An energy pathway to dissipation: geophysical and astrophysical flows and the case of rotating stratified turbulence

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Ocean Scale Interactions: *A tribute to Bach Lien Hua*

IFREMER, June 23 2014

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Geophysical astrophysical turbulence: input & output of energy

Pathways of energy flux to large scales or to small scales

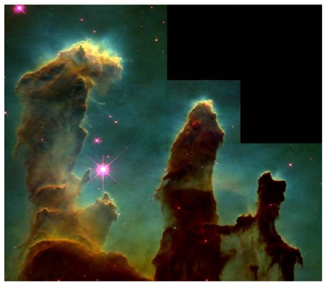
An apparent energetic paradox: where does the energy go?

Oceanic data

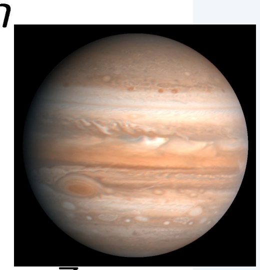
Results from large direct numerical simulations

Conclusions & perspectives

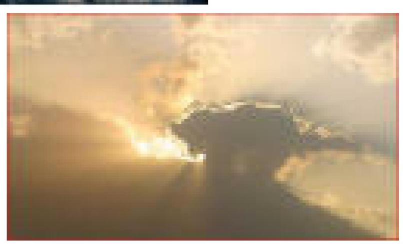
M100 galaxy 10^{23} m



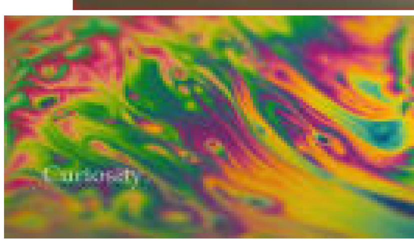
Eagle nebula 10^{18} m



Earth's atmosphere 10^{7} m



Clouds 10^{3} m

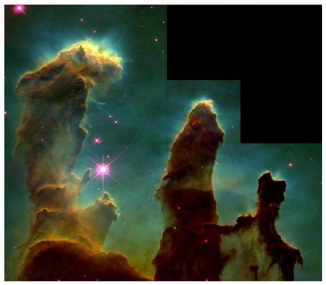


Soap film 10^{-1} m

Turbulence is observed from cosmological to quantum scales, in vastly different physical conditions with, in some instances, sizable magnetic fields, and more …

Slide after A. Celani

M100 galaxy 10^{23} m



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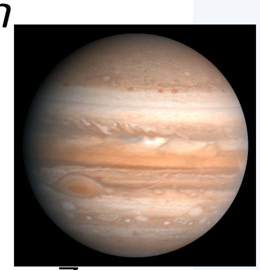

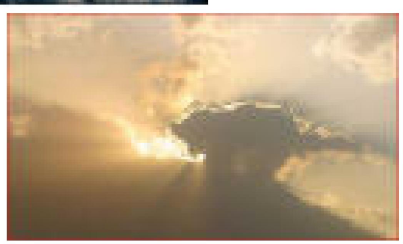

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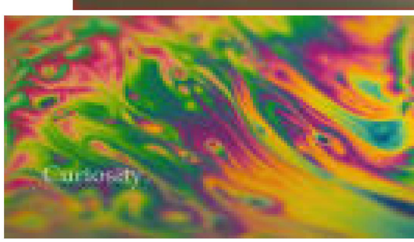
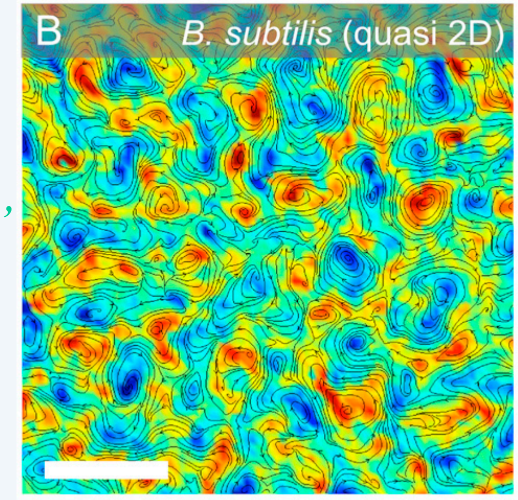


Soap film 10^{-1} m

Turbulent bacteria (Wensick et al., PNAS 2012)



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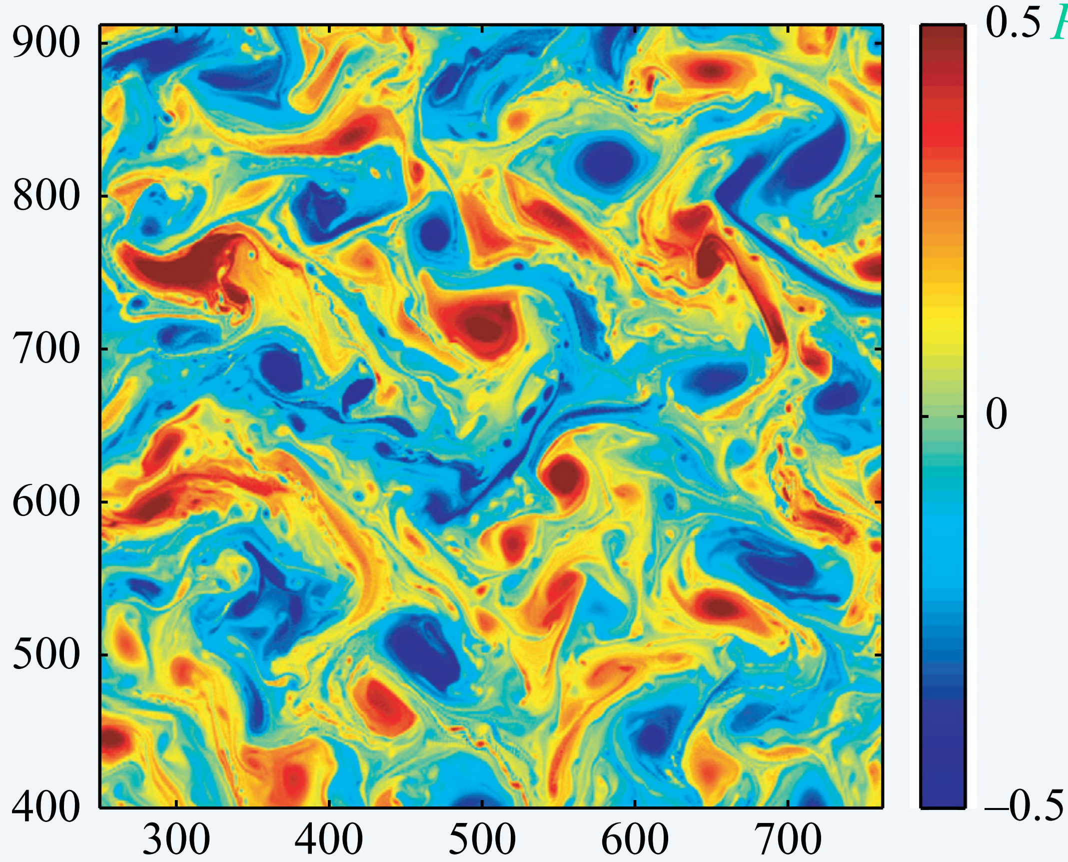
Slide after A. Celani

Surface density



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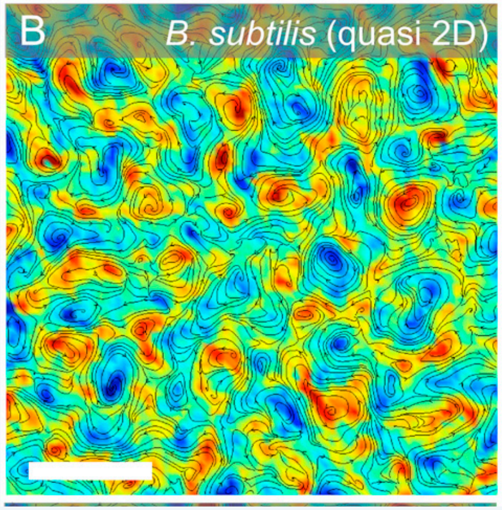


Self-organization

Capet, Klein, Hua, Lapeyre. McWilliams (2008),
"Surface kinetic energy transfer in surface quasi-geostrophic flows"

H II region in M17, excited by young hot stars

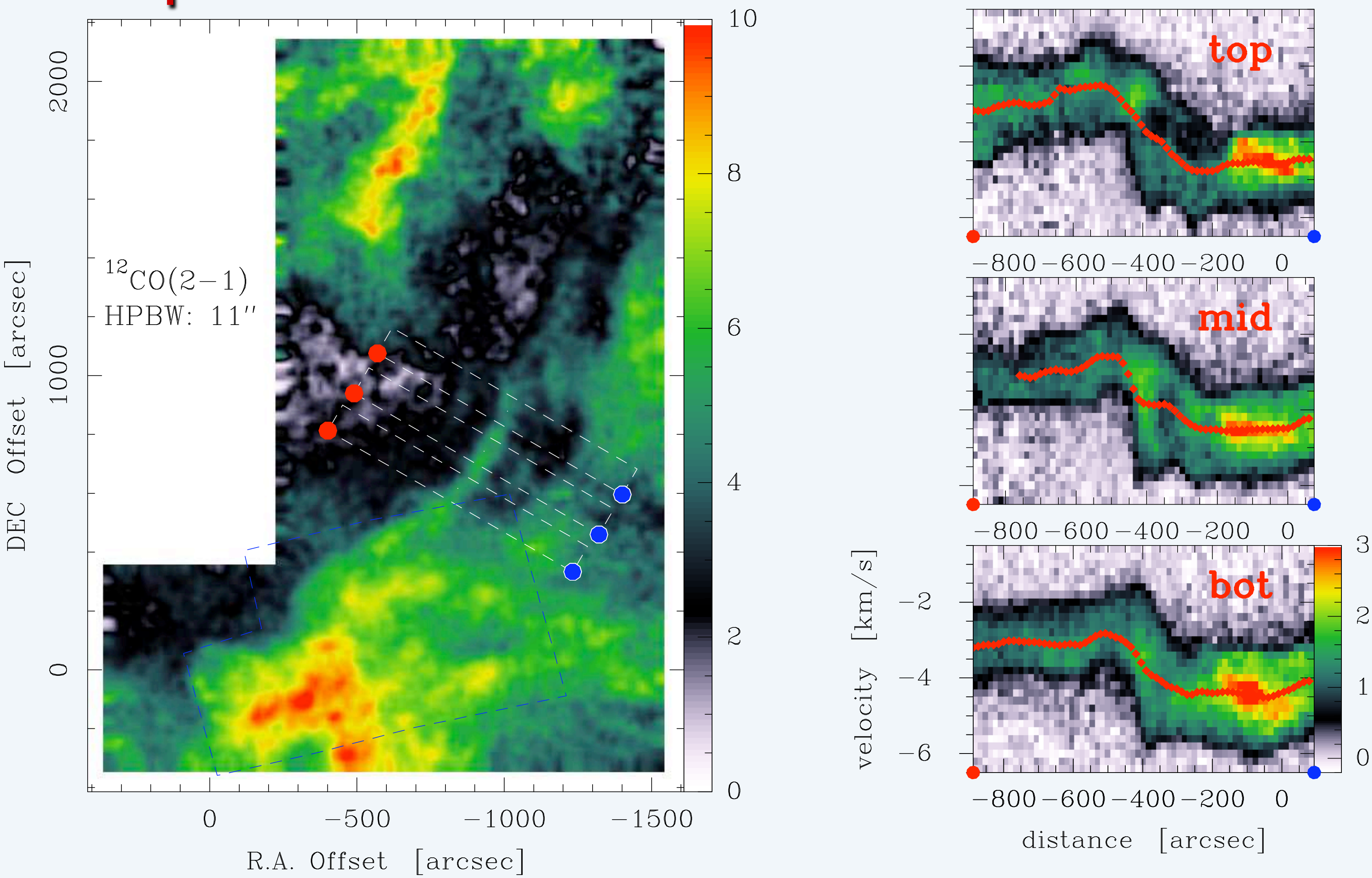
4x8.2m VLT Paranal *(ESO, Chile)*

H II region in M17, excited by young hot stars

4x8.2m VLT Paranal *(ESO, Chile)*

Angular resolution of milliarcseconds, equivalent to distinguishing the two headlights of a car at the distance of the Moon

Dissipative filaments in the interstellar medium

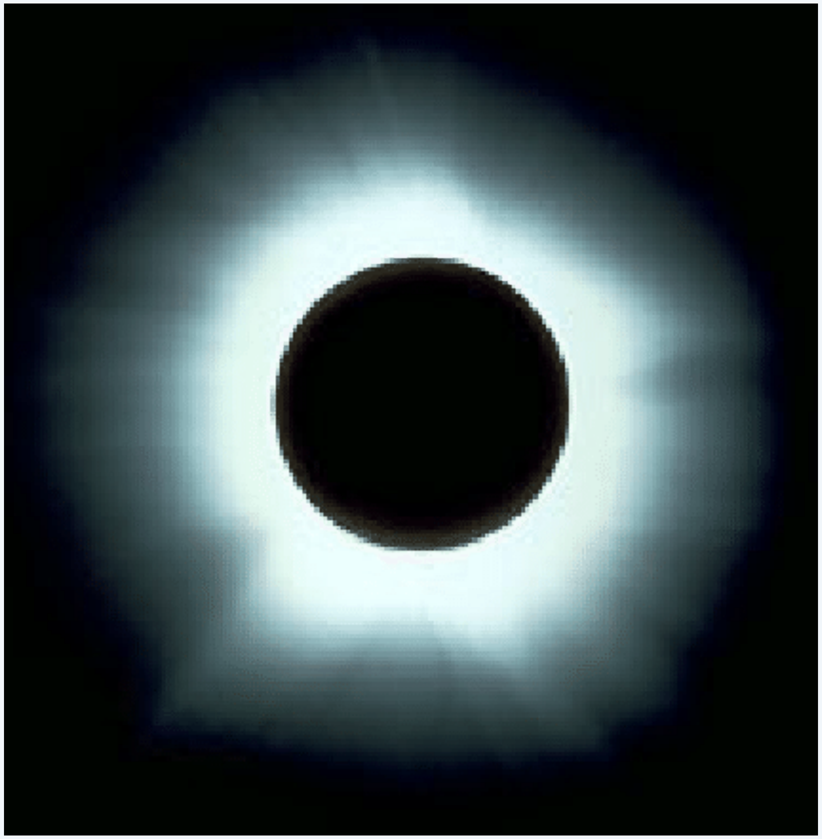


Resolution: 0.05 *km/s*, 3x10^7 x 10000 *km* (10”,10^{-2} pc) *(IRAM)*

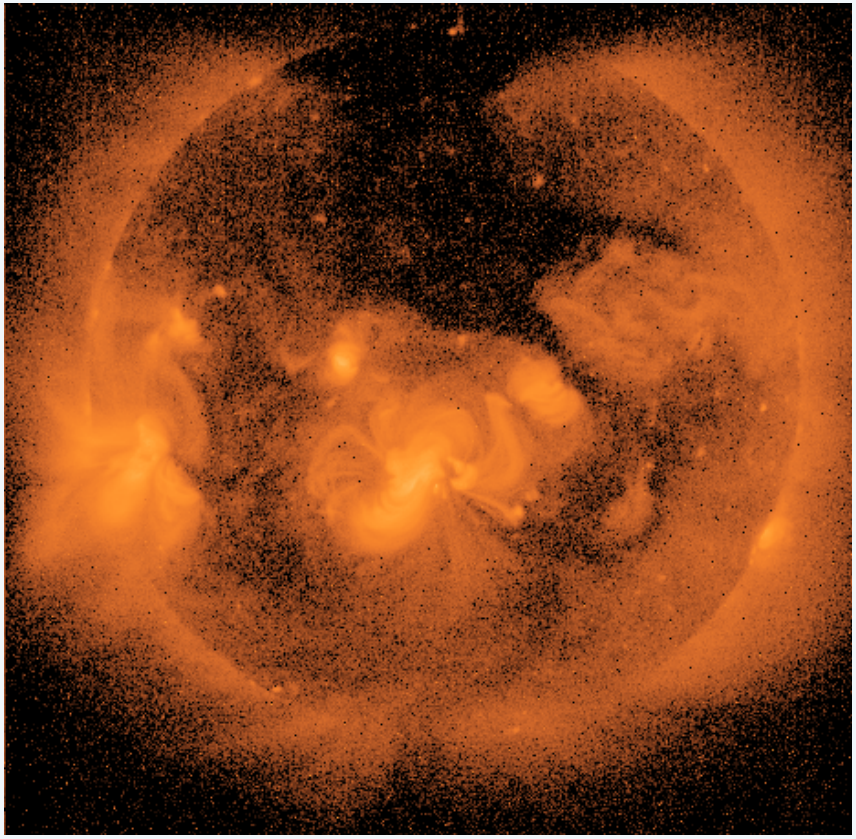
Self-similarity of shear layers from 800 mpc to 6 mpc

Hily-Brandt & Falgarone, 2009

Solar corona



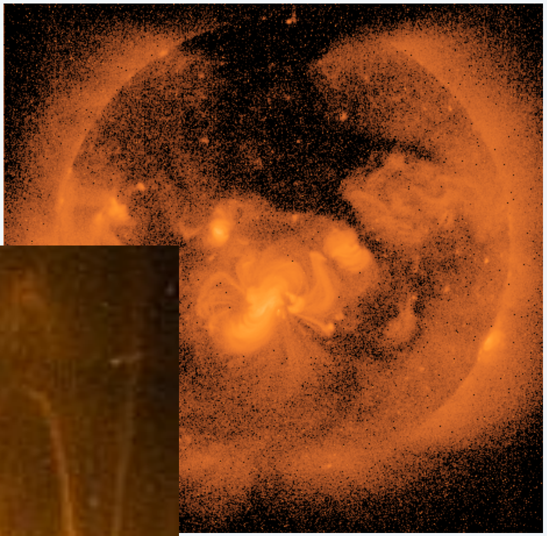
astron.berkeley.edu/~jrg/ ay202/img1731.gif

