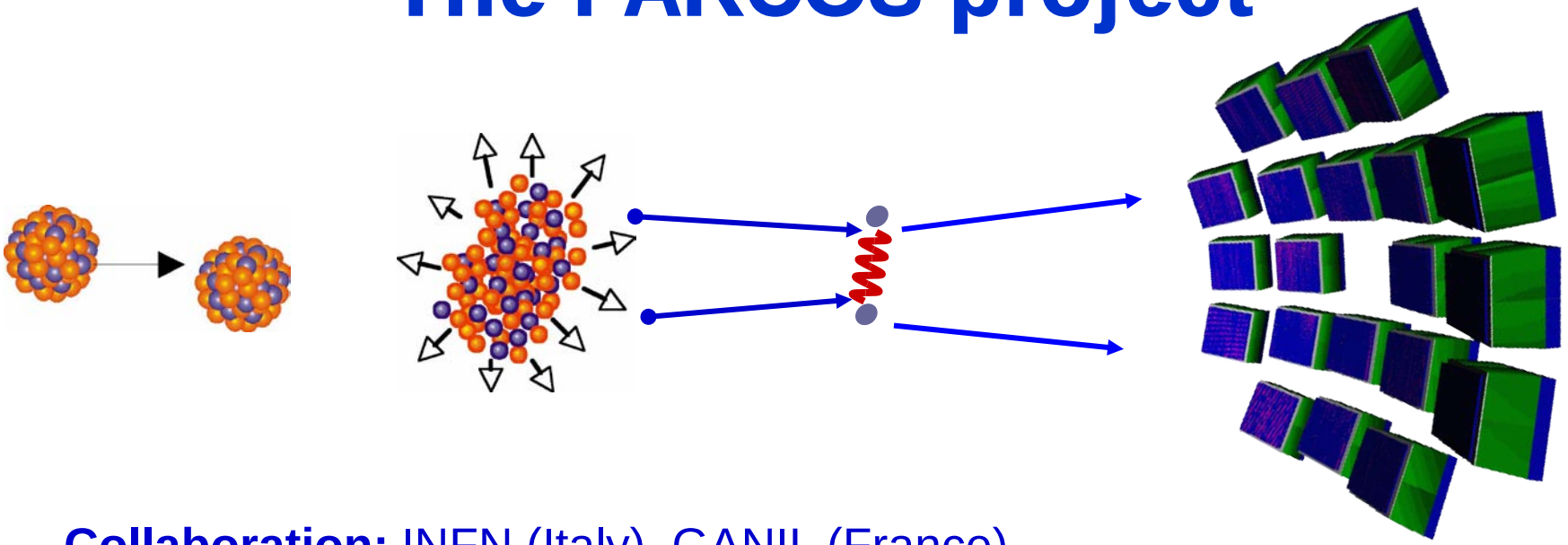
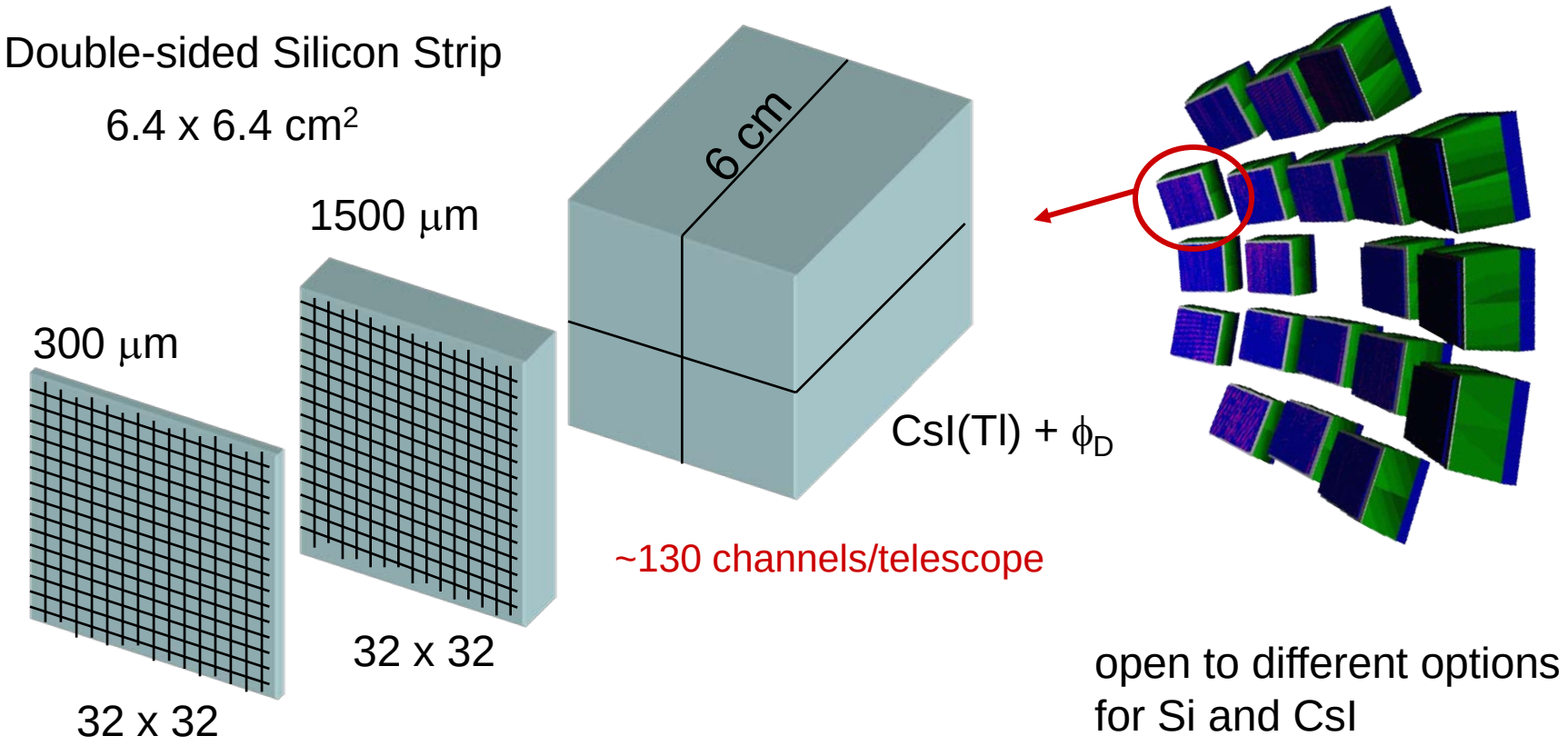
The FARCOS project



Collaboration: INFN (Italy), GANIL (France), Un. Huelva (Spain)… open

Synergies: NSCL-MSU (USA), WMU (USA)

FARCOS: **F**emtoscope **AR**ray for **CO**rrelations and **S**pectroscopy



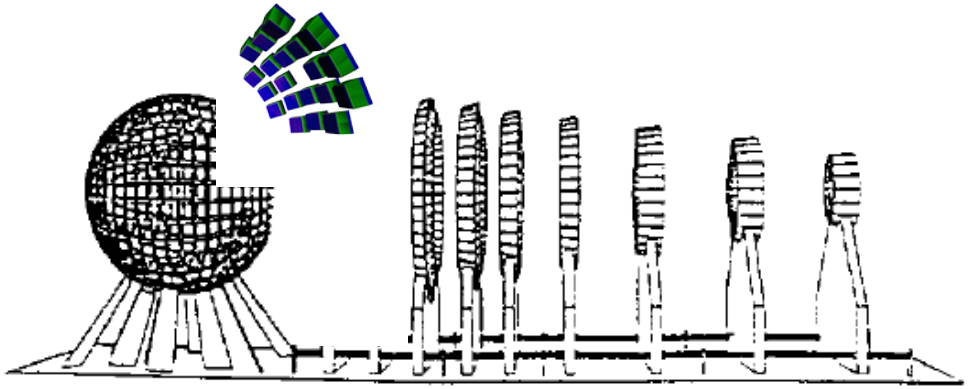
Angular resolution: ~0.2º at d=60 cm

Farcos array features

- High angular resolution (<0.5º):
- Detect both light and heavy fragments
- Flexibility: allow coupling to
  - 4π detectors, magnetic spectrometers, other correlators
  - Neutron detectors for n-p correlations (future
  - Transportability (different laboratories)
- Low energy experiments (Ex.: Spiral2, Spes)
  - pulse-shape on silicon and digitalization, interface to Fazia project
- Large density of channels (integrated electronics…)

Farcos as a “modular correlator”

Correlations



Event characterization (4π)

