Final Meeting of the INGV–SECURE Project

Roma, 11-12 March 2026

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

WP2 - Characterization of Earthquake Source and Seismic Wave Propagation in the Central Apennines

Data-Driven Empirical Modeling of Source Directivity Effects in a Ground Motion Model for Central Italy

L. Colavitti[1], G. Lanzano[2], S. Sgobba[1], F. Pacor[1]

[1] Department of Earth, Environmental and Life Sciences - DISTAV, University of Genoa, Genoa, Italy

[2] Istituto Nazionale di Geofisica e Vulcanologia - INGV, Milan, Italy

Università di Genova

ISTITUTO NAZIONALE DI GEOFISICA E VULCANOLOGIA

Motivation and Goals

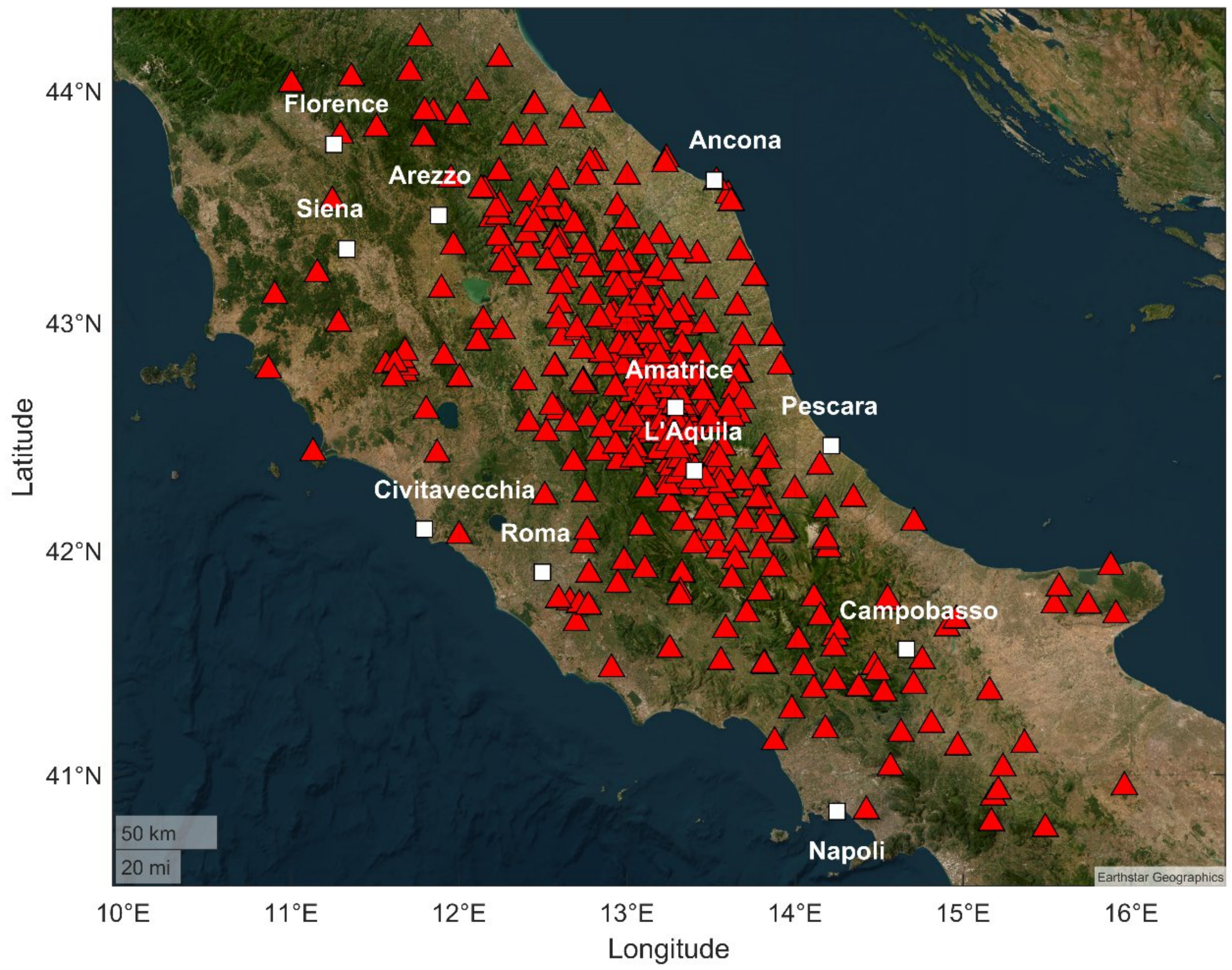
Earthquake **directivity** represents the **focusing of the wave energy** along the fault in **the direction of rupture propagation**

- **Extend the approach** for identifying directive events **from the frequency domain (FAS) 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**
- **Quantify the contribution due to the source directivity effect** into the shaking scenarios for non-ergodic models

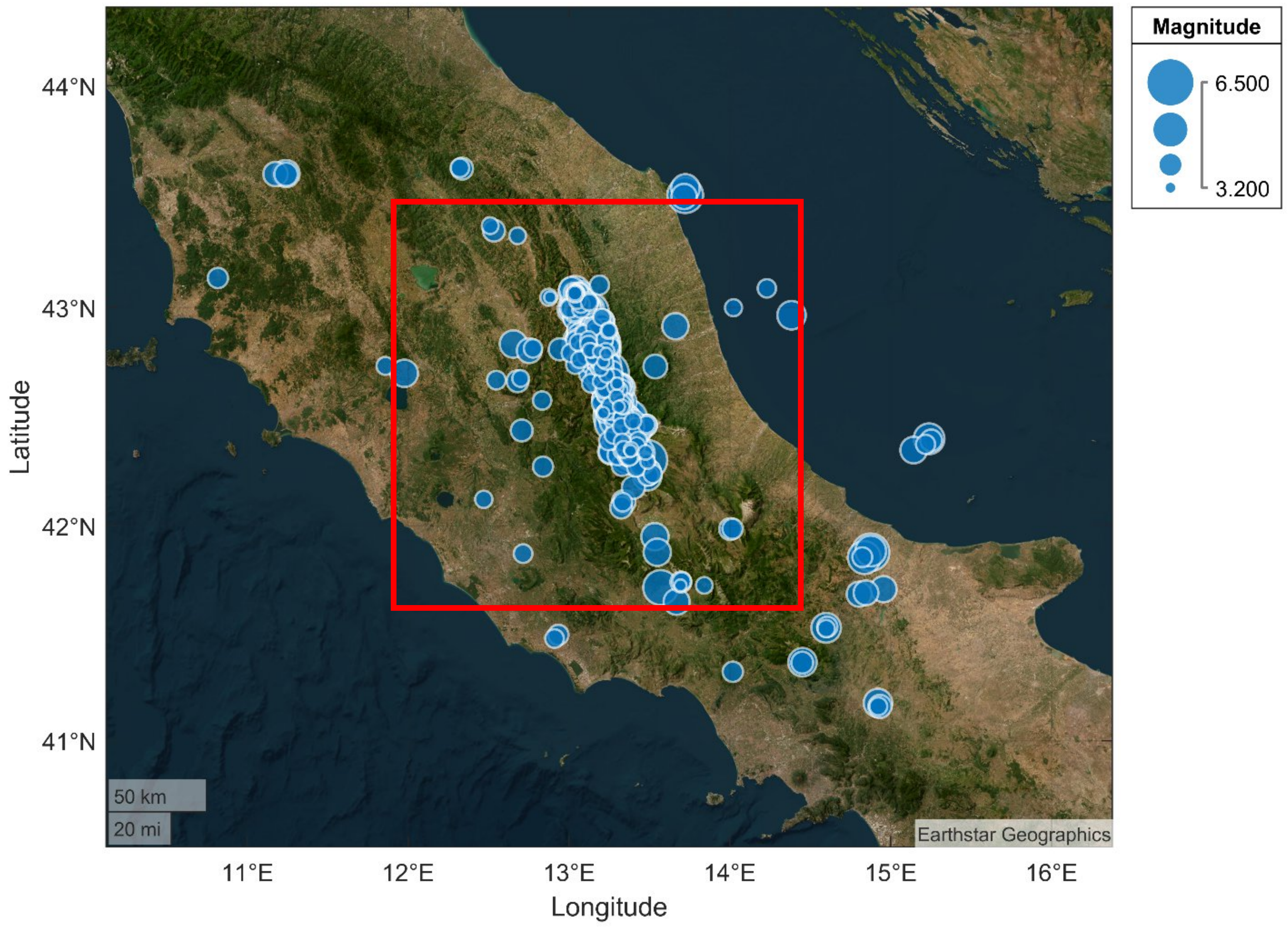
Dataset

Dataset with more than **35,000** seismic recordings from **2009 to 2018**

https://doi.org/10.13127/CI_dataset/CI-SA_flatfile

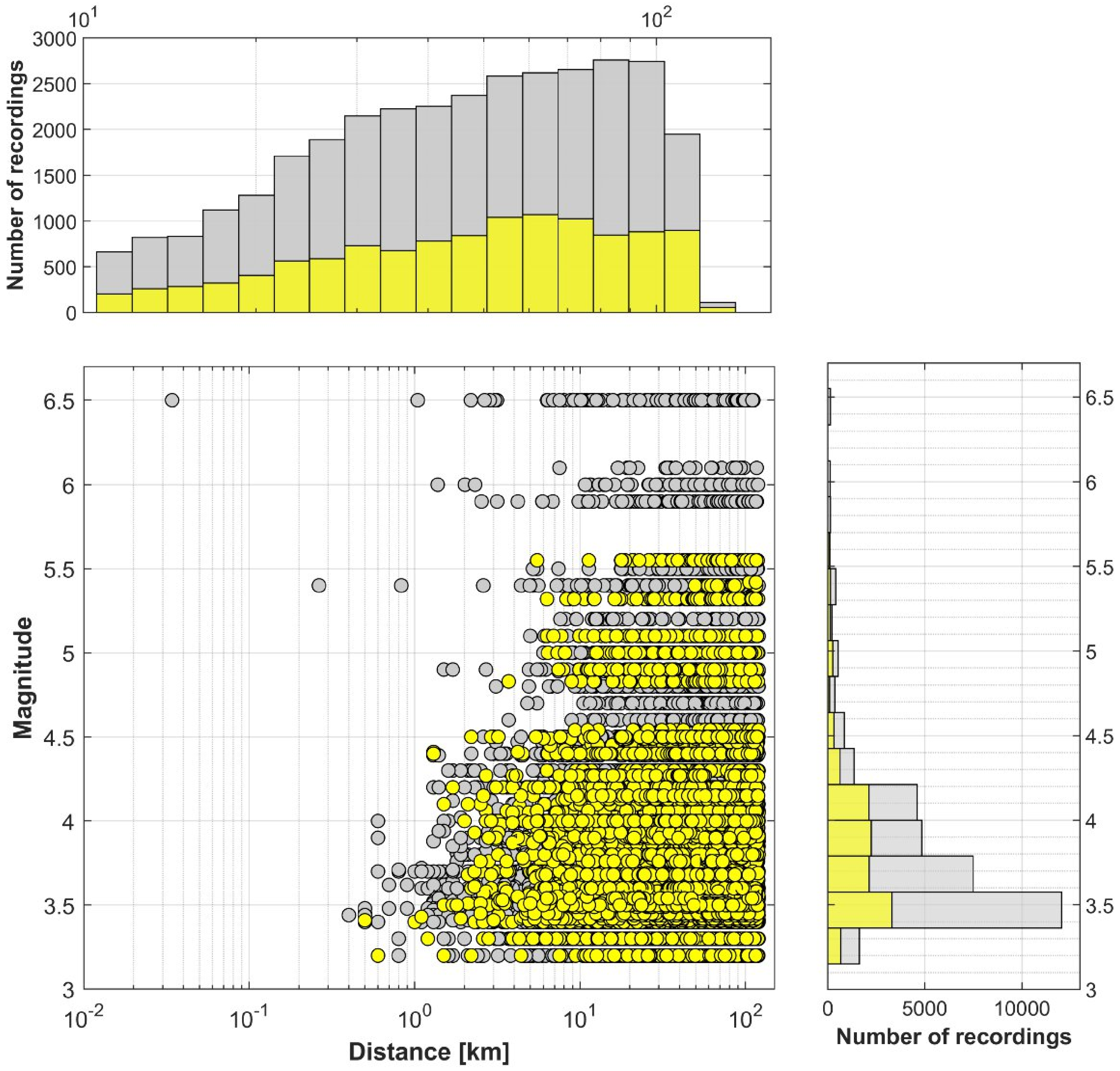


460 stations



456 events

Dataset



Dataset very well sampled in the distance **R [10-120 km]** and magnitude **M [3.2-6.5]**

Directive events are shown in yellow, which represents about **one third of the total events**

Method

$$log_{10}Y = a + F_M(M) + F_R(M,R) + \delta B_e + \delta S2S_{ref,s} + \delta L2L_{source} + \delta P2P_p + \delta W_0$$

