# Density fluctuations and fragment formation in the Fermi energy domain

Introduction

Spinodal instabilities

- from nuclear matter to finite systems
- introduction of isospin

Extra equal-sized fragment production: a fossil signature of spinodal instabilities

How to search for a weak fossil signal

- intra-event charge correlations – a very sensitive method
- experimental results:
  - the definitive presence of spinodal instabilities
  - the N/Z influence

Final comments

- coherence of this signature with other signals
- dominating role ? and chaoticity

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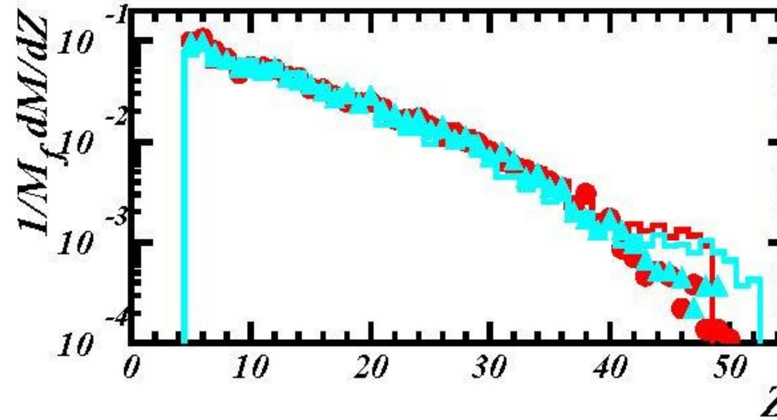
# How to form fragments (central collisions) in the Fermi energy domain

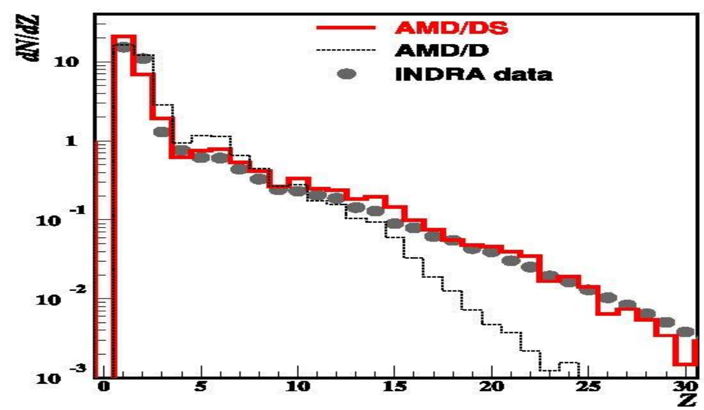
Two mechanisms proposed which both reproduce fragment size dist.

⇒Fragmentation process generated by spinodal instabilities amplified at low density
(Stochastic Mean Field approaches:SMF,BOB,BLOB)




central collisions – quasifusion
$^{129}$Xe+$^{nat}$Sn 32AMeV
$^{155}$Gd+$^{nat}$U 36AMeV
histograms (b=0) BOB + afterburner + exp. filter

INDRA coll. NPA 689 (2001) 940




=>Many-body correlations which are sufficient to produce fragments at early times
(molecular dynamics models: AMD, QMD)

central collisions
$^{129}$Xe+Sn 50AMeV AMD 0<b<4fm + afterburner + exp. filter

A. Ono, PPNP 105 (2019) 139

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Two mechanisms proposed which both reproduced fragment size dist.

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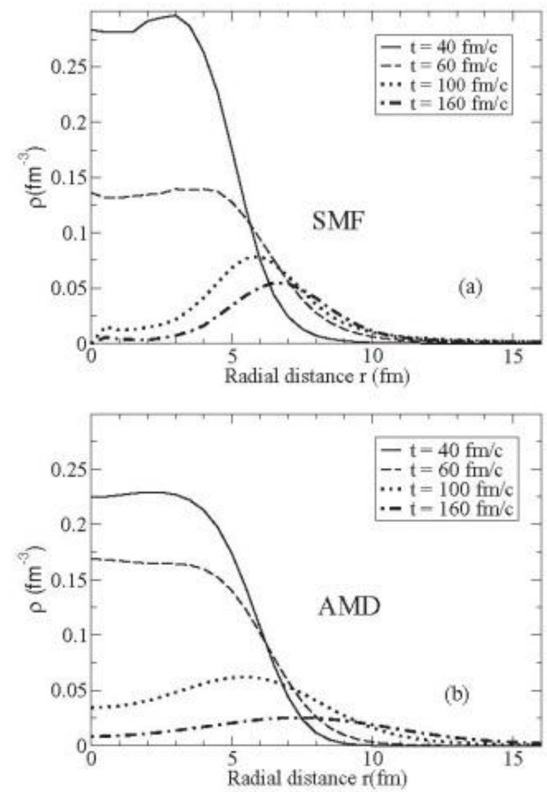
=>Many-body correlations which are sufficient to produce fragments at early times (molecular dynamics models: AMD etc…)




$^{112}Sn + ^{112}Sn$ b=0.5 fm 50 AMeV
Density profiles at several times
The qualitative evolution of the cycle compression-expansion is similar
AMD shows broader average density distribution than SMF as the system expands, pointing to a faster fragment formation

M. Colonna, A. Ono and J. Rizzo PRC 82 (2010) 054613

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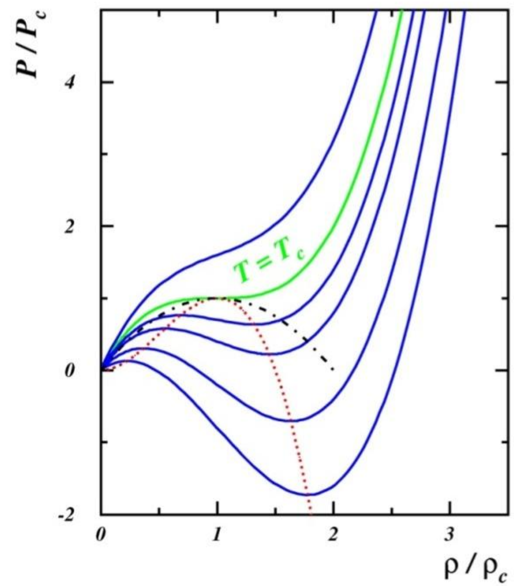
# spinodale zone mechanically unstable

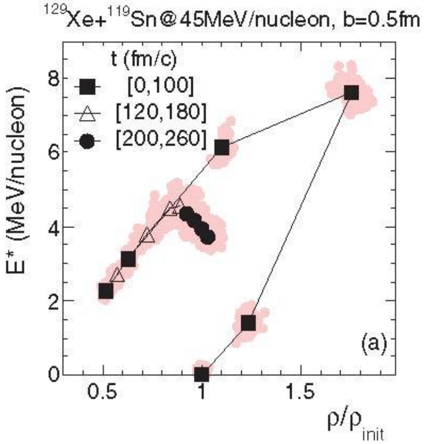
negative compressibility

$\delta P/\delta\rho<0$ $\rho_c \approx 0.3\text{-}0.4\ \rho_0$

unstable medium
density fluctuations exponentially amplified
=> Fragment formation




This unstable region is reached with central heavy ion collisions at Fermi energies




compression expansion phase
=> trajectory

E. Bonnet et al., PRC 89 (2014) 034608

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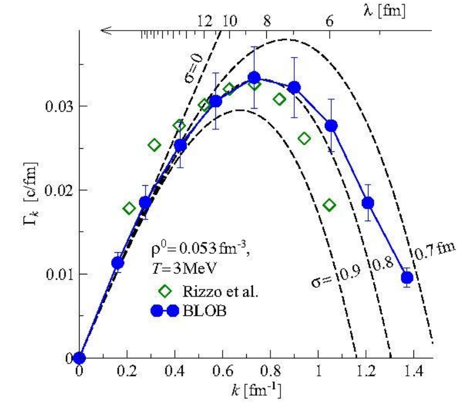
# spinodal instabilities
# density fluctuations are exponentially amplified

