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Dynamic rupture inverse modeling across broad spatial and temporal scales

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Earthquake physics

To understand how earthquake ruptures nucleate, propagate and arrest, we need:

- Laboratory experiments & theoretical considerations
  - Friction laws
  - Simulations & parametric studies -> understanding the roles of individual stress and frictional (dynamic) parameters

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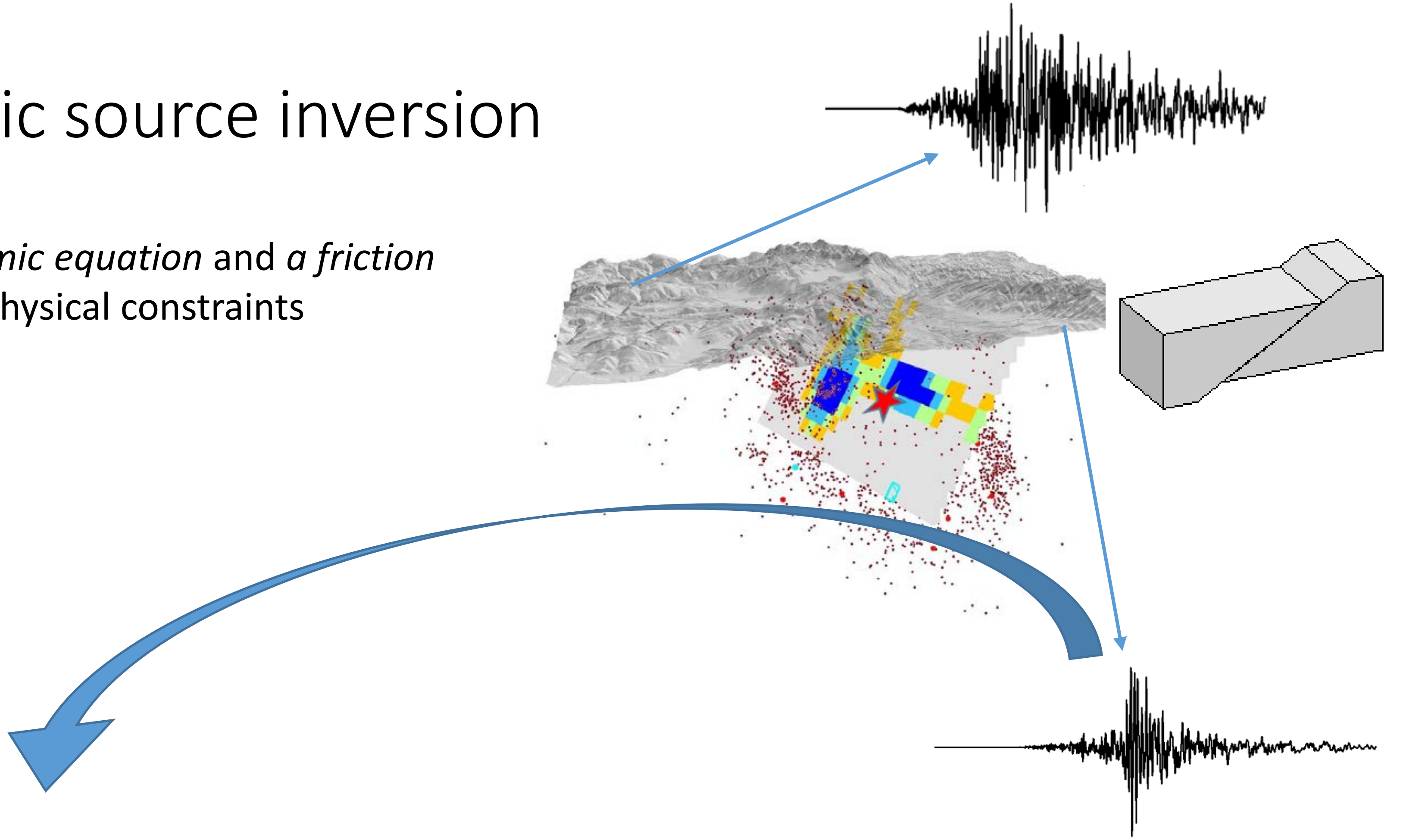
- Observational constraints
  - Modeling of observed (surface) data -> validation & plausible values of the dynamic parameters (including their spatial heterogeneity)
  - Testing dynamic models on temporal scales from fractions of seconds to weeks is challenging

Dynamic source inversion

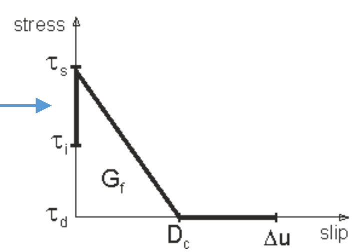
Elastodynamic equation and *a friction law* act as physical constraints



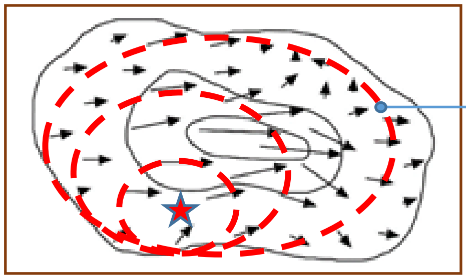
Fault plane

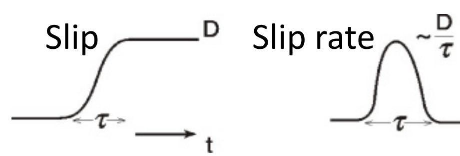
Distribution of
- prestress
- friction parameters

Friction law



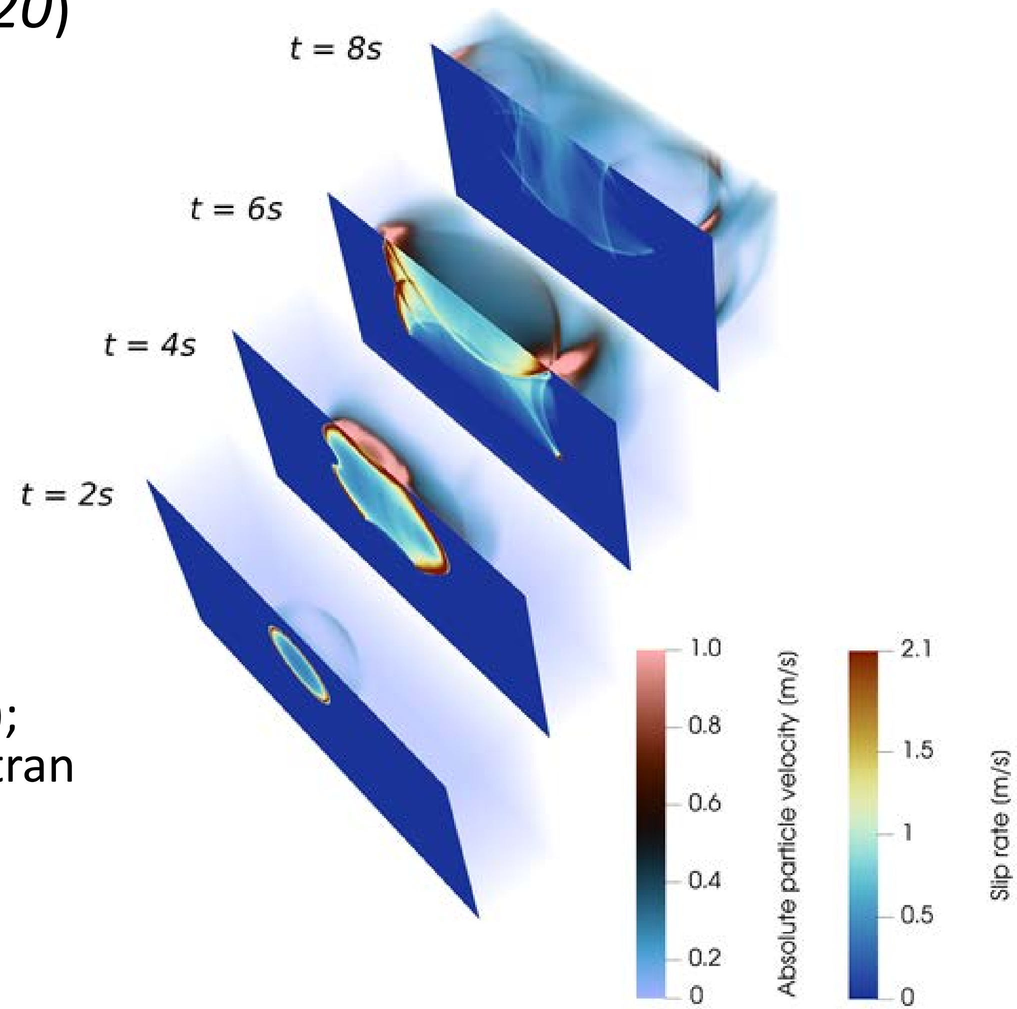
Dynamic rupture simulation





Forward solver (speed matters)

- FD3D_TSN (*Premus et al., 2020*)
- Vertical planar fault
- Community test with heterogeneous dynamic parameters
- Fault size 30x15km (grid step 100m)
- 12s of rupture propagation calculated in:
  - 3min on 1 CPU (Intel i9-9900K)
  - 20s on 1 GPU (Nvidia RTX 2700); ported using OpenACC in nvfortran
- Freely available on GitHub



Applications of Bayesian dynamic rupture inversions

- 2019 Mw6.2 Amatrice (Central Italy)
  - Gallovič et al. (JGR 2019b)
- 2020 Mw 6.8 Elazığ (Turkey)
  - Gallovič et al. (CommEE 2020)
- 2014 Mw 6.0 South Napa (California)
  - Premus et al. (Science Advances, 2022)
- 2017 Mw 6.3 Lesvos (Greece)
  - Kostka et al. (GJI 2022)
- 2011 and 2016 Mw 5.8 Ibaraki twins (Japan)
  - Gallovič (in prep.)

Presented at this workshop:

- 2004 Mw 6 Parkfield (California)
  - Schliwa et al. (submitted to JGR), talk on Monday
- 2023 Mw 7.8 Kahramanmaraş (Türkiye)
  - J. Premus, talk on Monday
- 2016 Mw 6.2 Tottori (Japan)
  - M. Hronek, poster A02 (upstairs)
- 2016 Mw ~4 Central Italy
  - Ľ. Valentová Krišková, poster A07 (upstairs)
- Synthetic tests, T. Miyamoto, poster B16 (this floor)

Waveform dynamic rupture inversions of large crustal earthquakes

Showcase example: The 2016 Mw6.2 Amatrice, Central Italy, earthquake

(Gallovič et al., 2019)

Overview of the 2016 Central Italy sequence

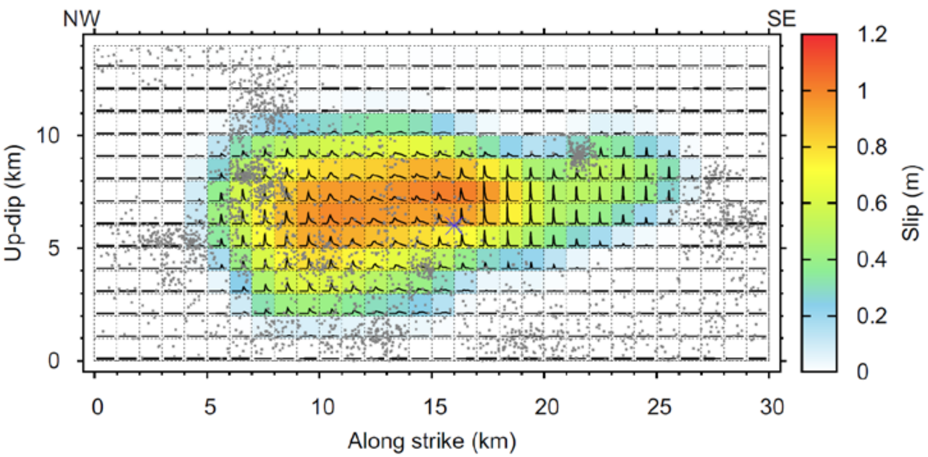
USGS

- Apennines, Central Italy
- Three M6 mainshocks
  - **Mw 6.2 Amatrice: August 24, 3:36**
  - Mw 5.9 Ussita: October 26, 21:18
  - Mw 6.5 Norcia: October 30, 08:40
- 300 casualties (mainly due to the 1st event)
- Kinematic inversions and tectonophysical interpretations by Pizzi et al. (2017).

