Instantaneous tracking of earthquake growth using prompt elasto-gravity signals (PEGS) and deep learning

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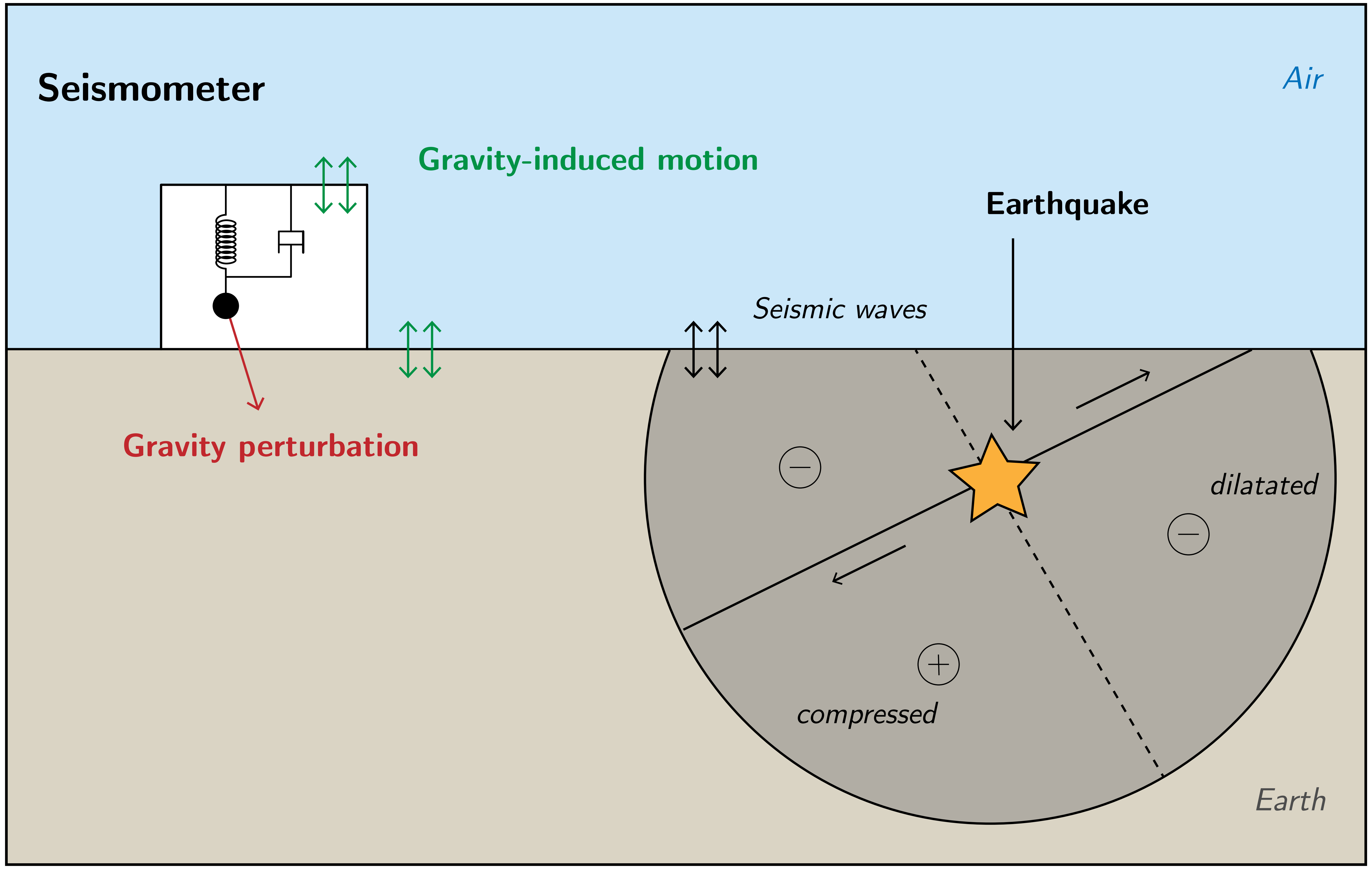
How do we model PEGS ?



Schematic representation at a time between earthquake onset and first P-wave arrival (direct elastic waves are inside the grey area)

As soon as an earthquake occurs (and thus ***before the arrival of seismic waves***), a weak signal is expected to be recorded at a broadband seismometer, due to the combination of :

- **direct effect** : the gravity perturbation induced by the earthquake rupture and the elastic waves *(Harms et al. 2015, Montagner et al. 2016)*

- **induced effect** : the elastic relaxation of the Earth, itself affected by the gravity perturbation *(Vallée et al. 2017, Juhel et al. 2018)*

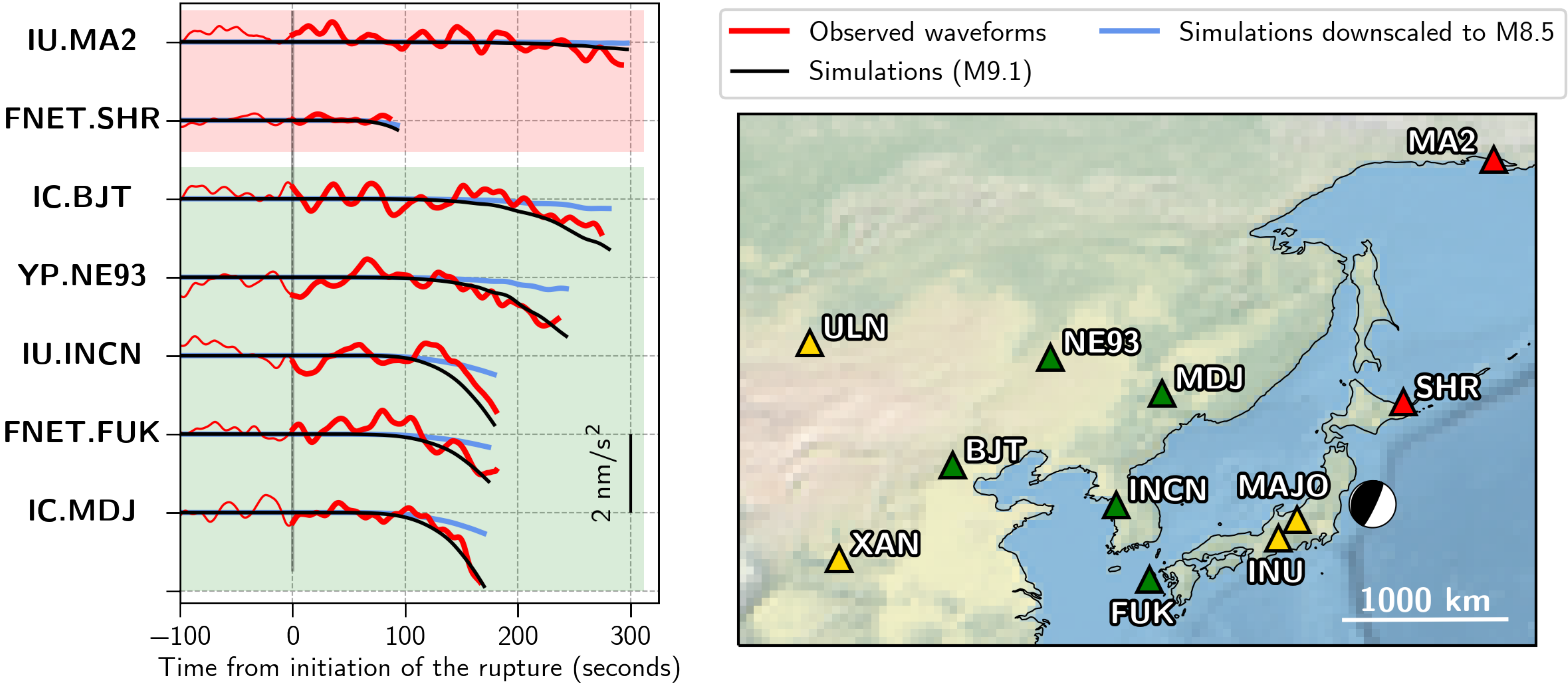
the 2011 M_w 9.1 Tohoku earthquake

Prompt elastogravity signals (PEGS) depend on :

- the earthquake focal mechanism
- the earthquake magnitude

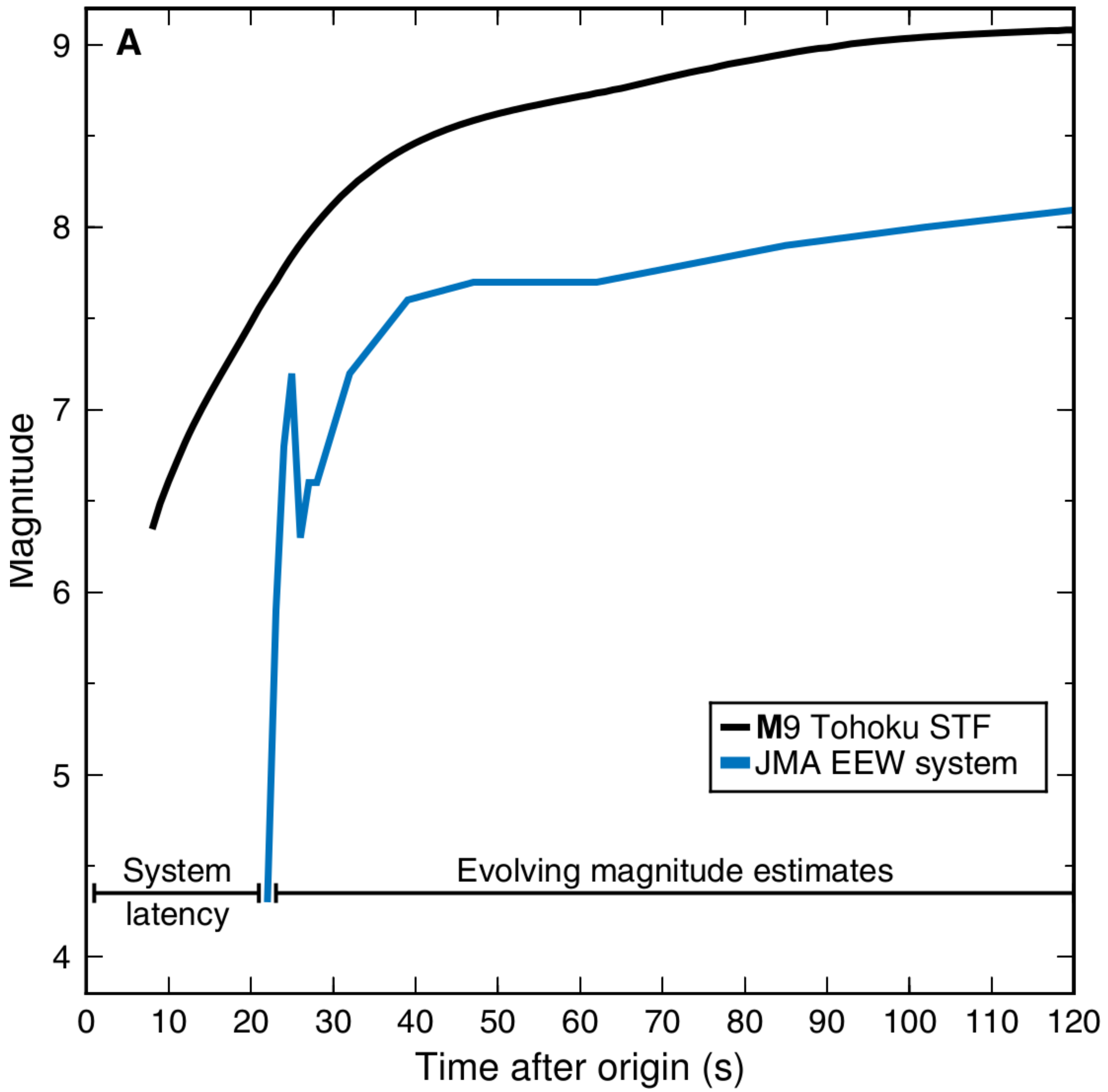
... within the duration of the rupture !

