Rotating stably stratified turbulence: Bolgiano-Obukhov scaling, wave-vortex partition and mixing

Annick Pouquet

Corentin Herbert & Raffaele Marino (ENS Lyon)
Pablo Mininni (U. Buenos Aires)
Duane Rosenberg (SciTex)

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Cargese, August 2016

pouquet@ucar.edu

Kolmogorov:

"*I soon understood that there was little hope of developing a pure, closed theory, and because of absence of such a theory the investigation must be based on hypotheses obtained on processing experimental data.*"

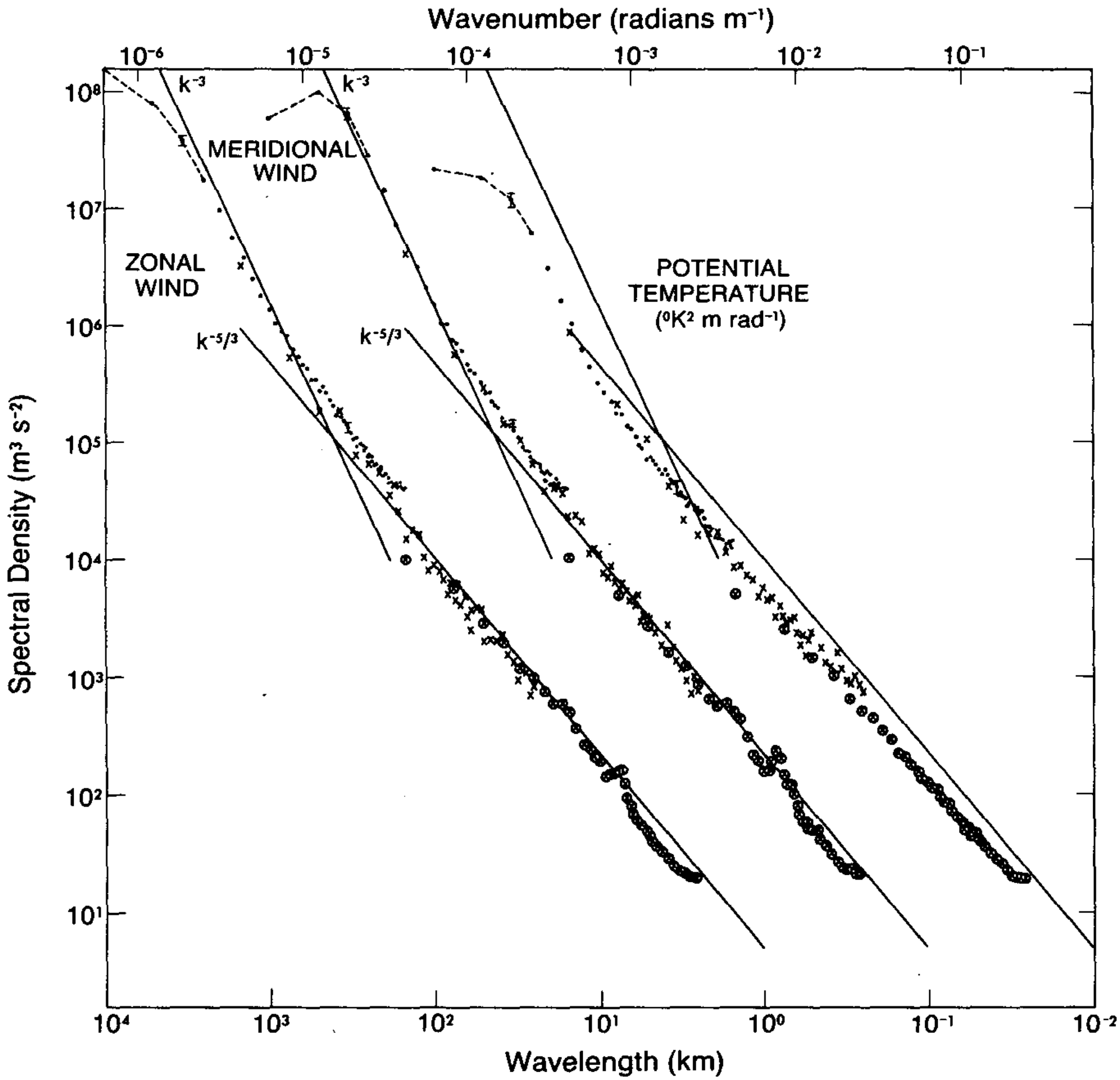


FIG. 3. Variance power spectra of wind and potential temperature near the tropopause from GASP aircraft data. The spectra for meridional wind and temperature are shifted one and two decades to the right, respectively; lines with slopes -3 and $-5/3$ are entered at the same relative coordinates for each variable for comparison.

$U \sim 20$ m/s

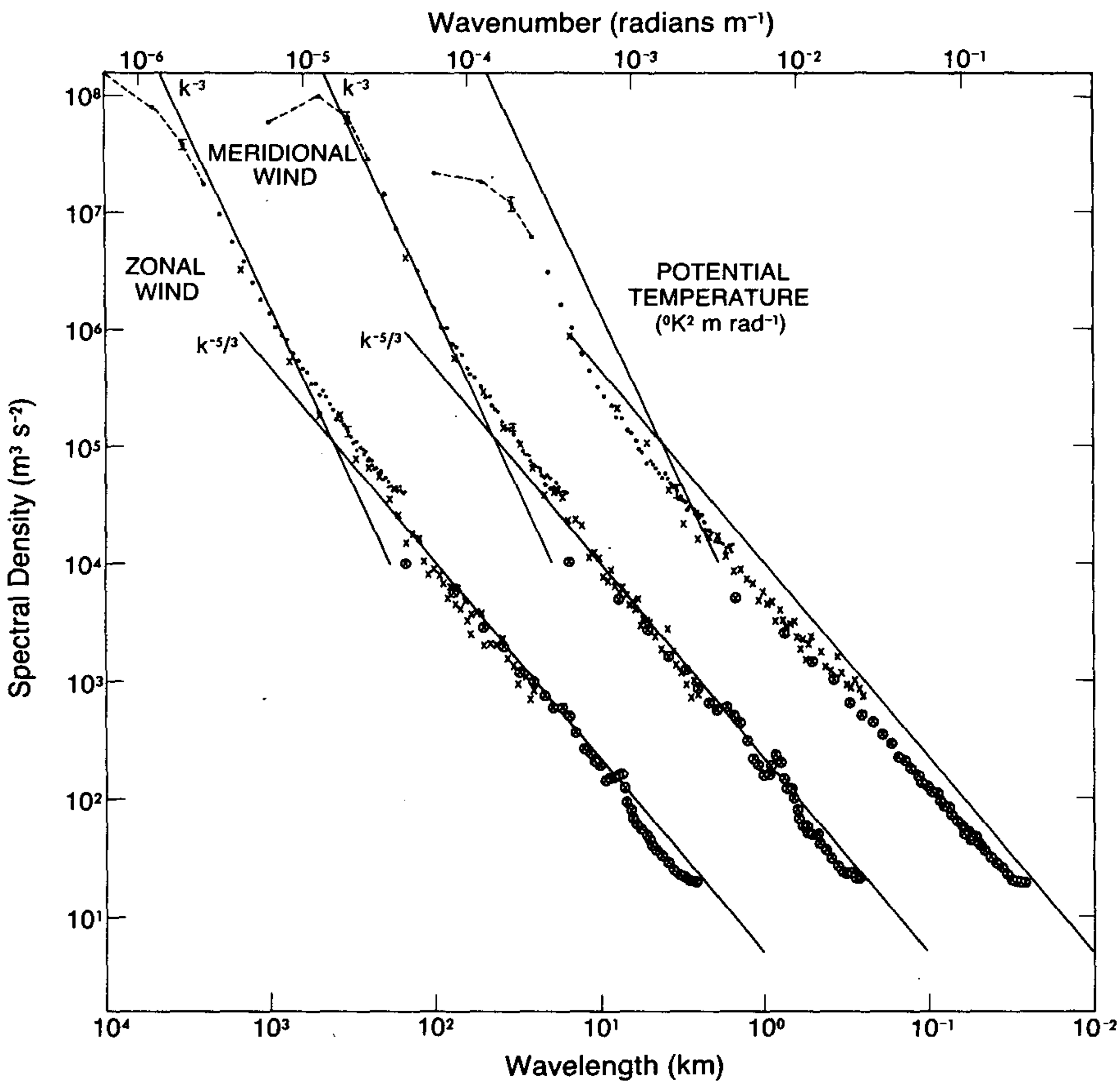
$N \sim 0.01$

$L_{Oz} \sim 100$ m

$\eta < 1$ mm →

Nastrom + 1985,87

Lindborg 2007



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Direction of energy flux?

$\eta < 1$ mm →

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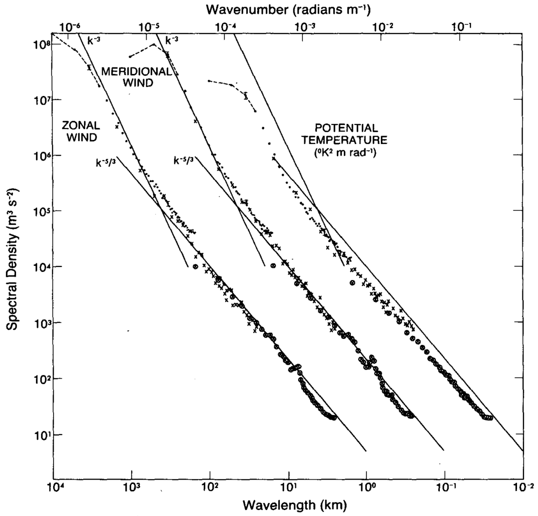

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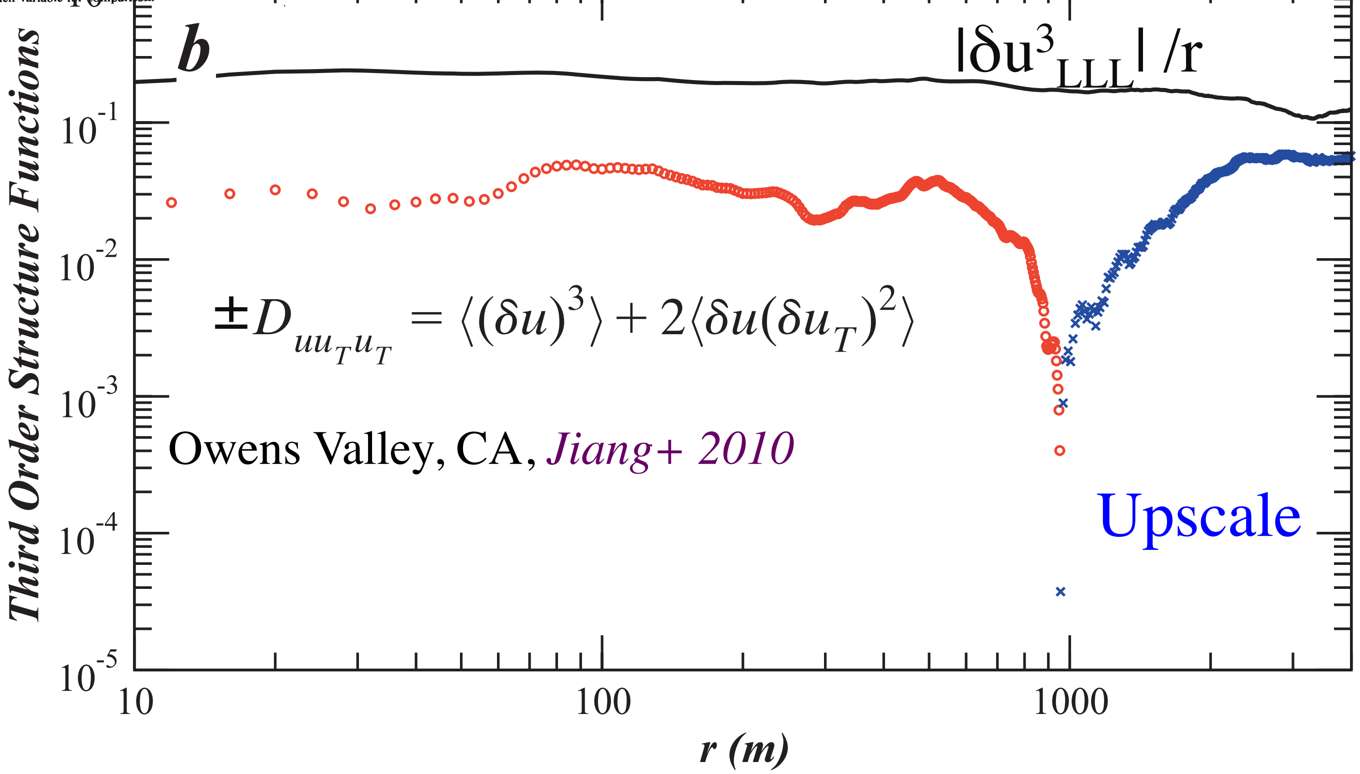

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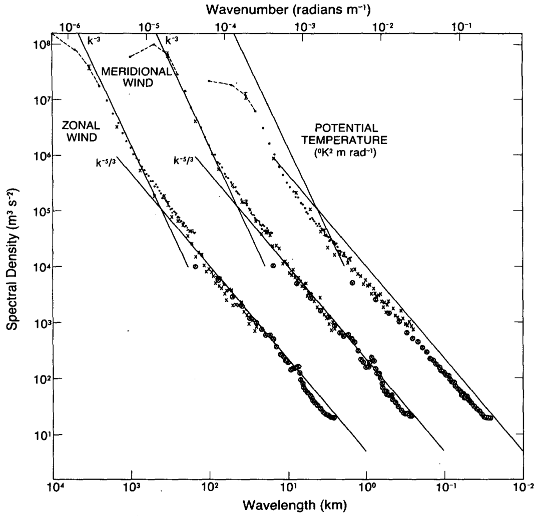

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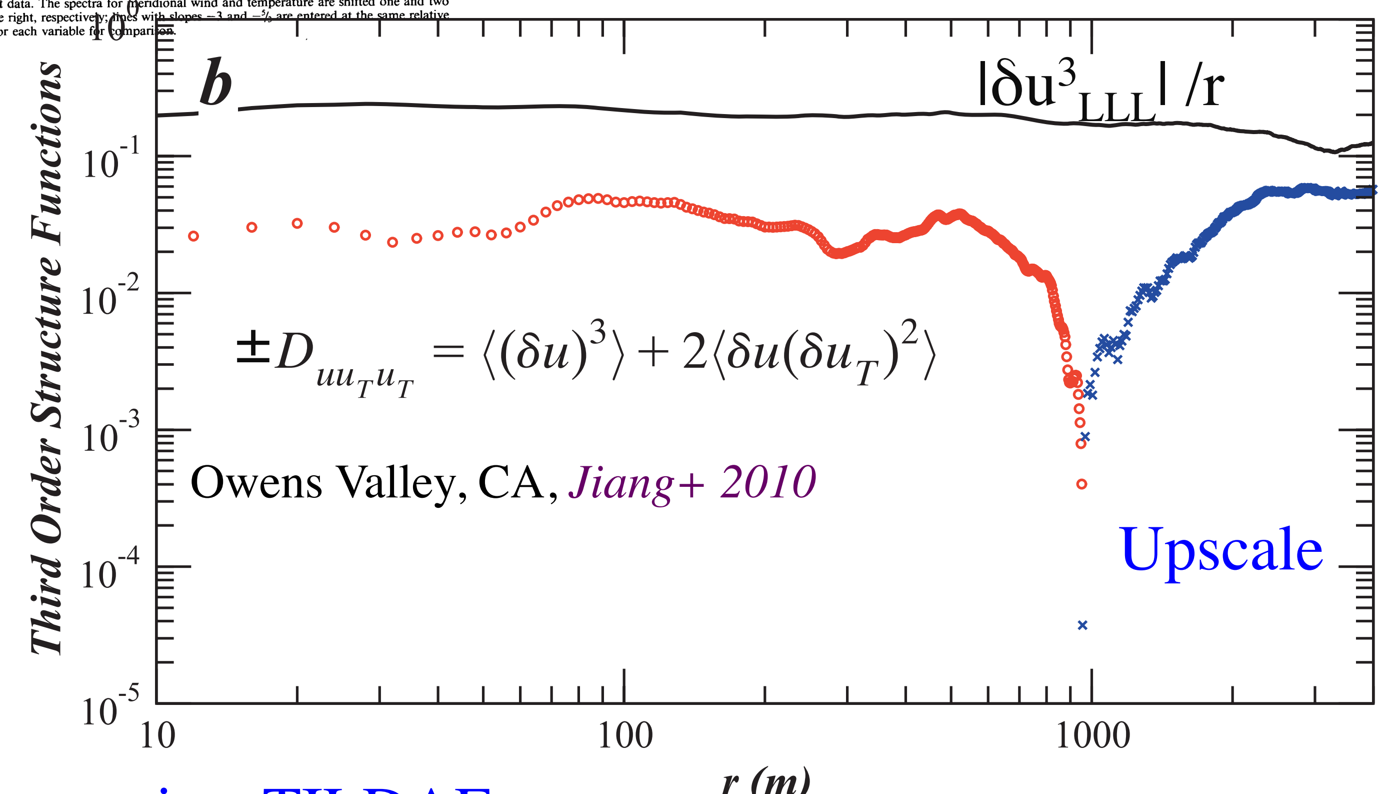

Direction of energy flux?

η < 1 mm

Antarctica: TILDAE exp. *(Marino+ 2017)*

Nastrom + 1985,87
Lindborg 2007

Incompressible Boussinesq equations
3D cubic box, periodic boundary conditions

$$\frac{\partial \mathbf{u}}{\partial t} + \boldsymbol{\omega} \times \mathbf{u} + 2\boldsymbol{\Omega} \times \mathbf{u} \;=\; -N\rho\hat{e}_z - \nabla\mathcal{P} + \nu\nabla^2\mathbf{u} \quad ,$$
$$\frac{\partial \rho}{\partial t} + \mathbf{u}\cdot\nabla\rho \;=\; Nw + \kappa\nabla^2\rho \ ,$$

Parameters, with f=2Ω:

$$Re = \frac{U_0 L_0}{\nu},\ Fr = \frac{U_0}{L_0 N},\ Ro = \frac{U_0}{L_0 f},\ Pr = \frac{\nu}{\kappa}\ , \qquad R_B = ReFr^2$$

The 2048^3, 3072^3 and 4096^3 runs:
$k_0 \sim 2.5$, N/f= 4.95, Re= 55000, Fr= 0.024, Ro= 0.12, Pr=1, R_B= 32

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$$\frac{\partial \rho}{\partial t} + \mathbf{u}\cdot\nabla\rho \;=\; Nw + \kappa\nabla^2\rho \;,$$

$[\varrho, \theta] = [L\, T^{-1}]$

Parameters, with f=2Ω:

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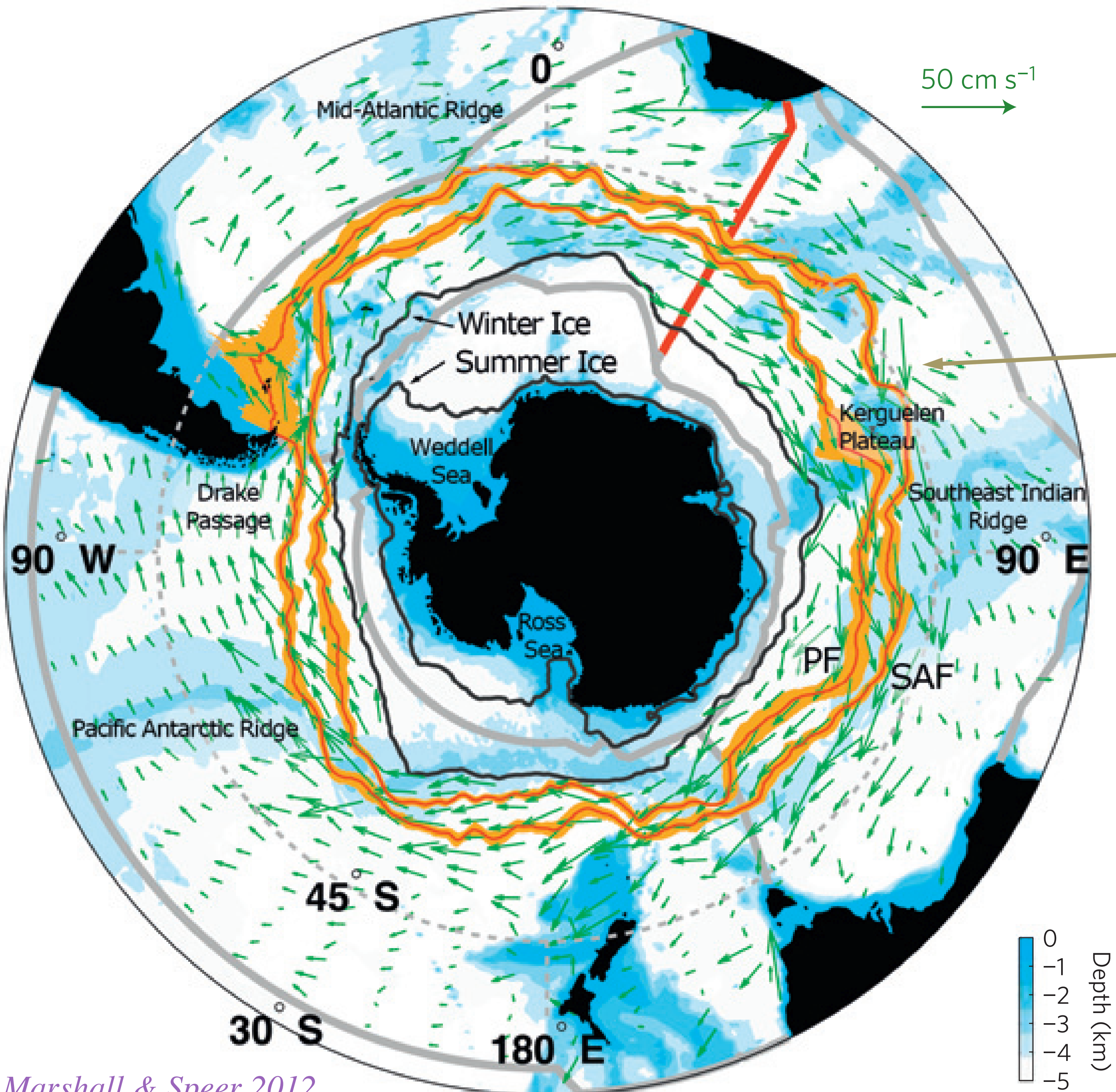


Cubic box of turbulence

next to Kerguelen Plateau 45S, 60E

Marshall & Speer 2012

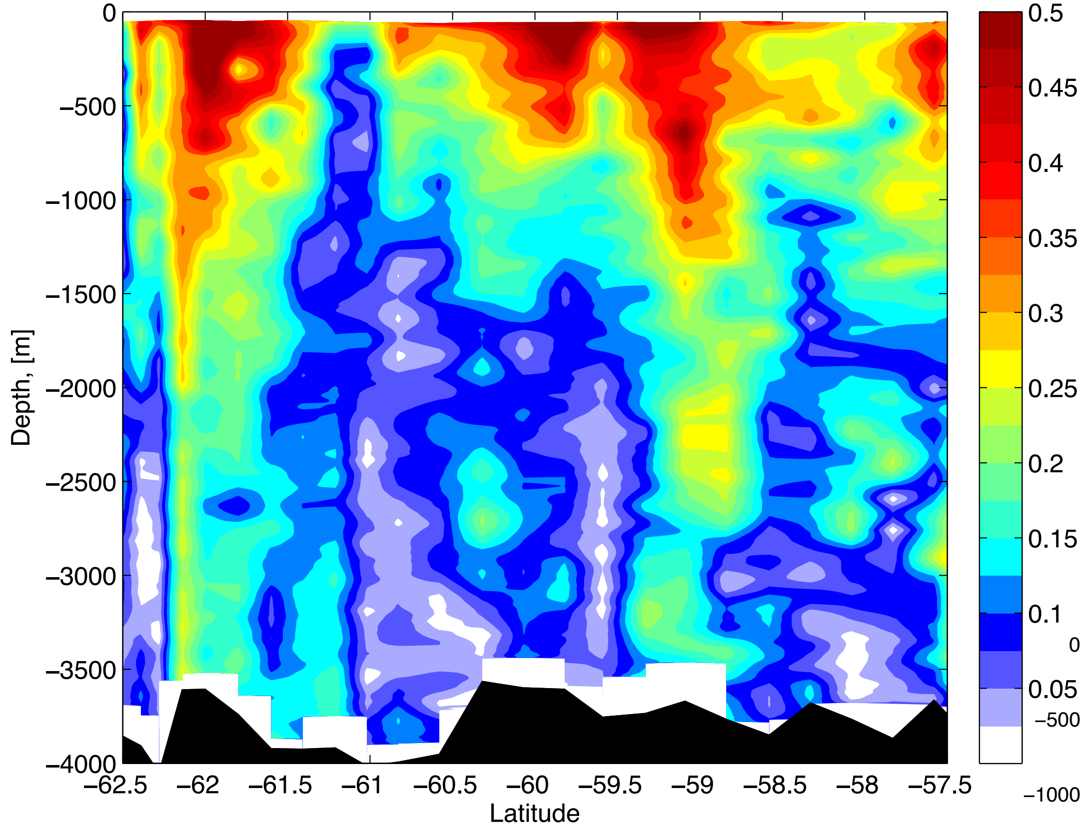


Figure 3-2: Flow speed (m s^{-1}) from the ALBATROSS section, Drake Passage.

