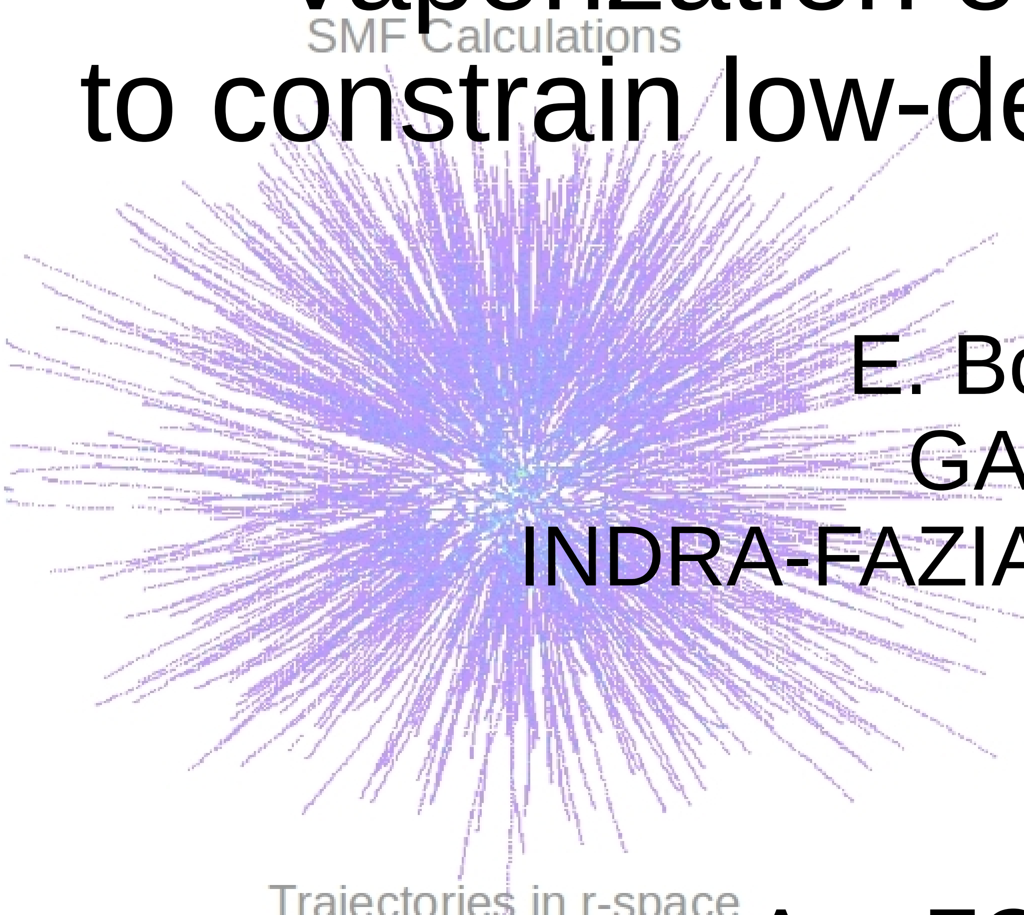
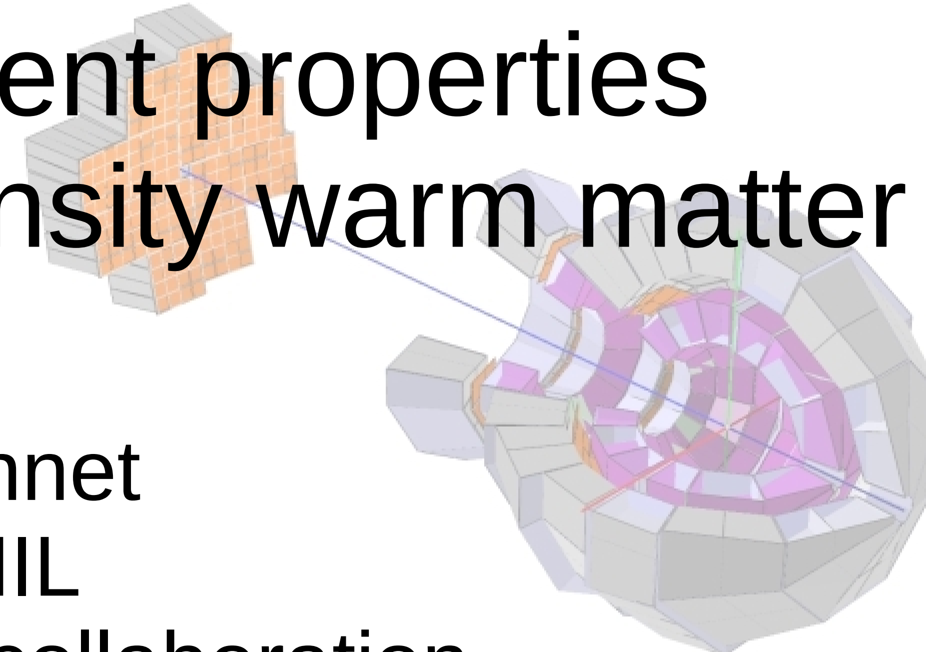
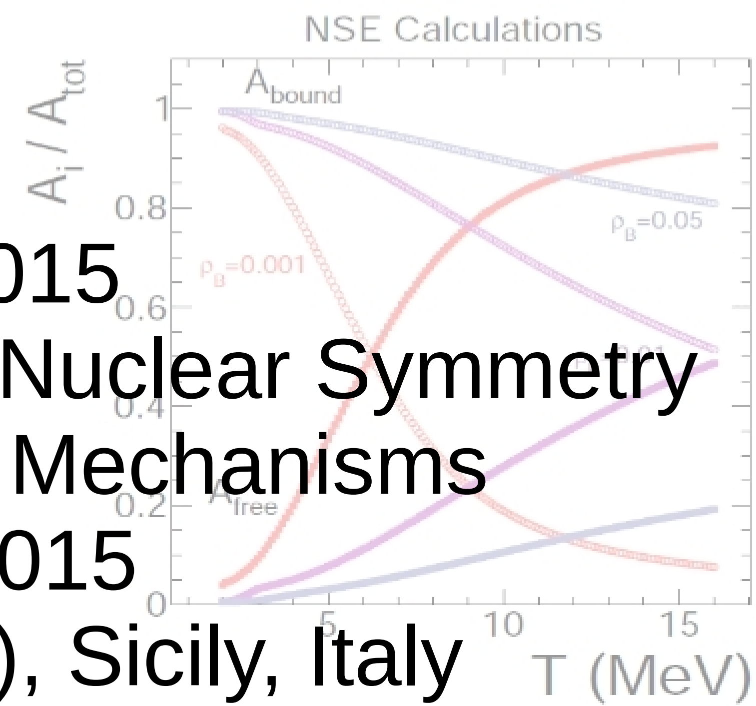
Vaporization event properties to constrain low-density warm matter





E. Bonnet
GANIL
INDRA-FAZIA collaboration



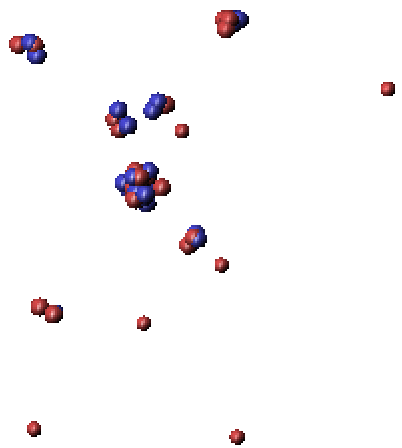
Asy-EOS 2015
International Workshop on Nuclear Symmetry Energy and Reaction Mechanisms
3-6 March 2015
Piazza Armerina (En), Sicily, Italy

BEGINING OF STATEMENT

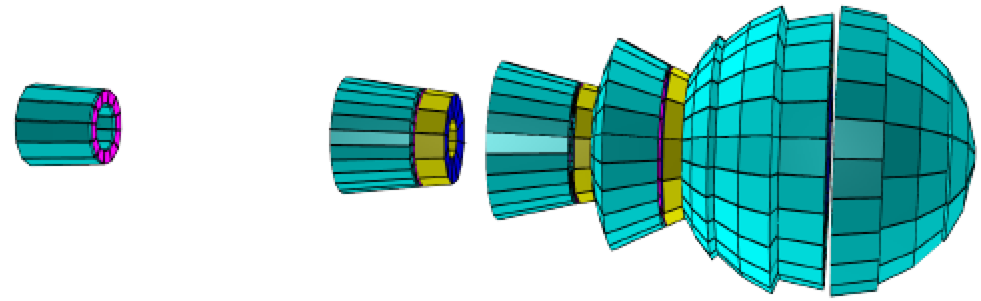
Results related to clusters production in HIC : practical point of view from experimental side and specially on the data analysis part …

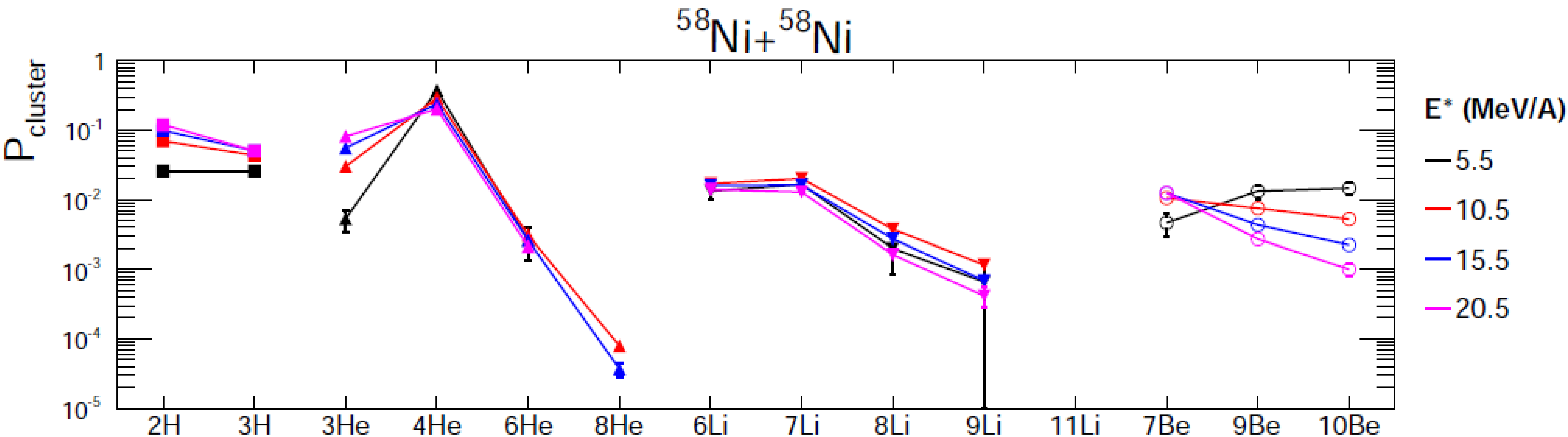
This statement is not only dedicated to clusters ...

Experimental event in p-space



INDRA 4π charged particles array





INDRA data - Cluster production in vaporization events

When you have experimental data and you want to bring constraints on theory, you can feel sometimes a little lost ...

Le grand BAZAR

When you have experimental data and you want to bring constraints on theory, you can feel sometimes a little lost ...

Le grand BAZAR

WHY ?

Le grand BAZAR

WHY ?

BECAUSE ...

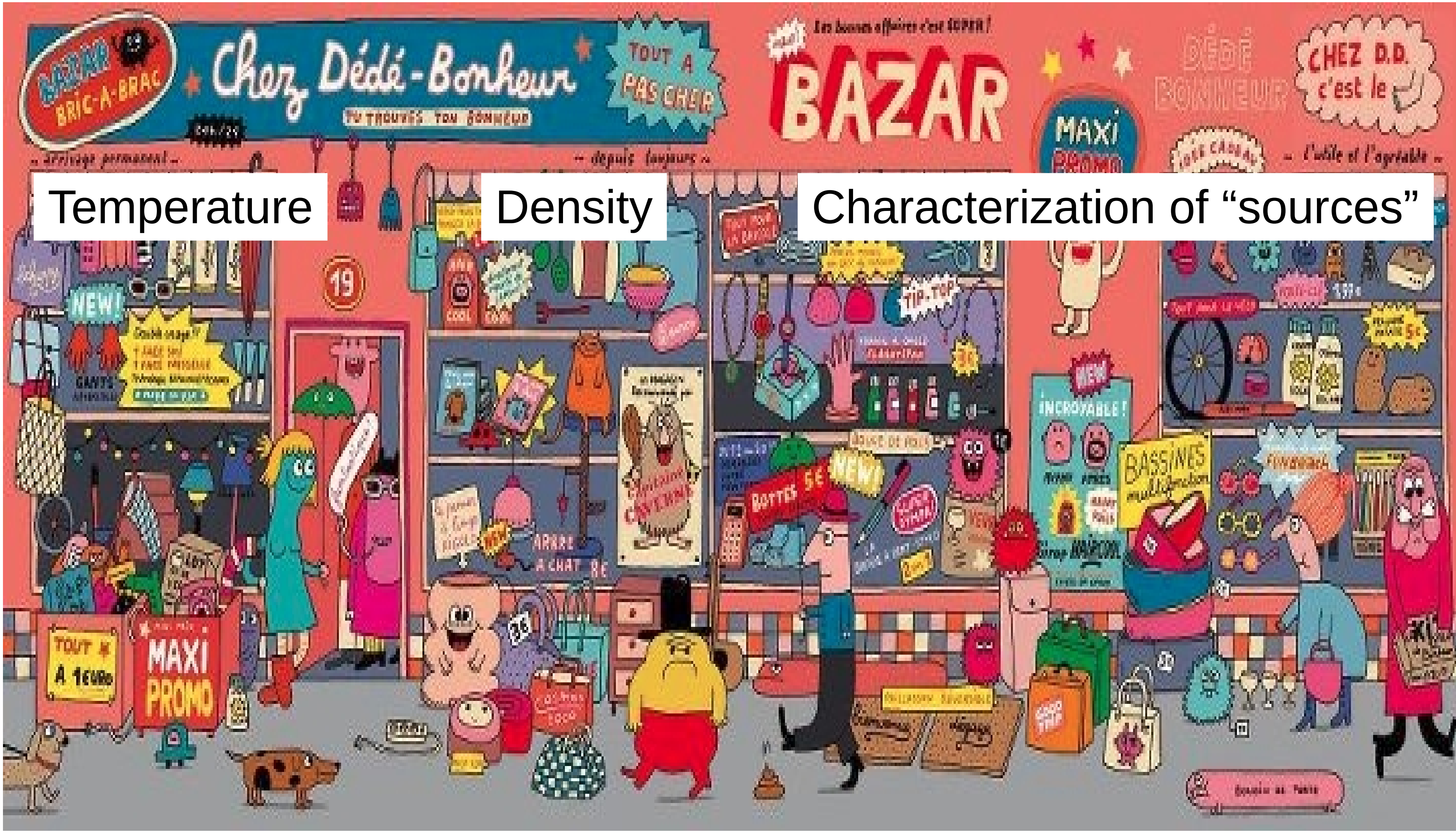
Le grand BAZAR

WHY ?

BECAUSE ...