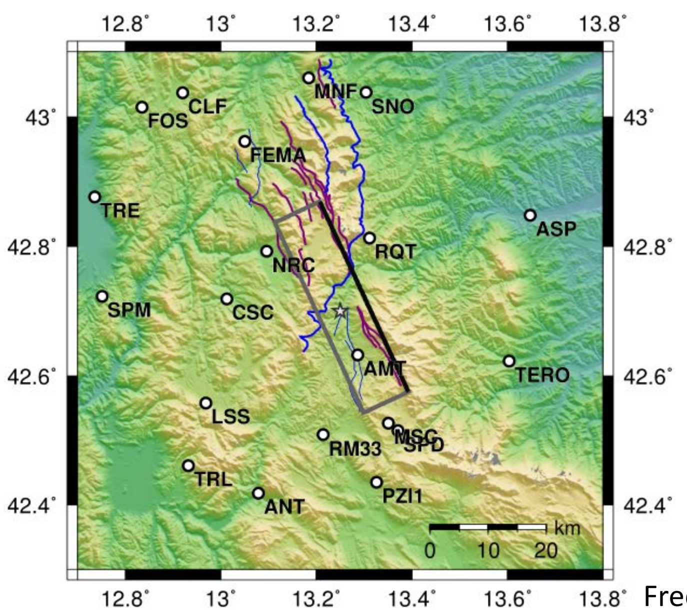
Best-fitting model from the Monte Carlo inversion (out of ~10^6 visited models)

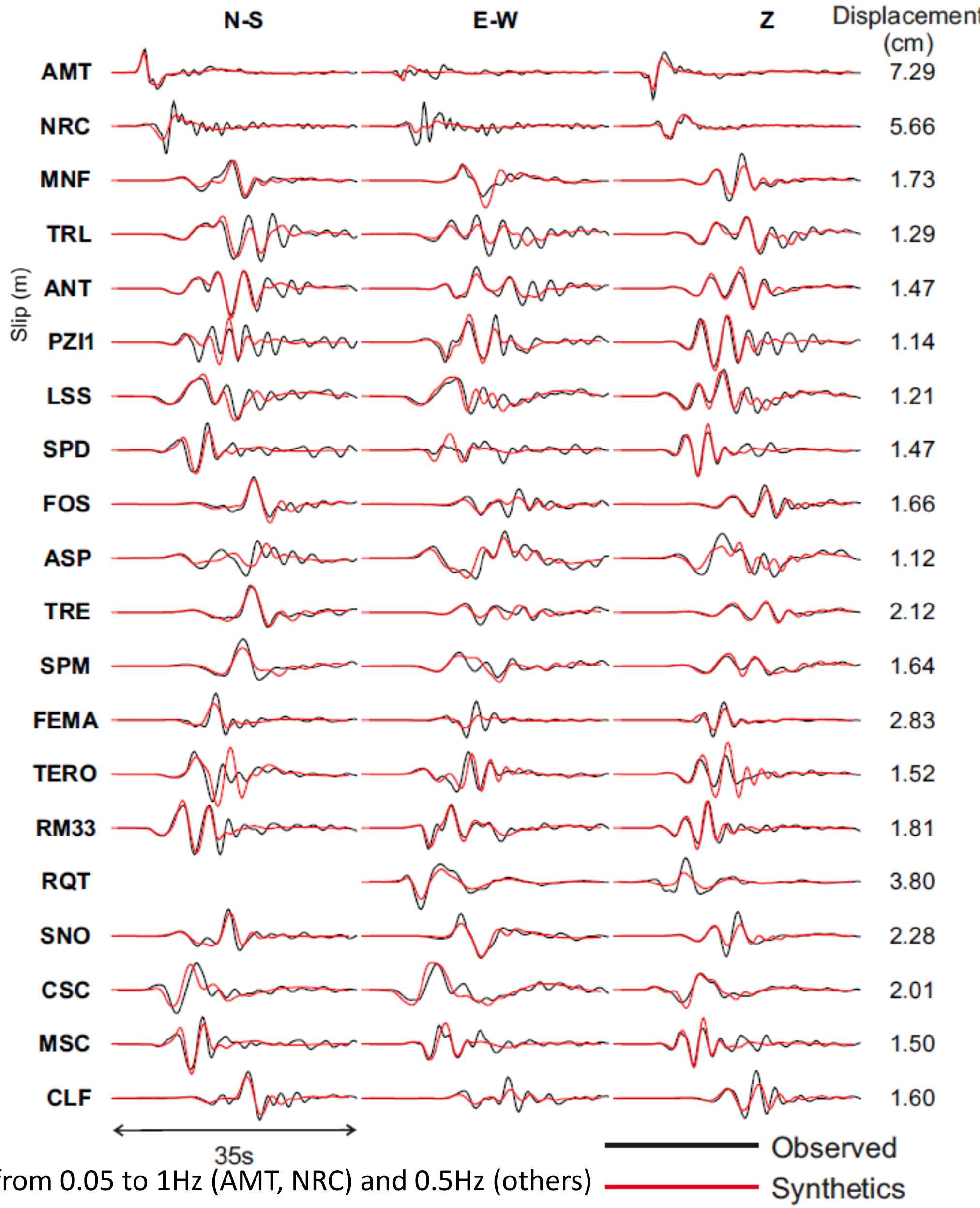
VR 62%

Forward simulation: 2 mins on CPU, 30s on GPU



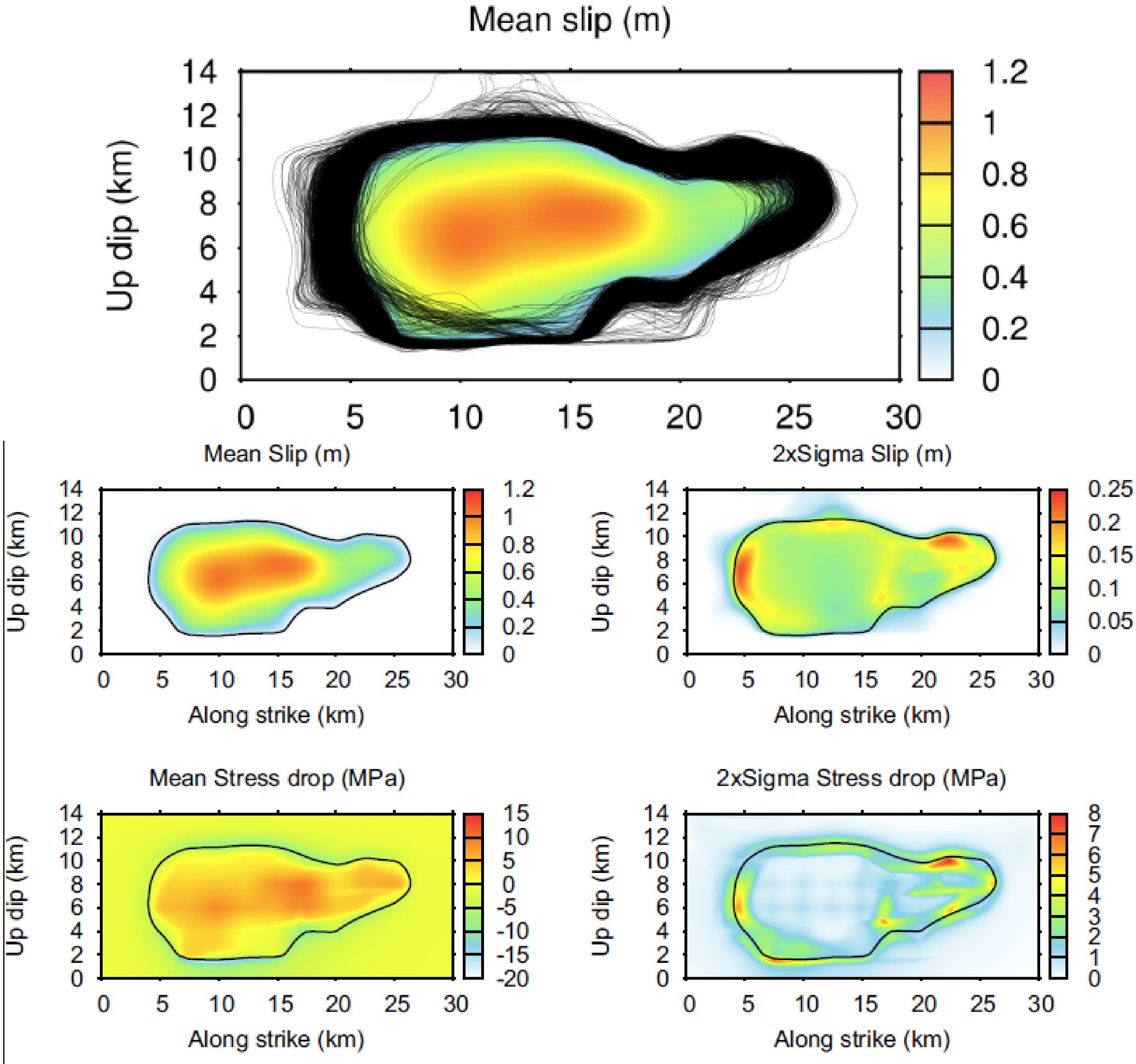
On-fault aftershocks relocated by Chiaraluce et al. (2017)





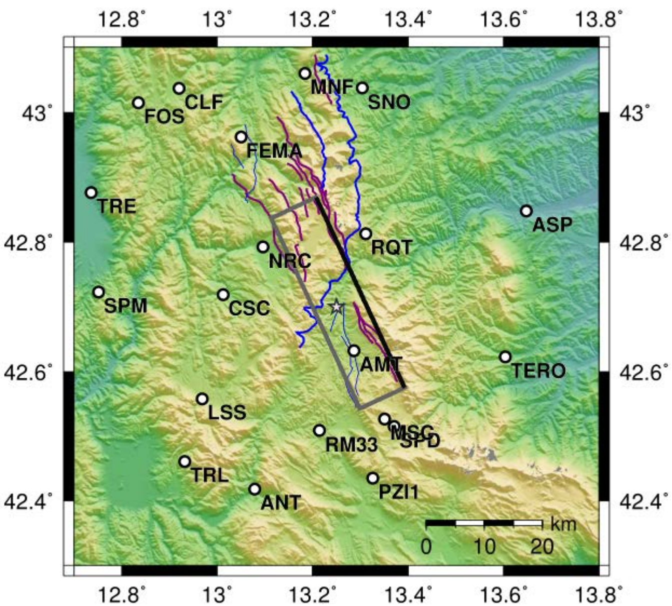
Frequency range from 0.05 to 1Hz (AMT, NRC) and 0.5Hz (others)

