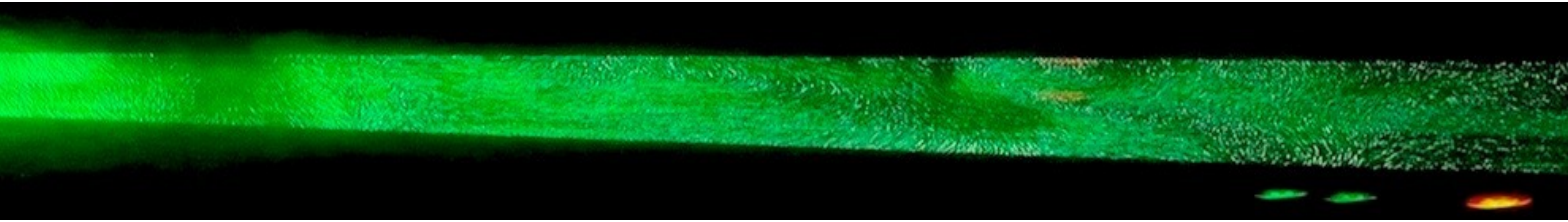

Superclustering of inertial particles in turbulence

Mickaël Bourgoin, Martin Obligado

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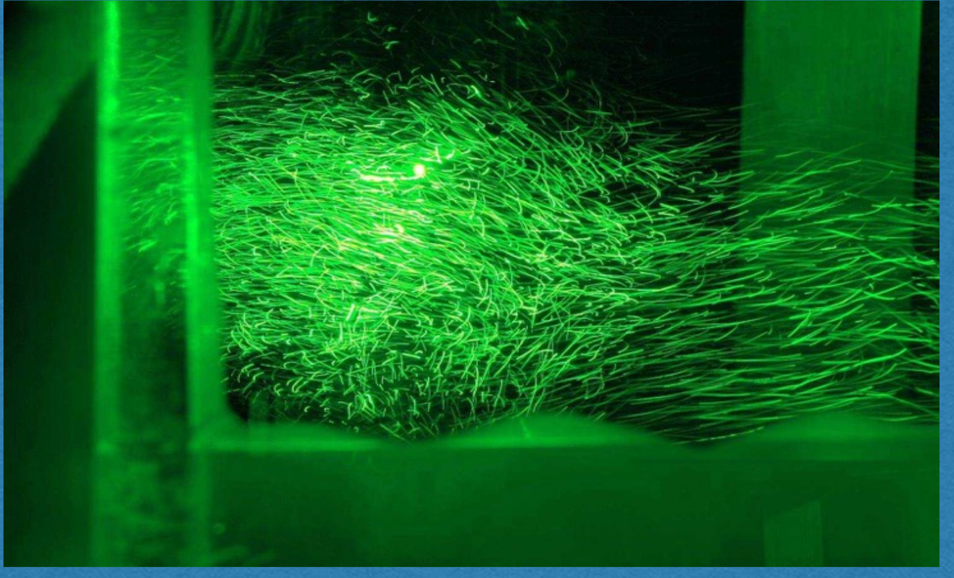
CNRS advancing the frontiers

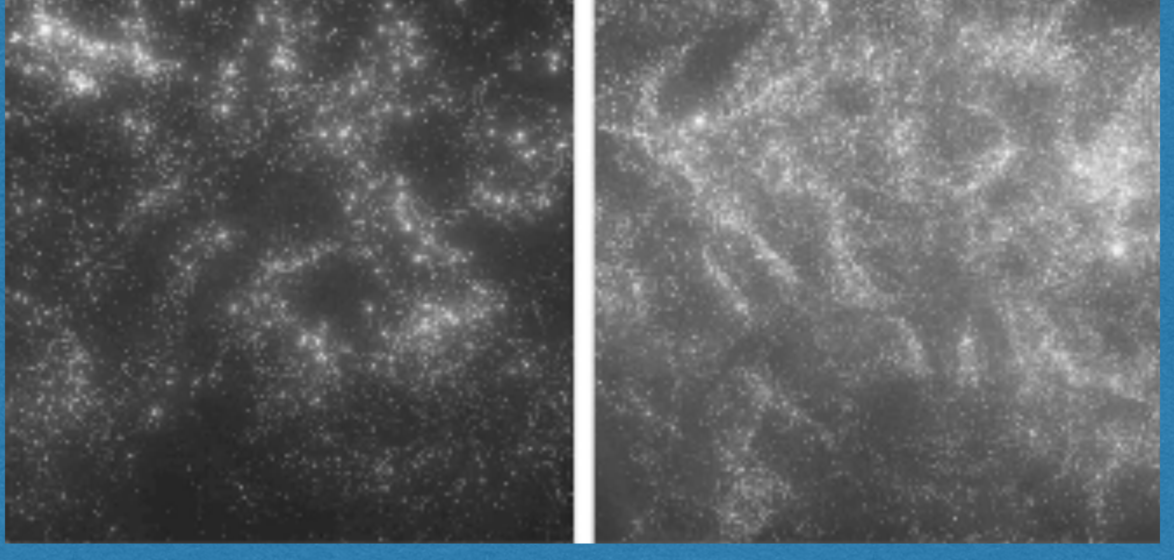
Tracer particles vs. Inertial particles

Tracers behave as fluid particles



PIV, LDV, PTV, etc.

Inertial particles do not follow exactly the flow



Wood, Hwang & Eaton. 2005

« material particles »

Ex: water droplets in air

Stokes number

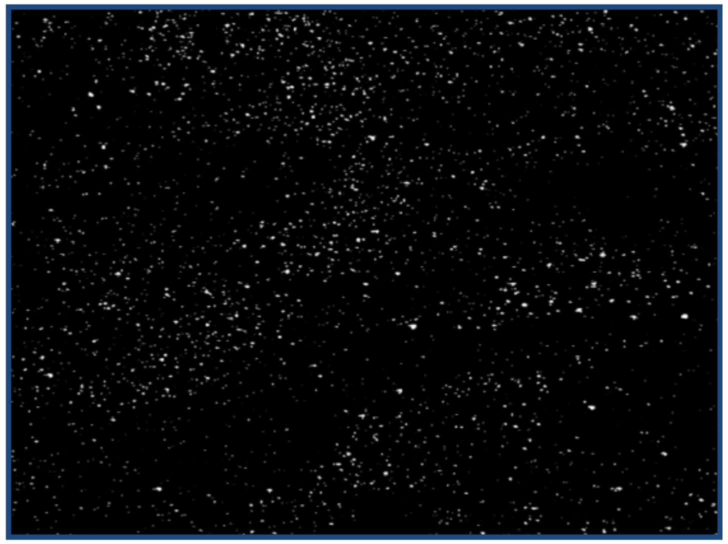
$$St = \tau_p / \tau_k$$

$$\tau_p = \frac{d^2 \rho_p / \rho_f}{18 \nu_f}$$

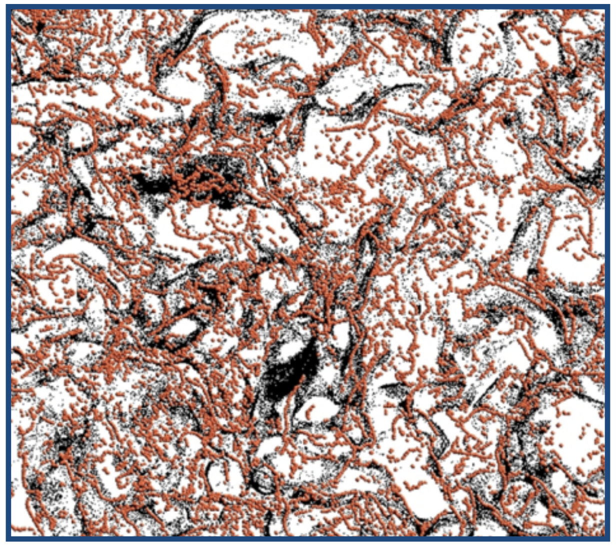
$$\tau_k = (\nu_f / \epsilon)^{1/2}$$

Preferential concentration of inertial particles

A striking feature: inertial particles experience preferential concentration



Aliseda, Cartellier, Hainaux & Lasheras. JFM, 468 (2002)



Goto & Vassilicos, PRL 100 (2008)

Relevant issues:

- impact on collision efficiency
- impact on settling velocity enhancement
- Collective dynamics
- Etc.

Possible interpretation:

- Dissipative dynamics of inertial particles
  Mehlig & Wilkinson, PRL 92 (2004) and others

$$\frac{\mathrm{d}\vec{v}}{\mathrm{d}t} = \frac{1}{\tau_p}(\vec{u} - \vec{v})$$

- Centrifugal expulsion from eddies
  (role of high strain-low vorticity points)
  Wang & Maxey, JFM 1993
- Sweep-stick mechanism
  (role of Zero acceleration points)
  Goto & Vassilicos, PRL 100 (2008)

