The different spatio-temporal scales of the solar magnetism

SURFACE PROCESSES II

From the small(est) scales, large(st) scales

Or how the advection of the smallest magnetic elements on the solar surface affects the toroidal-to-poloidal conversion in the solar cycle.

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Here it begins

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TURBULENT DIFFUSION IN THE PHOTOSPHERE AS DERIVED FROM PHOTOSPHERIC BRIGHT POINT MOTION

V. I. Abramenko[1], V. Carbone[2], V. Yurchyshyn[1], P. R. Goode[1], R. F. Stein[3], F. Lepreti[2], V. Capparelli[2], and A. Vecchio[2]

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[2] Dipartimento di Fisica, Universita della Calabria, I-87036 Rende, Italy

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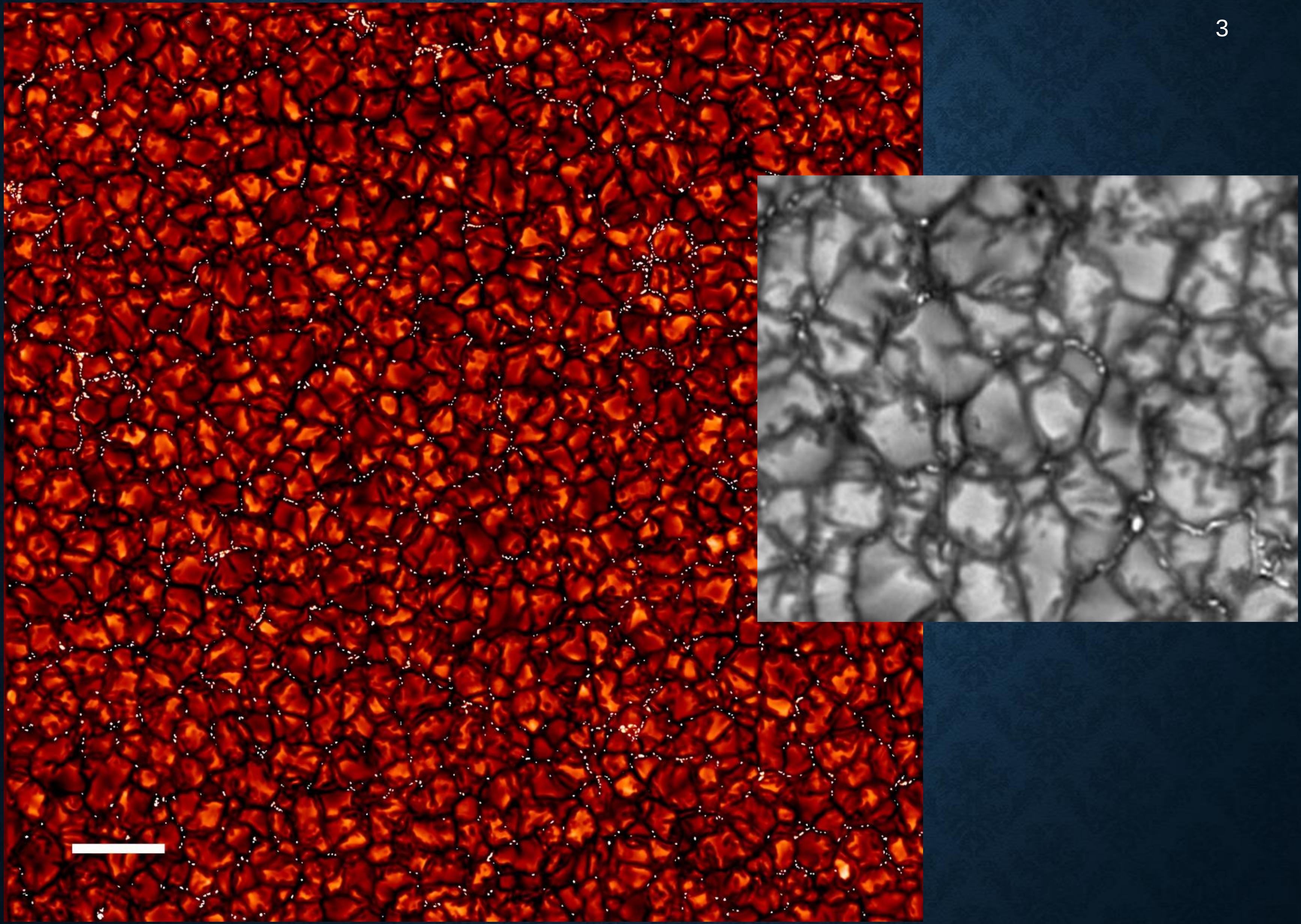
ABSTRACT

On the basis of observations of solar granulation obtained with the New Solar Telescope of Big Bear Solar Observatory, we explored proper motion of bright points (BPs) in a quiet-sun area, a coronal hole, and an active region plage. We automatically detected and traced BPs and derived their mean-squared displacements as a function of time (starting from the appearance of each BP) for all available time intervals. In all three magnetic environments, we found the presence of a super-diffusion regime, which is the most pronounced inside the time interval of 10–300 s. Super-diffusion, measured via the spectral index, γ, which is the slope of the mean-squared displacement spectrum, increases from the plage area ($\gamma = 1.48$) to the quiet-sun area ($\gamma = 1.53$) to the coronal hole ($\gamma = 1.67$). We also found that the coefficient of turbulent diffusion changes in direct proportion to both temporal and spatial scales. For the minimum spatial scale (22 km) and minimum time scale (10 s), it is 22 and 19 $km^2\ s^{-1}$ for the coronal hole and the quiet-sun area, respectively, whereas for the plage area it is about 12 $km^2\ s^{-1}$ for the minimum time scale of 15 s. We applied our BP tracking code to three-dimensional MHD model data of solar convection and found the super-diffusion with $\gamma = 1.45$. An expression for the turbulent diffusion coefficient as a function of scales and γ is obtained.

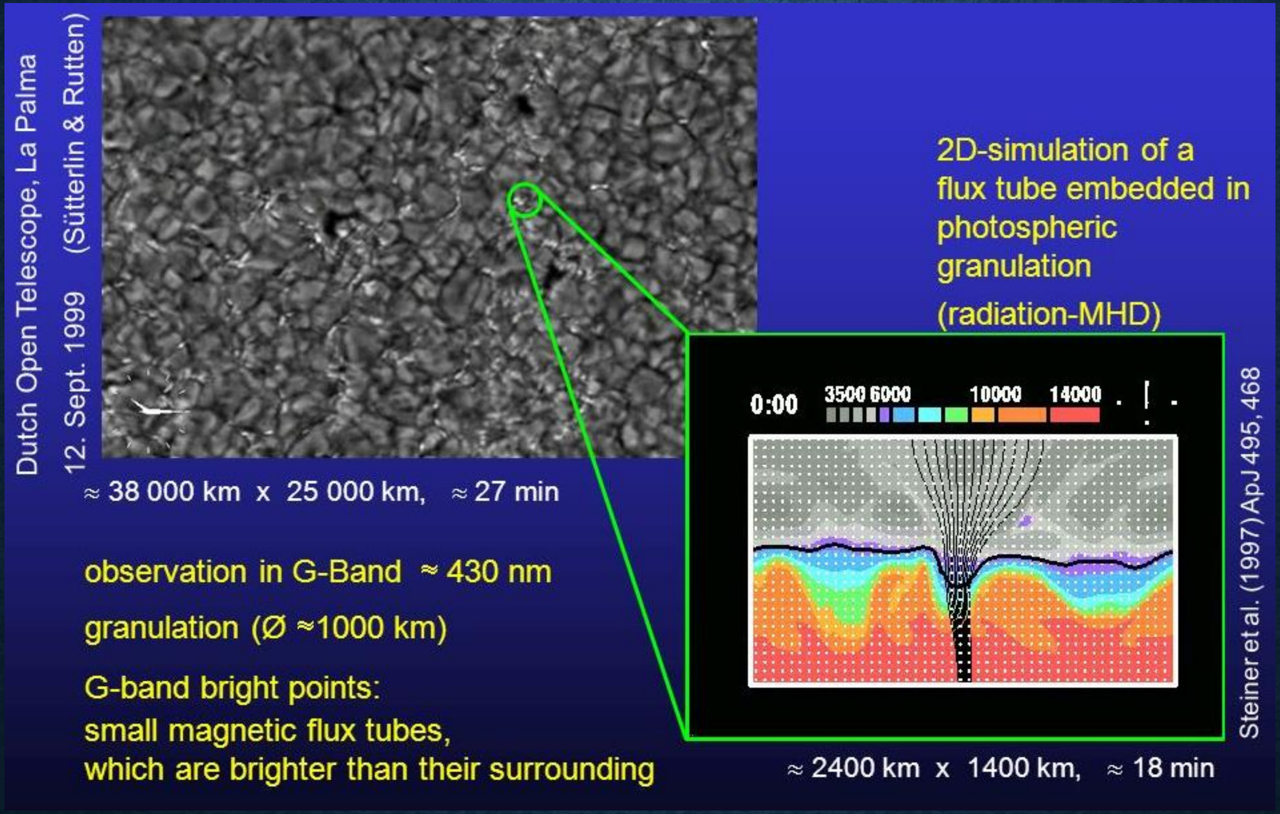
Key words: Sun: photosphere – Sun: surface magnetism – turbulence