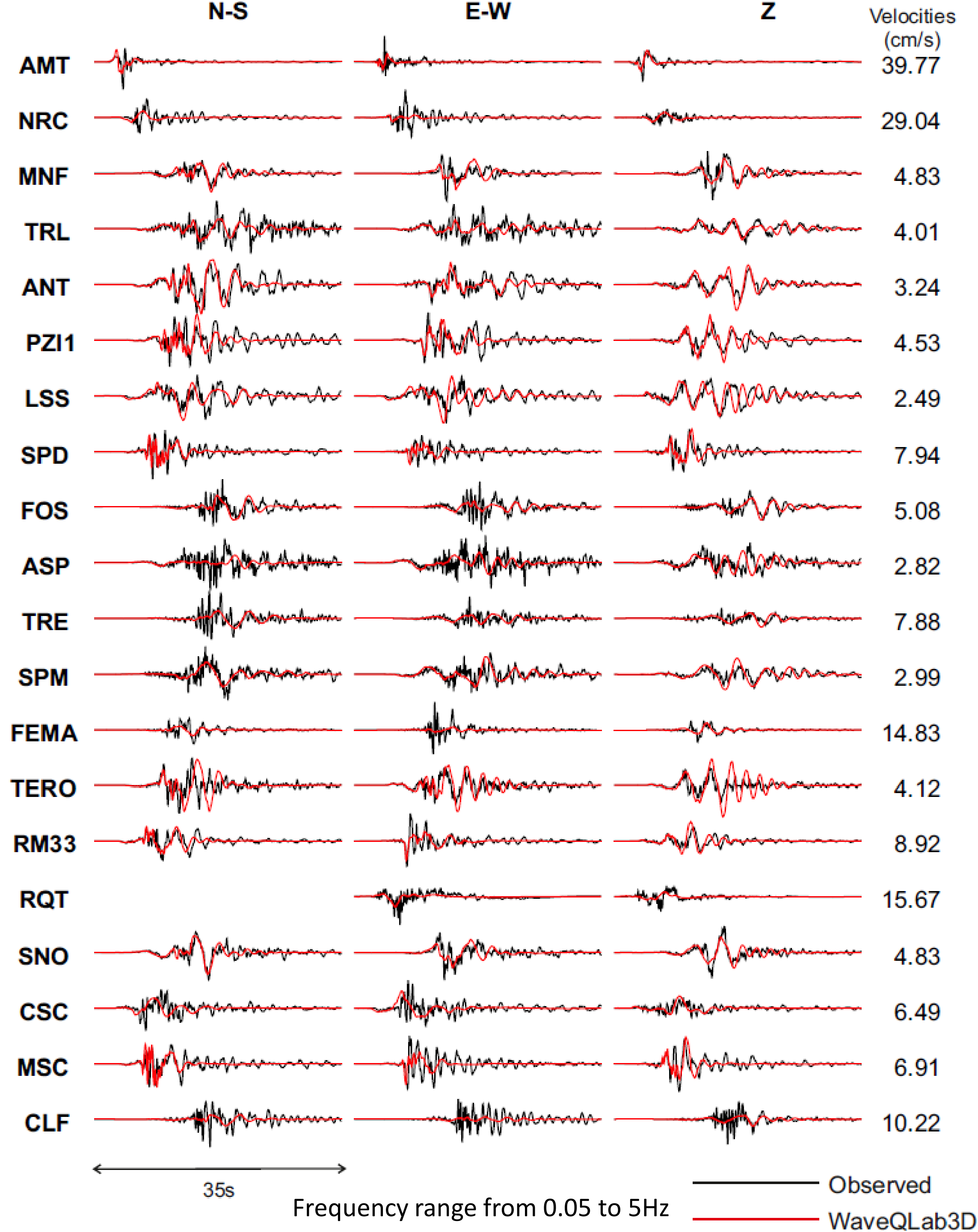
Uncertainty of rupture extent



Broadband simulation possible?

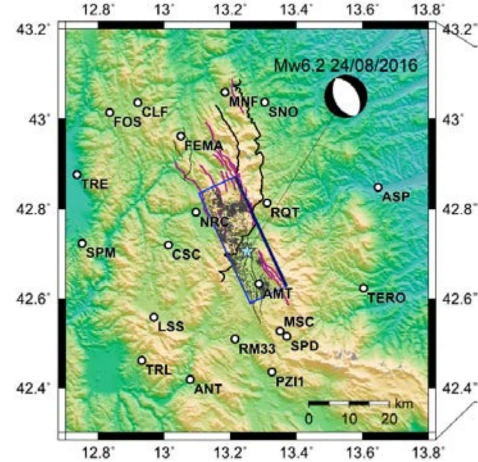
- Broadband velocity waveforms (up to 5Hz) predicted by our best-fitting model from the low-frequency inversion
- No source model modifications made





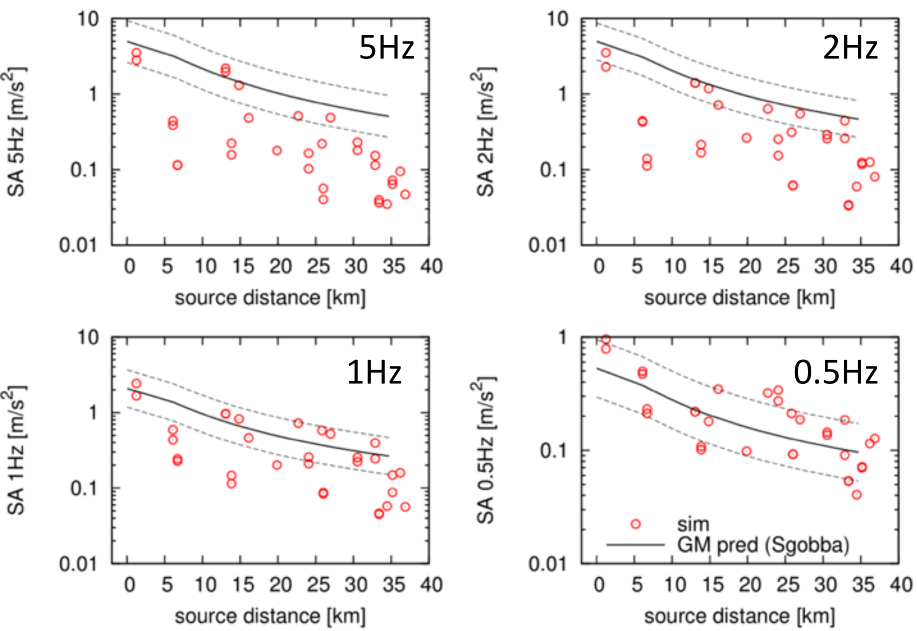
Frequency range from 0.05 to 5Hz

Example – Amatrice (comparison with Ground Motion Model)



Smooth dynamic rupture models do not radiate ω^2

Smooth

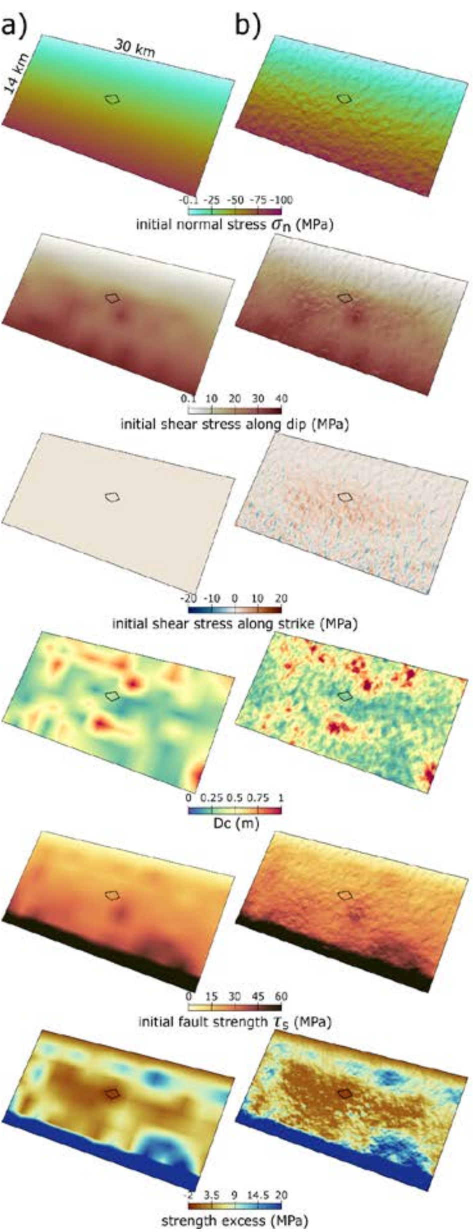


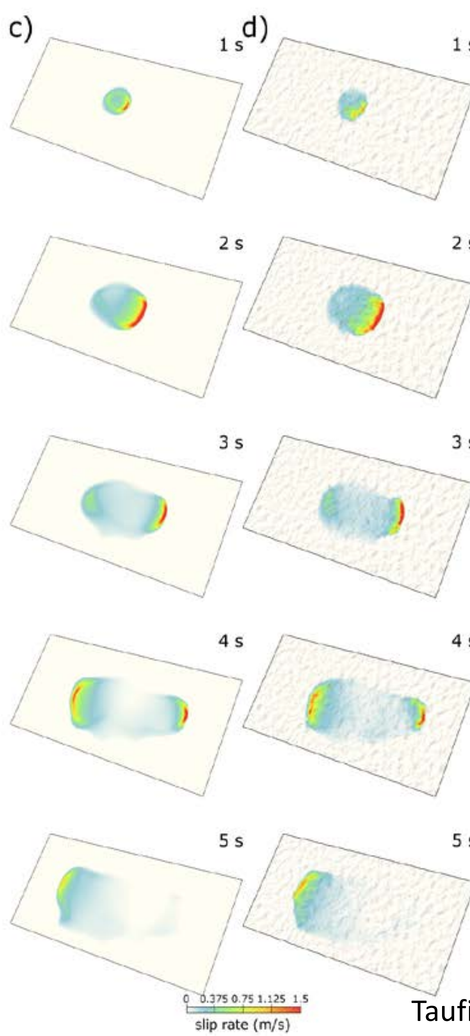
GM pred: Sgobba et al. (2021)

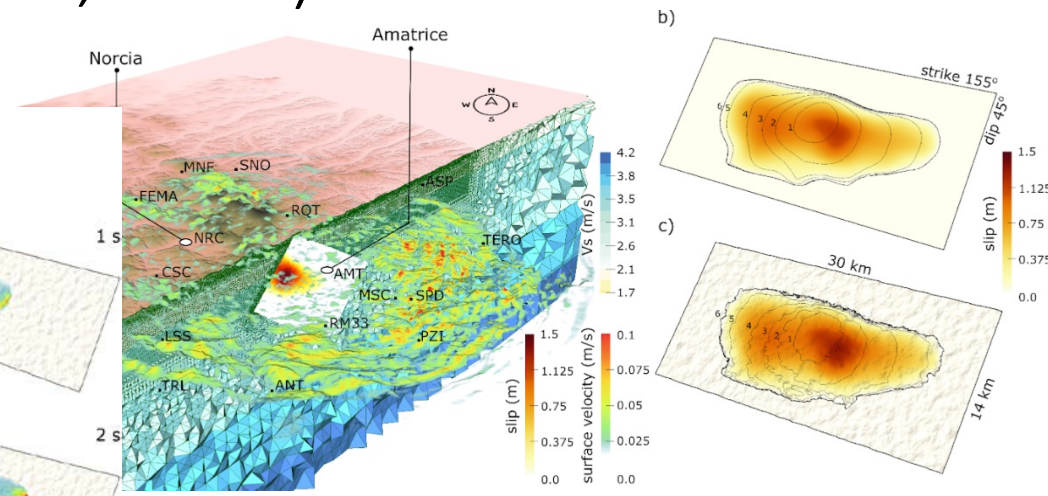
Towards broadband ground motion simulations

(how to introduce small-scale heterogeneity to dynamic rupture models)

Taufiqurrahman et al. (GRL, 2022)







Simulating 40 s of a broadband Amatrice dynamic rupture earthquake scenario including fault roughness, frictional heterogeneity, viscoelasticity and topography

Dynamic rupture source complexity enhances high-frequency generation, while topography effects elongate the synthetic coda signals, together yielding more realistic ground motions.

Taufiqurrahman, A.-A. Gabriel, T. Ulrich, Ľ. Valentová, F. Gallovič (2022). Broadband dynamic rupture modeling with fractal fault roughness, frictional heterogeneity, viscoelasticity and topography: the 2016 Mw 6.2 Amatrice, Italy earthquake, Geophys. Res. Lett. 49, e2022GL098872.

Fractal Gc model of Ide and Aochi (2005)

- Rupture starts from a small patch with small D_c associated with weak radiation.
- Events stop spontaneously without requiring a special stopping mechanism.
- Average fracture energy general increase as the rupture grows =>
    - Rupture velocity locally exceeds the shear wave speed but globally remains subshear
    - Fracture energy scales linearly with rupture size, in agreement with empirical studies
- Relation between size and frequency of events is a power law (explained by the triggering probability between patches).
- Initial phase of the moment rate does not predict the final magnitude due to the statistically self-similar random triggering growth.
- Properties of initial accelerating phase of moment rates agrees with an empirical statistical model (Renou et al., 2022).