Measurements in in the Southern Antartic Ocean

(Drake passage)

← of flow speed

and of buoyancy frequency

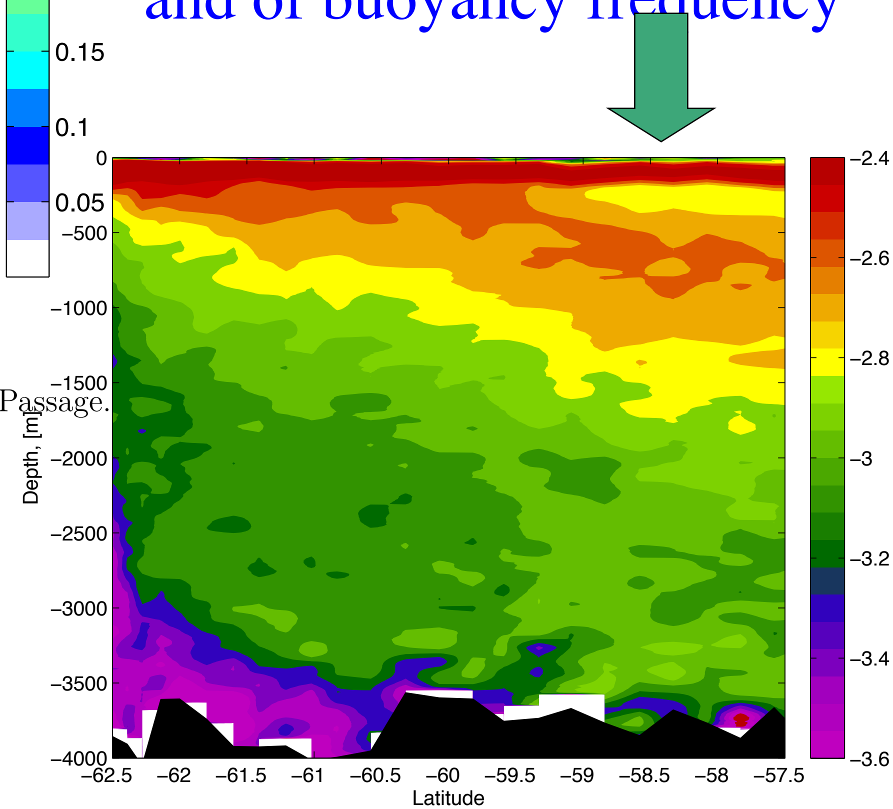
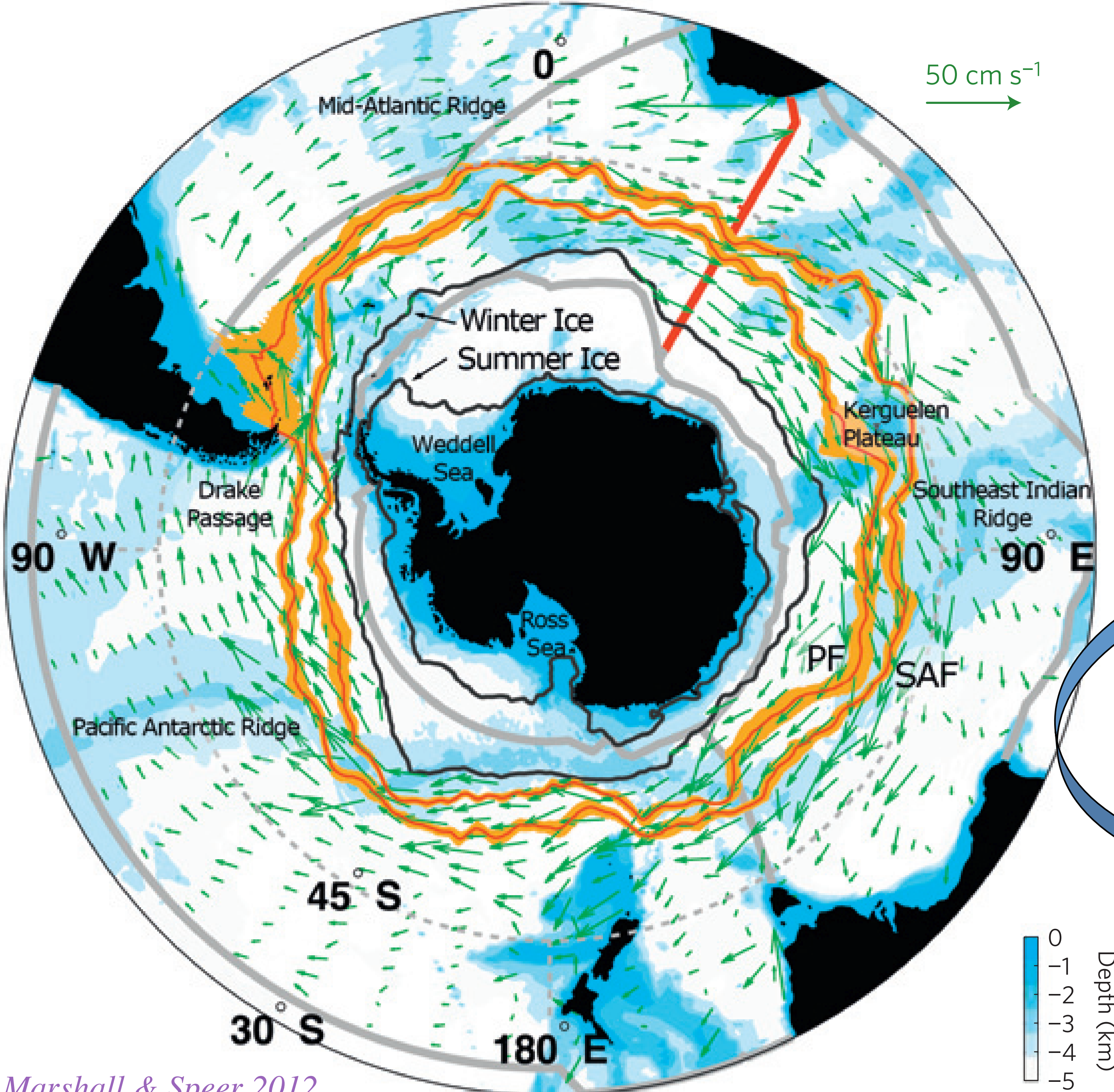


Figure 3-1: Buoyancy frequency (s^{-1}) in logarithmic scale from the ALBATROSS section, Drake Passage.

Nikurashin, 2009

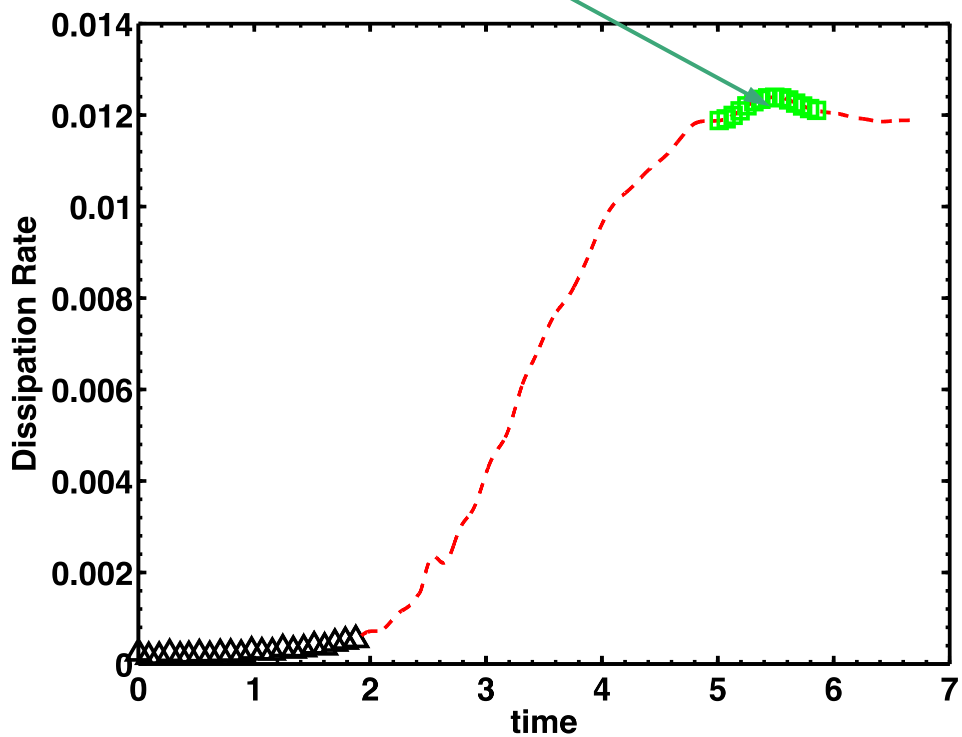


Marshall & Speer 2012

$L_0 \sim 1000m$
$U \sim 0.024 m/s$
$N = 0.001 /s$
$f = N/5$
Fr= 0.024
Ro = 0.12
$\nu = 10^{-6} m^2/s$
$Re = 2.\ 10^7$
$R_B \sim 10^4$

DNS run
Boussinesq
4096^3 grid
$\nu = 4.5\times10^{-4}\ m^2/s$
Re=55000
$R_B \sim 32$

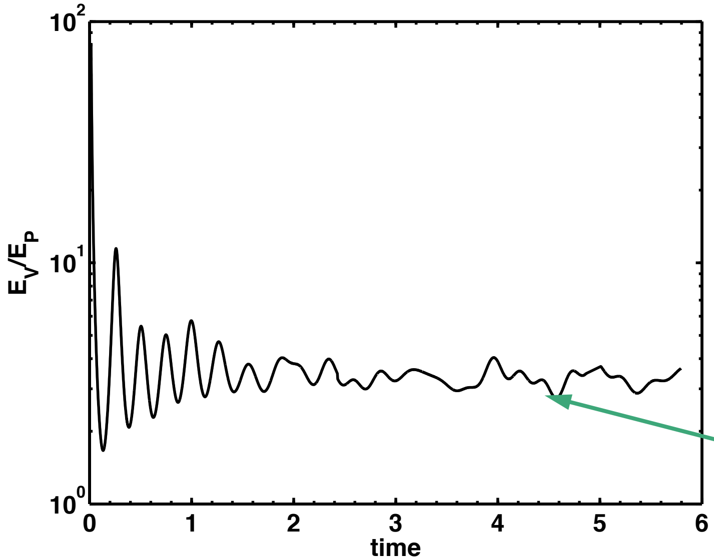
The short 4096^3 run
at peak of dissipation

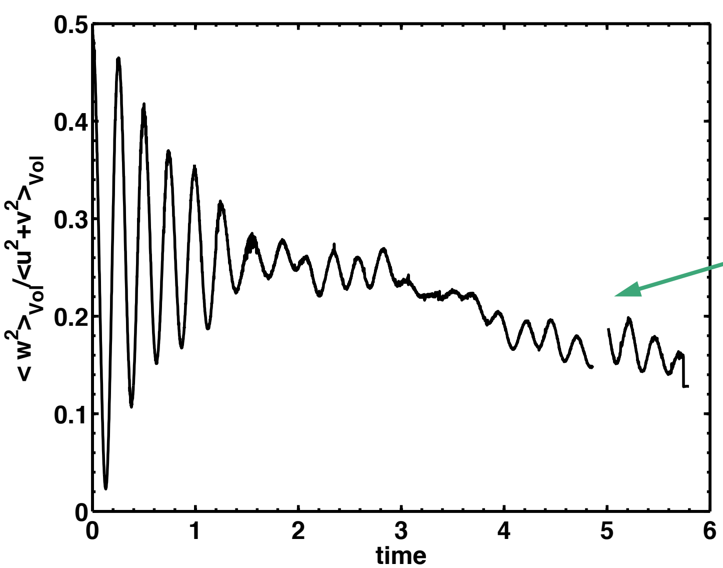


N/f=4.95
Fr=0.024, Ro=0.12
Re=55000, R_B=32

Spin-down
K_0=2.5

Triangles: 1536^3 grid- NSF
- - - - : 3072^3 grid- NSF
. . . Green: 4096^3 grid- DOE





Energy ratios

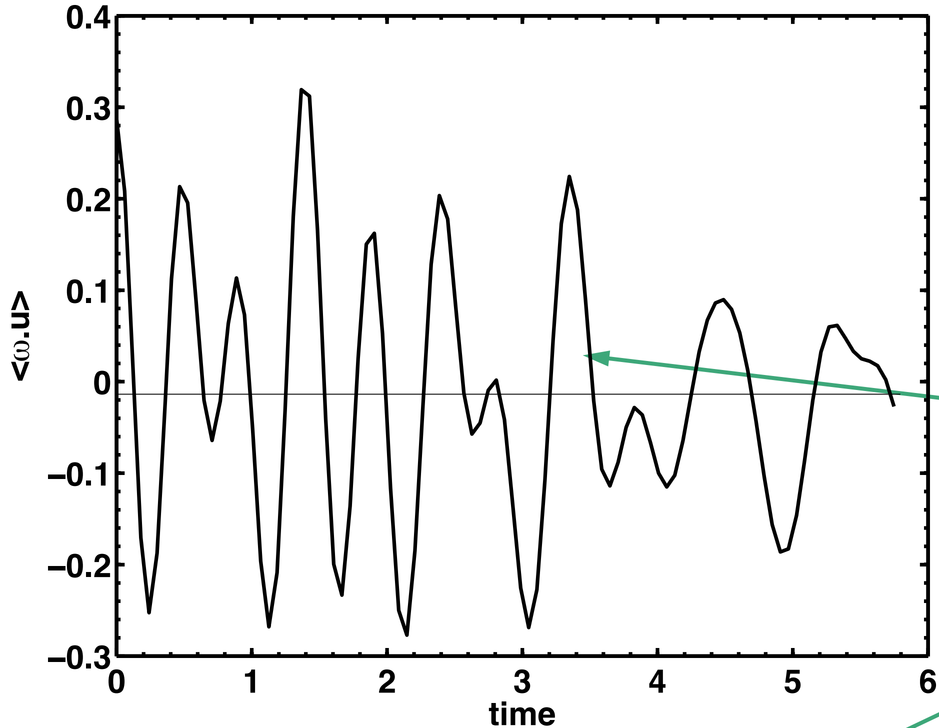
Fr=0.024, R_B=32

Kinetic to potential: ~ 3

And

Vertical to horizontal: ~ 0.12

4096^3 data



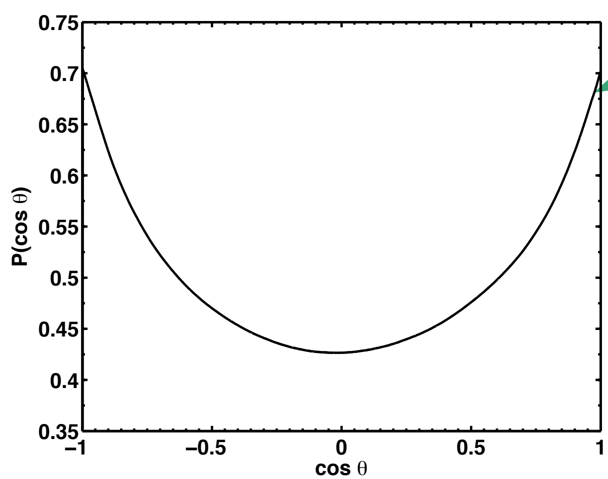
N/f=4.95

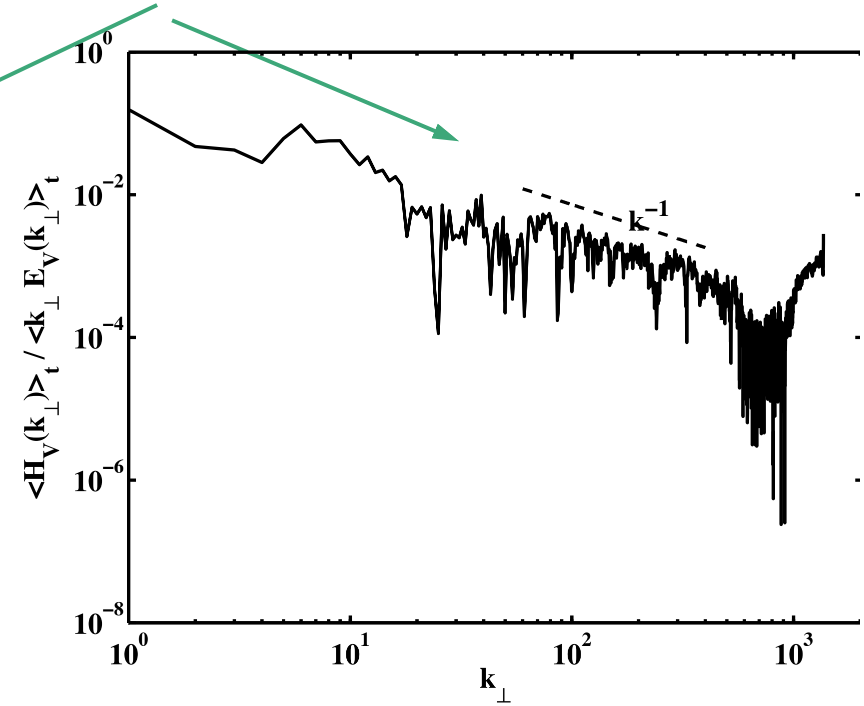
Fr=0.024, Ro=0.12

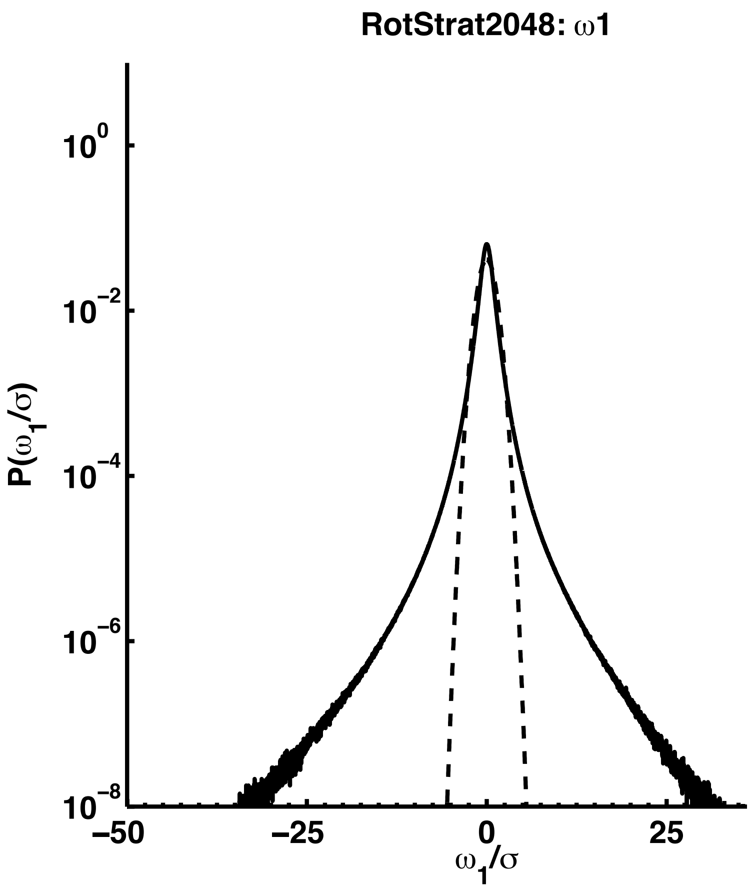
Re=55000, R_B=32

K_0=2.5, spin-down

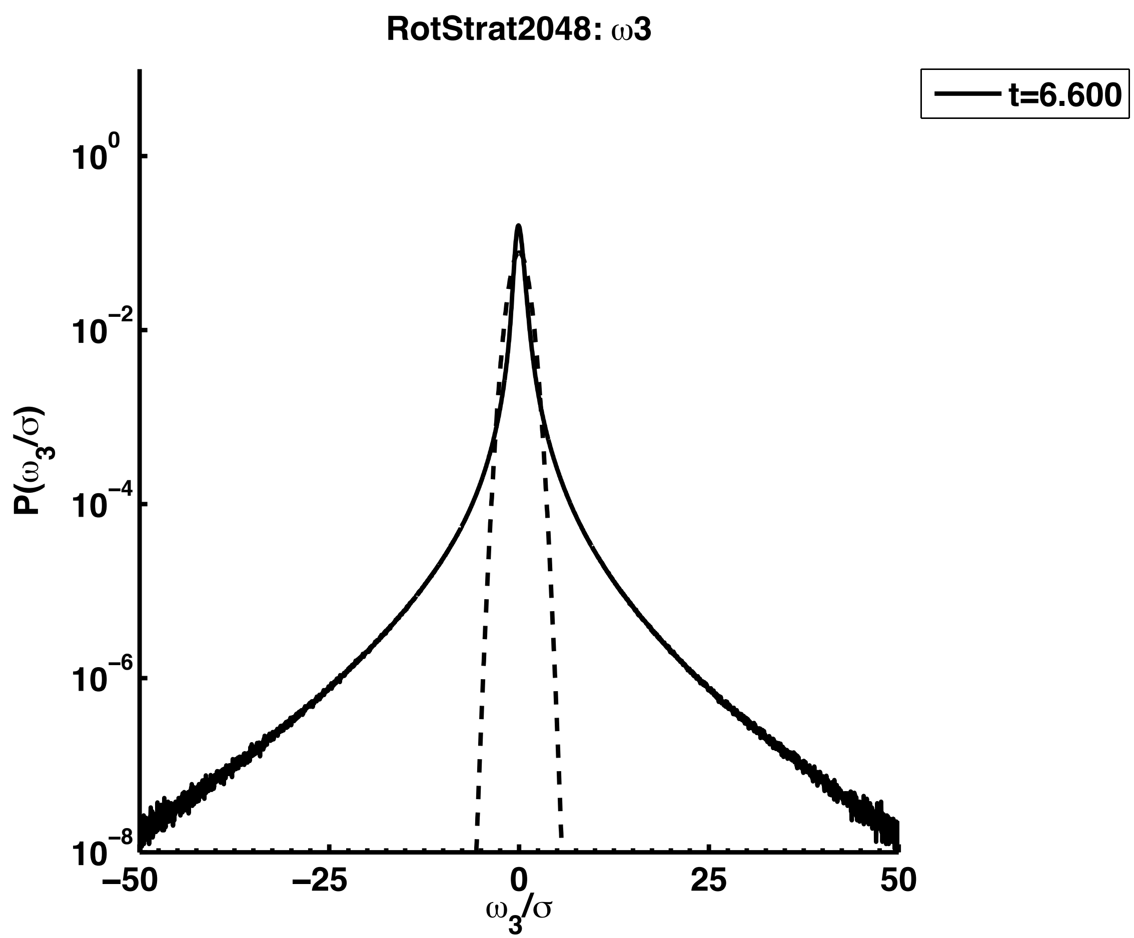
Total helicity and
PDF of relative helicity
and rel. helicity spectrum



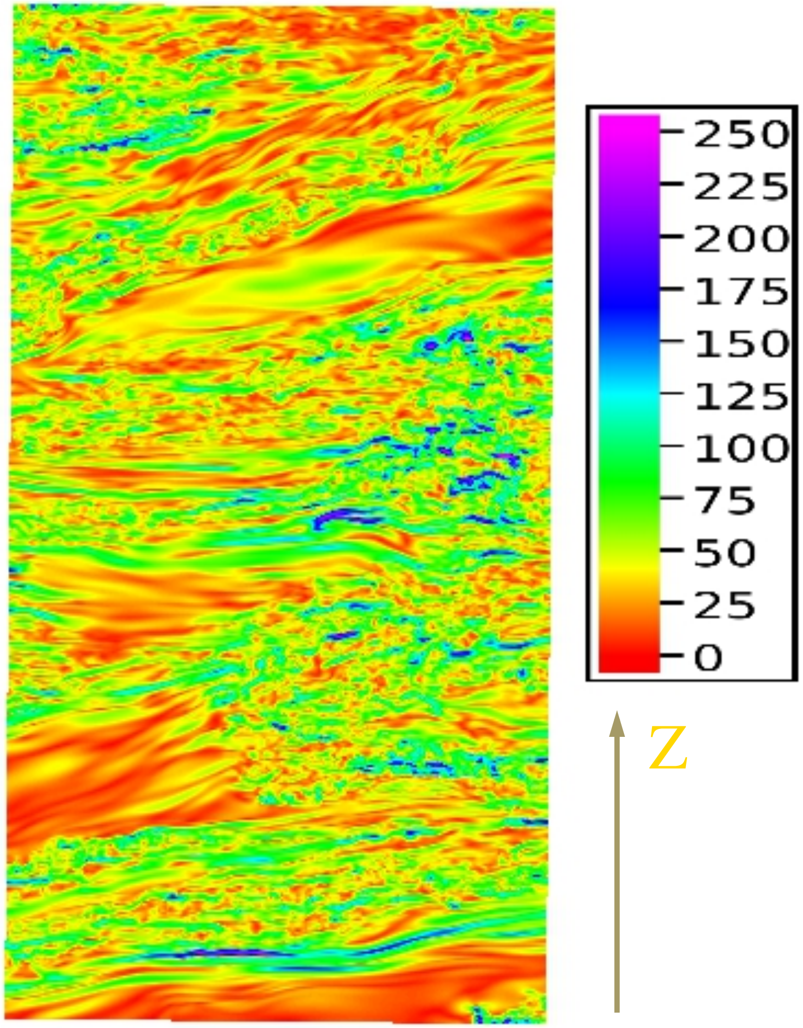




Vorticity components, 2048^3 run



$\omega_{rms} \sim 17$

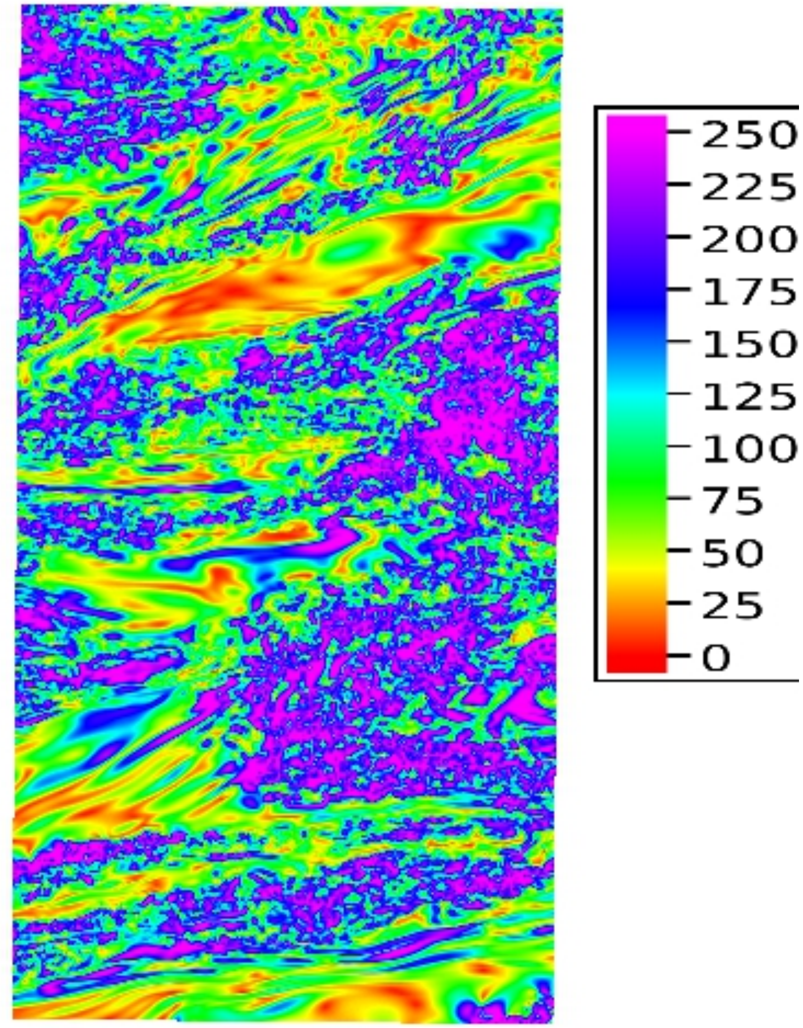


4096^3 run

0.7 X 0.4

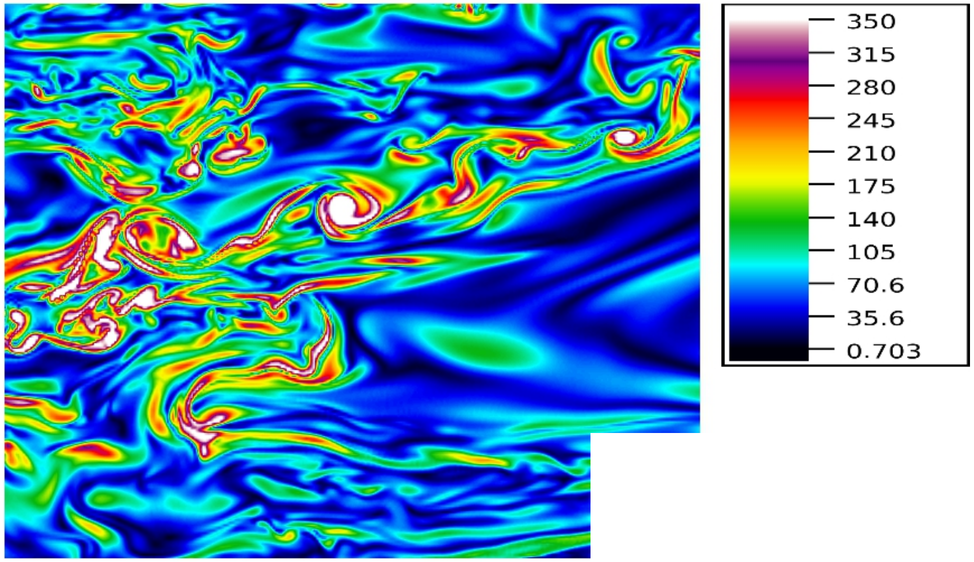
X 0.04

(PVR)



QG in small scales?

