Testing the Gallavotti-Cohen Fluctuation Theorem on the Solar Photosphere

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ABSTRACT

The understanding of fluctuations in systems far from equilibrium is one of the key issues of non-equilibrium statistical thermodynamics. The Fluctuation Theorem of Gallavotti and Cohen (1995) [GCFT] portrays some symmetry features of entropy production rate and deviations in non-linear and far from equilibrium regime. In this framework, the turbulent solar convection, observed in the photosphere and viewed as a dissipative non-equilibrium system near a steady state, provides an incomparable laboratory where to attempt a test the GCFT. In fact, solar convection flows emerge in the photosphere in terms of a structured pattern: the granulation. High resolutions spectro-polarimetric data acquired with Interferometric BIdimensional Spectropolarimeter (IBIS) instrument installed at the Dunn Solar Telescope (DST) are used to perform this analysis. Here, we present a preliminary analysis of the validity of the GCFT in the solar convection field. The statistical features of entropy production rate, which is at the core of the irreversibility, is estimated through the vertical heat flux. The vertical heat flux along the line of sight (LOS), in its turn, is evaluated using temperature and LOS velocity map obtained with spectro-polarimetric inversion using the NICOLE code and with the simplest center of gravity method.

THEORETICAL BACKGROUND

Linear thermodynamics of non-equilibrium predicts that in systems close to the equilibrium there is a spontaneous production of entropy:

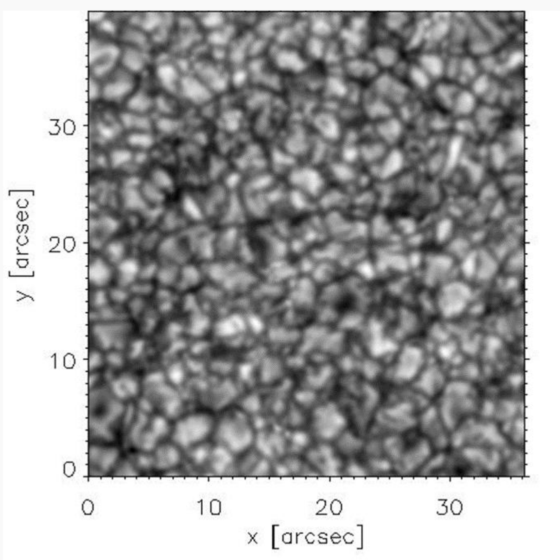
$$\sigma(\vec{r},t) = \sum_i J_i(\vec{r},t) X_i(\vec{r},t) > 0$$

When the fluctuations occur in a dissipative non-equilibrium and steady states, the GCFT can be written:

$$\lim_{\tau\to\infty} \frac{1}{\tau} \ln \frac{\pi_\tau(+\sigma)}{\pi_\tau(-\sigma)} = \sigma$$

DATASET and PRELIMINARY ANALYSIS

To perform this analysis, we make use of high resolution **spectro-polarimetric data** acquired on November 21th 2006 with the Interferometric Bidimensional Spectropolarimeter (IBIS) instrument installed at the Dunn Solar Telescope (DST), located at National Solar Observatory (Sacramento Peak, New Mexico). The extracted maps of the line-of-sight velocity and temperature has a resolution of 120 km (corresponding to 0.17 arcseconds), on a field-of-view of 35x35 Mm^2 on the solar surface, a time resolution of 89 seconds and spanning approximately one hour.



The solar surface convection is a good example of turbulent regime and the entropy production rate can be evaluate from the vertical heat flux:

$$\sigma(\vec{r},t) \approx v_0 j_z(\vec{r},t) \nabla_z \left(\frac{1}{T}\right)$$

The vertical heat flux, used as a proxy of the entropy production rate, is computed from line-of-sight (LOS) velocity maps and temperature maps:

$$j_z(\vec{r},t) \approx v_{LOS}(\vec{r},t)\,\delta T(\vec{r},t)$$

$$\delta T = T - T_0$$

To improve the statistics of our data, we compute a running average of j_z over different time intervals:

$$J_\tau(\vec{r},t) = \frac{1}{\tau}\int_t^{t+\tau} j_z(\vec{r},t')\,dt'$$

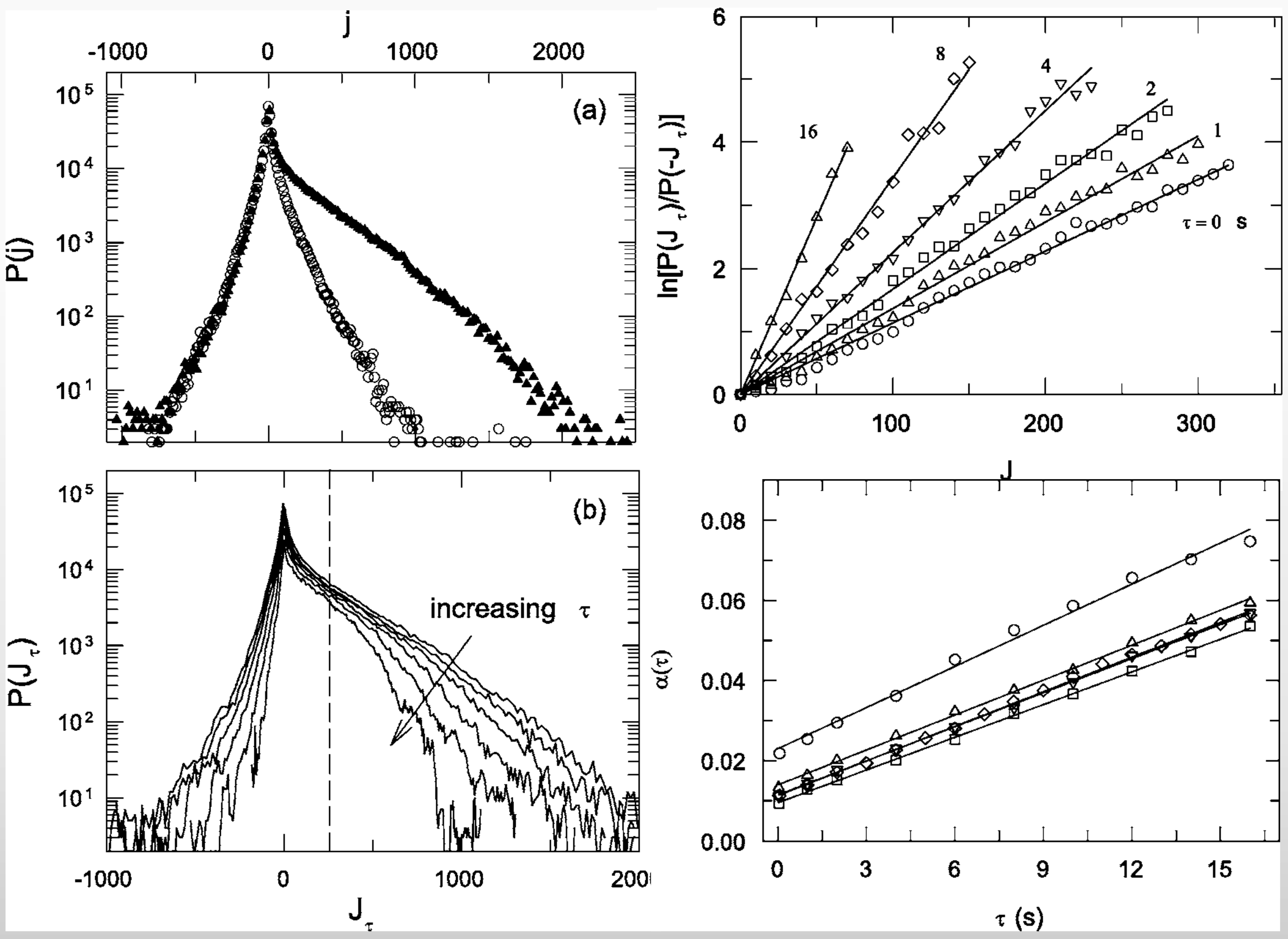
and thus the GCFT becomes:

$$\lim_{\tau\to\infty} \frac{1}{\tau} \ln \frac{\pi(+J_\tau)}{\pi(-J_\tau)} \approx \alpha J_\tau$$

FROM PREVIOUS LITERATURE (Shang et al. 2005)

Nowadays, we achieved a fair knowledge of systems with fluctuation near to the equilibrium, but the statistical properties of the fluctuations far from equilibrium in macroscopic systems, exposed to an external driving force (e.g. temperature gradient), are not completely understood.

