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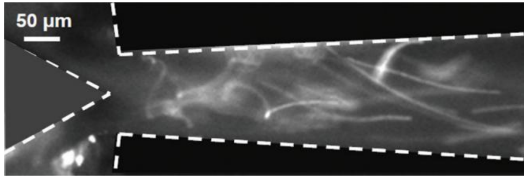
TURBO 3D: Complex flows and Lagrangian observables.

Victor de J. Valadão

University of Turin

Perugia - 27th May 2025.

Brief Review on 3D turbulence



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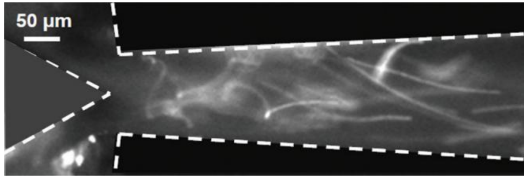

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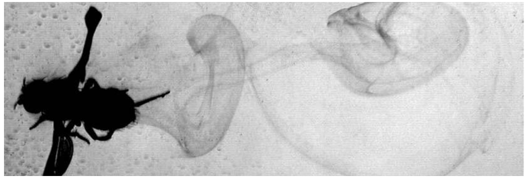

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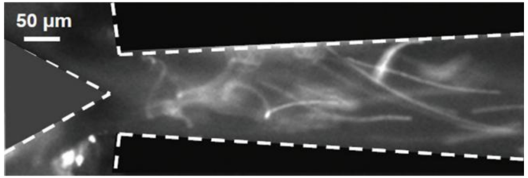

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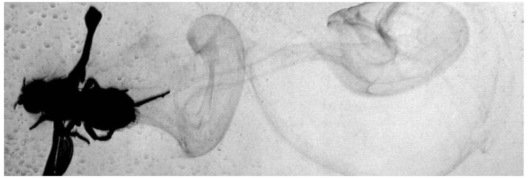

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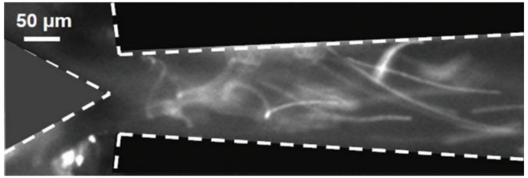

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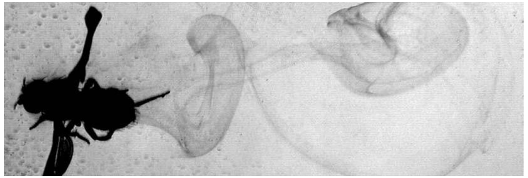

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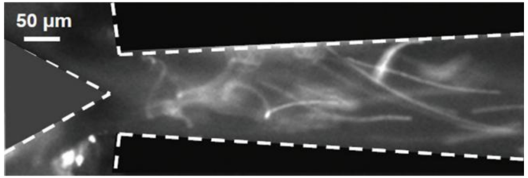

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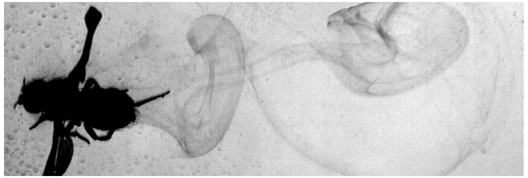

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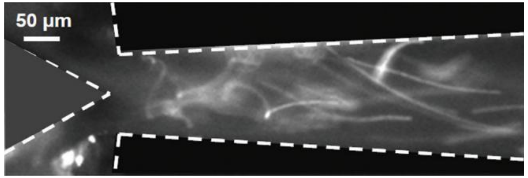

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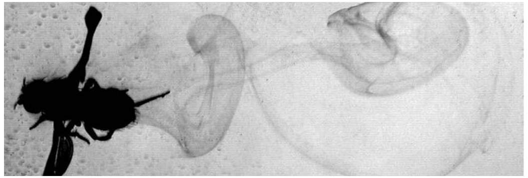

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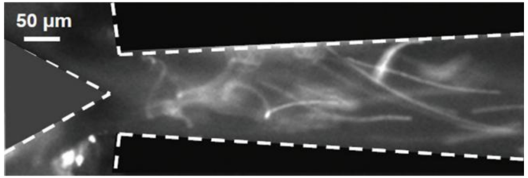

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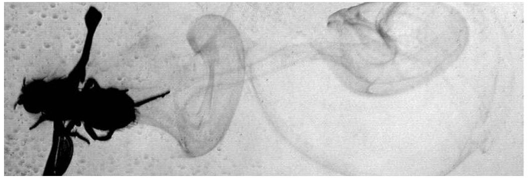

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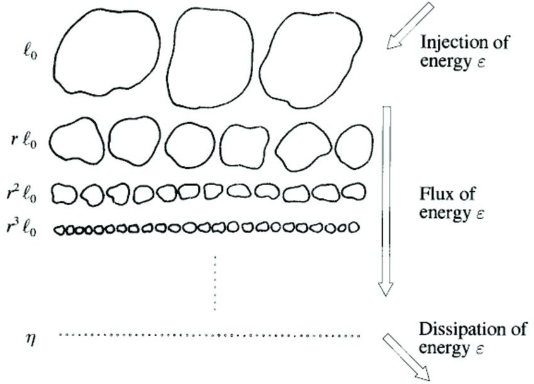

