experimental particle tracking in turbulent flows

Nicolas Mordant

Ecole Normale Supérieure de Paris
Laboratoire de Physique Statistique
CNRS UMR8550

why would one track fluid particles ?

Scalar dispersion:

how does it spread from the source ?

$$\langle \theta(\mathbf{x},t)\rangle = \int_{s\le t} ds \int_V d\mathbf{y}\; p_1(\mathbf{x},t;\mathbf{y},s) S(\mathbf{y},s)$$

➡ one particle statistics

Mixing:

how fast two chemicals become close together?
what is the magnitude of concentration fluctuations

$$\langle \theta(\mathbf{x}_1,t_1)\theta(\mathbf{x}_2,t_2)\rangle = \int_{s_1\le t_1} ds_1 \int_{s_2\le t_2} ds_2 \int_V d\mathbf{y}_1 \int_V d\mathbf{y}_2$$
$$\times\, p_2(\mathbf{x}_1,\mathbf{x}_2,t_1,t_2;\mathbf{y}_1,\mathbf{y}_2,s_1,s_2) S(\mathbf{y}_1,s_1) S(\mathbf{y}_2,s_2)$$

➡ two particle statistics

issues in particle tracking in turbulent flows

- single out individual particles
- track individual trajectories
- enough spatial resolution
- enough time resolution

- single particle statistics
  (trajectories, velocity, acceleration)
- multi-particle statistics
  (relative dispersion, shape evolution...)

Lagrangian tracking methods

- Doppler techniques:

  - ultrasound Doppler (Lyon, Grenoble)
  - Laser Doppler (Göttingen, Lyon)

➡ gives the velocity from a frequency modulation

- Imaging techniques: 3D particle tracking velocimetry

  - 1D silicon strip detectors (Cornell)
  - 2D cameras (Risoe, Göttingen, Cornell, Zurich)

➡ gives the trajectories

resolution requirements

ex: to achieve a measurement in a R_λ=1000 lab flow:

- temporal resolution (required for both methods):
  T_L/τ_η ~ 1000 and in experiments τ_η ~ 1ms

- spatial resolution (for imaging only):
  $L/\eta \sim R_\lambda^{3/2}$ ~4000 with η ~ 30 μm
  + measure over 2L
  + resolve scales sub η
  with 1/10 sub pixel resolution: several thousand pixels

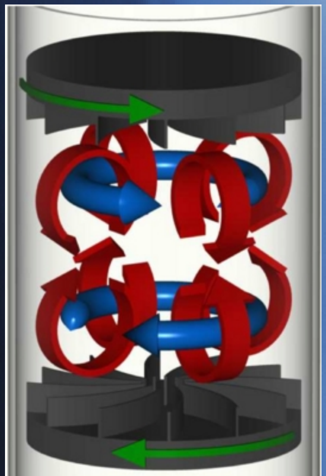
- frequency resolution (Doppler)
  resolution in frequency is the resolution in velocity
  maybe in competition with temporal resolution
  (time-frequency analysis)
  in general: parametric estimation

Doppler techniques

acoustic and optical versions developed in ENS Lyon:

- acoustics: ultrasound λ~0.6 mm
  large measurement volume (2L~10 cm)
  not so small particles

- optics: Laser λ~0.532 μm
  small measurement volume (~5 mm)
  small particles
  very good time resolution