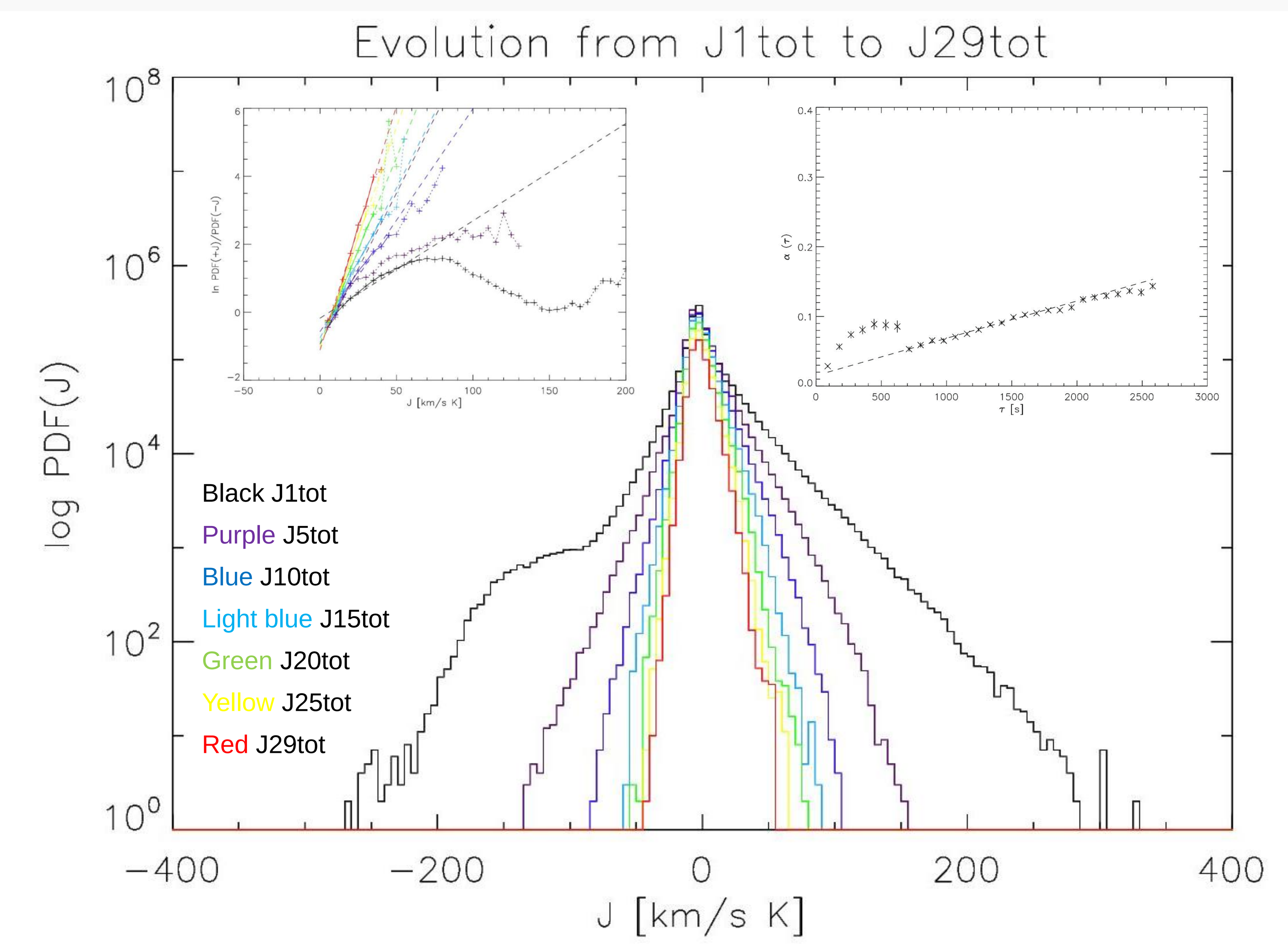
The GCFT has been verified in a **controlled experiment using a cylindrical cell filled with water** (with a Rayleigh number of the order of 10^9) in which a vertical temperature difference is applied.



Here, we present a preliminary analysis of the validity of the GCFT on the turbulent **solar convection** (with a Rayleigh number of the order of 10^{11}), observed in the solar photosphere with low magnetic field flux (B < 50 Gauss).

