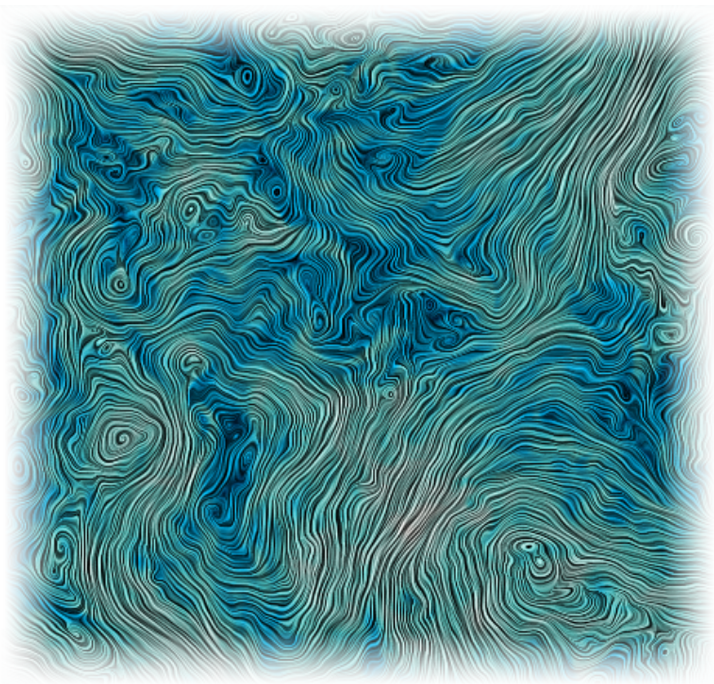
Gauging anisotropic scaling in plasma turbulence and topological change at the ion scales

Khurom H. Kiyani

Romain Meyrand, Fouad Sahraoui, Sandra Chapman



LPP

ÉCOLE POLYTECHNIQUE
UNIVERSITÉ PARIS-SACLAY

Theme issue on the topic of plasma turbulence

PHILOSOPHICAL TRANSACTIONS A

Volume 373 | Issue 2041 | 13 May 2015

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Theme issue: Dissipation and heating in solar wind turbulence

Article ID

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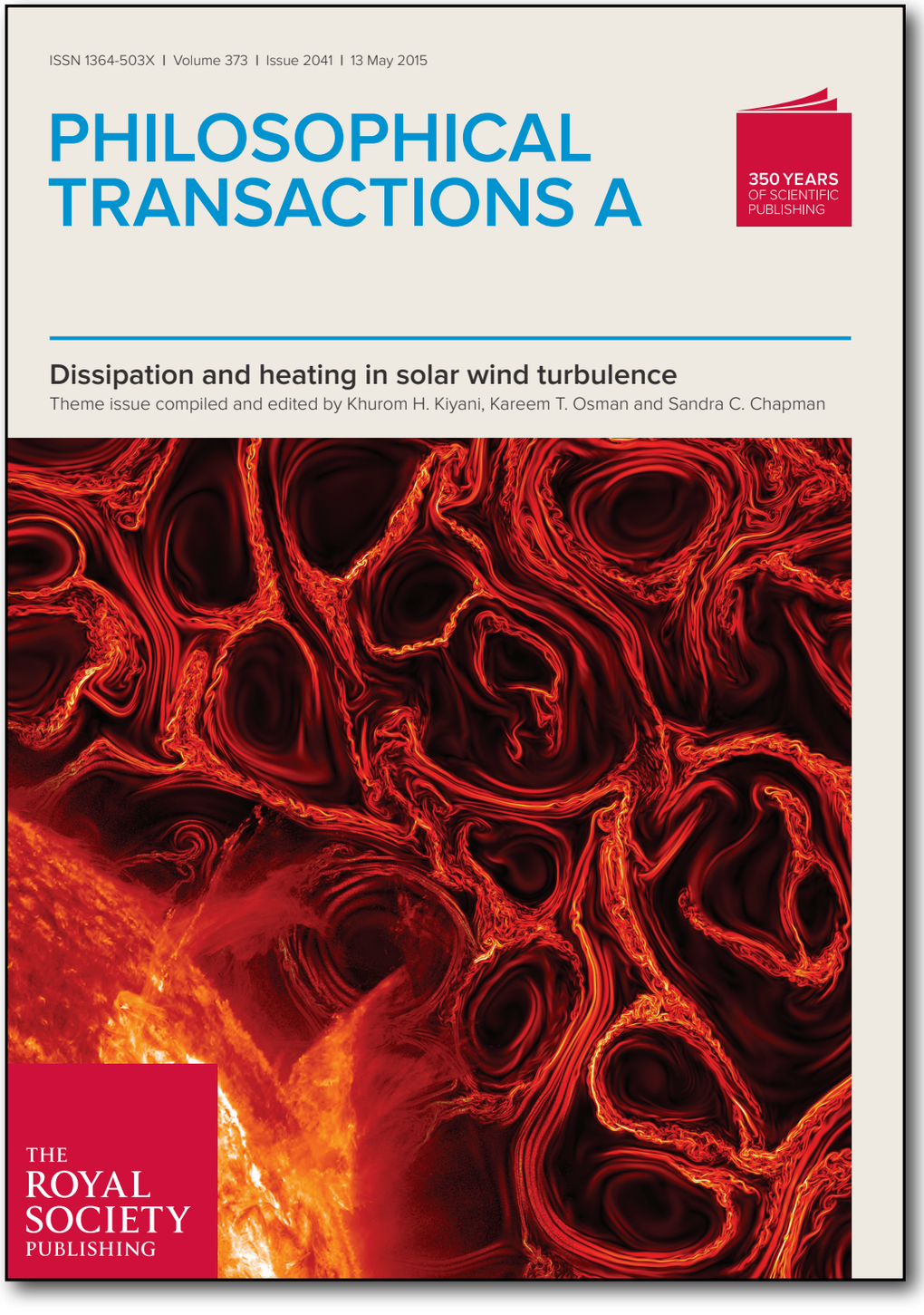
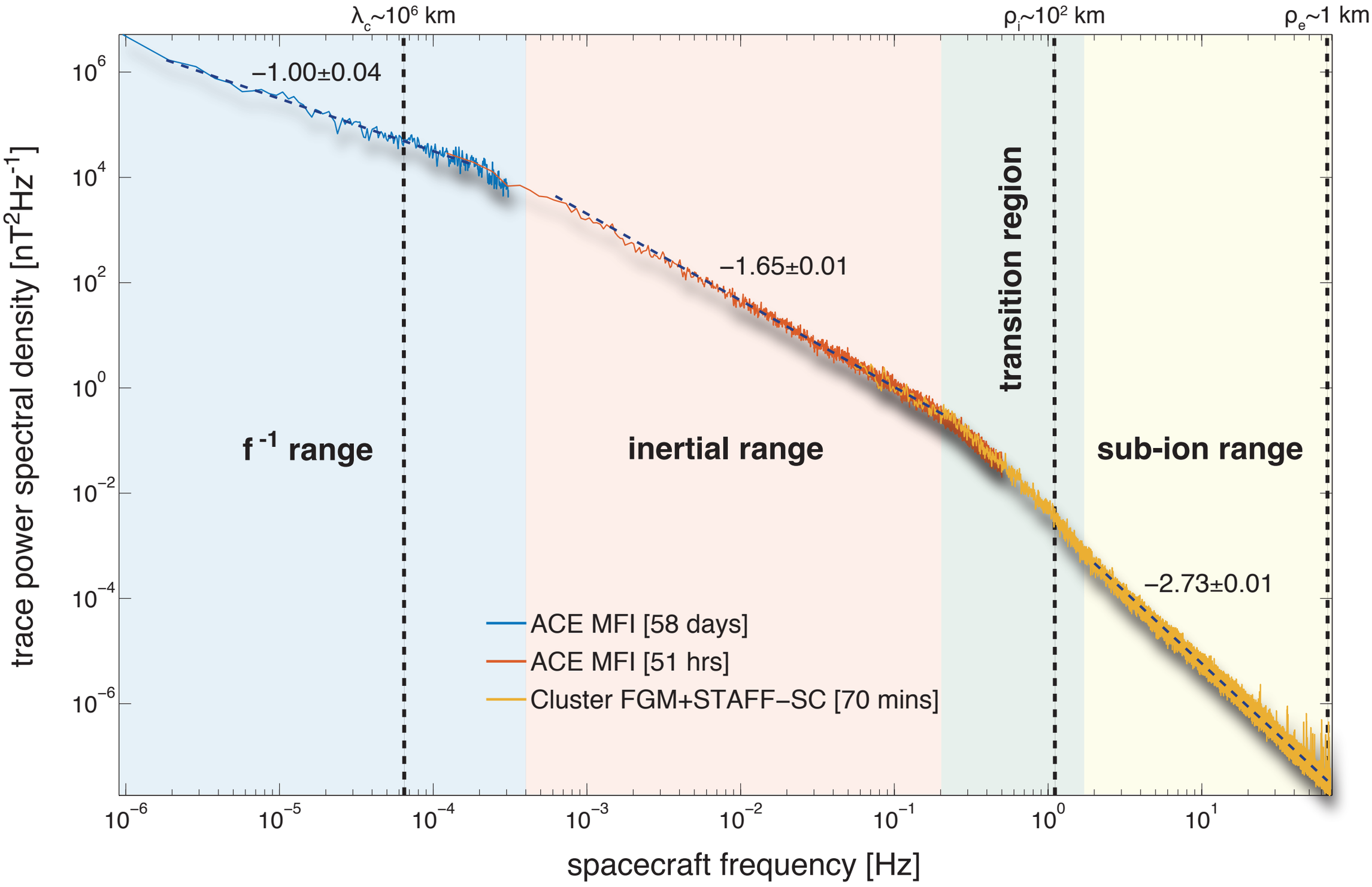
Theme issue on the topic of plasma turbulence

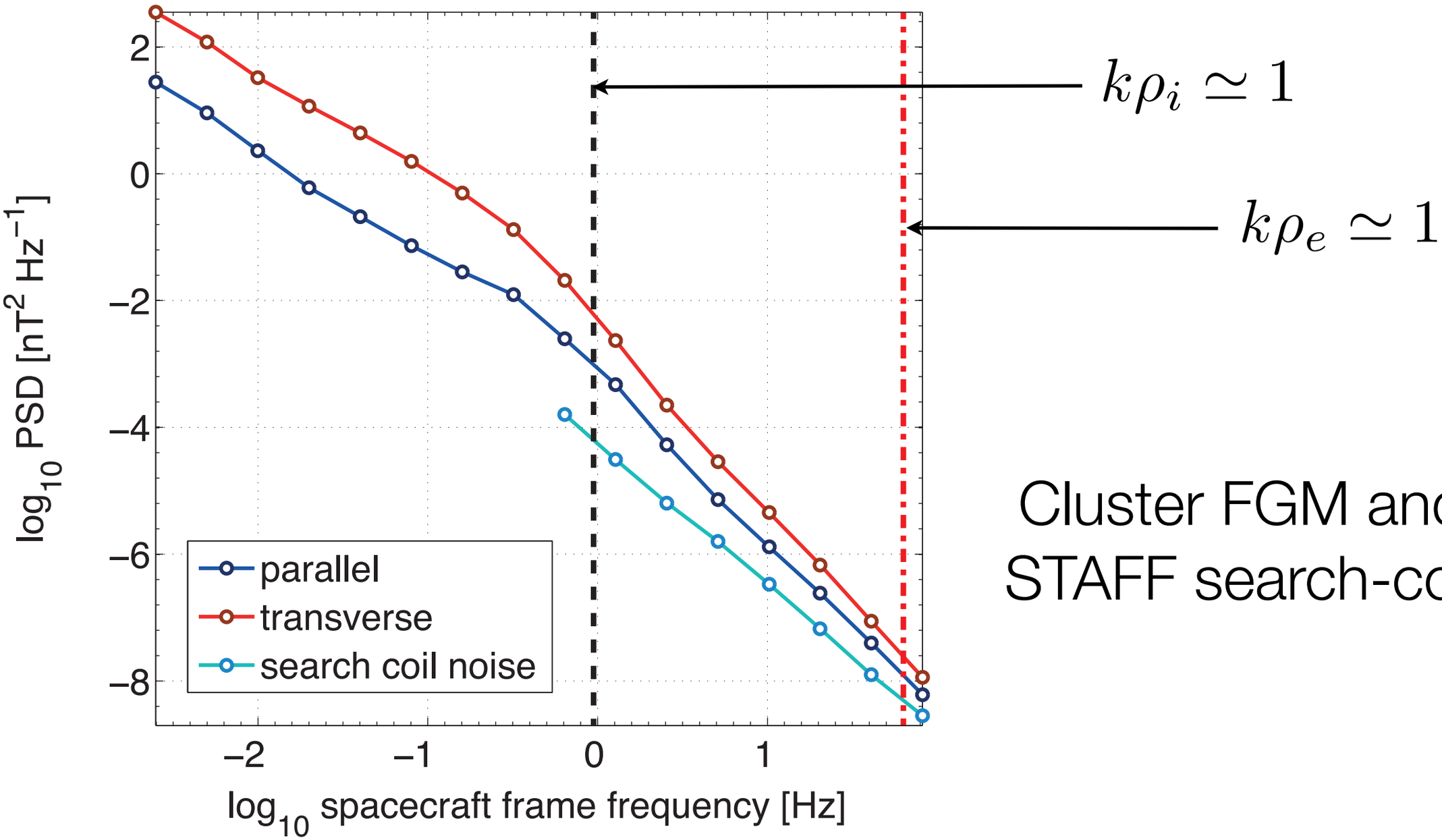


http://www.warwick.ac.uk/fac/sci/physics/research/cfsa/people/kiyani/philstransa.zip

Typical spectral density of solar wind turbulence



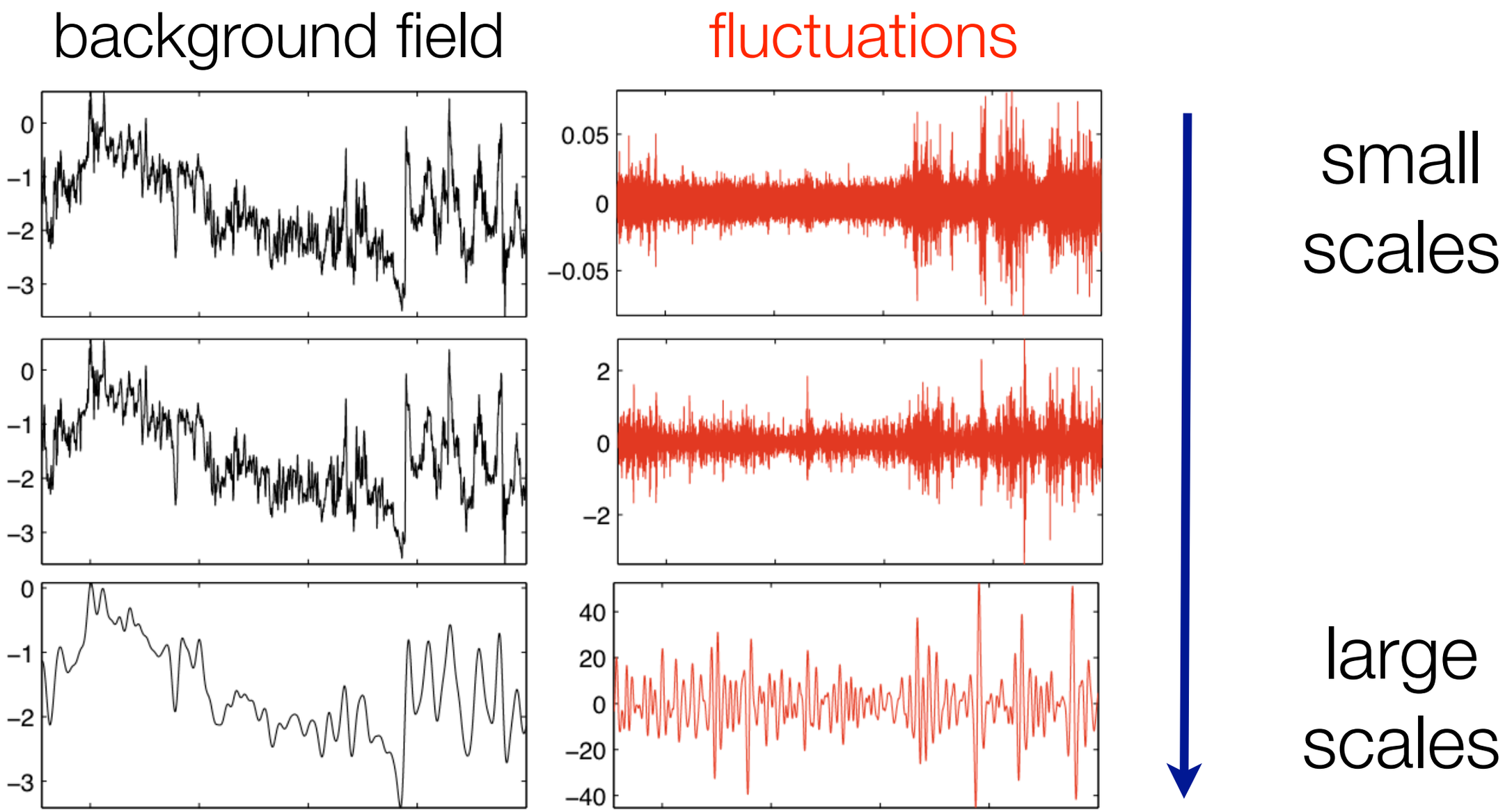
power spectral density {component anisotropy}



