Hot News from **INDRA**
&
the Scientific **INDRA+FAZIA** Program at **GANIL**

Olivier LOPEZ, LPC Caen, France
(INDRA-FAZIA collaboration)

Outlines

Hot news from INDRA

- **Isospin transport** and ***N/Z* equilibration**
  R. Bougault, et al., PRC 97, 024612 (2018)
- **Mean-Field fluctuations and dynamics** : **spinodal instabilities** in asymmetric *NM*
  B. Borderie, et al., accepted to PLB (2018)
- **Thermodynamics** : **caloric curves** for hot nuclei
  E. Vient, et al., accepted to EPJA (2018) : Thermometry
  E. Vient, et al., accepted to PRC (2018) : 3D calorimety
- **Thermo-statistics** : ***N/Z* dependence** of the **level density parameter (INDRA+VAMOS)**
  L. Augey and P. St-Onge, PHD 2018
- Improving **INDRA identification** : going beyond standard *E-ΔE* identification
  O. Lopez, M. Parlog, et al., NIM A ***884*** *(2018)*

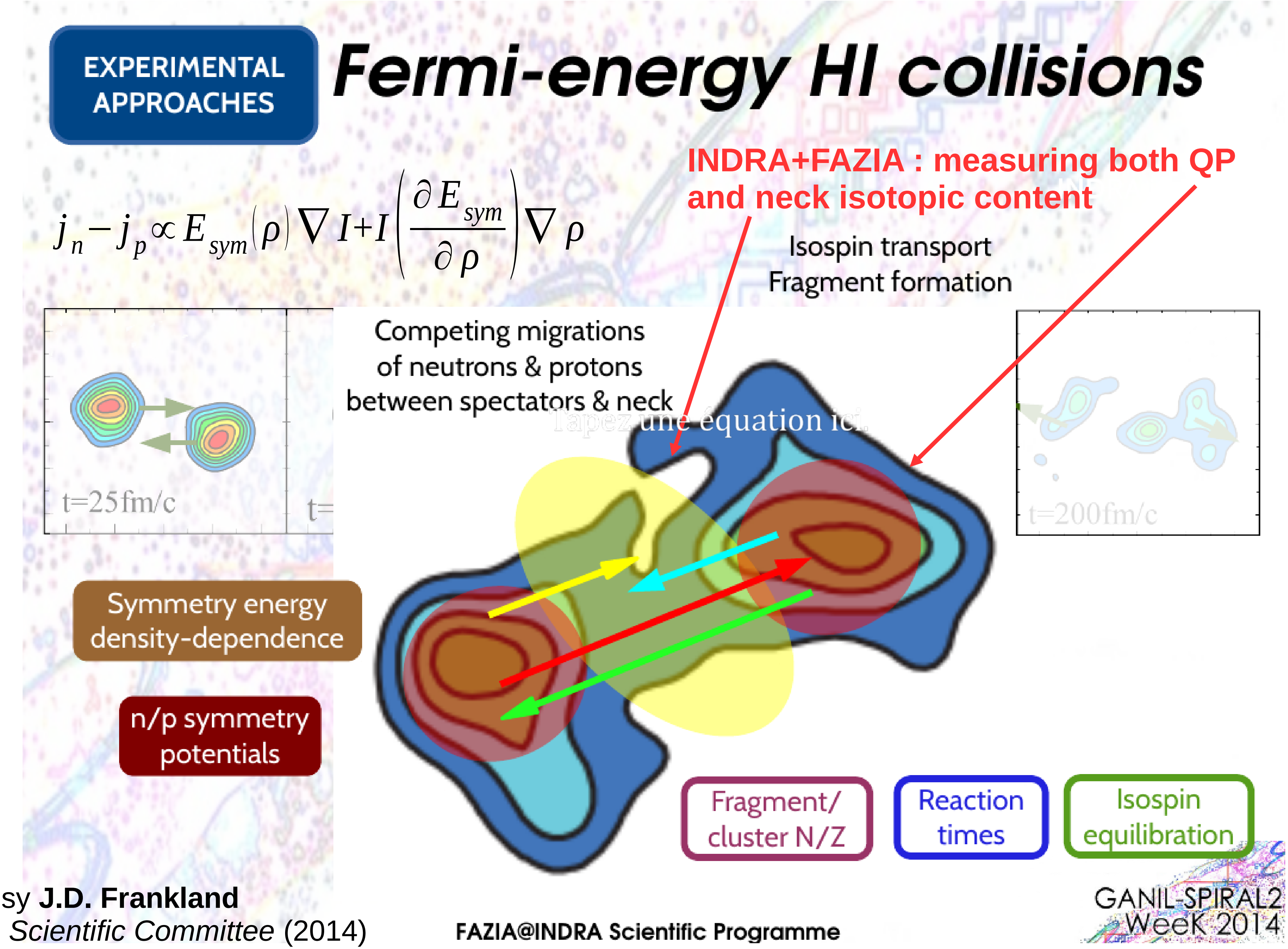
INDRA+FAZIA experimental program @ GANIL

- **FAZIA** status : **demonstrator commissioning**
- **INDRA+FAZIA** coupling
- Full program @ **GANIL for 2019-2022**

Isospin transport:

toward chemical equilibrium ?

Density Dependence of Symmetry Energy : neck + QP



EXPERIMENTAL APPROACHES

Fermi-energy HI collisions

INDRA+FAZIA : measuring both QP and neck isotopic content

$$j_n - j_p \propto E_{sym}(\rho)\nabla I + I\left(\frac{\partial E_{sym}}{\partial \rho}\right)\nabla \rho$$

Isospin transport
Fragment formation

Competing migrations
of neutrons & protons
between spectators & neck

Tapez une équation ici.

Symmetry energy density-dependence

n/p symmetry potentials

Fragment/ cluster N/Z

Reaction times

Isospin equilibration

FAZIA@INDRA Scientific Programme

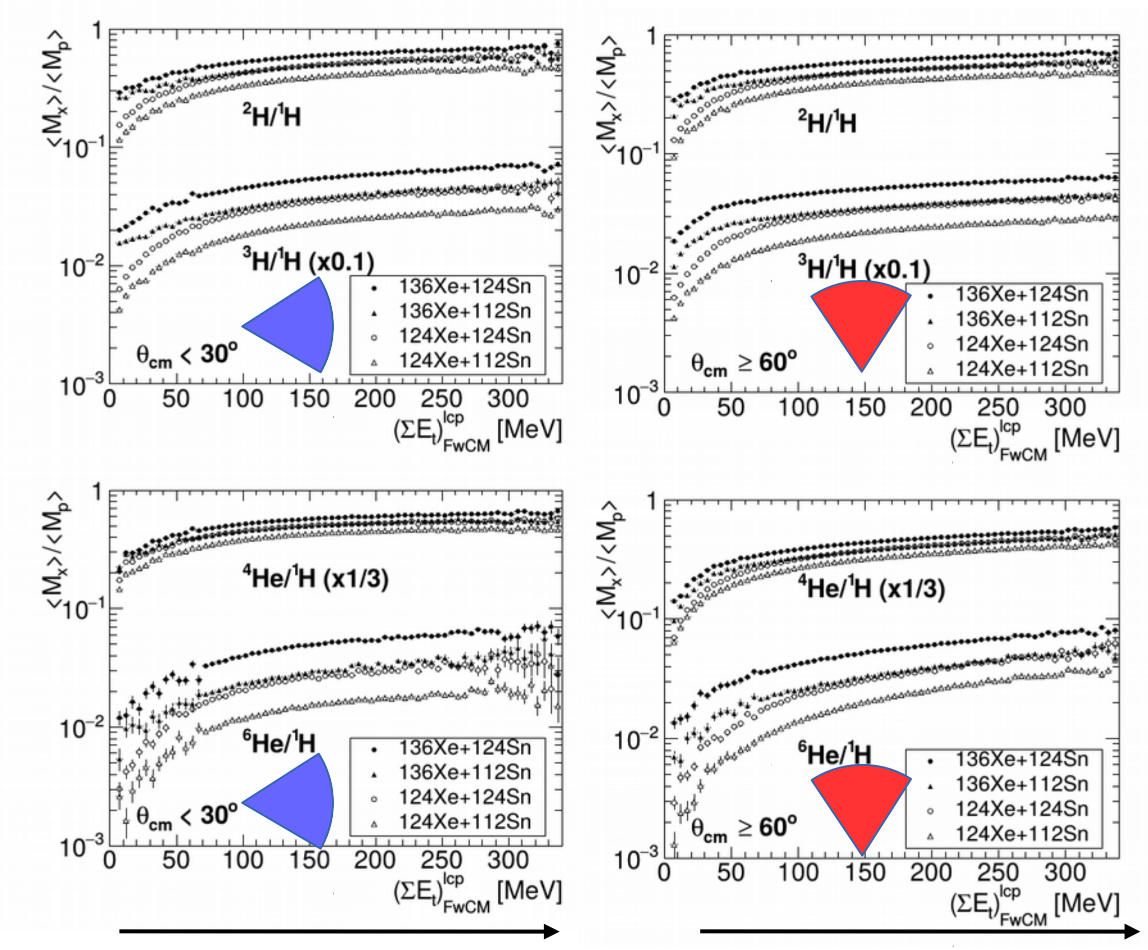
GANIL-SPIRAL2 Week 2014

Courtesy **J.D. Frankland**
GANIL Scientific Committee (2014)

Chemical equilibration : Isospin diffusion and migration

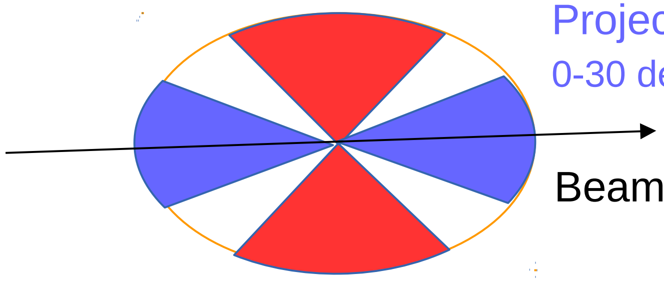
$^{124/136}$Xe + $^{112/124}$Sn at 32A MeV : INDRA data

Abundance ratios for small clusters/lcp : *d,t,^{3}He,α, ^{6}He*



centrality

centrality



Results in contradiction with

A.L. Kelsis, *et al.*, PRC 81, 054602 (2010)
Z.Y. Sun, *et al.*, PRC 82, 051603(R) (2010)

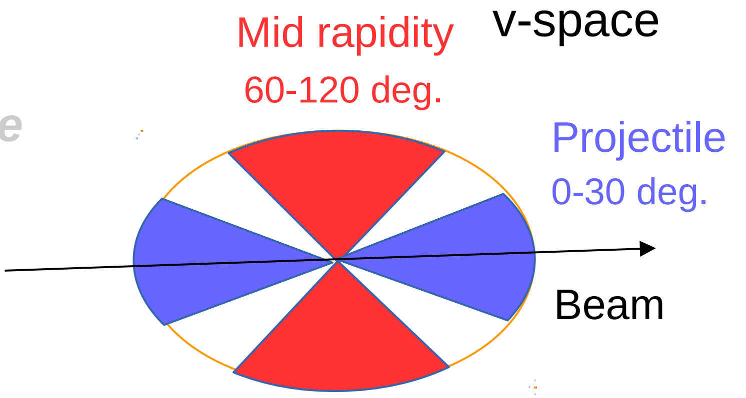
R. Bougault *et al*, (INDRA Coll.)
PRC **97**, 024612 (2018)

- **Chemical equilibrium is found** for *d,t,^{3}He,α,^{6}He* in **central collisions (*E_t>200 MeV*)**

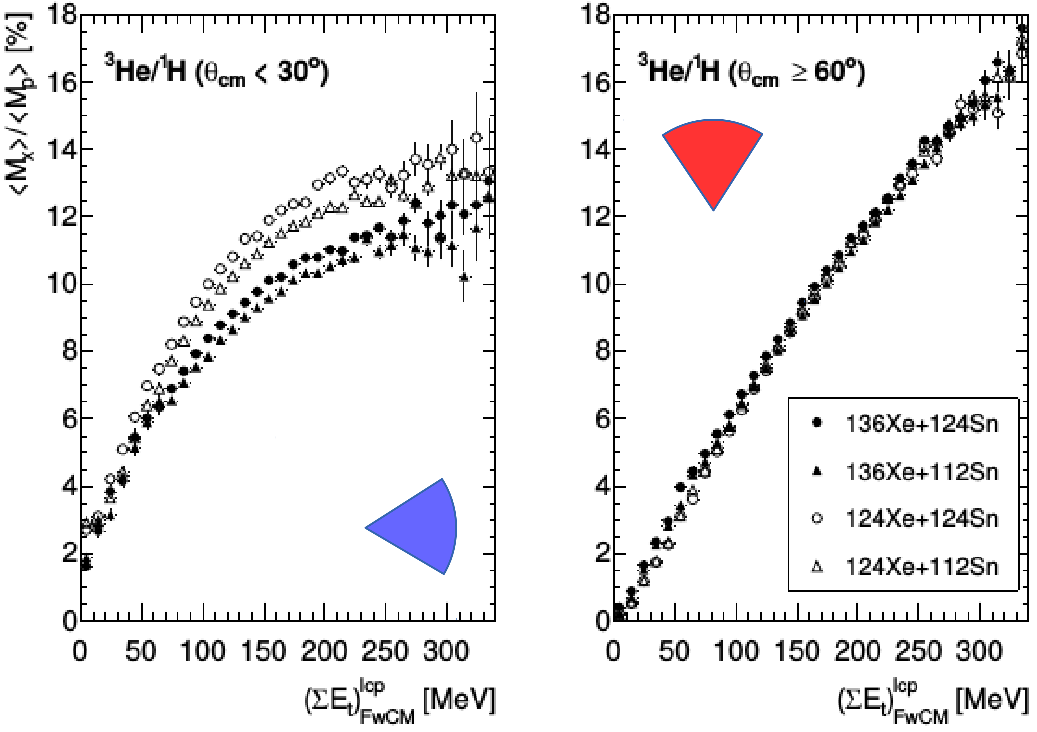
Chemical equilibration : Isospin diffusion and migration

$^{124/136}$Xe + $^{112/124}$Sn at 32A MeV : INDRA data

Abundance ratios for small clusters/lcp : *$d,t,{}^{3}He,\alpha,{}^{6}He$*



R. Bougault *et al*, PRC **97**, 024612 (2018)



centrality

Time sequence:

^{3}He emission prior to *N/Z* equilibration ?

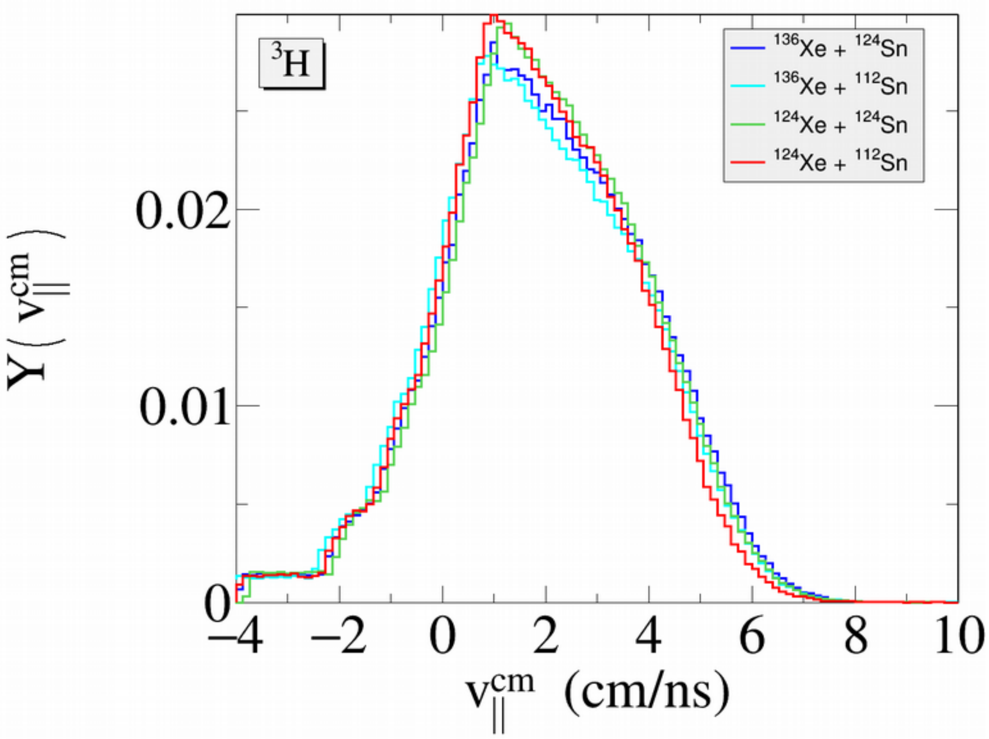
***N/Z* equilibration time ?**
A. Rodriguez Manso, *et al.*,
PRC 95, 044604 (2017)
See this conference

- **No Chemical equilibrium** for *^{3}He* in **central collisions**
- At mid-rapidity: *^{3}He* is **insensitive** to the entrance ***N/Z***

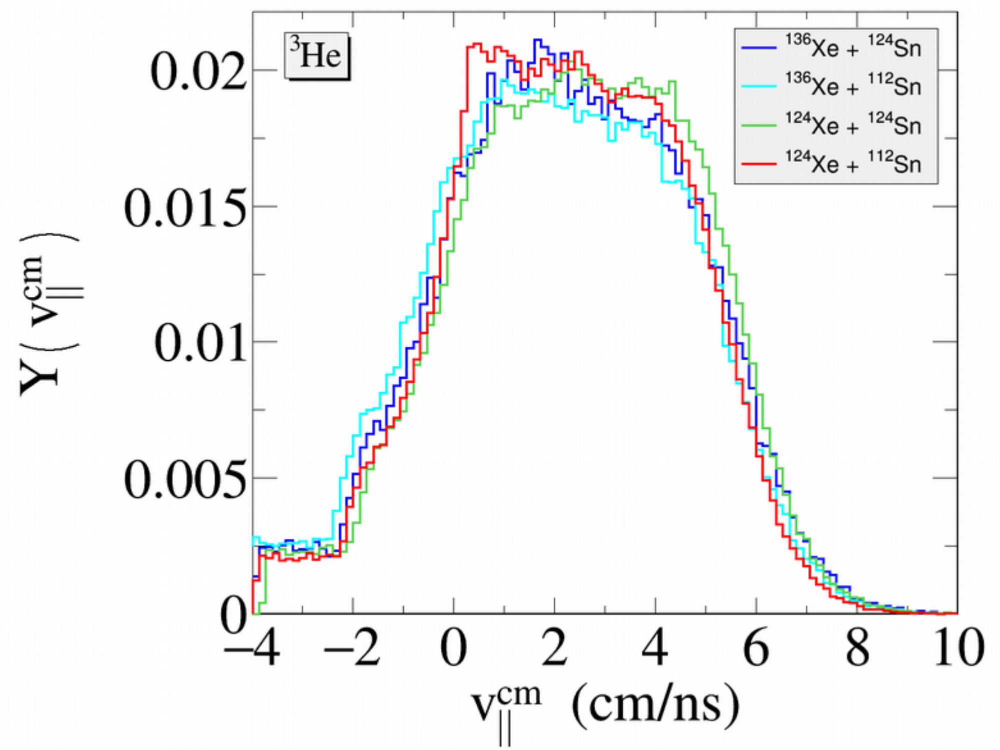
Transport properties in nuclear matter : *N/Z* equilibration

- Investigation of **experimental rapidity** distributions for ***^{3}H* and *^{3}He* at *32A MeV*** in **central collisions** (multiplicity selection)

High Multiplicity gate



M. Henri (LPC Caen), PHD Thesis (2018)



- Probe ***N/Z* equilibration** in central collisions for *$^{136/124}$Xe+$^{124/112}$Sn 32A MeV*
- **Coalescence model** for ***A=3*** clusters and comparison with experimental velocity distributions : better understanding of the **trends** and **yields**

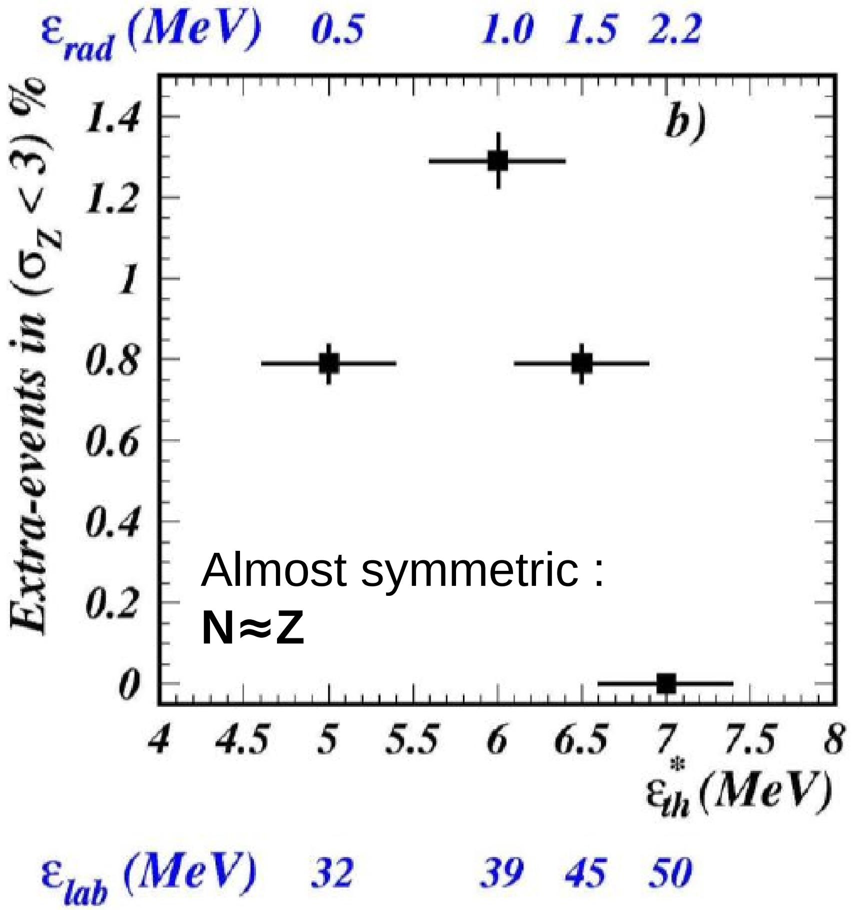
→ ***See M. Henri's talk in this conference***

Fragmentation :

