Statistical properties of turbulence in the presence of a smart small-scale control

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Extreme Dissipation and Intermittency in Turbulence - EUROMECH COLLOQUIUM 620

CREDITS: S. Colabrese, M. Buzzicotti, F. Bonaccorso (Univ. Tor Vergata, Rome-IT); A. Celani (ICTP Trieste-IT); K. Gustafsson (Univ. Gotheborg, SE); A. Mazzino (Univ. Genova, IT); F. Toschi (TuE , NL), P. Clark di Leoni (JHU, USA), G. Marazoglou (Reading Univ- UK) , R. Grauer (Bochum, GER), K. Jansen, DESY, GER), D. Mesterhazy IBM Zurich, CH), T. Rosenow (Bochum, GER), R. Tripiccione (Univ. Ferrara-IT)

STIMULATE
European Joint Doctorates

OLD QUESTIONS:

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3. NUDGING: AN EQUATION-INFORMED TOOL TO PROBE, ASSIMILATE AND RECONSTRUCT TURBULENCE DATA

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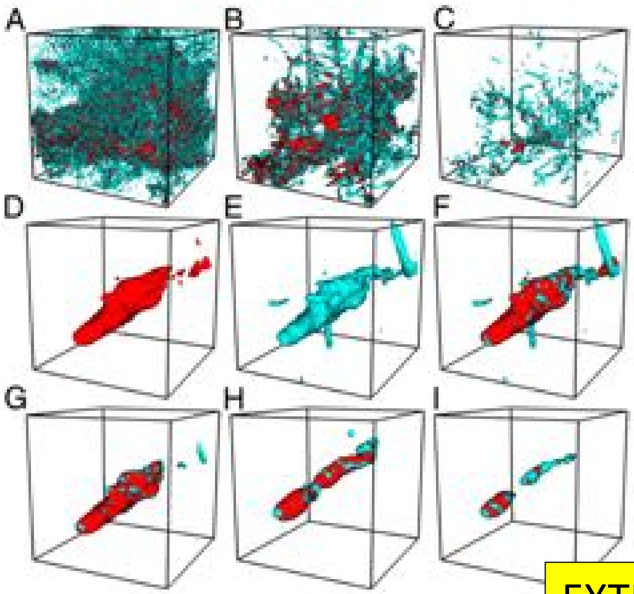
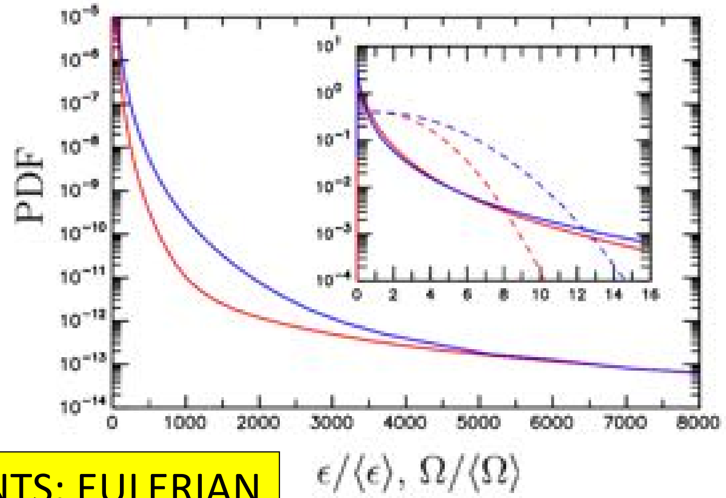
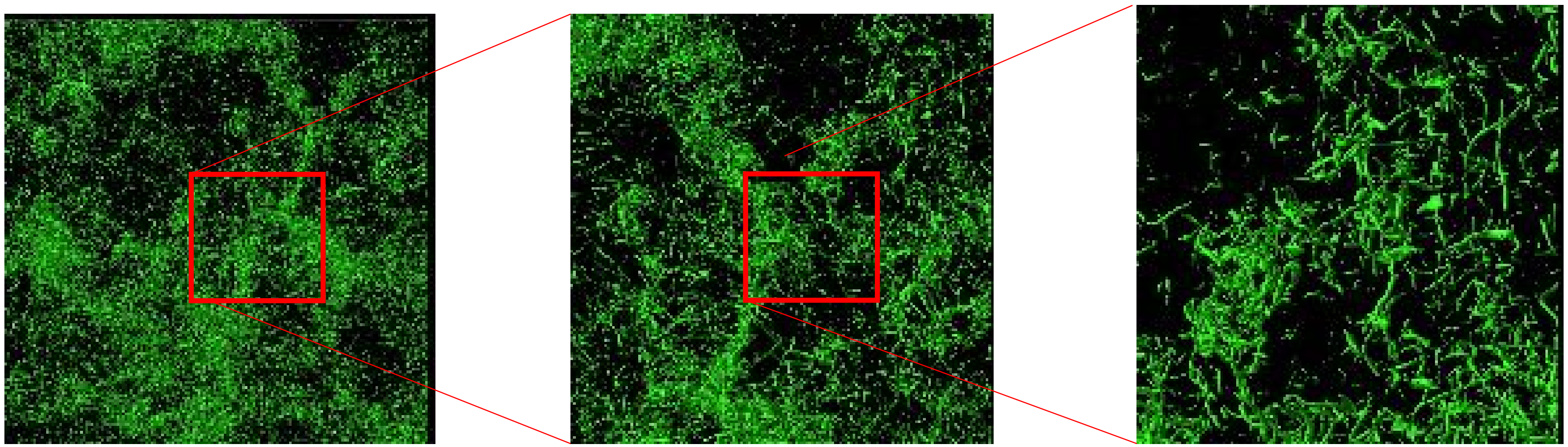
Extreme events in computational turbulence. P. K. Yeung , X. M. Zhai and K.R. Sreenivasan. PNAS 112(41) 12633 (2015)



