The Abdus Salam
International Centre for Theoretical Physics

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Conference and Euromech Colloquium #480

on

High Rayleigh Number Convection

4 - 8 Sept., 2006, ICTP, Trieste, Italy

How is the large scale flow influenced by the aspect-ratio in a cylindrical Rayleigh-Benard cell?

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USA

Aspect-ratio and Prandtl-number dependence

of plume motion and large-scale circulation

in cylindrical Rayleigh-Bénard samples

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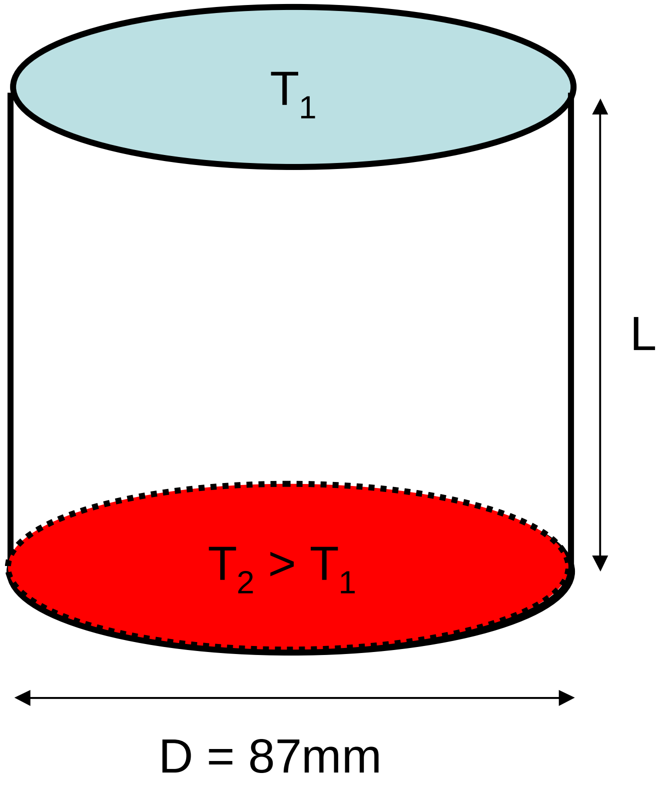
Rayleigh-Bénard convection cell



Rayleigh number

$$R = \frac{\alpha\, g\, \Delta T\, L^3}{\kappa\, \nu}$$

α thermal expansion coefficient

g acceleration of gravity

ΔT temperature difference

L cell height

κ thermal diffusivity

ν kinematic viscosity

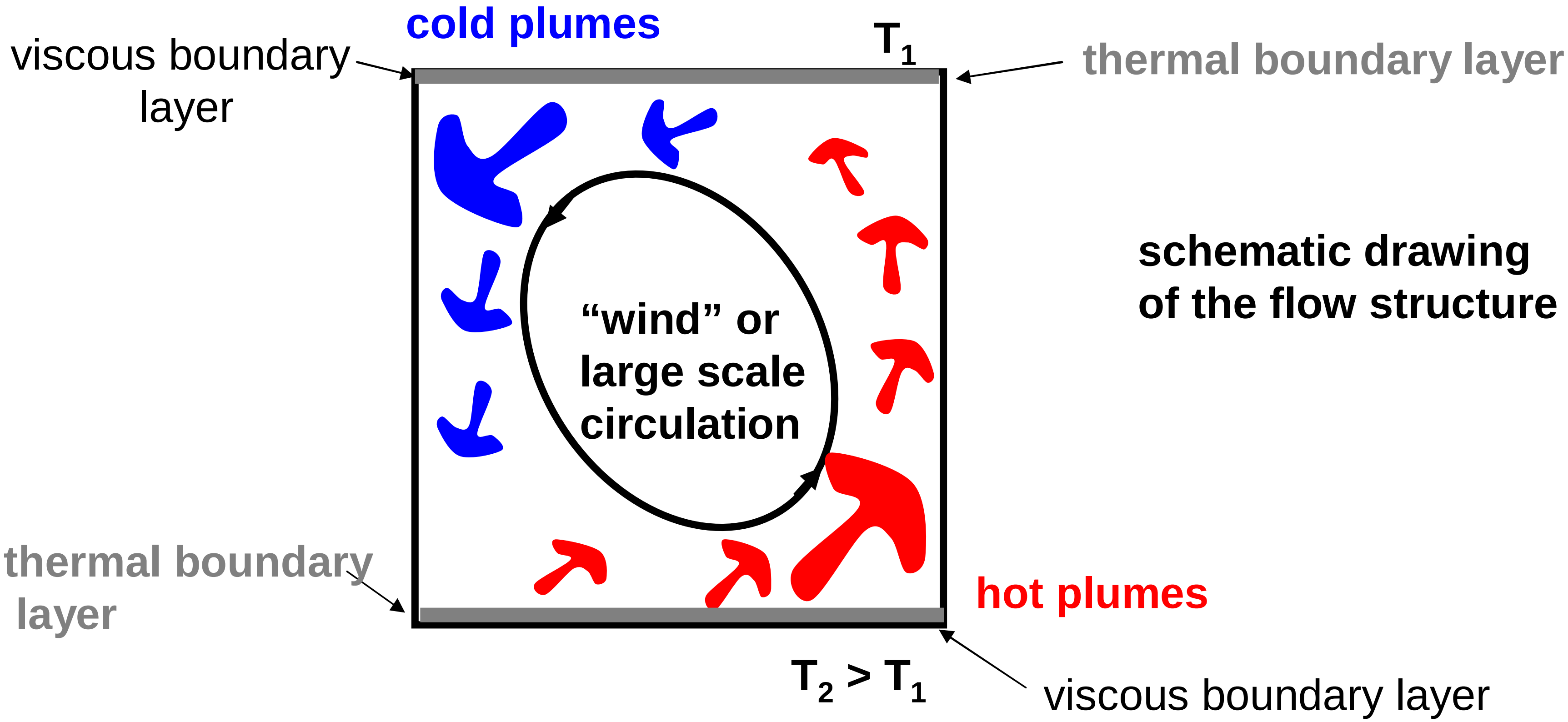
Aspect ratio

$$\Gamma = \frac{D}{L}$$

Prandtl number

$$\sigma = \frac{\nu}{\kappa}$$

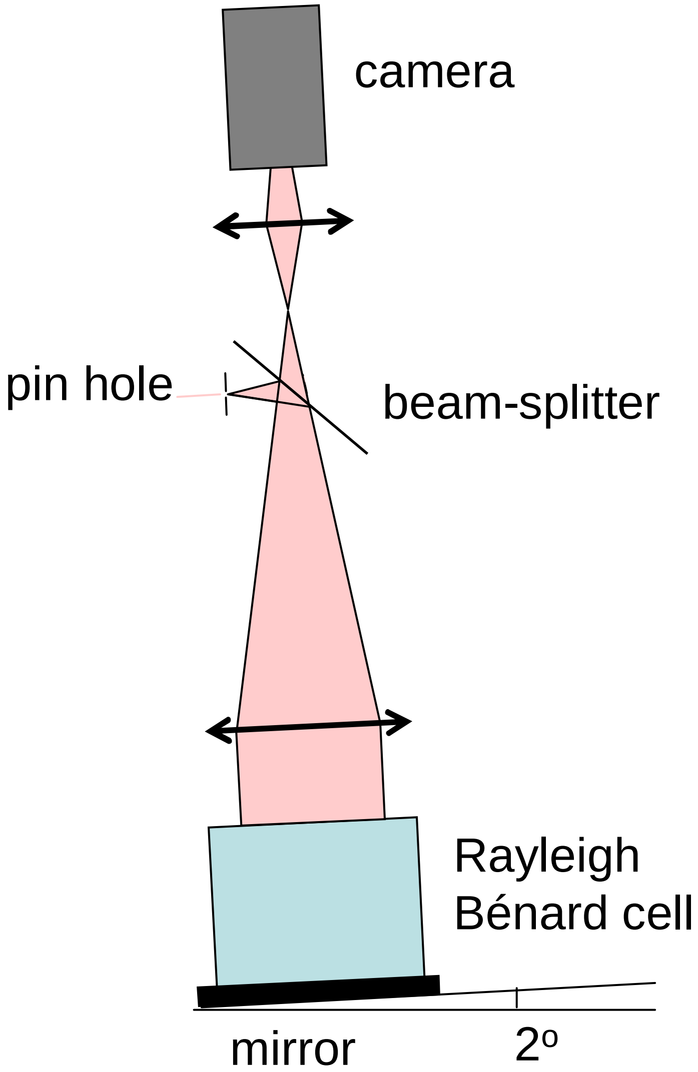
Turbulence



schematic drawing of the flow structure

X.-L. Qiu and P. Tong, Phys. Rev. E **66**, 026308 (2002)

Experiment set-up



Experimental conditions

- **Shadowgraph technique**
- **Cell tilted or not tilted**
- **Fluids : methanol : σ ~ 6.0**

  isopropanol : σ ~ 28.9
- **Aspect Ratio Γ = 1, 2 and 3**
- **"Turbulent" regime**

($4 \times 10^7 <$ R $< 5 \times 10^9$)

Methanol
$\Gamma = 1$
Rayleigh 4.2×10^8
Focus on the bottom plate

Image Analysis :

