# SYMMETRY ENERGY FROM NUCLEAR REACTIONS DYNAMICS

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NuSYM10, RIKEN,Wako,JAPAN

## I. INTRODUCTION

- isospin dynamics in nuclear fragmentation
- dynamical effects in nuclear fragmentation

## II. TRANSITION FROM MULTIFRAGMENTATION TO NECK FRAGMENTATION

- hierarchy in transverse velocity distributions
- relation to IMF's isospin structure

## III. DYNAMICAL DIPOLE MODE IN FUSION WITH EXOTIC NUCLEI

- Isovector collective response in entrance channel
- Gamma yield and angular distributions

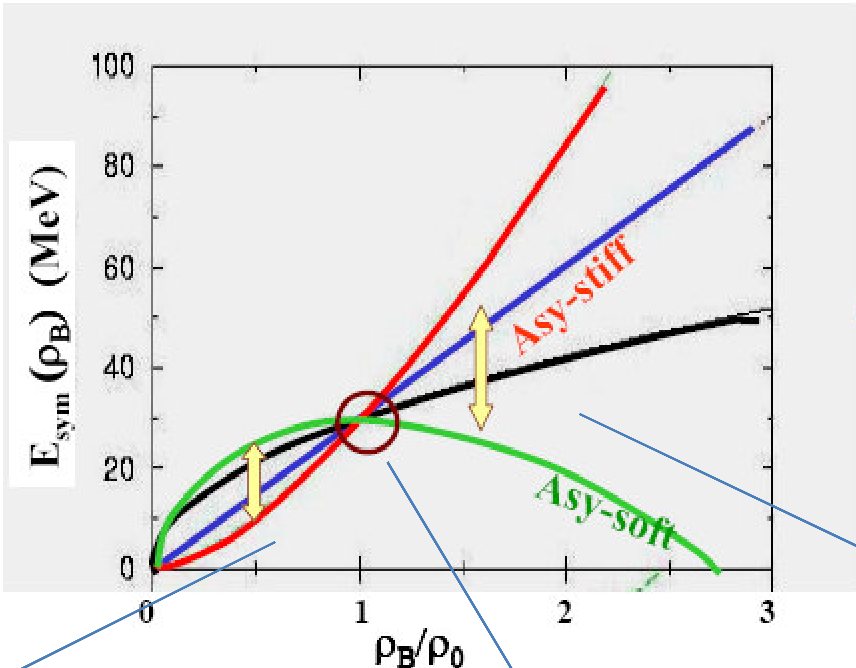
## IV. CONCLUSION

# ASY-EOS studies with Radioactive Beams: The Elusive Symmetry Energy

$$E(\rho_B, I) = E(\rho_B) + E_{sym}(\rho_B) I^2 + O(I^4) + \ldots$$

$$I = \frac{\rho_n - \rho_p}{\rho_n + \rho_p} \equiv \frac{\rho_3}{\rho_B}$$

$$E_{sym} = \frac{1}{2} \frac{\partial^2 E}{\partial I^2}\Big|_{I=0}$$




**AWAY FROM SATURATION:**
**HEAVY ION DYNAMICS**

**High density (intermediate energies)**
Isospin effects on:
-fragment production in central collisions
-"squeeze-out" nucleons and clusters
-meson production

**Low density (Fermi energies)**
Isospin effects in:
Nuclear multifragmentation
Neck fragmentation
Isospin diffusion

**Around saturation density**

$$E_{sym} \cong a_4 + \frac{L}{3}\left(\frac{\rho_B - \rho_0}{\rho_0}\right) + \frac{K_{sym}}{18}\left(\frac{\rho_B - \rho_0}{\rho_0}\right)^2$$

**Symmetry Energy Effects:**
- **isovector giant dipole resonance**
- **pygmy dipole resonance**
- **dynamical dipole mode**

## *I. FROM CENTRAL TO SEMI-CENTRAL COLLISIONS:* **MULTIFRAGMENTATION**

LIQUID-GAS PHASE TRANSITION IN BINARY SYSTEMS:
**ISOSPIN DISTILLATION**

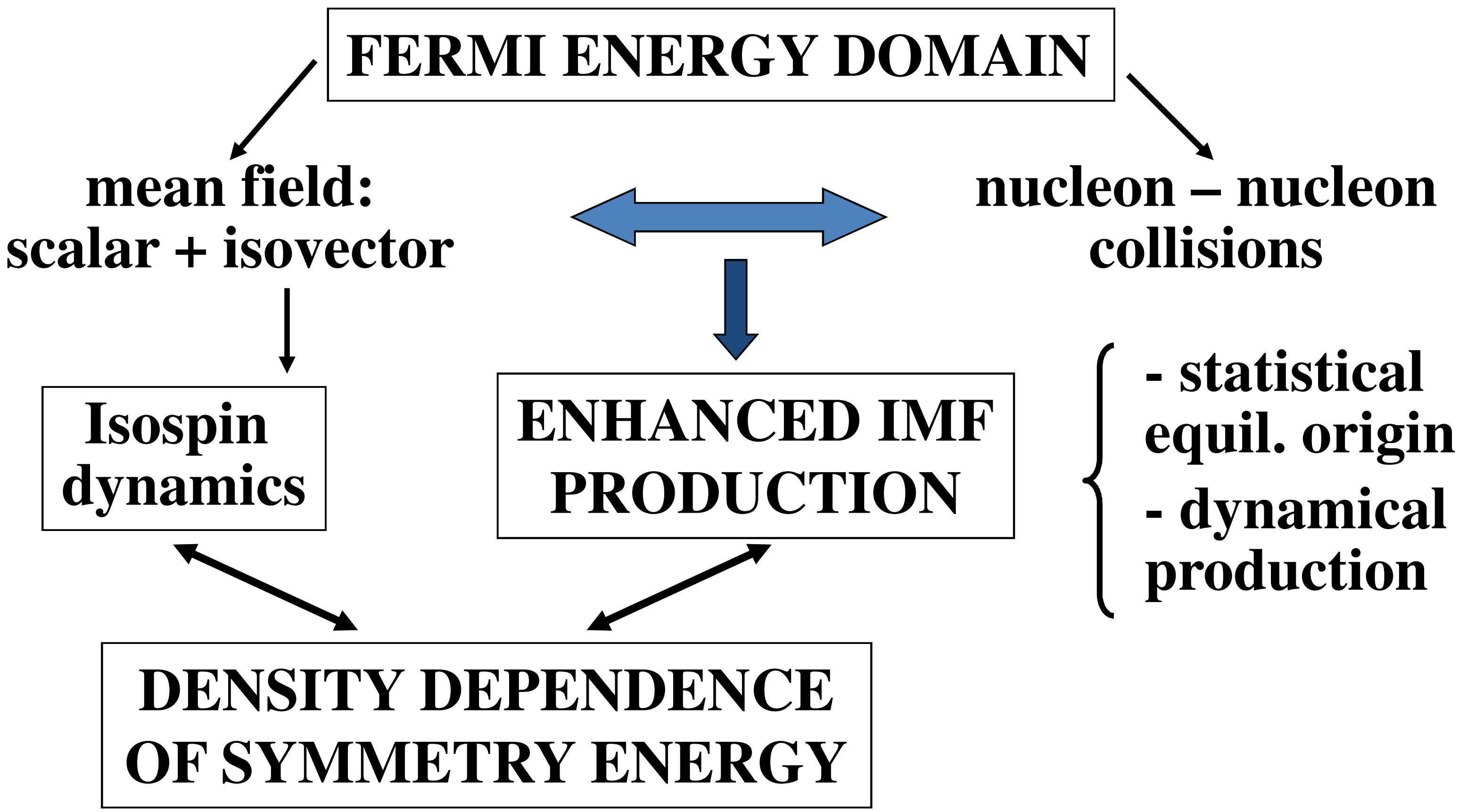
## *II. SEMI-PERIPHERAL COLLISION* **NECK FRAGMENTATION**

LOW DENSITY NECK ZONE:
**ISOSPIN MIGRATION (ENRICHMENT)**

## *III. FROM SEMI-PERIPHERAL TO PERIPHERAL COLLISIONS:* **BINARY REACTIONS**

CHARGE EQUILIBRATION:
**ISOSPIN DIFFUSION**

# ISOSPIN IN NUCLEAR FRAGMENTATION




## STOCHASTIC BNV TRANSPORT MODEL

Asy-EOS {
- asysoft
-asystiff
- superasystiff

# STOCHASTIC MEAN FIELD TRANSPORT EQUATION: VLASOV + NN-COLLISIONS and PAULI CORRELATIONS

Fluctuations

$$\frac{df(r,p,t)}{dt} = \frac{\partial f(r,p,t)}{\partial t} + \{f, h\} = I_{coll}[f] + \delta I_{coll}$$

$$h = \frac{p^2}{2m} + U[f] \qquad w^+(1-f) - w^- f$$

gain loss

**Self-Consistent Mean Field** ⟺ **Equation of State**

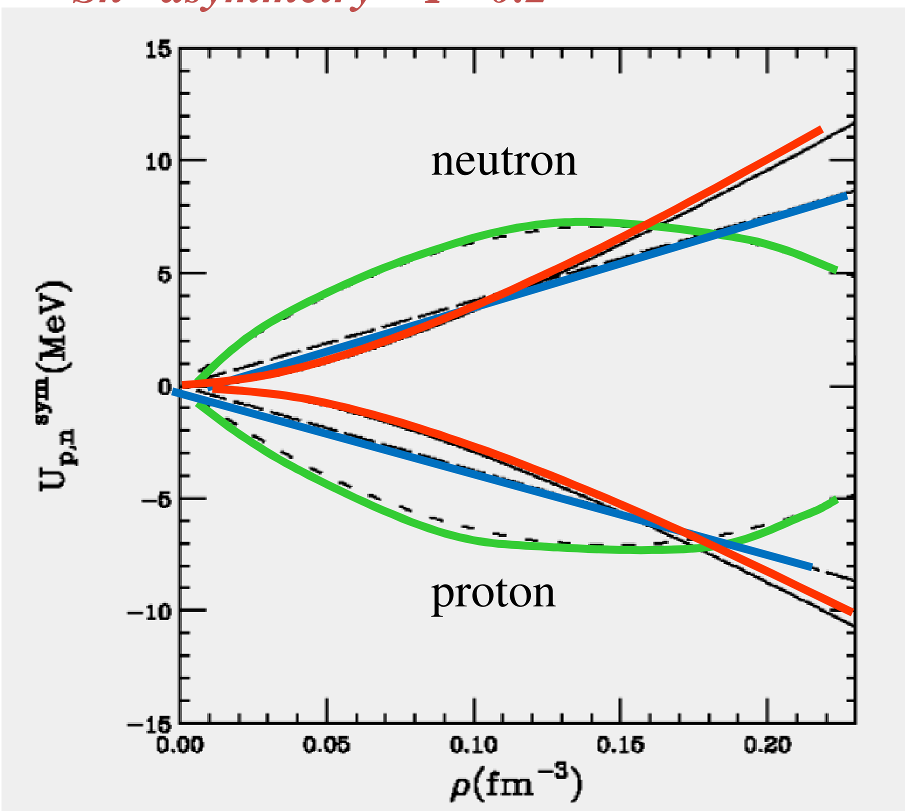
**SMF model** : fluctuations projected onto ordinary space ⟶ **density fluctuations δρ**

**V. Baran, M. Colonna, V. Greco, M. Di Toro**
**Phys.Rep. 410 (2005) 335**

# ISOVECTOR MEAN-FIELD

Density dependence

$^{124}$*Sn "asymmetry" I= 0.2*







$$U_q = \frac{\partial \varepsilon_{pot}(\rho_q, \rho_{q'})}{\partial \rho_q}$$

$$\frac{E_{sym}}{A}(\rho) = \frac{\varepsilon_F}{3} + \frac{C(\rho)}{2}\frac{\rho}{\rho_0}$$