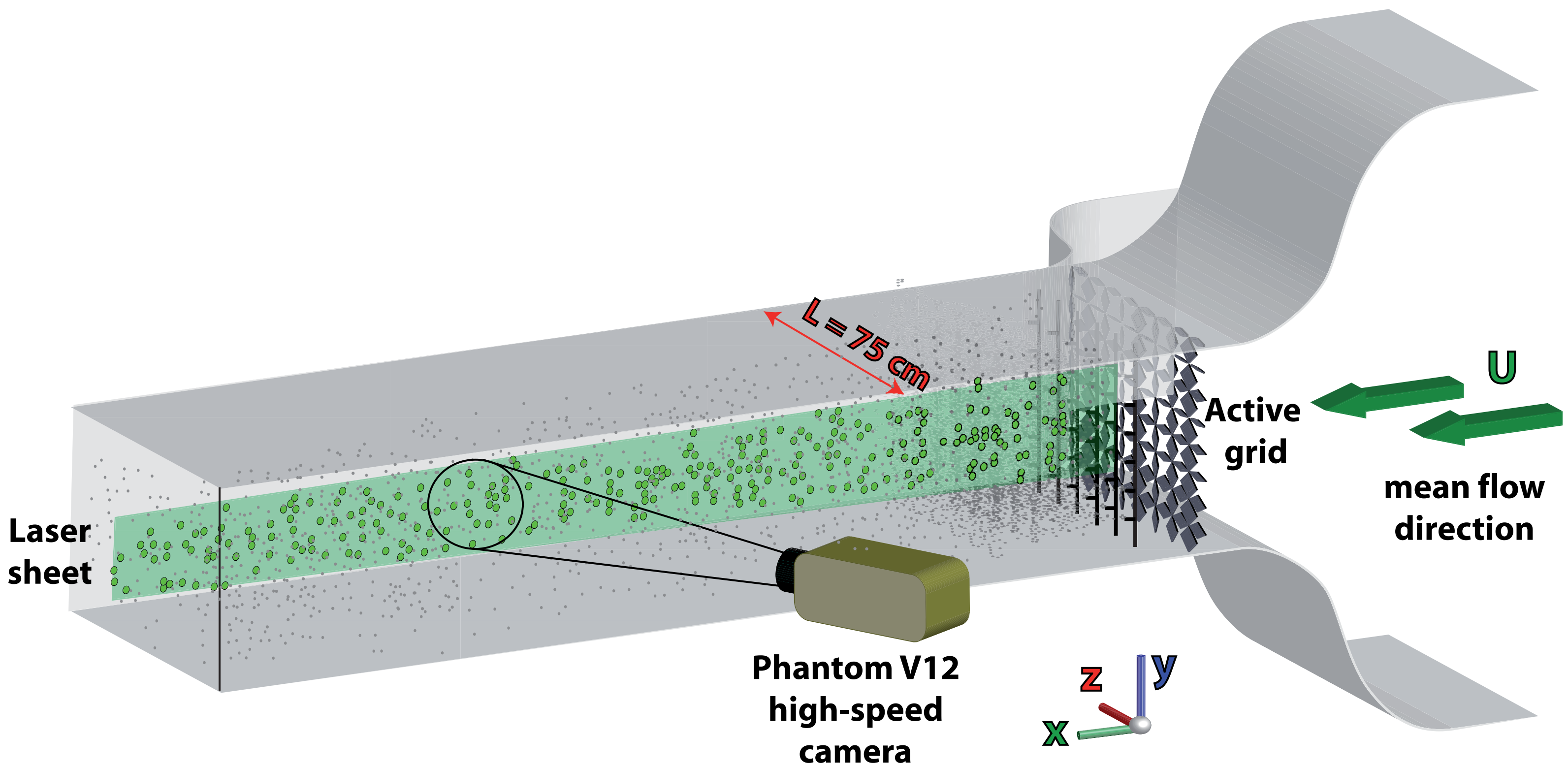
Some known properties

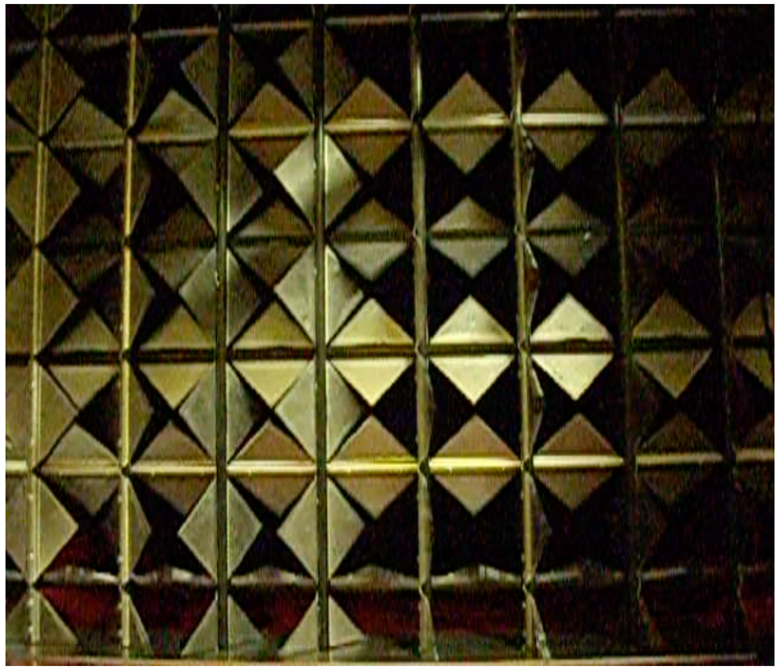
- Maximum for Stokes number around 1
- Clusters typical size of order 10 η
- Fractal cluster geometry

Do clusters clusterize ? (Super-clustering)

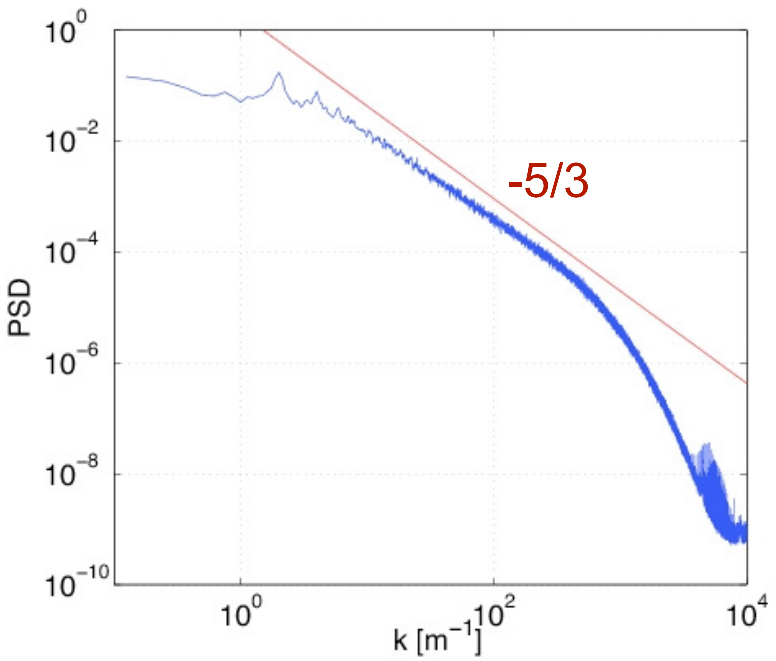
Experimental setup

Obligado et al., JoT 2014





Turbulent velocity spectrum

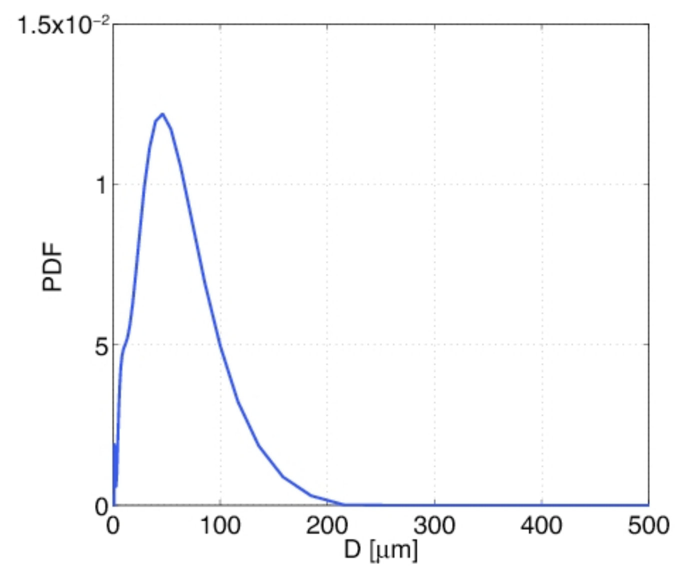


R_λ	U (m/s)	L (cm)	η (μm)	ϵ (m^{3}s^{-3})	St
234	3.4	13.0	280	.69	2.1
264	4.0	13.2	240	1.2	3.3
295	4.8	13.5	208	2.0	4.3
331	5.7	13.8	178	3.4	5.8
357	6.4	14.0	160	4.7	6.6
400	7.6	14.3	140	7.7	9.9

Note : here R_λ and St are equivalent

$$St = (d/\eta)^2(1 + 2\rho_p/\rho_f)/36$$

Size distribution



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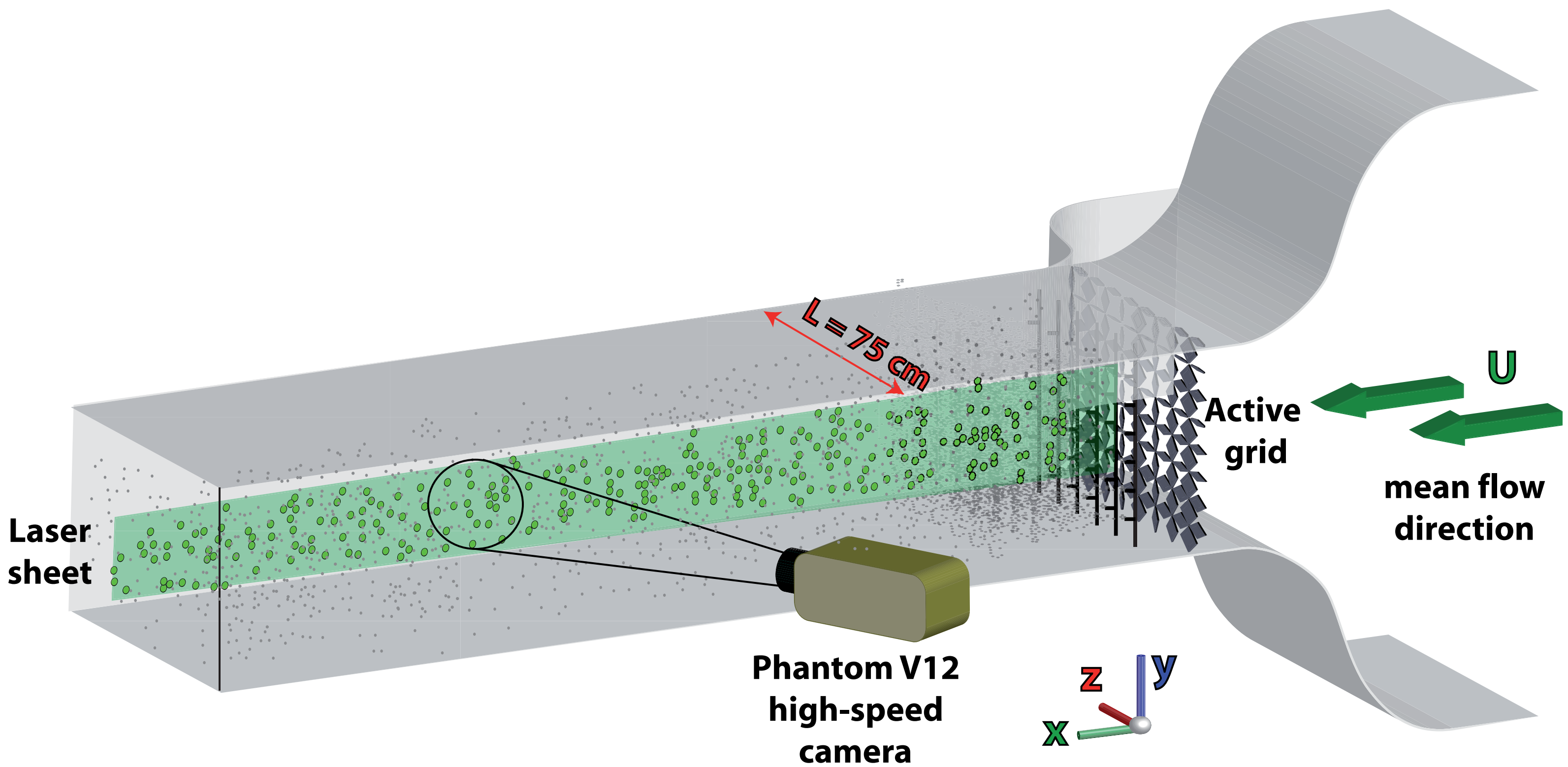
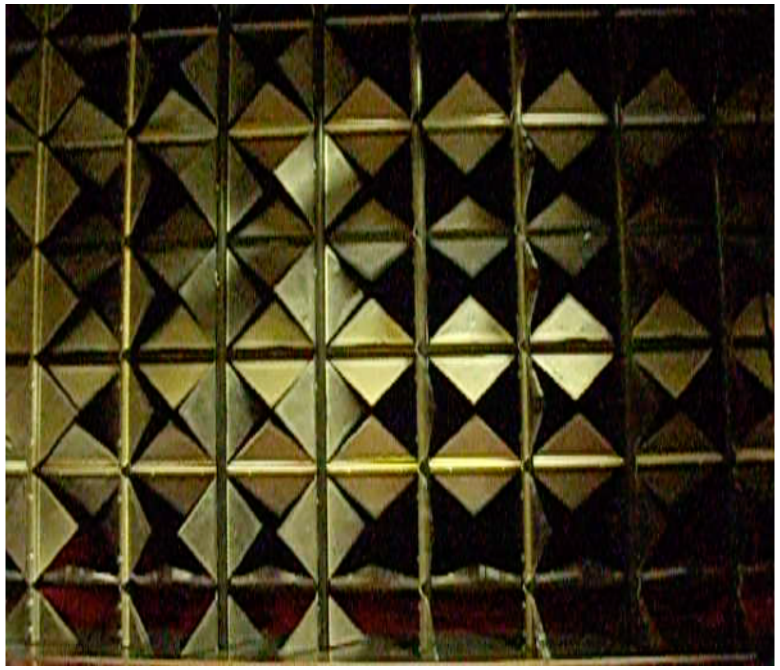
Obligado et al., JoT 2014





