How nuclear jets form and disintegrate into clusters in heavy-ion collisions

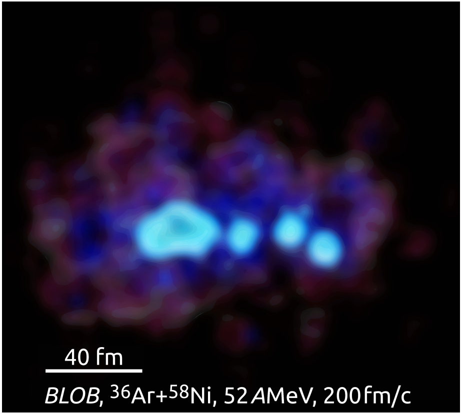
P. Napolitani, M. Colonna

1) "Nuclear jets" ?
   When Heavy-Ion Collisions (HIC) produce a stream of nuclear clusters and IMF

2) Modelling jets…
   and breaking them up

3) A few calculations in practice

4) Which conditions produce them ?
   Which instabilities break them up ?



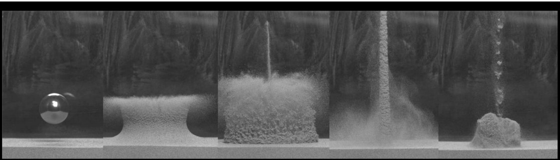
BLOB, ^{36}Ar+^{58}Ni, 52 *A*MeV, 200 fm/c

IWM-EC Catania 24 May 2018

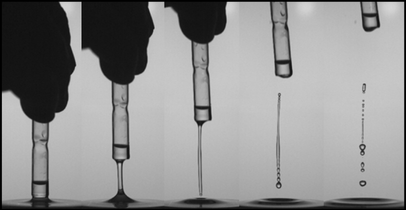
Jets, in nature

- *Jets*: widely encountered in nature from microphysics to cosmic scale

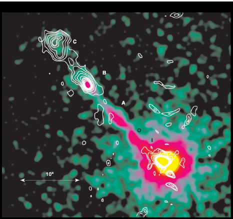
→ large variety of non-linear behaviours and
rupture mechanisms from very different sources of instabilities :



splash and granular eruption in send
Lohse et al. PRL93 198003



ligament from a dripping pipette,
Eggers & Villermaux Rep.P.Phys.71 036601

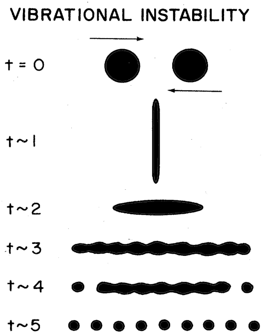


jet in quasar PKS 1127-145
X-ray, *harvard.edu*

Mach diamonds in the exhaust
Nasa

Jets, in nuclear physics ?

- Ultimate deformation in HIC : collimated flows of nucl. matter recalling jet dynamics
- HIC pioneers I : LCP (Fermi jets...[Bondorf PLB84(1979)])
- HIC pioneers II : IMF from surface instability à la Rayleigh [Da Vinci !, Savart, Plateau, Rayleigh, Chandrasekhar...]
  → emblematic to explain any stretched formation
  → usual practice in dissipative HIC : associating *columnar-like topologies to Plateau-Rayleigh* (PR) instability [Brosa,Grossman,Müller Phys.Rep.197 (1990) 167], at variance with *isotropic expanded topologies, associated to volume* (spinodal) instability [Chomaz,Colonna,Randrup PhRep 389 (2004) ; Ayik, Borderie...]
- Could nuclear jets arise from mechanisms unrelated to cohesive properties ?
  → microscopic insight on the type of instability



1976 visionary Griffin's proposal [R.Mod.Ph.48 467] *of a water-jet-like stretch in nuclear collisions, citing* [Adam et al. Appl.Ph.39 5173]

Handling instabilities in mean-field extensions

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

Stochastic-TDHF scheme

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

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)]

