Sub-diffusion, cage effects and collective re-arrangements in granular media

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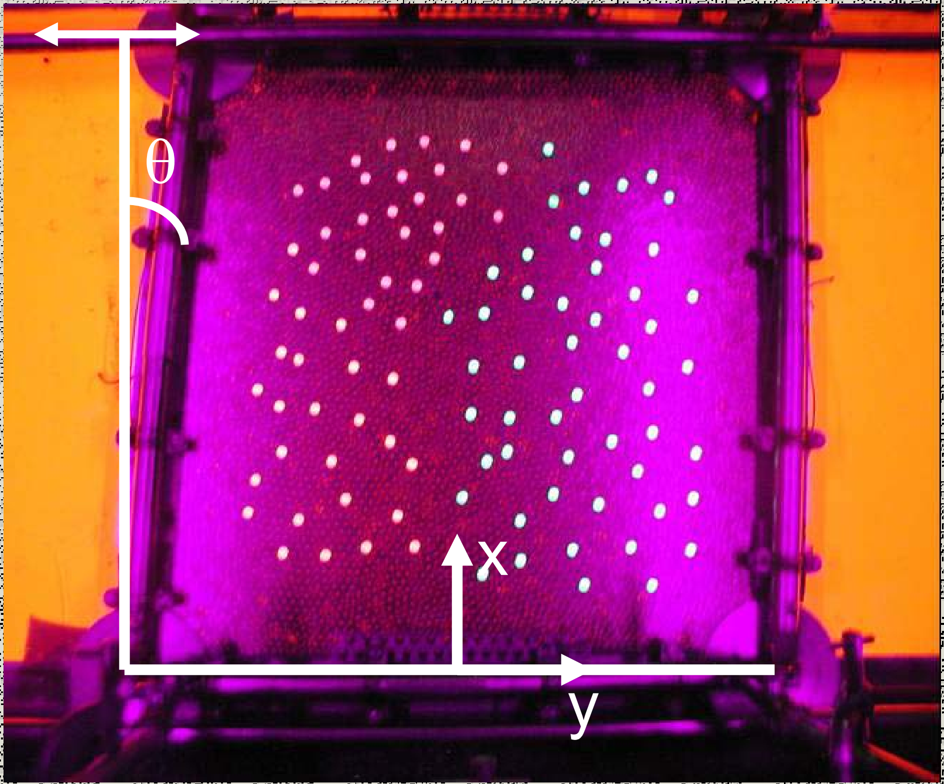
Introduction

- Various experiments on vibrated granular media indicate a possible analogy between glass and granular media.
  - Strength : the relation between thermal and a-thermal systems
  - Weakness : only at the macroscopic level (slow compaction experiment, Chicago and Rennes groups) or at the thermodynamical level (T_{eff}, D'Anna et al.)
- For glass forming systems sub-diffusion and slow relaxation have been associated with "cage effects" and "spatially heterogeneous dynamics"
  - Molecular Dynamics Simulations of hard spheres and Lenard Jones liquids provide a lot of data on the underlying microscopic mechanisms (Glotzer et al.)
  - Colloidal Suspensions Experiments at high density + confocal microscopy => direct observation of the individual particle paths (Weeks et al.)
- Here :
  - Experimental study of the diffusion properties and microscopic behaviors in a granular media, driven as differently as possible from a thermal excitation.
  - Can we give a precise meaning to the above analogy?

The experimental set up

- A 2D bi-disperse dry granular media under cyclic shear (not just an analog computer)



The system

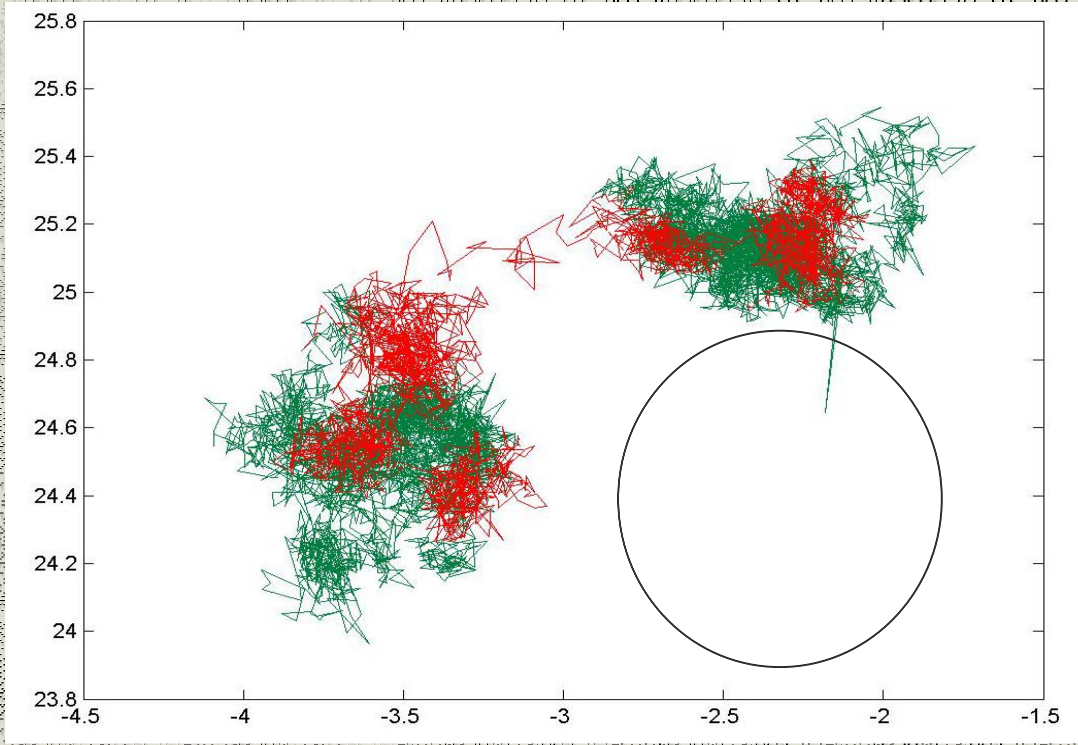
8000 particles
Bi-disperse (Ø=4 and 5mm)
Quasi-static shear
Constant Volume (Φ=0.86)

The protocol

10 000 cycles
θmax=10°; max strain=0.3
500 tracers are followed
A snapshot is taken at each cycle

- NB : Different from an analog computer (good models of friction are still lacking)