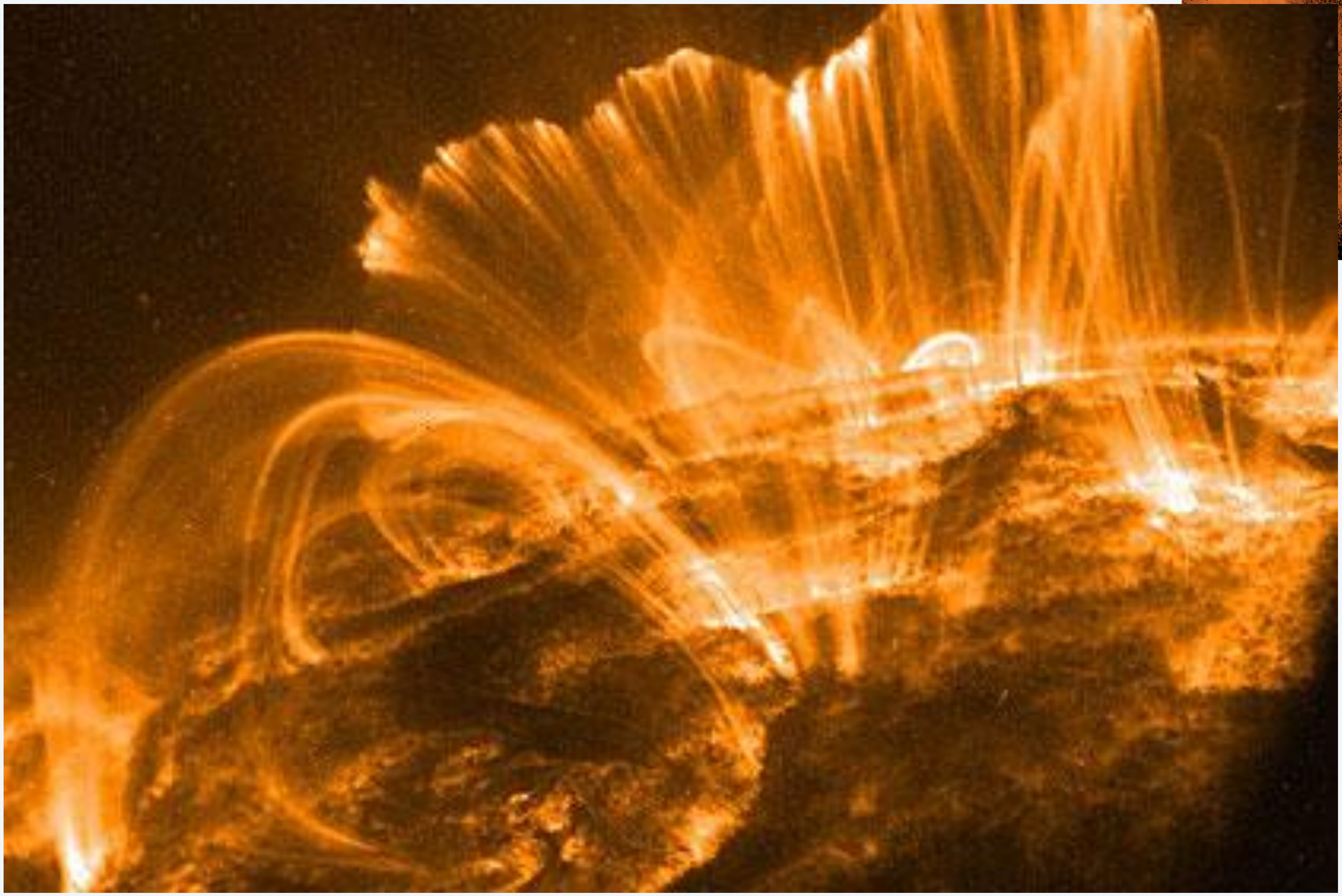


www.geophys.washington.edu/
Space/gifs/yokohflscl.gif

After Bhattacharjee, 2005

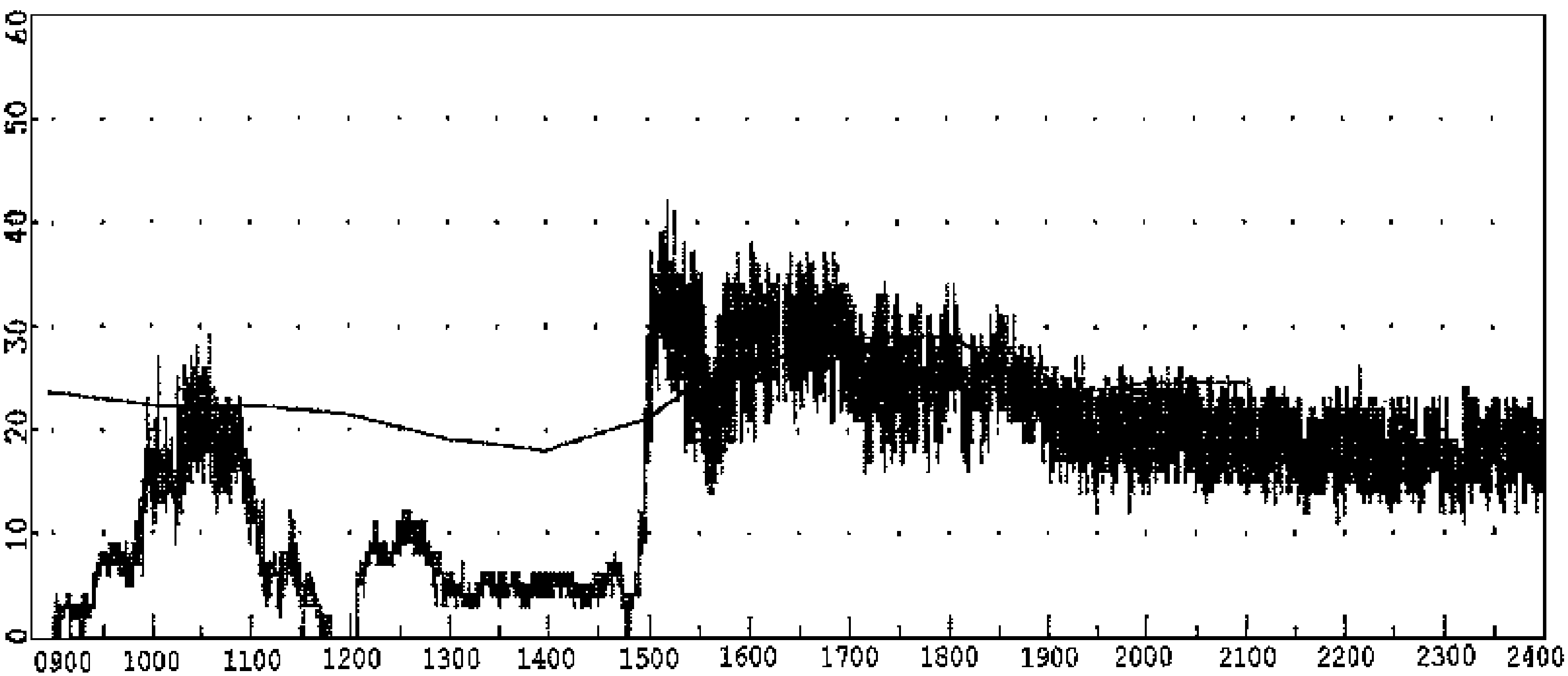
Solar corona





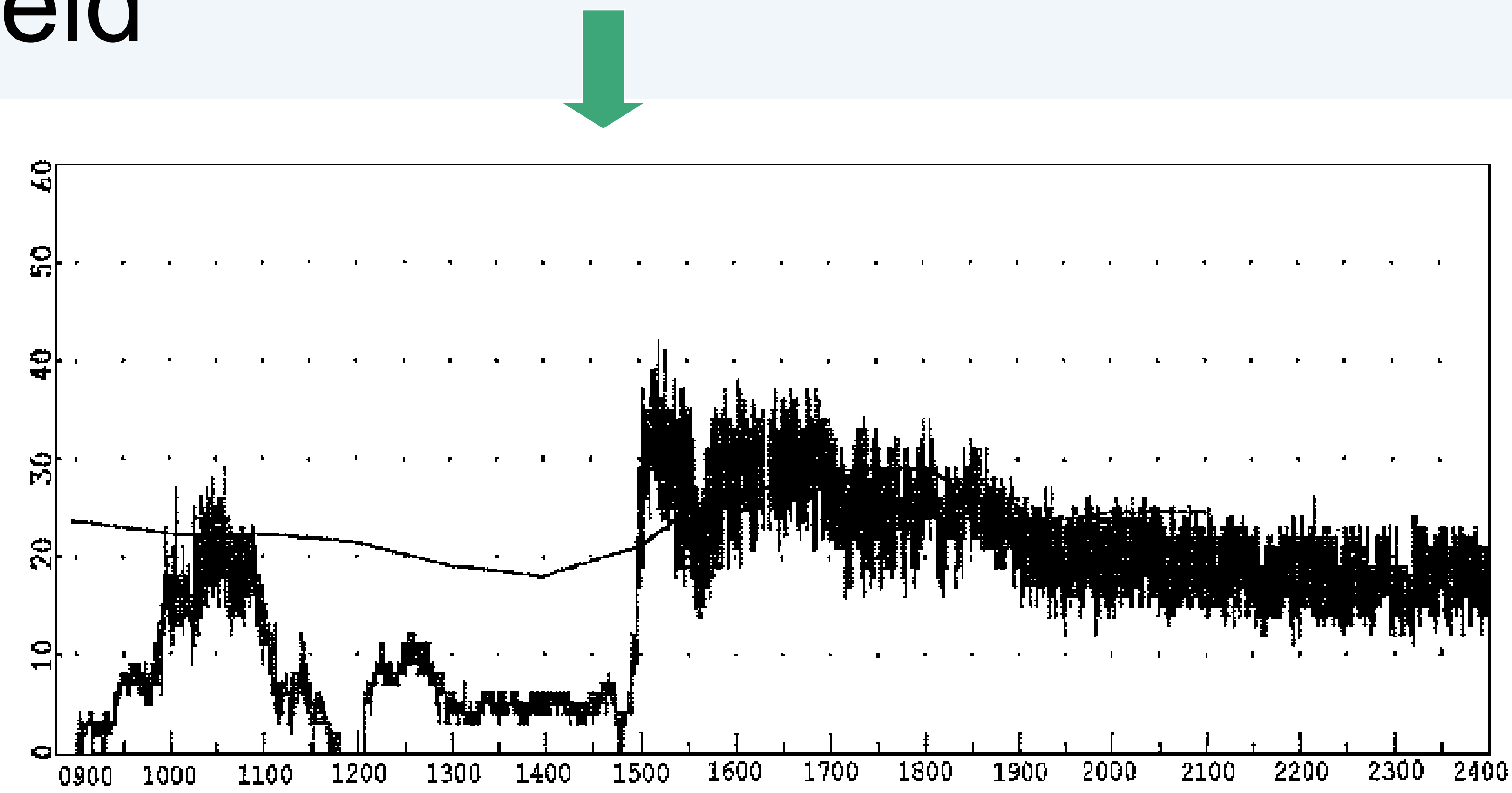
NASA: *tn_2518_thesunswrongwayroundheat*

Stochastic field



igure 6. Anemograph trace for Bellambi Point on 26 December 1996 (wind speed in knots), taken from Batt an
Leslie (1998), Fig. 7.

Stochastic field



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Turbulence: Complex fluid motions

Forces due to: Pressure gradients
Rotation
Gravity
Radiation, heating and cooling
Friction and viscous stresses
Supernovae
Magnetic fields
Chemistry, …

$$\frac{T_{dissipation}}{T_{nonlinear}} \qquad Re = U_0 L_0/\nu \gg 1$$

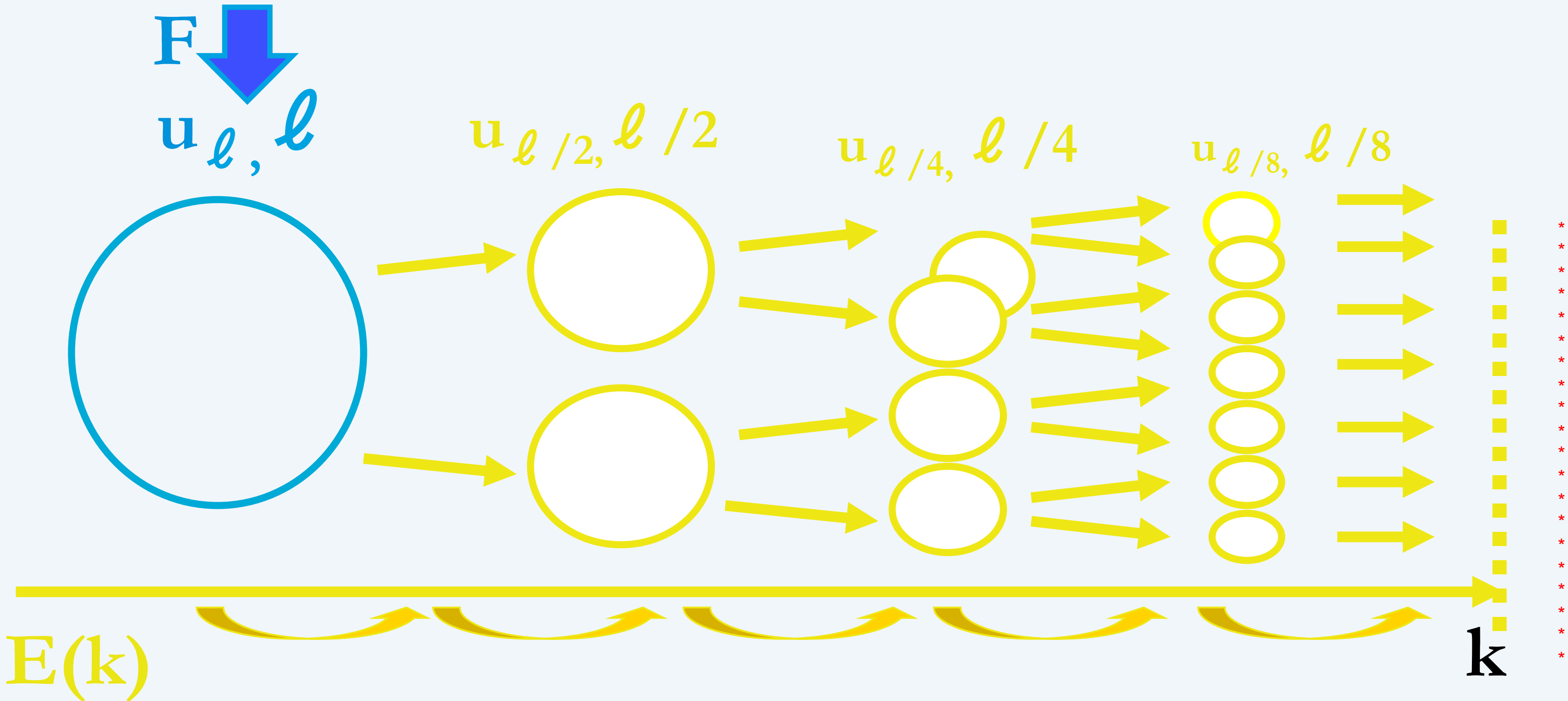
Reynolds number

Rossby and Froude numbers, …

Non-linear term → convolution in Fourier space
→ coupling between scales

Modeling through both eddy viscosity & eddy noise

Classical cartoon for turbulence

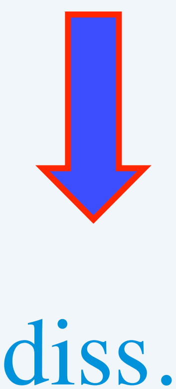


$\epsilon = dE/dt$: energy dissipation rate

$E \sim kE(k)$ (locality) and $\tau \sim \ell/u_\ell$ *(eddy turn-over time)*,

So: $\epsilon \sim u_\ell^3/\ell$

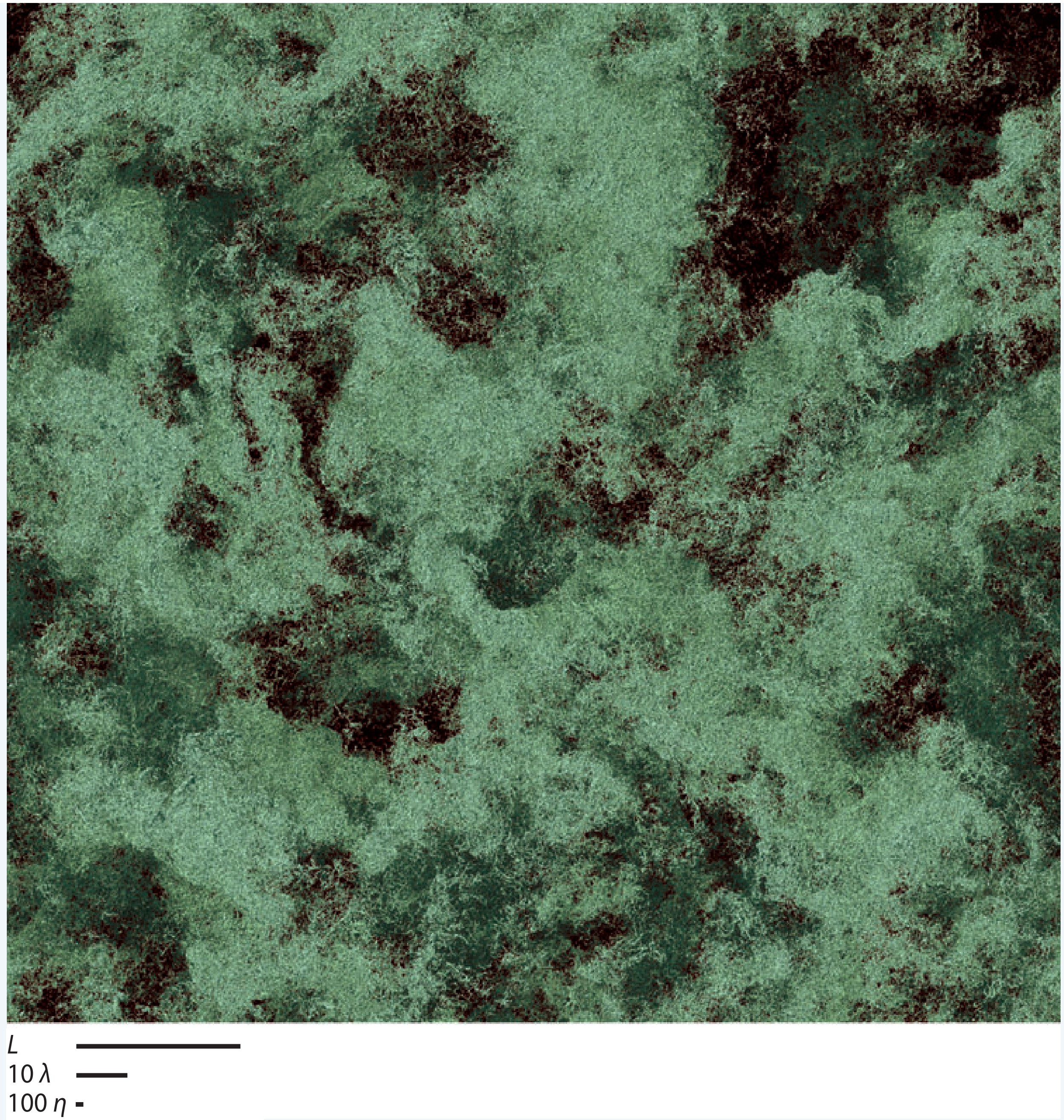
and $E(k) = C_K\, \epsilon^{2/3}\, k^{-5/3}$



What it looks like in the largest *to date* direct numerical simulation of fluid turbulence