Abramenko et al. 2011



Sanchez-Almeida 2010
The Swedish 1-meter Solar Telescope – La Palma

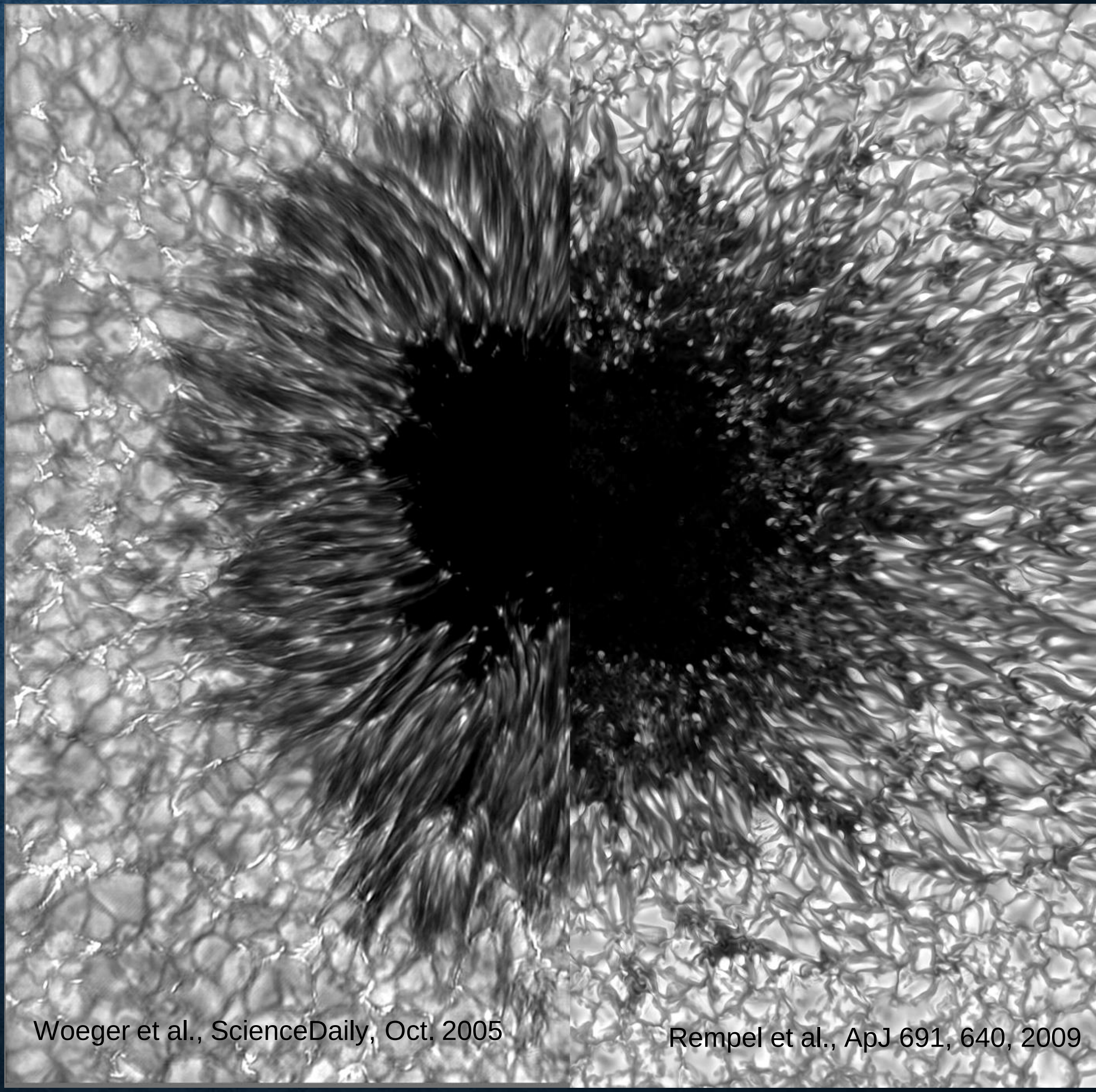
The small scales



Numerical simulation of the solar photosphere

Schussler, ESPM 2008:
“In 100 years we will have the computing power to perform MHD simulations from the large scales (1400 Mm) down to the dissipation scale (10 cm).”

In the meanwhile, need of models that can mimic the complexity of the solar dynamics



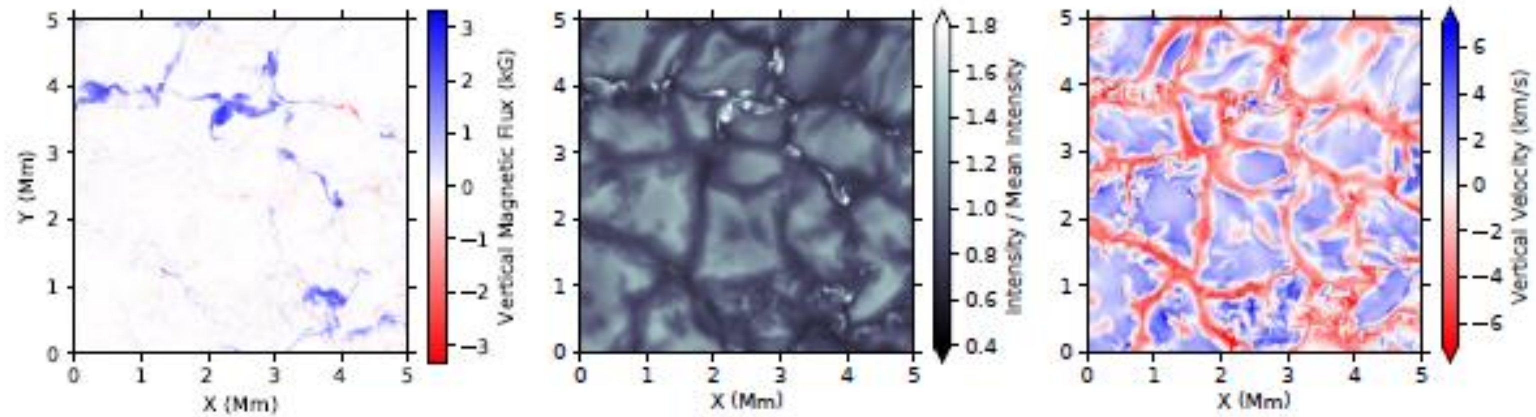


Figure 1. A common 5 × 5 Mm portion of the Rempel (2014) MURaM simulation showing, from left to right, vertical magnetic flux, white-light intensity, and vertical plasma velocity at the beginning of the analyzed time range (time stamp 040000). Over the full frame, peak values for I/I_{mean} are near 2.75, peak values for B_z are near 3.3 kG, and peak values for V_z are near 9.9 km s^{-1} and -11.9 km s^{-1}. (The full 24.5 × 24.5 Mm simulation is used in this paper.)

Magnetic diffusion value: “small”
Otherwise no **small scale** dynamo

The large scales

The flux-transport dynamo

Toroidal field
- Just below the CZ
- Created by shear

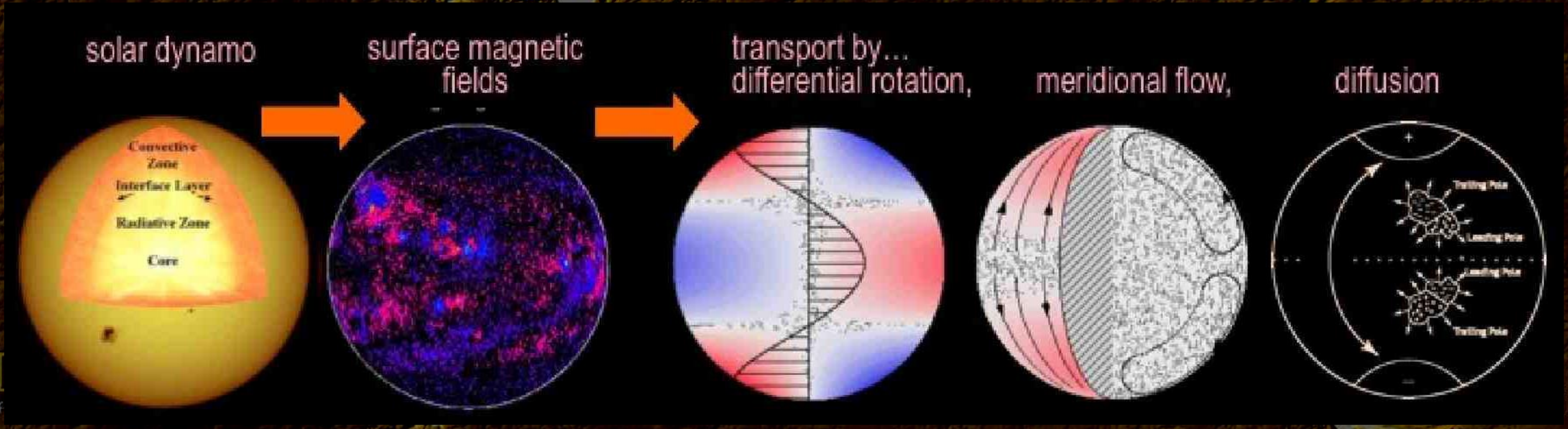
Buoyancy of flux tubes
- Tilted AR emergence
- Active latitudes

Decay by shredding
- Diffuse field

Meridional flow
- Poleward migration for a new poloidal field

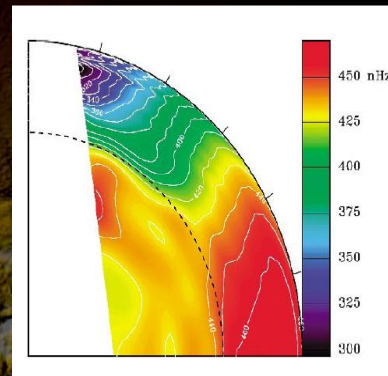
+ Right time scales
+ Right starting latitudes
+ Right tilt angle between emerging polarities
+ Variation of the meridional flow affects the cycle
- Decay of AR still a problem
- JUST a kinematic model

Rudiger & Hollerbach, *The Magnetic Universe*, Wiley-VCH, 2004



A kinematic dynamo model

MAIN INGREDIENTS:
Differential rotation
Diffusion
Meridional flow



- Surface B flux values strongly dependent on rotation rate and profile

- Period determined by the characteristics of the return flow

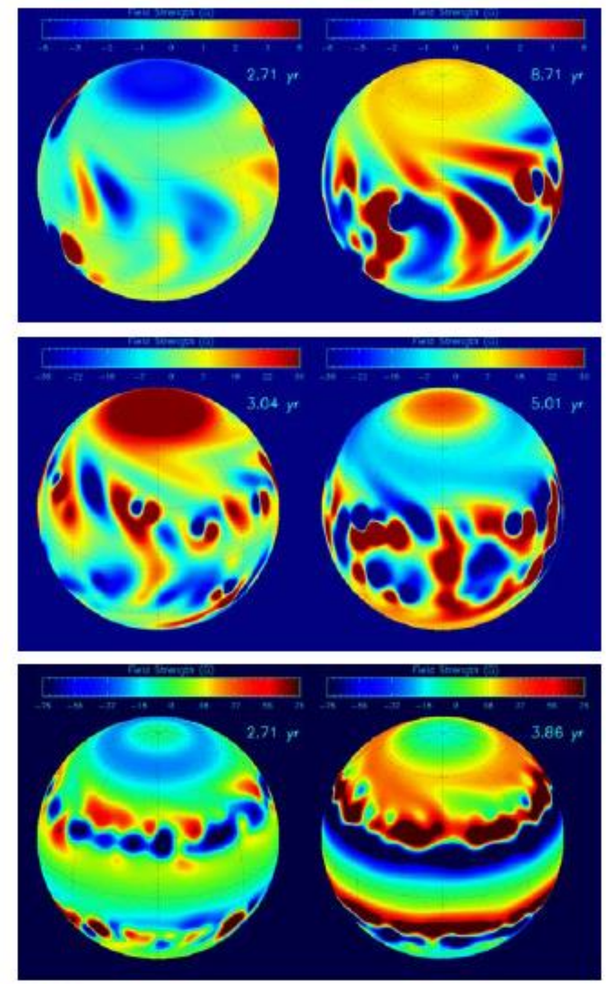


Fig. A.1. The surface distributions of magnetic flux for the Sun-like star with P_{rot} = 27 d (*top panels*), P_{rot} = 9 d (*middle panels*), and P_{rot} = 2 d (*bottom panels*), near the activity minimum (*left panels*) and the maximum phases (*right panels*). The colour scale for the magnetic field strength saturates at ±5, 30, and 75 G for top, middle, and bottom panels, respectively. The corresponding time-latitude diagrams for the azimuthally averaged magnetic field strength are shown in Figs. 5c, 7c, and 9c.

