FATA 2019

Fast Timing Applications
for Nuclear Physics and Medical Imaging
Acireale 3-5 September 2019

TOF in Heavy Ion Reaction:
CHIMERA detector & ISODEC experiment

Sara Pirrone

NEWCHIM – ISODEC collaboration

INFN - Sezione di Catania - Italy

INFN Istituto Nazionale di Fisica Nucleare

PROVANDO E RIPROVANDO

Outline

- Physics case and context
- Chimera detector
- ISODEC Experiment - results

Physics case and context

Heavy-ion collisions with stable and radioactive beams.

- **Low energy regime E < 15 MeV/A**

Fusion reaction mechanism (central collision) in competition with binary processes (ex: DIC, Quasi-Fission)

- **Intermediate (Fermi) energy regime (10 MeV/A < E < 100 MeV/A)**

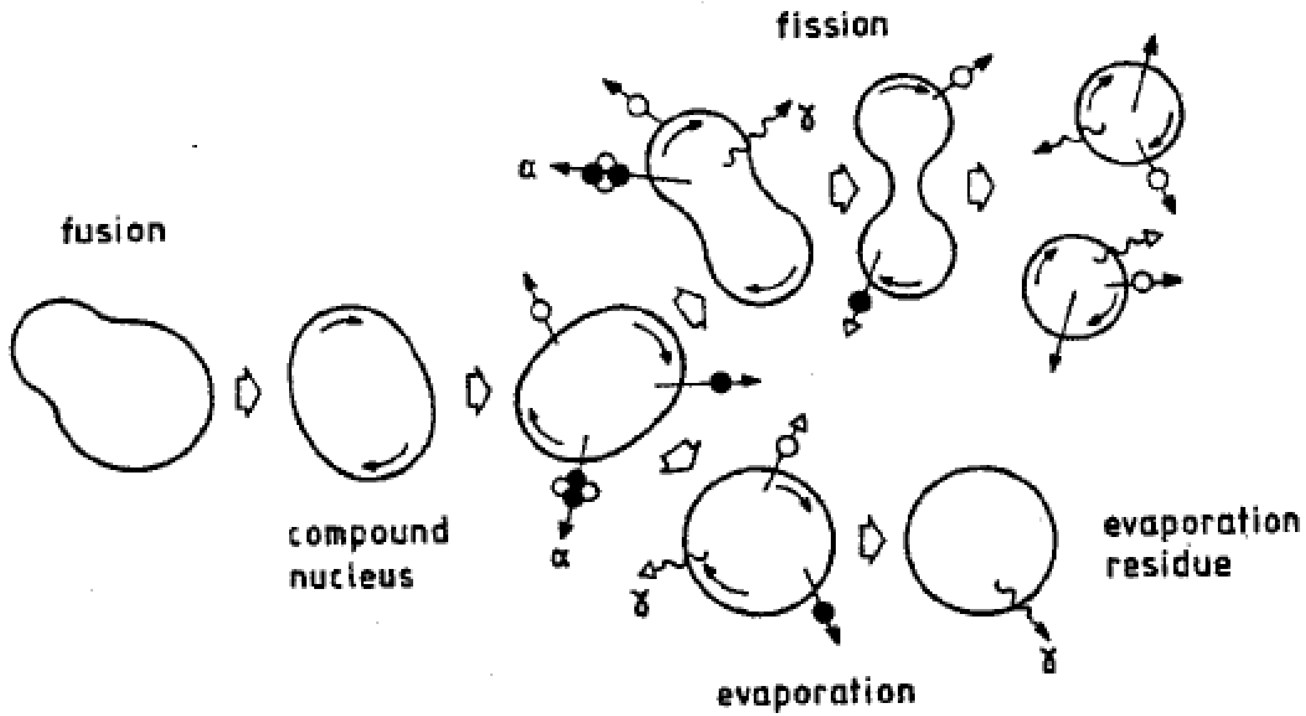
Multifragmentation reaction (central collision) in competition with neck formation (mid-peripheral collision) and binary process (peripheral collision)

HIC at low energy E/A < 15 MeV

Fusion reaction (central) in competition with
binary mechanisms (semiperipheral) dic, quasi-fission…