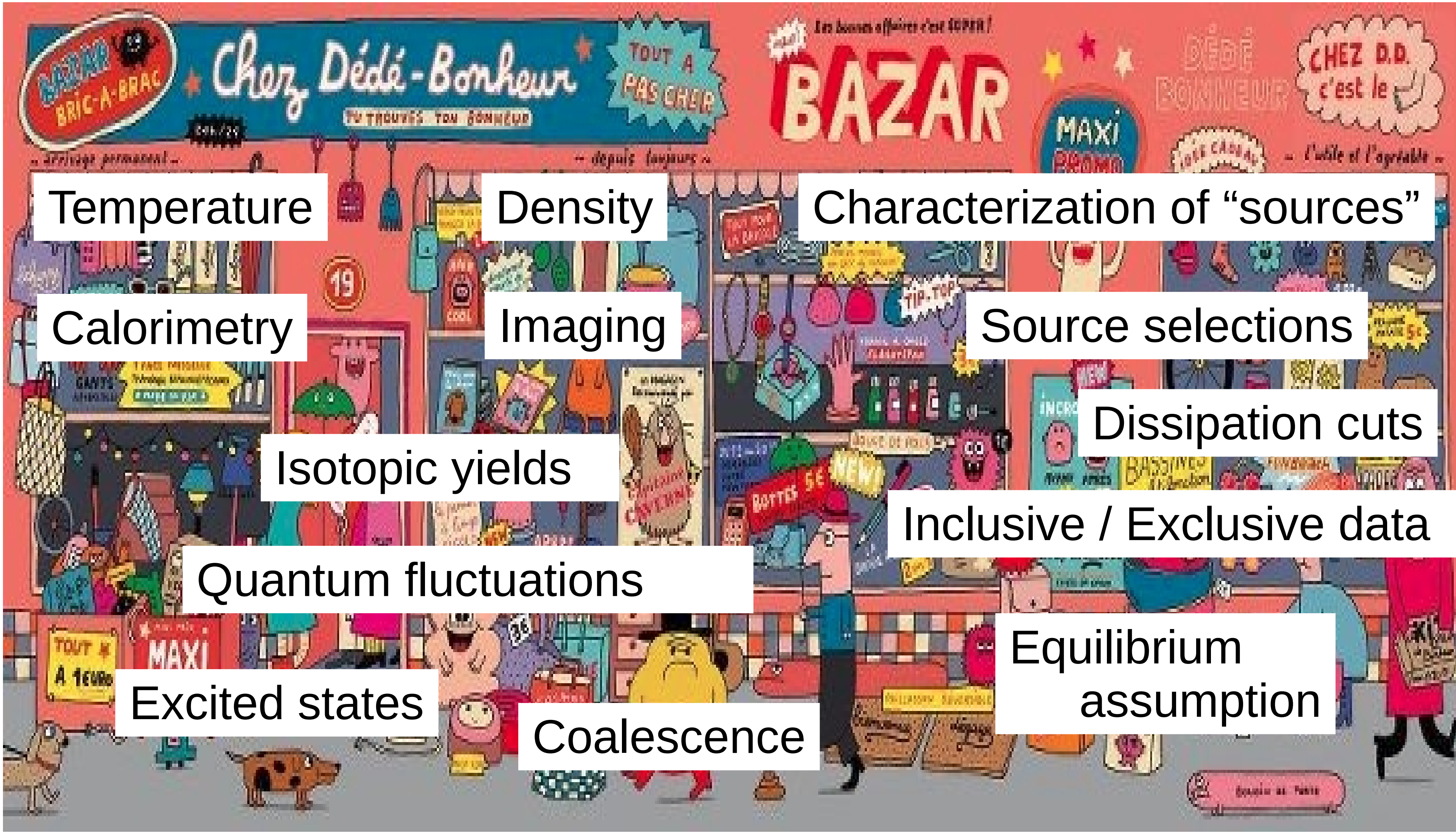
If you want your results to be useful to constrain EOS, you have to “localize” them in phase diagram

Le grand BAZAR



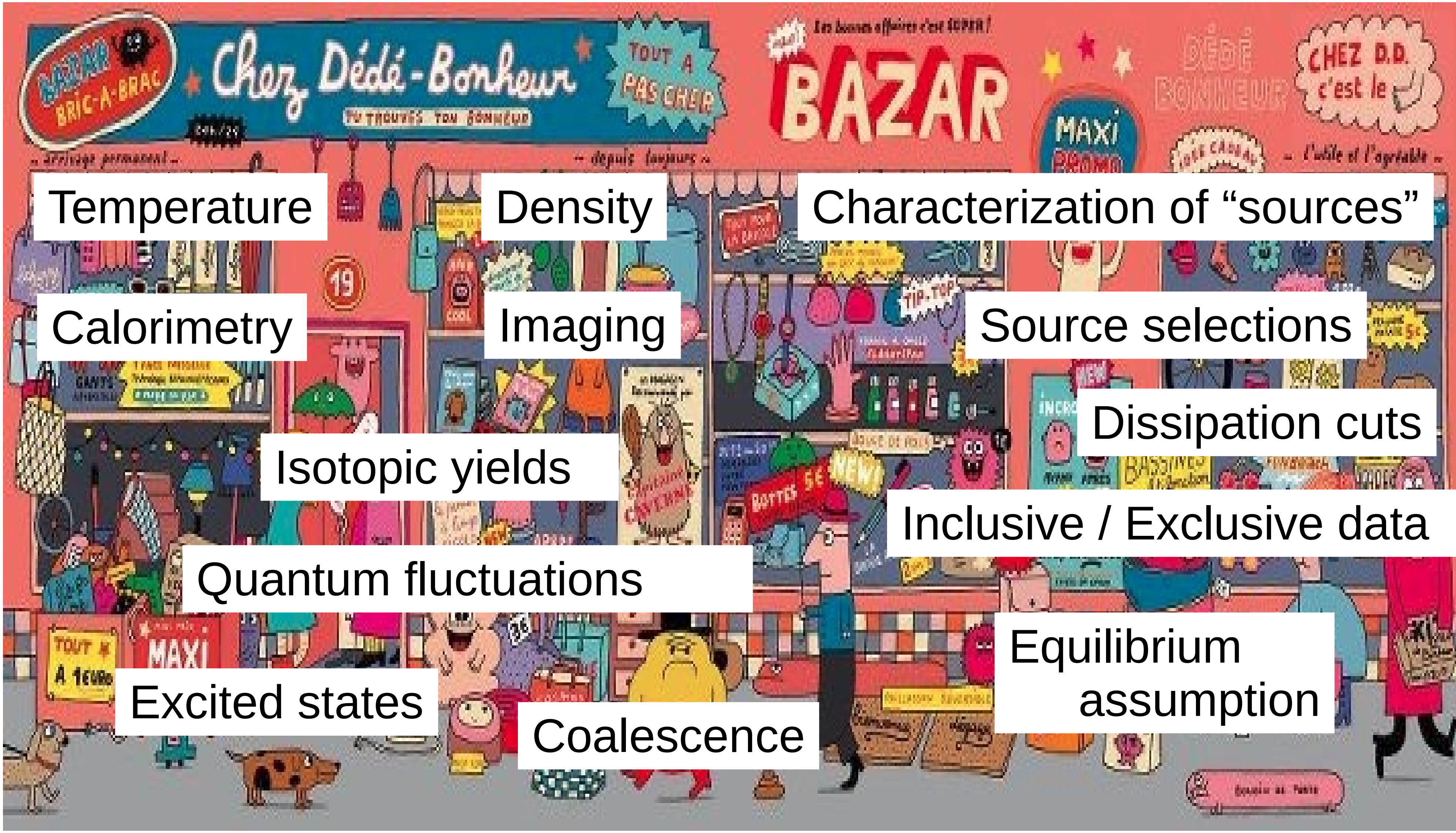
If you want your results to be useful to constrain EOS, you have to “localize” them in phase diagram

Le grand BAZAR



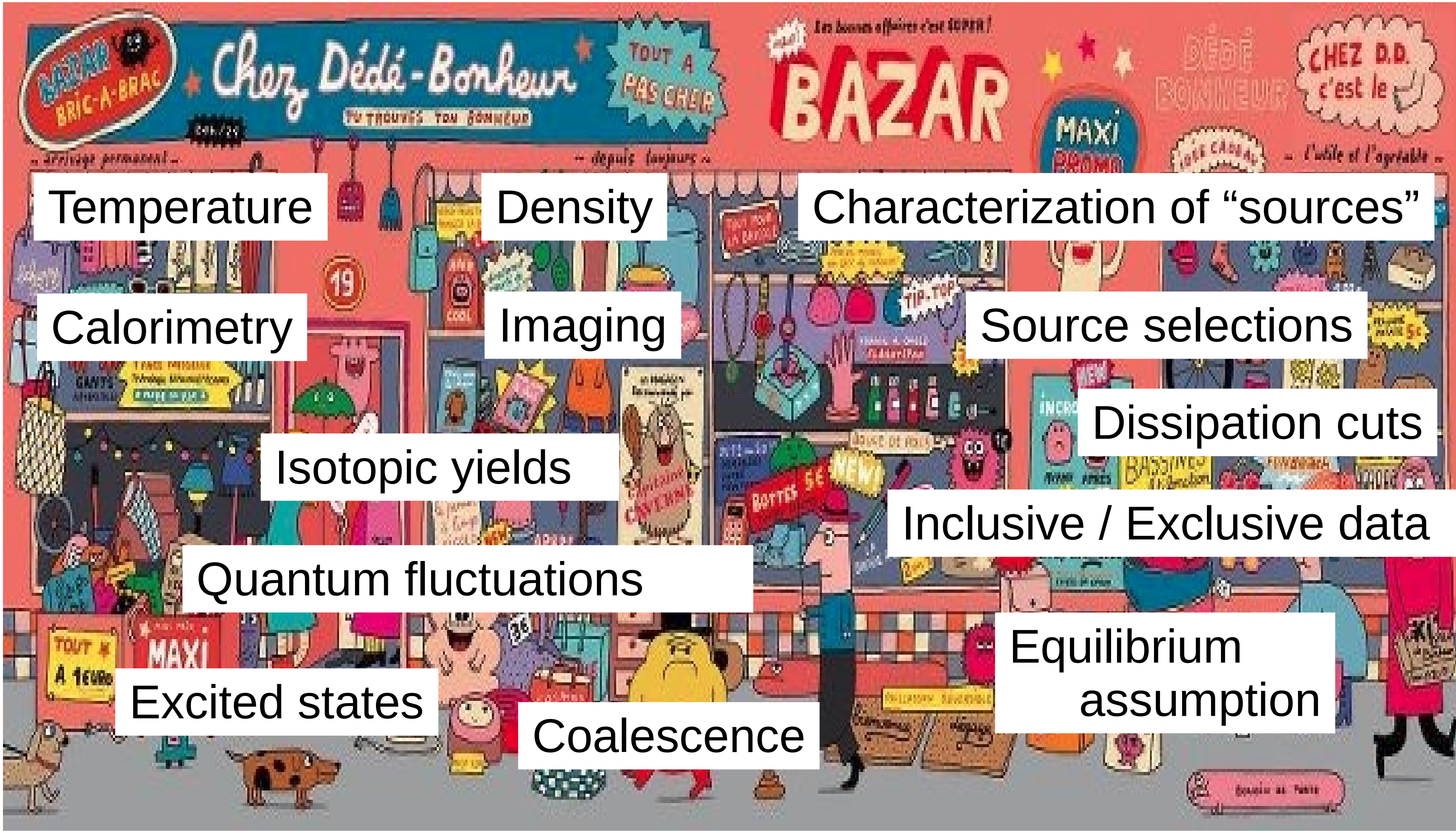
But, it exists many methods/techniques to do this ...

Le grand BAZAR



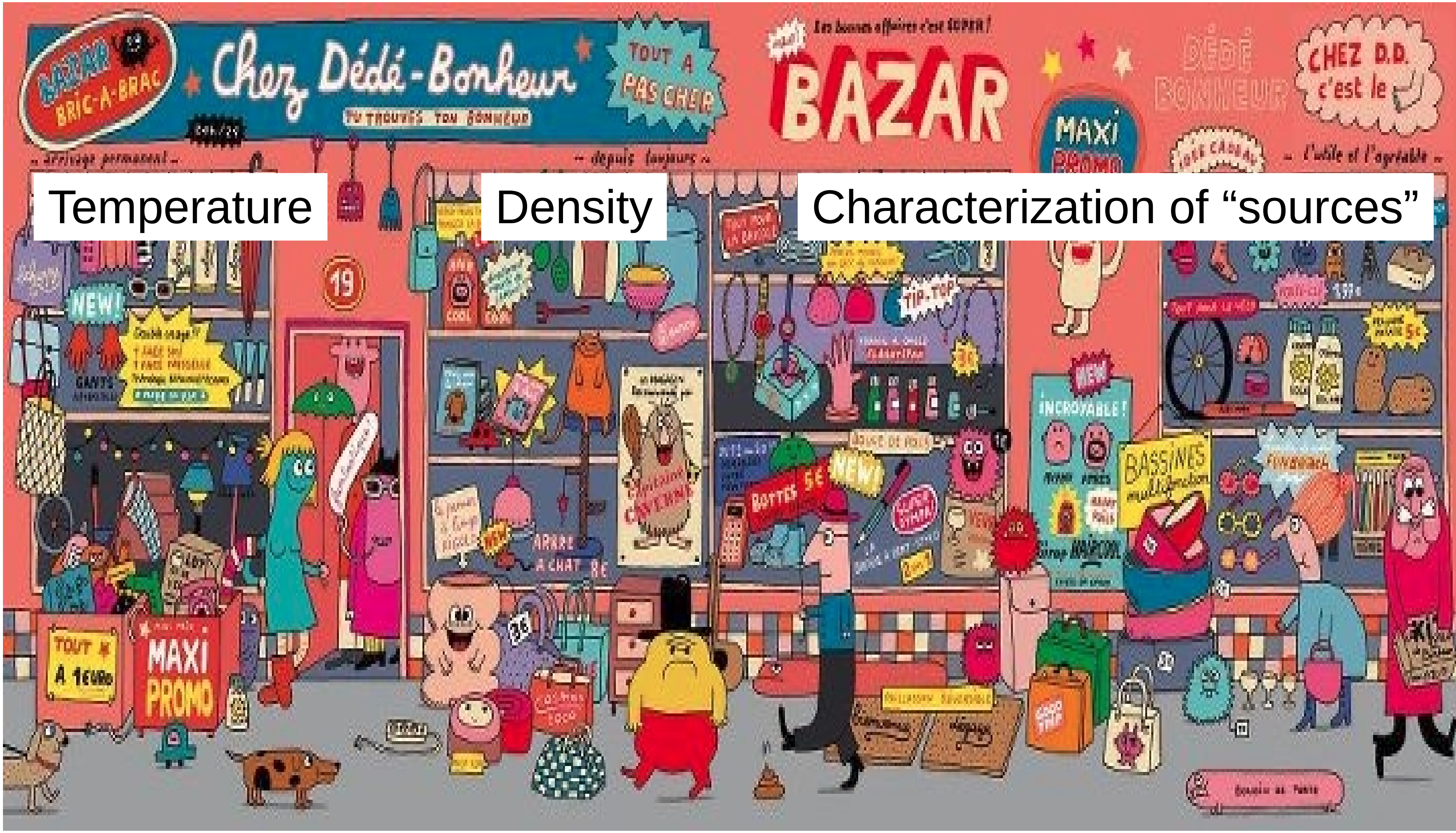
So the localization will depend of the chosen techniques to extract density, temperature, ...

Le grand BAZAR



Cross-checks of these techniques should be made
and common analysis and procedure should be defined ...

