Speed-of-light Seismology

Detection of Prompt Earthquake Gravity Signals

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Giovanni Losurdo (INFN, Pisa, Italy), Martin Vallée (IPG-Paris)

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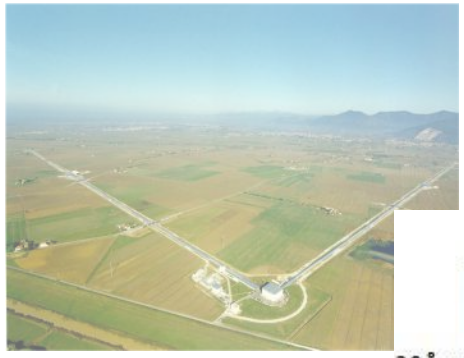
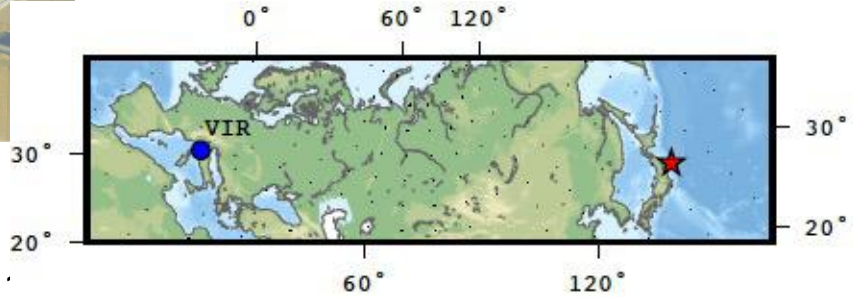
Outline: The story and the approach

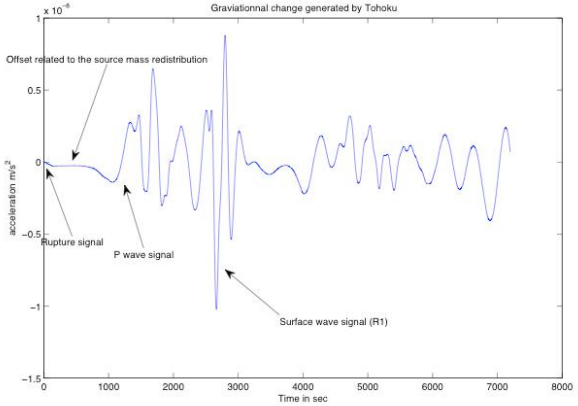
- **Motivation (2012)**



VIRGO
(*Gravitational wave Interferometer*)

normal mode calculation



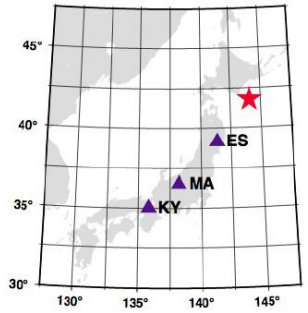


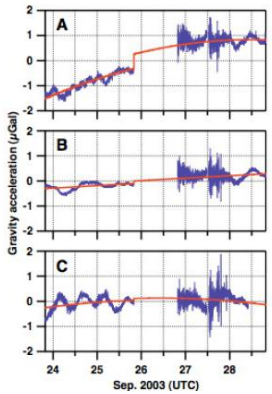
- **Search for « instantaneous » gravity signal**
  a) Very Large earthquakes:
  Sumatra (9.3; 26/12/04), Chile-Maule (8.8; 11)
  b) Instruments: Superconducting gravimeter, very broadband seismometers STS1

- Static and transient gravity anomalies (Okubo, 1991, 1992; Imanishi et al., 2004)

- Search for a prompt gravity signal: Kamioka SG data
  Statistical tests (Montagner et al., Nature Com., 2016)

- Controversy (Heaton, Nature Com., 2017)
- Broadband seismic data (Vallée et al., Science, 2017, Vallée and Juhel, JGR, 2019)



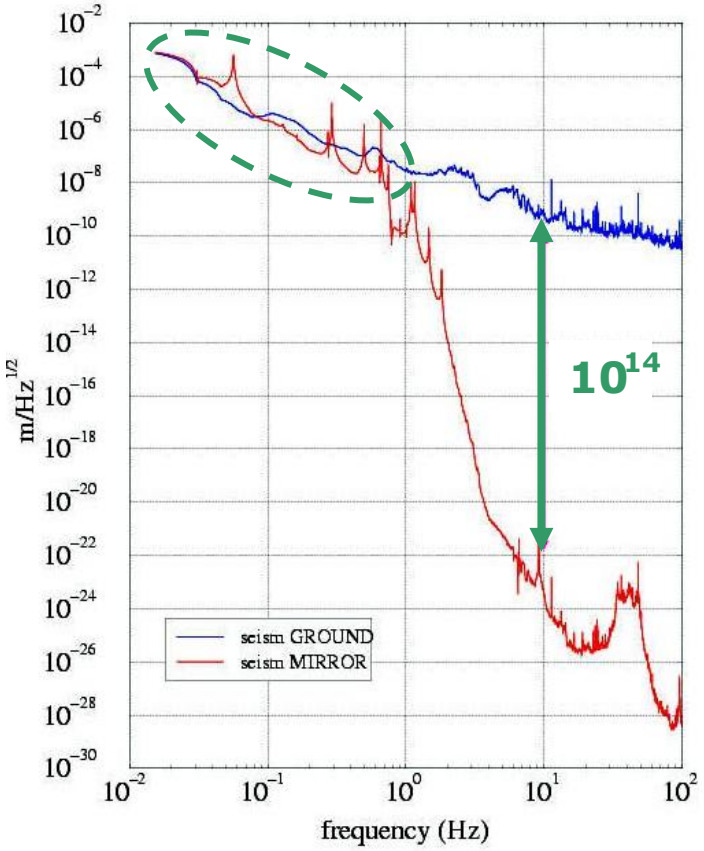


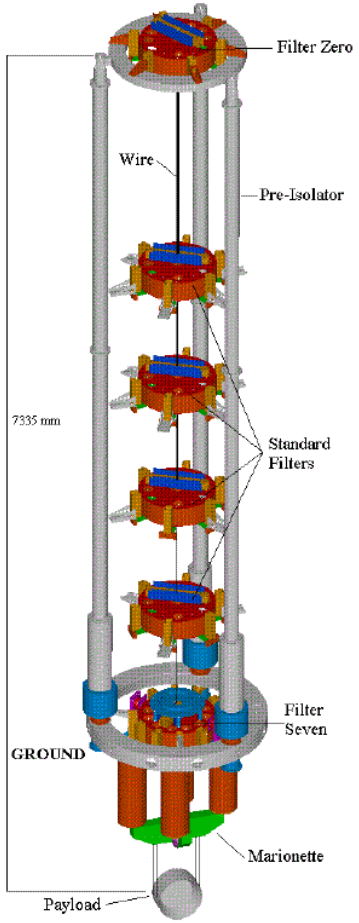
- Perspectives and ongoing projects : EEWS (Earthquake Early Warning Systems) (Juhel et al., JGR, 2018)

- PEGASEWS: Prompt Earthquake Gravity Anomalies: Seismic Early Warning System

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

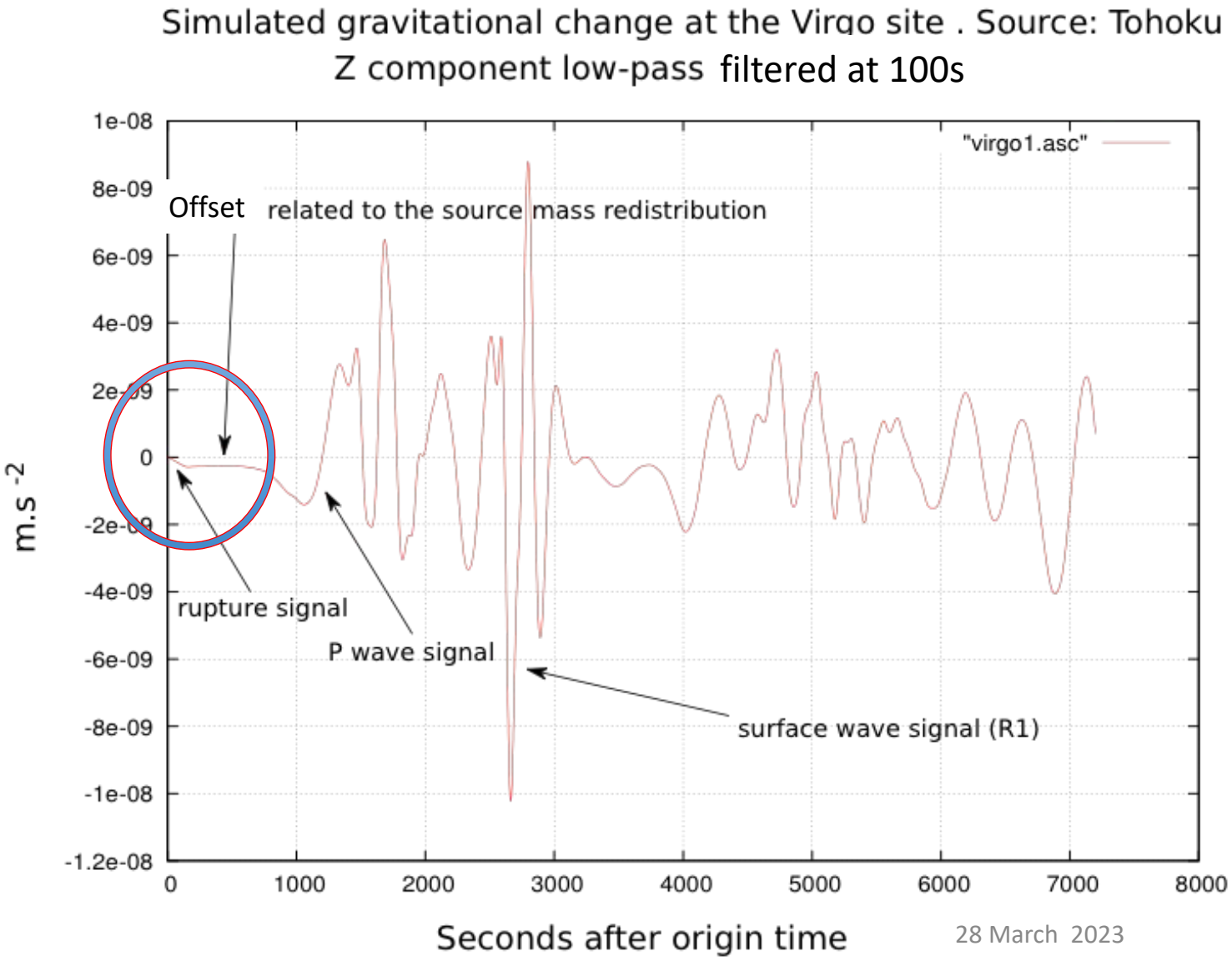
VIRGO (Italian – French Gravitational wave detector)