Asysoft

$$\frac{C(\rho)}{\rho_0} = 482 - 1638\,\rho$$

**L=20MeV**

Asystiff

$$\frac{C(\rho)}{\rho_0} = \frac{32}{\rho_0}$$

**L=75MeV**

Asy - superstiff

$$\frac{C(\rho)}{\rho_0} = \frac{32}{\rho_0}\frac{2\rho}{\rho + \rho_0}$$

**L=120MeV**

**CORRELATIONS BETWEEN ISOSPIN AND KINEMATIC OBSERVABLES**
**(Dynamical effects)**

↓

***MORE EXCLUSIVE ANALYSIS***

↓

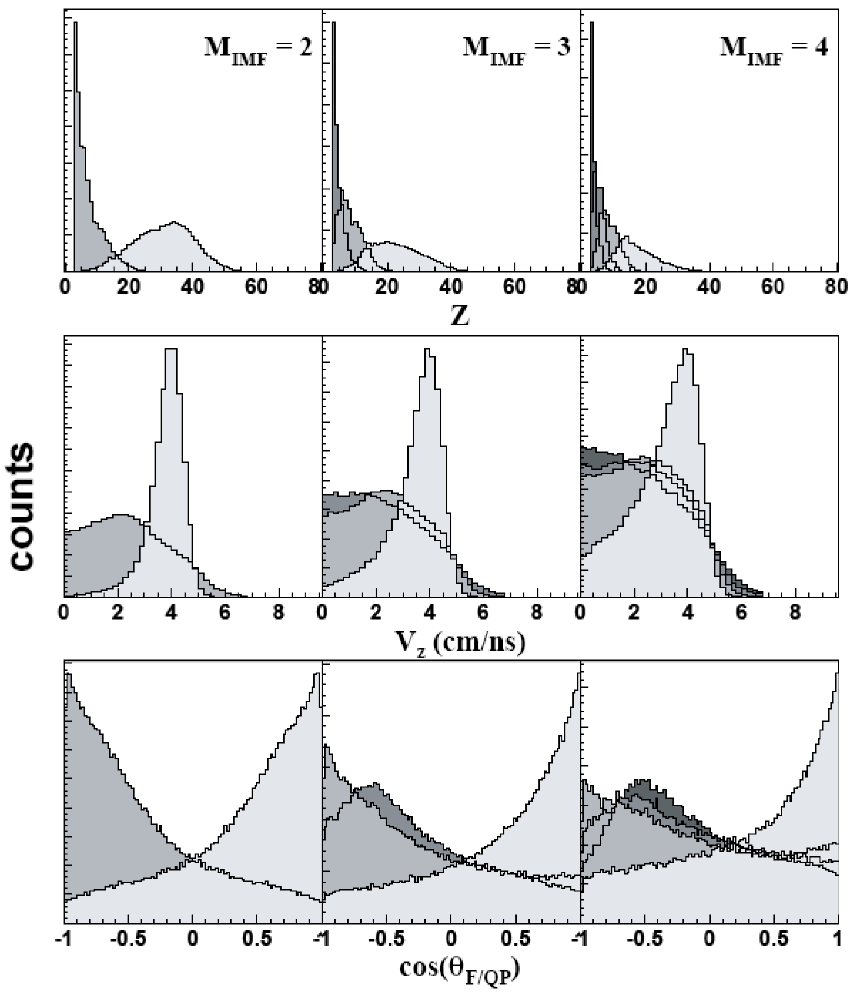
THE MOST SENSITIVE OBSERVABLES TO SYMMETRY ENERGY TERM

# EXPERIMENTAL INDICATIONS FOR DYNAMICAL EFFECTS IN NUCLEAR FRAGMENTATION

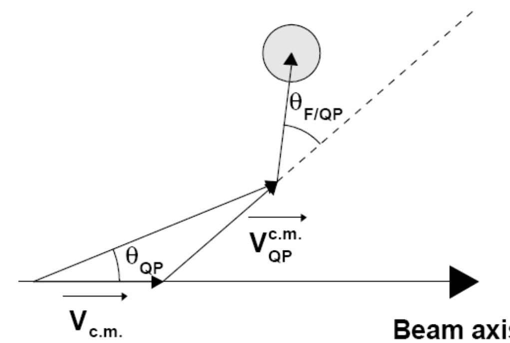
# DYNAMICAL EFFECTS IN QUASIPROJECTILE FRAGMENTATION

Xe+Sn at 50AMeV

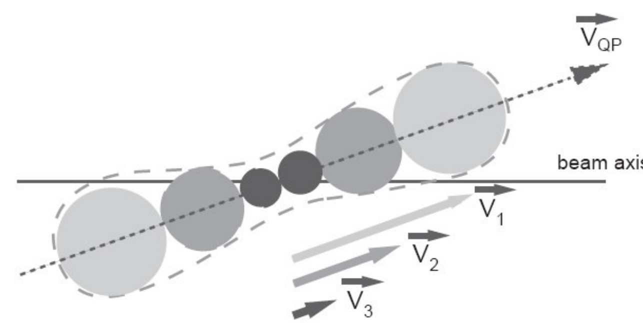
$M_{IMF}$- the multiplicity of fragments with Z>2 emitted by quasiprojectile




A hierarchy effect consistent with a strong deformation of quasiprojectile



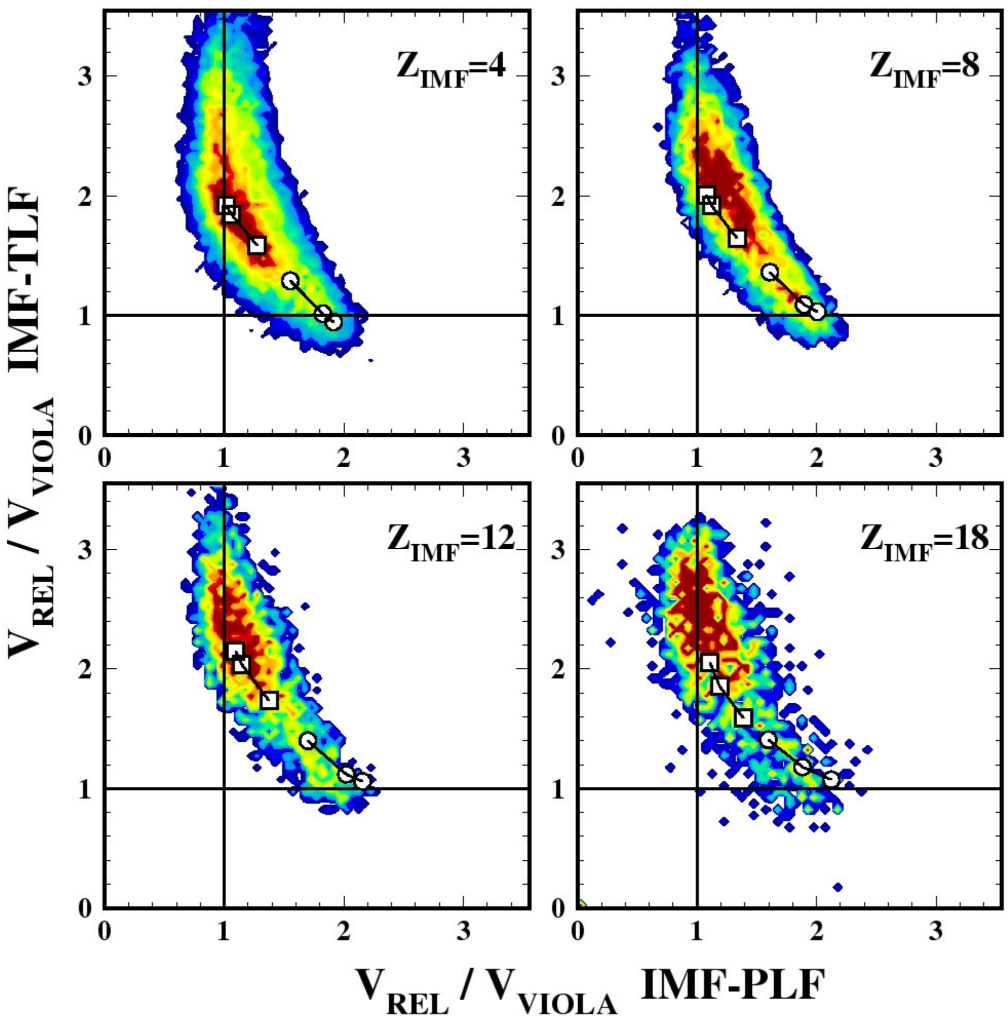

Fragments emission structure reflects the elongated neck structure.




J. Colin et al. (INDRA collaboration) Phys.Rev. C 67 064603 (2003)

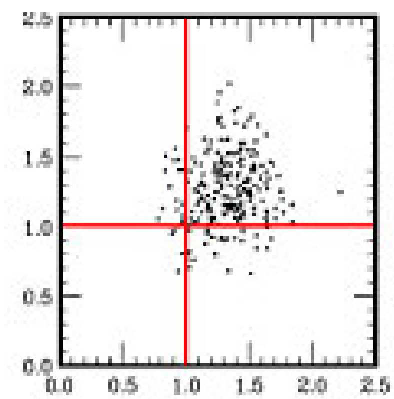
# DYNAMICAL EFFECTS IN NECK FRAGMENTATION

Chimera 124Sn+64Ni 35AMeV data, same E_loss selections




Note: stochastic BNV model accounts only for the “prompt” component of IMF’s

BNV



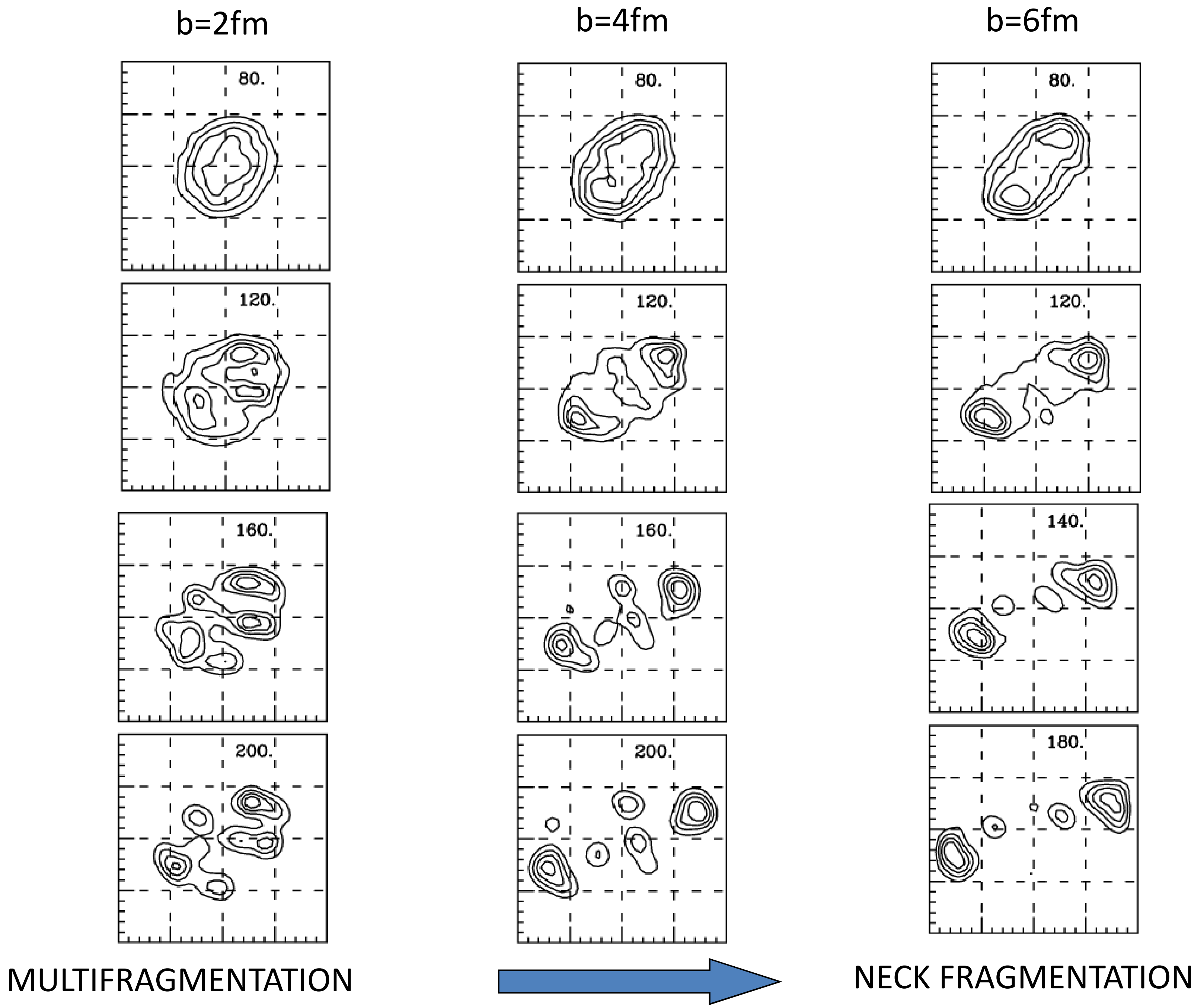

V.Baran,M.Colonna, M.Di Toro
Nucl. Phys A730 (2004) 329

E.De Filippo et al. (Chimera Coll.) PRC71(2005)044602 and 064604

# Fermi Energies

***Symmetry Energy below Saturation: Fragmentation***

# TRANSITION DOMAIN FROM MULTIFRAGMENTATION TO NECK FRAGMENTATION


b=2fm
b=4fm
b=6fm
80.
120.
160.
200.
80.
120.
160.
200.
80.
120.
140.
180.
MULTIFRAGMENTATION
NECK FRAGMENTATION

