Final Plenary Meeting SECURE

Dynamic Planet Project 2023–25

March 11-12, 2026 – Rome, Italy

WP3. Ground Motion Prediction Using Innovative Approaches

WP Leader

Sgobba S.

SECURE — REGIONAL-SCALE EARTHQUAKE GROUND MOTION PREDICTIONS THROUGH PHYSICS-BASED AND EMPIRICAL APPROACHES: A CASE STUDY CENTRAL ITALY

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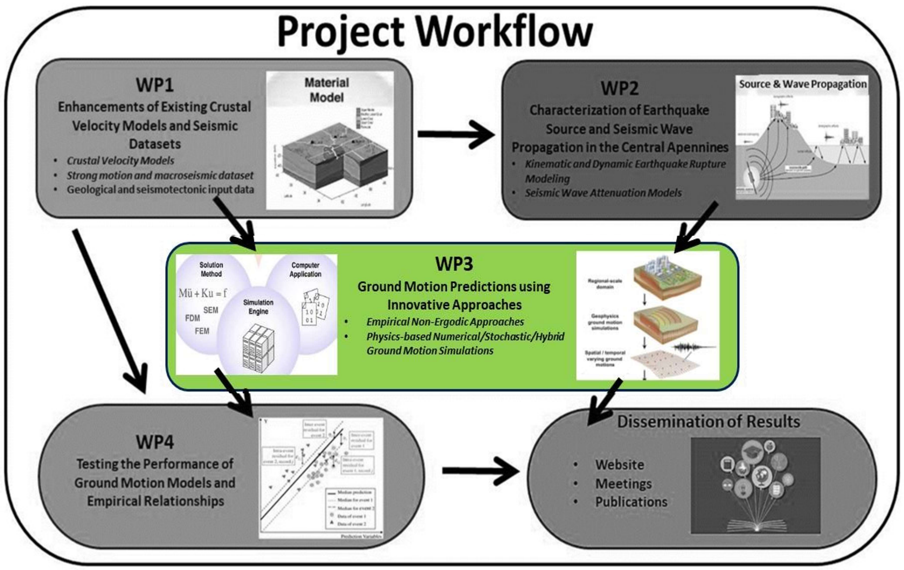
WP3 - Ground Motion Predictions using Innovative Approaches

- **WP3.1 Empirical Non-Ergodic Approaches** (*Sgobba S., Lanzano G., Pacor F., Rovida A., D'Amico V., Antonucci A., Gomez-Capera A., Bindi D., Picozzi M., Spallarossa D.*)
    - **16:30 Sgobba, S.,** Beyond Ergodicity and Stationarity: Advanced Approaches for capturing Spatio-Temporal Variability in Ground Motion Models
    - **16:50 Antonucci, A.**, Intensity Prediction Equations: Performance and Developments

- **WP3.2 Physics-based Numerical/Hybrid Ground Motion Simulations** (*Akinci A., Artale Harris P., Melini D., Munafò I., Pitarka A.*)
    - **17:05 Artale Harris, P./Cuius, A.**, Advancing Physics-Based Ground Motion Simulations through 1D and 3D approaches in central Italy.



PIANETA DINAMICO WORKING EARTH

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REGIONAL-SCALE EARTHQUAKE GROUND MOTION PREDICTIONS THROUGH PYHSICS-BASED AND EMPIRICAL APPROACHES: A CASE STUDY CENTRAL ITALY

Beyond Ergodicity and Stationarity: Advanced Approaches for capturing Spatio-Temporal Variability in Ground Motion Models

S. Sgobba, G. Lanzano, D. Bindi, F. Pacor, D. Spallarossa, M. Picozzi

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WP3 - Ground Motion Predictions using Innovative Approaches

WP3.1 Empirical Non-Ergodic Approaches

SECURE was conceived from the desire to answer the following questions:

- *How should we improve the **ground motion predictions in densely sample region** as central Italy?*

- *Do non-ergodic ground-motion models, including **spatial and temporal non-stationarity**, improve the prediction capability of ground shaking, also during a seismic sequence?*

- *Is it possible to **decrease the variability** by calibrating non-ergodic and non-stationary GMM?*

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Moving to NonErgodic GMMs

Ground Motion Models (GMMs) are Typically Global Averages (**Ergodic Model**)

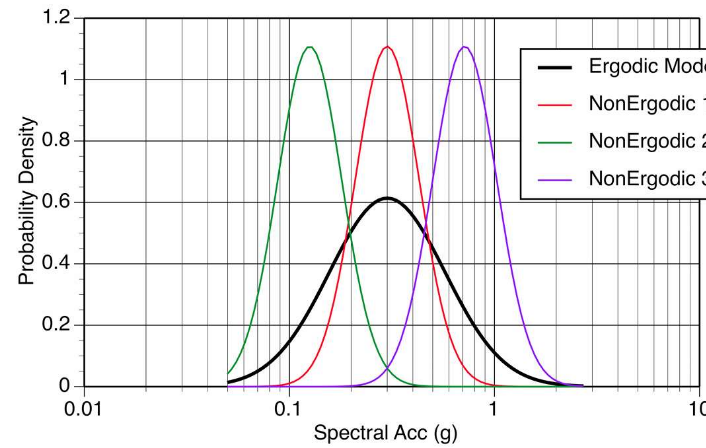
Moving to Non-Ergodic GMMs

Leftover residuals

Epistemic + aleatory variability

$$\mu_{ln\,IM} = \underbrace{[\ \overbrace{ln\,IM}^{\text{Ergodic Median}} + \overbrace{\delta p}^{\text{Nonergodic median}}\ ]}_{\text{Modelled effects}} + \underbrace{[\varepsilon_p, \varepsilon_r]_{\varepsilon}, \quad [\phi_p^2, \phi_r^2]_{\phi^2},}_{\text{Unmodelled effects}} \qquad \sigma = \sqrt{\phi_p^2 + \phi_r^2}$$

$$\delta p = \delta L2L_e + \delta S2S_s + \delta P2P_{es}$$



- Removes the **systematic terms** from the aleatory variability
- Regionalized GMMs terms account for systematic differences in the distance (attenuation), in source (median stress-drop) and location of the site

About 60% of the aleatory variance in ergodic GMMs is due to systematic effects (source, path, site). Epistemic uncertainty increases

