Heavy-ion collisions and EOS

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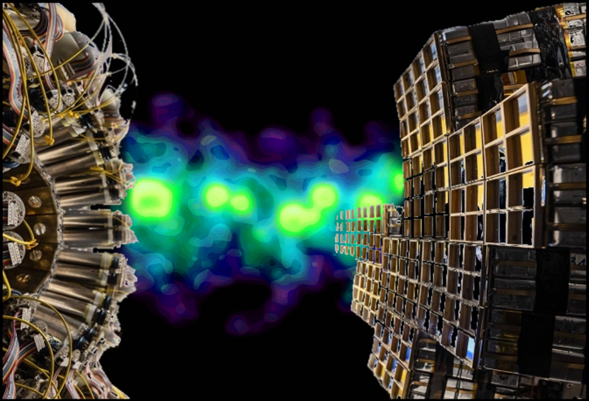
- How HIC can probe the EOS at (actual/upgraded) GANIL
- a suited modelling environment is ready and available
- building microscopic observables

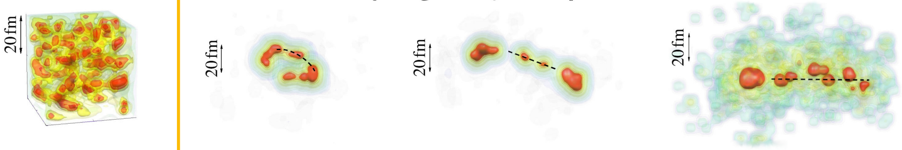


GCM, Caen 18 October 2022

HIC to probe the *EOS*

- HICs affect the density landscape of a nuclear system, from *collective modes* to *disordered perturbations*
  $\Rightarrow$ terrestrial laboratory probes for the nuclear EOS

NM | ***transient topologies in finite systems***



$\rho = 0.053\,\mathrm{fm}^{-3}$, $T = 3\,\mathrm{MeV}$, $t = 160\,\mathrm{fm/c}$

$^{197}\mathrm{Au}+^{197}\mathrm{Au}$ 15 AMeV (***arc***) $b = [5,6]\,\mathrm{fm}$, $t = 500\,\mathrm{fm/c}$

$^{197}\mathrm{Au}+^{197}\mathrm{Au}$ 15 AMeV (***neck***) $b = [9,10]\,\mathrm{fm}$, $t = 500\,\mathrm{fm/c}$

$^{36}\mathrm{Ar}+^{58}\mathrm{Ni}$ 74 AMeV (***jet***) $b = 0$, $t = 230\,\mathrm{fm/c}$

- But, at variance from some astrophysical scenarios, the HICs-EOS correlation is very indirect, because :
  1) in early stages timescales are comparable with the relaxation time of the nuclear interaction ($\sim 10^{-21}$s) $\Rightarrow$
     $\Rightarrow$ chaotic behaviour, *bulk instabilities*
  2) when moving from NM to finite systems, surface adds up $\Rightarrow$
     $\Rightarrow$ non-trivial geometries, *surface instabilities*

Role of symmetry energy and isospin transport

- In nuclear processes, from nuclear reactions to compact stars, *chemical potentials* μ_n, μ_p determine how neutrons and protons flow in the nuclear medium, according to the form of the nuclear interaction.

$$\mu_n = \frac{\partial(\rho e)}{\partial \rho_n}, \qquad \mu_p = \frac{\partial(\rho e)}{\partial \rho_p},$$

- Their difference → ∝ to the symmetry energy

$$\boxed{\mu_a = \frac{\mu_n - \mu_p}{2} = \frac{\partial(\rho e)}{\partial \eta} = 2\eta S(\rho)}\ , \qquad \eta = \frac{\rho_n - \rho_p}{\rho}$$

Isospin processes from drifts

- Currents of neutrons and protons stream towards their chemical-potential minima, driven by density gradients (*migration*) or concentration gradients (*diffusion*)

$$j_q = -\kappa \nabla \mu_q = D_q^{\rho} \nabla \rho - D_q^{\eta} \nabla \eta$$

- Their difference → introduces the symmetry energy and its derivative

$$j_a = j_n - j_p = D_a^{\rho} \nabla \rho - D_a^{\eta} \nabla \eta = -4\kappa \left(\overbrace{\frac{\partial S(\rho)}{\partial \rho} \eta \nabla \rho}^{migration} + \overbrace{S(\rho) \nabla \eta}^{diffusion} \right)$$

- If the ultimate fate is the disassembly of the system in a phase-transition-like process, the isospin content of the fragments is additionally affected by the phase separation (distillation).