Mean-field fluctuations

Spinodal decomposition: isoscalar *vs* isovector instabilities

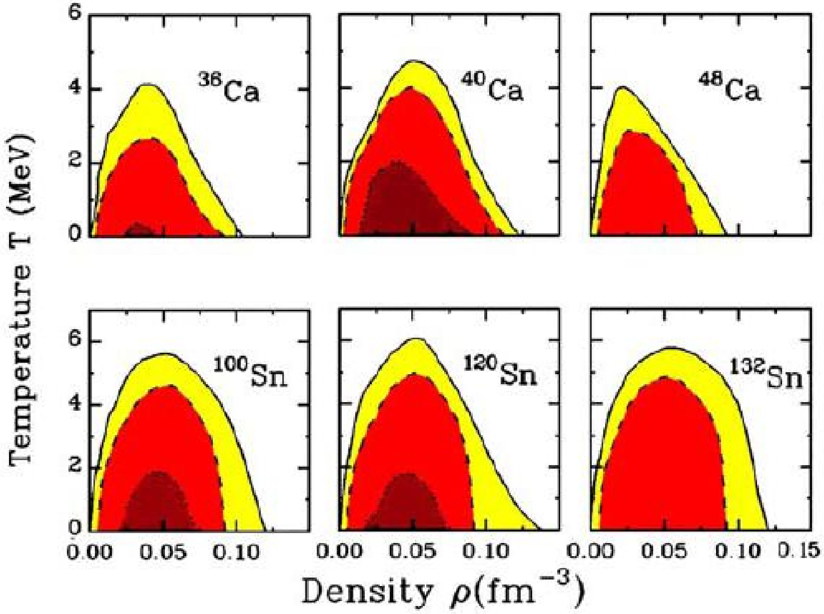
Spinodal decomposition and dynamics of fragmentation
High-order correlations in charge : *^{129}Xe+^{nat}Sn 32A-50A MeV*



Almost symmetric :
N≈Z

B. Borderie et al., (INDRA Coll.)
PRL **86**, 3252-3255 (2001)

Spinodal region is reduced → ***N/Z***



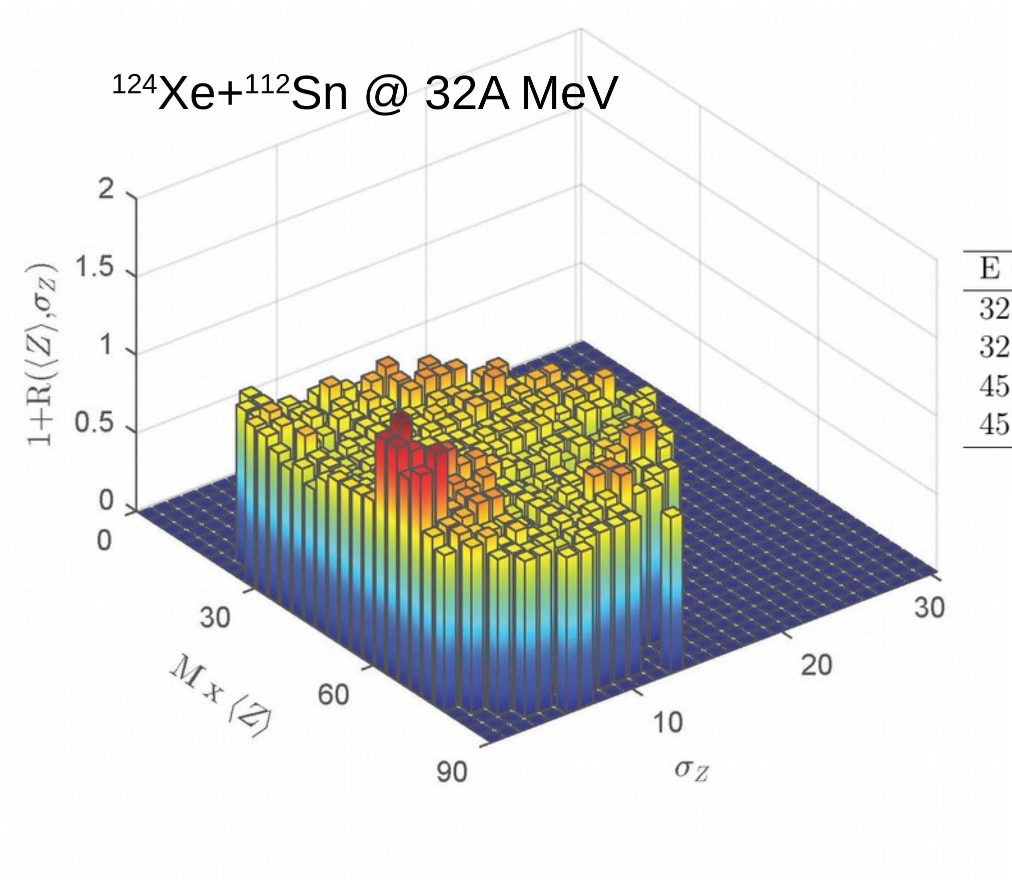
instability growth time dashed lines 100 fm/c
dotted lines 50 fm/c

M. Colonna *et al.*, PRL **88**, 122701 (2002)

- **Isospin dependence of the phase diagram ?**
- **Correlations with masses (isocalar) and isospin (isovector)**

Spinodal decomposition: isoscalar *vs* isovector instabilities

Same analysis done for **quasi-fused** events
^{124}Xe+^{112}Sn @ 32A,45A MeV
^{136}Xe+^{124}Sn @ 32A,45A MeV

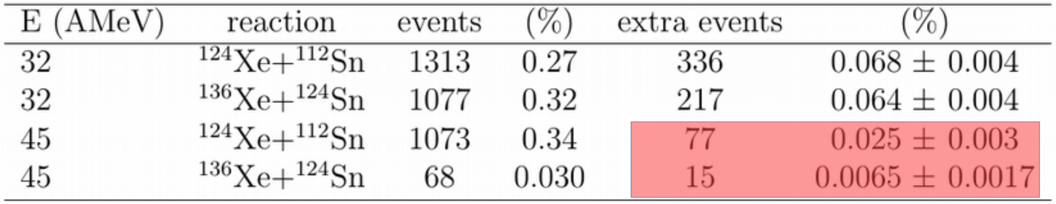


^{124}Xe+^{112}Sn @ 32A MeV

Spinodal instabilities are indeed reduced in neutron-rich matter …

Here between *I=0.21* (136+124) and *I=0.11* (124+112)

-50 % at 32A MeV
-80 % at 45A MeV



E (AMeV)	reaction	events	(%)	extra events	(%)
32	^{124}Xe+^{112}Sn	1313	0.27	336	0.068 ± 0.004
32	^{136}Xe+^{124}Sn	1077	0.32	217	0.064 ± 0.004
45	^{124}Xe+^{112}Sn	1073	0.34	77	0.025 ± 0.003
45	^{136}Xe+^{124}Sn	68	0.030	15	0.0065 ± 0.0017

Factor of 3

B. Borderie *et al.* (INDRA Coll.)
accepted in **PLB**

- **Equal-sized** fragments are **over-produced :** confirmation for **spinodal decomposition**
- **Statistical confidence** is **largely enhanced** (*10x* statistics) to overcome the **5σ limit** ...

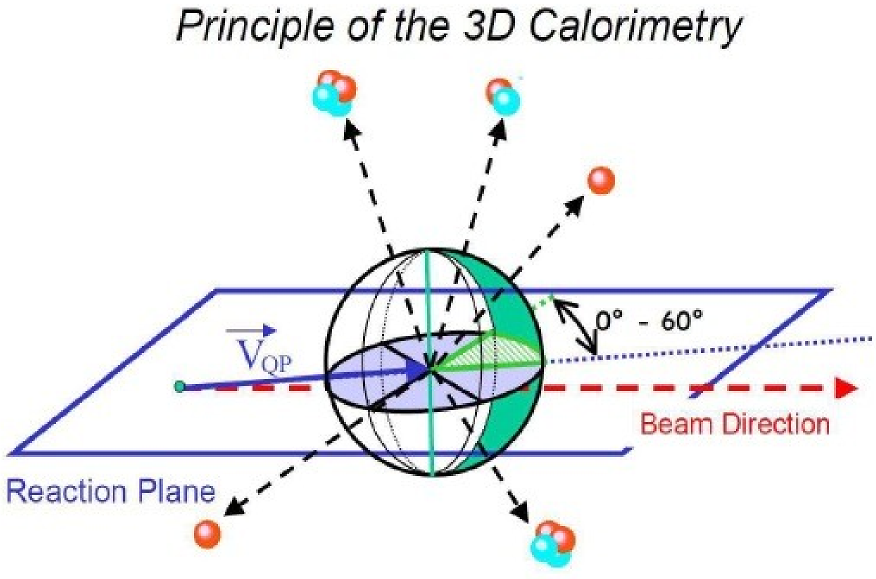
Hot nuclei Thermodynamics

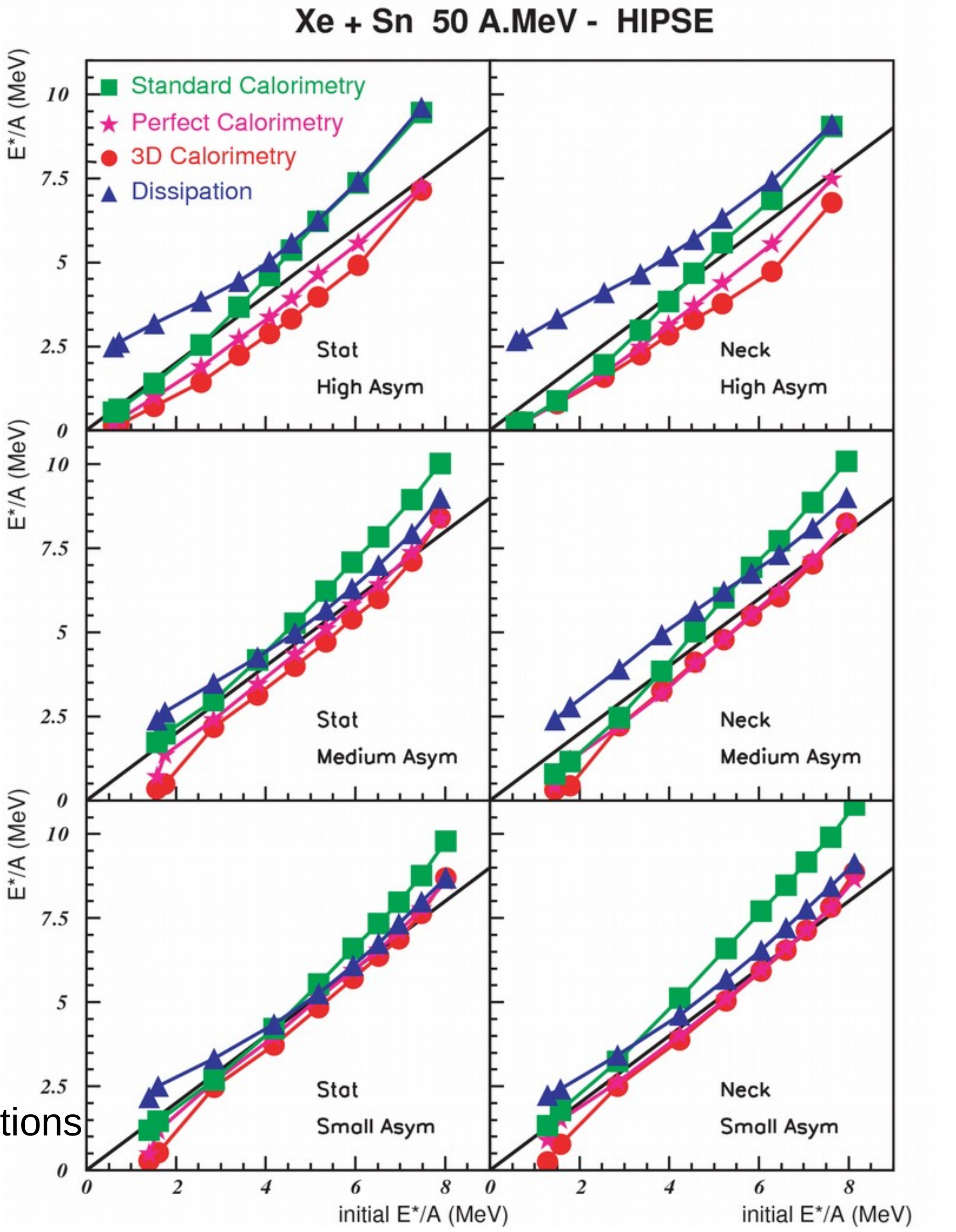
3D calorimetry for hot nuclei

Divide the **forward velocity hemisphere** in **angular slices** of azimuthal angle **φ**

Select the **best zone** (HIPSE) for evaporated particles from *QP* : **angular slice in φ=[0,60°]**

Need a **full 3D reconstruction** of *QP*

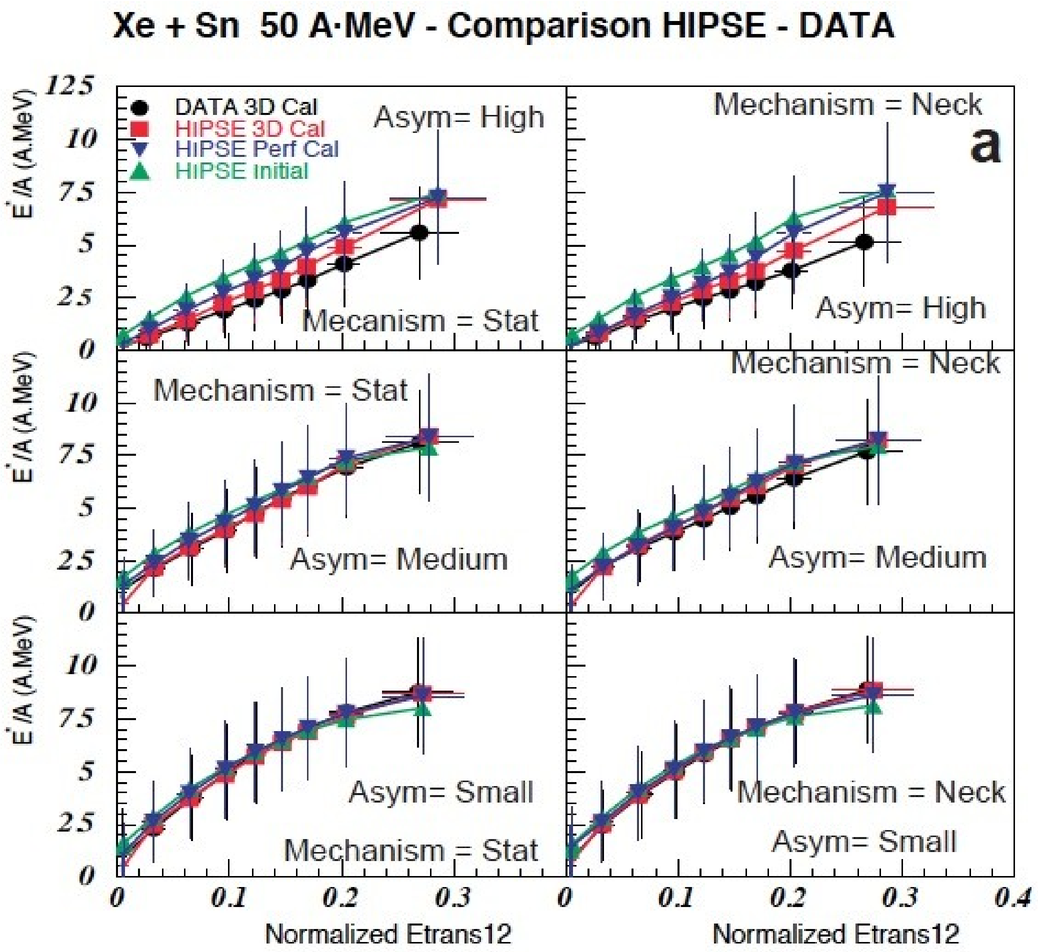


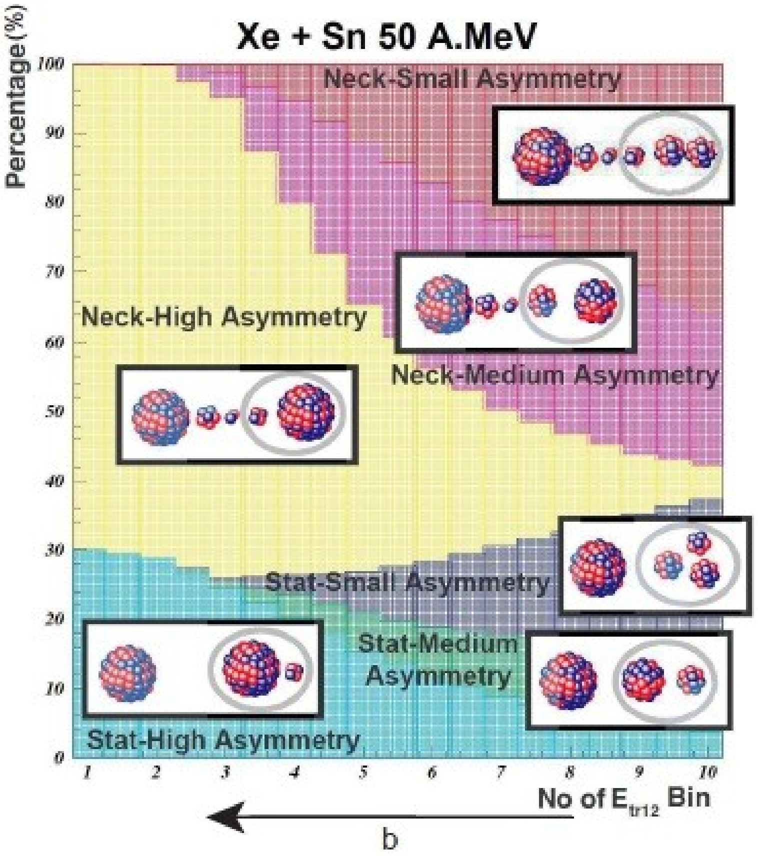


E. Vient, *et al.*, (INDRA Coll.) accepted to EPJA : simulations

E. Vient, *et al.*, (INDRA Coll.) accepted to PRC : results

3D calorimetry for hot nuclei





Analysis as a function of **neck asymmetry**

Systematic comparison between **exp. data and *HIPSE***

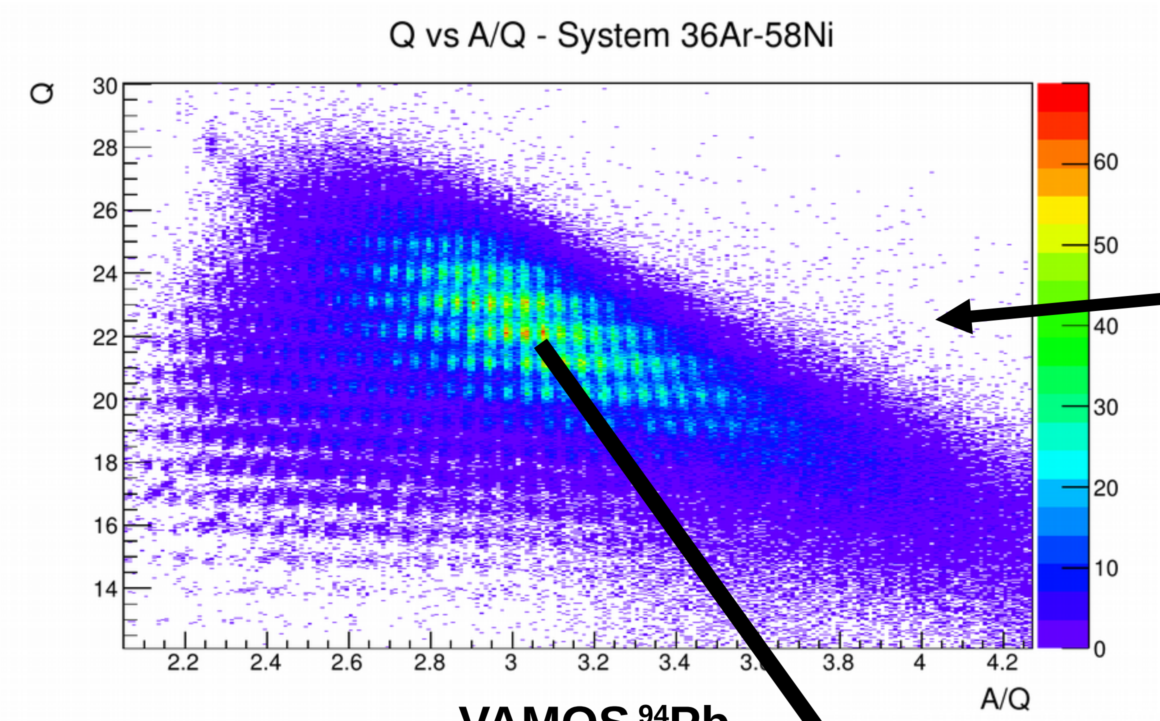
E. Vient, *et al.*, (INDRA Coll.) accepted to EPJA : simulations

E. Vient, *et al.*, (INDRA Coll.) accepted to PRC : results

Thermo-statistics :

Level Density parameter

Isospin dependence on level density parameter

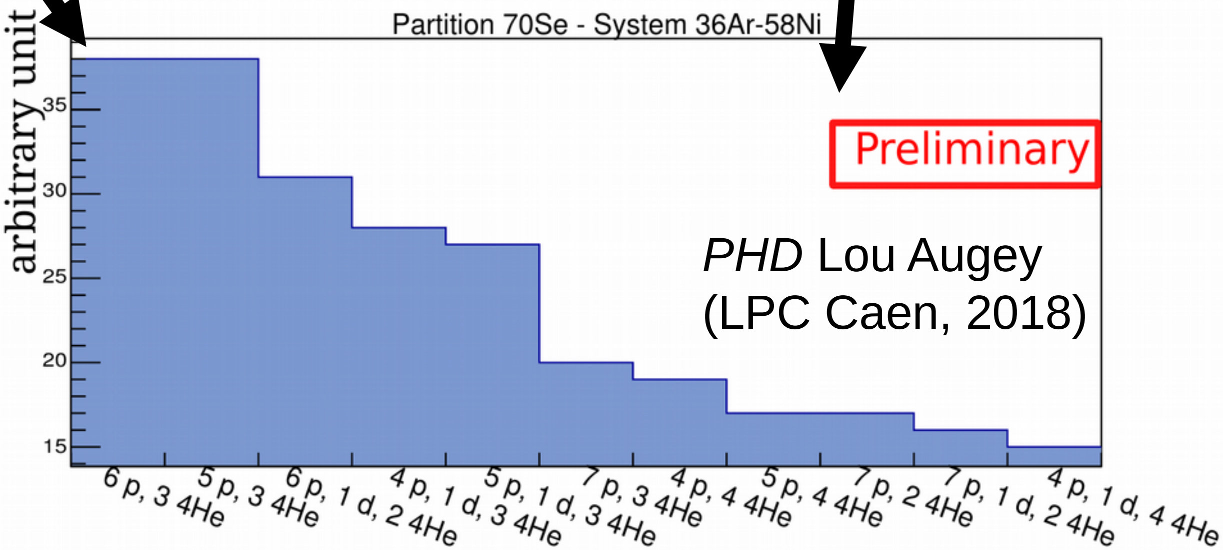


VAMOS ^{94}Pb

GANIL/SPIRAL1 @G1

INDRA *LCP*
p,d,t,^{3}He,α,^{6}He...

$^{94}_{46}Pd^* \rightarrow ^{70}_{34}Se + ...$



PHD Lou Augey
(LPC Caen, 2018)

All **evaporation channels**
(except neutrons) are evaluated !

