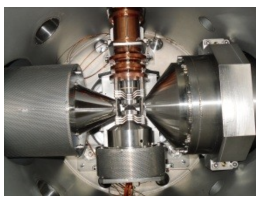
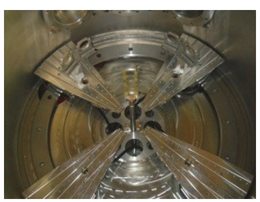
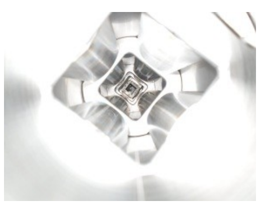



Recent results from INDRA and FAZIA

Olivier LOPEZ
LPC Caen, France

(INDRA-FAZIA Collaborations)

Outline

Recent results from INDRA (not exhaustive)

Chemical equilibrium in dissipative *HIC* at *32A* MeV : ^{124,136}Xe+^{112,124}Sn

Improving significantly the isotopic identification

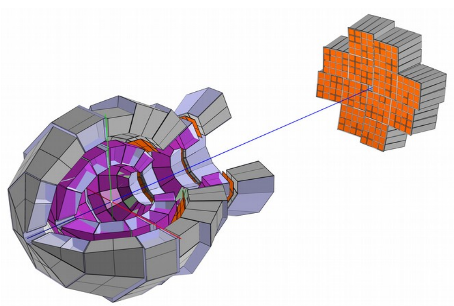
Transport properties above E_{Fermi} : σ_{NN}^{*} and *N/Z* equilibration

Recent progresses from FAZIA

Status of the 4-block experiments @ LNS Catania (2015-2017) :

- IsoFAZIA : see S. Valdré in the afternoon session (2015)
- FAZIASym : isotopic identification (2015)
- FAZIACor : cluster correlations in the nuclear medium (2017)

INDRA+FAZIA experimental program @ GANIL

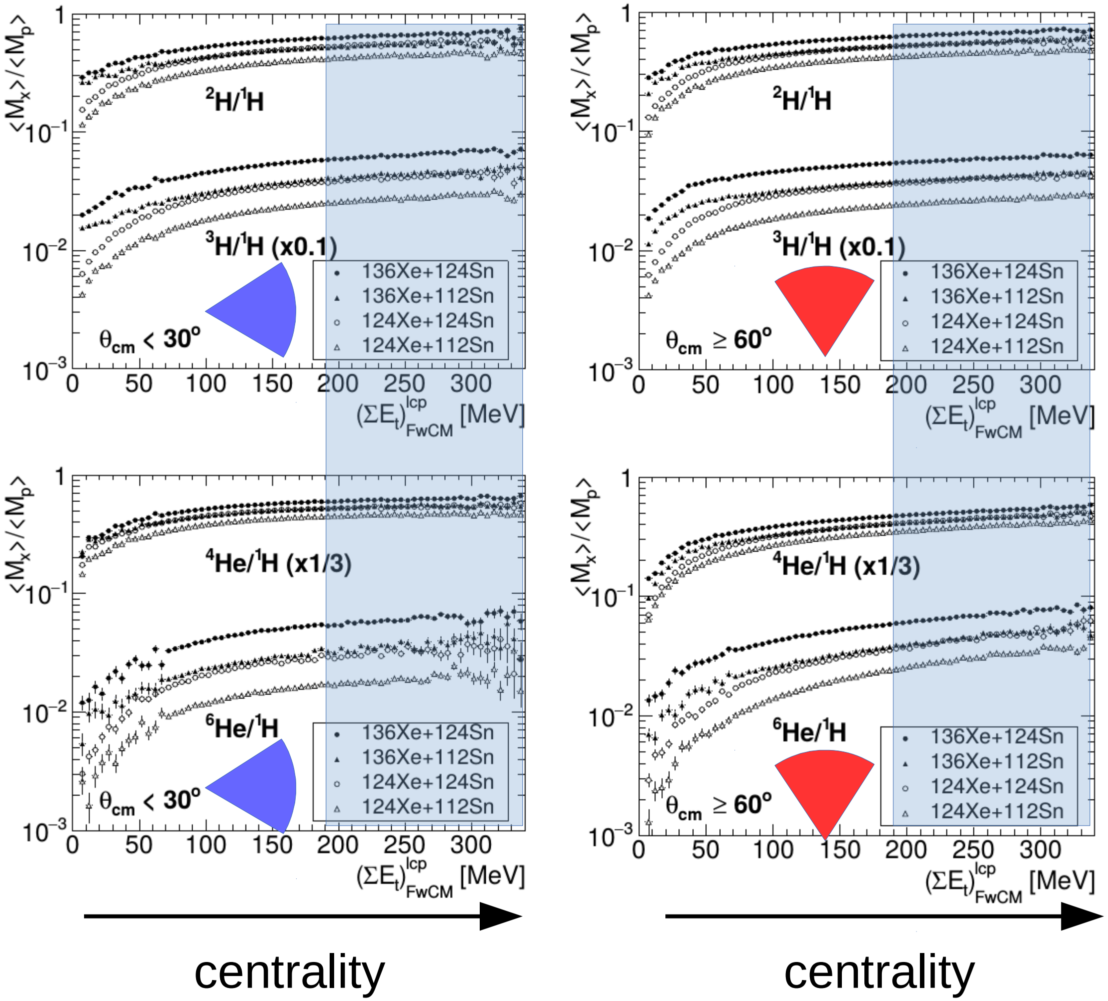


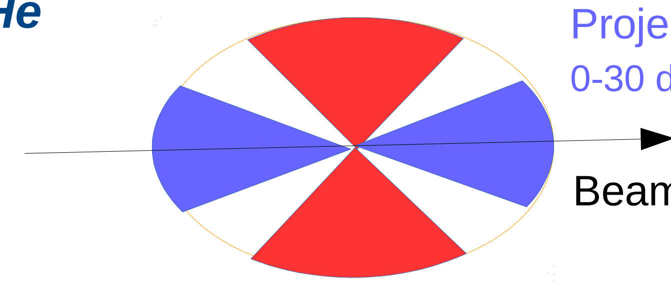
(some) recent results from INDRA

Chemical equilibration : Isospin diffusion and migration

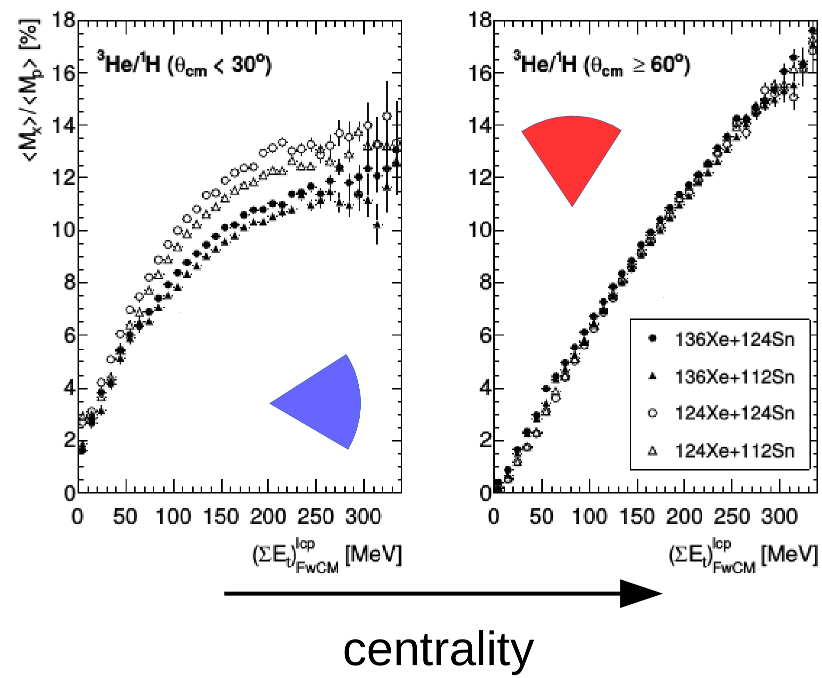
$^{124/136}$Xe + $^{112/124}$Sn at 32A MeV : INDRA data

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





R. Bougault *et al*, arXiv:1703.03694



- **Chemical equilibrium** for *d,t,^{3}He,α,^{6}He* in central collisions but *^{3}He* ratios are **different** and never show chem. equilibrium

^{136}Xe+^{112}Sn ≡ ^{124}Xe+^{124}Sn

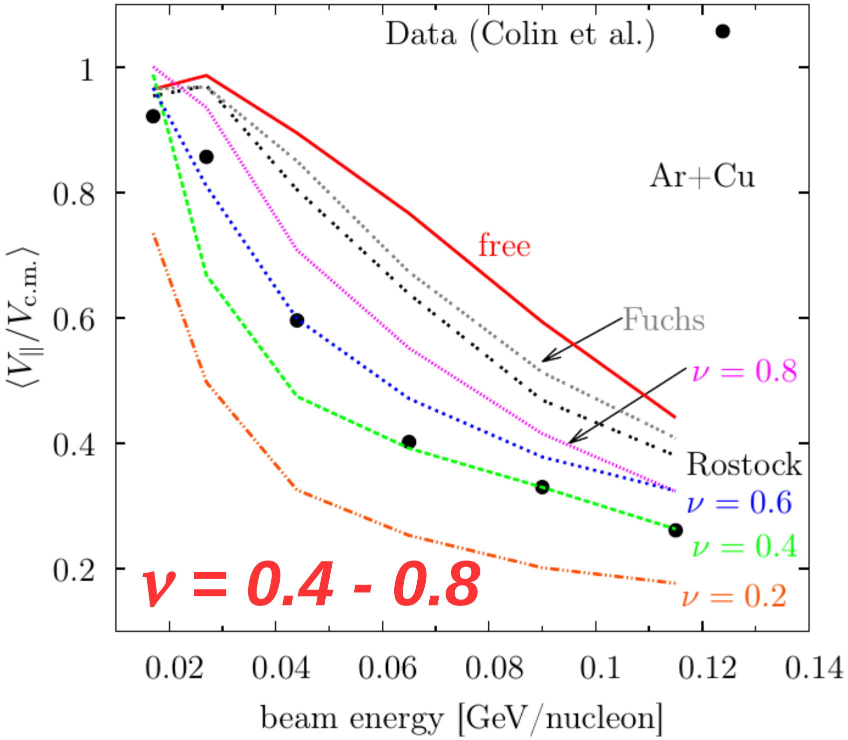
In-medium *NN* cross section (I)

Best param. in the Fermi energy domain : *P. Danielewicz, Acta. Phys. Pol. B **33**, 45 (2002)*
Tempered cross section from unitarity limit σ_0

