A new instrument in earthquake early warning system by detection and modeling of prompt gravity signals

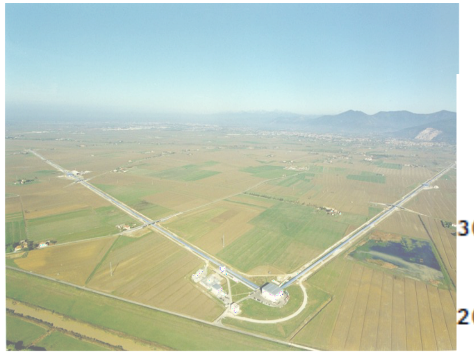
Kevin Juhel (IPG, APC Paris),

Jean-Paul Montagner (IPG-Paris), Jean-Paul Ampuero (IRD, Nice), Matteo Barsuglia (APC-Paris), Pascal Bernard, (IPGP), Giovanni Losurdo (INFN, Pisa, Italy), M. Vallée (IPGP)

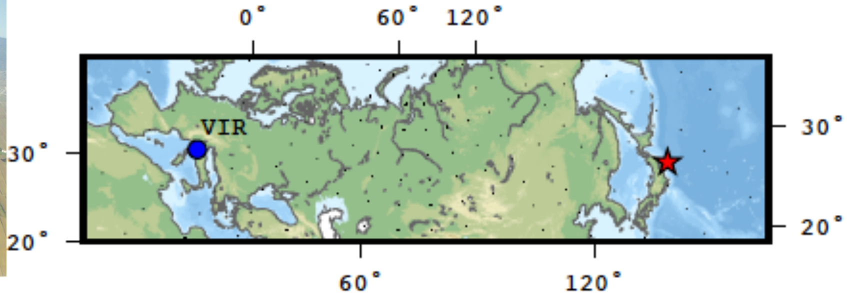
Outline: The story and the approach

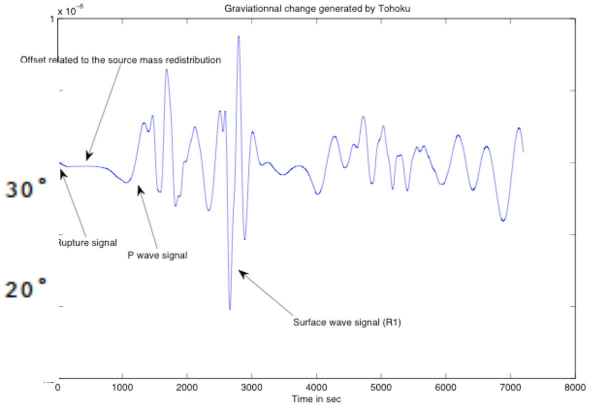
- **Motivation (2012)**

VIRGO
(*Gravitational wave Interferometer*)



normal mode calculation





- **Search for « instantaneous » gravity signal**
  a) Very Large earthquakes: Japan-Tohoku (9.0:-; 11/03/2011)
  b) Instruments: Superconducting gravimeter, very broadband seismometers STS1
- **EEWS (Earthquake Early Warning Systems)**

- **Search for a** prompt gravity signal: Kamioka SG data very broadband seismic data
  Montagner et al., Nature Com., 2016, Vallée et al., Science, 2017, Vallée and Juhel, JGR, 2019)
- Controversy (Heaton, Nature Com., 2017)

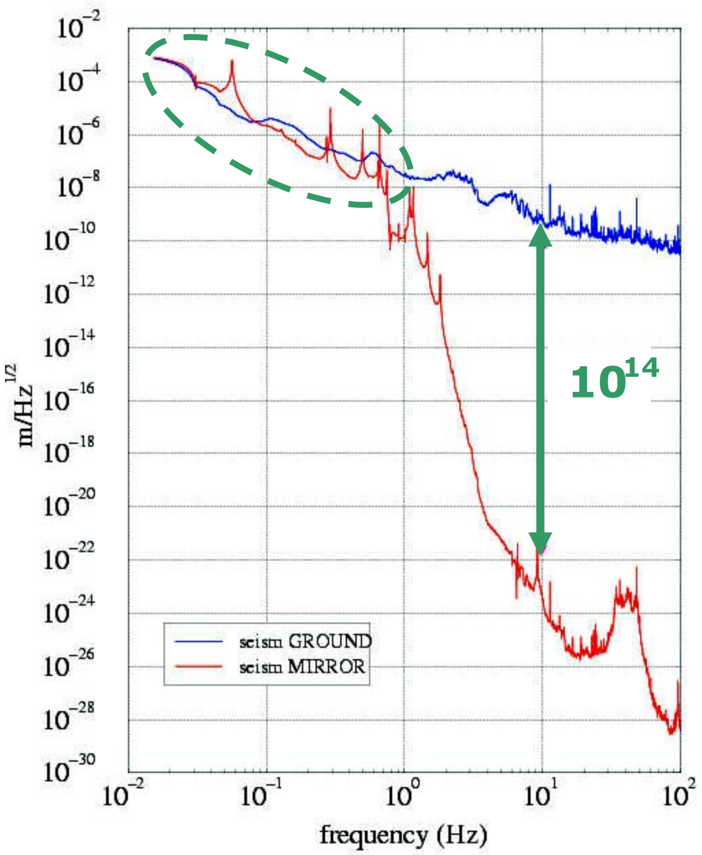
- **Need for New Instruments: TORSION Bars**

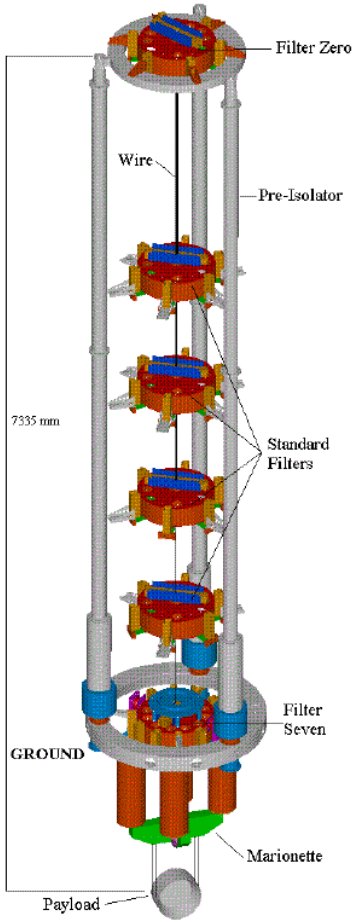
- **Perspectives and ongoing projects : EEWS (Earthquake Early Warning Systems)** (Juhel et al., JGR, 2018)

- **PEGASEWS: Prompt Earthquake GrAvity Signals: Early Warning Systems**

LABEX UnivEarthS (2012)- Geophysics Gravitational wave interferometers: VIRGO

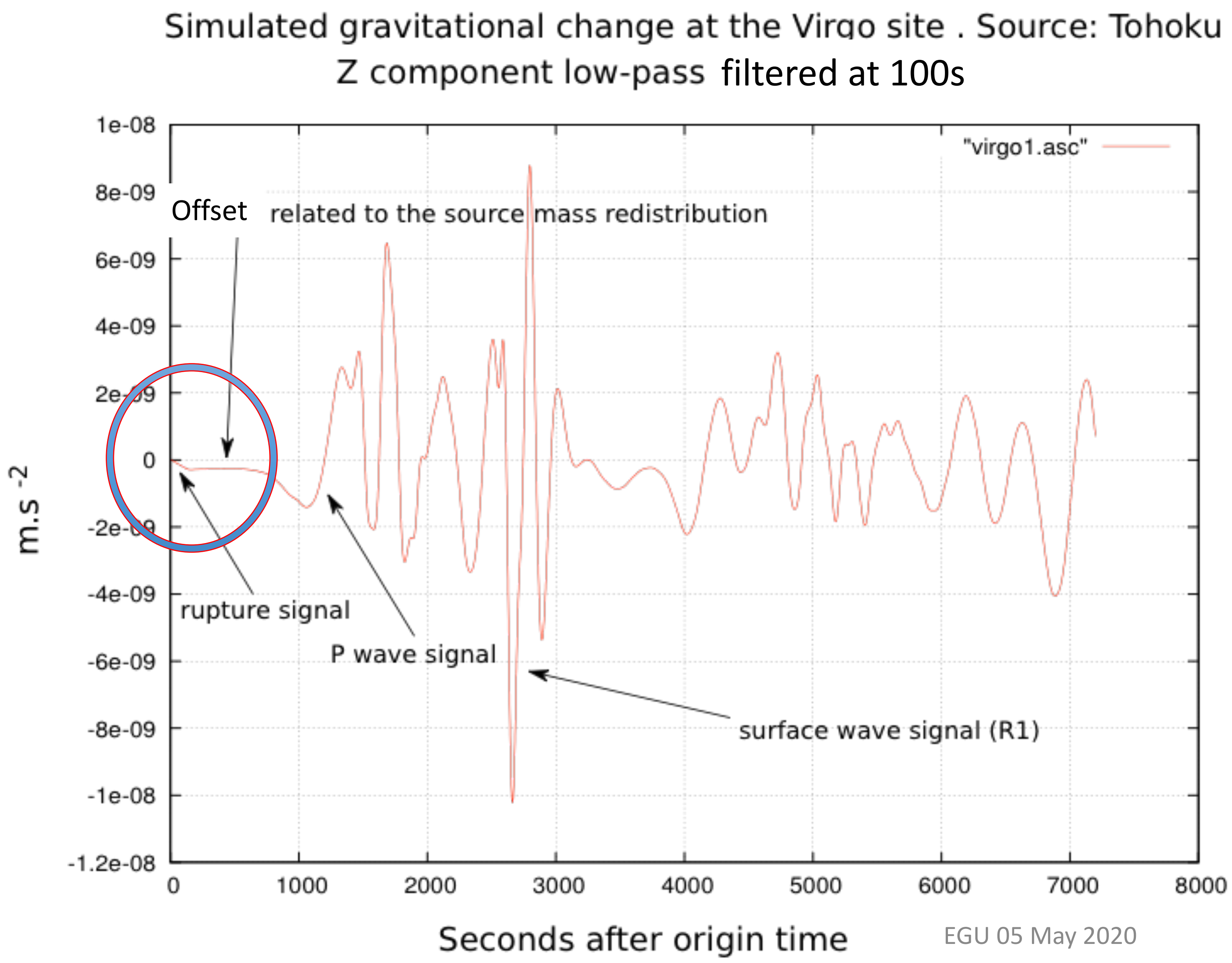
VIRGO (Italian – French Gravitational wave detector)





