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Geosystemics and L'Aquila earthquake of 6/4/2009: a seismological and magnetic approach

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0. Introduction: a systemic approach

When studying earthquakes we take advantage of a new way to see Earth System:

Geosystemics (*De Santis*, 2009) studies Earth system from a holistic point of view (a trans-disciplinary approach): it focuses on relations among parts of the system (in terms of **Entropy**, **Information production and transfer**). In this framework, we expect that **solid Earth** during an earthquake exchanges (both seismic and magnetic) **information** among **most of the parts involved in the process**. We will show here physical patterns of the data and propose a scheme of **integrated forecasting/prediction**.

About prediction

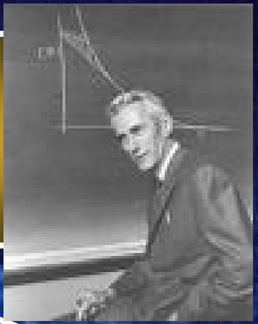
Prediction is very difficult...

...
especially of the future!
(N. Bohr)

...
and it is almost impossible if we do not consider the physics!
(ADS et al.)

Two ways to proceed in predicting a phenomenon:
1) pattern recognition without physics
2) pattern recognition with physics ←

1. The physics behind this work



Claude E. Shannon

Shannon Entropy

$$H(t) = -\sum_{n=1}^{N} p_n(t) \cdot \log\left[p_n(t) \right]$$

Shannon (1948) entropy of a "system" characterized by *N* independent states and a probability distribution $p_n(t)$

Benioff (1949) seismic strain due to an earthquake with magnitude M

$$\Omega(t) = 10^{0.75 M(t) + 2.4}$$

Benioff Strain

Hugo Benioff

Accelerated Strain Release (ASR)

(Varnes, 1989; Bufe & Varnes, 1993)

For brittle materials close to rupture (Voight, 1989):

$$\ddot{\Omega} - a\dot{\Omega}^{\alpha} = 0$$

Ω= strain; a, α= appropriate constants. Solution: $\Omega = \Omega_0 / \left(t_f - t\right)^{1-m}$

We can remove singularity considering the cumulative Benioff strain:

$$s(t) = \int \Omega dt = A + B\left(t_f - t\right)^{m}$$

$m \approx 0.3$

Approaching the main shock, a seismic sequence shows a power-law acceleration of the crustal seismic strain release depending on the time t_f

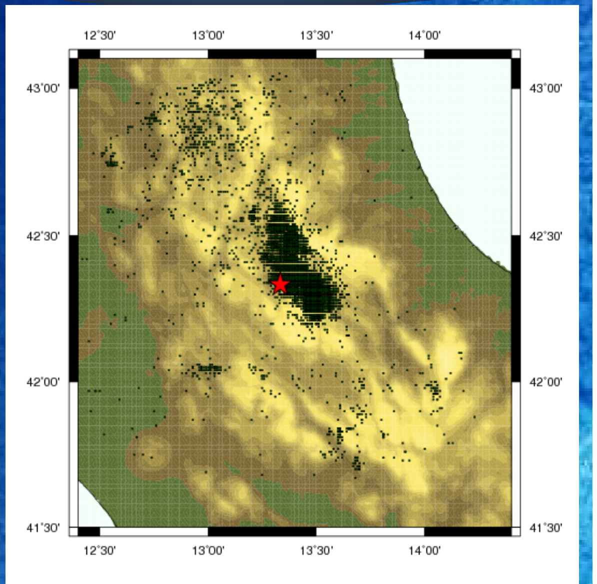
Critical points: inversion instability (it is better to impose some parameter, e.g. *m*); ASR provides a prediction of A,B,*m*, t_f even with no main shock; Bias in retrospective analyses

