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

Non-Ergodic Ground Motion Model for the N3 Central Italy Area: Results on Spatio-Temporal Variability

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Data and Methods

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Dataset: N3 Catalogue

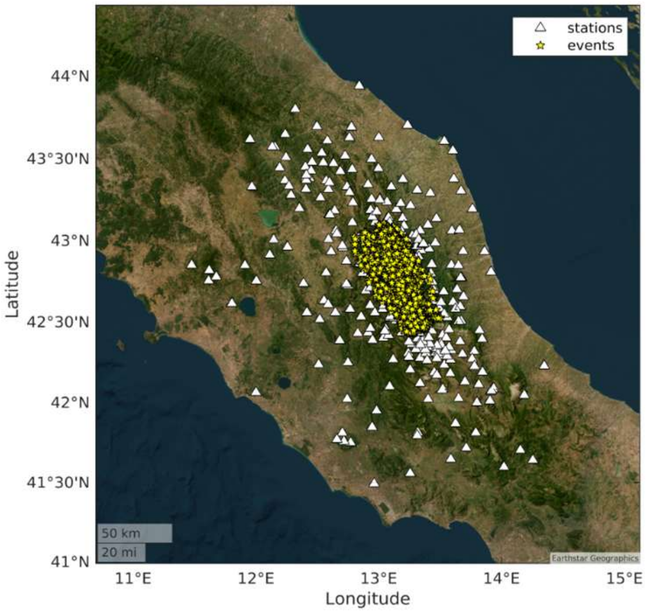
- Earthquakes in the Amatrice-Visso-Norcia area from 2006 to 2023
- Relocation of events (improvement of event depth estimation) M_L, M_w estimation by RAMONES (https://distav.unige.it/rsni/ramones.php?lang=it)

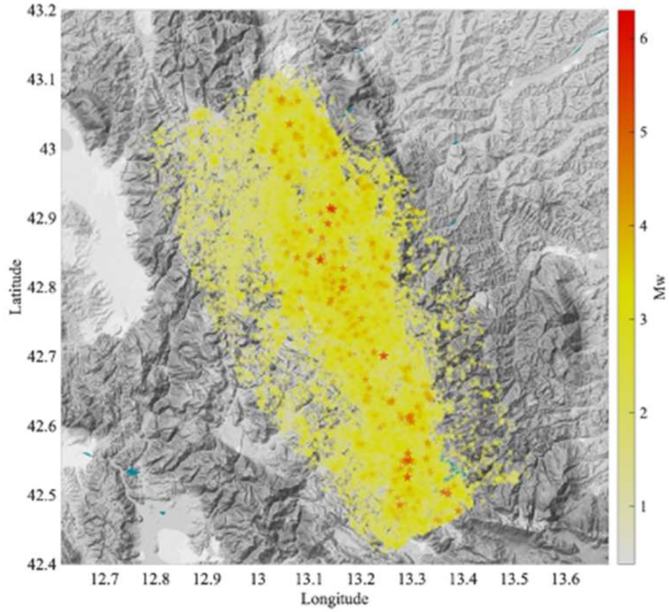
Parametric Table M>1.8

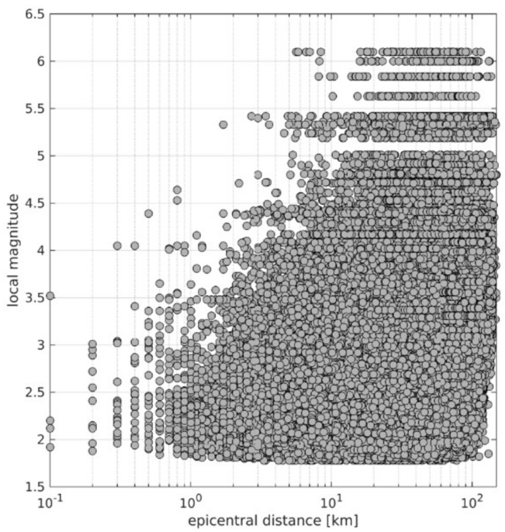
Records: 434.551

Events: 9.948

Stations: 452







NES (**NonErgodic Stationary** Model)

- The stationary **FAS** model includes **non-ergodic type variability** (dL2L term, dP2P, dS2S). Modeling based on **R_{hypo}**
- Approach consistent with **fully non-ergodic models** in the literature (e.g., *Dawood & Rodriguez-Marek 2013, Lavrentiadis et al. 2021, Sgobba et al., 2021, 2023, among others*)
- **Reduction in total aleatory variability** due to explicit modeling of dL2L, dP2P, and dS2S terms

Modelled effects

$$\log_{10}FAS = \boxed{a + b_1 M_l + b_2 M_l^2 + [c_1(M_l - M_{ref}) + c_2]\log_{10}\sqrt{R_{hypo}^2 + h^2} + c_3\left(\sqrt{R_{hypo}^2 + h^2} - R_{ref}\right)}$$
$$+ \delta_{ref} + \delta B_e|event + \delta S2S_s|station + \delta L2L_a|area\ source + \delta P2P_p|path + \delta W_{esap}$$

Unmodelled effects

Prediction at 6 reference rock sites!

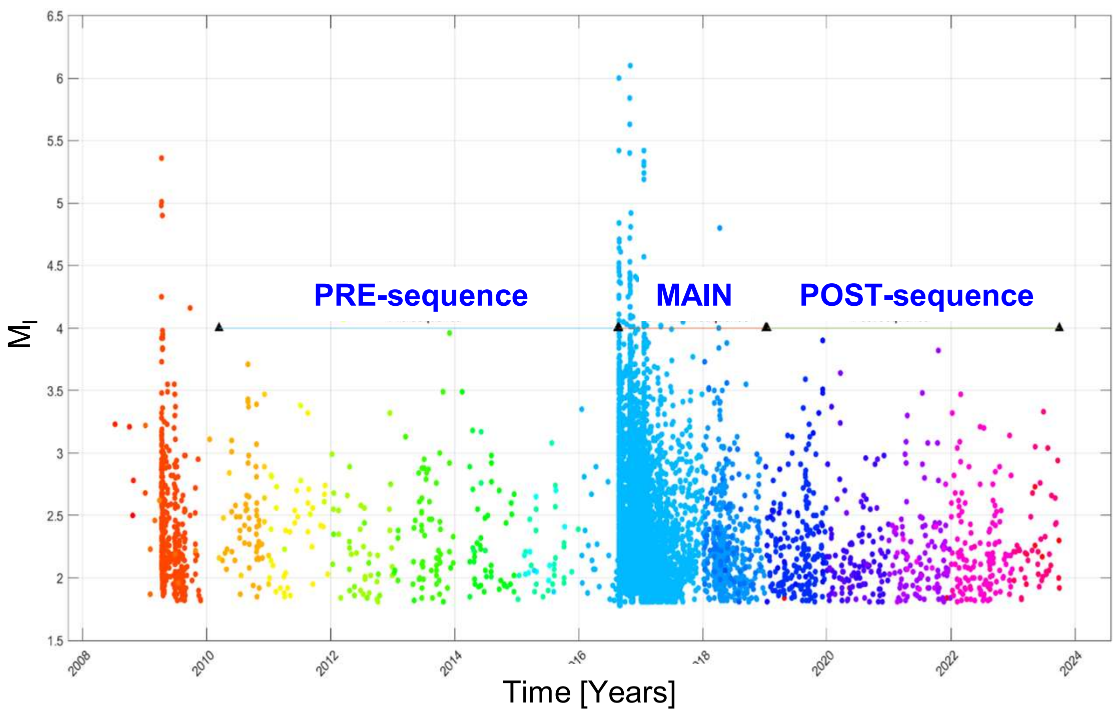
Method

Linear mixed-effect regression with *fitlme* di Matlab

NENS (**NonErgodic Non-Stationary** Model)

Nonstationarity with time: **1 mixed-effect nested model**

→ better for comparability and interpretability because fixed-effects remain the same



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

Dataset devided in 3 phases:

PRE-sequence

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

MAIN sequence

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

POST-sequence

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

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Results

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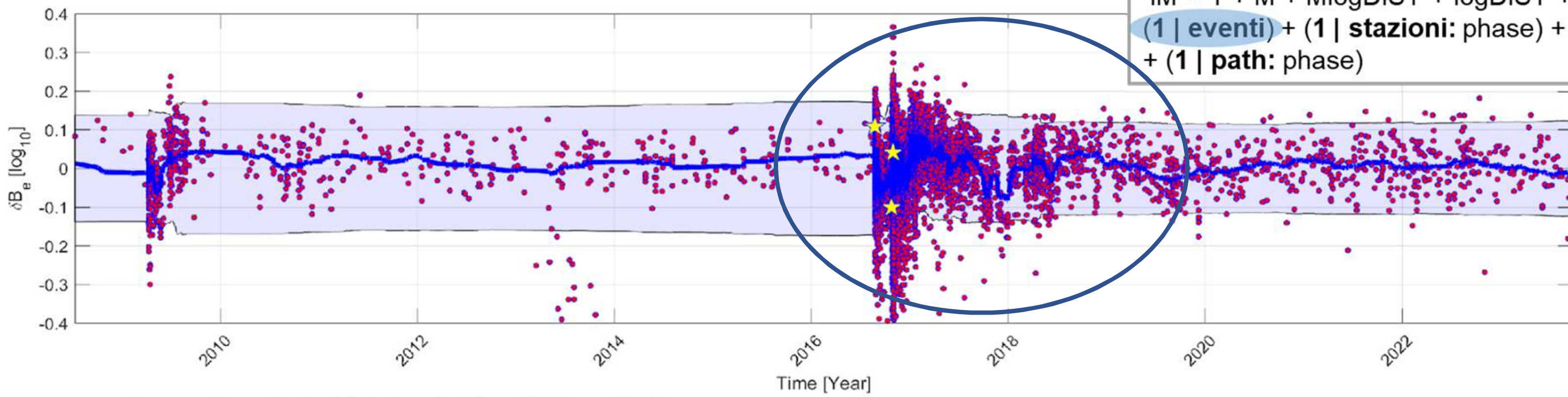
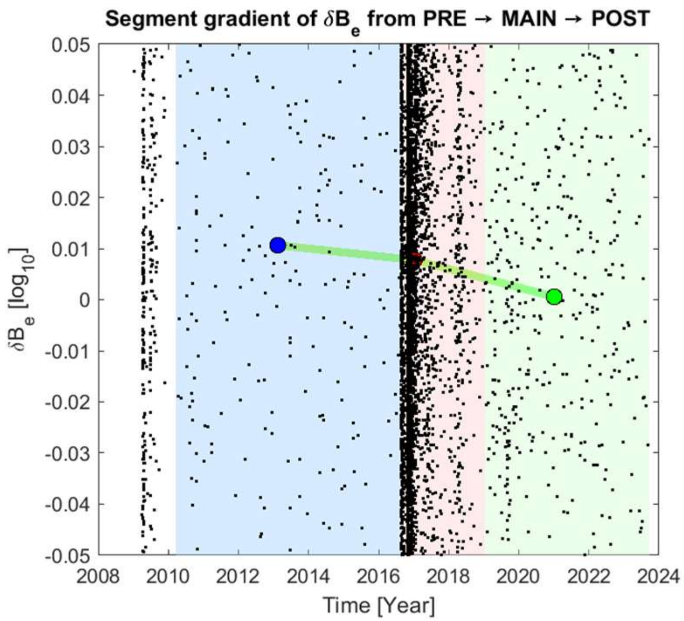
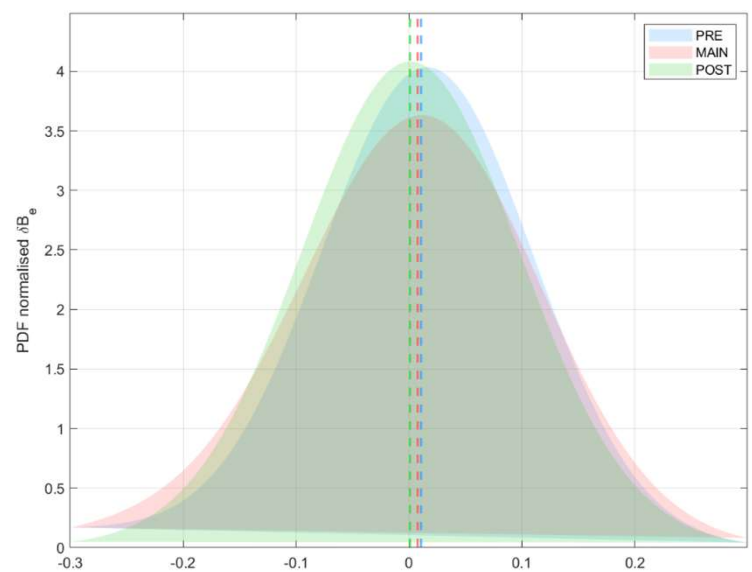
NENS: nonstationarity of dBe

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

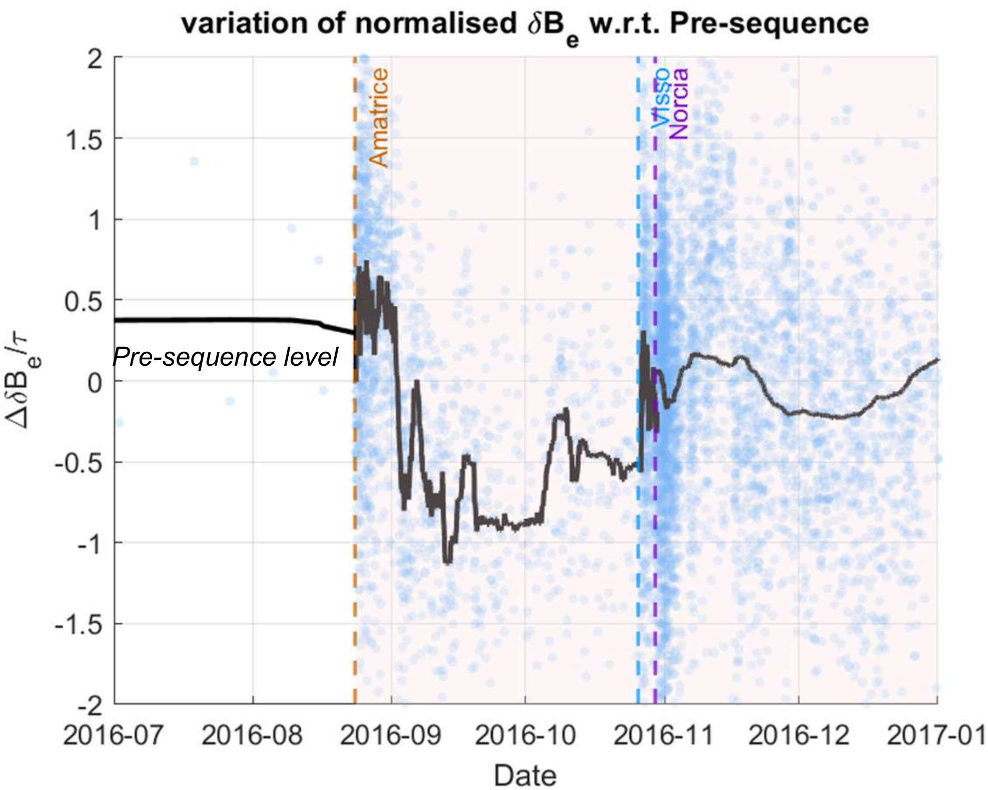
23 Hz

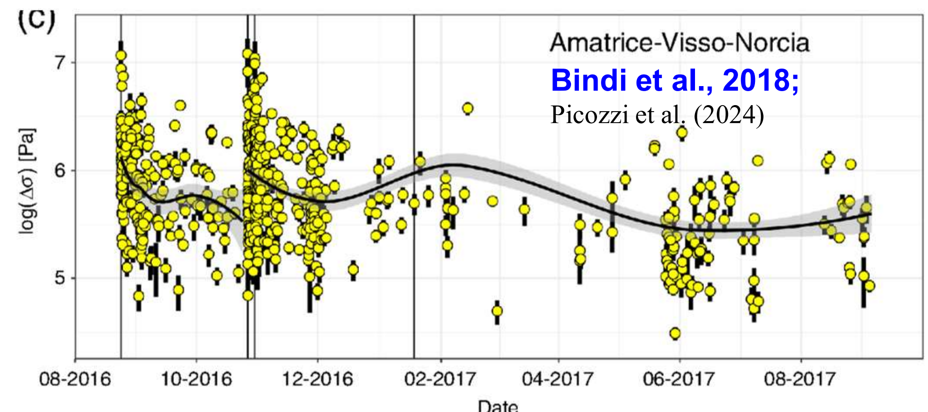


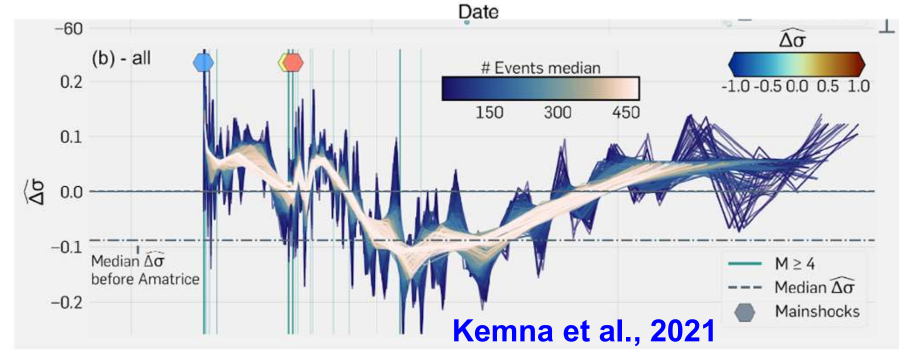




NENS: nonstationarity of dBe





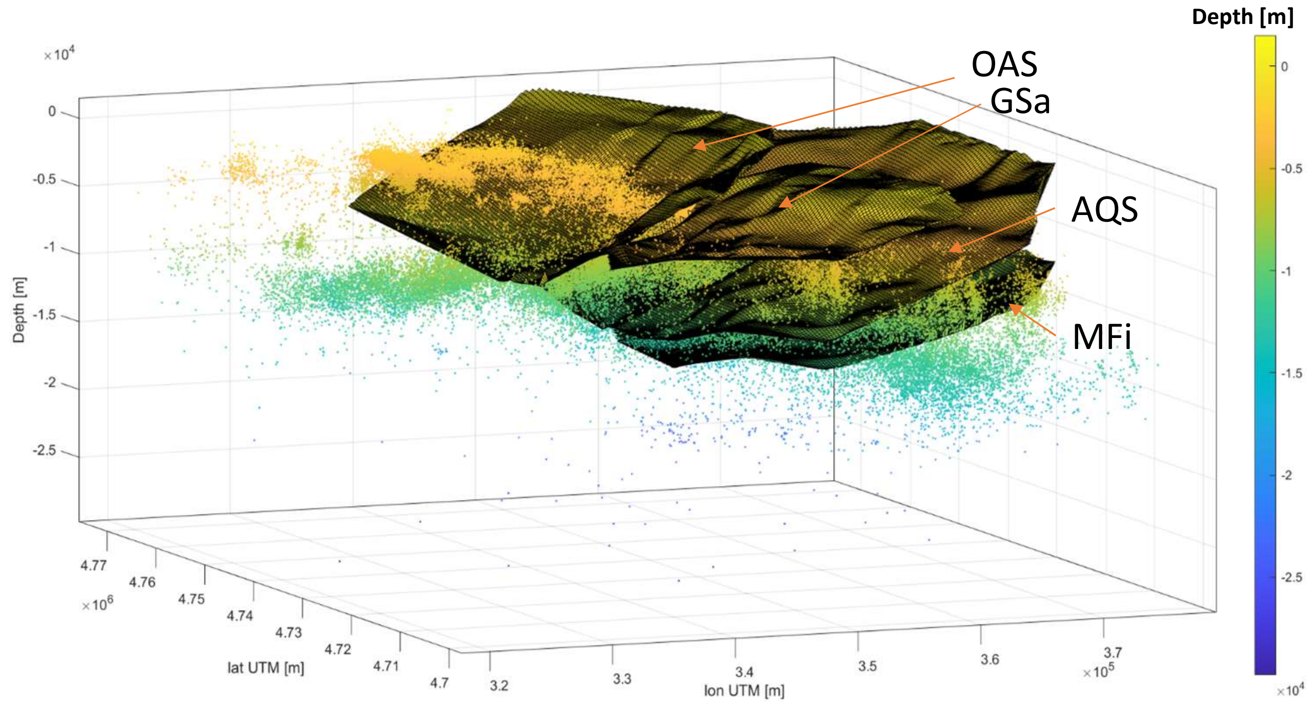


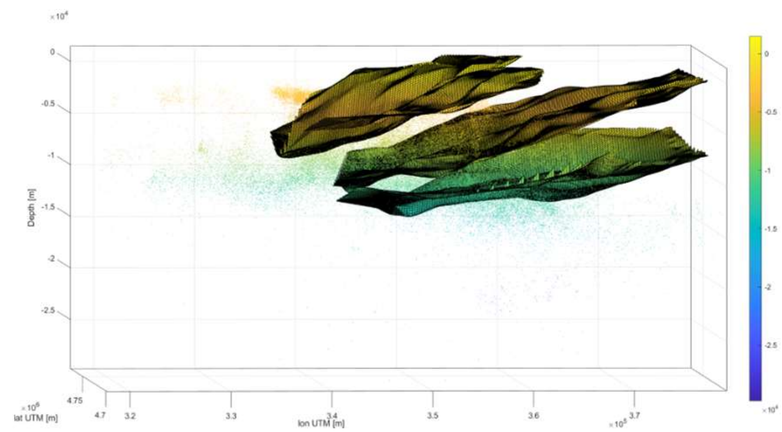
Several authors observe sudden decrease in the apparent stress observed in the aftershocks of main events

