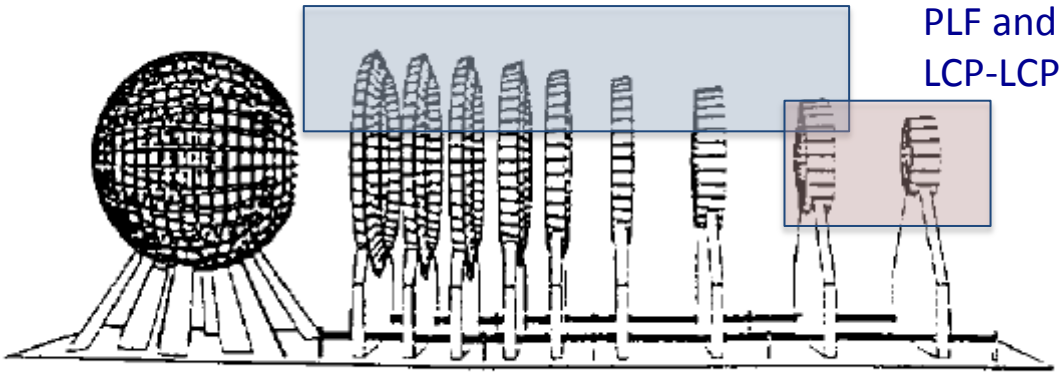
Topics of interest for Must2 in HIC

1. Density dependence of the symmetry energy: peripheral and central collisions
2. particle-particle correlations
   a. Imaging of emitting sources: space-time properties
   b. Invariant-mass spectroscopy: in-medium structure; density and temperature (EoS) effects on clustering → mechanisms for clustering organization of nuclear matter
3. Strong interplay dynamics-structure, EoS-clustering
4. Possible plans:
   a. LISE (2017-2018)
   b. Intermediate and preparatory step at LNS/stable + Chimera

2016 – Must2+Chimera/Farcos?

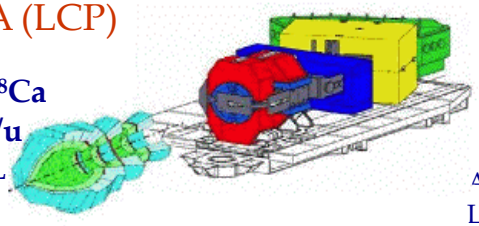
MUST2: ϑ>25º
Z=1,2 correlations
Mid-velodity

FARCOS: ϑ=5º-25º
Z=1-8 correlations
PLF and Mid-velocity
LCP-LCP and IMF-IMF correlations



VAMOS (QP)
INDRA (LCP)

^{40,48}Ca+^{40,48}Ca
35 MeV/u
GANIL



2007→2020…

A. Chbihi, G. Verde
LISE Workshop (Jan 2015)

^{40,48}Ca, ^{112,124}Sn (SIB)
$^{56-70}$Ni (RIB)
25-80 MeV/u
LNS, GANIL

Forwaed array (QP)
(FAZIA Dem., Chimera)

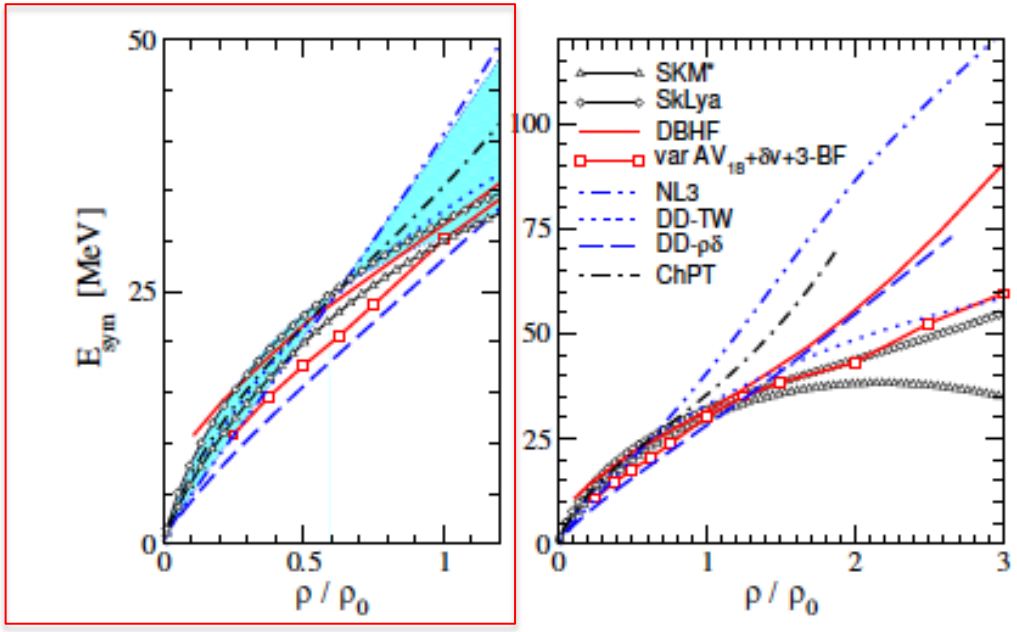
Correlators (LCP)
(MUST2, Farcos, FAZIA)

Density dependence of symmetry energy

Symmetric Asymmetric

$$E(r,\delta)/A = E(r,\delta=0)/A + E_{sym}(r)\times\delta^2$$

$$\delta = \frac{r_n - r_p}{r} = \frac{N-Z}{A}$$



Density dependence of symmetry energy

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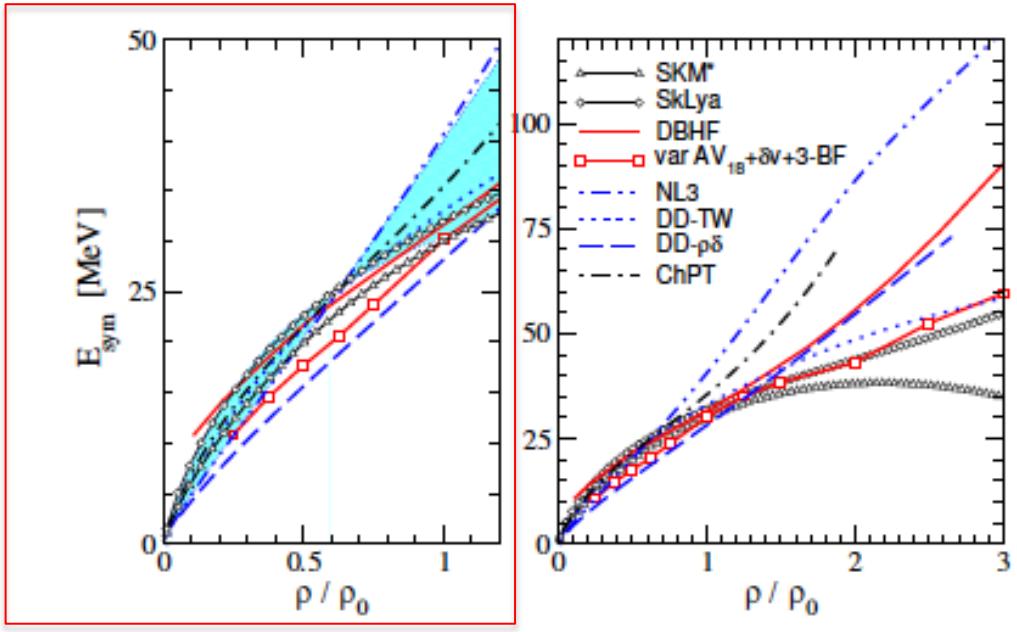
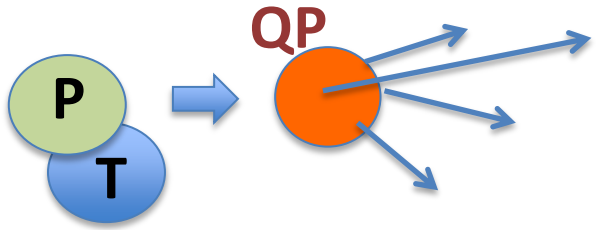


Mid-peripheral collisions

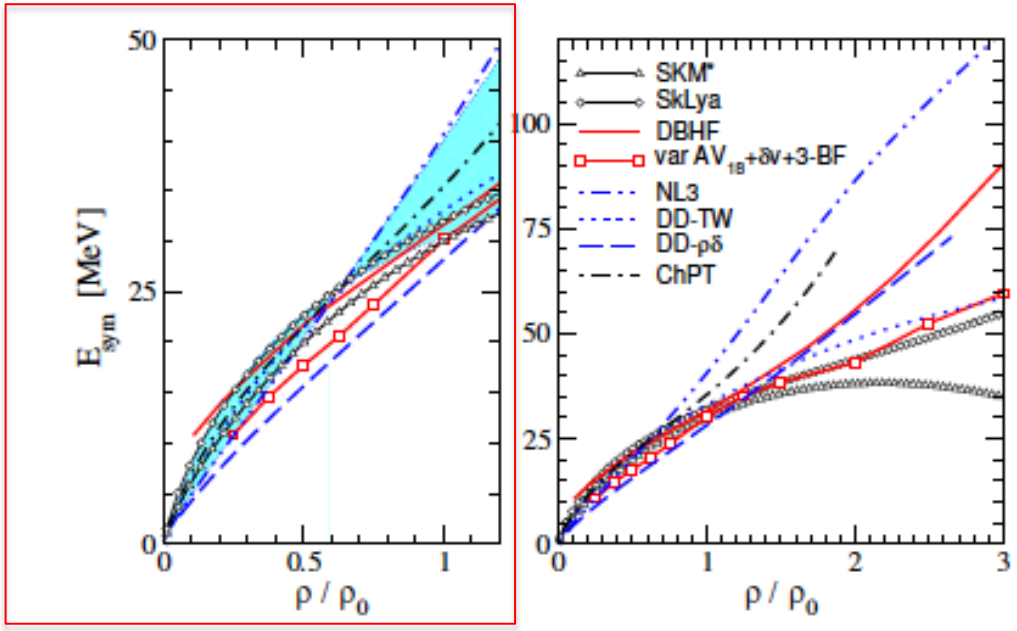


QP decay: $\rho \approx \rho_0$, T≈1-4 MeV
Heavy-Residue + LCP at
forward direction

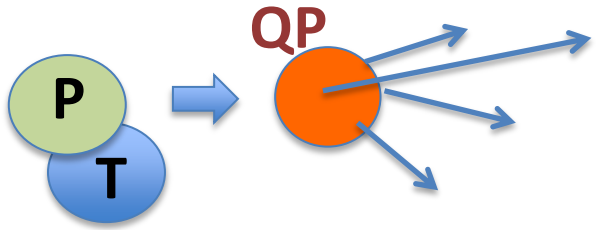
Density dependence of symmetry energy

Symmetric Asymmetric

$$E(r,d)/A = E(r,d=0)/A + E_{sym}(r)\times d^2 \qquad d=\frac{r_n - r_p}{r} = \frac{N-Z}{A}$$