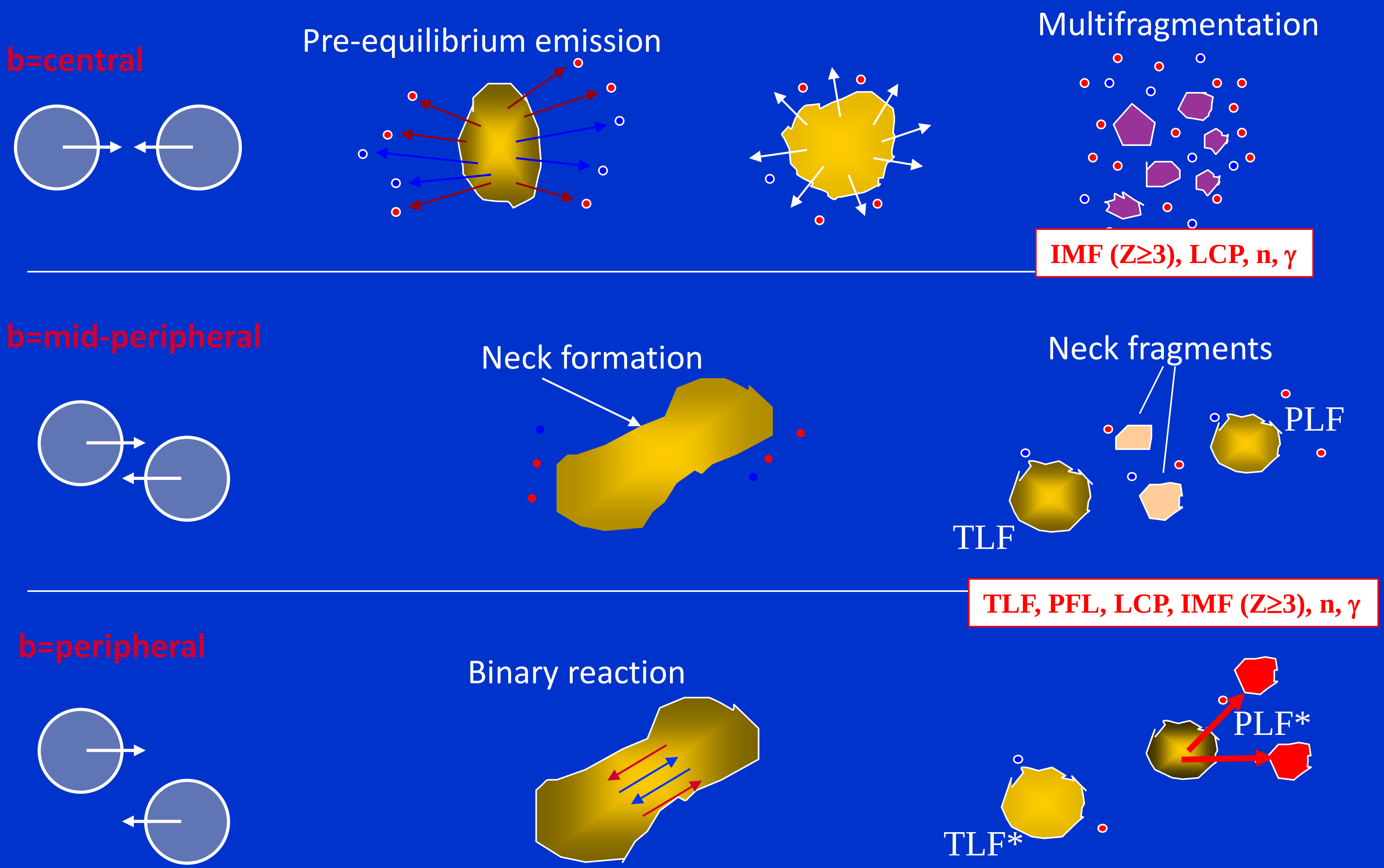
FF, LCP, n, γ

Central collision



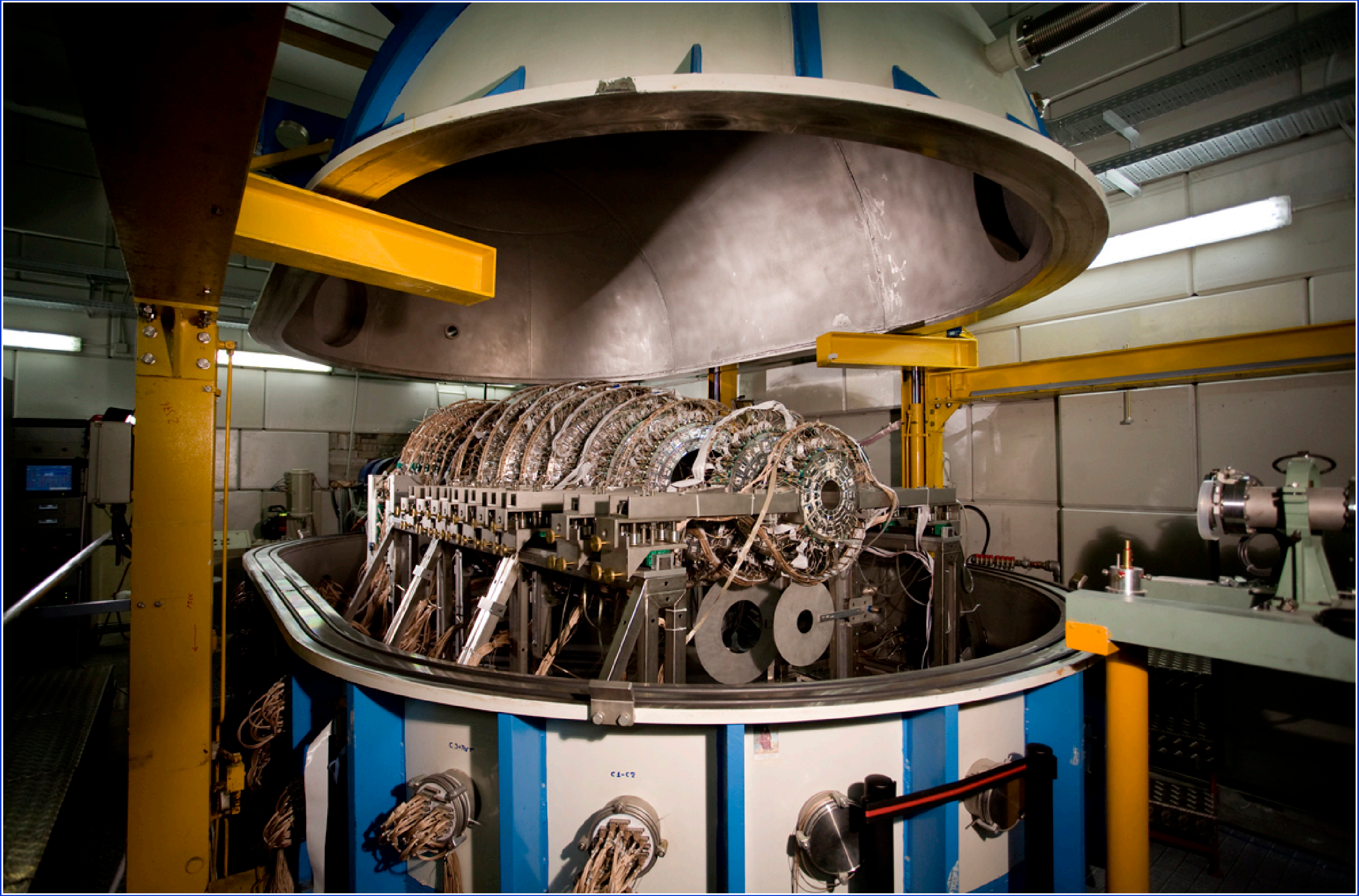
ER, LCP, n, γ

HIC at intermediate energies: 20 MeV<E/A< 100 MeV



CHIMERA @LNS

Charged Heavy Ion Mass and Energy Resolving array



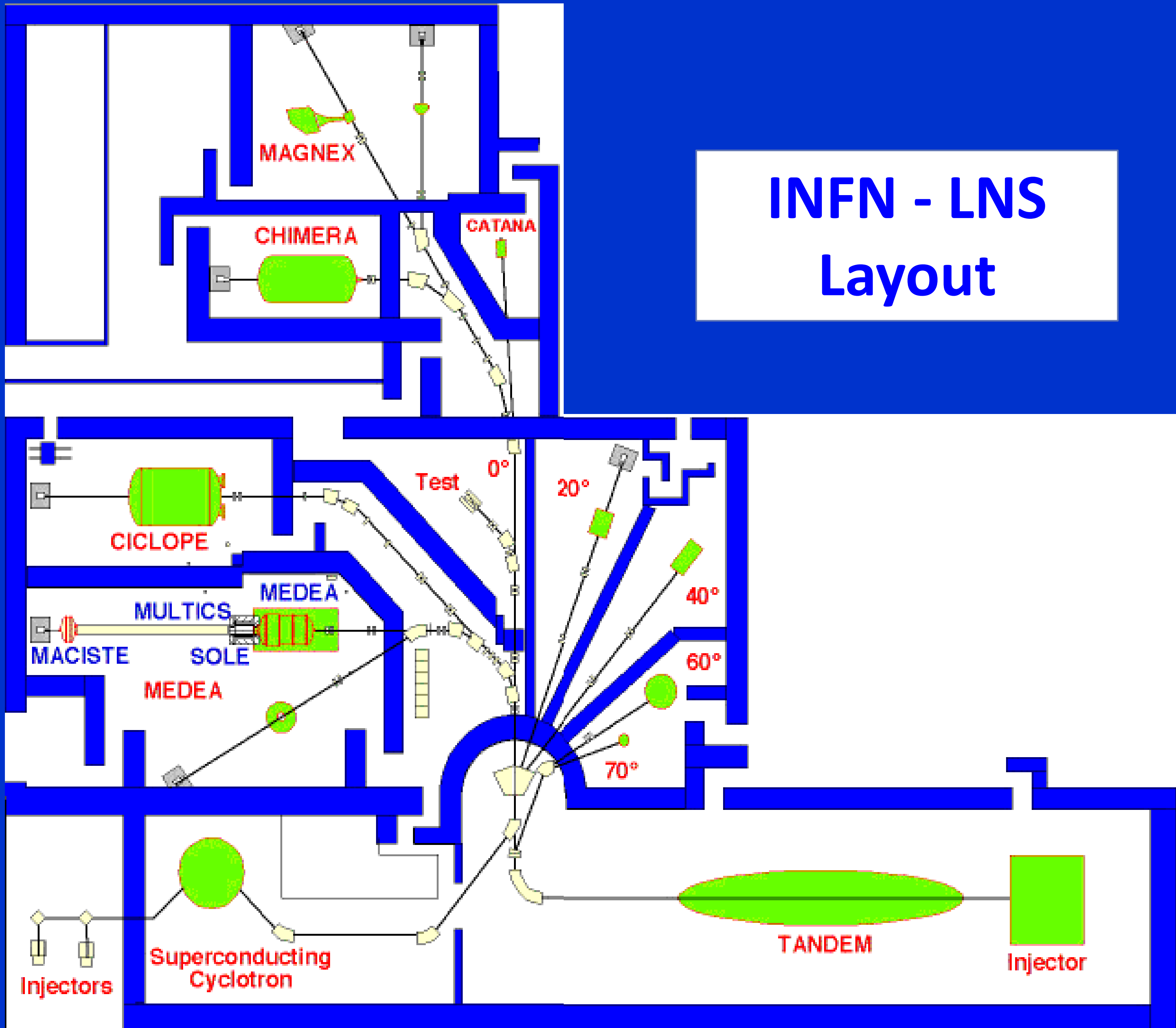
A. Pagano et al., NPA681 (2001) 331, A.Pagano et al. Nucl. Phys. New Int. Vol. 22, 1, (2012)

In Greek Mythology…..

Chimera was a fearsome, fire-breathing monster with a lion's head, a goat's body, and a dragon's tail. She terrorized the people of Lycia until their king, Iobates, asked the hero Bellerophon to slay her. Iobates had an ulterior motive; his son-in-law wanted Bellerophon killed and the king was sure the Chimera would do the job. But Bellerophon called in Pegasus, the winged horse, and brought the Chimera down from above. The beast lived on in people's imaginations, and English speakers adopted her name for any similarly grotesque monster, or, later, for anything fanciful.

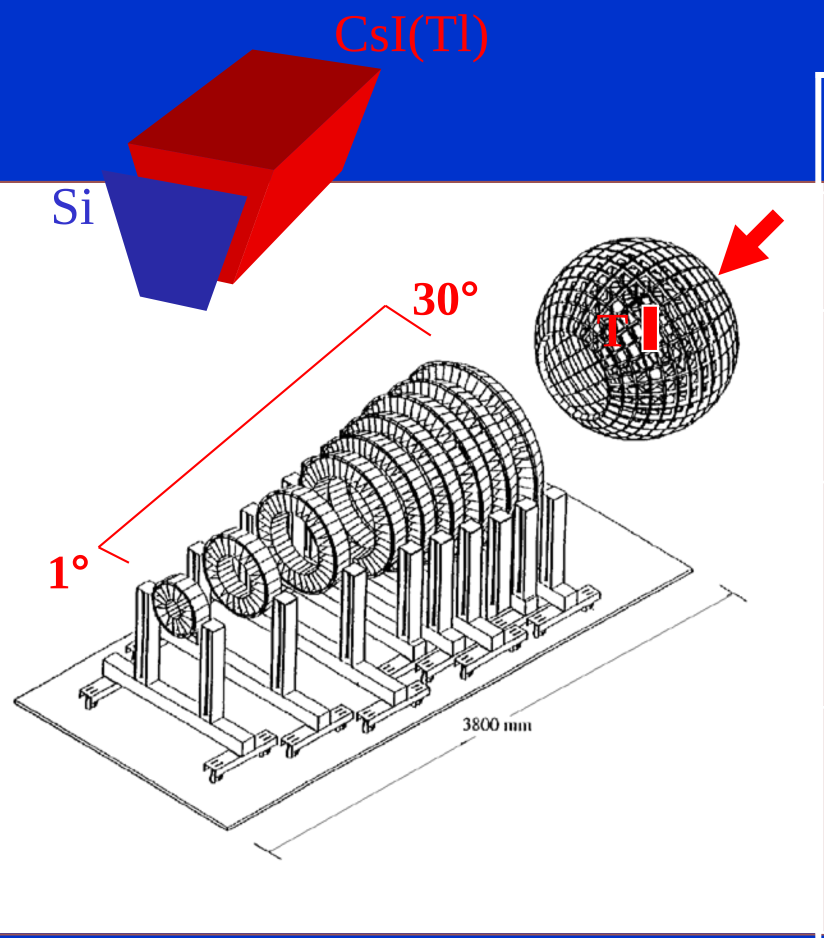
Chimera di Arezzo 400 BC – art of Etruscan- Museo Archeologico Nazionale - Florence