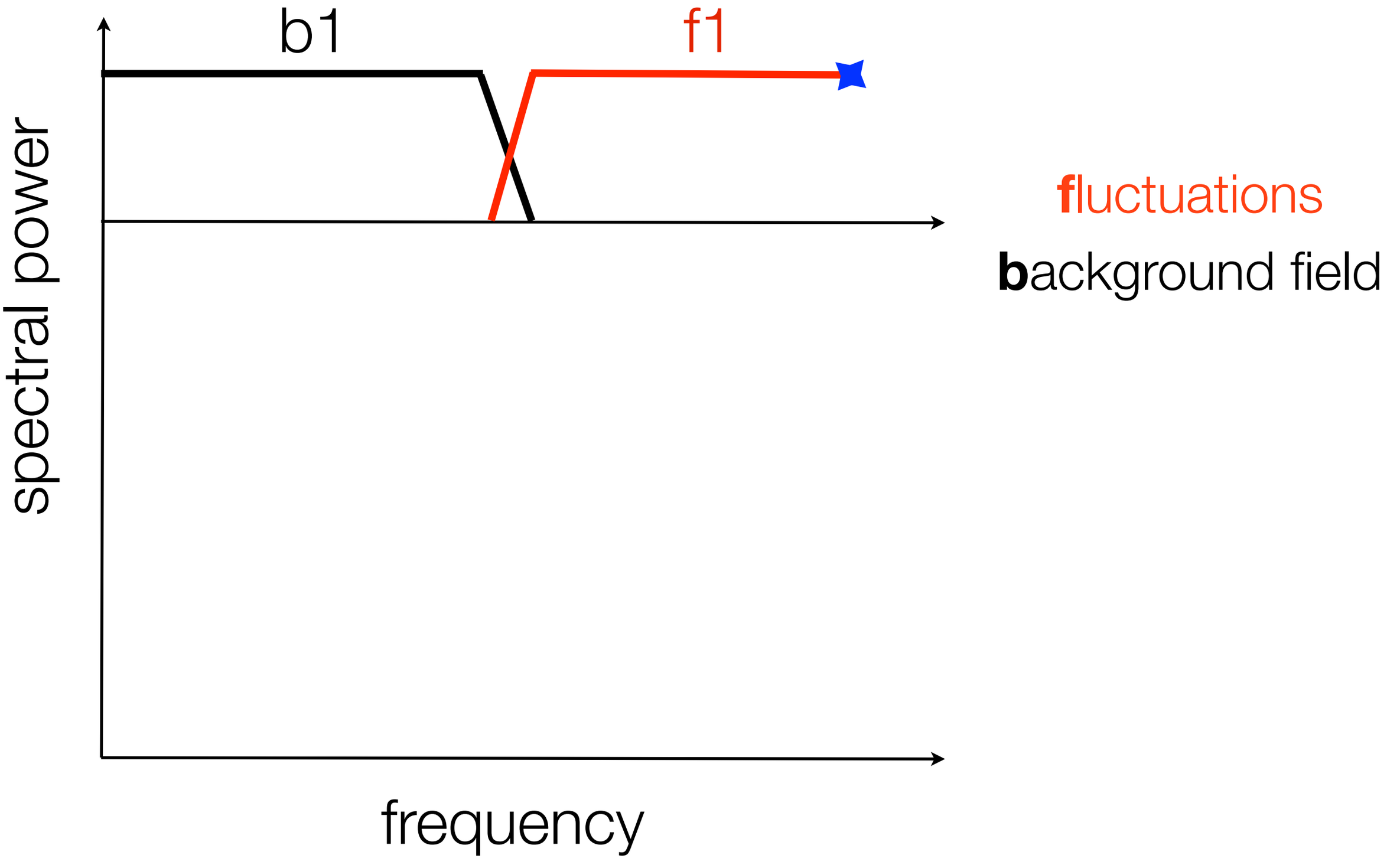
Cluster FGM and STAFF search-coil

Kiyani et al. ApJ (2013)

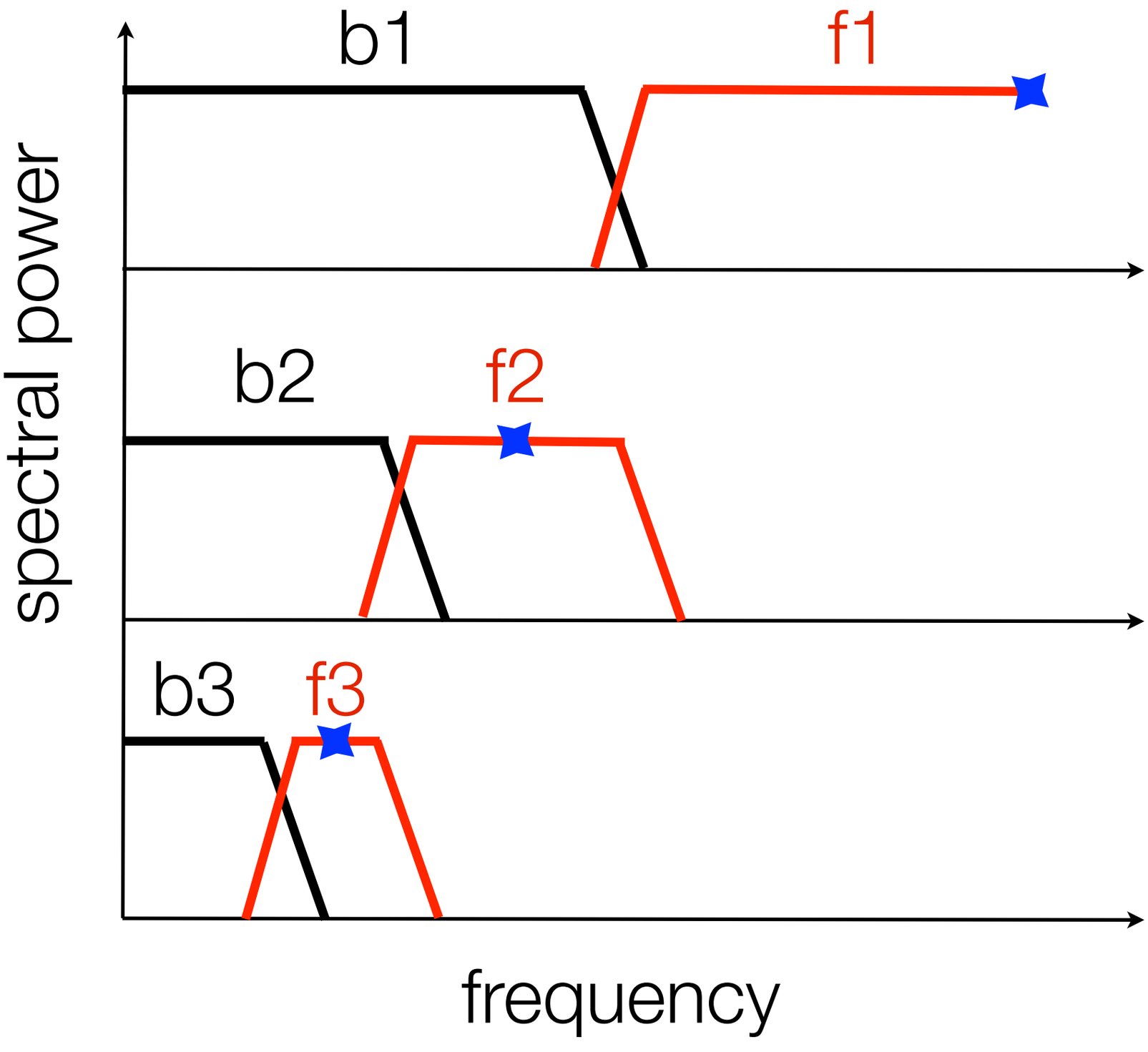
adaptive local scale-dependent fluctuations **and** background guide field



local scale-dependent fluctuations *and* background field using low/high pass filters



local scale-dependent fluctuations *and* background field using low/high pass filters

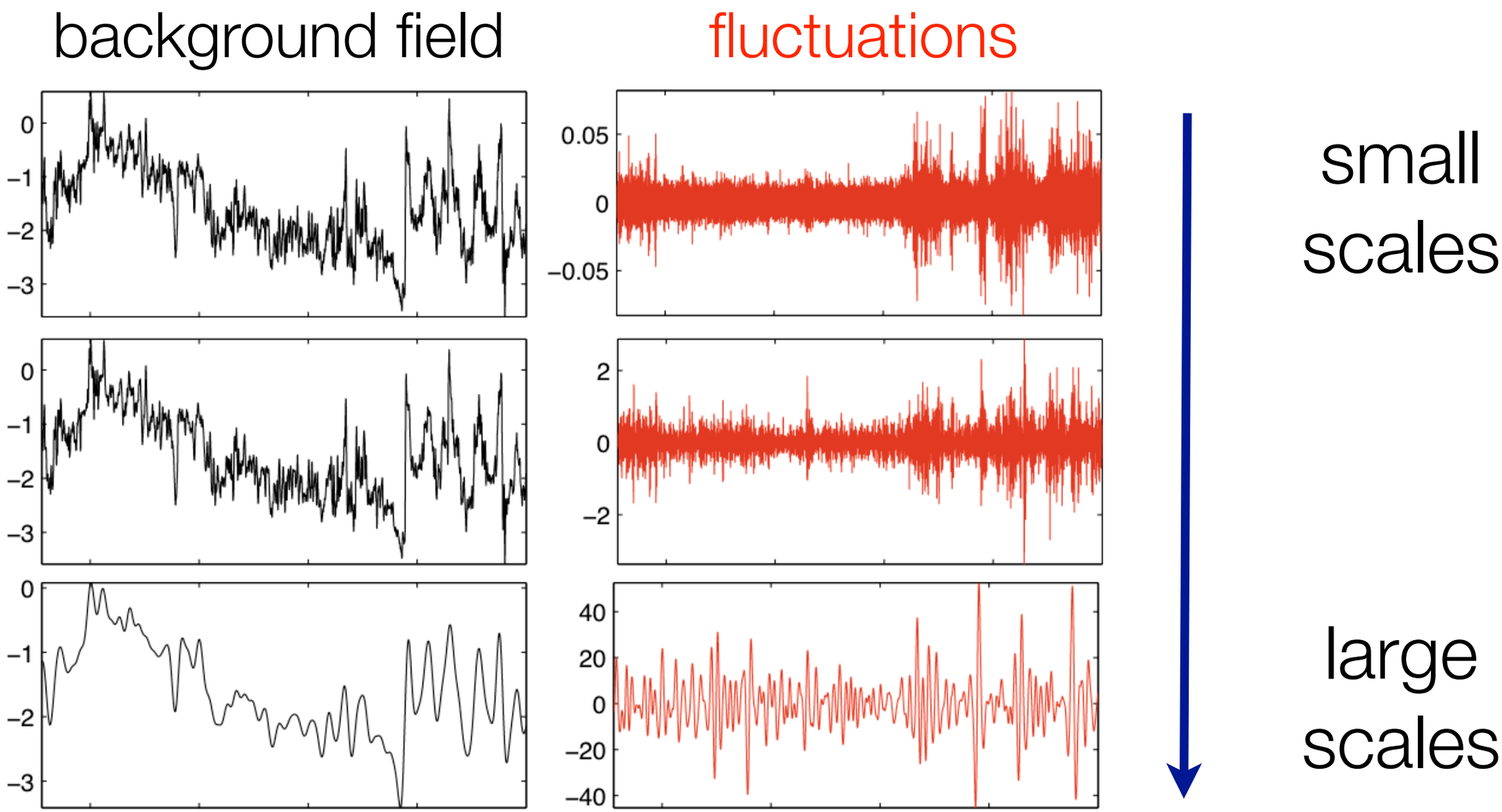


fluctuations

background field

filter bank implementation using quadrature mirror filters

adaptive local scale-dependent fluctuations **and** background guide field

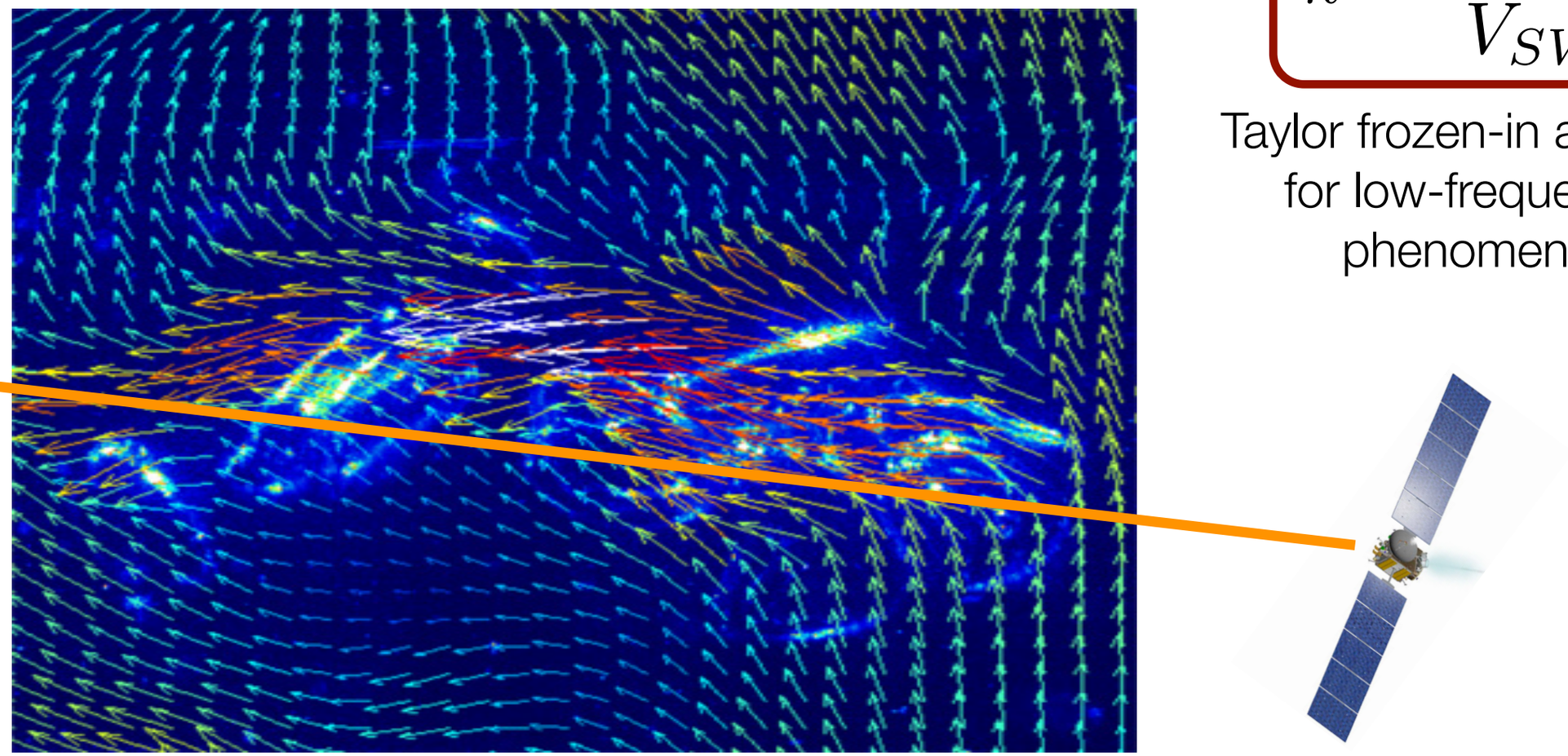


Each band (fluctuations) has its corresponding background field

angles of measurement w.r.t. B

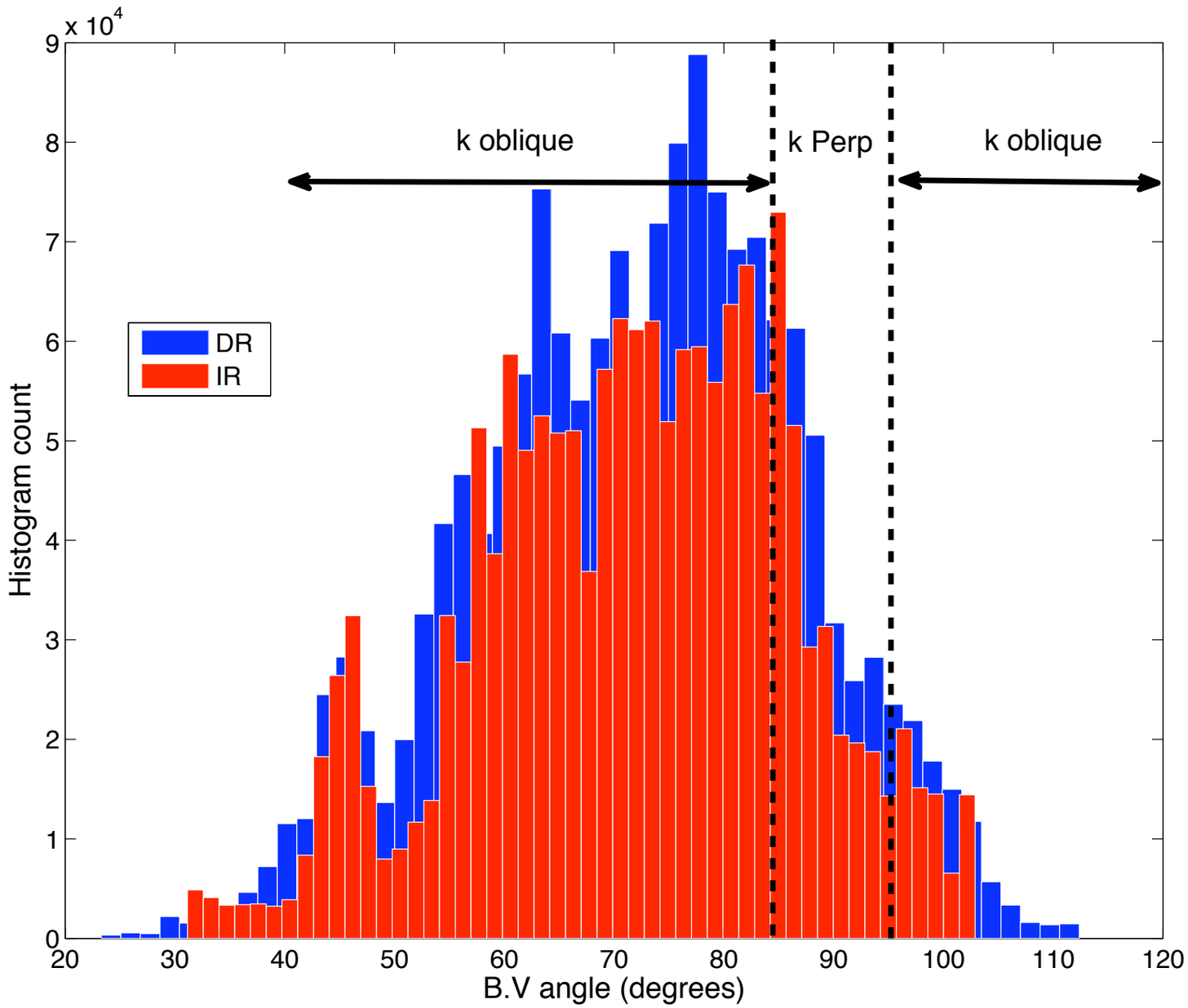
$$k = \frac{2\pi f_{sc}}{V_{SW}}$$

Taylor frozen-in approx, for low-frequency phenomena



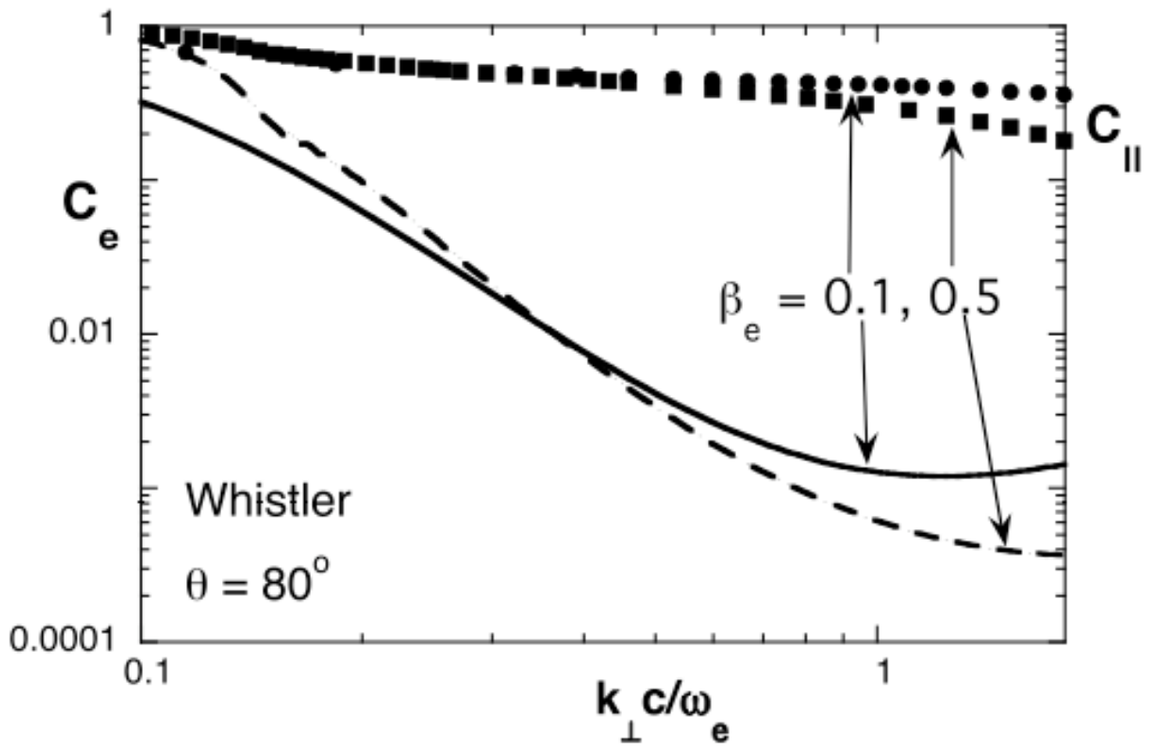
MHD $\frac{V_A}{V_{SW}} < 1$ else $\frac{V_\phi}{V_{SW}} < 1$