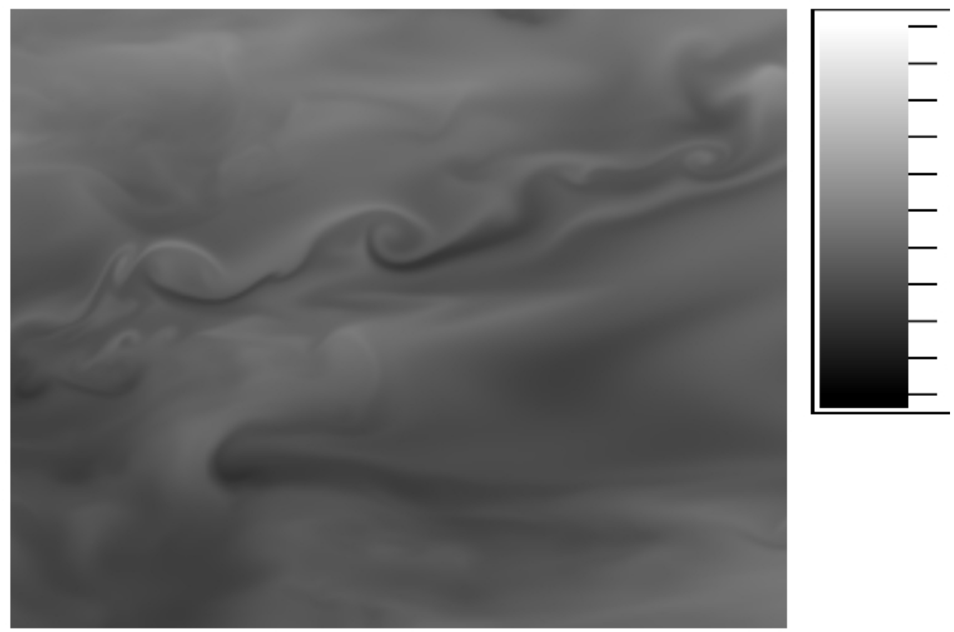
$$|[\partial_z u, \partial_z v]| \quad = \quad [N/f]^* \, |[-\partial_y\theta, \partial_x\theta]|$$



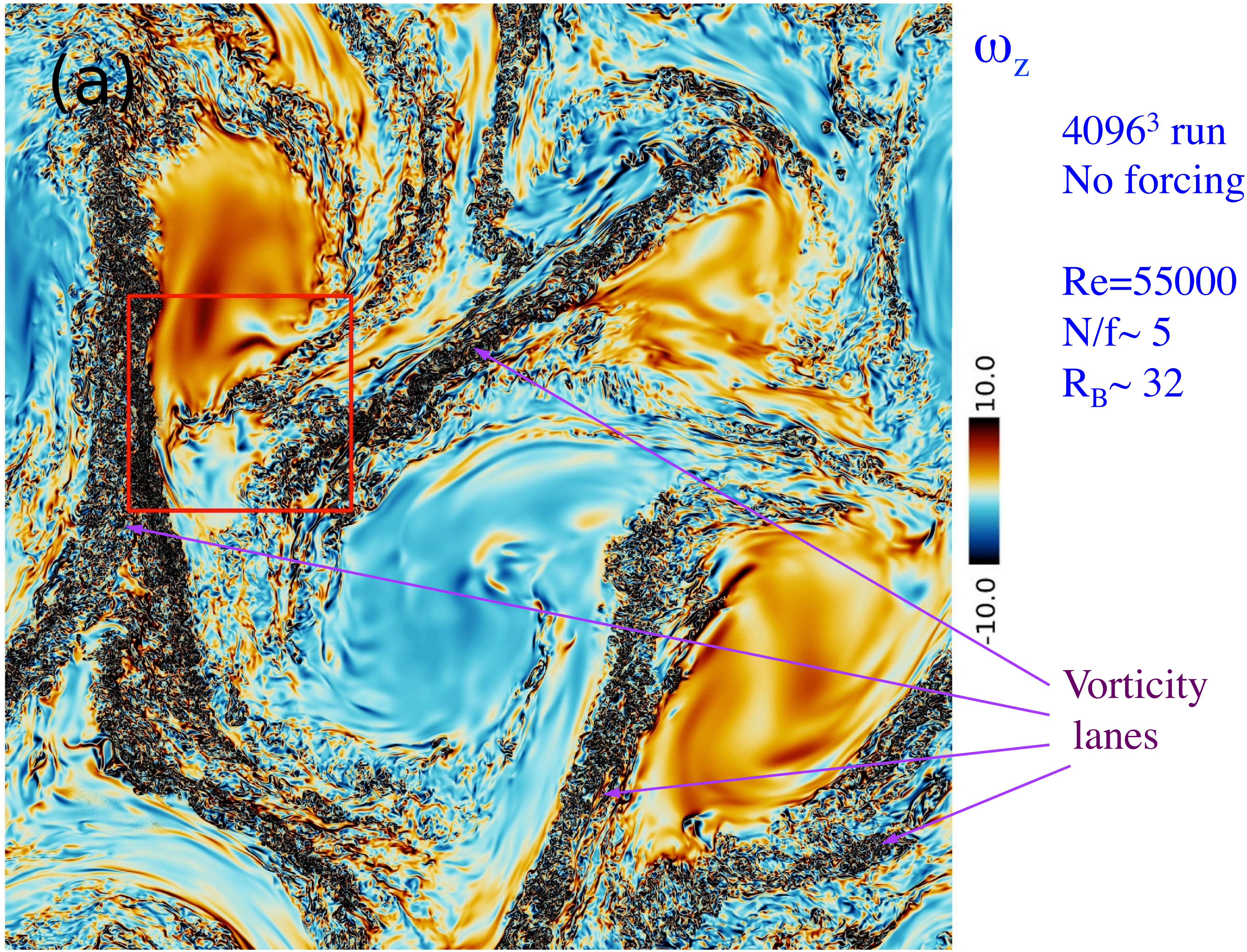
N/f=4.95
Fr=0.024, Ro=0.12
Re=55000, R_B=32
K_0=2.5, spin-down

z

Zoom:
Vertical vorticity (f~2.7)
Temperature fluctuations



Sub-volume [0.12 X 0.1 X 0.01][2π]^3*

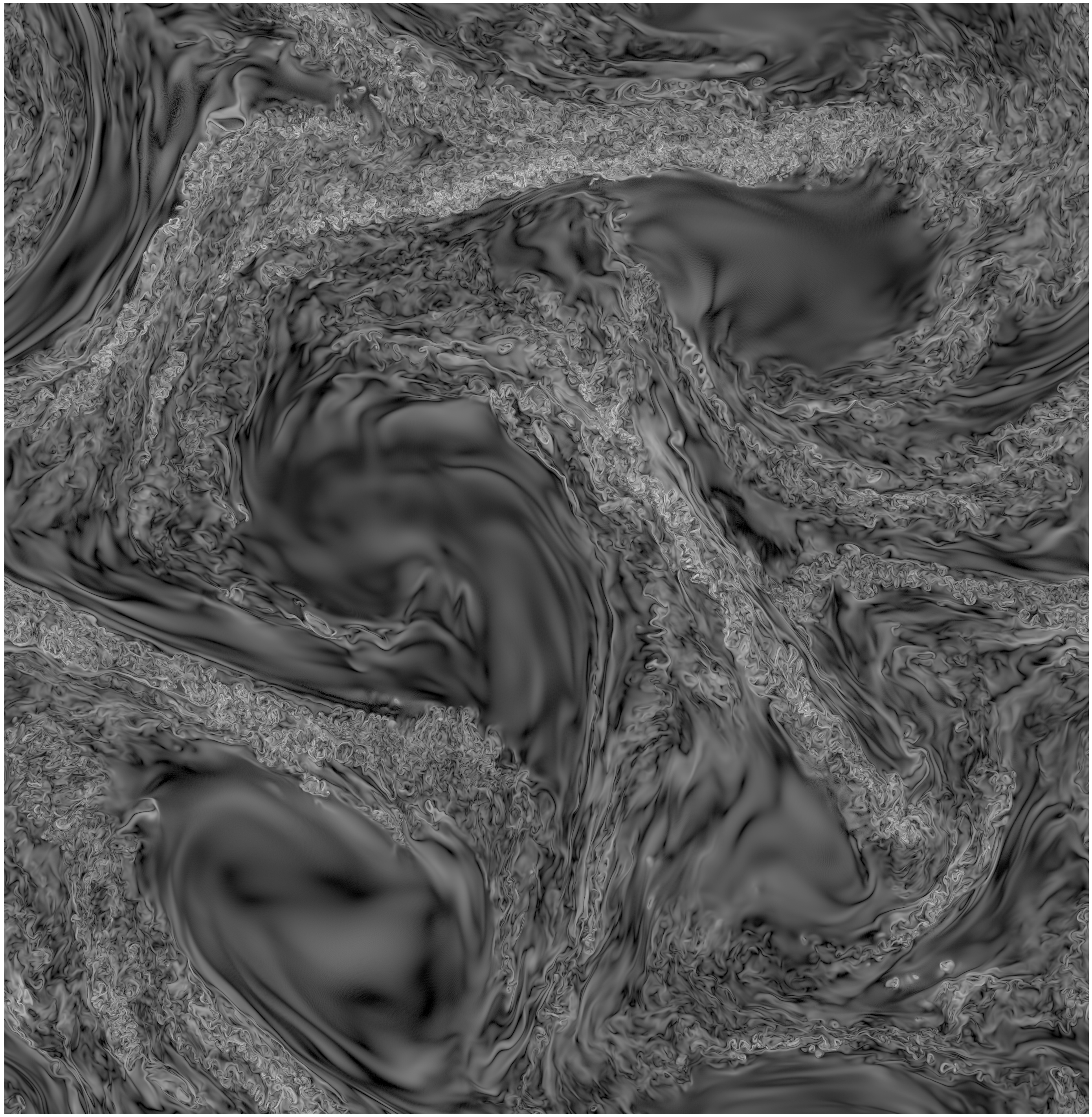

(a)
ω_z
4096^3 run
No forcing
Re=55000
N/f~ 5
R_B~ 32
10.0
-10.0
Vorticity
lanes

ω_{mag}

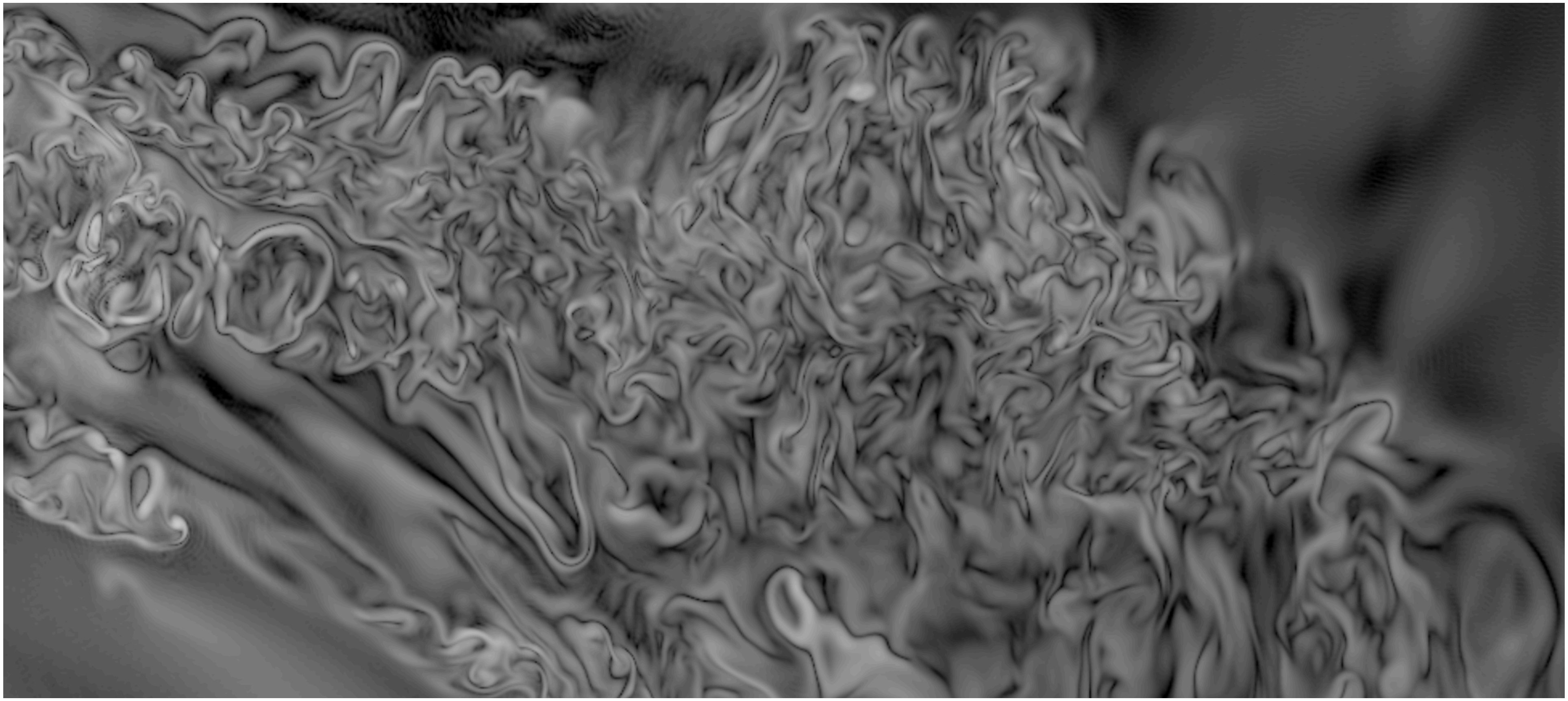
Full 4096^2 **res.**
Log scale

f=2.7, ω_{rms} ~17

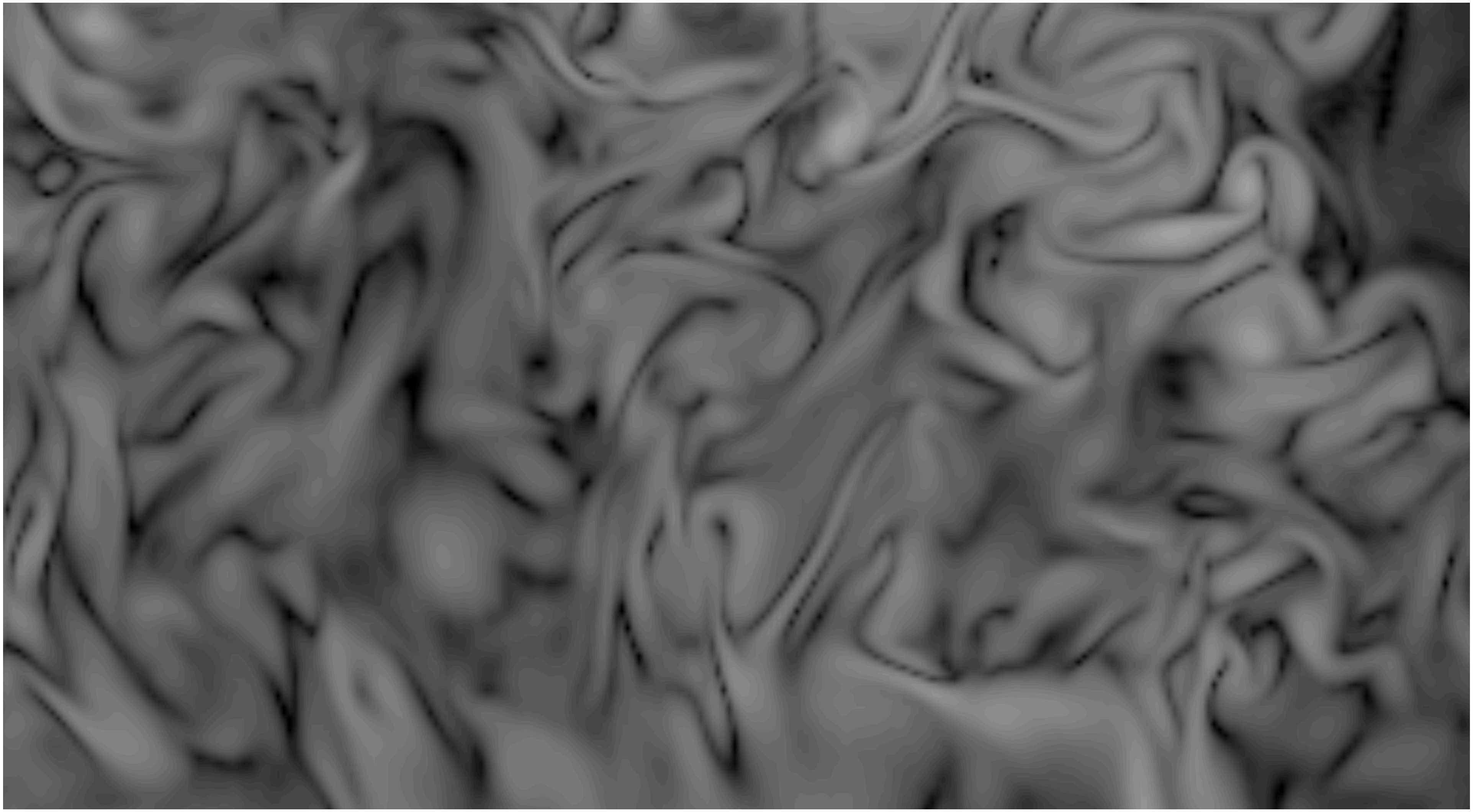
Re=55000
R_B=32



Zoom of ω_{mag} at full 4096^2 resolution, log scale, f=2.7, ω_{rms} ~17



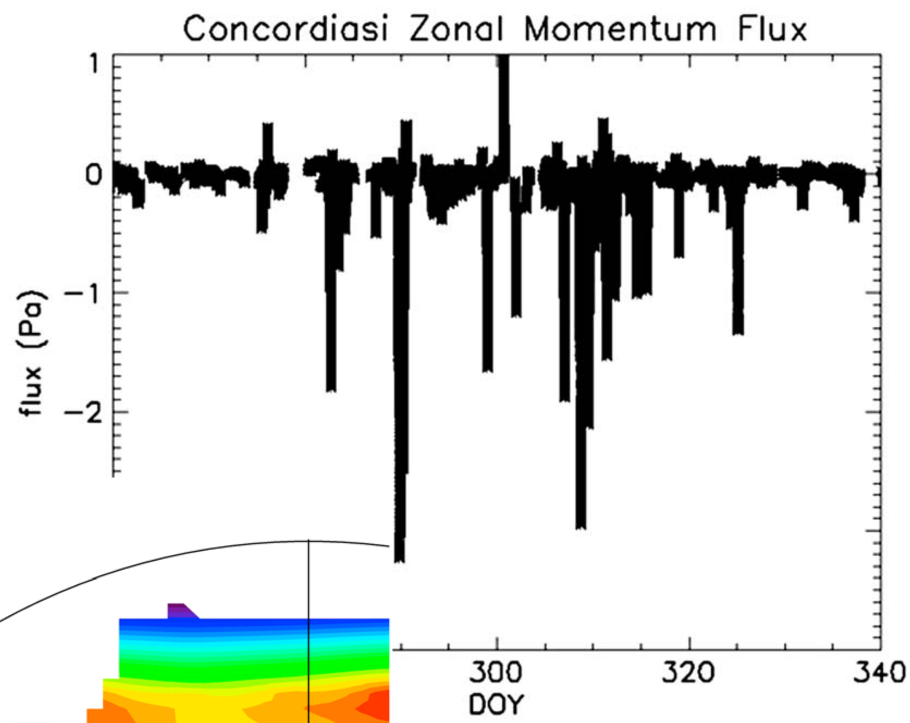
Max. zoom of ω_{mag} at full 4096^2 resolution, log scale, f=2.7, ω_{rms} ~17



Instability zones: Mountain flux

Walterscheid et al. JGR 121, 2016

<uw>
30s., 500km^2



s of vertical flux of zonal momentum over
as a function of day of year in 2010.

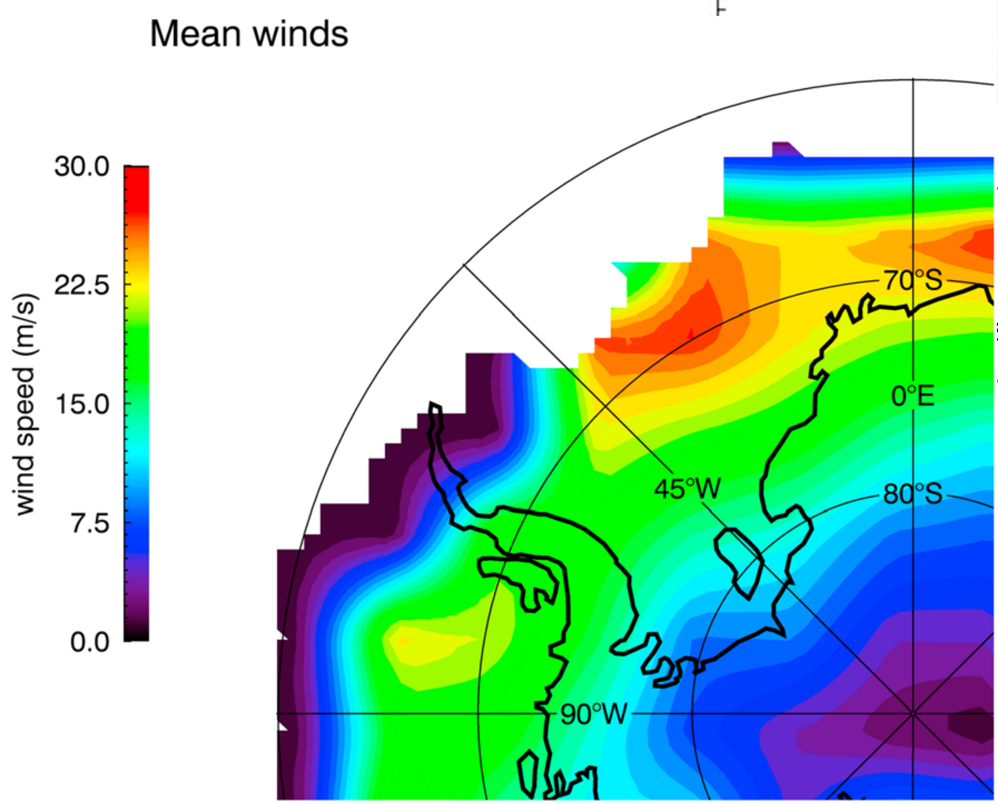


Figure 13. Campaign-averaged zonal wind speed at balloon altitude.

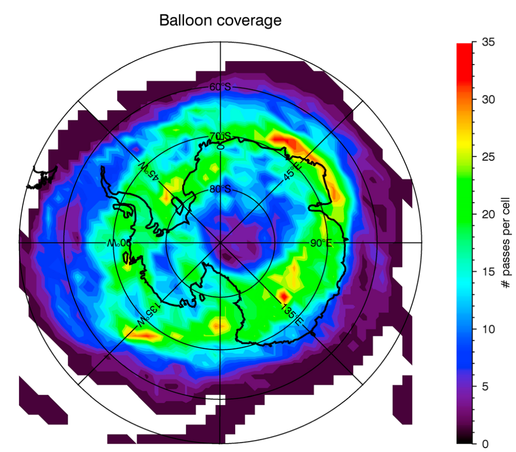


Figure 1. Geographical distribution of the number of Concordiasi balloon passes per 500 km × 500 km cell.

