



Recent results from INDRA

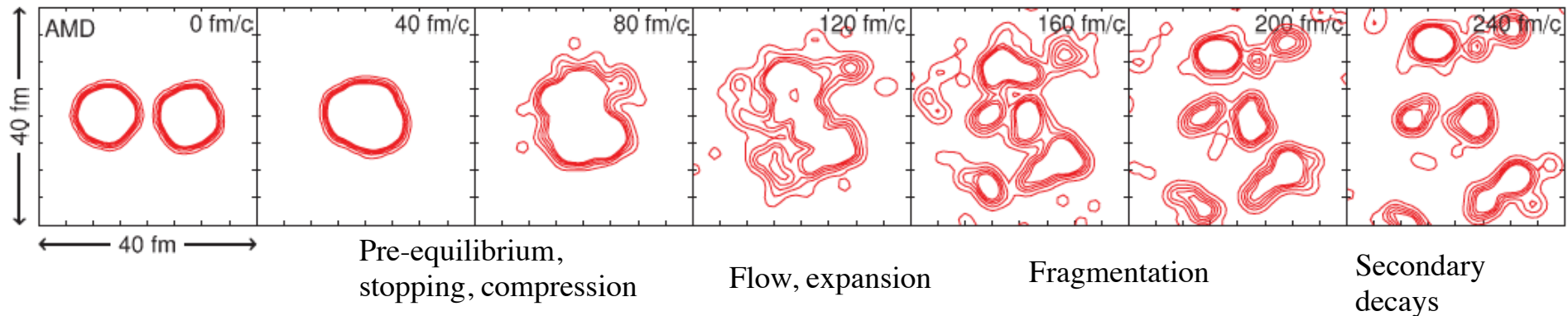
Abdou Chbihi
GANIL
For the INDRA collaboration

Recent results from INDRA

- Introduction to the INDRA talks
- Study of the reaction mechanisms from fission to multifragmentation
- Symmetry energy : INDRA-VAMOS experiments
- conclusions

Time evolution of central collisions at intermediate energies

M. Colonna, A. Ono and J. Rizzo PRC82, 054613 (2010)



Explore the EOS under laboratory controlled conditions

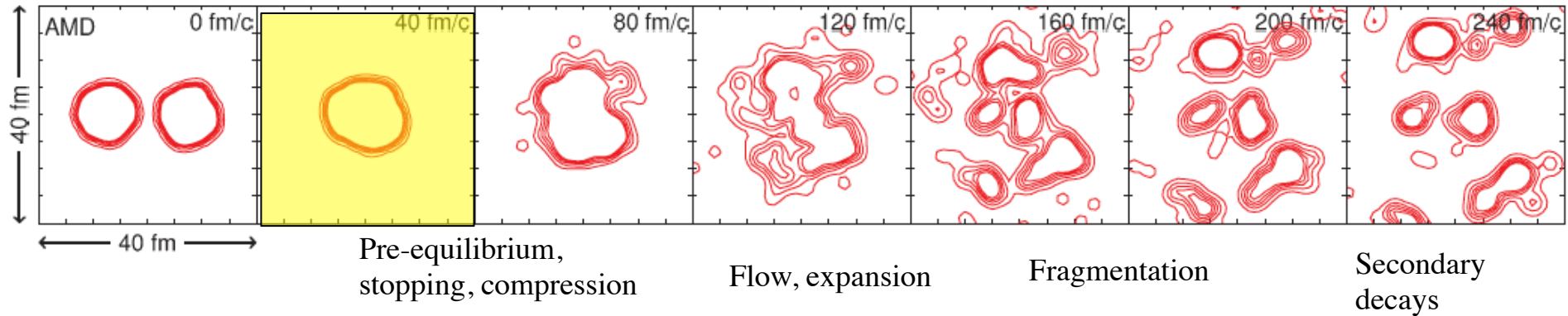
HIC is **Femtonovae** which mimic **Supernovae**

[ECT* 2014 : Simulating the Supernova Neutrinosphere with Heavy Ion Collisions](#)

Key words : stopping, collective flow, clusterization

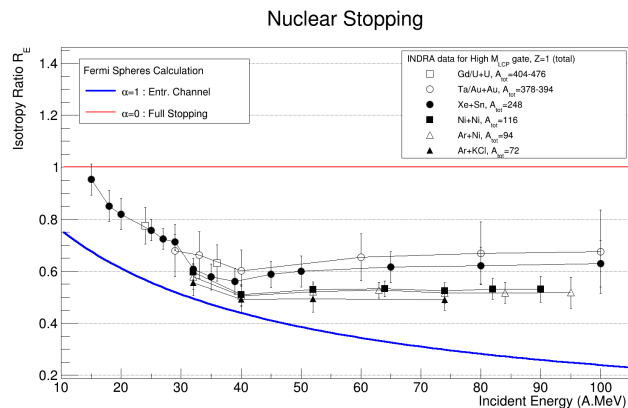
Time evolution of central collisions at intermediate energies

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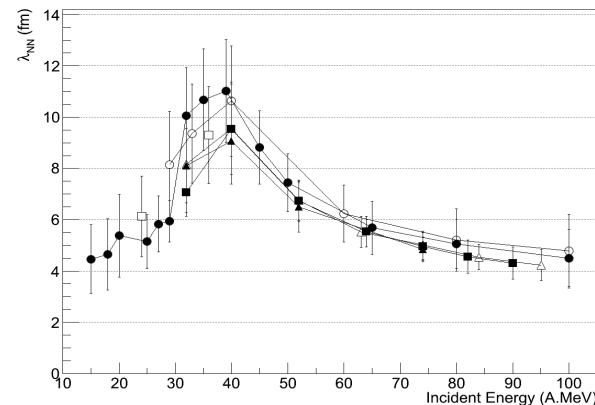
Nuclear Stopping : O. Lopez talk

- Minimum of stopping around the Fermi energy
- Full stopping is not achieved
- Transparency due to in-medium effect
- Determination of experimental mean free path λ_{NN}



May 2014

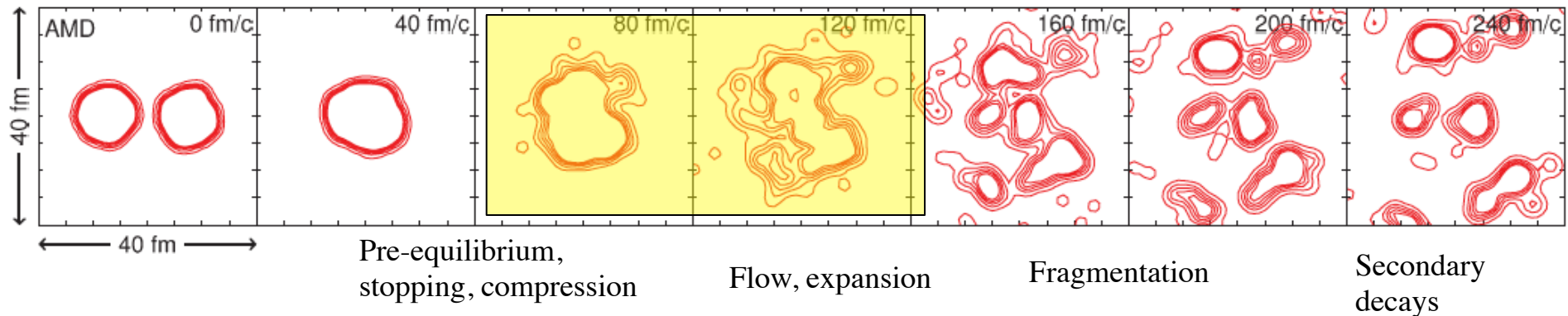
A. Chbihi



†

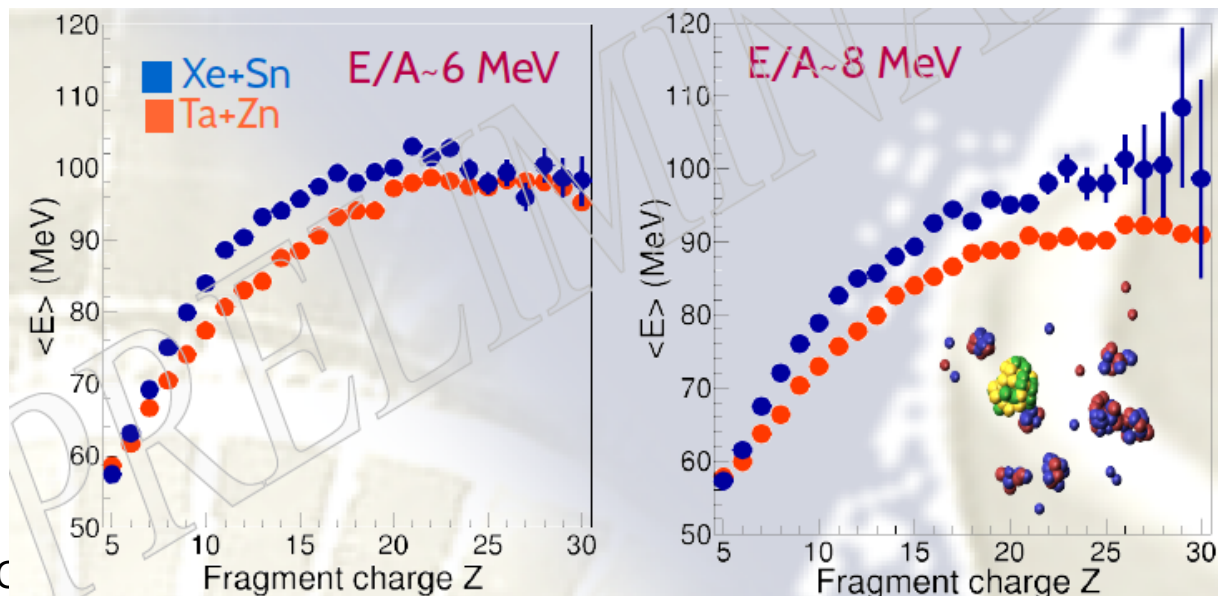
Time evolution of central collisions at intermediate energies

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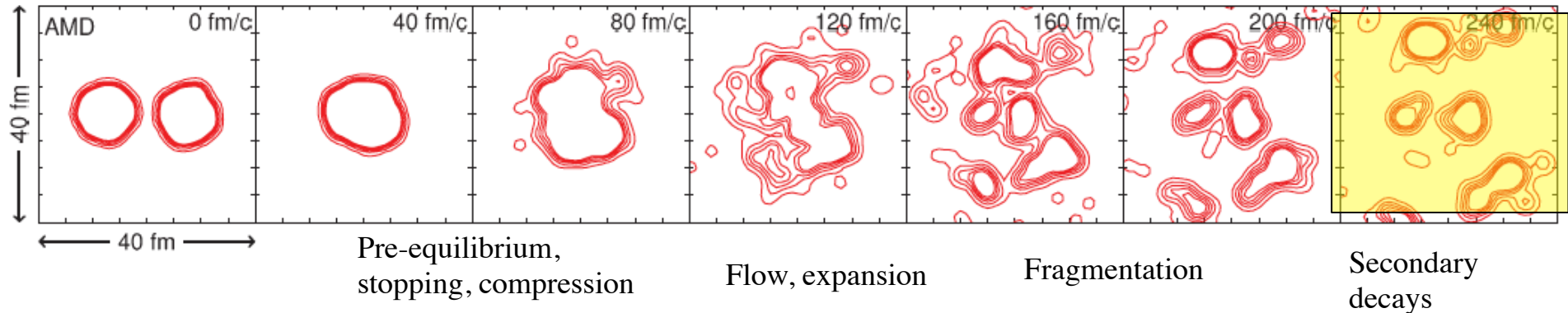
Radial flow: J. D. Frankland talk