From N. Abrahamson presentation

Dataset: N3 Catalogue

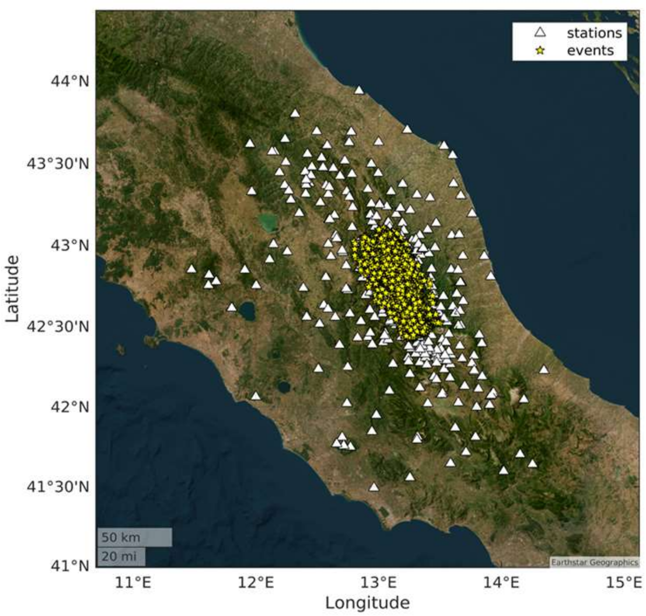
- ➢ **Earthquakes in the Amatrice-Visso-Norcia area from 2006 to 2023 (Spallarossa et al., 2020)**
- ➢ **Relocation of events (improvement of event depth estimation) M_L, M_w estimation by RAMONES (https://distav.unige.it/rsni/ramones.php?lang=it)**

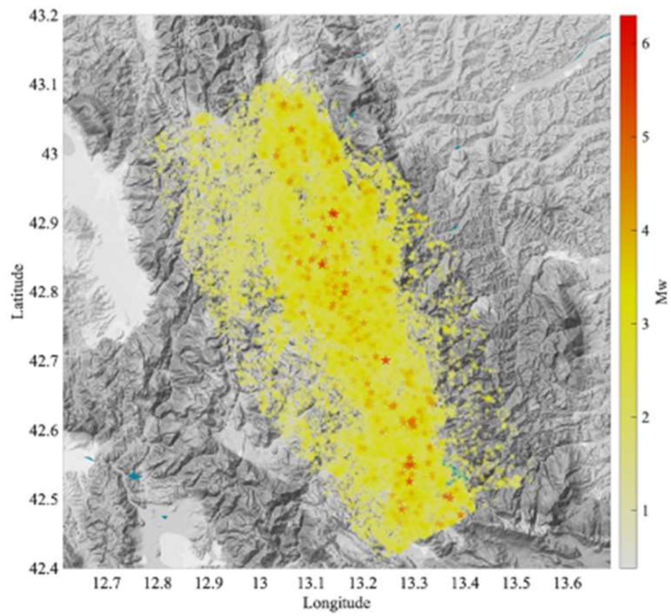
Records: 434.551

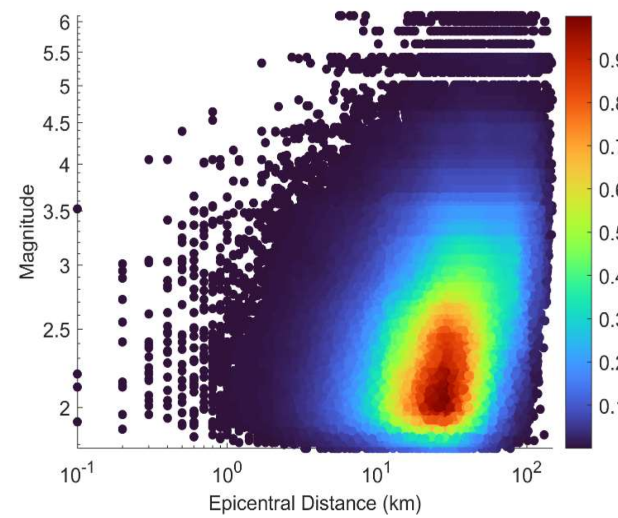
Events: 9.948

Stations: 452

M>1.8







Sgobba et al. (2026) under review BSSA

NENS (NonErgodic Non-Stationary Model)

- The stationary **FAS** model includes **non-ergodic type variability** (dL2L, dP2P, dS2S). Modeling based on **R_{hypo}**
- Nonstationarity with time (*temporal phase*): **1 multi-level nested model**
  → better for comparability and interpretability because fixed-effects remain the same

Modelled effects - fixed-effect functional form for magnitude and distance

$$log_{10}FAS = a + b_1\, M_l + b_2\, M_l^2 + \left[c_1\left(M_l - M_{ref}\right) + c_2\right] log_{10}\sqrt{R_{hypo}^2 + h^2} + c_3\left(\sqrt{R_{hypo}^2 + h^2} - R_{ref}\right) + \delta B_e + \delta S2S_{ref,s}(phase) + \delta L2L_{source}(phase) + \delta P2P_{path}(phase) + \delta W_{esp,0} \quad [2]$$

Unmodelled effects: time-dependent (random effects of the *phase*) for source-cluster, site, and path components

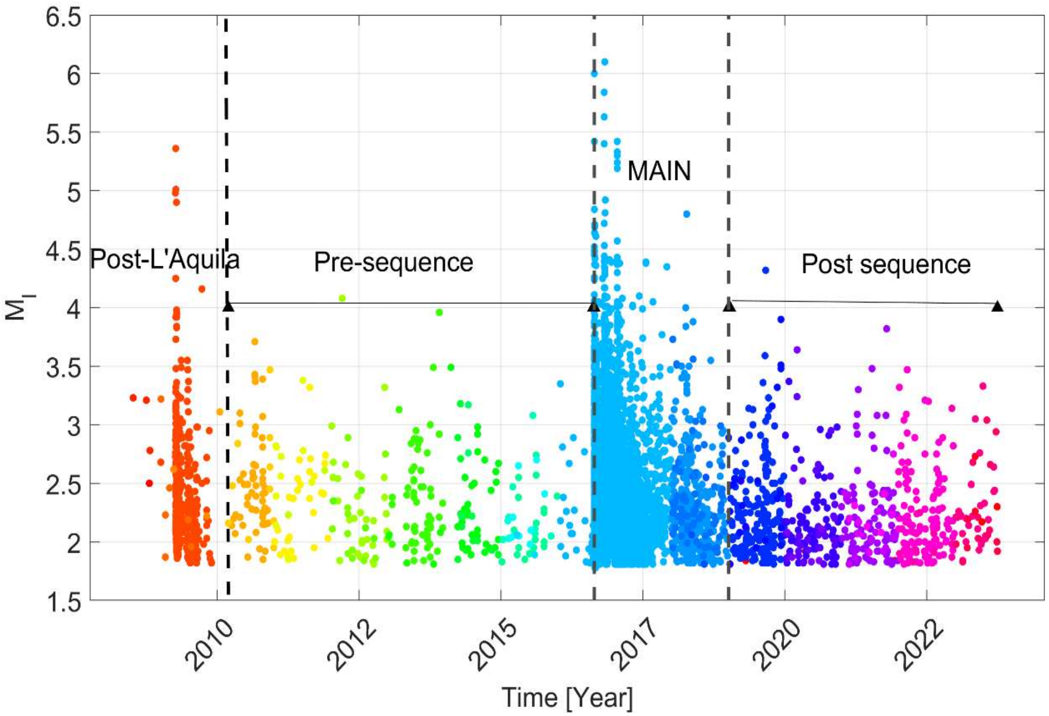
Prediction at 6 reference rock sites!

