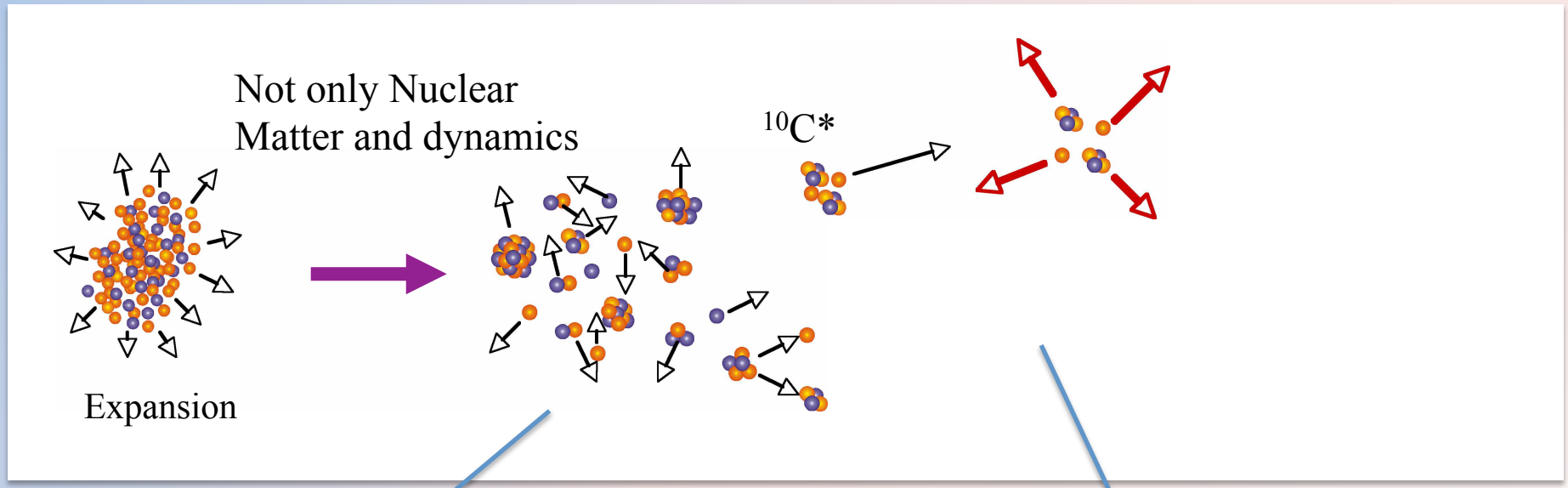
Particle-particle correlations in heavy-ion collisions



Dynamics, Equation of State, Nuclear Interaction, Nuclear Astrophysics (neutron stars, supernovae)

Unbound/exotic species produced in one single experiment
→ tools for spectroscopy

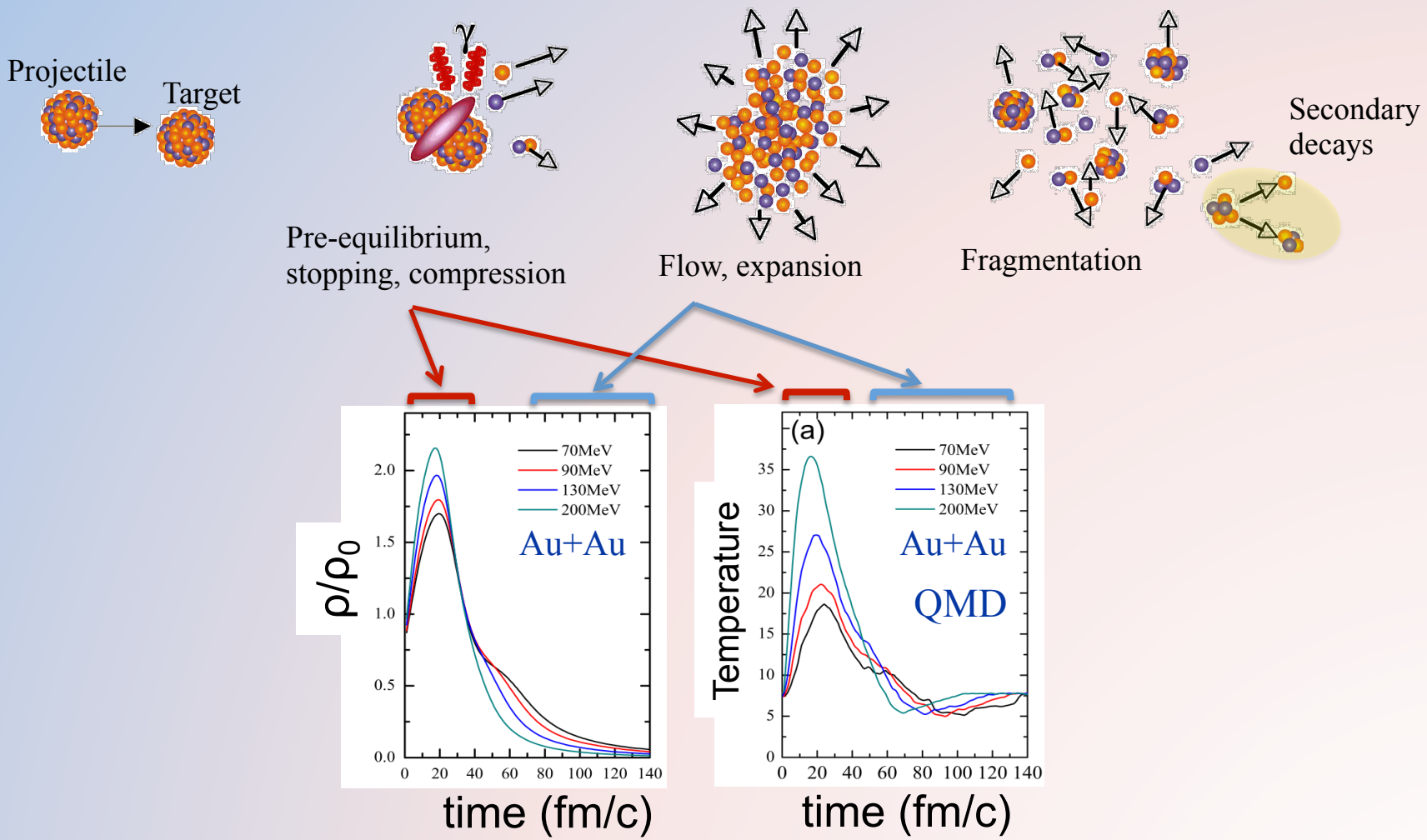
G. Verde
IPN Orsay, October 30-31, 2014

Outline

- Heavy-ion collisions
  - Equation of state and symmetry energy
  - Plenty of unbound states and resonances (for free)
- Correlation measurements:
  - Dynamics, EoS, Asy-EOS
  - tools from multi-particle decay spectroscopy
- Perspectives (SIB and RIB facilities)

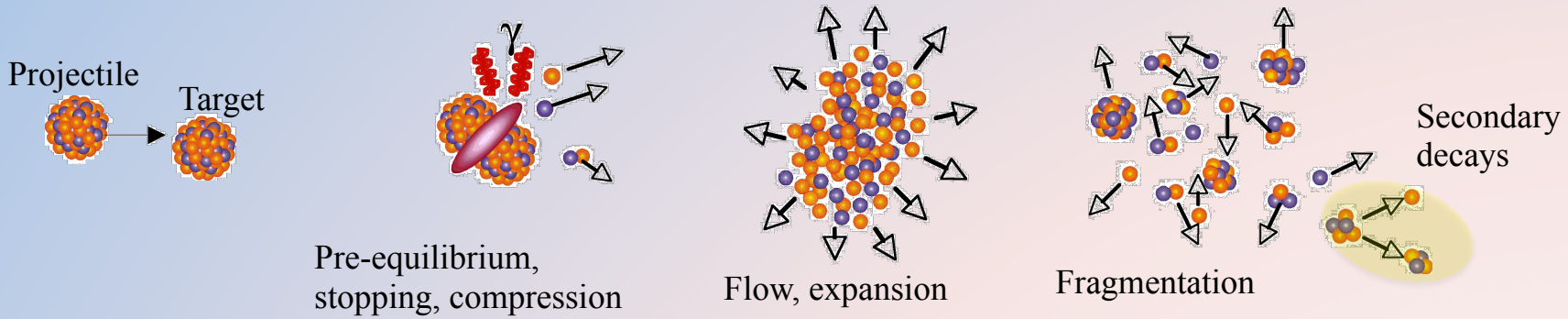
HIC: compressing and heating nuclear matter

