RIUNIONE PLENARIA SECURE

Variabilità spazio-temporale del parametro di attenuazione in alta frequenza κ
&
Parametrizzazione ingegneristica degli effetti di direttività di sorgente

L. Colavitti, G. Lanzano, S. Sgobba, F. Pacor,
R. Castro, D. Spallarossa, F. Gallovič

PIANETA DINAMICO
WORKING EARTH

Roma, 30 gennaio 2024

Variabilità spazio-temporale del parametro di attenuazione in alta frequenza κ

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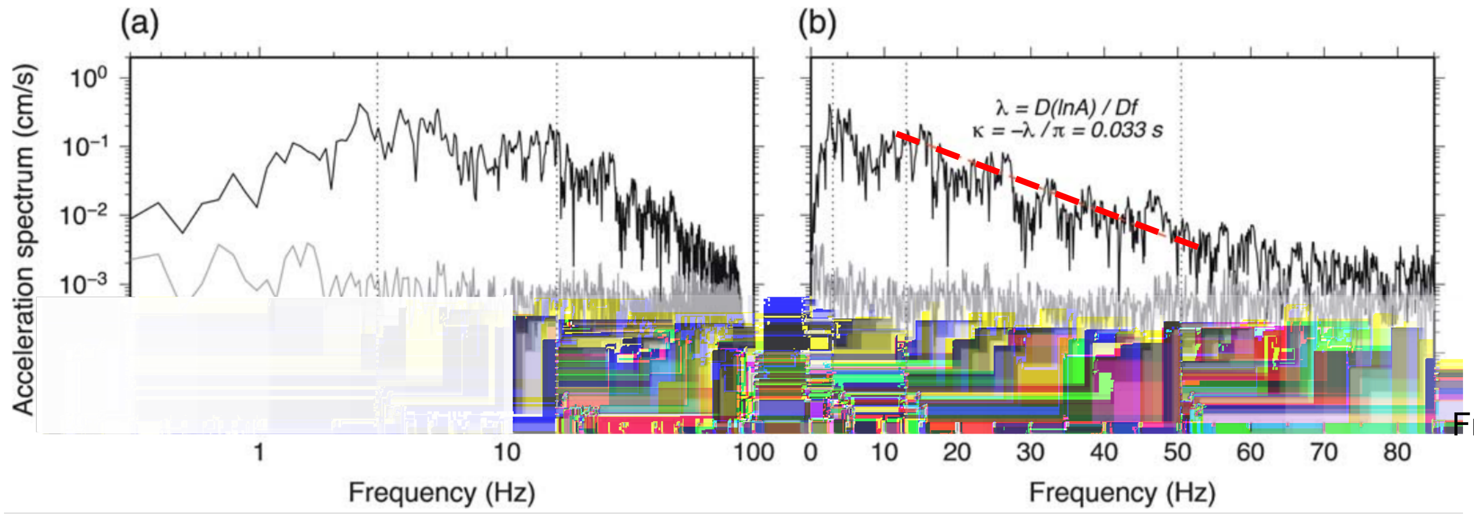
State of the Art

- The attenuation decay parameter **κ** is largely used in many **earthquake engineering applications**
- **κ describes the deviation at high frequencies** between observed Fourier amplitude spectra computed from seismograms and ω^2 model
- For Anderson and Hough (1984), above a certain frequency, the overall **shape of the spectrum decays exponentially with frequency**



From Ktenidou *et al*. (2014)

State of the Art

- **κ parameter increases with epicentral distance**, and includes the local effects due to geological characteristics near the recording site and the attenuation due to the regional structure
- The observed values of **κ** are the results of **path** effects, attenuation near the **source** and the recording **site**

$$\kappa(r) = \boxed{\kappa_0} + \boxed{\kappa_s} + \boxed{\kappa_{avg}(r)}$$

From Anderson (1991); Ktenidou *et al*. (2014)

Near-site attenuation parameter

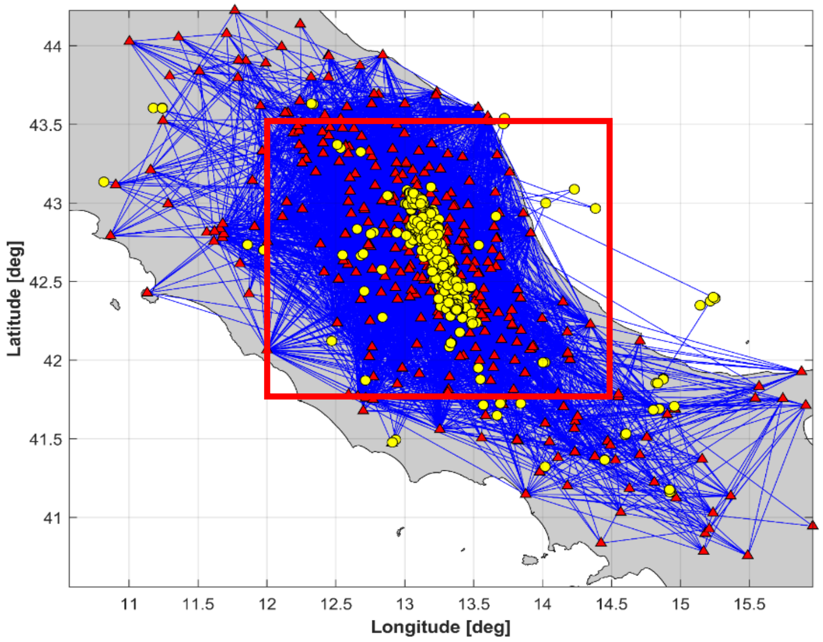
Near-source attenuation parameter

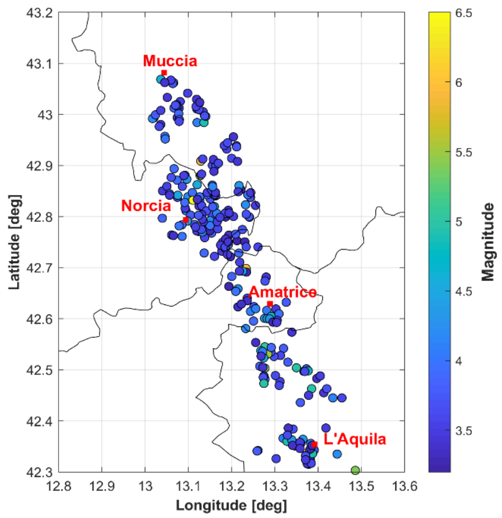
Average attenuation along the S-wave path

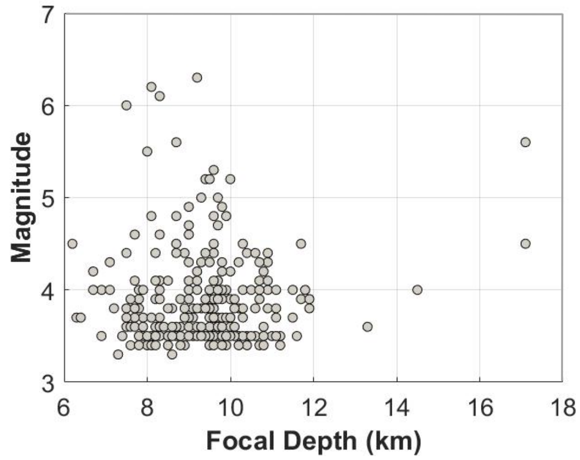
Goals: Analyze single contribution due to **site**, **source** and **S-wave path** and investigate spatial and temporal variability of κ using data set of a dense array

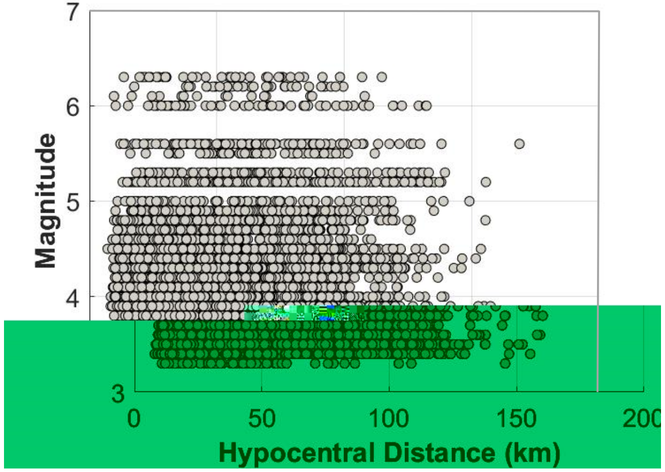
Dataset

Events with M > 3.5 in Central Apennines (2008-2018)