(Vallée et al. 2017, Juhel et al. 2018)



P-wave based vs. PEGS-based EEW

(Minson et al. 2018)



P-wave based earthquake early warning :

- Magnitude estimates based on 3-4 seconds of P-waves sature for large earthquakes
- System latency due to P-wave speed

PEGS based earthquake early warning :

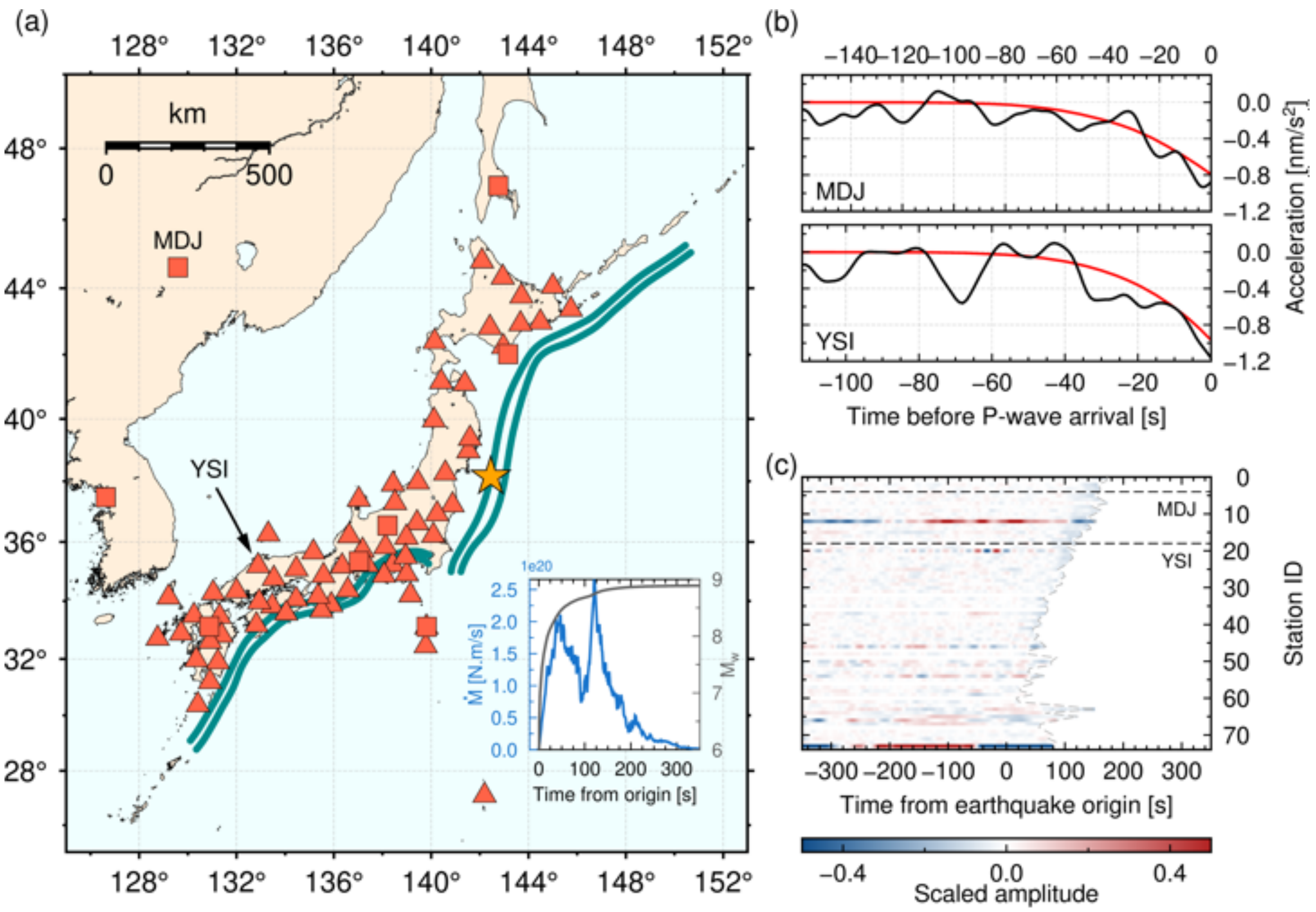
- No saturation for large earthquakes
- Information carried at the speed of light

Objective :

assessment of PEGS potential for early magnitude estimation

PEGSNet : the training database

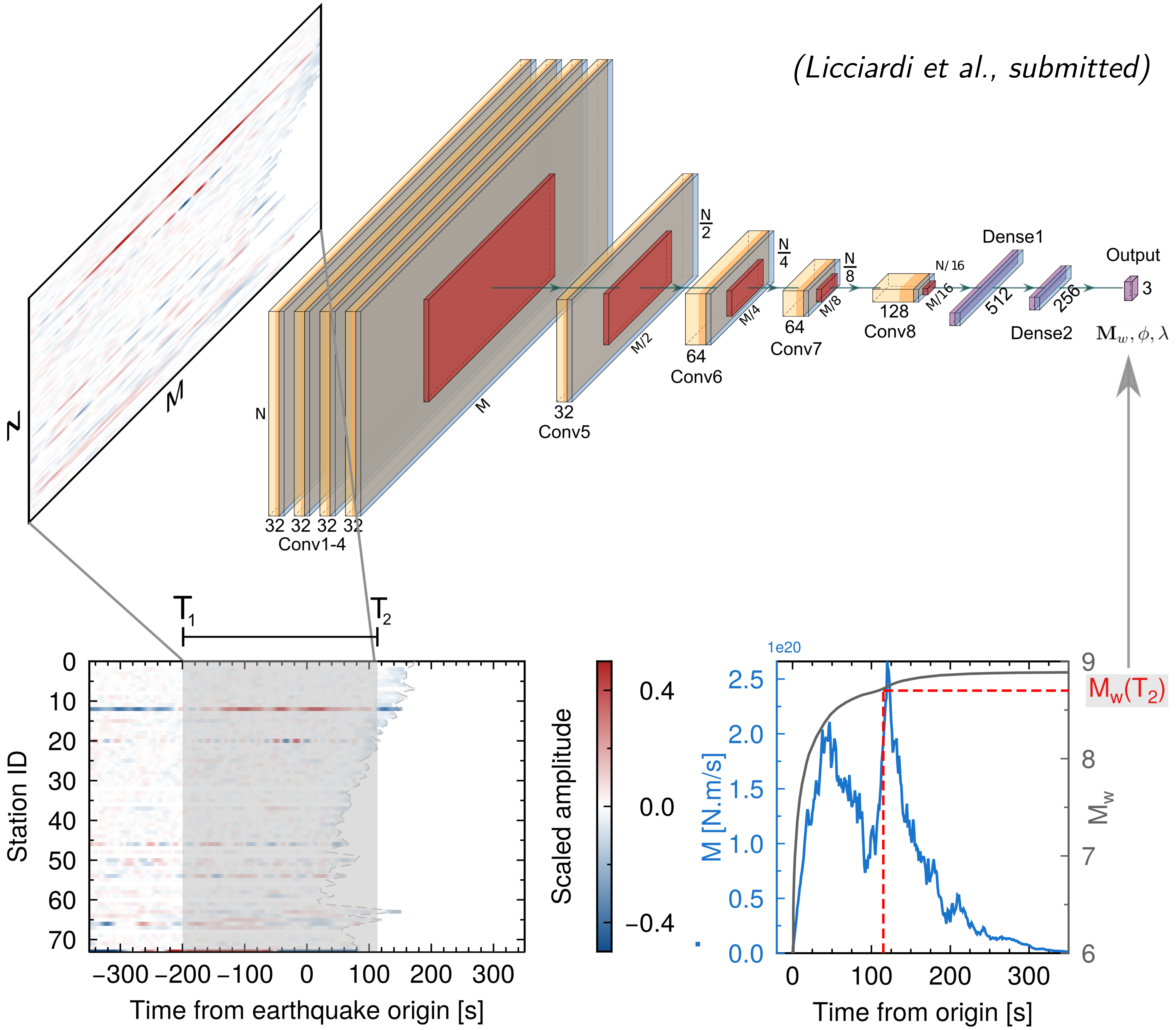
Few real observations of PEGS are available : *training must rely on synthetic data.*



- Real noise added to synthetic PEGS
- 500k synthetic earthquake sources
- Location, dip and strike from Slab2.0 *(Hayes et al. 2018)*
- M_w follows uniform distribution U *[5.5, 10.0]*
- STF empirical model *(Meier et al. 2017)*
- P-wave travel times assumed known

(Licciardi et al., submitted)

PEGSNet : architecture and learning strategy

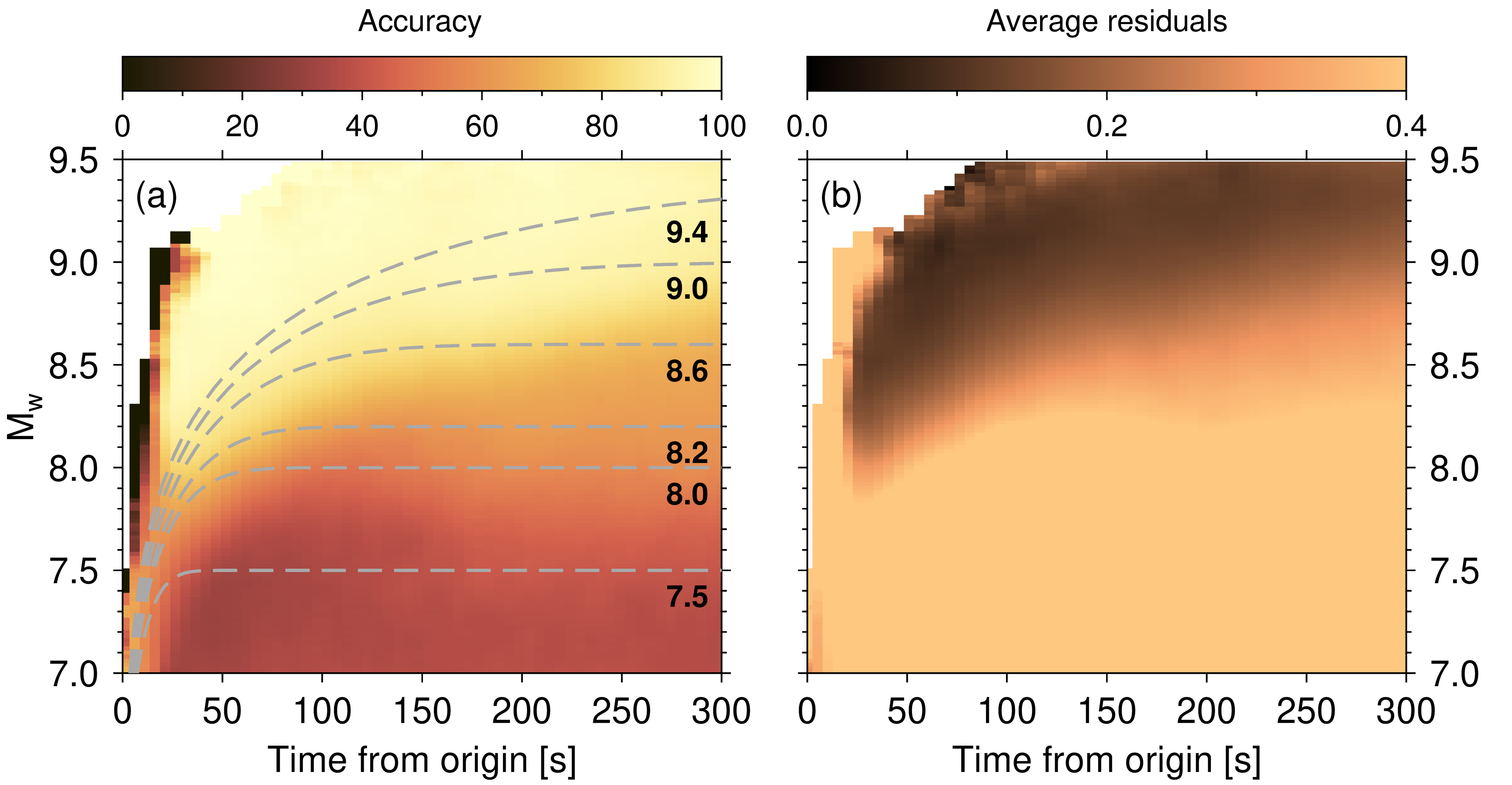


(Licciardi et al., submitted)

- T_1 is randomly chosen during training.
- The value of M_w at the end of the input window is used as label.
- The model learns patterns in the data as M_w evolves with time.
- The model is designed to track the evolving magnitude and not to forecast its value.

Results on test set : predictions accuracy

Successful prediction if the estimated $M_w(t)$ lies within $\pm$ 0.4 magnitude units from the ground truth value.

