Catching the earliest gravity signals of earthquakes: state-of-the-art and instrumentation needs

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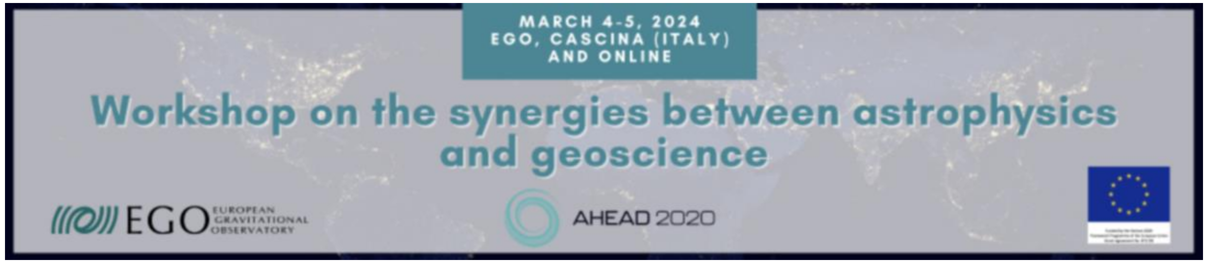
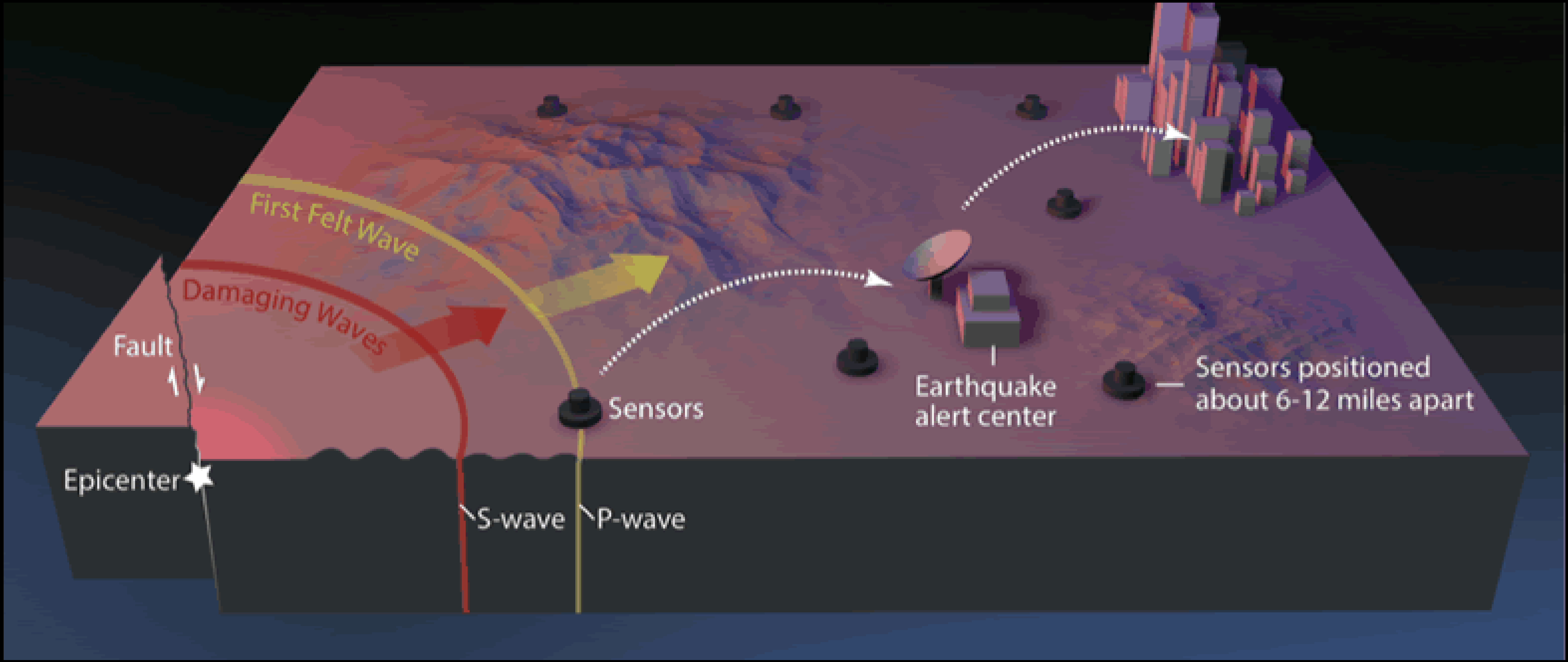


Overview

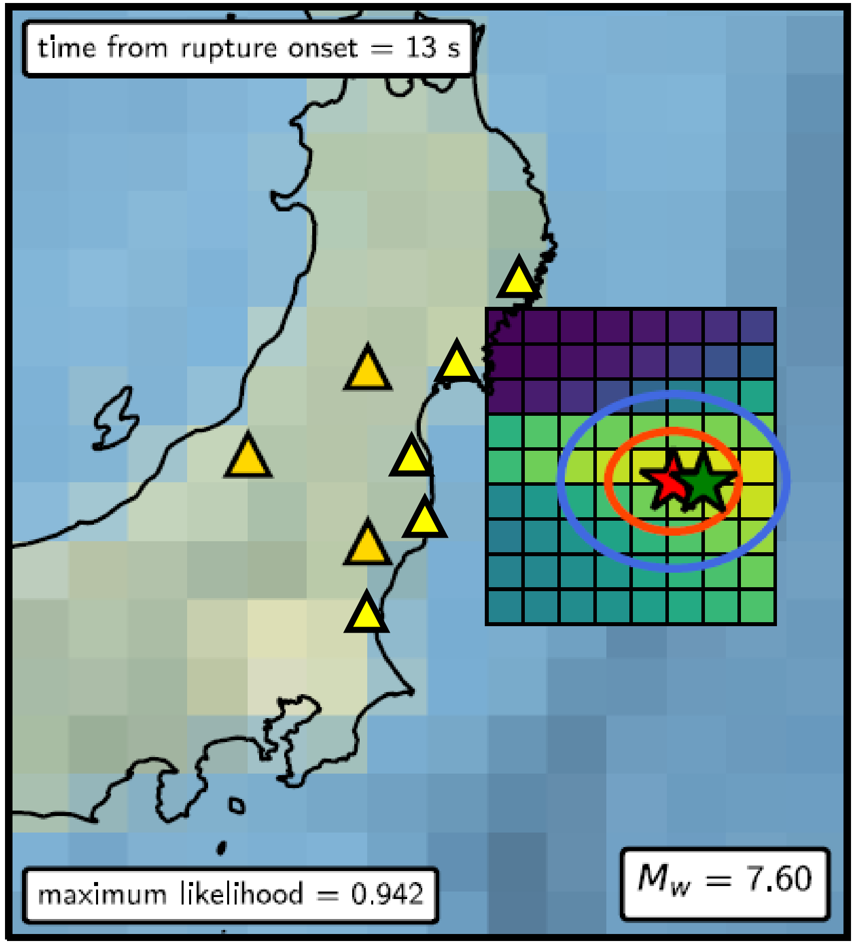
- **Motivation**: limitations of Earthquake Early Warning Systems
- **Theory** of transient gravity perturbations induced by earthquakes
- **Observation** of elasto-gravity signals generated by large earthquakes
- **Tsunami warning** based on elasto-gravity signals
- **Instrumentation needs** for earthquake warning with gravity signals

Earthquake Early Warning Systems



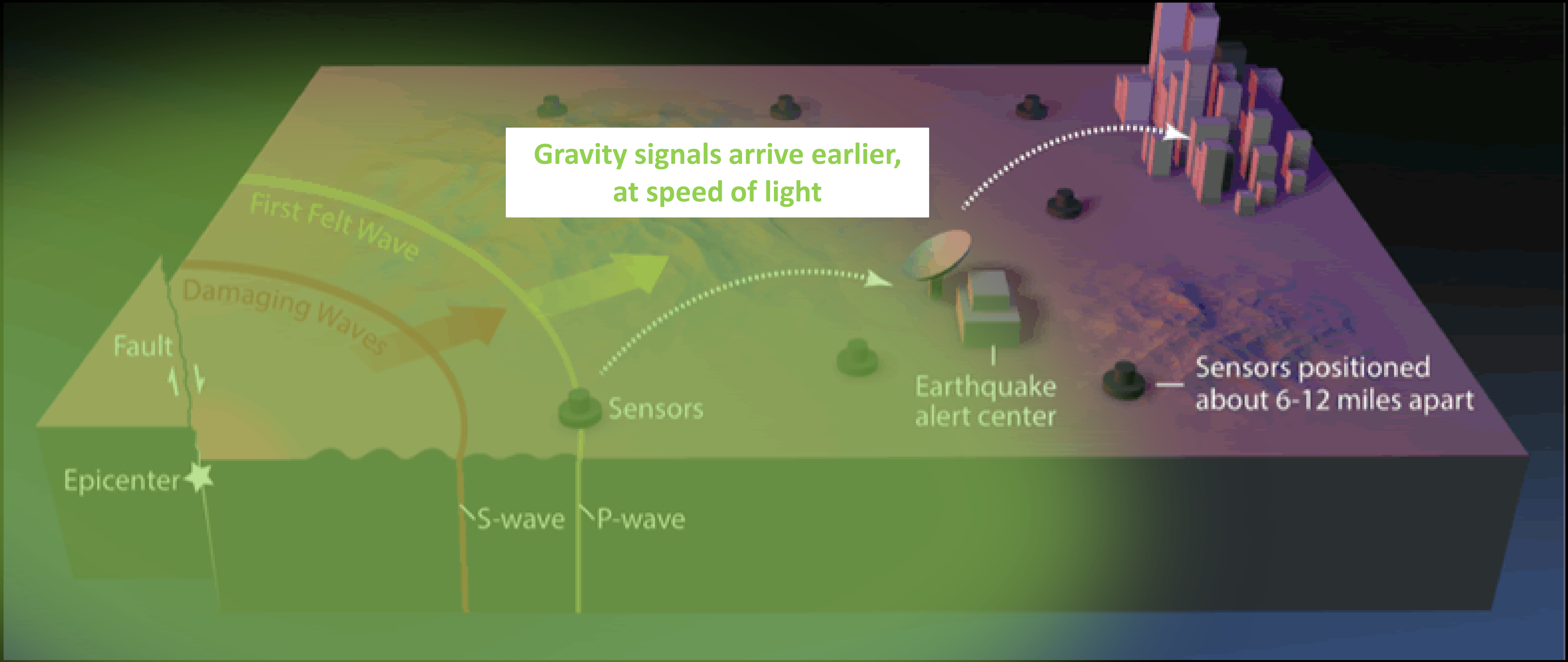
https://earthquake.usgs.gov/research/earlywarning

Off-shore earthquakes, inland sensors



Cost > $500,000,000

Earthquake Early Warning Systems



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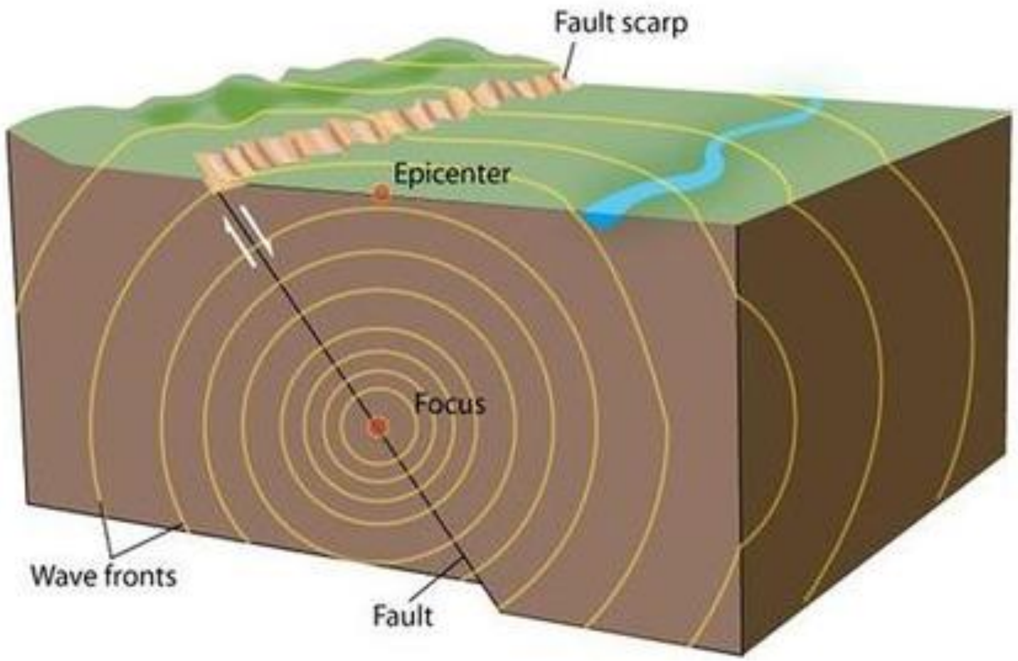
Earthquakes shift rock masses

Fault offsets and static deformation

https://temblor.net/

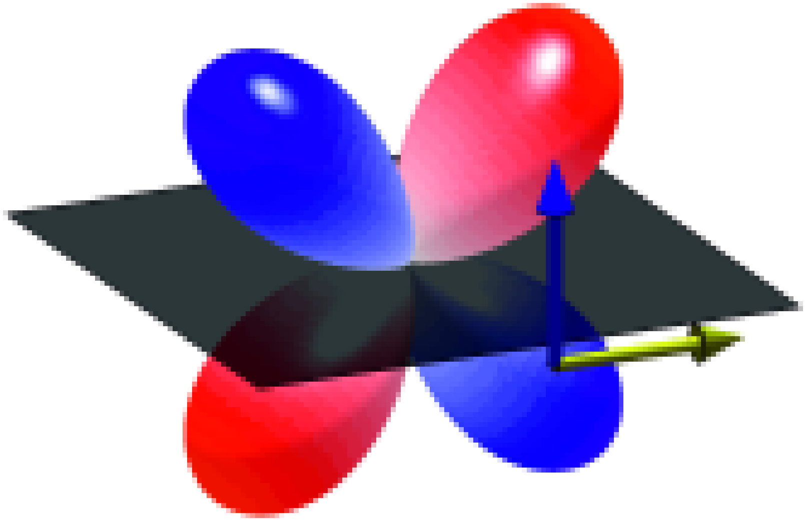
Wave mediated transient deformation



Density perturbations carried by P waves
+ deformation of material interfaces (e.g. free surface)