Seismic wall at f>1 Hz

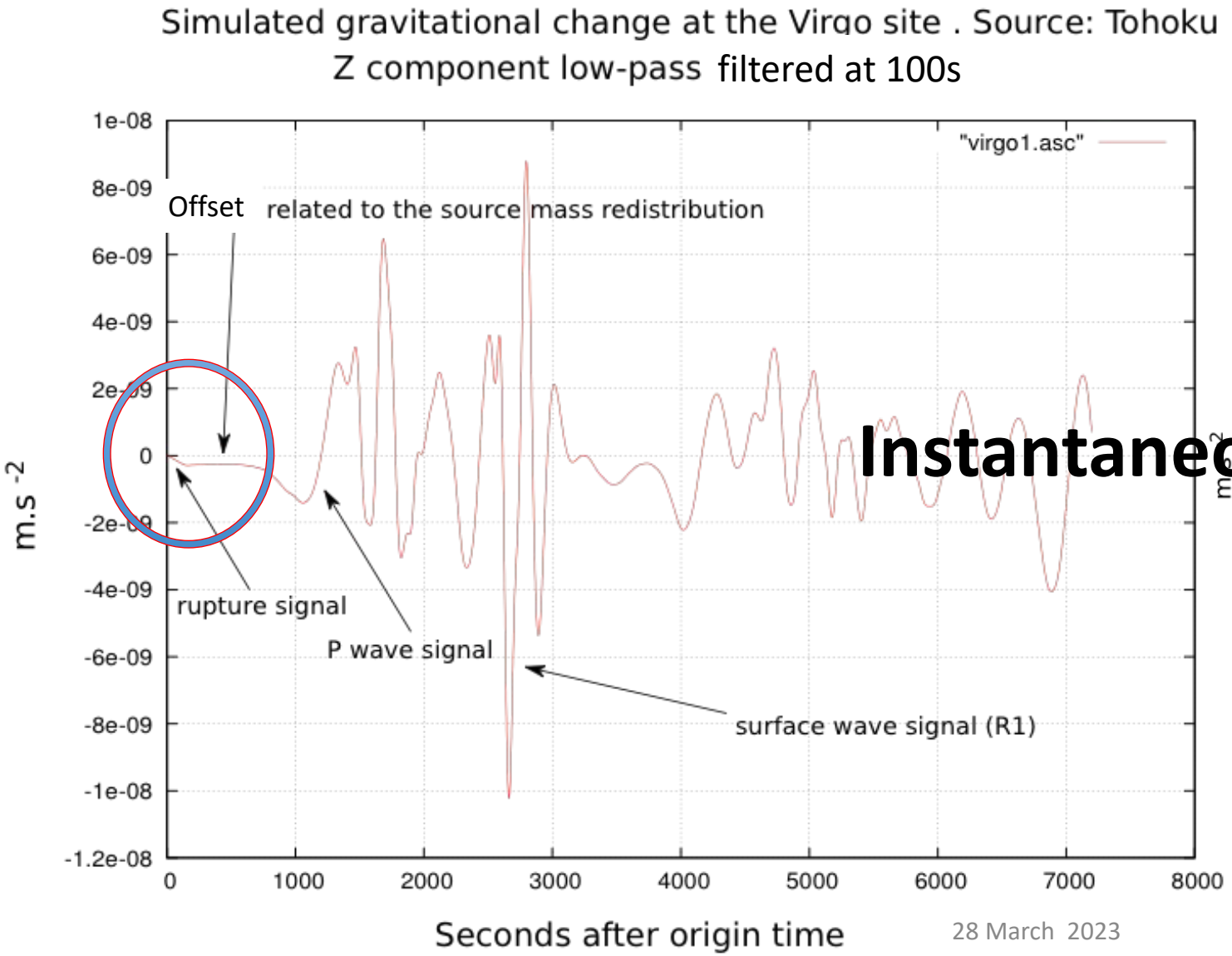
Motivation
NORMAL MODE THEORY



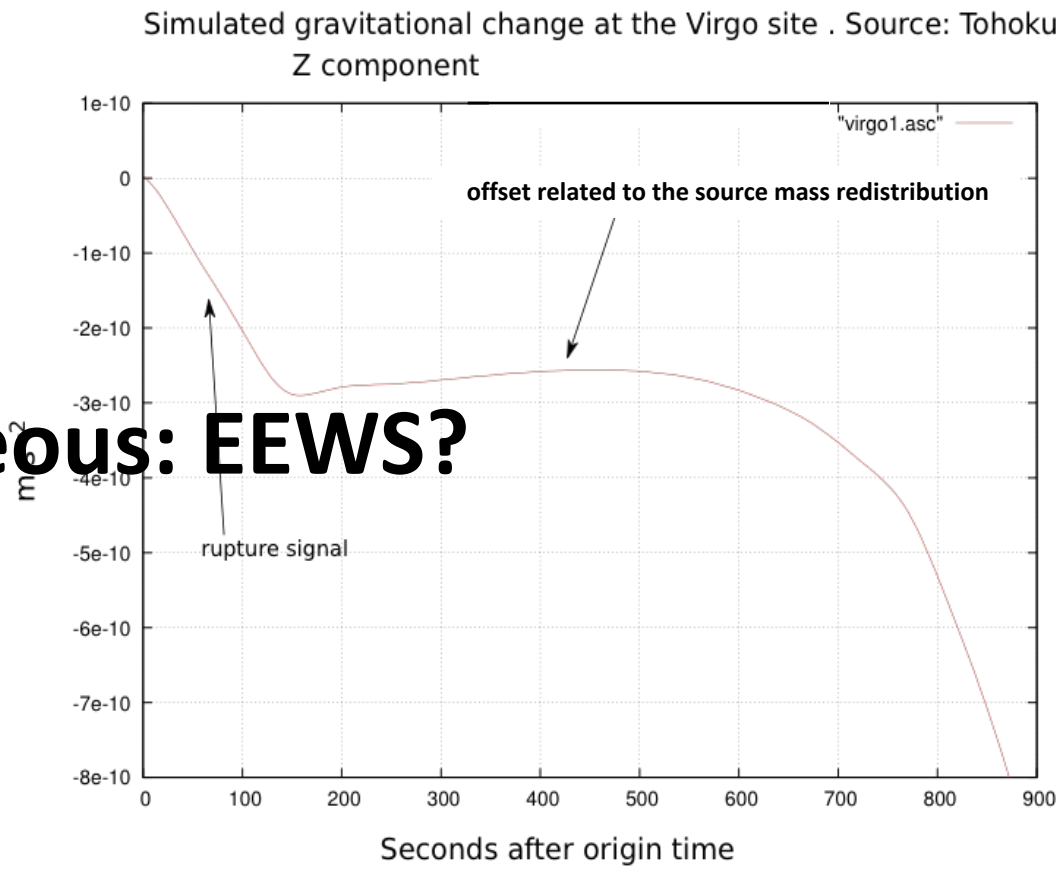
Theoretical signal
Before P-arrival:
0.03 μgal= 0.3nm/s^2
Very small

1 μgal = 10^{-8} m/s^2 =10 nm/s^2

Motivation
NORMAL MODE THEORY



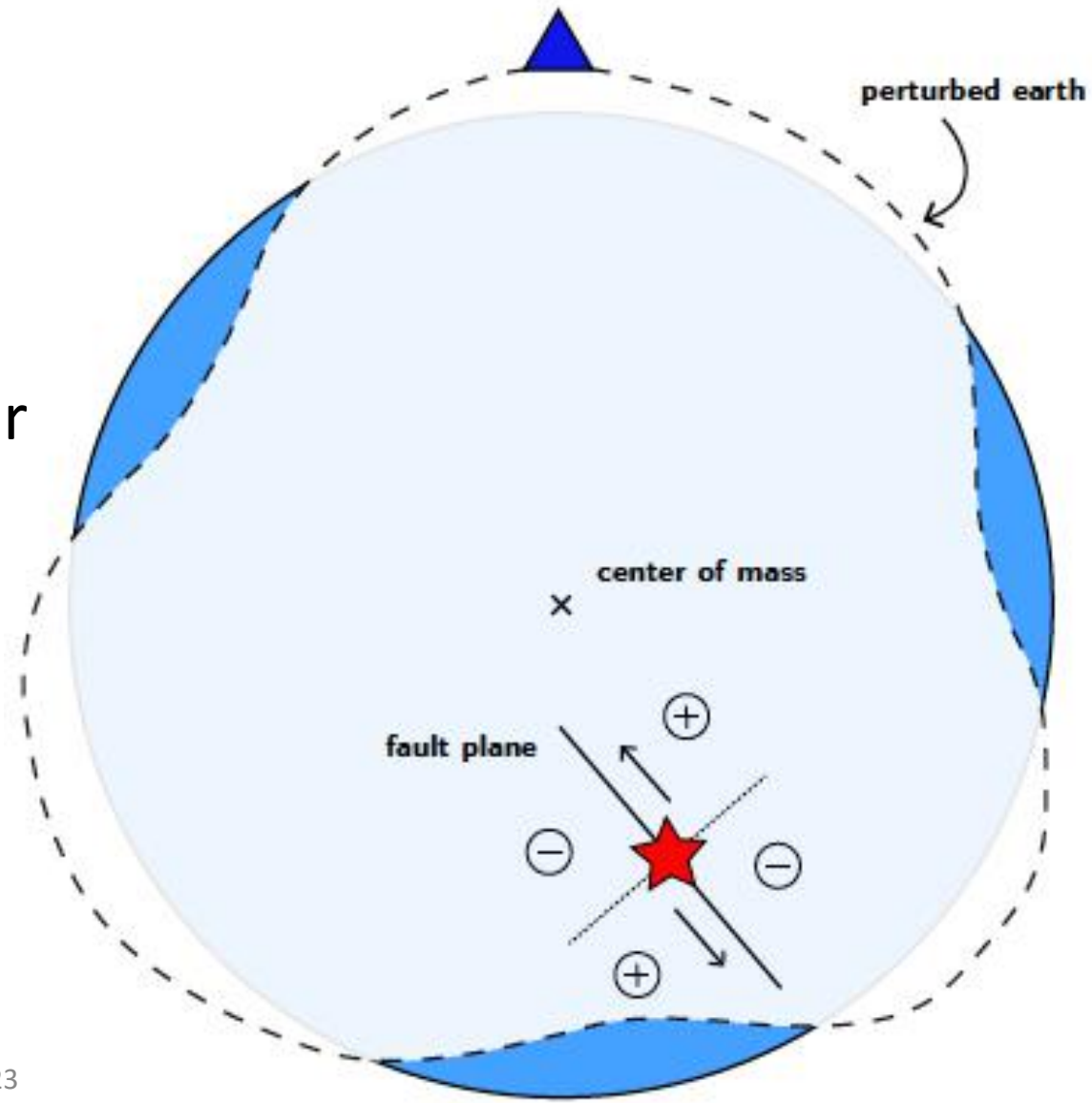
$\Delta \approx 90°$ (≈10 000km)



Instantaneous: EEWS?

Gravity perturbations induced by earthquakes?

Galileo Galilei
Free fall at Pisa Tower
(1604)

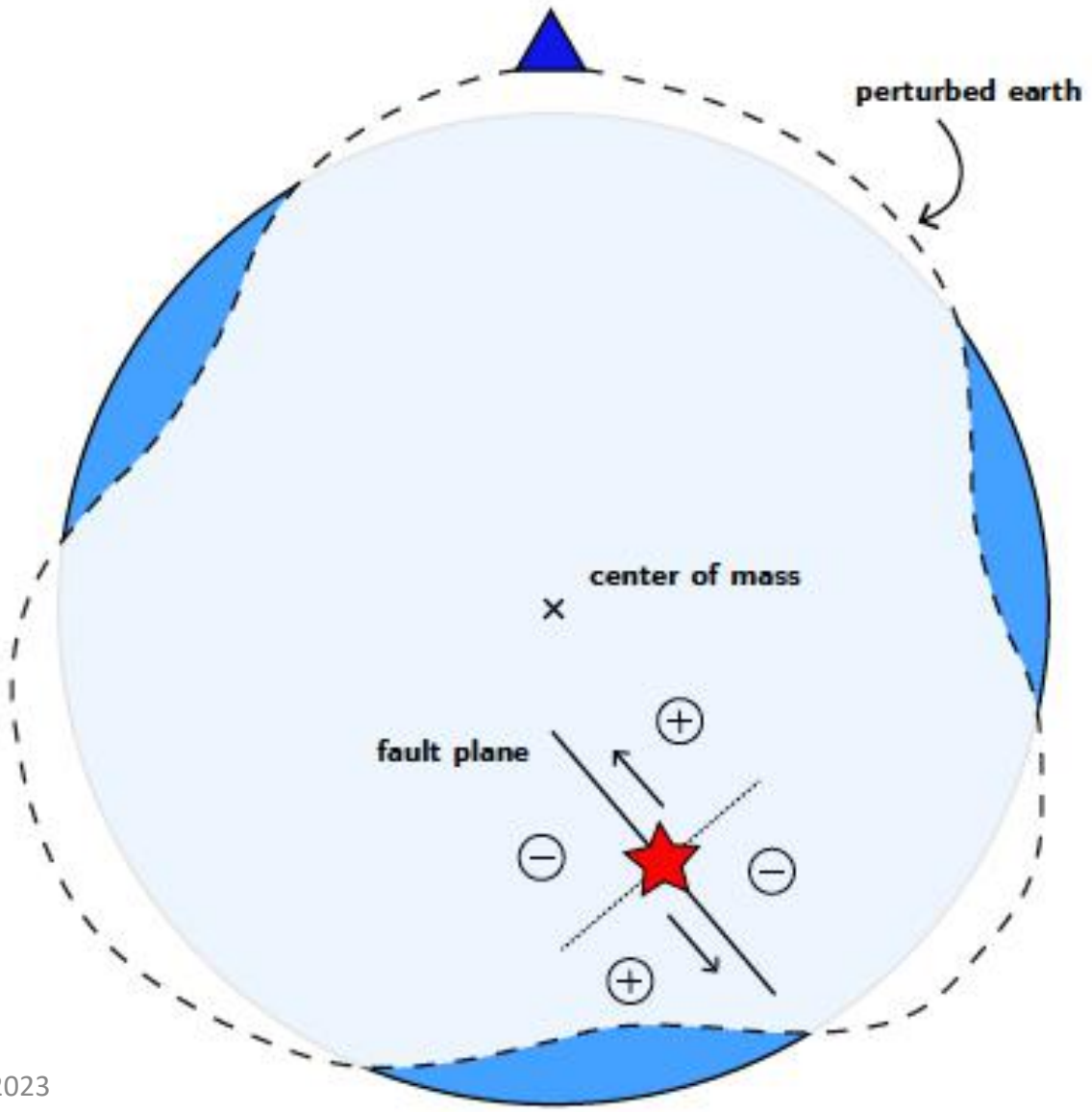


Isaac Newton:
Universal Gravitation Law (1685)