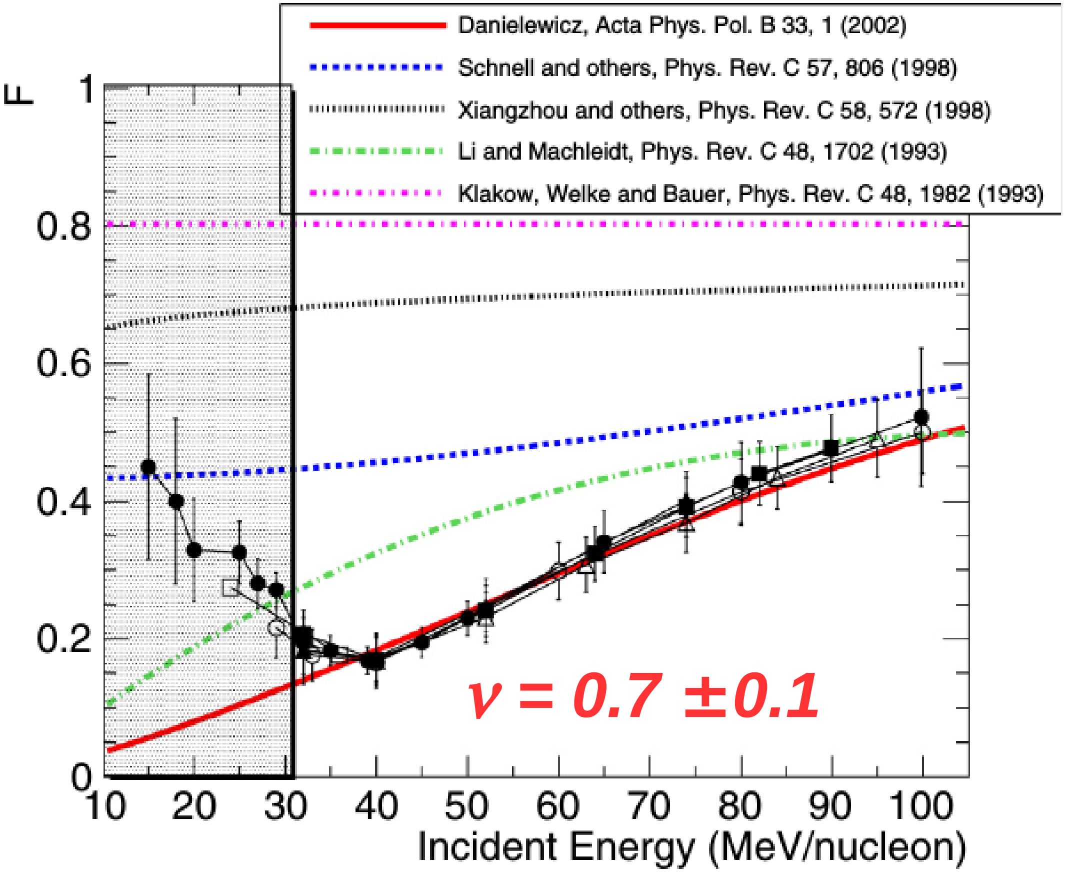
$$\sigma_{NN}^* = \sigma_0 \tanh(\sigma_{NN}^{free} / \sigma_0)$$

with : $\sigma_0 = \nu \rho^{-2/3}$ and : $\nu = 0.4 - 0.8$

MSU analysis on asymmetric systems :
LMT between 20A – 120A MeV
*E . Colin et al., PRC **57**, R1032 (1998)*



INDRA meta-analysis for symmetric systems
between *30A – 100A MeV*
*O. Lopez et al., PRC **90**, 064602 (2014)*



In-medium *NN* cross section (II)

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

observable	reaction system	energies [MeV]	best cross section reduction
LMT	$^{40}\mathrm{Ar}+\mathrm{Cu}$	17–115	Tempered w/ $0.4 \leq \nu \leq 0.6$
LMT	$^{40}\mathrm{Ar}+\mathrm{Ag}$	17–115	Tempered w/ $0.4 \leq \nu \leq 0.6$
LMT	$^{40}\mathrm{Ar}+\mathrm{Au}$	27–115	Tempered w/ $\nu = 0.8$
varxz	$\mathrm{Au}+\mathrm{Au}$	90–1500	Tempered w/ $\nu = 0.8$ or Rostock
varxz	$\mathrm{Ca}+\mathrm{Ca}$	400–1500	Tempered w/ $0.4 \leq \nu \leq 0.8$
R_z	$^{96}\mathrm{Zr}+^{96}\mathrm{Ru}$	400	Tempered w/ $\nu = 0.8$, Rostock, or Fuchs
	(and inverse)		

Recoil velocity (E,A)

$$\mathrm{LMT} = \left\langle \frac{v_{\parallel}}{v_{\mathrm{c.m.}}} \right\rangle$$

Rapidity variances (E,A)

$$varxz = \frac{\Delta y_x}{\Delta y_z},$$

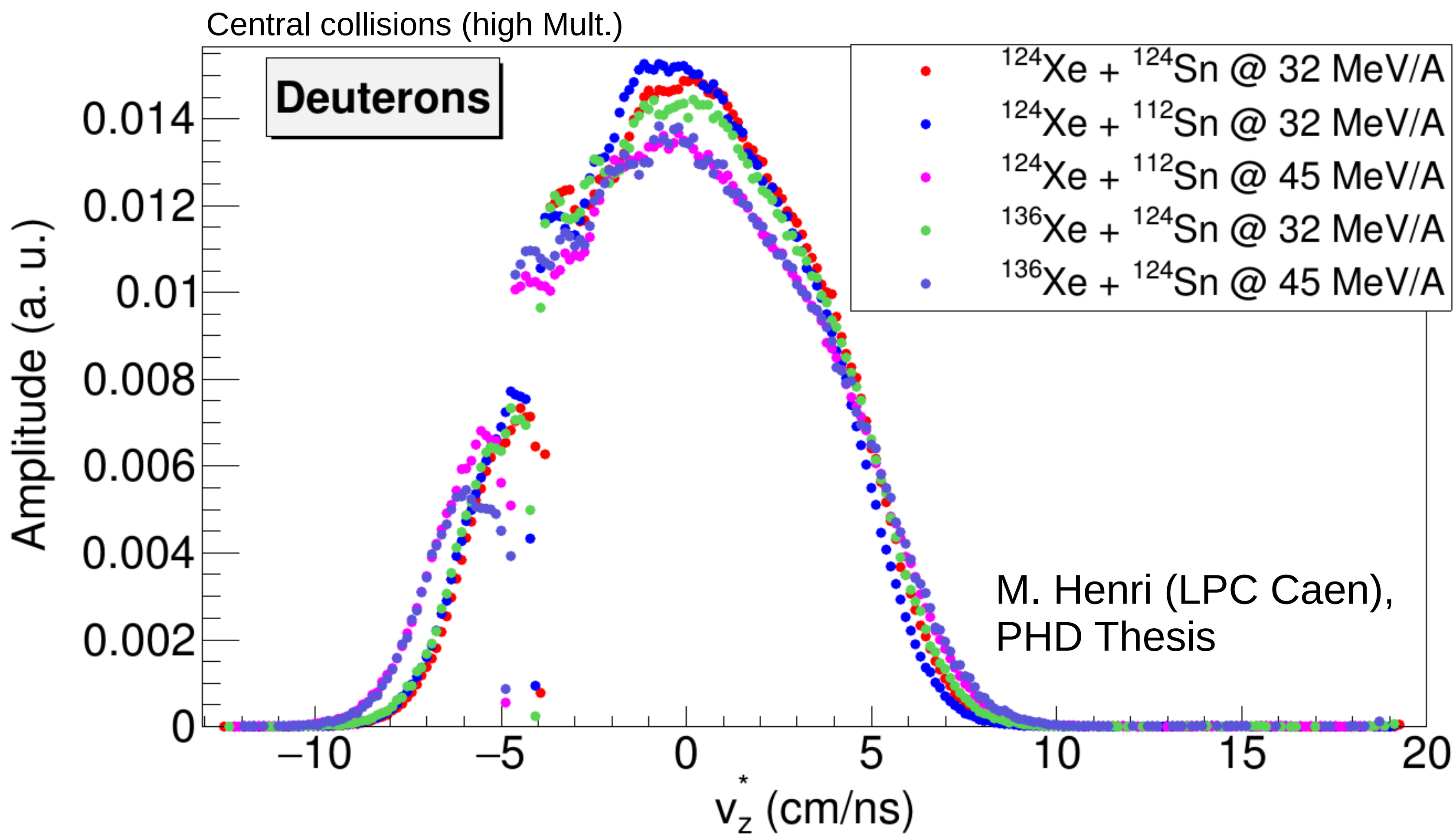
Isospin tracer (Z,A)

$$R_Z = \frac{2 \times Z - Z^{\mathrm{Zr}} - Z^{\mathrm{Ru}}}{Z^{\mathrm{Zr}} - Z^{\mathrm{Ru}}}$$

INDRA

INDRA+FAZIA

In-medium *NN* cross section (II)



$$\mathrm{LMT} = \left\langle \frac{v_{\parallel}}{v_{\mathrm{c.m.}}} \right\rangle$$

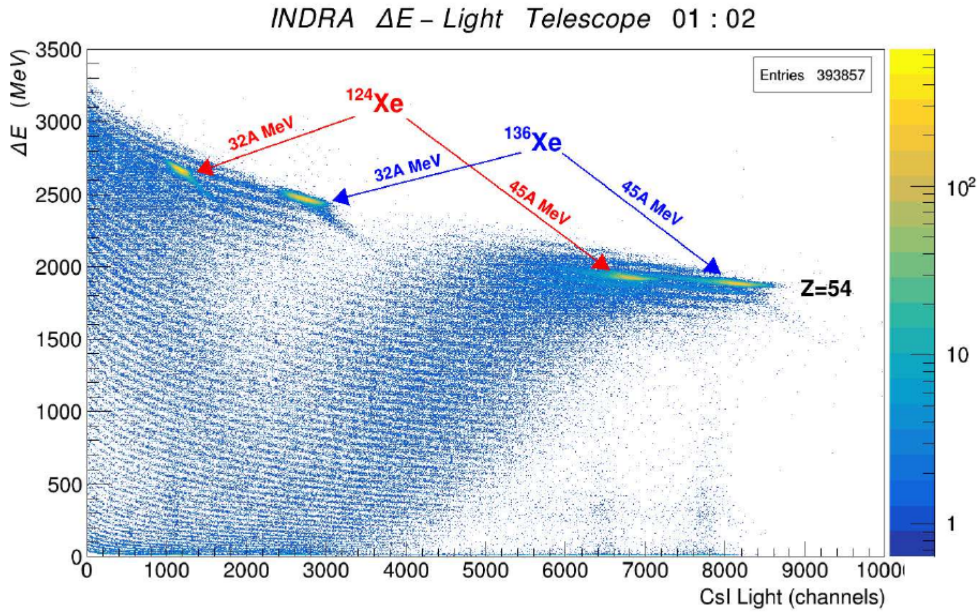
$$varxz = \frac{\Delta y_x}{\Delta y_z},$$

$$R_Z = \frac{2 \times Z - Z^{\mathrm{Zr}} - Z^{\mathrm{Ru}}}{Z^{\mathrm{Zr}} - Z^{\mathrm{Ru}}}$$

