44th GNGTS National Conference

Udine, 10-13 February 2026

Workshop di Microzonazione Sismica: dalla ricerca scientifica a nuovi standard, pratiche e linee guida

Criticità, spunti e proposte per input sismico e amplificazione locale: il contributo delle stime empiriche

Giovanna Cultrera[1], Salomon Hailemikael[1], Giovanni Lanzano[1], Carla Barnaba[2], Giovanna Laurenzano[2], Maria Rosaria Gallipoli[3], Guido Martini[1], Alessandro Peloso[4], Sara Sgobba[1], Francesca Pacor[1]

(1) INGV - (2) OGS - (3) CNR-IMAA - (4) ENEA

ISTITUTO NAZIONALE DI GEOFISICA E VULCANOLOGIA

OGS

ENEA

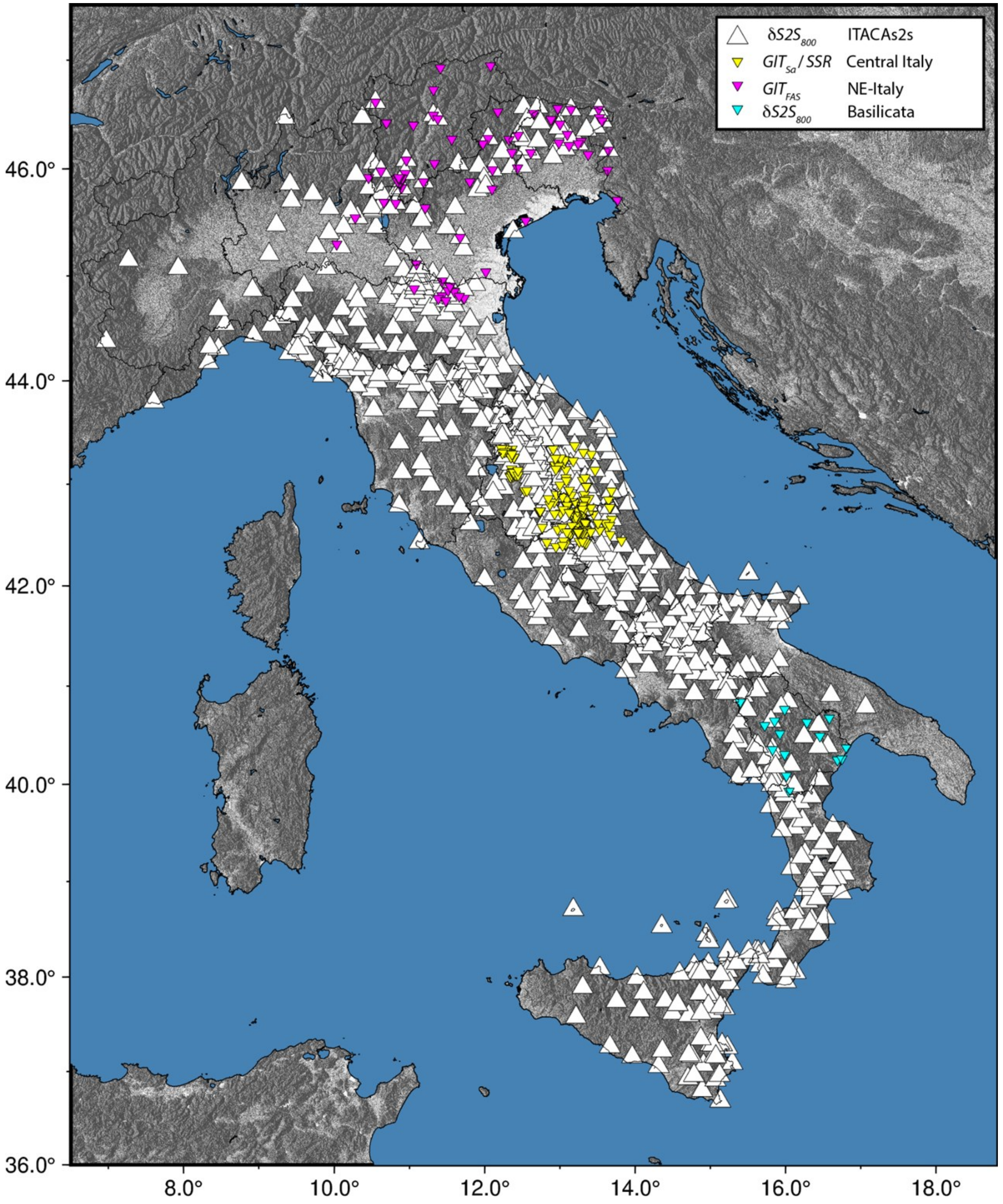
CentroMS

CENTRO PER LA MICROZONAZIONE SISMICA E LE SUE APPLICAZIONI

Empirical Data as the Direct Measure of Ground Motion

- **Shift to Direct Observation -** The use of empirical data (e.g. seismic recordings), is now a well-established practice
  - Empirical methods have matured significantly over the last decades
  - Provide a direct observation of ground motion rather than a simulation
  - Estimates derived from data are statistically robust

- **Scientific Basis -** Grounded in extensive observational databases, ensuring statistical significance:
  - ITACA 4.0: covering over 900 stations and ~42,000 records across Italy
  - Seismic sequences campaigns and local experiments



Distribution of sites across the Italian territory for which empirical ground-motion amplification estimates are available, distinguished by estimation method.

CentroMS
CENTRO PER LA MICROZONAZIONE SISMICA E LE SUE APPLICAZIONI

Reliability of Established Methodologies

- **Metric -** period-dependent Amplification Factors (AF) from Spectral Acceleration (Sa) or Fourier Amplitude Spectra (FAS) integrals over specific period bands

- **Techniques -** The approach utilizes extensively peer-reviewed methods: Standard Spectral Ratio (SSR), Generalized Inversion Technique (GIT), and Site-to-Site Residuals (delta S2S)

Selected intensity measure is the amplification factor (AF):