Seismic wall at f>1 Hz

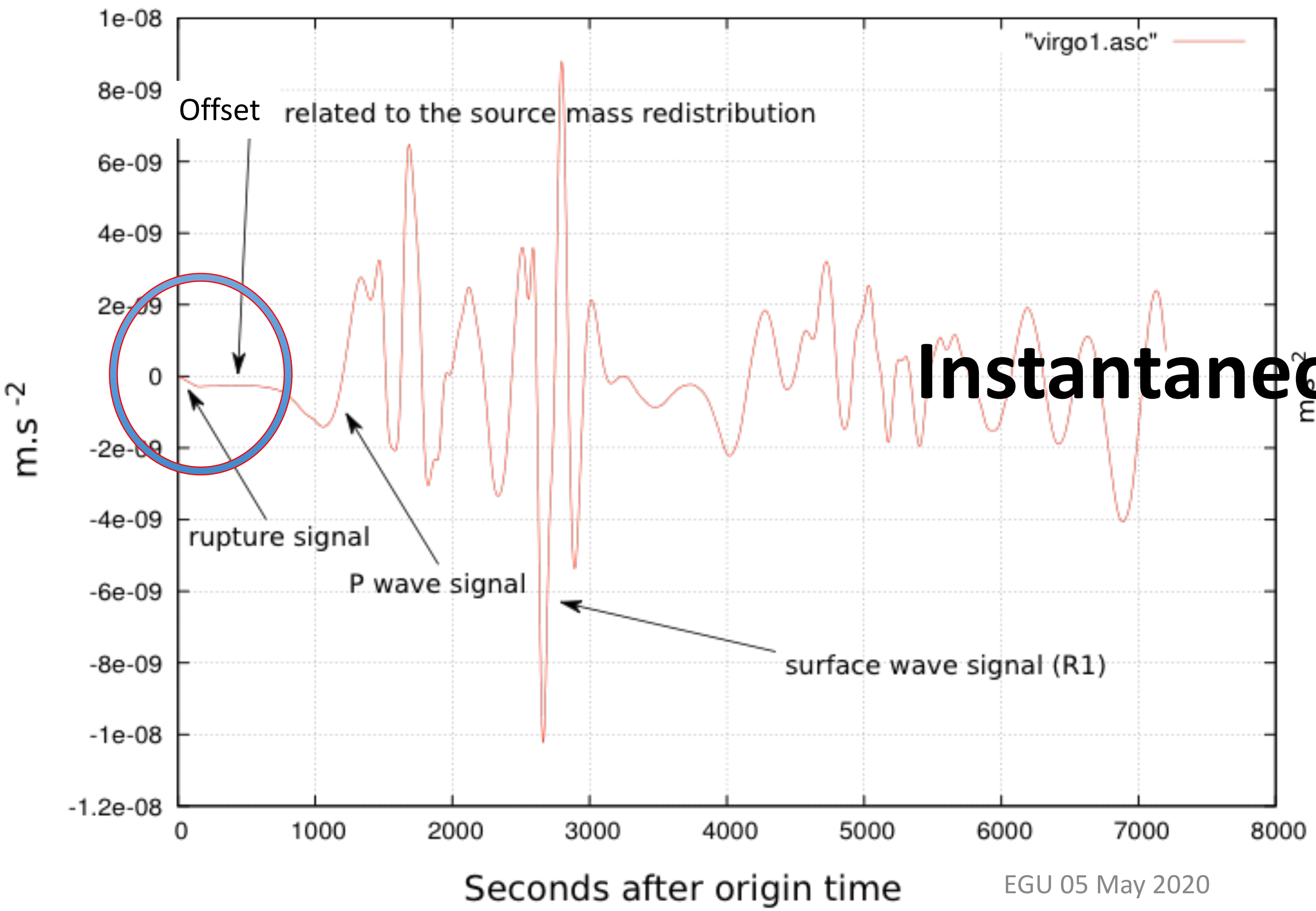
Motivation
NORMAL MODE THEORY



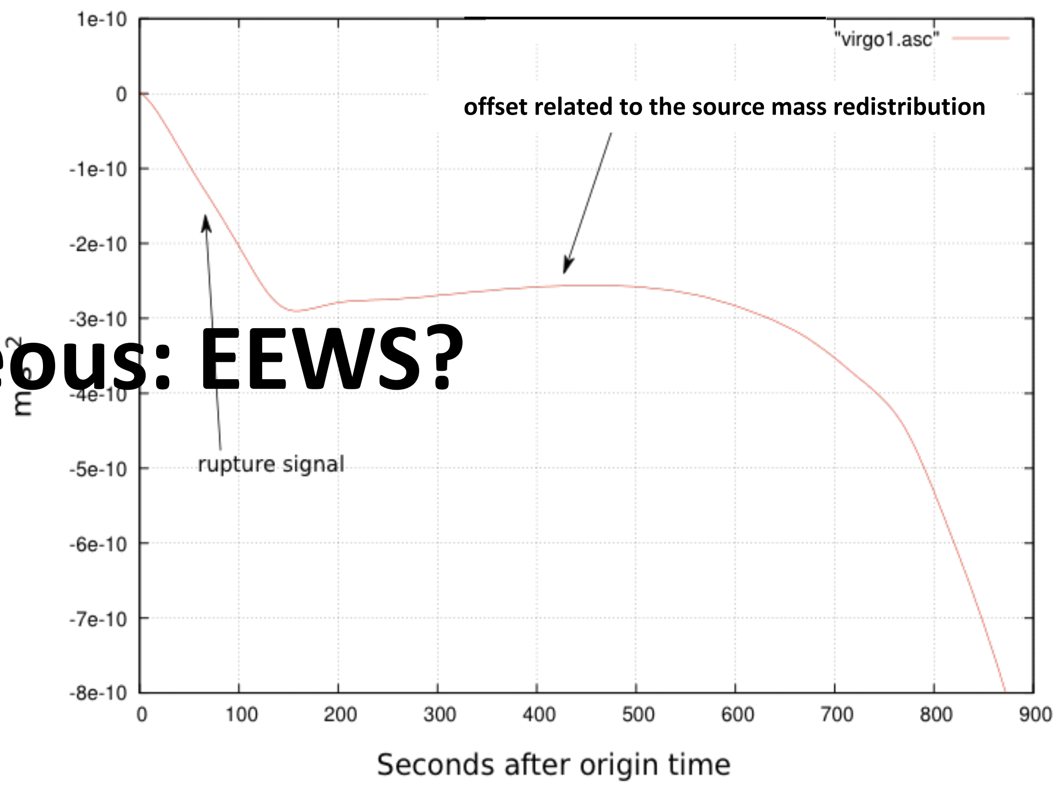
Theoretical signal
Before P-arrival:
0.03 µgal
Very small

1 µgal = 10^{-8} m/s^2 =10 nm/s^2

Motivation
NORMAL MODE THEORY



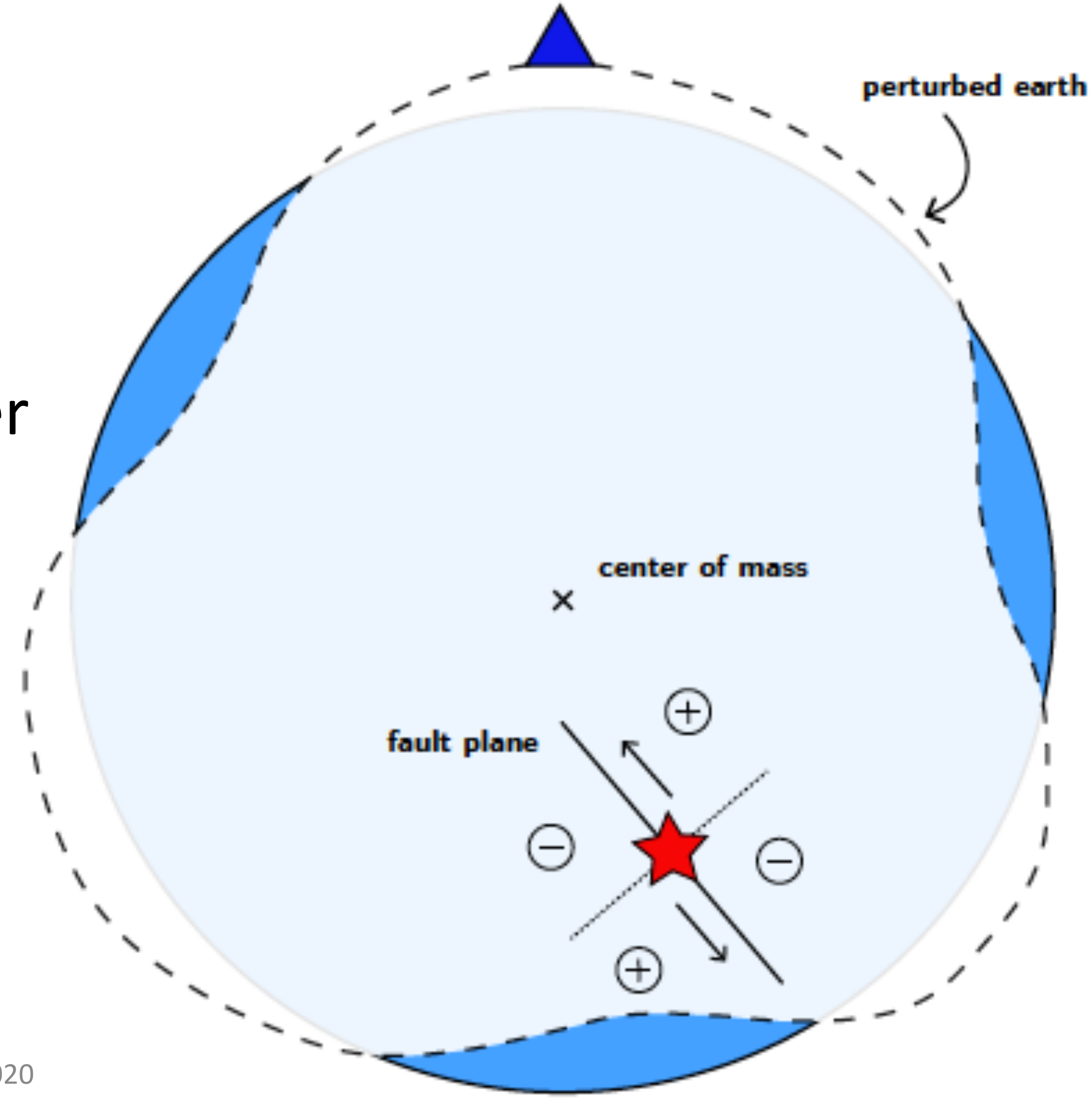
Δ ≈ 90° (≈10 000km)



Instantaneous: EEWS?

Gravity perturbations induced by earthquakes?

Galileo Galilei
Free fall at Pisa Tower
(1604)

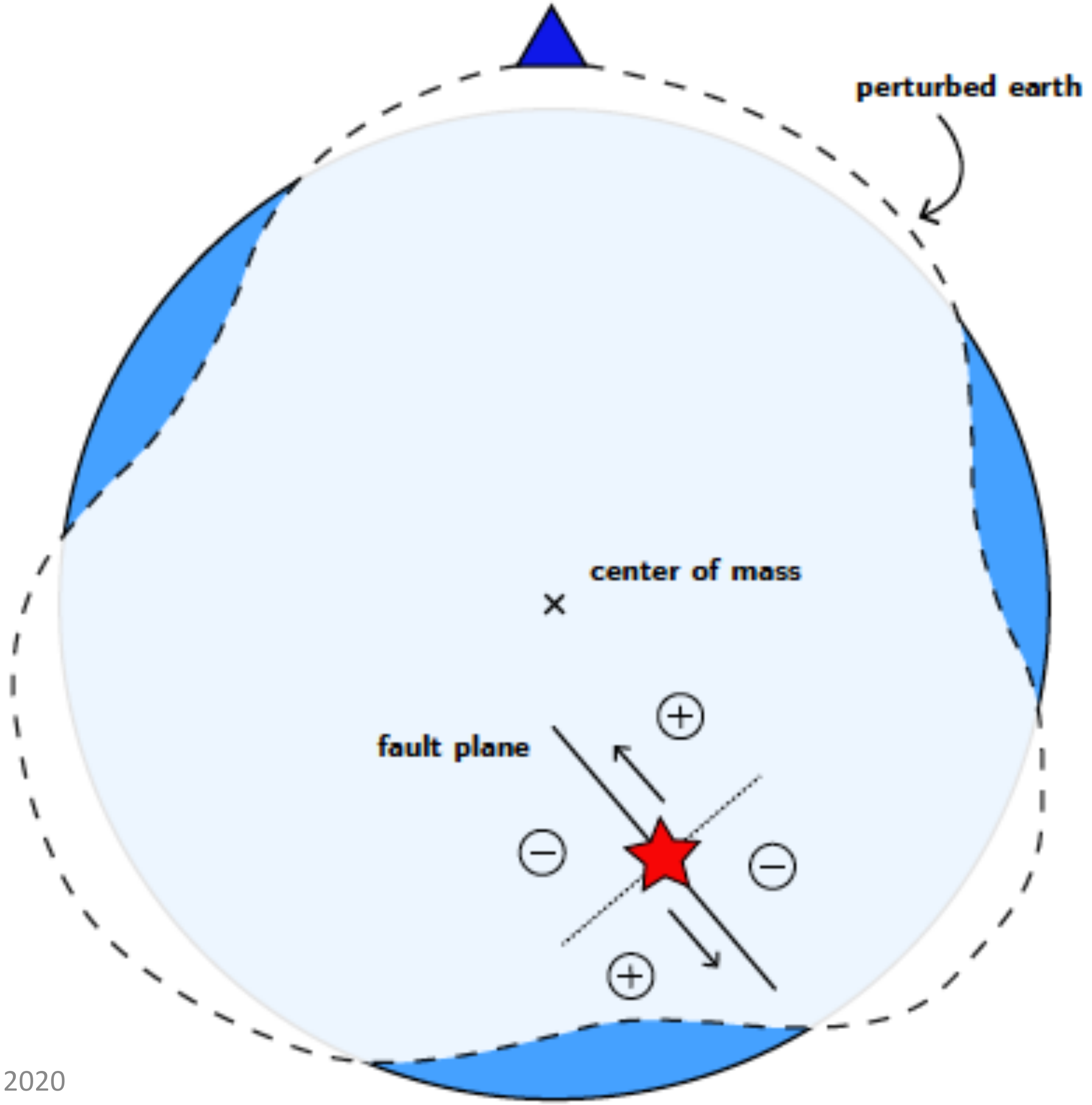


Isaac Newton:
universal gravitation law (1685)

Gravity perturbations induced by earthquakes

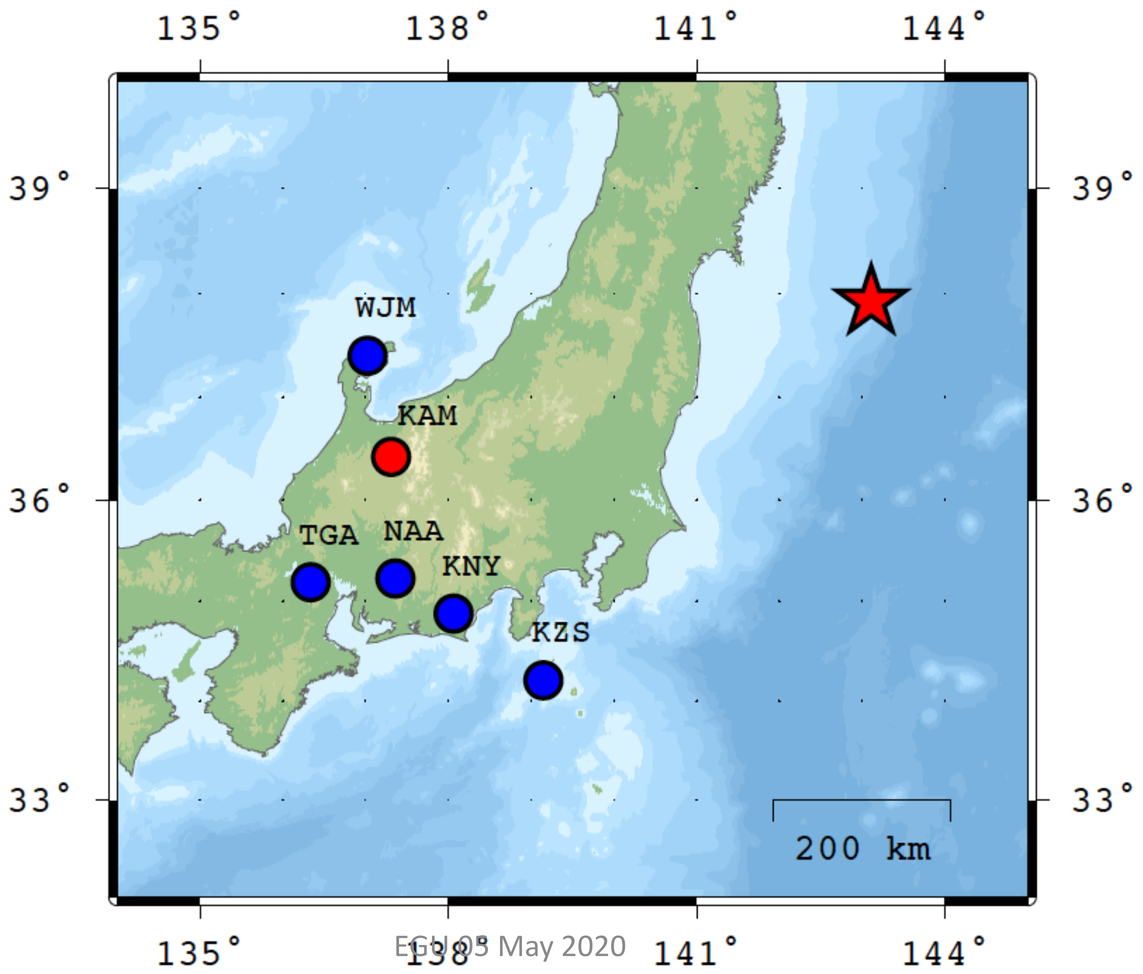
-Mass redistribution $-\nabla(\rho_0 \mathbf{u})$
-Free air gravity anomaly: perturbation of the Earth surface
Okubo, GJI, 1991, JGR, 1992, …