- Influence of radial collective flow on multif partitions in central Xe+Sn & Ta+Zn



Time evolution of central collisions at intermediate energies

M. Colonna, A. Ono and J. Rizzo PRC82, 054613 (2010)



Internal excitation energy of the fragments : $E^*/A \approx 3$ MeV

isospin dependence of nuclear level density parameter : G. Ademard talk

- Experiment coupling INDRA + Vamos,
- Ar+Ni @ $E/A \approx 13$ MeV \rightarrow $^{92-108}\text{Pd}$ excited at $E^*/A \approx 3$ MeV

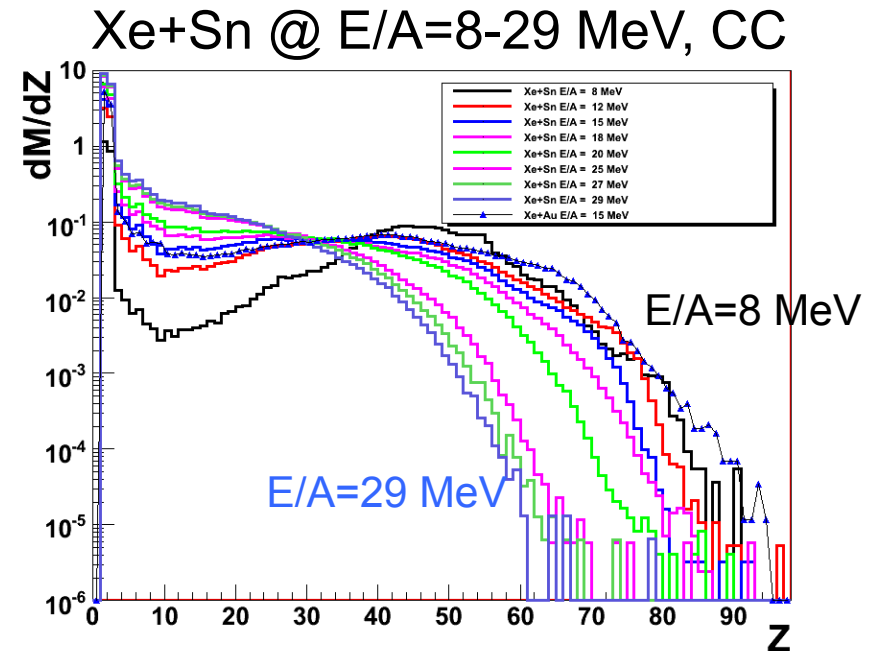
outline

- Introduction to the INDRA talks
- Study of reaction mechanisms from fission to multifragmentation
- Symmetry energy : INDRA-VAMOS experiments
- conclusions

From fission to multifragmentation

Study of the evolution of reaction mechanism occurring in HIC from low to IE

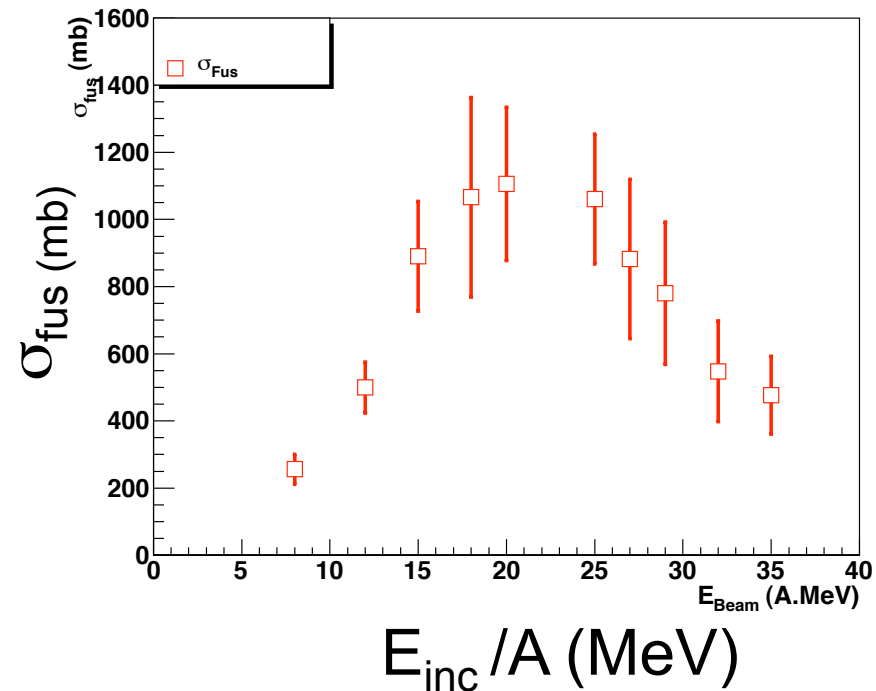
- Tool : 4π detector
- What can we Learn ?
 - ✓ Transition from low energy (DIC, fusion-fission) to IE (multifragmentation)
 - ✓ Bring insight for search for SHE
 - ✓ Stringent constraint on statistical & dynamical models



- Survey of heavy nuclei up to $Z \geq 80$ (77% tot)
- Suggests fusion of the colliding nuclei but massive transfer is not excluded
- High LCP multiplicities : dissip colli
- minima at $Z = 10$

From fission to multifragmentation

Fusion cross section

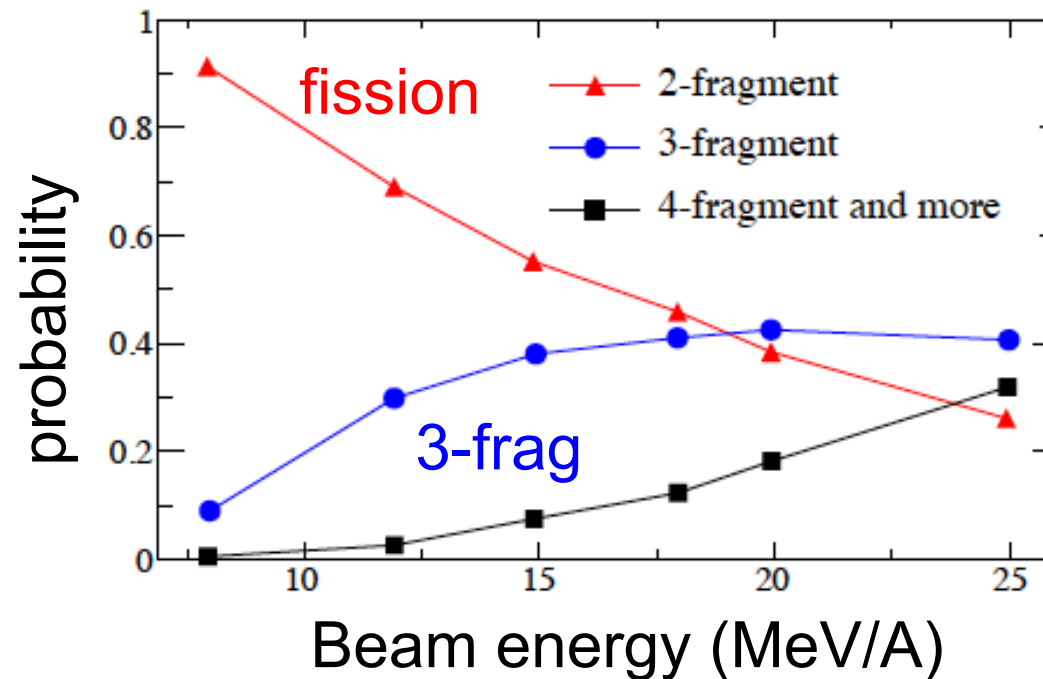


Maximum around 18-20 MeV/A $\sigma_{fus} : 1.2 \text{ b}$

From fission to multifragmentation

Decomposition on 2, 3, 4+ fragments ($Z > 10$)

Exit channel probability vs beam energy



From fission to multifragmentation

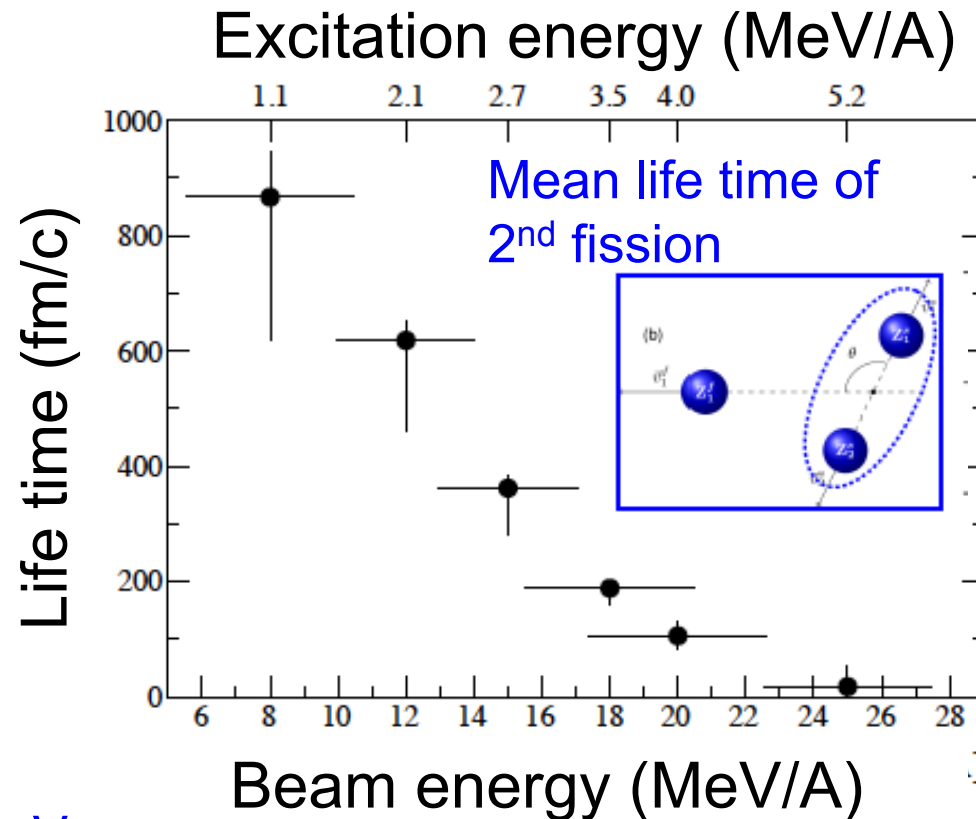
3-frag exit channel :
identify fission sequence
by comparison with TKE
systematics (Viola)