Laboratory controlled



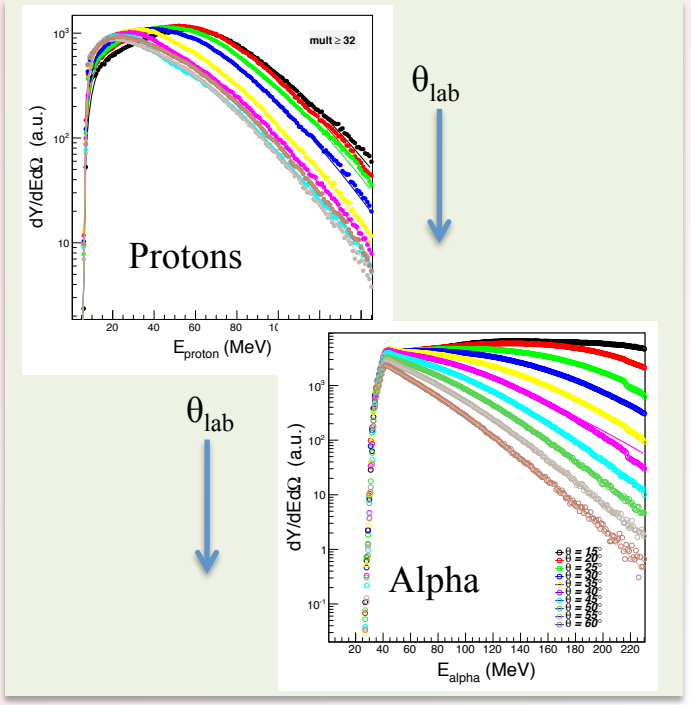
EoS *under laboratory controlled conditions*

Laboratory controlled



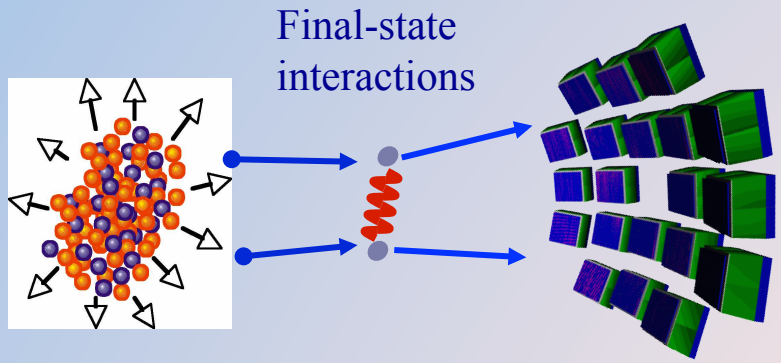
Measurements

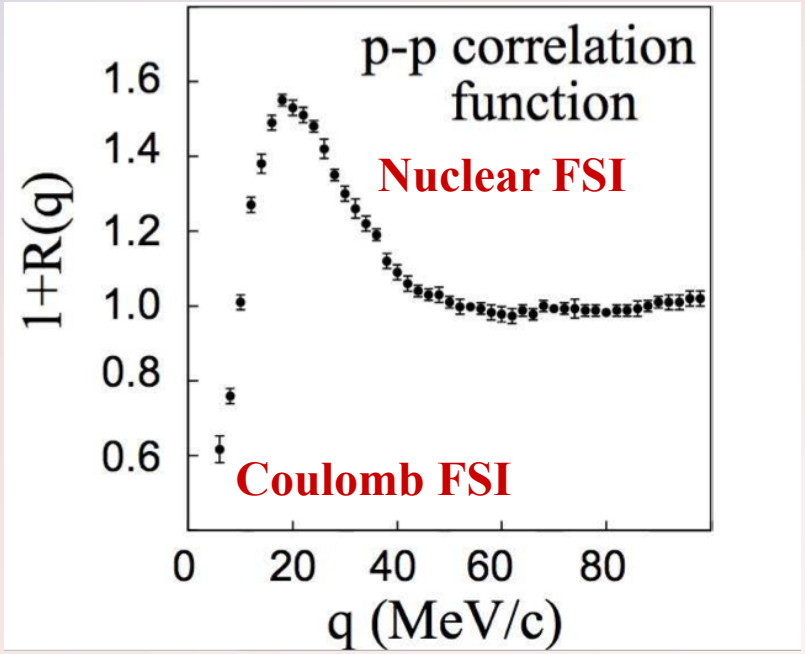
Energy and angular distributions



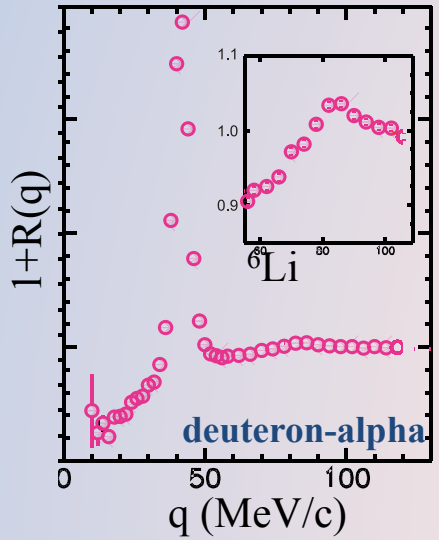
- Need back-tracing from final experimental distributions: when and where are particle produced?
- Space-time probes of emitting sources from particle-particle correlations

Building correlations





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



$$q=\mu\left|\vec{v}_1-\vec{v}_2\right|$$

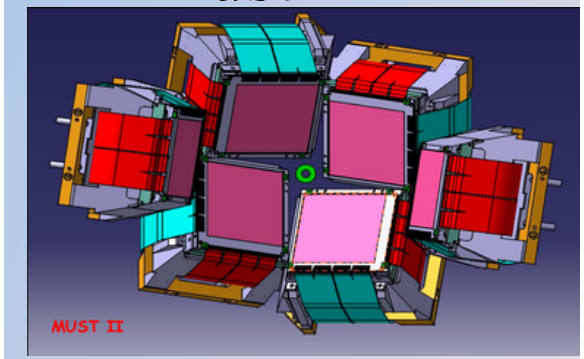
Experimental needs:

→ Large solid angle coverage

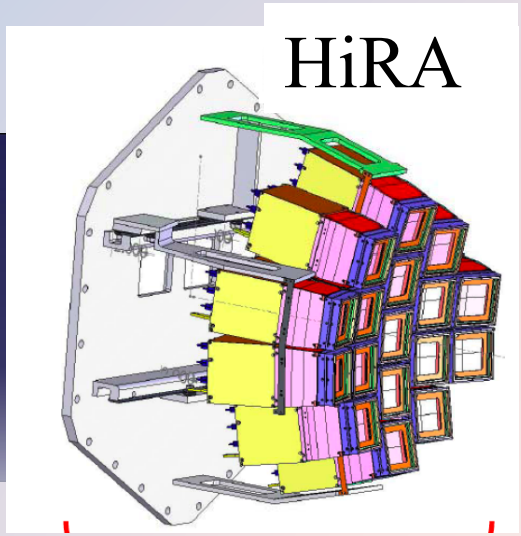
→ High angular resolution required:

High resolution arrays

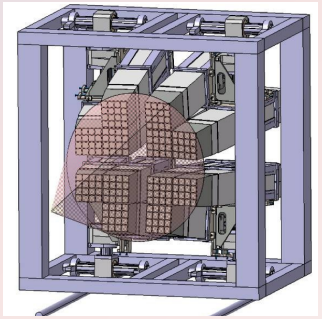
Must2

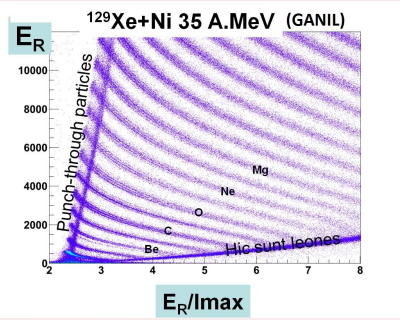


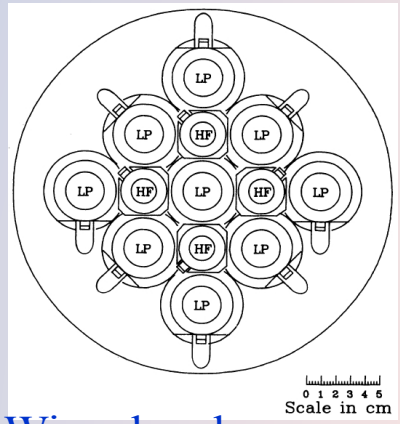
HiRA



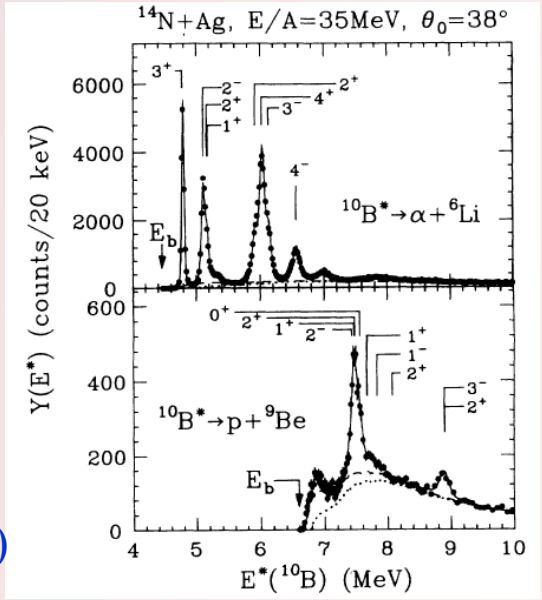
Fazia @ LNL, LNS, GANIL/Spiral2







Wire chambers
(high position resolution)