3D spatial clustering of events for non-ergodic model development

Area source based on 3D zonation and geologic clustering provides more realistic source and propagation contributions (i.e. **dL2L and dP2P**)

Adoption of **geologically-informed clustering** guided by crustal volumes. We consider **thrusts and major fault systems** as 3D structures from the **RETRACE3D** model (*Di Bucci et al., 2021*) data and interpolated in space. The structures introduced are characterised by their different location in depth

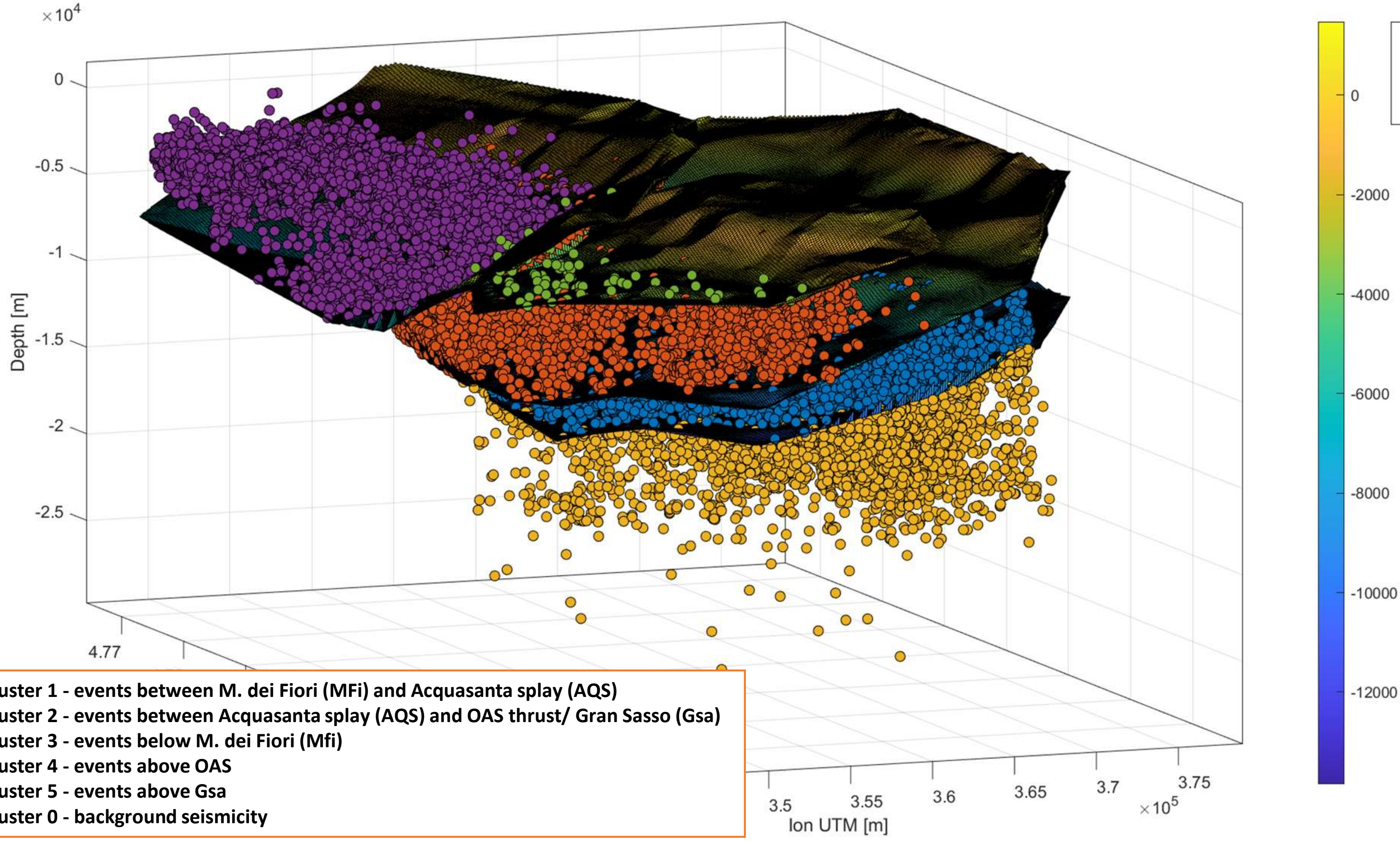




Main Thrust considered:

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

3D spatial clustering of events for non-ergodic model development



The events in the dataset that belong to the different **volumetric clusters succesively activated** are coloured differently

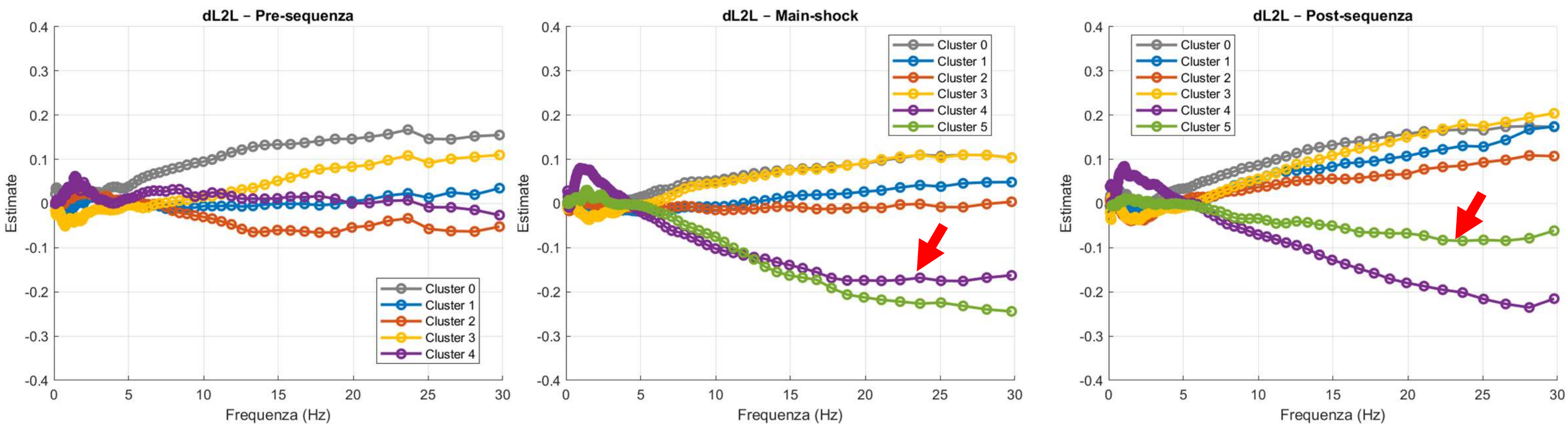
Captures fault dip, depth of events, different seismogenic volumes → *improved rappresentation of source clusters wrt 2D conventional models to capture spatial variations in source and paths*

Cluster 1 - events between M. dei Fiori (MFi) and Acquasanta splay (AQS)
Cluster 2 - events between Acquasanta splay (AQS) and OAS thrust/ Gran Sasso (Gsa)
Cluster 3 - events below M. dei Fiori (Mfi)
Cluster 4 - events above OAS
Cluster 5 - events above Gsa
Cluster 0 - background seismicity