INDRA

INDRA+FAZIA

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

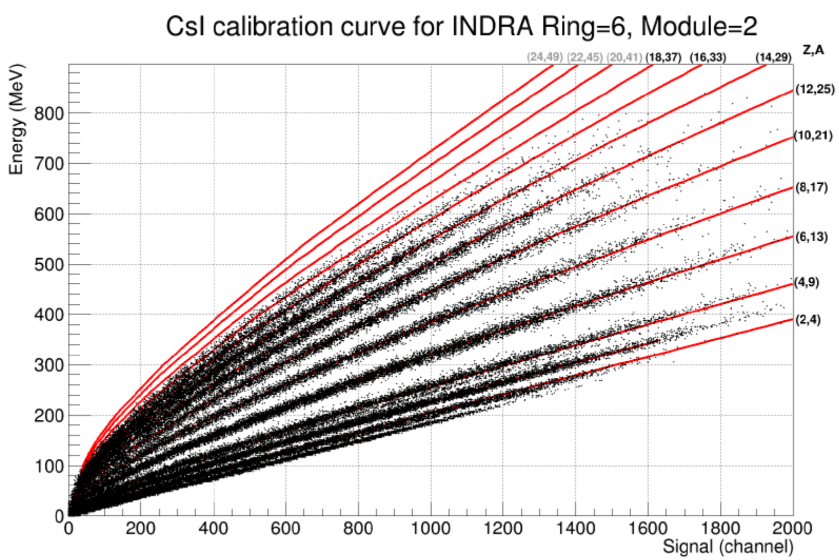


From Si-CsI raw matrices, get ***Z*** (grid) and
From CsI light output integration, get L_{exp}

- Start with an initial A_0 value (mass tables)
- From the calibrated ΔE silicon and $A \rightarrow E_{csI,0}$
- From Light-Energy formula*, then estimate L_0
- Iterate on $A \rightarrow E_{CsI,i} \rightarrow L_i$ until $L_i = L_{exp}$

Isotopic identification Z<12
Isotopic estimation (±3) up to Z=54 ...

+



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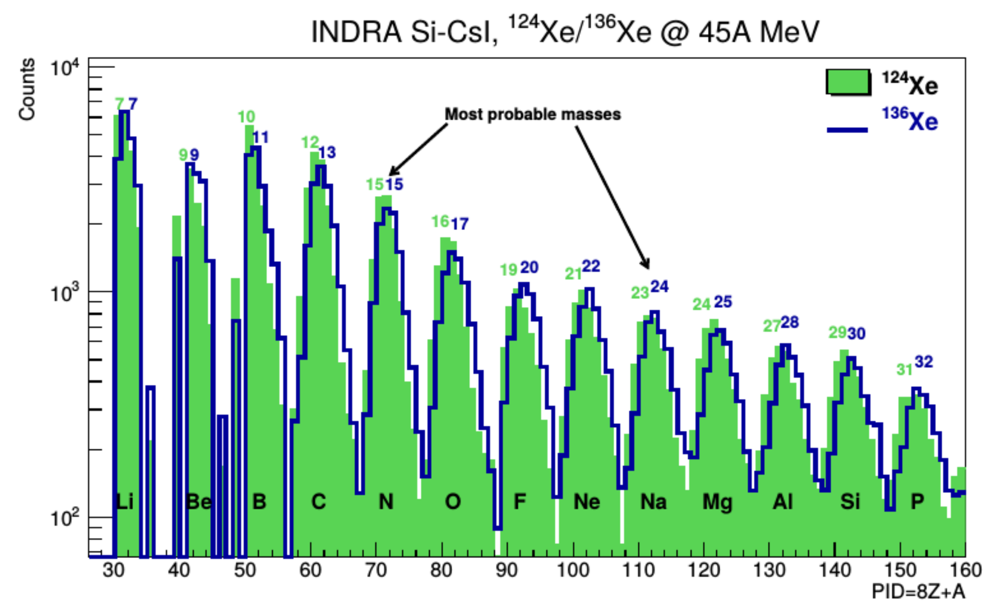


O. Lopez *et al*, *arXiv:1707.08863*
Submitted to NIM A

$$^*\mathcal{L}(E_0) = a_1E_0\left[1 - a_2\frac{AZ^2}{E_0}\ln\left(1+\frac{1}{a_2AZ^2/E_0}\right) + a_2a_4\frac{AZ^2}{E_0}\ln\left(\frac{E_0+a_2AZ^2}{a_3A+a_2AZ^2}\right)\right]$$

(some) recent progresses for FAZIA

FAZIA in 4-block configuration = 64 Si-Si-CsI telescopes

- IsoFAZIA : ^{84}Kr + $^{40,48}Ca$ @ 35 AMeV (Dec. 2015) ⇒ see talk by Simone Valdré
- FAZIASym : $^{40,48}Ca$ + $^{40,48}Ca$ @ 35 AMeV (June 2015)
- FAZIACor : ^{32}S/^{20}Ne +^{12}C @ 25,50 AMeV (March 2017)

FAZIASYM @ LNS
Dec. 9-20 2015

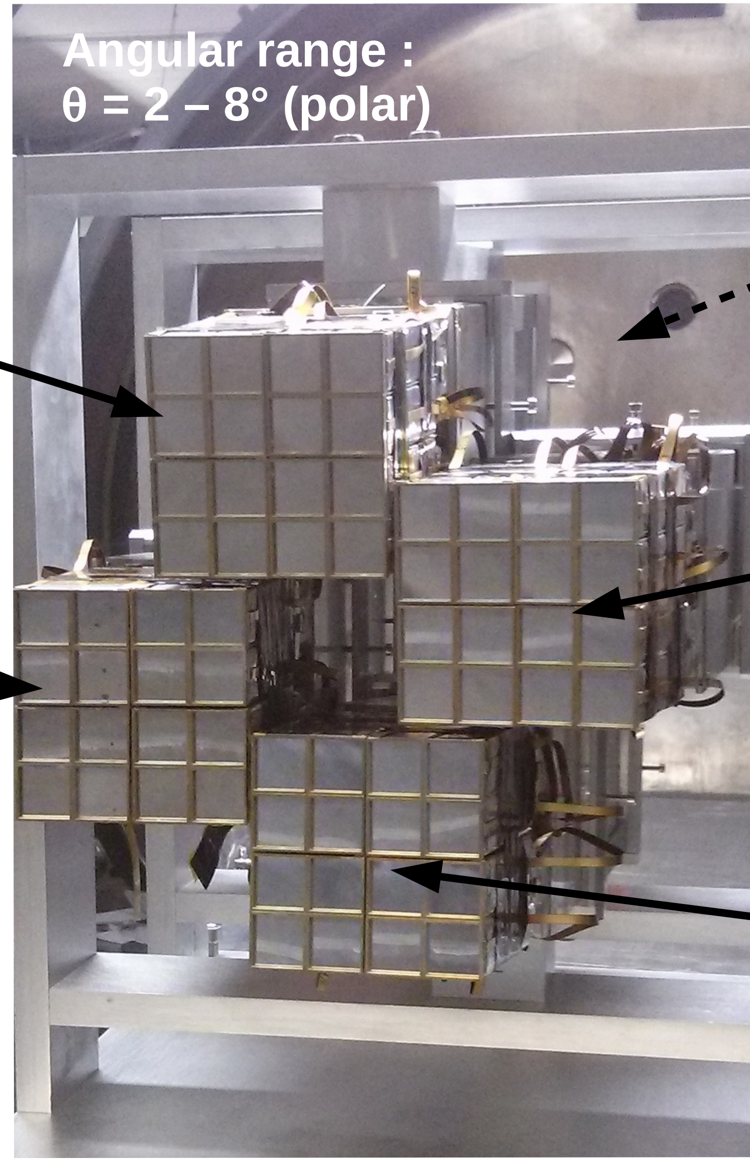
^{40}Ca + ^{40,48}Ca (+ C layer)
^{48}Ca + ^{40,48}Ca (+ C layer)
@ 35A MeV