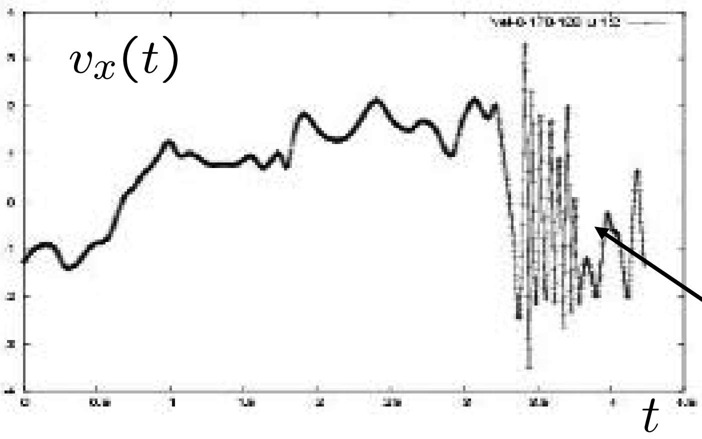


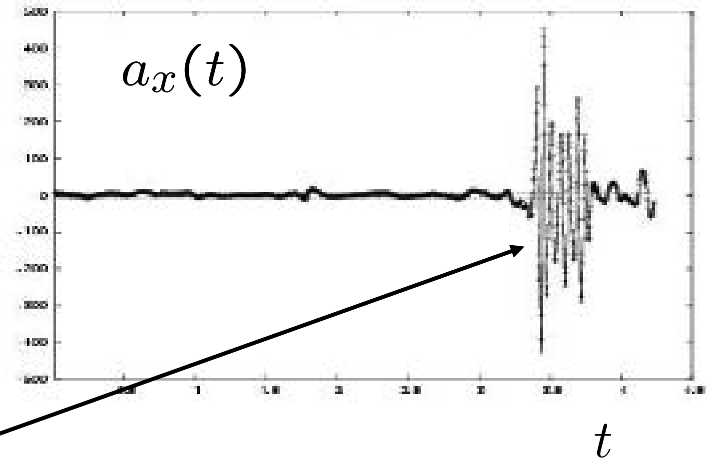
EXTREME EVENTS: EULERIAN

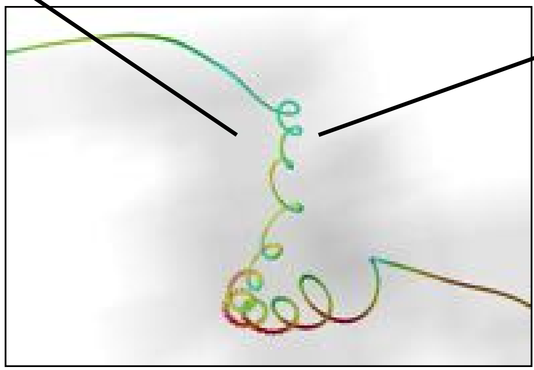


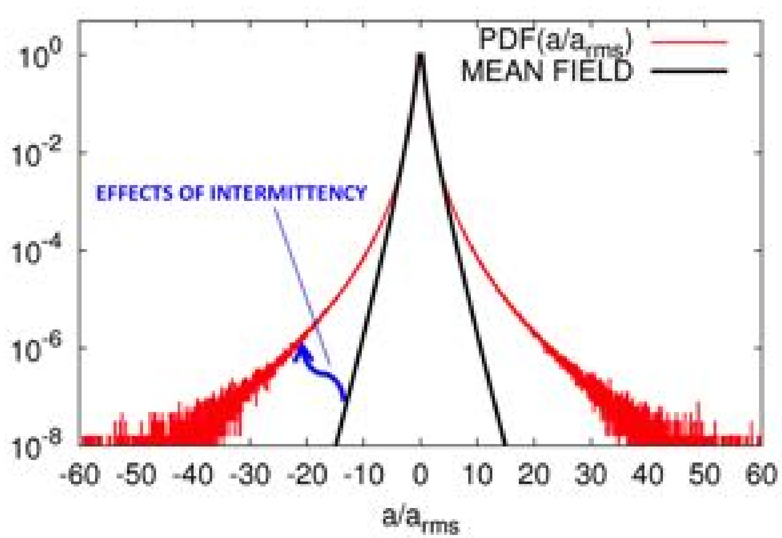
Watanabe and Gotoh, Phys. Fluids 19, 121701 (2007)

EXTREME EVENTS: LAGRANGIAN





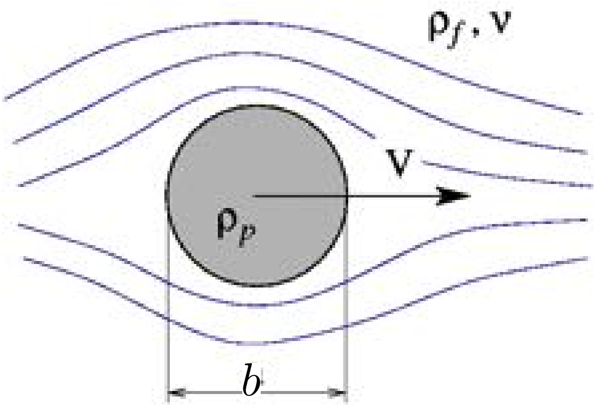




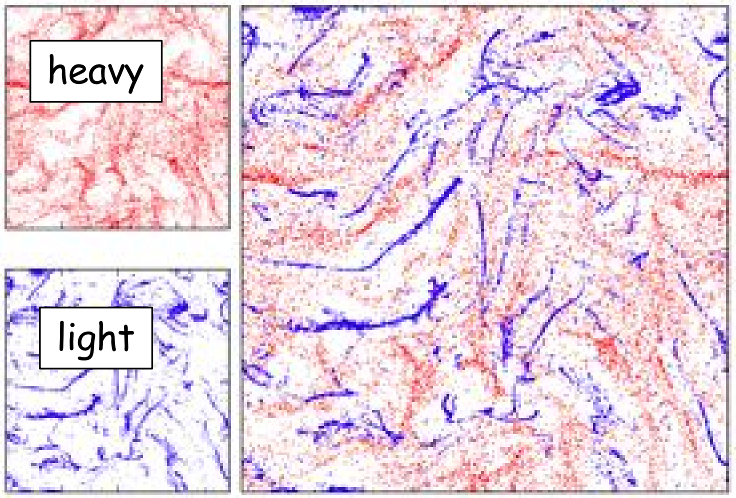
ACCELERATION PROBABILITY DISTRIBUTION FUNCTION (PDF) AT RE ~ 10⁵ [Bi04] COMPARED WITH THE PREDICTION FROM MEAN FIELD (KOLMOGOROV THEORY)

L.B., G Boffetta, A Celani, A Lanotte, F Toschi. Particle trapping in three-dimensional fully developed turbulence Physics of Fluids 17 (2), 021701 (2005)
La Porta, G.A. Voth, A.M. Crawford, J. Alexander et al. Fluid particle accelerations in fully developed turbulence. Nature, 409(6823), 1017 (2001)
N. Mordant, P. Metz, O. Michel and J.F. Pinton. Measurement of Lagrangian velocity in fully developed turbulence. Phys. Rev. Lett. 87(21), 214501 (2001)
F. Toschi and E. Bodenschatz. Lagrangian Properties of Particles in Turbulence. Annu. Rev. Fluid Mech. 41, 375 (2009)

INERTIAL PARTICLES IN COMPLEX FLOWS



$$\begin{cases} \partial_t \mathbf{v} + \mathbf{v}\cdot\partial_{\mathbf{x}}\mathbf{v} + \partial_{\mathbf{x}} P = \nu \Delta \mathbf{v} \\ \dot{\mathbf{X}}_i = \mathbf{U}_i \\ \dot{\mathbf{U}}_i = -\frac{\mathbf{U}_i - \mathbf{v}}{\tau} + \beta D_t \mathbf{v} - g(1-\beta)\hat{\mathbf{z}} \end{cases}$$



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

$\beta<1$ heavy particles

$\beta>1$ light particles

$$\tau = \frac{b^2}{3\nu\beta}$$

Drag: **Stokes Time**

Preferential concentration

Naive light(heavy) particles accumulate inside(outside) highly vortical regions

M.R. Maxey, J. Fluid Mech. **174**, 441 (1987); G. Falkovich et al, Phys. Rev. Lett. **86**, 2790 (2001)

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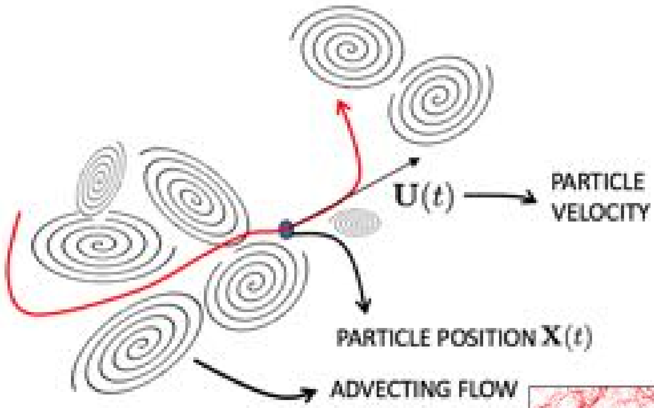
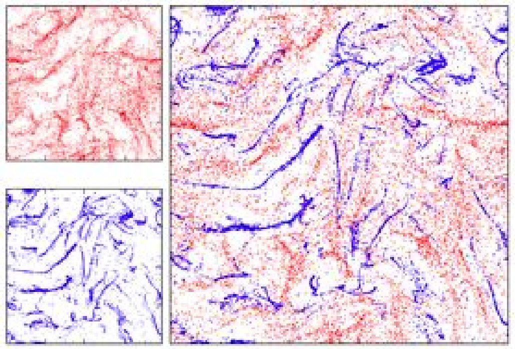
SMART INERTIAL PARTICLES IN COMPLEX FLOWS: HARNESS & CONTROL

$$\begin{cases} \partial_t \mathbf{v} + \mathbf{v}\cdot\partial_{\mathbf{x}}\mathbf{v} + \partial_{\mathbf{x}} P = \nu\Delta\mathbf{v} + \sum_{i=1}^{N_p} \delta(\mathbf{x}-\mathbf{X}_i(t))\mathcal{F} \\ \dot{\mathbf{X}}_i = \mathbf{U}_i \\ \dot{\mathbf{U}}_i = -\frac{\mathbf{U}_i-\mathbf{v}}{\tau} + \beta D_t\mathbf{v} - g(1-\beta)\hat{\mathbf{z}} \end{cases}$$