BLOB: fluct. introduced in full phase space from induced NN collisions




matter dispersion relation
P. Napolitani, M. Colonna PRC 97 2017 054609

Infinite nuclear matter: most unstable modes correspond to wavelengths lying around $\lambda = 2\pi/k \approx$ 8-10 fm
primitive fragments with nearly equal size around Ne ($A \approx \rho\lambda^3$)

and associated characteristic times around $1/\Gamma_k \approx$ 30-50 fm/c

Variational approach
to study small fluct. -> multipole expansion
of the velocity potential

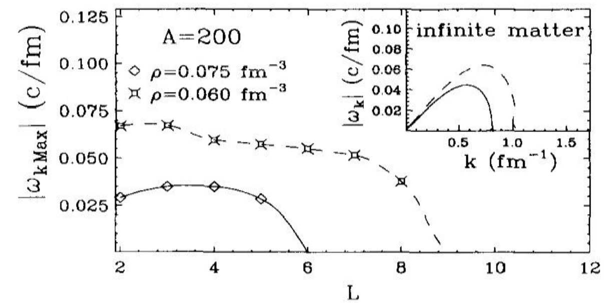



Fig. 3. Growth rates of the most unstable modes for a source with $A$ = 200 nucleons with a Fermi shape profile as a function of the multipolarity $L$ at central densities $\rho_0$ = 0.060 fm$^{-3}$ (dashed line) and $\rho_0$ = 0.075 fm$^{-3}$ (solid line). The insert shows the fluid dynamical dispersion relation for infinite matter as a function of the wave number $k$.

finite systems (A=200) – quasifusion nuclei :
breaking of the translational symmetry due to surface =>growth rates of the most unstable modes are nearly the same for different multipolarities L up to a maximum multipolarity $L_{max}$
=>partitions with nearly equal-sized primitive fragments depending on L

B. Jacquot, A. Ayik, Ph. Chomaz, M. Colonna PLB 383 (1996) 247

# Spinodal instabilities: introduction of isospin

A unique spinodal region in asymmetric nuclear matter
Only one type of instability (no chemical inst.)
Order parameter dominated by the isoscalar density => liquid-gas type transition

skyrme Gogny

Arrows indicate the directions of instability

first bisecting line
=> isoscalar density

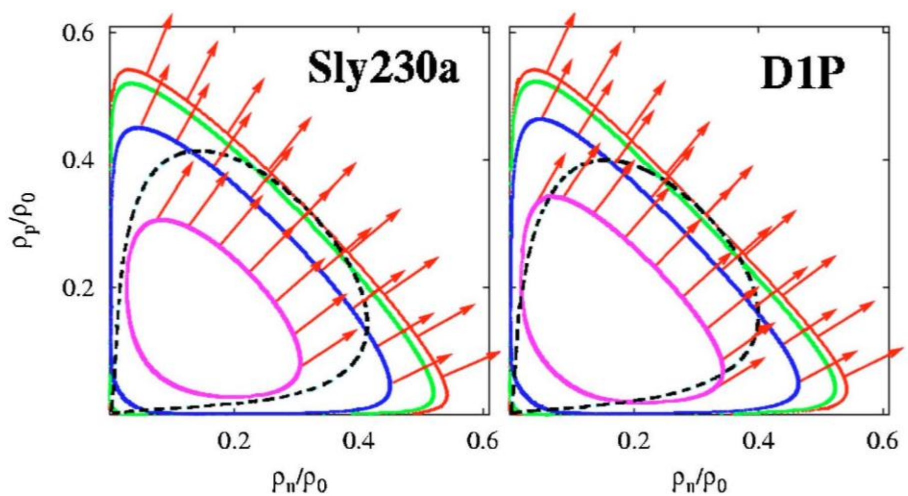



FIG. 4. This is the projection of the iso-eigenvalues on the density plane for Slya (left) and D1P (right). The arrows indicate the direction of instability. The mechanical instability is also indicated (dotted line).

contours of equal imaginary sound velocity i0.09c to i0.03c

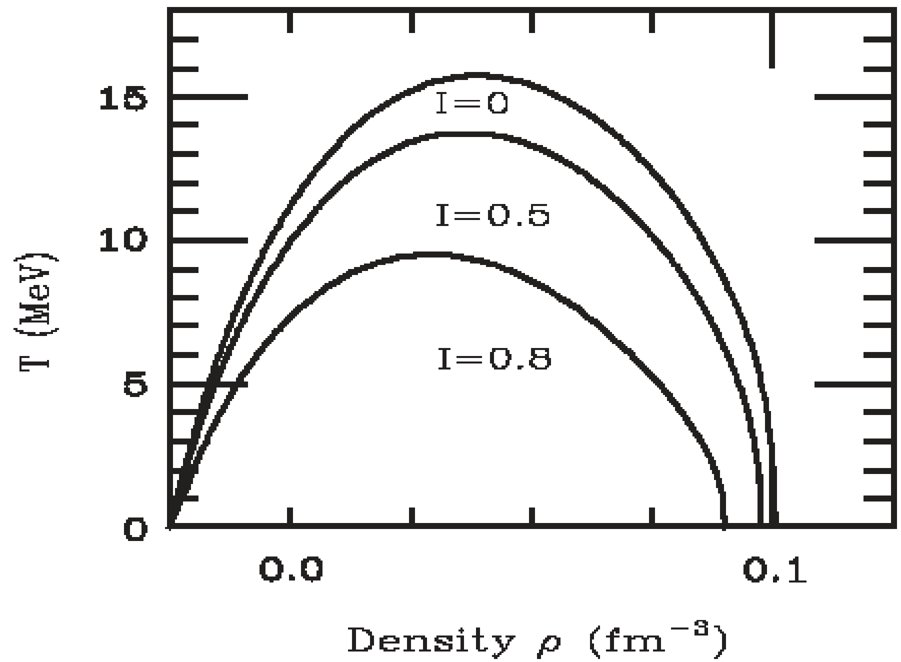
J. Margueron et al., PRC 67 (2003) 041602(R)

# Spinodal region/instabilities with isospin variation

I = (N-Z)/A

Nuclear matter – reduction of the region

Isospin asymmetry leads to shrinking of the spinodal region, reducing both $T_c$ and $\rho_c$



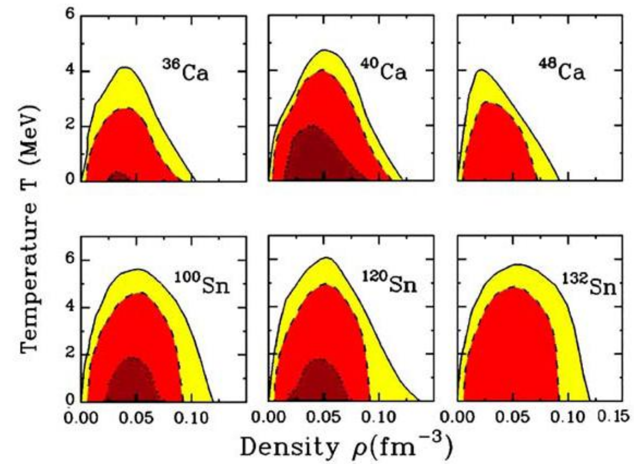

V. Baran, M. Colonna, M. Di Toro, A. B. Larionov, NPA 632 (1998)

# Spinodal region/instabilities with N/Z variation

Self consistent quantum approaches (TDHF+RPA modes)
=>more asymmetric systems are less unstable

Sn isotopes: shorter inst. growth times
disappear when N/Z changes from 1.4 to 1.64

Inst. regions with L=3




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

M. Colonna, Ph. Chomaz, S. Ayik, PRL 88 (2002) 122701

# Spinodal instabilities – a fossil signature is expected for finite nuclei

For infinite nuclear matter, the most unstable modes present in the spinodale region favor partitions of nearly equal-sized fragments (Z around 10)

But this simple picture is blurred by several effects

-the beating of different modes

-the coalescence of nascent fragments

For multifragmenting nuclei even more

- surface effects -breaking of the translational symmetry (equal-sized fragments for different multipolarities/ multiplicities)
- the decay of excited fragments (minor effect)
- hot nuclei produced by collisions have to stay long enough in the spinodal region ( ≈ 3 characteristic time: 100-150 fm/c for N/Z 1-1.4 and 200-300fm/c for larger N/Z)

=>Stochastic mean field simulations of collisions predict less than 1% of extra events with nearly equal-sized fragments (G. Tabacaru et al., EPJA 18 (2003) 103)

which means A FOSSIL SIGNATURE OF SPINODAL INST.

