How **volume** and **surface** *instabilities* *rival* in heavy-ion collisions

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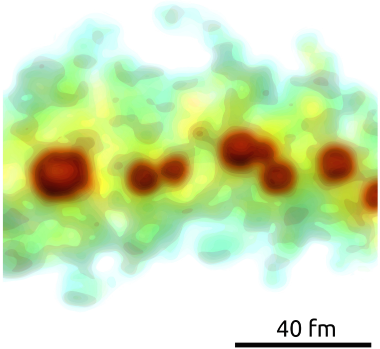
...in three steps :

1) *NM* : *"EOS view"* : Nucl. interaction leads to clusterisation at $\rho < \rho_{\mathrm{sat}}$
→ *microscopic time-dependent view* : modelling volume fluctuations (in a one-body approach)

2) *open systems* : + surface fluctuations

3) *HIC* : volume + surface instabilities
→ what happens ?



BLOB, ^{36}Ar+^{58}Ni, 74 *A*MeV, 280 fm/c

Modelling instabilities in mean-field extensions

For one mean-field trajectory n in τ_{BL} :

Stochastic-TDHF scheme

$$i\hbar \frac{\partial \rho_1^{(n)}}{\partial t} \approx [k_1^{(n)} + V_1^{(n)}, \rho_1^{(n)}] + \overbrace{\bar{I}_{coll}^{(n)}}^{\text{average coll. term}} + \underbrace{\delta I_{coll}^{(n)}}_{\text{fluctuating coll. term}}$$

after τ_{BL}, it yields $\rho_1^{(n)} \rightarrow \{\rho_1^{(n_\lambda)}; \lambda = 1, \ldots \text{sub}_\lambda\}$

[Reinhard,Suraud AnnPhys 216 (1992) ; AnnPhys 355 (2015)
Lacombe,Reinhard,Suraud,Dinh AnnPhys 373 (2016)]

Wigner tr. →

Boltzmann-Langevin

$f^{(n)}$: distribution functions
→ Fermi stat. at equilibrium

$$\frac{\partial f^{(n)}}{\partial t} = \{h^{(n)}, f^{(n)}\} + I_{UU}^{(n)} + \delta I_{UU}^{(n)}$$

Markovian contrib. :

$$\langle \delta I_{UU}^{(n)}(\mathbf{r}, \mathbf{p}, t) \delta I_{UU}^{(n)}(\mathbf{r}', \mathbf{p}', t') \rangle =$$
$$= \textbf{gain} + \textbf{loss} = 2\mathcal{D}(\mathbf{r}, \mathbf{p}; \mathbf{r}', \mathbf{p}', t')\delta(t - t')$$

[Ayik,Grégoire PLB212(1988) ; NPA513(1990)
Colonna,Chomaz,Randrup NPA567(1994)]

Boltzmann-Langevin One Body

$$\frac{\partial f^{(n)}}{\partial t} - \{h^{(n)}, f^{(n)}\} = I_{UU}^{(n)} + \delta I_{UU}^{(n)} = g \int \frac{d\mathbf{p}_b}{h^3} \int W(\text{AB}\leftrightarrow\text{CD})\, F(\text{AB}\rightarrow\text{CD})\, d\Omega$$

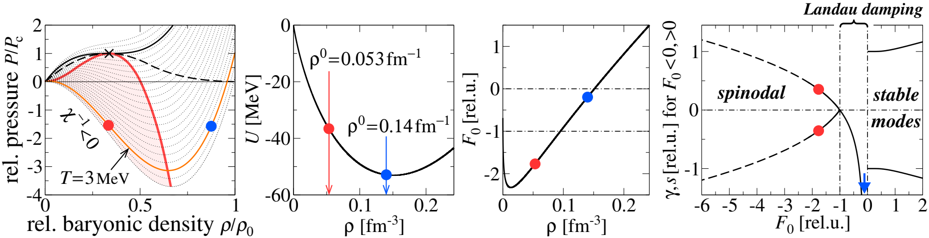
transition rate; occupancy

$$W(\text{AB}\leftrightarrow\text{CD}) = |v_A - v_B| \frac{d\sigma}{d\Omega} \; ; \quad F(\text{AB}\rightarrow\text{CD}) = \Big[(1-f_A)(1-f_B)f_C f_D - f_A f_B (1-f_C)(1-f_D)\Big]$$

