E. De Filippo (INFN Catania) for the EXOCHIM collaboration

Effects on dynamics and thermo-dynamics in heavy ion reactions on the symmetry energy

Kinematic correlations and fragment emission Time Scale links with the "isospin" dynamics.

The TimeScale experiments in direct ^{64,58}Ni + ^{124,112}Sn and reverse ^{124,112}Sn+^{64,58}Ni kinematics at 35 A.MeV

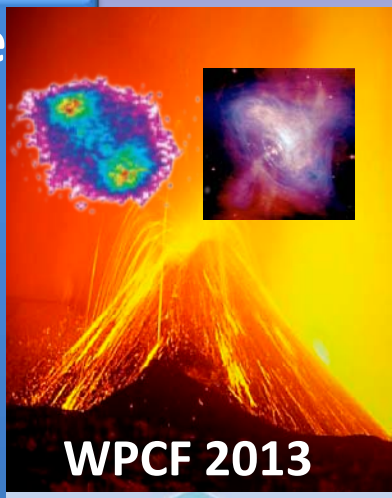
Physical cases:

Probing the symmetry energy term of EOS (comparisons with a Stochastic Mean Field (SMF) calculation) from "neck" fragmentation.

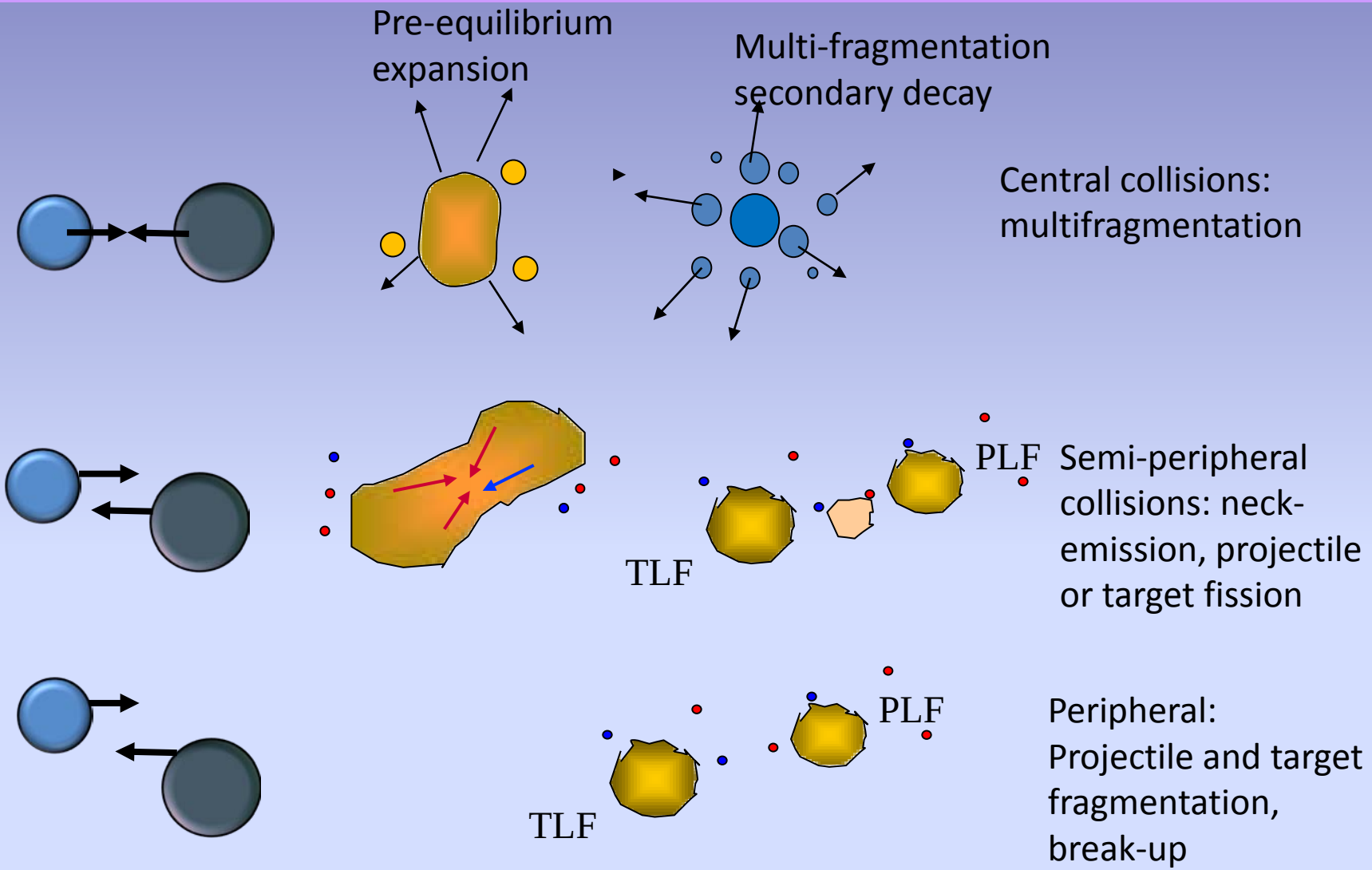
Exploring a low density asymmetric nuclear matter.
An experimental survey.

Particle-particle interferometry and symmetry term of EOS.

New perspectives for the future with Chimera + Farcos (Femtoscope Array for Correlations and Spectroscopy) device.

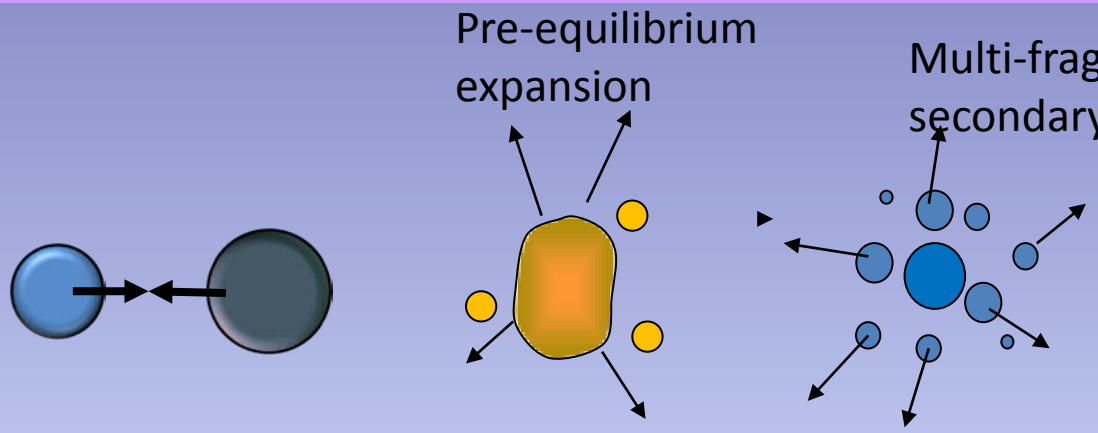


Heavy ion collisions at Fermi energies: different scenarios and mechanisms

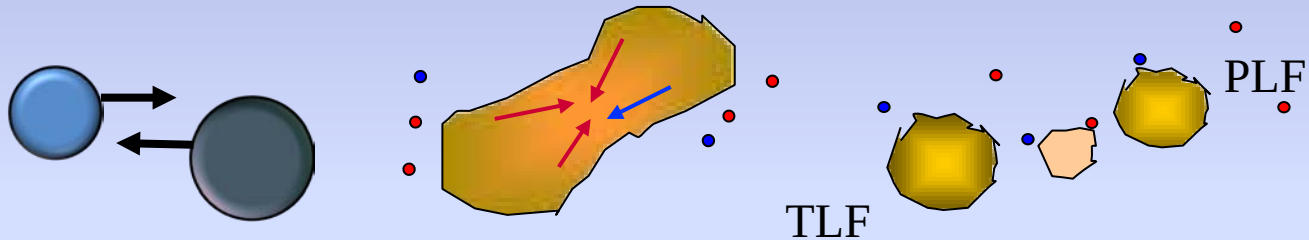


Particle emissions from the early phase of the dynamical evolution (**few fm/c**) up to later stages of statistical decay (**several hundreds of fm/c**) have been measured and are expected to coexist in the reaction products.

Heavy ion collisions at Fermi energies: different scenarios and mechanisms



Central collisions:
multifragmentation



Semi-peripheral collisions: neck-emission, projectile or target fission

Peripheral:
Projectile and target fragmentation, break-up

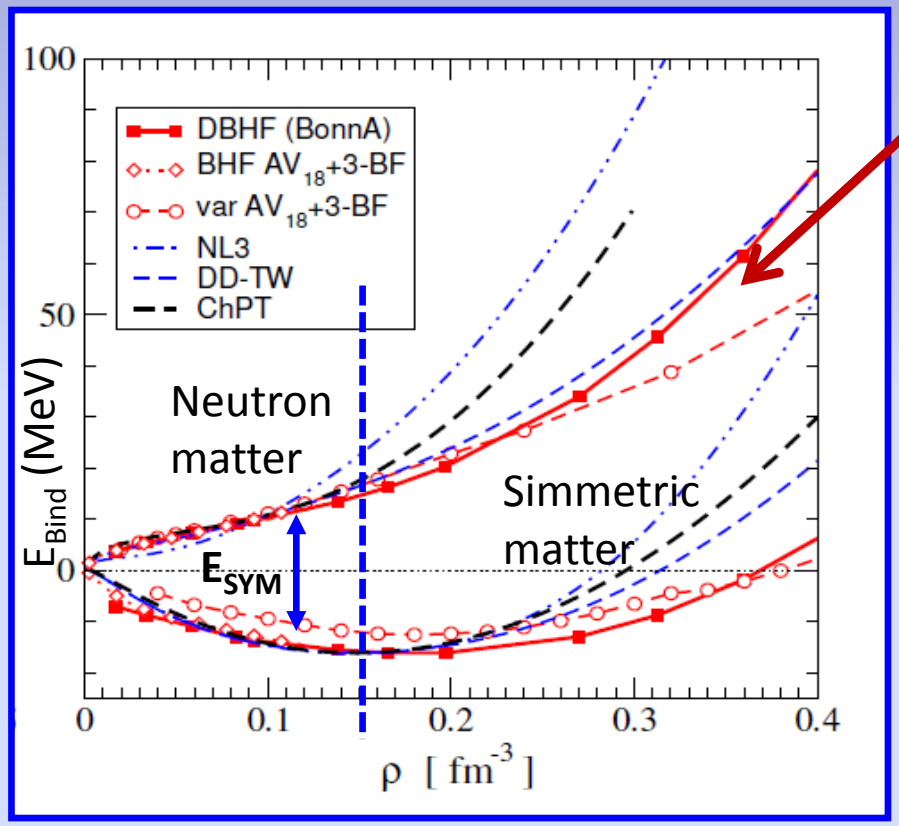
Particle emissions from the early phase of the dynamical evolution (**few fm/c**) up to later stages of statistical decay (**several hundreds of fm/c**) have been measured and are expected to coexist in the reaction products.

The key problem: the symmetry energy as a function of the barionic density

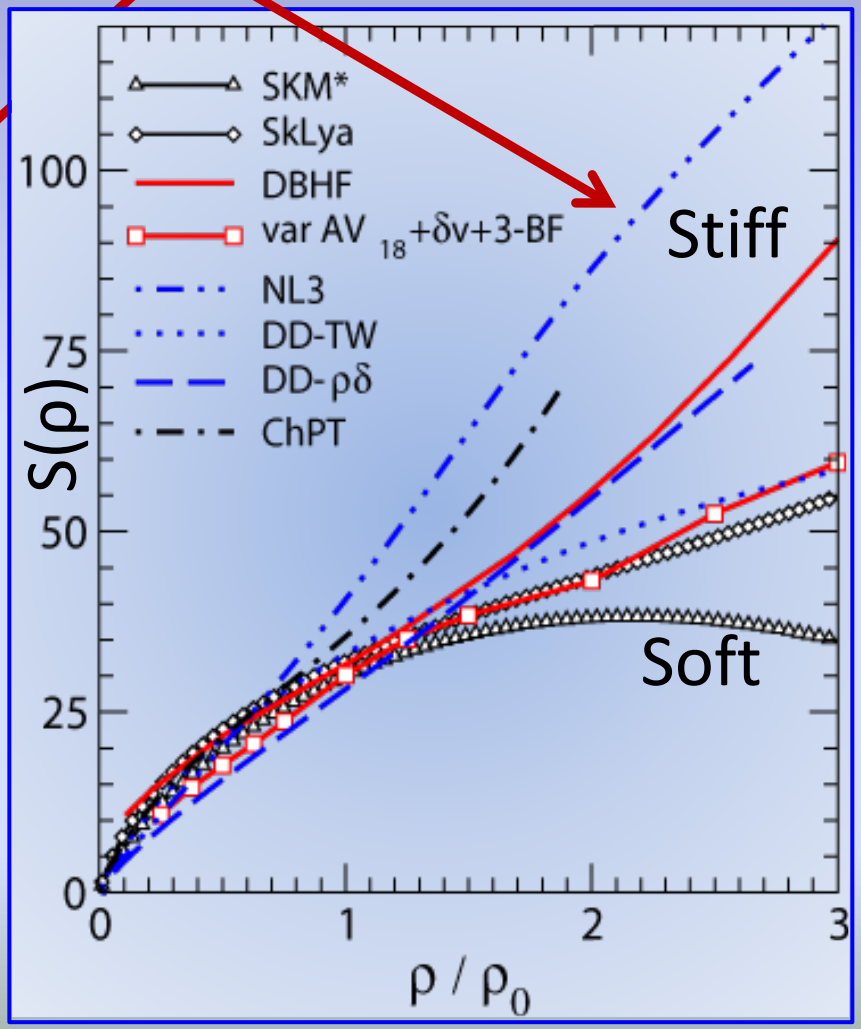
$$E(\rho,\delta) = E(\rho,\delta=0) + S(\rho)\delta^2$$