Coupling to 4π detectors for dynamics studies (LNS, GANIL, NSCL-MSU, …)

Coupling to magnetic spectrometers, n-det, …

Interface to next-generation detectors: Fazia, …

Physics case: dynamics and spectroscopy

1. **Dynamics: Femtoscopy and imaging in heavy-ion collisions**

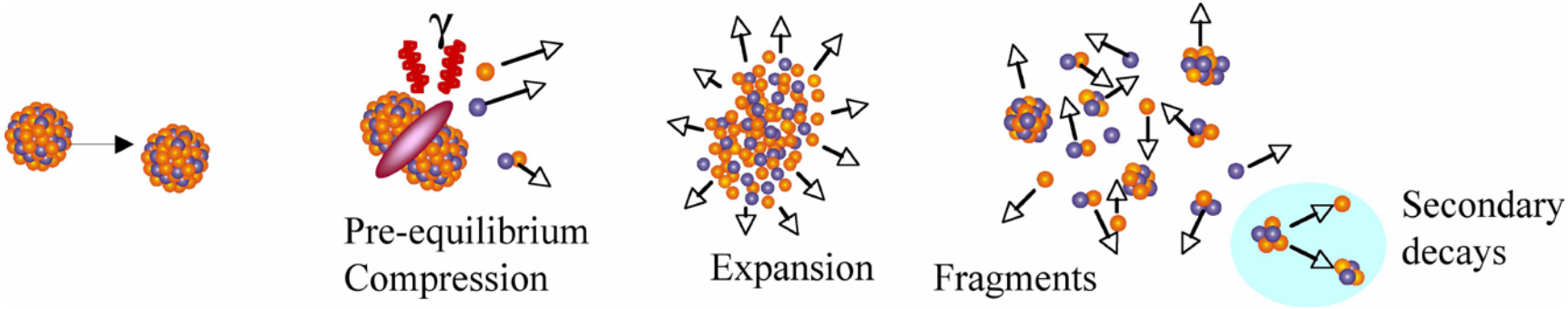
2. **Spectroscopy** of exotic nuclei:

   – **In heavy-ion collisions**
   MPCS: Multi-Particle Correlation Spectroscopy

   – **In direct reactions**

Heavy-Ion collisions

Complex but rich systems



Dynamics/Thermodynamics

EoS, Asy-EoS, Fusion/Fission, DIC, …

Spectroscopy

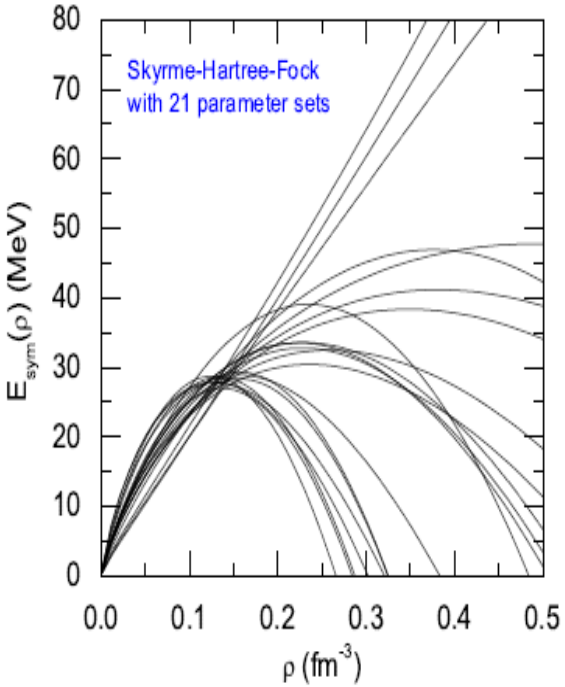
Unbound states, spins, branching ratios, sequential decay modes

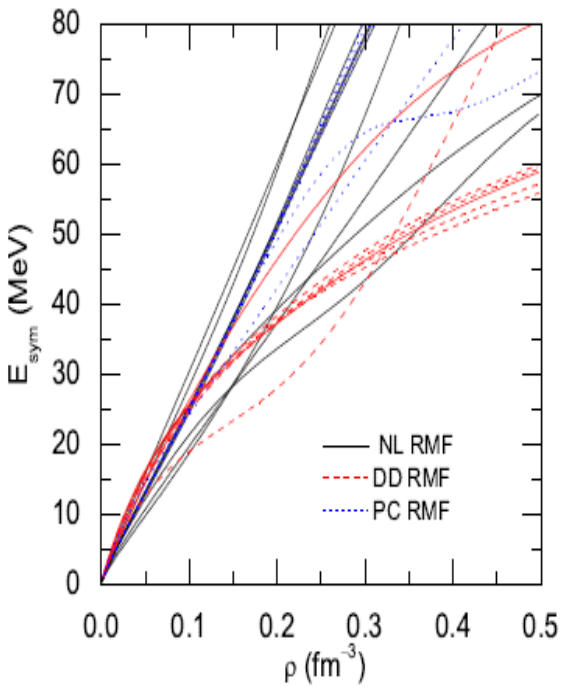
Density dependence of the asymmetry term in nuclear EoS

$$E(\rho,\delta) \approx E(\rho,\delta=0) + \boxed{E_{sym}(\rho)} \cdot \delta^2 \qquad \left(\delta = \frac{\rho_n - \rho_p}{\rho_n + \rho_p}\right)$$

???

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



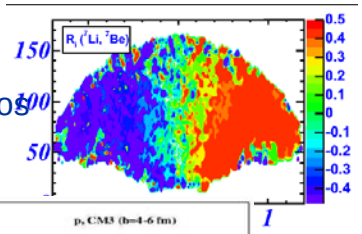


Many approaches… large uncertainties

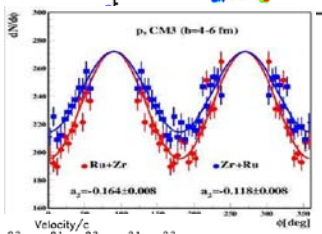
Microscopic many-body, phenomenological, variational

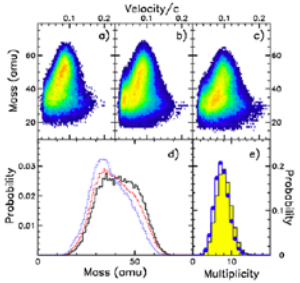
Symmetry Energy: who cares?