Dynamic gravity changes induced by earthquakes: theory (Harms et al, 2015)

A quadrupole gravity field



Gravity potential before the arrival of P waves:

$$\psi(\boldsymbol{r},t) = -\frac{3G}{r^3} R_p(\theta,\phi)\, I_2[M_0](t)$$

Distance decay

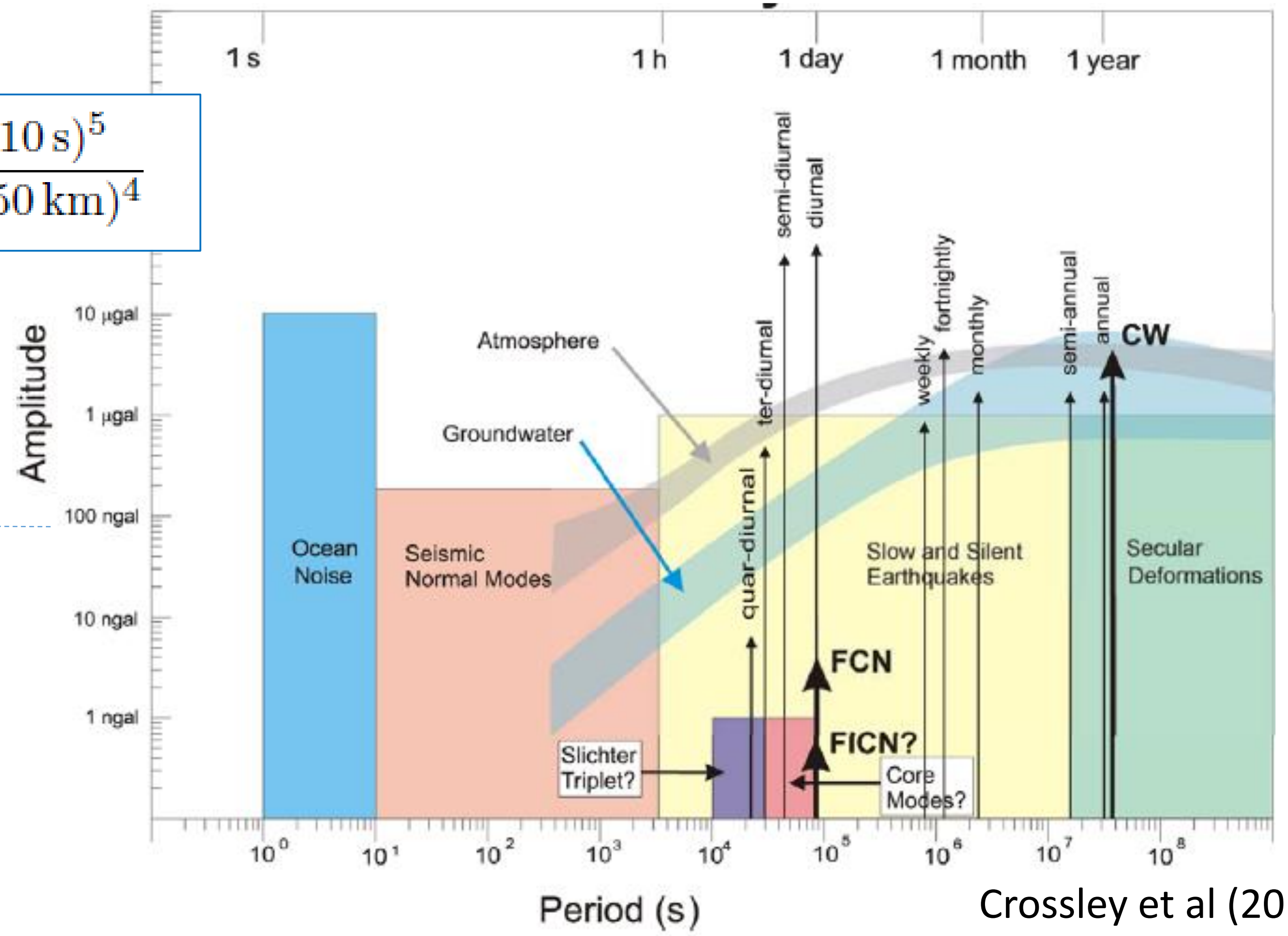
P-wave radiation pattern

Double time-integral of seismic moment

Spectrum of terrestrial gravity accelerations

$$\delta a = O(10^6)\frac{t^5}{r_0^4} \sim (1\mu\text{gal})\frac{(t/10\,\text{s})^5}{(r_0/50\,\text{km})^4}$$

$10^{-9}\ m/s^2$



Crossley et al (2013)

At 0.1-1 Hz the sensitivity of gravimeters and seismometers is limited by microseism (ocean) noise.

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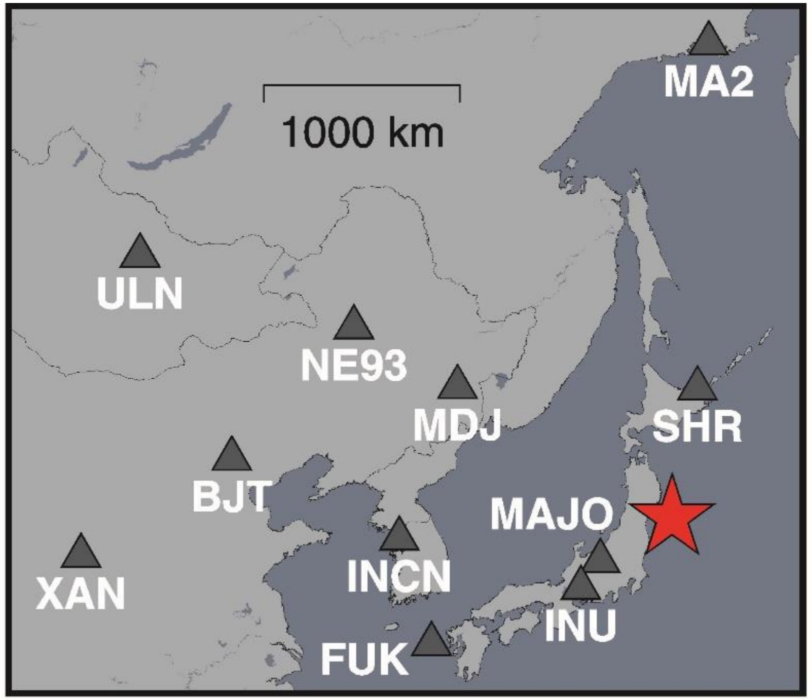
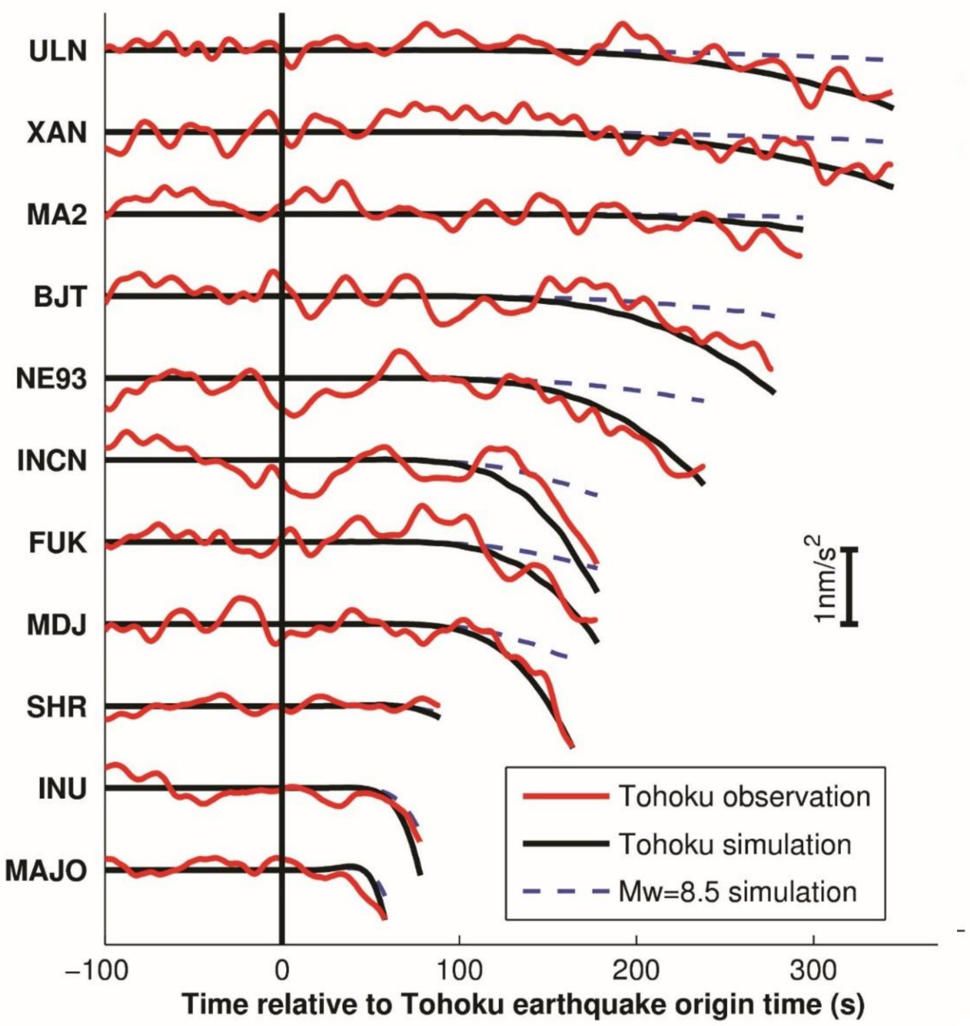
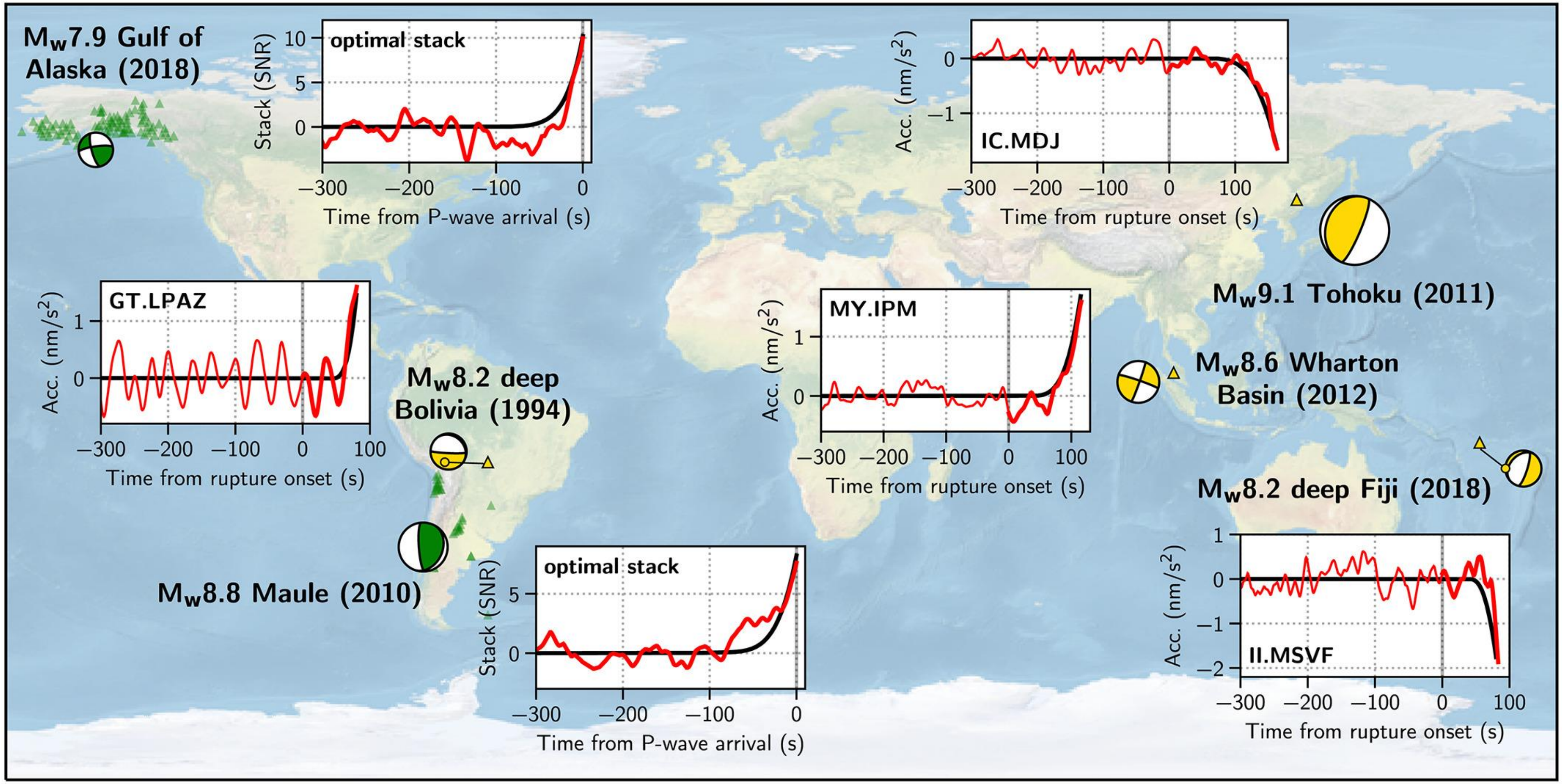
Discovery of prompt elasto-gravity signals (PEGS) of the 2011 Japan earthquake recorded by seismometers



Vallée et al. (Science, 2017)



Global observation of prompt elasto-gravity signals (PEGS)



Vallée and Juhel (2019)