Experimentally we indeed observe a Z distribution without any bumps revealing nearly equal-sized fragments.

**how to search for a possible very weak « fossil » signature?**
**And if yes can we observe a reduction of the signal with the increase of N/Z as theoretically predicted ?**

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# Spinodal instabilities – quasifusion events
# $^{124,136}$Xe + $^{112,124}$Sn 32,45 AMeV - experimental signature

INDRA 4π multidetector – very high statistics experiment 6-8 $10^7$ with $M \geq 4$
Quasi complete events ≥ 80% total charge of the system
Central collisions - compact shape events (quasifusion) through the additional condition that $\Theta_{flow} \geq 60°$ (kinetic energy flow tensor for fragments - $Z>4$)
32 AMeV 40mb (250mb) 45 AMeV 25mb (180mb)
(det.efficiency + selec.)

Previous situation:
results for $^{129}$Xe + $^{nat}$Sn 32-50 AMeV with poor statistics => confidence levels (2 to 3σ) too low to definitively establish the presence of spinodal inst.

New dedicated experiment (QF - $^{124,136}$Xe+$^{112,124}$Sn 32 and 45 AMeV) with much more statistics: 2-5 $10^5$ quasifusion events for each inc. energy

Method used: intra-event charge correlations
Very high sensitivity method down to levels of 0.002-0.003% extra production

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# Intra-event charge correlations

CHARGE CORRELATION METHOD

•A VERY SENSITIVE METHOD

FOR EACH EVENT $n_Z$ BEING THE NUMBER OF FRAGMENTS WITH CHARGE $Z$

$$\langle Z \rangle = \frac{1}{M} \sum_Z n_Z Z \tag{1}$$

$$\sigma_Z^2 = \frac{1}{M} \sum_Z n_Z (Z - \langle Z \rangle)^2 \tag{2}$$

CORRELATION FUNCTION

$$\left. \frac{Y(\sigma_Z, \langle Z \rangle)}{Y'(\sigma_Z, \langle Z \rangle)} \right|_M \tag{3}$$

⇑

UNCORRELATED YIELD
(EXACT MULTINOMIAL FORMULA
TOTAL CHARGE CONSERVATION)

# Intra-event charge correlations – uncorrelated yield

## Exact multinomial formula (P. Désesquelles PRC 65 (2002) 034604)

=> independent emission model with total charge conservation constraint which is mandatory to not distort CF values for weak signals

Partition constrained conditional probabilities $P_{cc}(N)$ N : partition

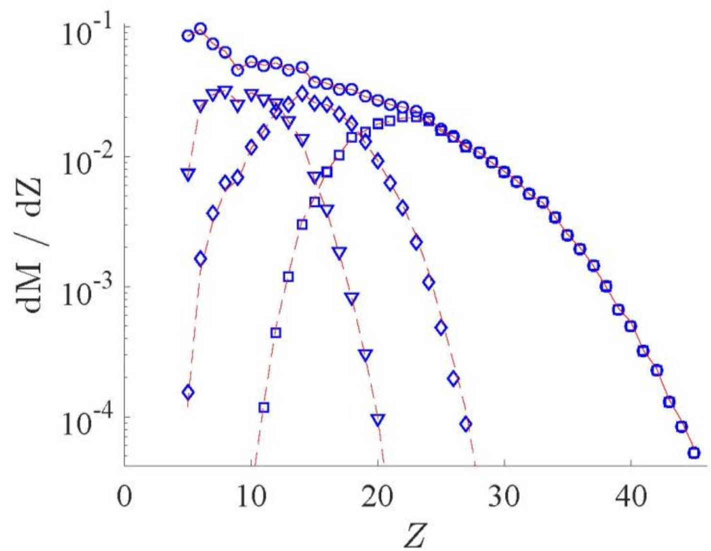
${}^{intr}P_z(z)$ : intrinsic probability of charge z

$$P_{cc}(N) = \alpha \, (\Sigma\, n_z)! \, \Pi \; {}^{intr}P_z(z)^{nz} \; \delta_{ztot} \, \Sigma\, z n_z$$

$n_z$ : number of fragments with charge z

$\alpha$ : normalisation factor $\Sigma\, P_{cc}(N) = 1$

${}^{124}Xe + {}^{112}Sn$ 32 AMeV M=4




${}^{intr}P_z(z)$ evaluated by inversion of the equ. by means of a recursive procedure of minimisation which stops when $10^{-12}$ between 2 steps is reached

# Presence of spinodal instabilities or not?

## $^{124}Xe + ^{112}Sn$ 32 AMeV – M= 3-6

stat. error
on num.≥50%
CF => 1

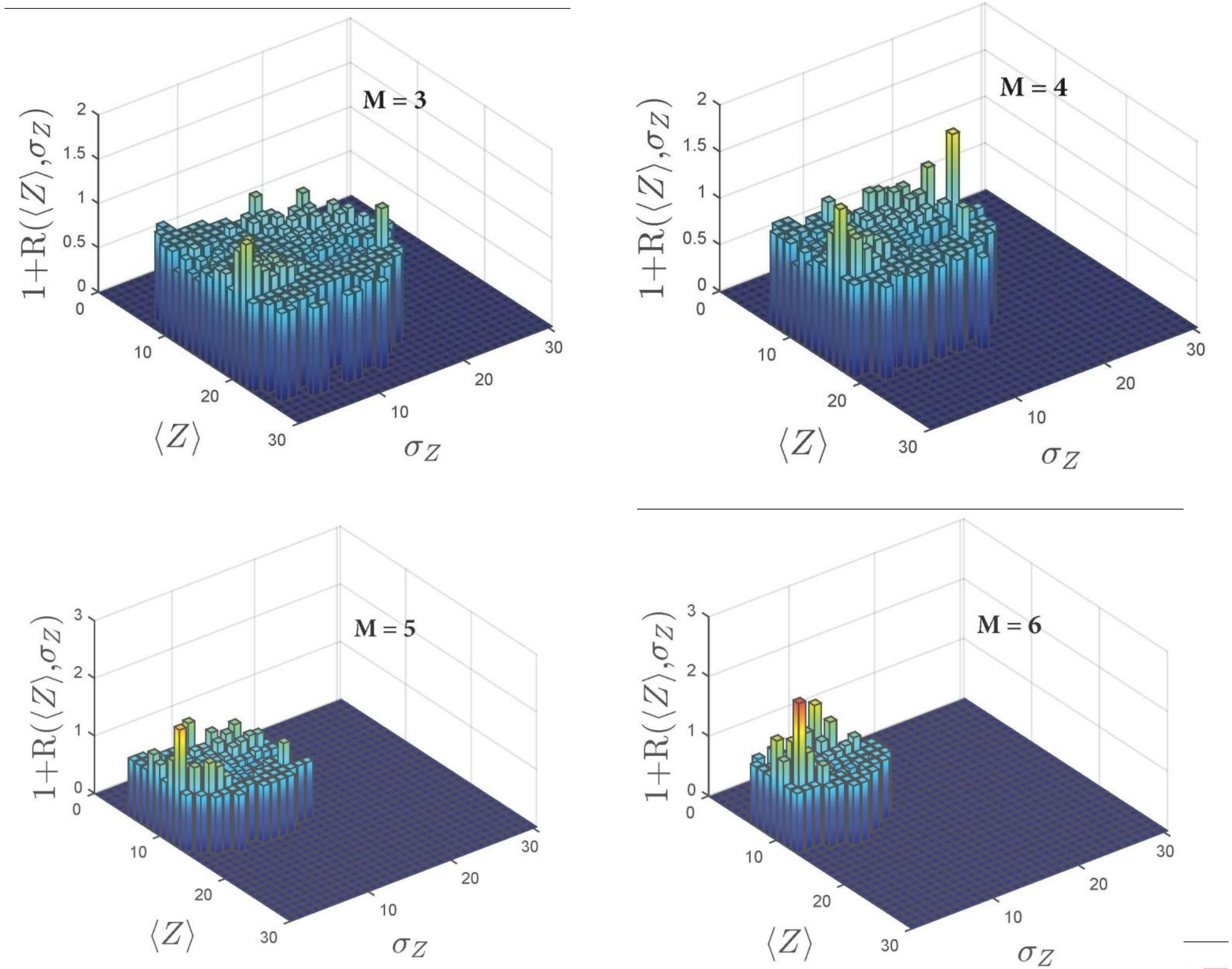
<Z> bin 1

$\sigma_Z$ bin 1

$\sigma_Z$ < 1
Peaks observed for

| $M_f$ | <Z> |
|---|---|
| 3 | 20-22 |
| 4 | 15-18 |
| 5 | 12-14 |
| 6 | 10-12 |