Lassa @ MSU
Imbalance ratios

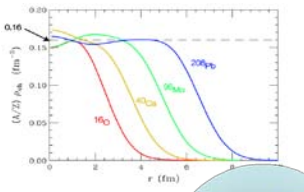


FOPI @ GSI
Elliptic flow



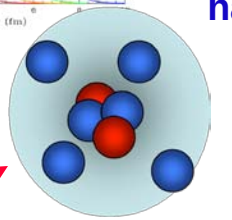


Chimera @ LNS
Competitiion Inc. Fusion / DIC



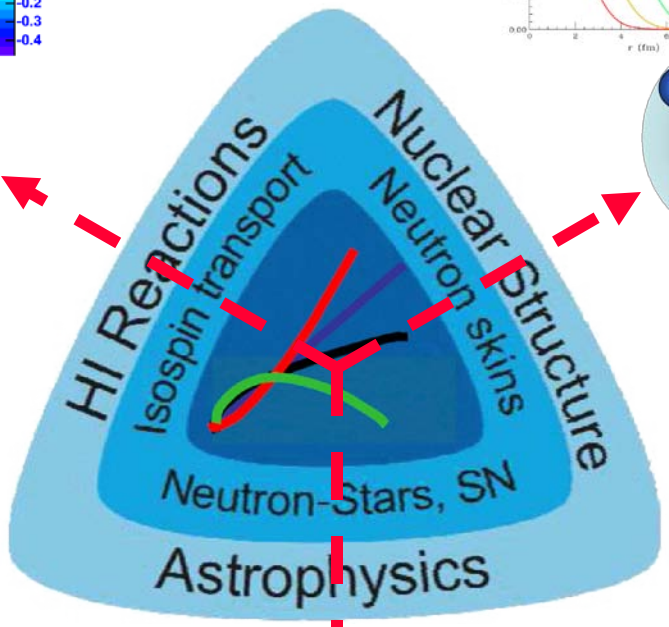
skins

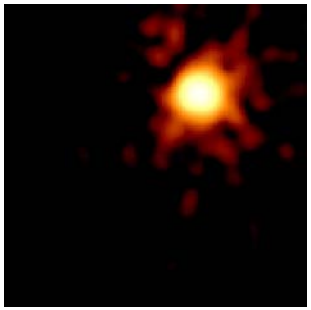
halos



resonances

GDR & PYGMY RESONANCE

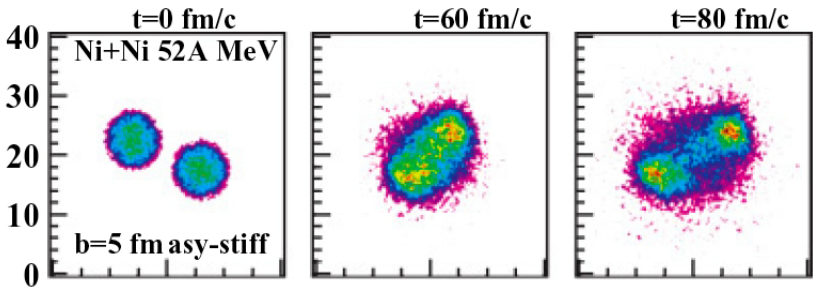




Supernovae,
neutron stars

Producing density gradients

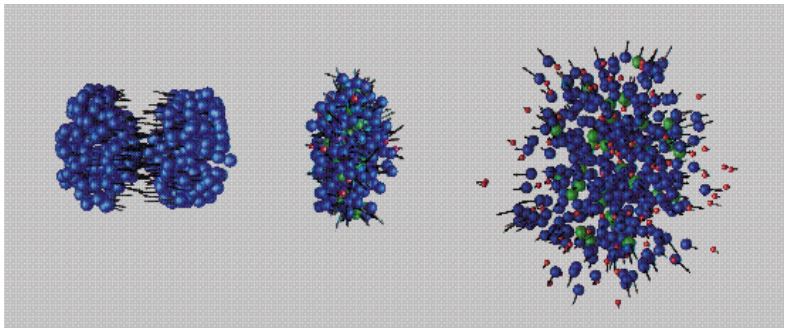
Intermediate energies: E/A=20-100 MeV



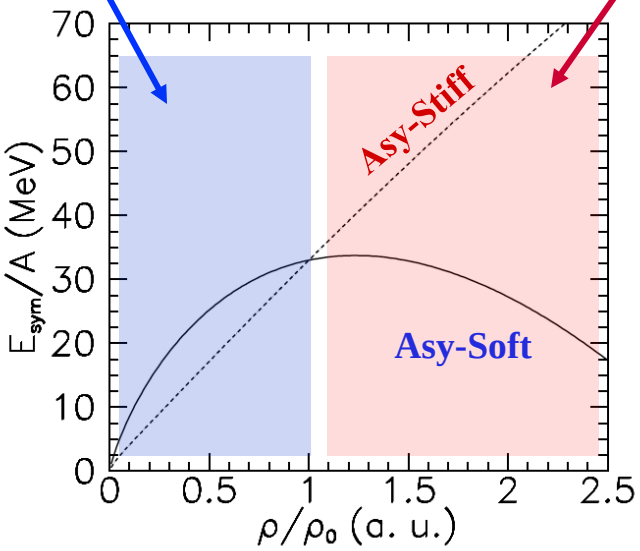
SMF - Baran, Colonna, Di Toro, Greco

Ganil, Eurisol, Frib, LNS, MSU, Spiral2 …

High energies: E/A>200 MeV



CSR, GSI/Fair, FRIB, Riken, …



Low density

High density

Chimera@GSI (now!)

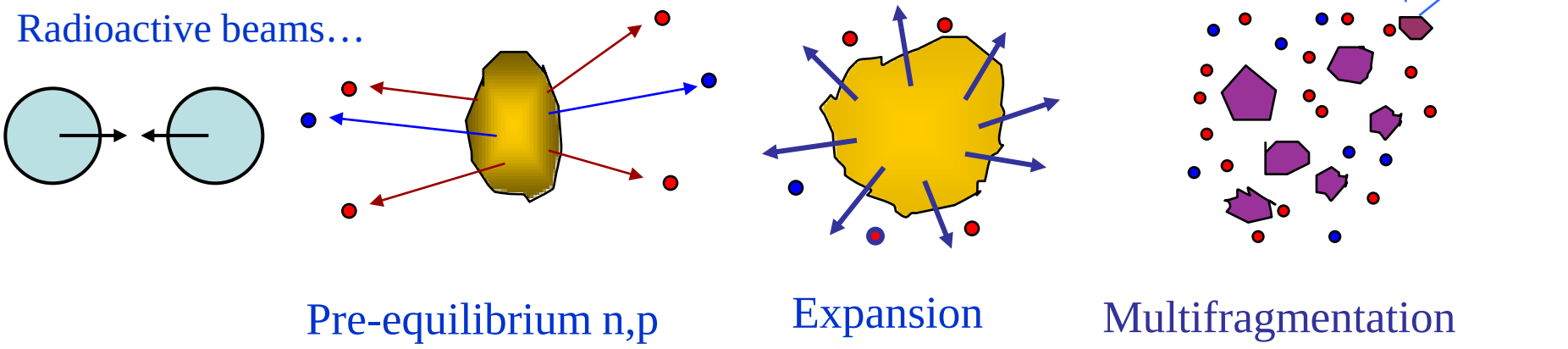
EoS-TPC@Riken/MSU

Intermediate energies

Large N/Z

$^{124}Sn+^{124}Sn$, $^{48}Ca+^{48}Ca$

Radioactive beams…



Pre-equilibrium n,p

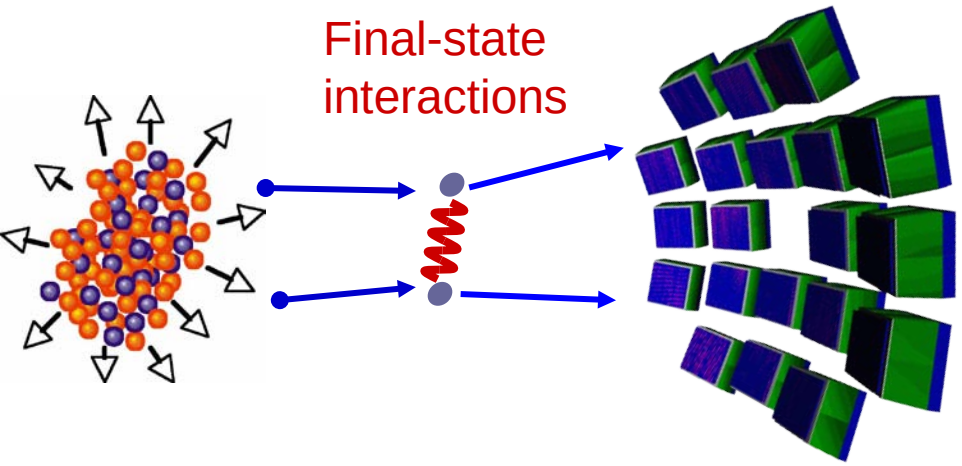
Expansion

Multifragmentation

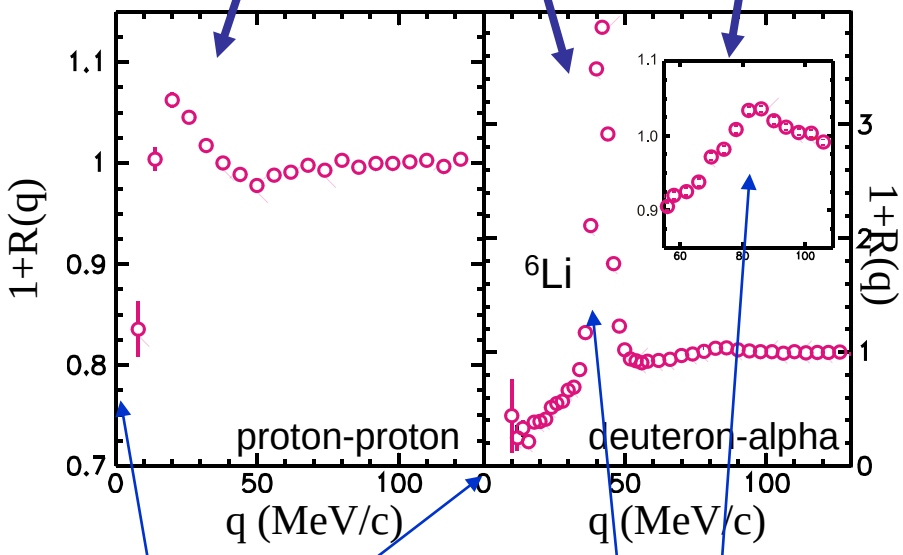
- Different degrees of freedom freeze-out at different times - When and where are particles produced?
- Need space-time probes
  ==> HBT, Femtoscopy

HBT in heavy-ion collisions

$$1 + R(q) = k \cdot \frac{Y_{coin}\left(\vec{p}_1, \vec{p}_2\right)}{Y_{evt.mixing}\left(\vec{p}_1, \vec{p}_2\right)}$$



Sensitive to space-time properties



High angular resolution required!