Isik et al., A&A 528, A135, 2011
Bonanno, Geophys. Astrophys. Fluid Dyn., 107, 2013

Diffusion: a key ingredient for kinematic dynamo models

MAIN INGREDIENTS:
Differential rotation
Diffusion
Meridional flow

Case SUN:
prescriptions matching measurements of solar flux emergence and evolution.
Case DISP:
same emergence as Case SUN, but dispersal 10 times less efficient.
Case LIN:
dependence of magnetic feature mobility on flux removed
Case LIN+DISP:
combination of LIN and DISP.

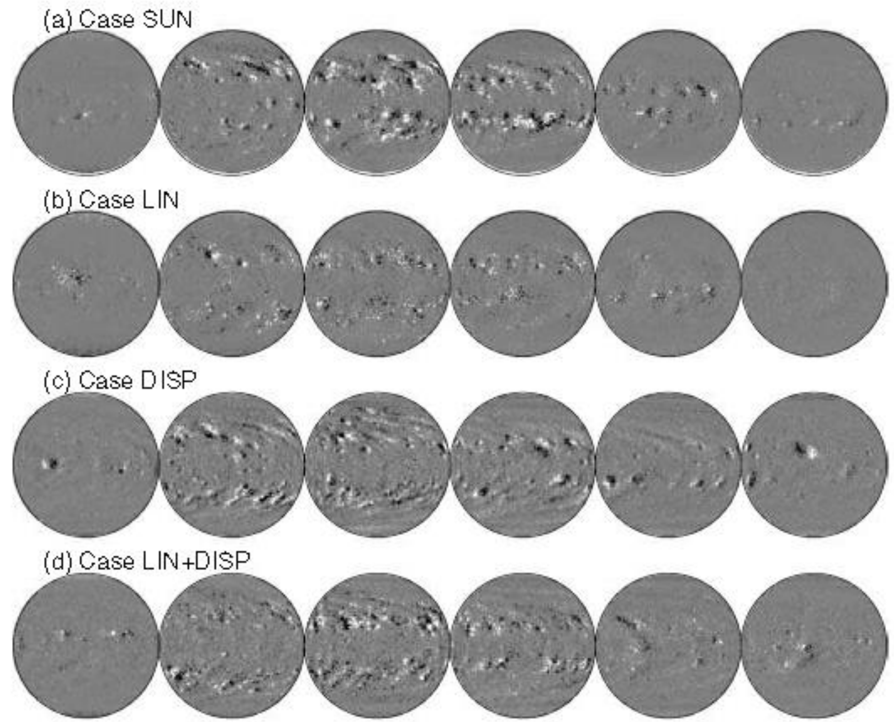


Figure 3. Equatorial views of Cases SUN, LIN, DISP, and LIN+DISP throughout half of a polarity (or a full sunspot) cycle, all scaled to $\pm 4 \times 10^5$ Mx cm^{-2}. The first and last images in each row correspond to successive minima in the sunspot cycle.

De Rosa, Proc. IAU, S233, 2, 25, 2006

- Surface B **diffusion strongly dependent on turbulent convection properties**

Turbulent diffusion coefficient in use:

~600 km^2/s for kinematic dynamos

<10 km^2/s for MURAM code simulations

Back to the start

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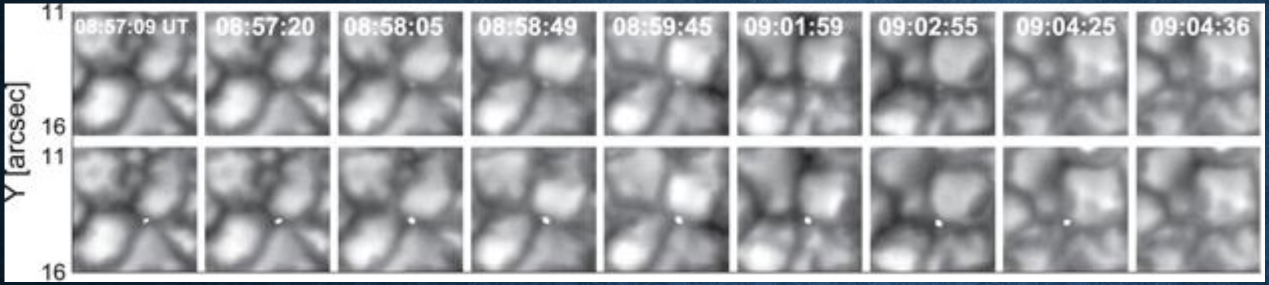
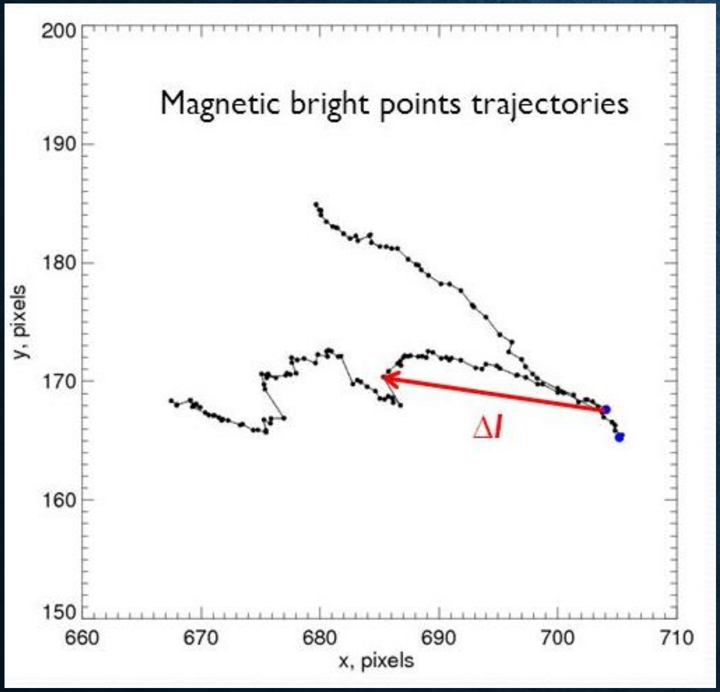
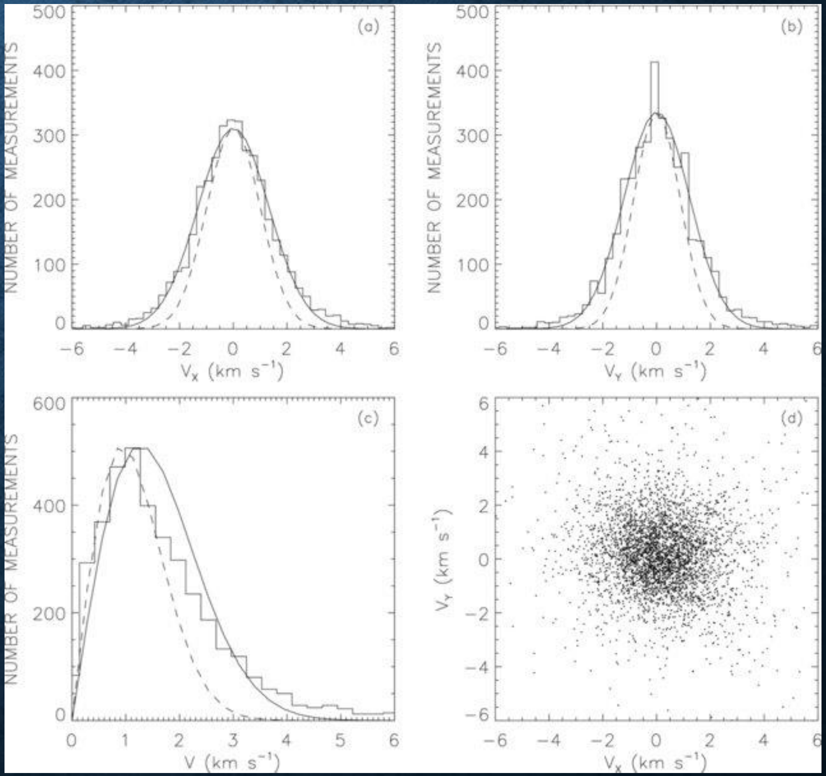
Abramenko et al. 2011

Anomalous diffusion!