**b=4 fm**

# CLEAR PRESENCE OF ENTRANCE CHANNEL MEMORY
# PLF and TLF residues

**A mixture of features coming from multifragmentation and neck fragmentation**

Three important time scales:

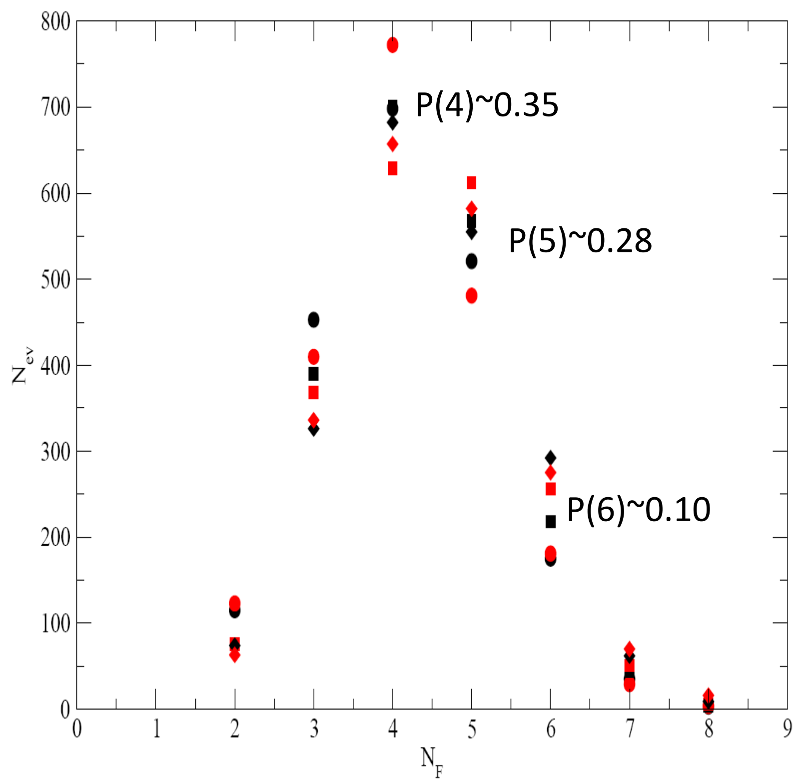
I. **Reaction (interaction) time**

II. **Fragment formation and growth time scale**

III**. Isospin transport time scales** → **distillation**
→ **migration**

# FRAGMENT MULTIPLICITY DISTRIBUTION

(b=4fm; Transition region)




Asysuperstiff EOS | Asysoft EOS

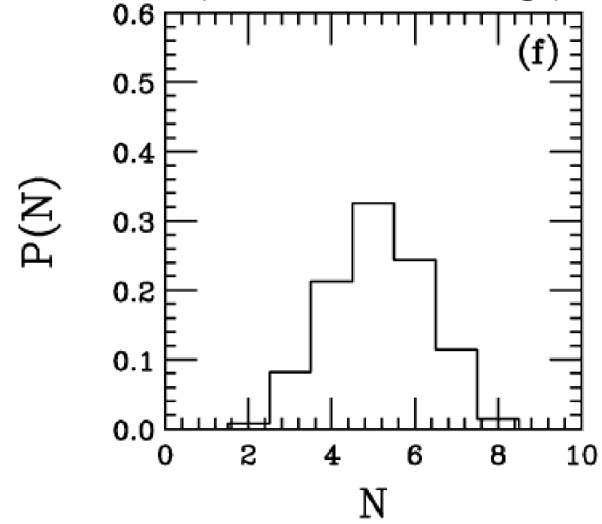
$^{124}Sn+^{124}Sn$

$^{112}Sn+^{112}Sn$

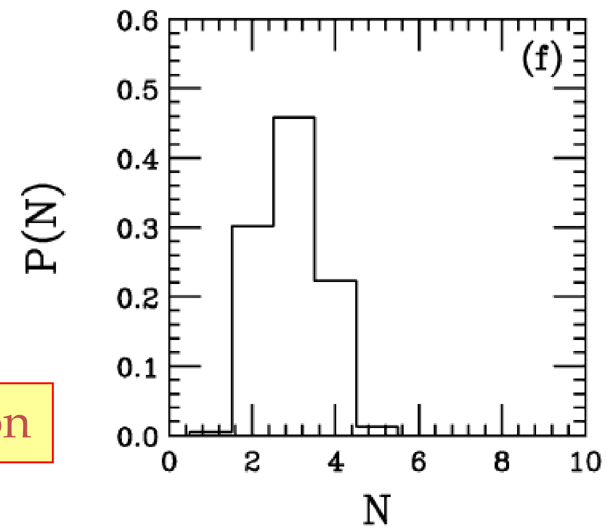
$^{132}Sn+^{132}Sn$

2000 events for each reaction

(b=2fm; Multifrag.)

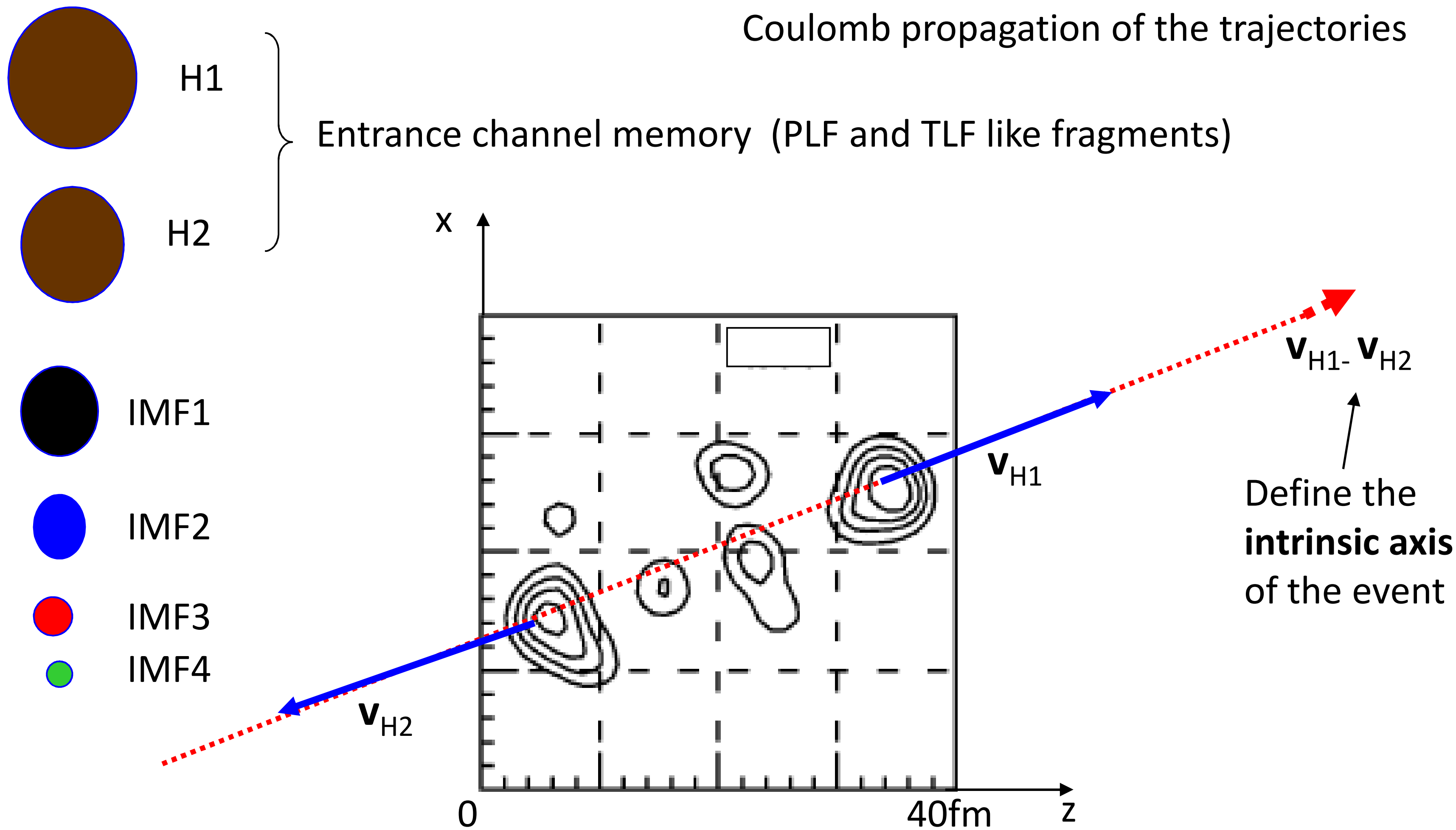



(b=6fm; Neck fragm.)



ANALYSIS METHOD

Coulomb propagation of the trajectories




$\mathbf{V}_{par}$ – the component of the fragment velocity along intrinsic axis

$\mathbf{V}_{tra}$ – the component of the fragment velocity perpendicular to intrinsic axis

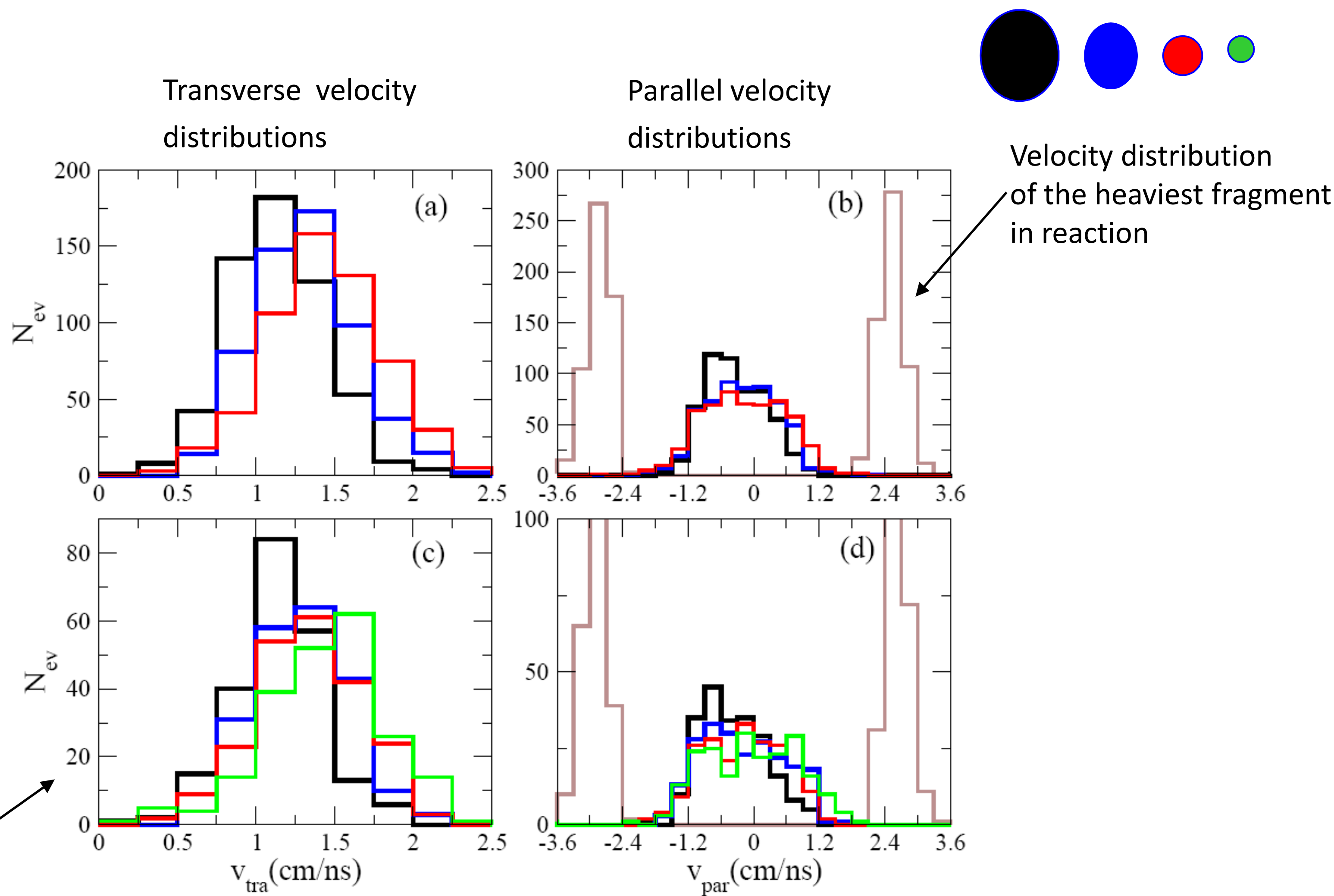
# HIERARCHY IN TRANSVERSE VELOCITY

$^{124}Sn+^{124}Sn$
b=4fm

ASYSOFT

**3 IMF**

**4 IMF**



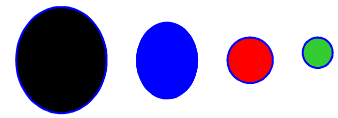

The lightest IMF's acquires the greatest transverse velocities

The IMF's velocity distributions along intrinsic axis are centred around mid-velocity region