Low q (θ_{rel}) measurements

Resonances

S.E. Koonin, PLB70 (1977) 43; *S.Pratt et al.*, PRC42 (1990) 2646

Extracting the emitting source function

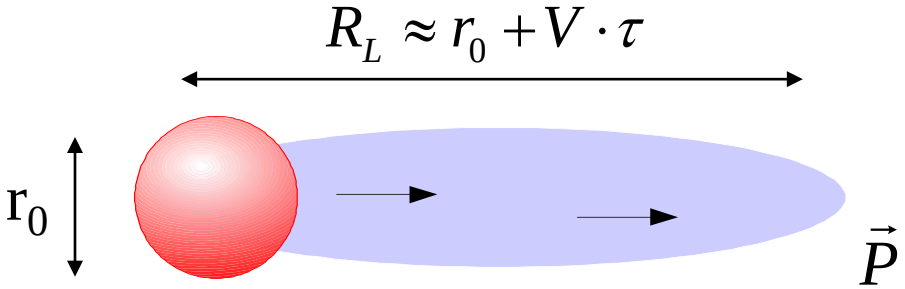
$$R(\vec{q},\vec{P}) = \int d\vec{r} \cdot S_{\vec{P}}(\vec{r}) \cdot K(\vec{r},\vec{q})$$

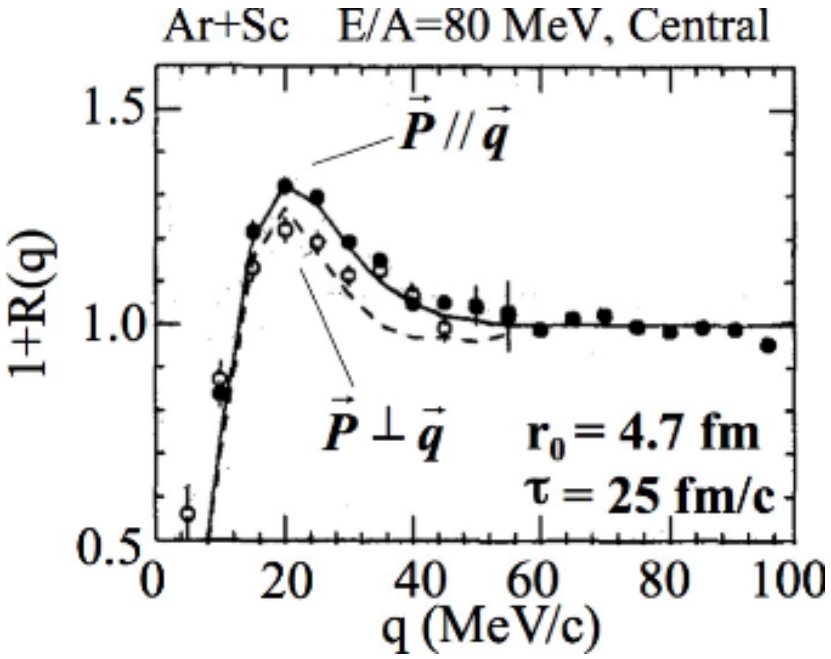
Koonin-Pratt Equation

Correlation function

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

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



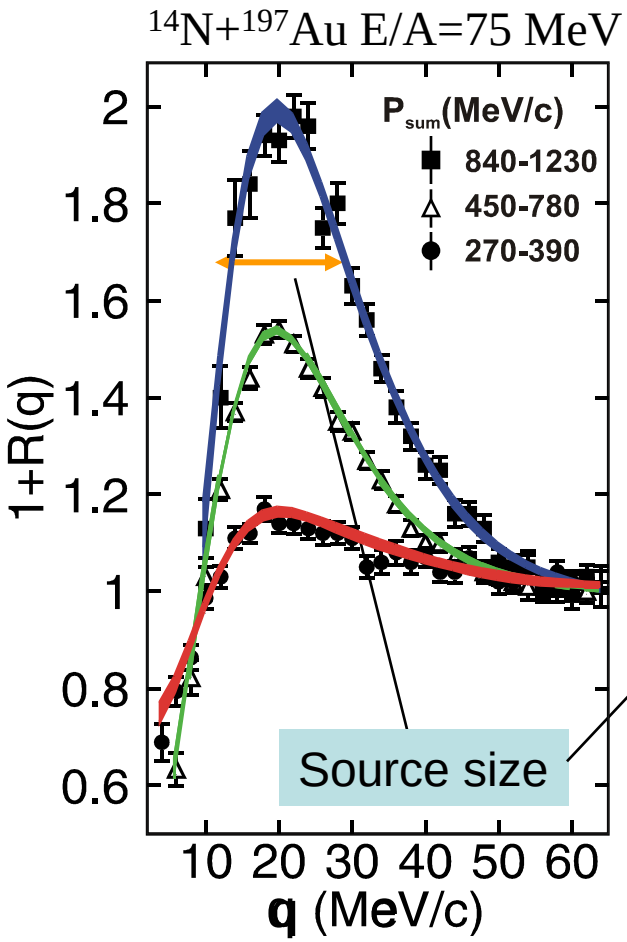


(θ,ϕ) resolution, large solid-angle, statistics, modularity (E_{beam})

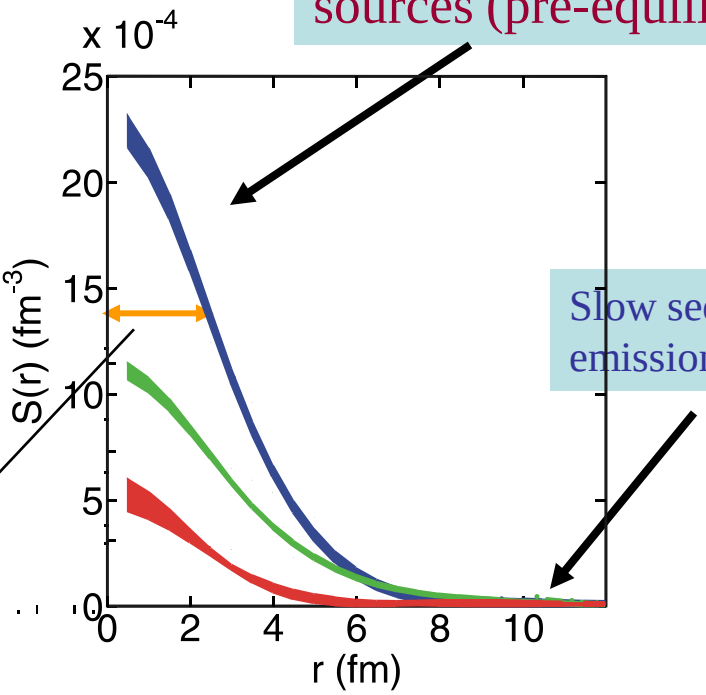
Imaging correlations, “Femtoscopy”

G. Verde et al., PRC65, 069604 (2002)

$$R(q) = 4\pi \int dr \cdot r^2 \cdot S(r) \cdot K(r,q)$$



Fast simultaneous emitting sources (pre-equilibium)



Slow sequential emissions (evap.)

