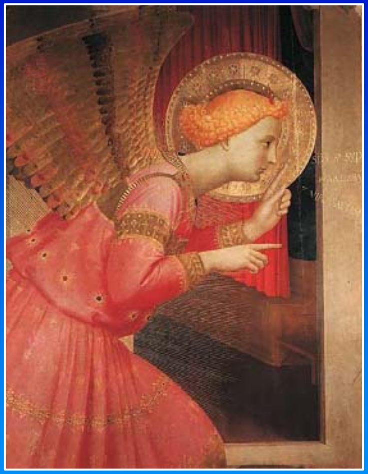


XIV Conference on
Theoretical Nuclear Physics in Italy
Cortona, October 29 – 31, 2013

Symmetry Energy (EOS) & Isospin Physics by CHIMERA detector

Sara Pirrone
EXOCHIM/ISODEC collaboration
INFN-Sezione di Catania

- **Physics Case**

- **Results from selected experiment with Chimera detector**

- **Conclusions & Perspectives**

Physics Case

$$E(\rho,\delta) = E(\rho,\delta=0) + E_{sym}(\rho)\delta^2$$

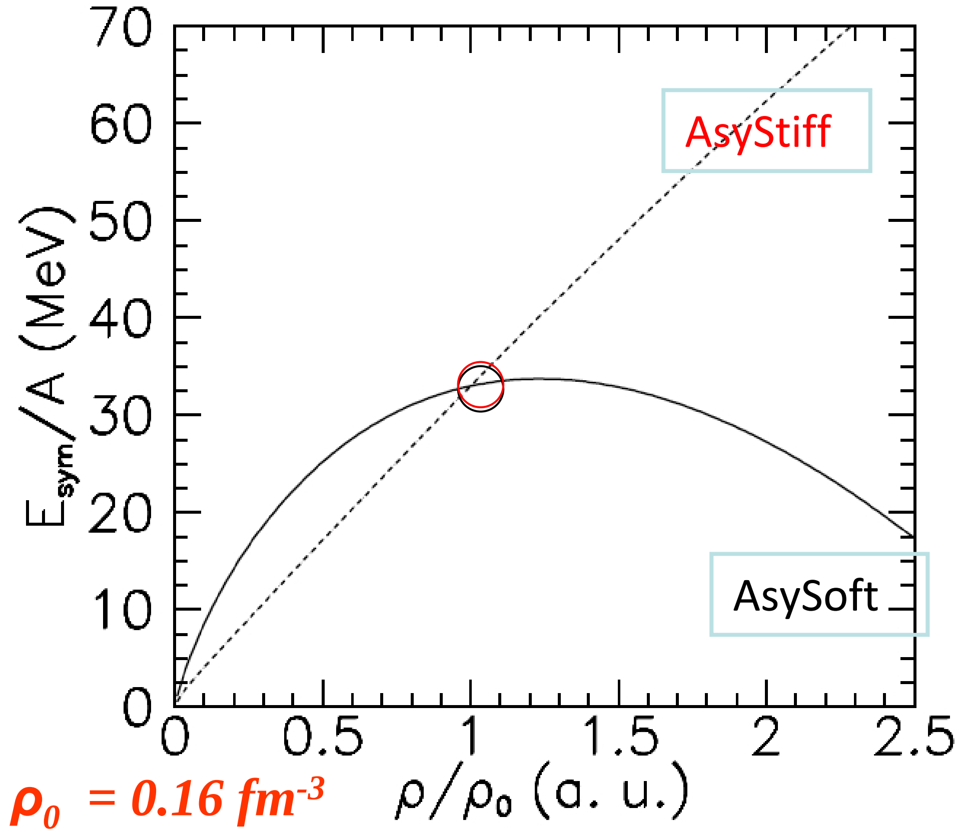
$$\delta = \frac{\rho_n - \rho_p}{\rho_n + \rho_p} = \frac{N-Z}{A}$$

$\rho = \rho_n + \rho_p$

$$E_{sym}(\rho) \approx (\rho/\rho_0)^\gamma$$

$\gamma < 1$ **Asysoft,**

$\gamma \geq 1$ **Asystiff**



$\rho_0 = 0.16\ fm^{-3}$

HIC provide a unique opportunity to create in laboratory transient states of nuclear matter in several conditions of density and temperature

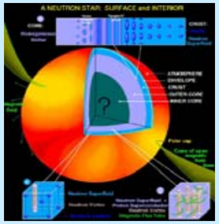
$\longrightarrow E_{beam}$

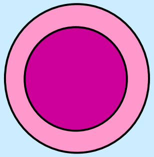
low density | **high density**

$\rho \leq \rho_0$ HIC up to Fermi energy **(N/Z)**

Isospin diffusion - migration
Neutron/proton ratio
Transvers collective flow of LCP
Ratio of fragments yields and isoscaling
Pygmy Dipole Resonance
Light cluster production
Mid-rapidity emission from the neck
Particle correlations, femtoscopy

Subsaturation
linked to n-skin structure (nuclei, n-star)





^{208}Pb

$\rho \geq \rho_0$ HIC Relativistic Energy

Adapted by M.Colonna

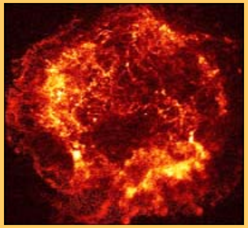
Coll. Elliptic Transverse flow (p, n, π)

n/p, ratios

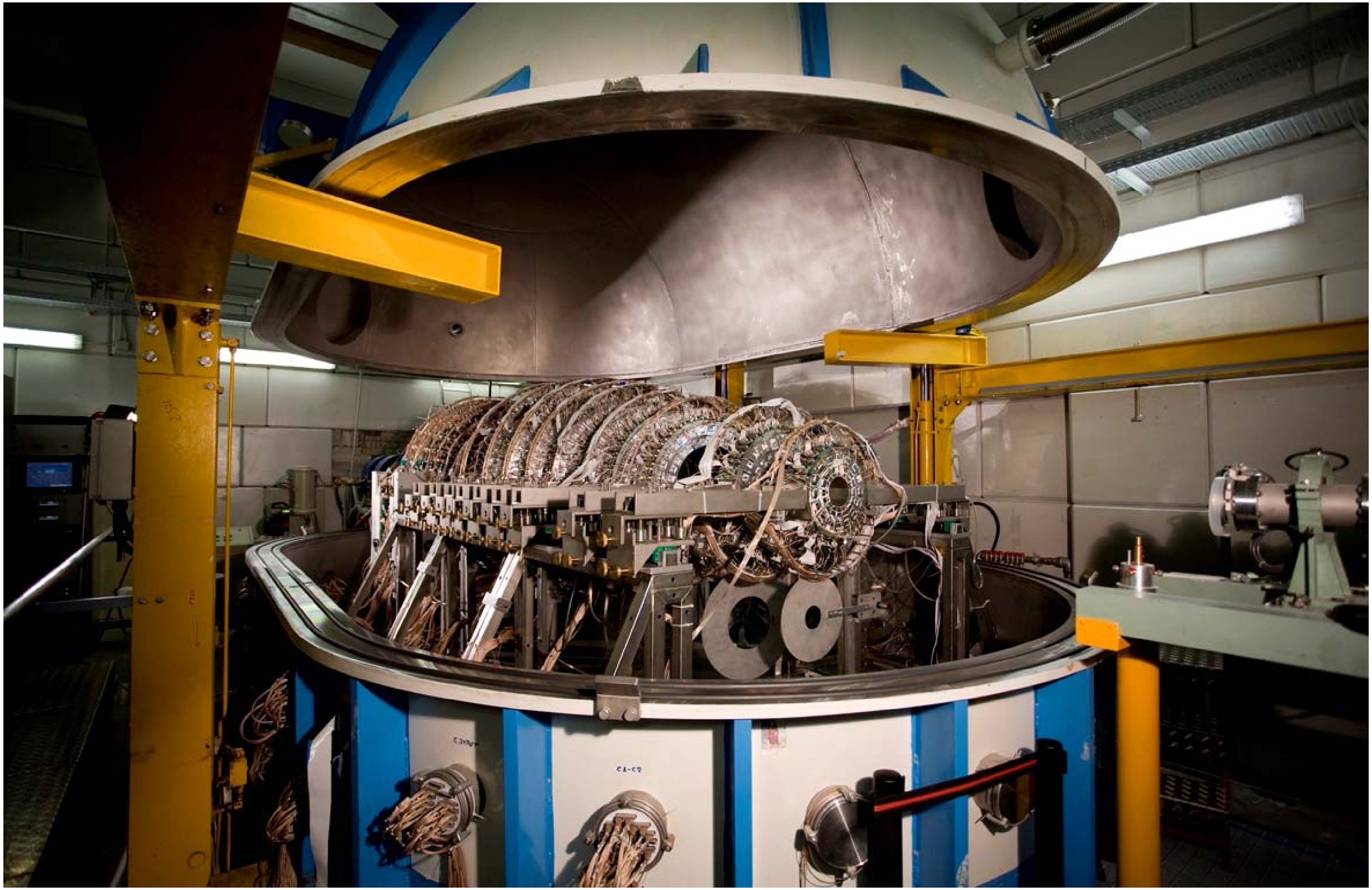
pions ratios

kaon ratios

Suprasaturation
linked to Supernova dyn.n-star cooling



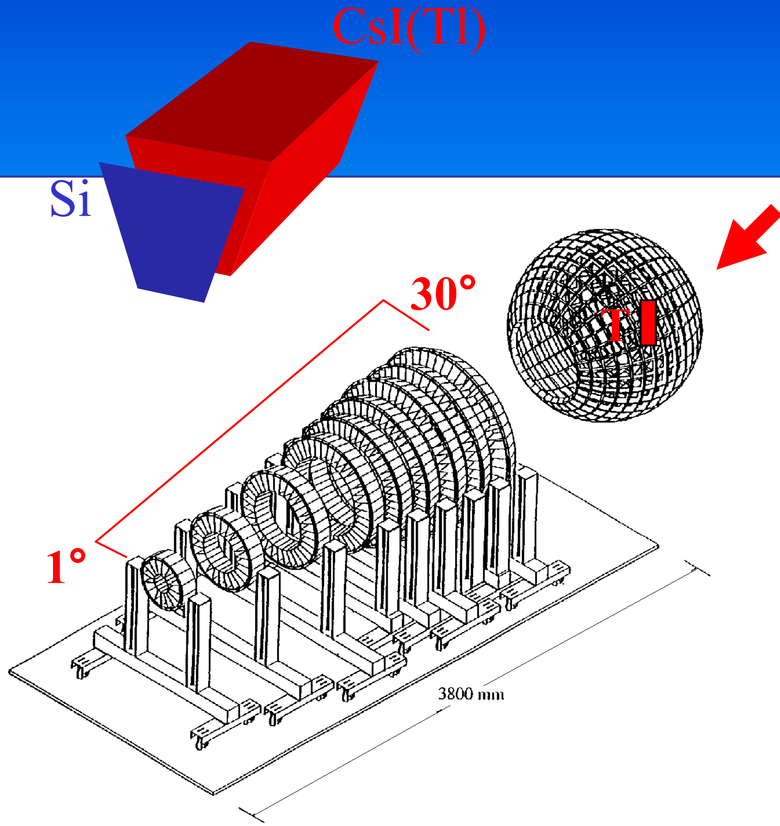
CHIMERA@LNS



A.Pagano et al., NPA734 (2004)

CHIMERA

Charge Heavy Ion Mass and Energy Resolving Array



Granularity	1192 telescopes Si (300μm) +CsI(Tl)
Geometry	RINGS: 688 telescopes 100-350 cm SPHERE: 504 telescopes 40 cm
Angular range	RINGS: 1°< θ < 30° SPHERE: 30°< θ < 176° 94% of 4π
Identification method	ΔE-E E-TOF PSD in CsI(Tl) PSD in Si (upgrade 2008)
Experimental observables and performances	TOF δt < 1 ns δE/E LCP (Light Charge Particles) ≈ 2% δE/E HI (Heavy Ions) ≤ 1% Energy, Velocity, A, Z, angular distributions
Detection threshold	≈ 1 MeV/A for H.I. ≈ 2 MeV/A for LCP

Dynamical range : from fusion, fusion-fission to multifragmentation reaction

Example of Chimera coll. contribution to isospin physics studies

- **Study of the systems $^{124}Sn+^{64}Ni$ and $^{112}Sn+^{58}Ni$ @35 A.MeV.** ***Neck emission, Time scale for fragment formation, fragment hierarchy, Dynamical fission (Chimera coll) LNS***

- **Isospin dependence in the competition between incomplete fusion and dissipative binary reactions in $^{40}Ca,^{48}Ca + ^{40,48}Ca, ^{46}Ti$ @25 AMeV** ***(Chimera coll.) LNS***

- **Study of isospin diffusion in the reactions $^{124}Sn+^{124}Sn$, $^{124}Sn+^{112}Sn$, $^{112}Sn+^{124}Sn$, $^{112}Sn+^{112}Sn$ @35 MeV.** ***(MSU-Chimera coll.). LNS***

- **Fast collinear partitioning of the $^{197}Au + ^{197}Au$ @15 A.MeV, system into three and four fragments of comparable size** ***(Chimera coll.) LNS***

- **Exploring the isospin dependence on decay from compound nucleus in the reactions $^{78,86}Kr + ^{40,48}Ca$ @10 A.MeV** ***(Chimera-Indra coll.) LNS***

- **Constraining the Symmetry Energy at Supra-Saturation Densities With Measurements of Neutron and Proton Elliptic Flow, Au+Au, $^{96}Zr+^{96}Zr$ and $^{96}Ru+^{96}Ru$ @400 A.MeV** ***(AsyEos-Chimera coll.) GSI***

In progress…

Study of the systems

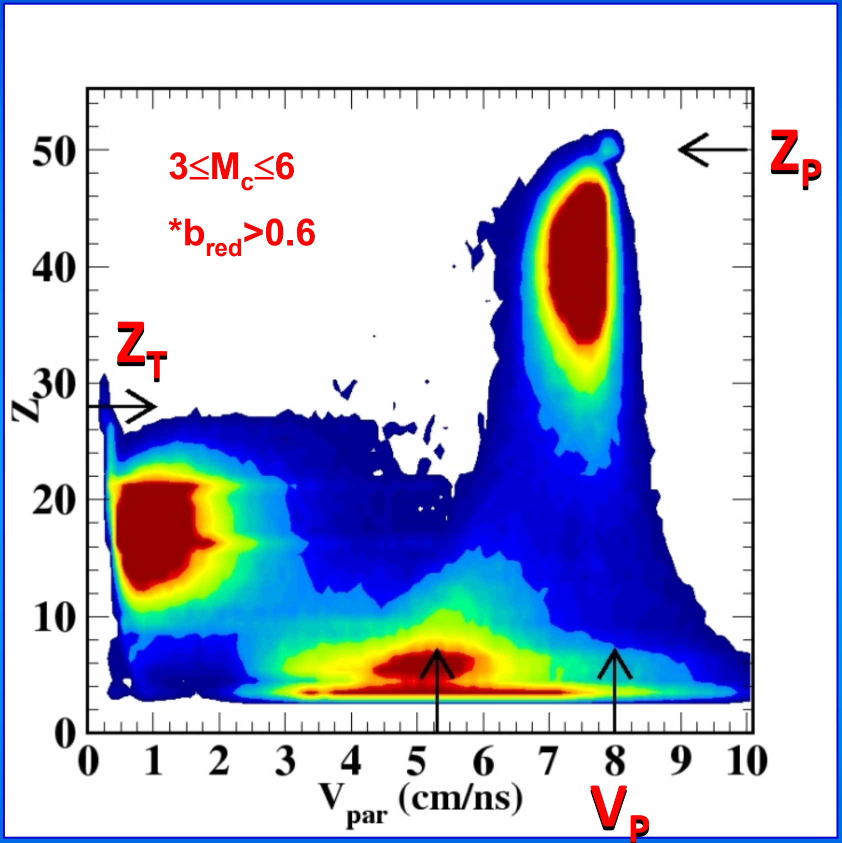
$^{112}Sn + ^{58}Ni$ (n-poor), $^{124}Sn + ^{64}Ni$ (n-rich)@ 35 AMeV