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

Large deviations at high densities

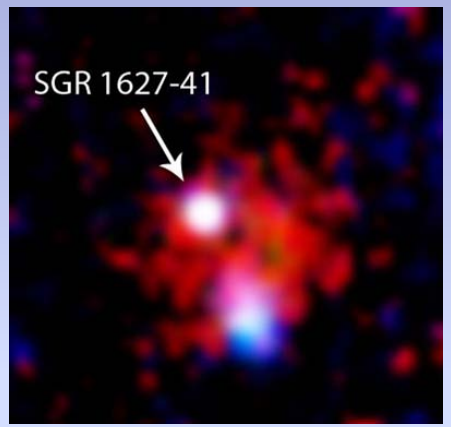


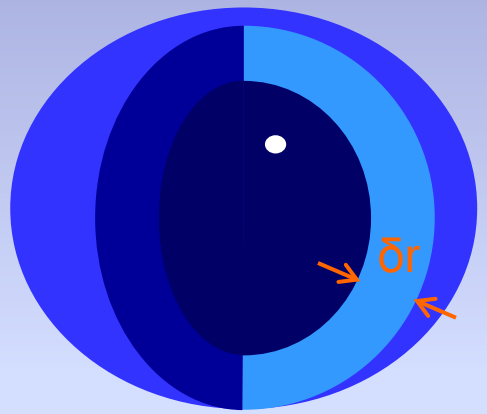
Fuchs and Wolter, EPJA 30, 5 (2006)



→See M. Cozma talk on friday

The key problem: the symmetry energy as a function of the barionic density





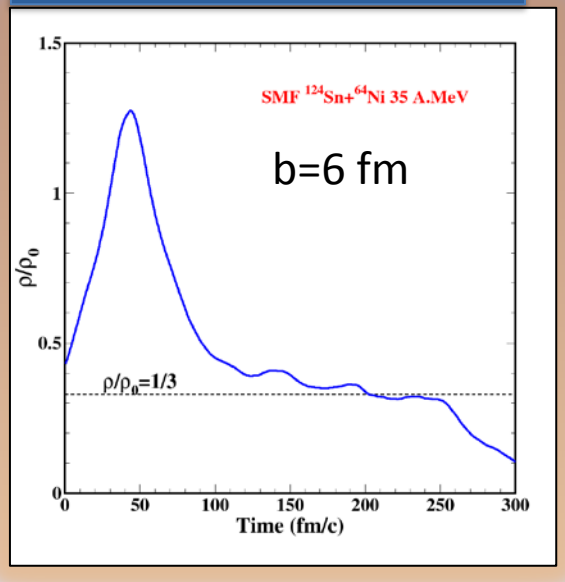
Neutron star
$\approx 10^{4}$ m

Neutron skin in ^{208}Pb
$\approx 10^{-15}$ m

→See M. Cozma talk on friday

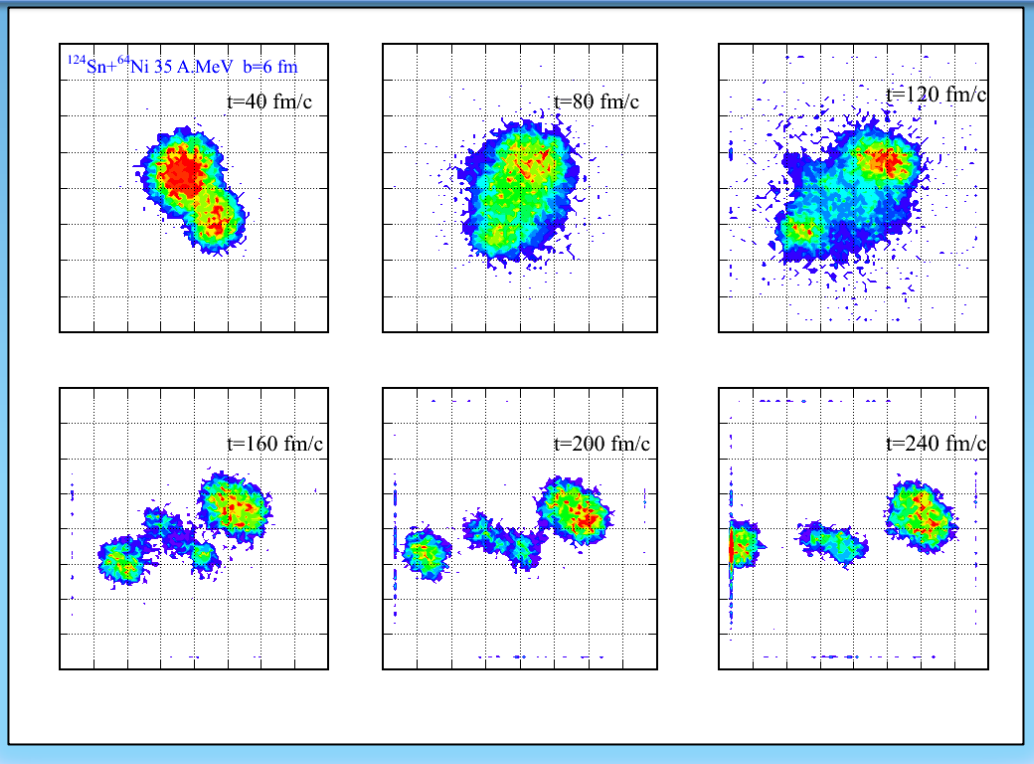
A Physical case: Neck fragmentation mechanism

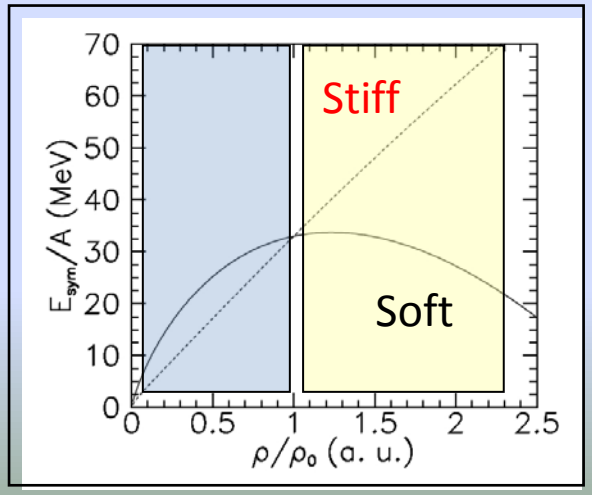
SMF $^{124}Sn+^{64}Ni$ 35 A.MeV



Time evolution of density

Time evolution of the density in the reaction plane in a ternary event at 6 fm. Density profile is shown at every 40 fm/c. Stochastic Mean Field (SMF) calculations





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

$$S(\rho) = S_0 + \frac{L}{3}\left(\frac{\rho-\rho_0}{\rho_0}\right) + \frac{K_{sym}}{18}\left(\frac{\rho-\rho_0}{\rho_0}\right)^2 + \ldots.$$

A Physical case: Neck fragmentation mechanism

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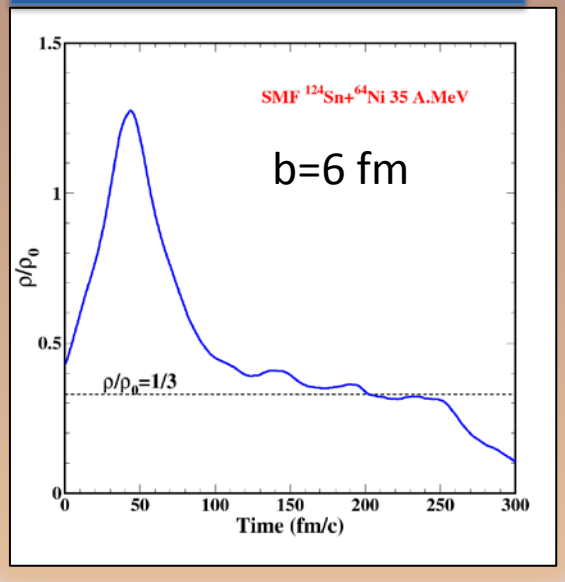

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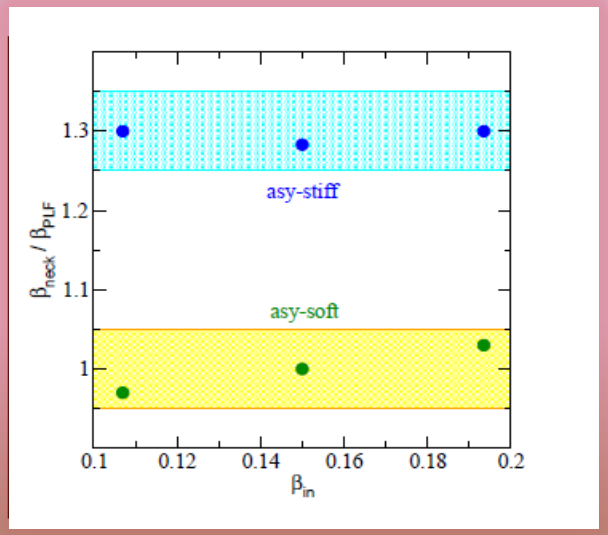
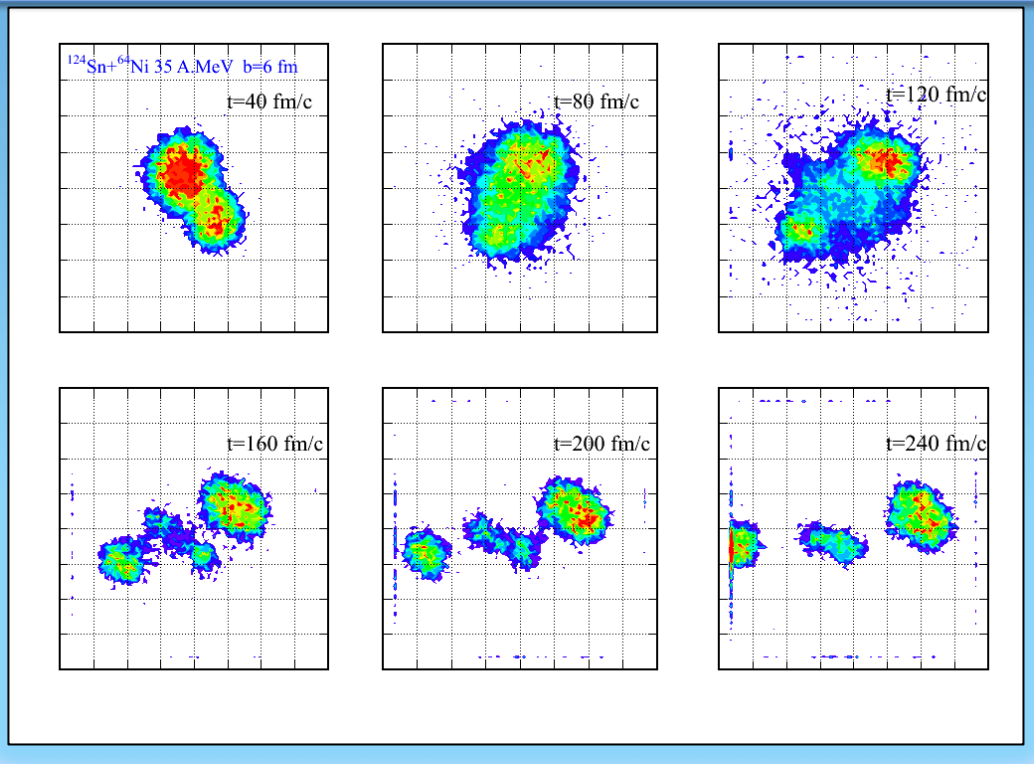


Time evolution of the density in the reaction plane in a ternary event at 6 fm. Density profile is shown at every 40 fm/c. Stochastic Mean Field (SMF) calculations



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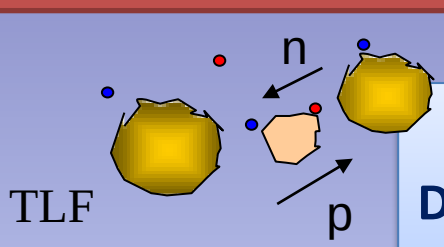
M. Colonna et al., J. Phys. CS, 413, 012018 (2013)

Isospin transport through the “neck”

V. Baran et al., PRC 72 064620 (2005)



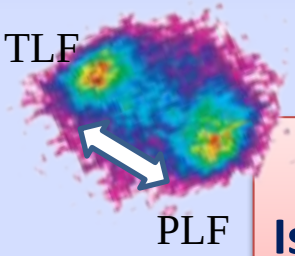
Isospin drift:

Density gradient

Depending on slope of the symmetry energy

Migration of neutrons in low density region

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



Isospin diffusion:

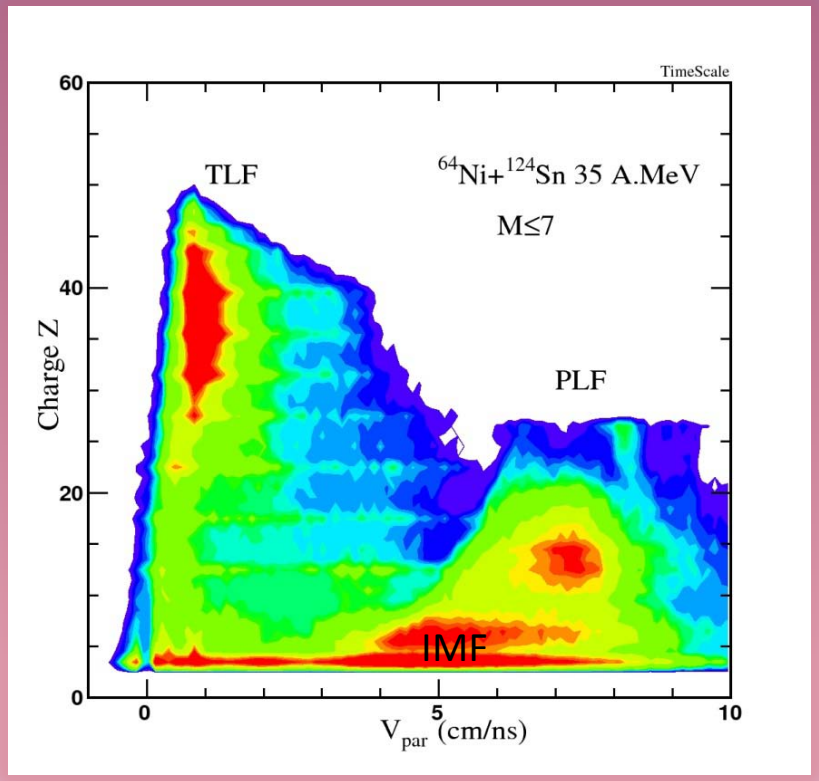
Isospin gradient (N/Z asymmetry in the initial system)