Typical trajectory

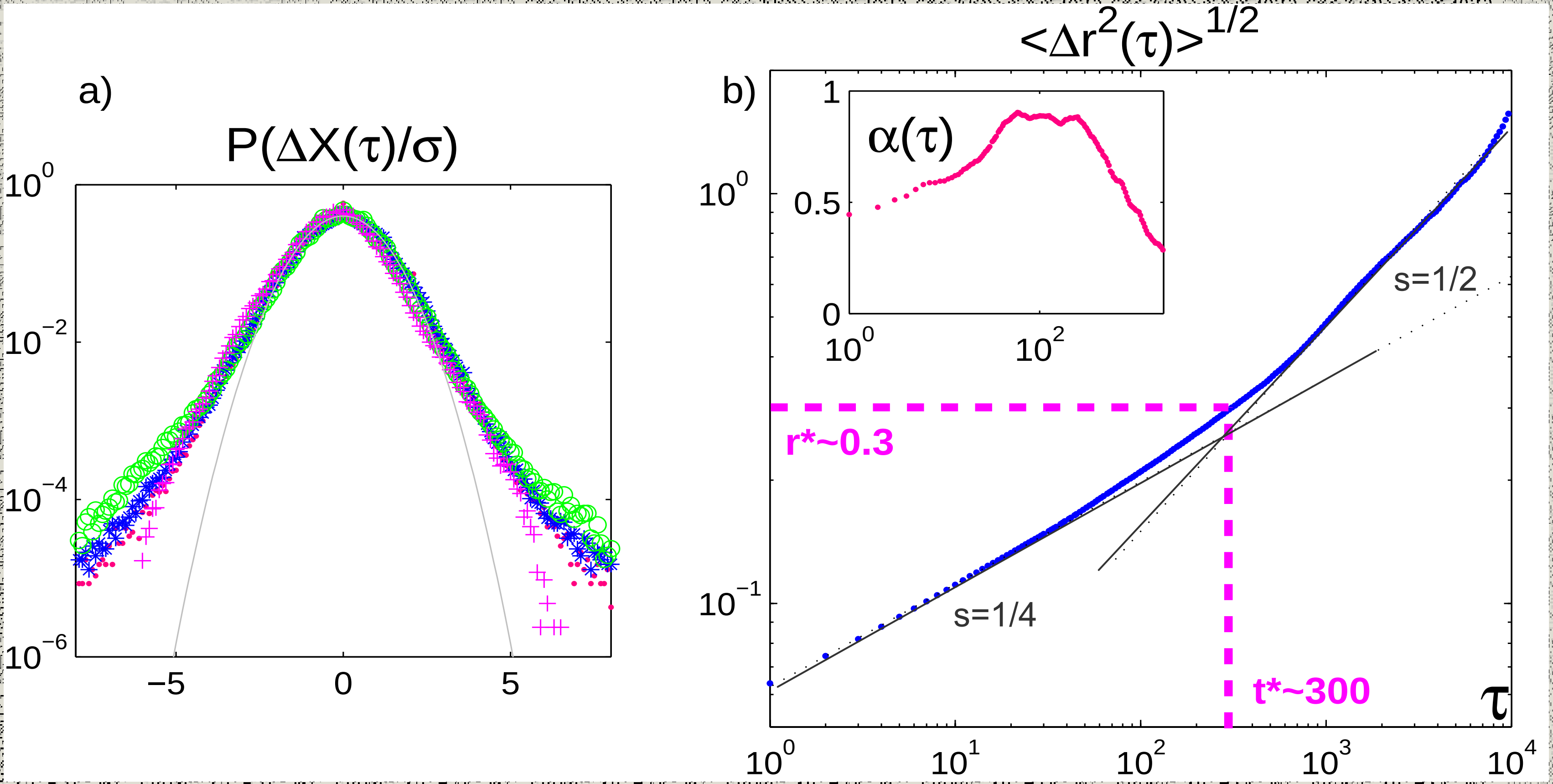


- Cage dynamics
- Small cages compared to the grain size

- NOTA BENE
  - Typically the same size relatively to the particle diameter as in D. Weitz experiments
  - Smaller than in S. Glotzer numerical simulations

Hard spheres vs. "soft" potentials ?