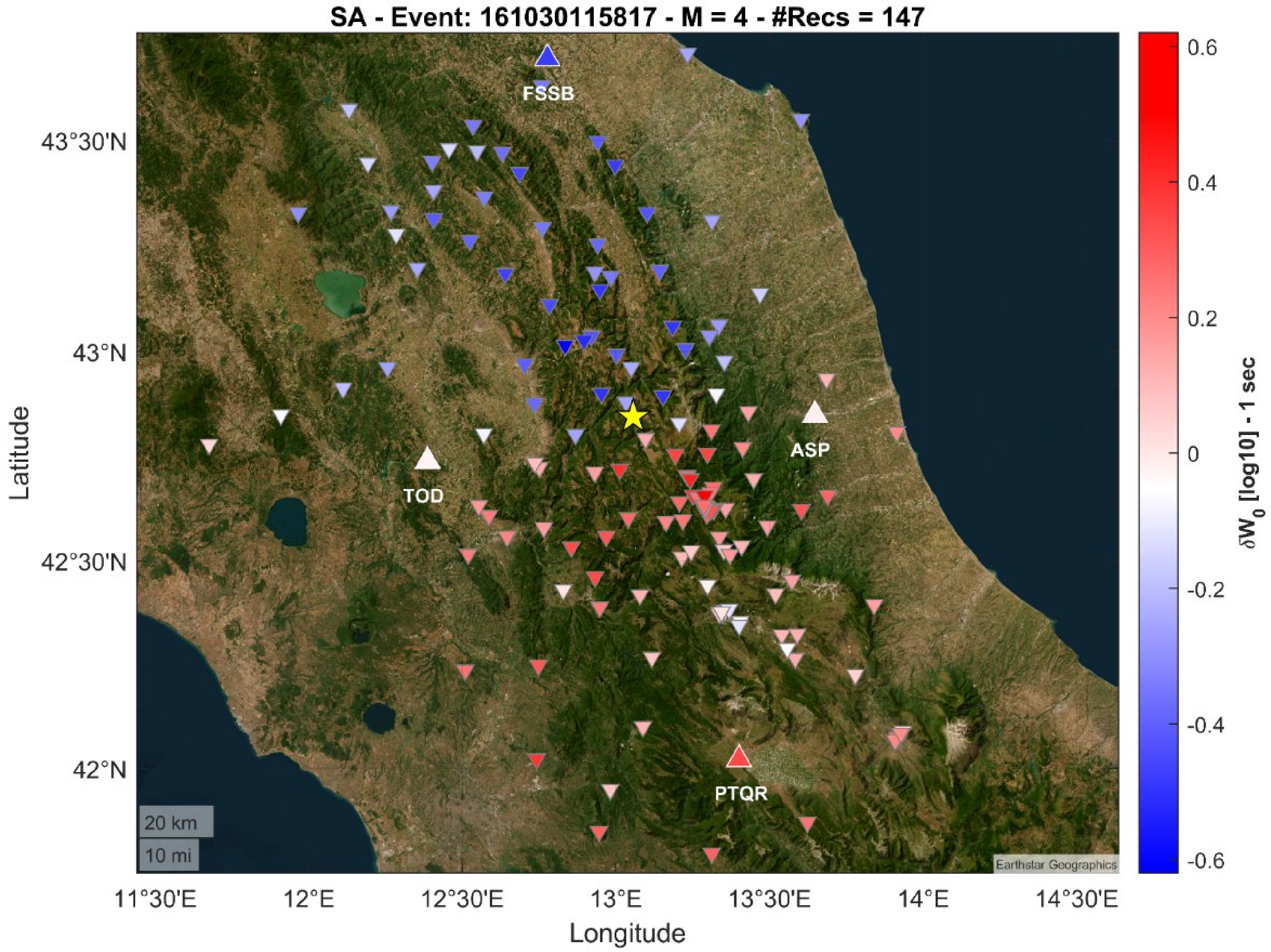
from Sgobba et al. (2021)

Fixed terms

Random terms

Aleatory variability linked to the directivity effect

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



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

Boatwright, 2007

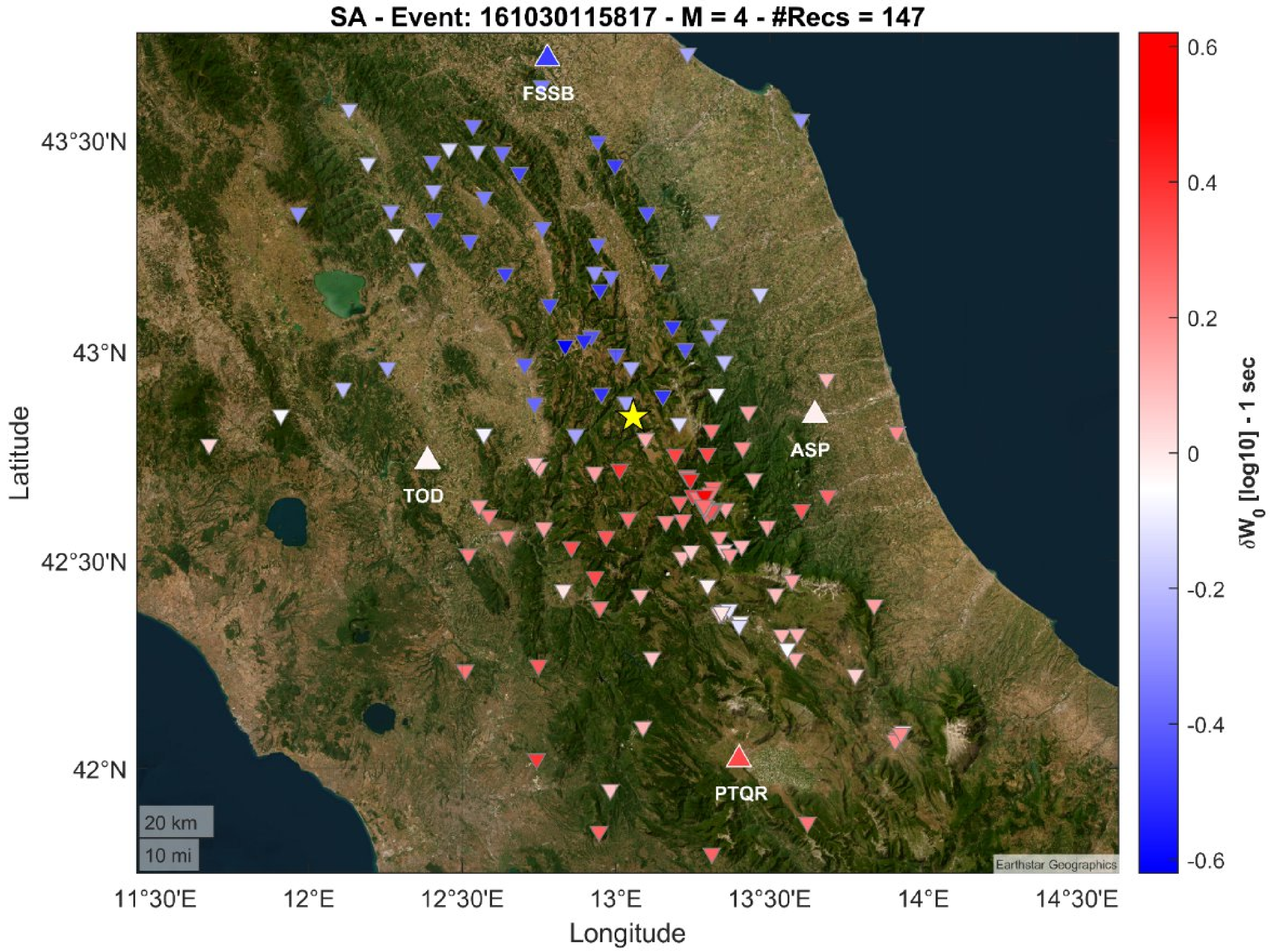
$k = 0.85$
$\alpha = 0.50$
n change with frequency

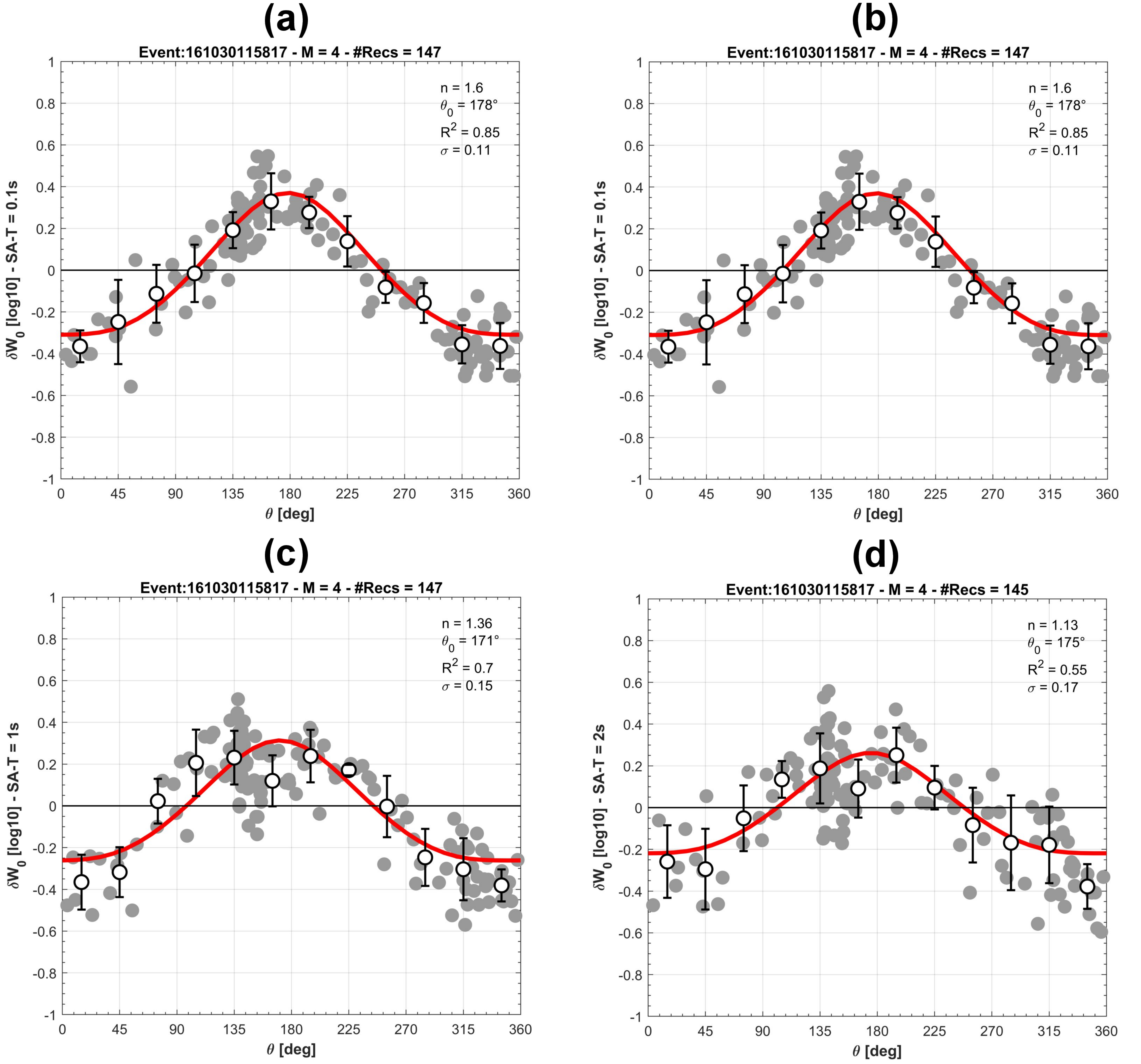
Method

SA values from 0.04 – 2 sec

M4 event of the 24 August 2016 at 23:22:05

a) T=0.1 s, **b)** T=0.5 s, **c)** T=1 s, **d)** T=2 s





Selection of directive events

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

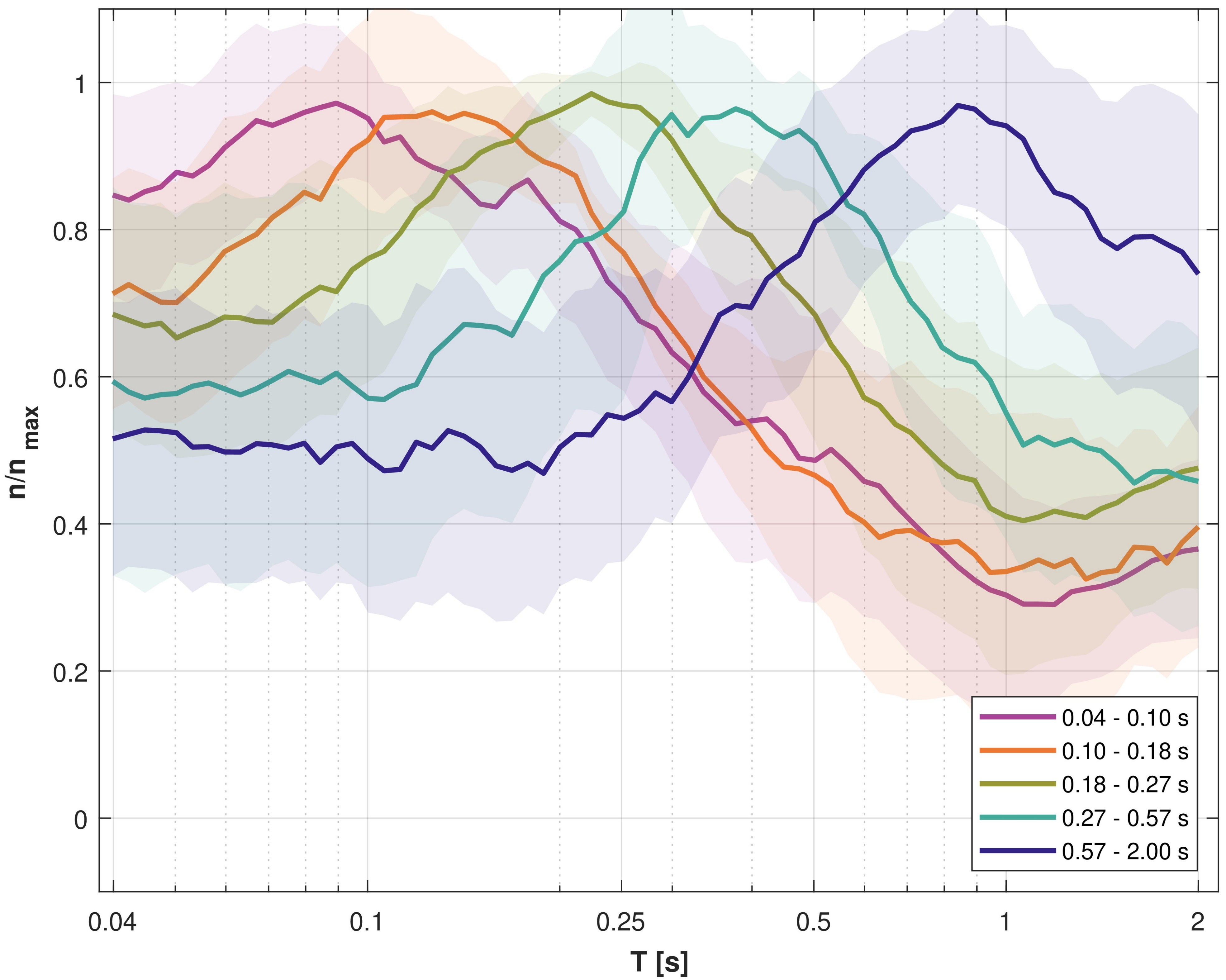
- **The standard deviation of the angle of direction of propagation is smaller than 20°** in the same range of period