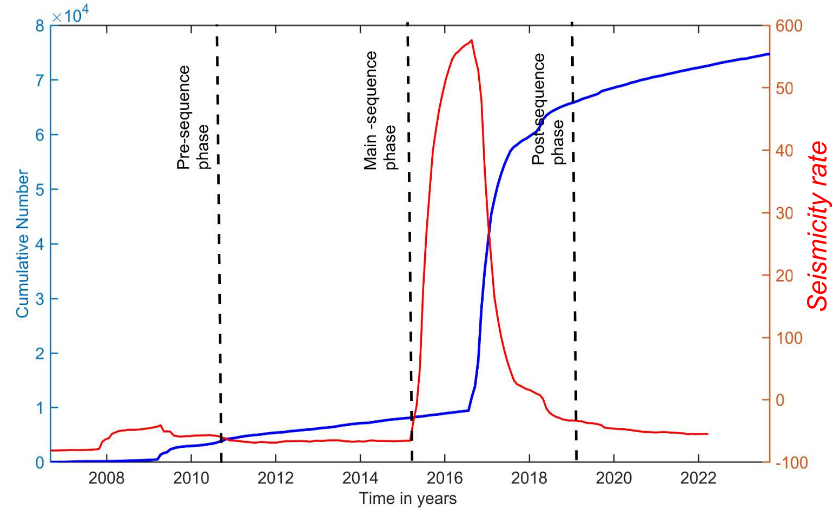
Method

Linear mixed-effect regression with <u>*fitlme*</u> di Matlab

NENS (NonErgodic Non-Stationary Model)

Temporal *phases* identification





<u>Dataset devided in 3 phases:</u>

PRE-sequence

('03/13/<u>2010</u> 18:56:11' - '08/16/2016 19:42:05')

MAIN sequence (Amatrice-Visso-Norcia)

('08/24/<u>2016</u> 01:36:32' - '01/05/2019 23:30:44')

POST-sequence

('01/13/<u>2019</u> 20:29:16' - '10/01/2023 09:38:14')

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Results

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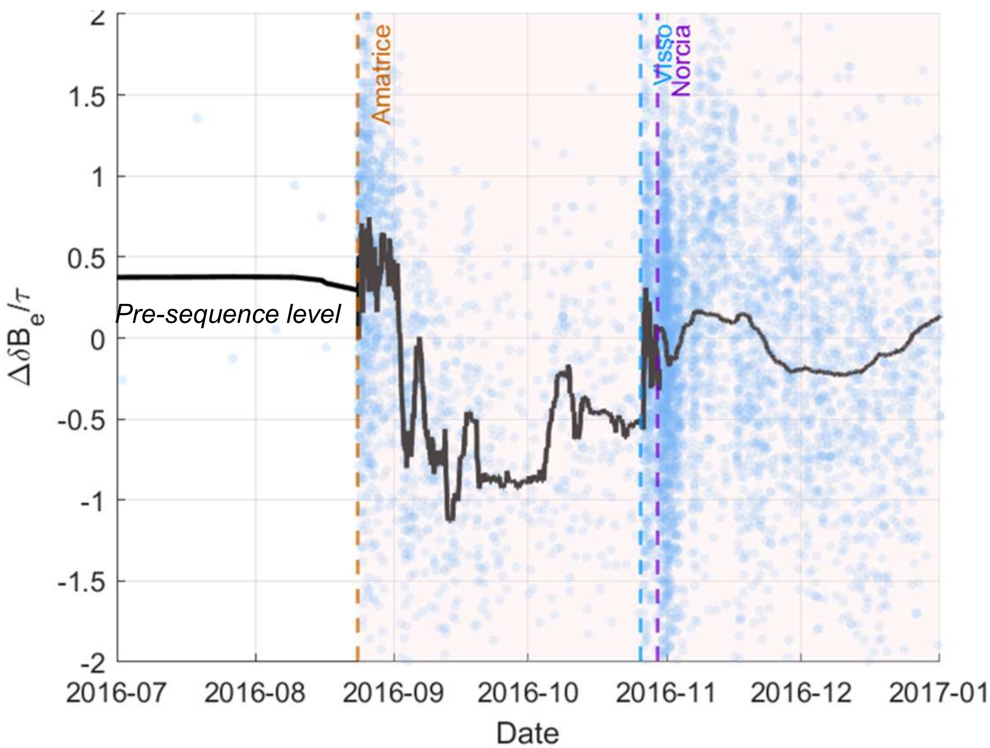
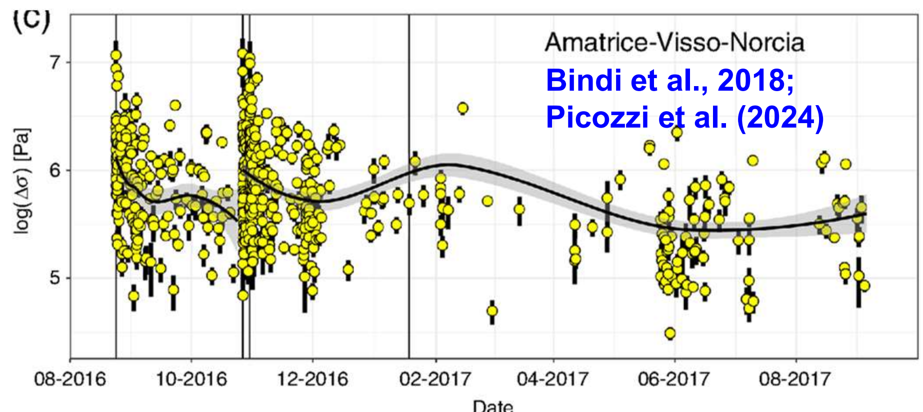
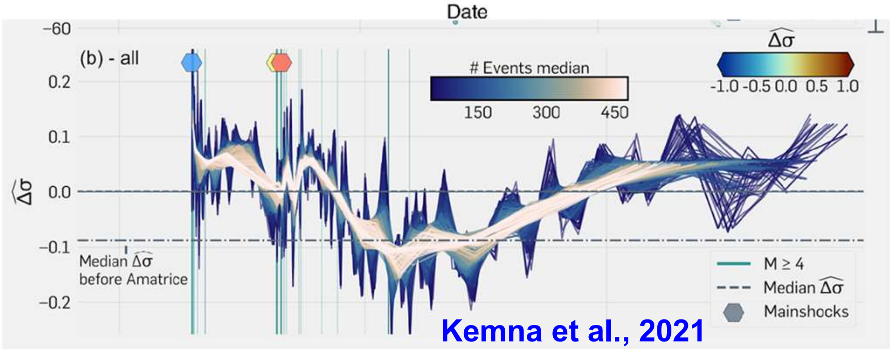
NENS: non-stationarity of δBe

IM ~ 1 + M + MlogDIST + logDIST + DIST + flag + M^2 + (1 | eventi) + (**1 | site:** phase) + (**1 | source:** phase) + (**1 | path:** phase)

