Exploring the EOS at low densities.

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- Nuclear equation of state
- Tool to probe density dependence of $E_{sym}(\rho)$
- Observable
  - Isospin diffusion
  - Isospin migration/Drift
  - width of isotopic distribution of fragments
- New measurements
- Conclusion

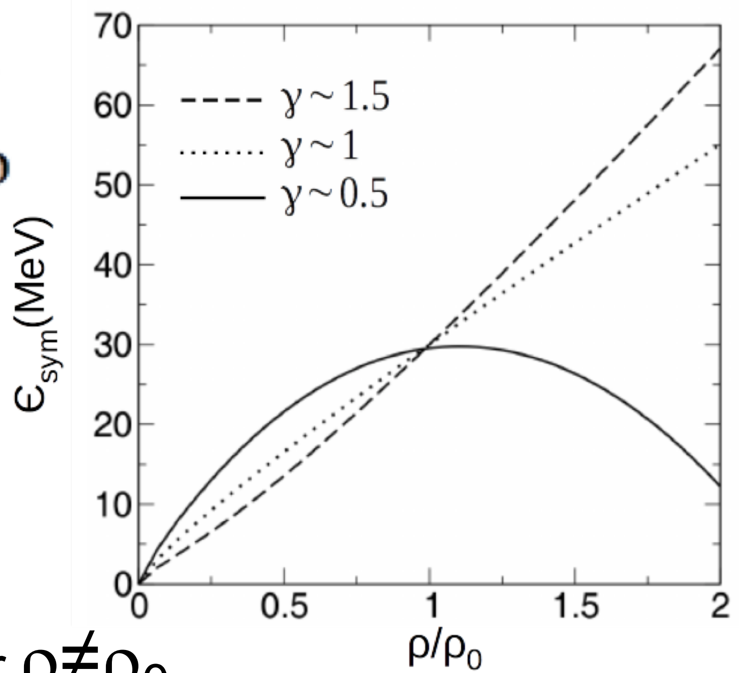
Nuclear equation of state

$$\epsilon(\rho,\delta)=\epsilon(\rho,\delta=0)+\epsilon_{sym}(\rho).\delta^2+\ldots$$

$$\delta=(\rho_n-\rho_p)/\rho$$

parametrization

$$\epsilon_{sym}(\rho)=\frac{C_{kin}}{2}\left(\frac{\rho}{\rho_0}\right)^{2/3}+\frac{C_{pot}}{2}\left(\frac{\rho}{\rho_0}\right)^{\gamma}$$



- The asymmetric term ε_{sym} is unknown for $\rho \neq \rho_0$
- Relevant to describe :
  - structure of exotic nuclei and the neutron skin
  - GDR, pygmy dipole
  - Dynamics of heavy-ion collisions
- relevant to the properties of astrophysical phenomena
  - mechanism of supernova explosion
  - cooling and composition of neutron star

[1] Bao-An Li et al., Phys. Rep. 464
[2] M. Colonna et al., EPJA50:30

[3] G. Martinez-Pinedo et al., Jour. Phys. G 41:044008
[4] T. Fischer EPJA50:46
[5] Ad. R. Raduta et. al, EPJA50:24

Tools to probe the EOS

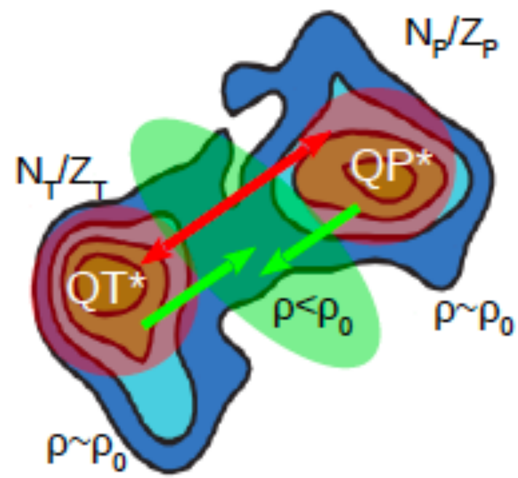
- **HIC at intermediate energies with asymmetric nuclei provide a unique opportunity:**
  - production of exotic nuclei with a wide isospin range
  - exploration of nuclear matter under extreme conditions of ρ, P, T and J
  - offer a unique terrestrial tool to produce nuclear matter in a large range of densities
  - explore the density dependence of the symmetry energy
  - At intermediate energies only low densities are explored
- **However, HIC is a complicated process (dynamics, evaporation...)**
- **Observables Esym**(ρ) :
  - Isospin diffusion
  - Isospin drift/Migration
  - Width of isotopic distribution of fragments produced in HIC

Isospin Transport

$$\delta = \frac{N-Z}{N+Z}$$

$$j_n - j_p = \left(D_n^{\rho} - D_p^{\rho}\right)\nabla\rho - \left(D_n^{\delta} - D_p^{\delta}\right)\nabla\delta$$

$$\propto \frac{\partial E_{sym}}{\partial \rho} \qquad \propto E_{sym}$$



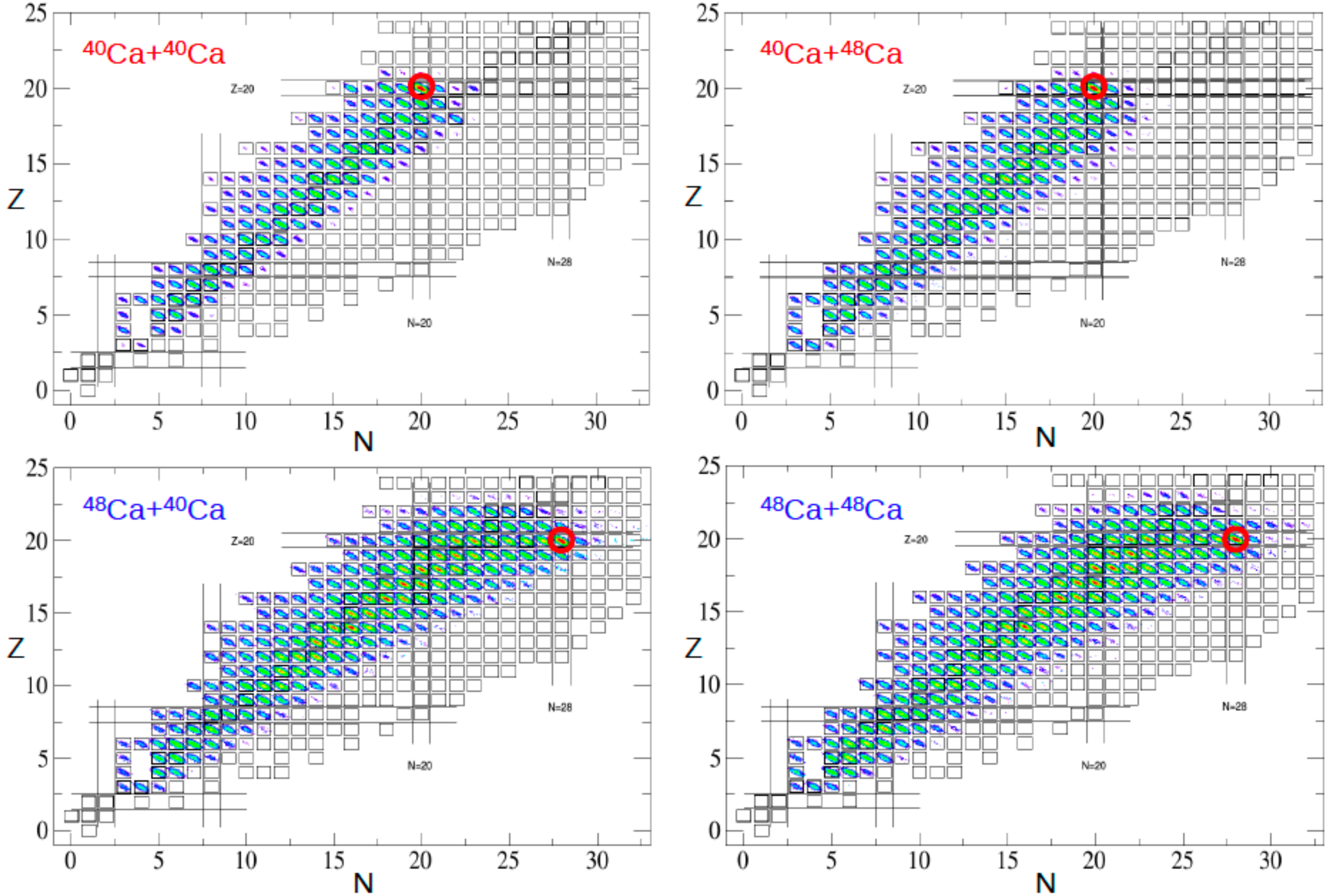
- the difference of the neutron and proton current between the 2 colliding nuclei
- density gradient: referred as drift or migration of the isospin
- isospin gradient: diffusion
- drift and diffusion depend on the interaction time :
  - Long == equilibration
  - Short == partial transparency