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

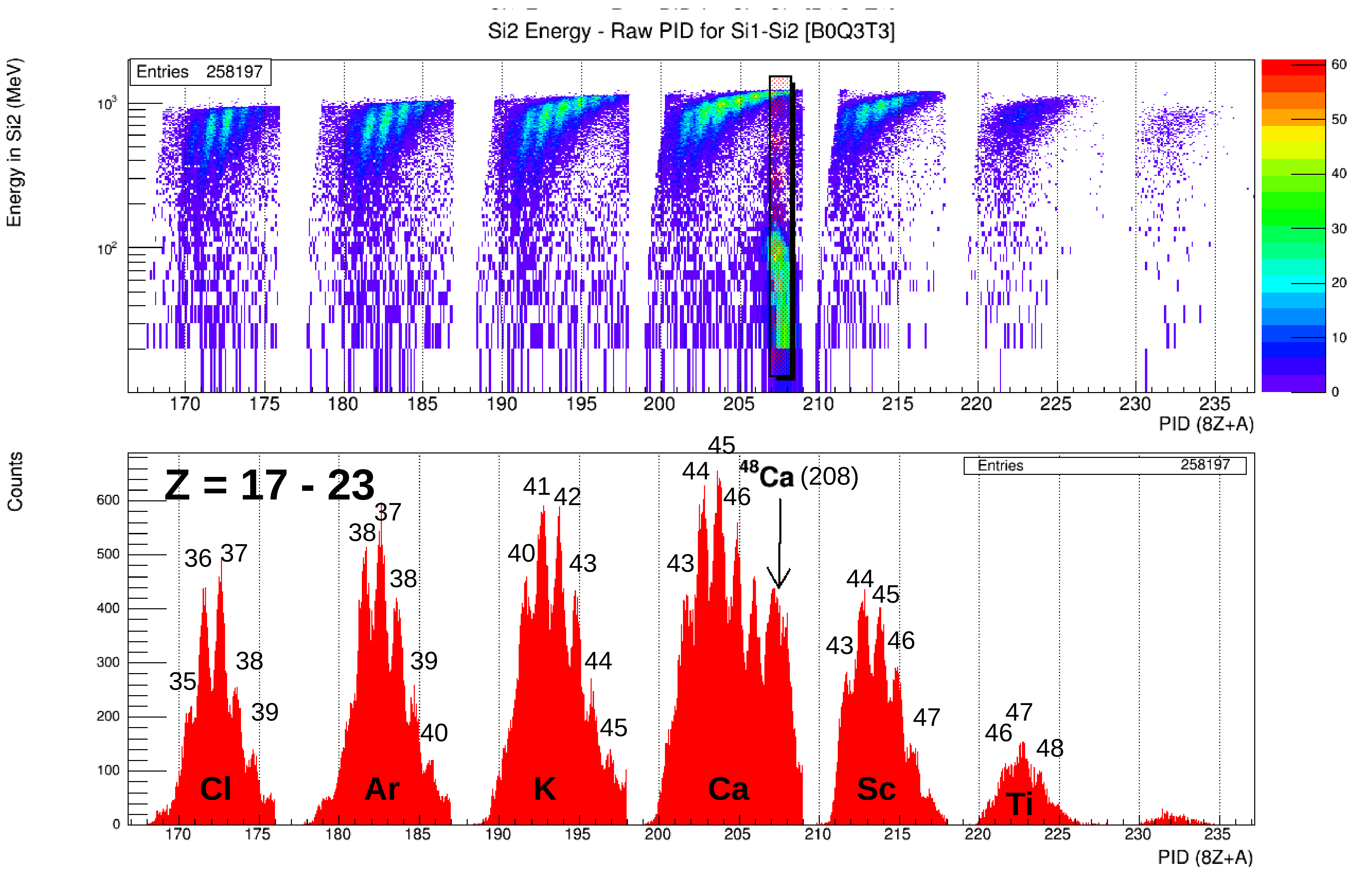
1 Block =
16 telescopes *Si-Si-CsI*

- 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

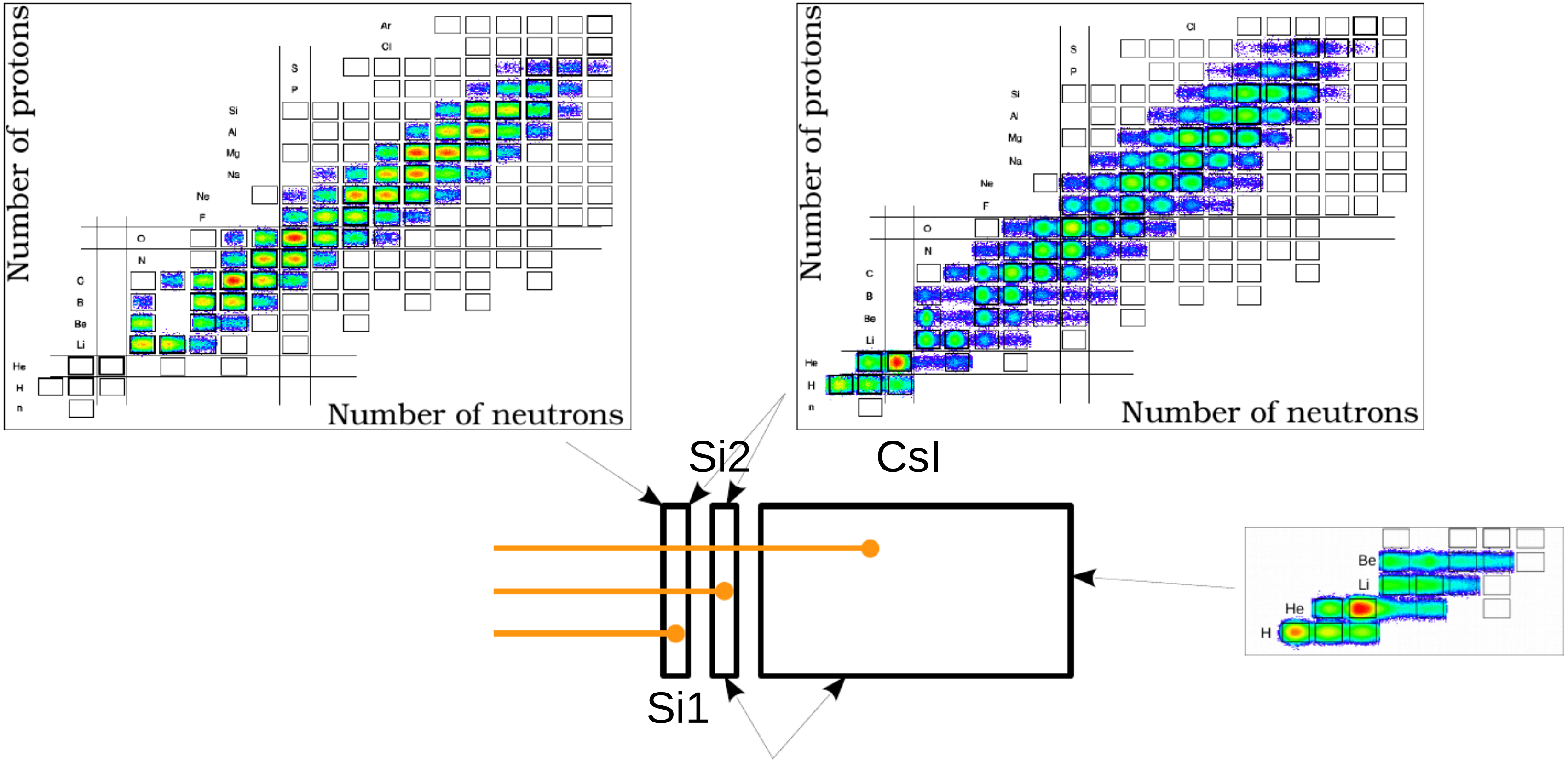


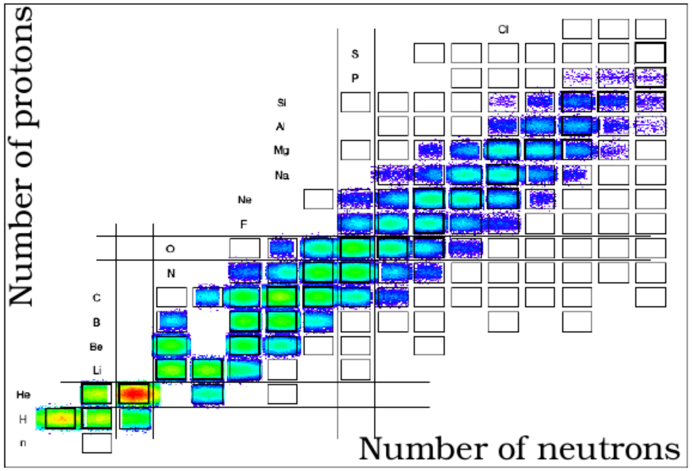
FAZIASym : Identification using AMI grid (II)



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

FAZIACor status for Identification



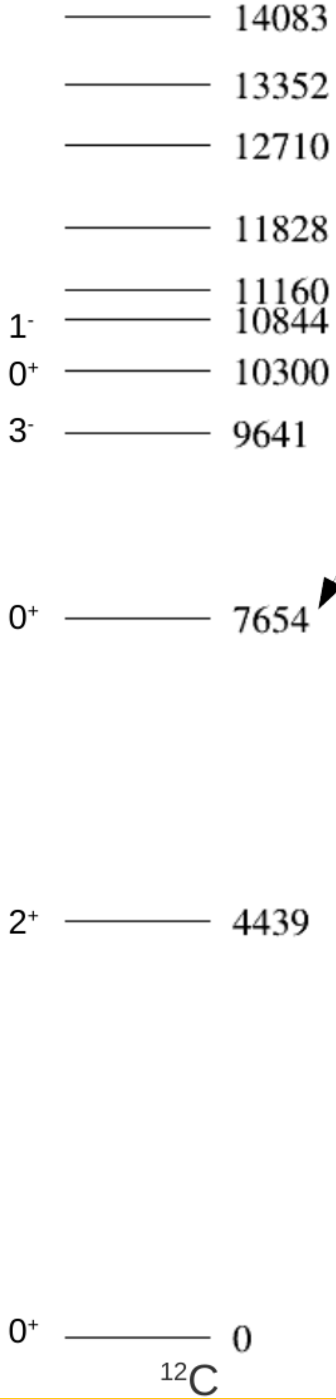


FAZIACOR data
LNS March 2017
SP: G.Verde & D.Gruyer
S, Ne + C at 25, 50MeV/A

Credits: FAZIA Collaboration

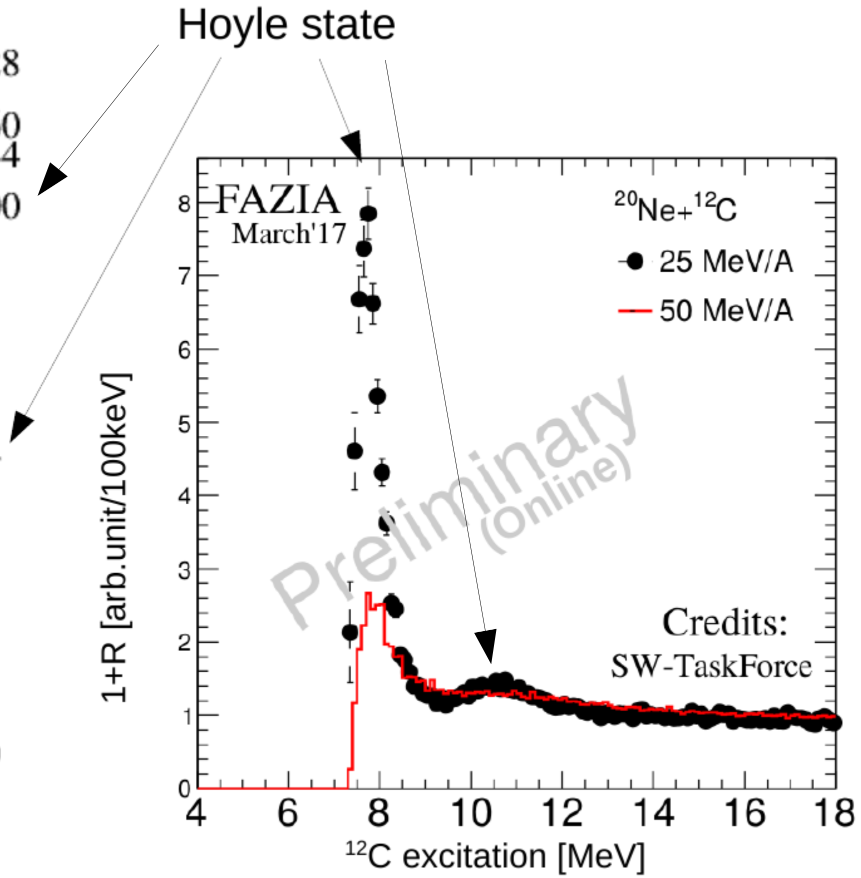
G . Verde (IPNO/LNS Catania)
D. Gruyer (LPC Caen)

FAZIACor : in-medium cluster correlations



Very preliminary results (online)

From E. Bonnet (GANIL)