2. A case study: L'Aquila M_w=6.3 earthquake

Geodynamics
Central Apennines as broad and complex system of normal faults

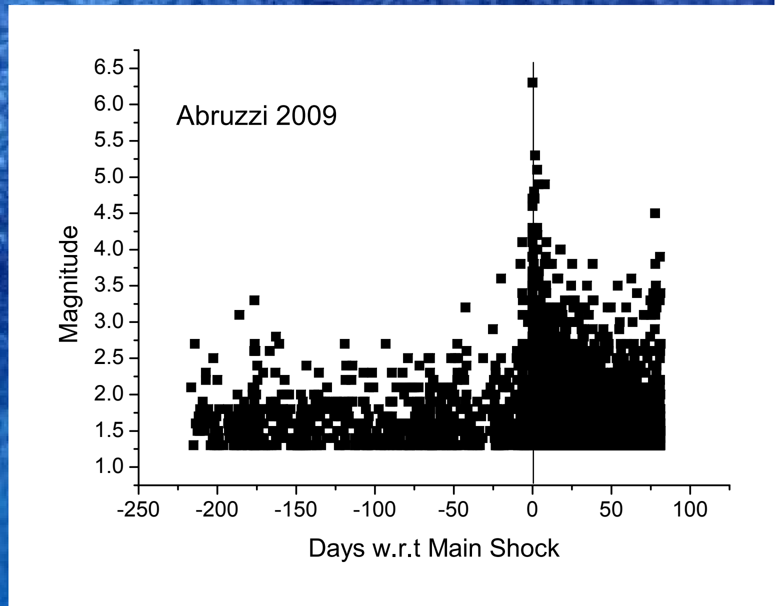
Seismic sequence and main shock

Spatial epicenters distribution



Main shock Source Parameters

6 Apr. 2009
M_w=6.3
01.32 GMT
42.35°N 13.38°E
Depth 9.5km



3. Seismic data analyses

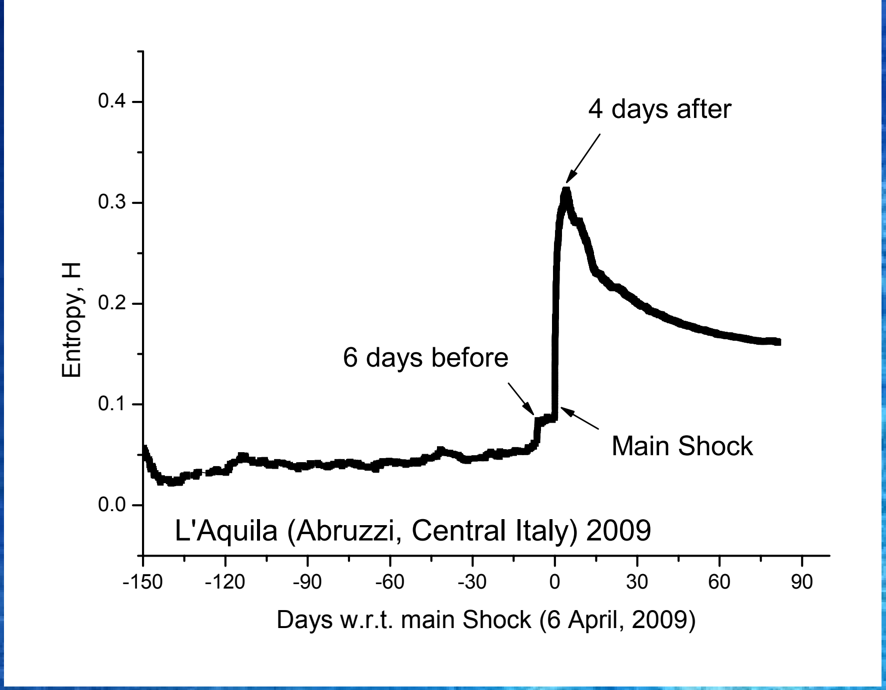
3.1 Shannon Entropy of Earthquakes

If we consider the earthquakes in a given region where the Gutenberg-Richter (GR) law is valid, we have a relationship with *b*-value