$$AF_i = Sa_i^{out}/Sa_i^{in} \;\; for\ i = 1,2,3$$

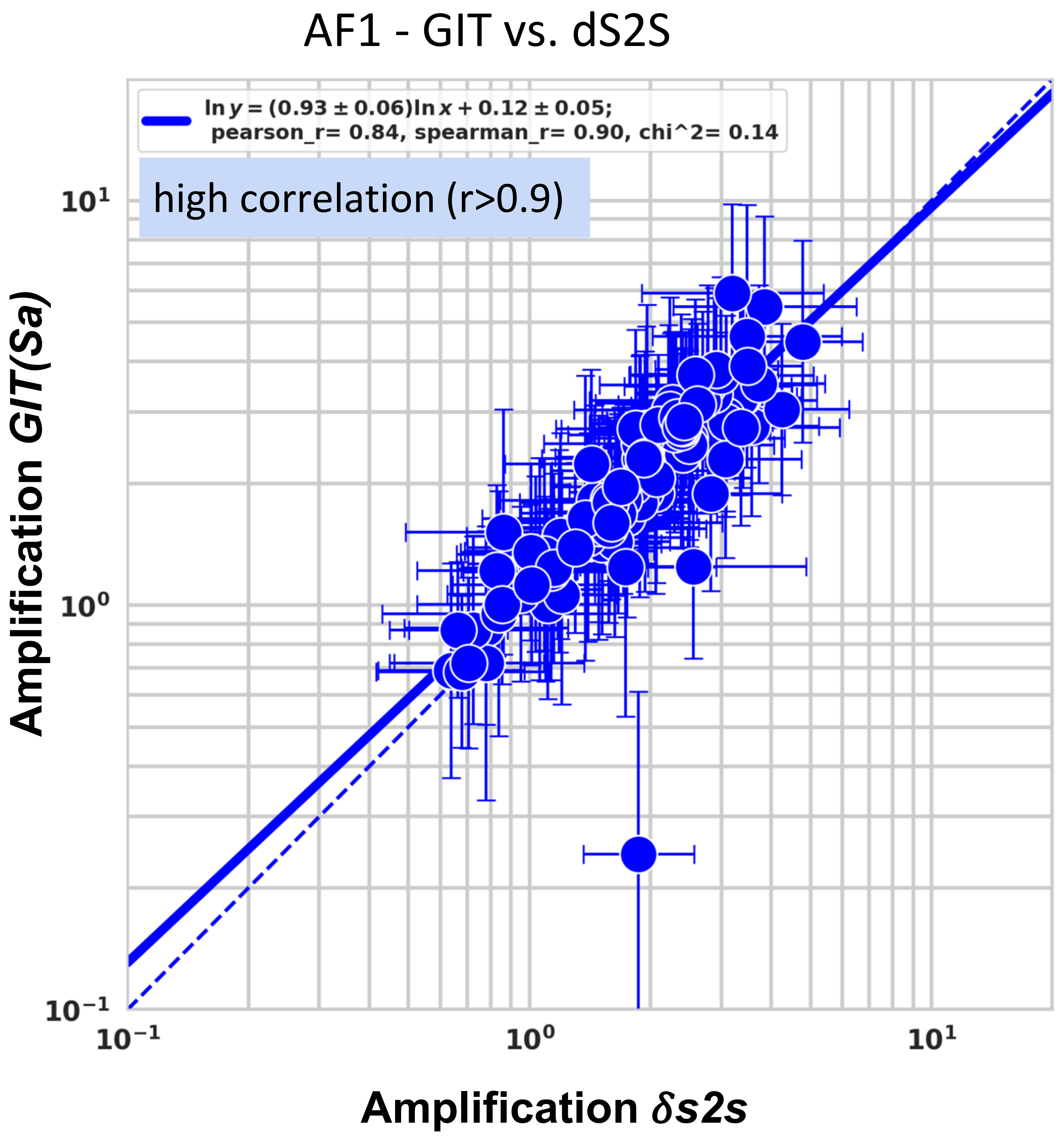
$$Sa_i^k = \frac{1}{\Delta T_i}\int_{\Delta T_i} Sa^k(T)dt \;\; for\ k = in,\ out$$

$$\Delta T_1 = 0.1 - 0.5\ s;\ \Delta T_2 = 0.4 - 0.8\ s\ and\ \Delta T_3 = 0.7 - 1.1\ s.$$

- ***δs2s,*** Sa_i^{in} predictions from ITA18 Model for Vs,30=800 m/s and Sa_i^{out} are the observed values, integral is approximated by averaging residuals within ΔT_i.
- ***GIT,*** Sa_i^{in} is the average of a set of hazard compatible accelerograms and Sa_i^{out} is obtained from convolution (*GIT, FAS*) or multiplication (*GIT,Sa*) of the site amplification function with the input.
- ***SSR,*** Sa_i^{out} *and* Sa_i^{in} are computed from recordings at the target site and reference station.

Consistency Among Empirical Estimates

- **High Correlation**: Independent empirical methods (δS2S, GIT, SSR) show remarkable correlation (Spearman's ρ>0.9) across all period bands.
- **Equivalent Distributions**: Statistical tests (Kolmogorov-Smirnov) confirm distributions from different methods are statistically equivalent.
- **Physics-Based Agreement**: Despite different algorithms, the methods consistently identify the same relative amplification patterns, confirming they are capturing the "true" physical response of the site

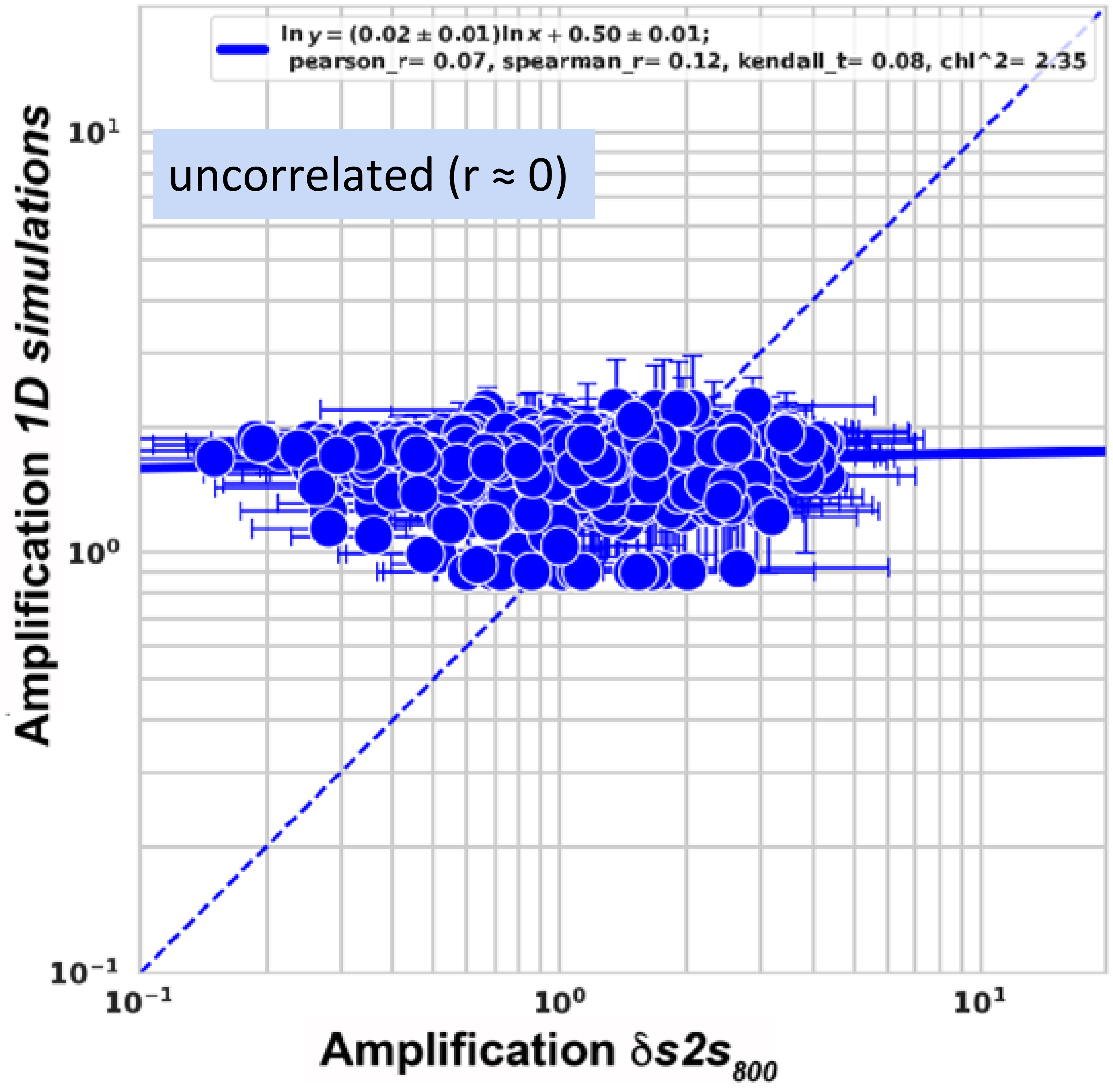


Data from Central Italy (100 sites)