Fission time deduced
from Coulomb trajectory
calculations

2nd fission occurs faster
and faster as E^*
increases

Undistinguishable from
simultaneous 3-frag
breakup above $E^*/A \approx 4$ MeV

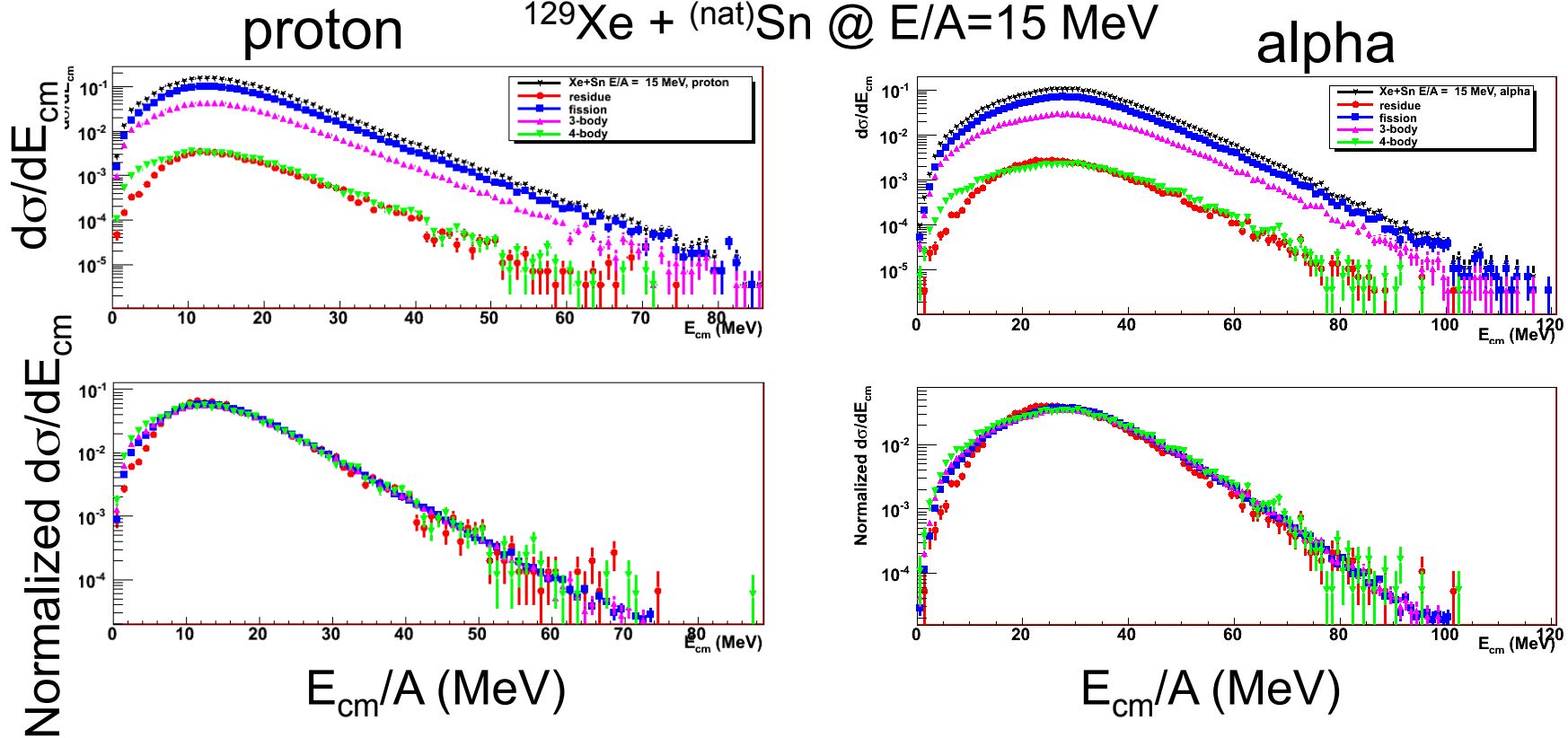
See poster and short talk of D. Gruyer...



D. Gruyer et al., EPJ Web of Conferences 62, 07006+ (2013)
and submitted to Physical Review Letters (arXiv:1309.7779)

Energy spectra of proton alpha in coincidence with 2-, -3 and 4-frag

$^{129}\text{Xe} + (\text{nat})\text{Sn} @ E/A=15 \text{ MeV}$

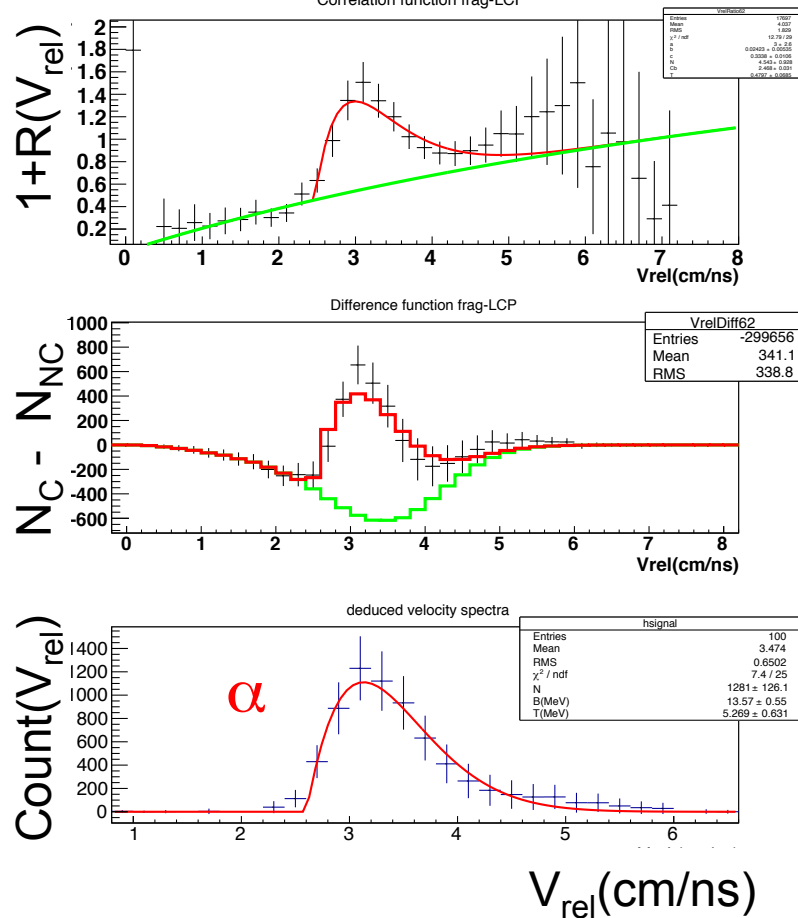


- Maxwellian shape
- Same slope for 2, 3, and 4 fragments → same temperature → same origin
- overproduction at $E_{cm} < 10$, increasing with Mfrag → secondary decay

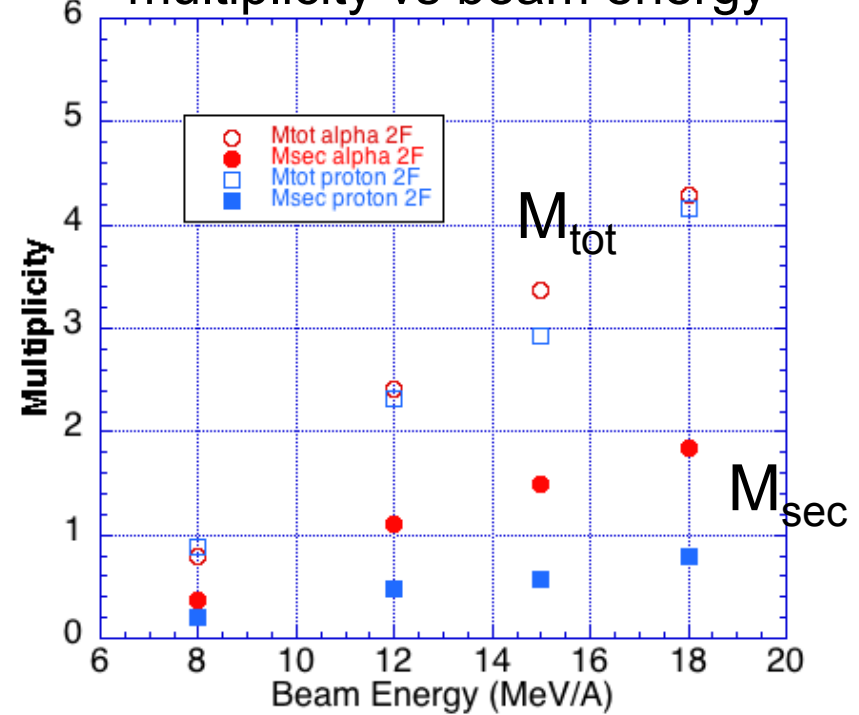
From fission to multifragmentation

Secondary decay contribution using fission frag-LCP correlation function

Xe+Sn @ E/A=12 MeV



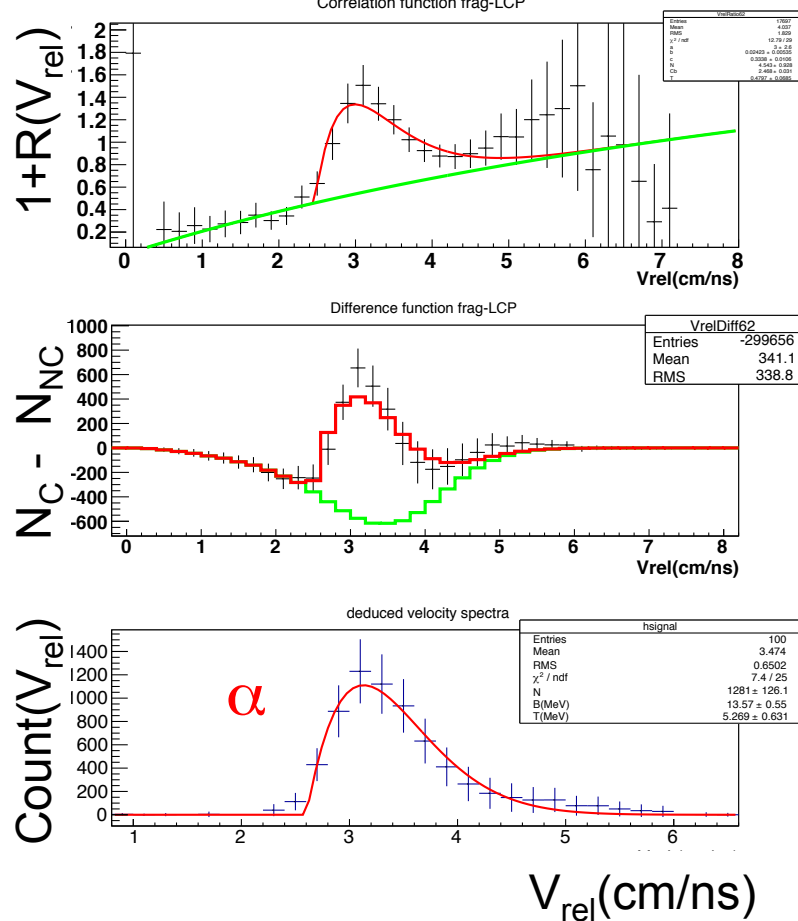
Secondary and total multiplicity vs beam energy



From fission to multifragmentation

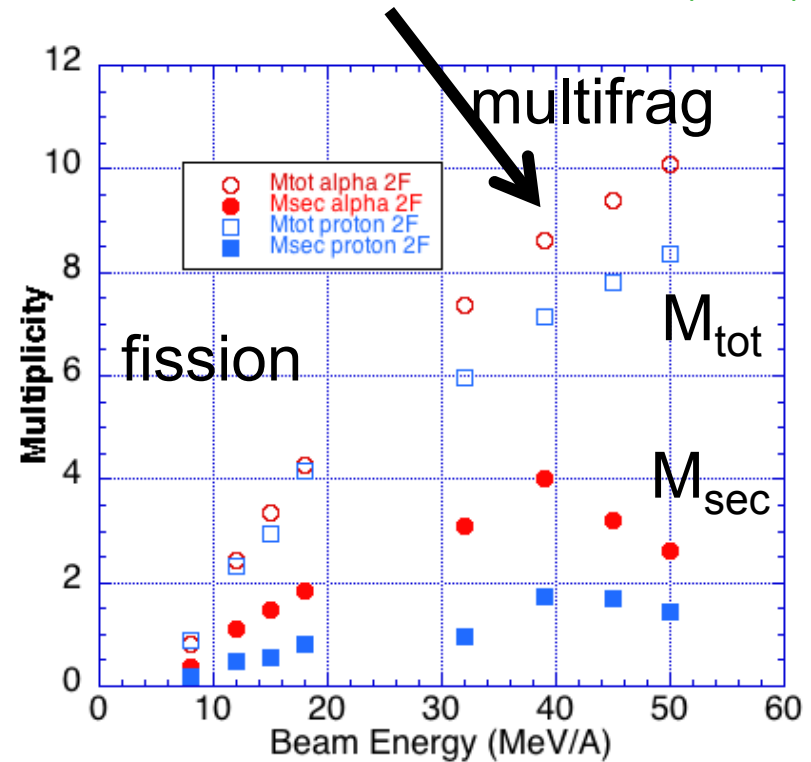
Secondary decay contribution for fission / multifragmentation fragments