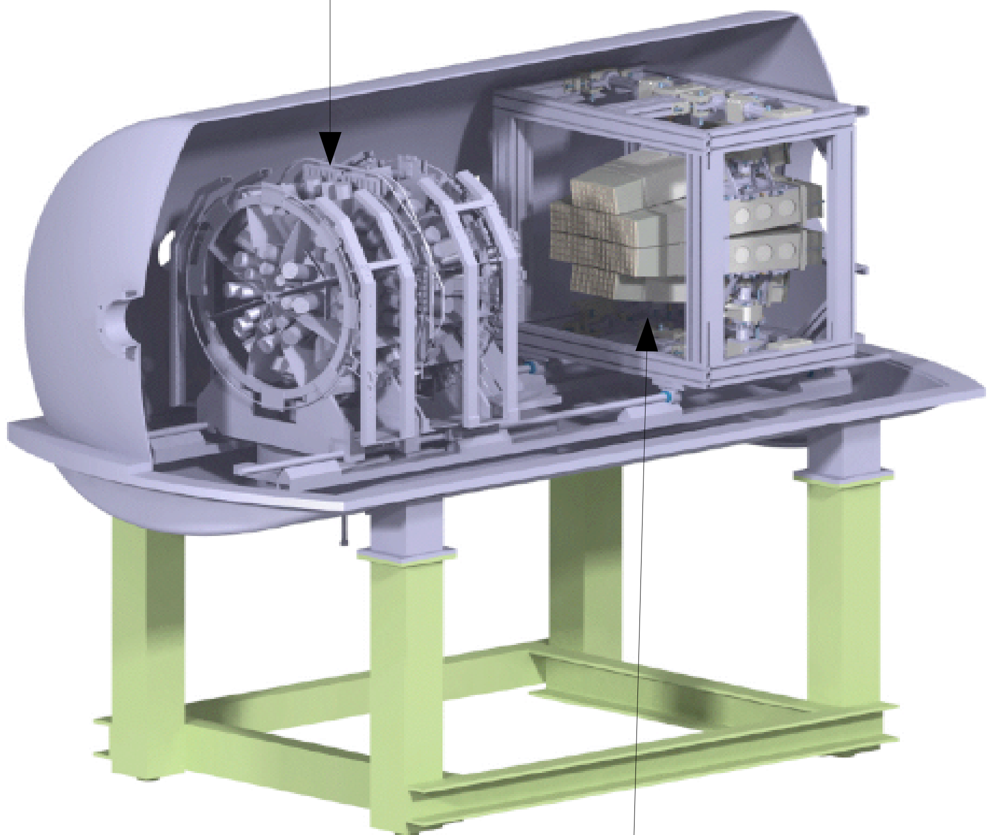


Online results are promising : in-medium clustering for light nuclei, here ^{20}Ne and ^{32}S with 3-α correlation (^{12}C*)

INDRA + FAZIA
Experimental program at GANIL

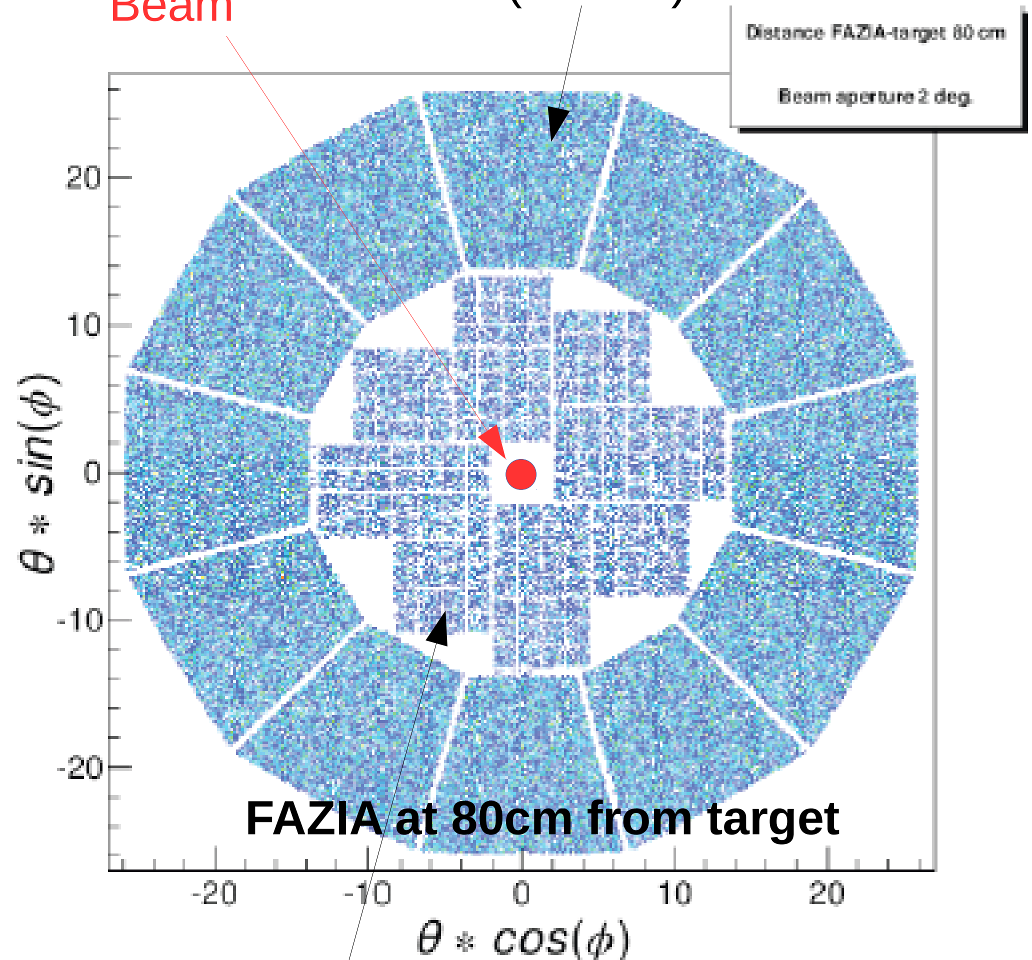
Coupling FAZIA demonstrator with INDRA

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



Beam

Ring 6/7 (INDRA)

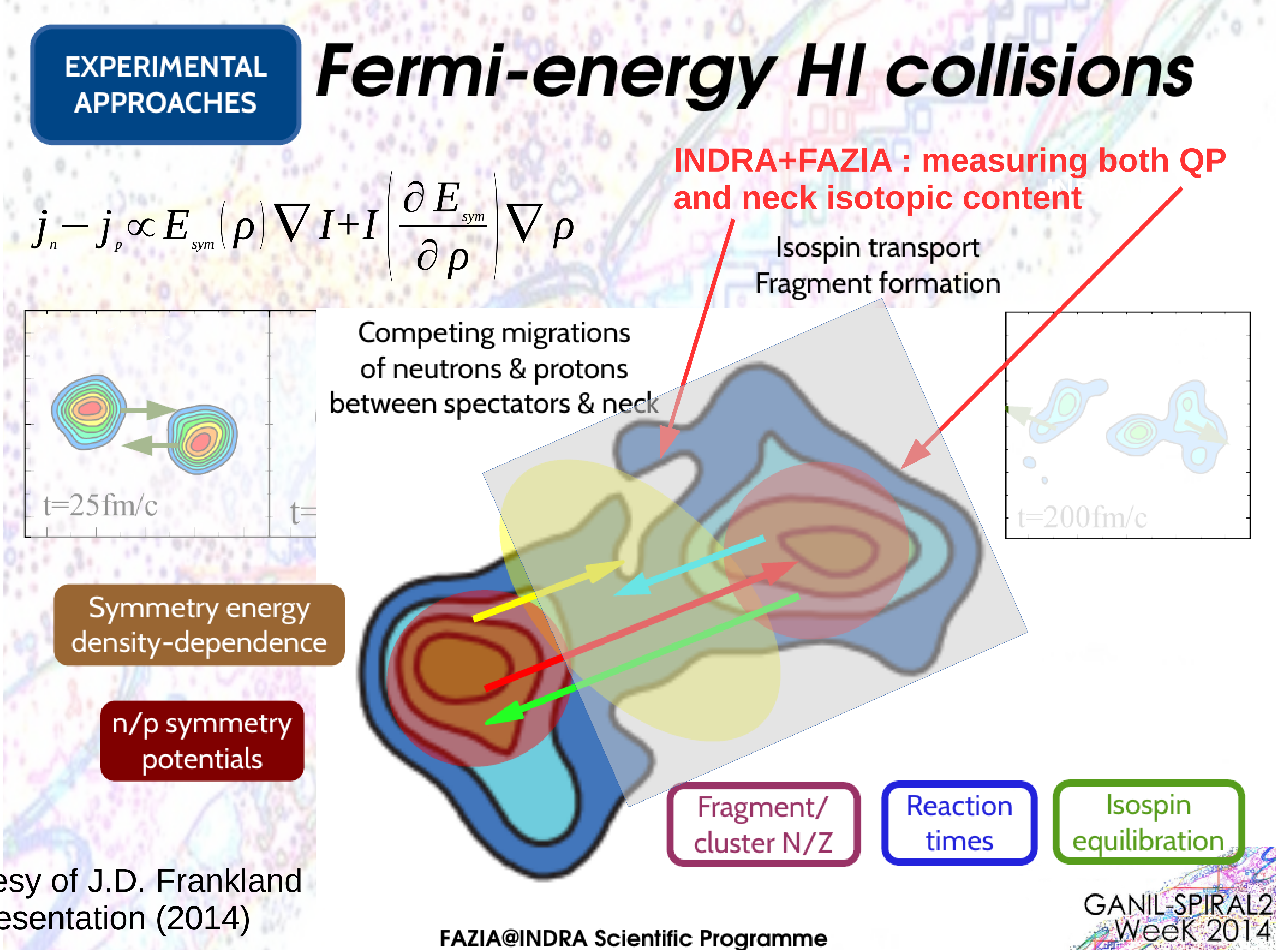


Transverse plane

FAZIA demonstrator (est. 2016), 12 blocks :
192 20x20mm^2 high-quality *Si-Si-CsI* telescopes
from 2 to 14 deg. + customized full digital electronics

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

Density dependence of the symmetry energy : neck + QP



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

Courtesy of J.D. Frankland
SC presentation (2014)

Density dependence of the symmetry energy : neck

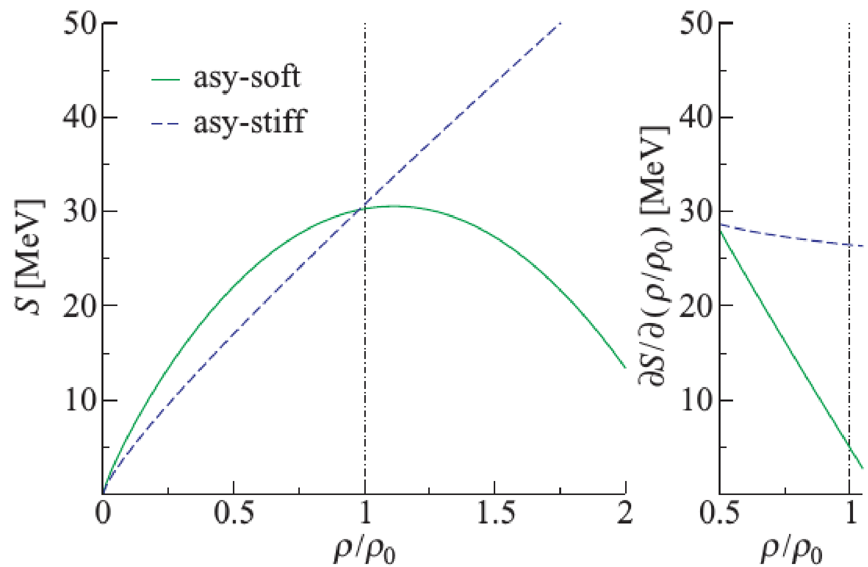
Ternary events for ^{68}*Ni*+^{68}*Ni* at *40A MeV*