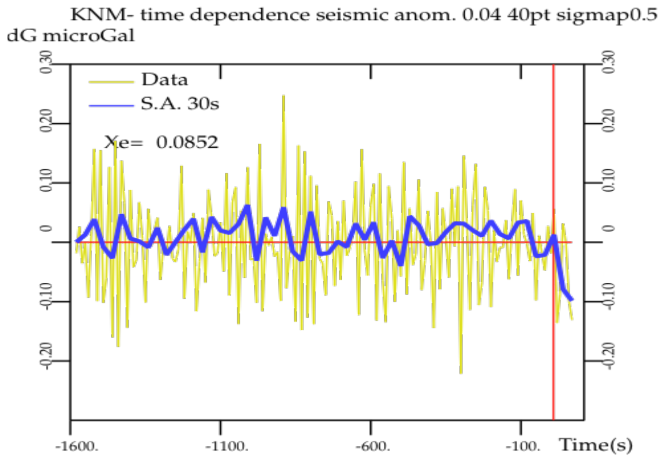
Theoretical Approach
-direct numerical calculations (plane case):
 (Harms et al., GJI, 2015, 2016)
 (Vallée et al., Science, 2018)
-Normal mode Theory (spherical case)
 (Juhel et al., GJI, 2018)

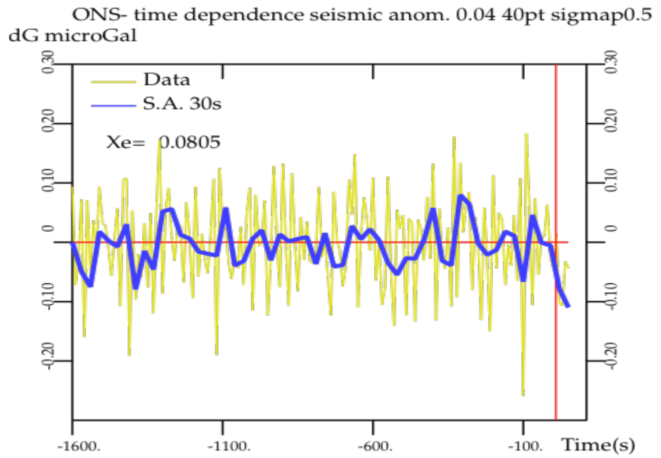


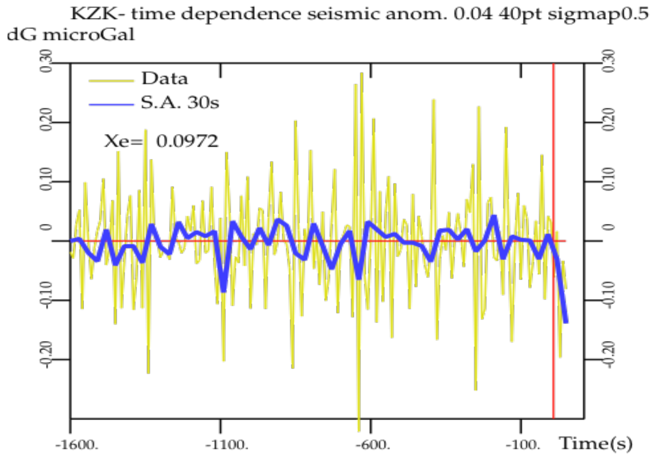
From Static to **Dynamic** gravity changes induced by earthquakes

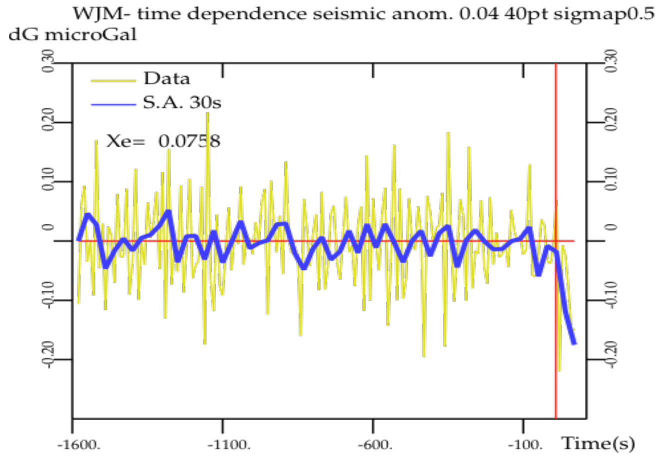
Superconducting gravimeter Kamioka
+ Broadband Japanese network F-NET (STS1, STS2…)

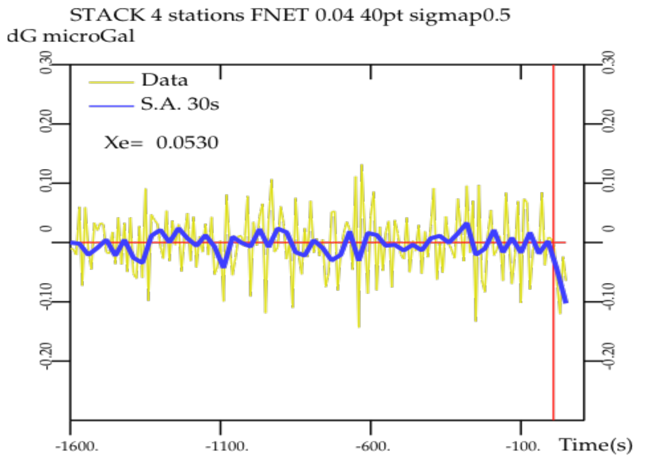


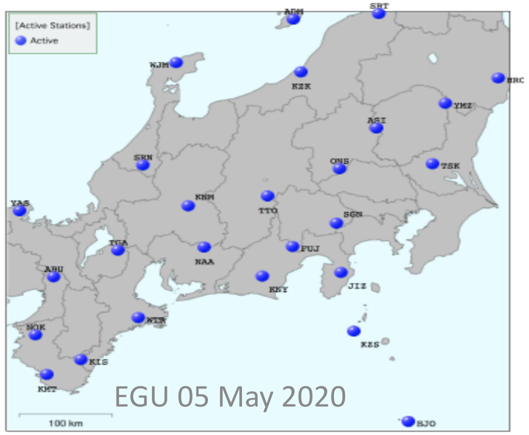




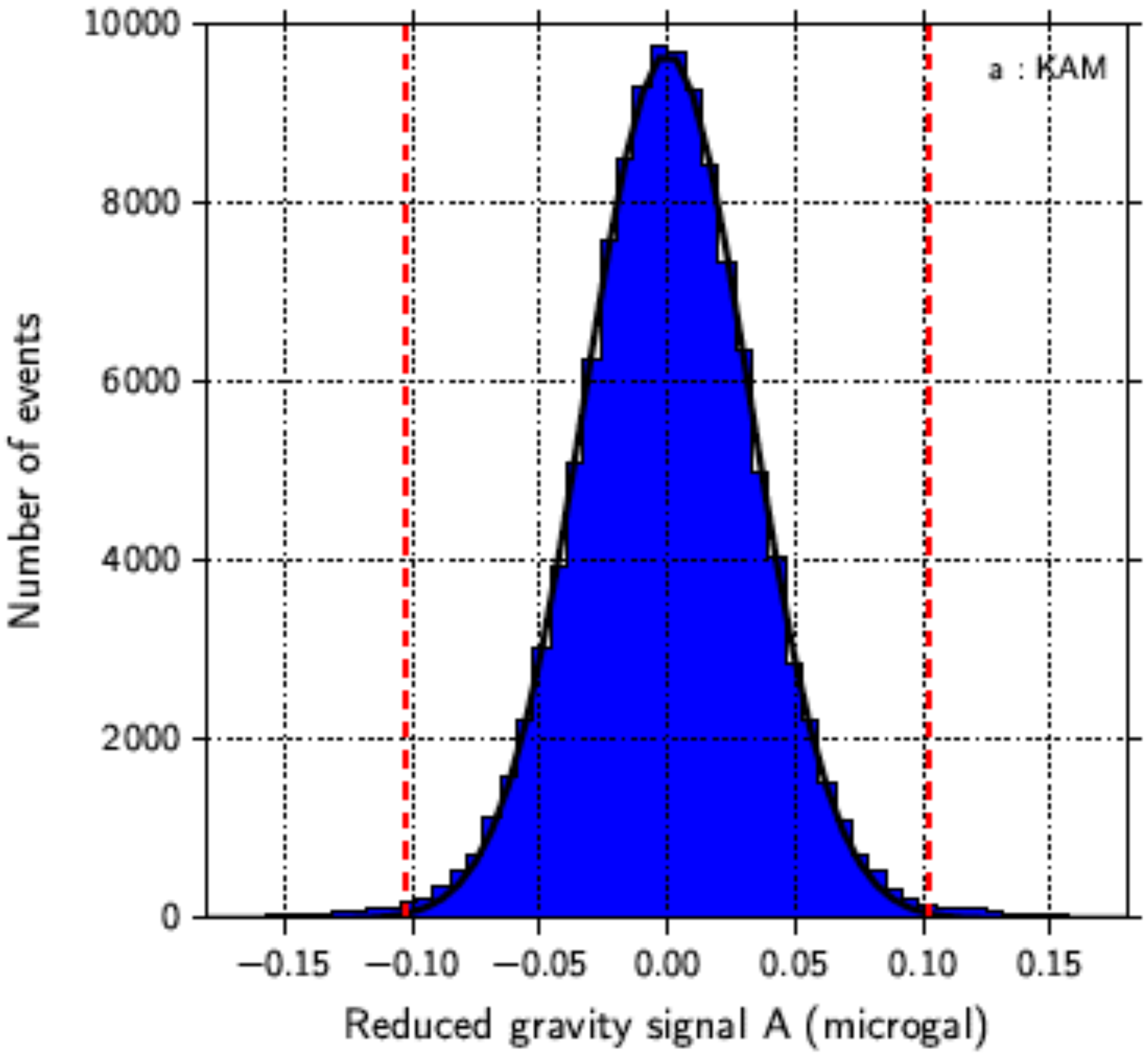






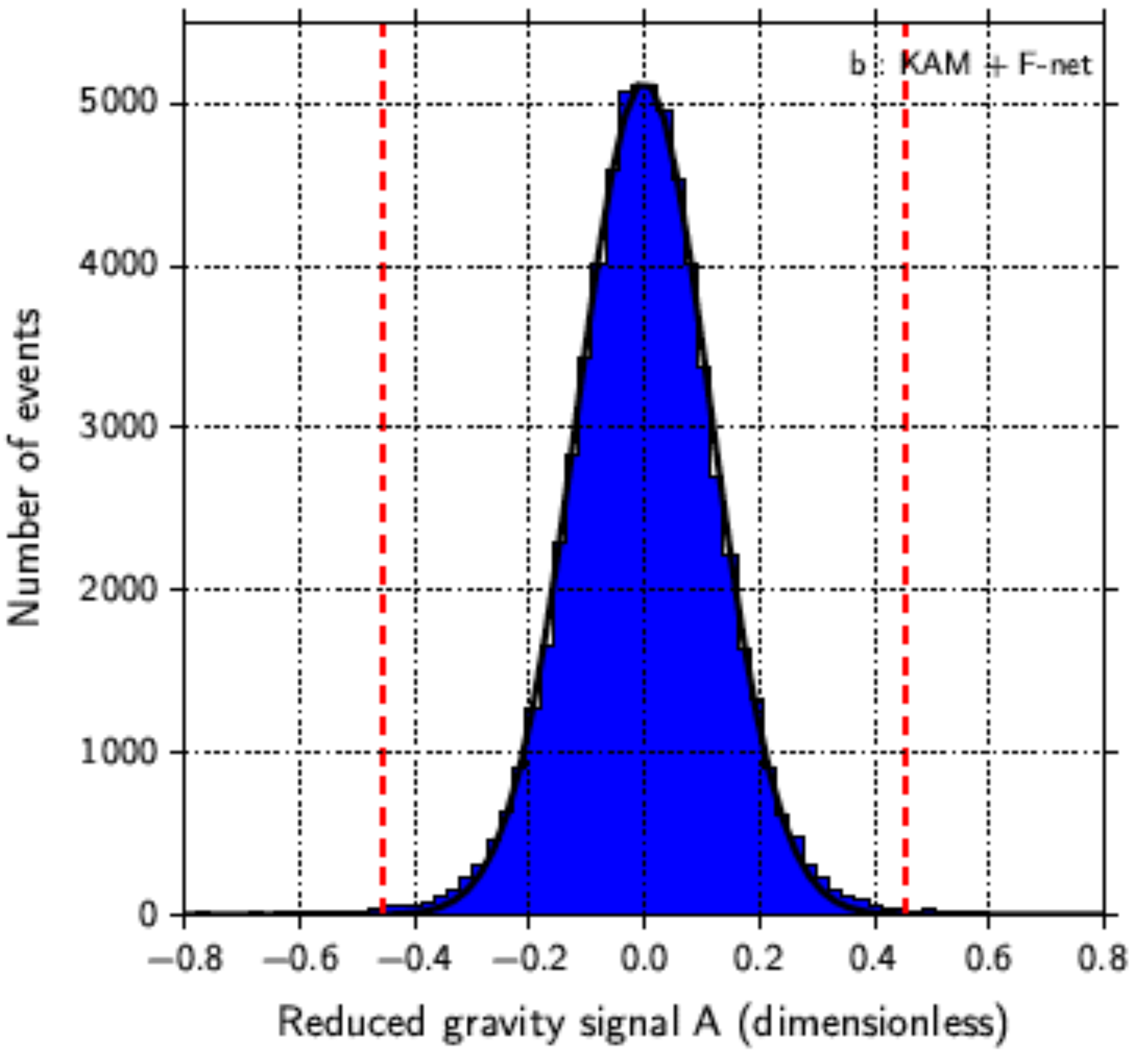


Speed-of-light signal:
Stack of japanese F-NET broadband data
+ SG Kamioka



For the Kamioka station only :