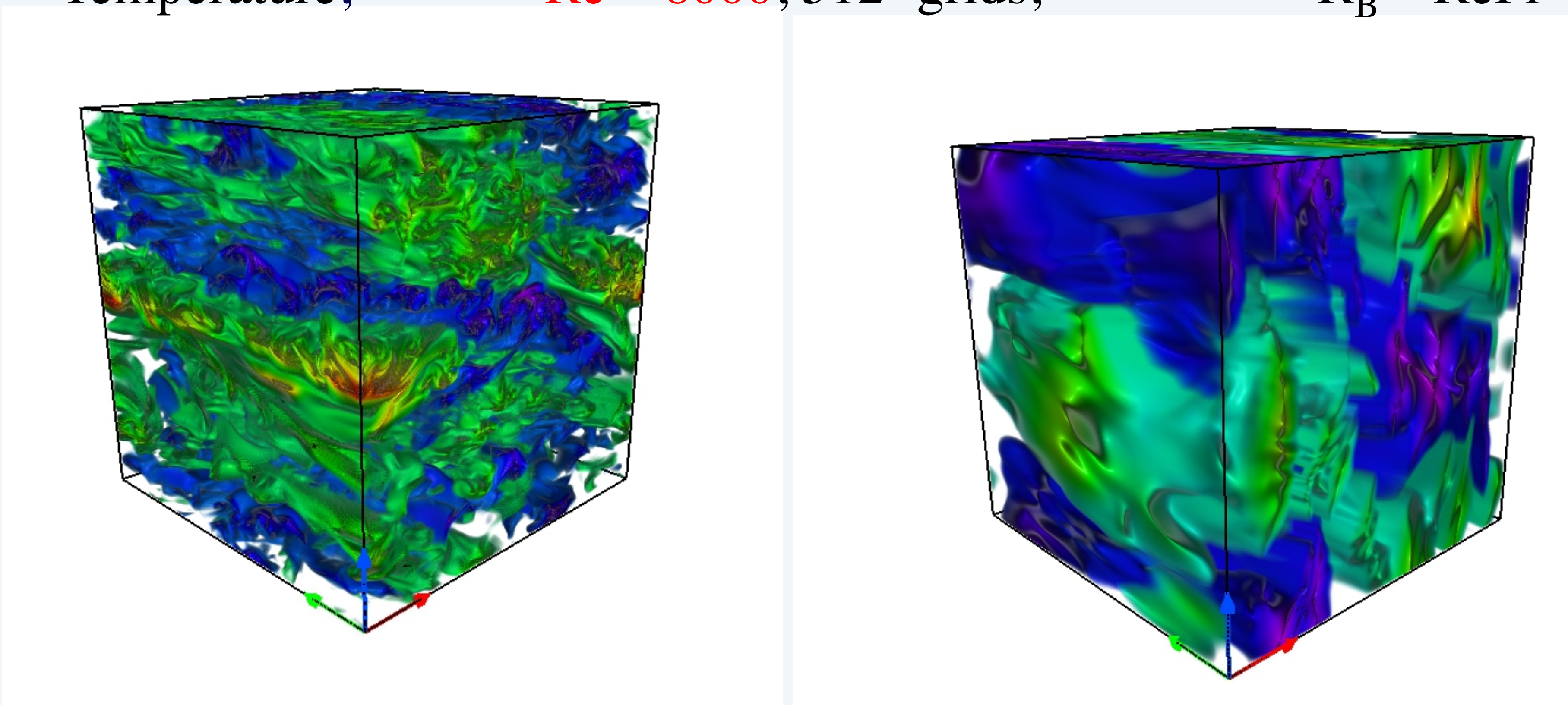
Incompressible, isotropic, 3D
Periodic boundary conditions
No other force but
pressure gradient and dissipation

64 billion grid points
(4096^3)



Ishihara Kaneda 2003, Earth Simulator

Temperature, $Re \sim 8000$, 512^3 grids, $R_B = ReFr^2$

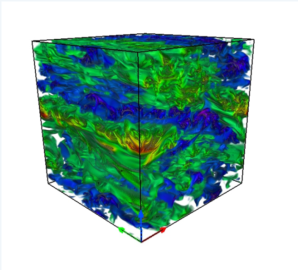


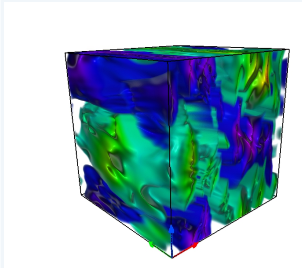
$Fr \sim 0.11$, $Ro \sim 0.4$,
$R_B \sim 100$, $N/f \sim 3.6$

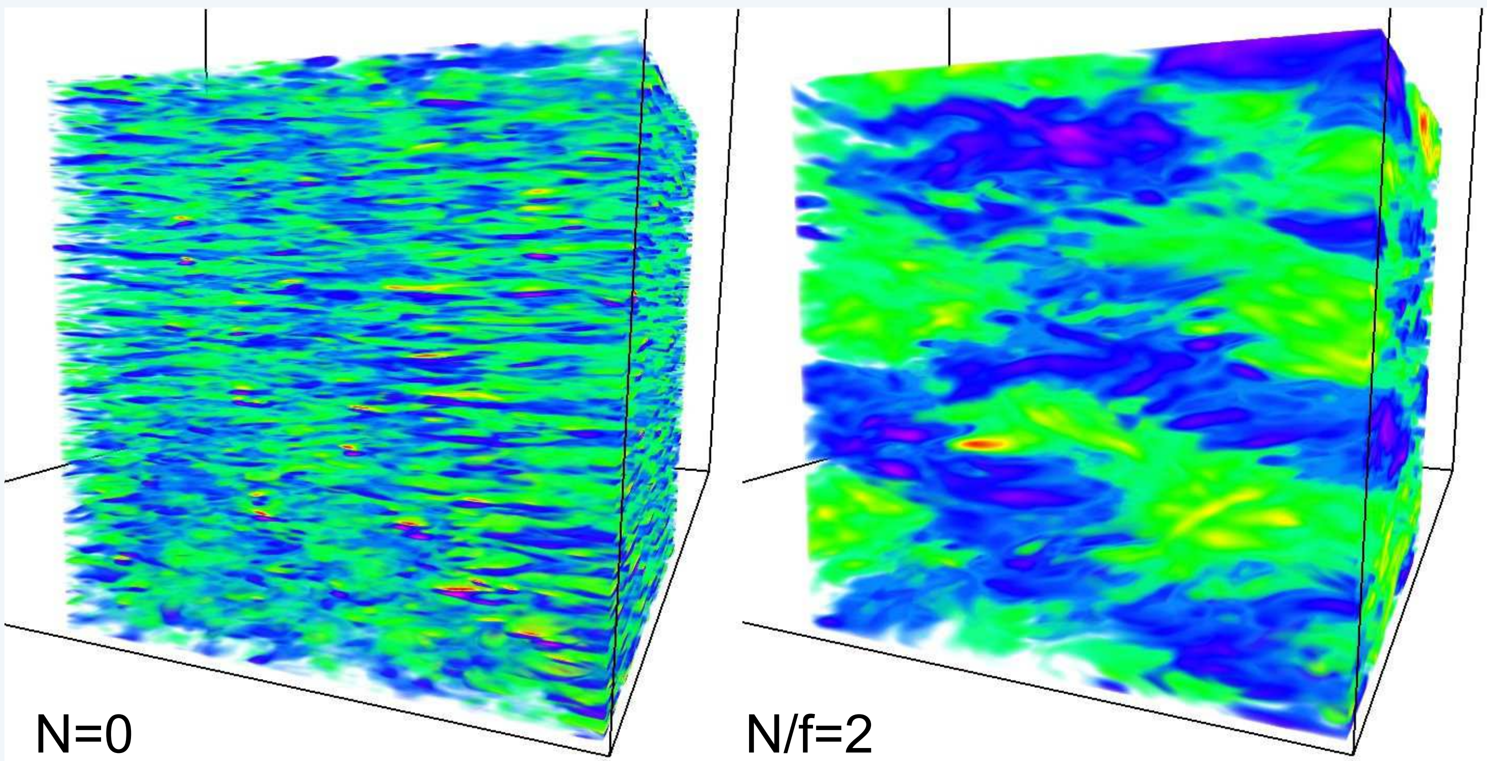
$Fr \sim 0.025$, $Ro \sim 0.05$,
$R_B \sim 5$, $N/f = 2$

Rendering using Vapor (NCAR freeware)

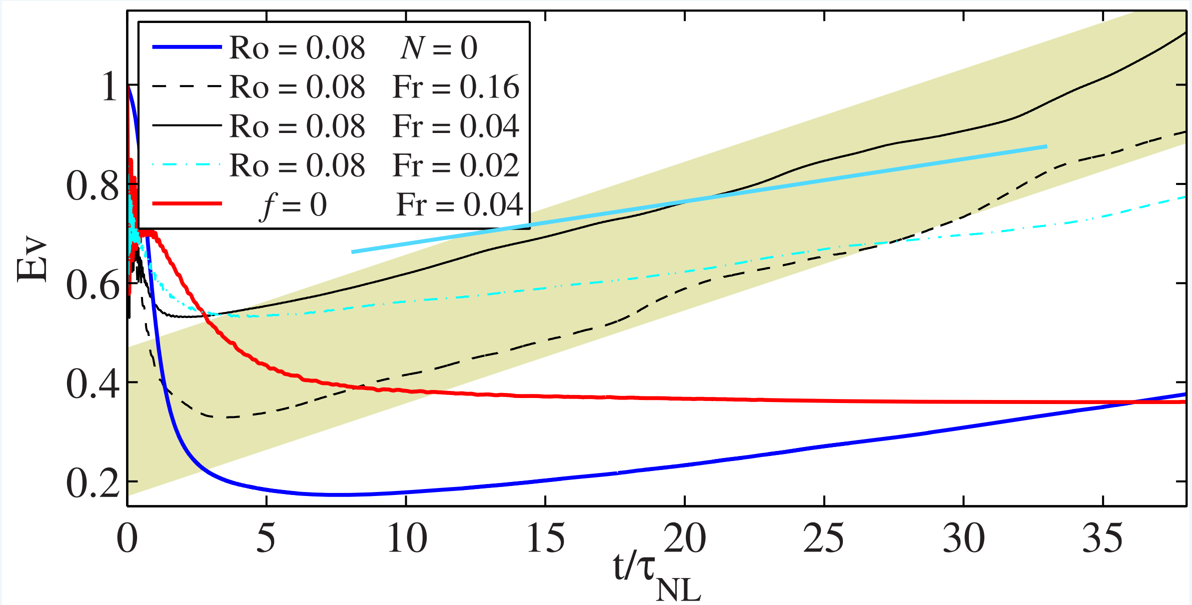
Marino et al., 2013

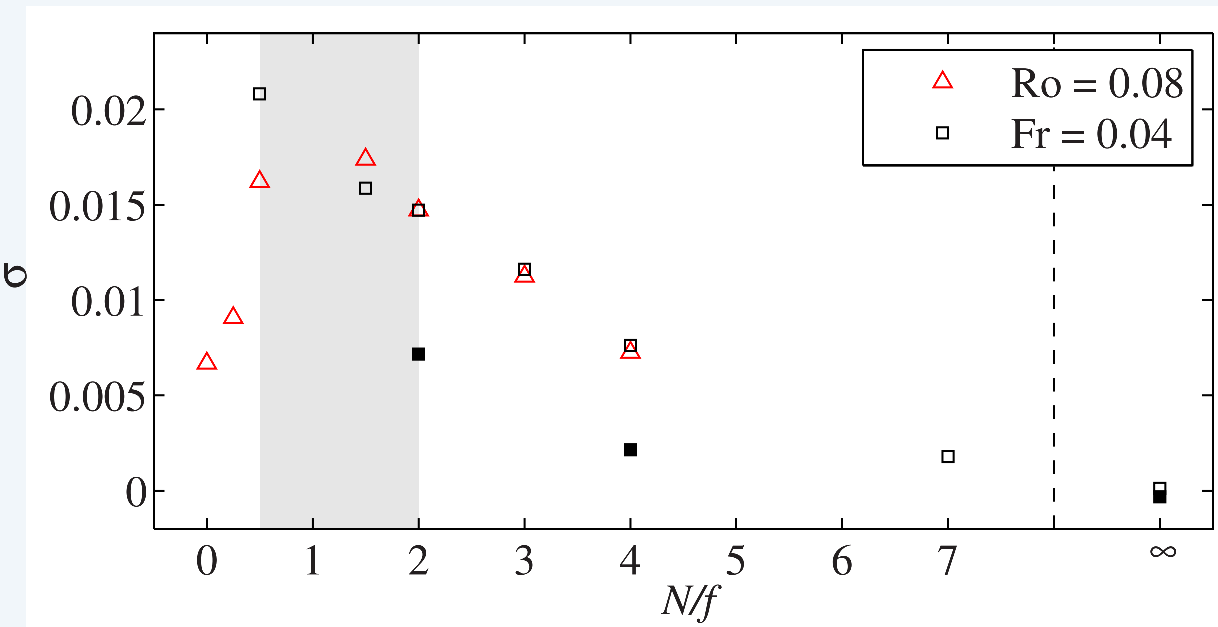






Marino et al., EPL 2013

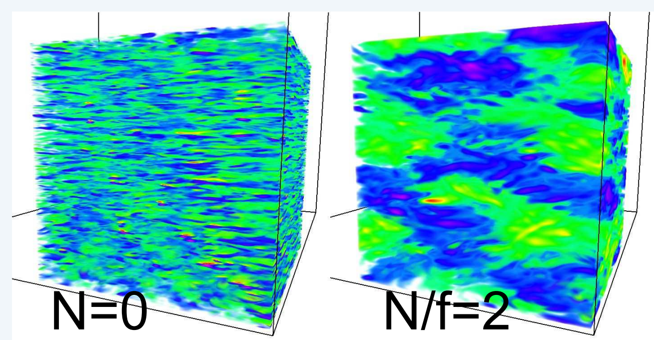




Growth rate of energy

512^3 or 1024^3 grids
k_F=22 or 40

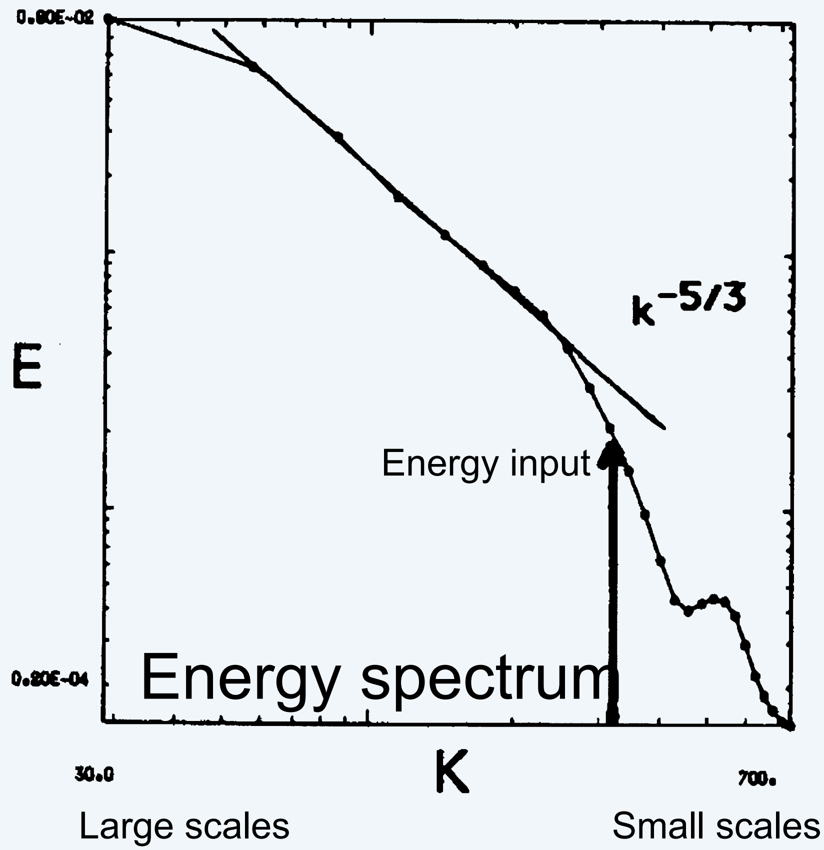
Re=1000

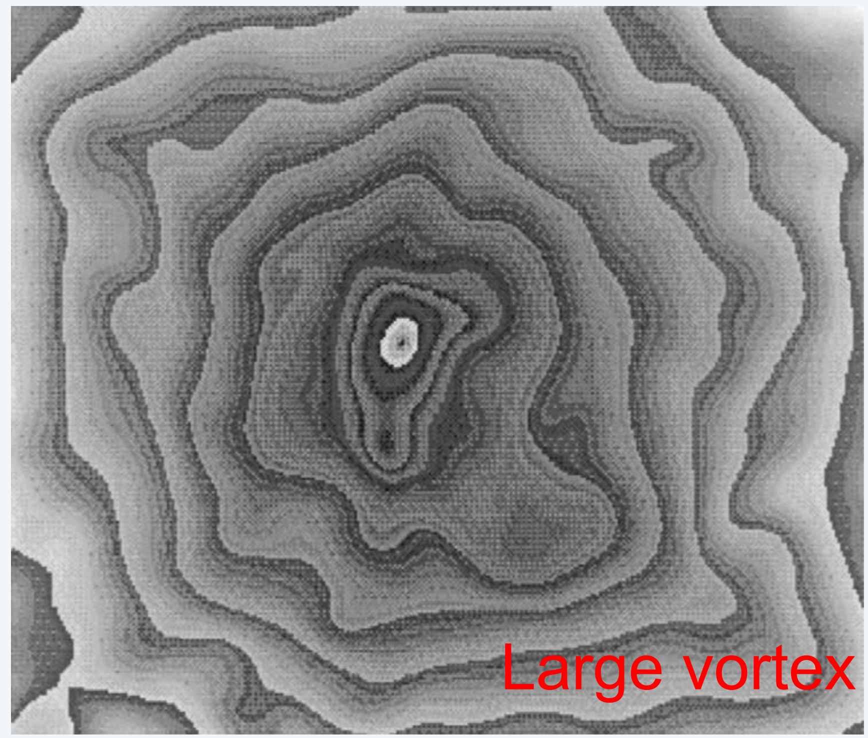


Marino et al., EPL 2013

Two dimensional fluid dynamics

Laboratory experiment

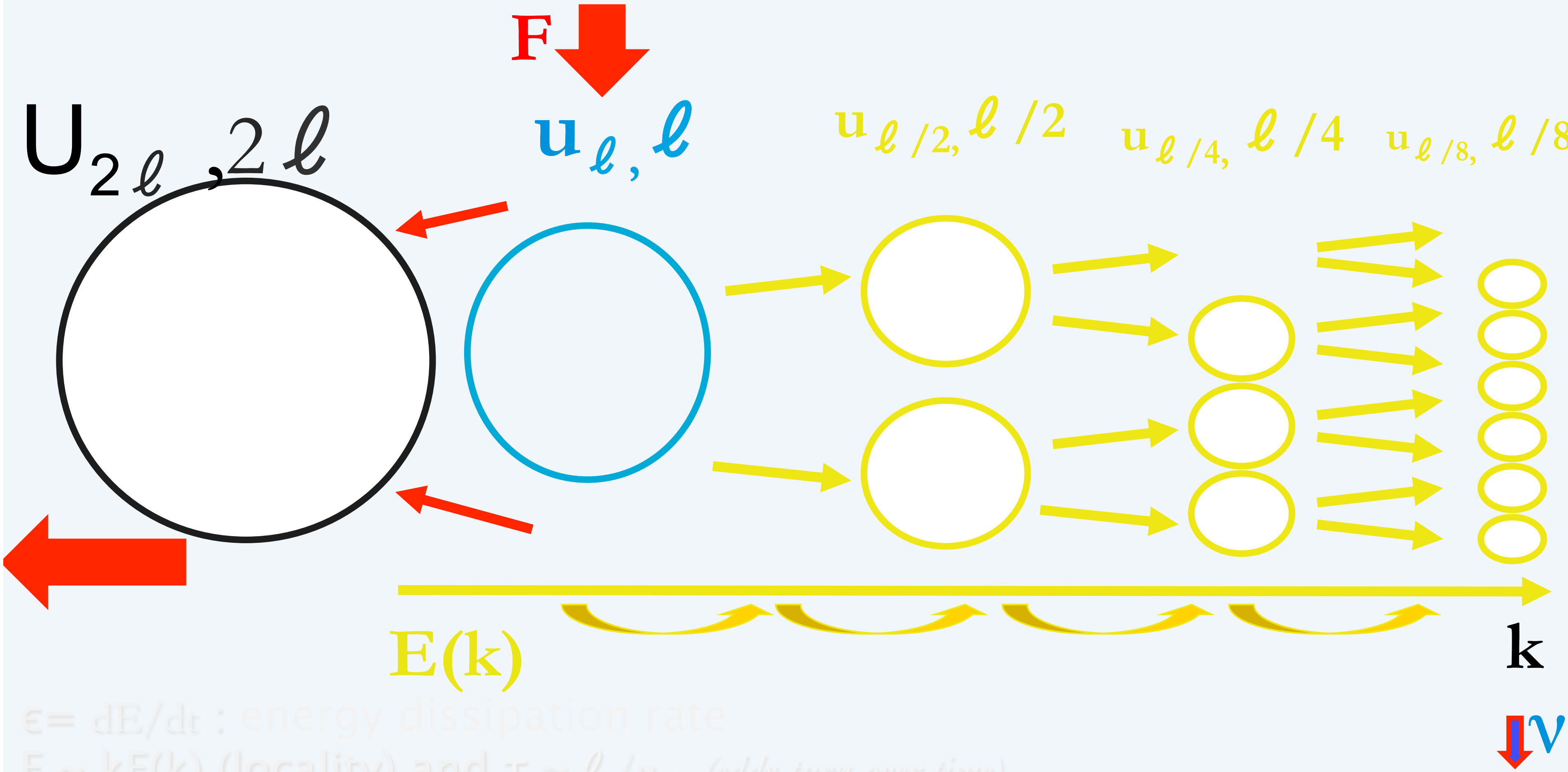




Atmosphere, ocean?

