State of the art numerical investigations of Lagrangian turbulence

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Research interests

Turbulence ABC

- Thermal convection
- Wall bounded flows / shear flows
- Turbulence modeling
- Statistical properties of turbulence
- Computational micro and nano-fluidics
- *Lagrangian turbulence*

Fluid Dynamics Turbulence

$$\partial_t \boldsymbol{v} + \boldsymbol{v} \cdot \nabla \boldsymbol{v} = -\nabla p + \nu \Delta \boldsymbol{v} + \boldsymbol{f}$$

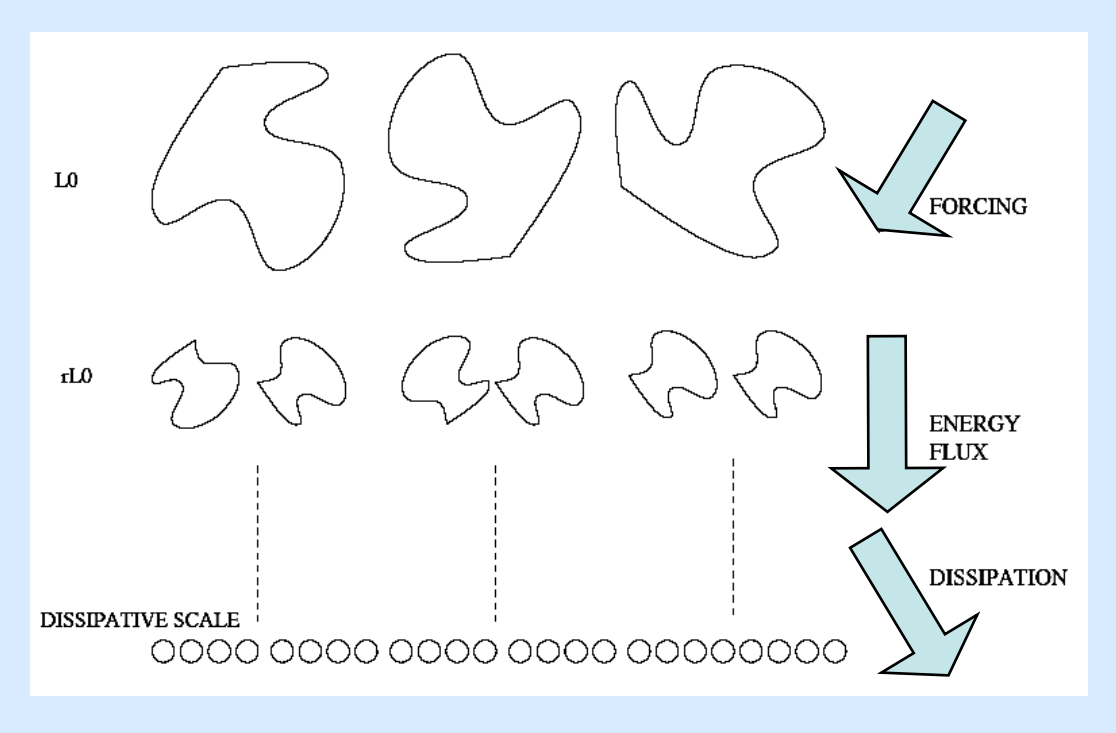
$$\partial \cdot \boldsymbol{v} = 0$$

$$Re = \frac{L_0 v}{\nu}$$

$$\eta \ll r \ll L_0$$

Inertial range

Energy flux

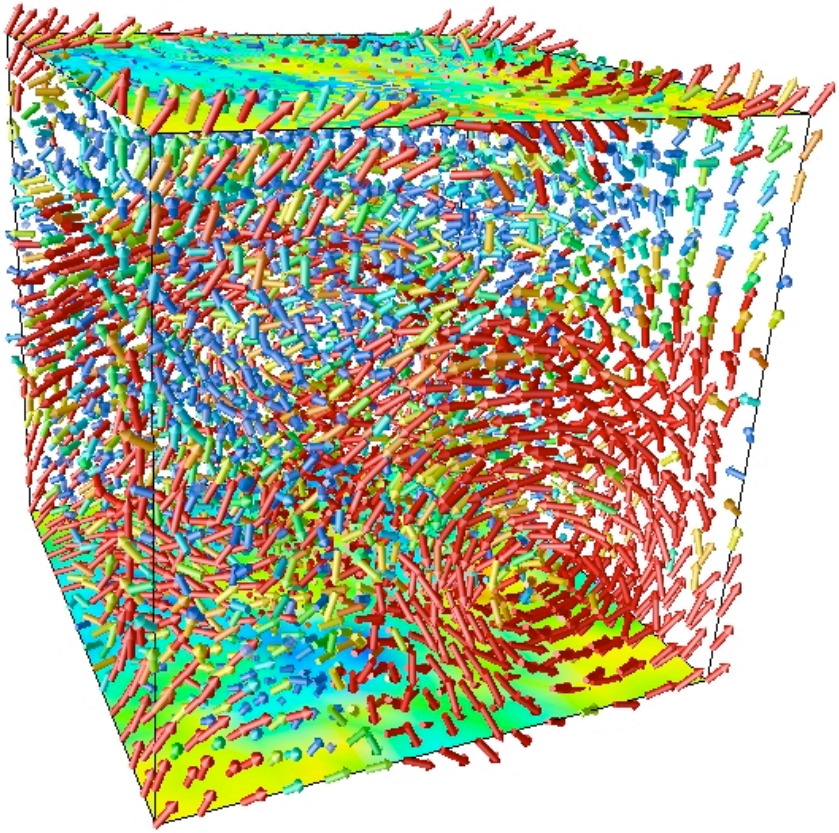


Turbulence: yesterday & today

Year 1500

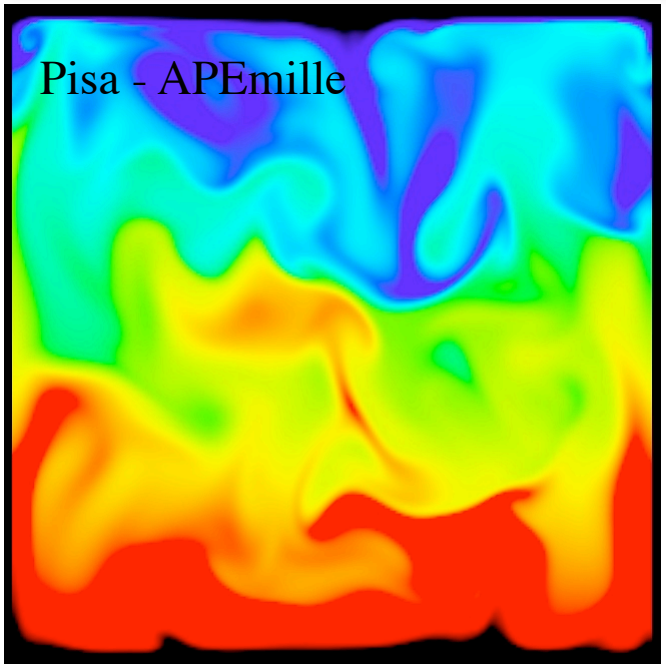
River Arno (Toscana, Italy)

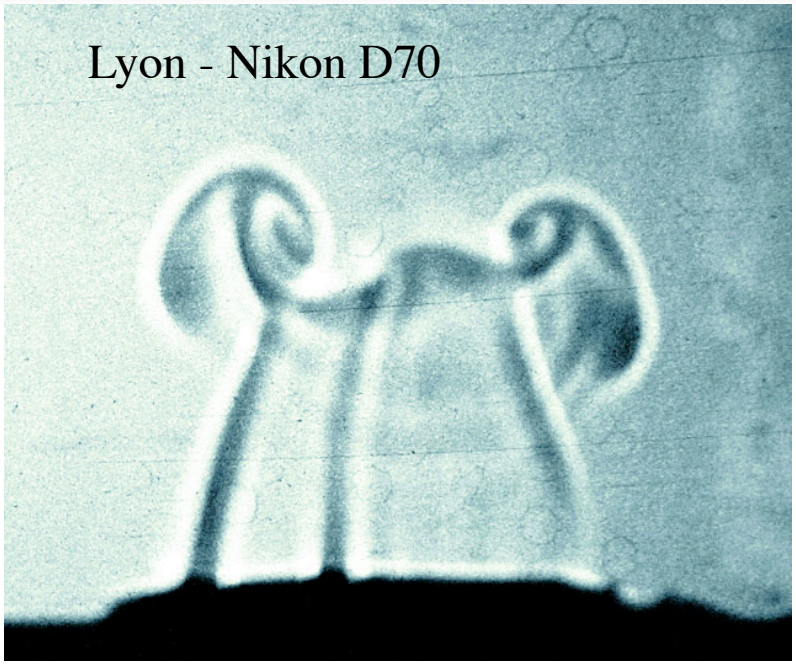
Year 2004

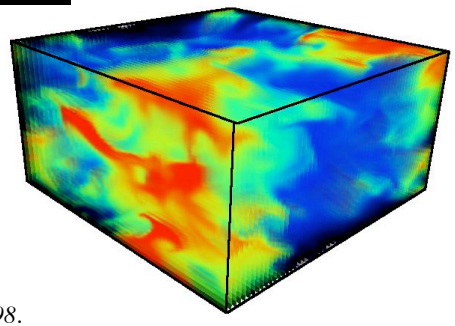


IBM SP4 (CINECA, Italy)

Thermal convection: Nu=Nu(Ra)







D. Lohse and F. Toschi. Ultimate state of thermal convection. *Physical Review Letters, 90:034502, 2003*

R. Benzi, F. Toschi, and R. Tripiccione. On the heat transfer in rayleigh-bénard systems. *Journal of Statistical Physics, 93(3-4):901, 1998*.