$$H(t) = k - \log b$$

k=0.072

b= 0.6-1.2 with physical significance



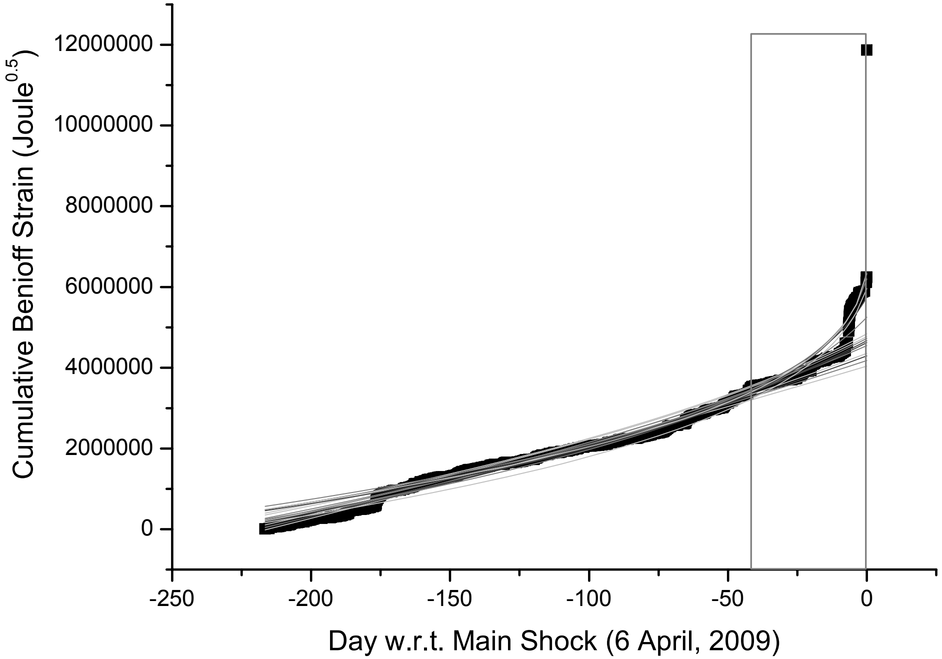
The case of L'Aquila: 3 entropy regimes and Main Shock belong to the main regime starting 1.5 hours before it

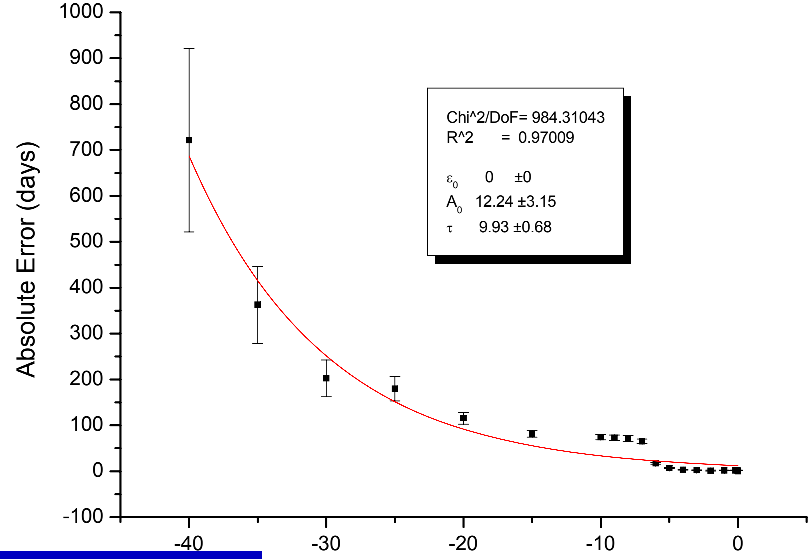
De Santis *et al*., submitted to BSSA

3.2 ASR and CHAOS

2009 L'Aquila seismic sequence as a chaotic process

De Santis et al., submitted to Tectonophysics





Exponential time decay of the error is evidence of chaos

But, Is there any magnetic effect involved in the process?