Depending on absolute value of the symmetry energy

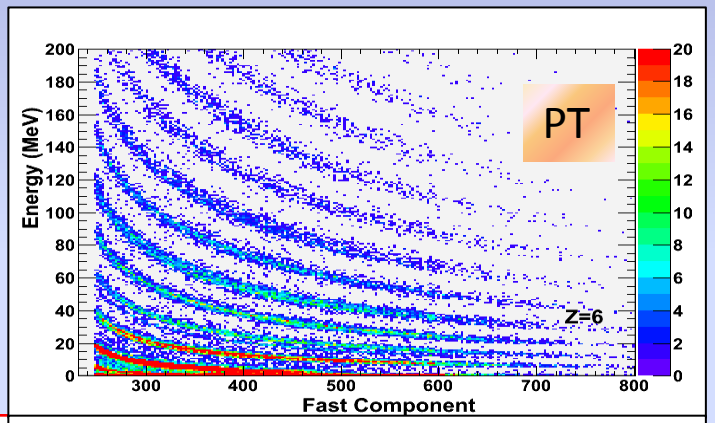
Isospin equilibration between projectile and target

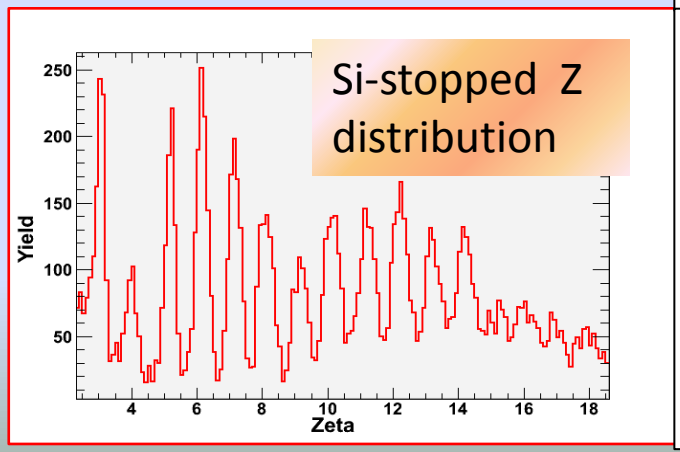
See M.B. Tsang talk on Friday

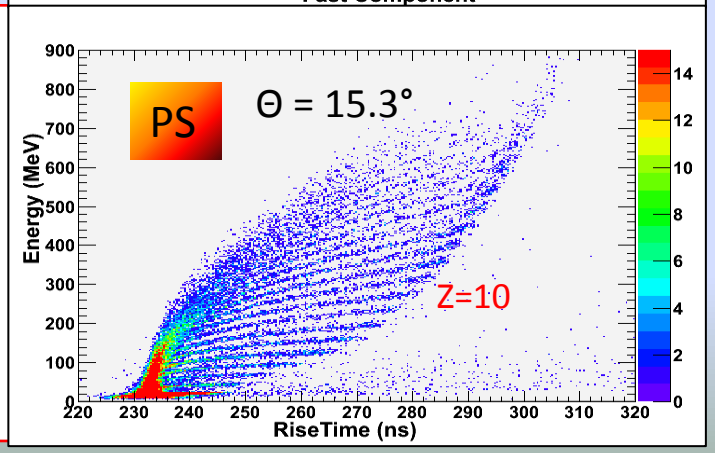
TimeScale experiment: 35 A.MeV ^{64}Ni + ^{124}Sn and ^{58}Ni + ^{112}Sn in direct kinematics

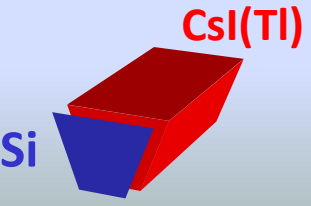


Almost complete events:
p/p_{tot}> 60%
Z/Z_{tot}> 60%
M_{tot}≤7









Correlation between Isospin Dynamics and emission Time-scale

- Disentangling dynamic and statistical emission: space-time characterization and correlations.

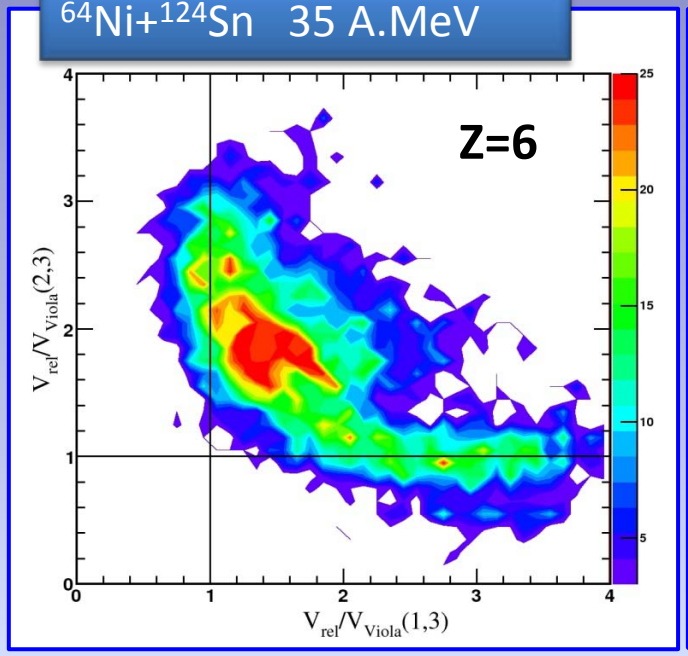
- Study of isotopic composition of fragments: isospin migration, neutron enrichment.

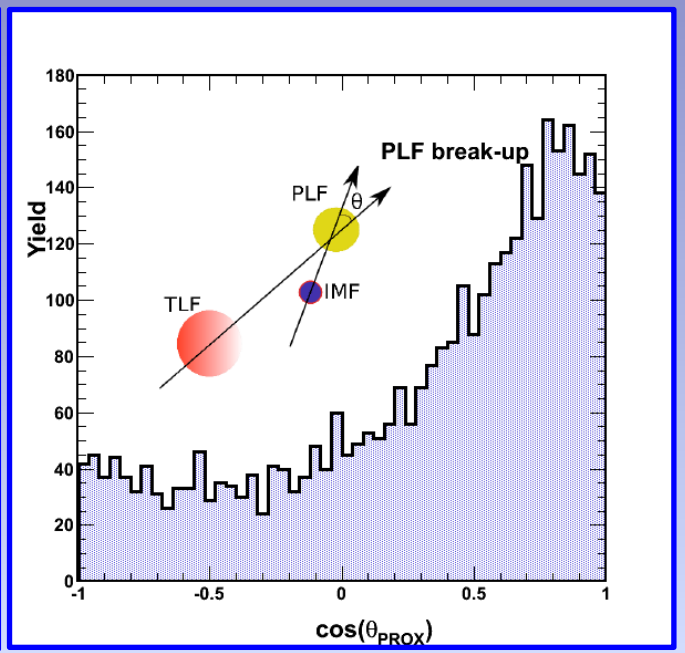
- Calculations: probing the density dependency of the symmetry energy using these new observables

Disentangling dynamical vs. statistical emission in ternary events

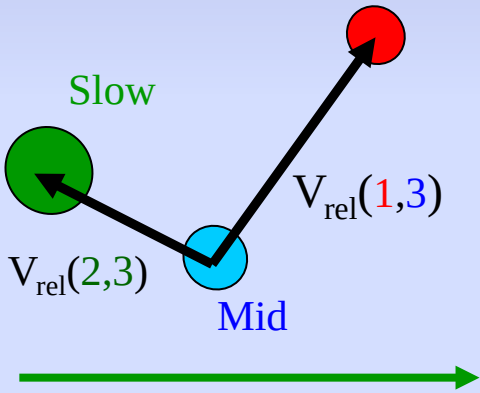
preliminary

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





cos(θ)≈±1
aligned emission of the lighter fragment in the backward emisphere of **PLF** (+1) and **TLF** (-1) towards midrapidity

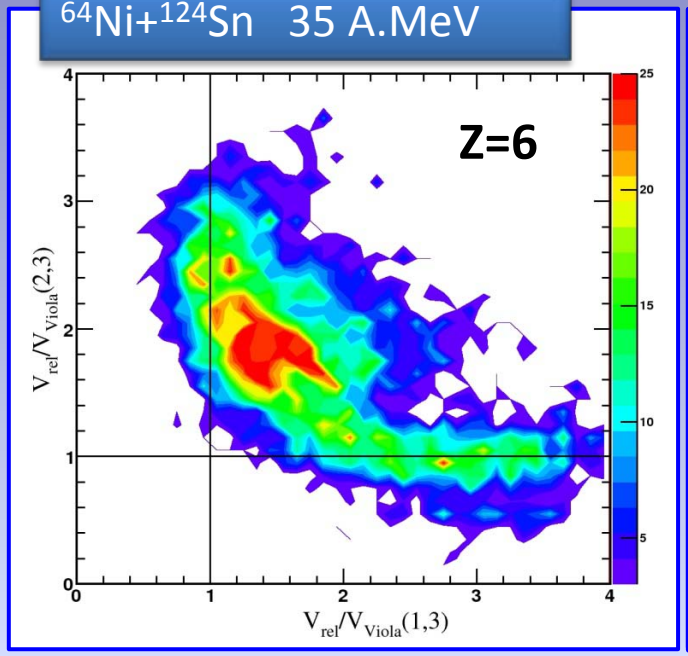


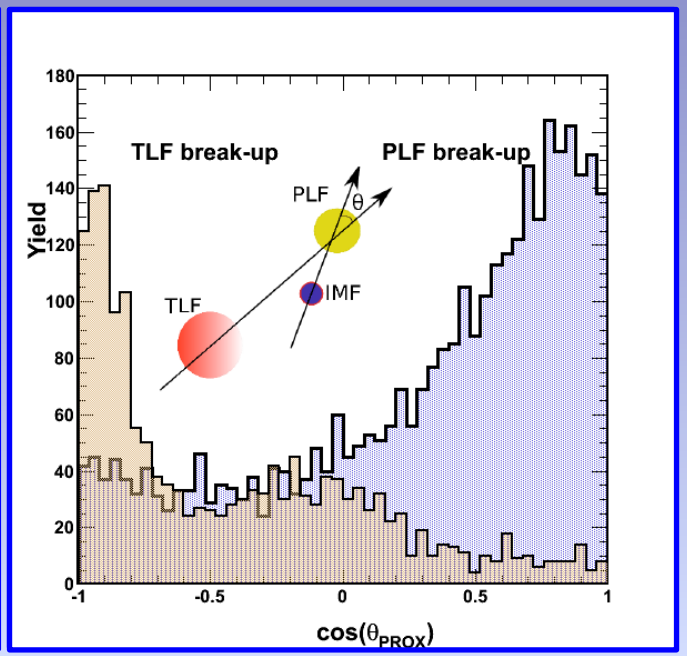
The three heaviest fragments are ordered according to decreasing value of parallel velocity.

Disentangling dynamical vs. statistical emission in ternary events

preliminary

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





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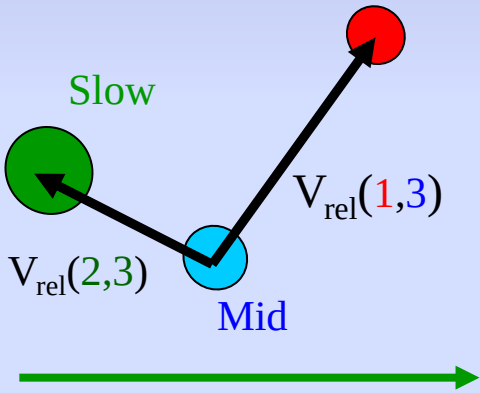

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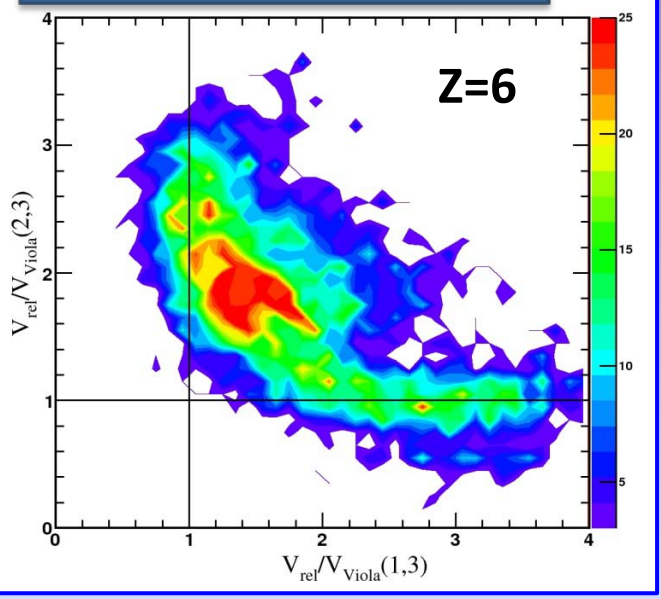
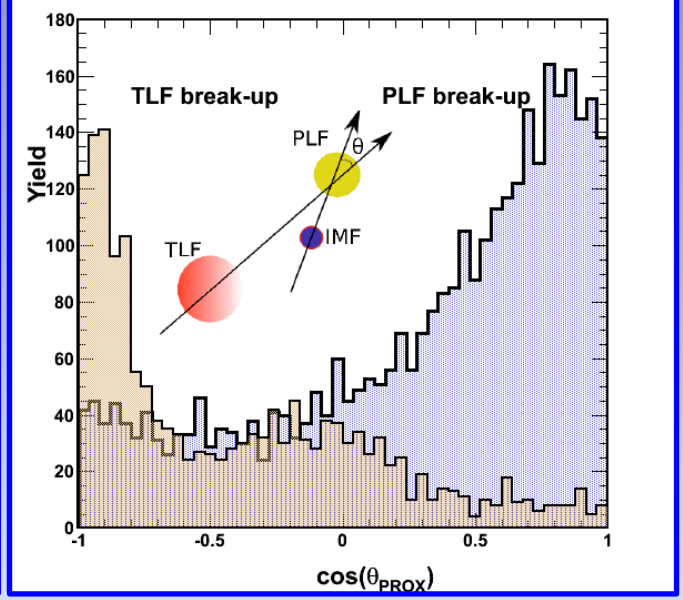
Disentangling dynamical vs. statistical emission in ternary events