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Andrey N. Kolmogorov

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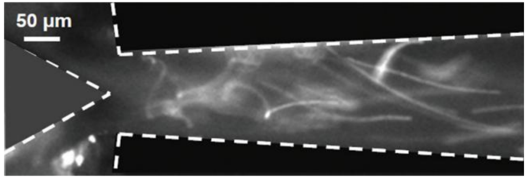

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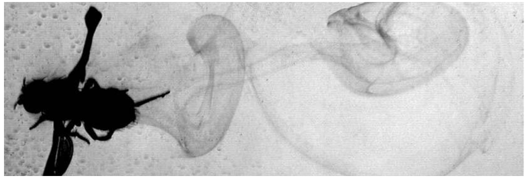

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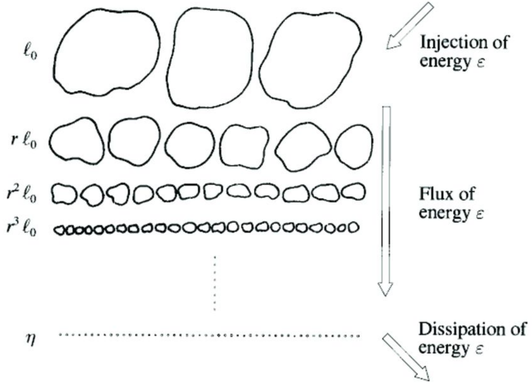

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$$E(k) = \frac{\langle |\vec{v}_k|^2 \rangle}{2} \propto \varepsilon^{2/3} k^{-5/3}$$

$$\ell_f^{-1} < k < \eta_\kappa^{-1}$$

$$\eta_\kappa = \left(\frac{\nu^3}{\varepsilon}\right)^{1/4}$$

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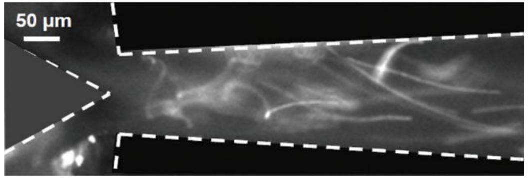

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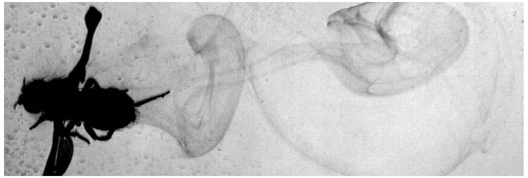

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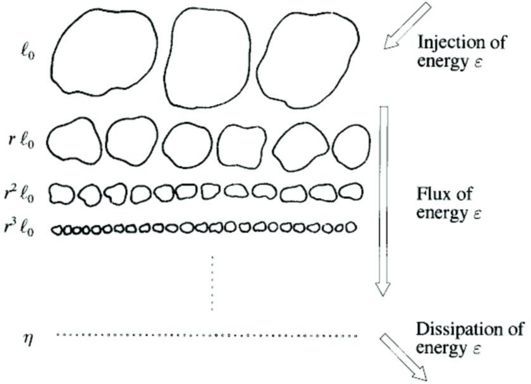

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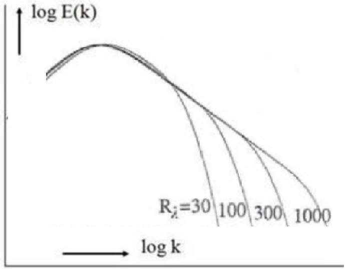

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Pseudospectral approach

Pseudospectral approach

- Solves NSE in the Fourier space;
- Linearity is easily solvable;
- Non-linear part is calculated in the physical space;
- Requires a succession of FFTs at each step;

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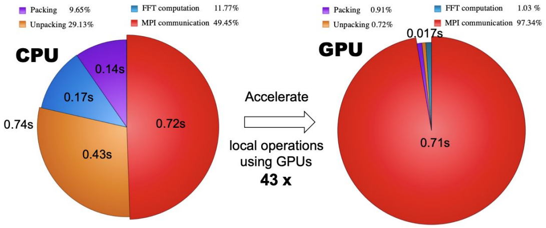

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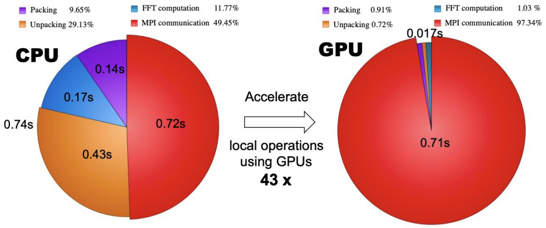

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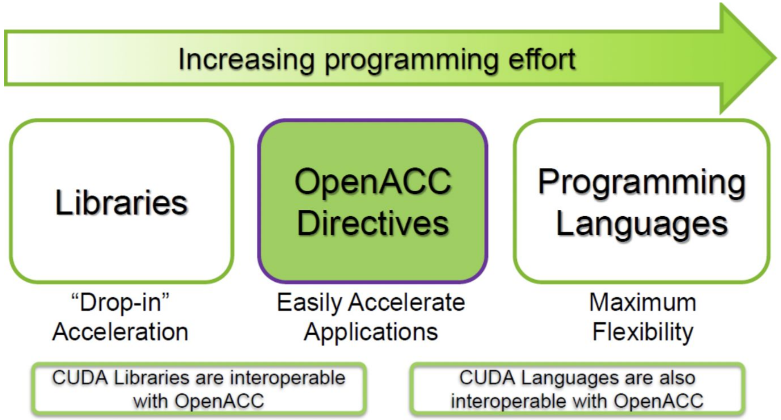