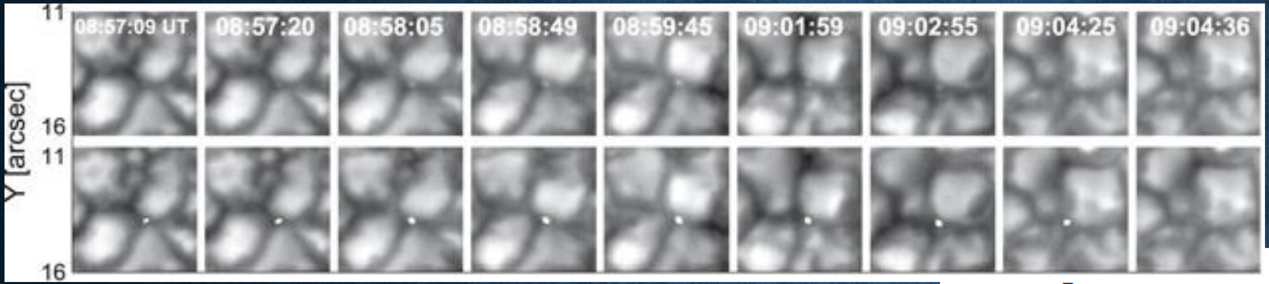


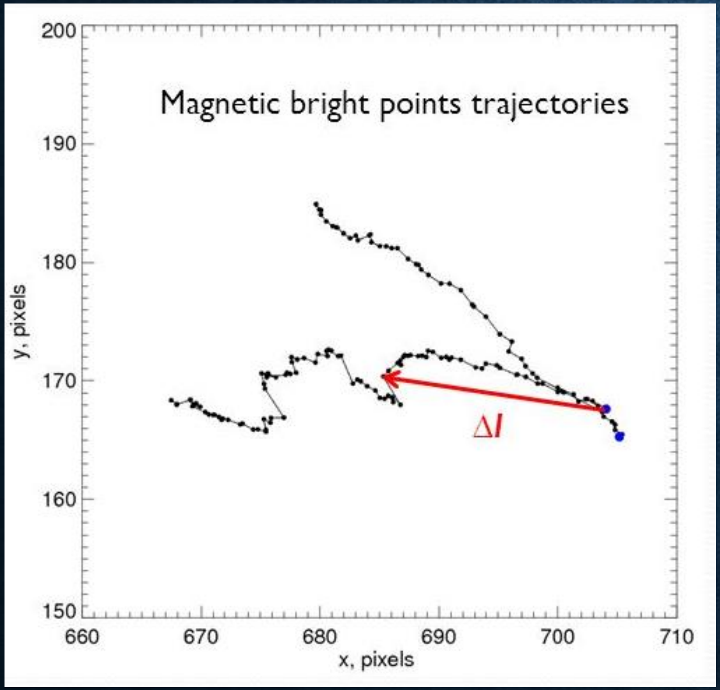


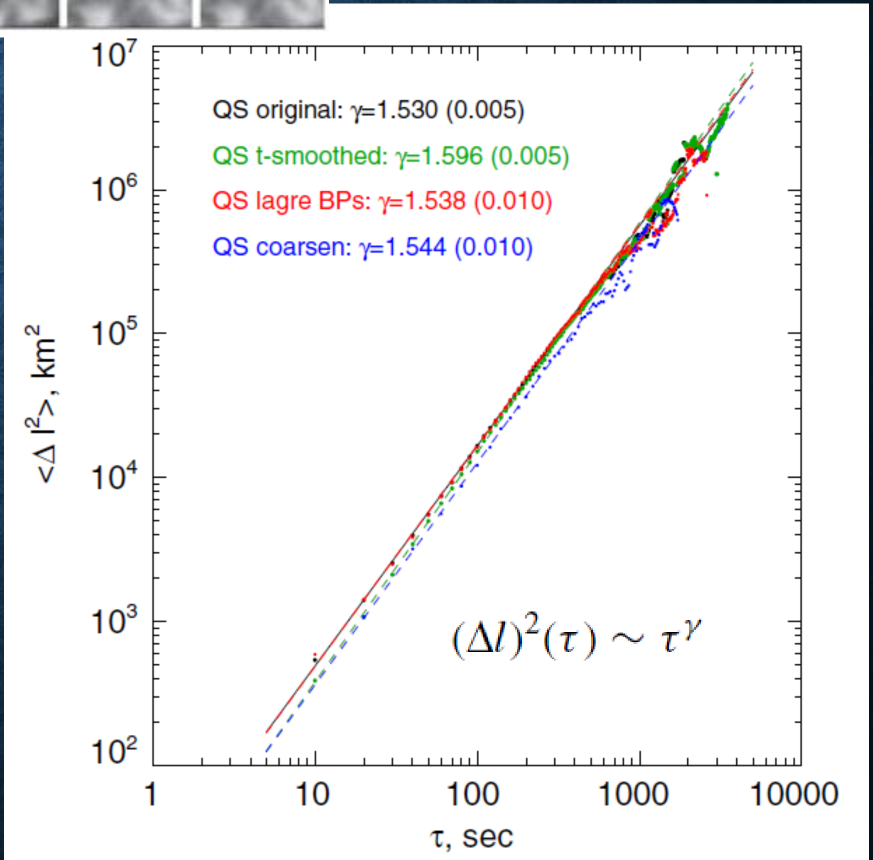


Chitta et al. 2012

Anomalous diffusion!

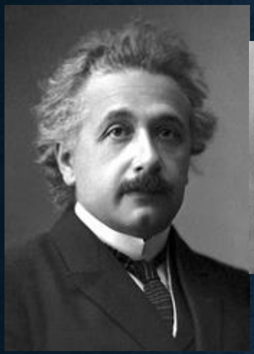






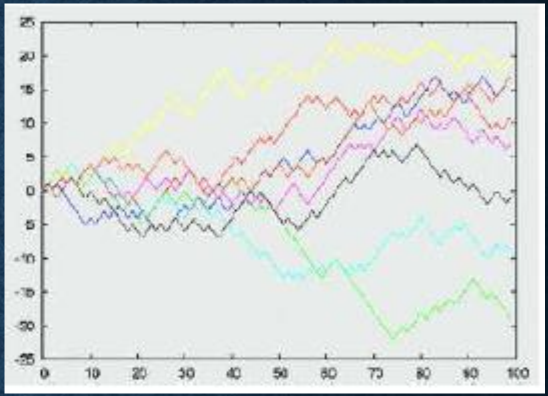
Abramenko et al. 2011

Normal and Anomalous Diffusion: A quick Tutorial




Einstein–Smoluchowski relation

$$\overline{x^2} = 2\,D\,t.$$



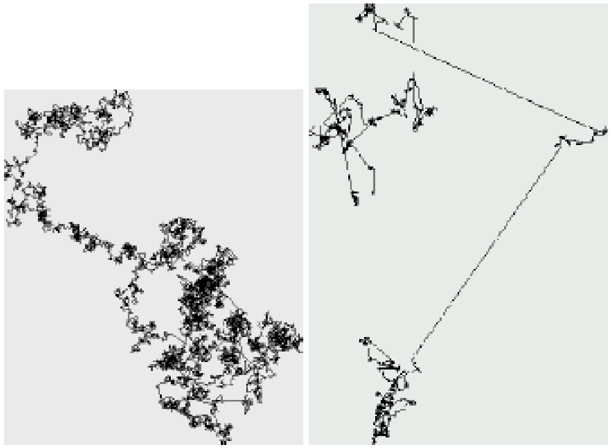
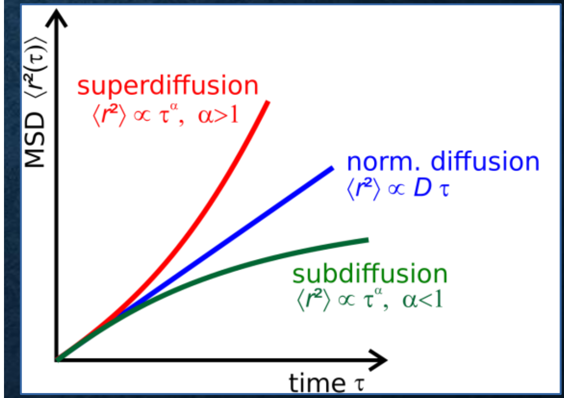


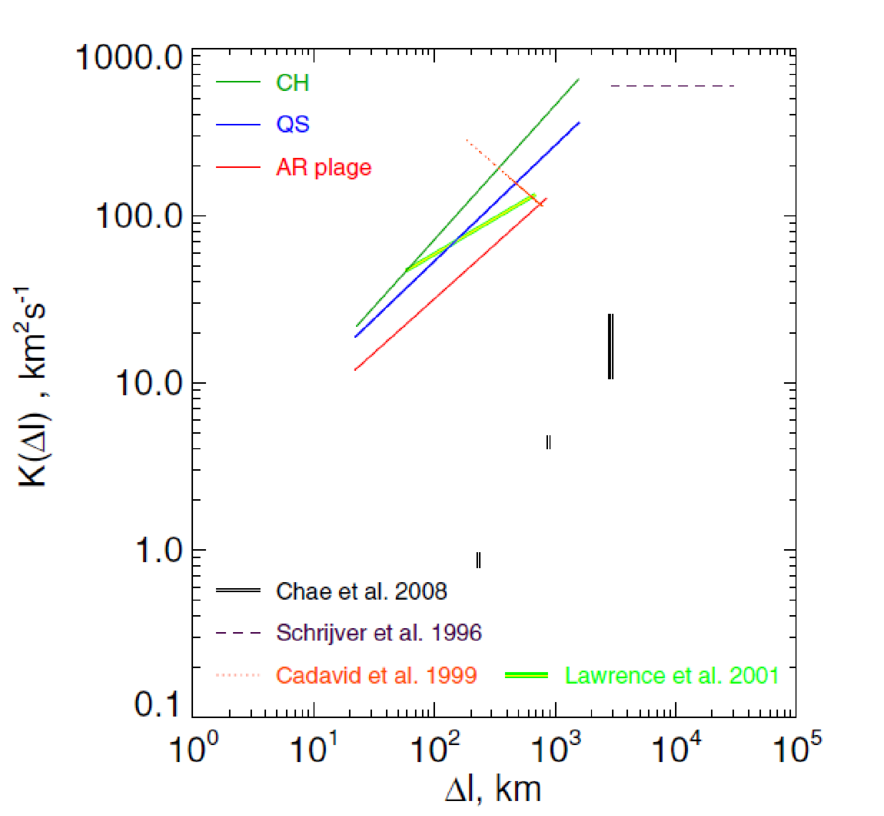
Fig. 4. (a) Random walk in dynamical systems close to equilibrium (normal diffusion; trajectory on the left), (b) random walk in dynamical systems far from equilibrium (anomalous diffusion; trajectory on the right).



"Phenomena of anomalous diffusion are very frequent, because any systems of interest are far from equilibrium, such as turbulent systems, or because the space accessible to the diffusing particles has a strange, e.g. fractal structure. The tools to model these phenomena, continuous time random walk, stochastic differential equations, and fractional diffusion equations, are still active research topics."
Vlahos et al. 2008

The diffusion coefficient changes from small to large scales

$$K(\tau) = \frac{1}{4}\frac{d}{d\tau}\langle l^2(\tau)\rangle,$$



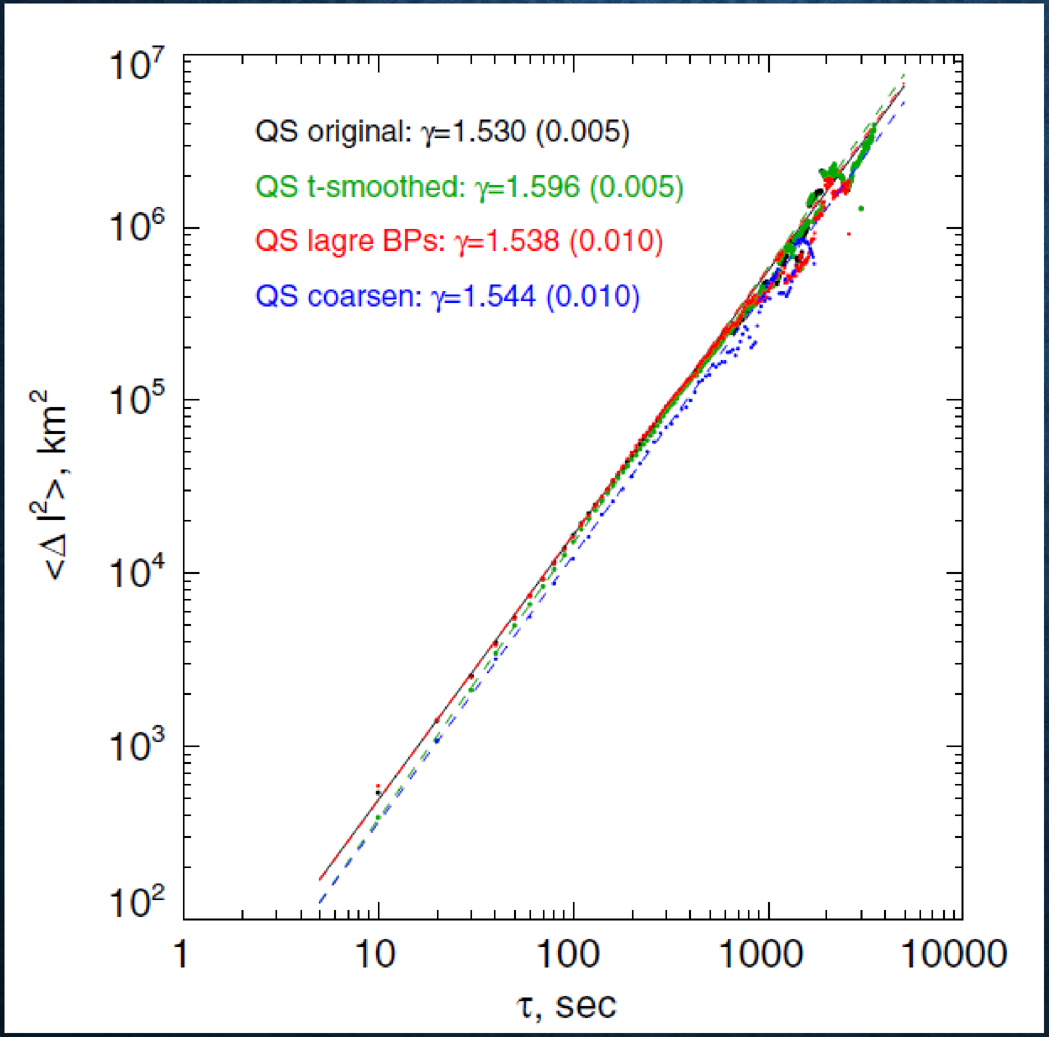
Abramenko et al. 2011

Table 3. Comparison of the mean values of diffusion index γ and diffusion coefficient D of small magnetic elements obtained in this study with some of those in the literature.

