CREDO
Cosmo-Seismic Task Report

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Outline

- Cosmic rays signatures as possible precursors of Earthquakes
- Change points in the data
- Cosmo-seismic correlations
- Machine Learning studies of cosmo-seismic correlations

Bayesian Analysis/Inference

Bayesian analysis is a statistical paradigm that shows the most expected hypotheses using probability statements and current knowledge.
One of the most frequent case is analysis of probable values of model parameters.

Bayes' theorem:

Likelihood Prior

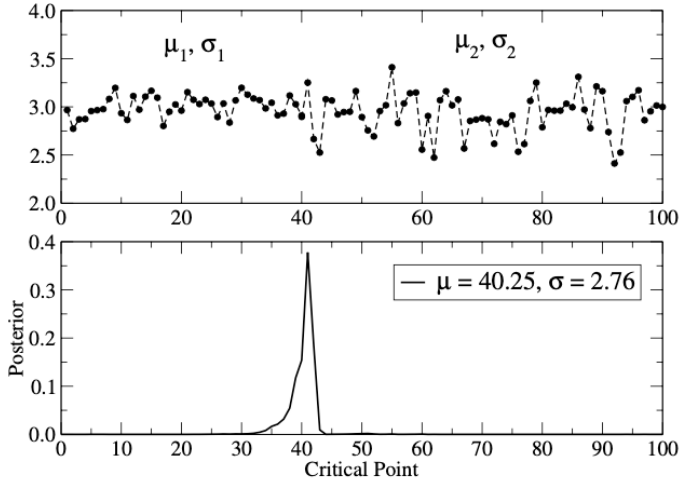
$$p(H_1 \mid D, I) = \frac{p(D \mid H_1, I)\, p(H_1 \mid I)}{p(D \mid I)}$$

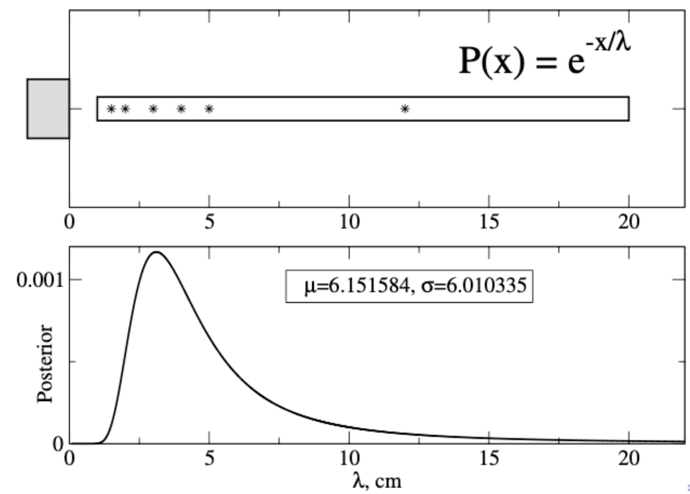
Posterior Evidence

Prior: knowledge before experiment (logically)
Likelihood: Probability for data if the hypothesis was true
Posterior: Probability that the hypothesis is true given the data
Evidence: normalization; important for model comparison

Generally, maximum likelihood (parameters which maximize the probability for data) **does not** give the most likely parameters!!!