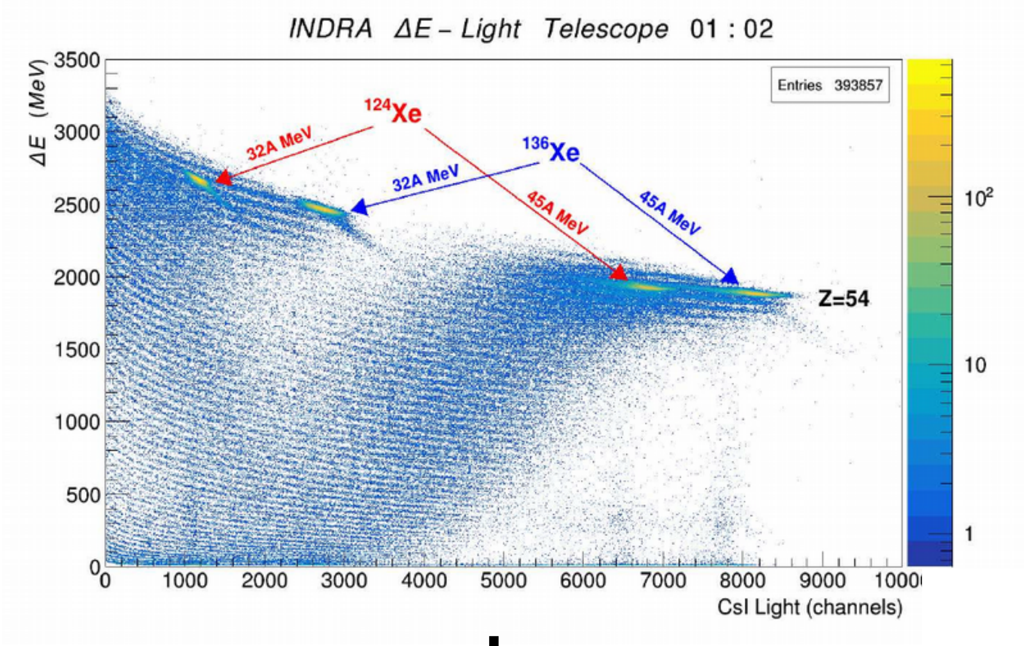
- Strong constraints on Stat. Models
- **Angular correlations** and
  time sequence are investigated

See P. St-Onge's talk in this conference

INDRA and *FAZIA*

Some (exciting) news

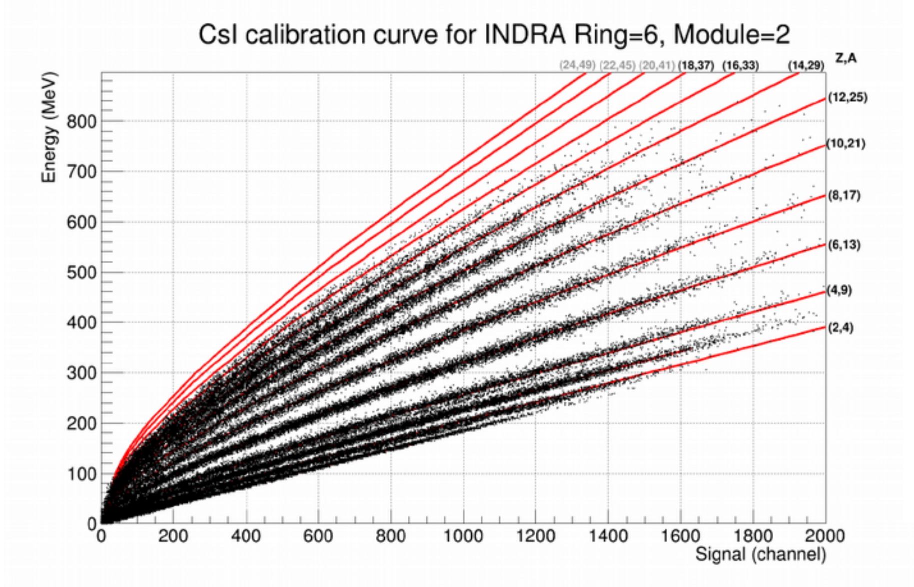
Improving isotopic identification for INDRA Si-CsI telescopes ...



Standard **CsI PSA/ E-ΔE** :
Isotopic ID up to ***Z=5-8***

With new method AME :
Isotopic ID up to Z=12-14
Mass estimate ±3 up to *Z=54* ...

+



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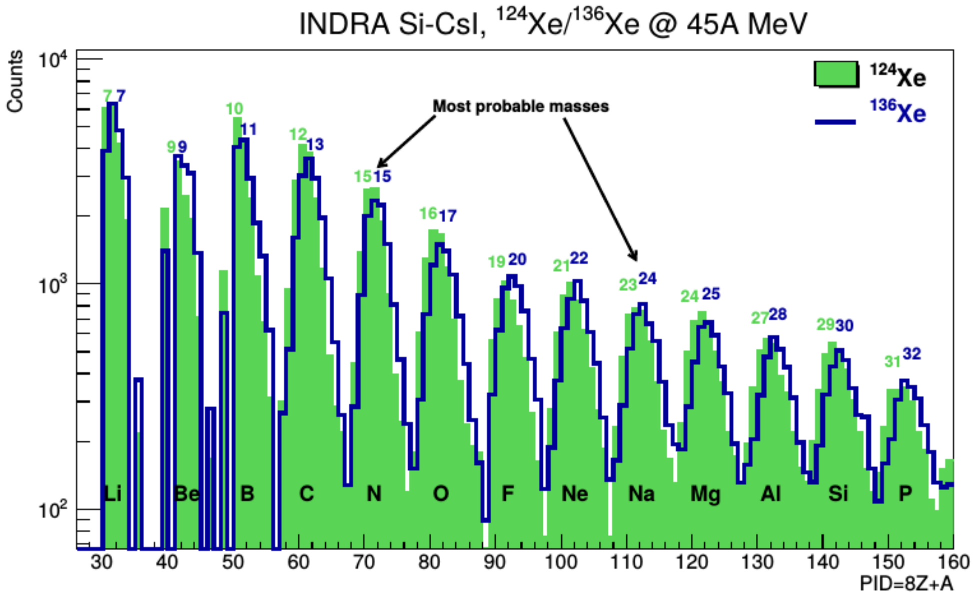
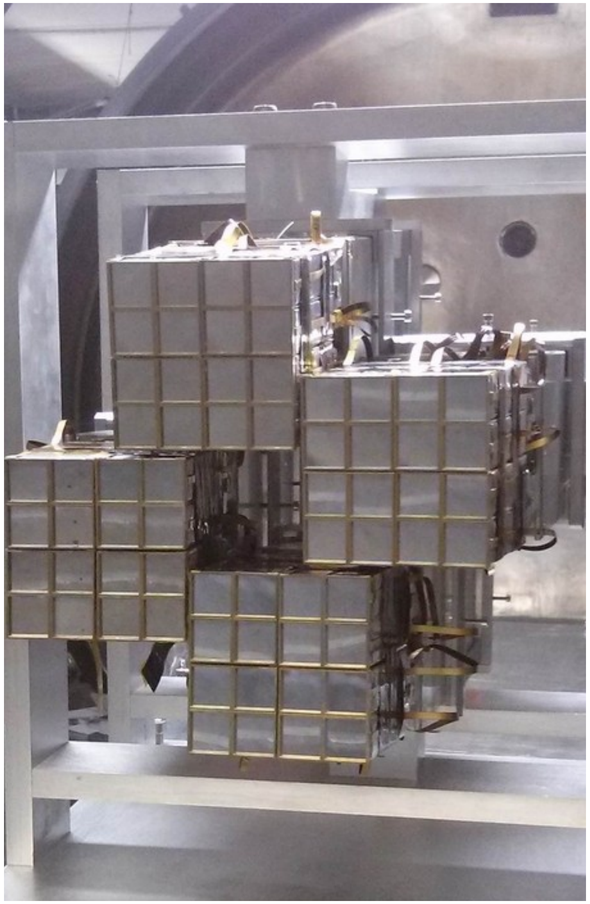


O. Lopez, M. Parlog *et al* (INDRA Coll.),
NIM A **884** (2018) 140-149

$$^{*}\mathcal{L}(E_0) = a_1 E_0 \left[1 - a_2 \frac{AZ^2}{E_0} \ln\left(1 + \frac{1}{a_2 AZ^2/E_0}\right) + a_2 a_4 \frac{AZ^2}{E_0} \ln\left(\frac{E_0 + a_2 AZ^2}{a_3 A + a_2 AZ^2}\right) \right] \quad (3)$$

FAZIA status : *N*-blocks configuration (*N=4,6*)

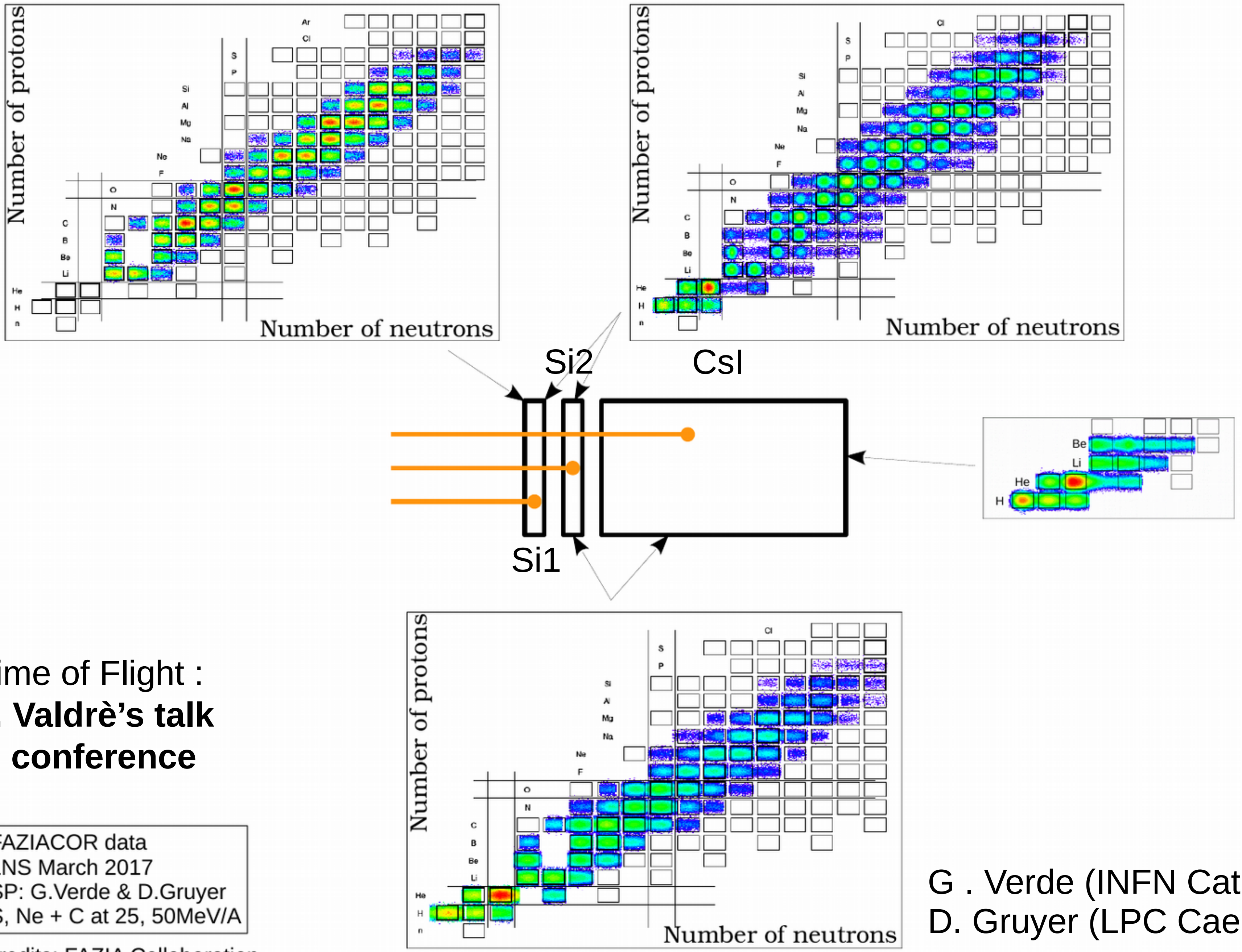
LNS 2017 : FAZIACOR
LNS 2018 : FAZIAPRE



FAZIA 12 blocks (demonstrator) is about to be commissioned at GANIL in the following months...

See D. Gruyer's talk in this conference
See A. Camaiani's talk in this conference

FAZIACor status for Identification



Also Time of Flight :
See S. Valdrè's talk in this conference

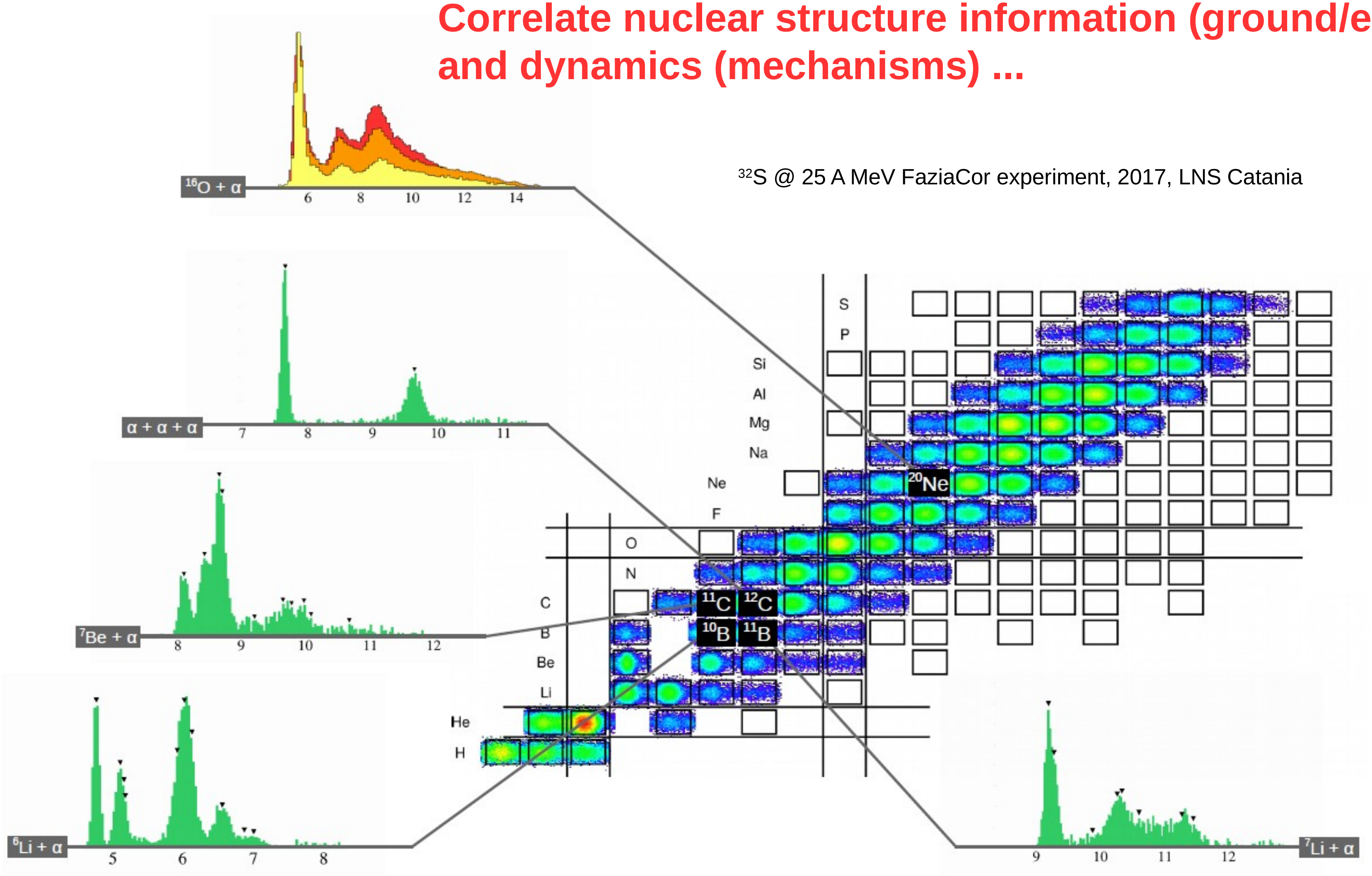
FAZIACOR data
LNS March 2017
SP: G.Verde & D.Gruyer
S, Ne + C at 25, 50MeV/A

Credits: FAZIA Collaboration

G . Verde (INFN Catania)
D. Gruyer (LPC Caen)

FAZIA: structure and dynamics using cluster correlations

Correlate nuclear structure information (ground/excited states) and dynamics (mechanisms) ...



^{32}S @ 25 A MeV FaziaCor experiment, 2017, LNS Catania

Courtesy : D. Gruyer for the FAZIA collaboration

See also D. Gruyer’s talk in this conference

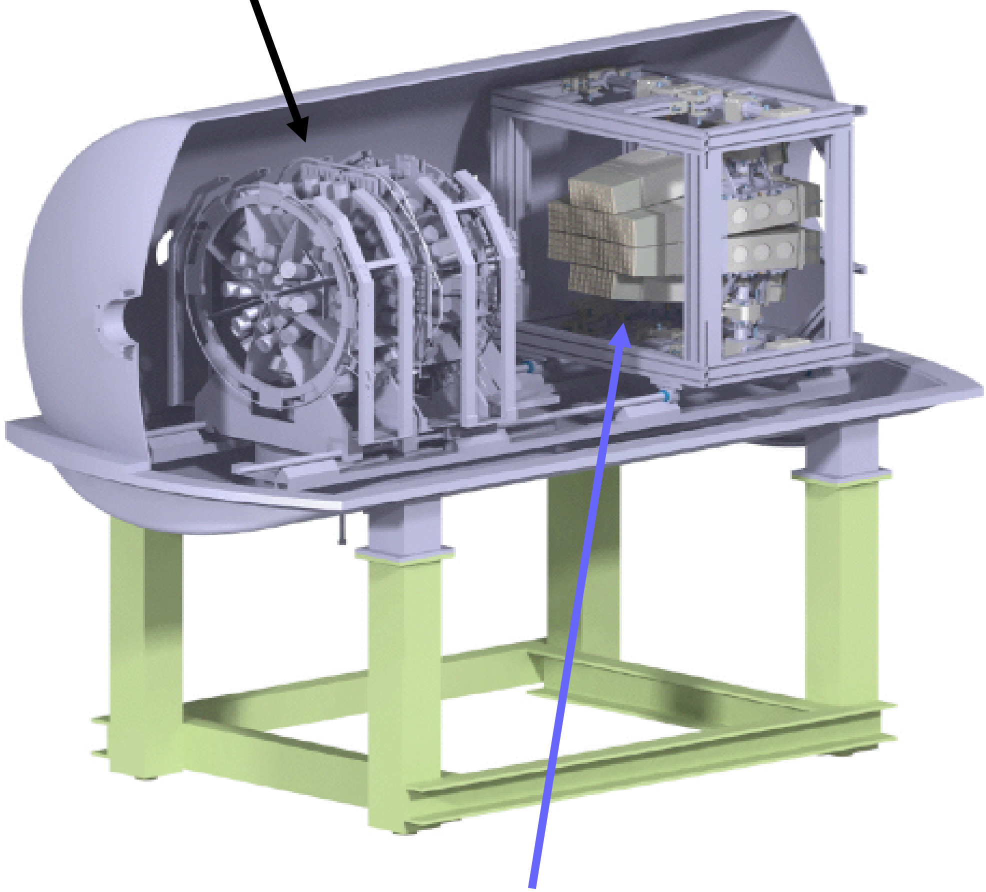
INDRA + FAZIA :

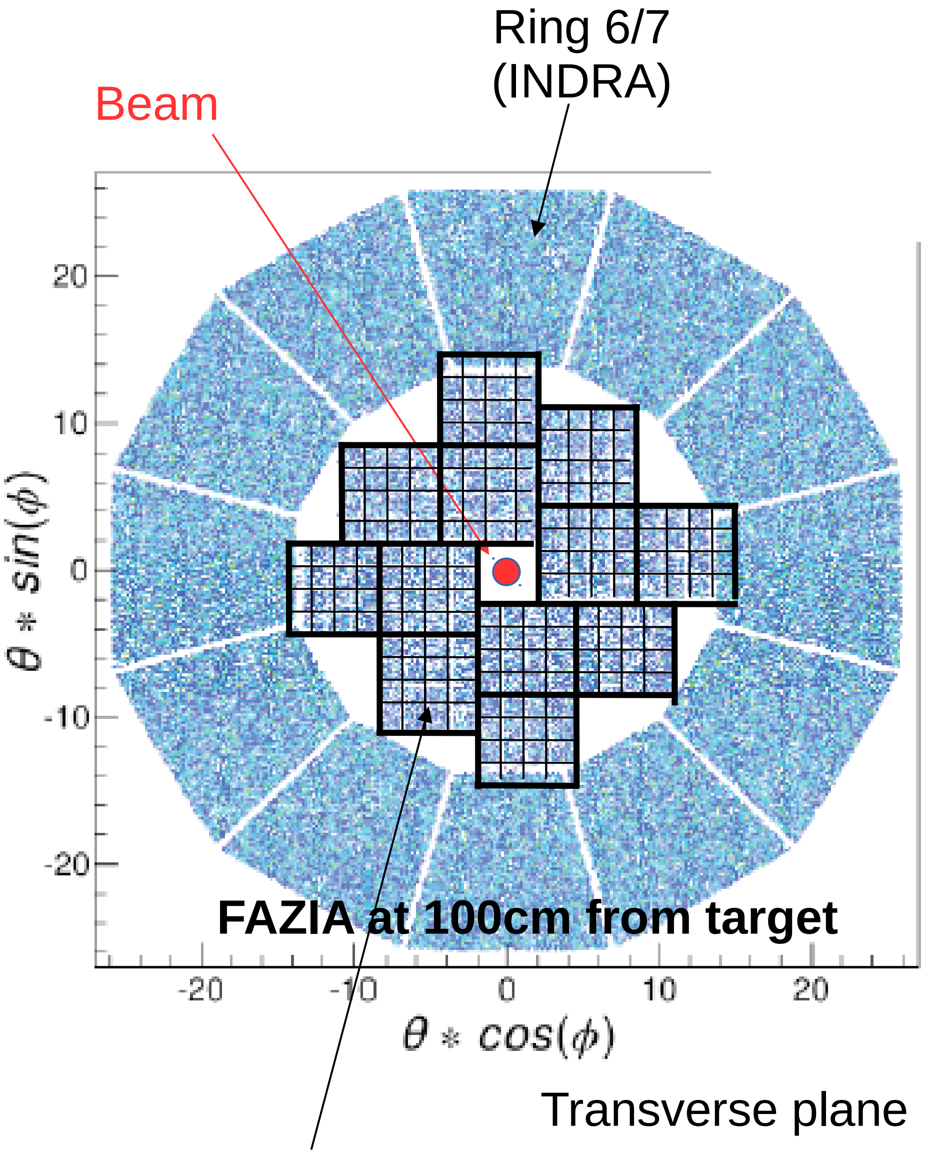
Scientific Program at *GANIL*

Coupling FAZIA demonstrator with INDRA

FAZIA (digital): *(Z,A)* ID up to *Z=25*
INDRA (analogic) : *(Z,A)* ID up to *Z=6-8*

INDRA in *D5* (rings 1,2/3,4/5 removed)