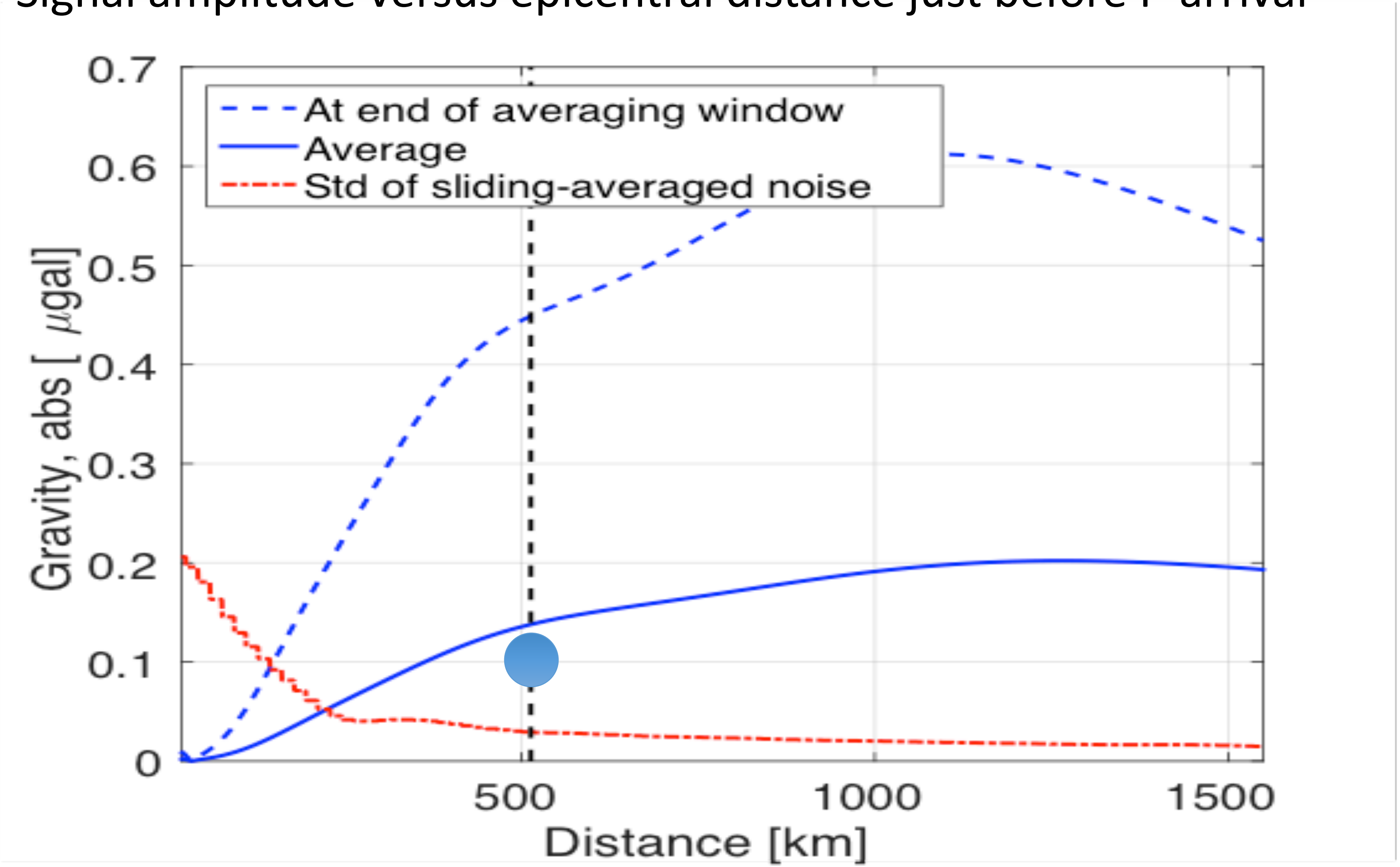
$p(A > A_{Tohoku}) = \mathbf{1.6\%}$



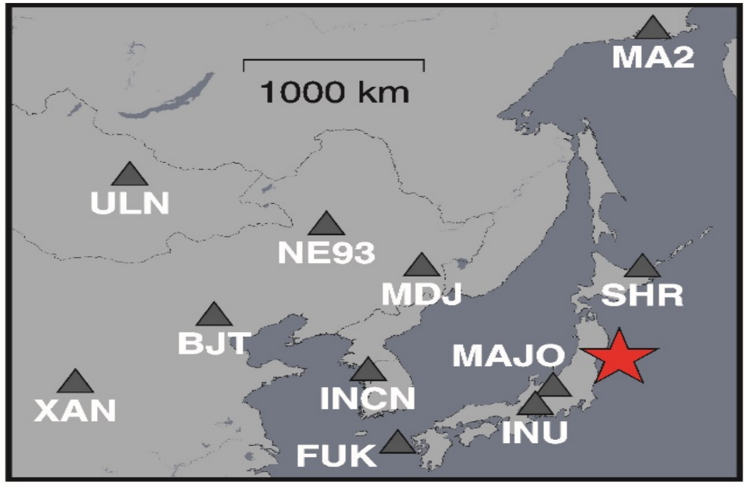
For a stacked waveform :
Kamioka + 5 F-net

$p(A > A_{Tohoku}) = \mathbf{0.82\%}$

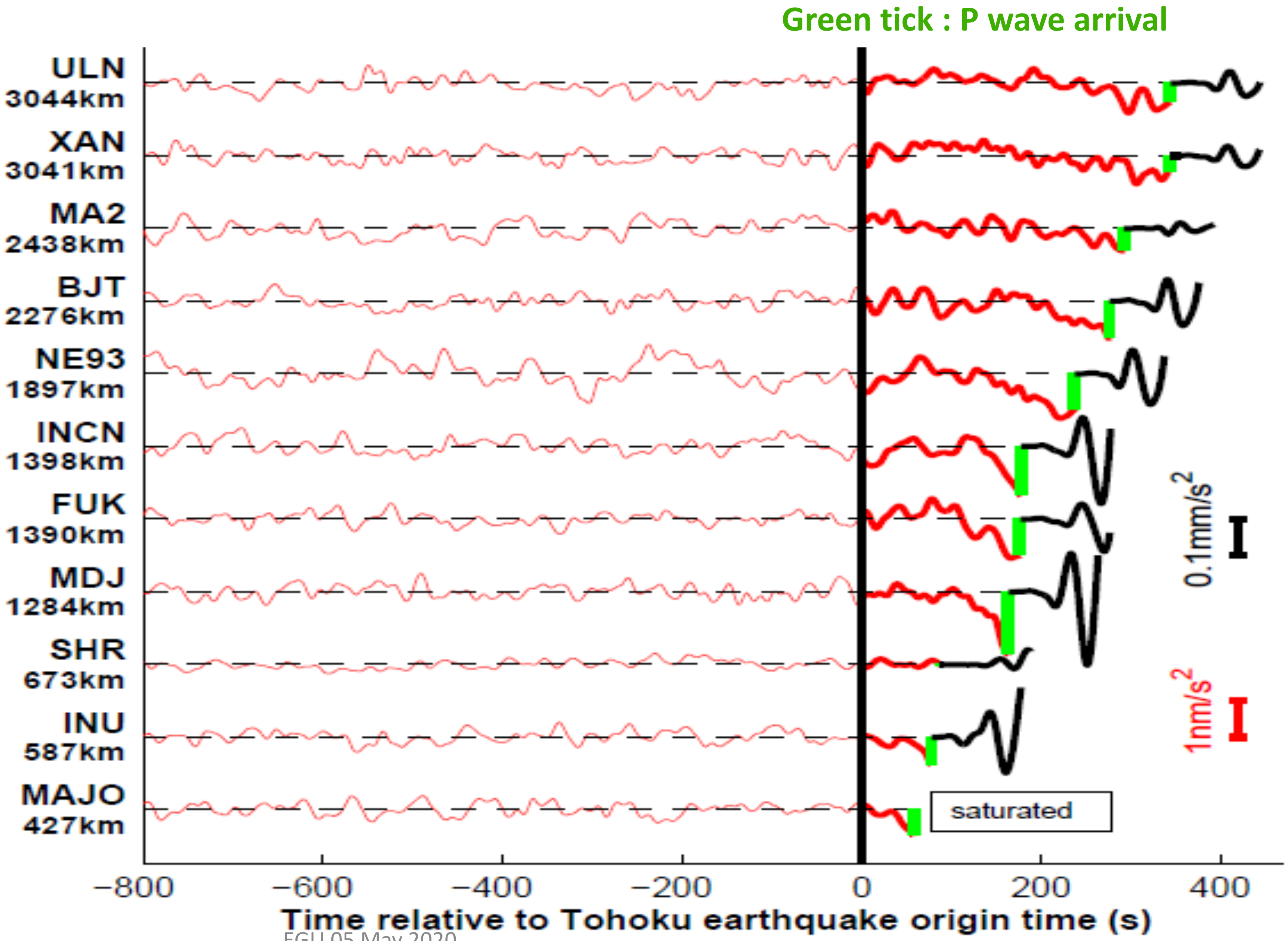
Signal amplitude versus epicentral distance just before P-arrival



Montagner et al., 2016



With seismometers, such a tiny signal requires excellent stations to be recorded

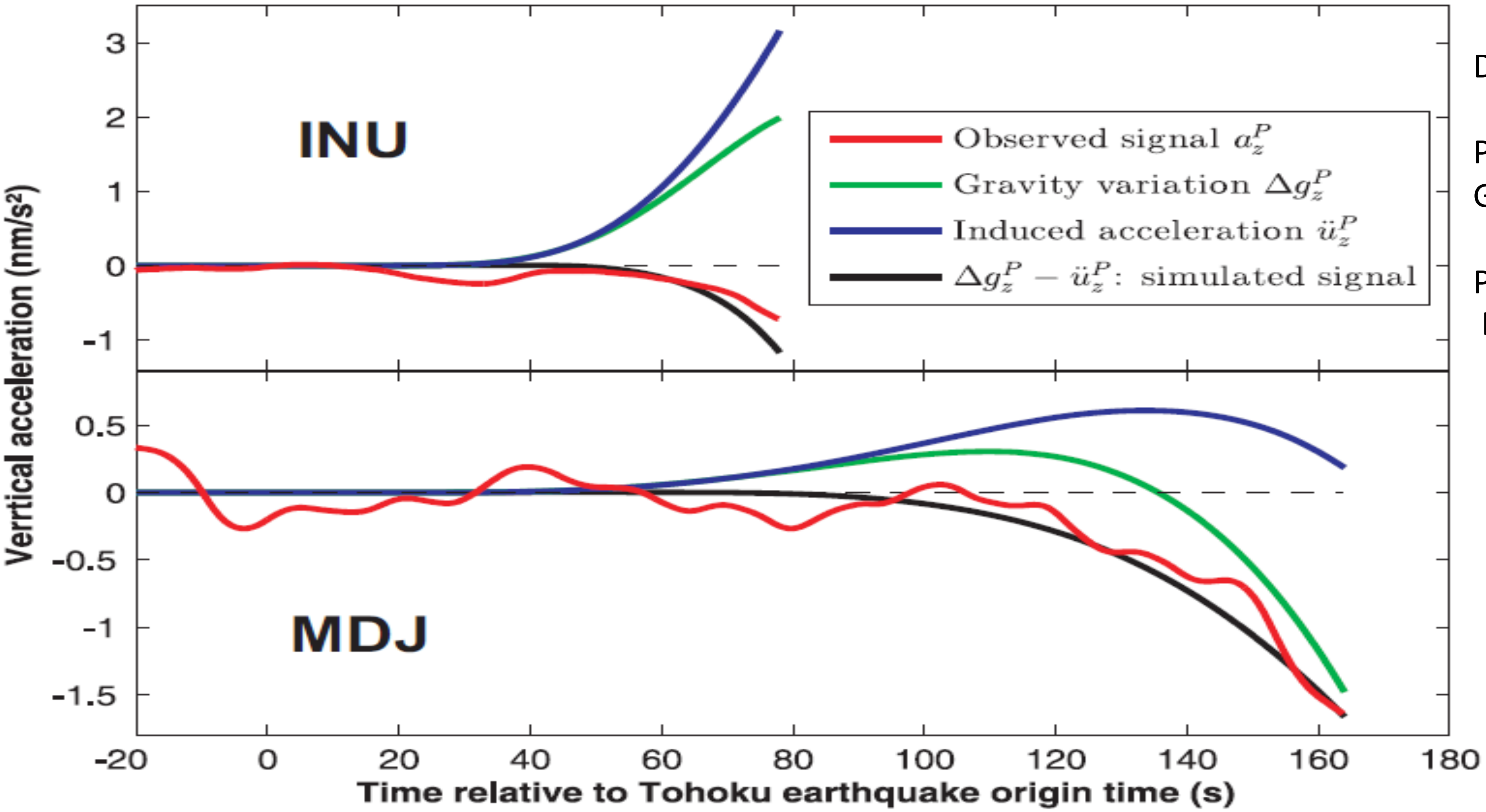


FDSN stations (IRIS or GEOSCOPE) + F-NET (Japan)
0.002-0.03Hz frequency range

Relative amplitudes between the pre-P and the post-P signals
Pre-P signals are 10^5 to 10^6 smaller

Vallée et al., Science, 2017

Data & simulations at INU (GEOSCOPE, G) and MDJ (IRIS-China, IC)