Chomaz, Colonna, Randrup Phys.Rep.389 (2004) ; Müller, Serot PRC52 (1995)

Probes and scales for nuclear dynamics

Deep inelastic :

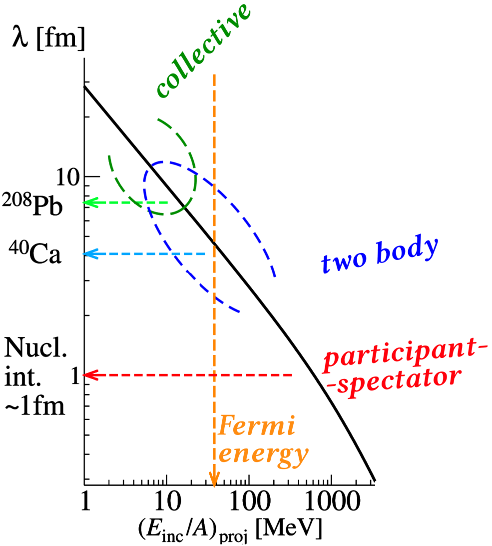
incident energy goes into collective modes and deformations ruled by surface-Coulomb energy interplay

e.g. : *$^{197}Au+^{197}Au$ at 15AMeV*

Around Fermi energy :

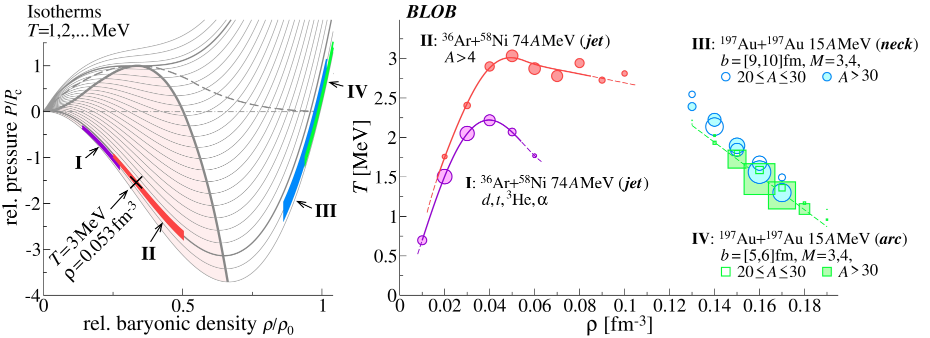
incident energy goes into two-body dissipation violent ρ perturbations, isospin drifts, bulk instabilities

e.g. : *$^{36}Ar+^{58}Ni$ at 74AMeV*, *$^{86}Kr+^{124}Sn$ at 35AMeV*



HIC to probe the *EOS* : a simulation result

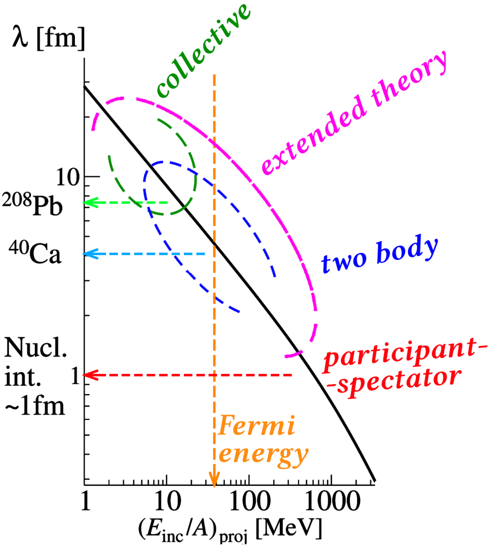
Example : Thermal and density condition of fragments and clusters at the rupture time of thread-like topologies in DI and Fermi-regime situations, in correlation with the EOS



[Napolitani2021 arXiv :2203.13736]

Requirements for a microscopic model

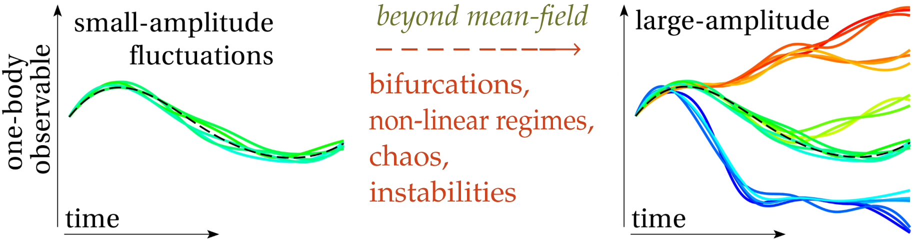
Goal :
Handling the interplay of
collective–dissipative modes
in one single extended theory