Reference	Origin of data	Telescope/ Spacecraft	Spatial resolution	Feature[a]	Lifetime[b,c] [sec]	γ^c	$D^{b,c}$ [$km^2 s^{-1}$]
This study	Stratospheric balloon	SUNRISE/SuFI	0.″14	IMBP	461	1.69	257
Chitta et al. (2012)	Ground	SST/CRISP	-	IMBP	180 – 240	1.59	(≈ 90)
Abramenko et al. (2011)	Ground	BBSO/NST	0.″11	IMBP[d]	(10 – 2000)	1.48	(19 – 320)
Manso Sainz et al. (2011)	Space	Hinode/SOT	0.″32[e]	IMBP	< 900	0.96	195
Utz et al. (2010)	Space	Hinode/SOT	0.″22[f]	IMBP	150	(≈ 1)	350
Chae et al. (2008)	Space	Hinode/SOT[g]	-	ME[d]	-	-	0.87
Lawrence et al. (2001)	Ground	SVST	0.″23	NMBP	9 – 4260	1.13	-
Cadavid et al. (1999)	Ground	SVST	0.″23[h]	NMBP	18 – 1320	0.76	-
					1500 – 3450	1.10	-
Hagenaar et al. (1999)	Space	SOHO/MDI	2.″3[i]	MFC	$< 1.0 \times 10^4$	(≈ 1)	70 – 90
					$> 3.0 \times 10^4$		220 – 250
Berger et al. (1998)	Ground	SVST	≈0.″2	NMBP[d]	(100 – 3800)	1.34	60
Lawrence & Schrijver (1993)	Ground	BBSO	-	ME[d]	-	0.92	250

Jafarzadeh et al. 2013

Can we do better?



Abramenko et al. 2011

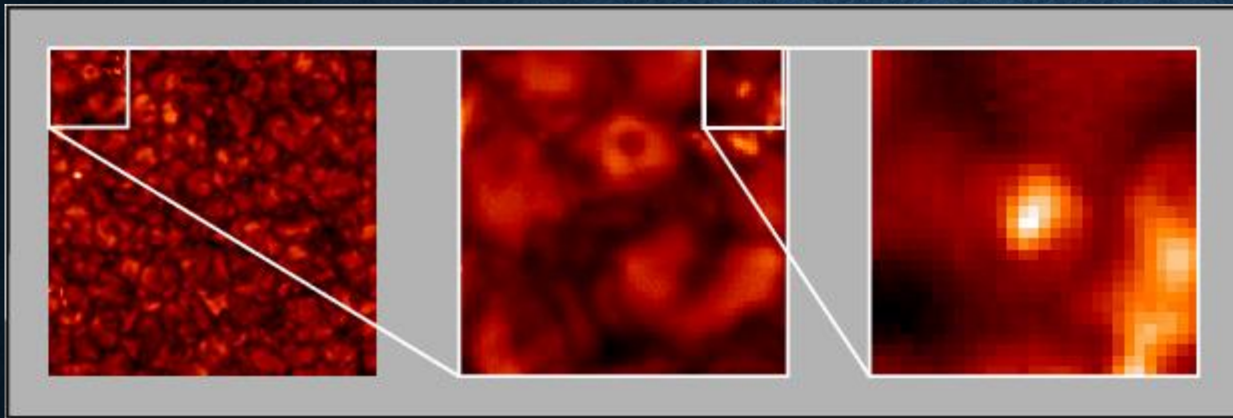
Richardson diffusion?

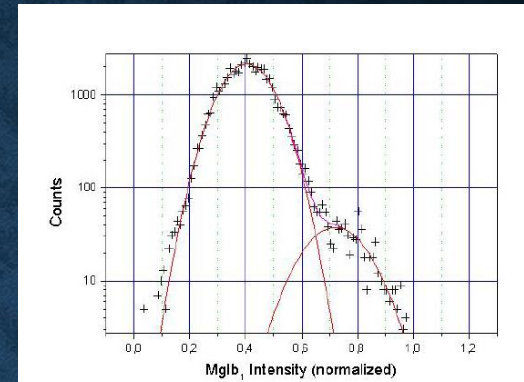
Fully turbulent medium?

Self-similar scaling?

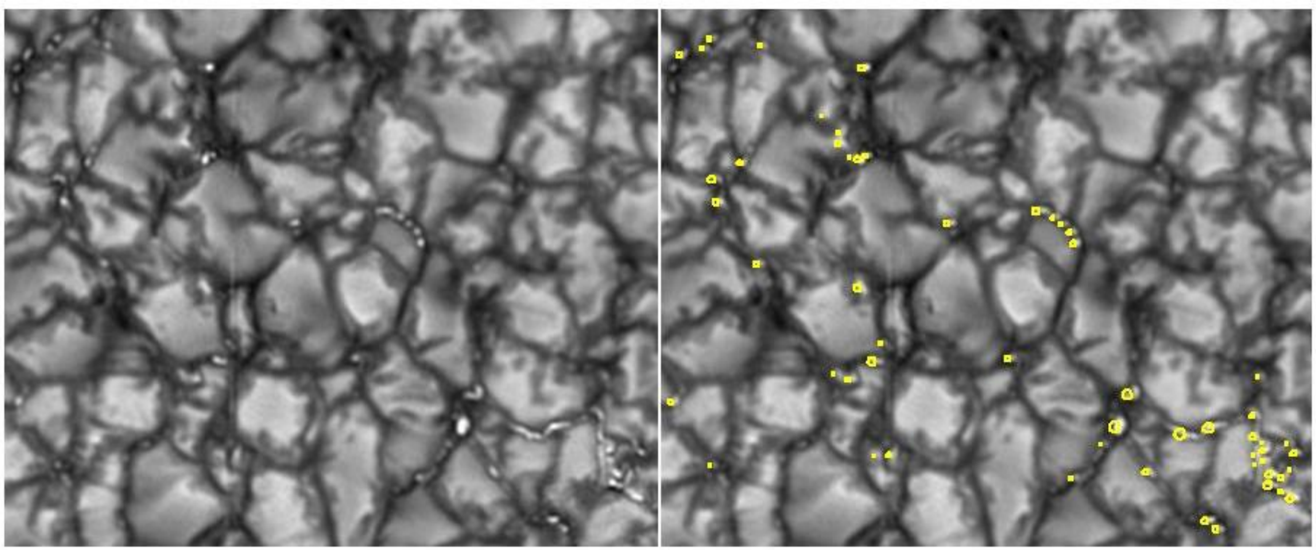
Methods ok?

Ranges explored?





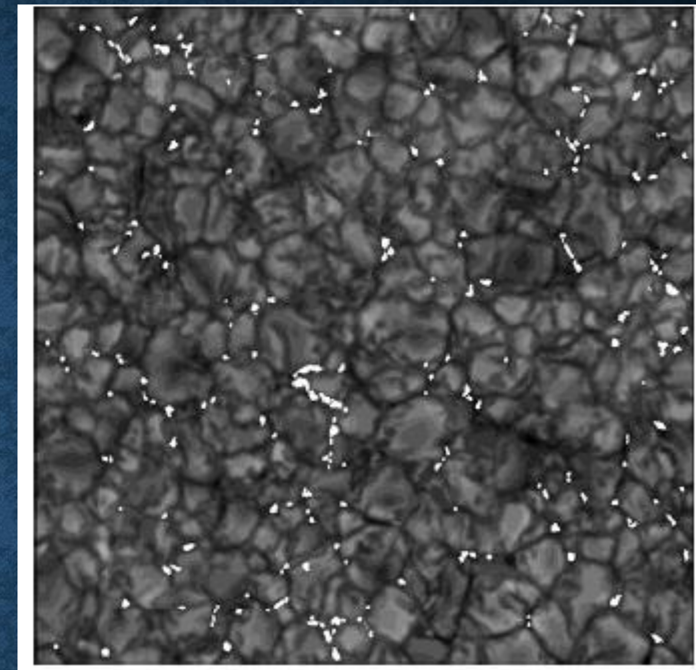
Bright points detection

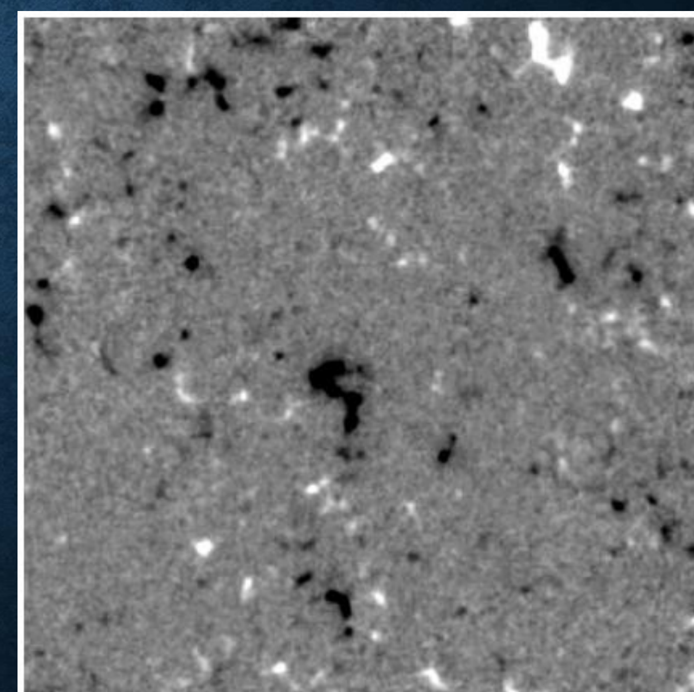


Detection criteria: lifetime longer than 20 s;
area larger than 2 pixels;
brightness above the mean image brightness.