Stably stratified turbulence: Bolgiano-Obukhov 1959 scaling

Main hypothesis: Inertial range with a constant buoyancy flux $u\theta^2/\ell$

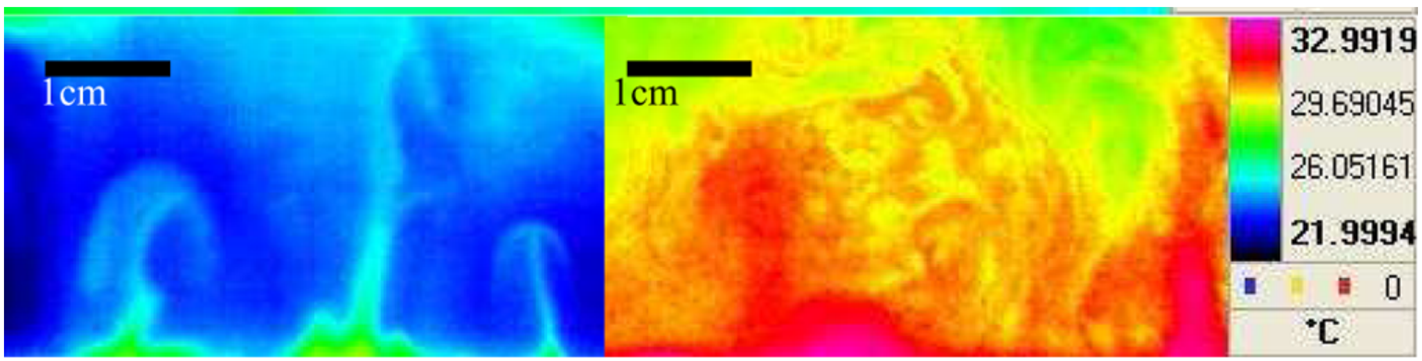
$E_{V,P}(k) = f(k, \varepsilon_P)$ with $\varepsilon_P = DE_P/DT$ of dimension m^2s^{-5}

→ $E_V(k) = \varepsilon_P^{2/5}\ k^{-11/5}$
→ $E_P(k) = \varepsilon_P^{4/5}\ k^{-7/5}$

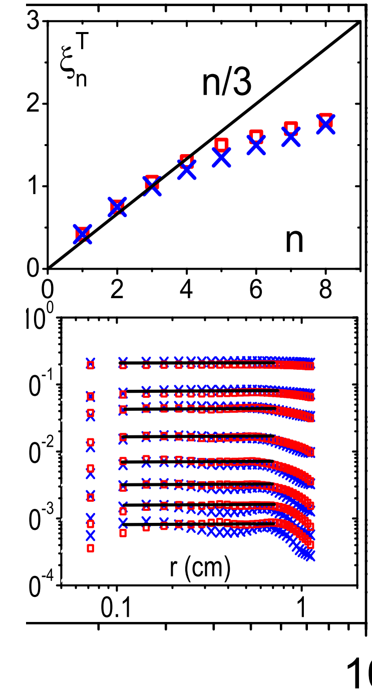
→ $U^2/\ell \sim \theta$ in the momentum equation

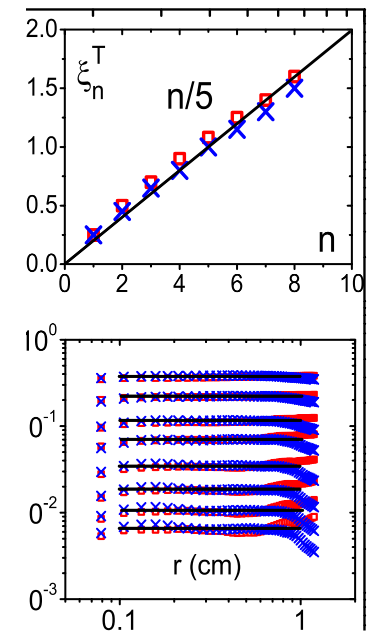
Elusive, … *Paradoxical* *(Lohse & Xia, Ann. Rev. Fluid Mech. 2010), …*

Seychelles et al. (2010) 2D soap bubble experiment



ΔT= 21C or 50C





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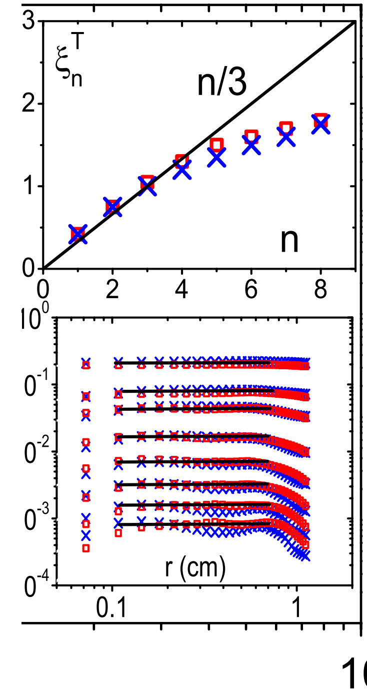
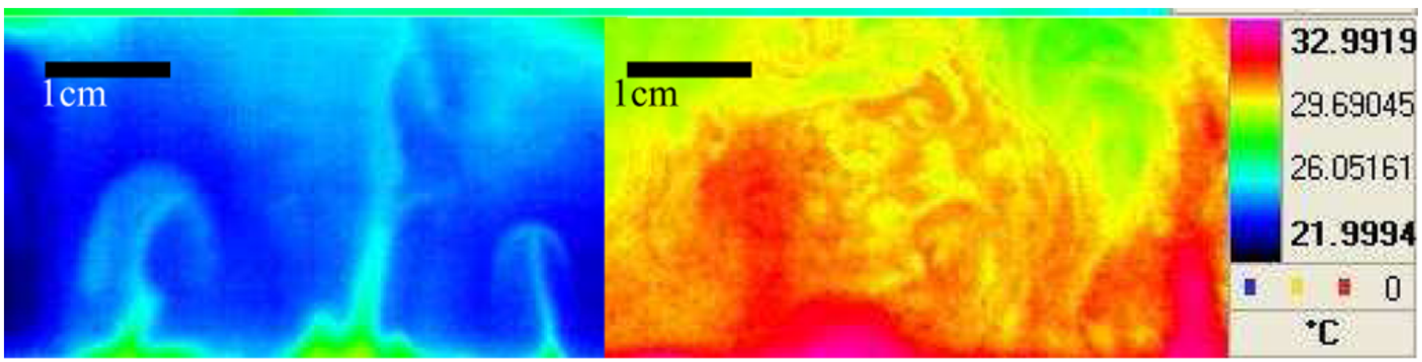
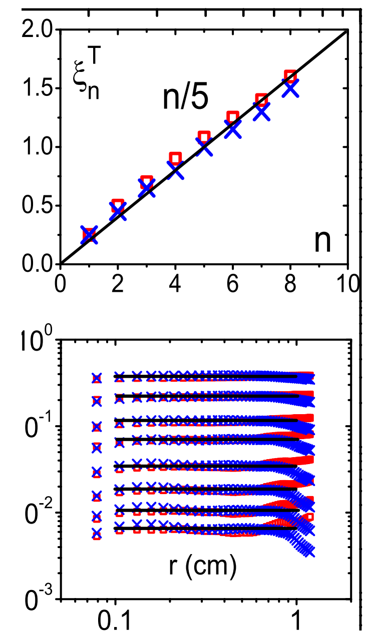


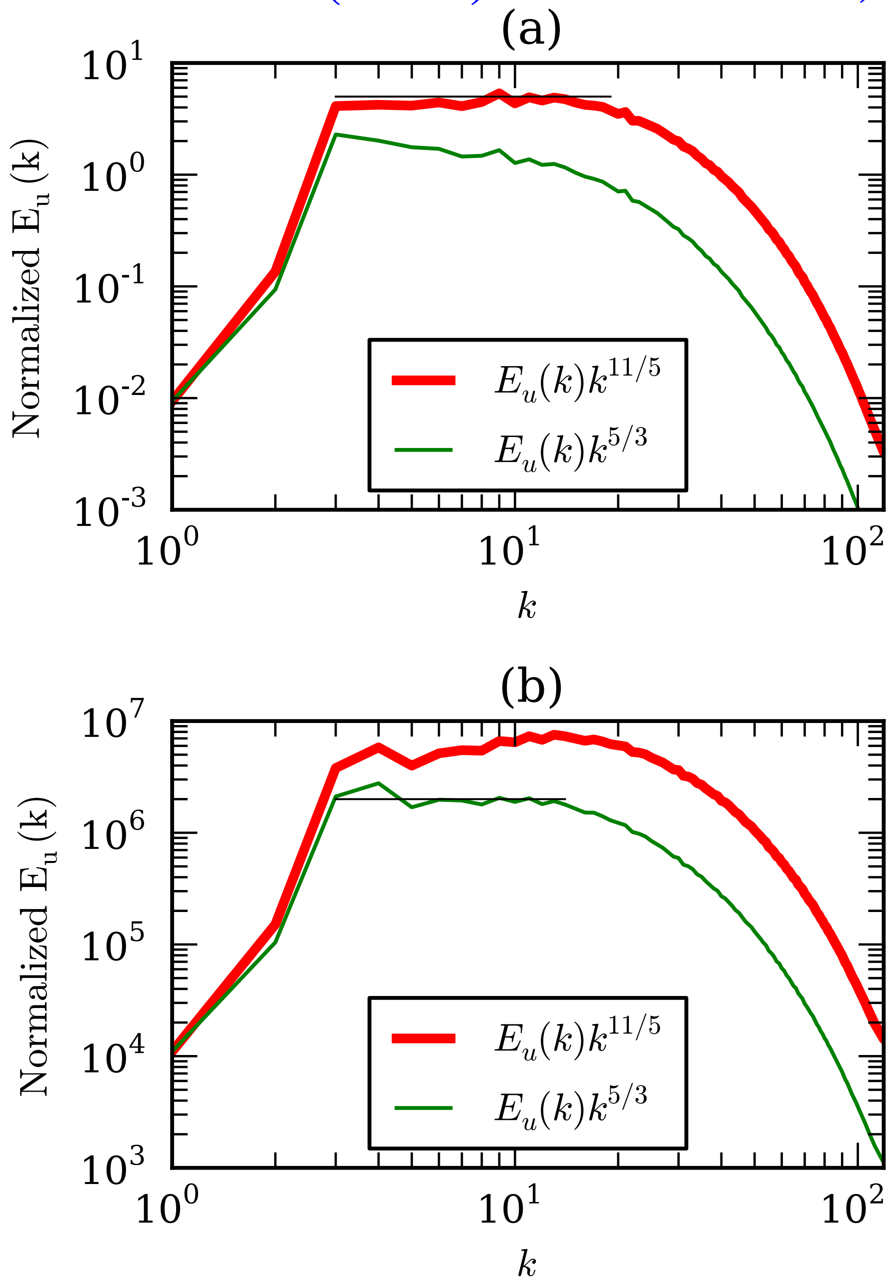


$\Delta T=$ 21C or 50C



Also in shell models of 2D flows *(Brandenburg, 1992; Boffetta+ 2012)*

Kumar+ (2014) 1024^3 3D run, no rotation



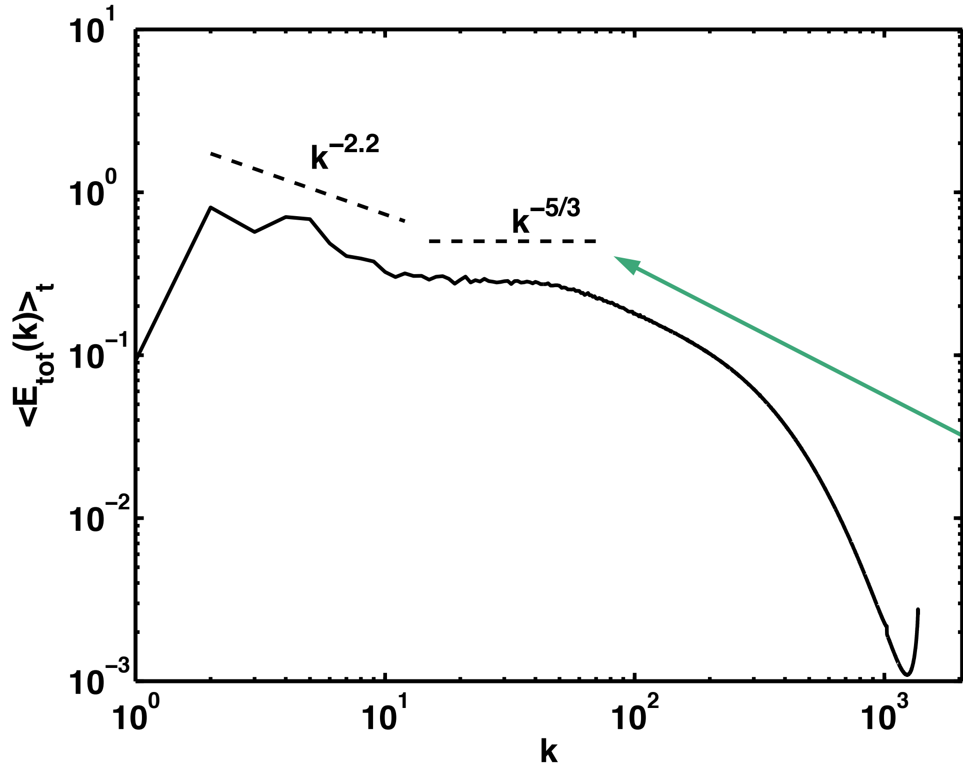
Re=650, large-scale forcing

Kinetic energy spectra compensated by either

BO (11/5), Fr=1.4

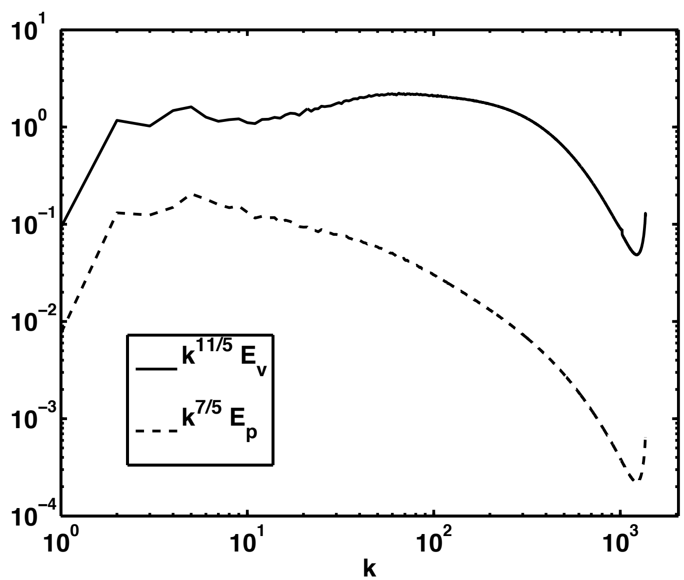
or

K41 (5/3), Fr=1000



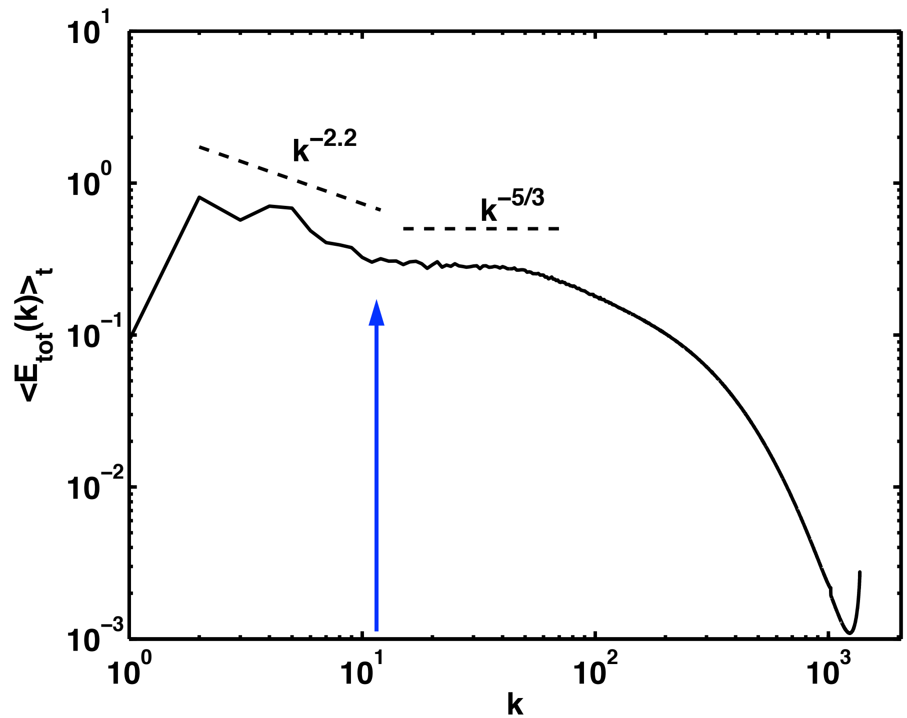
N/f=4.95
Fr=0.024, Ro=0.12
Re=55000, R_B=32
K_0=2.5, spin-down

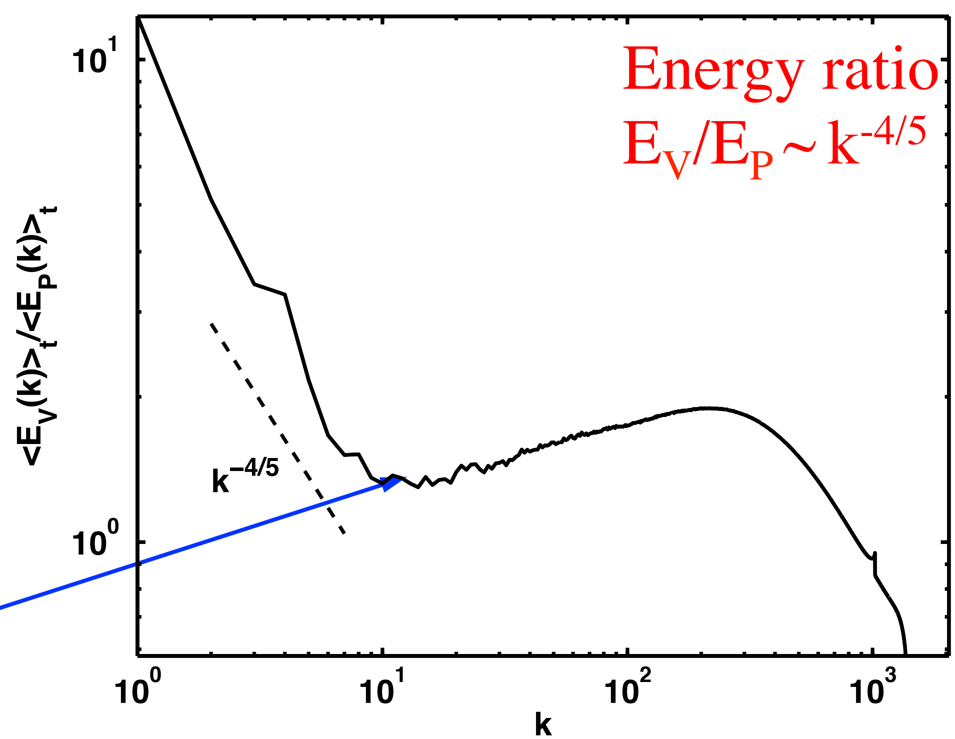
5/3-compensated
total energy
isotropic spectrum



Energy spectra:
kinetic (___) or
potential (- - -)
compensated
by 11/5 or 7/5:
Bolgiano-Obukhov scaling
in the large scales ($>L_{BO}$)

Total energy spectrum around peak

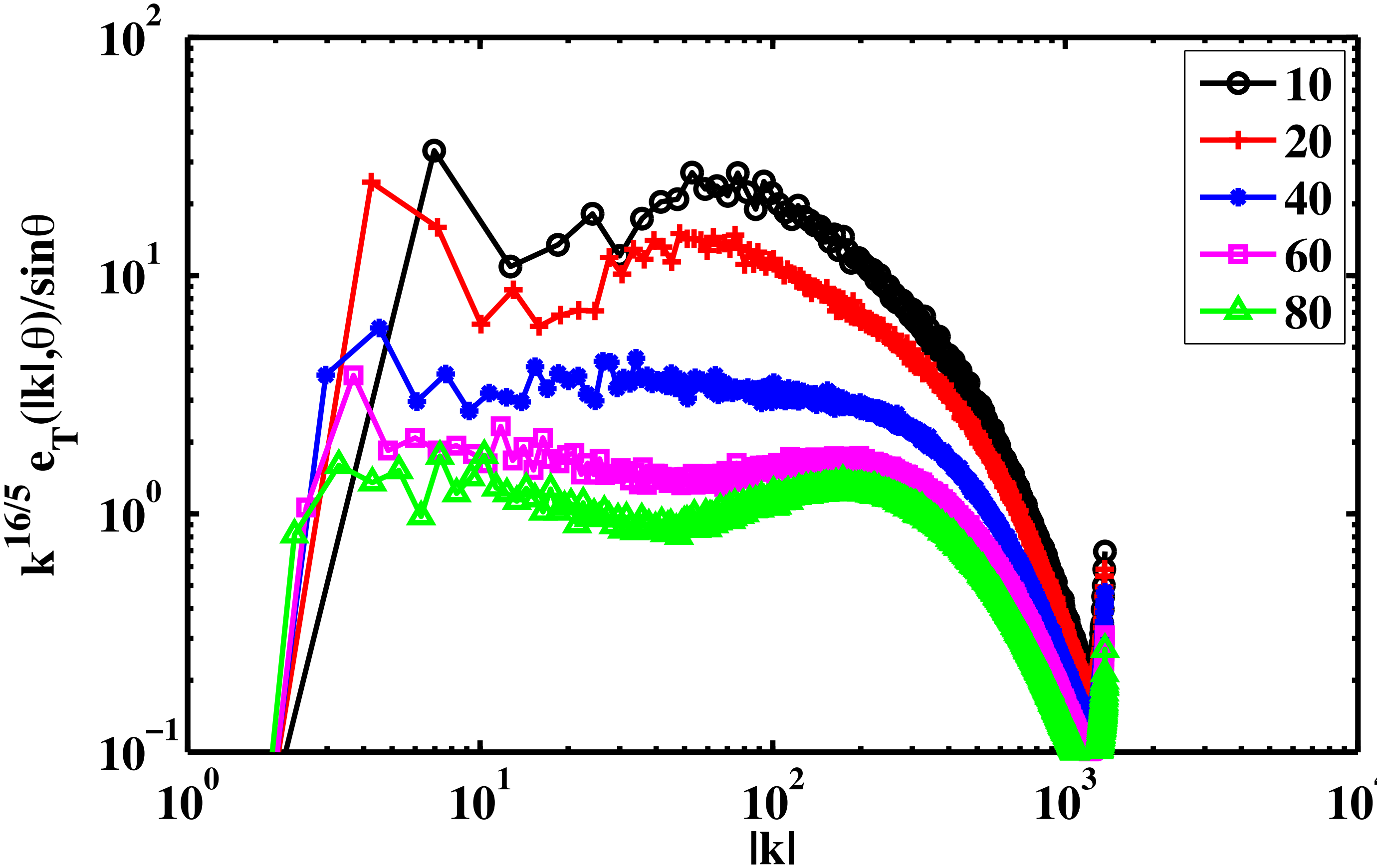


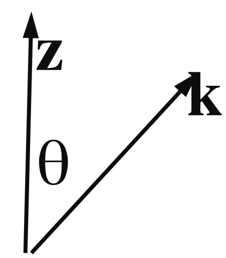


$$K_{BO} \sim \varepsilon_P^{3/4} \varepsilon_V^{-5/4} \quad \sim 11$$

N/f=4.95
Fr=0.024, Ro=0.12
Re=55000, R_B=32
K_0=2.5, spin-down

Compensated
total energy
angular spectra





Rosenberg et al. 2015

Vertical buoyancy flux:

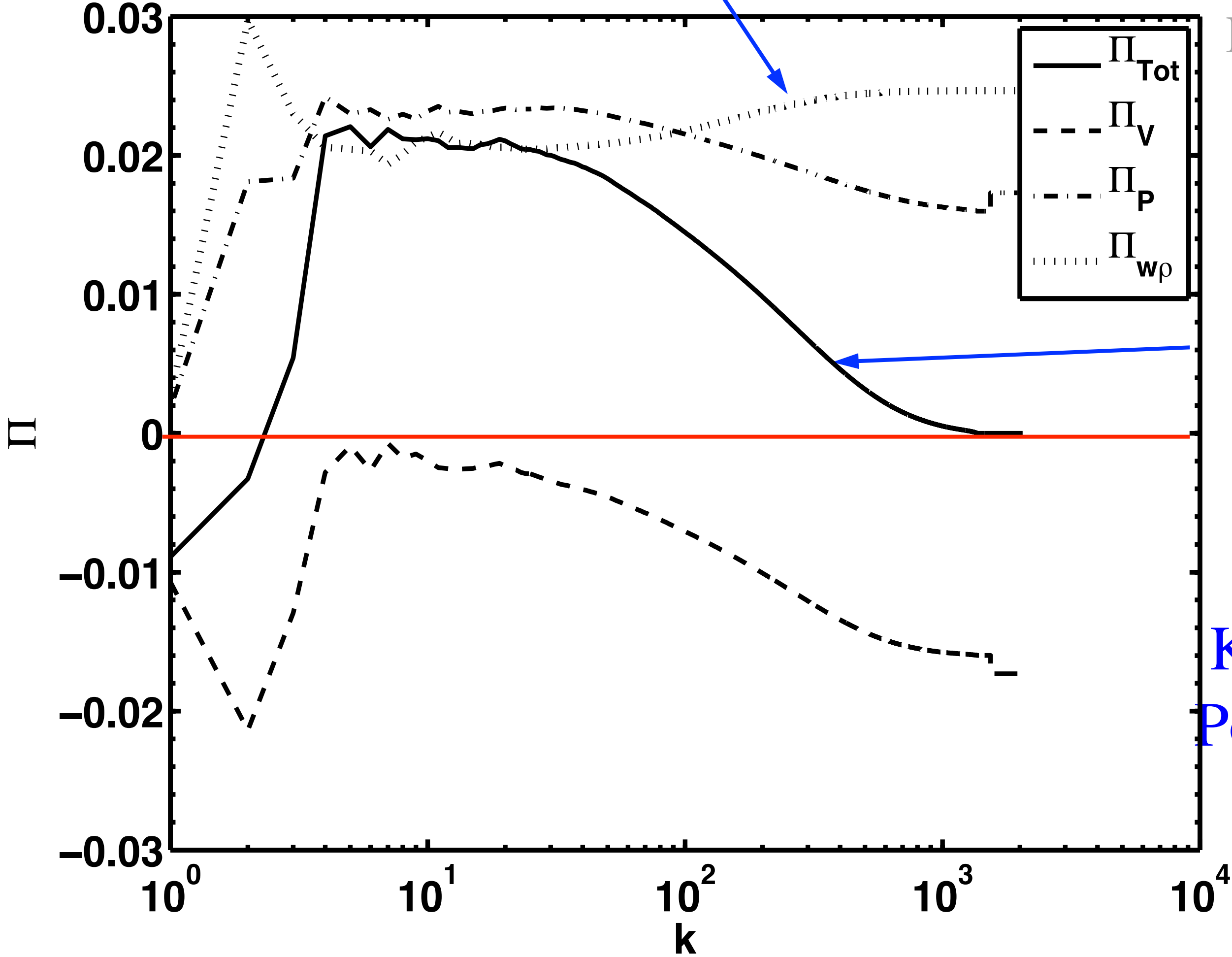
$$\Pi_{w\rho}(k) = \sum_{k'=0}^{k'=k} \sum_{k'<|k''|<k'+1} Re(\hat{w}(\mathbf{k''})\hat{\rho}(\mathbf{k''})^*) \ ,$$

4096^3 data, N/f=4.95

Fr=0.024, Ro=0.12

Re=55000, R_B=32

K_0=2.5, spin-down



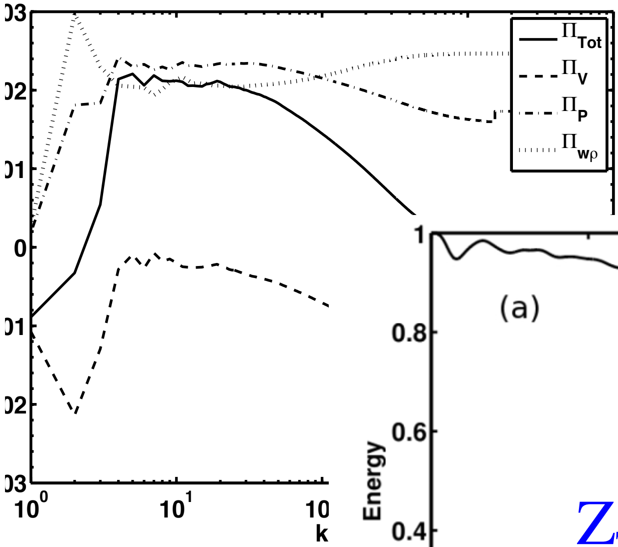
Isotropic energy flux and its components