L. Biferale, E. Calzavarini, F. Toschi, and R. Tripiccione. Universality of anisotropic fluctuations from numerical simulations of turbulent flows. *Europhys. Lett., 64(4):461–467, November 2003*.

E. Calzavarini, C. R. Doering, J. D. Gibbon, D. Lohse, A. Tanabe, and F. Toschi. Exponentially growing solutions in homogeneous rayleigh-bénard convection. *Physical Review E, 73:035301, 2006*.

E. Calzavarini, D. Lohse, F. Toschi, and R. Tripiccione. Rayleigh and prandtl number scaling in the bulk of rayleigh–bénard turbulence. *Phys. Fluids, 17:055107–1, 2005*.

E. Calzavarini, F. Toschi, and R. Tripiccione. Evidences of bolgiano-obhukhov scaling in three dimensional rayleigh-bénard convection. *Physical Review E, 66(1):016304, 2002*.

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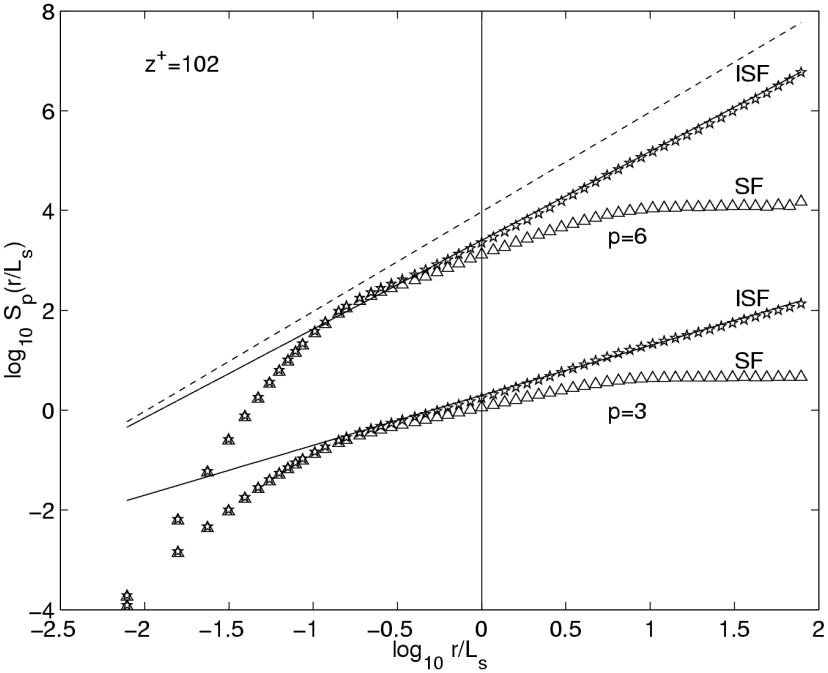
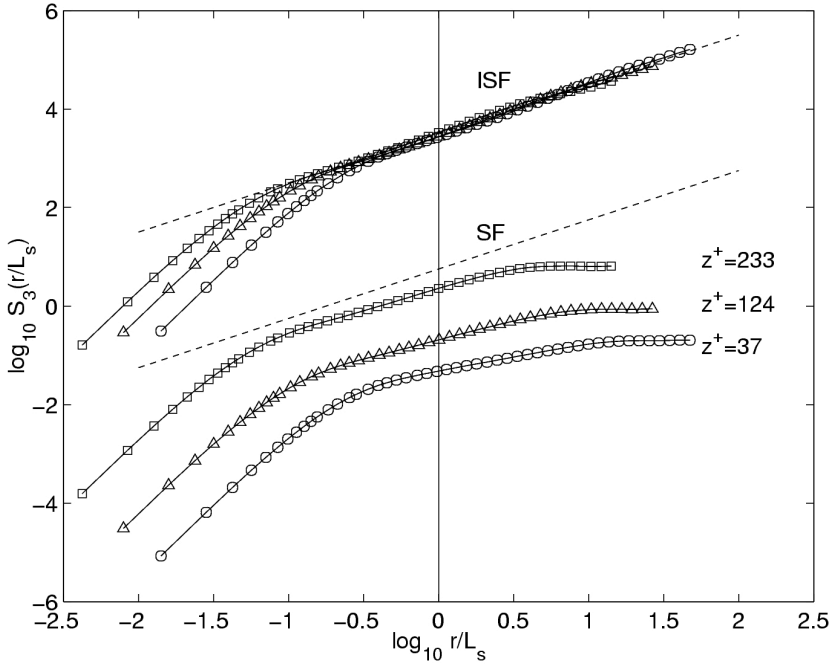
Non homogeneous, non isotropic flows

$$\tilde{S}^{(p)}(r) = \left\langle \left(\delta v^3(r) + r\mathcal{S}\delta v^2(r)\right)^{p/3} \right\rangle \sim r^{\zeta_p}$$

Wall bounded flows / shear flows





R. Benzi, G. Amati, C. Casciola, F. Toschi, and R. Piva. Intermittency and scaling laws for wall bounded turbulence. *Physics of Fluids, 11(6):1284, 1999*.
F. Toschi, G. Amati, S. Succi, R. Benzi, and R. Piva. Intermittency and structure functions in channel flow turbulence. *Physical Review Letters, 82(25):5044, 1999*.
E. Leveque, F. Toschi, L. Shao, and J.-P. Bertoglio. Shear-improved smagorinsky model for large-eddy simulation of wall-bounded turbulent flows. *J. Fluid Mech., 570:491–502, 2007*.
F. Toschi, E. Leveque, and G. Ruiz-Chavarria. Shear effects in non-homogeneous turbulence. *Physical Review Letters, 85(7):1436, 2000*.

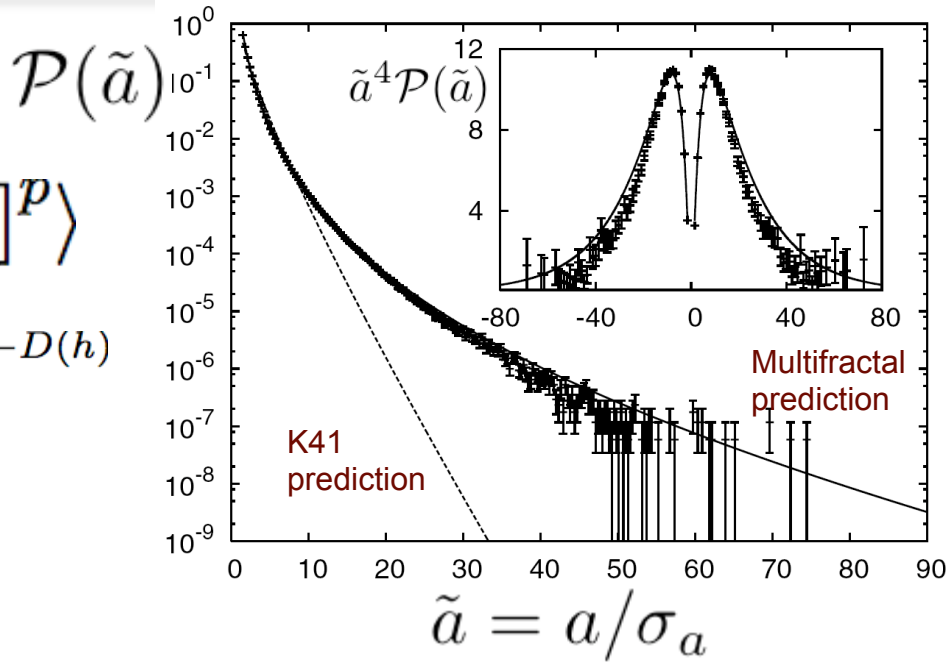
Major result, change of RKSH $\delta v(r)^3 \sim r \cdot \varepsilon_r \longrightarrow \delta v(r)^2 \sim \varepsilon_r/\mathcal{S}$