20 Hz







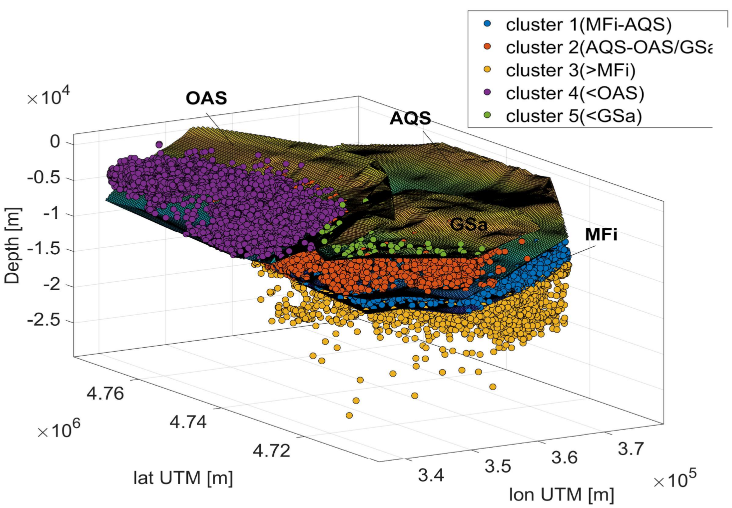
Several authors observe sudden decrease in the apparent stress observed in the aftershocks of main events

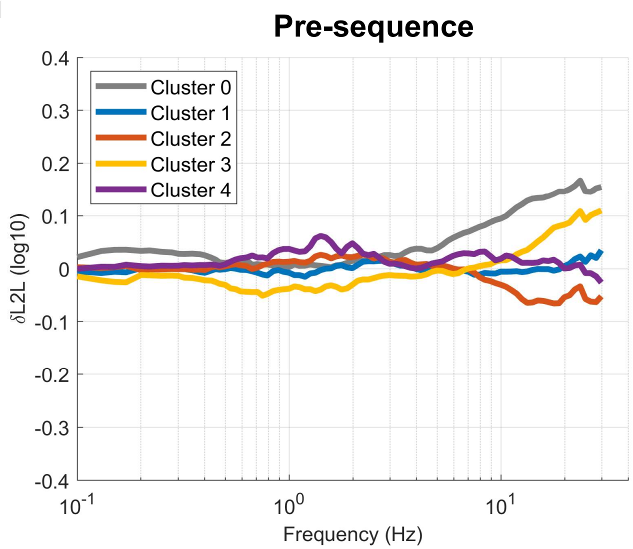
spectral content differed from typical crustal events, especially in the higher frequency range → reduction of ground motion at HF in sequence's earthquakes

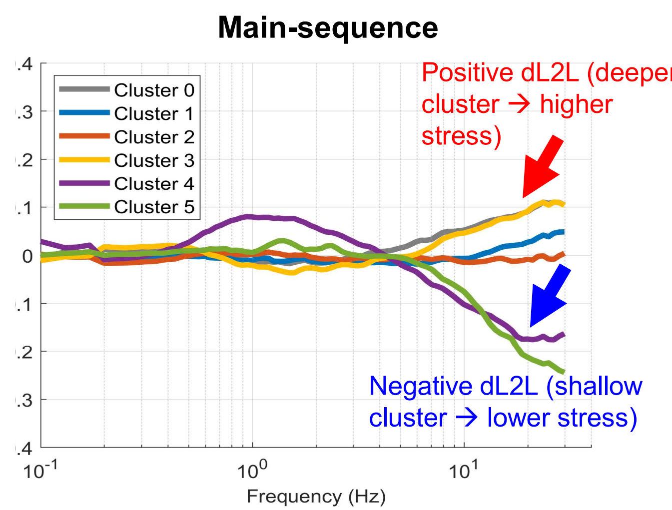
NENS: non-stationarity of location terms δL2L

IM ~ 1 + M + MlogDIST + logDIST + DIST + flag + M^2 + (**1** | **eventi**) + (**1** | **stazioni:** phase) + (**1** | **source:** phase) + (**1** | **path:** phase)

Random effect on the area source based on 3D zonation and geologically-informed clustering provides more realistic source and propagation contributions; *Sgobba et al. 2026 under review*





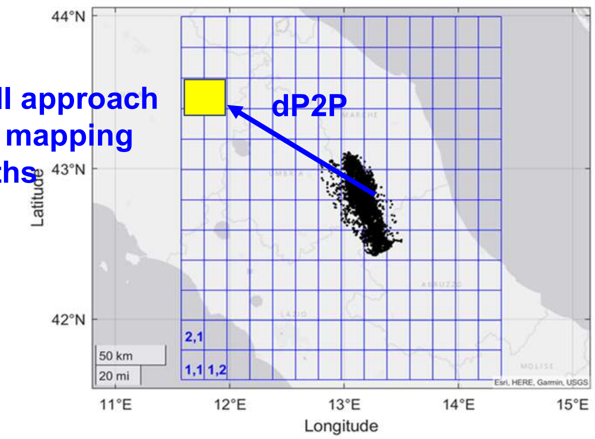


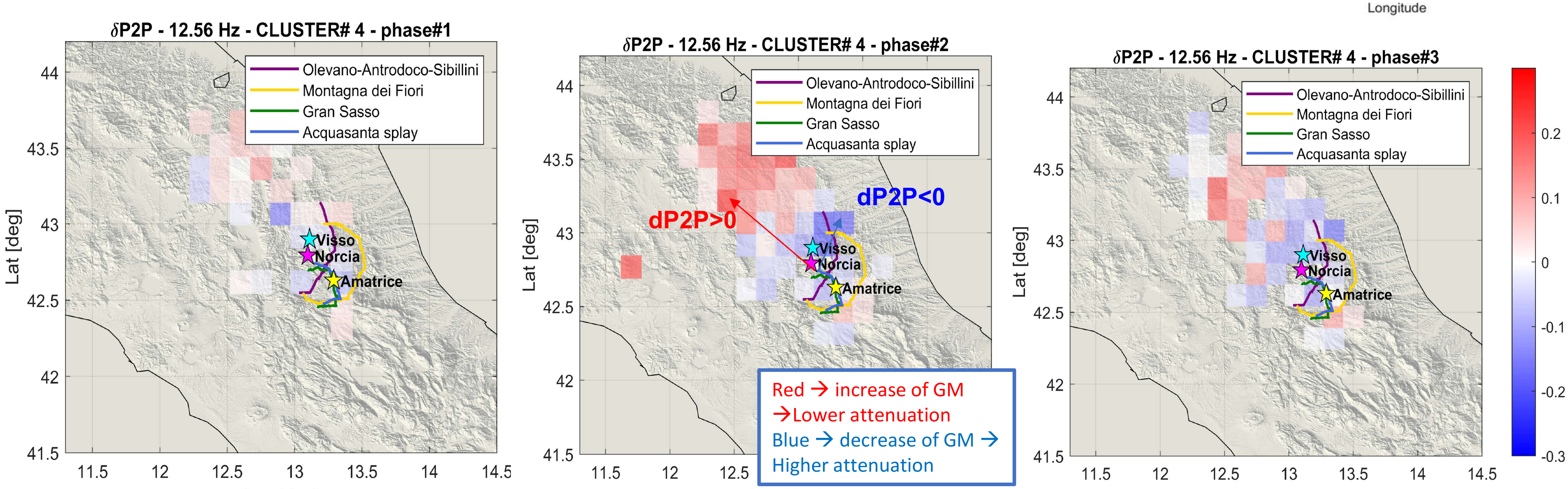
differences can be interpreted in relation to the increase of crustal stress with depth and not honmogeneous energy releas