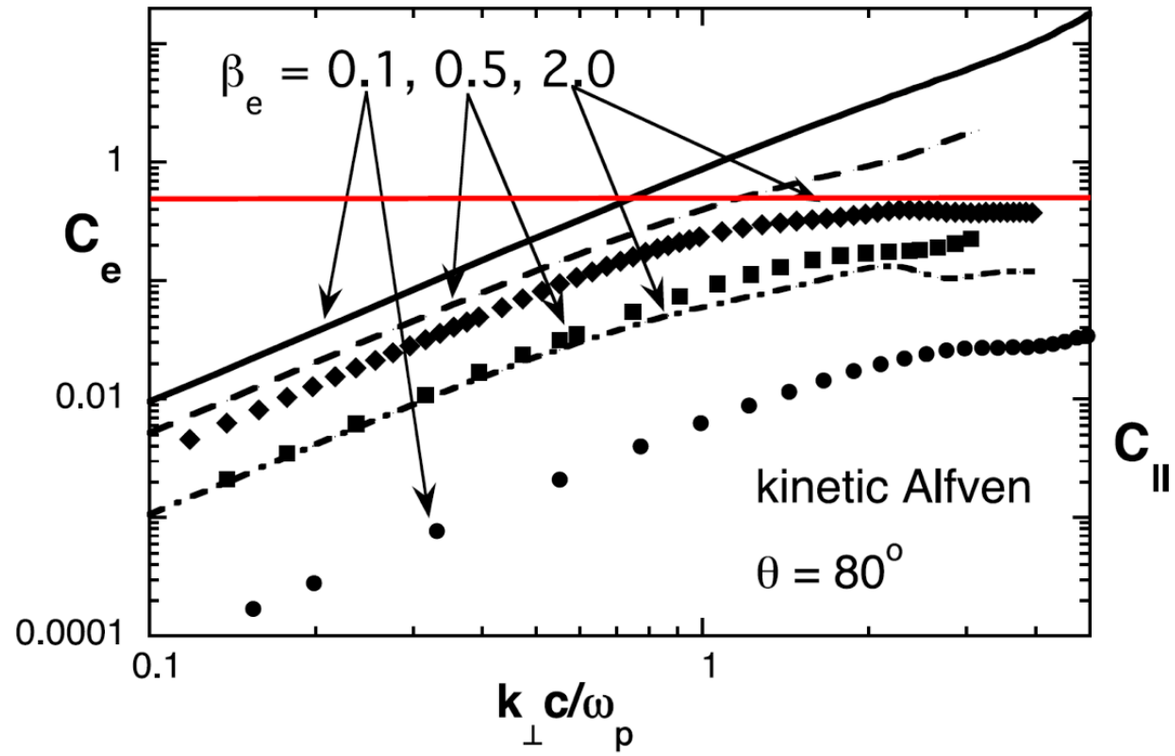
Anisotropy (angle between B and V)



Magnetic Compressibility and linear wave modes

$$C_{\parallel}(\mathbf{k}) \equiv \frac{\left|\delta B_{\parallel}(\mathbf{k})\right|^2}{\left|\delta \mathbf{B}(\mathbf{k})\right|^2}.$$

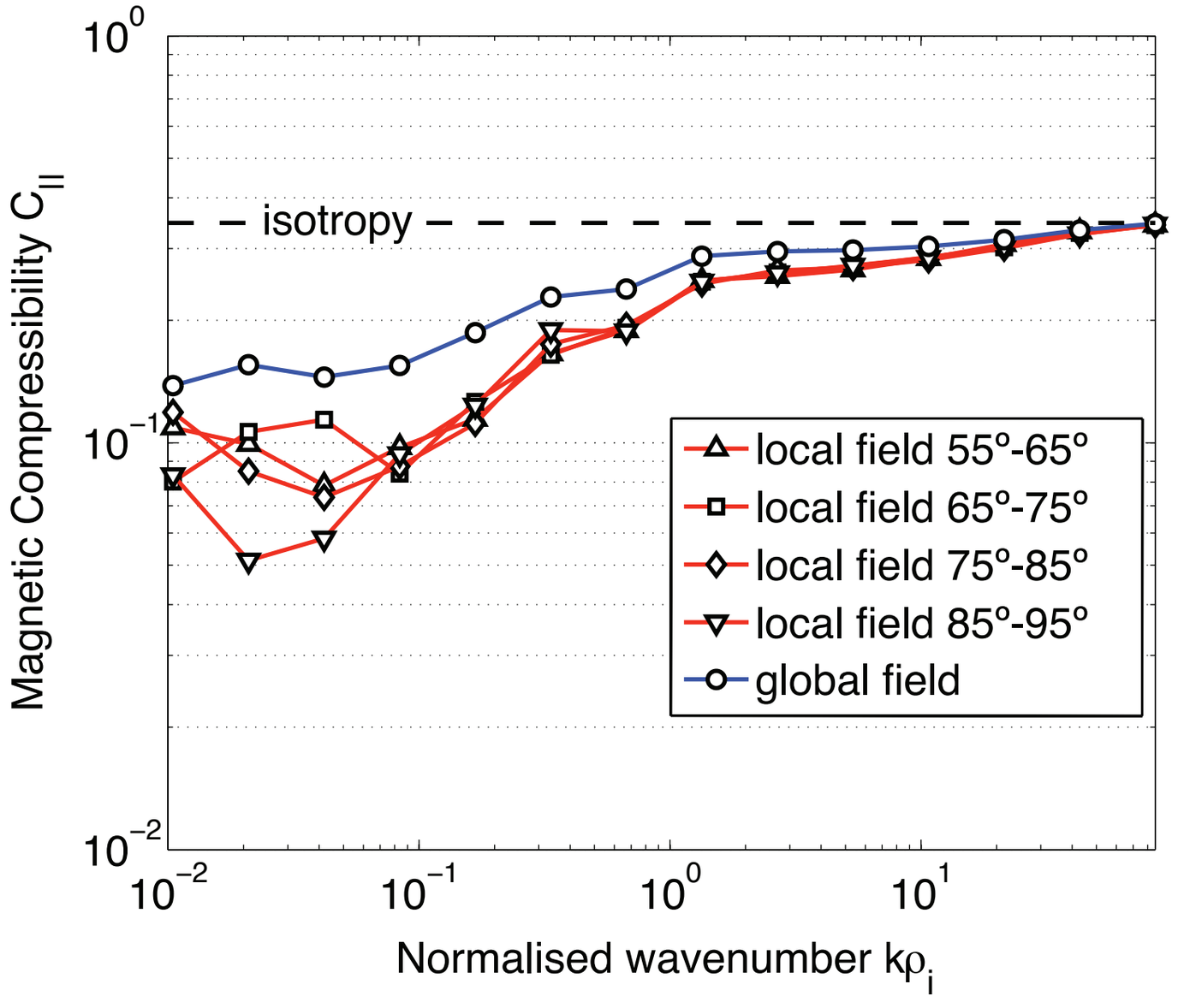




S P. Gary and C. W. Smith,
J. Geophys. Res **114**, A12105 (2009).

magnetic compressibility

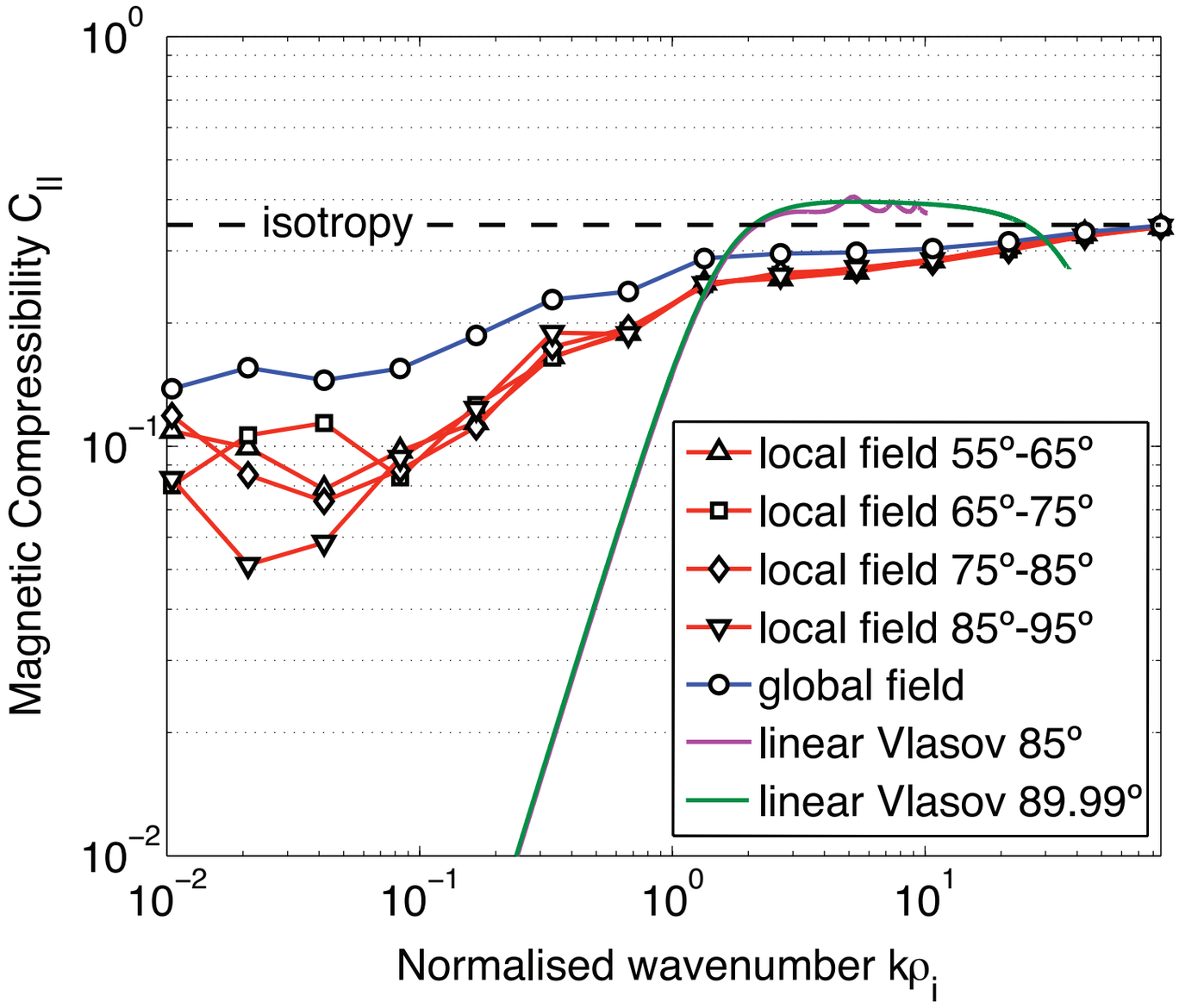
$$C_{\parallel}(f) = \frac{1}{N}\sum_{j=1}^{N}\frac{\delta B_{\parallel}^2(t_j,f)}{\delta B_{\parallel}^2(t_j,f)+\delta B_{\perp}^2(t_j,f)}$$



Kiyani et al. ApJ (2013)

kinetic Alfvén wave fluctuations

$$C_{\parallel}(f) = \frac{1}{N}\sum_{j=1}^{N}\frac{\delta B_{\parallel}^2(t_j,f)}{\delta B_{\parallel}^2(t_j,f)+\delta B_{\perp}^2(t_j,f)}$$



Kiyani et al. ApJ (2013)

Gary & Smith (2009)

Salem et al. (2012)
TenBarge et al. (2012)

Hall physics

Hall-MHD model

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{v} \times \mathbf{B}) + \frac{1}{\mu e n_e} \nabla \times (\mathbf{B} \cdot \nabla \mathbf{B}) + \eta \nabla^2 \mathbf{B}$$

inertial range

$k\rho_i << 1$

convective term dominates

[B-field frozen to ions]

dissipation range

$k\rho_i > 1$

Hall term dominates

[ions demagnetise]

Hall physics

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{v} \times \mathbf{B}) + \frac{1}{\mu e n_e} \nabla \times (\mathbf{B} \cdot \nabla \mathbf{B}) + \eta \nabla^2 \mathbf{B}$$

assume in the inertial range

$\nabla_\perp >> \nabla_\parallel$ [$k_\perp >> k_\parallel$]

and

$\delta B_\perp >> \delta B_\parallel$

supported by observations, simulations and theory

Hall physics

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{v} \times \mathbf{B}) + \frac{1}{\mu e n_e} \nabla \times (\mathbf{B} \cdot \nabla \mathbf{B}) + \eta \nabla^2 \mathbf{B}$$

$$\left.\frac{\partial \mathbf{B}_\parallel}{\partial t}\right|_{Hall} \sim \nabla_{\perp 1} \times (\mathbf{B} \cdot \nabla \delta \mathbf{B}_{\perp 2}) + \nabla_{\perp 2} \times (\mathbf{B} \cdot \nabla \delta \mathbf{B}_{\perp 1})$$

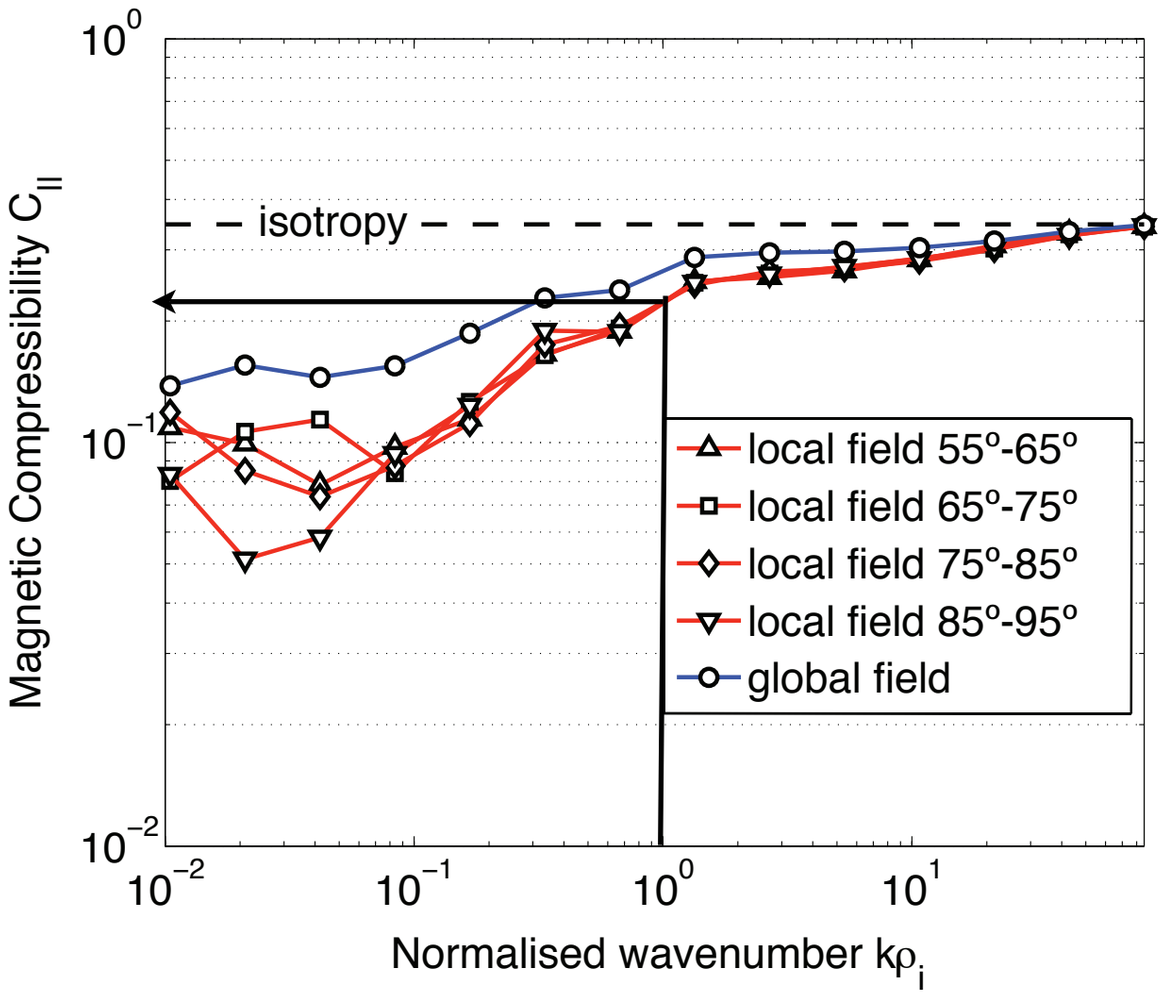
Hall physics

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{v} \times \mathbf{B}) + \frac{1}{\mu e n_e} \nabla \times (\mathbf{B} \cdot \nabla \mathbf{B}) + \eta \nabla^2 \mathbf{B}$$

$$\left.\frac{\partial \mathbf{B}_\parallel}{\partial t}\right|_{Hall} \sim \nabla_{\perp 1} \times (\mathbf{B} \cdot \nabla \delta \mathbf{B}_{\perp 2}) + \nabla_{\perp 2} \times (\mathbf{B} \cdot \nabla \delta \mathbf{B}_{\perp 1})$$

The Hall term isotropises components.