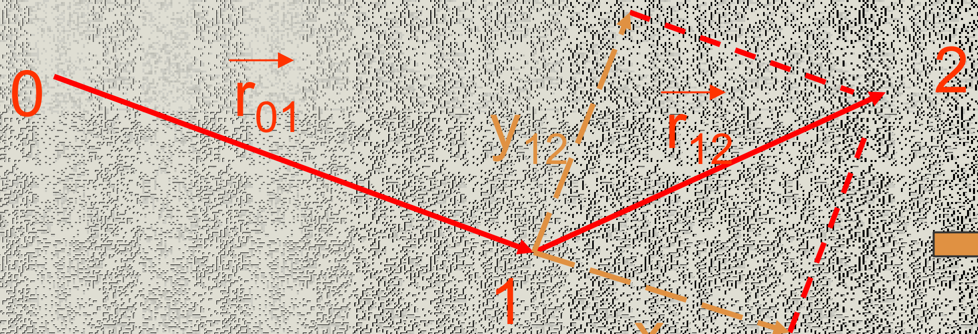
Intermittent moves and subdiffusion



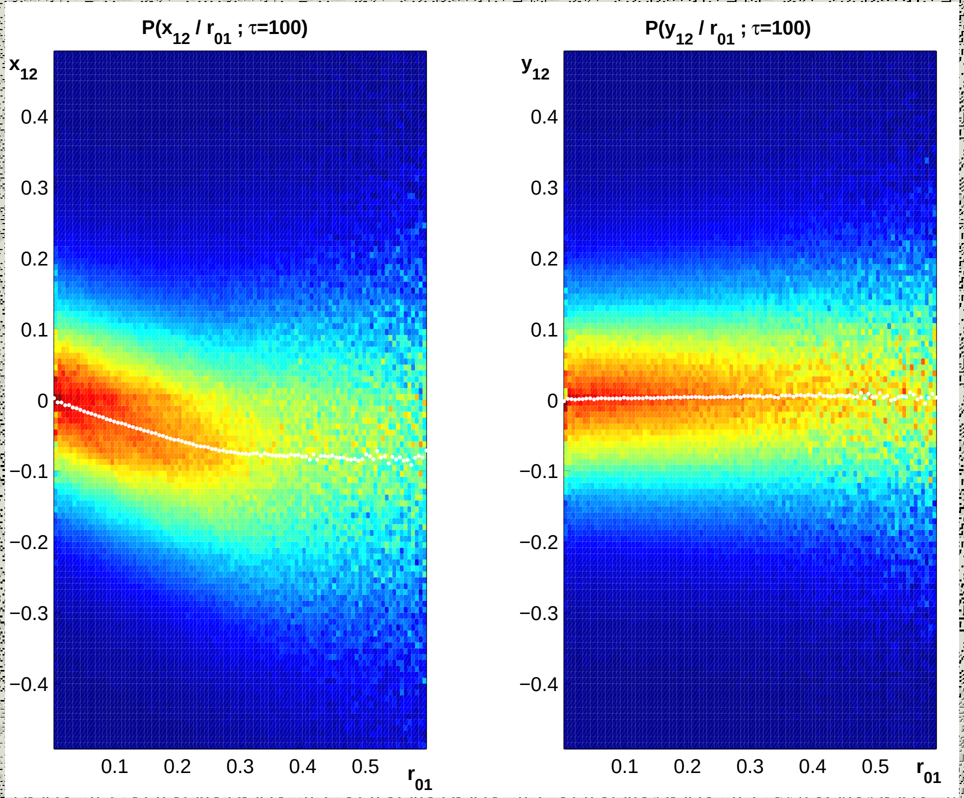
- Fat tails, Intermittency
- Non gaussianity factor depends on the timescale
- Crossover between sub-diffusive and diffusive motion at

r*=0.3 and t*=300

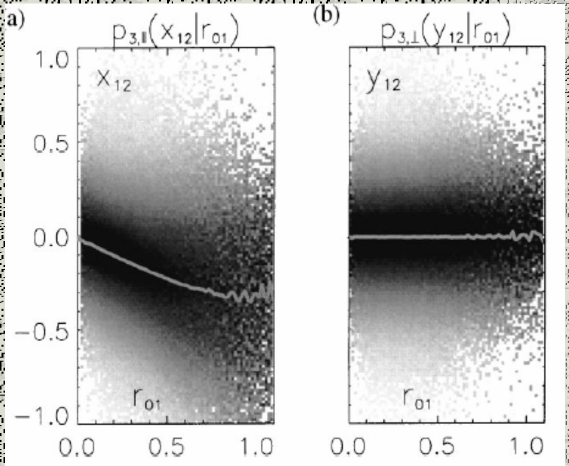
Anti-correlated moves (Doliwa and Heue



At a given timescale τ :



$P(x_{12}|r_{01},\tau)$ $P(y_{12}|r_{01};\tau)$



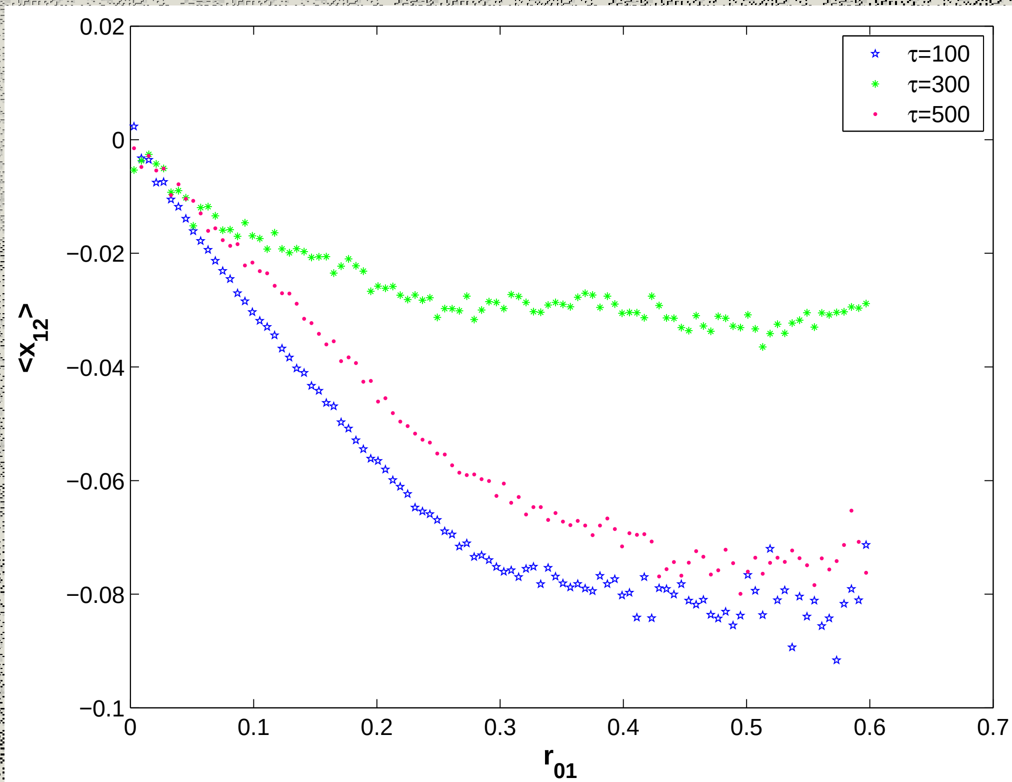
- $\langle y_{12} \rangle = 0$
- $\langle x_{12} \rangle < 0$
- for $r_{01} < r^*$

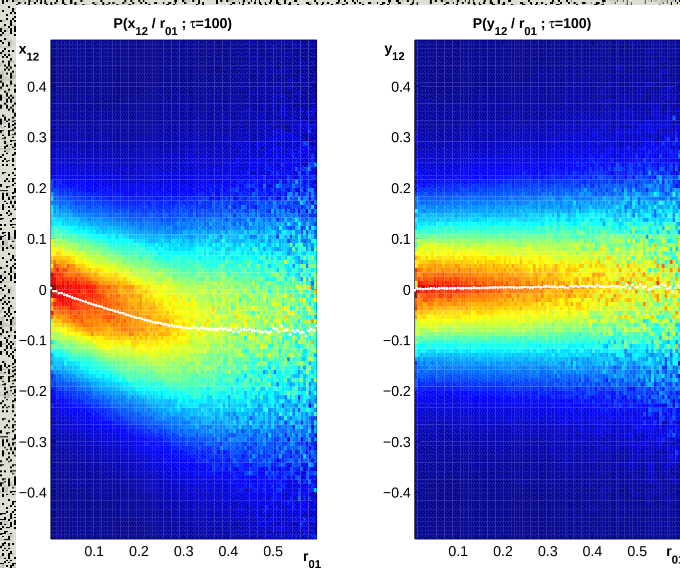
  $\langle x_{12} \rangle = c(\tau)\, r_{01}$
- for $r_{01} > r^*$