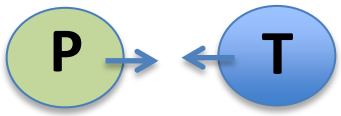


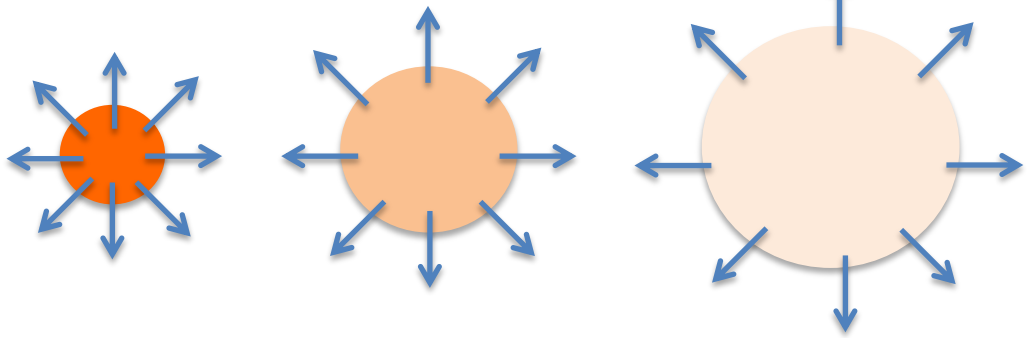
Mid-peripheral collisions



QP decay: $\rho\approx\rho_0$, T≈1-4 MeV
Heavy-Residue + LCP at
forward direction

Central collisions





$\rho\approx0.001\text{-}0.3\rho_0$
T≈1-7 MeV
Large solid angle coverage

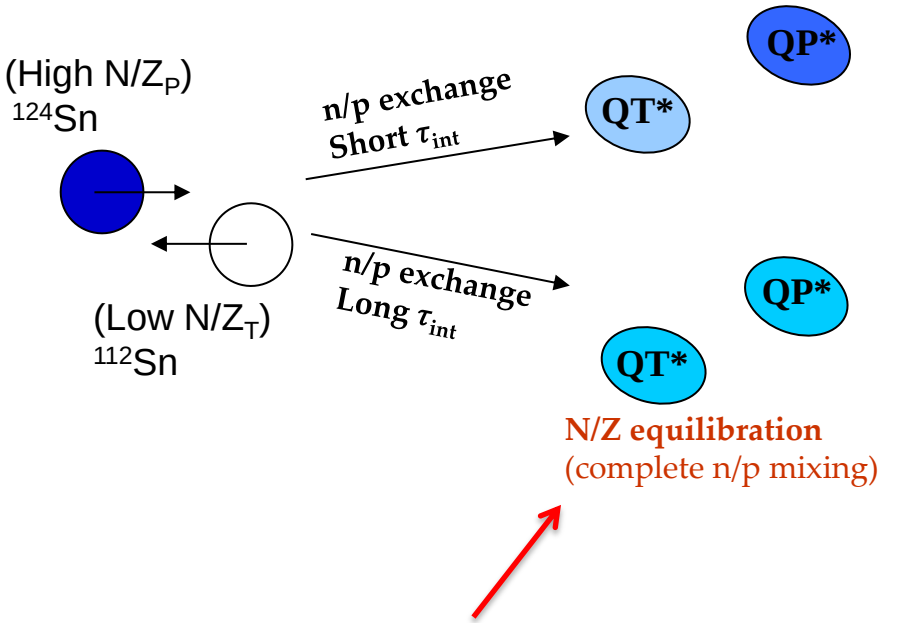
"Participant"decay

Experimental needs

- Collisions at intermediate energies between nuclei with different N/Z asymmetries: stable and exotic beamsGANIL/LISE, LNS for stable beams
- High large solid angle coverage (peripheral/central)
- Need high isotopic resolution in forward direction for QP reconstruction
- Need high angular and energy resolution at large angles for light particles (Z=1-2)
  - QP reconstruction and particle-particle correlations

Isospin diffusion and Correlations

E. Galichet et al. PRC79, 064614 (2009)
G. Verde et al., EPJA 30, 81 (2006)



Sensitivity to symmetry energy and EoS

Isospin diffusion and Correlations

E. Galichet et al. PRC79, 064614 (2009)
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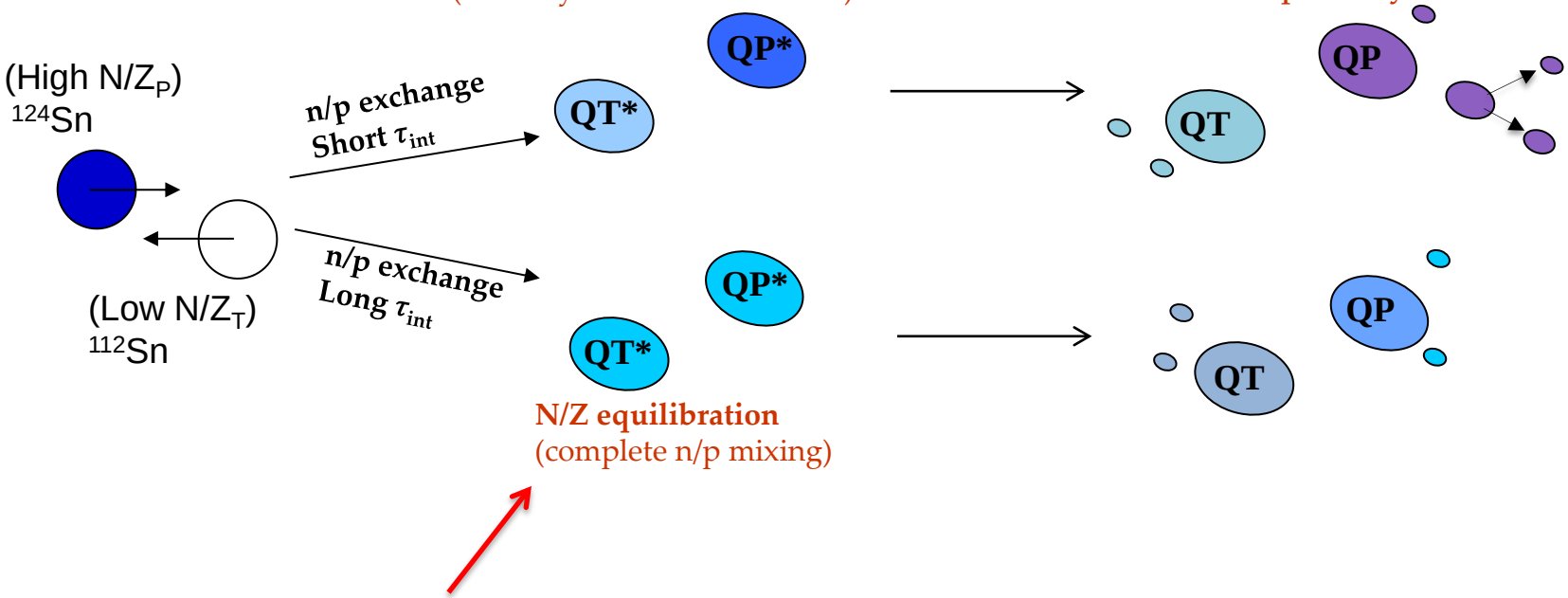


Sensitivity to symmetry energy and EoS

Need to reconstruct
Primary N/Z, E*, T, density
→ **Correlations LCP-QP**

VAMOS PLF (E503)
High Isotopic Resolution

detection

etry energy experiments

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

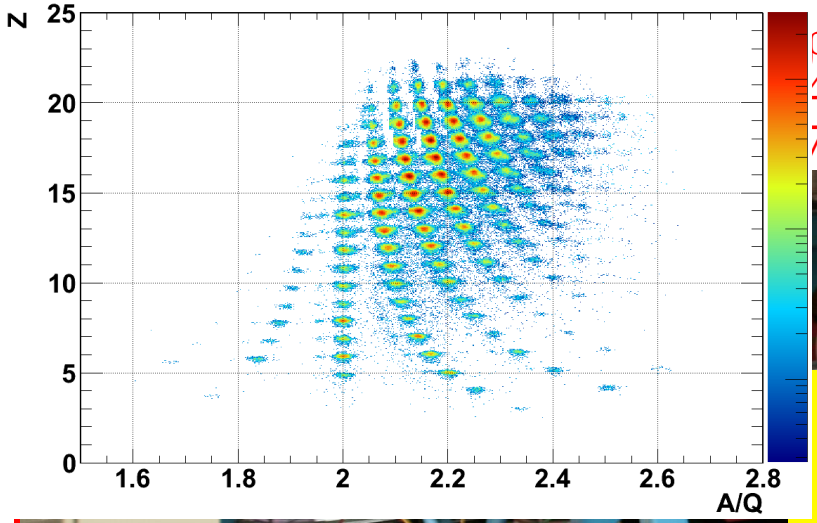
+ ^{48}

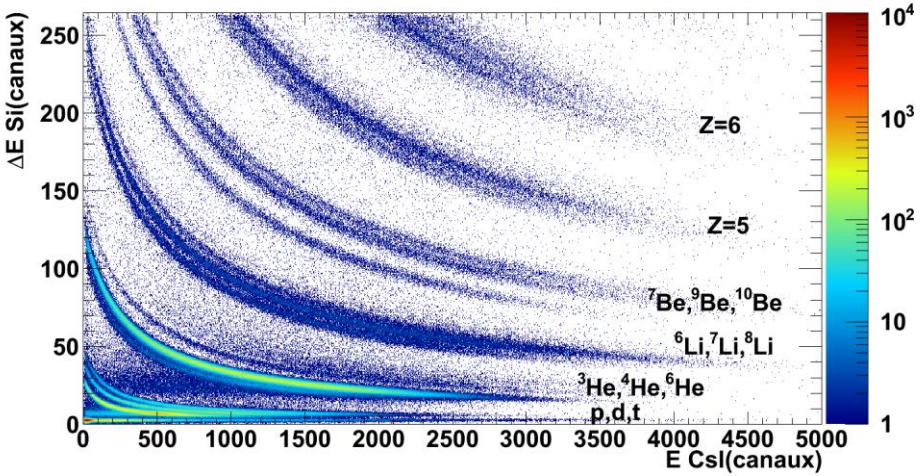
- ^{48}Ca + ^{40}
- ^{48}Ca + ^{48}

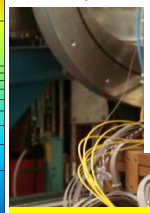
p (Tm):

401 , 1.

782 , 0.