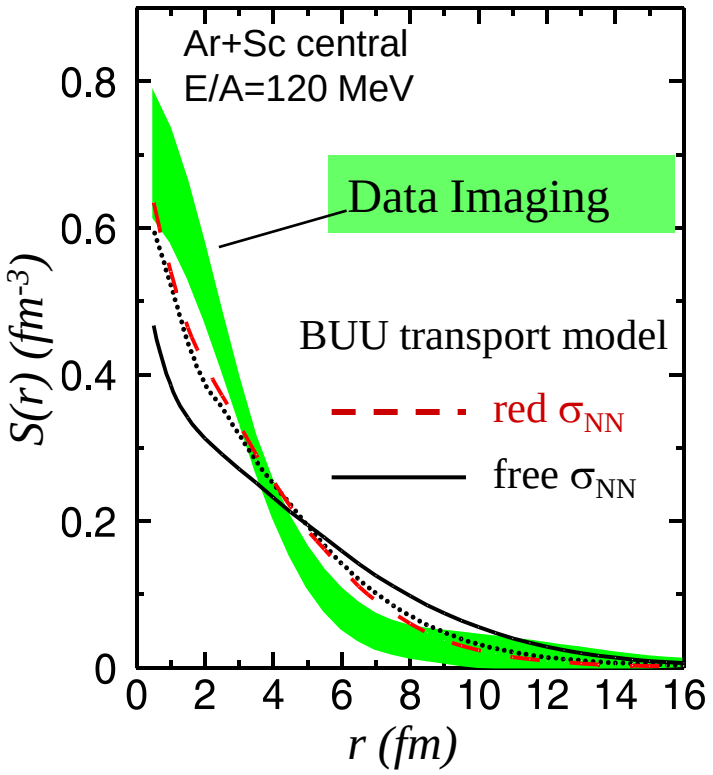
Space-time images

“Femtoscopy” - measuring sizes Δr~1 fm and times Δt~10^{-21}s

Source profile: probes of microscopic models

Image space-time profiles S(r) vs Model predictions

G. Verde et al., Phys. Rev. C67, 034606 (2003)

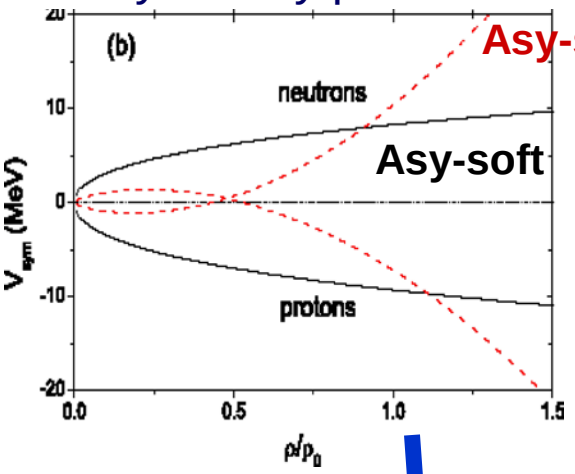


Probe transport properties:

- EoS, AsyEoS
- NN cross section in medium

Symmetry energy and imaging

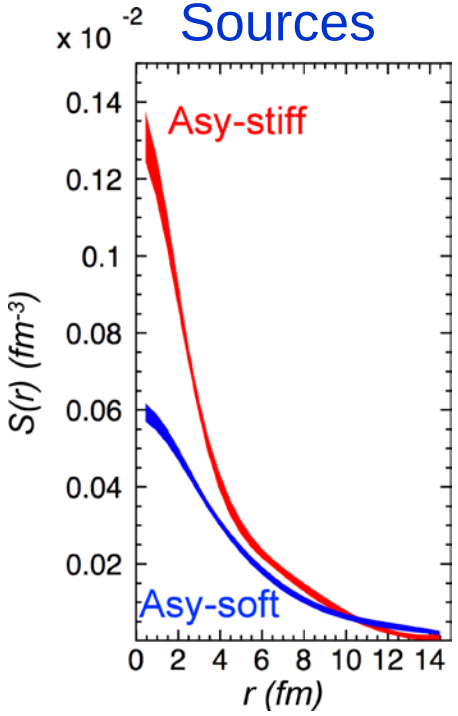
Symmetry potential



Density dependence of the symmetry energy affects the shape of the two-proton source profile

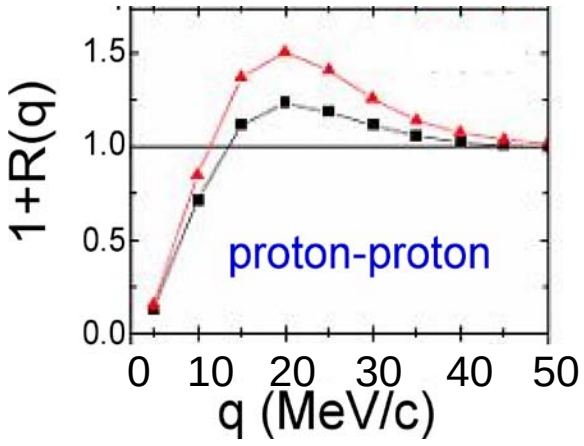
IBUU: $^{52}Ca+^{48}Ca$ E/A=80 MeV

Sources



Asy-stiff: more localized source

Correlations

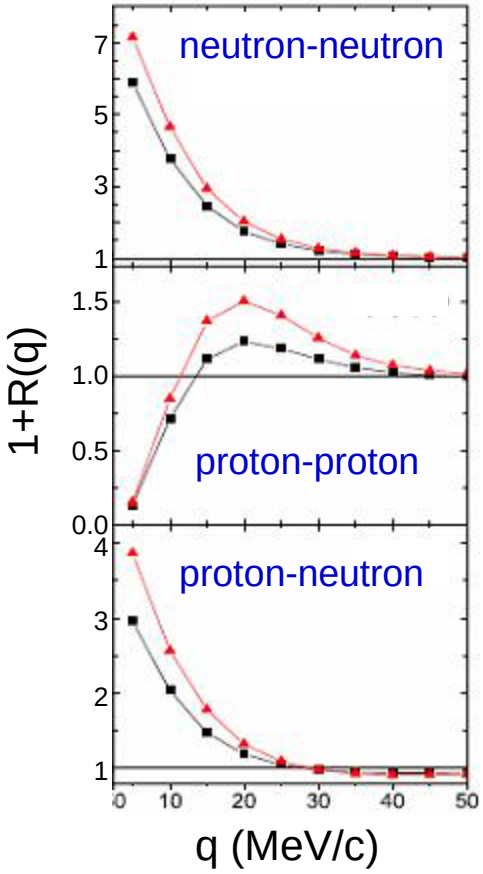


Bao-An Li et al.

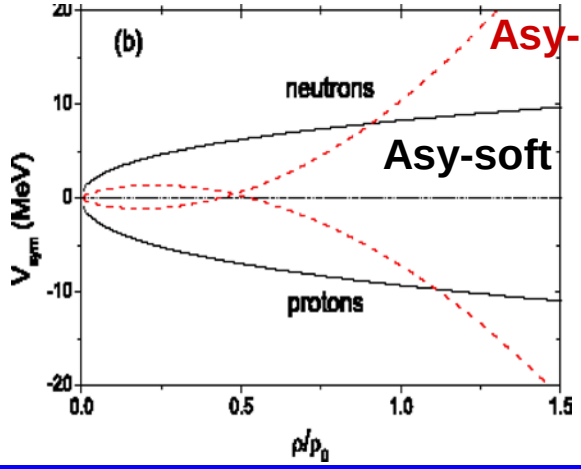
Future perspective: nn, np, pp correlations