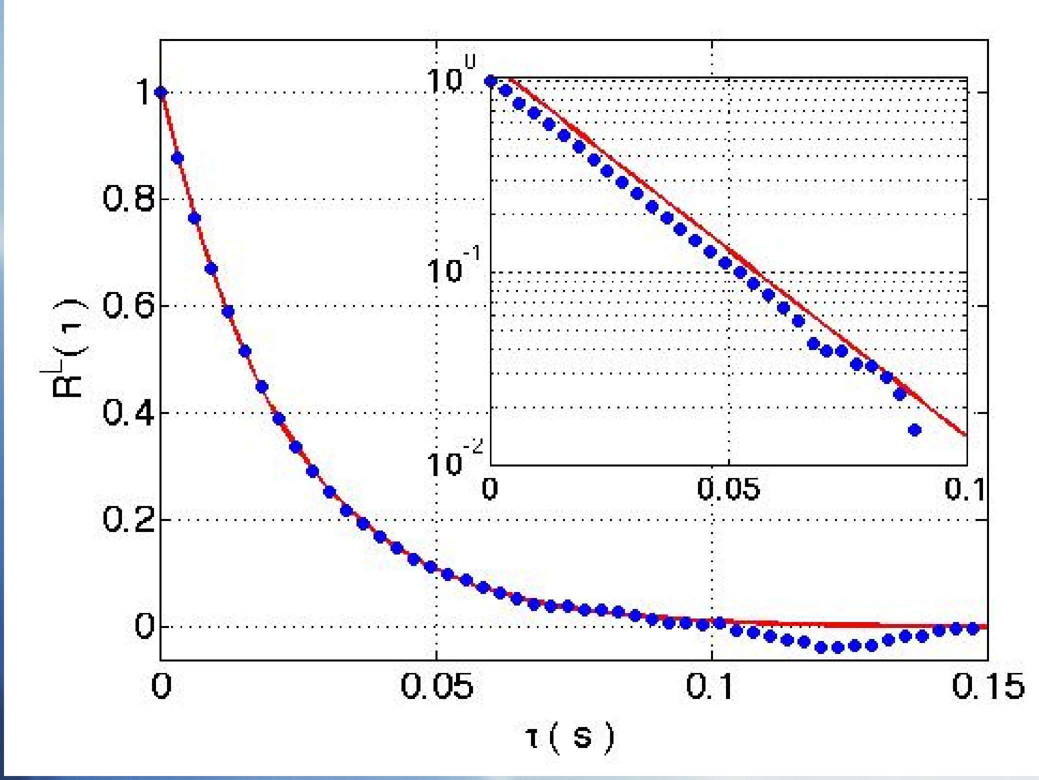


most presented results measured in variations
on a French washing machine theme

ultrasound Doppler technique

Lyon: Mordant, Michel, Metz, Pinton

large measurement volume: ultrasounds (about 2 times L)



velocity autocorrelation

Mordant, Metz, Michel & Pinton PRL 2001

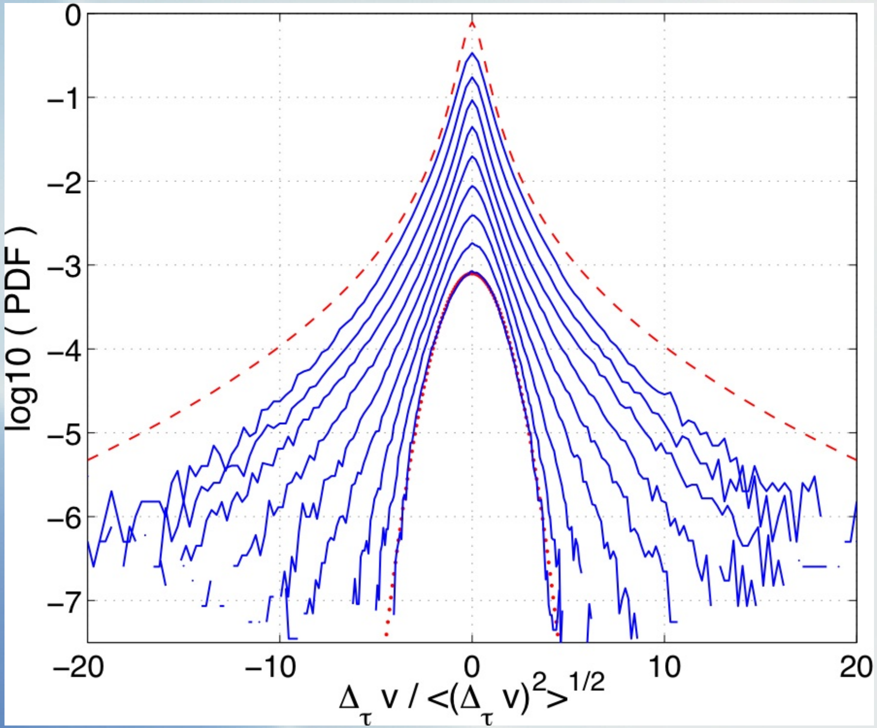
also in a air jet in Grenoble: *Gervais, Baudet, Gagne Exp Fluids 2007*

ultrasound Doppler technique

velocity time increments

$$\Delta_\tau v = v(t+\tau) - v(t)$$

intermittency



Mordant, Metz, Michel & Pinton PRL 2001

multifractal description by Chevillard et al. *PRL* 2003

ultrasound Doppler technique

Kolmogorov constant C_0 :