preliminary

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





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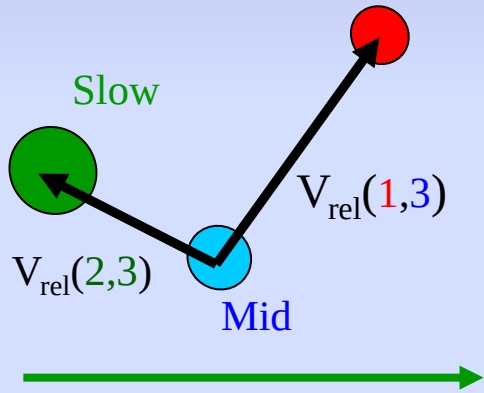
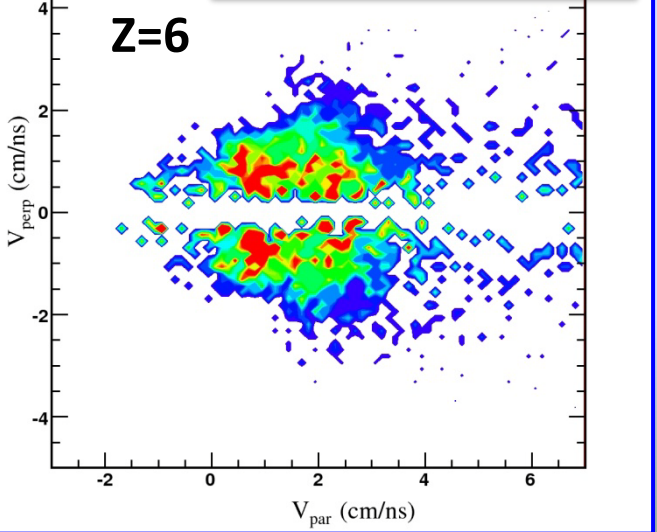
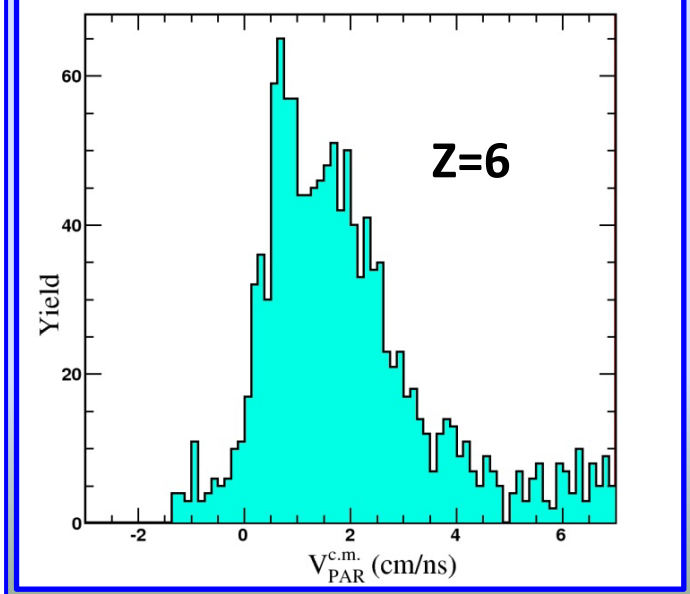


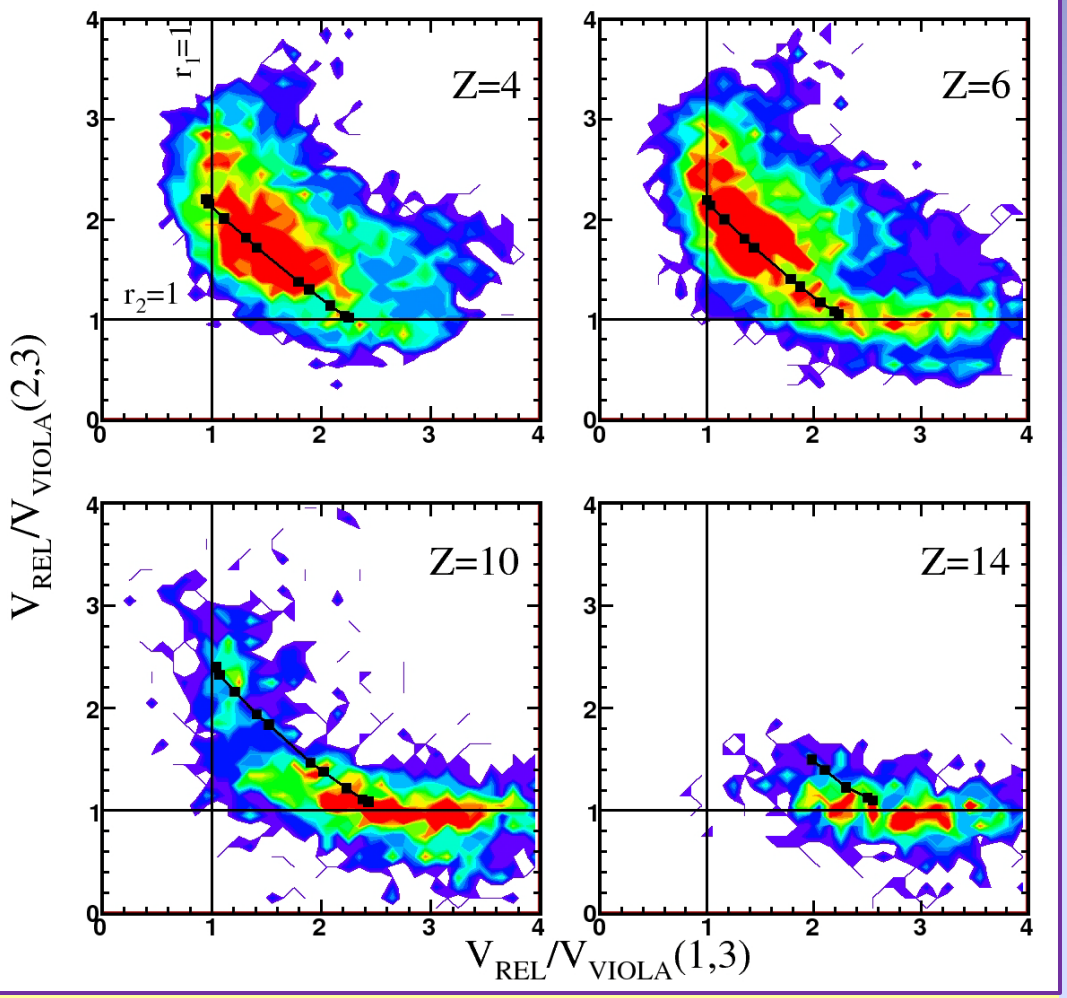
abs(cos(θ_{PROX})>0.8



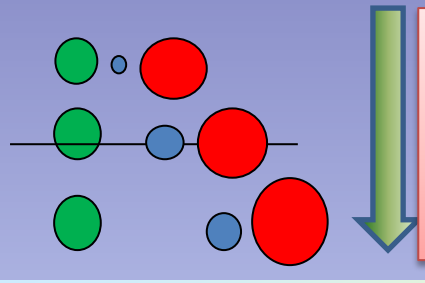


The three heaviest fragments are ordered according to decreasing value of parallel velocity.

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

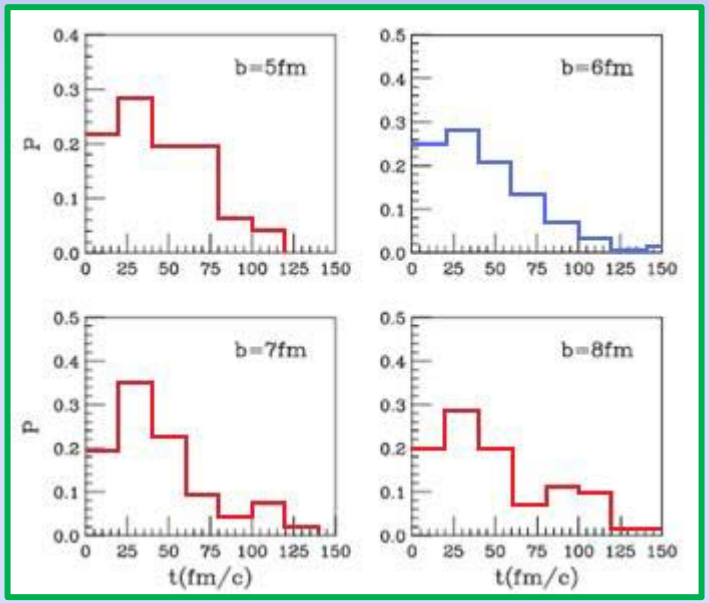


Relative velocities are expressed in units of the velocity corresponding to the Coulomb repulsion energy of a given subsystem according to the Viola systematics.



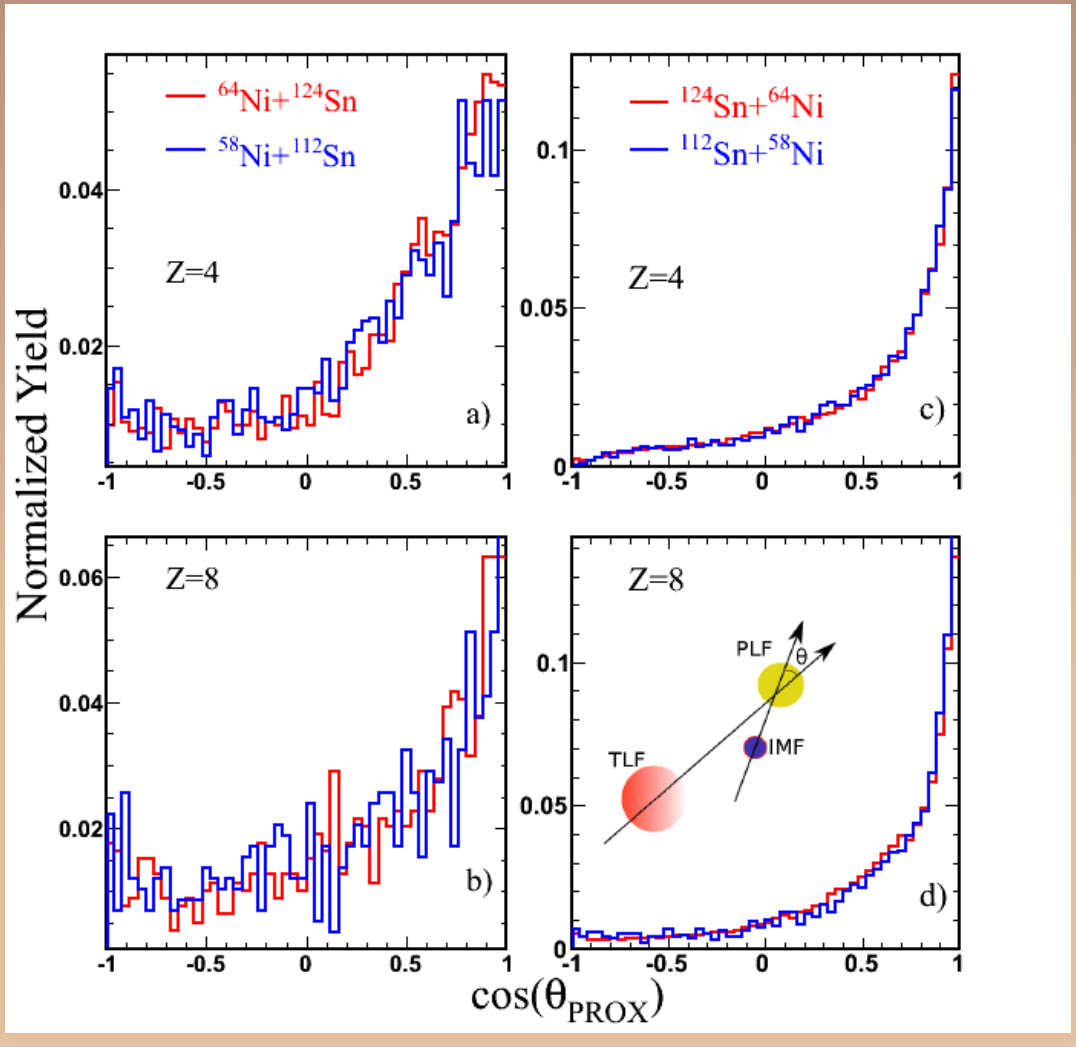
30 fm/c
.....
80 fm/c
120 fm/c

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

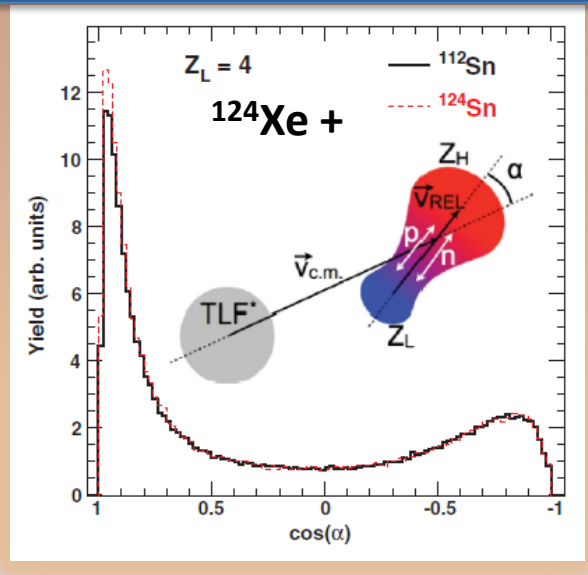


SMF: $^{124}Sn + ^{64}Ni$ probability of scission-to-scission time in neck fragmentation. *V. Baran et al. Phys. Rep 410, 335 (2005)*

Angular distributions: PLF break-up in **direct** (left) and **reverse** (right) kinematics