Empirical Estimates vs. numerical 1D simulation

Numerical 1D models (i.e. Falcone et al. 2021) - fail to match observed ground motion

AF1 - 1D vs. dS2S



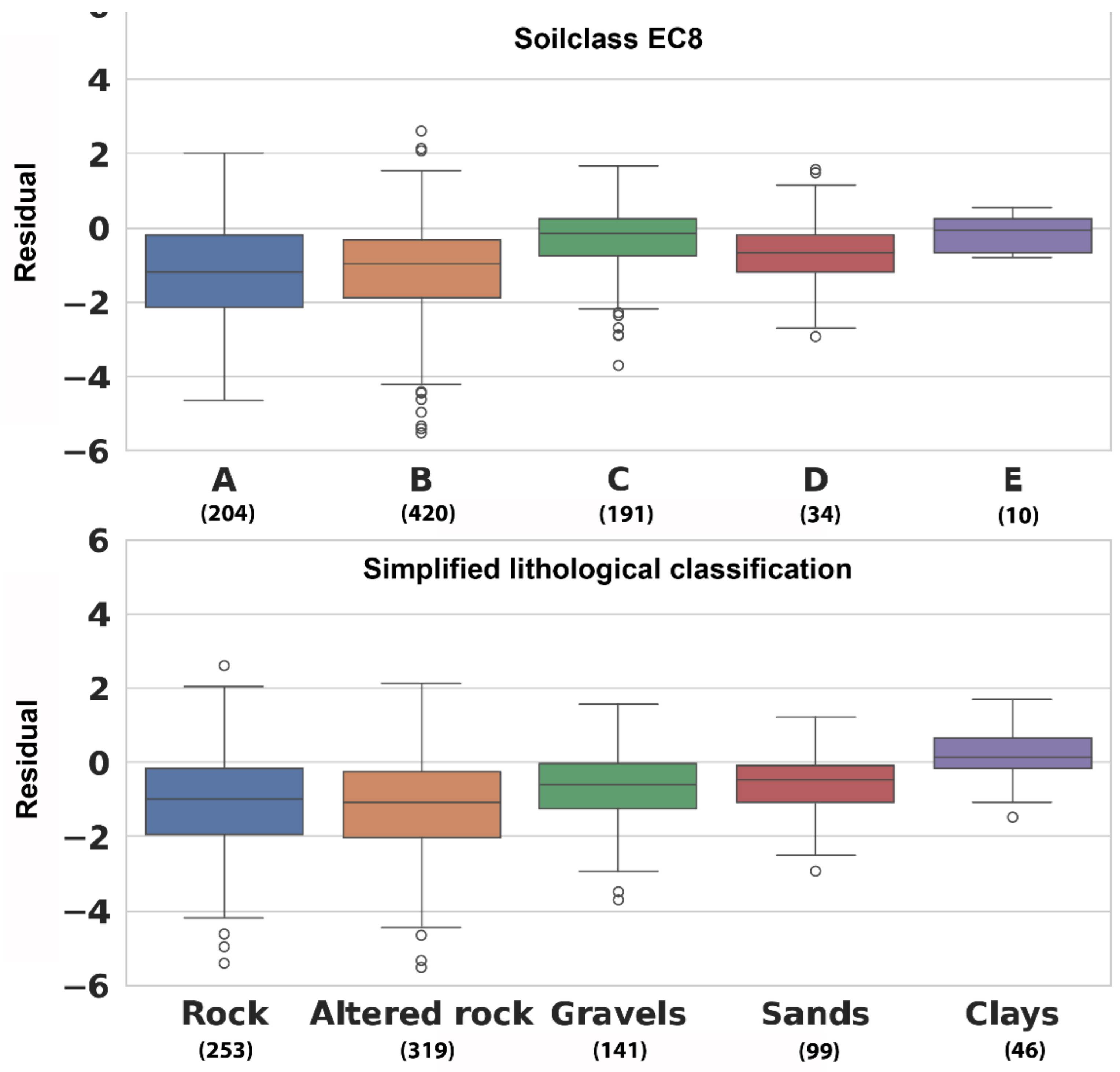
Data from 916 sites (national level)

Empirical Estimates vs. numerical 1D simulation

Numerical 1D models (i.e. Falcone et al. 2021) - fail to match observed ground motion:

- **about 5% of sites** → 1D underestimate empirical (residuals >1): deep basins (due to ignored 2D/3D effects)
- **30% of sites** → 1D is consistent with empirical (residuals around zero)
- **65% sites** (Appennine belt and in the Tyrrhenian side of the Italian peninsula) → 1D simulations overestimate the empirical amplification (negative residuals): rock (Class A/B)

$$Res_k = \frac{\ln\left(AF_{\delta s2s}\right) - \ln\left(AF_i\right)}{\sigma_{ln}}$$