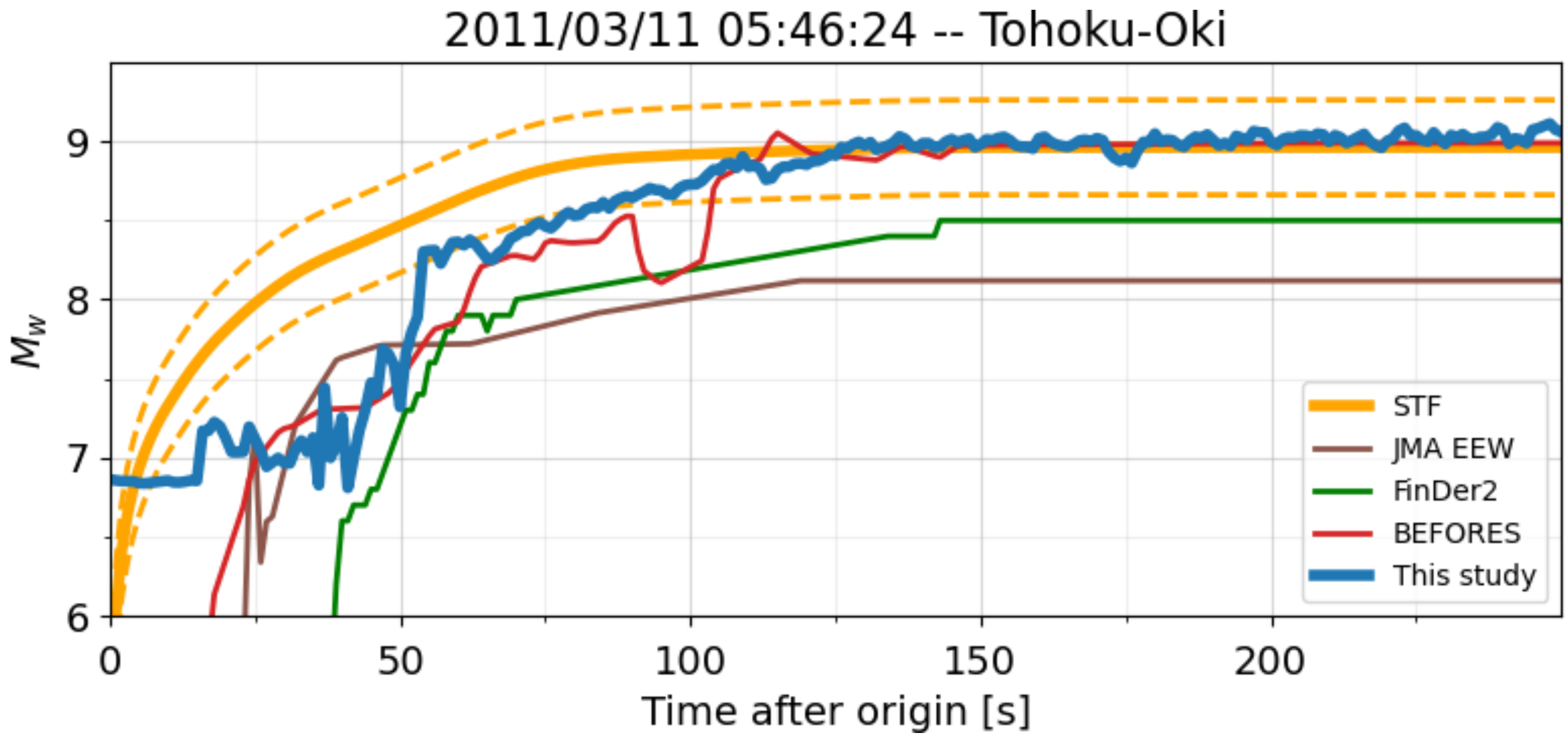


- **M_w > 8.6** : moment tracking with good accuracy and low error
- **8.2 < M_w < 8.6** : early tracking more difficult, final magnitude estimation achievable
- **M_w < 8.2** : poorly constrained by data, M_w 8.3 lower limit of PEGSNet sensitivity

Results on test set : $M_w = 9.0 \pm 0.05$

- Time-dependent performance of M_w predictions for events with true final M_w of 9 ± 0.05
- Magnitude $M_w(t)$ estimation with zero delay once $M_w > 8.3$ ($t > 40$ seconds)

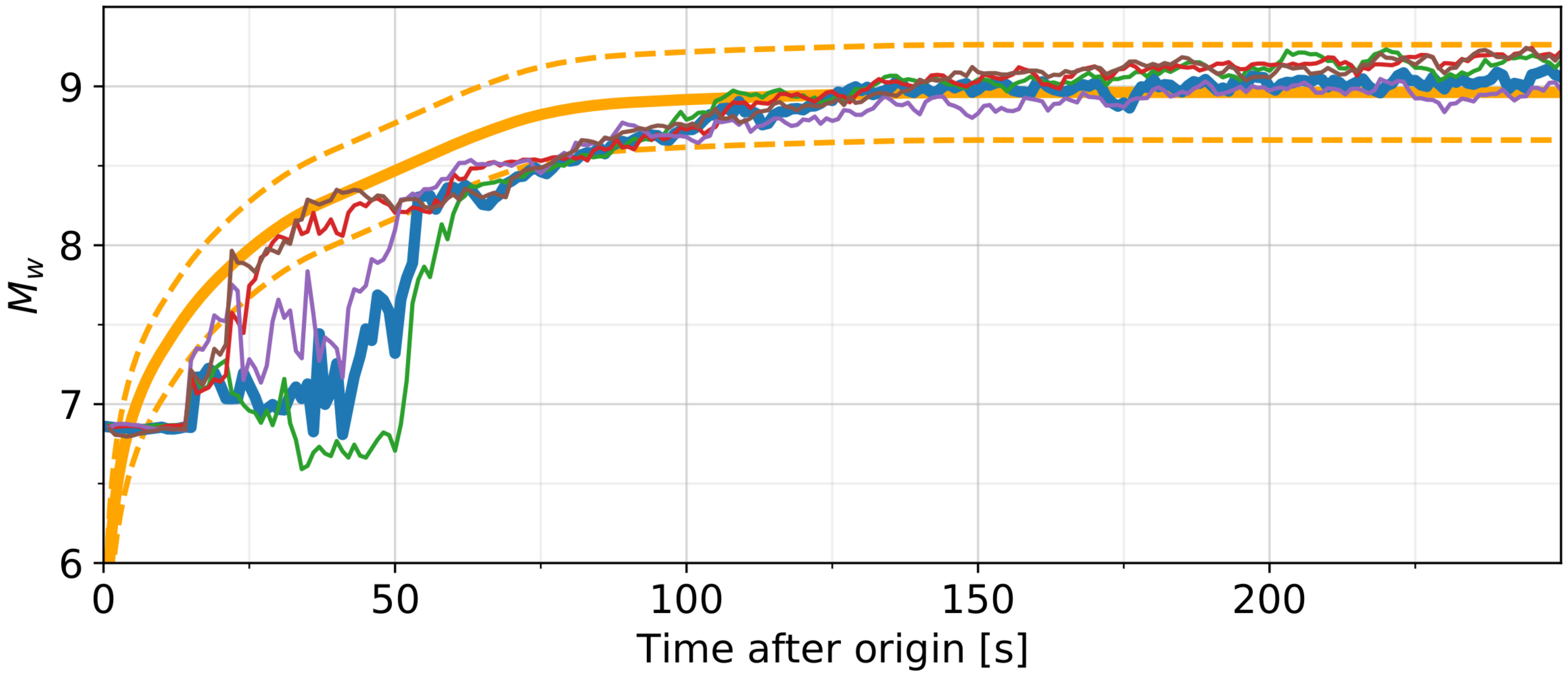
Real data : the 2011 M_w 9.1 Tohoku earthquake



(Licciardi et al., submitted)

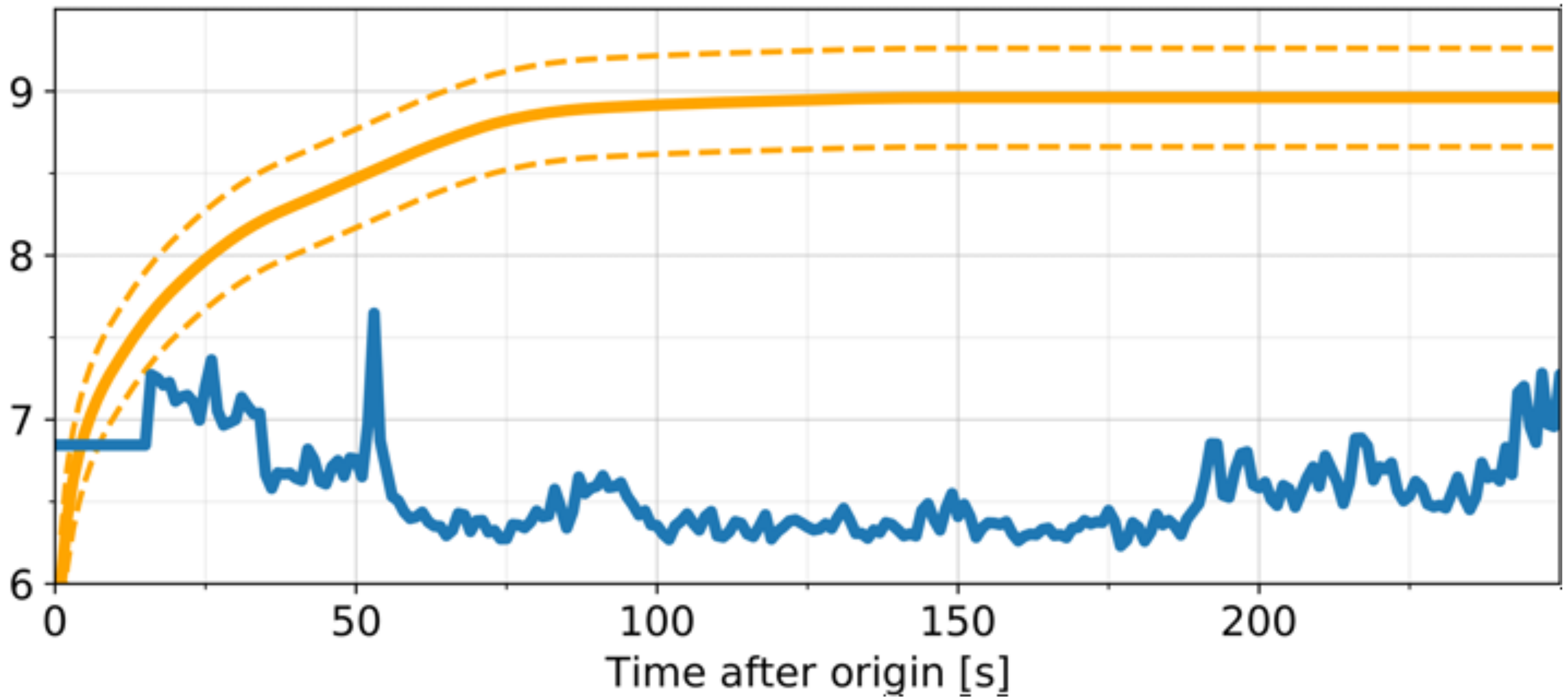
- Retrospective analysis, compared with 'true' STF and other EEWS performances.
- $\mathbf{50 < t < 100\ s}$: tracking with slight under-estimation, with a trend suggesting rupture is in progress.
- $\mathbf{t > 120\ s}$: correct prediction, when rupture is almost over.