DISTINCTION

PGS: Prompt Gravity Signal

PEGS: Prompt Elasto-Gravity Signal

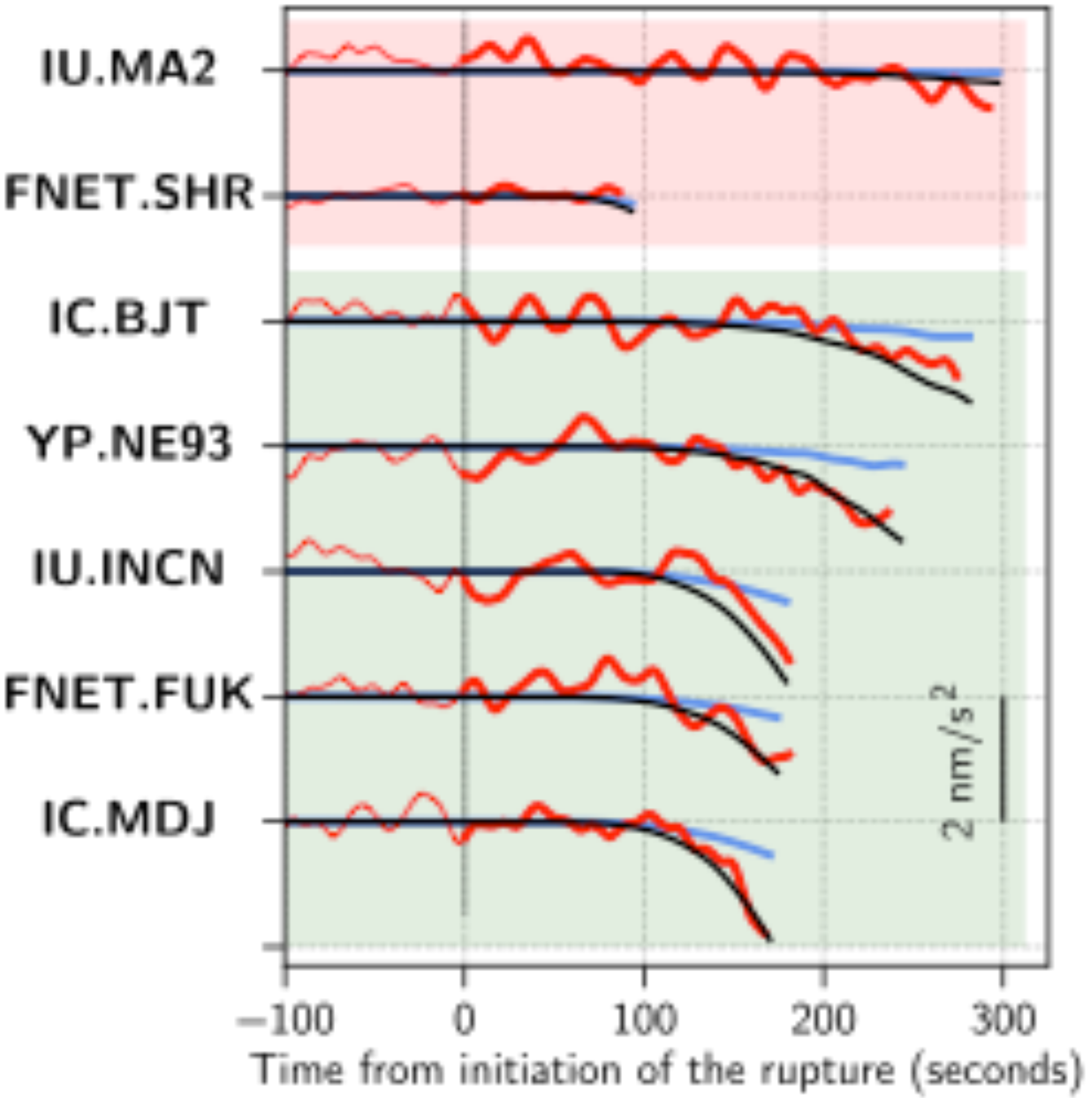
Heaton, Nature Com., 2017

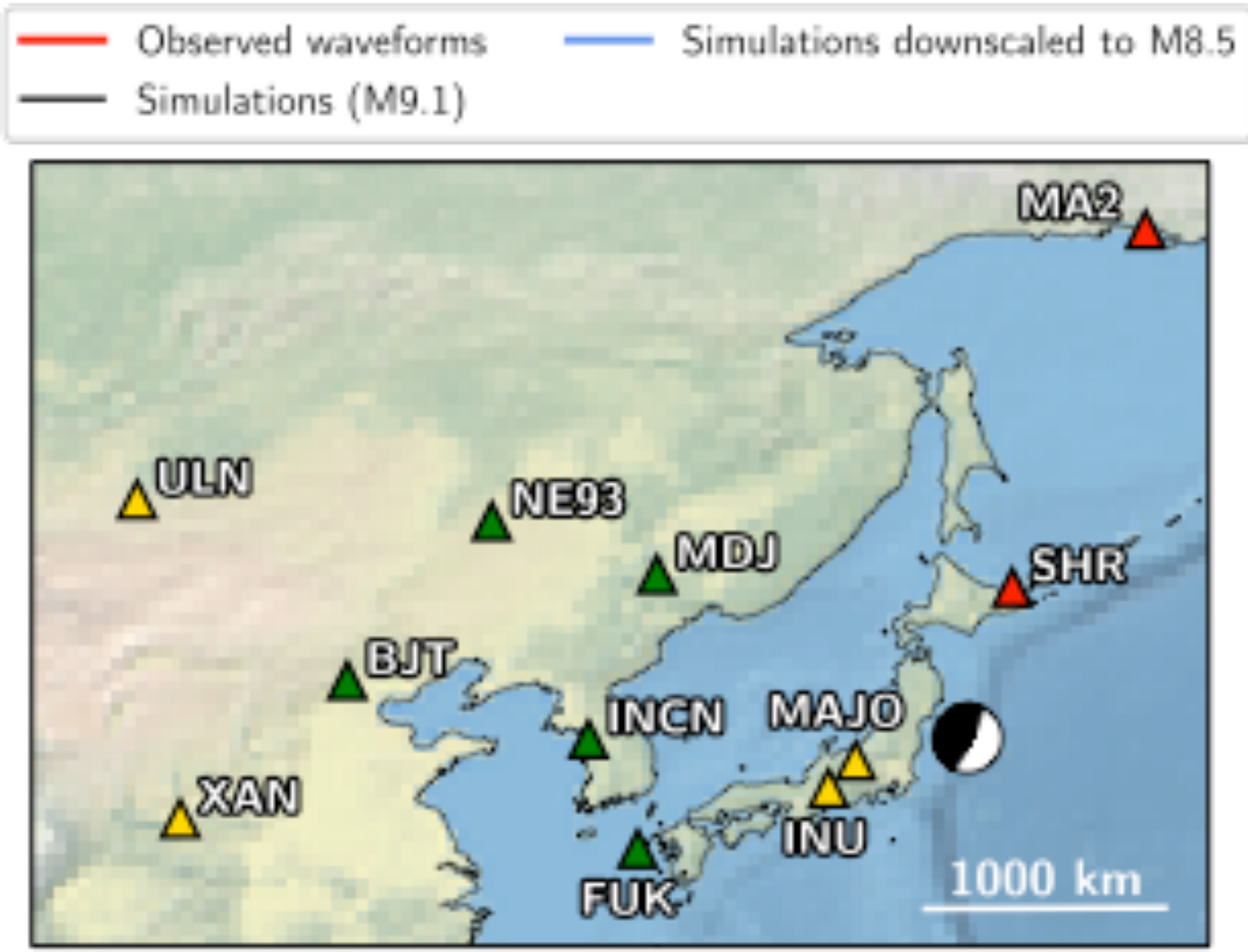
Vallée et al., Science, 2017

Juhel et al., G.J.I., 2018

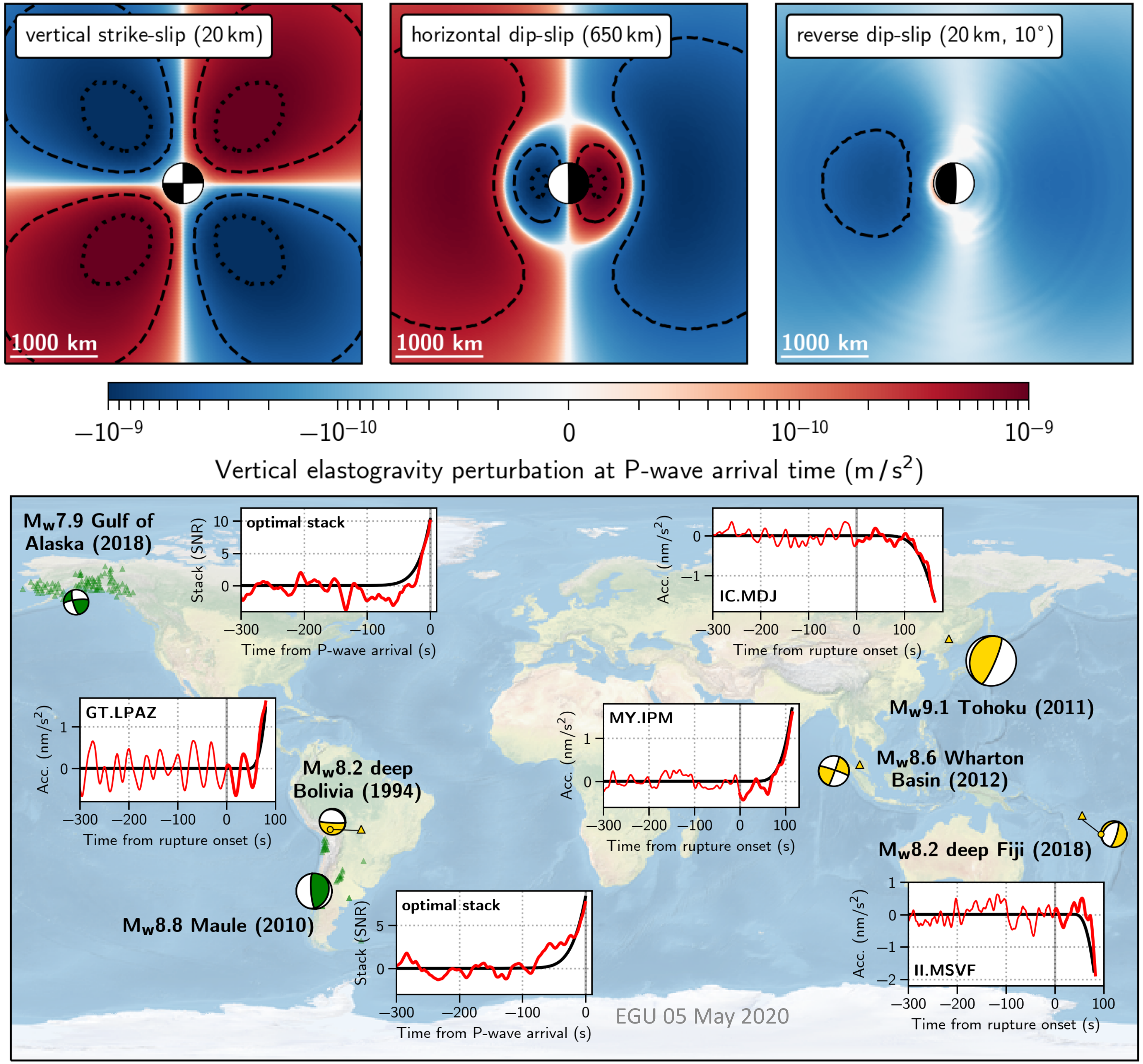
Prompt gravity signal and inertial acceleration do not cancel

Complete simulation at all stations





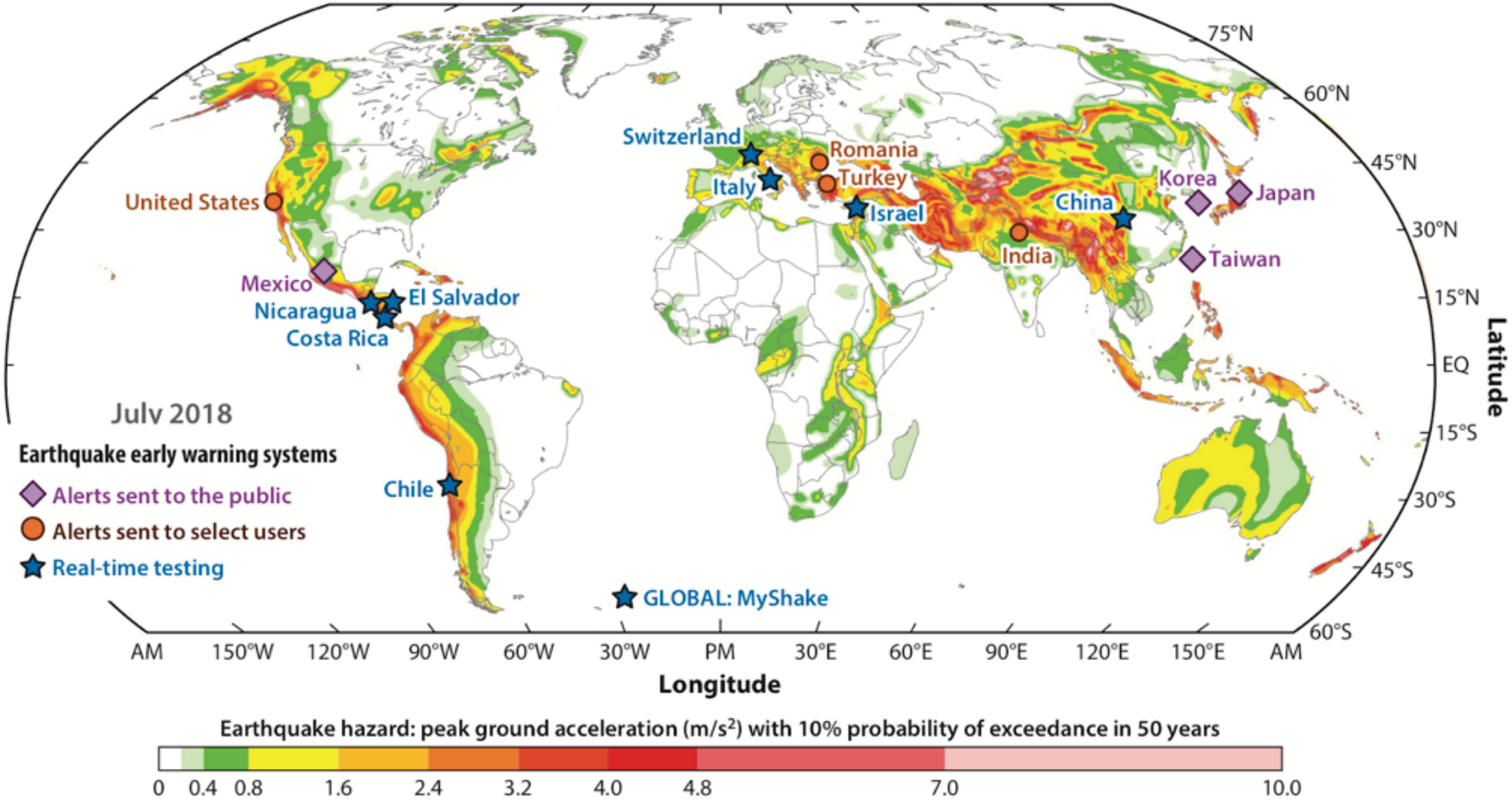
Vallée et al., Science, 2017



New detection of PEGS (prompt elasto-gravity signals) for other earthquakes

Vallée & Juhel, 2019

Earthquake Early Warning Systems in the World Based on P-wave detection



Status of EEWS around the world up to July 2018. Shown are the locations of systems that broadcast alerts to all members of the public (purple), systems distributing alerts to select users (orange), and systems undergoing real-time development and testing (blue).
The background colors indicate the seismic hazard (see colorbar legend) (From Allen et al., 2019).