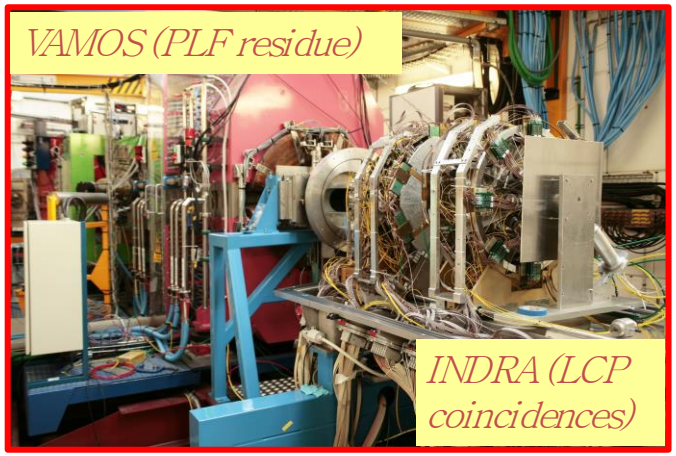






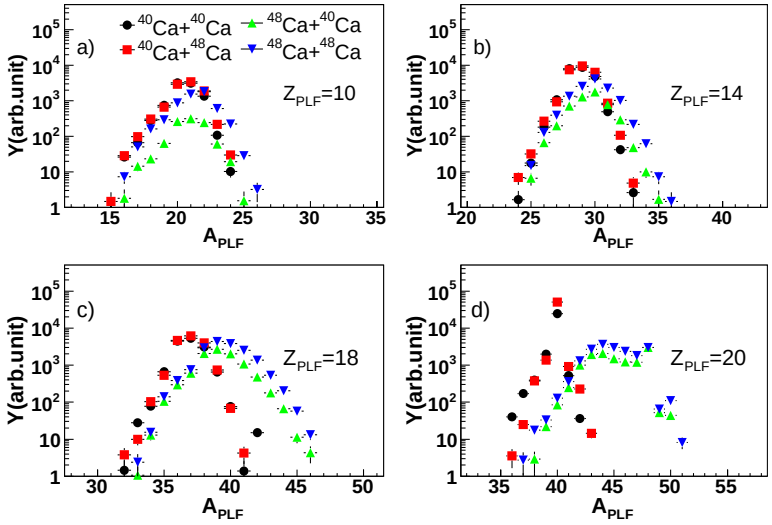
INDRA in coincidence LCP /IMF event characterization (b, QP* reconstruction)

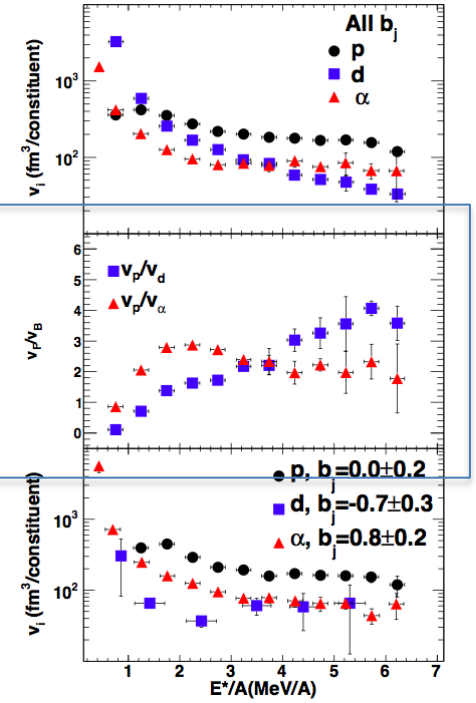
Indra-Vamos @ GANIL: isospin diffusion



Indra-Vamos experiment
40,48Ca+40,48Ca E/A=35 MeV

Vamos → **high quality isotopic distributions for heavy-fragments!**





- Coincidence with LCP in Indra→ reconstruct PLF

  Determine A, Z (N/Z), E*, T and Densities of PLF

- Boson Volumes << Fermion Volumes: Signals of boson condensation and fermion quenching?

P. Marini, H. Zheng, M. Boisjoli, G. Verde, A. Chbihi et al., submitted PRL

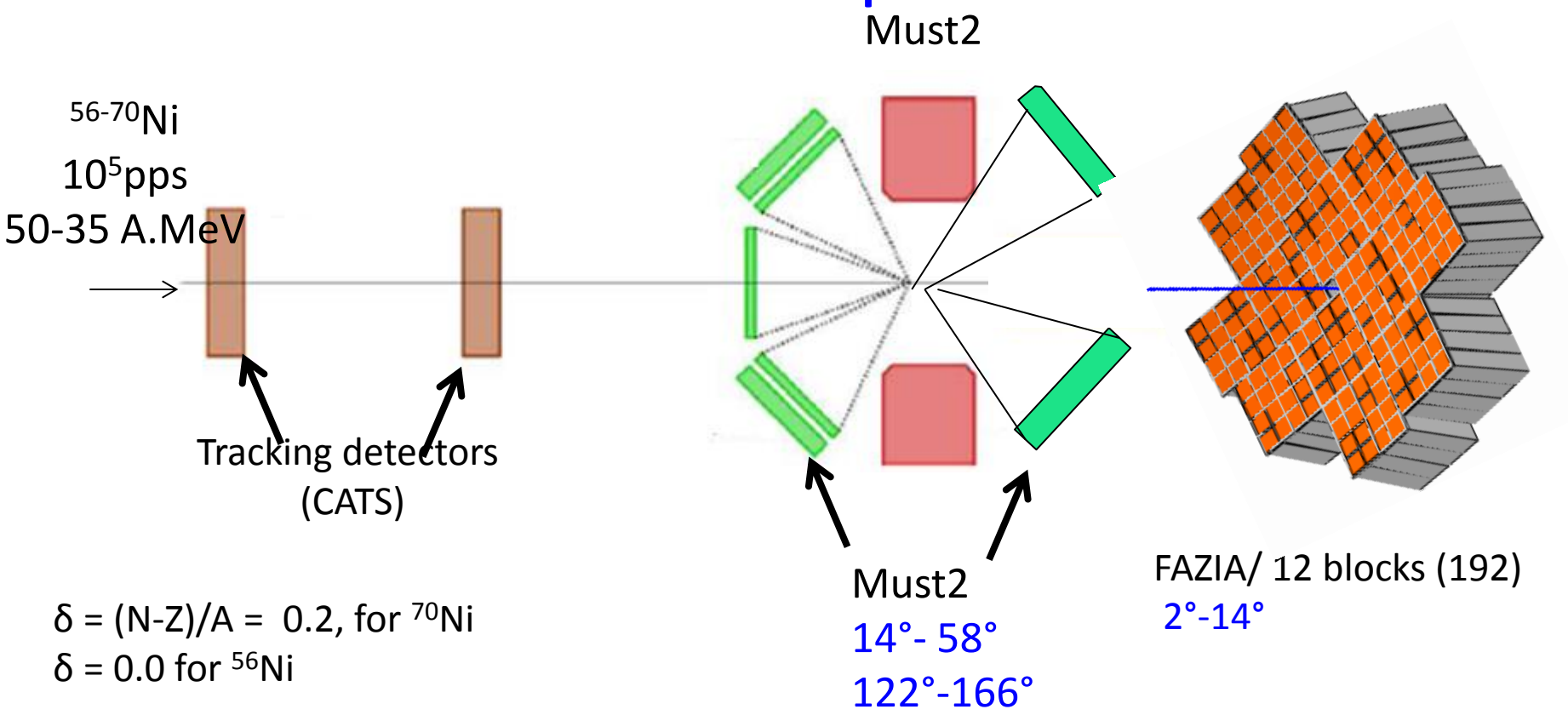
What plans for the future?

- Continue exploring these couplings spectrometers+ charged particle arrays (unique tools)
- Some limitations in INDRA/VAMOS campaign:
  - Difficult to perform measurements and analysis (lots of Brho to patch together, small solid angle, etc.)
  - No multi-particle correlations within acceptance (some decay channels lost)
- FAZIA demonstrator as an important option:

  → less isotopic resolution but better coverage and easier measurements

  → Multi-particle decays
- N/Z asymmetric beams @GANIL/LISE

Possible setup at LISE



$\delta = (N-Z)/A = 0.2$, for ^{70}Ni

$\delta = 0.0$ for ^{56}Ni

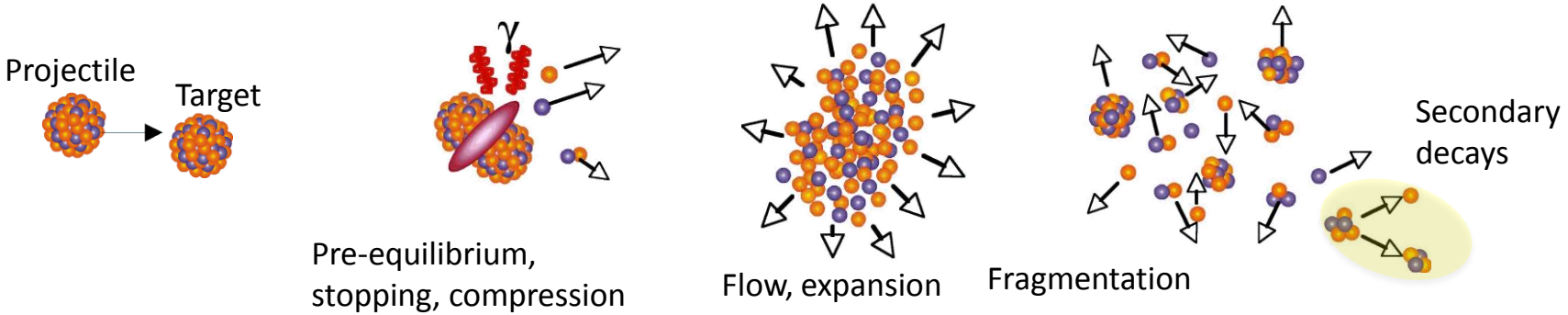
- Fazia 2°-14° : isotopic distributions of the PLF in coinc with LCP in Fazia and Must2 provide the primary isotopic distribution → E_{sym}, Isospin diffusion.
- Must2 14°- 58° and 122°-166° (it covers the MR region (90° CM)) :
  - ✓ correlation function for space-time characterization of sources
  - ✓ estimation of the density around the projectile and MR
  - ✓ In-medium short-lived nuclei as well as out-of-medium

Possible systems at LISE

Proj	56Ni	60Ni	64Ni	68Ni	70Ni
δ = (N-Z)/A	0	0.067	0.125	0.176	0.2
Target	**56Fe**	**60Ni**	**64Ni**	**68Zn**	**70Ge**
δ = (N-Z)/A	0.07	0.067	0.125	0.118	0.086
					70Zn
					0.143

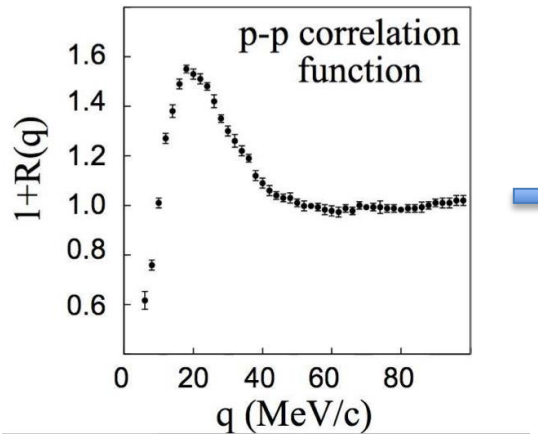
Proj-target combination either very: n-rich or different asym n/z

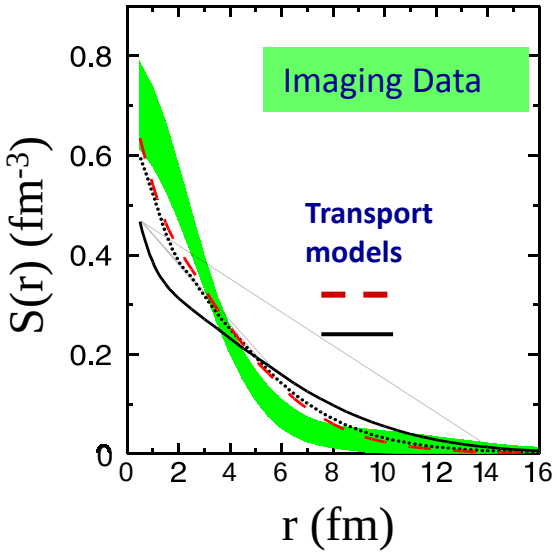
Central collisions-femtoscopy (easier at LNS/stable)



Femtoscopy (a.k.a. HBT, intensity interferometry, …)

$$1+R(q)=k\times\frac{SY_{coin}(\vec{p}_1,\vec{p}_2)}{SY_{evt.mixing}(\vec{p}_1,\vec{p}_2)}$$





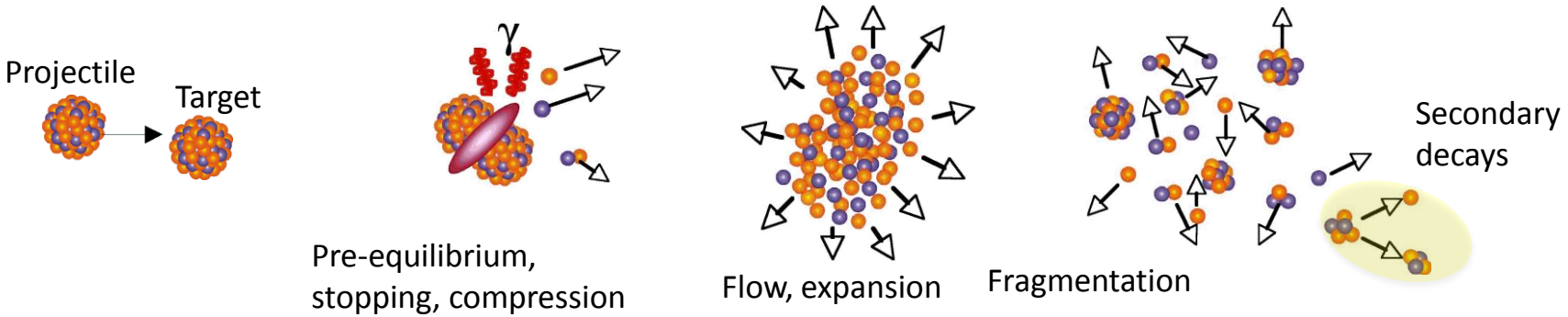
FSI: Nuclear and Coulomb

Fermions: asntisymmetrized WF

High angular resolution!