$\xrightarrow{\text{Wigner tr.}}$

Boltzmann-Langevin

$f^{(n)}$: distribution functions

→ Fermi stat. at equilibrium

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

Markovian contrib. : ↓

$$\langle\delta I_{\text{UU}}^{(n)}(\mathbf{r},\mathbf{p},t)\,\delta I_{\text{UU}}^{(n)}(\mathbf{r}',\mathbf{p}',t')\rangle=$$

$$=\textbf{gain}+\textbf{loss}=2\mathcal{D}(\mathbf{r},\mathbf{p};\mathbf{r}',\mathbf{p}',t')\,\delta(t-t')$$

[Ayik,Grégoire PLB212(1988) ; NPA513(1990)

Colonna,Chomaz,Randrup NPA567(1994)]

↓

Boltzmann-Langevin One Body

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

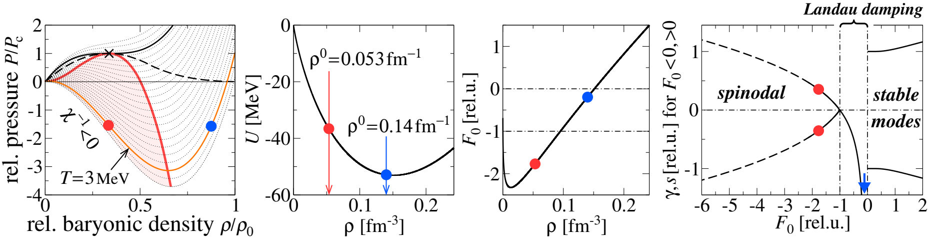
transition rate occupancy

$$W(\text{AB}\leftrightarrow\text{CD})=|v_{\text{A}}-v_{\text{B}}|\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega}\;;\quad F(\text{AB}\rightarrow\text{CD})=\Big[(1-f_{\text{A}})(1-f_{\text{B}})f_{\text{C}}f_{\text{D}}-f_{\text{A}}f_{\text{B}}(1-f_{\text{C}})(1-f_{\text{D}})\Big]$$

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]

Instabilities in zero-sound conditions in NM



unstable conditions : [Pomaranchuk (1959)]

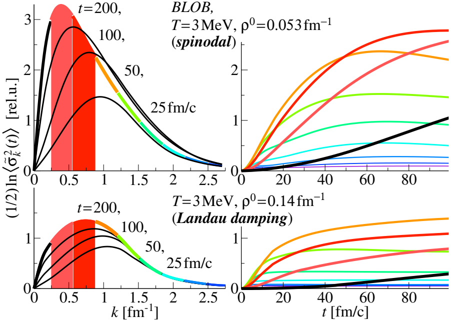
$$\chi^{-1} \equiv \rho\frac{\partial P}{\partial \rho} = \frac{2}{3}\rho\epsilon_F[1+F_0(k=0)] < 0$$

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

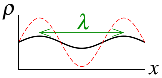
⇒ imaginary solutions $\gamma = is$ from

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

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



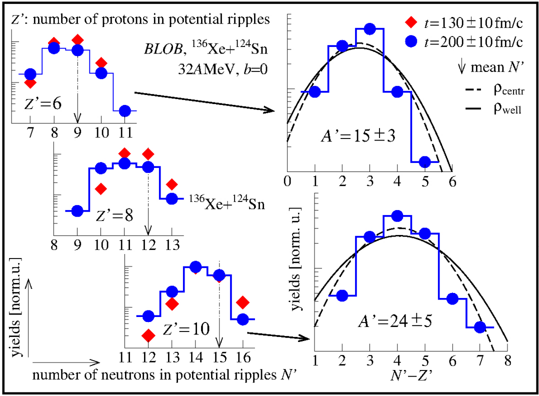
⇒ disturbance k amplified with growth rate $\Gamma_k = 1/\tau_k$