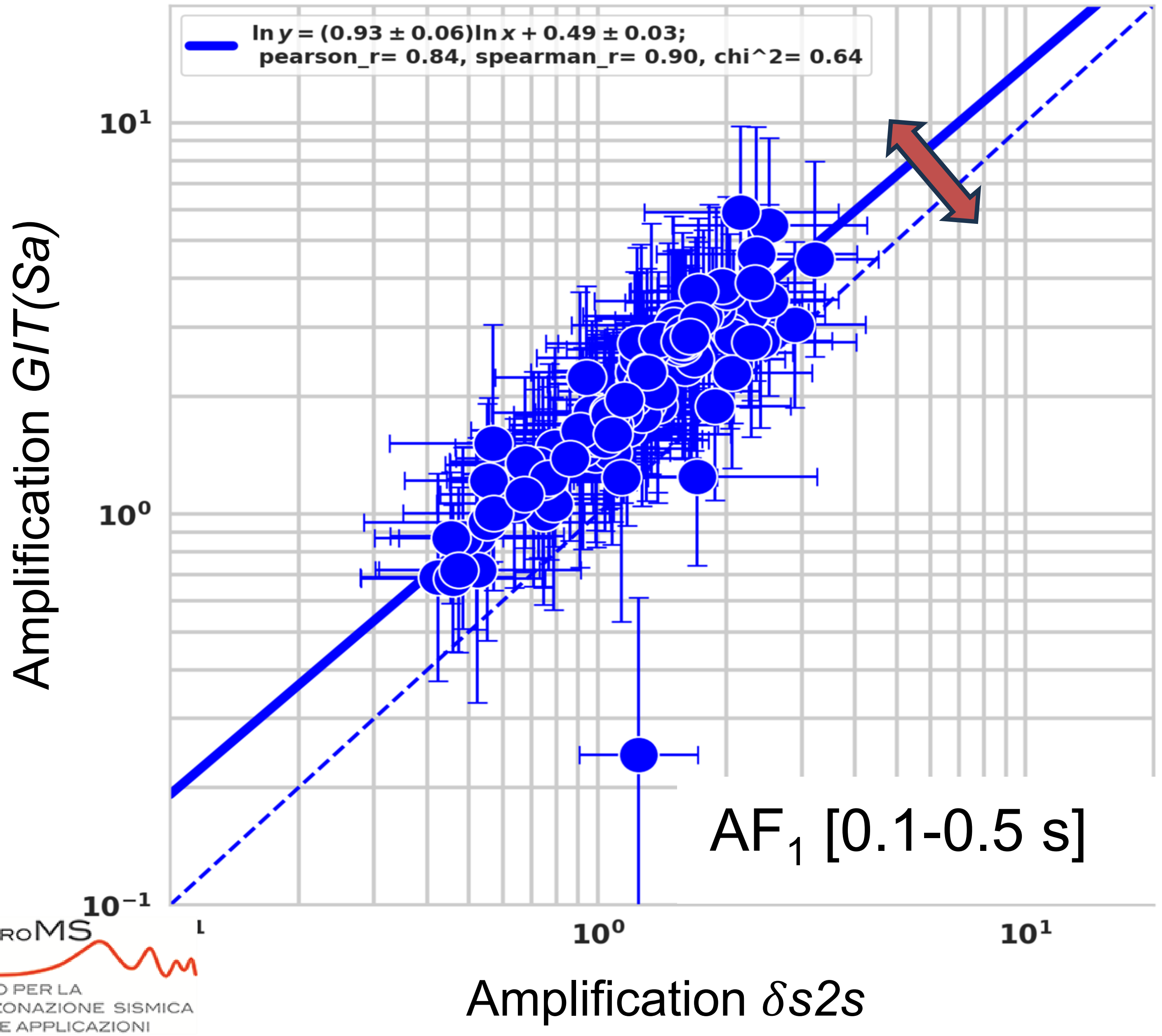
Data from 916 sites (national level)

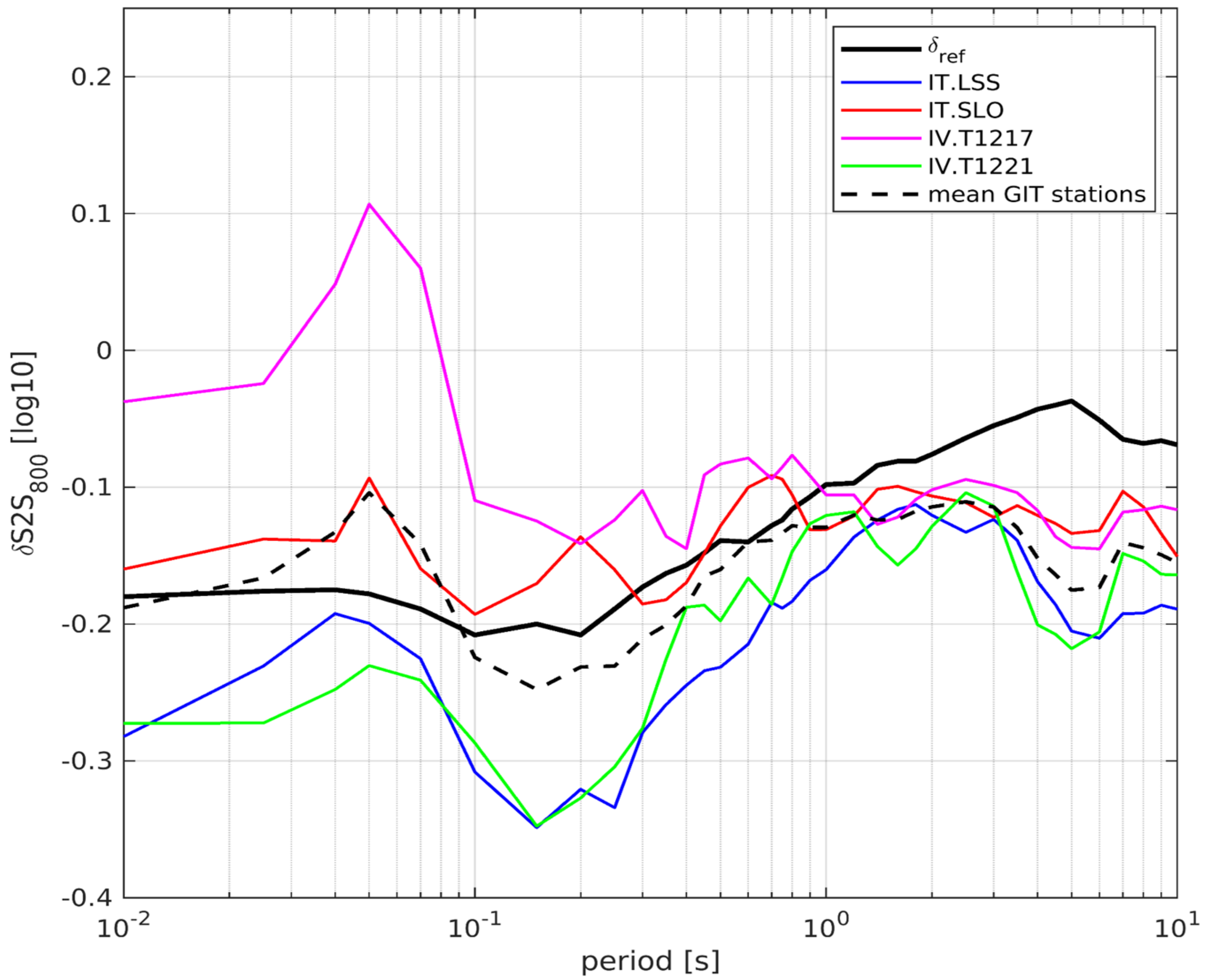
Challenge I - The Reference Site Definition

Generic-to-reference ground-motion

- **Ideally vs. Reality:** Defining a "standard rock" reference (VS,30 = 800 m/s) is complex; real rock sites often display weathering or topographic amplification

- **Systematic Deviations:** In Central Italy, a bias was observed between methods (dS2S vs. GIT) caused by reference sites showing non-negligible de-amplification or high-frequency attenuation