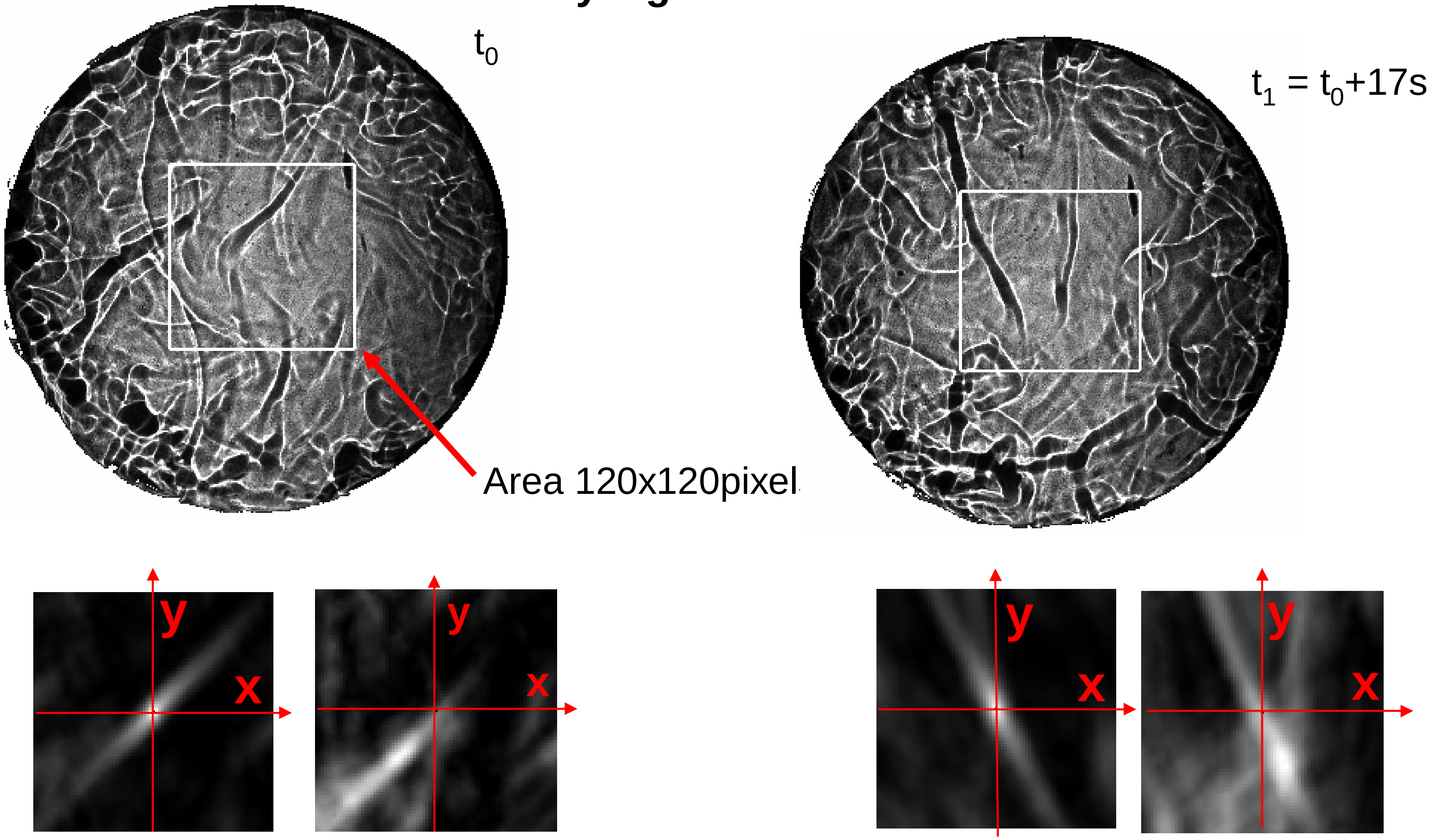
Density of plumes

Direction of the large scale flow

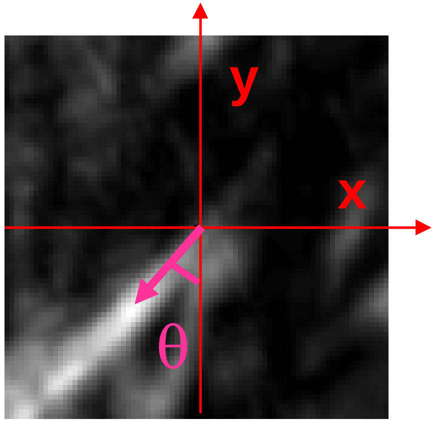
Velocity of the plumes

Calculation of the direction of the plumes

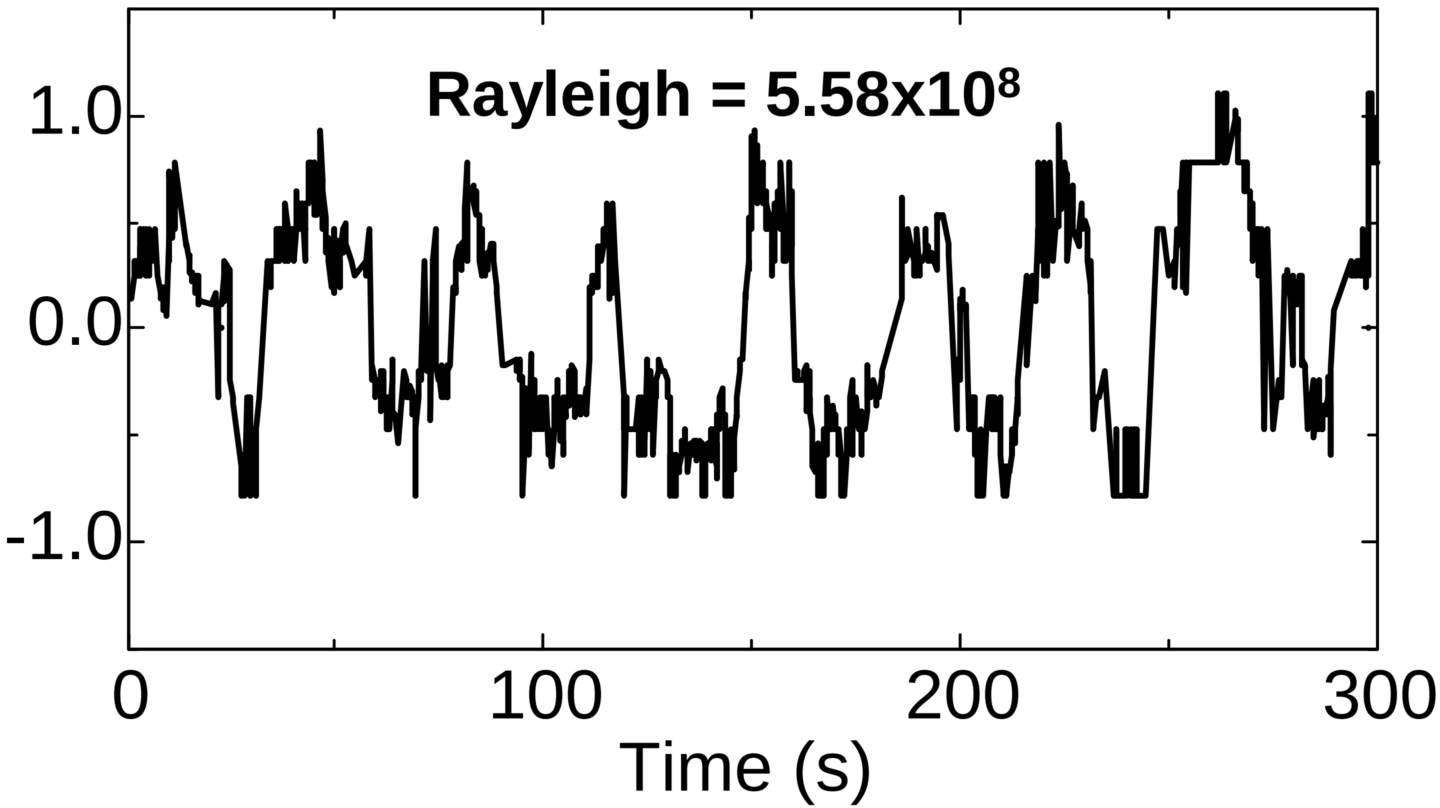
Rayleigh = 5.58×10^8



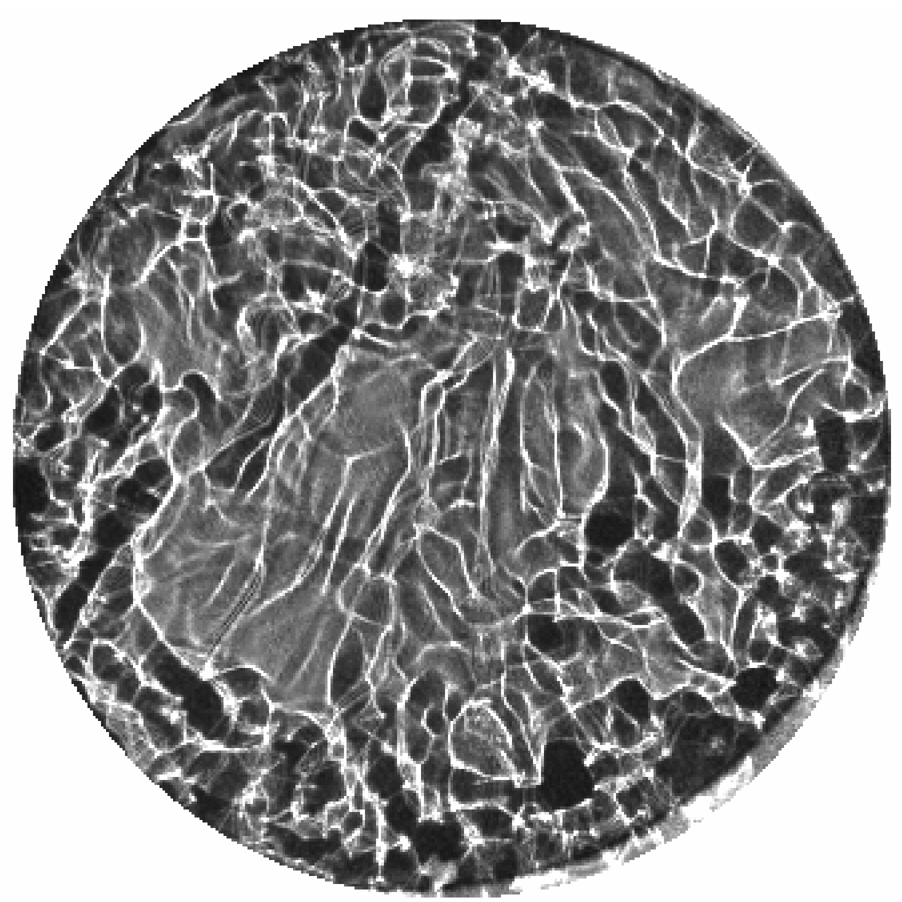
$C_a(\tau = 0s)$ $C_a(\tau = 1.22s)$ $C_a(\tau = 0s)$ $C_a(\tau = 1.22s)$

