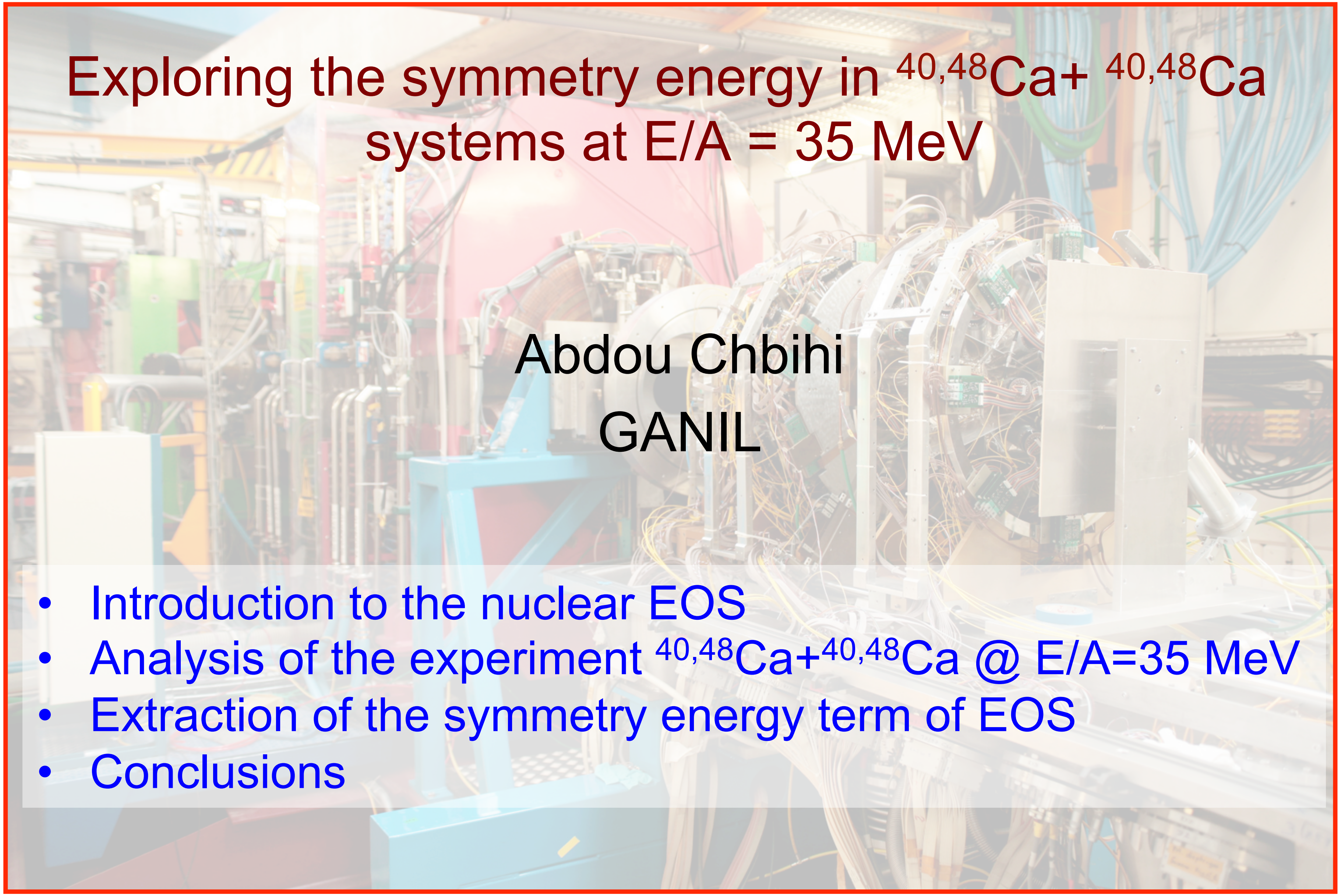


Exploring the symmetry energy in $^{40,48}Ca + ^{40,48}Ca$ systems at E/A = 35 MeV

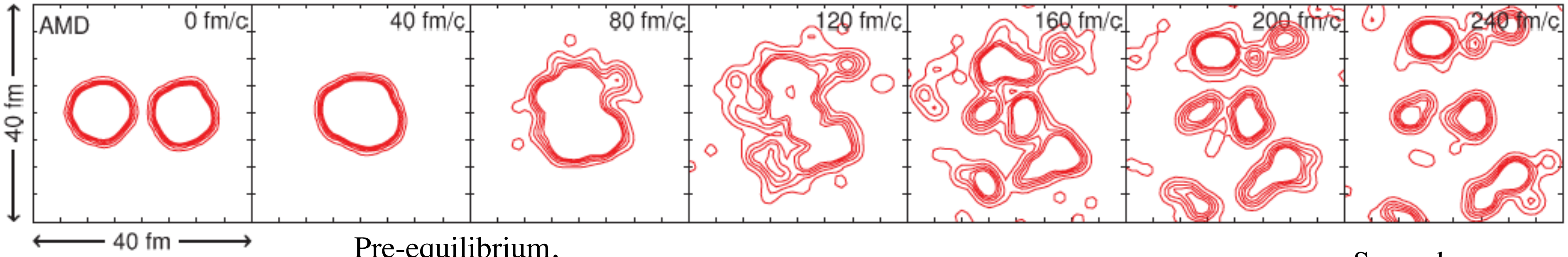
Abdou Chbihi

GANIL

- Introduction to the nuclear EOS
- Analysis of the experiment $^{40,48}Ca+^{40,48}Ca$ @ E/A=35 MeV
- Extraction of the symmetry energy term of EOS
- Conclusions

Time evolution of central collisions at intermediate energies

M. Colonna, A. Ono and J. Rizzo PRC82, 054613 (2010) Typical event of Xe+Sn @ E/A =50 MeV



Pre-equilibrium, stopping, compression

Flow, expansion

Fragmentation

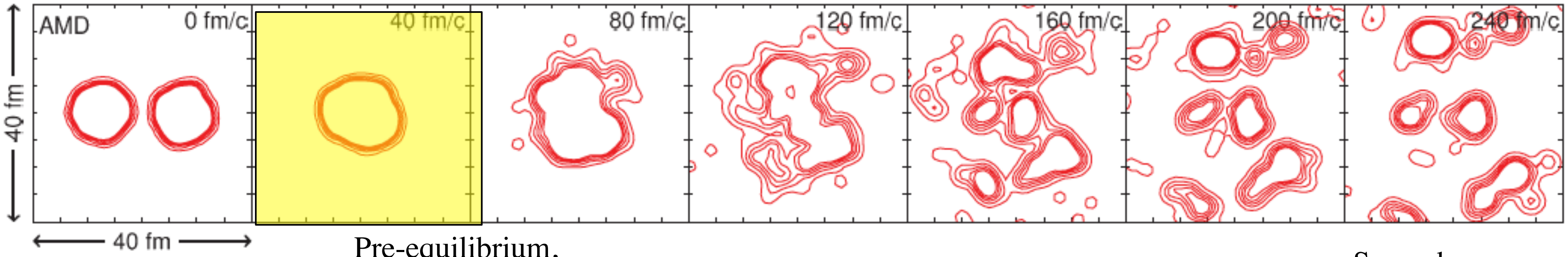
Secondary decays

- EOS and transport properties paly a fundamental role in the understanding of many a aspects of nuclear physics and astrophysics.
- Explore the EOS under laboratory controlled conditions
- HIC is Femtonovae which mimic Supernovae