Total (____): $\Pi_T = \Pi_V + \Pi_P$

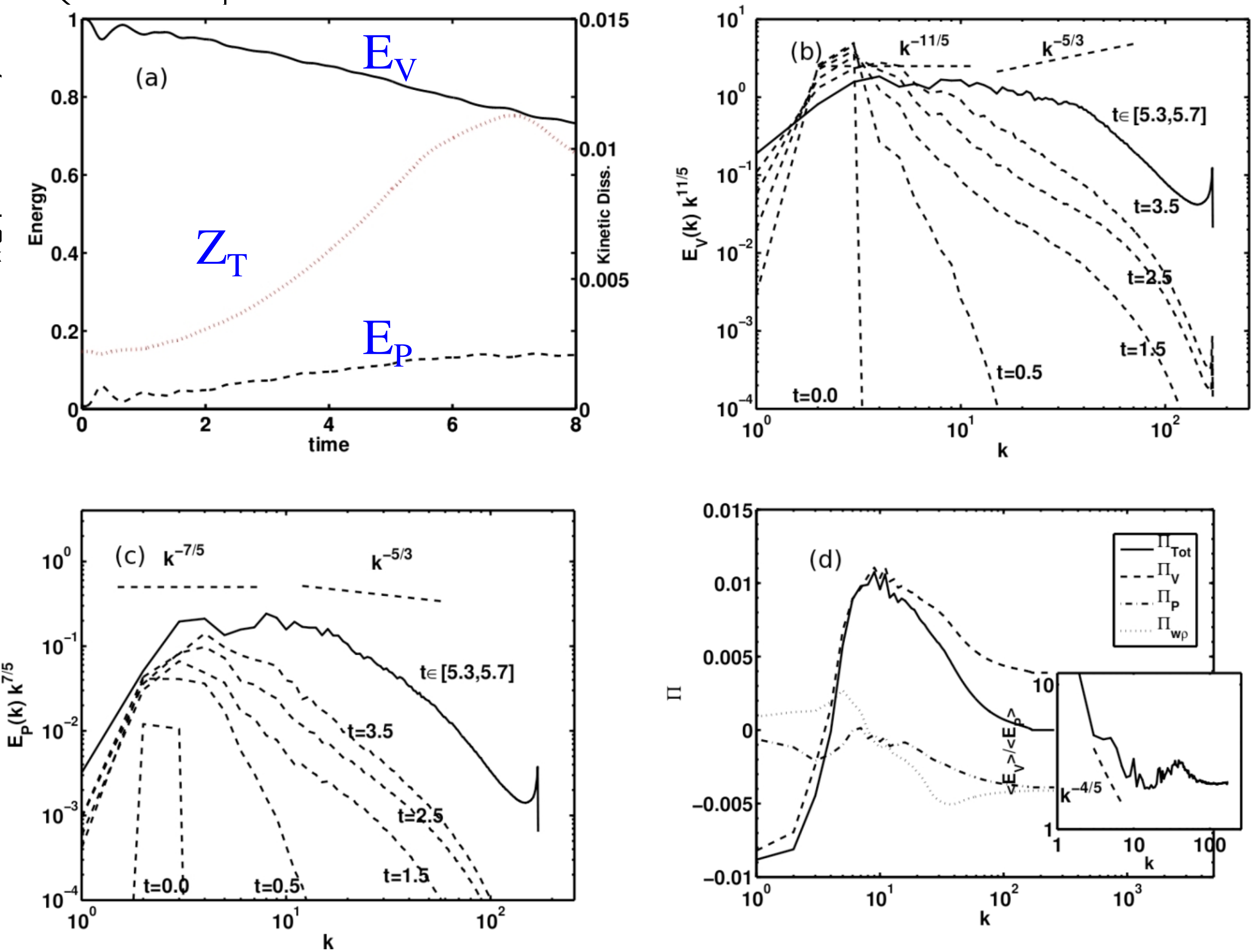
Kinetic (---): Π_V

Potential (-. -.): Π_P

Buoyancy flux: ……



Balanced initial conditions, 512^3 res.



Interplay of waves and eddies

- Field $X(k) = [u_i(k), \theta(k)]$ (i = 1, 3) decomposition on 0 & wave (+/-) modes of frequency σ *(Leith, 1980; Bartello, 1995; ... Use $\delta = div_H \boldsymbol{u_H}$ & ω_z)*:

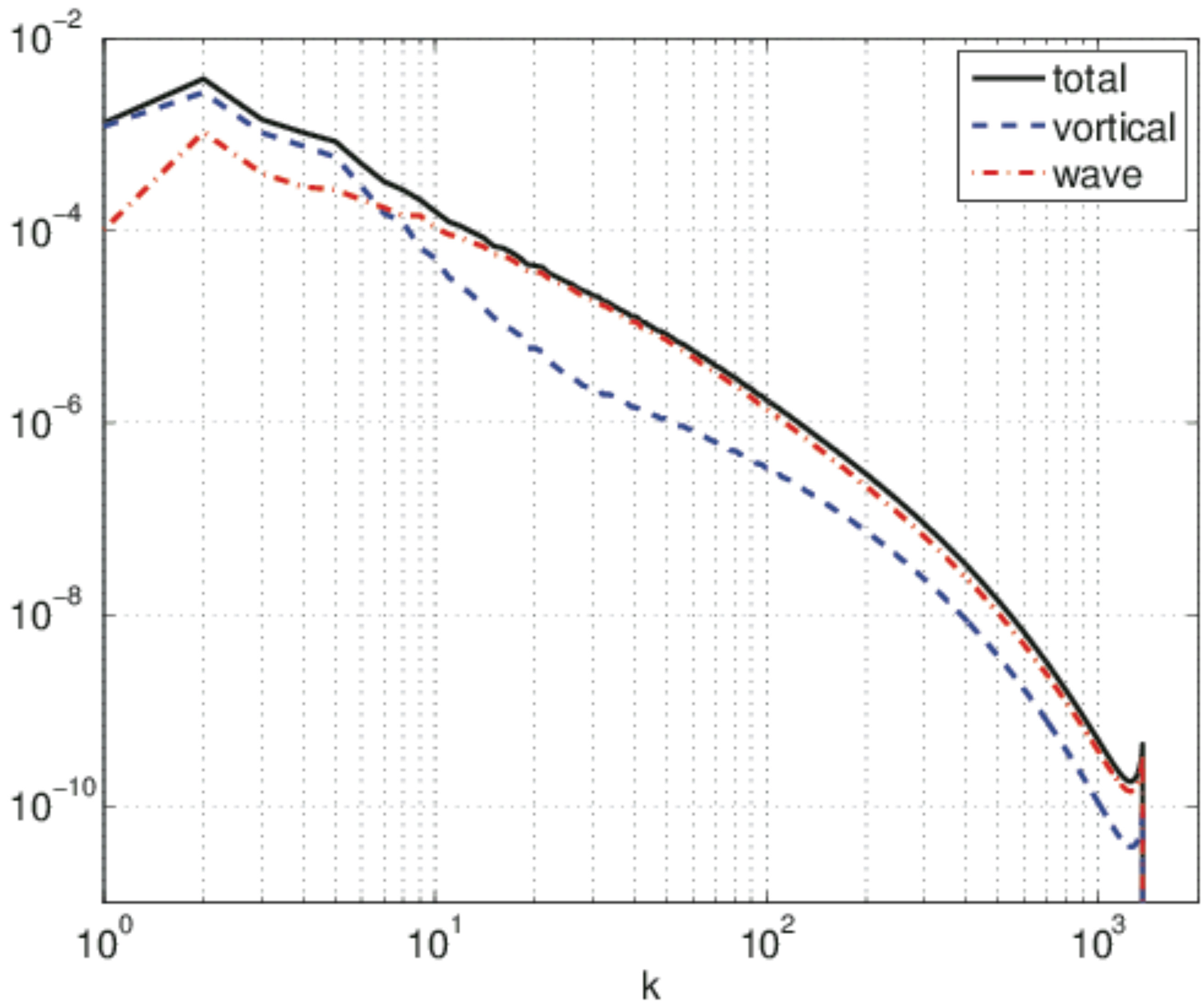
$$X(k) = A_0(k)X_0(k) + A_+(k)X_+(k) + A_-(k)X_-(k)$$

Linear (slow) dynamics is geo. & hydro. balanced, no vertical velocity and with all (linear) potential vorticity (since $\sigma\, \Pi_L = 0$, Smith Waleffe 2002)

- $E_0 = \langle u^2{}_0 + \theta_0{}^2 \rangle/2 = \Sigma_k |A_0(k)|^2 = \Sigma_k E_0(k)$
- $E_W = \langle u^2{}_w + \theta_w{}^2 \rangle/2 = \Sigma_k E_W(k) = \Sigma_k[|A_+(k)|^2 + |A_-(k)|^2] = \Sigma_k [E_+(k) + E_-(k)]$

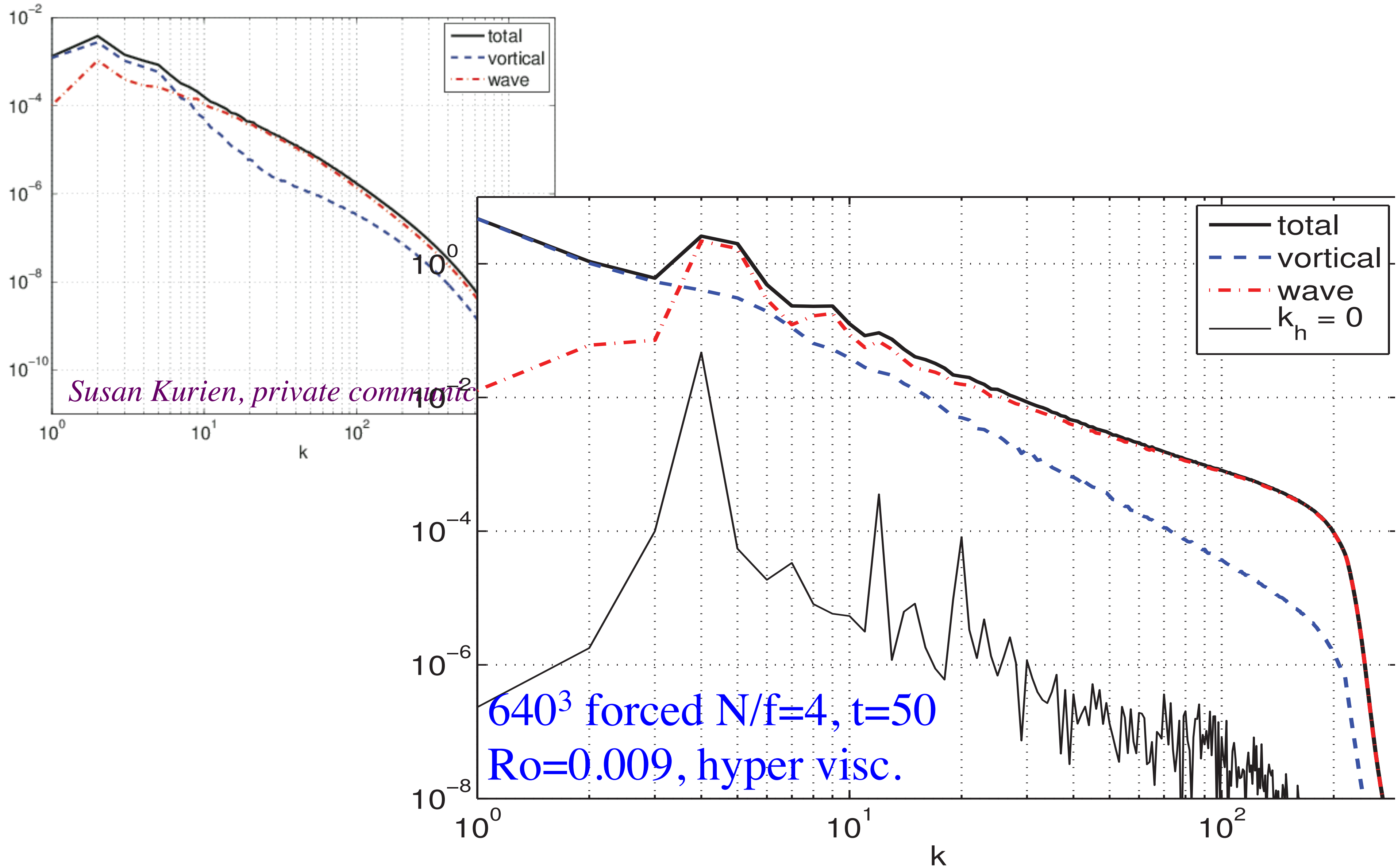
Corentin Herbert + 2014, 2015

4096 normal mode decomposition of total energy spectrum at peak R_B=32



Susan Kurien, private communication, 2014

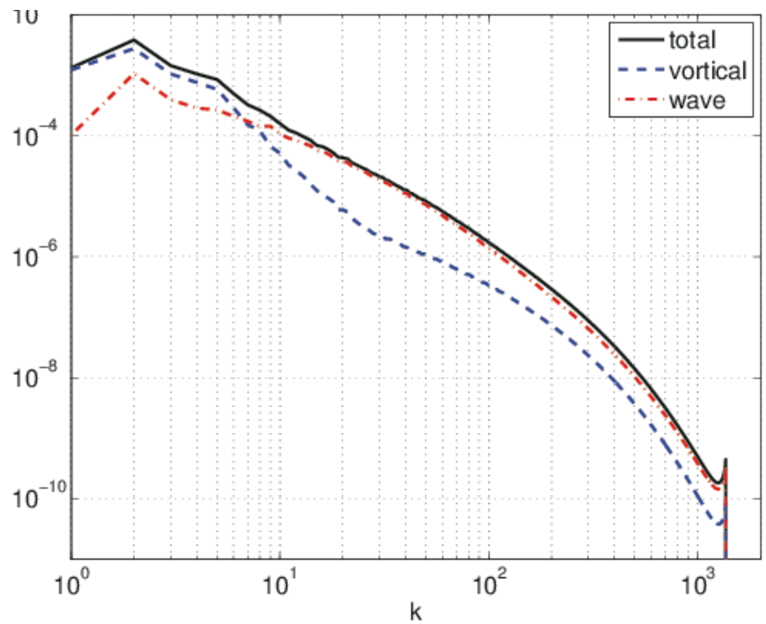
Normal mode decomposition of the total energy spectrum at peak, R_B=32

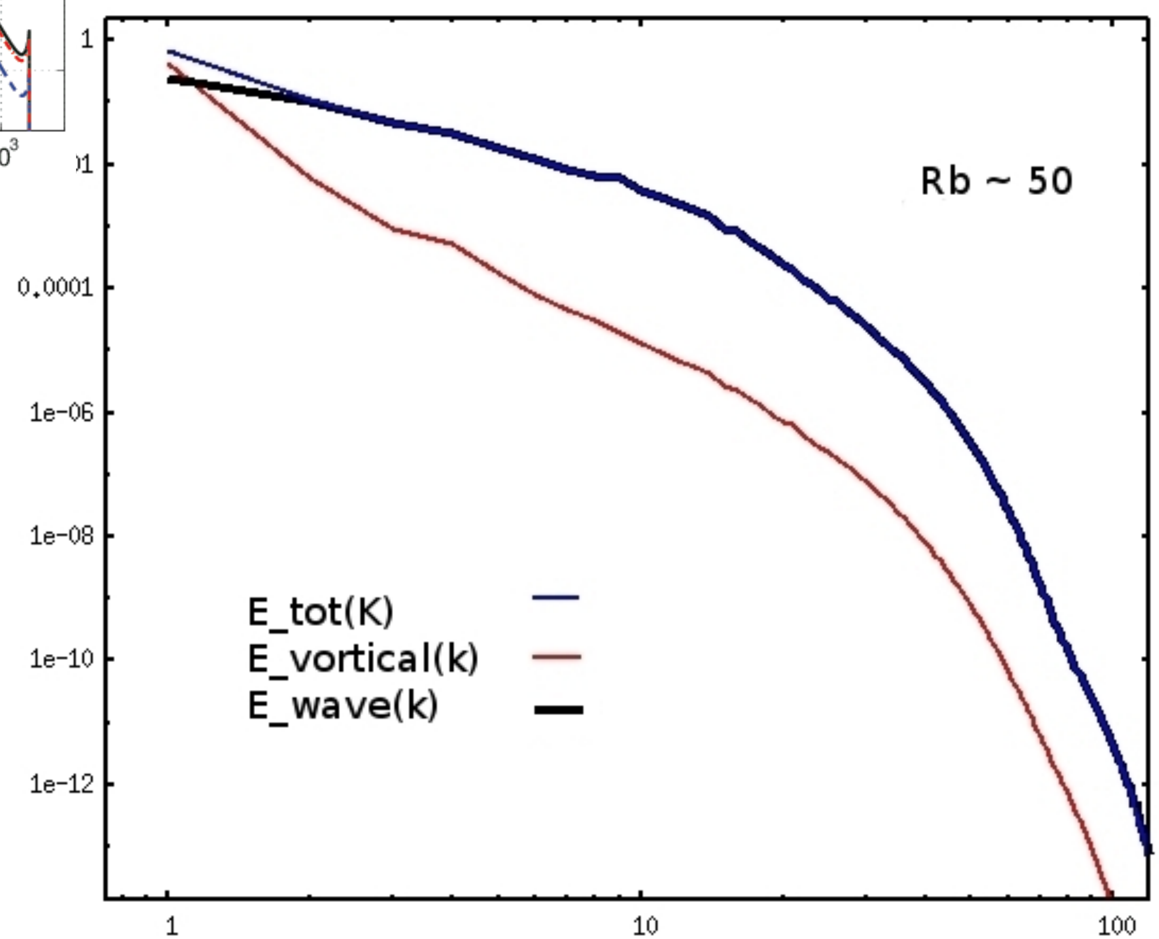


Kurien Smith 2014

Normal mode decomposition
512^3 runs

Re~ 10^4
Ro=0.038, N/f= ½
Fr-0.076, R_B~50



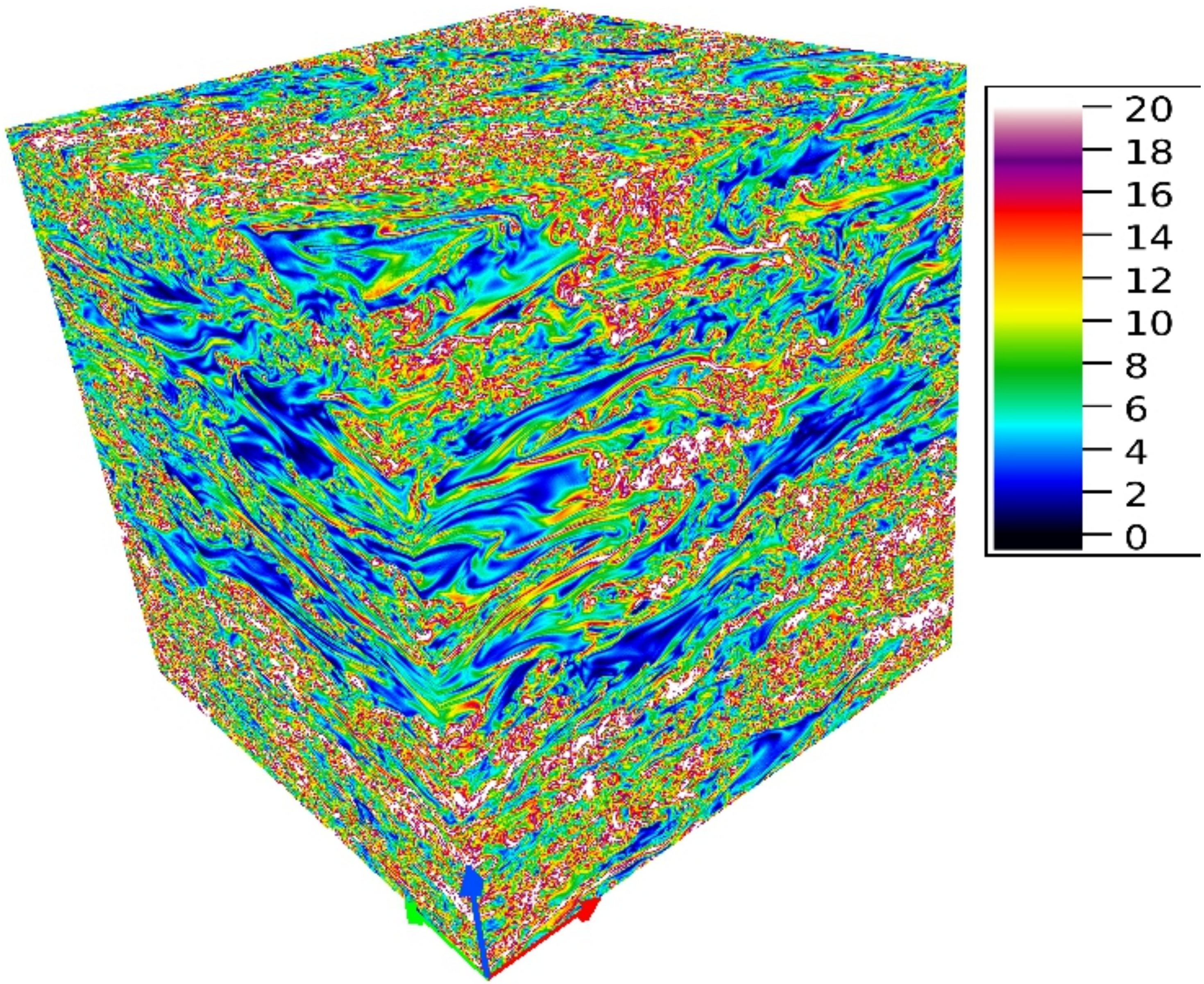


Marino et al., 2015

Mesophere Lower Thermosphere (MLT) run

N/f=137, Fr = 0.067, Ro = 9.2, Re ≃ 12000 and R_B = 53, 1024^3 grid

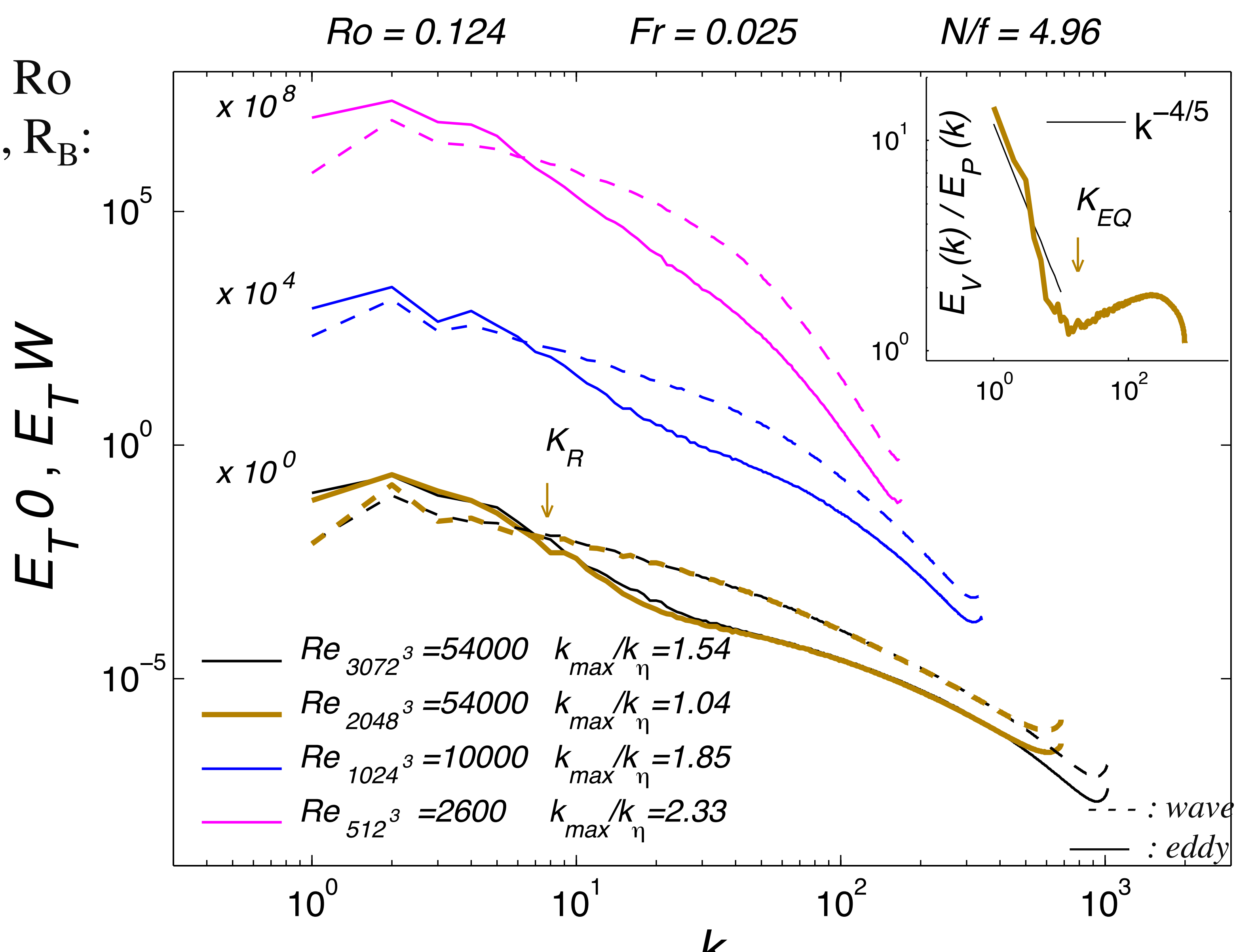
ω_{mag}



Interplay of waves and eddies

Same Fr and Ro
Different Re, R_B:
X 20

Change of
Regime
at K_R



Marino+ 2015

1024^3 res.