Total: 13597 tracked BBs for th=85 DN
7148 tracked BPs for th=120 DN

One exceptional Dataset





Duration: 50 min
Cadence: 5 sec

FoV: ~30x30Mm^2
Resolution: ~100km

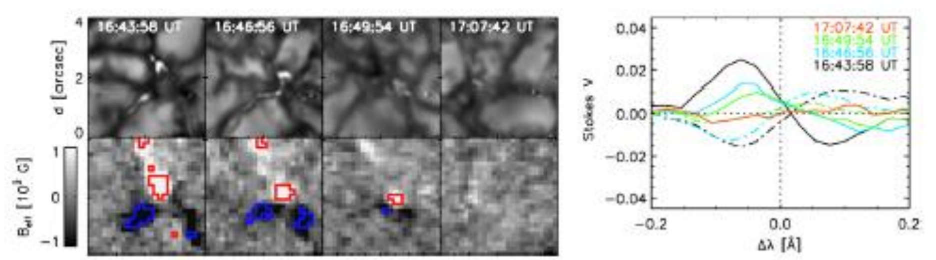


Figure 5. Selection of four instants from the BP cancellation process. First row: G-band filtergram. Second row: COG magnetic flux density (images are saturated at 100 G). Contour plot: kG fields regions as obtained from the inversion analysis of Stokes V profiles; positive (red contours) and negative (blue contours) polarity regions are represented. Right plot: FeI 630.25 nm Stokes V profiles calculated as average over a 0.″5 × 0.″5 box around the position of the minimum (solid line) and maximum (dot-dashed line) magnetic flux densities for each time instant. Stokes V profiles are normalized to the continuum intensities. For 17:07:42 UT a single 0.″5 × 0.″5 box fixed at the interaction point is used to calculate the average profiles.

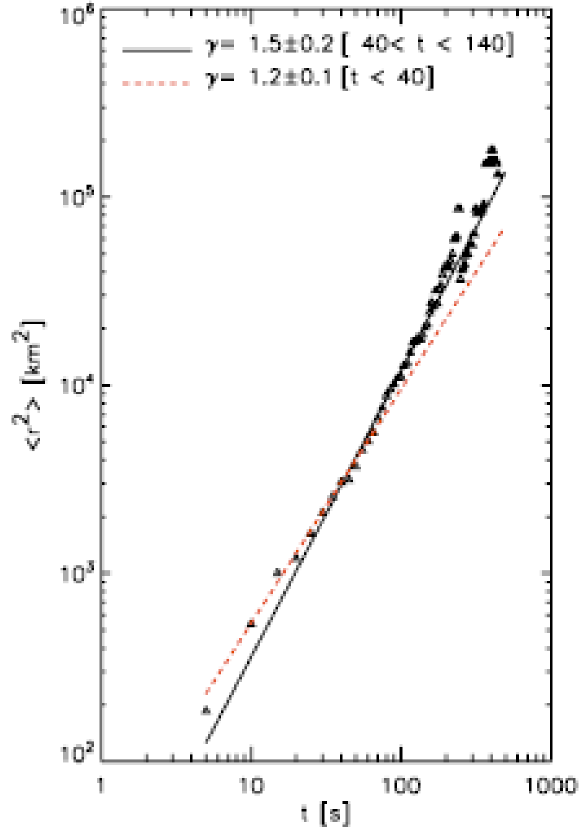
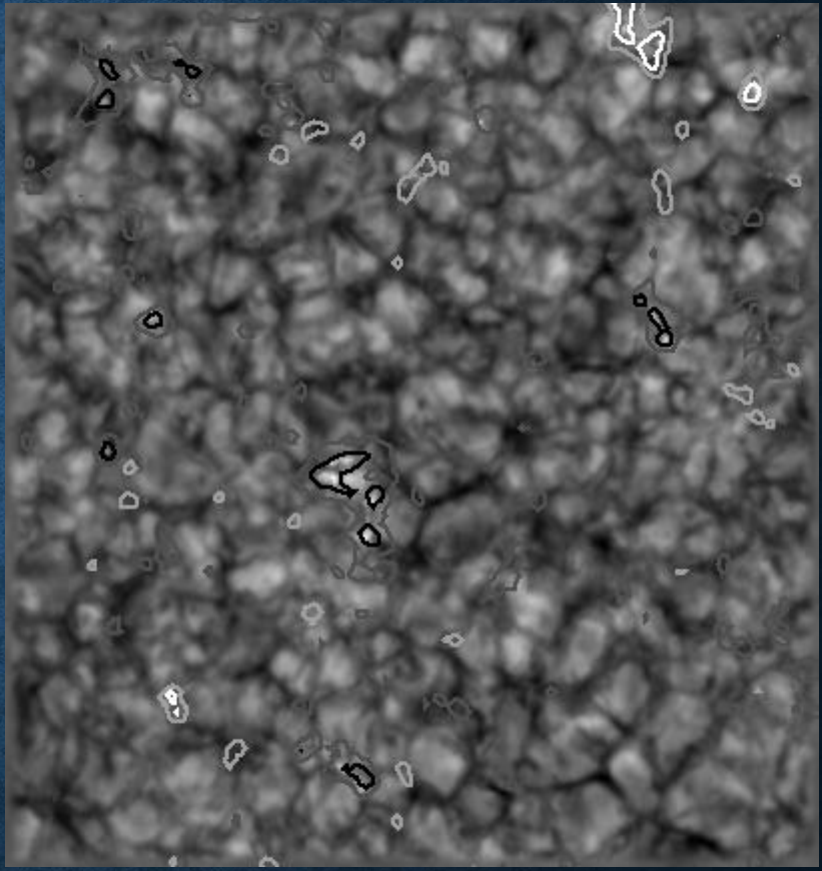
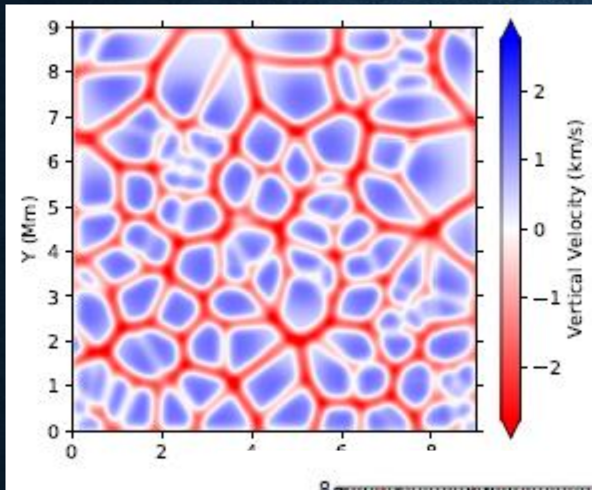


Fig. 1. Displacement spectrum for magnetic *G*-band bright points for a high-resolution data set acquired at the NSO-DST observatory. The lines represent power law fits for the ranges ($t < 40$ s) s and (40 s $\leq t <$ 140 s).



Del Moro et al. 2015

An advection simulation...



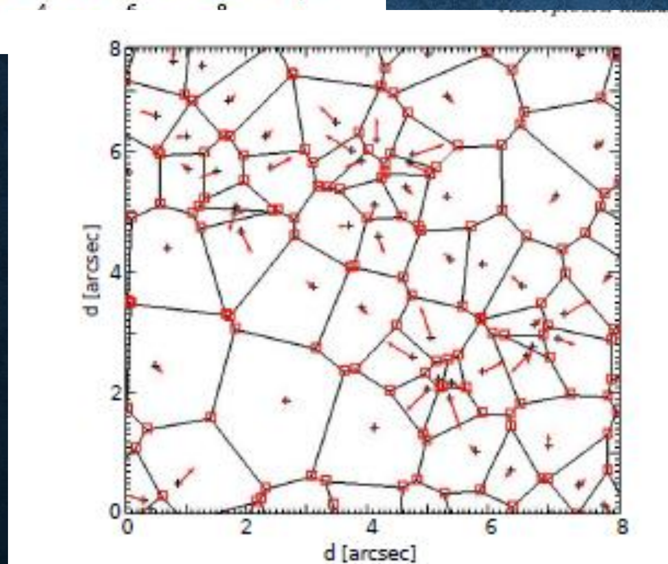
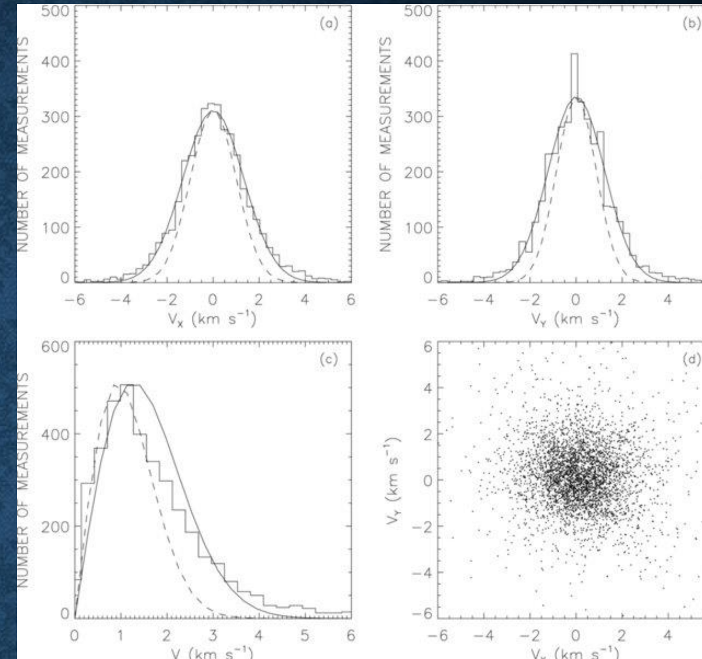
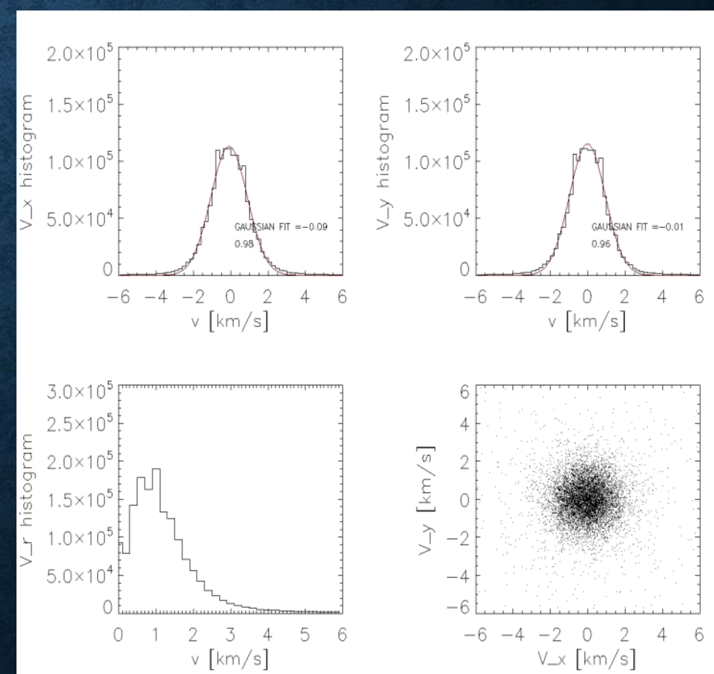
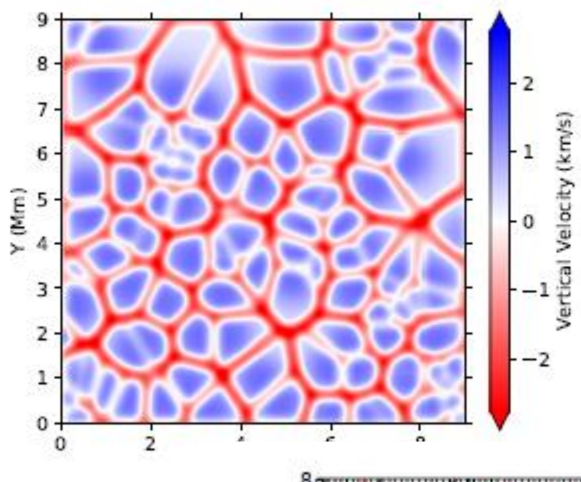