Chen S., *"Introduction to OpenACC"* (2016) @ bu.edu

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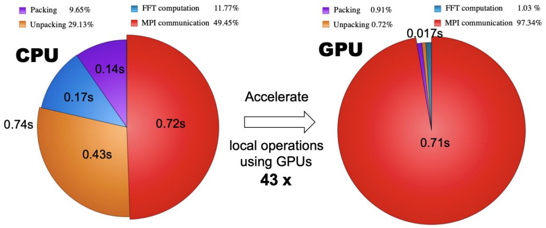

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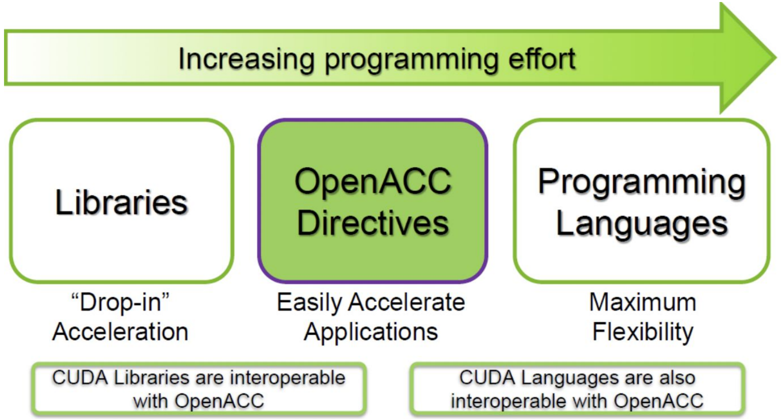