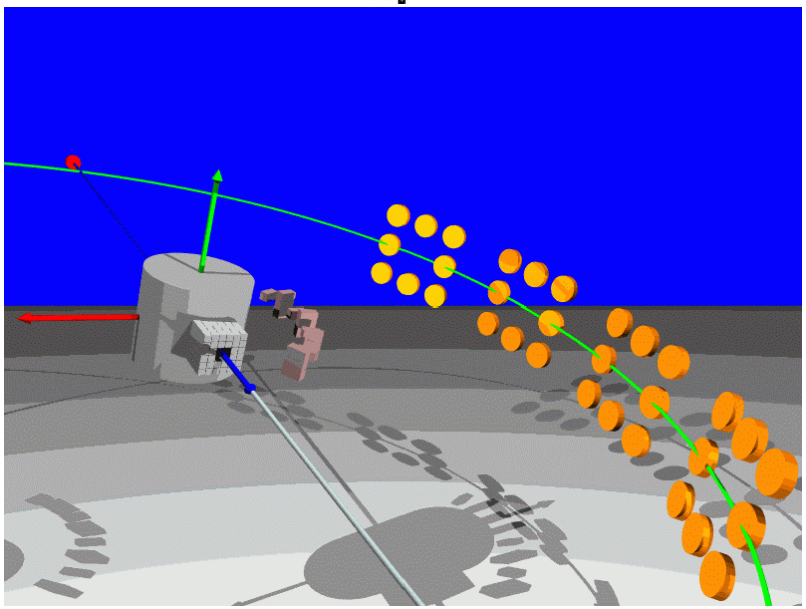
Correlation functions

IBUU: $^{52}Ca+^{48}Ca$ E/A=80 MeV



Symmetry potential



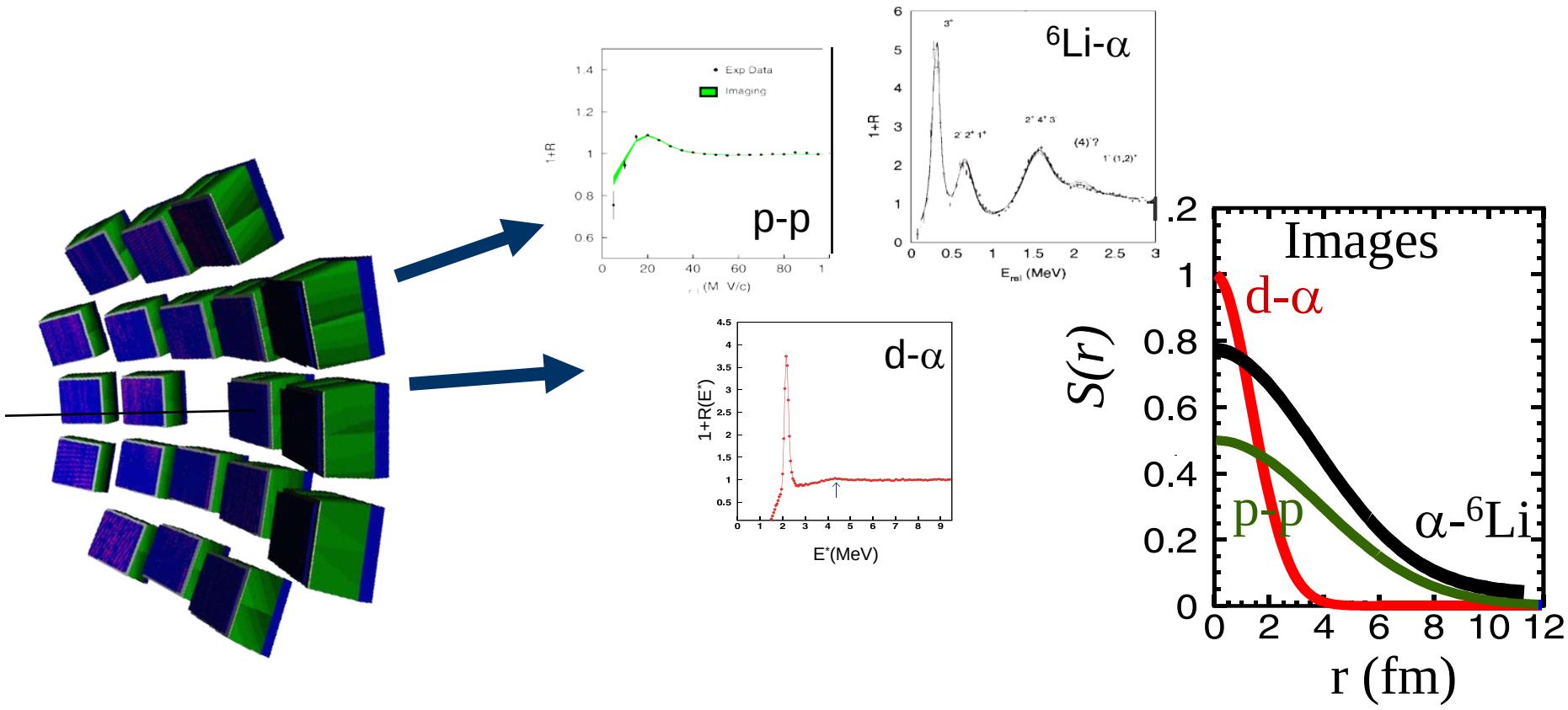


Chic collaboration

Proposal for an open discussion

Can we profit from the presence of EDEN in Catania to study np, nn and pp correlations?

Complex particle correlations



Different particles emitted by different sources and at different times (hierarchy) - multiple imaging (future perspective)

Event characterization required ! ==> **Coupling to 4π mandatory**

Possible experiments with Farcos

Reactions:

$^{40,48}Ca+^{40,48}Ca$ E/A=25-100 MeV

$^{112,124}Sn+^{112,124}Sn$ E/A=25-100 MeV

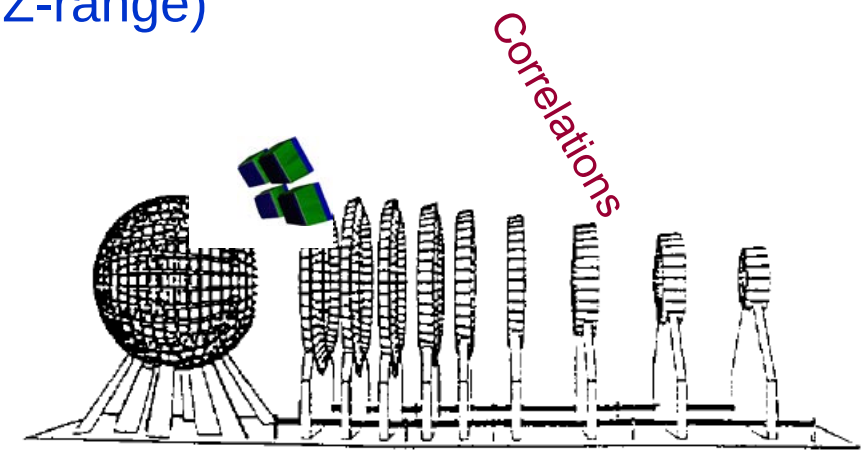
Radioactive beams (larger N/Z-range)

Laboratories:

•LNS (Chimera + Correl)

•GANIL (Indra + Correl)

•MSU (μBall + Correl)



Event characterization (Chimera)

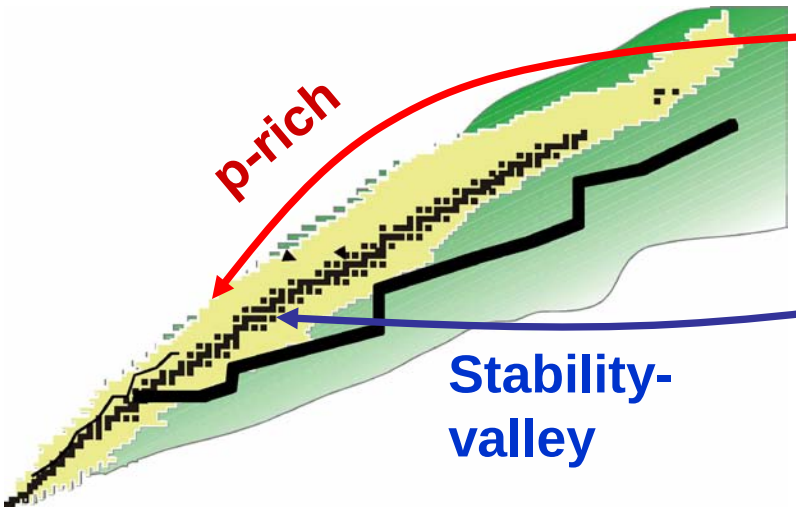
Future perspectives:

- Low energy experiments at LNL and Spes

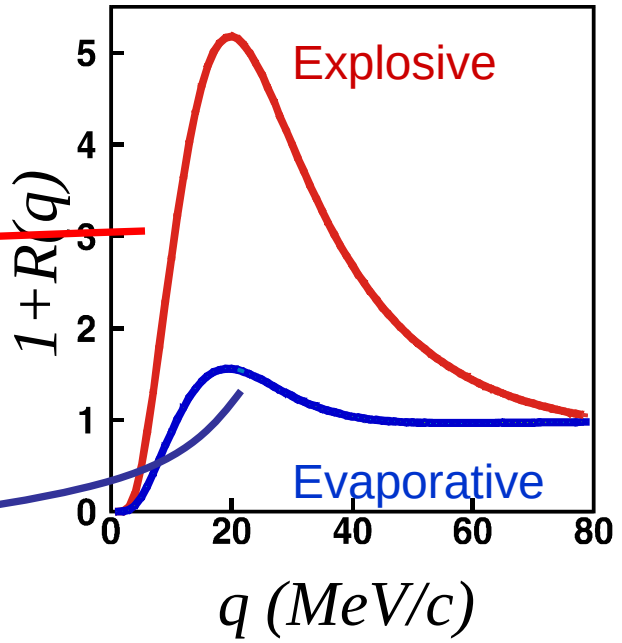
- Coupling to neutron detectors (np, pp, nn correlations)