Le grand BAZAR



Temperature

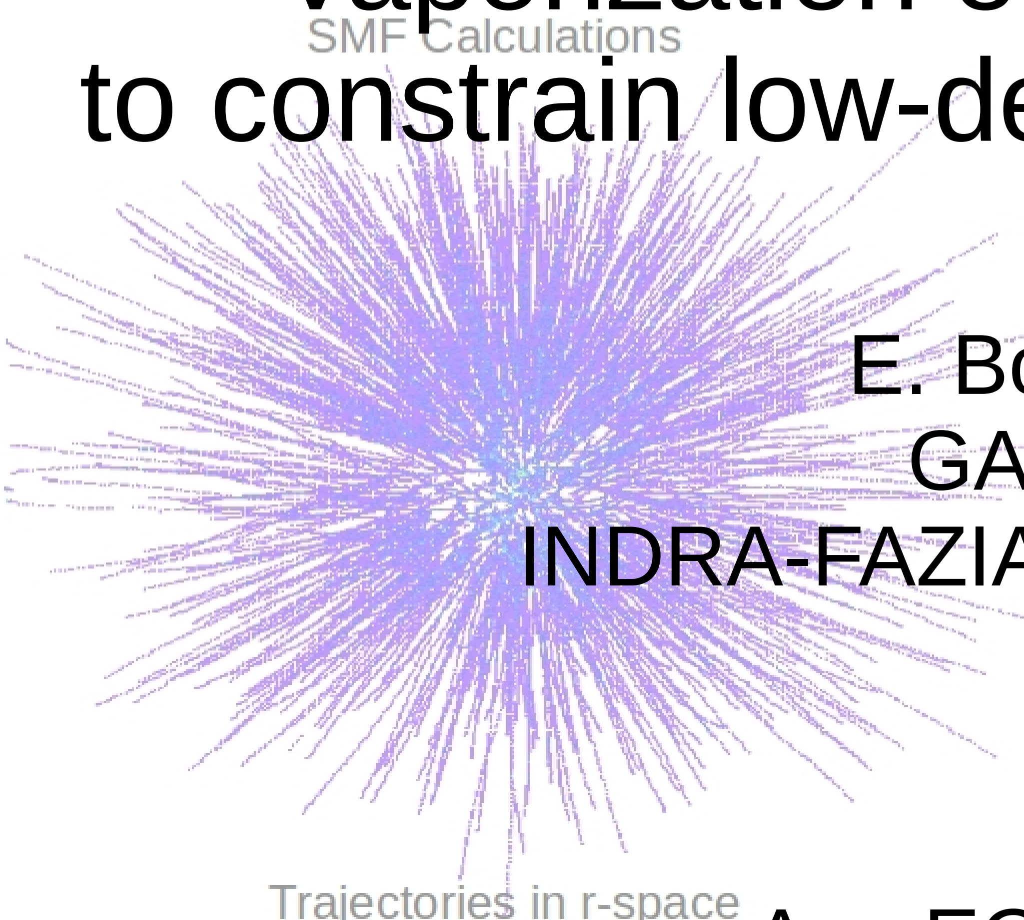
Density

Characterization of "sources"

Finally, we have to validate the reliability of these "estimations" respect to the control parameters of NSE models

END OF STATEMENT

Vaporization event properties to constrain low-density warm matter



E. Bonnet
GANIL
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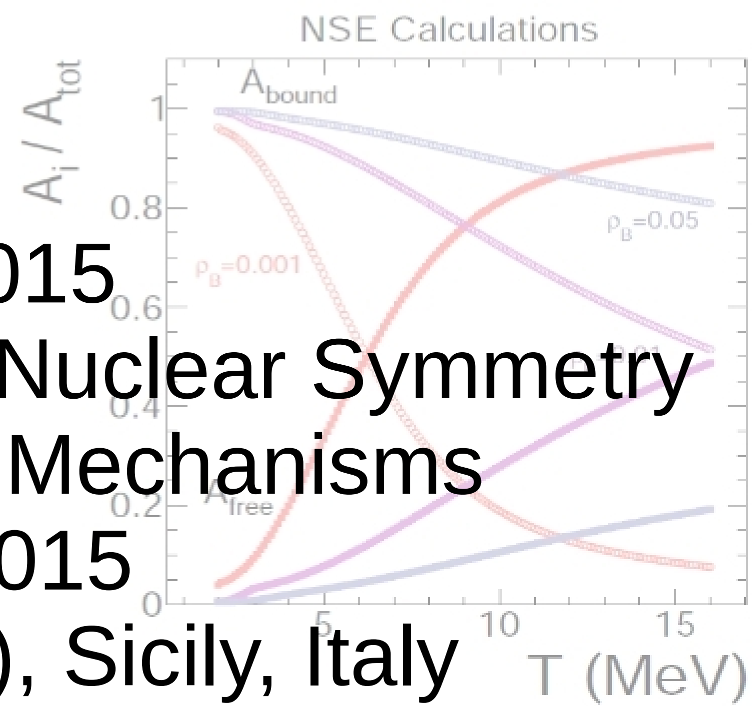

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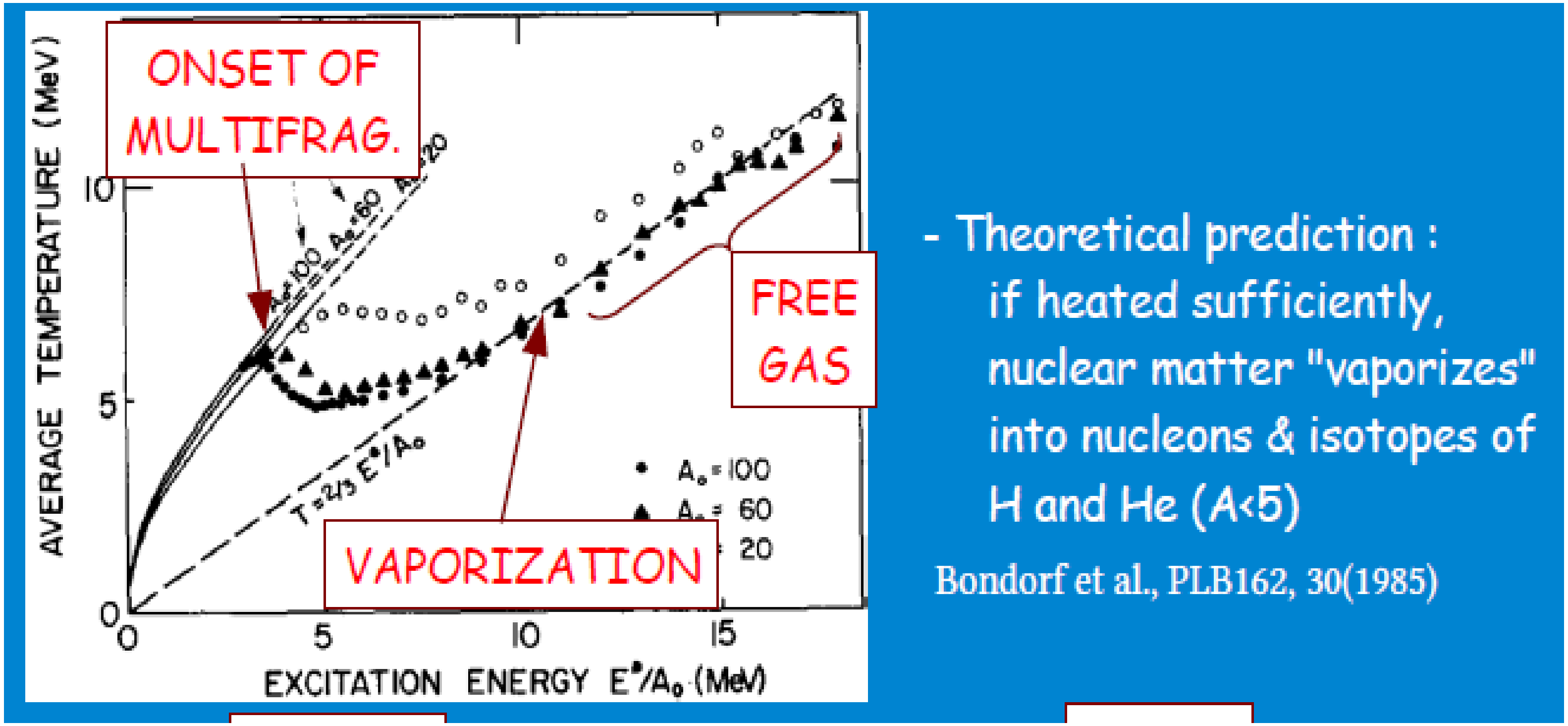
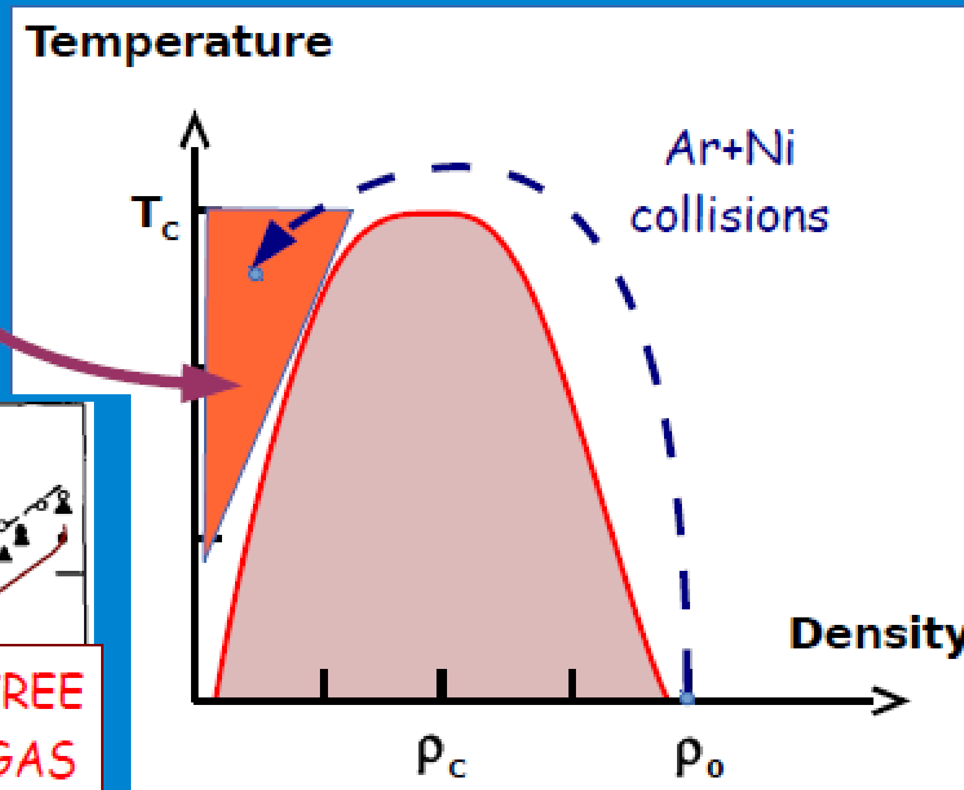
Vaporization ?

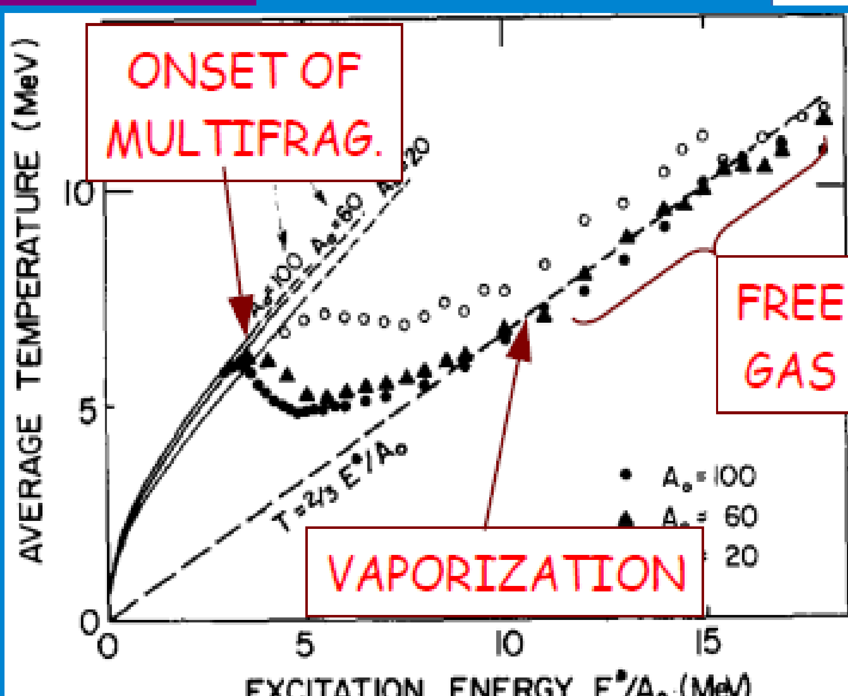
- When the system experience high excitation,it explodes in light particles without going through the spinodal region (instability region).
- It can be seen as the asymptotic gas phase of the liquid-gas first order phase transition in nuclei.



Vaporization & phase diagram

Low-density nuclear gas
at high temperature



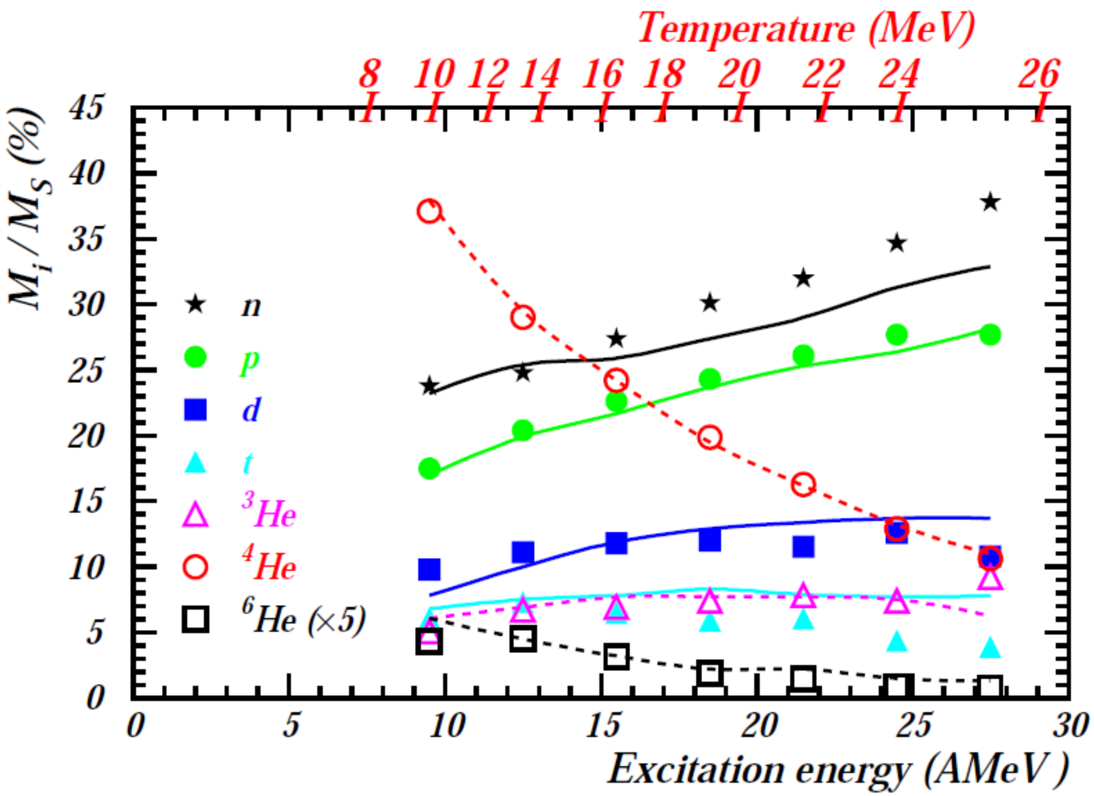


Experimental evidence of vaporization

- Experimental feeling in B. Tsang et al (1993)
  - Au+Au system in central collisions
  - poor reproduction using molecular dynamics calculation