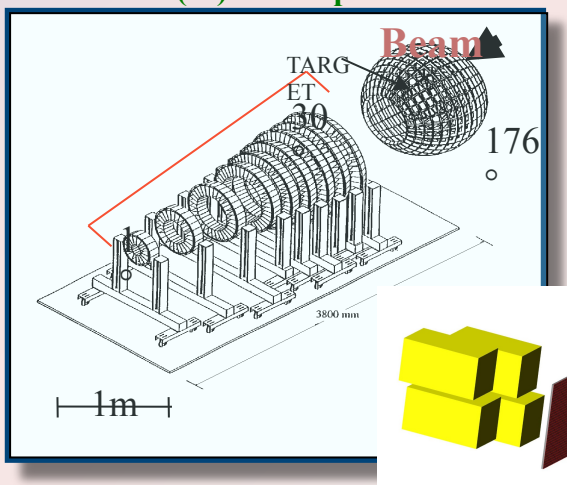
Position sensitivity: high performances!

T.K. Nayak et al., PRC45, 132 (1992)

Coupling to 4pi arrays (event characterization)

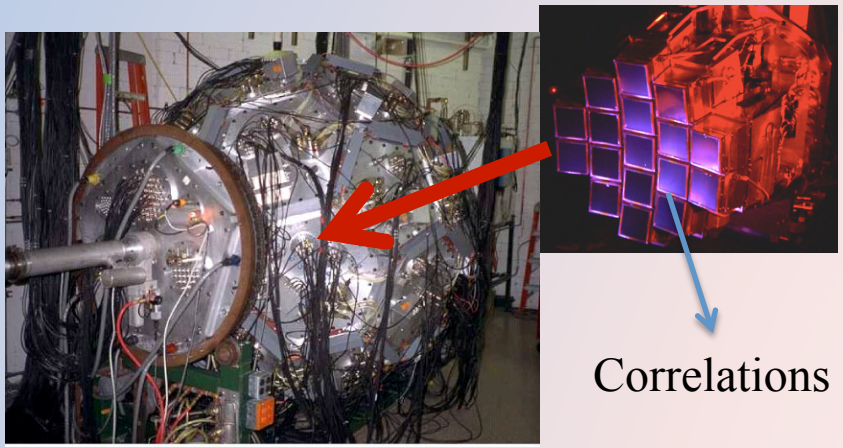
CHIMERA-PS & FARCOS

1192 Si-CsI(Tl) Telescopes



Farcos @ CT
(GET electronics)

MSU 4pi + HiRA Si-Strip array



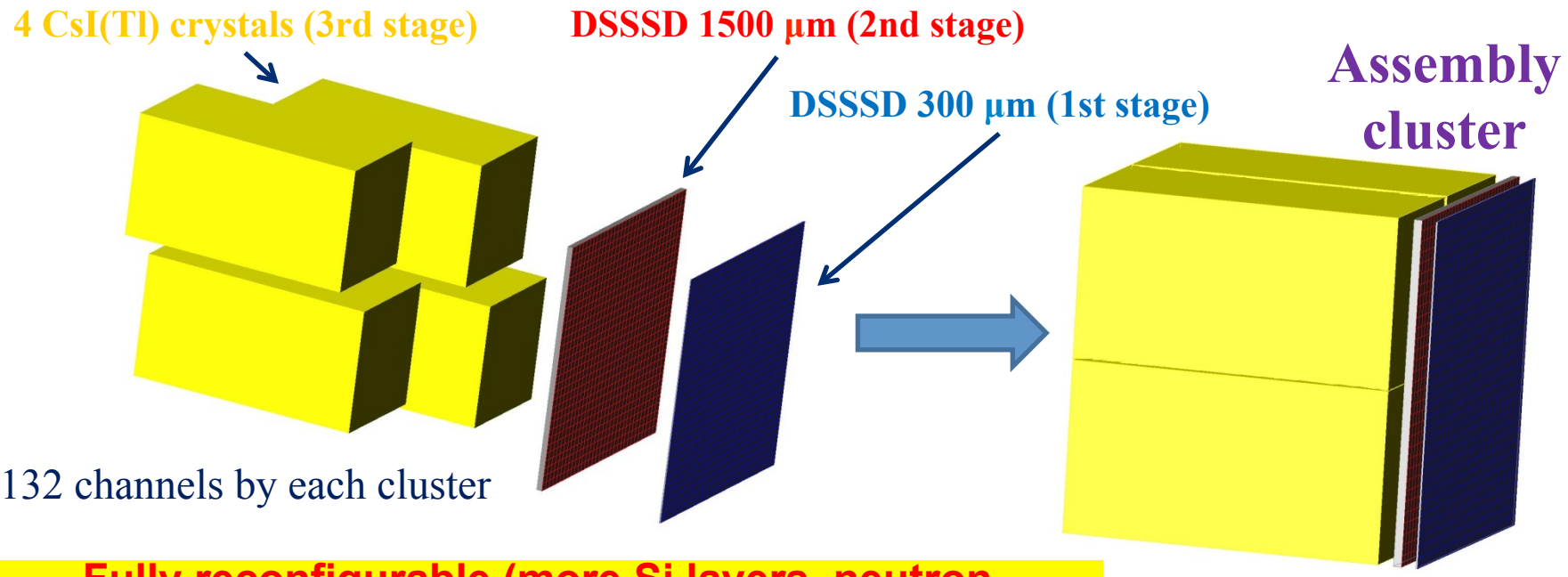
Correlations

Demonstrator already online @ LNS

…also Indra and Fazia + Correlators

Farcos: Femtoscope Array for Correlations and Femtoscopy

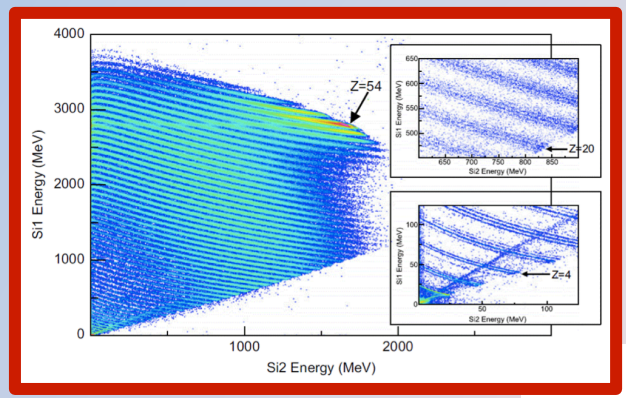
- Based on (62x64x64 mm^3) clusters
- 1 square (0.3x62x62 mm^3) DSSSD 32+32 strips
- 1 square (1.5x62x62 mm^3) DSSSD 32+32 strips
- 4 60x32x32 mm^3 CsI(Tl) crystals

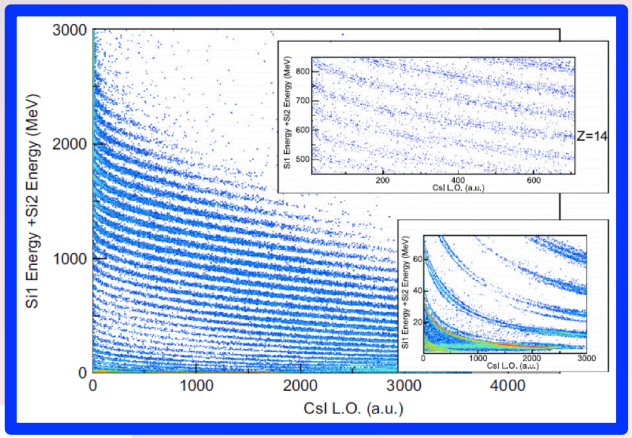


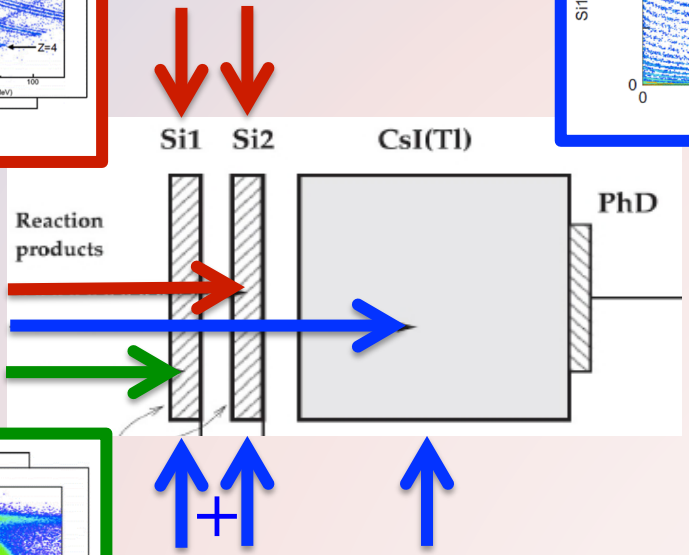
Fully reconfigurable (more Si layers, neutron detection, …)