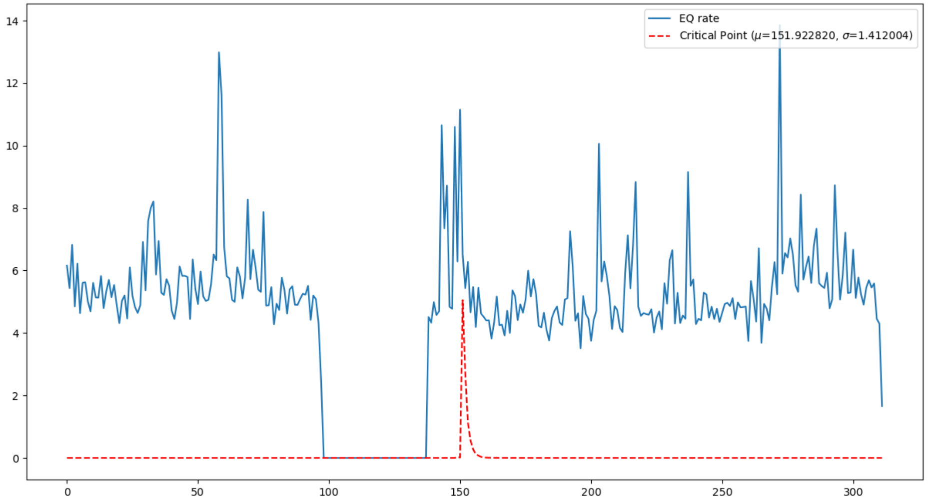
Bayesian Analysis

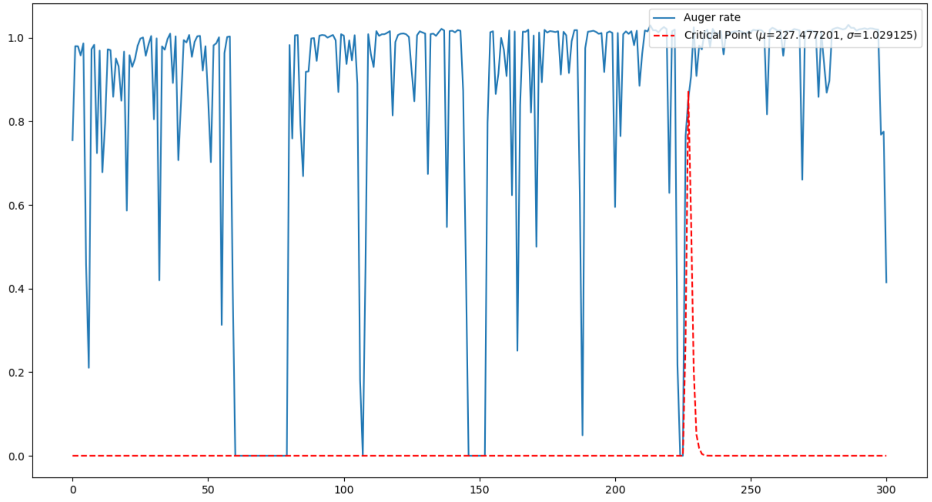




Change Points

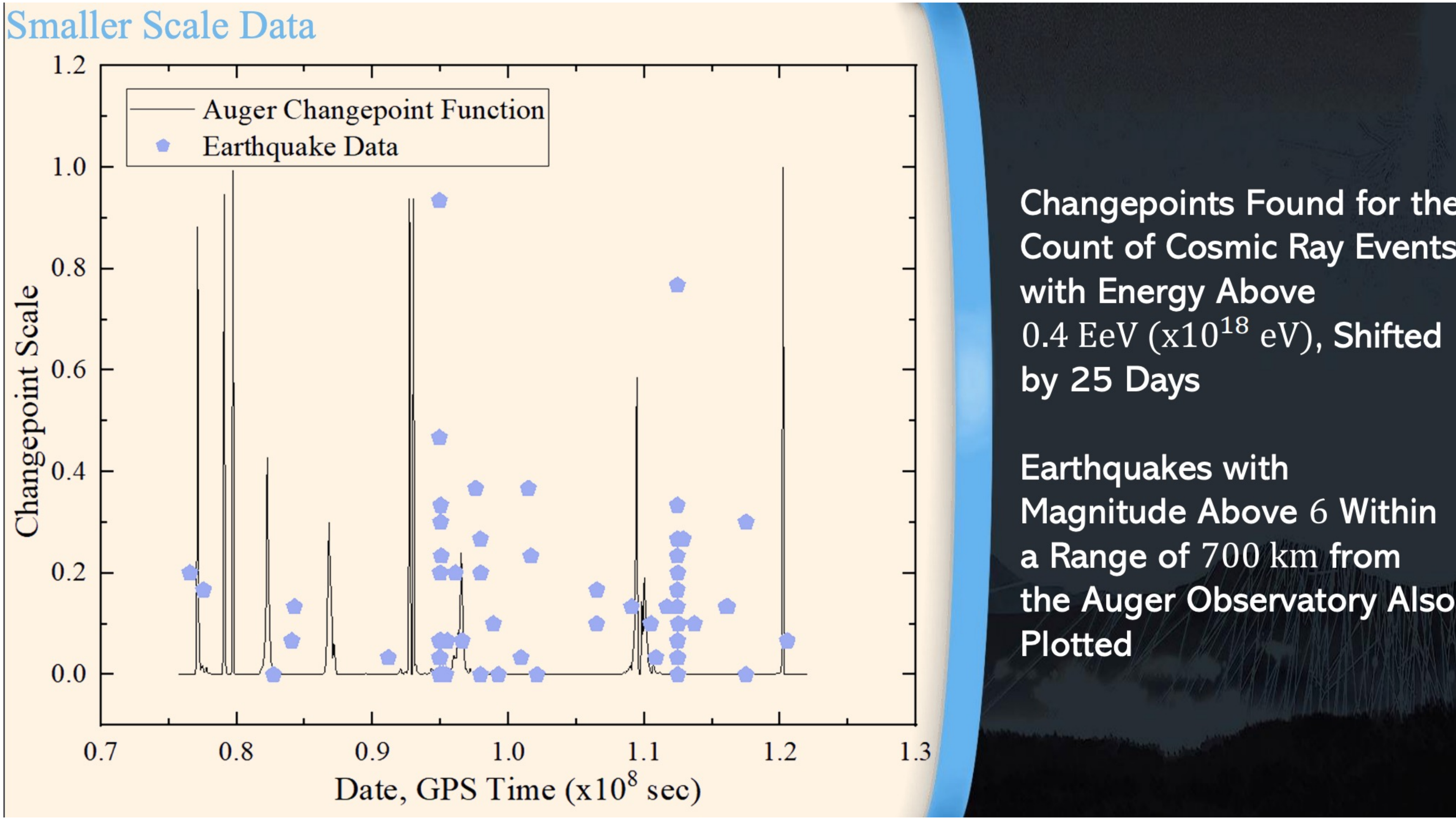
Detected changepoints for EQ rate (left) and Auger rate (right)