A, B, C, D : extended equal-isospin phase-space portions of size=nucleon imposed by the variance $f(1-f)$ in h^3 cells at equilibrium

[Napolitani,Colonna PLB726 2013 ; PRC96 (2017)]

Clusterisation in zero-sound conditions in NM



unstable conditions : [POMARANCHUK (1959)]

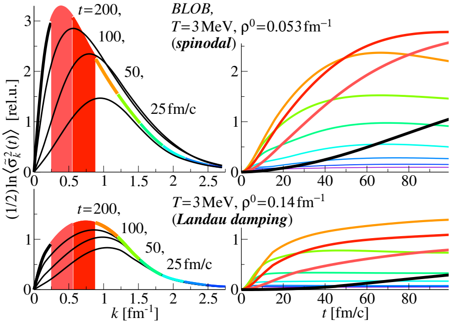
$$\chi^{-1} \equiv \rho\frac{\partial P}{\partial \rho} = \frac{2}{3}\rho\epsilon_F[1+F_0(k=0)] < 0$$

$$\Rightarrow F_0(k=0) < -1$$

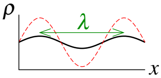
$\Rightarrow$ imaginary solutions $\gamma = is$ from

$$1 + \frac{1}{F_0(k)} = \gamma \arctan\frac{1}{\gamma}$$

$$\rightarrow |\gamma| = \frac{|\omega_k|}{kv_F} = \frac{1}{\tau_k k v_F}$$



$\Rightarrow$ disturbance k amplified with growth rate $\Gamma_k = 1/\tau_k$



From nuclear matter to open systems

- *NM* : unstable EOS sites →

→ dispersion relation : growth rate $\Gamma_{k,\mathrm{vol}}$ *for volume-unstable modes k*

$$1 + \frac{1}{\tilde{F}_0(k,T)} = \frac{\Gamma_{k,\mathrm{vol}}}{k v_F} \arctan\left(\frac{k v_F}{\Gamma_{k,\mathrm{vol}}}\right)$$

k-distribution presents UV cutoff as a function of the interaction range

$$U \to U \otimes g(k), \text{ with } g(k) = \mathrm{e}^{-\frac{1}{2}(k\sigma)^2}$$

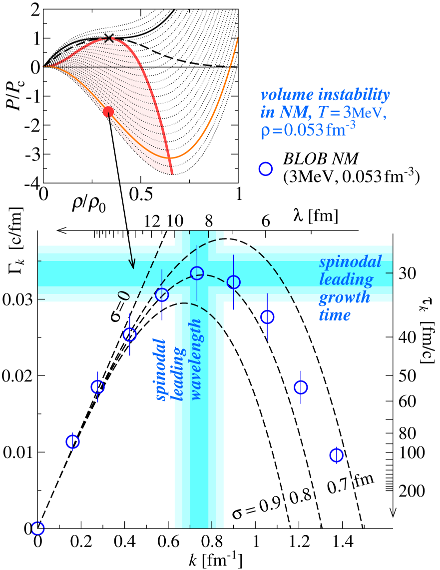
[Colonna,Chomaz PRC49 (1994) ; Kolomietz,Shlomo PRC60 (1999) ; Napolitani,Colonna PRC96 (2017)]

- Open systems : surface added

→ ruled by the same interaction term that imposes UV cutoff for k

⇒ fluctuations also act on surface

→ Rayleigh behaviour in addition to volume perturbations



Implementation

*simplified SKM** [Guarnera,Colonna,Chomaz PLB373 (1996)]

$$\frac{E_{\mathrm{pot}}}{A}(\rho) = \frac{A}{2}u + \frac{B}{\sigma+1}u^{\sigma} + \frac{C_{\mathrm{surf}}}{2\rho}(\nabla\rho)^2 + \frac{1}{2}C_{\mathrm{sym}}(\rho)u\beta^2$$

$K = 200$ MeV (soft) ; $C_{\mathrm{sym}}(\rho) = 32$(asy-stiff)

- momentum dependence omitted

residual term

- E-dependent screened σ_{NN} [Coupland Lynch Tsang Danielewicz Zhang PRC84 (2011)]

