Use of the prompt elasto-gravity signals (PEGS) for earthquake characterization

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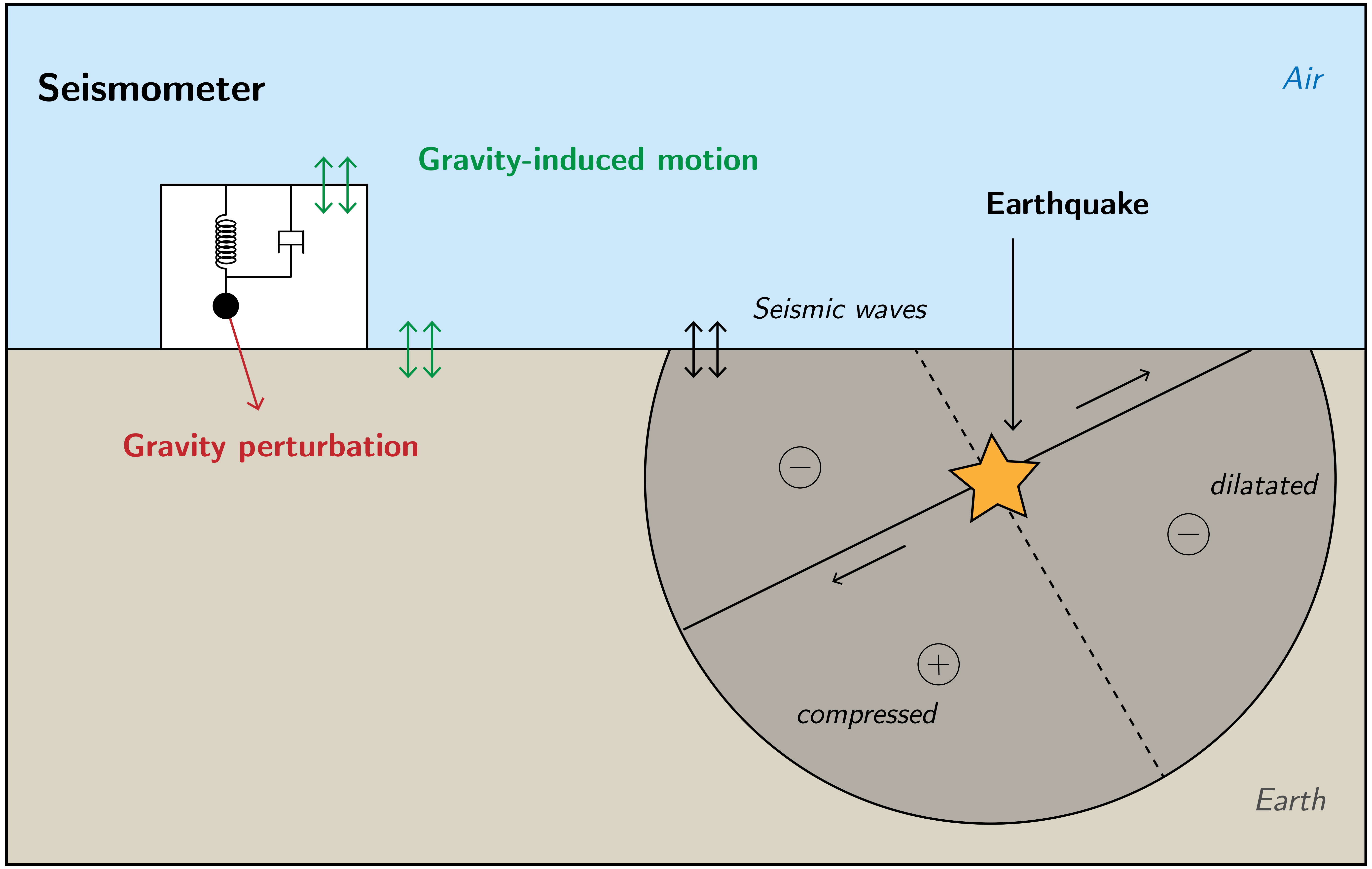
PEGS detection and simulation

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)

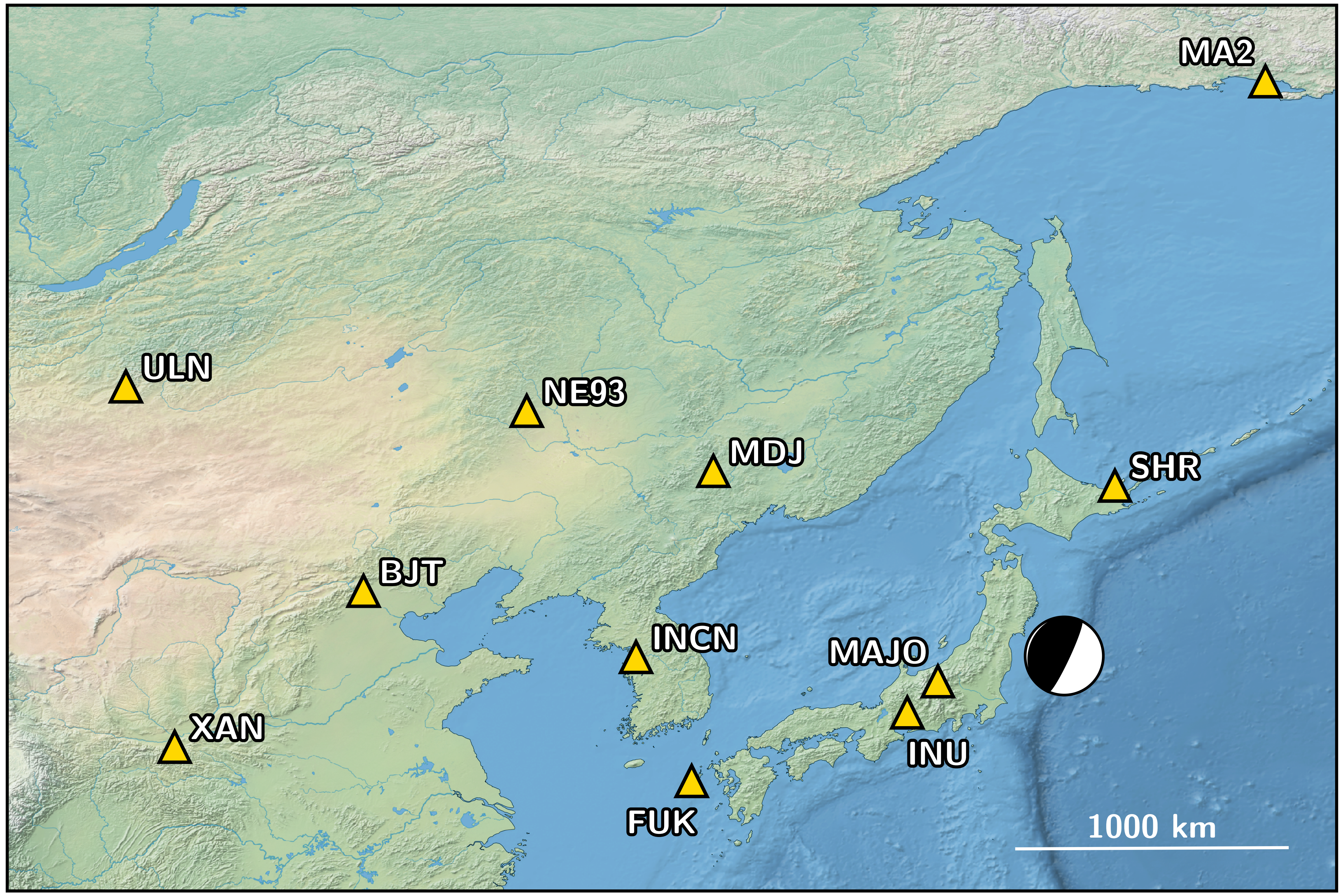
As soon as an earthquake occurs (and thus ***before the arrival of seismic waves***), a weak signal is expected to be recorded at a broadband seismometer, due to the combination of :

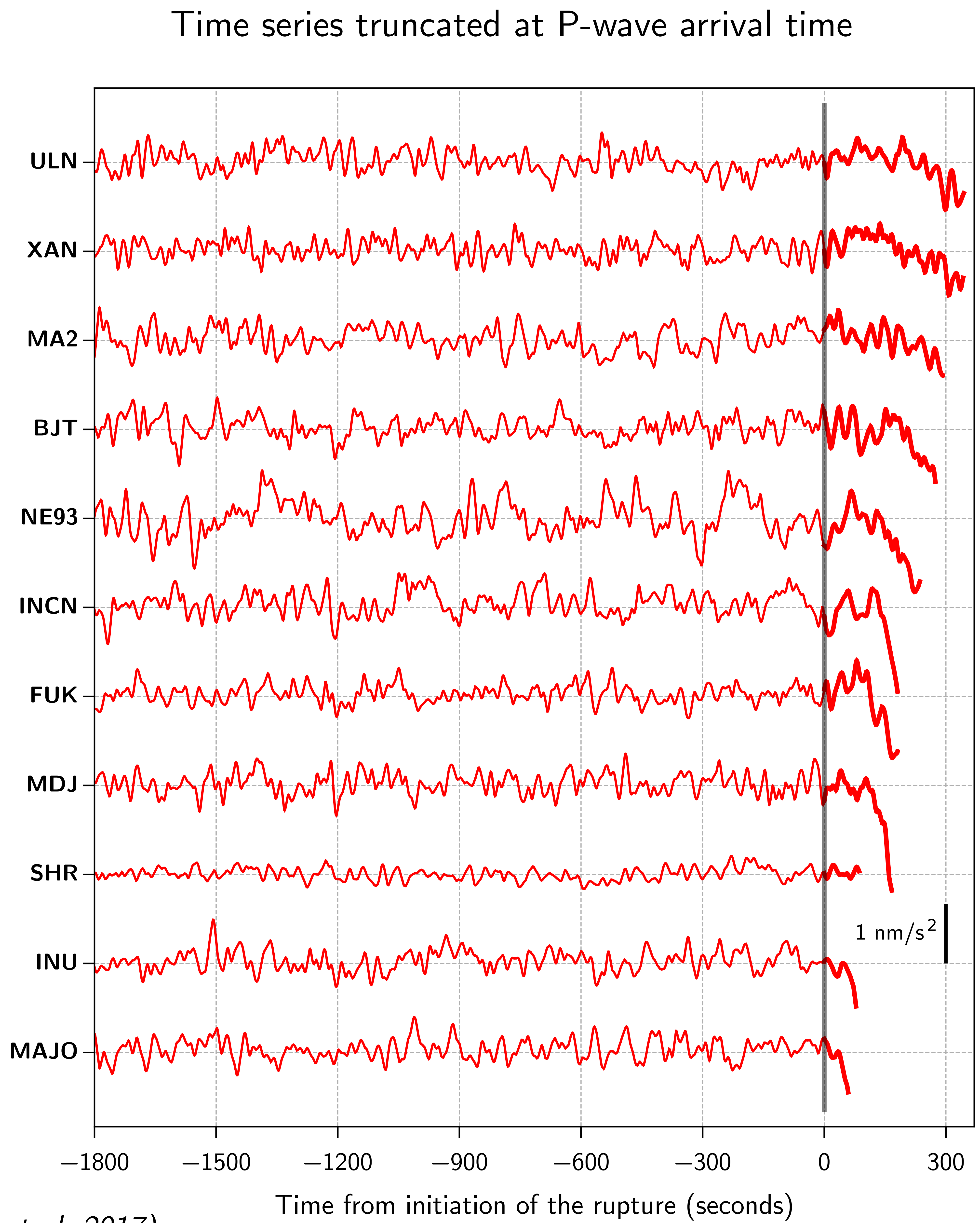
- **direct effect** : the gravity perturbation induced by the earthquake rupture and the elastic waves *(Harms et al. 2015, Montagner et al. 2016)*
- **induced effect** : the elastic relaxation of the Earth, itself affected by the gravity perturbation *(Vallée et al. 2017, Juhel et al. 2018)*

the 2011 M_W 9.1 Tohoku earthquake

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

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





(Vallée et al. 2017)