Oleksandr Skorenok, Ophir Moshe Ruimi, SSPP (2020)

Change Points



Clementine Mostyn, Bartosz Grygielski, SSPP (2021)

Discrete Fourier Transform:

$$y[k] = \sum_{n=0}^{N-1} x[n] \cdot e^{-2\pi ikn/N}$$

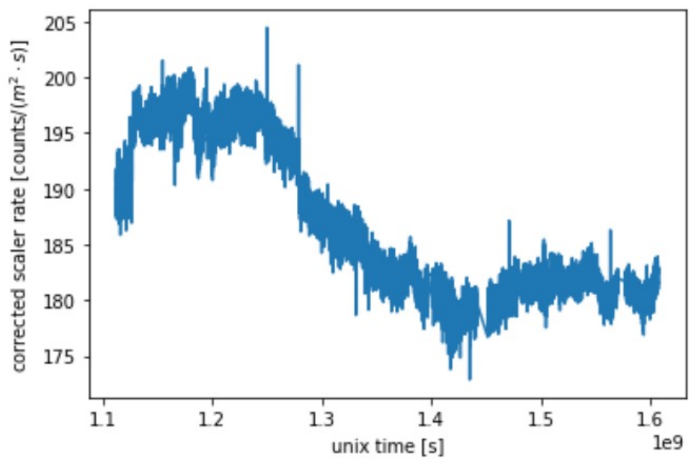


Figure: Cosmic rays data until 5 April 2021

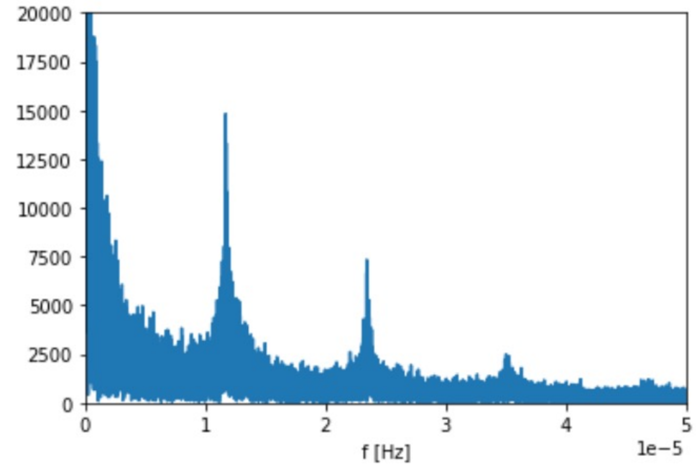


Figure: Fourier transform

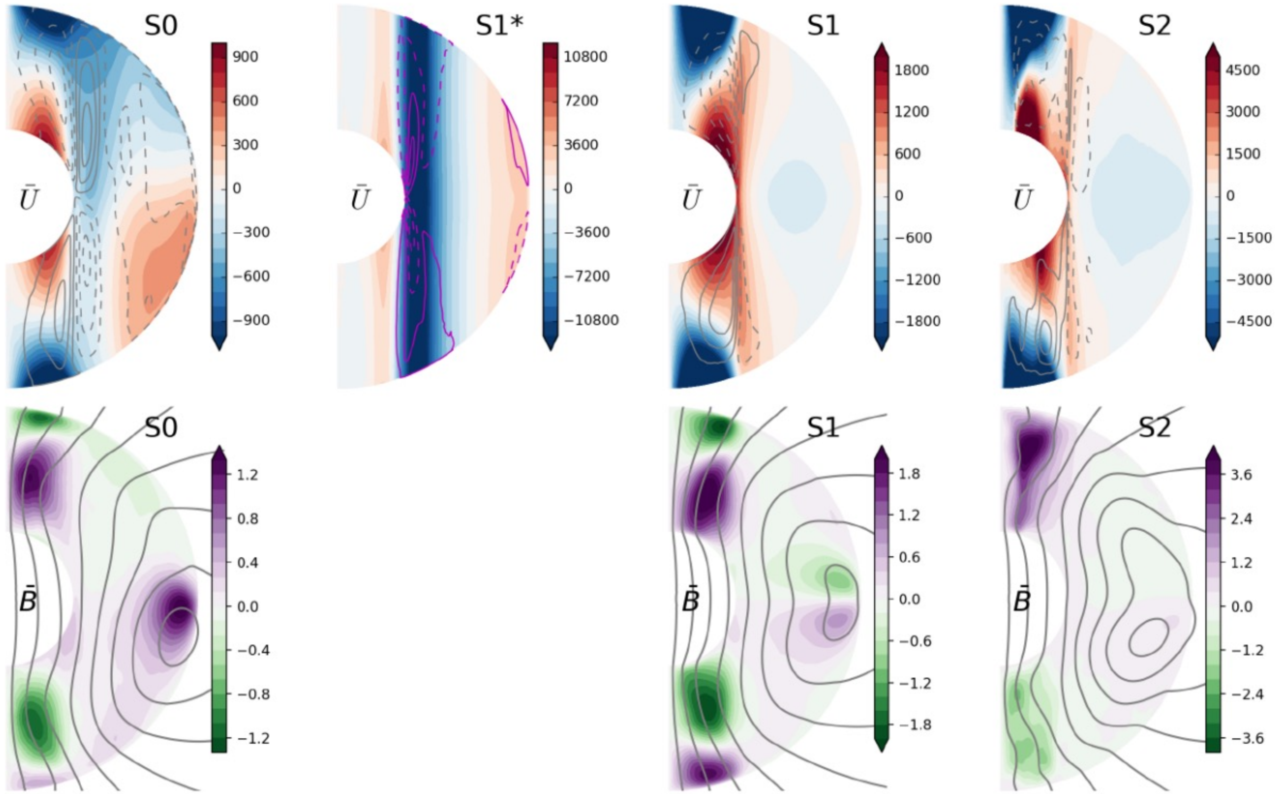
Hypothesis behind this correlation

Fluctuations of the flow of the outer core of Earth*

- The outer core produces the magnetic field of Earth due to its movement. Large earthquakes may