4. Geomagnetic data analyses

4.1 Transfer Function Entropy

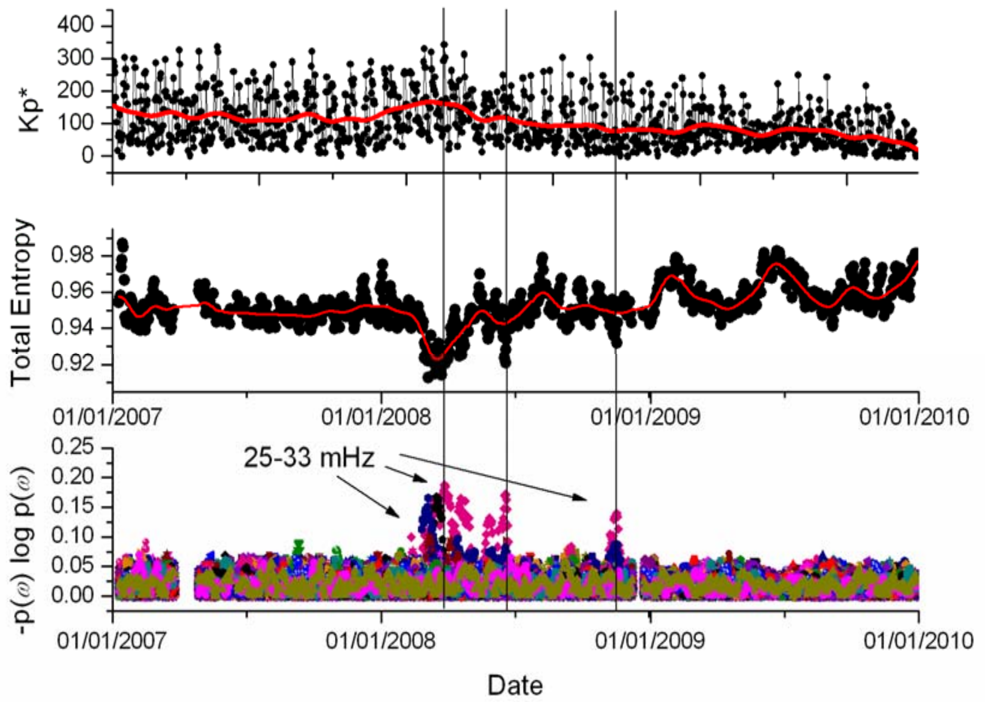
Z(ω) = *A(ω)* X(ω) + *B(ω)* Y(ω) **A(ω), B(ω)= Transfer functions**

Transfer Function Entropy

$$H_{TF}(t) = -\sum_{n=1}^{N} p_n(t) \cdot \log\left[p_n(t)\right]$$

$$p_n(t) = \frac{E_n}{E_t}; \quad E_t = \sum_n E_n$$

$E_n = n-th$ spectral amplitude



From the background entropy a few frequency contributions emerge at 25-33 mHz (skin depth ≈20 km): do they correspond to the depths activated initially by the seismic sequence? (see Cianchini et al., poster!)

4.2 Accelerated magnetic Strain Release (AMSR)

We expect that, if present, any magneto-tectonic effect is rather small but with large spatial extent. To detect it we compare two observatory time series, *u(t)* and *v(t)*, and define their discordance coefficient:

$$d(t_{day}) = 1 - r_{uv}(t_{day}) = 1 - \frac{\sum_{i=t_0}^{N} (u(t_i) - \bar{u})(v(t_i) - \bar{v})}{N\sigma_u \sigma_v}$$

Then we consider the following quantity :