Fundamental statistical properties of turbulence

The "standard model"

$$S_p(r) = \langle [\boldsymbol{v}(\boldsymbol{x}+\boldsymbol{r}) - \boldsymbol{v}(\boldsymbol{x})]^p \rangle$$

$$S_p(r) = \langle (\delta_r v)^p \rangle \sim \langle v_0^p \rangle \int_I dh \left(\frac{r}{L_0}\right)^{hp+3-D(h)}$$



$$S_p(r) \sim \left(\frac{r}{L_0}\right)^{\zeta_p}$$

Multi-fractal model
Parisi-Frisch 1995

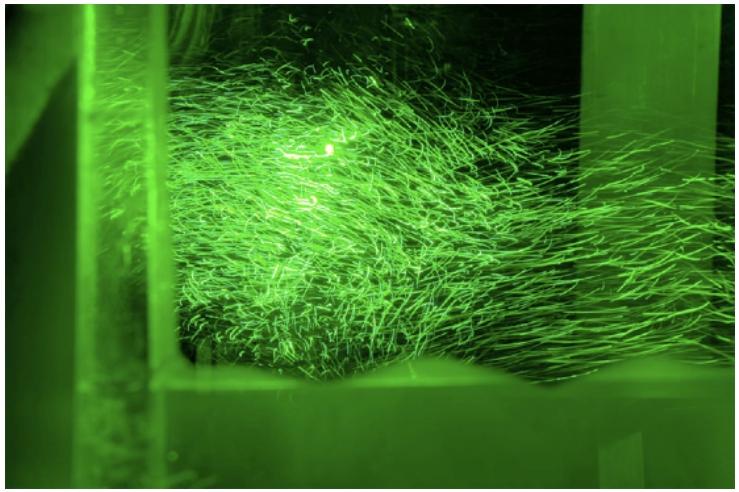
$$\eta \ll r \ll L_0$$

$$\zeta_p = \inf_h (hp + 3 - D(h))$$

$$\boxed{D(h)}$$

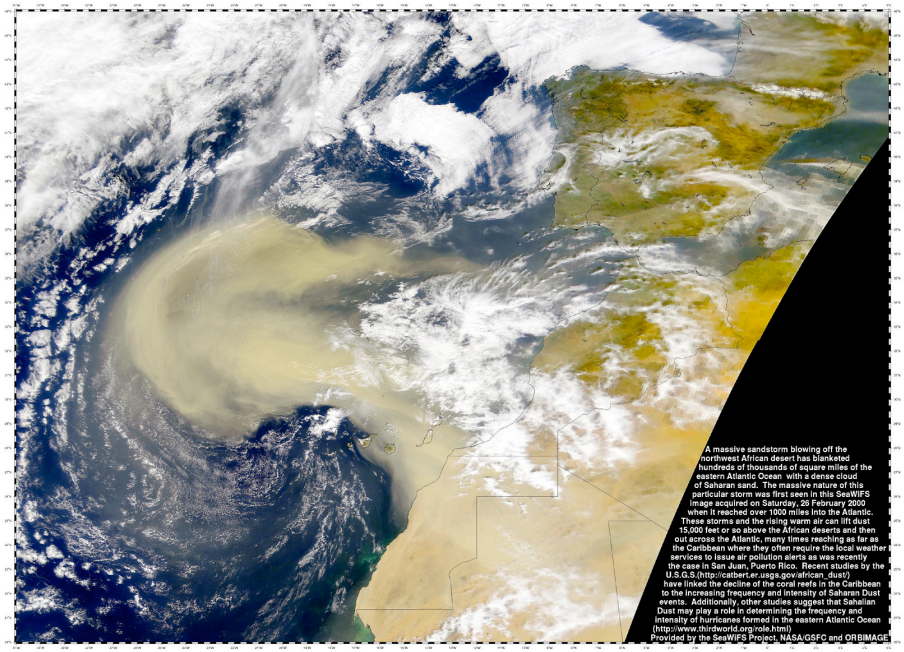
Lagrangian turbulence

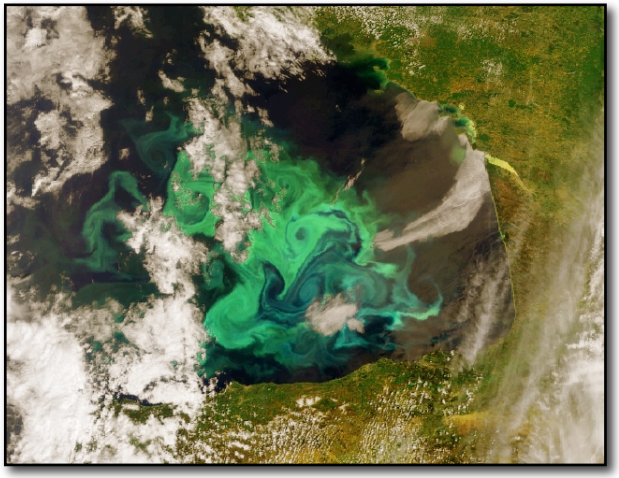
For a review:



Lagrangian Properties of Particles in Turbulence
Federico Toschi, Eberhard Bodenschatz
Annu. Rev. Fluid Mech. 2009. 41:375–404

Lagrangian turbulence: few examples



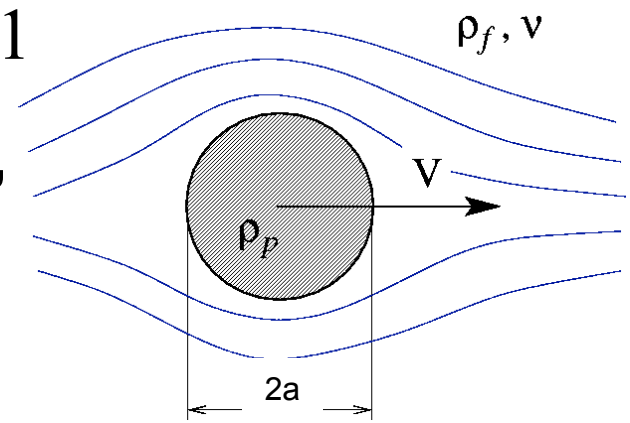


Model for particle's equation of motion

Particles with $a << \eta$ (Kolmogorov scale)

Particle Reynolds: $\mathrm{Re}_a = a\mathrm{v}_a / \nu << 1$

Dilute suspensions (no collisions), no gravity



$$\frac{d\mathbf{x}}{dt} = \mathbf{v}$$

$$\frac{d\mathbf{v}}{dt} = \beta \frac{D}{Dt}\mathbf{u}(\mathbf{x}(t),t) - \frac{1}{\tau_p}\left(\mathbf{v} - \mathbf{u}(\mathbf{x}(t),t)\right)$$

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

$$\tau_p = \frac{1}{3\beta}\frac{a^2}{\nu}$$

$$\boxed{St \equiv \frac{\tau_p}{\tau_\eta} = \frac{1}{3\beta}\frac{a^2}{\eta^2}}$$

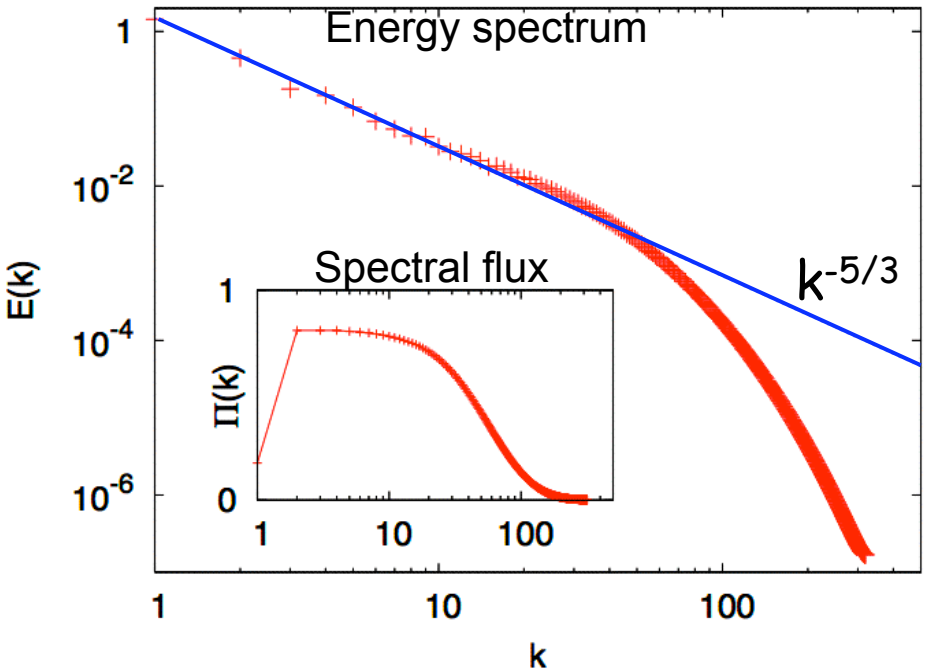
(essentially: Maxey & Riley *Phys. Fluids* 1983, T.R.Auton et al. *JFM* 1988)