CONTROL TOOLS

$$\begin{cases} \beta = \frac{3\rho_f}{\rho_f+2\rho} \rightarrow \frac{3\rho_f}{\rho_f+2\rho[\mathbf{w},T,c,\ldots]} \\ \tau = \frac{r^2}{3\nu\beta} \rightarrow \frac{r^2[\mathbf{w},T,c,\ldots]}{3\nu\beta[\mathbf{w},T,c,\ldots]} \end{cases}$$

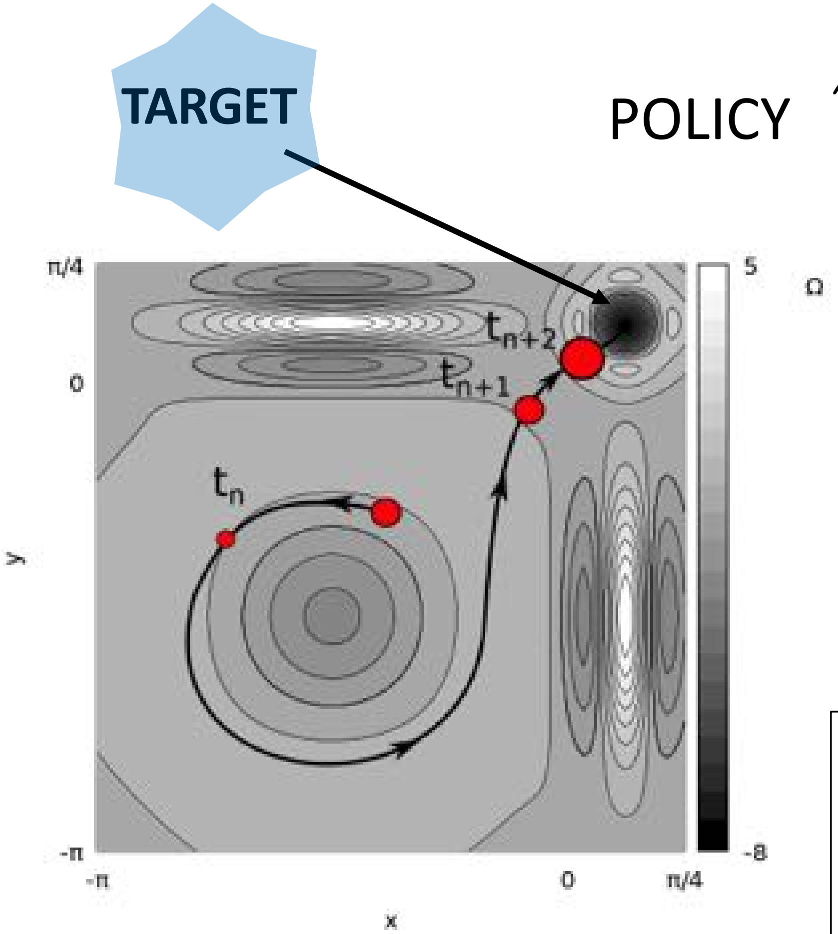


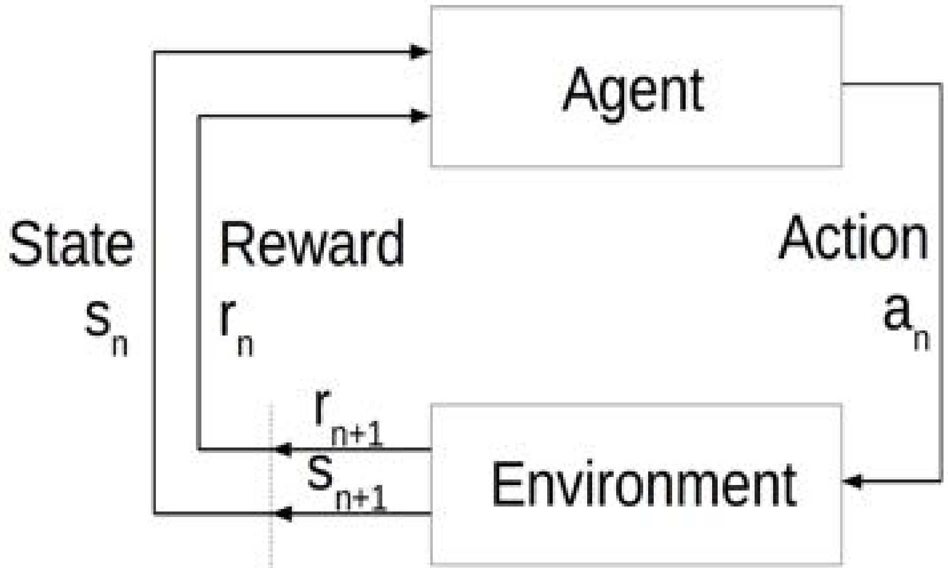


SMART INFLATABLE/DEFLATABLE INERTIAL PARTICLES IN COMPLEX FLOWS

POLICY $\pi : s \to a$

$$\begin{cases} \beta = \frac{3\rho_f}{\rho_f+2\rho} & \to \frac{3\rho_f}{\rho_f+2\rho[\mathbf{w},T,c,\dots]} \\ \tau = \frac{r^2}{3\nu\beta} & \to \frac{r^2[\mathbf{w},T,c,\dots]}{3\nu\beta[\mathbf{w},T,c,\dots]} \end{cases}$$





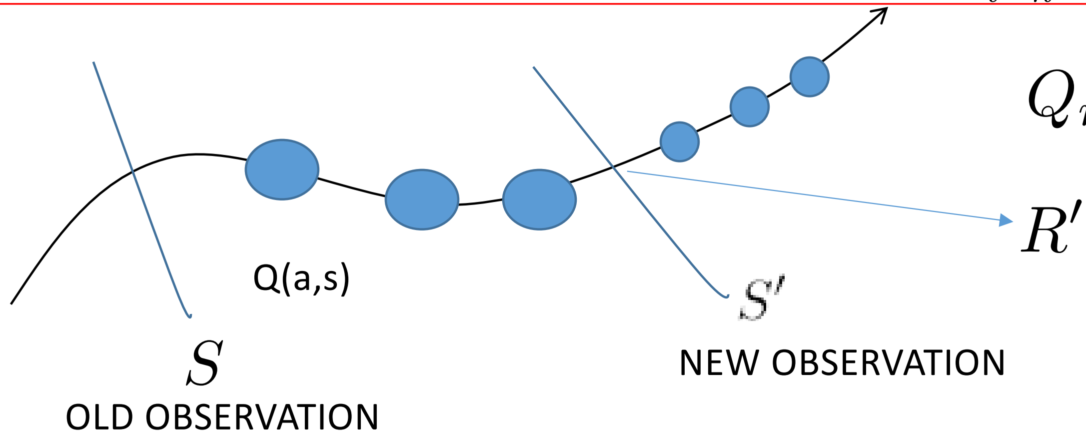
<u>Reinforcement learning</u> is a framework to find a good (optimal) POLICY for achieving given long-term tasks. It is widely used in artificial intelligence and machine learning. It is based on the interaction between a decision-maker (in our case the inertial particle) and the environment. The decision maker can change its behaviour in response to inputs from the system (in our case the flow). By trial and error the decision maker progressively learns how to behave optimally.