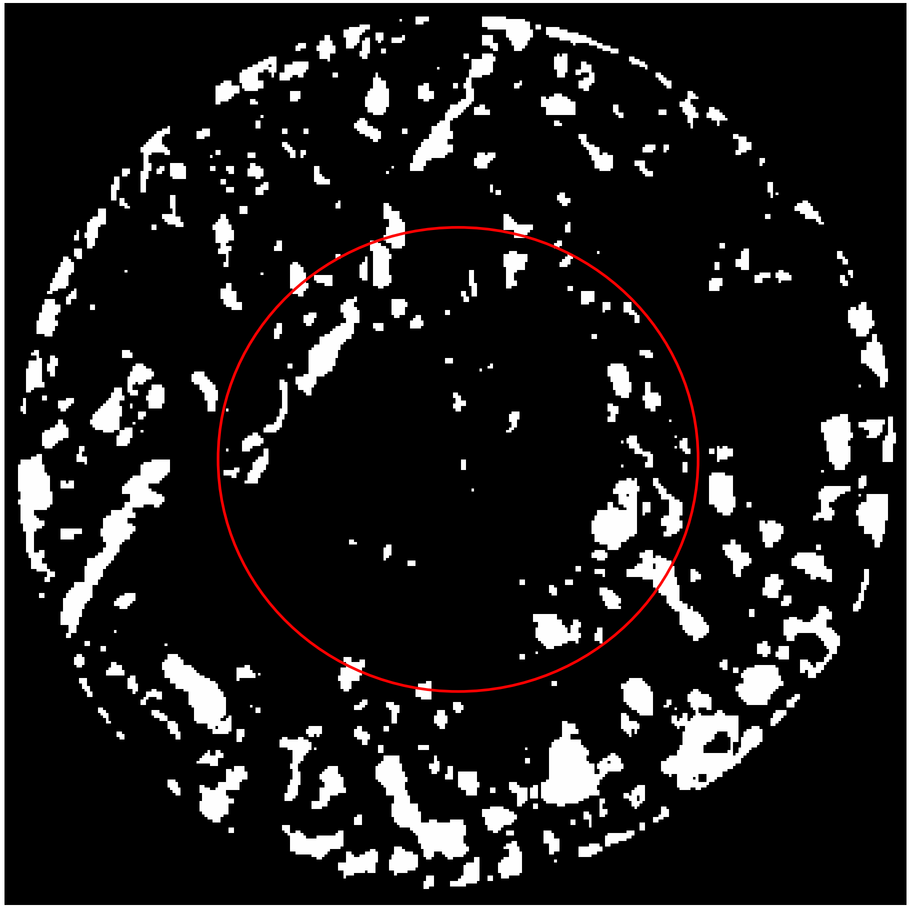


Oscillation in the direction of the plumes (angle θ)



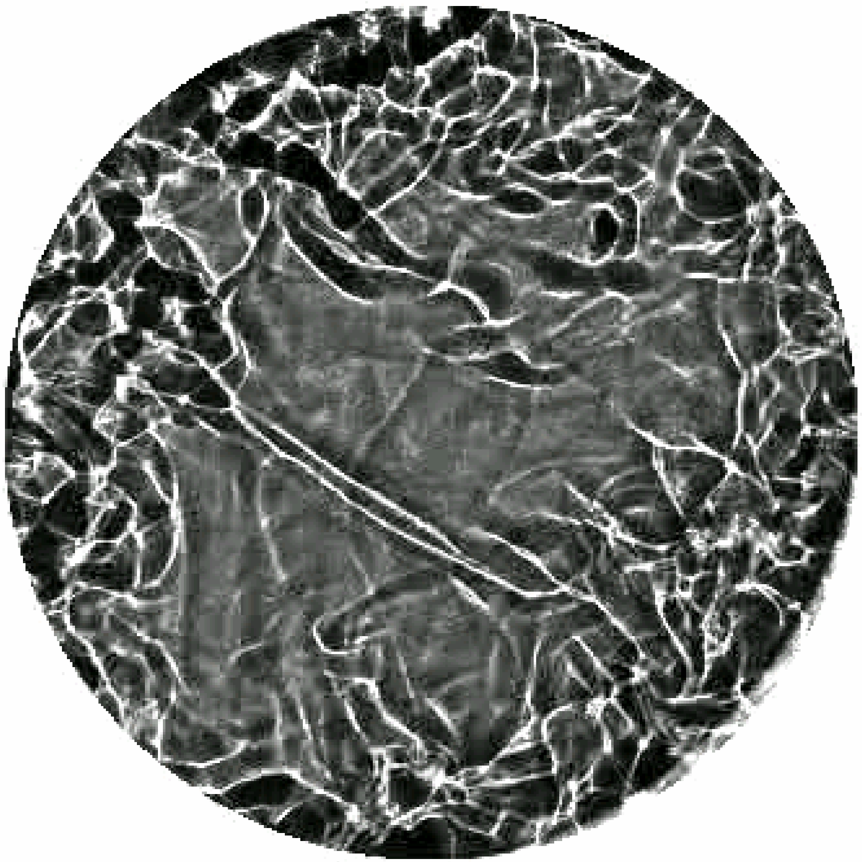
Density of plumes : application of a threshold





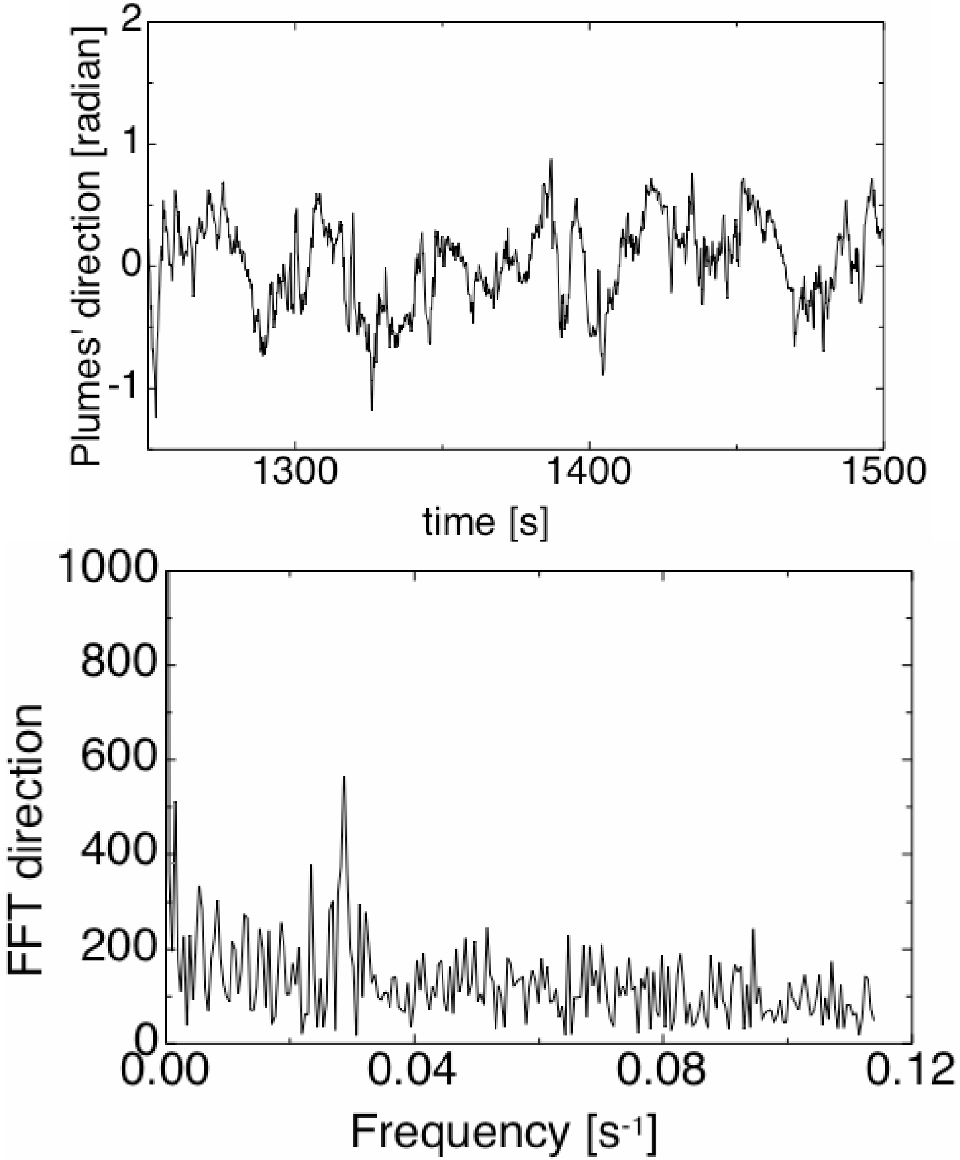
Area used for the calculation of the density of plumes : results are independent of the area used

Aspect Ratio 1, Rayleigh = $5.6x10^8$

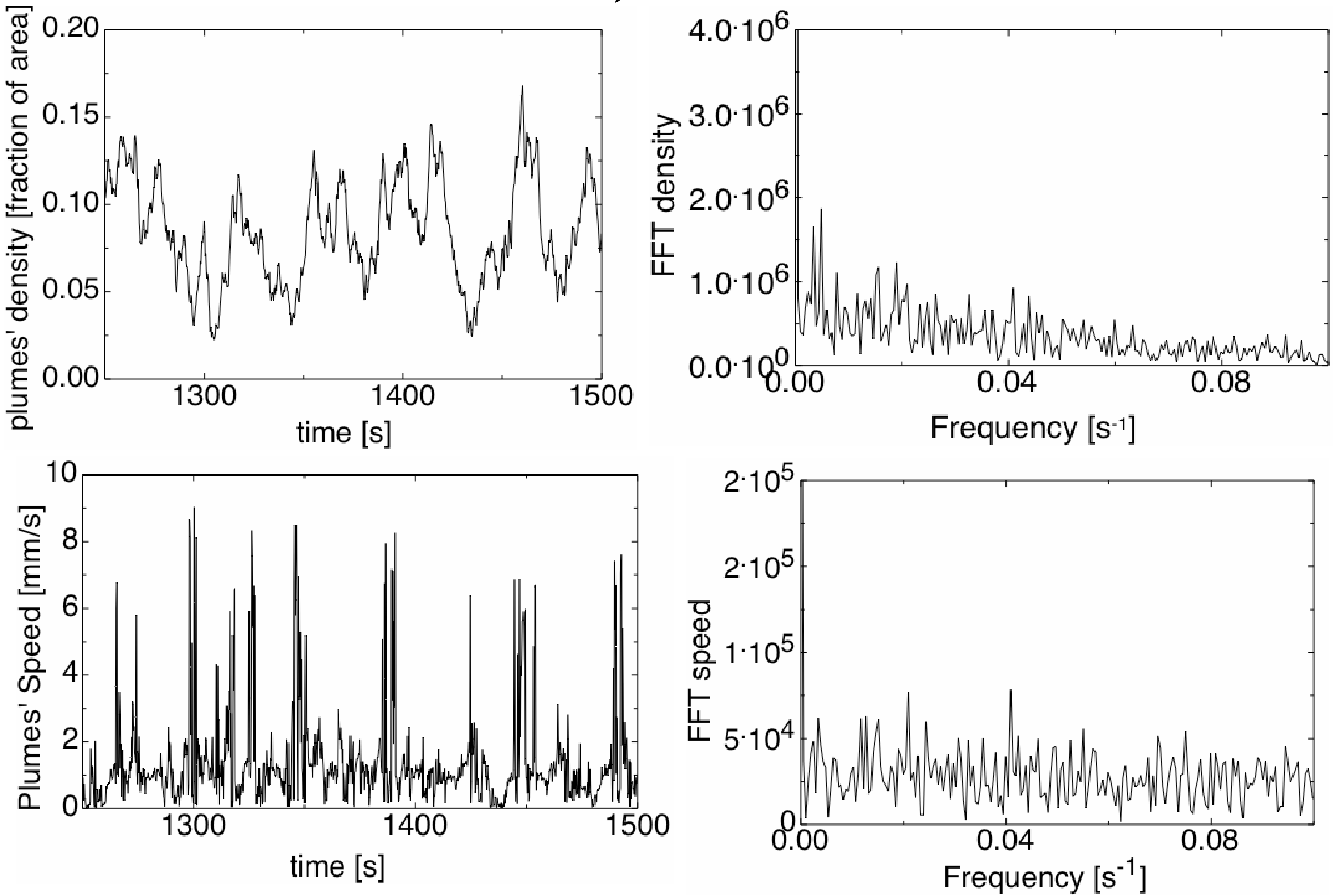


Methanol
x7.5 faster
(oscillation 35s)