Tabeling, 2002

Classical cartoon of **2D turbulence**



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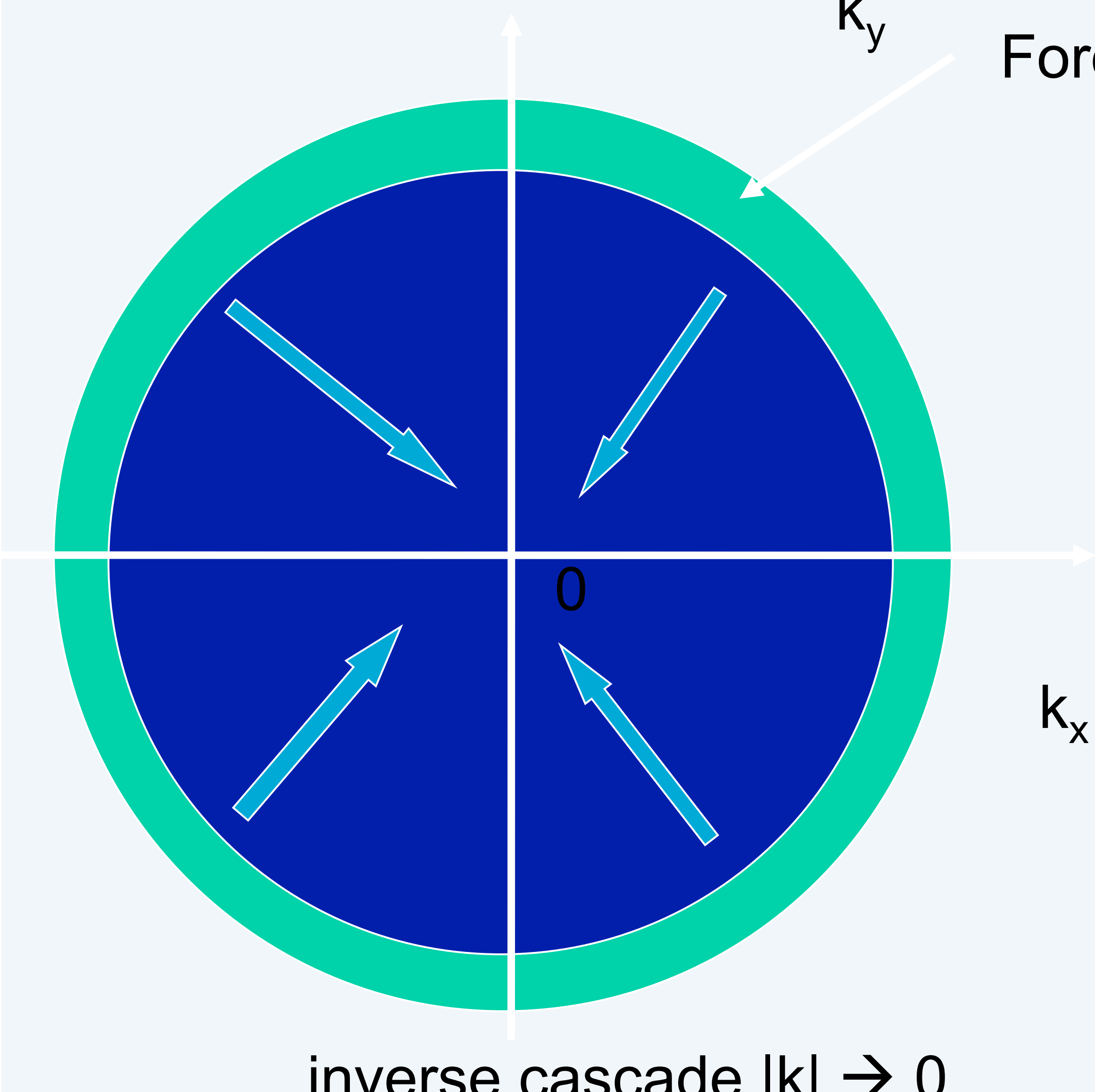
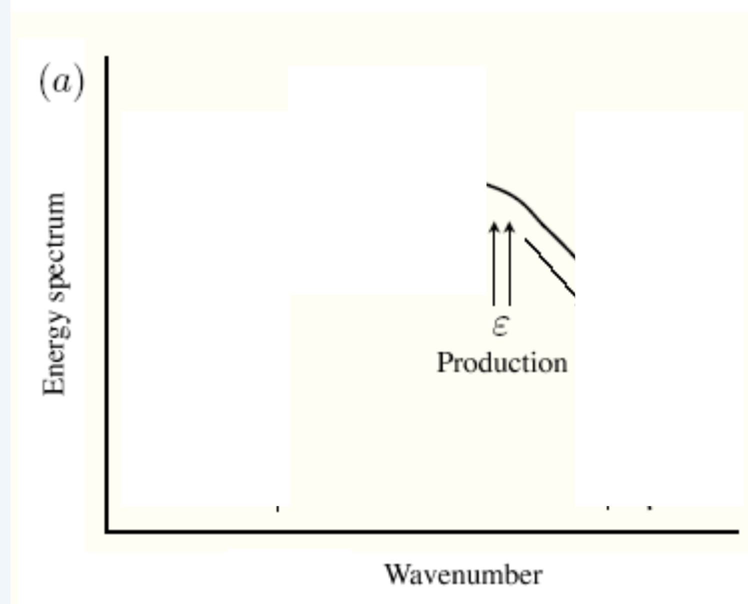
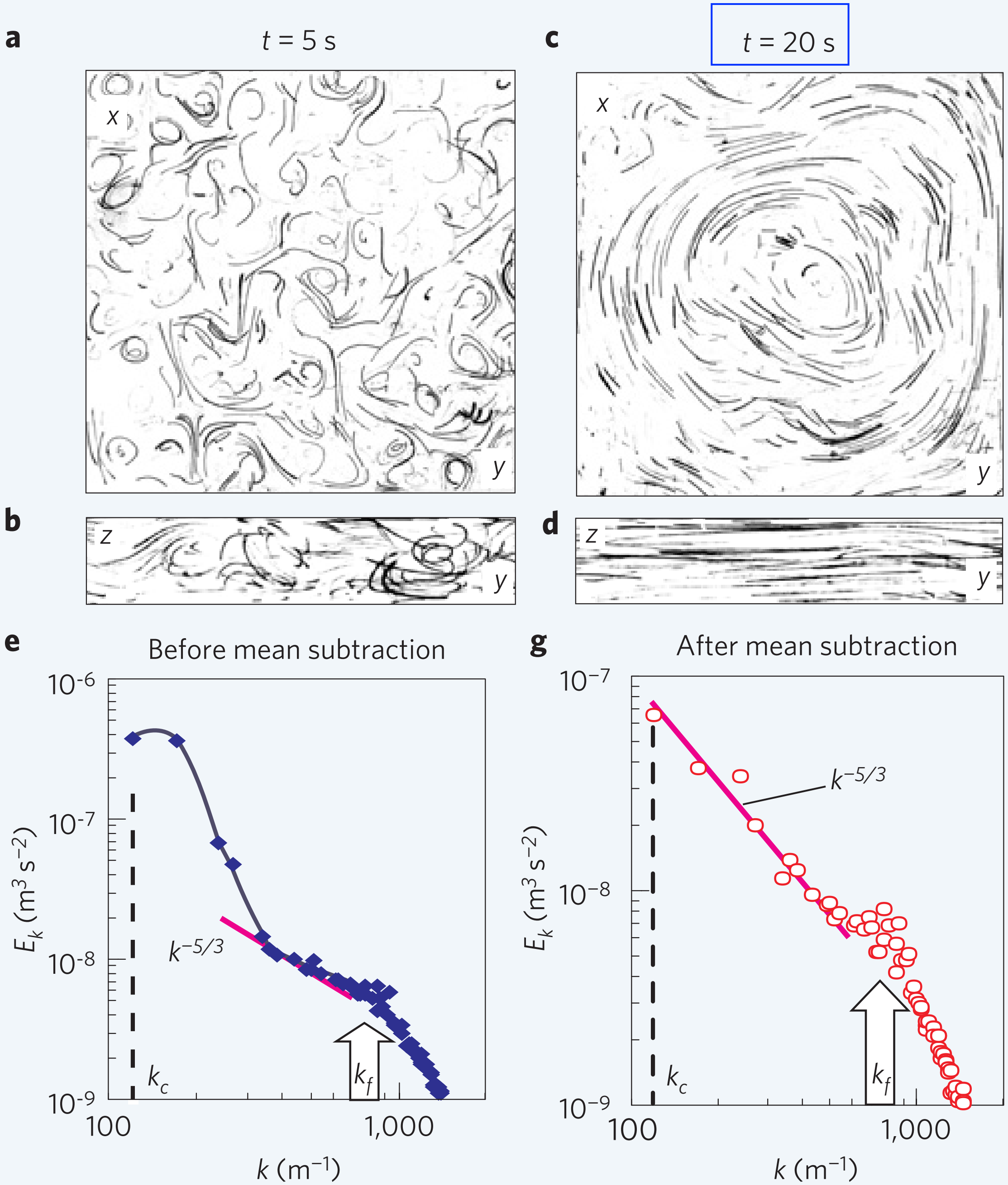
Two-dimensional turbulence



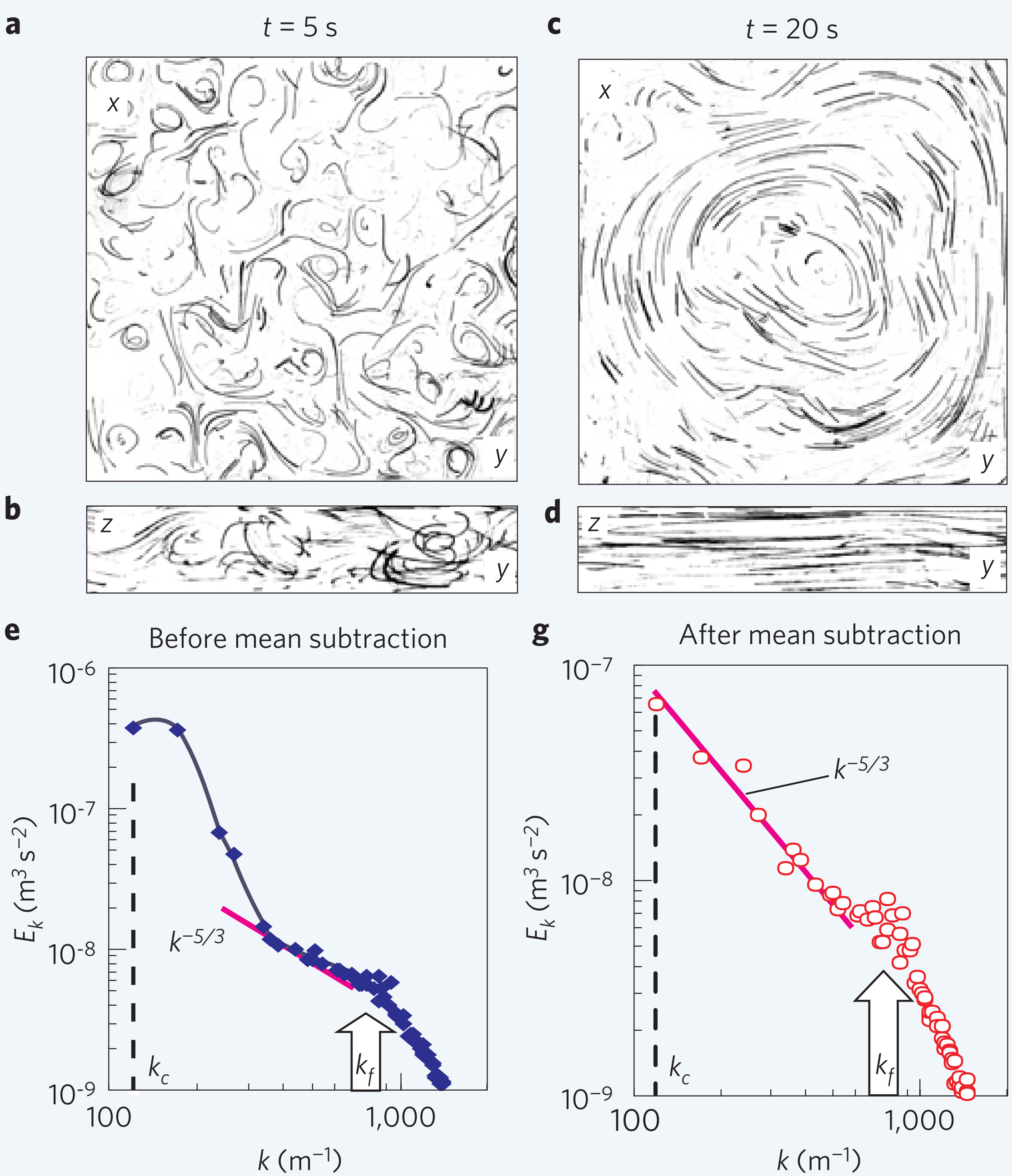


From Bach Lien Hua, Lorenz Lecture, AGU 2006



Experimental suppression of vertical motions in thick layers with forcing at small scale: interactions with vertical shear

Xia et al. 2011



Experimental suppression of vertical motions in thick layers with forcing at small scale: interactions with vertical shear

Numerically:
various aspect ratio of a box and 2D forcing:

Progressive apparition of inverse cascade of energy
(Celani et al. 2012)

Also: rotation *(Deusebio et al. 2014)*
Also: stratification *(Sonza et al. 2014)*

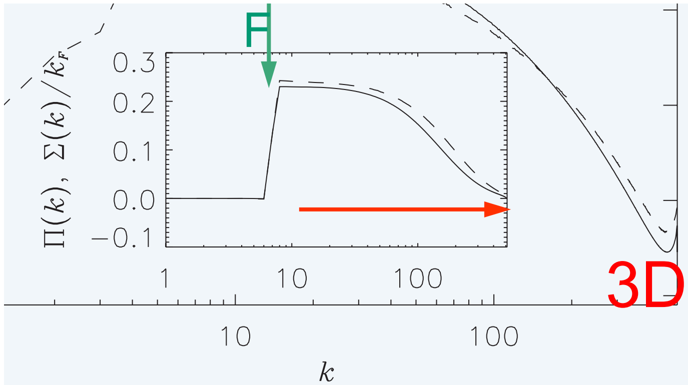
Celani et al. (2010), in the context of isotropic turbulence:

- … the cascade splitting described above, i.e., coexistence of 3D* and 2D* turbulence, should take place whenever the flow is confined in one direction, be it by material boundaries or by any other physical mechanism of dimensional reduction, e.g., stable stratification *.