S. Colabrese, K. Gustavsson, A. Celani and L. B. Smart Inertial Particles. PRF 3, 084301 (2018)

S. Colabrese, K. Gustavsson, A. Celani and L. B. Flow navigation by smart microswimmers via reinforcement learning. Phys. Rev. Lett. 118 (15), 158004 (2017)

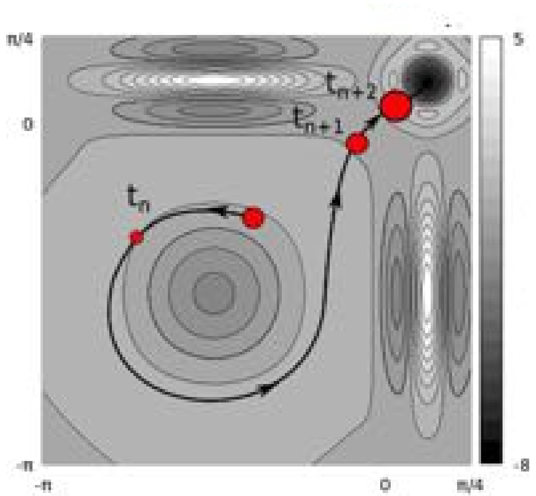
Sutton Barto (2017. Reinforcement Learning: An Introduction. (Cambridge University Press, 2017)

$$Q_n(s_i, a_j) = R_n + \gamma R_{n+1} + \gamma^2 R_{n+2} + \gamma^3 R_{n+3} + \cdots = \sum_{t=n}^{\infty} \gamma^t R_t$$

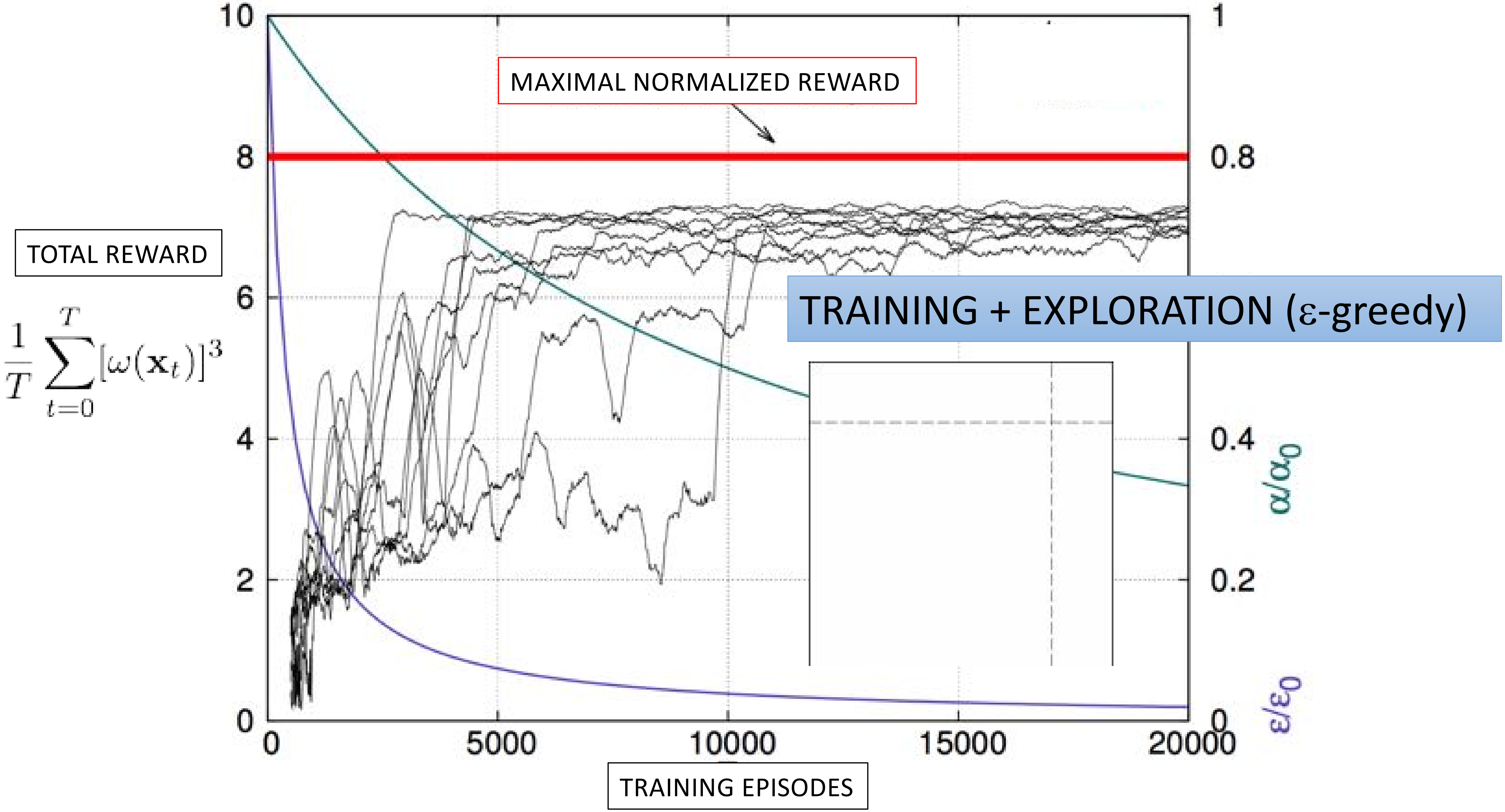


$$Q_n(s, a) = R_n + \gamma Q_{n+1}(s', a')$$

$$Q(s, a) \leftarrow Q(s, a) + \alpha[R' + \gamma \max_{a'} Q(s', a') - Q(s, a)]$$