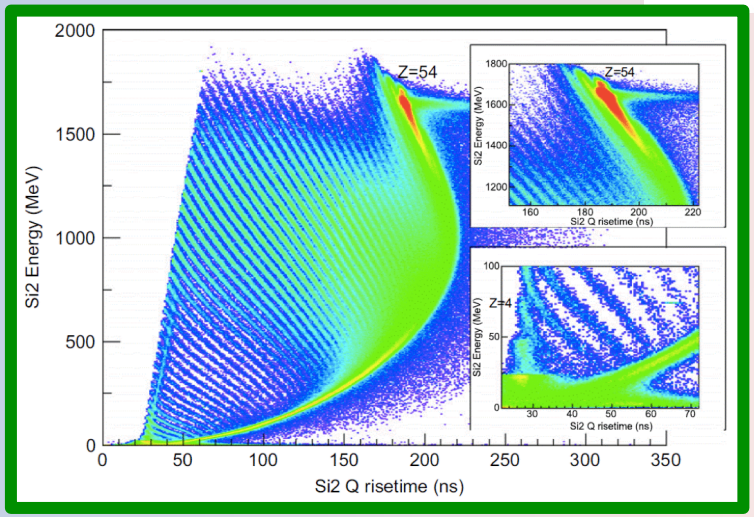
INFN, Catania & Milano

Fazia telescopes









IPN Orsay: Front-End Electronics

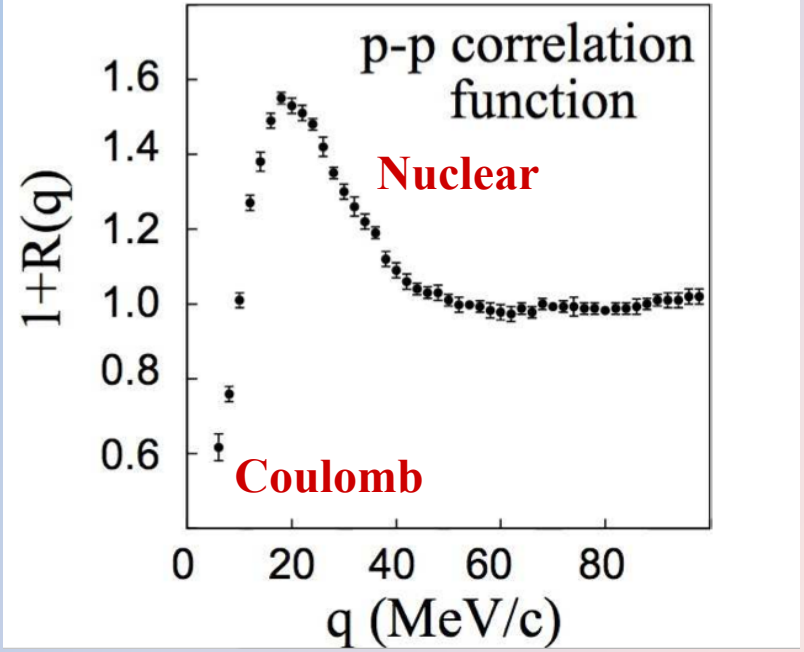
pp correlations, IMF-IMF correlations… non resonant correlations

Next experiment w demonstrator
LNS-Catania December 2014

What physics information?

- Images of emitting sources (imaging)→compare to models
- What is the size of an emitting source for a specific particle → "femtoscopy"
- What is the duration of emission process by that source
- Disentangle sources (pre-equilibrium, evaporation, secondary decays, etc.)
- Disentangle decay mechanisms: sequential vs direct/ simultaneous
- Emission chronology of different particle species

Proton-proton femtoscopy



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

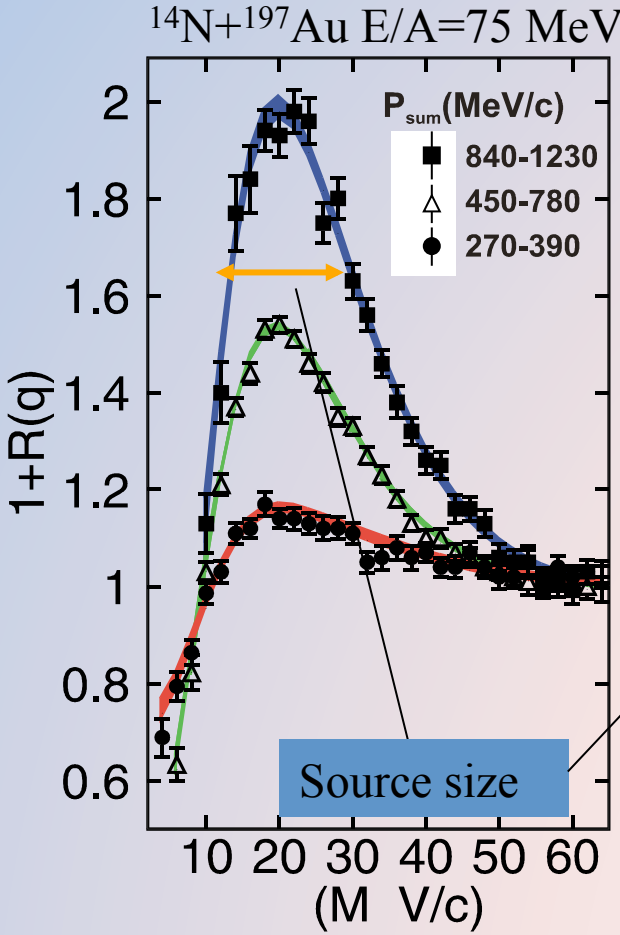
- Final State interactions (FSI)
  Nuclear → peak at 20 MeV/c
  Coulomb → anti-correlation at small q
- Anti-symmetrized two-particle wave function (fermions)

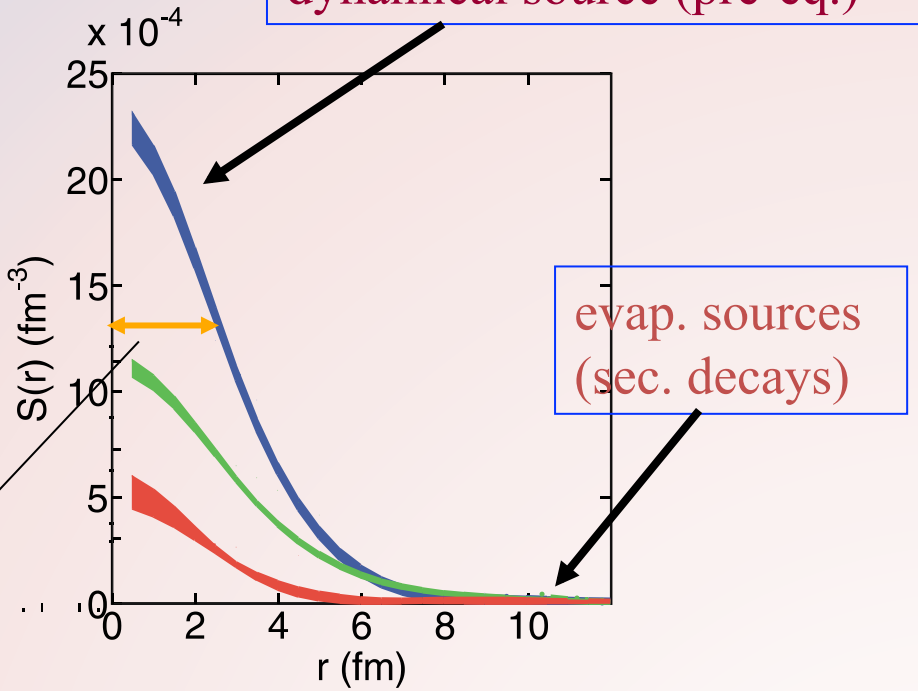
→ Spatial distribution of particles in their emitting sources during dynamical evolution of HIC