- Experimental observation by the INDRA collaboration
  - 36Ar+58Ni system in central and peripheral collisions
  - Characterization of its properties using QSM (NSE) model
    - Reproduction of cluster yields and mean kinetic energies
    - Check of equilibrium assumption looking at variances

Thermal and chemical equilibrium for vaporizing sources



- clusters up to 6He
- Grand canonical ensemble
- Excluded volume method
- Excited states up to Ne is included
- At E*=18.5 MeV/A, density fixed at $\rho_o/3$ to reproduce alpha-proton ratio

B. Borderie et al, Eur. Phys. J. A 6, 197-202 (1999)
F. Gulminelli and D. Durand, Nucl. Phys. A615 (1997) 117

Comparison with the predictions of a model describing the properties of a quantum weakly-interacting gas of nuclear species in thermal and chemical equilibrium

From theoretical side

- Low density warm nuclear matter has a renewed interest coming from the need in the description of neutrino sphere region during the core-collapse supernovae (Topical Volume EPJA 50 (2014), ECT*14 Workshop)
- Data in the subsaturation ($\rho<\rho_o$) densities region and finite temperature (T<20 MeV) are needed to constrain new developments and approaches in these topics :
  - “In-medium“ nuclear data shift
  - Non homogeneous matter, Gas-Clusters interaction, Surface effects ...
  - Isovector part of the energy functional (symmetry energy)
- The mixing of clusters in a nucleon gas is a particular state which is be reached in HIC, specially in vaporization
  - Yields of bound clusters are the straightforward observables in NSE models which can be extracted in experimental data

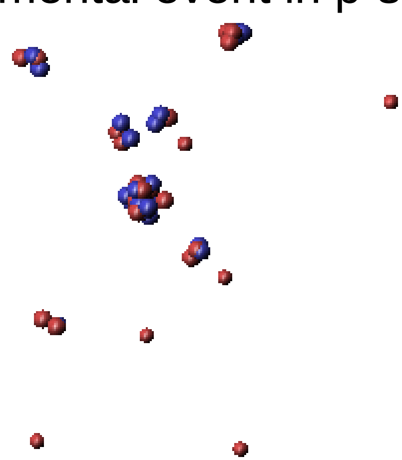
Vaporization process in the framework of neutrino sphere calculation

- Evolution with excitation energy of the composition of cluster yields
- Final clusters are produced by one source, which allows to extract event by event properties and build statistical ensemble
- Already shown that there is a good reproduction using QSM which assume thermodynamical equilibrium in grand canonical ensemble.
- Give sense to the definition of temperature, density
- Further comparison with available updated models can be done

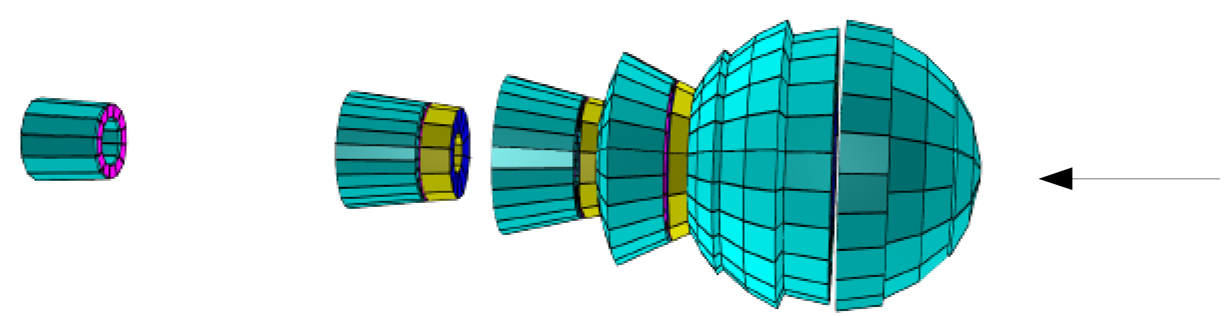
58Ni+58Ni collisions studied with INDRA@GANIL

- Beam energies : 32,40,52,64,74,82,90 MeV/A
- Focus on the Quasi-Projectile vaporization in light charge particles from proton up to Be isotopes.
- Focus on the forward hemisphere and keep only events with clusters up to Be : $Z_{max} \leq 4$

Experimental event in p-space



INDRA 4π charged particles array

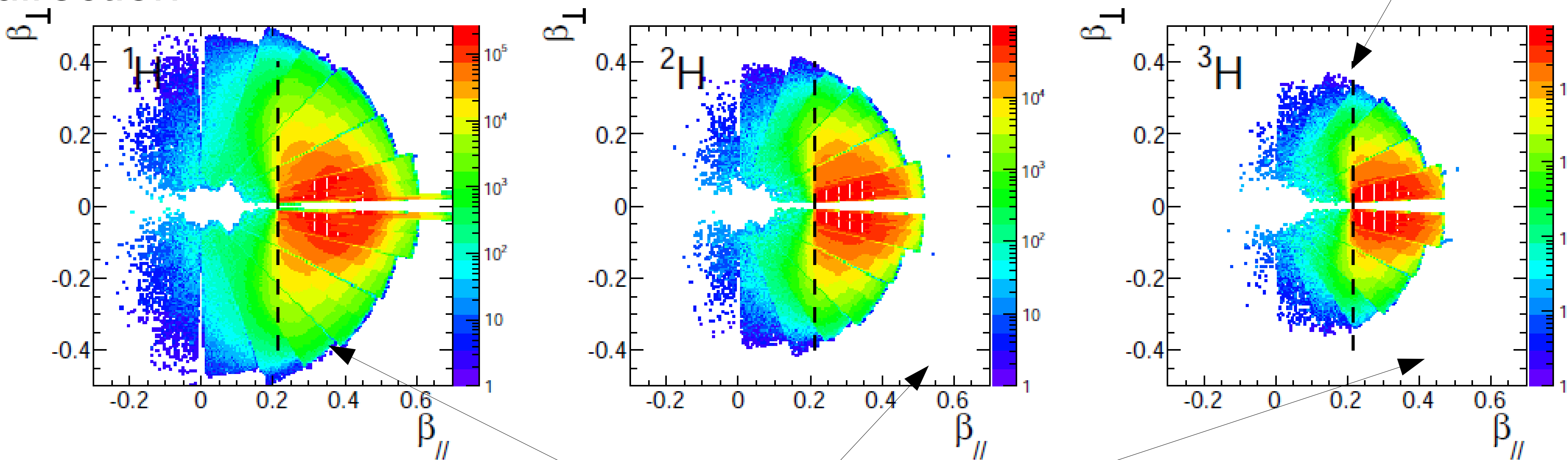


2D velocity space for 58Ni+58Ni@90MeV/A

Transverse direction

H isotopes

CM velocity



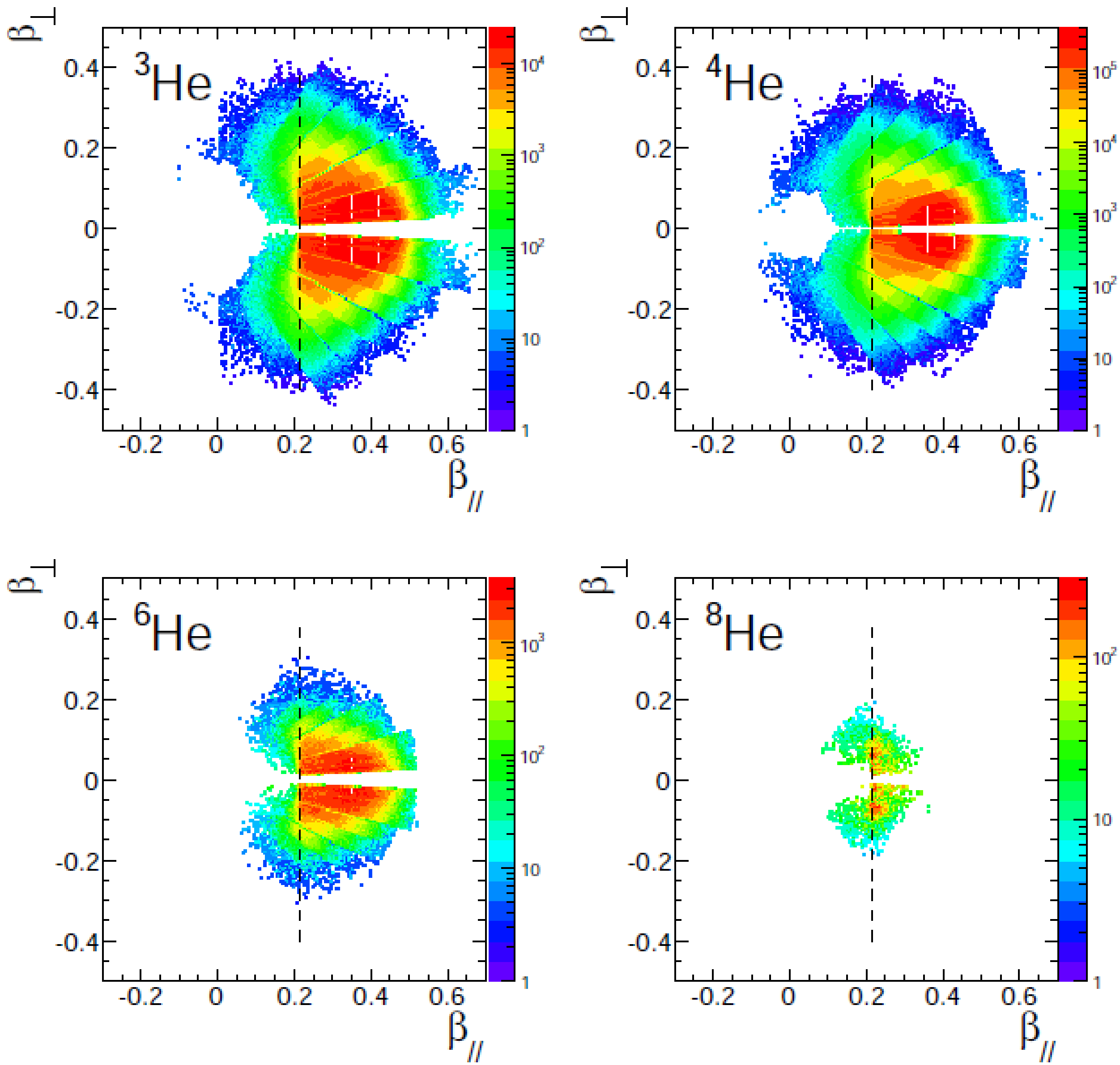
Beam direction

Only the forward hemisphere is used where full isotopic resolution is achieved

2D velocity space for 58Ni+58Ni@90MeV/A

Transverse direction

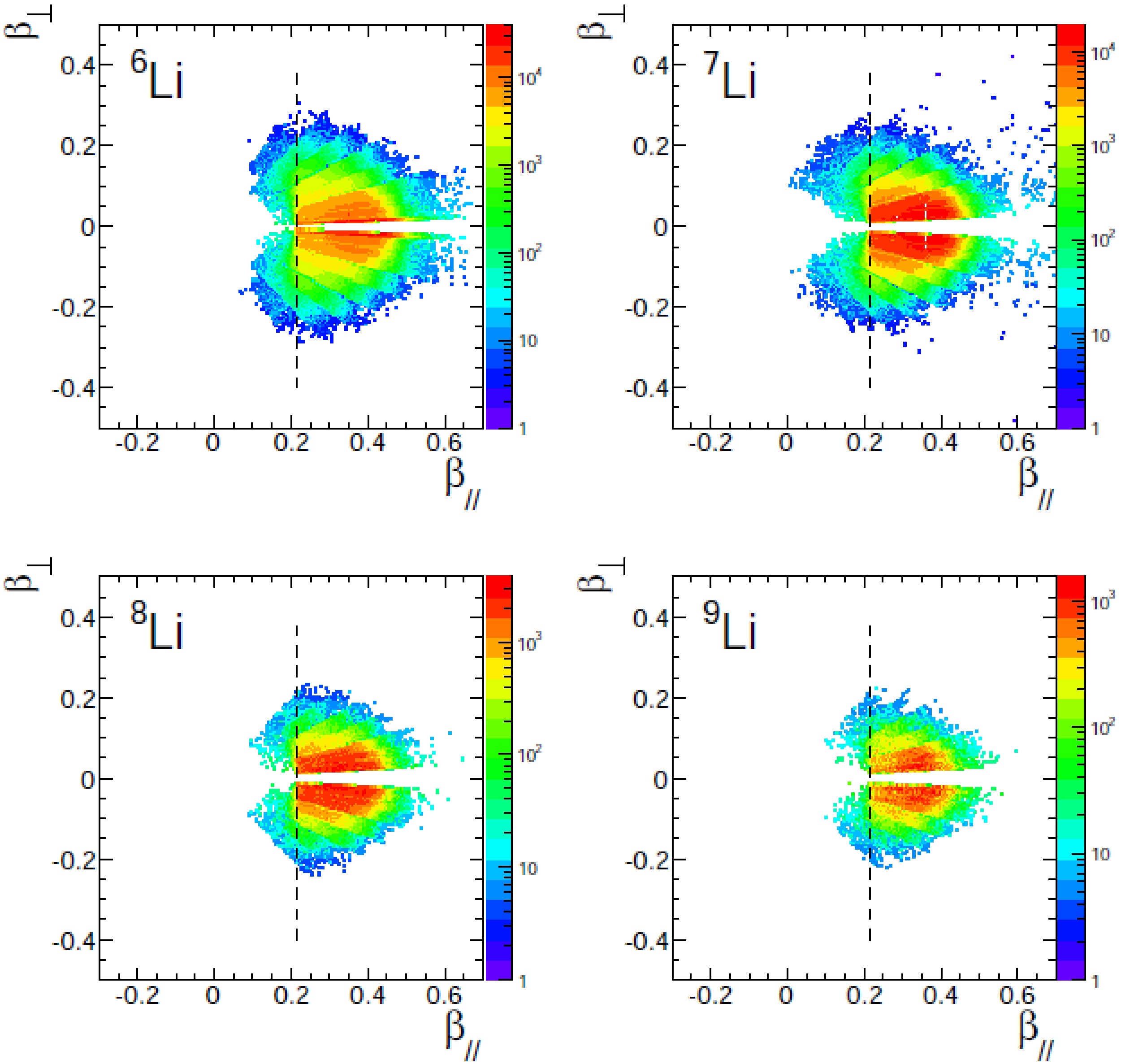
He isotopes



Beam direction

2D velocity space for 58Ni+58Ni@90MeV/A

Transverse direction



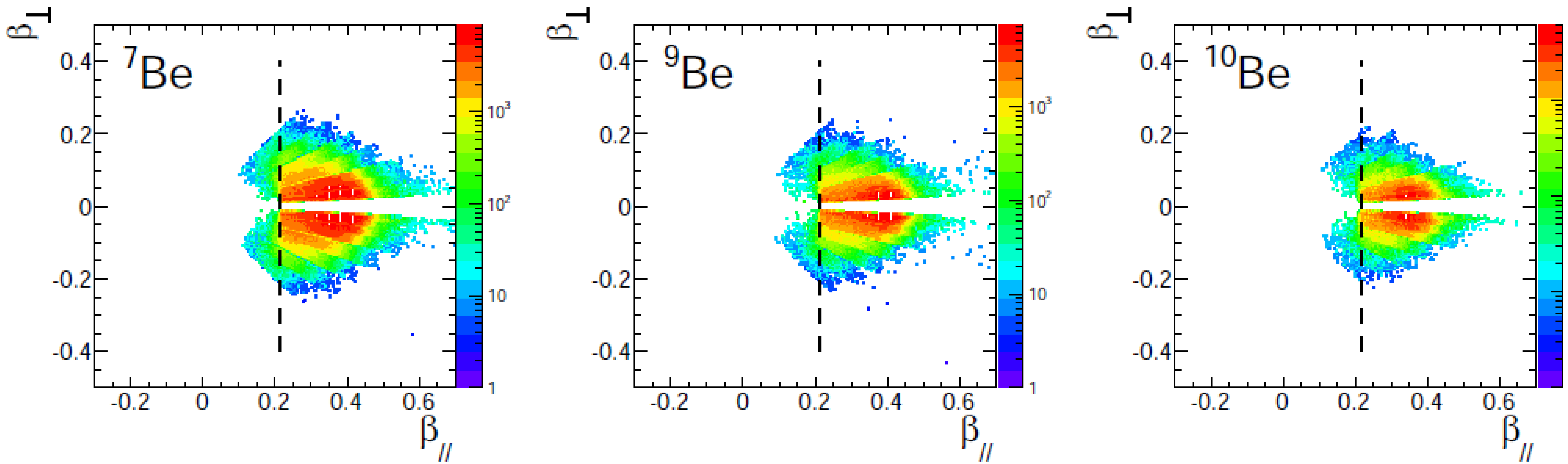
Li isotopes

Beam direction

2D velocity space for 58Ni+58Ni@90MeV/A

Transverse direction

Be isotopes



Beam direction

Calorimetry and event sorting

- We kept only events where total detected charge (Ztot) is greater than 90% of the Ni : Ztot ≥ 0.90*28