be associated with disturbances in the flow of matter that drives Earth's dynamo, which also affects the magnetosphere.
- This change of magnetosphere can possibly have an impact at the rate of the detection of cosmic rays, as it can change their trajectory.

**Hasn't been proved yet*

Hypothesis behind this correlation



Graph: N. Schaeffer, D. Jault , H.-C. Nataf, A. Fournier, 2017. Turbulent geodynamo simulations: a leap towards

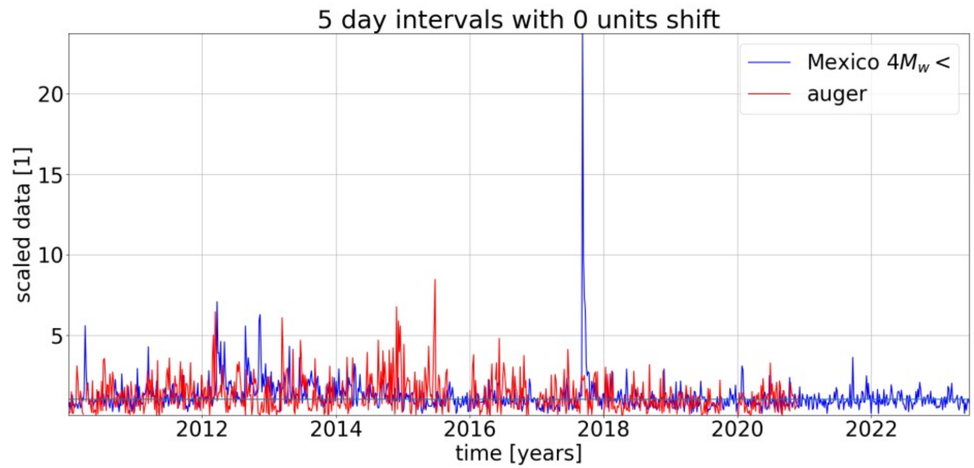
Time and longitude of the velocity and magnetic field of the outer core of Earth in three different simulations