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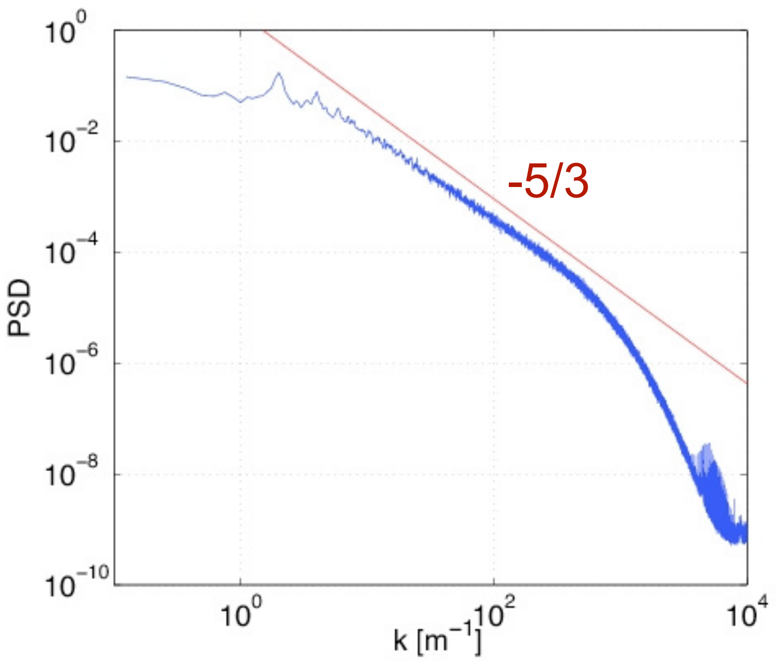

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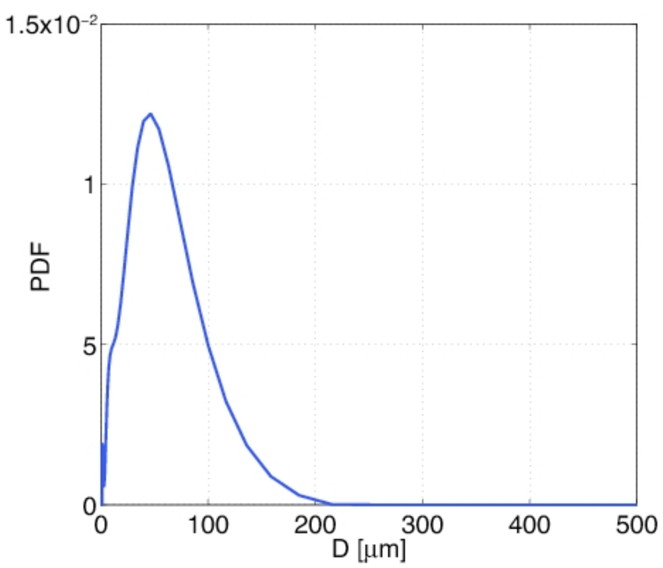
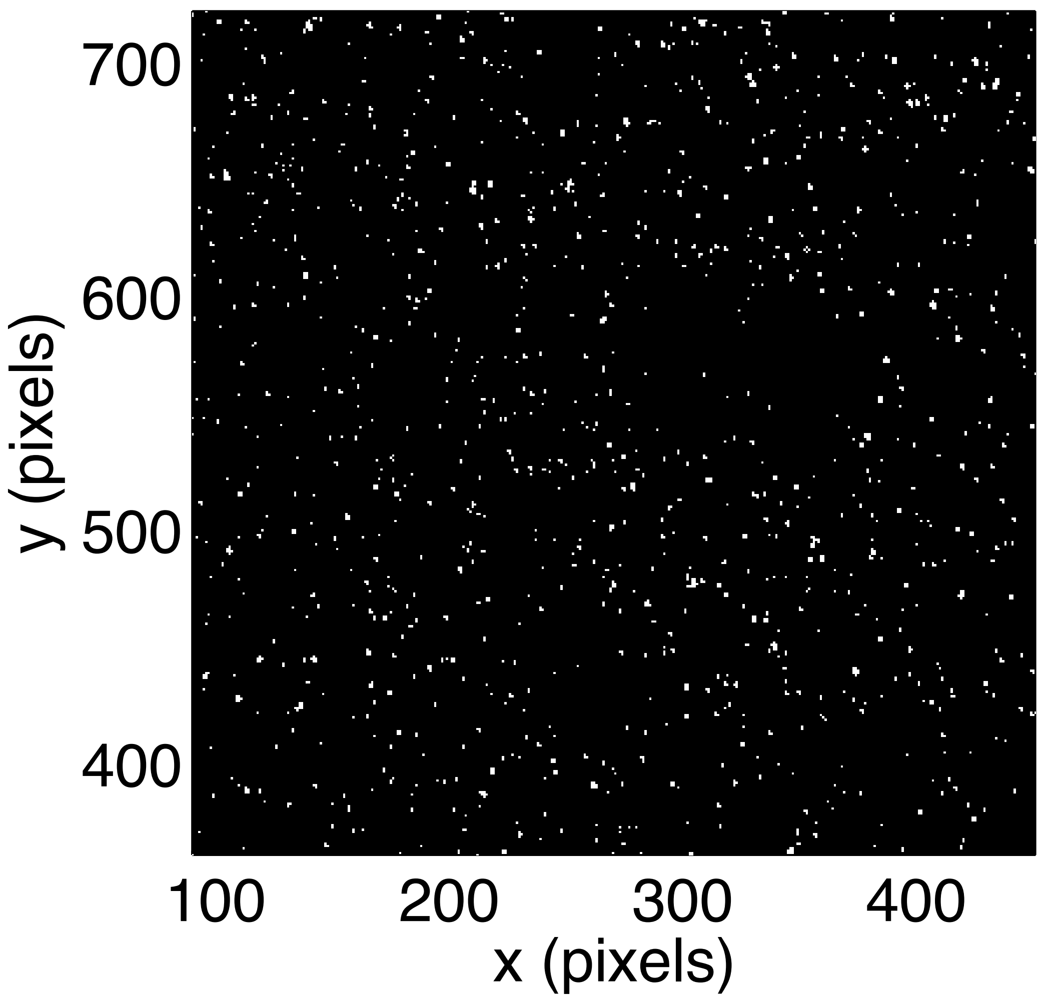
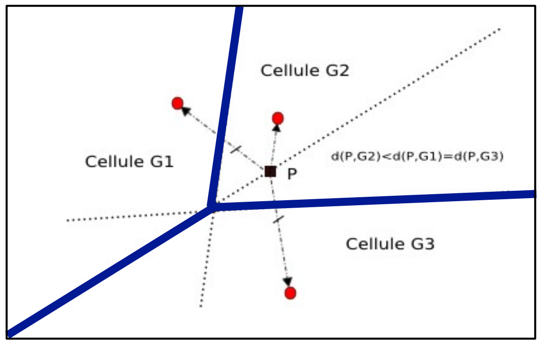
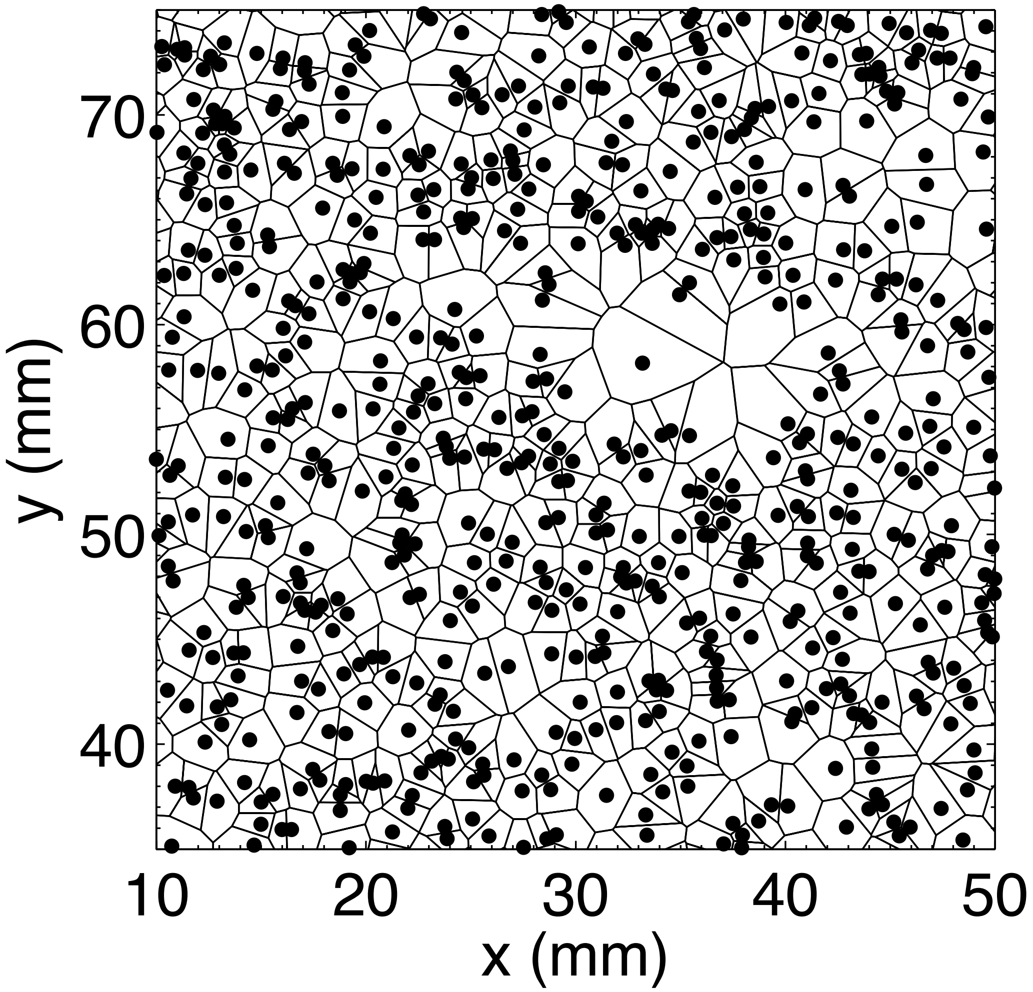