NENS: non-stationarity of δP2P

IM ~ 1 + M + MlogDIST + logDIST + DIST + flag + M^2 +
(**1 | eventi**) + (**1 | site:** phase) + (**1 | source:** phase)
+ (**1 | path:** phase)

Cell approach for mapping paths





pre-sequence

main-sequence

post-sequence

NENS: non-stationarity of δP2P

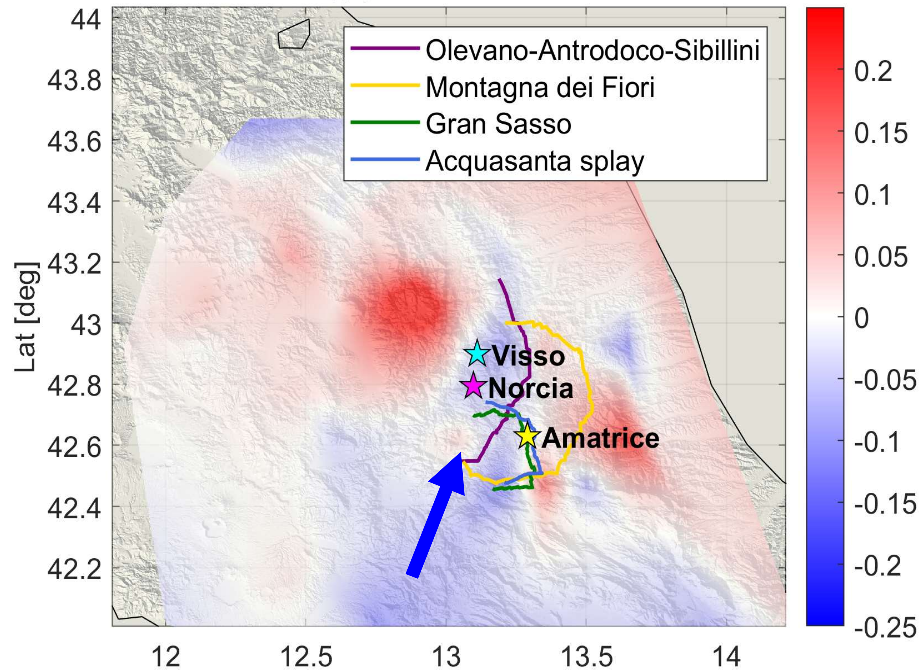
«Differential Maps»

increase of attenuation after the pre-sequence and a northestern movement of **attenuation anomaly** . This reduction of efficiency in transmitting seismic energy is possibly due to transient **changes in subsurface properties**, such as migration or dissipation of fluids or evolving crustal fracturation and damage (*Malagnini et al., 2022*). By the post-sequence phase (i.e., after 2019), the mean δP2P values tend to revert toward pre-sequence levels.

Variation during the sequences in the spatial distribution of the attenuation, with anomalies (high attenuation) moving from west to east and then north

Variation of δP2P between the main and pre-sequence phases

12.56 Hz – averaged across clusters

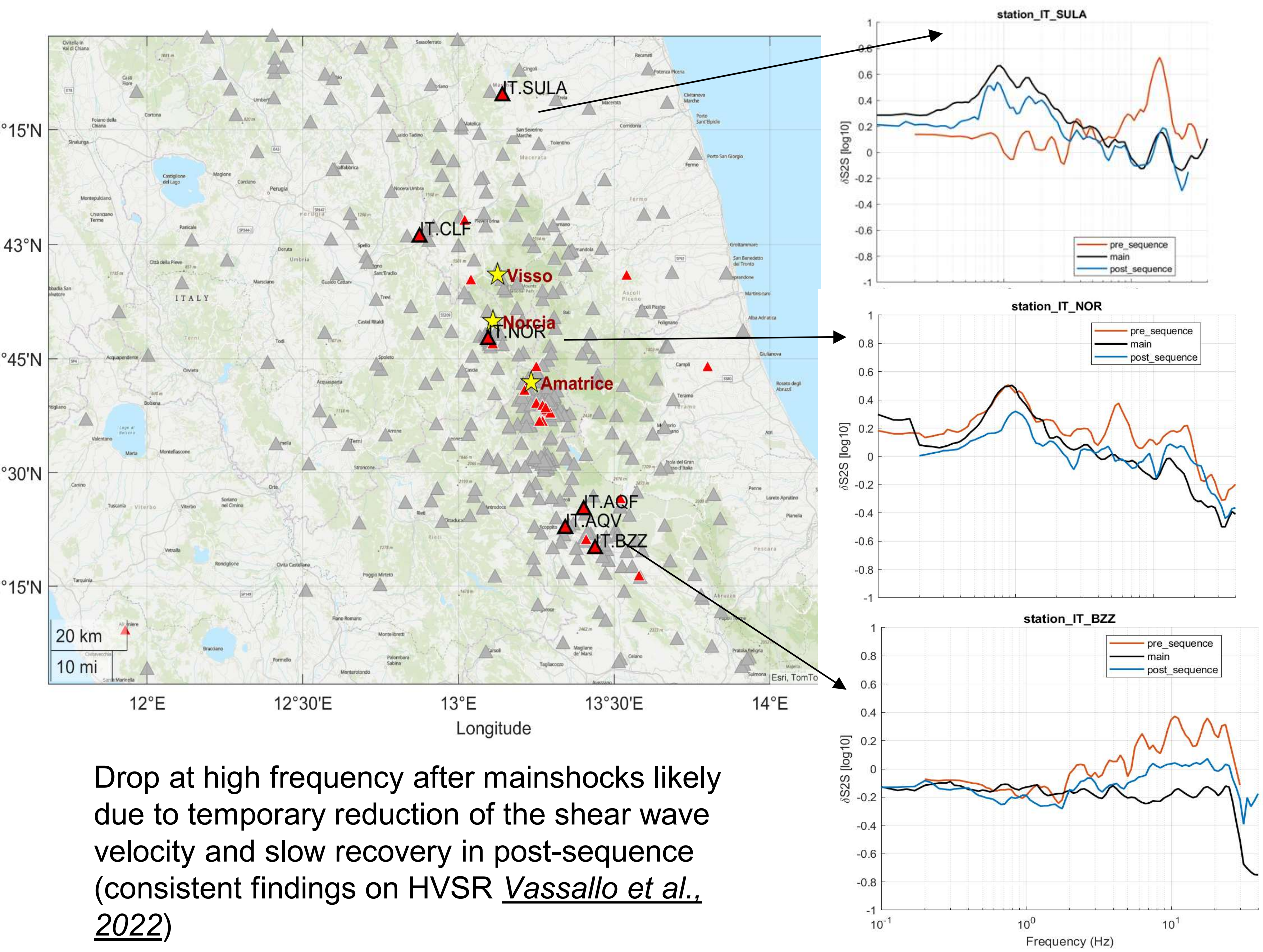


High attenuation delimited at N and S by OAS thrust and Gran Sasso thrust, respectively Sibillini/OAS, create a seismic impedance contrast.
→ **"barrier effect"** to wave transmission. This aligns with other studies e.g., *Gabrielli et al. (2022).*