Requirements for a microscopic model

- Heavy-ion collisions are *non-equilibrium processes* in large part
  ⇒ microscopic modelling (no equilibrium assumption)

- *Variances of single-nucleus properties* and *multiple-fragment production* is the result of *nonlinearities, fluctuations and bifurcations*
  ⇒ precise description of stable and unstable conditions



- sampling of the *dynamical process over its entire time span* (only standard sequential decay can be left over)
  ⇒ keeping stability, self-consistency, Fermi statistics, Pauli

Beyond-mean-field scheme

- Correlations beyond kinetic eq. approximately recovered by handling several mean fields

$\rightarrow$ generated from the action of a fluctuating seed on the one-body density

For one MF trajectory n in τ_{BL} :

Stochastic-TDHF scheme

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

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
$\rightarrow$ Fermi stat. at equilibrium

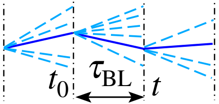
$$\frac{\partial f^{(n)}}{\partial t}=\{h^{(n)},f^{(n)}\}+I_{\text{UU}}^{(n)}+\delta I_{\text{UU}}^{(n)}$$

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)]

- Diffusion coeff. $\mathcal{D}$ from *Langevin term* $\rightarrow$
  $\rightarrow$ intermittent fluctuation revival and bifurcations
  in the spirit of the *Brownian motion*



Mean-field point of view, adopting BLOB

Boltzmann-Langevin One Body

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

transition rate occupancy

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

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]

Mean field : suited for isovector/isoscalar transport

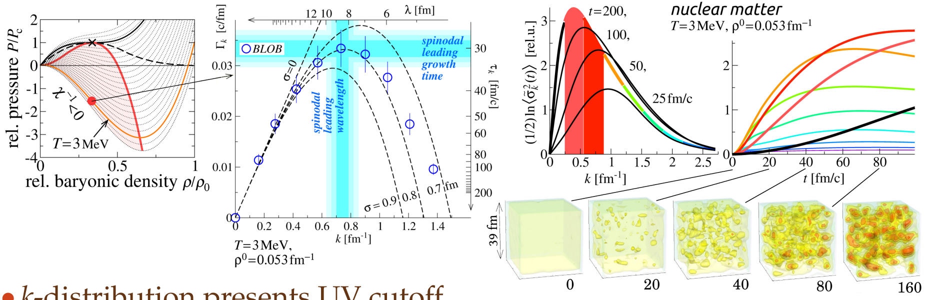
Collision term : fluctuations inducing fragment and cluster separation

→ we can apply BLOB to fragment phenomenology in HIC

Clusterisation in nuclear matter from bulk instabilities

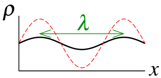
- nuclear interaction leads to clusterisation below saturation density and in unstable EOS sites (negative incompressibility $\chi^{-1} < 0$).

$\rightarrow$ dispersion relation *for volume-unstable modes k*



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

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

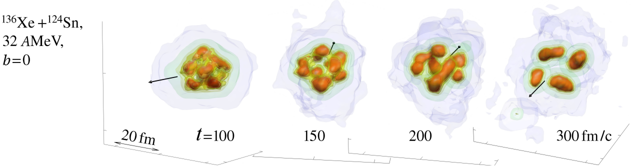


- leading $k \rightarrow$ most probable spinodal wavelength around 8fm at $\rho_0/3$
- possible interference : larger *k* recombine into smaller *k*

Napolitani,Colonna PRC96 (2017)]

Clusters and fragments emerging in open systems

• most probable spinodal fragment size corresponds to the leading k in NM, i.e. O to Ne, while heavier elements arise from recombination due to mean-field resilience in *isotropic systems*.