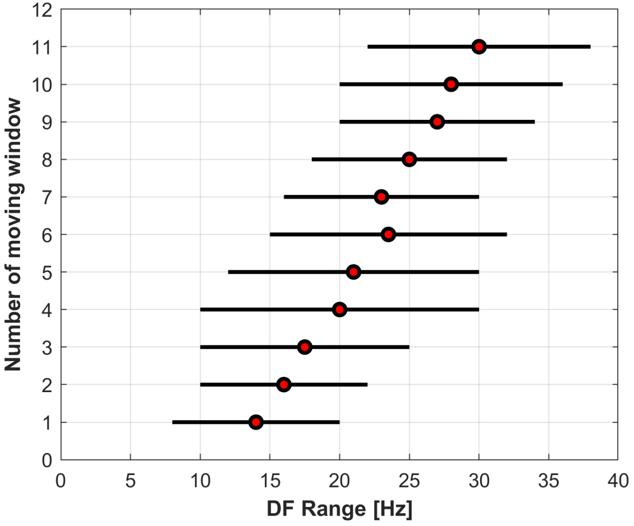


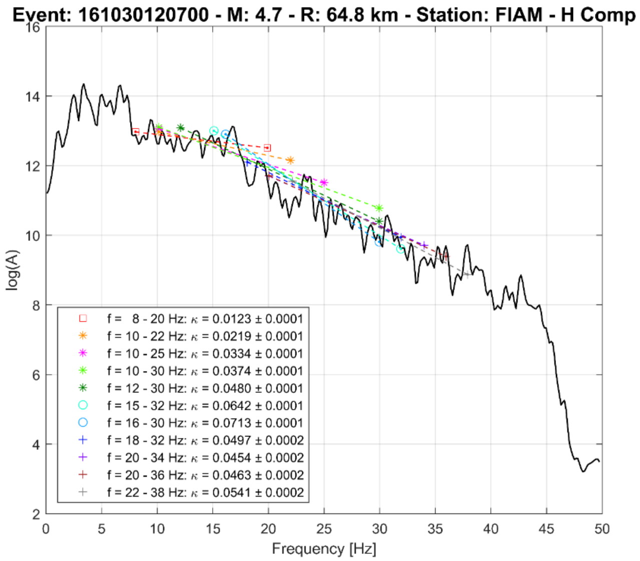
- Events detected by at least 3 stations
- Standard Deviation of κ / κ < 0.50

- 266 earthquakes
- 353 stations
- 13’952 recordings

Method

- 11 frequencies band between 8-38 Hz
- Computation of κ_0 according Anderson and Hough (1984) method





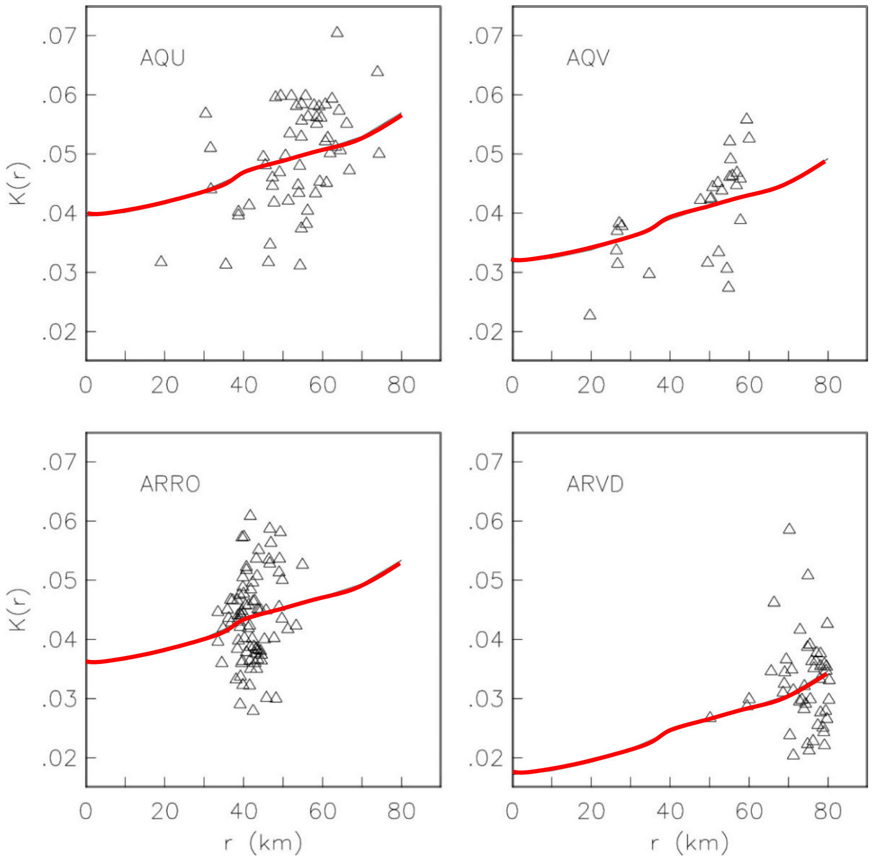
- If one of the 11 intervals have SNR < 3, the estimate of κ is rejected
- Average value at least 6 out of 11 intervals
- The median of κ is discarded if the standard deviation is larger than 0.015 s

Estimation of $\kappa_{avg}(r)$

$$\kappa(r) = \kappa_0 + \kappa_S + \boxed{\kappa_{avg}(r)}$$

We compute the average attenuation along the S-wave using a **non-parametric approach** as in Anderson (1991) and Fernández *et al*. (2010)

- The shape of $\kappa_{avg}(r)$ is the same for all sites, but is scaled by the respective value of of κ_0
- We observe a great variability, which mirrors a spatial variability of the attenuation between the different source-station paths

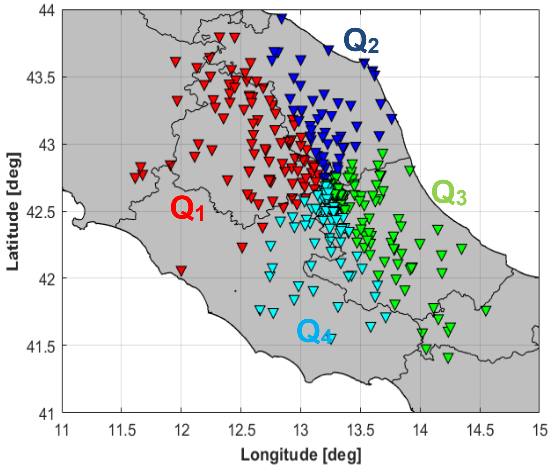


Castro *et al*. (2022) - SRL

Estimation of $\kappa_{avg}(r)$

$$\kappa(r) = \kappa_0 + \kappa_S + \boxed{\kappa_{avg}(r)}$$

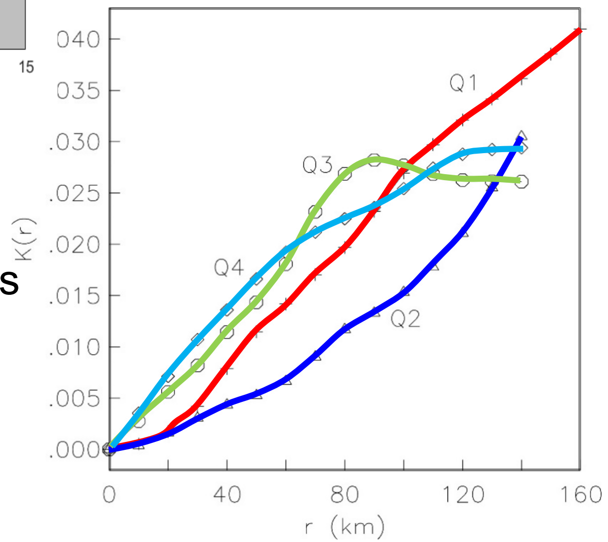
The great variability mirrors a spatial variability of the attenuation between the **different source-station paths**



4 "Rough" division

- ✓ For distance > 100 km, **Q_1 shows greater attenuation** than the other quadrants
- ✓ **Q_2 shows less attenuation** than the other zones
- ✓ **Q_3 and Q_4 show a decrease in κ** between 80 - 100 km, probably related to an **high Q**

4 non-parametric curves



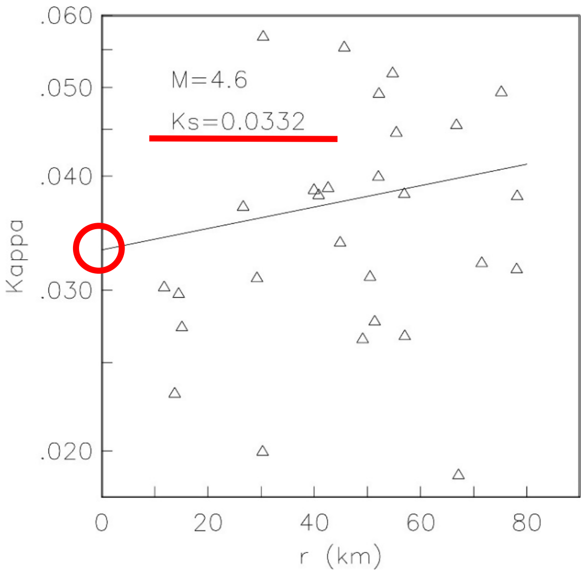
Higher values in the **southern sectors** may be related to a **highly segmentation** (see Akinci *et al*. 2020, Gabrielli *et al*. 2021)