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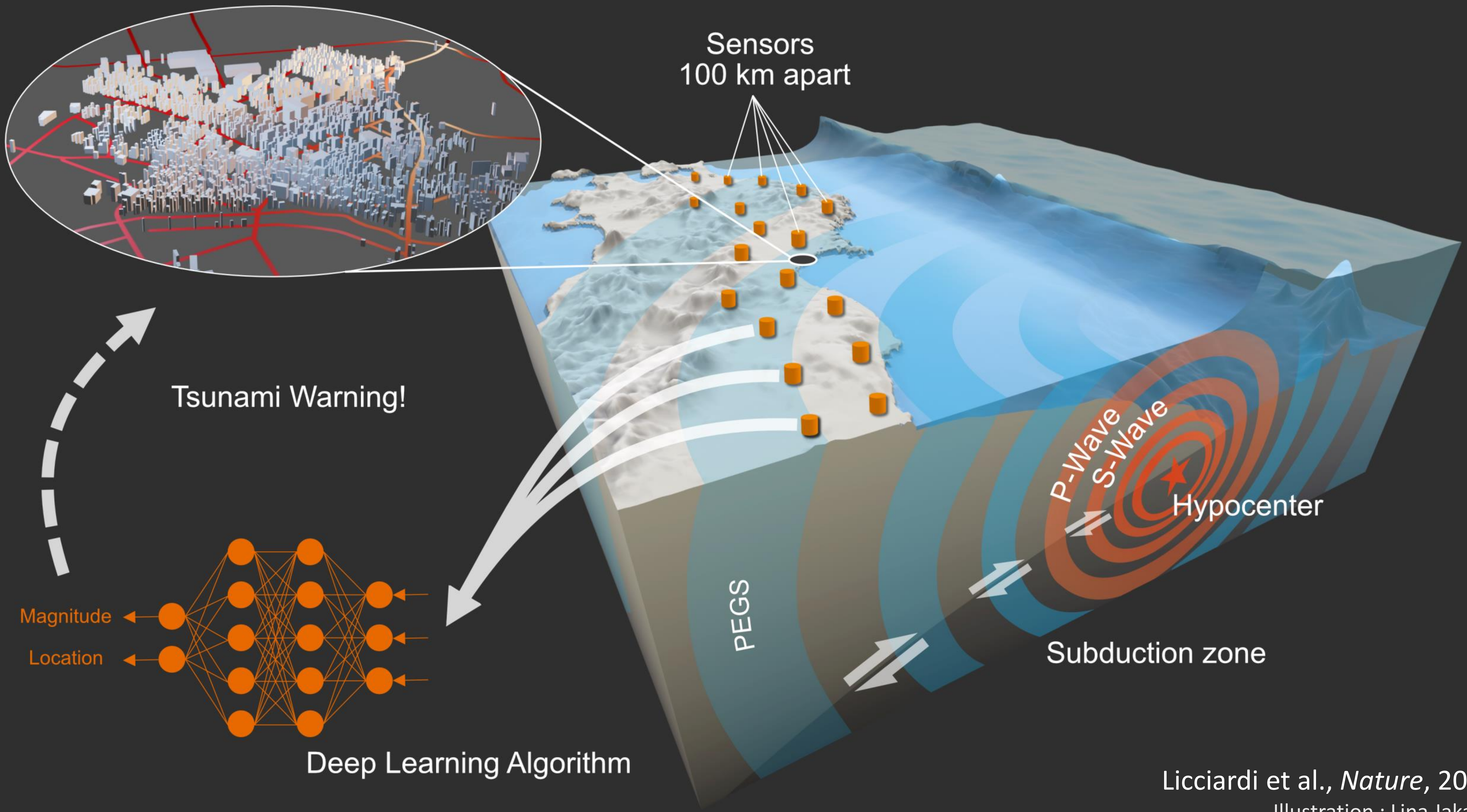
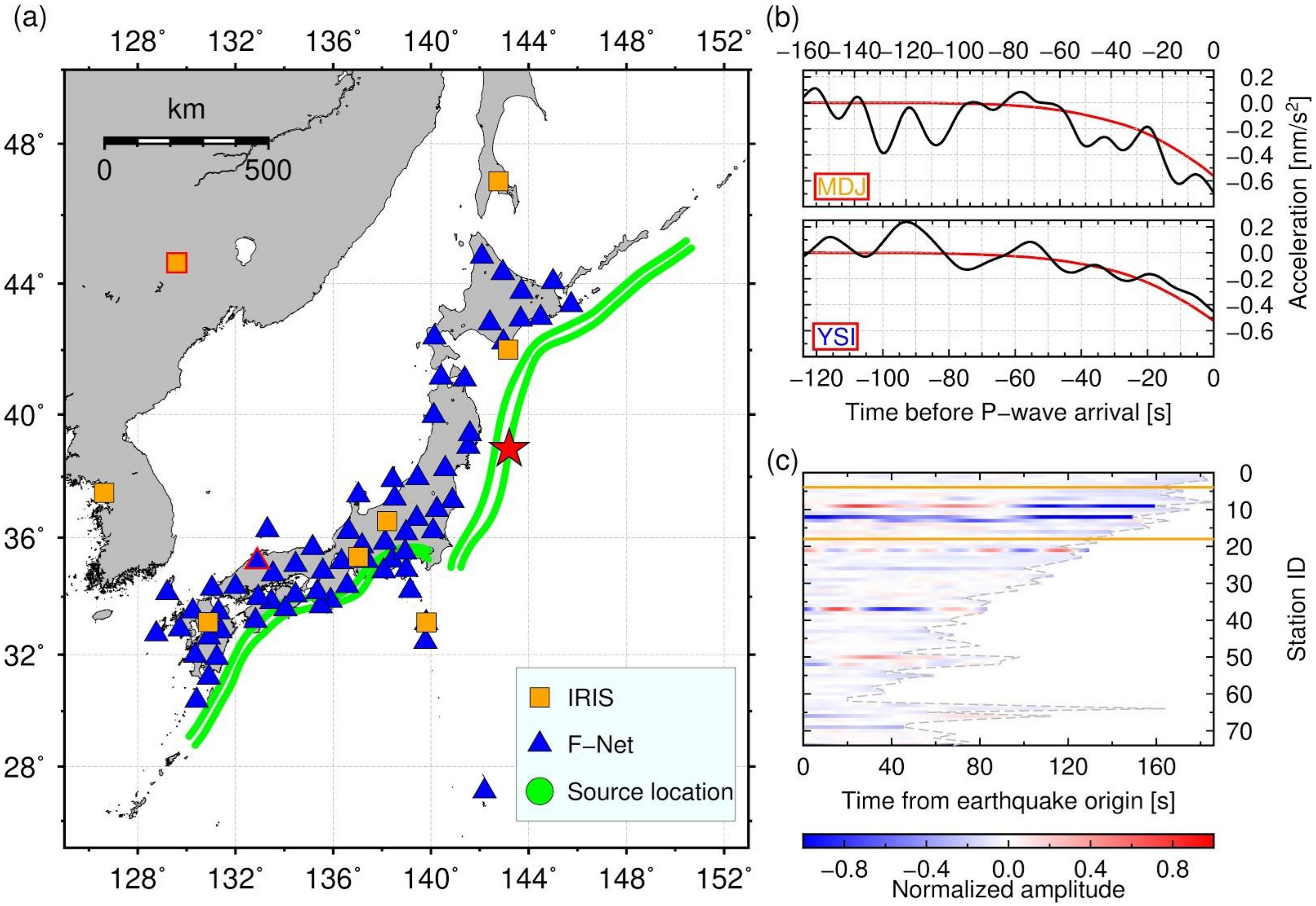