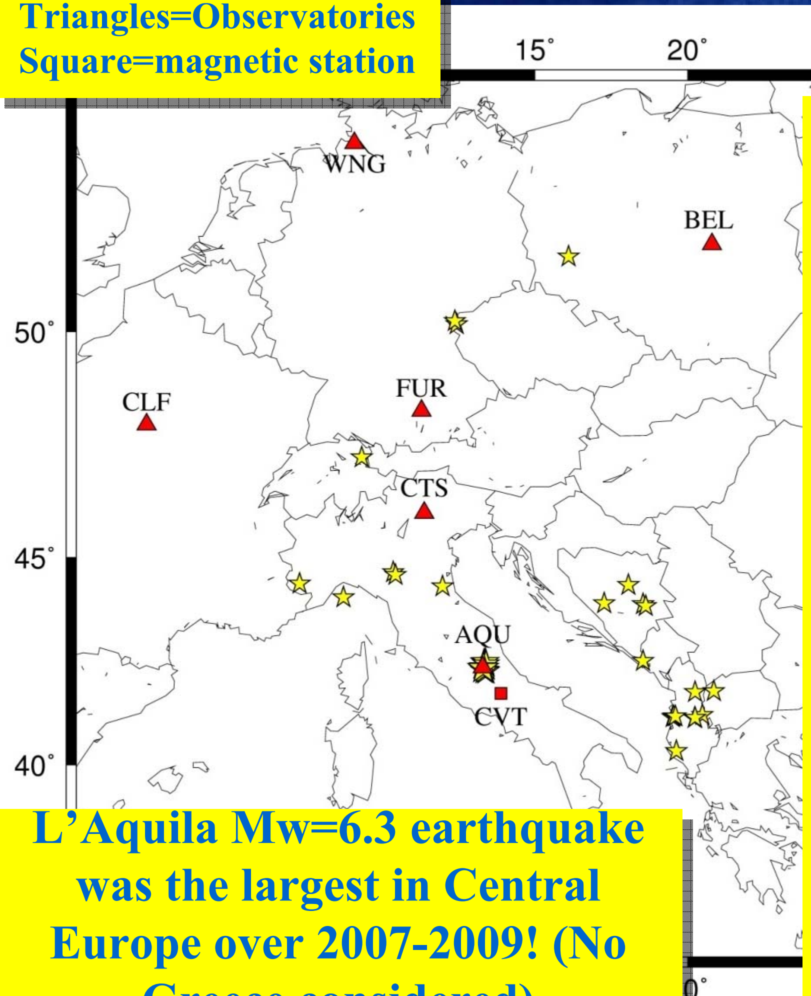
$$s(t_{day}) = \int d(t)dt$$

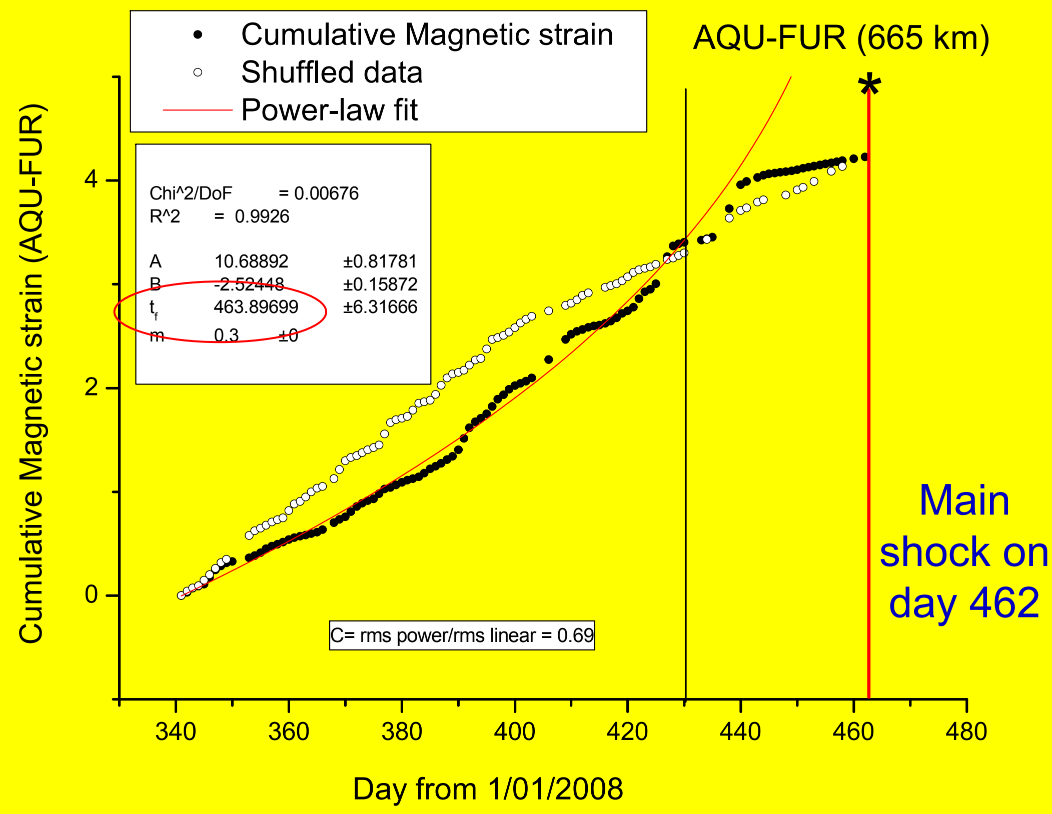
as proportional to the cumulative seismic strain so we call it Cumulative Magnetic Strain