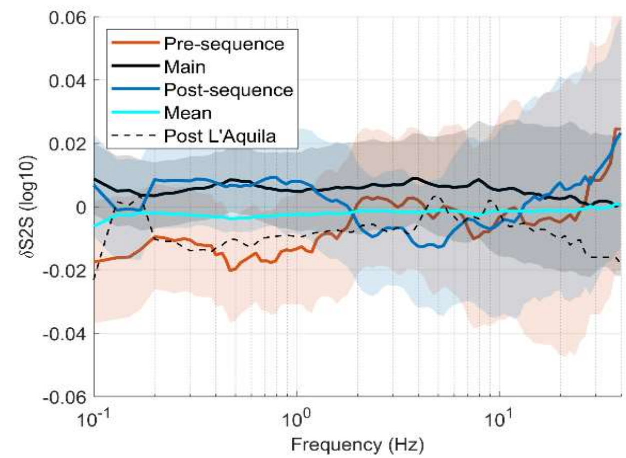
Sgobba et al. (2026) under review BSSA

NENS: non-stationarity of δS2S

IM ~ 1 + M + MlogDIST + logDIST + DIST + flag + M^2 + (**1 | eventi**) + (**1 | site:** phase) + (**1 | source:** phase) + (**1 | path:** phase)



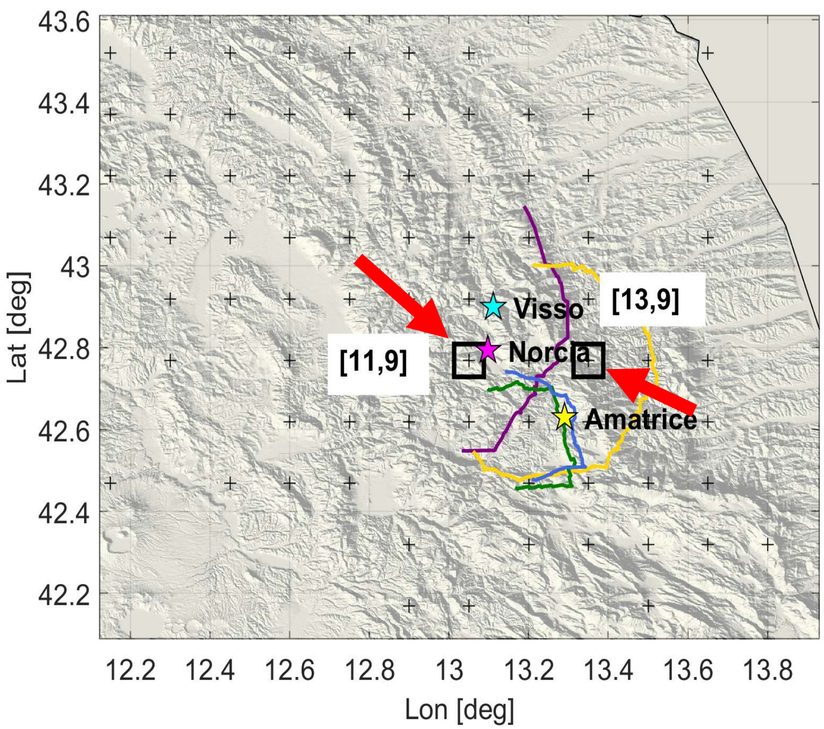
Drop at high frequency after mainshocks likely due to temporary reduction of the shear wave velocity and slow recovery in post-sequence (consistent findings on HVSR *Vassallo et al., 2022*)

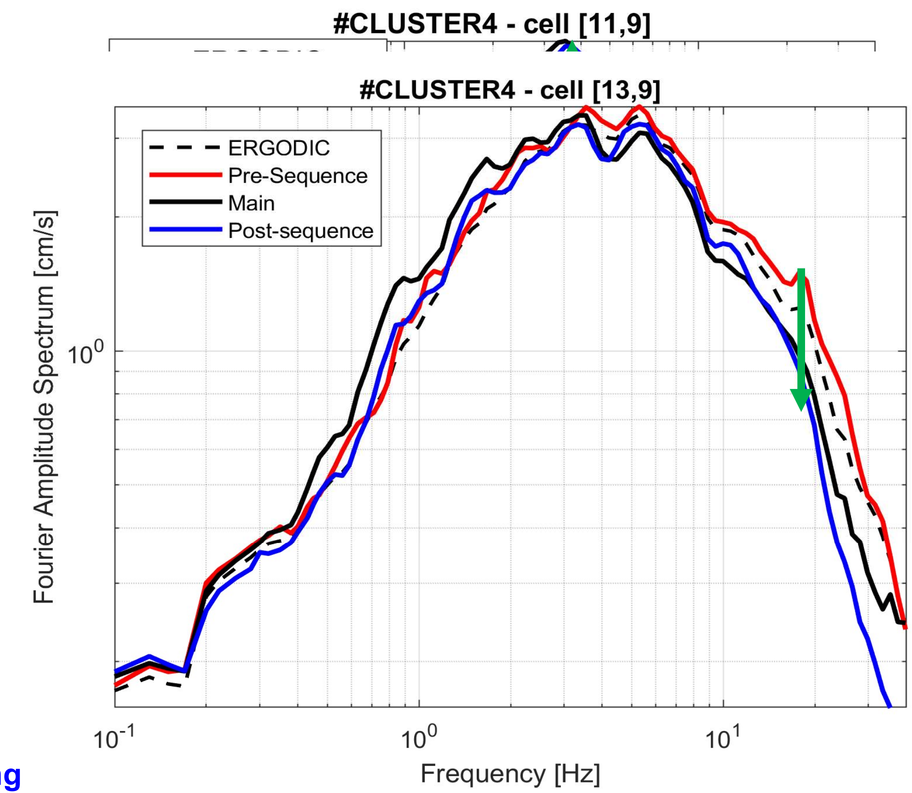


Temporal variation in site response occurred at approximately **10%** of the total stations. This phenomenon is primarily concentrated at stations located within the near-source region and/or situated in intramontane basins

NENS: impact on spectral predictions

M = 5.0
Rhypo = 10 km





The total correction term tends to be **negative on average at HF during the sequence**. This suggests that dynamic effects **overall reduce the ground motion** compared to a median stationary ergodic prediction

Conclusions

- With dense datasets, it is feasible to move toward more context-aware ground motion models that <u>break the traditional assumptions of ergodicity and stationarity</u>.
- The NENS models allow us to **capture these nonstationarities** in the GMM random terms, related to:
  - ✓ **Source dynamics** (e.g., apparent stress, 3D seismic clustering)
  - ✓ **Propagation properties** (e.g., anelastic attenuation, fluid migration)
  - ✓ **Site response** (e.g., shear-wave velocity reduction post-mainshock)
  - ✓ **Aleatory variability** doesn’t change w.r.t. an equivalent stationary model