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```fortran
!$acc parallel loop collapse(2) present(z, u, v, fkx, fky)
do j=1,NY
do i=1,NX2P1
  z(1,i,j)=+fkx(i)*u(2,i,j)+fky(j)*v(2,i,j)
  z(2,i,j)=-fkx(i)*u(1,i,j)-fky(j)*v(1,i,j)
end do
end do
!$acc end parallel loop
```

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Turbo 2D

$$\partial_t \omega + v_i \partial_i \omega + (-1)^n \nu \partial^{2n} \omega + (-1)^m \mu \partial^{2m} \omega = F$$

$$v_i = \epsilon_{ij} \partial_j \psi \qquad \hat{\omega}(k,t) = k^\alpha \hat{\psi}(k,t)$$

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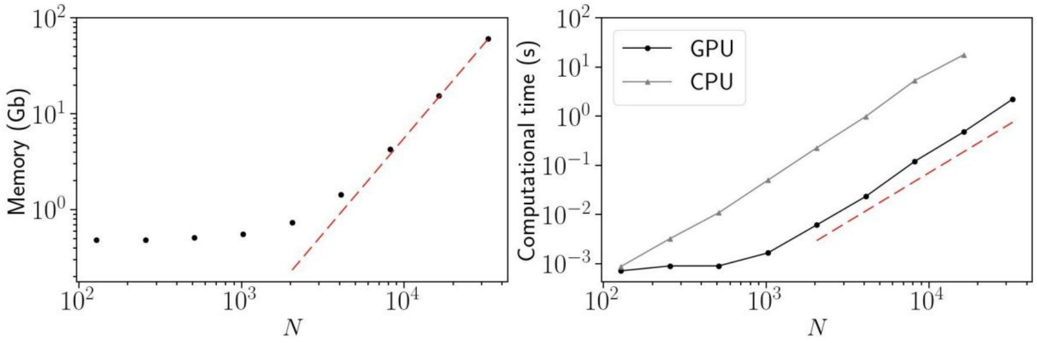

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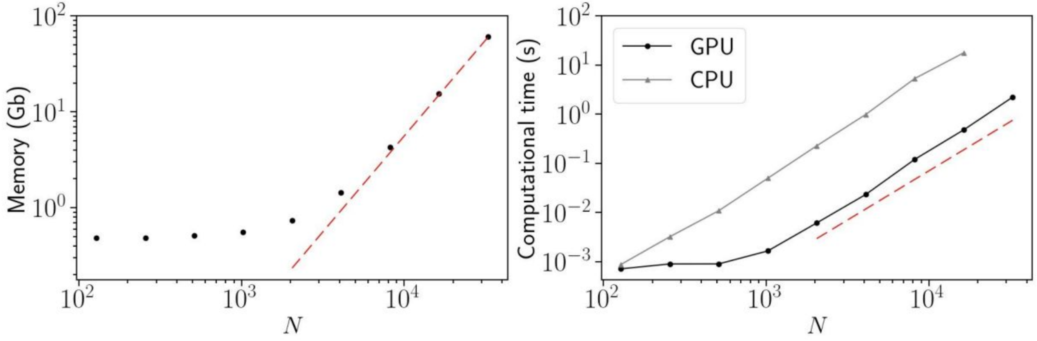

Up to N^2=(32768)^2

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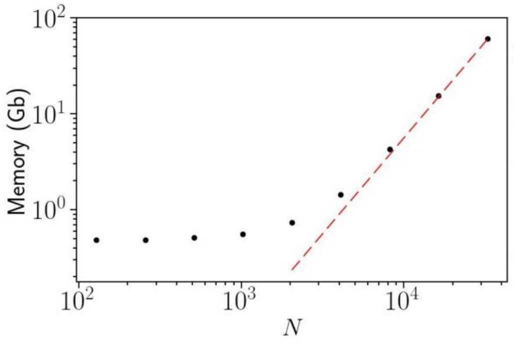

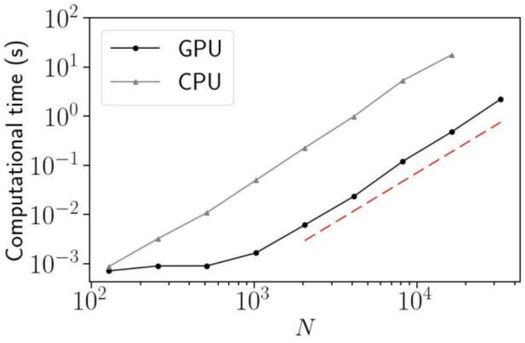

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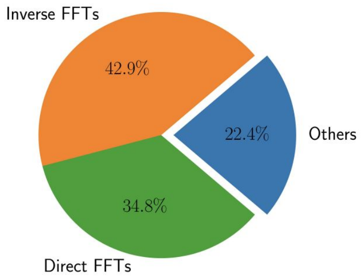

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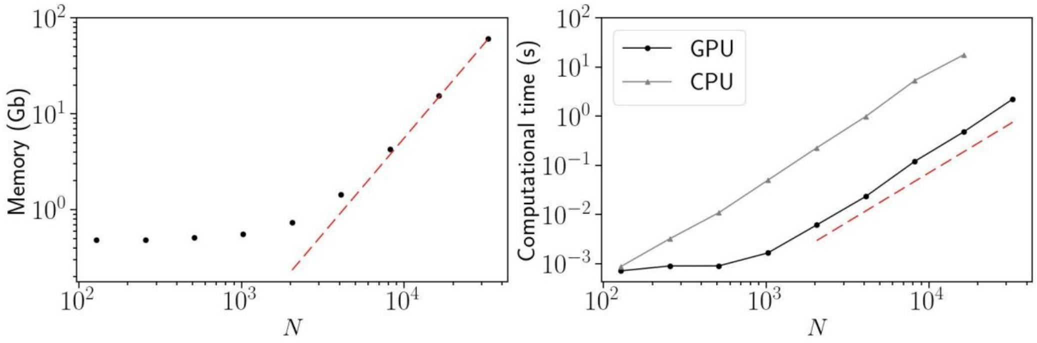