Quantifying clustering with Voronoï tessellation

Voronoï Tesselation



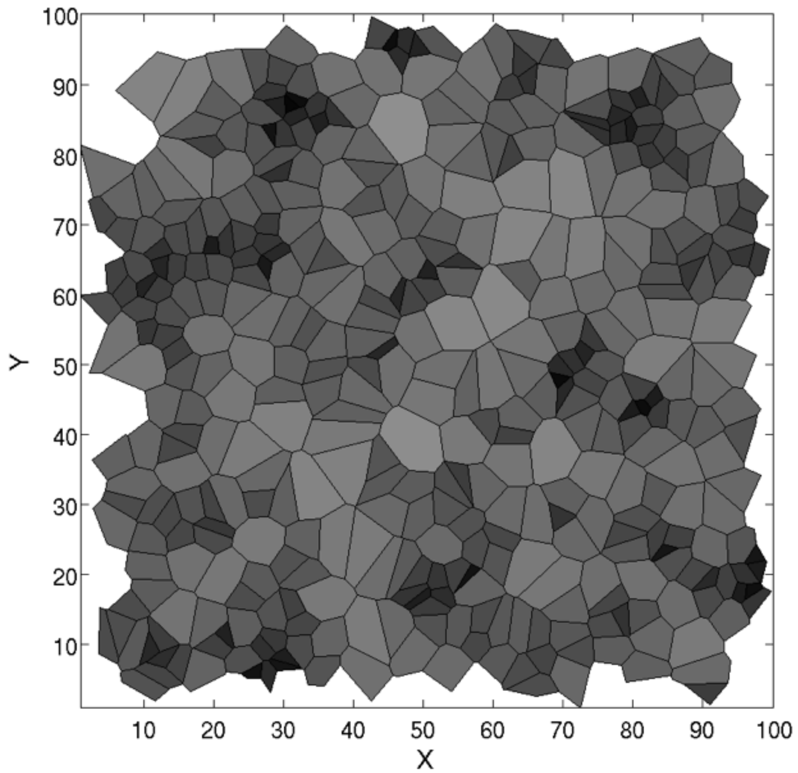


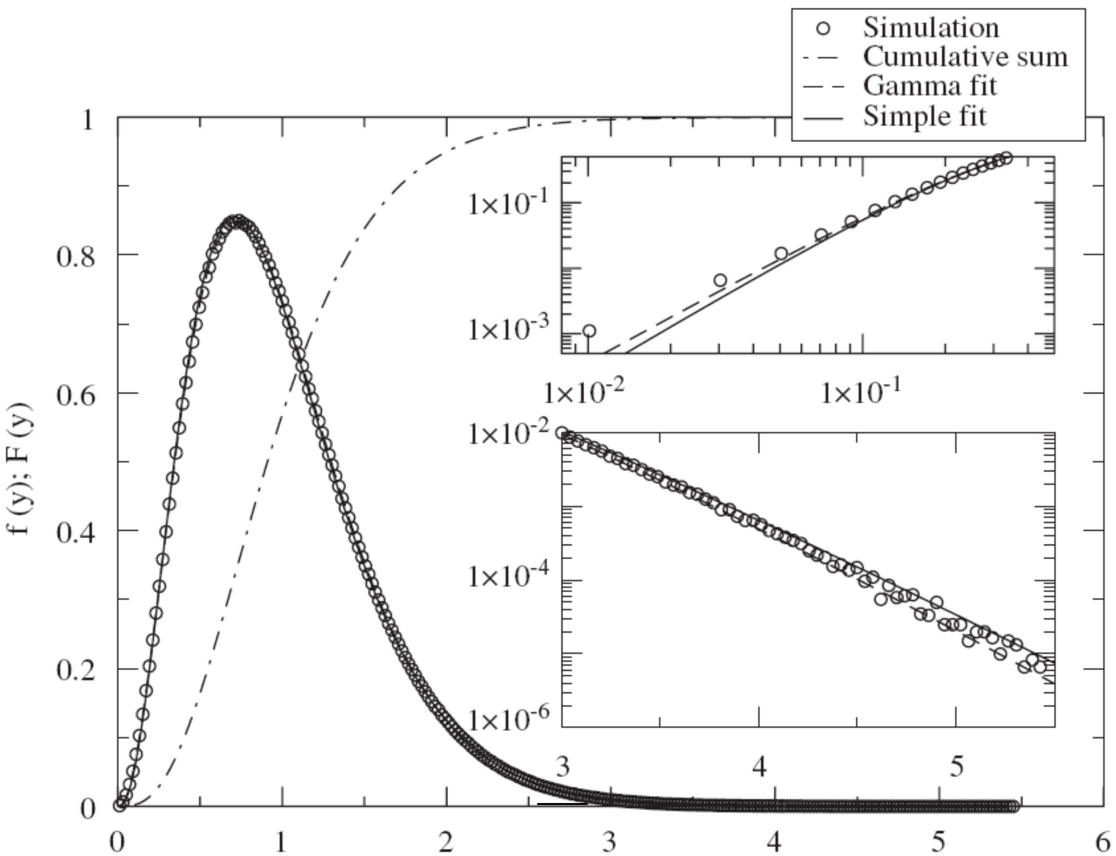


- Local concentration is estimated at an intrinsic length scale $C_{\text{loc}} = A^{-1}$
- Both global and local (multi-scale) information.
- Allow cluster identification and characterization.
- Easily ported to Lagrangian framework (tracking of Voronoï cells).

Quantifying clustering with Voronoï tessellation

Voronoï Tesselation - some known properties





$\bar{\mathcal{A}} = C_0^{-1}$

Average Voronoï area does not carry any structural information

$\mathcal{V} = \mathcal{A} / \bar{\mathcal{A}}$

Normalized Voronoï area

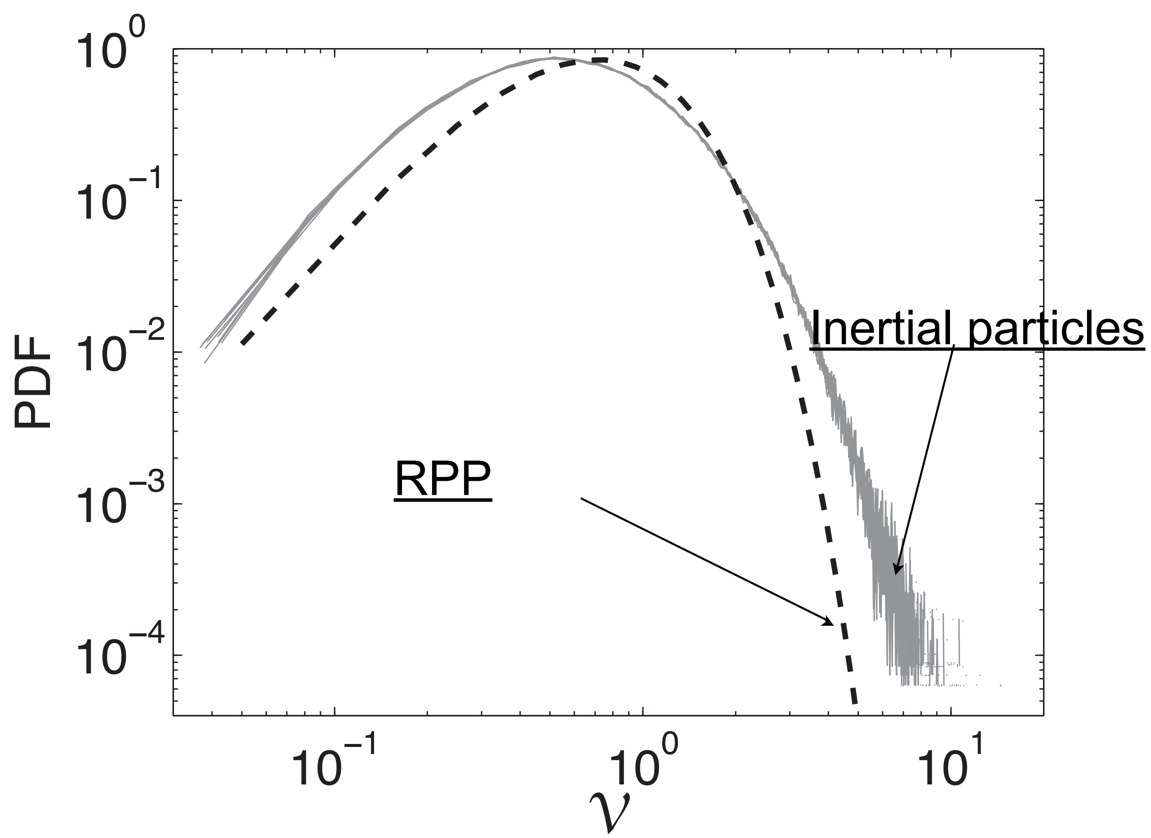
Random Poisson Process (RPP)

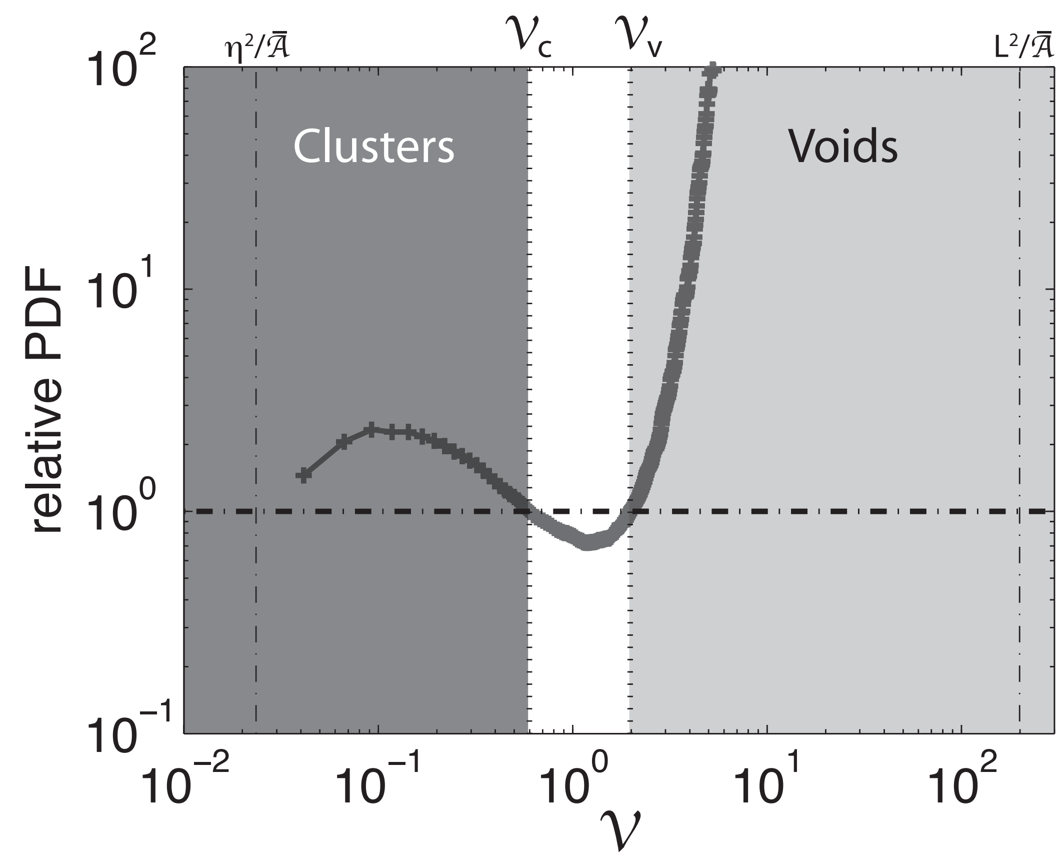
- No known analytical form of the PDF of *A* for a RPP, but it is well approximated by Gamma function.
- $\sigma_{\mathcal{V}}^{\mathrm{RPP}} = \sqrt{< \mathcal{V}^2 >_{\mathrm{RPP}} - 1} \simeq 0.53$

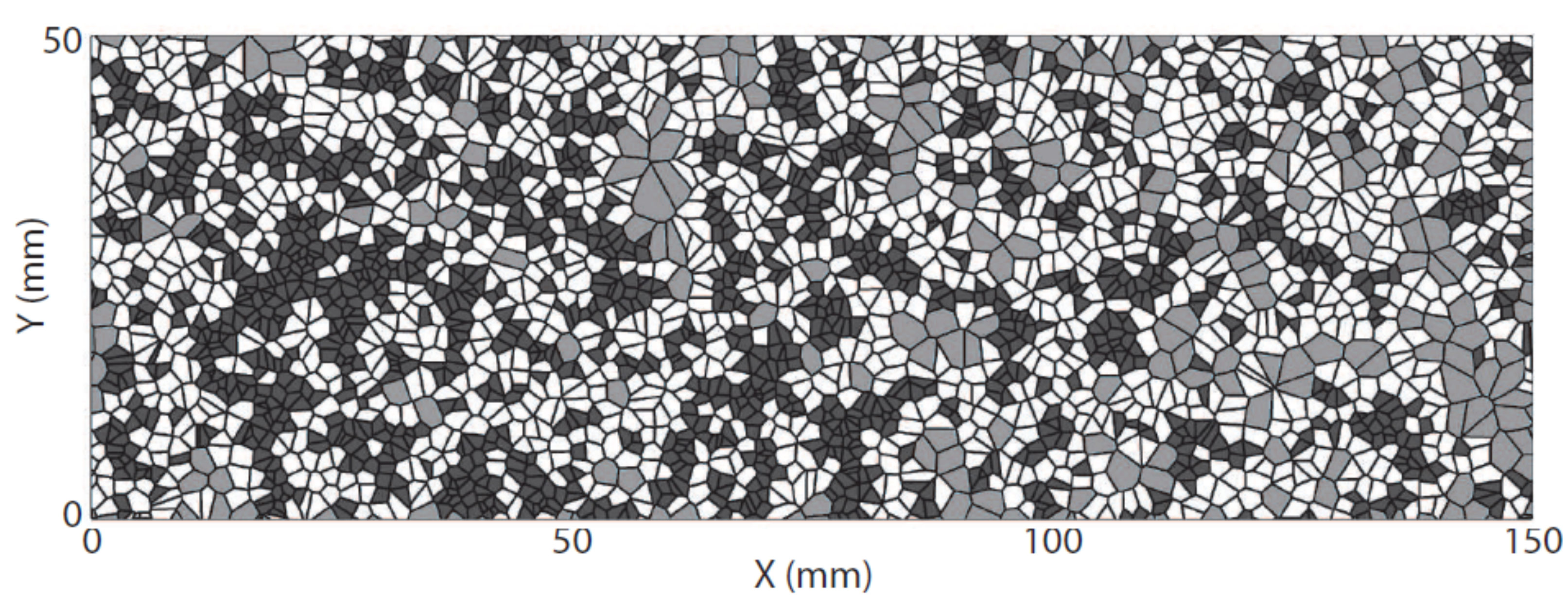
Clusters definition

Voronoï Analysis

Monchaux et al., PoF 2010
Monchaux et al., IJMF 2012
Tagawa et al., JFM 2012
Obligado et al., JoT 2014