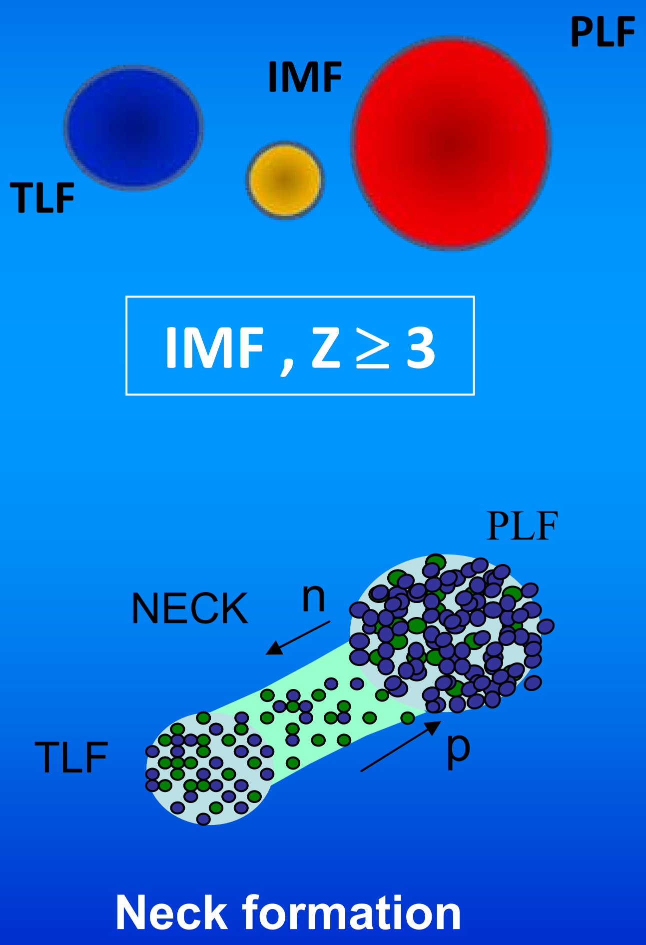
Time scale for fragment formation, fragment hierarchy,

Neck Emission - Dynamical fission

Ternary and semiperipheral events selection

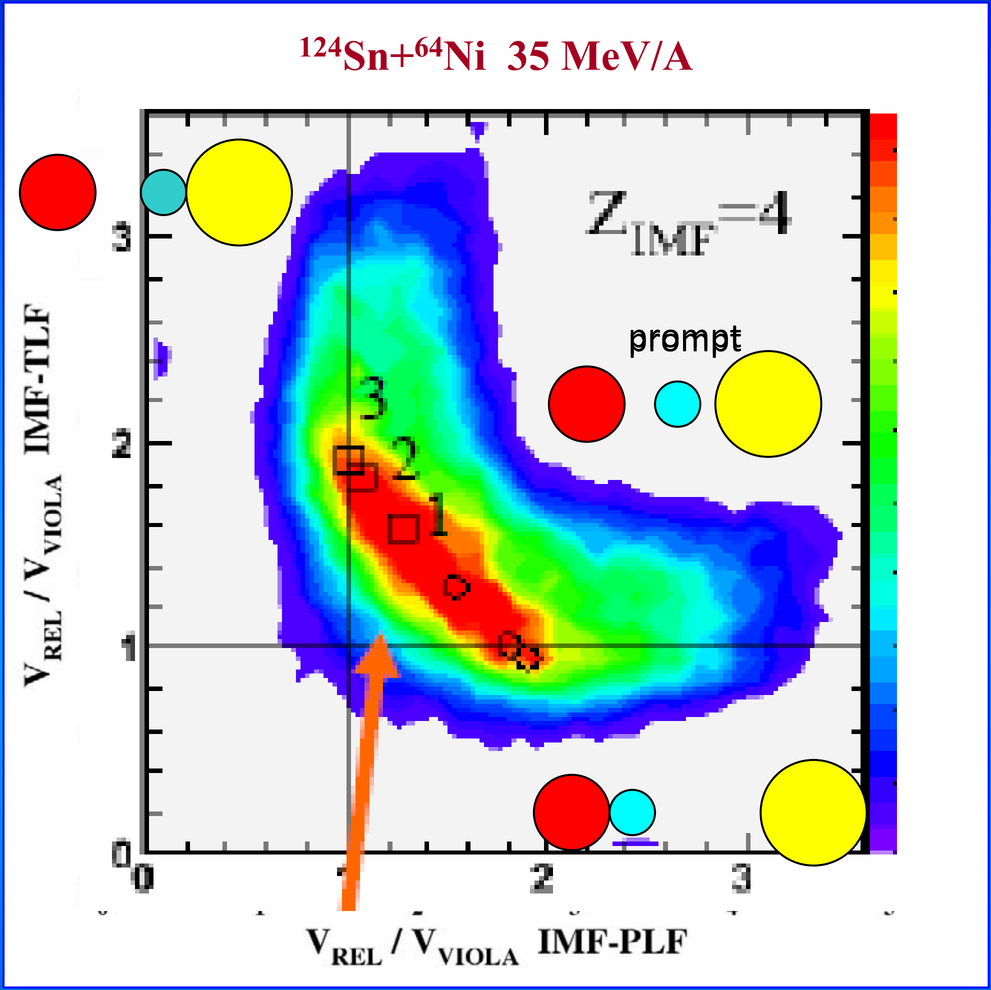
$^{124,112}Sn + ^{58,64}Ni$ @ 35 AMeV

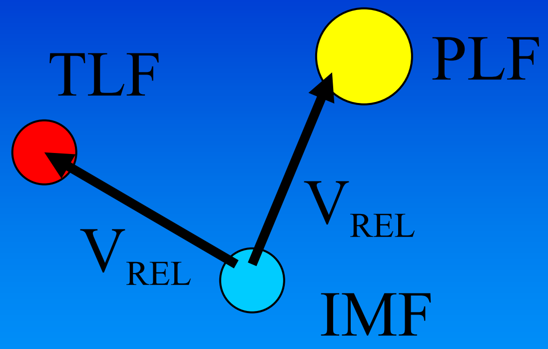




E.De Filippo et al. PRC71,44602 (2005)

TIME SCALE: Emission Chronology by velocity correlation





Relative velocities are expressed in relationship with the Viola velocity (pure Coulomb repulsion)

Viola et al Nucl. Phys. A472, 318 (1987)

E.De Filippo et al. PRC71,44602 (2005)

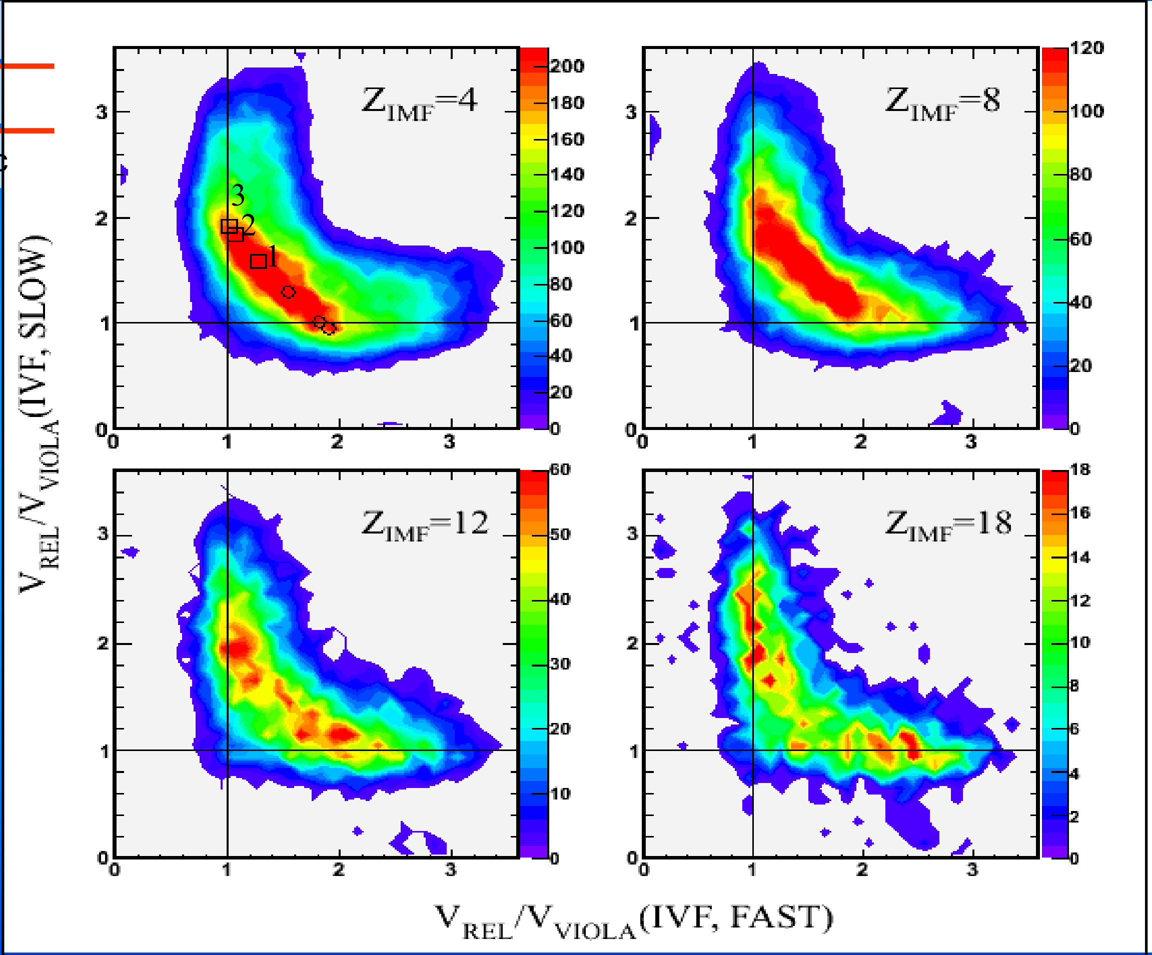
v_{rel}/v_{viola} =1	SEQUENTIAL DECAY OF IMF FROM PLF (or TLF),	$t \geq 120$ fm/c	(2,3)
$v_{rel}/v_{viola} \neq 1$	NON-STATISTICAL EMISSION OF IMF ,	t ~ 40 fm/c	(1)

TIME SCALE: Emission Chronology by velocity correlation

IMF

$^{124}Sn + ^{64}Ni$ 35 MeV/A

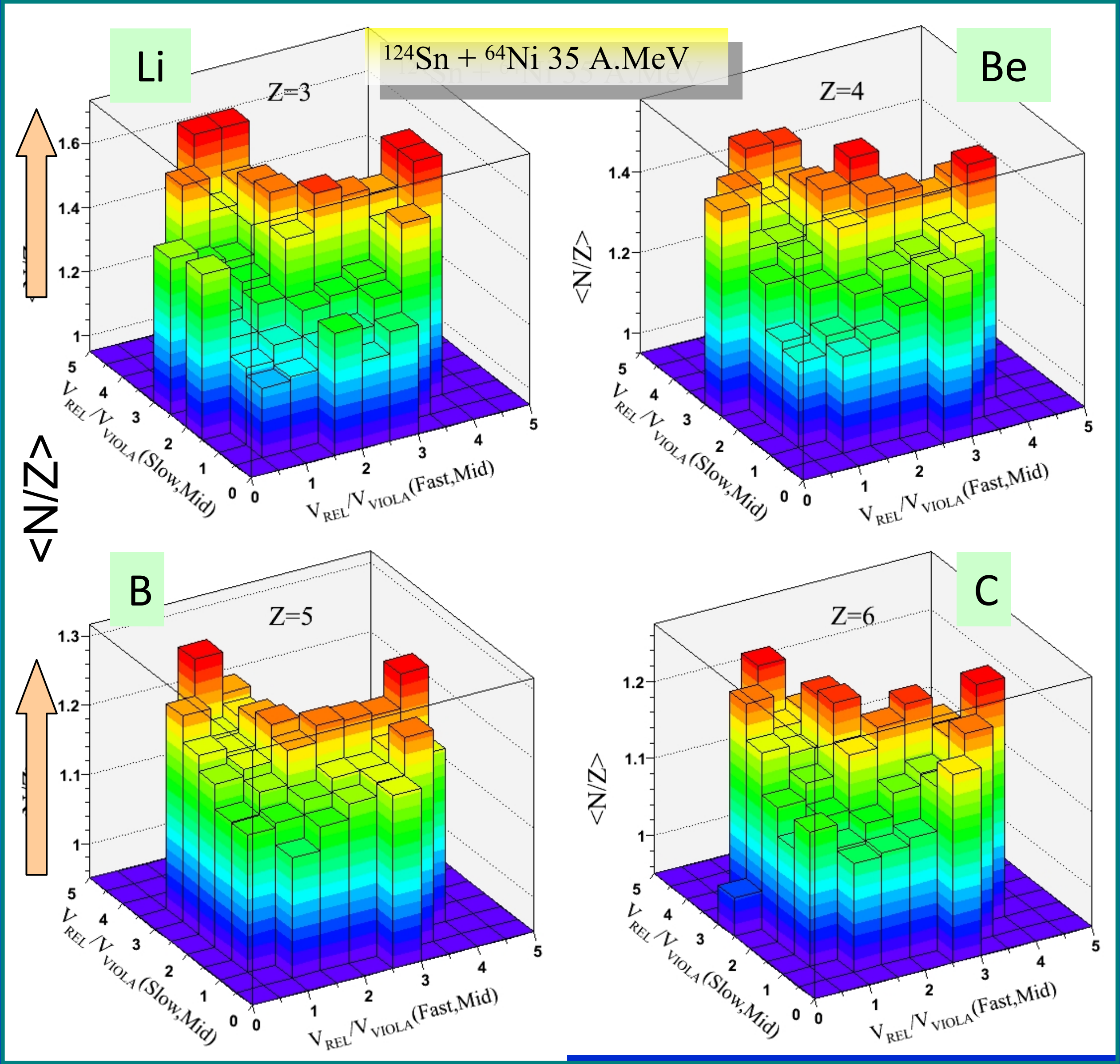
1	40 fm/c
2	80 fm/c
3	120 fm/c



Emission chronology: light fragments are produced earlier (~40 fm/c) than heavier ones (~120 fm/c)

E.De Filippo et al, PRC86 014610 2012

Correlations with IMFs (Z ≤ 8) isotopic properties

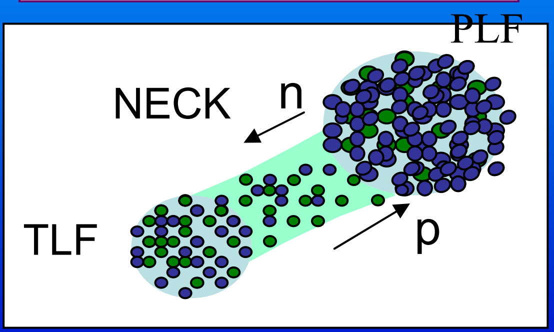


The correlation shows that the greatest neutron enrichment is linked to greater deviations from Viola systematics, that is to fast prompt emission of IMF.