Inversion analysis of KP equation

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

G. Verde et al., PRC65, 069604 (2002)
P. Danielewicz, D.A. Brown





dynamical source (pre-eq.)

evap. sources (sec. decays)

Y_{total}=*Pre-equilibrium* + *Evaporation*

Y_{fast} + Y_{slow}

- Integral of source → Y_{fast}/Y_{slow} Estimate contributions from secondary decay emissions:

EoS of asymmetric nuclear matter

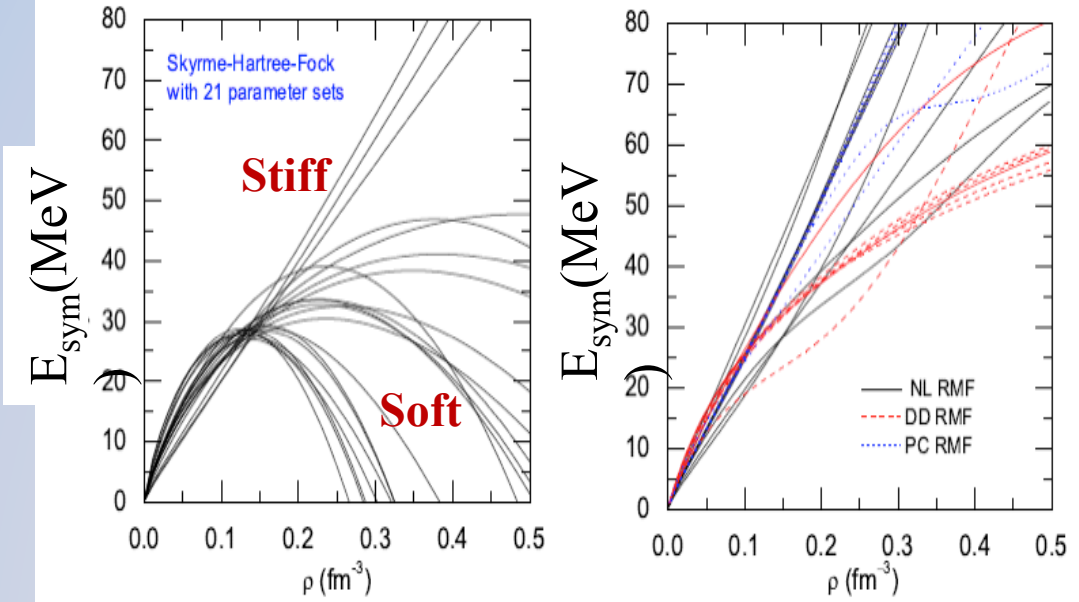
$$E(\rho,\delta) = E(\rho,\delta=0) + \boxed{E_{sym}(\rho)\cdot\delta^2} + O(\delta^4)$$

Asymmetry term

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

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

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



Many approaches… large uncertainties….

Microscopic many-body, phenomenological, variational, …

Especially at high densities (three-body forces)

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

Increase δ asymmetry by studying systems with large N/Z asymmetry

→ RIB facilities (Eurisol, SPES, …)

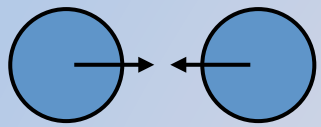
→ **STABLE BEAM studies important!**

Brown, Phys. Rev. Lett. 85, 5296 (2001)

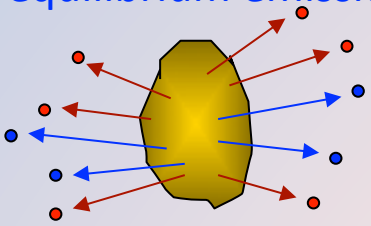
Fuchs and Wolter, EPJA 30, 5 (2006)

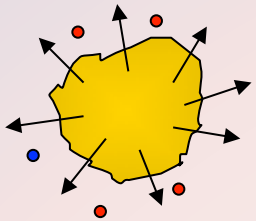
Symmetry energy and femtoscopy

b=central

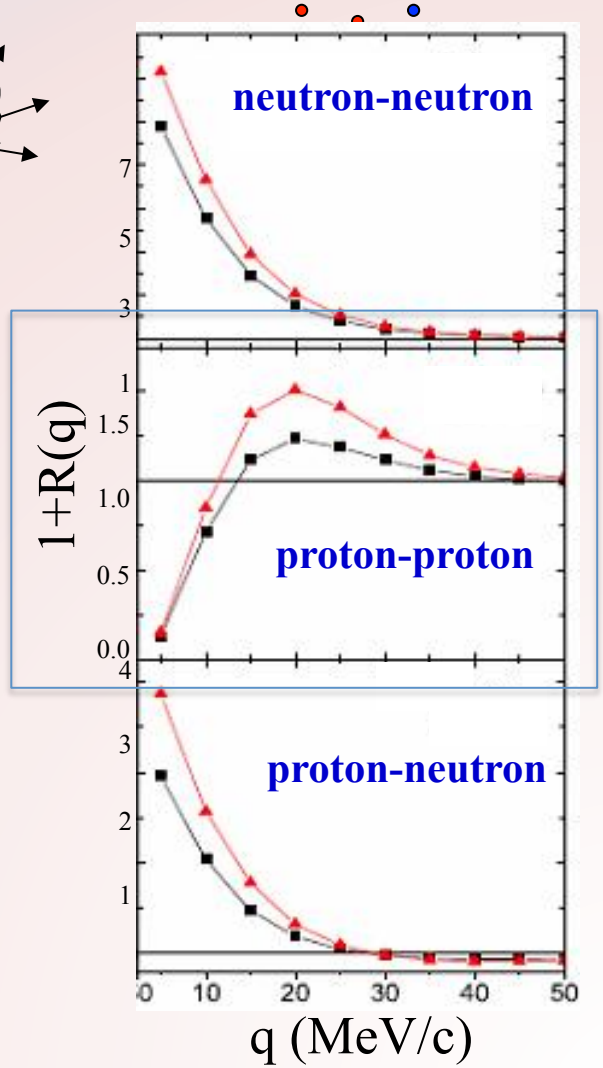


Pre-equilibrium emission

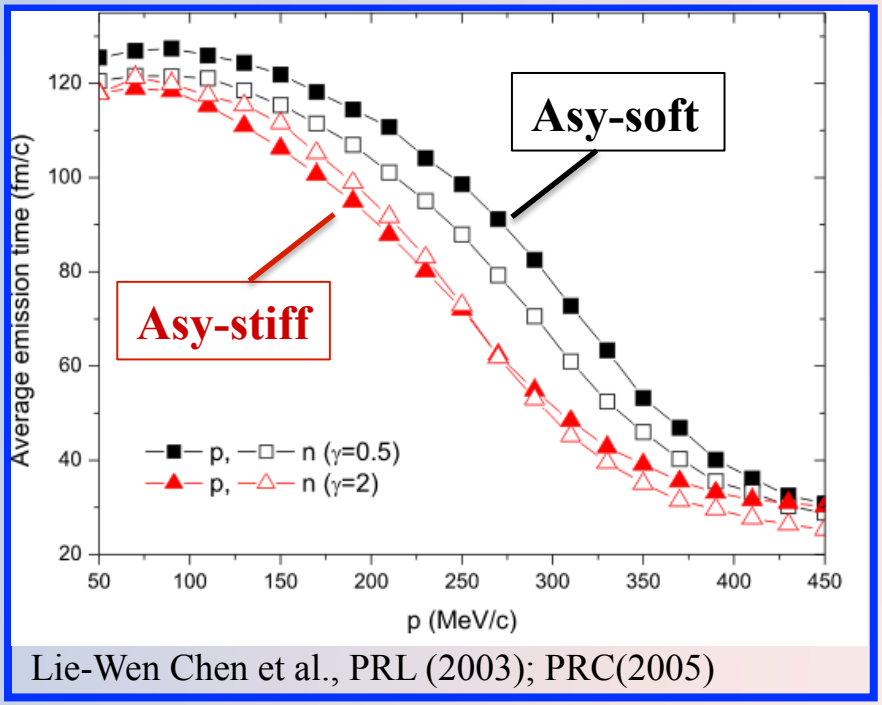




Correlation functions



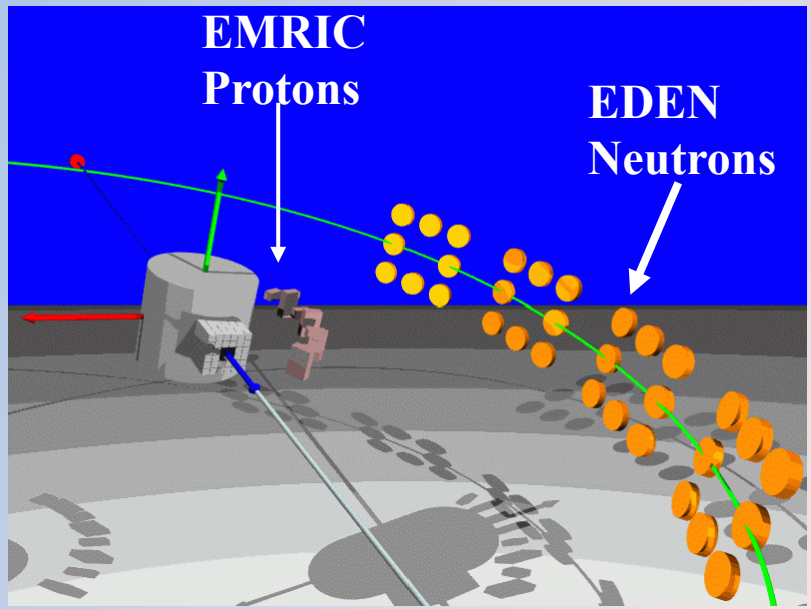
Neutron/proton emission times vs. E_{sym}