$$\langle (v(t+\tau) - v(t))^2 \rangle = C_0 \epsilon \tau$$

and

$$\langle v(t+\tau) v(t) \rangle = \sigma^2 \exp\left(-\frac{\tau}{T_L}\right)$$

then $T_L = \frac{2\sigma^2}{C_0 \epsilon}$

here C_0~4 at R_λ=800

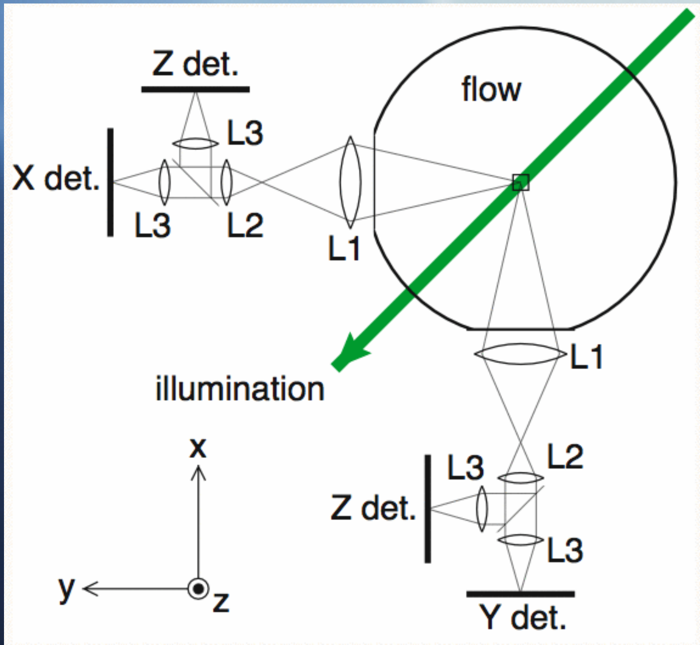
other recent estimate: Göttingen C_0~6 at a similar R_λ
(Xu, Ouellette & Bodenschatz *ETC11 proc.*)

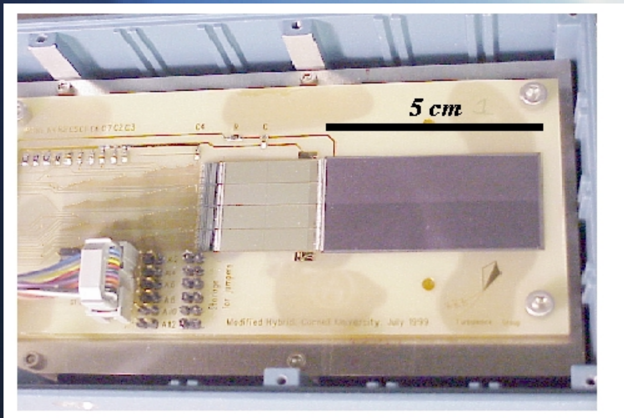
important for stochastic modeling of dispersion:

$$dv = -\frac{v}{T_L} dt + \sqrt{C_0 \epsilon}\, dW(t)$$

fluid particle acceleration

Cornell University (E. Bodenschatz)





to get the acceleration:
resolve the smallest temporal
and spatial scales

imaging technique:
4 linear cameras (silicon strip detectors)
trajectory of single particles

resolution:
70,000 frames/s
8 μm/pixel ($<\eta$)

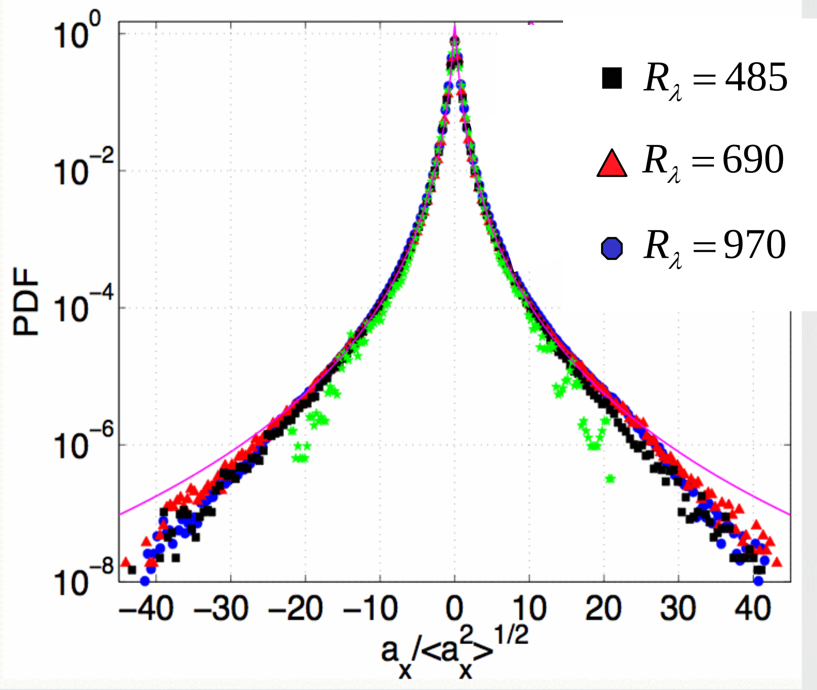
Voth, La Porta, Crawford, Alexander & Bodenschatz
J. Fluid Mech. **469** (2002)