Gravity perturbations induced by earthquakes

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

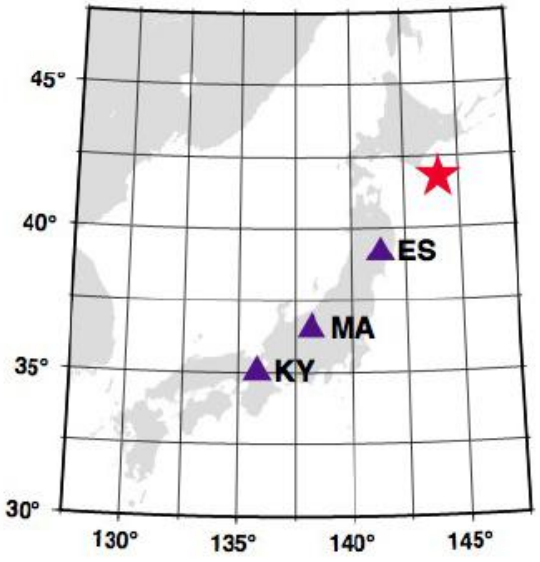
Theoretical Approach
-direct numerical calculations (plane case):
(Harms et al., GJI, 2015, 2016)
(Vallée et al., Science, 2017)
-Normal mode Theory (spherical case)
(Juhel et al., 2019)

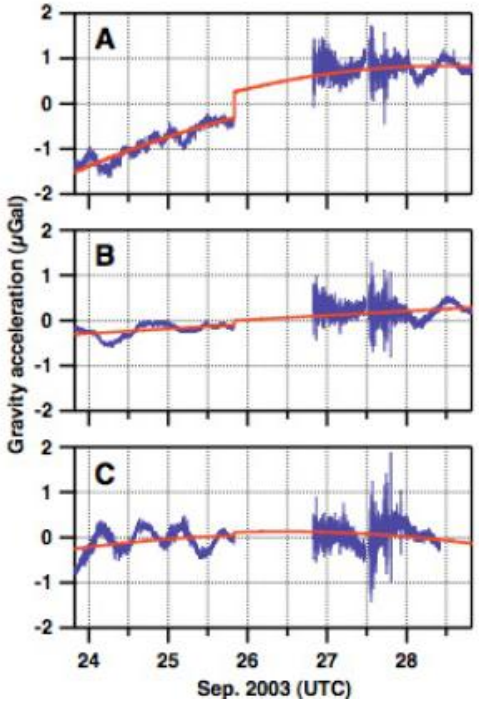


Static gravity changes induced by earthquakes already measured

- Ground-based stations: Superconducting gravimeters after large earthquakes

  (2003 M=8.0 Tokachi-oki earthquake)

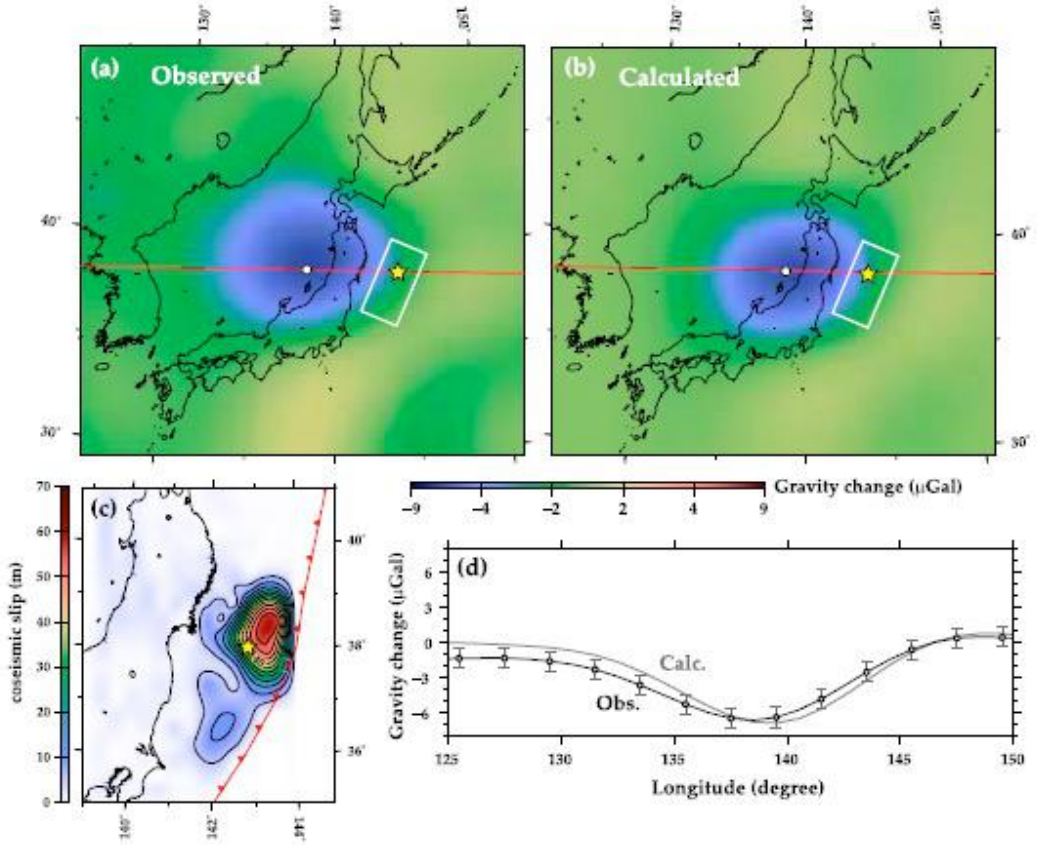




Imanishi et al. (Science, 2004)

- GRACE / GOCE satellites

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



Matsuo and Heki (2011)

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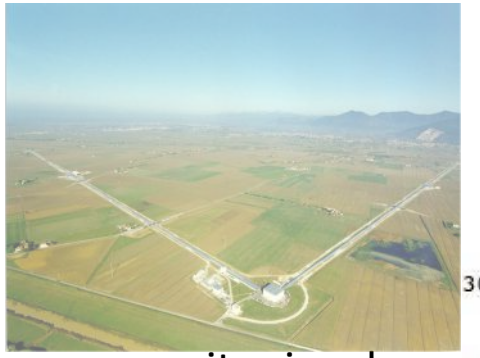
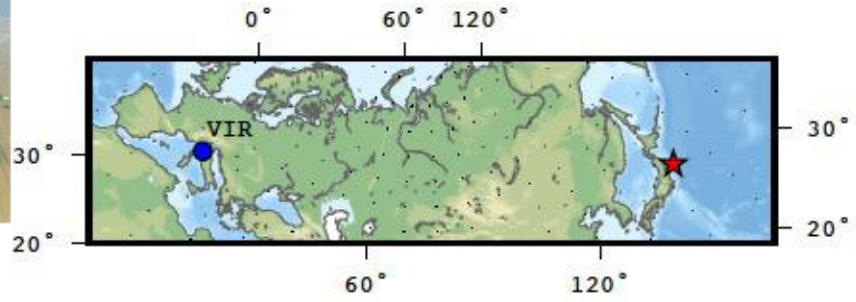
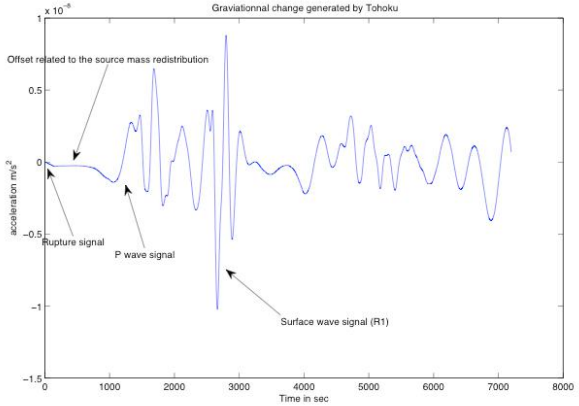
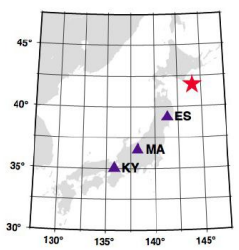


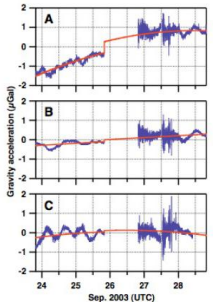
normal mode calculation





- Search for « instantaneous » gravity signal
  a) Very Large earthquakes:
  Sumatra (9.3; 26/12/04), Chile-Maule (8.8; 27/02/2010), Japan-Tohoku (9.0:-; 11/03/2011)
  b) Instruments: Superconducting gravimeter, very broadband seismometers STS1
- Static and transient gravity anomalies (Okubo, 1991, 1992; Imanishi et al., 2004)





- **Search for a prompt gravity signal**: Kamioka SG data (Montagner et al., Nature Com., 2016)

- Controversy (Heaton, Nature Com., 2017)
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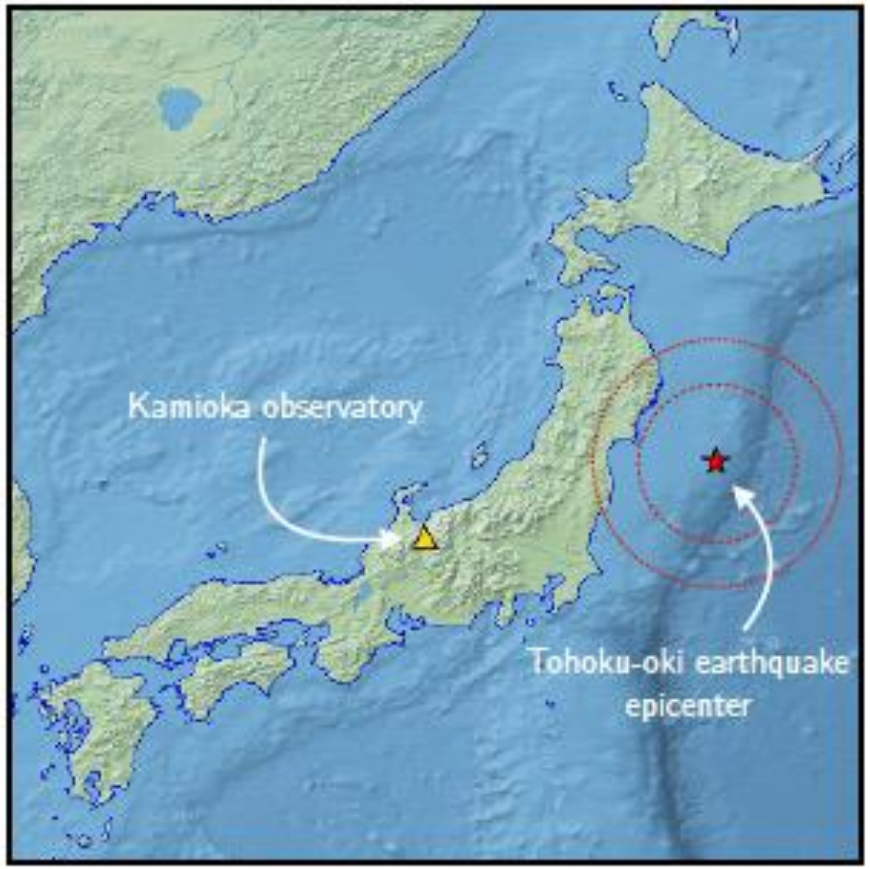
The choice of Kamioka SG (superconducting gravimeter) data for Tohoku-oki Earthquake



WHY KAMIOKA?