INFN - LNS Layout



CHIMERA

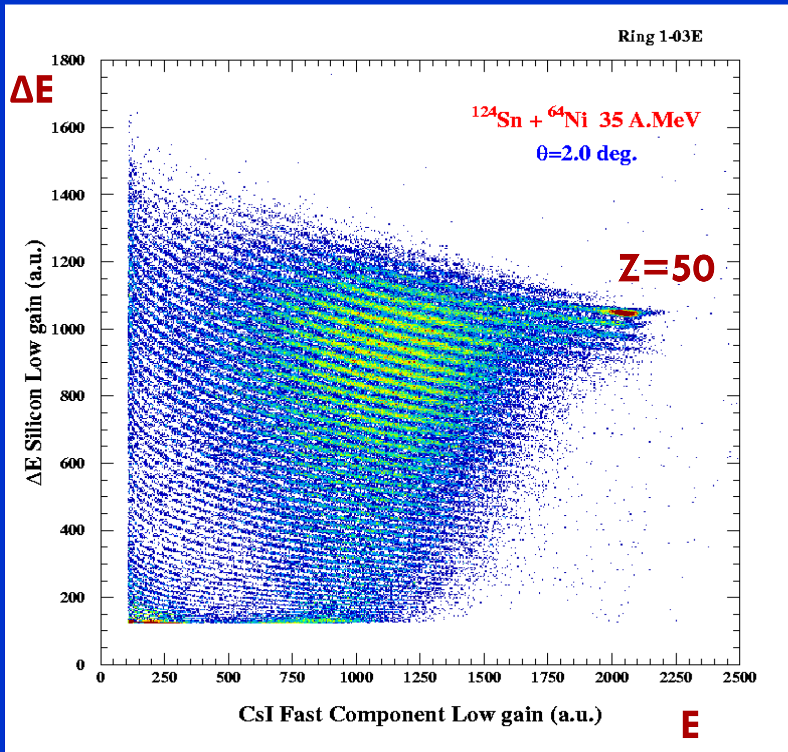
Charge Heavy Ion Mass and Energy Resolving Array

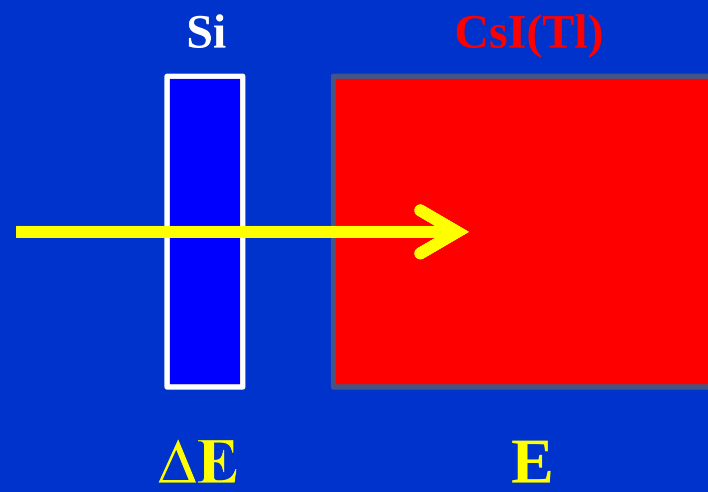


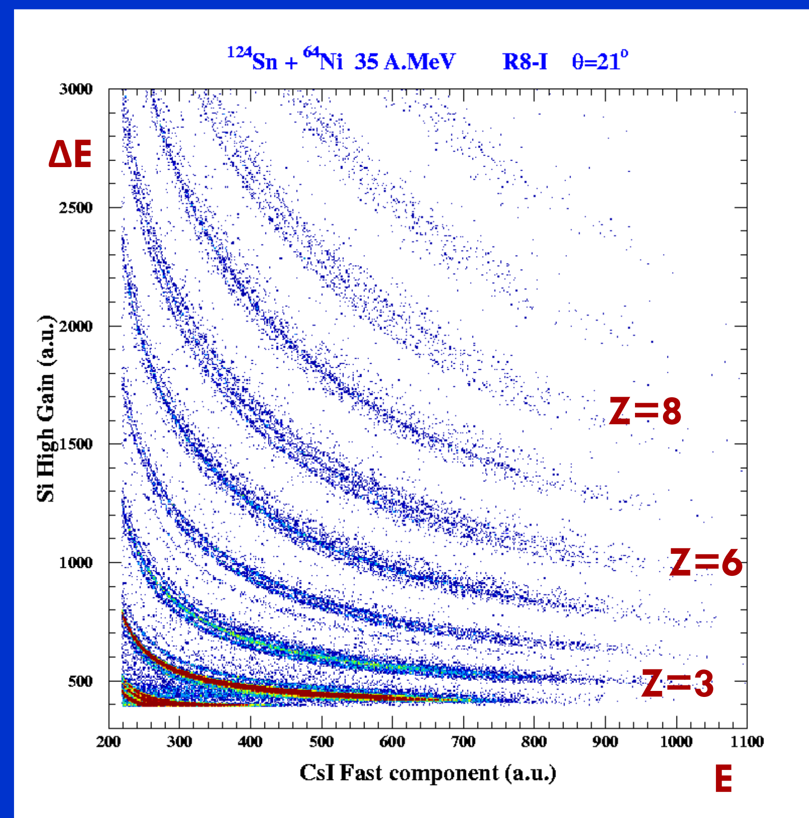
Granularity	1192 telescopes Si (300μm) +CsI(Tl)
Geometry	RINGS: 688 telescopes 100-350 cm SPHERE: 504 telescopes 40 cm
Angular range	RINGS: 1°< θ < 30° SPHERE: 30°< θ < 176° 94% of 4π
Identification method	ΔE-E E-TOF PSD in CsI(Tl) PSD in Si (upgrade 2008)
Experimental observables and performances	TOF 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 few MeV/A to 100 MeV/A