Low energy HIC
Isospin effects on femtoscopy

Dynamics studies towards the drip lines

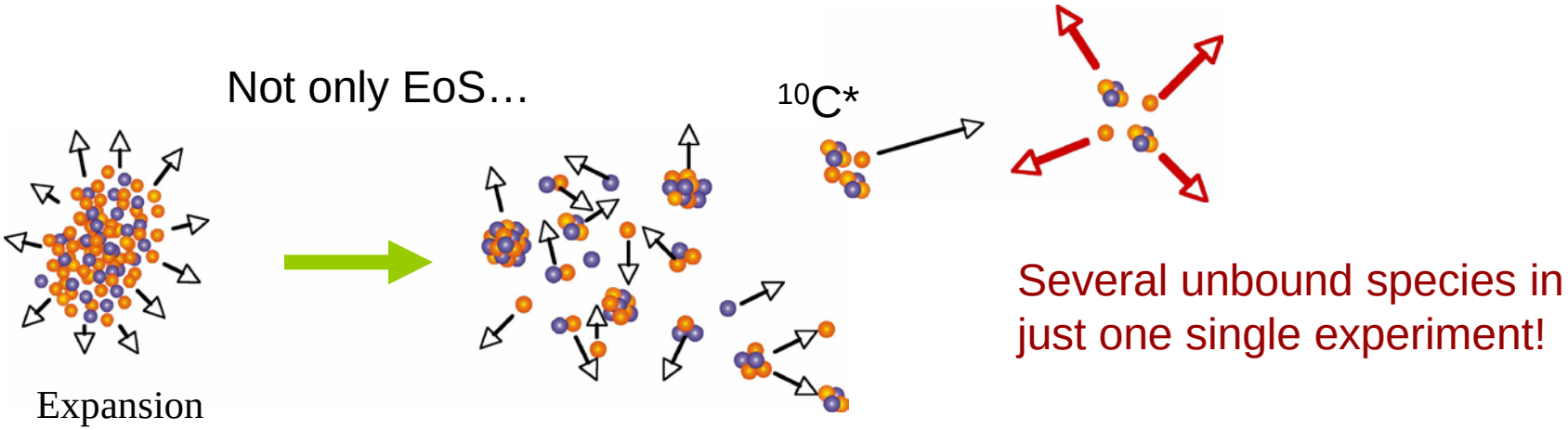


Correlation functions



- **Important: low thresholds and measure very low q-values!**
- Applications in structure studies (α-n clustering of exotic nuclei, halos, exotic shapes, exotic decays) - multiple particle correlations

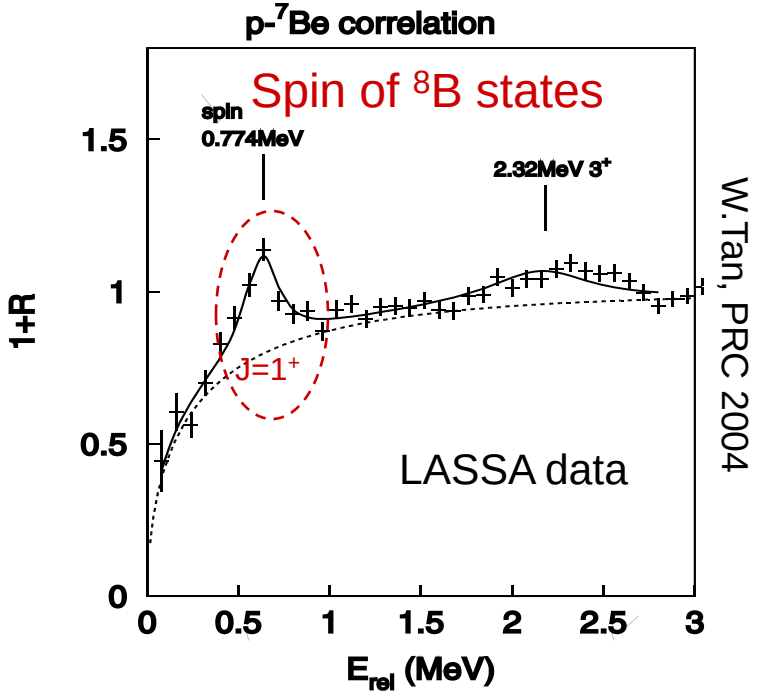
Multi-Particle Correlation Spectroscopy (MPCS)



HIC and correlations as a spectroscopic tool

MPCS in heavy-ion collisions

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

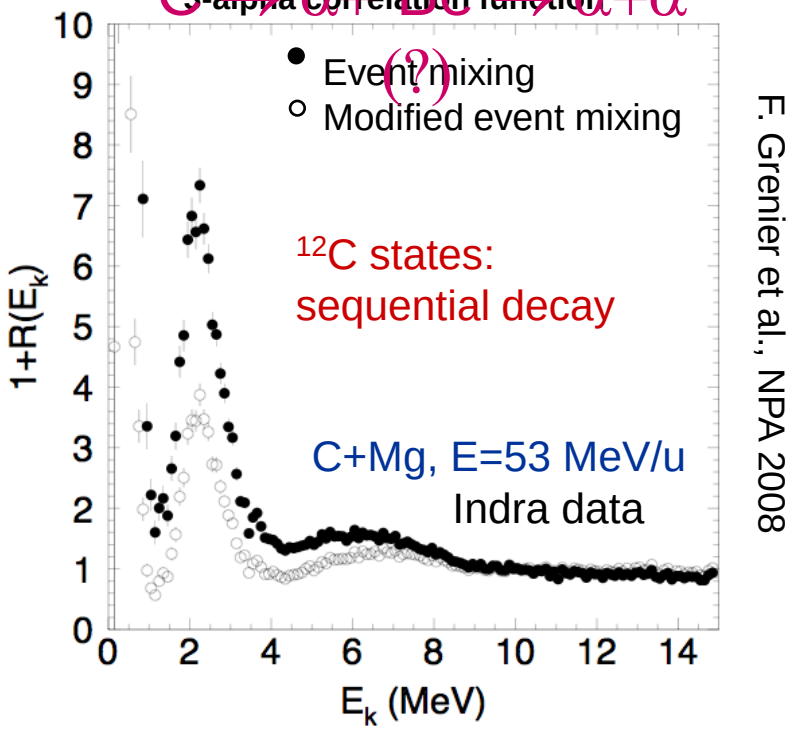


$^{12}C \rightarrow \alpha+\alpha+\alpha$

(?)

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

(?)

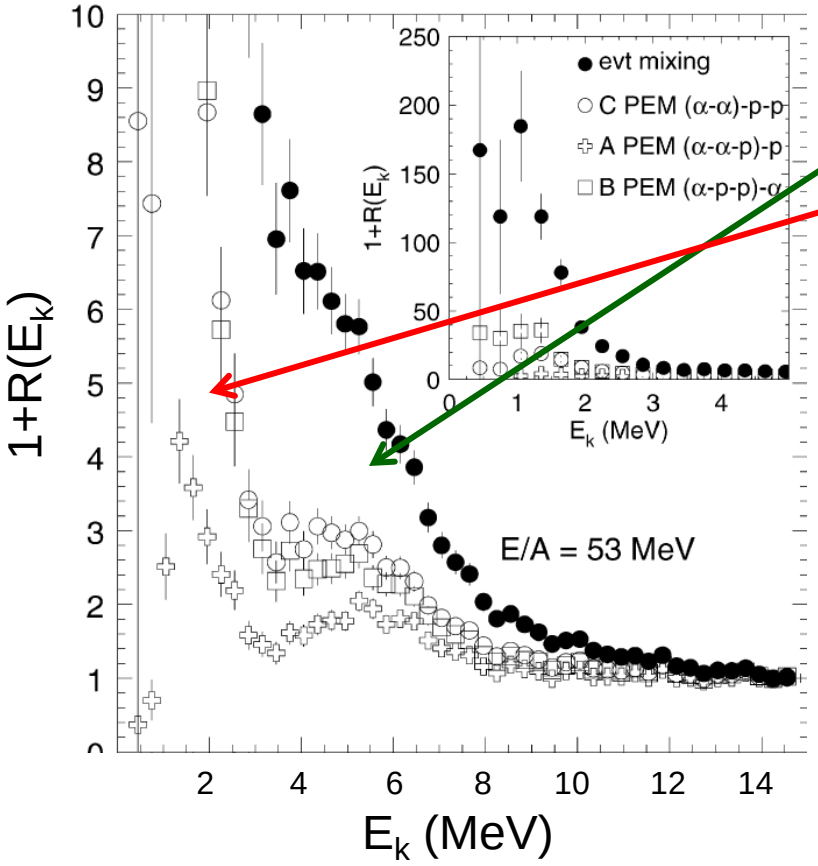


Accessing spins and branching ratios (sequential decay paths)