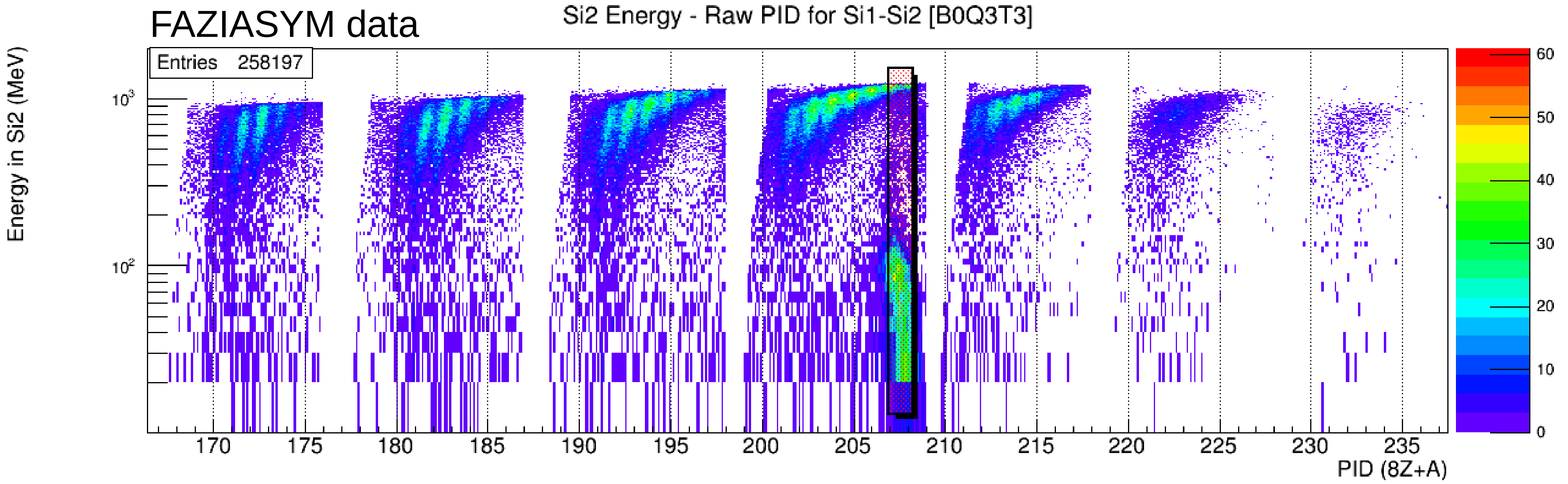


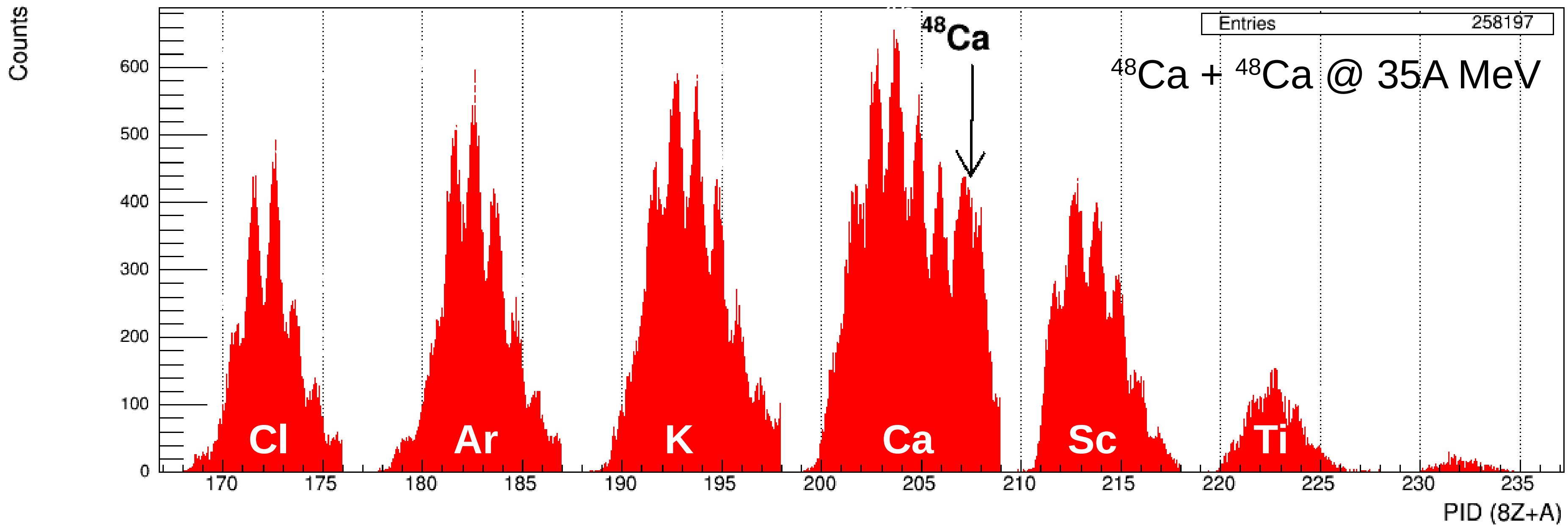


FAZIA demonstrator: *12* blocks of *16* telescopes
192 **High-Quality *Si-Si-CsI*** telescopes
from *2* to *14* deg. + dedicated **Full Digital Electronics**

Between *2-14* deg.
FAZIA geom. acceptance *82%* (*90%*)
Granularity *x2* as compared to *INDRA*

FAZIASym : Identification using AMI* grid





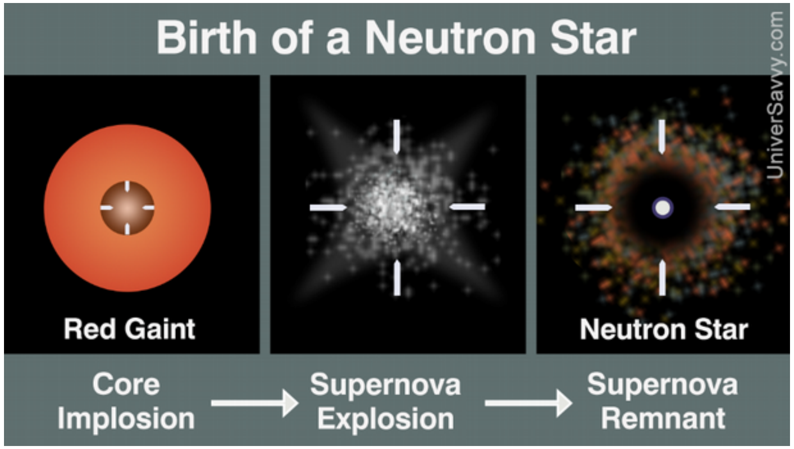
* Advanced Mass Identification :
M. Parlog and O. Lopez
Article in progress

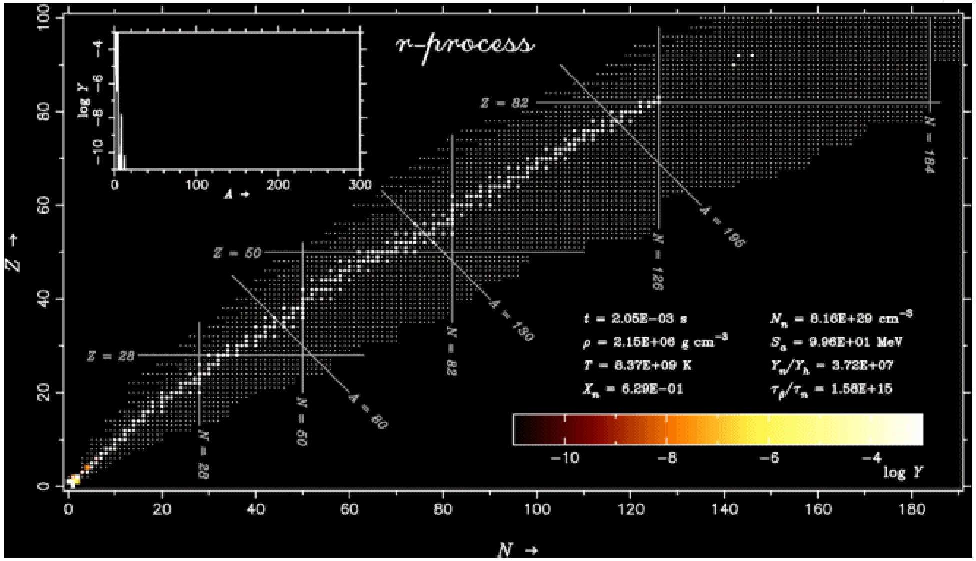
- Isotopic Identification is OK up to *Z≈20-22*

→ ***See A. Camaiani's talk in this conference***

Nuclear *EOS*

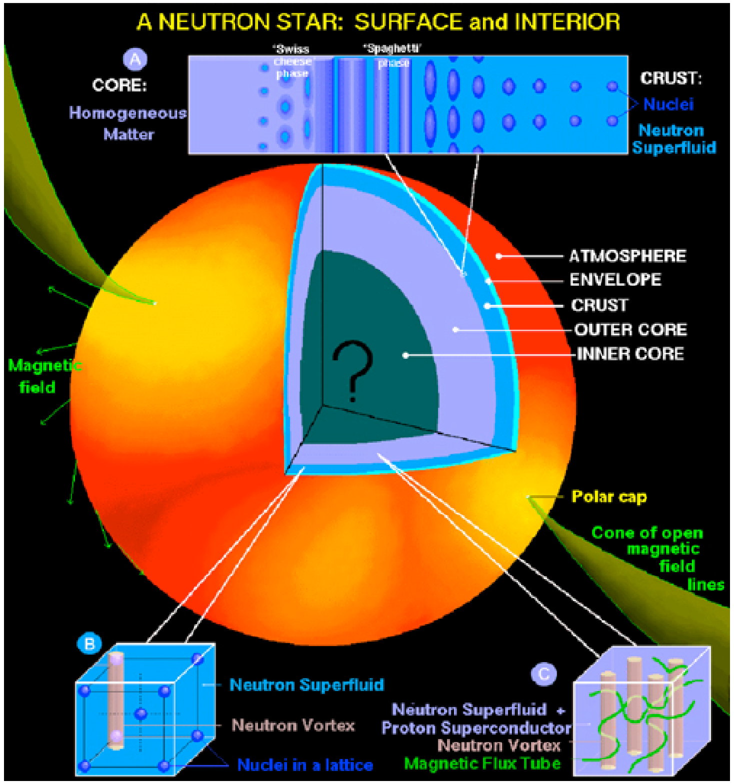
Nuclear *EOS* and Supernovae





Neutron Stars (*NS*) are ideal systems for investigating dense (nuclear) matter !

Detection of *GW* and multi-messenger observables considerably reinforces terrestrial *EOS* studies



NS core collapses and *NS* binary mergers:

- *EOS* (isoscalar/isovector) : shock waves
- E_{sym} : *r*-process and nucleosyntheis
- Cooling : d-URCA and Neutrinosphere (low density nuclear matter)

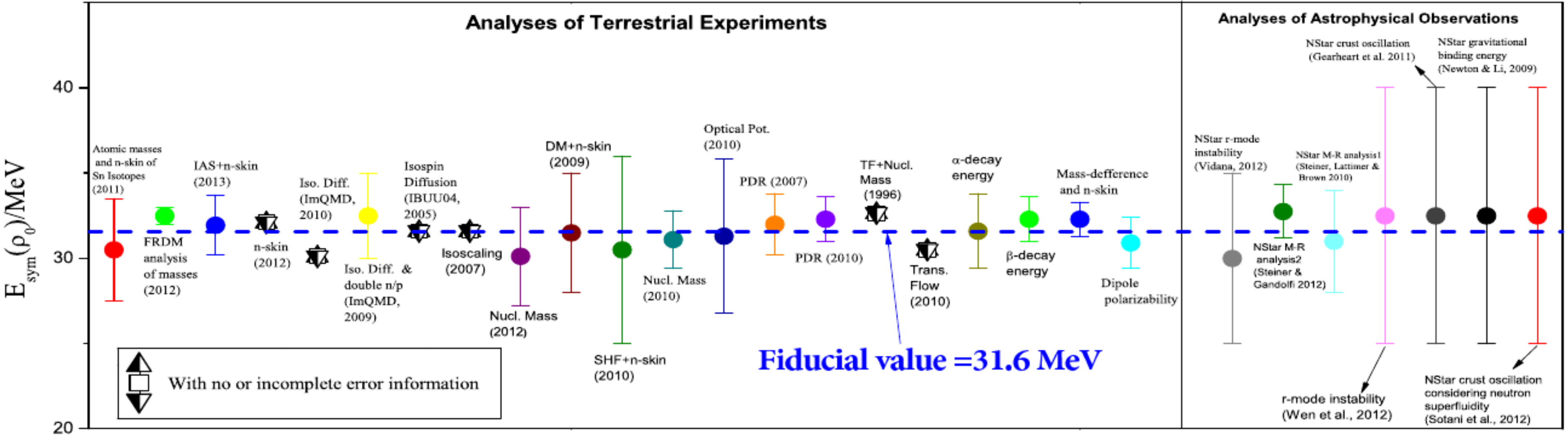
NS structure :

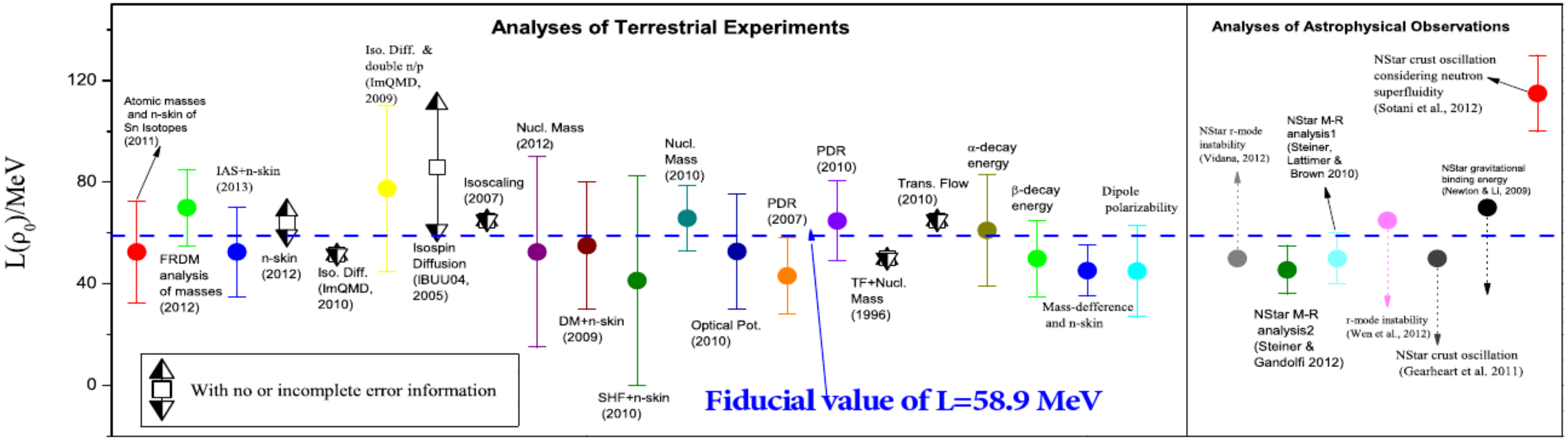
- Crust : pasta phases (frustation/clusters)
- Crust/Core transition: L,K_{sym}
- Core : hyperons (strange matter, QCD)

Symmetry Energy around ρ_0 : status

Latest world-wide evaluations for $E_{sym}(\rho_0)$ and slope parameter $L(\rho_0)$

B.A. Li and X. Han, Phys. Lett. B727 (2013) 276





Today (2018) :

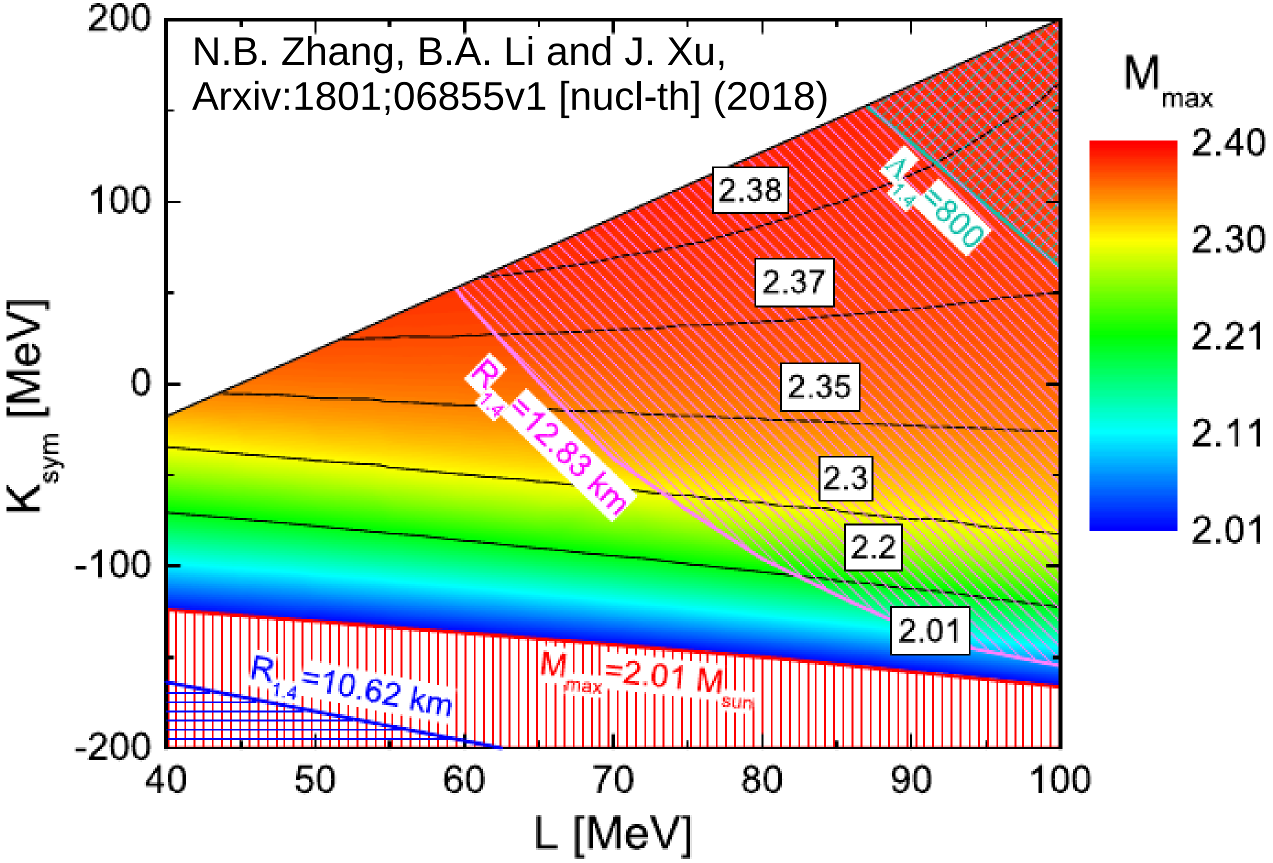
$E_{sym}(\rho_0) = 31.9 \pm 2.5$ MeV → 8% rel. uncertainty

$L(\rho_0) = 55.3 \pm 25$ MeV → 45% rel. uncertainty

$K_{sym}(\rho_0)$ not constrained → >100%

Observational constraints on isovector EOS

- **Canonical** Neutron Star radius : $R_{1.4} = 10.62 – 12.83\ km$
- Neutron Star **maximal mass** : $M_{max} > 2.01M_o$
- **Tidal deformability** : $\Lambda_{1.4}<800$ ***(new)***



N.B. Zhang, B.A. Li and J. Xu,
Arxiv:1801;06855v1 [nucl-th] (2018)

→ **Excluded areas are bounded by $M_{max}< 2.01M_o$ and $R_{1.4}> 12.83\ km$**

K_{sym} = -150 - 60 MeV, L = 40 - 80 MeV

M_{max} ≈ 2.37 for ***L ≈ 60 MeV*** and ***K_{sym} ≈ 50 MeV***

Symmetry Energy around ρ_0

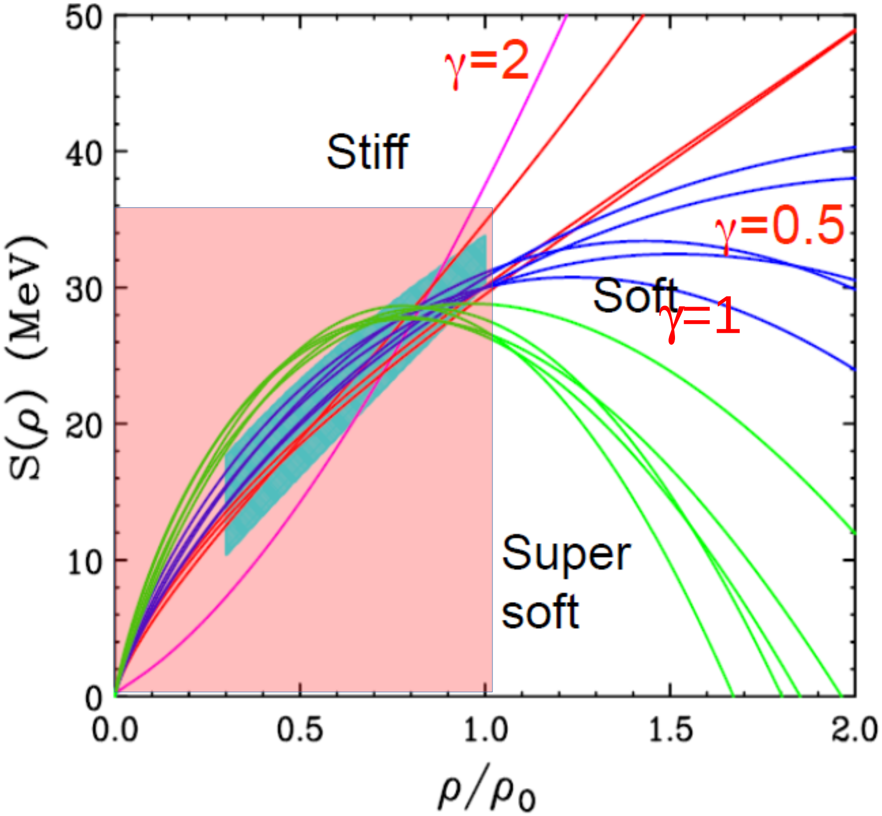
$$E/A(\rho,\delta) = E/A(\rho,0) + \delta^2 \cdot S(\rho)$$

$$\delta = (\rho_n - \rho_p)/(\rho_n + \rho_p) = (N-Z)/A$$

- Constraints for **Astrophysics** (*NS*) and for **Laboratory experiments**
- Needed for **transport models** and nuclear matter studies (Thermodyn.)
- Link to the ***NN* interaction** (isovector) in the nuclear medium ($m^*_{n,p}$)

B.A. Li, B.J. Cai, L.W. Chen and J. Xu
Prog. In Part. And Nucl. Phys. 99 (2018) 29-119

M.B. Tsang, Prog. Part.Nucl.Phys. 66, 400 (2011)
Brown, Phys. Rev. Lett. 85, 5296 (2001)



Density dependence for *SE*

$$S(\rho) = S_k(\rho/\rho_0)^{2/3} + S_i(\rho/\rho_0)^{\gamma}$$

$$L(\rho) = 3\rho \left.\frac{\partial S(\rho)}{\partial \rho}\right|_{\rho=\rho_0}$$

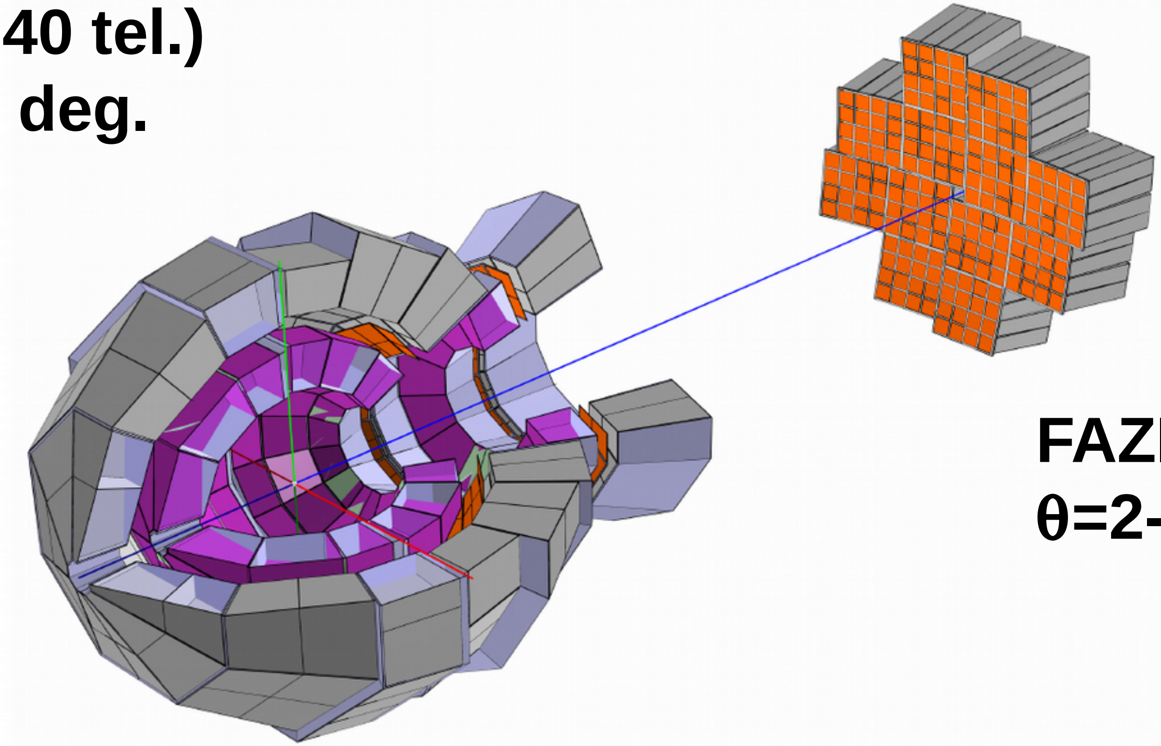
$$K_{sym}(\rho) = 9\rho^2 \left.\frac{\partial^2 S(\rho)}{\partial \rho^2}\right|_{\rho=\rho_0}$$

INDRA + FAZIA scientific program at GANIL (2019+)

1/ Nuclear Equation of State : ρ-scan for E_{sym} at $\rho<\rho_0$: *GANIL PAC 2018*

- **Density dependence** for **Symmetry Energy**: **isospin diffusion** in *DIC*, **Isoscaling** , **neutron enrichment** in the neck (**migration/diffusion)**
- ***EOS* at low density**: **vaporization** and **cluster mixing** with nucleon gas
- **In-medium** clusters formation: **clustering @ low density** (α–Hoyle states,
  cluster correlations in n-rich/poor systems)

INDRA (240 tel.)
θ=14-176 deg.