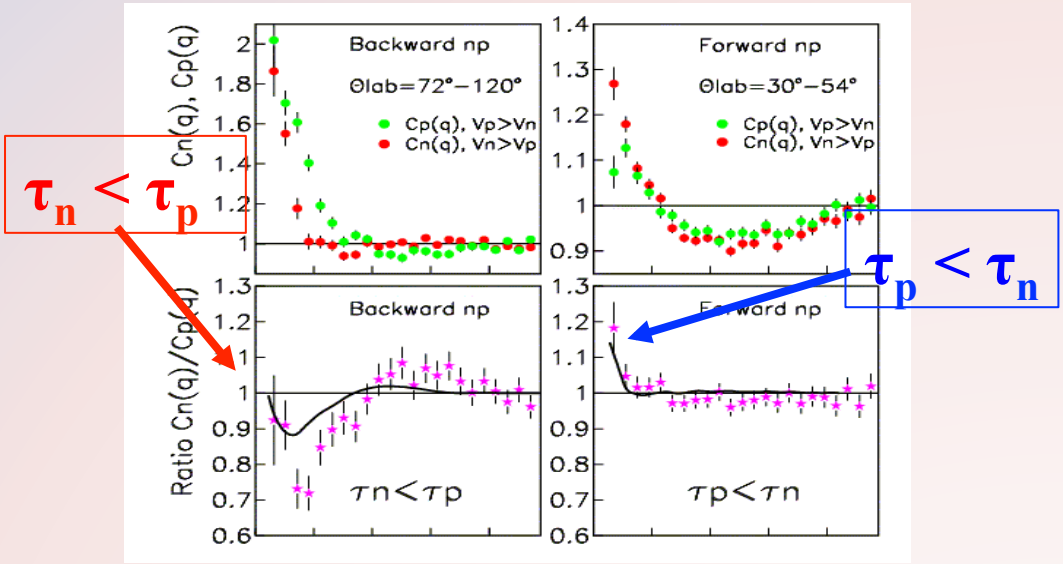


Lie-Wen Chen et al., PRL (2003); PRC(2005)

Unlike particle correlations: emission chronology

Ghetti *et al,* PRL 91 (2003) 092701

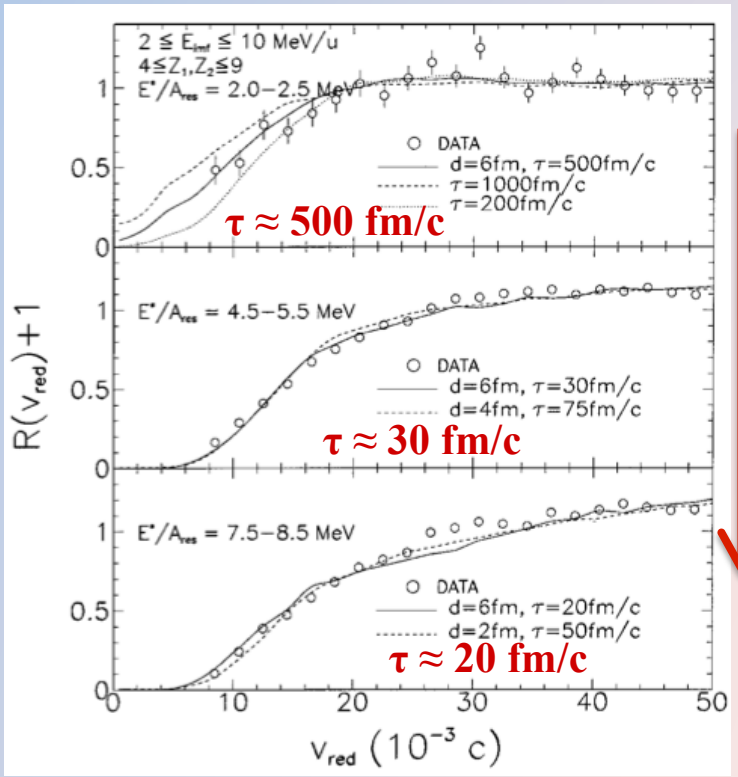




- Unique toolsfor Esym still not explored enough
- Extend to all particle species: asymmetric particles (t, 3He, …) and symmetric particles (d,α,6Li, …)
- Important with both SIB (LNS,GANIL) and RIB facilities (N/Z increase in beam-target combinations)

IMF-IMF correlations

π^-, p + Au 8.0, 8.2, 9.2, 10.2 GeV/c

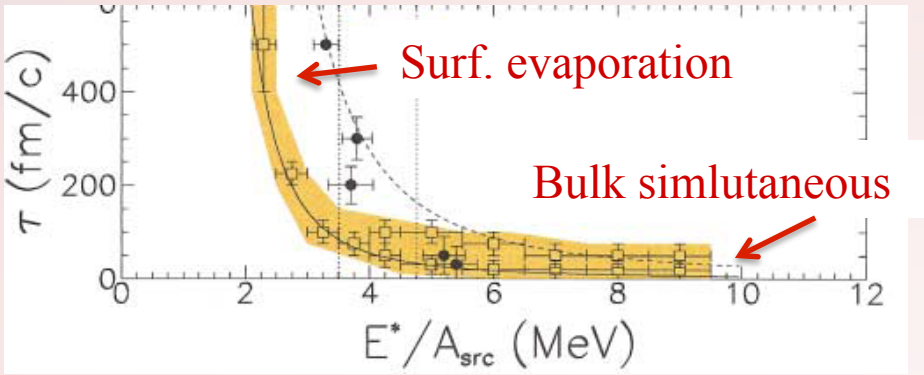


Increasing E*/A

Thermally expanding and decaying source

ISiS data @ Brookhaven

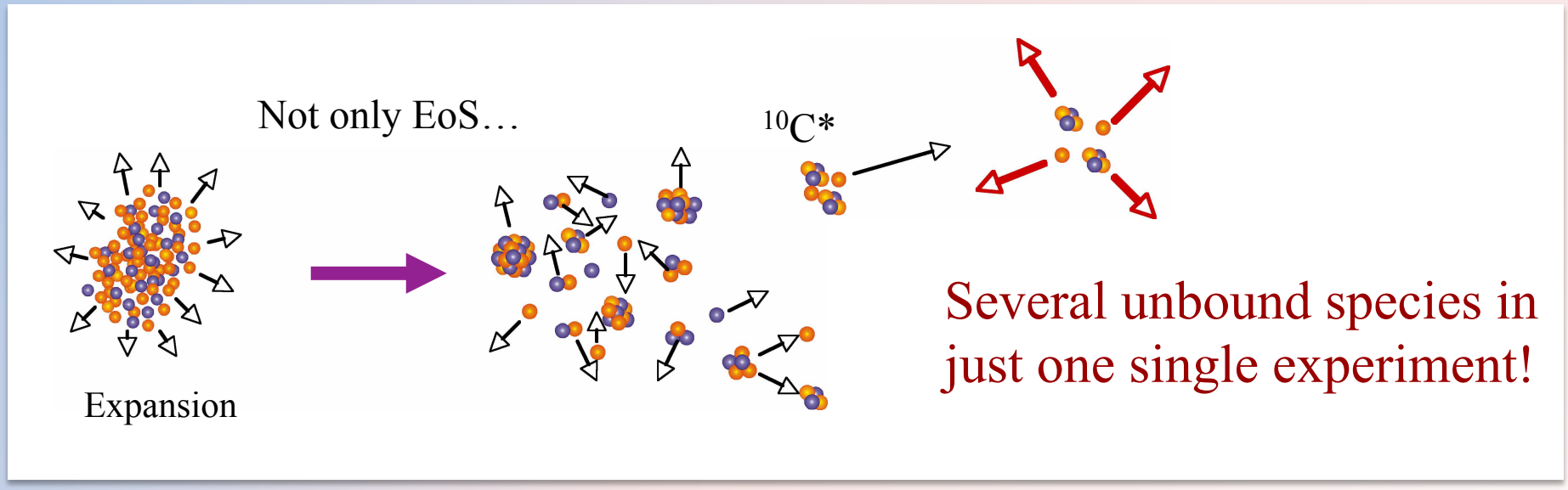
L. Beaulieu et al., PRL84 (2000) 5971



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

Isotopicaly resolved IMF-IMF/IMF-LCP correlations:
Chimera, Fazia + Correlators (Must2, Farcos)