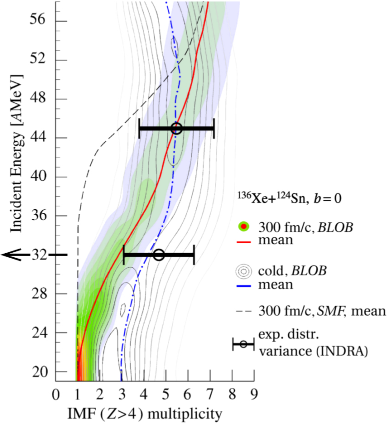


Isospin of emerging fragments in open systems

$N'-Z'$ distr. for forming clusters around C and Ne, before and during fragment formation :

$$Y \approx \exp[-(\delta^2/A')\,C_{\mathrm{sym}}(\rho)/T]$$

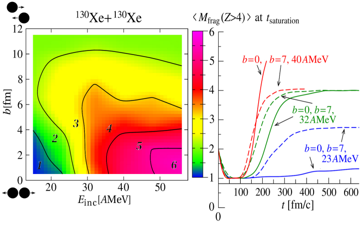




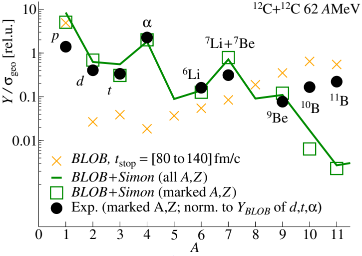
Overview on dissipative HIC with BLOB

fragments → isotropic bulk

instability to stretched topologies

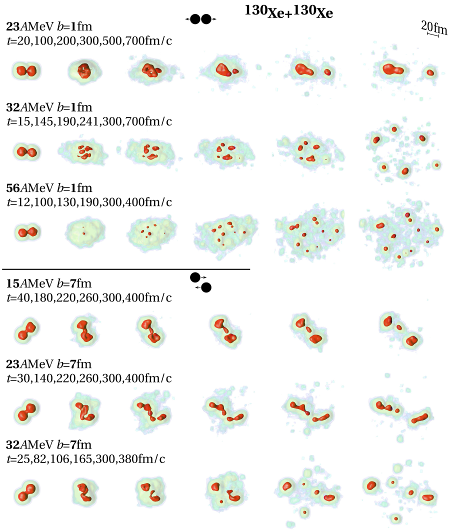


clusters (from potential ripples)



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

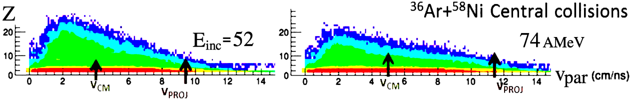
Central / peripheral (BLOB) :



Case : *projectile* + *heavier target* in the *Fermi* domain, $b = 0$

Exp, *new analysis* Ar+Ni@*INDRA*

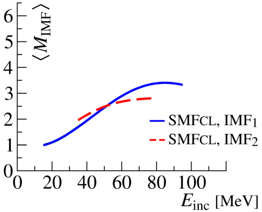
from L.FRANCALANZA IOP CONF.SER.863(2017)012061 :

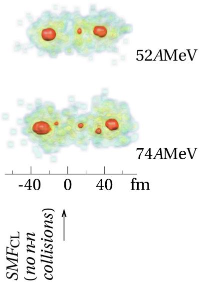


- Mostly at 52 to 74*A*MeV → no QP
- stream of IMF with *Z* up to≈10

SMFcl, *collisional dissip. / fluct. OFF*

- 1 to 3 IMF among two bulges
- similar multiplicity of *'IMF1'(w/o n, p)* and *'IMF2'(w/o n, p, d, t, ^{3}He, α)*





^{36}Ar+^{58}Ni
260fm/c

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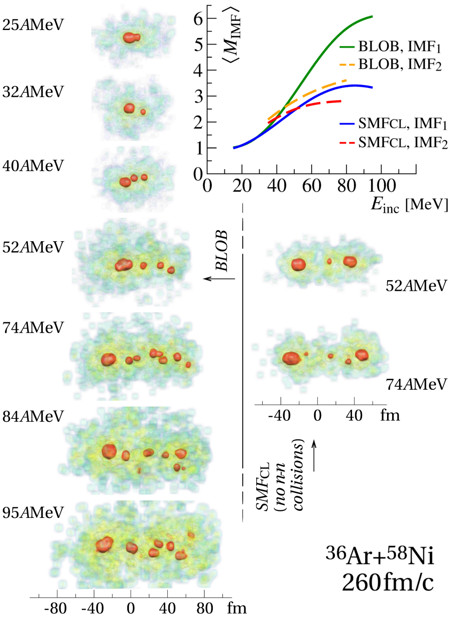
BLOB, *all fluctuations activated*