## HIERARCHY IN TRANSVERSE VELOCITY

$^{124}Sn + ^{124}Sn$
b=4fm

ASYSOFT



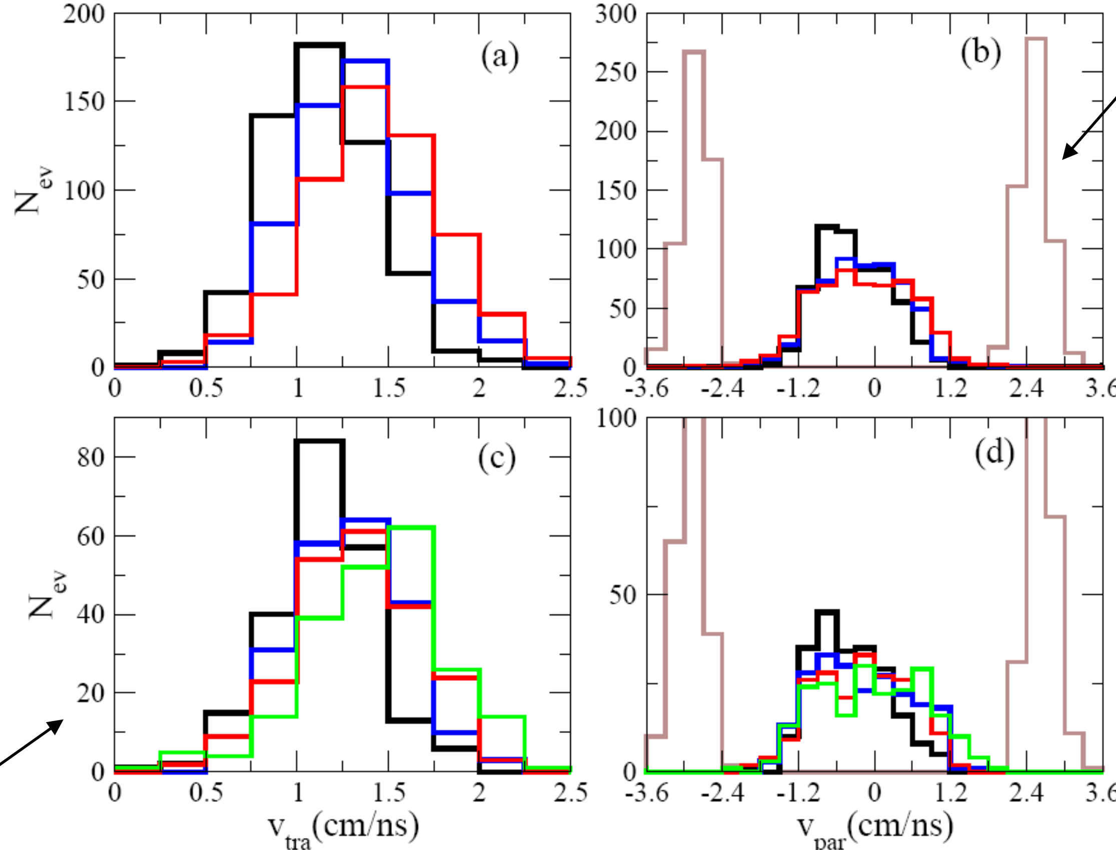
Transverse velocity distributions

Parallel velocity distributions

Velocity distribution of the heaviest fragment in reaction

**3 IMF**

**4 IMF**



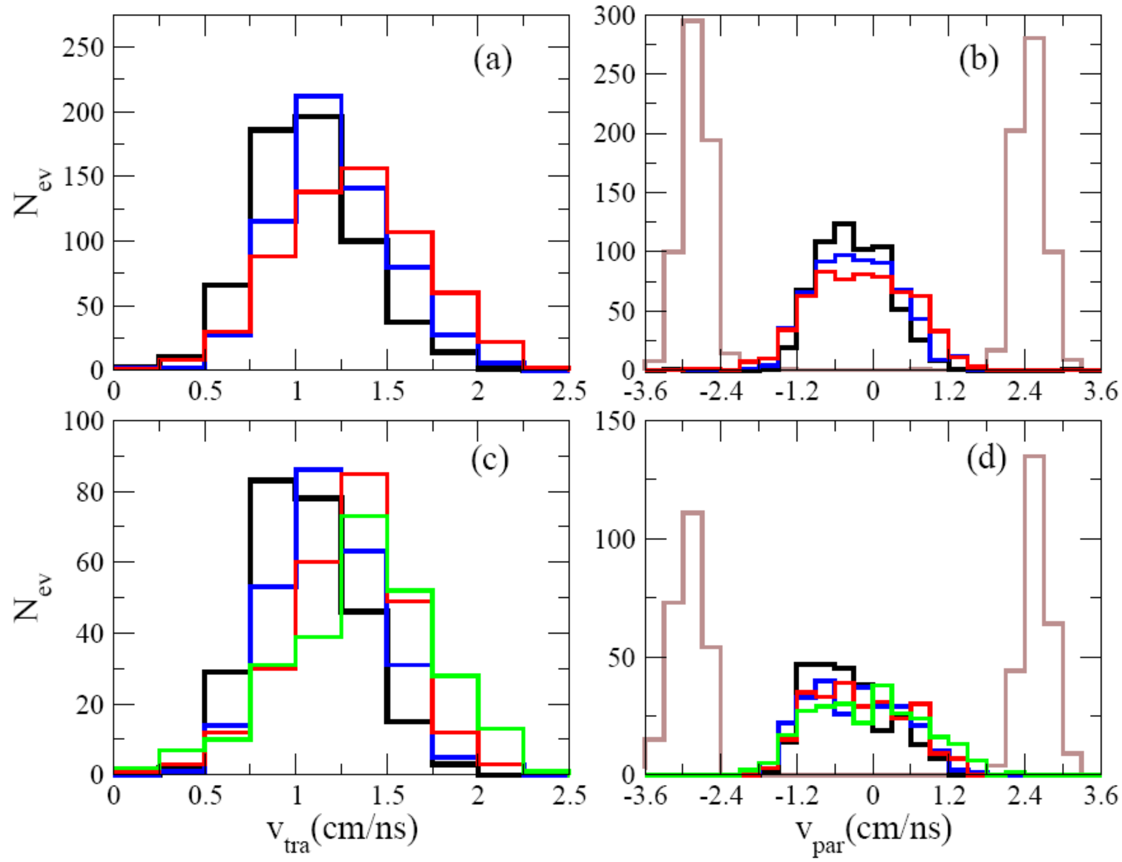

The lightest IMF's acquires the greatest transverse velocities

The IMF's velocity distributions along intrinsic axis are centred around mid-velocity region

## HIERARCHY IN TRANSVERSE VELOCITY

$^{124}Sn + ^{124}Sn$
b=4fm

ASYSUPERSTIFF



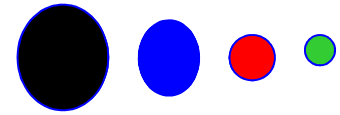

Broader distributions for lighter IMF's

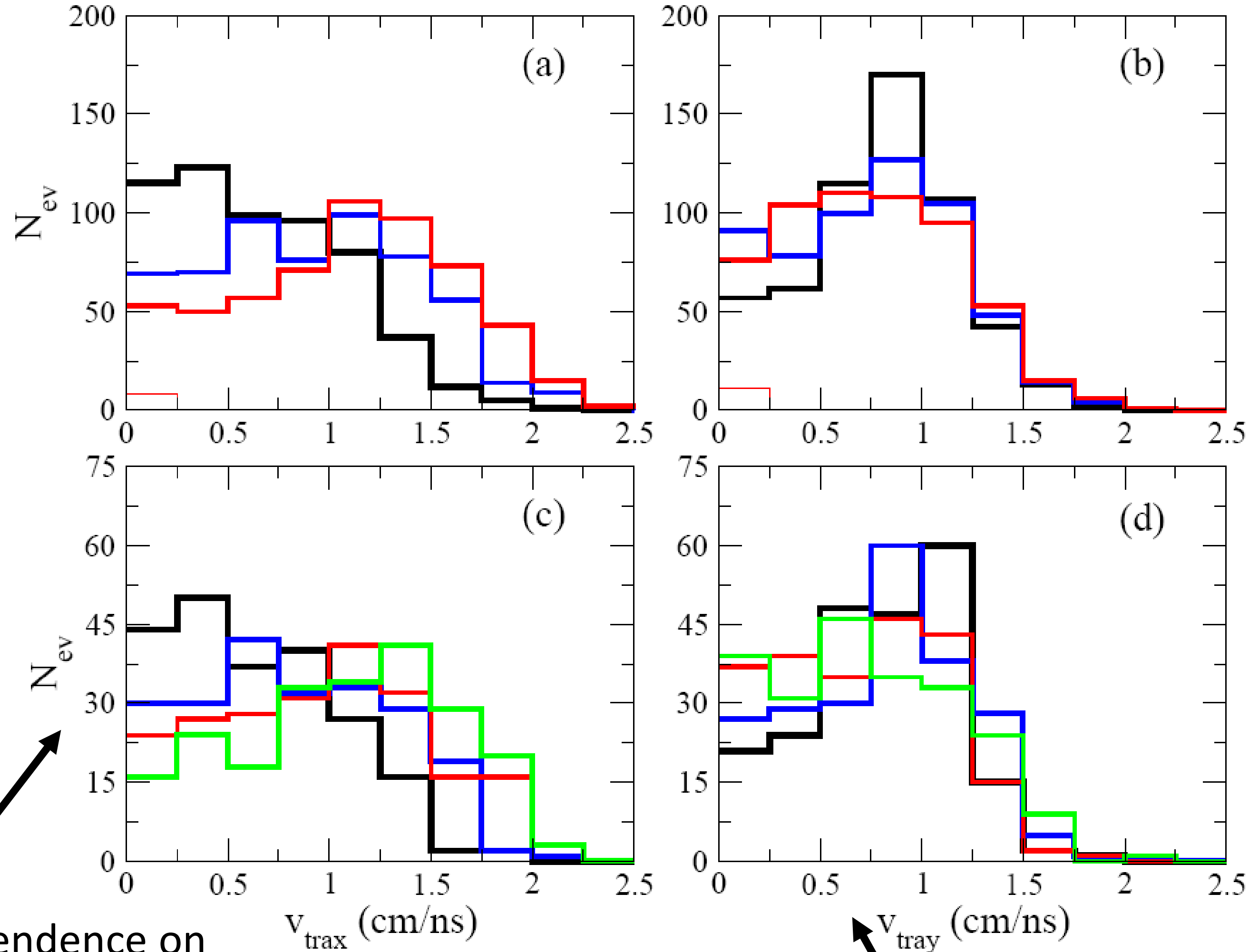
**In plane transverse velocity:**

can be related to the incomplete dissipation
of entrance channel collective energy?