ECT* 2014 : Simulating the Supernova Neutrinosphere with Heavy Ion Collisions

Experimental probe of nuclear stopping

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

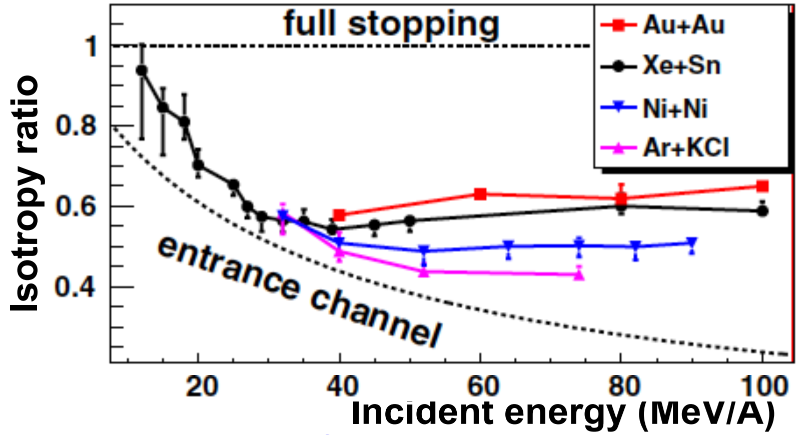


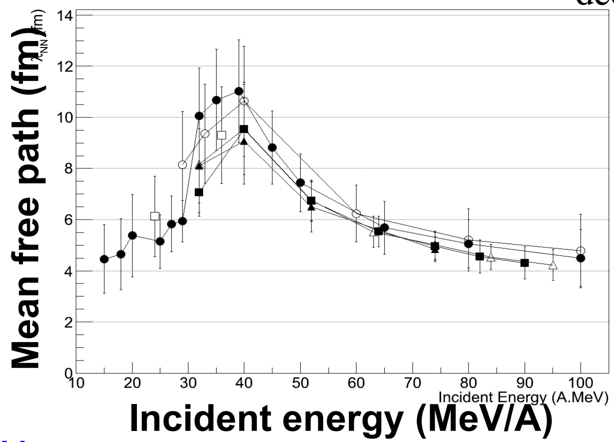
Pre-equilibrium, stopping, compression

Flow, expansion

Fragmentation

Secondary decays



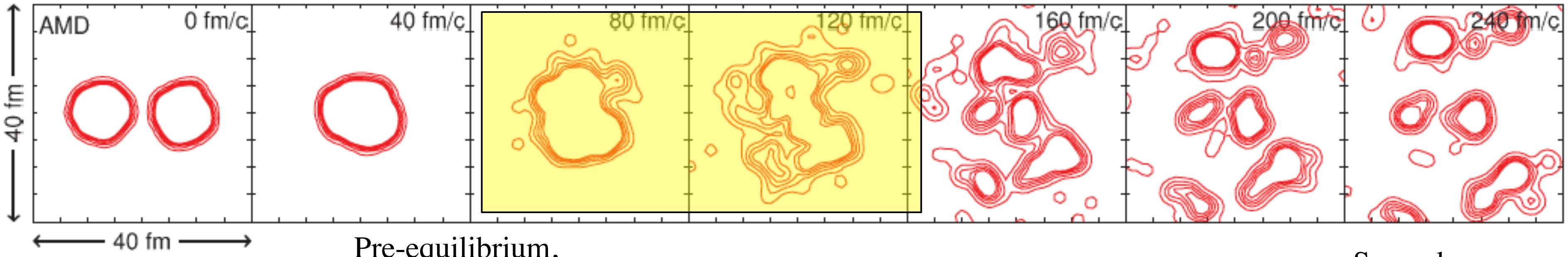


- Minimum of stopping around the Fermi energy
- Full stopping is not achieved
- Transparency due to in-medium effect
- Determination of experimental mean free path λ_{NN}, σ_{NN}

G. Lehaut et al., PRL 104, 232701 (2010)
O. Lopez et al., PRC (submitted)
W. Reisdorf et al., PRL 92,232301 (2004

Experimental probe of collective flow

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



Pre-equilibrium, stopping, compression

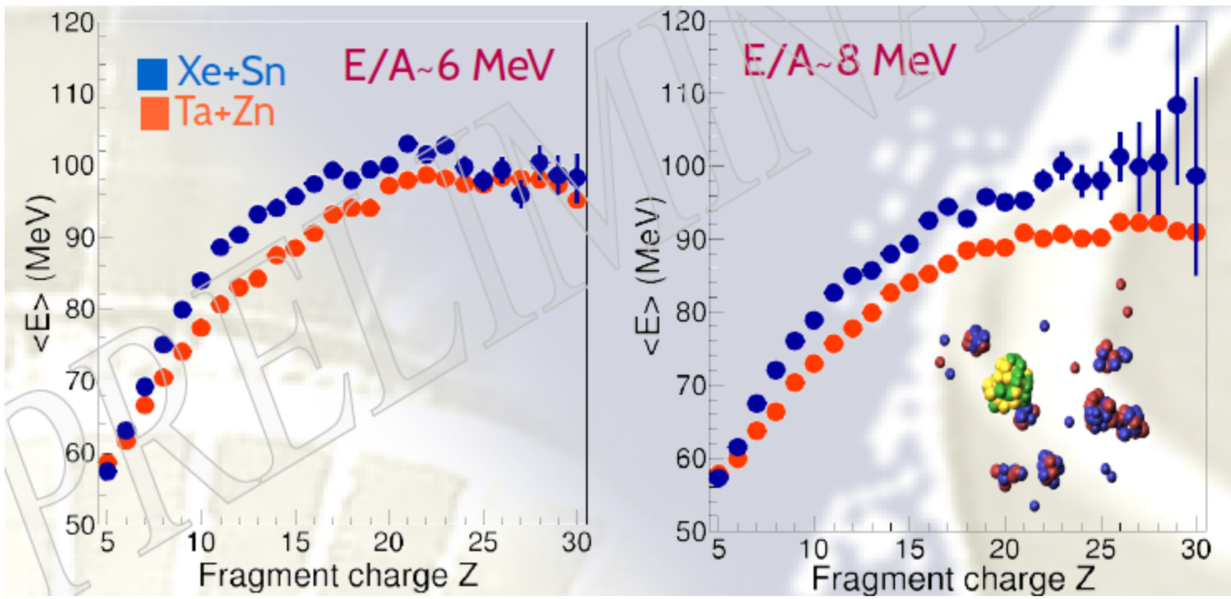
Flow, expansion

Fragmentation

Secondary decays

Radial flow:

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

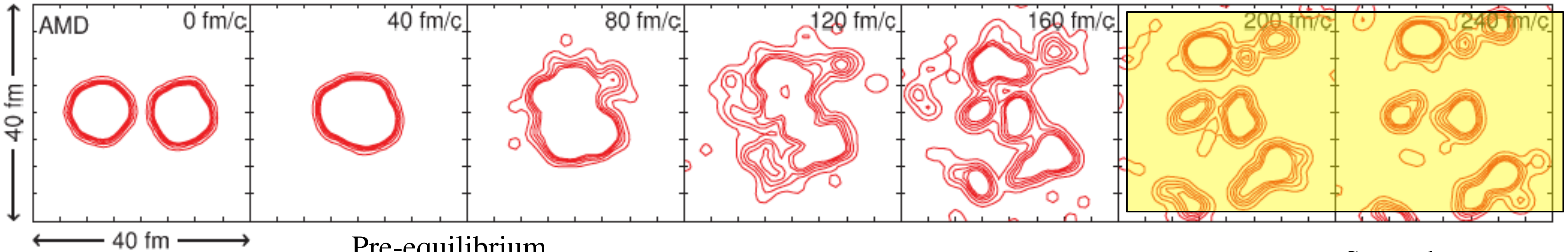


Amount of the radial collective energy governs the degree of fragmentation of hot nuclei