- comp.nucl. (QT) + forward jet ⇒ collimated stream of IMF
- greater growth rate and earlier saturation of *'IMF1'(w/o n, p)* ⇒ prompt LCP production
- < 52AMeV → binary favoured, > 74AMeV → jet widens, A_1-jet asymmetry reduces



Density survey

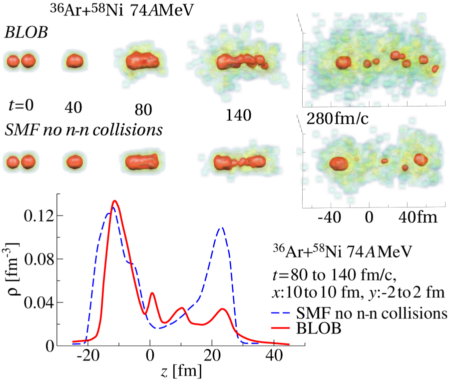
SMFcl

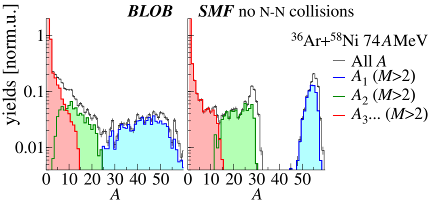
- resembles neck fragmentation, with A_2 and $A_{3...}$ separated
- $\nabla\rho$ towards midrapidity

BLOB

- A_2, $A_{3...}$ part of the same distribution
- $\rho \sim 1/4\rho_{sat}$ in the jet, in potential ripples around the collision axis
- $\rho \sim 1/10\rho_{sat}$ in surrounding tails
- large forward $\nabla\rho$ towards the jet

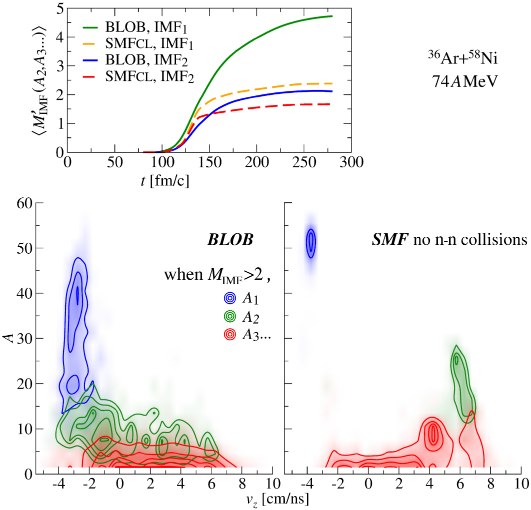
→ columnar hot low-ρ volume forms inside and outside the target, it ruptures with short t-scale





Hierarchy of fragment sizes

- LCP production in BLOB $\Rightarrow M$ of $(\cancel{A_1}, A_2, A_3...)$ continues to grow beyond simple rescission (plus neck)
- IMF in the jet favour size ordering where A decreases with the forward velocity component in BLOB. the opposite in SMFcl



Fragment nesting sites

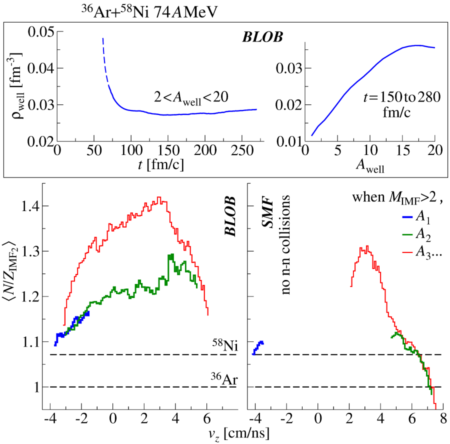
- Fragment formation chronology and density environment indicate that a nuclear surface does not preexist

- smaller fragments than $A \sim 10$ emerge in the density tails

Huge $\nabla\rho$ in both approaches, but different effects :

- in SMFcl, A_2 reflects QT, A_3 exhibits neutron flow towards the neck → isospin migration

- in BLOB, A_2 more neutron rich than the system, A_3 even more → distillation-like process



Some analysis and interpretations

- Jet as a cylinder with density $\rho < \rho_{\text{sat}}$,
- radius r extracted from the forward production,
- $\lambda \sim$ average spacing among blobs,
- Fluctuations mainly injected till reseparation

→ taken as $t = 0$ for fluctuation growth.