Castro *et al*. (2022) - SRL

Estimation of κ_S

$$\kappa(r) = \kappa_0 + \boxed{\kappa_S} + \kappa_{avg}(r)$$

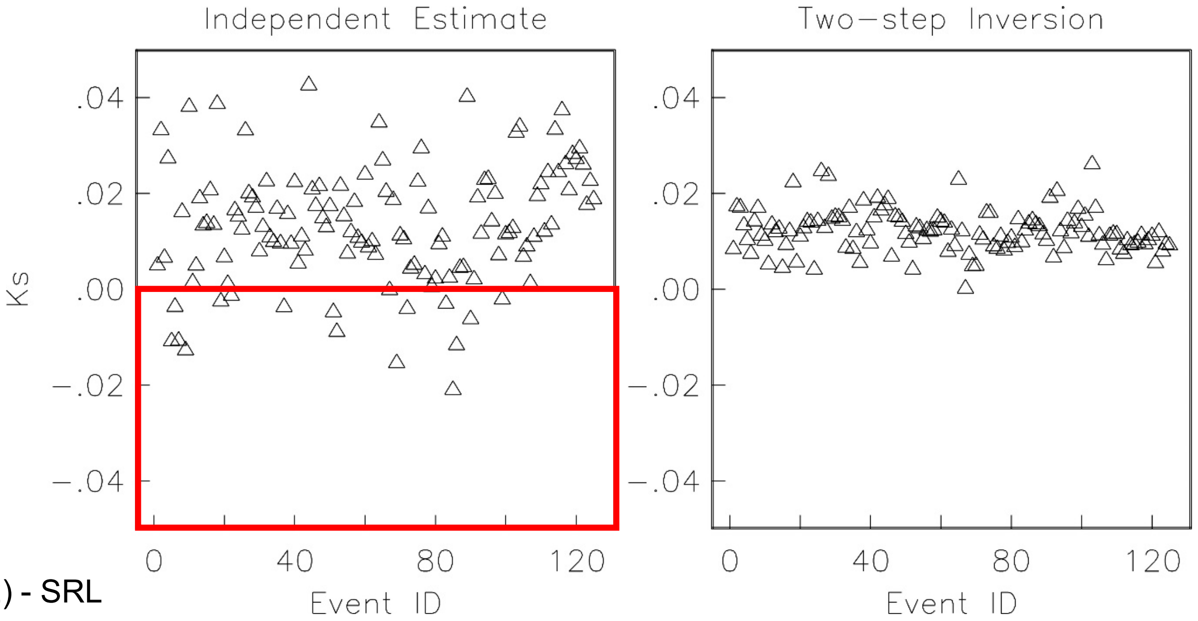
Independent estimated of κ_S for one event



Castro *et al*. (2022) - SRL

The intersection of the fitting line with the origin gives the value of κ_S, still need to be corrected by the mean κ_0 of the sites

κ_S for all events

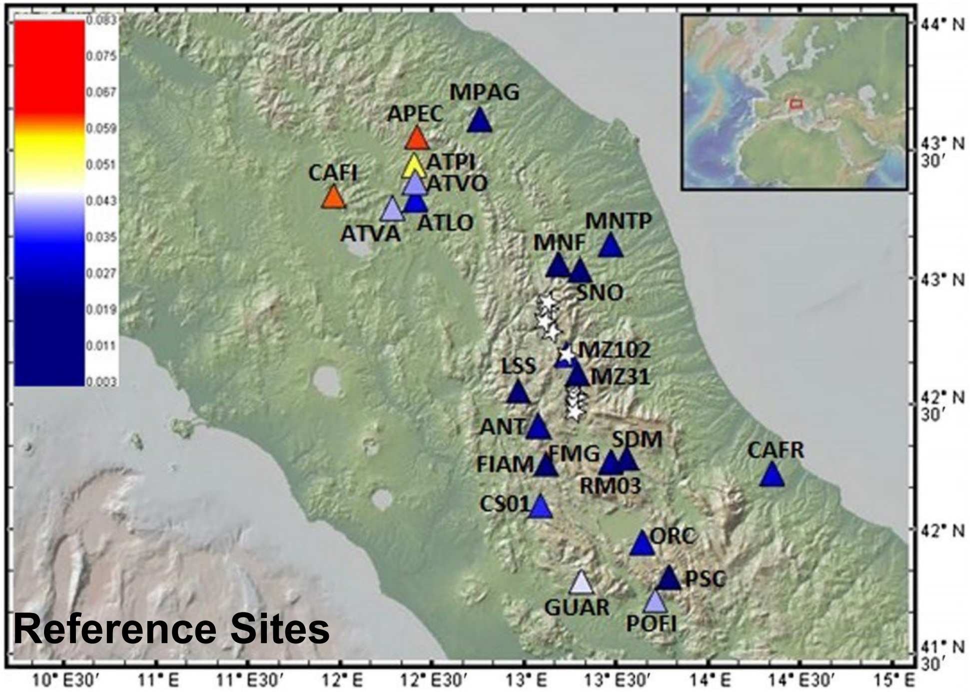


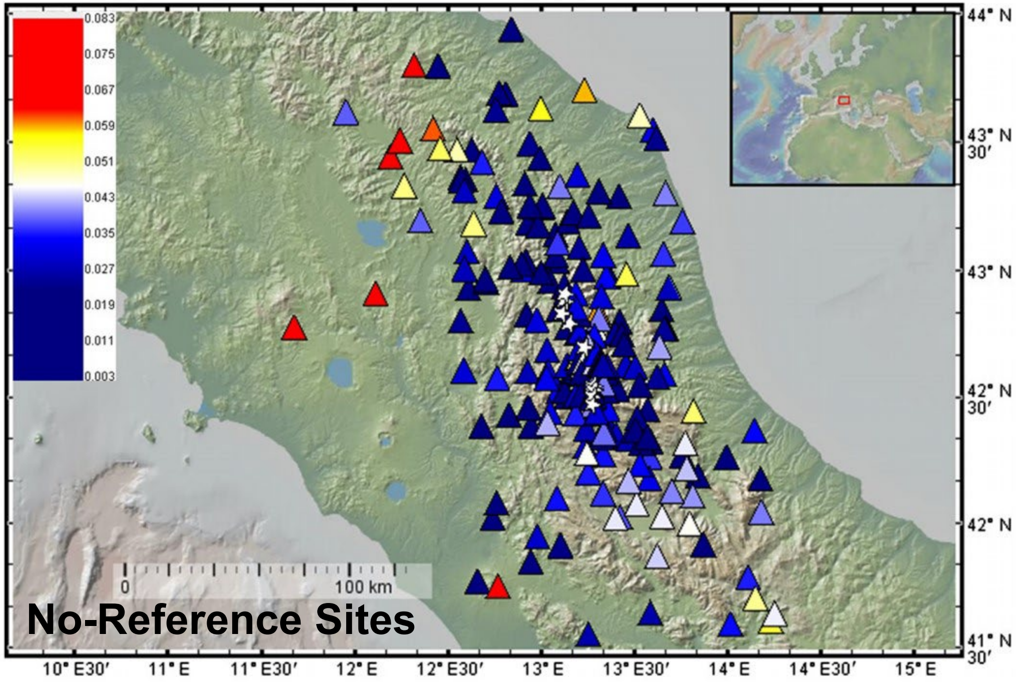
Two-step inversion to reduce the variability of κ_S

Spatial variability of κ_0

$$\kappa(r) = \boxed{\kappa_0} + \kappa_s + \kappa_{avg}(r)$$

Castro *et al*. (2022) - SRL



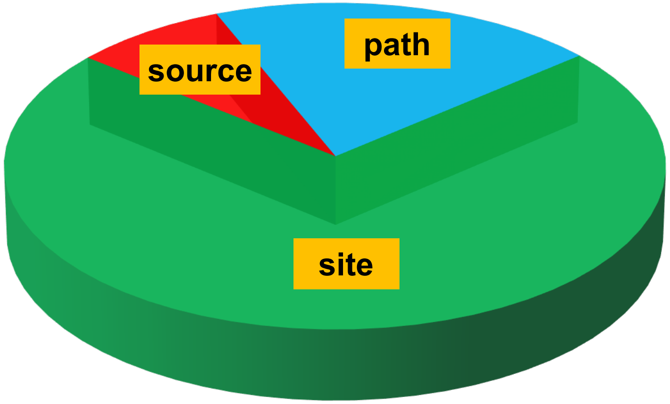


- Sites with low values of κ_0 are located on hard-rock outcrops while sites with high values are close to sedimentary basins
- Most of the sites show low values of κ_0 (<0.02 s), suggesting a weak correlation with $V_{s,30}$ map

Take-home message (1)

- In the Central Italy study area, the fundamental contribution of the total decay parameter is related to the site, with κ_0 corresponding to around **72%** of the total κ (mean **0.0298 ± 0.0133**)
- The near-source decay parameter κ_s has a mean value of **0.003 ± 0.006** and represents **7.5%** of the mean value of the observed κ
- The component $\kappa_{avg}(r)$ contributes with around **20%** with respect to the overall κ