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%**)

Directivity Parametrization

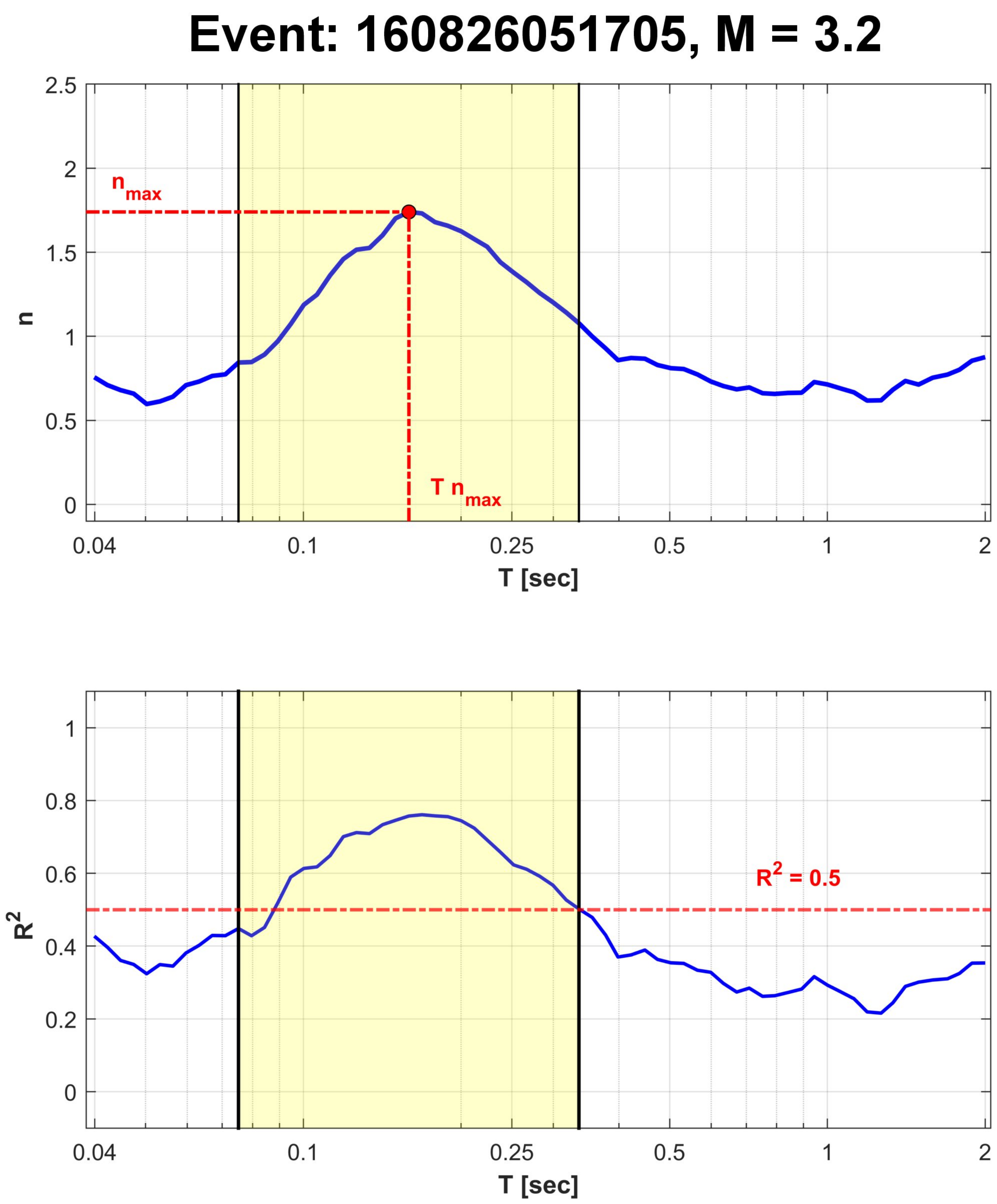


Clear **shift on directivity**, defined by n factor, at characteristic **frequency bands**