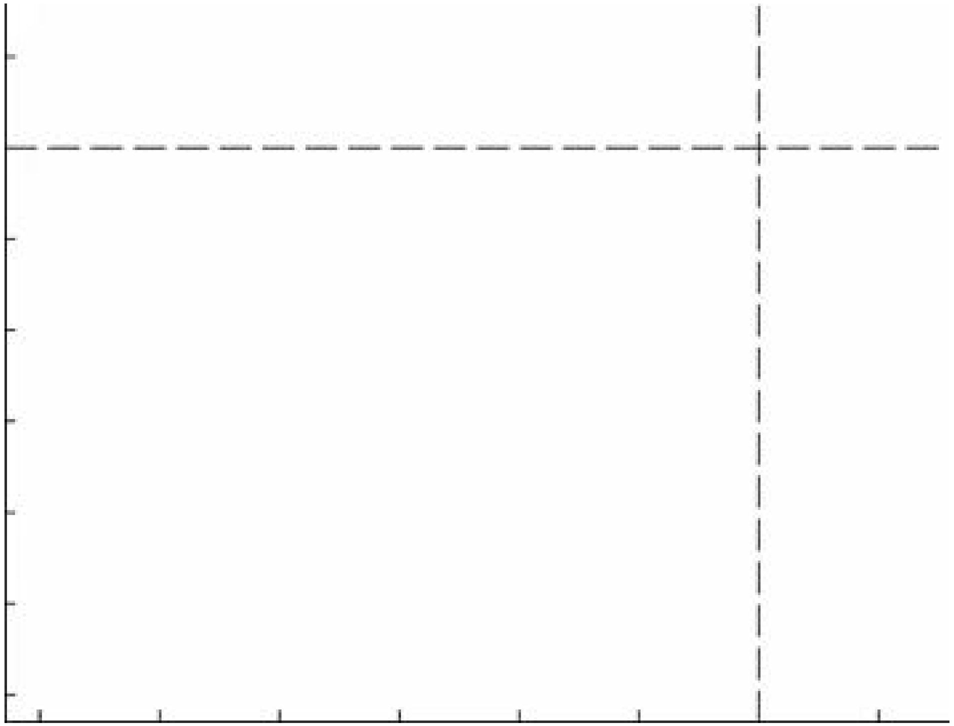


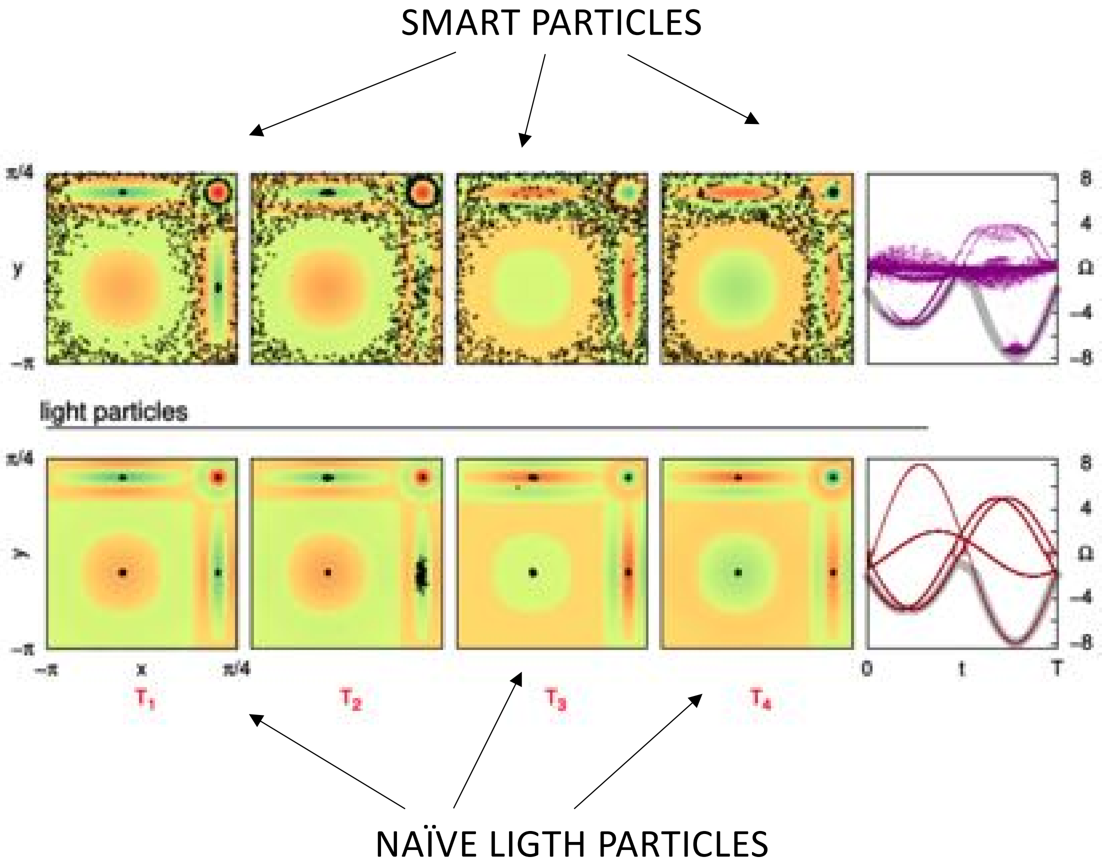
$$\pi_n \longrightarrow \pi_{n+1} \longrightarrow \cdots \pi_{opt}$$



MAXIMAL NORMALIZED REWARD
TOTAL REWARD
$\frac{1}{T}\sum_{t=0}^{T}[\omega(\mathbf{x}_t)]^3$
TRAINING + EXPLORATION (ε-greedy)
TRAINING EPISODES
α/α_0
$\varepsilon/\varepsilon_0$
0
2
4
6
8
10
0
0.2
0.4
0.8
1
0
5000
10000
15000
20000

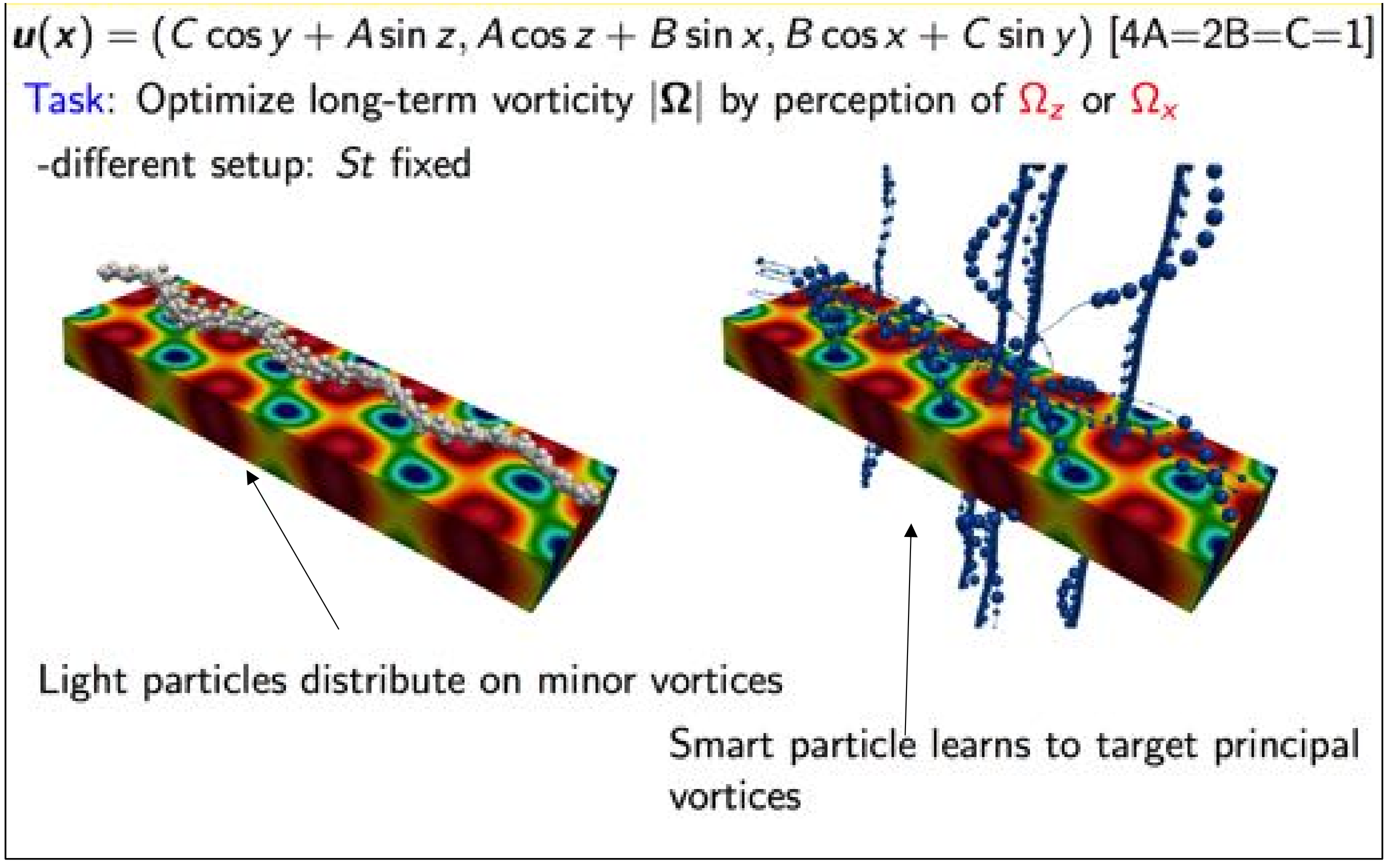
SMART INERTIAL PARTICLES TRAINED TO FOLLOW HIGHEST VORTICITY REGION IN A TIME DEPENDENT FLOW