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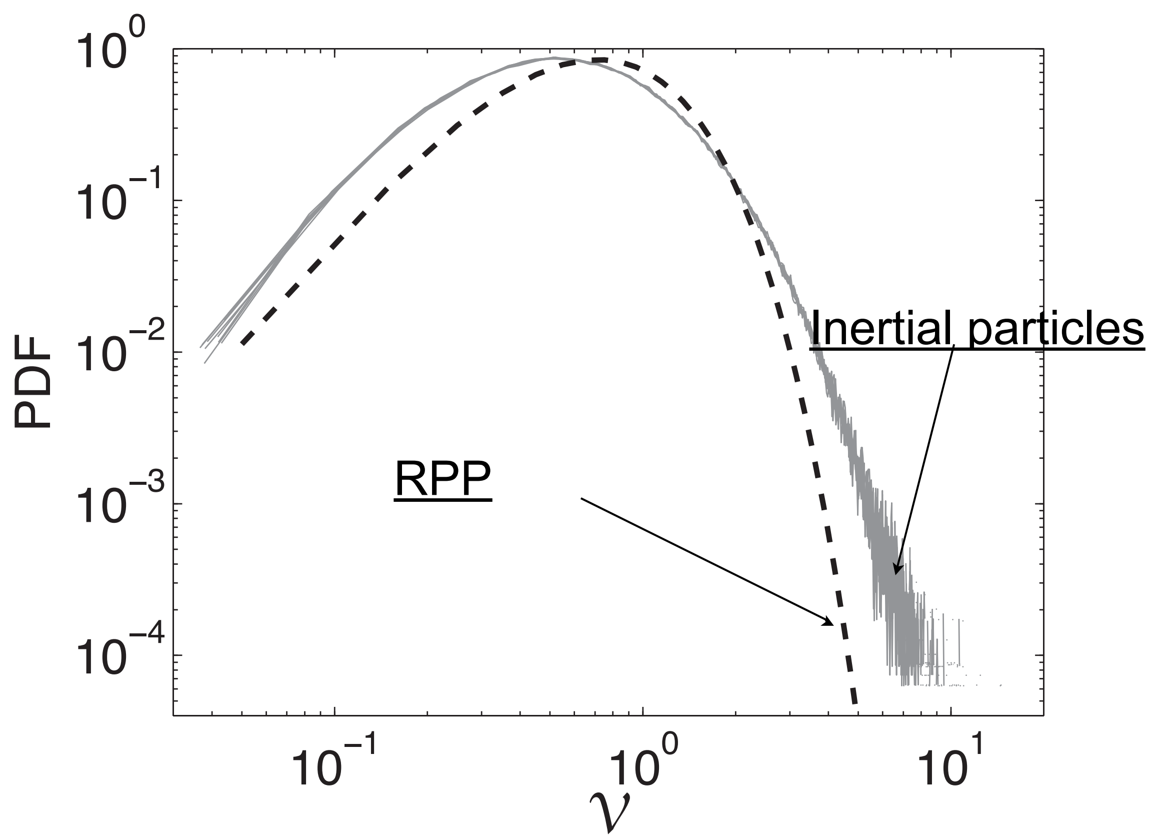

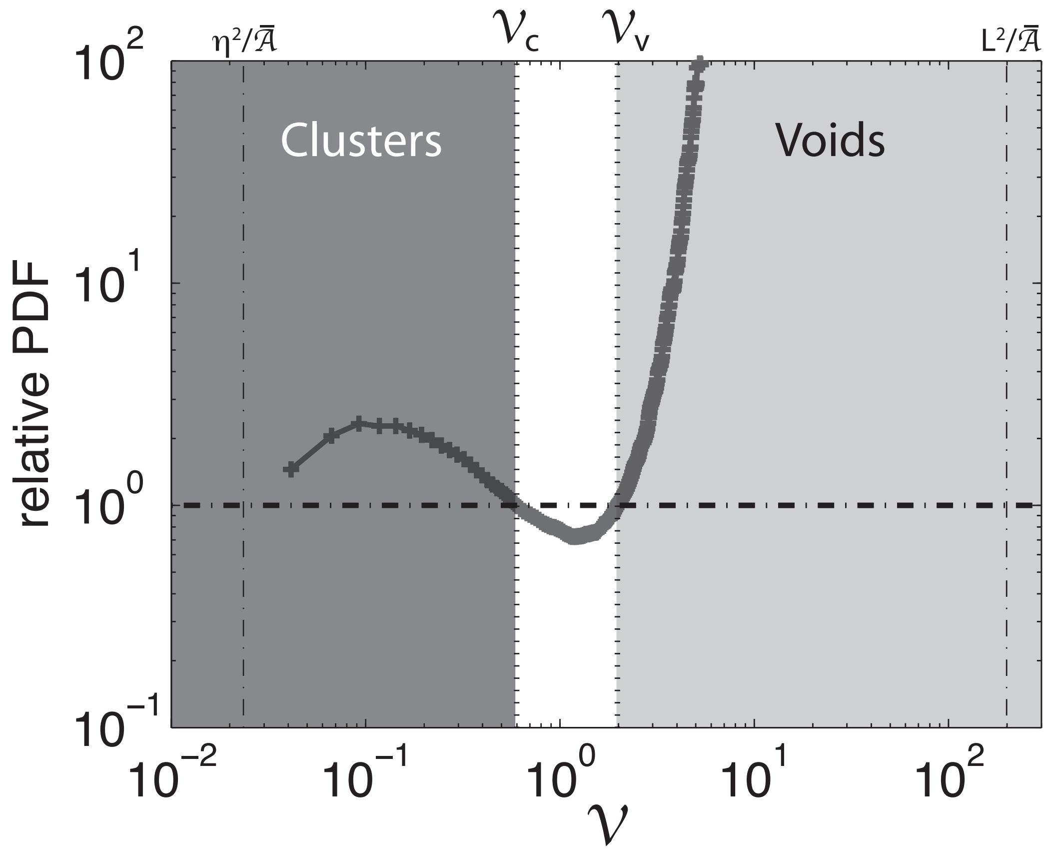

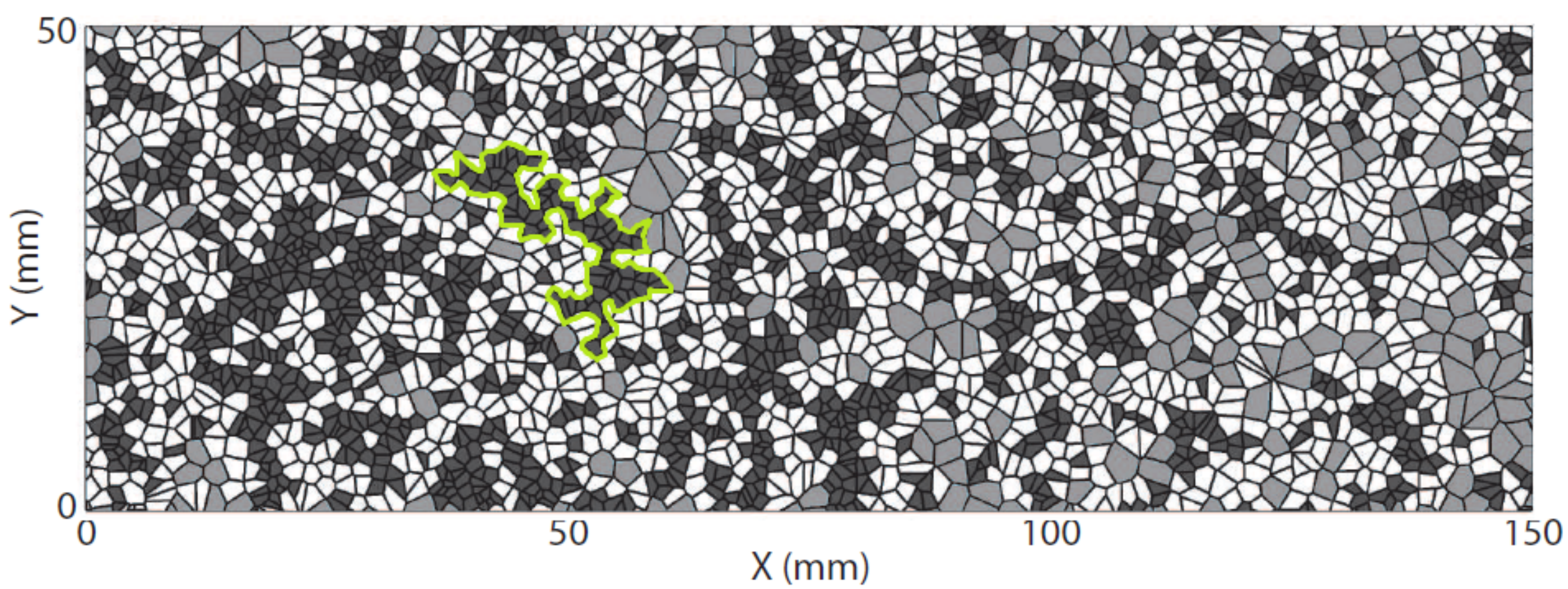

Clusters definition

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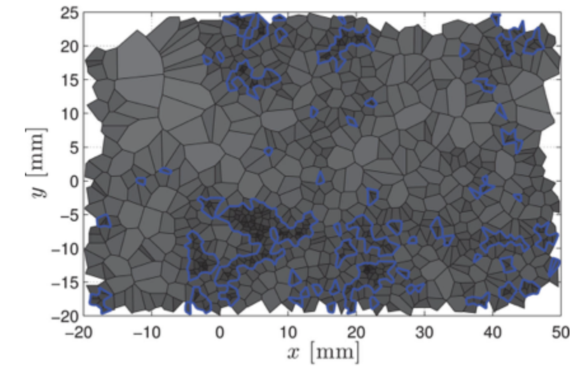