  $\langle x_{12} \rangle = \text{cte}$

Anti-correlations (II)

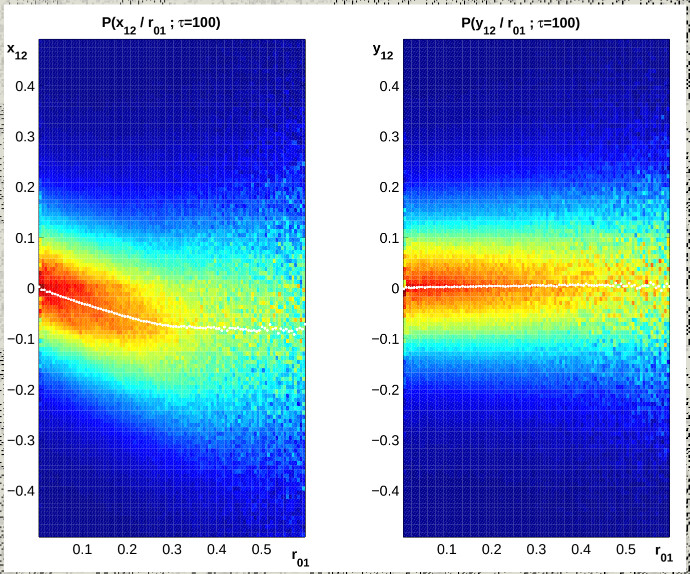
Varying the timescale τ :

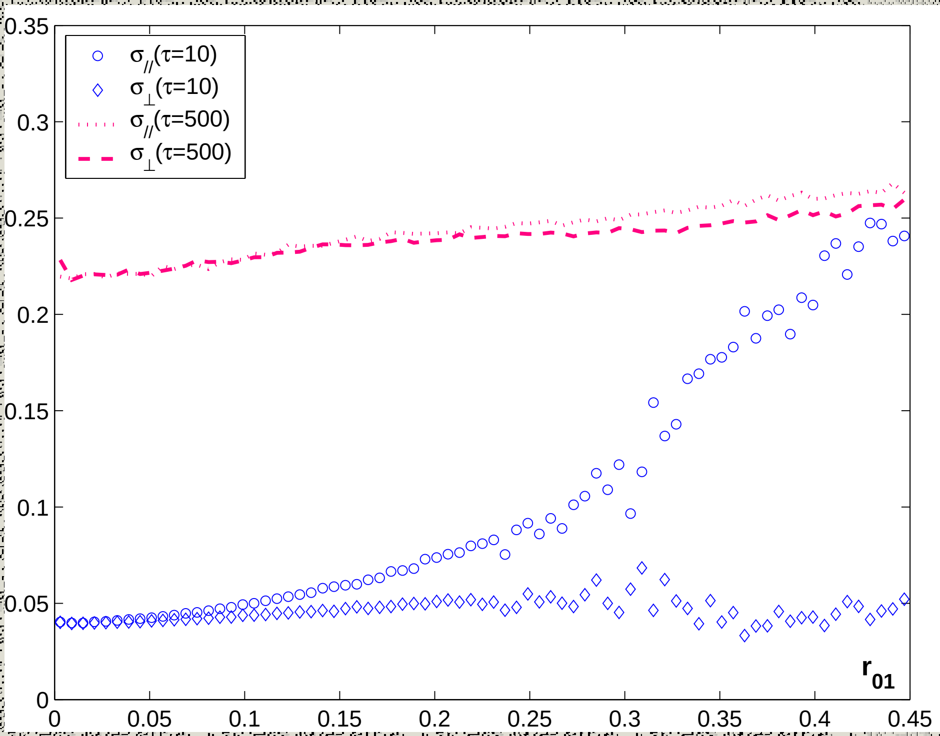




- $\forall \tau < t^*$, the saturation occurs for $r_{01} = r^*$
- For $\tau > t^*$, the anti-correlations vanishes

Heterogeneities (I)





- For $\tau<t^*$, rms (x_{12}) increases with r_{01} : propensity to move is larger for previously rapidly moving particles
- While rms(y_{12}) remains constant : preferentially parallel to the previous move
- => suggest the string-like cooperation observed by Donati et al.

Heterogeneities (II)