Experiments to probe $E_{sym}(\rho)$

- ♦ $^{40}Ca+^{40}Ca$ N/Z = 1 @ E/A=35 MeV
- ♦ $^{40}Ca+^{48}Ca$ N/Z=1.2 diffusion
- ♦ $^{48}Ca+^{40}Ca$ N/Z=1.2 diffusion
- ♦ $^{48}Ca+^{48}Ca$ N/Z=1.4

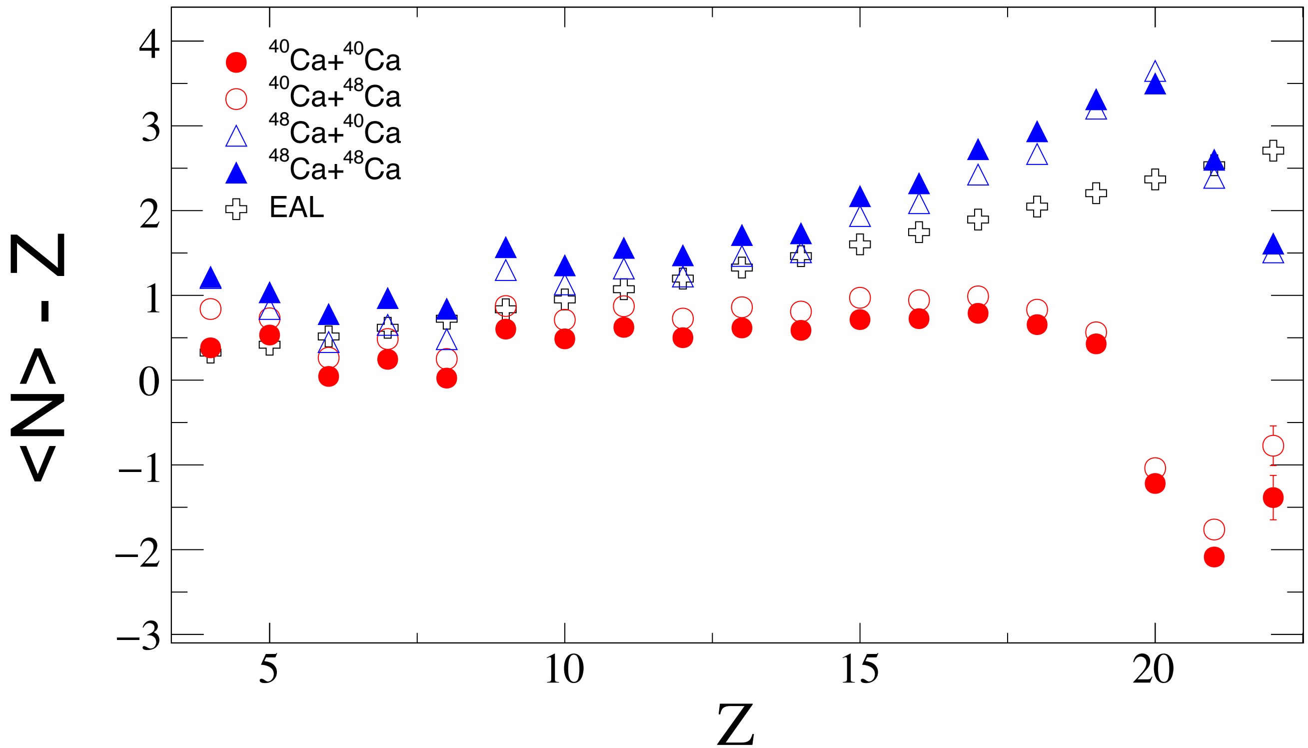
- ♦ **VAMOS high acceptance spectrometer, angle 2-7°**
  - ➢ charge and mass identification (more than 10 isotopes / Z)
  - ➢ 12 Brho sets measurements in order to cover the whole velocity range of fragments
  - ➢ special attention to the normalization between Brho based in Zgoubi package.
  - ➢ thanks to Q. Fable and P. St-Onge, did a lot effort to perform this normalization.
- ♦ **INDRA 4π detector, 7-176°**
  - ➢ Z identification for Z>4
  - ➢ Z and A identification for Z<5

Chart of Nuclides identified in VAMOS



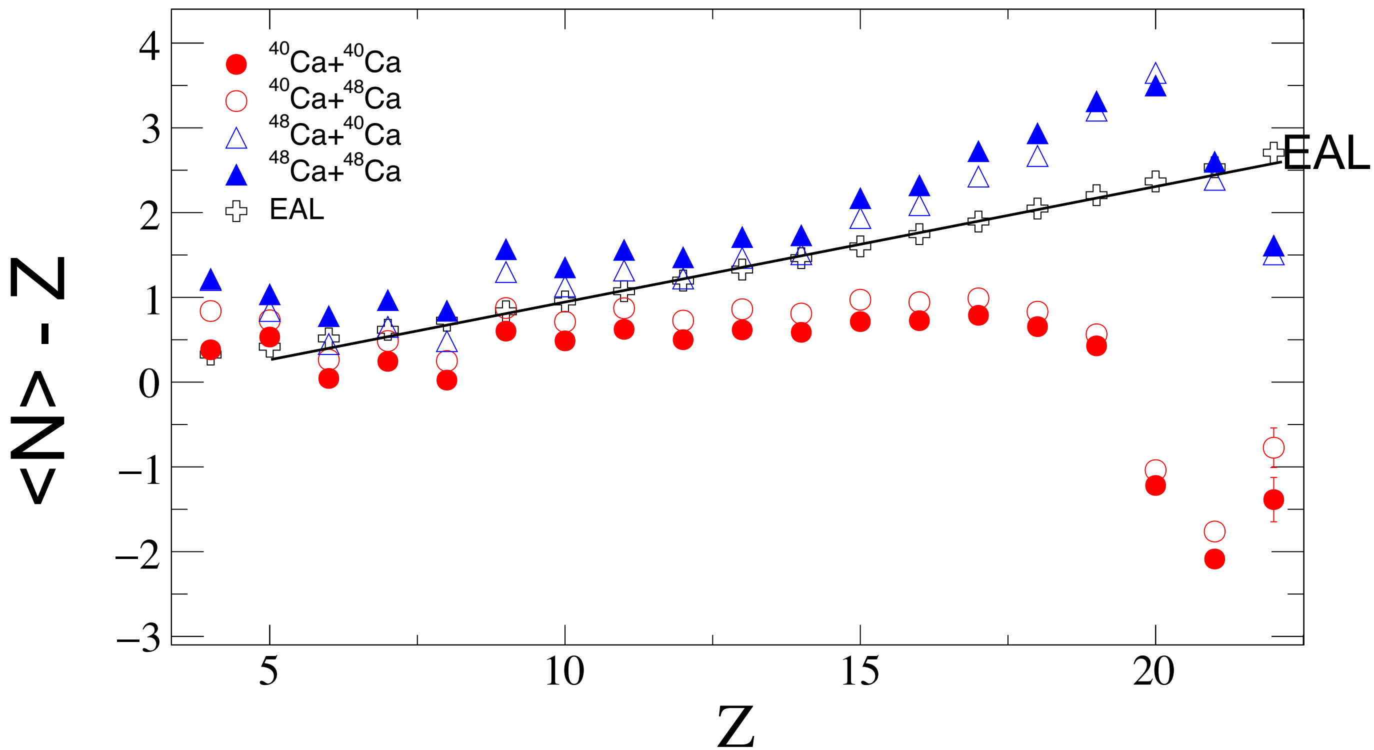
Identification in charge and mass for a wide range of isotopes for Z=5-22
Proton drip line is populated