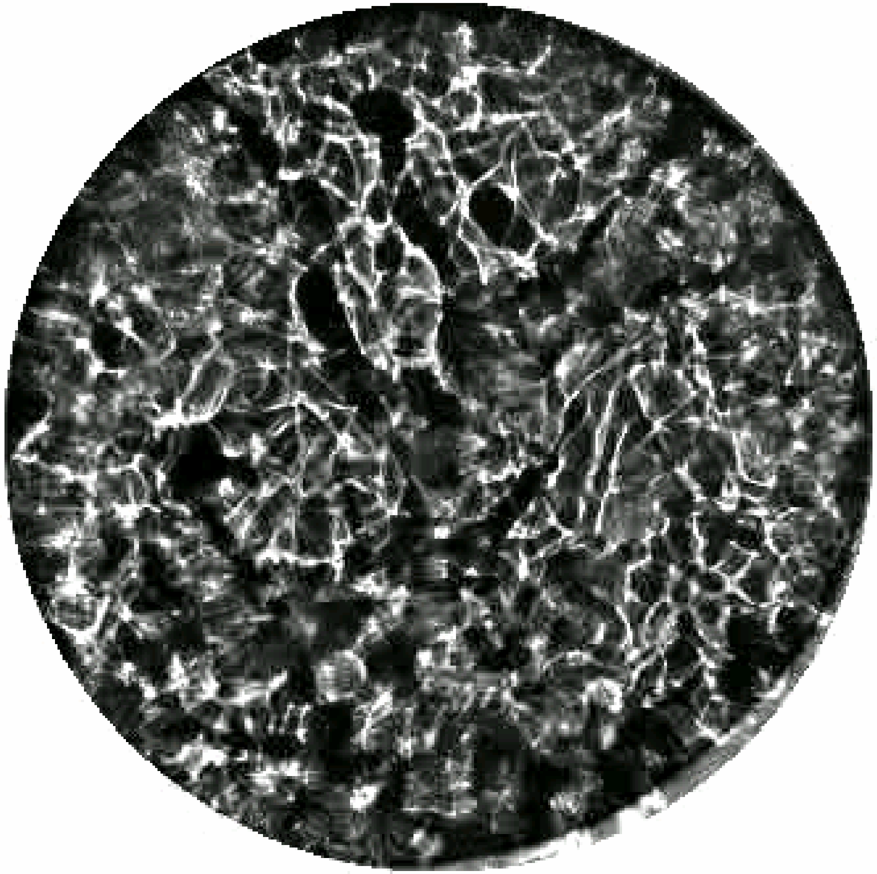
Γ= 1, Oscillation of the orientation of the large scale flow, Methanol, R = 5.6×10^8



Γ= 1, no periodic oscillation of the plumes' density or speed, Methanol, R = $5.6x10^8$

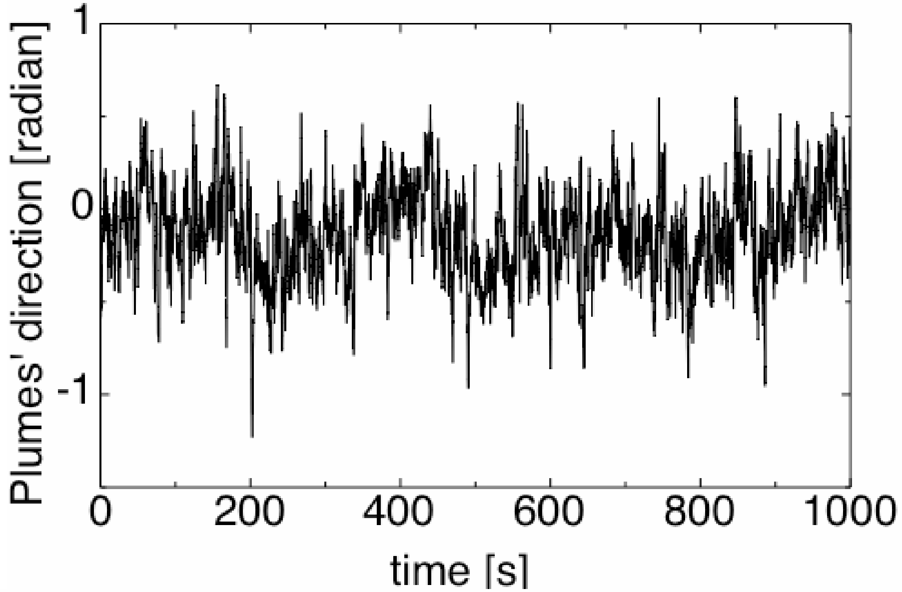


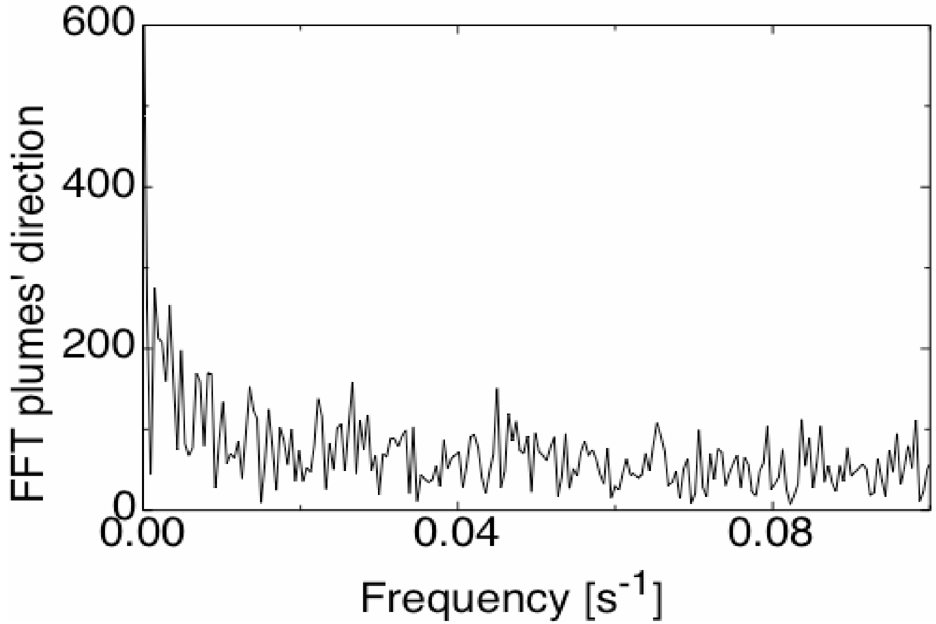
Aspect Ratio 2, Rayleigh = 2.32×10^8



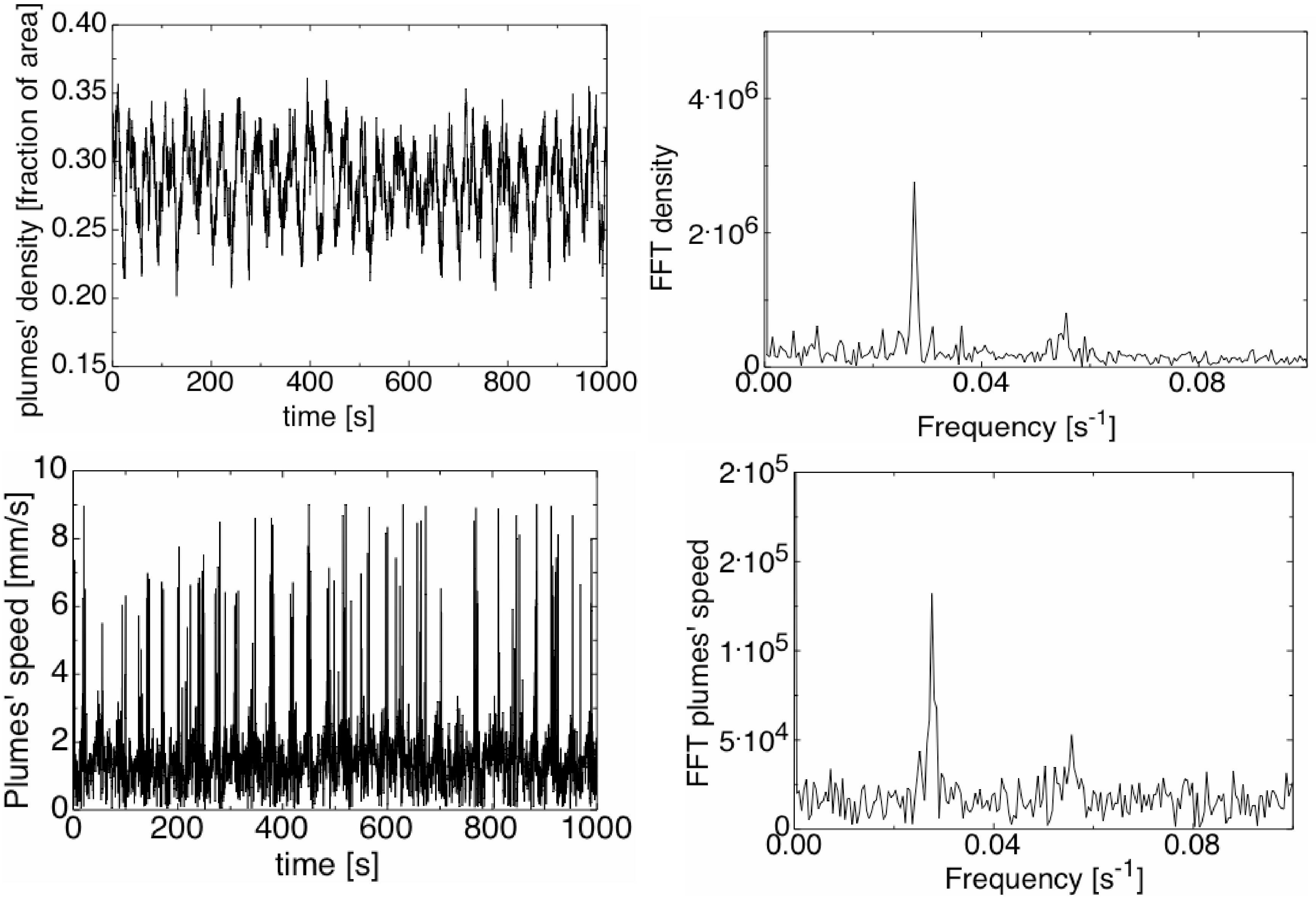
Methanol
x7.5 faster
(oscillation 36s)