transition range



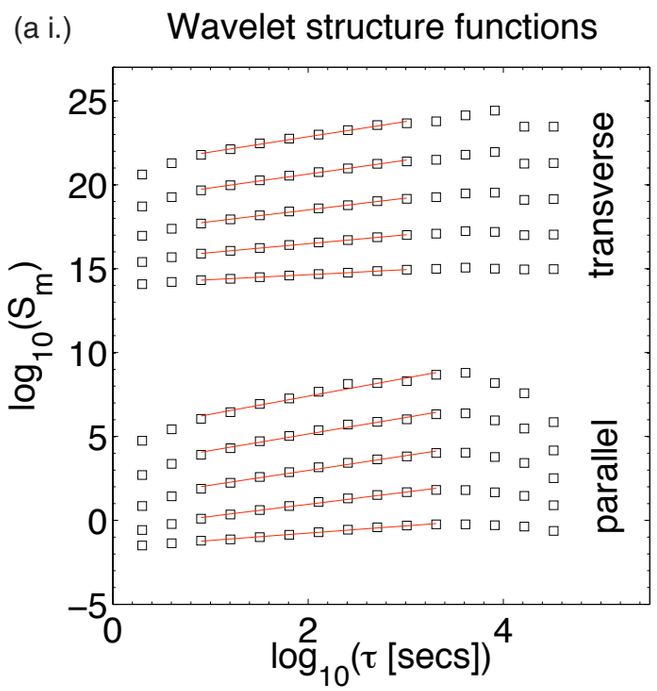
at $k\rho_i = 1$

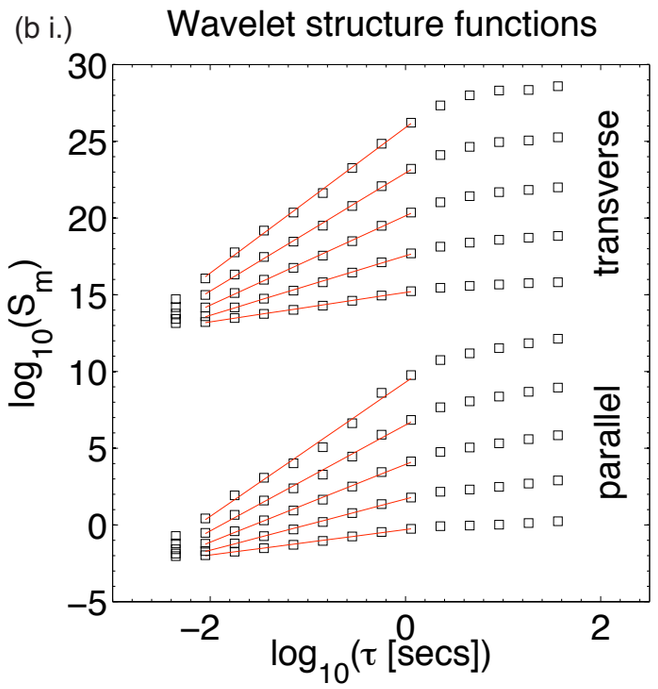
Convective 50%

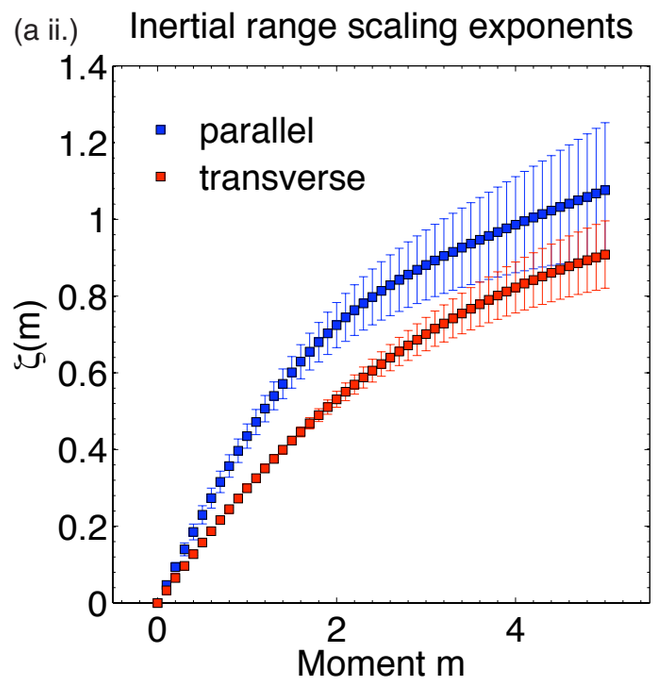
Hall 50%

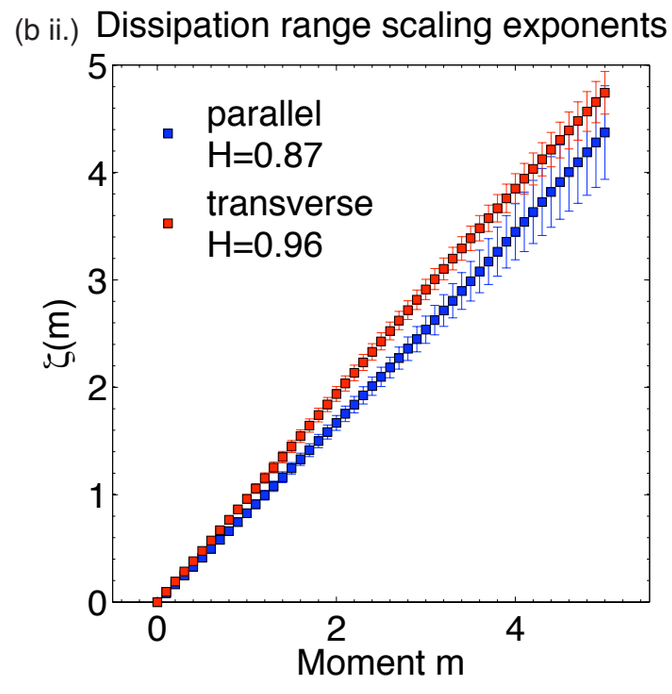
$$C_{\parallel} \simeq 0.5 \times 0.33 + 0.5 \times 0.1 \simeq 0.22$$

higher order scaling









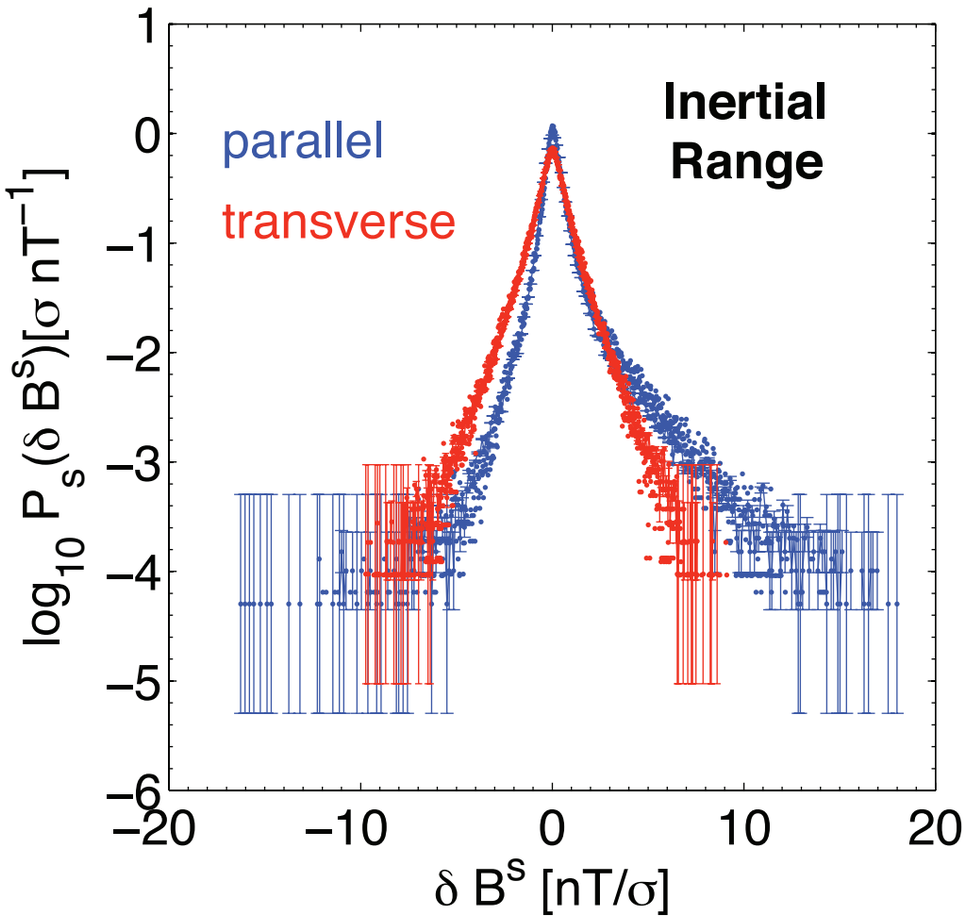
Structure Functions

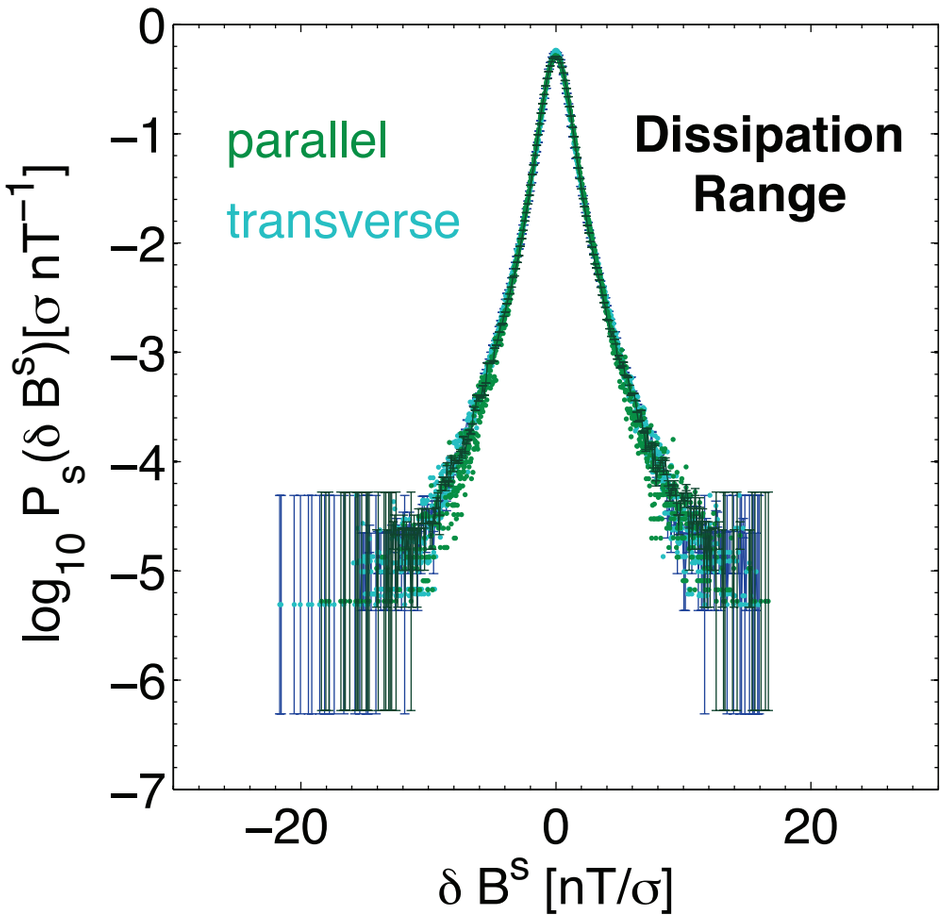
$$S^m_{\parallel(\perp)}(\tau) = \frac{1}{N}\sum_{j=1}^{N}\left|\frac{\delta B_{\parallel(\perp)}(t_j,\tau)}{\sqrt{\tau}}\right|^m$$

note: Inertial range data is from ACE

Also see:
K. H. Kiyani et al.
Phys. Rev. Lett.
103, 075006 (2009)

standardised probability densities





isotropy

Kiyani et al.
ApJ (2013)

Effects of varying plasma beta [ERMHD]

$$\frac{\partial \mathbf{B}_\perp}{\partial t} = -\frac{c}{4\pi e n_e} \nabla_\perp \times \left[\mathbf{B} \cdot \nabla \mathbf{B}_\parallel \right]$$

$$\frac{\partial \mathbf{B}_\parallel}{\partial t} = -\frac{\beta_i \left(1 + Z/\tau\right)}{2 + \beta_i \left(1 + Z/\tau\right)} \frac{c}{4\pi e n_e} \nabla_\perp \times \left[\mathbf{B} \cdot \nabla \mathbf{B}_\perp \right]$$

includes density variations in a linear way

Schekochihin (2009) and Cho & Lazarian (2009)

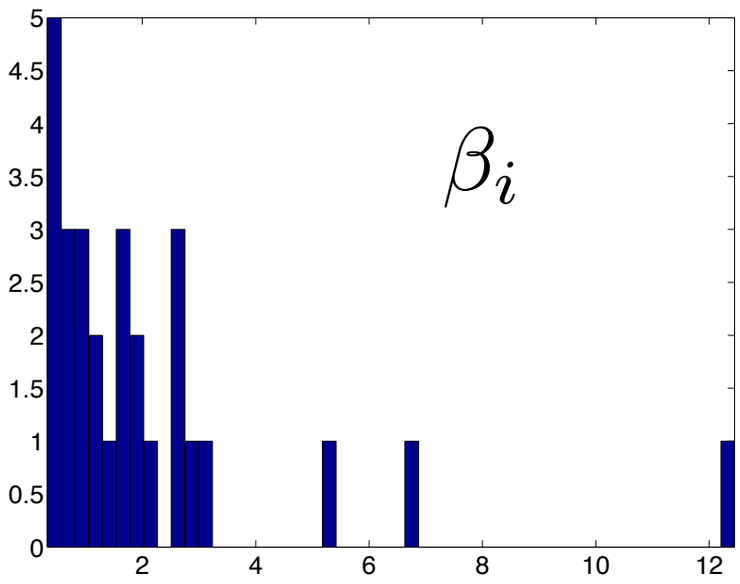
Survey study

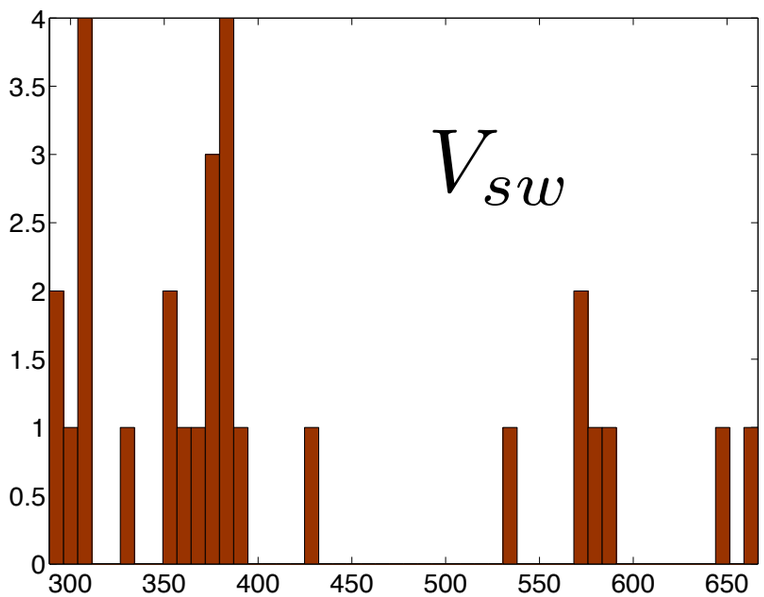
Interval	Date/Time (UT)	SC	|B| [nT]	$\sigma_{\|B\|}$	β_i	σ_{β_i}	n_i [cm^{-3}]	σ_{n_i}	T_e/T_i	σ_{T_e/T_i}	$T_{i\|\|}/T_{i\perp}$	$\sigma_{T_{i\|\|}/T_{i\perp}}$	$\|V_{sw}\|$ [km s^{-1}]	$\sigma_{V_{sw}}$	θ_{BV} [deg]	$\sigma_{\theta_{BV}}$	Sample Size
01	2006/03/07 14:00-14:32 UT	[3,3,2]	3.01	12.35	3.17	46.67	6.42	4.87	2.17	28.82	1.16	46.31	384.32	0.78	79.00	18.99	43,905
02	2006/03/07 14:32-14:53 UT	[3,3,2]	2.42	9.81	5.21	33.27	6.79	4.18	2.15	30.02	1.08	40.23	382.15	0.81	92.00	15.22	31,499
03	2006/03/07 14:53-15:04 UT	[3,3,2]	1.71	28.46	12.45	75.86	6.89	4.23	2.34	31.53	1.05	44.19	380.00	0.71	82.00	25.61	16,498
04	2006/03/07 15:04-15:40 UT	[2,3,2]	3.06	10.27	2.89	39.32	6.74	5.38	2.37	26.04	1.07	42.45	376.95	3.01	96.00	10.42	49,906
05	2007/01/27 18:00-19:50 UT	[3,1,2]	4.84	2.36	1.08	31.86	11.96	5.17	2.71	30.81	1.29	46.65	301.65	1.81	140.00	10.00	151,406
06	2007/01/27 21:20-21:50 UT	[3,3,2]	4.34	4.33	2.00	29.68	15.41	3.64	2.22	28.35	1.10	44.52	309.75	0.65	86.00	5.81	40,905
07	2007/01/27 21:50-23:20 UT	[3,3,2]	4.78	5.25	1.63	28.04	15.25	3.88	2.21	24.99	1.04	38.97	309.42	0.83	99.00	9.09	130,906
08	2004/02/22 03:10-04:20 UT	[3,3,2]	8.75	2.32	0.57	26.78	12.39	3.84	2.76	25.75	1.28	47.11	383.45	1.90	73.00	10.96	100,905
09	2004/02/22 04:20-04:50 UT	[3,3,2]	8.18	2.80	0.74	25.65	12.89	5.06	2.50	22.34	1.32	43.51	374.27	1.55	87.00	11.49	40,906
10	2004/02/24 17:10-18:10 UT	[3,1,NA]	5.57	1.40	0.93	45.45	7.64	4.36	NA	NA	0.91	62.11	388.67	1.57	71.00	14.08	81,810
11	2004/02/21 17:24-17:50 UT	[3,3,2]	8.49	2.06	0.43	25.15	9.12	3.81	2.98	23.02	1.46	35.89	376.24	0.73	66.00	7.58	38,999
12	2004/02/21 18:15-19:30 UT	[3,3,2]	8.45	4.02	0.49	30.06	9.69	7.50	2.78	24.26	1.31	45.16	368.87	1.46	85.00	15.29	108,406
13	2007/02/05 15:40-19:10 UT	[3,3,1]	4.93	5.46	1.00	22.71	8.49	4.47	2.53	14.63	1.08	24.05	331.67	0.92	97.00	8.25	306,812
14	2007/02/22 12:10-13:30 UT	[4,3,1]	3.24	5.75	1.84	29.23	11.41	8.11	3.37	19.00	1.00	35.23	304.50	3.79	110.00	12.73	108,518
15	2007/02/22 13:30-14:20 UT	[4,3,1]	2.23	29.42	6.68	51.40	12.88	10.37	2.59	15.95	0.82	28.55	305.62	2.39	111.00	8.11	74,999
16	2007/02/22 14:20-17:00 UT	[4,3,1]	4.14	5.81	1.11	25.56	9.15	9.48	2.65	15.46	0.93	26.45	296.07	4.50	109.00	5.50	235,907
17	2004/01/27 00:00-02:00 UT	[3,1,1]	9.87	3.84	0.44	14.32	7.87	7.96	1.82	12.38	0.81	20.58	428.90	1.40	102.00	6.86	171,812
18	2007/02/23 01:50-02:50 UT	[1,1,1]	3.62	3.06	1.65	21.73	9.01	2.94	2.68	17.64	0.84	27.93	288.81	0.67	NaN	NaN	81,812
19	2007/01/30 05:20-08:10 UT	[1,1,2]	6.01	4.98	1.54	44.87	2.75	7.95	0.41	43.48	0.67	61.00	649.29	2.75	77.00	20.78	246,818
20	2002/02/19 00:32-01:10 UT	[3,1,2]	9.18	8.43	0.94	46.14	27.97	7.76	1.53	46.24	1.18	67.59	353.42	0.98	116.00	6.90	56,999
21	2002/02/19 01:10-02:45 UT	[3,1,2]	7.45	11.31	1.64	47.89	27.79	11.58	1.46	42.18	0.90	55.03	364.10	1.00	80.00	23.75	142,500
22	2002/02/19 02:45-03:30 UT	[3,1,2]	10.18	2.66	0.33	34.57	13.40	7.00	3.30	32.71	0.85	52.45	356.48	1.98	70.00	11.43	63,405
23	2001/04/05 22:35-23:32 UT	[1,1,2]	7.29	5.29	0.75	36.91	3.10	18.63	0.85	42.45	0.53	52.84	533.51	1.69	95.00	7.37	67,027
24	2002/02/11 19:19-20:29 UT	[3,1,2]	7.45	2.52	0.77	36.32	3.55	6.40	1.23	32.90	0.91	49.12	569.55	2.33	82.00	13.41	96,812
25	2007/01/30 00:00-01:20 UT	[4,1,4]	4.52	7.30	2.58	51.48	2.57	6.90	0.45	41.92	0.75	58.89	666.52	2.35	75.00	24.00	2,151,828
26	2007/01/20 12:10-13:20 UT	[3,1,4]	3.83	3.33	2.10	53.64	1.75	9.06	0.44	51.58	0.54	59.57	588.85	2.43	78.00	14.10	1,890,002
27	2007/01/20 13:20-14:10 UT	[3,1,4]	3.45	3.71	2.54	67.42	1.88	7.28	0.56	70.28	1.16	57.71	577.89	3.03	59.00	21.53	1,350,005
28	2007/03/28 04:00-04:40 UT	[4,1,4]	4.06	4.44	2.68	54.38	2.32	6.56	0.49	57.37	0.86	55.87	568.74	2.79	66.00	22.73	1,071,818