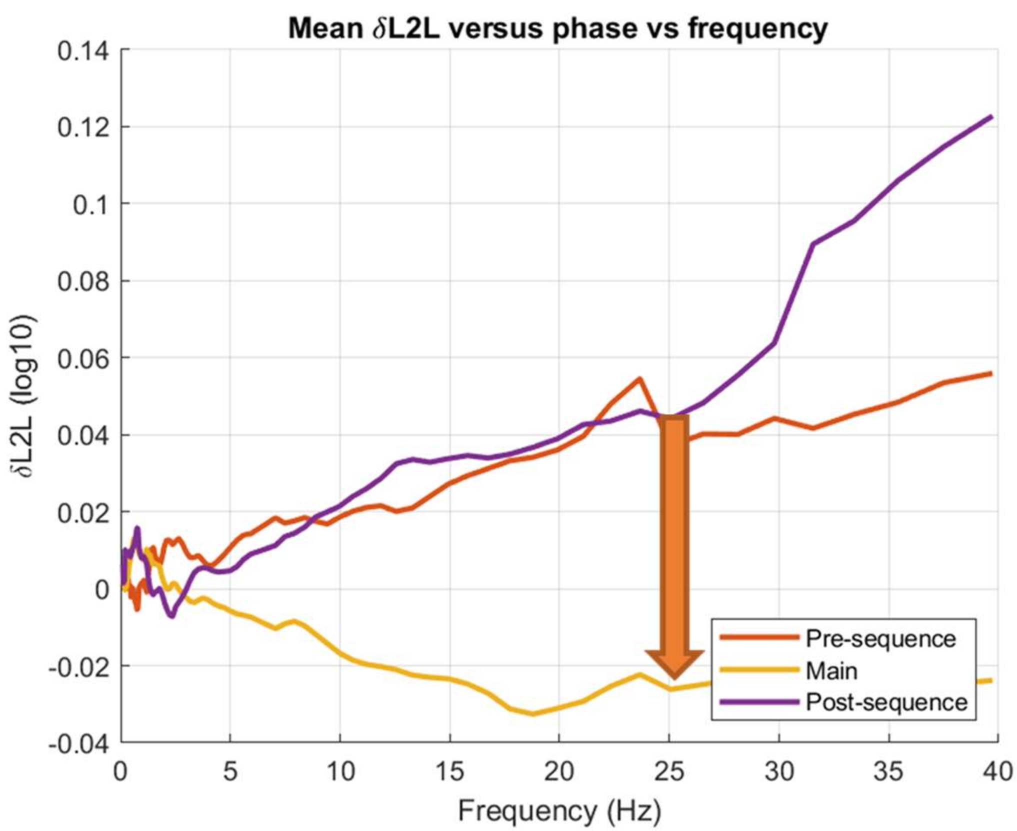
NENS location-to-location terms

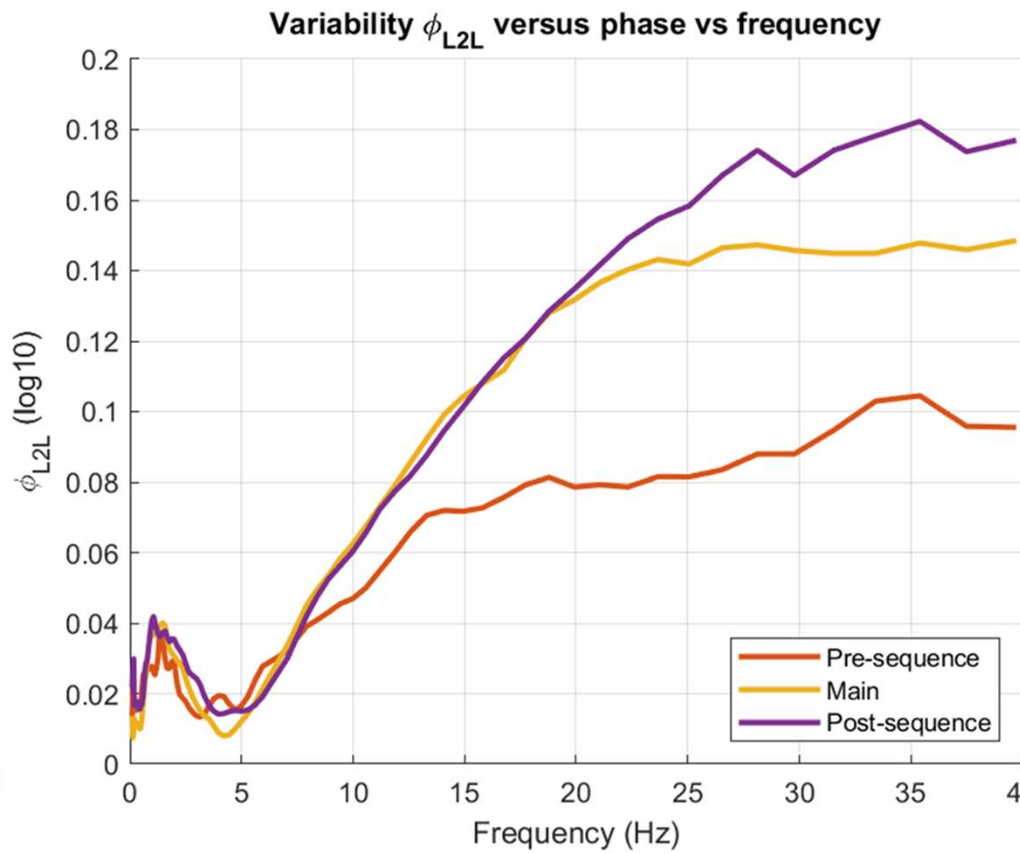
IM ~ 1 + M + MlogDIST + logDIST + DIST + flag + M^2 + (**1 | eventi**) + (**1 | stazioni:** phase) + (**1 | source:** phase) + (**1 | path:** phase)

Relatively lower values for **shallow earthquakes (cluster 4-5)**
and higher values for **deeper clusters (3-1) in the main phase**
differences can be interpreted in relation to the increase of crustal stress with depth
(i.e. effects not fully captured by the model in Rhypo) and not honmogeneous energy releas

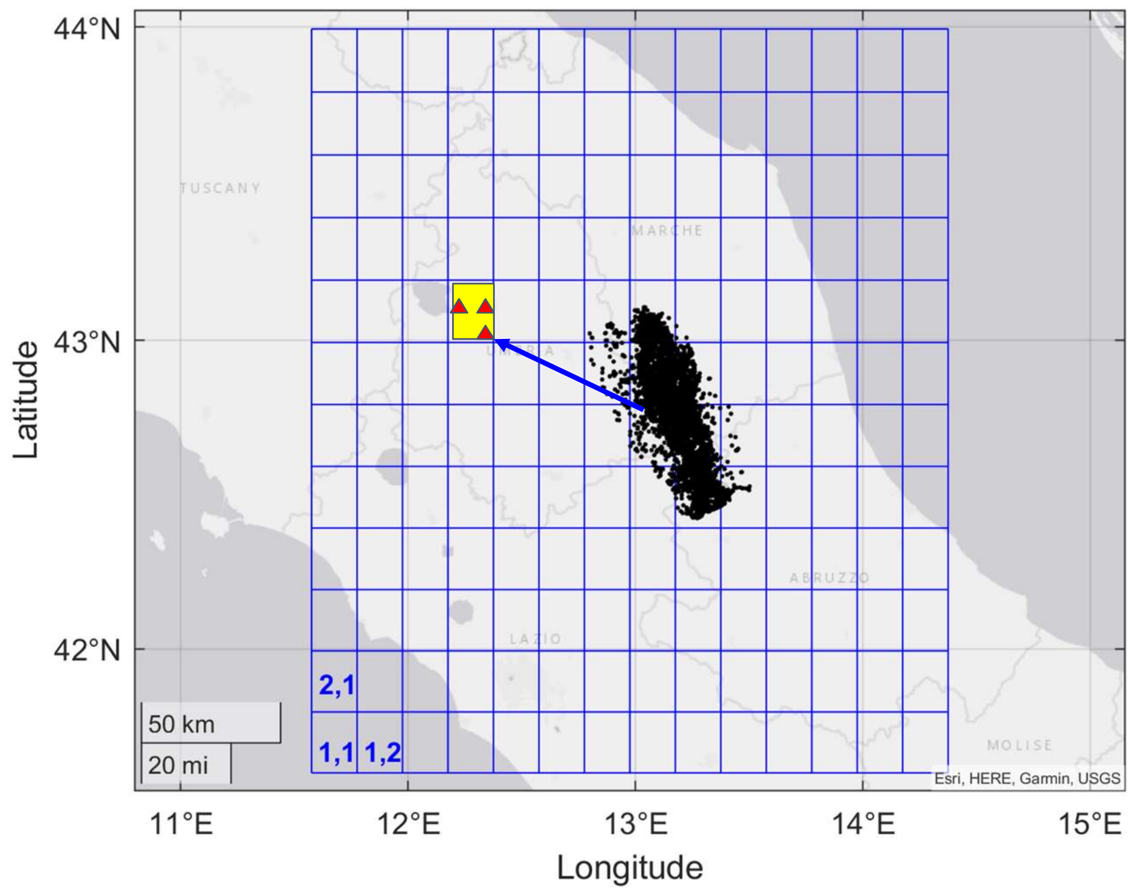


NENS location-to-location terms





NENS model:
Sampling of Path terms

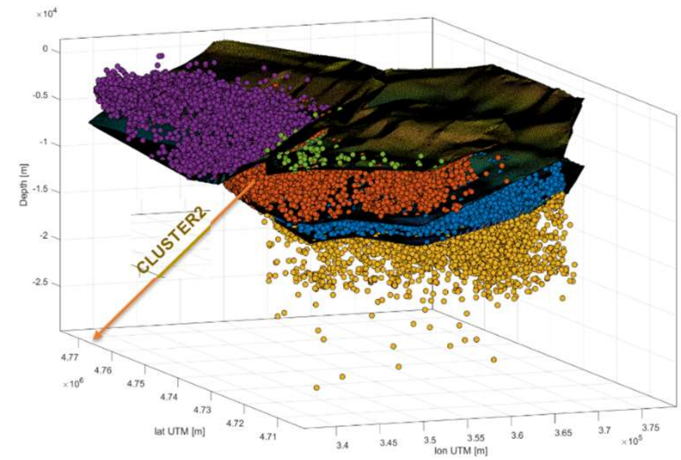


IM ~ 1 + M + MlogDIST + logDIST + DIST + flag + M^2 + (**1 | eventi**) + (**1 | stazioni:** phase) + (**1 | source:** phase) + (**1 | path:** phase)

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

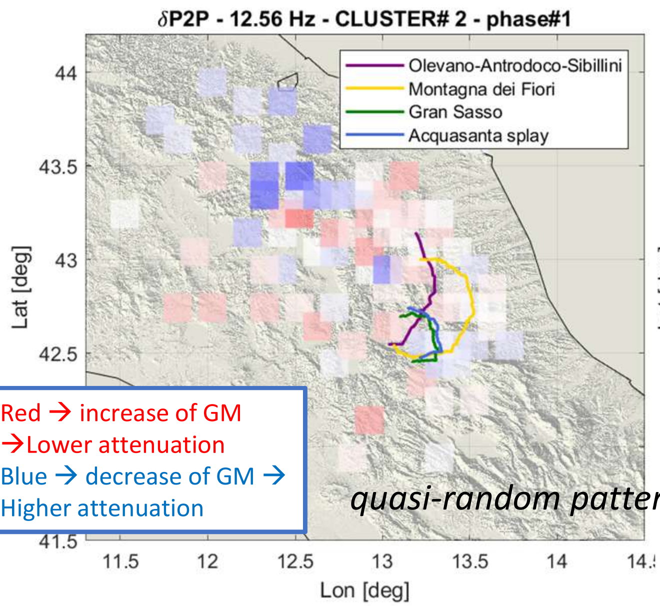
NENS: nonstationarity of dP2P



CLUSTER#2

(size 0.15°x0.15°)
Nstat per cell >=3

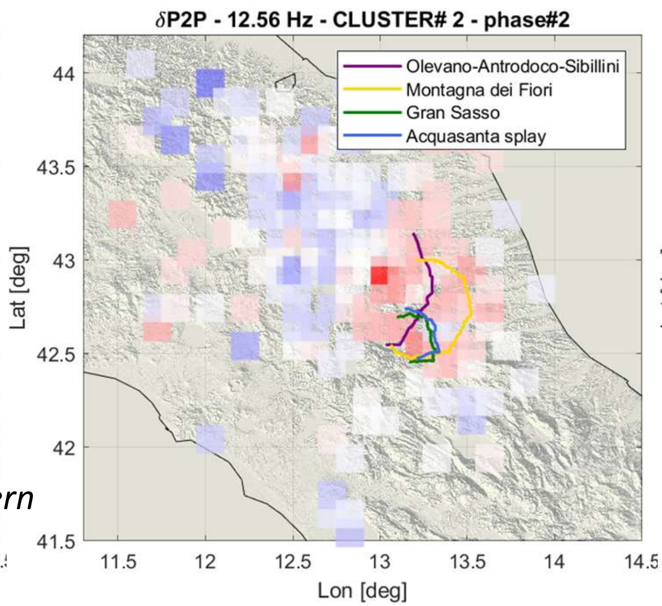
Distinct **patterns of propagation** capturing anisotropies of anelastic attenuation