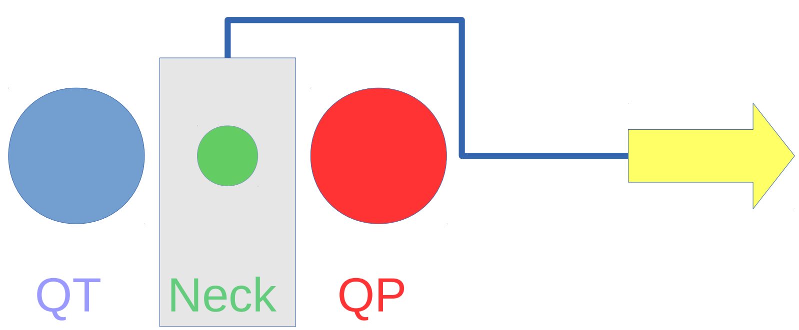
1 QT + *1 neck IMF* + *1QP*

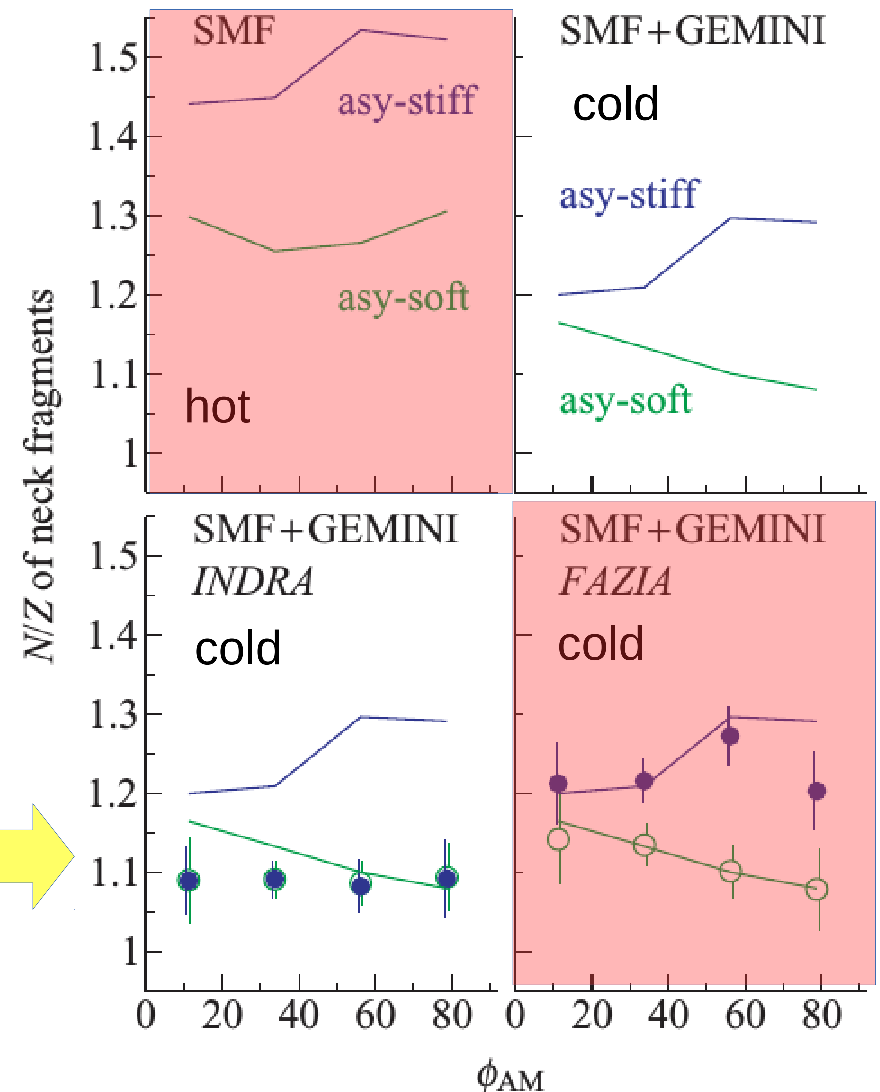
0.45 < b_{red} < 0.75

SMF simulations $^{58/68}$*Ni*+$^{58/68}$*Ni 15A*, *40A* MeV

P. Napolitani et al., PRC ***81****, 044619 (2010)*







FAZIA data could be sensitive to E_{sym} stiffness ...

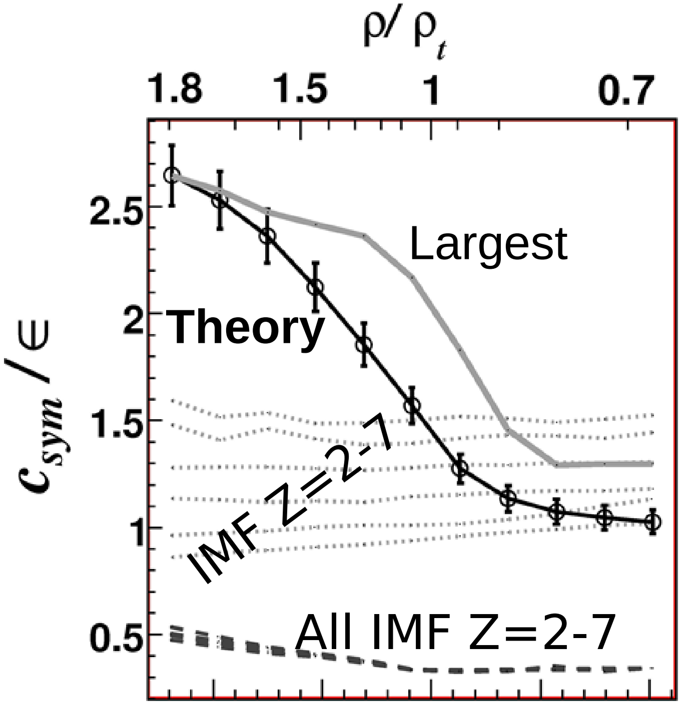
Density dependence of the symmetry energy : QP

- **Isoscaling:** observed scaling law of fragment (*N,Z*) production for two reactions involving different isotopes (ex. $^{40/48}Ca$, $^{124/136}Xe$)
- **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*)

Example : $^{40,48}Ca+^{40}Ca$ @ *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

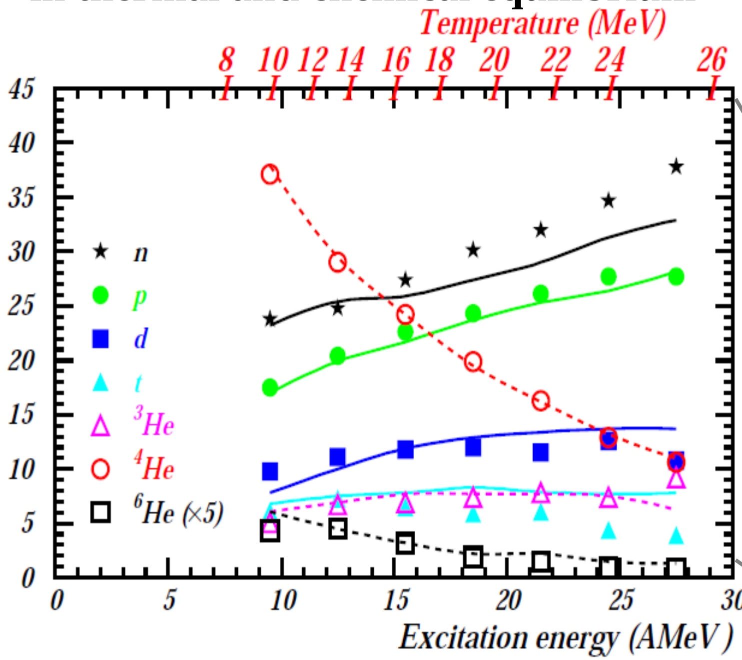


G. Lehaut *et al.* (INDRA coll.), *Phys. Rev Lett.* **102**, 142503 (2009)

Vaporization @ low density

Vaporization process: a bridge between nuclear physics and astrophysics

Vaporization events of Ar-like projectiles well described by a **weakly-interacting quantum gas of nuclear species in thermal and chemical equilibrium**



B. Borderie et al., (INDRA collaboration) EPJ A 6 (1999)
F. Gulminelli et al., NPA 615 (1997)

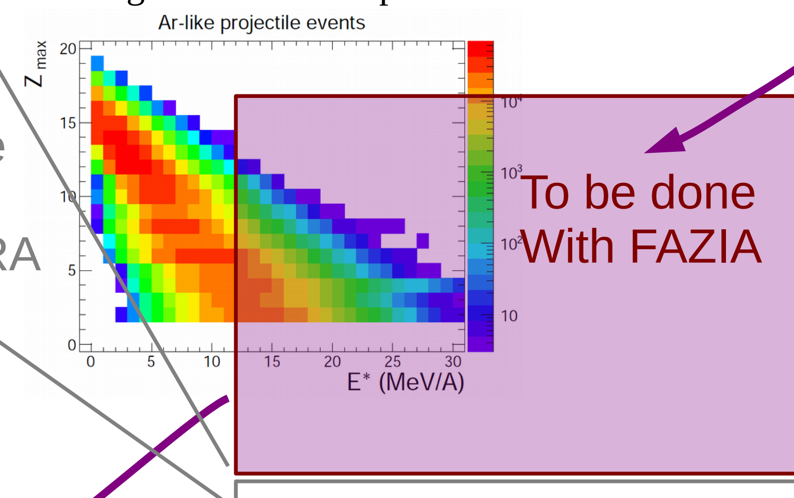
Vaporization of hot nuclei described as their complete explosion into light particles (neutrons and hydrogen and helium isotopes).