No forcing

$k_0 \sim 2.5$

$\theta(t=0)=0$

Id	Fr	Ro	Ro/Fr	Re	$\mathcal{R}_B$	–	Id	Fr	Ro	Ro/Fr	Re	$\mathcal{R}_B$
1	0.00129	0.12952	100.15	10905	0.01824		34	0.08839	0.61873	7	8525.4	66.61
2	0.002307	0.11535	50	9895.3	0.05267		35	0.09211	4.6056	50	11016	93.47
3	0.006078	0.12038	19.805	10678	0.39452		36	0.09902	9.2829	93.75	7717.1	75.66
4	0.006421	0.63255	98.507	9270.5	0.38225		37	0.09911	6.8828	69.444	7717.9	75.81
5	0.007347	0.22532	30.667	13945	0.75279		38	0.09989	0.49448	4.9502	8200.5	81.83
6	0.01165	0.30505	26.182	14679	1.9927		39	0.10038	9.411	93.75	10747	108.3
7	0.01192	2.9804	250	13504	1.9192		40	0.1007	6.993	69.444	10754	109.05
8	0.01271	0.63538	50	8933.1	1.4425		41	0.10167	7.0606	69.444	16226	167.73
9	0.02098	0.14679	6.9963	11079	4.8773		42	0.13318	0.32923	2.472	7563.2	134.15
10	0.02150	0.46444	21.6	13449	6.2177		43	0.13614	0.67308	4.944	7603.2	140.92
11	0.02253	0.11157	4.95	10977	5.57		44	0.14014	0.98247	7.0106	7442.2	146.16
12	0.02618	4.5819	175	12044	8.26		45	0.14222	1.4063	9.8881	7327.7	148.22
13	0.02800	0.14002	5	10722	8.41		46	0.16318	9.791	60	9576.1	255
14	0.03015	9.4215	312.5	10522	9.56		47	0.18841	37.481	198.94	2520.7	89.48
15	0.03332	4.5814	137.5	13020	14.45		48	0.20152	5.0381	25	8718.2	354.06
16	0.03646	9.1153	250	13217	17.57		49	0.20159	10.08	50	8756.8	355.87
17	0.03774	0.13994	3.708	10534	15.00		50	0.2059	40.96	198.94	6272.1	265.89
18	0.04094	0.60719	14.832	9842.9	16.50		51	0.25825	10.33	40	8575.7	571.95
19	0.04221	0.21106	5	14841	26.44		52	0.34081	0.84249	2.472	5024.4	583.59
20	0.04527	3.0177	66.67	12790	26.21		53	0.37971	11.391	30	7116.6	1026.1
21	0.04737	4.4406	93.75	8881.9	19.93		54	0.3966	42.192	106.38	1983.7	312.03
22	0.04803	4.5028	93.75	12366	28.53		55	0.46877	1.1719	2.5	4500.4	988.95
23	0.04870	4.5657	93.75	18586	44.08		56	0.55387	11.077	20	7138.8	2190
24	0.04897	9.1824	187.5	18550	44.49		57	0.61542	1.5386	2.5	5012.1	1898.3
25	0.04940	9.2627	187.5	12769	31.16		58	0.89372	2.2343	2.5	4707.8	3760.3
26	0.05656	0.28278	5	13730	43.92		59	1.2497	12.497	10	6473.2	10110
27	0.05679	0.1404	2.472	9747.6	31.44		60	2.6918	13.459	5	4019.3	29123
28	0.060595	3.0297	50	11649	42.77		61	5.4829	13.707	2.5	4257.7	1.28×10^5
29	0.062114	0.61418	9.8881	9639.4	37.19		–					
30	0.066925	920.23	13750	11486	51.45		62	0.01212	Inf	Inf	15225	2.24
31	0.06715	9.2332	137.5	11728	52.88		63	0.02678	Inf	Inf	11804	8.46
32	0.073074	3.0448	41.667	12211	65.20		64	0.06692	Inf	Inf	11487	51.44
33	0.08608	0.4304	5	12111	89.74		65	0.20147	Inf	Inf	8796.7	357.07

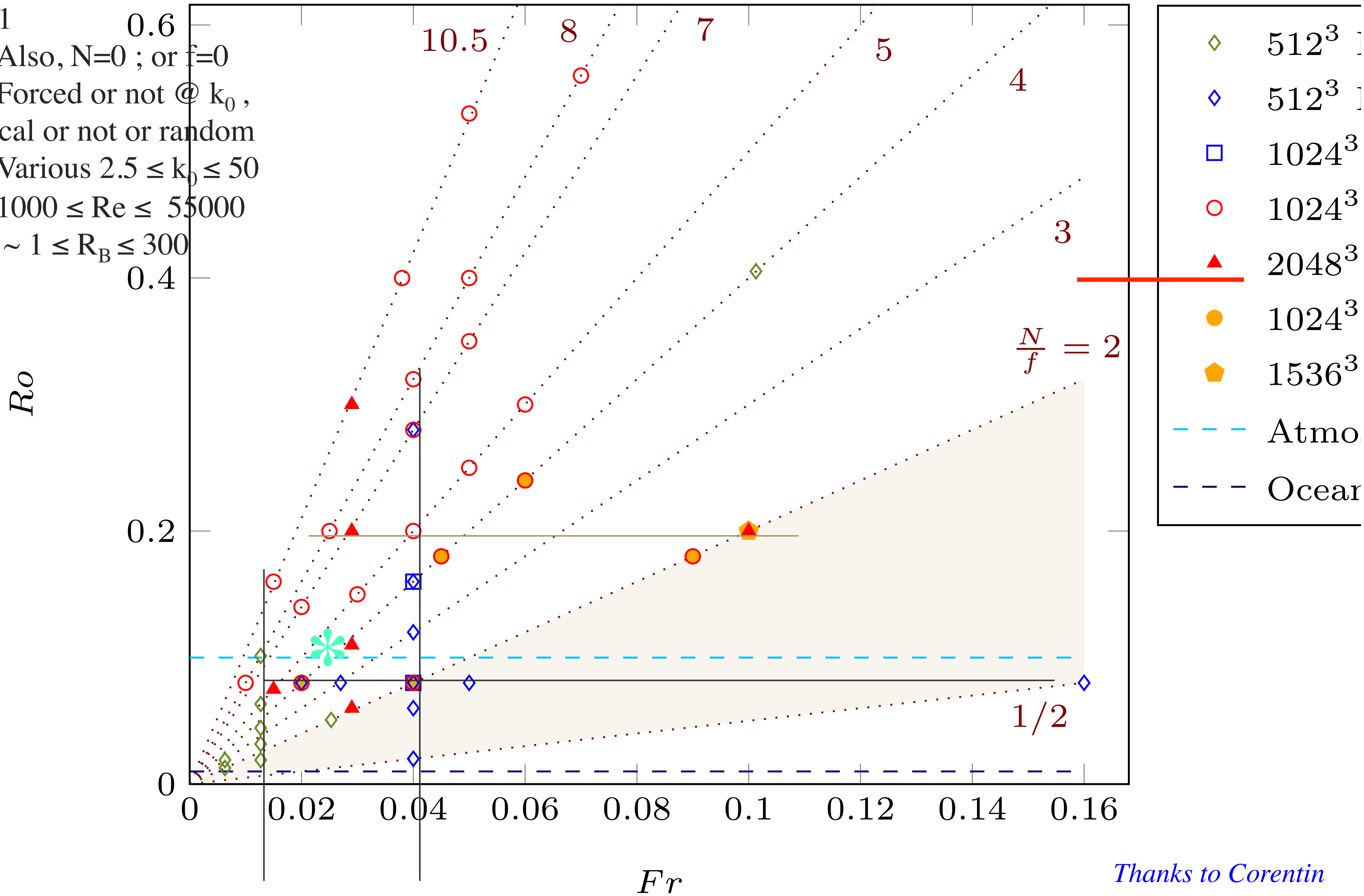
Id	Fr	$\mathcal{R}_\omega$	N/f	Re	k_η/k_M	ϵ_D	r_ϵ	L_{int}	L_B	ℓ_{Oz}	ℓ_{Ze}
1	.0013	13.5	100	10905	.53	.27	.018	2.57	.02	.0001$_*$	.100
2	.0023	11.5	50	9895	.50	.20	.02	2.60	.038	.00025$_*$	.090
3	.0061	12.4	20	10678	.49	.23	.015	2.64	.10	.00097$_*$	.086
4	.0064	60.9	98	9270	.52	.22	.02	2.40	.097	.001*	1.08
5	.0073	26.6	31	13945	.64	.23	.035	2.49	.115	.0012*	.206
6	.0116	36.9	26	14679	.68	.25	.012	2.56	.187	.002*	.30
7	.0119	346.	250	13504	.68	.26	.018	2.38	.178	.0026*	10.4*
8	.0127	60.	50	8933	.53	.22	.023	2.35	.187	.003*	1.126
9	.0210	15.4	7	11079	.53	.23	.021	2.72	.358	.007*	.140
10	.0215	53.9	22	13449	.69	.24	.02	2.41	.325	.007*	.680
11	.0225	11.7	4.95	10977	.54	.204	.026	2.78	.39	.01*	.106
12	.0262	503	175	12044	.73	.243	.026	2.22	.36	.01*	22.3*
13	.0280	14.5	4.95	10722	.56	.020	.031	2.74	.482	.014*	.158
14	.0301	966	312	10522	.74	.22	.03	2.05	.388	.012*	64.5*
15	.0333	523	137	13020	.77	.26	.025	2.31	.534	.014*	22.6*
16	.0365	1048	250	13217	.77	.26	.028	2.33	.53	.017*	67.1*
17	.0377	14.4	3.7	10534	.59	.20	.039	2.71	.64	.025	.176
18	.0409	60.	15	9843	.61	.22	.040	2.52	.648	.026	1.51
19	.0422	25.7	4.95	14841	.78	.22	.038	2.65	.703	.028	.315
20	.0453	341	67	12790	.81	.25	.038	2.30	.654	.027	14.8*
21	.0474	418	94	8882	.63	.24	.042	2.29	.682	.030	27.7*
22	.0480	501	94	12366	.82	.24	.042	2.27	.685	.031	28.1*
23	.0487	622	94	18586	1.11*	.24	.042	2.26	.690	.031	28.2*
24	.0490	1251	187	18550	1.11*	.25	.042	2.25	.691	.031	80.2*
25	.0494	1047	187	12769	1.26*	.26	.038	2.27	.706	.030	77.5*
26	.0566	33.1	4.95	13730	.85	.20	.059	2.57	.914	.053	.589
27	.0568	13.9	2.5	9748	.63	.185	.052	2.61	.930	.051	.197
28	.0606	327	50	11649	.86	.23	.054	2.19	.835	.047	16.8*
29	.0621	60.3	9.9	9639	.67	.22	.057	2.48	.968	.057	1.78
30	.0669	98623	13750	11486	.88	.23	.059	2.16	.910	.057	91863
31	.0671	1000	137	11728	.88	.24	.057	2.18	.921	.057	91.7*
32	.0731	336	42	12211	.90	.24	.062	2.24	1.03	.069	18.6*
33	.0861	47.4	4.95	12111	.94	.19	.094	2.37	1.283	.116	1.294

Id	Fr	$\mathcal{R}_\omega$	N/f	Re	k_η/k_M	ϵ_D	r_ϵ	L_{int}	L_B	ℓ_{Oz}	ℓ_{Ze}
34	.0884	57.1	7	8525	.73	.20	.09	2.32	1.29	.115	2.14
35	.0921	483	50	11016	.96	.22	.086	2.12	1.22	.109	38.5*
36	.099	815	94	7717	.74	.22	.088	2.09	1.30	.122	110.*
37	.0991	605	69	7718	.75	.22	.088	2.09	1.30	.121	70.*
38	.0999	44.8	4.95	8200	.75	.20	.10	2.28	1.429	.142	1.57
39	.1004	976	94	10747	.98	.23	.091	2.07	1.30	.124	113.*
40	.1007	725	69	10754	.98	.23	.090	2.07	1.31	.124	72.*
41	.1017	899	69	16226	1.33*	.236	.090	2.06	1.32	.126	73.*
42	.1332	28.6	2.5	7563	.76	.198	.108	2.12	1.77	.213	.828
43	.1361	58.7	4.95	7603	.79	.21	.12	2.10	1.80	.231	2.53
44	.1401	84.8	7	7442	.80	.21	.12	2.05	1.81	.235	4.35
45	.1422	120.3	10	7328	.80	.217	.12	2.02	1.81	.236	7.39*
46	.1632	958	60	9576	1.07*	.22	.136	1.91	1.96	.292	136.*
47	.1884	1882	199	2521	.39	.17	.148	1.98	2.35	.392	1100*
48	.2015	470	25	8718	1.09*	.21	.153	1.80	2.28	.40	50.*
49	.2016	943	50	8757	.84	.21	.154	1.80	2.29	.40	141.*
50	.2059	3244	199	6272	.84	.19	.163	1.85	2.39	.438	1229*
51	.2582	957	40	8576	1.13*	.22	.169	1.76	2.86	.598	151*
52	.3408	59.7	2.5	5024	.87	.21	.171	1.53	3.27	.791	3.07
53	.3797	961	30	7117	1.16*	.22	.187	1.53	3.65	.973	160.*
54	.3966	1879	106	1984	.40	.17	.176	1.66	4.13	1.09	1199*
55	.4688	78.6	2.5	4500	.89	.207	.186	1.42	4.18	1.24	4.89
56	.5539	936	20	7139	1.17*	.21	.203	1.55	5.41	1.82	162.*
57	.6154	109	2.5	5012	.88	.179	.215	1.60	6.19	2.25	8.88*
58	.8937	153	2.5	4708	.89	.197	.203	1.49	8.35*	3.56	14.1*
59	1.25	1005	10	6473	1.21*	.243	.199	1.39	10.9*	5.46	173.*
60	2.69	853	4.95	4019	.81	.31	.186	1.42	24.0*	17.0*	190.*
61	5.48	894	2.5	4258	.84	.34	.191	1.45	50.*	51.*	202.*
62	0.012	∞	∞	15225	.69	.278	.012	2.56	.195	.002*	∞
63	.0268	∞	∞	11804	.73	.264	.026	2.17	.366	.01*	∞
64	.0669	∞	∞	11487	.88	.23	.059	2.16	.910	.057	∞
65	.2015	∞	∞	8797	1.09*	.21	.153	1.81	2.29	.40	∞

Present rot-strat data *(Mostly Marino -ENS, & Rosenberg, SciTex)*

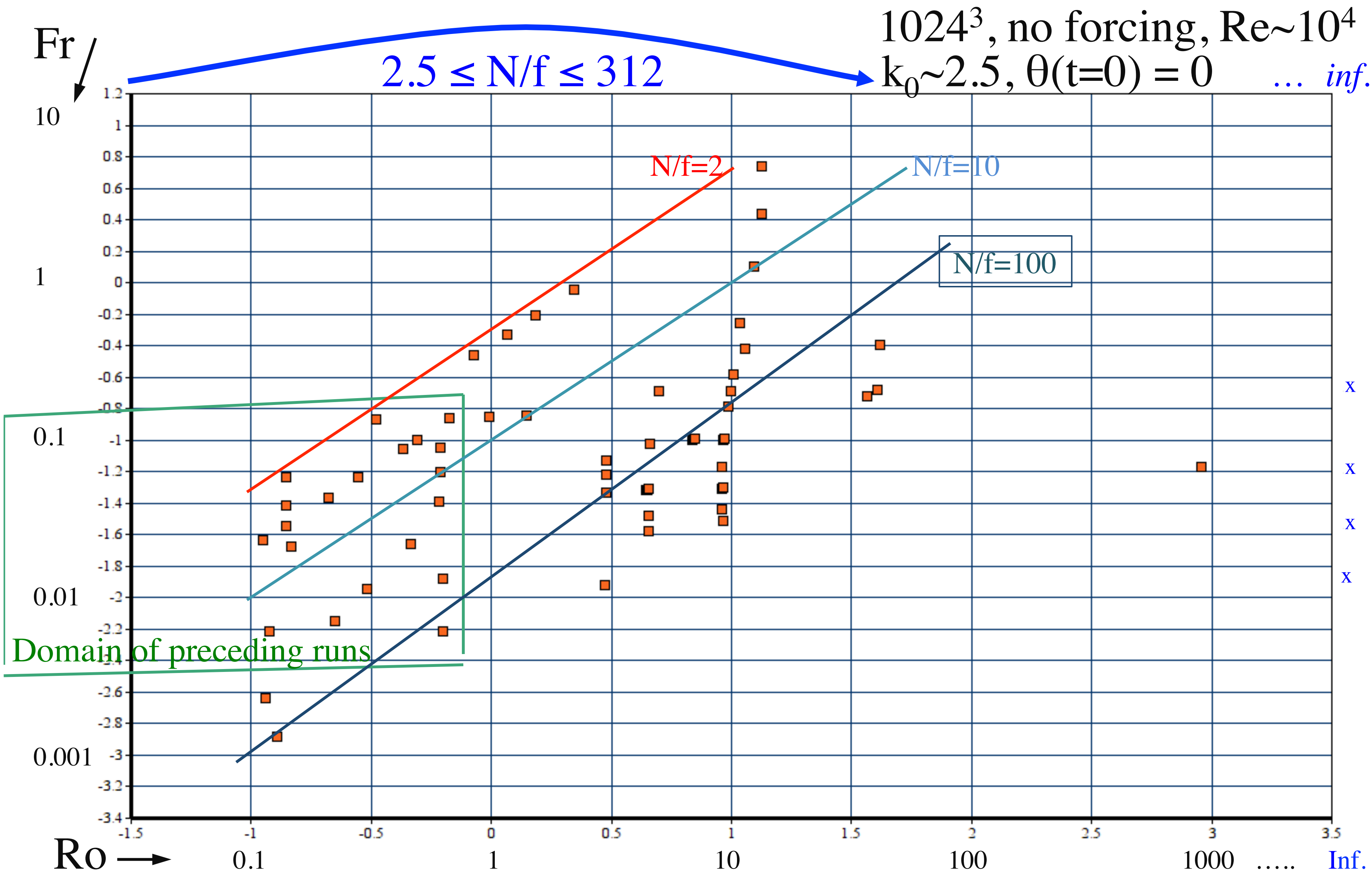
Pr=1

- Also, N=0 ; or f=0
- Forced or not @ k_0 , helical or not or random
- Various $2.5 \leq k_0 \leq 50$
- $1000 \leq Re \leq 55000$
- $\sim 1 \leq R_B \leq 300$



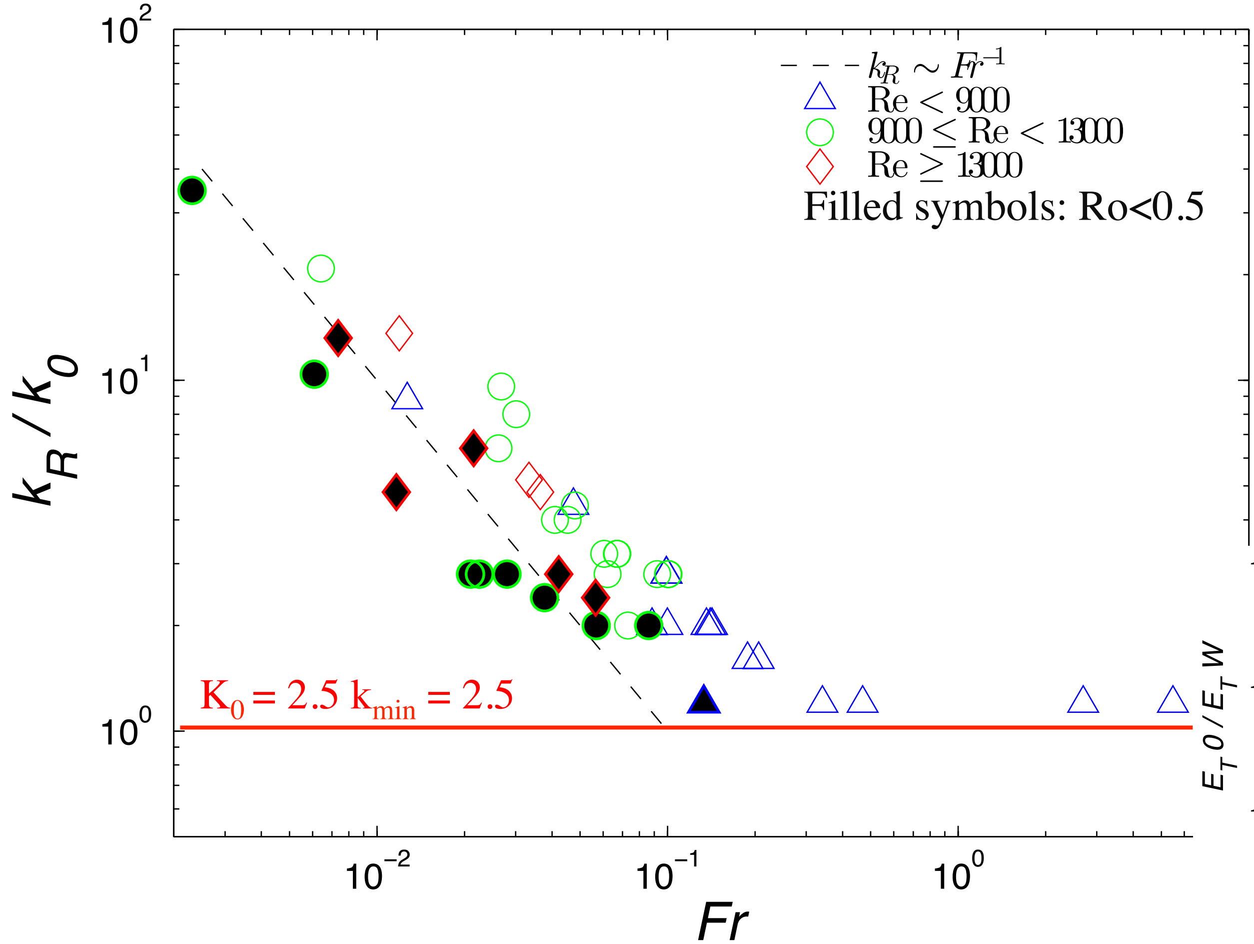
Thanks to Corentin

CPU: NSF (XSEDE & Yellowstone/NCAR); DOE

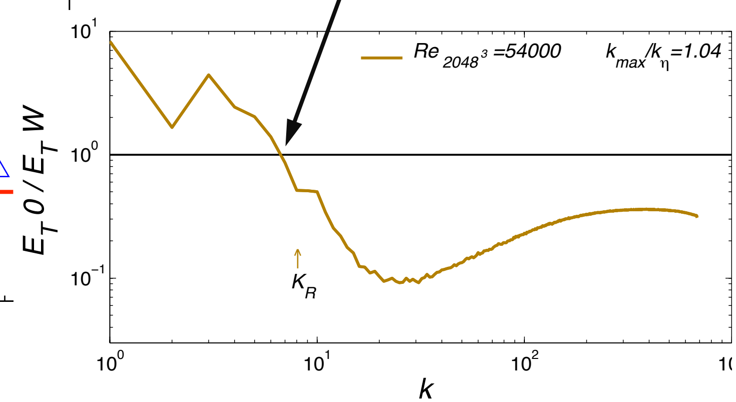


Thanks to John

Interplay of waves and eddies

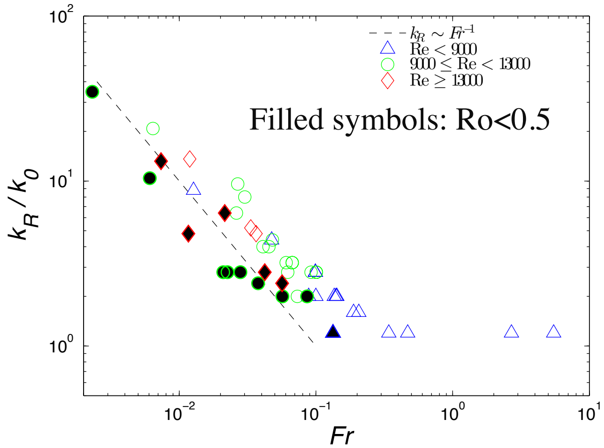


$E_0(k_R) / E_W(k_R) = 1$

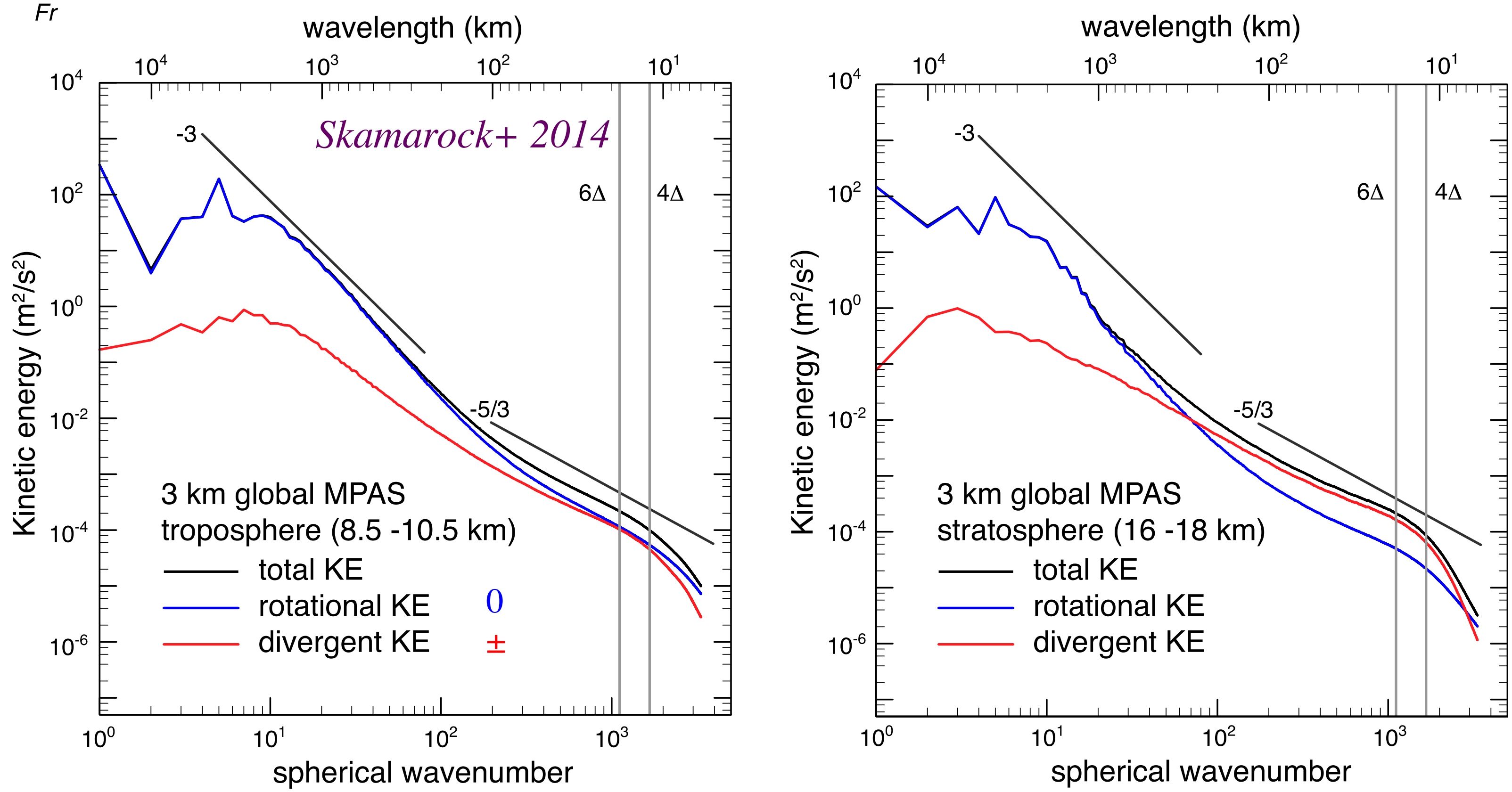


Is $L_R = 2\pi/K_R \sim 1/N \sim L_B = U_0/N$?