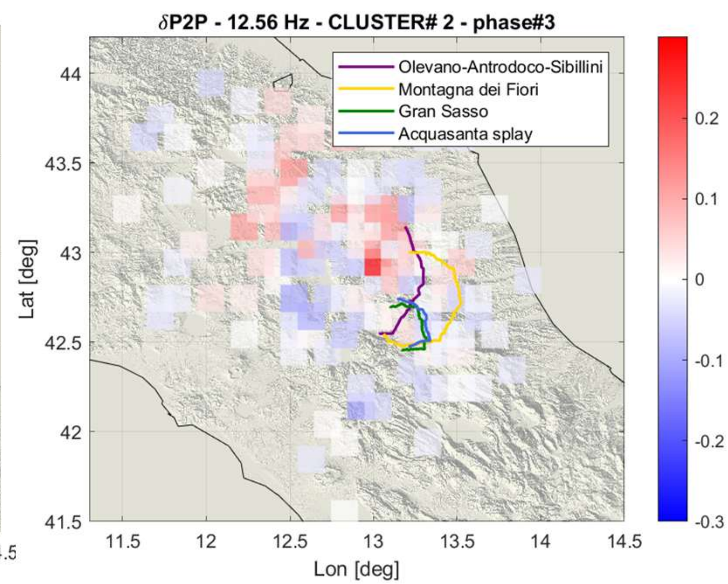
Red → increase of GM →Lower attenuation
Blue → decrease of GM → Higher attenuation

quasi-random pattern

pre-sequence



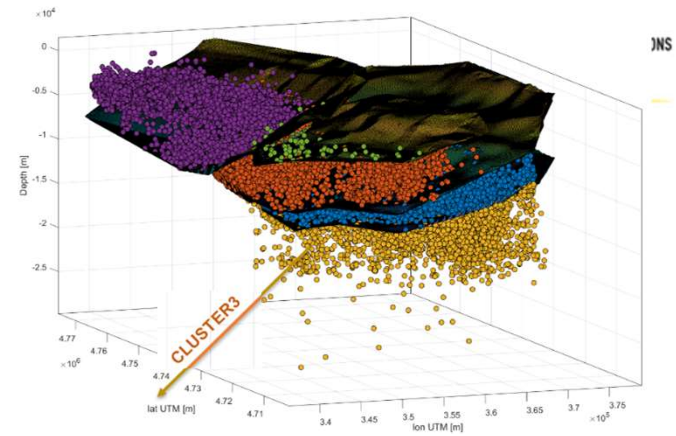
main-sequence

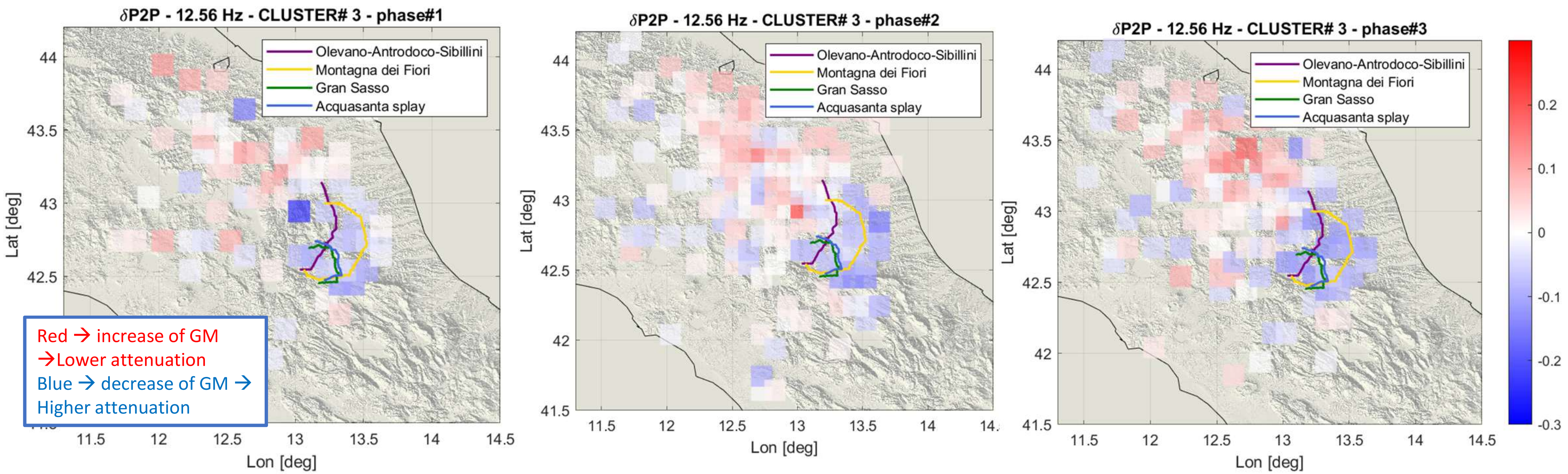


post-sequence

NENS: nonstationarity of dP2P

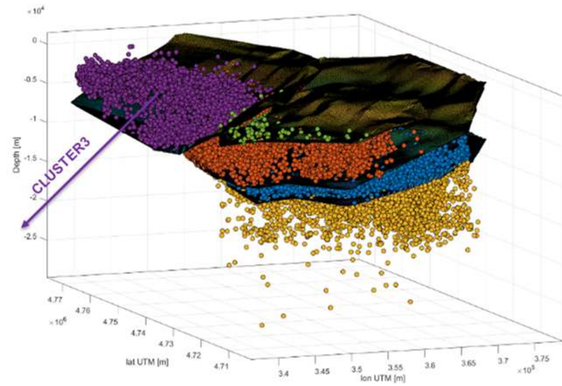
CLUSTER#3





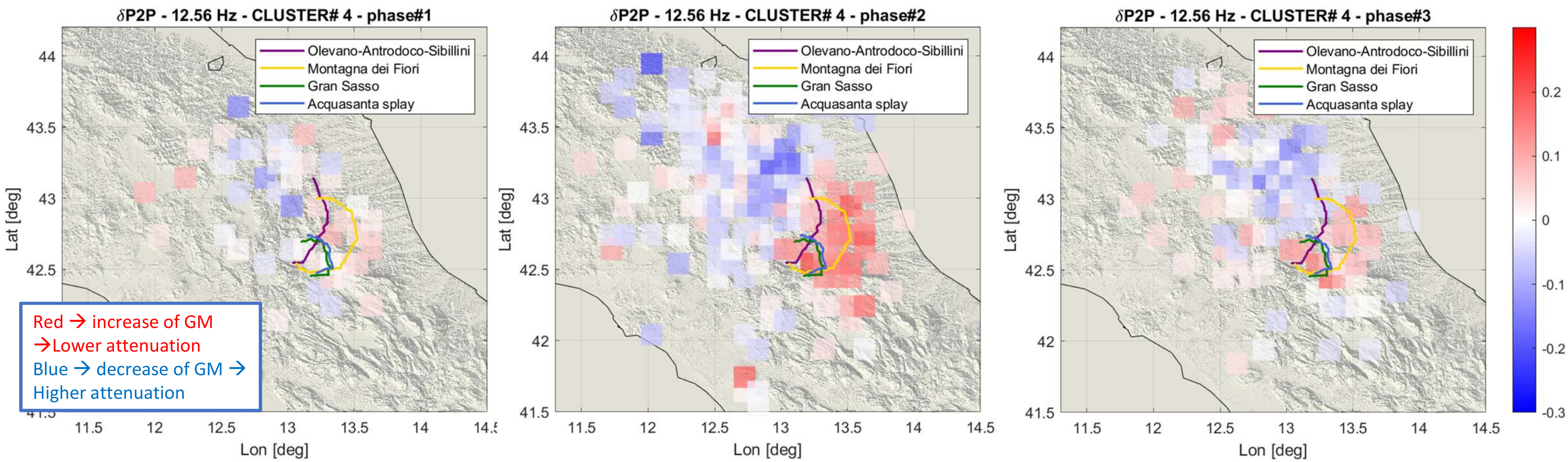
pre-sequence main-sequence post-sequence

NENS: nonstationarity of dP2P



CLUSTER#4

Sibillini/OAS, create a seismic impedance contrast.
This can cause scattering effect, which reduces the energy transmitted beyond the structure
→ **"barrier effect"**



pre-sequence main-sequence post-sequence

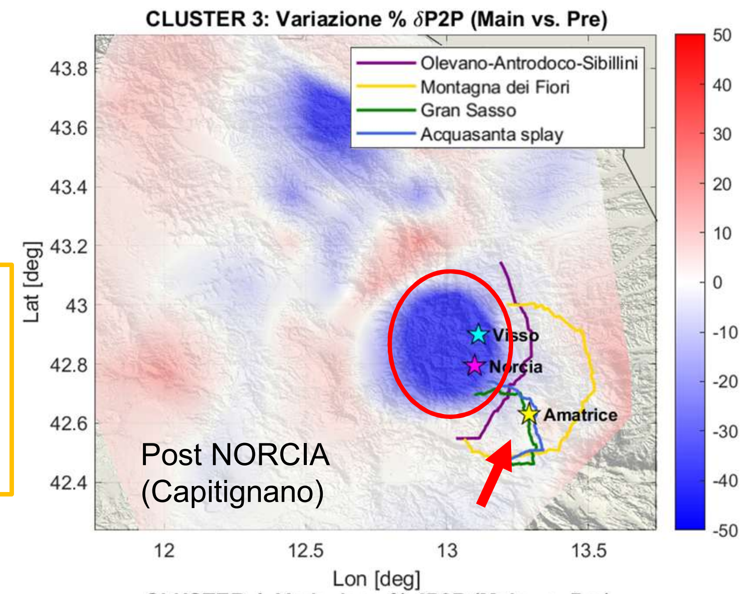
NENS: nonstationarity of dP2P «Differential Maps»