- Not far from Tohoku earthquake epicenter (~500km)

- Excellent station (installed in a mine) with a low noise level (1nGal = 10^{-11} m/s^2) Kamiokande Observatory

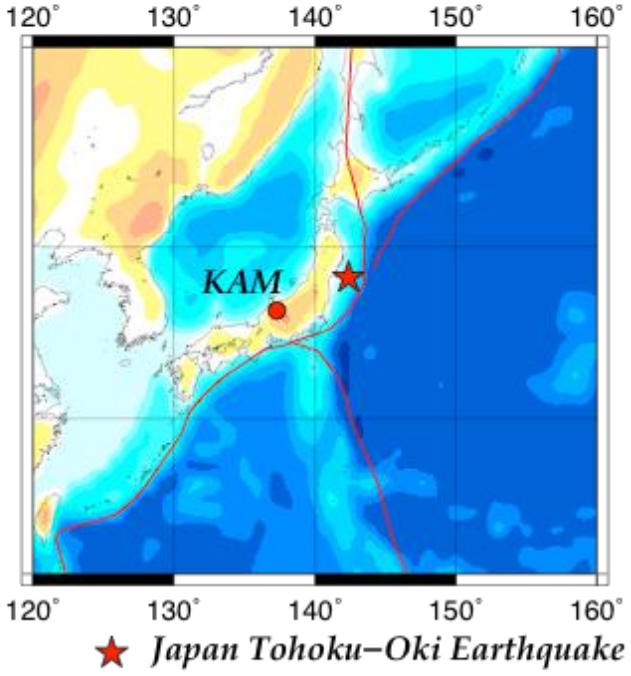
- Superconducting gravimeters are so far the best instruments measuring the Earth gravity field

- Station operated in the framework of GGP (Global Geodynamics Project)

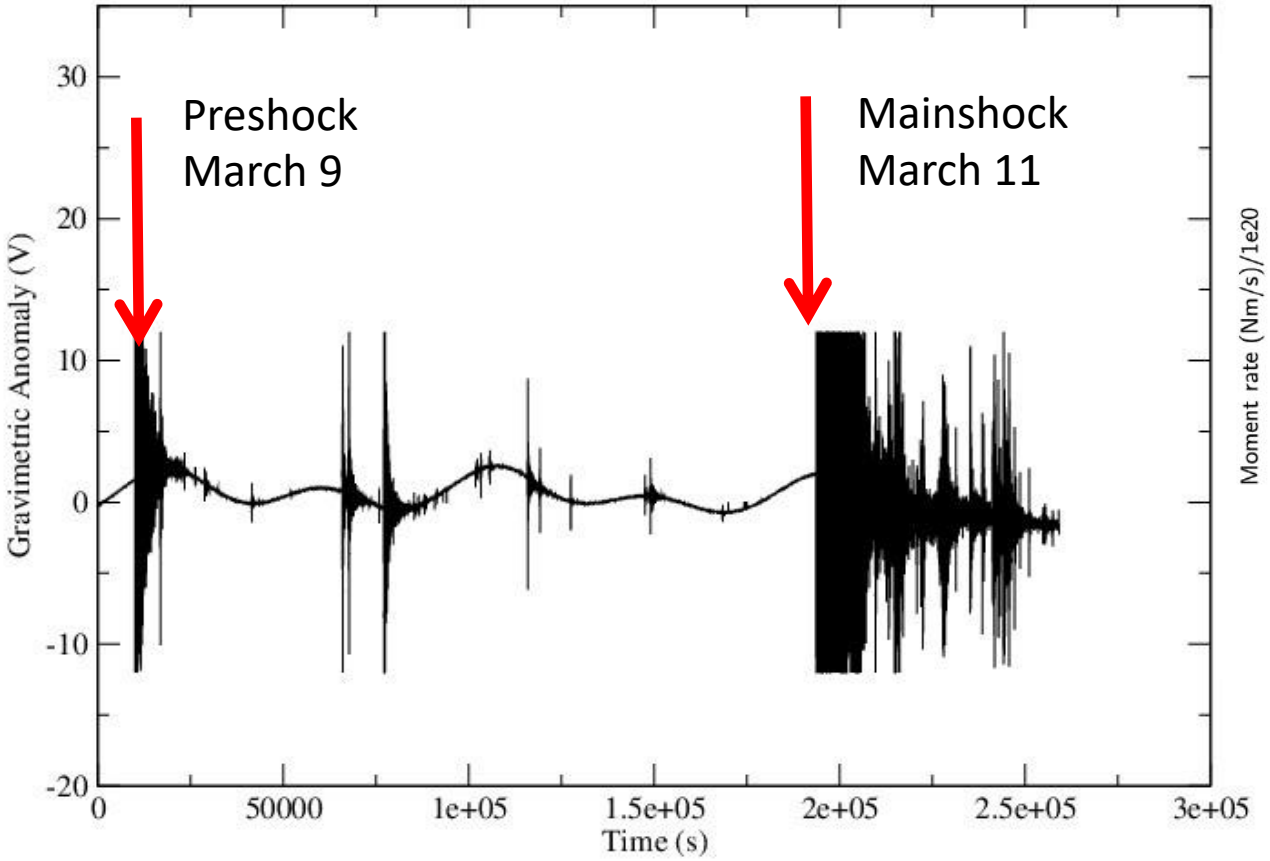
- Continuous data recording at 1sps (1Hz), on contrast with other SG instruments (1spm ≈ 0.0167Hz)

- Data easily accessible (thanks to Dr. Tamiura)

Transient gravity changes induced by earthquakes?

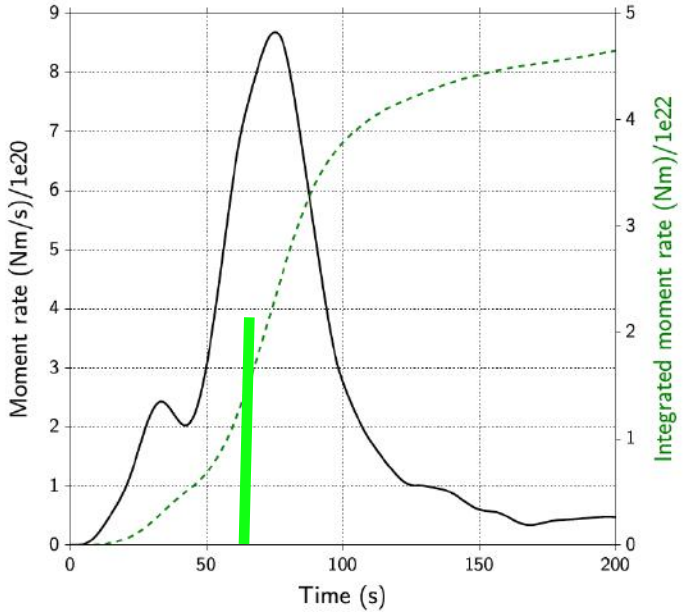


SG data at Kamioka Observatory
≈500 km from the Tohoku-oki epicenter



Time (seconds from March 9th 2011 00:000:00) 3 days span

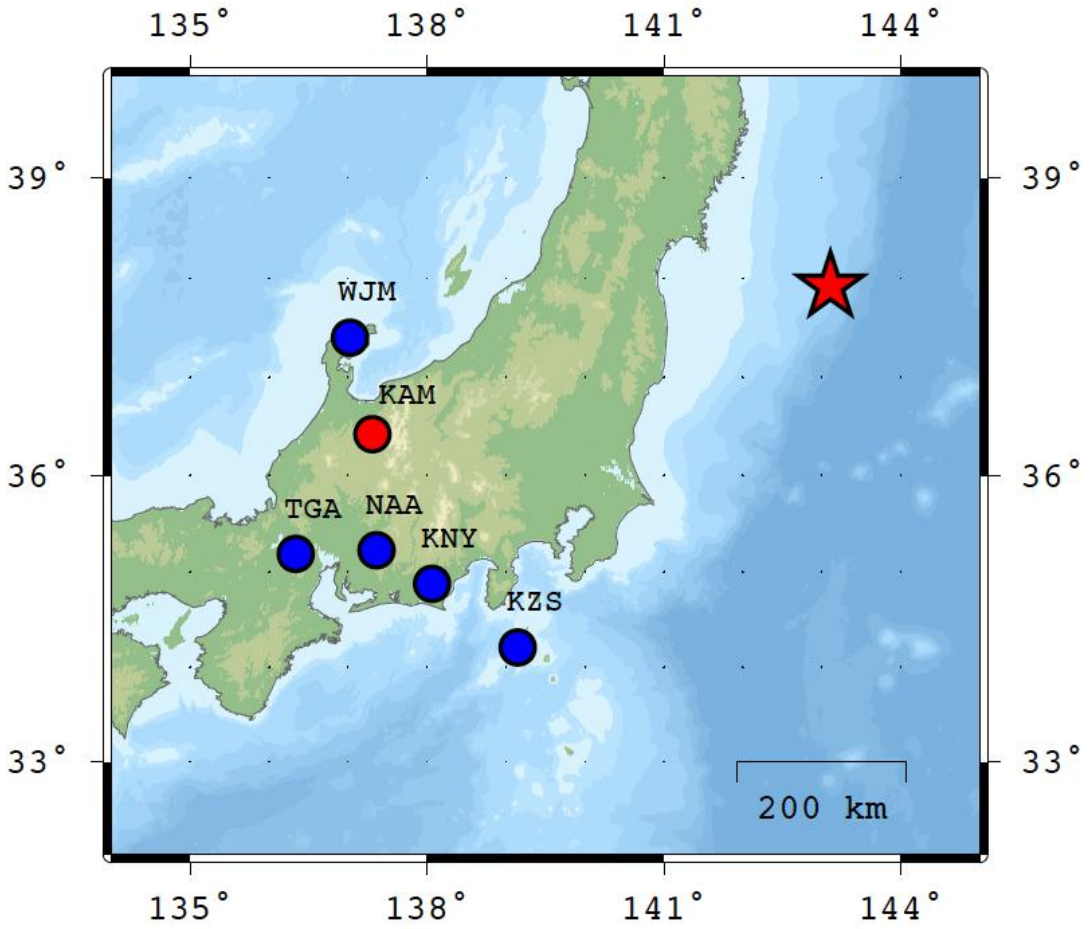
P-waves arrive at Kamioka
68s after t_{eq}



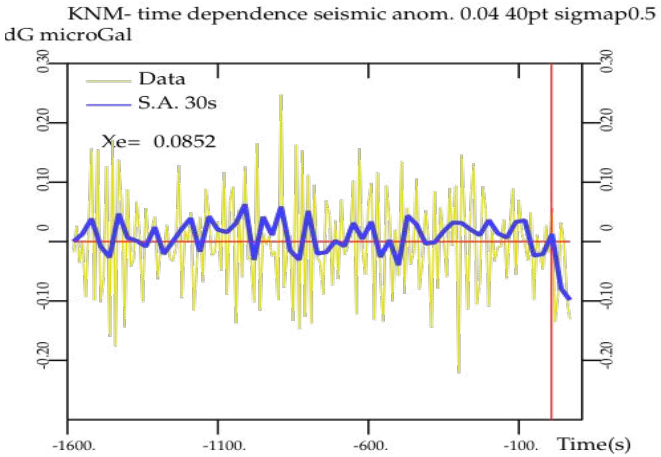
≈30-40% moment release
up to 60s (Wei et al., 2012))