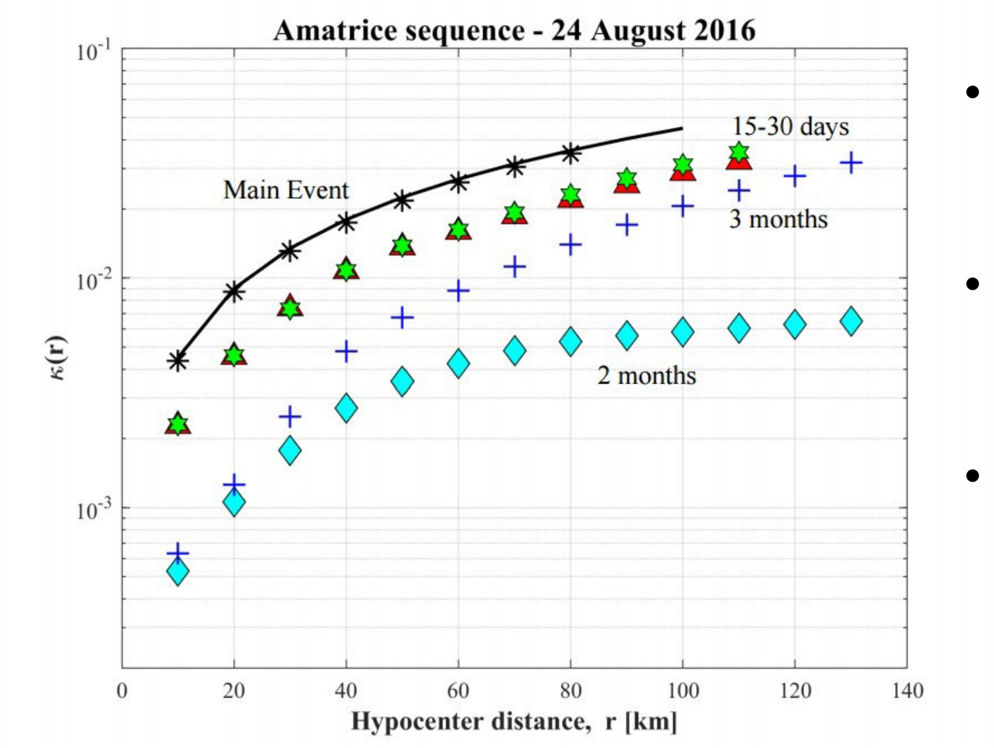
$$\kappa(r) = \boxed{\kappa_0} + \boxed{\kappa_s} + \boxed{\kappa_{avg}(r)}$$



Total value of κ:
0.0412 ± 0.0177

Temporal variability of $\kappa_{avg}(r)$

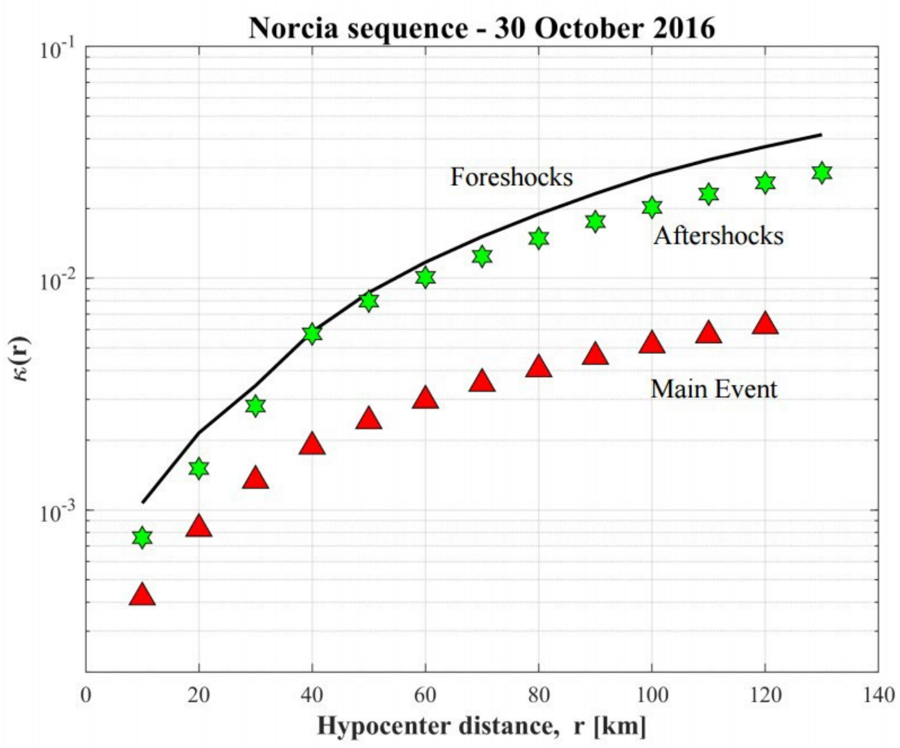
2016 Amatrice-Visso-Norcia sequence



Castro *et al*. (2022) - BSSA

- We observe a **regional drop (85% decrease) of the attenuation parameter κ** within 2 months after the Amatrice earthquake
- After this period, $\kappa_{avg}(r)$ starts increasing for the next month, probably due to **fluids re-distribution** (see Malagnini *et al*. 2022)
- Then, $\boldsymbol{\kappa_{avg}(r)}$ tends to return to toward the attenuation **values observed before the main event**, when the earthquake cycle is completed

Temporal variability of $\kappa_{avg}(r)$



2016 Amatrice-Visso-Norcia sequence

- The **Norcia main event** generated a **significant attenuation drop**, possibly related with an **increase in tectonic stress and migration of fluids** outside the epicentral zone (according to Gabrielli *et al*. 2022 low scattering, low attenuation and so low $\kappa_{avg}(r)$)

Foreshocks analyzed from 8 October to 29 October 2016

Aftershocks analyzed from 30 October to 16 November 2016

Castro *et al*. (2022) - BSSA

Temporal variability of $\kappa_{avg}(r)$

2009 L'Aquila sequence

137 earthquakes **M ≥ 3.2** in a **radius < 20 km** of the main event

Hypo. distance **r <170 km** recorded by **at least 3 stations**

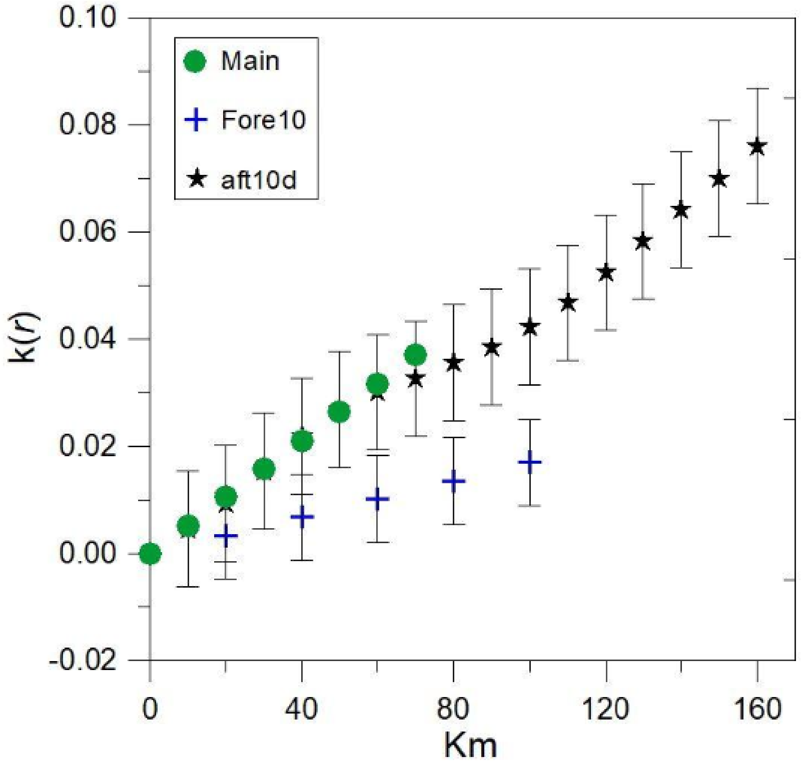
Castro *et al*. (2024) *in review* - GJI