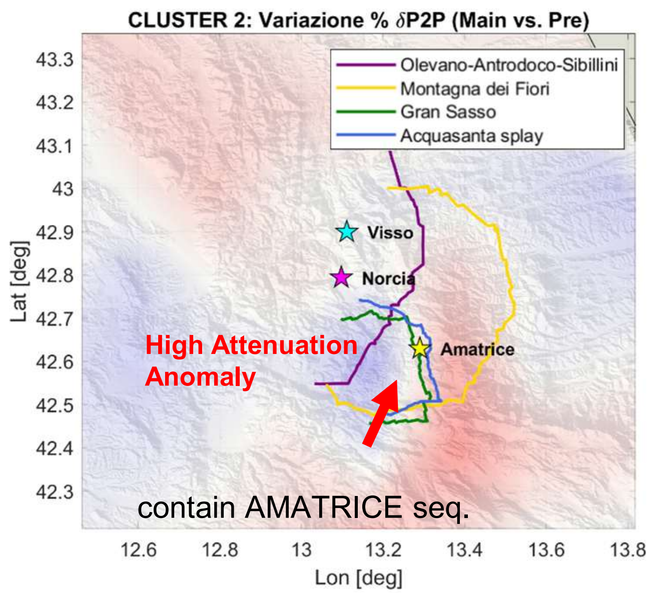
1. <u>Amatrice</u>: High attenuation delimited at N and S by OAS thrust and Gran Sasso thrust, respectively (<u>Gabrielli et al., 2022</u>)

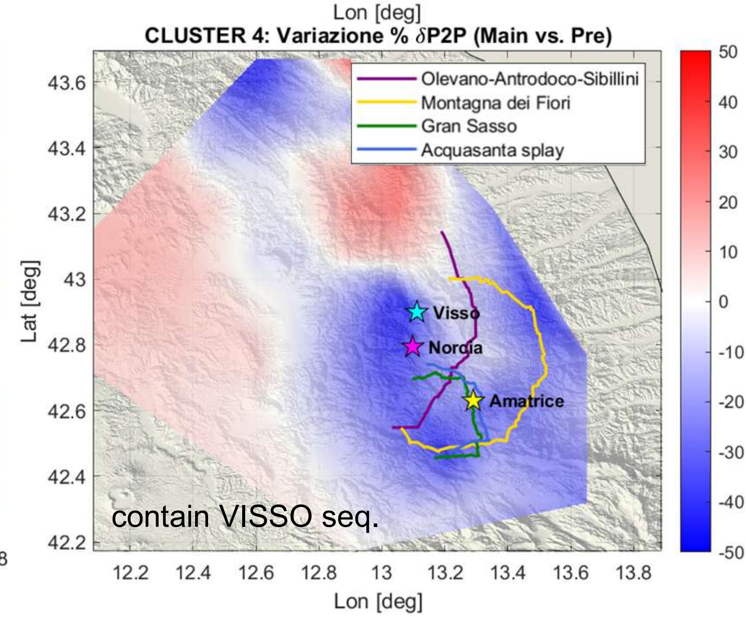
2: <u>Visso</u>: increase of attenuation in the Sibillini area at S-SW of Norcia/Amatrice

3. <u>Norcia</u>: increase of attenuation at northernmost of the Visso area after the pre-sequence. This fluid migration towards the Visso area was also identified by <u>Malagnini et al. (2022)</u>, who calculated fluid flow patterns and suggested a northward fluid movement after the Amatrice mainshock

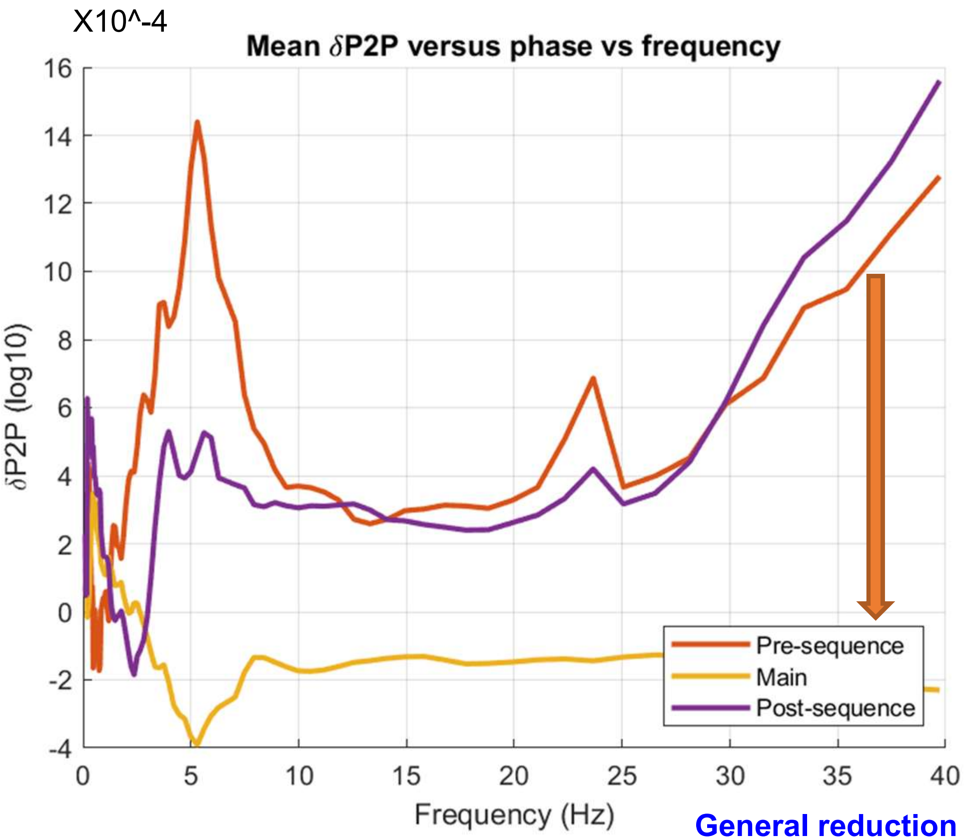
Variation during the sequences in the spatial distribution of the attenuation, with anomalies (high attenuation) moving from west to east and then north