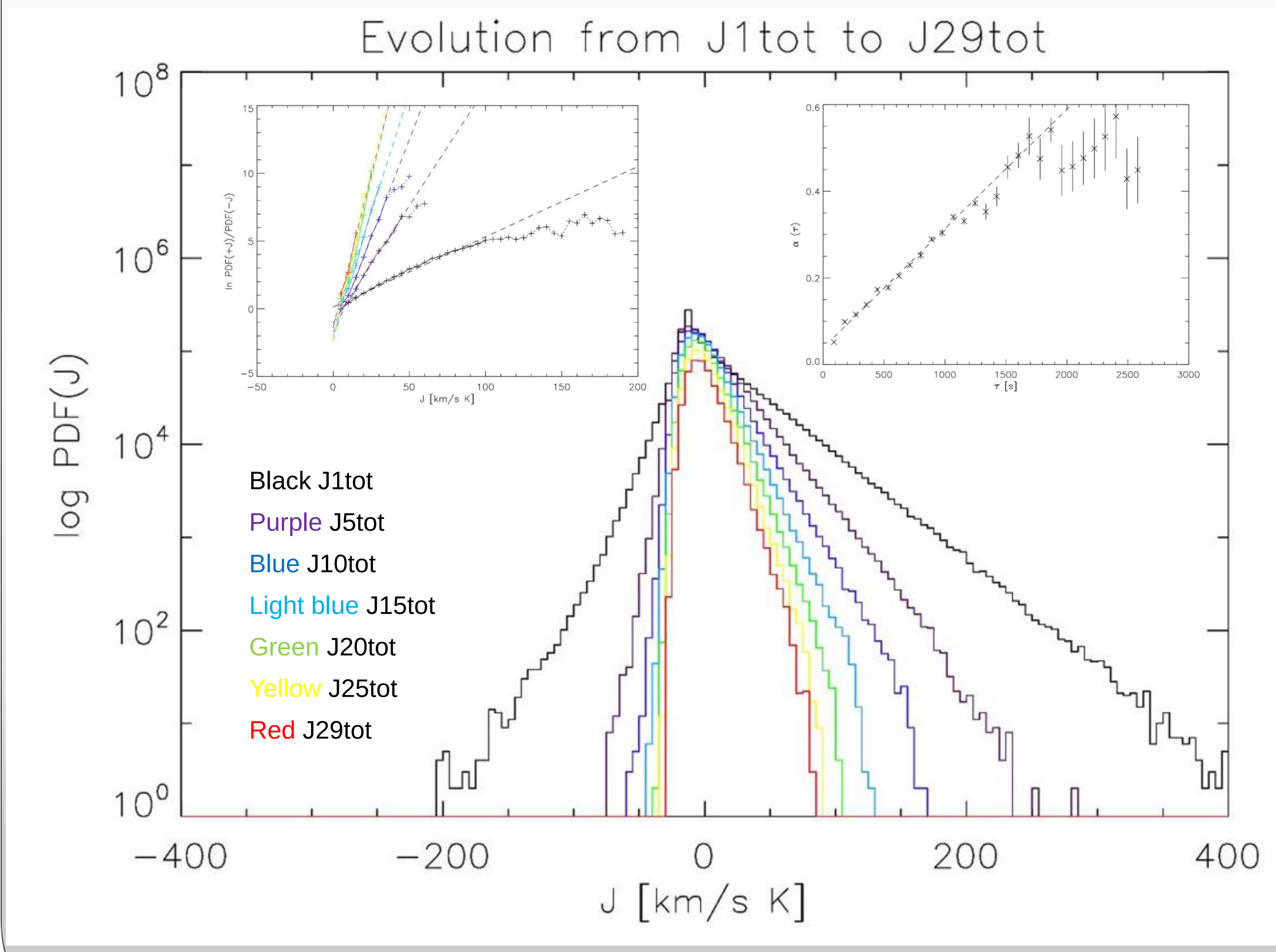
Spectro-polarimetric Inversions

In this case, the LOS velocity and temperature maps have been extracted using the NICOLE (Socal-Navarro, 2015) inversion code.



Center of Gravity Method

In this case, the LOS velocity maps have been computed using the Center of Gravity Method (COG, Rees and Semel, 1979) and the temperature maps have been evaluated from broad band images assuming the black body radiation law.



Conclusion

We tested the validity of the Gallavotti-Cohen Fluctuation Theorem on the solar surface.

We used data prepared with two methods: the NICOLE inversion technique and the center of gravity method.

The coefficients of the linear fit to α(τ) are m=5*10^{-5} and q=0.01 (for the inversions) and m=3*10^{-4} and q=0.04 (for the COG method).

This is the first evidence that the solar convection in quiet solar photospheric regions satisfies the conditions/symmetries of the GCFT for a Non-Equilibrium Steady-State.