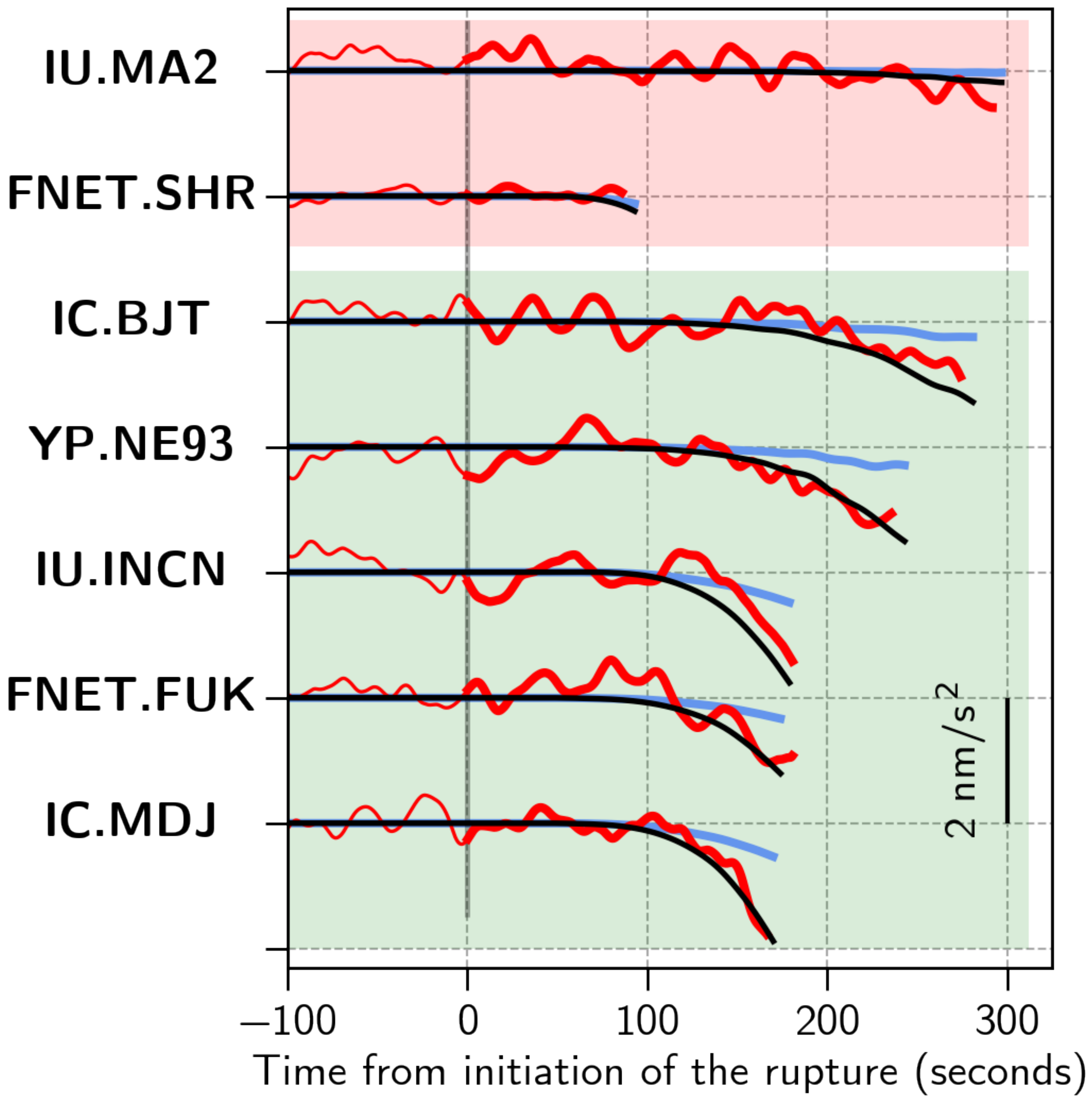
the 2011 M_w 9.1 Tohoku earthquake

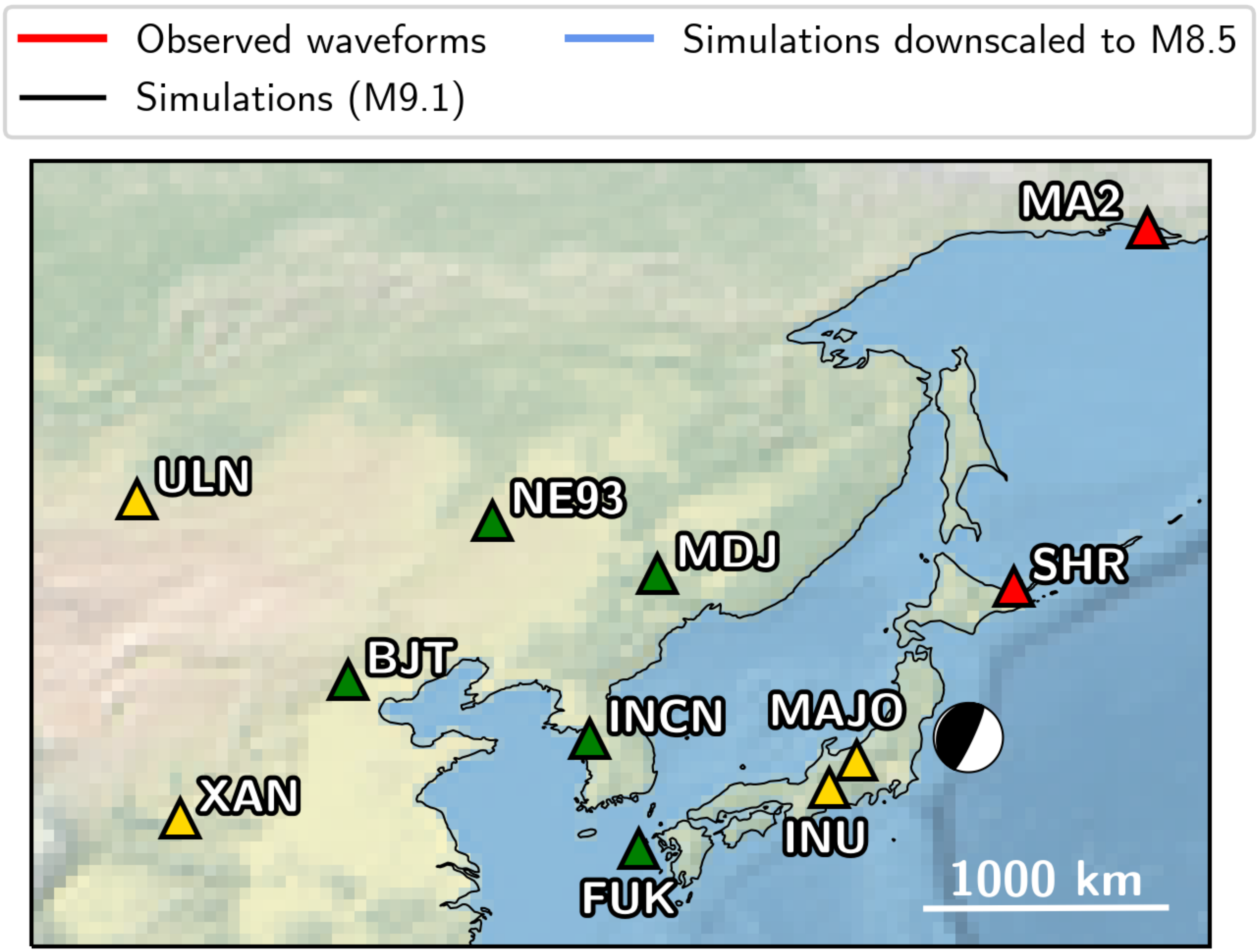
Prompt elastogravity signals (PEGS) depend on :

- the earthquake focal mechanism
- the earthquake magnitude

... within the duration of the rupture !

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



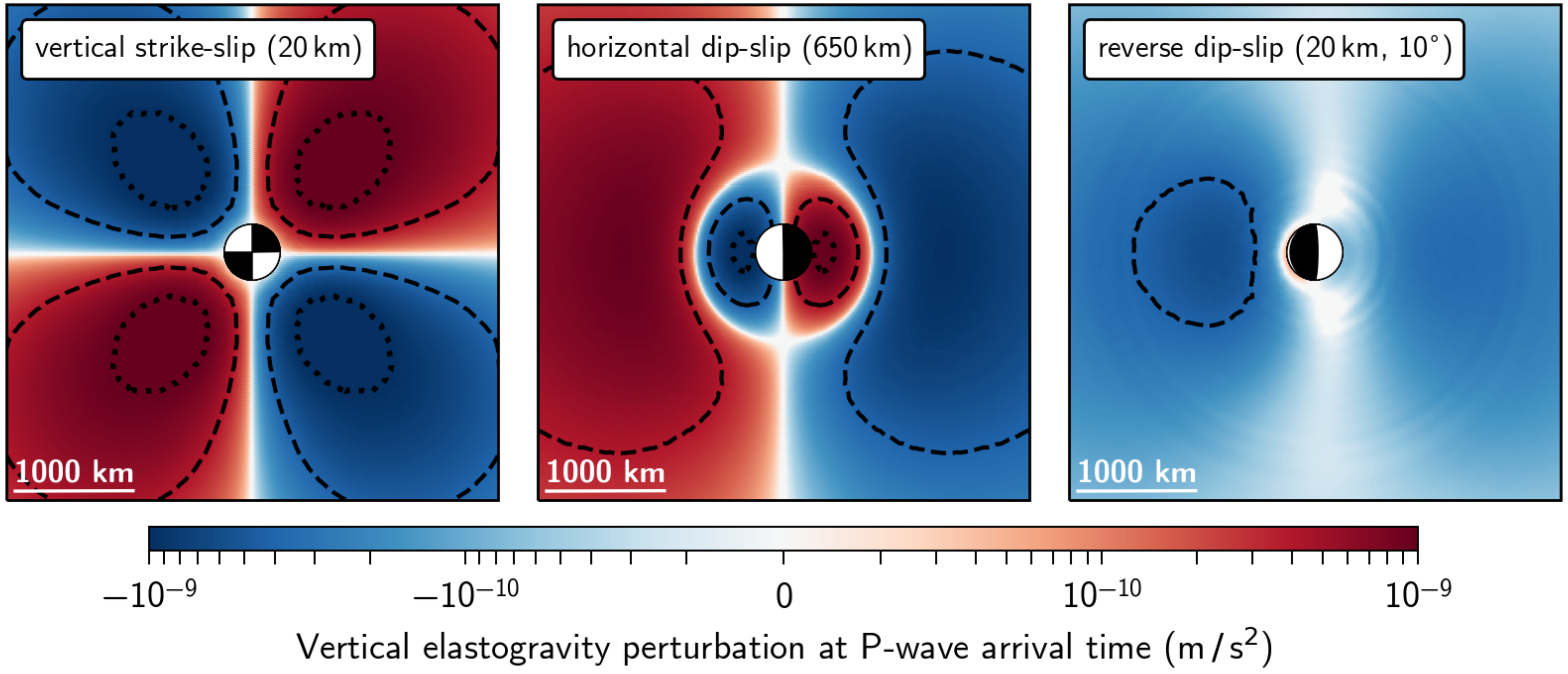


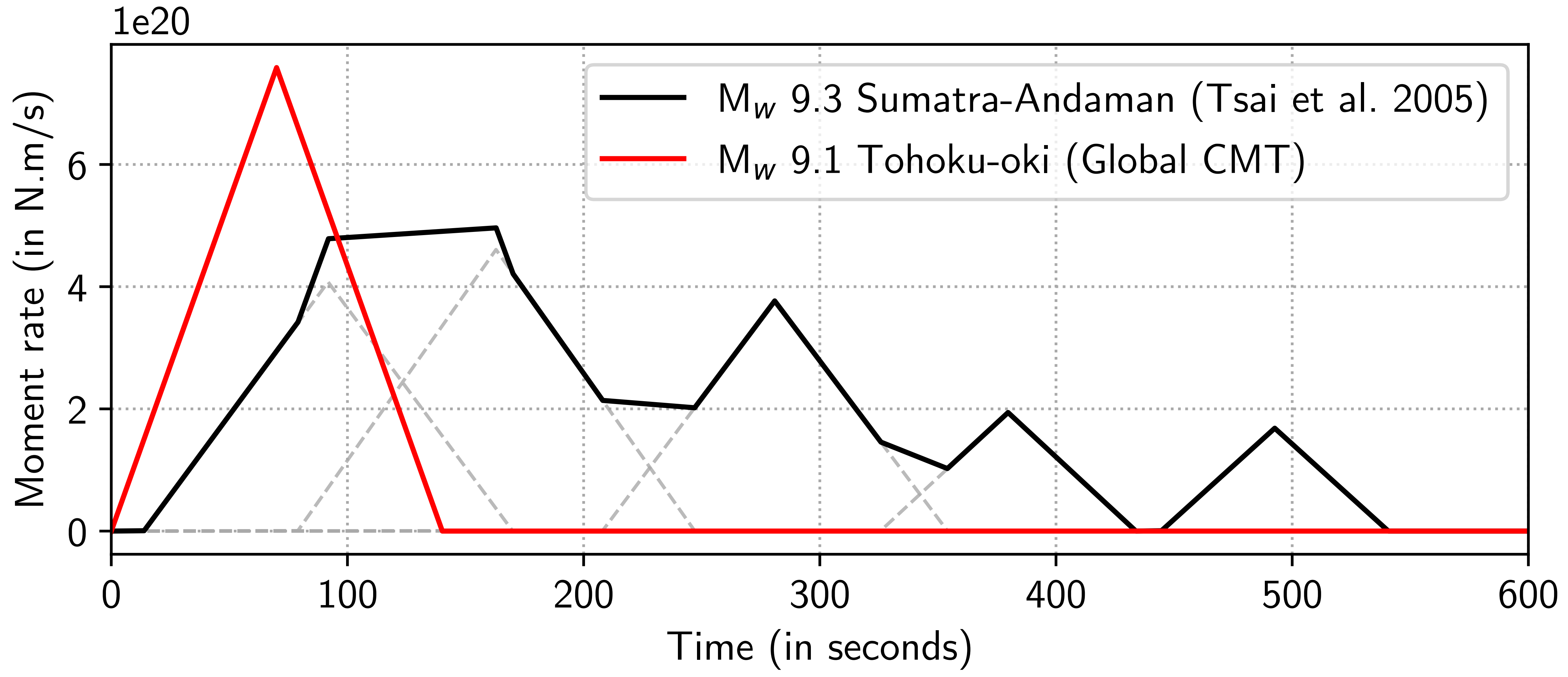
Factors controlling PEGS detectability

- 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



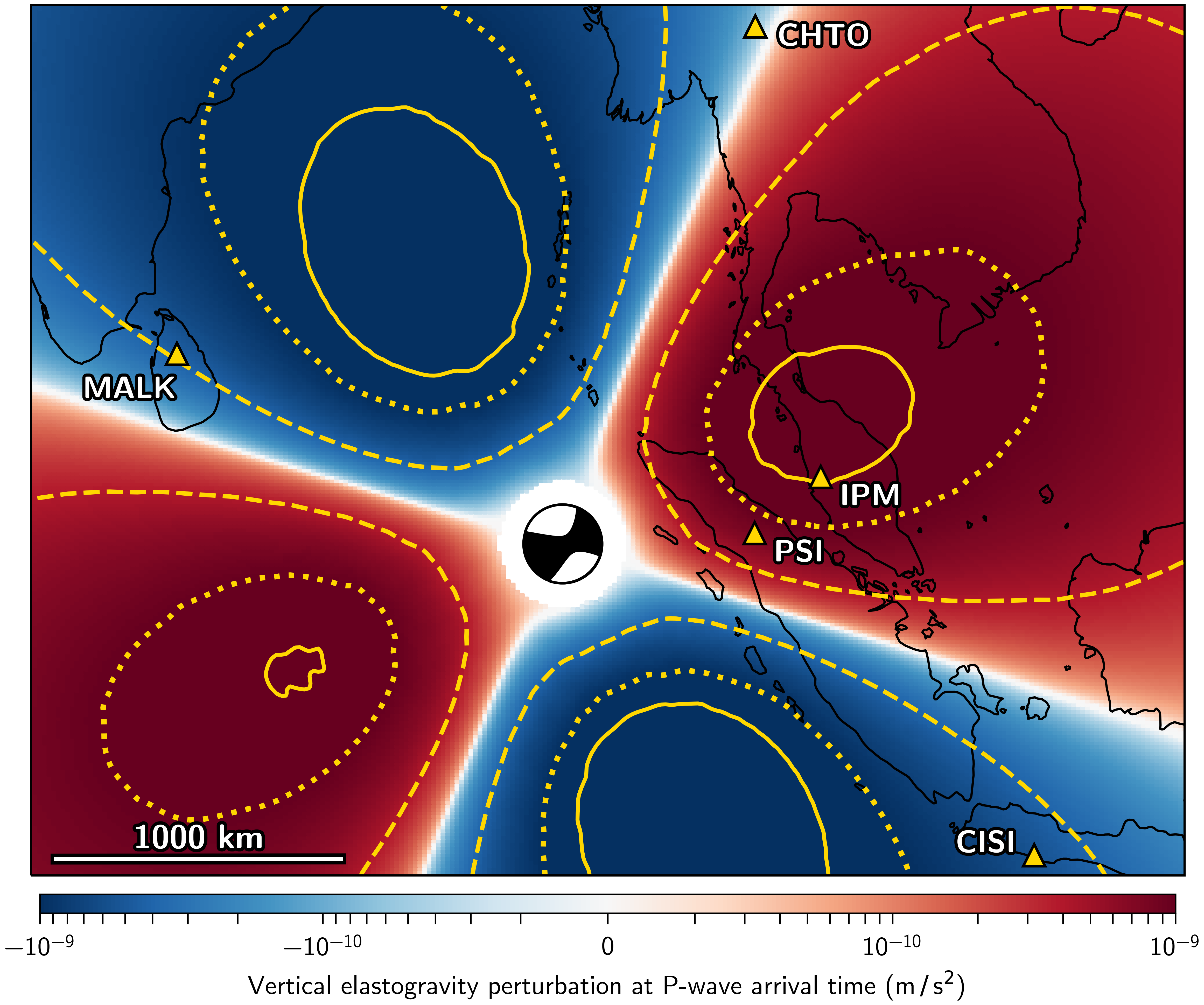


- Direct relation between STF and gravity perturbations : a **rapidly growing STF** increases signal observability