Average neutron excess vs Z_{vamos}



- The fragments measured for the 48Ca projectile are more n-rich than those for the 40Ca projectile for all Z's.
- small effect of the target is observed (open symbols)

Average neutron excess vs Z_{vamos}

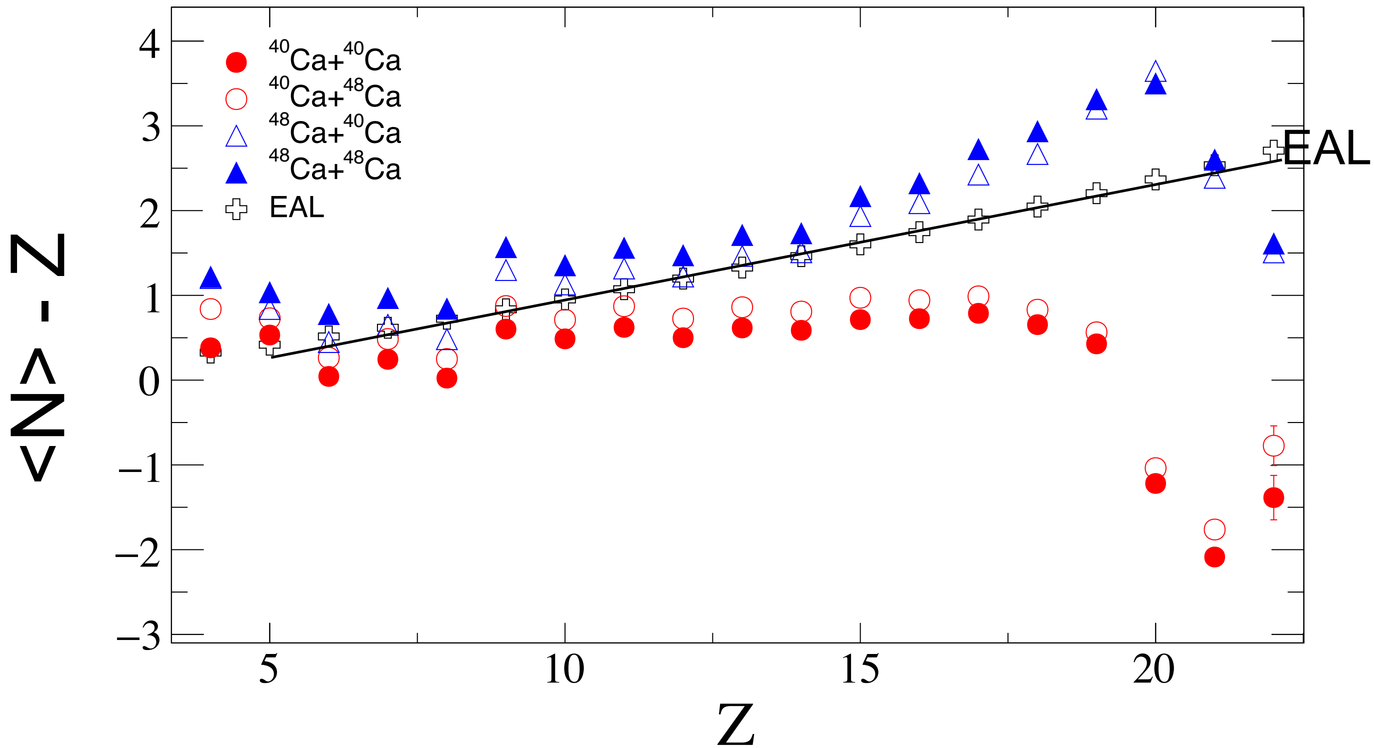


- EAL defined as the line in N. Chart towards which an ER of excited source moves as it cools.
- For Z = 20
  - For 48Ca projectile we observe <N>-Z = 3.5;
  - For 40Ca projectile we observe <N>-Z = -2
- In both cases we reach the EAL

R. J. Charity, Phys. Rev. C 58, 1073 (1998)

- This is the first direct measurement of the EAL.

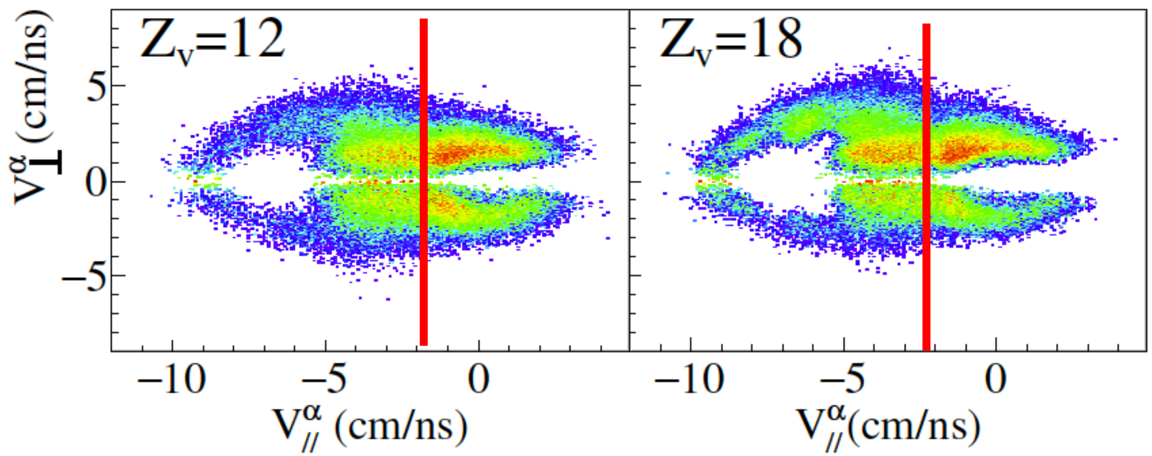
Average neutron excess vs Z_{vamos}



- reaching the EAL is the interplay between isospin diffusion and secondary decay
- How to disentangle the two contributions ?
- Using observables involving/based ratio of n-rich / n-poor systems, (isoscaling, imbalance ratio) to minimize the effect of secondary decay.
- reconstruction of primary quantities