Charge Identification by ΔE-E



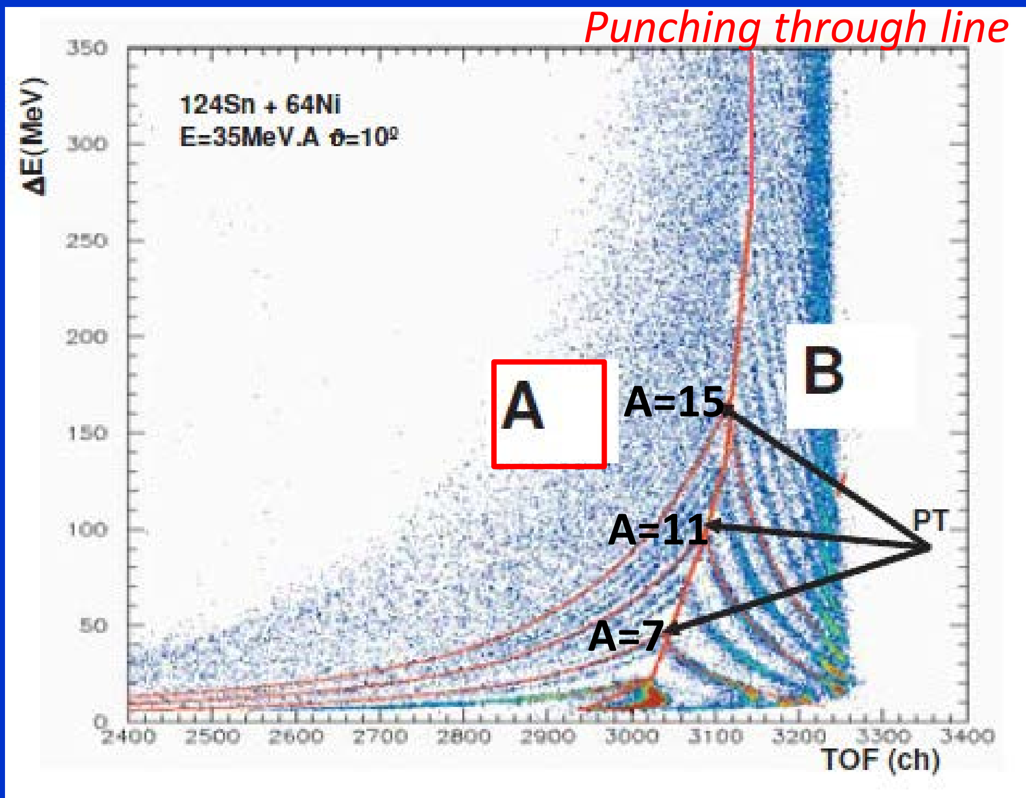


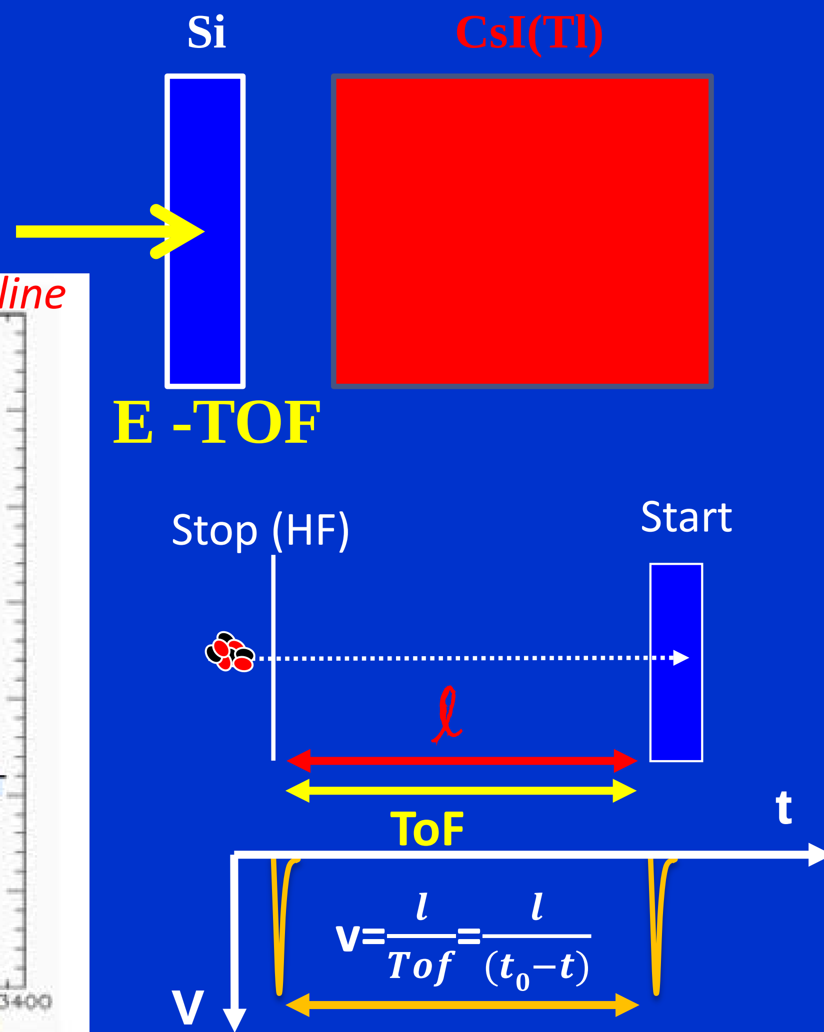


Bethe – Bloch Formula

$$\Delta E \propto \Delta x (AZ^2)/E$$

Mass Identification by E-ToF

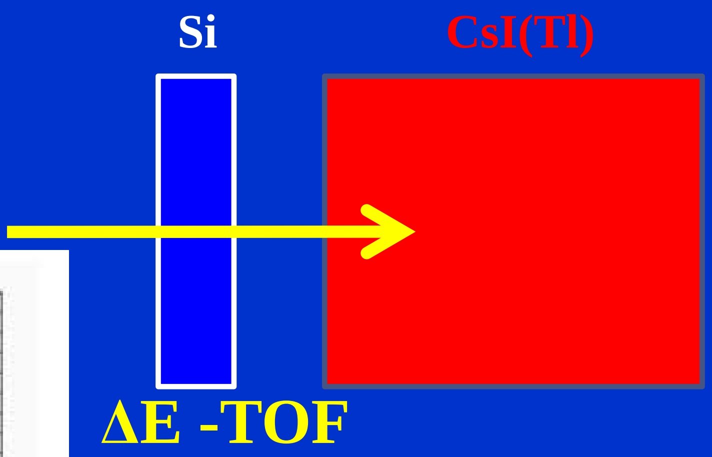


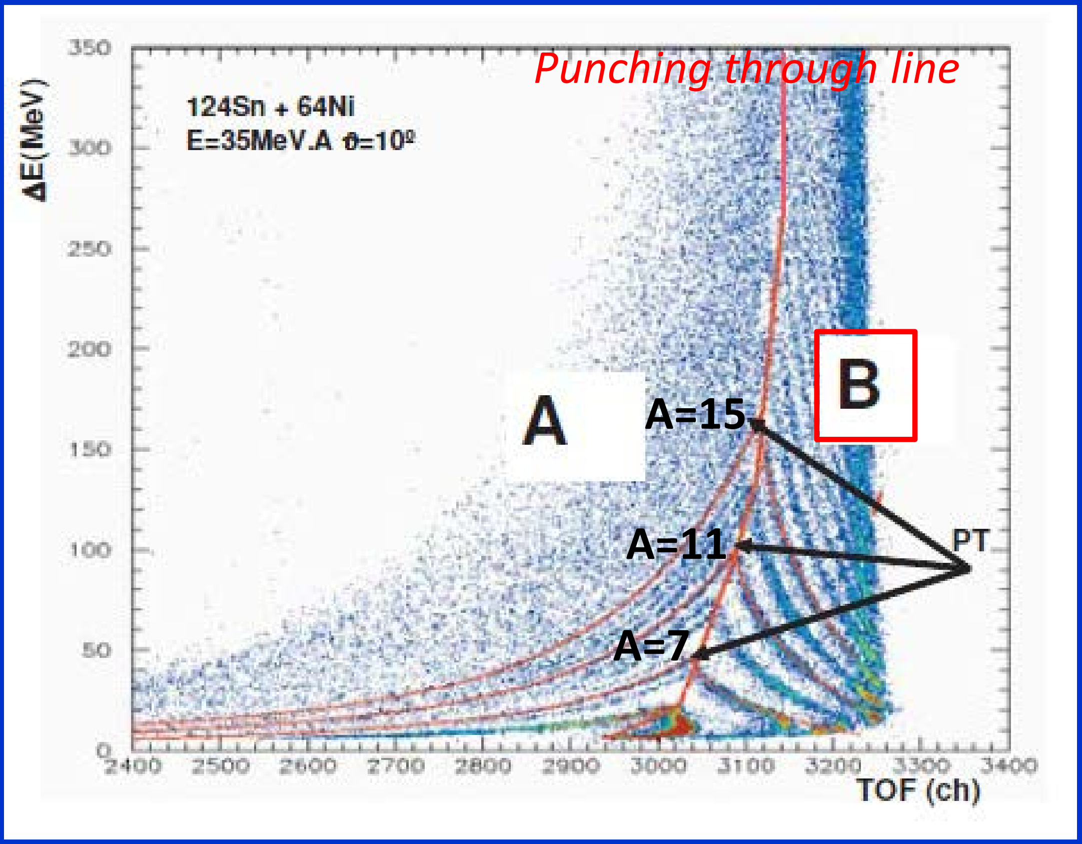


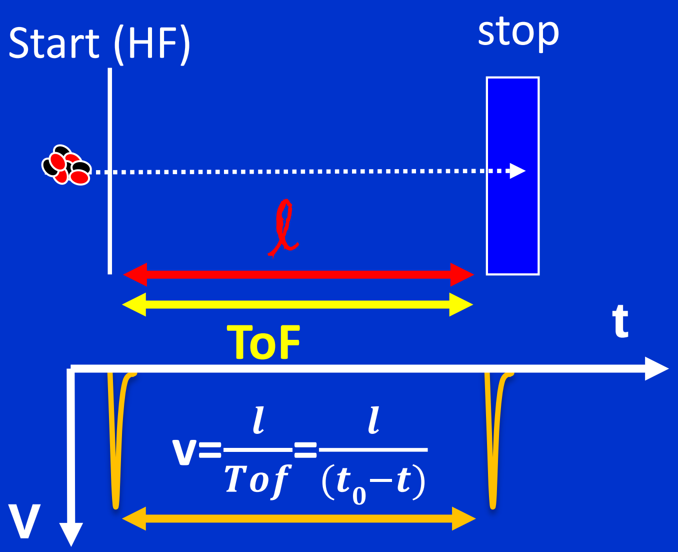
$$E = \frac{1}{2}Mv^2 = \frac{1}{2}\frac{Ml^2}{(t_0 - t)^2}.$$

$$M = \frac{2(t_0 - t)^2 E}{l^2}.$$

Mass Identification by E-ToF

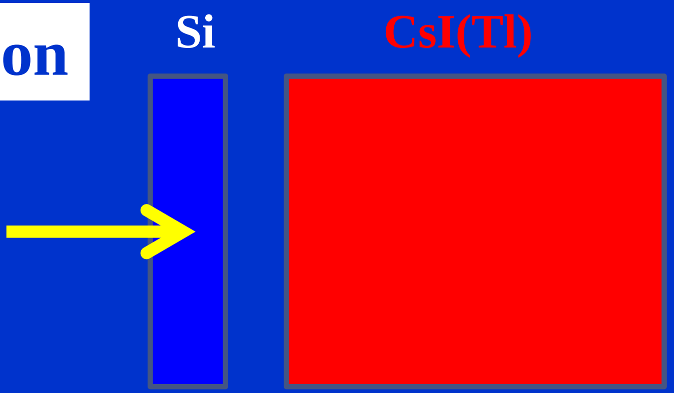


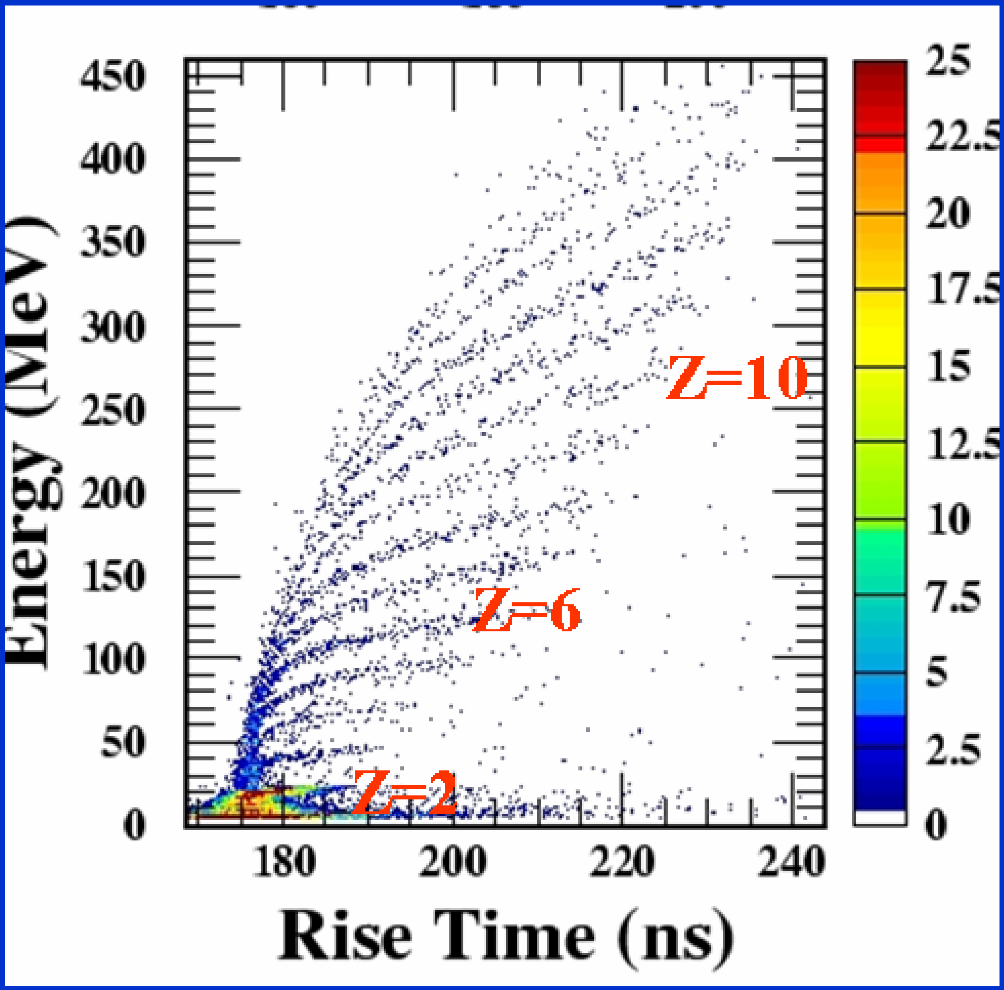




$$\Delta E \propto \frac{Z^2}{v^2} = \frac{Z^2(t_0 - t)^2}{l^2}.$$

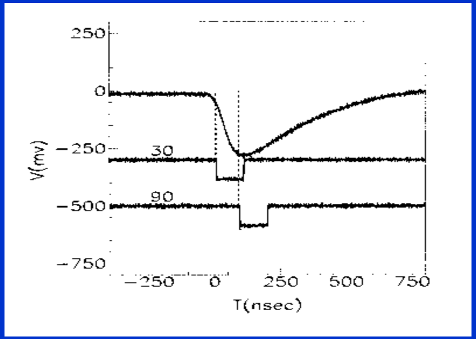
Charge Identification by PSD in Silicon





E- Rise Time (PSD_Silicio)