The neutrino-sphere, where the last scattering of neutrinos occurs during the collapse of the supernovae core, is a warm low-density neutron-rich matter. The energetics of these low density neutron-rich matter is determined by the **symmetry free energy far from saturation which is poorly known.**

Vaporization events of 40,48Ca-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

Done with INDRA



P. Papakonstantinou et al., Phys. Rev. C 88 (2013) 045805.
Ad. R. Raduta et al., Eur. Phys. J. A (2014) 50:24.

Example : ^{58,64}Ni + ^{58,64}Ni 50A -90A MeV

Unique set of experimental data to constrain theoretical descriptions. Dedicated calculations will be done with the recently proposed extended NSE model, which is optimized to study equilibrium properties of subsaturation exotic matter Constrain the symmetry free energy far from saturation

INDRA + FAZIA scientific program at GANIL

Isovector dependence of the nuclear interaction and EOS

- **In-medium properties of clusters** : clustering @ low density (i.e. α–Hoyle states), cluster emission in n-rich/poor systems

- Study of **EOS at low density** : vaporization and cluster mixing with nucleon gas

- **Density dependence** of the symmetry energy: isospin diffusion in *DIC*, isoscaling using the largest fragment, neutron enrichment in the neck (migration/diffusion)

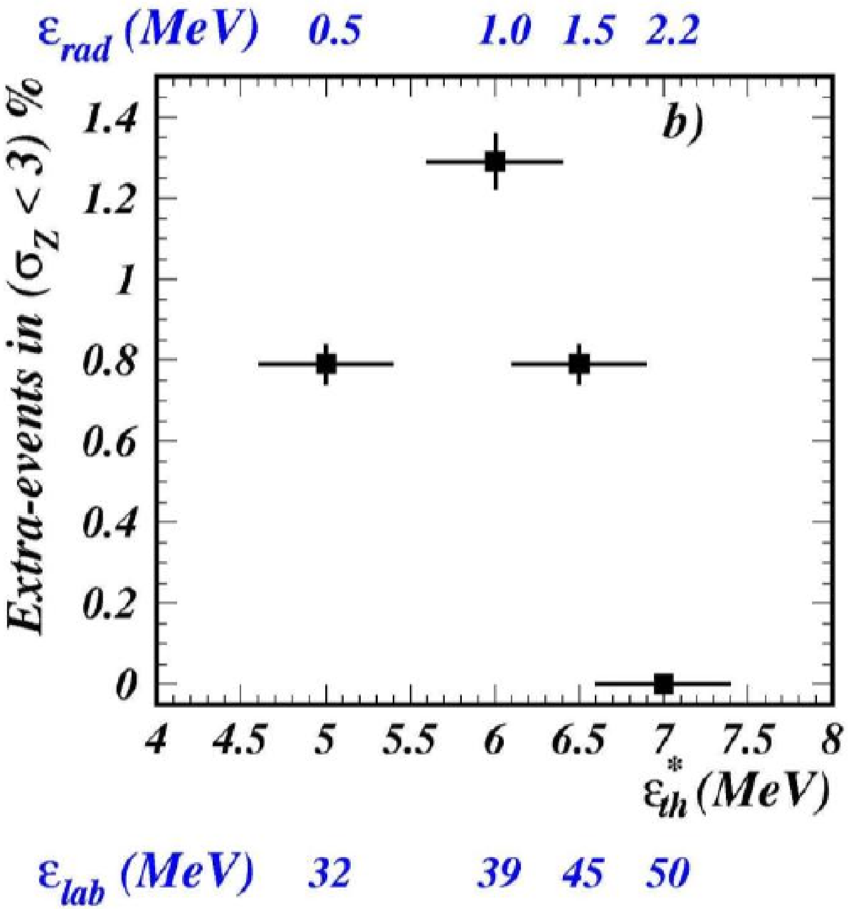
- **Transport properties** @ Fermi energy : *NN* collisions in the isovector sector, isospin tracer, short-range correlations in nuclei, effective masses, and also : radial flow, viscosity ...

End

Spinodal decomposition: isoscalar *vs* isovector instabilities

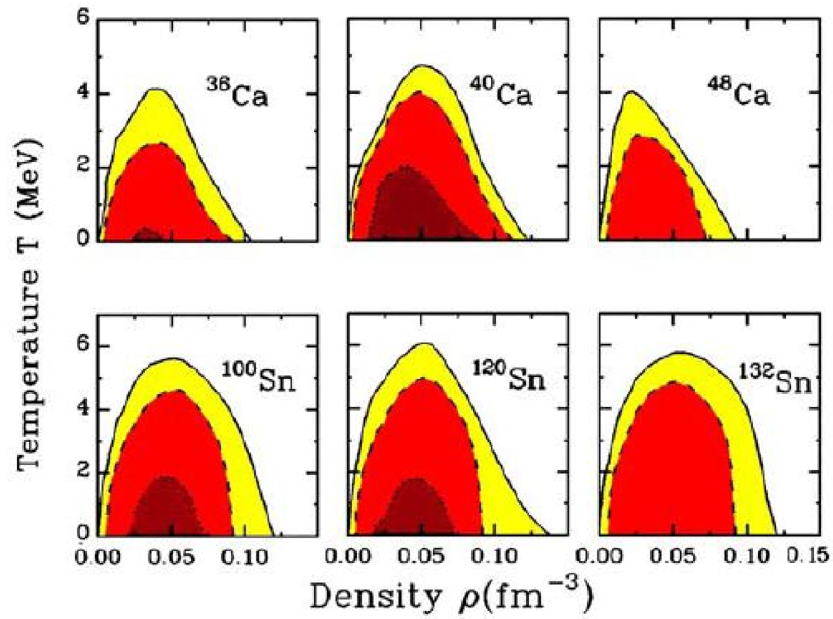
Spinodal decomposition and dynamics of fragmentation

High-order correlations in charge : ^{129}Xe+^{nat}Sn 32A-50A MeV



B. Borderie et al., **PRL 86 (2001)**

Spinodal region is reduced → N/Z



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

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

- Isospin dependence of the phase diagram ?

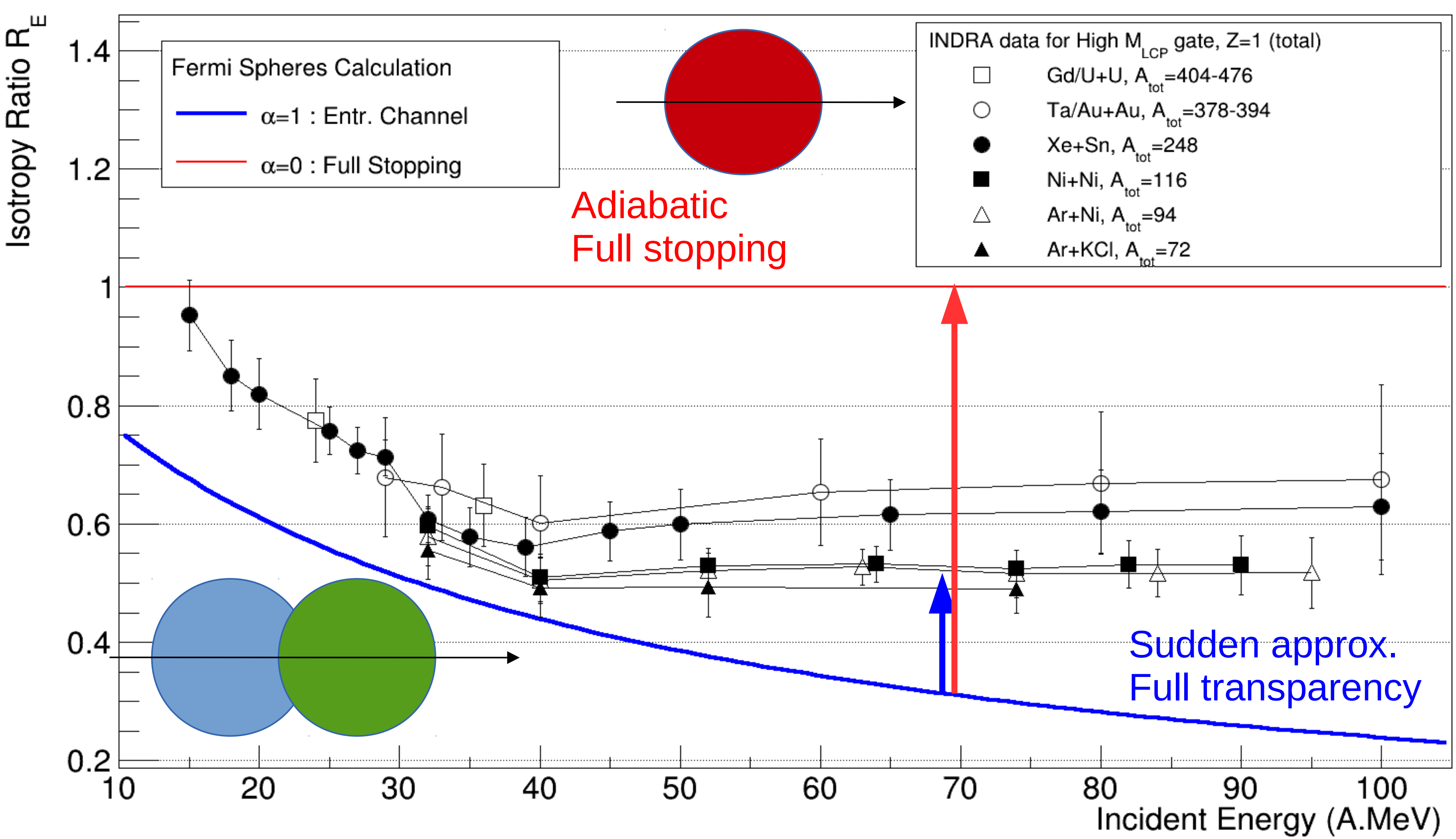
- Correlations with masses (isocalar) and isospin (isovector)