** together with rotation*

** 3D: To-small-scale energy flux* *or [exclusive]*

2D: to-large-scale energy flux (``cascade'')



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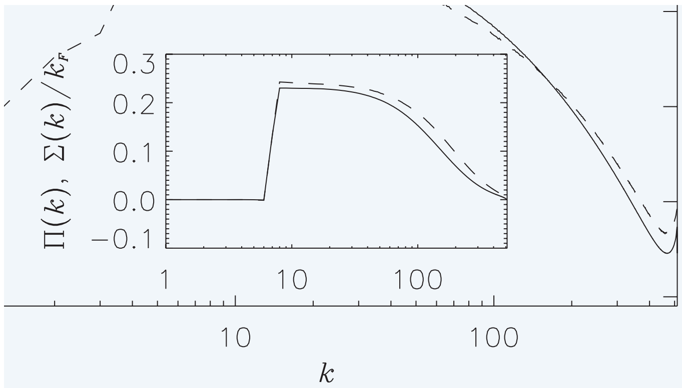

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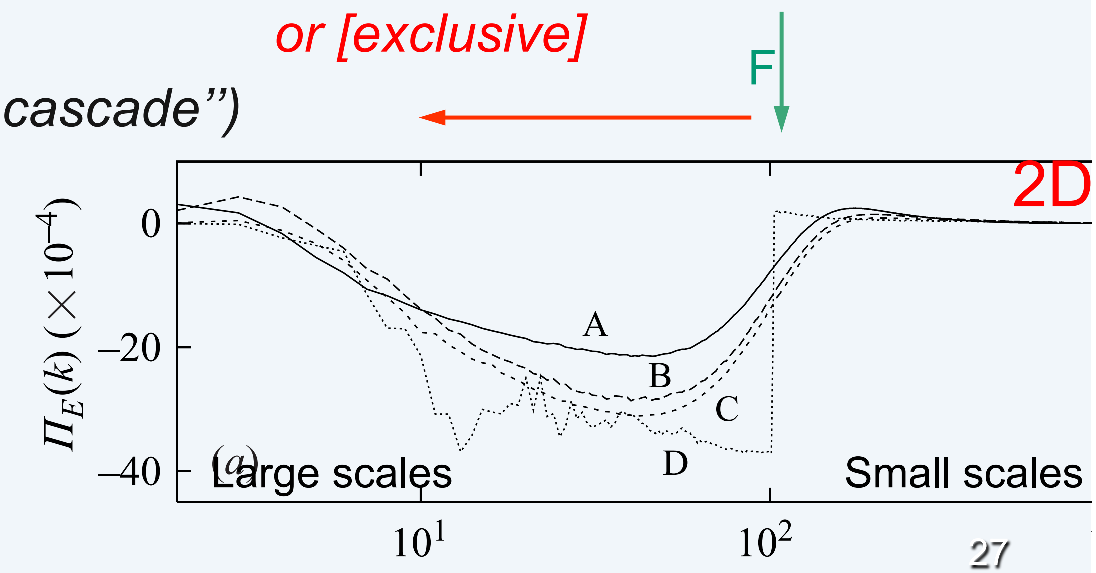
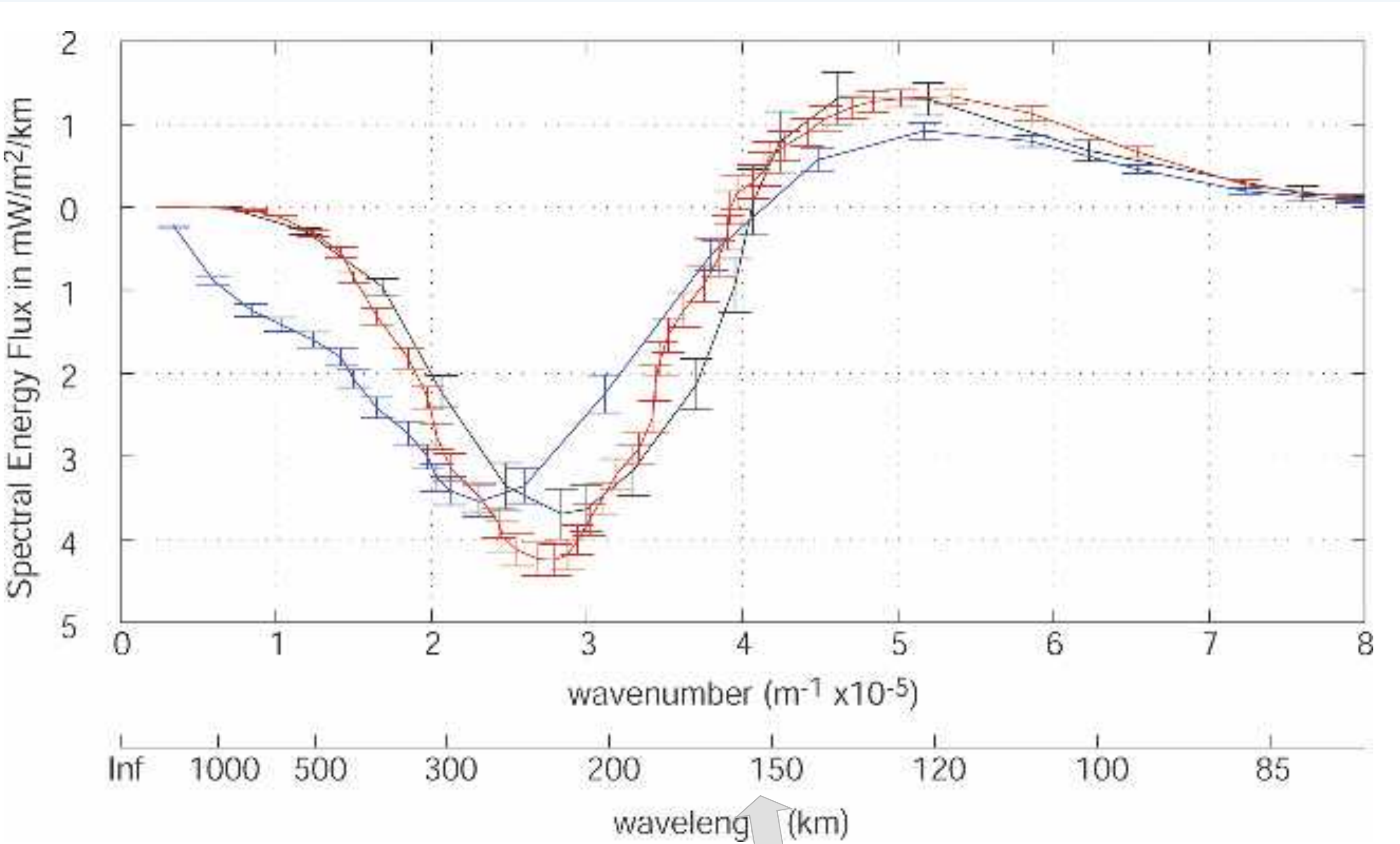


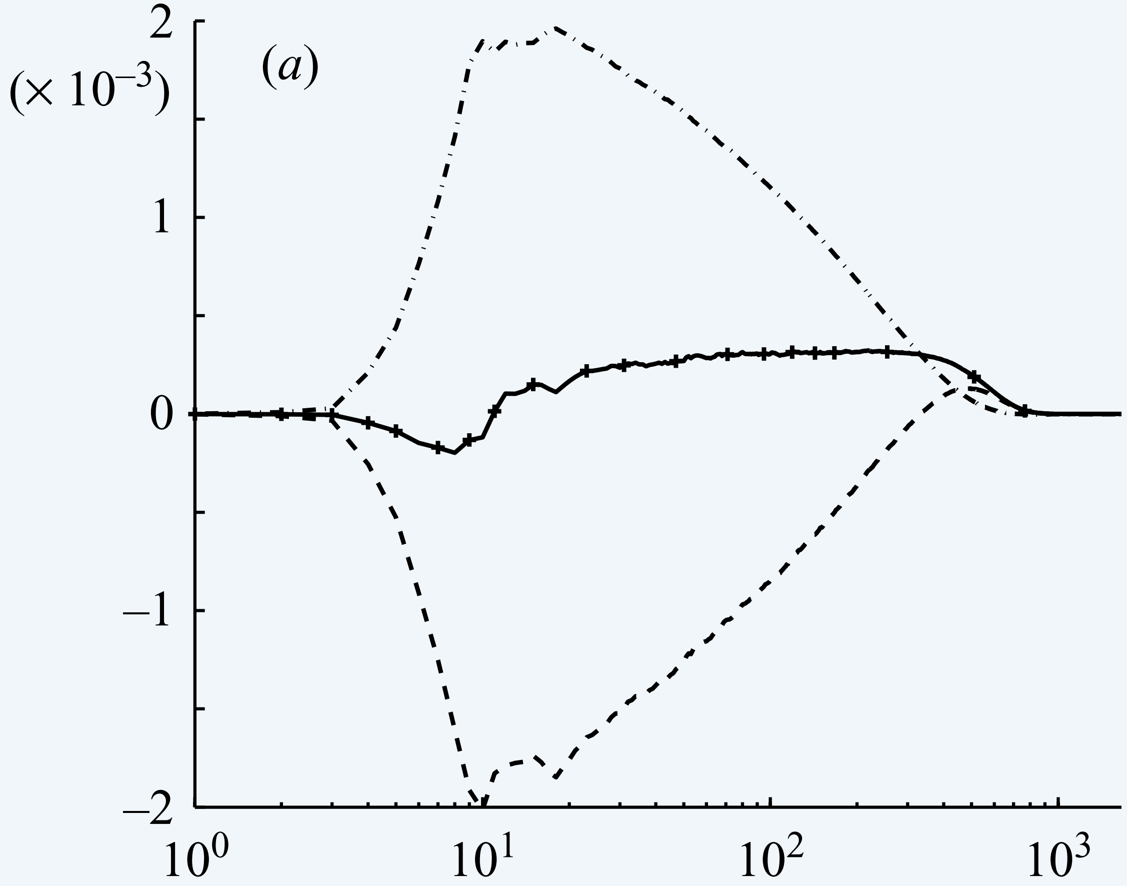
Kinetic energy flux
ACC, 10+yrs data *every 10 days ~ T_{NL}*



Deformation radius

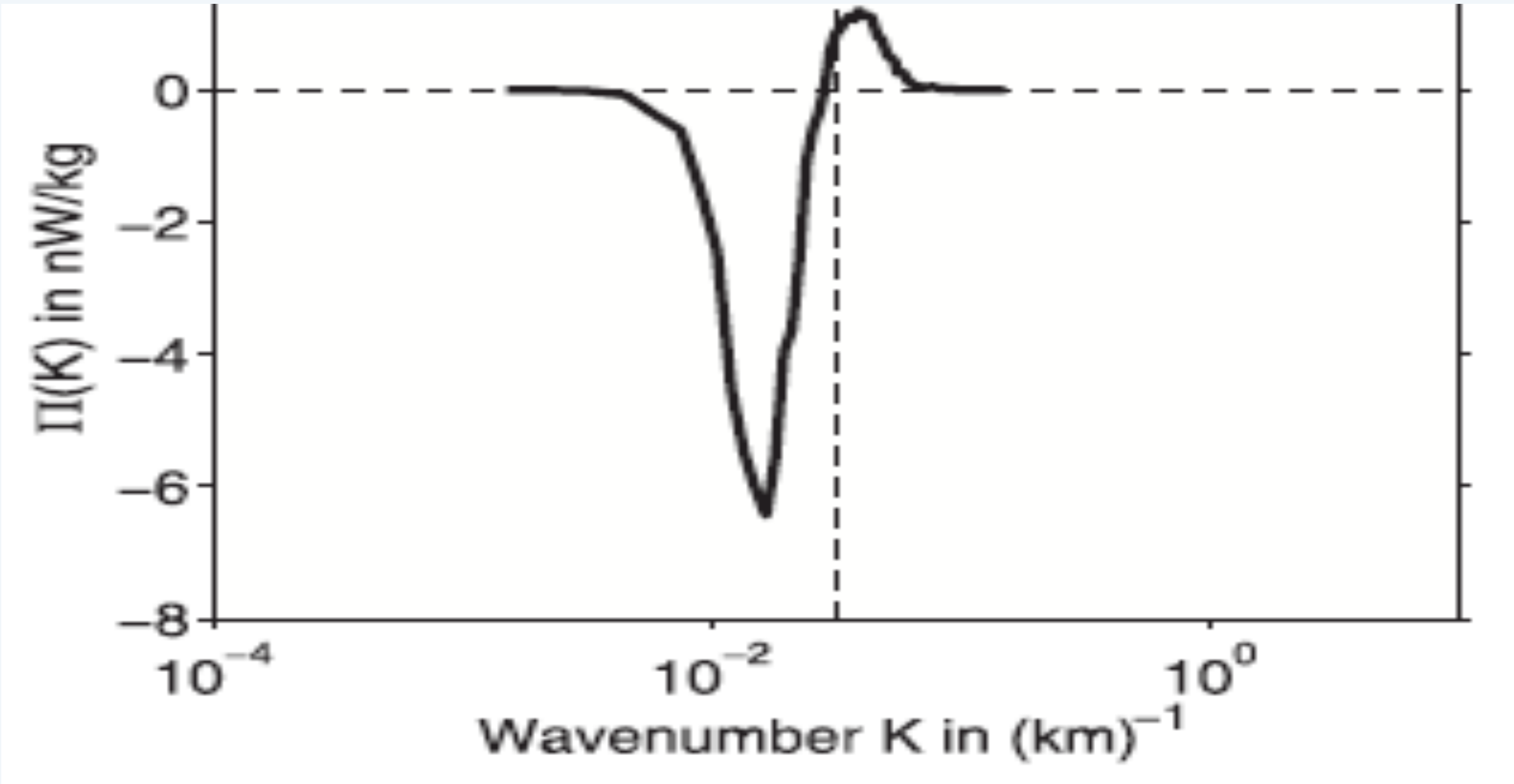
Scott JPO 2005

Kinetic energy flux
SQG



Capet, Klein, Hua, Lapeyre, McWilliams JFM 2008

AVISO data (Kuroshio), energy flux



Arbic et al., J. Phys. Oceano. 2013

A paradox?

- *Capet et al. (2008c), numerical model (ROMS+KPP):*

… we hesitate to draw any strong conclusions about the efficacy of a mesoscale inverse KE *{Kinetic Energy}* cascade in our solutions, although our results indicate it does occur to some degree …

** Scott et al. (2011), oceanic data analysis:*

despite great effort in studying the ocean's energy budget in the last two decades, the bulk of the dissipation of the most energetic oceanic motions remains unaccounted for.

** Arbic et al. (2013), modeling but commenting on data:*

… It is therefore difficult to say whether the forward cascades seen in present-generation altimeter data are due to real physics (represented here by eddy viscosity) or to insufficient horizontal resolution.

Run: MIT-GCM,

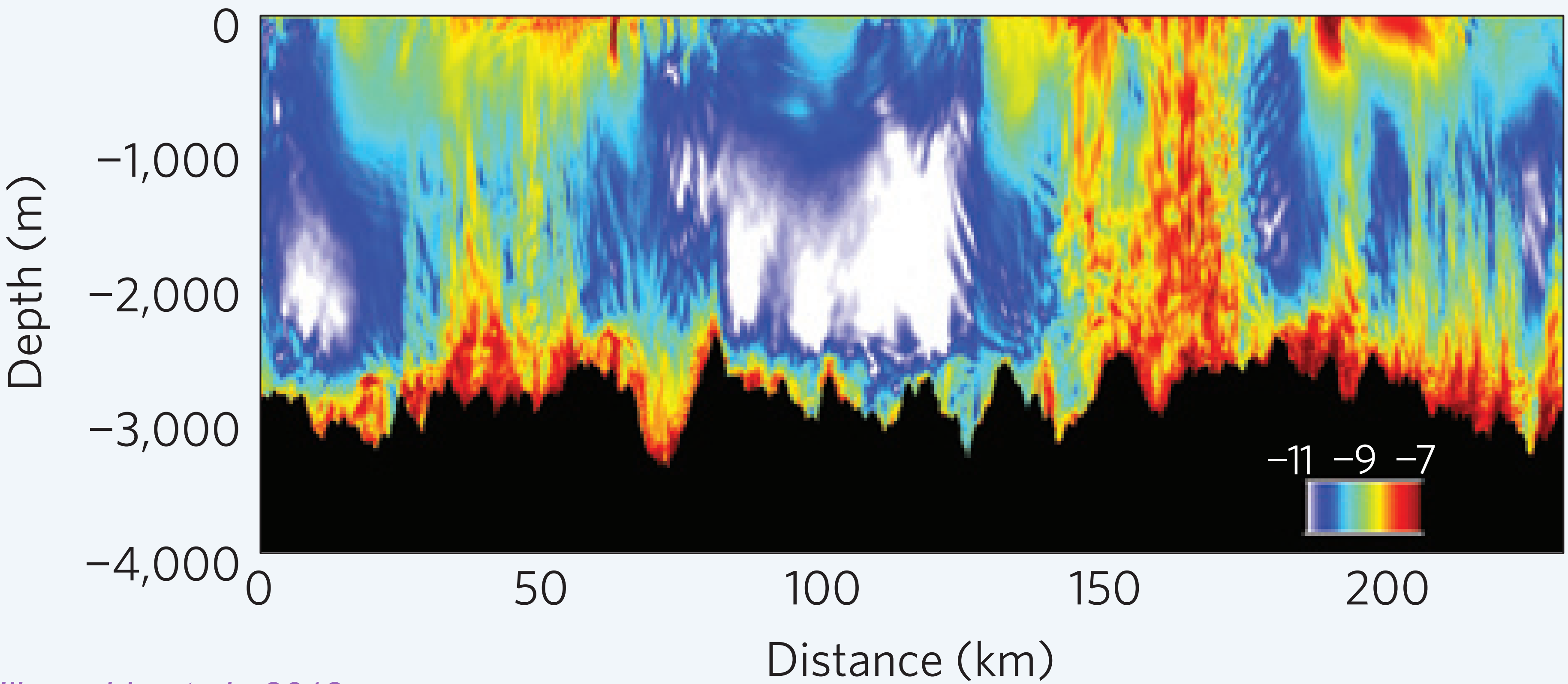
N/f~ 4.7, Grid ~ 1200^2 X 200 points , 230×230 km^2 x 4km

U ~ 10cm/s, N=7×10^{-4}/s, high Prandtl number

$R_{perp} \sim 7 \times 10^7$, $R_Z \sim 7 \times 10^3$

Energy dissipation 10^{-10}

→ 10^{-8} W/kg



Nikurashin et al., 2013

Measurements in in the Southern Artic Ocean

(Drake passage)

← of flow speed

and of buoyancy frequency

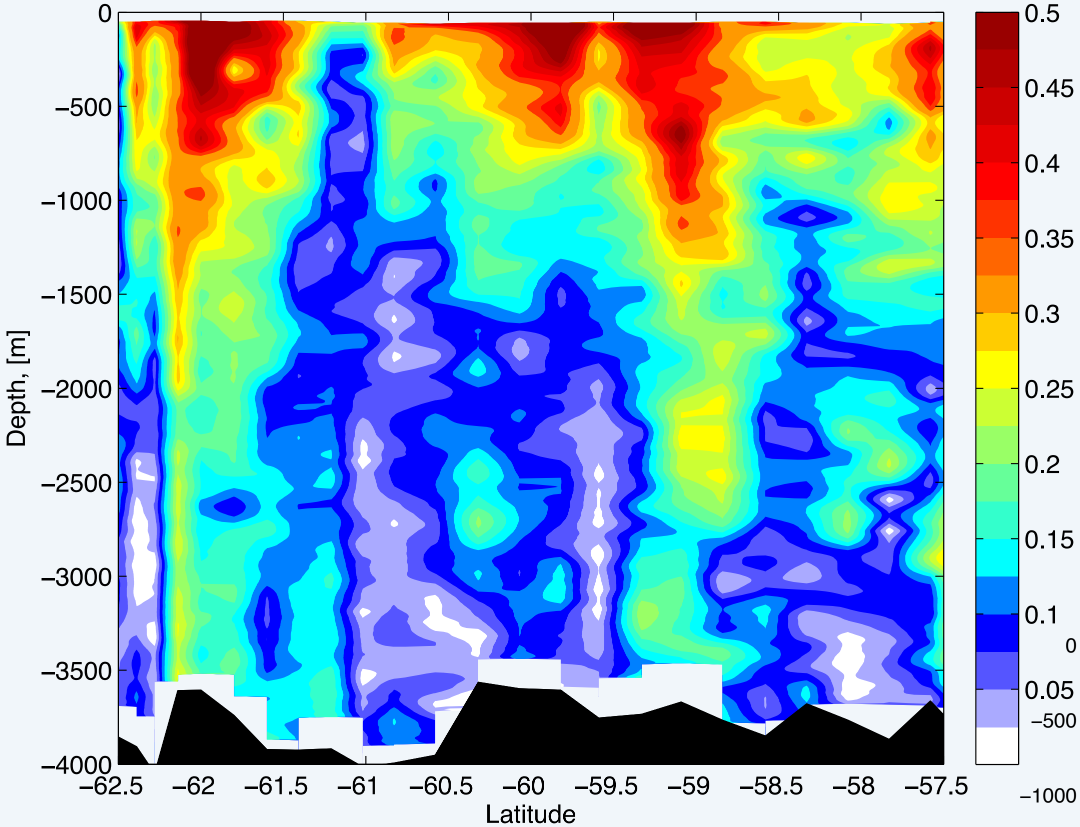


Figure 3-2: Flow speed (m s^{-1}) from the ALBATROSS section, Drake Passage.