4079 values estimates of **κ**

Temporal variability of $\kappa_{avg}(r)$

2009 L'Aquila sequence

Castro *et al*. (2024) *in review* - GJI



Foreshocks analyzed 10 days before 06 April 2009

Aftershocks analyzed 10 days after 06 April 2009

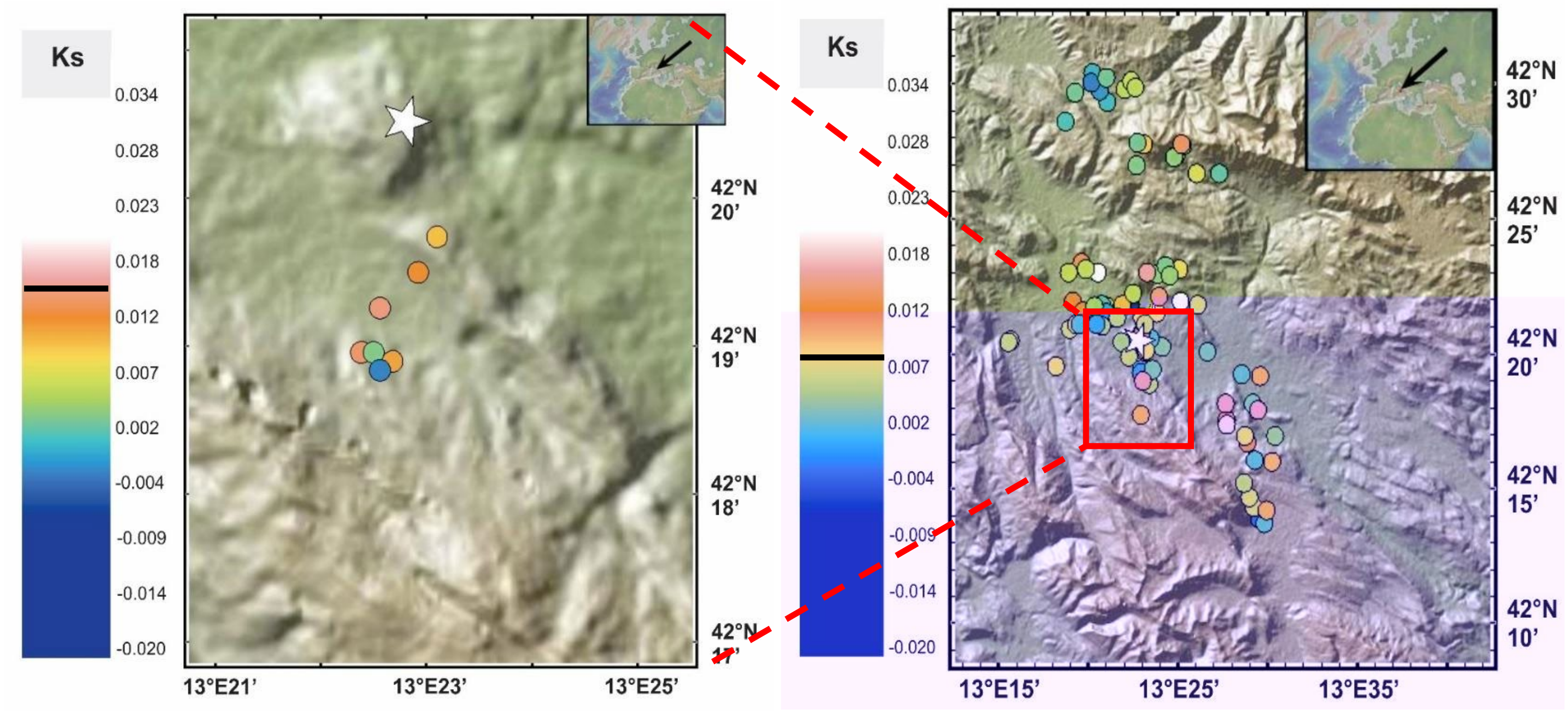
- Lowest regional attenuation $\kappa_{avg}(r)$ observed 10 days before the mainshock may be the **result of high stress accumulated near the epicentral area**
- During the **main rupture**, the **attenuation increased since the stress dropped** during the fault rupture
- During the **10-days aftershocks κ_{avg}(r) did not change** much (almost constant stress?)

Temporal variability of κs

Castro *et al*. (2024) *in review* - GJI

2009 L'Aquila sequence

10 Days Foreshocks | **10 Days Aftershocks**



K_s = 0.0155 s | **K_s = 0.0081 s**

κ_s was **very high** where the main rupture started, indicating the presence of **fluids** lubricated the faults and initiated the rupture

The **10 days aftershocks** that focus around the mainshock have **high κ_s and those located north of the mainshock have lower values**

These observations are **consistent with previous studies** (Di Luccio *et al.*, 2010; Lucente *et al.*, 2010)

Take-home message (2)

- **Variations of fluid pressure conditions** can cause large scatter which may explain the **spatial variability of κ_s** observed in our study
- From our preliminary analysis of the Central Italy sequences, **the temporal variation of** $\kappa_{avg}(r)$ could be a valuable indicator to monitor the **earthquake cycle in Central Italy**
- The **integration of κ studies** with other parameters (e.g. Vp/Vs, energy index, radiated seismic energy) may be useful to **study the preparatory phases of future earthquakes**

Ongoing Studies and Future Perspectives

- **Better constrain** (also with no-seismic data) the **κ** parameter
- Do a further analysis to **estimate κ_{avg}(r) with an *a priori*** geologic information
- Compilation of a **reliable map of κ_0** for all whole the Italian peninsula, finding possible effects of non-linearity for the κ_0 parameter
- **Compare spectrum for the attenuation medium** with the method of Calderoni and Abercrombie (2023)
- **Compare** spatio-temporal value of regional **κ with recent works on Q-tomography** (Gabrielli *et al*. 2022; Gabrielli *et al*., 2023)
- We can consider the **temporal variation of κ_{avg}(r)** as a *proxy* to **study the preparatory phase** of an earthquake (Picozzi *et al*., 2022; Picozzi *et al*., 2023)

WP2.1 Kinematic and Dynamic Earthquake Rupture Modeling

Parametrizzazione ingegneristica degli effetti di direttività di sorgente

Leonardo Colavitti[1,2], Giovanni Lanzano[1], Francesca Pacor[1], Sara Sgobba[1], Frantisek Gallovič[3]

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Goals

- **Extende the approach for** identifying directive events from the frequency domain (FAS) as shown in Colavitti *et al*. (2022) to **the spectral amplitude (SA)**
- **Build a fully data-driven directivity model** that can be used to predict seismic ground motion using a few number of independent parameters
- **The shaking scenarios** of non-ergodic models should take into account the **contribution due to the source directivity**

State of the Art

- Earthquake directivity represents the focusing of the wave energy along the fault in the direction of rupture propagation
- The importance of this effect is very well known for large-magnitude events, while is still an open issue for small-to-moderate events

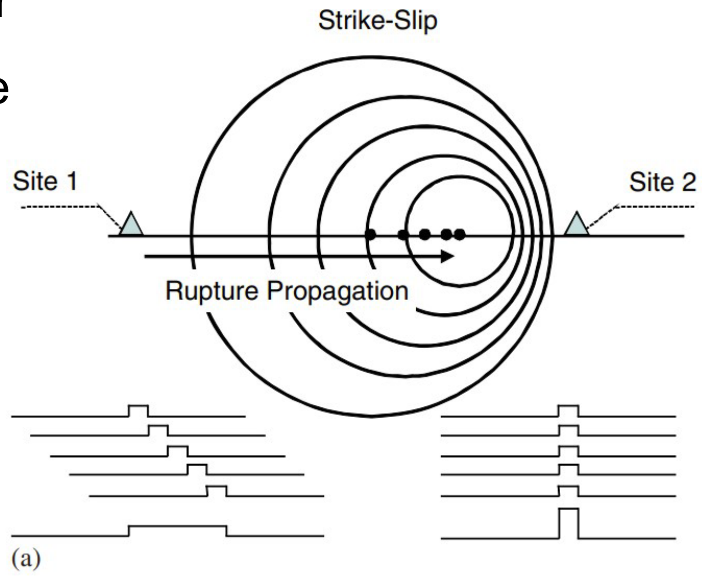
Modelization of directivity effects in the GMMs

GFs simulations

- Somerville, *Phys. Earth. Planet. Inter.*, 2003
- Iervolino and Cornell, *Bull. Seism. Soc. Am.*, 2008
- Shahi and Baker, *Bull. Seism. Soc. Am.*, 2011
- Spagnuolo et al., *Geophys. J. Int.,* 2012

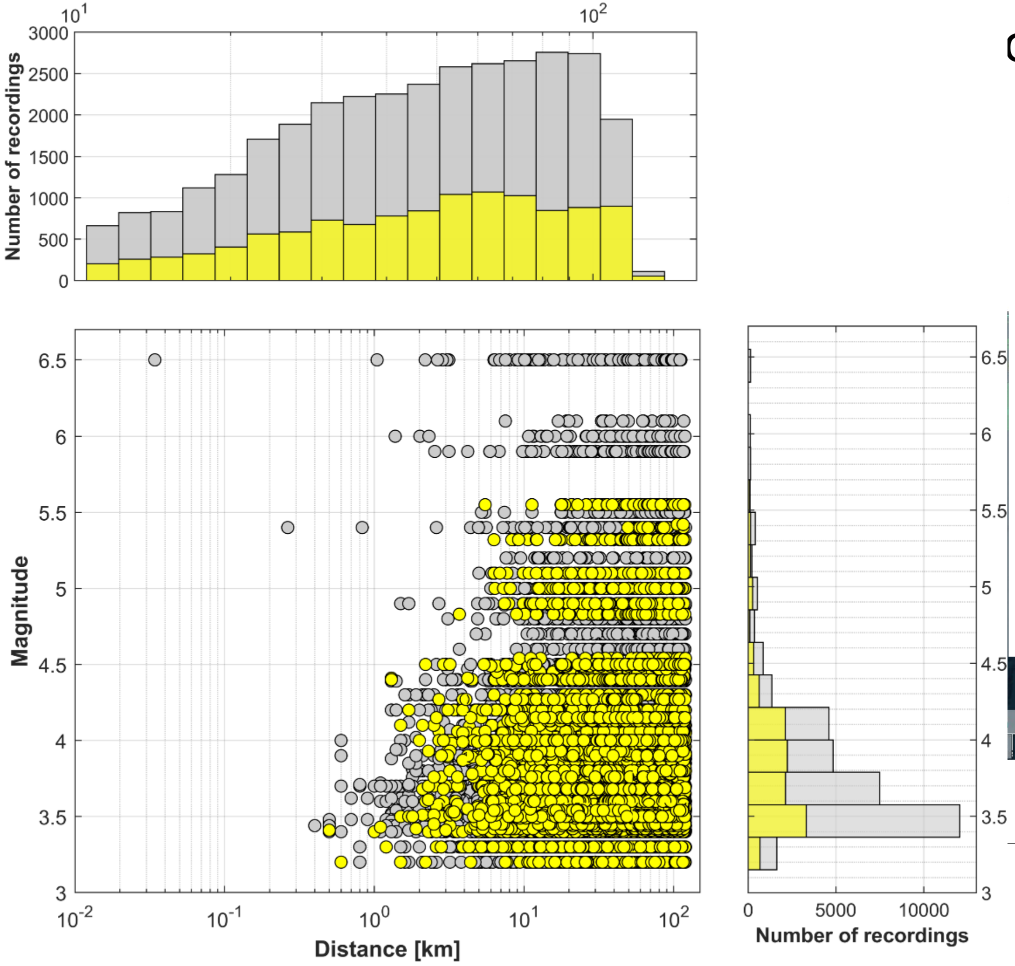
Empirical evidence

- Calderoni *et al.*, *J. Geophys. Res.*, 2017
- Ren et al., *Tectonics*, 2017
- Wang et al., *J. Geophys. Res,* 2019
- Calderoni *et al.*, *Seimol. Res. Lett.*, 2023