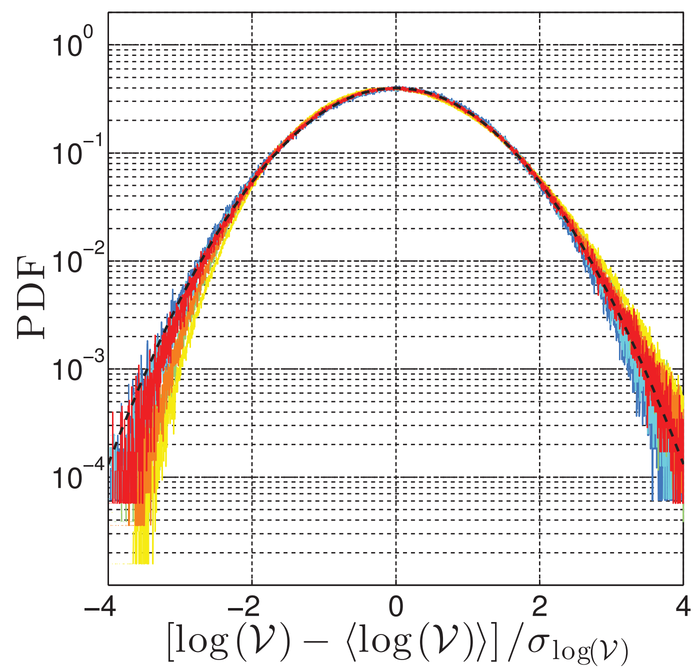
Monchaux et al., PoF 2010

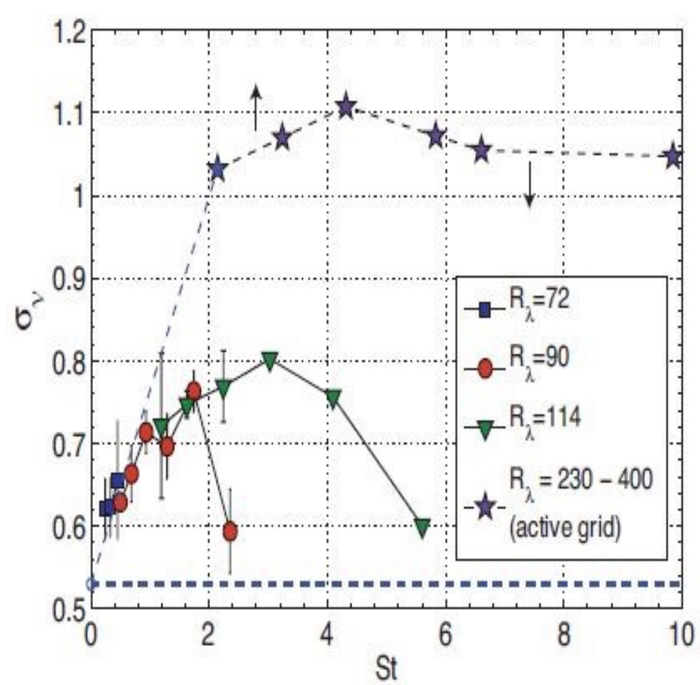
Monchaux et al., IJMF 2012

Tagawa et al., JFM 2012

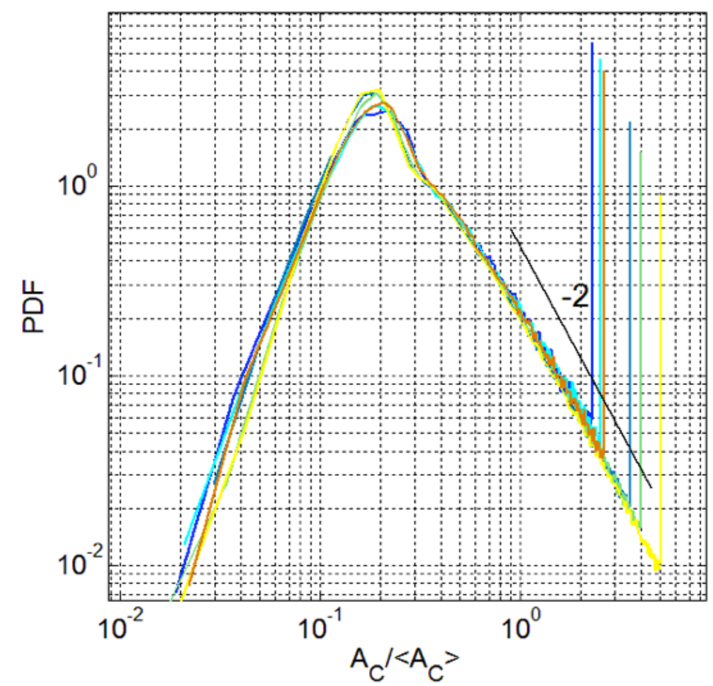
Obligado et al., JoT 2014

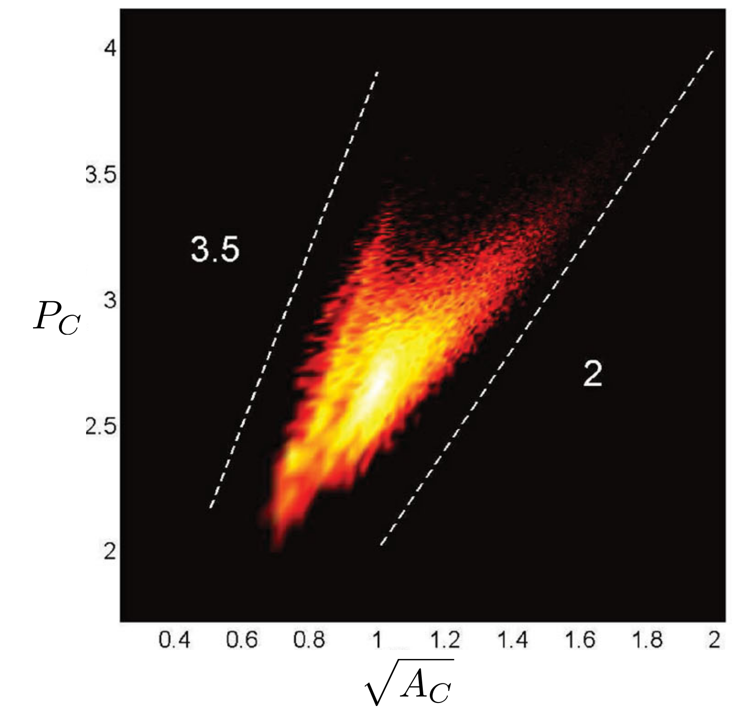
Statistics of Voronoï areas

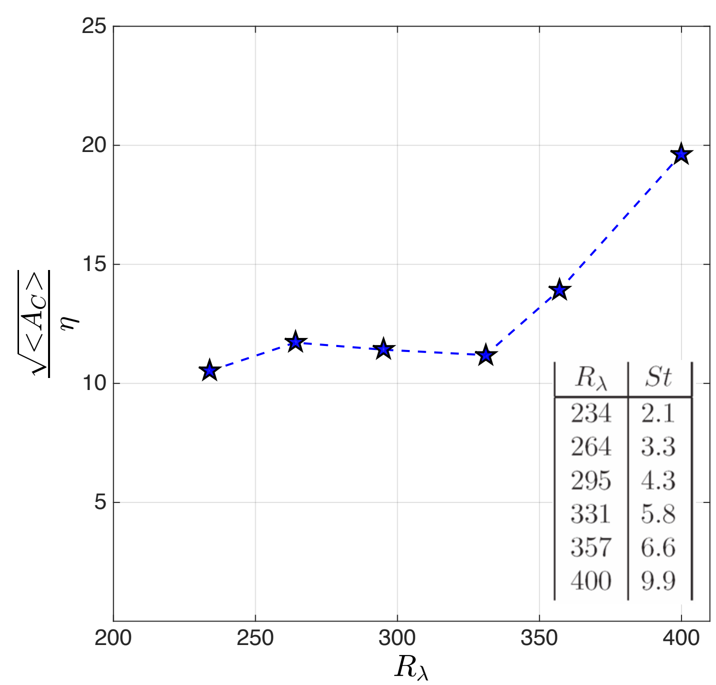




Clusters geometry







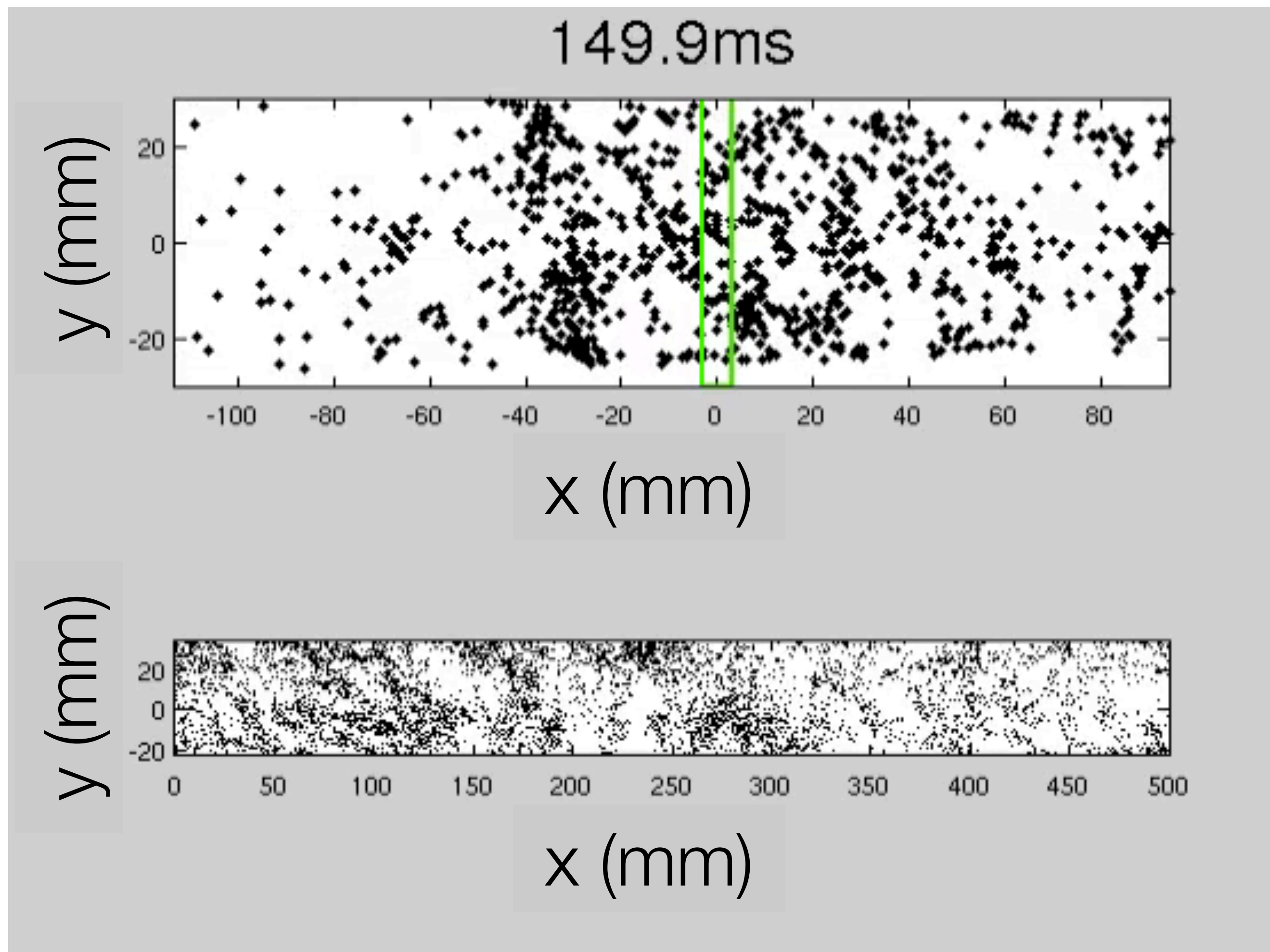
Some known properties

- Maximum for Stokes number around 1
- Clusters typical size of order 10 η
- Fractal cluster geometry

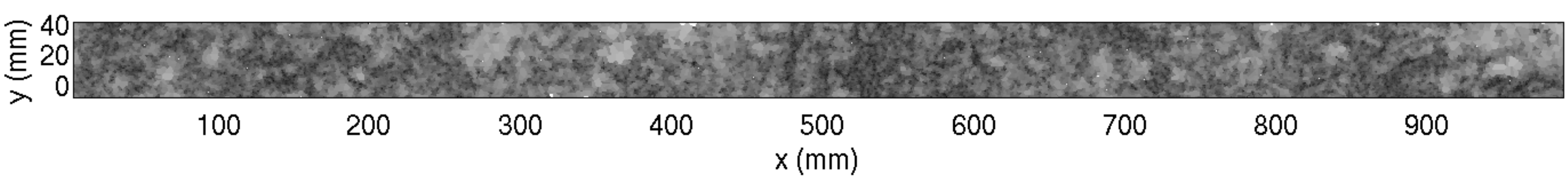
Taylor hypothesis applied to high speed imaging