$M_f \times \langle Z \rangle \approx$ cste
as expected for
finite systems



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# Intra-event charge correlations – quasifusion nuclei

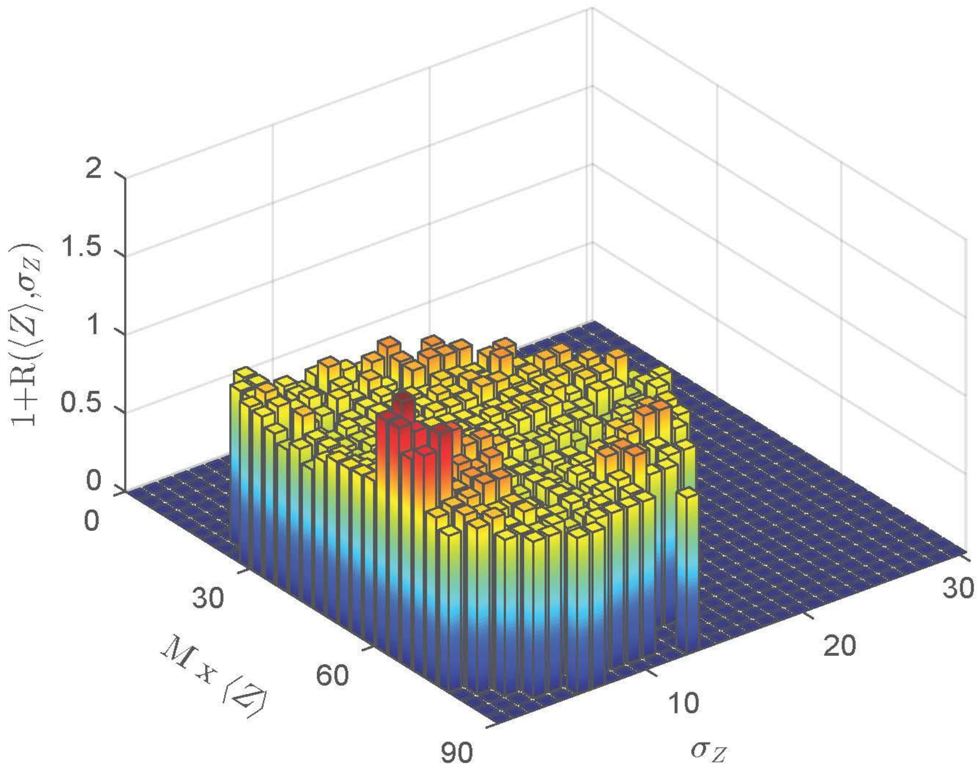
as partitions with nearly equal-sized frag. depending on M are observed
=> we can built CFs for all events whatever their multiplicity
by replacing <Z> by M x <Z>
uncorrelated yields constructed and weighted in proportion to events of each M

$^{124}$Xe + $^{112}$Sn 32 AMeV – M= 3-6 => CF signals ≈ 1.6 – 1.3

M x <Z> (bin = 3): peaks 60-63, 63-66, 66-69 and 69-72
$\sigma_Z$ < 1

significant peaks for
2 < $\sigma_Z$ < 1

broadening comes from deexcitation of primary fragments with around 3 AMeV excitation energy which generates an extra $\sigma_Z$ value of around one Z unit




BB et al. (INDRA Coll.), PLB 782 (2018) 291

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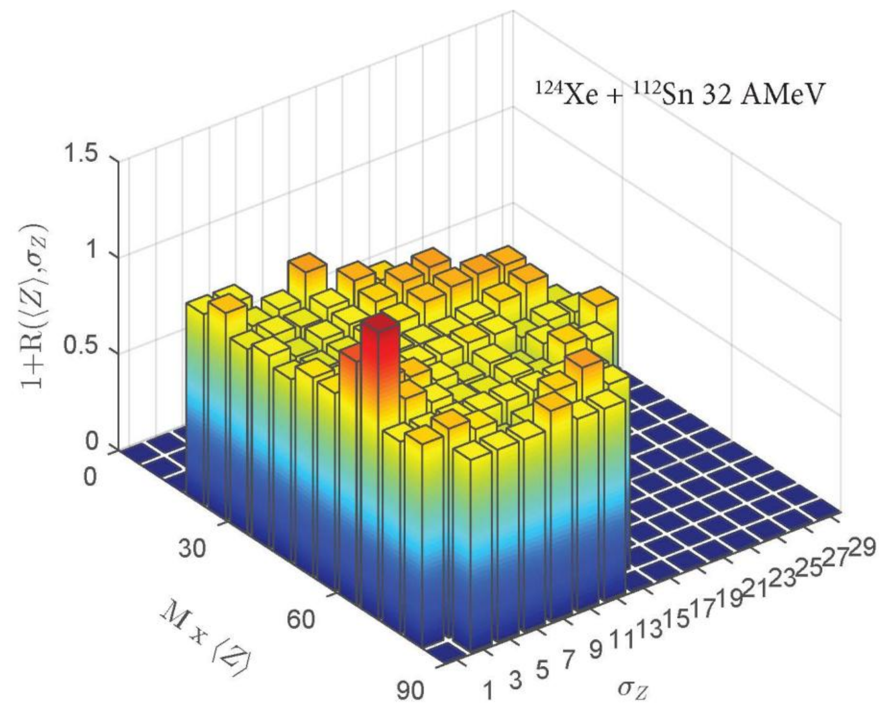
# same figure with M x <Z> - bin 6 and $\sigma_Z$ - bin 2

## conf. level CFs 6.1 and 7.3 σ

## signature: CFs = 1.27 and 1.50

M x<Z>
60-66 and 66-72

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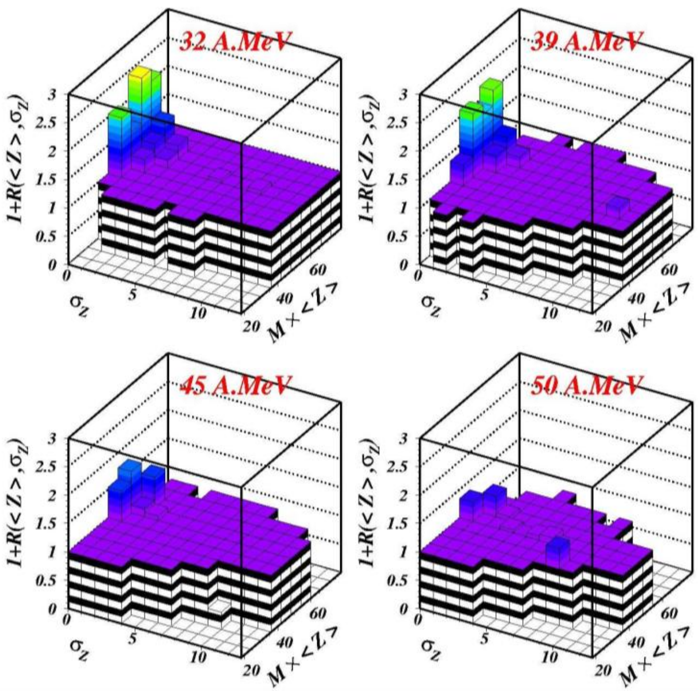
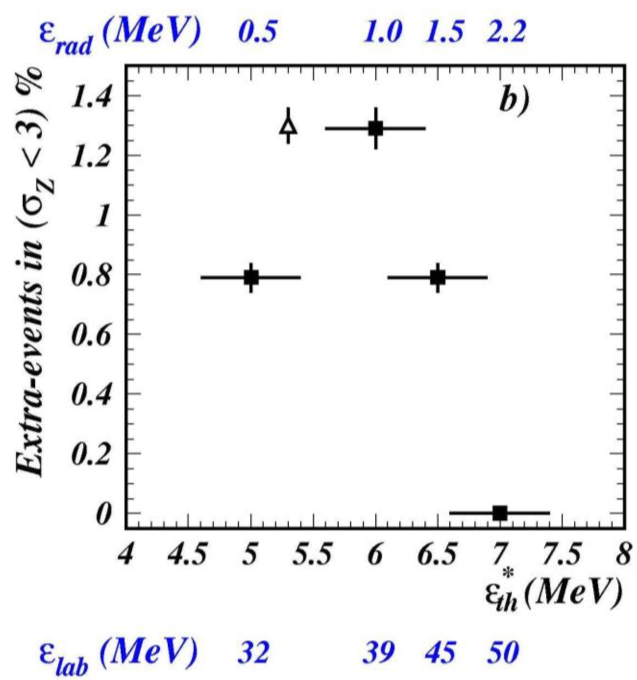
**fossil signature with confidence level of 2-3 σ (previous experiments)**