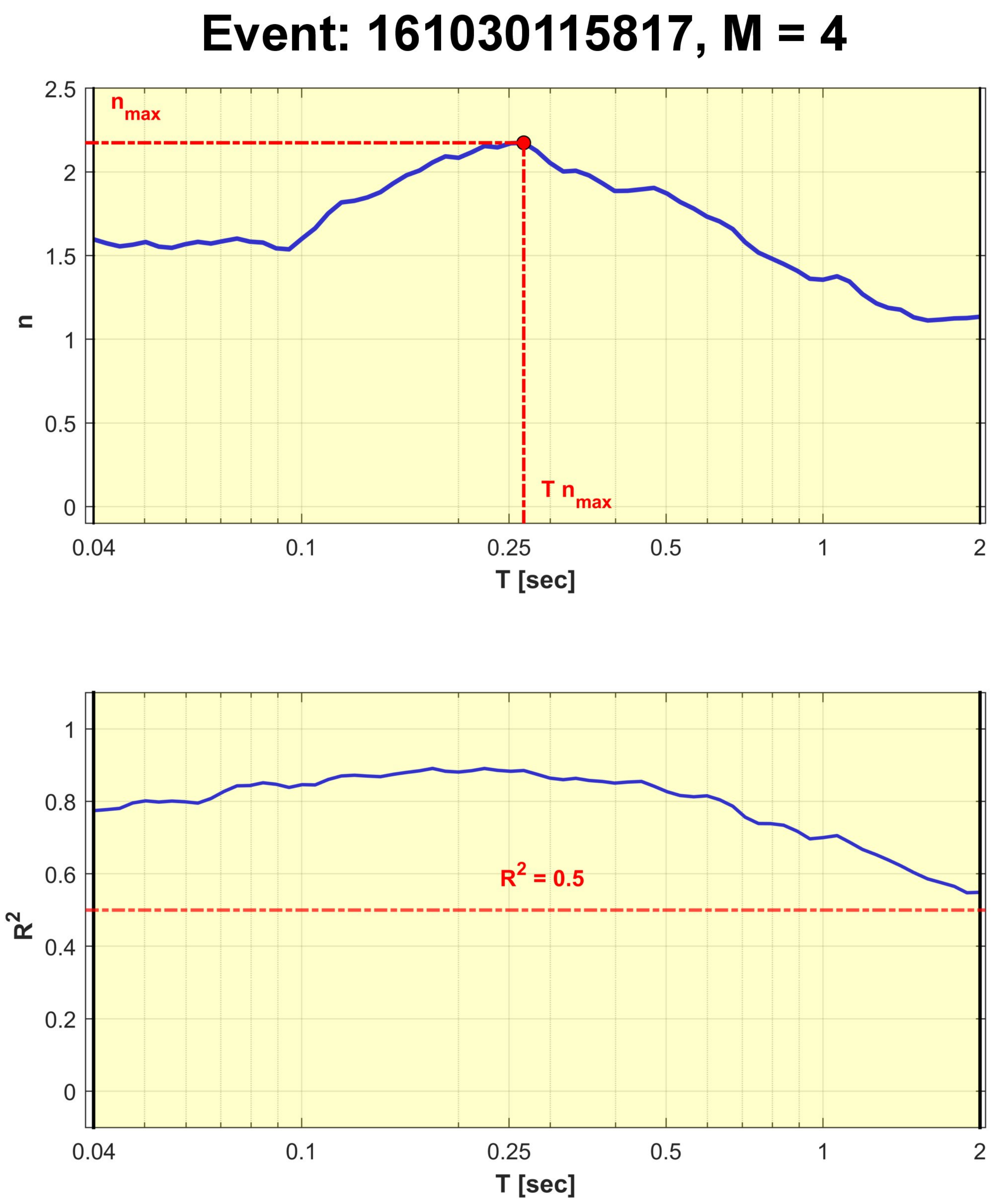
⇩

A normalization curve is required

Directivity Parametrization



Narrow directivity band



Broad directivity band

n_{max}

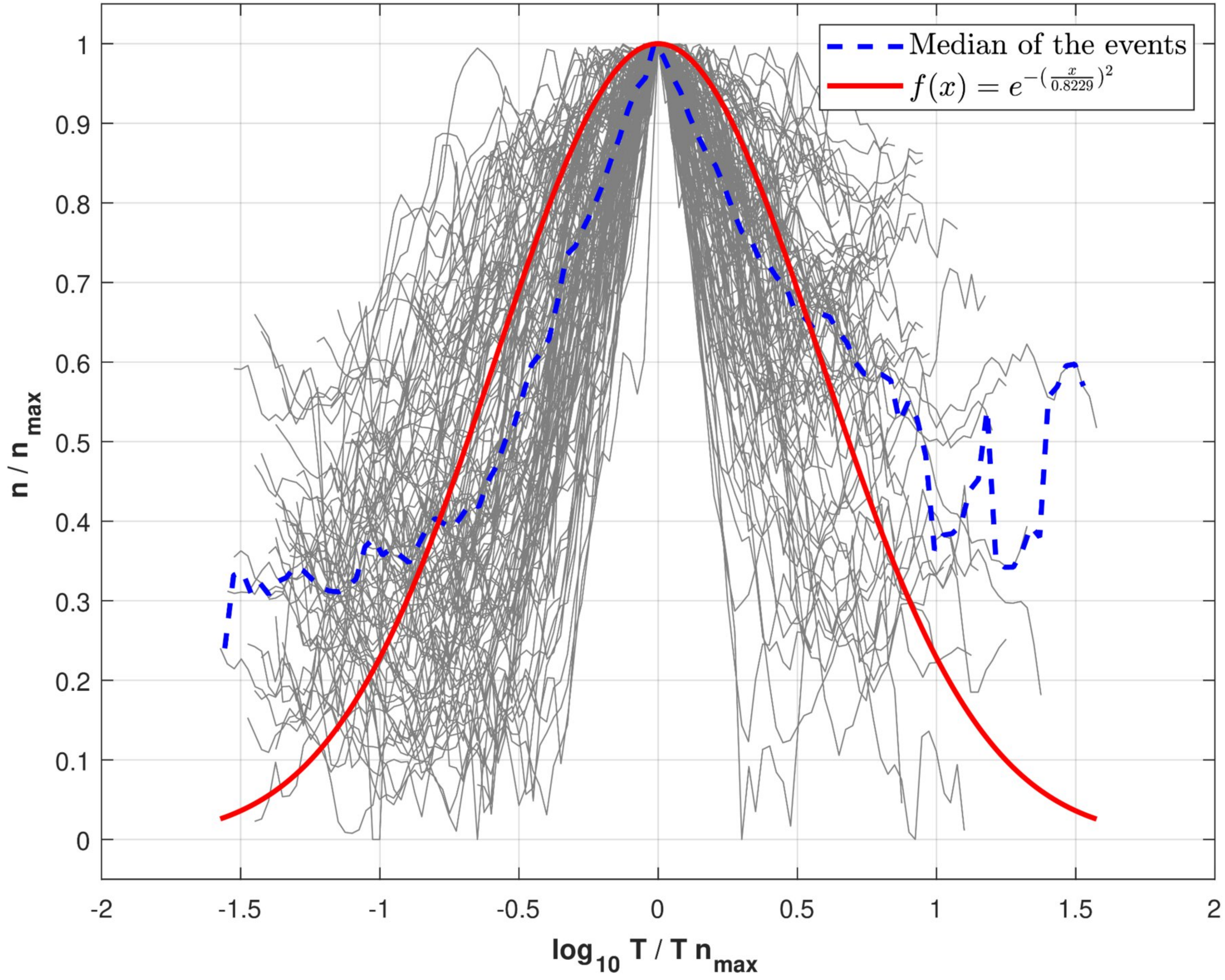
Peak of directivity

$T\ n_{max}$

Period of the peak of directivity

Directivity Parametrization

Spectral normalization via Gaussian Fit



$$f(x) = a_1 * \exp\left[-\left(\frac{x - b_1}{c_1}\right)^2\right]$$

<u>Gauss coefficients</u>

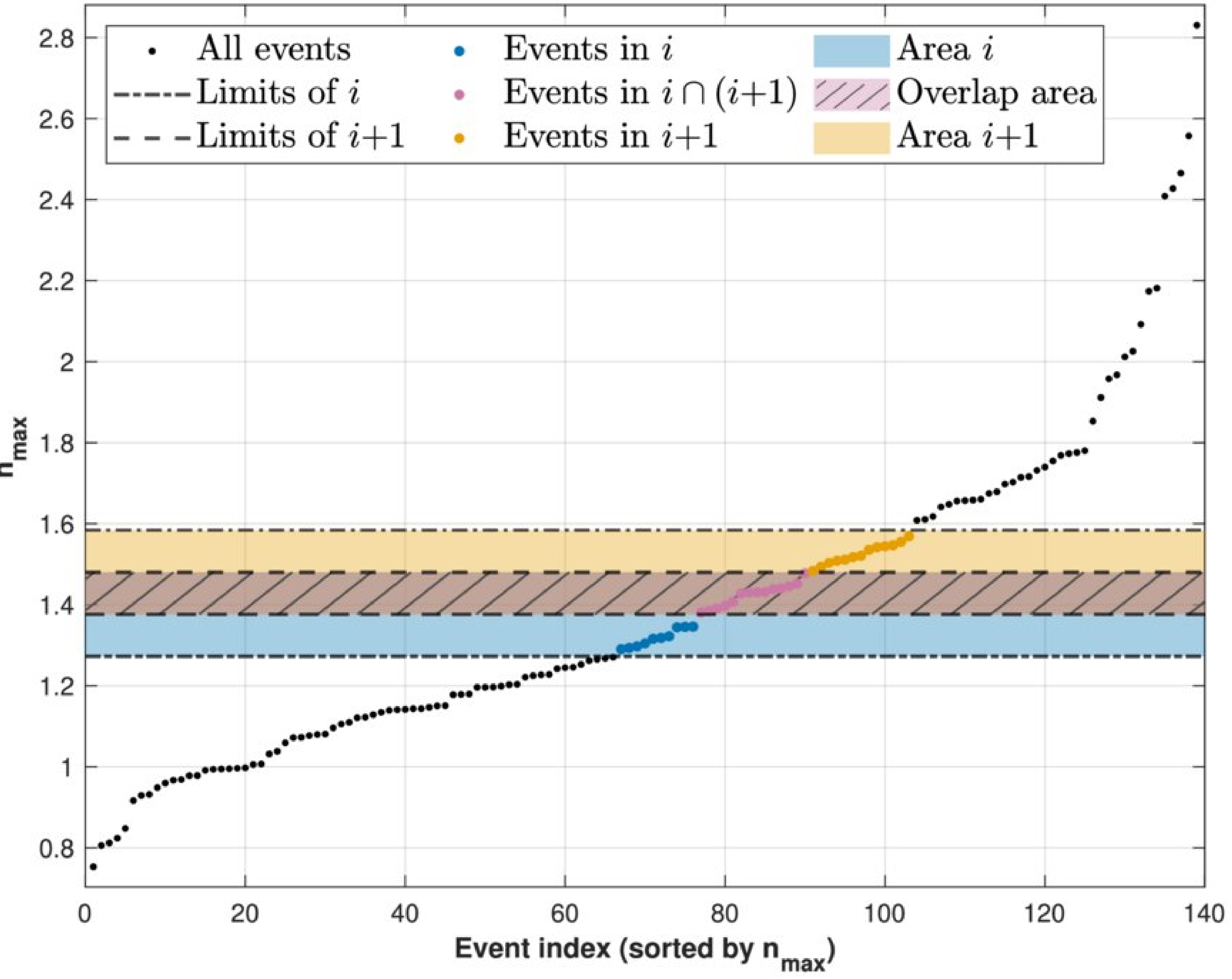
a_1= 1 (Amplitude)
b_1= 0 (Median)

$$\frac{n}{n_{\max}} = \exp\left[-\left(\frac{\log_{10}(\frac{T}{Tn_{\max}}) - b_1}{c_1}\right)^2\right]$$

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

Directivity Parametrization

Modeling the bandwidth of the directivity effects

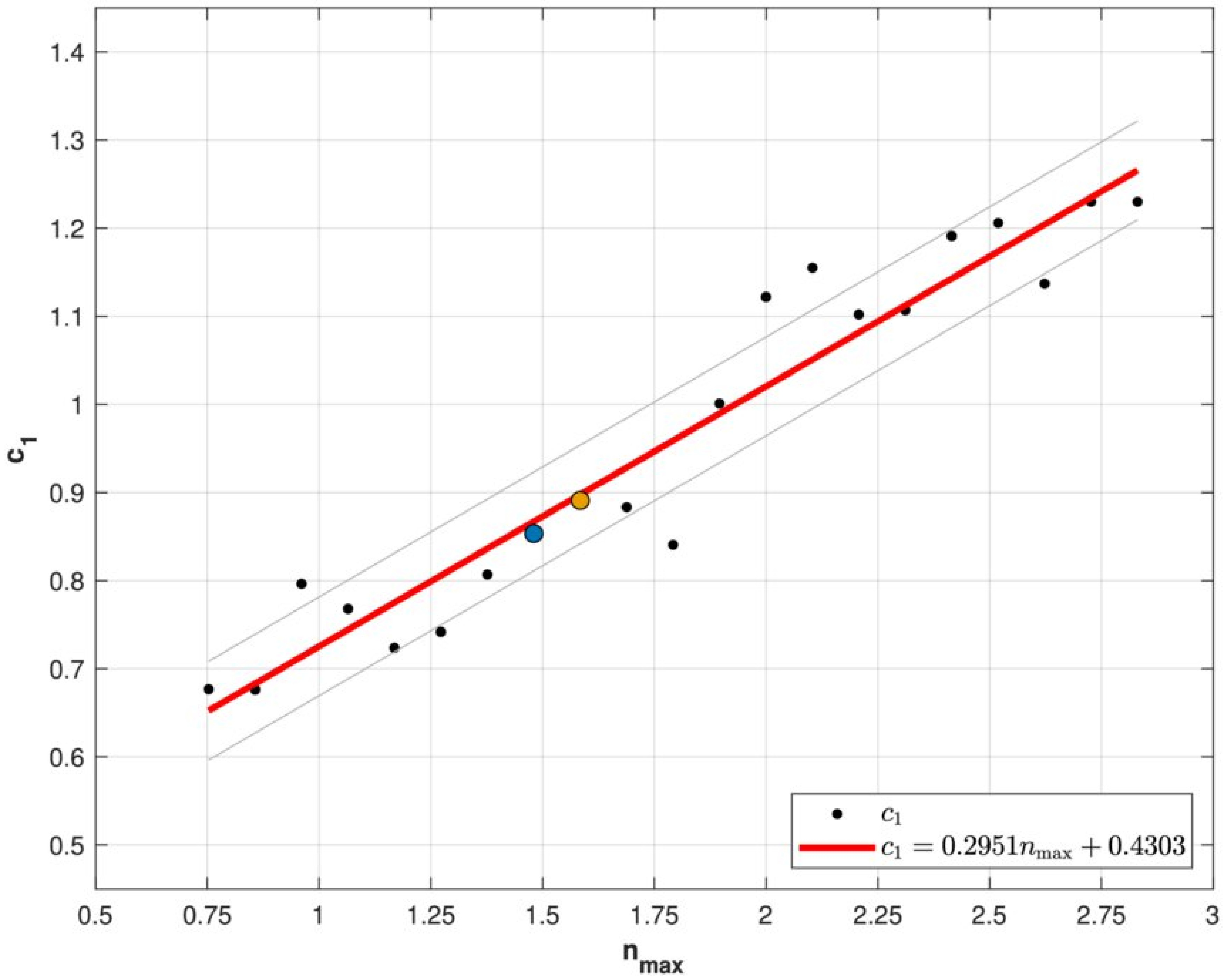


In order to model c_1 as a continuous function of n_{max}, we **subdivided the dataset of directive events based on the value of** n_{max}

Directivity Parametrization

Modeling the bandwidth of the directivity effects

The values of c_1 **increase with** n_{max}, as expected, **suggesting a linear fitting of the empirical data**



Directivity Parametrization

Magnitude scaling of peak period

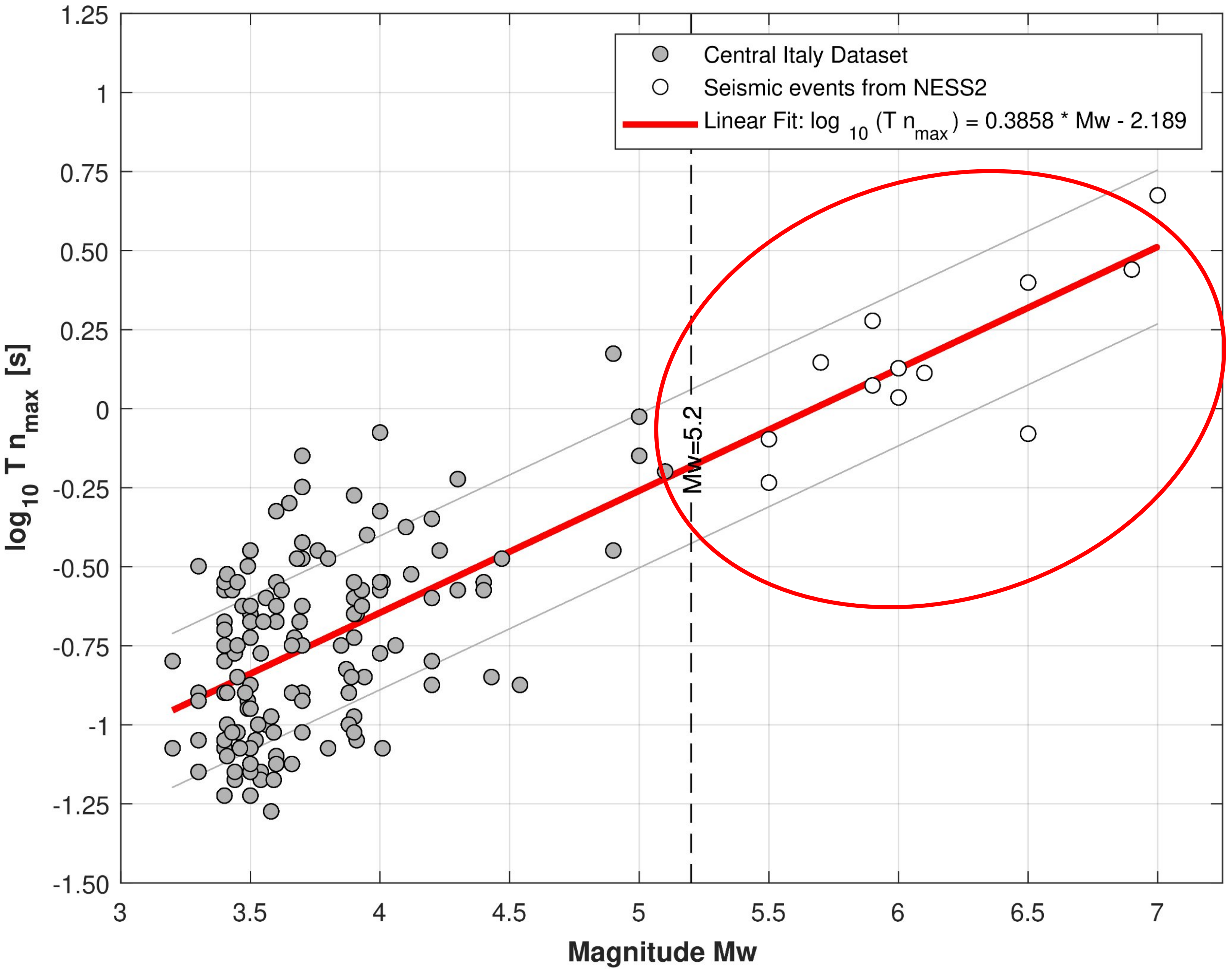


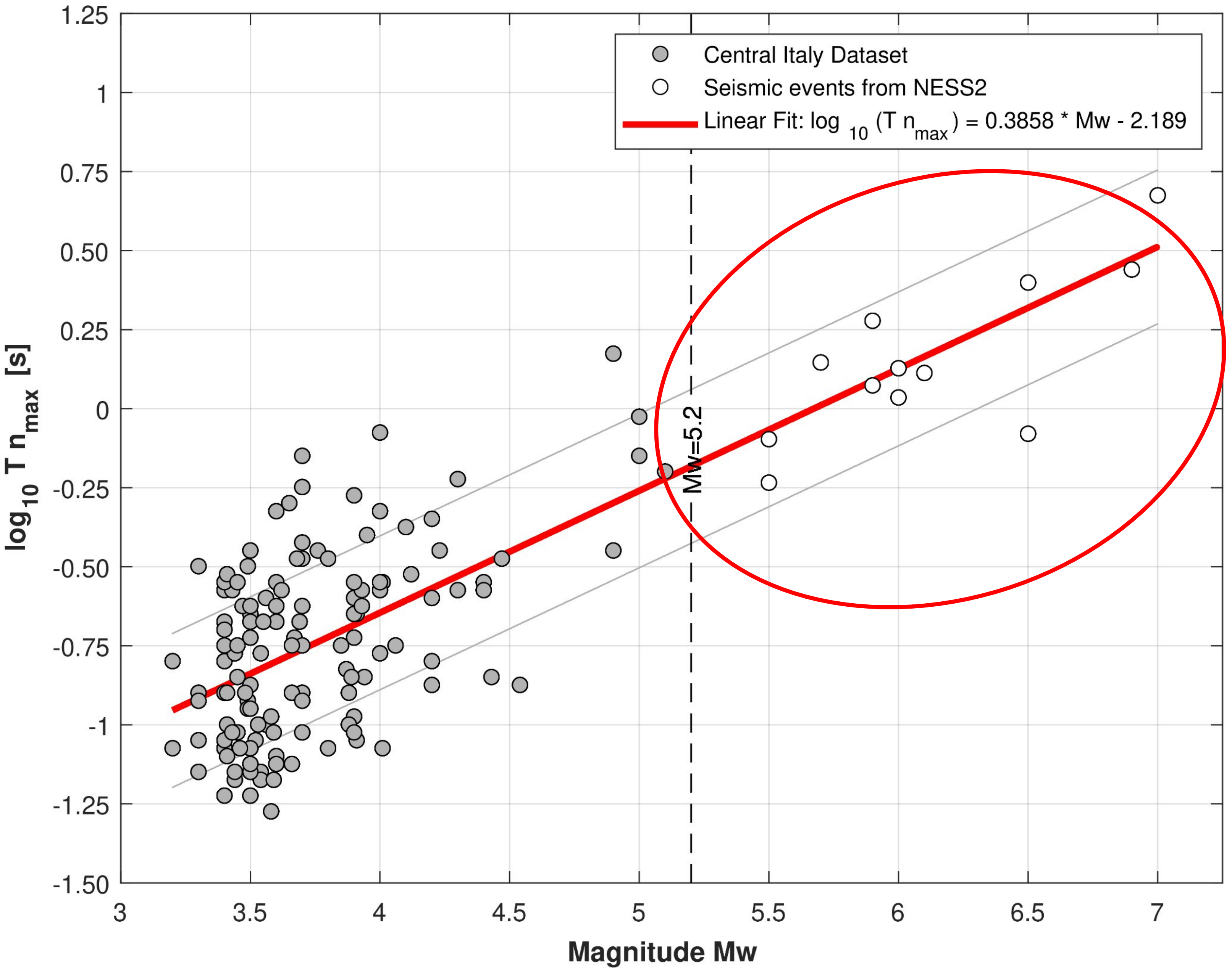
TABLE 1
Summary of the Parameters of the Normal-Fault Events in Near-Source Strong-Motion, Version 2.0 – NESS2.0 (Sgobba, Felicetta, *et al.*, 2021) with Pulse Records (M_w > 5.2)