Dealing with noise



Synthetic PEGS + noise from different pre-event recordings

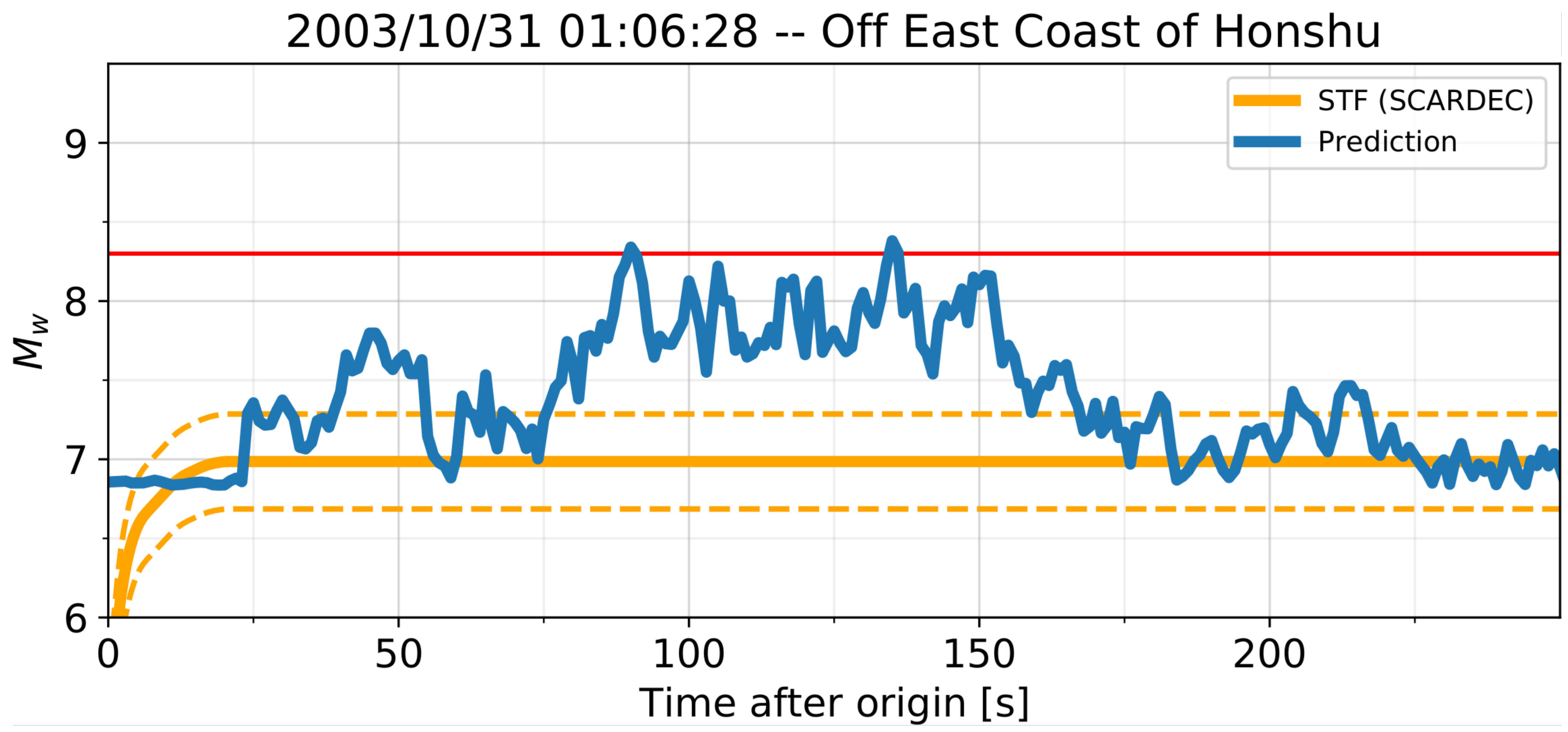
- t < 55 s : high variability due to noise
- t > 55 s (M_w > 8.3) : similar predictions
- PEGSNet able to generalize well to real data