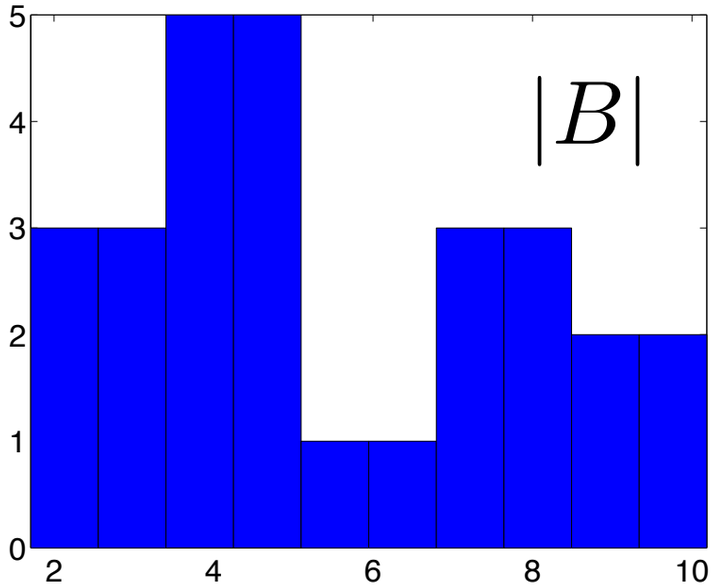
Table A1

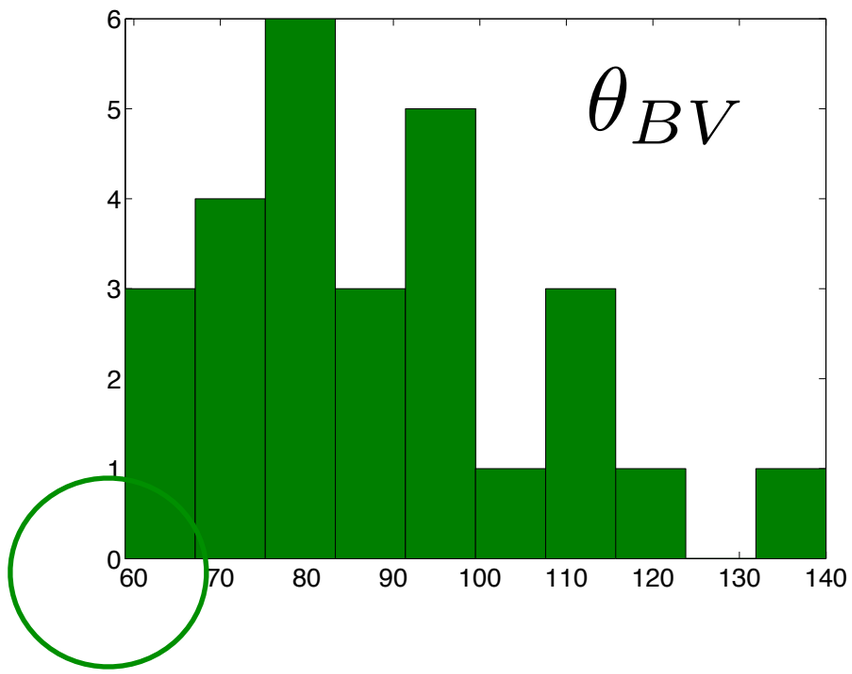
Plasma parameters, along with their variability/errors for all 28 Cluster intervals used in this study: SC is the particular Cluster spacecraft used for the [FGM/STAFF-SC,CIS,PEACE] instrument respectively in the interval; $|B|$ is the magnetic field magnitude; β_i, n_i and V_{sw} are the ion plasma beta, number density and solar wind speed respectively; T_e and T_i are the electron and ion temperatures respectively; θ_{BV} is the angle between the local background magnetic field and the mean solar wind velocity vectors; and $\|$ and $\perp$ designate parallel and perpendicular to the magnetic field vector respectively. All these quantities are mean averages over the interval. All 'errors' (labelled with σ) are percentage errors, calculated by dividing the typical variability – represented by the standard deviation – of the relevant quantity in the interval by the mean value. Intervals 25-28 are intervals where the instruments were operating in burst mode i.e. where the magnetic field sampling (after joining the FGM and STAFF-SC signals) is approximately 450 Hz; the rest of the intervals are sampled in normal mode with nominal magnetic field sampling at approximately 25 Hz.

28 data intervals from the cluster mission



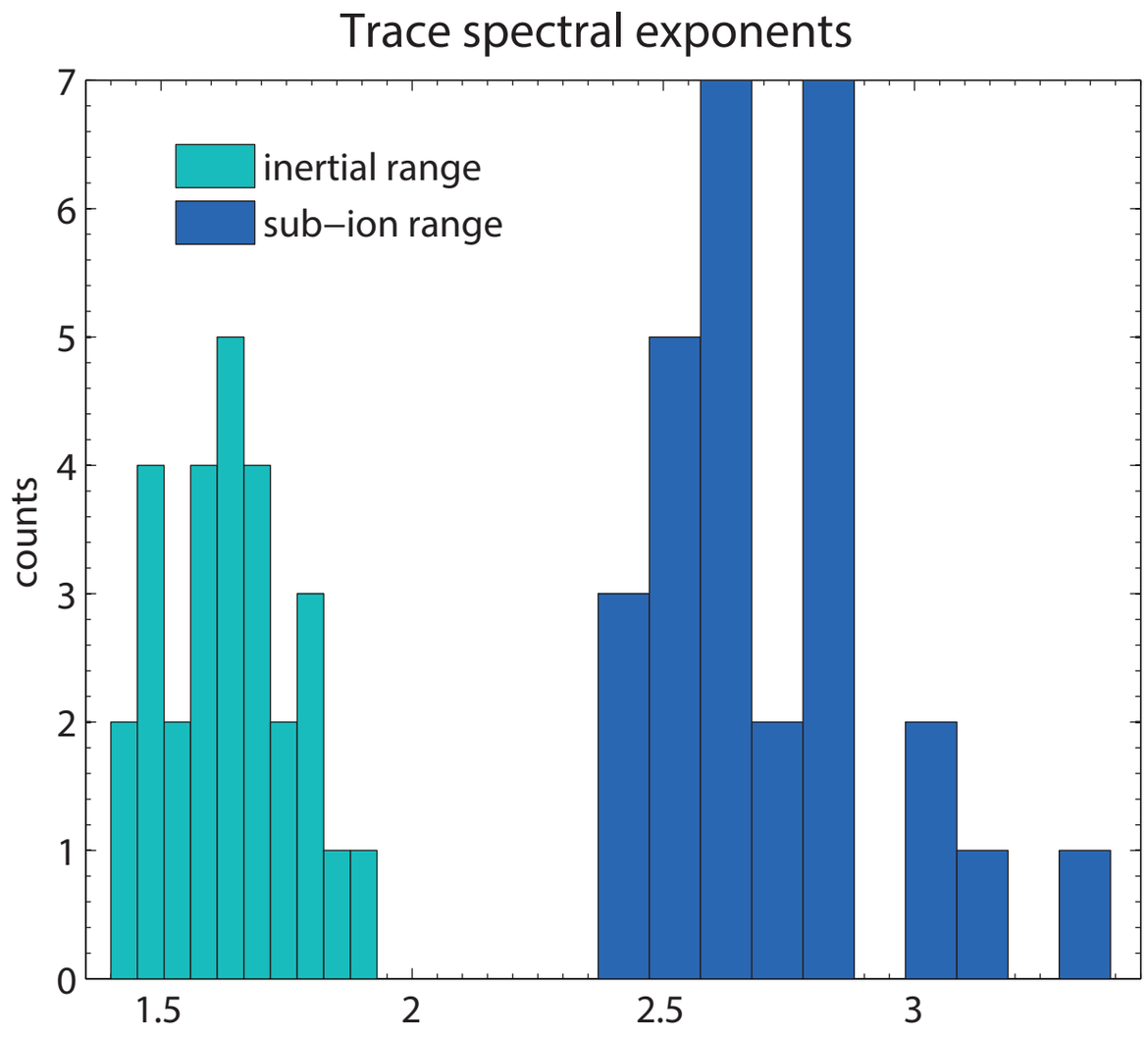






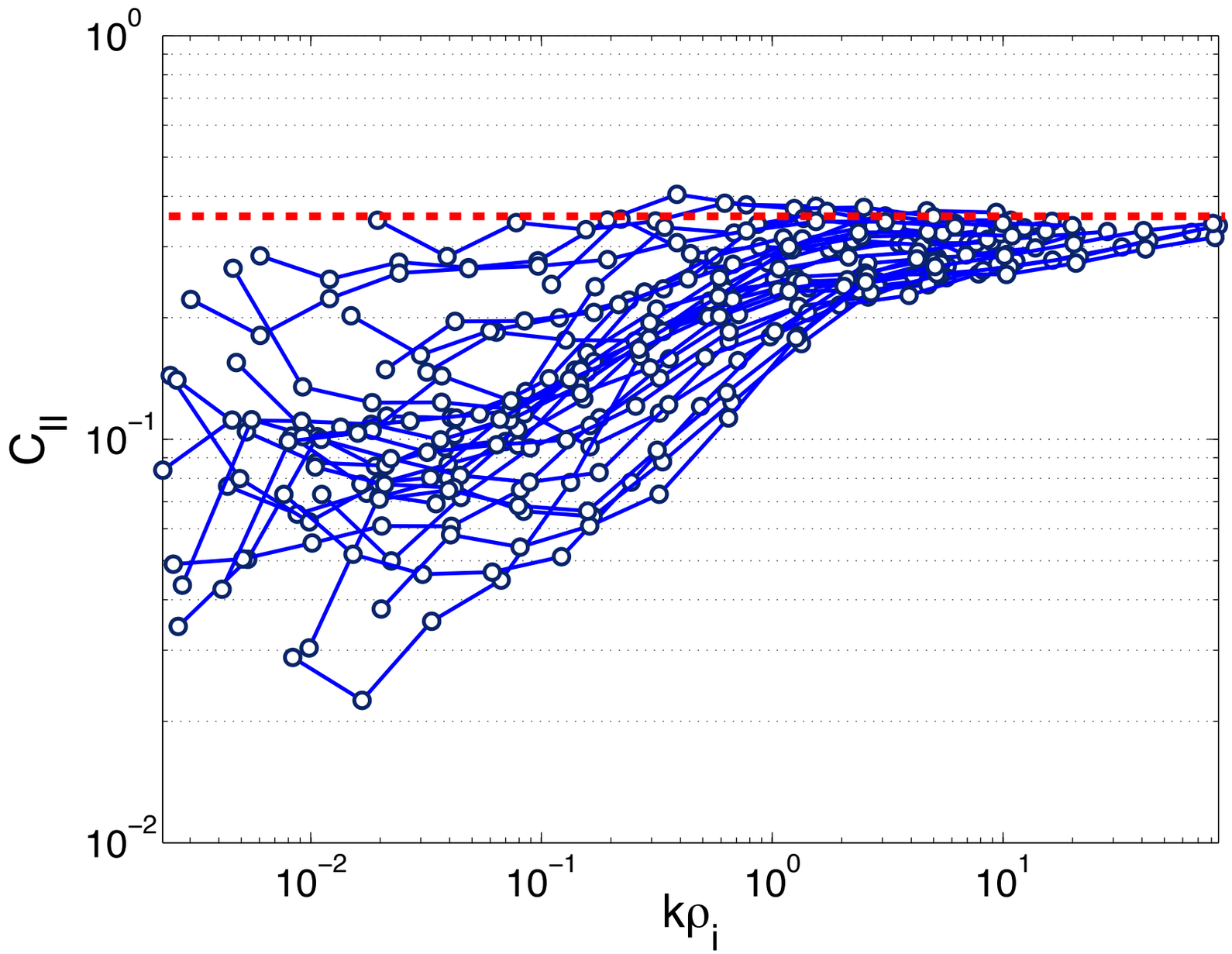
stationary plasma parameters

results: spectral slopes (trace)



see also: Smith et al. (2006) and Sahraoui et al. (2013)

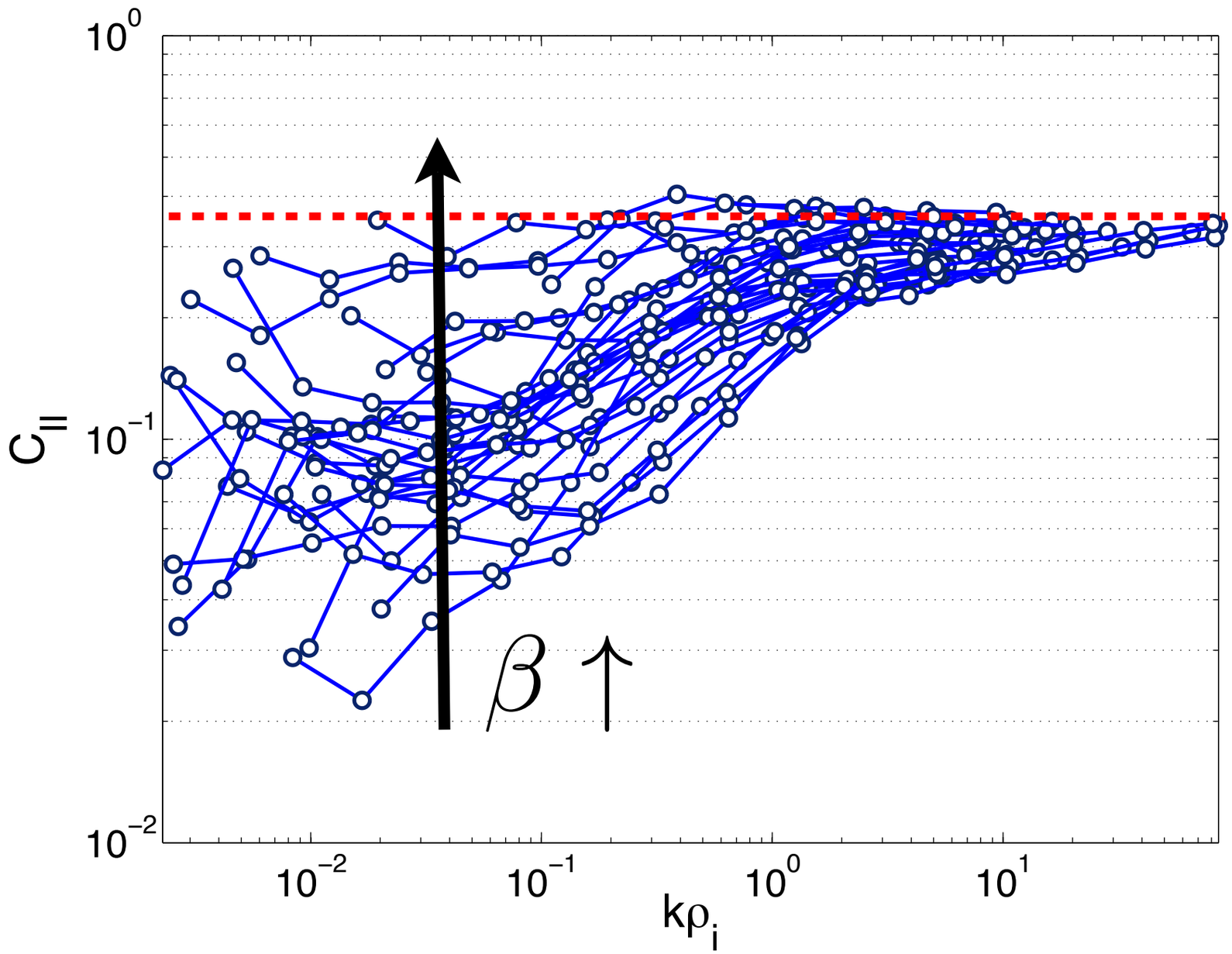
Magnetic compressibility variation with beta



isotropy

see also:
Smith, Vasquez and Hamilton, JGR (2006)