- To sort events, we choose the excitation energy E* obtained by calorimetry (energy balance)

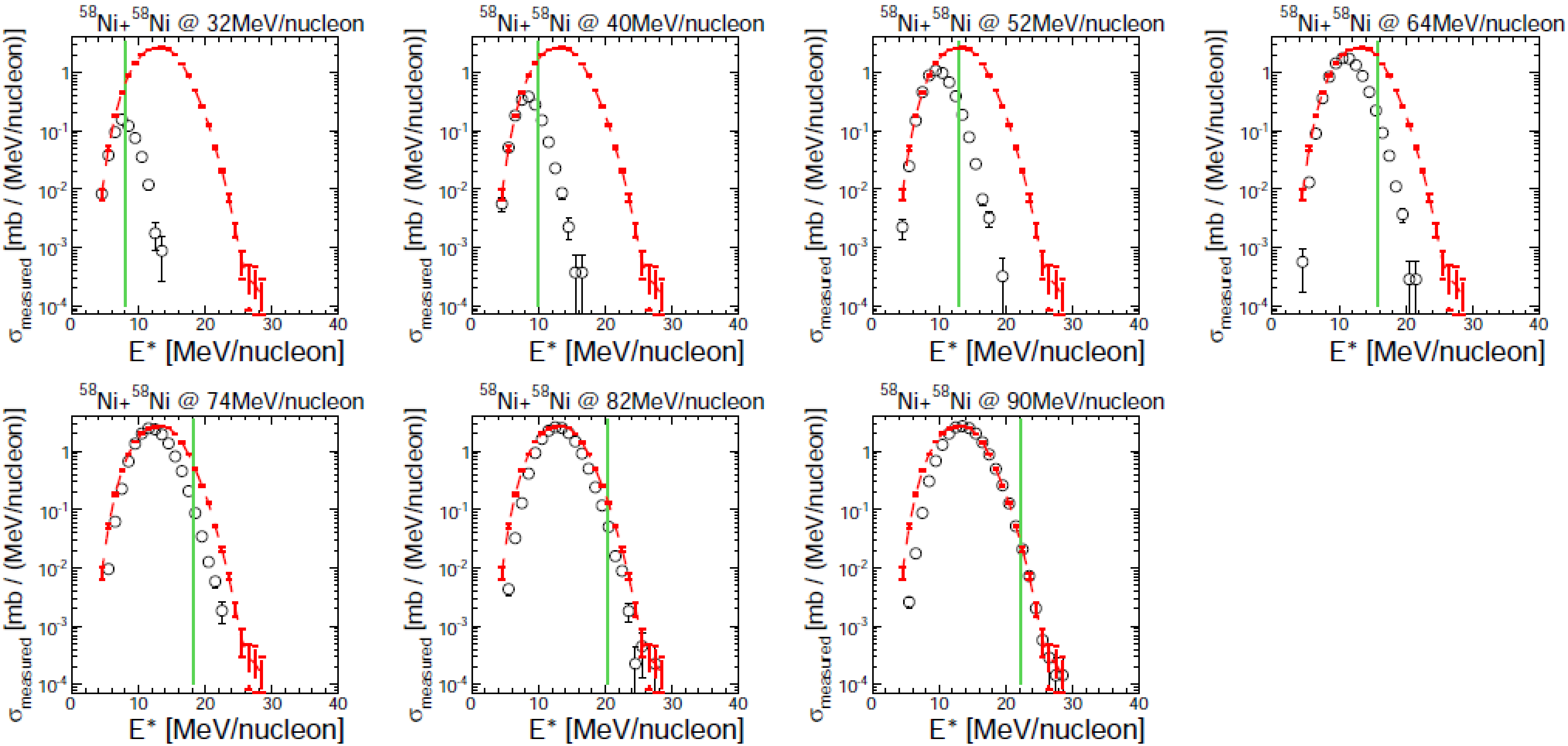
  $Qs+E^* = \text{Sum}\ (Ek + Q)_{\text{charged}} + Mn(En+Qn)$

- Concerning the undetected neutrons :
  - As all charged products are isotopicaly resolved, the neutron multiplicity (Mn) is deduced directly by the mean of mass conservation : Mn=58/28*Ztot-Atot
  - The estimation is made using the Fermi gas (FG) relation between temperature and excitation energy $E^*/A=aT^2$ ($a = 1/10\ MeV^{-1}$)
  - We assume volume emission in the Boltzmann statistics : En=3/2T

- Finally, $\alpha T^2 + \beta T + cte = 0$ equation is resolved

58Ni+58Ni : cross section of vaporization events

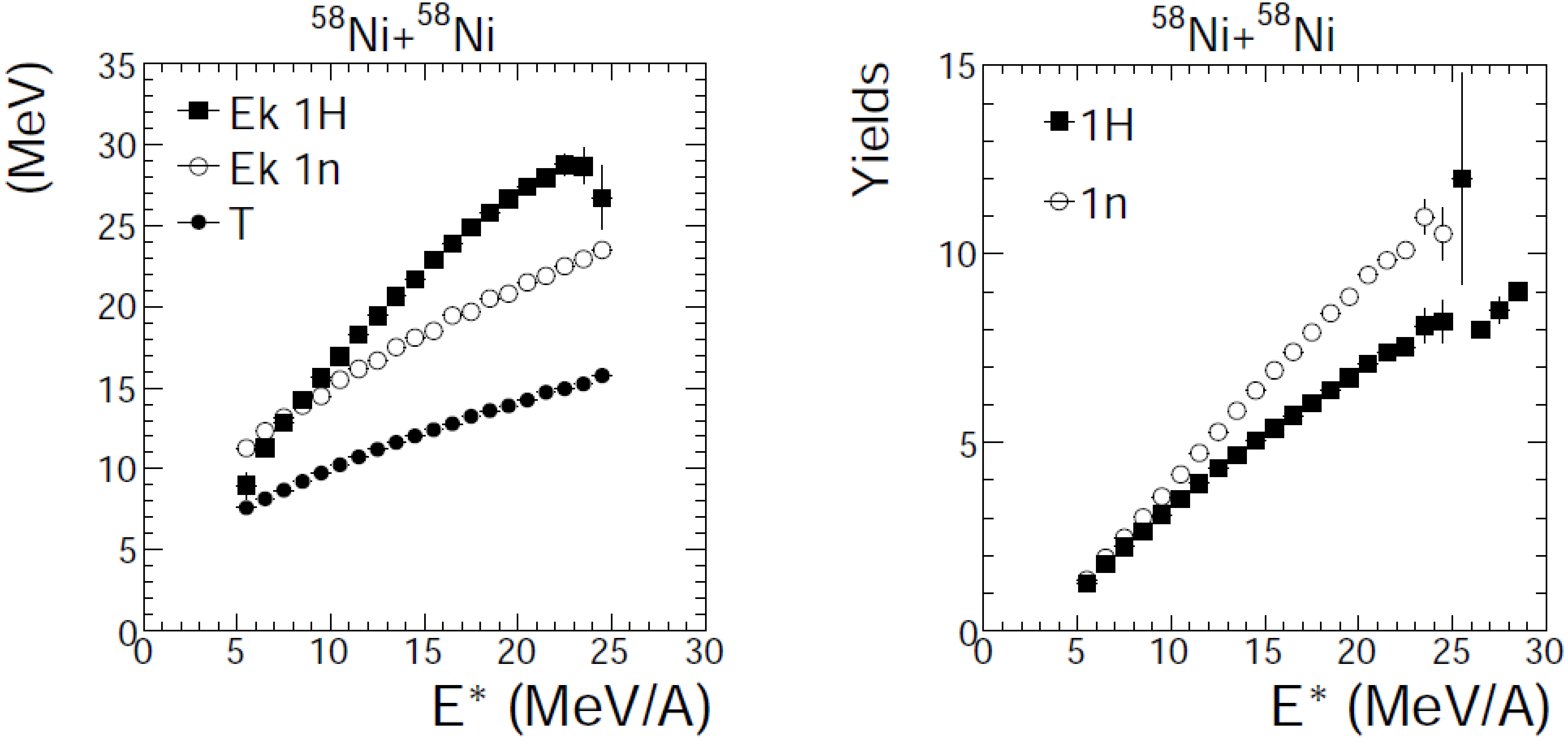
Measured cross section = 137 mb (not corrected from efficiency)



Red dashed line is the envelope deduced summing all beam energies

As an indication, Green line is the available CM energy

58Ni+58Ni : outputs of the calorimetry



FG temperature and neutrons mean properties

Temperature, Neutron Yield and densities “à la” Albergo

Based on isotopic yields
S. Albergo et al, Nuovo Cimento A 89 (1985)
Often used and adapted (Kris Hagel presentation for example)

$$T_{\mathrm{HHe}} = 14.3 \ \mathrm{MeV}\left(\ln\left[1.59\frac{Y_\alpha Y_d}{Y_t Y_h}\right]\right)^{-1/2}$$

Temperature

$$Y_n = Y_p \frac{Y_t}{Y_h} f_\delta(T)$$

$$f_\delta(T) = \exp[(E_h - E_t)/T][(m_n m_h)/(m_p m_t)]^{3/2}$$

Neutron yields

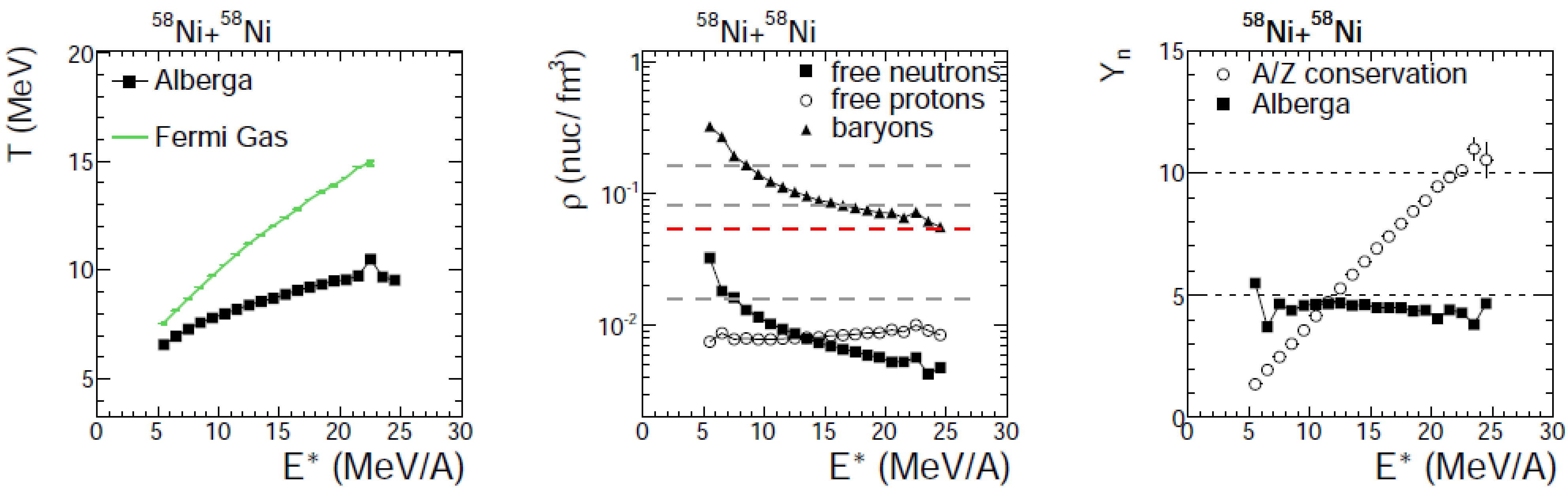
$$n_p = 0.62 \times 10^{36}\, T^{3/2} \exp[-19.8/T]\,\frac{Y_\alpha}{Y_t}$$

$$n_n = 0.62 \times 10^{36}\, T^{3/2} \exp[-20.6/T]\,\frac{Y_\alpha}{Y_h}$$

$$n_B = (n_p/Y_p)\sum_i A_i Y_i$$

Densities

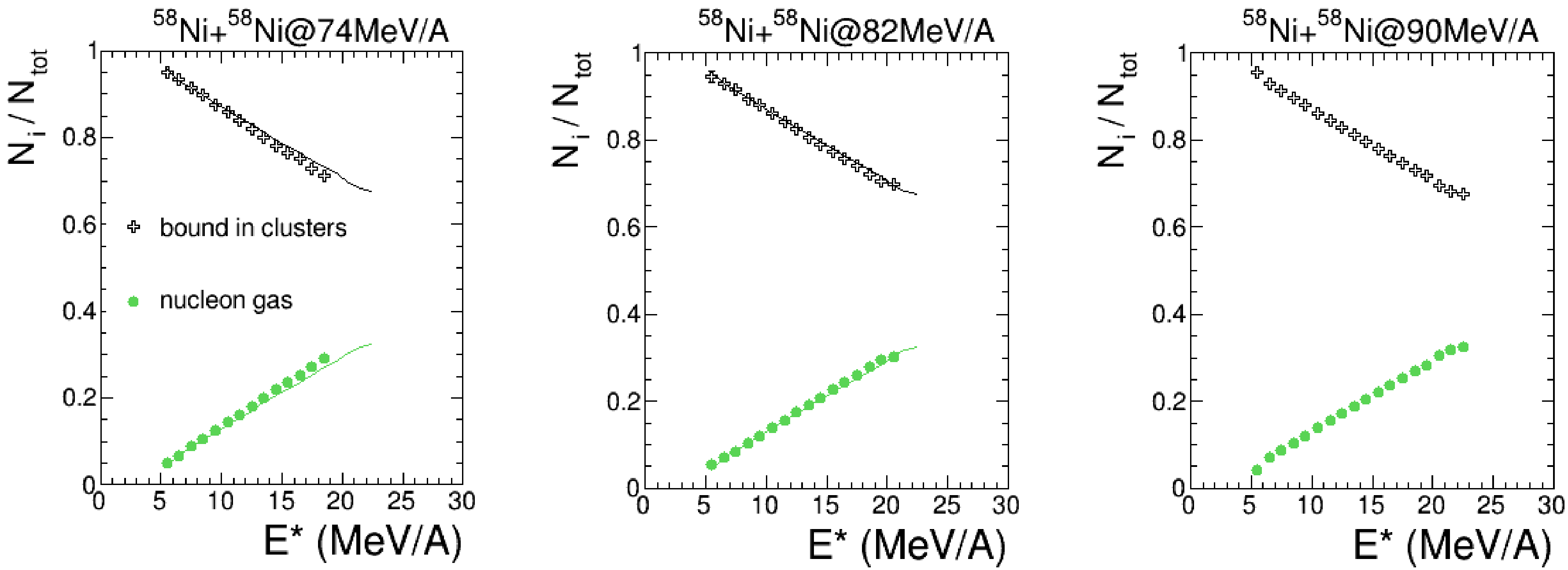
Neutron Yield, temperature and densities "à la" Albergo



- Density values for nucleon gas are around $\rho_o/20$.
- Baryonic denity between $\rho_o/2$ and $\rho_o/3$ compatible with Freeze-Out density used in QSM.
- Isotopic ratio temperature is lower
- For the estimation of neutron yields, it is constant on an excitation energy range of 20MeV/A, which is quite surprising ...