Emitting
Source image

Central collisions-femtoscopy (easier at LNS/stable)



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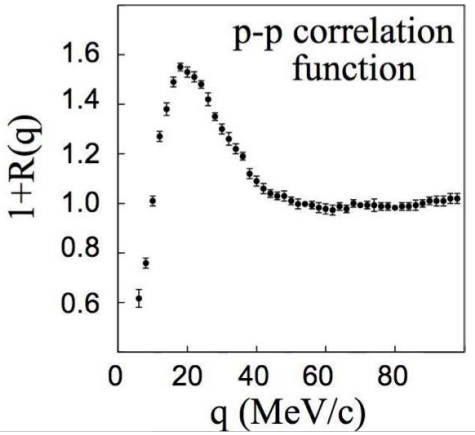
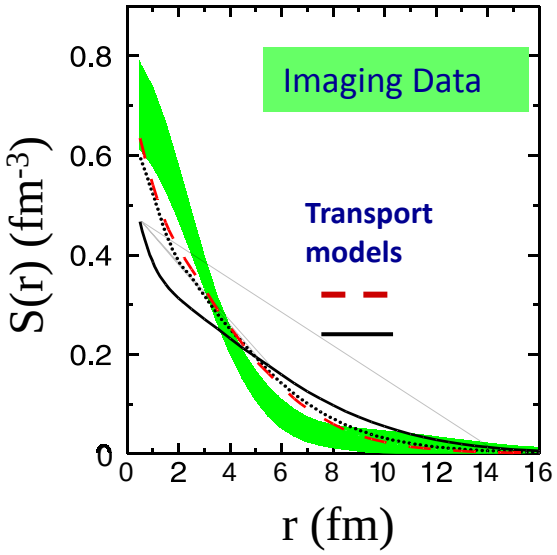


FSI: Nuclear and Coulomb
Fermions: asntisymmetrized WF
High angular resolution!



Emitting Source image

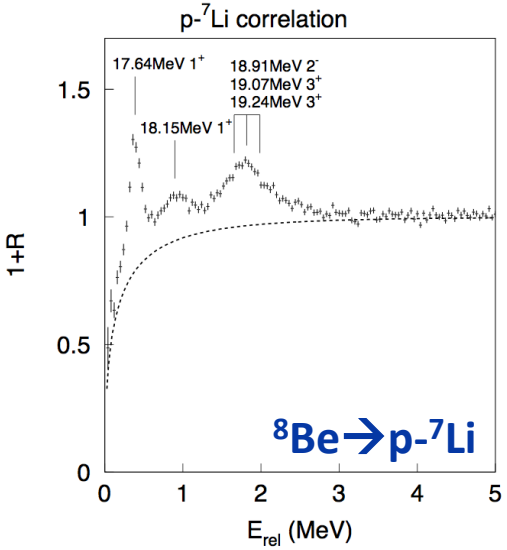
- Emission volumes (densities) and times → EoS, AsyEoS

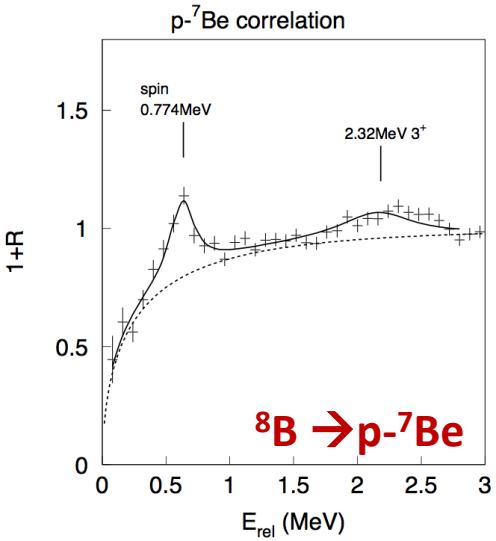
- Disentangle **pre-equilibrium Vs evaporation** At what stage are particles emitted? Emission Chronology…

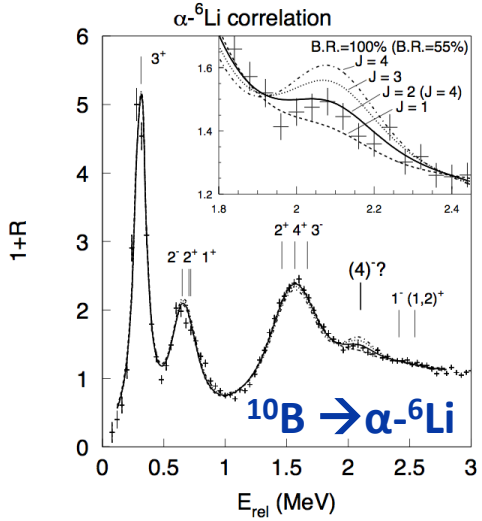
- Comparison to transport models → EoS, symmetry energy, NN in-medium cross sesction, …

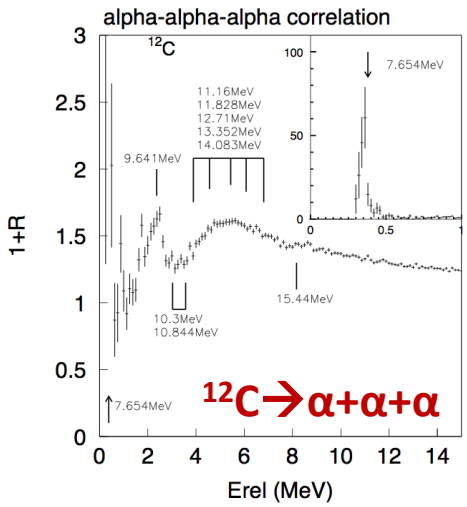
Multiple correlations in same experiment

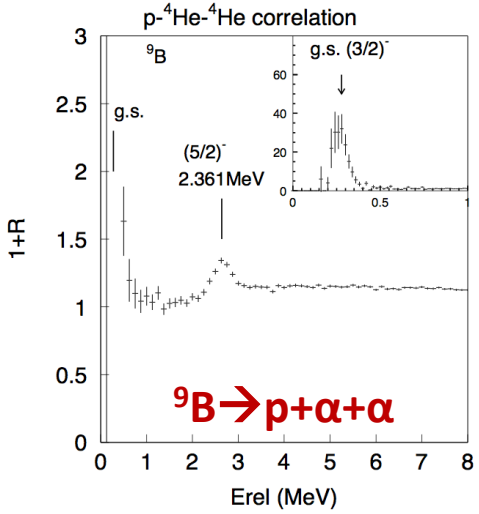
Xe+Au E/A=50 MeV

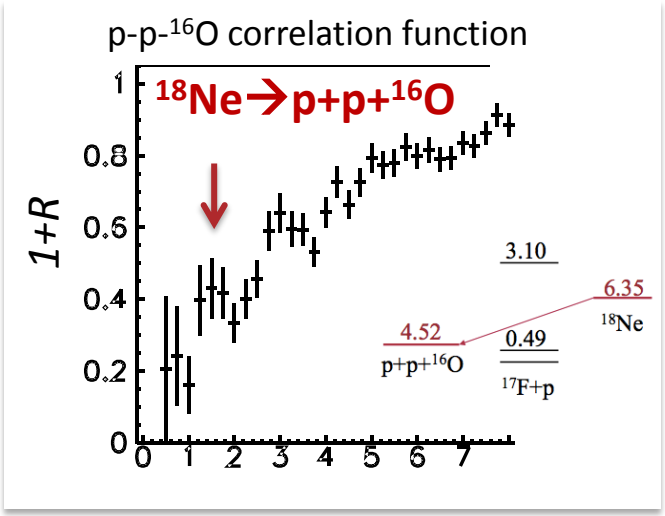




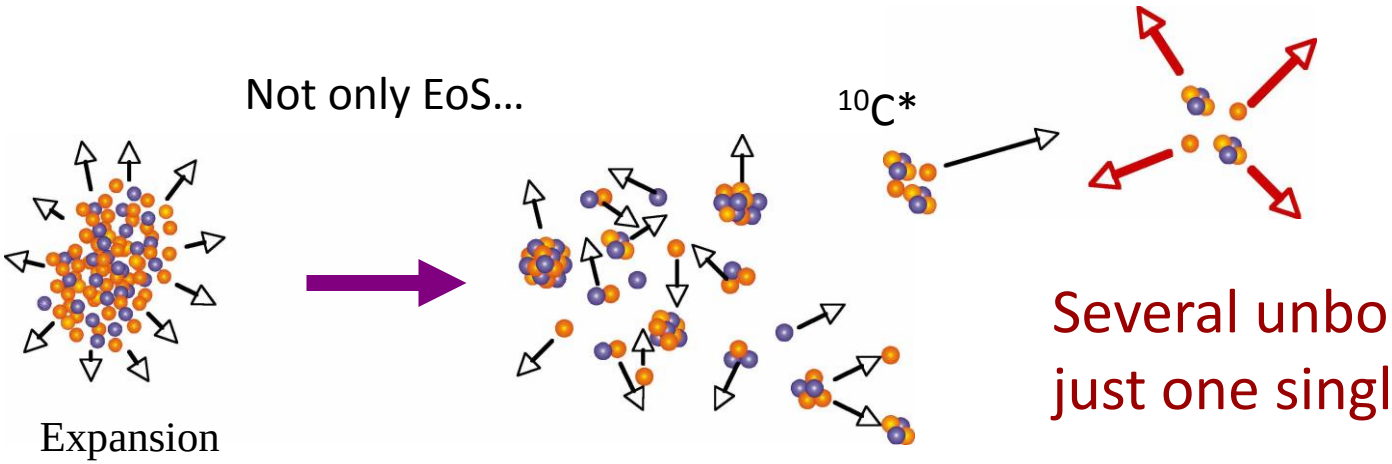








Invariant mass spectroscopy



Several unbound species in just one single experiment!