CINECA keyproject 1024^3 DNS+tracers

N	Re_λ	η	L	T_L	τ_η	T	δx	N_p
512	183	0.01	3.14	2.1	0.048	5	0.012	$0.96\ 10^6$
1024	284	0.005	3.14	1.8	0.033	4.4	0.006	$1.92\ 10^6$

Pseudo spectral code - dealiased 2/3 rule - normal viscosity - 2 millions of passive tracers- code fully parallelized with MPI +FFTW - Platform IBM SP4 (sust. Performance 150Mflops/ proc) - 50000 cpu hours - duration of the run: 40 days

Lagrangian database
$(x(t),v(t),a(t)=-\nabla p+\nu\Delta u)$
with high temporal resolution

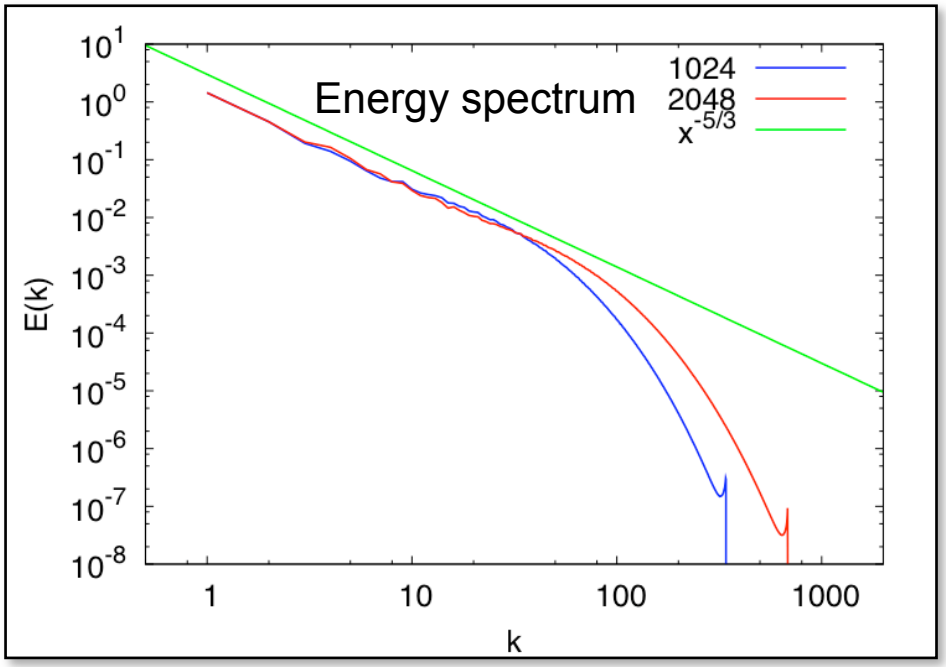


DEISA 2048^3 DNS with tracers & heavy

N	Re_λ	η	L	T_L	τ_η	T	δx	N_p
2048	400	0.0025	3.14	1.8	0.02	5.9	0.003	$2\ 10^9$

Pseudo spectral code - dealiased 2/3 rule - normal viscosity - 2 billions of passive tracers & heavy particles- code fully parallelized with MPI+FFTW - Platform SGI Altix 4700 - 400000 cpu hours -

duration of the run: 40 days over 3 months.



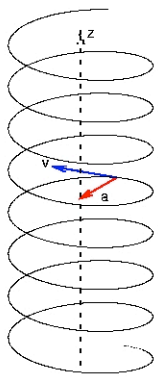
Lagrangian database $(x(t),v(t),u(t),\partial_i u_j(t))$ at high resolution

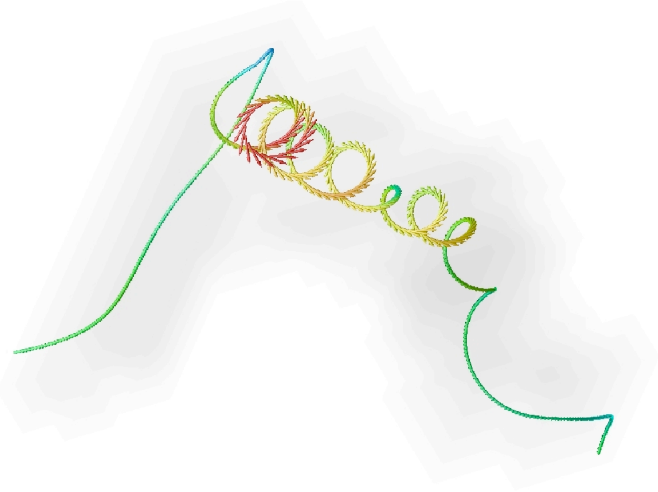
Small scale bottleneck and vortex filaments

Centripetal and longitudinal acceleration

Centripetal $\boldsymbol{a}_c = \boldsymbol{a} \times \hat{\boldsymbol{v}}$

Longitudinal $\boldsymbol{a}_l = (\boldsymbol{a} \cdot \hat{\boldsymbol{v}})\hat{\boldsymbol{v}}$