Mixing of clusters in a nuclear gas

- A≥2 (bound clusters) + A=1 gas (neutrons and protons)
- What the percentage of nucleons in each part ?
- Linear dependence with E*



Yields of bound clusters

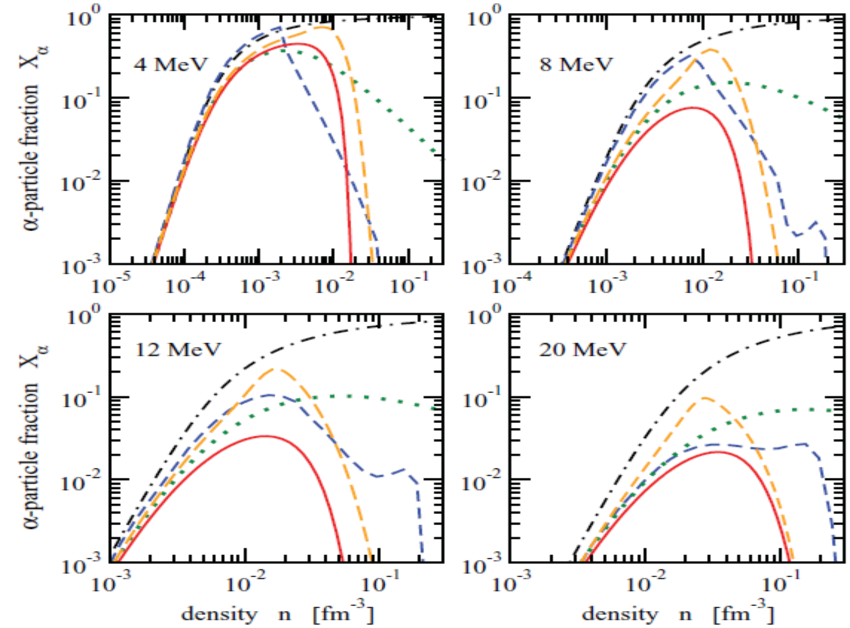
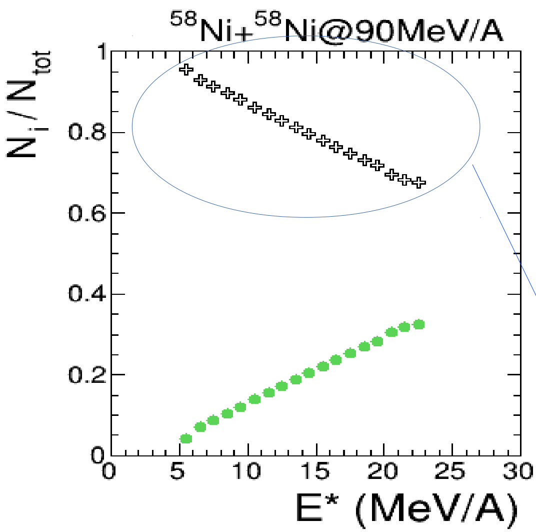
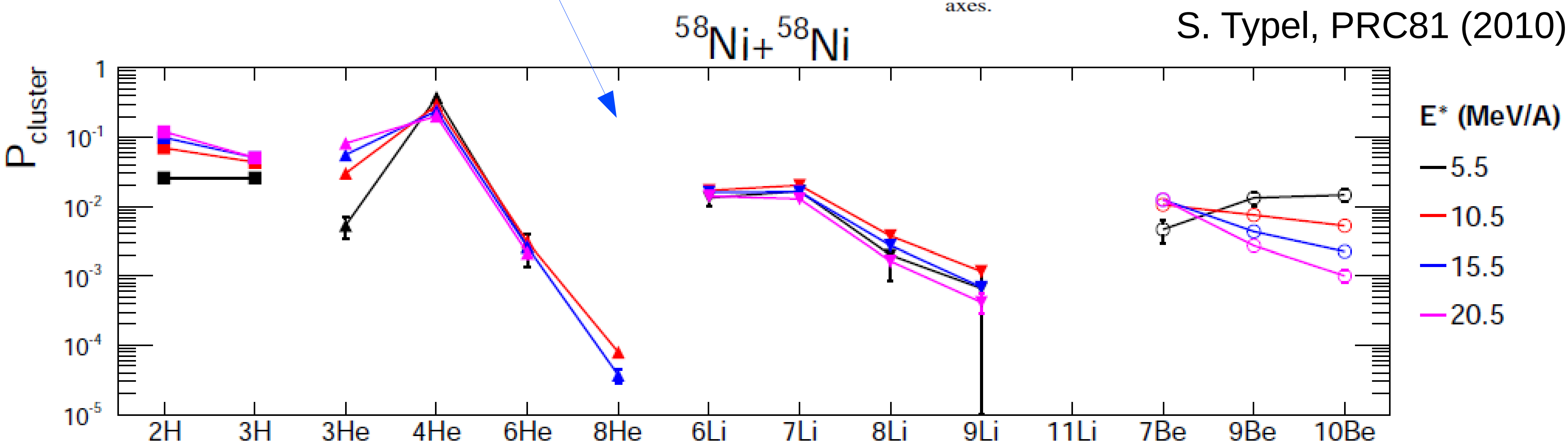


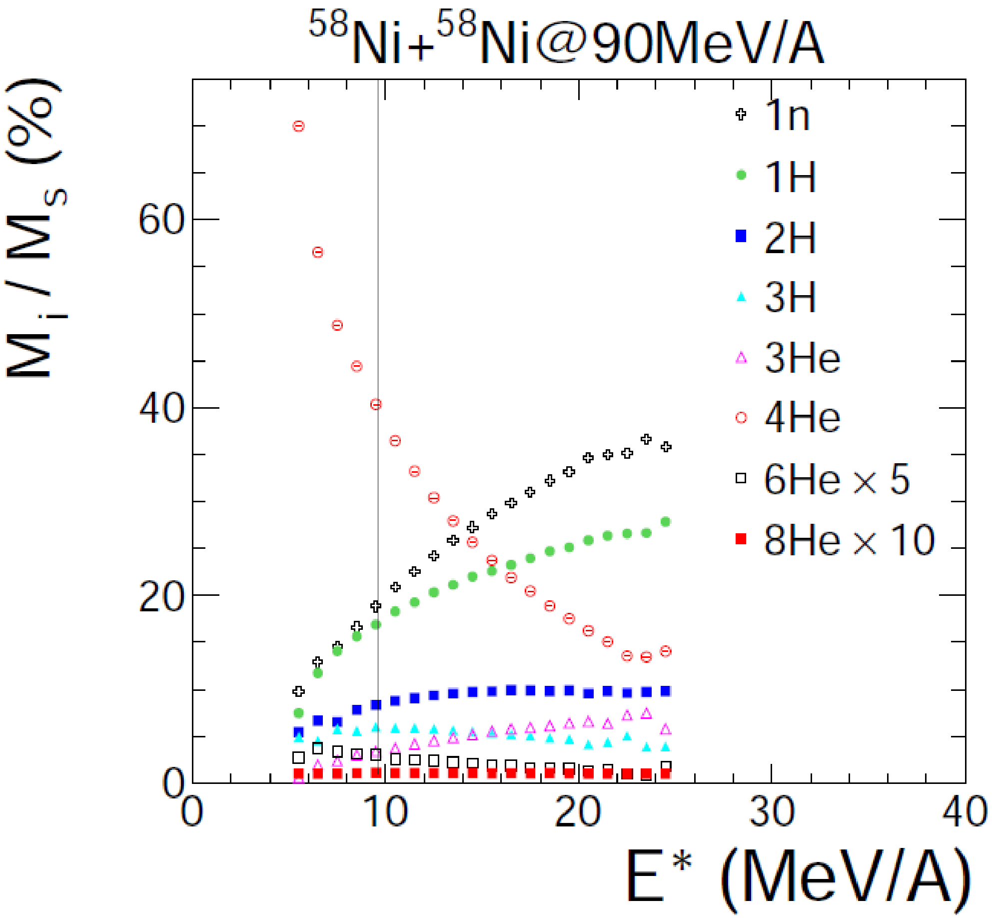
FIG. 15. (Color online) Comparison of α-particle fractions in symmetric nuclear matter as a function of the density at four temperatures for the virial expansion (black dashed-dotted lines), NSE (green dotted lines), the EoS of Shen *et al.* [29] (blue dashed lines), the generalized RMF model (red solid lines), and the QS approach (orange dashed lines). Note the different scales on the *x* axes.

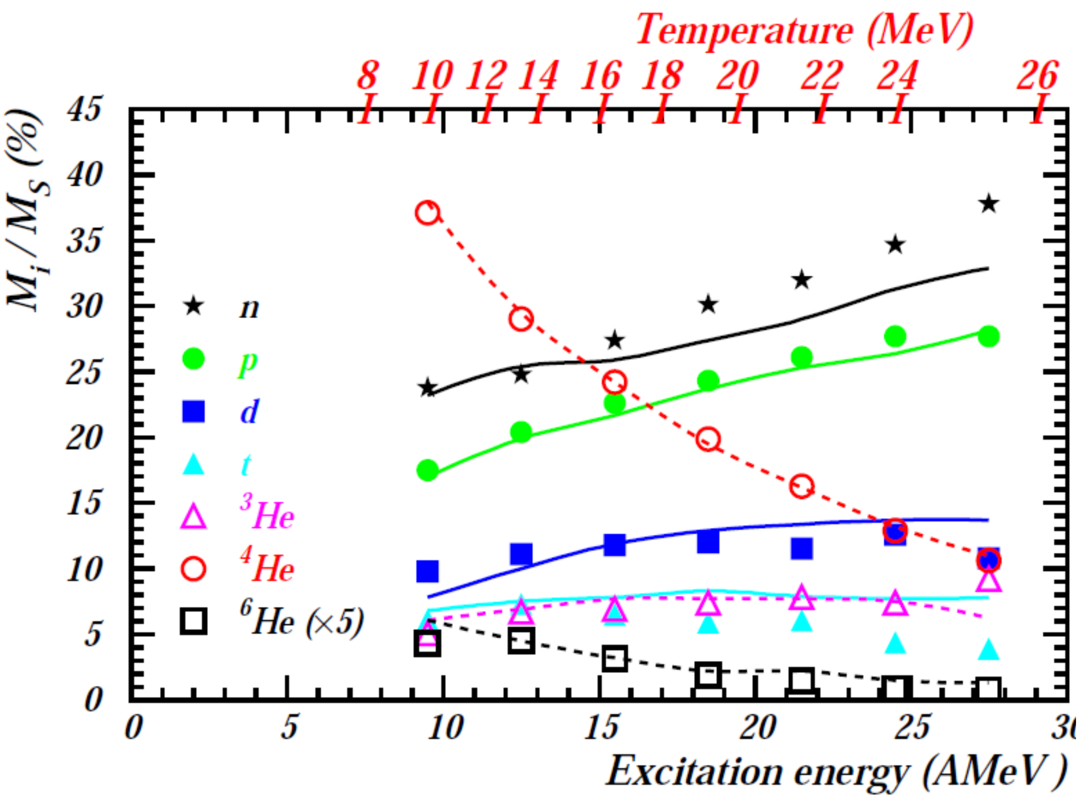
S. Typel, PRC81 (2010)