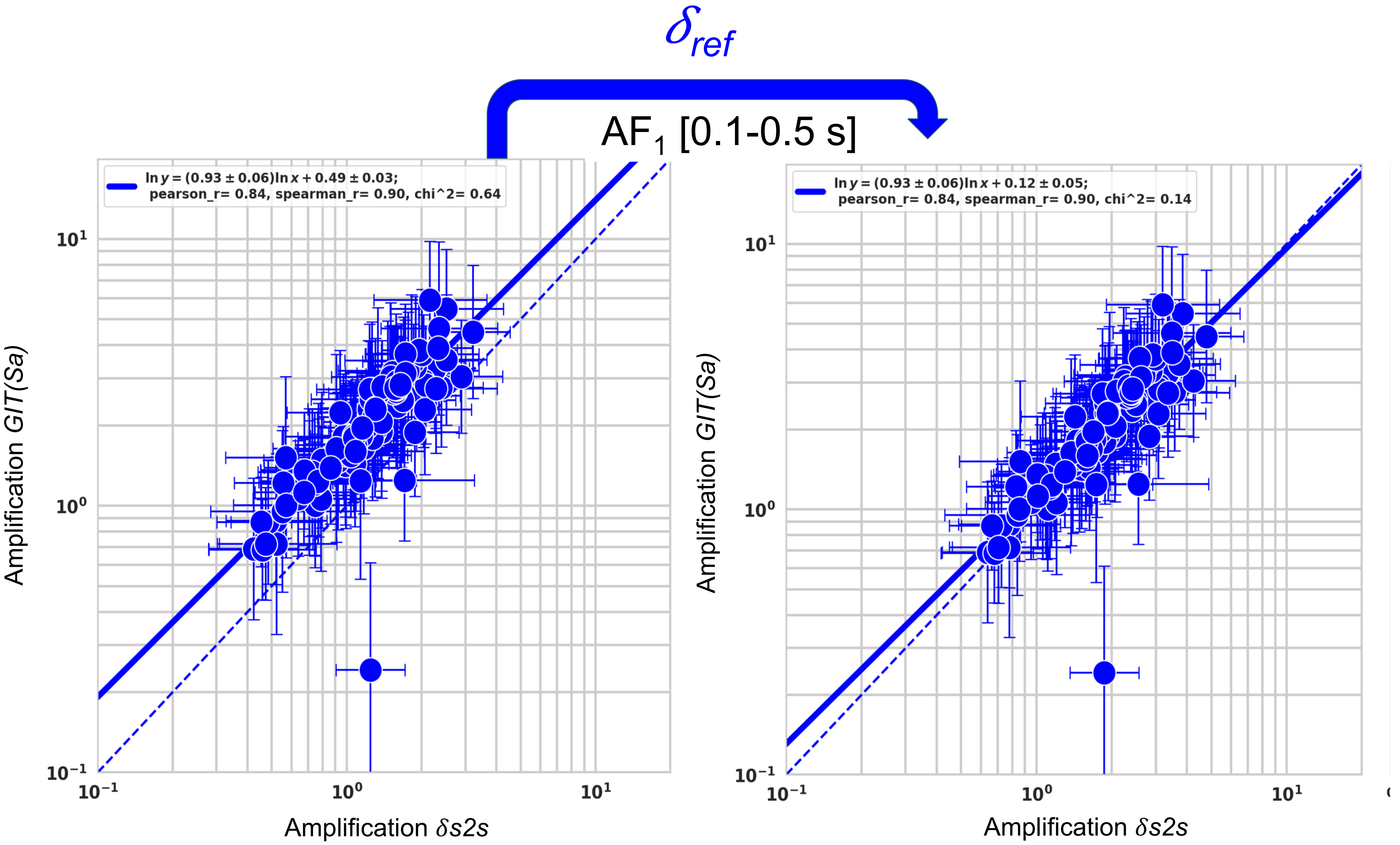


generic-rock conditions include several stations with non-negligible ground motion amplifications

Challenge I - The Reference Site Definition

Generic-to-reference ground-motion

- **Correction Strategy:** Applying a "generic-to-reference" scaling factor successfully removes these biases, aligning distributions from different methods
- **selected reference sites**: characterized by low or absent local ground motion amplification
- **correction function** (δref), for generic-to-reference ground-motion scaling: by computing the residuals between the ITA-18 GMM for generic rock conditions and the ground motion recorded at reference sites

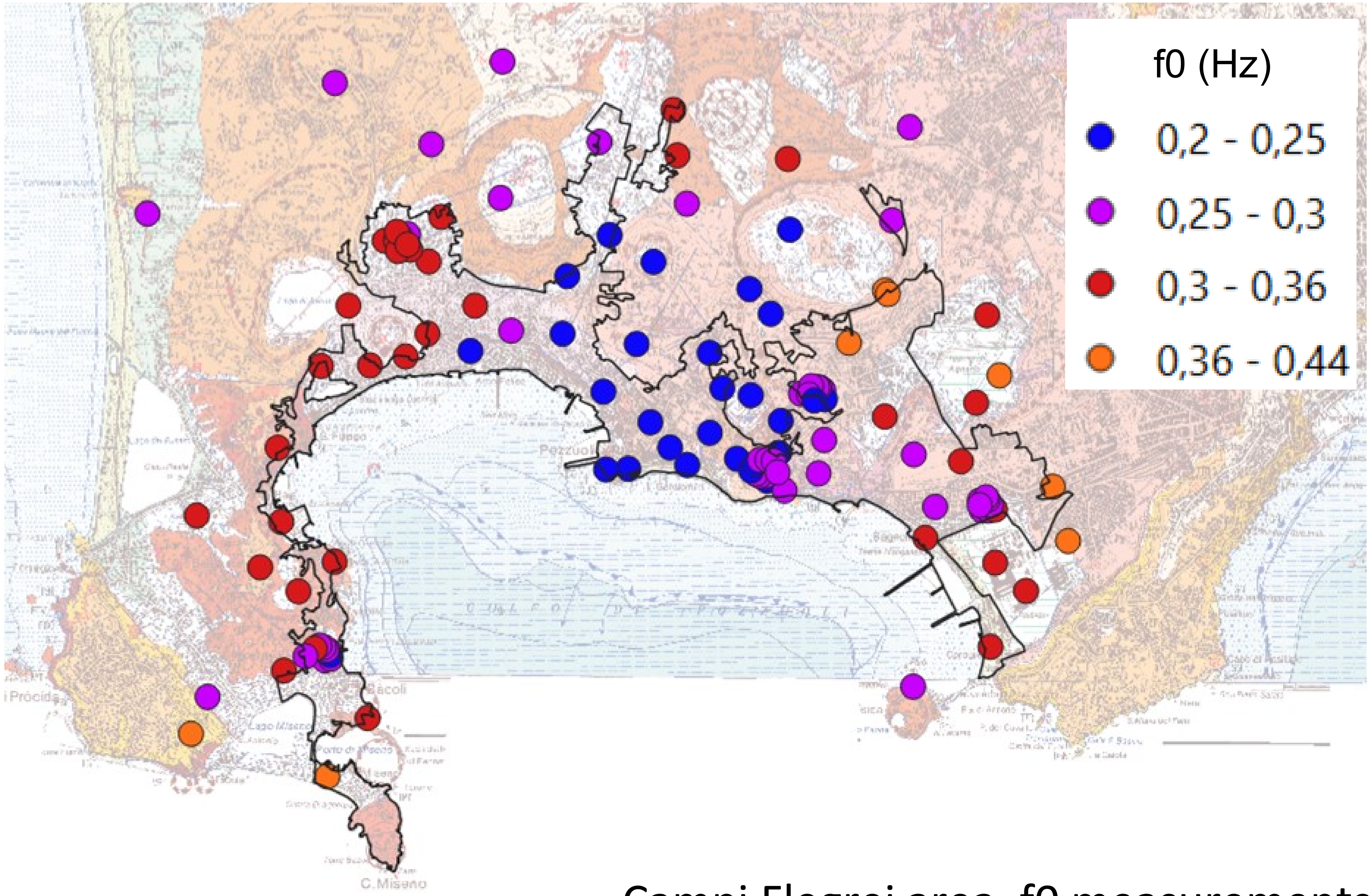


Application of δ_{ref} at the site amplification estimates in Central Italy (hereinafter $\delta S2S_{ref}$) compensates for the systematic deviations previously observed between $\delta S2S_{800}$ and the GIT_{Sa} amplification