Accelerated magnetic Strain Release (AMSR)

We apply AMSR to ten couples of geomagnetic observatory time series, finding the same power-law pattern

Stars=M>4 earthquakes
Triangles=Observatories
Square=magnetic station

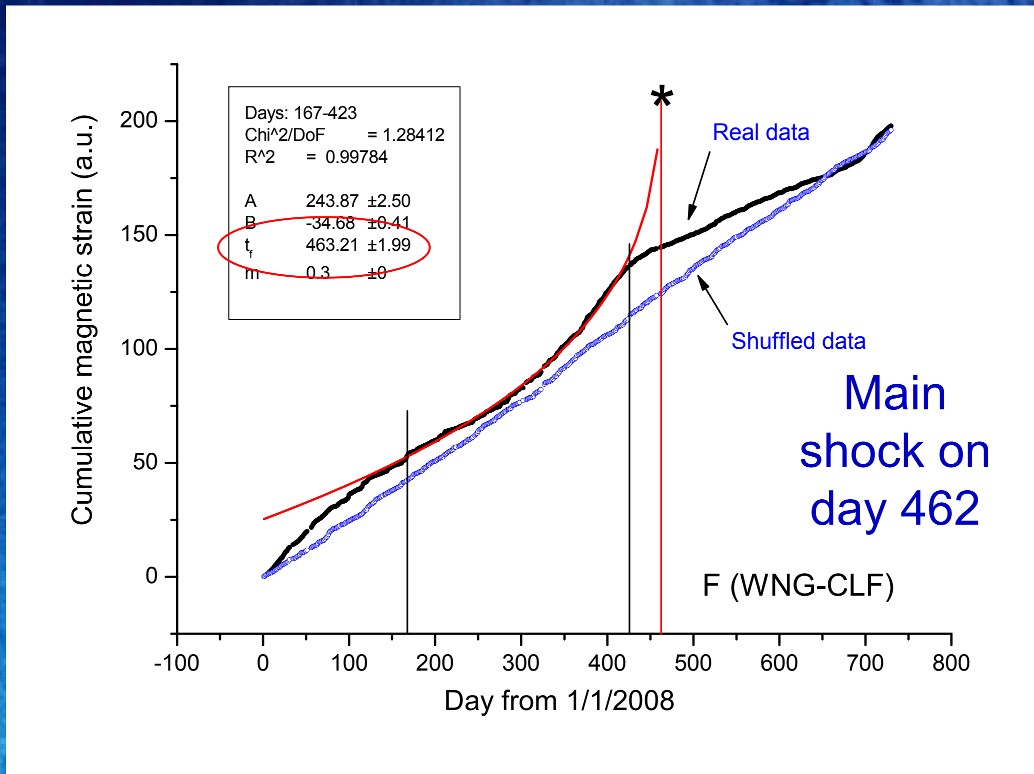




L'Aquila Mw=6.3 earthquake was the largest in Central Europe over 2007-2009! (No Greece considered)