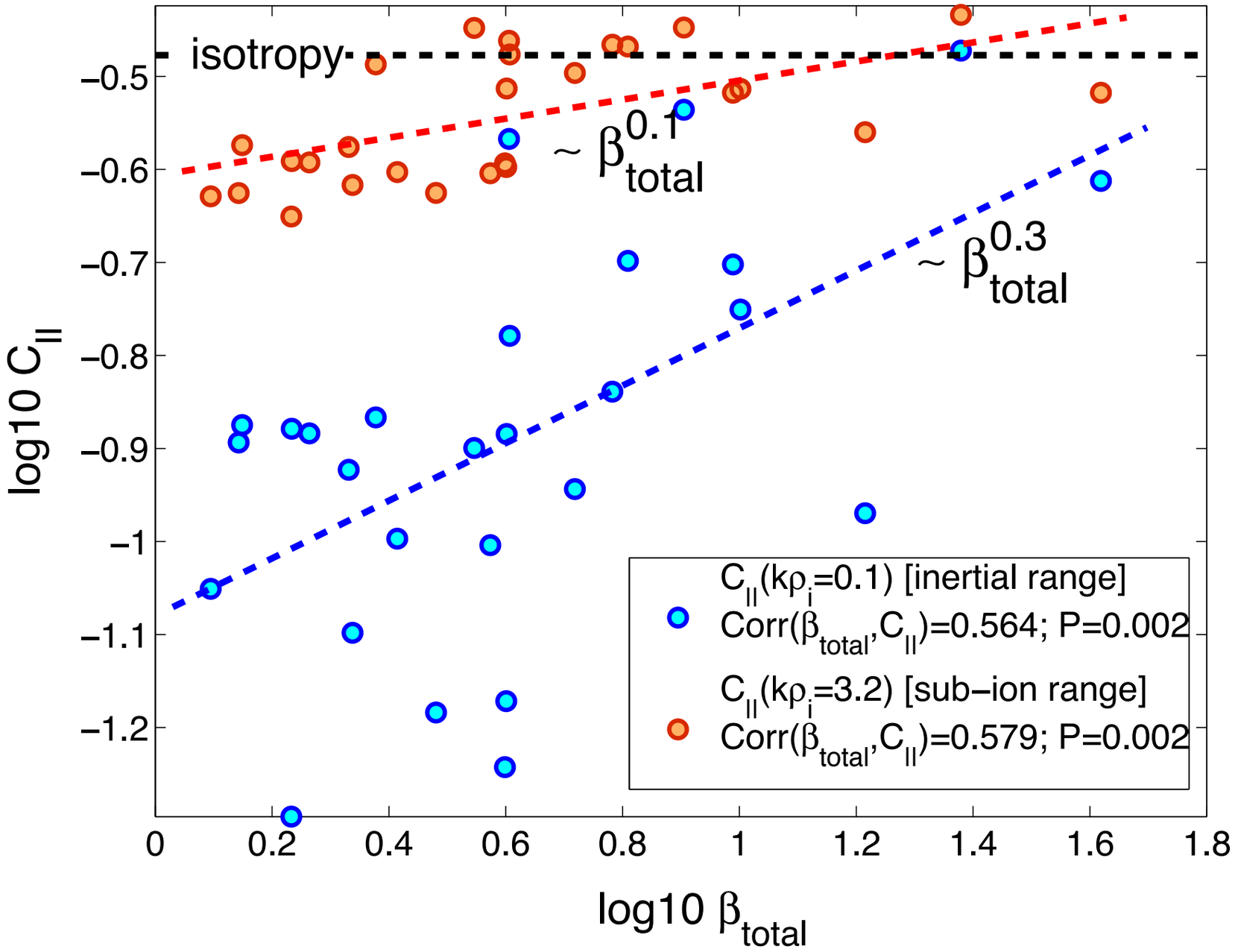
Magnetic compressibility variation with beta



isotropy

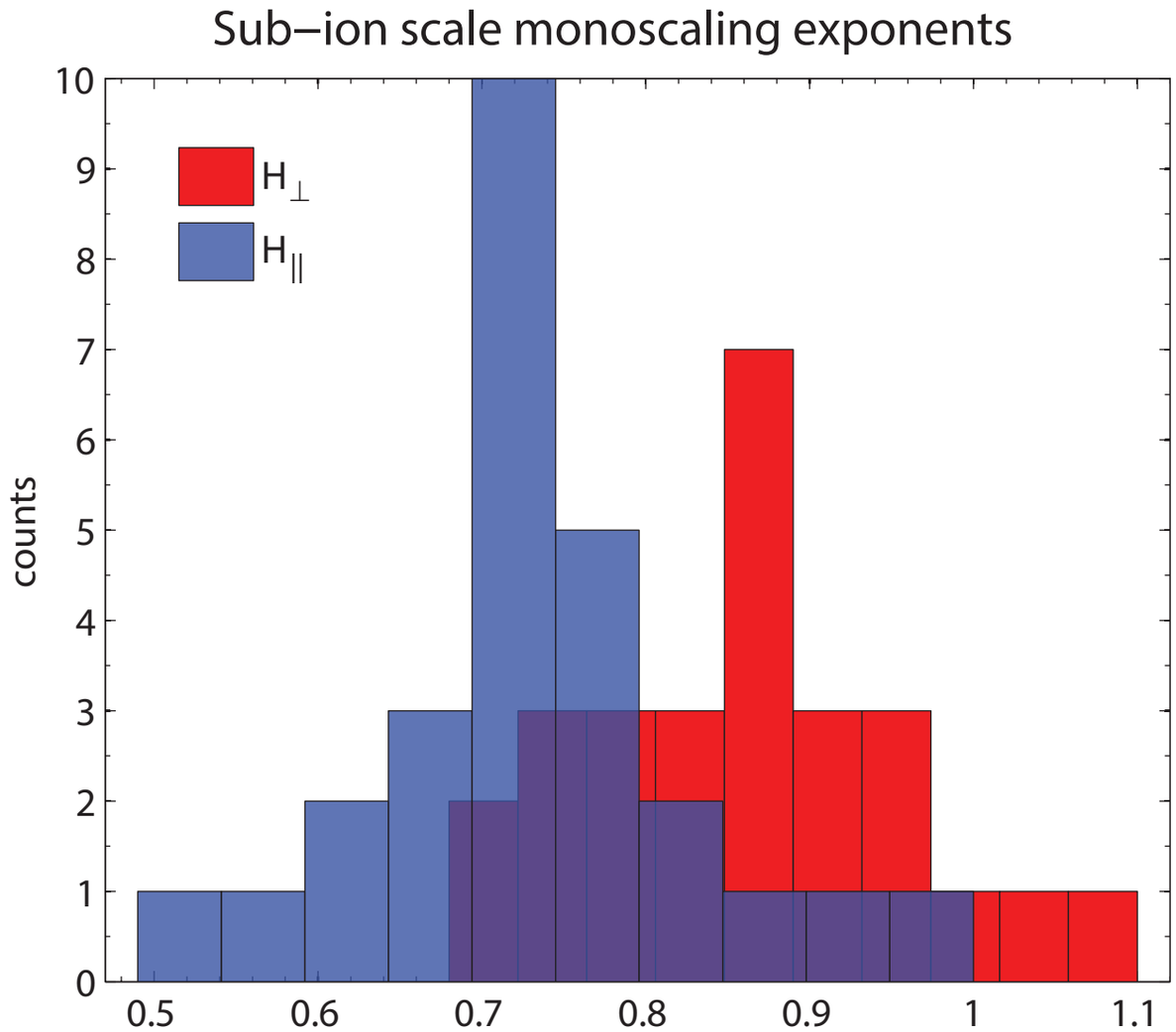
see also:
Smith, Vasquez and Hamilton, JGR (2006)