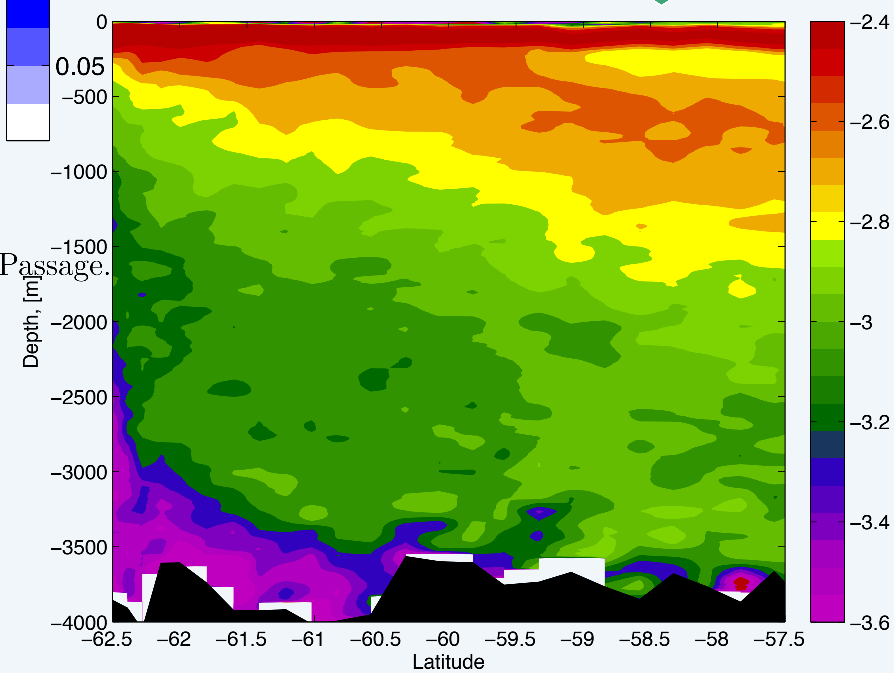
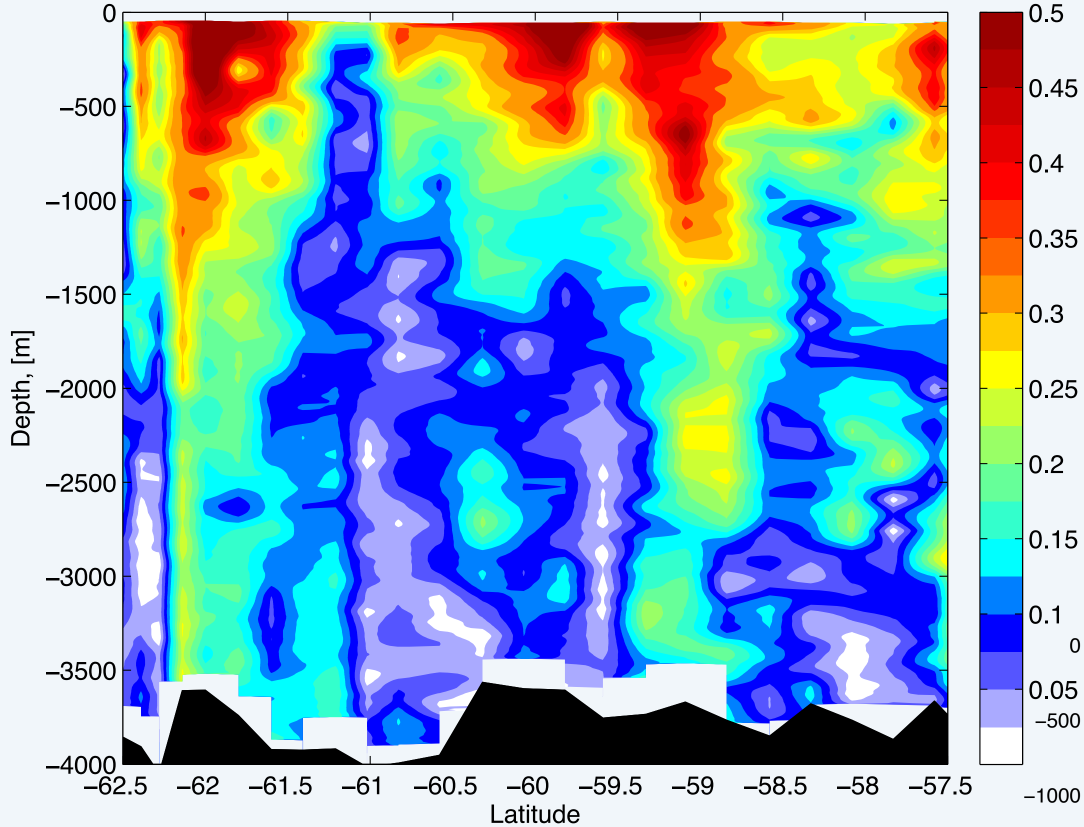


Figure 3-1: Buoyancy frequency (s^{-1}) in logarithmic scale from the ALBATROSS section, Drake Passage.

Nikurashin, 2009



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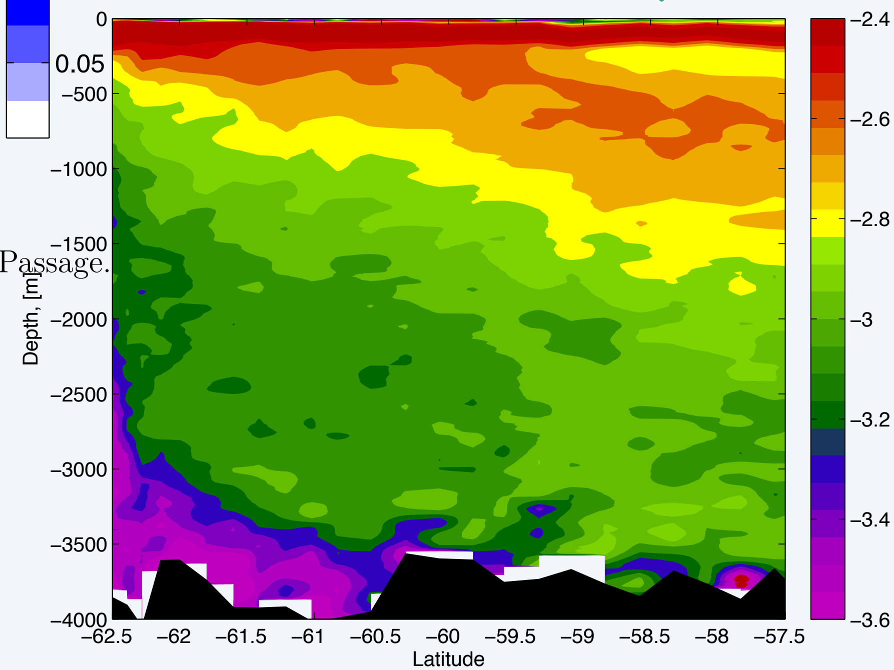
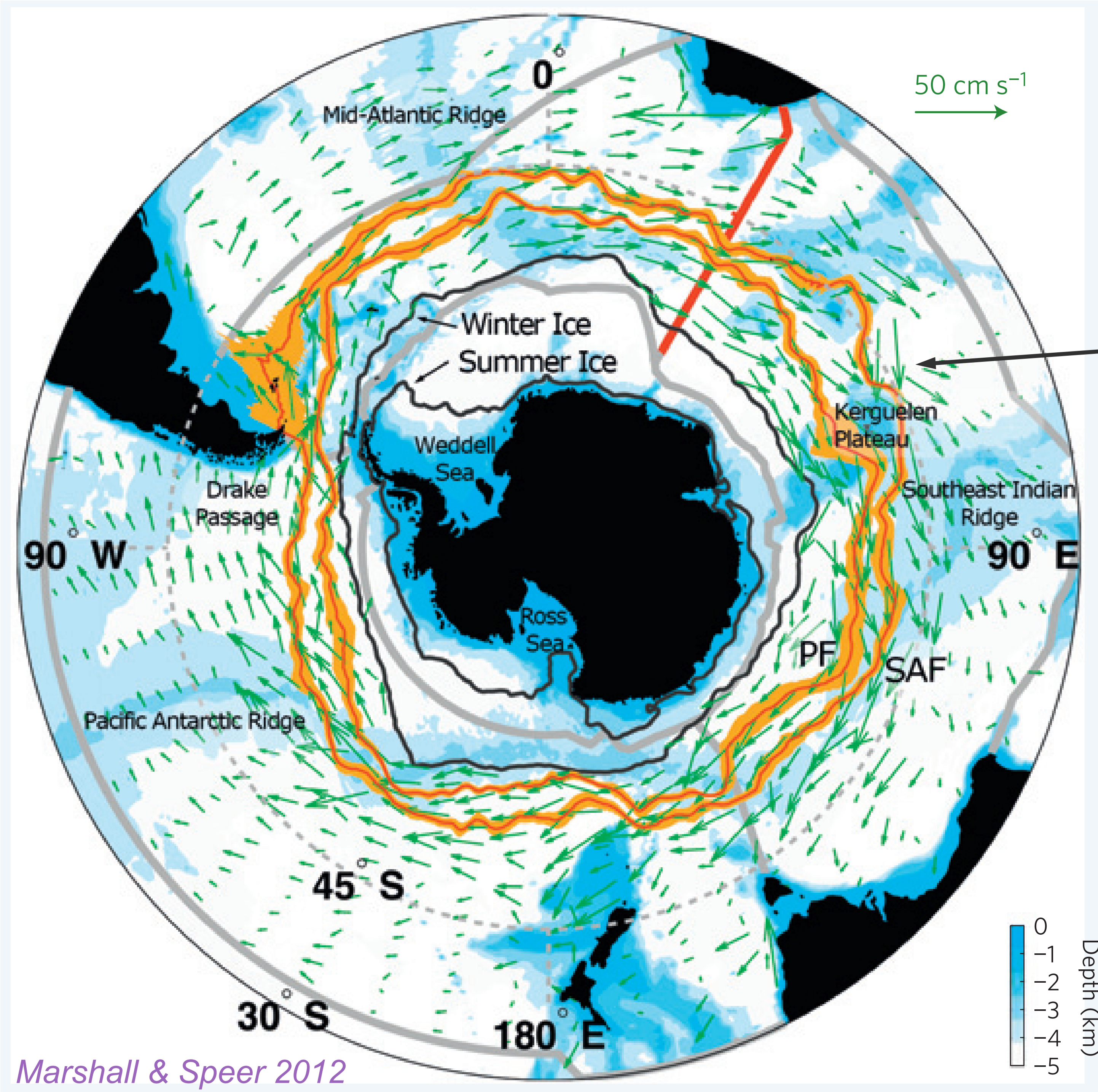


Figure 3-1: Buoyancy frequency (s^{-1}) in logarithmic scale from the ALBATROSS section, Drake Passage.