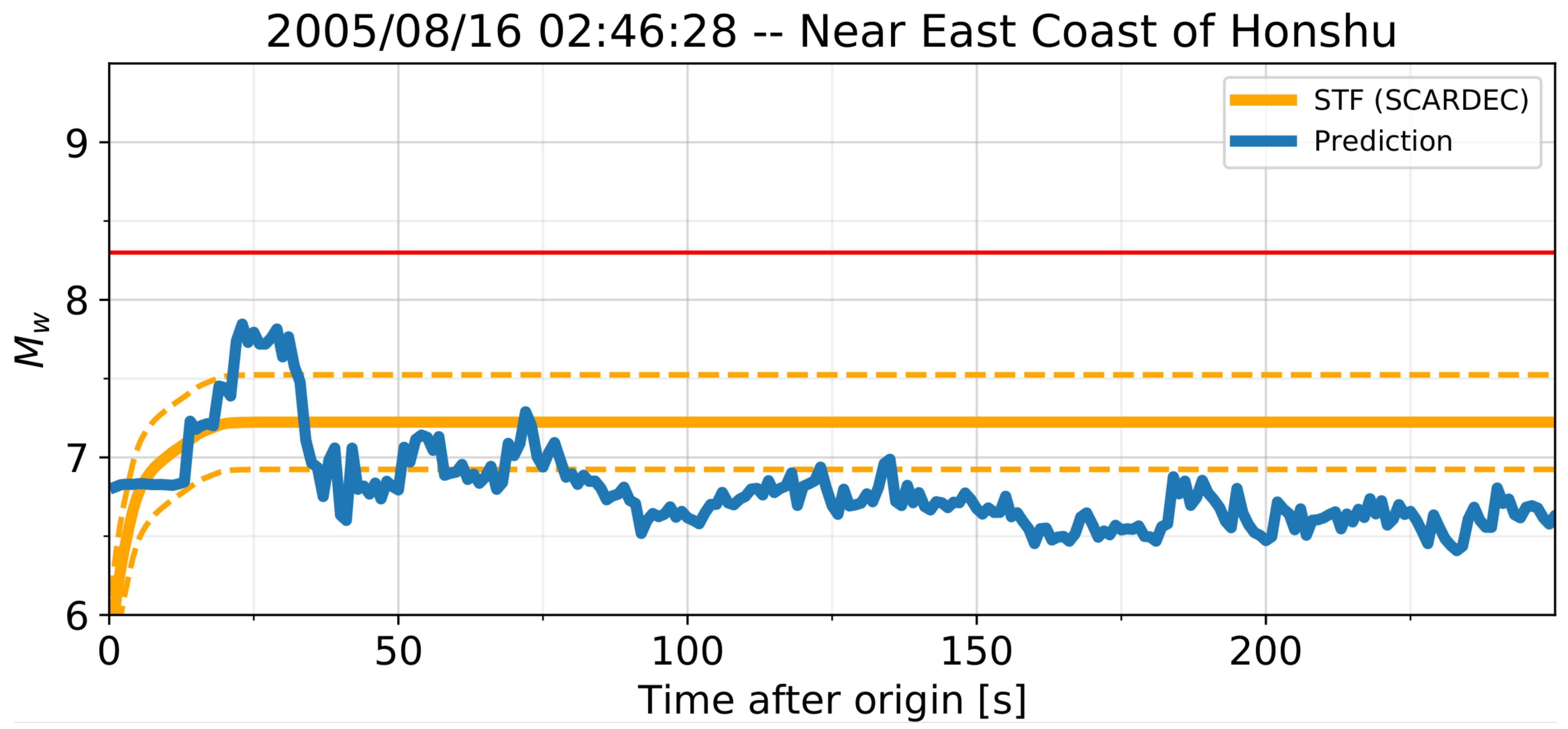


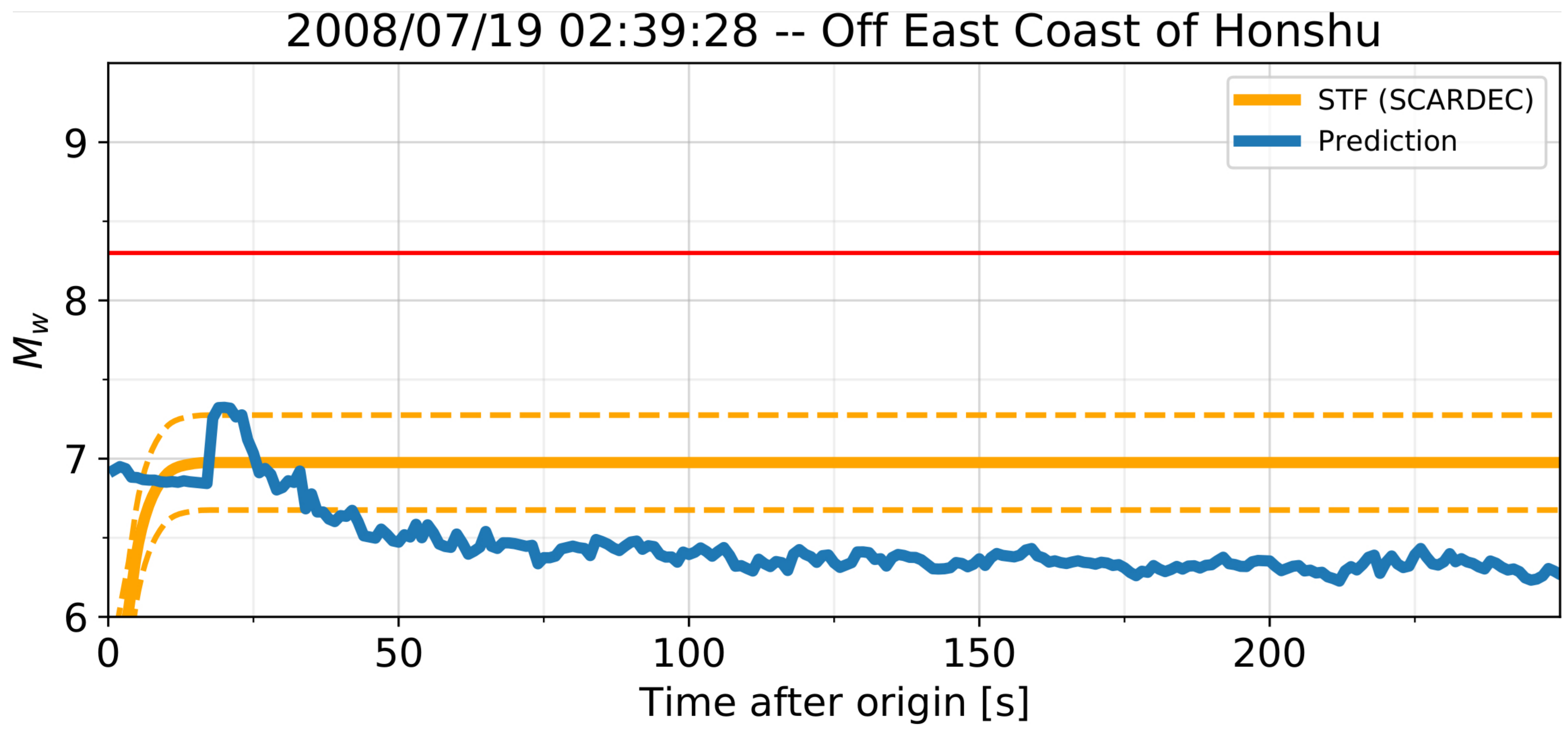
Pre-event noise only, no PEGS

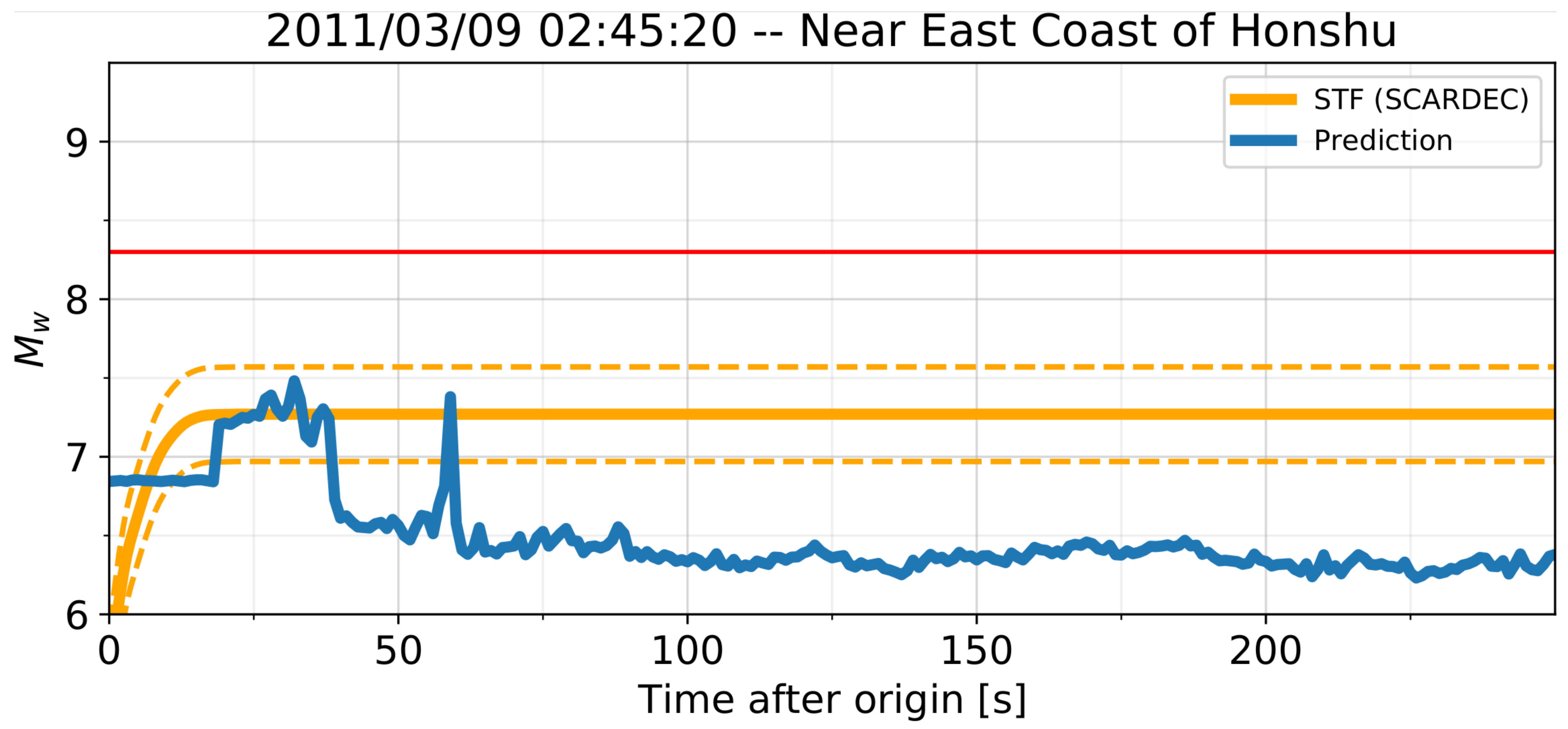
- Predicted M_w is always below model sensitivity
- M_w = 6.5 is a baseline value for noise

Real data : M_w < 8 earthquakes









Conclusions

- **Instantaneous tracking of moment release** (no saturation, zero time delay)
- Can be combined with other observables (seismic, GNSS) to increase performance in real time
- Tohoku-oki timeliness about 50 seconds, time scale for tsunami early warning
- Applicability to $M_w > 8.3$ Japanese subduction earthquakes
- Easy to scale to different focal mechanisms and tectonic settings

Thank you

How do we model PEGS ?

Initial gravity field

Rupture and seismic wave propagation :

transient redistribution of masses

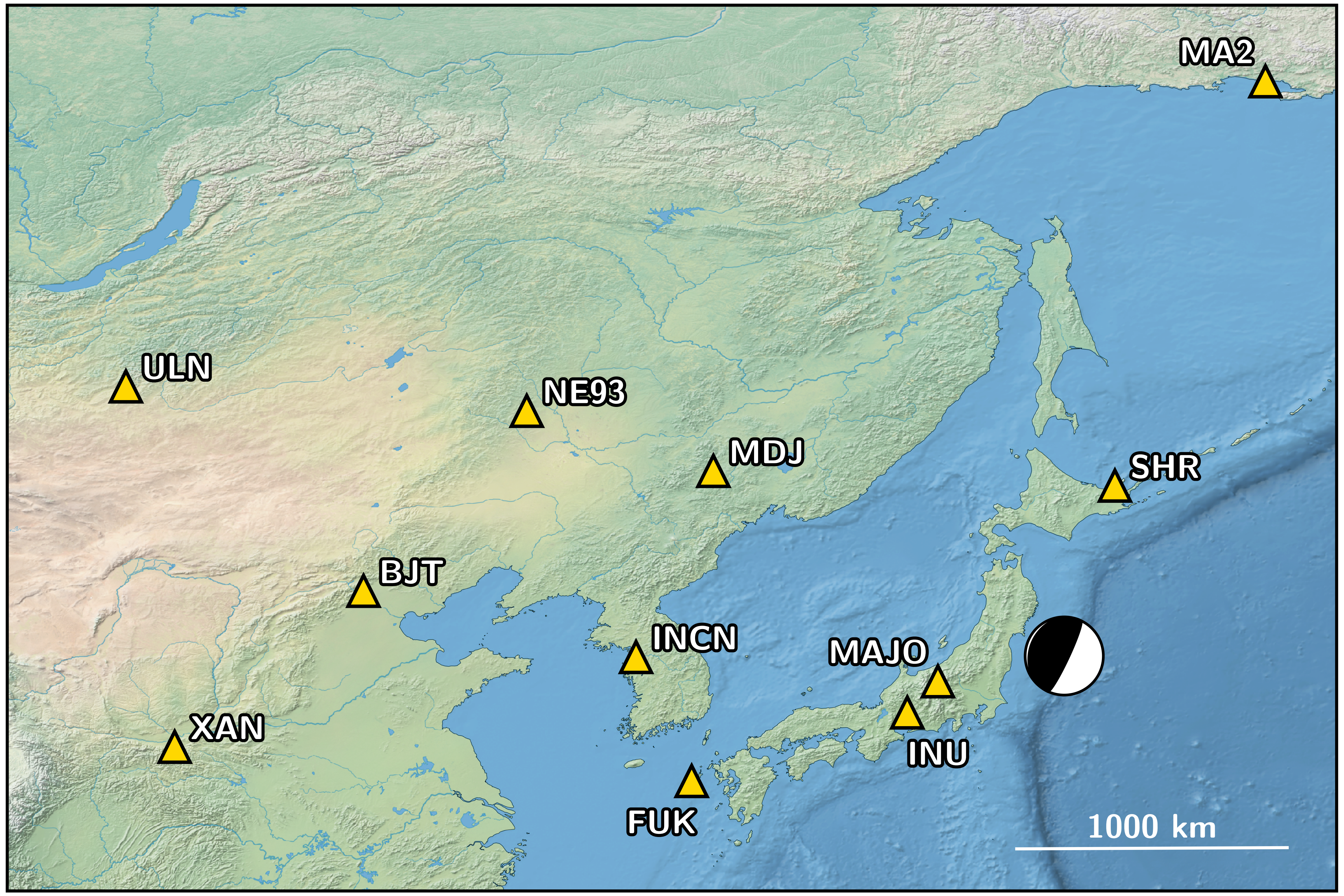
⟶ *remote, instantaneous* recording

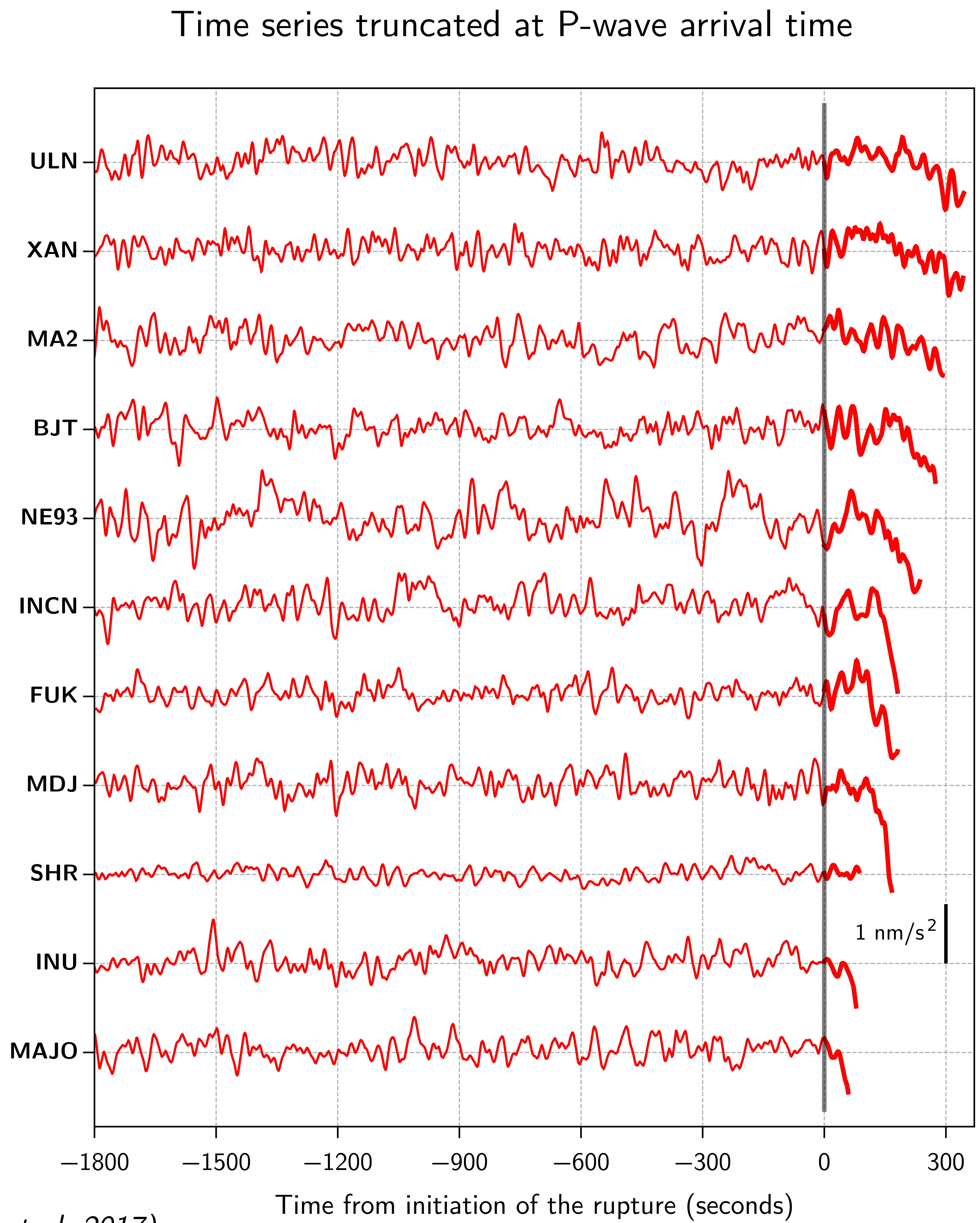
Seismic waves arrival

the 2011 M_w 9.1 Tohoku earthquake

- Bandpass filtering : 0.002 - 0.03 Hz
- Criterion to evaluate data quality : ± 0.8 nm/s² in the 30 min-long interval preceding the event

Selected broadband stations :
- networks : IC, IU, G, F-net
- from 400 to 3000 km
- good azimutal coverage