Γ= 2, no oscillation of the orientation of the large scale flow, Methanol, R= $2.32x10^8$

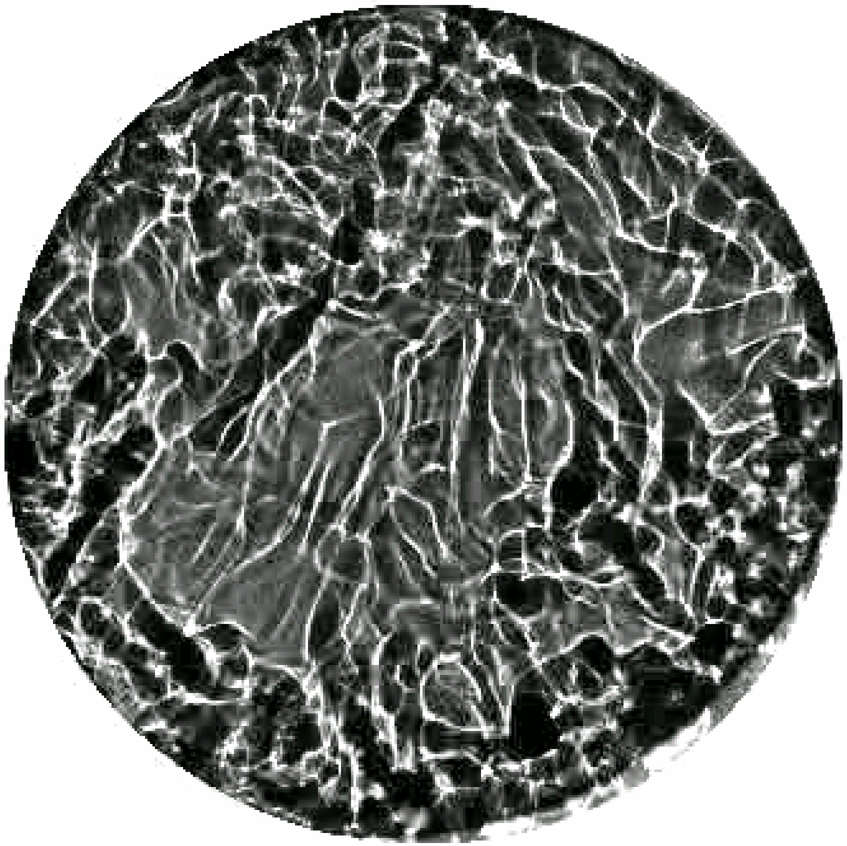




Γ=2, periodic oscillation of the plumes' density or speed, Methanol, R = 2.32x10^8



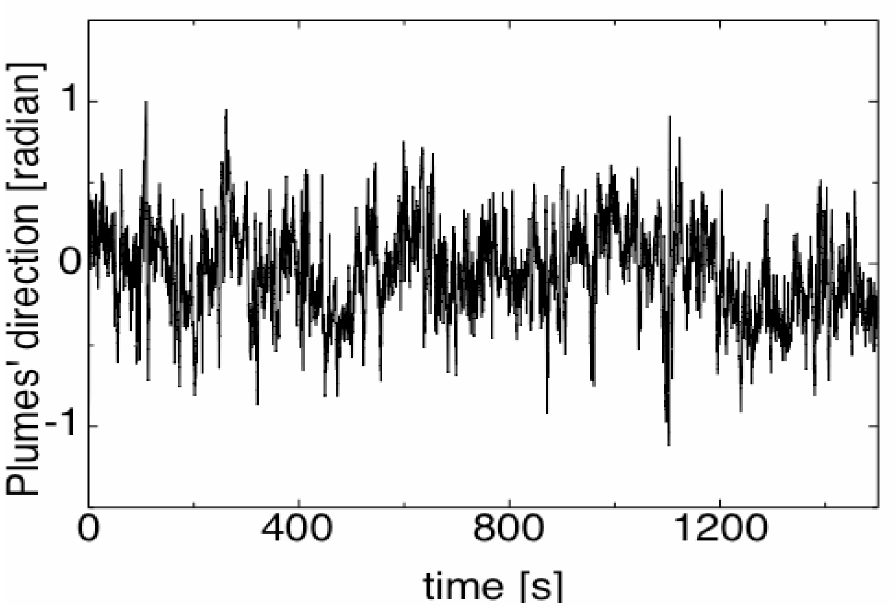
Aspect Ratio 2, Rayleigh = 1.16×10^8

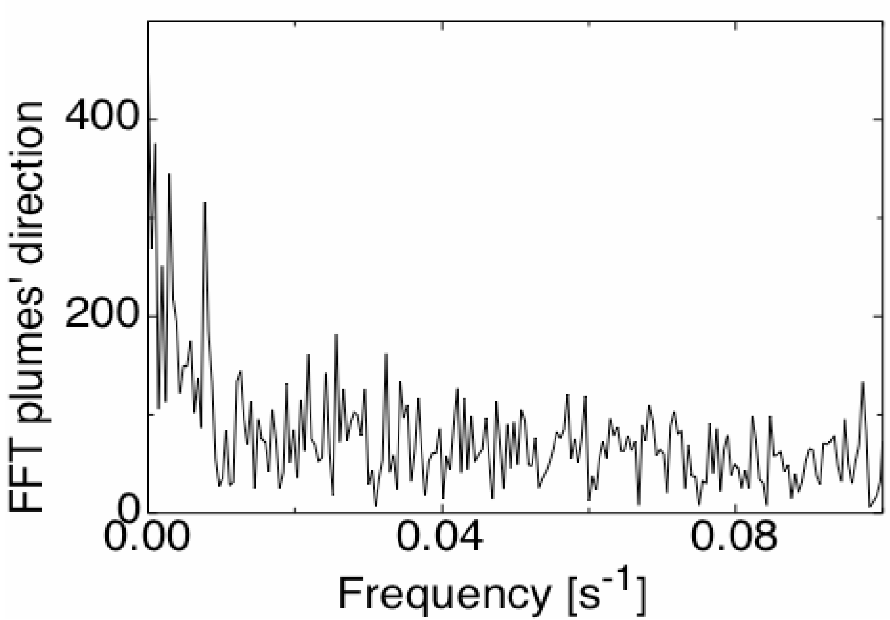


Methanol
x6 faster
(oscillation 49.2s)

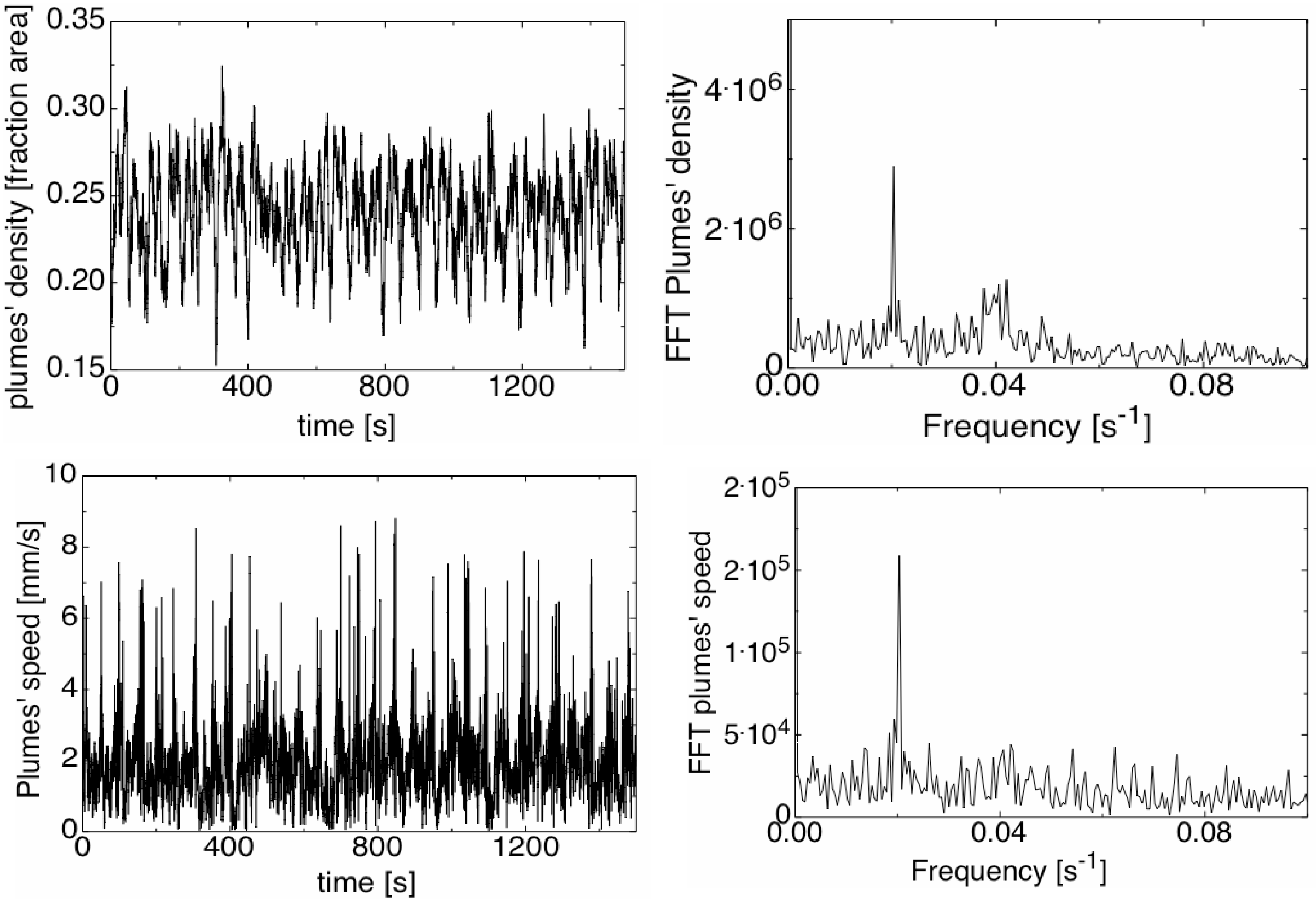
Γ= 2, no oscillation of the orientation of the large scale flow

Methanol, R = 1.16×10^8





Γ=2, periodic oscillation of the plumes' density or speed, Methanol, R = 1.16x10^8



For all Rayleigh numbers investigated :