FAZIA (192 tel.)
θ=2-14 deg.

Symmetry Energy

at $\rho<\rho_0$

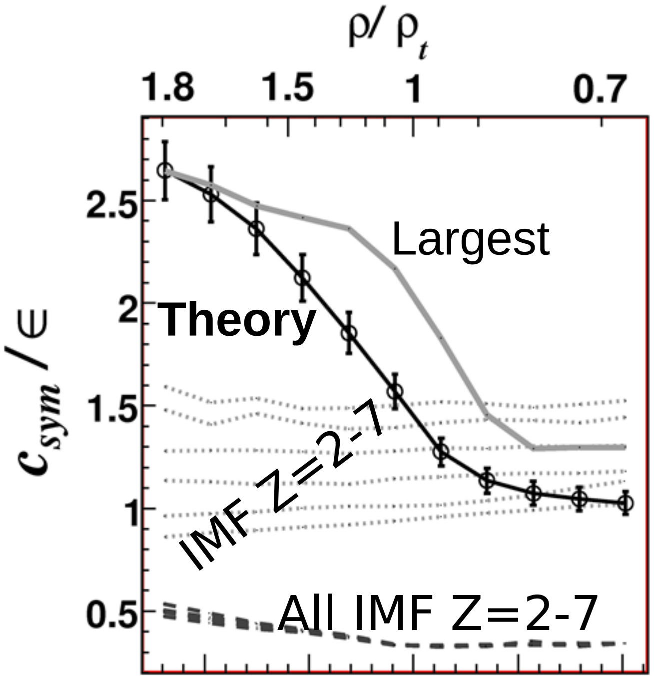
Density Dependence of Symmetry Energy : QP ($\rho<\rho_0$)

- **Isoscaling:** observed scaling law of fragment (*N,Z*) production for two reactions involving different isotopes (ex. $^{58/64}Ni, ^{124/136}Xe$)
- **Isoscaling**: can be related to the symmetry energy
- **Relationship**: different parametrizations from macro/microscopic approaches

3D Lattice-Gas Model: the isotopic distribution of the largest cluster in each event is more sensitive to the symmetry energy of the fragmenting system as compared to previous studies using mostly Light or Intermediate Mass Fragments (*Z=1-8*)

Physics case for INDRA+FAZIA : $^{58/64}Ni + ^{58/64}Ni$ @ *35A - 50A* MeV

- Measure the **isoscaling law** of the **largest fragments** for selected impact parameters
- Measure the density of the fragmenting system through **fragment-fragment correlations**
- Extract the **density dependence** of the symmetry energy as presented here

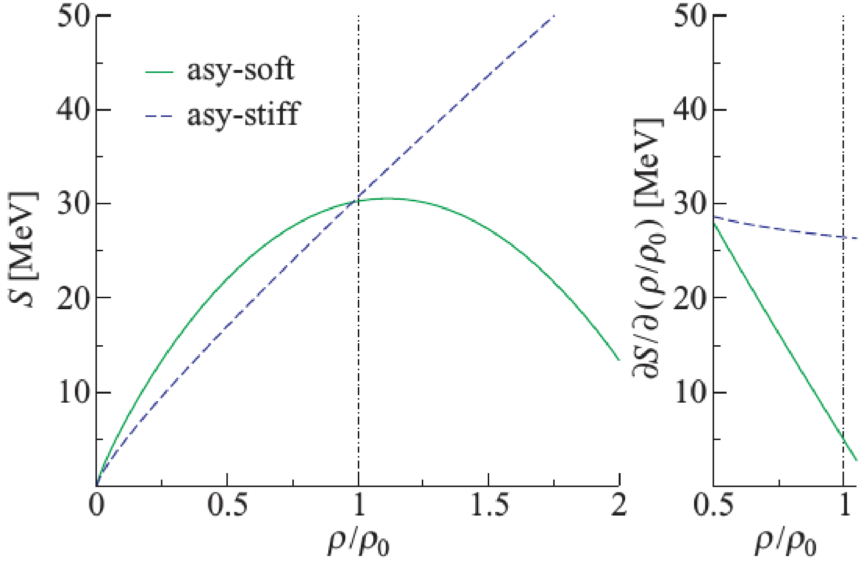


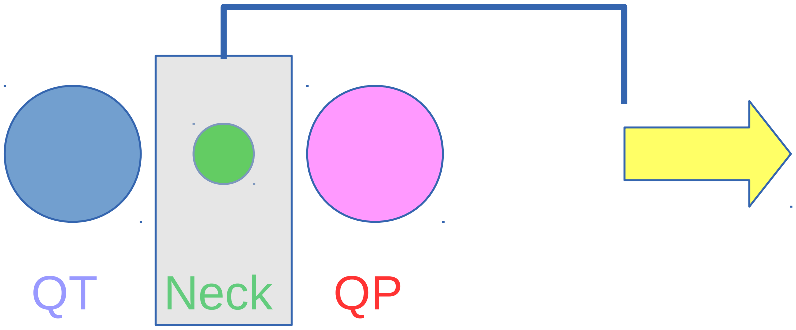
G. Lehaut *et al.* (INDRA coll.), *Phys. Rev Lett.* **102**, 142503 (2009)

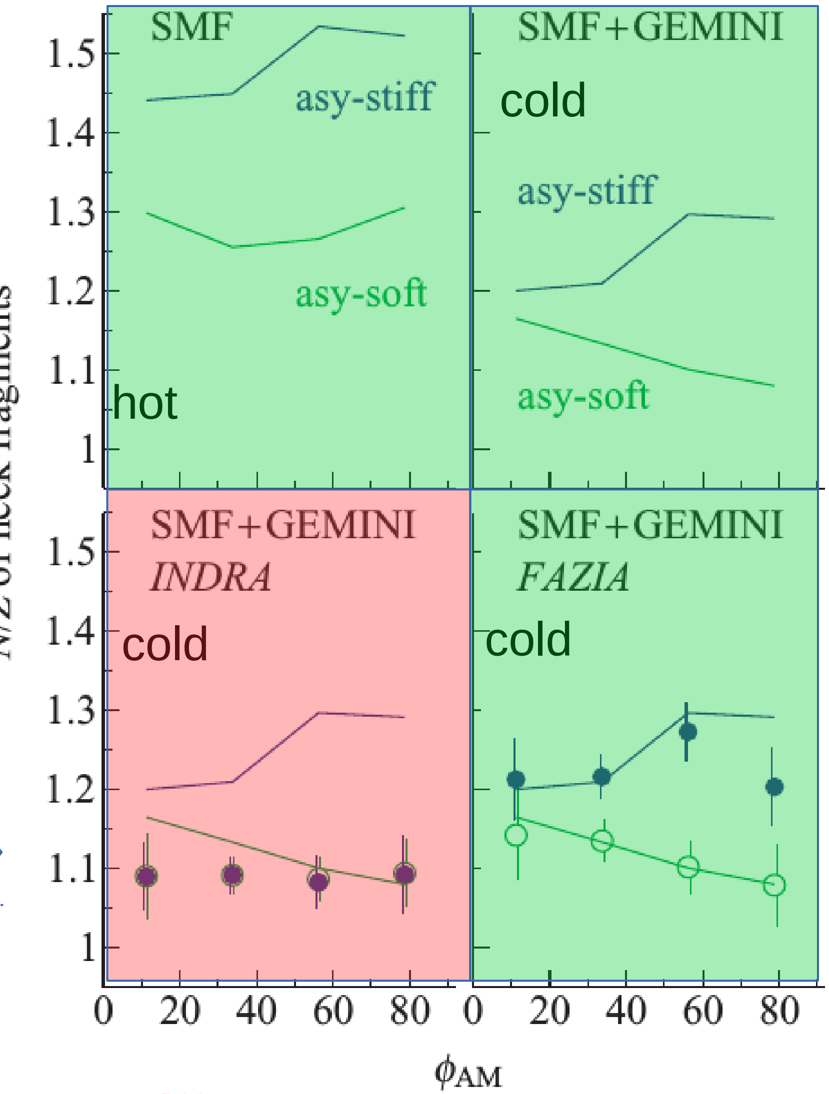
Density Dependence of Symmetry Energy : neck

SMF simulations $^{58/64}$*Ni*+$^{58/64}$*Ni 40A* MeV
P. Napolitani, et al., PRC ***81****, 044619 (2010)*

Ternary events for ^{64}*Ni*+^{64}*Ni* at *40A MeV*
1 QT + ***1 neck IMF*** + *1QP*
0.45 < b_{red} *< 0.75*







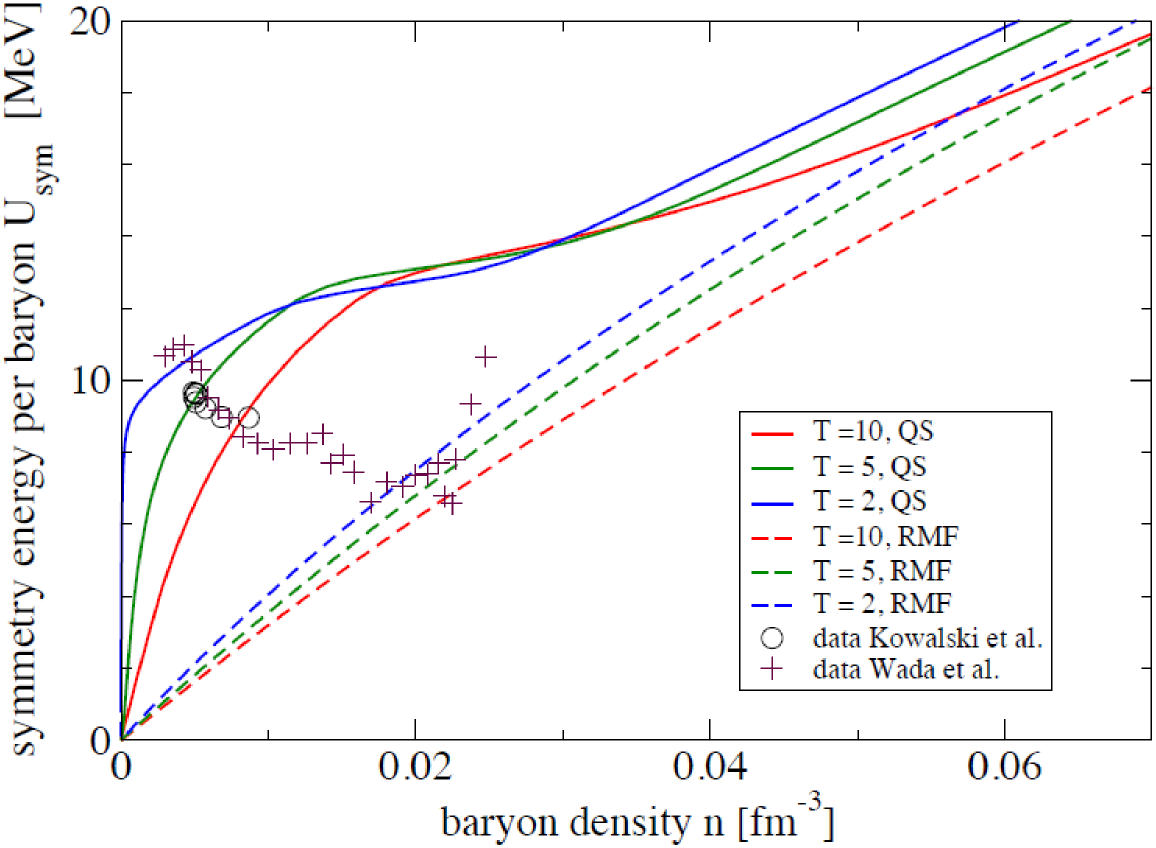
FAZIA should greatly enhanced the sensitivity to E_{sym} stiffness !

Symmetry Energy

at $\rho \ll \rho_0$

Symmetry energy for $\rho \ll \rho_0$

Prediction of the nuclear EOS : symmetry energy at subsaturation density ($\rho<\rho_0/10$) and finite temperature (*T=2-10 MeV*)



Data versus

- **Relativistic Mean Field**
  (*RMF* without cluster)

- **Quantum Statistical Model** (*QSM*)

K. Hagel, J.B. Natowitz, G. Röpke
Eur. Phys. Journal A **50** (2014) 39

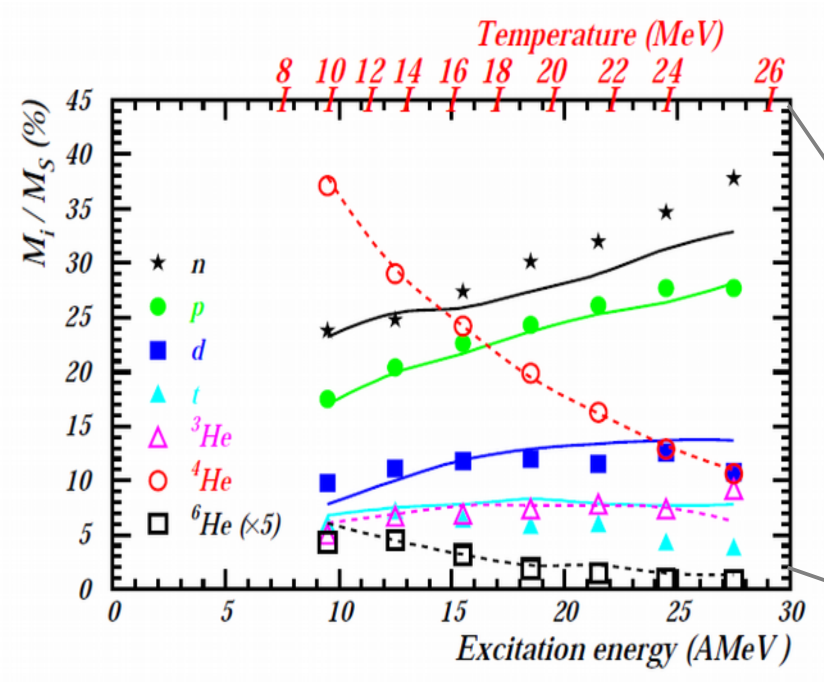
S. Kowalski, *et al.*, PRC **75**, 014601 (2007)
R. Wada, *et al.*, PRC **85**, 064618 (2012)

Relativistic Mean field (no clusters): linear decrease of E_{sym}
QSM : formation of clusters leads to an increase of E_{sym} at (very) low densities

Symmetry Energy for $\rho<<\rho_0$

Vaporization : a bridge between nuclear physics and astrophysics

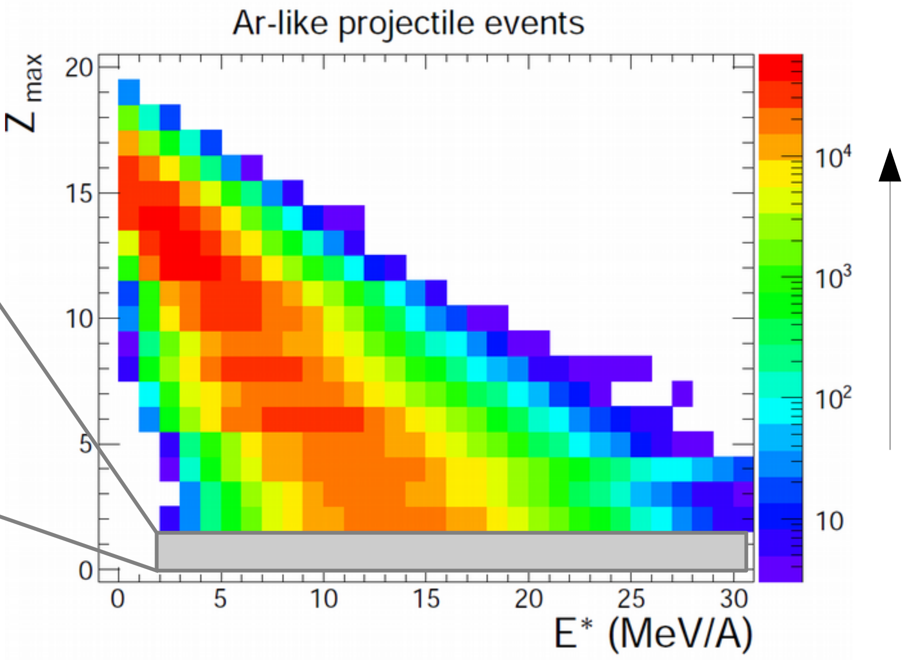
Described by a **weakly-interacting quantum gas of nuclear species in thermal and chemical equilibrium**



B. Borderie *et al.*, (INDRA Coll.) Eur. Phys. J. A **6** (1999)
F. Gulminelli *et al.*, Nucl. Phys. A **615** (1997).

Done with INDRA $Z_{max}<3$

Vaporization events of *Ni*-like projectiles with FAZIA
- Evolution of the **cluster mixing** among **nucleon-gas**
- Including isotopes heavier than helium
- **In-medium properties** of clusters
- Exploring **densities, temperatures and N/Z** on the path from **multifragmentation** to **vaporization**



To be done with FAZIA $Z_{max}>2$

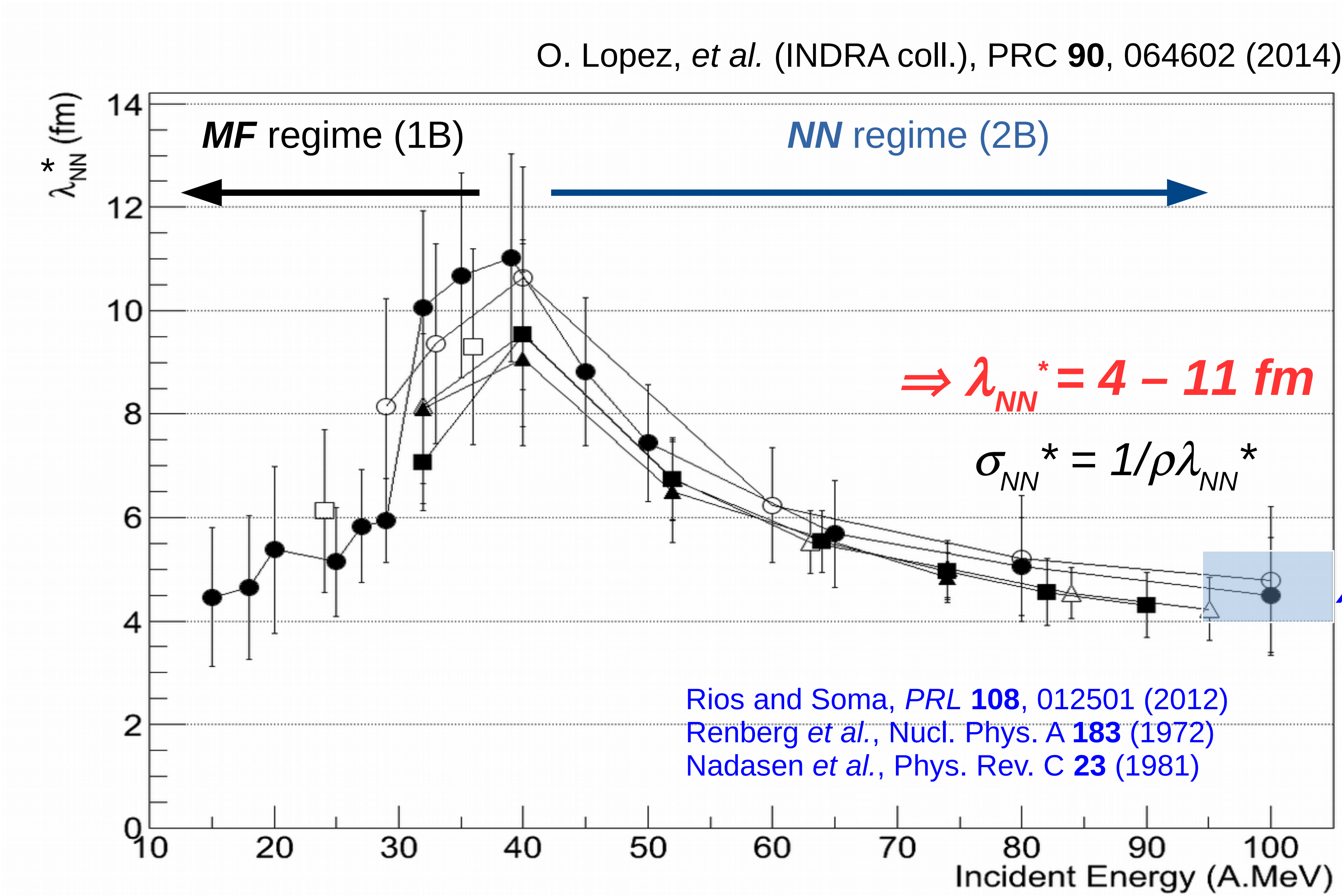
Physics Case for INDRA+FAZIA: ^{58,64}*Ni* + ^{58,64}*Ni 50A - 90A MeV*