Spectroscopic tools:

- Reconstruct unbound states from correlations of two- and multi-particle decays
- Plenty of states in one single experiment
- Spin of states, branching ratios for simultaneous and sequential decays
- Compare direct reactions to HIC and in-medium decay
- Alpha clusters

12C decay into 3α (preliminary)

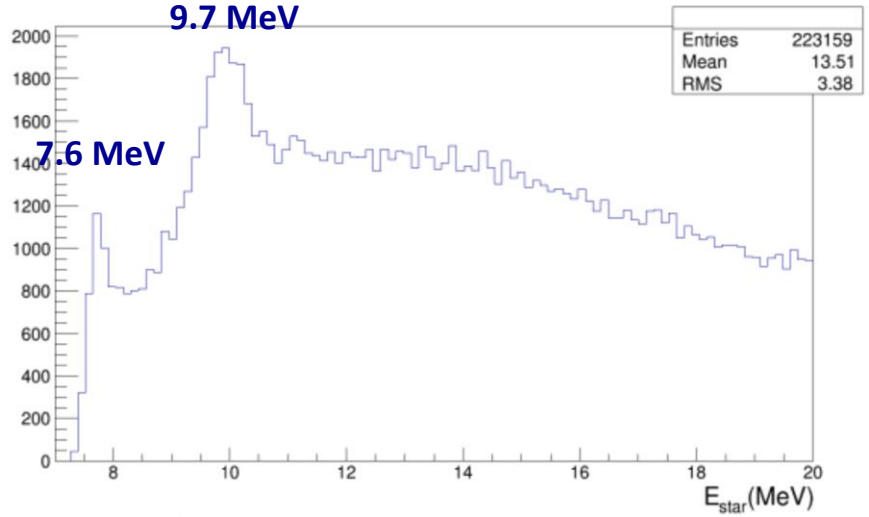
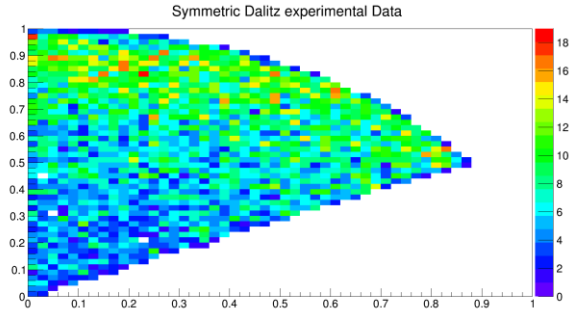


Figure 3: Yields of correlated 3α particles as function of excitation energy.

L. Quattrocchi PhD Thesis

12C + 24Mg E/A=35 MeV, Chimera

Data: preliminary



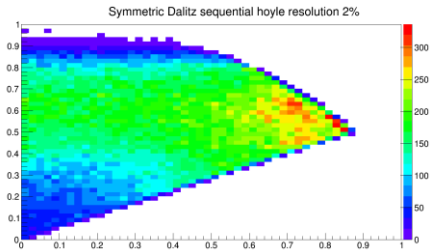
$$(3\rho)^2 = 3(\varepsilon_j - \varepsilon_k)^2 + (2\varepsilon_i - \varepsilon_j - \varepsilon_k)^2$$

$$x = \sqrt{3}(\varepsilon_j - \varepsilon_k),$$

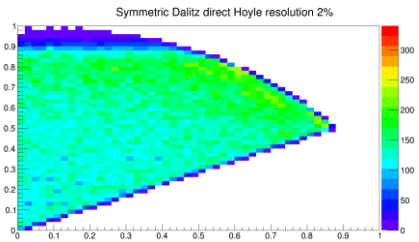
$$y = 2\varepsilon_i - \varepsilon_j - \varepsilon_k.$$

Itoh et al. PRL 113, 102501 (2014)

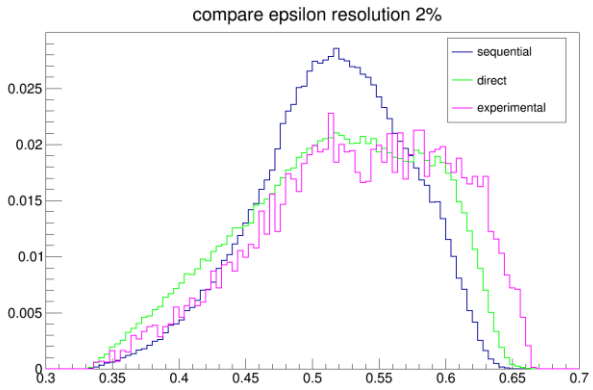
Decay simulations - Hoyle state



Sequential



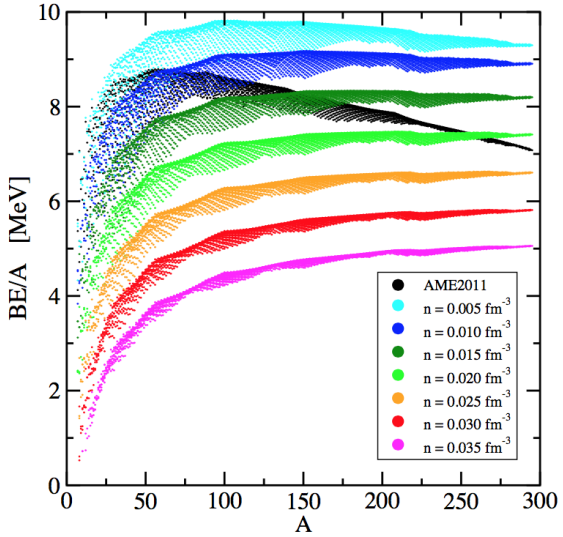
Direct 3-body



Not purely sequential decay

Clustering and EoS studies

S. Typel et al.
gRDF approach on EoS for asymmetric nuclear matter



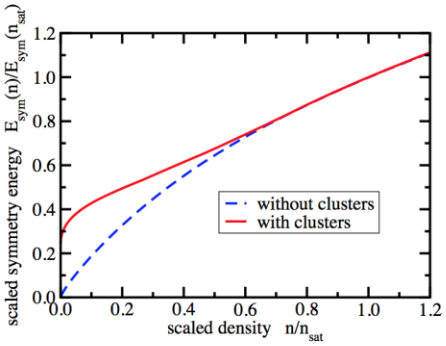


Figure 5. Scaled symmetry energy of nuclear matter at zero temperature as function of the scaled density in the gRDF model with parametrization DD2 without (blue dashed line) and with (red full line) cluster formation taken into account. Figure adapted from reference [14].

In-medium structure properties

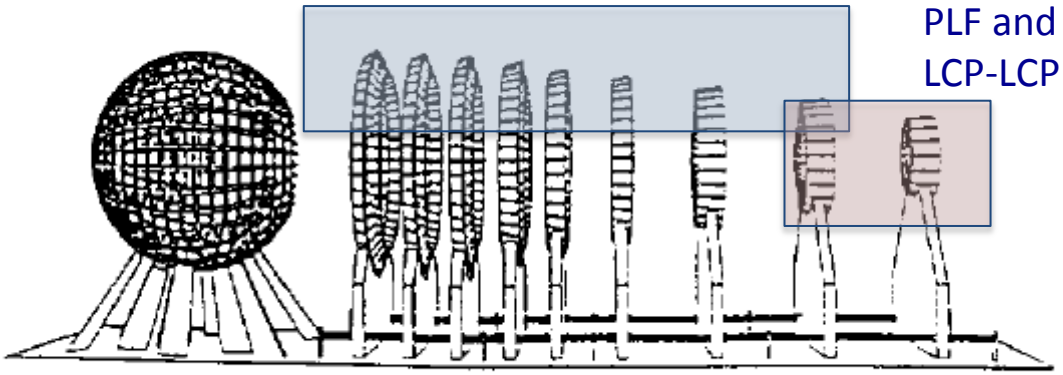
- **Spins, Decay branching ratios, alpha clusters, etc.**

Effects of clustering on predictions for EoS and symmetry energy

2016 – Must2+Chimera/Farcos?

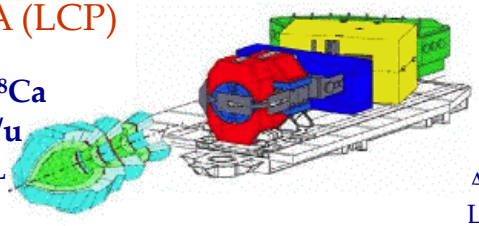
MUST2: ϑ>25º
Z=1,2 correlations
Mid-velodity

FARCOS: ϑ=5º-25º
Z=1-8 correlations
PLF and Mid-velocity
LCP-LCP and IMF-IMF correlations



VAMOS (QP)
INDRA (LCP)

^{40,48}Ca+^{40,48}Ca
35 MeV/u
GANIL



2007→2020…

A. Chbihi, G. Verde
LISE Workshop (Jan 2015)

^{40,48}Ca, ^{112,124}Sn (SIB)
$^{56-70}$Ni (RIB)
25-80 MeV/u
LNS, GANIL

Forwaed array (QP)
(FAZIA Dem., Chimera)

Correlators (LCP)
(MUST2, Farcos, FAZIA)

Possible campaign @ LNS

Measuring light particle correlations (Z=1 and 2) to access: E_{sym}, emission chronology, reconstruction of primary fragment E*, A, Z, …; size of sources with HBT vs coalescence

Geometry for correlators: PLF decay and Mid-velocity decay

Possible HIC systems @ LNS: Energy, N/Z and A scan:

- 40,48Ca + 40,48Ca E/A=20-45 MeV
- 58,64Ni + 58,64Ni E/A=20-45 MeV
- 112,124Sn + 112,124Sn E/A=20-45 MeV

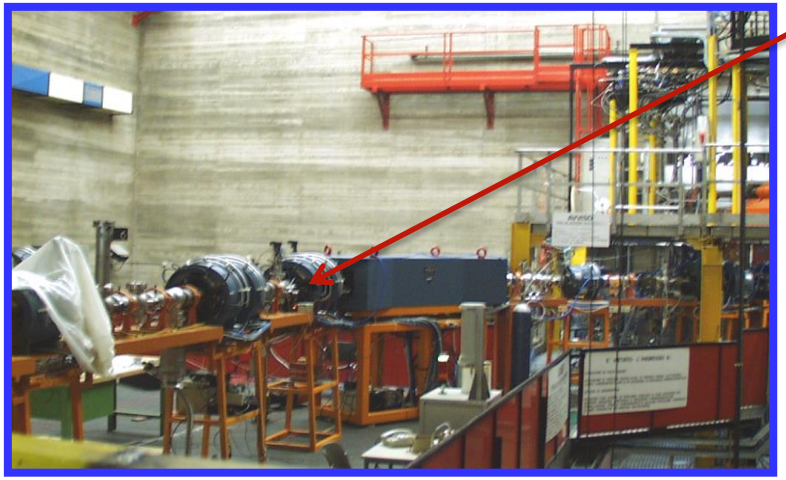
Energy scan → Disentangle space and time extent of emitting sources
N/Z and A scan → Disentangle Mass (EoS) and Esym (Asy-EoS) effects
Size (A) scan → Disentangle Size effects from N/Z effects

Projectile fragmentation beams from FRIB@LNS
Selected physics cases with direct reactions in inverse kinematics (same campaign)

Detectors: Chimera
+MUST2/FARCOS (total of 14-16 telescopes for large solid angle correlator)

exotic beams @ LNS

Projectile fragmentation beams



Ex: Primary beam: ^{20}Ne E/A=45 MeV/A
Production target: ^{9}Be (500 μm)
Fragments transported and tagged event-by-event by ΔE-ToF