Xe+Sn @ E/A=12 MeV



Z (= 62) - α

S. Hudan et al., PRC67, 064613 (2003)



Decrease in M_{sec} for Ebeam/A > 39 MeV reflects saturation on excitation energy

outline

- Introduction to the INDRA talks
- From fission to multifragmentation
- **Symmetry energy : INDRA-VAMOS experiments**
- conclusions

Exploring the symmetry energy with HIC

$$E(\rho, \delta) / A = E(\rho, \delta = 0) / A + S(\rho) \cdot \left(\frac{\rho_n - \rho_p}{\rho_n + \rho_p} \right)^2$$

- information on the EOS: need to study fragments at freeze-out, BEFORE secondary decays :
- But remember: observables measured after secondary decay (need back-tracing)
 - isotopic distributions,
 - Isoscaling

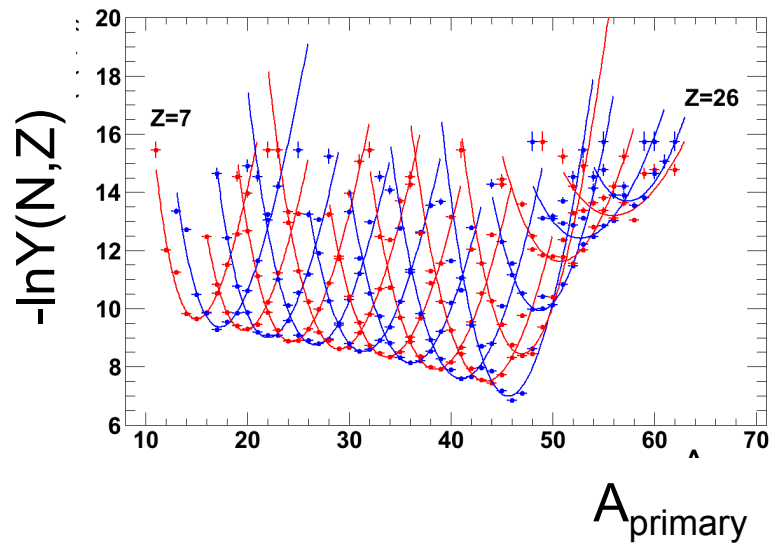
Accessing the symmetry energy

AMD simulations: $^{48}\text{Ca}+^{48}\text{Ca}$ and $^{40}\text{Ca}+^{40}\text{Ca}$, $E/A=35$ MeV and $b > 6$ fm

Primary fragment distributions

A. Ono et al., Phys. Rev. C70, 041604(R) (2004)

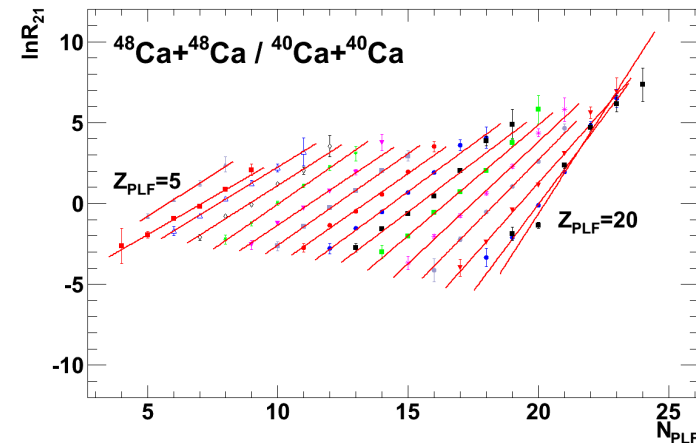
From isotopic distribution...



$$-\ln Y(N, Z) = \xi(Z)N + \eta(Z) + \xi(Z) \frac{(N - Z)^2}{N + Z}$$

$$\xi(Z) \propto 1/\sigma \propto C_{sym}(Z)/T$$

From isoscaling...



$$\frac{Y_2(N, Z)}{Y_1(N, Z)} = C \exp(\alpha N + \beta Z)$$

isocaling parameter

$$\alpha = \Delta\mu_n / T, \beta = \Delta\mu_p / T$$

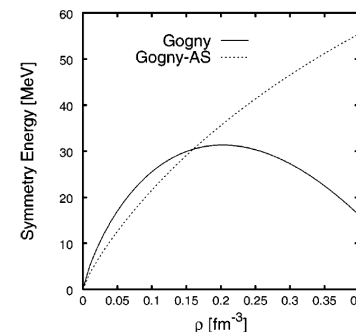
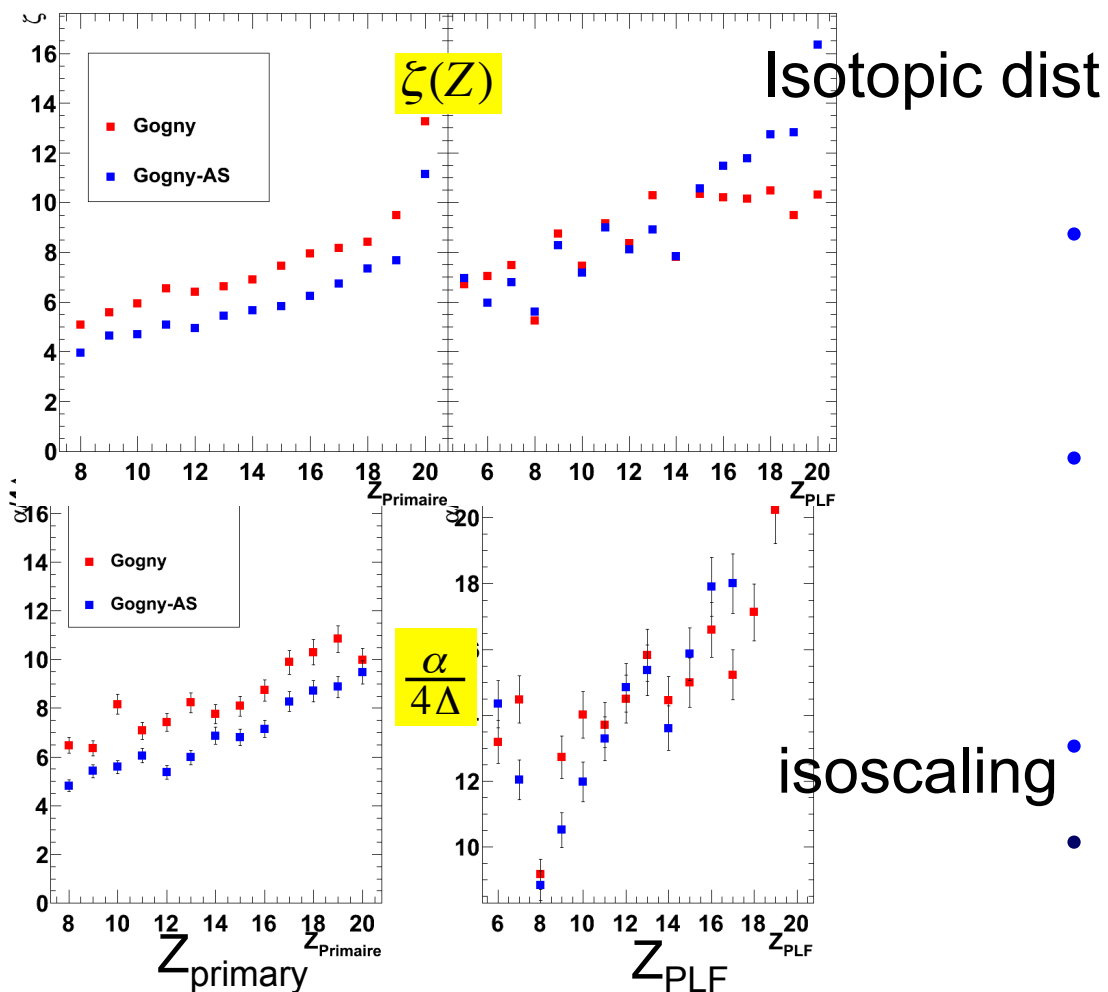
$$\frac{\alpha}{4\Delta} = C_{sym}(Z)/T$$

$$\Delta = \left(\frac{Z}{\langle A_1 \rangle}\right)^2 - \left(\frac{Z}{\langle A_2 \rangle}\right)^2$$

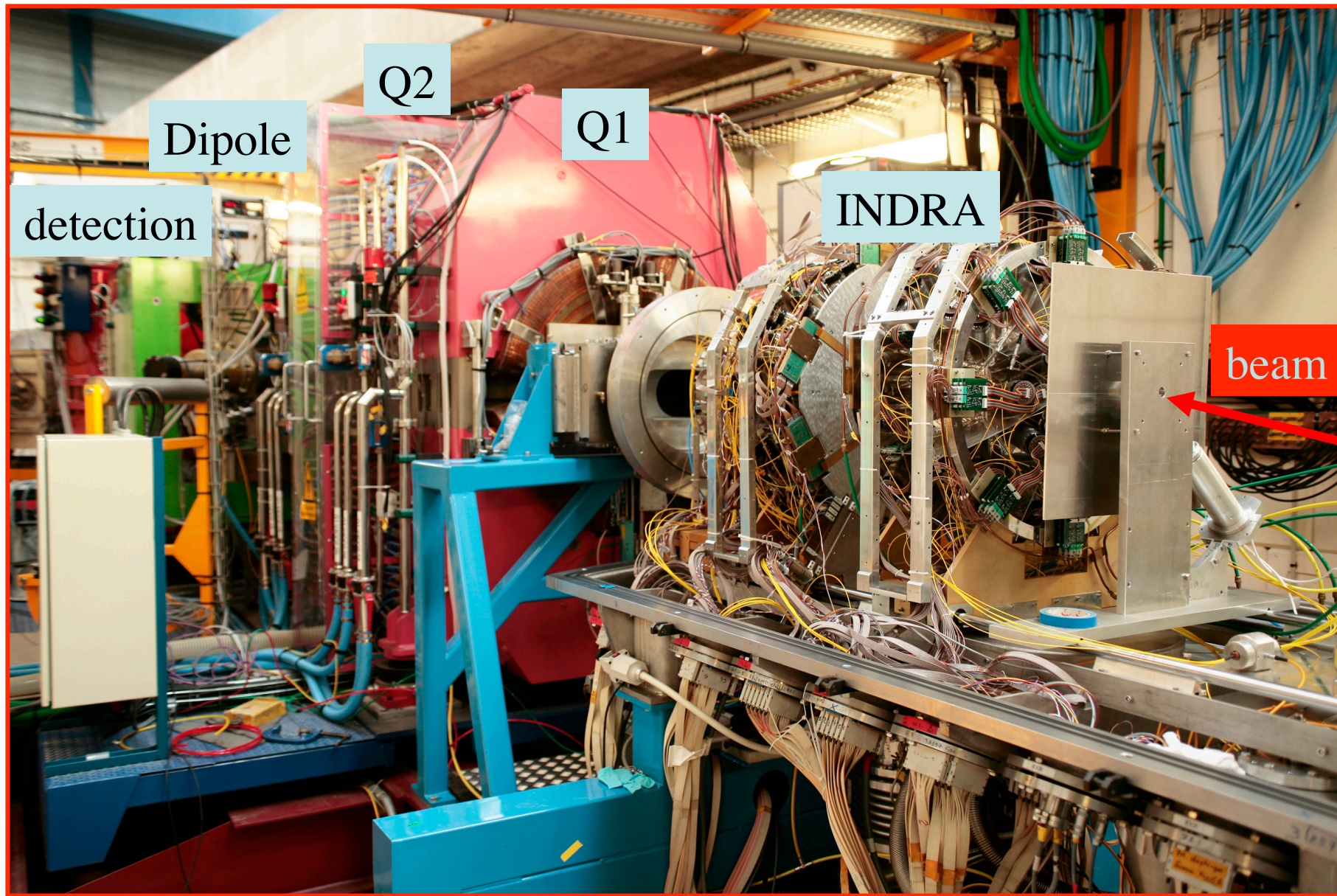
Effects of secondary decays

primary

GEMINI : secondary



- After decay : Cannot distinguish between the two interactions (soft/stiff)
- Secondary decays need to be taken into account for comparison to experimental data
- Statistical model
- Or/and : experimentally provide the primary distributions