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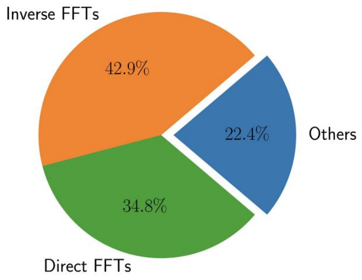

Functionalities:

- Simulation of Generalized active Transport Equations;
- Simulation of Passive scalar transport;
- Eulerian Predictability simulation;
- Lagrangian Predictability Simulation; (NEW)
- Inertial Particles. (UNDER DEV)

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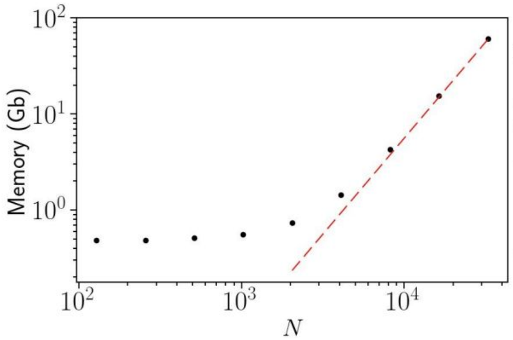

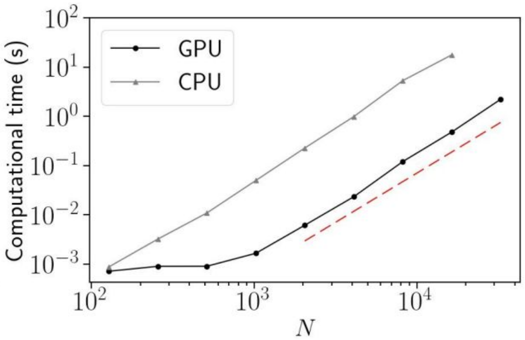

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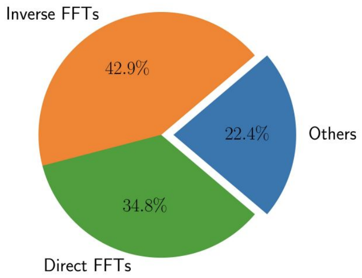

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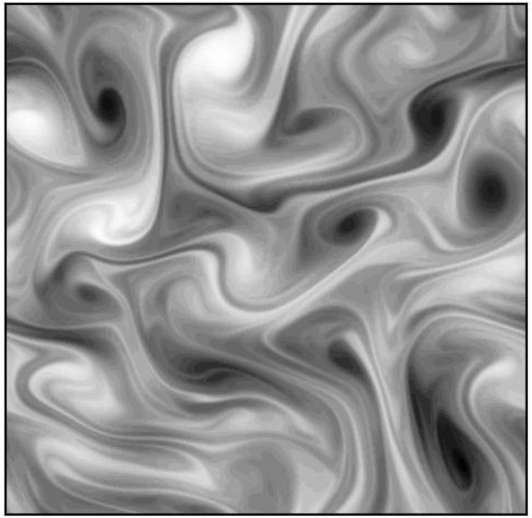
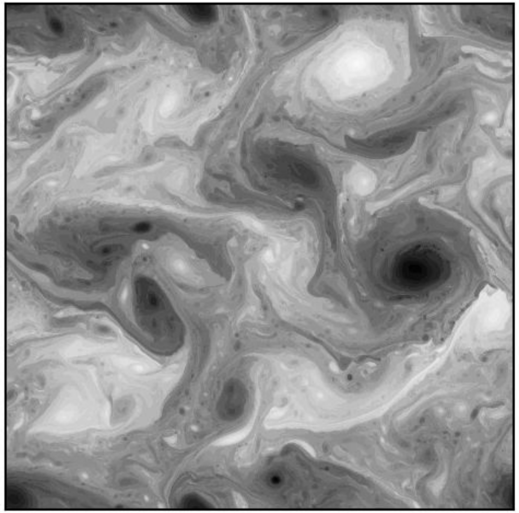
Papers

1. V. J. Valadão, T. Ceccotti, G. Boffetta, and S. Musacchio, Phys. Rev. Fluids 9, 094601. 2024.
2. Valadão V. J., Boffetta G., De Lillo F., Musacchio S., and Crialesi-Esposito M.; Journal of Turbulence, 1-10. 2025.
3. V.J. Valadão, F. De Lillo, S. Musacchio, G. Boffetta. ArXiv preprints: arXiv:2504.07914. 2025 (Under Review at Journal of Fluid. Mech.).