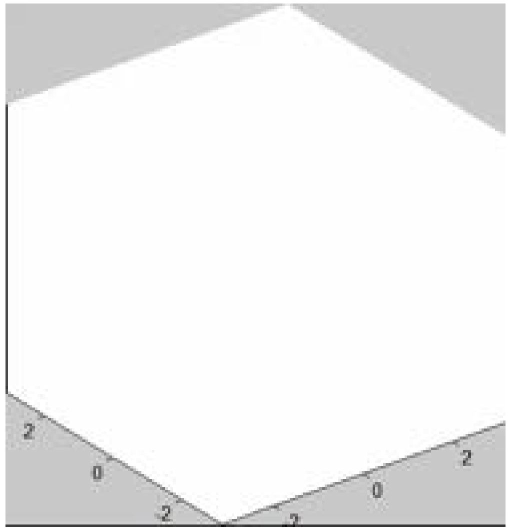




S. Colabrese, K. Gustavsson, A. Celani and L. B. Smart Inertial Particles. PRF 3, 084301 (2018)

ASYMMETRIC ABC FLOW





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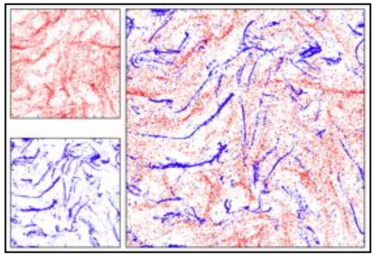
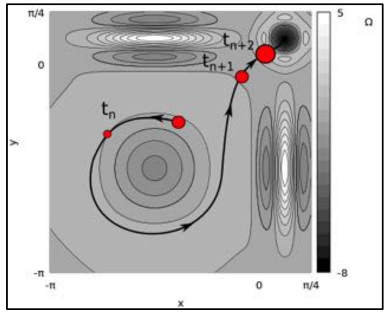
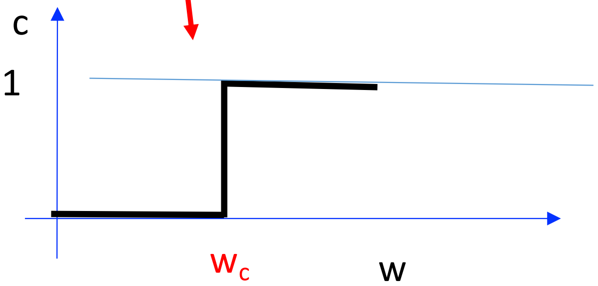


SMART LAGRANGIAN PROBES (TWO-WAY COUPLING): DRAG/PENALIZATION TERM ON INTENSE VORTICITY STRUCTURES



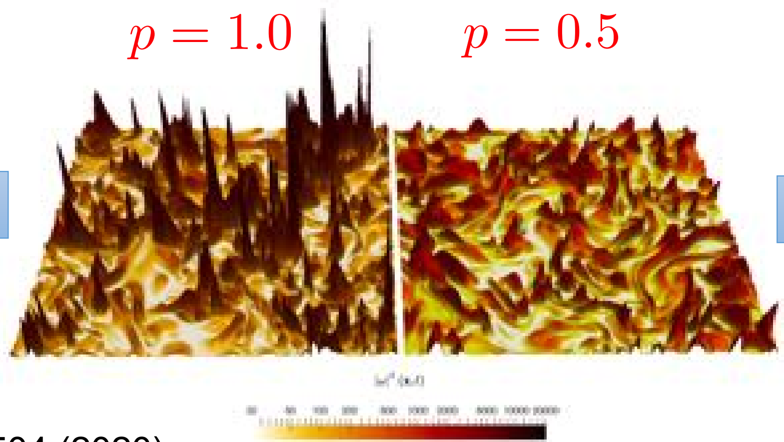
$$\begin{cases} \partial_t \boldsymbol{u}(\boldsymbol{x},t) & = \boldsymbol{u}(\boldsymbol{x},t)\cdot\nabla\boldsymbol{u}(\boldsymbol{x},t) + \nu\Delta\boldsymbol{u}(\boldsymbol{x},t) + \boldsymbol{f}(\boldsymbol{x},t) - c(\boldsymbol{x},t)\boldsymbol{u}(\boldsymbol{x},t) \\ \nabla\cdot\boldsymbol{u}(\boldsymbol{x},t) & = 0, \end{cases}$$



$$\omega_c = p\,\omega_{MAX}$$

$$c(\boldsymbol{x},t) = \beta\,\frac{\tanh[(\omega_c - \omega(\boldsymbol{x},t))] + 1}{2}.$$

NO-CONTROL



CONTROL

M Buzzicotti, L Biferale, F Toschi
Physical Review Letters 124 (8), 084504 (2020)