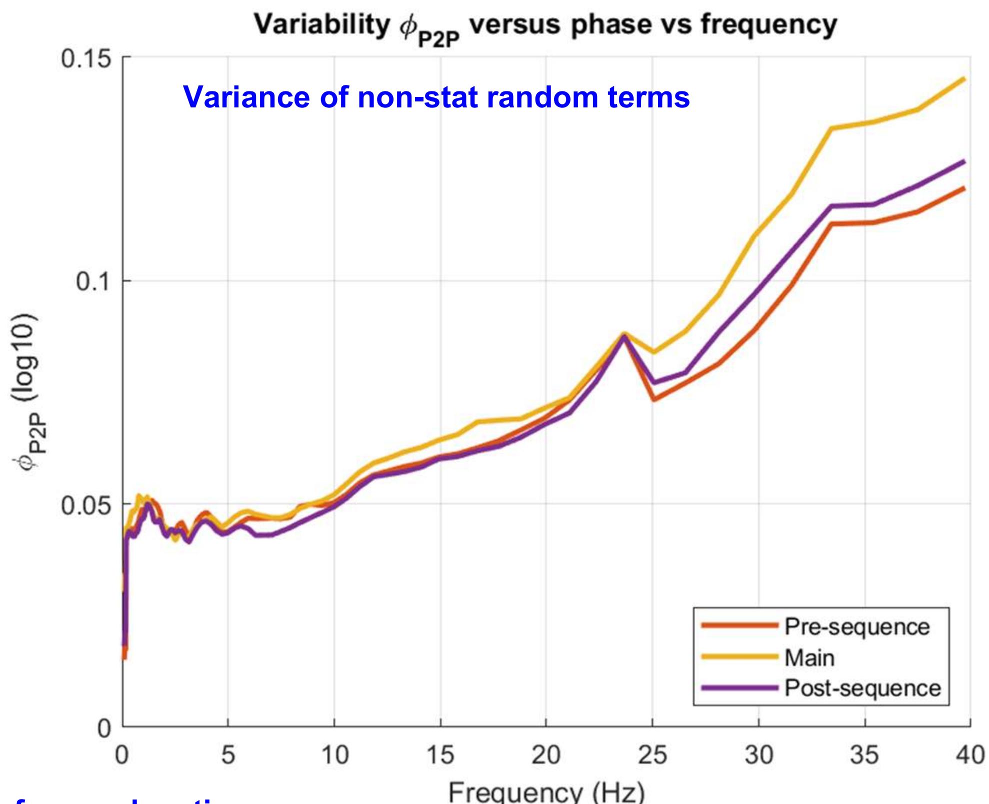






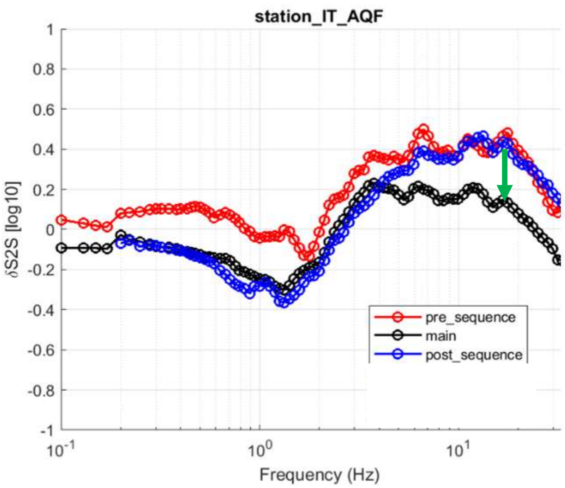
NENS: nonstationarity of dP2P

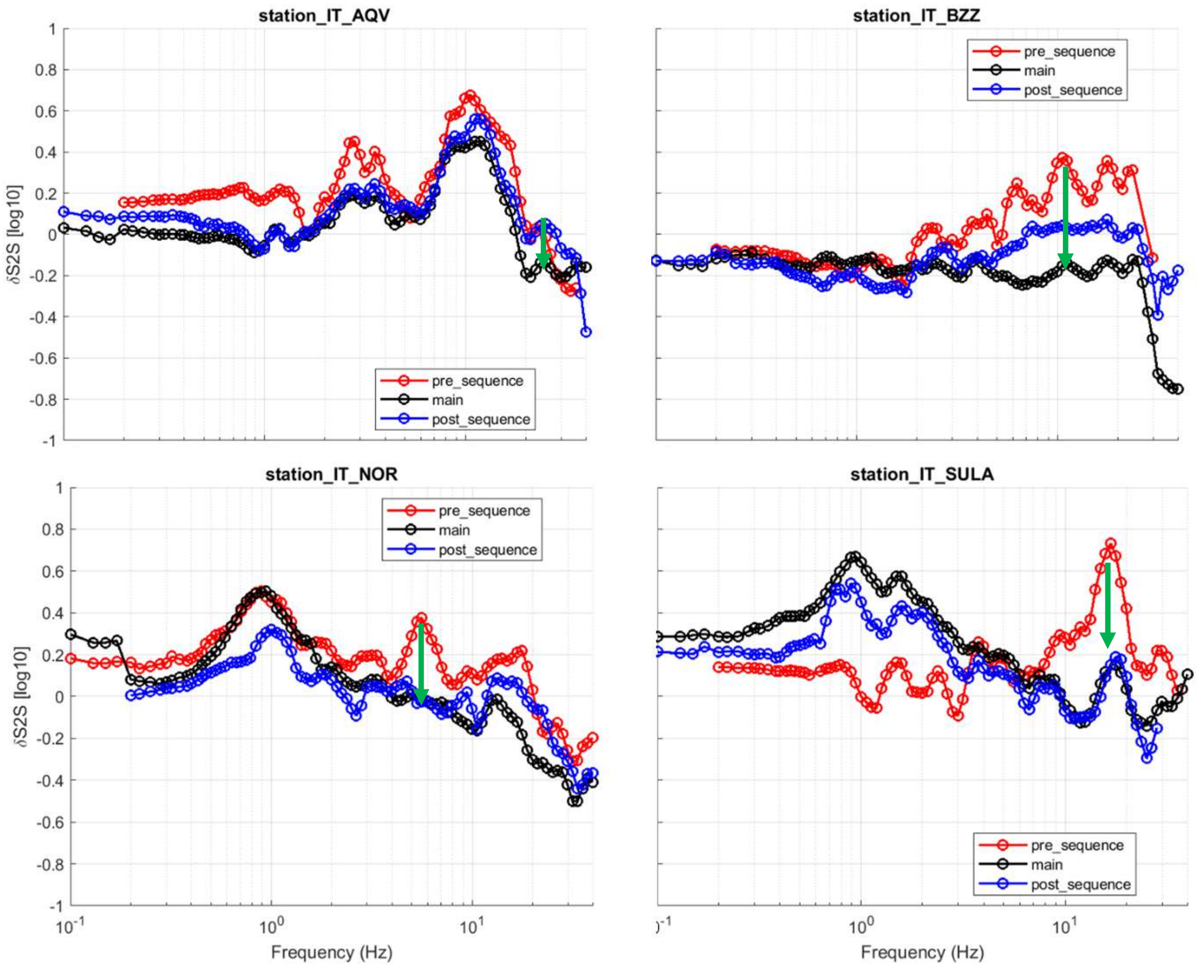




General reduction of ground motion
due to increase of attenuation

NENS: nonstationarity of dS2S

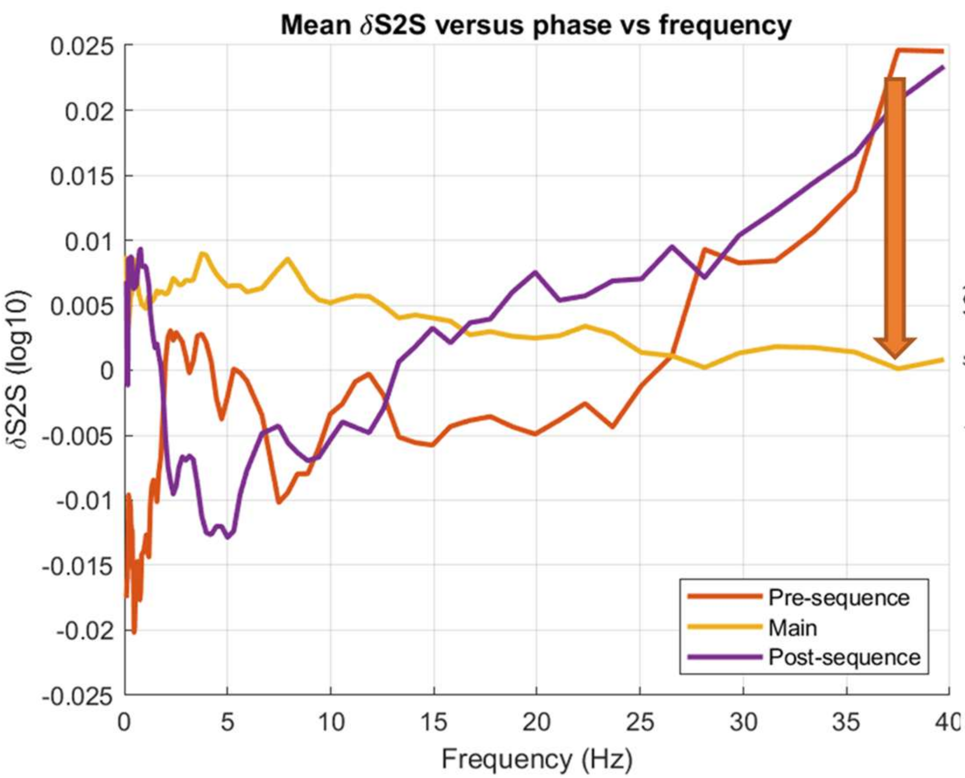


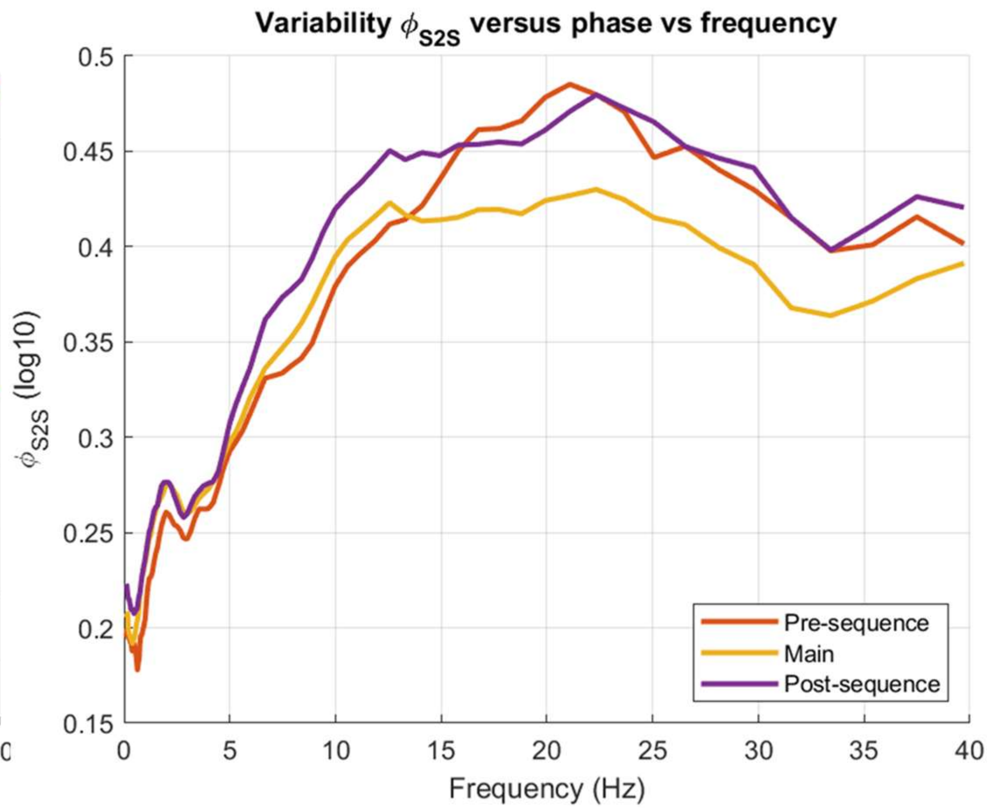


IM ~ 1 + M + MlogDIST + logDIST + DIST + flag + M^2 + (**1** | **eventi**) + (**1** | **stazioni:** phase) + (**1** | **source:** phase) + (**1** | **path:** phase)