E. Bonnet et al.,
Nucl. Phys. A816, 1 (2009)
Phys. Rev. Lett. 105 (2010)
J.D. Frankland et al., in prep

Production of fragments and secondary decay

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



Pre-equilibrium, stopping, compression | Flow, expansion | Fragmentation | Secondary decays

- Primary fragments are excited :
- $E^*/A \approx 3$ MeV

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

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

- Information on the EOS: need to study fragments at freeze-out, BEFORE secondary decays : PRIMARY FRAGMENTS
- Observables : Isotopic distribution of fragments and isoscaling
- But : observables measured after secondary decay (need back-tracing)

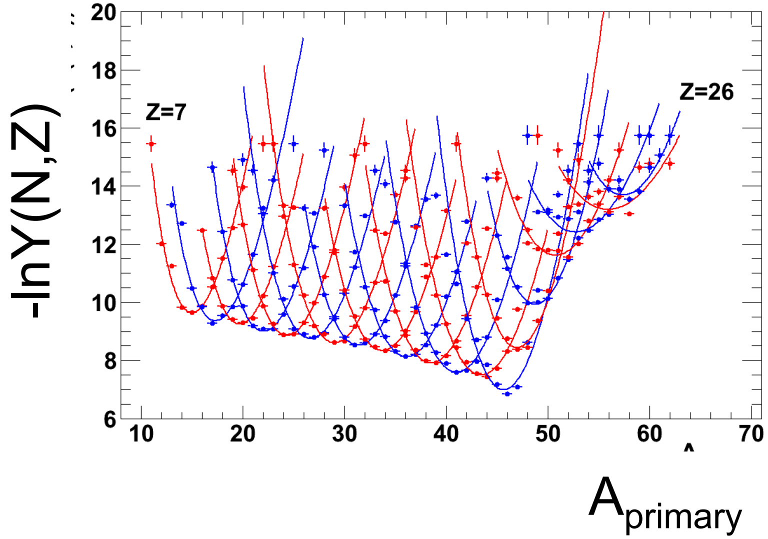
Accessing the symmetry energy

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

Primary fragment distributions

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

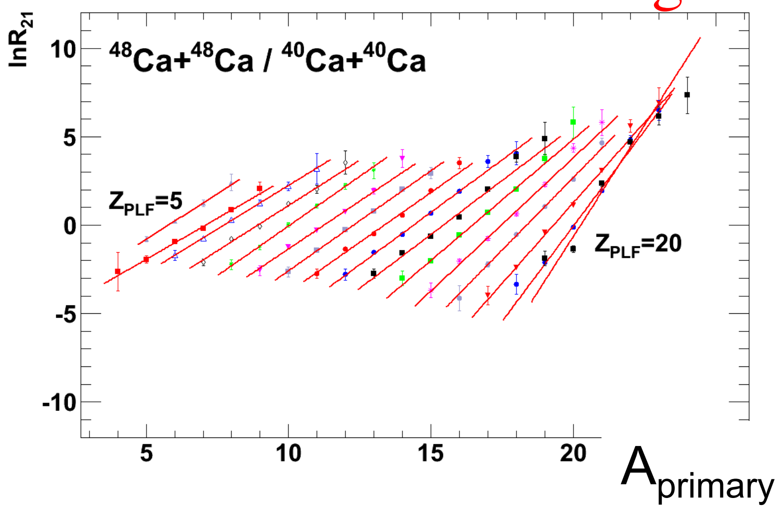
From isotopic distribution…



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

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

From isoscaling…



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

isocaling parameter

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

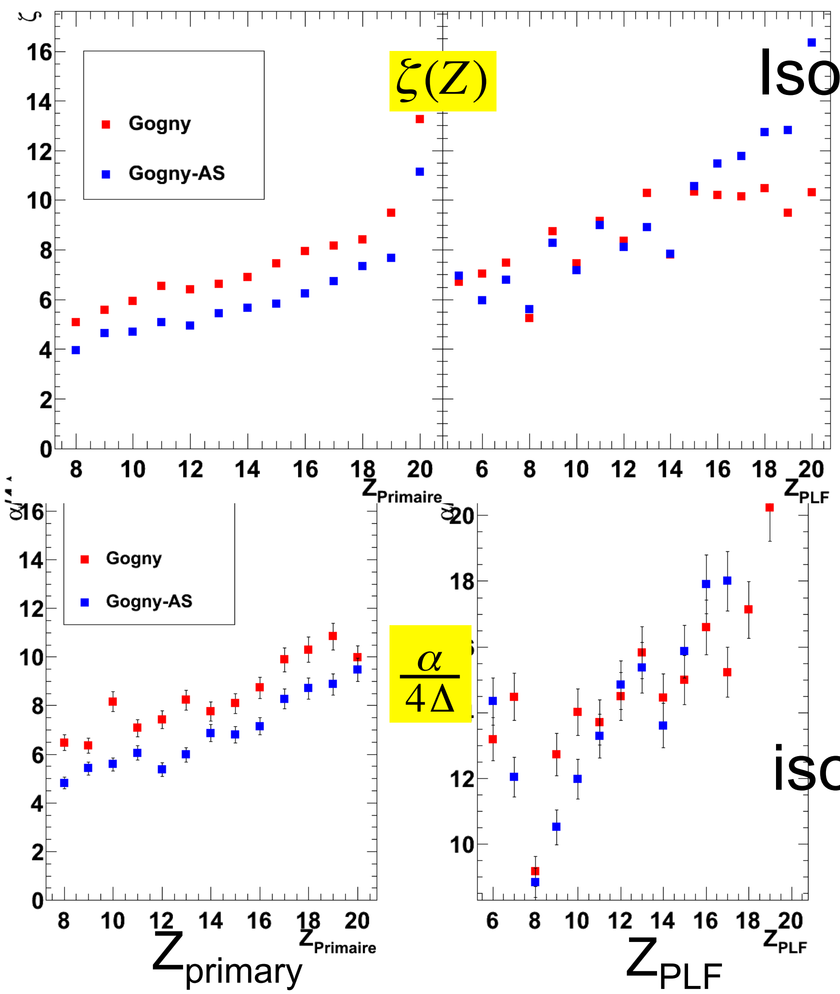
$$\frac{\alpha}{4\Delta} = C_{sym}(Z)/T$$

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

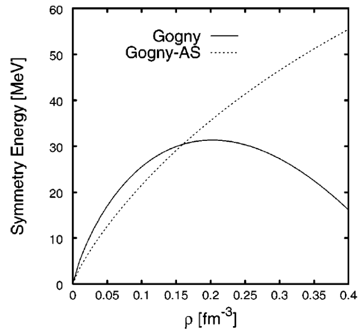
Effects of secondary decays

AMD primary   GEMINI : secondary

Isotopic dist



isoscaling



- 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

VAMOS PLF (E503)