Licciardi et al., *Nature*, 2022

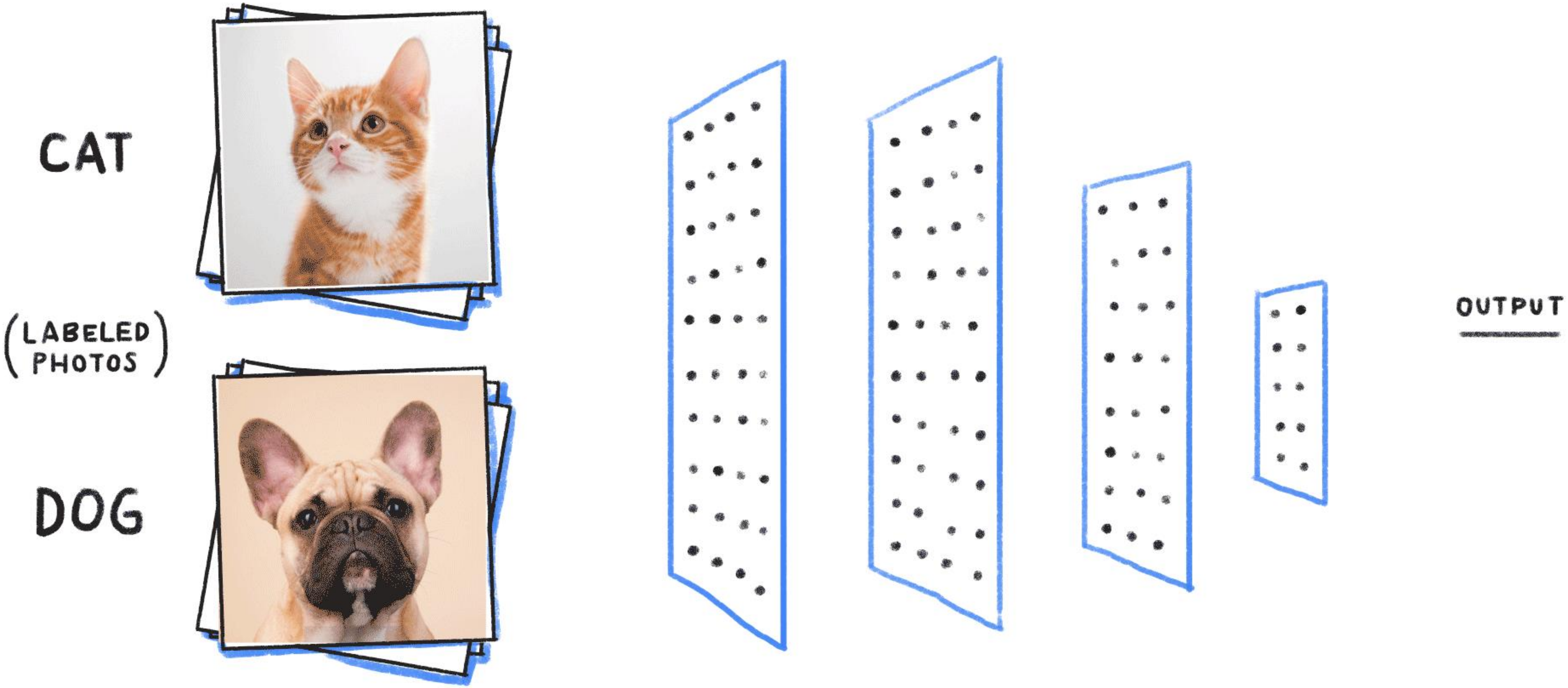
Illustration : Lina Jakaite

Synthetic database of PEGS

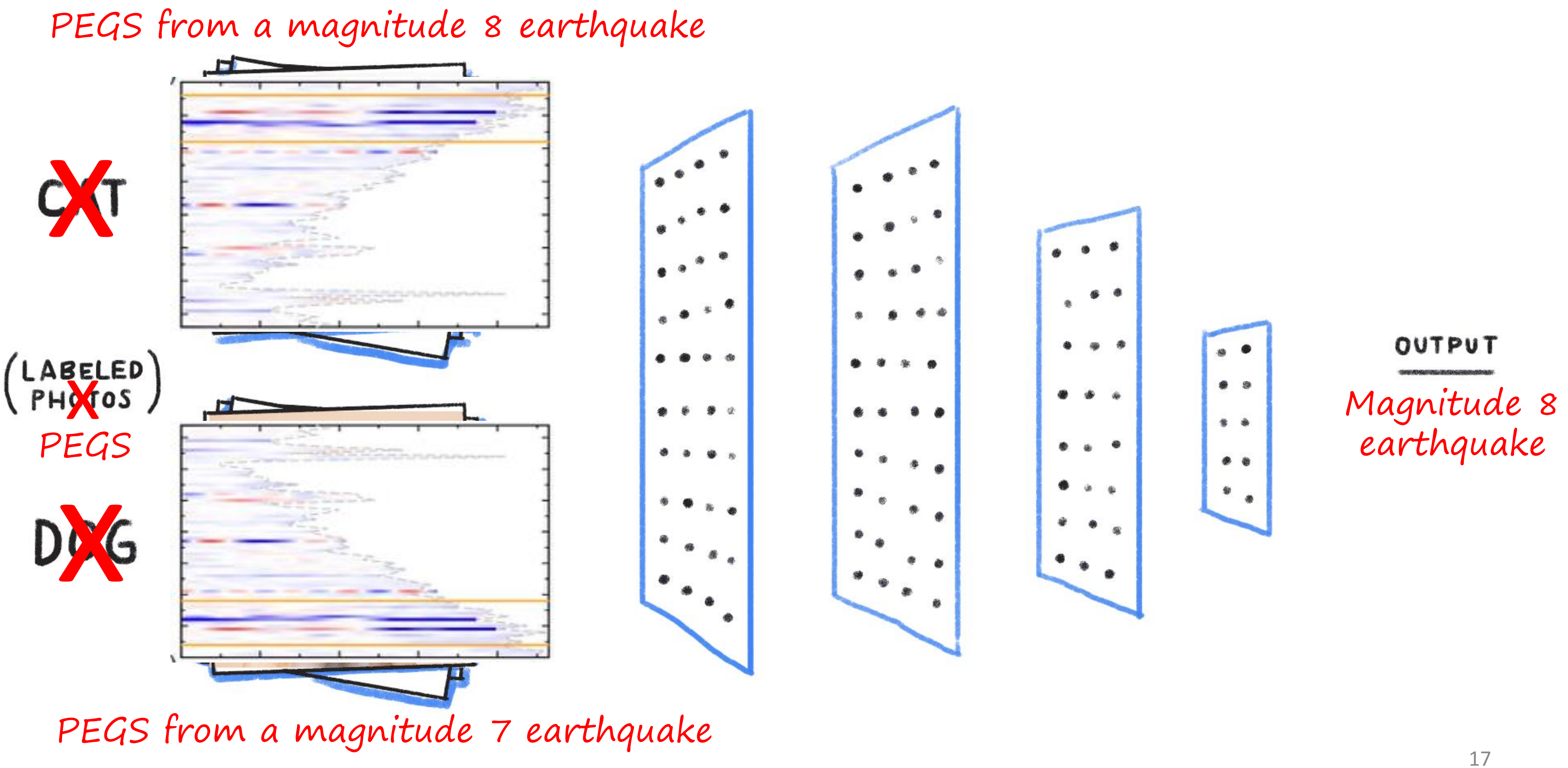


Licciardi et al., *Nature*, 2022

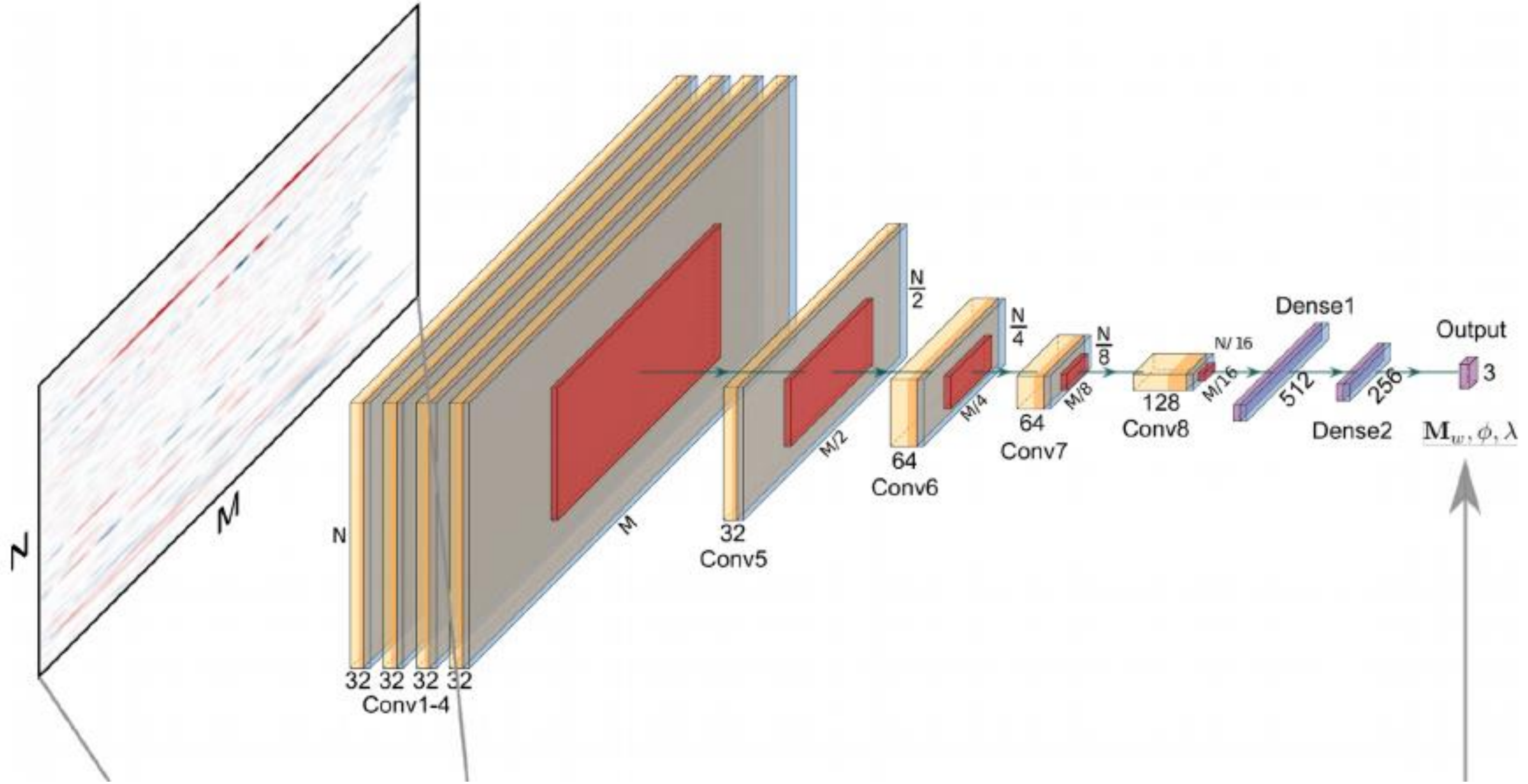
Image recognition



PEGS recognition

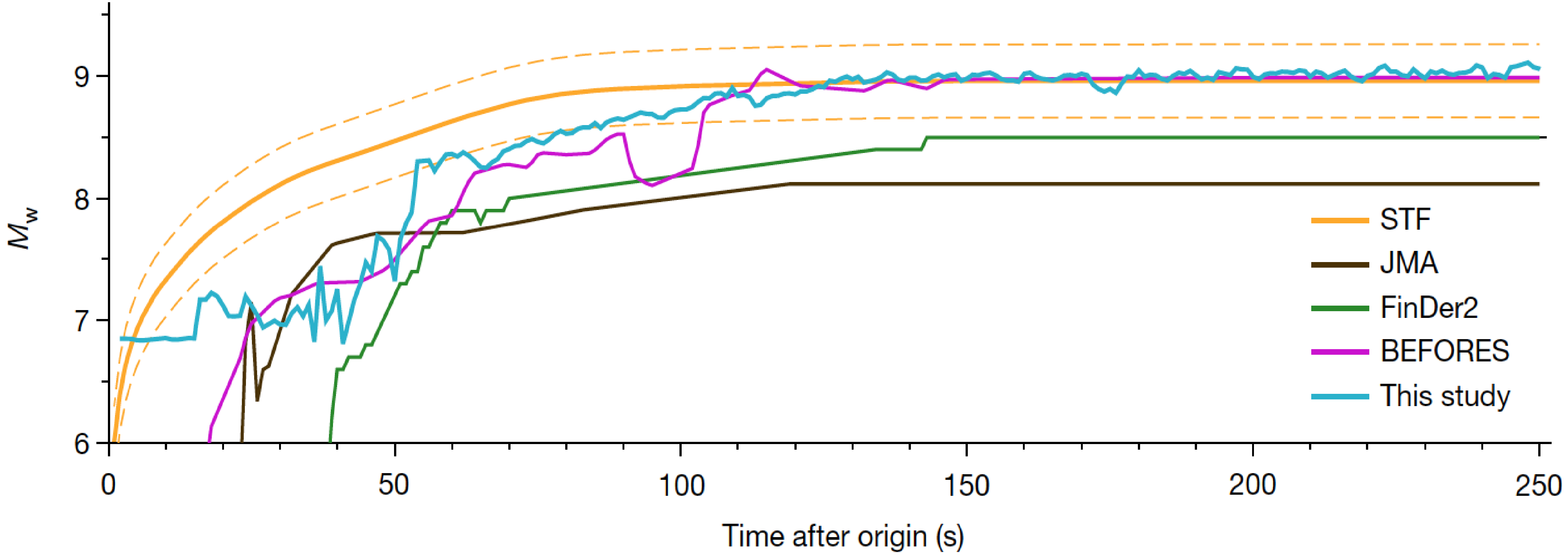


PEGSnet architecture (Convolutional Neural Network)



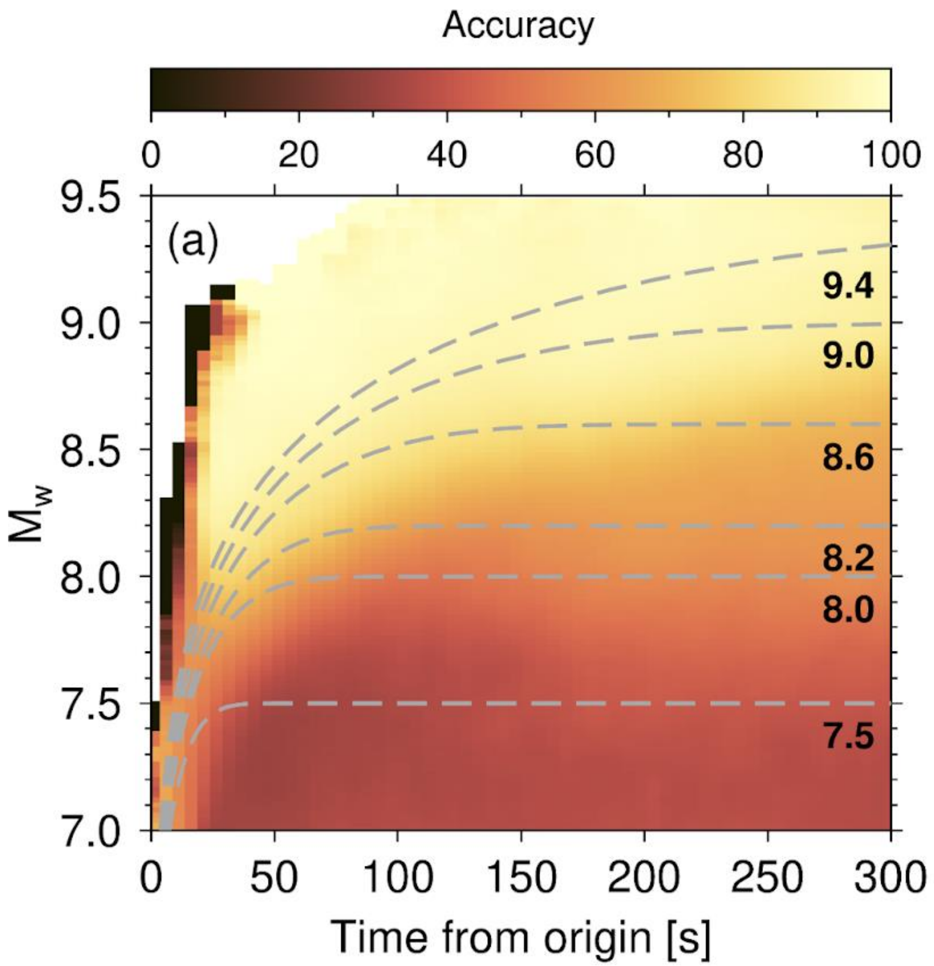
Licciardi et al., *Nature*, 2022

Performance on the Tohoku-Oki earthquake (Magnitude 9)



Licciardi et al., *Nature*, 2022

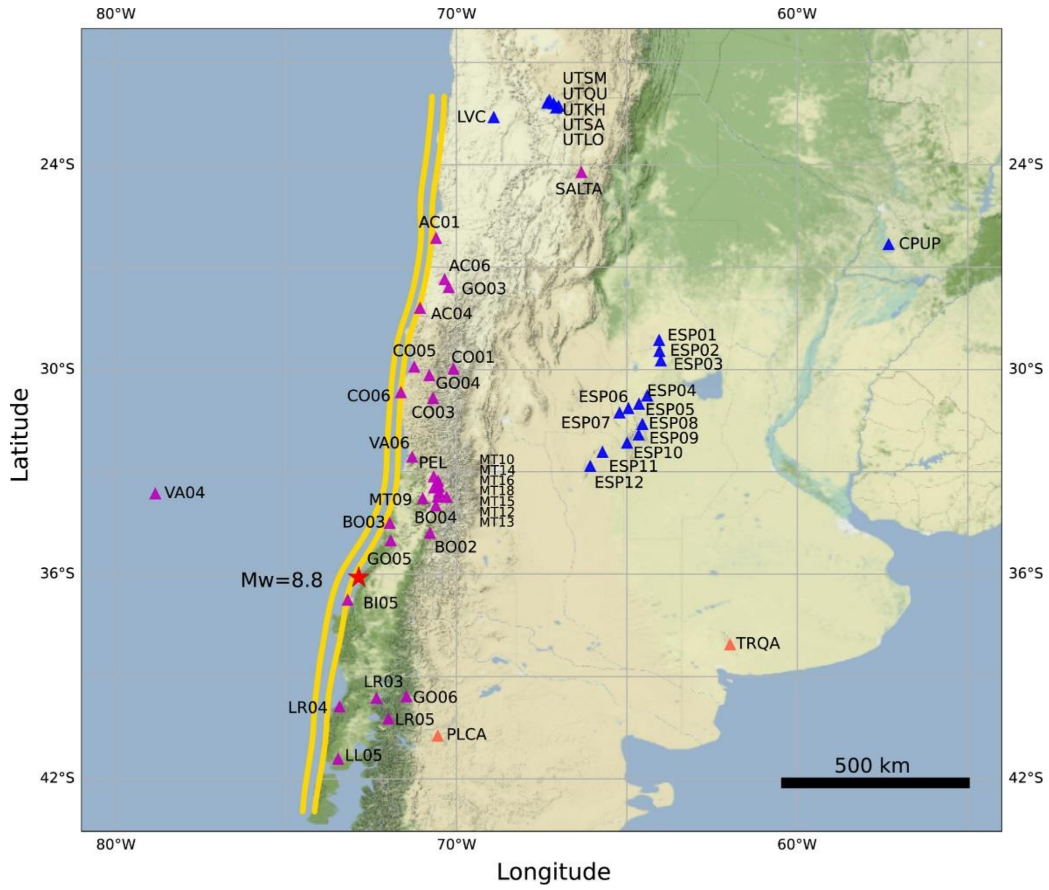
General performance in Japan: Works for Magnitude ≥ 8.3