the 2012 M_w 8.6 Wharton Basin earthquake

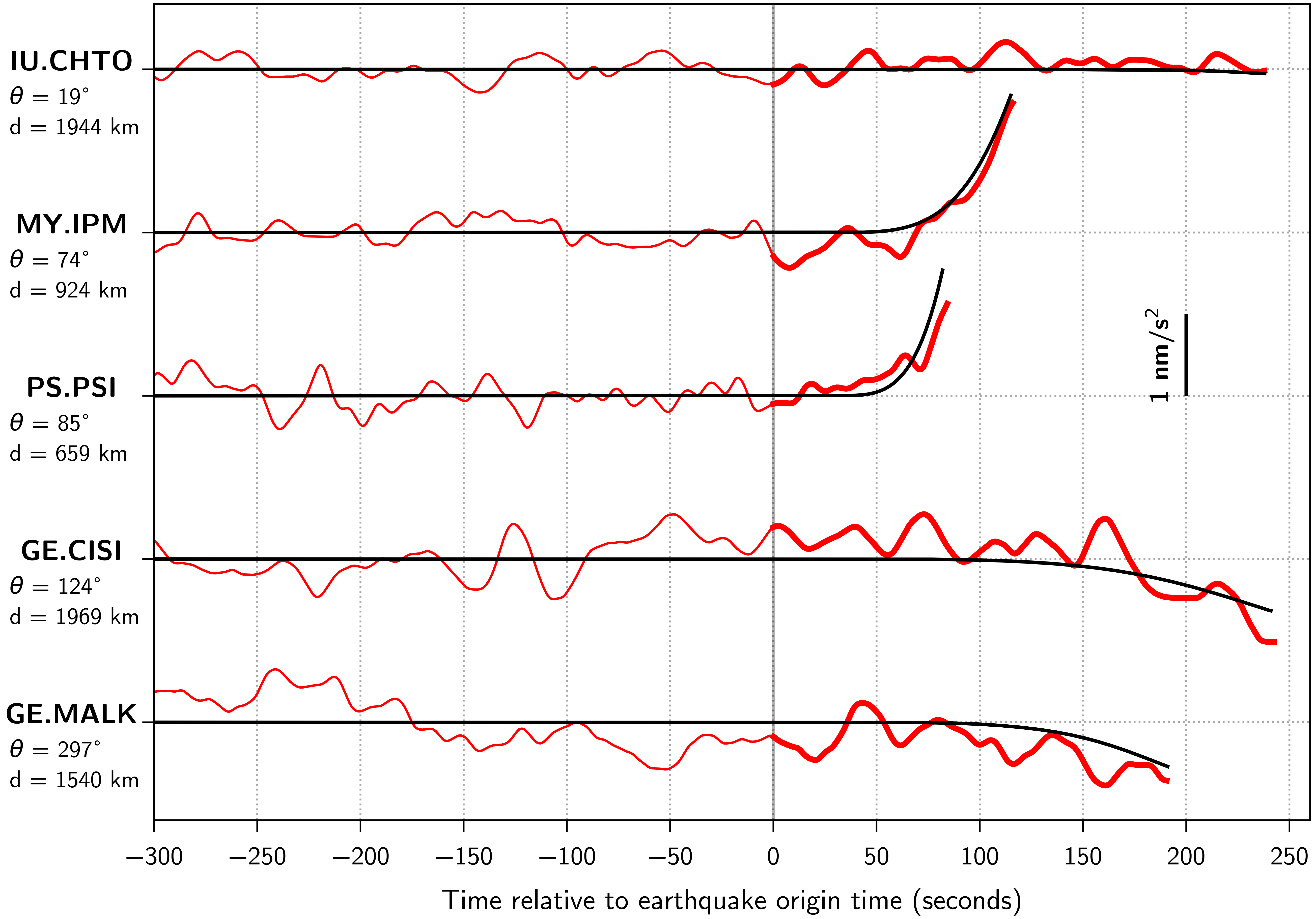
(Vallée and Juhel, 2019)

Predicted PEGS amplitudes (GCMT)



dashed: +/- 0.4 nm/s² | dotted: +/- 1.0 nm/s² | solid: +/- 1.3 nm/s²

Observed and modeled waveforms (SCARDEC)

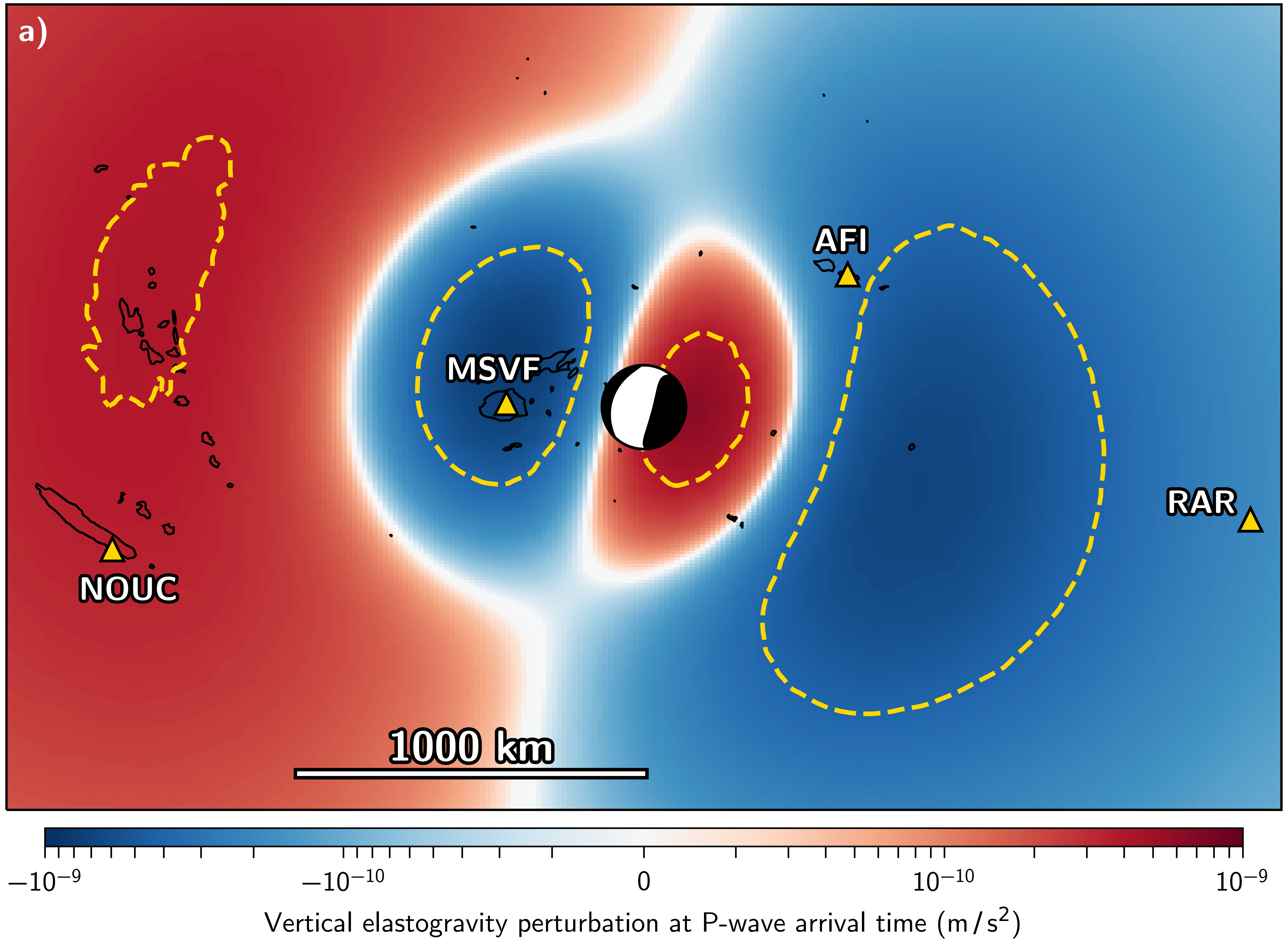


Good agreement between observed and modeled PEGS

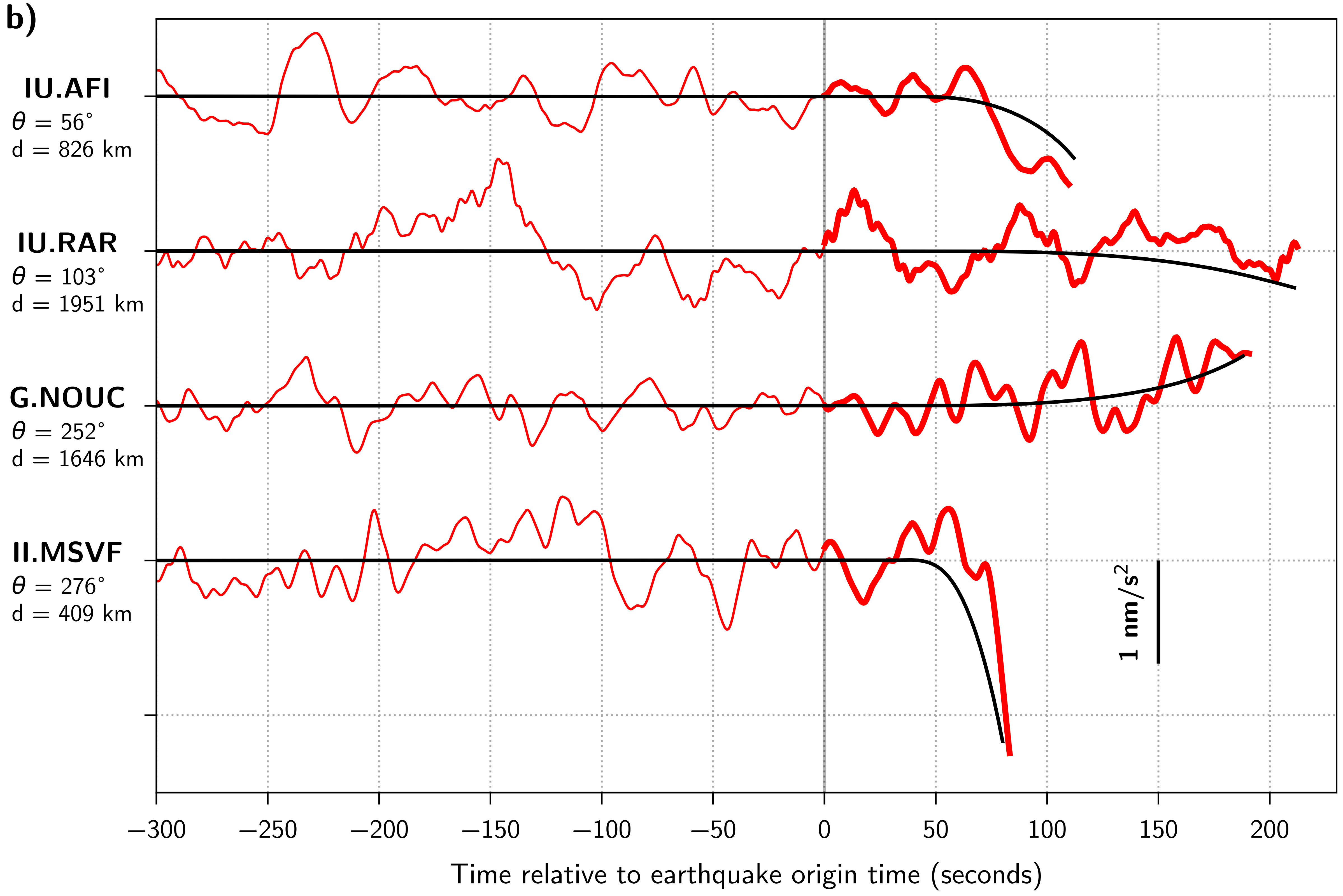
the 2018 M_w 8.2 deep Fiji earthquake

(Vallée and Juhel, 2019)

Predicted PEGS amplitudes (GCMT)



Observed and modeled waveforms (SCARDEC)