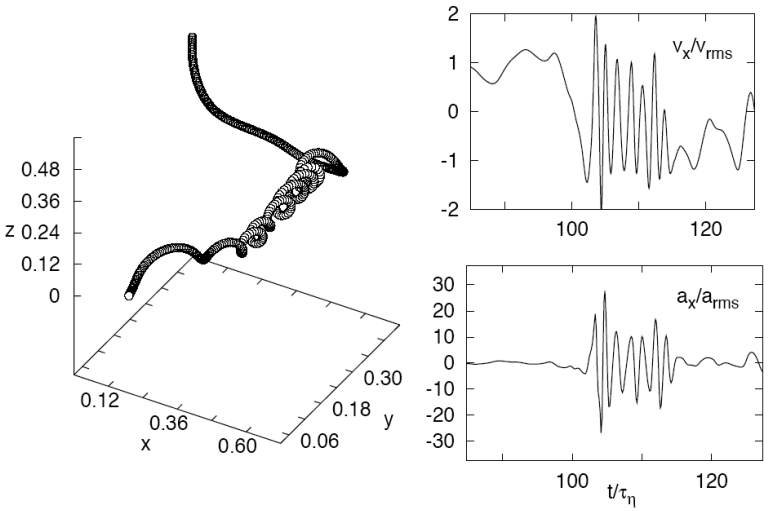
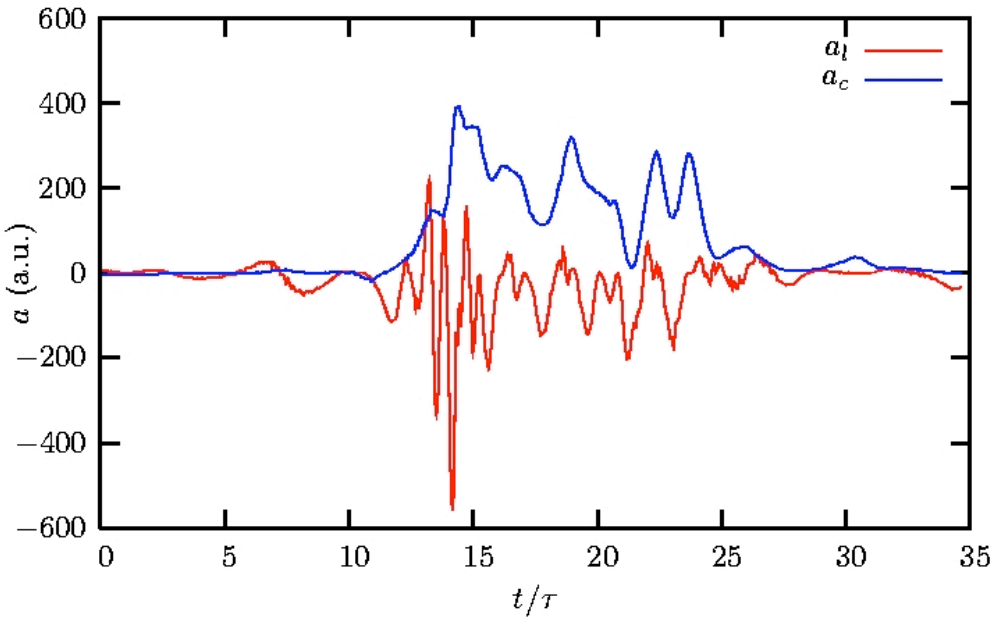
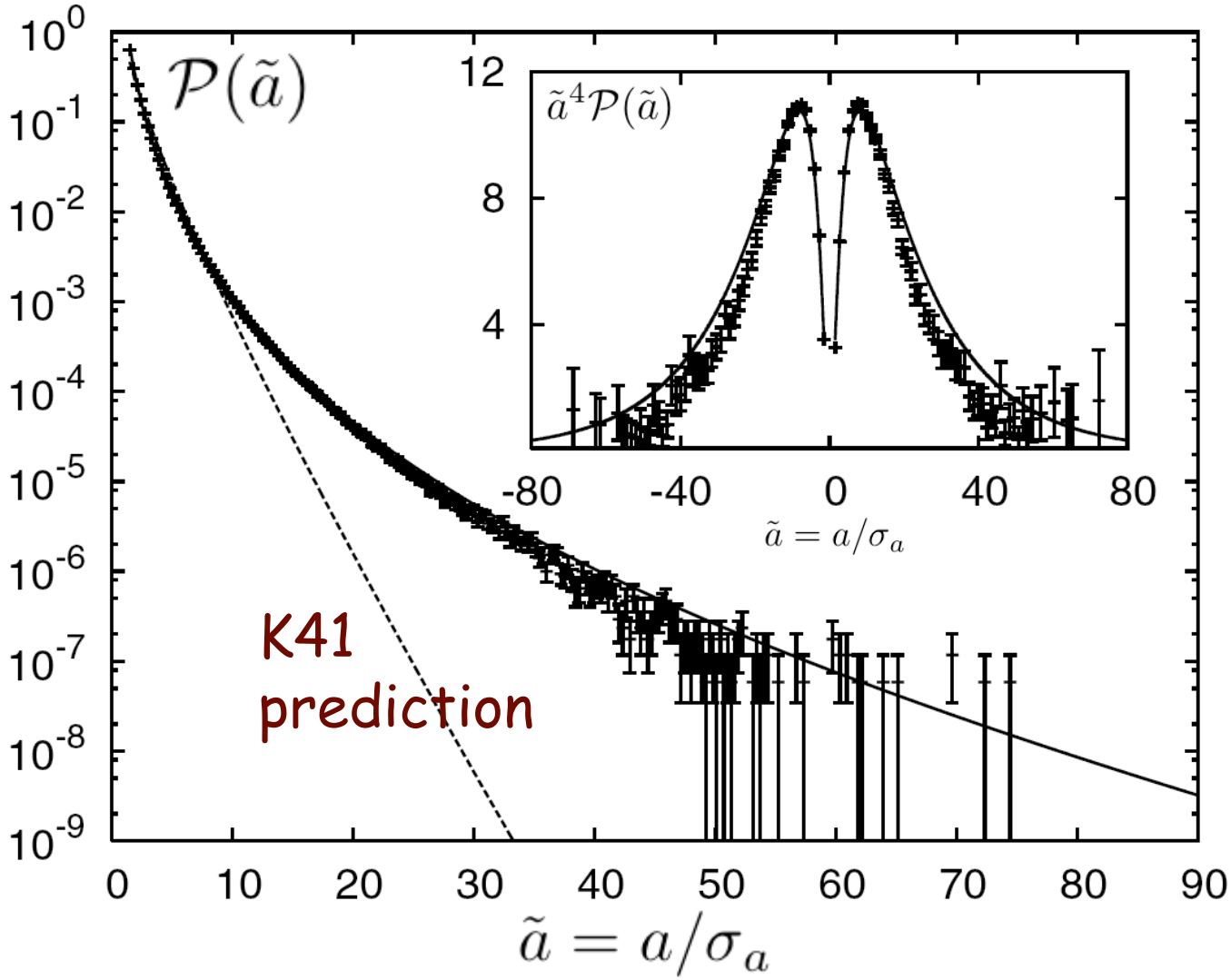


FIG. 1: Trajectory and time series. Left panel: 3D trajectory of a trapping event in vortex filament. Acceleration and velocity fluctuations here reach about 30 and 2 r.m.s. values, respectively (right panels).



Acceleration p.d.f., DNS results



Multifractal
prediction

Multifractal Statistics of Lagrangian Velocity and Acceleration in Turbulence,
L. Biferale, G. Boffetta , A. Celani, B. J. Devenish, A. Lanotte and F. Toschi, **93**, 6 PRL 2004

Lagrangian velocity statistics

Let us introduce some observables

We do not have much fantasy! So we “copy” from Eulerian turbulence: structure functions

$$S_p(r) \equiv \langle (u(x+r) - u(x))^p \rangle \sim r^{\zeta_E(p)}$$

$$S_p(\tau) \equiv \langle (v(t+\tau) - v(t))^p \rangle \sim r^{\zeta_L(p)}$$

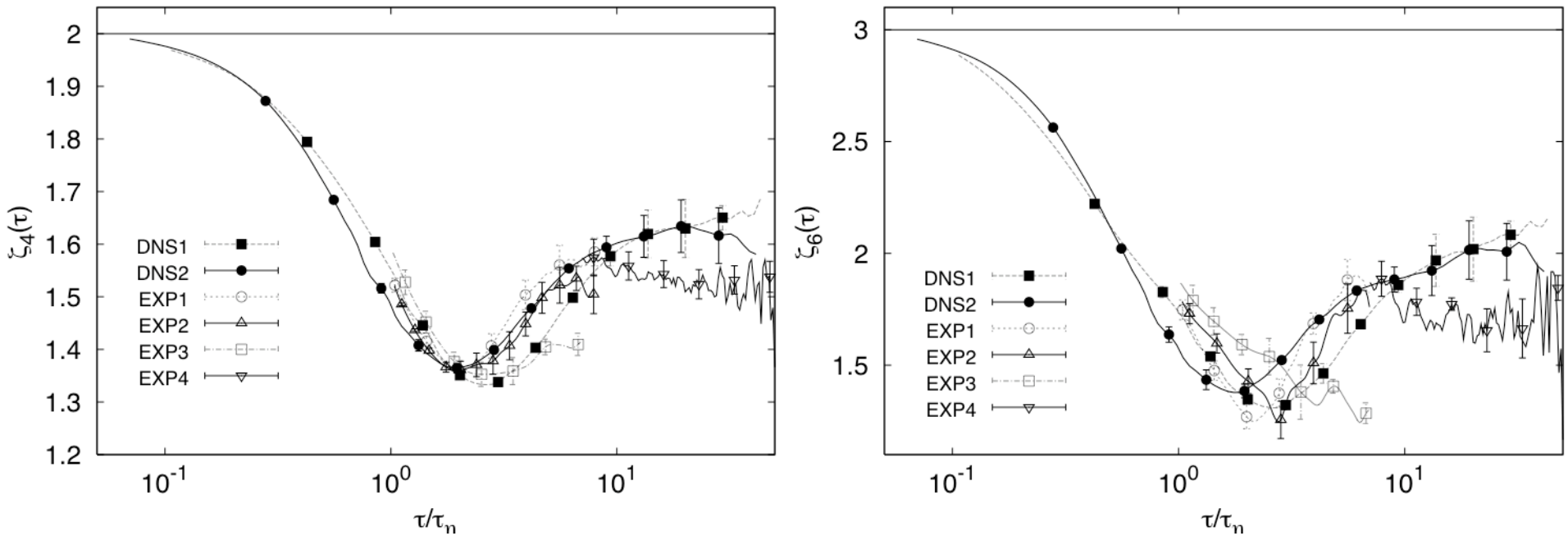
How to estimate $\zeta_L(p)$?