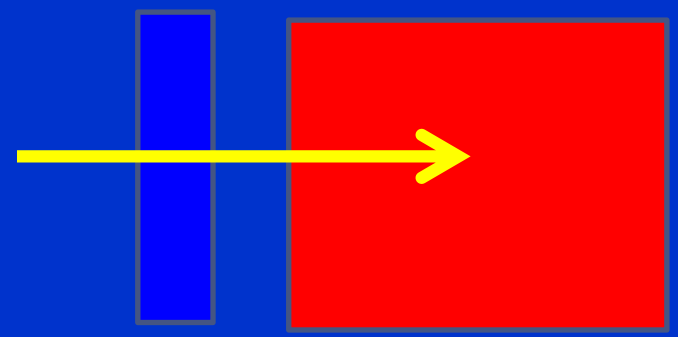
Rise time = f (Z, E)

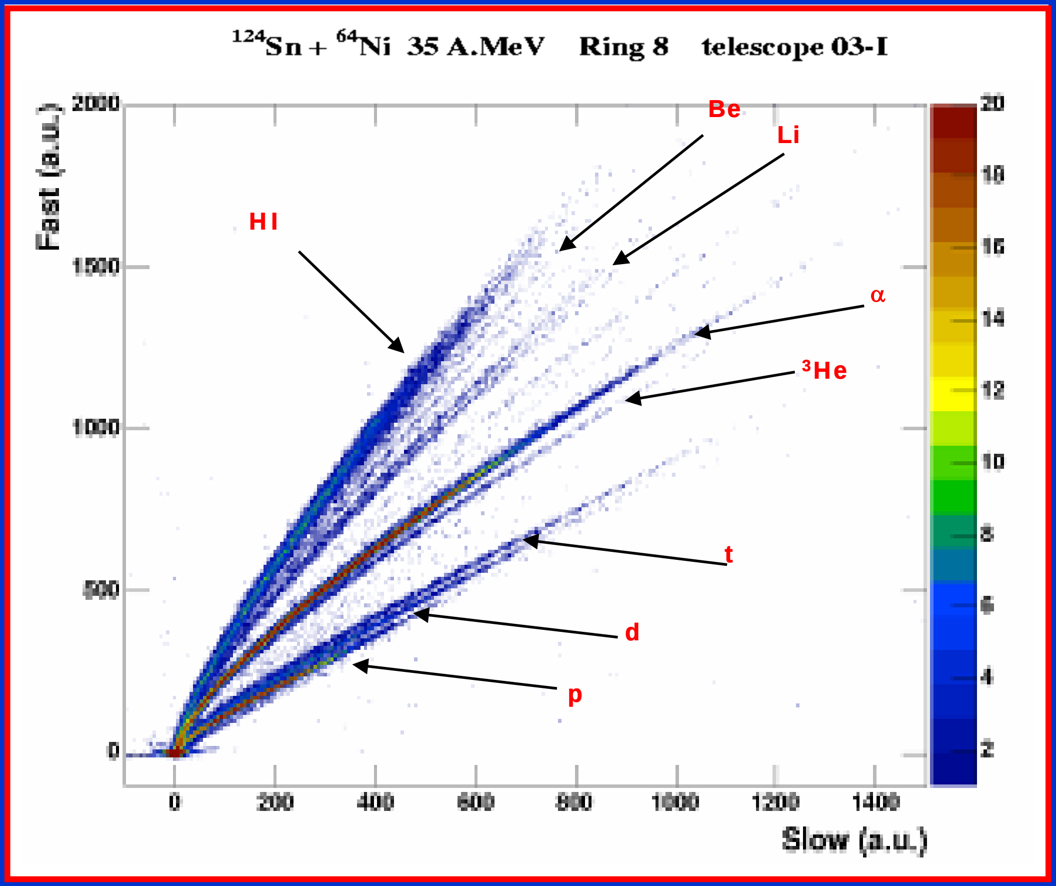


Rise time measurement with two discriminators with different constants eg: 30% and 90%

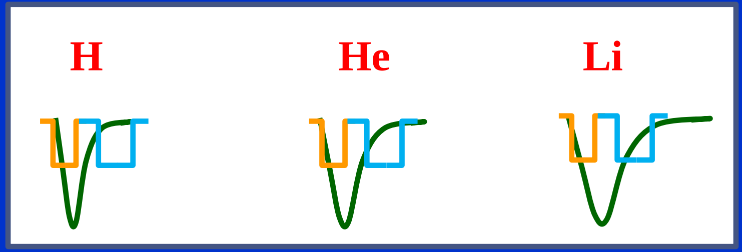
→ time delay between the two triggers is linked to signal rise time

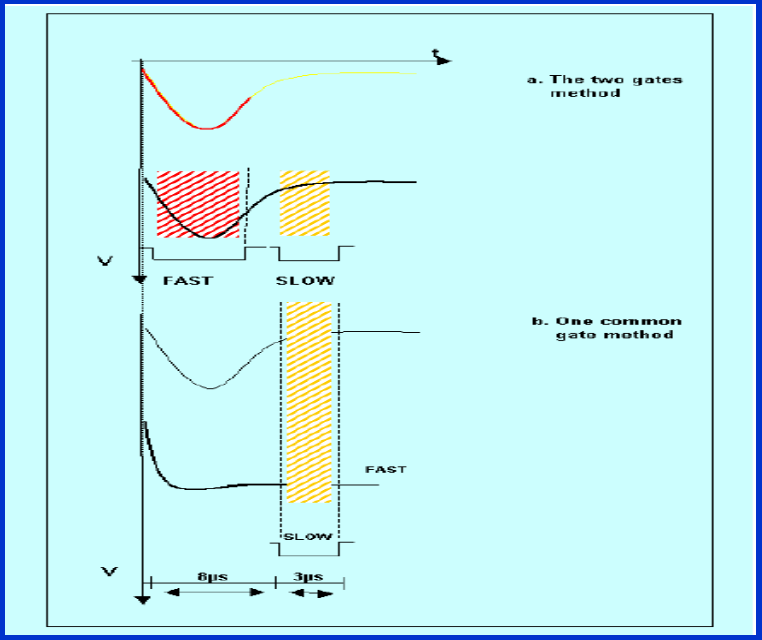
LCP identification (A,Z) by PSD in CsI(Tl)





E fast- E Slow
PSD CsI(Tl)



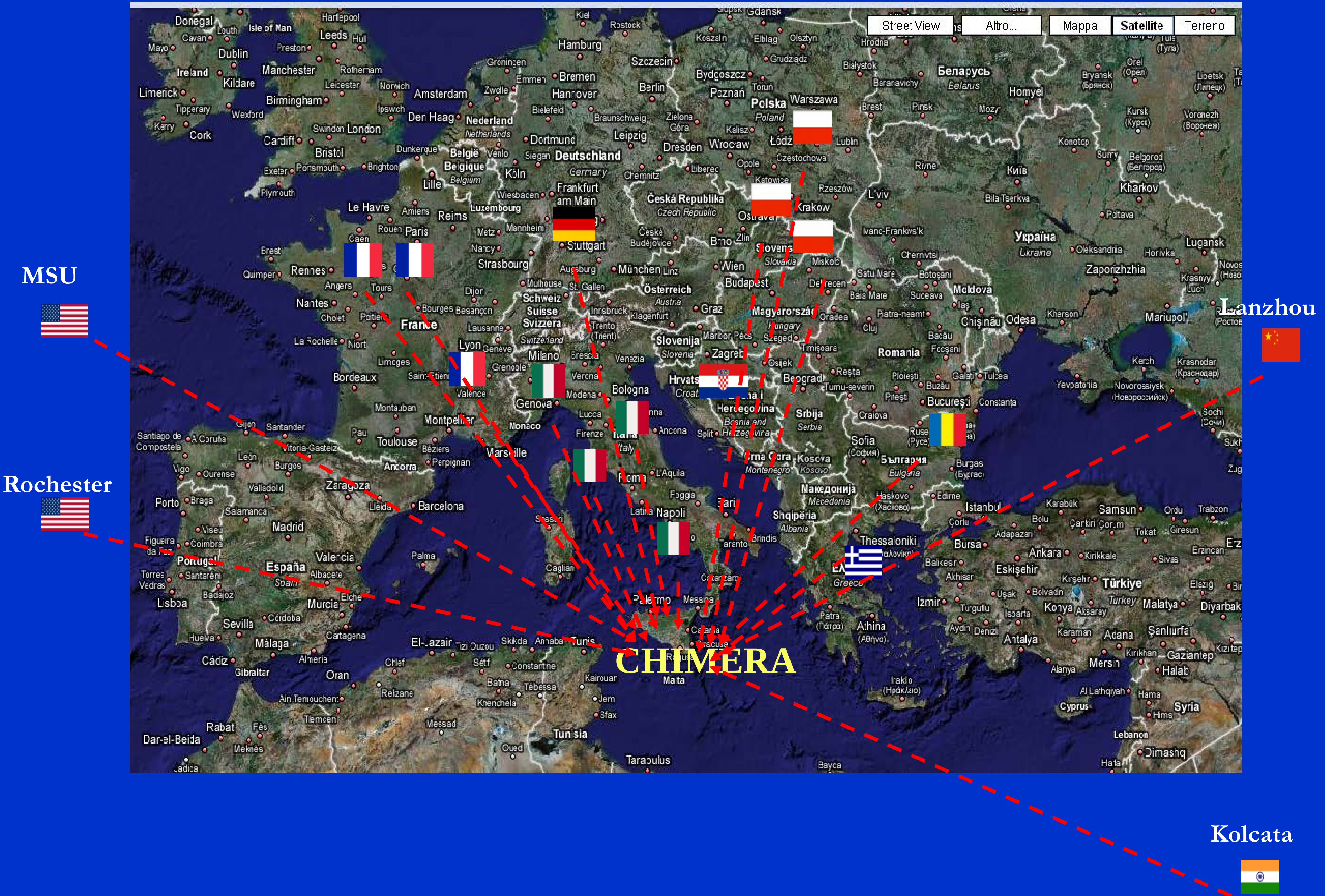


Experiments with CHIMERA (2000 - up today)