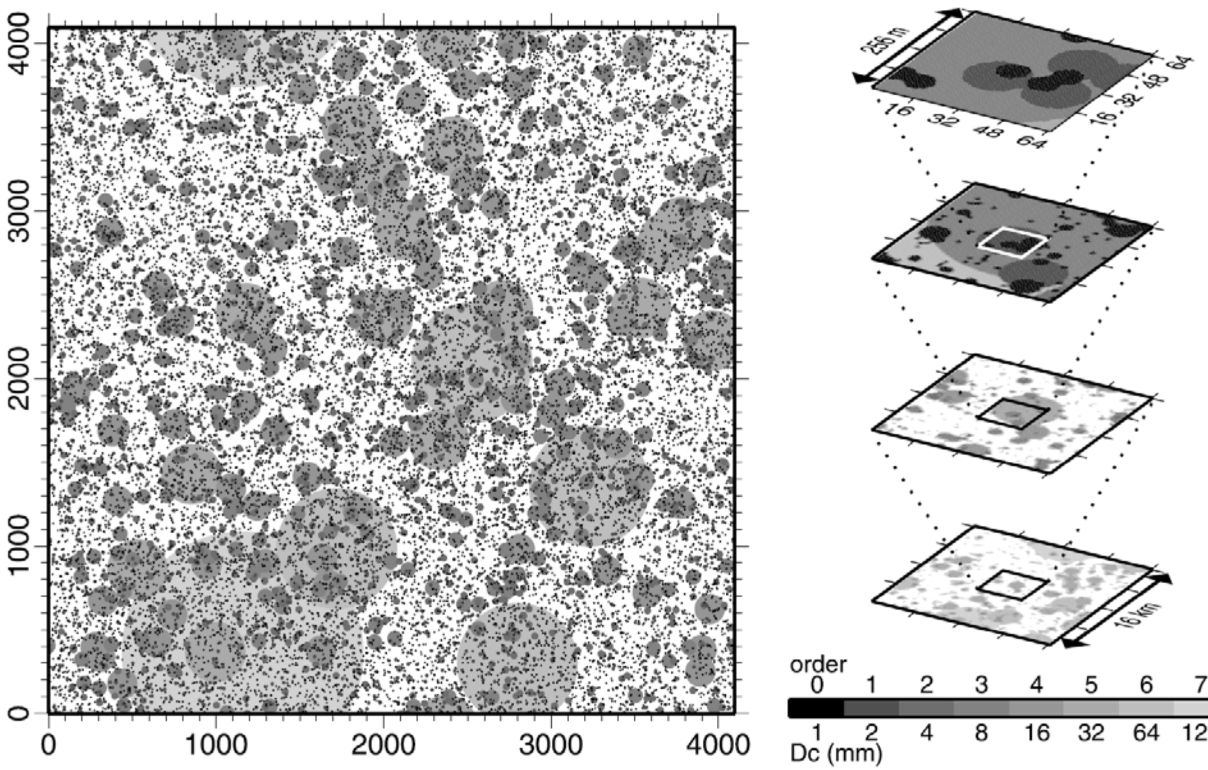


Figure 3. An example of D_c distribution in two dimensions using a set of circular patches. We randomly distribute eight different orders of patches in 4096 × 4096 model space with periodic boundaries, which we consider to be 16 km × 16 km. This model space is treated as four subspaces of different scale through three renormalizations as shown at the right.

Multiscale Dc model of Ide and Aochi (2005)

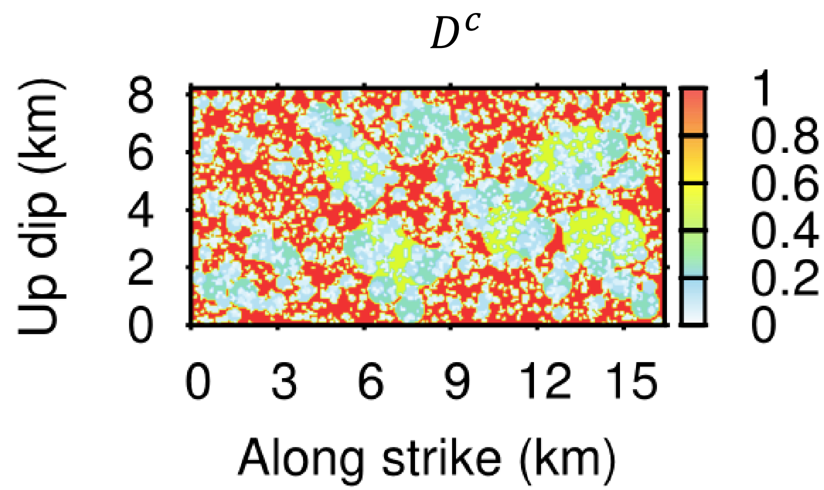
$n = 1..n_{levels}$

$r_n = 2^{-n} r_0$ $\qquad$ $r_0 = {}^{1}/_{8} \min(L, W)$

$N_n = 2^{Dn} N_0$ $\qquad$ $N_0 = {}^{L}/_{W}$

$D = 2$

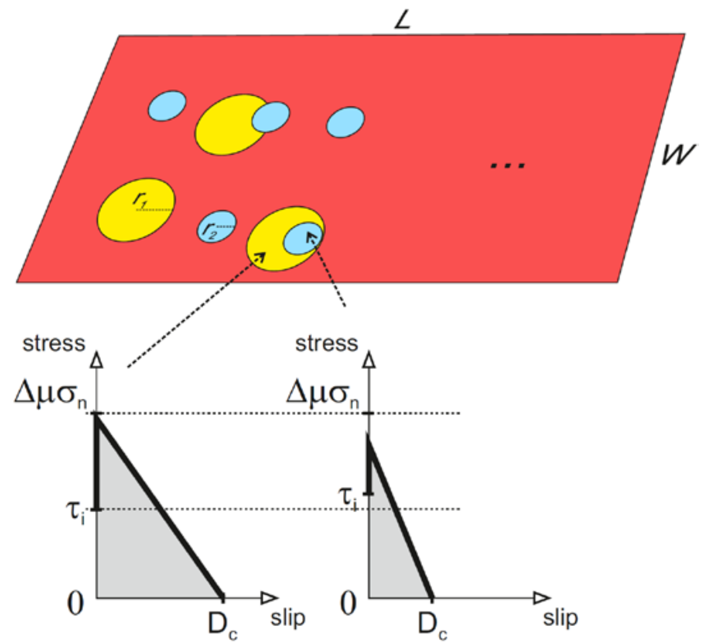
$D_n^c = 2^{-n}$ $\qquad$ $D_0^c = 1$ (background)



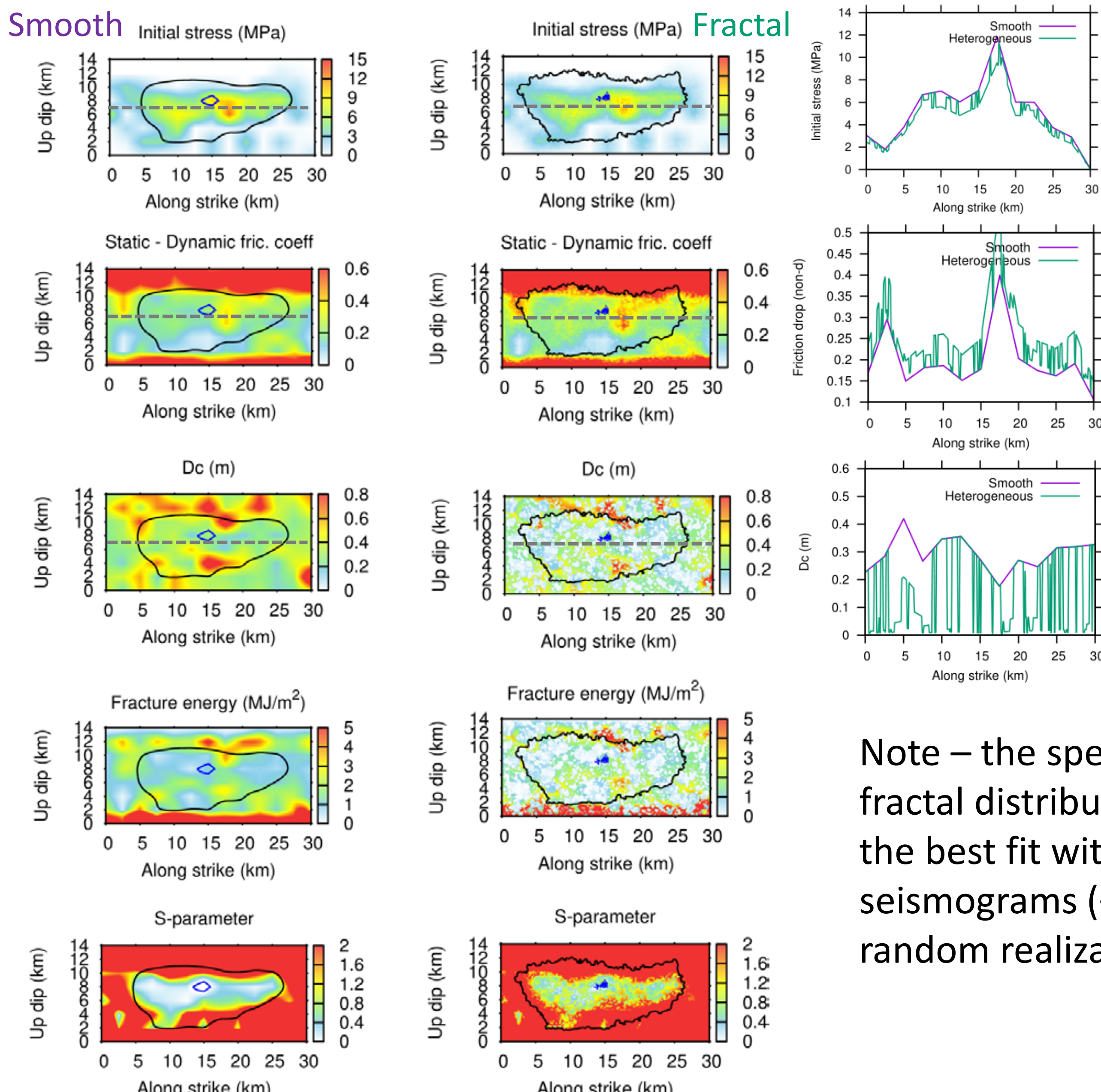
$\downarrow r_n \ \downarrow D_c \ \uparrow T_{ini} \ \downarrow \Delta\mu$

$$T_{ini} = T_{smooth}\left(1 - 0.2\,\frac{\log \frac{\min(D^c)}{D^c}}{\log \min(D^c)}\right)$$

$$\Delta\mu = \Delta\mu_{smooth}\left(1 + 0.4\,\frac{\log \frac{\min(D^c)}{D^c}}{\log \min(D^c)}\right)$$



Example – Amatrice

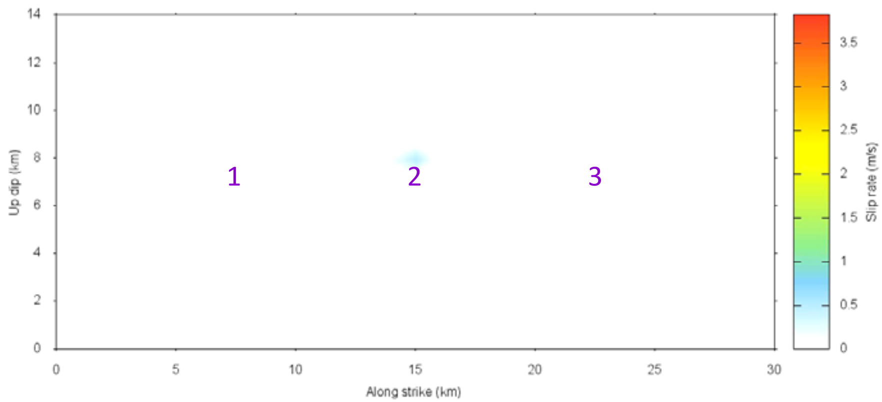


Note – the specific realization of the fractal distribution found to obtain the best fit with low-frequency seismograms (<0.5Hz) out of 500 random realizations.