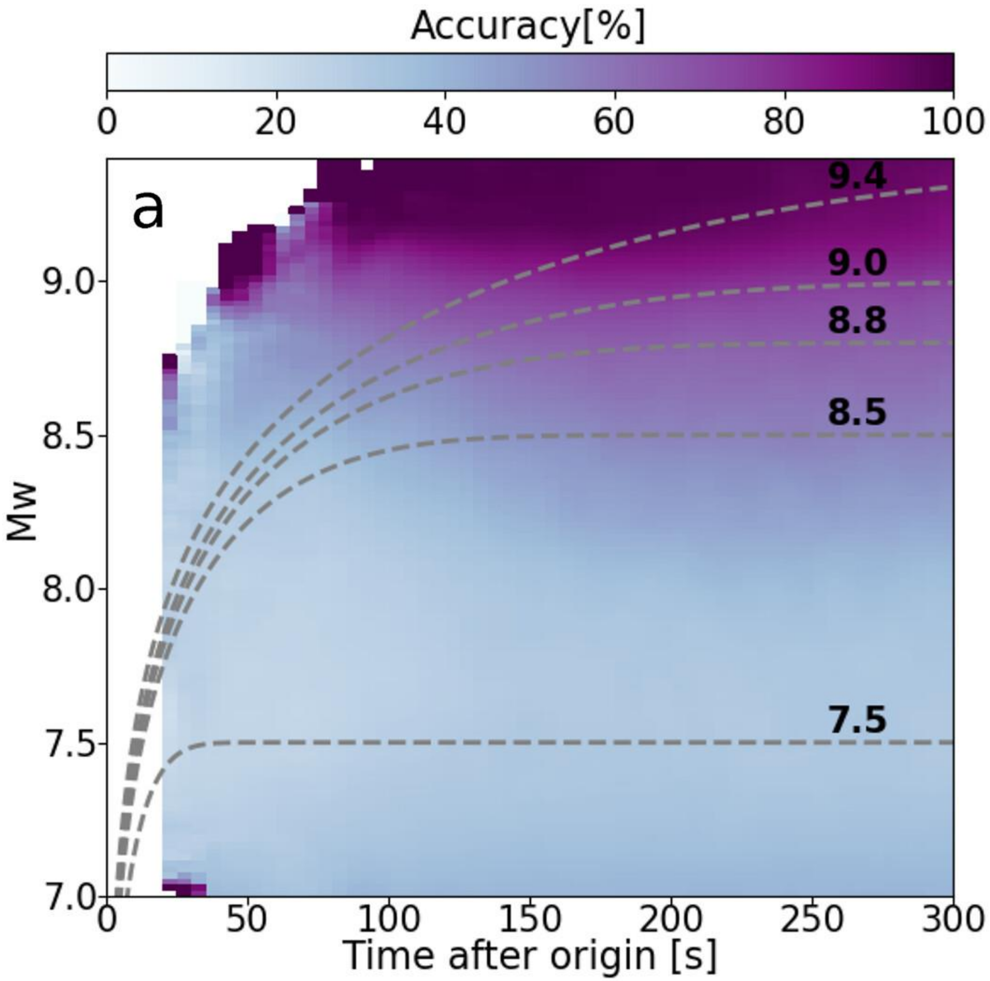


Licciardi, Bletery et al., *Nature*, 2022

Performance in Chile: Works for Magnitude ≥ 8.7

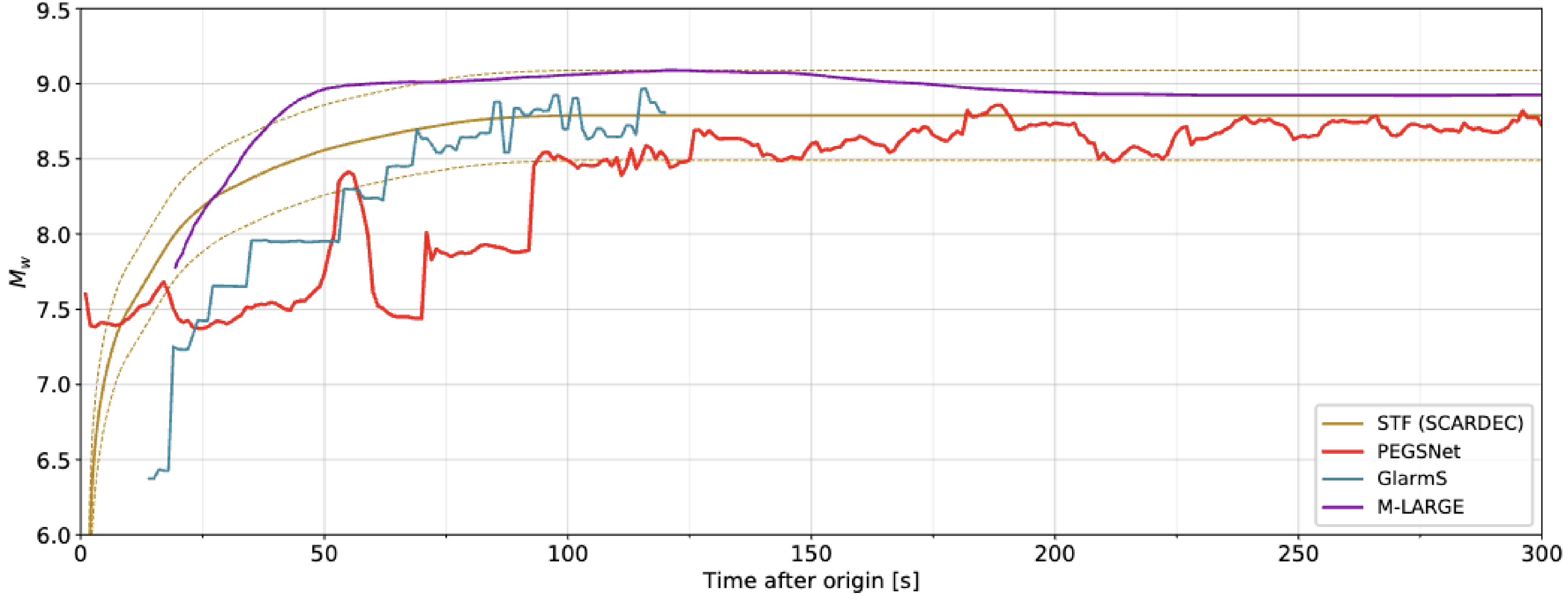
Seismic network





Arias et al., *JGR*, 2023

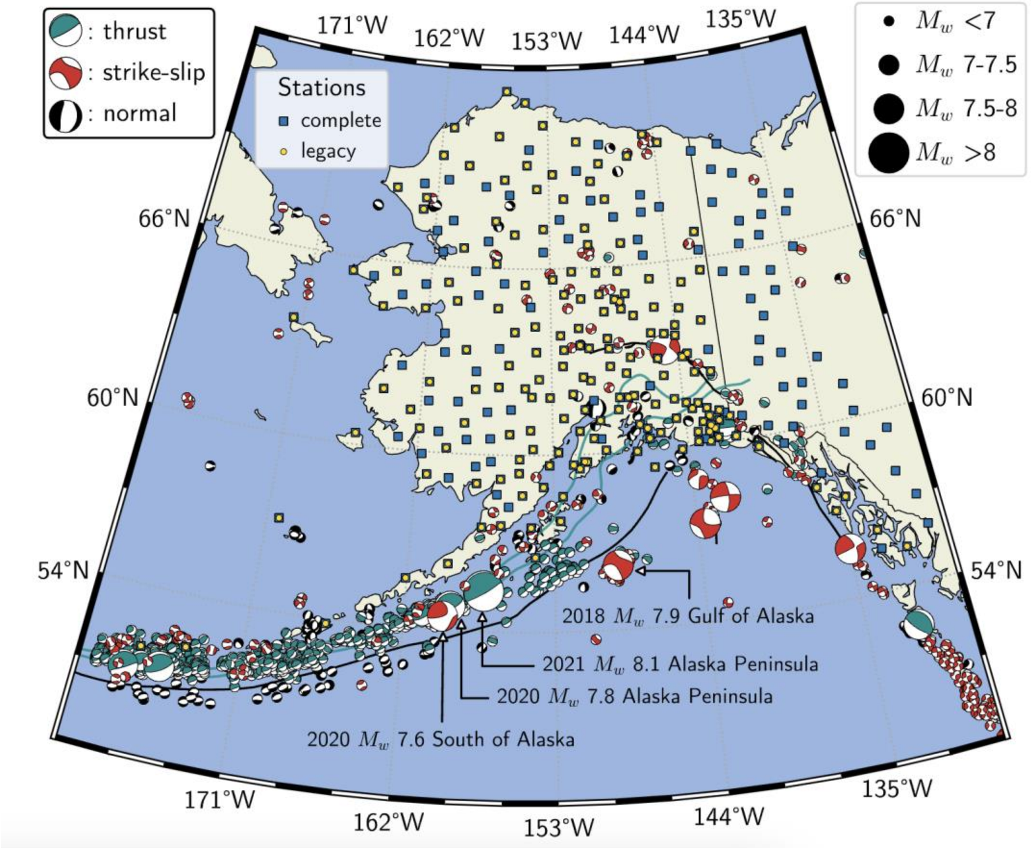
Performance on the Maule earthquake (Magnitude 8.8)