Putting all yields together

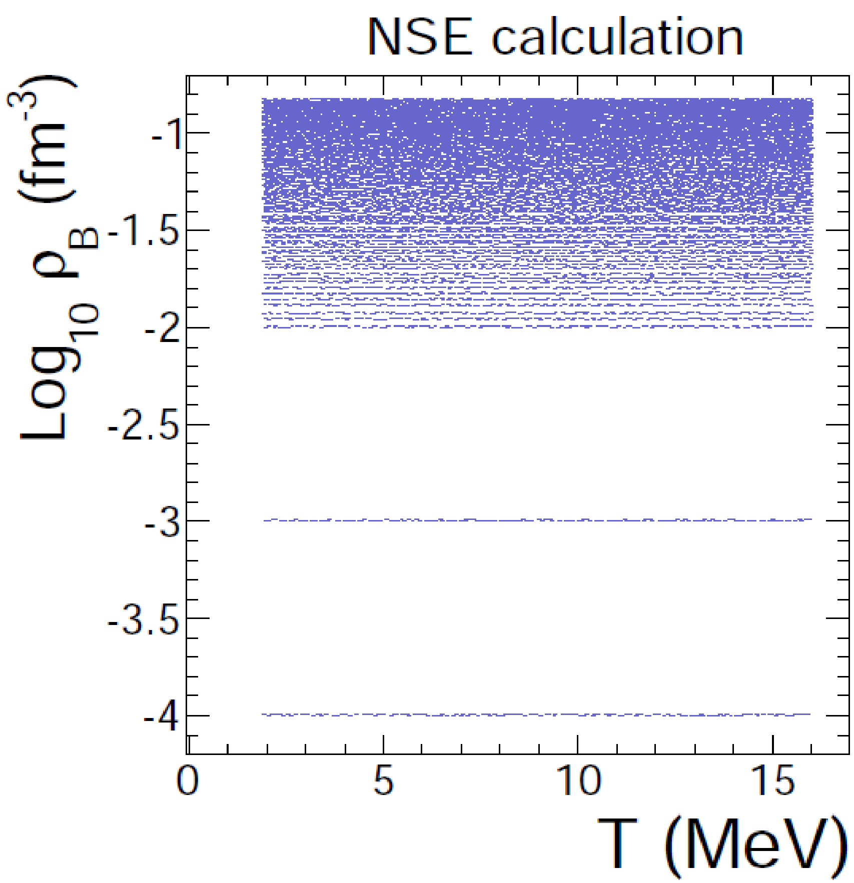




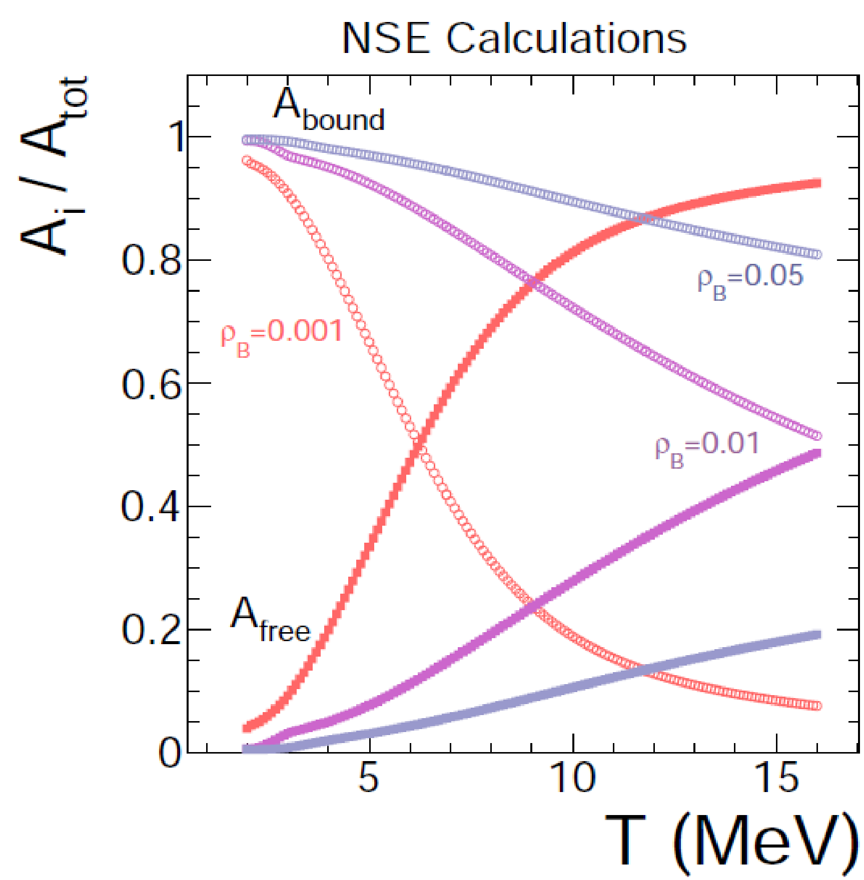
Very similar trends for two source sizes (factor of 1.6)

Start comparison with NSE model developed by F. Gulminelli and A. Raduta

Start comparison with NSE model developed by F. Gulminelli and A. Raduta

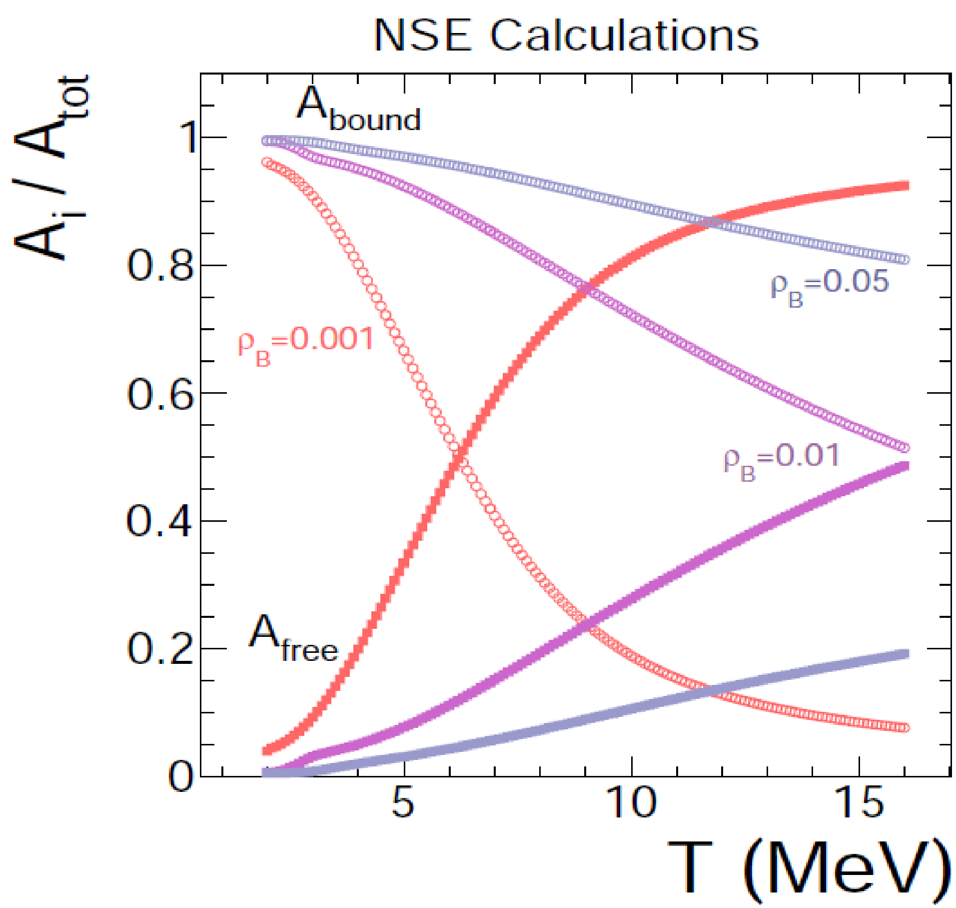


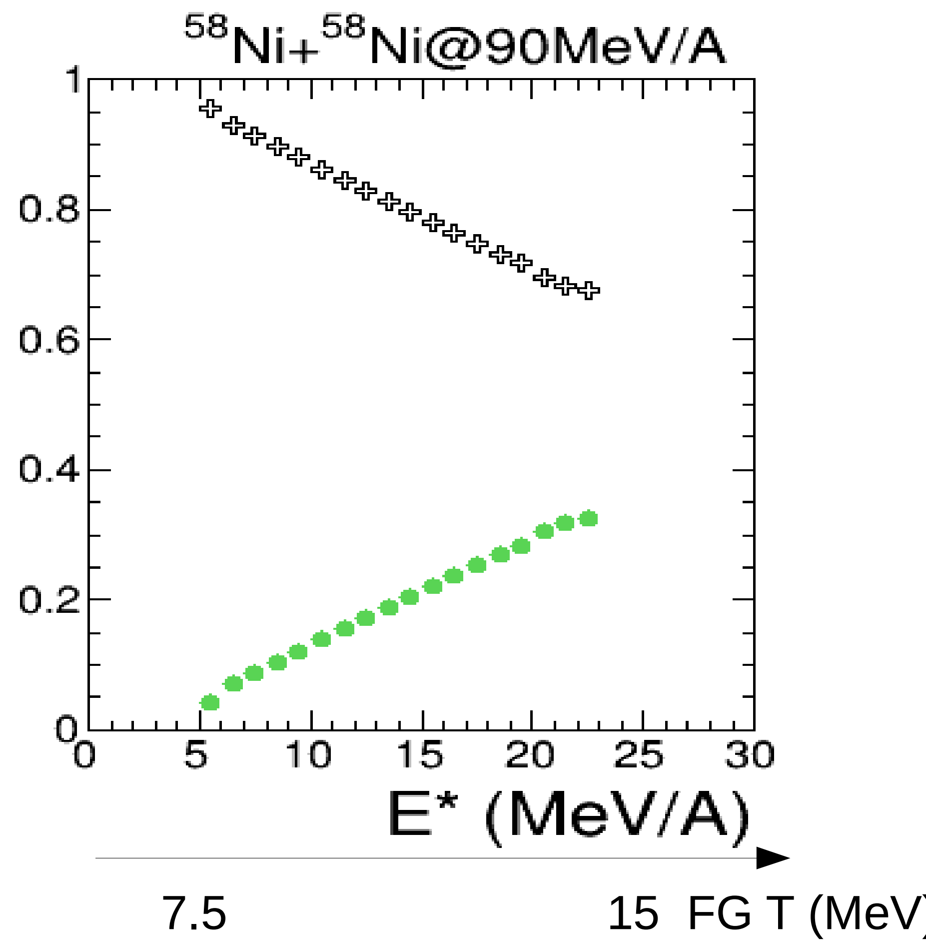
Sample temperature and density values



Evolution of nucleon repartition Between gas and bound clusters

Start comparison with NSE model developed by F. Gulminelli and A. Raduta





Work in progress to prepare the future INDRA-FAZIA campaign which will be focused on more neutron-rich systems

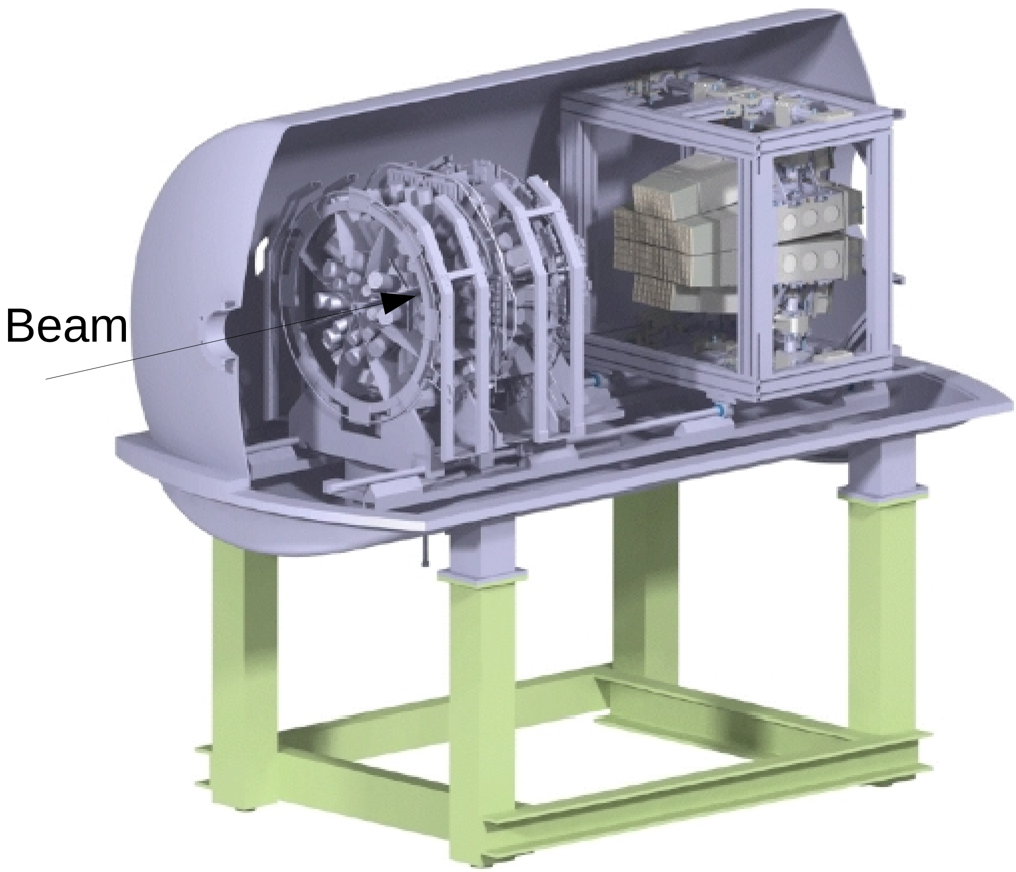
(Near) future

LoI INDRA-FAZIA@GANIL for 2016+

N/Z dependence of the dynamics in dissipative collisions, from evaporation towards vaporization