Stopping power in central HIC

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

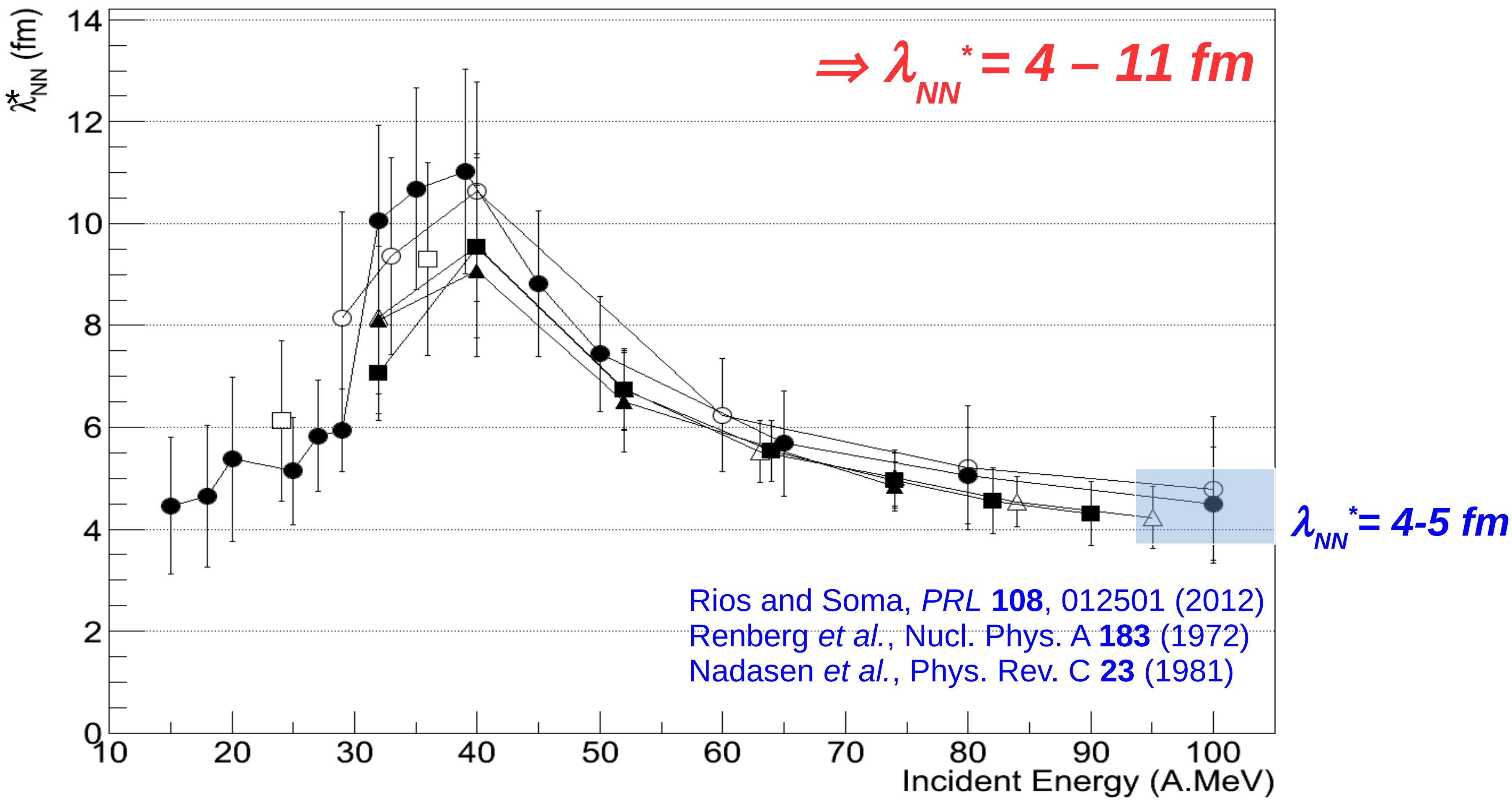
Nuclear Stopping

$$R_E(\alpha) = \frac{1}{1 + 5(\alpha P_{rel}/P_{Fermi})^2}$$



Nucleon mean free path in nuclear medium

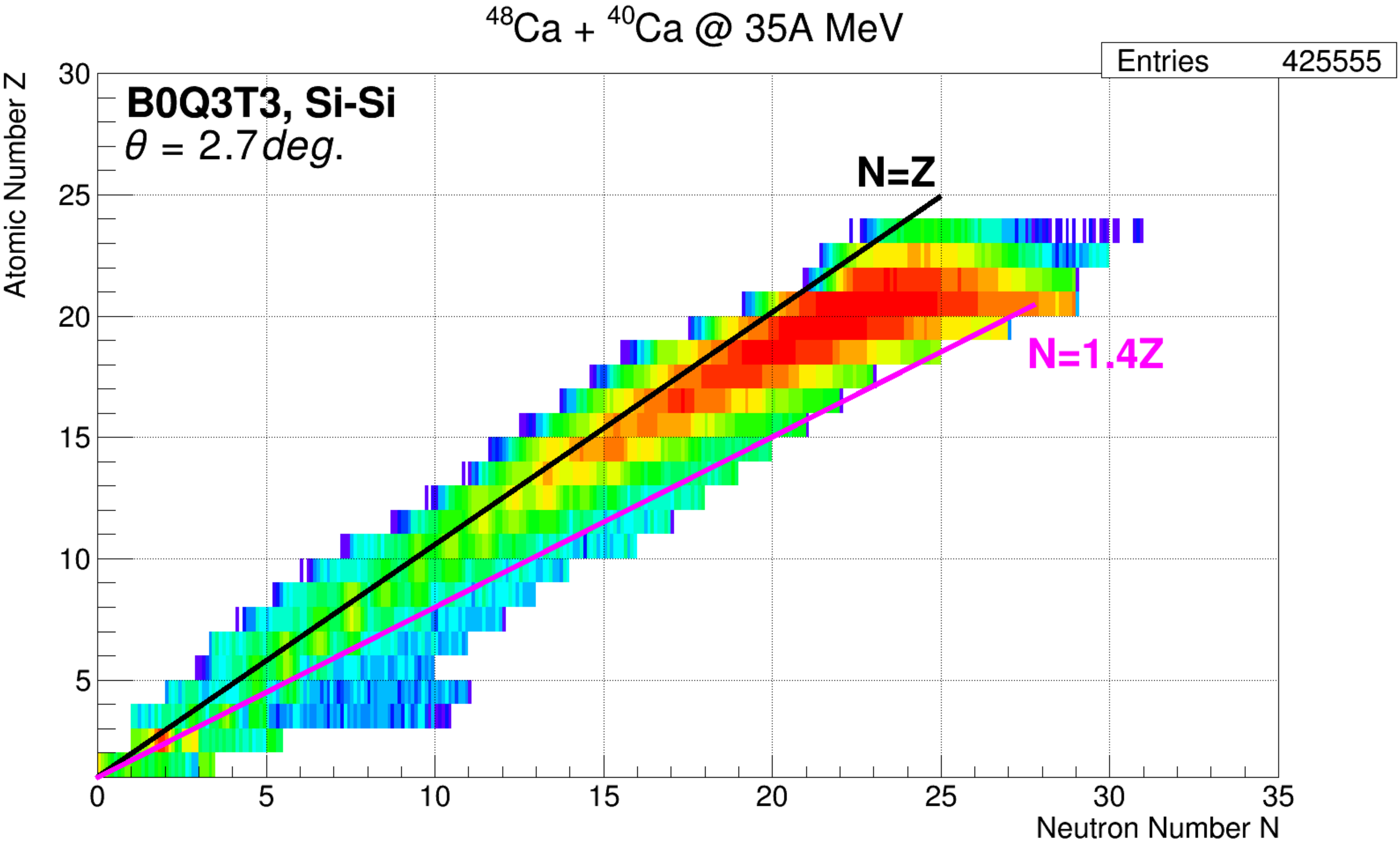
Assuming: $<\lambda_{NN}^{*}> = L/d$



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

- Contradictory findings with *SMF* by E. Bonnet, *et al.*, PRC 89, 034608 (2014)

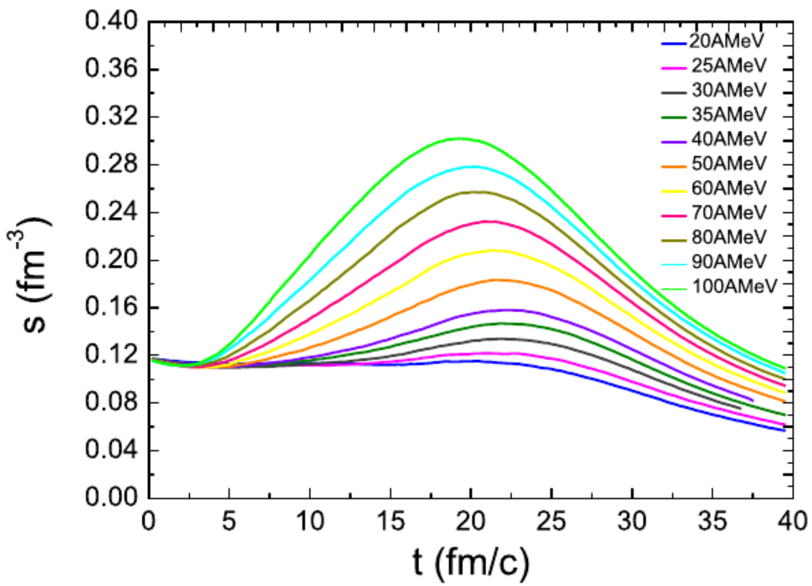
FAZIASym : Isospin diffusion for ^{48}Ca QP



Only inclusive events … preliminary !

Shear viscosity in nuclear matter : how far from the *perfect fluid ?*

IQMD calc. for 129Xe+119Sn central collisions :
Entropy density with momentum-dependent
Skyrme interaction (K=200 MeV)

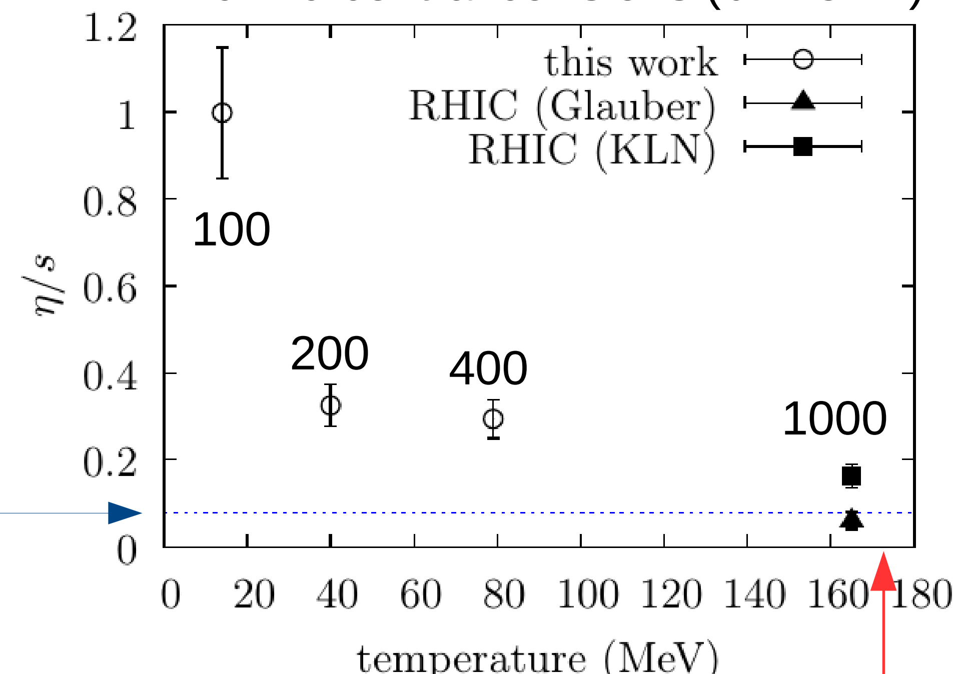


H. L. Liu, Y. G. Ma, A. Bonasera, X. G. Deng,
O. Lopez, and M. Veselsky,
To be published in PRC
η is contrained by INDRA data from stopping

Boltzmann-Uehling-Uhlenbeck simulations
RHIC energies : *Glauber MC* model

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

Au+Au central collisions (b<1.5 fm)



Universal lower limit 1/4π

Critical Temperature ~ 170 MeV