Dynamical description of heavy-ion collisions at Fermi energies

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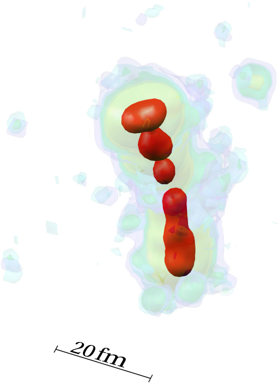
^{130}Xe + ^{130}Xe 32 *A*MeV
b=7 fm t=420 fm/c



- Modelling fragment formation
- Fast and slow processes
- Focus on spinodal fragmentation
- Focus on neck fragmentation
- Focus on distillation
- *Putting all together*

Reaching Fermi energies : extensions and reductions

When moving to Fermi E, phase space allows for N-N collisions (not Pauli blocked)

↓

Extension to collisional dynamics

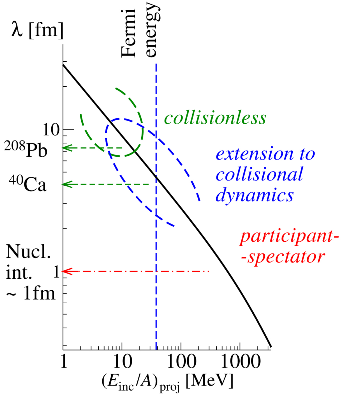
- All features of collisionless dynamics

+...

- dissipation → stopping and flow
- phase-sp. isoscalar/isovector fluctuations

Predominant feature of Fermi E is fragment formation and exit channel variety

⇒ Reduction of ρ-functional representation (coherent states, no E-level scheme)



BLOB approach

- BLE for a fermionic system :

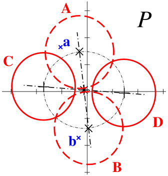
$$\dot{f} = \partial_t f - \{H[f], f\} = \bar{I}[f] + \delta I[f]$$

- BLOB : Fluctuations from *N-N correlations* in full phase space

At *a given time t*, in $(\mathbf{r}_a, \mathbf{p}_a)$, for *elastic coll.* :

$$\dot{f}_a(\mathbf{r}_a, \mathbf{p}_a) = g \int \frac{d\mathbf{p}_b}{h^3} \int d\Omega \; W(\mathrm{AB} \leftrightarrow \mathrm{CD}) \, F(\mathrm{AB} \rightarrow \mathrm{CD})$$

(P.Napolitani, M.Colonna, PLB726(2013)382)



trans. rate : $W(\mathrm{AB} \leftrightarrow \mathrm{CD}) = \left\langle |v_a - v_b| \frac{d\sigma}{d\Omega} \right\rangle_{\mathrm{AB} \rightarrow \mathrm{CD}} = \left\langle W(\mathrm{ab} \leftrightarrow \mathrm{cd}) \right\rangle_{\mathrm{AB} \rightarrow \mathrm{CD}}$

occupancy : $F(\mathrm{AB} \rightarrow \mathrm{CD}) = \bar{f}_\mathrm{A} \bar{f}_\mathrm{B} f_\mathrm{C} f_\mathrm{D} - f_\mathrm{A} f_\mathrm{B} \bar{f}_\mathrm{C} \bar{f}_\mathrm{D} = \left\langle F(\mathrm{ab} \rightarrow \mathrm{cd}) \right\rangle_{\mathrm{AB} \rightarrow \mathrm{CD}}$

occupancy variance : fluctuations amplitude determined by the variance $= f(1-f)$ in a phase space cell h^3 at equilibrium.

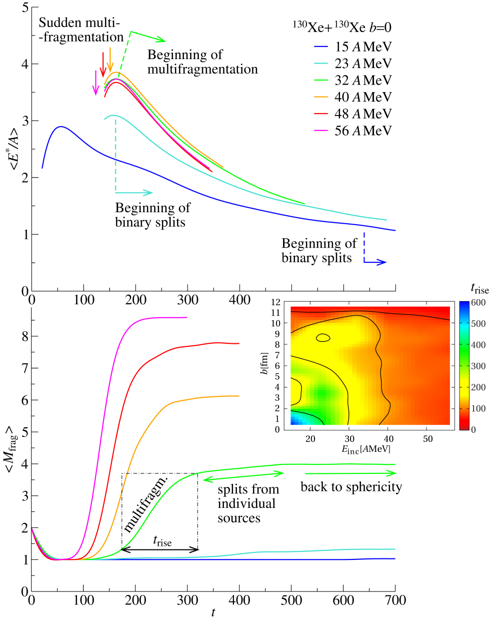
$\Rightarrow$ Wave packets should contain N_{test} = num. of test particles contained in the system $/A$