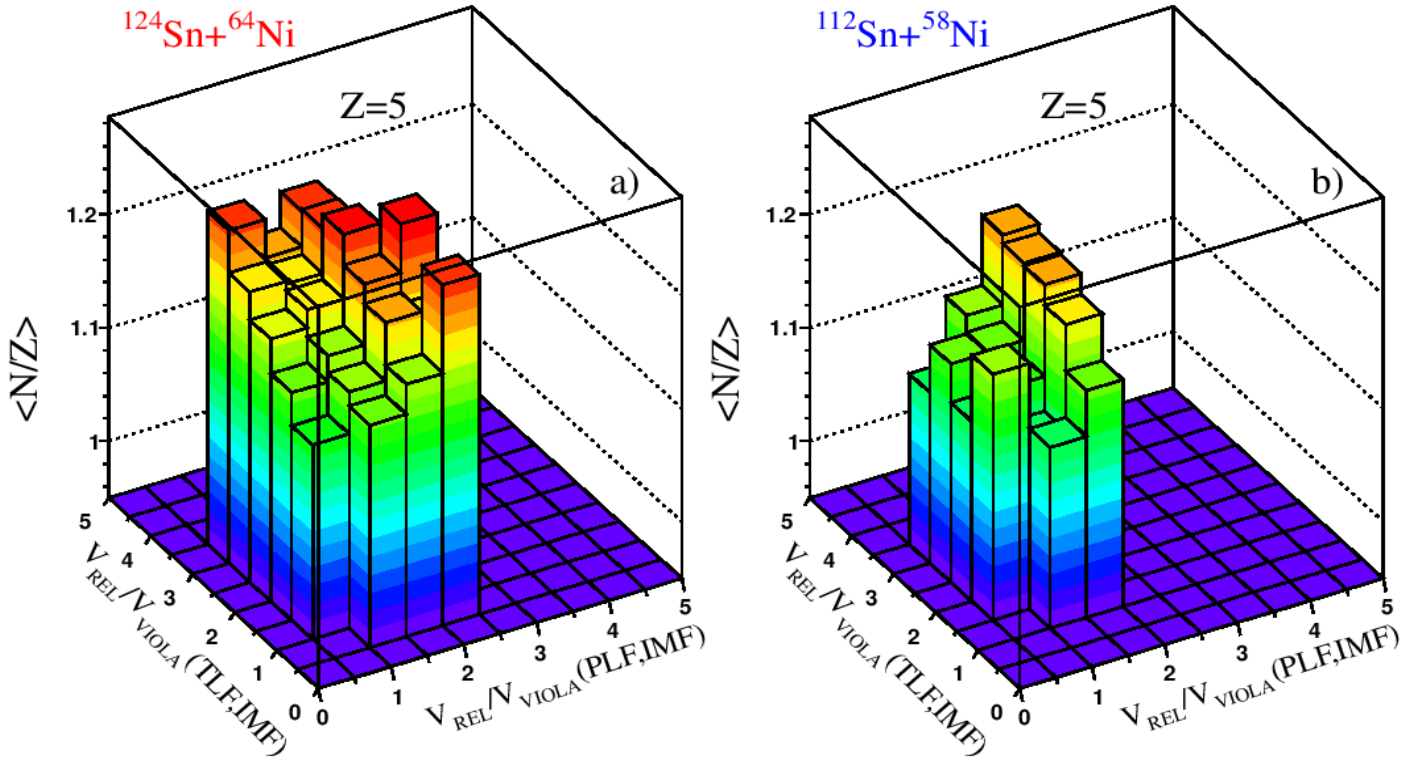
Enhancement of backward fragment yield relative to the forward component



S. Hudan et al., PRC **86** 021603(R)

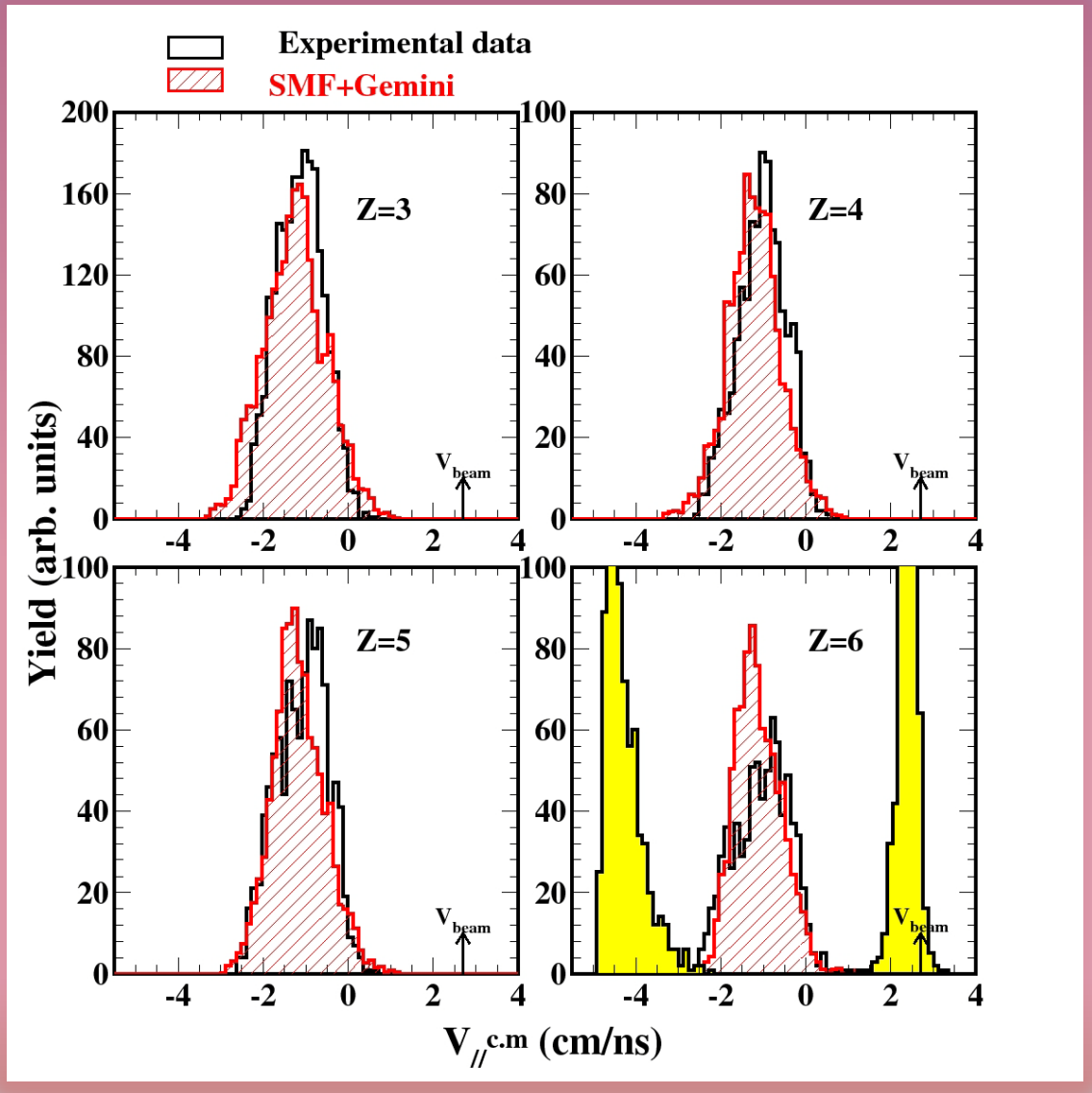
See E.d.F. et al, NN2012 Conference Proceedings, S. Antonio (Texas, USA), May 27-June 1 2012 Jour. Phys. CS 420 (2013).

Correlations between <N/Z> for Z=5 and relative velocities in the r1-r2 plane for a neutron rich and a neutron poor system



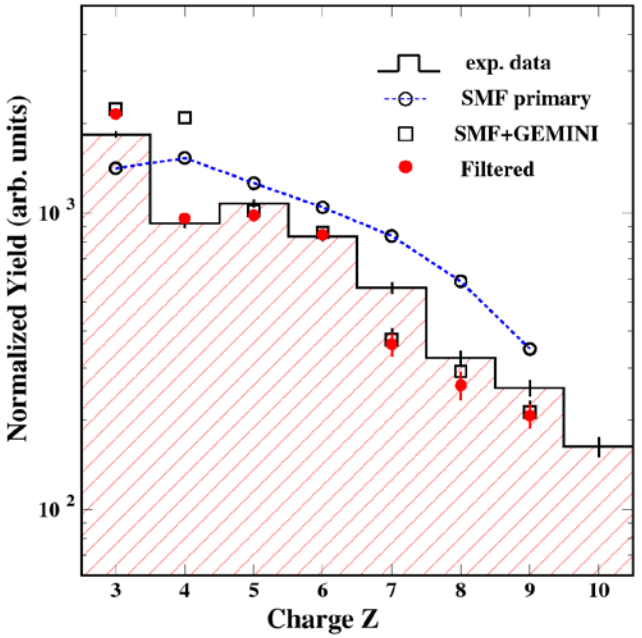
Correlating isospin and kinematical observables: a powerful constraint for transport theories

Stochastic Mean Field (SMF) + GEMINI: IMFs $V_{//}$ spectra



Calculated distributions are filtered by detectors acceptance, thresholds, time-of-flight experimental resolution.