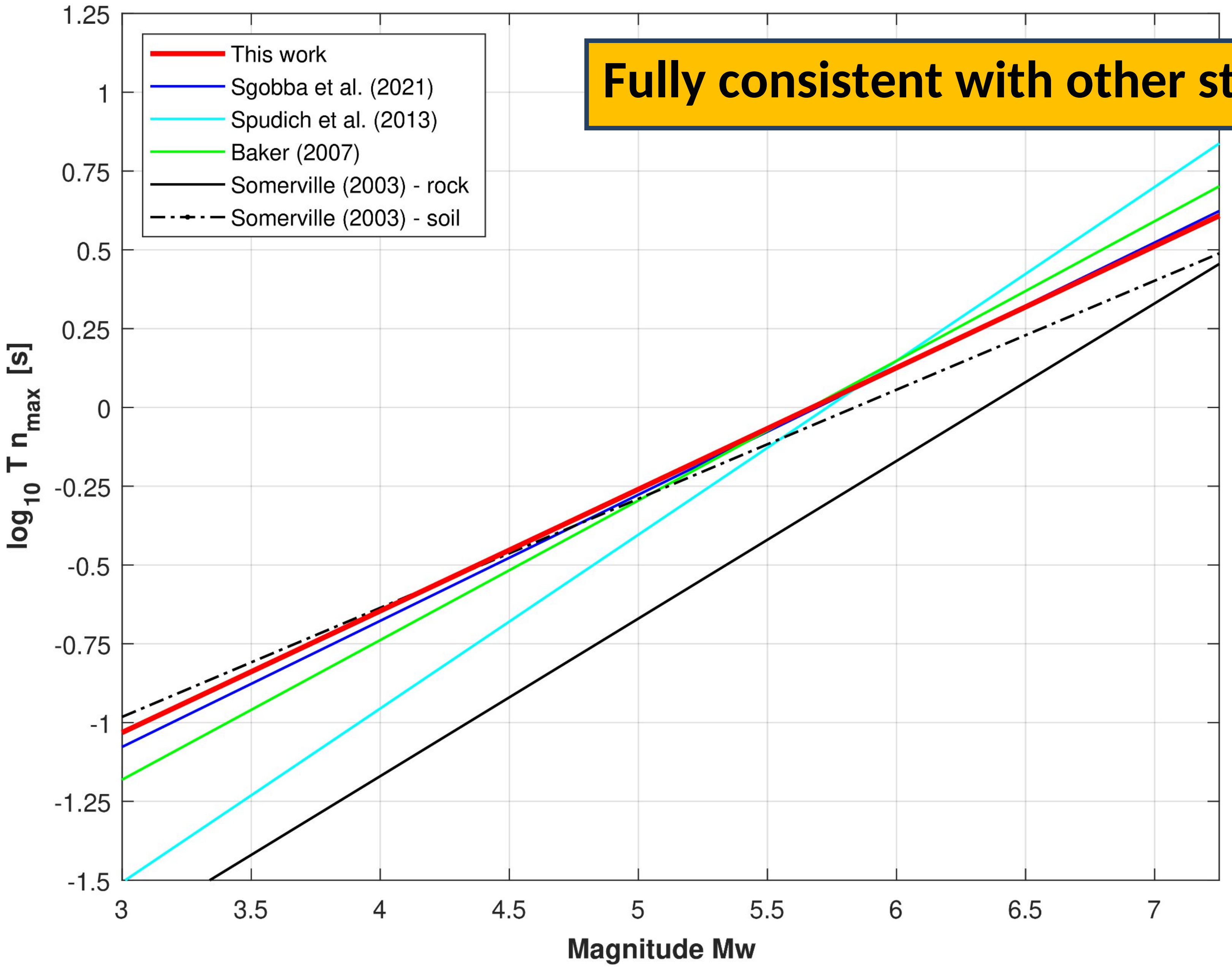
Event	Date (UTC) (yyyy/mm/dd hh:mm:ss)	Magnitude	Nrecs	*Tp* (s)	Std. Dev.
Irpinia (Italy)	1980/11/23 18:34:53	6.9	2	2.7545	1.4998
Kalamata (Greece)	1986/09/13 17:24:34	5.9	1	1.8970	–
Aigio (Greece)	1995/06/15 00:15:47	6.5	1	0.8330	–
Umbria–Marche (Italy)	1997/09/26 00:33:11	5.7	1	1.4	–
Umbria–Marche (Italy)	1997/09/26 09:40:24	6.0	2	1.0850	0.2376
L'Aquila (Italy)	2009/04/06 01:32:40	6.1	4	1.2968	0.4453
L'Aquila (Italy)	2009/04/07 17:47:37	5.5	5	0.8008	0.3430
Kumamoto (Japan)	2016/04/15 16:25:06	7.0	14	4.7285	3.0264
Amatrice (Italy)	2016/08/24 01:36:32	6.0	4	1.3422	0.7045
Ussita (Italy)	2016/10/26 19:18:06	5.9	4	1.1847	0.1395
Norcia (Italy)	2016/10/30 06:40:18	6.5	7	2.5060	1.7953
Capitignano (Italy)	2017/01/18 10:14:12	5.5	3	0.5833	0.0950

Add events with M_W **> 5.2** worldwide with normal style of faults according to the **NESS2 catalogue** (Sgobba et al., 2021)

Directivity Parametrization

Magnitude scaling of peak period





Fully consistent with other studies

Add events with M_W **> 5.2** worldwide with normal style of faults according to the **NESS2 catalogue** (Sgobba *et al.*, 2021)

Workflow

INPUT PARAMETERS

$\boldsymbol{M_W}$ (moment magnitude)

$\boldsymbol{n_{max}}$ (maximum directivity amplitude)

$\boldsymbol{\theta_0}$ (angle of maximum directivity)

1) Estimate $\boldsymbol{T\, n_{max}}$ **using linear relation with** $\boldsymbol{M_W}$ (extended using pulse-like periods T_p from the NESS2.0 database)

2) **Gaussian distribution** of $\log_{10}\frac{T}{T\, n_{max}}$ as a function of $\frac{n}{n_{max}}$;

shape factor $\mathbf{c_1}$ **depends linearly on** $\boldsymbol{n_{max}}$

3) Calculate the **azimuthal variation of the amplitude** of the motion using the directivity coefficient C_d, (angle of maximum directivity θ_0, $k = 0.85$ and Mach number $\alpha = \frac{v_r}{c} = 0.50$ fixed)

Workflow

INPUT PARAMETERS

M_W (moment magnitude)

n_{max} (maximum directivity amplitude)

θ_0 (angle of maximum directivity)

1) Estimate $T\ n_{max}$ **using linear relation with** M_W (extended using pulse-like periods T_p from the NESS2.0 database)

The **final directivity-corrected prediction** Y_{corr} is obtained as:

$$log_{10} Y_{corr}(\theta, T, M_W, n_{max}, R_{JB}) = log_{10} Y(M_W, R_{JB}) + \boldsymbol{\delta D2D(\theta, T, M_W, n_{max})}$$

shape factor $\mathbf{c_1}$ **depends linearly on** n_{max}

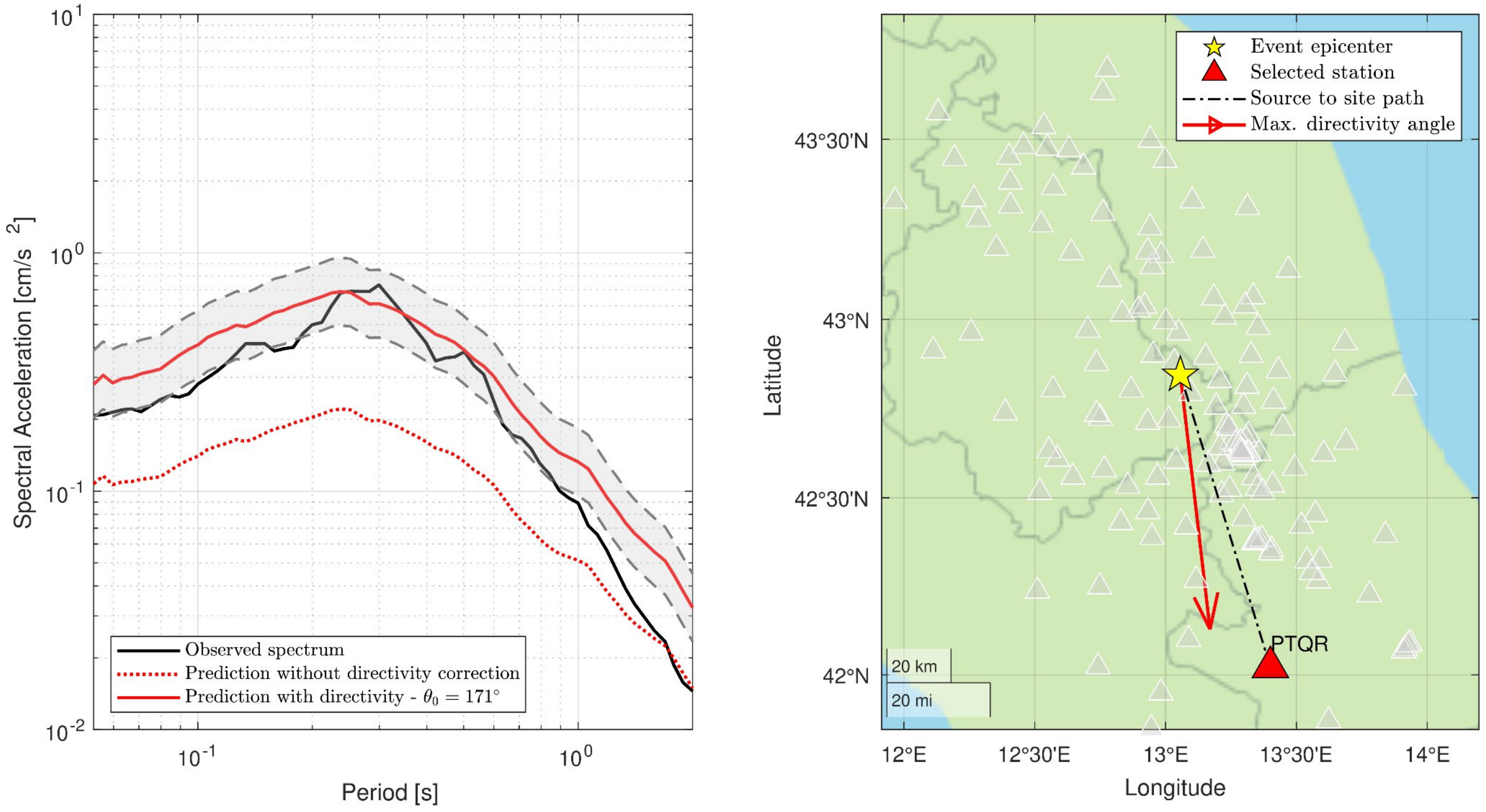
3) Calculate the **azimuthal variation of the amplitude** of the motion using the directivity coefficient C_d, (angle of maximum directivity θ_0, $k = 0.85$ and Mach number $\alpha = \frac{v_r}{c} = 0.50$ fixed)