Chronology

Set of BLOB calculations

- *soft EOS* ($k_{inf} = 200$MeV)
- *linear asy-EOS* (Guarnera,Colonna,Chomaz PLB373 (1996) 297)
- W with in-medium σ_{NN} (Danielewicz Acta Phys.Pol.B33 (2002) 45)
- Dynamics till saturation of fragm. multiplicity ($\neq$ F.O. !)

System : ^{130}Xe+^{130}Xe (recalling widely investigated Sn-to-Xe region see reviews in EPJA 50 (2014))

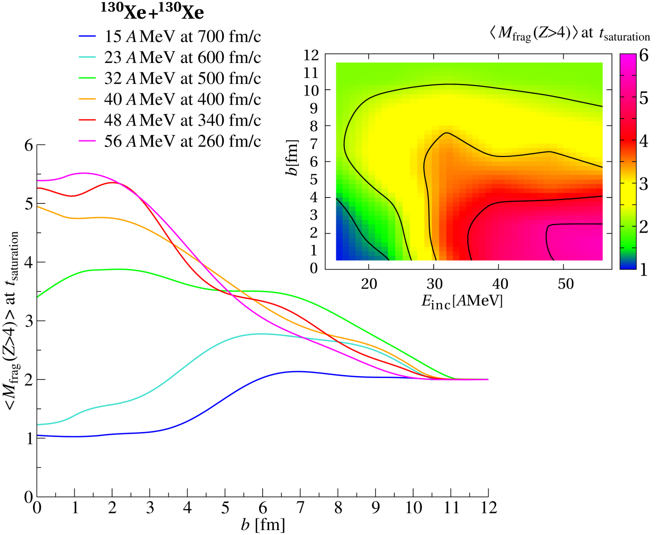


Multiplicity survey

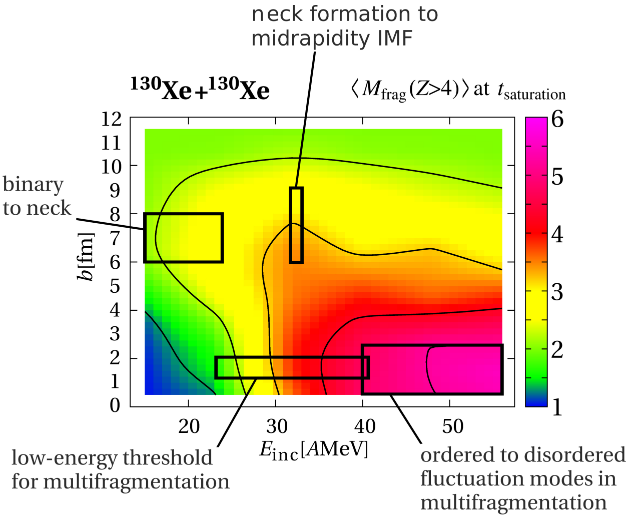
along b-E_{inc} landscape,

- Large variation of reaction times
- Large variation of fragment multiplicity (for $Z > 4$) (mostly around 30*A*MeV)

⇒ several transitions of mechanisms ?