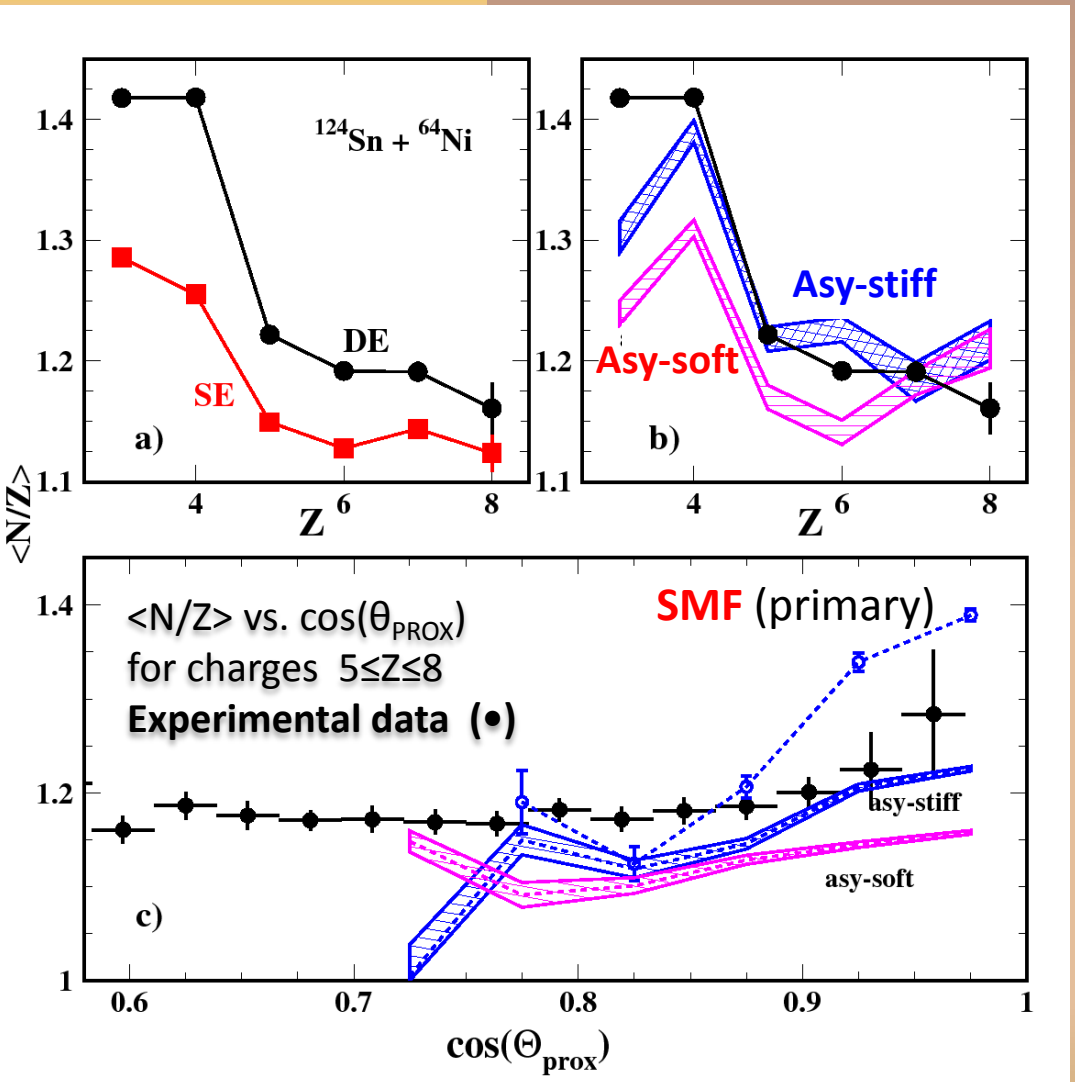
IMFs charge distributions



Phys. Rev. C ***86*** *014610 (2012)*

Stochastic Mean Field (SMF) + GEMINI calculation

^{124}Sn+^{64}Ni 35 A.MeV



Phys. Rev. C ***86*** *014610 (2012)*

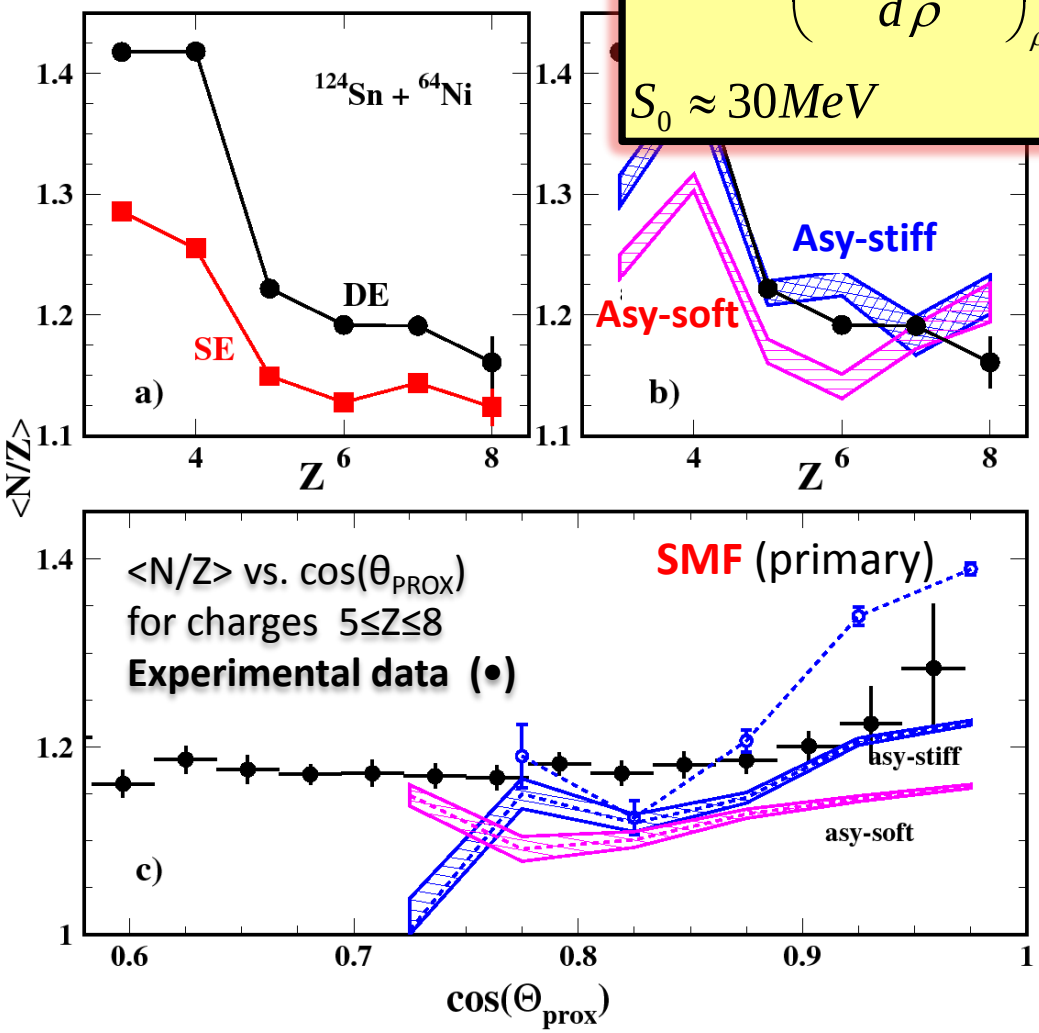
Experimental <N/Z> distribution of IMFs as a function of their atomic number compared with results SMF+GEMINI calculations (hatchad area) for two different parametrizations of the symmetry potential (asy-soft and asy-stiff)

- Dynamically emitted particles
- Statistically emitted particles

See also: S. Hudan et al., PRC **86** 021603(R).
K. Brown et al., arXiv:1305.1320 (2013)

Stochastic Mean Field (SMF) + GEMINI calculation

^{124}Sn+^{64}Ni 35 A.MeV



$$L = 3\rho_0 \left(\frac{dE_{sym}(\rho)}{d\rho} \right)_{\rho=\rho_0} = \begin{cases} \approx 80\pm10 \text{ MeV for the asy-stiff} \\ \approx 25 \text{ MeV for the asy-soft} \end{cases}$$

$$S_0 \approx 30 MeV$$

results SMF+GEMINI calculations (hatchad area) for two different parametrizations of the symmetry potential (asy-soft and asy-stiff)

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Phys. Rev. C ***86*** *014610 (2012)*

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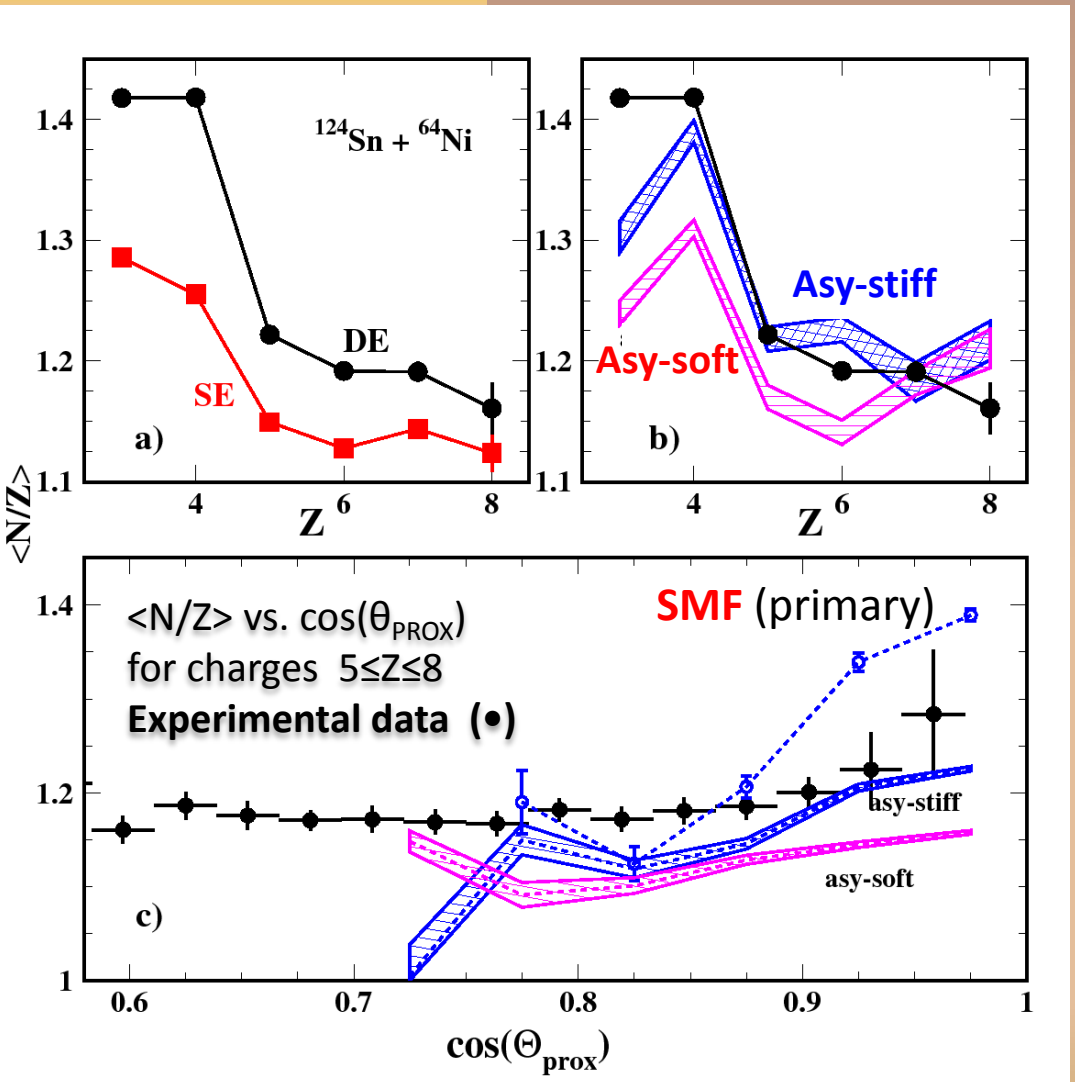

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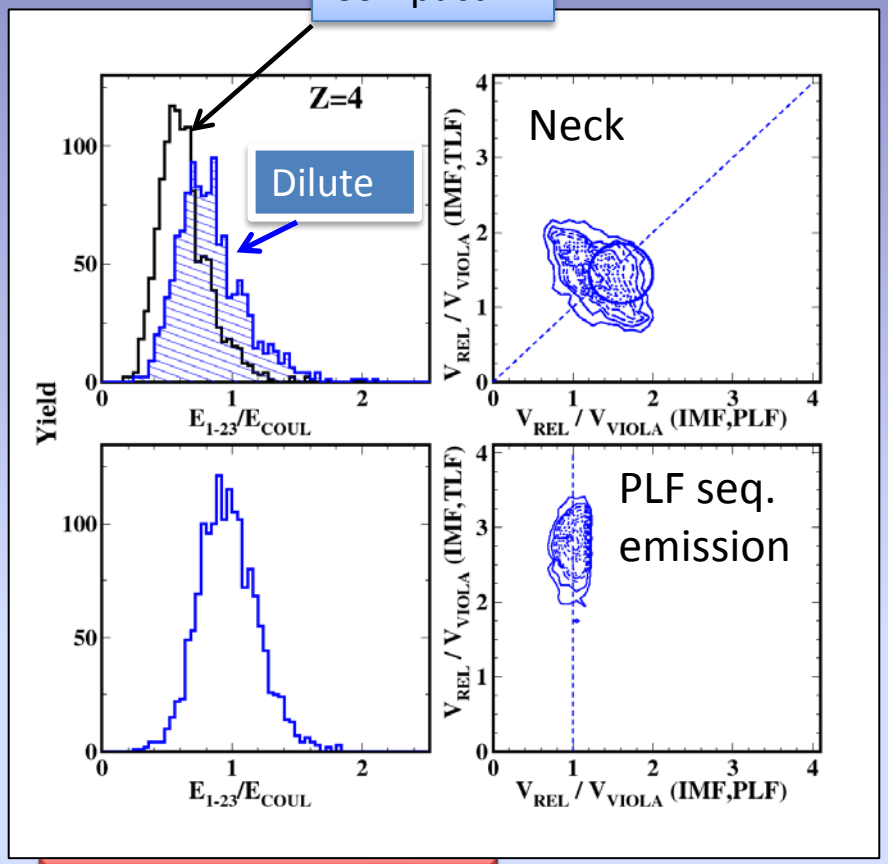
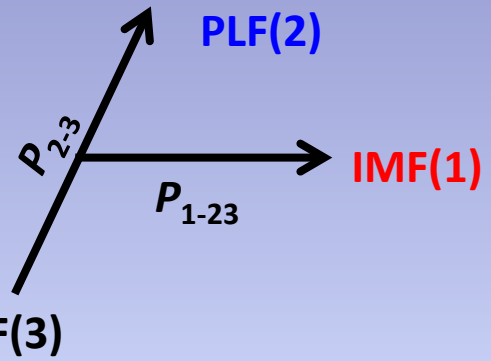
Density determination: three body analysis in the experimental data

Preliminary



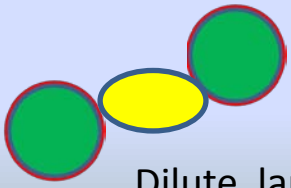
^{124}Sn+^{64}Ni 35 A.MeV

In the 3-bodies center-of-mass system:

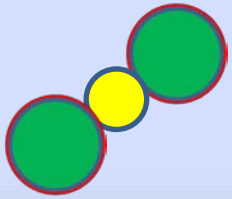


$$E_{TOT}^{c.m.} = E_1 + E_2 + E_3 = \frac{p_{1-23}^2}{\mu_{1-23}} + \frac{p_{23}^2}{\mu_{23}} = E_{1-23} + E_{23}$$

The ratio $E_{1\text{-}23}/E_{COULOMB}$ is calculated considering for the IMFs a dilute configuration with $r_0=1.8A^{1/3}$ fm (filled histogram corresponding to about 0.05 ρ_0) resulting from average values of SMF calculation (ρ=0.05-0.06 1/fm^3)



Dilute, large radius



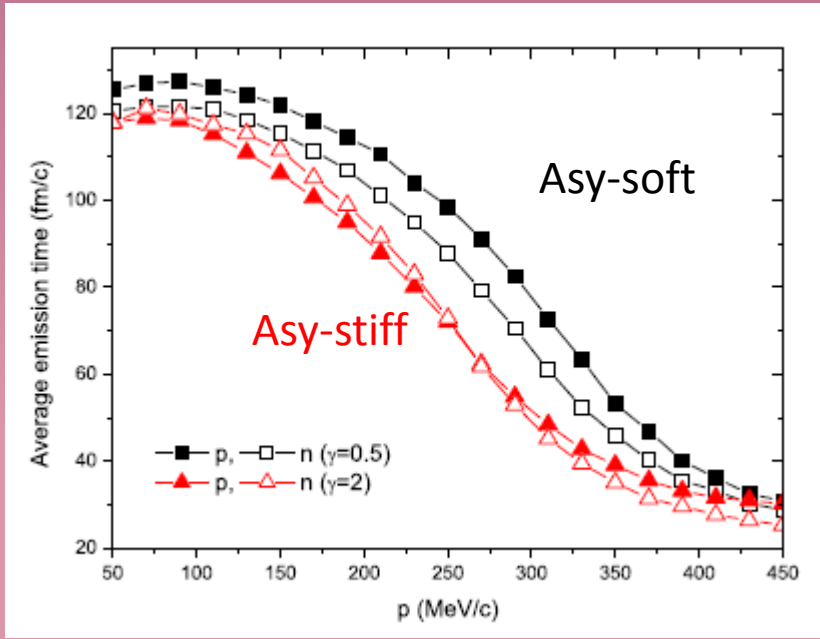
Compact, normal radius

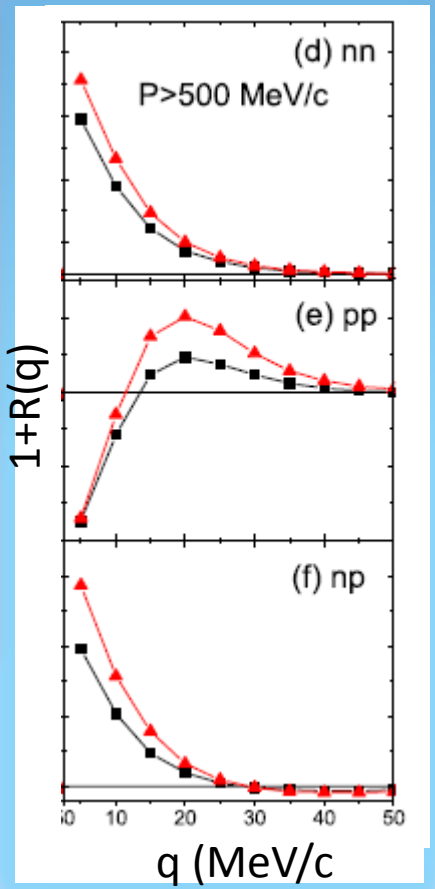
INPC Firenze 2013 proceedings: to be published