High Isotopic Resolution

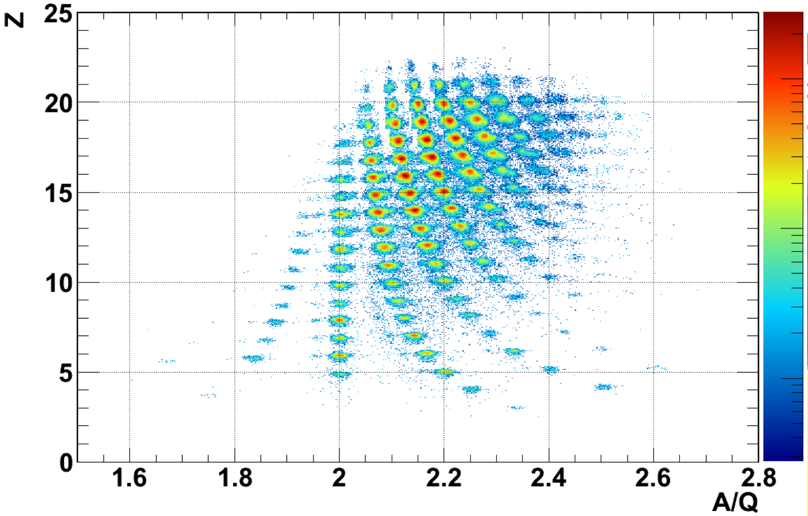
detection

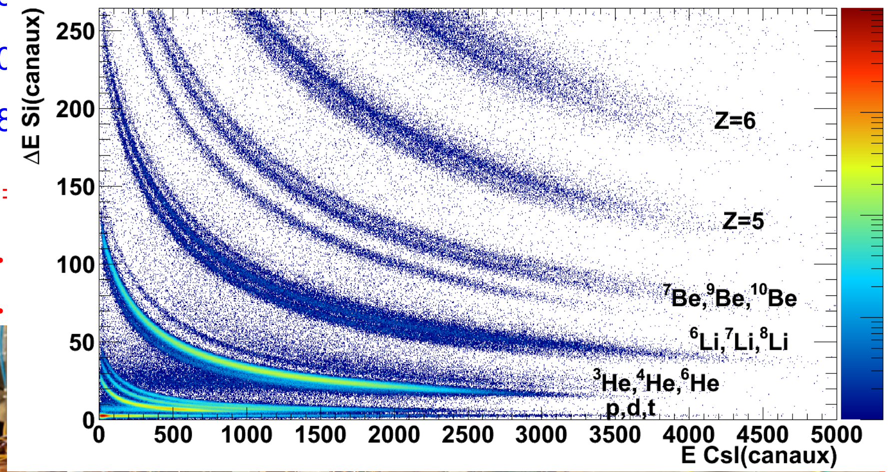
…etry energy experiments

…a + ^{40}Ca @ E/A = 35 MeV

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

ρ (Tm)…
…401 , 1.…
…782 , 0.…



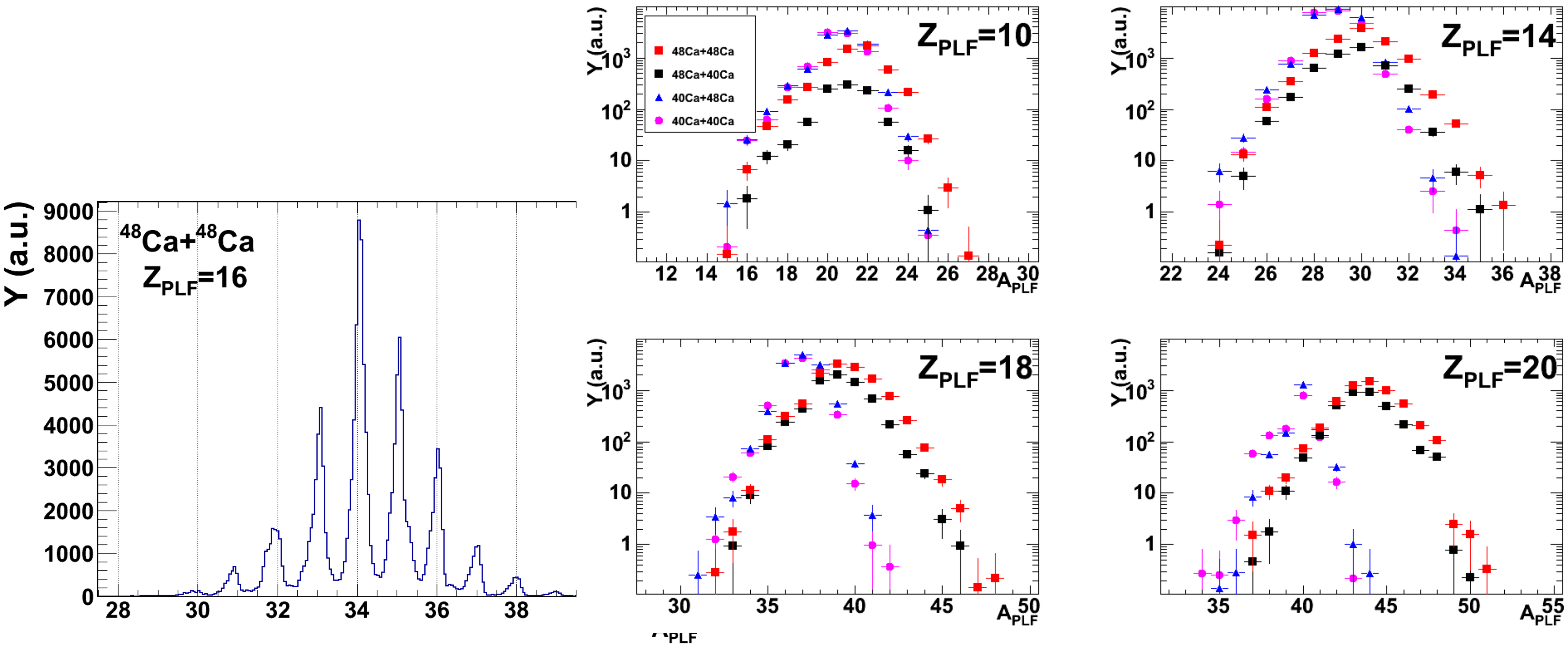


INDRA in coincidence LCP /IMF

event characterization

(b, excitation energy)

Isotopic distributions of PLF

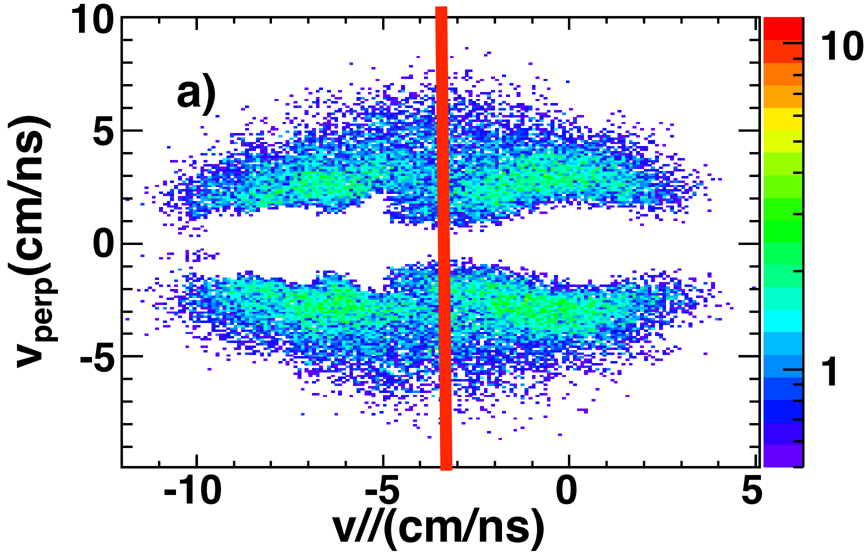


- Broad A_{PLF} distributions (more than 13 isotopes)
- Sensitive to the n-richness of the system
- N/Z up to 1.58 (11% N/Z ^{48}Ca) very exotic