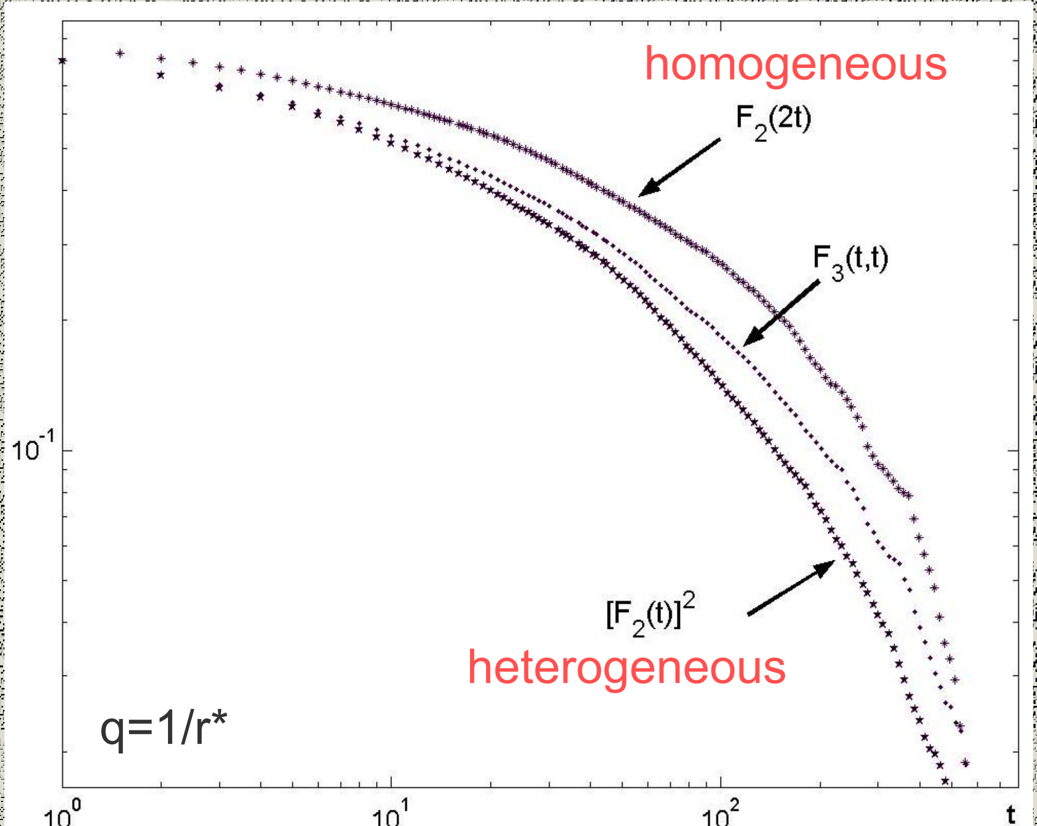
(Doliwa and Heue

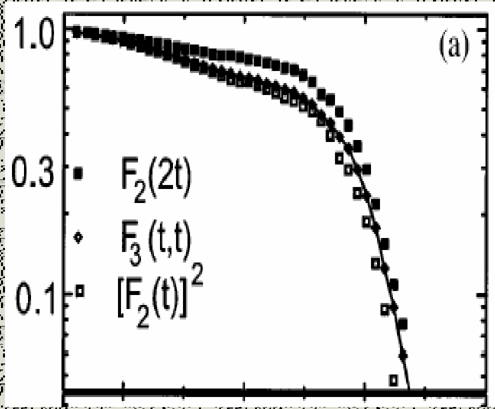
$F_2(t)=<\cos(q.r_{01})>$; $F_2(2t)=<\cos(q.r_{02})>$;

$F_3(t,t)=<\cos(q.r_{12})\cos(q.r_{01})>$

Purely Homogeneous Dynamics: $F_3(t,t)=F_2(t)^2$

Purely Heterogeneous Dynamics: $F_3(t,t)=F_2(2t)$

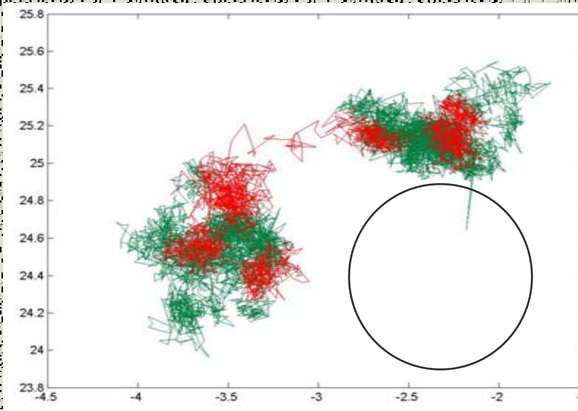




- The dynamics has a significant heterogeneous part (already in the β-regime)

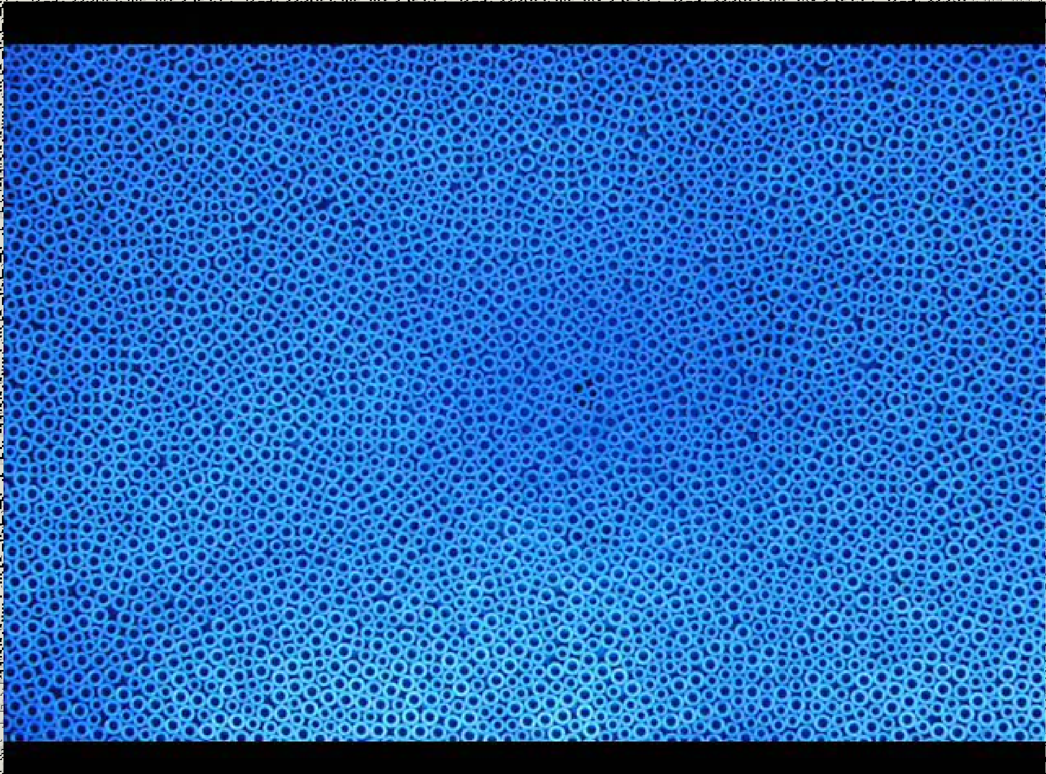
Cages and collective dynamics

- Cages are rather small (r*=0.3)
- What are cages?
- How many grains are involved in a cage re-arrangement?