$$\tau_\eta \ll \tau \ll T_L$$

In Eulerian turbulence we have

$$\zeta_E(p) = \inf_h (hp + 3 - D(h))$$

Local scaling exponents

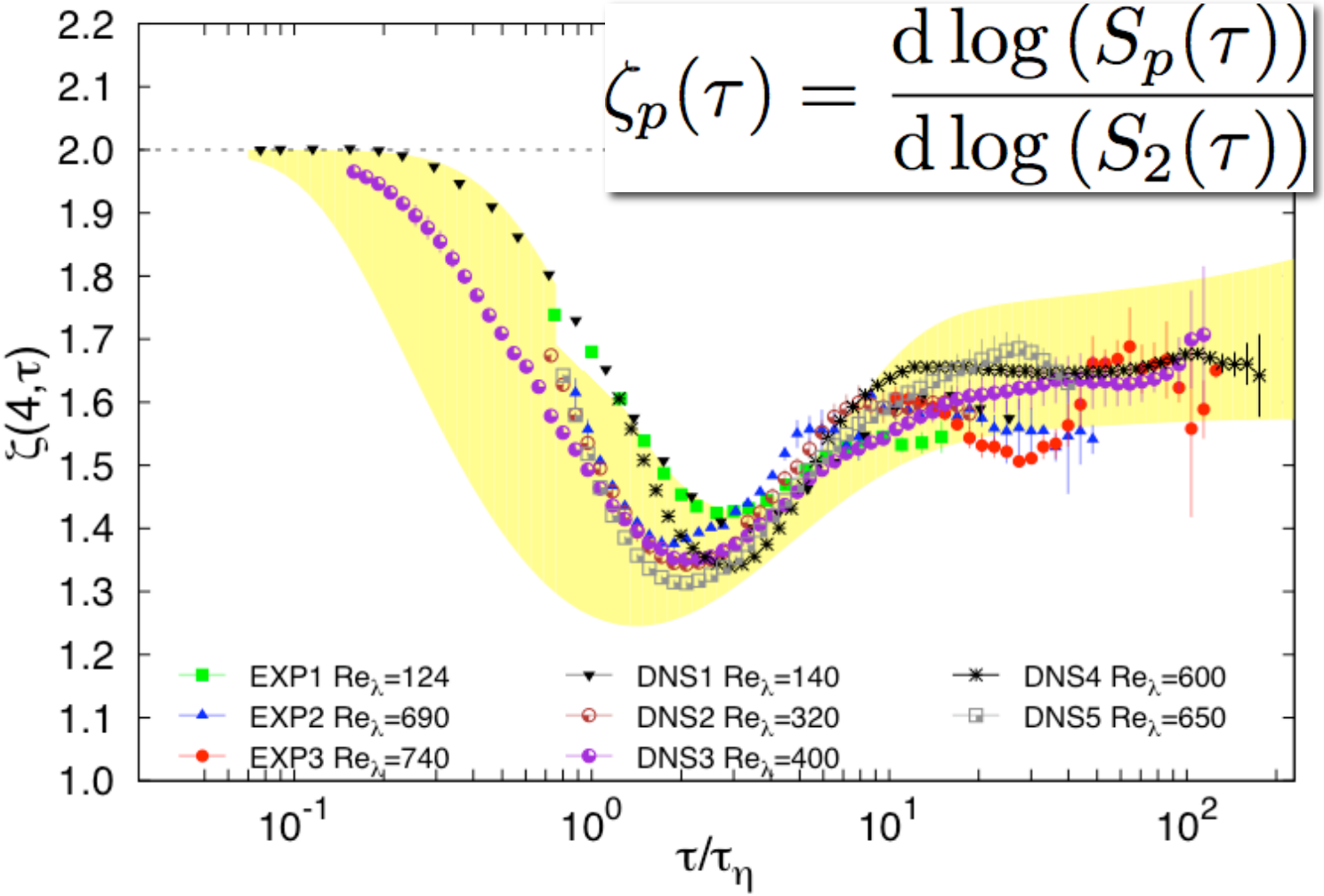


$$\zeta_p(\tau) = \frac{\mathrm{d}\log\left(S_p(\tau)\right)}{\mathrm{d}\log\left(S_2(\tau)\right)}$$

L. Biferale, E. Bodenschatz, M. Cencini, A. S. Lanotte, N. T. Ouellette, F. Toschi, and H. Xu.
Lagrangian structure functions in turbulence: A quantitative comparison between experiment and direct numerical simulation.
Physics of Fluids, 20(6):065103–12, 2008.

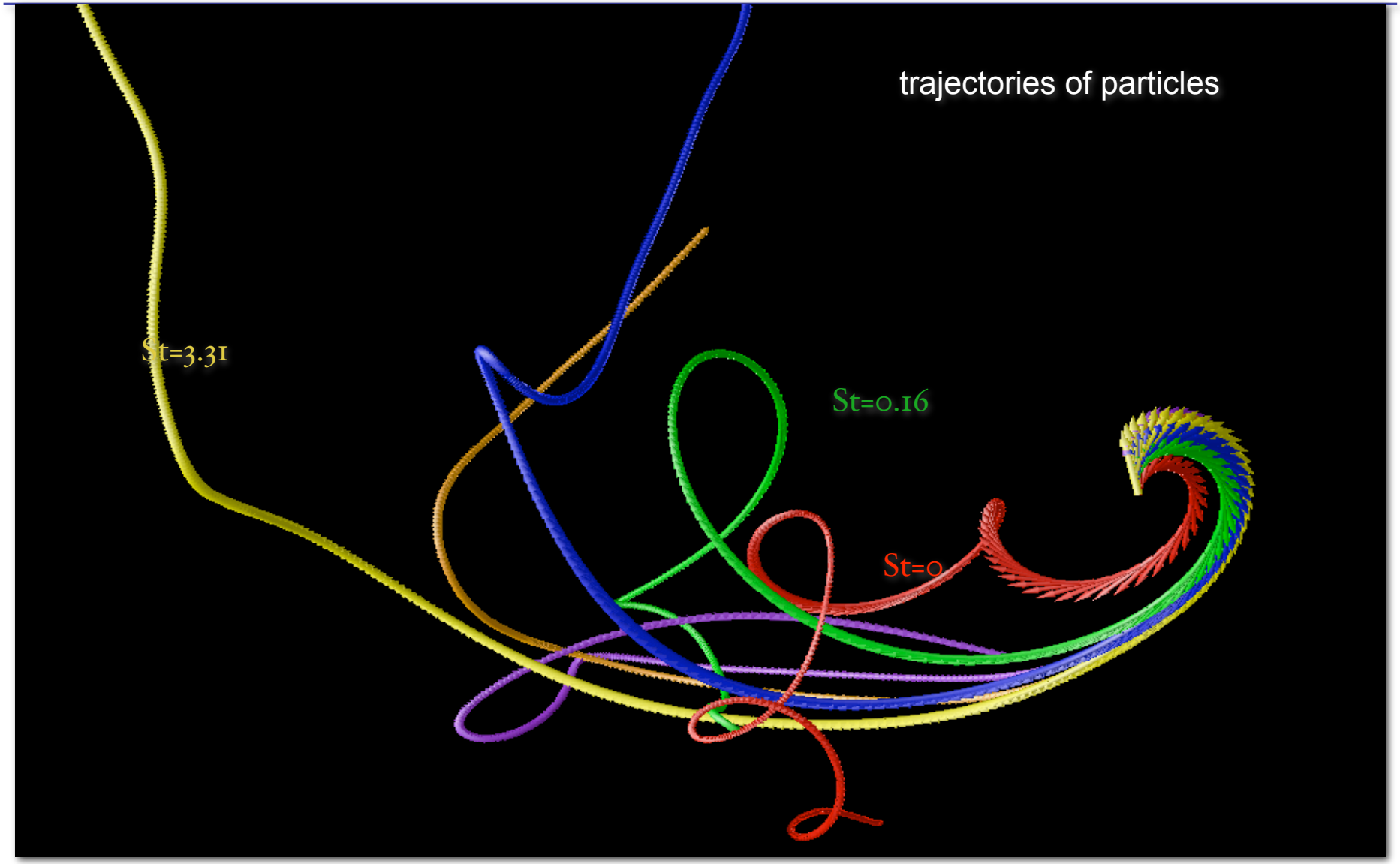
DNS and experiment show a very good agreement