Reconstruction of primary fragments

$Z_{PLF} = 20$

proton



Corrected for the reaction plan

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

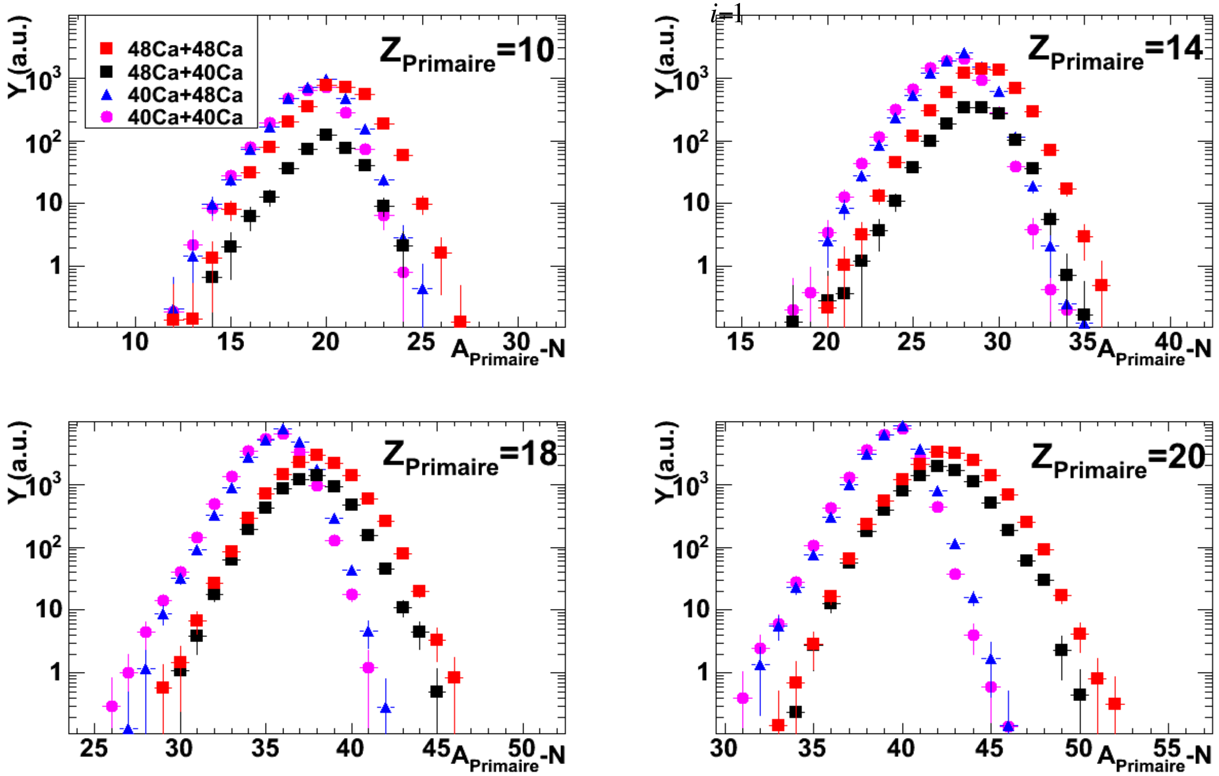
$$Z_{pr} = Z_{PLF} + \sum_{i=1}^{M_{LCP}} Z_i$$

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

Reconstruction of primary fragments

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

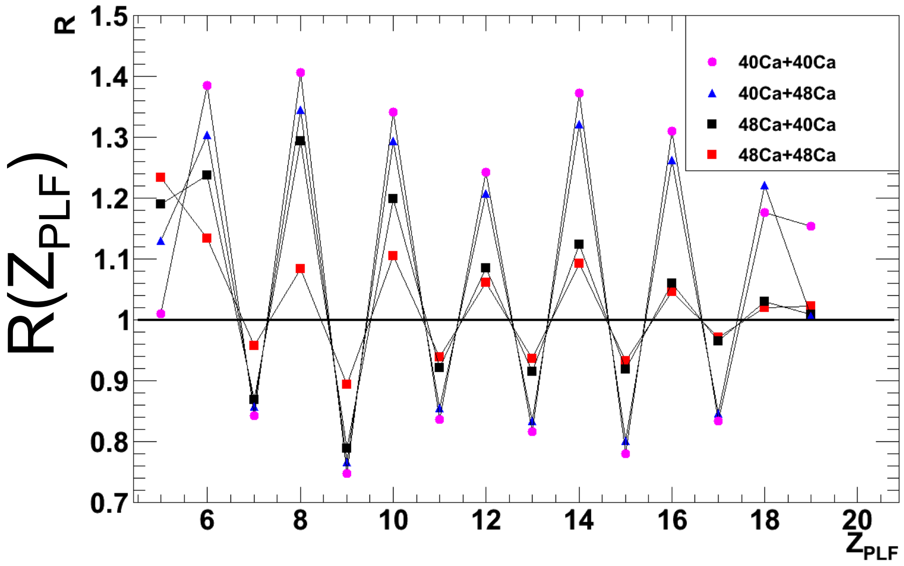
- Up to 20 isotopes
- Average value and σ increases with Z_{pr}
- Small differences for light Z_{pr}
- Strong dependence on the n-richness of the system for heavy fragments
- small dependence on the n-richness of the target



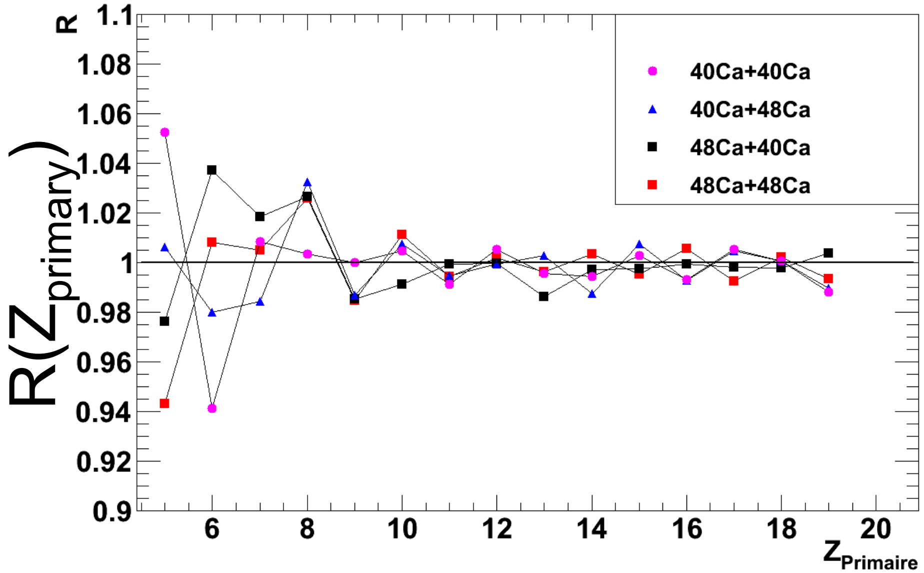
$$A_{pr} - M_n$$

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



Test of the reconstruction



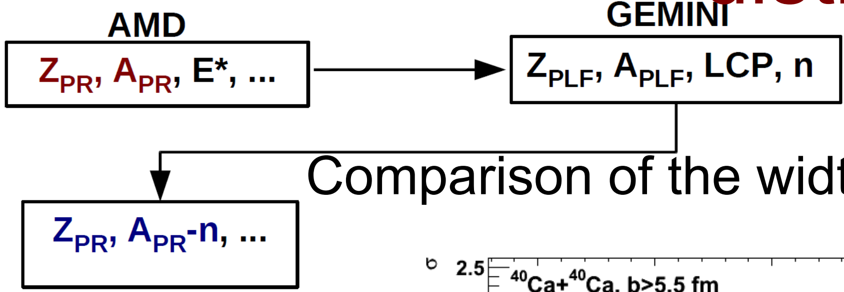
$R(Z) = Y(Z)/Y(Z)_{smoothed}$

The staggering is determined by secondary evaporative stage

No sensitivity to dynamics.