- Equation of State (EOS) of Nuclear Matter;
- Neck emission, Time scale for fragment formation, fragment hierarchy,
- Isospin influence on the reaction mechanisms.
- Clusters in nuclei
- Fusion and Fission - Dynamical fission
- Reactions and Structure – Unstable nuclei
- Nuclear Astrophysics and Exotic States
- New facilities (FRIBS) and detectors (FARCOS correlator – neutron detectors)

Review : E. De Filippo and A. Pagano EPJ A50, 32, 2014

CHIMERA- International collaborations



ISODEC Experiment

$^{78,86}Kr + ^{40,48}Ca$ at E = 10 AMeV

First experiment at low energy by using CHIMERA.

The most of the particles are stopped in the Silicon detector

1) PSD Silicon detector

charge identification

2) TOF measurement - velocity measurement

mass identification

reaction mechanism disentangling

ISODEC Experiment

$^{78}Kr + ^{40}Ca \rightarrow ^{118}Ba^*$ "n-poor"

$^{86}Kr + ^{48}Ca \rightarrow ^{134}Ba^*$ "n-rich"

E = 10 AMeV

Study of the influence of the isospin and of the neutron enrichment of the CN, on the reaction mechanism, on the decay process and on the formation and emission of complex fragments (IMF, $Z \geq 3$)

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

ΔN=16 neutrons

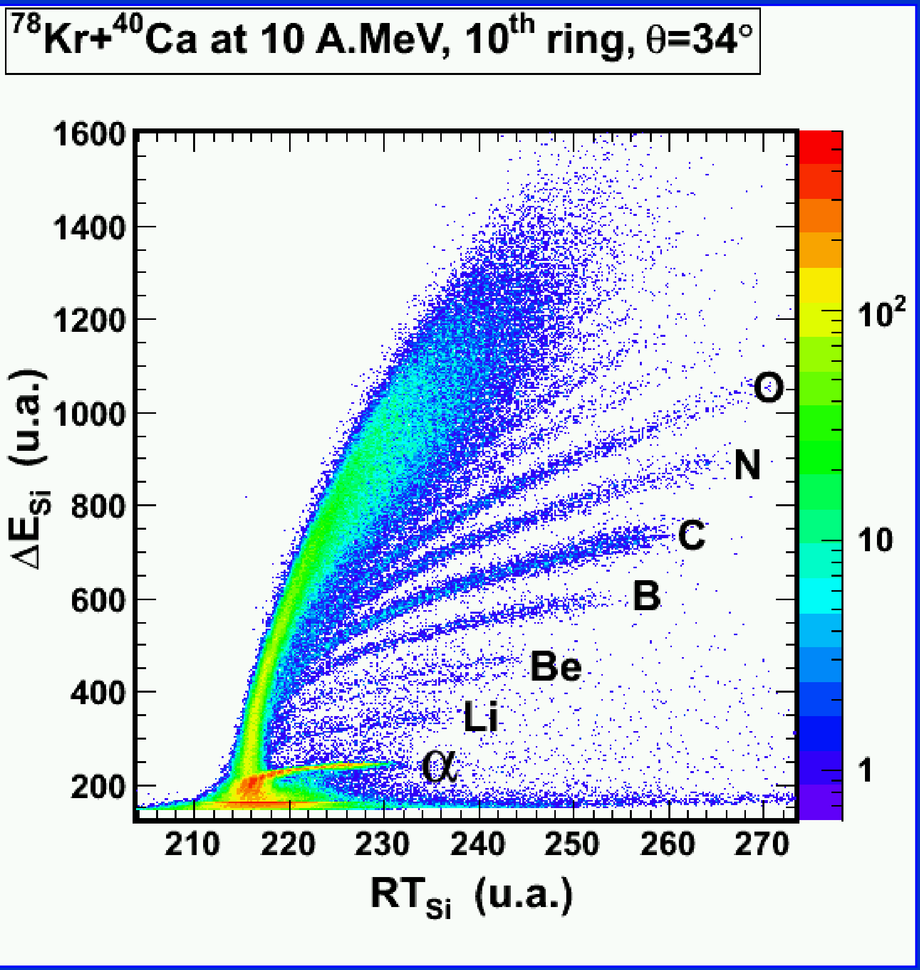
S. P. et al., Eur. Phys. J. A 55 (2019) 22

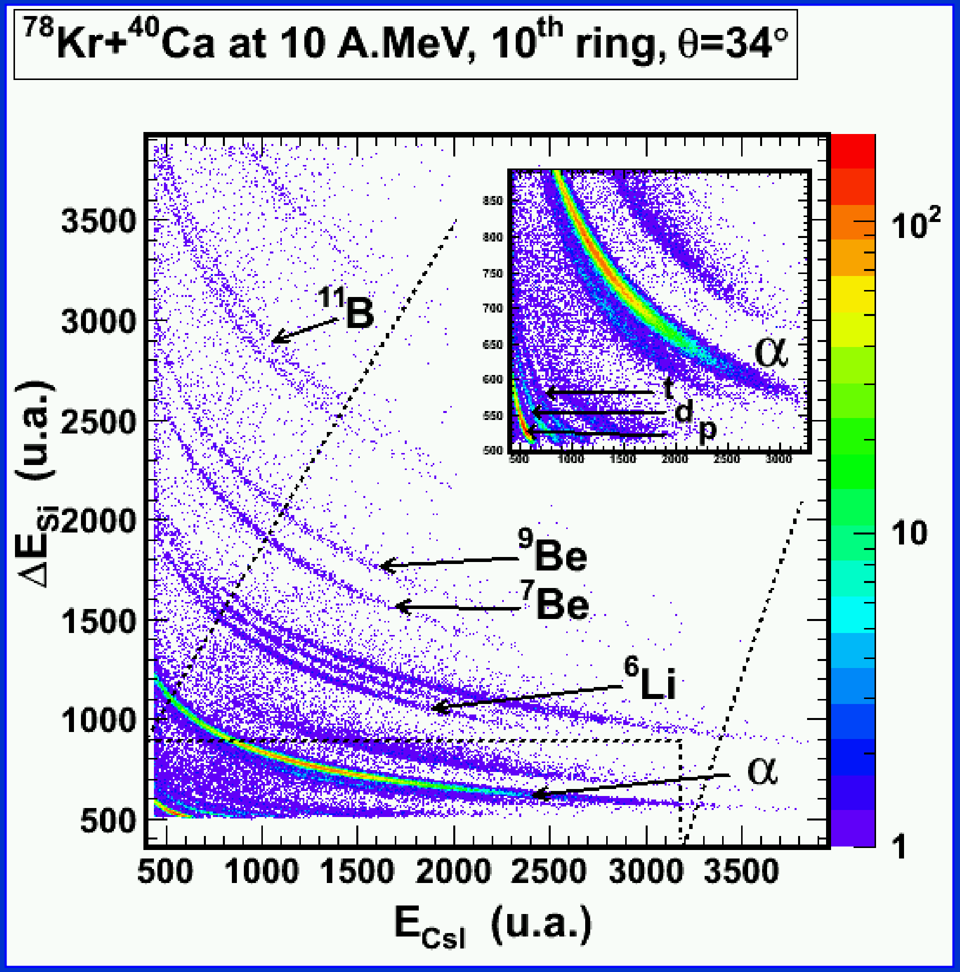
S. Pirrone et al., Journal of Physics: Conf. Series 515 (2014) 012018
G. Politi et al., JPS Conf. Proc. Vol. 6 (2015) 030082
B. G. Nuovo Cimento C39 (2016) 275

IMF Isotopic Identification

PSD in Silicon

ΔE-E , Si-CsI(Tl)