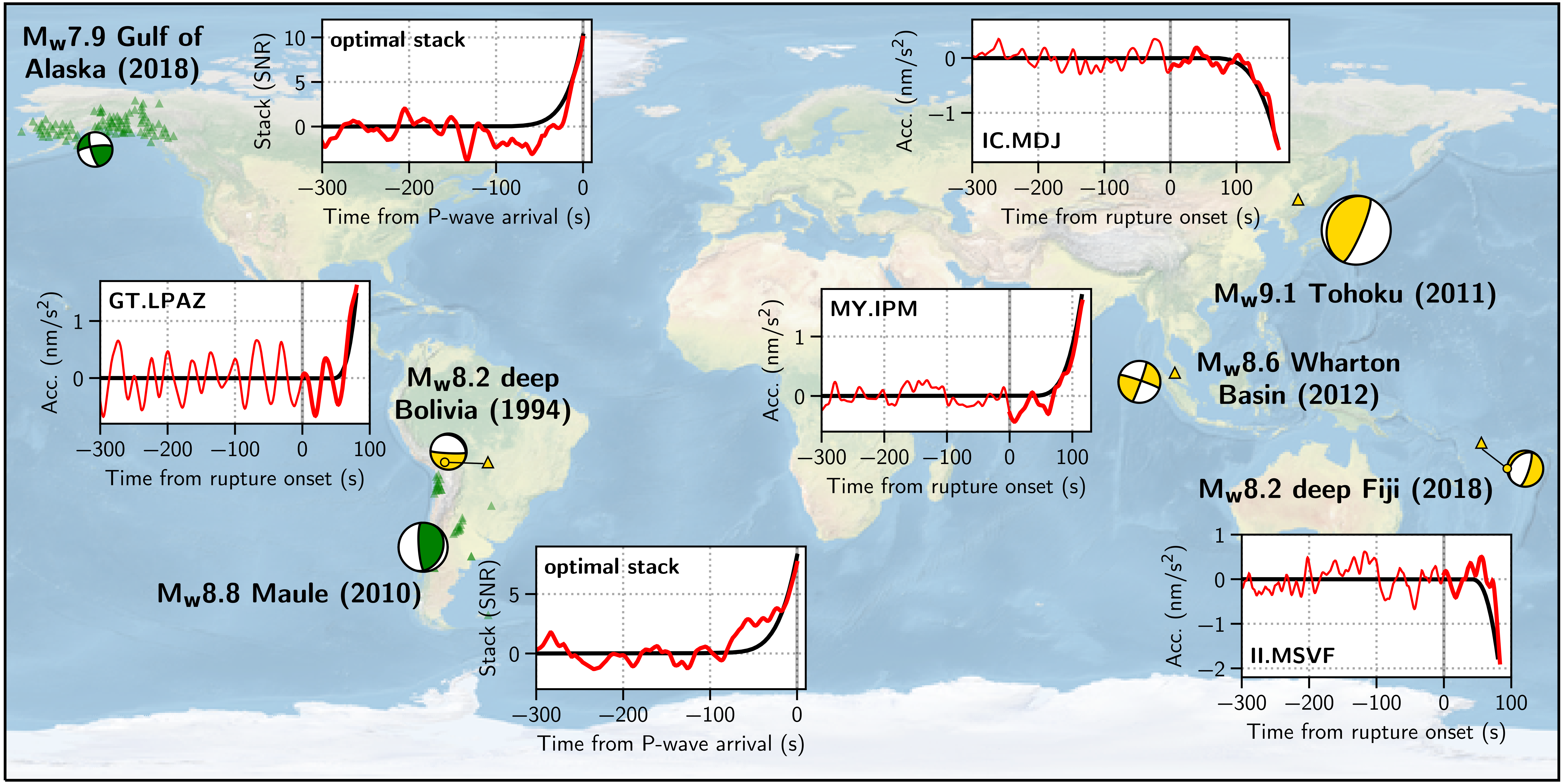




(Vallée et al. 2017)

PEGS observations

(Vallée and Juhel, 2019)



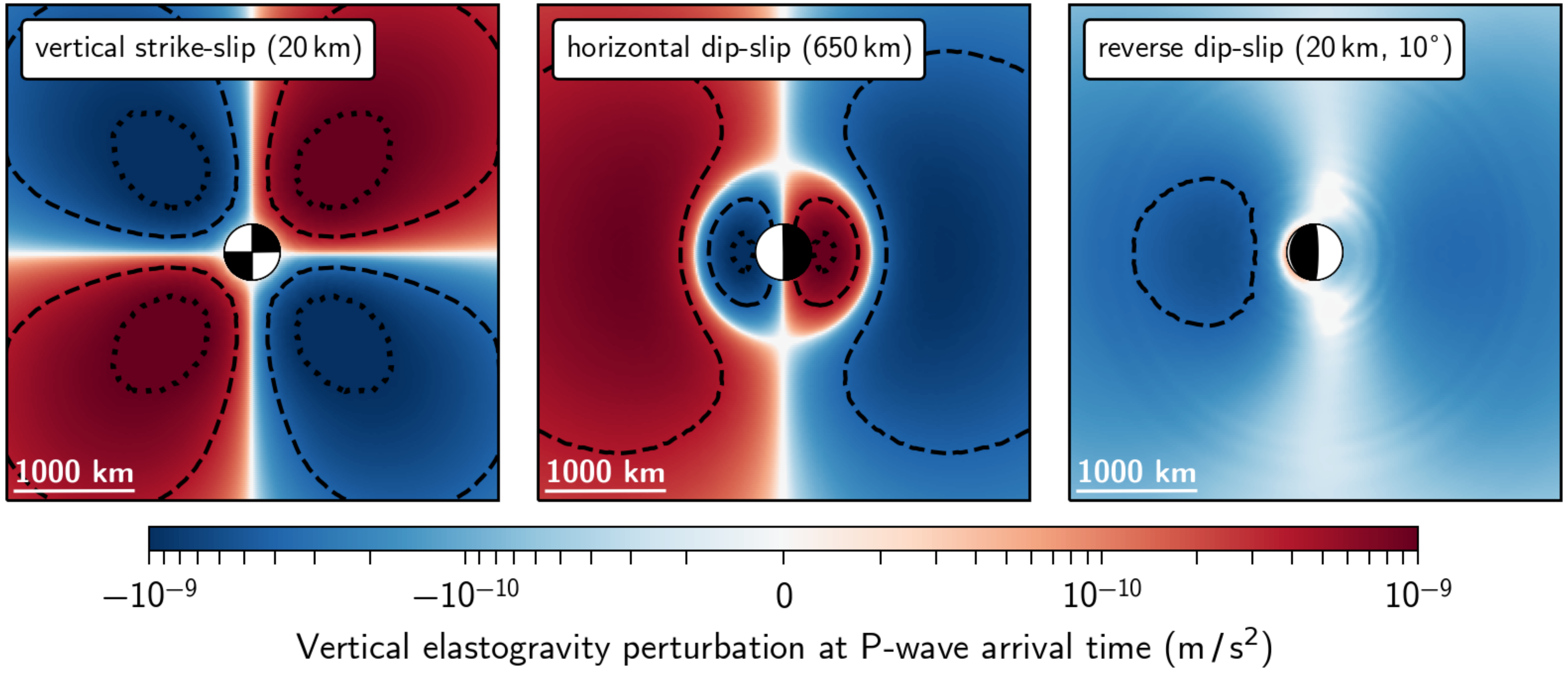
- Single stations or array-based observations
- Observational limit : $M_w = 7.9$

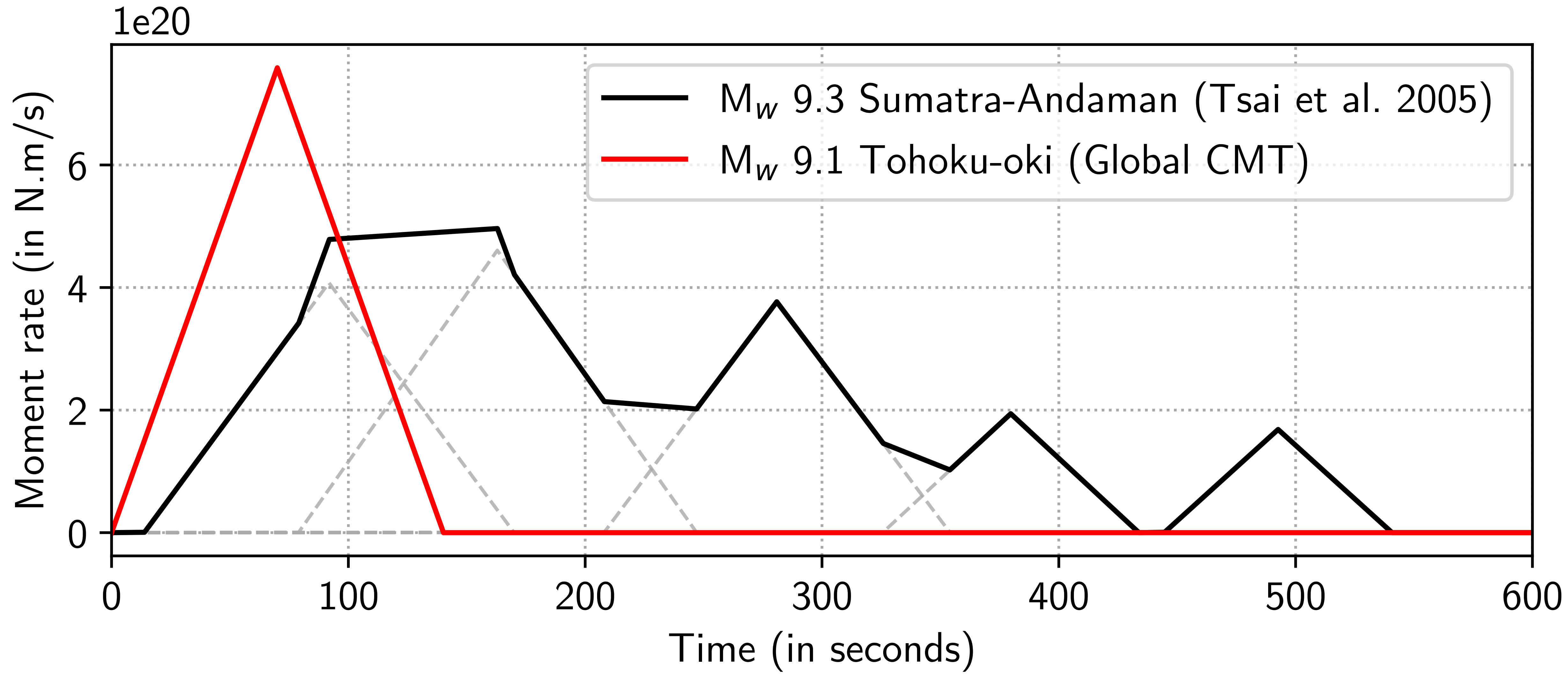
Factors controlling PEGS detectability

- For a given M_w and STF, **strike-slip** and **deep earthquakes** generate larger PEGS than thrust earthquakes on shallow dipping interfaces

(Vallée and Juhel, 2019)

dashed : +/- 0.4 nm/s² | *dotted : +/- 1.0 nm/s²*





- Direct relation between STF and gravity perturbations : a **rapidly growing STF** increases signal observability

Elementary moment tensors

Computation of the input synthetic database

Weighted sum of 4 elementary moment tensors :

(Aki and Richards, 2002)

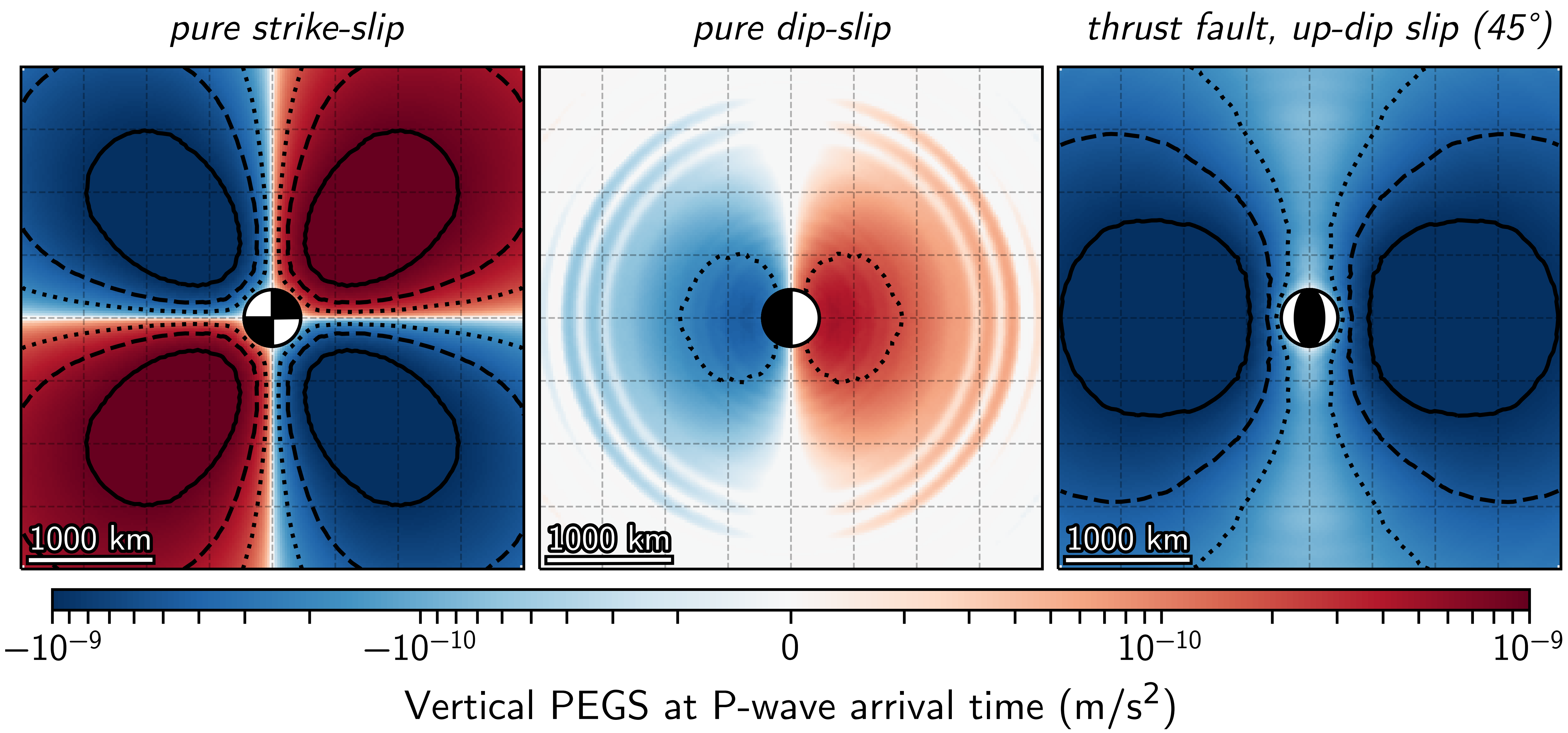
$$\mathbf{M} = \cos\delta\cos\lambda\,\mathbf{M}^{(1)} + \sin\delta\cos\lambda\,\mathbf{M}^{(2)} - \cos 2\delta\sin\lambda\,\mathbf{M}^{(3)} + \sin 2\delta\sin\lambda\,\mathbf{M}^{(4)}$$