**(QF $^{129}Xe+^{nat}Sn$ 32-50 AMeV)**

**spurious peaks at low $\sigma_Z$ are present (low statistics)**

Variation of the incident energy from 32 to 50 AMeV and quantitative comparison with predictions of BOB ( open point).

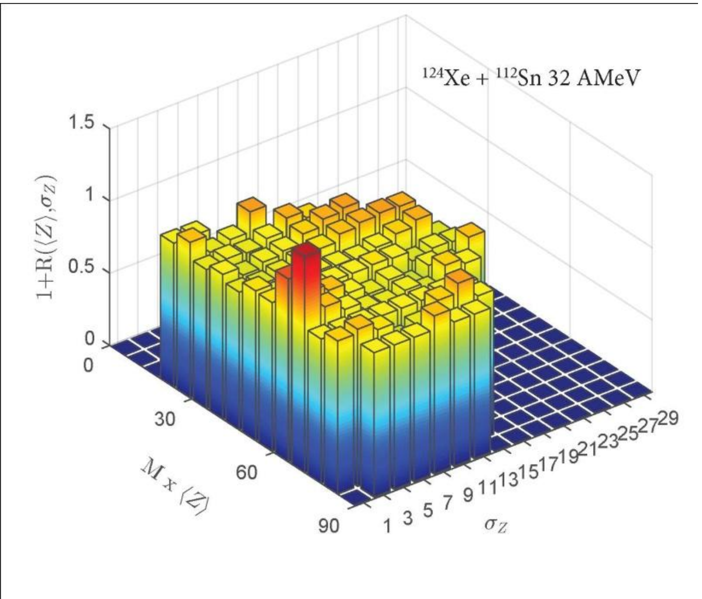


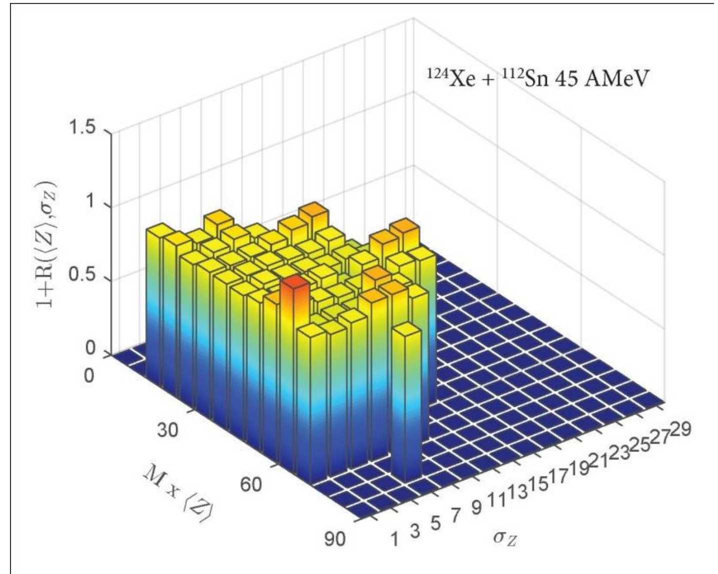

G. Tăbăcaru et al. EPJA 18 (2003) 103

B.B. et al. PRL 86 (2001) 3252

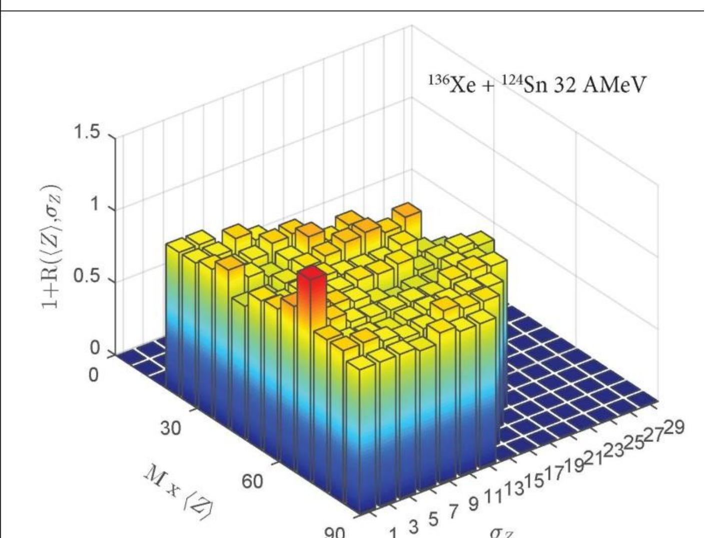
# Summary - figures with M x <Z> - bin 6 and $\sigma_Z$ – bin 2
# CF values 1.5 to 1.08 - conf. level CFs 2.08 to 7.29 σ



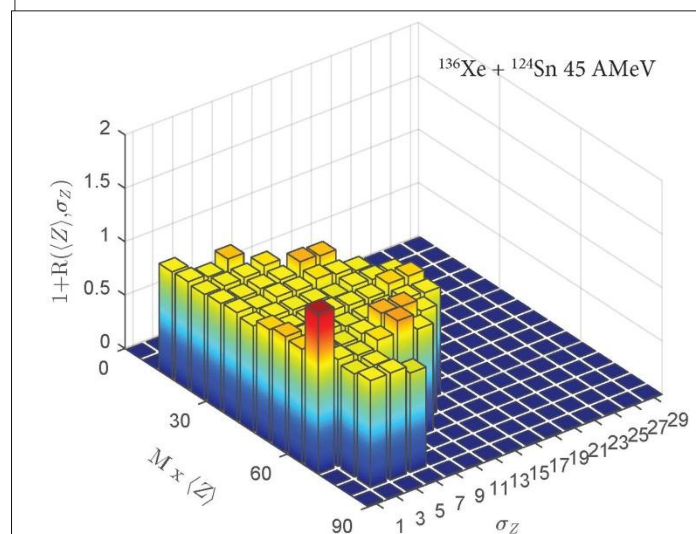

6.1σ
7.3σ




0.8σ
2.3σ




3.0σ
6.5σ




2.1σ

# Central collisions - quasifusion spinodales instab. and N/Z influence
## Summary

## To search for a possible very weak « fossil » signature?

Confirmation at a confidence level of 6-7σ that spinodal instabilities are present (32 AMeV).