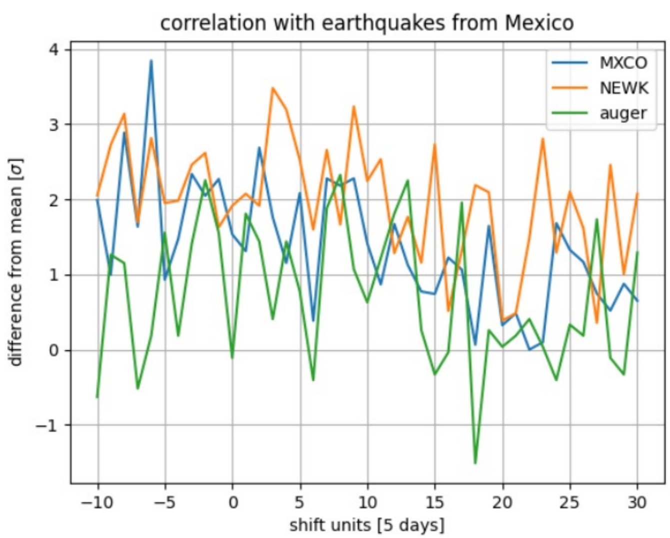
Borbála Farkas, Alexandros Mylonas, SSPP (2023)

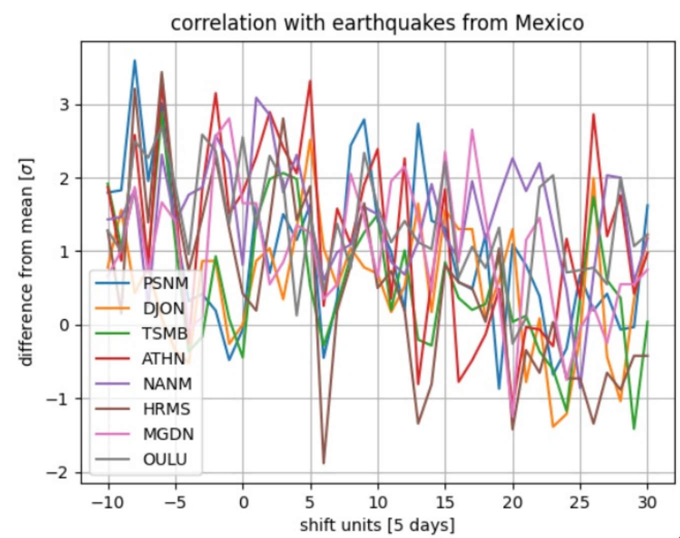
Correlation

Middle America

- 2 NMDB stations
- Pierre Auger
- Chiapas, Oaxaca: $8.2M_w$ 07/09/2017







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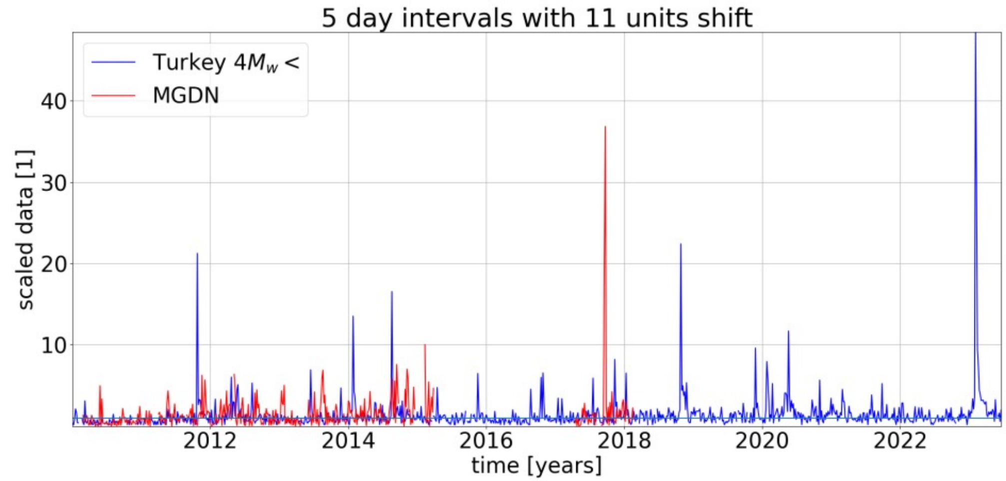
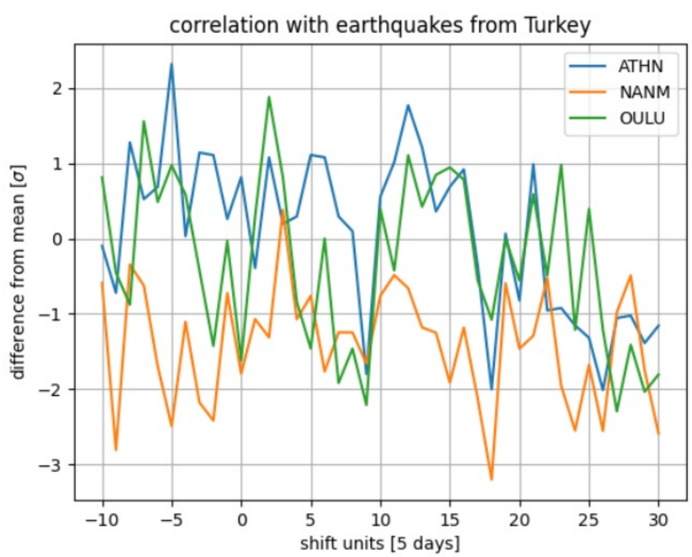
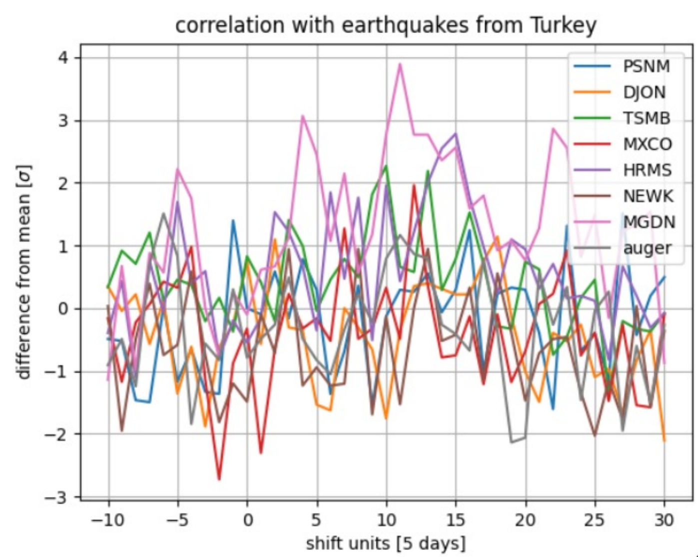
Data