Multi-Particle Correlation Spectroscopy

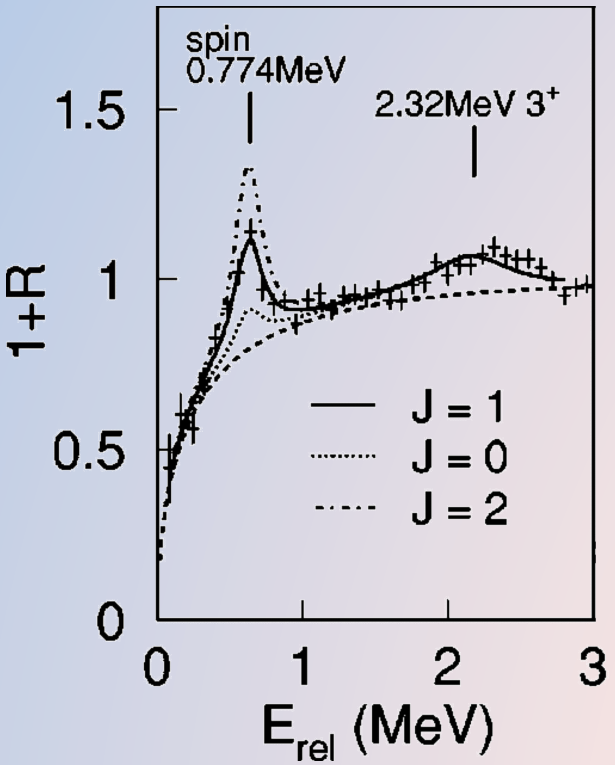


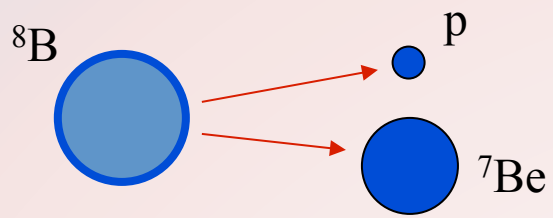
HIC and correlations as a spectroscopic tool

^{8}B unbound states in central HIC

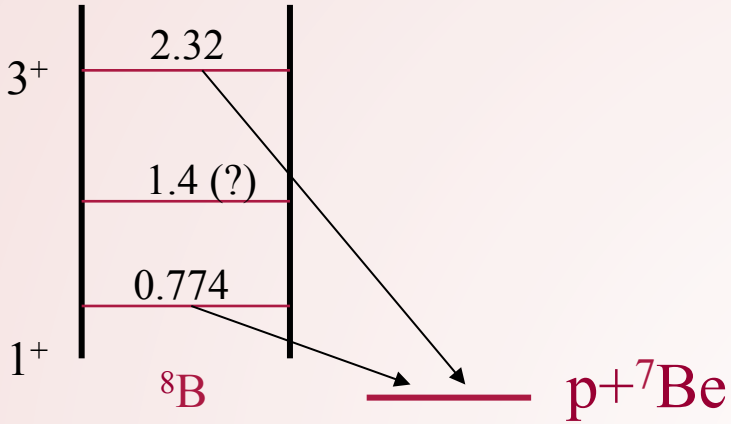
Xe+Au E/A50 MeV Central collisions – LASSA @ MSU

p-^{7}Be correlations





States of ^{8}B → p+^{7}Be



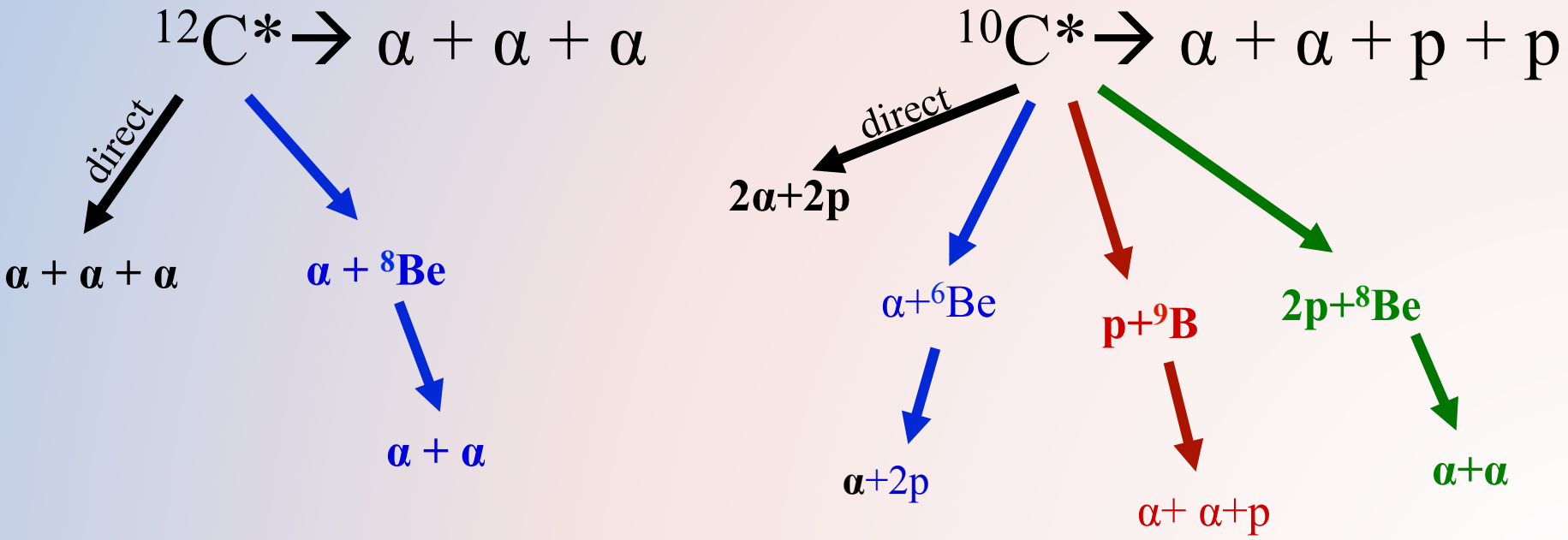
W.P. Tan et al. Phys. Rev. C69, 061304 (2004)