The signature is a fossil signature and concerns only 0.068 – 0.064% of events at most

The finite size effects concerning the extra production of partitions with nearly equal-sized frag. and corresponding to different multipolarities are carefully observed on the four systems studied

## Can we observe a reduction of the signal with the increase of N/Z?

| Inc. Energy (AMeV) | | 32 | 45 |
|---|---|---|---|
| M x <Z> | | 60-72 | 54-66 |
| N/Z = 1.27 | | 0.068(0.004)% – 336 evts | 0.025(0.003)% - 77 evts |
| | total number of events | 494445 | 307161 |
| N/Z= 1.50 | | 0.064(0.004)% - 217 evts | 0.0065(0.0017)% - 15 evts |
| | total number of events | 335709 | 229835 |

At 45 AMeV a large reduction with the increase of N/Z is observed consistent qualitatively with the increase of the instability growth time and the reduction of the reaction time

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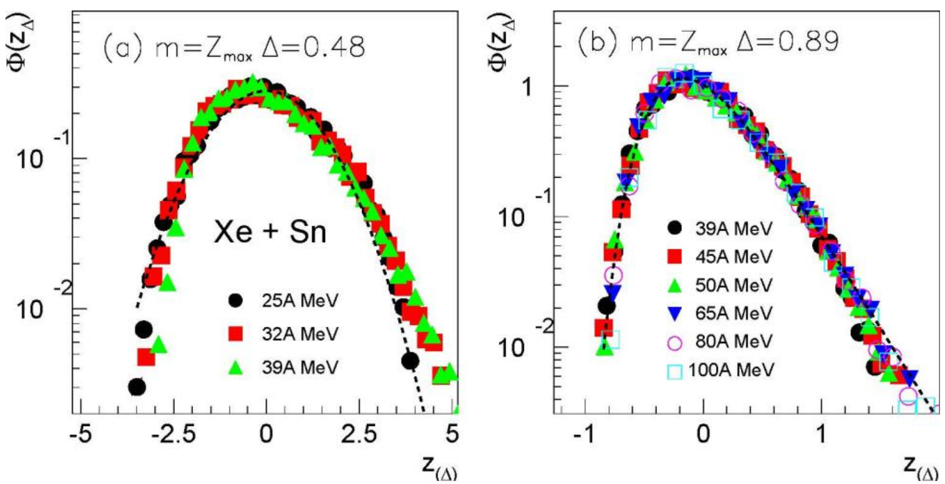
# Final comments
# Coherence of this signature with other signals

Universal fluctuations ($\Delta$-scaling) to determine order parameter, m, of PT
$\langle m\rangle^{\Delta} P(m) = \Phi((m-\langle m\rangle)/\langle m\rangle^{\Delta})$   $\langle m\rangle$ is the mean value of the distribution P(m)
$\Delta=1/2$ ($\sigma^2_m \sim \langle m\rangle$) -> $\Delta=1$ ($\sigma^2_m \sim \langle m\rangle^2$) should be observed

Central $^{129}Xe+^{nat}Sn$ collisions $m=M_{tot}$ no – $m=Z_{max}$ yes




$\Delta$ changes ~ 39 AMeV
quasi-gaussian to gumbellian

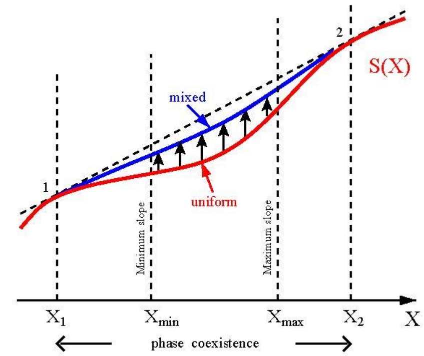
J.D. Frankland et al. (INDRA and ALADIN coll.) PRC 71 (2005) 034607

$Z_{max}$ is an order parameter => aggregation scenario coherent with spinodal fluctuations occuring in the hot expanding nuclear matter formed in collisions

Liquid-Gas phase transition in nuclei, BB and J.D. Frankland, Prog. Part. Nucl. Phys. 105 (2019) 82

# Coherence of this signature with other signals

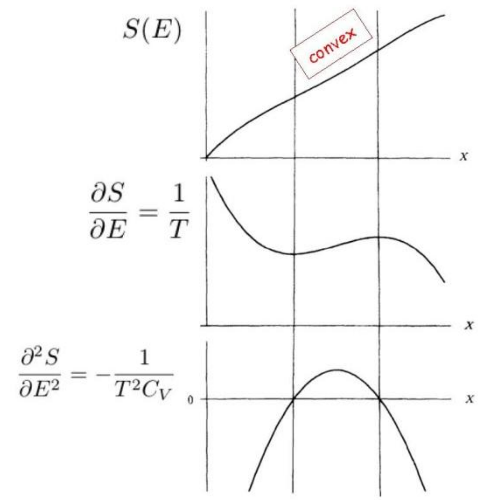
## Convexity of entropy and spinodal zone ($X_{min}$ -> $X_{max}$)




P. Chomaz, M. Colonna, J. Randrup Phys. Rep. 389 (2004) 263

**Predicted specific signals of phase transition which are a direct consequence of the local convexity of entropy expected for finite systems have been observed.**

**negative heat capacity with a microcanonical sampling**



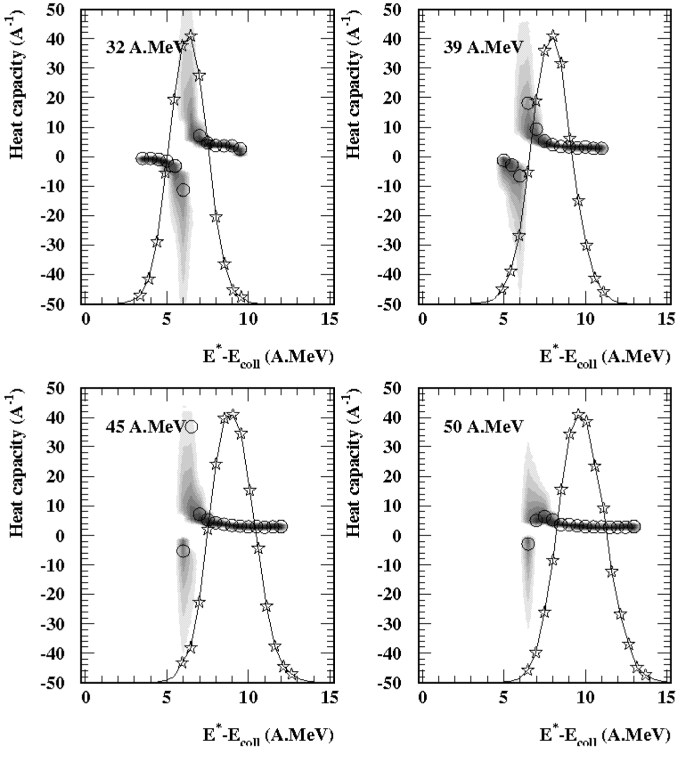

Liquid-Gas phase transition in nuclei,
BB and J.D. Frankland, PPNP 105 (2019) 82

# Correlation between negative heat capacity signal and spinodal signal
## ($^{129}Xe$ + $^{nat}Sn$)

32 AMeV: deeply in the spinodal region

45 AMeV: at the border of the spinodal region

⇒Good agreement with spinodal signals

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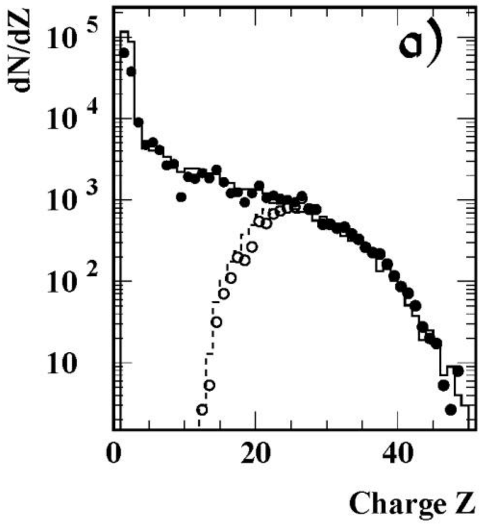
# Final comments
## Spinodal instabilities: dominating role? and chaoticity

Due to the weakness of the signature: it could be that even if spinodal inst. are present they are not the only ones to produce fragments.