E. Bonnet, R. Bougault, A. Chbihi, J.D. Frankland, D. Gruyer, O. Lopez and S. Piantelli
(*for the FAZIA Collaboration*)

FAZIA demonstrator at [2°,14°] coupled with INDRA



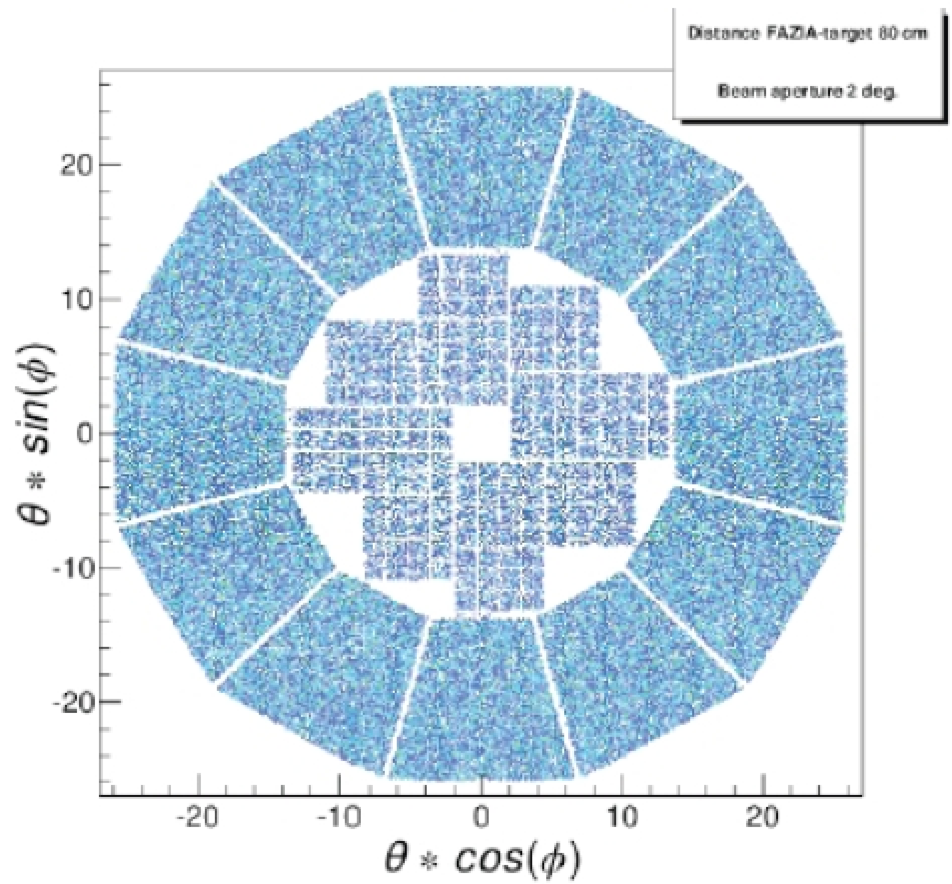


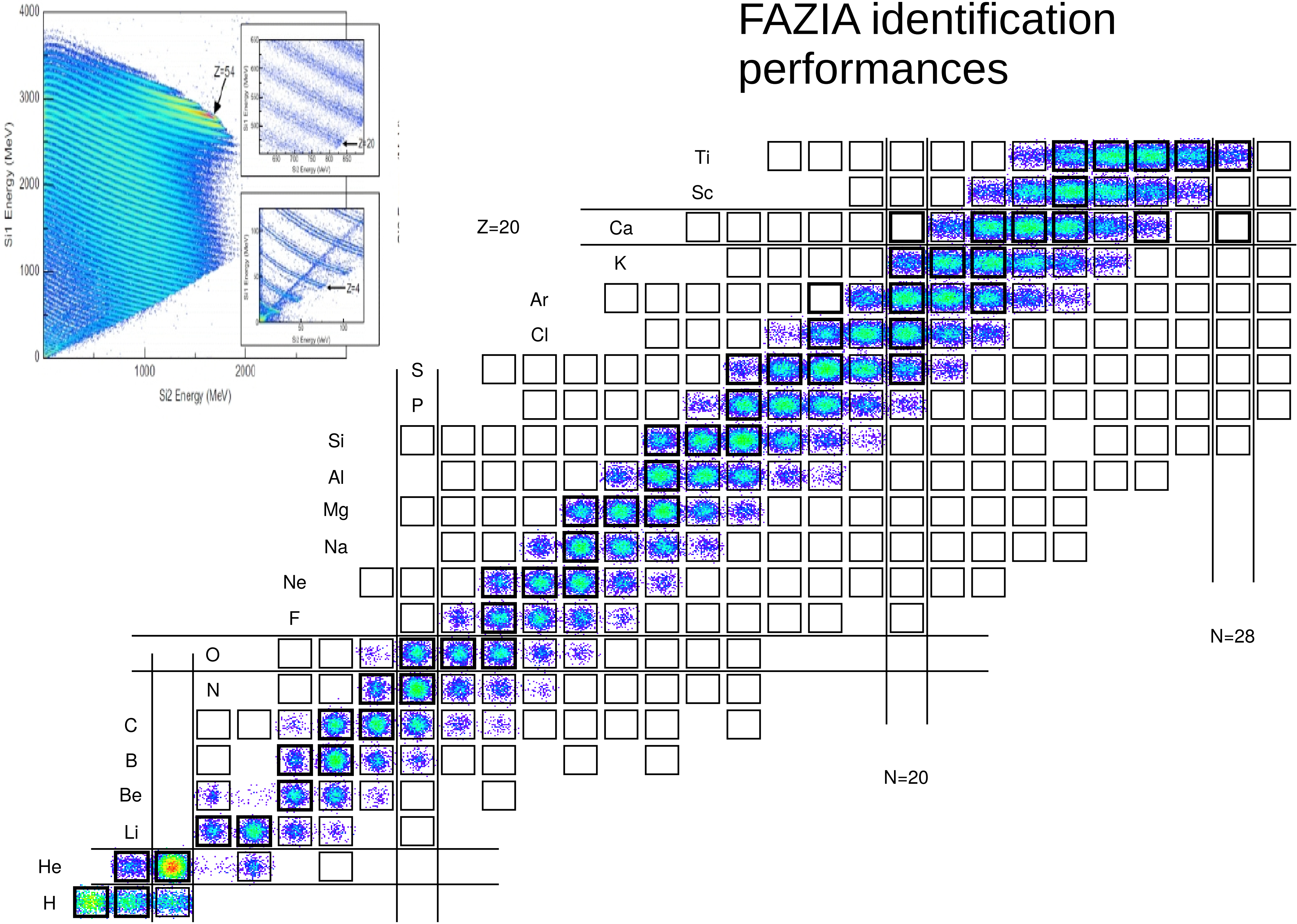
Figure 2: ***On the left****: FAZIA demonstrator coupled to INDRA multidetector;* ***on the right****: Response of the FAZIA demonstrator located at 80 cm from the target, inside INDRA. Only angular range from 14 to 27° of INDRA is presented in this figure.*

No limit in the size of the cluster for the definition and characterization of isotopic yields

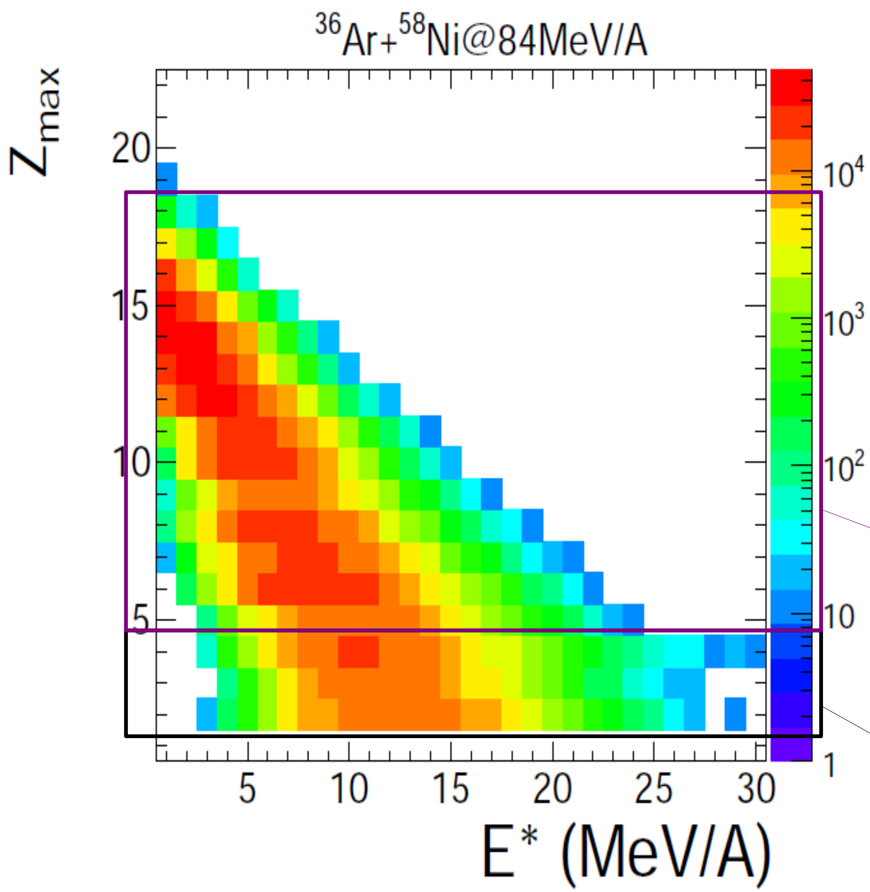
One of proposed study in this LoI is :

- The study of vaporization in the reaction $^{40,\mathbf{48}}\mathbf{Ca}$+^{40}Ca up to 88 MeV/A
- Exclusive information on **cluster yields** on all the accessible sub-saturation densities
- Explore the continuous path between multifragmentation and vaporization and focus on **neutron rich source**

FAZIA identification performances



Vaporization in ^{36}Ar, ^{40,48}Ca and ^{58}Ni



Exclusive high quality data will be available in large range in :

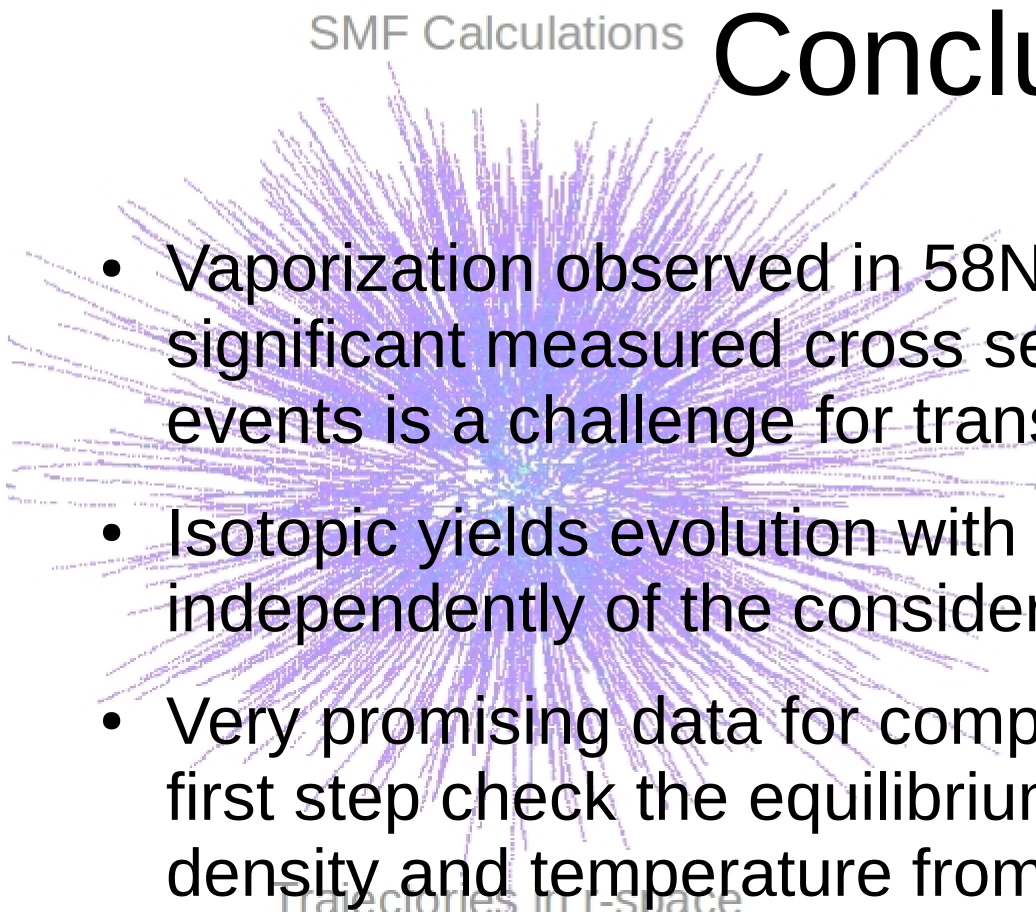
- Mass A<60
- Temperature T<20 MeV
- Sub saturation density until $\rho_o / 4$
- Charge Asymmetry N/Z up to 1.4

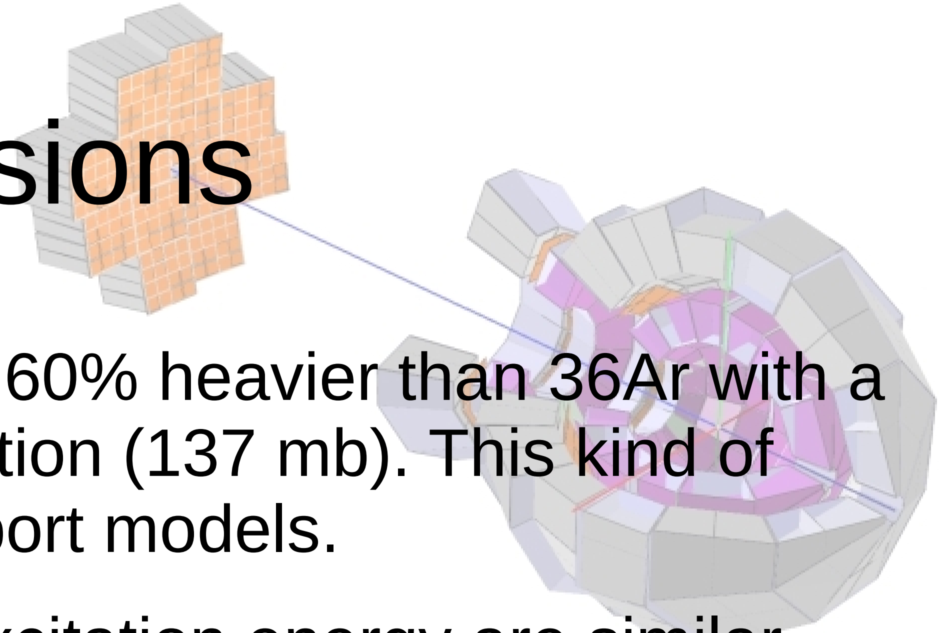
To be done with INDRA-FAZIA

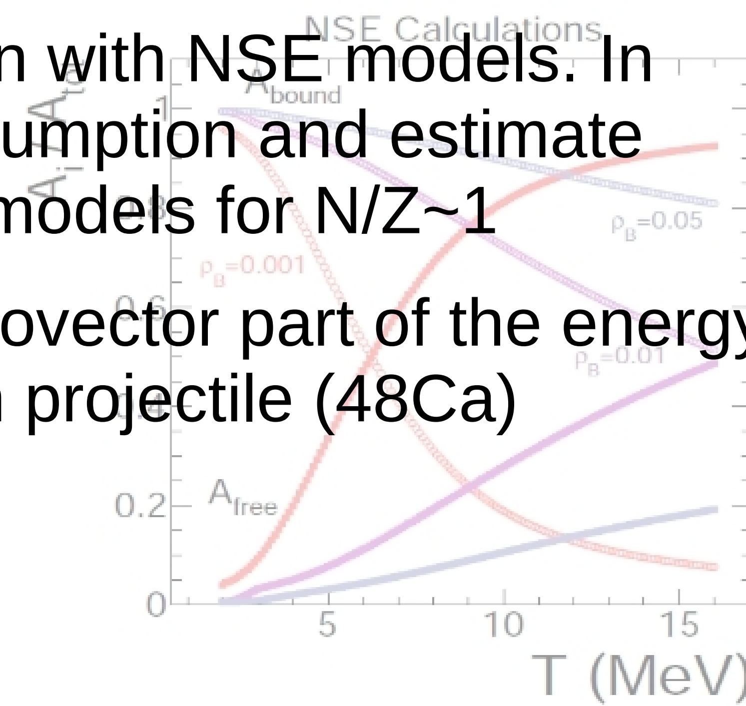
Already done with INDRA

Conclusions

- Vaporization observed in 58Ni, 60% heavier than 36Ar with a significant measured cross section (137 mb). This kind of events is a challenge for transport models.
- Isotopic yields evolution with excitation energy are similar independently of the considered sizes
- Very promising data for comparison with NSE models. In first step check the equilibrium assumption and estimate density and temperature from the models for N/Z~1
- Constrain the symmetry energy (Isovector part of the energy functional) using more neutron rich projectile (48Ca)

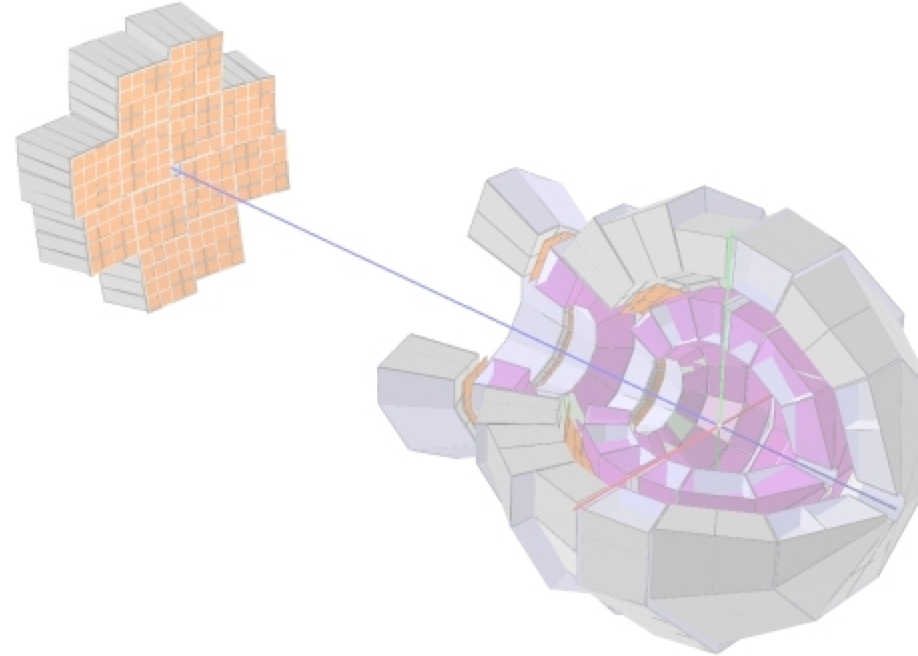






SMF Calculations

Trajectories in r-space



Thank you for your attention

NSE Calculations