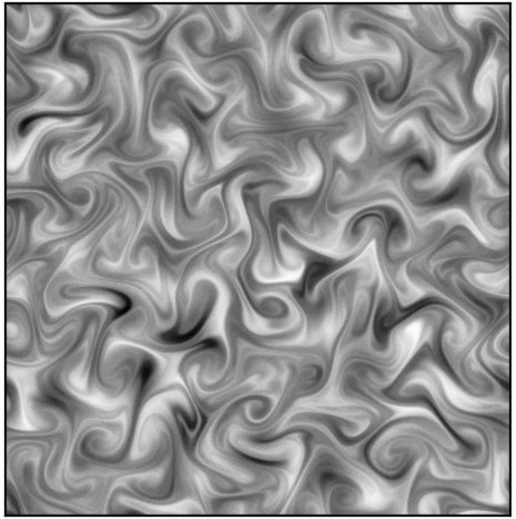
Some nice images



Navier-Stokes Turbulence

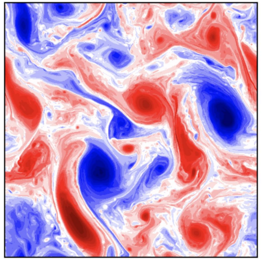


Surface Quasi-geostrophic Turbulence



Passive-scalar advection

Eulerian x Lagrangian Predictability



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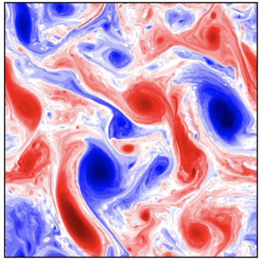
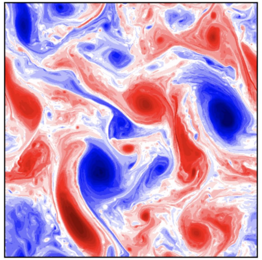


θ' θ

Eulerian x Lagrangian Predictability



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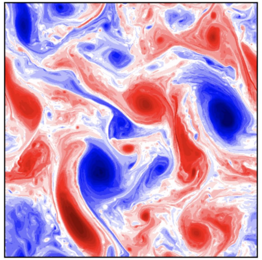

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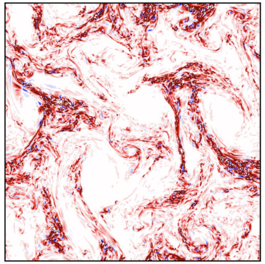

θ' θ $\mathcal{O}(\delta \ll \sqrt{E})$

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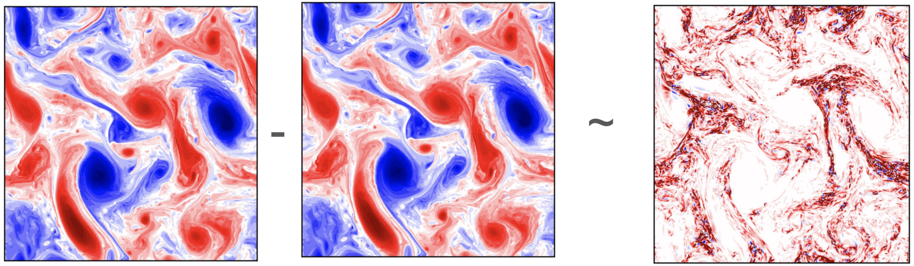
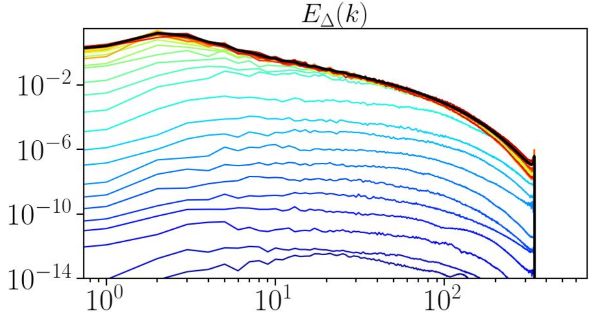


θ' - θ ~ $\mathcal{O}(\delta \ll \sqrt{E})$



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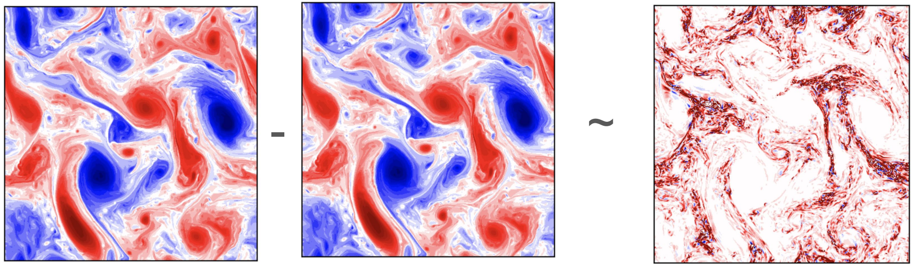

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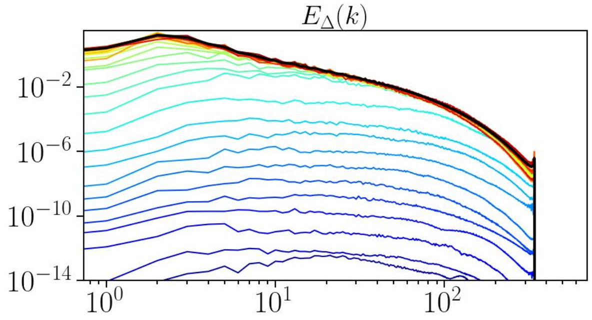