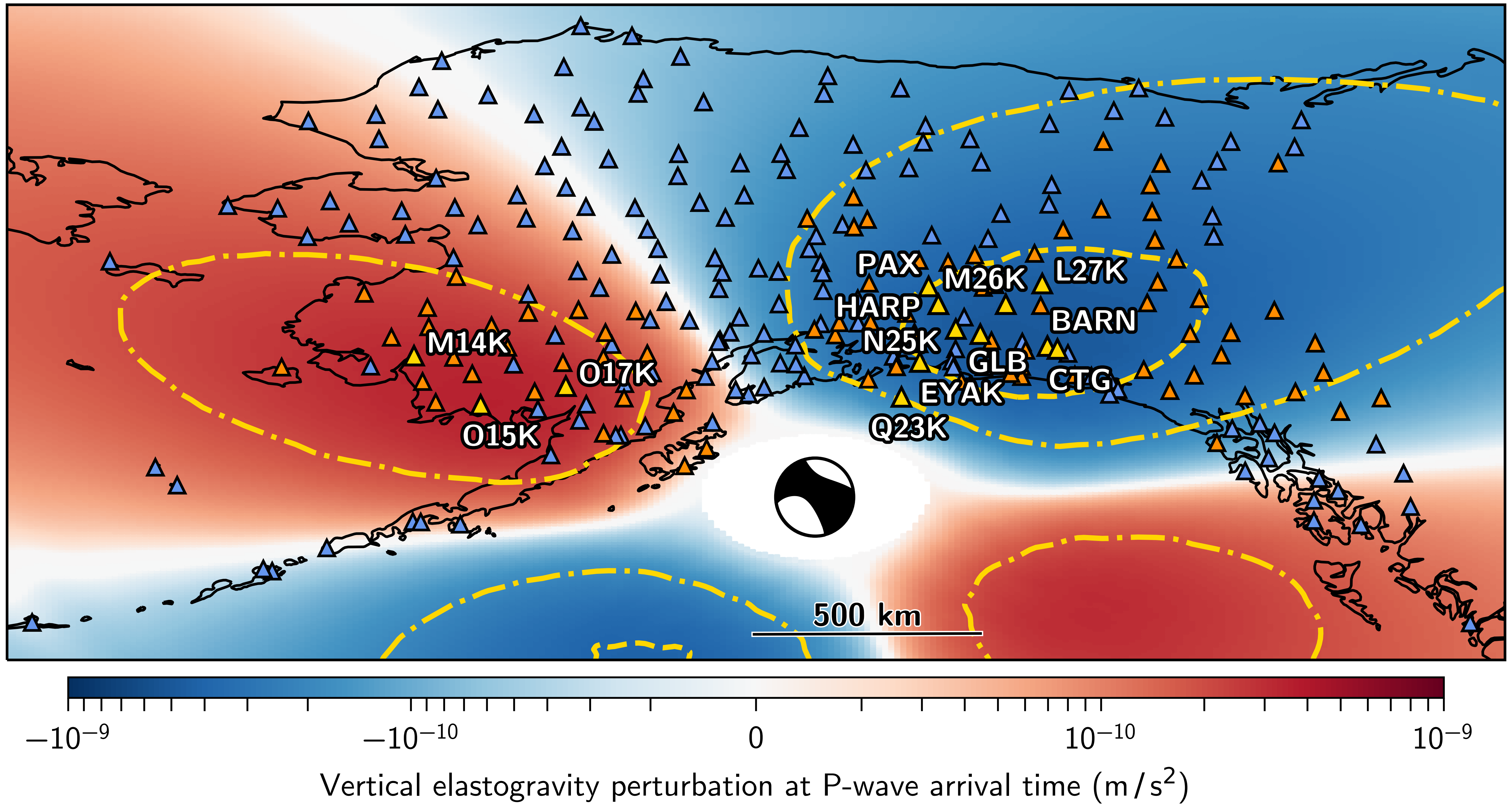
dashed: +/- 0.4 nm/s^2

Good agreement between observed and modeled PEGS

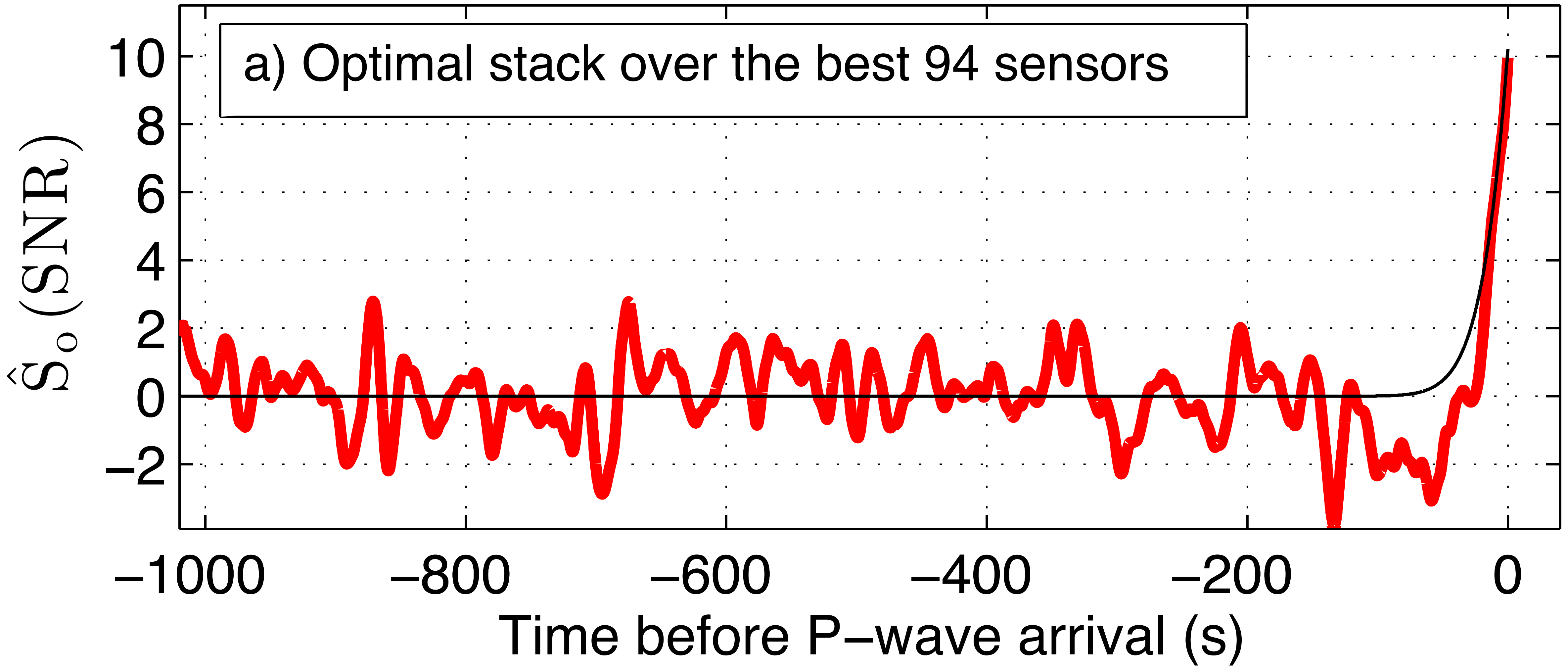
the 2018 M_w 7.9 Gulf of Alaska earthquake

- PEGS detection requires **good broadband stations** in a relatively **quiet seismic period**
- For earthquakes generating PEGS close to seismic noise, detection can be achieved by **combining observations at several sensors**

(Vallée and Juhel, 2019)



dashed-dotted: +/- 0.2 nm/s²
dashed: +/- 0.4 nm/s²

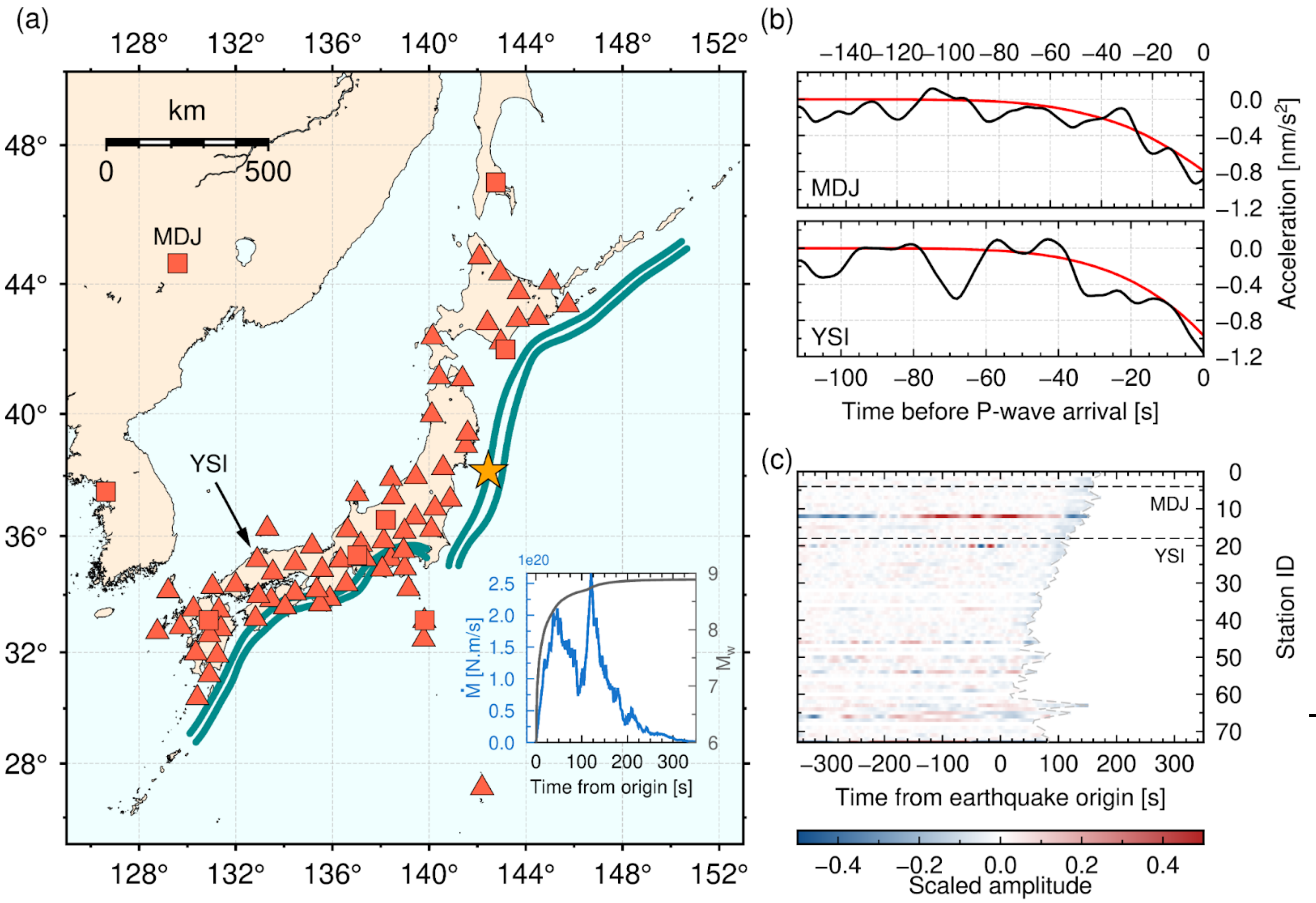


Waveform stack, in P-wave arrival reference-time, weighted by sensor quality and expected amplitude

⟶ PEGS recorded with SNR = 10

How can we use PEGS
for early magnitude estimation
in an operational EWS ?

Deep learning

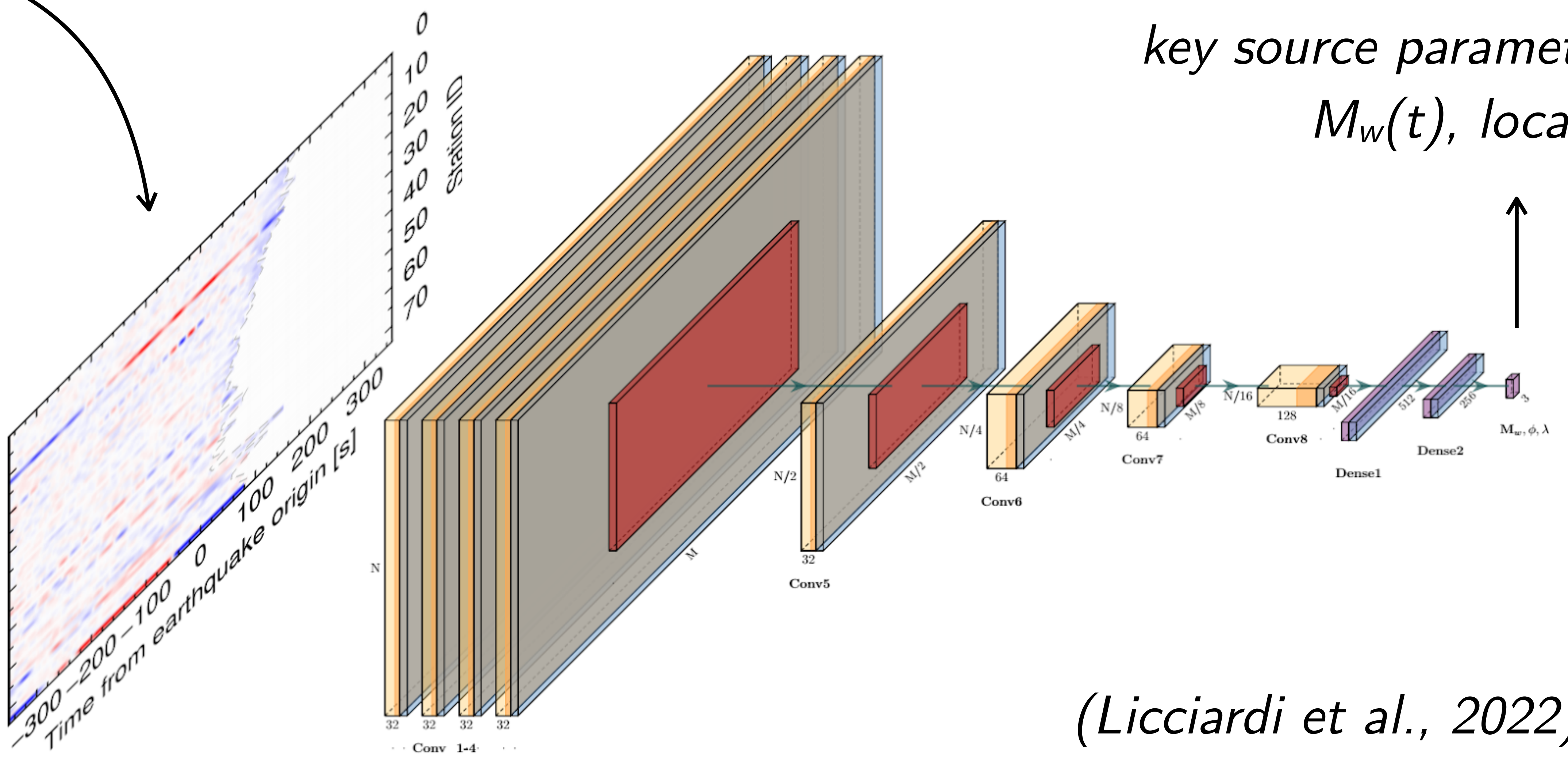


(Licciardi et al., 2022)