➡ ***See E. Bonnet's talk in this conference***

Transport properties

Energy dissipation : Mean free path in nuclear matter

O. Lopez, *et al.* (INDRA coll.), PRC **90**, 064602 (2014)



$\Rightarrow \lambda_{NN}^* = 4 - 11$ fm

$\sigma_{NN}^* = 1/\rho\lambda_{NN}^*$

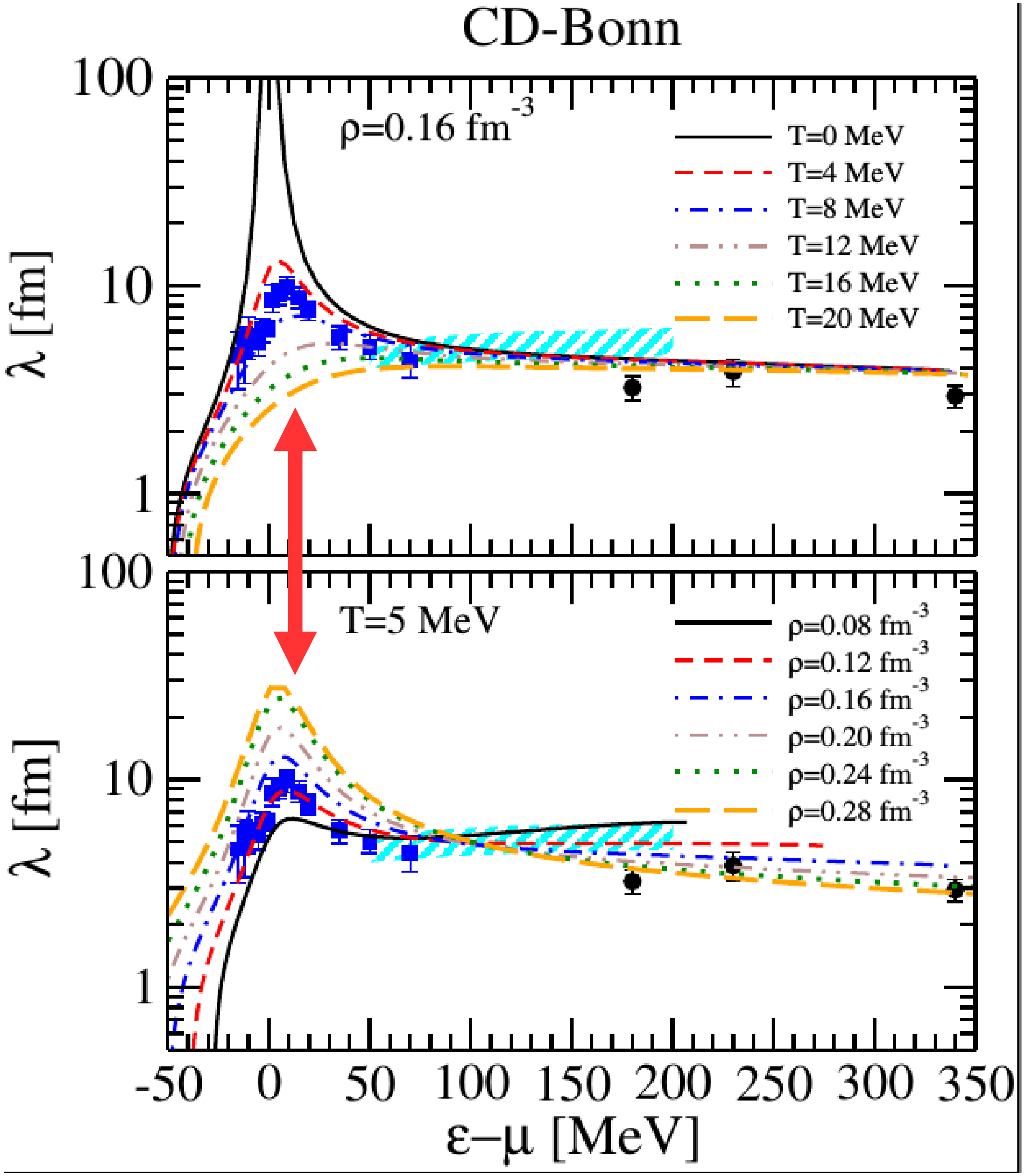
$\lambda_{NN}^* = 4\text{-}5$ fm

Rios and Soma, *PRL* **108**, 012501 (2012)
Renberg *et al.*, Nucl. Phys. A **183** (1972)
Nadasen *et al.*, Phys. Rev. C **23** (1981)

- **$\lambda_{NN} \geq R$: complete stopping and thermalization not achieved...**
  J. Su and F.S. Zhang, PRC 87, 017602 (2013) [AMD]

- **Contradictory** findings by E. Bonnet, *et al.*, Phys. Rev. C 89, 034608 (2014) [SMF]

Mean free path and *EOS* : microscopic calculations



Quantum Field Theory : Self-consistent Green Functions with realistic effective interaction (CD-Bonn) :

A. Rios and V. Soma, *PRL* **108**, 012501 (2012)

- Calculations at $\rho = \rho_0$ for different temperatures

$T \approx 5$ MeV

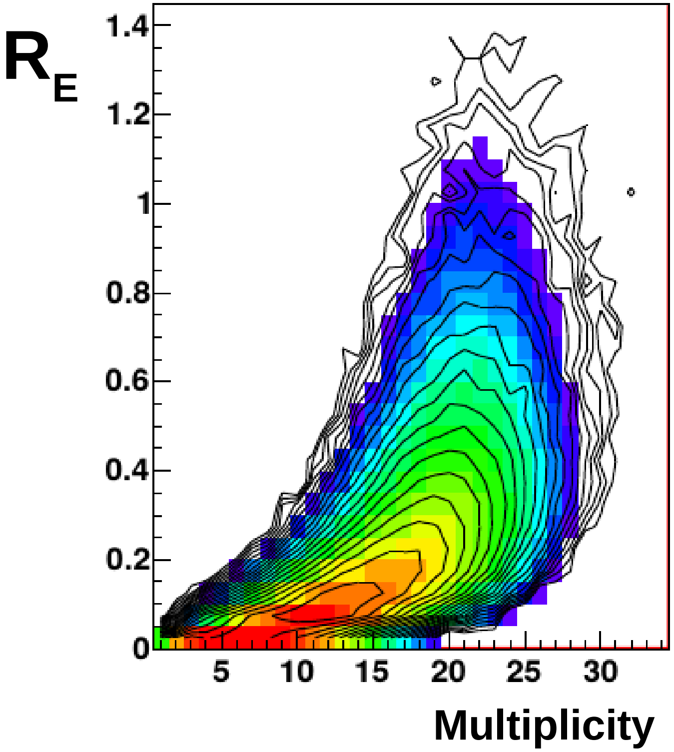
- Calculations at ***$T = 5$ MeV*** for different densities

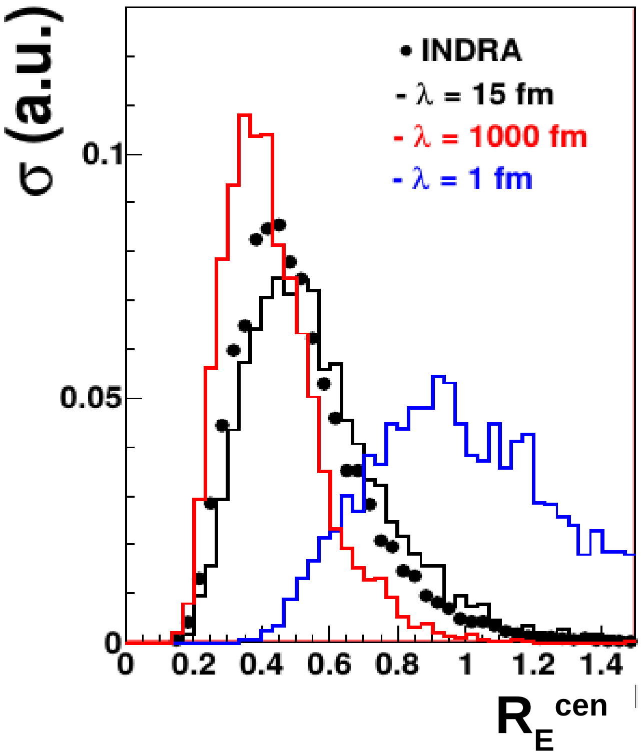
$\rho = 1 - 1.3\ \rho_0$

Enhanced sensitivity for *$E \approx E_{Fermi}$*

Mean free path and thermalization : transport model

INDRA data / ***ELIE*** model (micro/macro) for the isotropy ratio R_E : $^{58}Ni+^{58}Ni$ @ 40*A MeV*





λ : mean free path for *NN* collisions in the participant zone

→ R_E is compatible with λ~15 fm >> $r_0A_{tot}^{1/3}$ (5 fm) around 30A-50A MeV

Full thermalization is not achieved for central collisions (*b*<2fm) since the number of collisions per participant $N_{coll} \propto A_{tot}^{1/3}/\lambda$ **<< 1**

➡ ***See also D. Durand's talk in this conference***

INDRA + FAZIA scientific program at GANIL (2019+)

1/ Nuclear Equation of State : ρ-scan for E_{sym} at $\rho<\rho_0$: *GANIL PAC 2018*

- **Density dependence** for **Symmetry Energy**: **isospin diffusion** in *DIC*, **Isoscaling** , **neutron enrichment** in the neck (**migration/diffusion)**
- ***EOS* at low density**: **vaporization** and **cluster mixing** with nucleon gas
- **In-medium** clusters formation: **clustering @ low density** (α–Hoyle states, **cluster correlations** in n-rich/poor systems)

2/ Transport Properties in dense matter : *NN* interaction

- **Stopping** and ***N/Z* equilibration** in nuclear medium ($\lambda_{NN}, \sigma_{NN}, m^*$)
- **In-medium *NN* int.** : **isovector** and **tensor** dependences (**n/p, short-range**)
- **Viscosity** of nuclear matter (connection with **phase transitions**)

3/ Hot Nuclei Thermodynamics : Phase Transitions

- **3D-**exploration for the **Phase Diagram** (isospin/density/temperature), **spinodal decomposition (**nature of **phase transition)**
- **Level density** at finite temperature (**isospin dependence**)

Many thanks to all people from INDRA and FAZIA collaborations

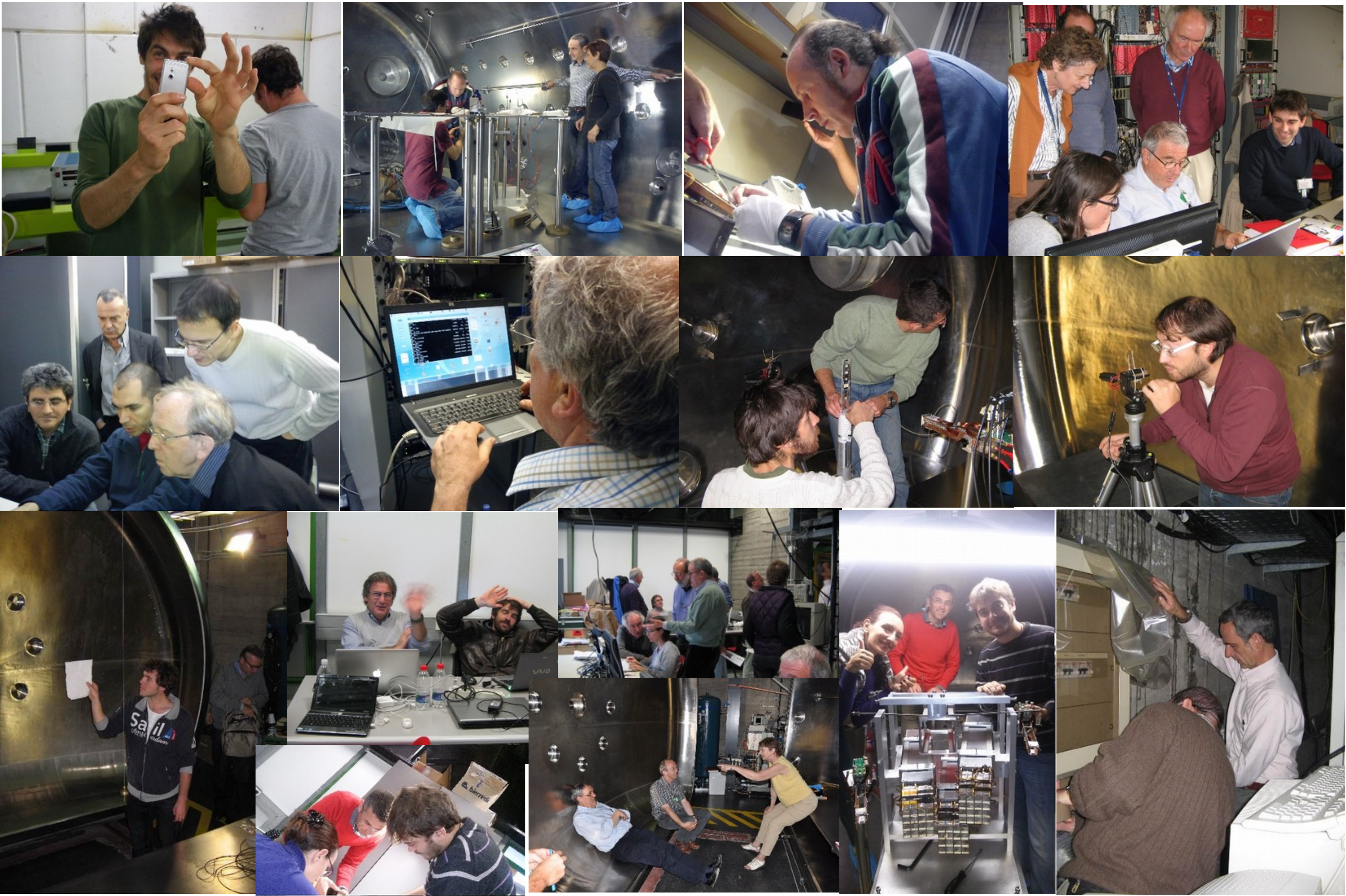
Especially :

L. Augey, E. Bonnet, B. Borderie, R. Bougault, D. Durand, J.D. Frankland, D. Gruyer, M. Henri, N. Le Neindre, E. Vient, P. St-Onge for the materials

And a special thought to :

M.F. Rivet and E. Rosato

FAZIA @ work !



The End

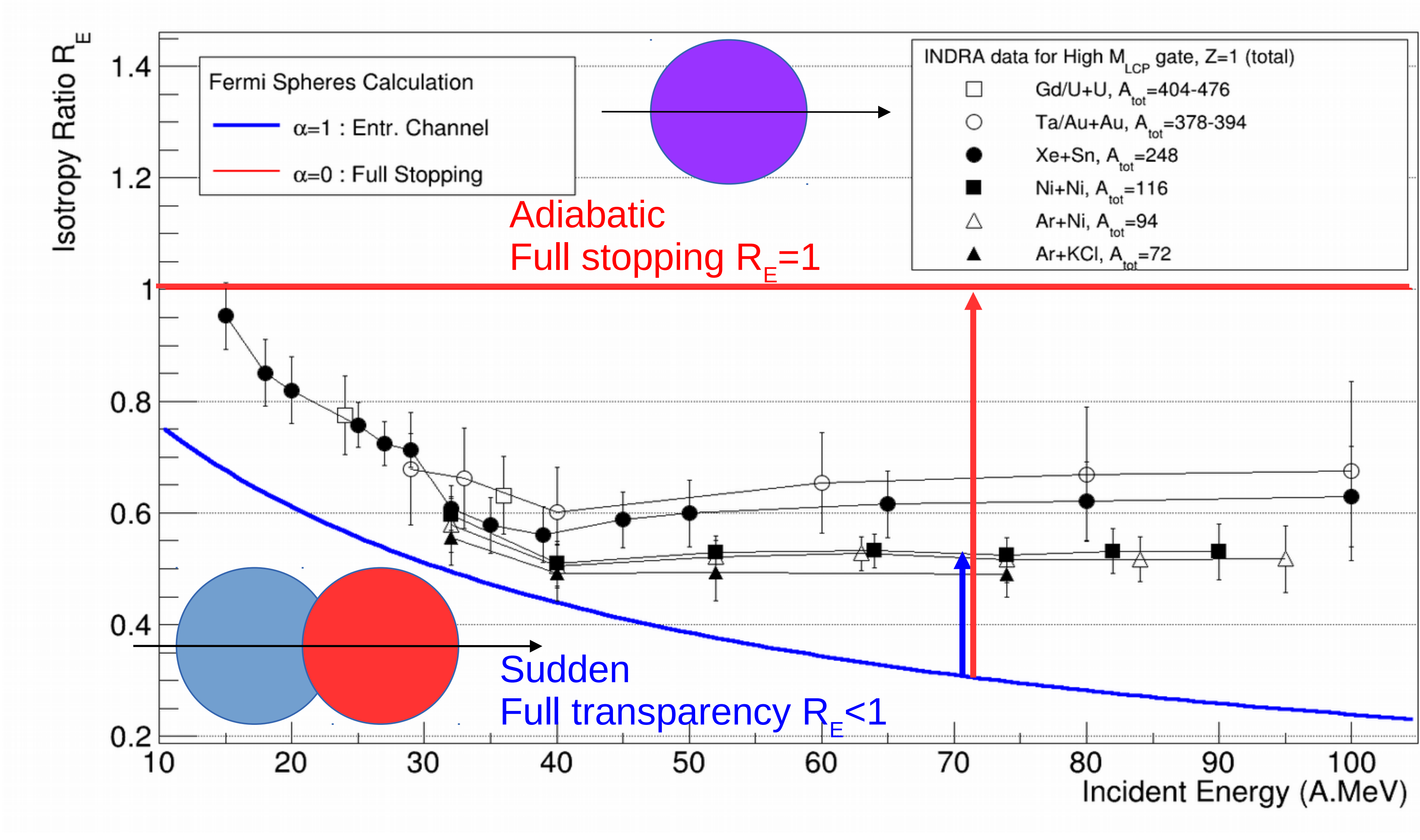
Transport properties in central collisions

Experimental probe → stopping : transparency/translucency

42 (quasi)-symmetric systems,
Only protons for <R_E>...

Isotropy ratio R_E :
Transverse vs Longitudinal *CM* energy

$$R_E = \frac{\Sigma_i^N E_i^\perp}{2\Sigma_i^N E_i^{//}}$$



Adiabatic
Full stopping R_E=1

Sudden
Full transparency R_E<1

O. Lopez *et al.* (INDRA coll.),
PRC **90**, 064602 (2014)

Radial flow : toward an experimental determination

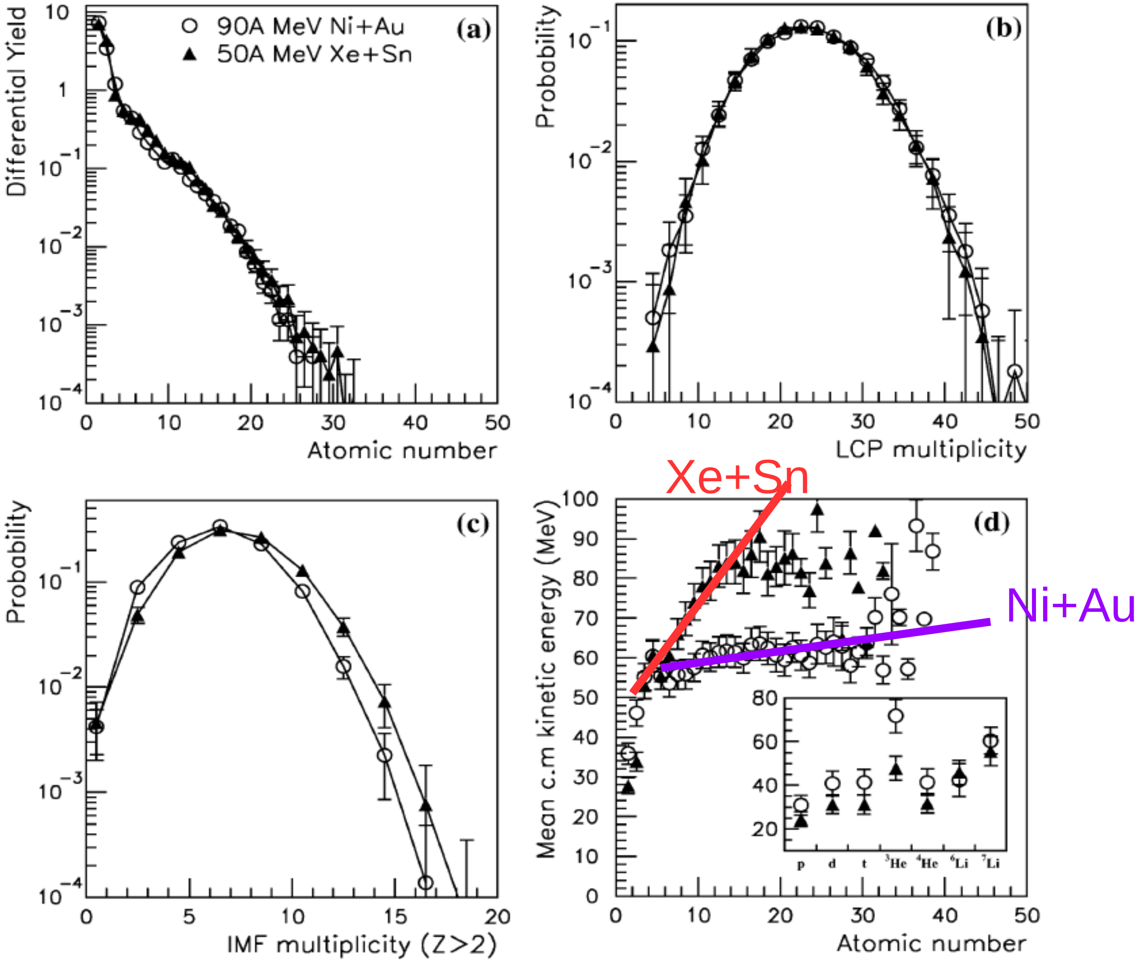
From **central collisions** at same ***E**** or ***T*** :

- ➢ Same fragmentation pattern:
  Partitions and multiplicities are similar

- ➢ Differences for the Kinetics :

→ **Radial flow ε_{rad}**

→ **Experimental determination of ε_{rad} for *Z>4* with isotopic resolution (A)**



N. Bellaize *et al.* (INDRA coll.), Nucl. Phys. A **709**, 367 (2002)

Proposed experiment

- ➢ Cover the Fermi energy domain
- ➢ Benefit from the maximal *N/Z* with stable beams at E_{fermi}
- ➢ Also study the **isospin diffusion/migration** in dissipative collisions