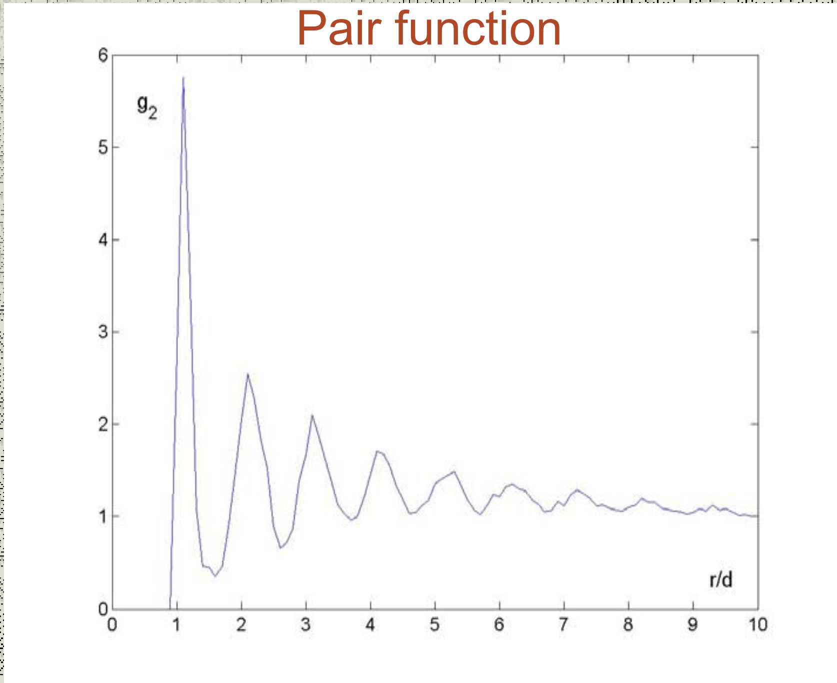


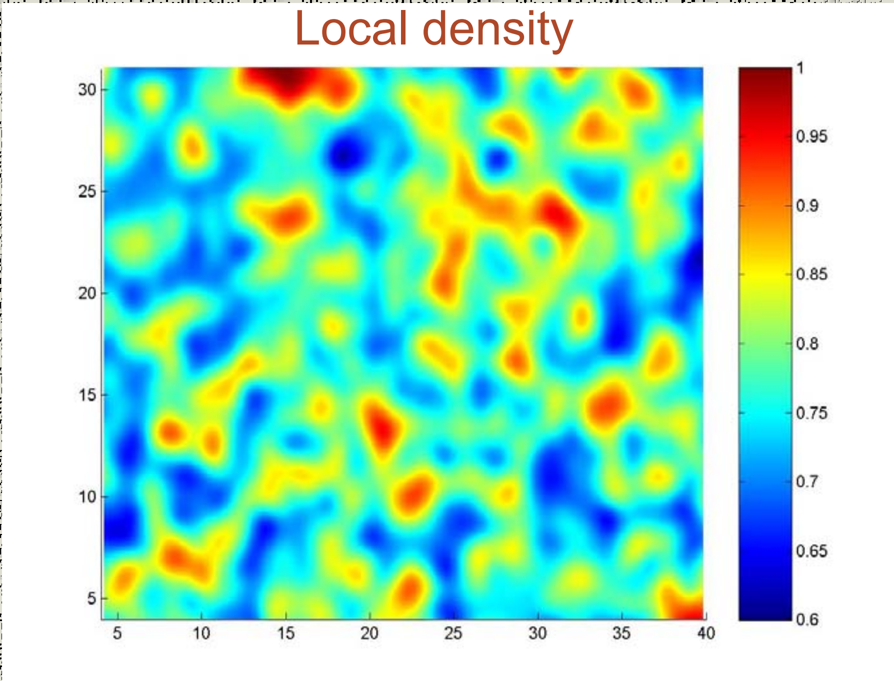
⇒ Need to follow all particles

⇒ New exp. set up



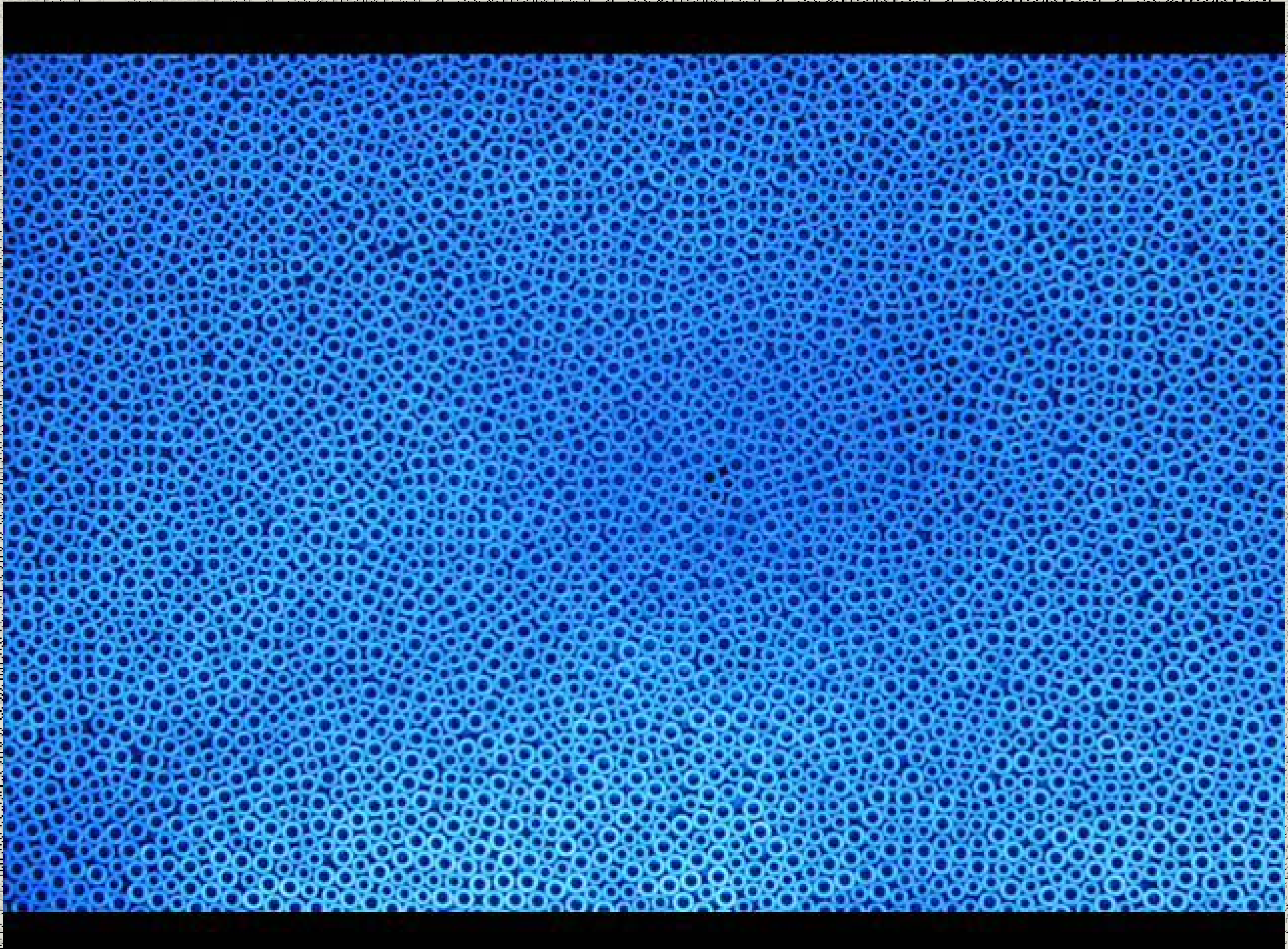