Magnetic compressibility variation with beta



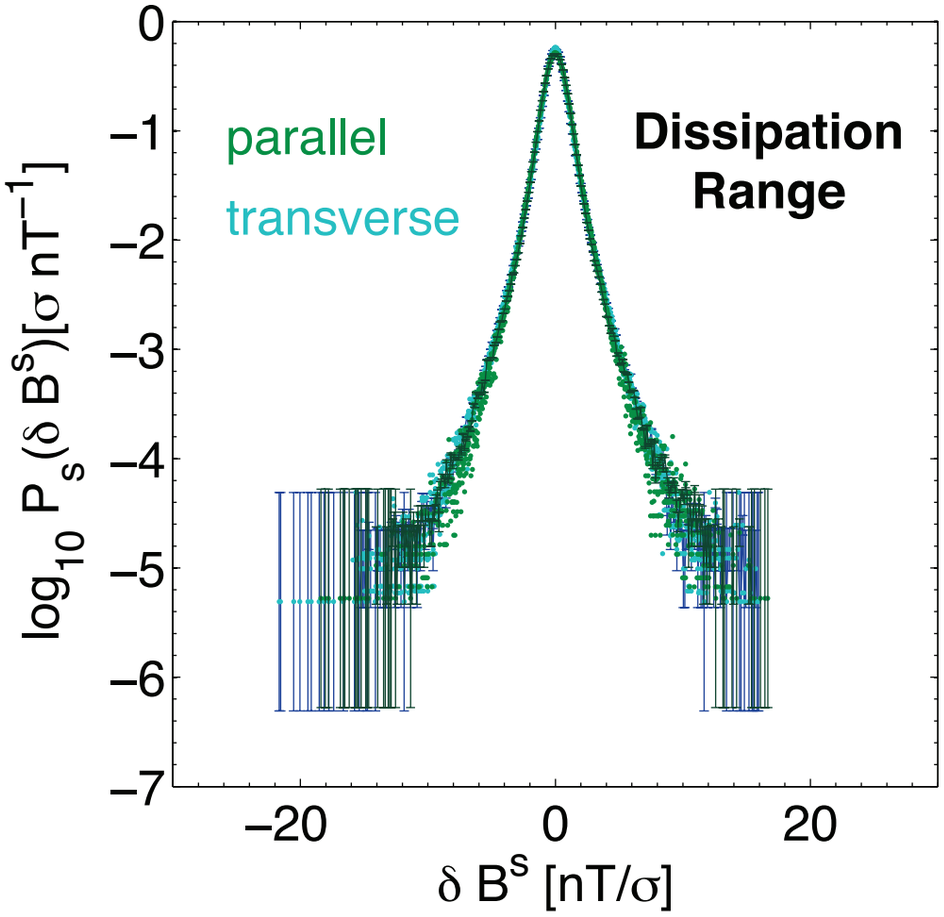
results: scaling

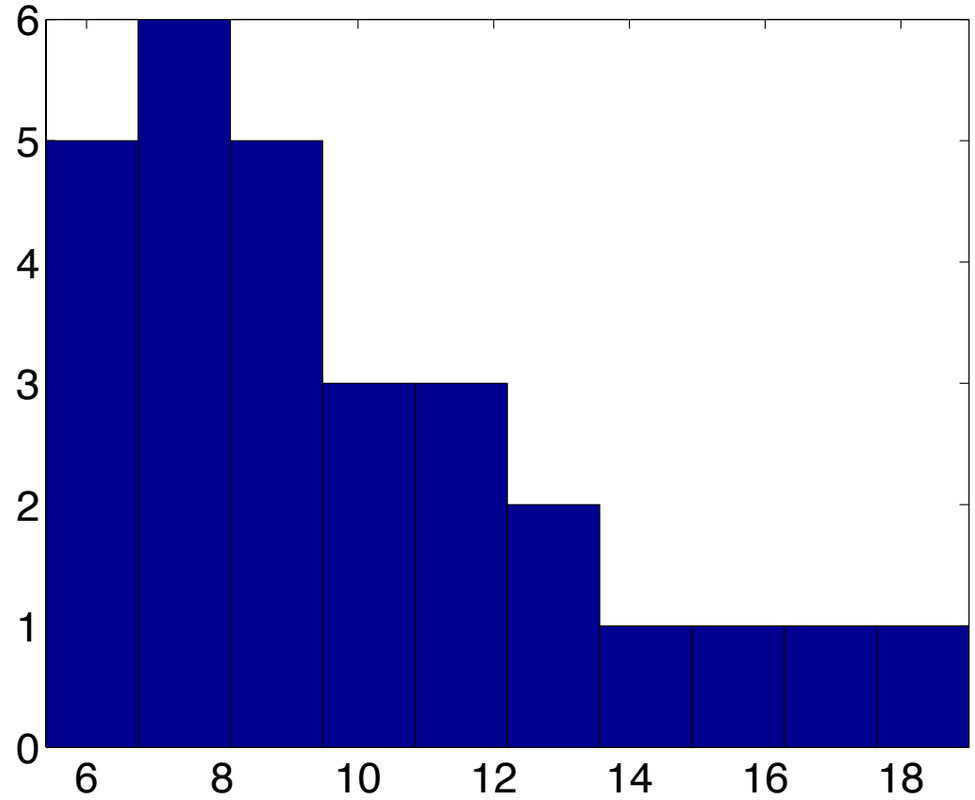
all monoscaling at sub-ion scales



$$H_{\perp} > H_{||}$$

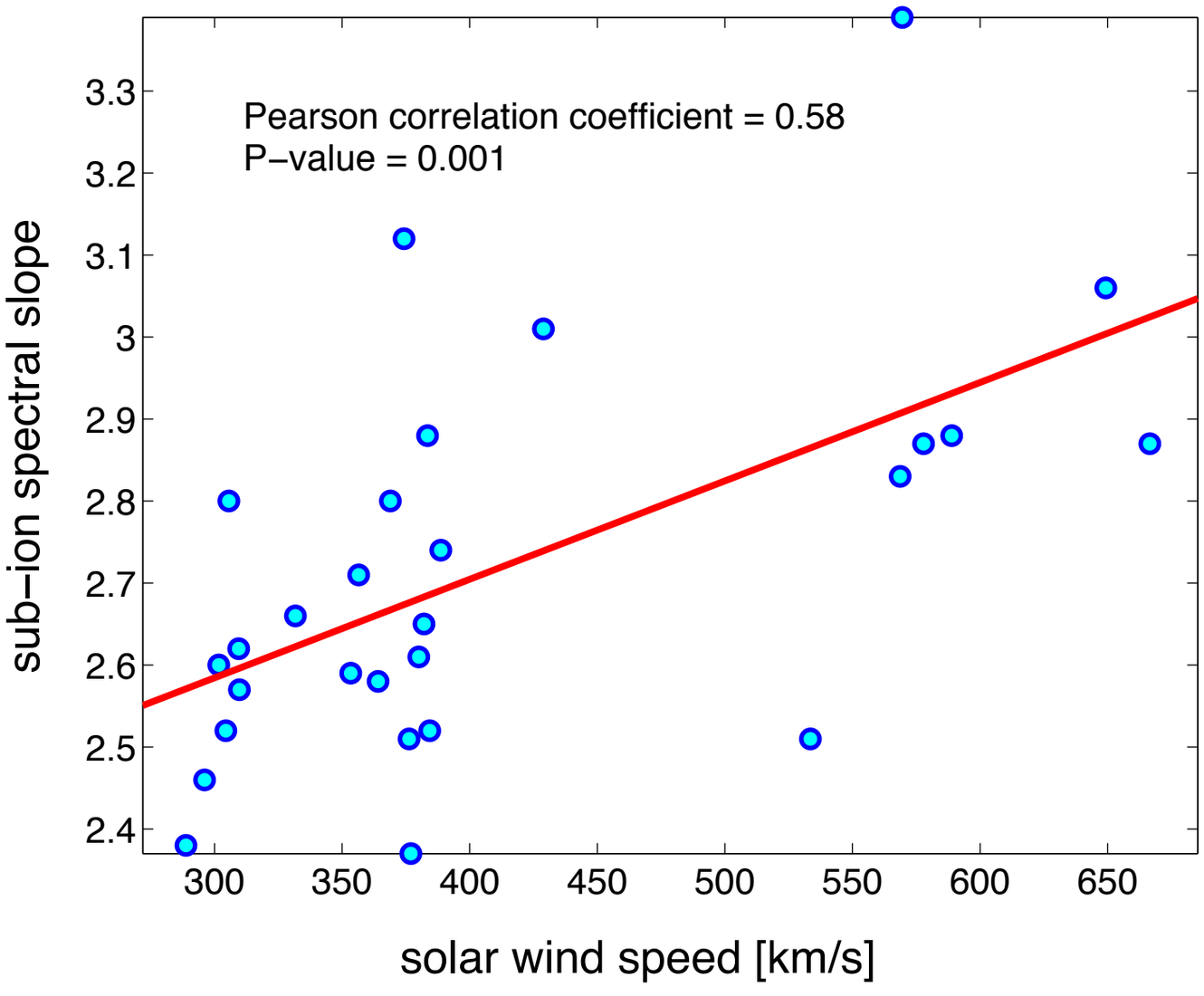
results: intermittency and heavy tails



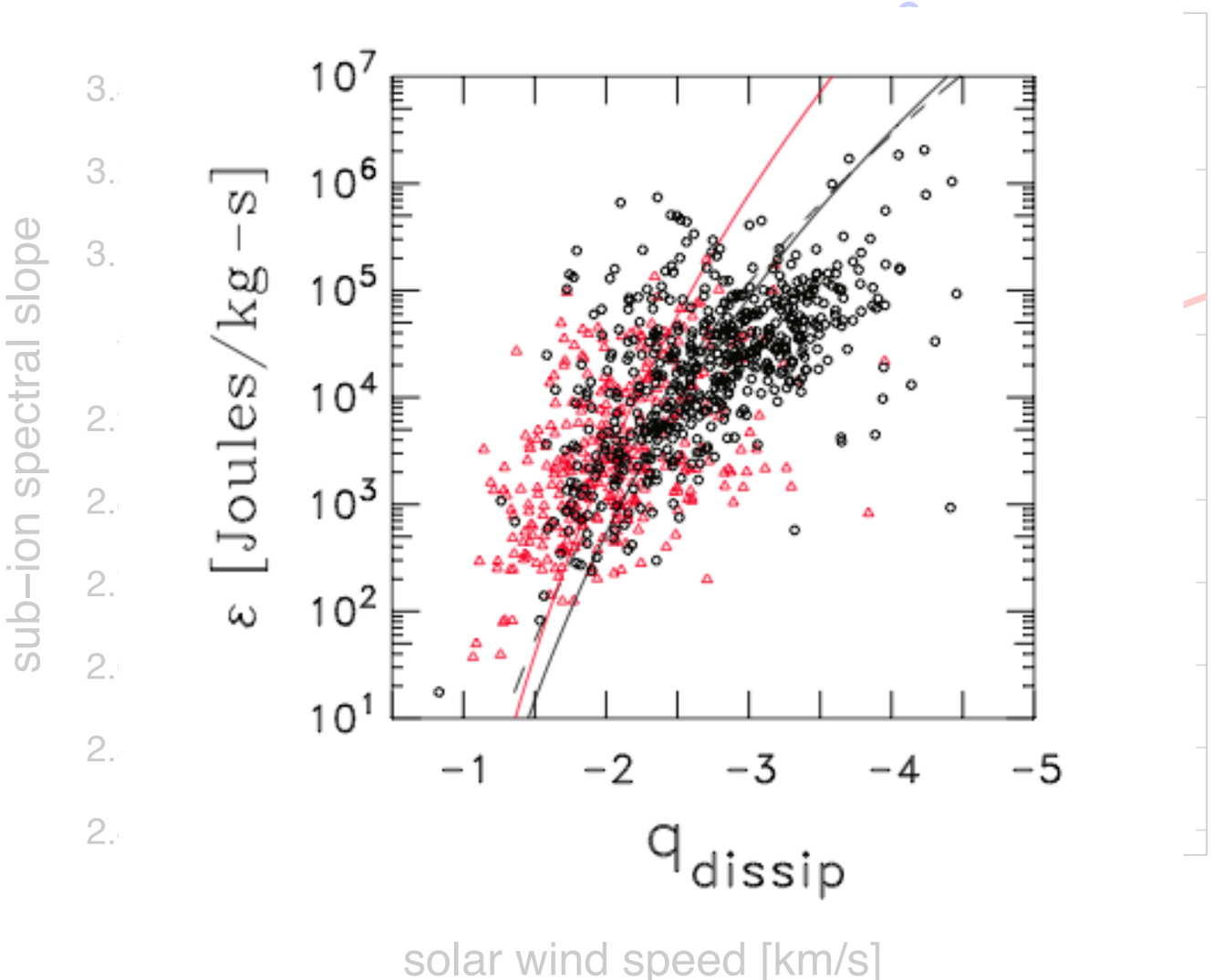


kurtosis

results: solar wind speed variation



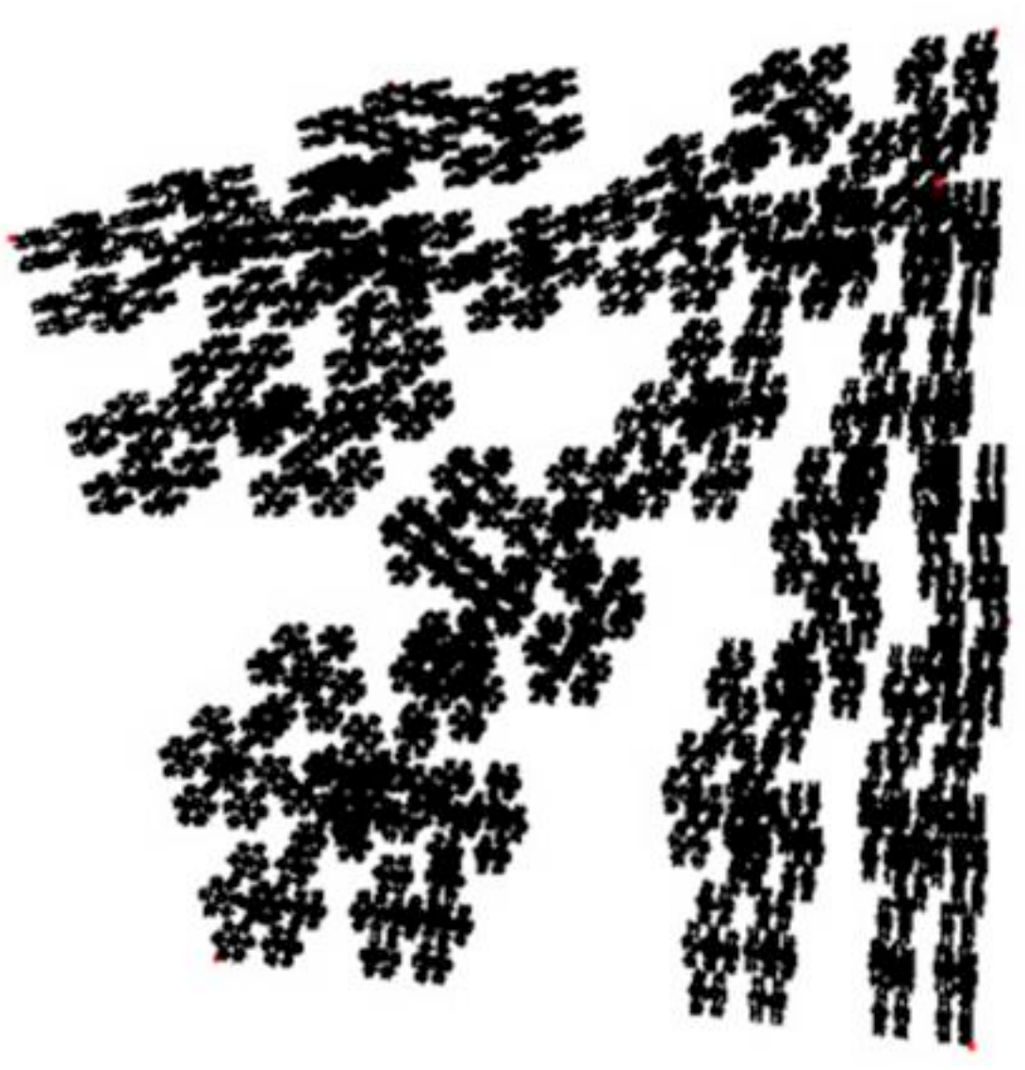
results: solar wind speed variation



Macbride, Smith & Foreman (2008) and Smith et al. (2006)

Scaling, fractals and physics

Monofractal dissipation

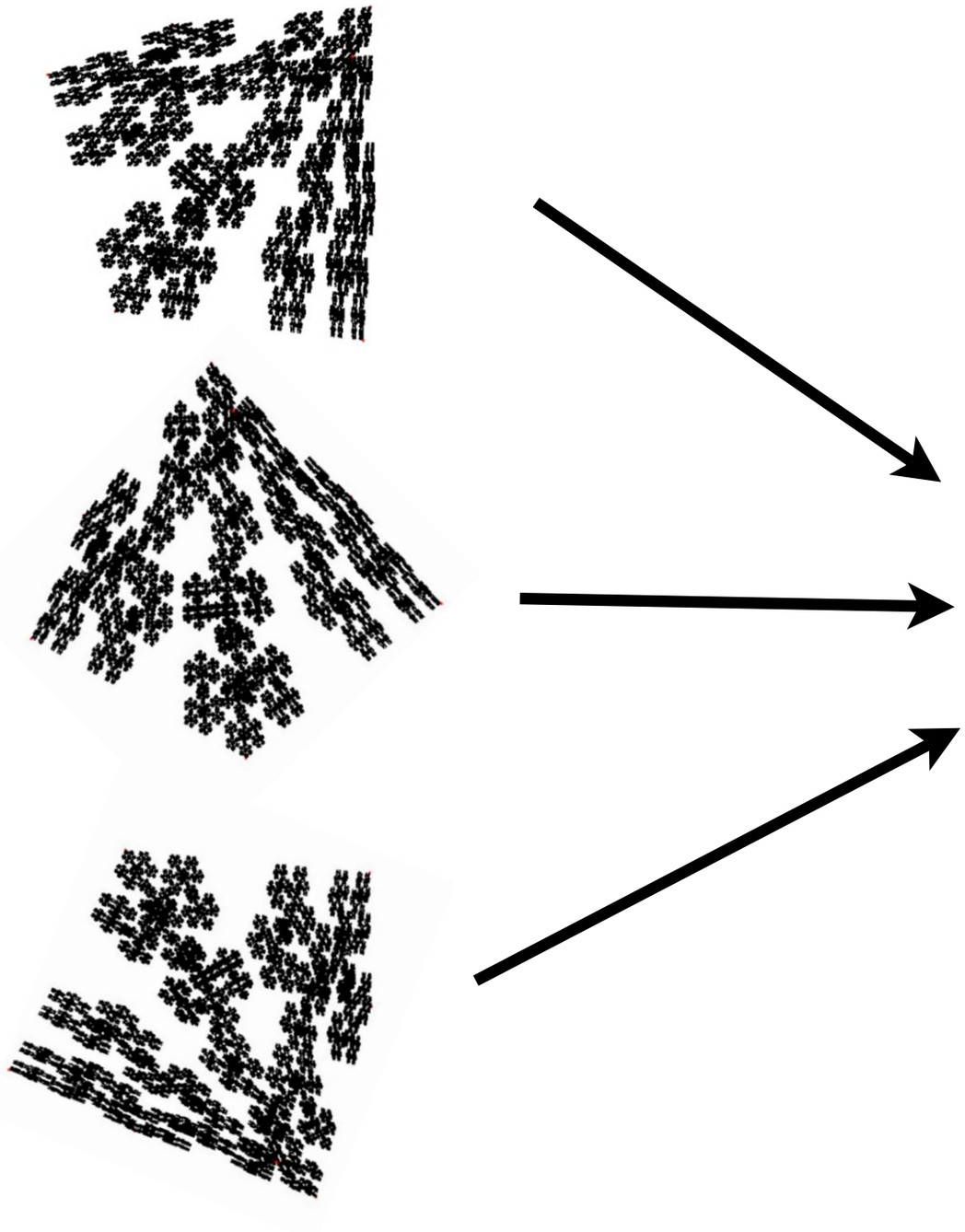


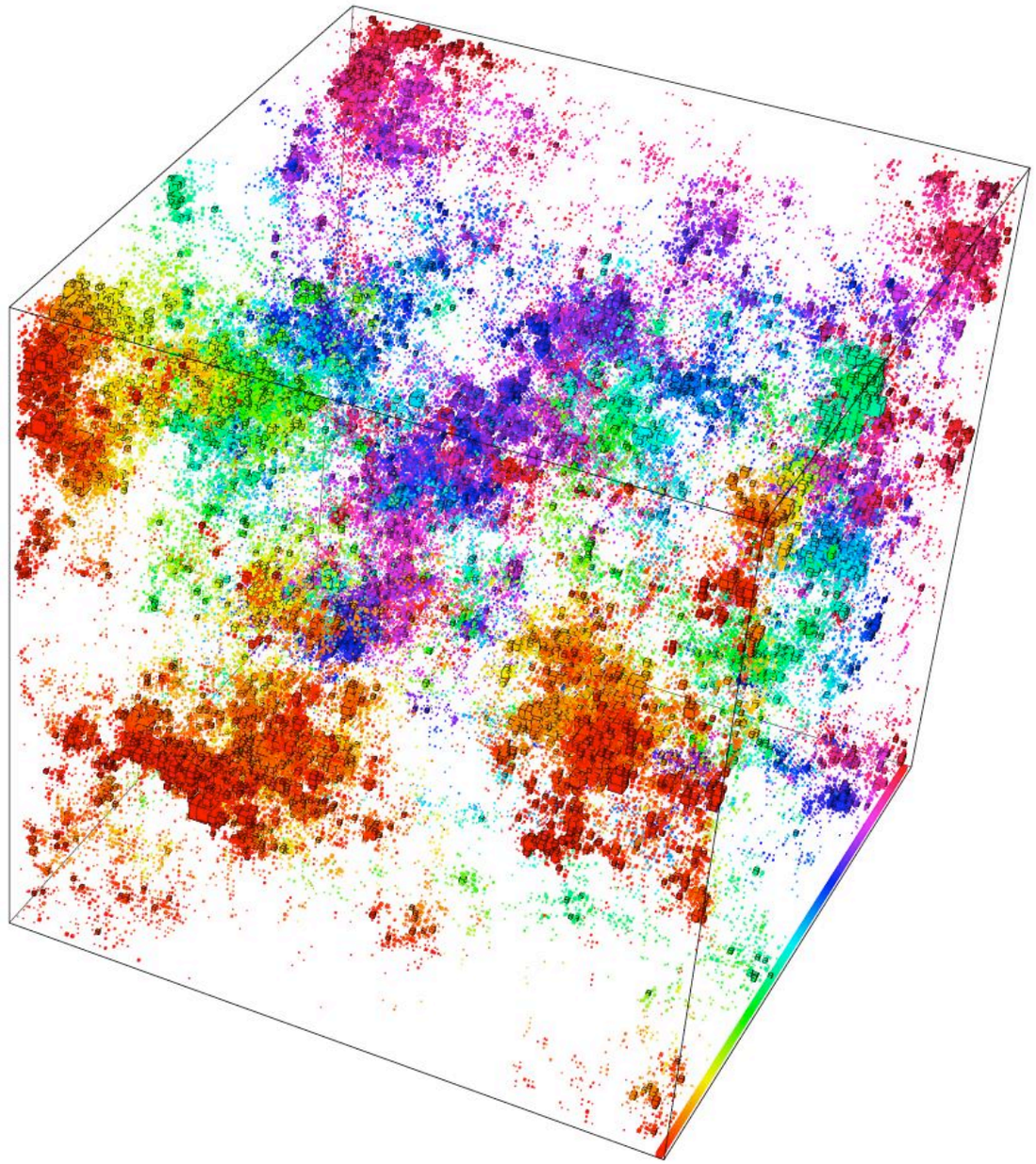
Single exponent *H* living on a fractal set of dimension *D* where dissipation occurs

Global Scale Invariance

Cantor ‘dust’ courtesy of Andrew Top: http://www.andrewtop.com/IFS3d/IFS3d.html

Multifractal dissipation



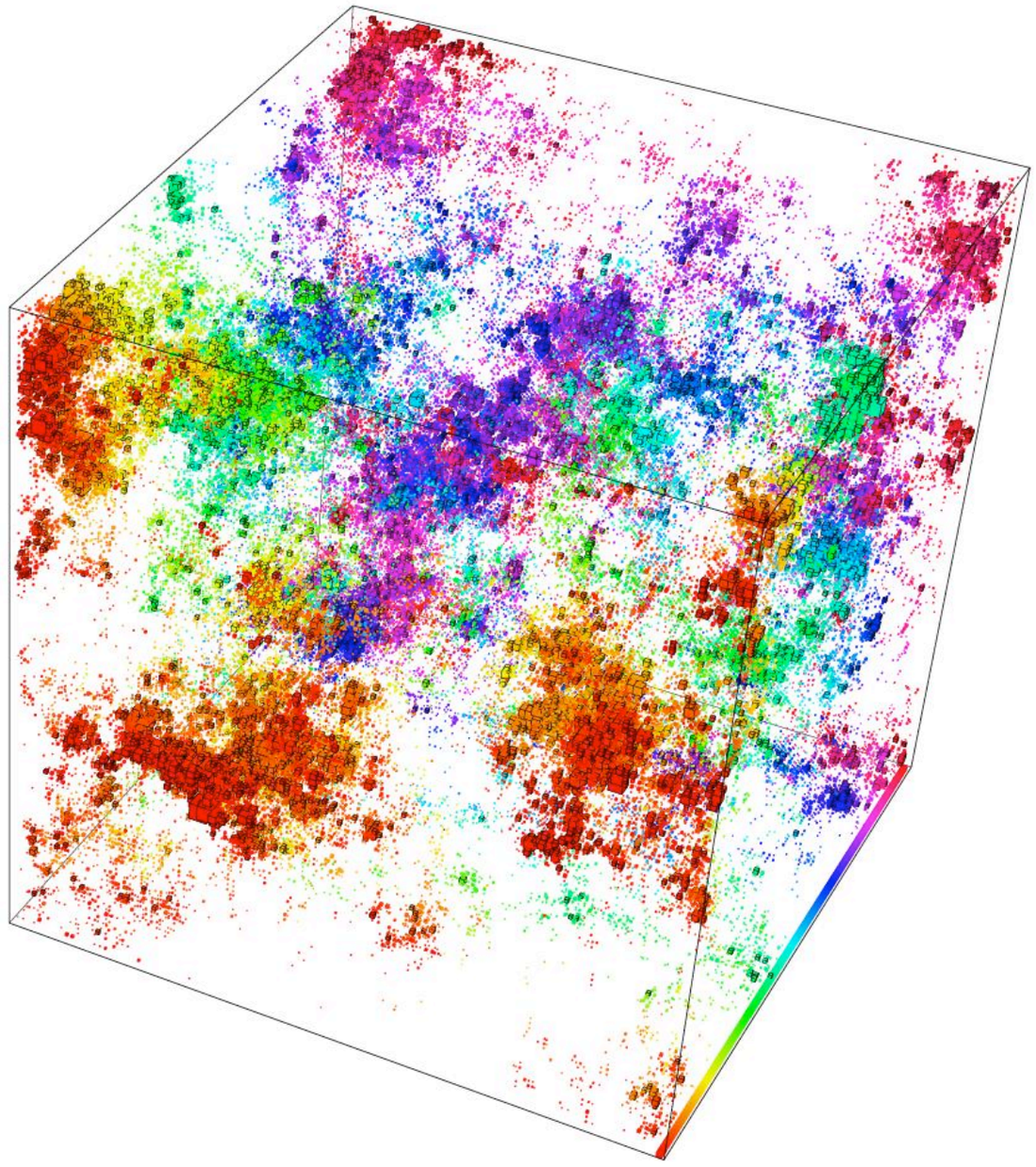


Courtesy of R. Roemer (Warwick): multifractal electronic wavefunction at metal insulator transition in 3D Anderson model

Multifractal dissipation

multiple exponents *h* living on a fractal sets of dimension *D(h)* where dissipation occurs

Local Scale Invariance



Speculation on the physics

EUROPHYSICS LETTERS 1 March 1991

Europhys. Lett., **14** (5), pp. 439-444 (1991)

A Prediction of the Multifractal Model: the Intermediate Dissipation Range.

U. FRISCH (*) and M. VERGASSOLA (*) (**)

(*) *CNRS, Observatoire de Nice - B.P. 139, 06003 Nice Cedex, France*
(**) *Dipartimento di Fisica, Università «La Sapienza»*
P.le A. Moro 2, I-00185 Roma, Italy

(received 1 November 1990; accepted in final form 12 December 1990)

PACS. 47.25C – Isotropic turbulence.

Abstract. – It is shown that the multifractal model of fully developed turbulence predicts a new form of universality for the energy spectrum $E(k)$, which can be tested experimentally. Denoting by R the Reynolds number, $\log E/\log R$ should be a universal function of $\log k/\log R$. This includes an *intermediate dissipation range* in which a continuous range of multifractal scaling exponents are successively turned off by viscosity.