IN REACTION PLANE TRANSVERSE VELOCITY

OUT OF REACTION PLANE TRANSVERSE VELOCITY





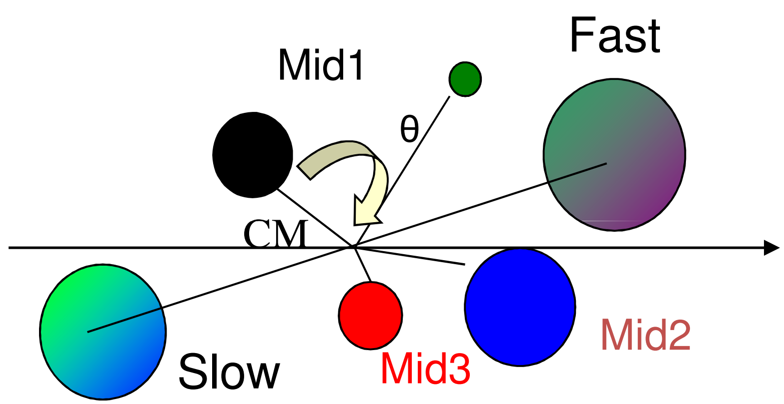

Thermal Expansion + Coulomb effects

Clear dependence on the IMF rank in hierarchy

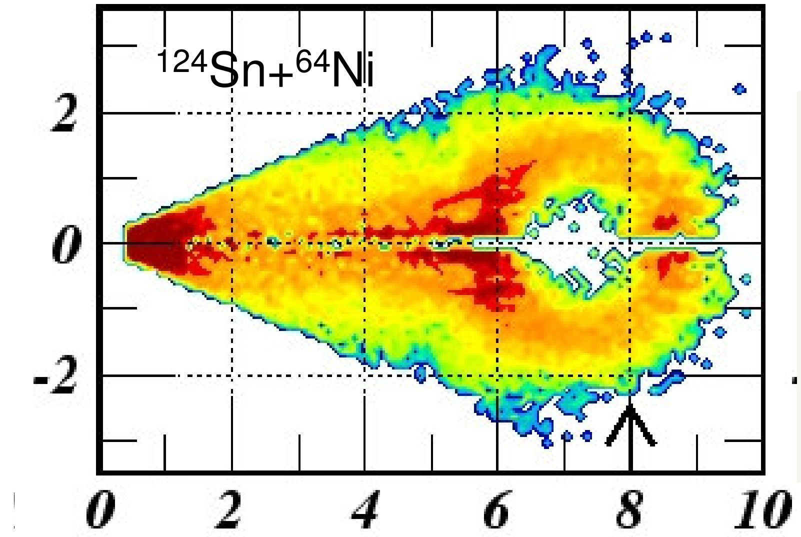
It is difficult to disentangle any dependence on the IMF rank in hierarchy

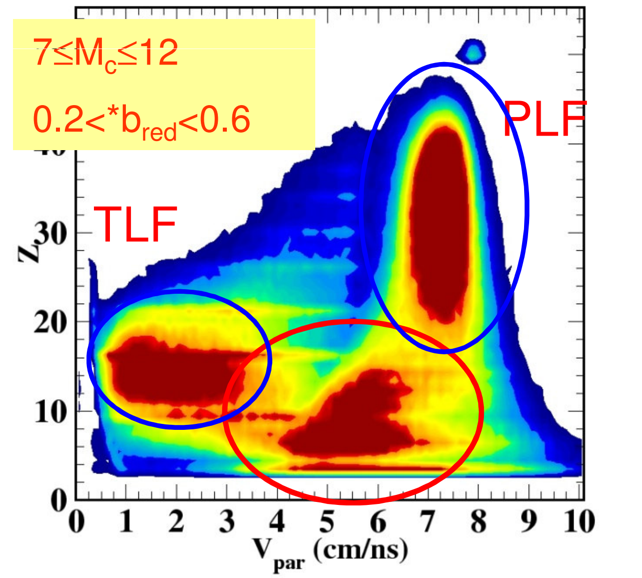
# BEYOND TERNARY EVENTS.....

For heavy systems Colin et al. *(Phys. Rev. C67 064603 (2003)* have observed a "hierarchy" effect in longitudinal velocity: ranking in bigger charge induces a ranking in "parallel" velocity, mainly observed in aligned multiple "breakup" of elongated PLF and TLF



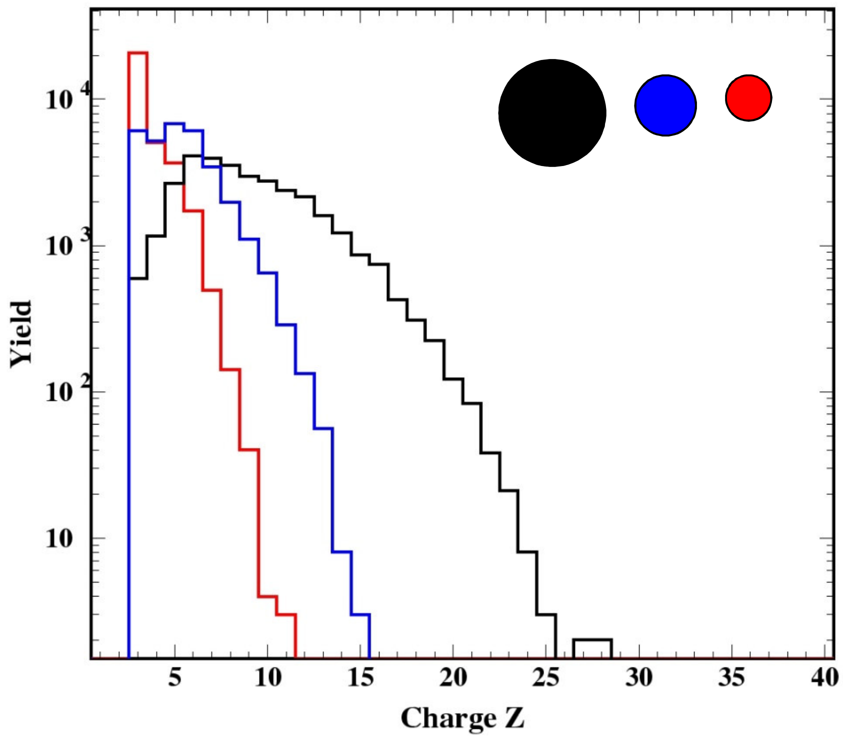

We want to look for other possible signatures of the neck fragmentation process.




At least 3 fragments or more + PLF + TLF in the same event

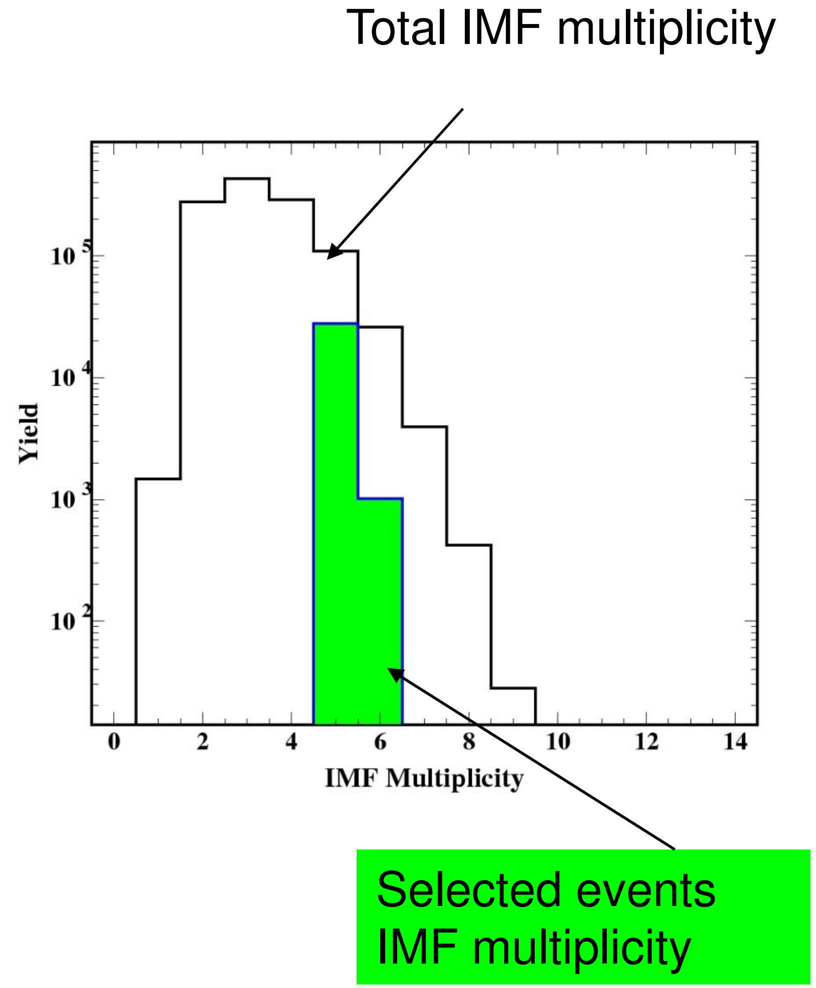
## Charge and fragments multiplicity distributions




Charge distribution of the fragments in the selected $V_Z$-$V_{par}$ mid-velocity zone

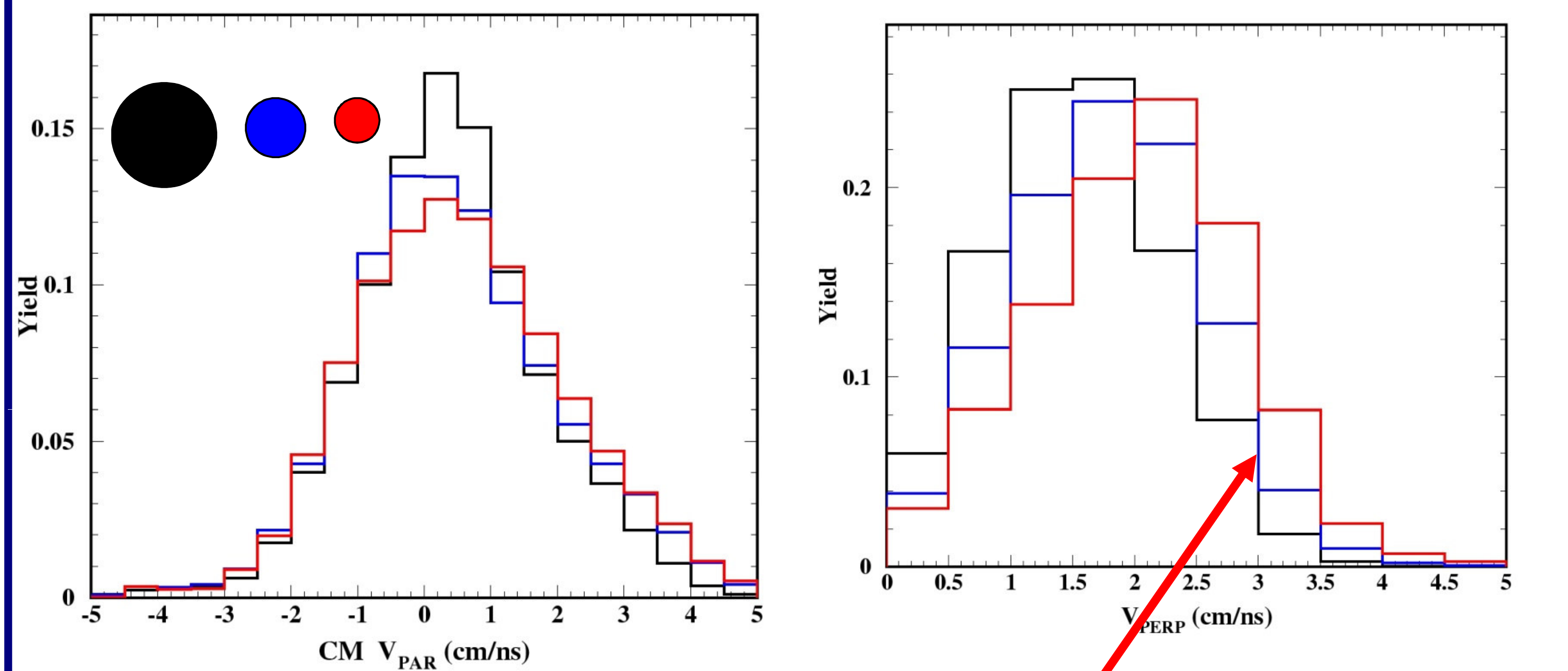
7≤M≤12

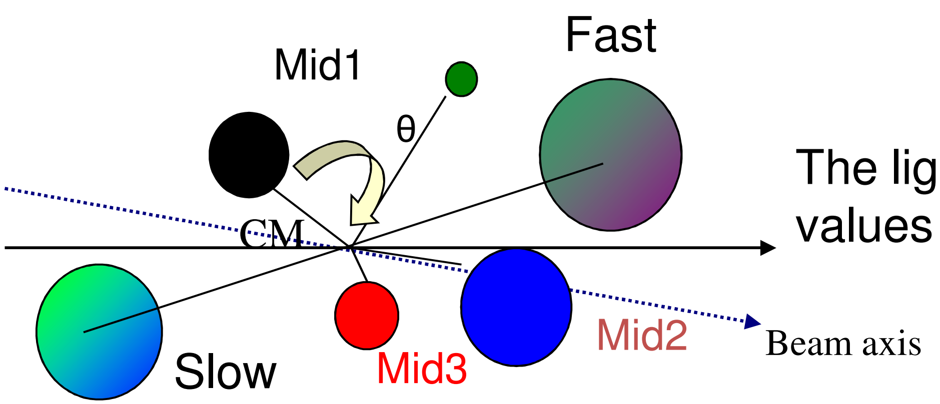
PLF, TLF and at least 3 fragments in the same event



# Parallel and trasversal velocity distributions.

Exp $^{124}Sn+^{64}Ni$: velocities components calculated respect to the PLF – TLF separation axis