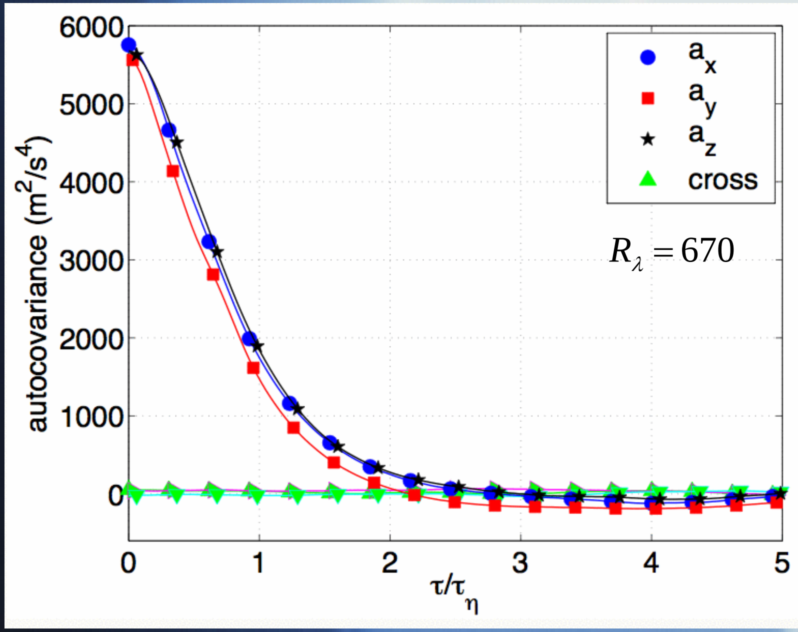
Mordant, Crawford & Bodenschatz *PRL* ***93*** *(2004)*

fluid particle acceleration

highly non Gaussian distribution of the acceleration components

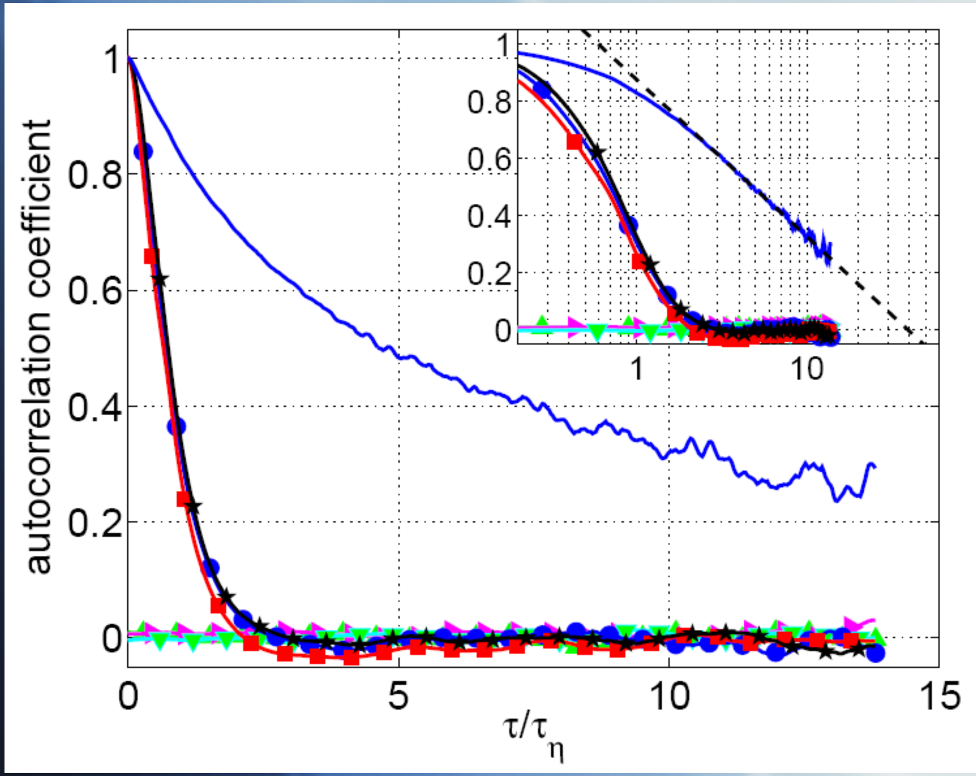
very large accelerations (>1000g)