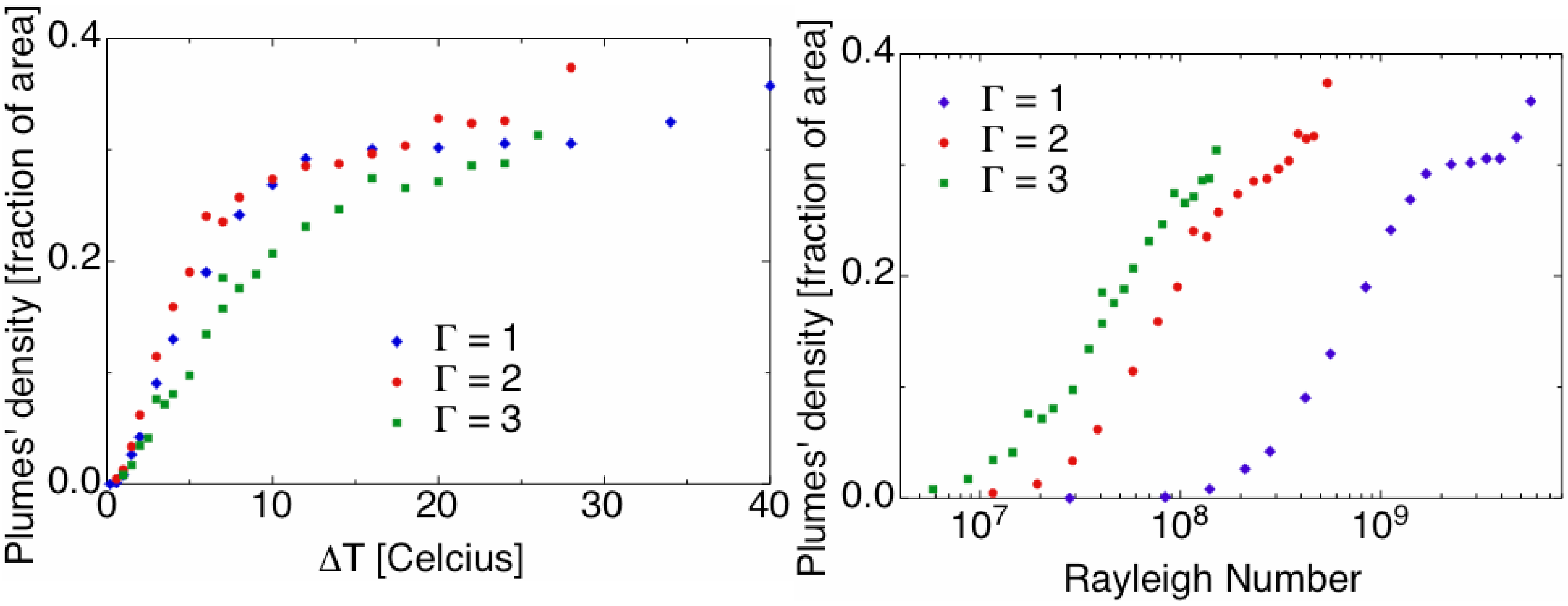
Γ = 2 and 3 : strong periodic oscillations of the plumes density and velocity, but no oscillations of the direction of the large scale flow

Γ = 1 : periodic oscillations of the direction of the large scale flow

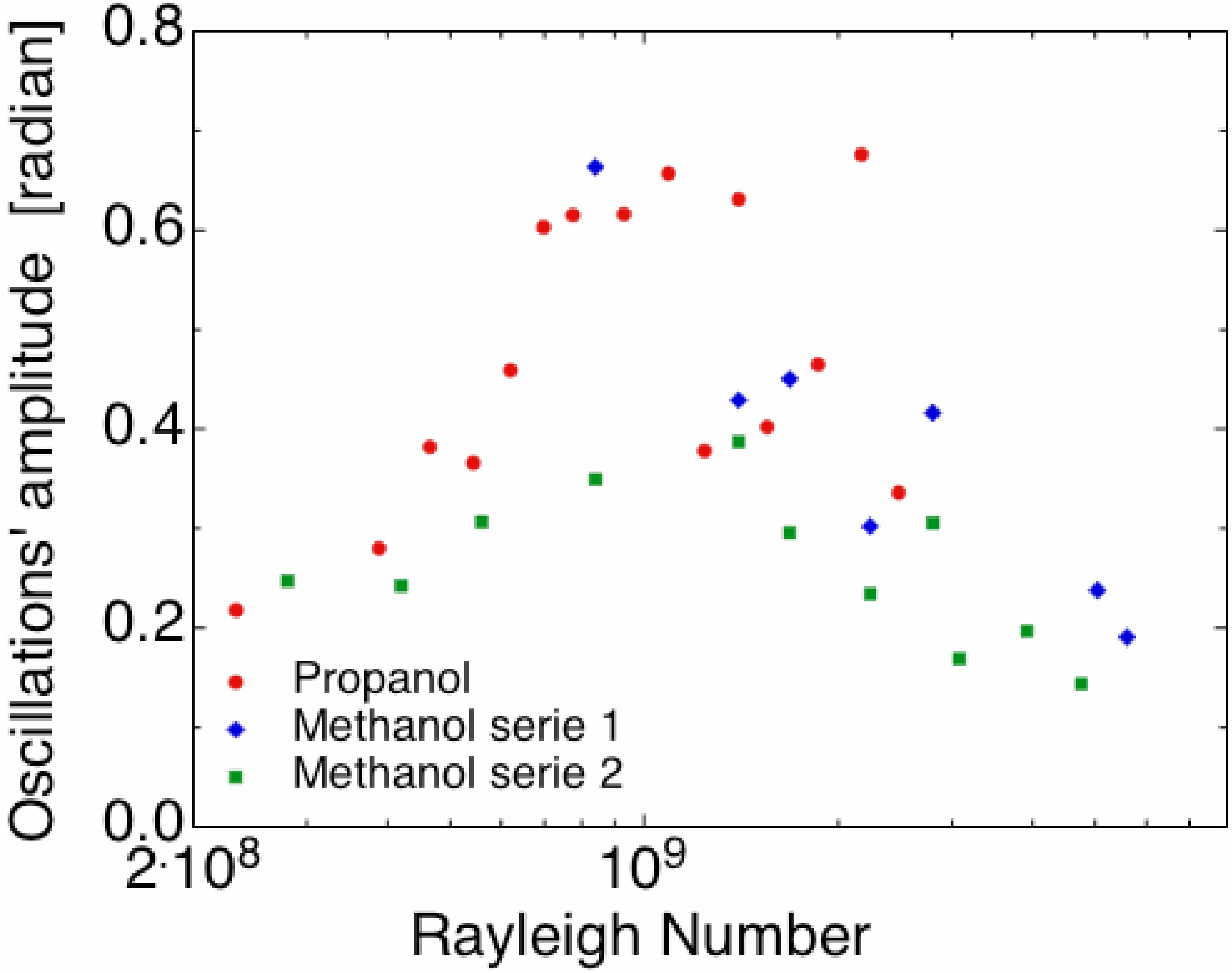
Evidences a transition in the hydrodynamic regime between Γ = 1, and Γ = 2 or 3

Gives new interest in the model of Villermaux Phys. Rev. Lett. **75**, 4618 (1995), which involves destabilization of the thermal boundary layer

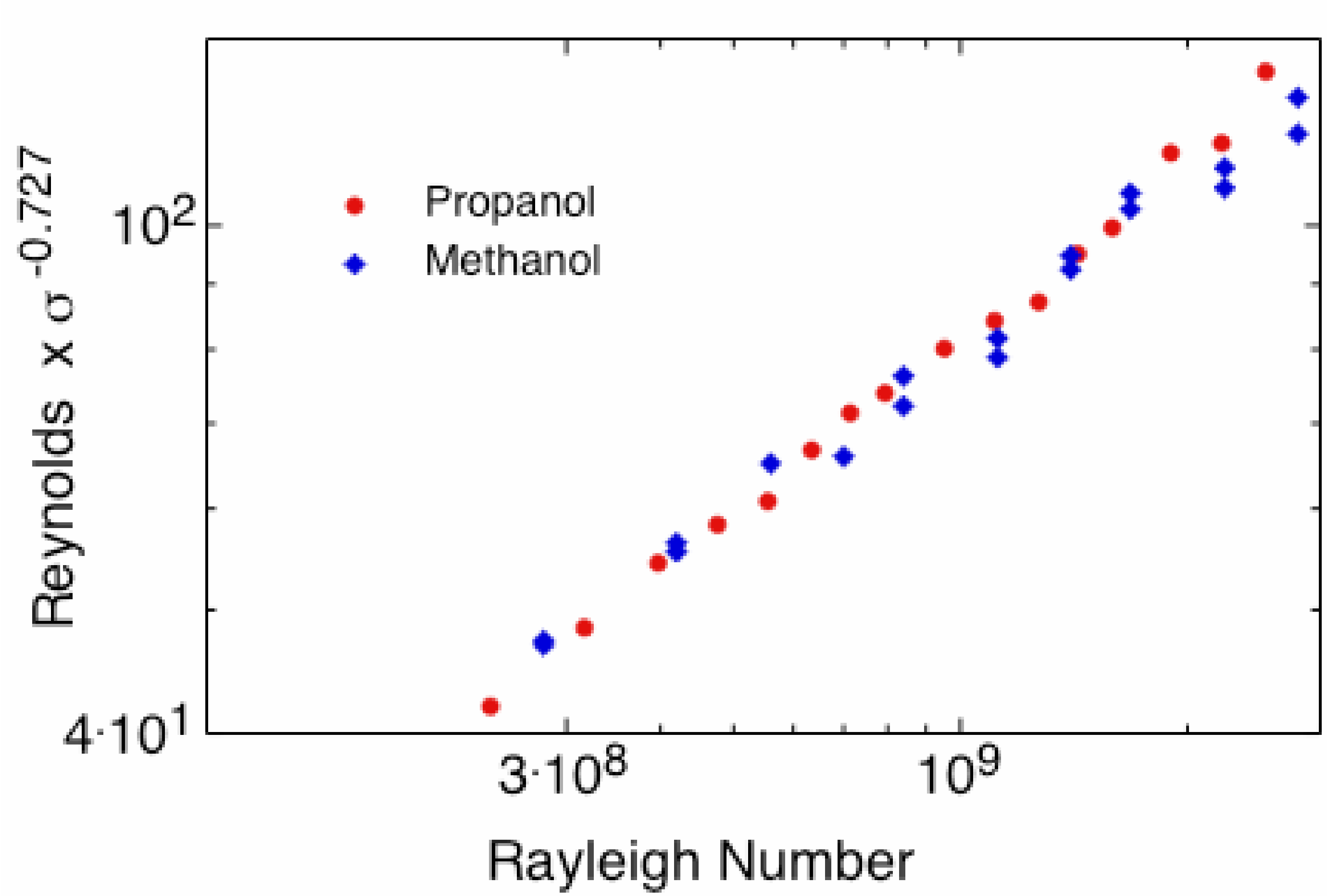
Density of plumes : scaling with Rayleigh or with the temperature difference ?