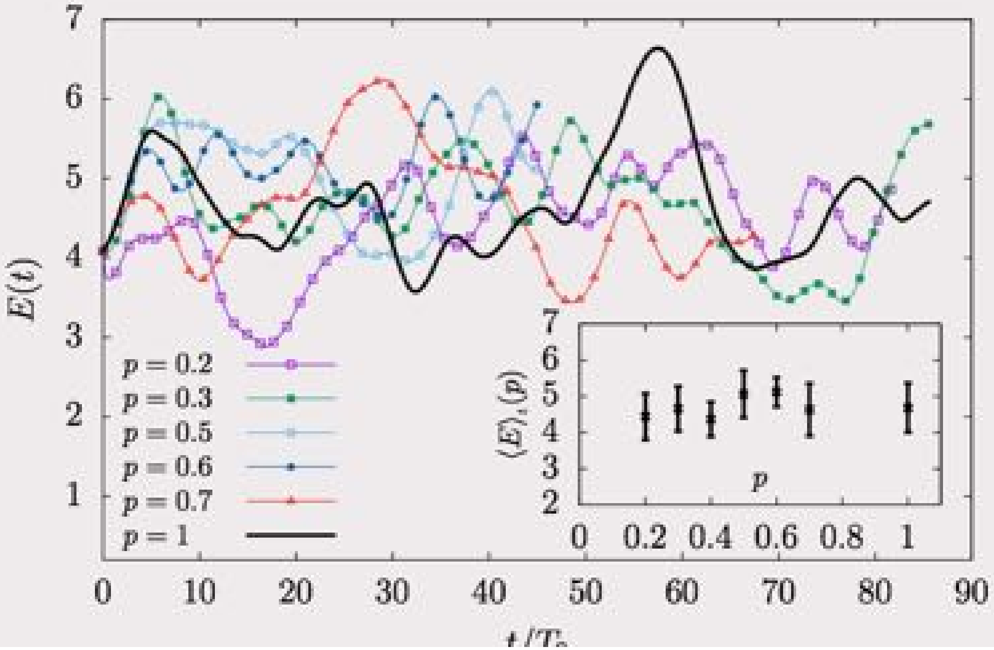
Navier Stokes, with small scale forcing

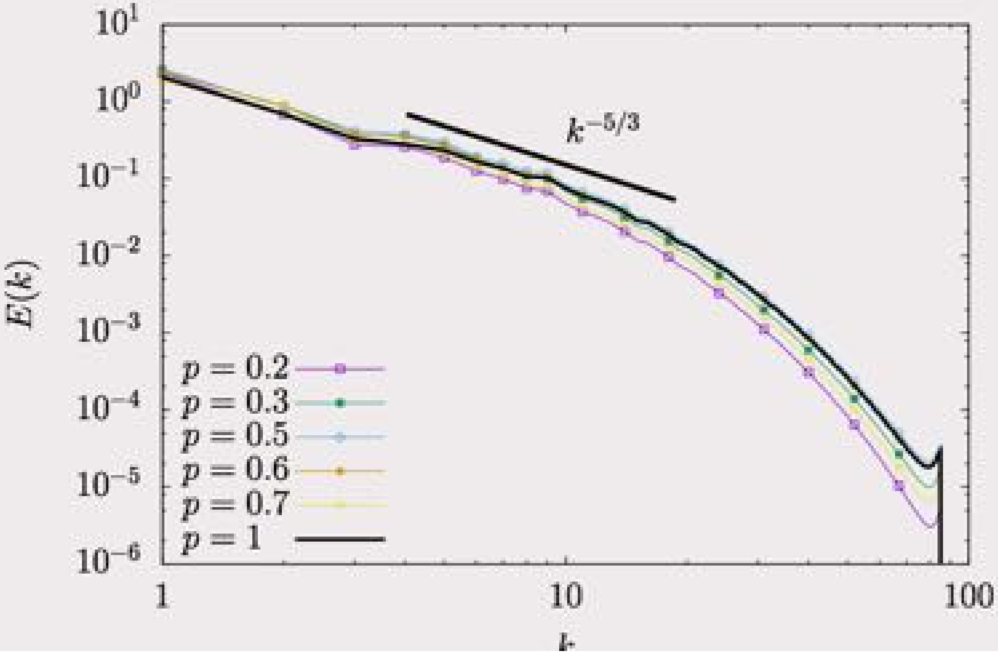
Control	N	β	c	k_f	ε_f	f_0	τ_f	ν
Off	256	-	-	$[0.5:1.5]$	2.2	0.16	0.6	5.2×10^{-3}
Off	1024	-	-	$[0.5:2.5]$	5.5	0.14	0.23	8×10^{-4}
On	256	$[0.1\div50]$	$[0.1\div0.7]$	$[0.5:1.5]$	2.2	0.16	0.6	5.2×10^{-3}
On	1024	50	$[0.05\div0.6]$	$[0.5:2.5]$	5.5	0.14	0.23	8×10^{-4}

$$\frac{1}{2}\partial_t\langle \boldsymbol{u}^2\rangle = \nu\langle\Delta\boldsymbol{u}^2\rangle - \langle c\,\boldsymbol{u}^2\rangle + \langle \boldsymbol{u}\cdot\boldsymbol{f}\rangle$$

$$\begin{cases} E(t) = & \frac{1}{2}\langle \boldsymbol{u}^2\rangle \\ \varepsilon_\nu(t) = & \nu\langle\Delta\boldsymbol{u}^2\rangle \\ \varepsilon_c(t) = & \langle c\,\boldsymbol{u}^2\rangle \\ \varepsilon_f(t) = & \langle \boldsymbol{u}\cdot\boldsymbol{f}\rangle \end{cases}$$

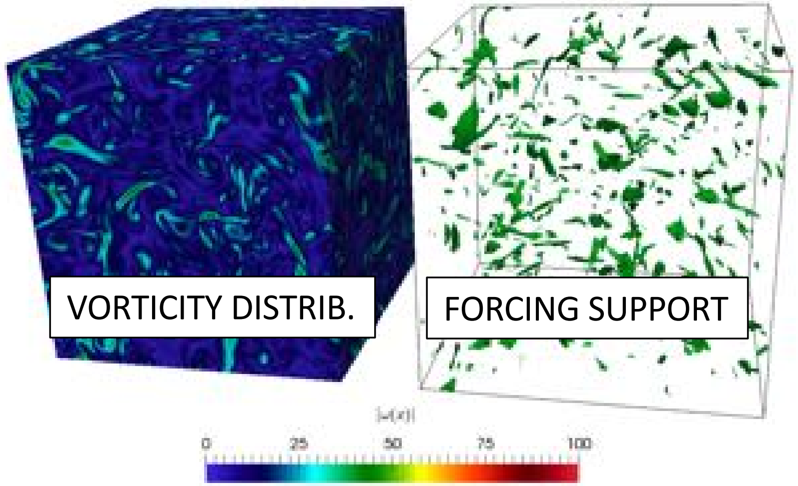
Energy and energy spectra



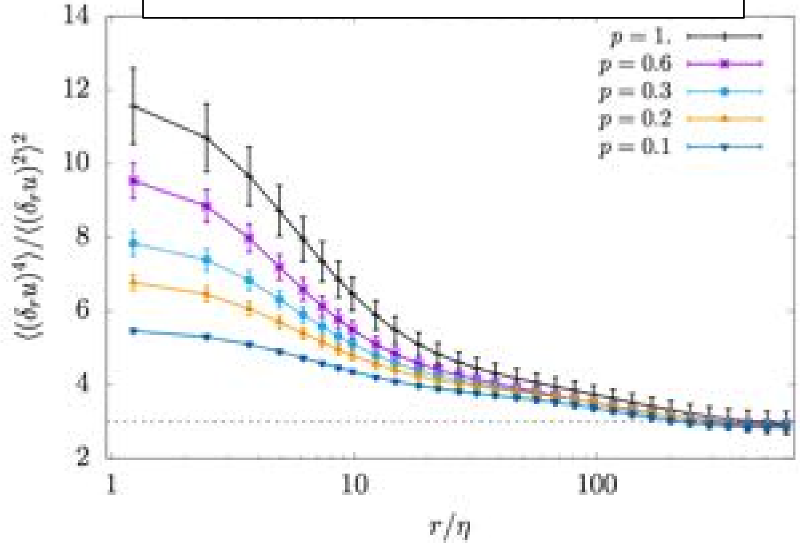


TAMING EXTREME EVENTS BY AD-HOC LAGRANGIAN DISSIPATION

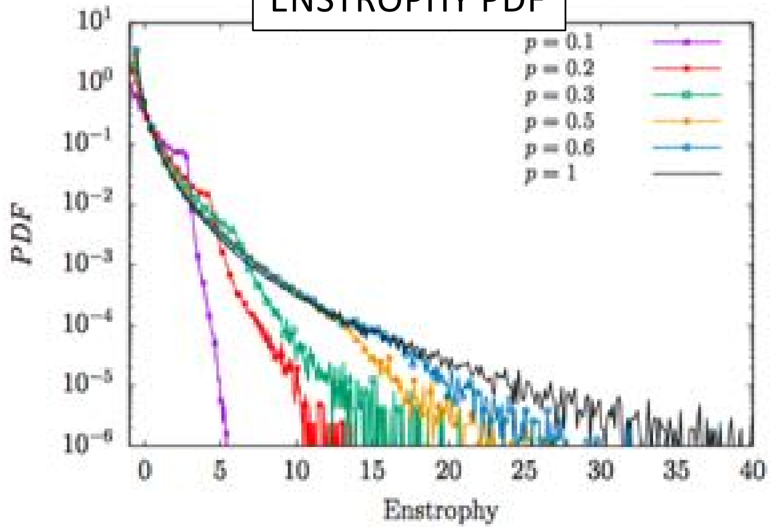
WITH M. BUZZICOTTI AND F. TOSCHI
[UNPUBLISHED]