Experimental setup and input data examples from the synthetic database

input: synthetic data + empirical noise

key source parameters: $M_w(t)$, location

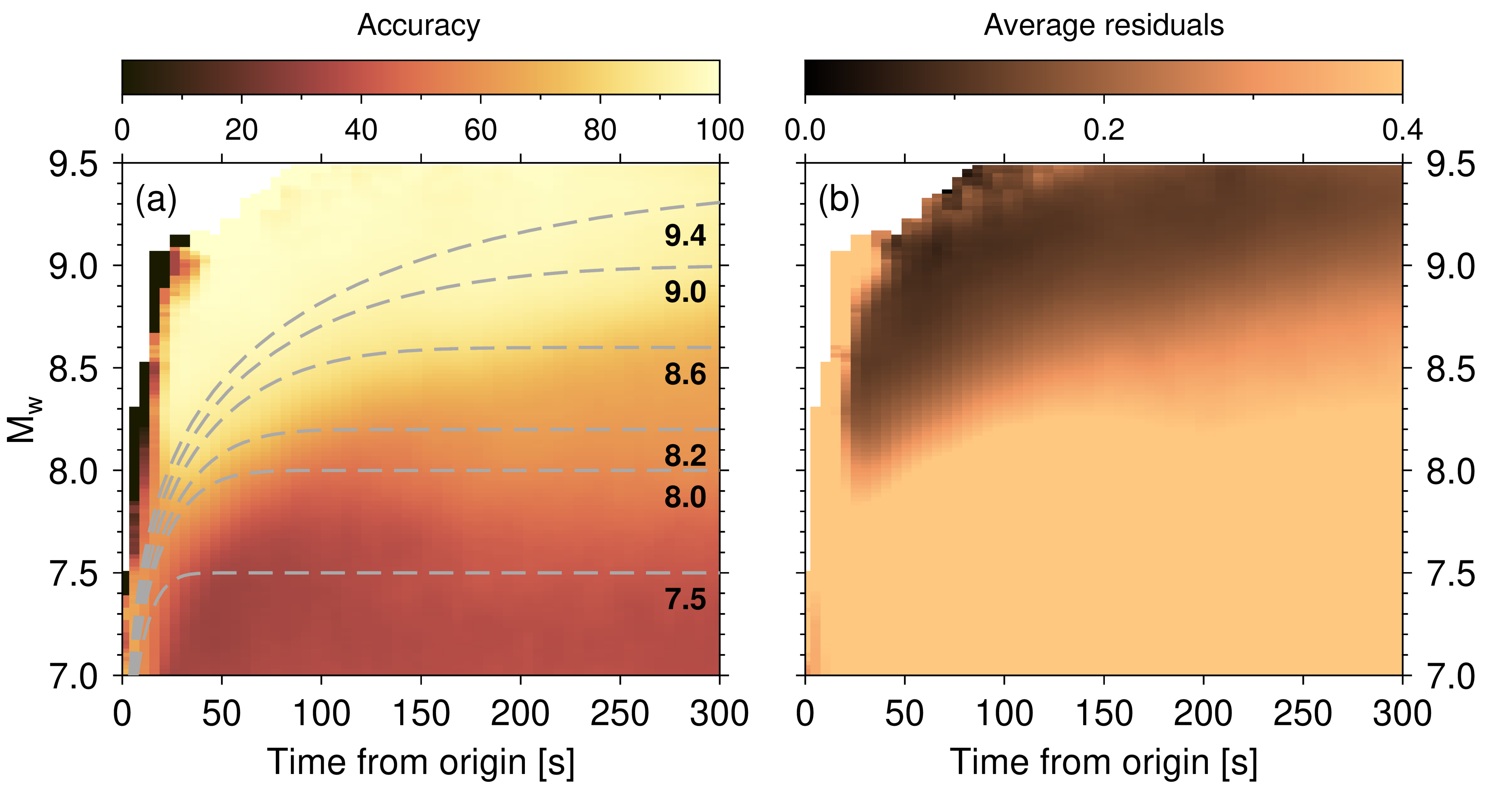


(Licciardi et al., 2022)

PEGSNet: a deep convolutional neural network (CNN) that combines convolutional layers and dense layers in sequence

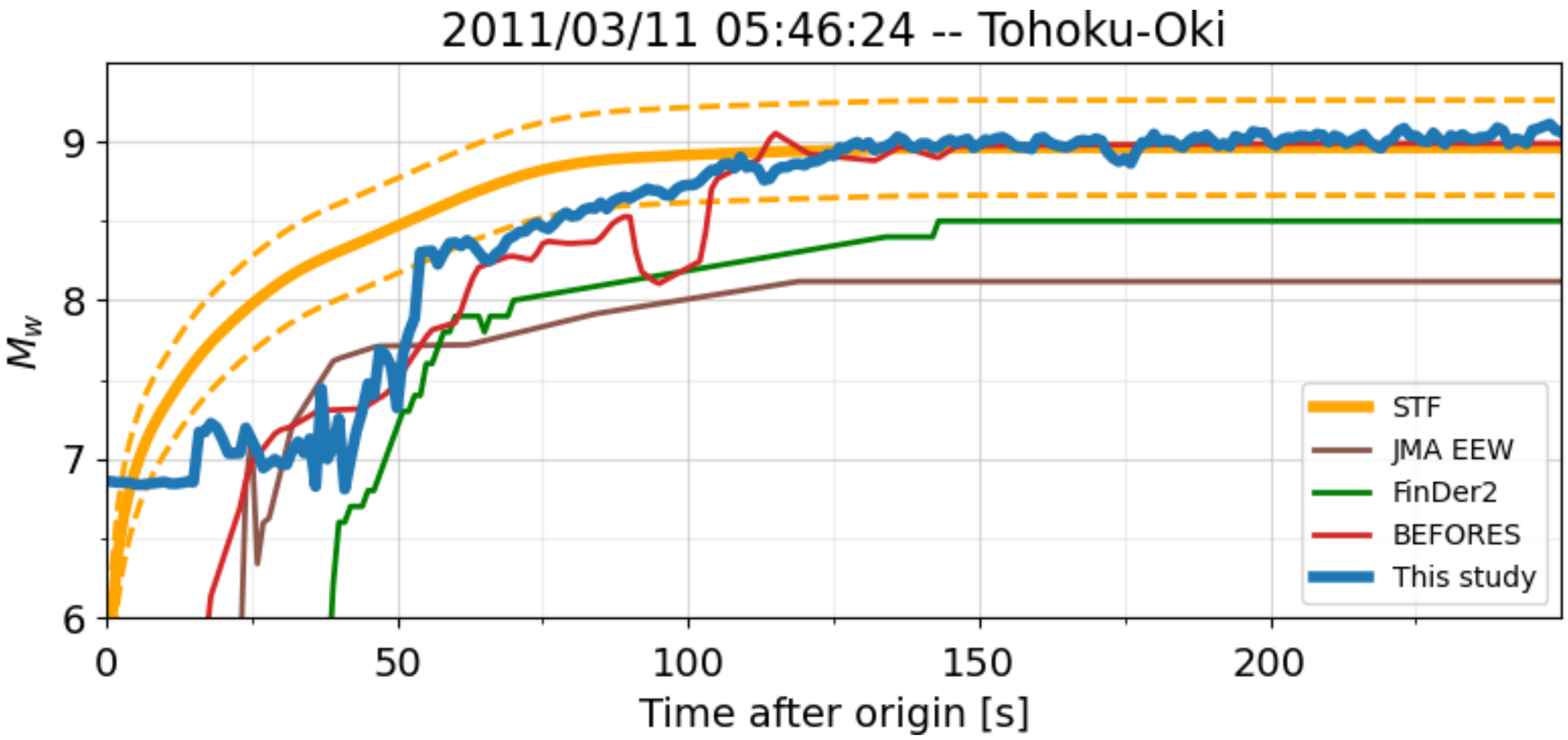
Results on test set : predictions accuracy

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

Real data : the 2011 M_w 9.1 Tohoku earthquake



(Licciardi et al., 2022)

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

Conclusions

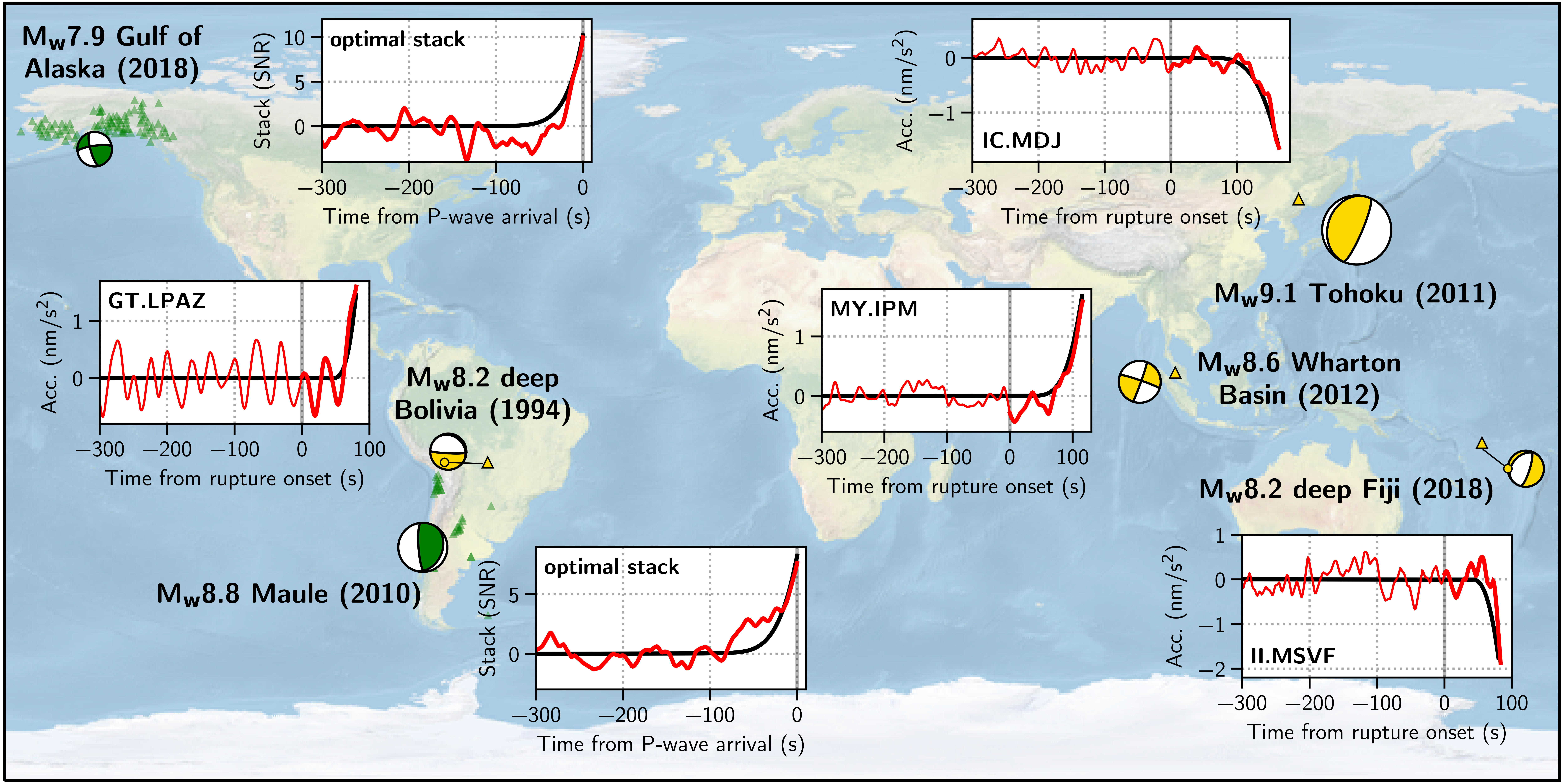
Conclusions

- Unambiguous PEGS observations from earthquakes in the M_w [7.9 - 9.1] range, in different tectonic settings.
- Detection enabled by the global deployment of very broadband sensors (single-station or array-based observations, depending on the observation conditions).
- Due to its sensitivity to key source parameters, PEGS can be a powerful tool for large earthquake monitoring, and can be combined with other observables (seismic, GNSS) to increase performance in real time.
- Using deep learning : instantaneous tracking of moment release (no saturation, zero time delay).