DSSD Tagging detector

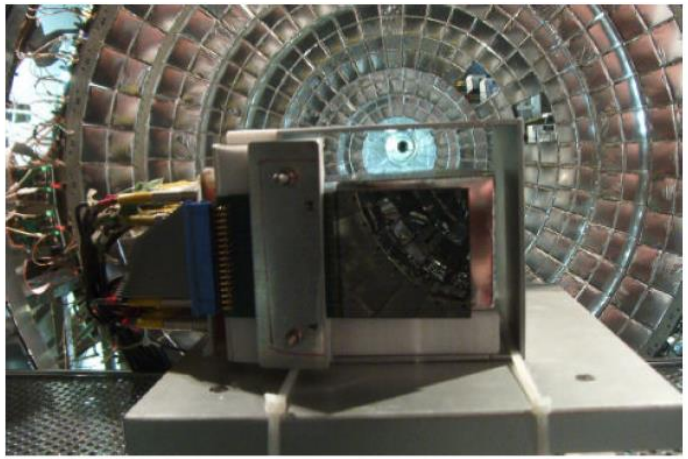
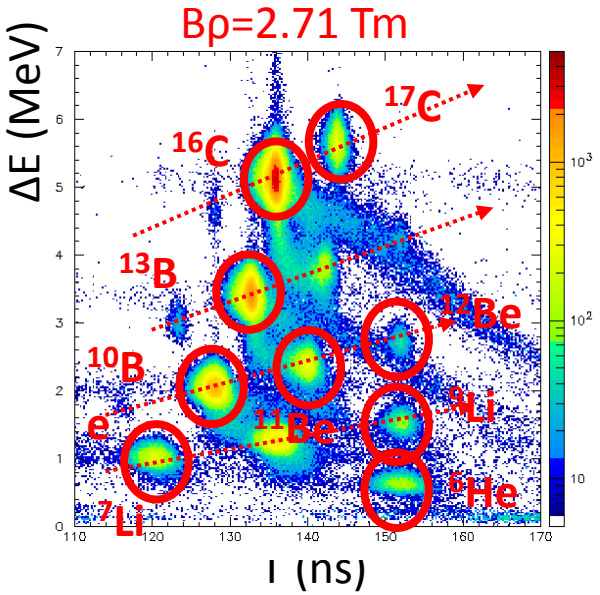
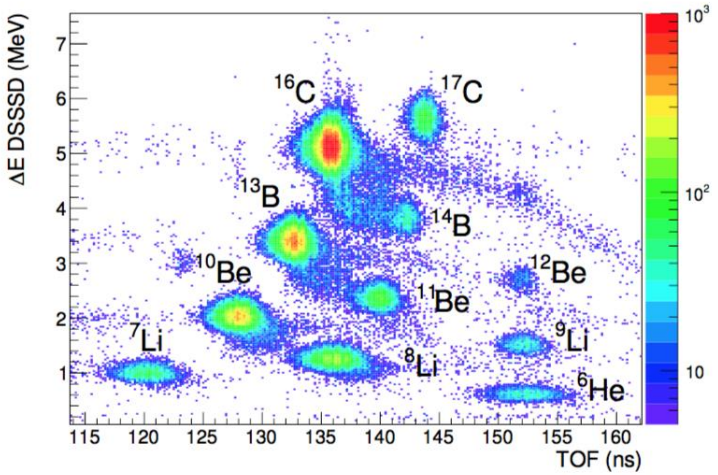


Figure 3: The detectors array mounted inside the Ciclope scattering chamber. The CHIMERA rings are also visible.



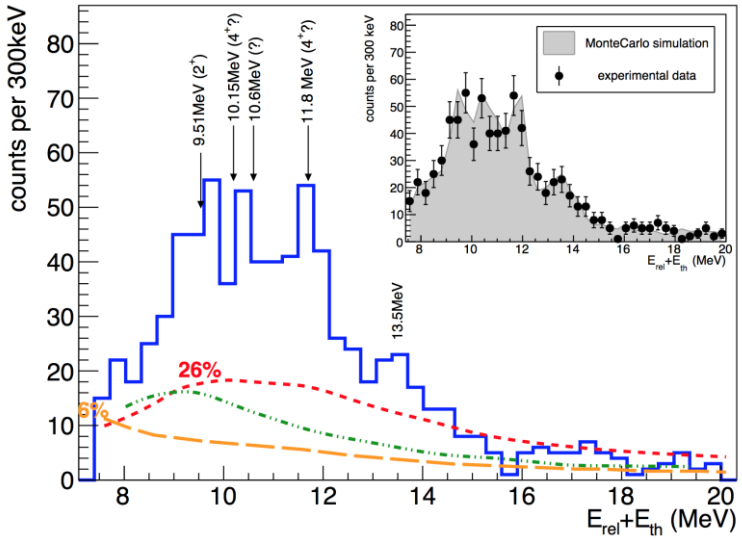
Direct reactions in inverse kinematics and multi-particle correlations

Recent highlight from correlations at LNS with Chimera



18O E/A=55 MeV →
^{10}Be (~54 MeV/u) + CH_2, CD_2 (4 x 10^4 /sec)
^{16}C (~50 MeV/u) + CH_2, CD_2 (10^5 /sec)

Decay of 10Be → 6He + 4He
Decay of 16C → 6He + 6He + 4He



Decay of 10Be → 6He + 4He
Invariant mass spectroscopy

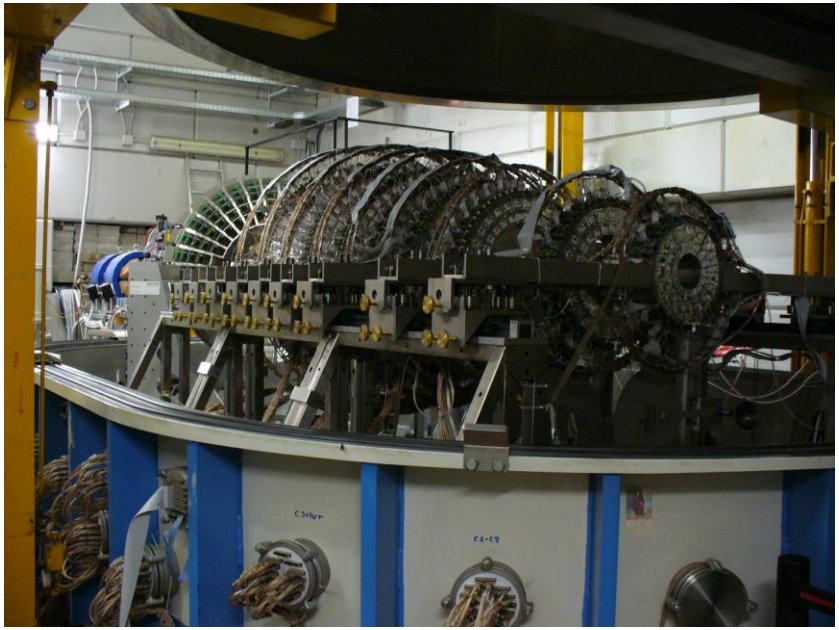
Resolution reduced by using Chimera → improvements with Farcos and Must2 may be expected

Campaign at LNS: status

- Interest by local group in Catania (Chimera) exists (as of 3rd of June 2015, yesterday)
- Mechanics and DAQ support/coupling? OK
- If OK:
  - PAC: expected in autumn
  - Technical-collaboration meeting in Catania (see chamber, flanges, etc.) –
  - Physics task group: start writing proposals to be inserted in campaign of measurements → Geometry, angles → Flanges, chamber constraints etc.

end

Chimera @ LNS



Analog pulse shape : Si and CsI(Tl)

good

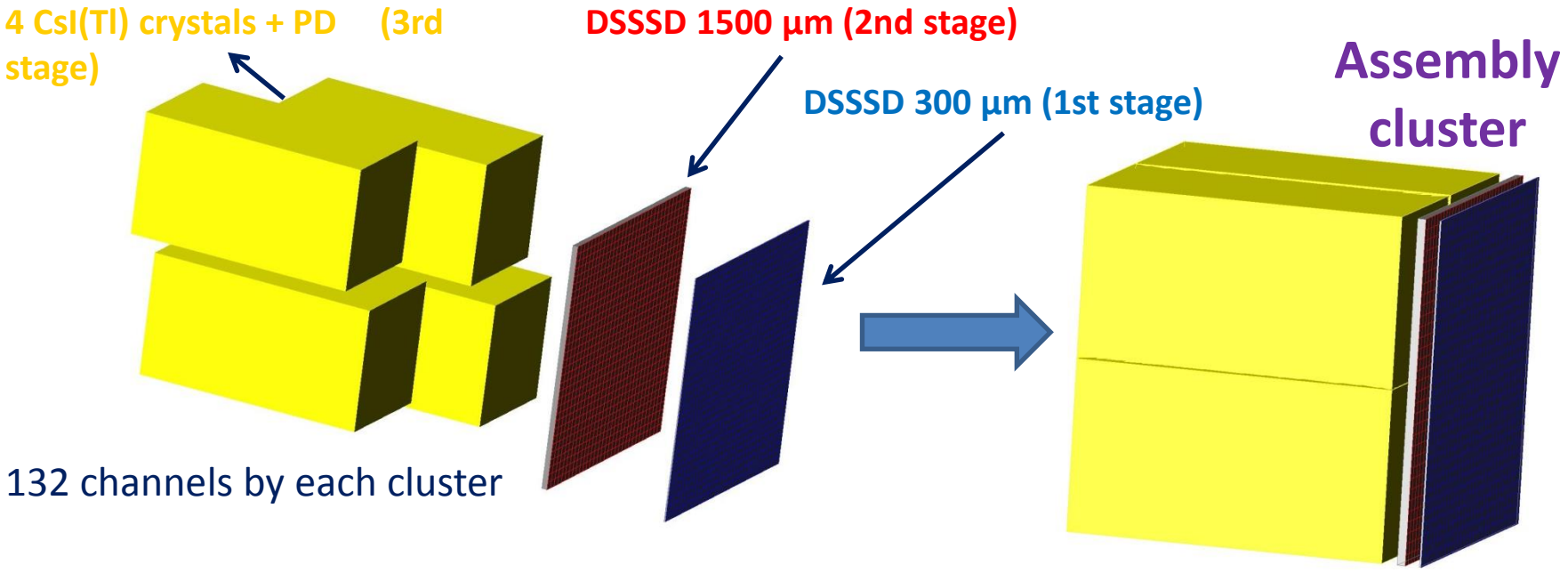
- 4pi coverage, large chamber (good for coupling)
- Low thresholds (PSA)
- Z>2 detection optimized
- Event characterization

not as good

- Limited angular resolution
- Limited performances for light particle detection

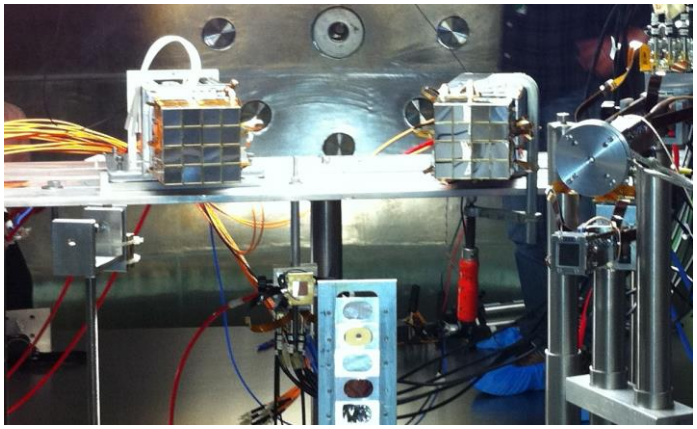
Farcos: Femtoscope Array for Correlations and Femtoscopy