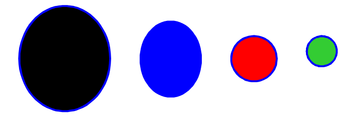



The lightest fragment is shifted toward higher values of trasversal velocity

# CORRELATIONS BETWEEN IMF's ISOSPIN CONTENT AND HIERARCHY EFFECTS

$^{124}Sn + ^{124}Sn$

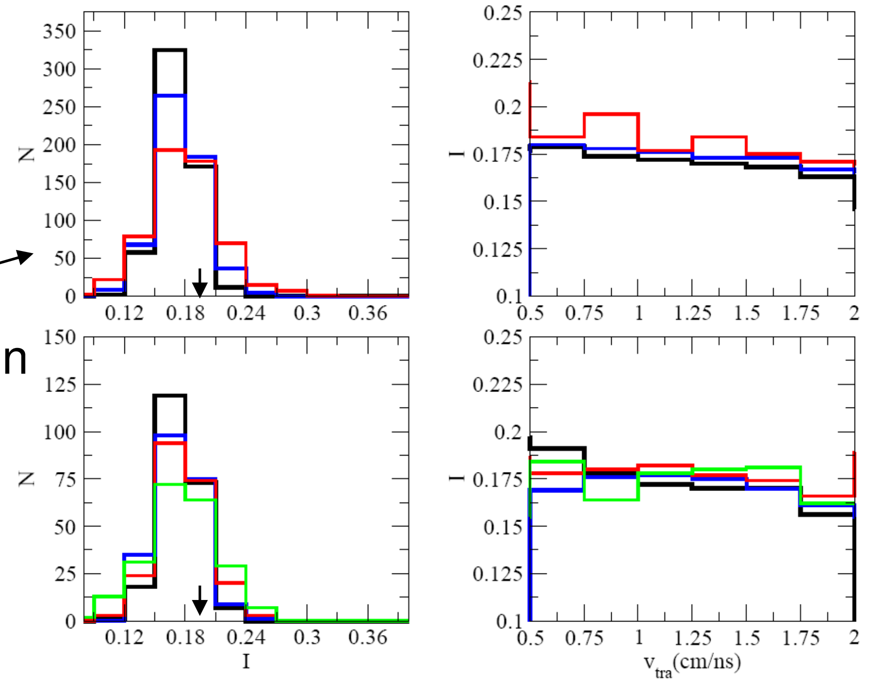


ASYSOFT

3 IMF

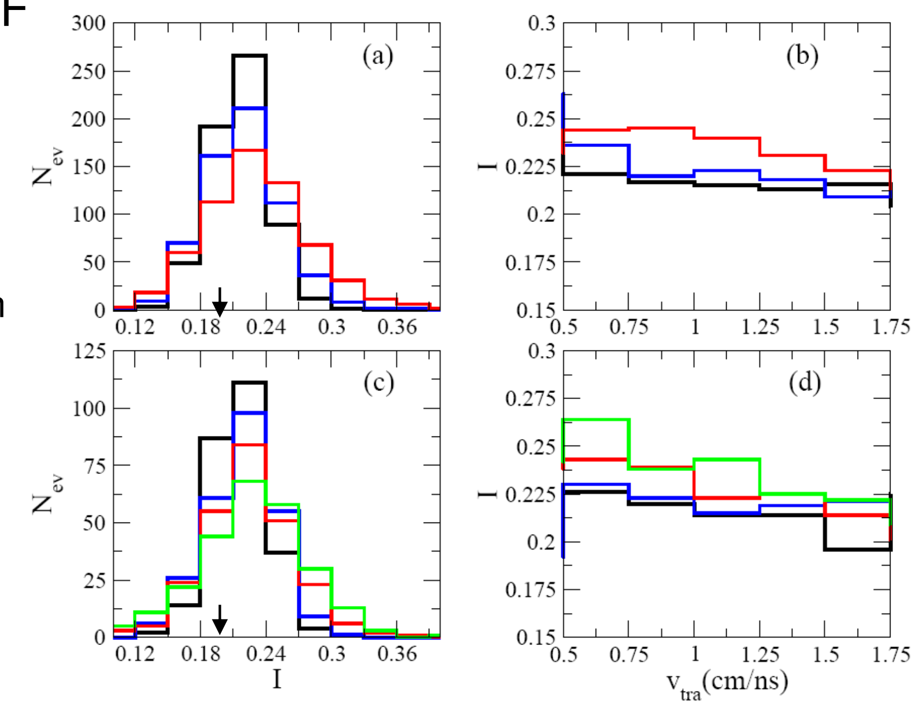
Narrow distribution

4 IMF




SUPERASYSTIFF

Dependence of
the isospin distribution
widths on the
IMF rank in hierarchy

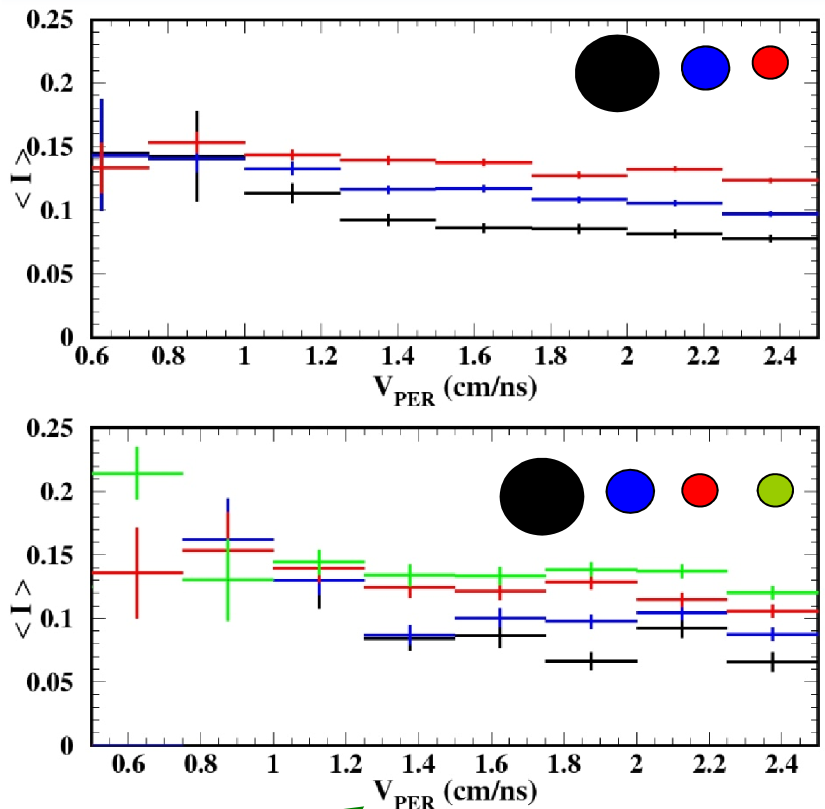



The average asyymetry **I** increases with the rank in hierarchy in some Transverse velocity bins

# Fragment isotopic composition

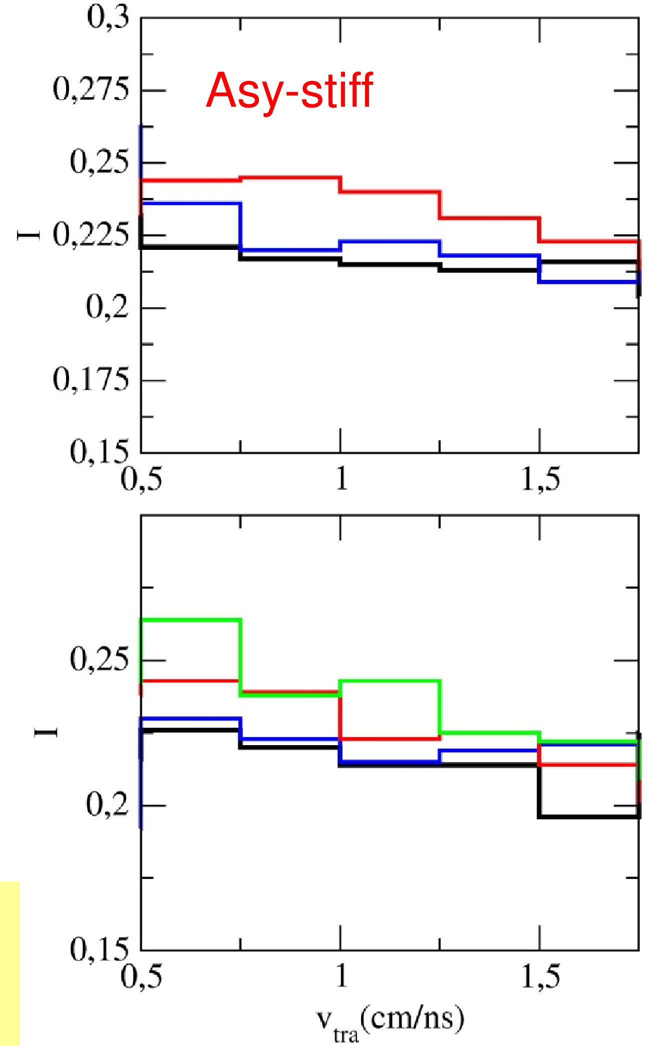
$$I = \frac{N-Z}{A}$$

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




Transverse velocity

$^{124}Sn+^{124}Sn$ 50 A.MeV




Large n-enrichment fragments with asy-stiff, but decreasing with $V_{per}$

SMF calculation, V. Baran et al.