Results

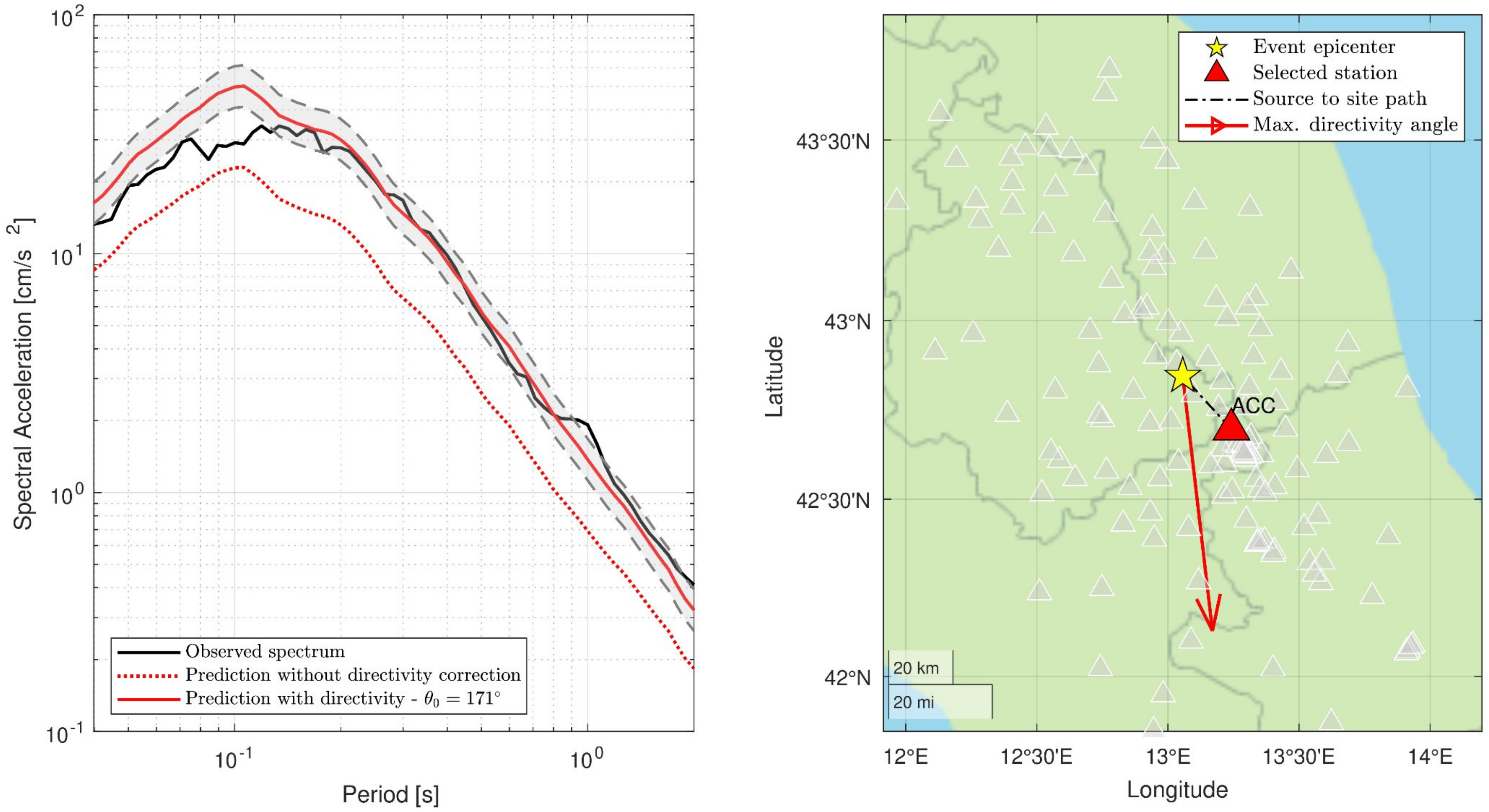
Application to a real case scenario

Far-Field | **FORWARD DIRECTIVITY** | **Near-Field**

Event: 161030115817 - M = 4 - Station: PTQR - Azimuth: 163°



Event: 161030115817 - M = 4 - Station: ACC - Azimuth: 137°

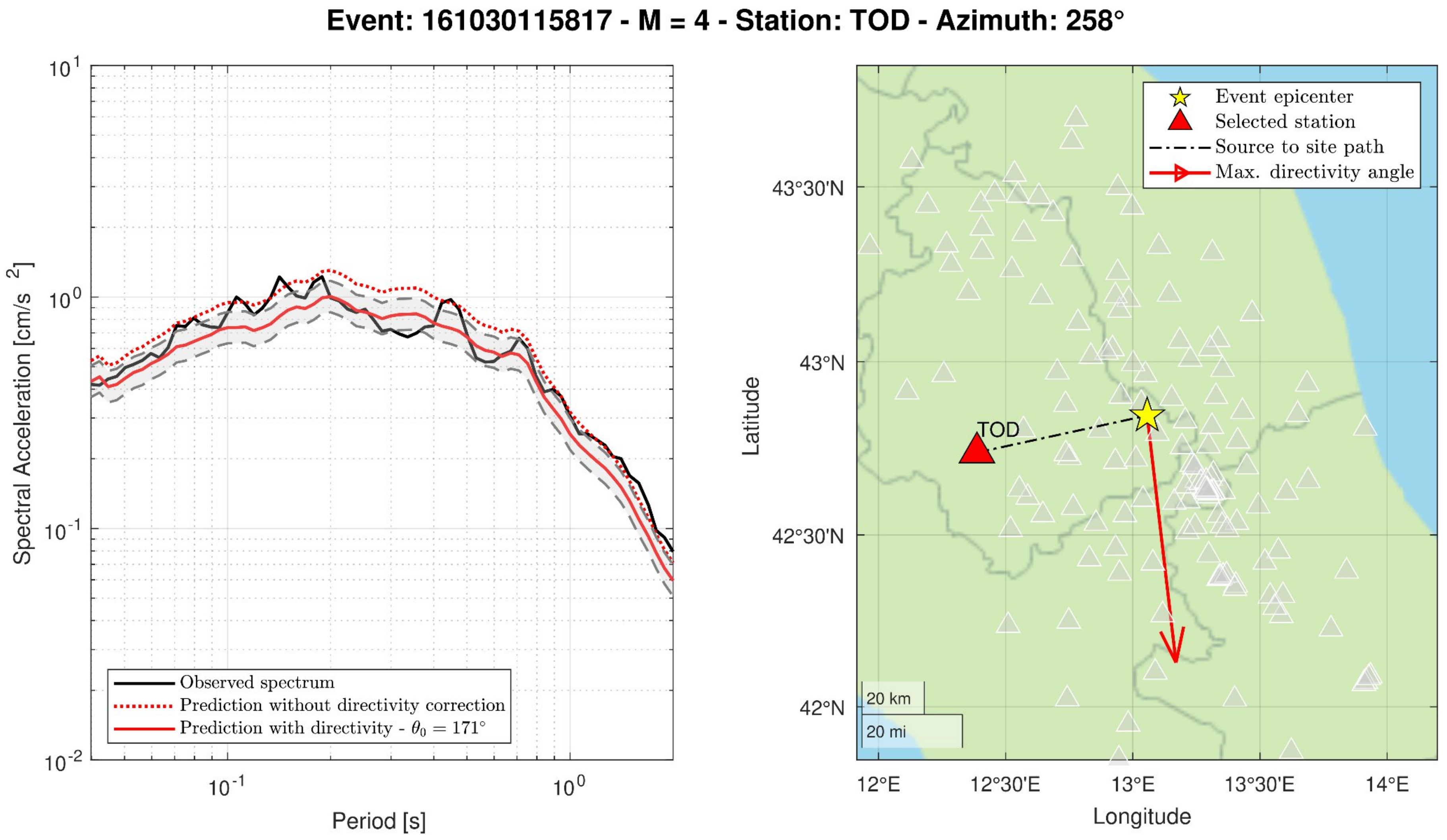


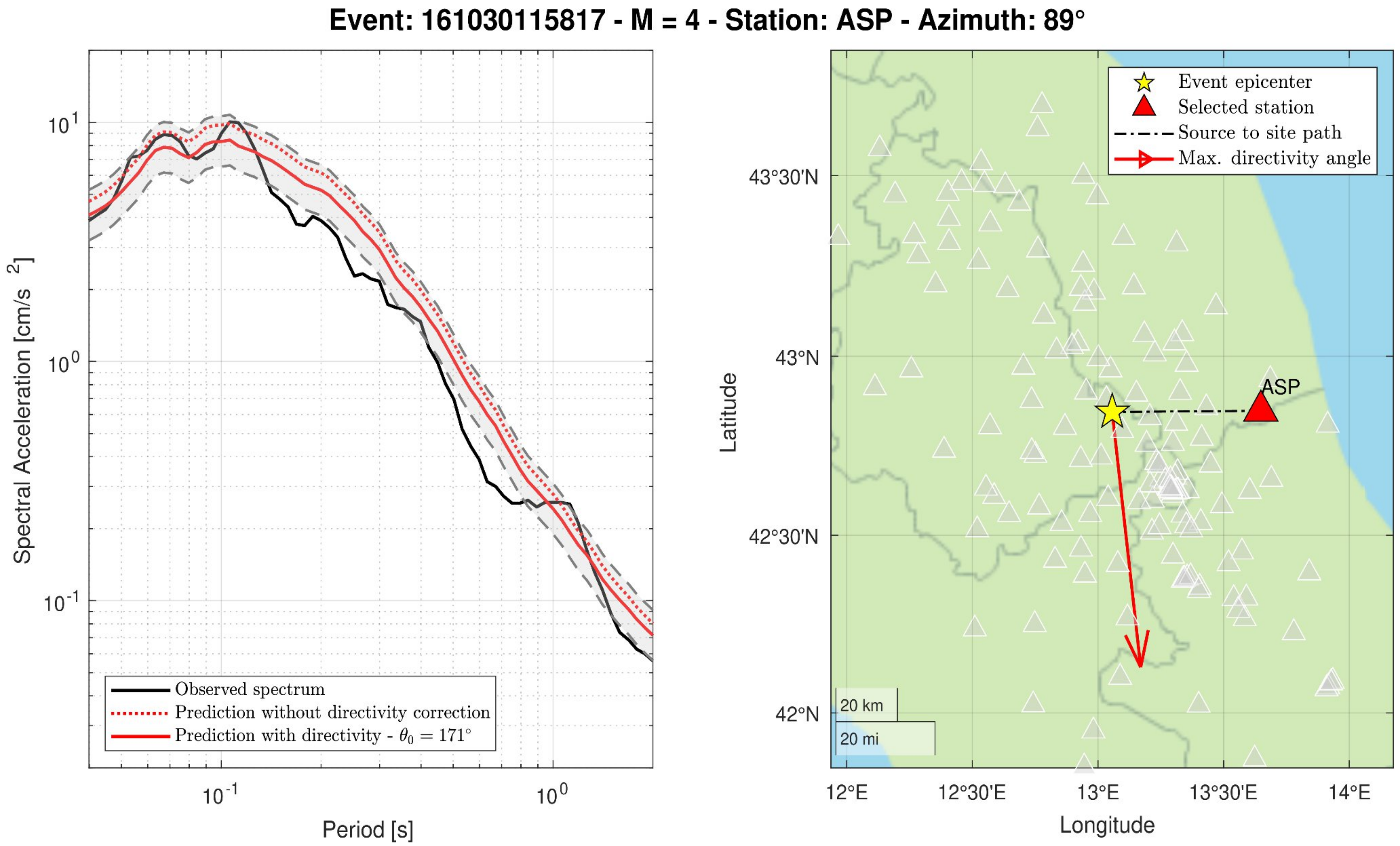
In the **forward directivity** cases, the correction factor due to the directivity source enhances the spectral amplitudes and **significantly improves the agreement between predicted and observed spectra**

Results

Application to a real case scenario

NEUTRAL POSITION





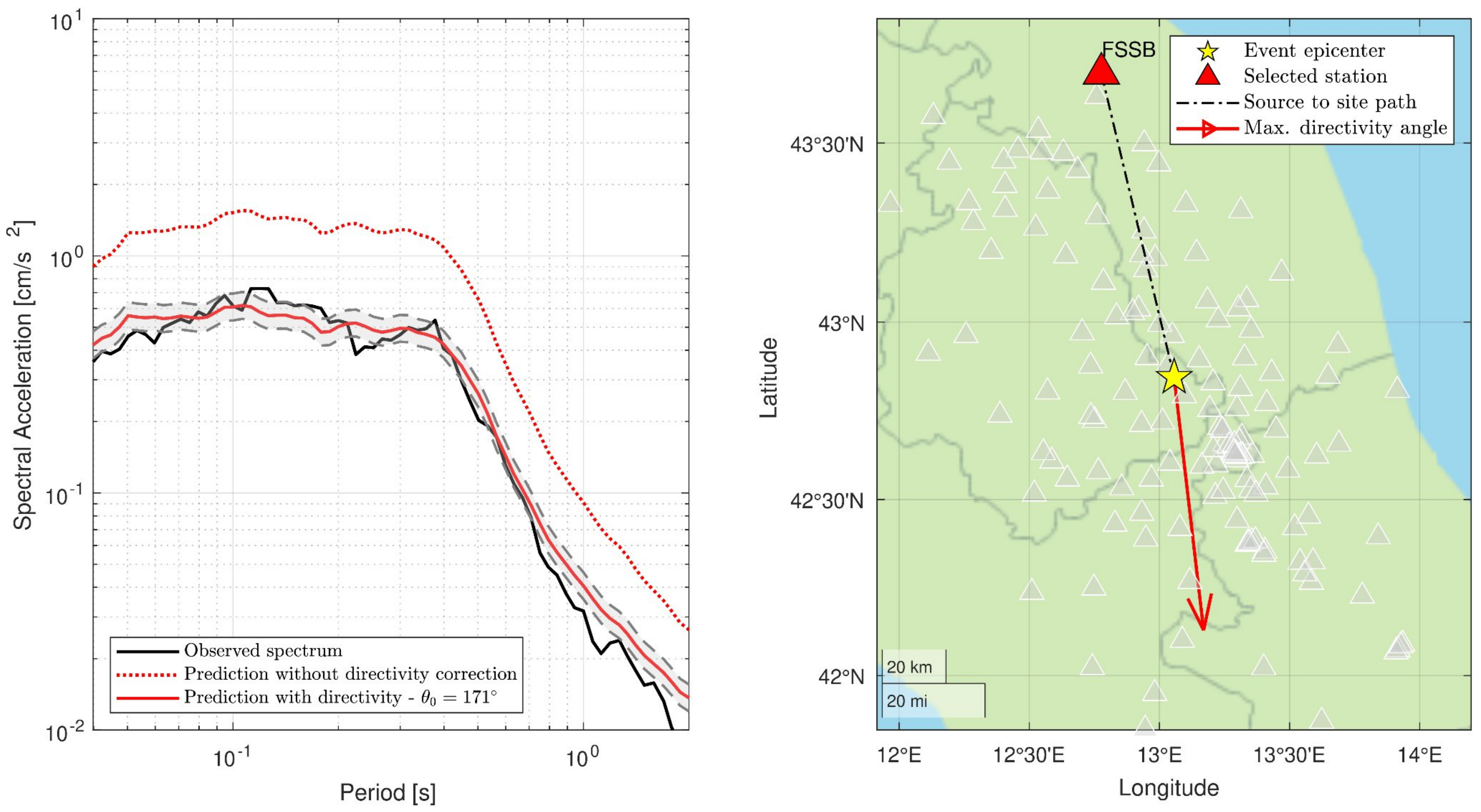
The **impact** of the **directivity correction for stations in the neutral position cases is negligible**