Particle-particle correlations and symmetry energy: a difficult task

IBUU simulations
$^{52}Ca + {}^{48}Ca$ E/A=80 MeV, Central collisions
L.W. Chen, V. Greco , C. Ko, B-An Li, PRC68, 014605(2003)

$$1 + R(q) = k \cdot \frac{\Sigma Y_{coinc}(\vec{p}_1, \vec{p}_2)}{\Sigma Y_{evt.mixing}(\vec{p}_1, \vec{p}_2)}$$





Shorter neutron and proton average emission times and more similar n and p emission times with Esym - stiff

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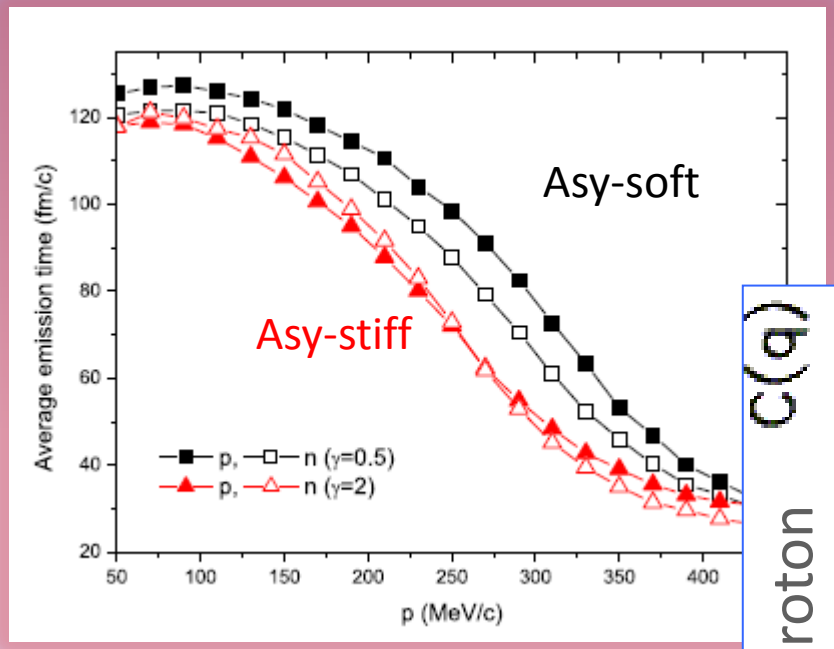

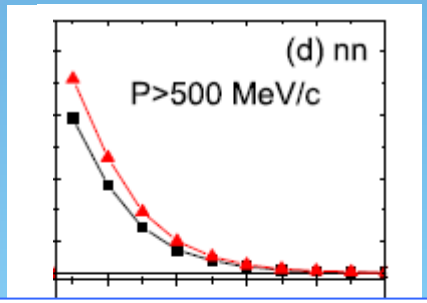

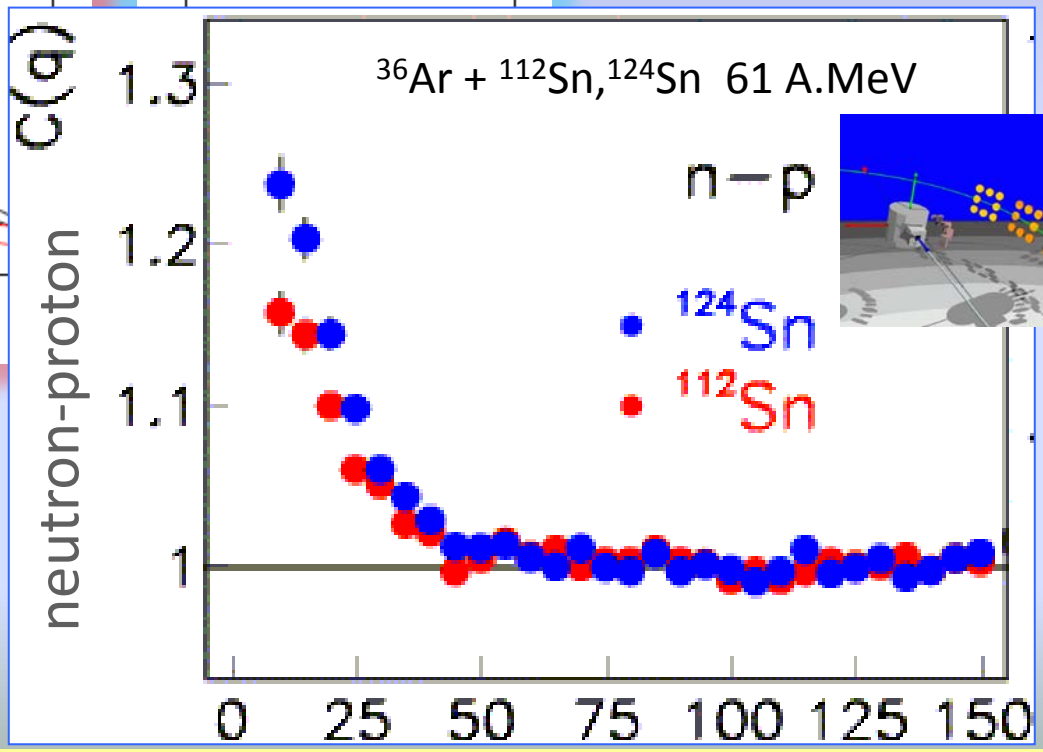

Shorter neutron and proton average emission times and more similar n and p emission times with Esym - stiff

R. Ghetti et al., PRC 69 031605 (2004) CHIC collaboration

Particle-particle correlations and symmetry energy: a difficult task

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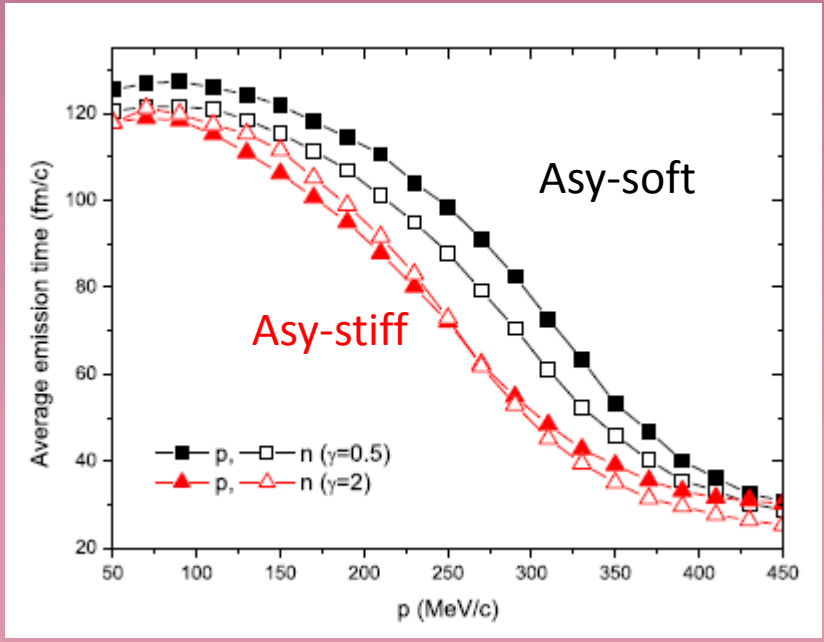

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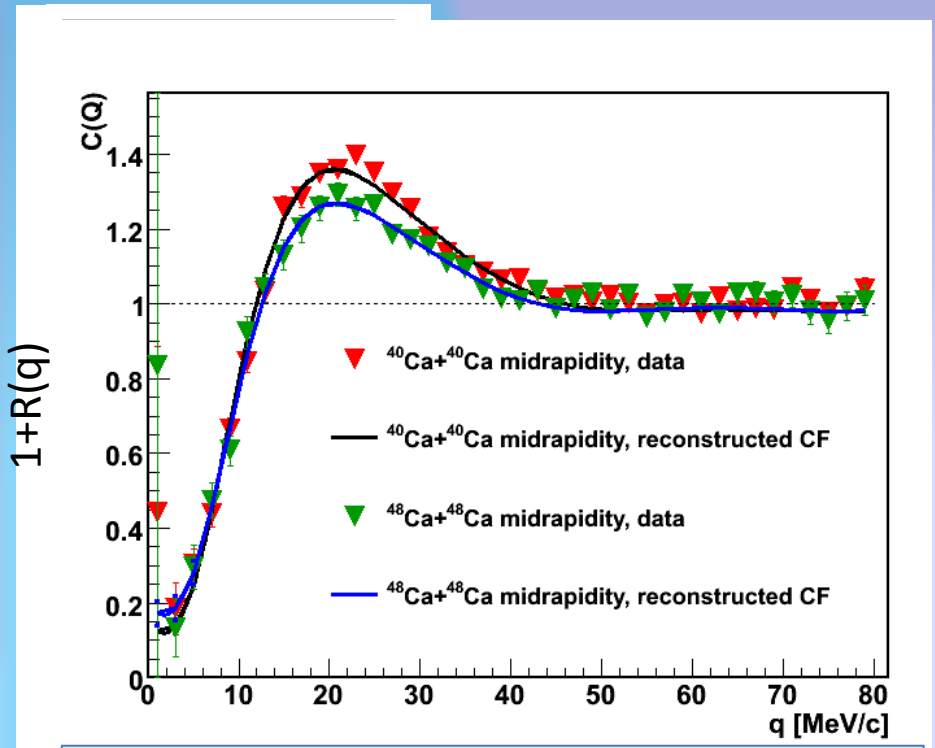
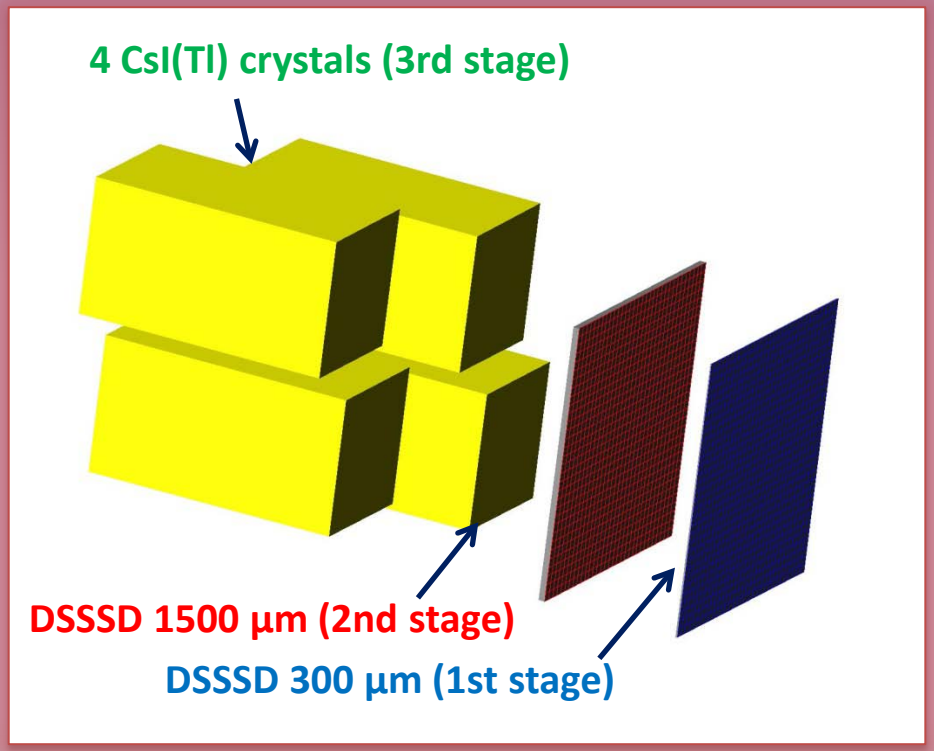


See Henzl et al., PRC85 014606 (2012)
Larger source size for more n-rich systems: Asy-EOS, size effect… ?

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

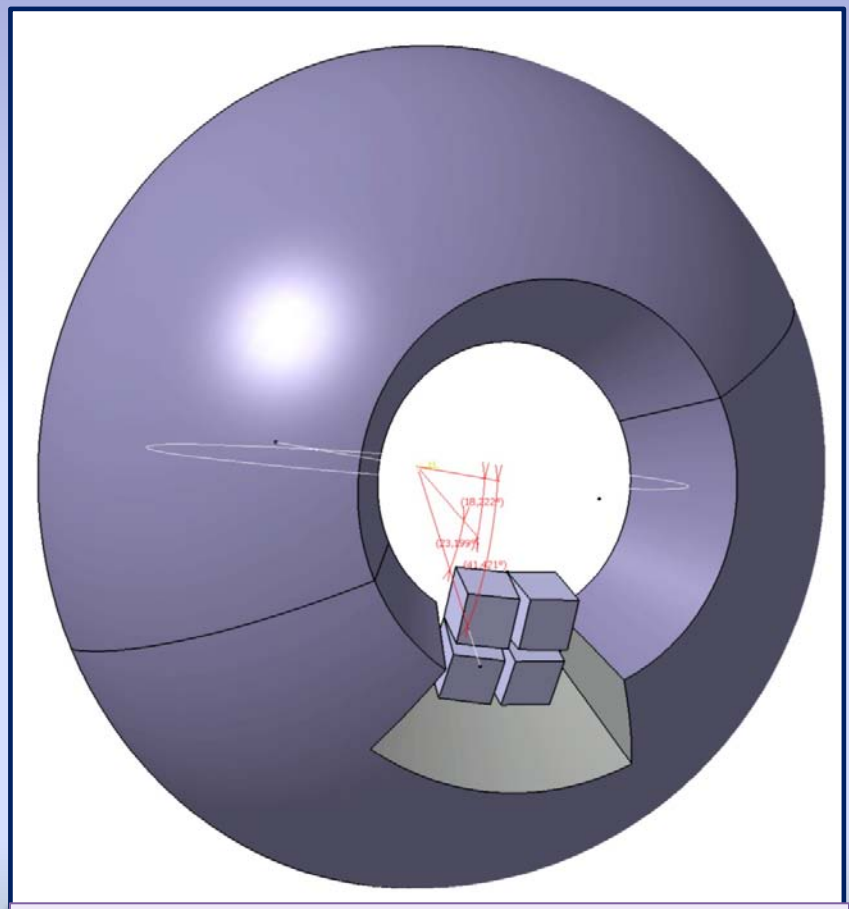
FARCOS: Femtoscope Array for COrrelations and Spectroscopy (INFN, Ganil, Huelva . . .)