- **Effect on ground motion predictions: decrease in predicted ground motion** amplitudes ON AVERAGE during main sequence at HF compared to stationary ergodic models, due to dissipative phases (e.g., fluid presence, scattering)

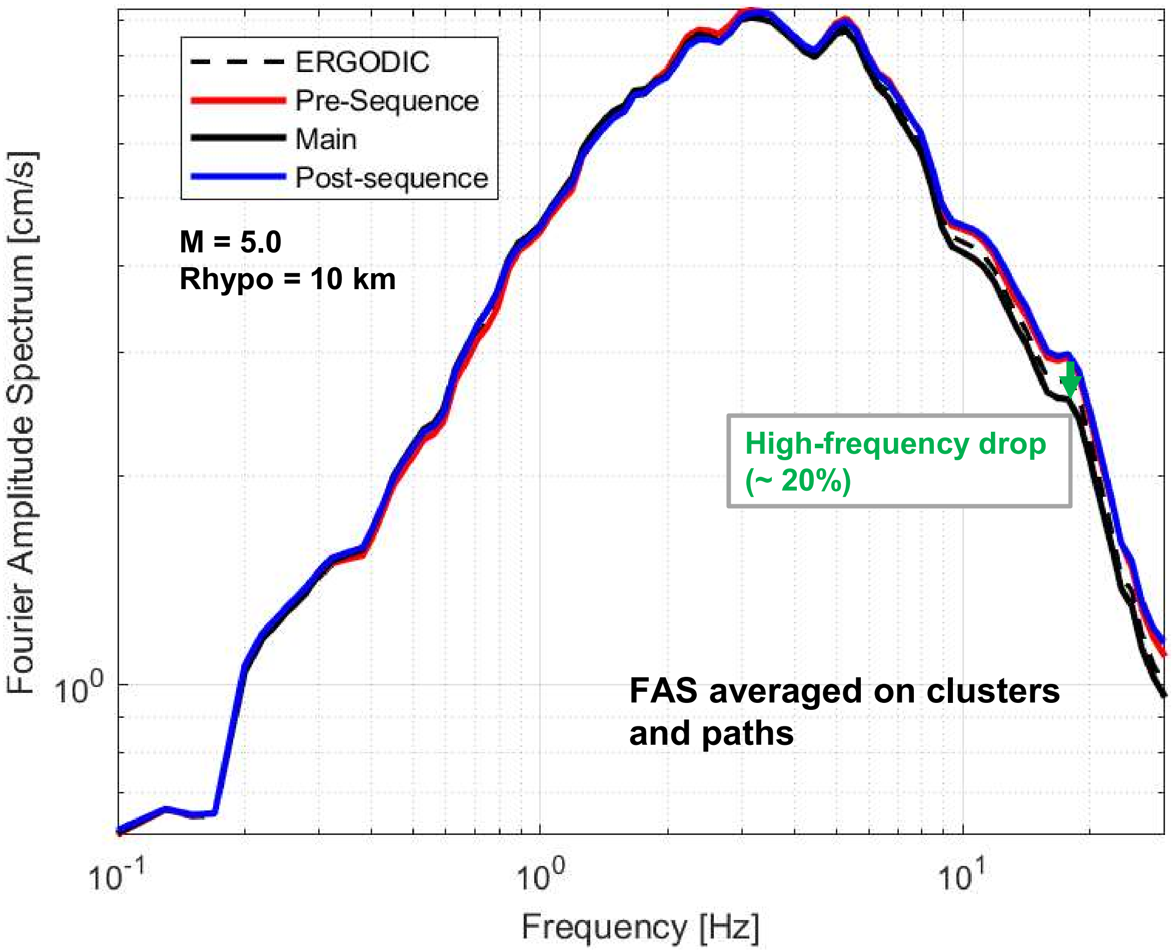
→ **small impact in terms of variability reduction w.r.t. stationary models**

→ ***<u>BUT… we can capture more significant local variations</u>***

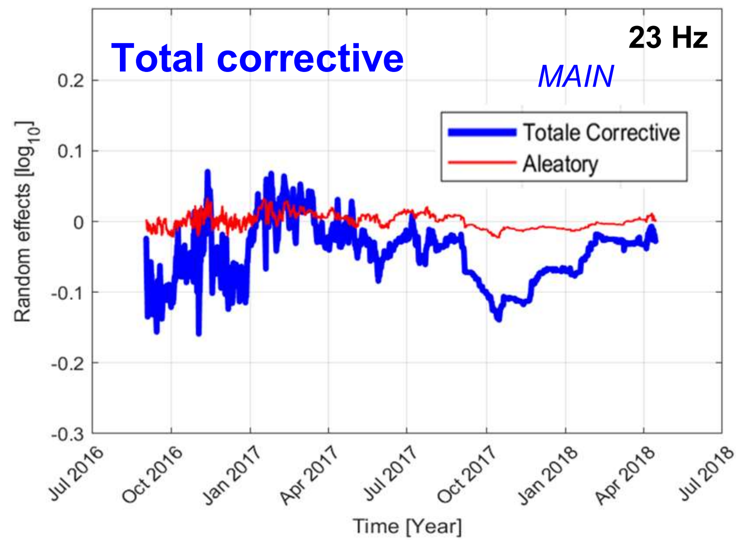
→ *<u>useful for **scenario**-based predictions, short-term forecast and **preparatory phase** analysys…**to be cross-checked with results from GIT!**</u>*