Dispersion relations :

Surface (Rayleigh-Brosa approach) for jets in Ar+Ni

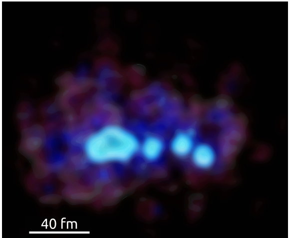
$$\Gamma_k^2 = \frac{\gamma(\rho)}{\rho r^3} \frac{I_1(kr)}{I_0(kr)} kr(1 - k^2 r^2) \quad \gamma(\rho) : \text{surf. tension}$$

Volume (Linear resp. in NM) Colonna Chomaz Randrup PhRep389(2004) NPA567 (1994) ; Napolitani Colonna PRC96 (2017))

$$\Gamma_k = \frac{1}{2} \frac{\partial}{\partial t} \ln < \tilde{\sigma}_k^2(t) >_{\text{paths}}$$

Gaussian smearing σ in $\mathcal{R}$ space

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



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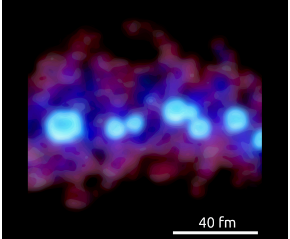
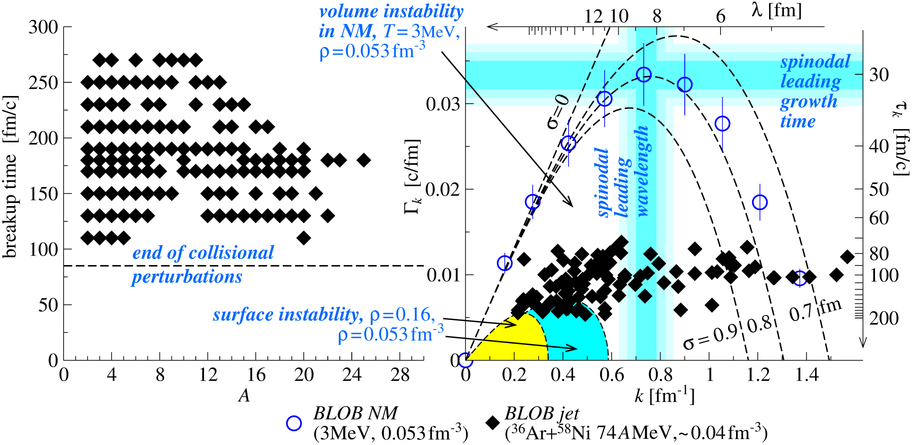


BLOB, ^{36}Ar+^{58}Ni, 74 *A*MeV, 280 fm/c

Surface versus volume instability

- time scale intermediate between volume/surface
- clusters undergo recombination (small λ feed large λ)
- clusters present small spacing for Rayleigh
- surface disp. relation expands at low ρ in a more volume-like shape
- volume disp. relation reduces (ultraviolet cutoff) with surface term



Conclusions

- It does not seem possible to produce jets disrupting into many small IMF from pure surface instabilities. Volume instabilities actually dominate due to the loss of surface tension at low ρ
- Purely statistical considerations involving barriers for binary splits would not apply to this mechanism
- Very rapid out-of equil. clusterisation process $\Rightarrow$ very collimated granular-like jet → fancy similarity with dray-sand jets !
- Not a specific feature of this model, seen also in TDHF → see V. De La Mota's talk
- Interesting exp. for *A*- and *I*-devices ?