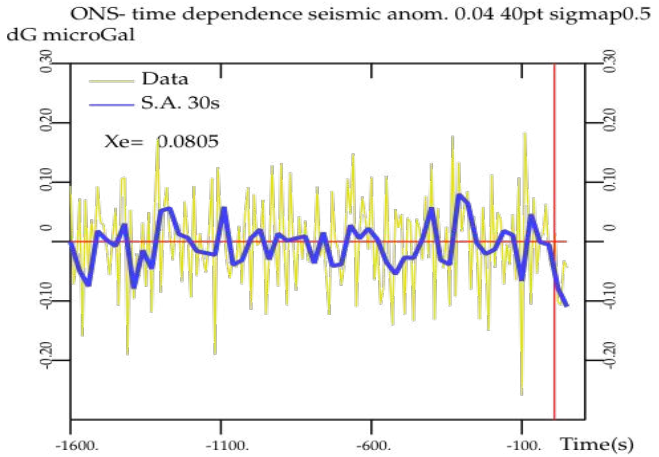
From Static to **Dynamic** gravity changes induced by earthquakes

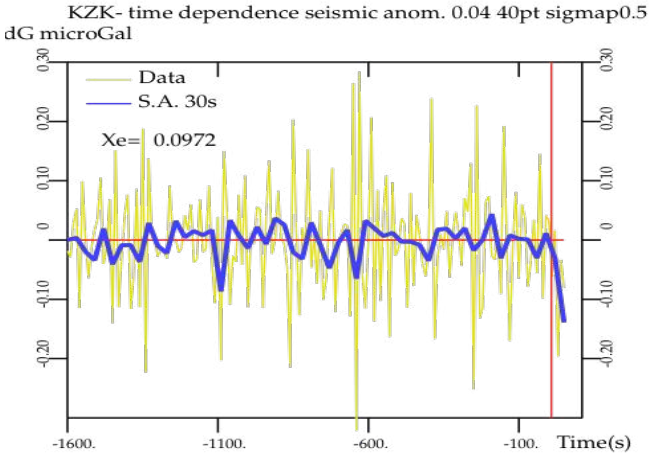
Superconducting gravimeter Kamioka
+Broadband Japanese network F-NET (STS1, STS2…)

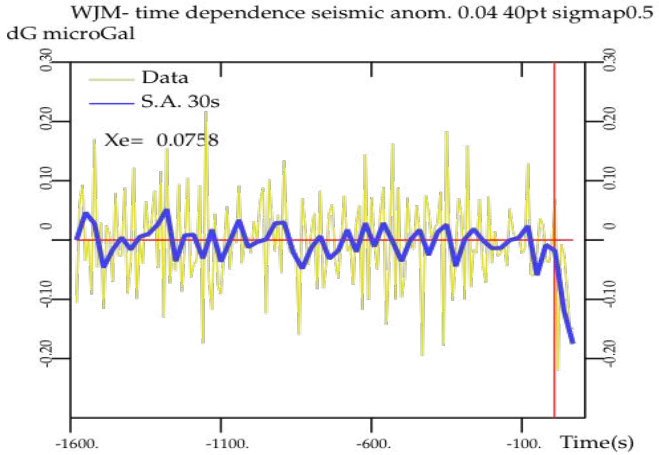


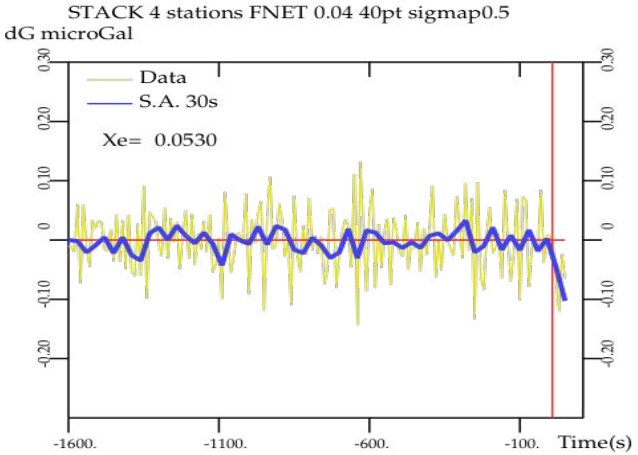
Speed-of-light signal: Stack of Japanese F-NET broadband data + Kamioka SG

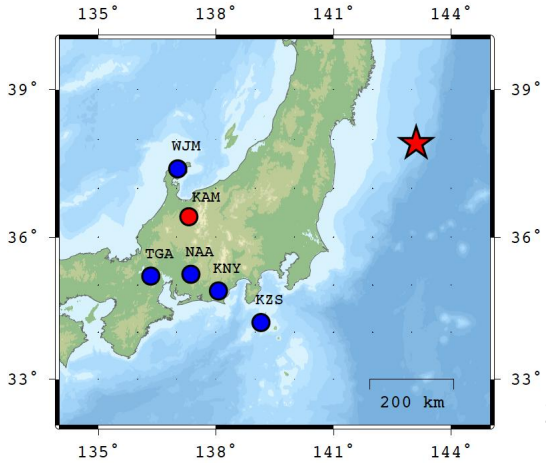












28 March 2023

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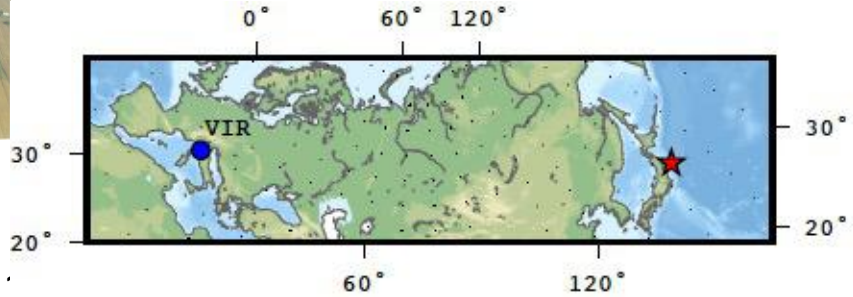

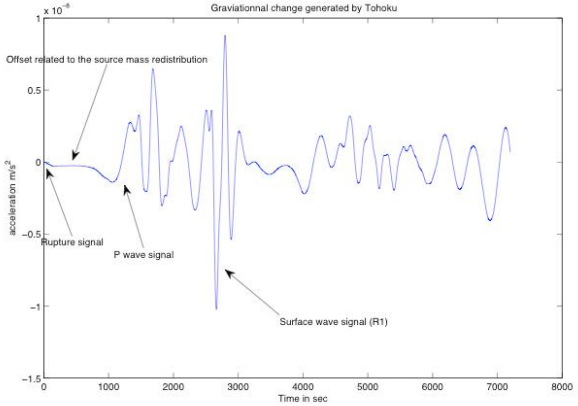

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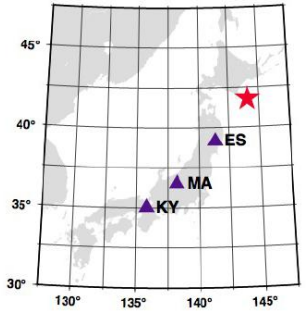

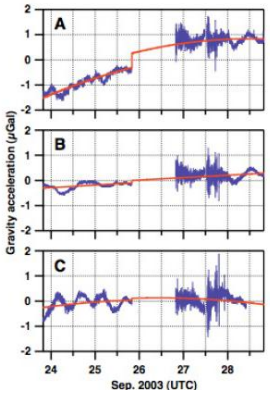

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- Broadband seismic data (Vallée et al., Science, 2017, Vallée and Juhel, JGR, 2019)
- Perspectives and ongoing projects : EEWS (Earthquake Early Warning Systems) (Juhel et al., JGR, 2018)
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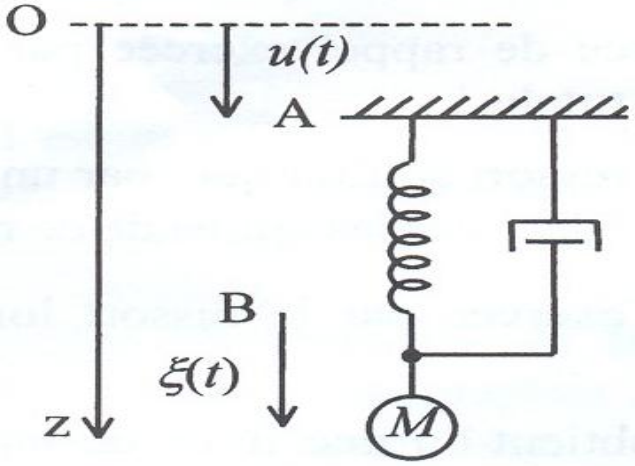
Insights from the set of self-gravitating equations

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

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

Seismometer



$$\frac{d^2\xi}{dt^2} + \frac{D}{M}\frac{d\xi}{dt} + \frac{k}{M}\xi = \Delta g - \frac{d^2u}{dt^2}$$

A seismometer records **the difference between the ground acceleration and the gravitational perturbations**

Insights from the set of self-gravitating equations

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

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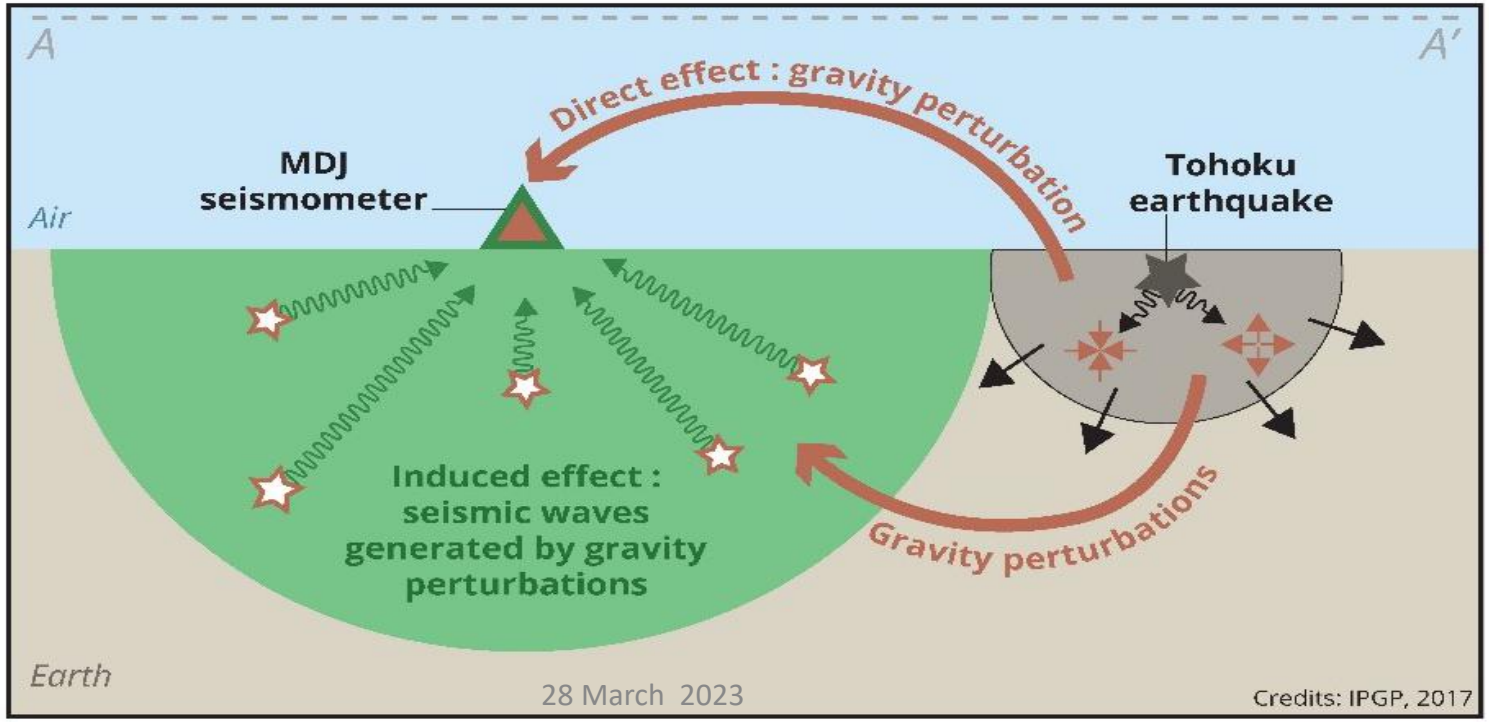
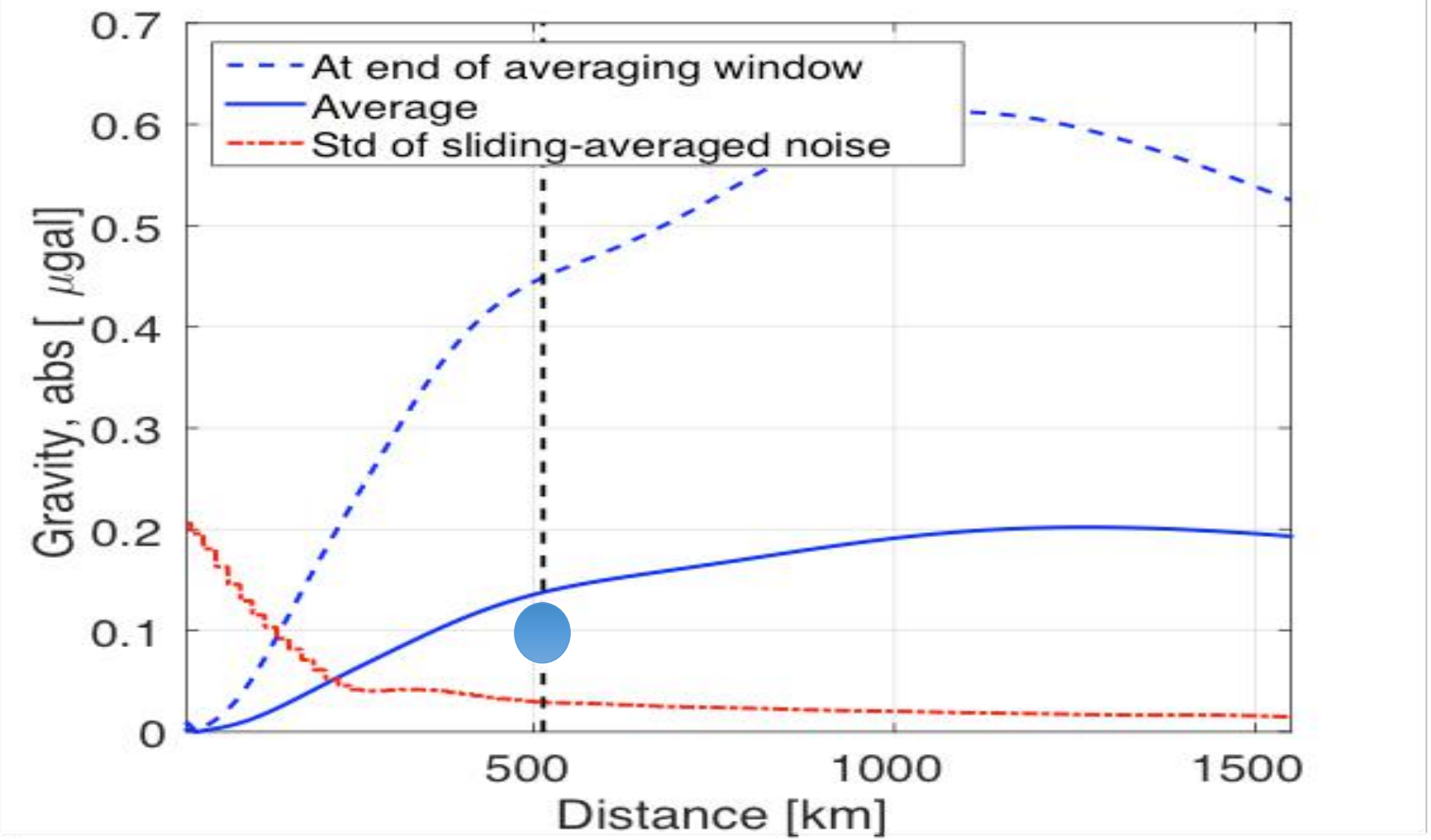
Illustration of the modeling approach (Vallée et al., 2017)