Reconstruction of the primary Z_{pr} and A_{pr} distributions

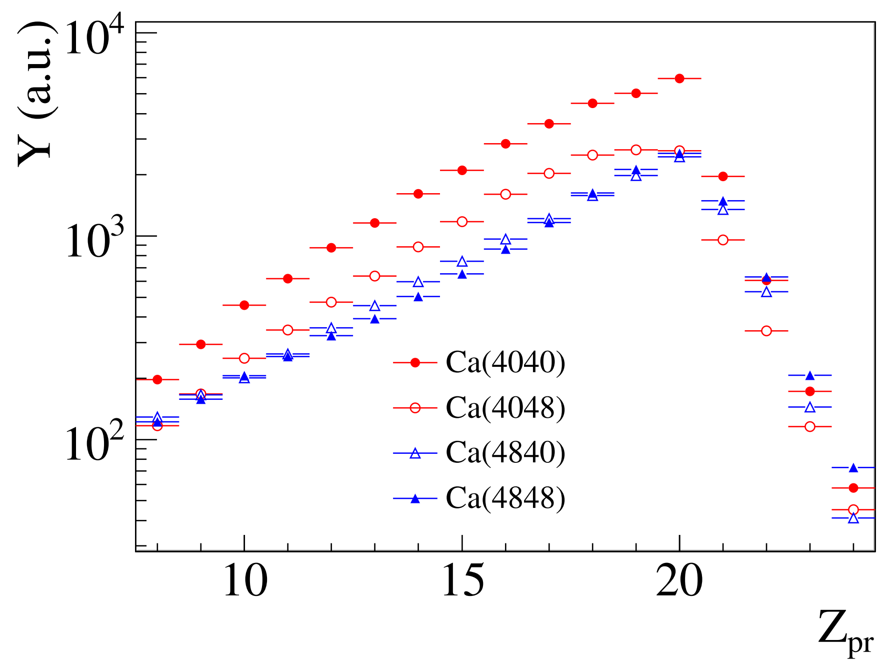
Why?
The observable can be distorted by the secondary decay of the primary isotopic distribution,
→affect the extracted E_{sym}



calorimetry:

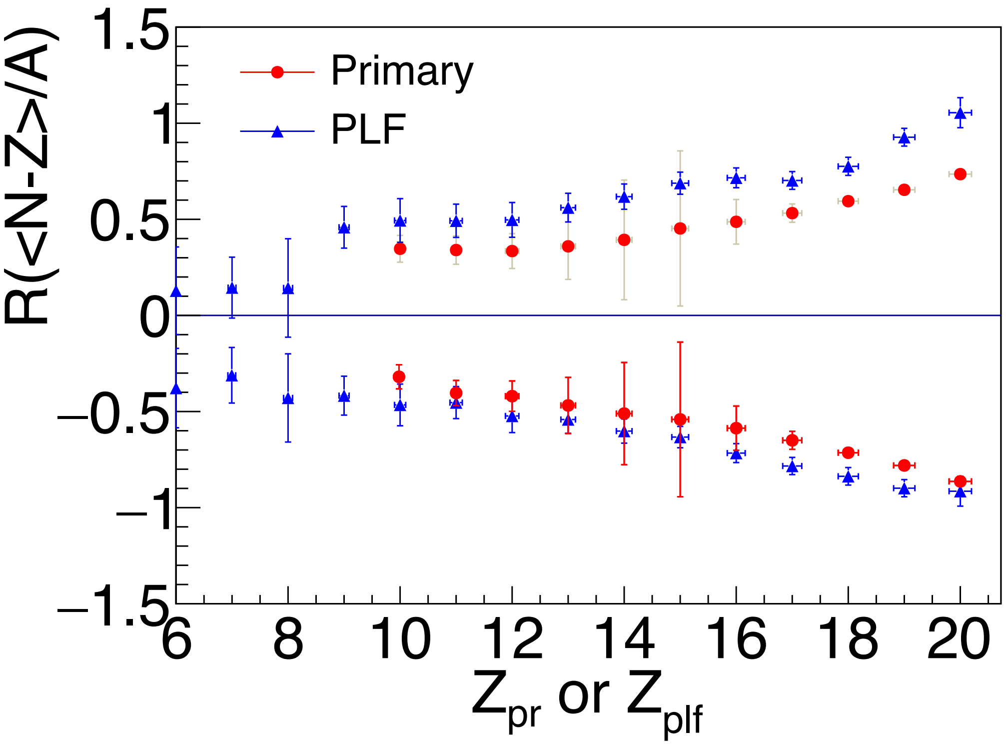
$$Z_{pr} = Z_{PLF} + \sum_{i=1}^{M_{LCP}} z_i \quad (9)$$