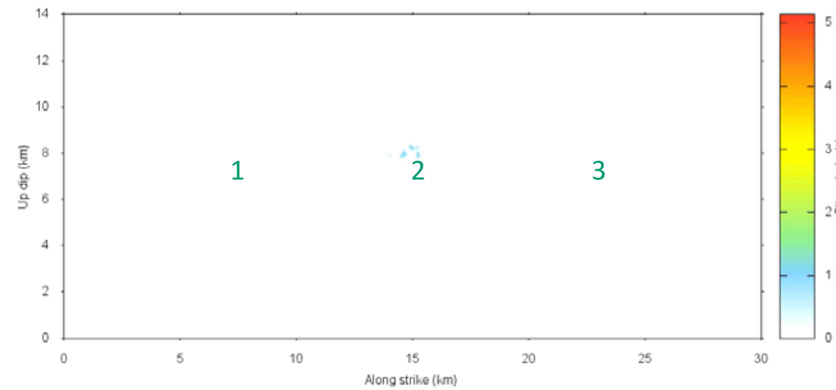
Gallovič et al. (2019)

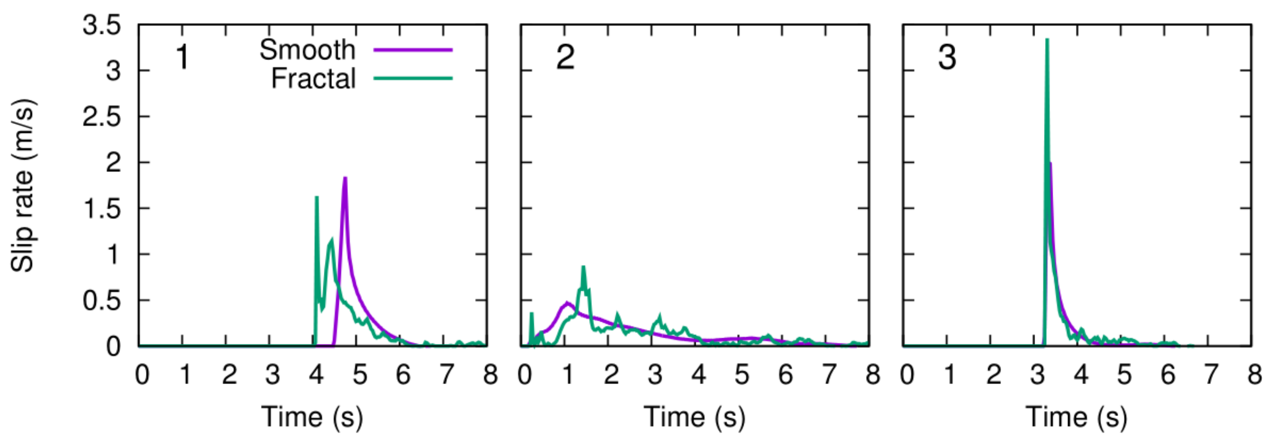
Example – Amatrice

Smooth



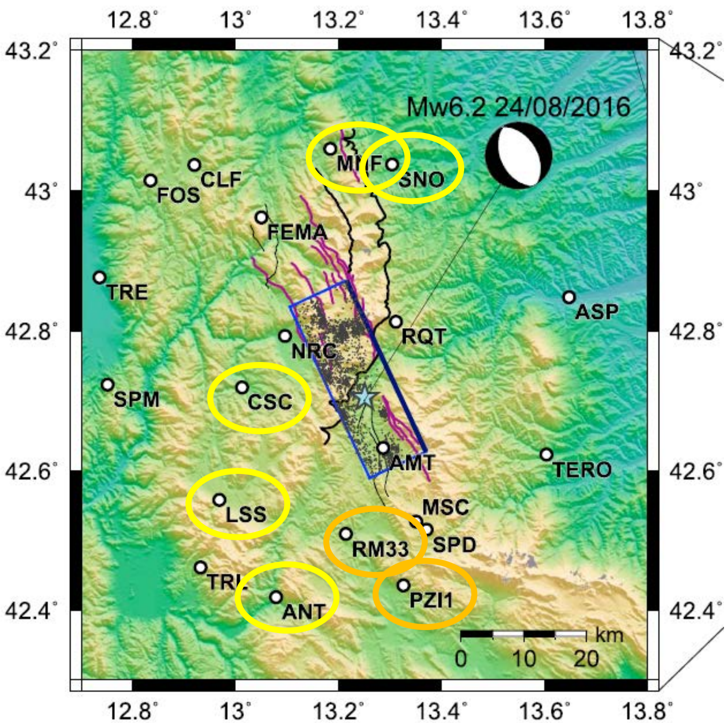
Fractal

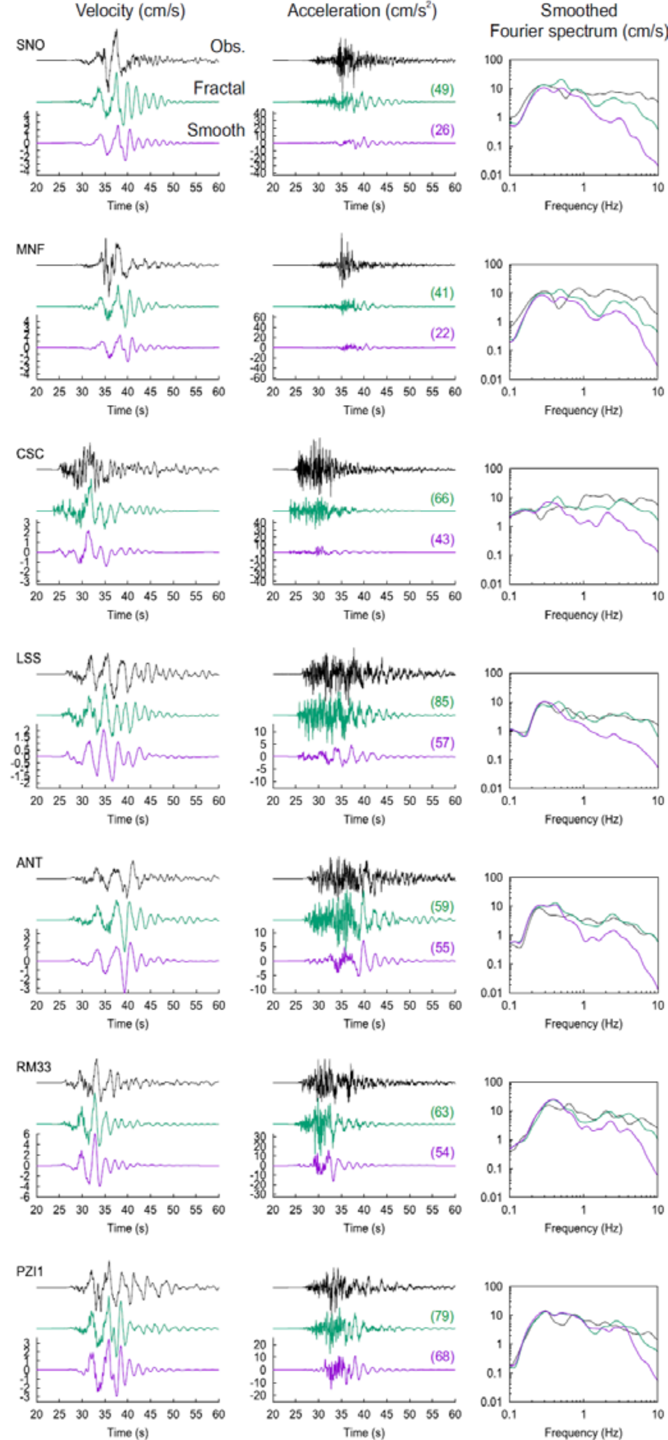




FD3D_TSN performs the calculation in about 30 minutes up to 10 Hz on a single GPU

Example – Amatrice



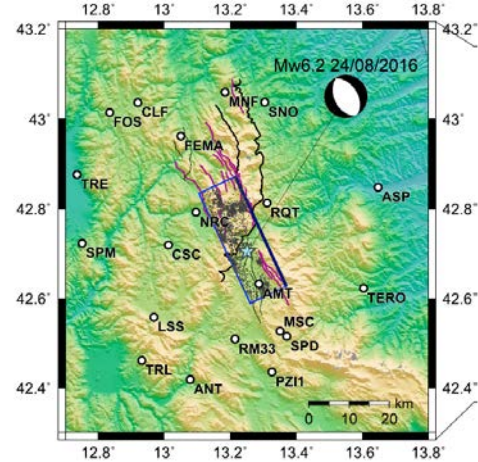


Observed

Fractal

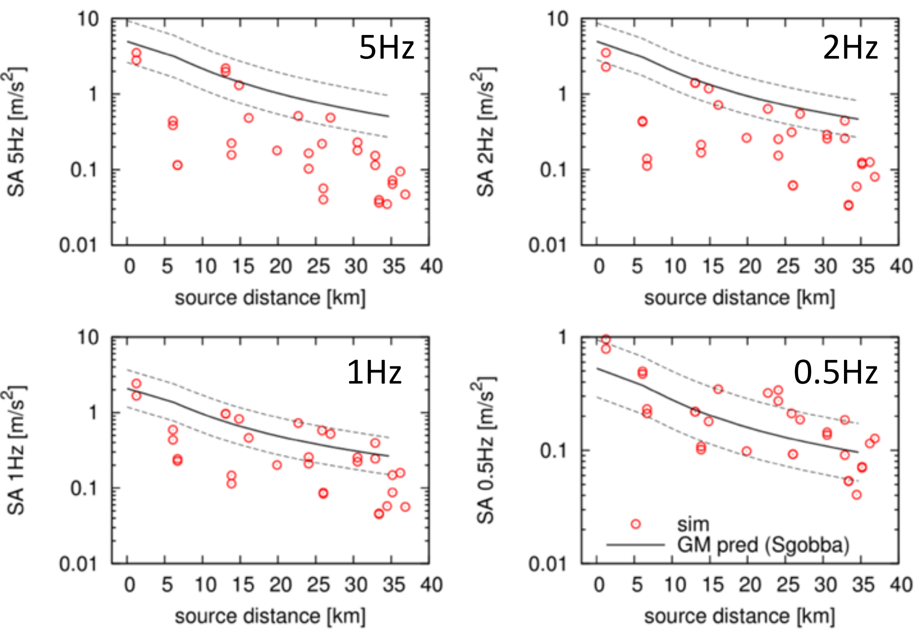
Smooth

Example – Amatrice (comparison with Ground Motion Model)

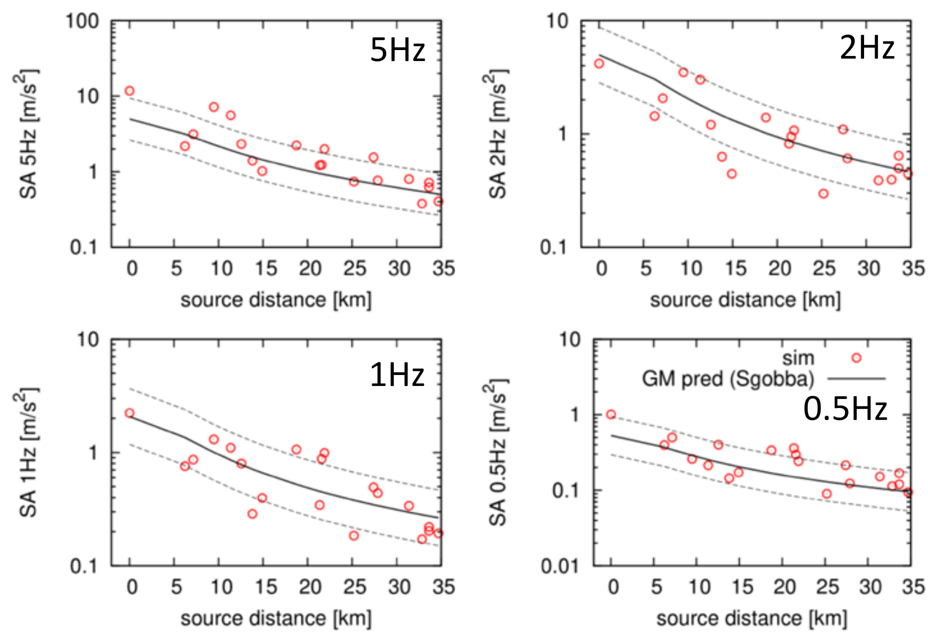


Gallovič, F., Valentová, Ľ. (2023). Broadband strong ground motion modeling using planar dynamic rupture with fractal parameters, J. Geophys. Res. Solid Earth 128, e2023JB026506.