where

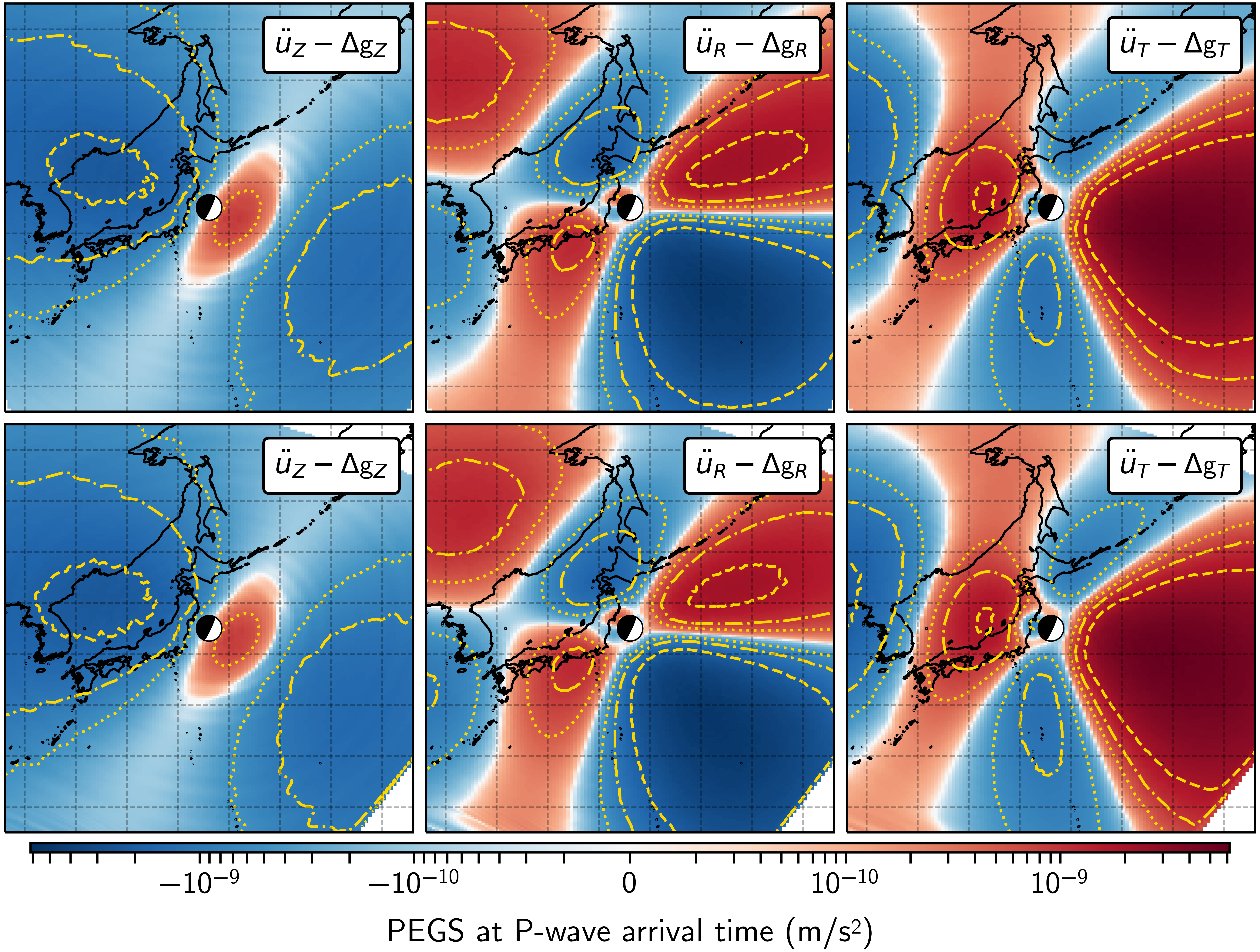
$$\mathbf{M}^{(1)} = M_0 \begin{pmatrix} 0 & 0 & -\cos\phi_s \\ 0 & 0 & -\sin\phi_s \\ -\cos\phi_s & -\sin\phi_s & 0 \end{pmatrix}, \mathbf{M}^{(2)} = M_0 \begin{pmatrix} -\sin 2\phi_s & \cos 2\phi_s & 0 \\ \cos 2\phi_s & \sin 2\phi_s & 0 \\ 0 & 0 & 0 \end{pmatrix},$$

$$\mathbf{M}^{(3)} = M_0 \begin{pmatrix} 0 & 0 & \sin\phi_s \\ 0 & 0 & -\cos\phi_s \\ \sin\phi_s & -\cos\phi_s & 0 \end{pmatrix}, \mathbf{M}^{(4)} = M_0 \begin{pmatrix} -\sin^2\phi_s & \frac{1}{2}\sin 2\phi_s & 0 \\ \frac{1}{2}\sin 2\phi_s & -\cos^2\phi_s & 0 \\ 0 & 0 & 1 \end{pmatrix}.$$

dotted: +/- 0.2 nm/s²
dashed: +/- 0.5 nm/s²
solid: +/- 1.0 nm/s²



Elementary moment tensors



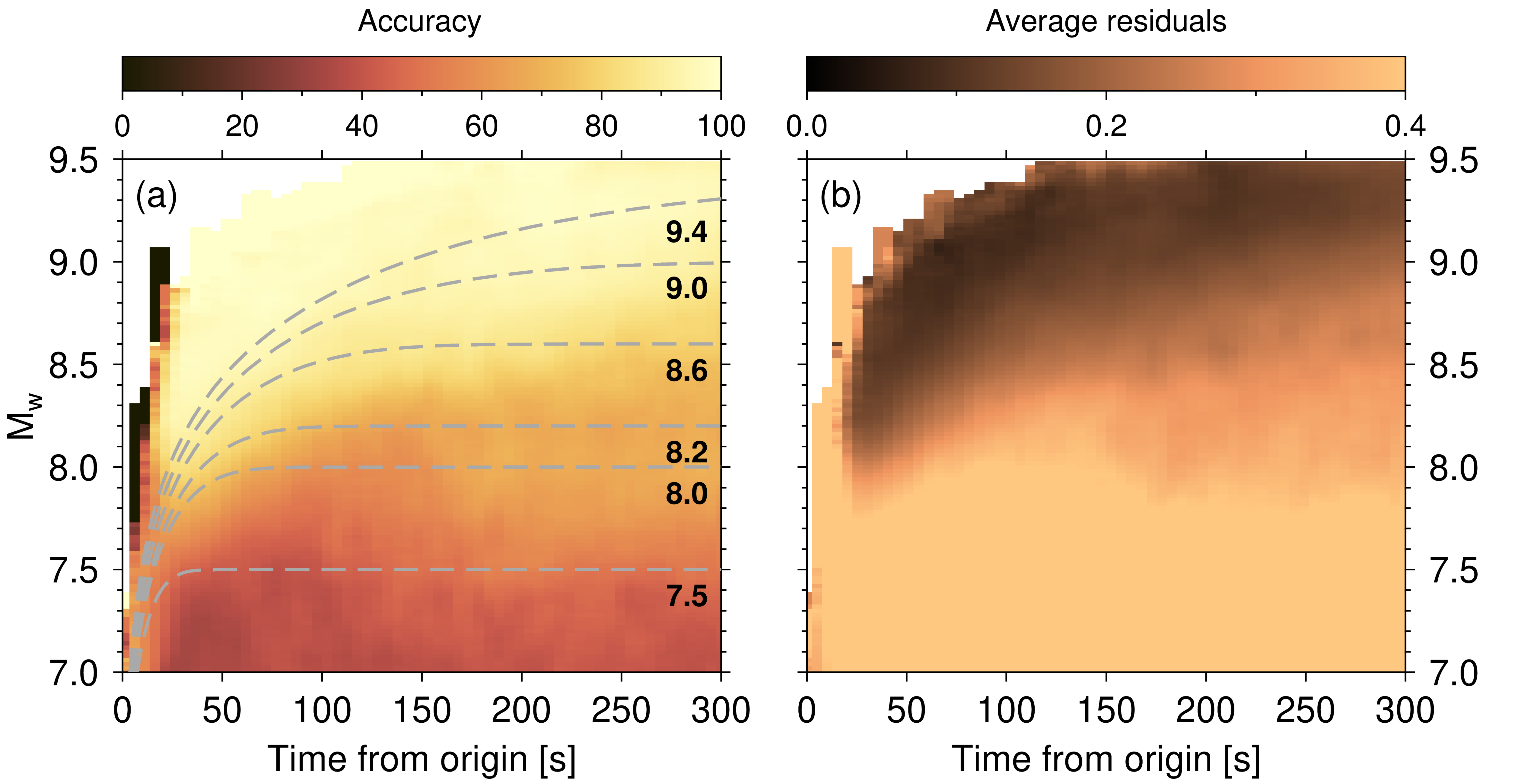
Direct computation using Global CMT moment tensor as input

Decomposition using the best double-couple solution :

- strike = 203°
- dip = 10°
- rake = 88°

Results on test set : low noise conditions (0.5 nm/s²)

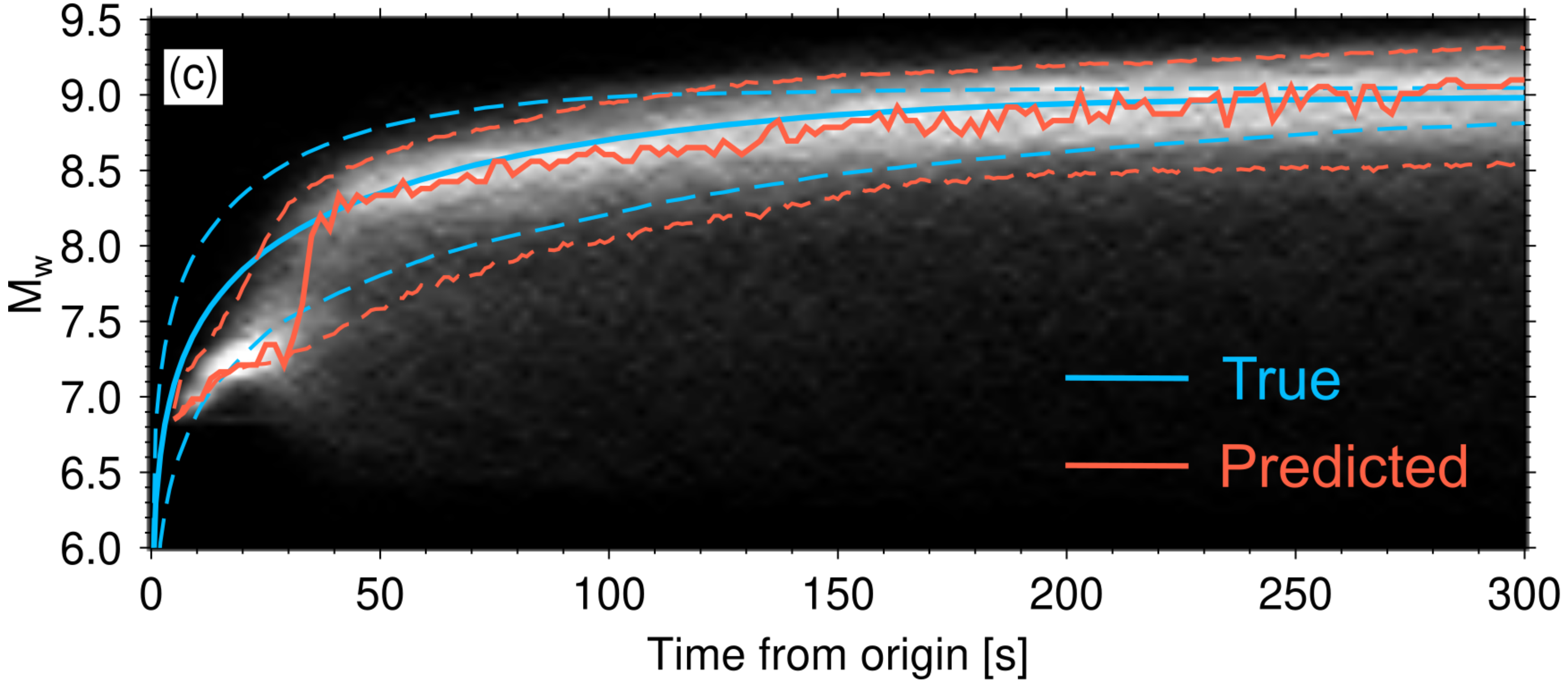
Successful prediction if the estimated $M_w(t)$ lies within $\pm$ 0.4 magnitude units from the ground truth value.