Universality of Lagrangian Turbulence

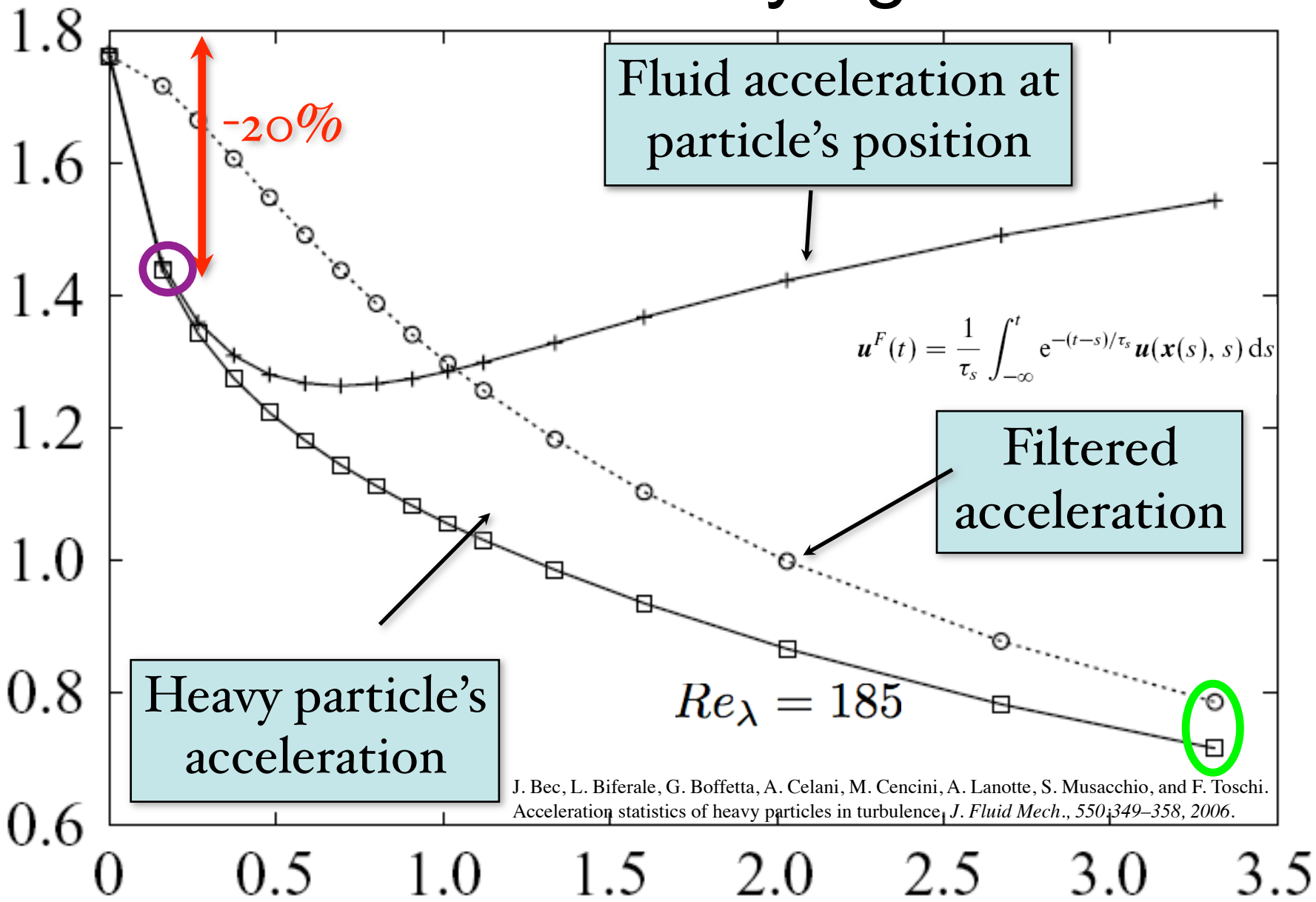


A. Arneodo, R. Benzi, J. Berg, L. Biferale, E. Bodenschatz, A. Busse, E. Calzavarini, B. Castaing, M. Cencini, L. Chevillard, R. T. Fisher, R. Grauer, H. Homann, D. Lamb, A. S. Lanotte, E. Leveque, B. Luthi, J. Mann, N. Mordant, W. C. Muller, S. Ott, N. T. Ouellette, J. F. Pinton, S. B. Pope, S. G. Roux, F. Toschi, H. Xu, and P.K. Yeung
Universal intermittent properties of particle trajectories in highly turbulent flows. *Physical Review Letters, 100(25):254504–5, 2008.*

Starting inside a vortex, but with different inertia



Acceleration at varying Stokes



J. Bec, L. Biferale, G. Boffetta, A. Celani, M. Cencini, A. Lanotte, S. Musacchio, and F. Toschi. Acceleration statistics of heavy particles in turbulence, *J. Fluid Mech., 550:349–358, 2006*.