CentroMS
CENTRO PER LA MICROZONAZIONE SISMICA E LE SUE APPLICAZIONI

Challenge II - The Spatial Gap

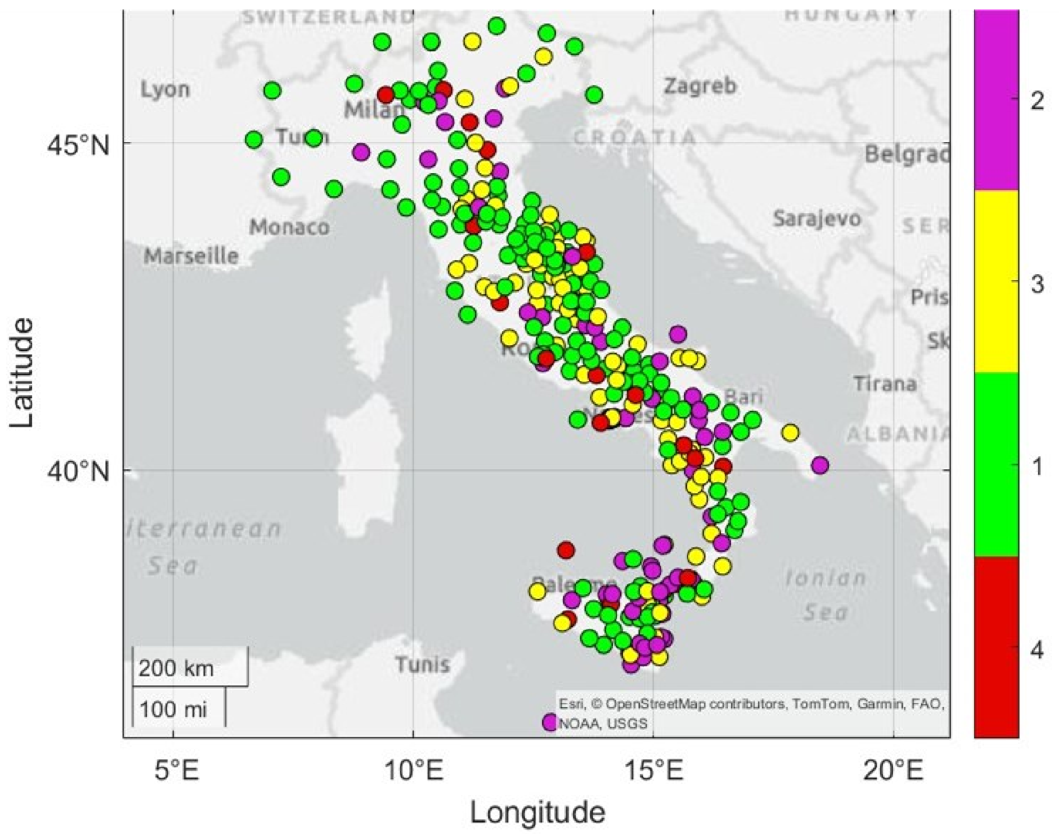
- **Point-Based Limitations:** Empirical estimates are inherently valid strictly at the recording station location, creating a challenge for areal microzonation
- **Microzonation** requires areal coverage, not just single point
- **Local Variability:** High-resolution cluster analysis reveals that sites just hundreds of meters apart can exhibit distinct amplification behaviors
- **The "Zonation" Hurdle:** Moving from a "station point" to a "homogeneous zone" requires robust proxies to bridge the spatial gaps

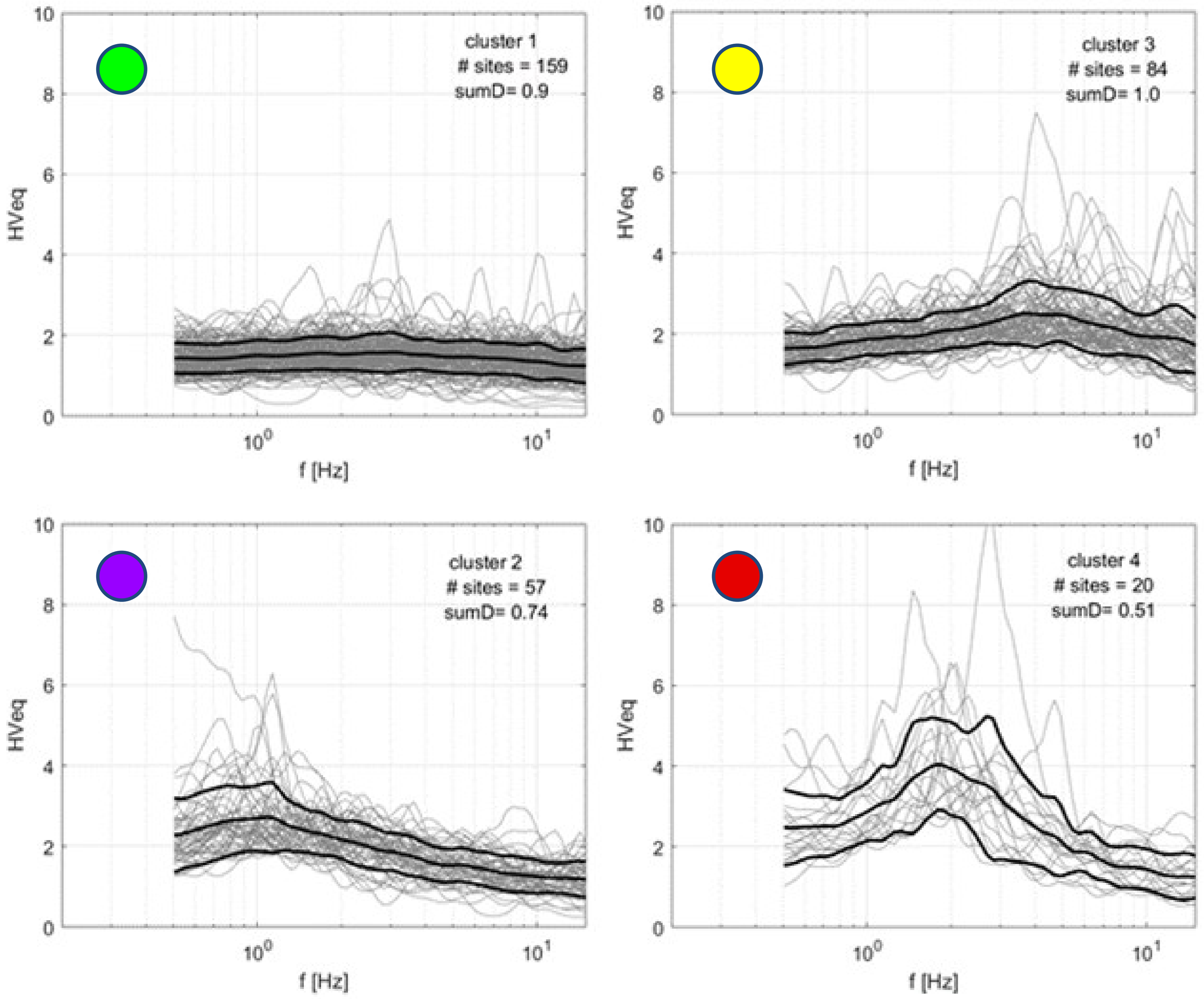


Campi Flegrei area, f0 measurements (Cultrera et al., Session 2.2)