Smooth



Fractal



GM pred: Sgobba et al. (2021)

Beyond the Brune model: Dynamic rupture inversion of apparent source spectra of small earthquakes

Source spectra from the generalized inversion technique (GIT)

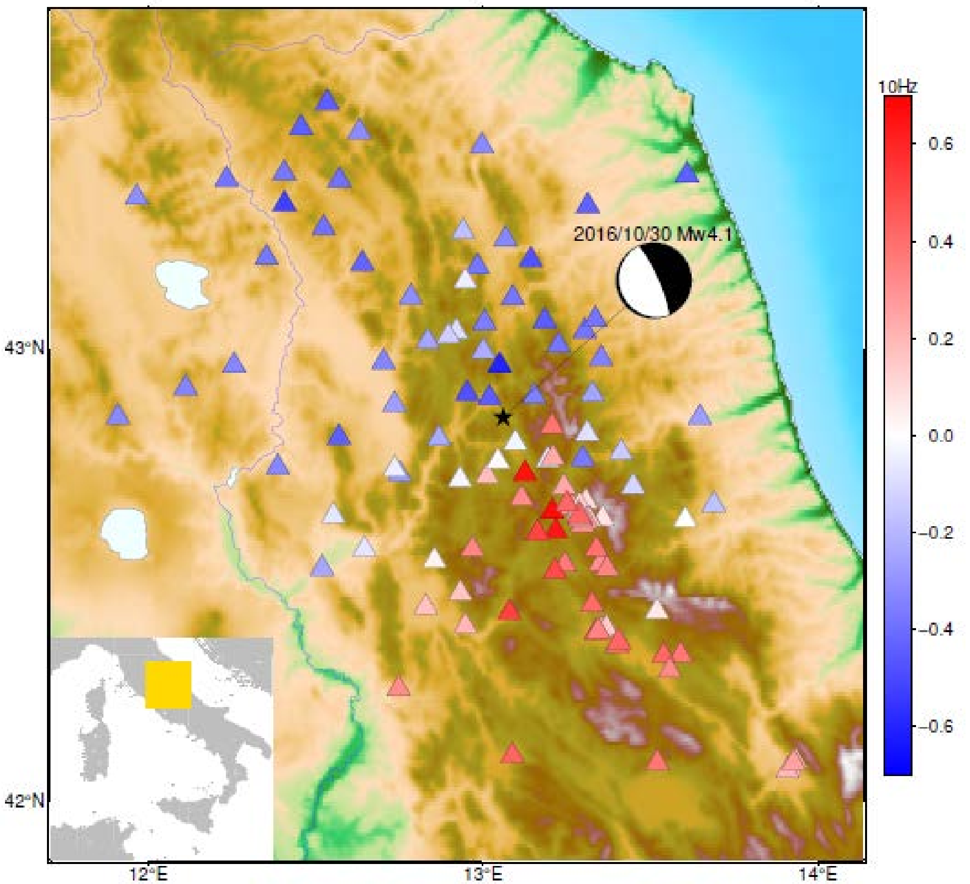
- Decomposition of *S*-wave acceleration amplitude spectra at station *j* for event *i*:

$$\log_{10} A_{ij}(f) = \log_{10} S_{ij}(f, M_i) + \log_{10} P_{ij}(f, r_{ij}) + \log_{10} G_j(f)$$

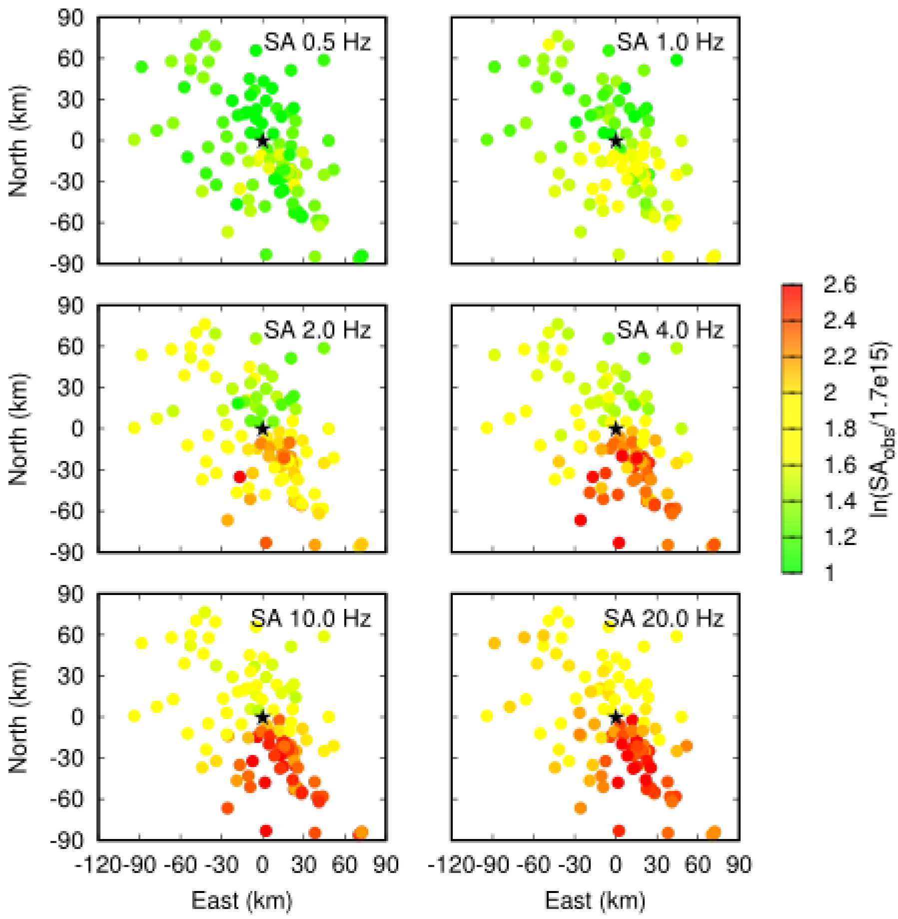
  where S_{ij} corresponds to the apparent source spectra of event *i* at station *j*, P_{ij} is the attenuation function comprising geometrical spreading and frequency-dependent attenuation, and G_j is the site response at station *j*

- Decomposition performed over many events in Central Italy (Bindi et al., 2009; Pacor et al., 2016; Oth et al., 2008)
- Frequency range 0.5-25Hz
- Pacor et al. (2016) and Colavitti et al. (2022) demonstrated a significant directivity effect of several events in Central Italy

Spatial variability of the empirical apparent source spectra



20161030_0000130

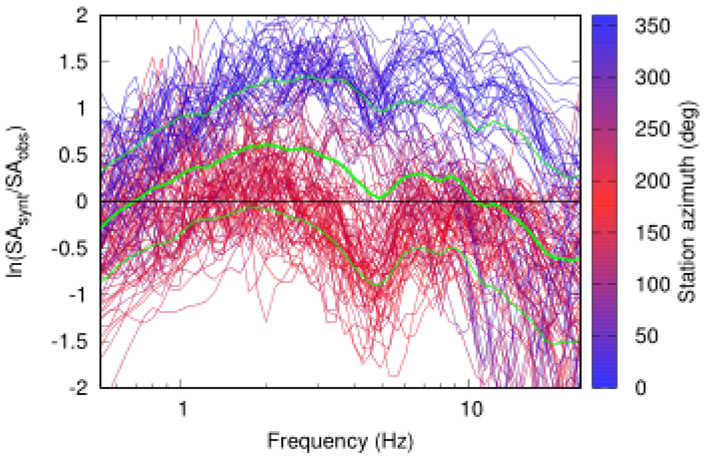


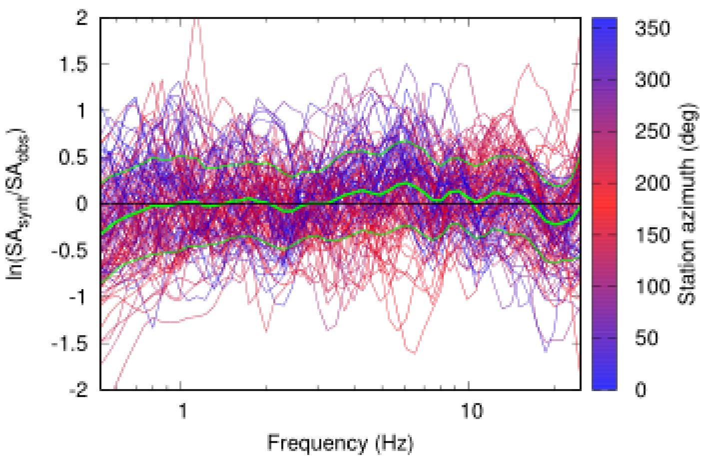
Inverted best-fitting models (bias plot)

Poor fit for a circular smooth rupture due to unexplained

- azimuthal dependence
- high-frequency spectral level

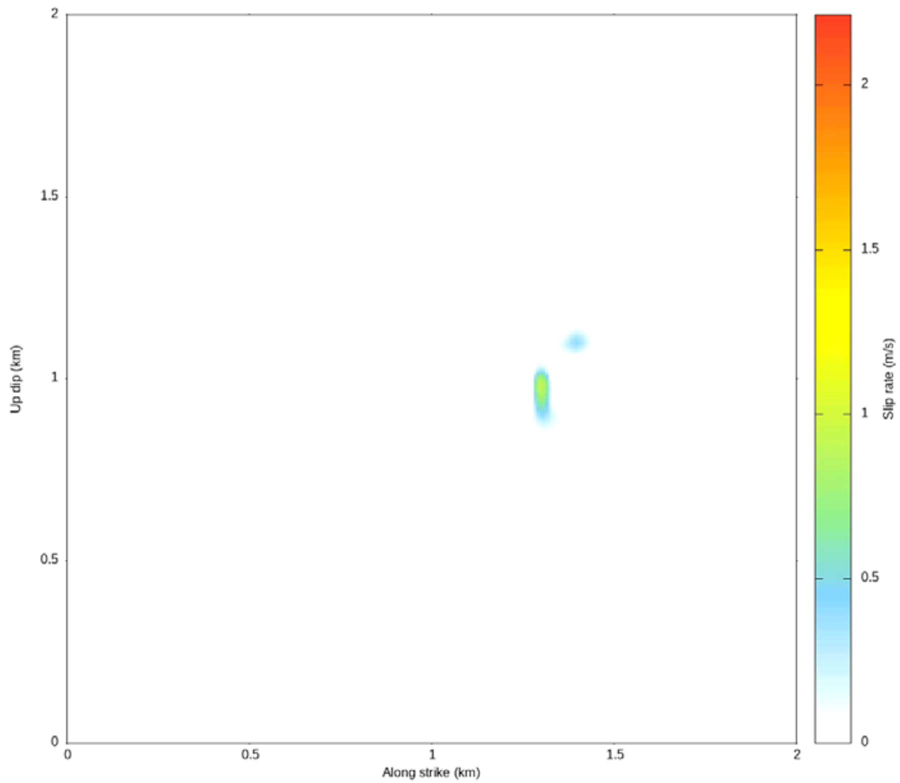
20161030_0000130





Inverted best-fitting models (rupture evolution)