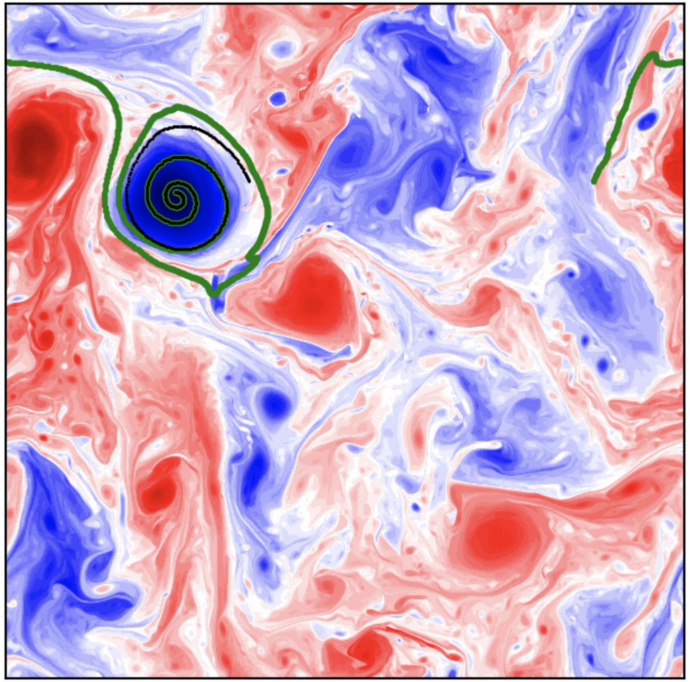

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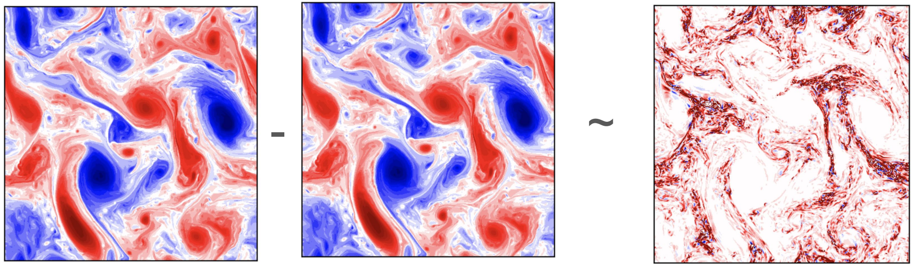
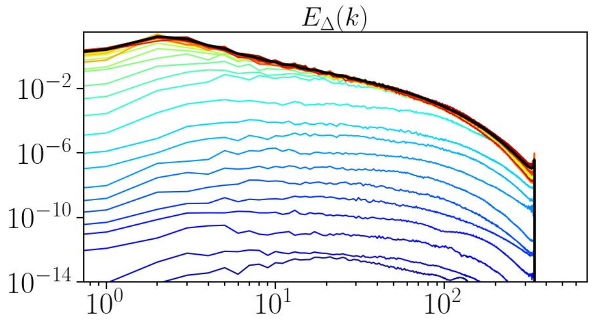
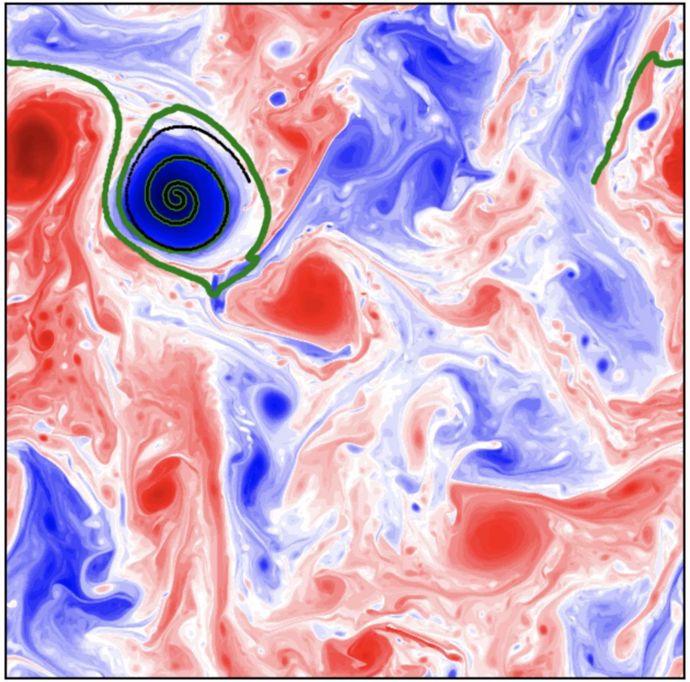


$$\theta' \quad - \quad \theta \quad \sim \quad \mathcal{O}(\delta \ll \sqrt{E})$$



$$\dot{\boldsymbol{v}}_p = \frac{\boldsymbol{u}(\boldsymbol{x}_p(t), t) - \boldsymbol{v}_p(t)}{\tau_s} . \qquad \epsilon = \frac{\rho_0}{\rho_p} \qquad \tau_s = \frac{2R_p^2}{9\nu\epsilon}$$



Turbo 3D

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- Requires a MULTI-GPU approach (memory bottleneck);
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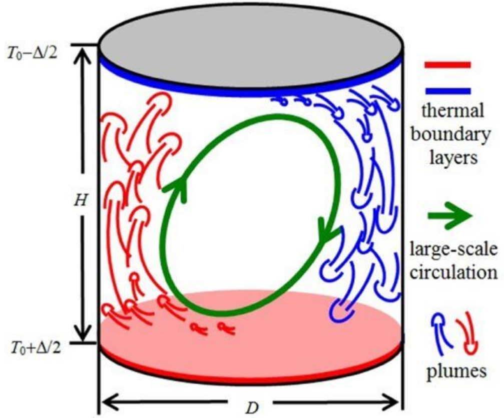

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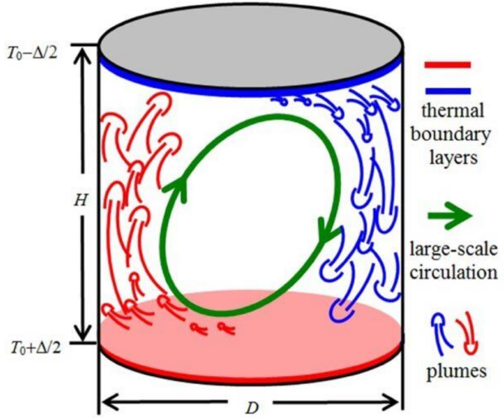

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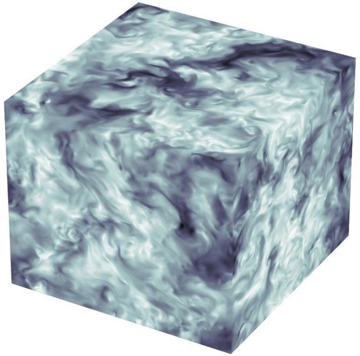
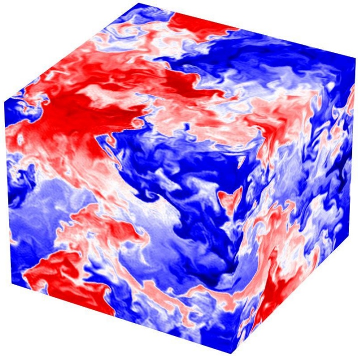
Homogeneous Rayleigh-Bénard (HRB)

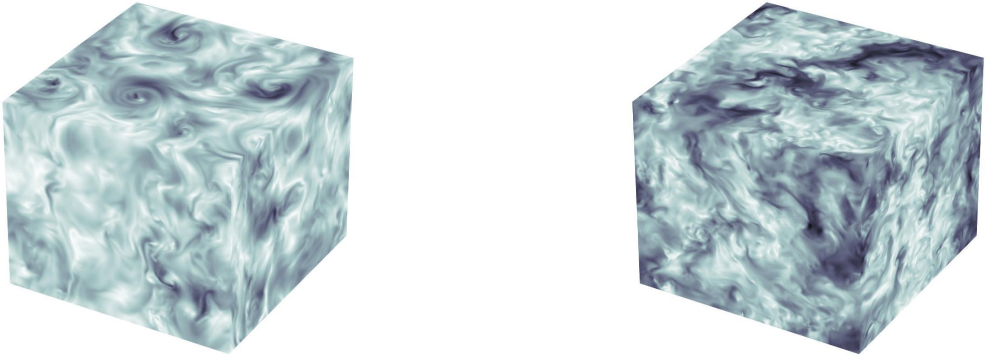