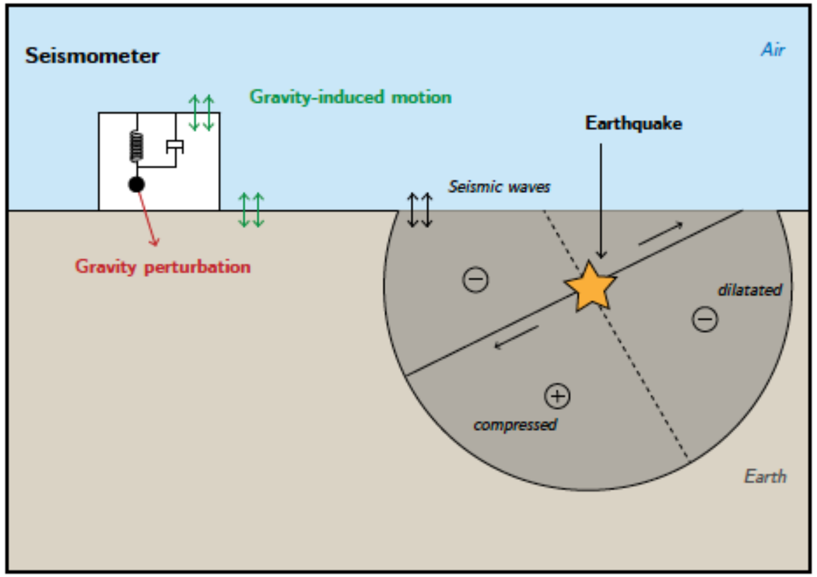
NEED FOR NEW INSTRUMENTS
(gradient of the gravity field)

Sub-Hz gravitational –wave detection

1) Superconducting gradiometers

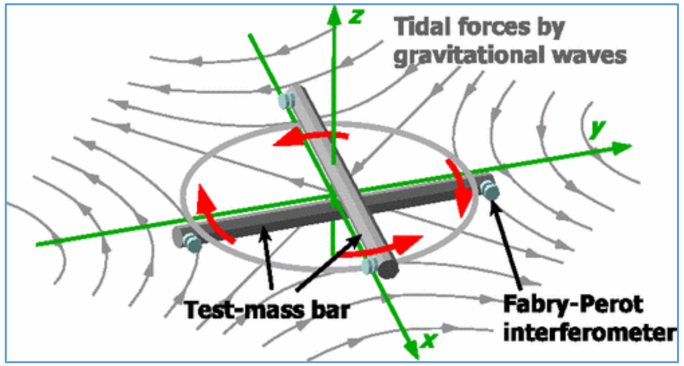
2) Atom interferometers

3) Torsion bar antennas
   (Collaboration with Univ. Tokyo)



PEGASEWS detector

Prompt Earthquake GrAvity Signals- Early Warning System



Barsuglia et al. 2018

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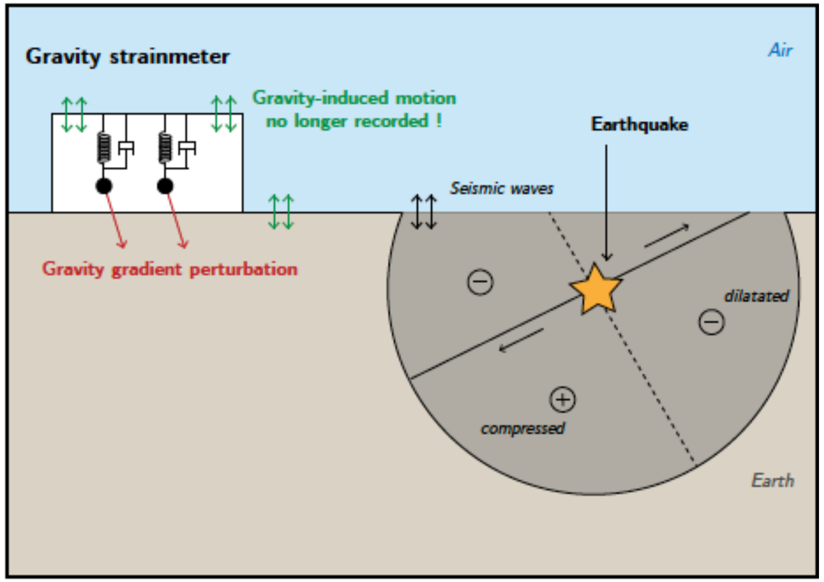
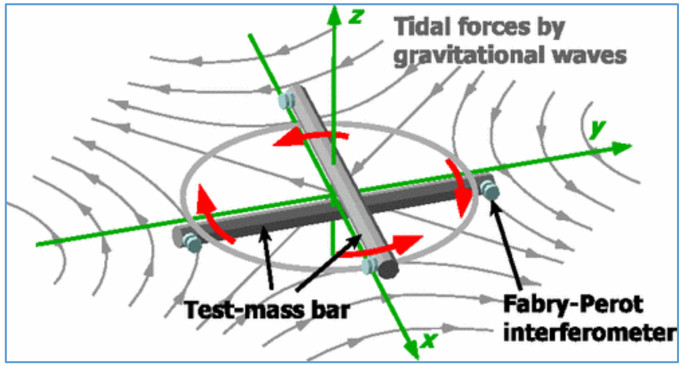


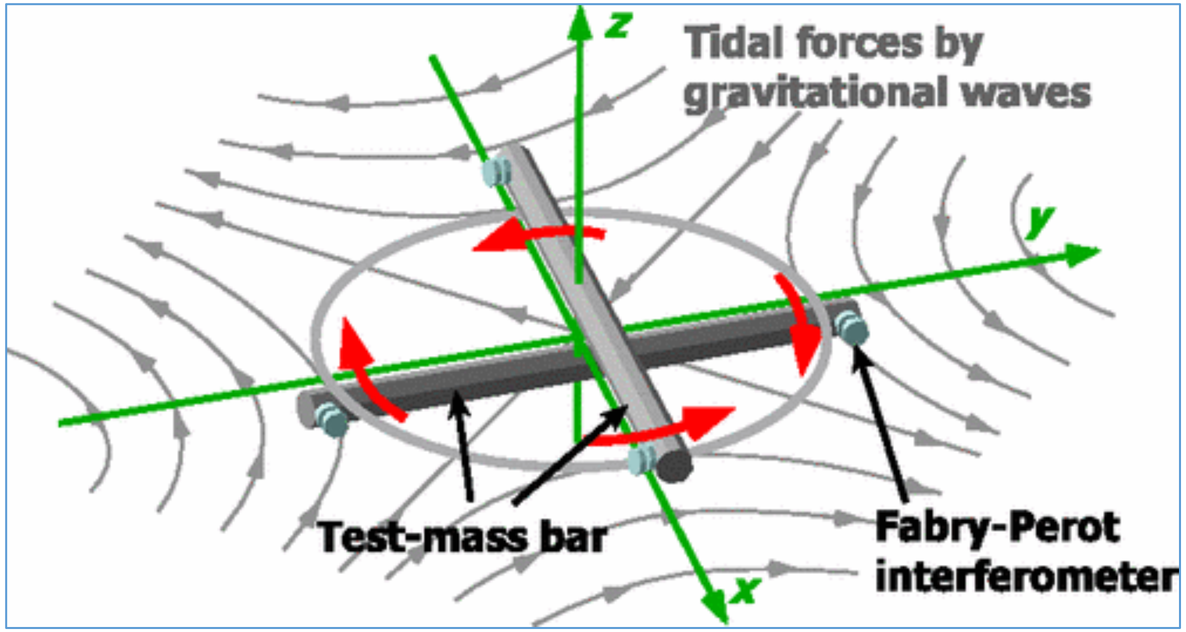


PEGASEWS detector

Prompt Earthquake GrAvity Signals- Early Warning System

Barsuglia et al. 2018

Sub-Hz Gravitational wave detectors: TOBA

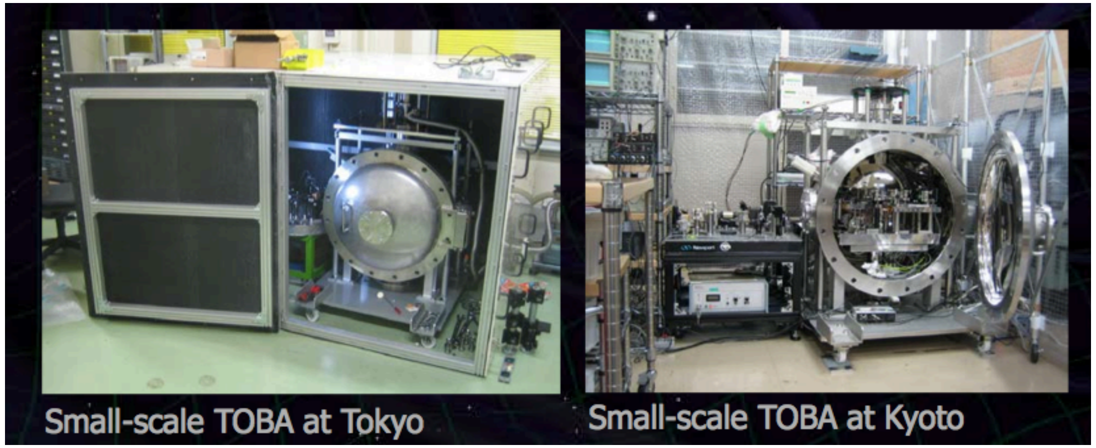


TOBA concept (torsion-bar antenna)-
University of Tokyo   (Ando et al., 2010)

Devices designed to measure **gravitational waves**, minute distortions of space-time that are predicted by Einstein's theory of **general relativity**
Max Sensitivity 0.1Hz (seismic band)

Present sensitivity 10^{-8}

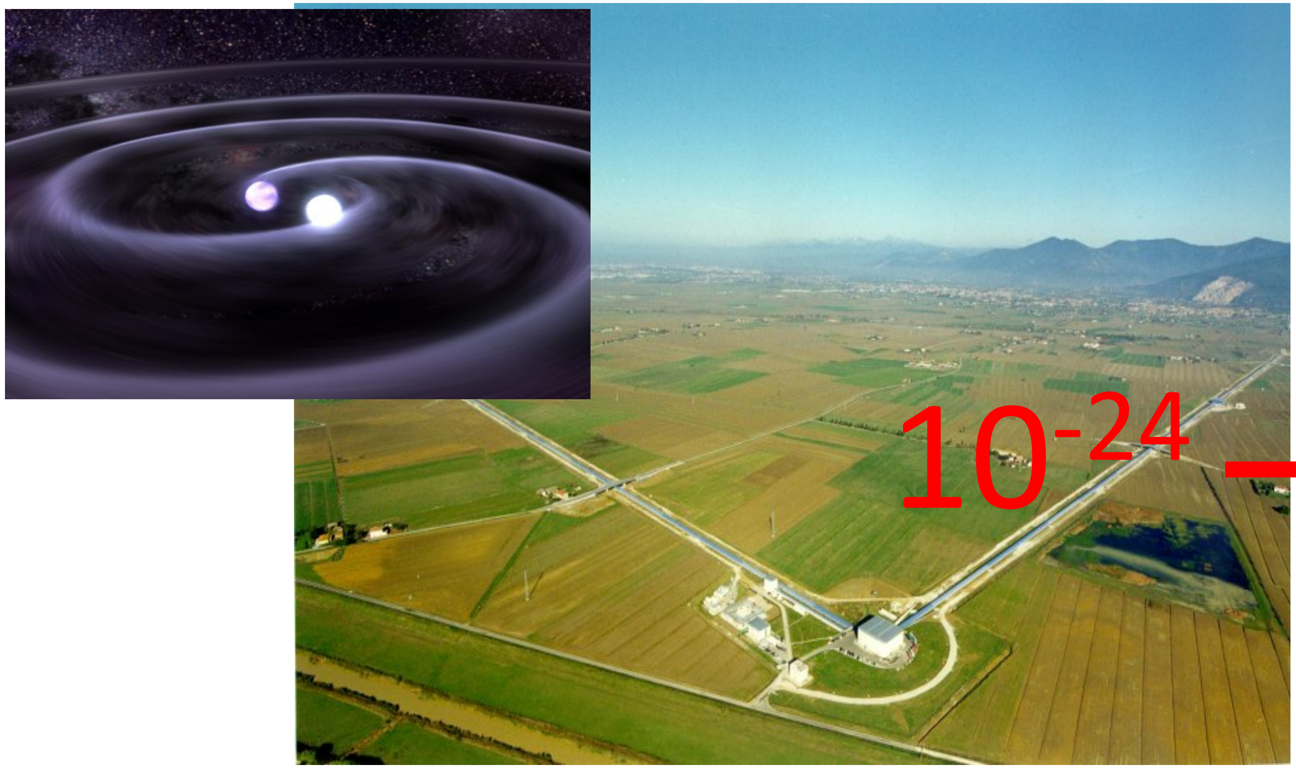
=> goal **PEGASEWS** 10^{-15} √Hz

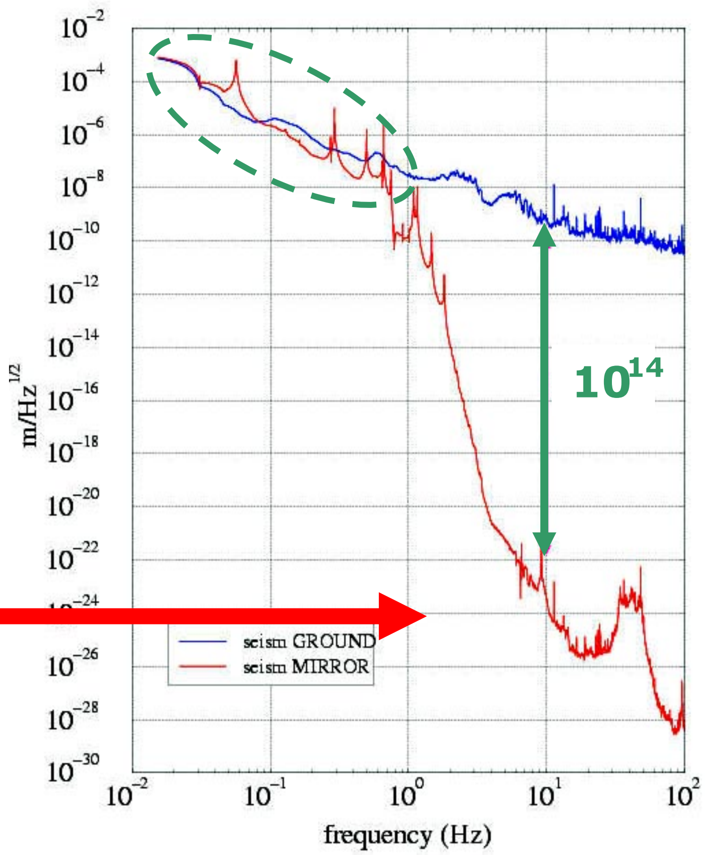


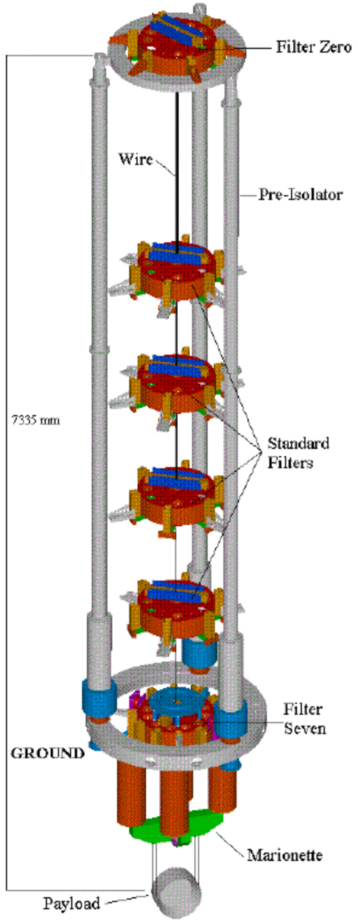
LABEX UnivEarthS (2012)- Geophysics
Gravitational wave interferometers: VIRGO

VIRGO (Italian – French Gravitational wave detector)