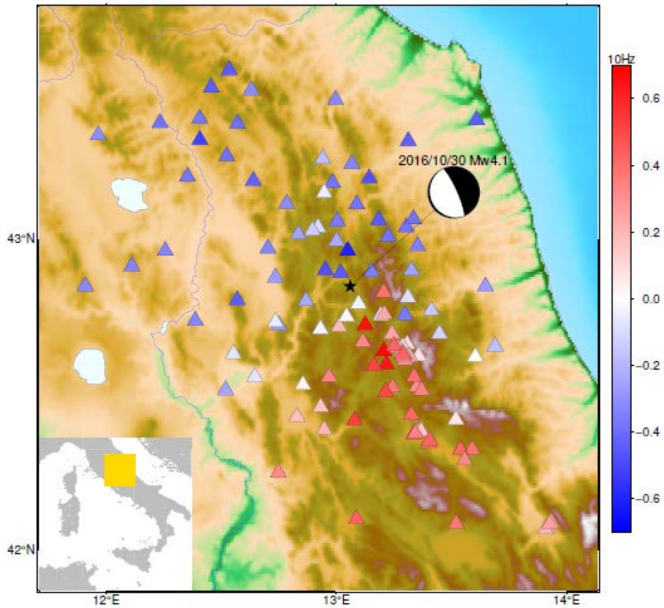
20161030_0000130

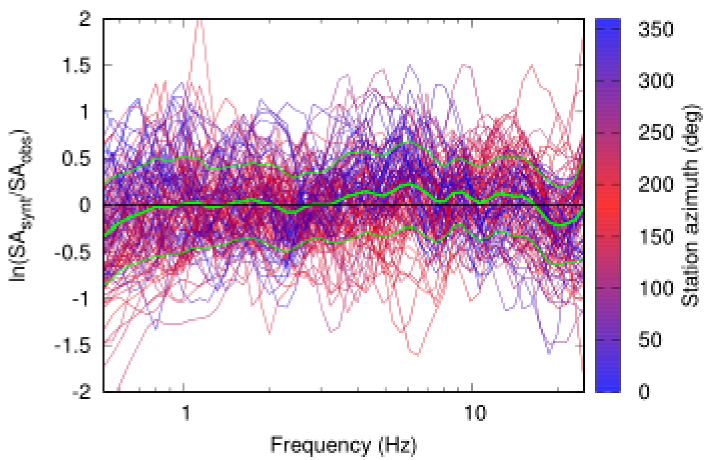


10x slowed down

Inverted best-fitting models (bias plot)

20161030_0000130





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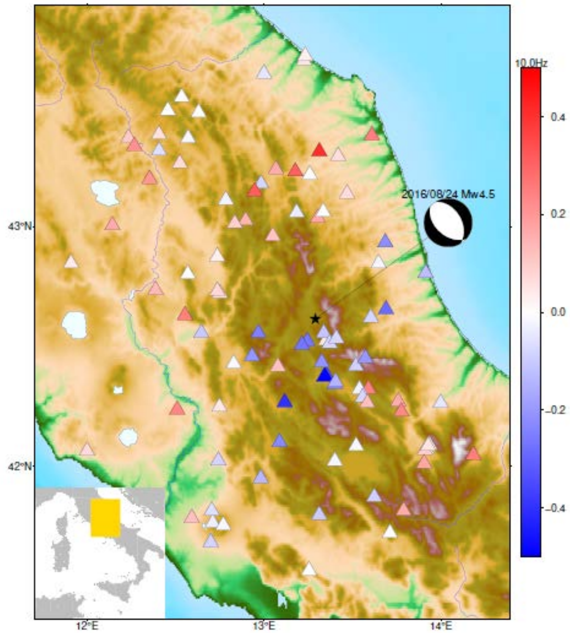
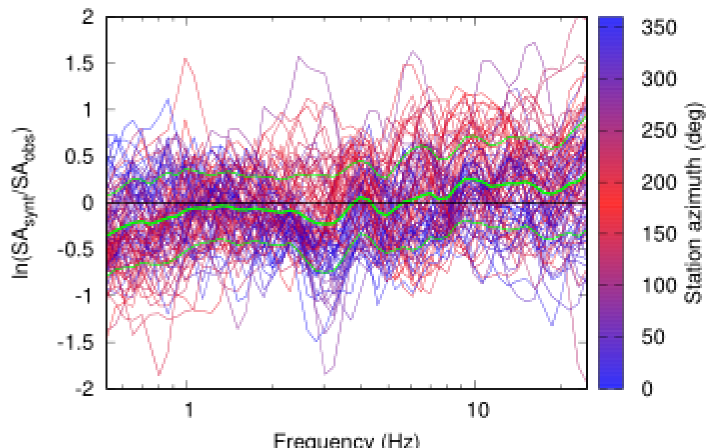




Poster A07

Inversion of ASTFs

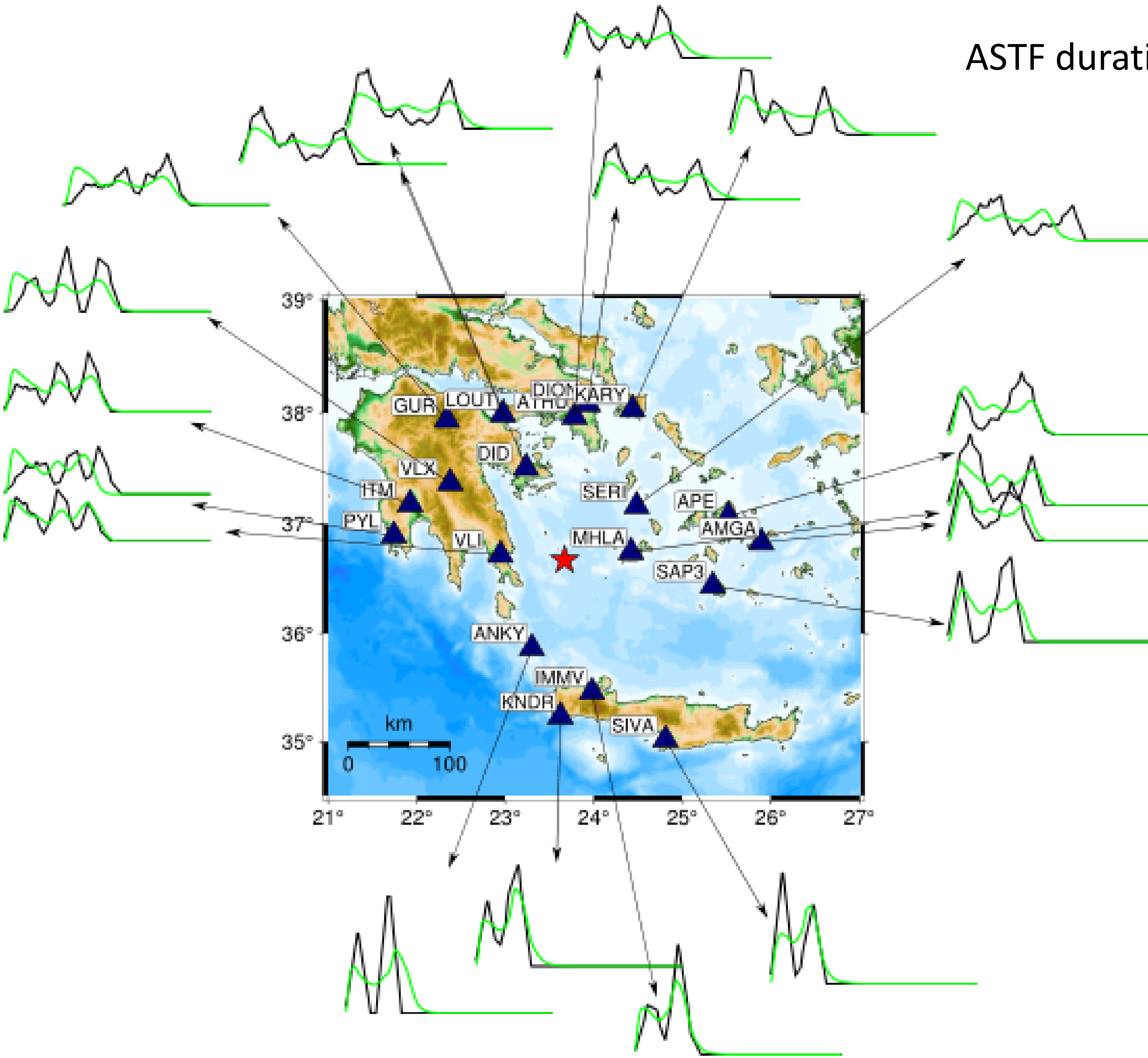
China Sea deep event

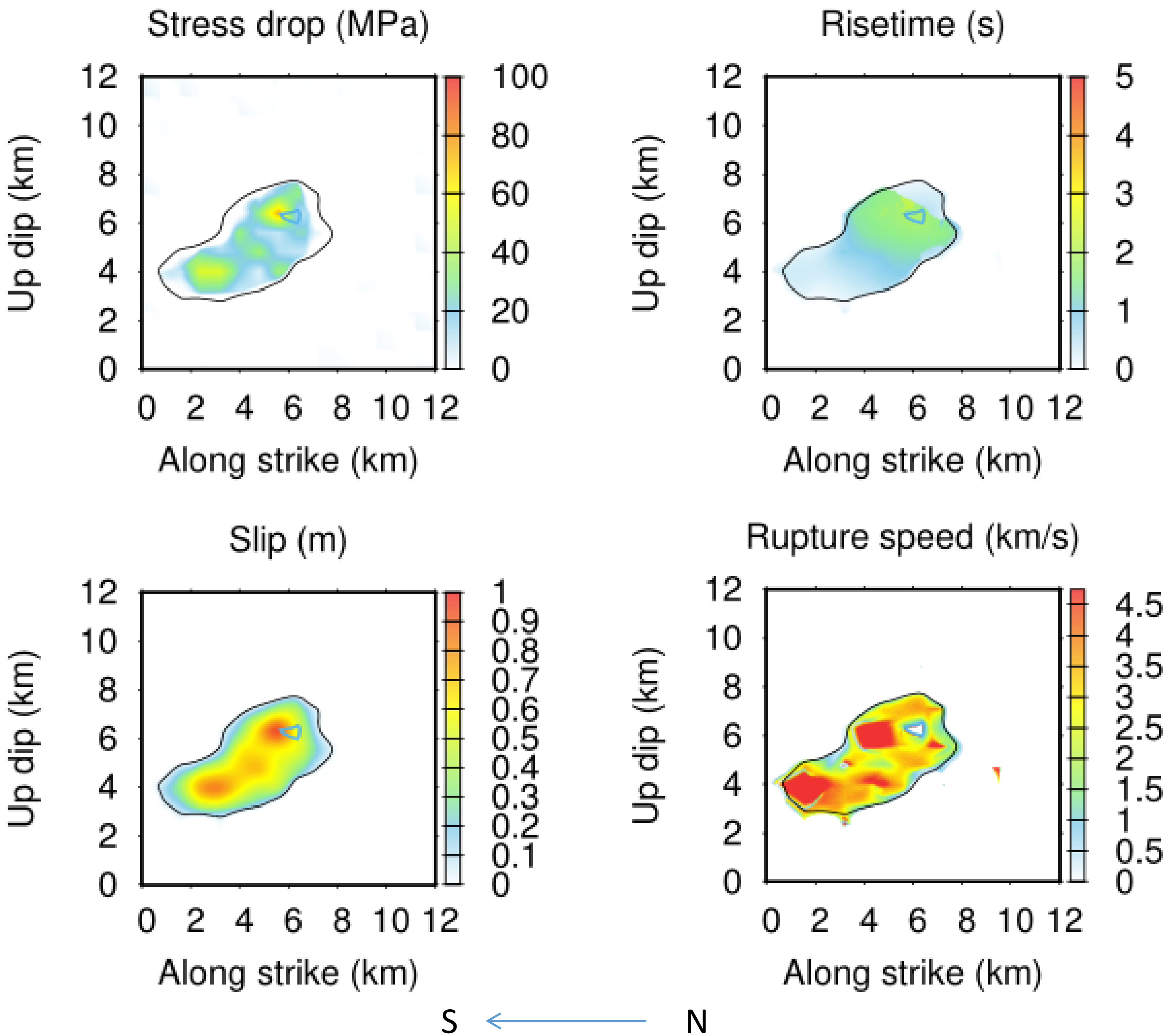
Aegean Sea mid-deep event

Aegean Sea intermediate-depth earthquake

- Parameters of the event
  - Depth 95 km
  - Origin time: 2014-08-29
  - Mw5.8
  - Subvertical fault plane along the Hellenic slab
- Assumed parameters of the model
  - Friction law: Slip weakening
  - Normal stress (PREM): 2.8GPa, const.
  - Velocity model (PREM): Vp=8.4km/s, Vs=4.75km/s, const.
- Dynamic rupture inversion of apparent source time functions (ASTFs) obtained by EGF deconvolution (Plicka et al., 2022).