time dynamics related to the Kolmogorov time scale

fluid particle acceleration



Mordant, Crawford & Bodenschatz *PRL* ***93*** *(2004)*

acceleration magnitude
correlated over
integral time scales

trapping in vortices

see also Mordant, Lévêque, Pinton *NJP* 2004, *PRL* 2002

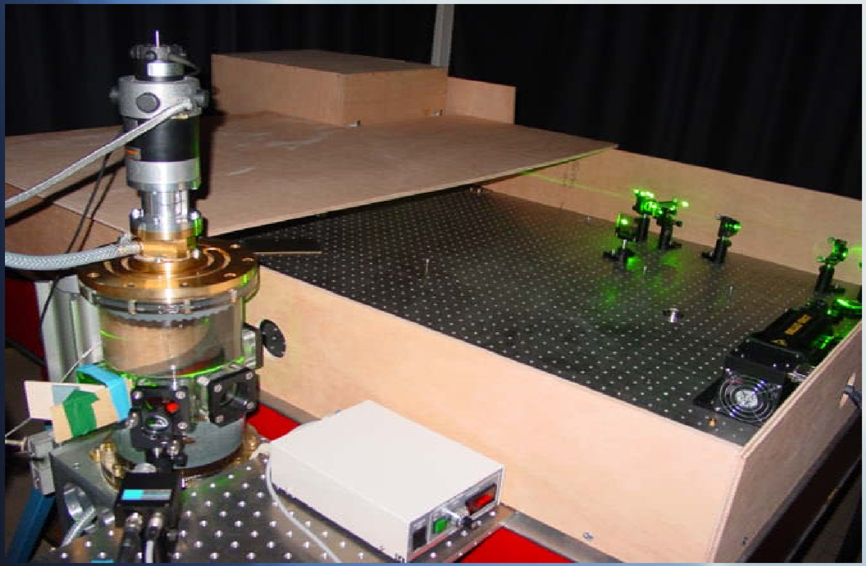
fluid particle acceleration using Laser Doppler

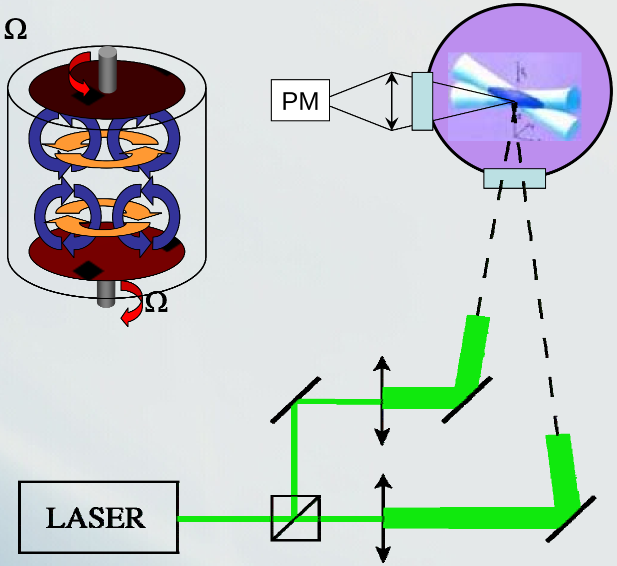
new experiment in Lyon

R. Volk, G. Verhille, N. Mordant, J.-F. Pinton

based on classical LDV but with wide beams

1W laser, measurement volume ~ $(5\ mm)^3$





fluid particle acceleration using Laser Doppler

reproduces Cornell data very accurately

	R_λ	a_0
Lyon	690	~ 6.2
Cornell	680	6.2±0.4

$$\langle a^2 \rangle = a_0 \epsilon^{3/2} \nu^{-1/2}$$

inertial particles (preliminary results)

$$\frac{dv_p}{dt} = \beta \frac{Du}{Dt} - \frac{v_p - u}{\tau_s}$$

(very small particles)

$$\tau_s = \frac{a^2}{3\nu\beta}$$

$$\beta = \frac{3\rho_f}{2\rho_p + \rho_f}$$

effective inertia of the particle

3 types of particles:

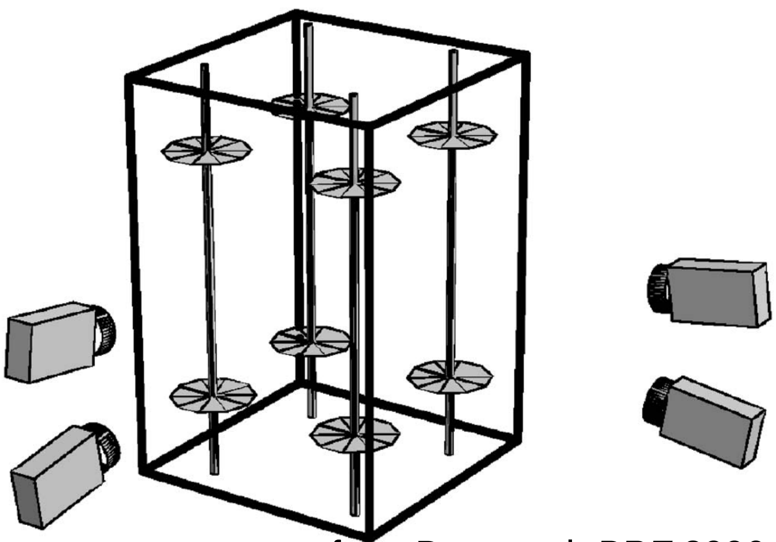
• latex:	d=1.06	$\beta \sim 1$	$a/\eta=1$	neutral
• plastic:	d=1.4	$\beta=0.8$	$a/\eta=1.5$	heavy
• bubbles	d=1.3 10^{-3}	$\beta \sim 3$	$a/\eta \sim 2.5$	light

inertial particles (preliminary results)

no clear change in acceleration distribution

clear change in acceleration variance

multi-particles measurements



from Berg et al. *PRE* 2006

typical measurement:
relative dispersion of 2 particles

technique: 3D PTV using
multiple cameras

experimental issues:

- have pairs close enough at the initial time:
  large seeding density and resolution of the small scales
- track particles for a long time ($\sim T_L$):
  low enough seeding density (max 1000 particles in view)
- observe large separations (~L):
  large field of view (about 3L)

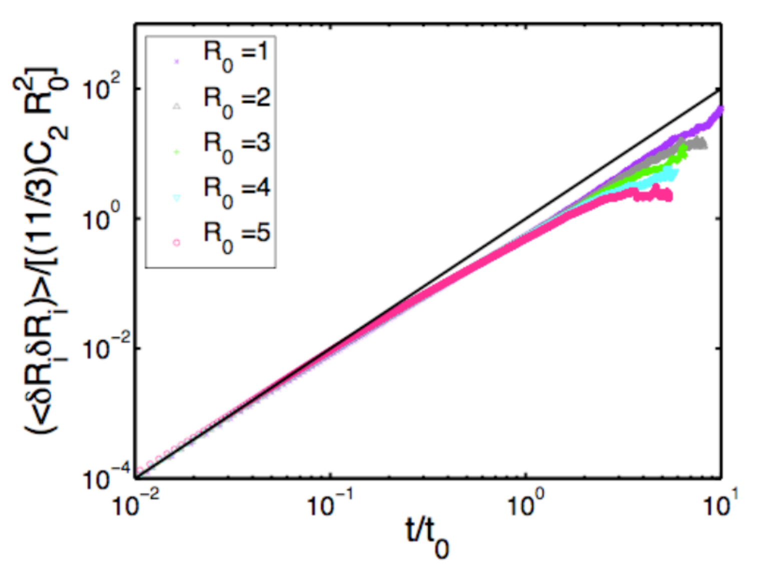
with current cameras moderate Reynolds number

particles pairs

expected separation following the Richardson prediction

$$\langle r^2 \rangle = g\epsilon t^3$$

for a initial position in the inertial range



for the current exp. (R_λ~600)
the particles do not forget
their initial separation
before reaching the integral length scale

$$\left\langle \left(\frac{r}{r_0}\right)^2 \right\rangle = \frac{11}{3} C_2 r_0^2 \left(\frac{t}{t_0}\right)^2$$