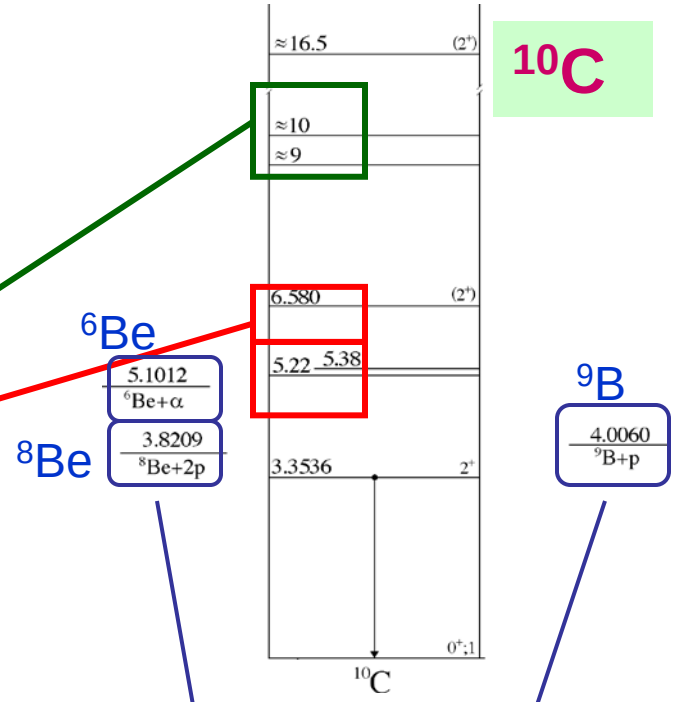
Multi-α correlations: Hoyle and Boson condensate states

2α-2p correlations: states in $^{10}C^*$

p-p-α–α four-particle correlations



F. Grenier, A. Chbihi, G. Verde et al., Nucl. Phys. A811 (2008) 233



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

^{10}C ➔ $^{8}Be+2p$ ➔ $(\alpha+\alpha)+2p$

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

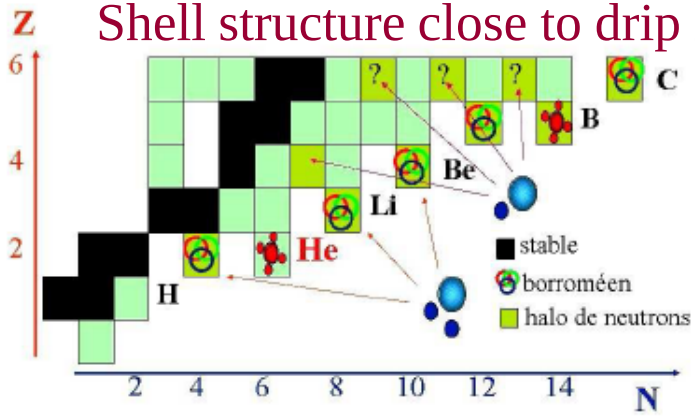
Disentangle sequential decay paths

Direct reactions with RIBs

Use the array in stand-alone mode or couple it to other detectors

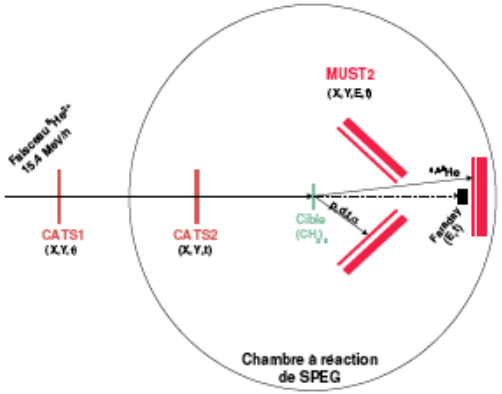
Spectroscopy: “stand-alone” mode

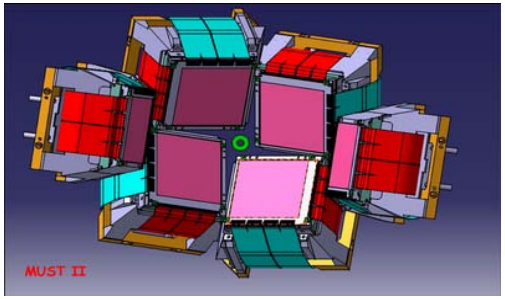
Shell structure close to drip lines



Direct reactions in inverse kinematics

Ex: Must2 expts





^{8}He beam @ Spiral (GANIL)
E/A=15.4 MeV

$^{8}H + p \rightarrow {}^{7}He + d$

$^{8}H + p \rightarrow {}^{6}He + t$

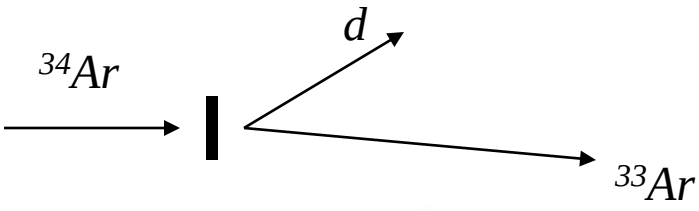
Similar experiments at LNS (FRIBS), GANIL, Spiral/Spiral2, Spes

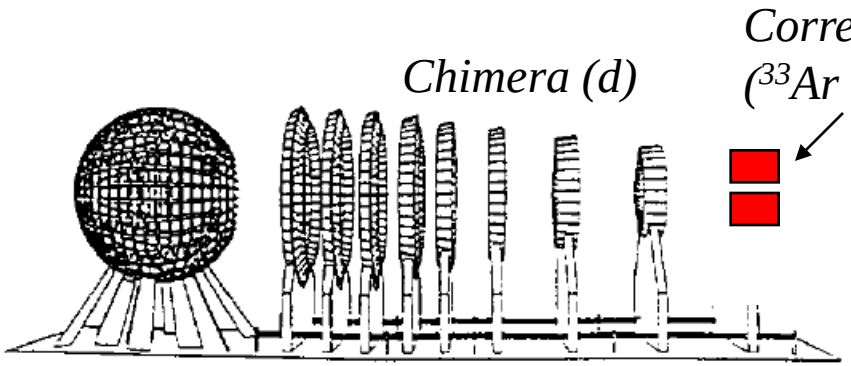
At low energies pulse shape on 1st silicon may be relevant

Spectroscopy: “coupling” mode

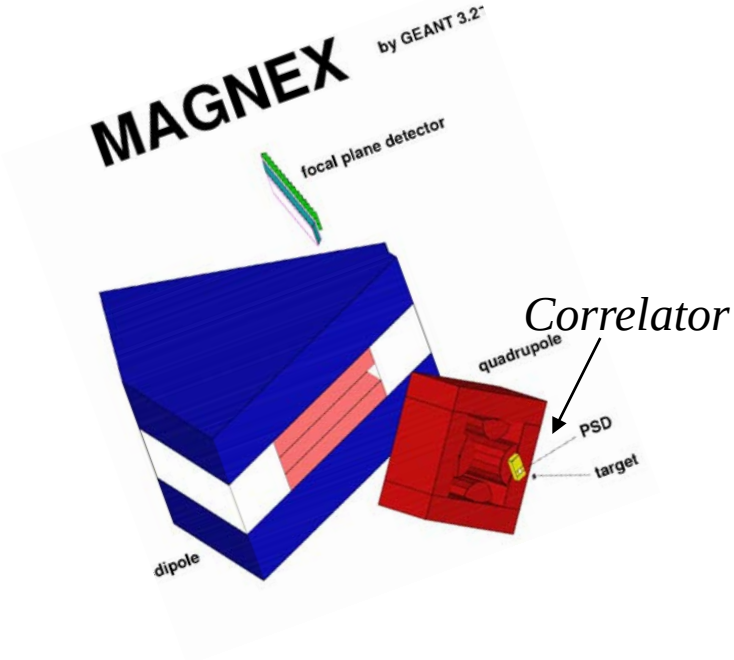
FRIBS beams at the LNS of Catania

$^{34}Ar+p \rightarrow {}^{33}Ar+d$





Day-1 experiment at the INFN-LNS



- Other options: coupling to Magnex
- Farcos for the light particle and Magnex for the heavy core

□γ-ray detector

So what?

- Reinforce international efforts towards *femtoscopy* at low and intermediate energies
- Dynamics and spectroscopy
- Farcos array in Catania (a simple project)
  - Angular resolution ($\delta\theta,\delta\phi<1^{o}$), Pulse-shape for low E experiments, Flexibility, modularity, transportability: coupling to 4π detectors, spectrometers, n-det
  - Interfacing to other projects: Fazia, other si-strip arrays
- Integrated electronics: internationally based working groups

Workshop in 2011

- Catania, probably spring or early fall 2011
  - Integrated electronics for silicon detectors, present and future solutions

You are all very welcome:
need to build up synergies