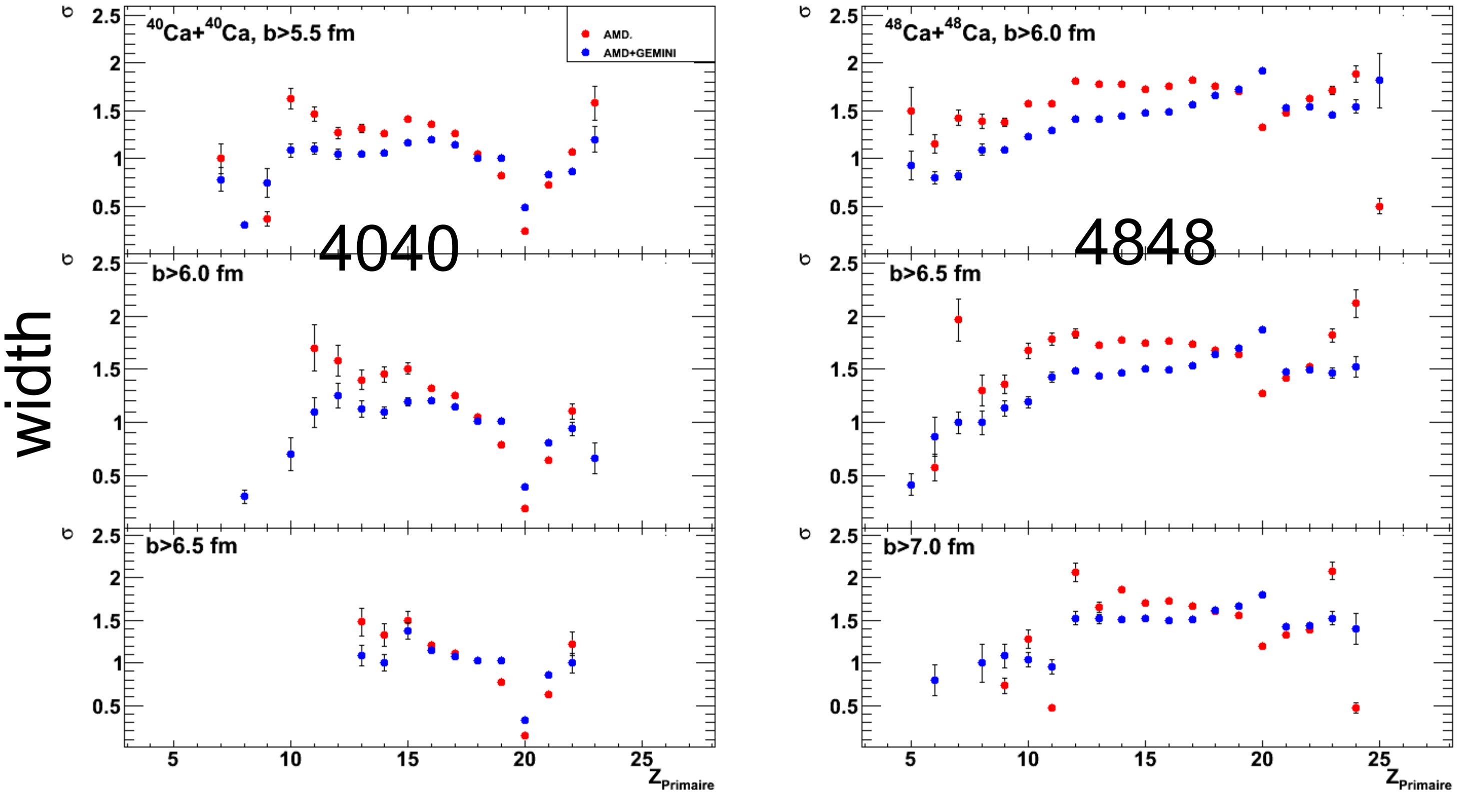
Validity of method: peripheral collisions and Z>12

Neutron influence on the width of isotopic distributions



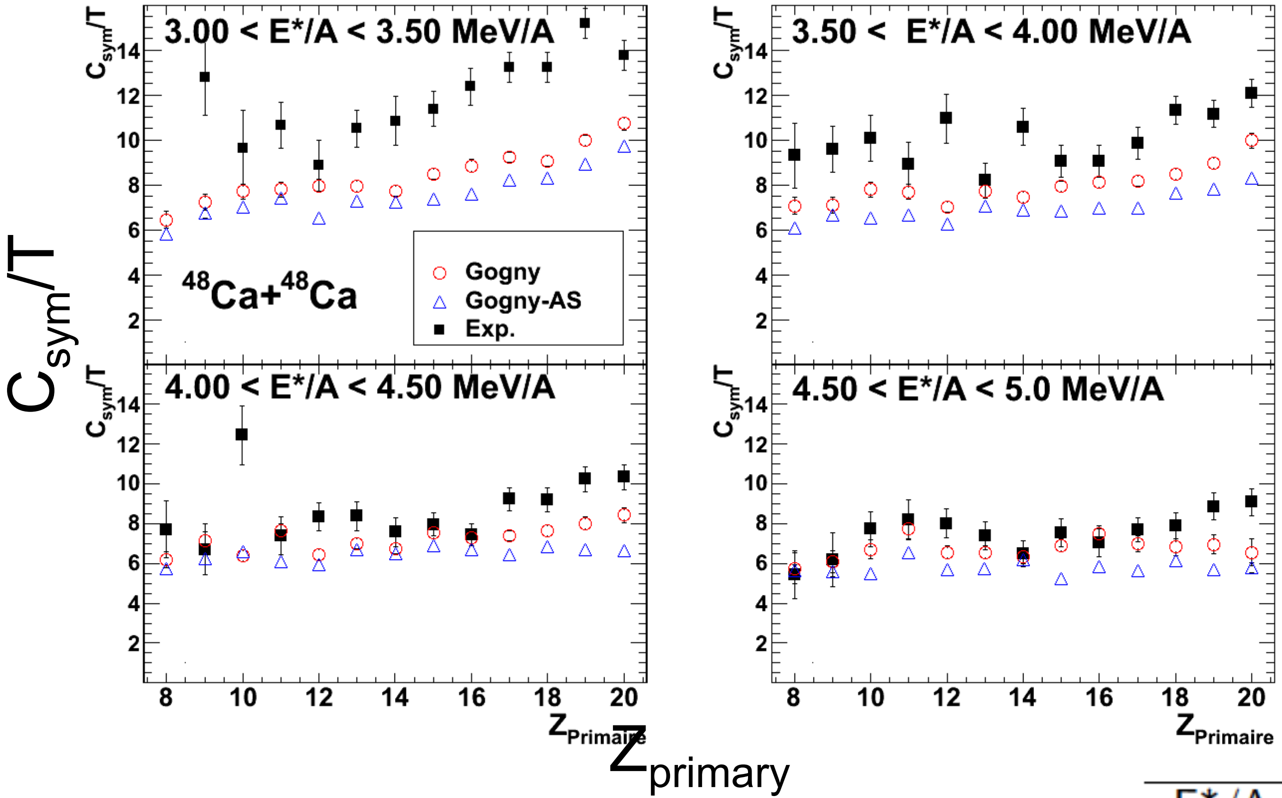
$$A_{pr} - M_n = A_{PLF} + \sum_{i=1}^{M_{LCP}} A_i$$