Thank You

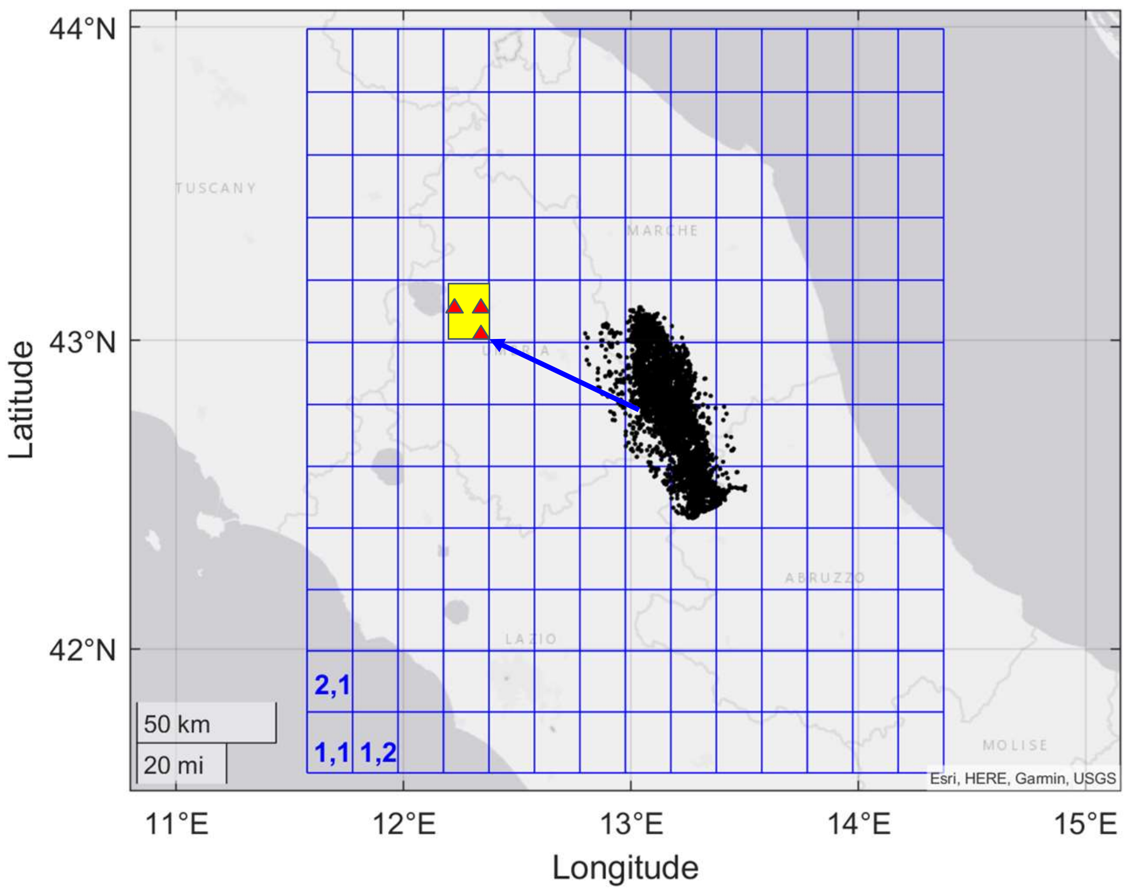
NENS: impact on spectral predictions



The total correction term tends to be **negative on average during the sequence**. This suggests that dynamic effects **overall reduce the ground motion** compared to a median stationary prediction



NENS model:
Sampling of Path terms



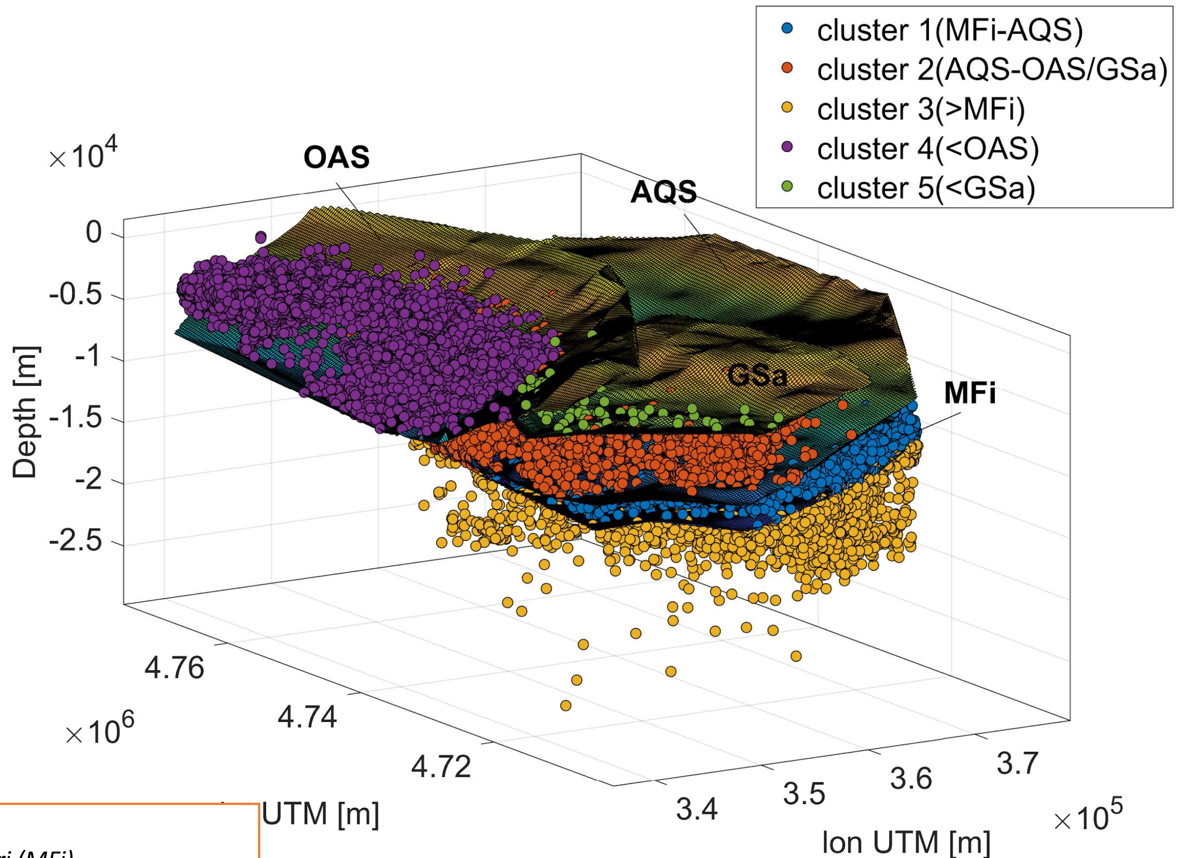
IM ~ 1 + M + MlogDIST + logDIST + DIST + flag + M^2 + (**1 | eventi**) + (**1 | stazioni:** phase) + (**1 | source:** phase) + (**1 | path:** phase)

Cell Approach

cell-paths (0.15° - size) for sampling propagation from cluster of events to cell (*Dawood and Rodriguez-Marek, 2013*)
associates each source-station path with an average attenuation term, allowing local variations in seismic motion propagation to be mapped

3D spatial clustering of events for constraining non-ergodic effects

Random effect on the area source based on 3D zonation and geologically-informed clustering provides more realistic source and propagation contributions (i.e. **dL2L and dP2P**); *Sgobba et al. 2026 under review*



The events in the dataset that belong to the different **volumetric clusters in the region**

Captures fault dip, depth of events, different seismogenic volumes → *improved rappresentation of source clusters wrt 2D conventional models to capture spatial variations in source and paths*

Main Thrust considered:

- *Montagna dei Fiori (MFi)*
- *Acquasanta splay (AQS)*
- *Olevano-Antrodoco-Sibillini (OAS)*
- *Gran Sasso (Gsa)*

Sgobba et al. (2026) under review BSSA

WP3 - Previsioni del Moto del Suolo Utilizzando Approcci Innovativi

Deliverable	Description	Months
WP3_D3	Non-stationary NE-ground motion model	36
WP3_D5	A regional intensity attenuation model for central Italy, obtained by means of regional correctives assessed with the analysis of the residuals	36
WP3_D6	Georeferenced shaking scenarios from physics-based ground motion simulations for the selected M>6.0 earthquakes in Central Apennines	34
WP3_D7	Time histories and a series for ground motion parameters including the permanent displacement	34
WP3_D8	Distribution of the simulation codes that developed and used in the project	36