ASTF duration: 4s





Stress drop (MPa)
Risetime (s)
Slip (m)
Rupture speed (km/s)
Up dip (km)
Along strike (km)
S
N

Joint inversion of co- and post-seismic slip

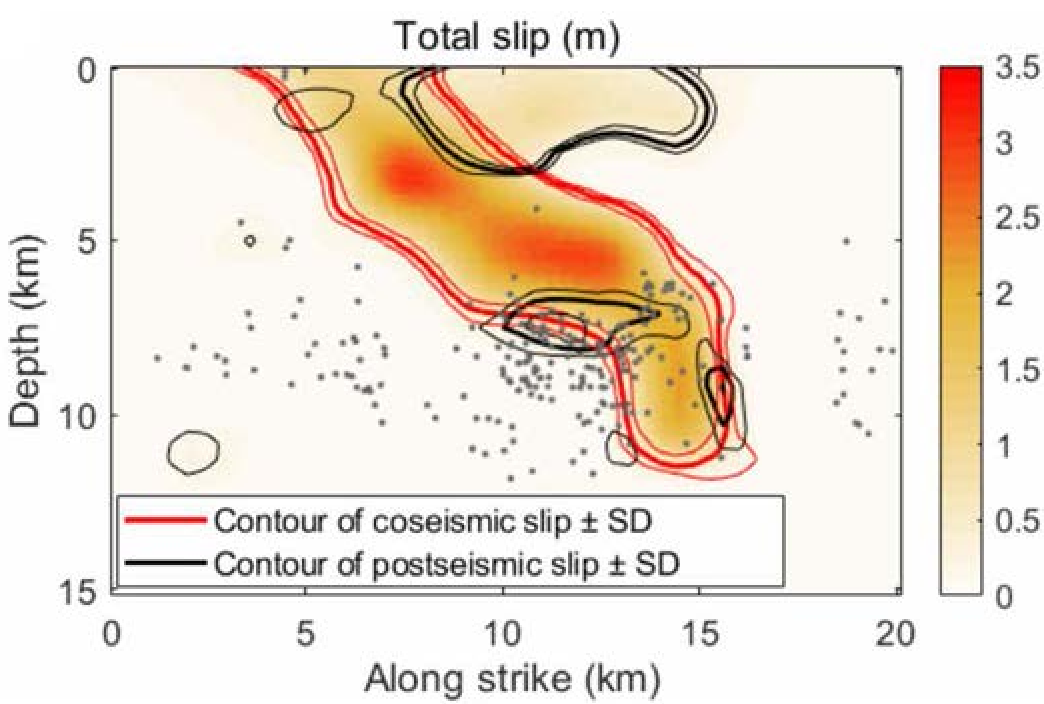
From seconds to days/weeks

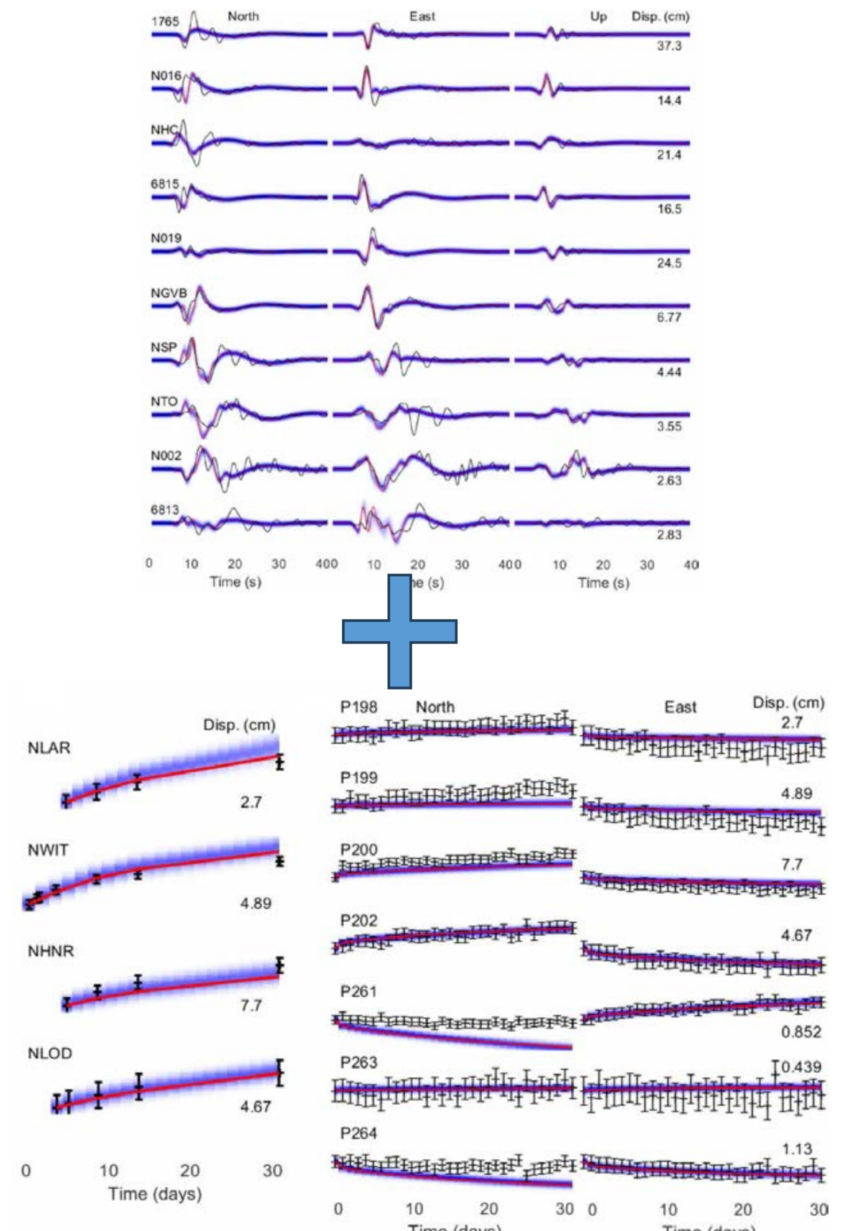
2014 Mw6.0 Napa

2004 Mw 6.0 Parkfield

Joint inversion of co- and post-seismic slip

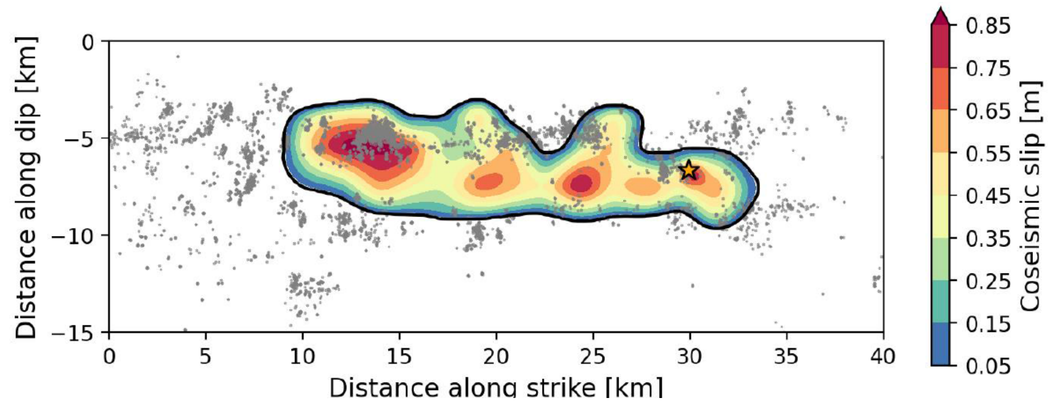
- 2014 Mw 6.0 South Napa (California)
- Premus et al. (Science Advances, 2022)
- Friction law: rate&state with rapid velocity weakening

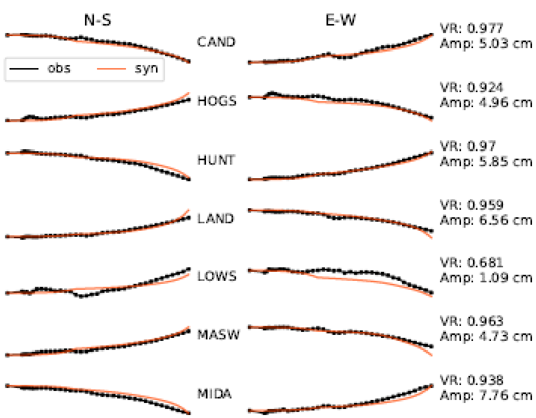


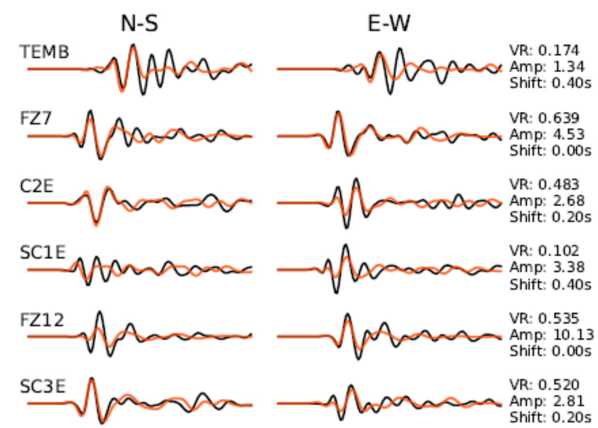


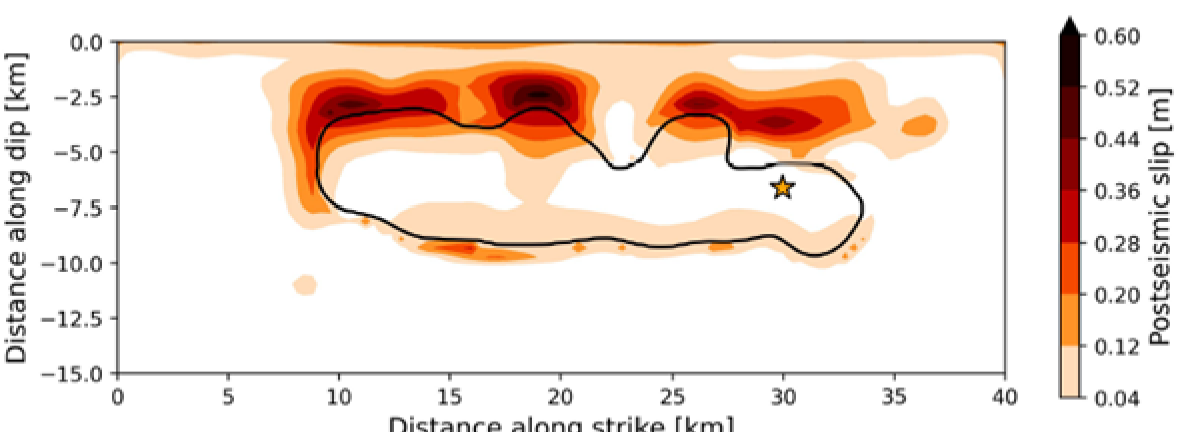
Joint inversion of co- and post-seismic slip

- 2004 Mw 6 Parkfield (California)
- Schliwa et al. (submitted to JGR)
- Friction law: rate&state with rapid velocity weakening









Summary

Recent improvements in dynamic rupture modeling:

- Beyond kinematic inversions: Dynamic rupture inversions of well-recorded events from observed data using synthetic (or empirical) Green's functions
- Beyond Brune source spectral modeling: Dynamic source inversion of apparent source time functions or spectra directly for stress drop and other source parameters (rupture size, radiation efficiency)
- Beyond kinematic broadband simulations: Dynamic rupture scenario simulations constrained by GMM

Limitations of the dynamic modeling:

- Computationally very intense task
- Our fast rupture simulation code, limited to buried ruptures or vertical faults, can be sufficient in many applications

Co-funded by the European Union

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Thank you for your attention…