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

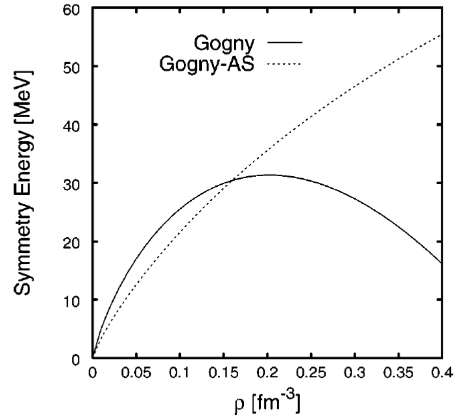


Differences in the width between AMD and AMD-N as uncertainties when applied to data

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



From width of isotopic dist



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

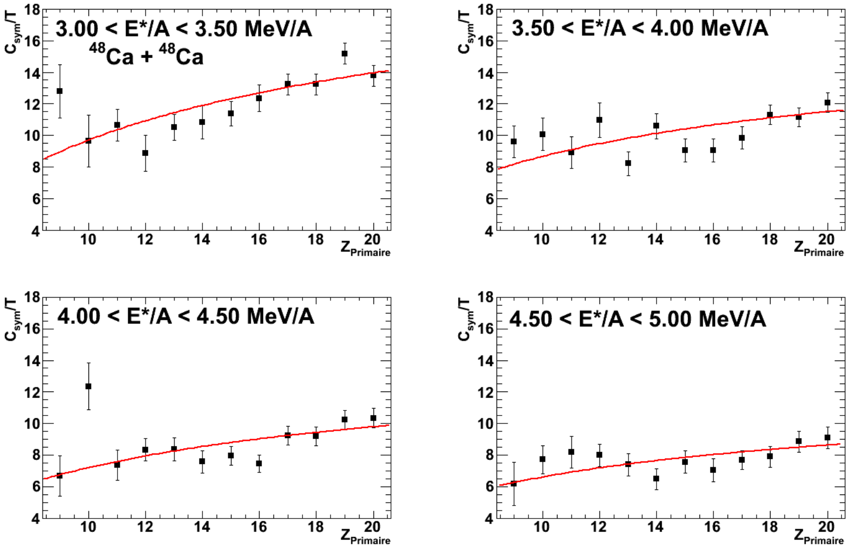
E*/A (MeV/A)	Gogny	Gogny-AS
3.00 - 3.50	**3.54**	4.36
3.50 - 4.00	**2.25**	3.16
4.00 - 4.50	**2.17**	2.68
4.50 - 5.00	**1.16**	2.07

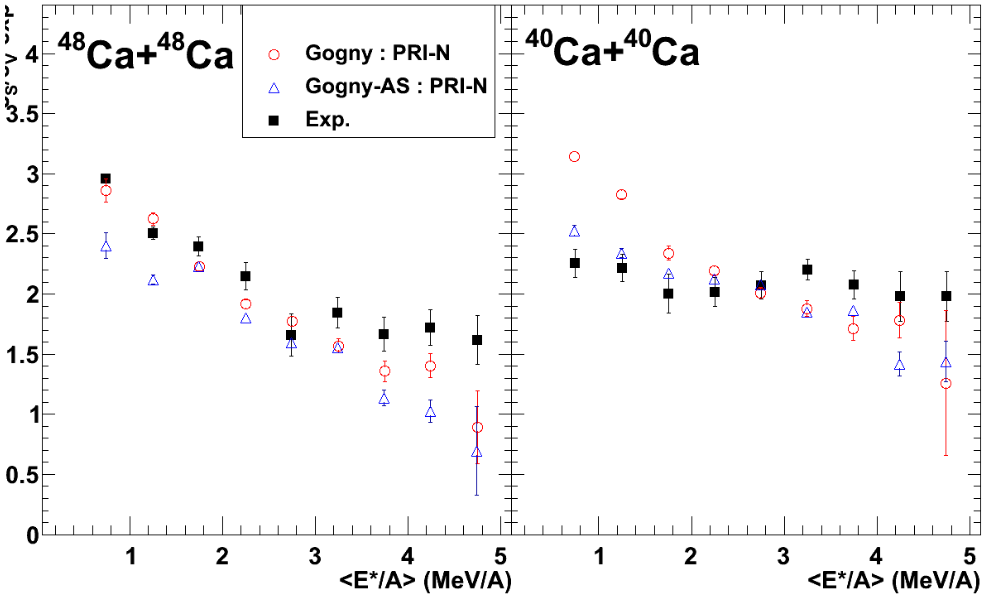
Temperature obtained from slope of p-spectra 4-6 MeV
Values of Csym around 30 MeV
Consistent with the values of saturation density
The method is validated and should be applied to more dissipative collisions