FLATNESS VELOCITY INCREMENTS

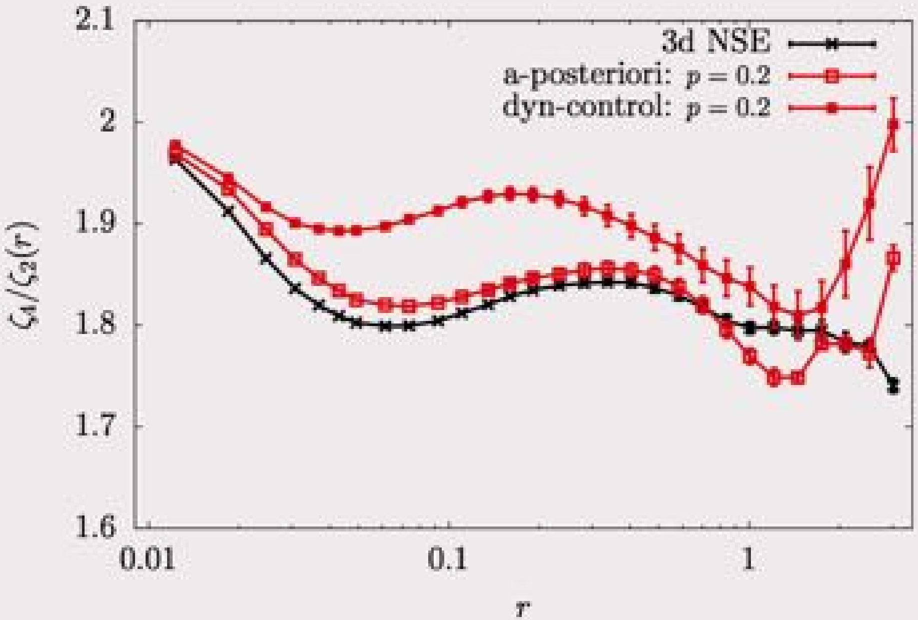


ENSTROPHY PDF

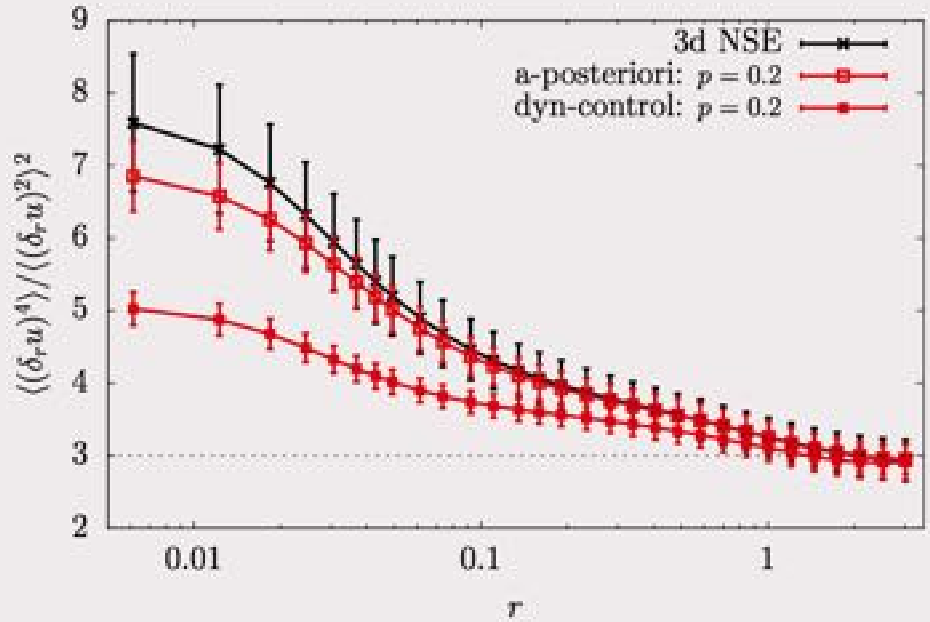


Intermittency

Structure functions (local slopes)



Flatness

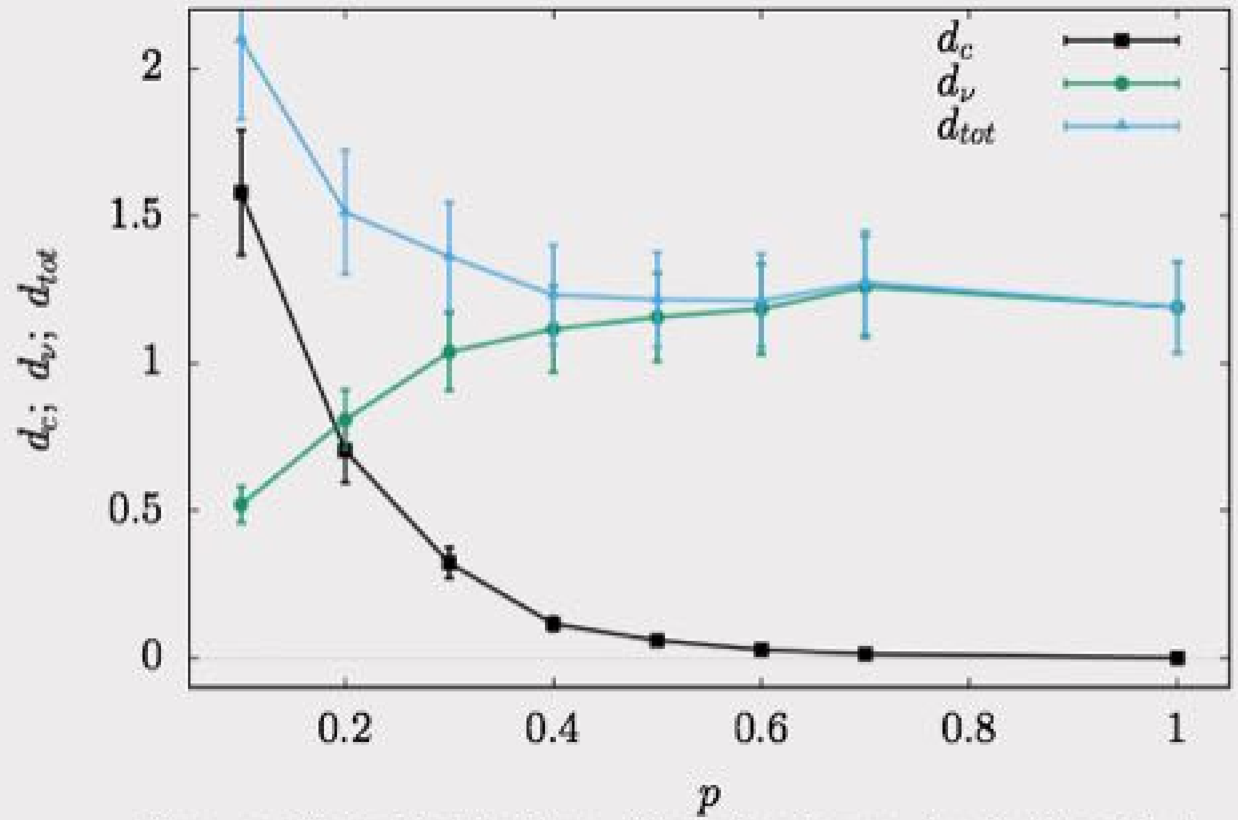


Drag reduction?

$$d_\nu = \frac{\varepsilon_\nu \; L_0}{\boldsymbol{u}_{rms}^3}$$

$$d_c = \frac{\varepsilon_c \; L_0}{\boldsymbol{u}_{rms}^3}$$

$$d_{tot} = \frac{(\varepsilon_c + \varepsilon_\nu) \; L_0}{\boldsymbol{u}_{rms}^3}$$



Drag coefficient for the three dissipative terms, due to viscosity d_ν (green line), control term on small scales d_c (black line), and sum of the two d_{tot} (cyan line). Results are shown as a function of the threshold $\omega_c = p\ \omega_{max}$ for the $N = 256^3$ simulations with a small-scales forcing amplitude $\beta = 5$.

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