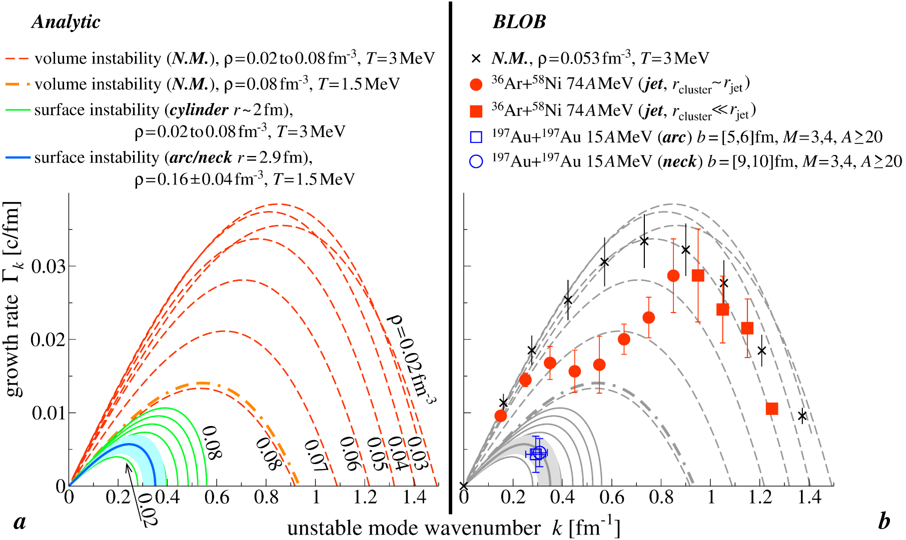


• Open systems introduce a surface, ruled by the same interaction term imposing UV cutoff for k, deformations and instabilities of Plateau-Rayleigh type, depending on surface tension, local density and temperature

• Clusters in BLOB are treated like the formation of any other heavier fragment : they emerge naturally from potential ripples and are not related to cluster-production cross sections.

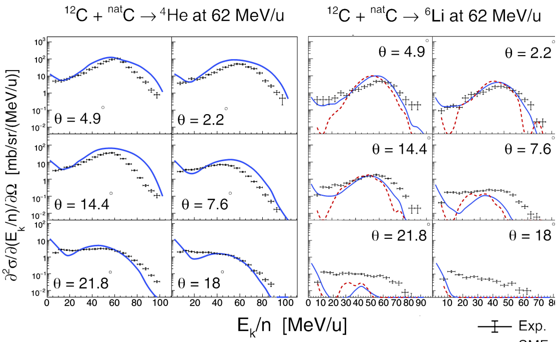
HIC to probe the *EOS* : a simulation result on dispersion relations

Example : Dispersion relations to compare volume and surface instabilities

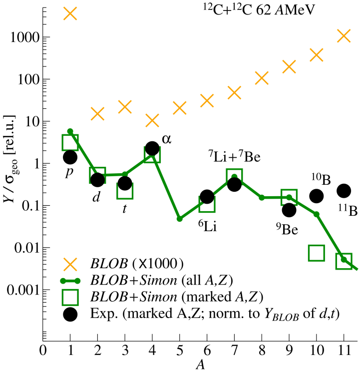


[NAPOLITANI2021 ARXIV :2203.13736]

Example of α production for medical applications



[C. Mancini-Terracciano et al. Med. 67 (2019),116]



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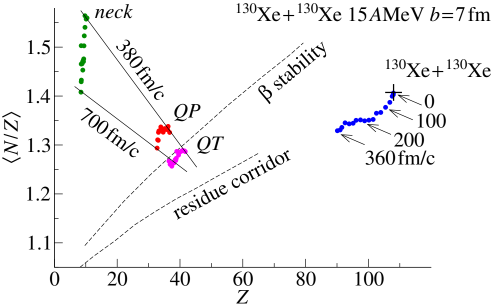
Isospin drifts along the neck at Fermi energy

(Semi)peripheral coll. at Fermi E determining $\rho < \rho_{\text{sat}}$ along a neck→

→ combination of migration and diffusion [Baran et al. PRep410 (2005), B.A.Li et al. PRep464 (2008)]

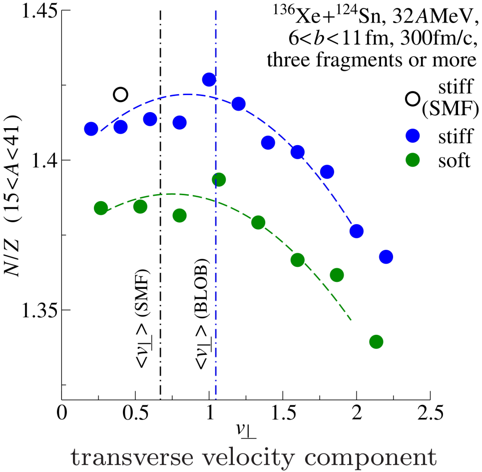
→ one fragment (rarely two) could leave the system and carry isospin observables (from isotopic content and kinematics). [Baran et al. PRC85 (2012), Lionti et al. PLB625 (2005), Montoya et al. PRL73 (1994), DiToro et al. EPJA30 (2006), Hudan et al. PRC86 (2012), De Filippo et al. PRC86 (2012), Brown et al. PRC87 (2013), Jedele et al. PRL118 (2017), Rodriguez Manso et al. PRC95 (2017)...]