Surface to volume contribution

Fit with $c(A) = c_V + c_S A^{-1/3}$

$$C_{sym} / T \approx 1 - \frac{C_s}{C_v}(2Z)^{-1/3}$$

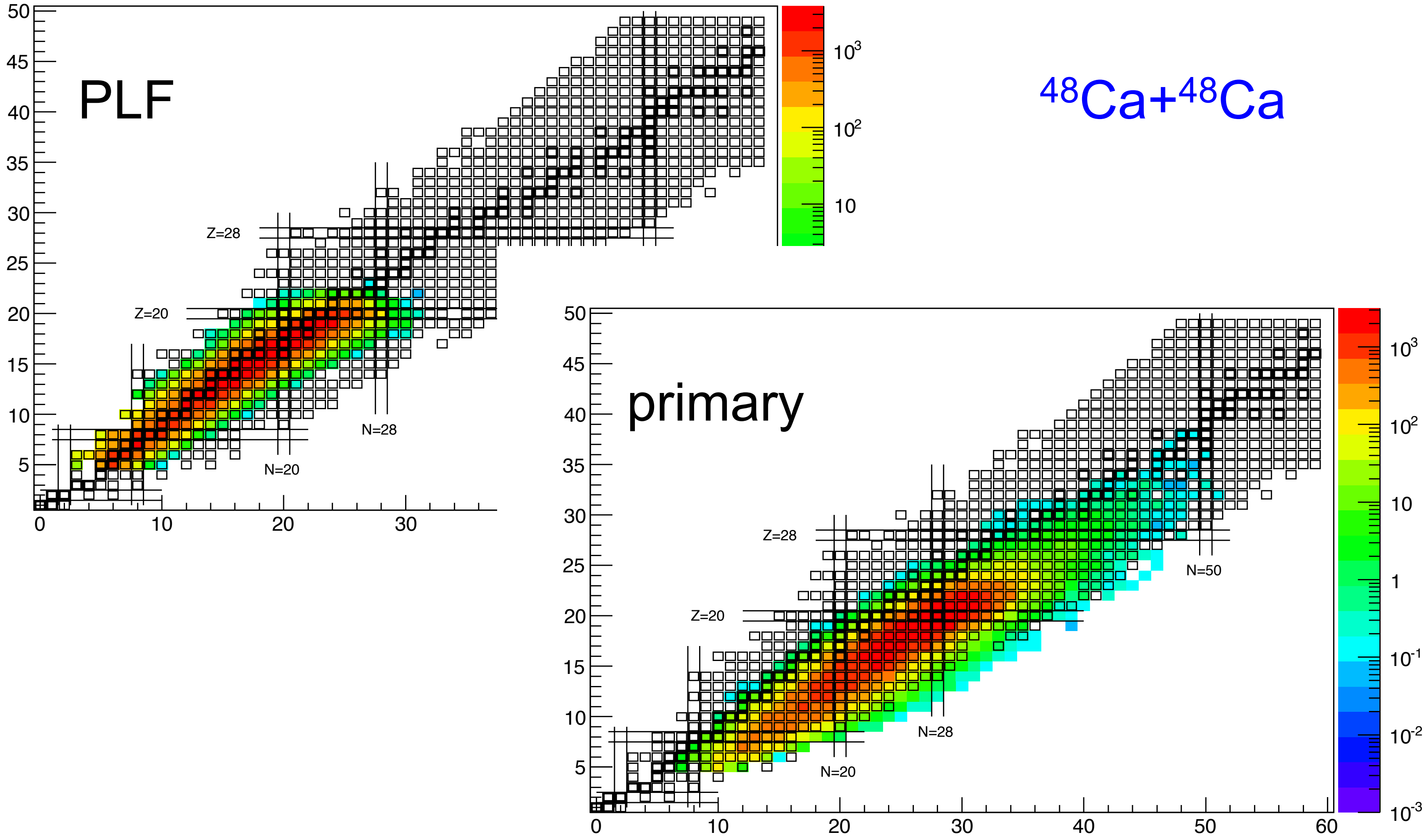




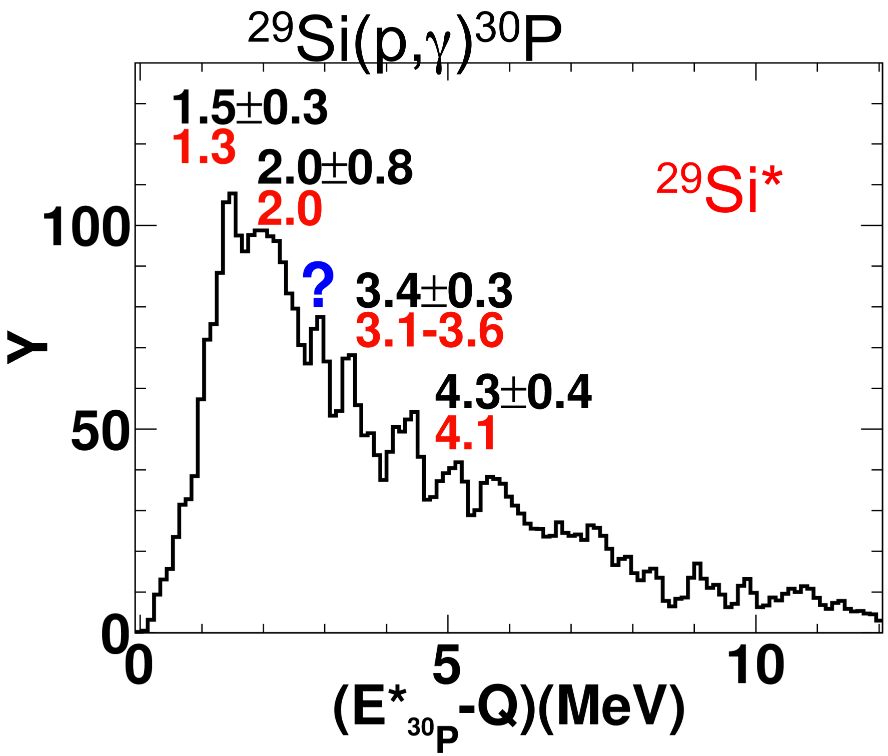
Surface effect is important
No big difference between the two interactions

Production of exotic nuclei

beyond the drip lines



Spectroscopy of ^{29}Si



^{32}P->p+$^{31}Si^*$

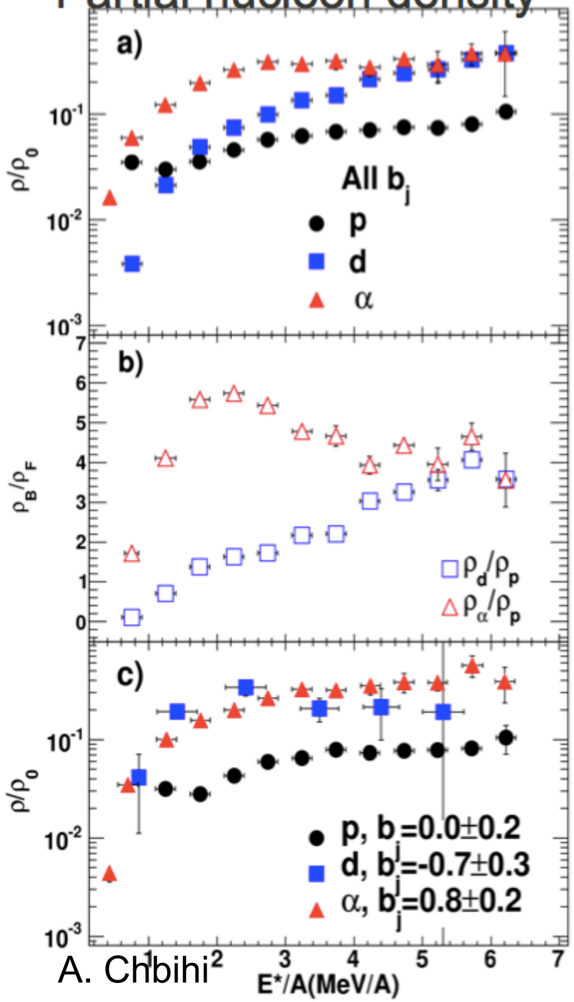
->n+ $^{30}Si^*$

->$^{29}Si^*$+n

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

Signals of boson condensation and fermion quenching

Partial nucleon density



- VAMOS to select QP + INDRA to reconstruct its identity and E*
- Study of fluctuations of multiplicity and quadrupole momentum accounting for the QUANTAL nature of the probe particle (A. Bonasera et al)
- Determine Excitation energy, density, temperature event-by-event

Signals of boson condensation and fermion quenching in the dilute phase?

(P. Marini et al., in preparation)

Summary and Conclusions

- Exploration of $E_{sym}(\rho)$ with HI-Collisions ($^{48,40}Ca+^{48,40}Ca$)
- Observables : isotopic distribution & isoscaling
- Accessing the symmetry energy
  - Take into account the secondary effects
  - Primary experimental isotopic distributions
    - Zprimay distributions were reconstructed experimentally
    - Aprimary – neutrons distributions reconstructed exp. but need to take into account the effect of neutron emission on the Apr – 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
- Esym was extracted for peripheral collisions, the values obtained are consistent with the value at normal density :
- work is in progress for central collisions

A. Chbihi, G. Verde, E. Bonnet, J.D. Frankland, M. Boisjoli, P. Marini, J. Moisan, B. Sorgunlu, F. Rejmund, M. Rejmund, J.P. Wieleczko,
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