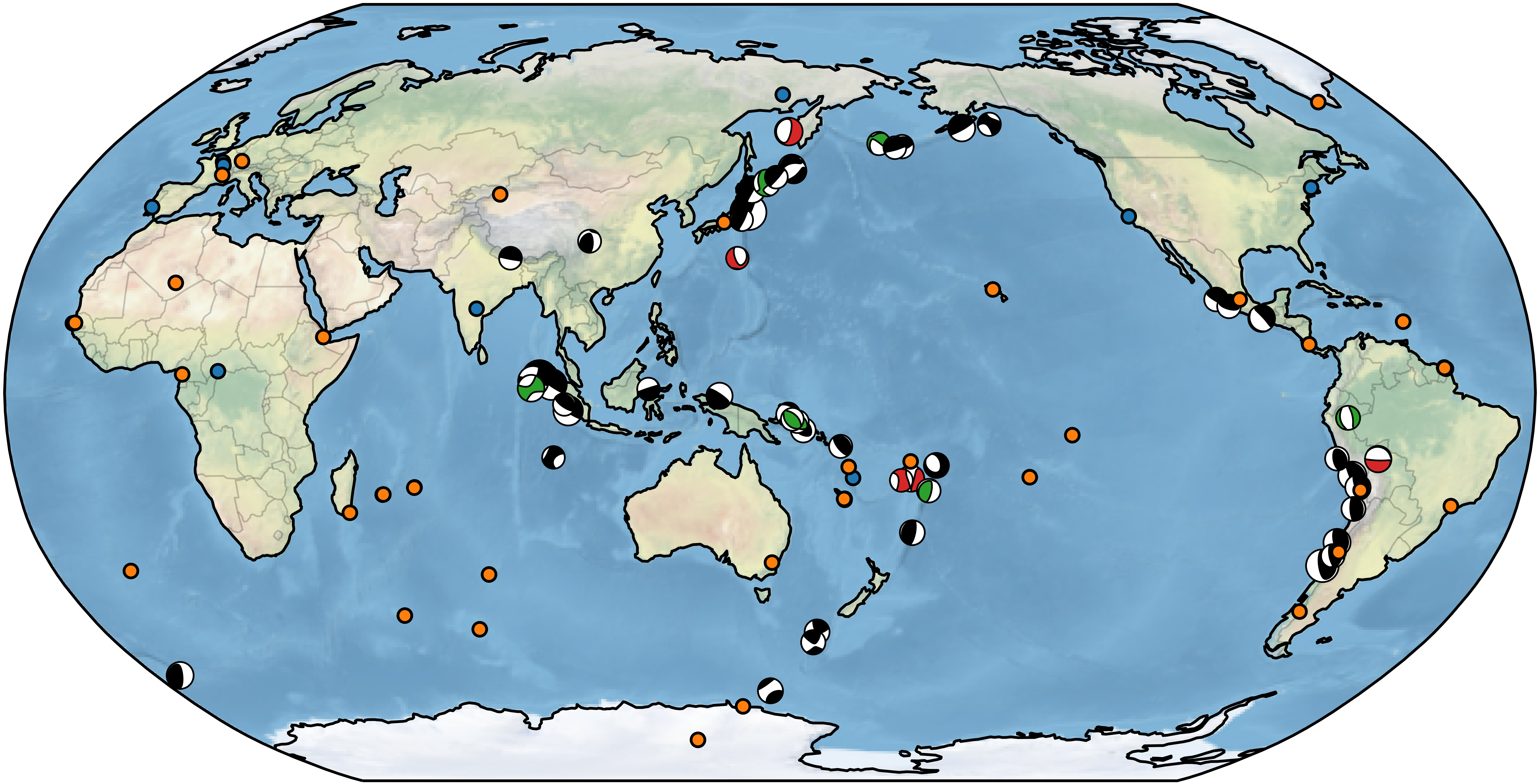
Thank you

PEGS observations

PEGS observations so far



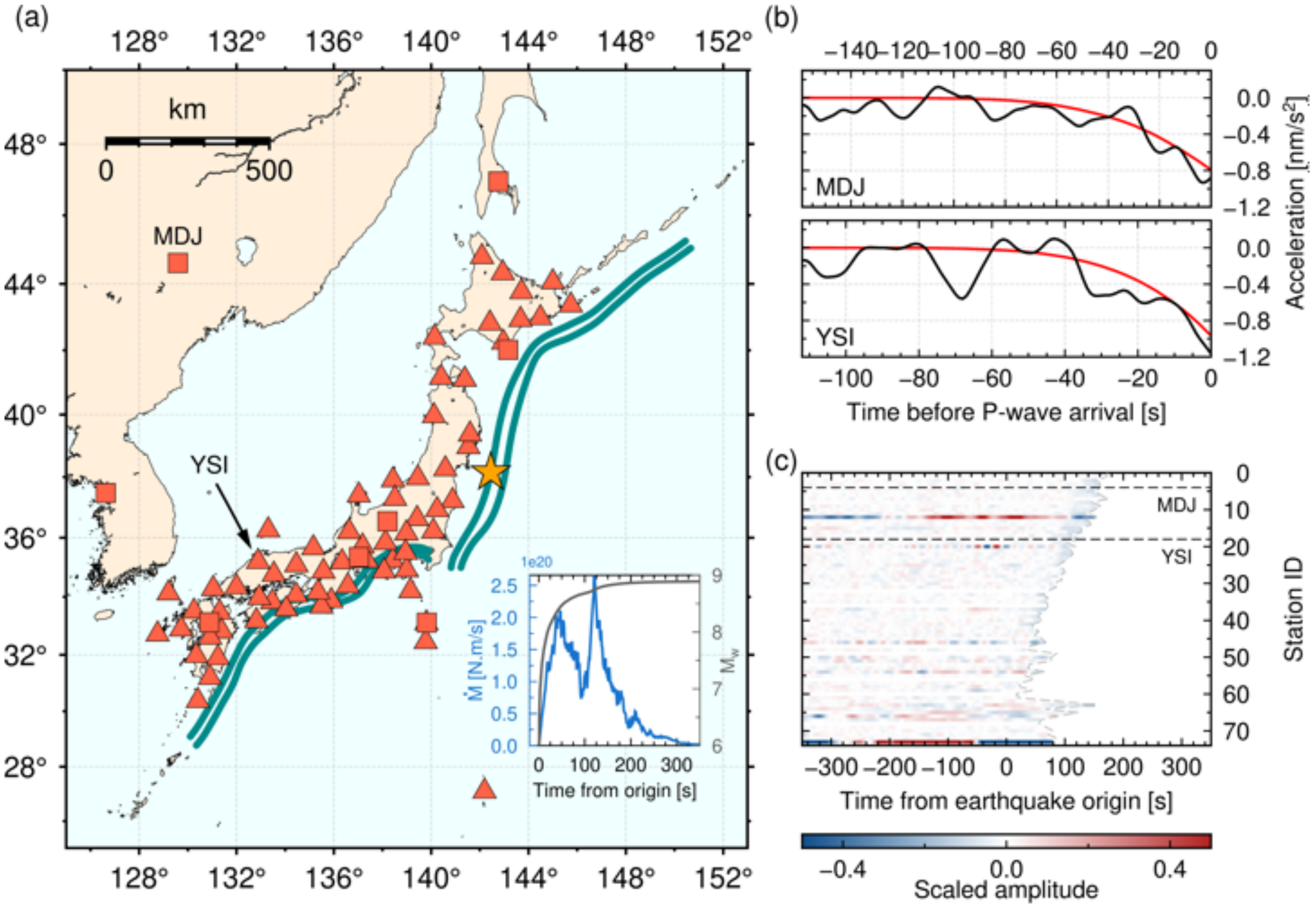
Candidates for PEGS observations



PEGSNet

PEGSNet : the training database

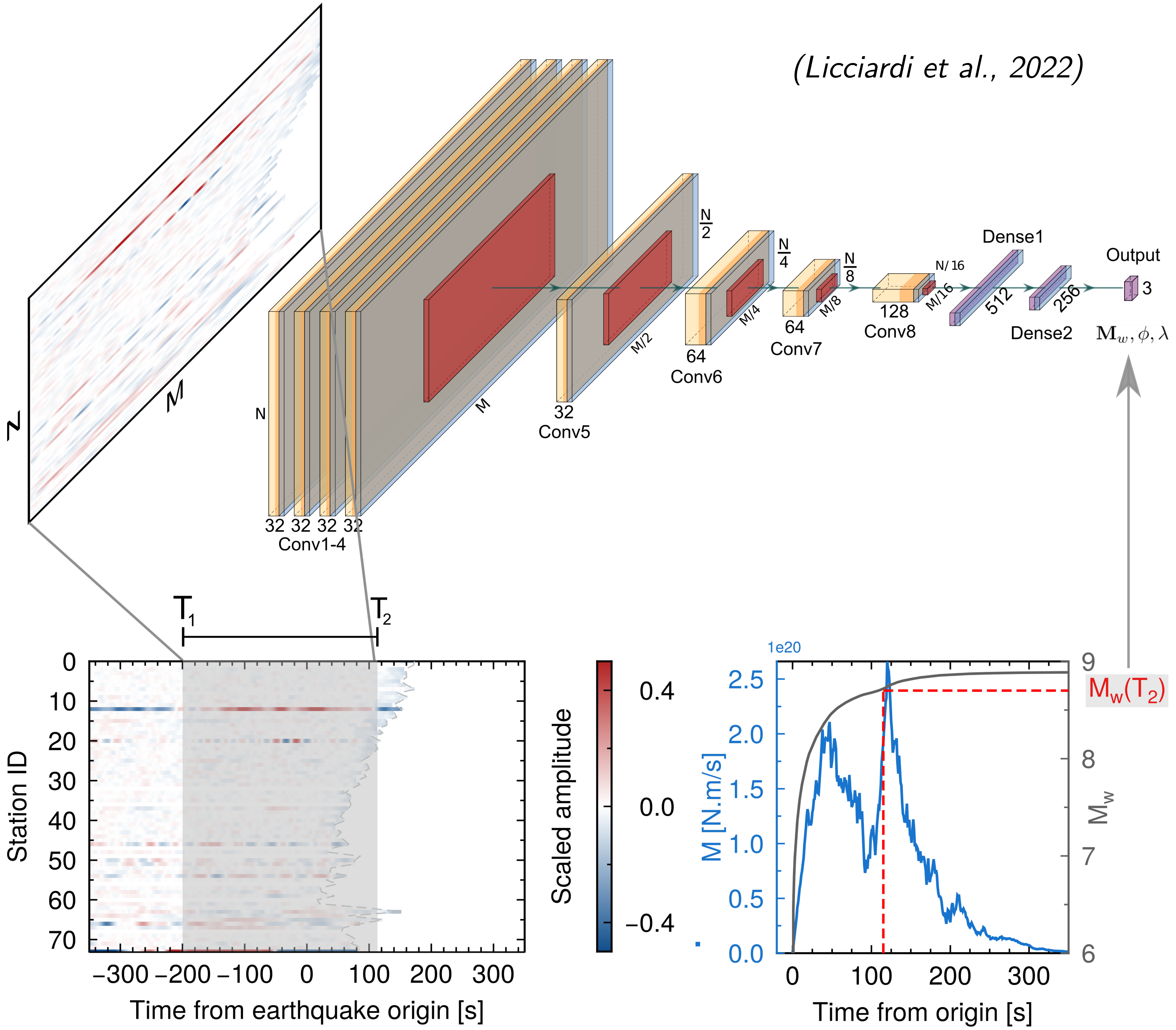
Few real observations of PEGS are available : *training must rely on synthetic data.*



(Licciardi et al., 2022)

- 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

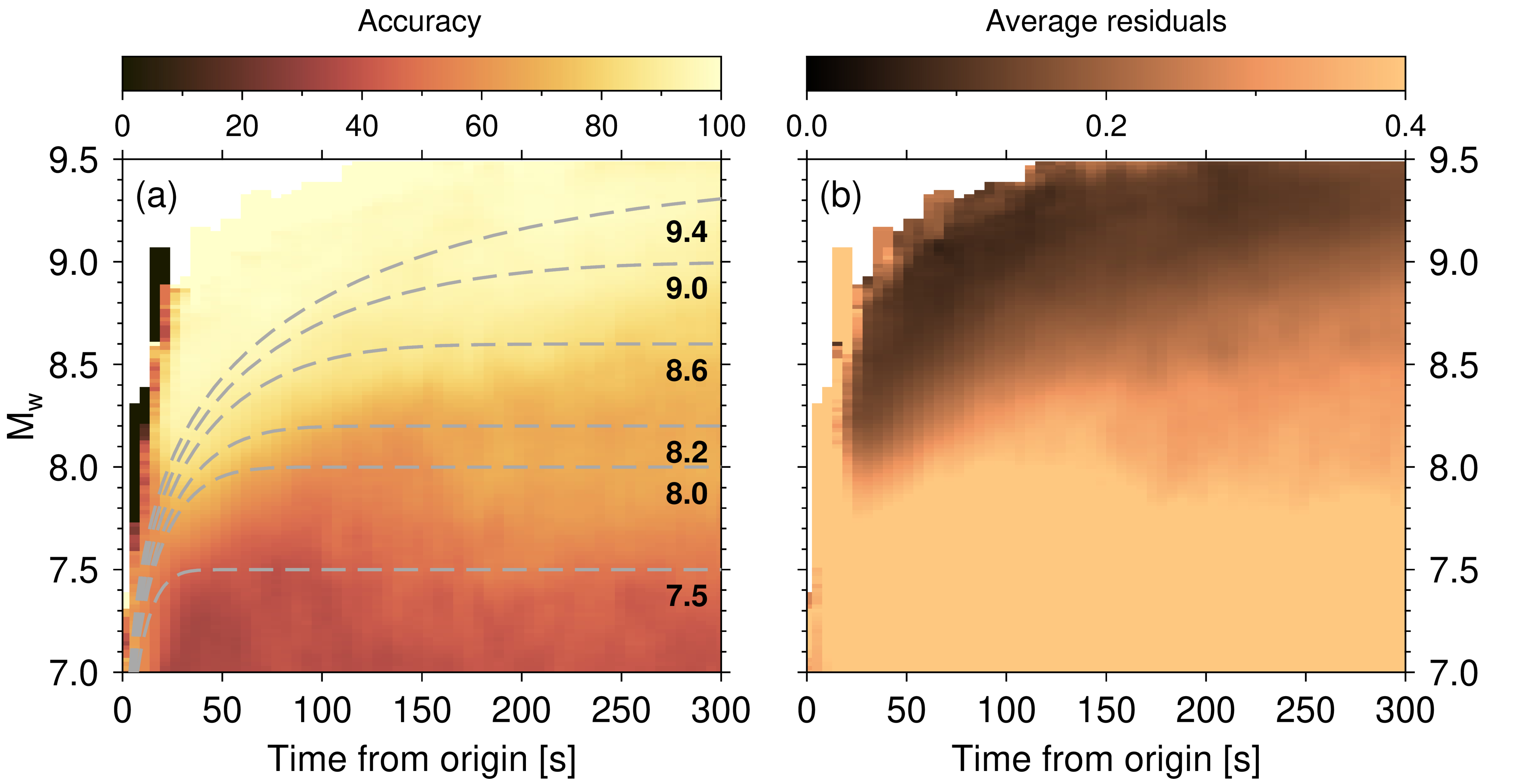
PEGSNet : architecture and learning strategy



- 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 : low noise conditions (0.5 nm/s^2)

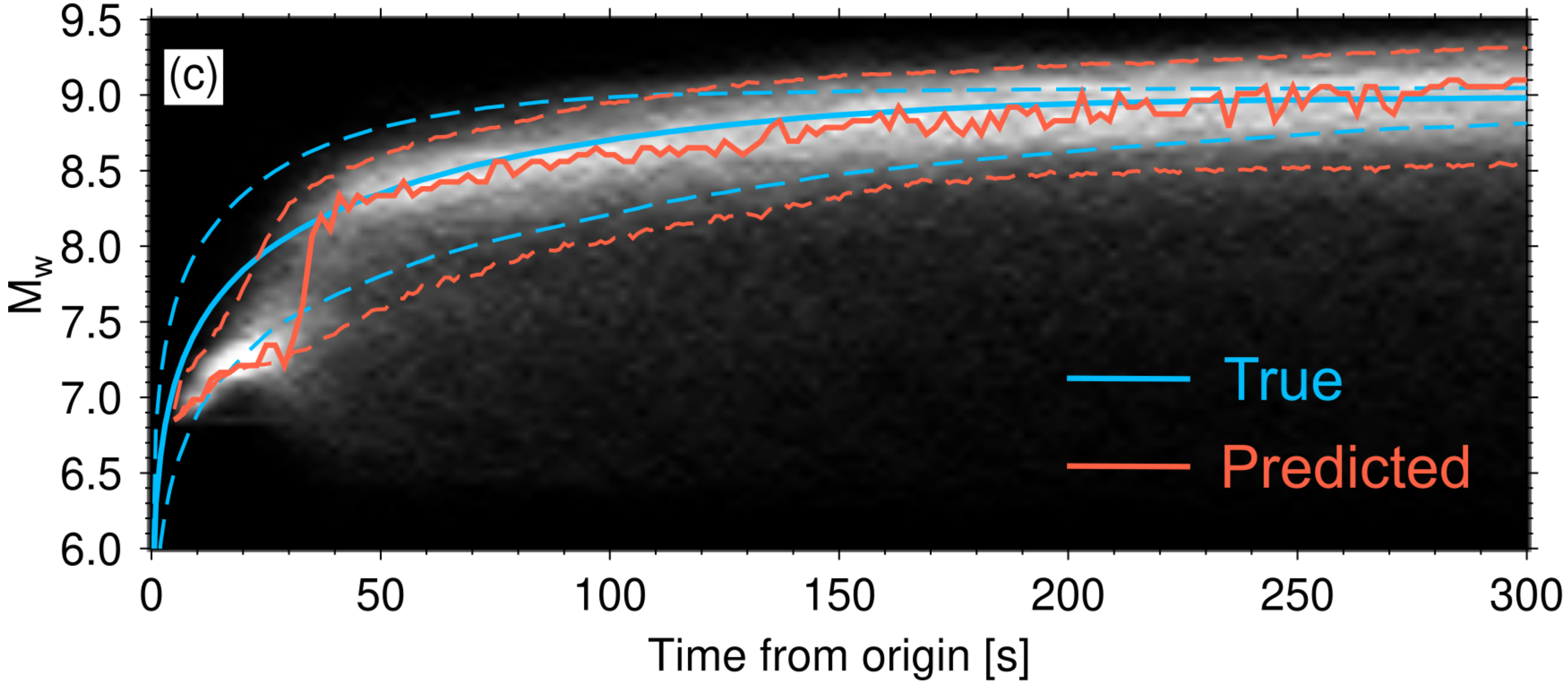
Successful prediction if the estimated $M_w(t)$ lies within $\pm$ 0.4 magnitude units from the ground truth value.