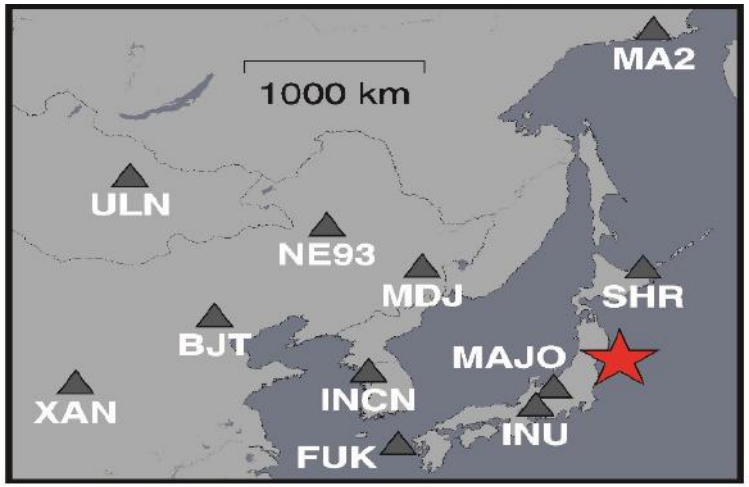


Courtesy of Martin Vallée

Signal amplitude versus epicentral distance just before P-arrival



Montagner et al., 2016

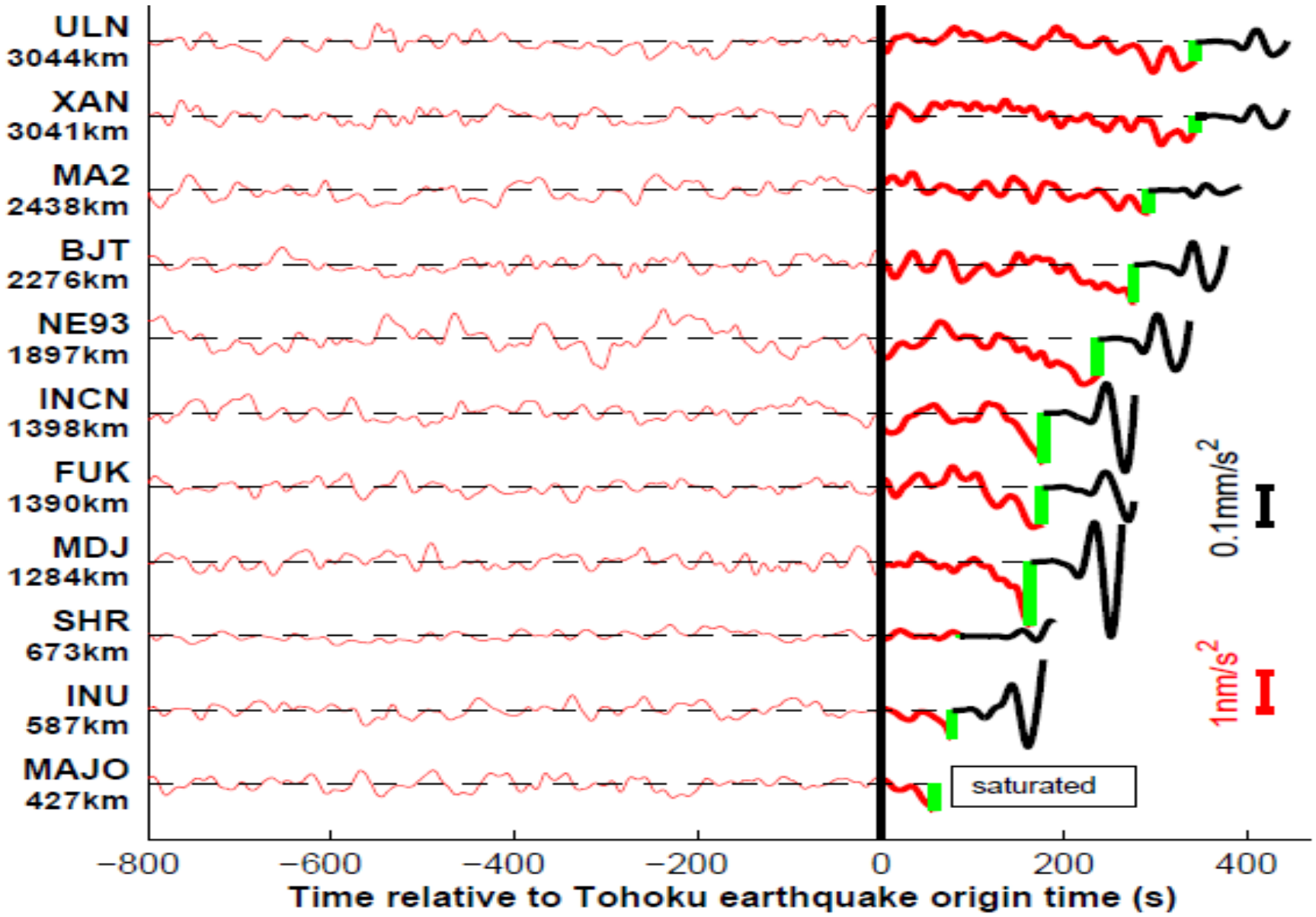


FDSN stations (IRIS or GEOSCOPE) + F-NET (Japan)
0.002-0.03Hz frequency range

Relative amplitudes between the pre-P and the post-P signals

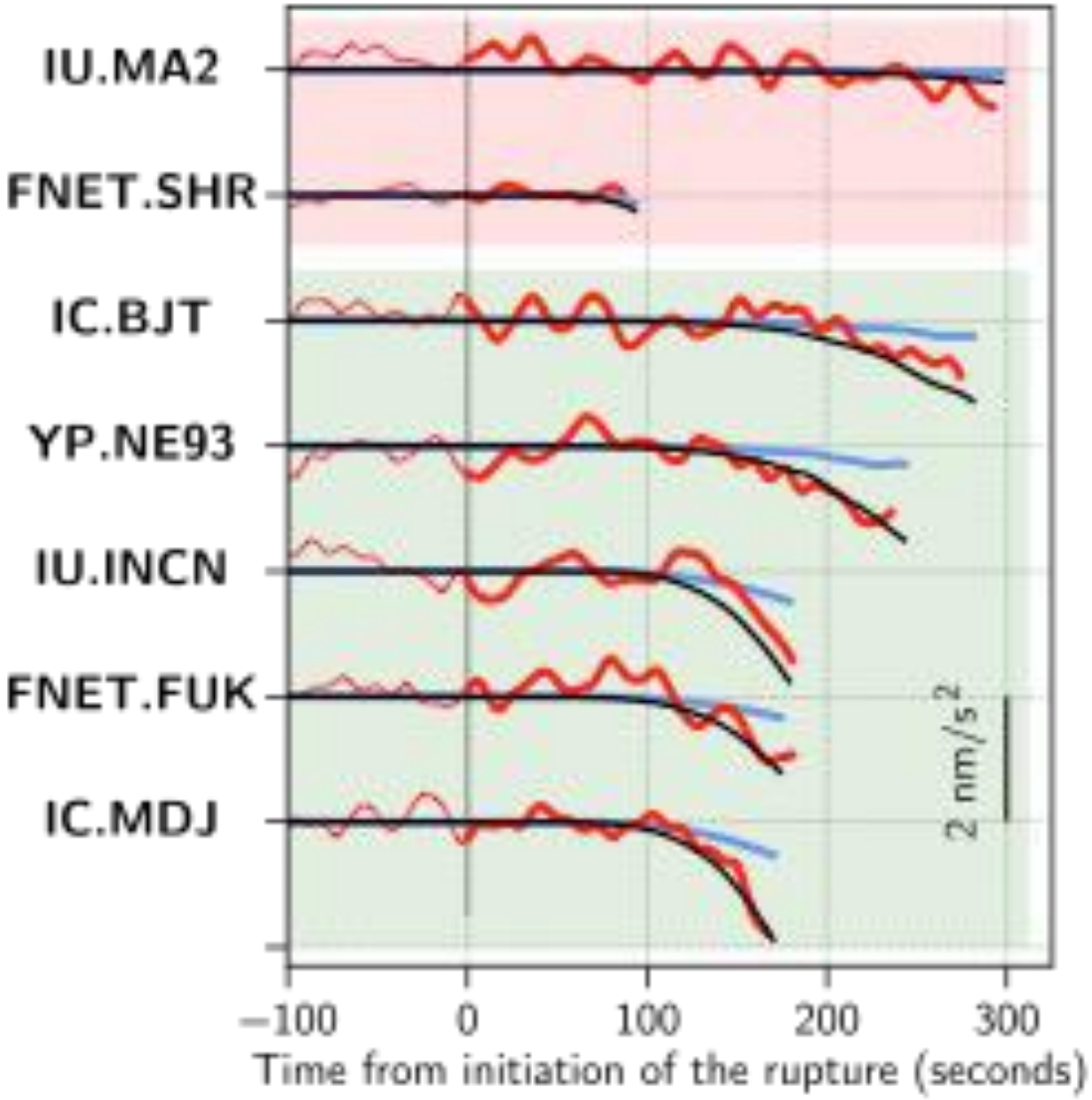
Pre-P signals are 10^5 to 10^6 smaller

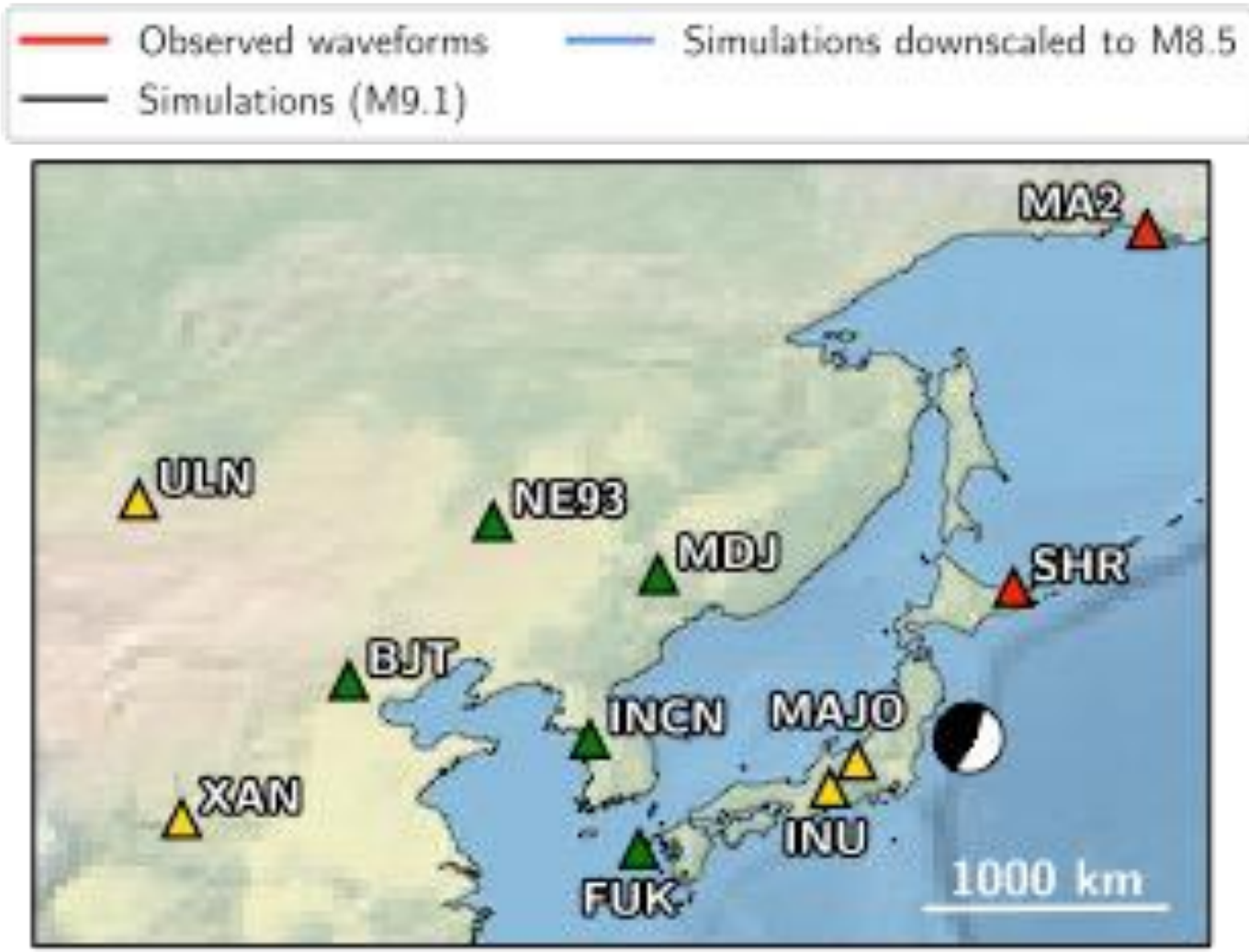
Green tick : P wave arrival