^{124,129,136}Xe @ 30, 39, 50 AMeV on ^{40,48}Ca and ^{nat}Sn targets

Radial flow : toward an experimental determination

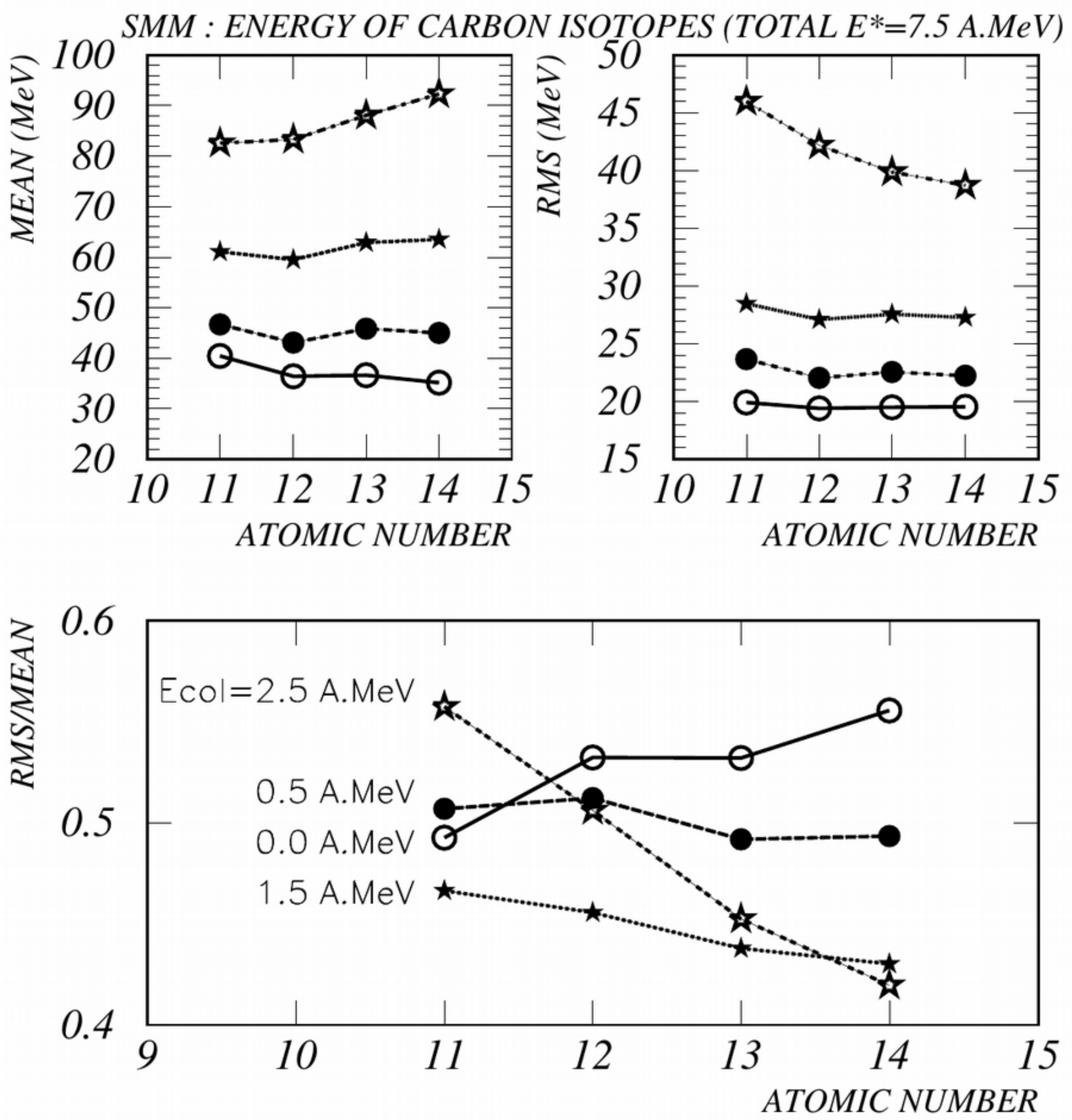
SMM Calculations

Z=90, E*/A=7.5 MeV

ρ= ρ_0/3

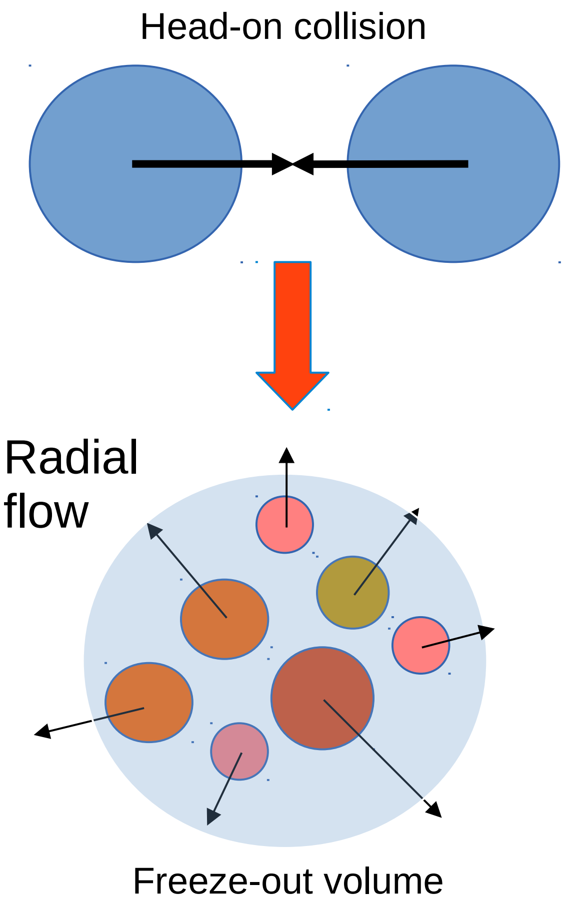
Carbon isotopes

Even better for higher species ?...



Courtesy of R. Bougault

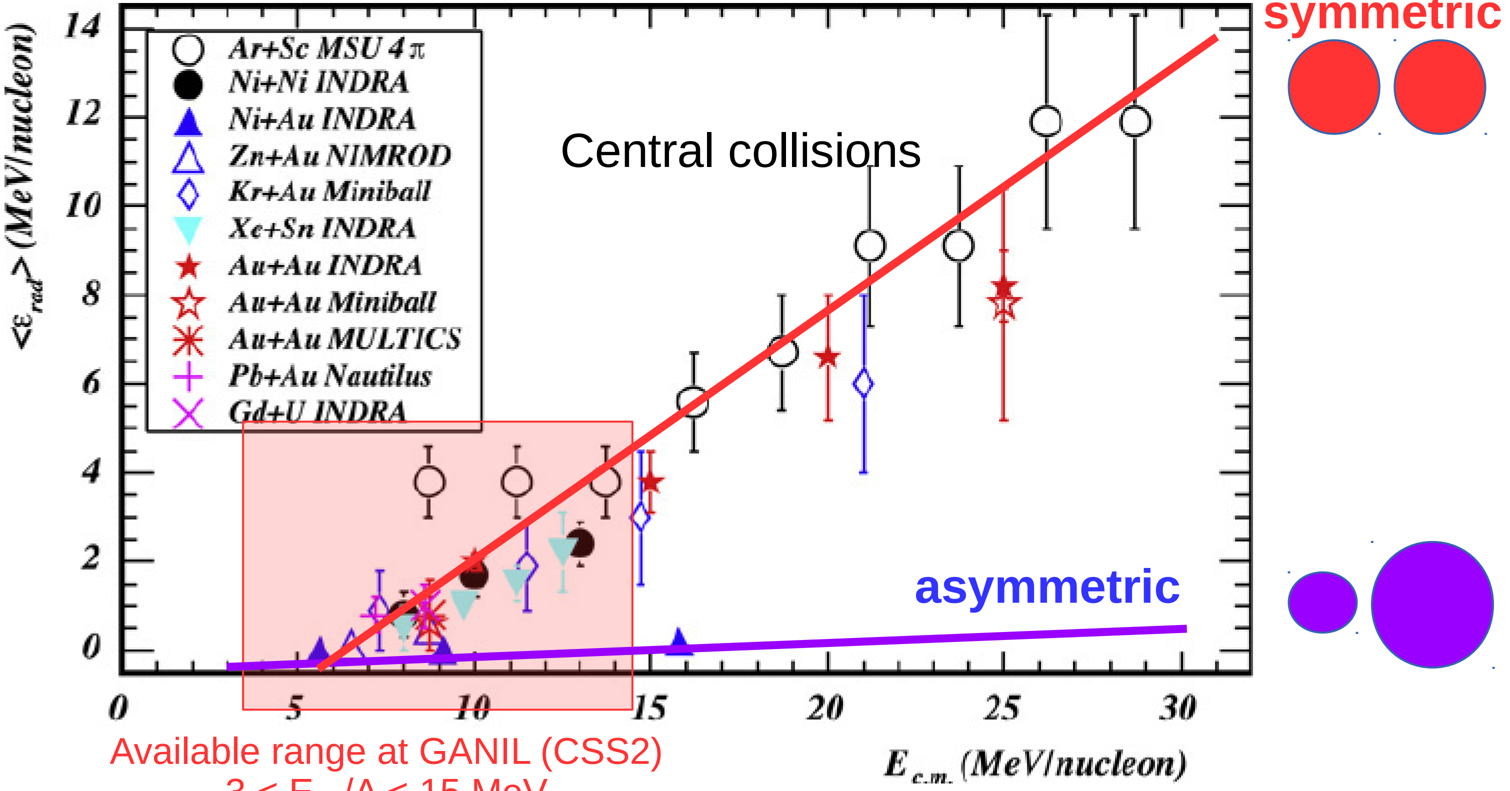
Radial Flow systematics


Head-on collision

Radial flow

Freeze-out volume

B. Borderie *et al.*, *Prog. In Part. Sci. And Nucl. Phys.* **61**, 551 (2008)



Available range at GANIL (CSS2)
$3 < E_{cm}/A < 15$ MeV

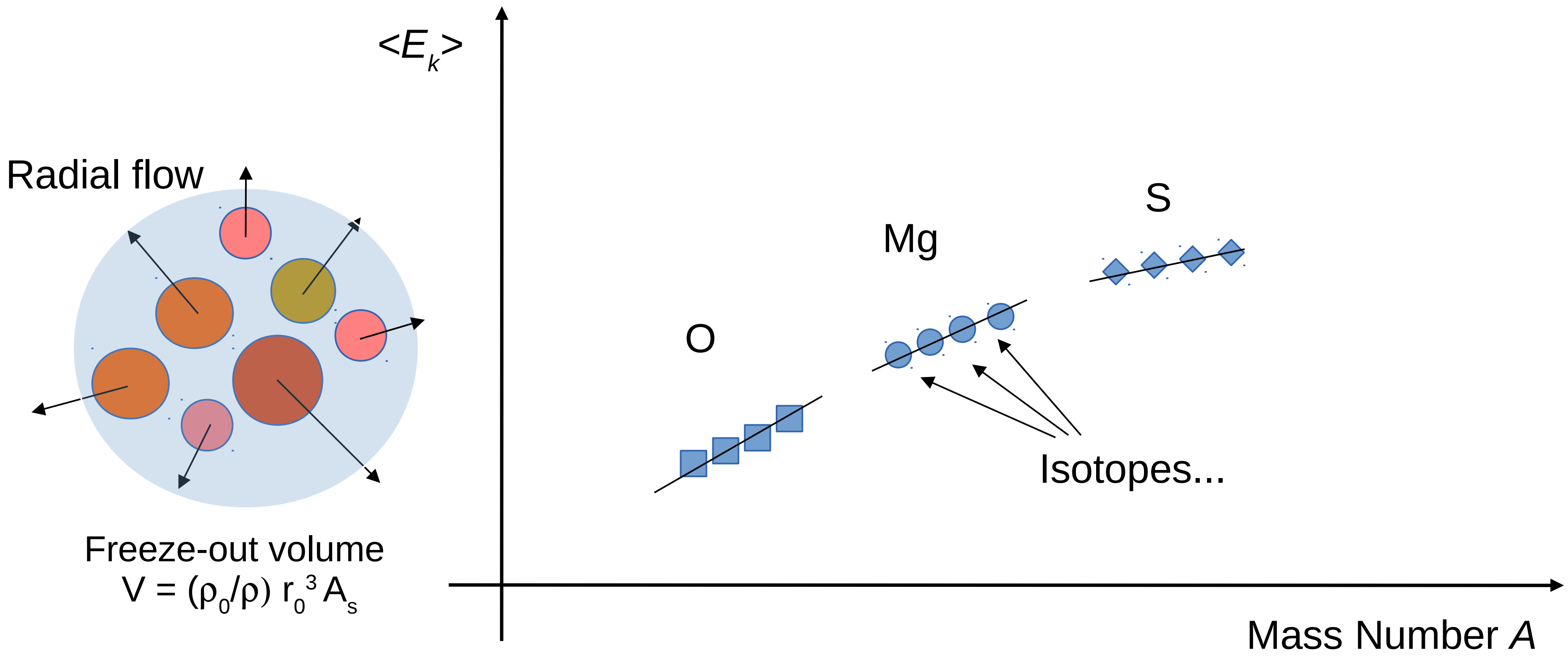
- **Linear behavior** as a function of E_{cm} *: at* $E_{cm}/A=10$ *MeV, we get :* $\varepsilon_{rad}=1.5\text{-}2$ ***AMeV***
  but **some discrepancies** appear ...

- Radial flow is obtained from **multifragmentation models** (SMM-like) : **freeze-out volume**

→ **model-independent estimation for radial flow is needed...**

Radial flow : toward an experimental determination

3 components for E_k : $$\langle E_k \rangle = \langle E_{coul}(Z) \rangle + \langle T \rangle + \langle E_{rad}(A) \rangle$$



Freeze-out volume
$V = (\rho_0/\rho)\, r_0^3 A_s$

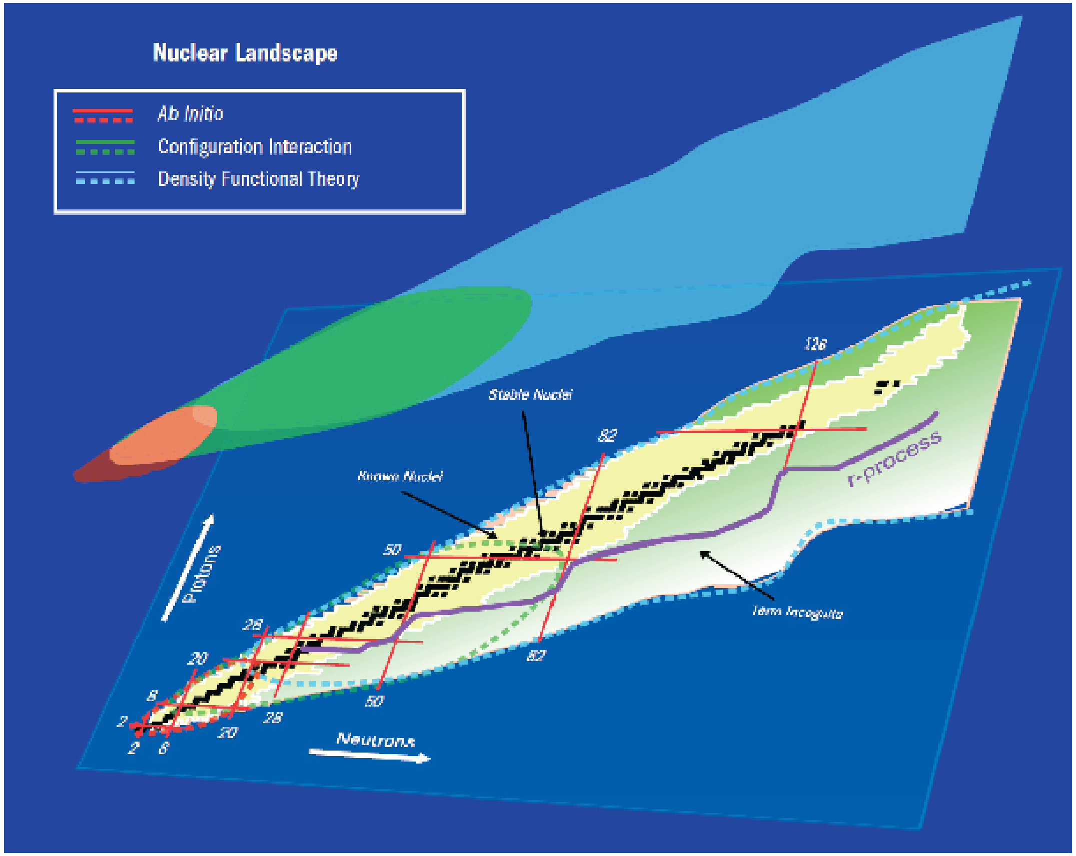
- Coulomb : $\langle E_{coul}(Z) \rangle \;\alpha\; Z\,(Z_s - Z_0)\,(\rho/\rho_0)^{1/3}$

- Thermal : $\langle T \rangle$: thermal component, no dep.

- Radial : $\langle E_{rad}\,(A) \rangle = \langle \varepsilon_0 \rangle \,.\, A$ where $\langle \varepsilon_0 \rangle$ is the average radial flow component

Microscopic Description of Nuclei

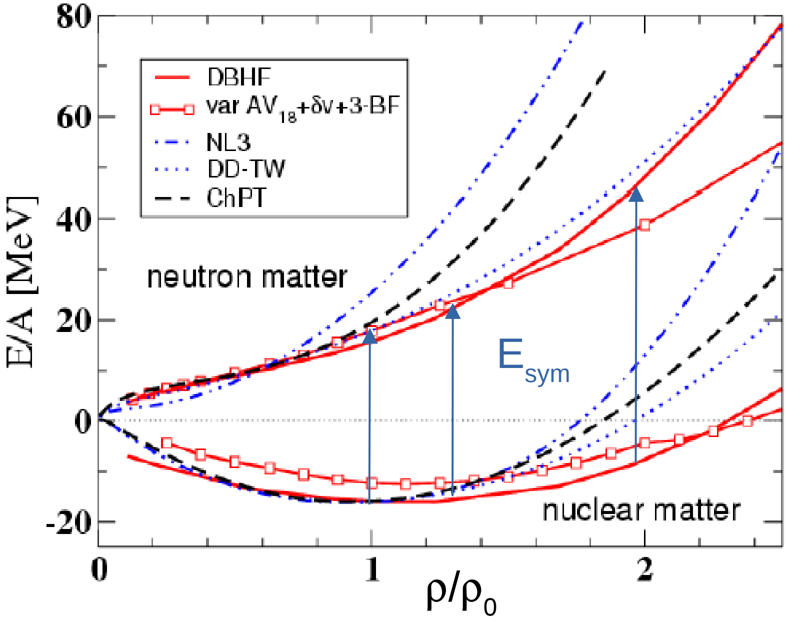
Self-consistent Mean-Field (*EDF*) calculations are probably the only possible framework to understand the structure of medium and heavy nuclei.



$$E = \langle\psi \mid H \mid \psi\rangle$$

$$\boldsymbol{H = E[\rho]}$$

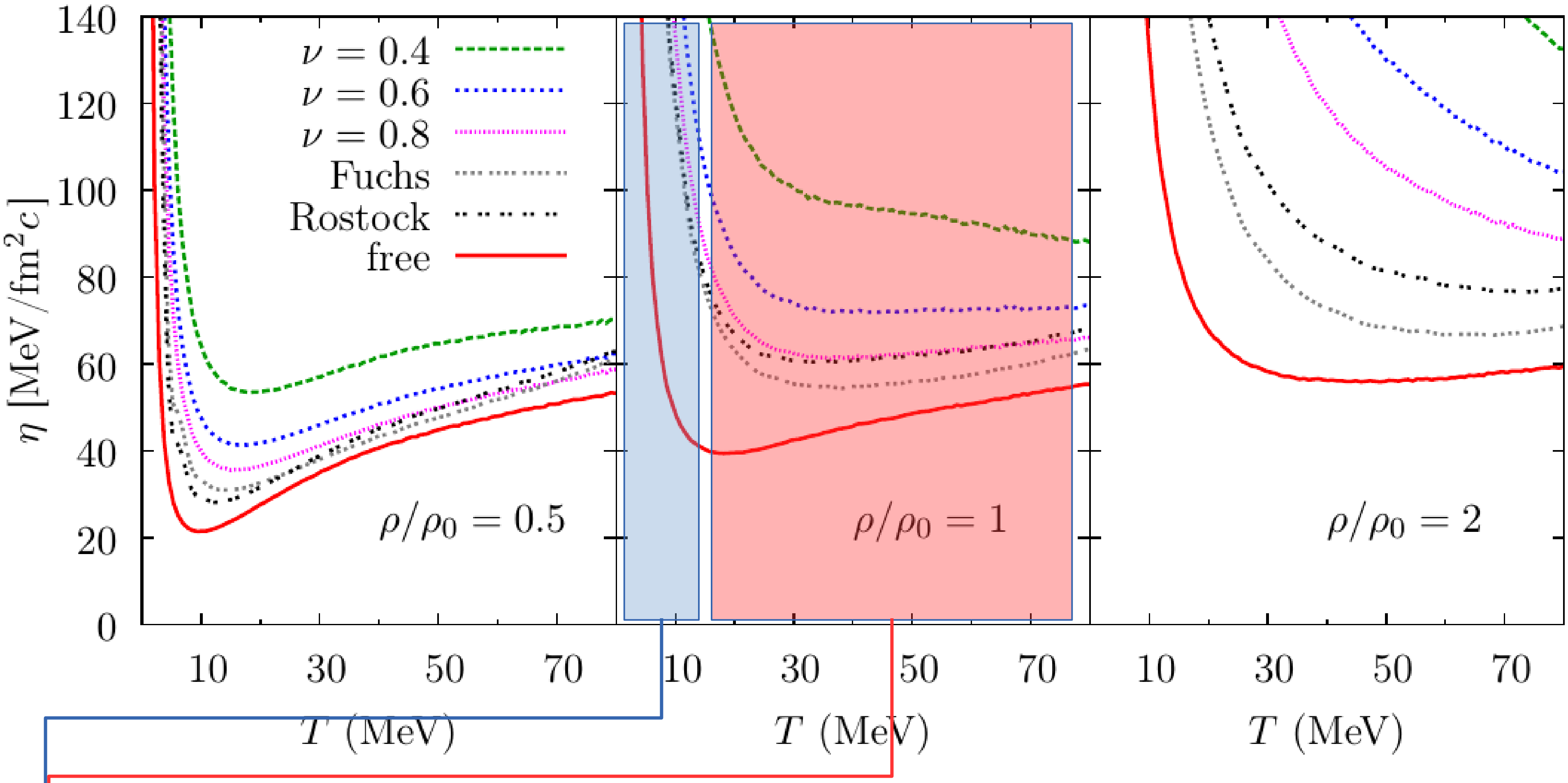
Energy-Density Functionals



Direct link to EOS and Symmetry Energy

Shear viscosity and phase transition

B. Brent and P. Danielewicz, [nucl-th] arxiv:1612.04874v1 (2016)



Degenerate Fermi fluid at low *T* : due to Pauli exclusion principle
Lack of collisions → **High viscosity,** *η* goes as *1/T*

Classical (nucleon) gas at high *T* : *η* goes as √*T*

Phase transition...