Dipole
detection

Q2

Q1

INDRA

beam

VAMOS

PLF (E503) or residues (E494s)

High Isotopic Resolution

INDRA

beam

*INDRA in coincidence LCP /IMF
event characterization
(b , excitation energy)*

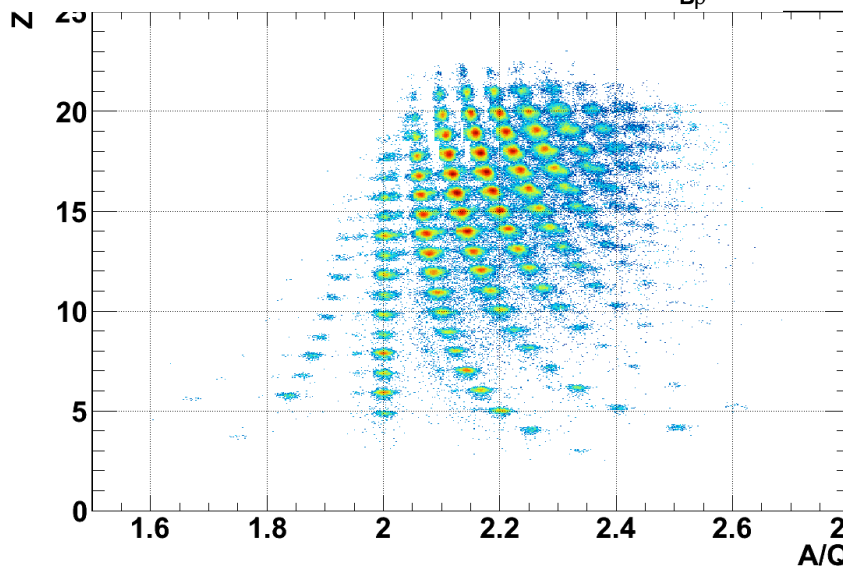
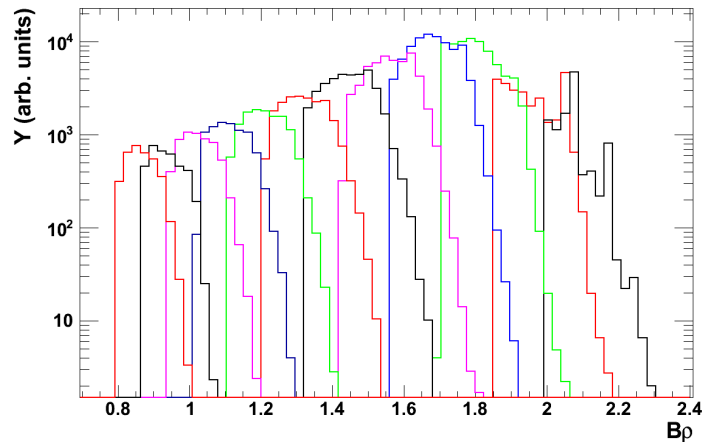
Experiments coupling INDRA-VAMOS

Symmetry energy experiments

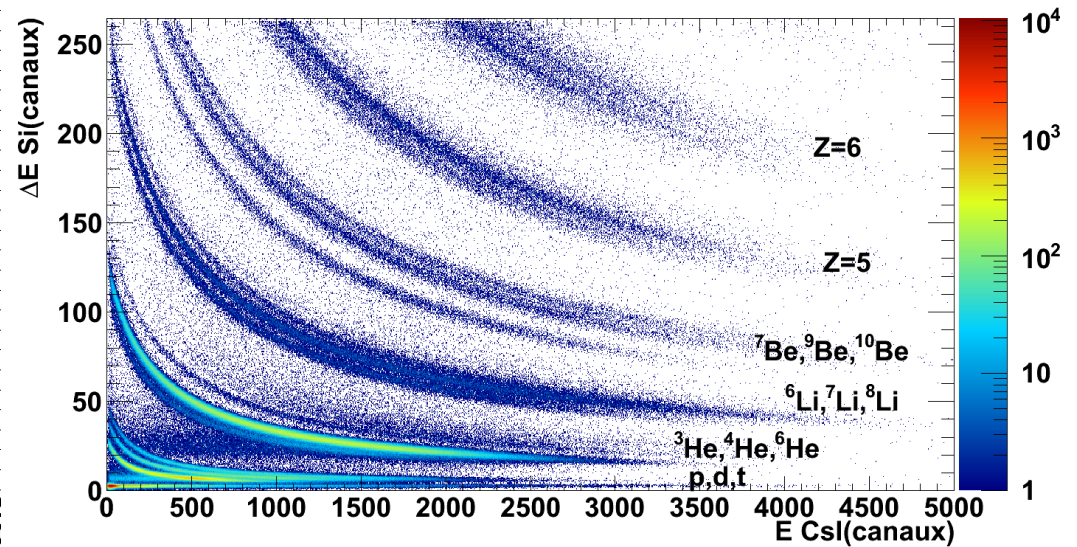
- $^{40}\text{Ca} + ^{40}\text{Ca}$ @ $E/A = 35$ MeV
- $^{40}\text{Ca} + ^{48}\text{Ca}$ @ $E/A = 35$ MeV isospin diffusion
- $^{48}\text{Ca} + ^{40}\text{Ca}$ @ $E/A = 35$ MeV isospin diffusion
- $^{48}\text{Ca} + ^{48}\text{Ca}$ @ $E/A = 35$ MeV

For $B\rho$ (Tm) = 2.2, 2.12, 1.957, 1.80, 1.656, 1.523, 1.401, 1.289, 1.186, 1.091, 1.004, 0.923, 0.849, 0.782, 0.719, 0.661

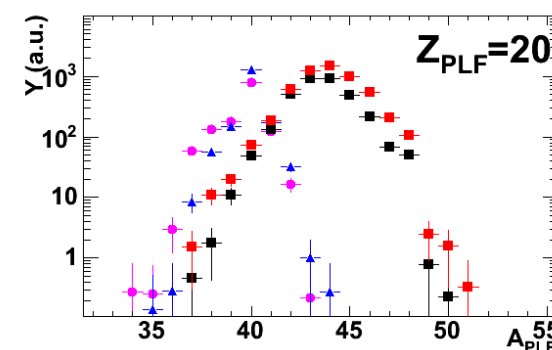
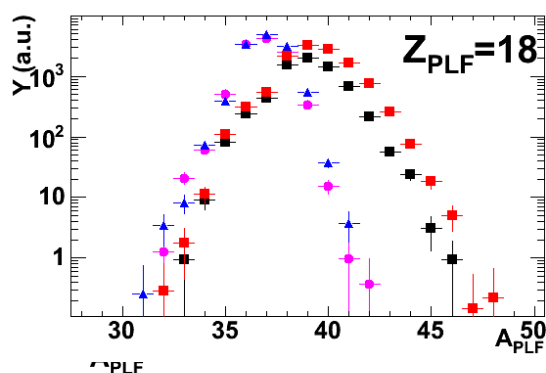
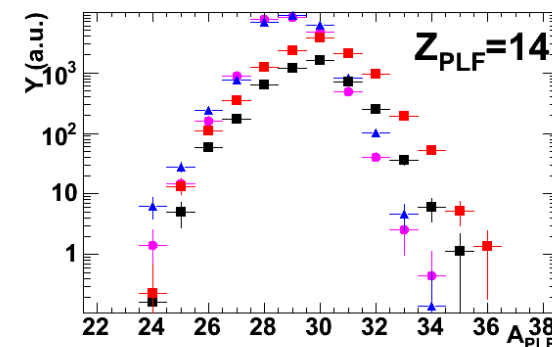
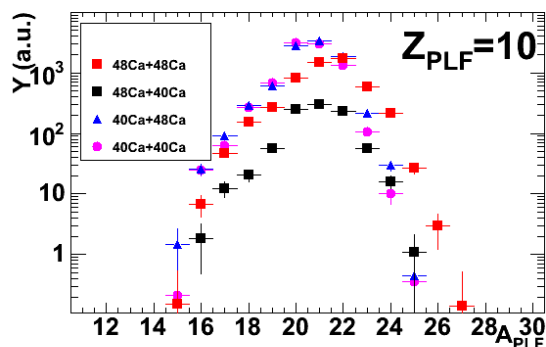
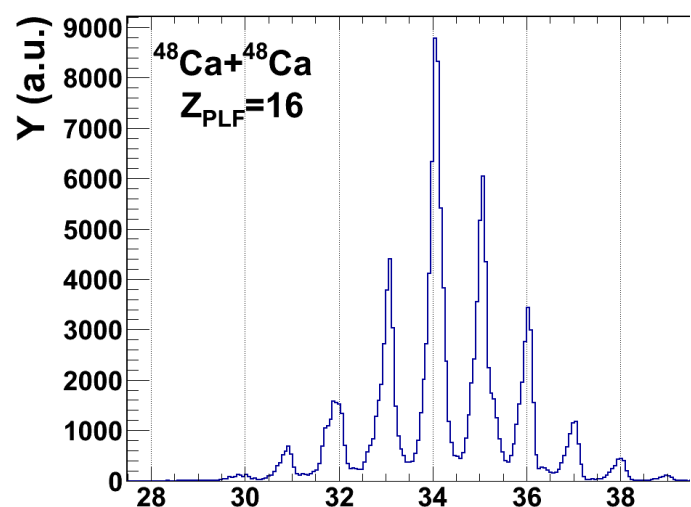
VAMOS Spectrometer