# Coulomb Barrier

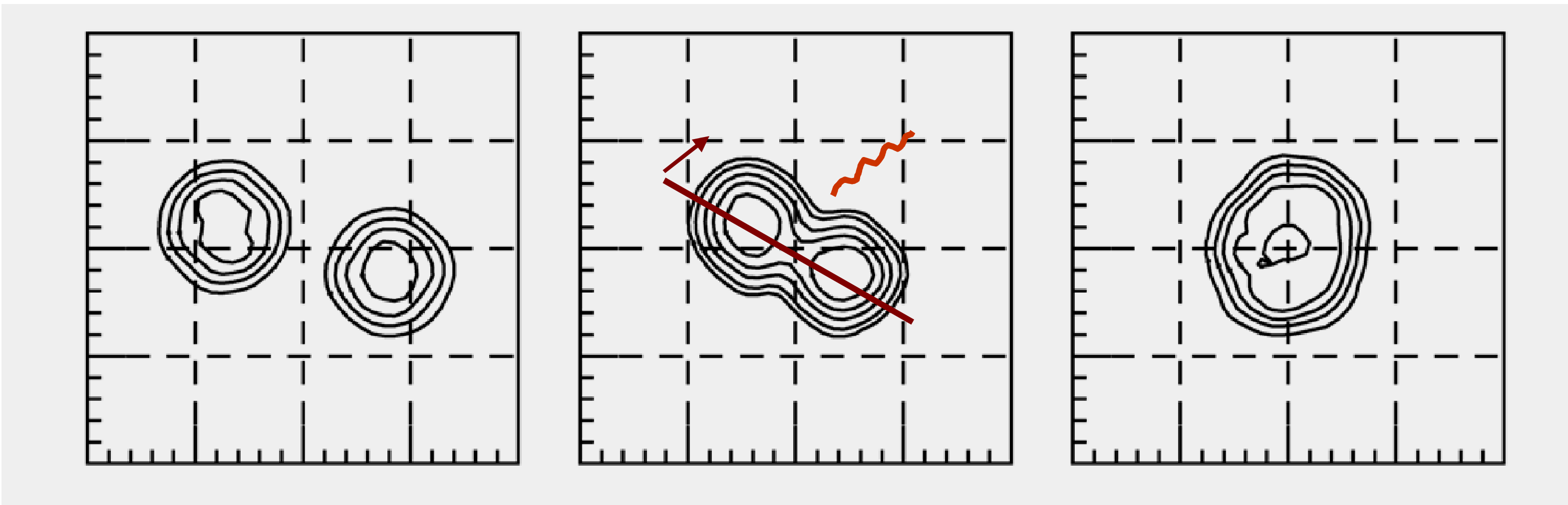
# Pre-equilibrium Dipole Radiation

**Charge Equilibration Dynamics:**

**Stochastic** → **Diffusion**

**vs.**

**Collective** → **Dipole Oscillations of the Di-nuclear System ⇒Fusion Dynamics**



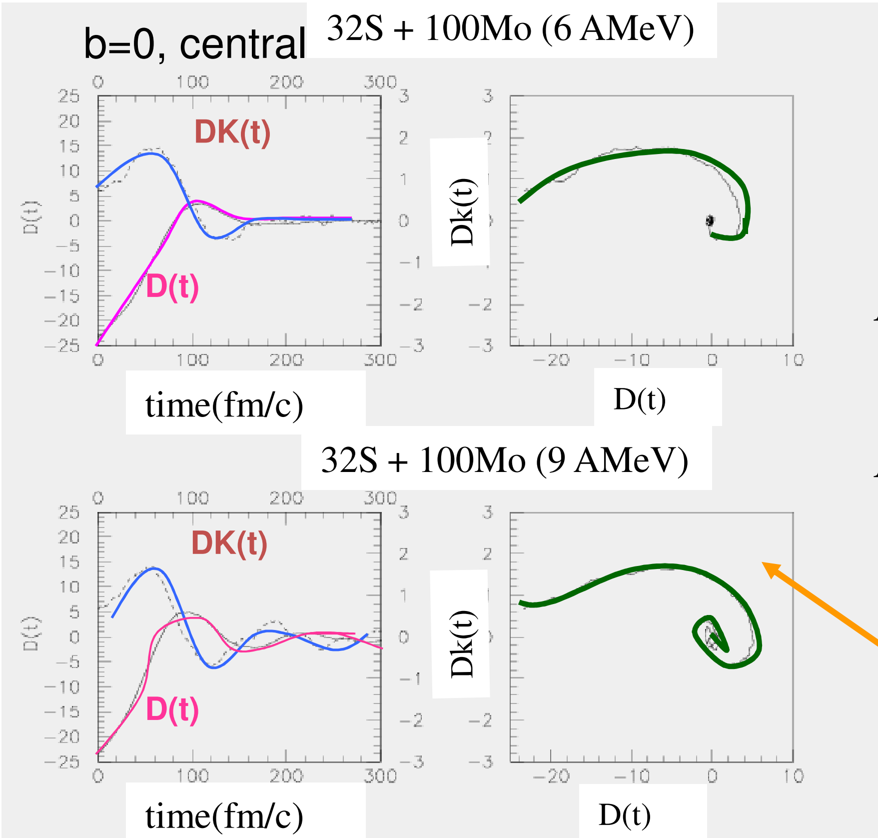
$$D_0 = \frac{Z_1 Z_2}{A}\left(\frac{N_1}{Z_1} - \frac{N_2}{Z_2}\right)(R_1 + R_2)$$

**Initial Dipole**

**D(t) : bremss. dipole radiation**

***CN: Statistical GDR***

**Cooling on the way to Fusion**




# Pre-equilibrium dipole emission

$$D(t) \equiv \frac{NZ}{A}\left[X_p(t) - X_n(t)\right] \rightarrow X_{p,n} \equiv \frac{1}{Z,N}\Sigma x_i^{p,n}$$

$$DK(t) \equiv P_p - P_n \rightarrow P_{p,n} \equiv \frac{1}{Z,N}\Sigma p_i^{p,n}$$

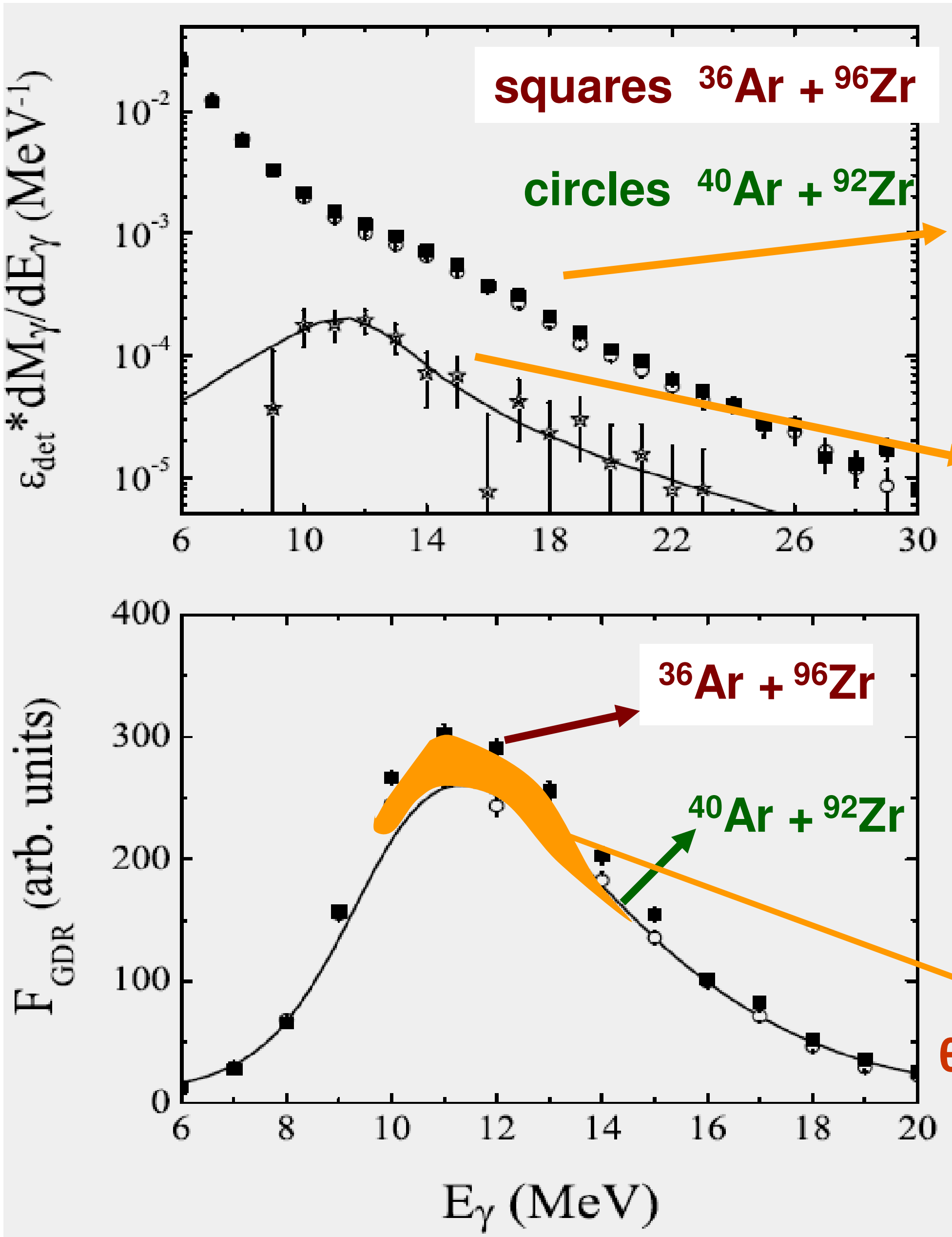
**Phase Space→ Collective Oscillations!**

***Bremsstrahlung: Quantitative estimations***

$$\frac{dP}{dE_\gamma} = \frac{2e^2}{3\pi\hbar c^3 E_\gamma}\left(\frac{NZ}{A}\right)^2 \left|D''(\omega)\right|^2$$

*V.Baran, D.M.Brink, M.Colonna, M.Di Toro, PRL.87(2001)*

# D.Pierroutsakou et al., New Medea Exp. at LNS-Catania,




**16AMeV Fusion events: same CN selection**

**(np)-bremsstrahlung-subtracted spectra at $\theta_\gamma$=90° vs. Beam Axis**

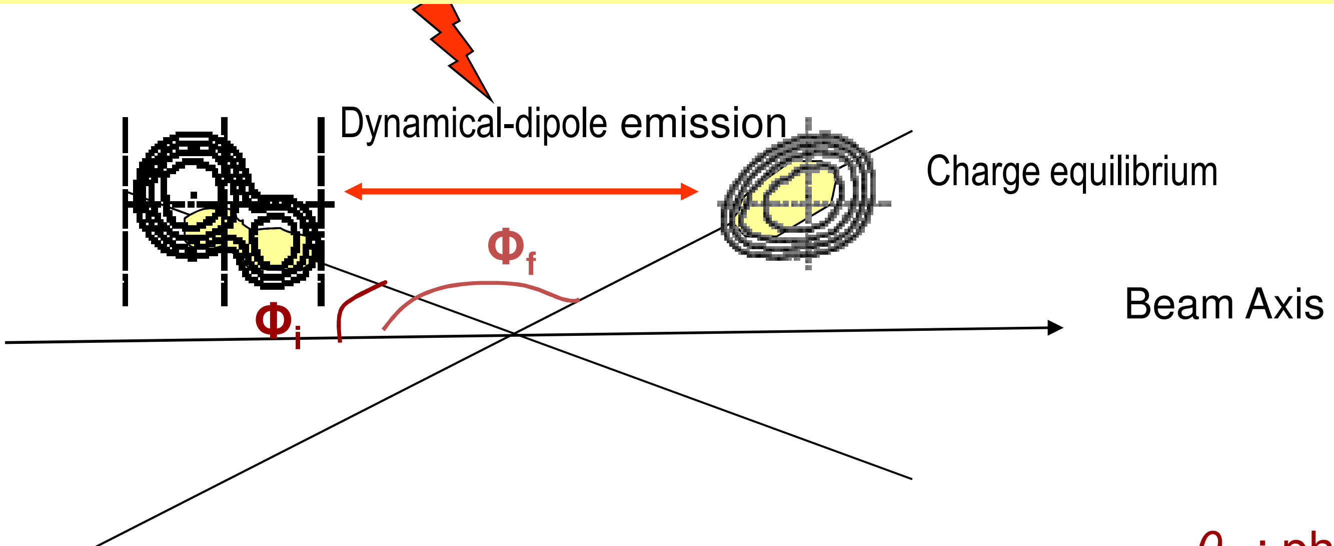
**Difference**

**Linearized spectra:**

**$\theta_\gamma$-study of the extra-yield with MEDEA**

**B.Martin et al., PLB 664 (2008) 47**

# *Rotation on the Reaction Plane of the Emitting Dinuclear System*




$$W(\vartheta_\gamma) = W_0\left[1 + a_2 P_2(\cos\vartheta_\gamma)\right], a_2 = -\left(\frac{1}{4} + \frac{3}{4}x\right)$$

$$x = \cos(\Phi_i + \Phi_f)\frac{\sin(\Delta\Phi)}{\Delta\Phi}, \Delta\Phi = \Phi_f - \Phi_i$$

$\theta_\gamma$ : photon angle vs beam axis

**All rotation angles probed**

**$\Delta\Phi=2\pi \rightarrow x=0 \rightarrow a_2=-1/4$ : Statistical result, Collective Prolate on the Reaction Plane**

**Fixed angle**

**$\Delta\Phi=0 \rightarrow \Phi_i = \Phi_f = \Phi_0$** $\rightarrow$ $W(\vartheta_\gamma) \propto \left[1 - (1 - \sin^2\Phi_0)P_2(\cos\vartheta_\gamma)\right]$

*No rotation: $\Phi_0=0 \rightarrow \sin^2\theta_\gamma$ pure dipole*

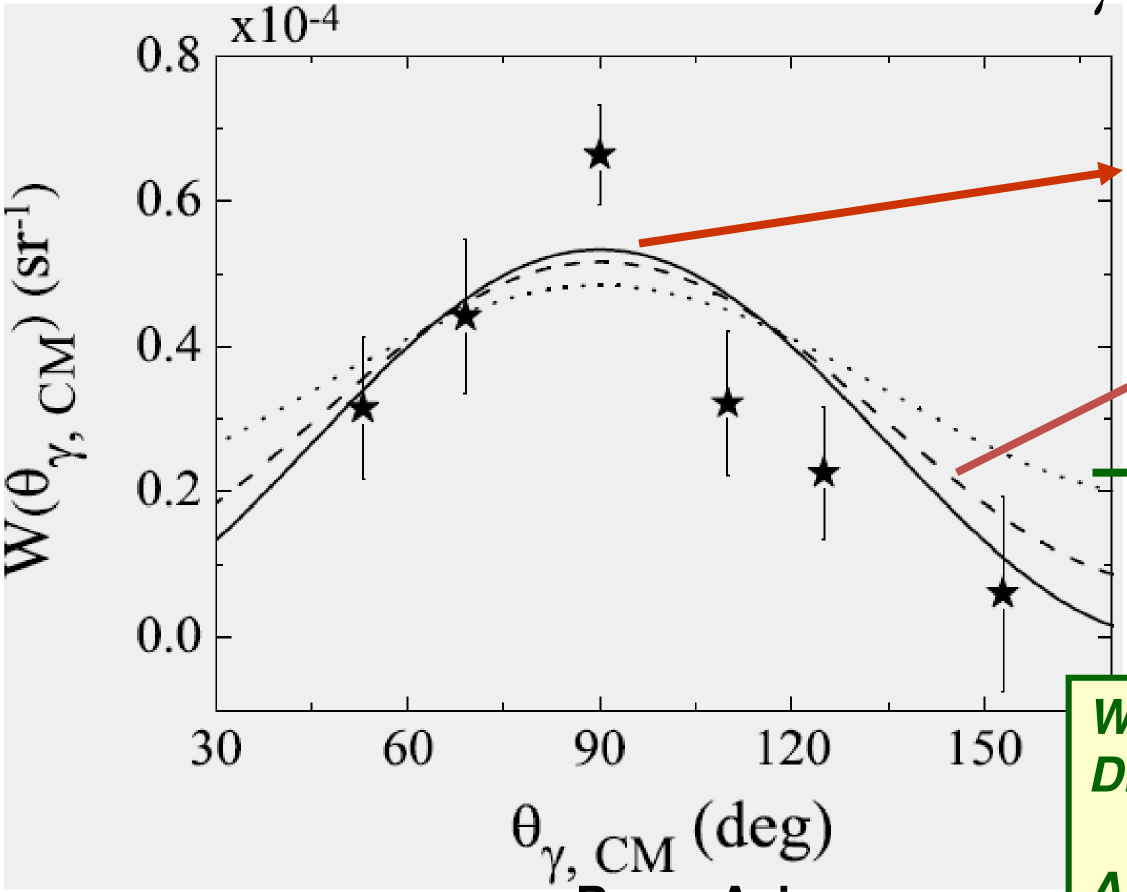
**Dominant since the prompt dipole is rapidly damped?**
**Angular Distribution → Dyn.Dipole Lifetime**