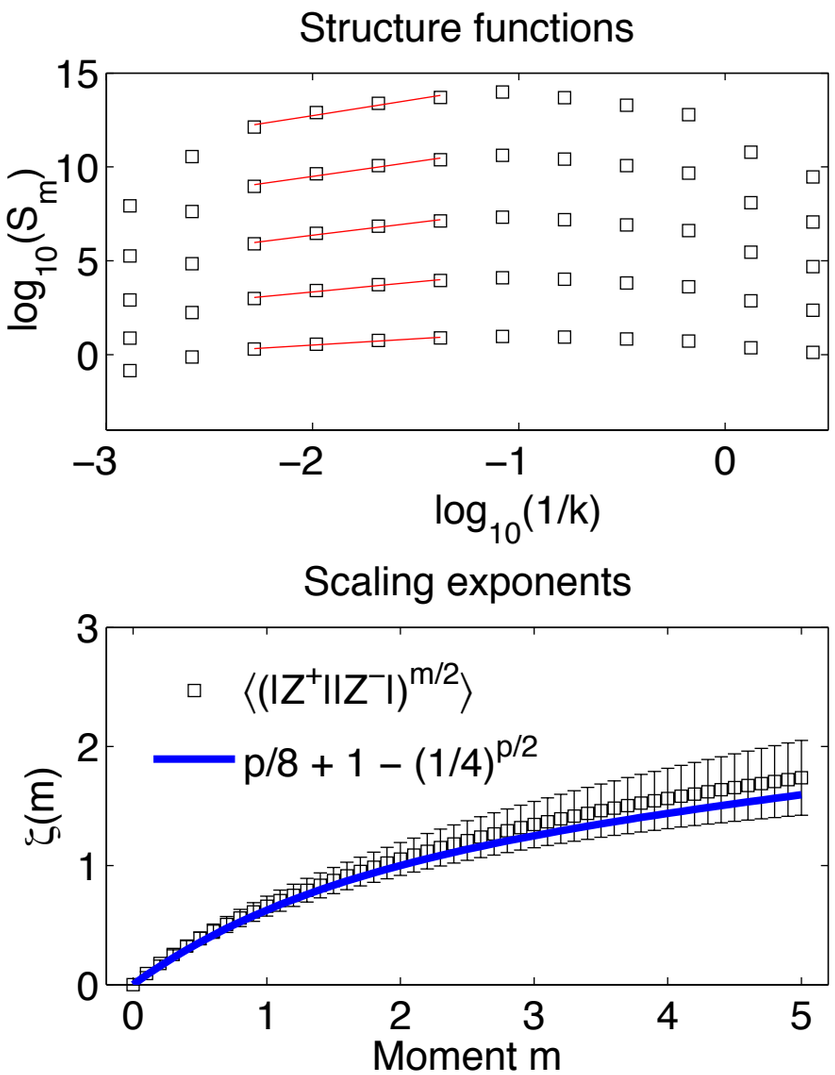
see also Chevillard, Castaing, and Levˆeque, Eur. Phys. J. B 45, 561–567 (2005)

Using fluid models to explore structural changes

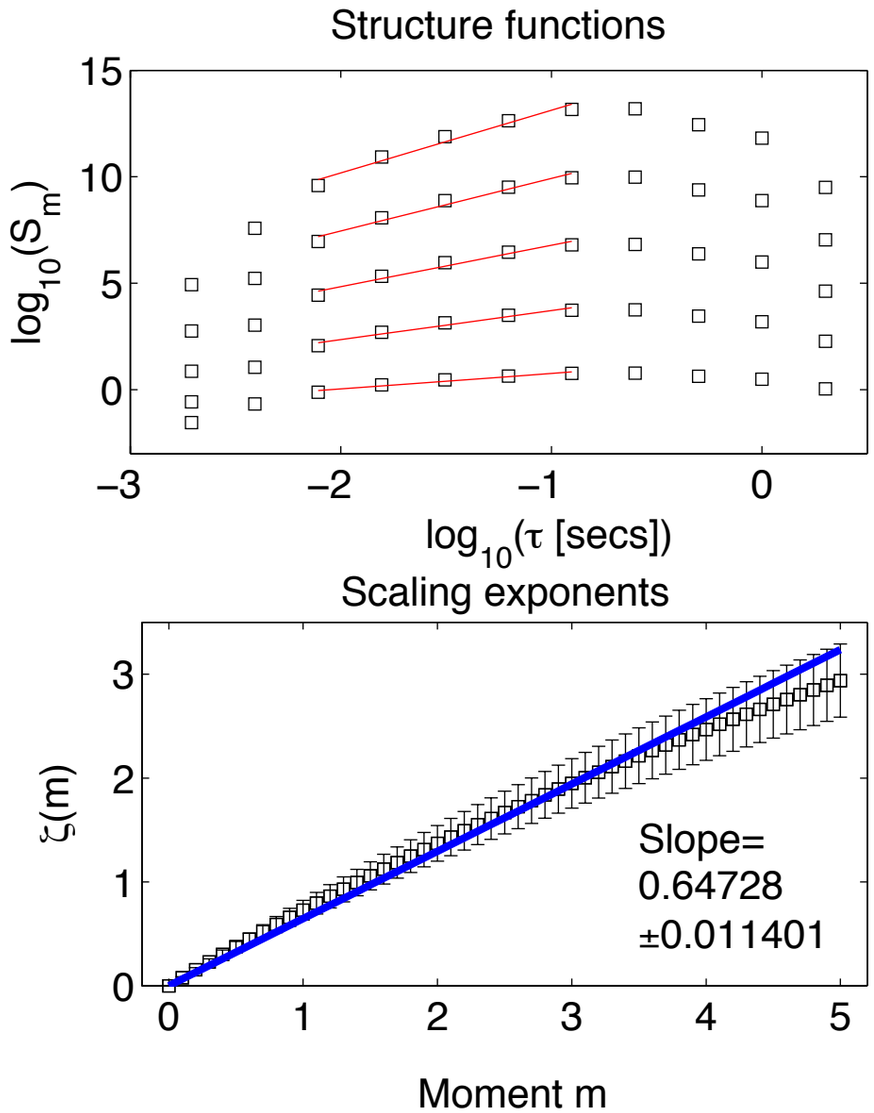
Use simulations to see if the scaling can be replicated by fluid models containing relevant physics and to explore the topology of structures involved

Using fluid models to explore structural changes

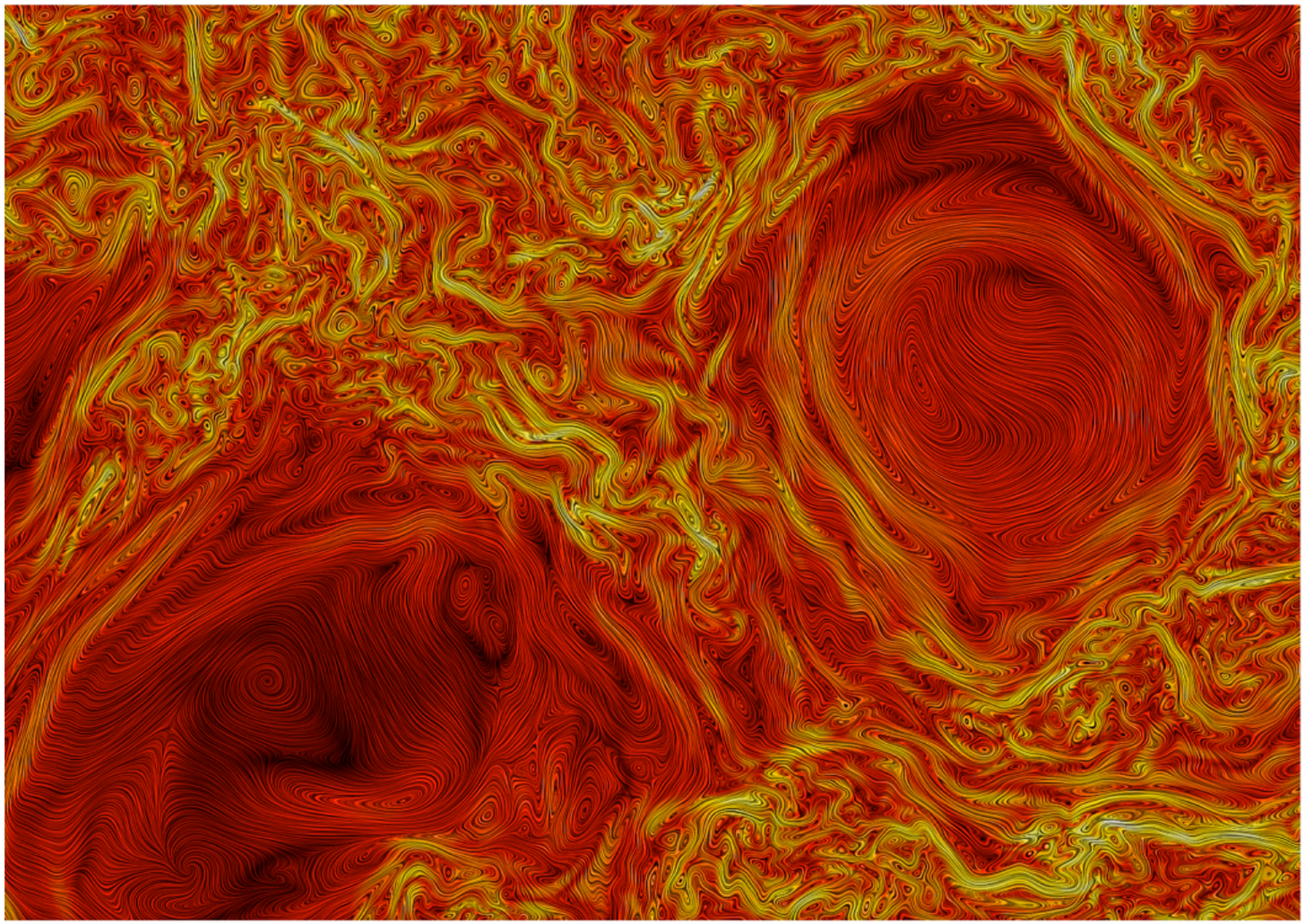
MHD

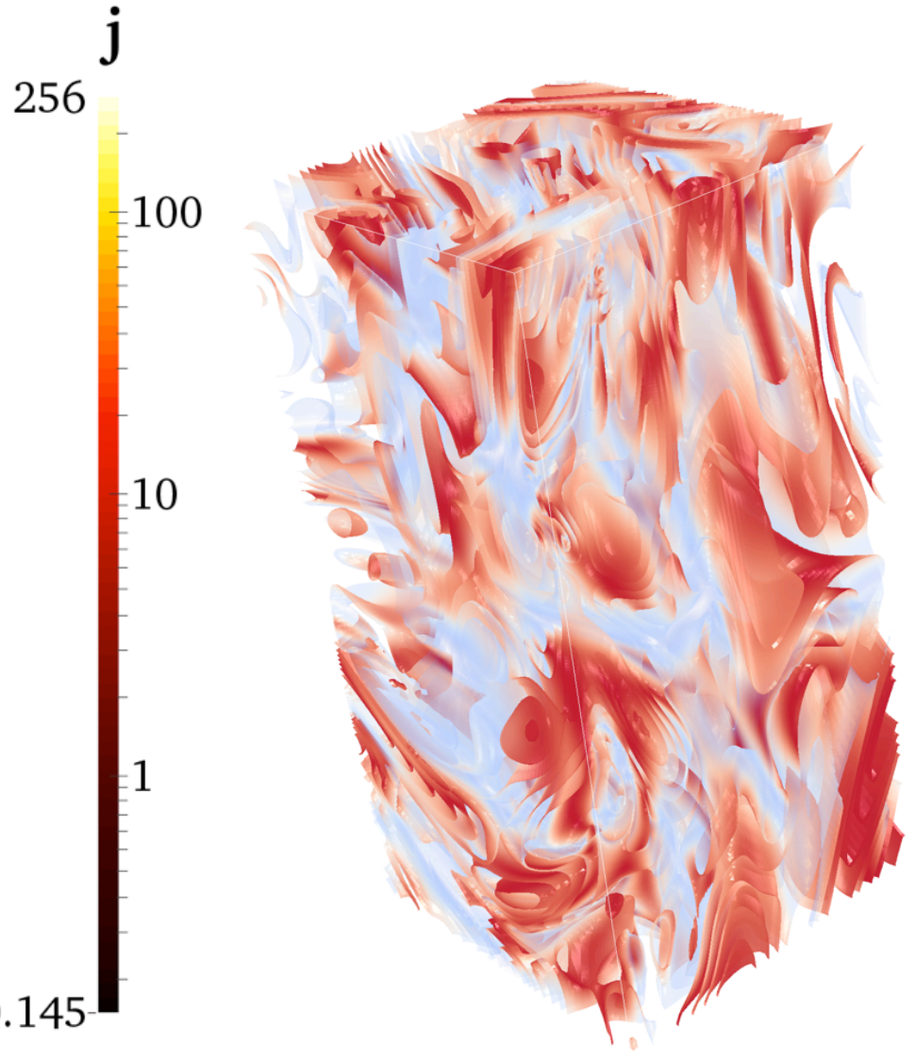


EMHD



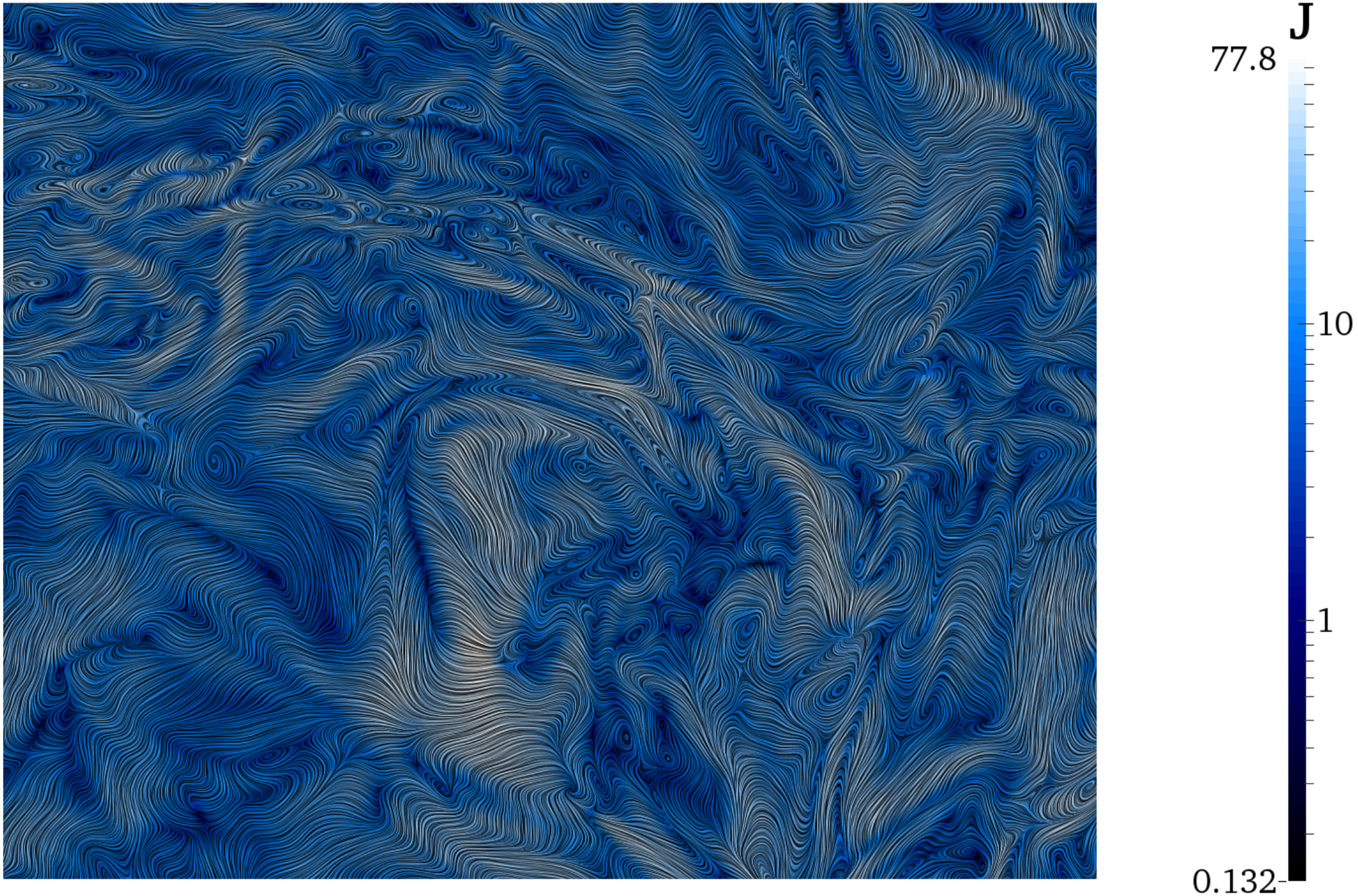
LIC visualisation -- mostly current sheets in MHD





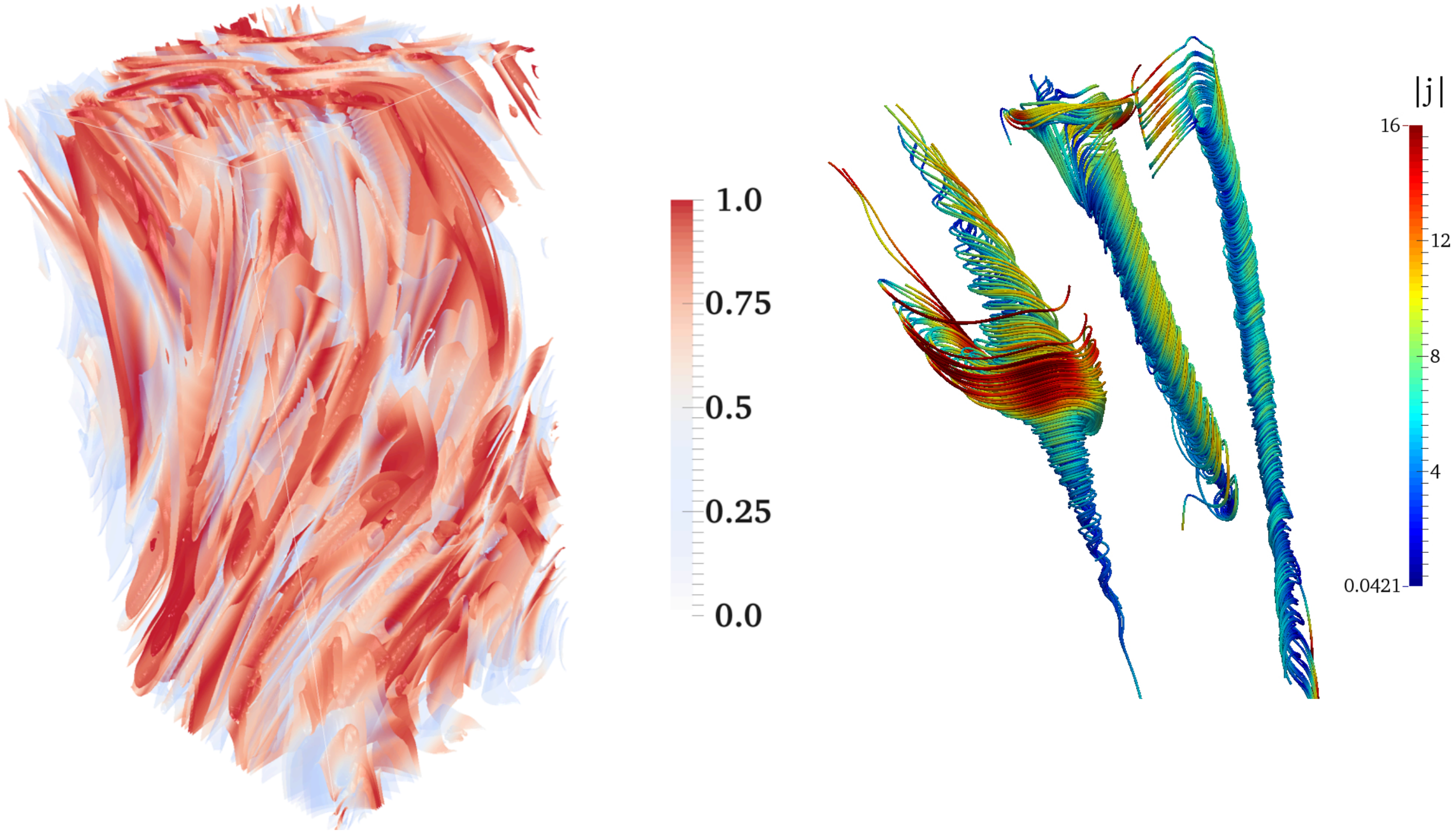
MHD with strong guide field [1536^2 X 128 decaying]

LIC visualisation of filamentary structures in EMHD



Electron MHD [1024^3 decaying]

visualisation of filamentary structures in EMHD -- Beltrami fields [(Curl B) X B=0] & Hall physics



take home message

- Enhanced magnetic compressibility @ sub-ion scales. With strong beta variation.
- Near component isotropy at sub-ion scales.
- PDFs show higher levels of intermittency at such scales; ubiquitous multi->monoscaling transition in all intervals.
- Simulations reproduce this scaling behaviour and -- using them as a proxy for what is happening -- we see that there is a transition from a current sheet dominated regime to one which is filament dominated.