$$A_{prwon}(Z_{pr}) = A_{PLF}(Z_{pr}) + \sum_{i=1}^{M_{LCP}} a_i$$



E*

Imbalance ratio applied to the neutron excess



For a given neutron rich nuclei A and neutron poor B, A+A, B+B, A+B reactions

$$R_i(X) = 2\frac{X - (X_{A+A} + X_{B+B})/2}{X_{A+A} - X_{B+B}}.$$

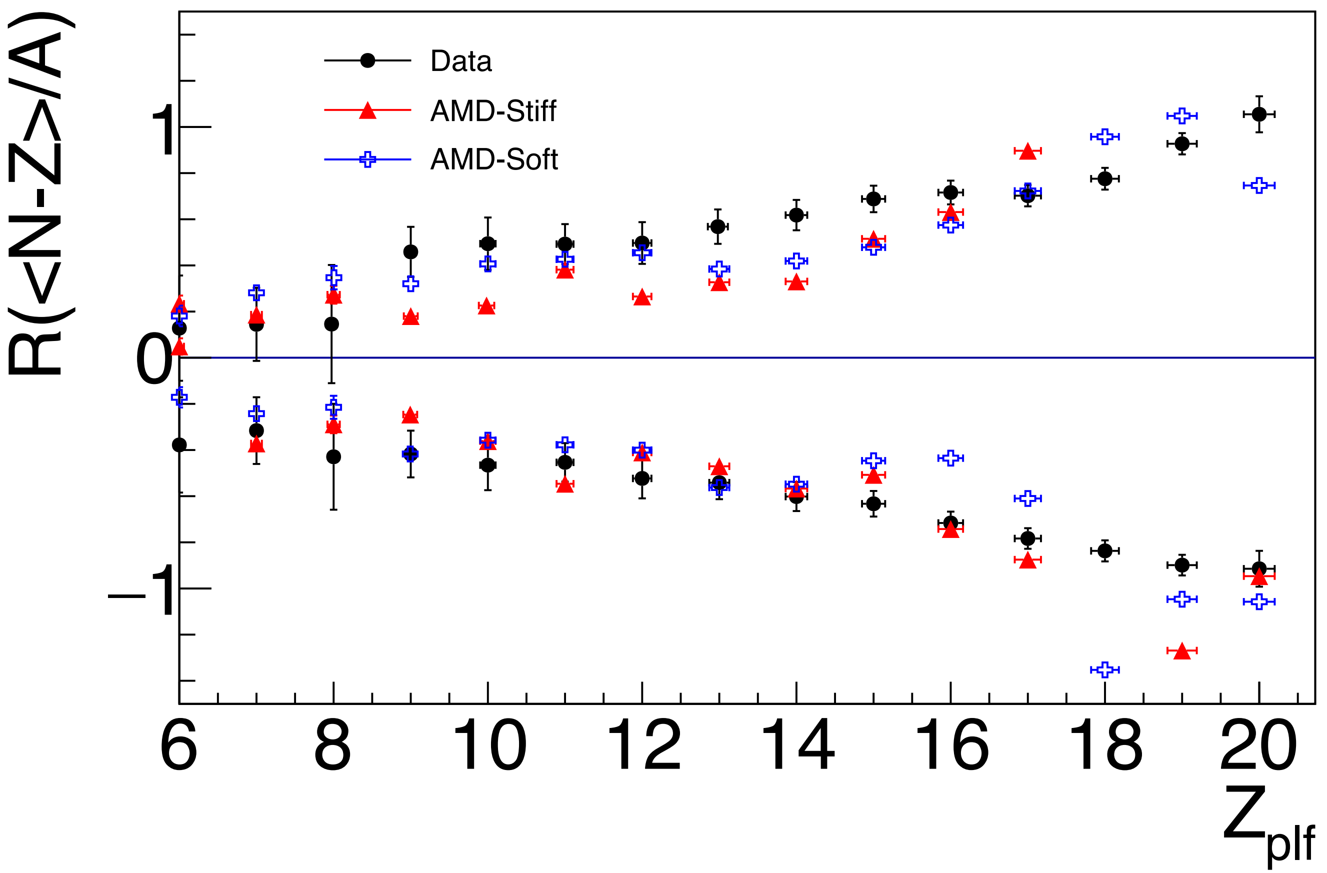
x sensitive to isospin = <N-Z>/A

R = 0, equilibration, diffusion

R = +/- 1, no equilibration, no diffusion

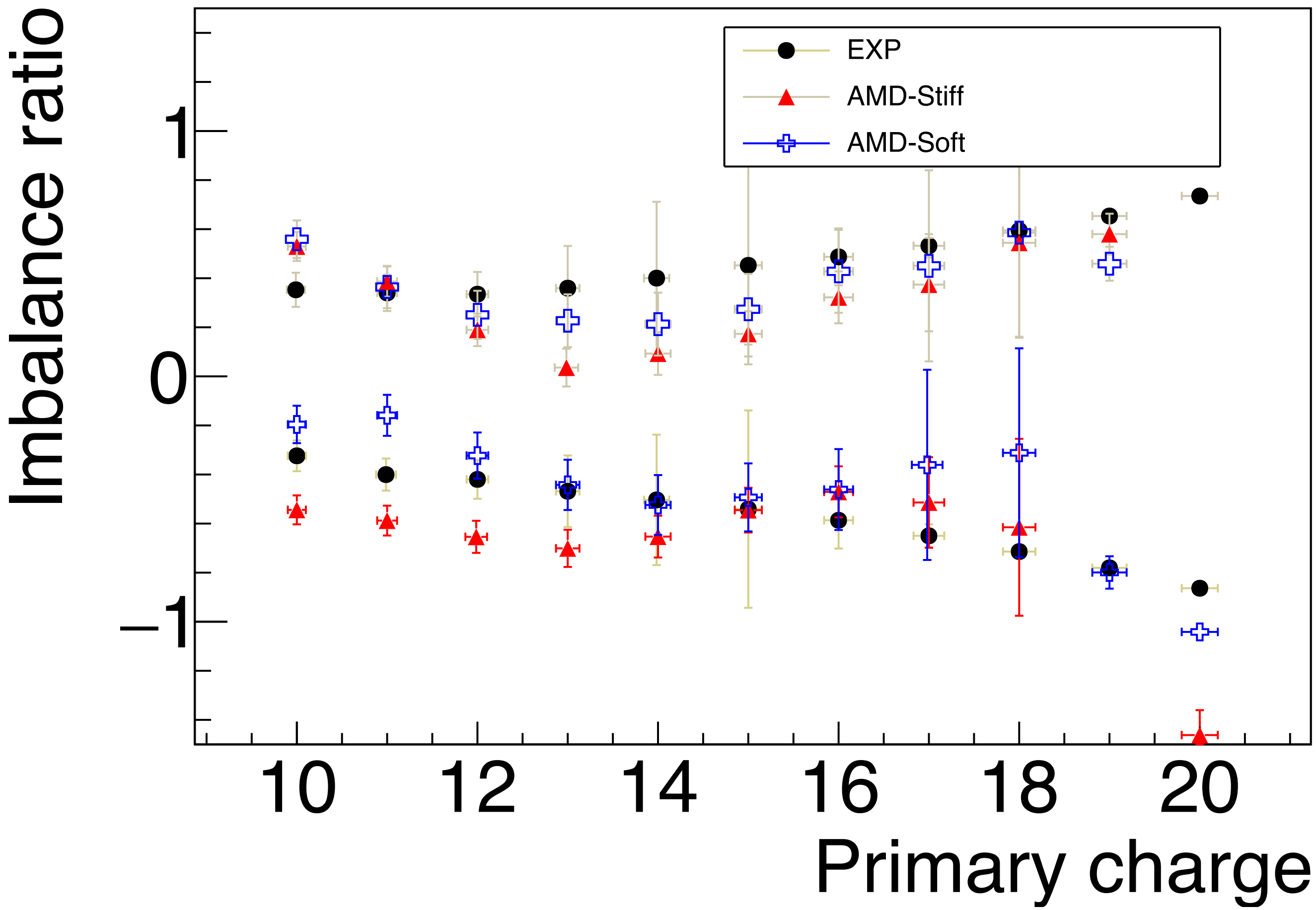
- complete equilibration is not reached
- differences between primary and secondary are observed

comparison to AMD (transport model)



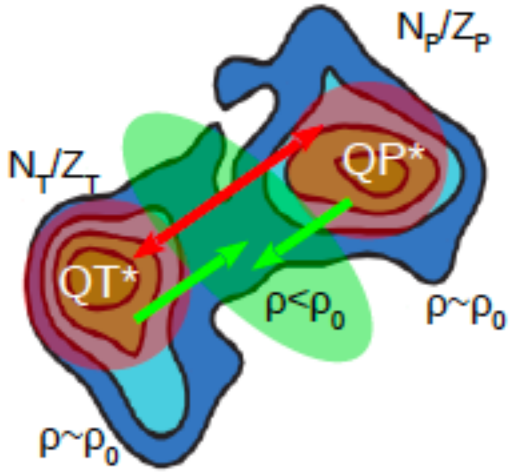
- AMD (antisymmerized molecular dynamics) : reproduction of data
- hard to distinguish between the two interactions.
- Comparison to the primary quantities might help to distinguish between the two interactions...

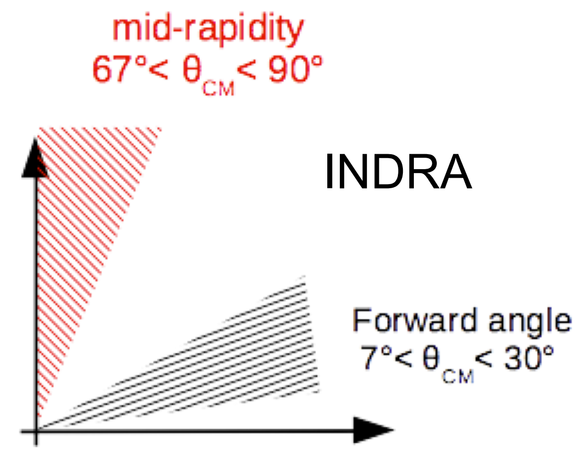
Imbalance ratio applied to primary fragments