Proposal I - Spatialization Strategies

- **Goal**
  To identify homogeneous zones where the empirical AF from a single station is statistically valid for the surrounding area
- **Strategies**
  - **Cluster Analysis:** Grouping sites with similar geophysical signatures (e.g., HVSR curves from noise and earthquakes) to define "characteristic" amplification behaviors

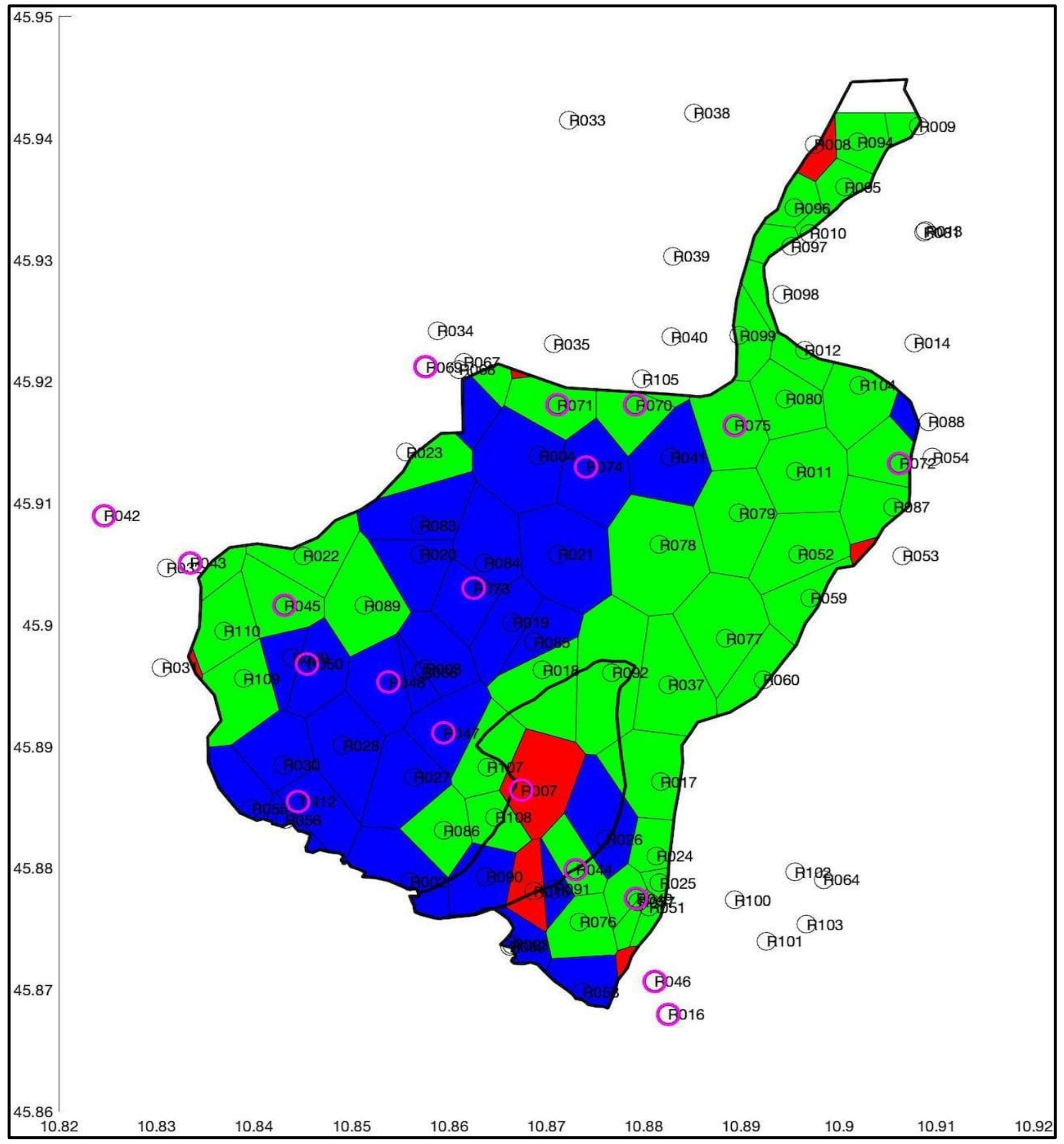




HVSR from 320 sites of RSN network
http://crisp.ingv.it (Cultrera & Mercuri, BEE 2025)