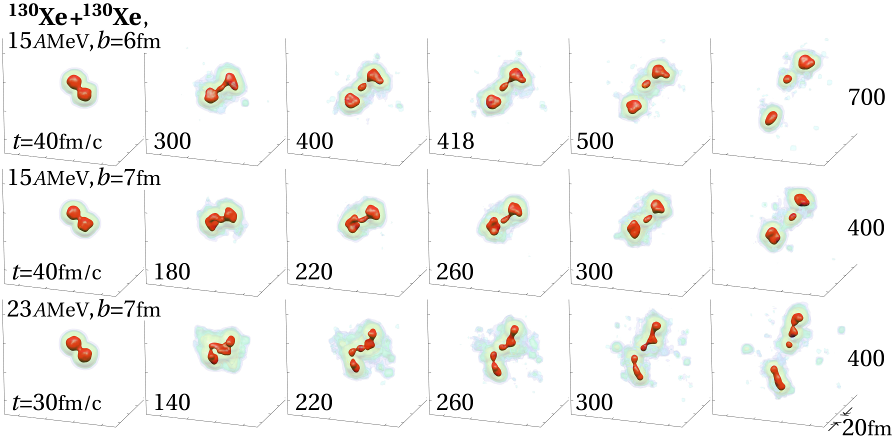
Exploring Fermiland



Exp : Kohley, Yennello EPJA 50 (2014) 31 ; DeFilippo, Pagano EPJA 50 (2014) 32 ; Ademard et al., EPJA 50 (2014) 33…

Theo : B.-A.Li C.M.Ko W.Bauer, Int.J.Mod.Phys. E7 (1998) 147 ; Baran et al., Phys.Rep. 410 (2005) 335 ; EPJA 50 (2014)…

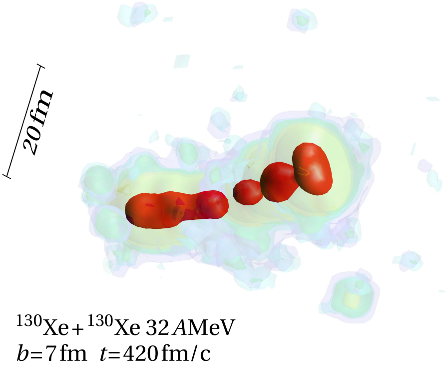
Neck fragmentation



Exp : G.Casini et al., PRL 71, 2567 (1993) ; F.Bocage et al. NPA676 (2000) 391 ; E.DeFilippo et al. PRC71 (2005) 044602…

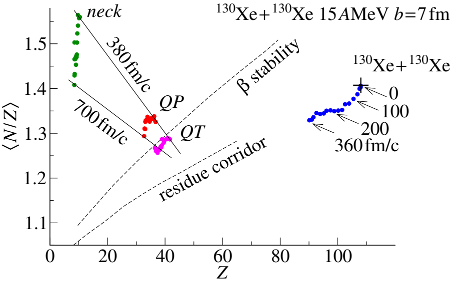
Isoscalar / isovector neck features

Isoscalar) : *hierarchy of sizes* in neck fragmentation :



Colin et al. PRC67 (2003) 064603

Isovector) : *Isospin migration* towards the neck :



(reduced effect if the neck joins back to QP/QT)

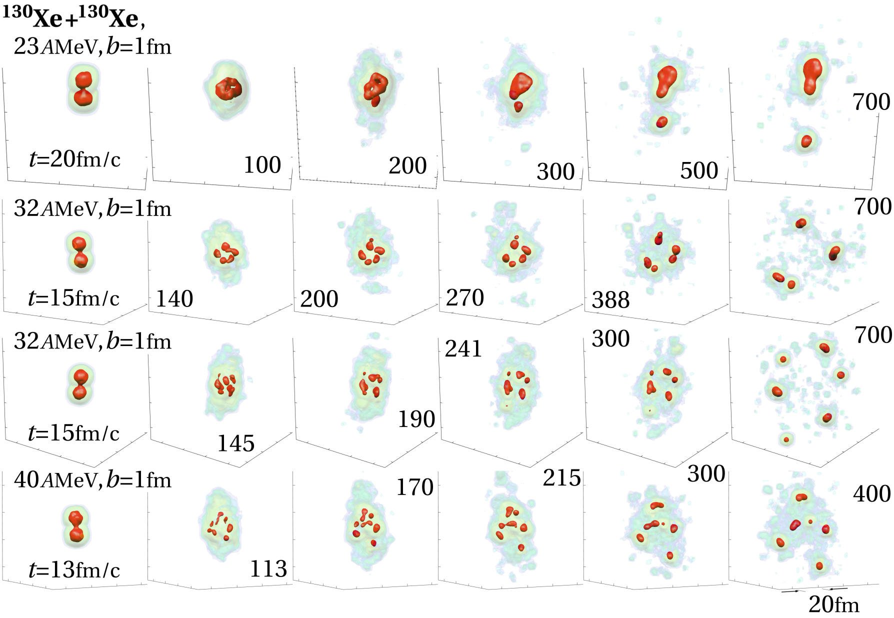
Lionti,Baran,Colonna,DiToro, PLB625 (2005) 33…