Isospin observables from the neck at Fermi energy

→ one fragment (rarely two) could leave the system and carry isospin observables (from isotopic content and kinematics).

- In theory (BLOB), isotopic content and kinematics of neck fragments are highly sensitive observables, they can distinguish between different forms of the nuclear interaction.
- In practice, the position of the emitting source and time is difficult to measure.

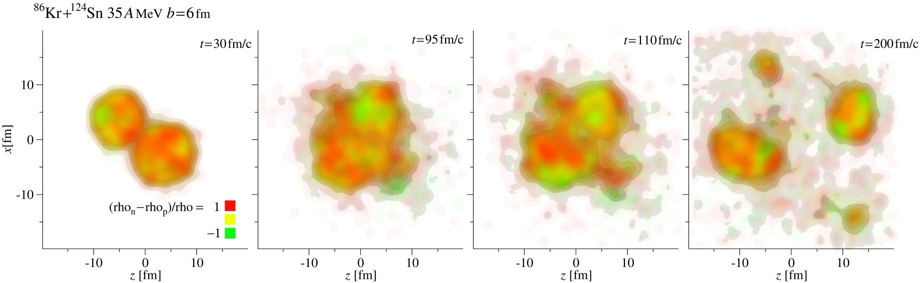


Density fluctuations

Test : Kr+Sn at 35AMeV with BLOB (one stochastic event)

- Matter drifts outward but the flow is along the reaction plane
- a large flat disk of low density ($\rho \sim \rho_{sat}/4$) neutron-rich matter forms
- from the disk, fragments and clusters arise at midrapidity and are emitted with a dominant perpendicular component

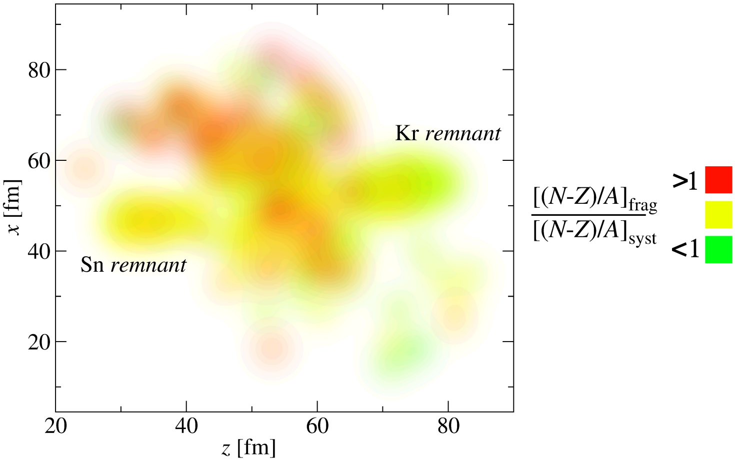
Distribution of $\eta = \frac{\rho_n - \rho_p}{\rho}$:



isotopic composition of arising fragments

Test : Kr+Sn at 35AMeV with BLOB (500 stochastic events at 300fm/c)

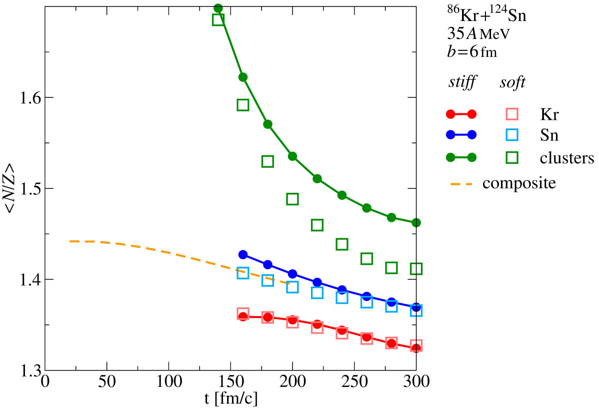
Distribution of fragment central positions at 300fm/c :



possible isospin observable

Test : Kr+Sn at 35AMeV with BLOB (stiff versus soft isov. contribution)

Time-dependent evolution of isotopic content :



• Strong dependence on the form of the interaction (larger difference than the difference of isotopic content of the two participants !)

Brief practical perspectives

- Microscopic models are more explanatory than event generators, but they require some preparatory work (i.e. searching for a specific intricate observable)

→ A modelling initiative is in preparation where theory-experiment collaboration is promoted from the model-environment preparation to the simulations

- In parallel, we aim at developing even more sophisticated models where common assumptions are further reduced (i.e. semiclassical assumptions, locality assumptions...)