BLOB) $\delta I \longrightarrow$ fluct. in full phase space

or a simplified form :

SMF) $\delta I \longrightarrow$ separately treated as a stochastic force related to U_{ext}

$\Rightarrow$ fluctuations projected on spacial ρ

or a truncated form :

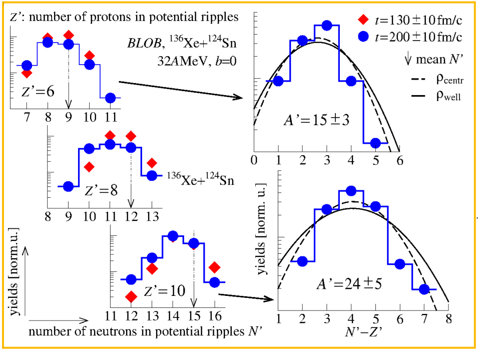
SMF-collisionless) $\delta I \longrightarrow$ from mean-field noise,

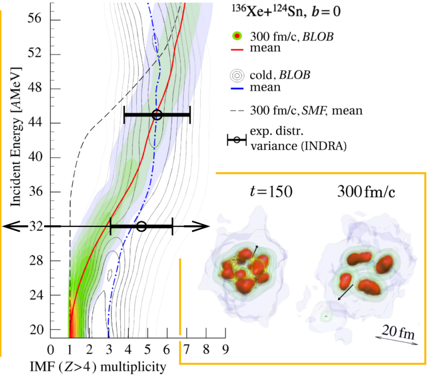
no collisional contributions

Simulation of a spinodal process in an open system

To isolate volume perturbations : central coll. at Fermi energy inducing large stopping, isotropy, $\rho \ll \rho_{\rm sat} \rightarrow {}^{136}$Xe+^{124}Sn 32$A$MeV [Borderie PLB782 (2018)]

- *Isoscalar* : isotropic disintegration into clusters around C and Ne
- *Isovector* : variance δ^2 of $N' - Z'$ distr. of potential ripples in accordance with the fluctuation-dissipation th. : $Y \approx \exp[-(\delta^2/A')\, C_{\rm sym}(\rho)/T]$
- *Distillation behaviour* : $< N' - Z' >$ more n-rich in more volatile phases





Simulation of a Plateau-Rayleigh process in an open system

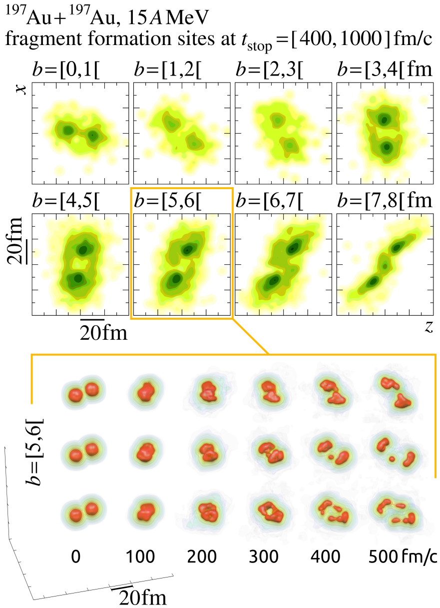
To isolate surface instabilities :

toroidal topologies (! ! ! !)
→ symmetric semiperipheral coll. below Fermi energy with heavy system, to keep T low and $\rho \sim \rho_{sat}$
→ ^{197}Au+^{197}Au 15AMeV

[Chimera : Skwira-Chalot et al. PRL101 (2008)]

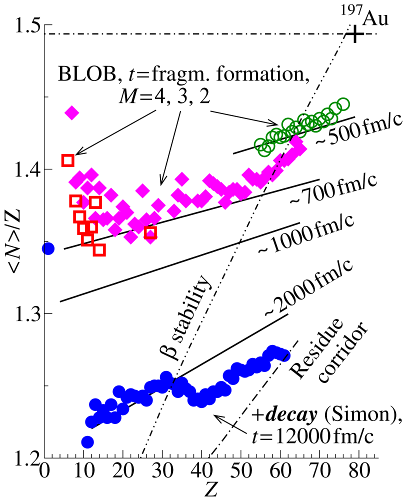
- *BLOB* : b=[5to6]fm : toroidal-like config. breaks into 2, 3, 4 fragments
  [Sainte-Marie, stage (2018)]