- **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**



132 channels by each cluster

See T. Minniti talk (Wednesday)



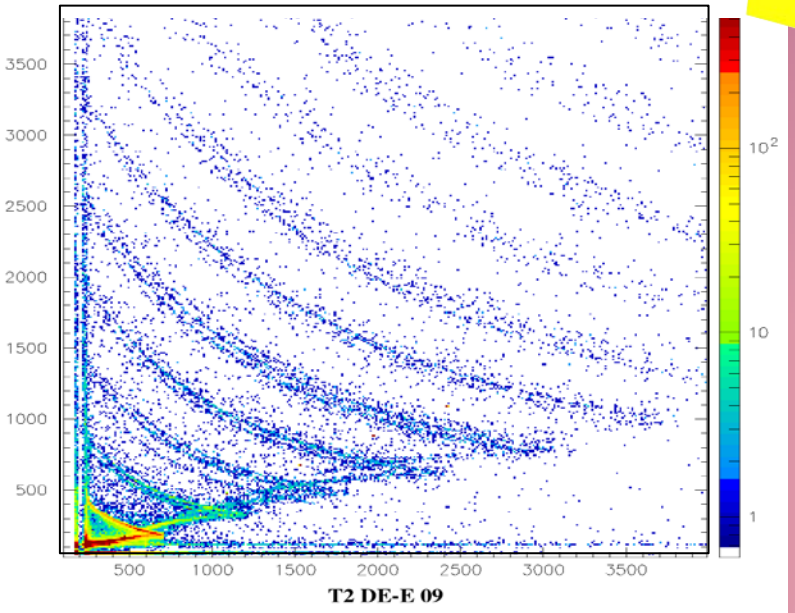
4 telescopes 25 cm from the target

θ_{lab} ~ 16-44 deg, $\Delta\phi$ ~ 45 deg

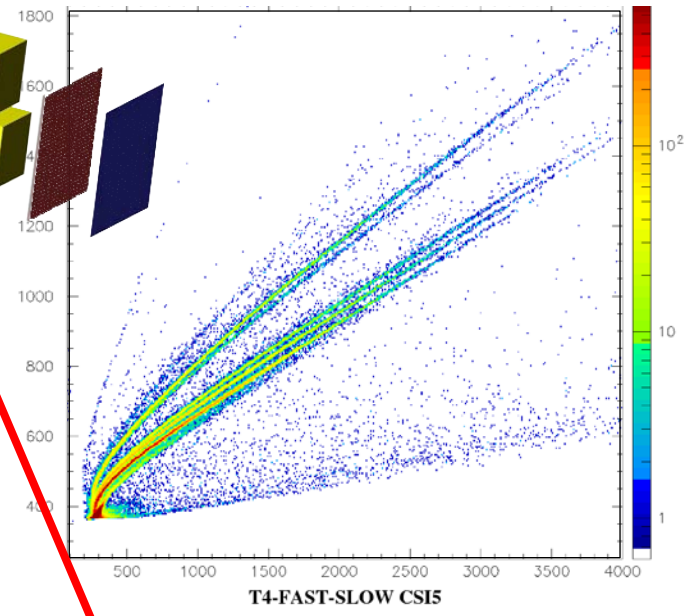
The INKIISSY (INverse KInematics ISobaric SYstems) $^{124}Xe + {}^{64}Zn$ (April 2013)

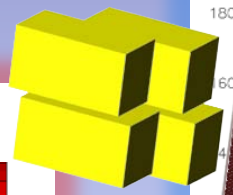
Study of Mass vs Isospin effects with the $^{124}Xe+^{64}Zn$ and $^{124}Sn+^{64}Ni$ reactions

DE-E (300-1500 µm) T2 Farcos



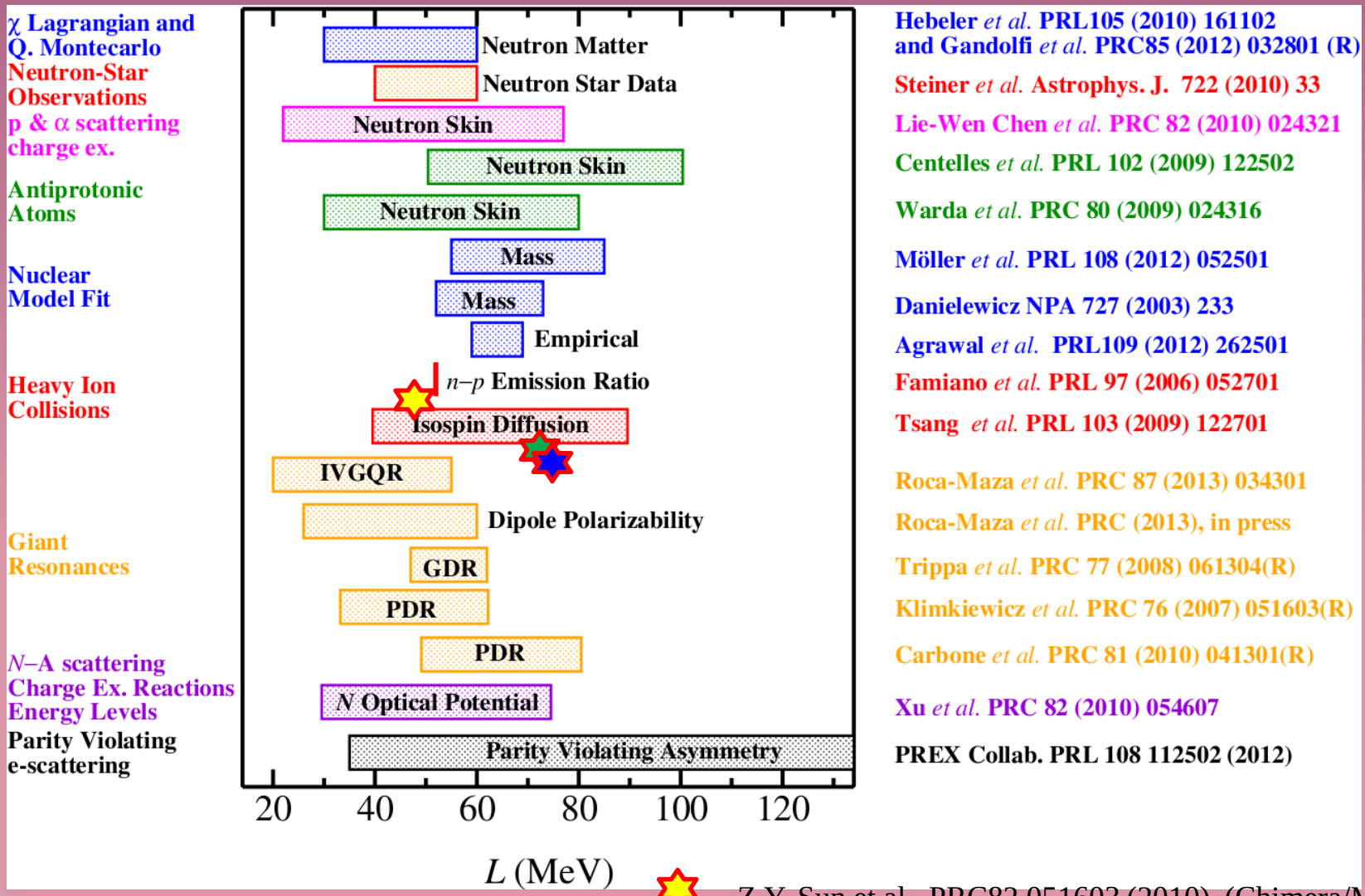
FAST-SLOW T4 Farcos





LNS 2013 experiment: particular of the CHIMERA sphere and of the compact Farcos modules.

Collection of available estimates of the slope parameter L

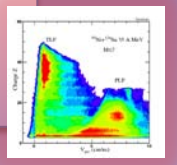


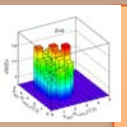
Adapted from X. Vinas et al., arXiv:1308.1008 (2013)

Z.Y. Sun et al., PRC82 051603 (2010) (Chimera/MSU data)
E. Galichet et al. PRC 79 064615 (2009) (INDRA data)
E.d.F. et al. PRC 86 014610 (2012) (Chimera data)

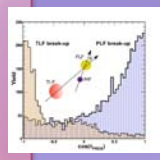
SUMMARY

We have studied with the 4π detector **CHIMERA** the two reactions ^{64,58}**Ni+**^{124,112}**Sn** and ^{124,112}**Sn +** ^{64,58}**Ni** at the same energy of relative motion (35 A.MeV)

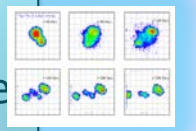


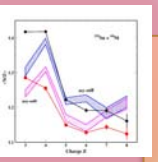


We have introduced a method to disentangle sequential from dynamically emitted particles at midrapidity and we have correlated the isotopic composition of Intermediate mass fragments with their emission timescale. Dynamically emitted IMF shows larger values of <N/Z> isospin asymmetry and stronger angular anysotropies supporting the concept of "*isospin migration*" in neck fragmentation mechanism.

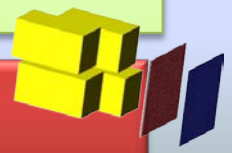


A phenomenological estimation of the density in ternary neck events show that, as stated by transport model calculations, neck fragments are formed in presence of a density gradient





We compared the data to a Stochastic Mean Field (SMF) simulation obtaining valuable constraints on the symmetry energy term of nuclear EOS at subsaturation densities. A stiff $E_{SYM}(\rho)$ behaviour with L≈80, corresponding to a linear density dependence, better reproduces the data.



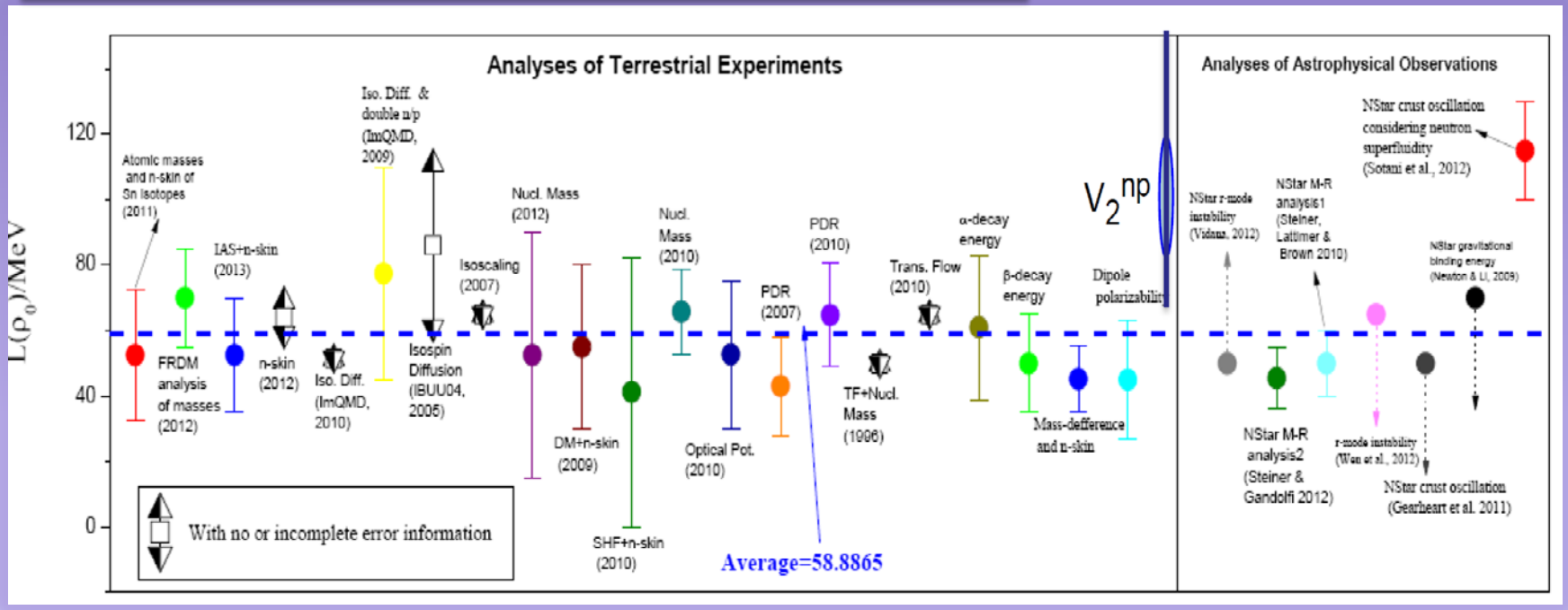
The Chimera+Farcos prototype: an array for the study of particle correlations with high angular and energy resolution coupled with 4π detectors

This is a collective work of CHIMERA and EXOCHIM collaborations.

In particular all people of TIMESCALE , TIMESCALEZn and INKIISSY experiments listed below :

L. Acosta, C. Agodi, F. Amorini, L. Auditore, V. Baran, I. Berceanu, M. Buscemi, T. Cap, G. Cardella, M. Colonna, E. De Filippo, M. Di Toro, L. Francalanza, E. Geraci, S. Gianì, L. Grassi, A. Grzeszczuk, P. Guazzoni, J. Han, E. La Guidara, G. Lanzalone, I. Lombardo, C. Maiolino, T. Minniti, A. Pagano, E.V. Pagano, M. Papa, E. Piasecki, R. Planeta, S. Pirrone, G. Politi, A. Pop, F. Porto, L. Quattrocchi, F. Rizzo, E. Rosato, P. Russotto, S. Santoro, K. Siwek-Wilczynska, I. Skwira, A. Trifirò, M. Trimarchi, G. Verde, M. Vigilante, J. Wilczyński, L. Zetta.

Image from Bao-An Li (NuSymm 2013)



Nuclear Symmetry energy: Topical issue of EPJA

EPJA Editor : prof. Angels Ramos

Bao-An Li, I. G. Verde, I. Vidana (guests editors)