Vallée et al., Science, 2017

Complete simulation at all stations





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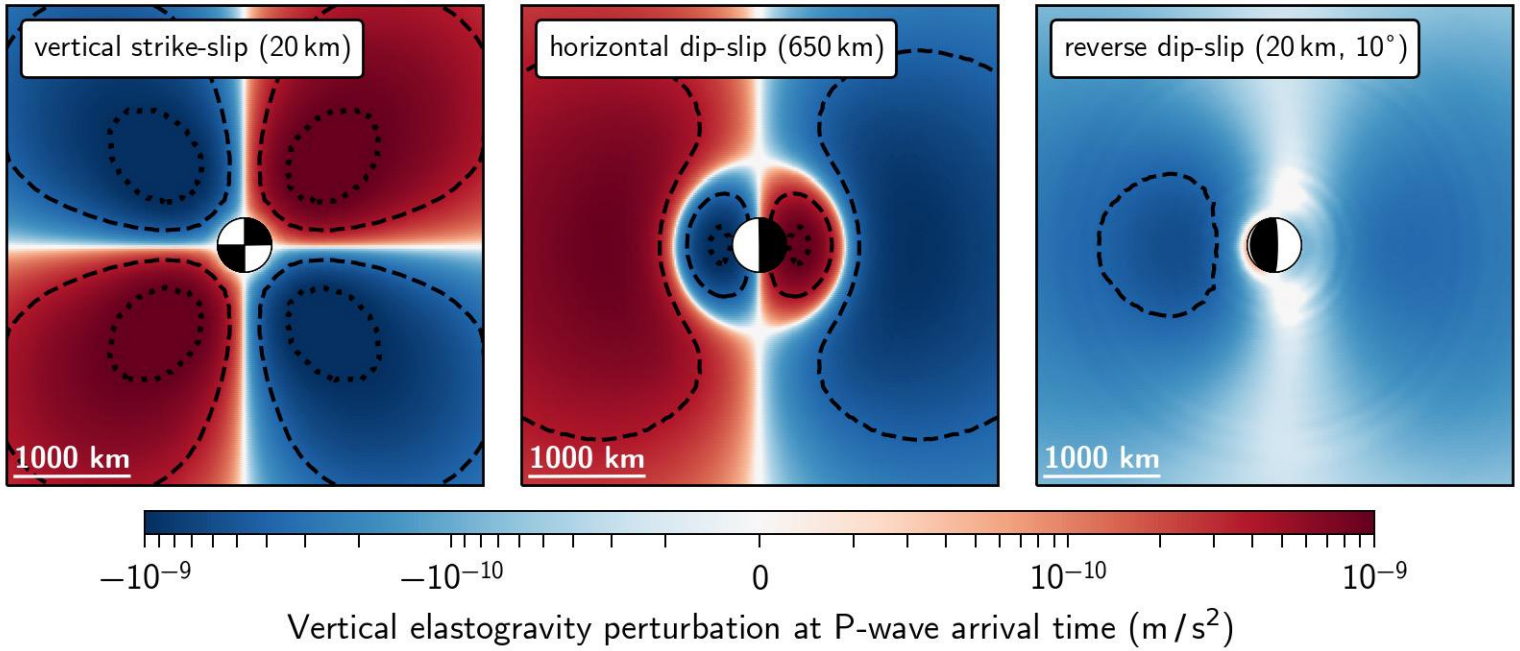

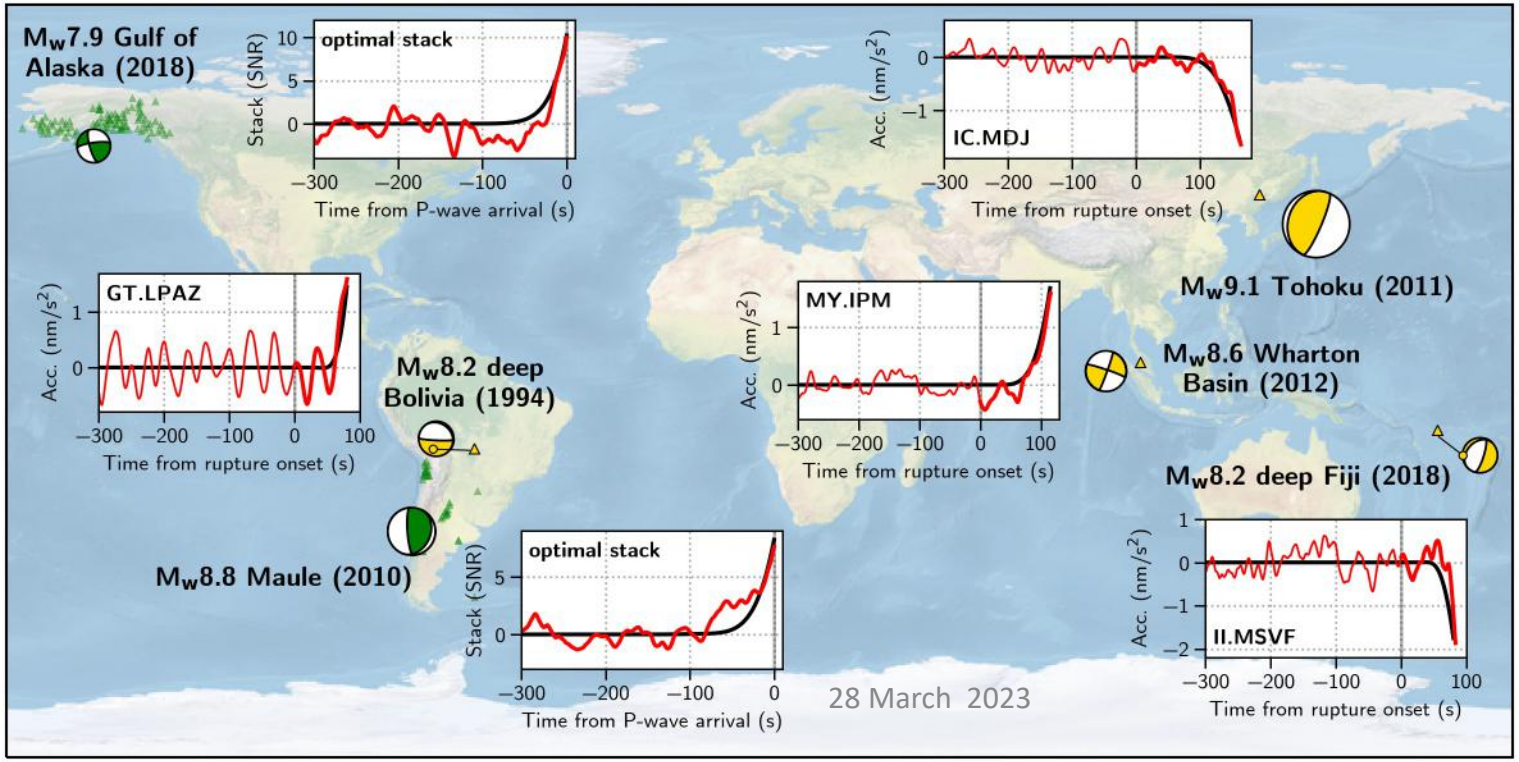

New detection of PEGS (prompt elasto-gravity signals) for other earthquakes

Vallée & Juhel, 2019

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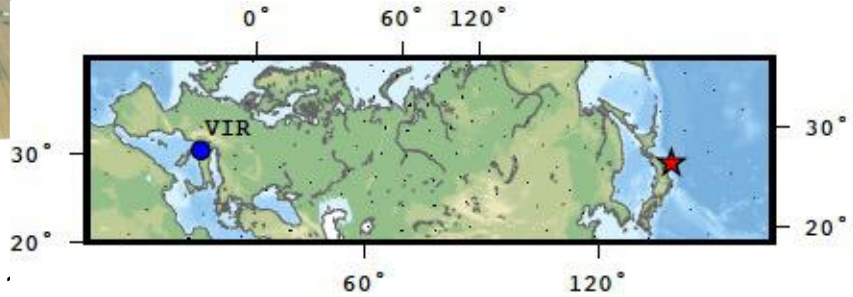
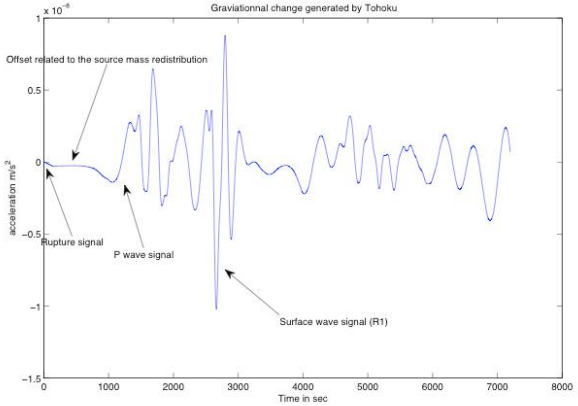
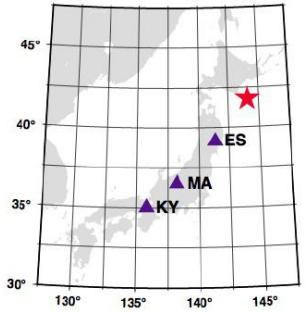
normal mode calculation