Middle East

- 3 NMDB stations
- Kahramanmaraş: $7.8 M_W$ 6/02/2023







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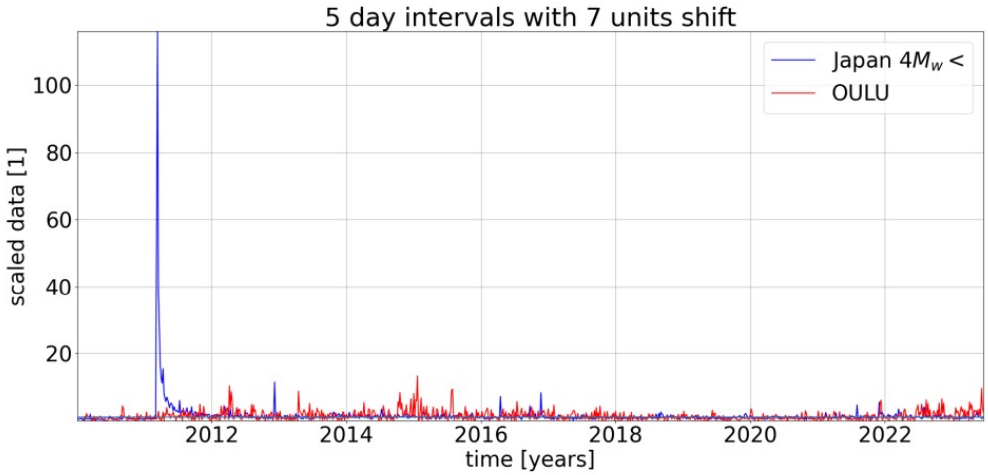
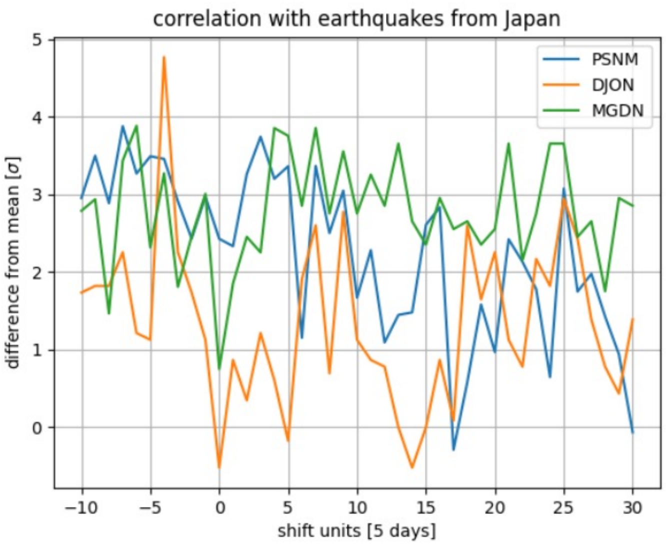
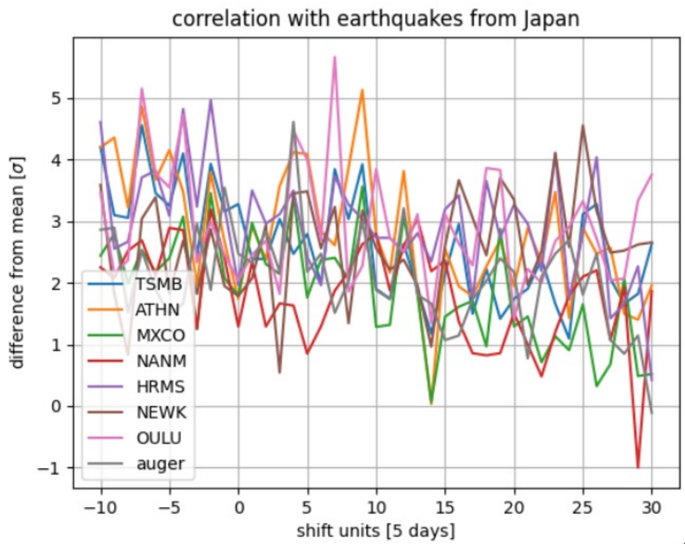
Japan