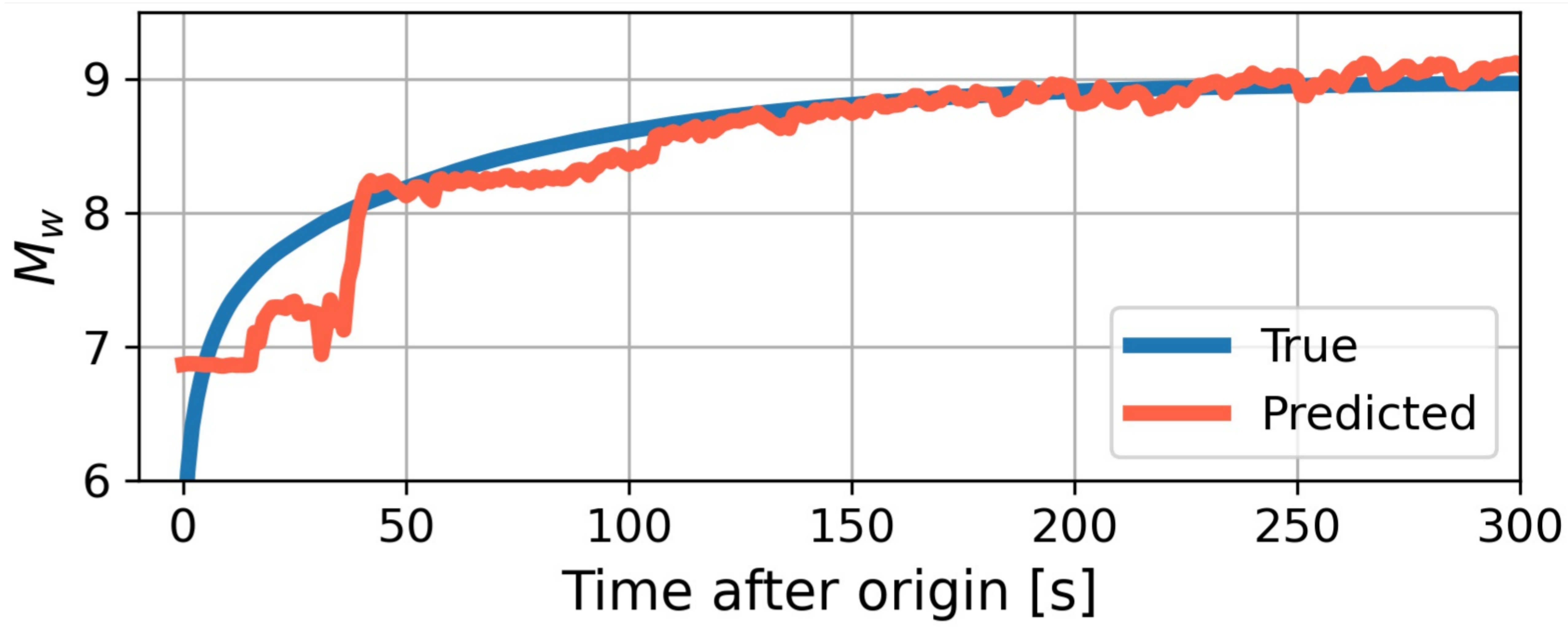
- Under favorable noise conditions : $\sigma_{noise} < 0.5$ nm/s^2
- **$7.9 < M_w < 8.3$** : final M_w prediction with 70-80% accuracy, 150 seconds from origin time.

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

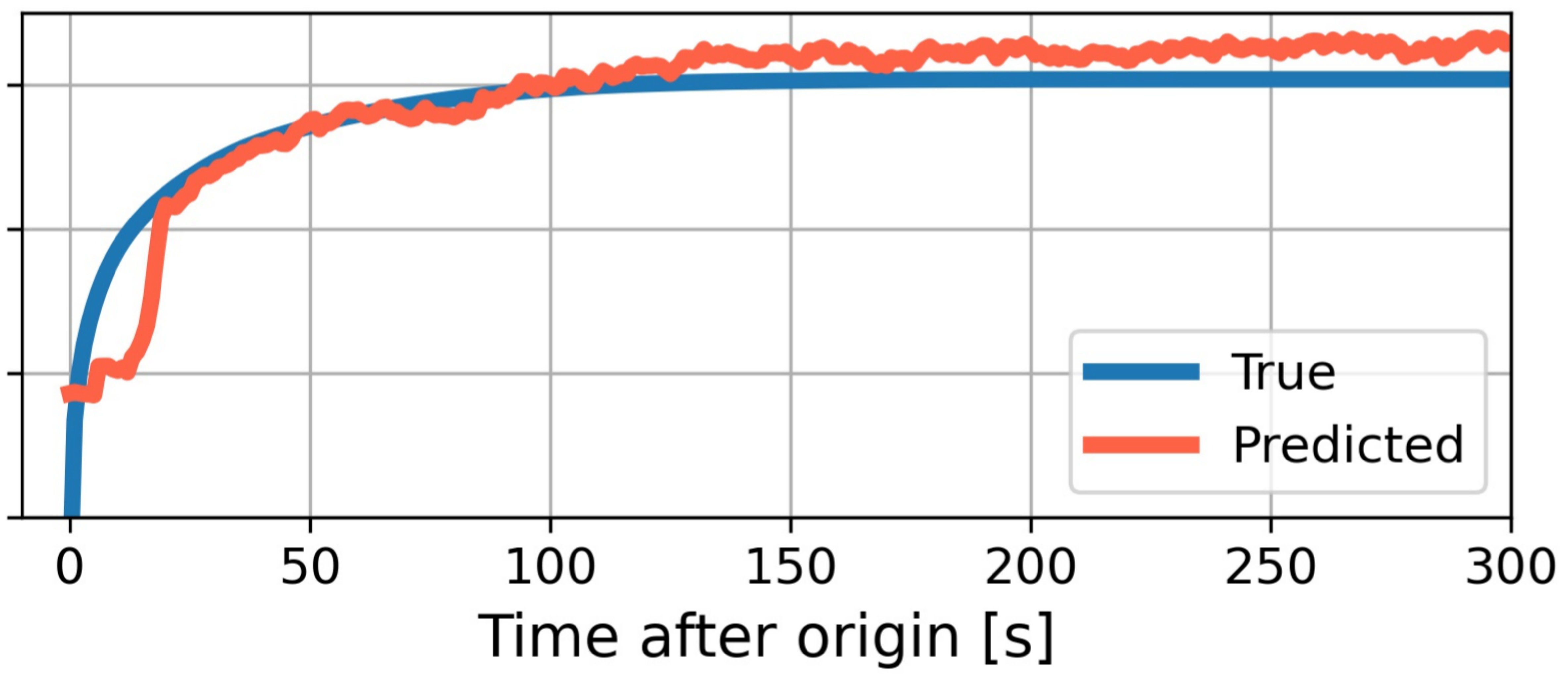
- Magnitude $M_w(t)$ estimation with zero delay once $M_w > 8.3$
- Ability to recover the actual moment release sooner or later, depending on the source onset