Amplitude of the oscillations of the large scale flow ($\Gamma = 1$)



Influence of the Prandtl number σ, Γ = 1



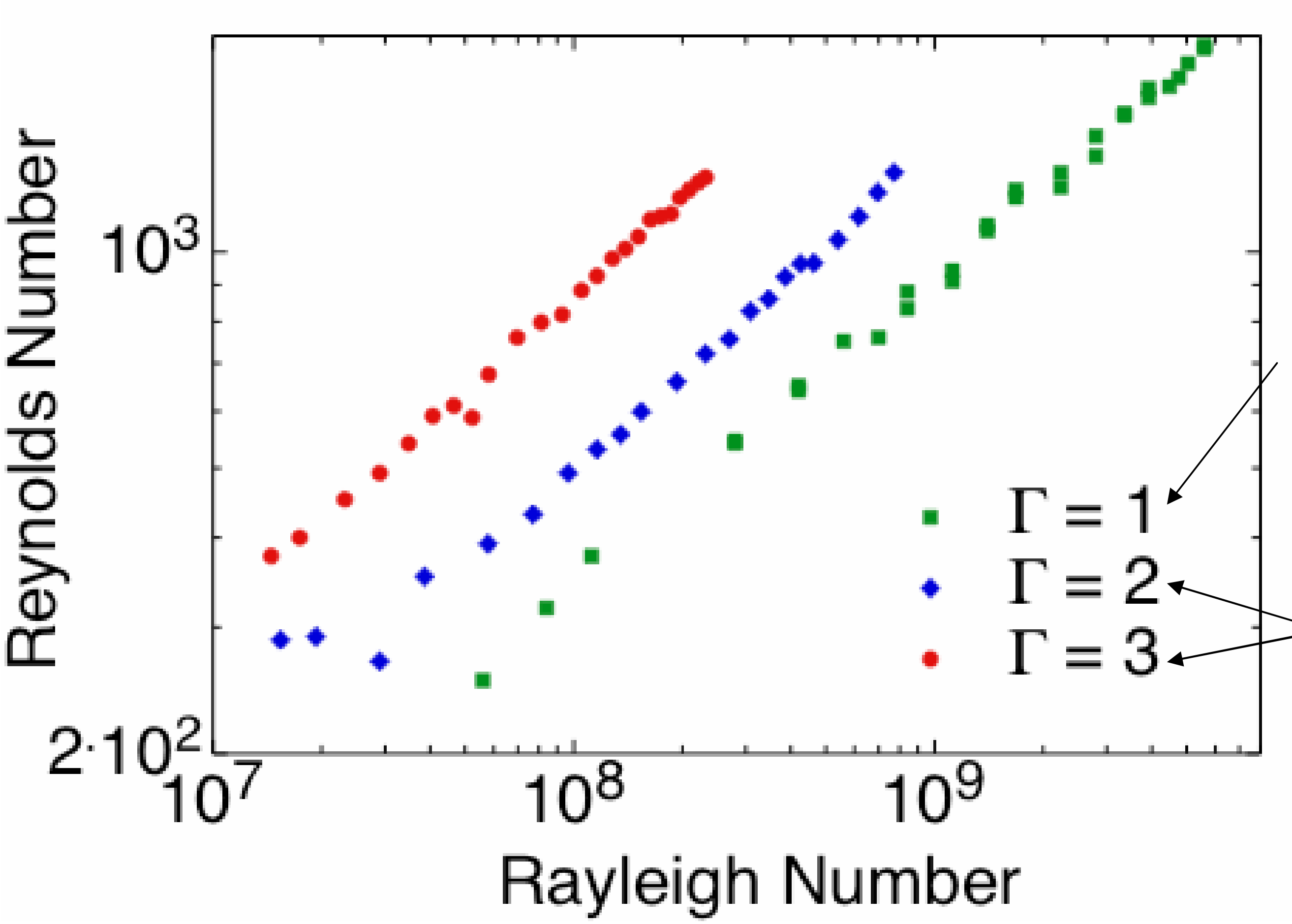
Reynolds = $2L^2 f_p / \nu$

L cell height

f_p plumes' frequency

ν viscosity

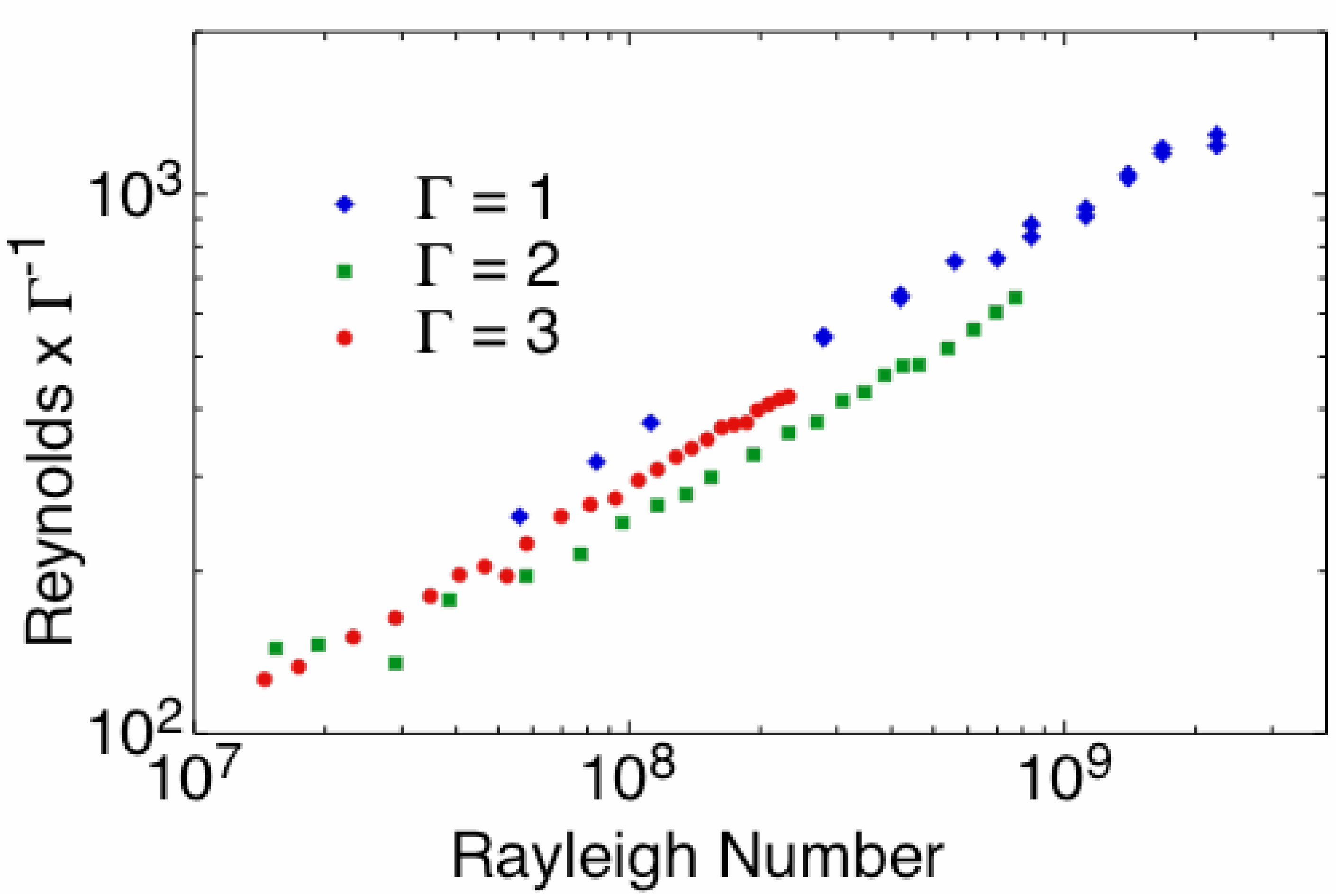
Influence of the aspect ratio, fluid = methanol