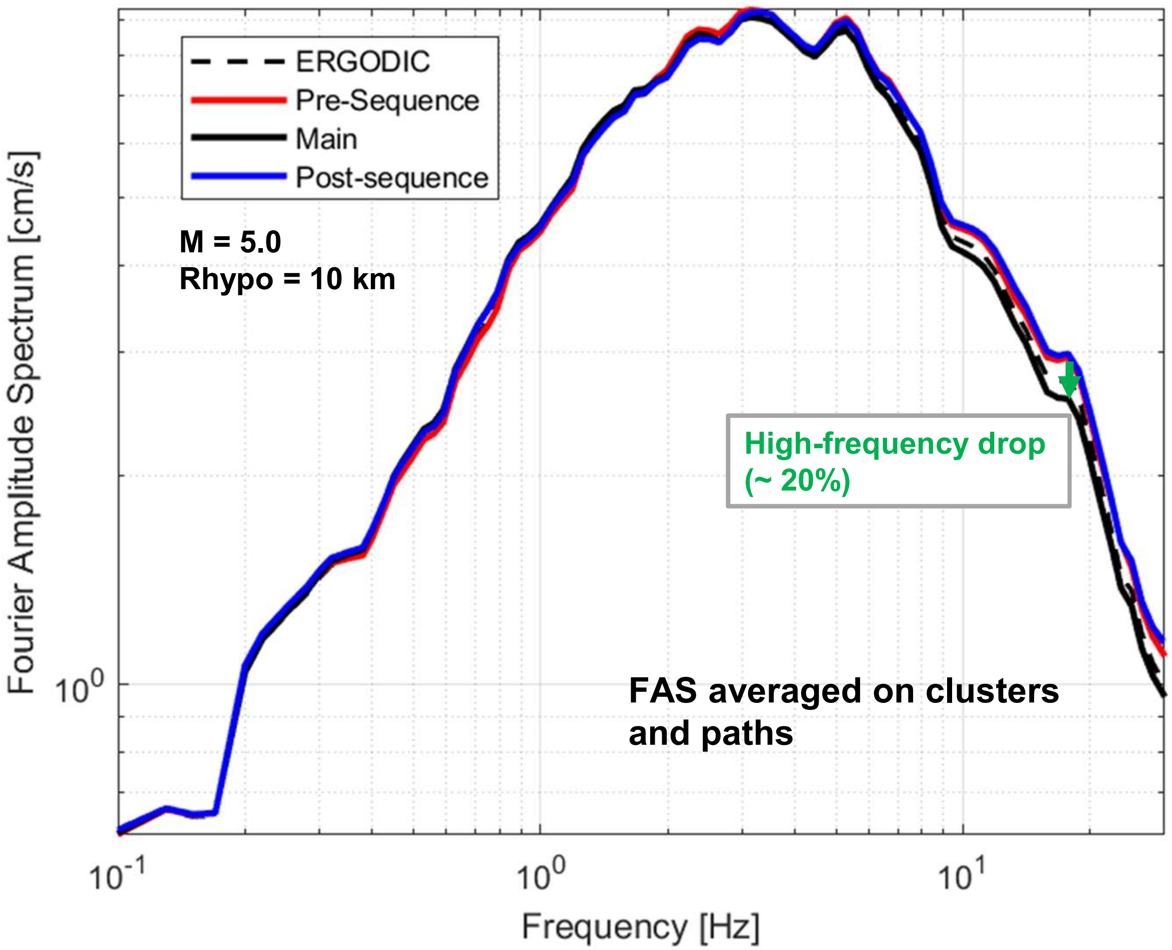
Drop at resonant frequency after mainshocks due to temporary reduction of the shear wave velocity and slow recovery in post-sequence (consistent findings on HVSR *Vassallo et al., 2022*)

NENS: nonstationarity of dS2S

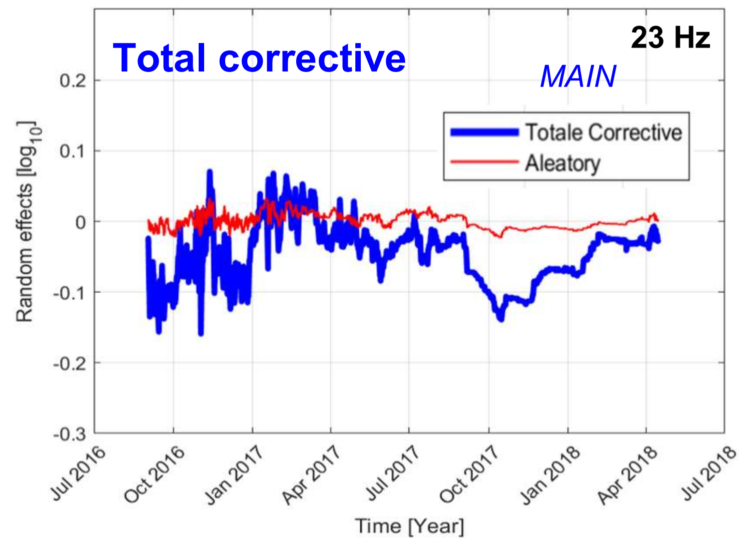




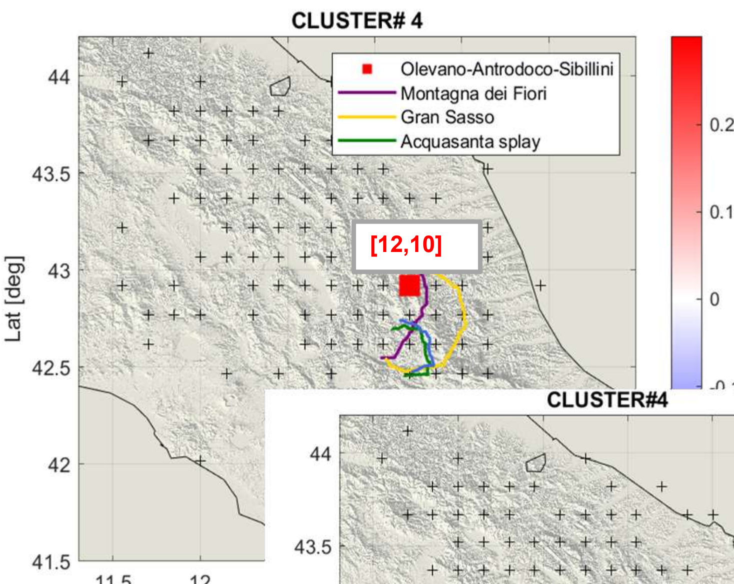
NENS: impact on spectral predictions



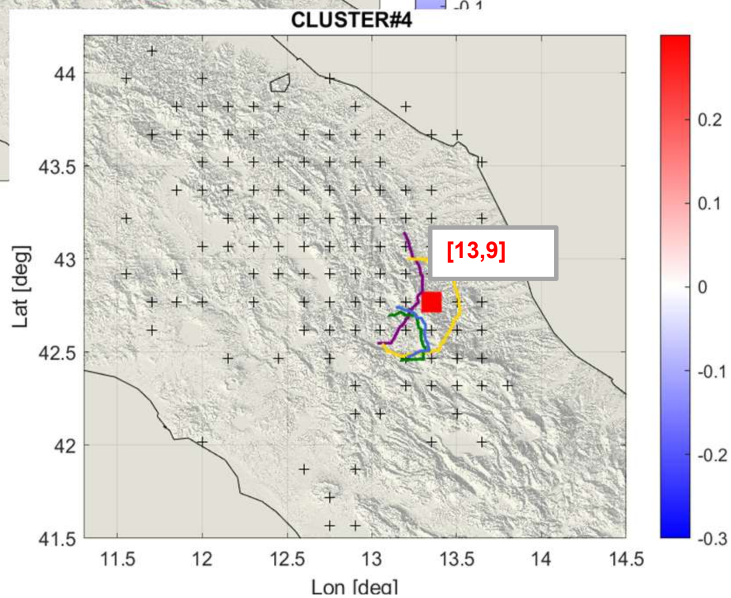
The total correction term tends to be **negative on average during the sequence**. This suggests that dynamic effects **overall reduce the ground motion** compared to a median stationary prediction

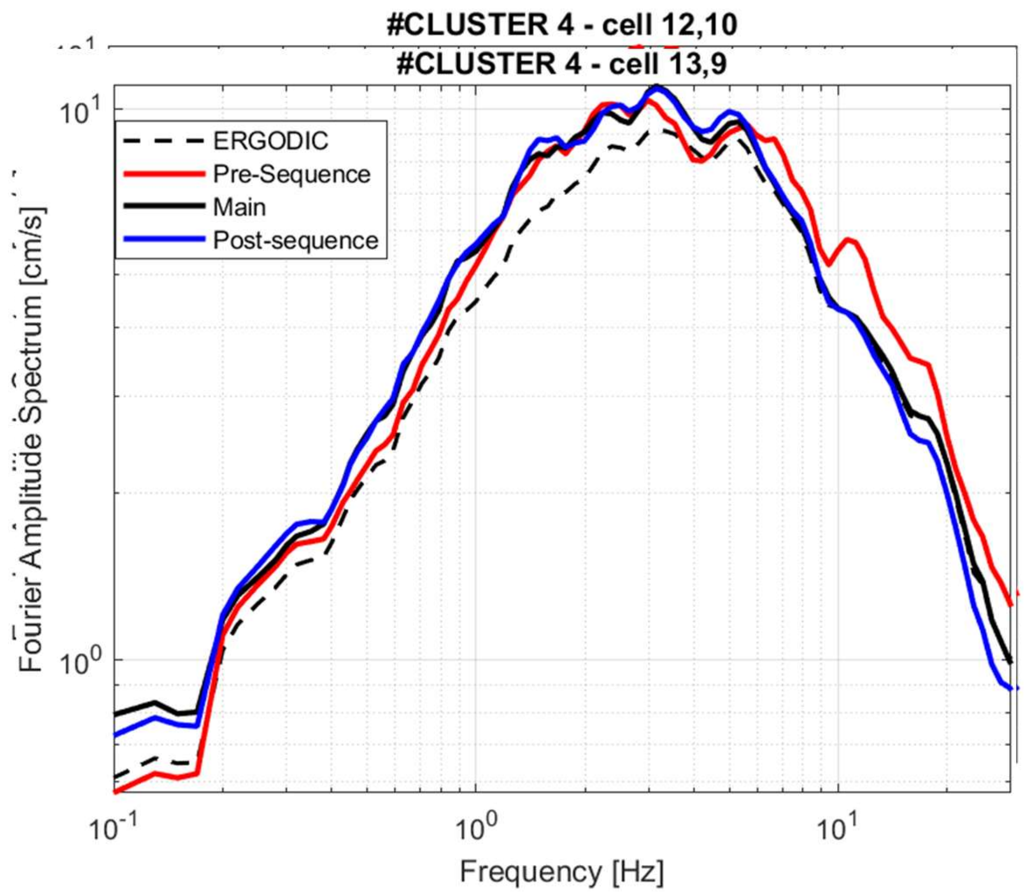


NENS: impact on spectral predictions



M = 5.0
Rhypo = 10 km





Conclusions

- ❑ Ground Motion shows strong **non-stationarity in space and time**
- ❑ 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)
  - ✔ **Time-varying 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 during main sequence at HF compared to stationary models, due to dissipative phases (e.g., fluid presence, scattering)

→ *on average minimal impact on the global predictions w.r.t. stationary/ergodic models*

→ ***BUT**… may be important for **scenario**-based predictions and short-term forecast! OR for **preparatory phase** analysys…*