We can select

Dynamical emission

Statistical emission

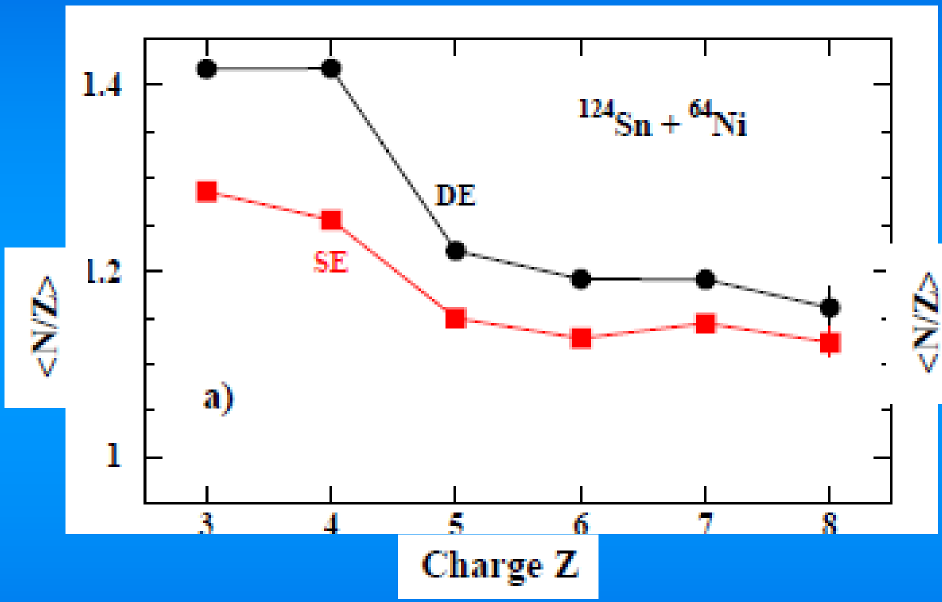


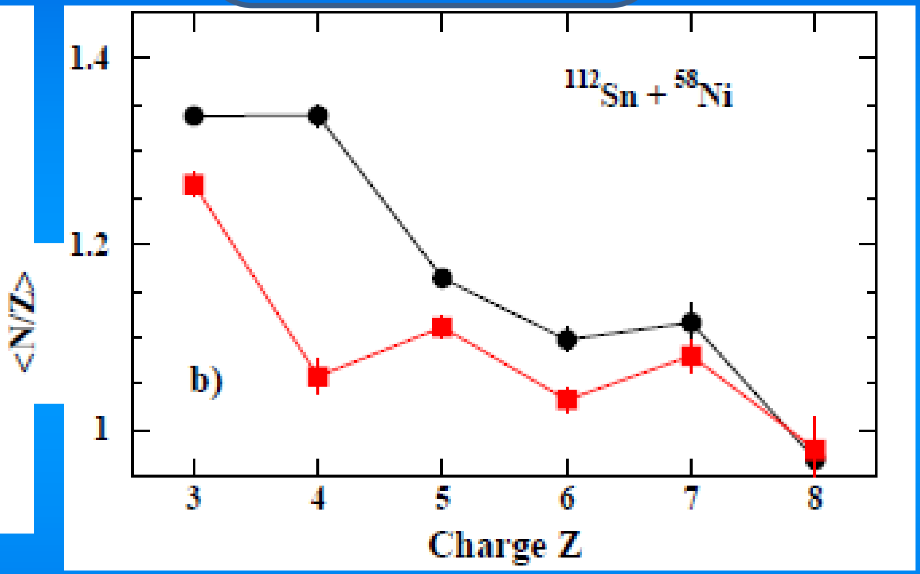
E.De Filippo et al. PRC71,44602 (2005)

Dynamical and Sequenzial emission of IMF

Dynamically emitted particles

Statistically emitted particles





Neutron rich system

Neutron poor system

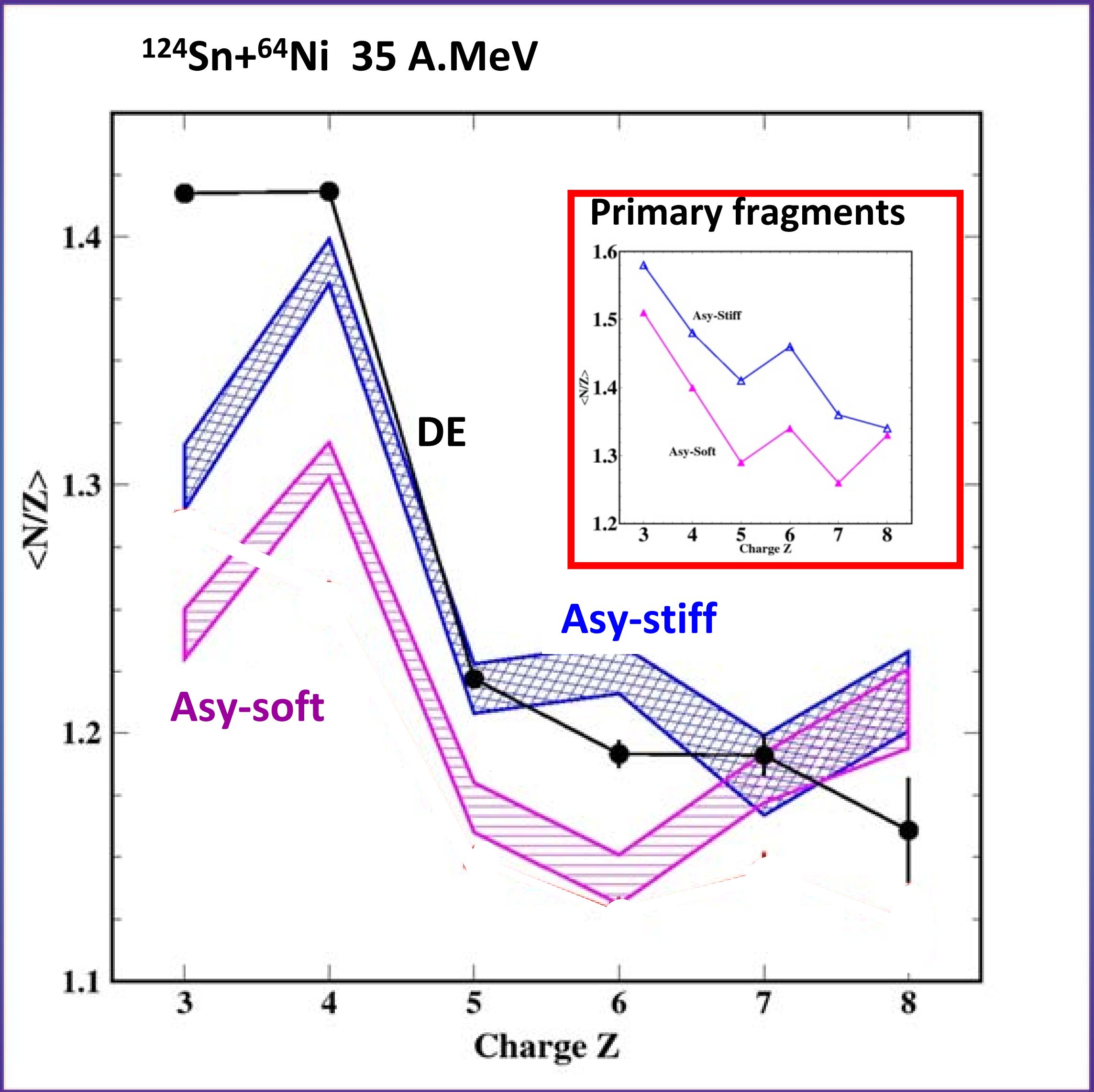
n-rich system

- Entrance channel memory effect
- Reduction in staggering effect

E.De Filippo et al,

PRC86 014610 2012

Stochastic Mean Field (SMF) + GEMINI calculation



SMF - microscopic approach that describe the evolution of systems by **Boltzmann-Nordheim-Vlasov transport equation.**
The model includes **nuclear mean field dynamics** and **effect of fluctuations.**

V. Baran et al. Nucl. Phys. A730 329 (2004).

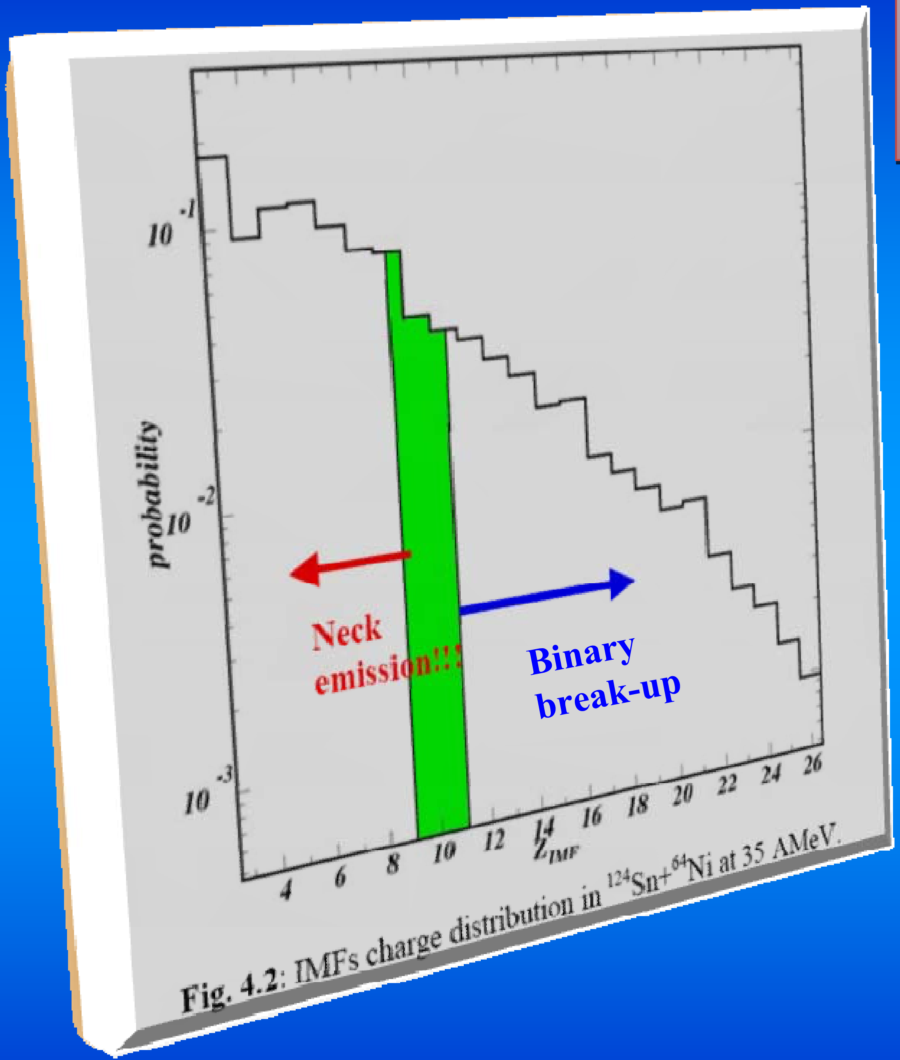
● Dynamically emitted particles

Data consistent with γ ≈ 1

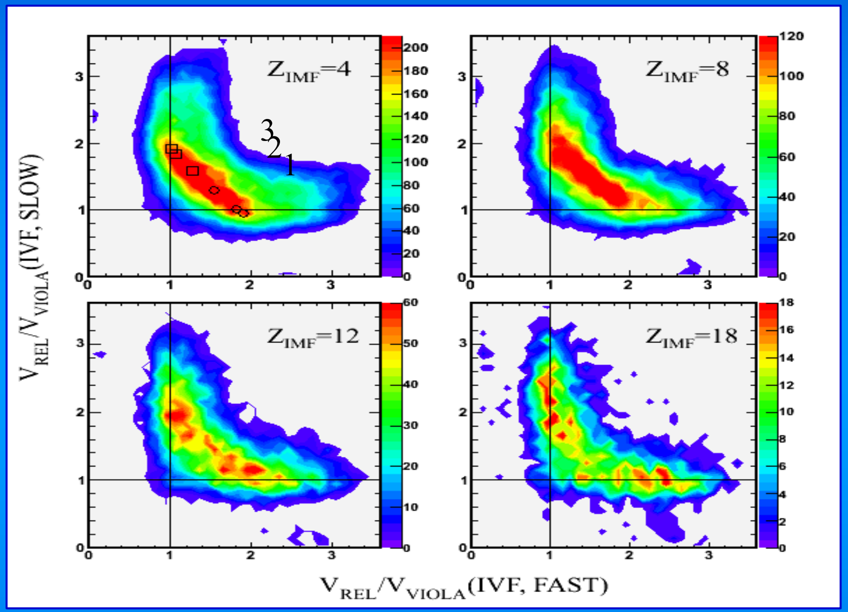
E.De Filippo et al, PRC86 014610 2012

Calculations performed by: M. Colonna

From early prompt neck fragmentation to PLF dynamical fission



With respect to the prompt neck emission, the emission of heavy IMFs from projectile-like fragment break-up appears at a later stage

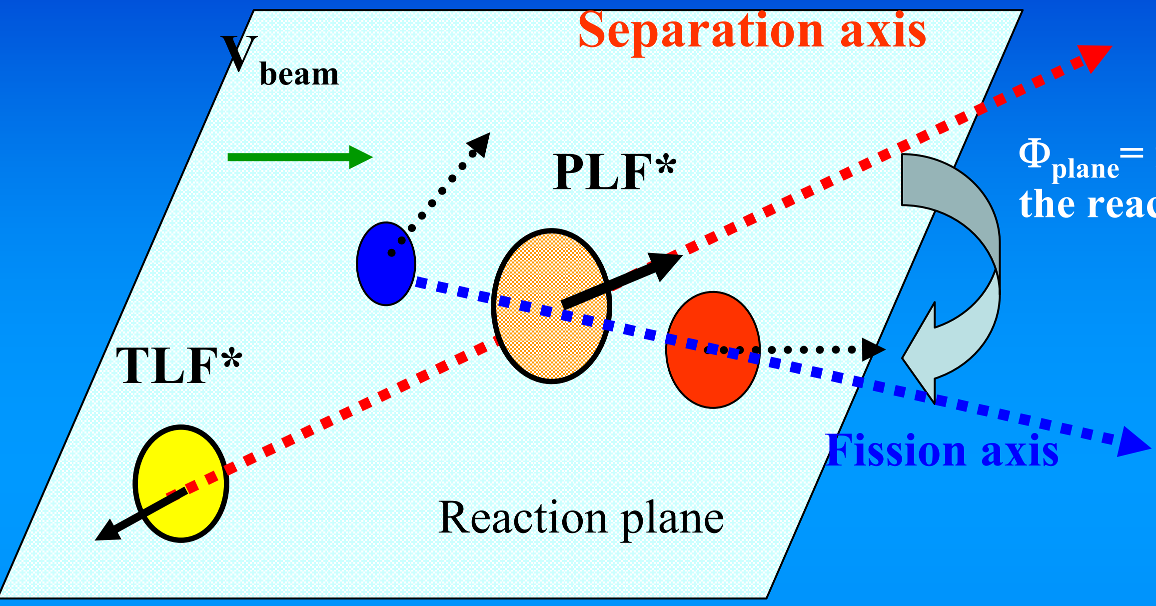


The time-scale of the process is one of the the signature among different mechanisms:

1)Early neck fragmentation (40-120 fm/c)
2)Dynamical fission (120-300 fm/c)
3)Equilibrated fission (>1000 fm/c)

Dynamical Fission: in $^{124}Sn+^{64}Ni$ and $^{112}Sn+^{58}Ni$ @35 A.MeV

$A_P=A_H+A_L$



Φ_{plane}= fission angle on the reaction plane

Statistical fission is characterized by isotropic fission fragment angular distribution,

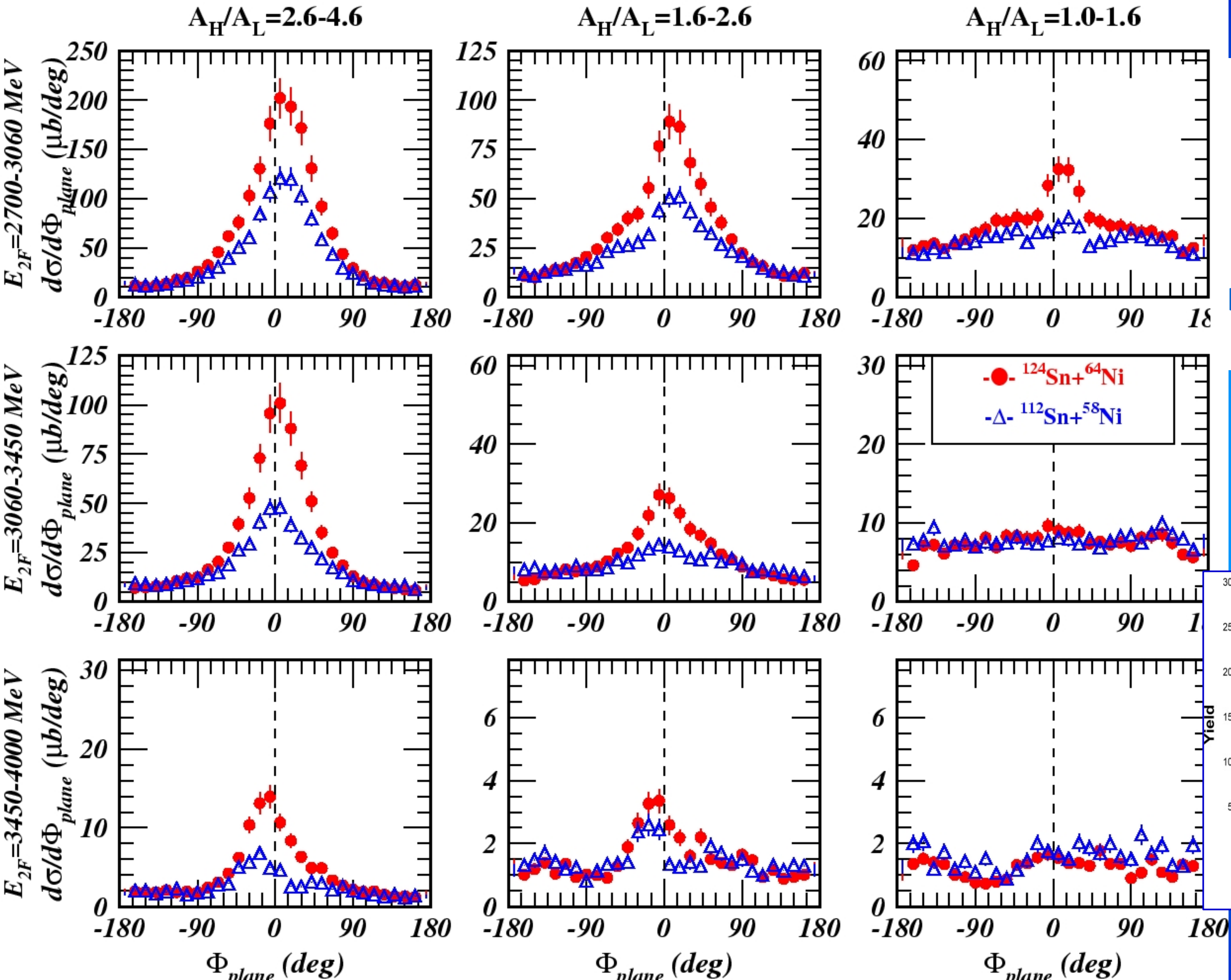
Dynamical Fission is characterized by fast AL fragment emission preferentially backwards in the PLF reference system, i.e., towards the target nucleus

E. De Filippo et al., Isospin collaboration, Phys. Rev. C71, 064604 (2005)
P. Russotto et al., Int. J. Mod. Physics E15 410 (2006)
P. Russotto et. al. Phys. Rev. C81, 064605 (2010)

Fission-like fragments angular cross sections (I)

● $^{124}Sn+^{64}Ni$

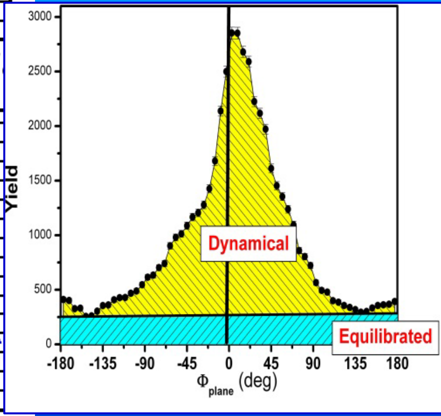
△ $^{112}Sn+^{58}Ni$



Forward peaked

Dynamical Fission cross section is greater in the neutron rich system →

(a factor ~2) !

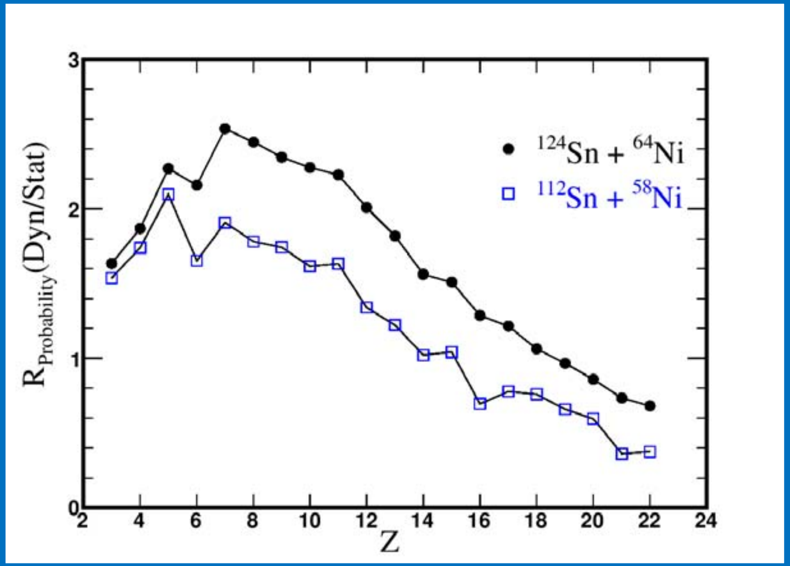


Φ_{plane}=fission angle in the reaction plane

P. Russotto et al., PRC 81 064605 (2010)

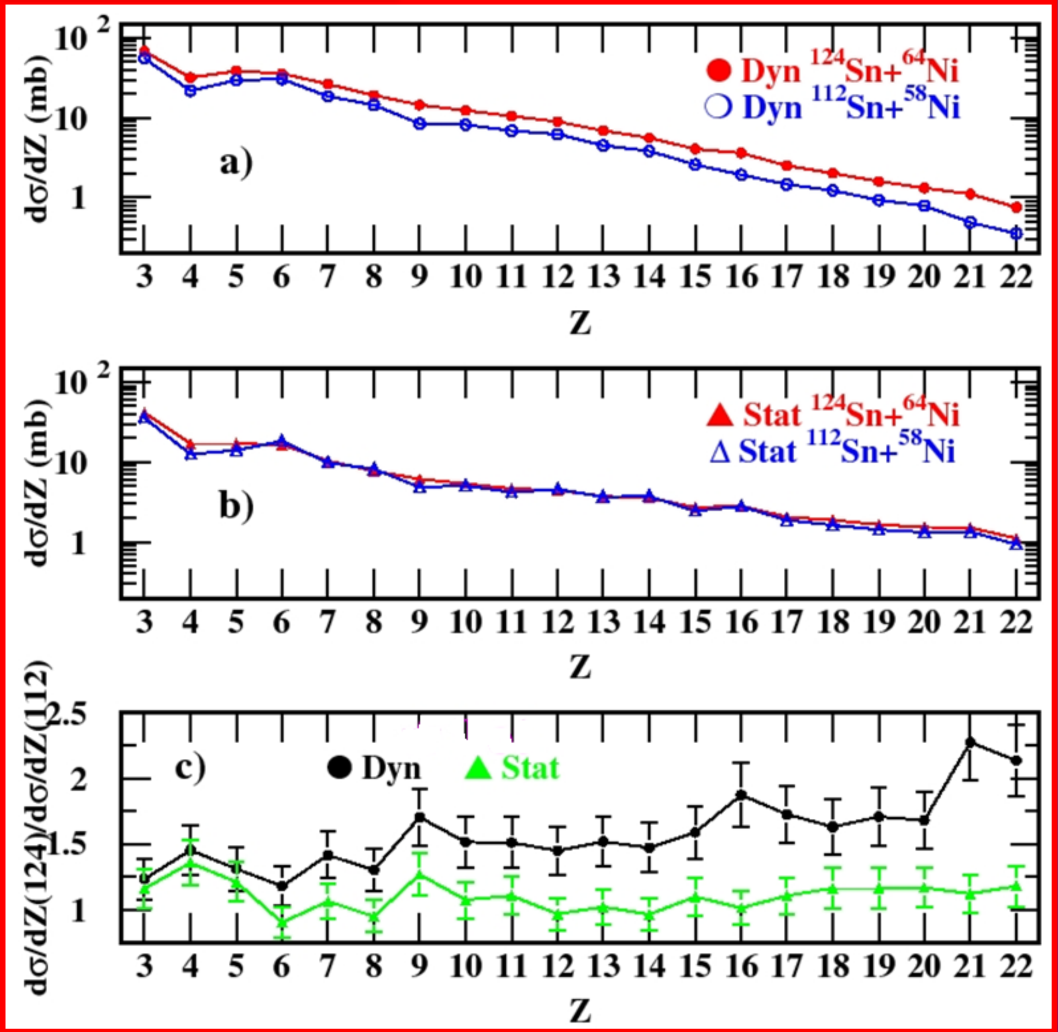
Comparison of IMFs cross sections for $^{124}Sn+^{64}Ni$ and $^{112}Sn+^{58}Ni$

P. Russotto et al. ,
submitted, PRC (2013)



Probability ratio of dynamical and statistical emission

Cross-sections



Dynamical component: enhanced in the neutron rich (especially for heavier IMF)
Statistical component: almost equal (A ratio: 188/170 ~1.1)

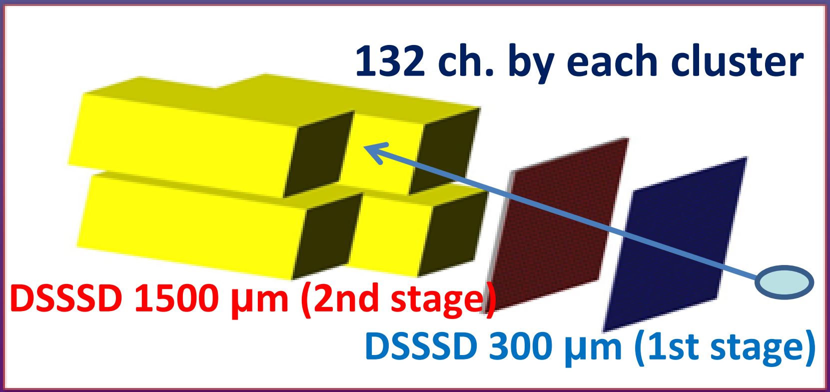
The InKiIsSy (INverse KInematics ISobaric SYstems) April 2013

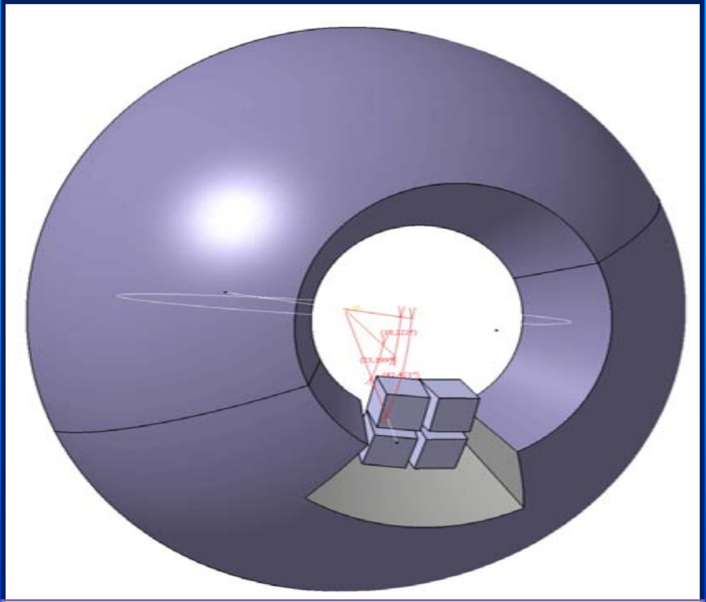
The idea is to use uses a projectile/target combination $^{124}Xe+^{64}Zn$, having the same mass of the n-rich $^{124}Sn+^{64}Ni$ system, and a N/Z near to the n-poor one $^{112}Sn+^{58}Ni$ at the same bombarding energy of 35 A.MeV using the 4π CHIMERA and a Farcos module.