Comparison of three extreme cases

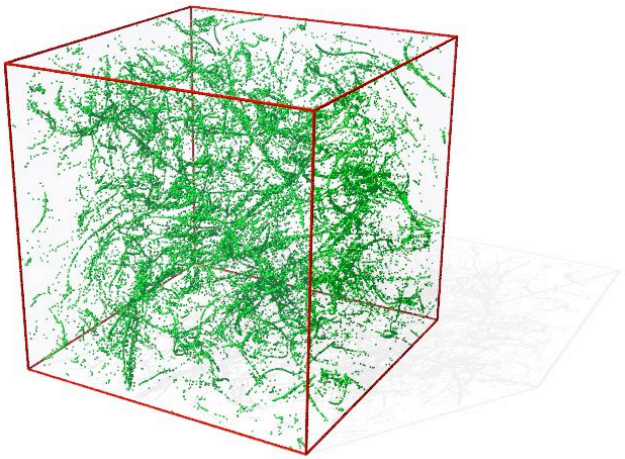
β = 0, heavy

β = 1, tracer

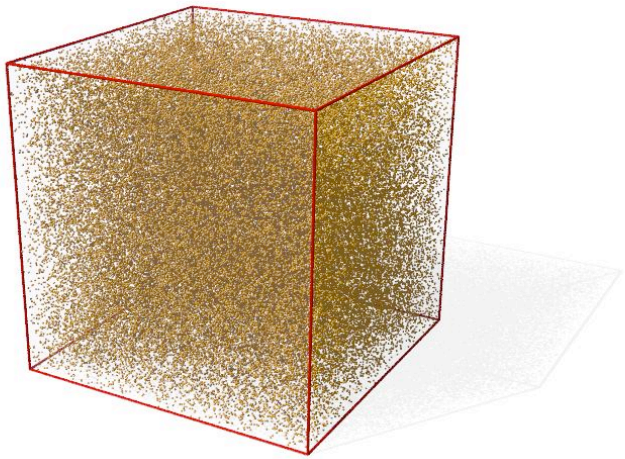
Poisson distribution

β = 3, bubble

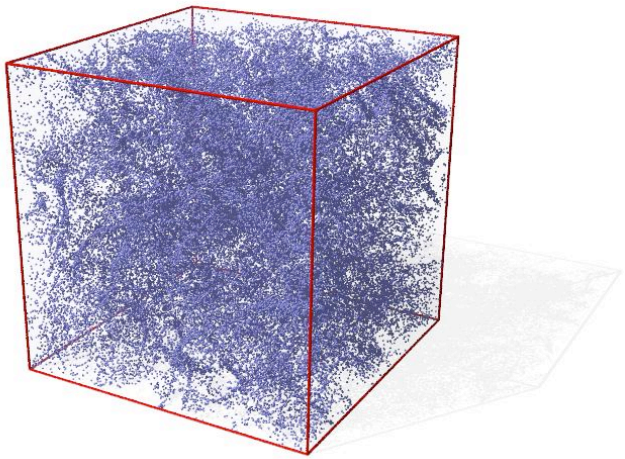
bubble



tracer



heavy

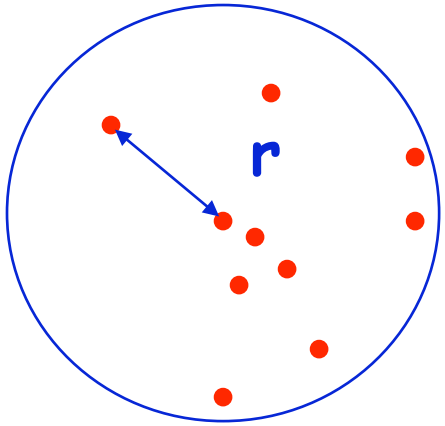


St=0.6 10^5 particles

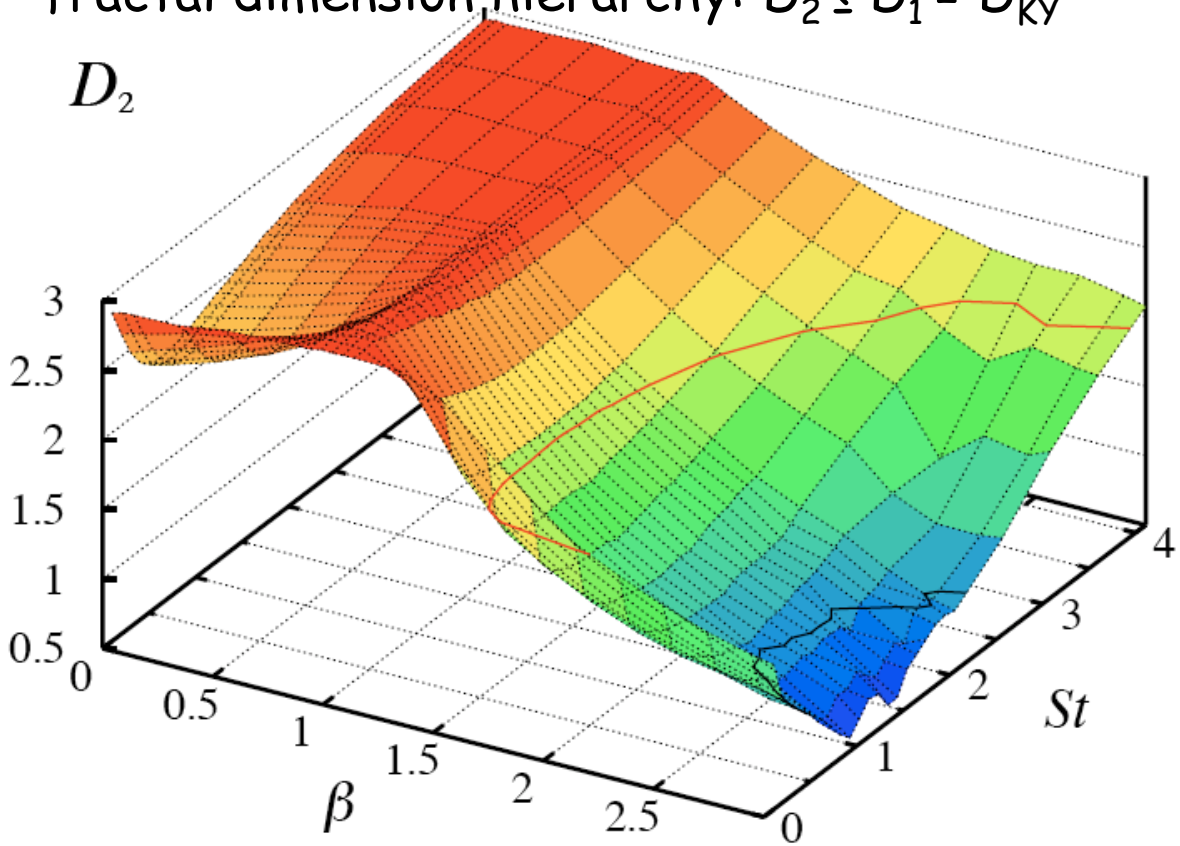
Correlation dimension D_2

$P_2(r)$ Probability to find a couple of particle whose distance is below r.

At $r \ll \eta$ $P_2(r) = A\, r^{\boxed{D_2}}$



fractal dimension hierarchy: $D_2 \leq D_1 = D_{KY}$



Same features as D_{KY}

More accessible in experiments

Morphological analysis of point clouds

E. Calzavarini, M. Kerscher, D. Lohse, and F. Toschi. Minkowski functionals: Characterizing particle and bubble clusters in turbulent flow. *J. Fluid Mech., 607:13–24, 2008*.

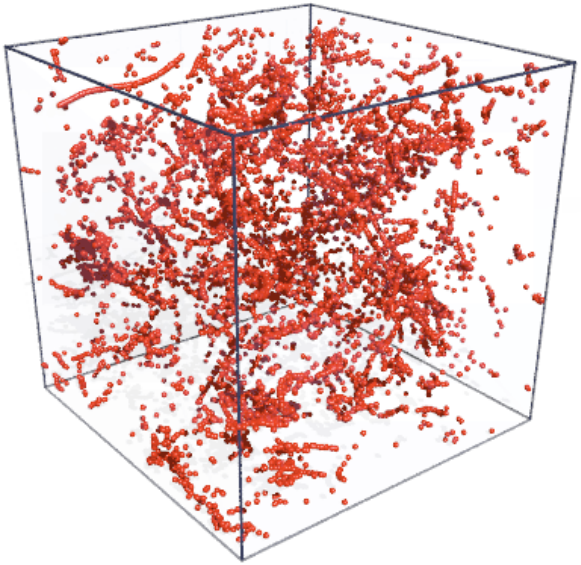
- Put balls $\mathcal{B}_r(\mathbf{x}_i)$ with radius ***r*** around each particle ***i***
- Let ***r*** increase
- Measure total **volume**, **surface**, **mean curvature** and **Euler characteristic** of the emerging structure

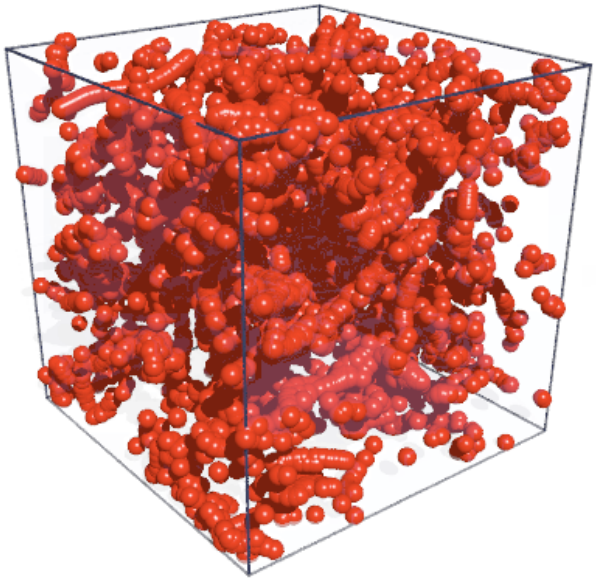
$$\mathcal{A}_r = \bigcup_{i=0}^{N} \mathcal{B}_r(\mathbf{x}_i)$$

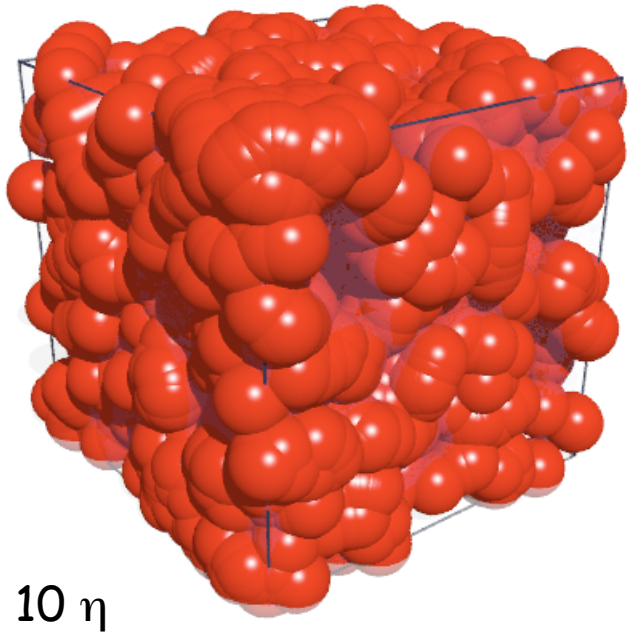
Minkowski functionals provide complete morphological characterization of point cloud!

Visualization of A_r

$2 \cdot 10^4$ particles with $\beta=3$ and St=1







radius = 0.5 η

radius = 3 η

r

radius = 10 η

Program for the future, towards real world:

- Neutrally buoyant case
  - Smaller that the dissipative scale of turbulence **and** with same density of advecting field
- Heavy particle case
  - Smaller that the dissipative scale of turbulence **but** with density much higher that advecting field
  - One way coupling
  - **Two way coupling**
- Generic density contrast case
  - One way coupling
  - **Two way** and four way coupling (collisions)
- Non idealized particles
  - **Finite particle size**, non spherical geometry case
- Thermal effects (both stable and unstable conditions)
- Intrinsic dynamics (i.e.droplest in clouds)
  - Radii growth
  - Coalescence

international CFD database

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CFD database

Computational Fluid Dynamics database

This is the web site of the **free CFD database**, kindly hosted by Cineca supercomputing center (Bologna, Italy).

The administrator of the site, in charge of registering new users on the site is: Federico Toschi. Please refer to him any question or comment regarding this web site.

If you wish to contribute to this DNS database of fluid-dynamics data by sharing your raw data or computer codes you are welcome; please contact the administrator of the site.

upcoming events

Computational Physics and New Perspectives in Turbulence
Nagoya - Japan, 2006-09-11

« March 2006 »

Su	Mo	Tu	We	Th	Fr	Sa
			1	2	3	4
5	6	7	8	9	10	11
12	13	14	15	16	17	18
19	20	21	22	23	24	25
26	27	28	29	30	31	

Thank you

http://cfd.cineca.it