Midrapidity

- more than one neck IMF, eventually very forward emitted

Baran,Colonna,DiToro,Zus PRC85 (2012) 054611 ; Rizzo,Colonna,Baran,DiToro PRC90 (2014) 054618...

spinodal multifragmentation & re-aggregation



spinodal multifragmentation & re-aggregation

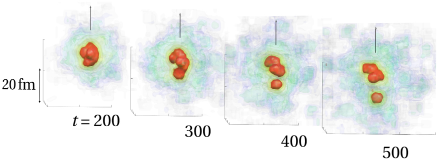
- Spinodal regime : wavelength of the leading isoscalar mode λ is refleced in fragm. sizes → IMF of similar $A_{\mathrm{frag}} \approx \rho(\lambda')^3$ ($\approx$ region O, Ne)

Theo : Chomaz,Colonna,Randrup Phys.Rep. 389 (2004) 263

Exp : B.Borderie et al. PRL 86 (2001) 3252 ; G.Tabacaru EPJA 18 (2003) 103

- Low-energy multifragmentation threshold : recombining of fragments → loss of size asymmetry and reduction of multiplicity → similar effect in relativistic proton-induced spallation :

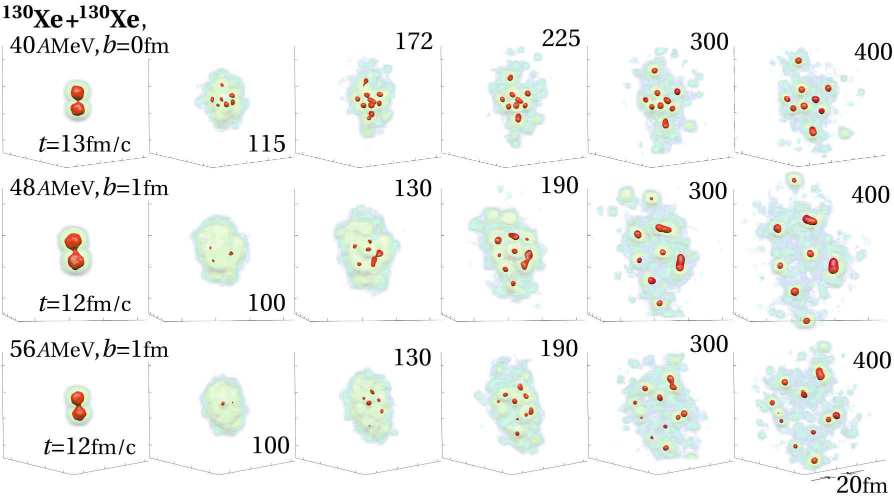
^{136}Xe+p 1 AGeV



Napolitani Colonna PRC 92 (2015) 034607

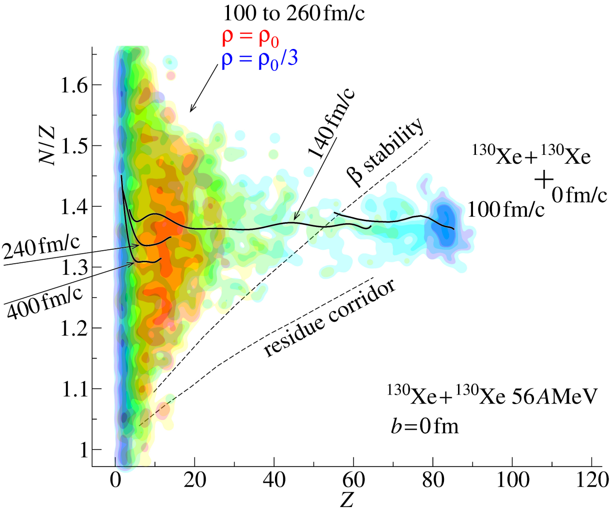
- High-energy multifragmentation threshold : no more ordered modes → loss of size asymmetry