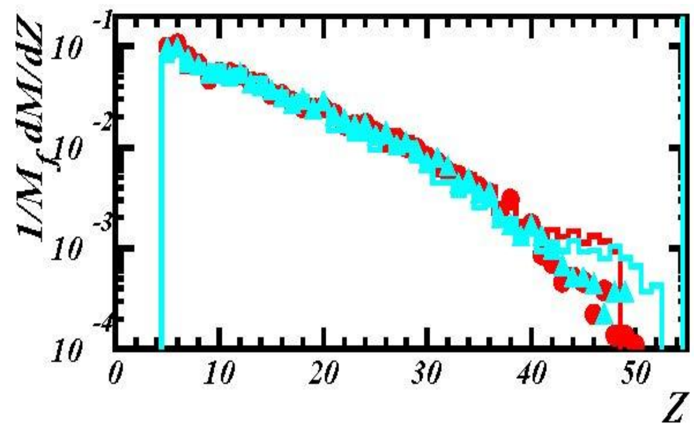
Chaoticity driven by spin. inst. (beating of modes, breaking of translational symmetry, coalescence) but also from fluctuations due to many-body correlations (AMD).

Dynamics is filling at least a large part of phase space, it is why both statistical (SMM) and dynamical (BOB) models are able to well reproduce fragment production




$^{129}Xe+^{nat}Sn$ 32AMeV quasifusion

<- SMM BOB ->




BB, J.D. Frankland, PPNP 105 (2019) 82

**Can we have reliable quantitative values from transport theory for % of extra events? => A challenge to transport theory**

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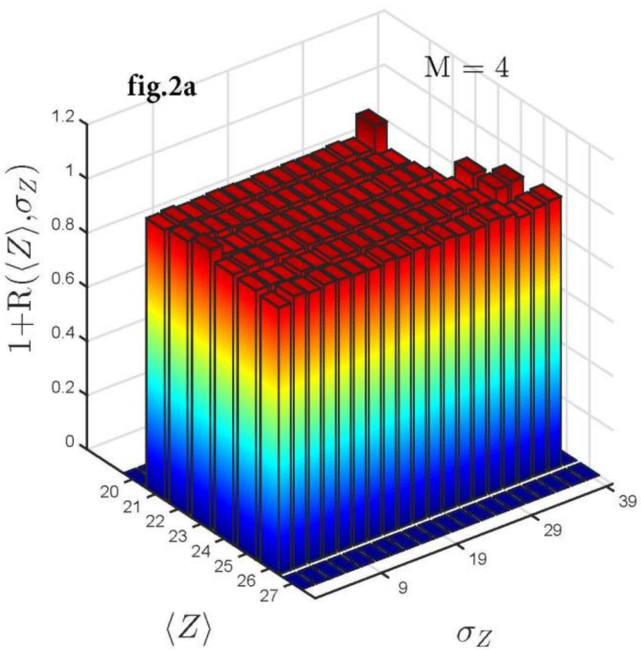
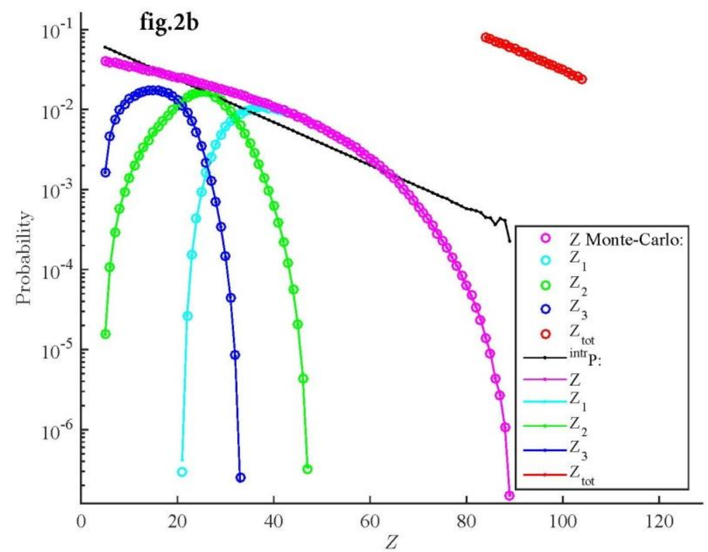
# sensitivity of the intrinsic probability method

**Monte Carlo simulation – events >= 80% of Zsystem=104 – fragments Z>4 charged reaction products produced according to P(Z) prop.to exp(-0.1Z)**

300000 events => CF values in the range 0.95-1.05 for low $\sigma_Z$ (<2)

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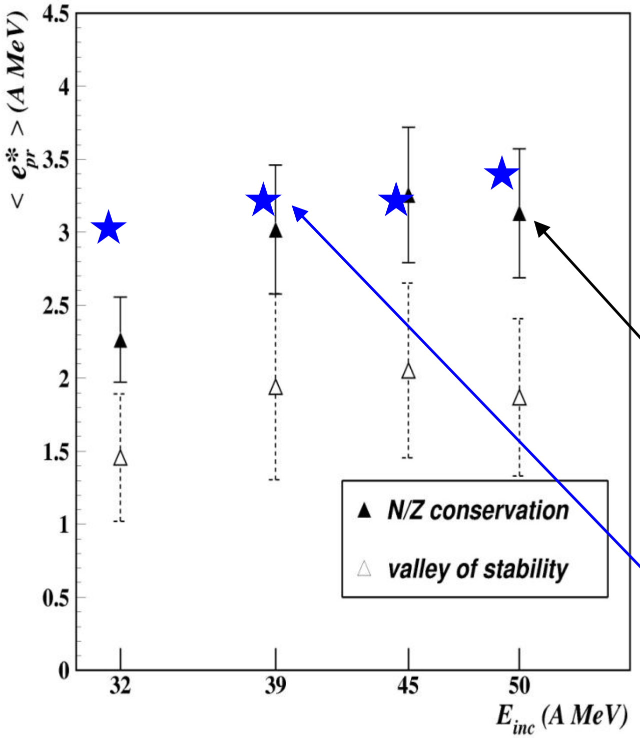
# E* of primary fragments




QF: Xe + Sn  32-50AMeV

‹E*› limited to ~ 3-3.5 MeV

deduced from fragment-particule correlations
S. Hudan et al., PRC 67 (2003) 064613

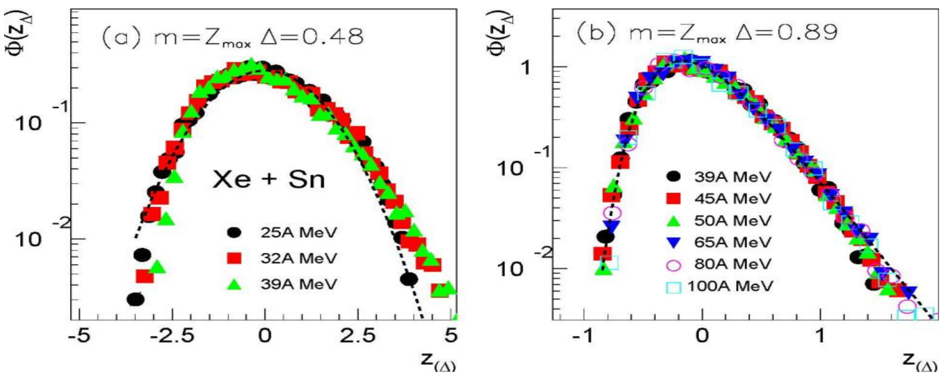
simulation

and 20% (60%) of measured LCP are emitted at the freeze out stage for multifragmenting hot nuclei with an excitation energy of 5.5 (9.0) AMeV