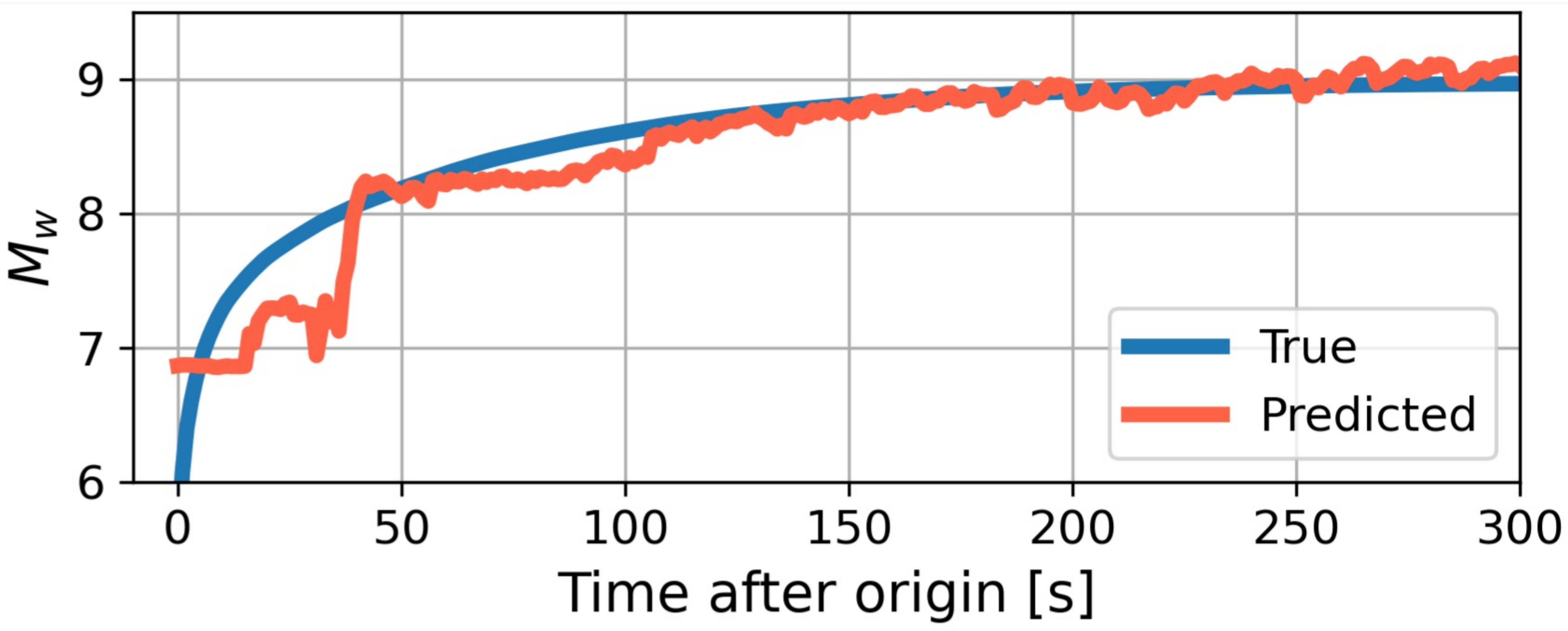
- Under favorable noise conditions : $\sigma_{noise} < 0.5$ nm/s²
- **7.9 < M_w < 8.3** : final M_w prediction with 70-80% accuracy, 150 seconds from origin time.

Results on test set : $M_w = 9.0 \pm 0.05$

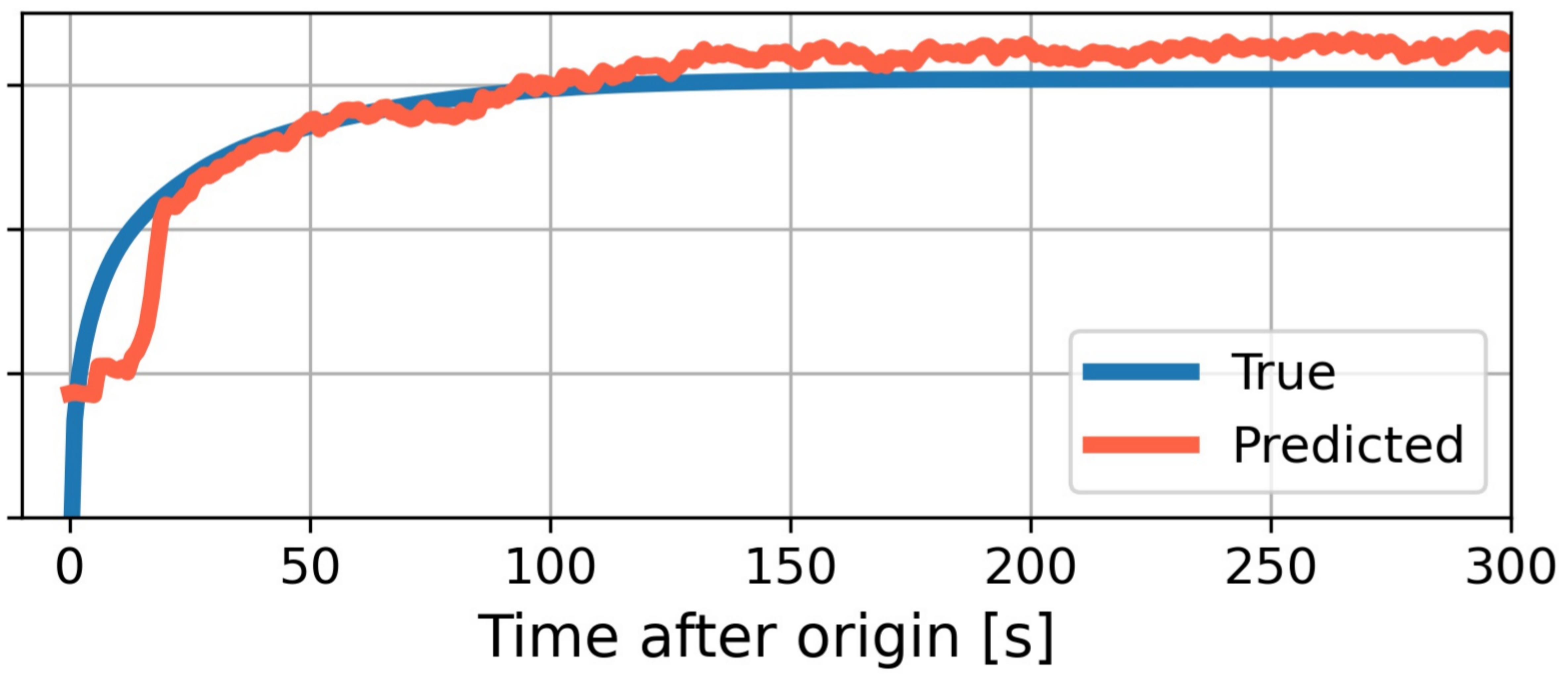
- Magnitude $M_w(t)$ estimation with zero delay once $M_w > 8.3$
- Ability to recover the actual moment release sooner or later, depending on the source onset



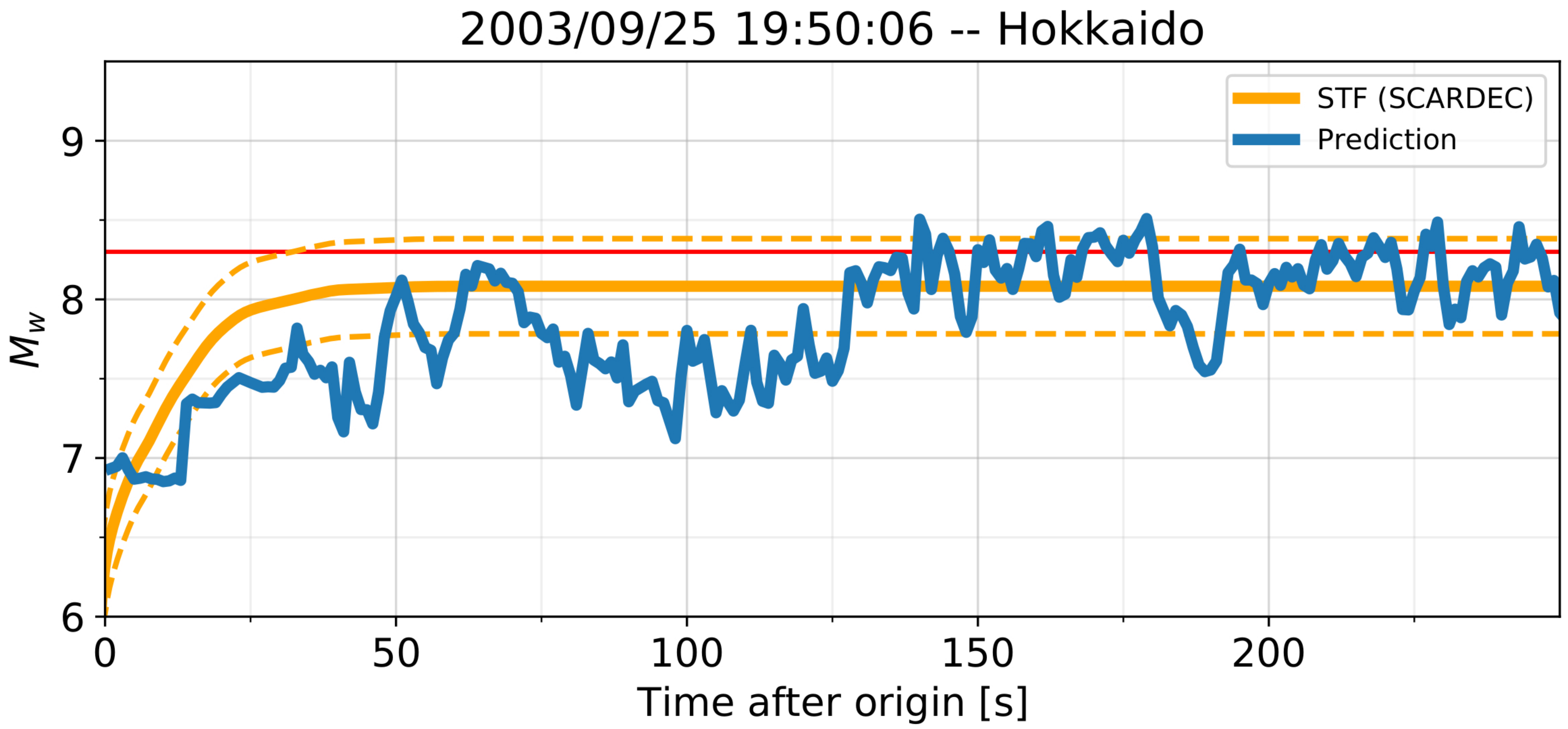
Slow onset



Fast onset



Real data : the 2003 M_w 8.2 Hokkaido earthquake



- At the edge of PEGSNet's lower sensitivity limit
- Final magnitude estimation after around 2 minutes, with expected lower accuracy and higher errors