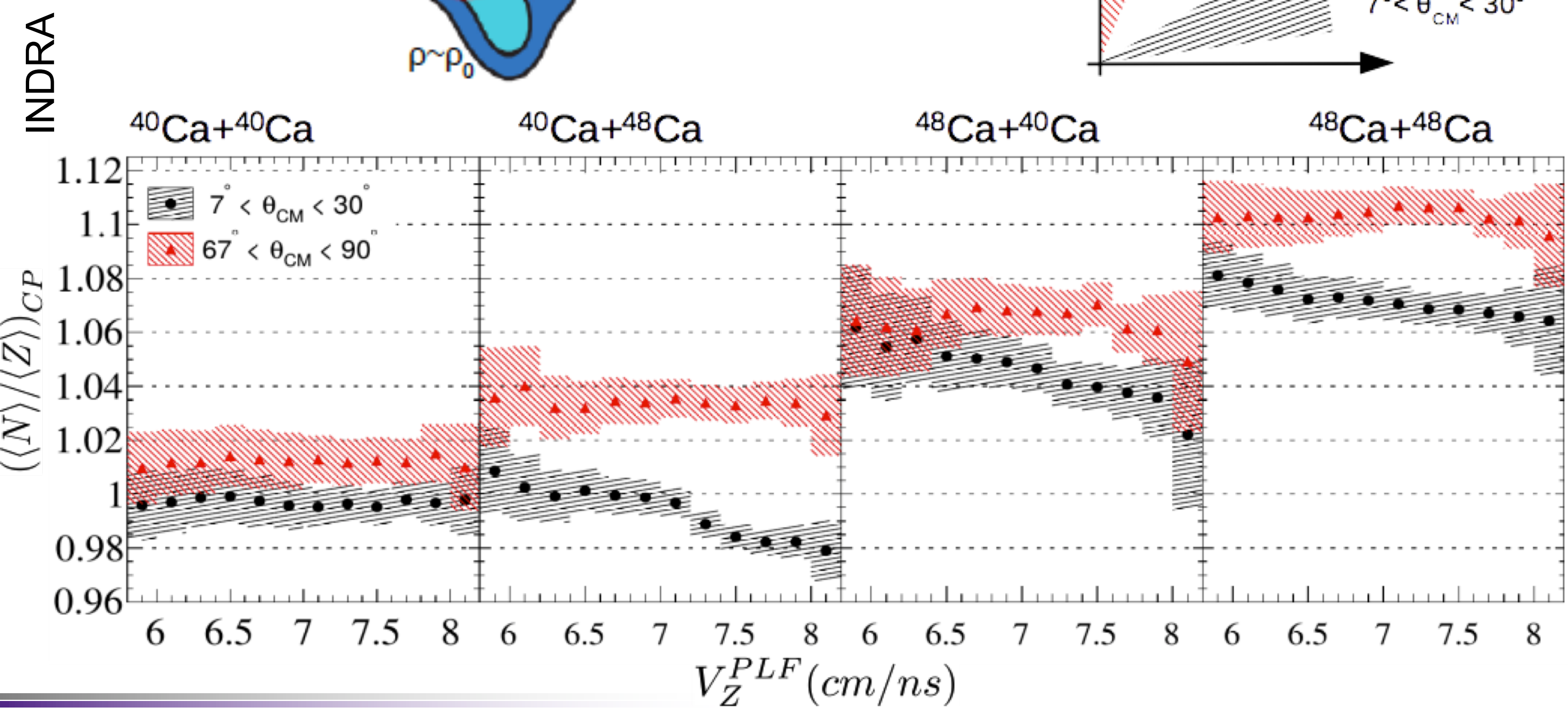


- better sensitivity to the primary fragments
- AMD-Soft (Gogny) reproduces the reconstructed primary fragments

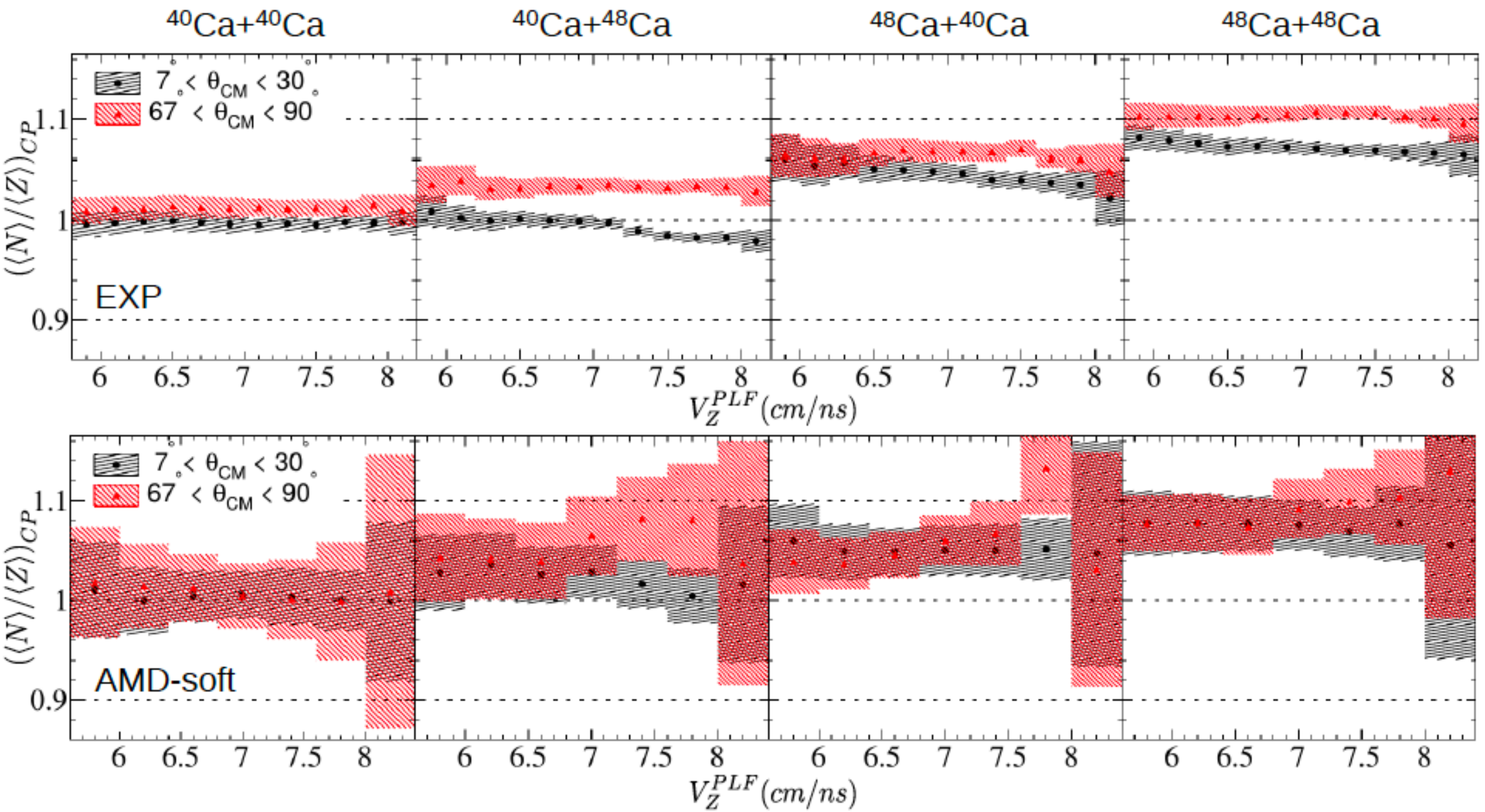
Isospin migration







Isospin migration comparison to AMD



- **AMD : not enough statistic to show differences of the $(N/Z)_{CP}$ of LCP emitted at mid-rapidity and at projectile zone.**

$E_{sym}(\rho)$ from the width of isotopic distribution of fragments

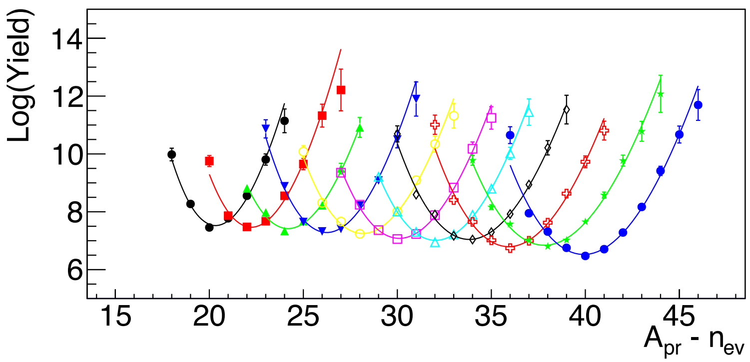
symmetry energy from the width of the primary isotopic distributions