Some information on the structure



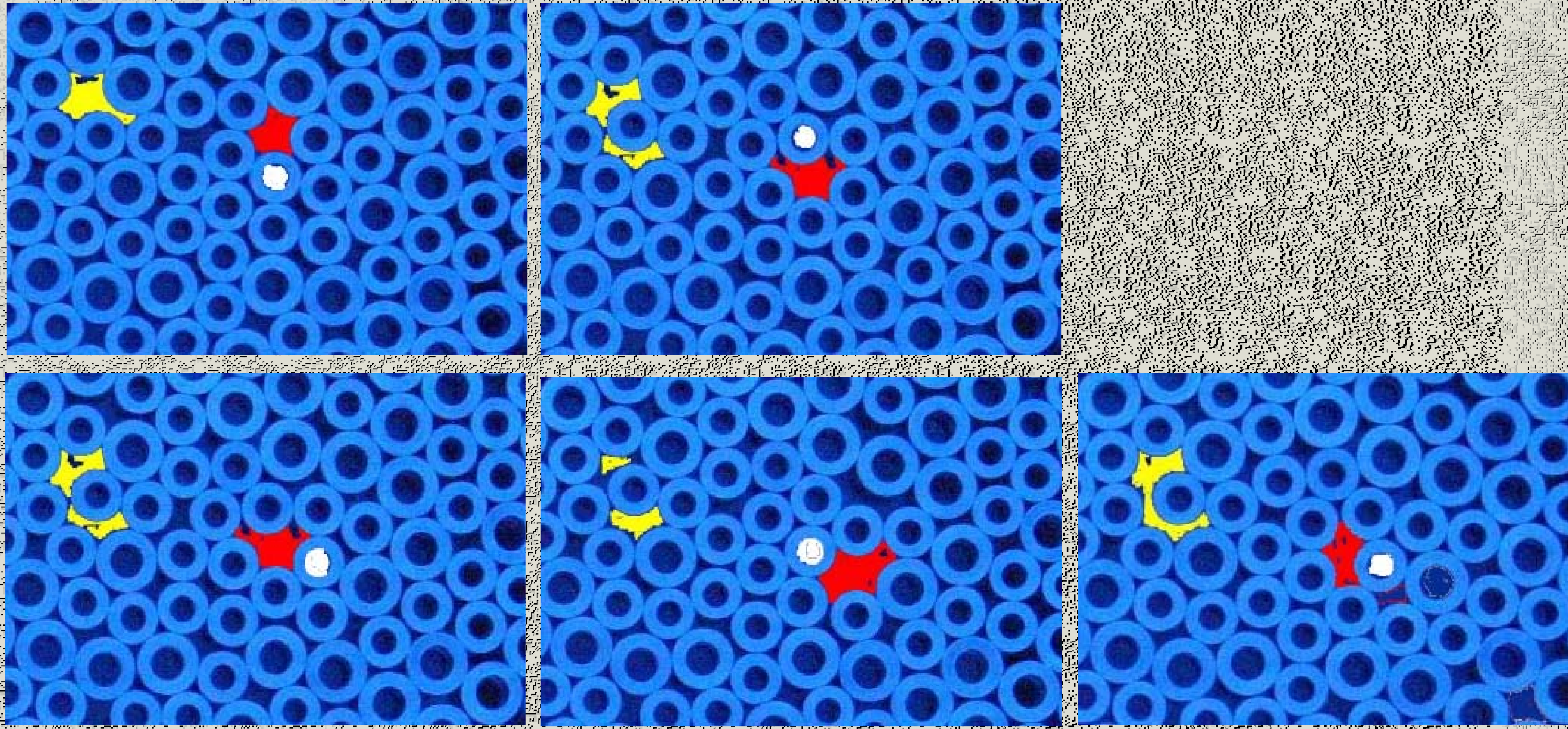


- A rather long ranged structure
- Significant fluctuations in the local density
- Work under progress :spatio-temporal structure