→ $U \sim 0.05$ m/s

→ $N \sim 0.001$ /s

Nikurashin, 2009

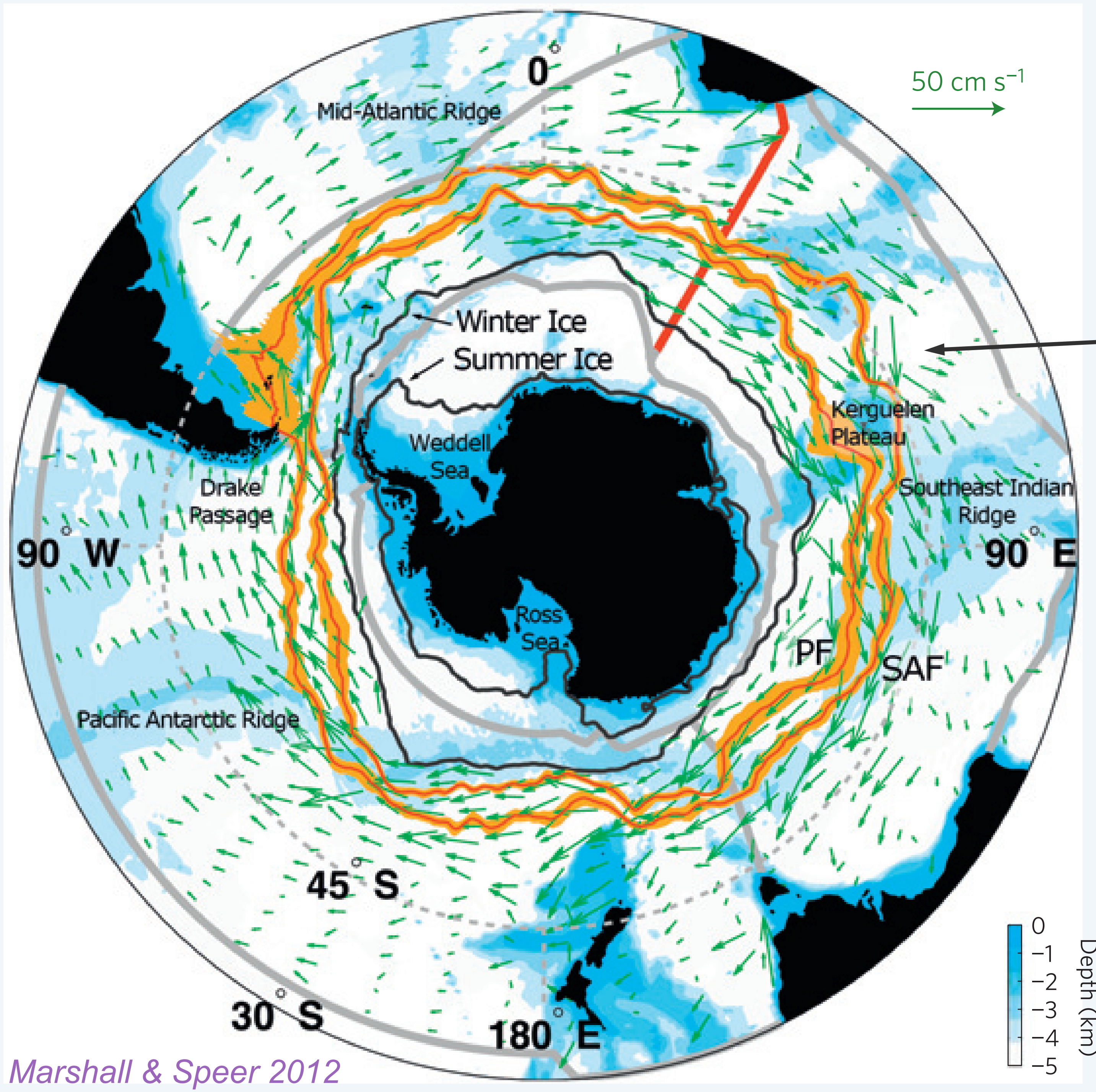


$5km^3$

next to Kerguelen Plateau 45S, 60E

$L_F \sim 500m$

$\nu = 10^{-6}\, m^2/s$



$5 km^3$

next to Kerguelen Plateau 45S, 60E

$L_F \sim 500m$

$U \sim 0.04 m/s$

$N = 0.001 /s$

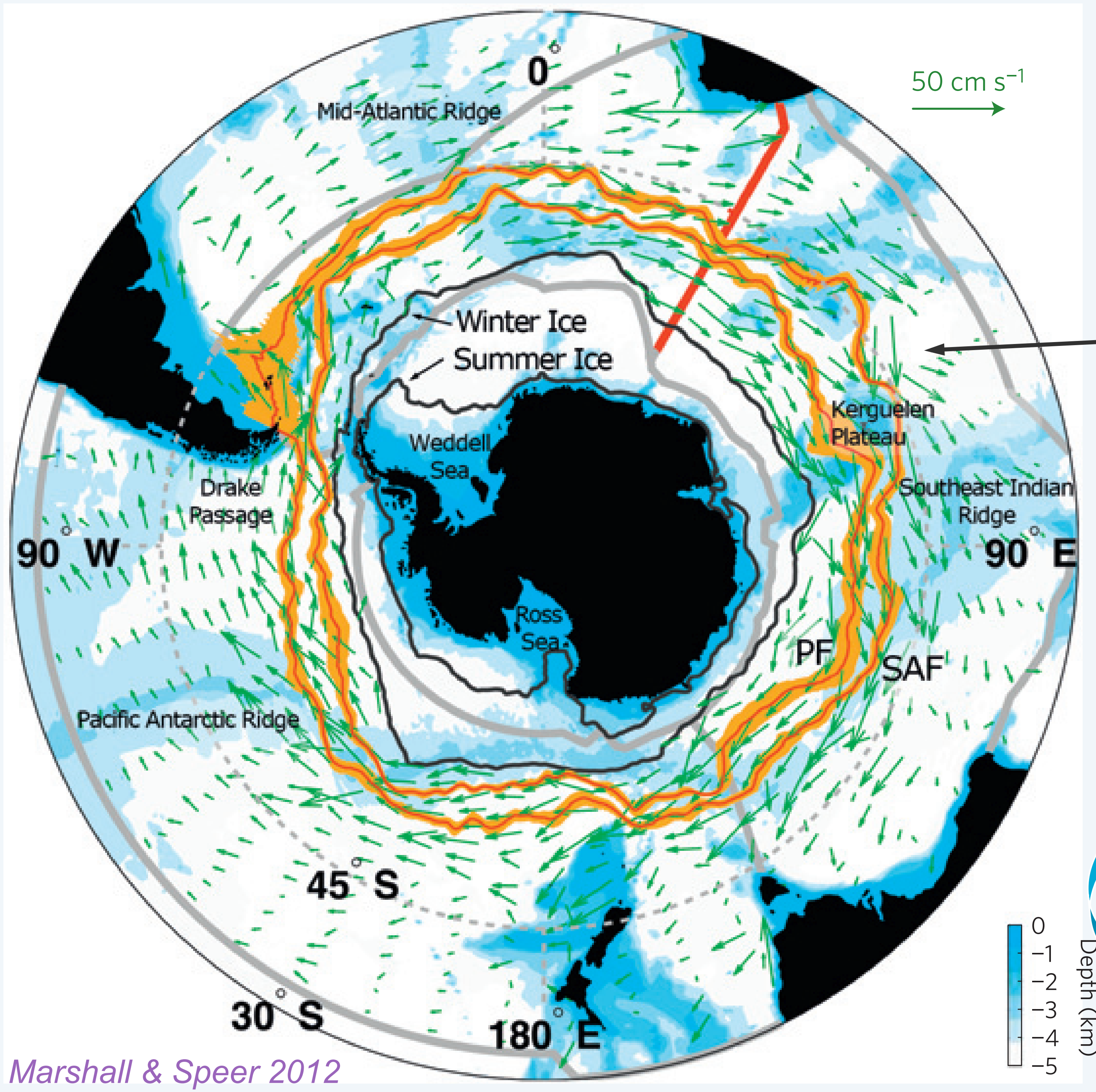
$f = N/10$

$\nu = 10^{-6} m^2/s$

$Re = 2x\ 10^7$

Fr= 0.08

Ro = 0.8

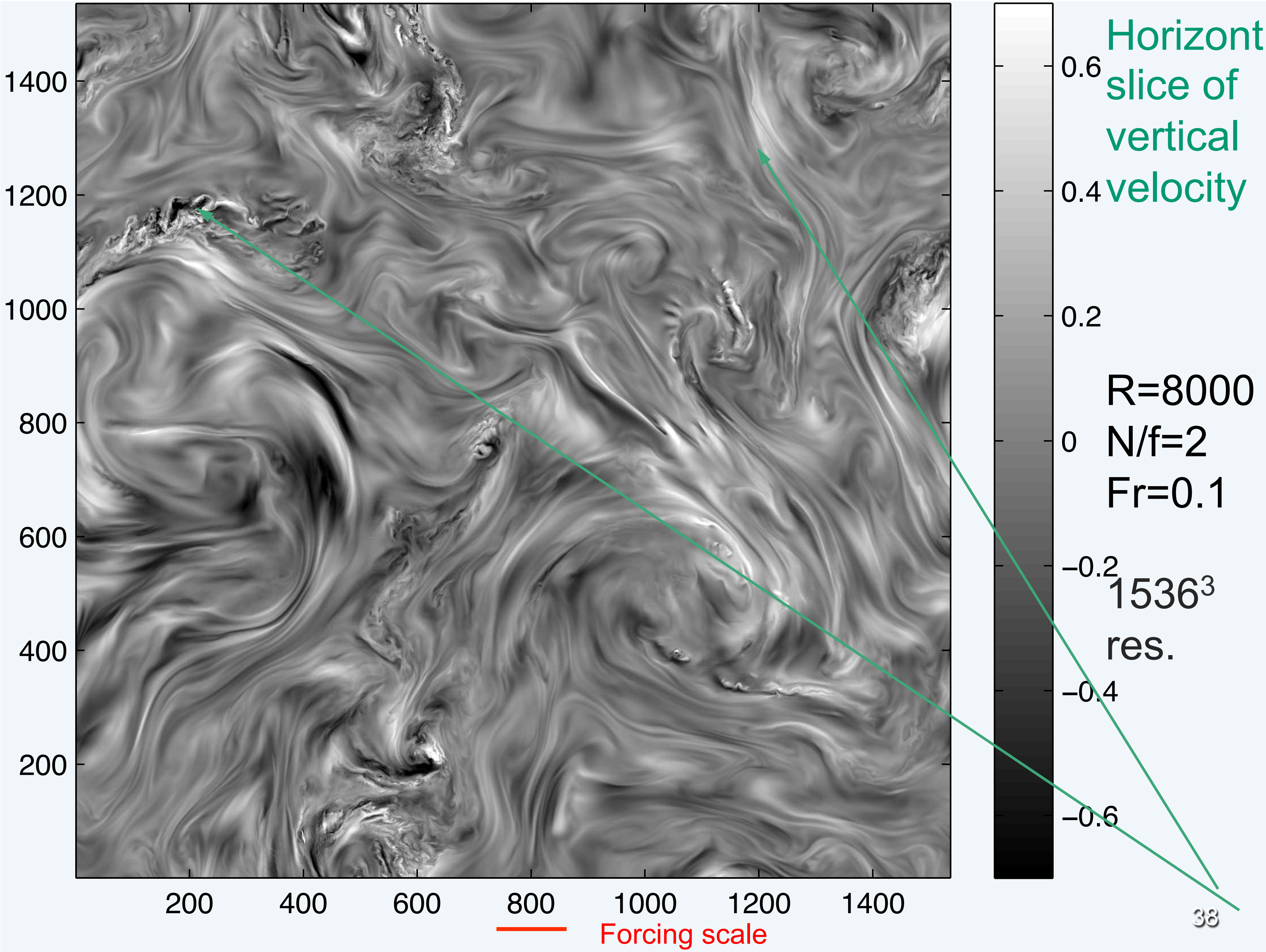


Marshall & Speer 2012

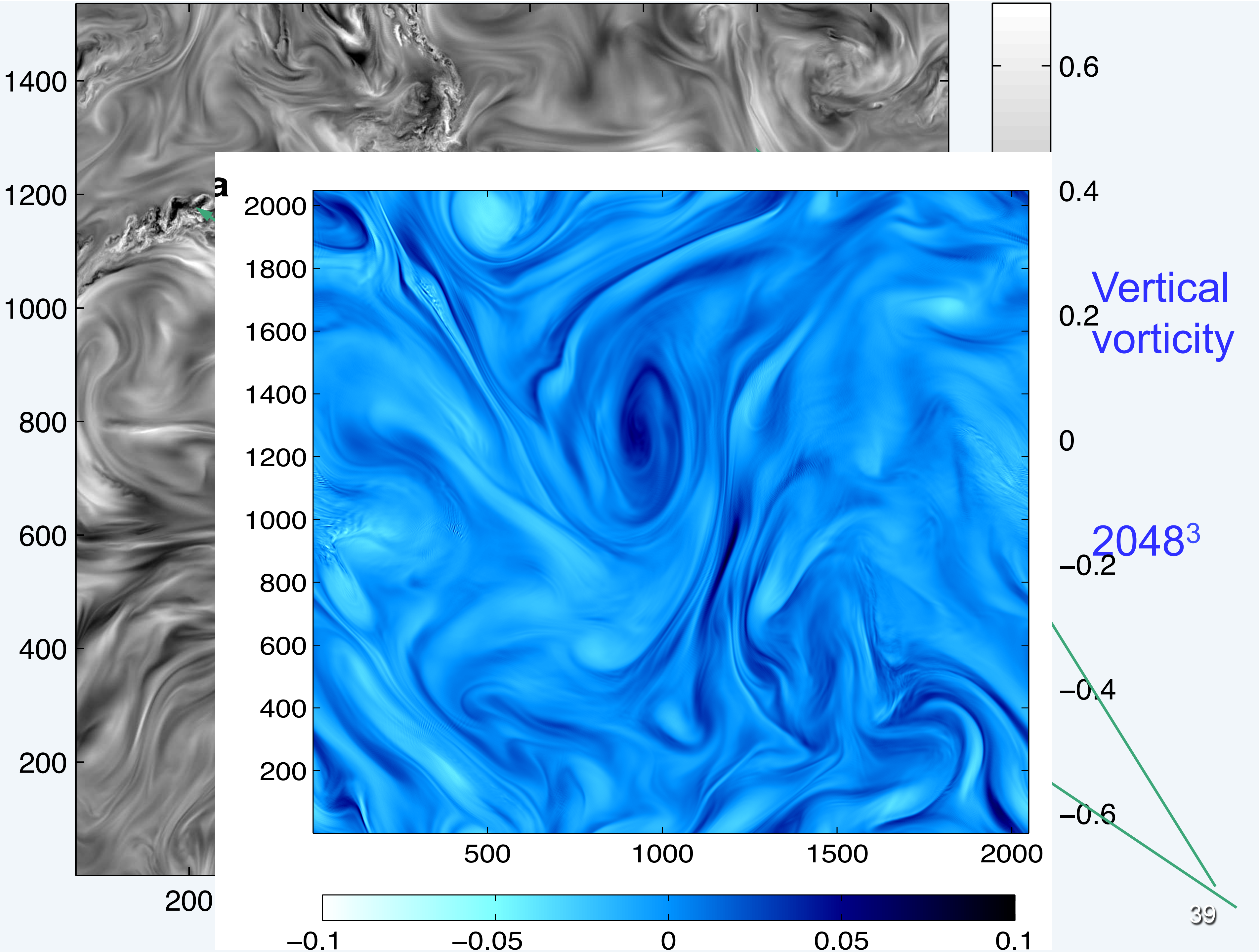
$5km^3$
next to Kerguelen Plateau
45S, 60E

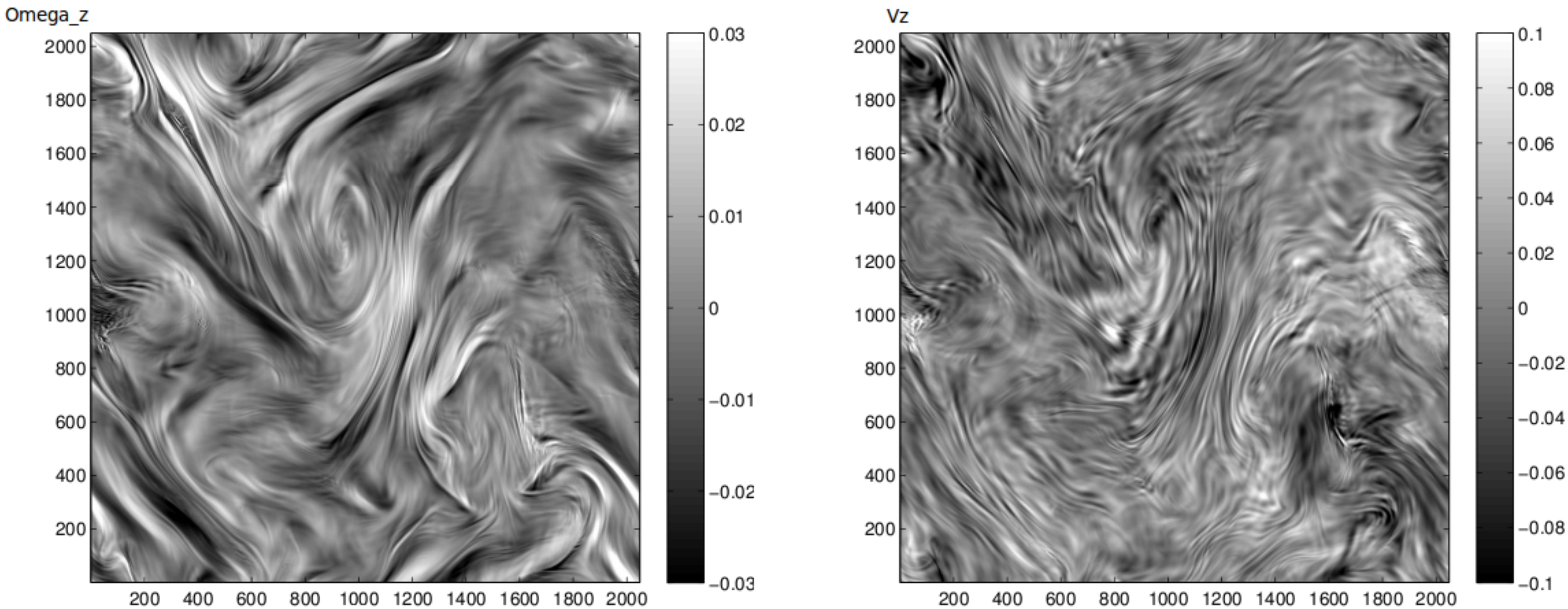
L_F~ 500m
U~ 0.04m/s
N=0.001 /s
f=N/10
$\nu = 10^{-6}\ m^2/s$
Re= 2x 10^7
Fr= 0.08
Ro = 0.8

DNS run
Boussinesq
Up to 2048^3 grid
$\nu = 8x\ 10^{-4}\ m^2/s$
Re=24000



Horizont. slice of vertical velocity
R=8000
N/f=2
Fr=0.1
1536^3 res.
Forcing scale
1400
1200
1000
800
600
400
200
0.6
0.4
0.2
0
−0.2
−0.4
−0.6


1400
1200
1000
800
600
400
200
200
0.6
0.4
0.2
0
−0.2
−0.4
−0.6
a
2000
1800
1600
1400
1200
1000
800
600
400
200
500
1000
1500
2000
−0.1
−0.05
0
0.05
0.1
Vertical vorticity
2048^3



2048^3

Marino et al., in preparation

Grids of 1024^3, 1536^3 and 2048^3 points, K_F=[10,11]

Run	Re	Fr	Ro	N/f	$\mathcal{R}_B$	R_Π	α
10a	5000	0.020	0.08	4	2.0	5.77	-3.99
10b	5000	0.045	0.18	4	10.1	2.70	-2.93
10c	5000	0.060	0.24	4	18.0	1.36	-2.34
10d	4000	0.040	0.08	2	6.4	9.04	-3.99
10e	5000	0.090	0.18	2	40.5	1.62	-2.12
15a	8000	0.100	0.20	2	80.0	1.08	-1.87
20a	12000	0.1	0.2	2	120	1.05	-1.77

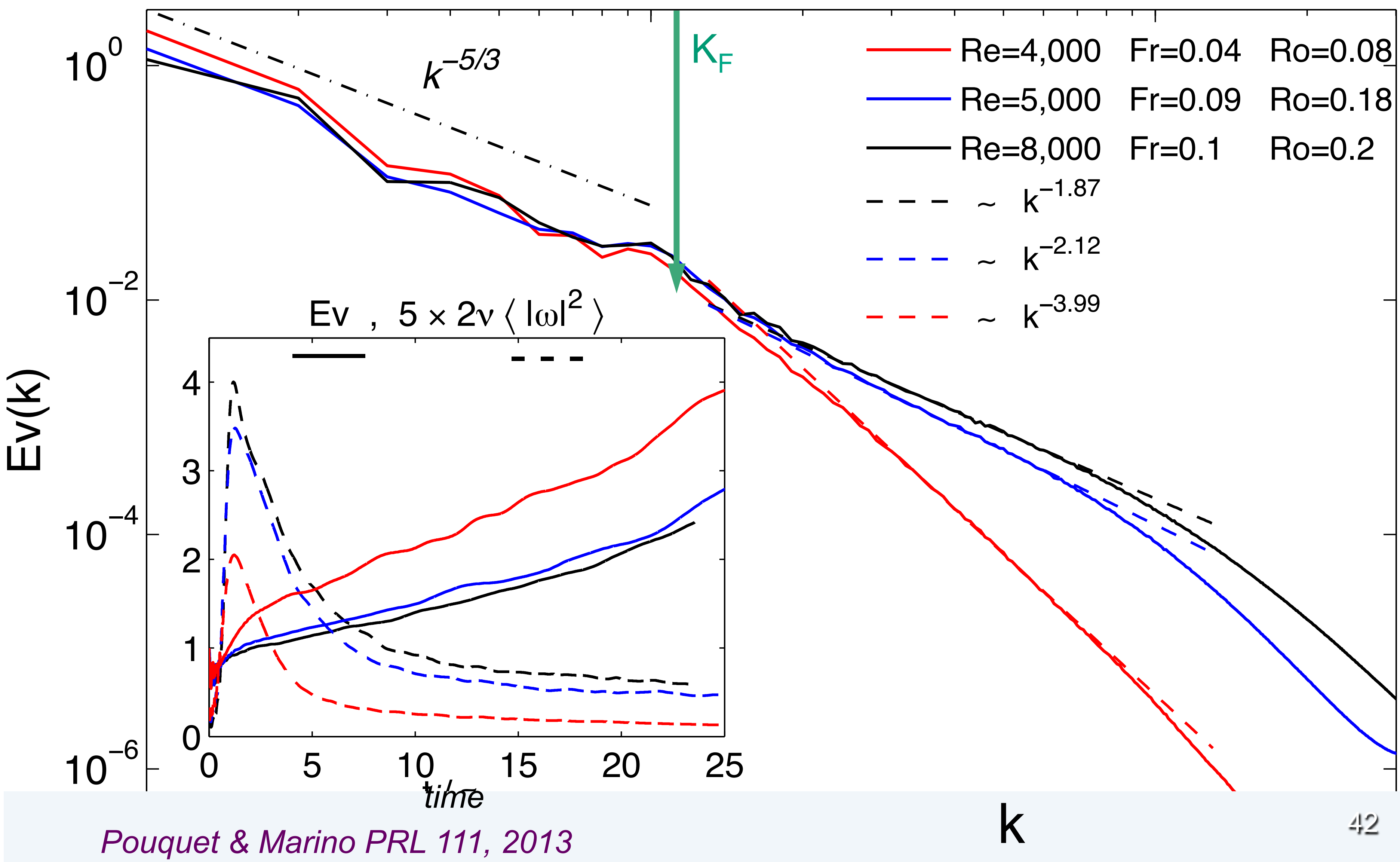
$Re=UL/\nu$, $Fr=U/[LN]$, $Ro=U/[Lf]$

$R_B=ReFr^2$

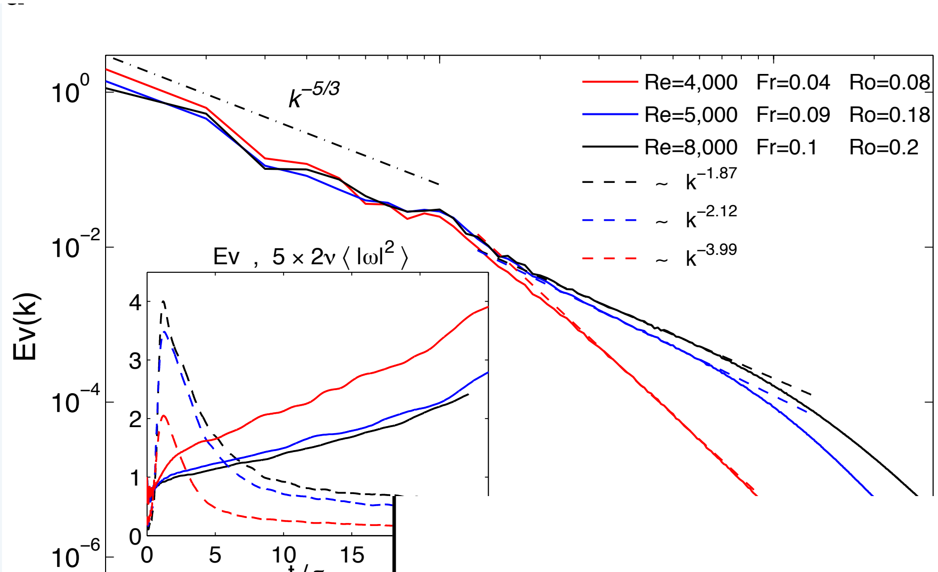
$R_\pi = \varepsilon_I/\varepsilon_D$, $E(k) \sim k^{-\alpha}$