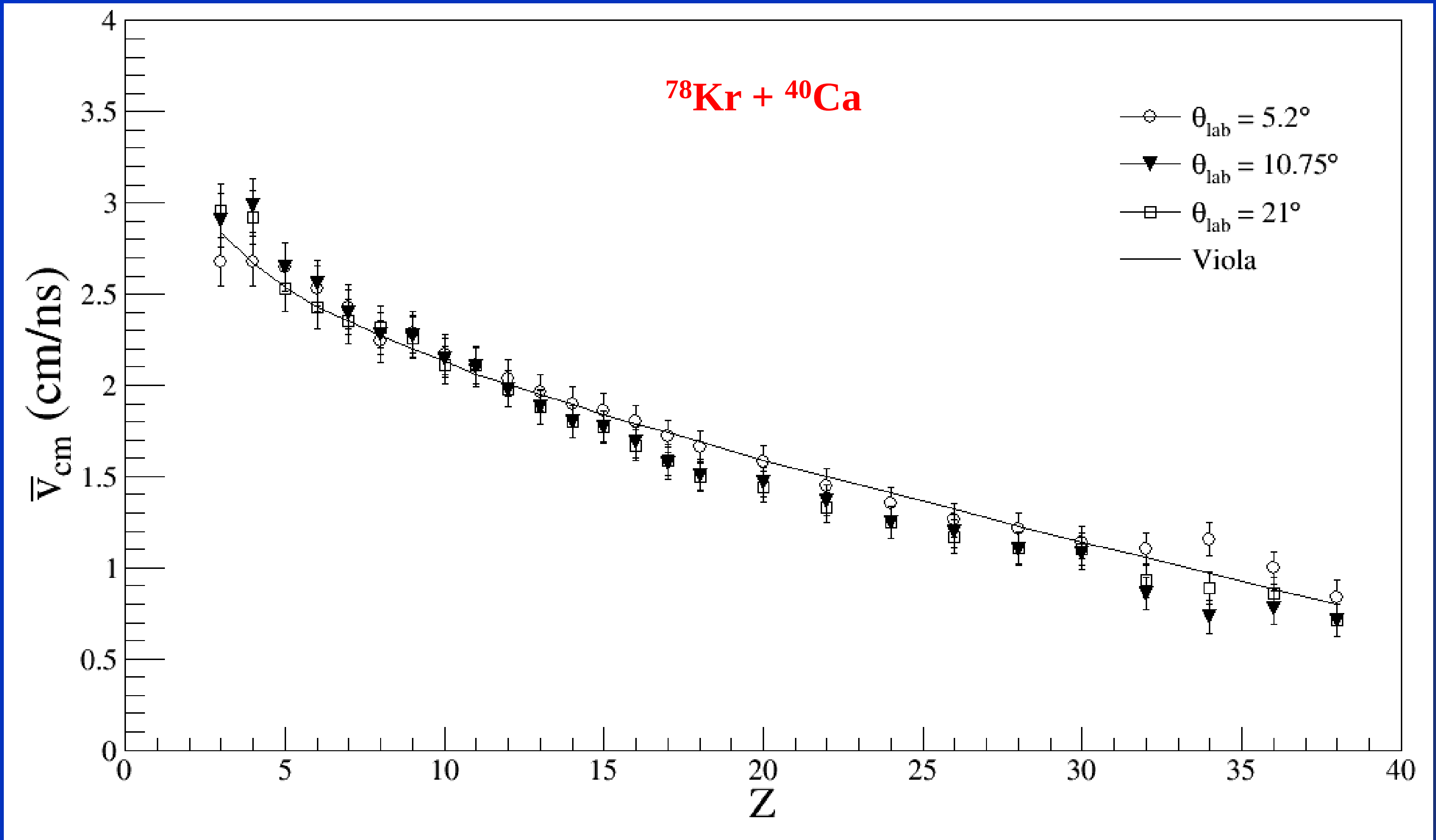




S.P. et al, Journal of Physics- Conf. Series 515 (2014) 012018

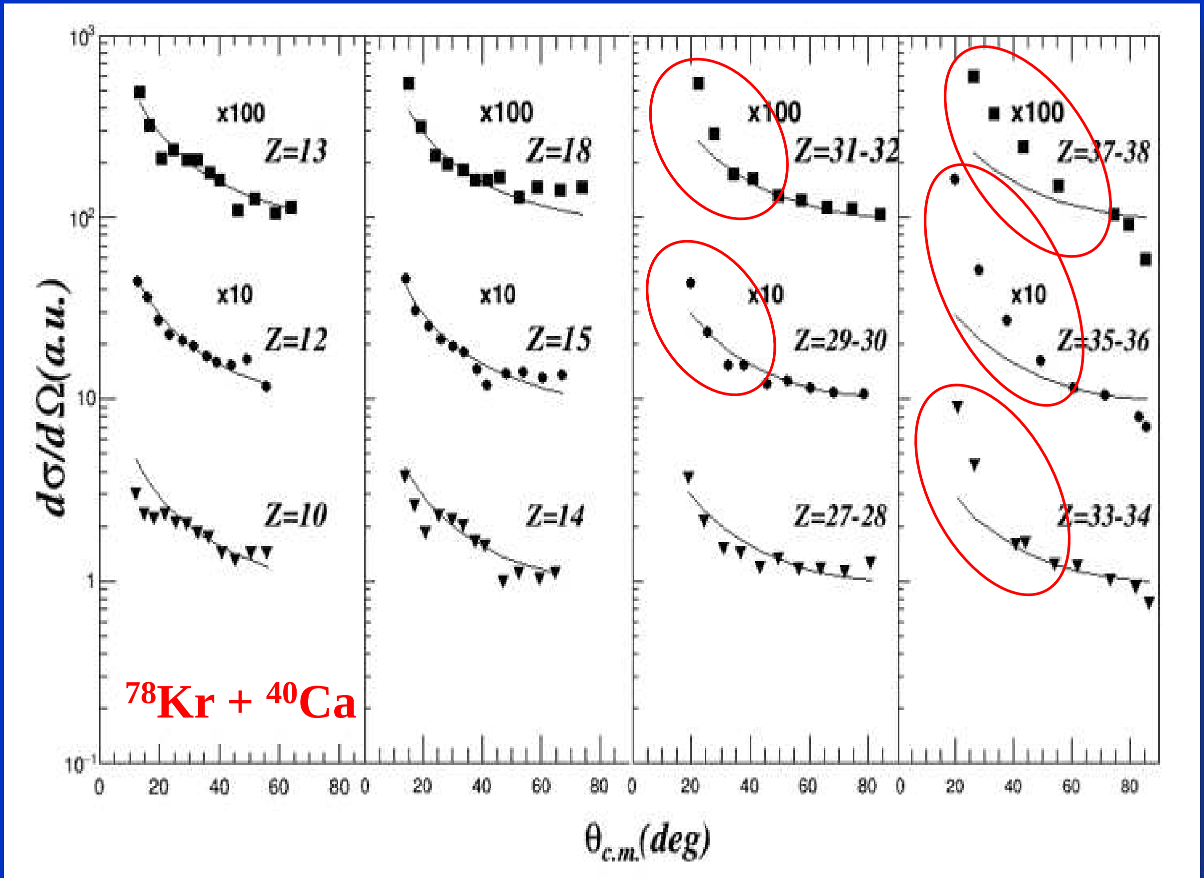
Average Velocity for fragments Z=3-38 in the CM frame

- **Independent from emission angle and decreasing with Z → equilibrated process**
- **Good agreement with Viola systematic for fission (D.J. Hinde, NPA472 (1987) 318)**
- **Regular behavior slightly disregarded for Z>30, maybe due to a dynamical mechanism contribution**



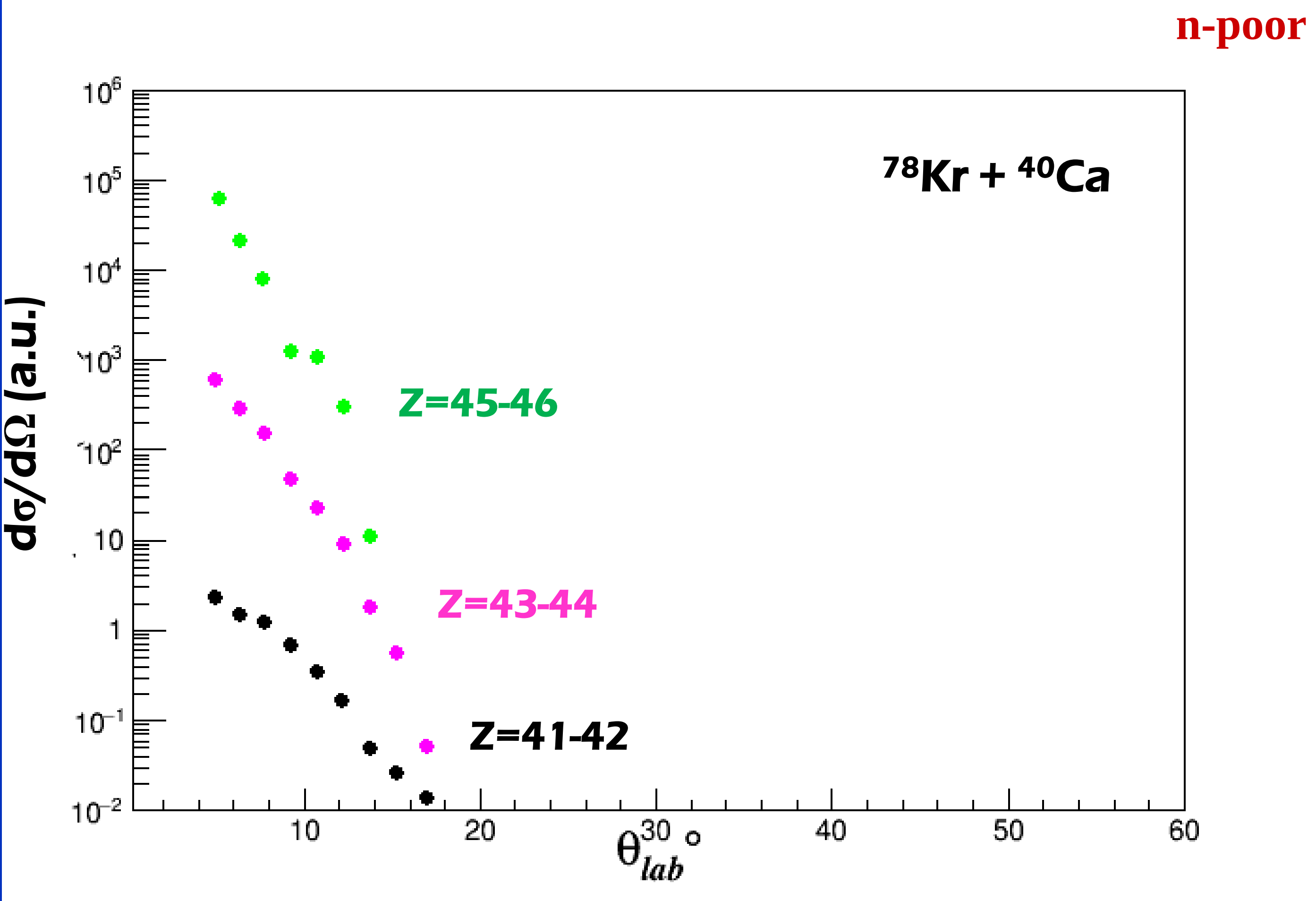
Signature of a binary process dominated by the Coulomb interaction