FAZIASYM @ LNS
Dec. 9-20 2015

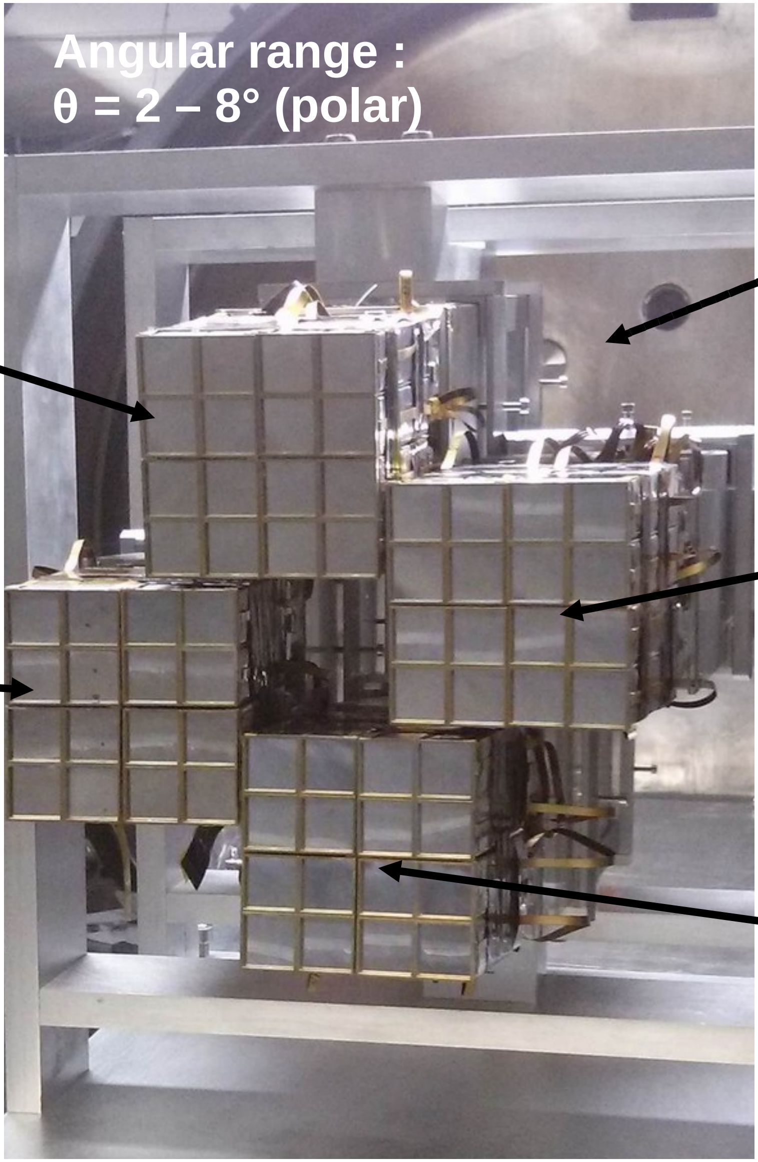
^{40}*Ca* + ^{40,48}*Ca* (+ *C* layer)
^{48}*Ca* + ^{40,48}*Ca* (+ *C* layer)
@ 35A MeV

$\theta_{grazing}$ (^{40}Ca) = 1.93°
$\theta_{grazing}$ (^{48}Ca) = 1.85°

1 Block =
16 telescopes *Si-Si-CsI*

- Si(NTD) : 300 μm thick.
- Si(NTD) : 500 mm thick.
- CsI(Tl) : 10 cm thick.

Q,I readout from PACI
In-vacuum Front-End Electronics
Sampling at 250 MhZ, 14 bits



Angular range :
θ = 2 – 8° (polar)

Block 0

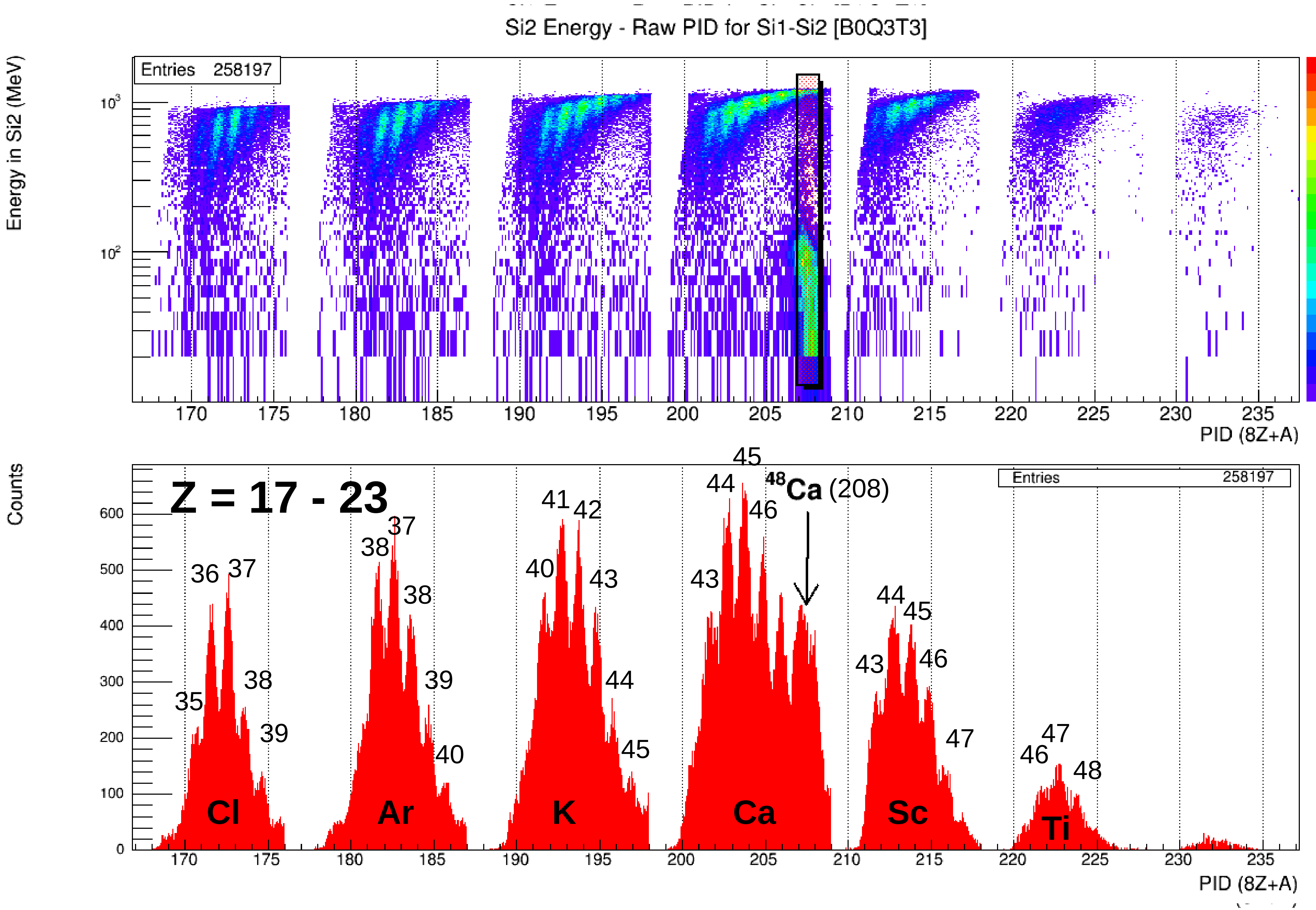
Block 1

Block 2

Block 3

Downstream Telescope for Rutherford scattering (B4)

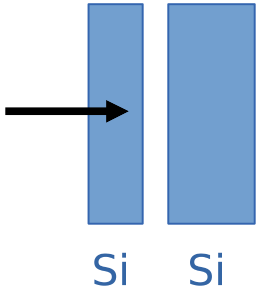
FAZIASym : Identification using AMI grid (II)

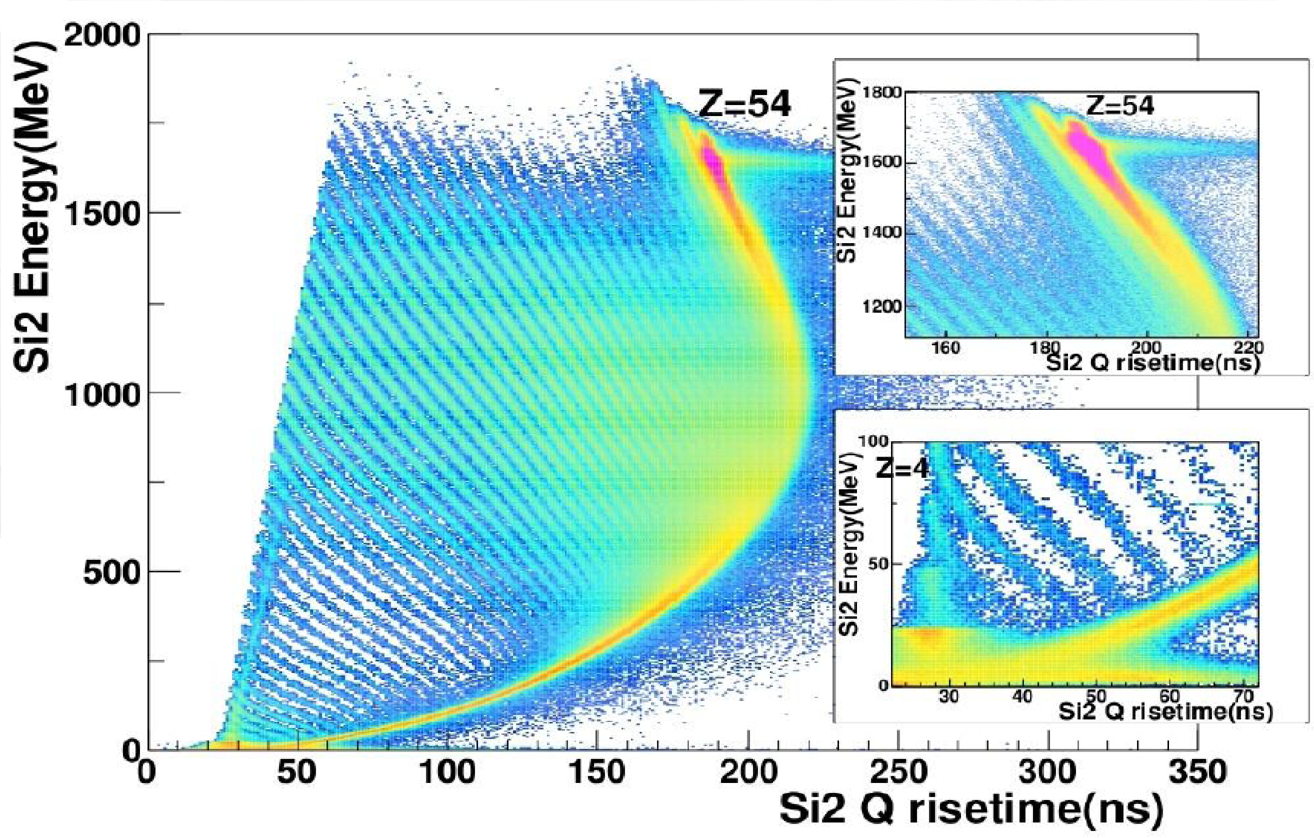


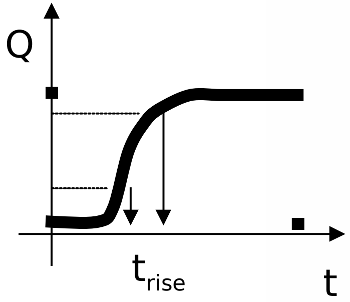
Isotopic Identification is OK up to Z=20, even for ^{48}Ca combining *PSA* + *E-ΔE*

FAZIA Phase 1 : Pulse Shape Analysis

Some results at the end of phase 1:
Pulse Shape Analysis from E – Charge Rise Time



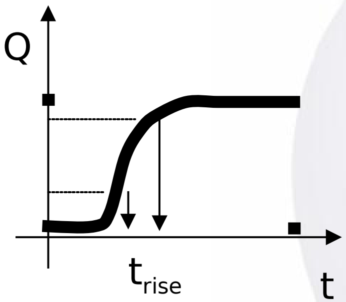


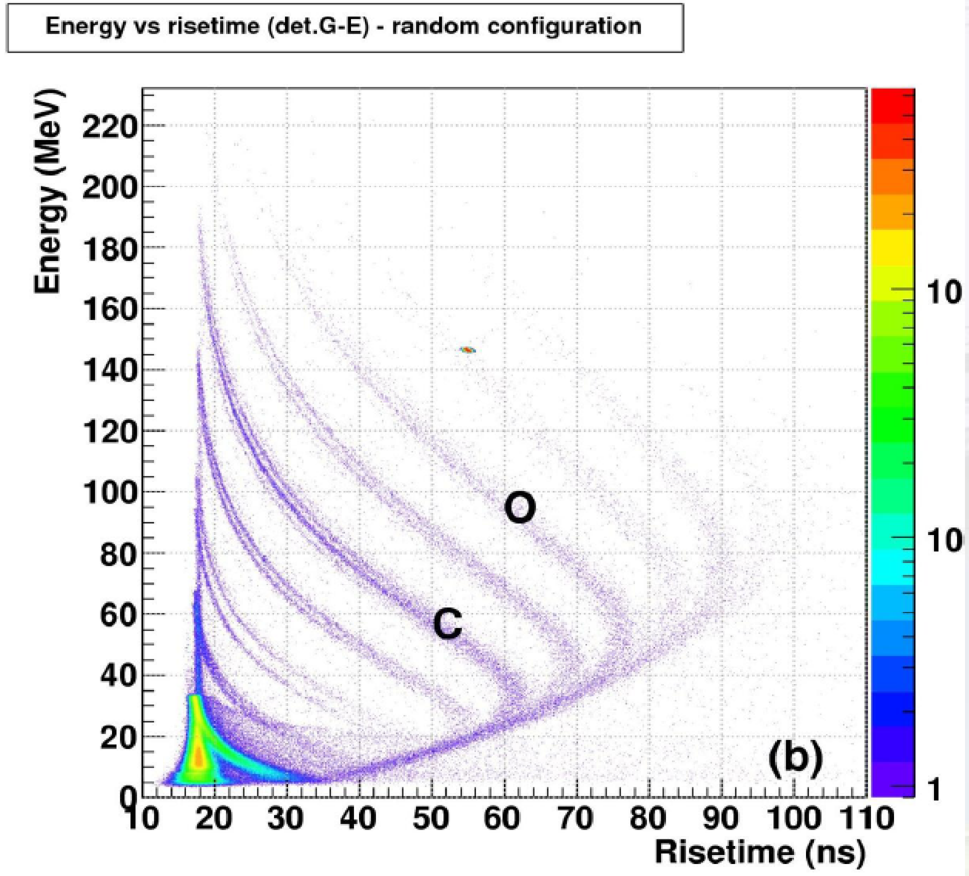


S.Carboni et al., NIMA 664 (2012) 251

FAZIA Phase 1 : Pulse Shape Anaysis

Some results at the end of phase 1: Mass resolution from Pulse Shape Analysis Energy vs. charge rise time



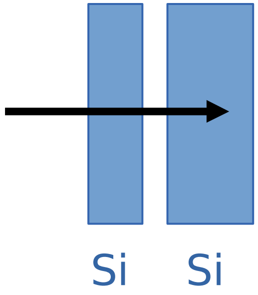


High gain
^{32}S beam@473MeV

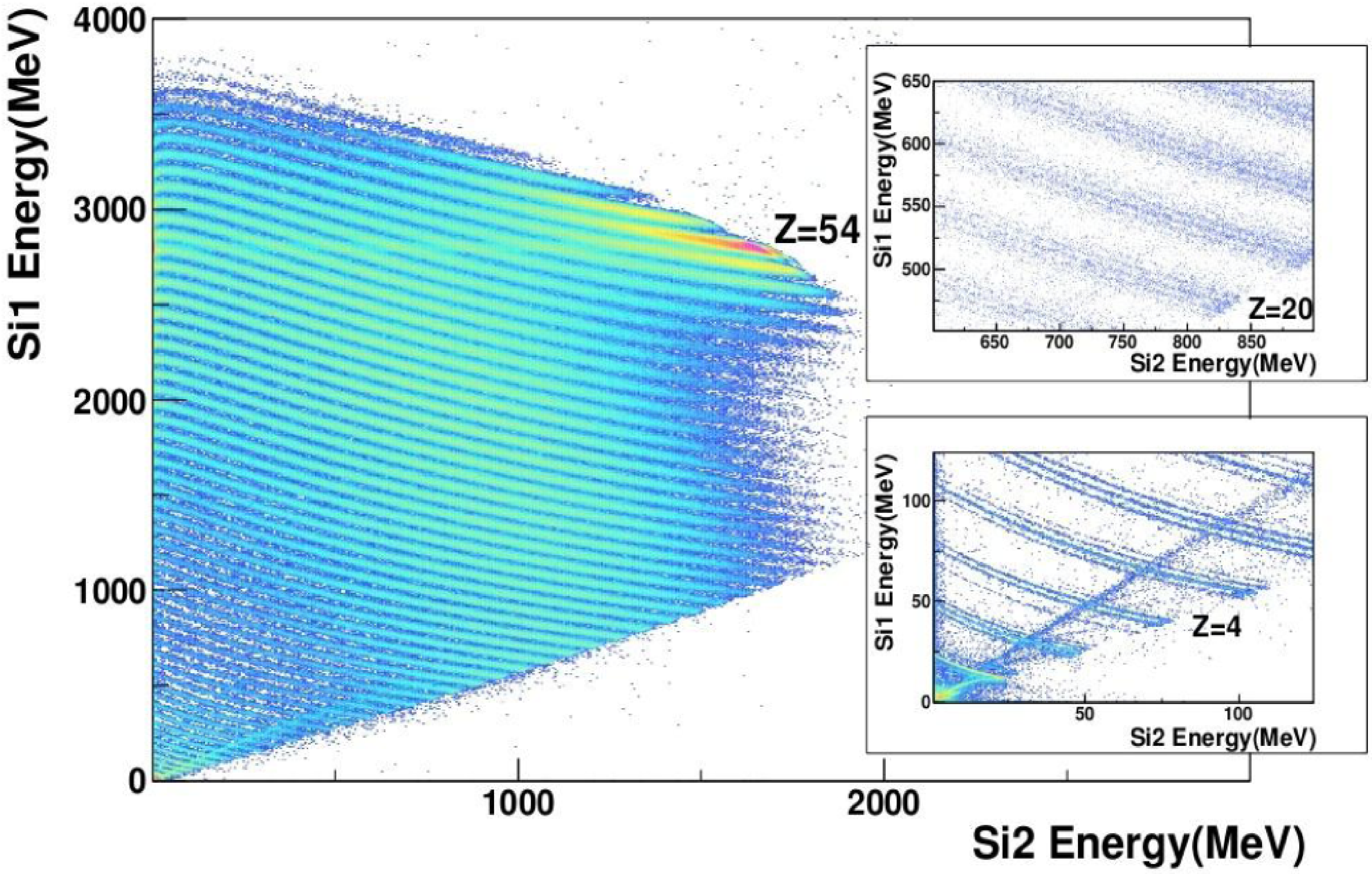
L.Bardelli et al., NIMA 654 (2011) 272

- Isotopic identification for **Z=3-9 !**

FAZIA Phase 1 : *ΔE-E* identification



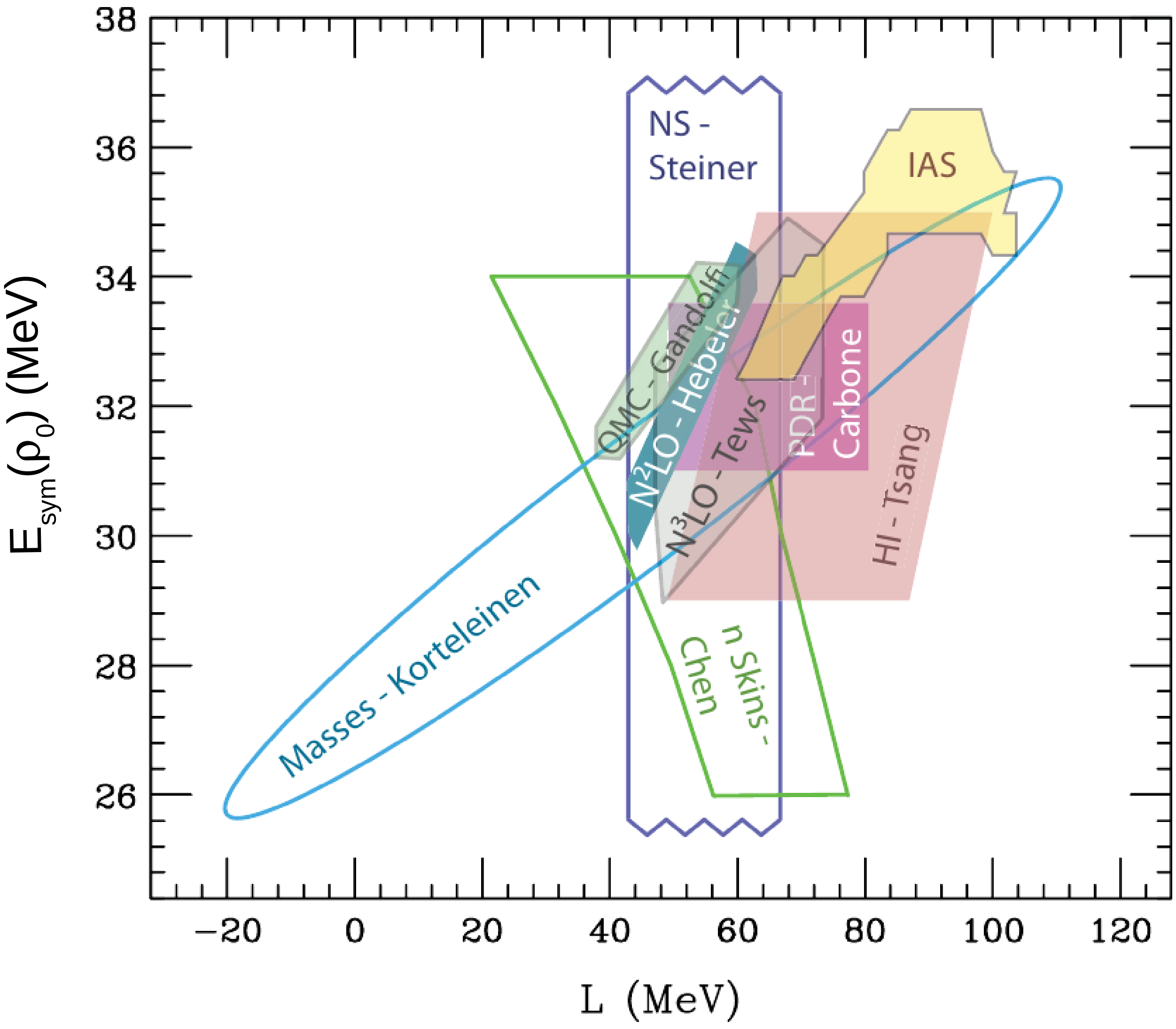
Some results at the end of phase 1: ΔE(Si1) – E (Si2)



S.Carboni et al., NIMA 664 (2012) 251 *Energy = max of shaped signal (trapezoidal filter)*

Constraints from Nuclear Physics in terrestrial investigations

P. Danielewicz, P. Singh and J. Lee, ArXiv:1611.01871v2 [nucl-th]



L is loosely constrained : L = 60 ± 20 MeV