Pouquet & Marino, PRL 2013, +

Spectra and temporal evolution, N/f=2

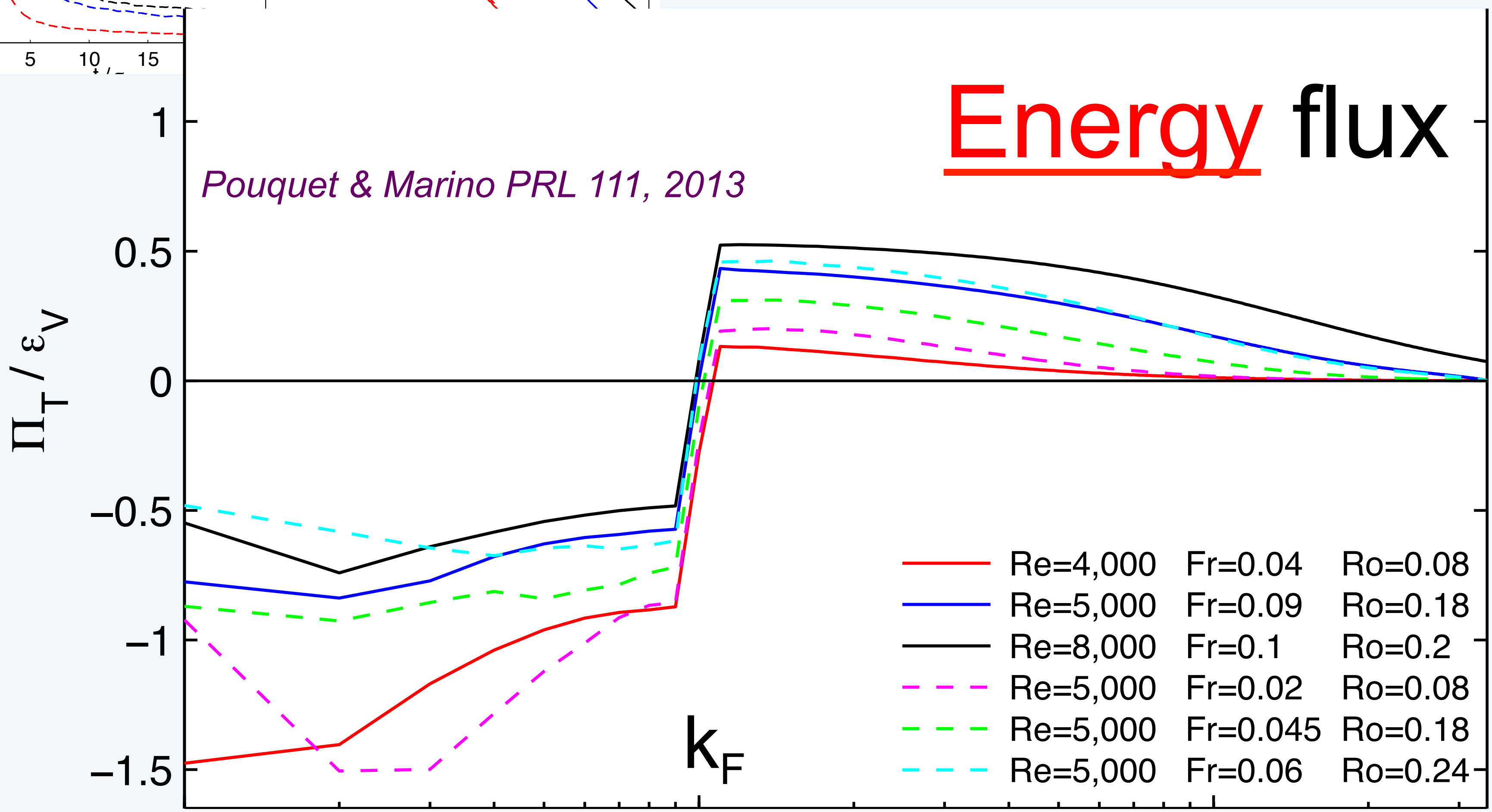


Pouquet & Marino PRL 111, 2013

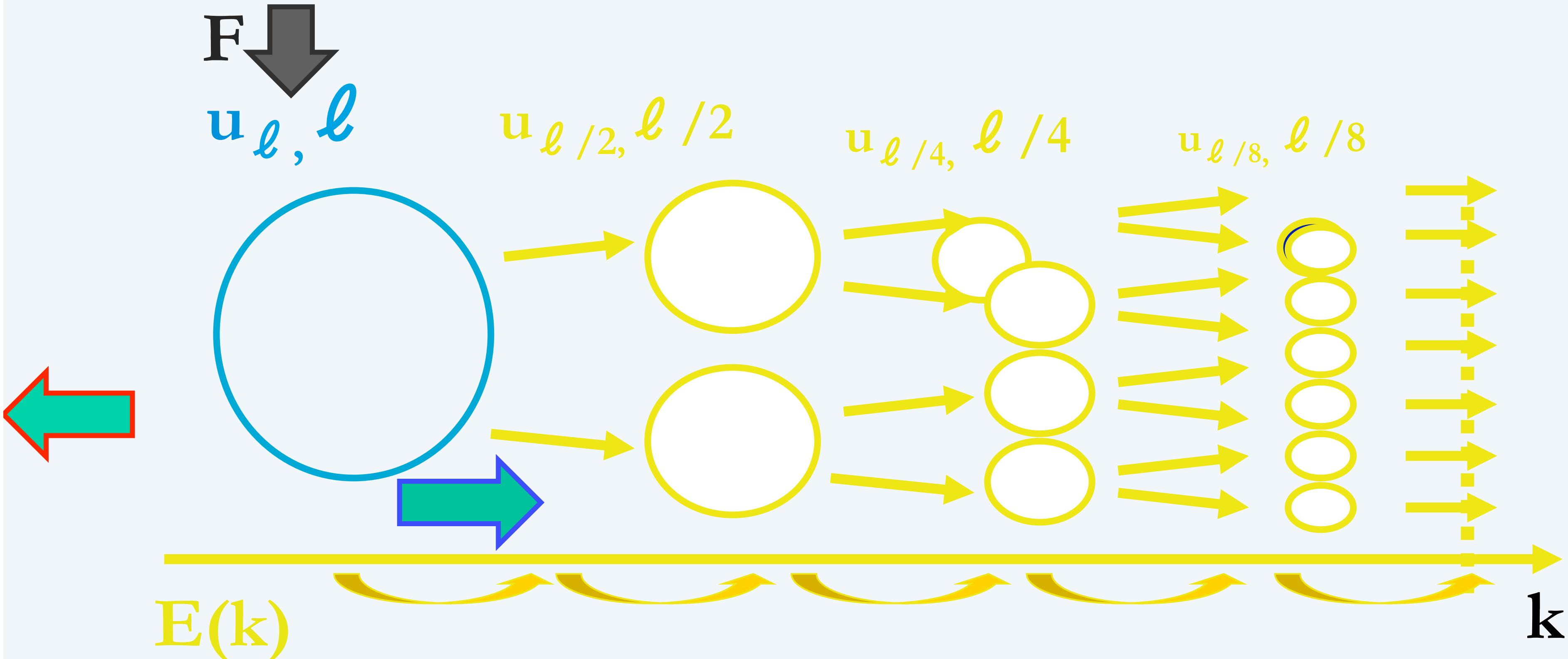


5/3 at large scale.

Evolution towards 5/3 at small scale as R_B grows



*Less classical picture of **quasi-2D** turbulence*

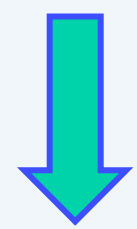


$\epsilon = dE/dt$: energy dissipation rate

$E \sim kE(k)$ (locality) and $\tau \sim \ell / u_\ell$ *(eddy turn-over time)*,

So: $\epsilon \sim u_\ell^{3} / \ell$

and $E(k) = C_K \, \epsilon^{2/3} \, k^{-5/3}$



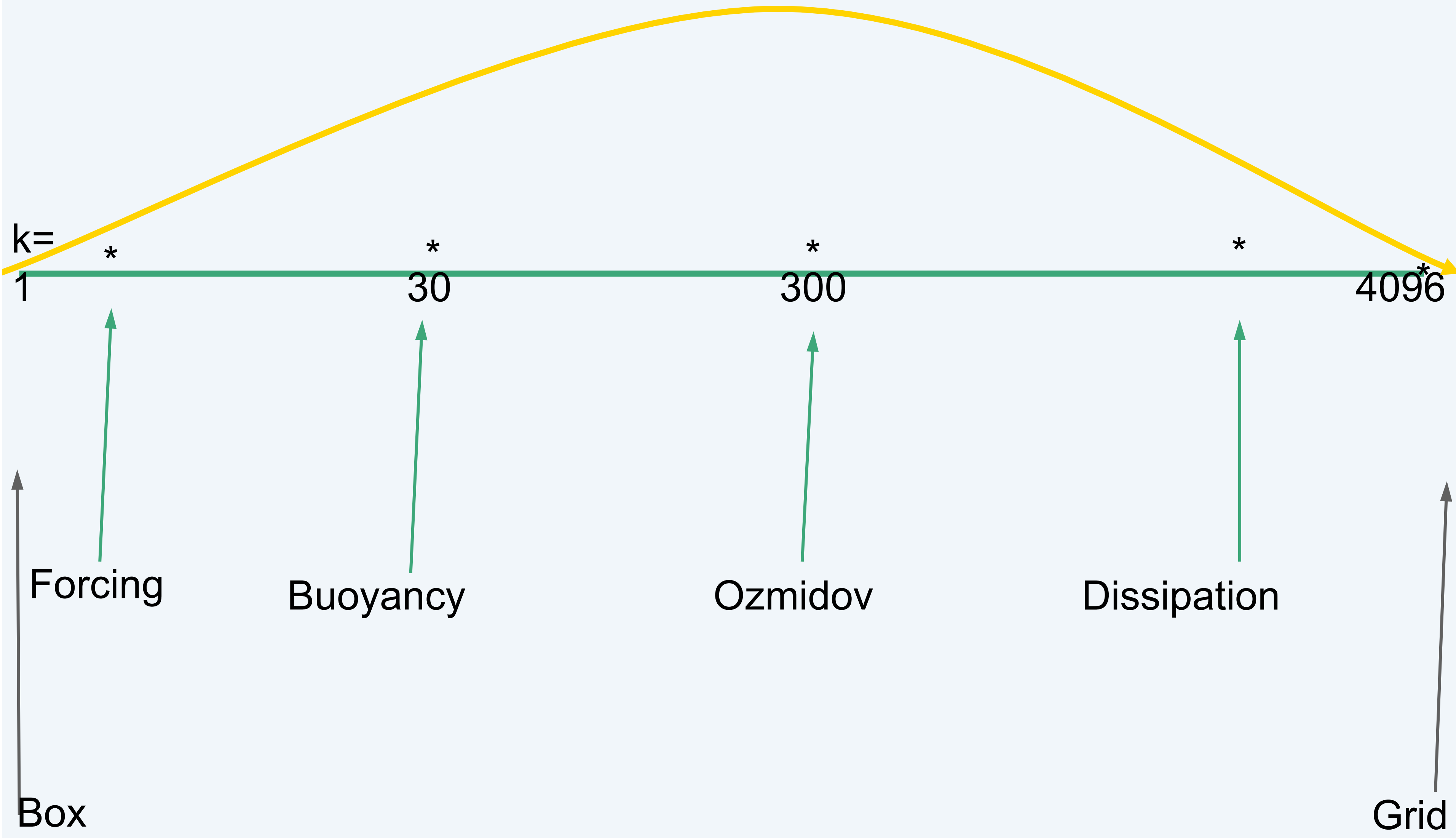
ν

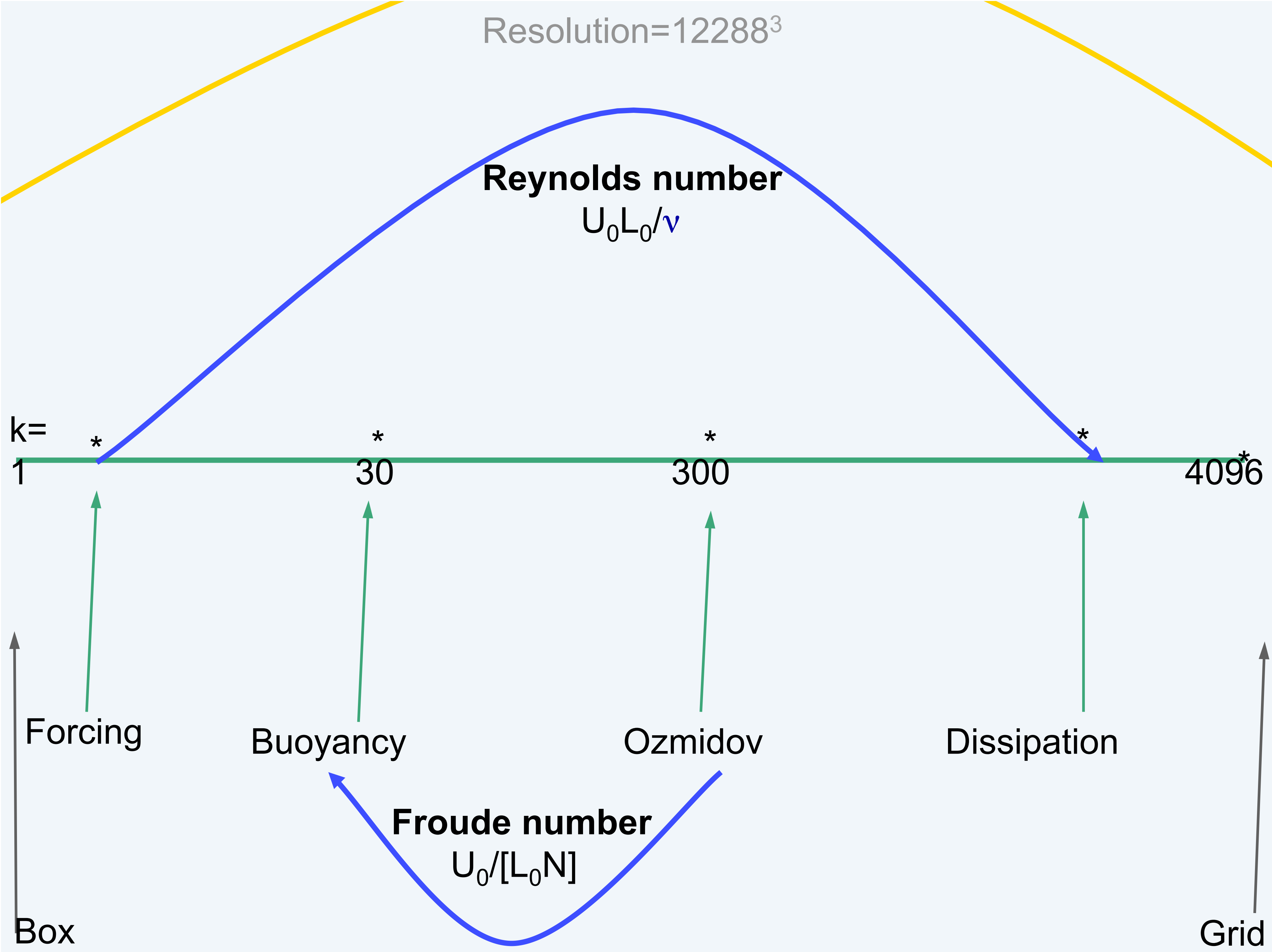
- As a matter of conclusion:

  – The lack of resolution when there is more than one inertial range: the emergence of two characteristic scales (buoyancy and Ozmidov)

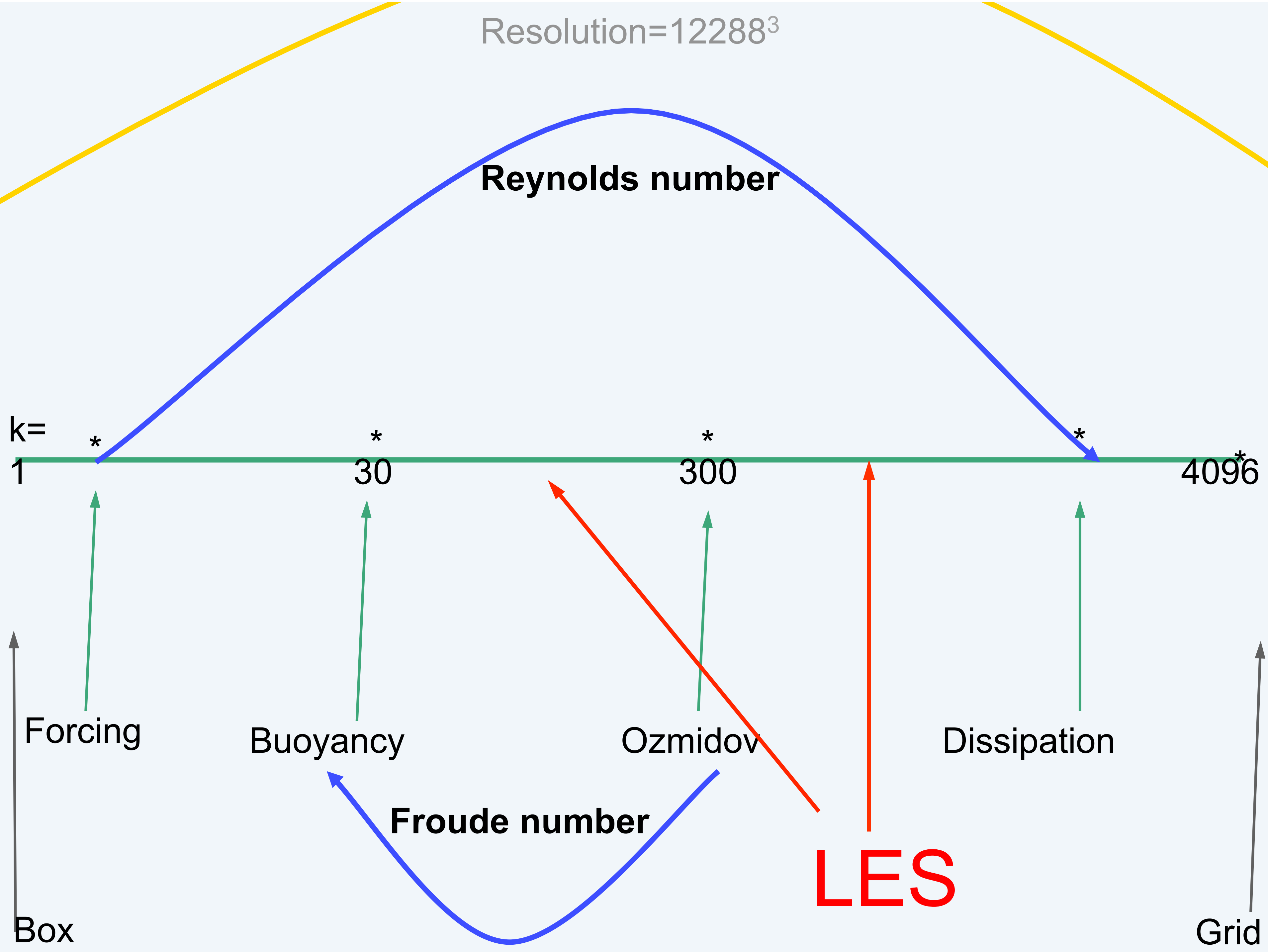
  → *A proposition for what would be a really big run of stratified (and rotating?) turbulence*

Grid of 12288^3 points





Resolution=12288^3
Reynolds number
U_0L_0/ν
k=
*
*
*
*
*
1
30
300
4096
Forcing
Buoyancy
Ozmidov
Dissipation
Froude number
$U_0/[L_0N]$
Box
Grid



Resolution=12288^3
Reynolds number
k=
*
*
*
*
*
1
30
300
4096
Forcing
Buoyancy
Ozmidov
Dissipation
Froude number
LES
Box
Grid

Future work and open questions

- Anisotropic analysis and normal-mode analysis
- Higher values of N/f (up to 20+) and Re (up to $2X10^4$)
- *Long-time accumulation at k=1, & large-scale friction?*

- *Different forcing, e.g. two-dimensional (balanced)*
- *Anisotropic box* *(cf Deusebio et al. 2014)*

- Role of conservation of potential vorticity?
- Role of non-local interactions? Of over-turning?

- Models of dual energy cascade with stat. mechanics *(Thalabard et al., 2014)* or *w.* phase transitions *(Sashesanayan et al. 2014)* or w. anisotropic eddy viscosity (>0, <0)?

- Thank you for your attention

*“In this unfolding conundrum of life and history there is such a thing as being too
late ... We may cry out desperately for time to pause in her passage, but time is
adamant to every plea and rushes on. Over the bleached bones and jumbled residue of numerous civilizations are written the pathetic words: "Too late". ‘’*

Martin Luther King Jr, 1967

After Clive Hamilton, Utopias in the Anthropocene, American Sociological Association 2012