"disordered" multifragmentation



Isospin distillation at low-density

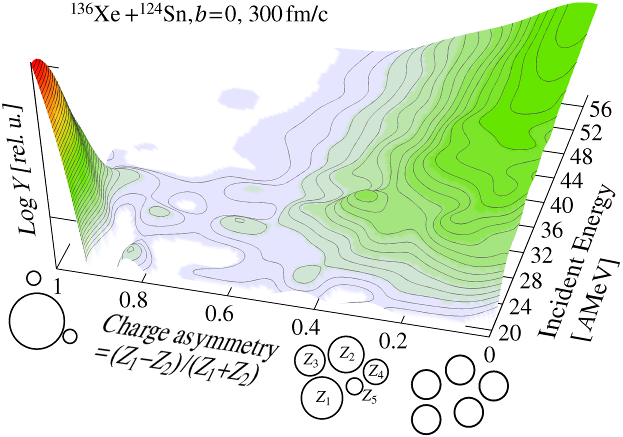
- *distillation* :
more *n* in the most volatile phase



(Muller, Serot, PRC 52 (1995) 2072 ; B.-A.Li, C.M.Ko, NPA 618 (1997) 498 ; Ducoin et al. NPA 781 (2007) 407 ; Colonna et al. PRC 78 (2008) 064618 ; Colonna, PRL 110 (2013) 042701…)

1^{st} o. phase trans. in central collisions

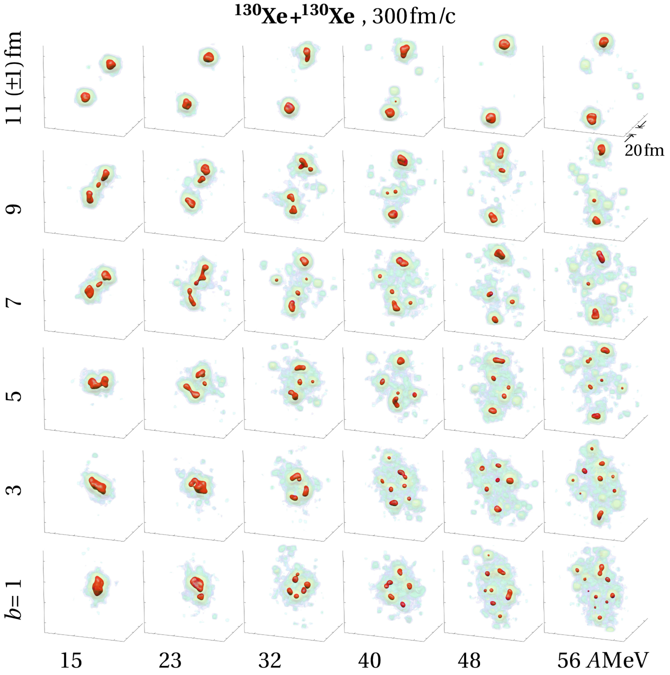
Same macroscopic initial conditions → E fluctuations
→ oscillation between two energetically favoured configurations.
Studied in a similar system for $b = 0$ (P.N.,M.Colonna PLB726(2013)382) :



→ 1^{st} o. phase trans. features found as a result of fragm. dynamics
(recolling bimodality : E.Bonnet et al. PRL103 (2009) 072701 ; M.Pichon et al. NPA779 (2006) 267)

Map of dynamical processes at Fermi E

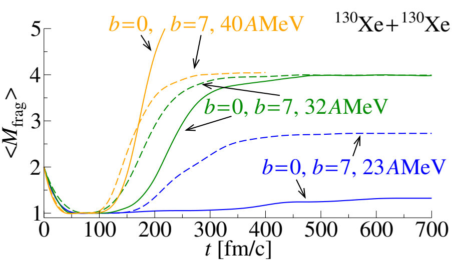
Examples of most probable mechanisms leading to IMFs at 300 fm/c where fragments are present



Conclusions

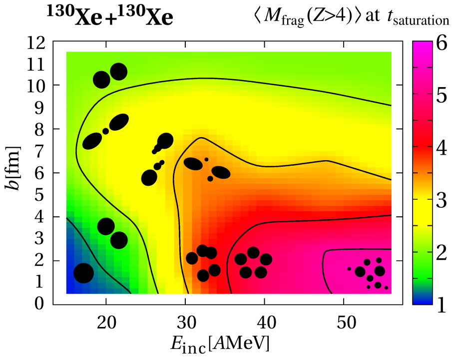
• From a full survey of the dynamical process (including the out-of-equilibrium stage, and even allowing for some model dependence) we can expect for intermediate-size nuclear systems :

1) Processes over different time intervals :



2) : Variety of exit channels

→ Fermi-*E* “bestiary” :



• The clustering process should complete the above picture.