INDRA, 4π detector

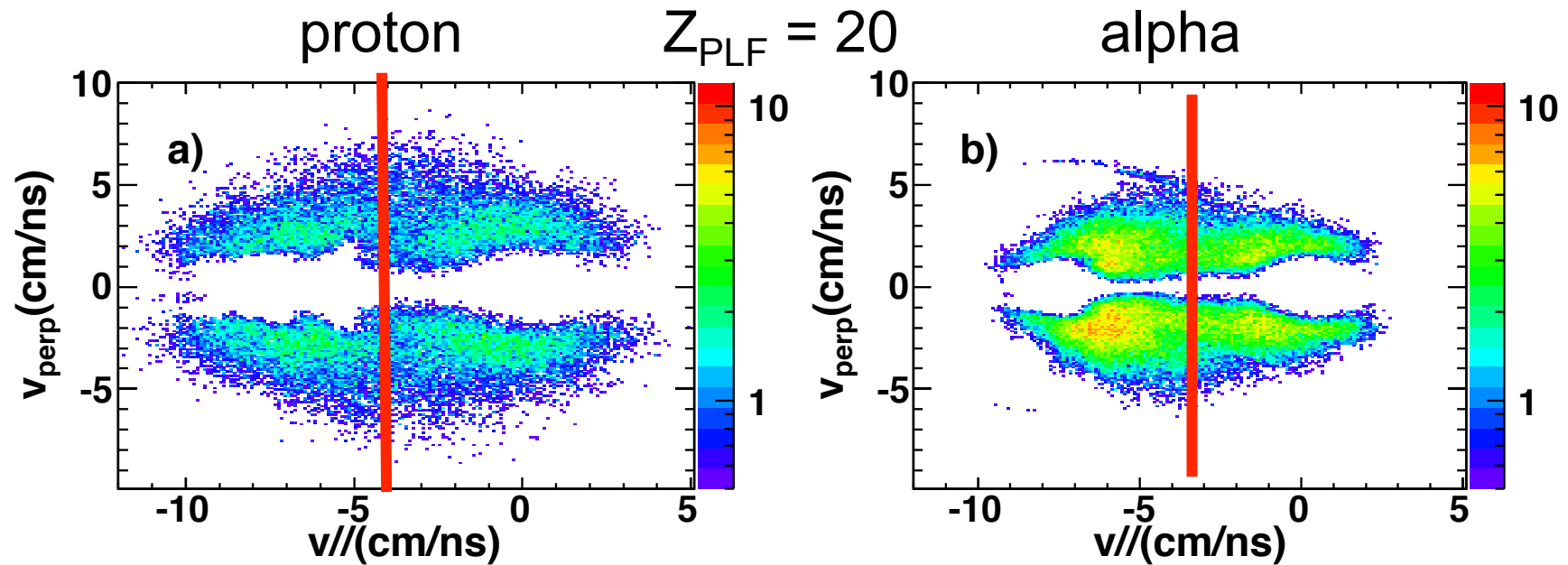


Isotopic distributions of PLF



- Broad A_{PLF} distributions (more than 13 isotopes)
- Sensitive to the n-richness of the system
- N/Z up to 1.58 (11% N/Z ^{48}Ca) very exotic

Reconstruction of primary fragments



Corrected for the reaction plan

For $V_{//}^{cm} > 0$

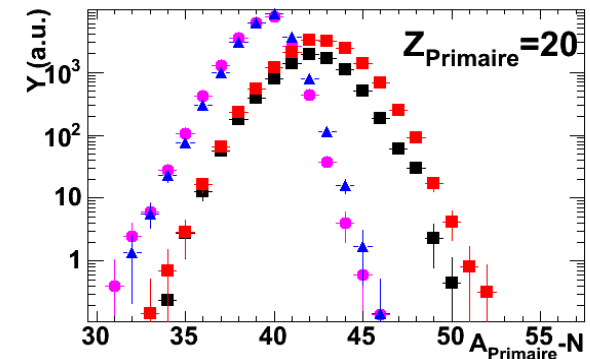
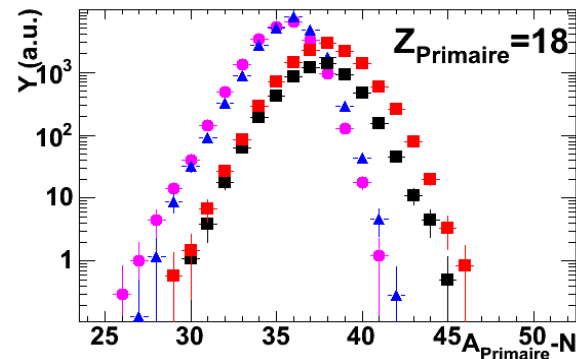
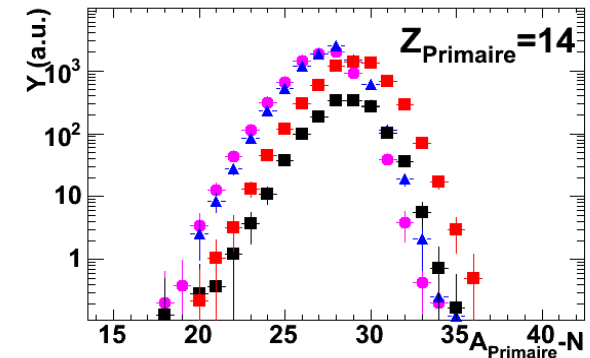
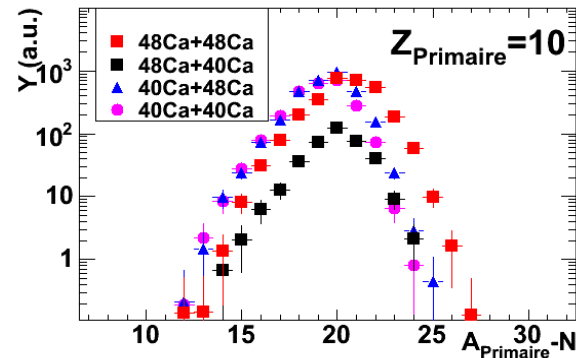
$$Z_{pr} = Z_{PLF} + \sum_{i=1}^{M_{LCP}} Z_i$$

$$A_{pr} - M_n = A_{PLF} + \sum_{i=1}^{M_{LCP}} A_i$$

reconstruction of primary fragments

- Up to 20 isotopes
- Average value and σ increases with Z_{pr}
- Small differences for light Z_{pr}
- Strong dependence on the n-richness of the system for heavy fragments
- small dependence on the n-richness of the target

$$A_{pr} - M_n = A_{PLF} + \sum_{i=1}^{M_{LCP}} A_i$$



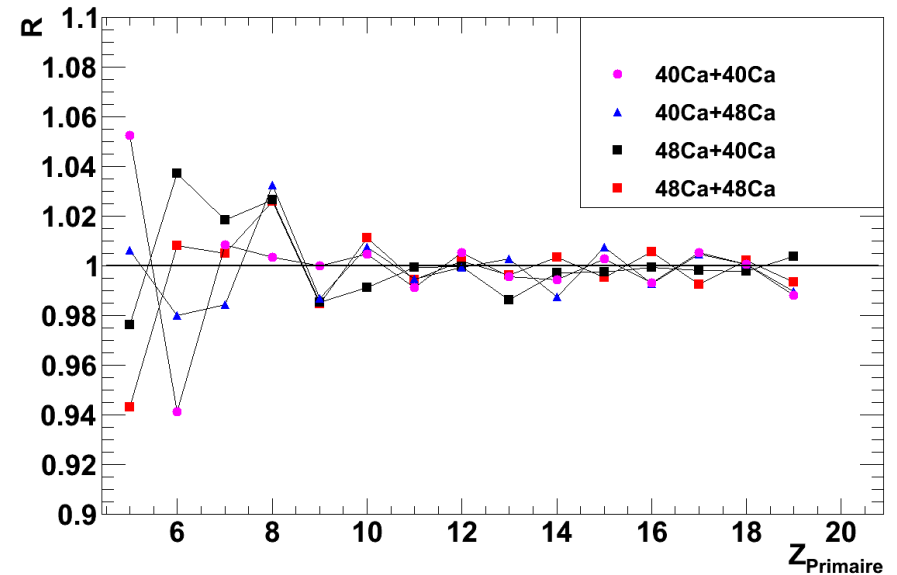
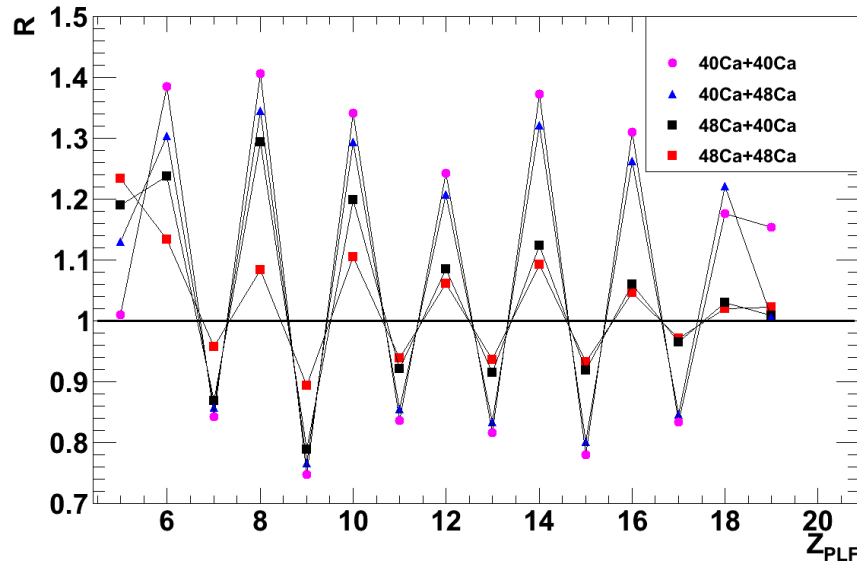
$$A_{pr} - M_n$$

Can be used as an observable

Evaluation of the effect of neutron emission on the width : AMD+GEMINI

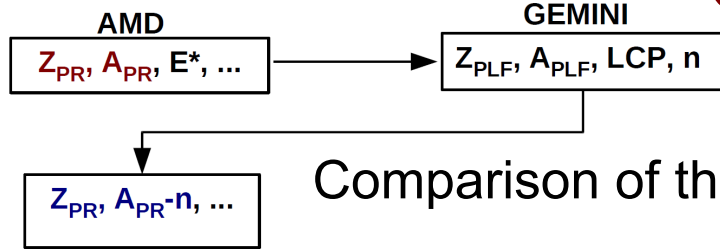
It will be used as correction to the data.