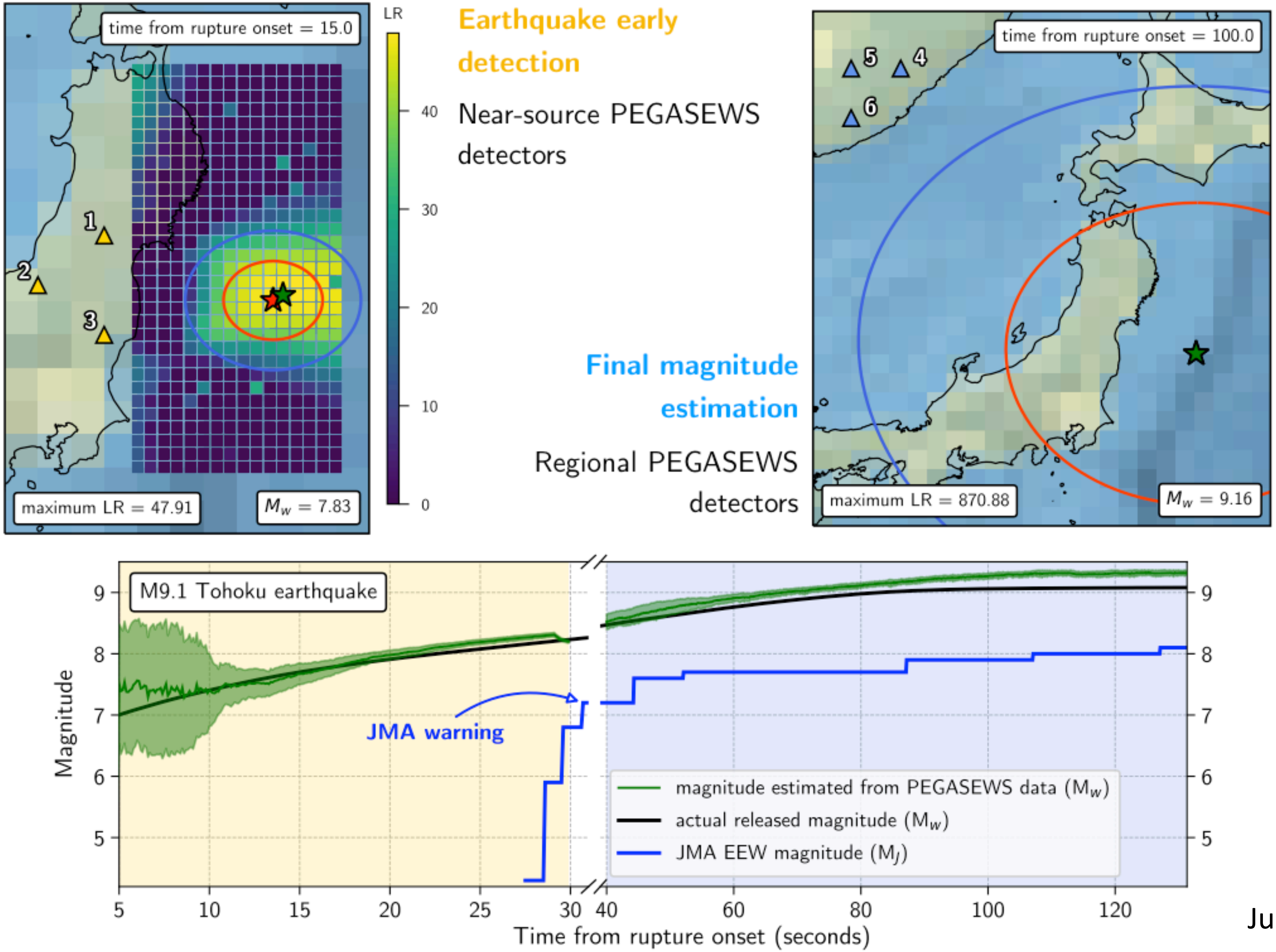
10^{-18} -> 10^{-24}





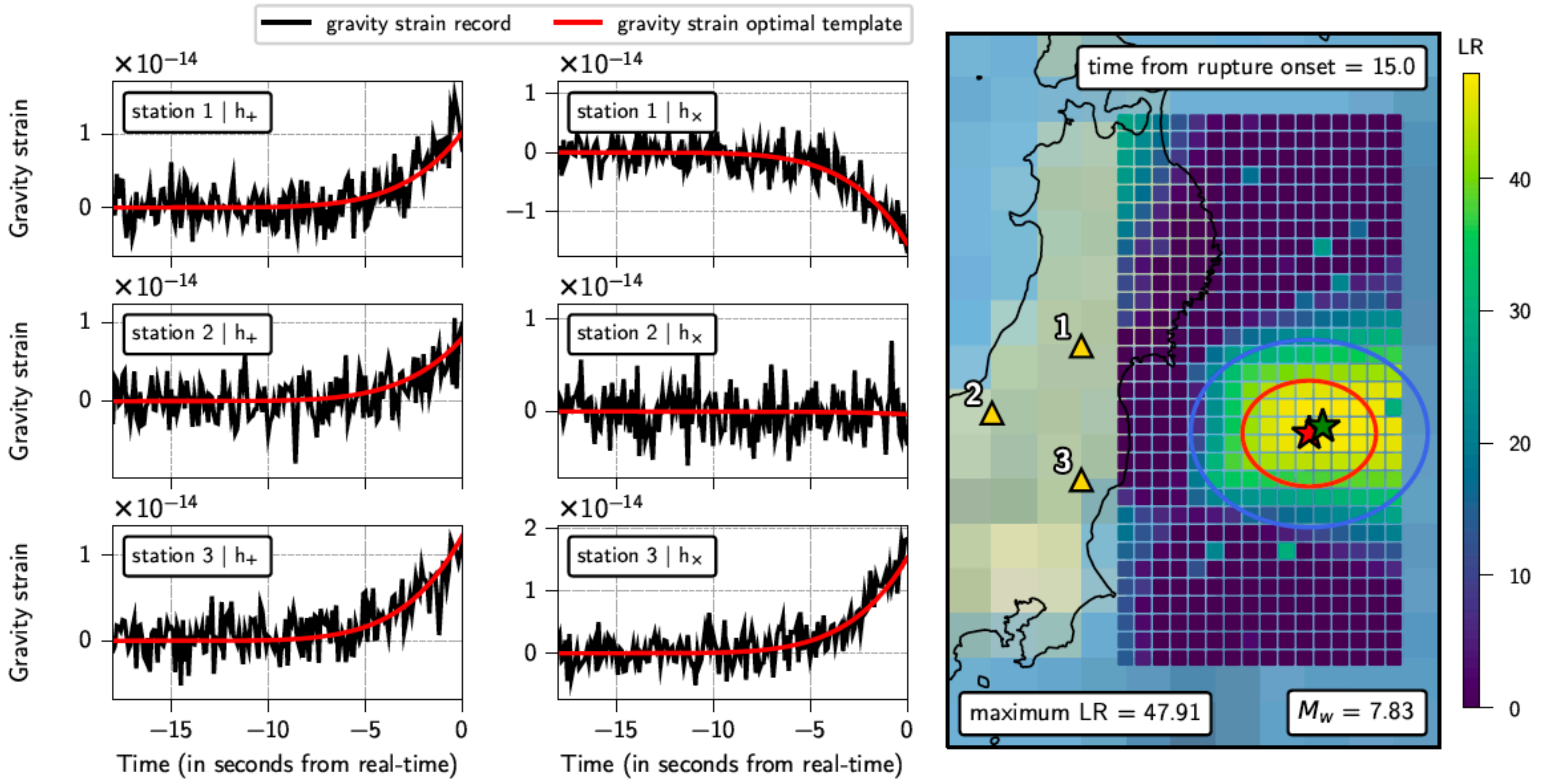


Seismic wall at f>1 Hz



Juhel et al., 2019

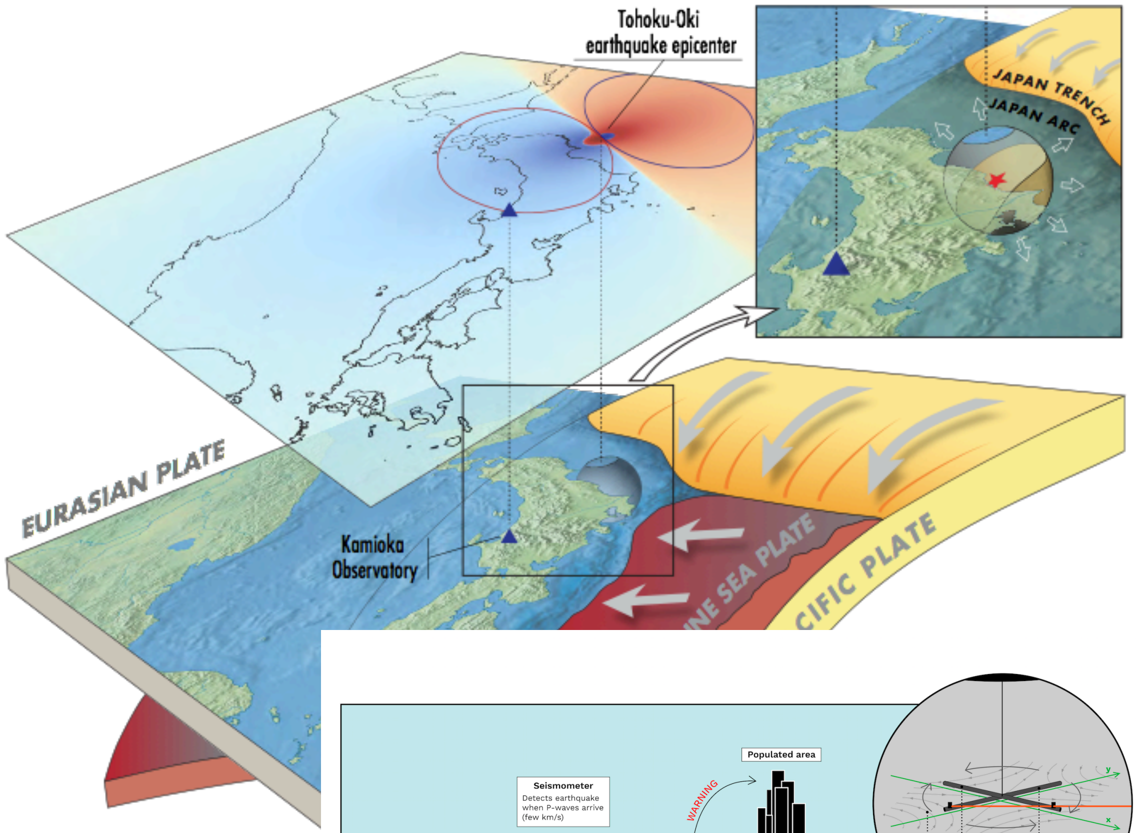
What can we expect with a network of 3 PEGASEWS detectors?

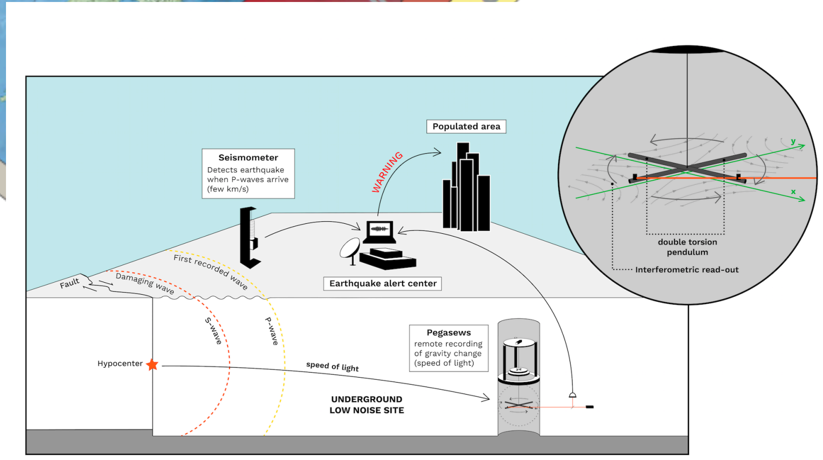


Juhel et al., 2019

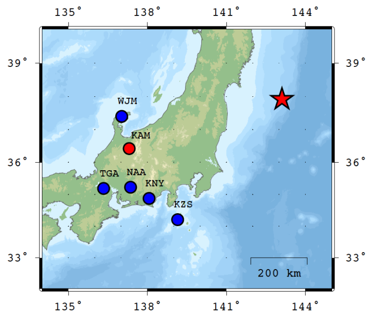
Conclusions:

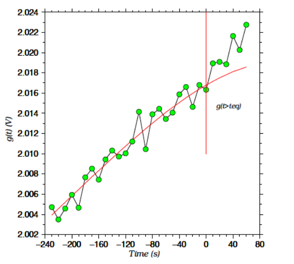
From Gravity field to **Earthquake Early Warning Systems**



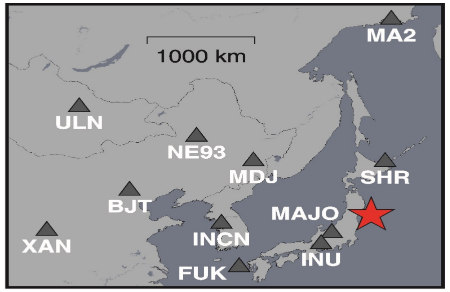


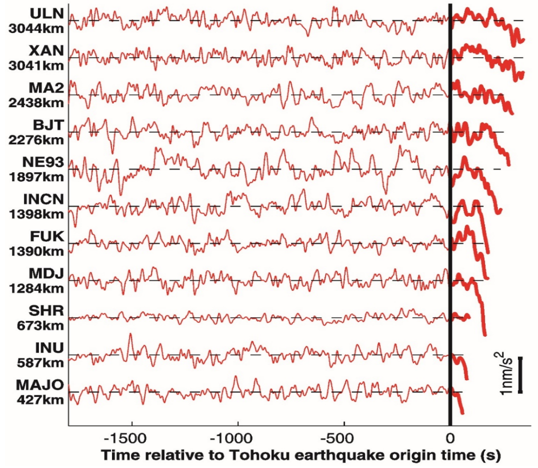
- Detection of a prompt gravity signal for Tohoku eq.: Very, very small $<10^{-9}$ m/s^2





- Detection on Superconducting gravimeter, VBB stations in Japan and Eastern Asia ≈-0.1-0.2μGal at 500-1000km (Montagner et al., 2016; Vallée et al., 2017)
- For other earthquakes (Vallée & Juhel, 2019)