- 3 NMDB stations
- Tōhoku: $9.1M_w$ 11/03/2011







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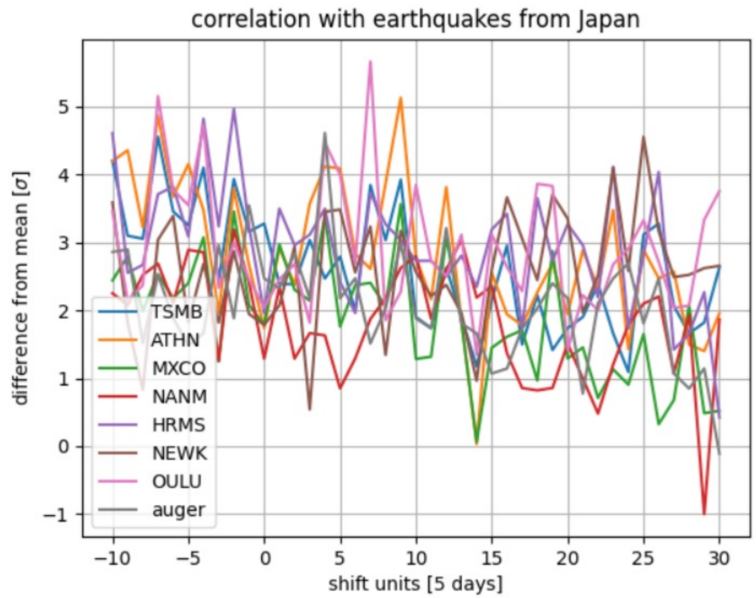
Conclusion and future work

Is the correlation between earthquakes and cosmic rays localized?

- 3 earthquake locations
  11 cosmic ray detectors
- Bayesian changepoint analysis is not applicable
- <u>over 5σ correlation</u> between earthquakes in Japan and Oulu station in Finland
- Other planets: Moon, Mars
- Machine Learning Algorithms for Forecasting Seismic Activity



THE QUEST FOR THE UNEXPECTED

Victor Manuel Velasco Herrera et al., 2022. Long-Term Forecasting of Strong Earthquakes in North America, South America, Japan, Southern China and Northern India With Machine Learning

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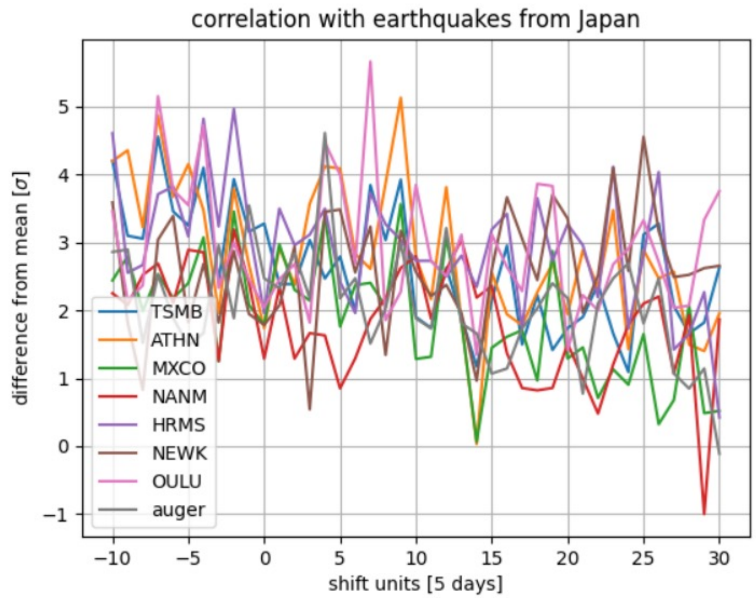

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Earthquake-focused performance