Staggering effect for PLF and primary frag



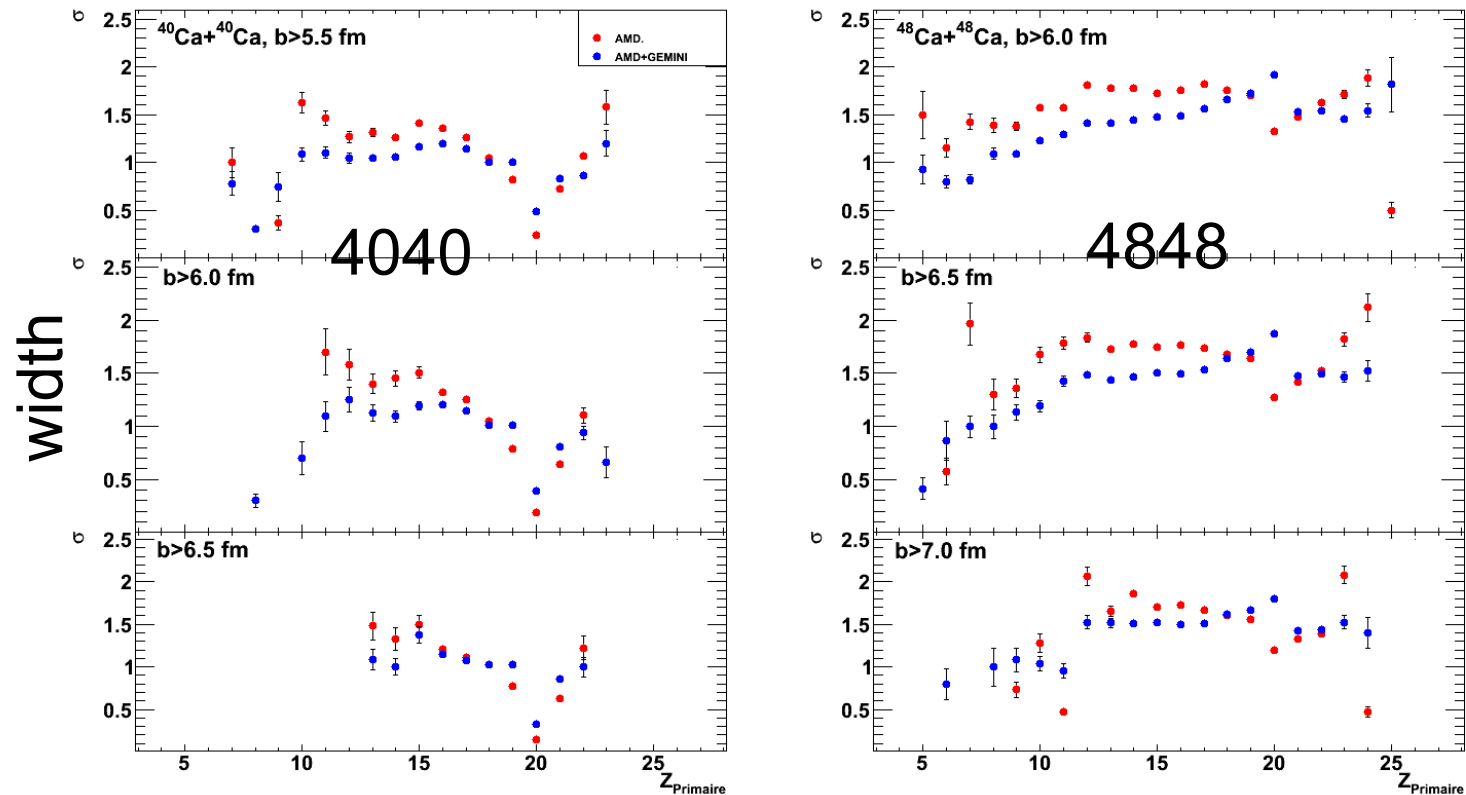
The staggering is determined by secondary evaporative stage
No sensitivity to dynamics.

Neutron influence on the width of isotopic distributions



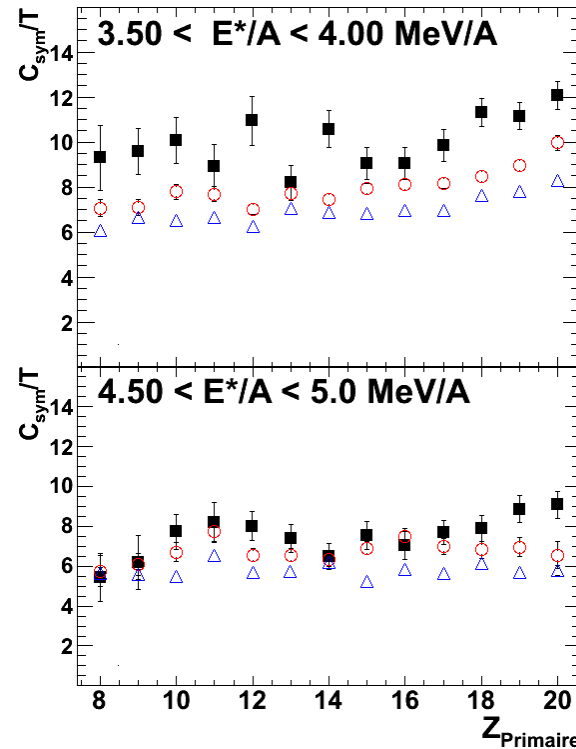
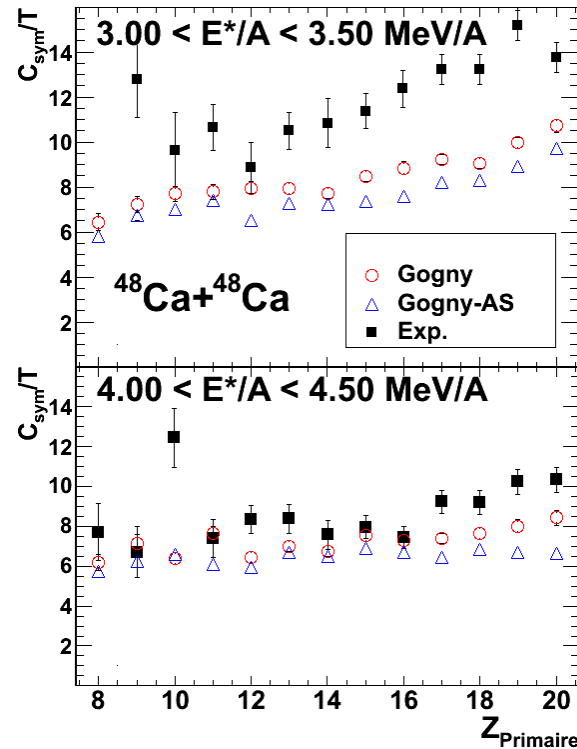
$$A_{pr} - M_n = A_{PLF} + \sum_{i=1}^{M_{LCP}} A_i$$

Comparison of the width of iso-dist **AMD (hot)** and **AMD-N(GEMINI)**

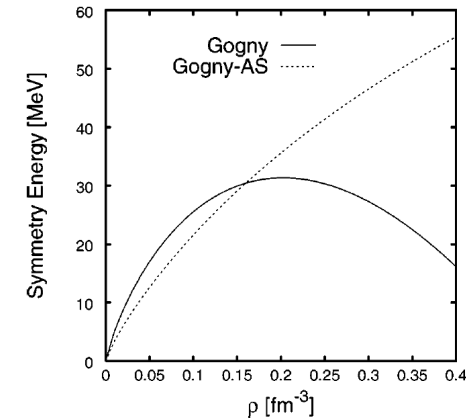


Differences in the width between **AMD** and **AMD-N** as uncertainties when applied to data

Symmetry energy term vs the excitation energy comparison with AMD-N(Gemini), $b > 6$ fm



From width of isotopic dist

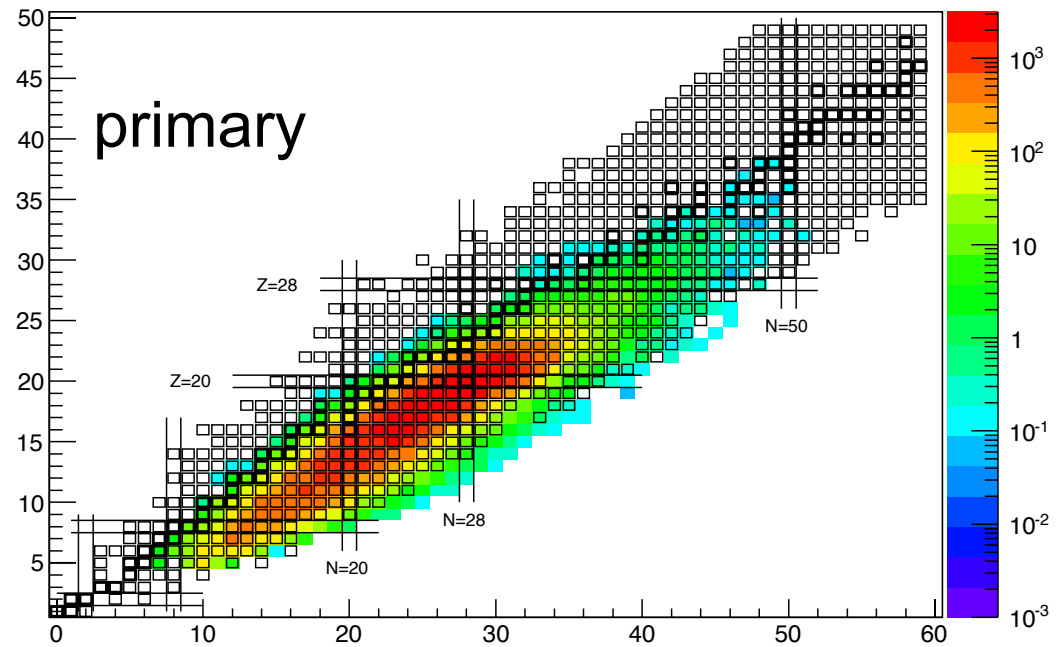
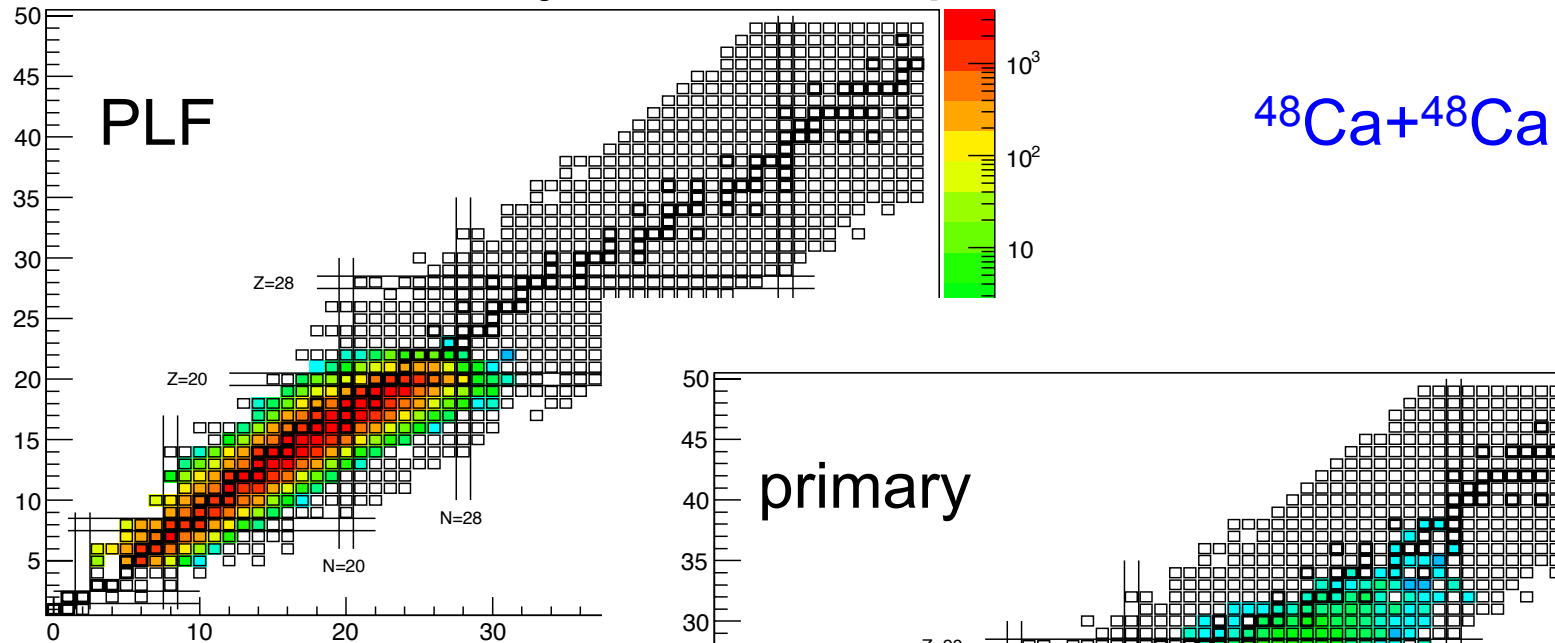