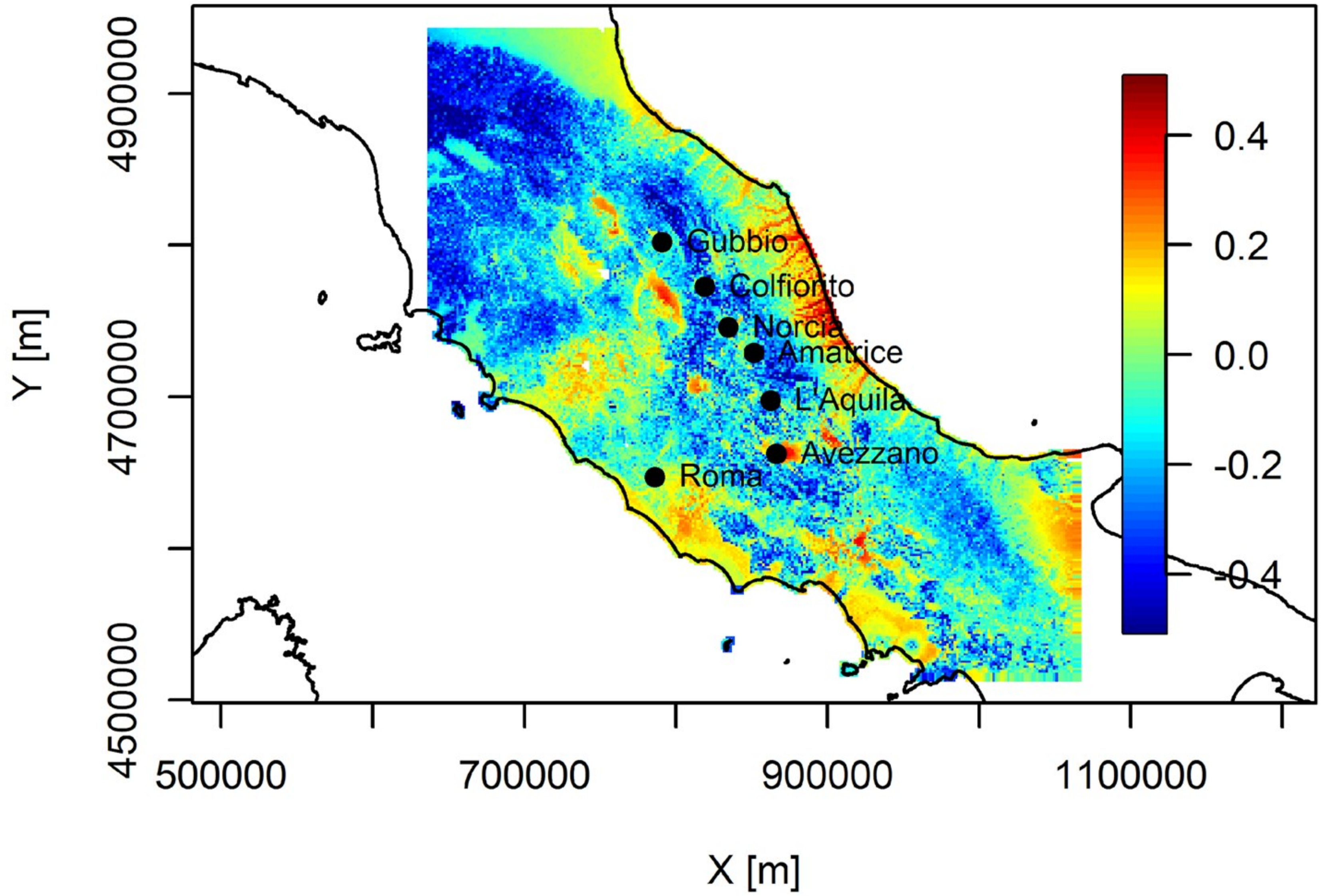
Proposal I - Spatialization Strategies

- **Strategies (continue)**
  - **Integration of Noise Data:** Using dense seismic noise measurements (HVSR) as a bridge to densify datasets and link temporary points to permanent station benchmarks
  - **Geostatistical Extrapolation:** Employing Machine Learning and Kriging to correlate empirical AFs with available proxies (geology, slope, VS,30) for areal mapping



CentroMS
CENTRO PER LA MICROZONAZIONE SISMICA E LE SUE APPLICAZIONI

Example of spatialization Alto Garda area (Laurenzano et al. SDEE 2023)



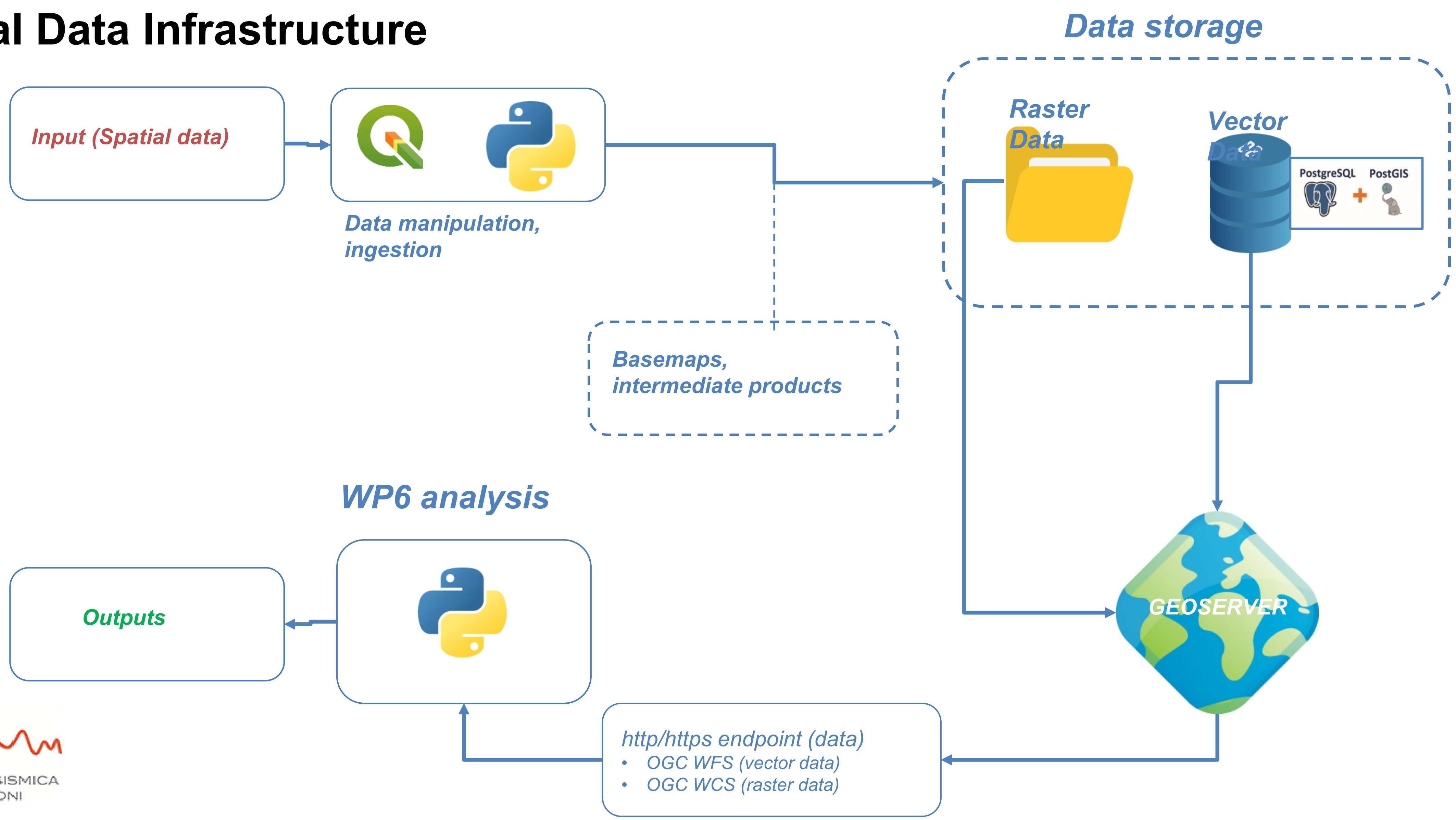
Sgobba et al., SDEE 2024

Infrastructure Requirements

Building a robust empirical framework requires high-quality database foundation:

- **Data Homogenization:** standardizing data format and processing methods
- **Interoperability** between the database and professional analysis software and(or other databases
- **Integrity & Availability:** Ensuring long-term preservation and constant availability of the data to support engineering workflows

Spatial Data Infrastructure



Data ETL example:

- Topology check, verify geometry validity (QGis)
- Spatial join over stations layer (QGis)
- Load results in the geodb (Postgresql/PostGIS)
- Layer Field Names consistency check

As long as the data structure remains unchanged, the data is ready to be accessed by users.

Key messages

Main Message:

- Empirical data (specifically Amplification Factor - AF) represents the direct measure of ground motion
- The methods are well-established, robust, and consistent.
- Simplified 1D modeling is an unbiased predictor for only ~35% of sites; it is insufficient for complex geological contexts

Challenges:

- Limitations of point-based estimates
- reference site definition
- need for local earthquake recordings (to remove regional propagation effects).

Proposals:

- Increase studies on spatialization (extrapolating point data).
- Crucial Workflow Change: Professionals should use empirical AFs as a benchmark for linear numerical simulations before adding non-linear components.
- The Path Forward: The future of microzonation lies in a hybrid approach: anchored in direct empirical observation and spatially extended through advanced geostatistics

Thank you for your attention

Speaker: Giovanna Cultrera

Contacts: giovanna.cultrera@ingv.it