System	N/Z Projectile	N/Z target	N/Z compound
$^{124}Sn+^{64}Ni$	1.48	1.29	1.41
$^{124}Xe+^{64}Zn$	1.30	1.13	1.24
$^{112}Sn+^{58}Ni$	1.24	1.07	1.18

A new setup: the 4π CHIMERA + 4 modules of FARCOS prototype

- **Based on (62x64x64 mm³) clusters**
- **1 square (0.3x62x62 mm³) DSSSD 32+32 strips**
- **1 square (1.5x62x62 mm³) DSSSD 32+32 strips**
- **4 60x32x32 mm³ CsI(Tl) crystals (6 cm)**





4 telescopes 25 cm from the target
θ_{lab} ~ 16-44 deg, $\Delta\phi$ ~ 45 deg

Study of the systems

$^{40,48}Ca + ^{48,40}Ca$ @ 25 AMeV

Isospin effects on reaction mechanism and fragment production

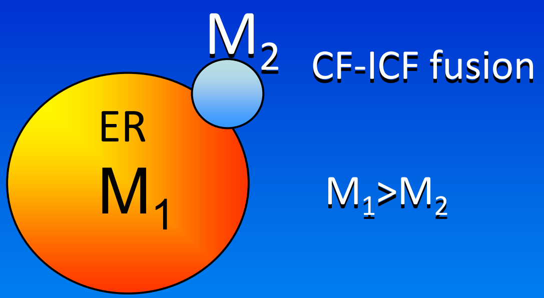
Study of N/Z effects on reaction mechanism and fragment production in central and semicentral collision at 25 AMeV (near multifragmentation trheshold)

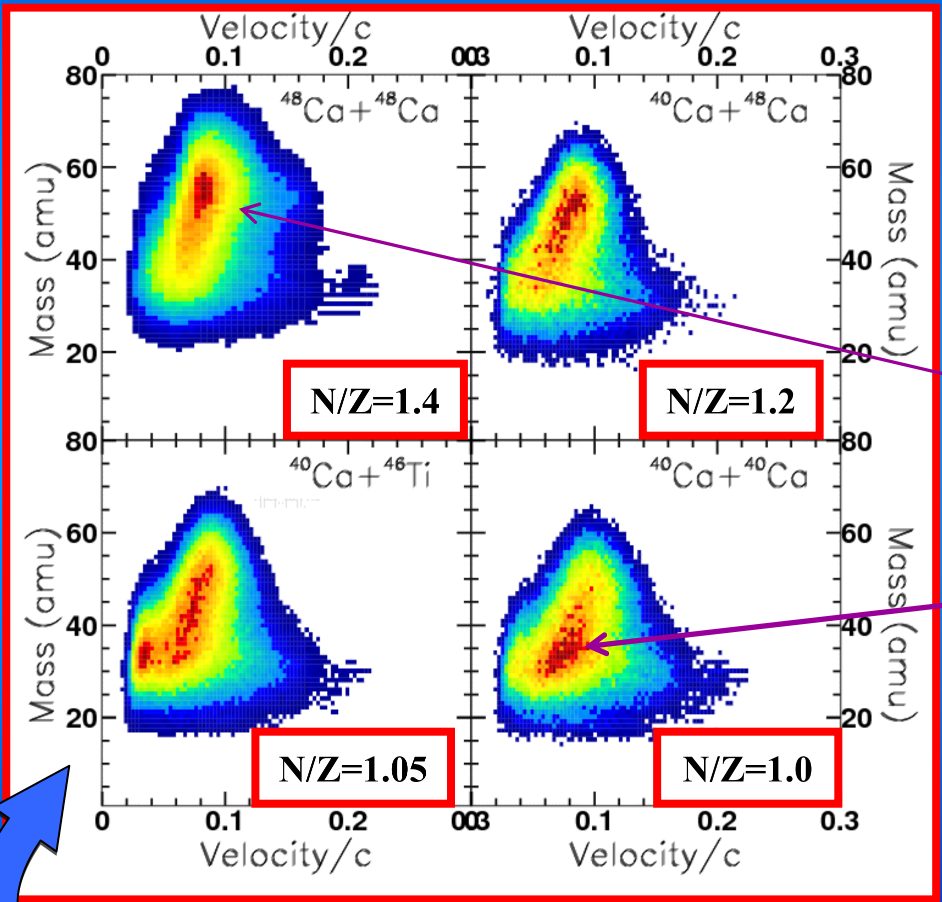
$^{40}Ca + ^{40}Ca$	$N/Z_{tot} = 1.0$
$^{40}Ca + ^{46}Ti$	$N/Z_{tot} = 1.05$
$^{40}Ca + ^{48}Ca$	$N/Z_{tot} = 1.2$
$^{48}Ca + ^{48}Ca$	$N/Z_{tot} = 1.4$

Selected quasi- central collisions - M_1, M_2 two biggest fragment

$^{48}Ca + ^{48}Ca$, $^{40}Ca + ^{48}Ca$ @25 A.MeV

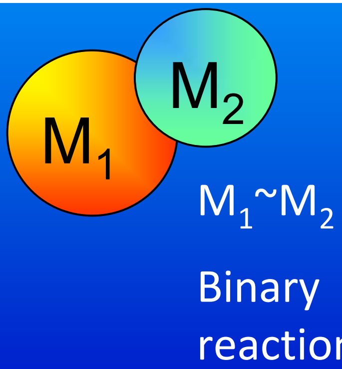
$^{40}Ca + ^{46}Ti$, $^{40}Ca + ^{40}Ca$

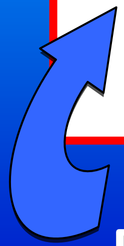




The **N/Z** degree of freedom strongly influences the *reaction mechanism*

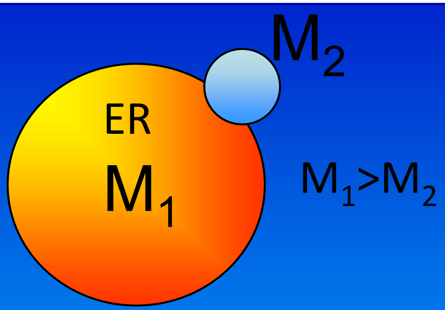
- **Larger N/Z → one massive fragment emission as in CF -ICF events (ER)** $M_1>M_2$
- **Lower N/Z → lighter and faster mass emission as in binary-like events (BL)** $M_1 \sim M_2$

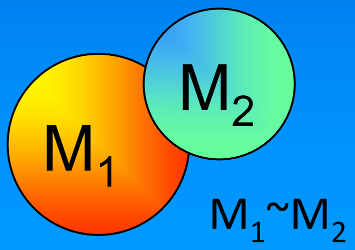




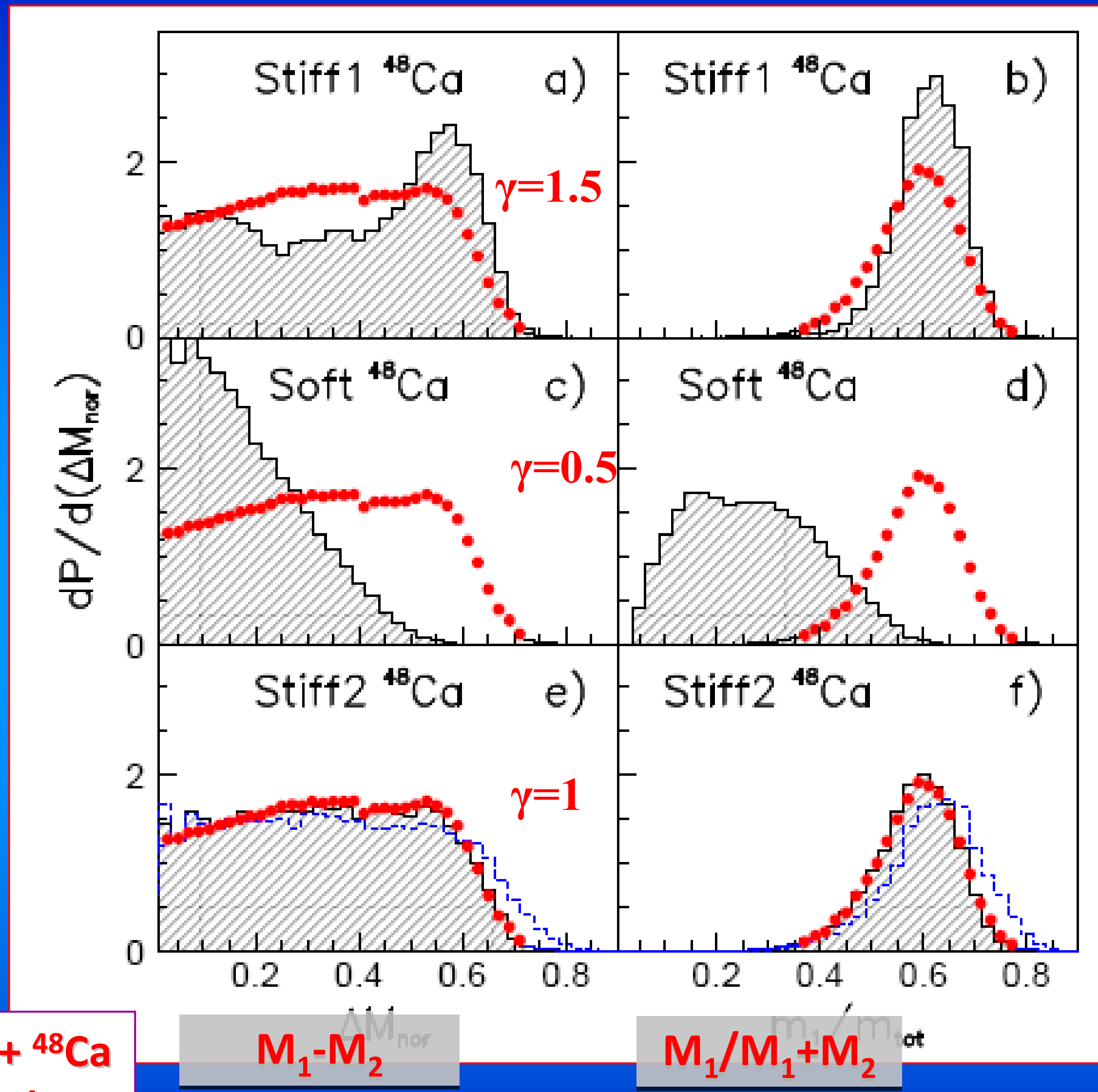
Mass of heaviest fragment

Comparison with Co MD (Constrained Molecular Dynamics) II + Gemini





Comparisons with CoMD-II model indicates a sensitivity of the reaction mechanism to the asy-EOS : the best agreement is with a slightly stiff (γ=1) symmetry term

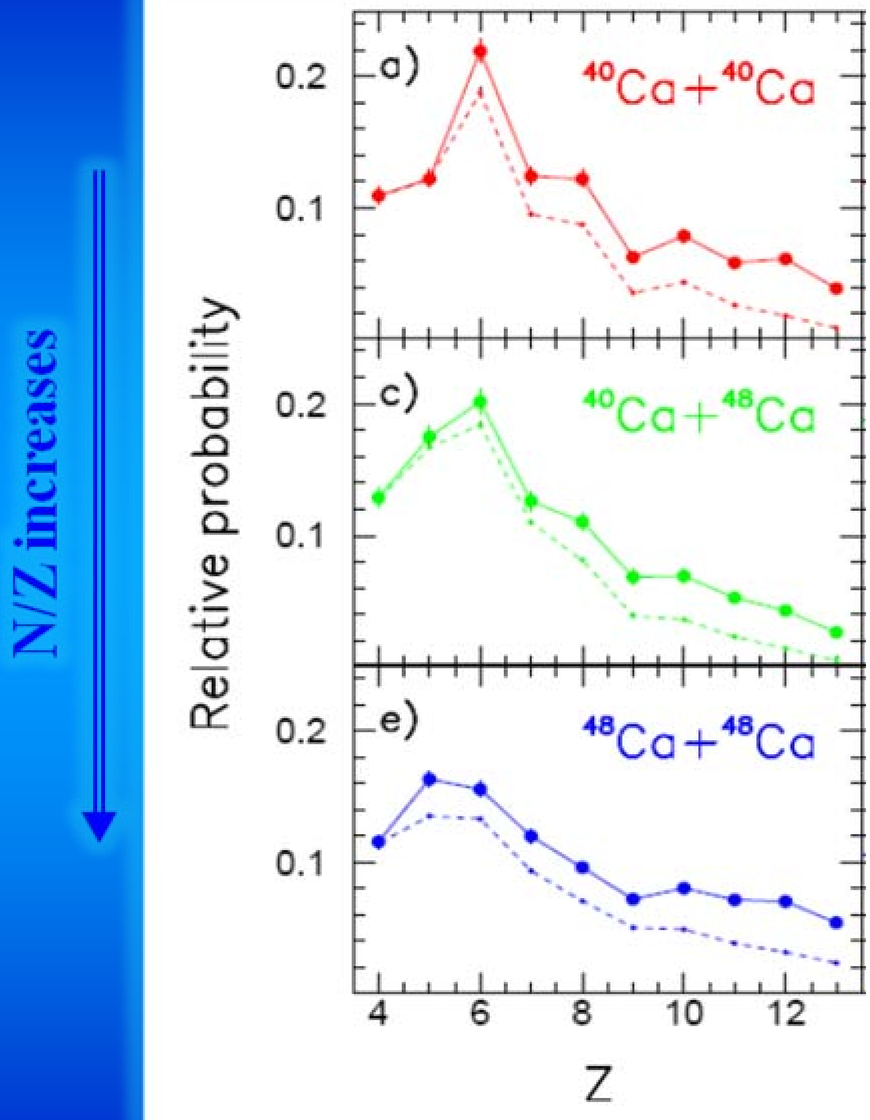


$^{40}Ca + ^{48}Ca$

• data

F. Amorini et al., Phys. Rev Lett. 102 112701 (2009)
I.Lombardo et al., Phys. Rev. C82 014608 (2010)
M. Papa and G. Giuliani, EPJ A39 (2009)

Even -odd effects on Z and N distributions of light fragments



^{40}Ca + ^{40}Ca, ^{40}Ca + ^{48}Ca,
^{48}Ca + ^{48}Ca 25 A.MeV

n-rich system

- Reduction in staggering effect

I. Lombardo et al. Phys. Rev. C84 024613 (2011).

Study of the systems

$^{78,86}Kr + ^{40,48}Ca$ @10 AMeV

Isospin influence on the reaction and emission mechanism of IMF (Z≥3)

- Collisioni fra ioni pesanti con fasci stabili ed esotici
- Regime a bassa energia $E/A \leq 15$ MeV/A
- Meccanismo di reazione FUSIONE

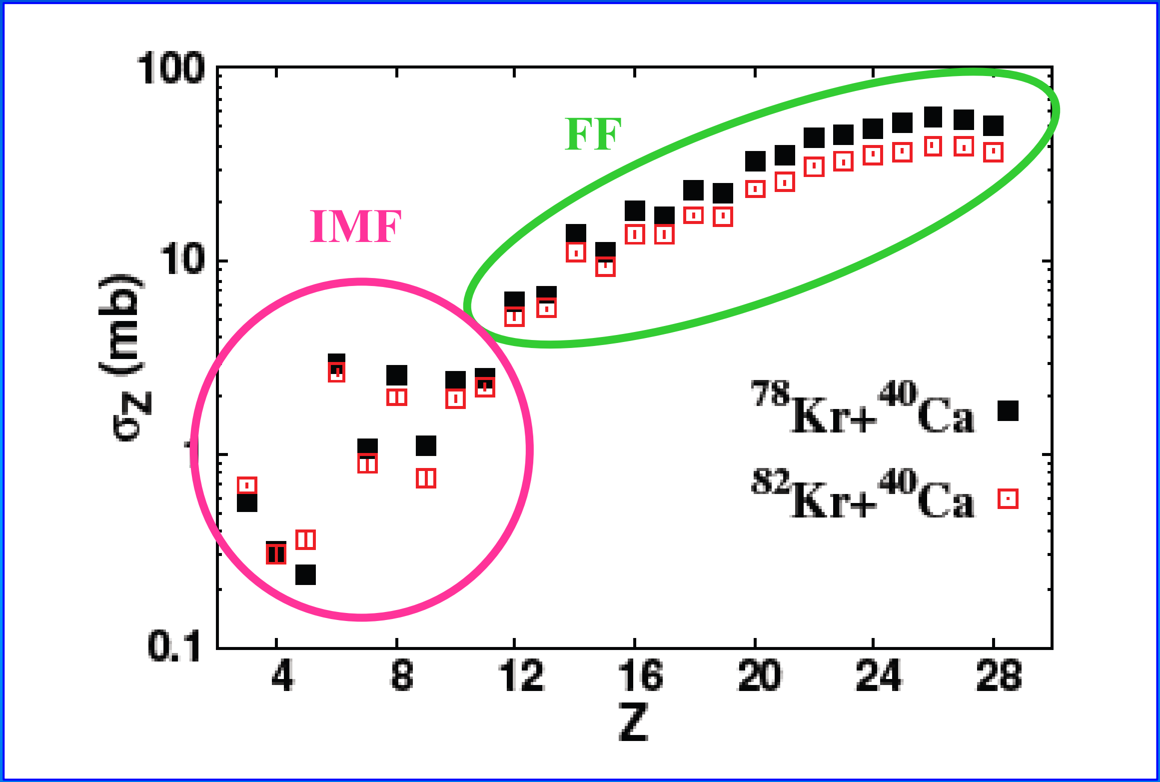
dipendenza dall'isospin (N/Z) del meccanismo di formazione e emissione dei frammenti di massa intermedia ($Z \geq 3$) dal CN