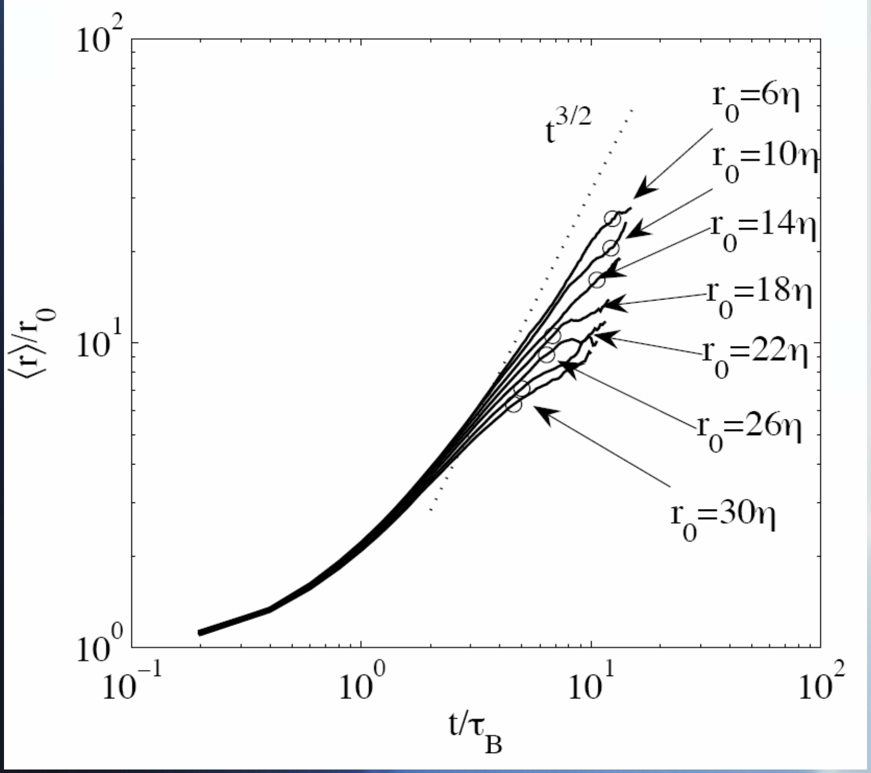
Batchelor scaling

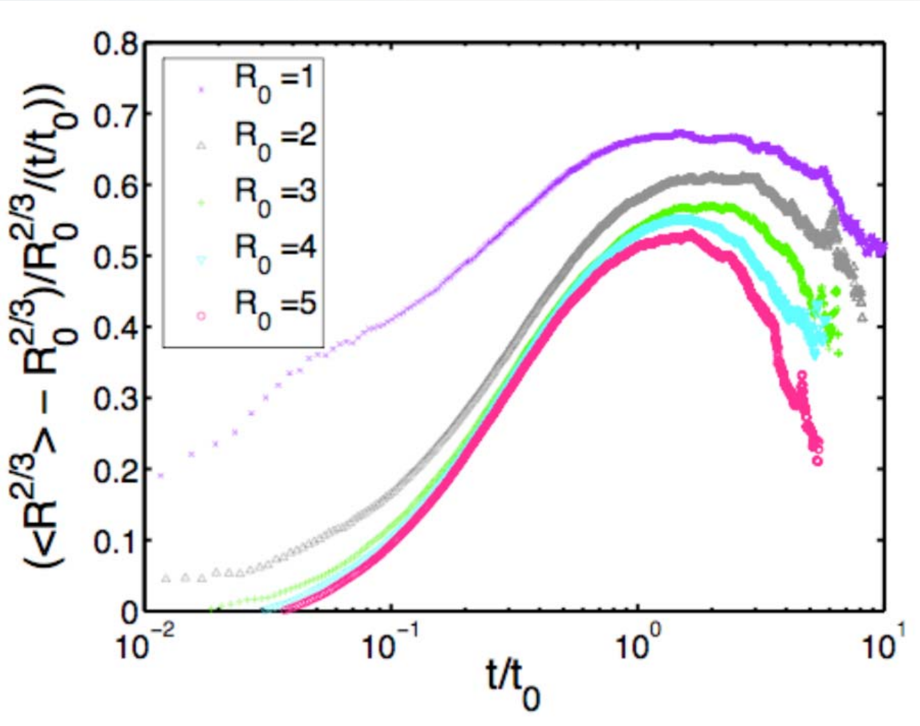
$$t_0 = \left(\frac{r_0^2}{\epsilon}\right)^{1/3}$$

Bourgoin, Ouellette, Xu, Berg, Bodenschatz
Science 2006

particles pairs

no clear Richardson scaling:
requires a very large Reynolds number
and small initial separations (~10η)