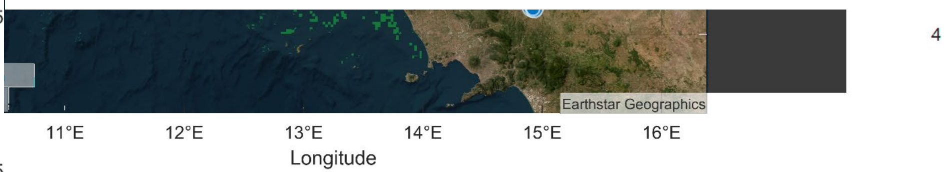
from Chioccarelli and Iervolino (*Eqk. Eng. Struct. Dyn.*, 2010)

Dataset



cordings from 2009 to 2018

- Dataset very well sampled in the distance R [10-100 km] and magnitude ranges and M [3.2-6.5]
- Directive events are shown in yellow, which represents about the 30% of the total events



456 events

Method

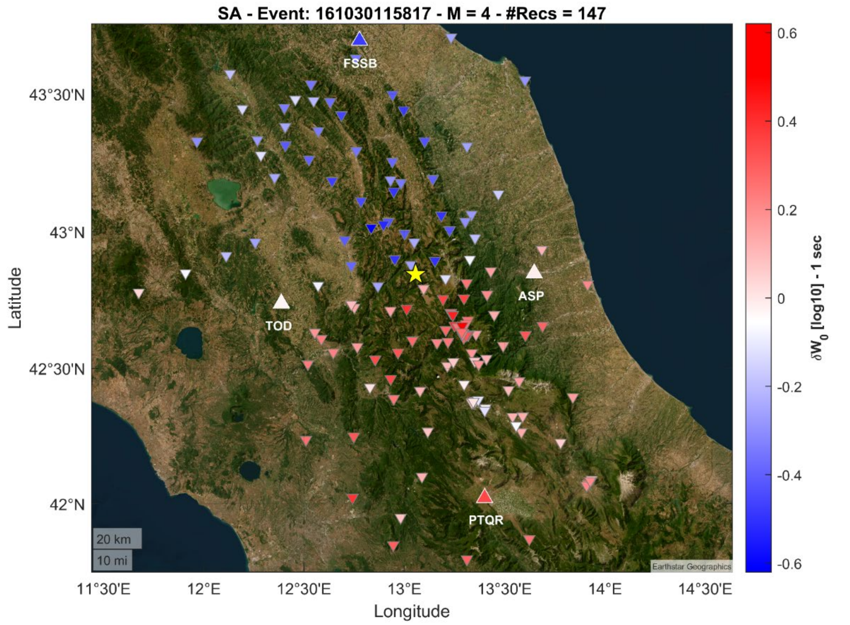
Aleatory variability linked to the directivity effect

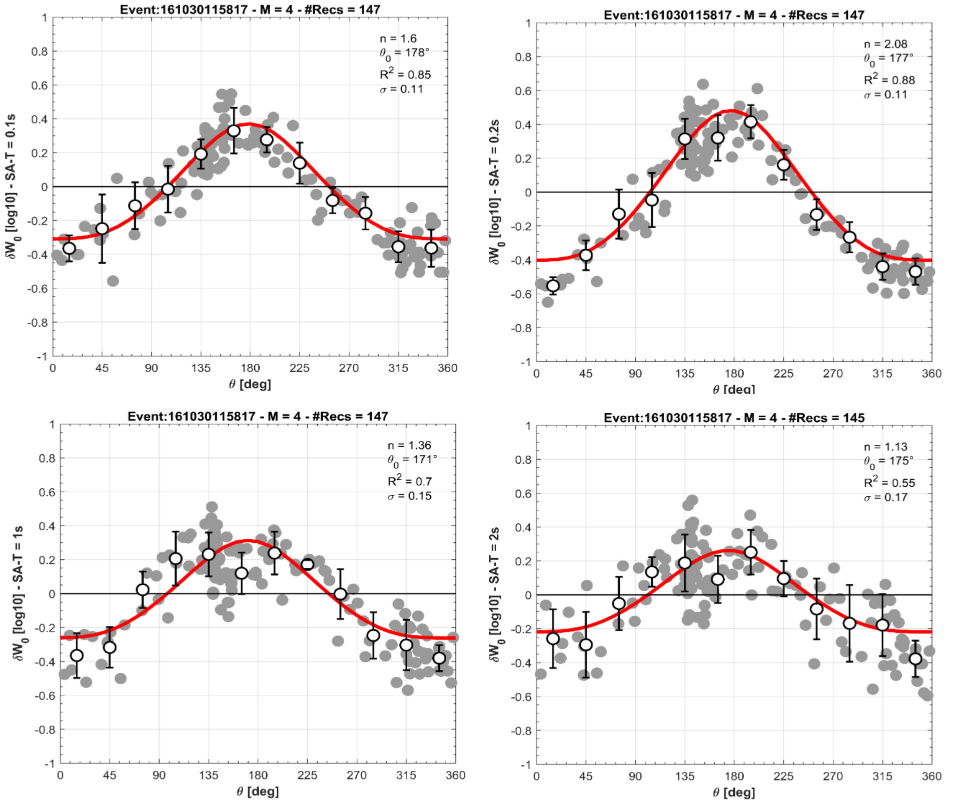
$$\underbrace{\log_{10}Y = a + F_M(M) + F_R(M,R)}_{\text{Fixed terms}} + \underbrace{\delta B_e + \delta S2S_{ref,s} + \delta L2L_{source} + \delta P2P_p}_{\text{Random terms}} + \boxed{\delta W_0}$$

$$\delta W_0 = \boldsymbol{\delta D2D(\theta)} + \delta W_{nodir}$$

Fixed terms **Random terms**

SA values from 0.04 – 2 sec





$$C_d = \sqrt{\frac{k^2}{\left[1 - \left(\frac{v_r}{c}\right)\cos(\theta - \theta_0)\right]^2} + \frac{(1-k)^2}{\left[1 + \left(\frac{v_r}{c}\right)\cos(\theta - \theta_0)\right]^2}}$$

Boatwright, 2007

Choice of directive events

- The coefficient of determination R^2 is greater than 0.50 for at least 10% of the periods investigated

- The standard deviation of the angle of the direction of propagation is smaller than 20° in the same range of period

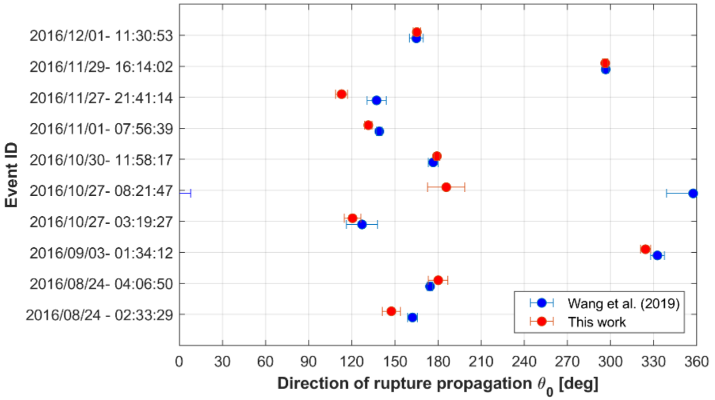
With the criteria we adopted in Colavitti *et al*. (2022):

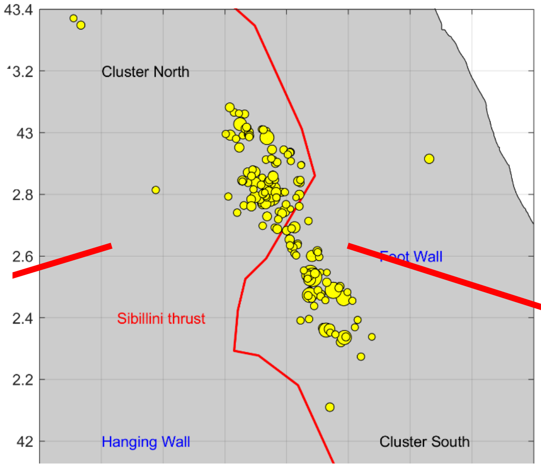
- For **FAS** Analysis, directivity events are 162/456 (**35%**)
- For **SA** Analysis, directivity events are 175/456 (**38%**)

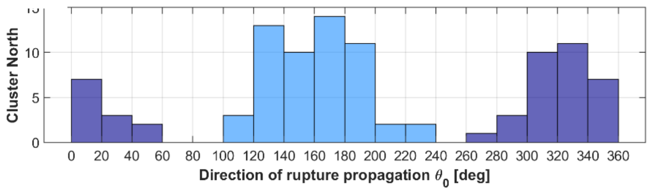
136 events (30%) presents directivity both in FAS and in SA