- **per ottenere informazioni:**

- parametro densità dei livelli, (proprietà termiche, E*, $m_{effective}$)
- barriera di fissione, (Esym, energia di Wigner)
- viscosità, (accoppiamento effetti collettivi-intrinseci, E_F)

E475S INDRA @GANIL E = 5.5 AMeV

^{78,82}Kr + ^{40}Ca → ^{118,122}Ba* (~ 100 MeV)



$3 \leq \theta \leq 44°$ IC-Si-CsI forward part

- Energy, ang. Distr. RP
- Charge distribution
- Cross section decay mode

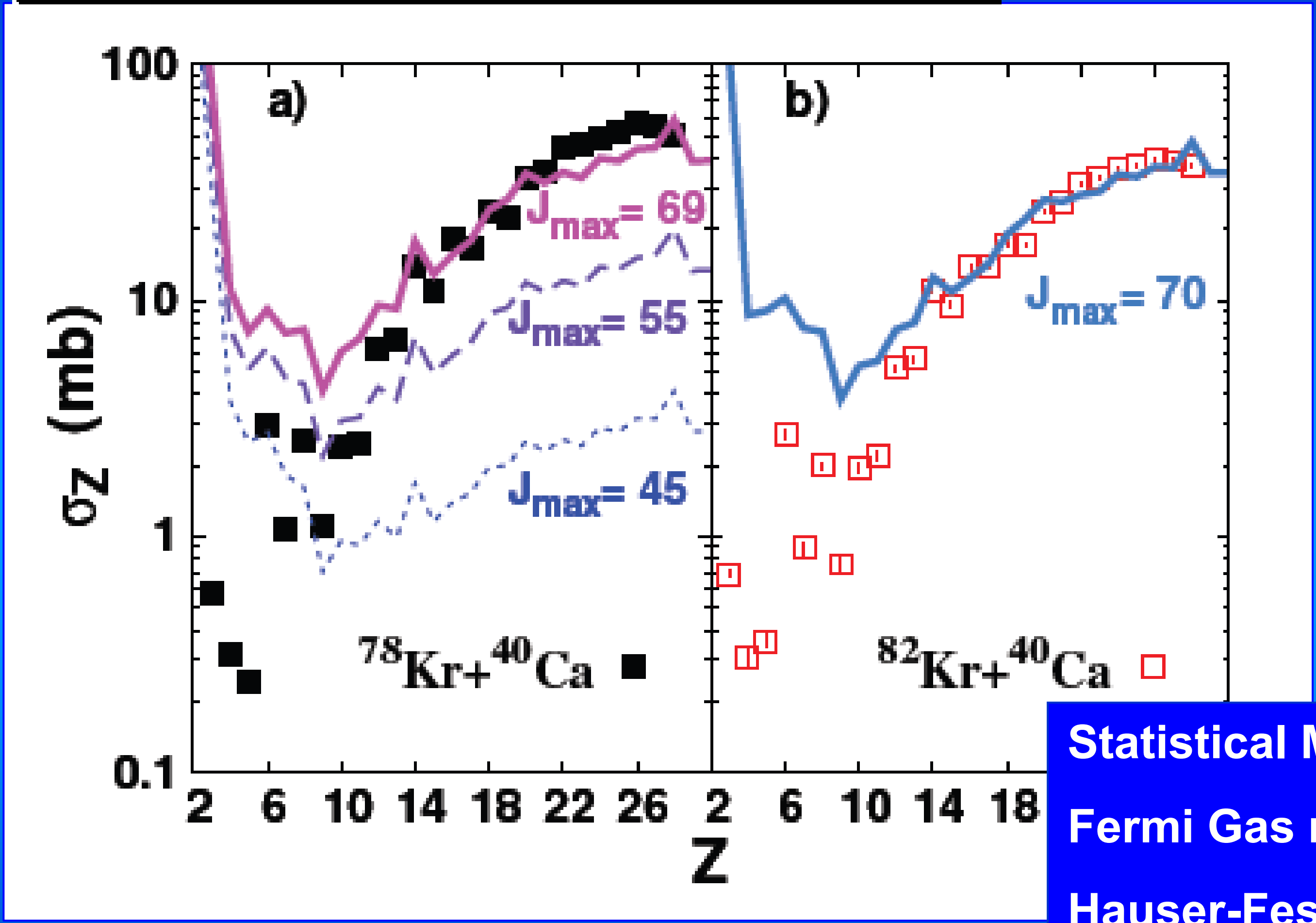
CN neutron rich (o)

- 30% less fission ($Z \geq 14$)
- Less even-odd staggering of IMF ($6 \leq Z \leq 12$)

G. Ademard et al. PRC 83 (2011) 054619

Comparison with transition state model
GEMINI code

• R.J.Charity et al, Nucl.Phys.A483 (1988)
•D.Mancusi et al, PhysRev C 82 (2010)



Statistical Model

Fermi Gas model (level density)

Hauser-Feschbach for LCP's

Trantion state model for IMF Z>2

FRLDM barrier from Sierk

Structure effect NOT considered

G. Ademard et al. PRC 83 (2011) 054619

G. Ademard et al.   PRC 83 (2011) 054619

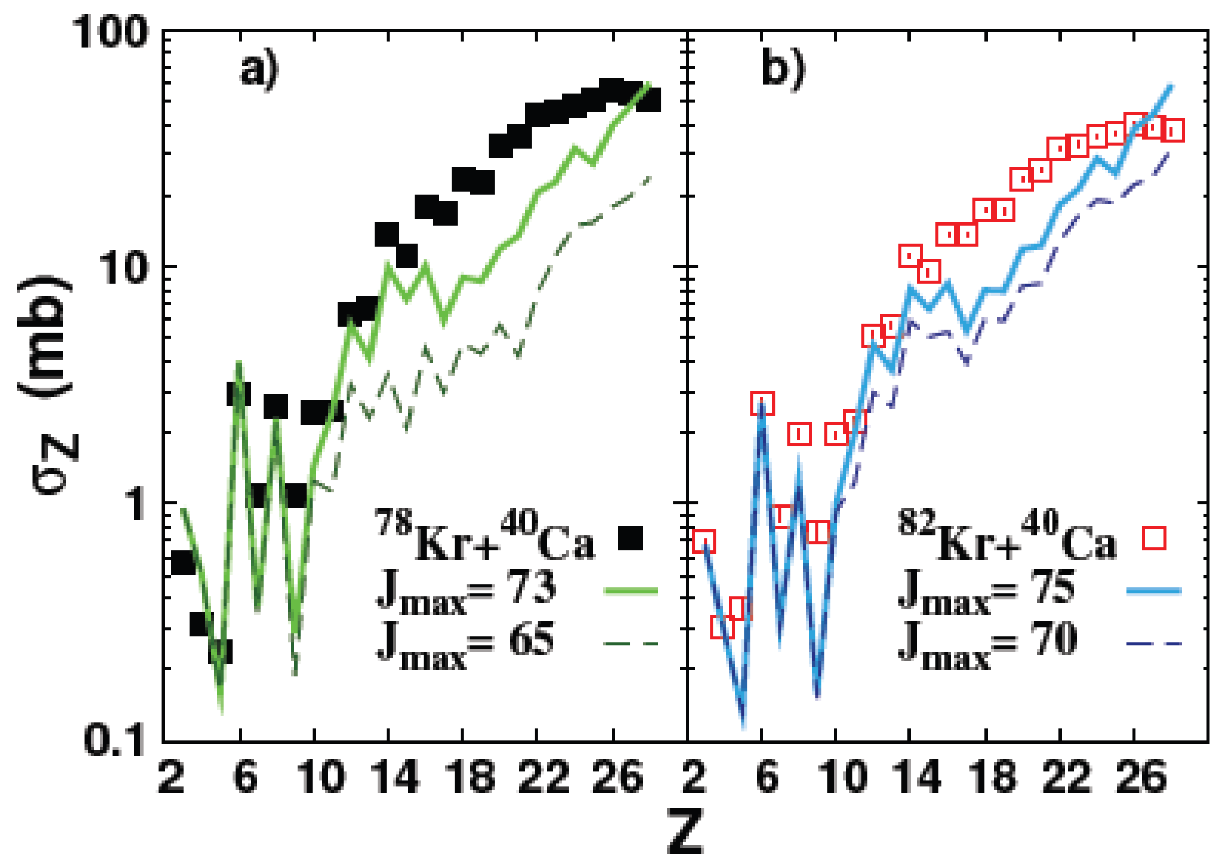
Dynamical model

DNS in competition to CN

Quasi-fission phenomena

N/Z dependence not considered

DSN (di-nuclear system) -model



Sh.A.Kalandarov et al.

PRC82 (2010)

ISODEC CHIMERA@LNS E = 10 AMeV

$^{78}Kr + ^{40}Ca \longrightarrow ^{118}Ba$

$^{86}Kr + ^{48}Ca \longrightarrow ^{134}Ba$

- **Higher energy**

  Influence on the amplitude of the staggering, on the temperature of the emitting system.

- **Isotopic separation of IMF**

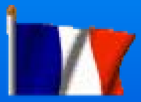
  to investigate the staggering effects looking at the isotopic distribution of IMF.

- **Exploration of a larger domain in N/Z of the system (stable beam!)**

  to study the dependence from the N/Z on the mechanism of complex fragment emission from CN

- **Exclusive measurements in a large angular range**

CN	^{118}Ba	^{134}Ba
E*(MeV)	215	270
V_B(MeV)	90	87
E_{CM}/V_B	2.9	3.5
$(N/Z)_{tot}$	1.11	1.39



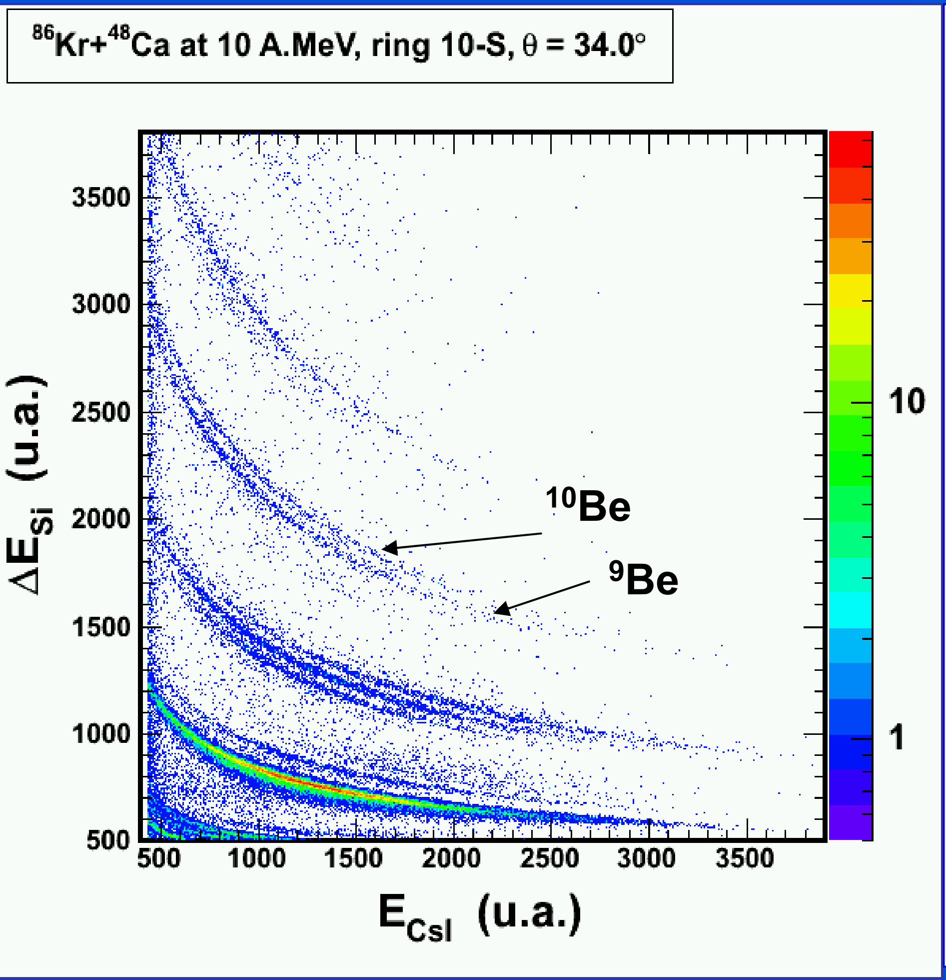
ITA-FRA Collaboration

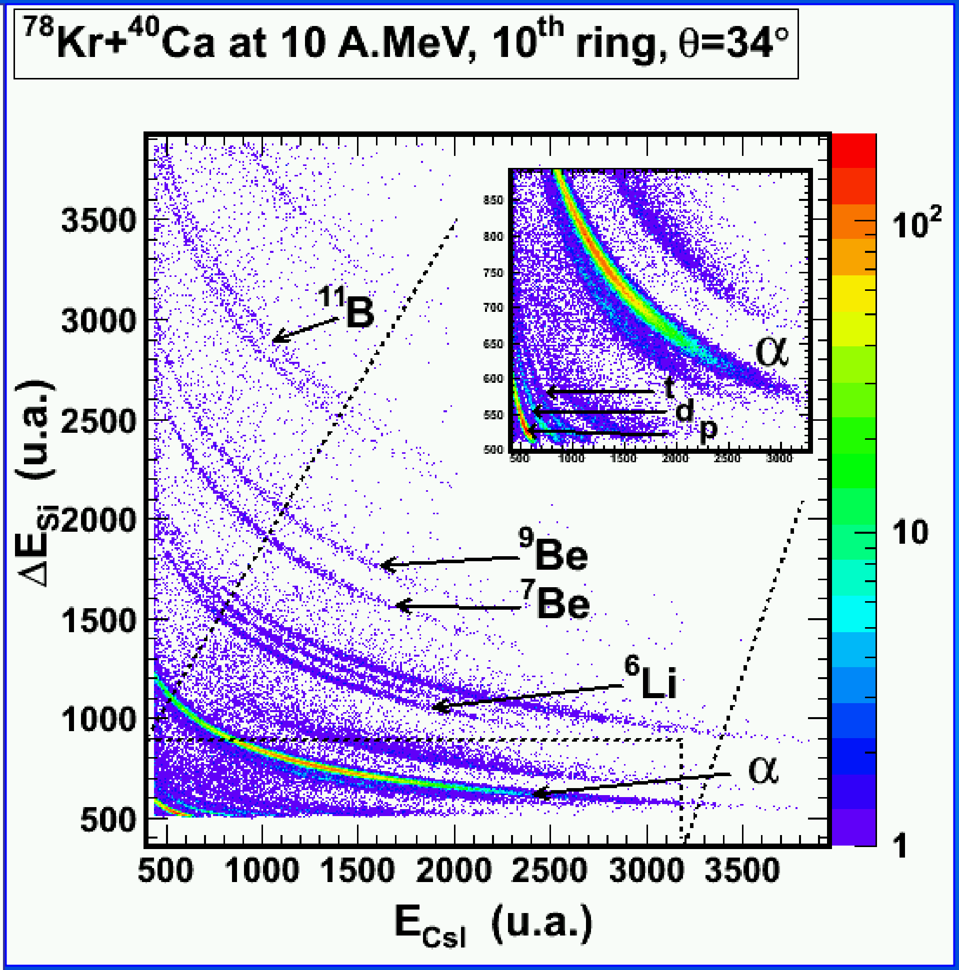
LEA COLLIGA agreement

(GANIL & INFN LNL-LNS)