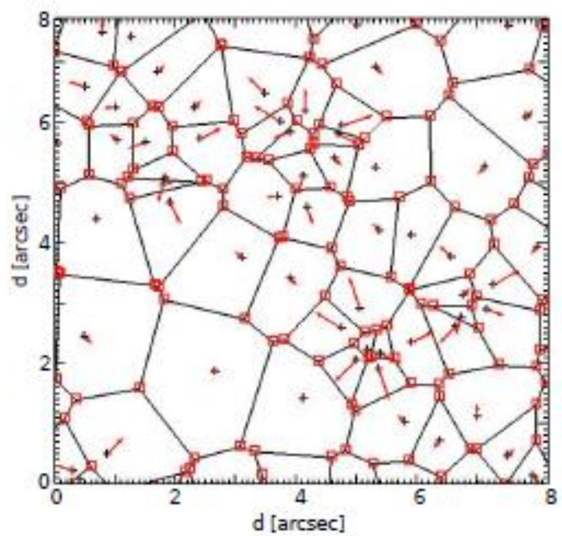
Fig. 3. A snapshot from the simulation. The black crosses represent the advection centres; the red vectors are the displacement (5× exaggeration) to be applied to the centres due to the neighbours' action; the red boxes on the Voronoi tesselation highlight the cell vertexes, which are used as tracers to compute the displacement spectrum. For the sake of visualization, only about a twentieth of the simulation domain is shown.





An advection simulation...





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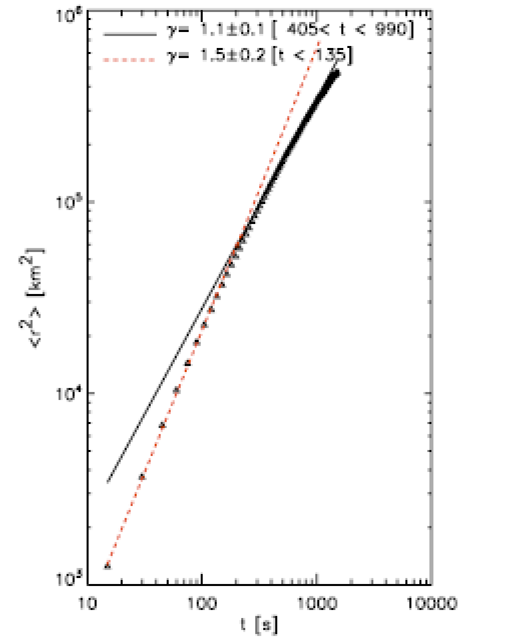

Fig. 4. Displacement spectrum for the Voronoi tessellation vertexes of the advection simulation. The lines represent power law fits for the ranges ($t < 135$ s) and (405 s $\leq t < 1000$ s).

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After all…

No need of Richardson diffusion

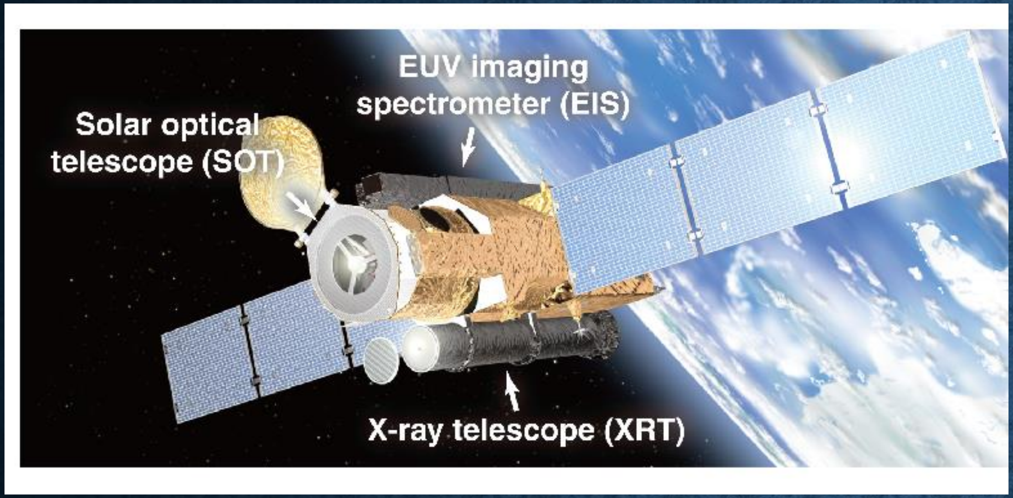
Diffusion coefficients you may use:

~500 km^2/s for large scales (depending on B strength)

<10 km^2/s for small scales

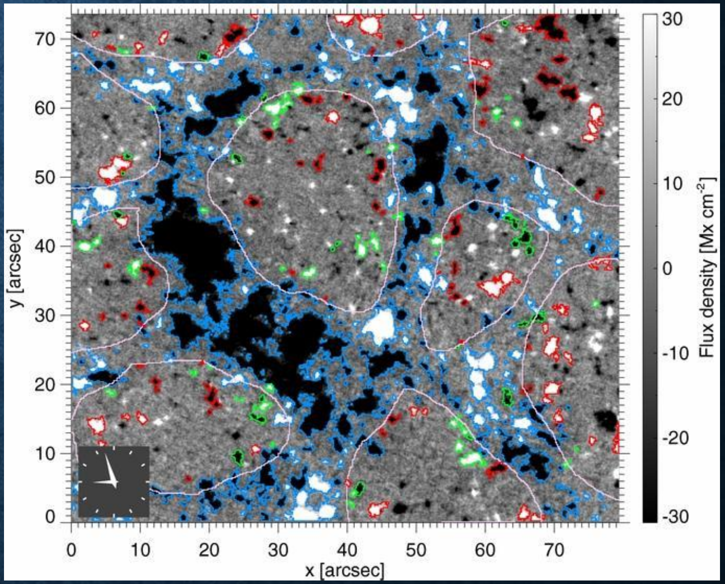
"The diffusion coefficient value depends on the scale"

Another exceptional Dataset



Duration: ~25 hours
Cadence: 90 sec

FoV: $\sim 50 \times 50 Mm^2$
Resolution: ~200km



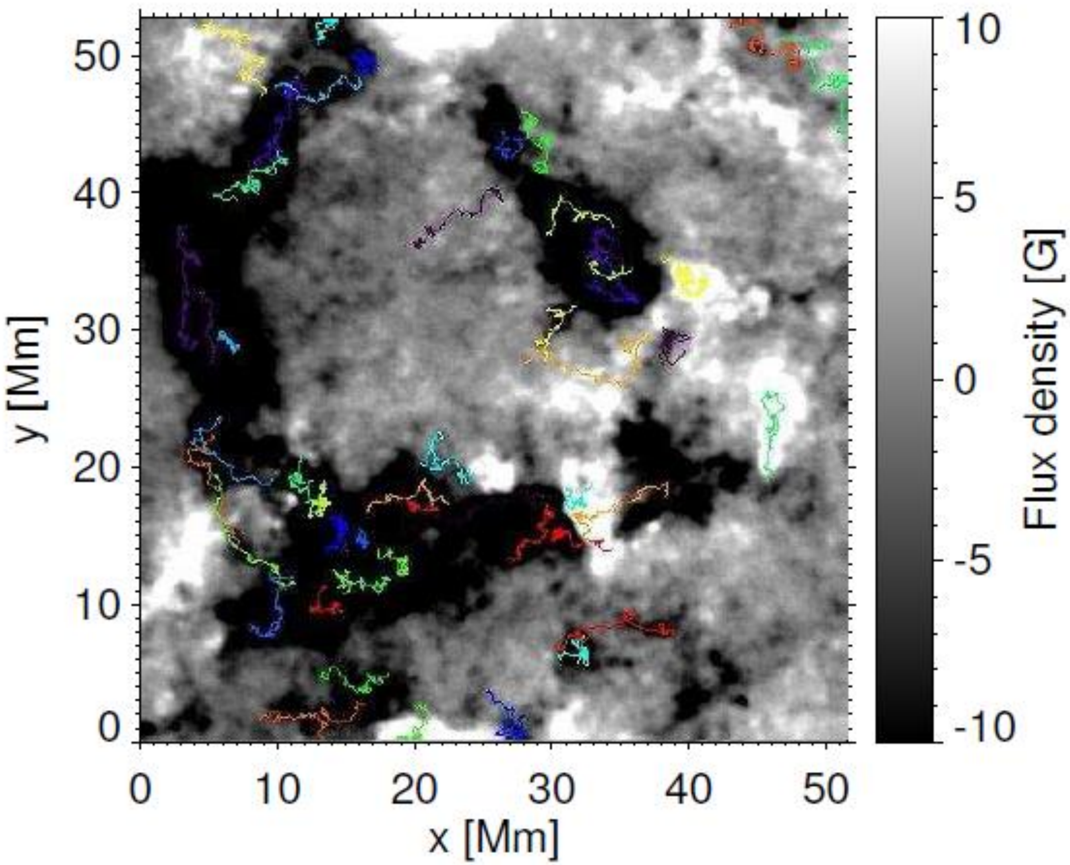
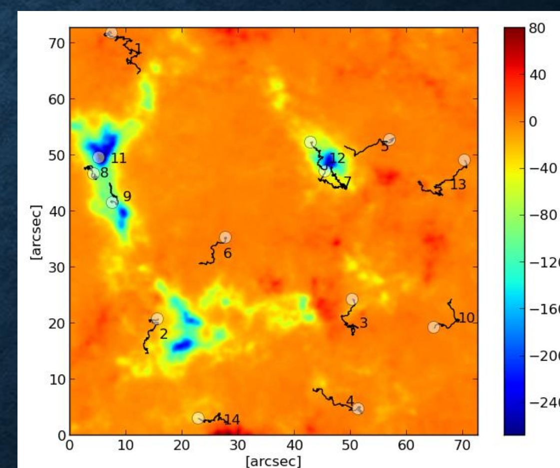


Fig. 1.— Mean magnetogram saturated at ±10G. The coloured tracks represent the trajectories of the 50 longest living magnetic elements. Their lifetimes spans the range from ~ 4 to ~ 11 hours.