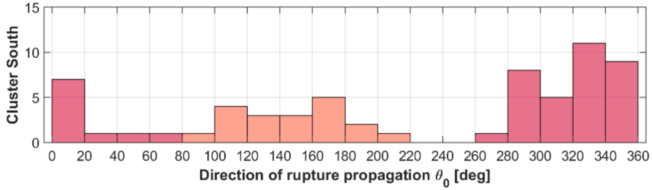
Results - FAS

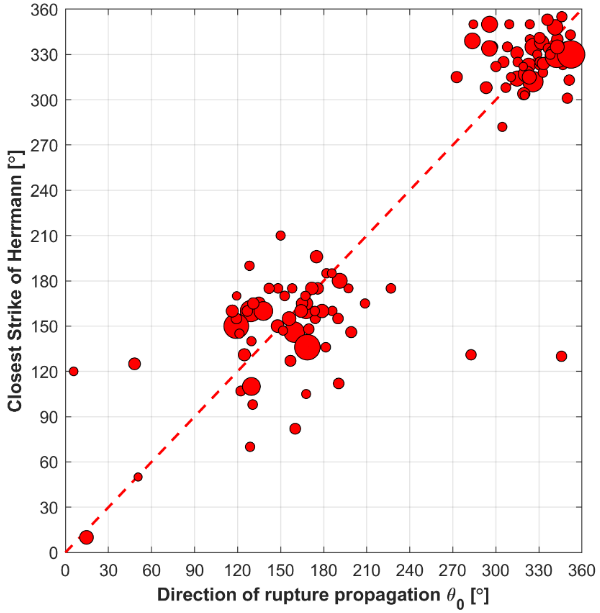
Direction of Rupture propagation









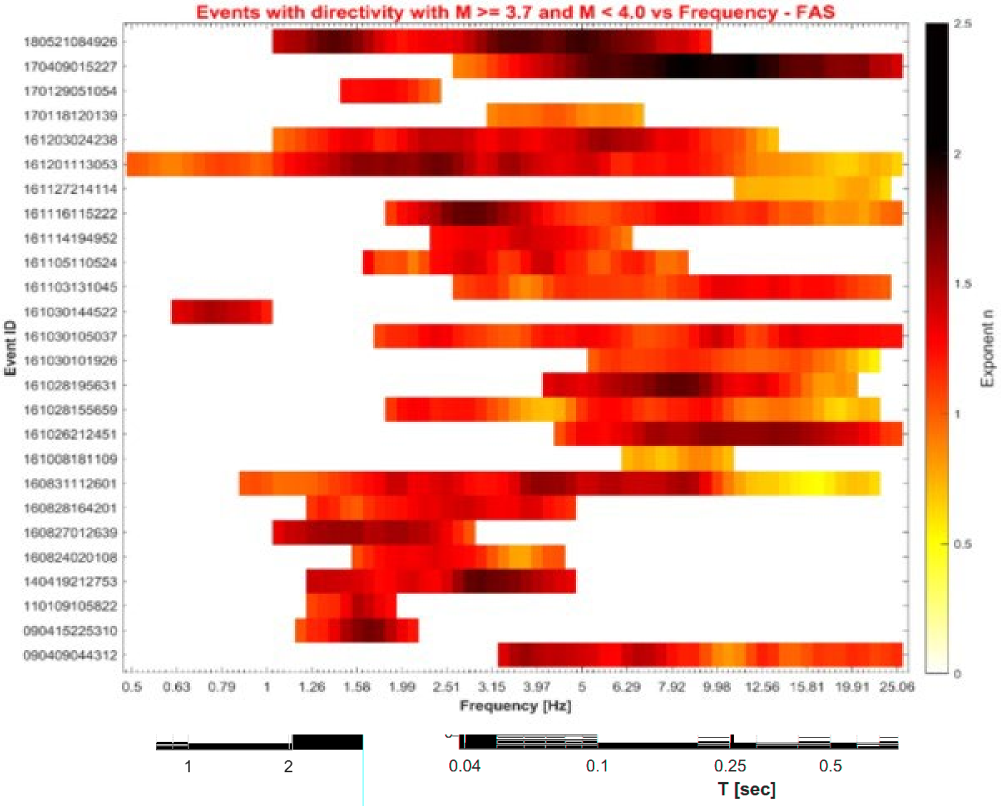


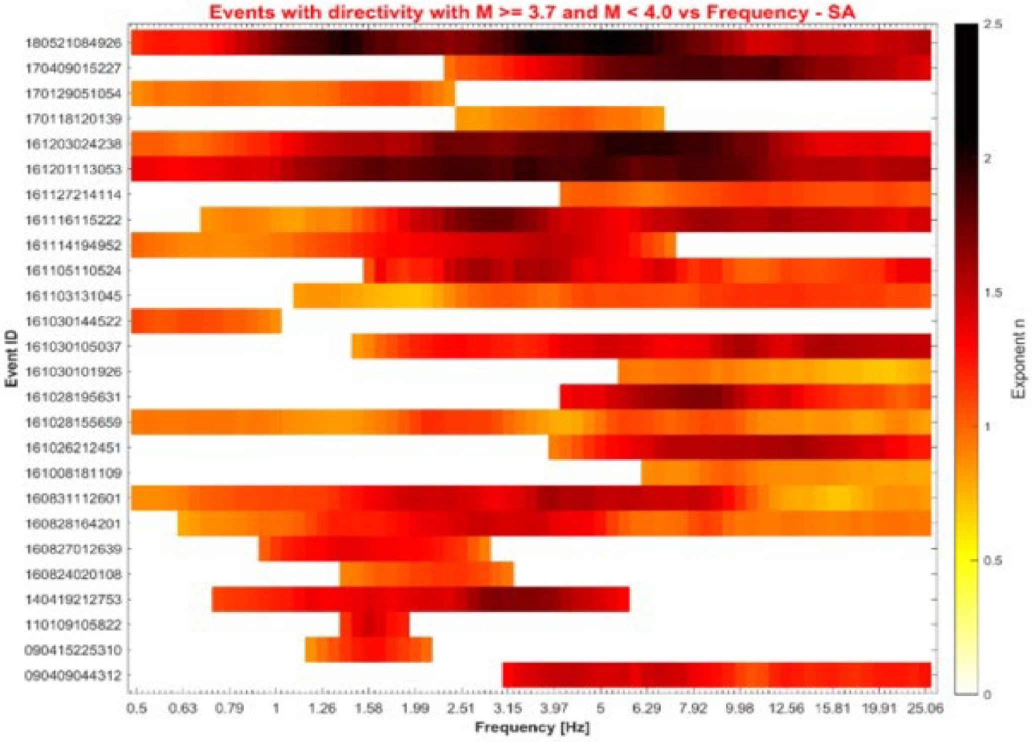
Results are consistent with previous investigations obtained with other methods!

Colavitti *et al*. (2022) – JGR - SE

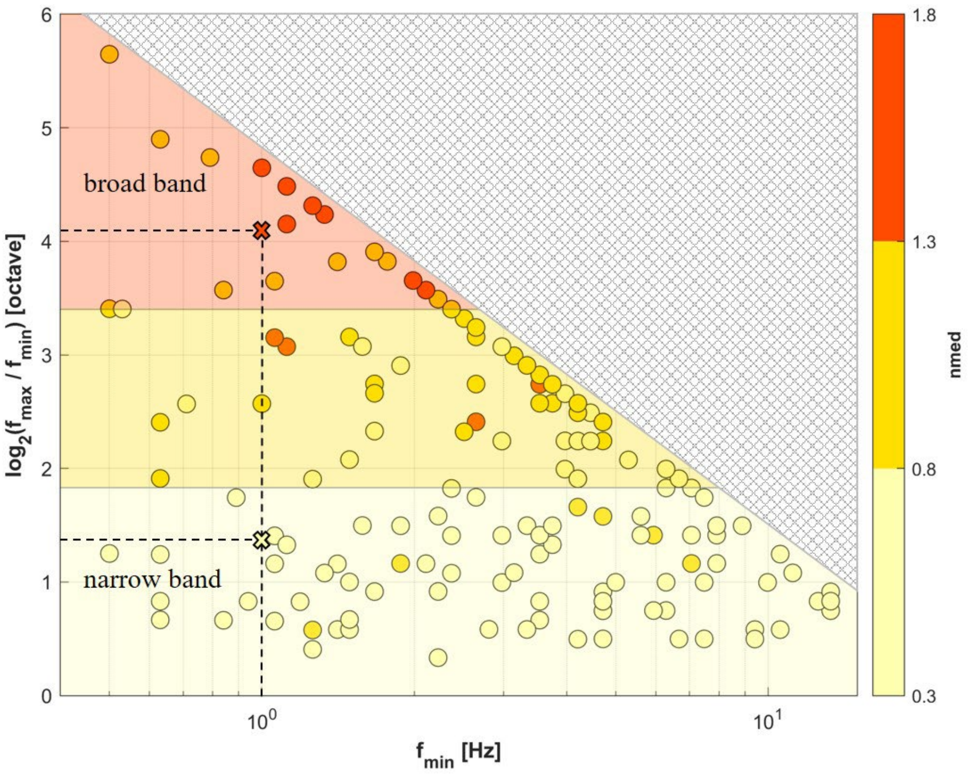
Comparison SA-FAS

event ID: 161030115817 - M =4





Directivity Parametrization



Colavitti *et al*. (2022) – JGR - SE

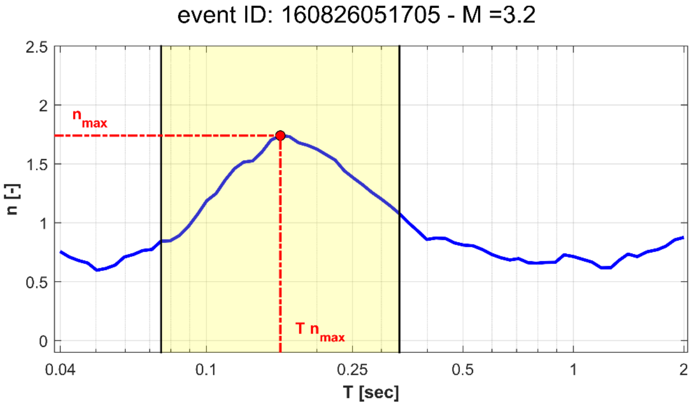
Relation between minimum frequency f_{min}, the directivity amplitude, proportional to n_{med} and bandwidth, defined as $\log_2(f_{max}/f_{min})$