Reconstruction of large scale fields

“Linear Camera” reconstruction

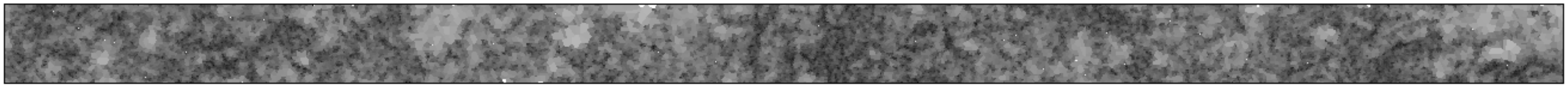


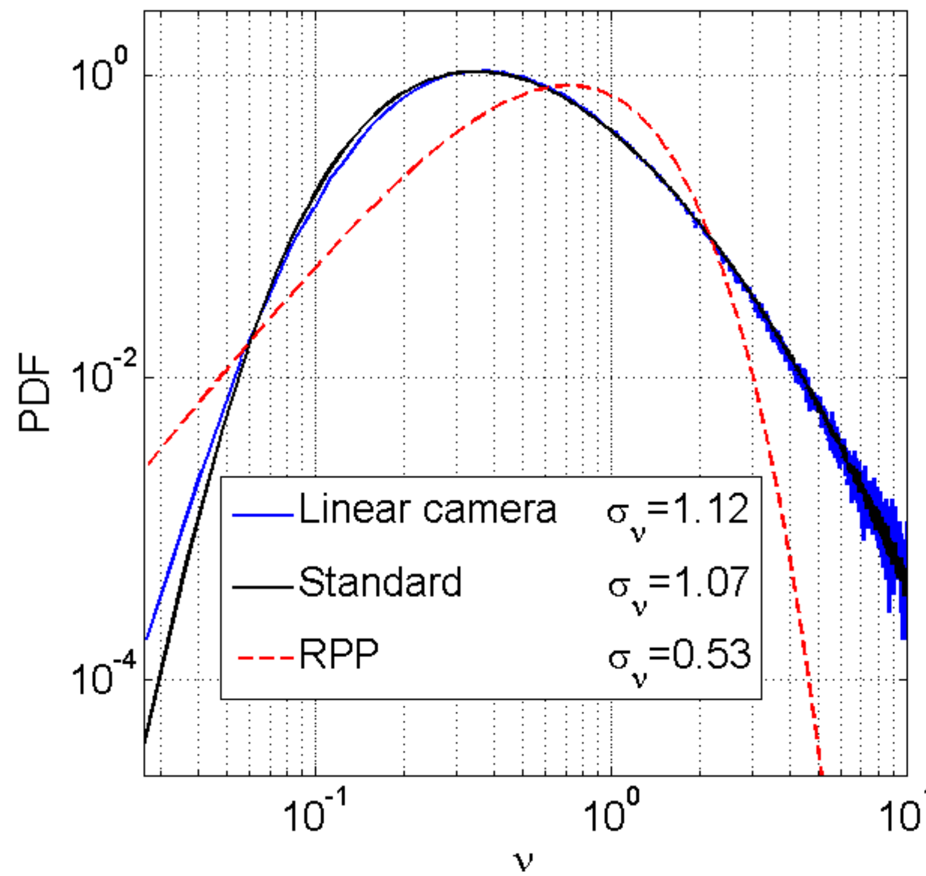
We can reconstruct a large scale field and apply Voronoï Tesselation :



Validation of Taylor hypothesis

Voronoï analysis of particles centers

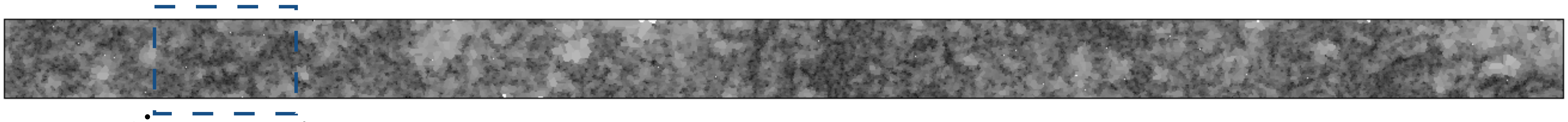


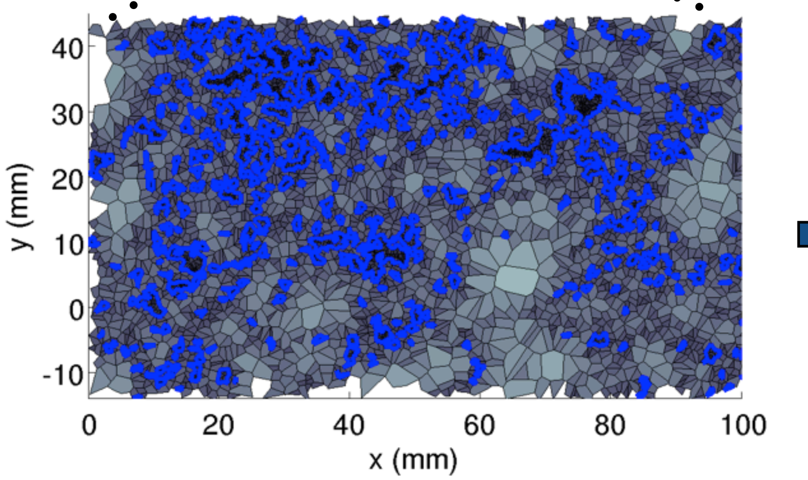


Statistics of Voronoï areas reconstructed using the Taylor hypothesis are identical than the statistics obtained with the classical image per image analysis

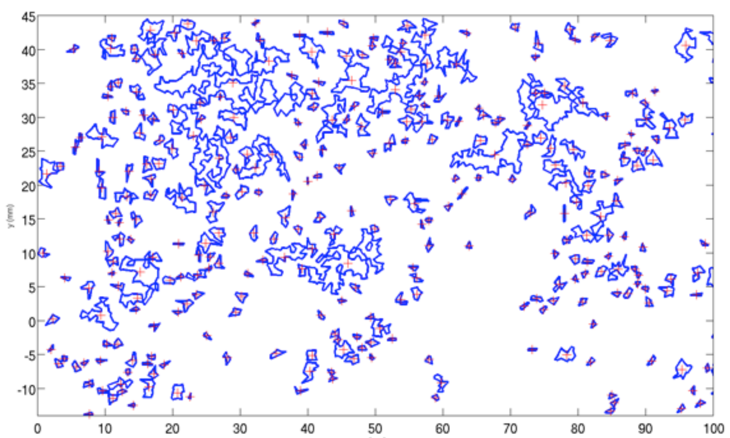
Evidence of Super-Clustering

Voronoï analysis of cluster centers

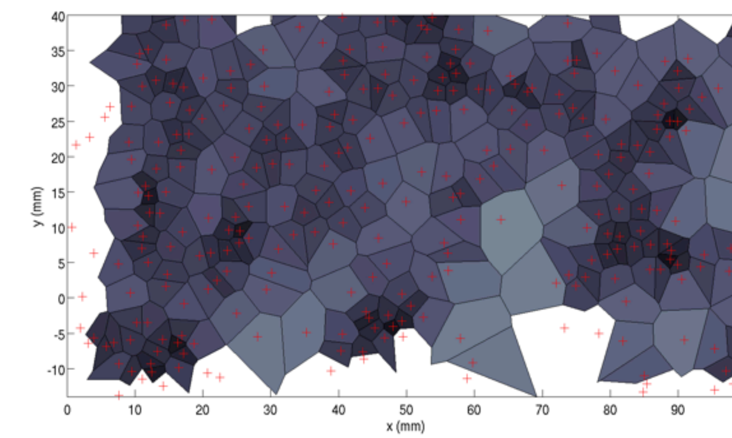




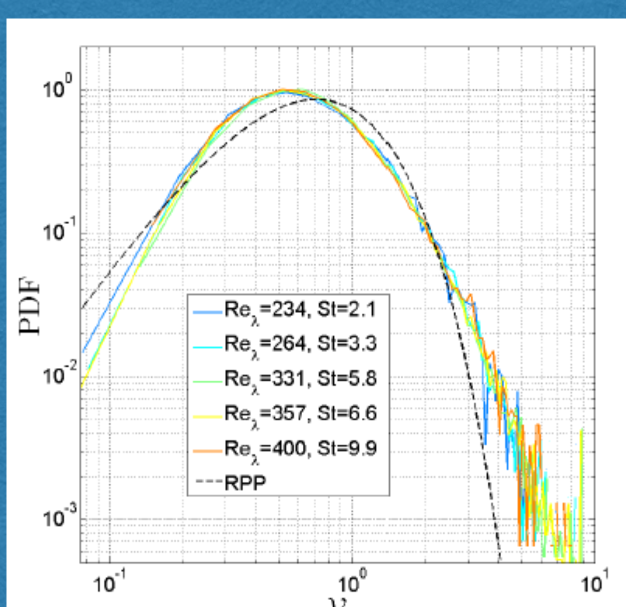
1. Identify clusters of particles from Voronoï diagram



2. Find clsuters of mass



3. Voronoï analysis of clusters center of mass

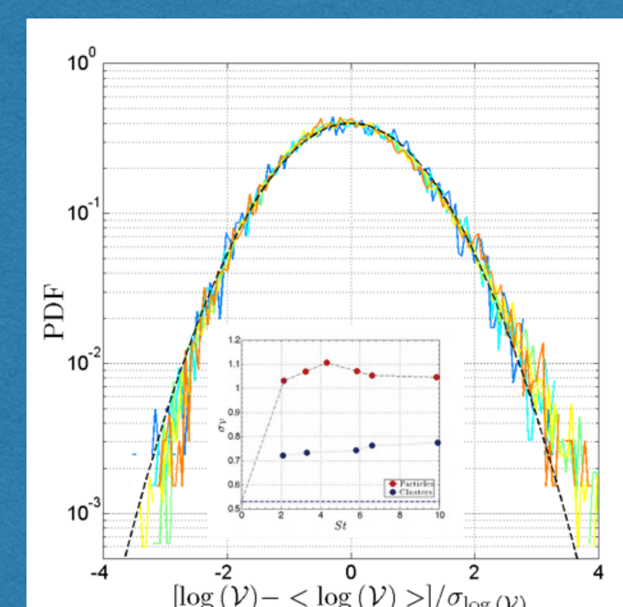


Super-clustering !

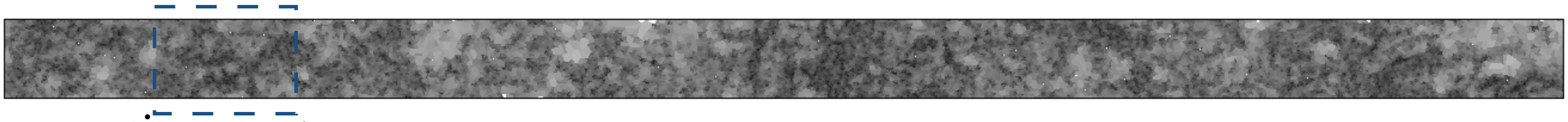
Log-normal Super-clustering

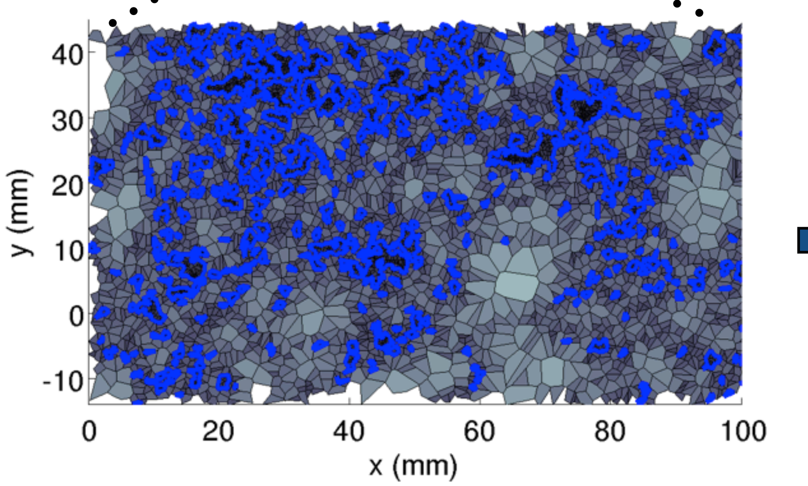
(Similar behavior as particle clusters)