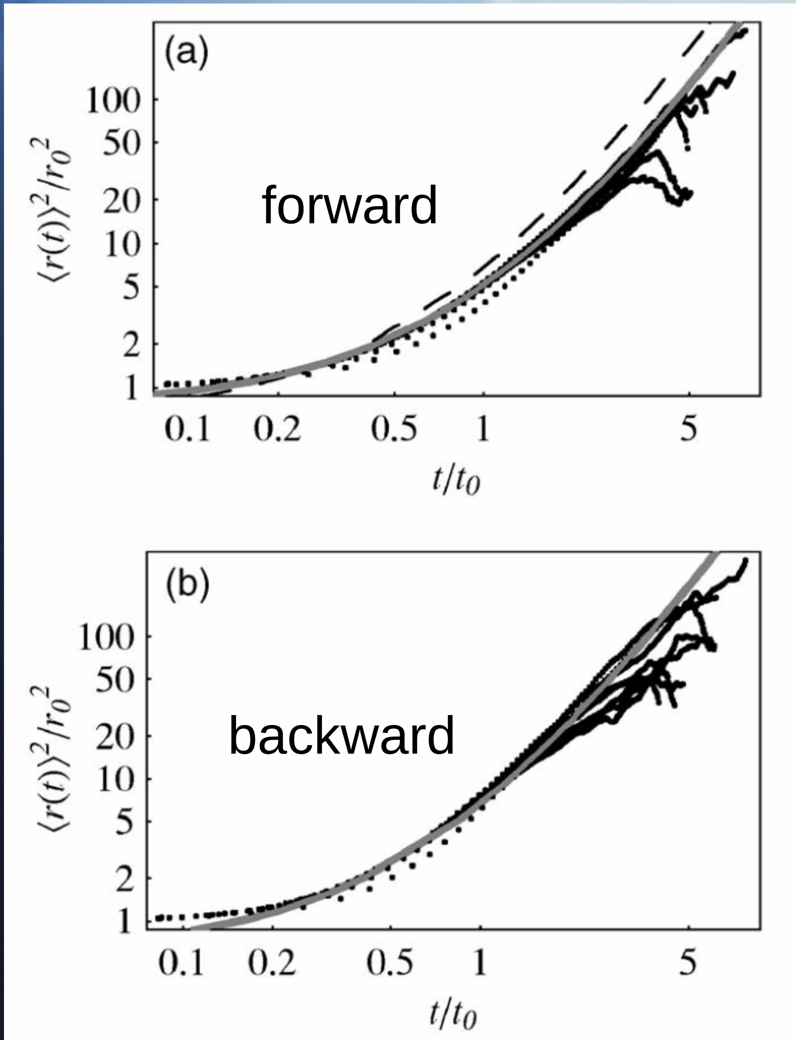


Luthi, Ott, Berg & Mann *J. of Turbulence* 2007

Bourgoin et al. *Science* 2006

backward vs forward dispersion

mixing is concerned rather with backwards scattering ie
how two particles come close together



backward dispersion
is faster (2x)
than forward dispersion

link with coarse grained
velocity gradient tensor

Berg, Lüthi, Mann & Ott *PRE* 2006

see also Xu, Ouellette,
Nobach & Bodenschatz *ETC11 proc.*

tetrahedra

matrix of inertia

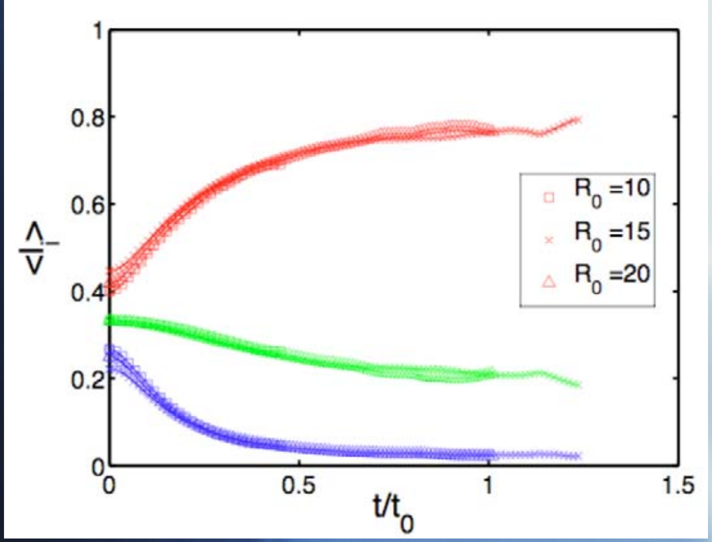
$$[\rho_1, \rho_2, \rho_3]$$

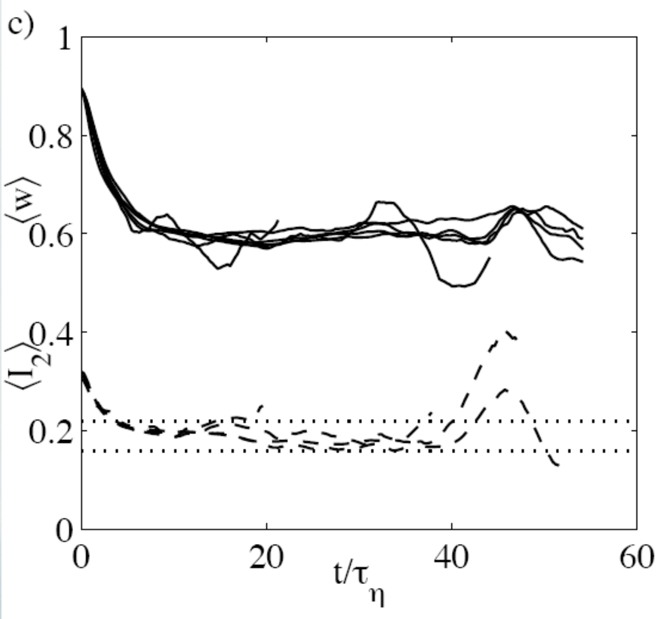
$$\begin{aligned}\rho_1 &= (X_1 - X_2)/\sqrt{2}\\ \rho_2 &= (2X_3 - X_2 - X_1)/\sqrt{6}\\ \rho_3 &= (3X_4 - X_3 - X_2 - X_1)/\sqrt{12}\end{aligned}$$

normalized eigenvalues

$$I_i = \frac{g_i}{g_1 + g_2 + g_3}$$

shape evolution toward planar shapes





Xu, Ouellette, Bodenschatz *Proc. ICNM5* 2007

Luthi, Ott, Berg & Mann *J. of Turbulence* 2007

Lagrangian stats

- well resolved 1 particle measurements
- acceleration measurement:
  - strongly non Gaussian distribution
  - long time correlations
- inertial particles / bubbles measurements
- multiple particle measurements in progress