Average Precision (AP) is a commonly used Machine Learning (ML) metric for assessing classifier performance. It's useful for optimization and statistical significance testing but doesn't provide much insight into actual model performance in our context. AP evaluates every individual prediction (made on an hourly basis) without addressing questions such as:

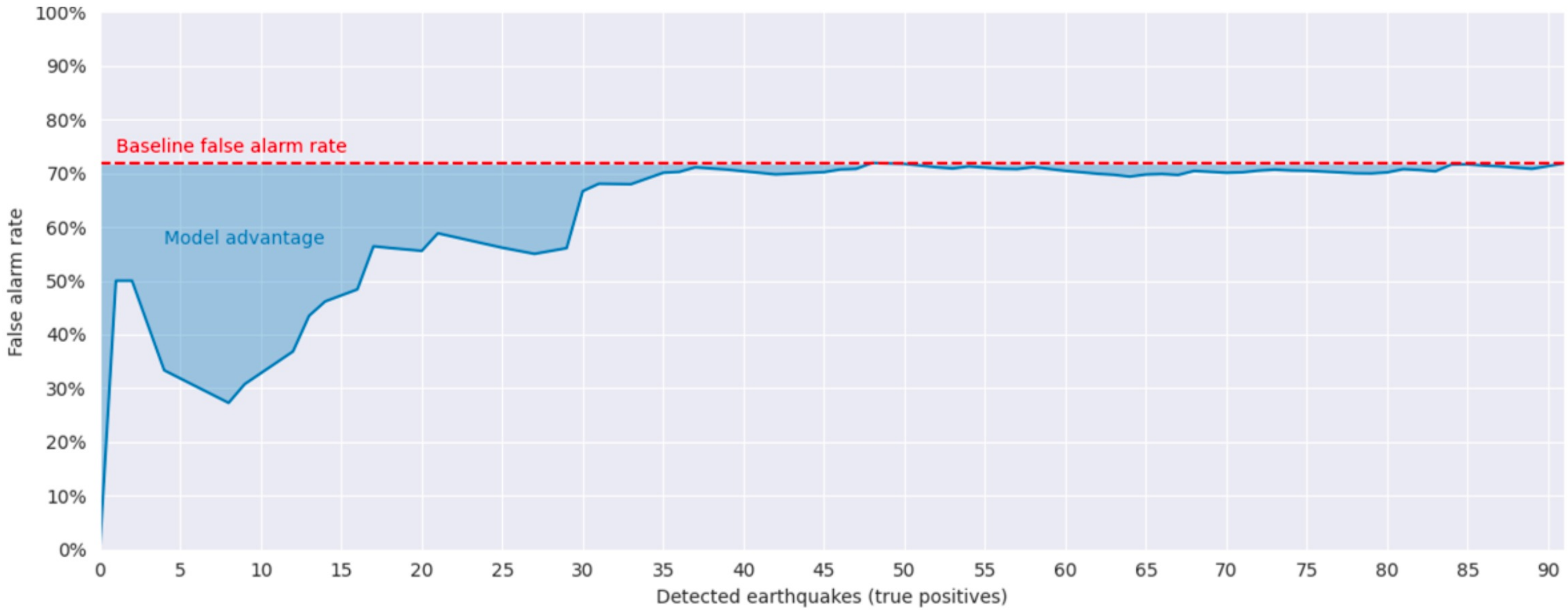
- How many earthquakes can we detect in advance?
- What is the false alarm ratio at a specific "detected earthquakes" level?

Earthquake-focused performance

To answer these questions, we've developed an earthquake-focused metric with these assumptions:

- We count false positives (FP) and true positives (TP) over a 14-day period (forecast horizon).
- A false positive (false alarm) is recorded if any false positive alert occurred within the 14-day period.
- A true positive (detected earthquake) is recorded if any alarm occurred within the 14 days preceding an earthquake.

Earthquakes detection trade-off curve



The baseline false alarm rate is the average false alarm rate expected from a random model.

Noemi Zabari, Kamil Zielinski (AstroTeq.ia, 2024)

Statistical significance test

- 300,000 experiments conducted
- each with a different seed.

- predictions were uniformly distributed random numbers between 0 and 1.
- None of these experiments could exceed the AP performance of the model,
- indicating a strong significance of 6 sigma or more.

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Conclusions

The Machine Learning (ML) approach appears **to confirm** the existence of cosmo-seismic correlation.

While the raw metrics might not seem impressive (AP 0.320 vs 0.288), they could translate into significant real-world effects. It seems we can forecast at least a few percent of massive earthquakes with a decent false alarm rate (below 30%).

- **It's important to remember that earthquakes are currently almost entirely unpredictable.**
- This result could be the **starting point** for more significant findings with the potential to save thousands of lives.

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