Super-Clustering is less pronounced than clustering



Super-clusters identification





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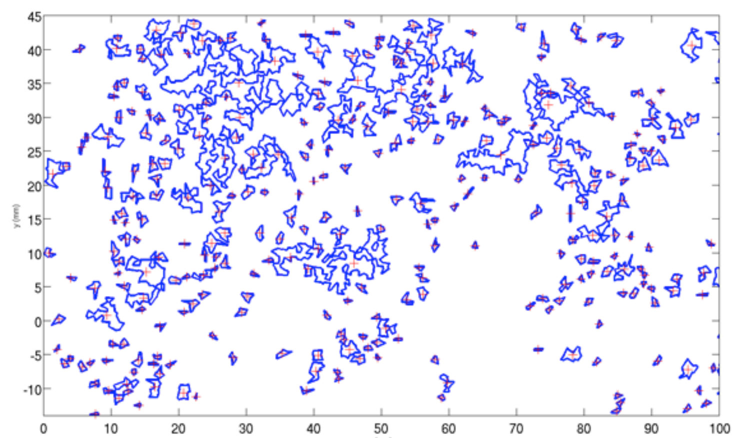

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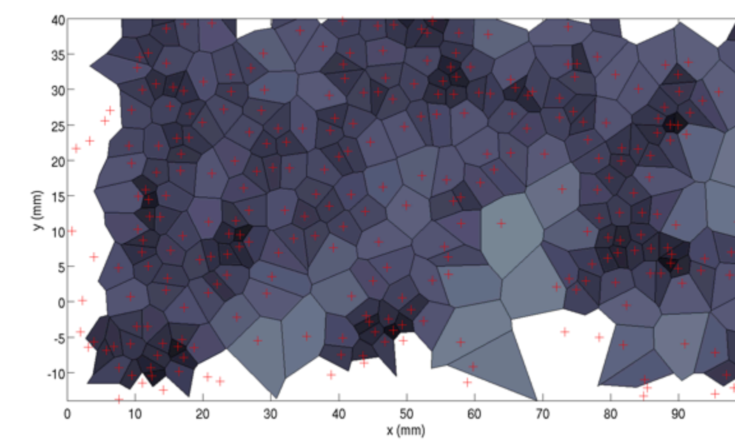

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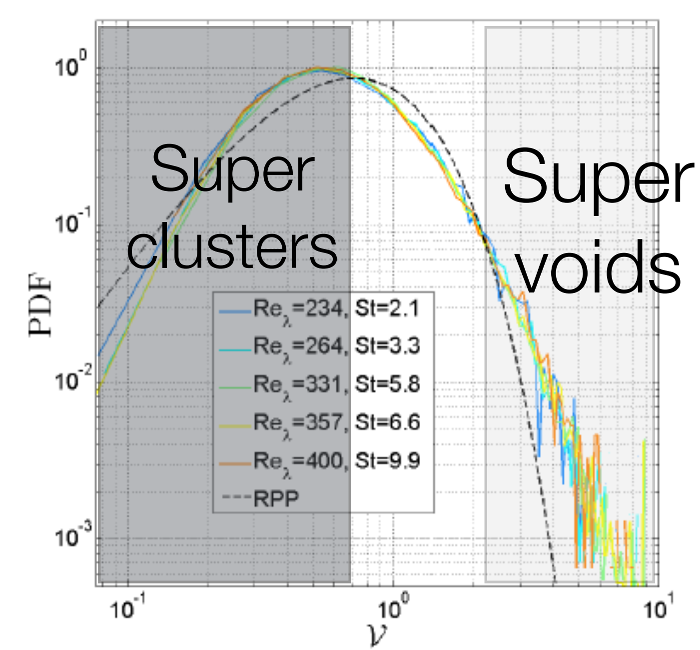
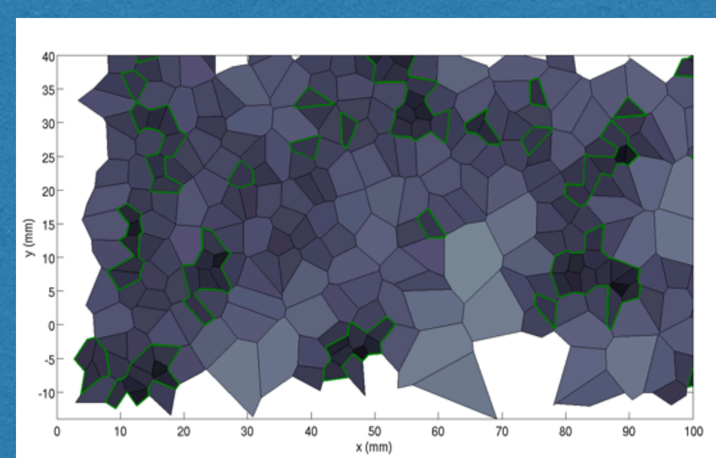
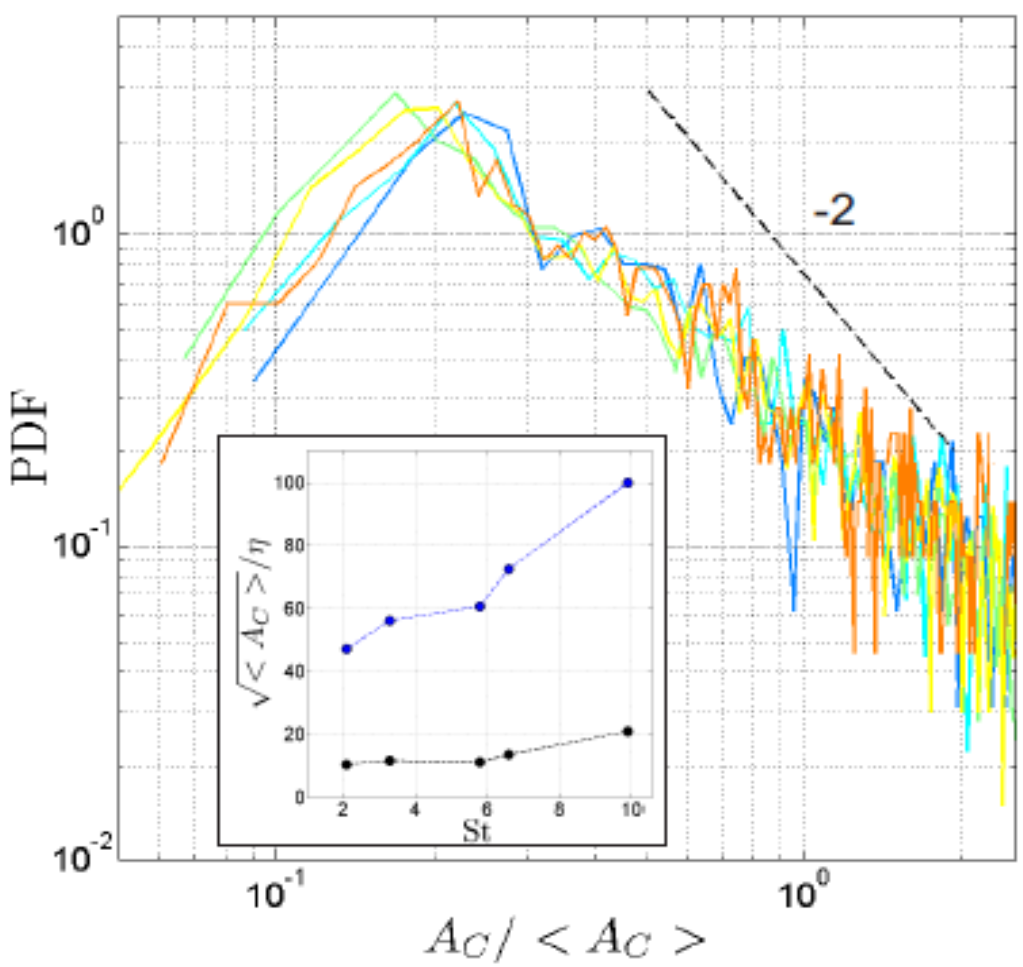




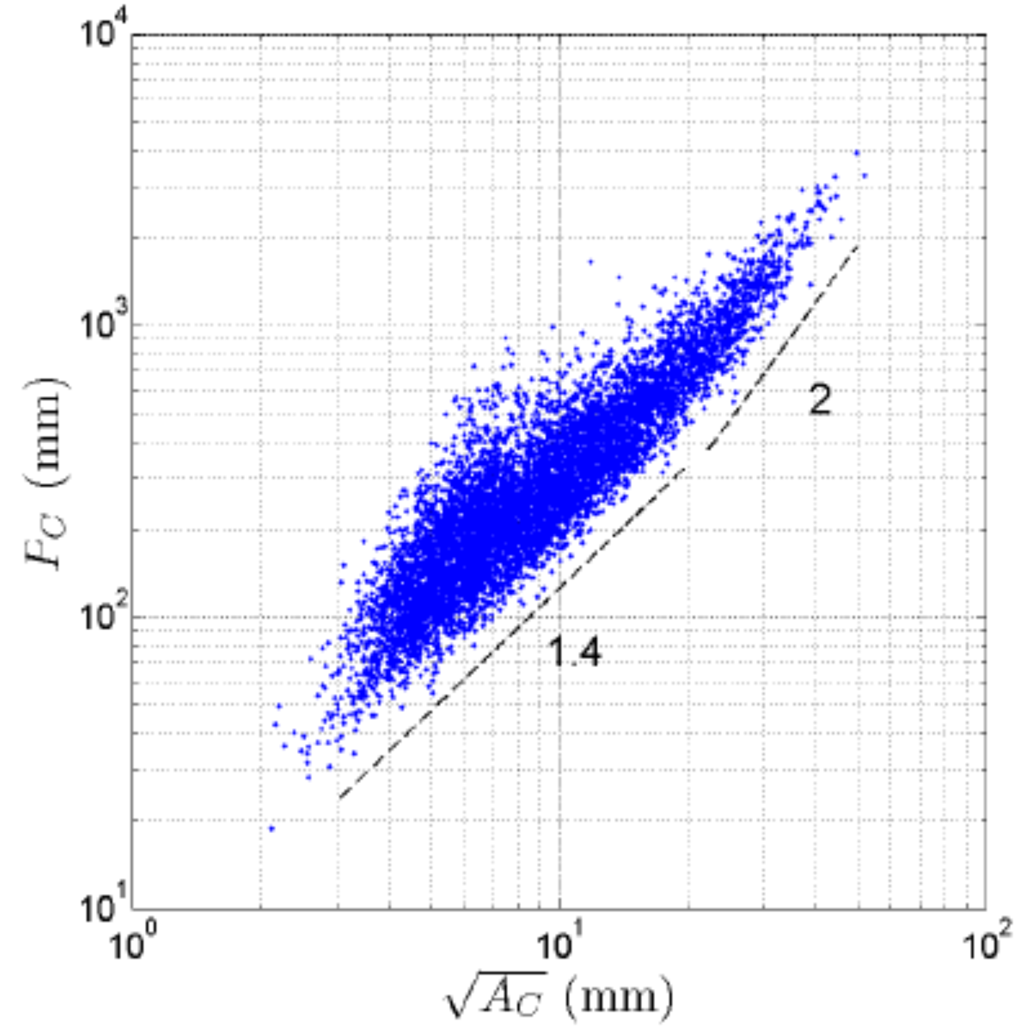
Super-clusters

Super-clusters geometry

Super-clusters have a typical size ~ 50 - 100 η



Super-clusters have fractal geometry



Take Home messages

- Inertial particles in turbulence tend to segregate in clusters
  - Lognormal distribution of Voronoï areas
  - Maximum of clustering for St~1
  - Fractal geometry
  - Typical size ~ 10 η
- Clusters of inertial particles tend to segregate in super-clusters
  - Lognormal distribution of Voronoï areas
  - Clustering less pronounced than for particles themselves
  - Fractal geometry
  - Typical size ~ 50 - 100 η, increases with St (or Reynolds)
- Perspectives
  - Disentangle trends with St and Reynolds ?
  - Dynamical aspects of clusters and super-clusters ?
  - Hyper-clusters ?

Thank you !