Results

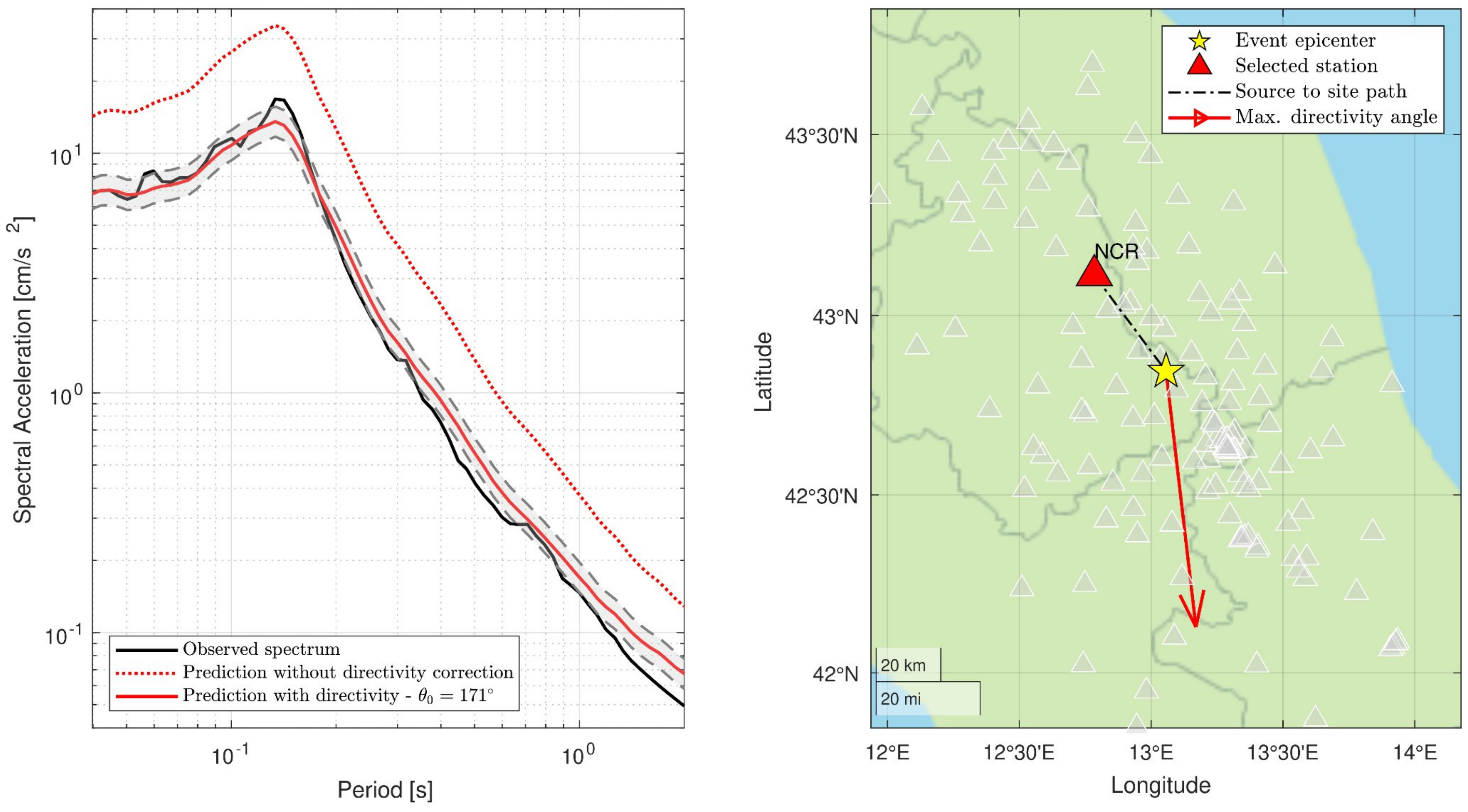
Application to a real case scenario

Far-Field | **BACKWARD DIRECTIVITY** | **Near-Field**

Event: 161030115817 - M = 4 - Station: FSSB - Azimuth: 347°



Event: 161030115817 - M = 4 - Station: NCR - Azimuth: 323°



In the cases with **backward directivity**, the prediction **without the directivity correction tends to overestimate the observed ground motion**, while the application of our model yields **a much better match with respect to the observed spectrum**

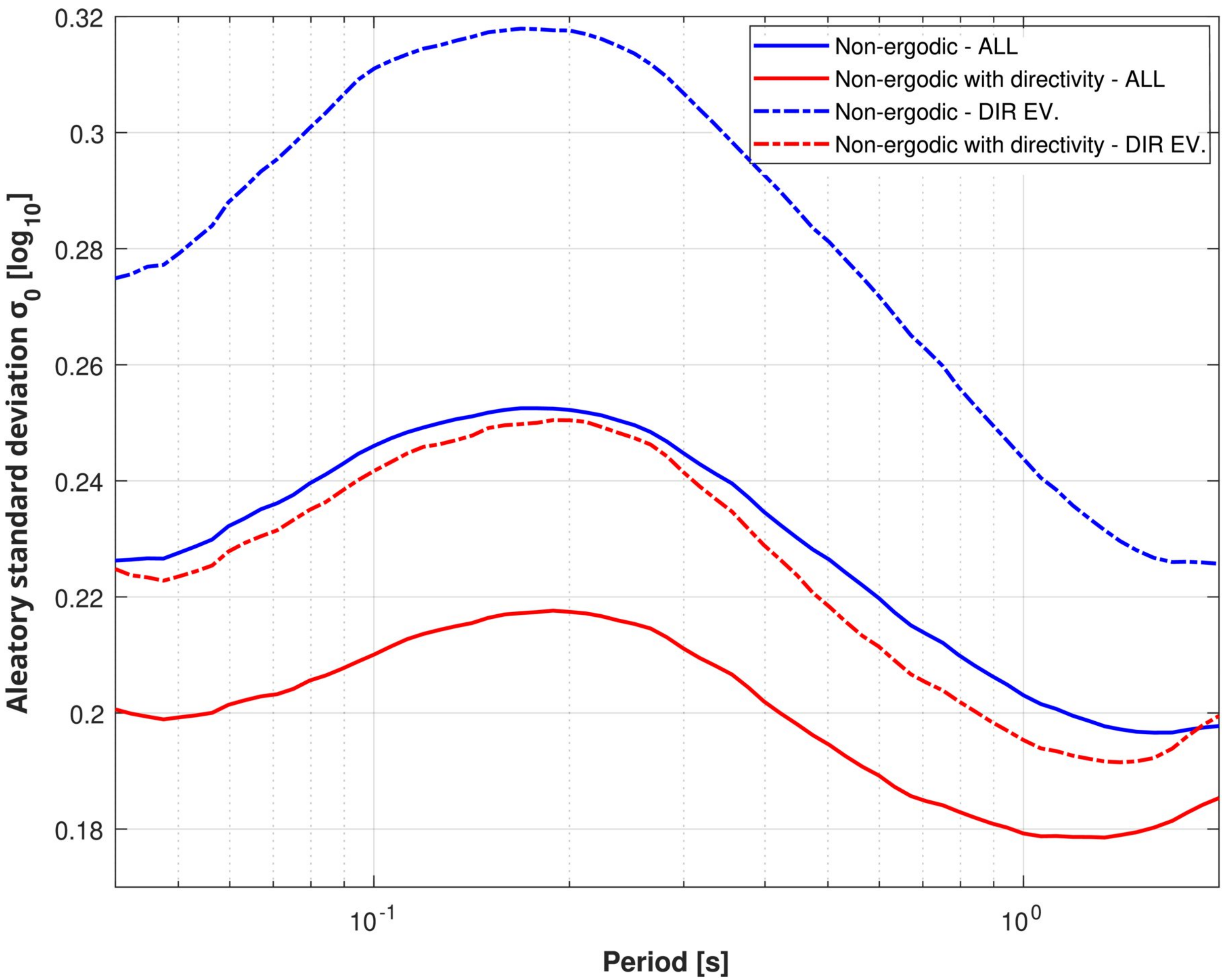
Results

Standard deviation assessment

Overall, this improvement **is systematic and consistent across the events analyzed in the Central Italy**

The application of the directivity model consistently reduces the σ_0 across all periods with an **average reduction of about 13%**

For the **directive events**, the reduction of σ_0 is stronger, with an **average reduction of about 20%** across all periods



Conclusion and Future Developments

We developed a fully data-driven model to parametrize the directivity effects into a GMM for Central Italy **using a few number of independent parameters**

Future directions:

- Application of the method to a larger and spatially wider database (e.g., **ITACAext 2.0**), including seismic sequences from the last ~60 years and **focal mechanisms other than normal faulting**
- Extension of the period range to **T > 2 s (up to ~10 s)** to better represent **large-magnitude events**
- Introduction of **fault geometry** in the computation of **event-to-site azimuths**, moving beyond the **point-source representation**

Development of a probabilistic description of n_{max} and the **occurrence rate of directive events** enabling the model to be integrated into a **fully probabilistic PSHA workflow**

Colavitti et al. (2026) BSSA

Empirical Modeling of Source Directivity Effects into a Ground-Motion Model for Central Italy

Leonardo Colavitti[*1], Giovanni Lanzano[2], Sara Sgobba[2], and Francesca Pacor[2]

ABSTRACT

Assessing the spatial variability of seismic shaking in the epicentral area of an earthquake is one of the major challenges to be addressed in seismic hazard estimates. Among the main contributions to the ground-motion variability, source directivity plays a predominant role, inducing spectral amplifications in the direction of rupture propagations, even for small- to moderate-magnitude earthquakes. The scope of this work is to provide an empirical predictive model that can be used to modulate the ground-motion amplitudes, according to the expected source directivity effects. The proposed directivity corrective term is built for acceleration spectral ordinates, parameterizing the azimuthal trend of the leftover residuals of a fully nonergodic regional model, after removing the systematic effects of source, site, and propagation. Our study is focused on the area of Central Italy, which is dominated by a complex system of normal faults that has generated several seismic sequences in the past 30 yr. The residual analysis is carried out using the recordings of 456 events in magnitude ranging from 3.2 to 6.5, showing that about one-third of the examined earthquakes exhibit a clear ground-motion azimuthal pattern. The directivity correction model is based on three empirical relations, which describe (1) azimuthal variations modeled via a theoretical directivity factor, (2) spectral variation of directivity amplitude using a first-order Gaussian function, and (3) the correlation between moment magnitude and the period of maximum directivity effect. We demonstrated that the introduction of a source directivity correction, applied to a real-case scenario, has a considerable impact and may result in a 20% reduction of aleatory variability with respect to the uncorrected nonergodic model. This model offers an empirically based and physically consistent framework for capturing spatial variations in ground shaking, thereby improving the reliability of seismic hazard evaluations and informing risk mitigation strategies.

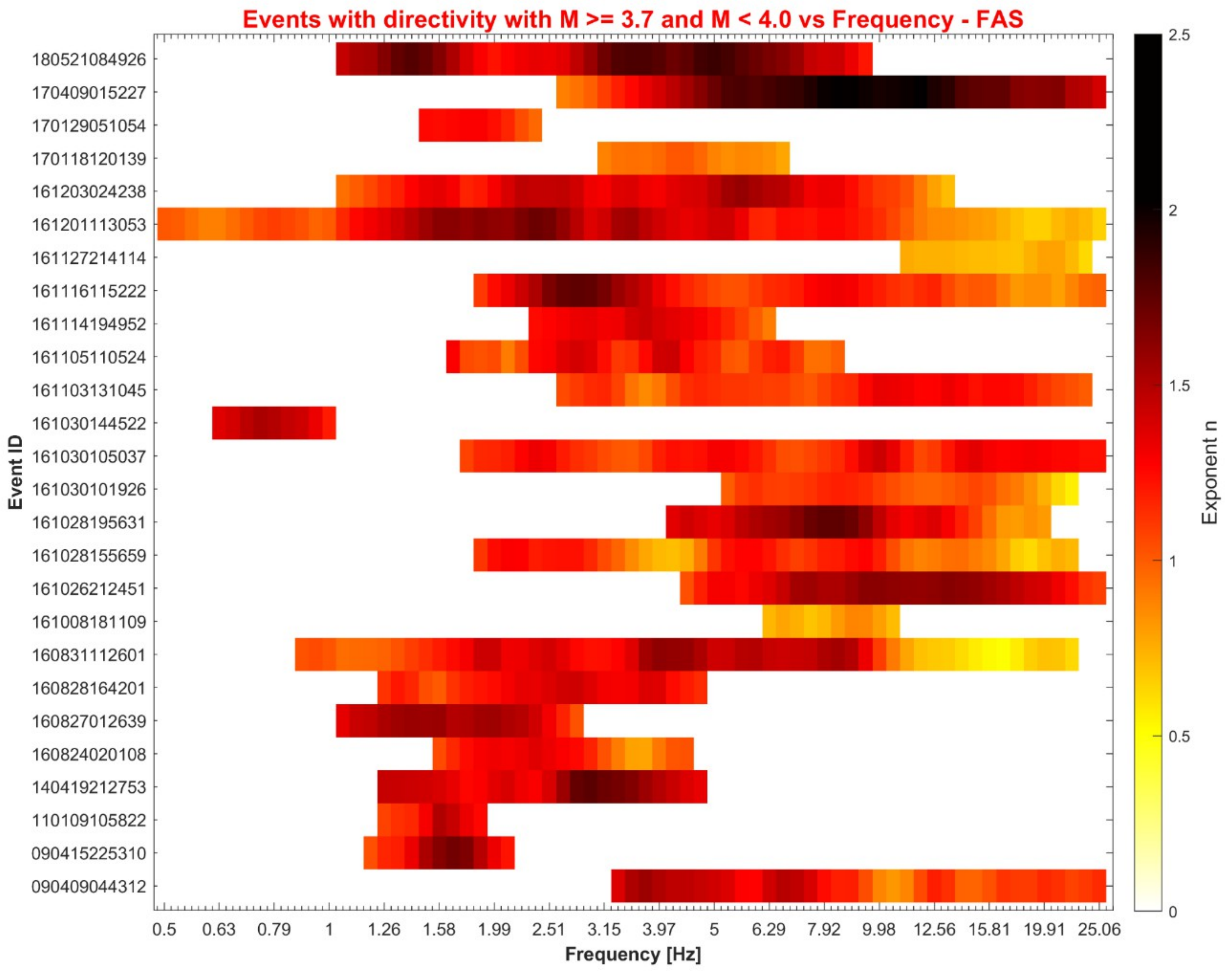
Thank you for your attention!