Sequential decay modes in projectile fragmentation

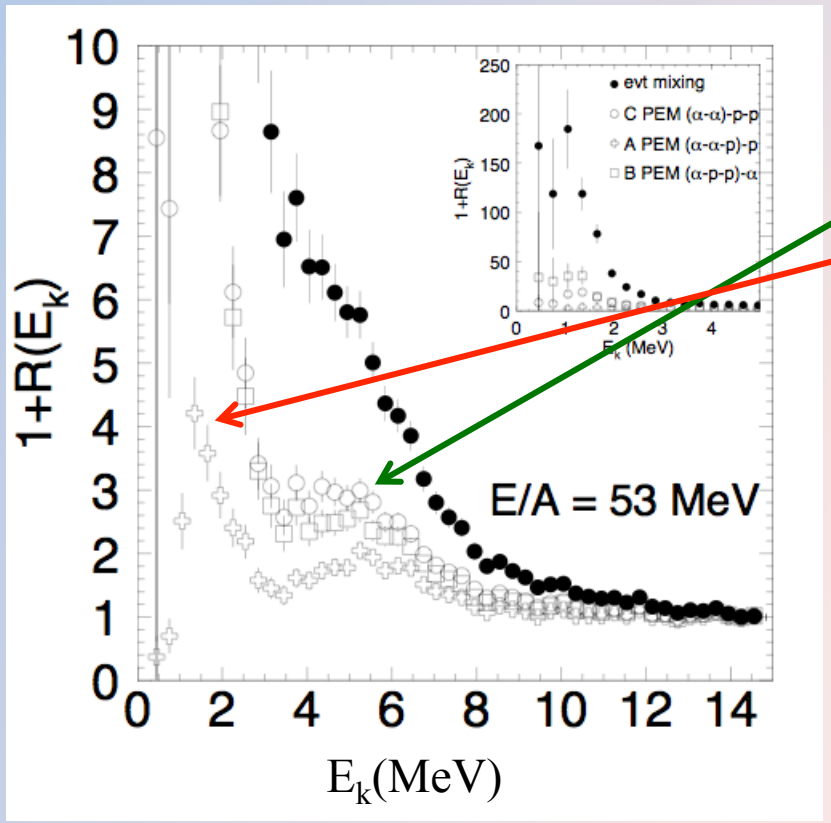
- Peripheral projectile fragmentation

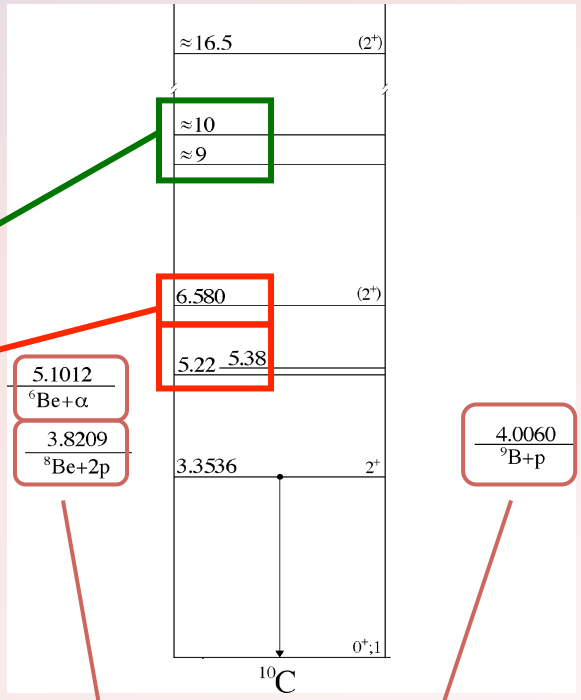
  $^{12}C+^{24}Mg$ E/A=53, 95 MeV (Indra@GANIL)

  Decay of ^{12}C and ^{10}C quasi projectiles (QP*)



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





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

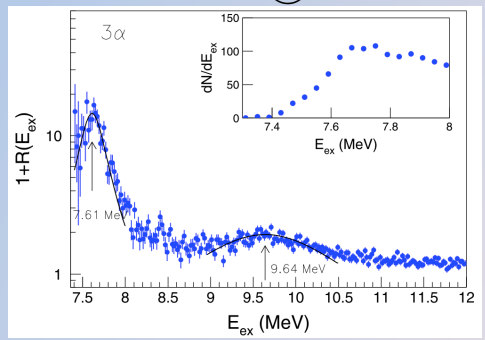
$^{10}C \rightarrow {}^{8}Be+p+p \rightarrow (\alpha+\alpha)+p+p$

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

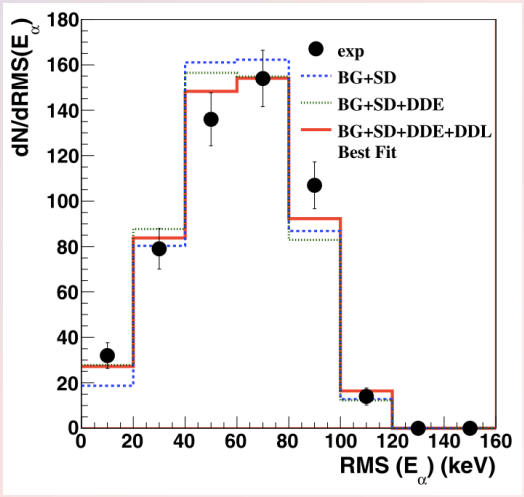
F. Grenier et al., Nucl. Phys. A811 (2008) 233

Sequential vs Simultaneous decay mechanisms

CHIMERA @ LNS



$^{12}C \rightarrow 3\alpha$ decays in 40Ca+12C at E/A=25 MeV



A. Raduta et al., PLB (2011)

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

direct

$\alpha + \alpha + \alpha$

DDE

$\alpha + {}^{8}Be$

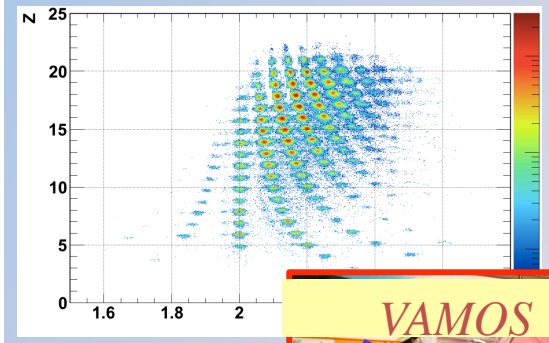
$\alpha + \alpha$

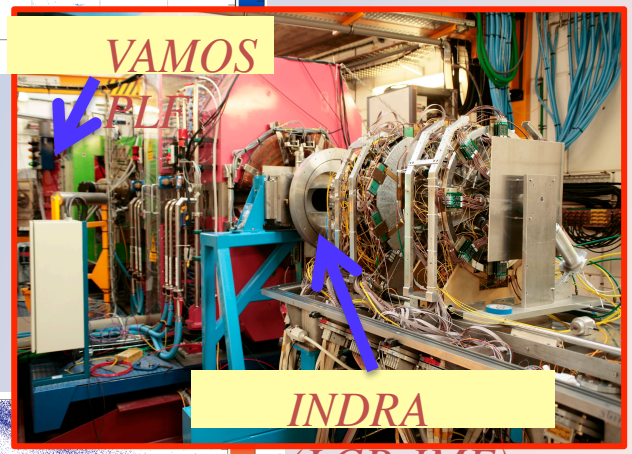
SD

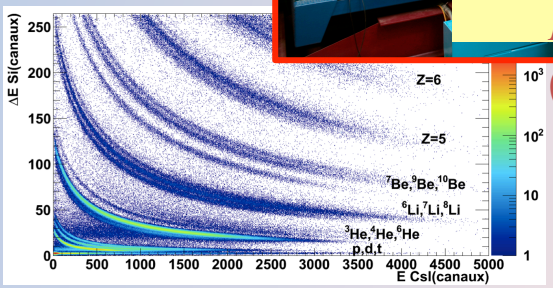
DDL

Explore relative contributions from different decay mechanisms (sequential vs direct)

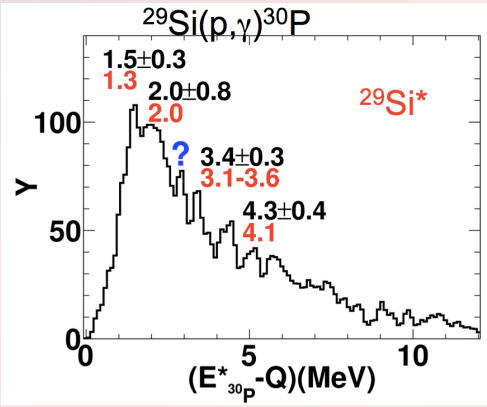
Decays of exotic PLF*

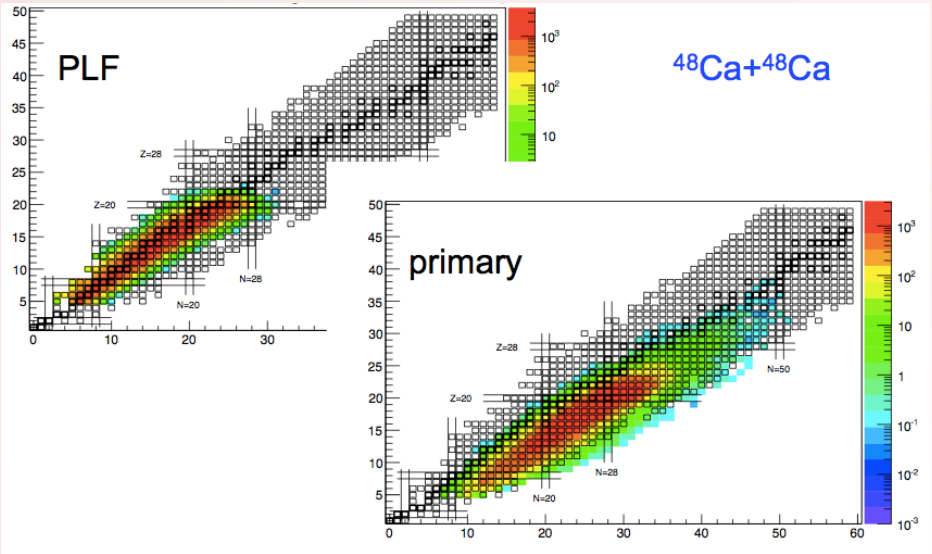






proton – ^{29}Si correlations





A. Chbihi, P. Marini, et al.