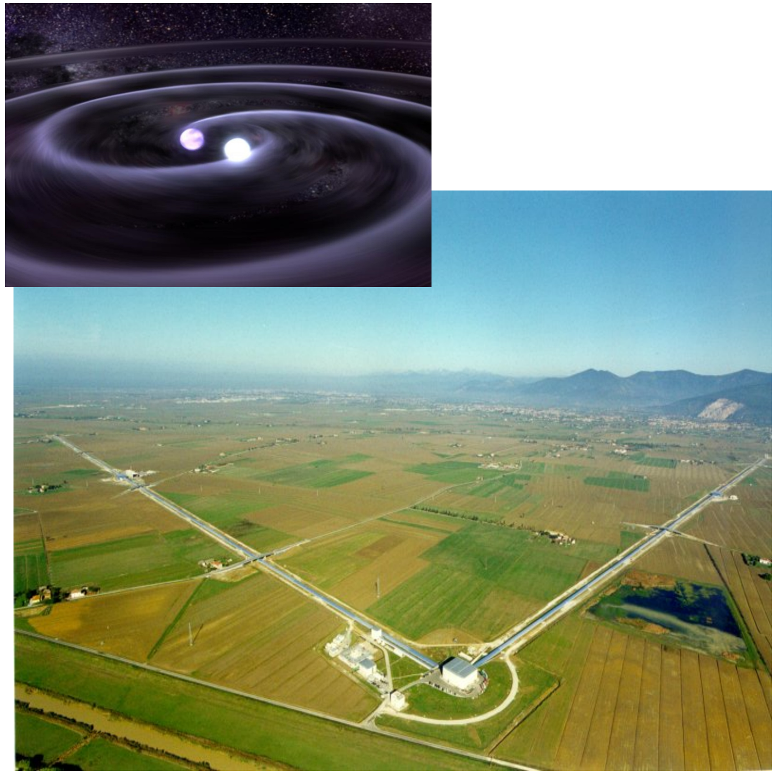
- **EEWS: magnitude estimate**
- Need for new gravity Instruments (TOBA, Atom Interferometers, superconducting gravimeters) In the frequency range 0.01-1Hz

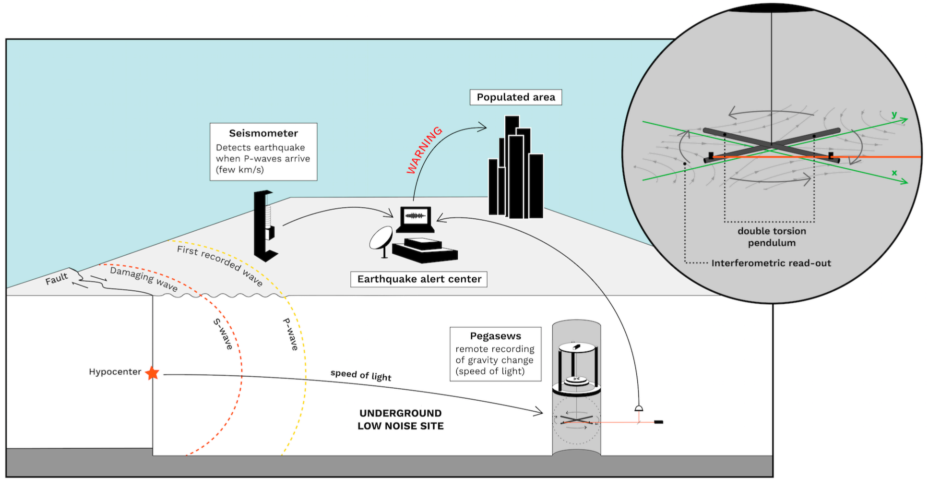
Conclusions

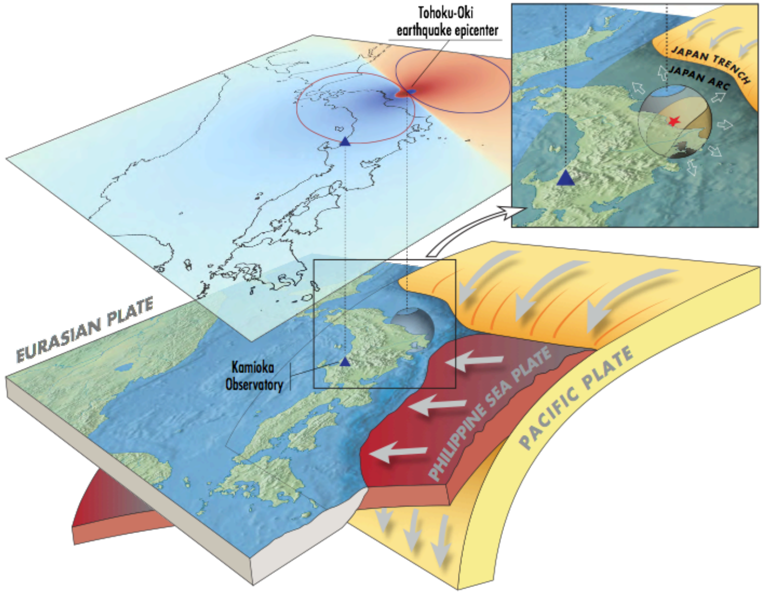
From gravitational waves to **Earthquake Early Warning Systems**

Speed of light seismology

PEGASEWS project



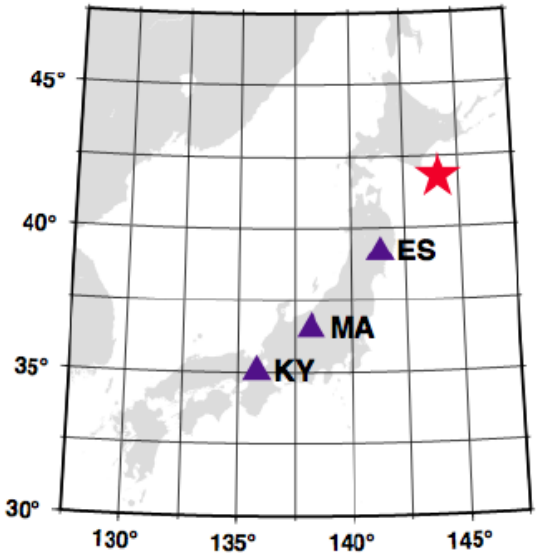


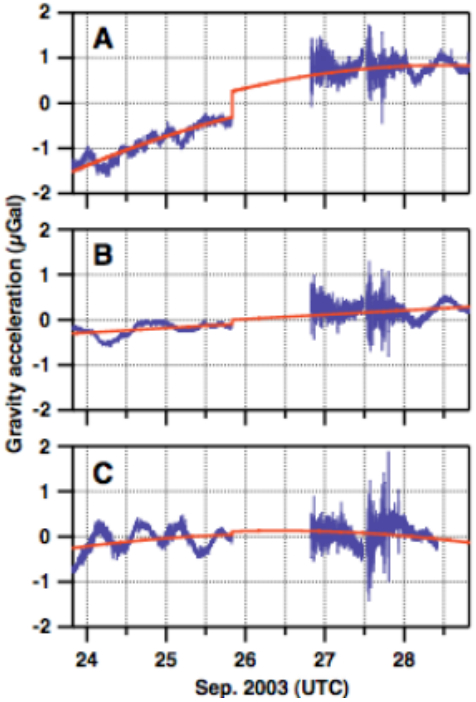


Static gravity changes induced by earthquakes measured

- Ground-based stations: Superconducting gravimeters after large earthquakes

(2003 M=8.0 Tokachi-oki earthquake)

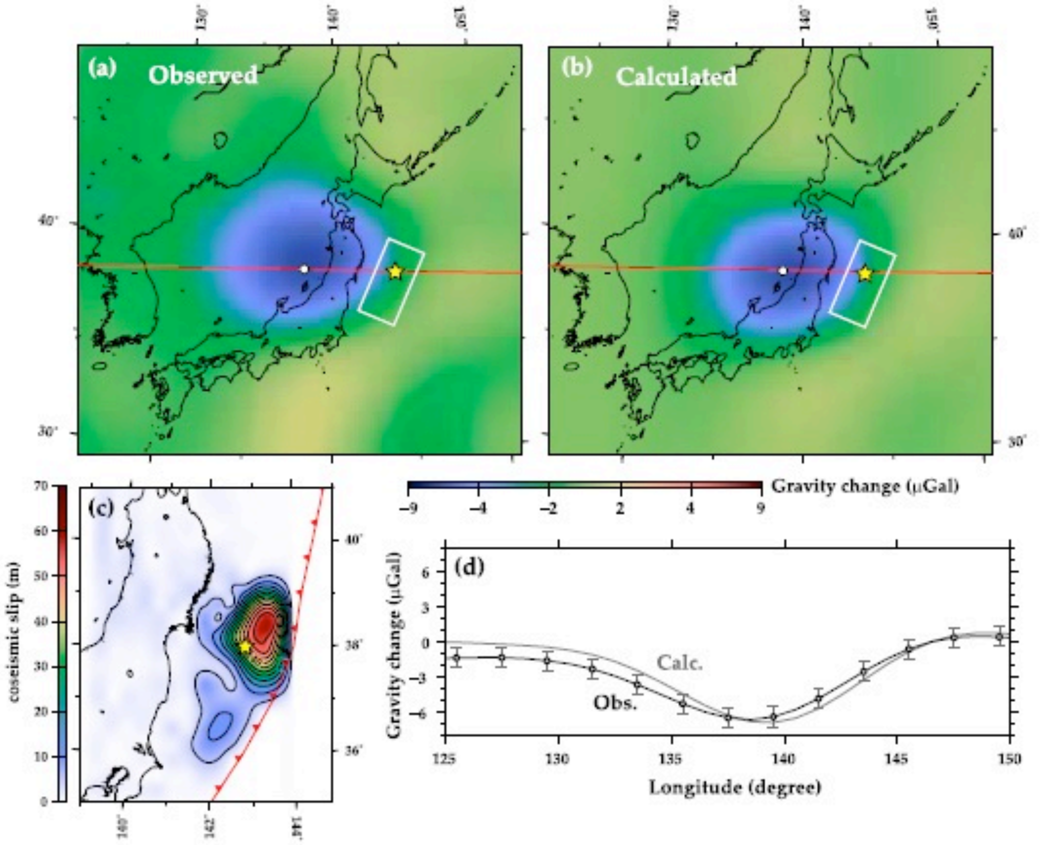




Imanishi et al. (Science, 2004)

- GRACE / GOCE satellites

gravity changes after versus before large earthquakes (2011 M9.0 Tohoku-oki earthquake)



Matsuo and Heki (2011)

Insights from the set of self-gravitating equations

$$\begin{cases} \rho_0\, \ddot{\mathbf{u}} &= \boldsymbol{\nabla} \cdot \boldsymbol{\sigma} + \Delta\rho\, \mathbf{g_0} + \boldsymbol{f} + \rho_0\, \boldsymbol{\Delta}\mathbf{g}\,, \\ \nabla \cdot \boldsymbol{\Delta}\mathbf{g} &= -4\pi G\, \Delta\rho\,, \\ \Delta\rho &= -\nabla \cdot (\rho_0\, \mathbf{u})\,, \end{cases}$$

Force balance equation

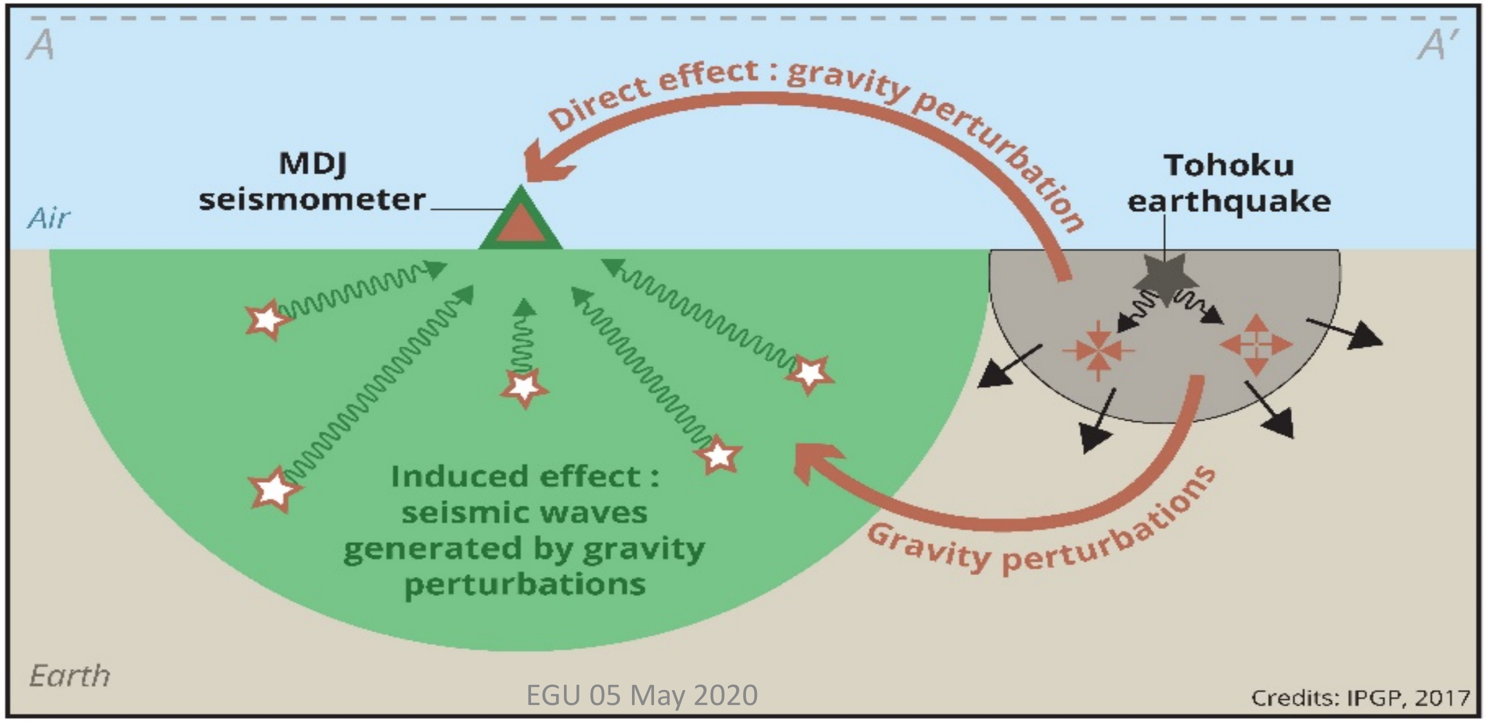
Poisson equation

Continuity equation

In this general formulation, there is **a full coupling** between the gravitational perturbation **Δg** and the displacement **u**

However ***Δg*** and ***Δρ*** are coupled to the **displacement** field while **the force term** directly infuences the **acceleration**

Illustration of the modeling approach (Vallée et al., 2017)



Courtesy of
Martin Vallée