S.Piantelli et al., NPA 809 (2008) 111

# Coherence of this signature with other signals

**Central $^{129}Xe+^{nat}Sn$ collisions** $m=M_{tot}$ no – $m=Z_{max}$ yes




Δ changes ~ 39 AMeV

J.D. Frankland et al. (INDRA and ALADIN coll.) PRC 71 (2005) 034607

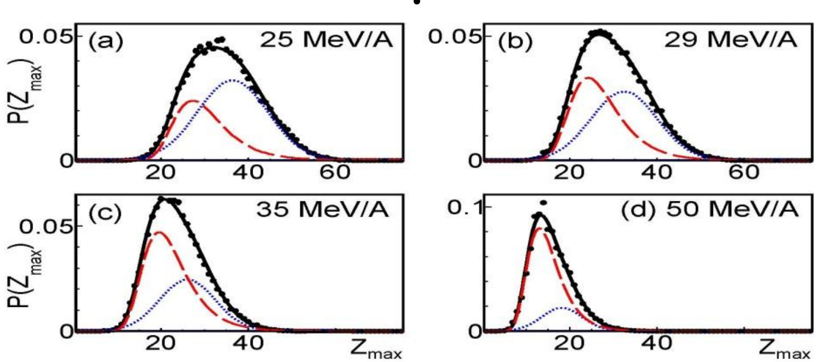
Gumbel distr.: $\Phi(m) \sim \exp(-m-\exp(-m))$ exponential tail on the extremal side

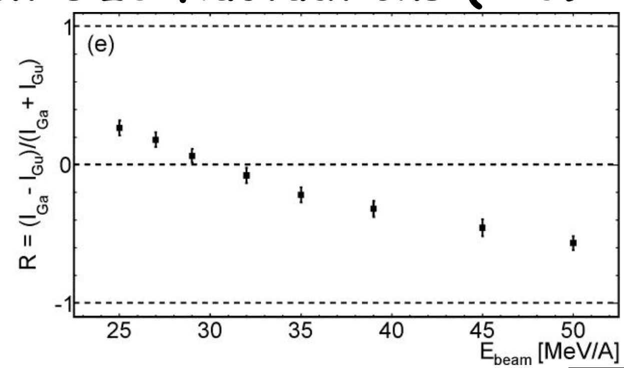
Irreversible aggregation model (Smoluchowski equation)

$P(Z_{max}) = (R+1)/2.f_{Gauss}(Z_{max}) + (1-R)/2.f_{Gumbel}(Z_{max})$

composition of fit evolves in a regular way from gaussian to gumbellian

R ≈ -0.45 corresponds to maximum frgment size fluctuations (~ 39 AMeV)




Liquid-Gas phase transition in nuclei, BB and J.D. Frankland, Prog. Part. Nucl. Phys. 105 (2019) 82

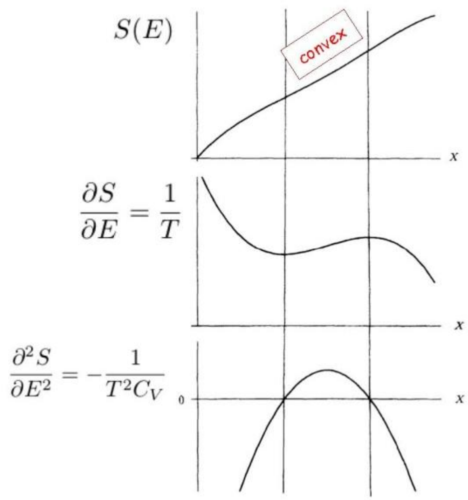
Bernard Borderie

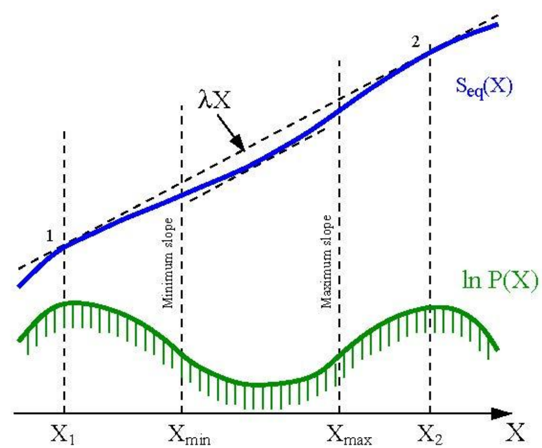
ECT Trento May 20-24 2019

INSTITUT DE PHYSIQUE NUCLÉAIRE ORSAY

# Coherence of this signature with other signals

Negative heat capacity with a microcanonical sampling and related
Backbending for pressure-constrained caloric curves
Bimodal distribution of an order parameter (charge of the heaviest fragment) with a canonical sampling



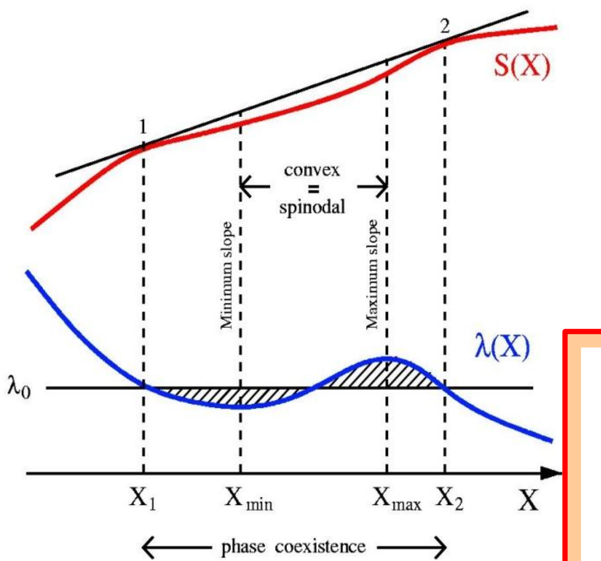

Liquid-Gas phase transition in nuclei, BB and J.D. Frankland, PPNP 105 (2019) 82

# Finite syst. and first order phase transition
# convexity of entropy

**X** extensive variable
(E, N, V)

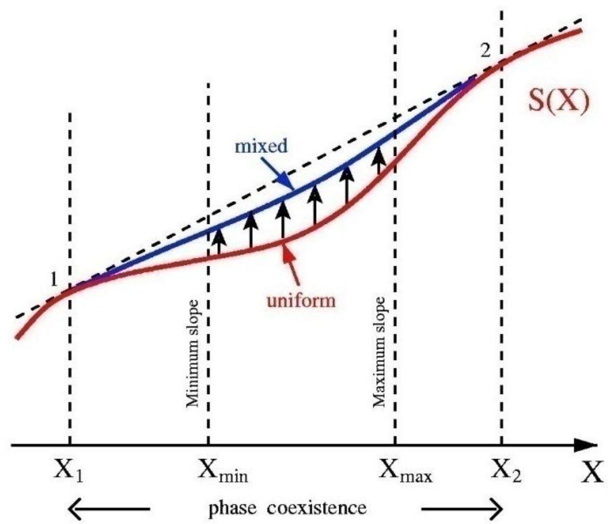
Conjugate
intensive variable
$\lambda(\mathbf{X}) = \partial S / \partial X$
(1/T, - μ/T, P/T)

## NEGATIVE HEAT CAPACITY

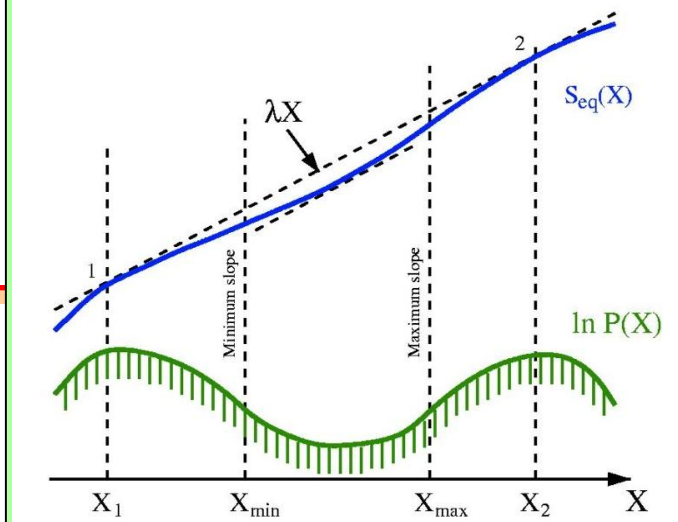



μ canonical sampling
(Fixed value of X)

## SPINODAL INSTABILITY




## BIMODALITY




Canonical-Gaussian sampling

$P(X) \sim \exp(S(X) - \lambda X)$

**Ph. Chomaz et al., Phys. Rep. 389**