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

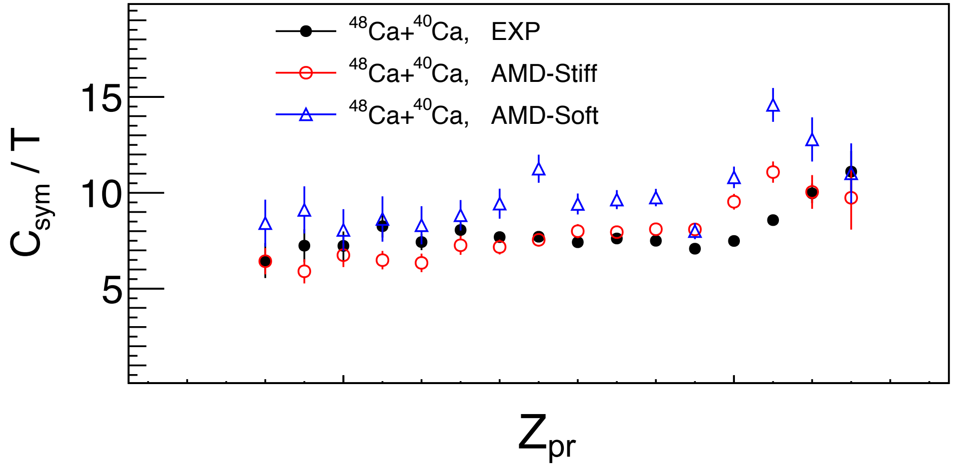
Assuming a grand-canonical ensemble
Isotopic distribution Y(N,Z) :

$$Y(N,Z) = F(N,Z,T).\exp\frac{B(N,Z)}{T}.\exp\frac{N\mu_n+Z\mu_p}{T}$$

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

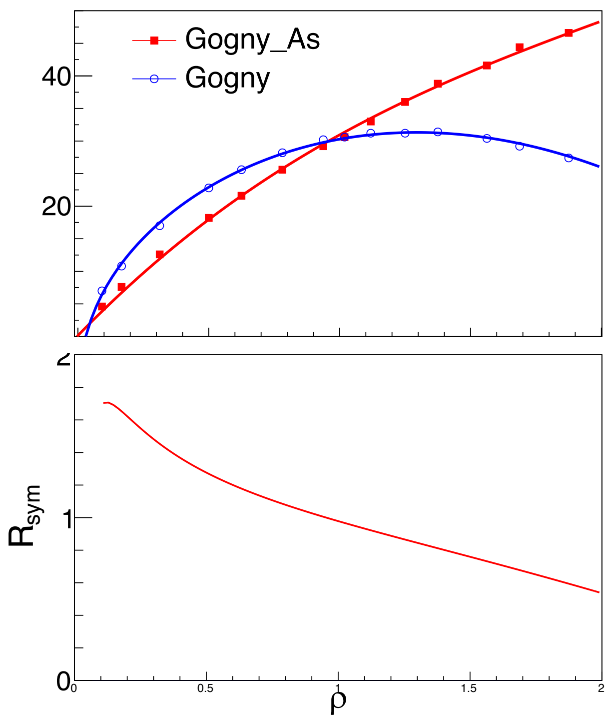


$$\zeta(Z) \propto 1/\sigma \propto C_{sym}(Z)/T$$

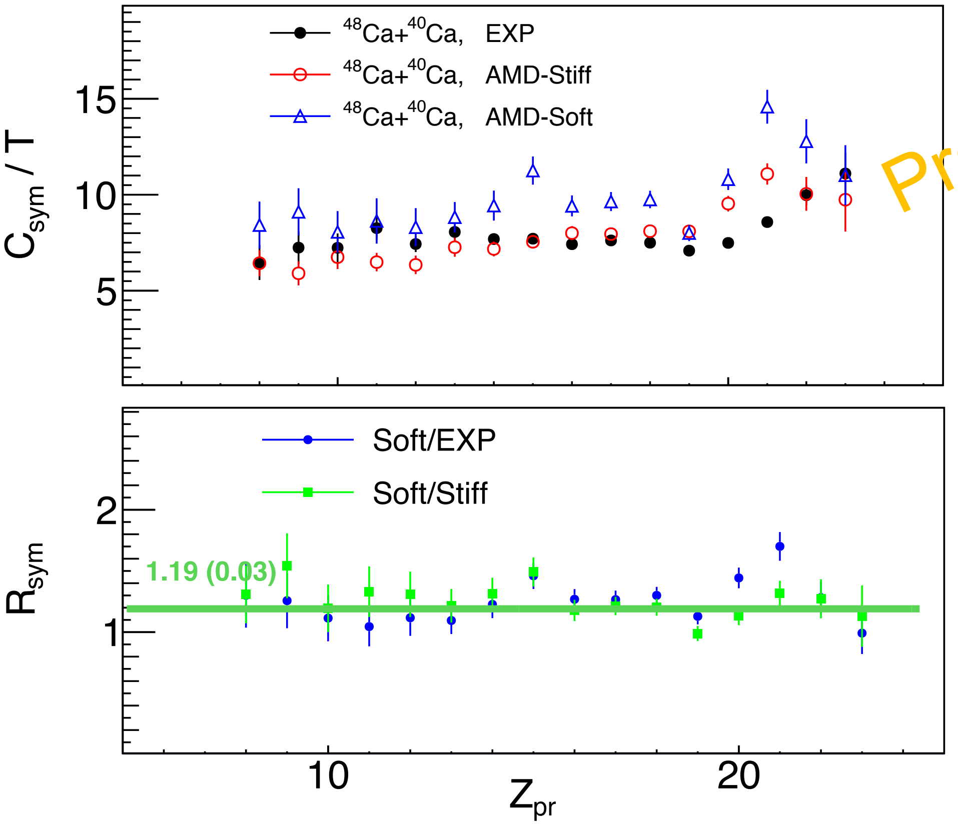


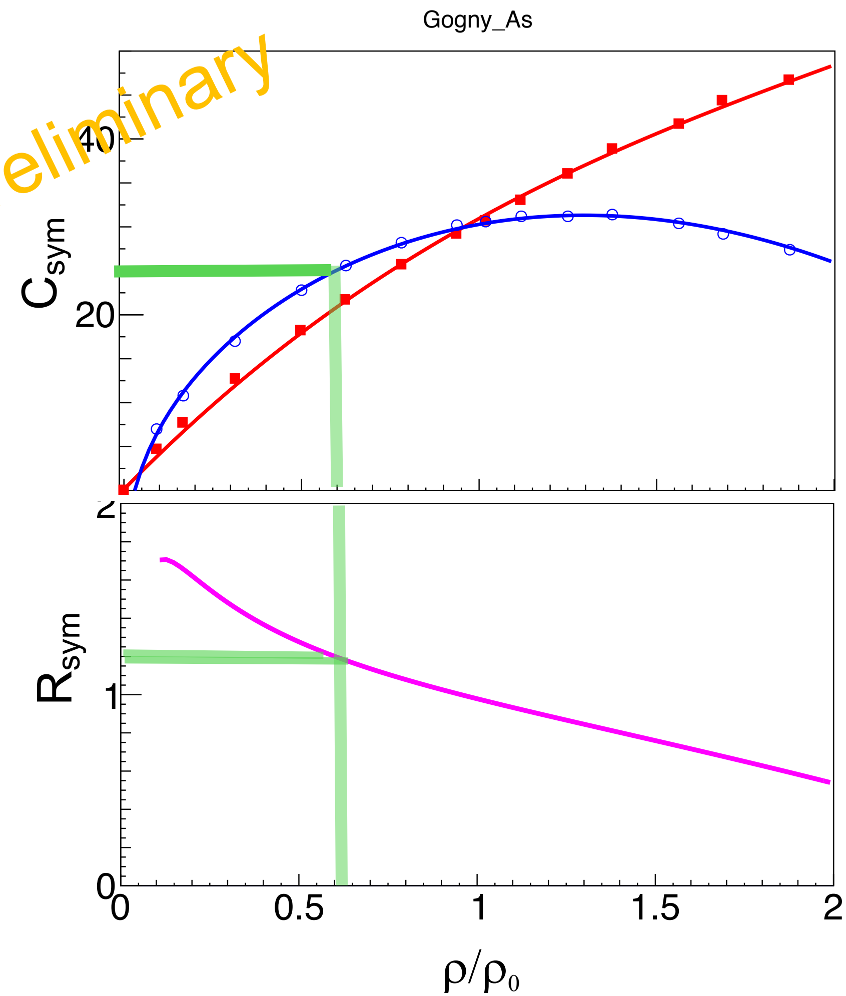
How to get rid of the temperature?