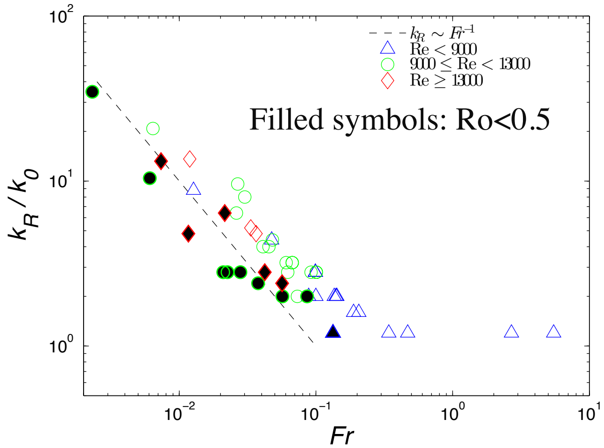
Interplay of waves and eddies



This result of Skamarock+ is compatible with N decreasing with altitude

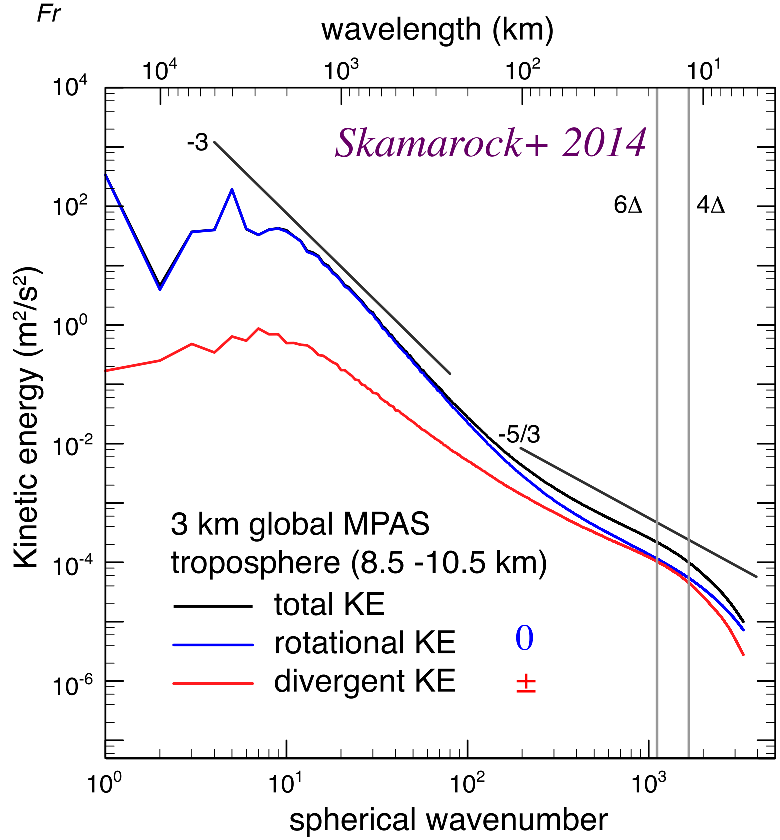


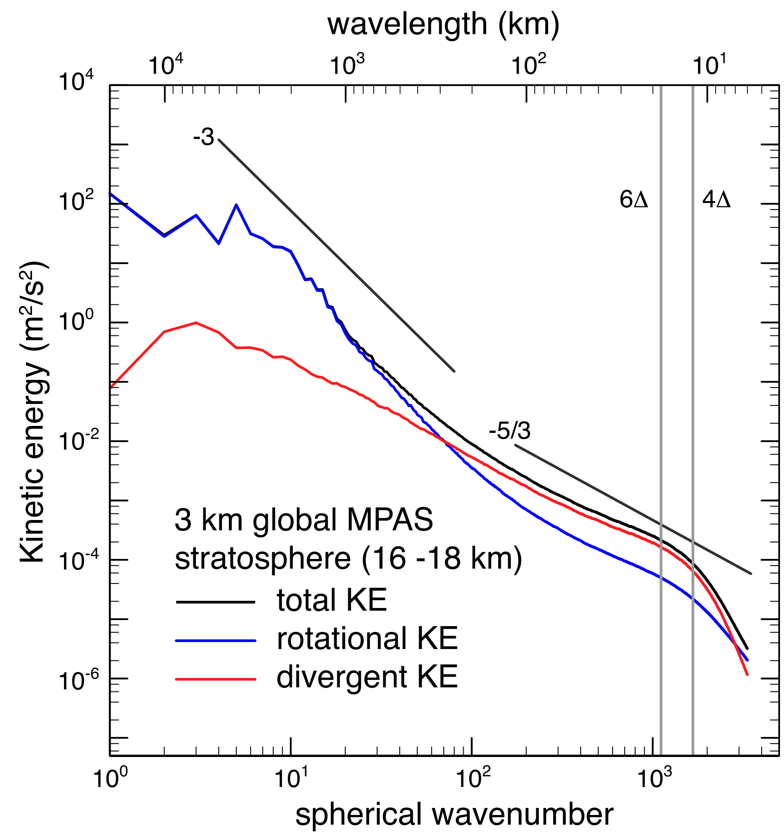
Interplay of waves and eddies



This result of Skamarock+ is compatible with N decreasing with altitude

Consequences for modeling?

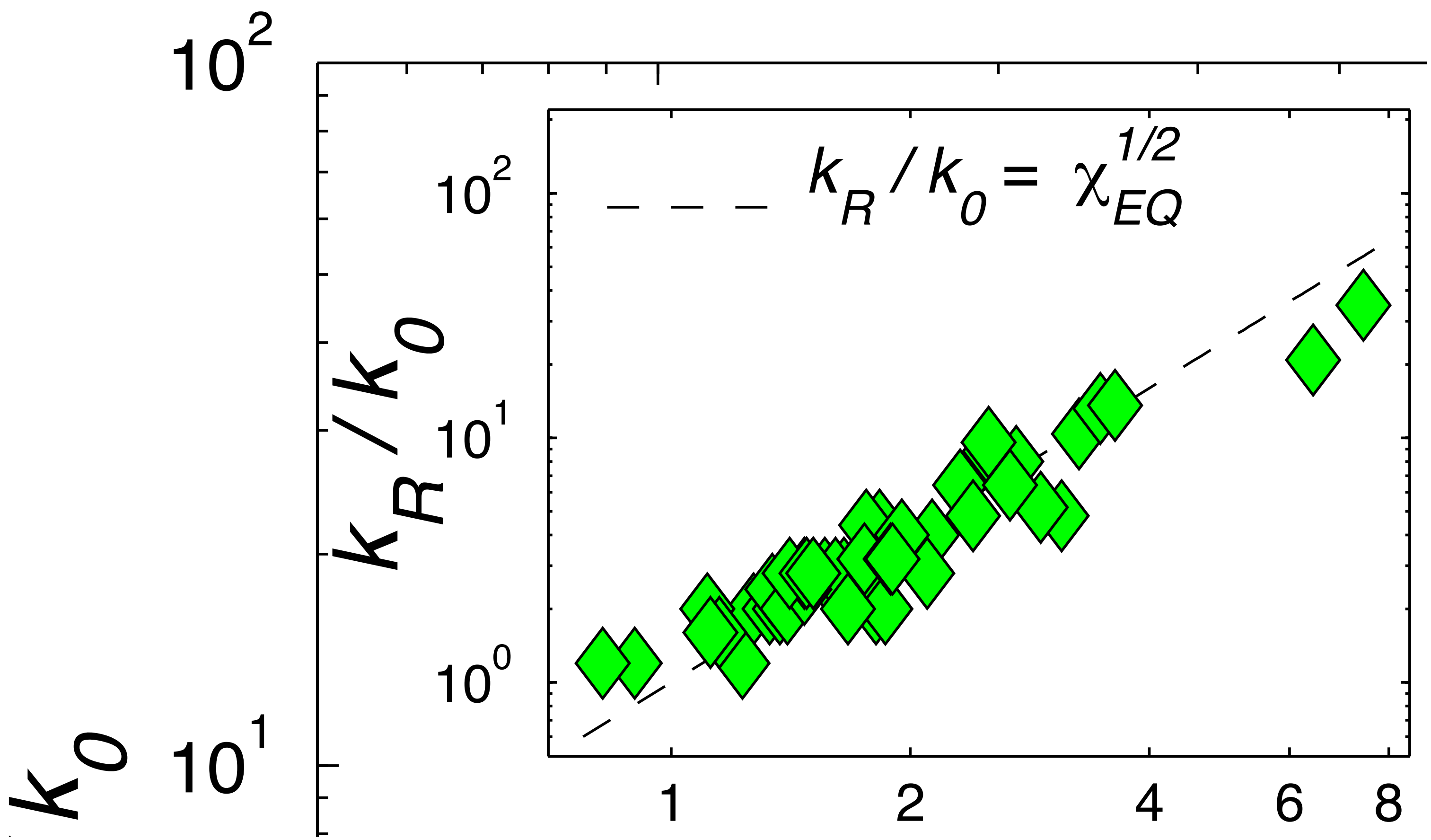




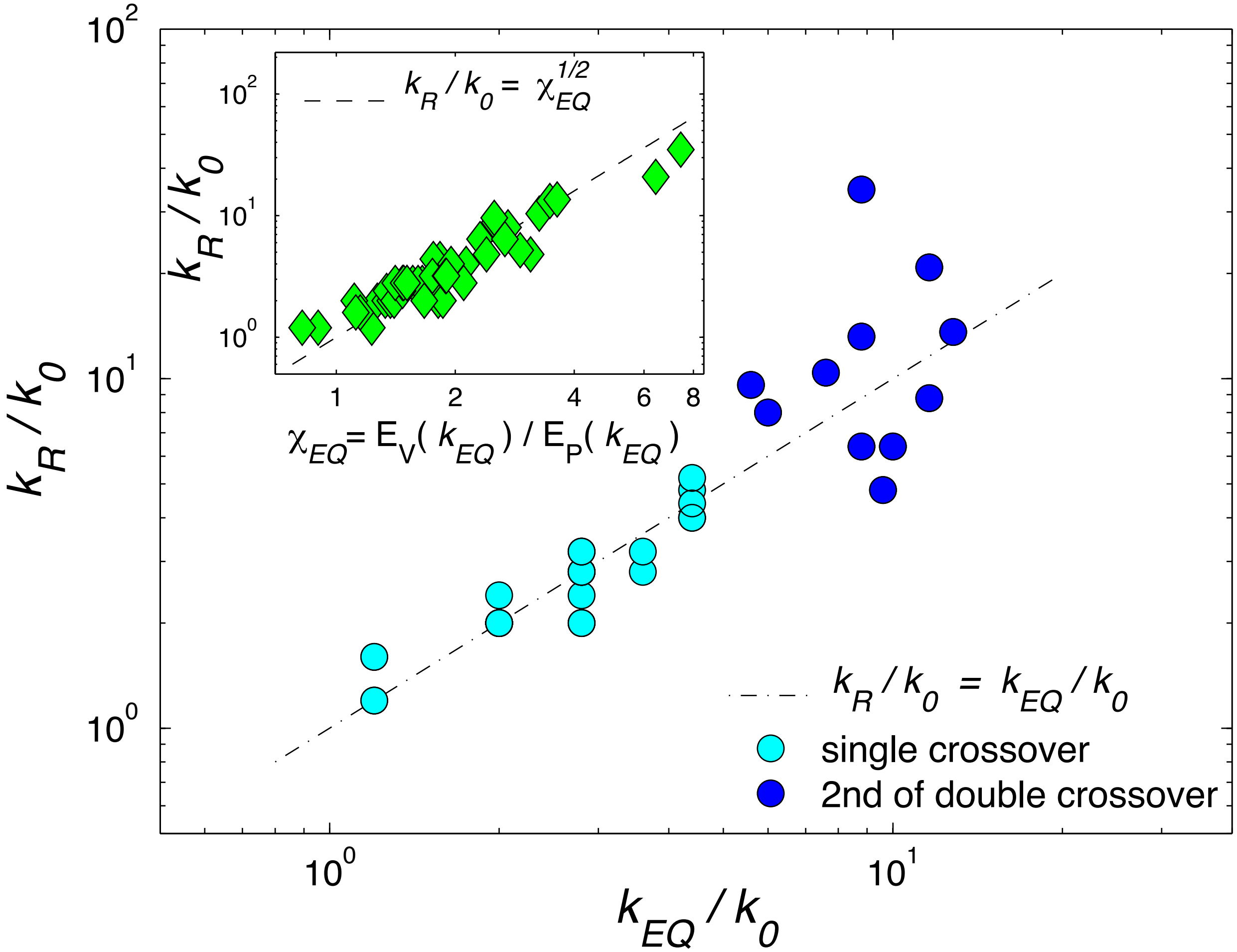
Interplay of waves and eddies

$\chi_{EQ} = E_V(k=k_{eq}) / E_P(k=k_{eq})$

Data → $K_R/k_0 \sim u_{rms}/\theta_{rms}$
$\sim 1/Fr$



Interplay of waves and eddies

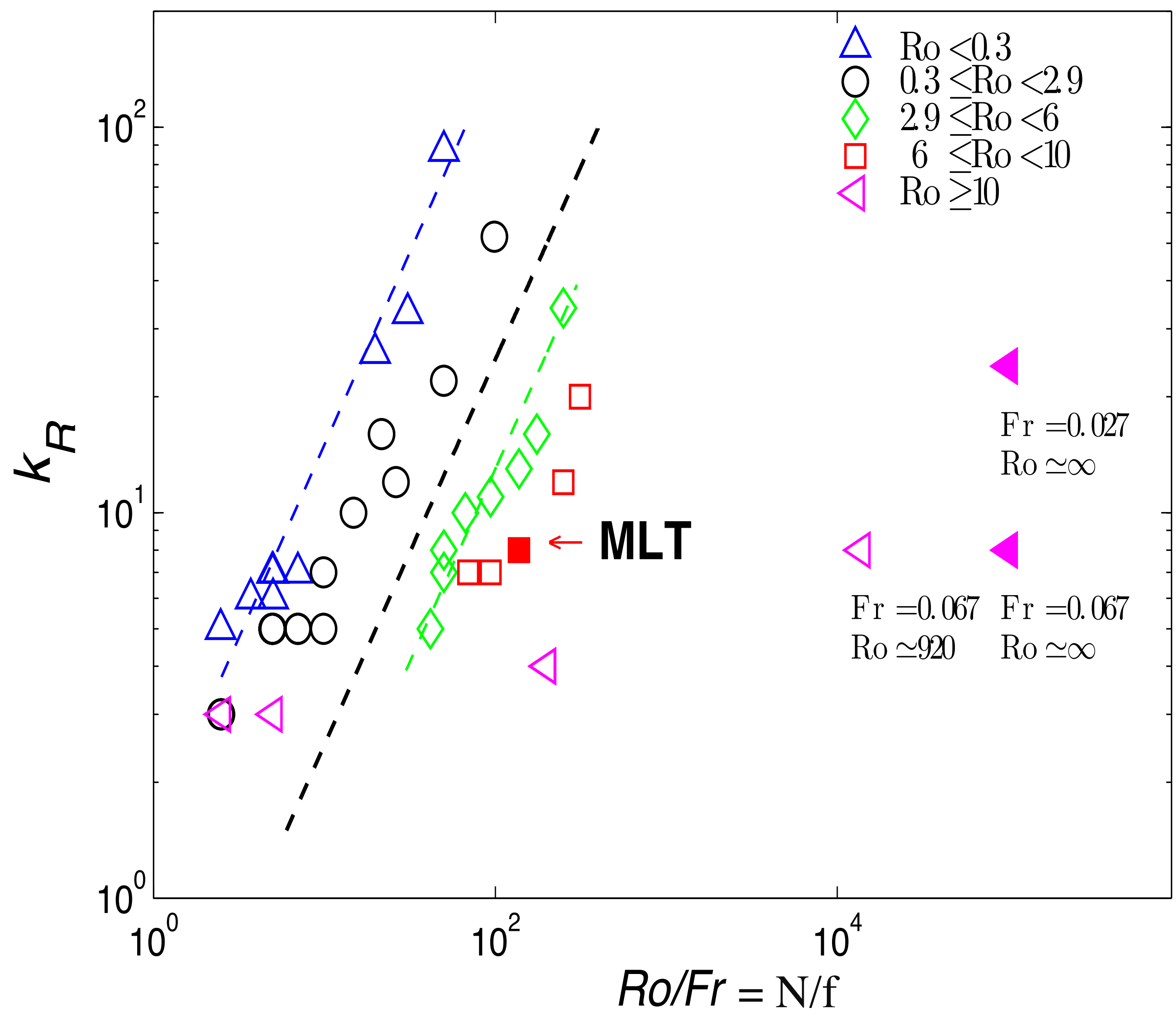


$K_R/k_0 \sim u_{rms}/\theta_{rms}$
$\sim 1/Fr$

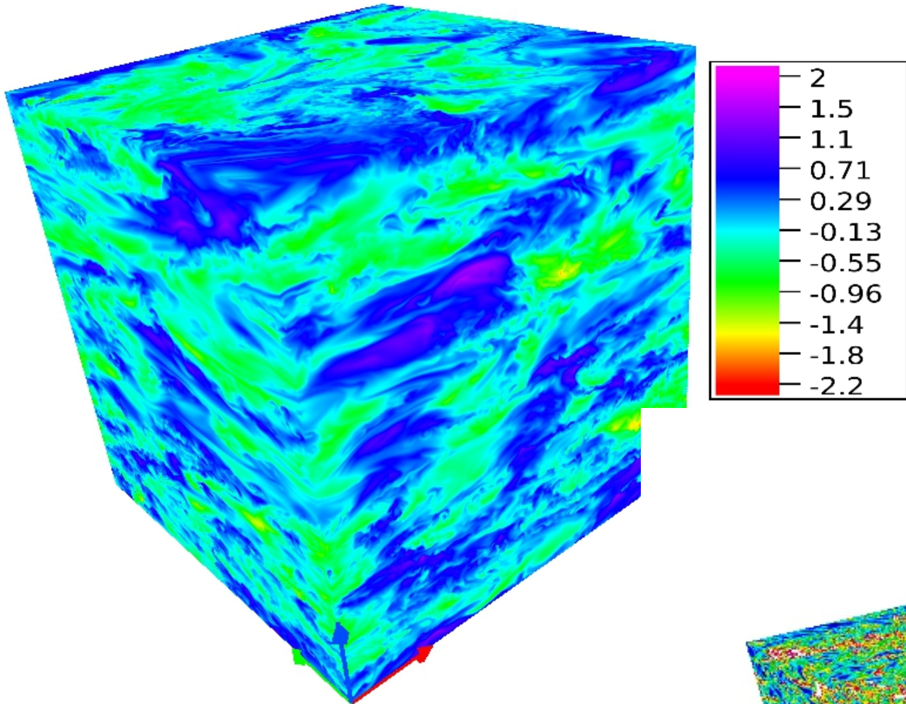
K_R : change in wave/vortex dominance
$\sim K_{EQ}$: wvnb at which minimum of $E_V(k)/E_P(k)$, χ_{EQ}, is reached

Interplay of waves and eddies

$K_R \sim a(Ro)/Fr$

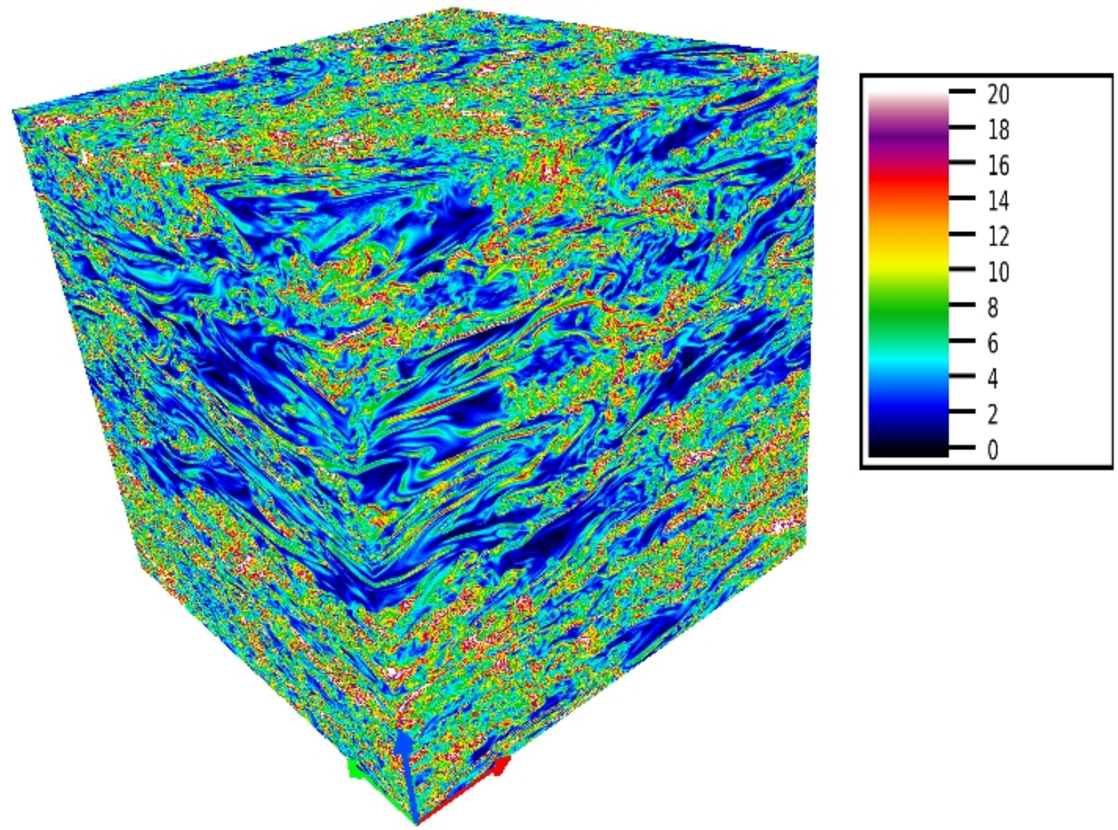


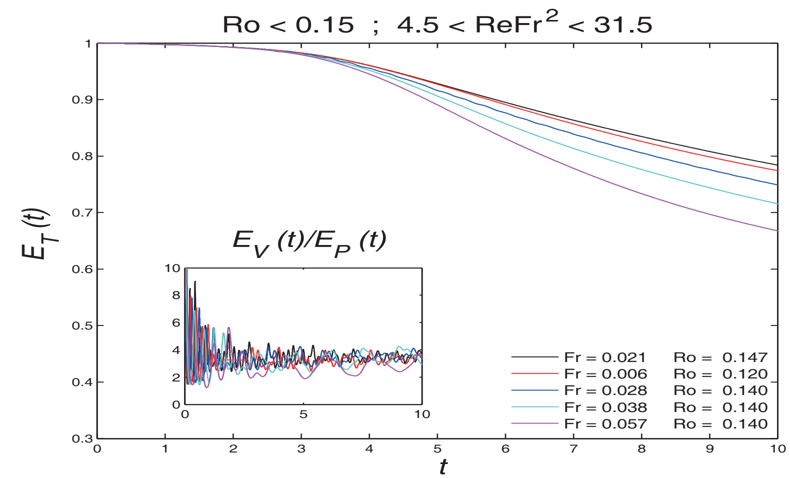
Energy pathway to dissipation and mixing