$$\sigma = \sqrt{\frac{1}{N} \sum_i (\text{exp} - \text{calc})^2}$$

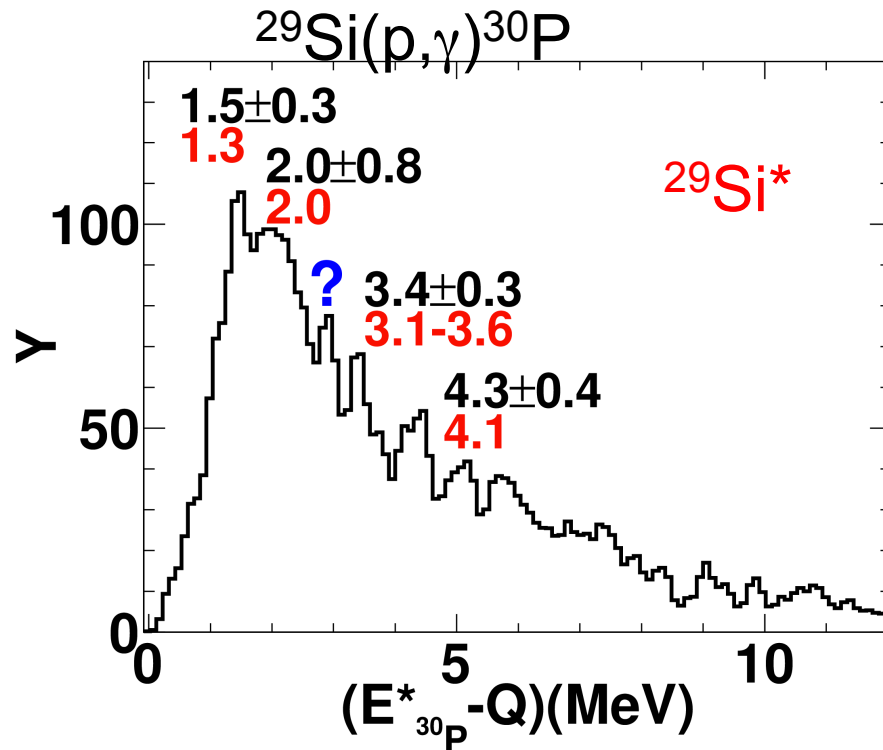
Temperature obtained from slope of p-spectra 4-6 MeV
Values of C_{sym} around 30 MeV
Consistent with the values of saturation density
The method is validated and should be applied to more
dissipative collisions

E^*/A (MeV/A)	Gogny	Gogny-AS
3.00 - 3.50	3.54	4.36
3.50 - 4.00	2.25	3.16
4.00 - 4.50	2.17	2.68
4.50 - 5.00	1.16	2.07

Production of exotic nuclei beyond the drip lines



Spectroscopy of ^{29}Si



$^{32}\text{P} \rightarrow p + ^{31}\text{Si}^*$

$\rightarrow n + ^{30}\text{Si}^*$

$\rightarrow ^{29}\text{Si}^* + n$

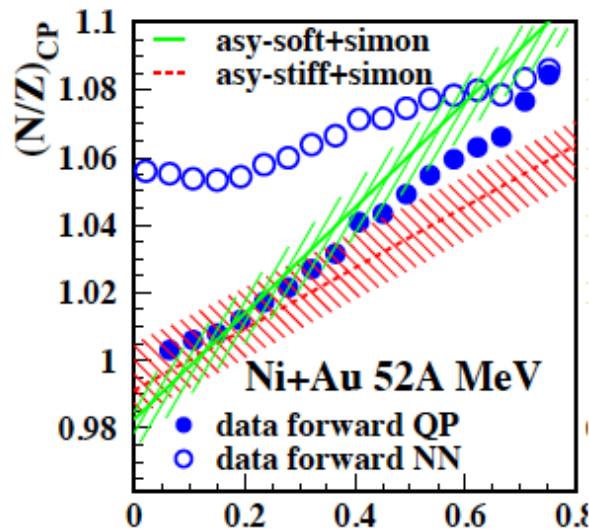
- Experimental reconstruction (correlation techniques)
- Study excited states of exotic nuclei
- Study cluster states in nuclei (in progress)

Isospin equilibrium ?

Directly observed from experiments ; G. Ademard *et al.*, arXiv :1310.5000

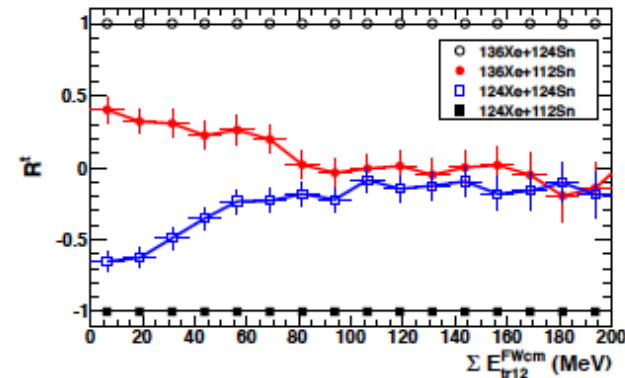
for total system masses ~ 250 , $N/Z=1.38$, at $E_{c.m.}=8-9$ A MeV.

Ni+Au at 52 A MeV



$$\tau_{eq} < 4 \times 10^{-22} \text{ s}$$

4 Xe+Sn at 32 A MeV



$$R_{QP}^x = \frac{2(x^M - x^{eq})}{(x^H - x^L)}; \quad x^{eq} = (x^H + x^L)/2$$

$$x = M_t$$

$$\tau_{eq} = 6 \pm 1 \times 10^{-22} \text{ s}$$

Summary and Conclusions

- Experimental study of Xe+Sn @ $E/A=8-29$ MeV
- Determination of fusion cross section, max $\sigma = 1.2$ b, around $E/A=18-20$ MeV
- Life time of the 2nd fission was determined : simultaneous break up above $E^*/A = 4$ MeV.
- Estimation of secondary decay for proton and alpha particle shows continuous evolution from fission to multifragmentation

Summary and Conclusions

- Exploration of $E_{\text{sym}}(\rho)$ with HI-Collisions
- Observable : isotopic distribution of frag & isoscaling
- Accessing the symmetry energy
 - Take into account the secondary effects
 - Primary experimental isotopic distributions
 - Z_{primary} distributions were reconstructed experimentally
 - $A_{\text{primary}} - \text{neutrons}$ distributions reconstructed exp. but need to take into account the effect of neutron emission on the $A_{\text{pr}} - \text{neutrons}$ distributions
 - Staggering effects are washed with this reconstruction
- Both methods (isoscaling and isotopic distributions) can be used to extract the symmetry energy term if applied for primary quantities
- E_{sym} was extracted for peripheral collisions, the values obtained are consistent with the value at normal density :
- **work is in progress for central collisions**

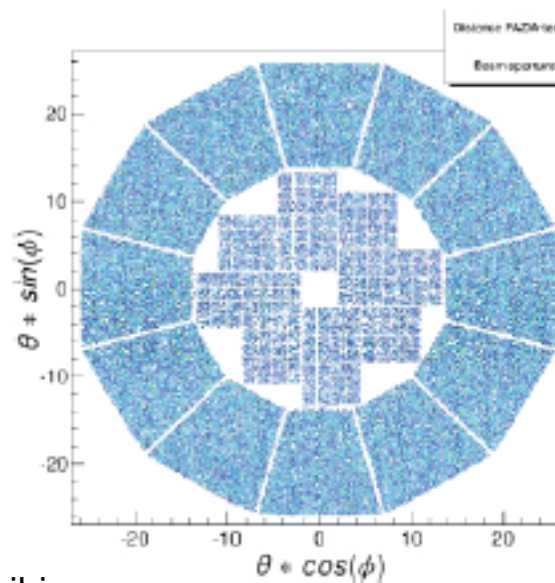
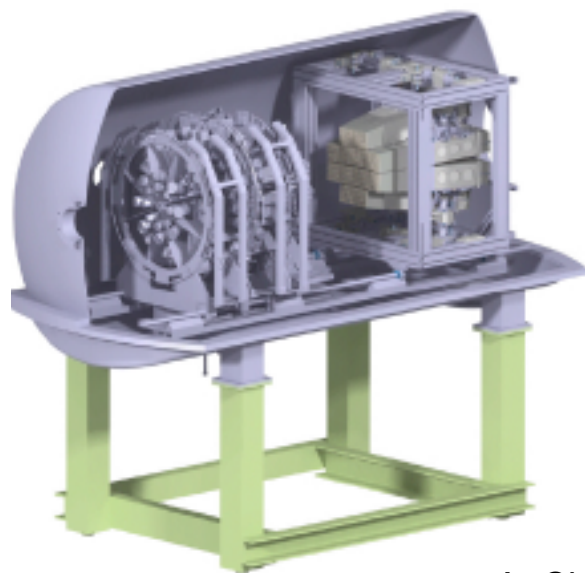
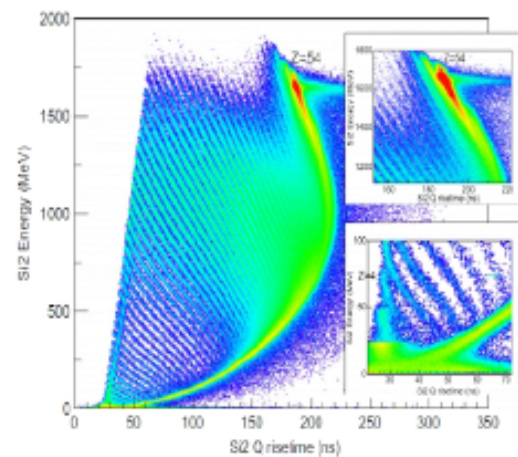
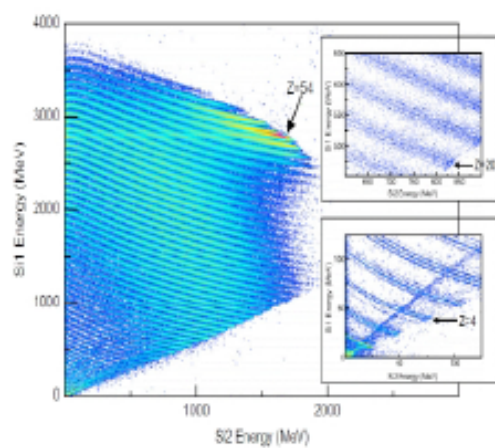


PAC Date:	EXP # (Do not fill in):
April 2014	LoI

Letter Of Intent

Title: N/Z dependence of the dynamics in dissipative collisions, from evaporation towards vaporization		
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Phone: +33 2 31 45 46 25	Fax:	Email: eric.bonnet@ganil.fr
Backup Spokesperson: O. Lopez Address: LPC Caen		
Phone: +33 2 31 45 29 62	Fax:	Email: lopezo@lpccaen.in2p3.fr
<u>GANIL Scientific Coordinator:</u> A. Chbihi		
Collaboration: Participant names, institutions, and indicate students (S), and post-doctoral fellows (PD): FAZIA collaboration fazia2.in2p3.fr/spip		
Abstract: In this Letter of Intent, we describe the experimental program that we want to perform with the FAZIA demonstrator coupled to the INDRA detector at GANIL. This scientific program concerns the exploration of the N/Z (isopin ratio) dependence of the dynamics in dissipative collisions, from evaporation towards vaporization processes. The experimental program requires a charged particle detector array that covers as much as possible of the whole 4π solid angle with high efficiency and		

perspectives



A. Chbihi, G. Verde, E. Bonnet, J.D. Frankland, M. Boisjoli, P. Marini, J. Moisan, B. Sorgunlu, F. Rejmund, M.
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 Sarmishtha Bhattacharya, P. Napolitani
 GANIL, CEA, IN2P3-CNRS, FRANCE
 INFN, Catania, ITALY
 B. Borderie, E. Galichet, N. Le Neindre, M.F. Rivet
 IPN Orsay, IN2P3-CNRS, FRANCE
 R. Dayras, L. Nalpas, C. Volant
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