- 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

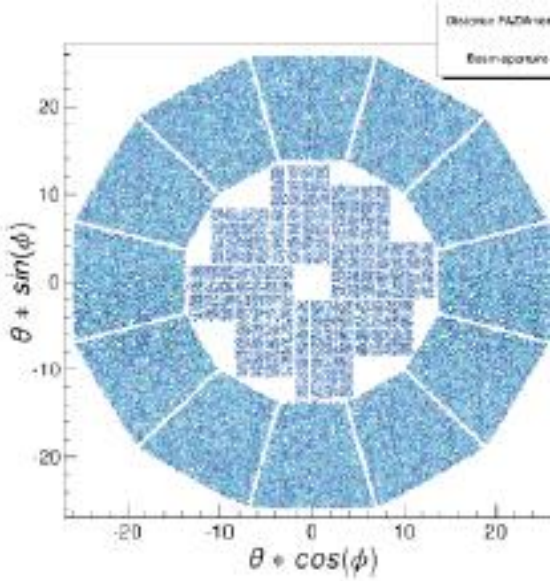


FAZIA preliminary schedule

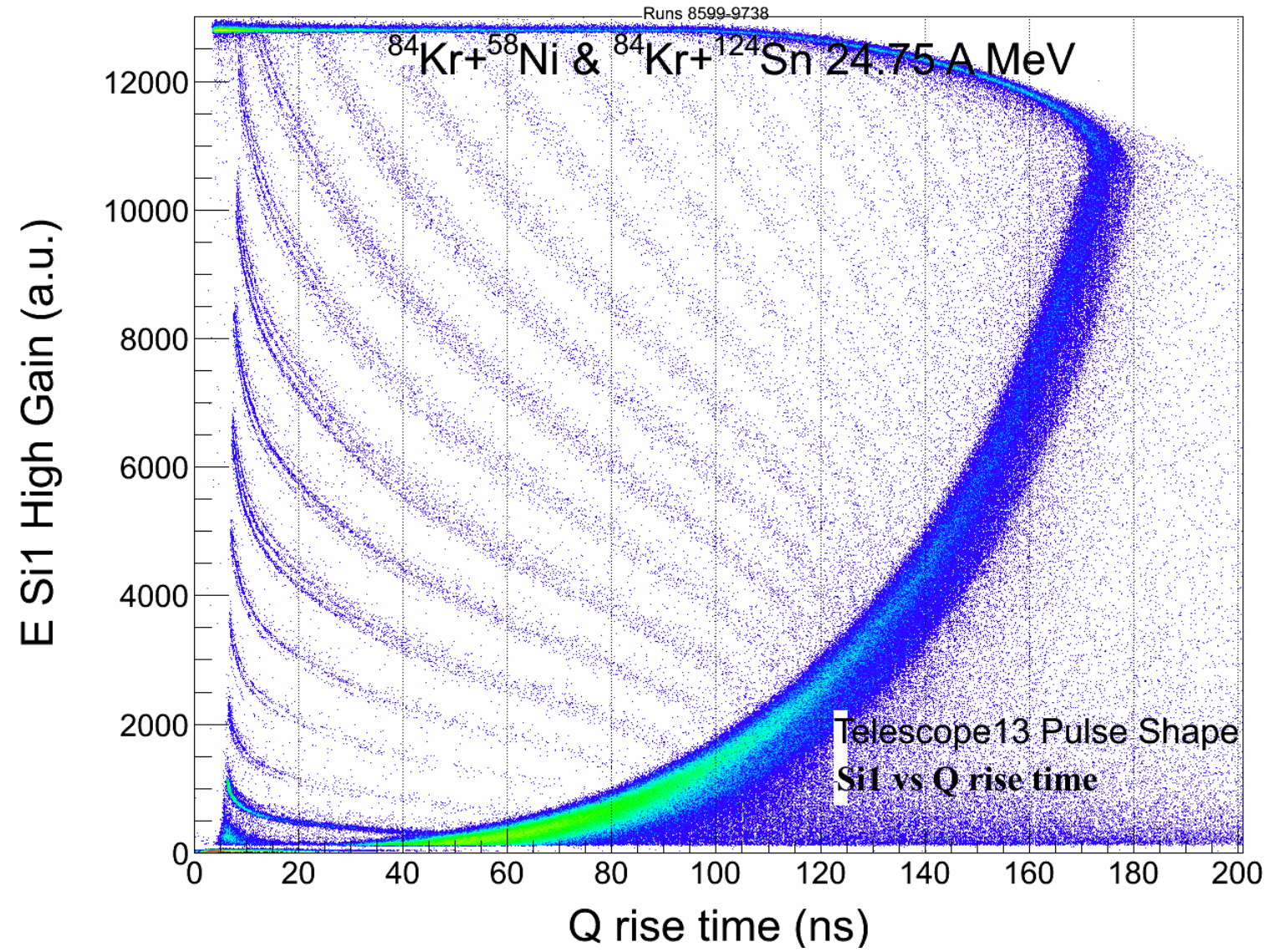
LNS 2 blocks test Dec 2014



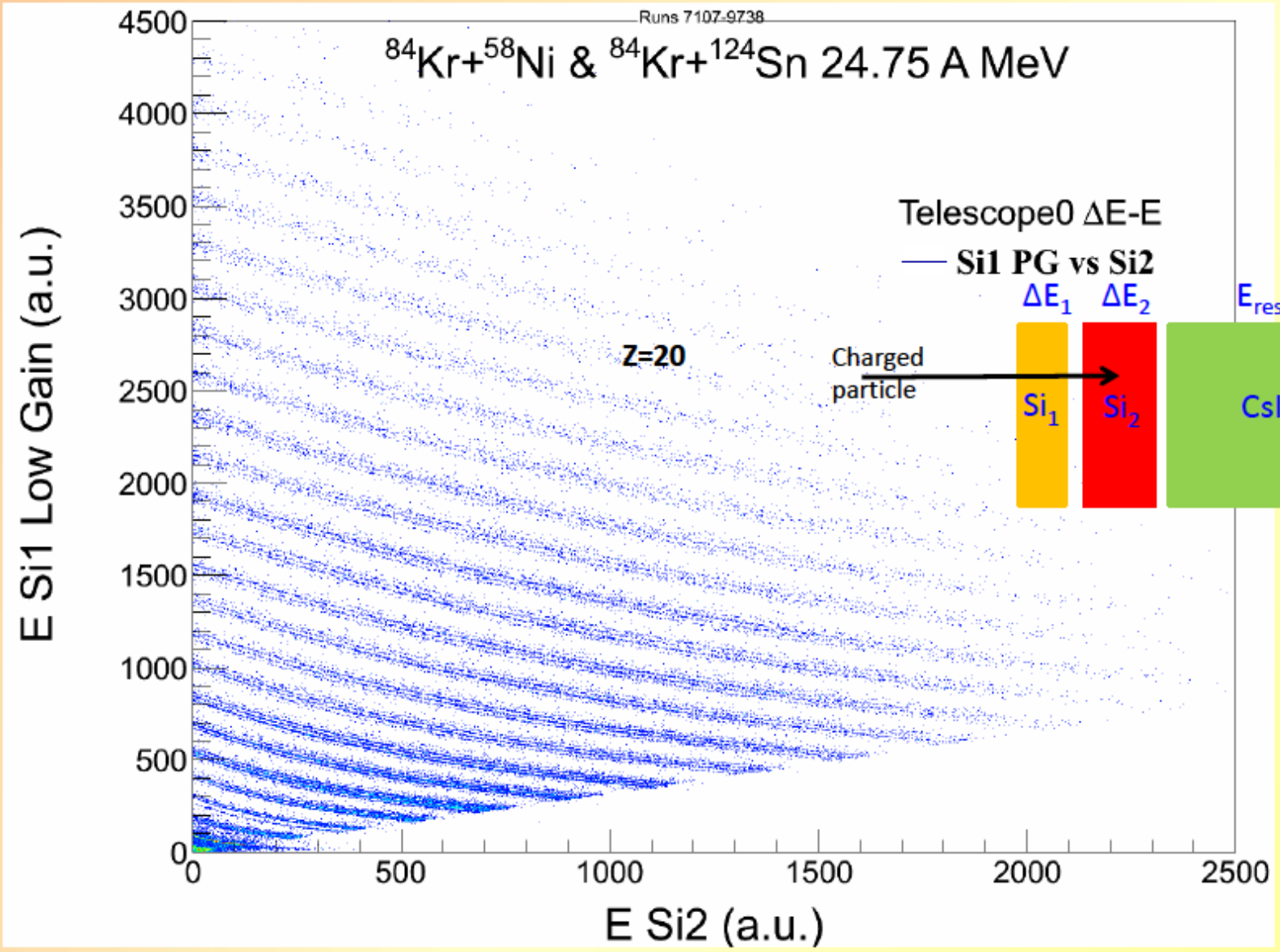
2015 : FAZIA, 4/6 blocks; 2 exp@LNS (This week!)
2016 : commis. of 12 blocks @ GANIL
2017 : FAZIA@INDRA
2017-2018 : FAZIA@LISE