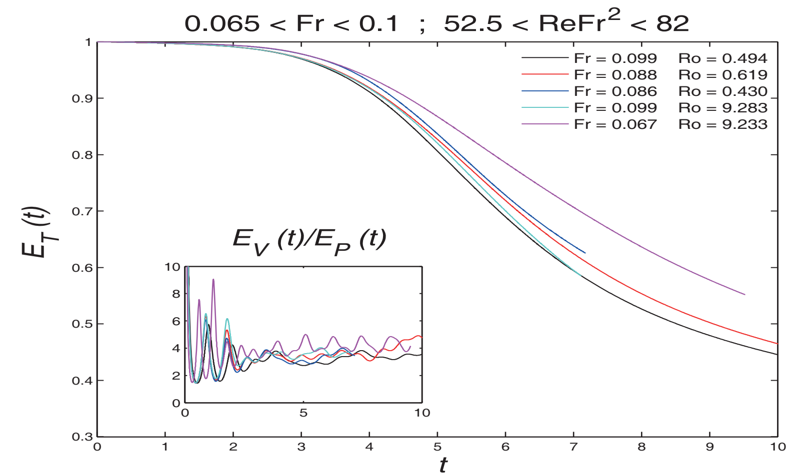


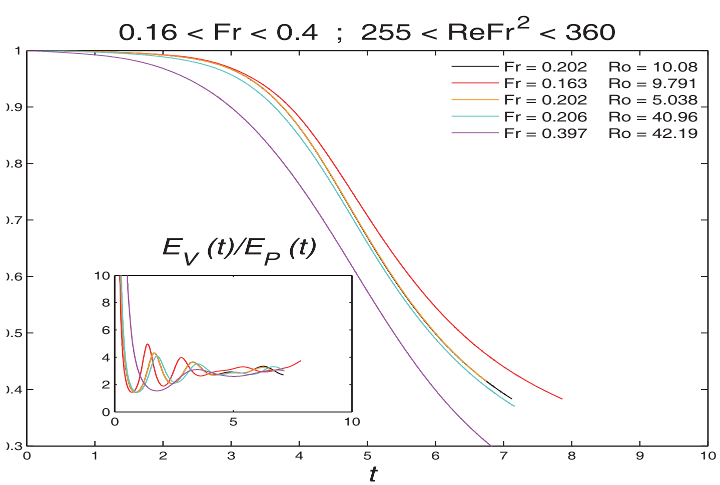
← Temperature and its gradient

N/f=137, R_B=53





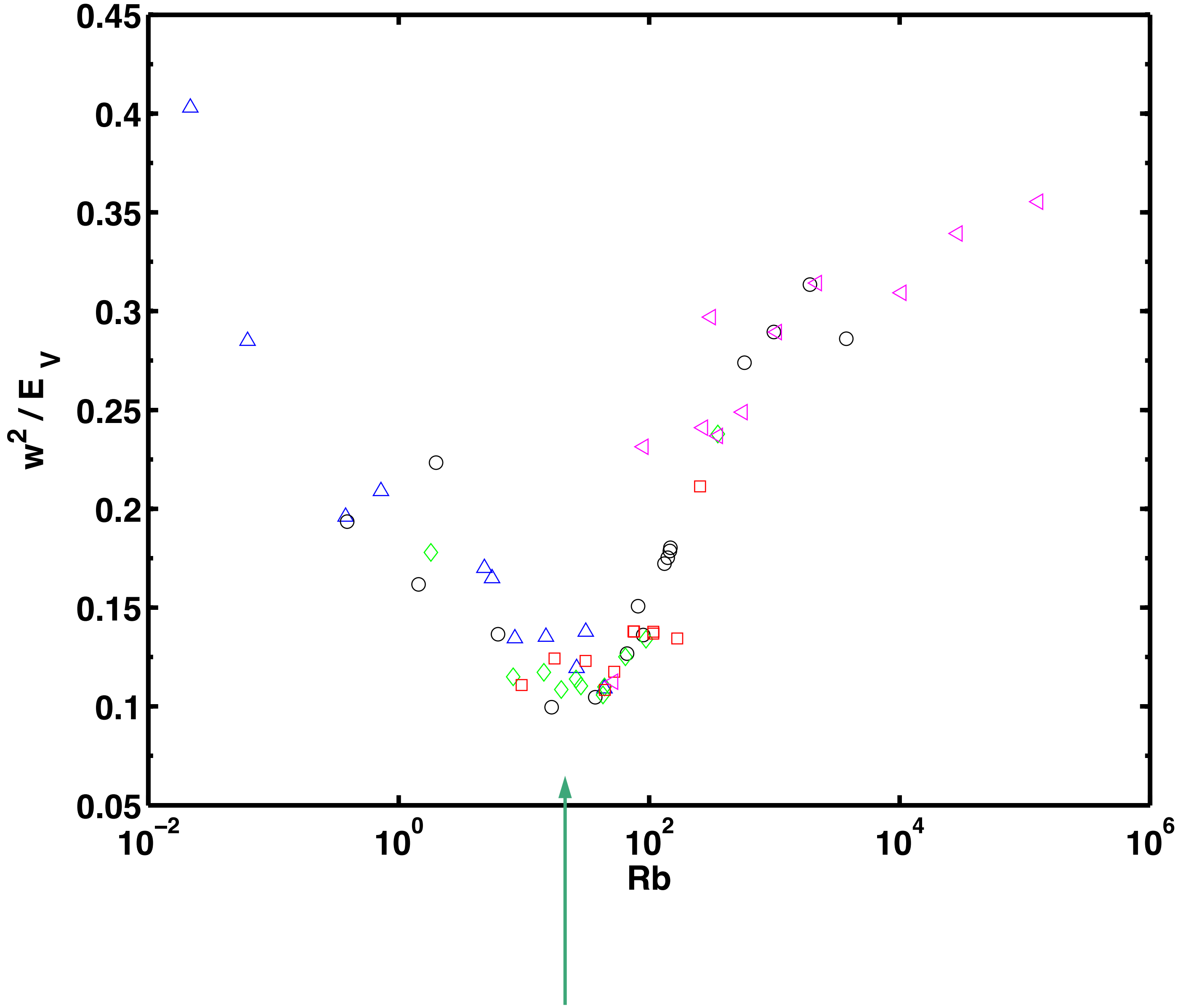




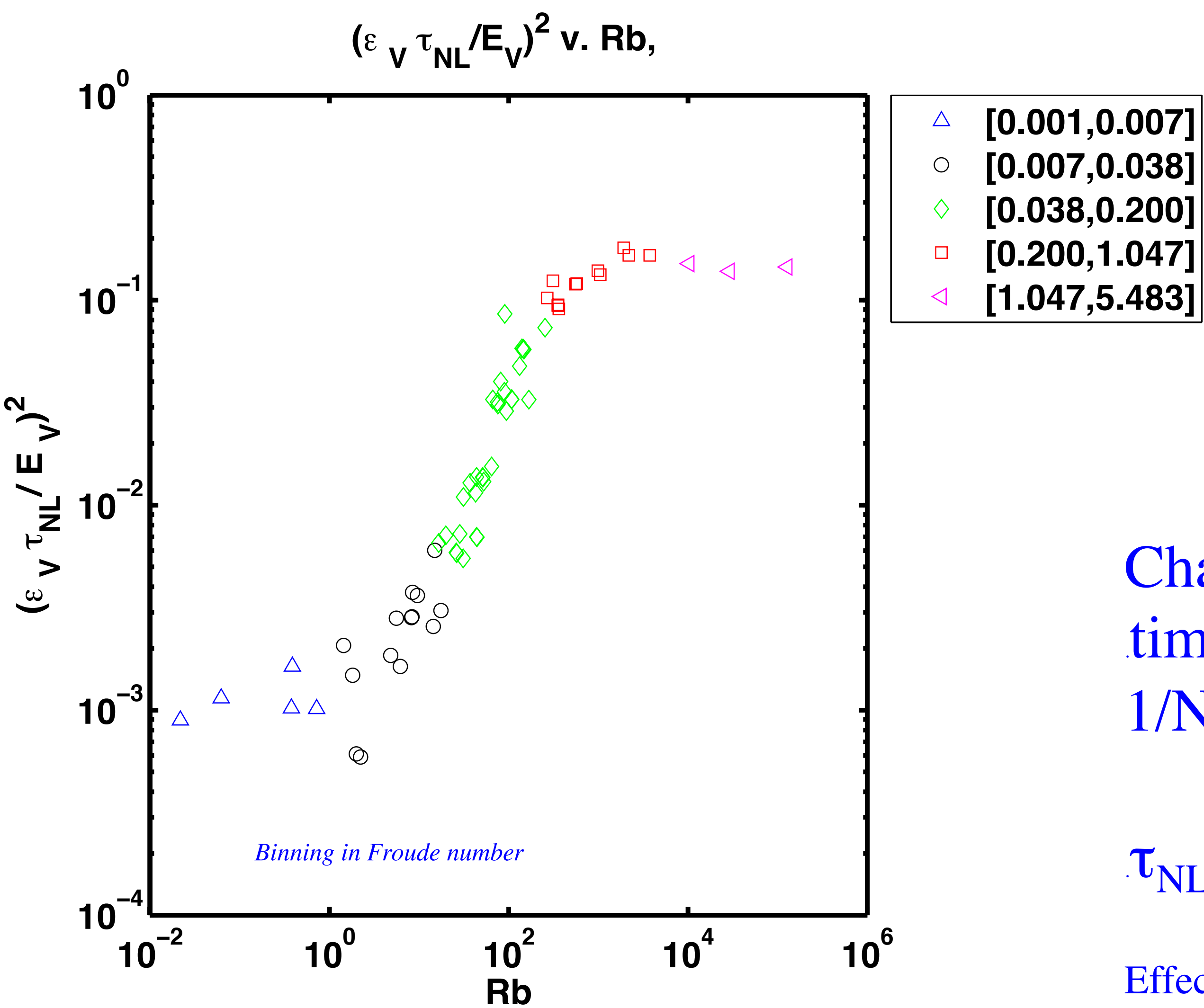
- The kinetic to potential energy ratio ~3, is insensitive to parameters

- Peak of dissipation occurs at approx. the same time except at very low Fr

- The rate at which energy dissipates increases with R_B



0.45
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
w^2 / E_v
10^{-2}
10^0
10^2
10^4
10^6
Rb



Characteristic times:
1/N , 1/f

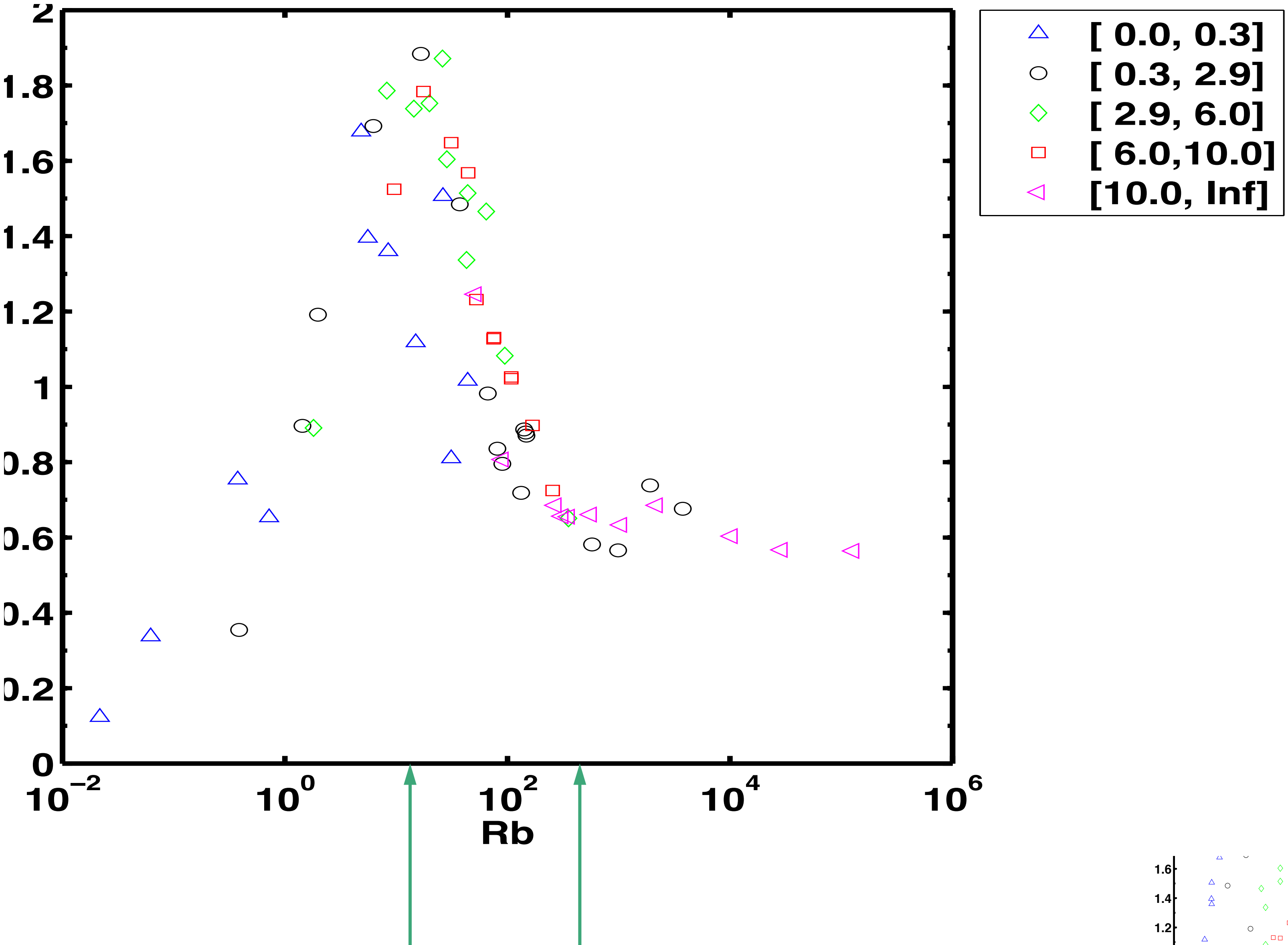
$\tau_{NL} = L_0/U_0$

Effective dissipation:

$T_v = E_v/\varepsilon_v$,
$T_p = E_p/\varepsilon_p$

$[\tau_{NL}/T_v]^2$: 0.001 → → 0.1

→ Effective dissipation (much) slower than nonlinear times

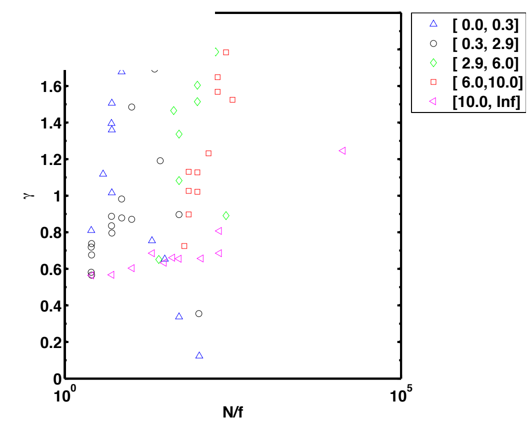


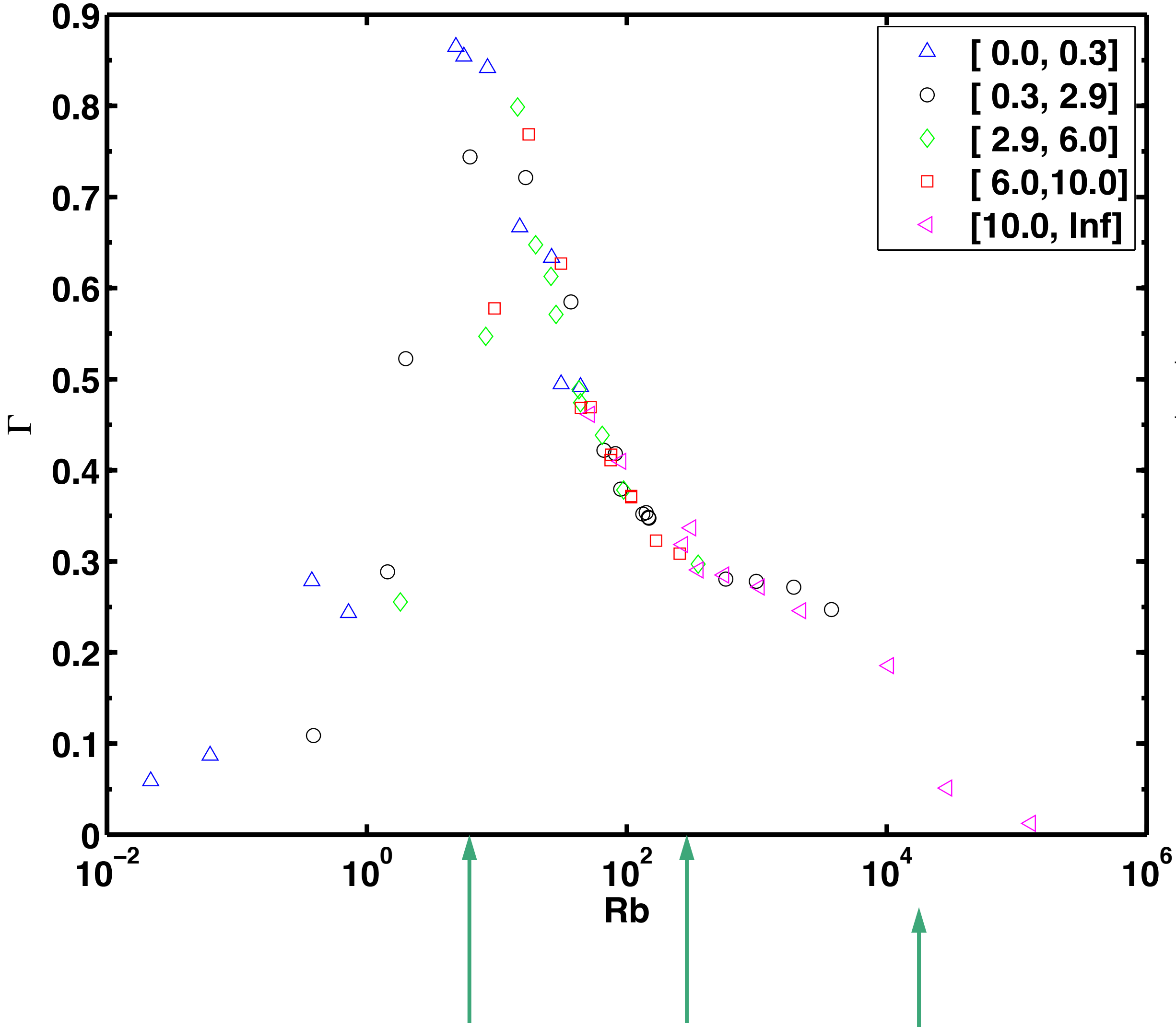
$\gamma = T_v / T_p$

$=[E_V/E_P][\varepsilon_p/\varepsilon_v]$

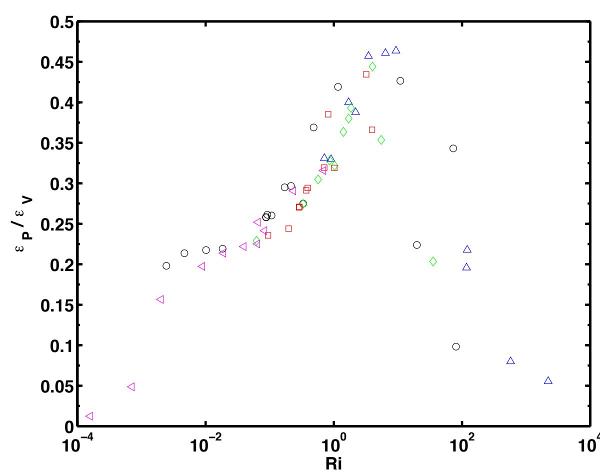
w. binning in Ro

Role of
Reynolds?
and of
$E_P(t{=}0){=}0$?

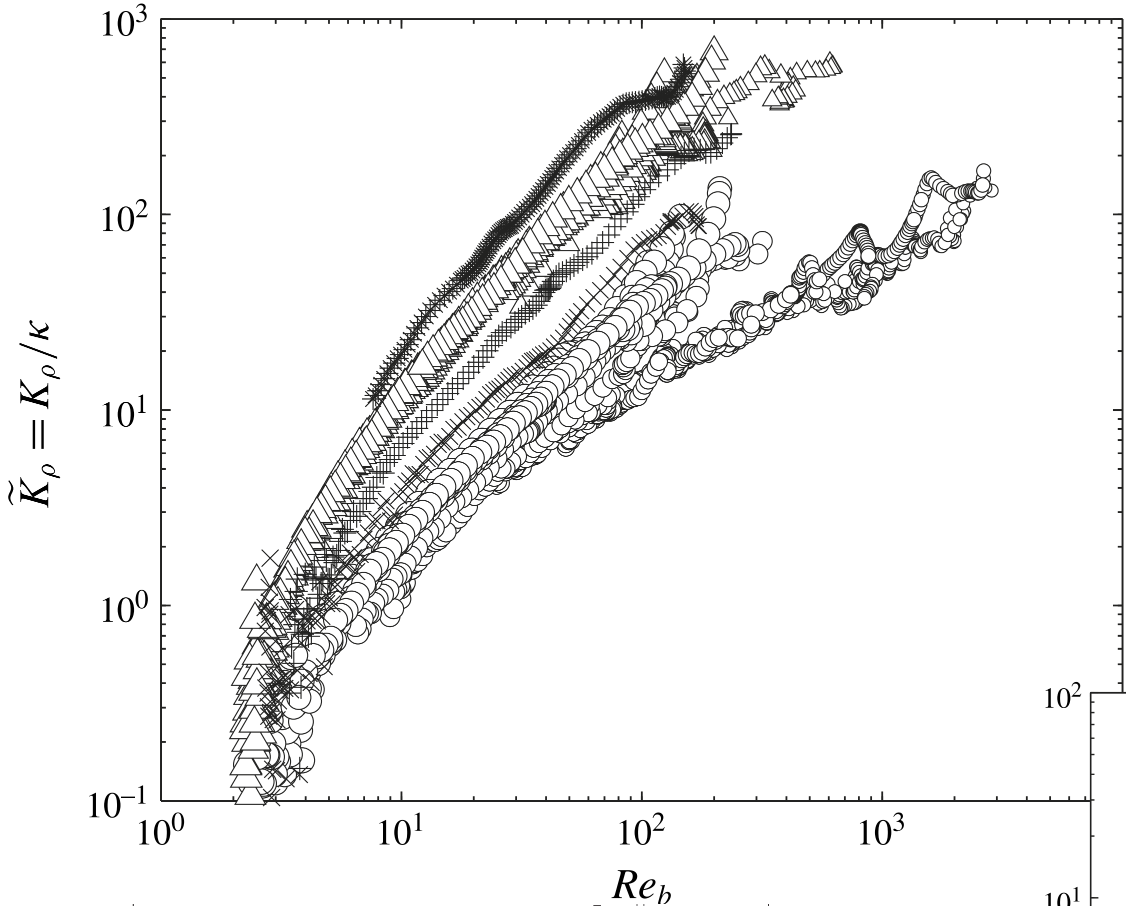


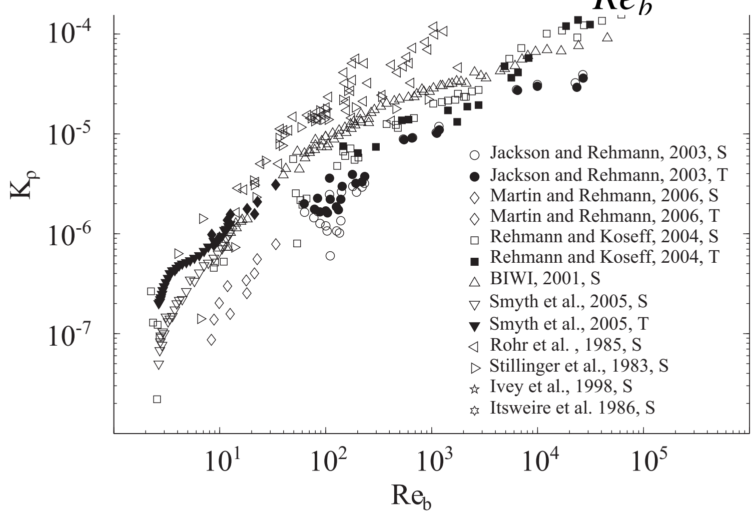


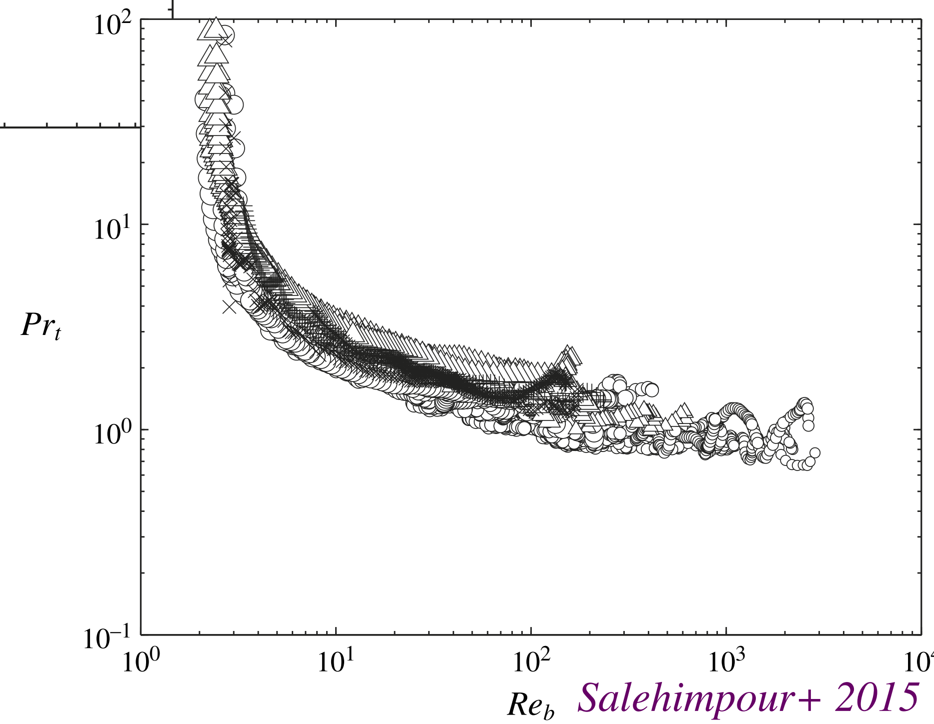
$$\Gamma = \varepsilon_P/[\varepsilon_V - \varepsilon_P]$$



Normalized anomalous diffusivity and turbulent Prandtl number as a fn of R_B







Salehimpour+ 2015

Conclusions and questions

- Large resolutions allow for scale separation and thus to distinguish between *(multiple)* regimes within a flow
- Evidence for Bolgiano-Obukhov scaling at large scale and complex interplay between velocity and buoyancy modes & fluxes
- Local instabilities and strong local variations (dissipation, PV, …)

- Waves and eddies partition and local small-scale dynamics
- Role of rotation, inverse cascade, of walls and B.C. *in the BO scaling?*
- Role of forcing (3D *vs*. 2D, vortices *vs*. waves, …), of large-scale friction, of non-local interactions & large-scale instabilities?

^ How much in **RST** and how is it structured and characterized: Intermittency in velocity itself? Generalized model for intermittency of V in **RST**? Helicity?
^ Role of temperature fluctuations, balanced or not, in I.C. or forcing?
^ Reynolds number in mixing: does mixing saturate?

^ What models for vorticity lanes in **RST**?

^ How many transitions in $R_B = ReFr^2$? *(4k, Fr~.15, Ro=.7, R_B~1200; or Fr~.25, Ro=.5, R_B~3100)*

Some questions in **R**otating **S**tratified **T**urbulence

^ How much in **RST** and how is it structured and characterized:

- Intermittency in velocity components themselves?
- Generalized model for intermittency of V in **RST**?
- Helicity?

^ Role of

^ temperature fluctuations, balanced or not, in I.C. or forcing?

^ Reynolds number in mixing: does mixing saturate?

^ What models for vorticity lanes in **RST**?

^ How many transitions in $R_B = ReFr^2$? *(4k, Fr~.15, Ro=.7, R_B~1200; or Fr~.25, Ro=.5, R_B~3100)*

“*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, Denver 2012

Geophysical High Order Suite for Turbulence *(D. Gomez & P. Mininni)*

- Pseudo-spectral DNS, periodic BC cubic *(also 2D), single/double precision*; Runge-Kutta for incompressible Navier-Stokes, SQG & Boussinesq. Includes rotation, passive scalar(s), MHD + Hall term
- *GHOST, from laptop to high-performance, parallelizes linearly up to 130,000 processors, using hybrid MPI/Open-MP (Mininni et al. 2011, Parallel Comp. 37)*
- LES: alpha model & variants (Clark, Leray) for fluids & MHD
- Helical spectral (EDQNM) model for eddy viscosity & eddy noise
- Lagrangian particles *(w. A. Pumir)*
- Gross-Pitaevskii & Ginzburg-Landau *(PM+M. Brachet)*
- **Data, forced:** 2048^3 Navier-Stokes and 1536^3 & 3072^3 with rotation, both w. or w/o helicity. Rotating stratified turbulence w. 2048^3 grids forced at intermediate scale
- **Data, spin-down MHD**:1536^3 random + 6144^3 ideal & 2048^3 w. T-Green symmetry
- Decaying rotating stratified flow, N/f~5, Re=5.5 10^4, 2048^3 , 3072^3 & 4096^3 grids.
- Decaying rotating stratified flow, 2.5<N/f<300, Re up to 1.8 10^4, R_B up to 10^5, 1024^3 grid.

mininni@df.uba.ar duaner62@gmail.com marino@ucar.edu

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