$$\partial_t \boldsymbol{v} + (\boldsymbol{v}\cdot\boldsymbol{\nabla})\boldsymbol{v} + 2\boldsymbol{\Omega}\times\boldsymbol{v} - \nu\nabla^2\boldsymbol{v} = -\boldsymbol{\nabla}P - g\frac{\delta\rho}{\rho_0}\boldsymbol{e}_z$$

$$\partial_t\delta\rho + (\boldsymbol{v}\cdot\boldsymbol{\nabla})\delta\rho - \kappa\nabla^2\delta\rho = \gamma\boldsymbol{v}\cdot\boldsymbol{e}_z$$

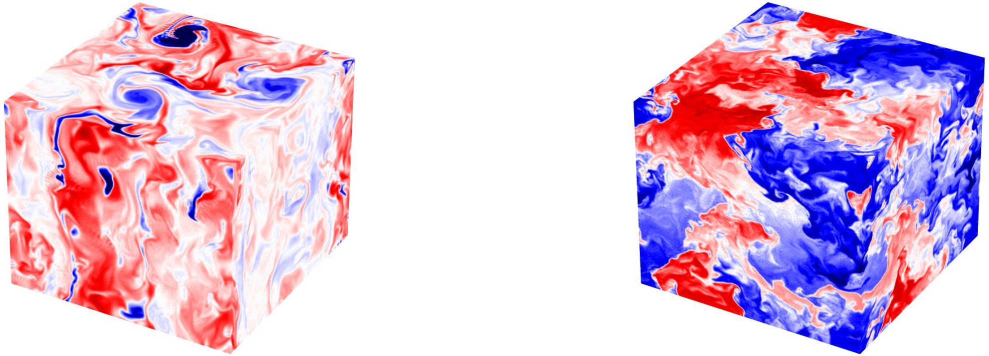


HRB





Rotating HRB



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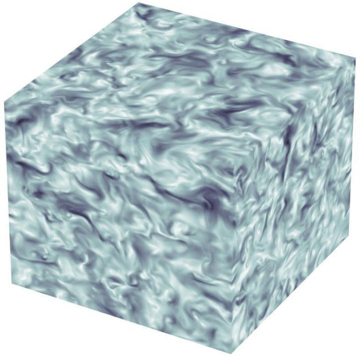
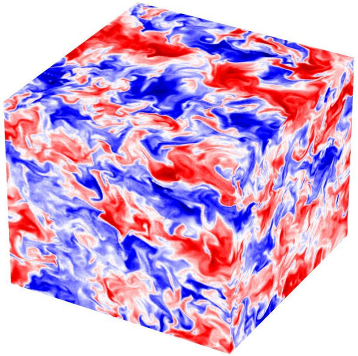
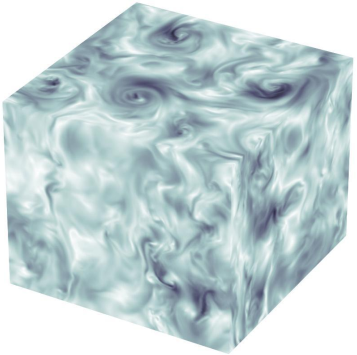


Homo & Iso Turb





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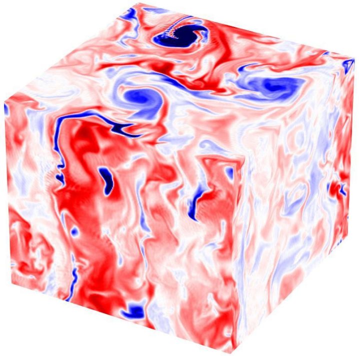
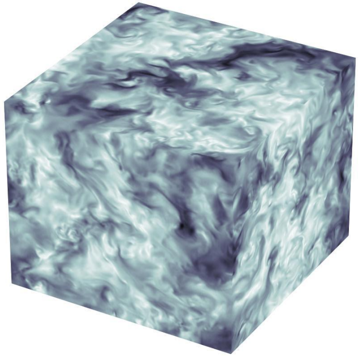
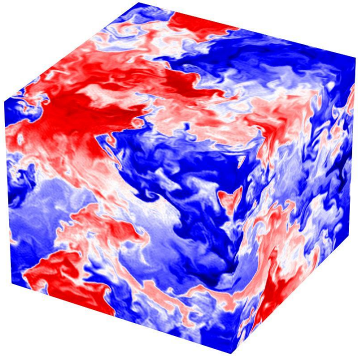




HRB



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Filippo De Lillo

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Thank you for your attention!

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