Stangalini et al. 2015

Giannattasio et al. 2013

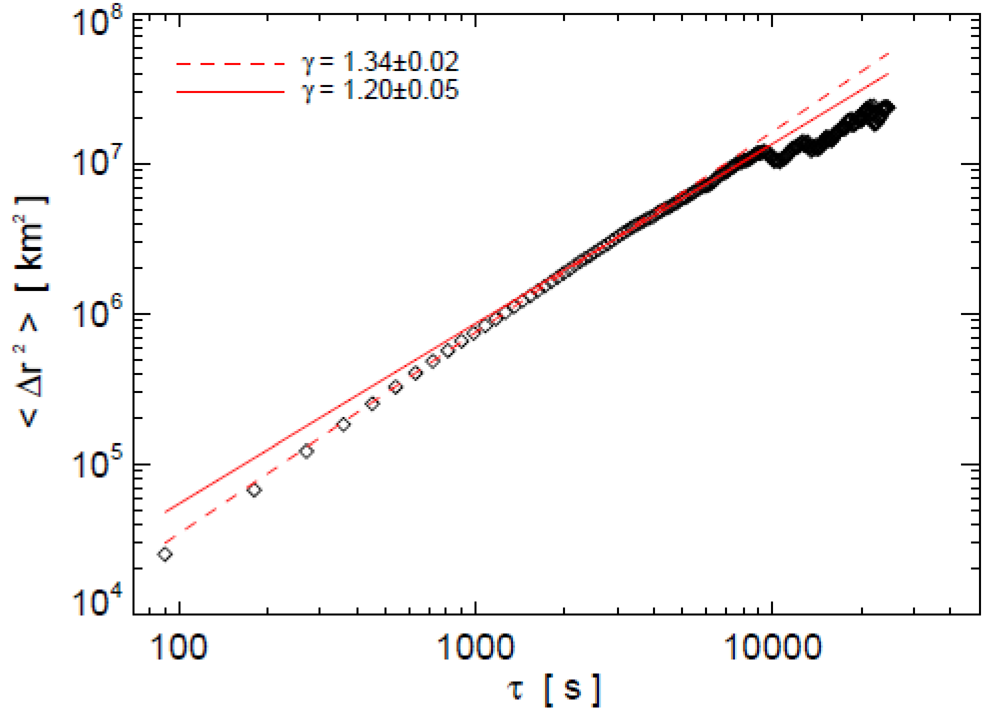
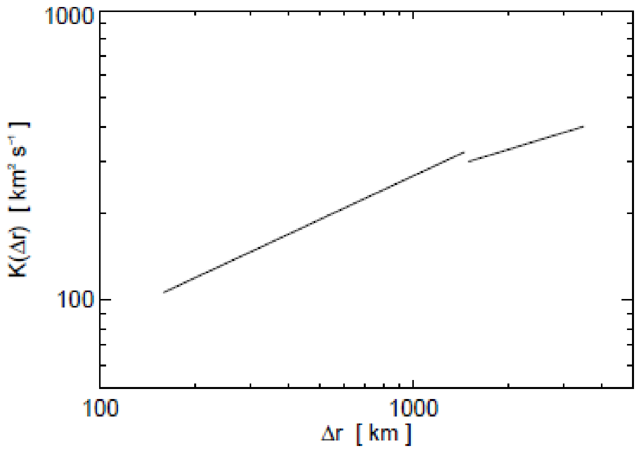


Fig. 4.— Displacement spectrum for all the 16925 magnetic elements far from the boundaries tracked in the field of view. The dashed line fits the data points up to ∼ 2000 s; the solid line fits the data points up to ∼ 10000 s.



Giannattasio et al. 2013

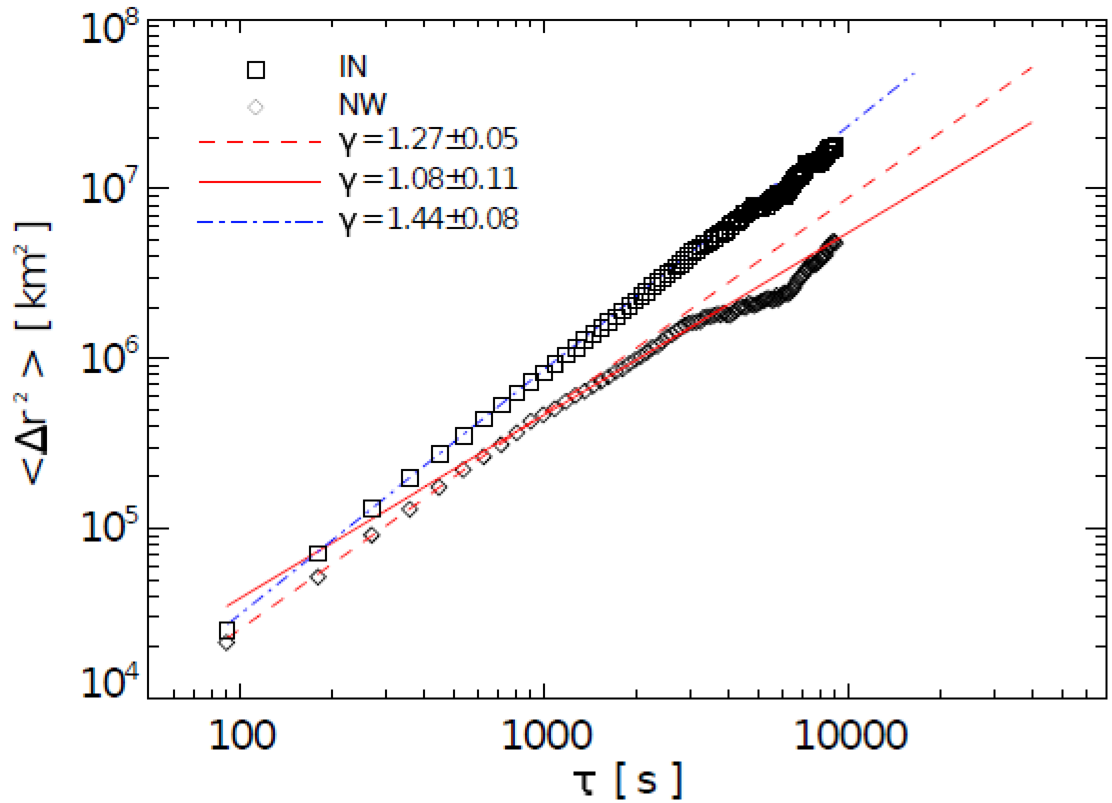
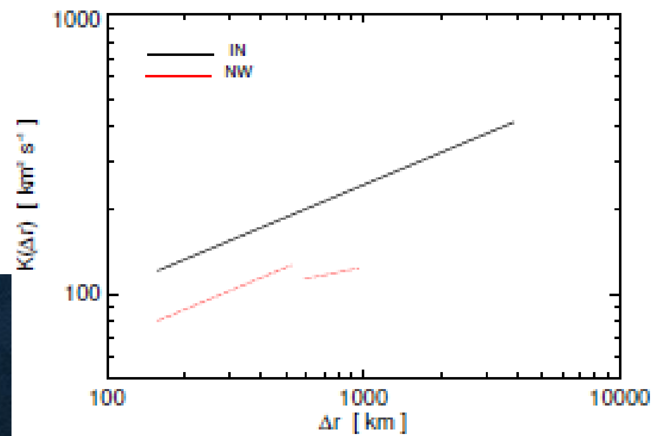


Fig. 2.— Displacement spectrum for IN (black squares) and NW (black diamonds) magnetic elements. The blue dash-dotted line fits the IN data points. The red lines fit the NW data points for $\tau \lesssim 600$ s (dashed line) and $\tau \gtrsim 600$ (solid line).



“the lower diffusivity of magnetic elements in NW regions allows to amplify more easily the magnetic fields therein”

Giannattasio et al. 2014a

Diffusion coefficients you may use:

~500 km^2/s for large scales (depending on B strength)

<10 km^2/s for small scales

"The diffusion coefficient value depends on the scale and the position"

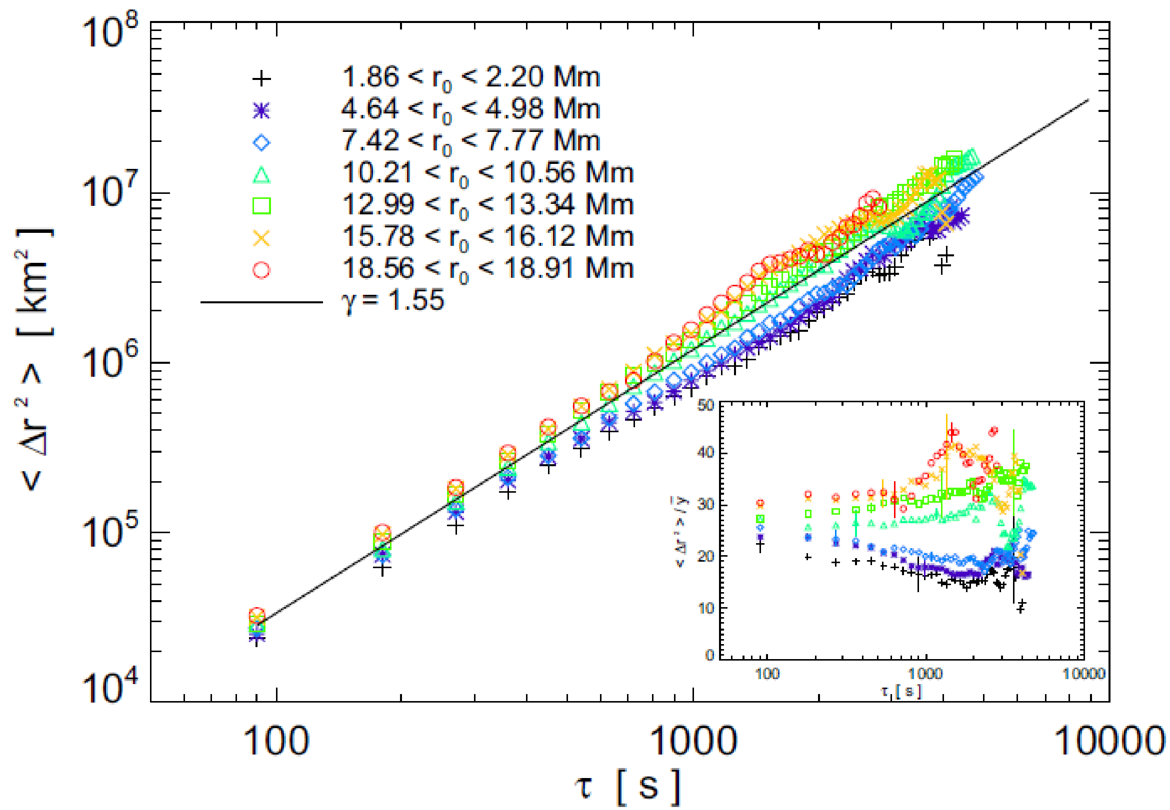


Fig. 4. Mean square separation $\langle \Delta r^2(\tau, r_0) \rangle$ for seven different and equally spaced values of r_0. The black solid line corresponds to the fitting curve $\bar{y}$ of Fig. 2. In the *inset* the compensated mean square separation $\langle \Delta r^2(\tau, r_0) \rangle / \bar{y}$ is shown. The errors (vertical bars) are shown only for a few data points.

Giannattasio et al. 2014b