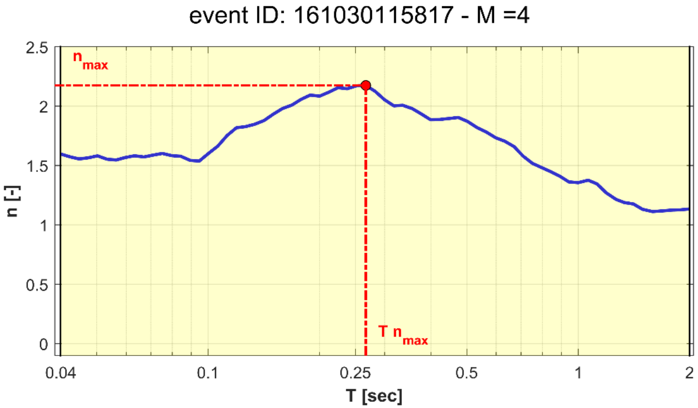
Relationship **a bit more complicated** (not linear) than we thought

Directivity Parametrization

Narrow directivity band

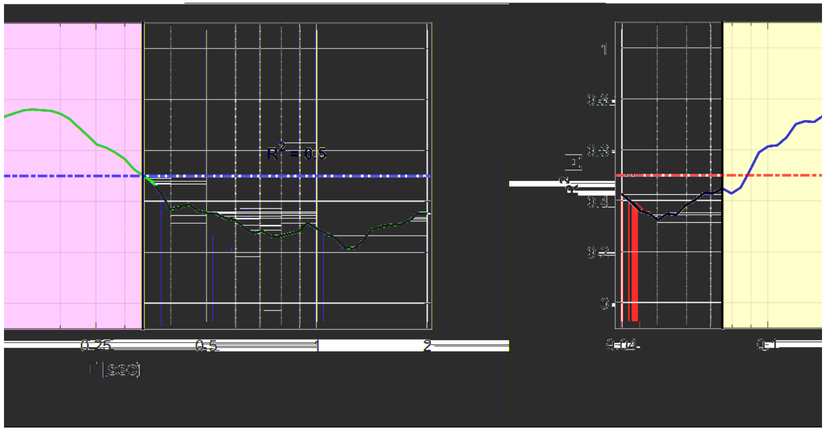
Broad directivity band

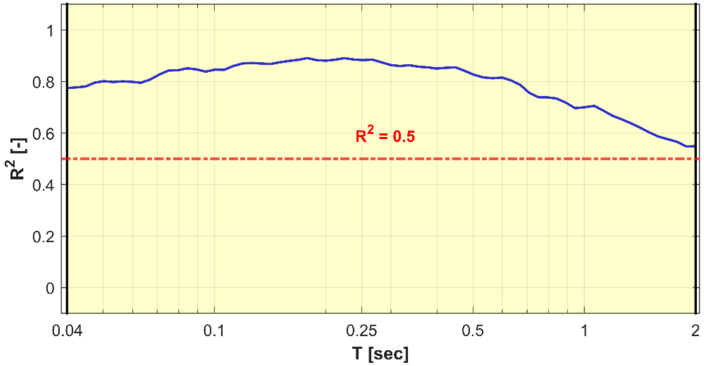




n_{max}
Peak of directivity

Tn_{max}
Period of the
Peak of directivity





Colavitti *et al*. in prep.

Directivity Parametrization

Parametrization with Gauss function 1

After some quality control,
we get 139 observations

$$y = a_1 * \exp(-((\log10\ x - b_1)/c_1)^2$$

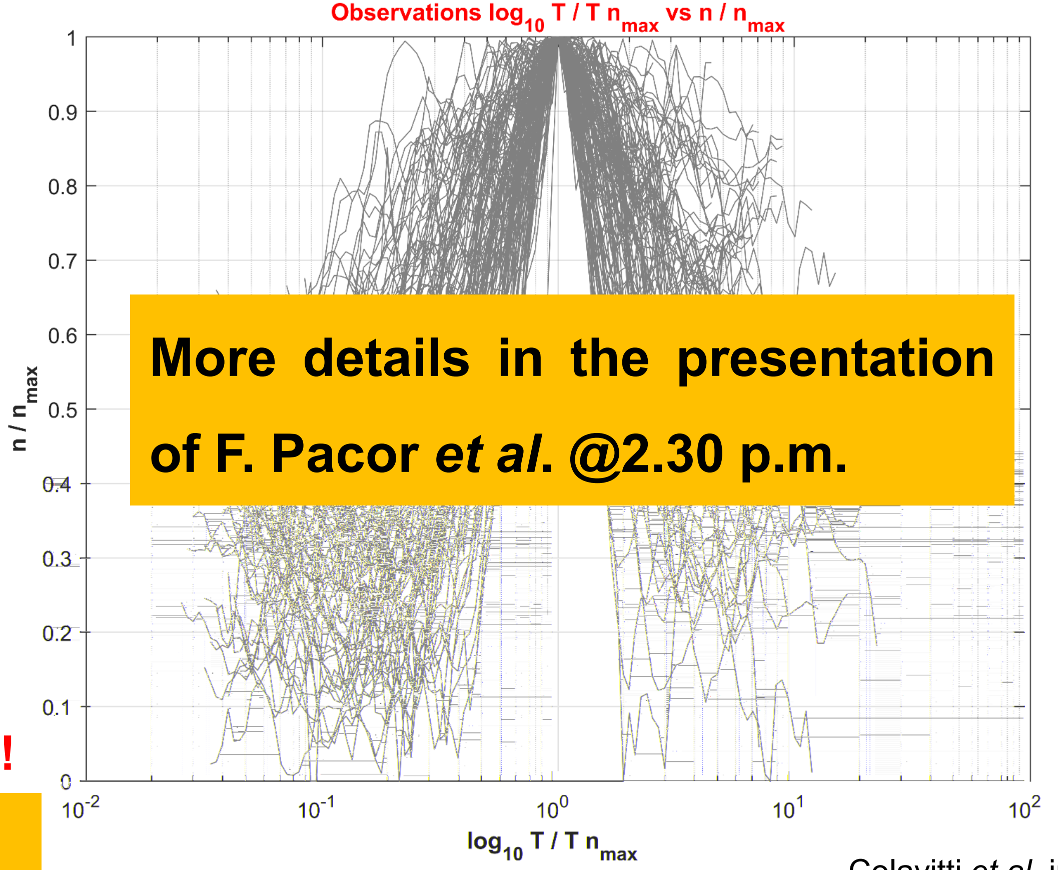
$$\frac{n}{n_{max}} = a_1 * \exp(-((\log10 \frac{T}{T_{n_{max}}} - b_1)/c_1)^2$$

Gauss coefficients

a_1 = 1 (Amplitude)
b_1 = 0 (Median)

c_1 is the only parameter that controls the shape of the gaussian!

$$\frac{n}{n_{max}} = \exp(-((\log10 \frac{T}{T_{n_{max}}})/0.8229)^2$$



More details in the presentation of F. Pacor *et al.* @2.30 p.m.

Colavitti *et al.* in prep.

WP 2.1

Ongoing Studies and Future Perspectives

- Results obtained in this study provide a useful hint regarding **source directivity** as a **frequency-dependent band-limited phenomenon**
- Possible **comparison** with the work of **Calderoni *et al*. (2017)** in the same zone
- Preliminary results regarding the source directivity parametrization suggest that it is reliable to adopt a **Gaussian curve of order 1** considering the **input values of magnitude and directivity level (n_{max})**
- The next challenging point we are working on is to **apply the model to a scenario of a future potential earthquake** in Central Italy to provide a useful tool for predictive analysis ➡ WP 3.1

Products

WP 2.2

- ✓ R. R. Castro, L. Colavitti, C. A. Vidales-Basurto, F. Pacor, S. Sgobba, G. Lanzano (2022). Near-Source Attenuation and Spatial Variability of the Spectral Decay Parameter κ in Central Italy. *Seismol. Res. Lett.* 93(4): 2299-2310. https://doi.org/10.1785/0220210276.
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