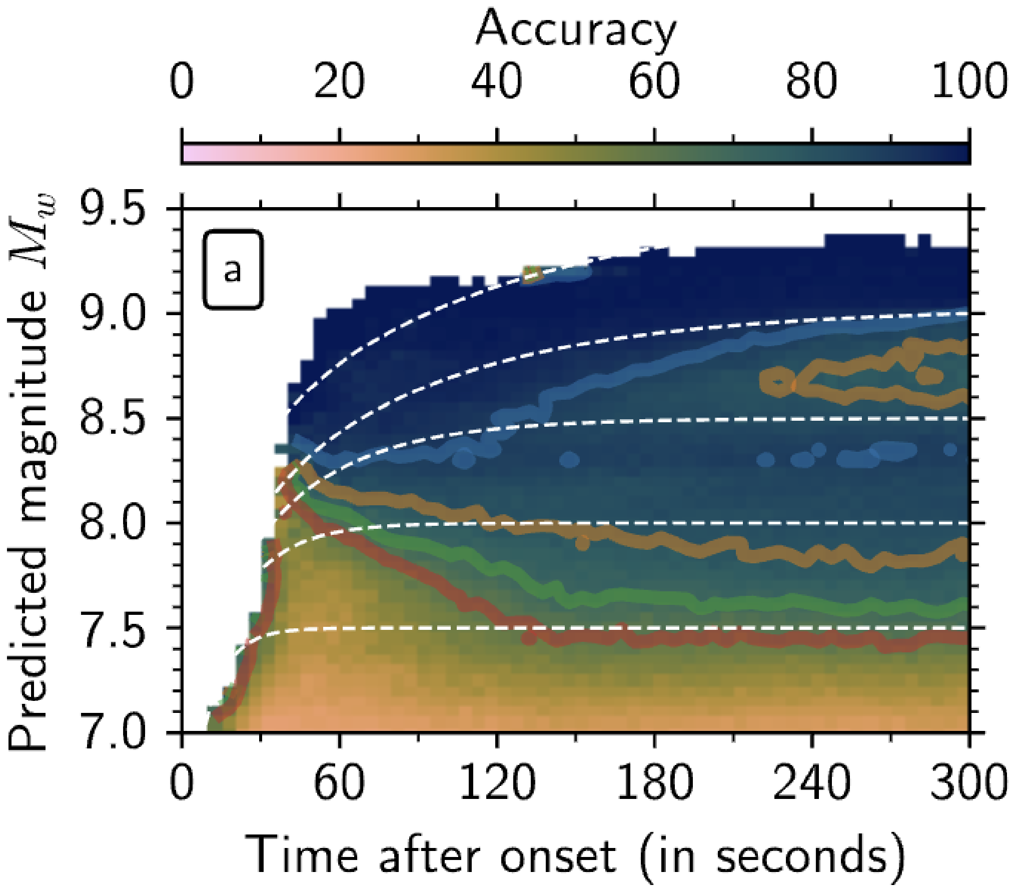


Arias et al., *JGR*, 2023

Performance in Alaska: Works for Magnitude ≥ 7.8

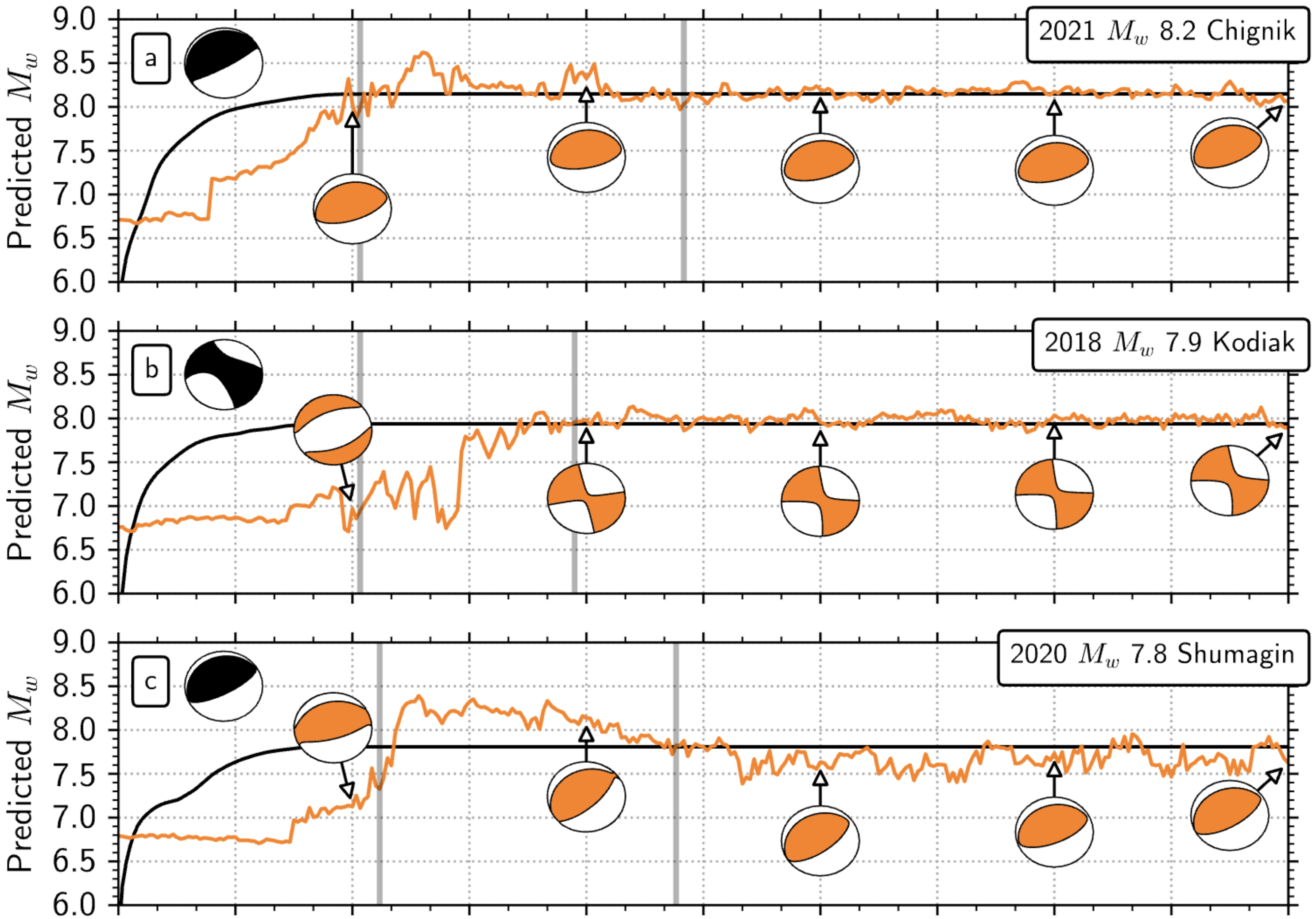
Seismic network





Juhel et al., *in prep.*

Performance on 3 Magnitude ≥ 7.8 earthquakes

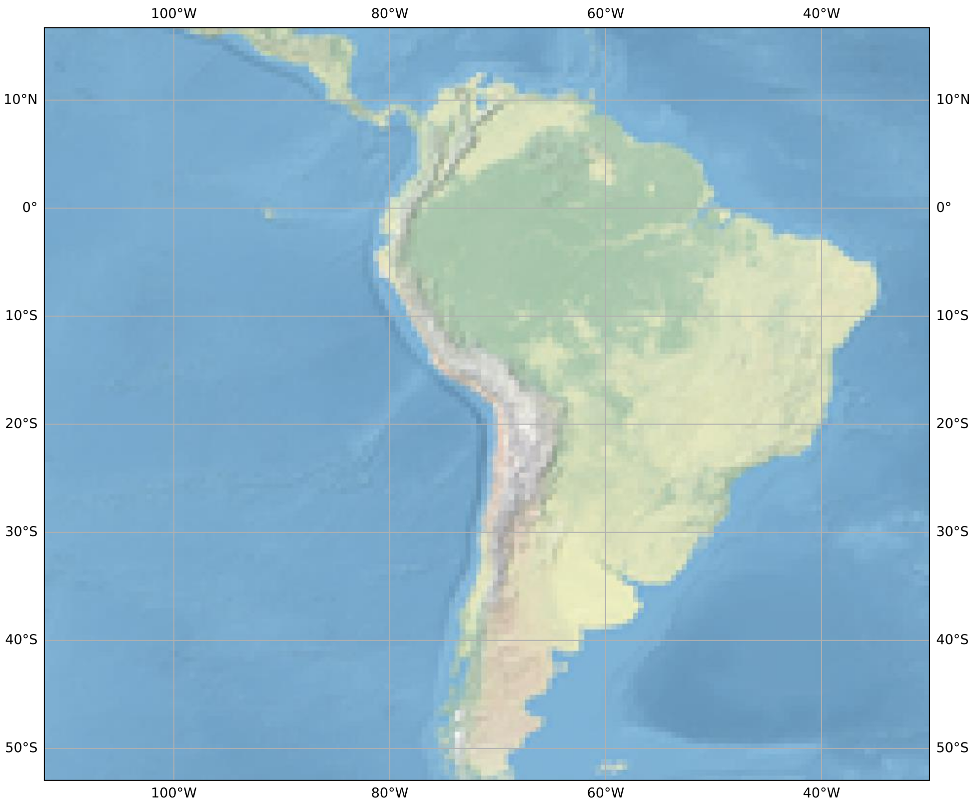


Juhel et al., *in prep.*

Implementation in the early warning system of Peru

Lima

Seismic network



PERÚ Ministerio del Ambiente

IGP Instituto Geofísico del Perú

BICENTENARIO PERÚ 2021

Arias et al., *in prep.*

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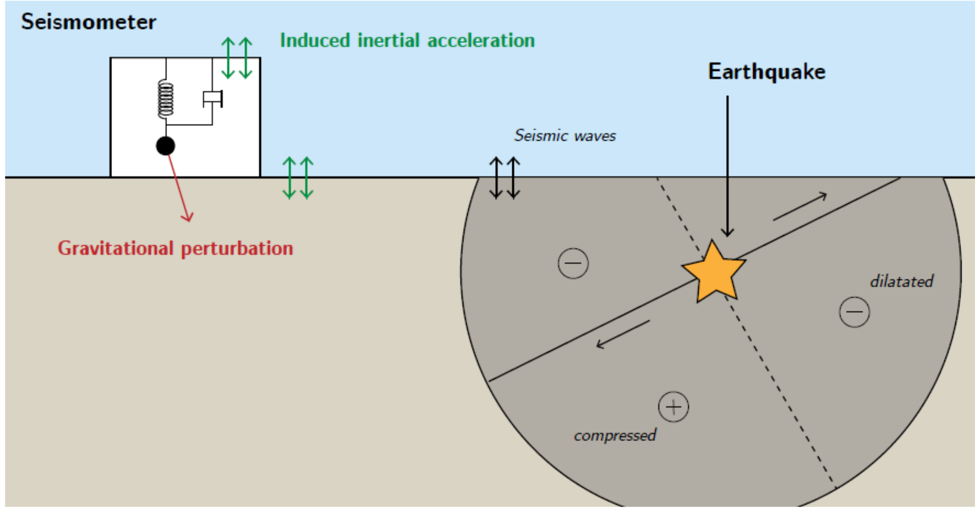
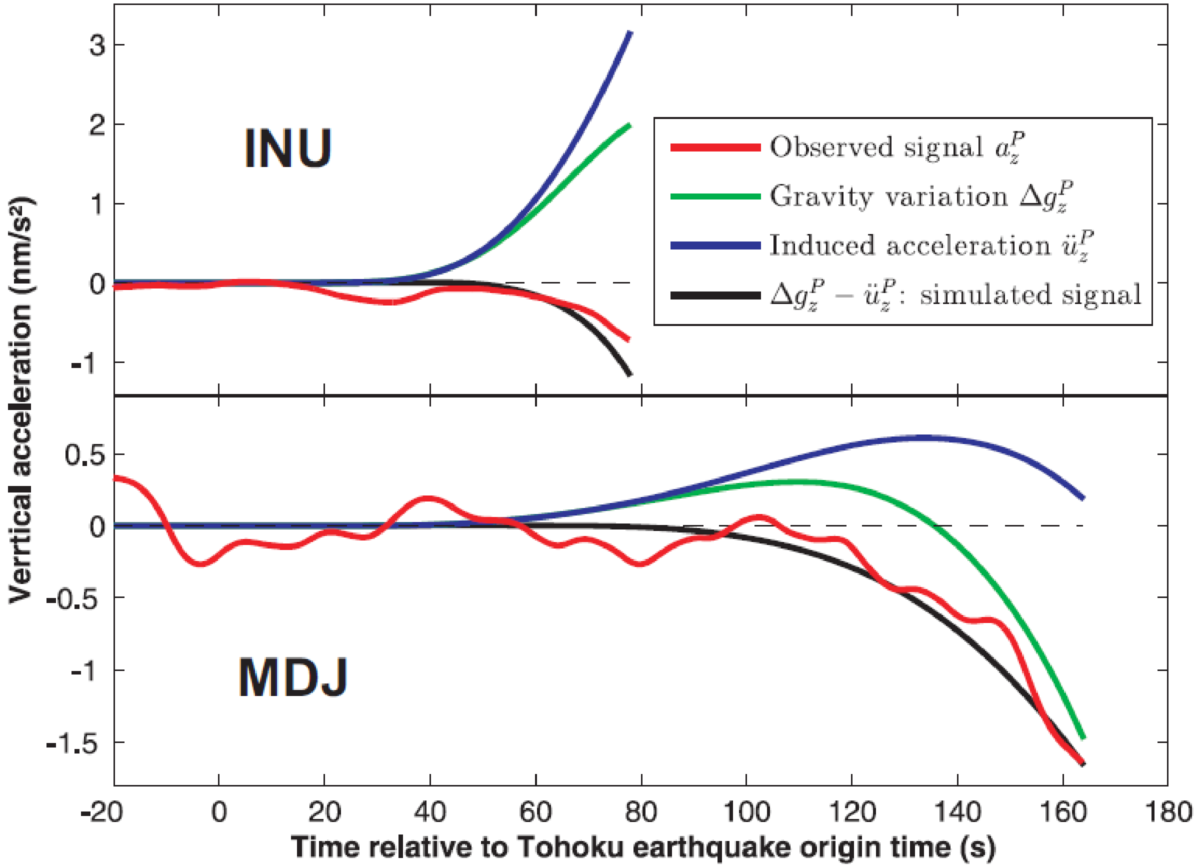


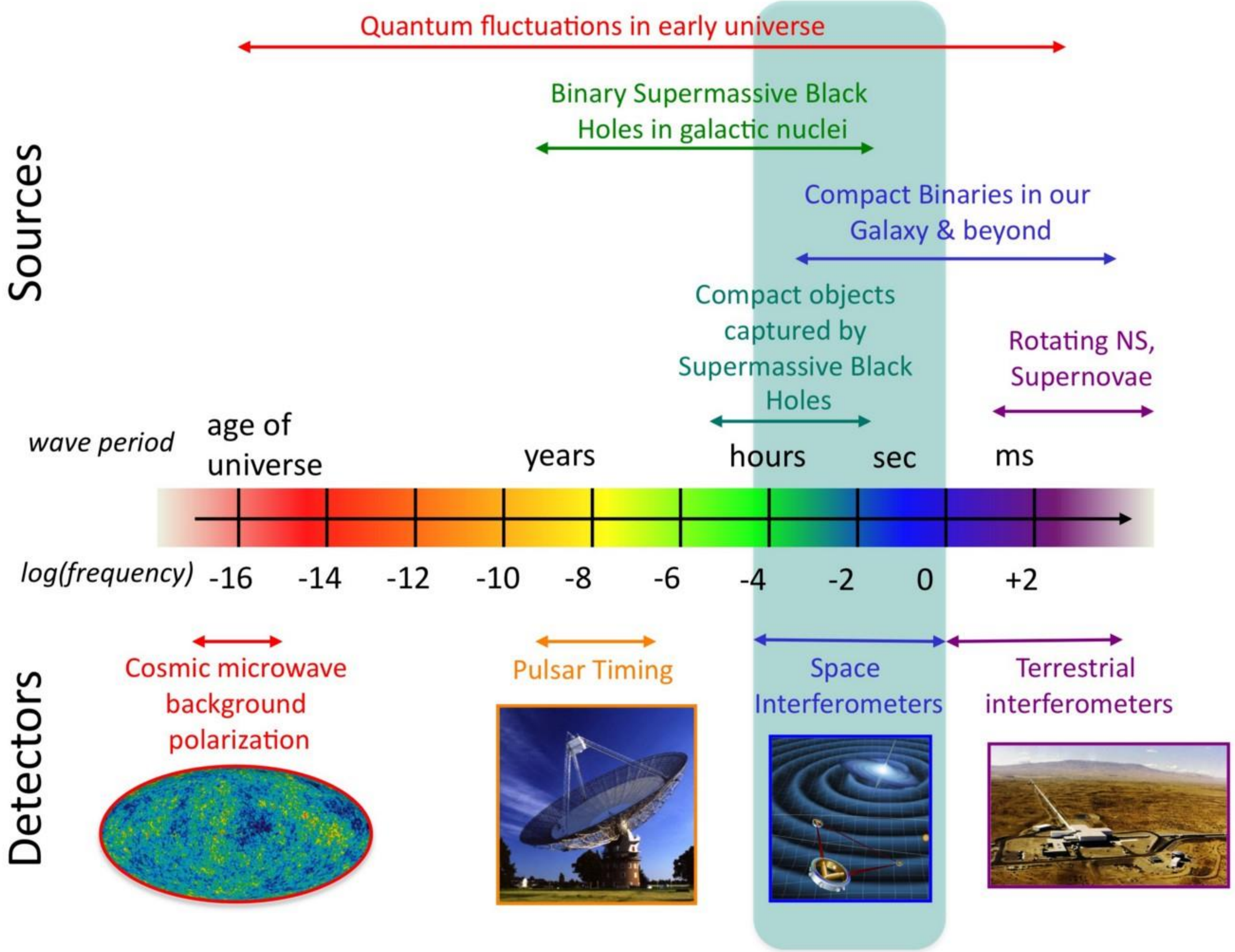


Prompt gravity changes induce ground accelerations, which are also recorded by seismometers and gravimeters.

Inertial sensors are coupled to the ground, they actually record the difference between gravity acceleration and ground acceleration

Vallée et al. (2017)

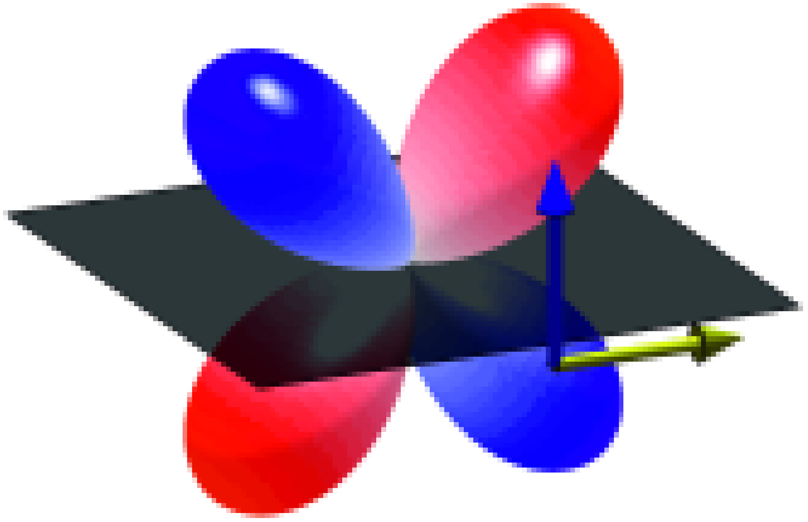
The Gravitational Wave Spectrum



NASA Goddard Space Flight Center

Dynamic gravity changes induced by earthquakes: theory

A quadrupole gravity field



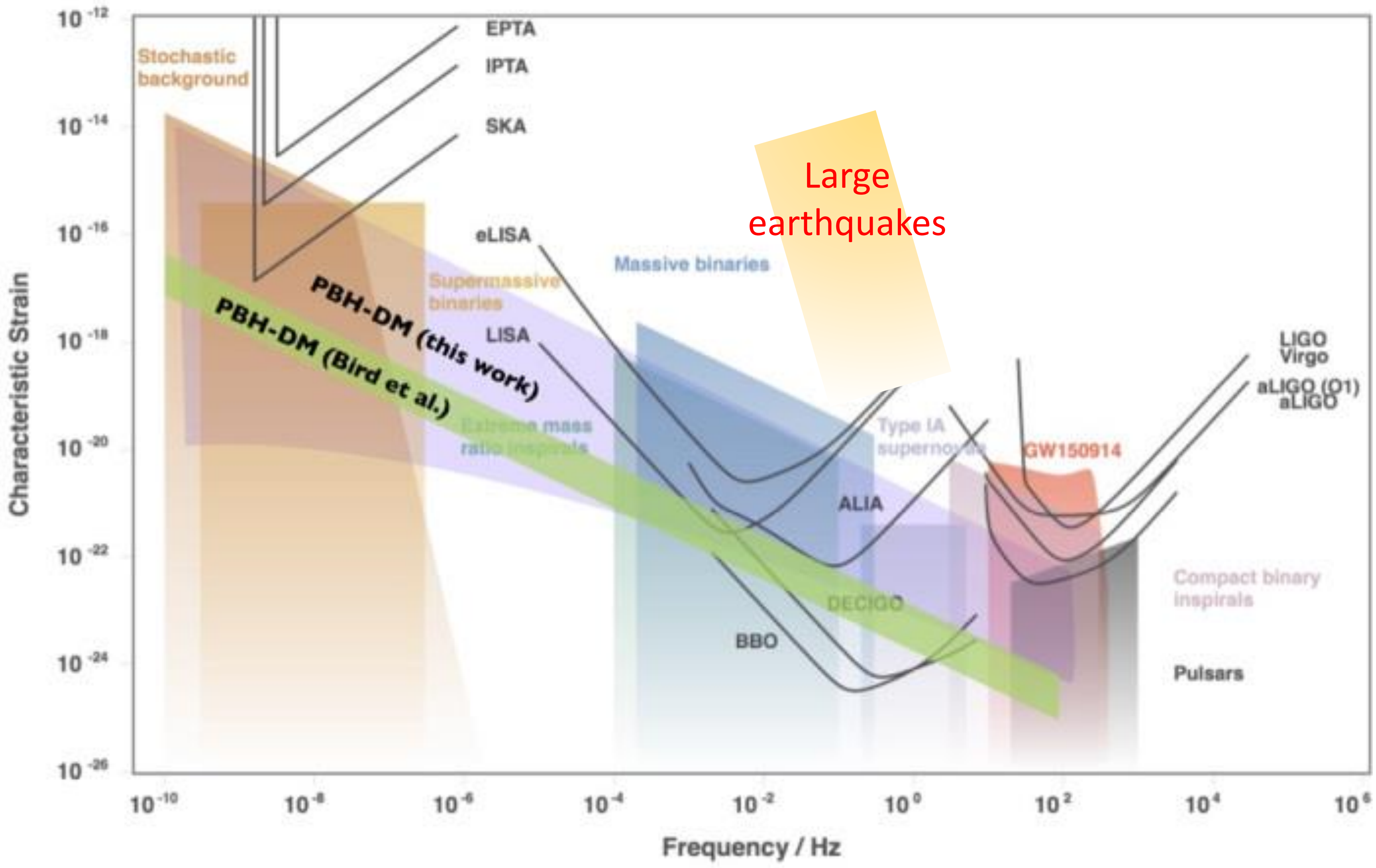
Gravity strain:

$$h(r,t) = \frac{G}{r^5} S(\theta,\phi)\, I_4[M_0](t) \sim \mathbf{1/f^7}$$

Distance

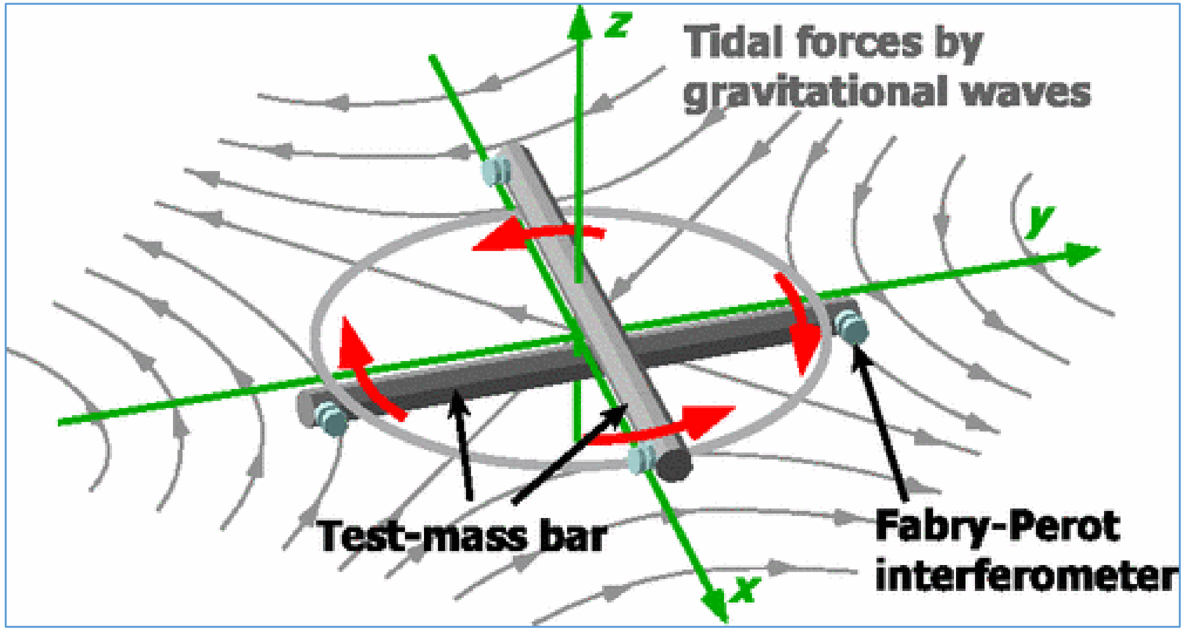
angular pattern

Fourth time-integral of seismic moment



https://arxiv.org/abs/1610.08479

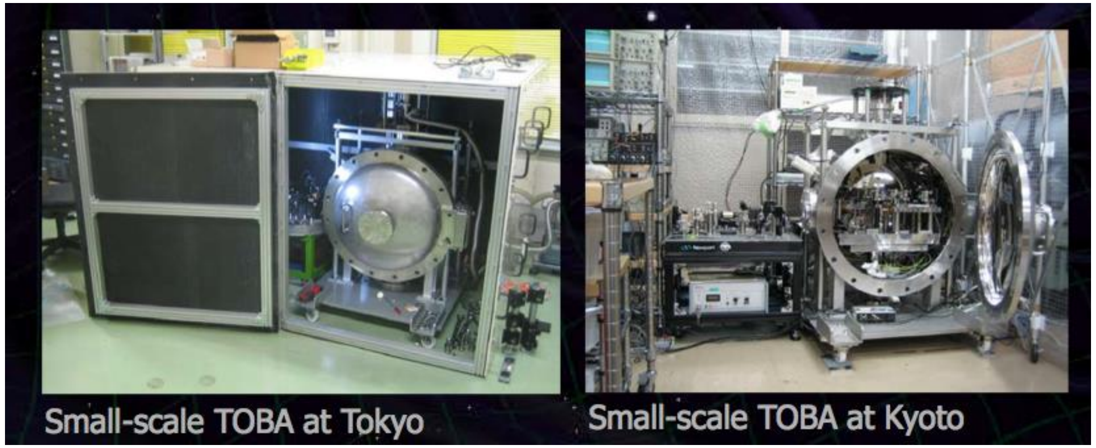
Low-frequency GW detector concepts



TOBA concept (torsion-bar antenna)
Ando et al (2010)

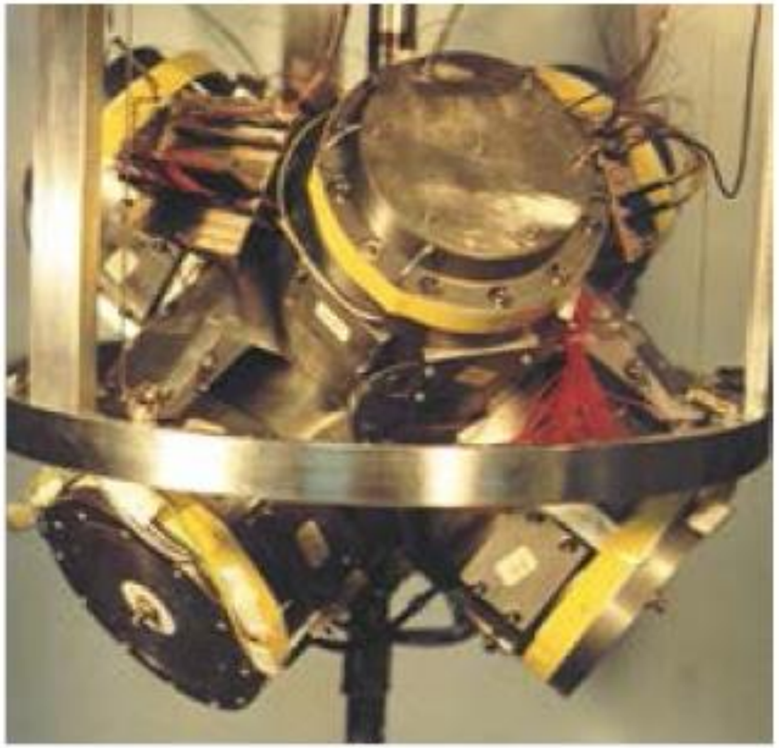
Devices designed to measure **gravitational waves**, minute distortions of space-time that are predicted by Einstein's theory of **general relativity**

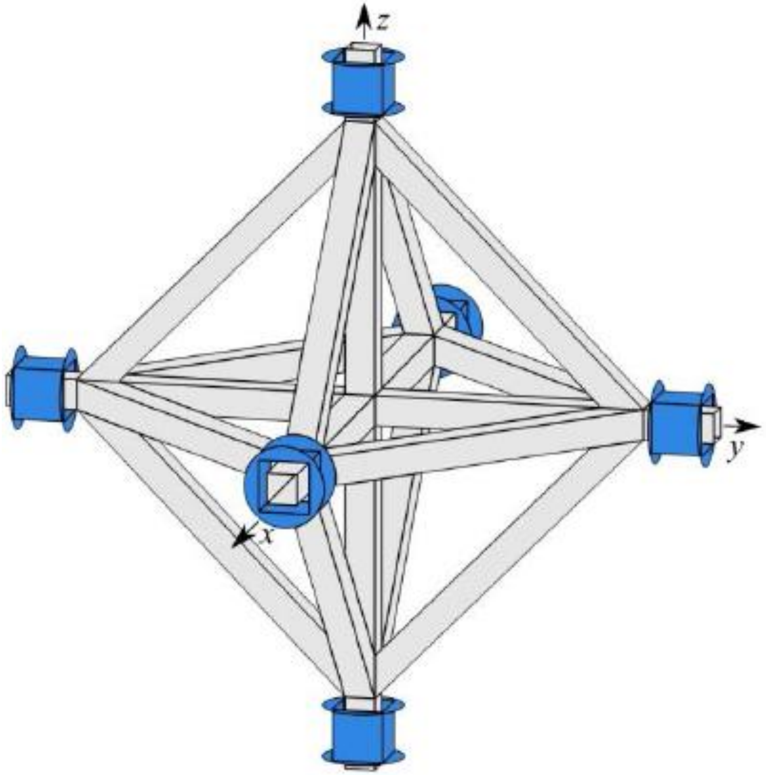
Laser-atom interferometers
Torsion-bar antennas (TOBA)



Superconducting gravity gradiometer

Ho-Jung Paik's SOGRO concept
(Moody et al 2002; Paik et al 2016)





Sensitivity of next-generation gravity strain meters

Juhel et al (2018)

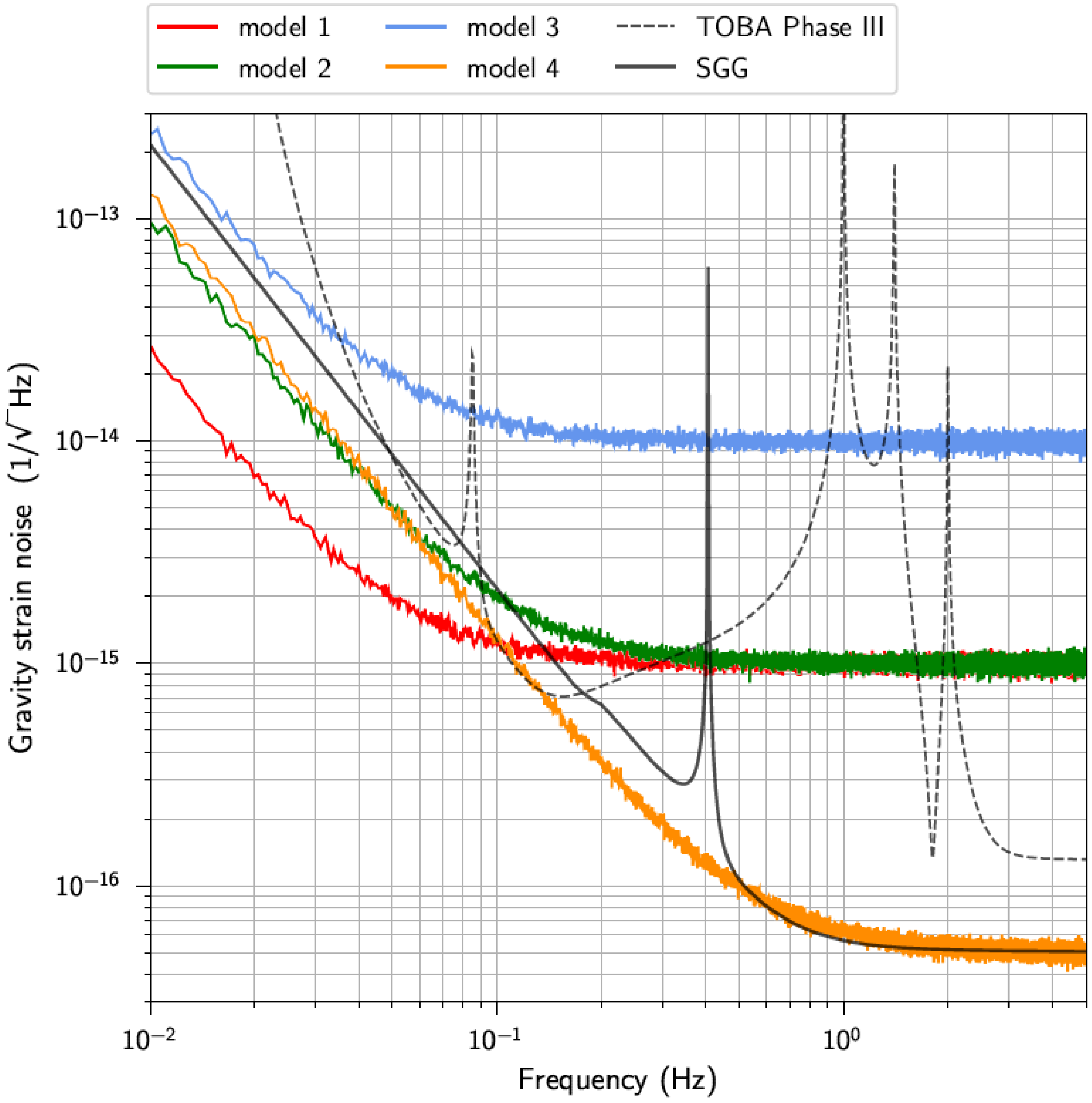
Designed for high sensitivity around 10 s

Assumes cancelation of Newtonian noise (gravity perturbations induced by local seismic and infrasound waves)