# *Dipole Angular Distribution of the Extra-Yield: Anisotropy!!*

**36Ar+96Zr vs. 40Ar+92Zr: 16AMeV Fusion events:**

**same CN selection**

$$W(\vartheta_\gamma) = W_0[1 + a_2 P_2(\cos\vartheta_\gamma)]$$




**vs Beam Axis**

**a2 = -1→Pure Dipole oscillation along the Beam Axis→ ~ $\sin^2\theta_\gamma$**

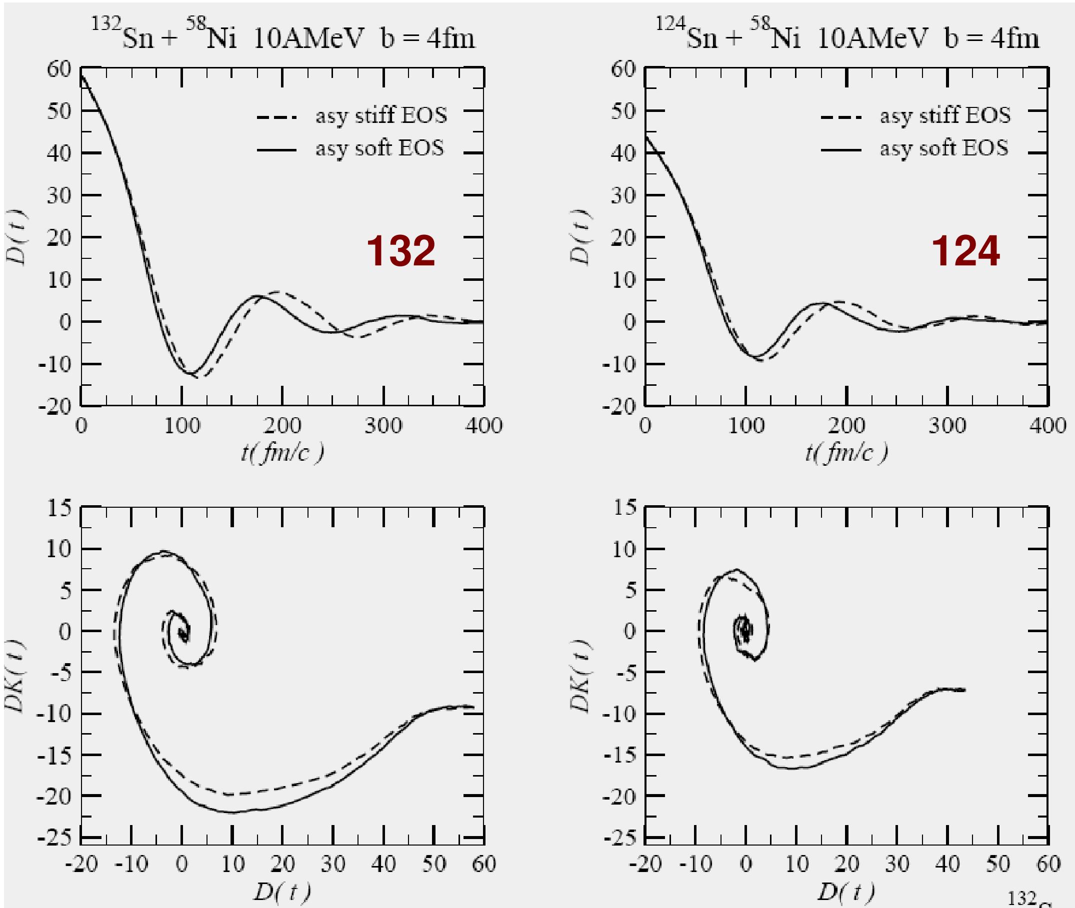
**a2 = -0.8**

**a2 = -0.5**

***Widening: rotation of the Prompt Dipole Axis vs the Beam Axis***
↓
***Accurate Angular Distrib. Measure: Dipole Clock!***

**B.Martin et al., PLB 664 (2008) 47**

# The "Monster" $^{132}$Sn Dynamical Dipole: Symmetry Energy




**10AMeV, b=4fm**

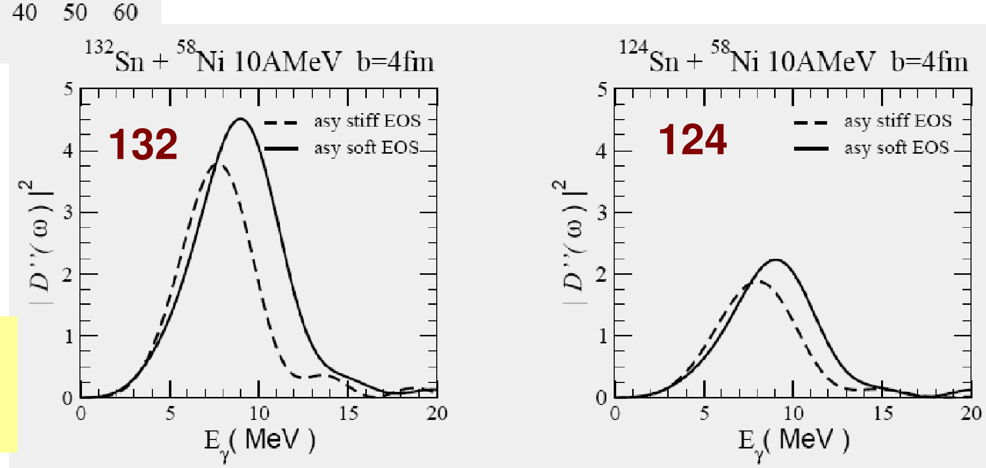
**PRC 79 (2009) 021603**

**Prompt Dipole Oscillations**

—— Asy soft
- - - - Asy stiff

**Phase Space Correlations**

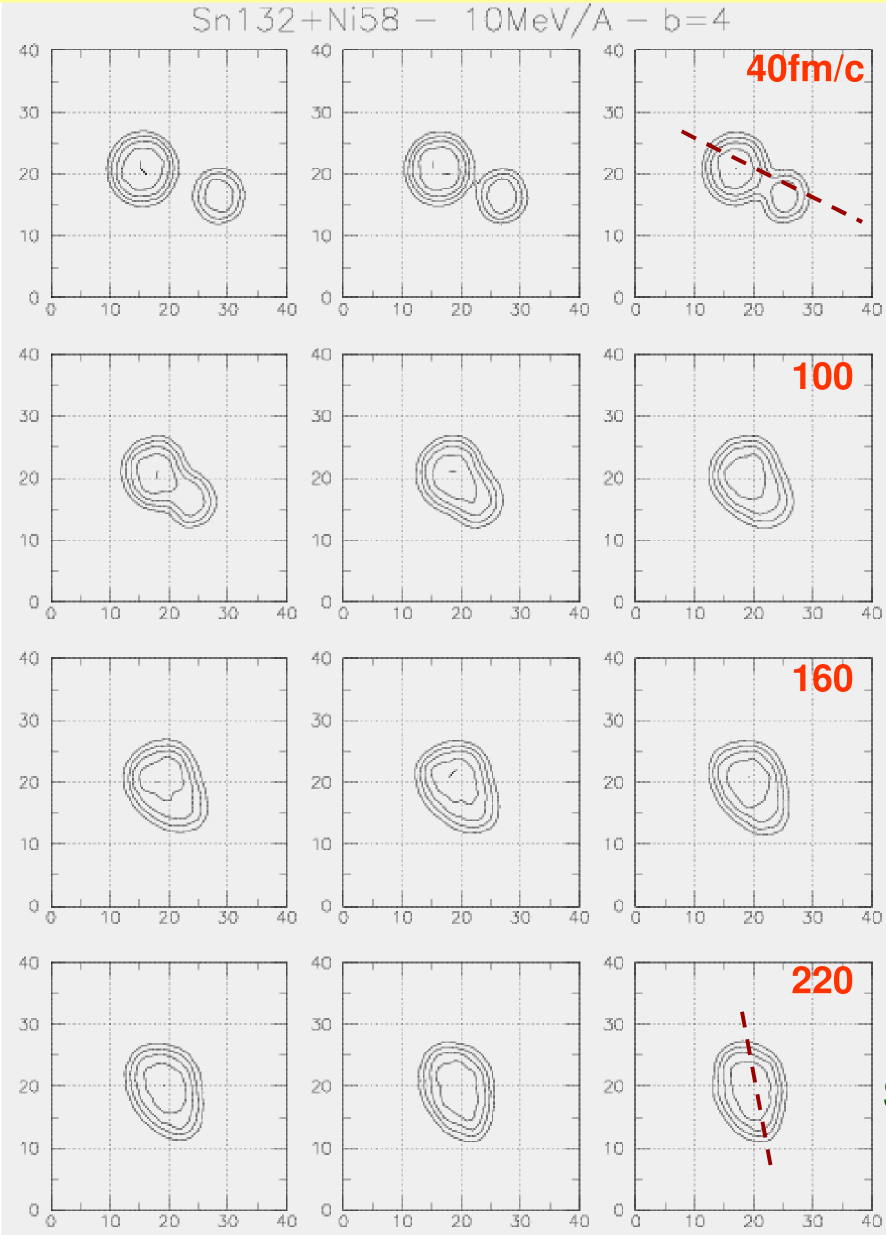
***Power Spectrum***




**ASYSOFT**: ***Larger Yield (25%)***
***Larger Centroid Energy***
***Larger Width***

**Present problems: Beam Intensities**
**Low energy facilities**

# Density Plots on the Reaction Plane: Rotation of the Oscillation Axis vs the Beam Axis

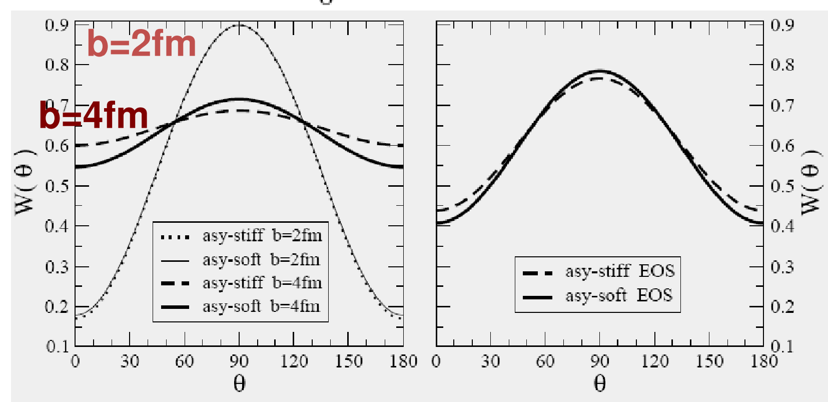



**132Sn:**
**The Monster Dipole *Case***

Weighted anisotropies:

$$W(\theta) = \sum_{i=1}^{t_{max}} \beta_i W(\theta, \Phi_i)$$

$$P(t) = \int_{t_0}^{t} \mid D''(t) \mid^2 \, dt / P_{tot}$$




**Total Angular Distribution**

Still emitting,..although damped

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# CONCLUSIONS

## SYMMETRY ENERGY EFFECTS:

### TRANSITION FROM MULTIFRAGMENTATION TO NECK FRAGMENTATION

Hierarchy in the transverse velocity relative to event intrinsic axis

Correlation between the isospin content and position in mass hierarchy

Dependence of IMF isospin composition on the transverse velocity and rank in mass ordering

### DYNAMICAL DIPOLE MODE IN FUSION REACTION WITH EXOTIC NUCLEI

Gamma yield is influenced by the density dependence of symmetry term around and below saturation density

Photon angular distribution is a result of the interplay between entrance channel dynamics and the collective isovector response