Direct observation of the dynamics

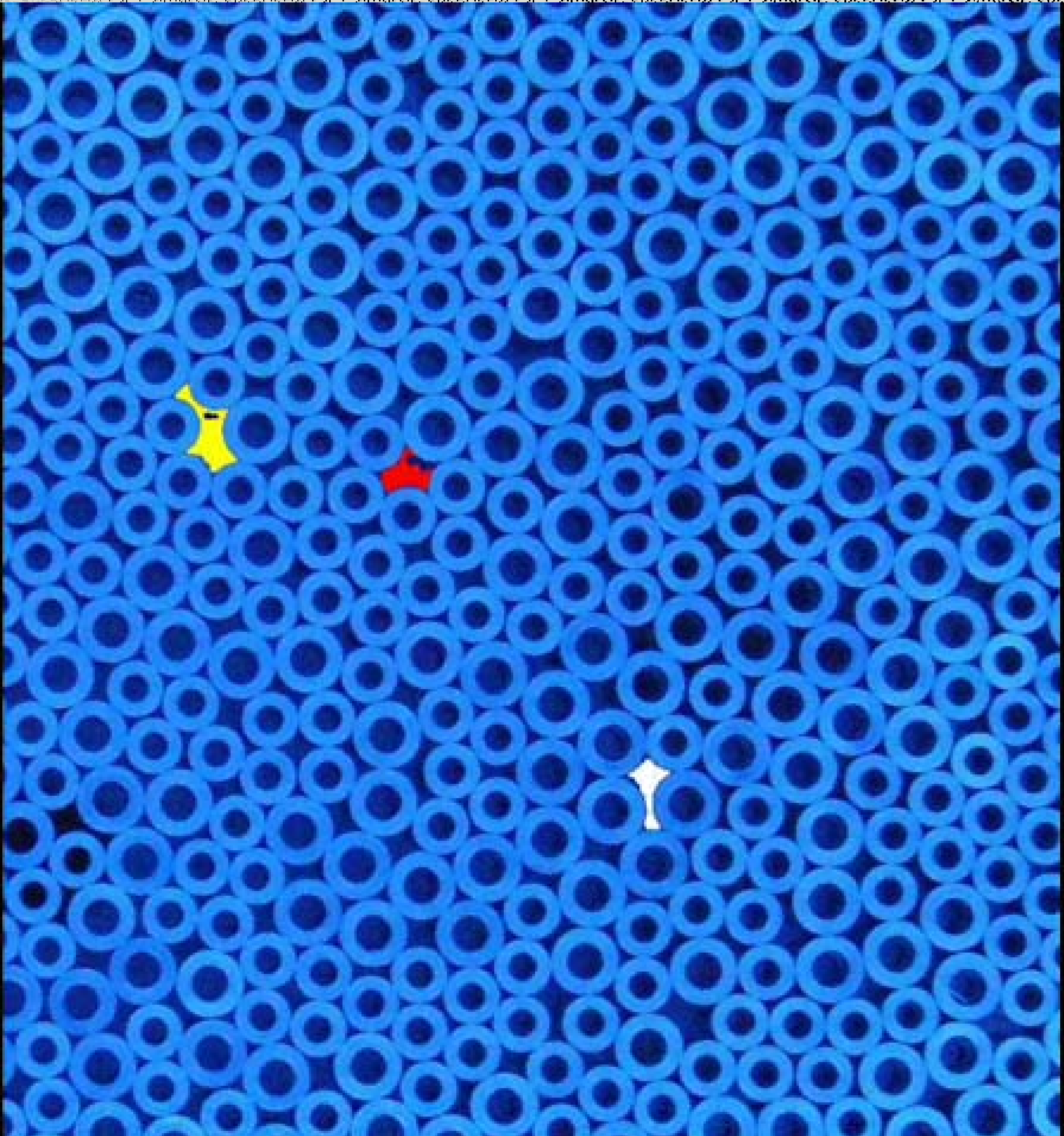


A closer look at the grain scale



- Void redistribution allows cage re-arrangement
- Dynamics facilitation (but also inhibition)
- How long is the range of the correlations?

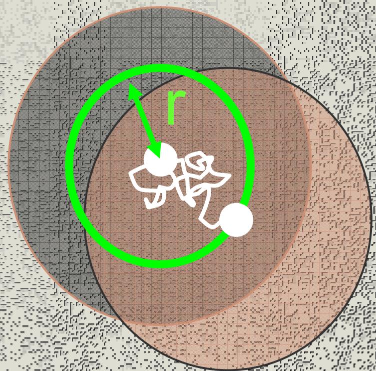
A broader look at the dynamics



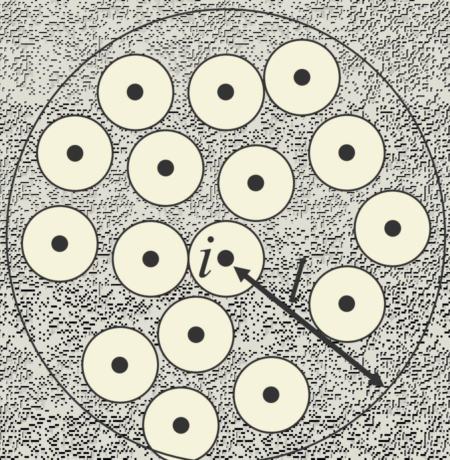
First quantitative estimations

Hurley and Harrowell

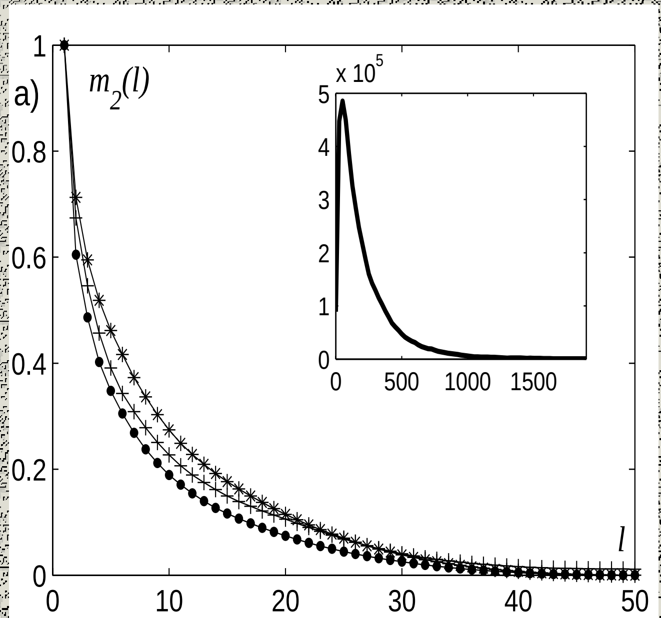
$$m_2(l) = \langle (T_{i,l} - T_{av})^2 \rangle / \langle (T_{i,1} - T_{av})^2 \rangle$$

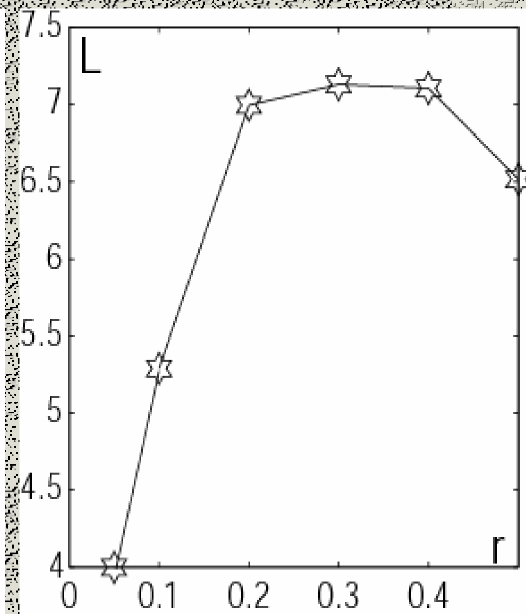


$T_i(r)$: time for grain i to reach the circle of radius r



$T_{i,l}(r) = \langle T_i \rangle$ inside C(i,l)





The correlation length is maximum at the scale of the cage re-arrangements => up to 7 particles diameters

Conclusion and Perspectives

- Dense granular media are analogous to glasses in the sense that their diffusion properties are identical at timescales larger that the thermal regime.
- => It is a good idea to make use of theoretical ideas from glasses in the field of dense granular media
- => A granular experimental set-up is an efficient tool to study glasses at the particle level.
- Further work will deal with :
  - A more precise study of the microscopic dynamics (Clusters?, Strings?, Dynamical heterogeneities?, χ_4)
  - The study of a response function (RFD, Teff?)
  - Aging with or without compaction