Obtained form the oscillation frequency

Obtained from the plumes density

Absence of linear scaling with the aspect ratio



Reynolds number measurements based on

- Velocity measurements of the large scale flow

$$R_{eU} = UL / \nu$$

- Measurements of the plumes turn-over time τ

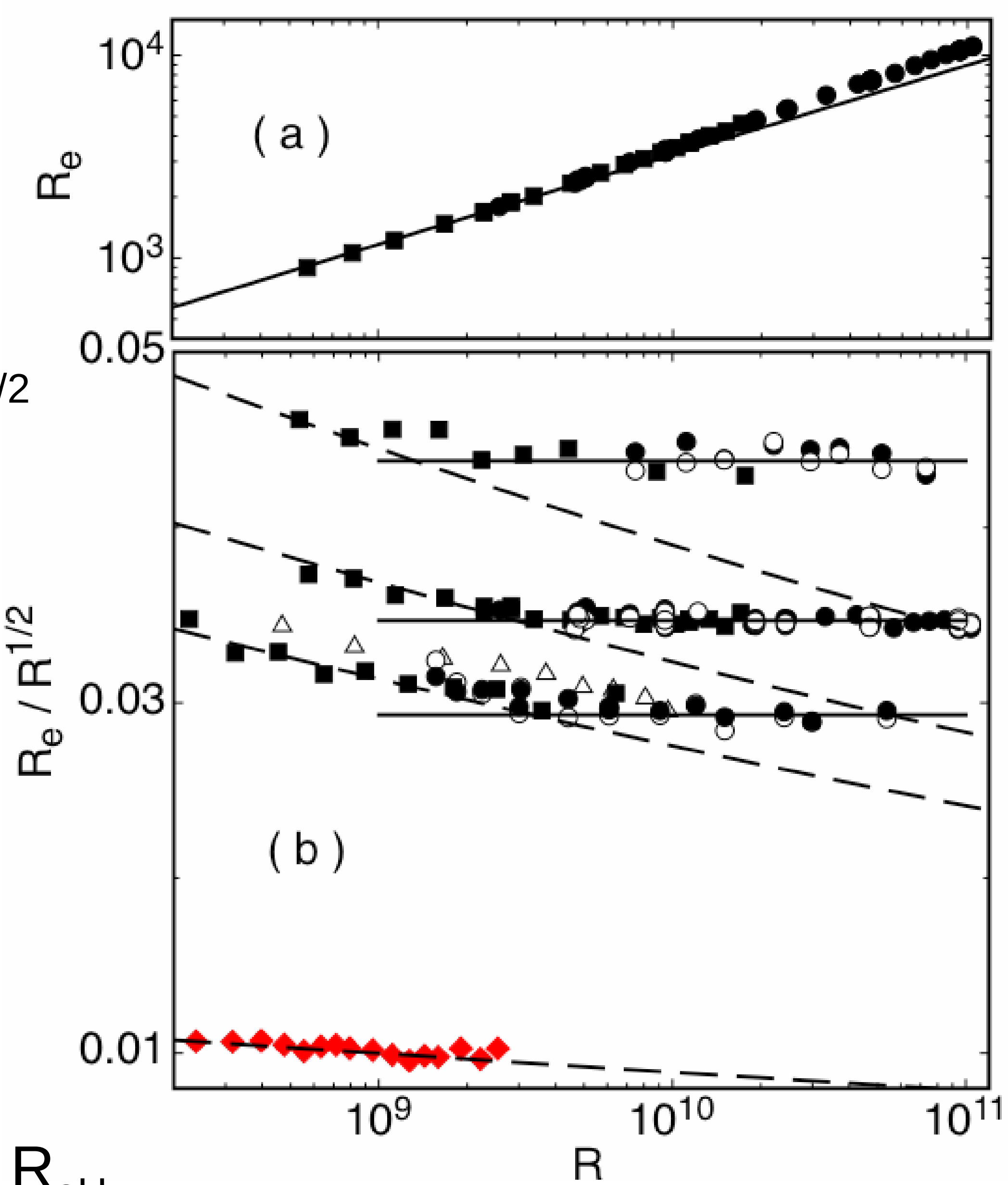
$$R_{e\tau} = (2L / \tau)(L / \nu)$$

- Oscillation frequency f_θ of the large scale flow orientation

$$R_{ef} = (2L\, f_\theta)(L / \nu)$$

$R_{e\tau} = (2L / \tau)(L / \nu)$

$R_{e\tau} = 0.106\ \sigma^{-3/4}\ R^{1/2}$



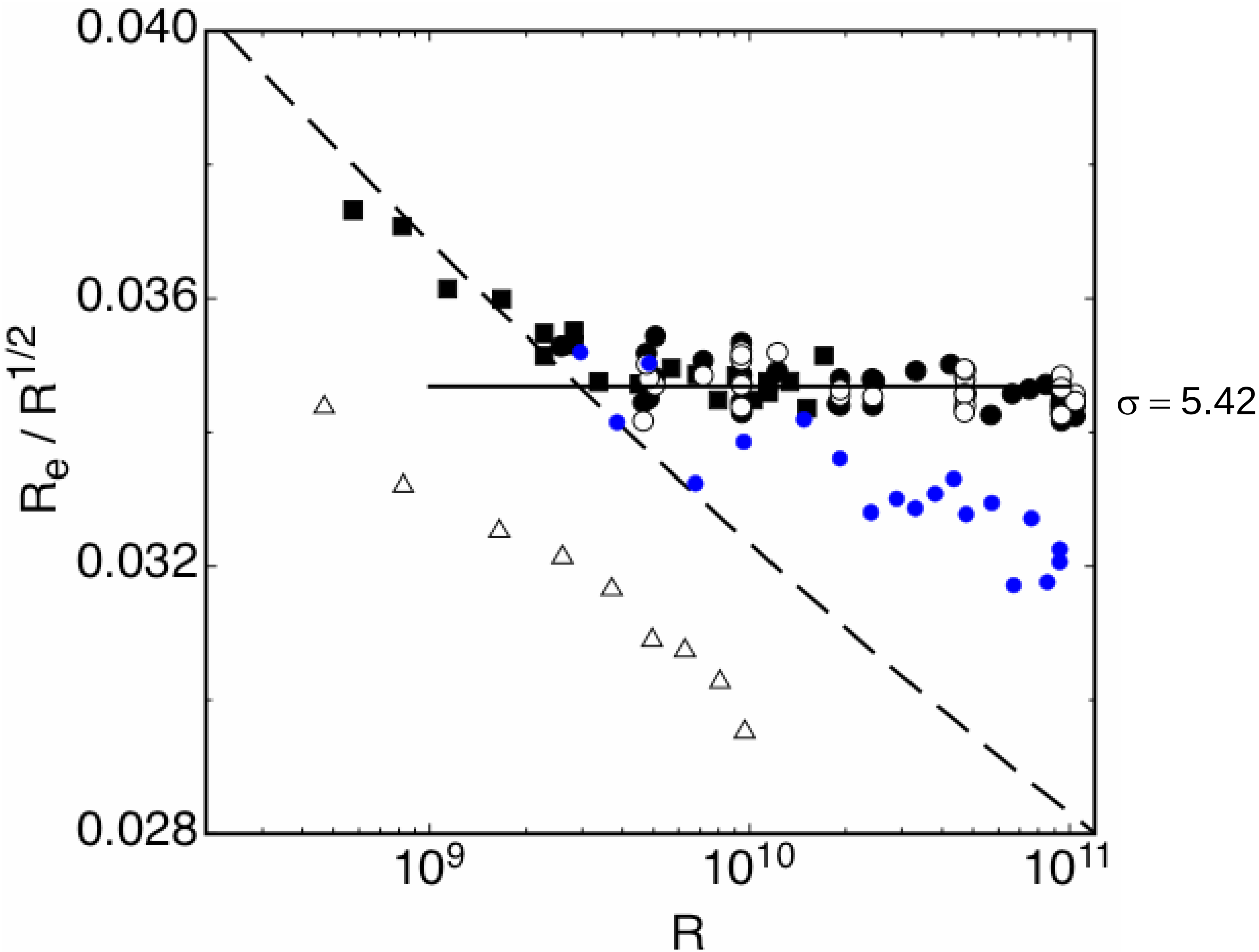
■ Medium Sample
● Large Sample
■ ● cross correlation
□ ○ auto correlation

} $R_{e\tau}$

◆ propanol, plume osc. R_{ef}

△ water, T_{mean} ~ 29°C, σ = 5.5
X.-L. Qiu and P. Tong,
Phys. Rev. E 66, 026308 (2002). R_{eU}

----- Grossmann and Lohse, Phys. Rev. E (2002) **66** 016305



△ water, T_{mean} ~ 29°C, σ = 5.5
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■ Medium Sample
● Large Sample
■ ● cross correlation
□ ○ auto correlation
} $R_{e\tau}$

● oscillation of the Plume direction R_{ef}

Question of scaling raised by S. Grossmann : consequences of $N \sim R^{1/3}$ and $Re \sim R^{1/2}$?

$\varepsilon_u = R\,(N - 1)\,\sigma^{-2}$

ε_u average viscous dissipation

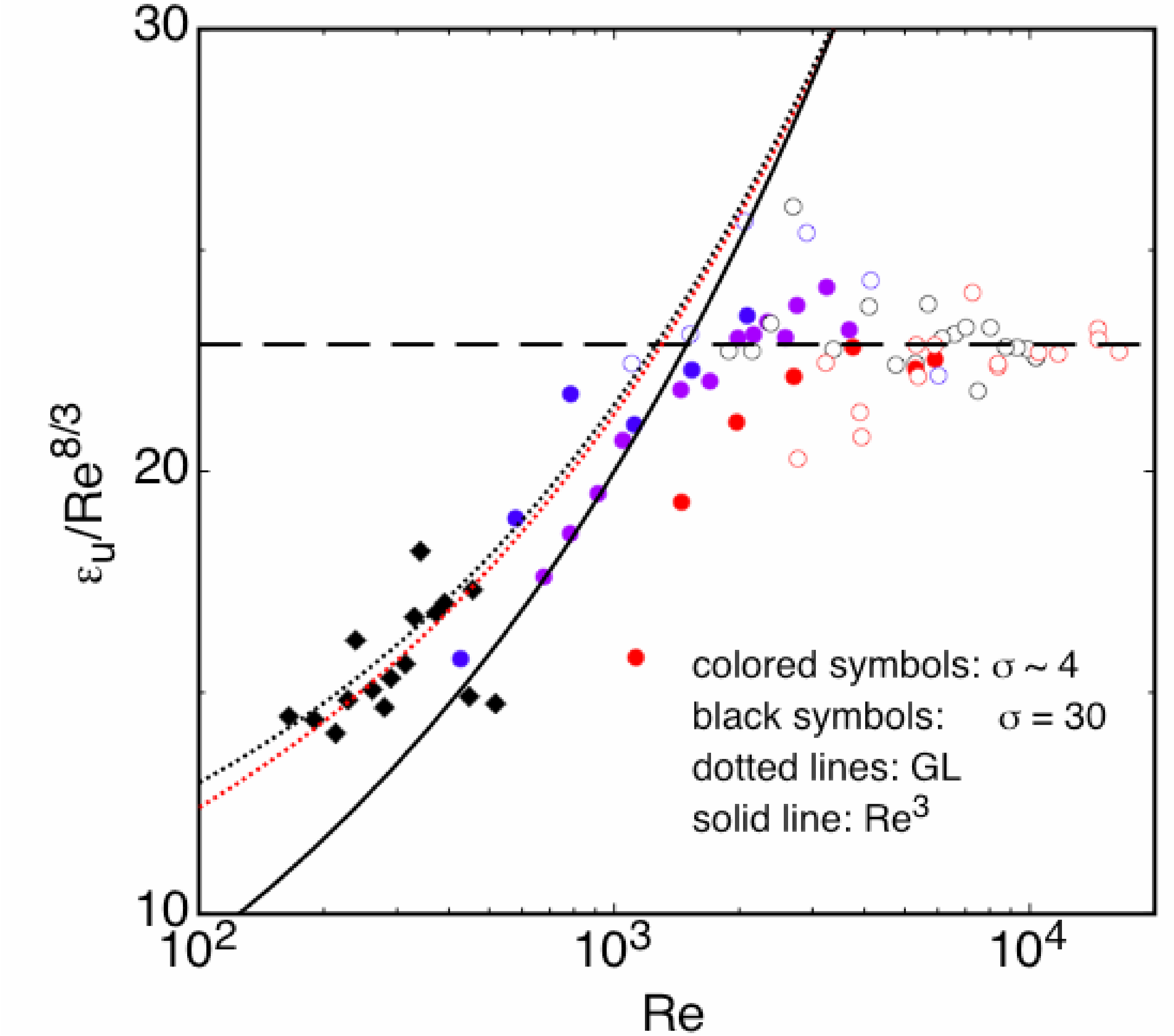
If we consider the experimental result $Re \sim R^{1/2}$, $N \sim R^{1/3}$

$\varepsilon_u \sim R^{4/3} \sim Re^{8/3}$

In the bulk regime (Kolmogorov) : $\varepsilon_u \sim Re^3$

In the boundary layer regime : $\varepsilon_u \sim R^{5/2}$

Experimental results :



Conclusion

The density of plumes scales roughly as the temperature difference between the top and bottom plates

The viscous dissipation do not follow the Kolmogorov (bulk-regime) law and also not the Boundary Layer regime

-at $R \sim 3x10^9$, there is a sharp transition of $R_{e\tau}$ (Reynolds number based on the plume turn-over time)

-$R < 3x10^9$, the Reynolds numbers measured by the 3 different ways coincide and are consistent with the prediction of Grossmann&Lohse

-$R > 3x10^9$, there are differences between the different ways of measuring R_e, and $R_{e\tau}$ and R_{ef} differ from the GL prediction.