- ratio of AMD-Soft/Exp(Esym)
- ratio of AMD-Soft/Stiff (density)
- assuming the nucleon density is same for the two interaction
- one can extract the density of the excited system



determination of density, C_{sym} and Temperature

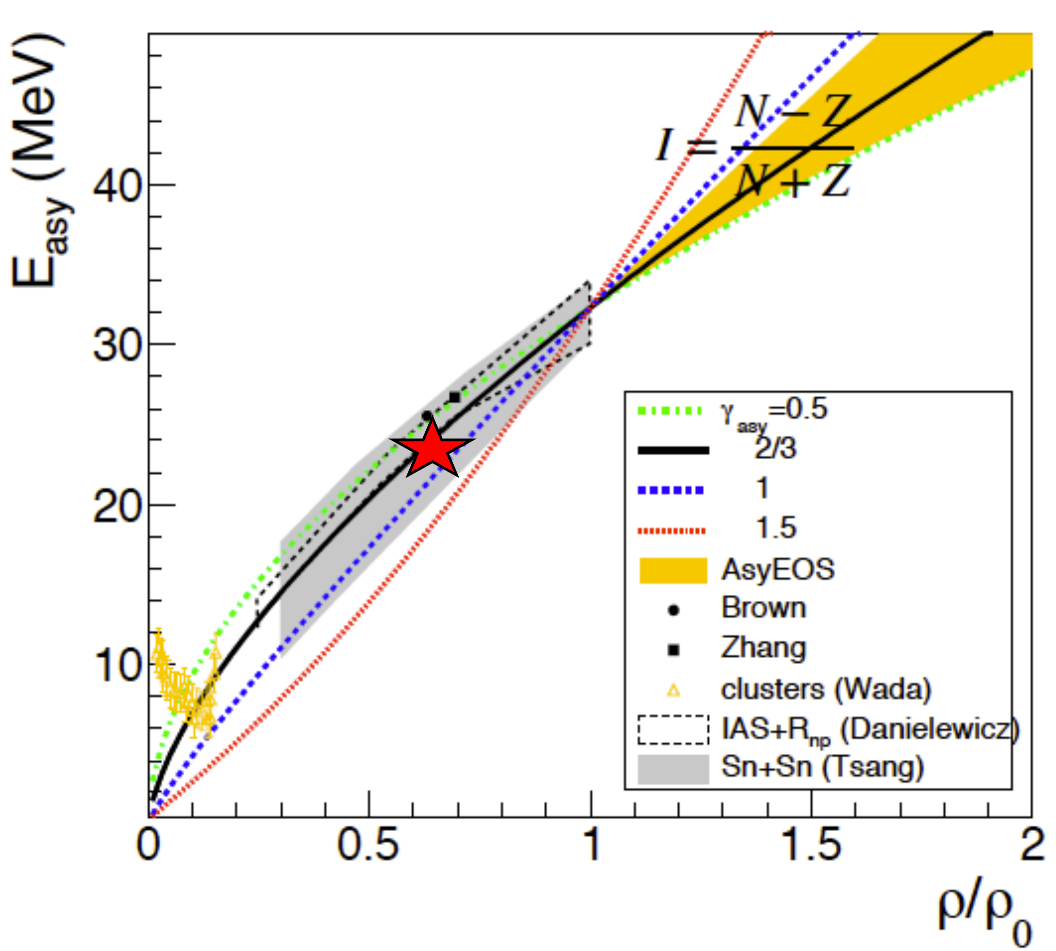




ρ/ρ_0 =0.65 (0.05),
C_{sym}= 24 (0.5) MeV;
T = 3.4 – 4.8 MeV

Lin et al., PhysRevC.89.021601_2014
Liu et al., PhysRevC.90.014605_2014

Constraining the density dependence of the symmetry energy

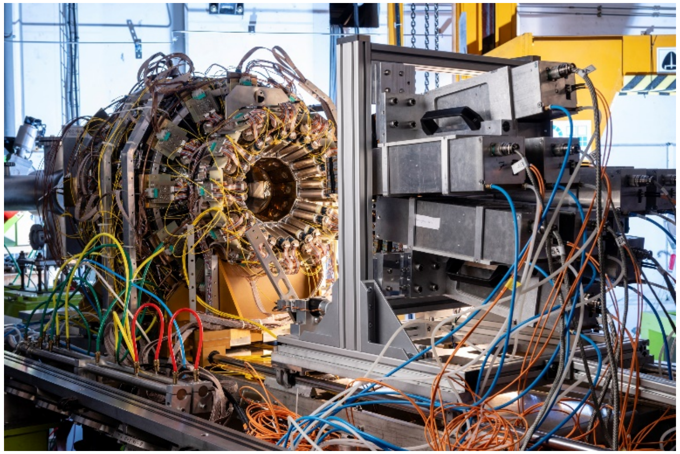


Several points are extracted for different E*

courtesy of A. Le Févre

2019 INDRA-FAZIA campaign

FAZIA was coupled for the first time with INDRA, replacing the forward part of this 4π multidetector for charged particles.

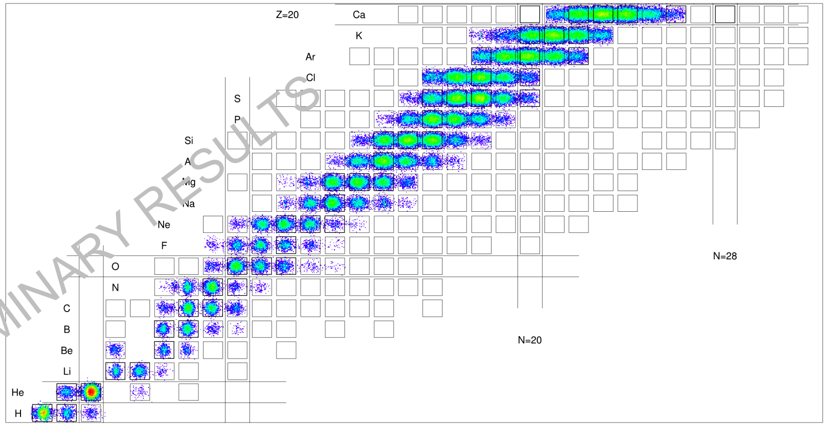


→ The combination of these detectors allowed for the first time a complete A and Z identification of multi-fragment reactions

→ ^{58,64}Ni + ^{58,64}Ni @ E/A = 32 & 50 MeV

→ better acceptance

→ Z and A (up to Z = 24)



Typical Z & A identification obtained with FAZIA during the experiment

Spokespersons: O. Lopez (LPC, France), S. Piantelli (INFN, Italy)

conclusion

- Imbalance ratios indicate no complete equilibration for secondary and primary fragments. However EOS soft-interaction reproduces the data.
- observation of isospin migration in coincidence with PLF size
- AMD reproduces the observed drift but no sensitivity to EOS soft and stiff interactions, work in progress
- Consistent way to deduce ρ, C_{sym} and T from the width of the primary isotopic distributions
- We have a set of data that for the first time measure different isospin sensitive observables in the same reaction.
- The set of data is open to comparison to all transport models engaged to link data to the symmetry energy.
- Q. Fable et al, PRC+PRL in preparation

Q. Fable, P. St-Onge, P. Marini, M. Boisjoli, S. Velardita, and INDRA coll