Angular distributions of fragments in CM frame



- 1/sinϑ behavior, expected for a production via a long lived system –> fission like mechanism from equilibrated source
- Z > 28 stronger contribution at smaller angles, confirming a not fully equilibrated binary mechanism

Angular distributions in the LAB frame for Z > 40



Strongly forward peaked /bell shape - expected for Evaporation Residues - ER

Gomez Del Campo et al, PRC 19 (1979) 2170

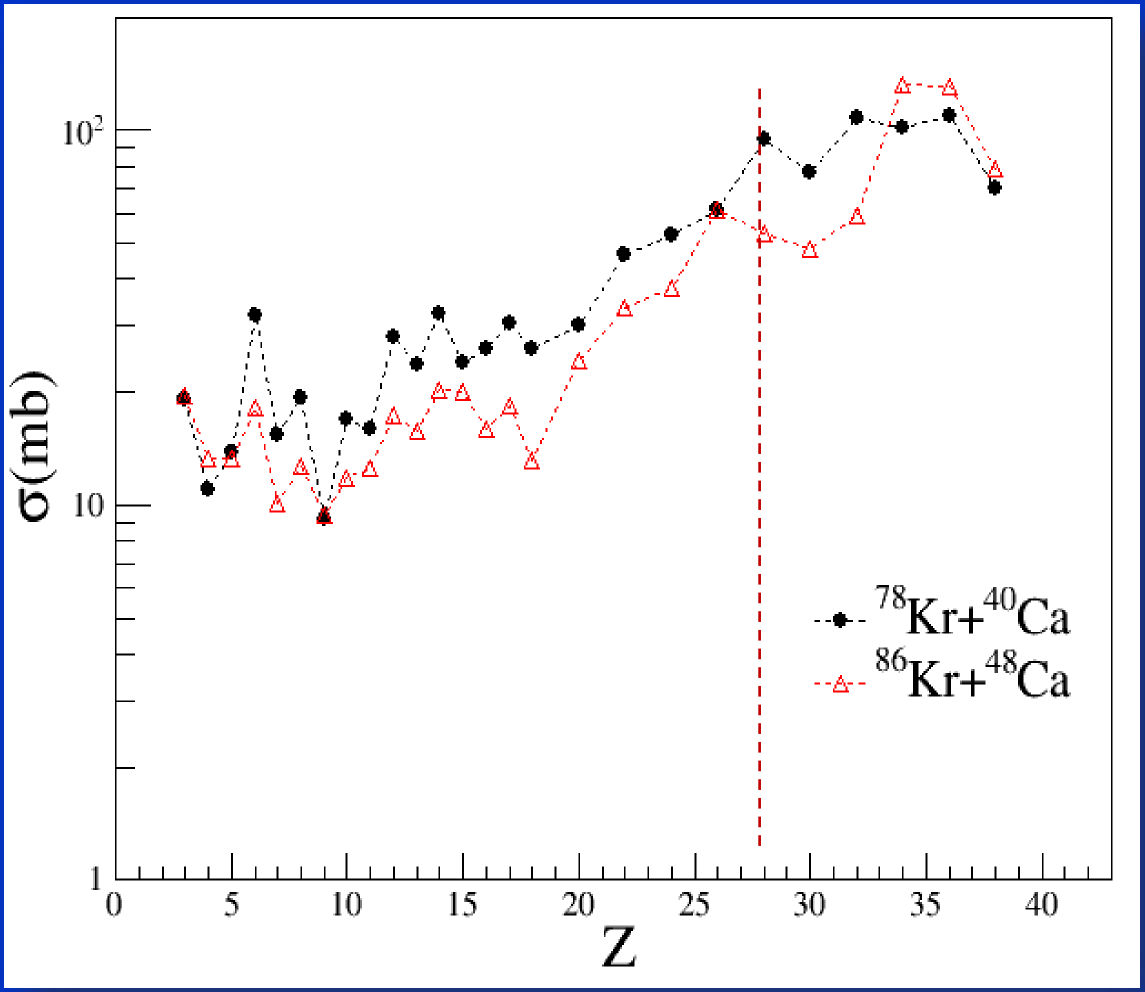
IMF Charge Distribution (n-poor n-rich systems)

- **Fragments production globally favored for n-poor system**

- **Odd-even staggering behaviour, more pronounced in the n-poor system**

  In agreement with:
  I. Lombardo et al., PRC 84 (2011) 024613
  G. Casini et al., PRC 86 (2012) 011602

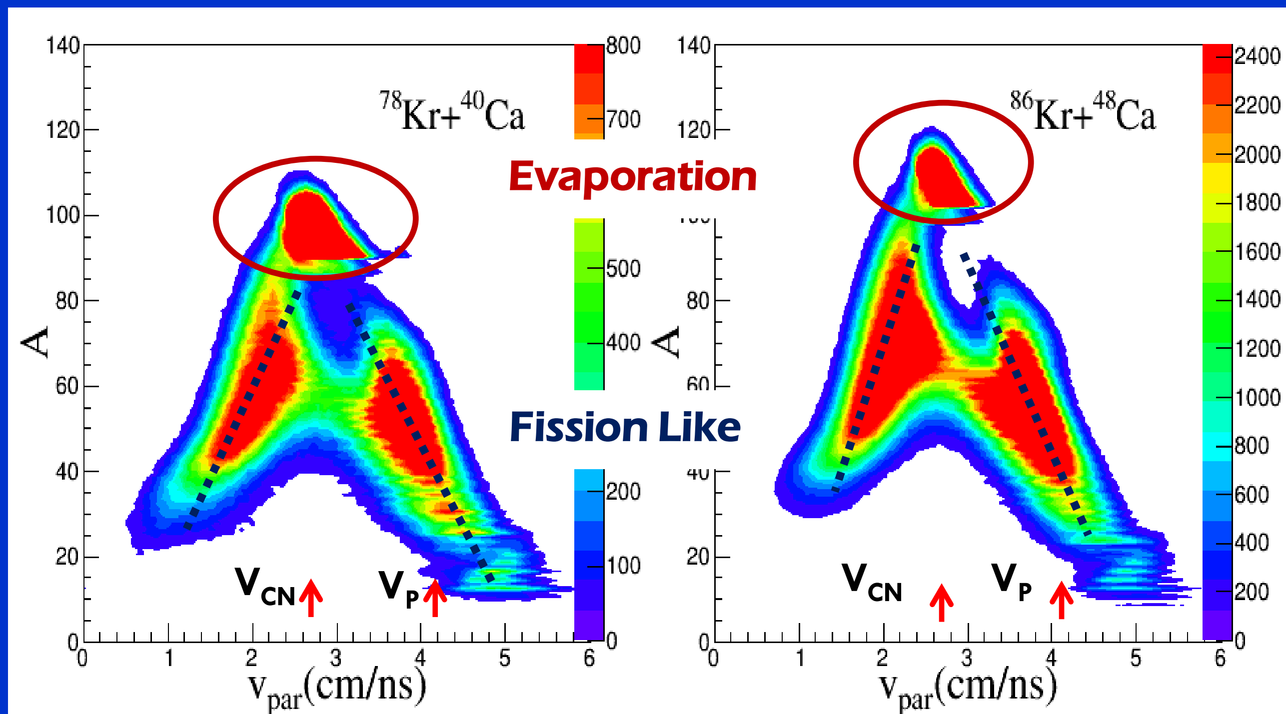
- **Charge distribution not symmetric with respect to $Z_{CN}/2=28 \rightarrow$ presence of dynamical process**



Further information from Complete Events

multiplicity ≥ 2 $0.8\ M_{CN} \leq M_{tot} \leq 1.1\ M_{CN}$ $0.6 \leq p_{tot}/p_{beam} \leq 1$

Correlation between fragment mass and parallel velocity



Evaporation Residues and Fission Like fragments

are evident in both systems

Cross sections measurements

	σ_{ER} (mb)	σ_{FL} (mb)	σ_{fus} (mb)	σ_{reac}^{qp} (mb)
^{78}Kr+^{40}Ca	455±70	850±120	1305±190	2390±250
^{86}Kr+^{48}Ca	400±60	530±85	930±145	2520±260

S. P. et al., Eur. Phys. J. A (2019) 55, 22

- **Fusion-Evaporation process is comparable for the two systems**
- **Fission-Like process prevails for the n-poor system**
- **Difference σ_{Reac} - σ_{Fus} more pronounced for the n-rich system (more DIC)**

Conclusions

- The ISODEC experiment realized by using the CHIMERA array is only an example among the many experiments that benefits of the TOF technique in the field of Nuclear Physics.

- R3B@GSI or ALICE@CERN are other important examples in a different energy range.

- The TOF technique (in general) can get improvement from the Nuclear Physics studies, and the mutual collaboration among different communities will be a great resource for the future.

NEWCHIM – ISODEC Collaboration

S. Pirrone[1], G. Cardella[1] , E. De Filippo[1], E. Geraci[1,2], B.Gnoffo[1,2], G. Lanzalone[3,5], N.S. Martorana[2,3], A. Pagano[1], E.V. Pagano[3], M. Papa[1], G. Politi[1,2]F. Rizzo[2,3], P. Russotto[3], M. Trimarchi[1,4]

1) INFN, Sezione di Catania, Italy
2) Dipartimento di Fisica e Astronomia «Ettore Majorana» Università di Catania, Italy
3) INFN, Laboratori Nazionali del Sud, Catania, Italy
4) Dipartimento di Scienze Matematiche e Informatiche,Scienze Fisiche e Scienze della Terra, Università di Messina, Italy
5) Università degli Studi "Kore", Enna, Italy