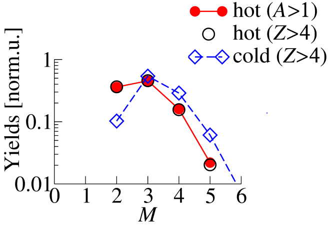
- *SMF* : similar pattern at 23AMeV but fragment separation not achieved [Rizzo Colonna Baran DiToro PRC90 (2014)]

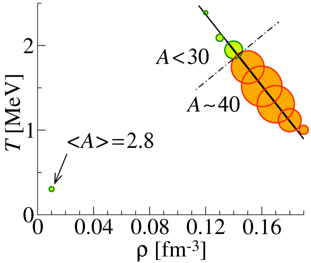


Close-up on clusterisation along arc-like formations

^{197}Au+^{197}Au, 15 AMeV, b=[5,6], ***BLOB***







- large rate of ternary/quaternary splits at t > 500fm/c
- isospin : fission-like, small $\nabla\rho$, no distillation $\leftrightarrow$ $\rho \sim \rho_{\rm sat}$

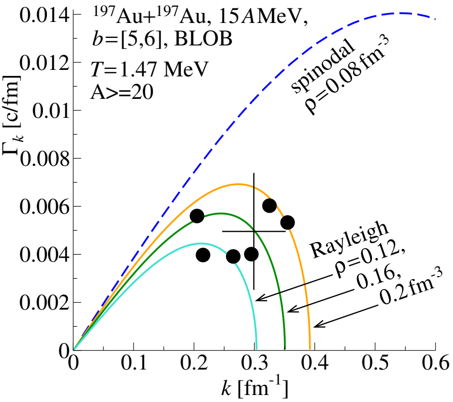
Plateau-Rayleigh instability close to normal density

Analytic (lines) :
Ideal dispersion relation for a columnar configuration of radius r (average neck size), associated to the surface tension γ
[Brosa Grossmann Müller PRep197 (1990)]

$$(\Gamma_{k,\text{surf}})^2 = \frac{\gamma}{\rho r^3} \frac{I_1(kr)}{I_0(kr)} kr(1 - k^2 r^2)$$

• γ should take into account :
ρ_{local}, ρ_n, ρ_p [Iida Oyamatsu PRC69 (2004)] and T

Numeric (dots) :
direct cluster-correl. 1st-o analysis : (timing from inhomogeneity growth, geometry from ρ-distributions of nucl. necks)



• Au+Au : Rayleigh process, well distinct from spinodal behaviour (larger times, larger wavelengths)

Phenomenology of "nuclear jets"

To compose conditions for volume and surface instability :

asymmetric central collisions around (or above) Fermi energies
→ ^{36}Ar+^{58}Ni 74AMeV

SMFcl, *collisional dissip. / fluct. OFF*

- 1 to 3 IMF among two bulges
- neutron flow towards midrapidity

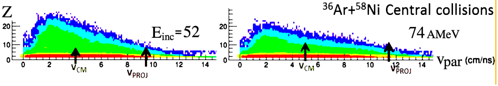
BLOB, *all fluctuations activated*

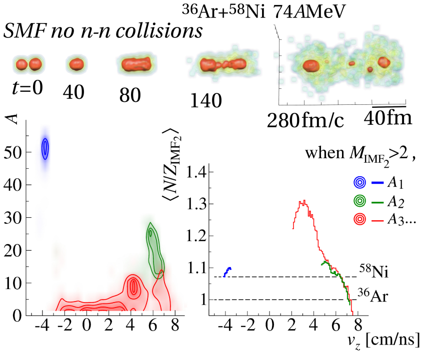
- comp.nucl. (QT) + forward jet

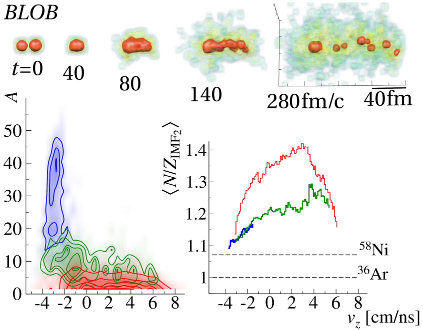
⇒ collimated stream of LCP/IMF, *Z* up to ≈ 10, *A* decreasing forward