Accelerated magnetic Strain Release

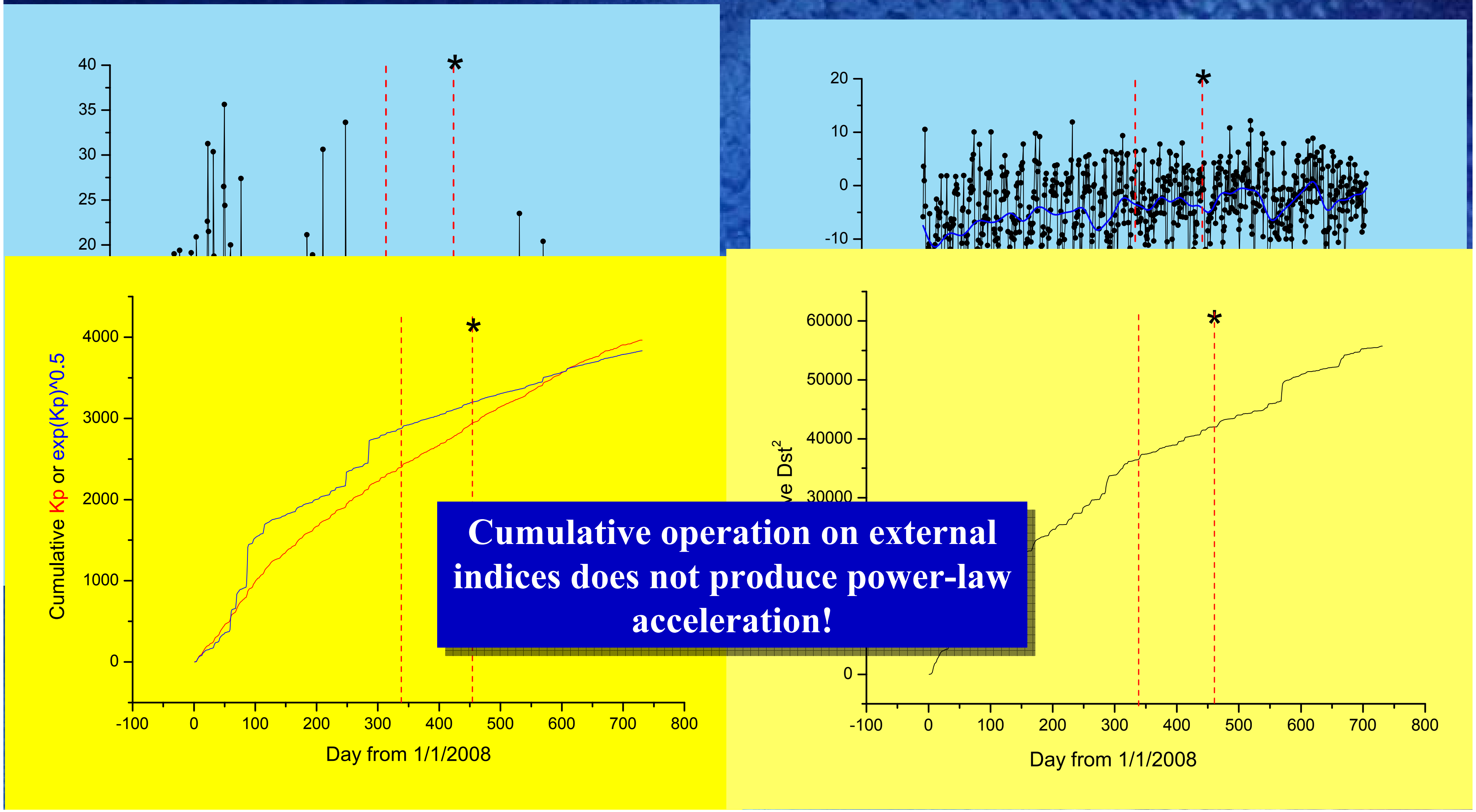
We find acceleration even in two other geomagnetic observatories as indication of a very large spatial extent of the phenomenon



L'Aquila 6/04/2009 earthquake represented the largest shock in Europe in the period 2007-2009 (excluding Greece)

Accelerated magnetic Strain Release

External factors do not contribute to AMSR



Cumulative operation on external indices does not produce power-law acceleration!

5. Conclusions

An integrated seismic/magnetic technique based on the Entropy and on ASR+ Chaos has been applied to seismic and magnetic data of L'Aquila with following results:

1.L'Aquila seismic sequence evolved as a chaotic point process:
ASR+chaos can be a powerful combined strategy to forecast the main shock

2. An analogous magnetic technique (AMSR) has been introduced that shows similar temporal results although no spatial indication is provided

3. Combination of both methods together with Entropy considerations should provide the best results

4. Warning! We learnt a lot from a retrospective modelling, but what would happen with Forward modelling (real forecasting)?

❖ Further analyses are needed on more seismic sequences both in retrospective and (more important!) in **forward (real) forecasting/predictions**!

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