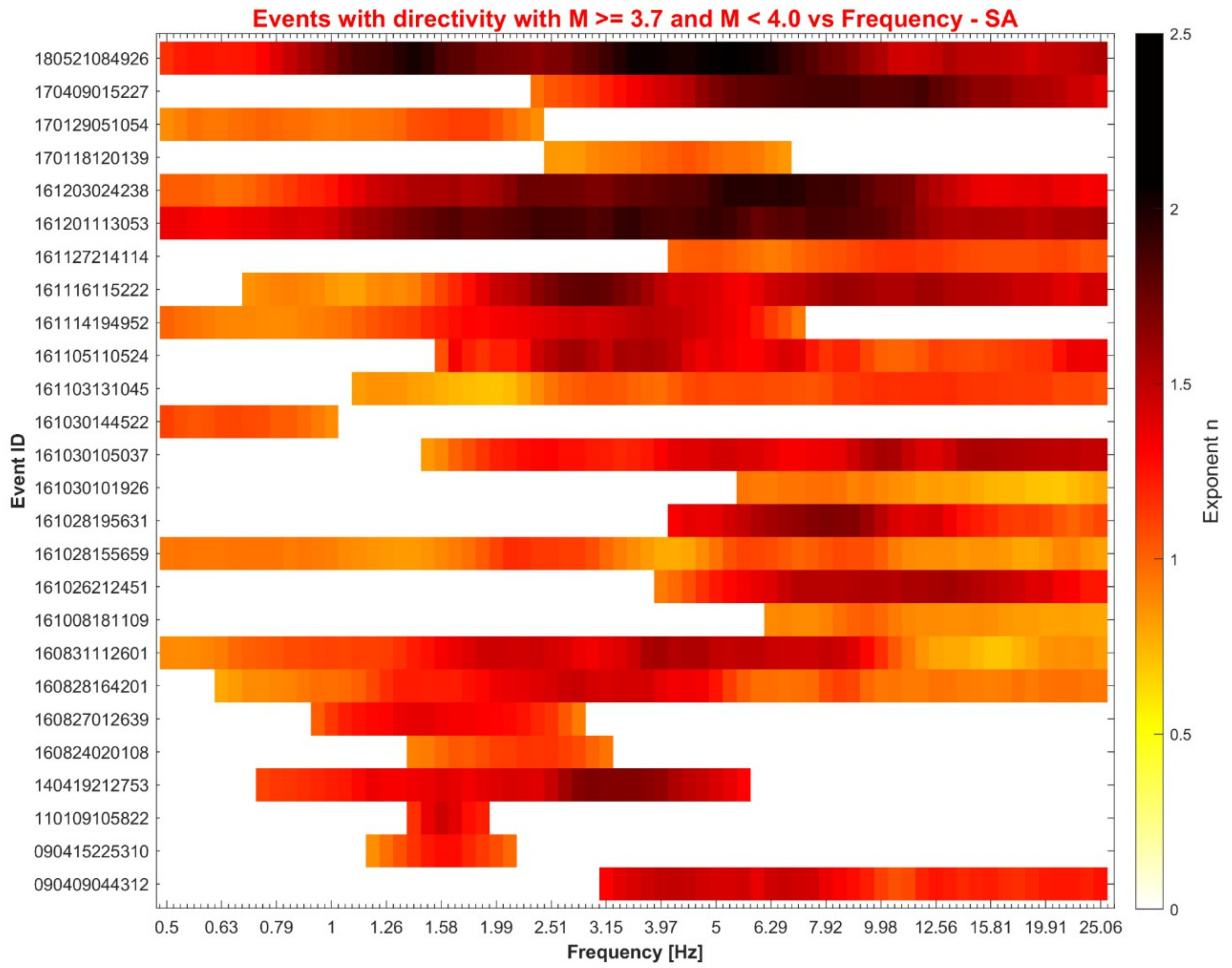
Leonardo Colavitti, PhD

leonardo.colavitti@edu.unige.it

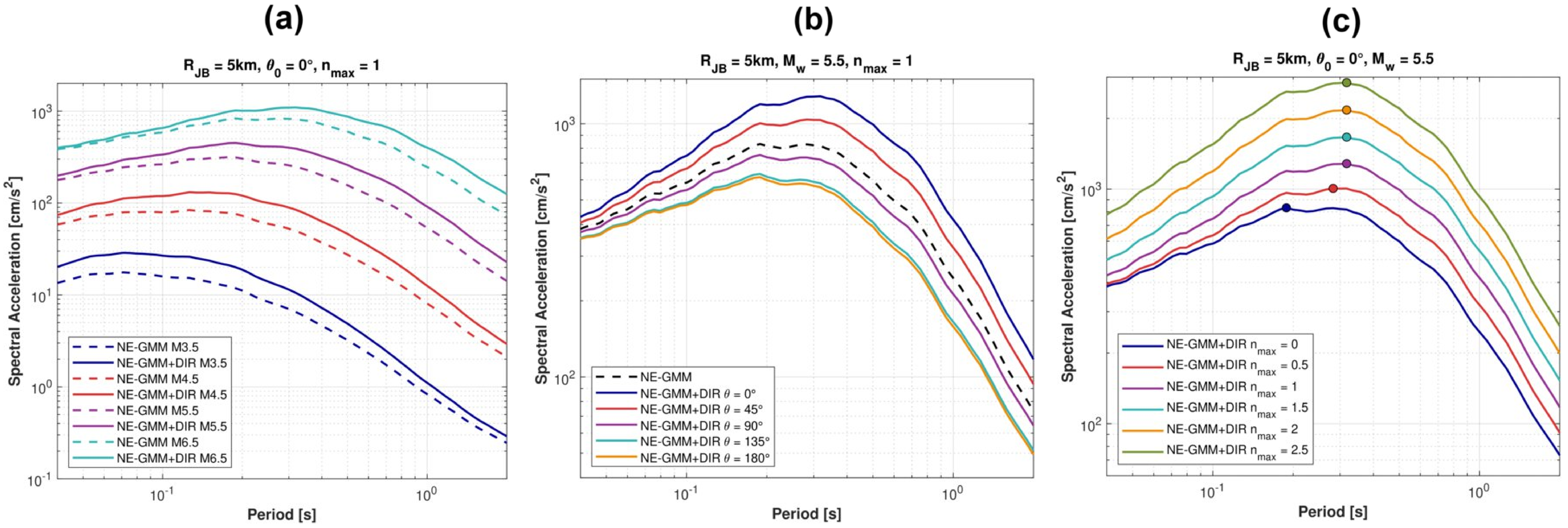
SECURE REGIONAL-SCALE EARTHQUAKE **GROUND MOTION PREDICTIONS** THROUGH PYHSICS-BASED AND EMPIRICAL APPROACHES: **A CASE STUDY CENTRAL ITALY**

Comparison SA-FAS

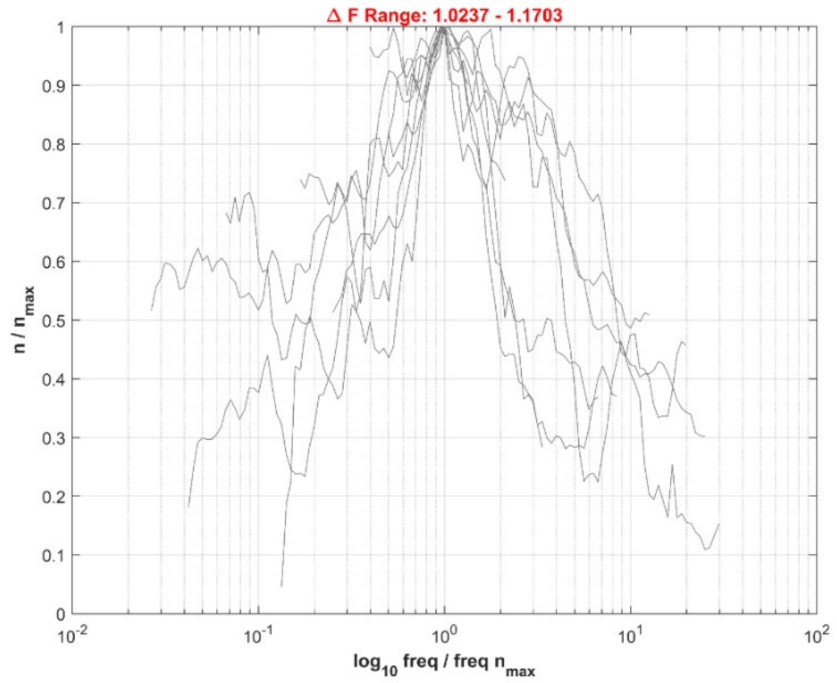


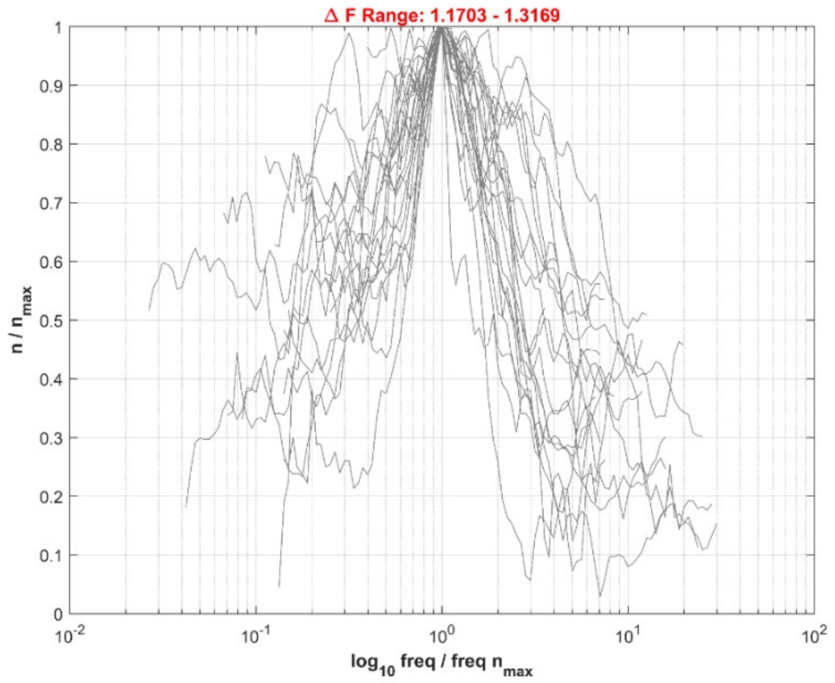


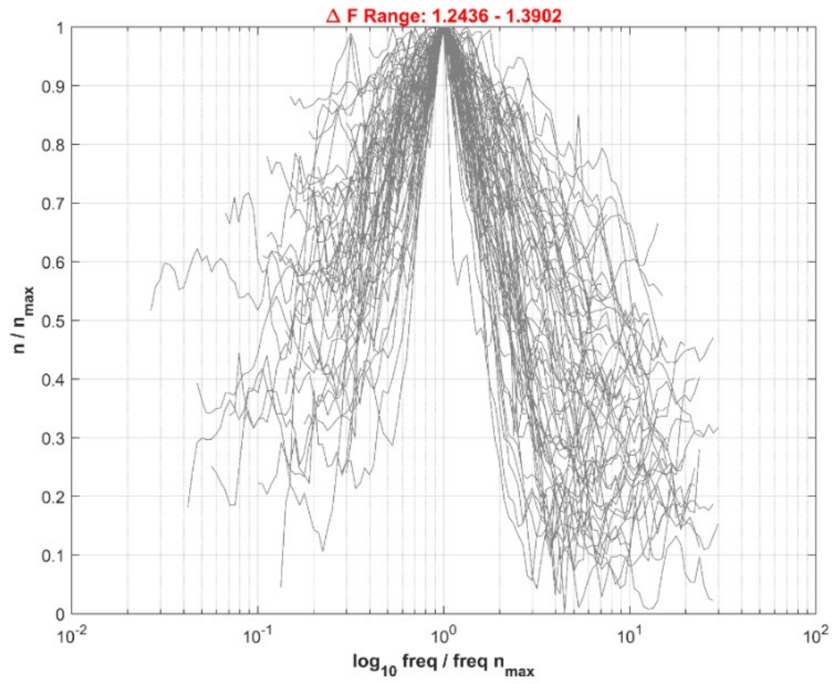
Directivity correction

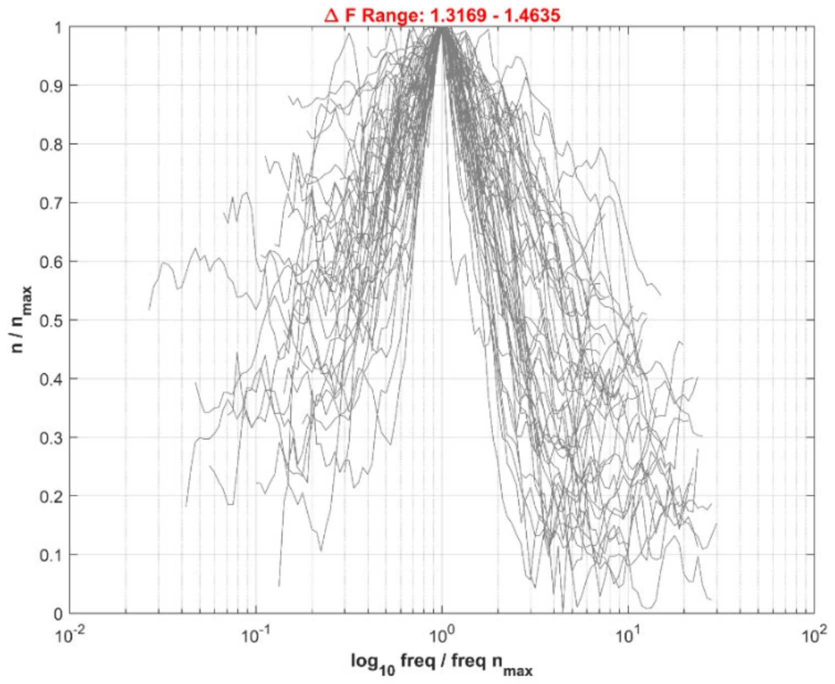


Comparison SA-FAS









Aleatory Standard Deviation

$$\sigma_{tot} = \sqrt{\tau^2 + \phi_{S2S}^2 + \tau_{L2L}^2 + \phi_{P2P}^2 + \boldsymbol{\sigma_0}}$$