IMF Isotopic Identification

PSD in Silic ΔE-E , Si-CsI(Tl) -E , Si-CsI(Tl)



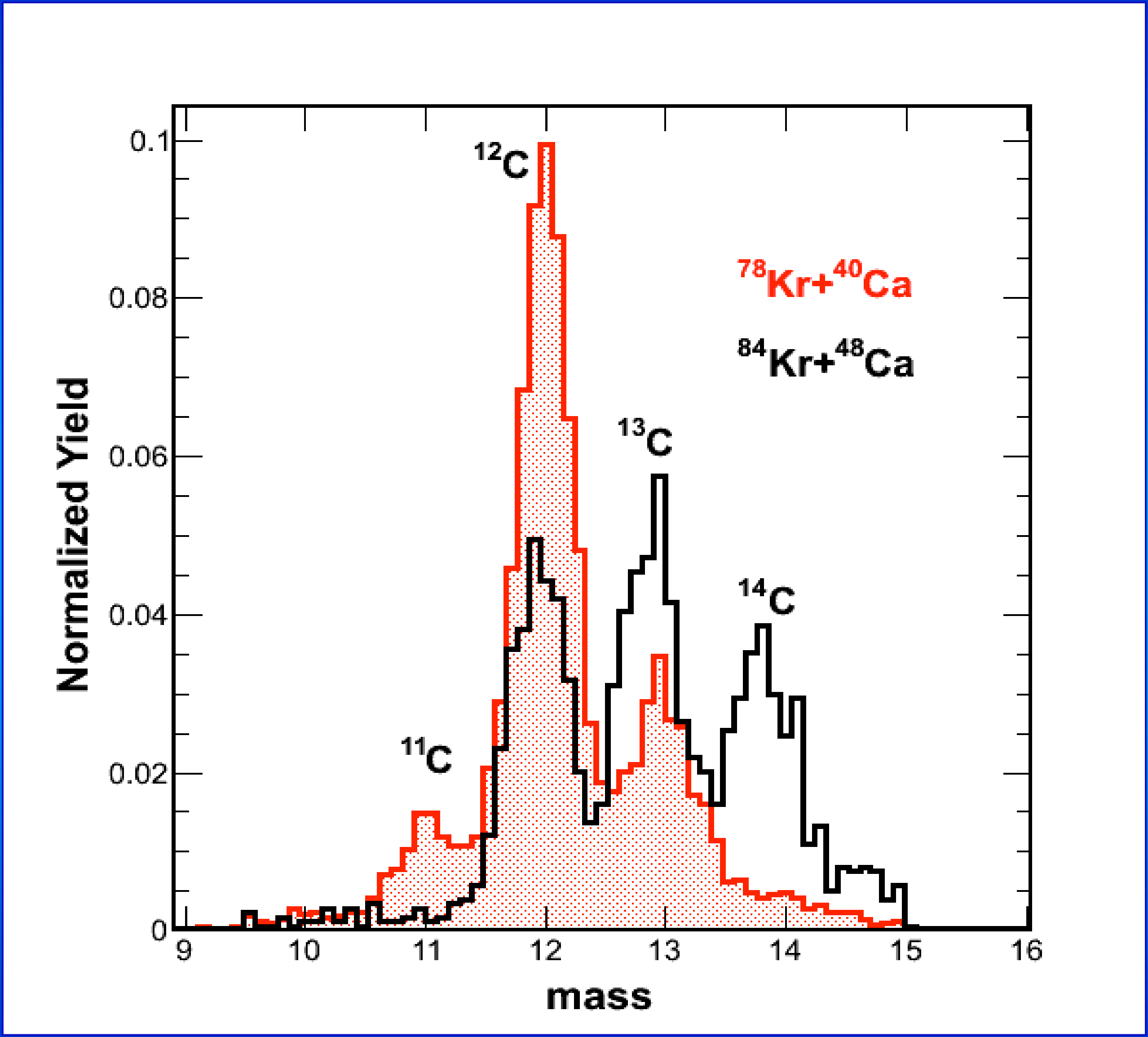


n-rich

n-poor

Distribuzione in Massa Carbonio

ϑ = 15°

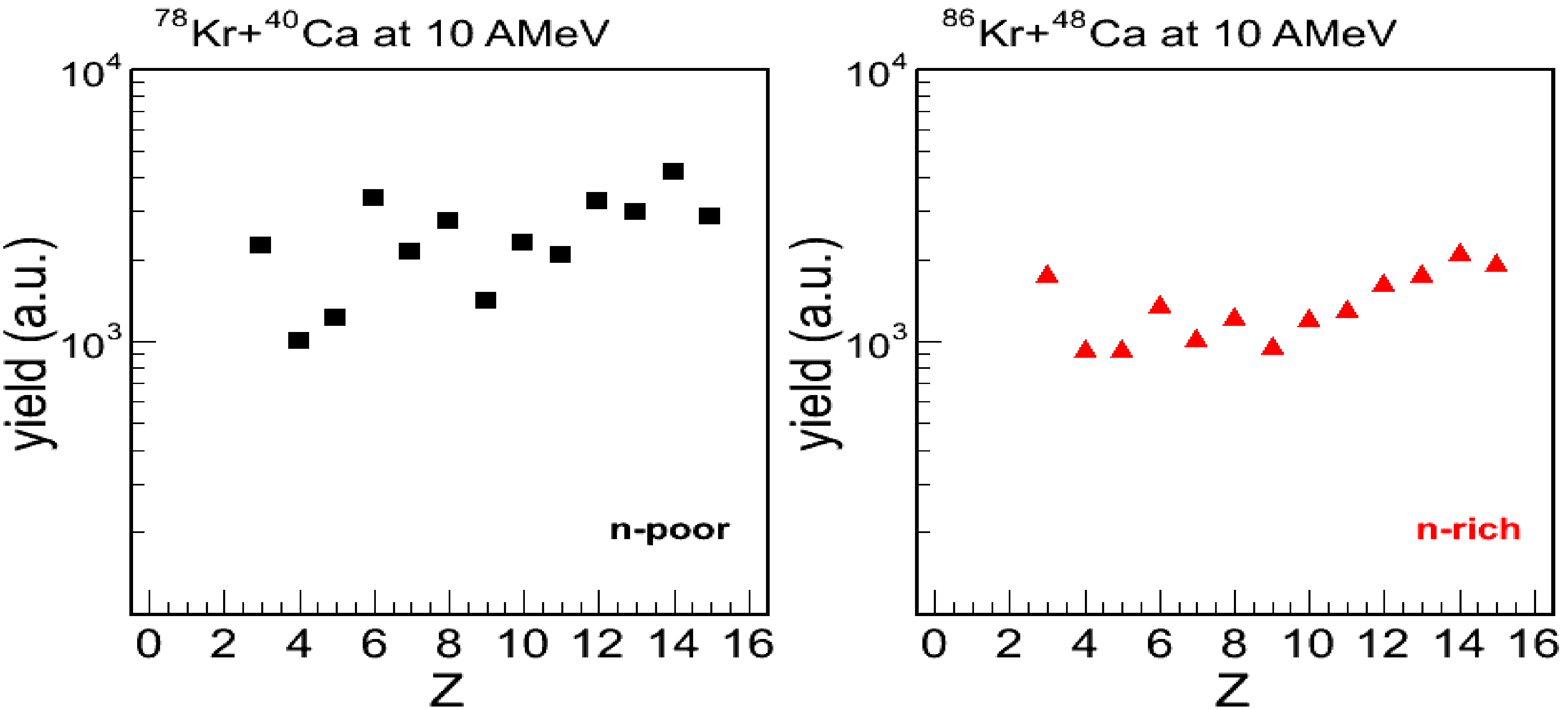


S.P. et al., EPJ Web of Conf. 17,16010 (2011) ,G.Politi et al, EPJ Web of Conf. 21 (2012) 02003
M.La Commara et al., Proc.of the IWM2011, GANIL,Caen, France (in press) 2012

- influenza Isospin (N/Z)
- influenza forza di pairing
- influenza effetti di struttura (M. D'Agostino et al., NPA 861 (2011) 47)
- connessione con il termine Esym (modelli)

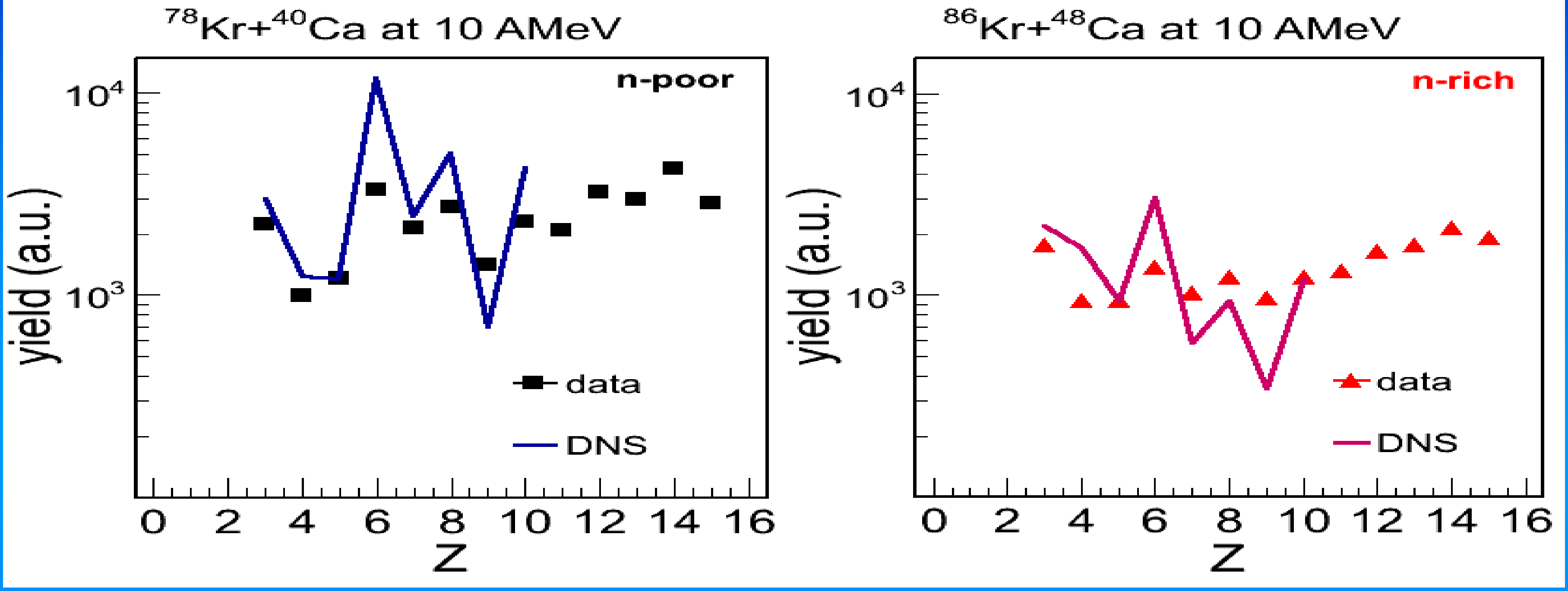
Tesi B.Gnoffo 2013

Confronto Rese Normalizzate PRELIMINARE 10.5° ≤ ϑ ≤ 15.5°



Very preliminary comparison with DiNuclear System (DNS) code

Simulation performed for the TOTAL cross section and normalized at Z=5



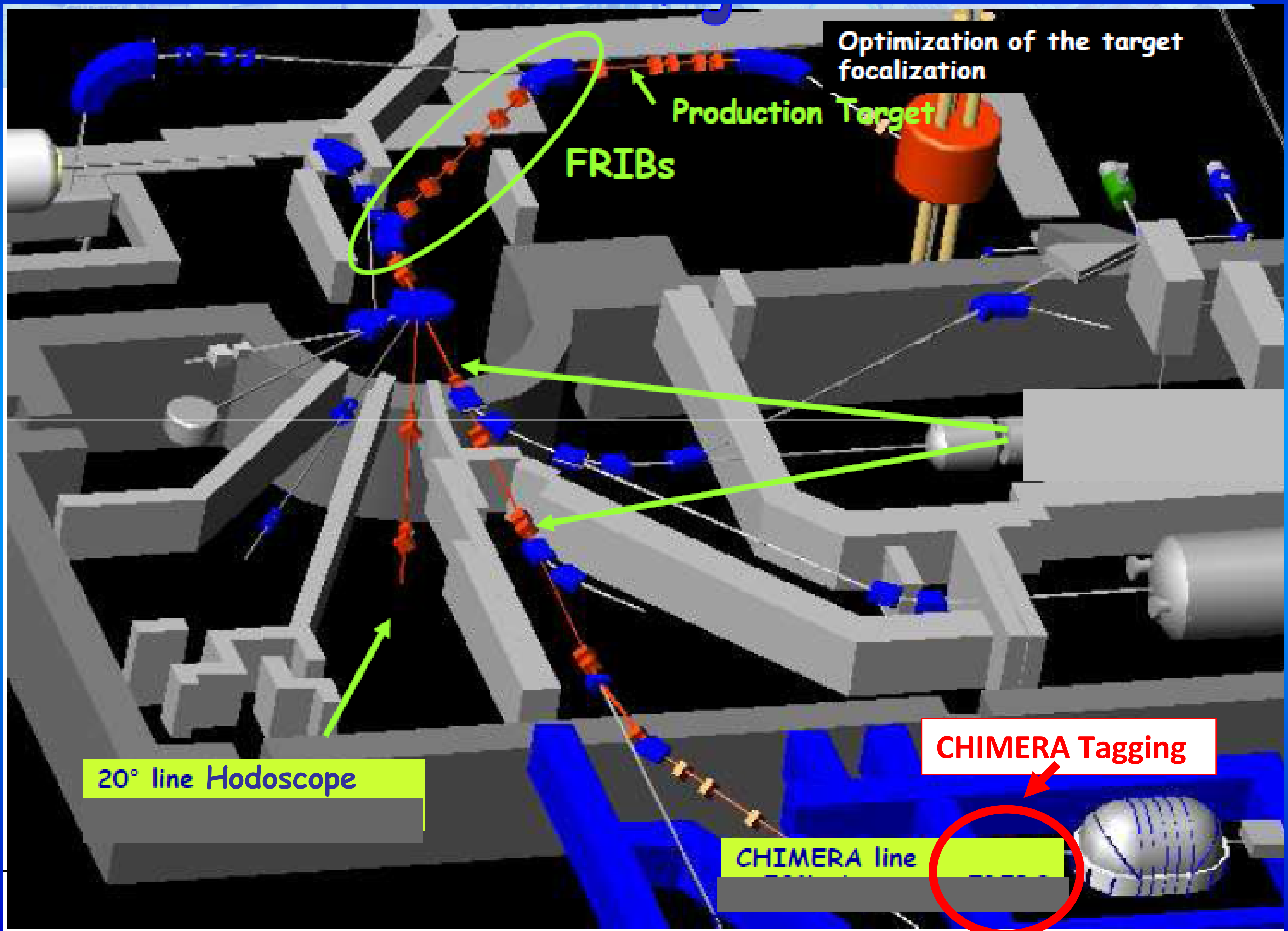
DNS seems to reproduce slightly better the n-poor system