Stopped in the first Si

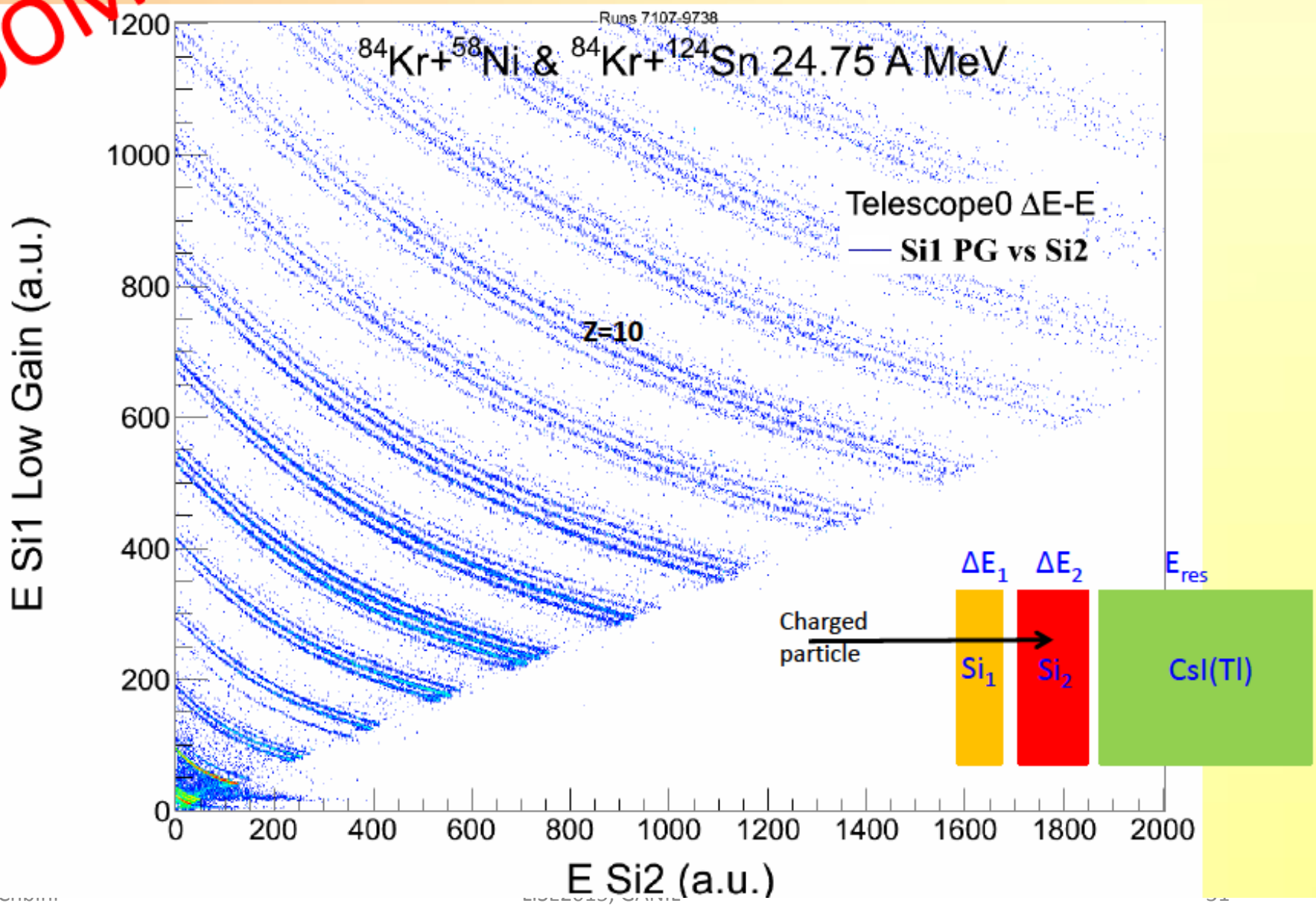


Cartes ΔE-E Si1 vs Si2



Cartes ΔE-E Si1 vs Si2

ZOOM

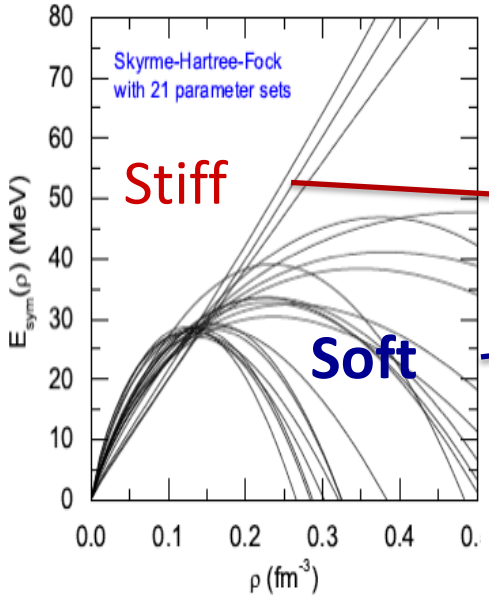


Symmetry energy and correlation functions

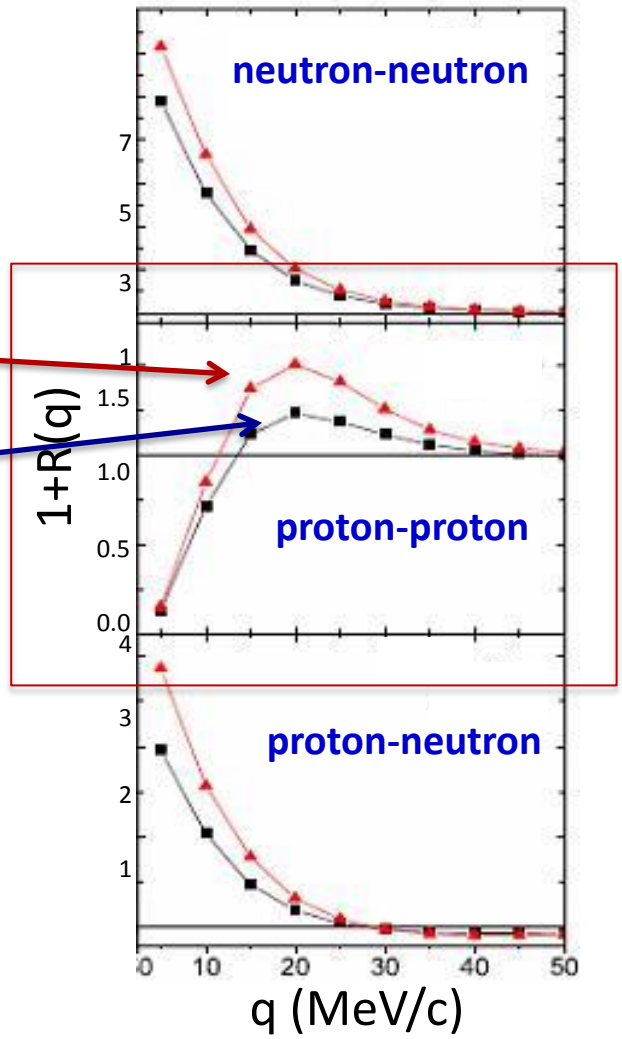
IBUU simulations

$^{52}Ca+^{48}Ca$ E/A=80 MeV Central collisions

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



Correlation functions

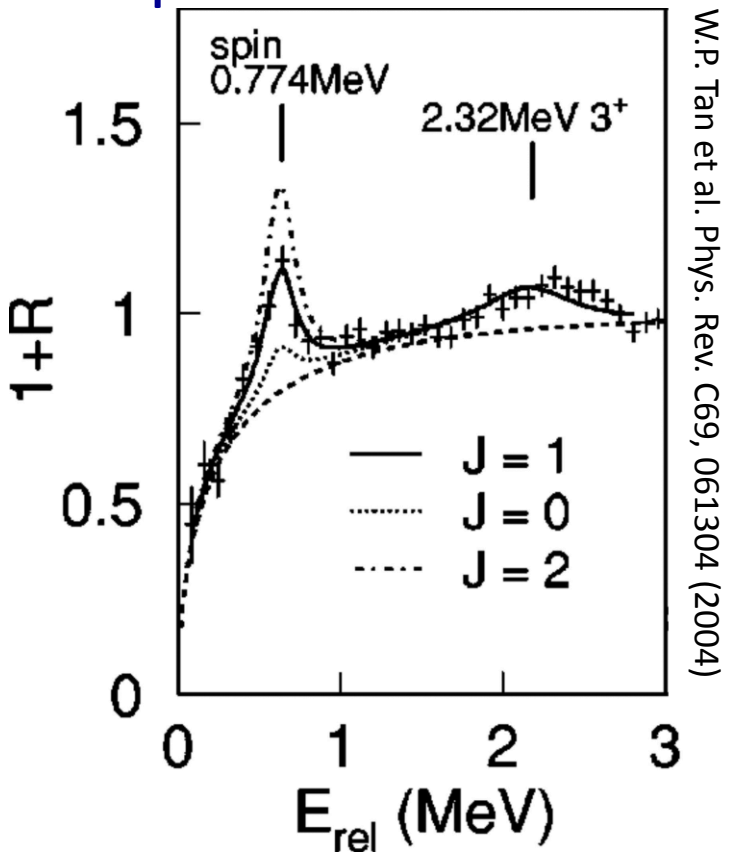


- Proton-proton correlation sensitive to E_{sym}
- nn and np also… but difficult… (later projects)
  - → use: **t-^{3}He, t-t and ^{3}He-^{3}He**
  - → Longer term… nn, np… (?)

^{8}B unbound states in central HIC

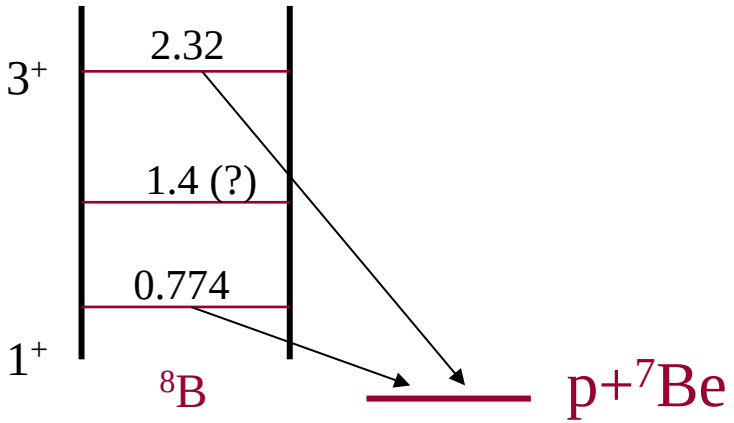
Xe+Au E/A50 MeV Central collisions

p-^{7}Be correlations



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

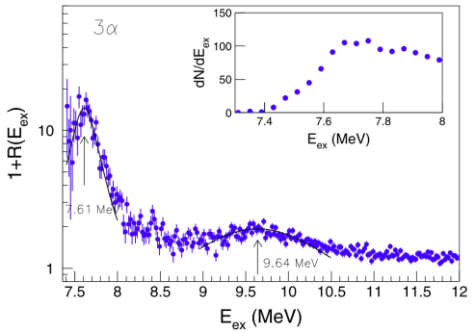
States of ^{8}B → p+^{7}Be



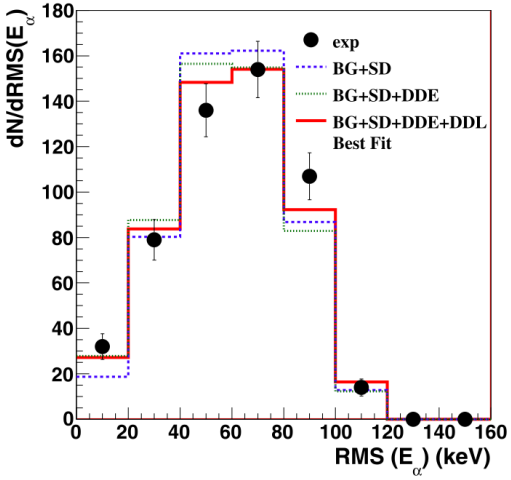
Relative height of resonances constraints the spin of states

Sequential vs Simultaneous decay in Hoyle state

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

α + α + α

DDE

α + ^{8}Be

α + α

SD

DDL

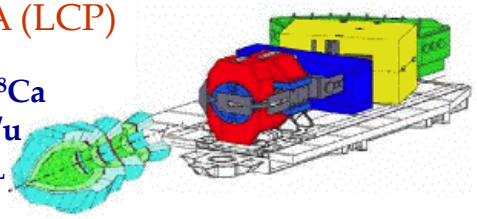
Explore relative contributions from different decay mechanisms (sequential vs direct)

Perspectives for dynamics at LISE

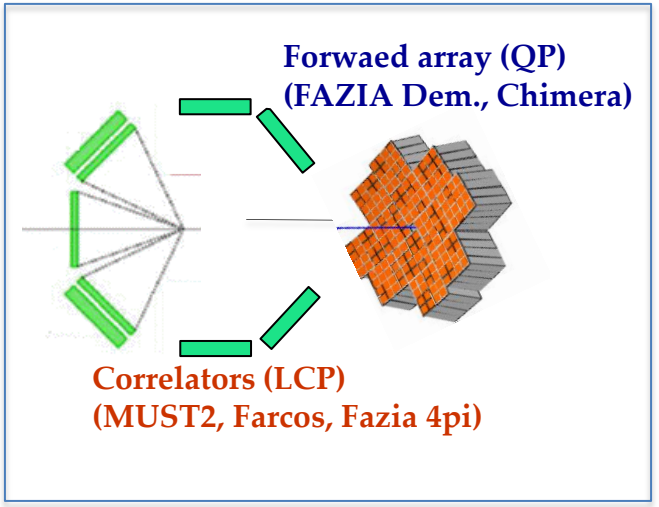
A. Chbihi, G. Verde
LISE Workshop (Jan 2015)

VAMOS (QP)
INDRA (LCP)

$^{40,48}Ca+^{40,48}Ca$
35 MeV/u
GANIL



2007→2018…



$^{40,48}Ca$, $^{112,124}Sn$ (SIB - LNS)
$^{56\text{-}70}Ni$ (RIB - LISE)
25-80 MeV/u

- Need both stable and exotic beams
- Stable at LNS in 2016 : intermediate and preparatory step (same energy regime as at LISE)