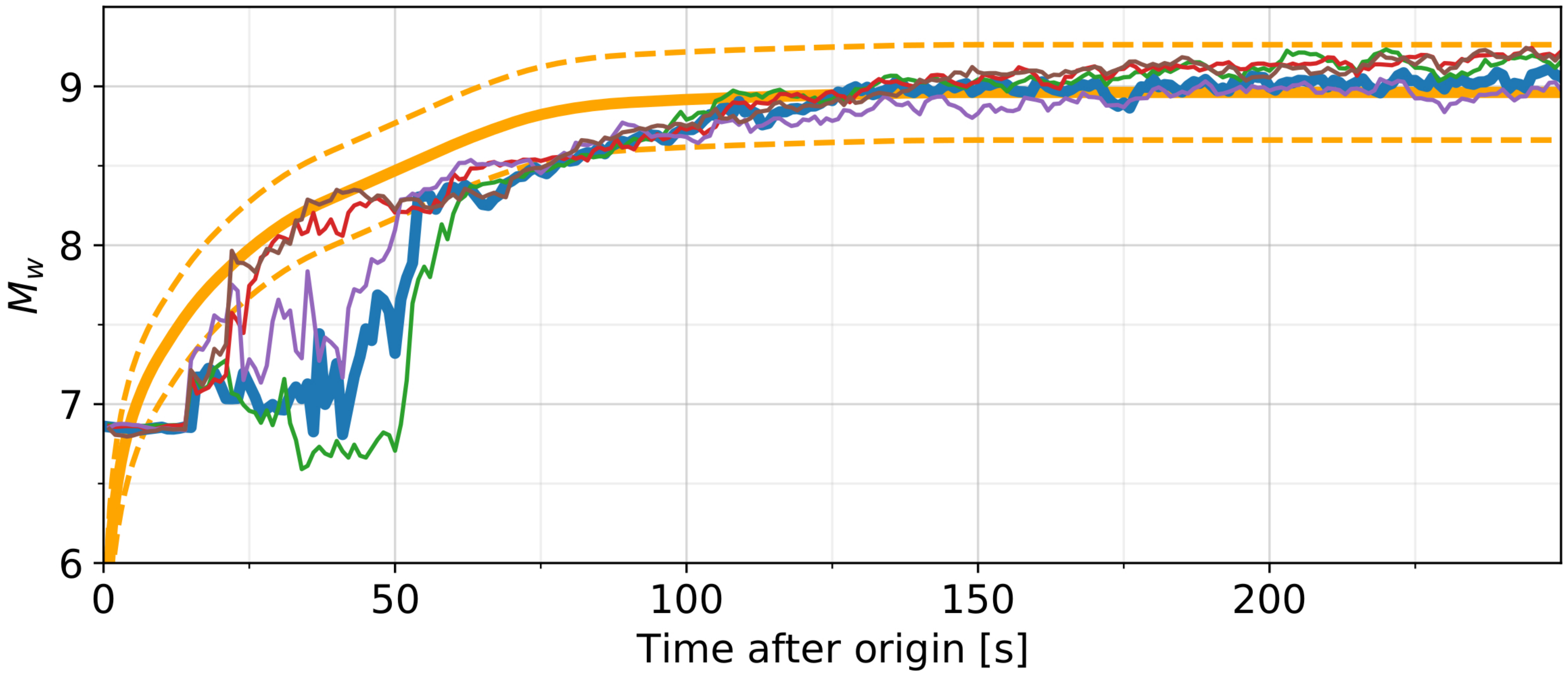
Slow onset



Fast onset

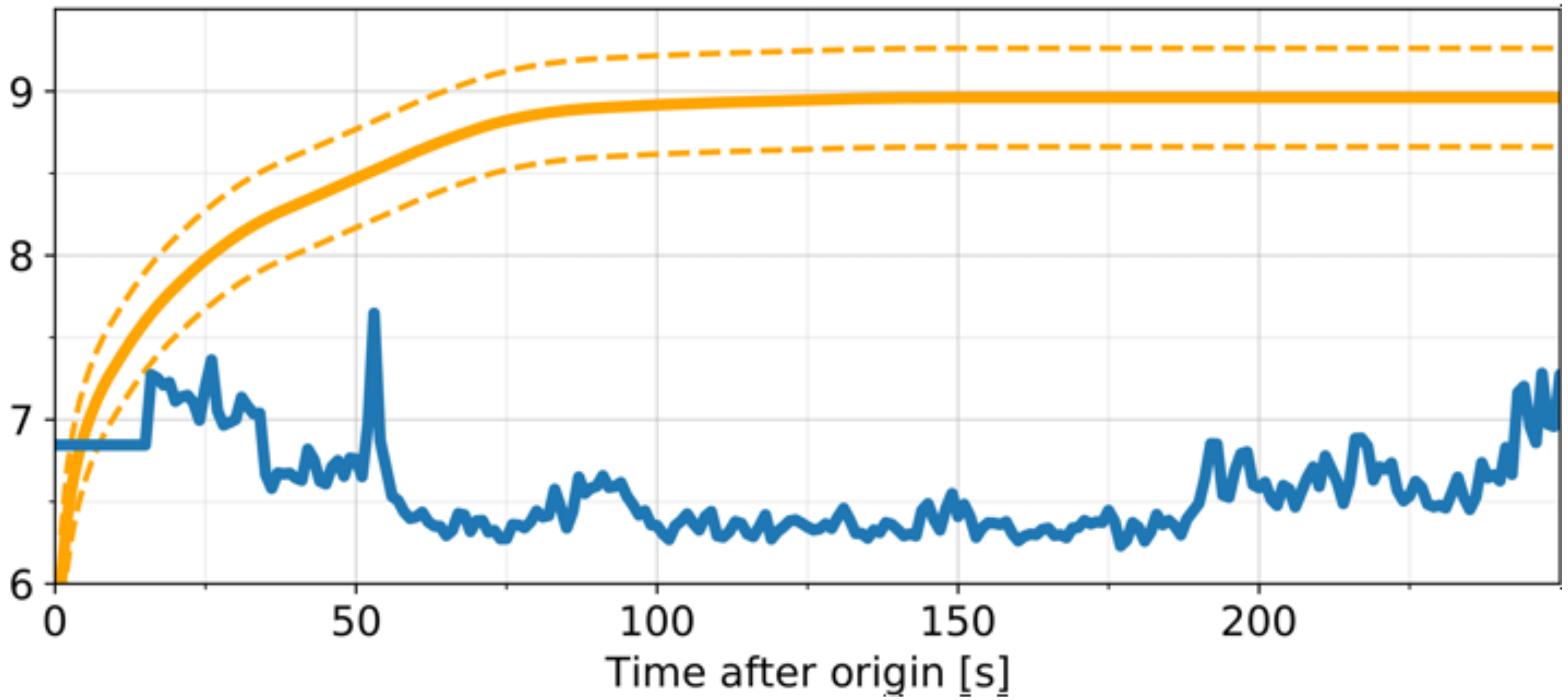


Dealing with noise



<u>Synthetic PEGS + noise from different pre-event recordings</u>

- 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



<u>Pre-event noise only, no PEGS</u>

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

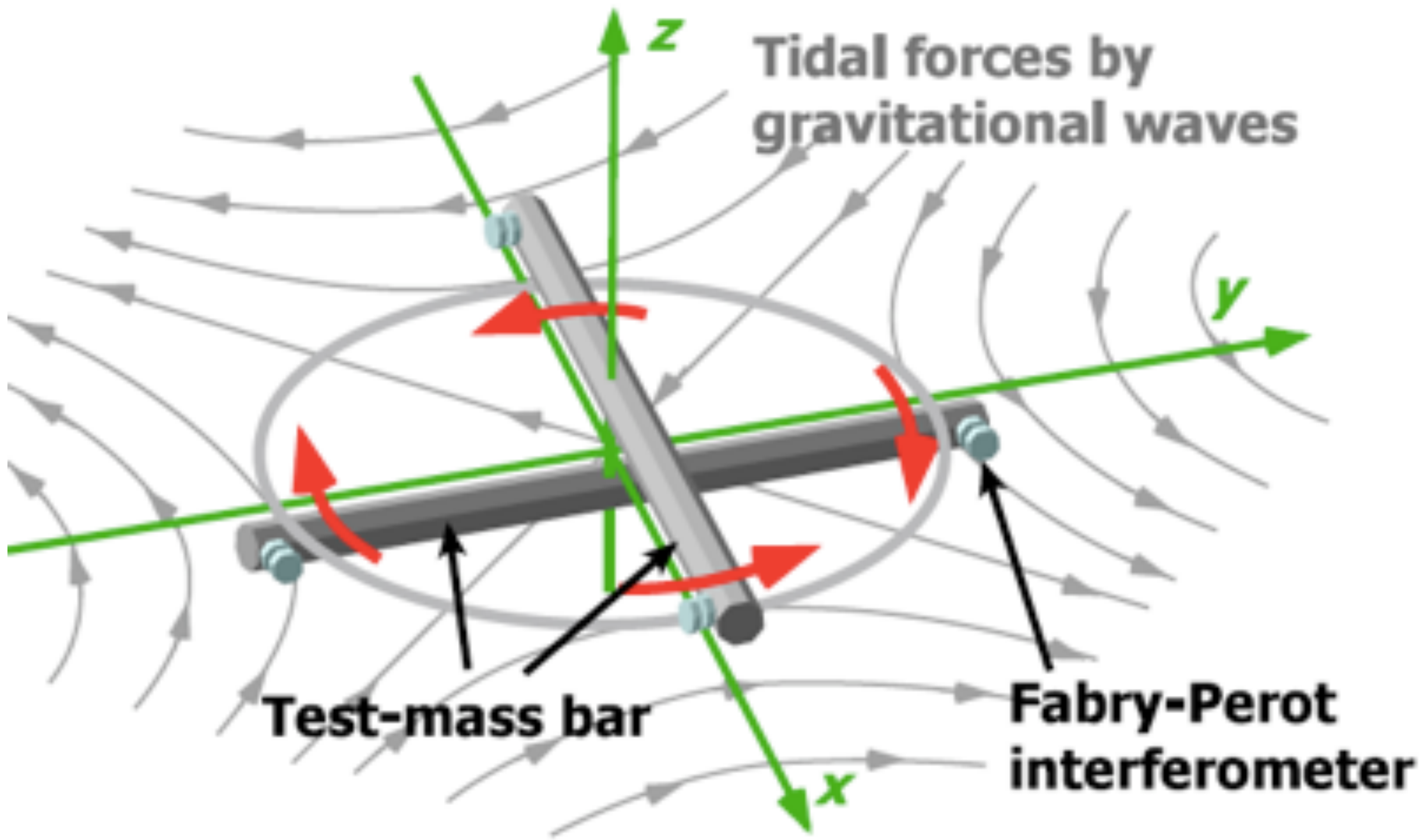
Improving monitoring capabilities: in the future

How can we improve earthquake monitoring capabilities ?

With **gravity strainmeters** :

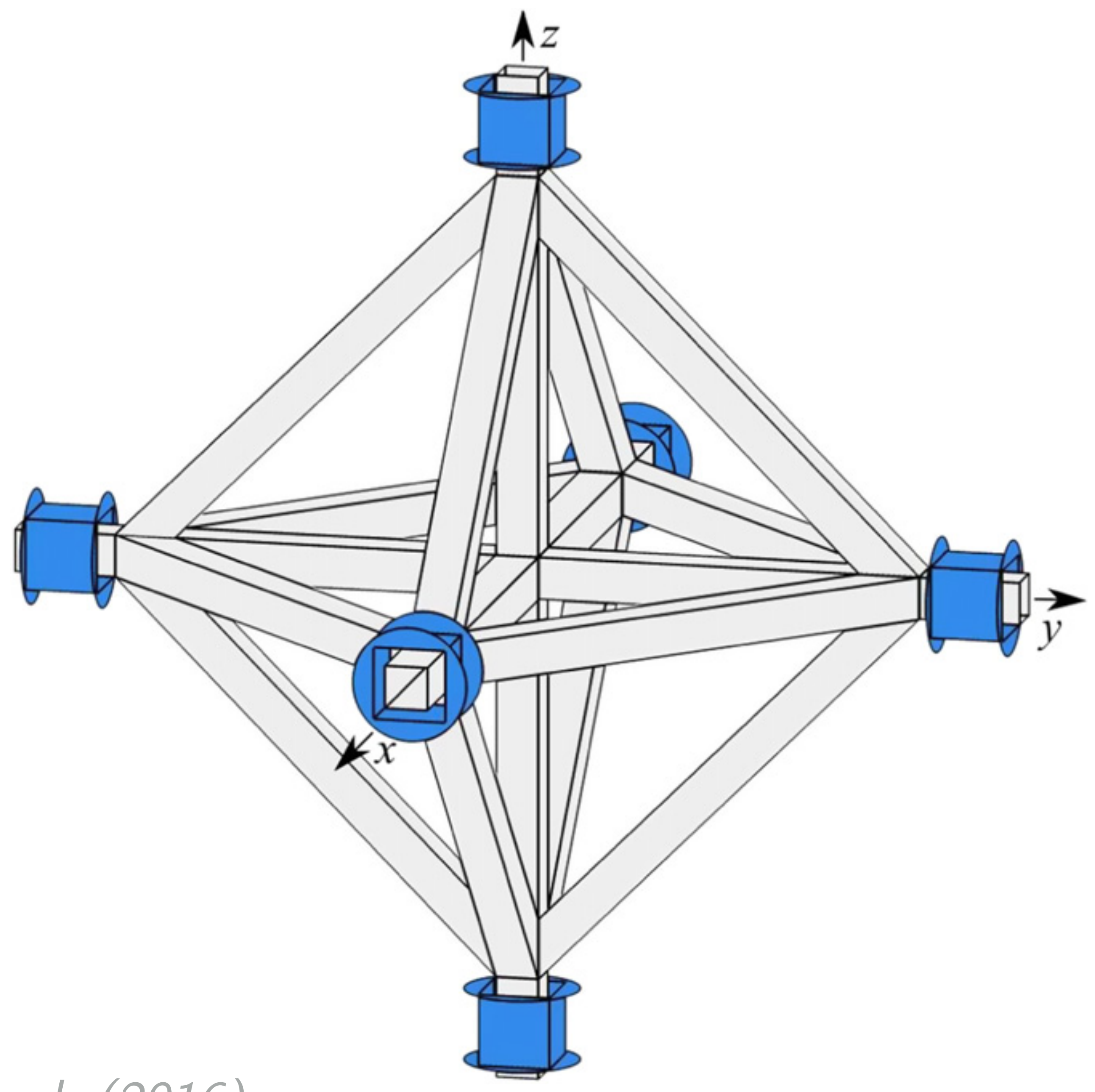
- under development :
  - torsion bars
  - gravity gradiometers
- initial goal : detection of Gravitational Waves at $f < 1$ Hz
- prototypes at target sensitivity in a few years

Torsion bar : relative rotation



from http://www.gw-indigo.org

Gradiometer : relative displacement

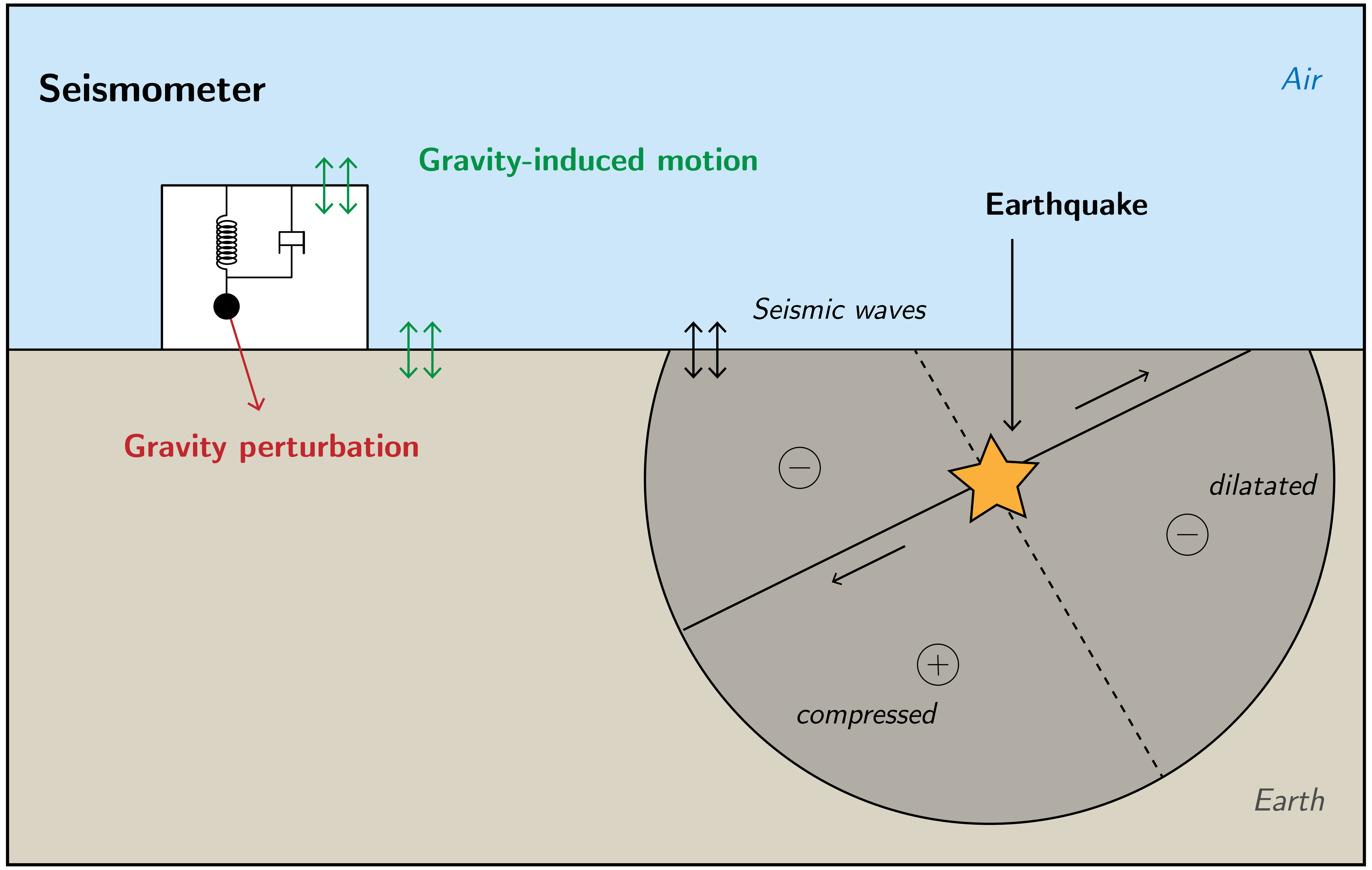


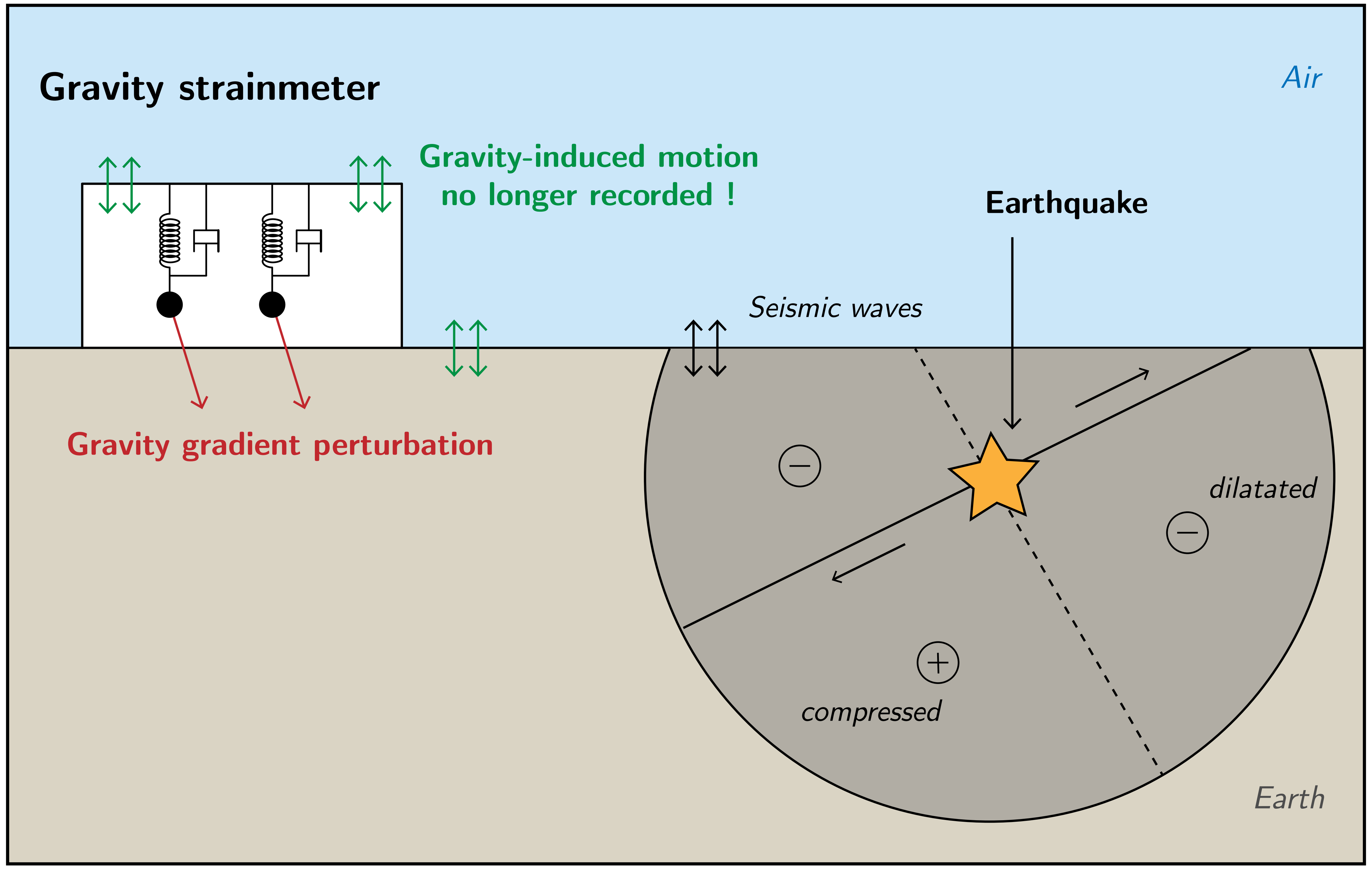
from Paik et al. (2016)

Early response of a seismometer *vs.* a gravity strainmeter

Now : PEGS

In the future : PGS





Gravitational acceleration : $\boldsymbol{a}(\boldsymbol{r},t) = \delta\boldsymbol{g}(\boldsymbol{r},t) - \ddot{\boldsymbol{u}}(\boldsymbol{r},t)$

Gravity strain : $\boldsymbol{h}(\boldsymbol{r},t) = \int_0^t \int_0^{\tau'} \boldsymbol{\nabla}\delta\boldsymbol{g}(\boldsymbol{r},\tau)\, d\tau d\tau'$

limitations :
- background seismic noise
- compensation between δg and ü

differential measurement :
- noise reduction
- ü no longer recorded