New systems with higher N/Z would bring new insights

^{94}Kr + ^{40,48}Ca 10 AMev ^{132,140}Ba* E* ~ 320 MeV

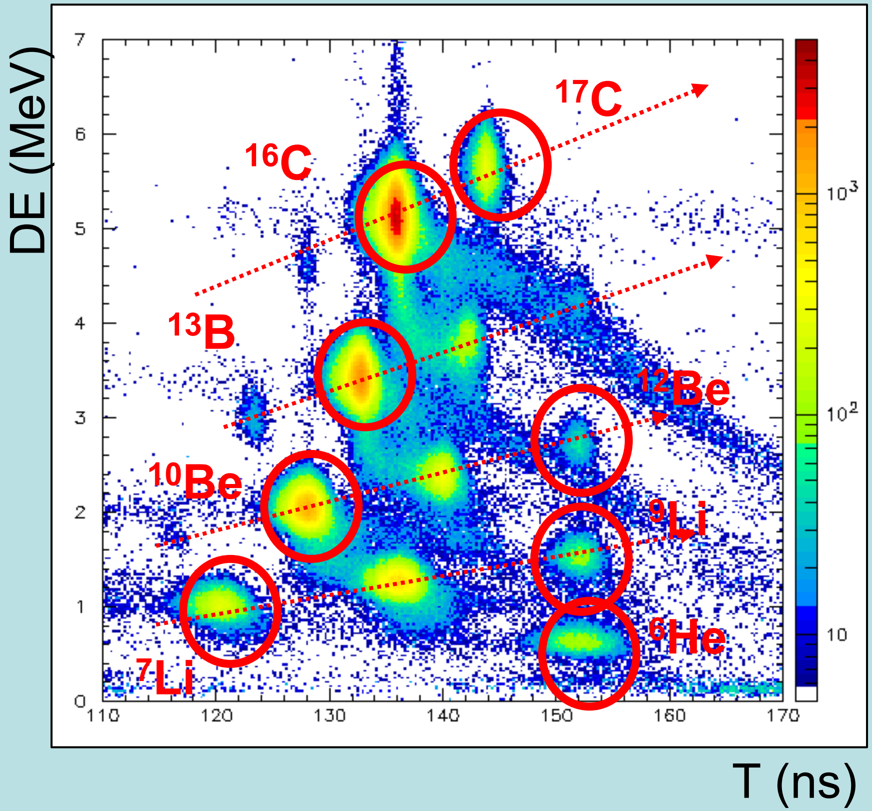
LOI @ SPES

In-flight fragmentation beams @ LNS



In-flight fragmentation beams @ LNS
Production Tests at the CHIMERA beam line

$^{18}O + {}^{9}Be$ (1.5 mm) at 55 MeV/A

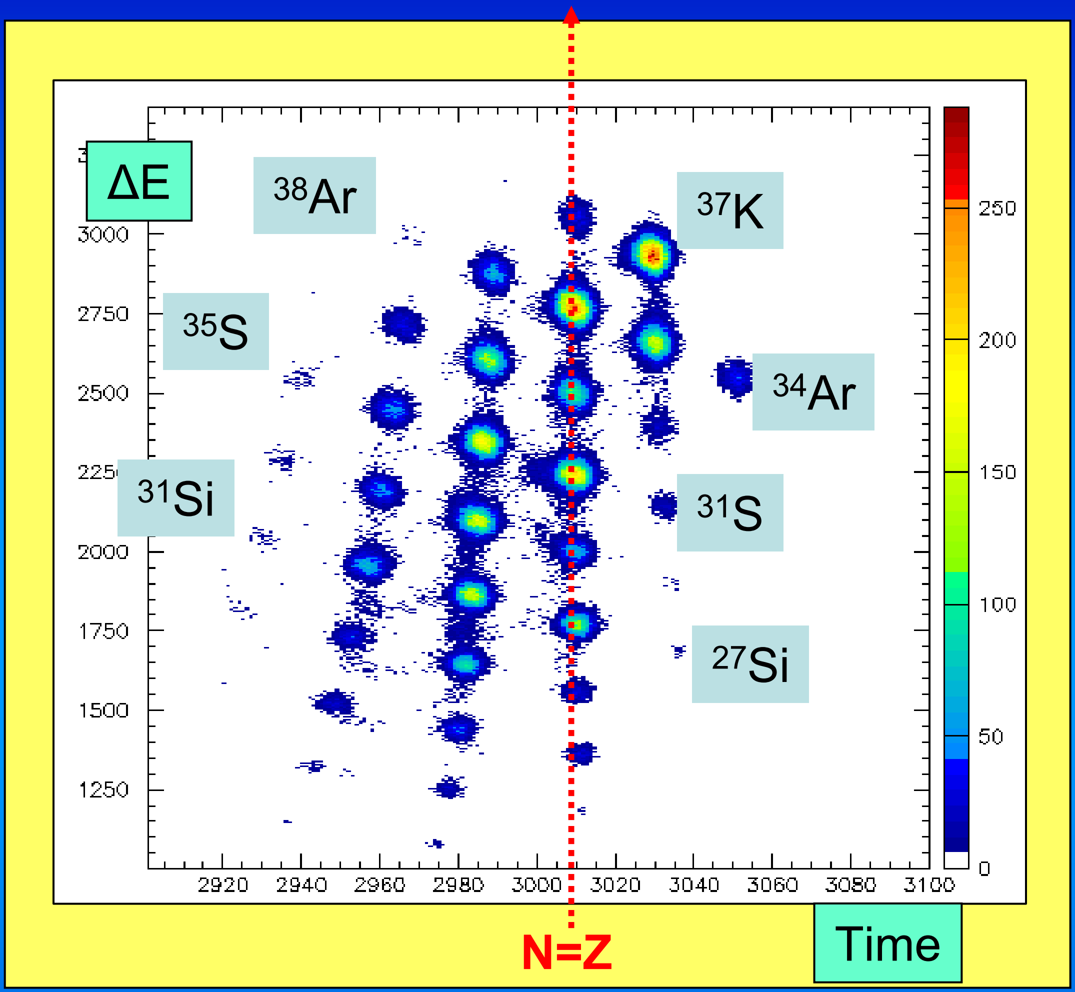


Primary beam 88W, 5.5×10^{11} p/s

	Khz	
^{16}C	40	
^{17}C	4	
^{13}B	23	
^{11}Be	6	magn. Set. Bρ=2.71 Tm
^{10}Be	21	
^{8}Li	11	

E of secondary beam 40-50 MeV/A

^{36}Ar + ^{9}Be (0.5 mm) 42 MeV/A,



primary beam 25W - 1x10^{11} p/s

	Khz	
^{37}K	14.0	
^{36}Ar	12.0	
^{35}Ar	8.5	
^{34}Ar	1.8	magnetic settings
^{33}Cl	1.5	
^{34}Cl	6.5	
^{31}S	0.8	
^{32}S	10.0	
^{28}Si	5.0	
^{29}Si	6.5	

Energy secondary beams 20-25 MeV/A

$^{70}Zn + {}^{9}Be$ (0.25 mm) 40 MeV/A,

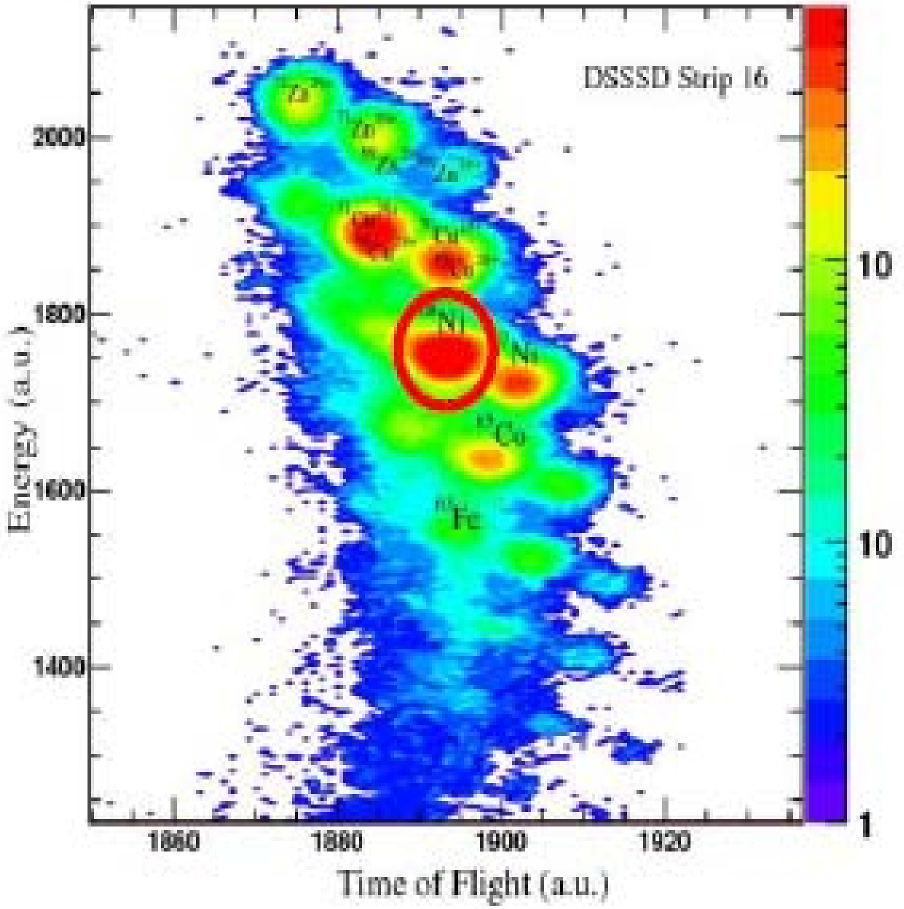


Fig.4 Identification scatter plot of ^{68}Ni fragm ntation beam

primary beam 100W

^{68}Ni
Rate 20kHz
Energy 28 MeV/A

Search for iso-scalar excitation of the PIGMY resonance in ^{68}Ni nuclei

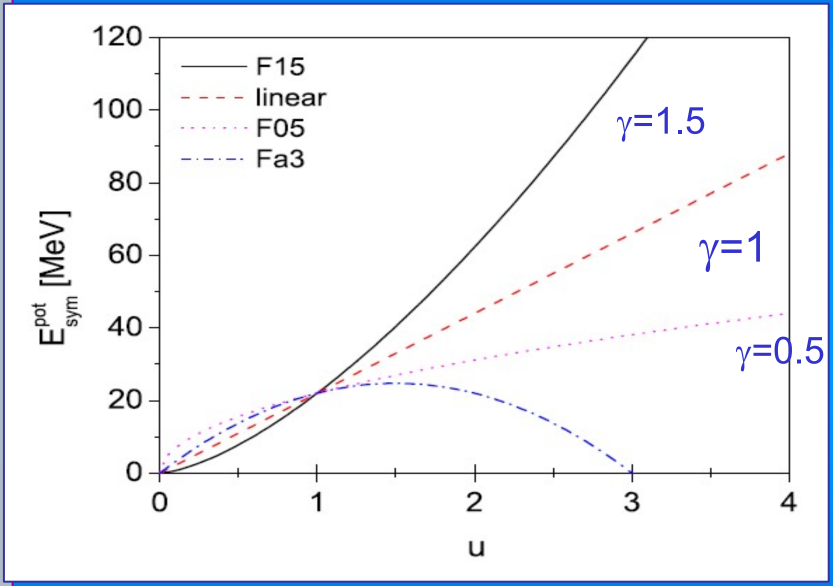
G.Cardella, E.G.Lanza
for the EXOCHIM coll.

Conclusion

Experimental results from HIC realized with stable beam and with the 4π CHIMERA detector were presented.

We put in light as reaction mechanism, i.e. decay and emission processes, dynamics, time scale and composition of the produced fragments, are dependent from the influence the ISOSPIN on the effective nuclear interaction.

The obtained results on E_{sym} are all consistent, even if yet large uncertainties, with an slightly ASYSTIFF ($\gamma = 1$) parametrization of the Esym, both in *sub-saturation* and *supra-saturation* ρ regions.



Perspectives

We need :

- **Reduce experimental error bars**
- **Perform more complete analyses**
- **Improve theoretical description**

It will be very interesting to extend this meausurements with the radiactive beams.
In preparation experiment by using *Fragmentation beams* @LNS and the new facilities as *SPES @LNL* and with detectors at high specialization, (as well as neutron detectors and correlators).

Use of new RIB facilities (exotic neutron rich, proton rich beams) . Isospin effects are enhanced by increasing the system asymmetry. Comparison with stable beam needed.

This will make possible to refine and to improve our knowledge.

EXOCHIM - collaboration

F.Amorini[6], L.Auditore[7,8], C.Beck[9], I.Berceanu[10], E.Bonnet[5], B.Borderie[11], G.Cardella[1], A. Chbihi[5], M.Colonna[6], A.D'Onofrio[4,12], J.D.Frankland[5], E.Geraci[2,1], E.Henry[13], E.LaGuidara[1,14], G.Lanzalone[15,6], P Lautesse[16], D.Lebhertz[5], N.LeNeindre [17], I.Lombardo[4], D.Loria[7,8], M.LaCommara[3,4], S. Pirrone[1], G.Politi[1,2], J.P.Wieleczko[5], G.Ademard[5], E.DeFilippo[1], B.Gnoffo[2], M.Vigilante[3,4], K.Mazurek[5], A.Pagano[1], M.Papa[1], E.Piasecki[18], F.Porto[2,6], M.Quinlann[13], F.Rizzo[2,6], E.Rosato[3,4], P.Russotto[2,6], W.U.Schroeder[13], G.Spadaccini[3,4], A.Trifirò[7,8], J.Toke[13], M.Trimarchi[7,8], G.Verde[1,]L. Acosta,, V. Baran, L. Francalanza, S. T. Cap, G. Gianì, L. Grassi, A. Grzeszczuk, P. Guazzoni, J. Han, C. Maiolino, T. Minniti, E.V. Pagano, A. Pop, F. Porto, L.Quattrocchi, J. Wilczyński, L. Zetta.

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