At high frequencies f>0.1 Hz:
shot + seismic noise ≈ flat noise

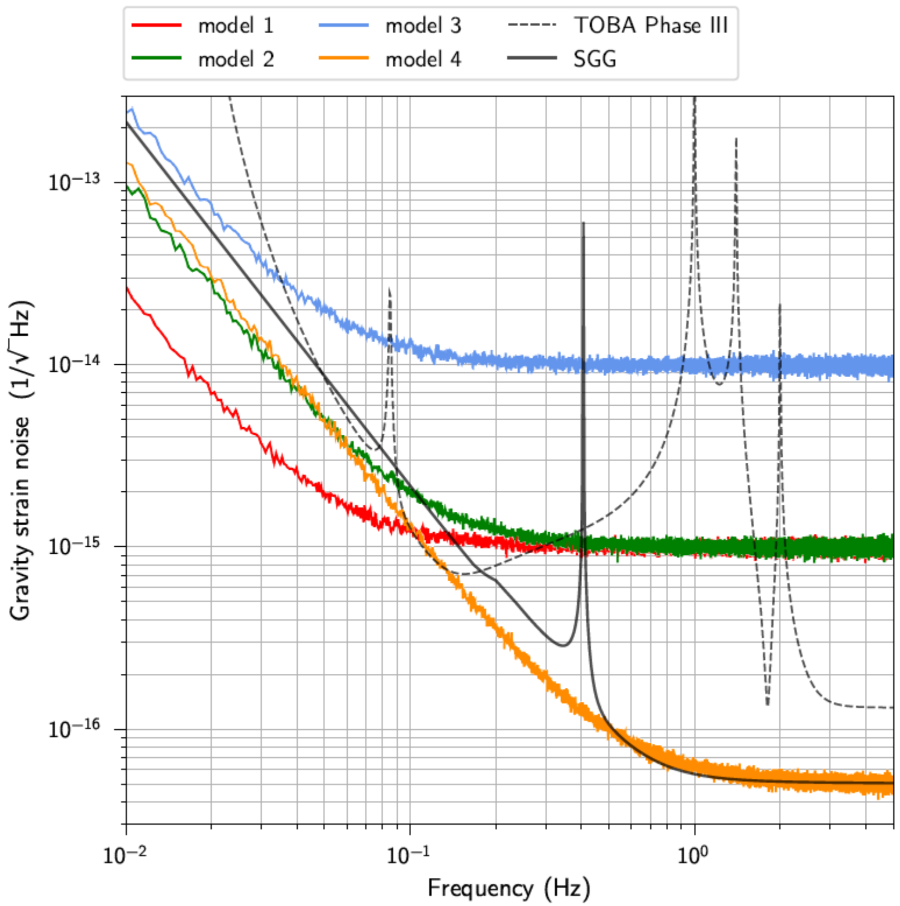
At intermediate frequencies 0.01<f<0.1 Hz:
thermal + seismic + shot noise ≈ $1/f^2$

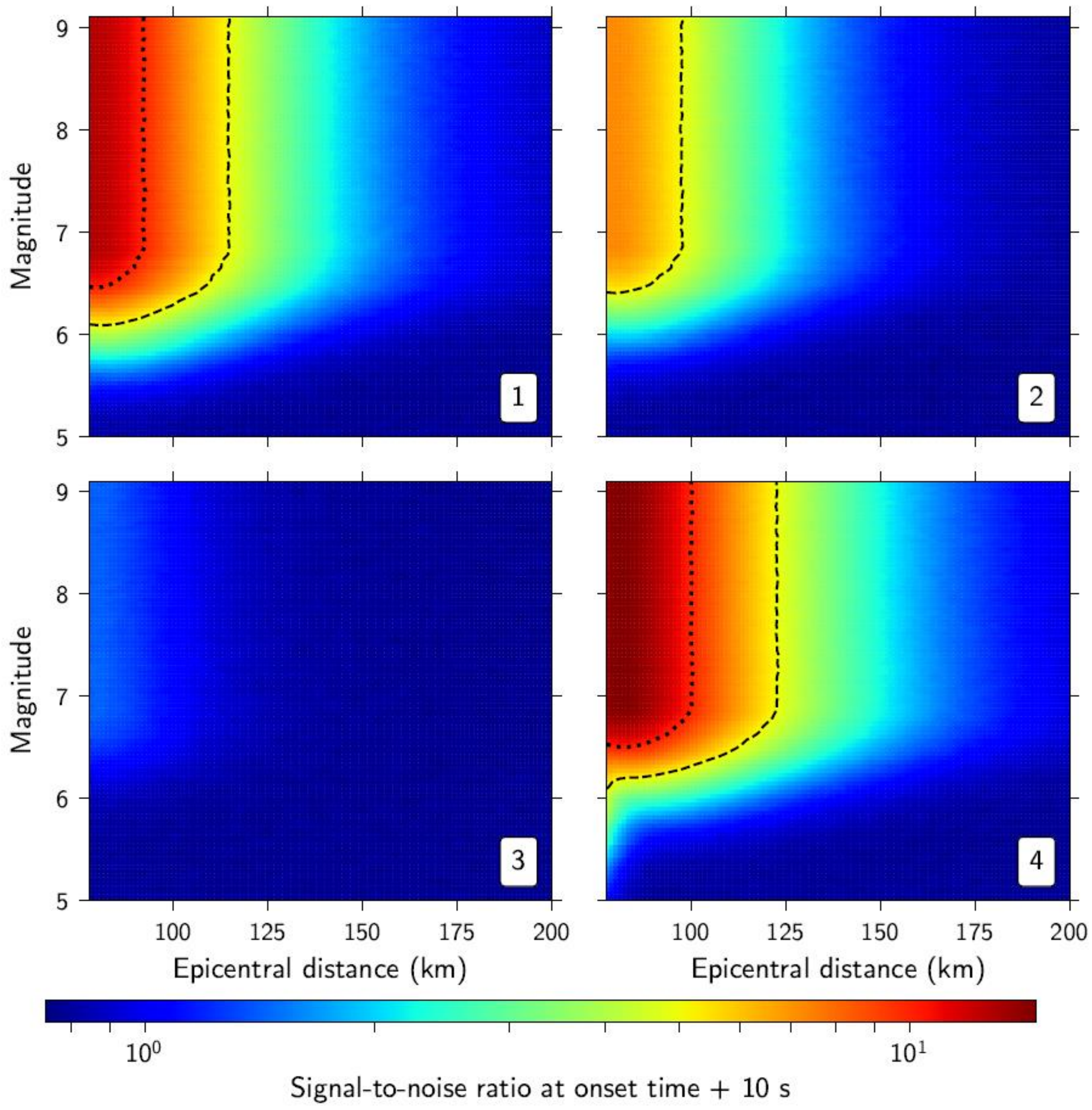
At low frequencies f<0.01 Hz: lack of seismic isolation or control system noise



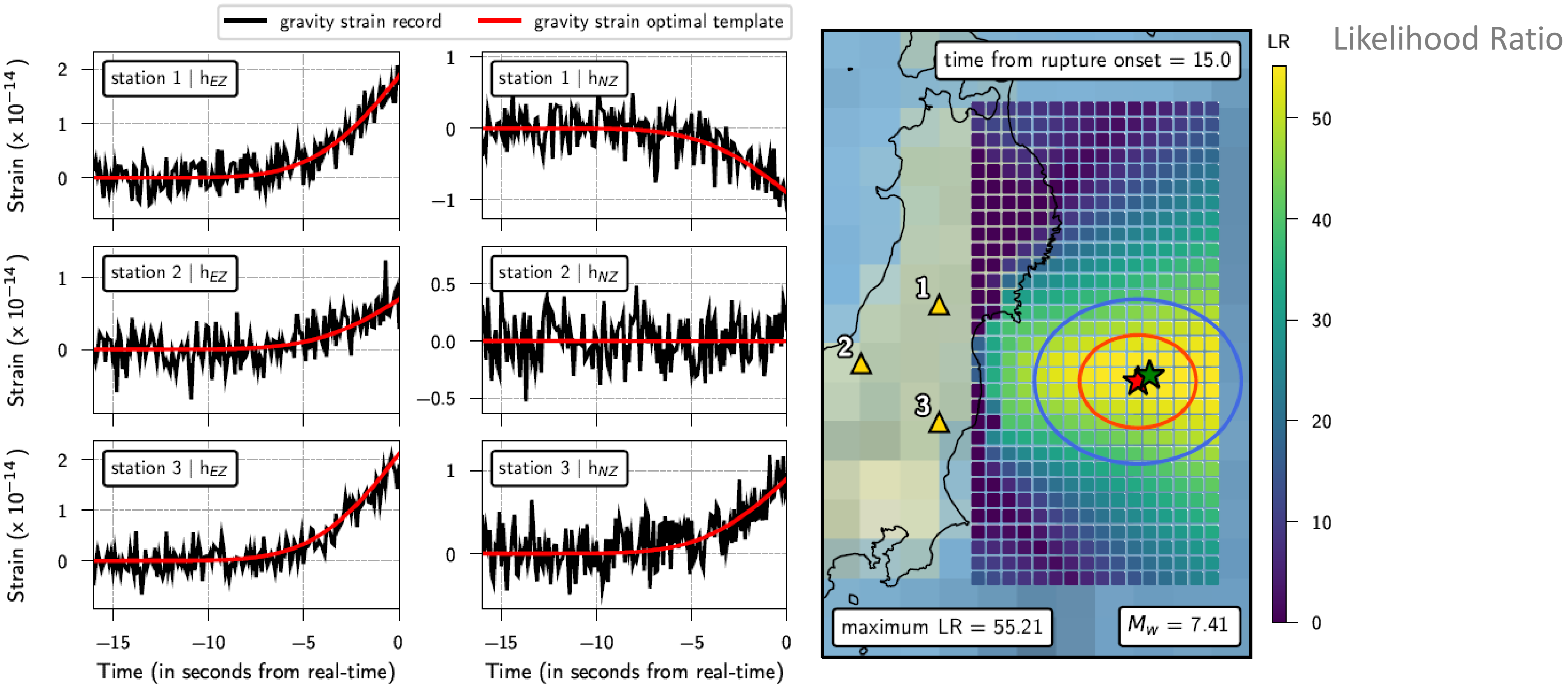
Earthquake detection SNR

Juhel et al (2018)



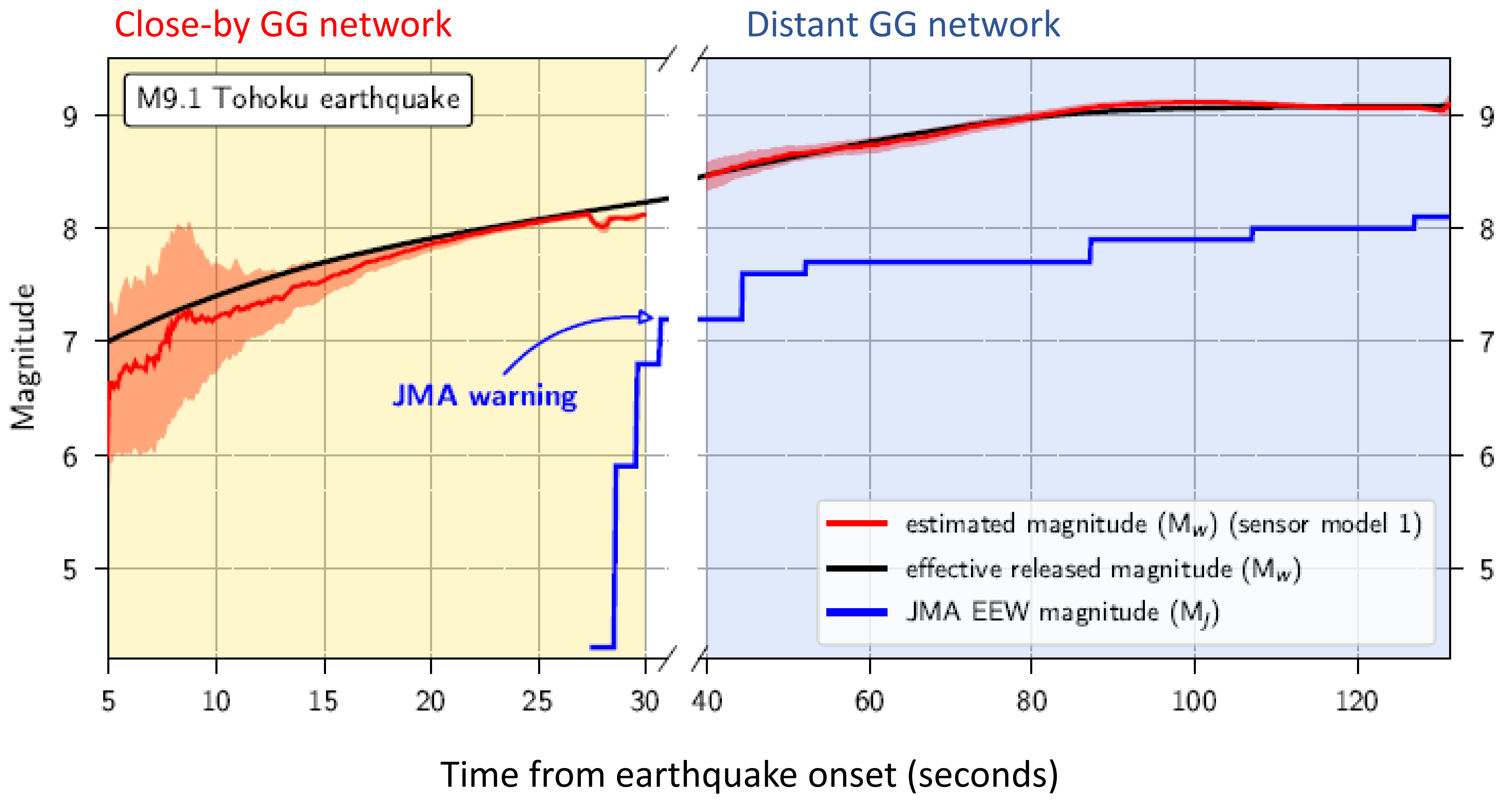


Simulation of the M9.1 2011 Tohoku, Japan earthquake



Detection, source location and magnitude estimation 15 seconds after earthquake starts

Performance of magnitude estimation



Conclusions

- Earthquakes generate gravity perturbations before the arrival of seismic waves
- Gravity signals generated by **very large earthquakes** can be recorded **after 1 min** by seismometers → contribution to tsunami warning
- The gravity signals of moderate earthquakes at short times (~10 s), are tiny but within reach of next-generation gravity-gradient sensors
- Advantage for EEWS: improved warning times, reduced blind zone

  → Earthquake warning sooner and for all

- **Need new gravity-gradient instruments with sensitivity in gravity strain of $10^{-15}/\sqrt{Hz}$ at 0.1 Hz**