- *n*-enrichment hierarchy : A_1,A_2,A_3

exp : L.Francalanza IOPConf.Ser.863(2017)012061 :





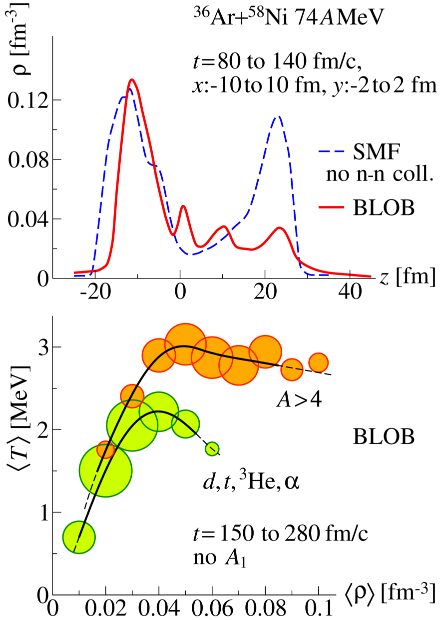


Imposing competing conditions : low ρ+ high anisotropy

• *BLOB vs SMFcl* :
Huge $\nabla\rho$ in both approaches, but opposite isospin behaviour (distillation vs migration) reflecting opposite size ordering.

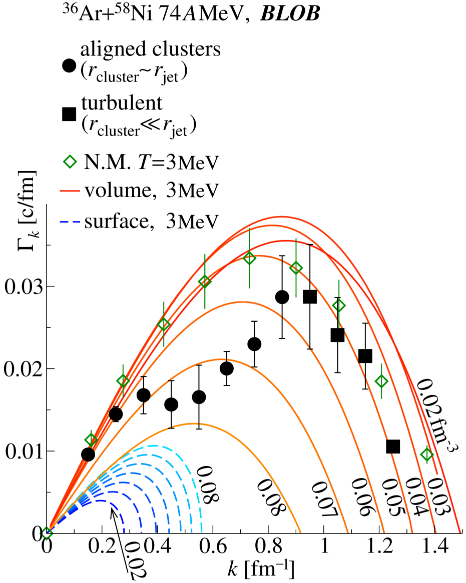
• *BLOB* :
significant ρ drop, involving the spinodal region ($A > 4$) and even below for $d, t, {}^3$He$, \alpha$

→ Dispersion relation can be evaluated (1st o. approx) from the forward section of the stream of clusters from ρ, T conditions.



Surface-volume competition in terms of $\rho - k - \Gamma$

- similar to NM calculation at comparable ρ, T conditions
- *"granular behaviour"* : clearly outside of the surface instability region → clusterisation from volume instabilities despite the highly deformed topology
- combination of different values of ρ → maximum shifts to smaller wavelengths → lighter cluster production
- At small k possible signature from combination between surface and volume contributions



Conclusions

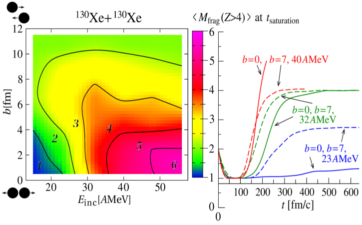
• *In modelling*,
different types of instabilities
(surface/volume)
act differently on observables
(A hierarchy, chronology, sizes, isospin...)

⇒ Disregarding their competition may yield large uncertainties

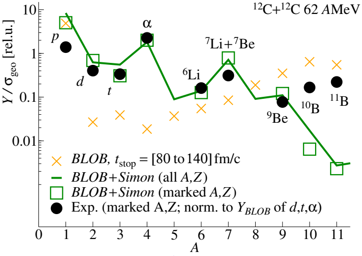
• *In experiments*, [*speculative ! ! !*]
inducing conditions for competing instabilities may be an attempt to prepare systems at low density with custom dynamical conditions (deformation, ρ, T,...)

Overview on dissipative HIC with BLOB

fragments → isotropic bulk instability to stretched topologies



clusters (from potential ripples)



[DATA : M.DeNapoli et al Phys.Med.Biol 57 7651 (2012)]

Central / peripheral (BLOB) :