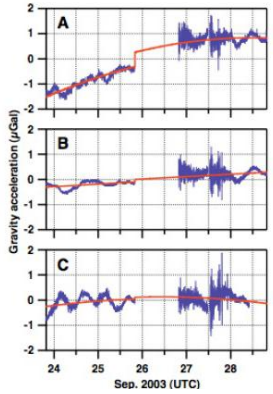




- **Search for « instantaneous » gravity signal**
  a) Very Large earthquakes:
  Sumatra (9.3; 26/12/04), Chile-Maule (8.8; 11)
  b) Instruments: Superconducting gravimeter, very broadband seismometers STS1

- Static and transient gravity anomalies (Okubo, 1991, 1992; Imanishi et al., 2004)
- Search for a prompt gravity signal: Kamioka SG data
- Statistical tests (Montagner et al., Nature Com., 2016)



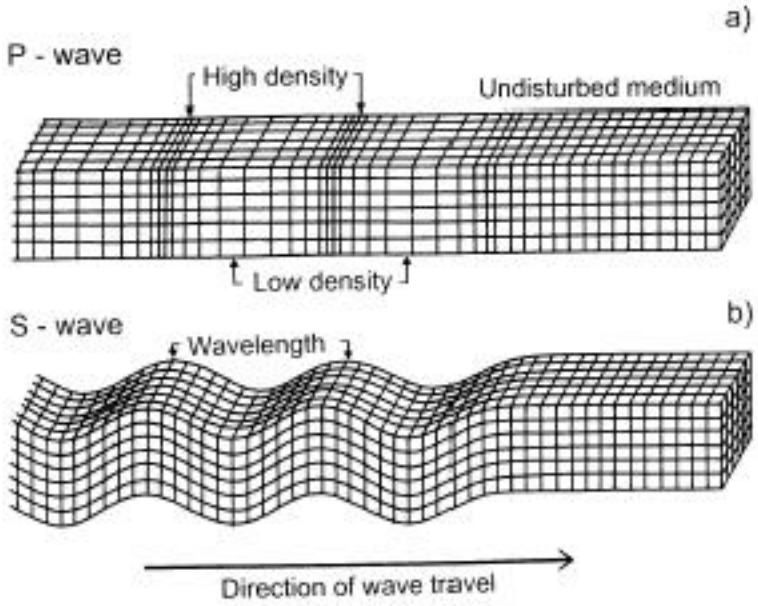


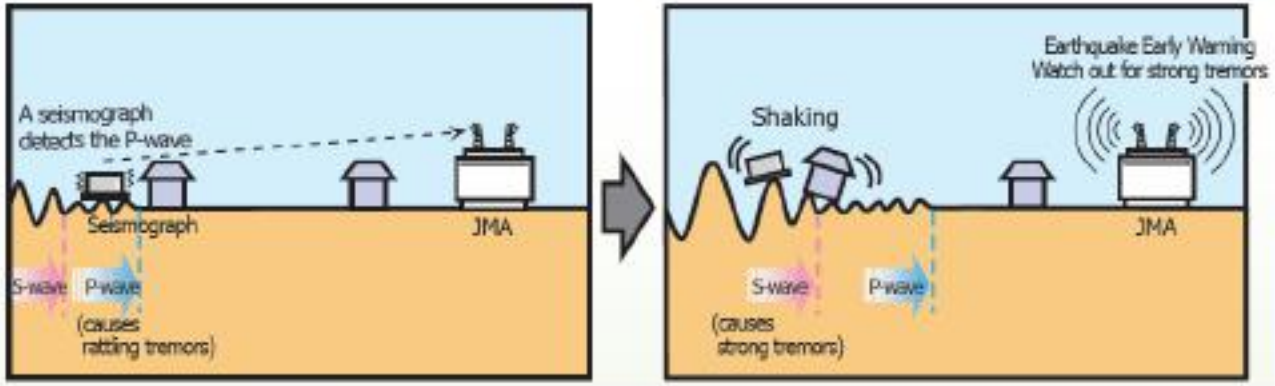
- Controversy (Heaton, Nature Com., 2017)
- Broadband seismic data (Vallée et al., Science, 2017, Vallée and Juhel, JGR, 2019)

- **Perspectives and ongoing projects : EEWS (Earthquake Early Warning Systems)**

- PEGASEWS: Prompt Earthquake Gravity Anomalies: Seismic Early Warning System

Earthquake early-warning systems

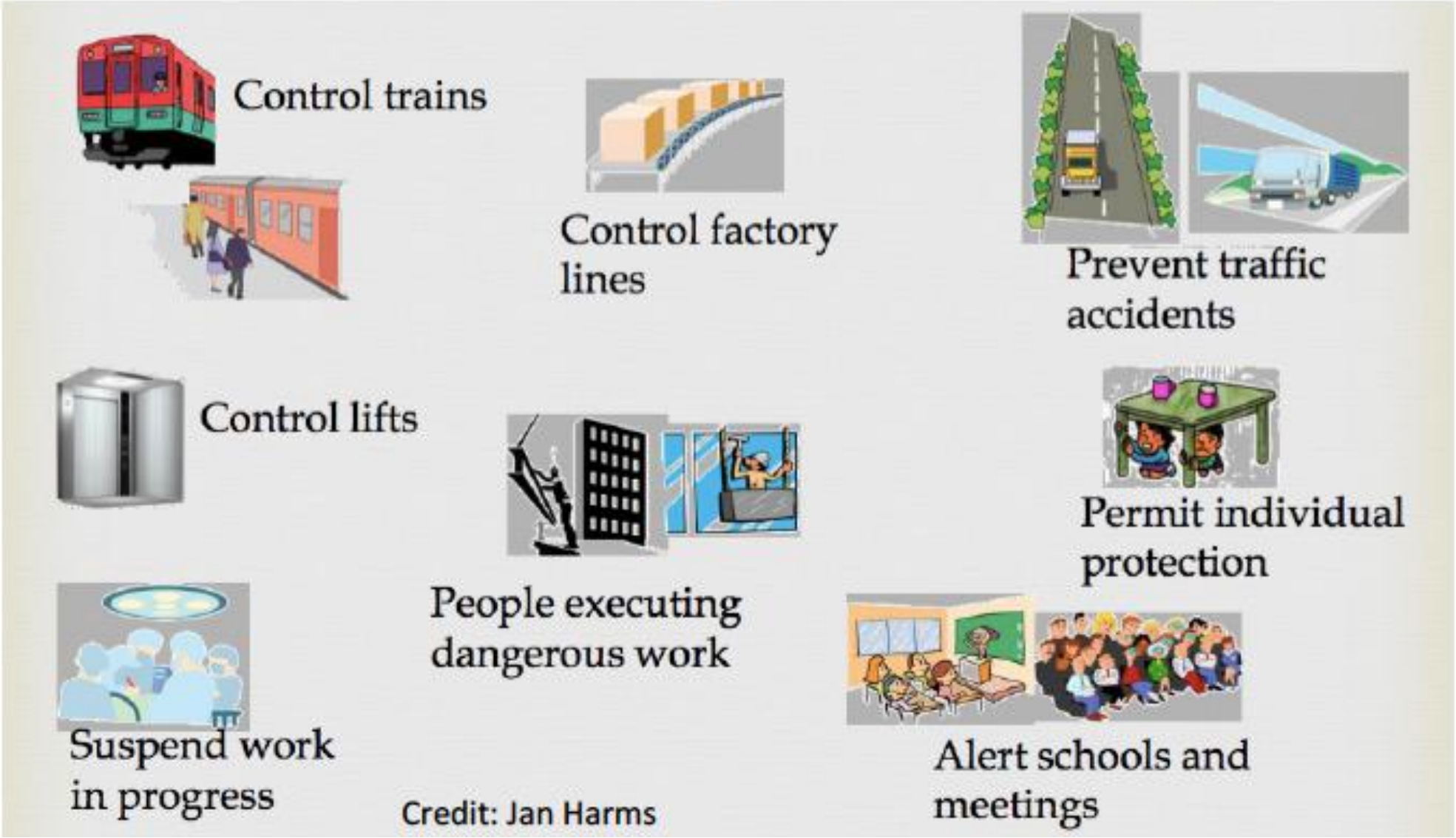




Source: Japan meterological agency

For example (for some densities) : P-waves ~ 5 km/s S-waves~ 2.5 km/s

Benefits of early-warning systems

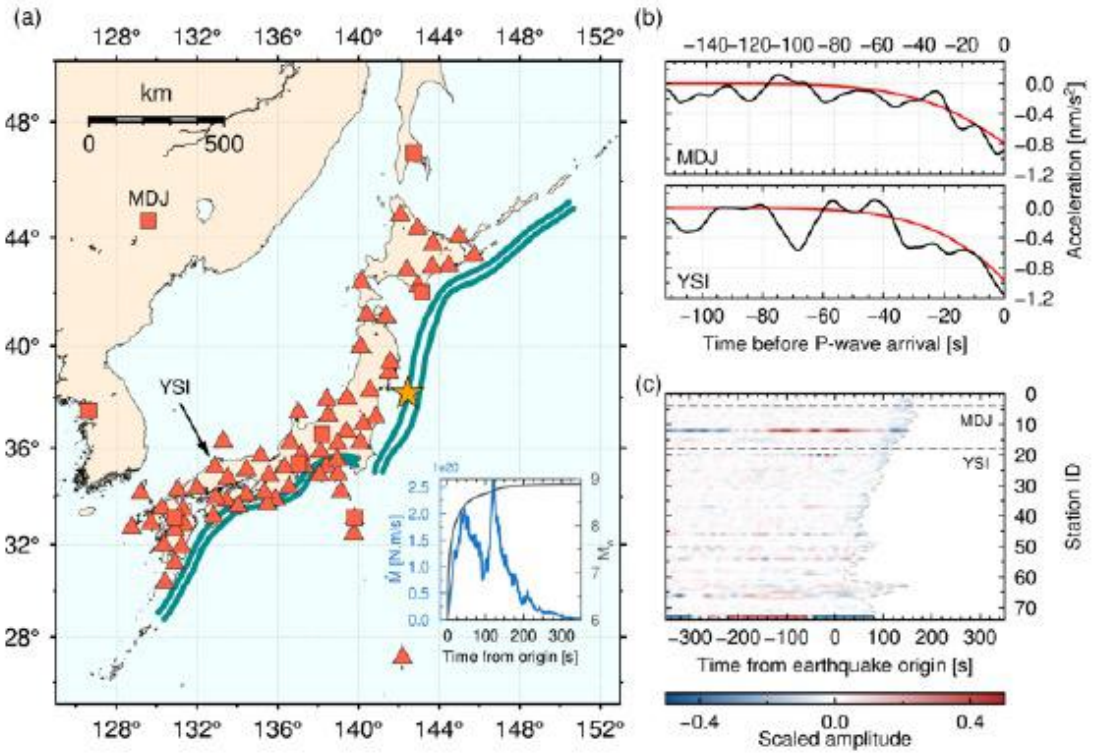


SEARCH FOR DETECTABILITY OF PEGS WITH VERY BROADBAND SEISMOMETERS
HOW CAN WE USE PEGS FOR EARLY MAGNITUDE ESTIMATE IN AN EEWS?

PEGS: prompt elastogravity signals; EEWS: earthquake early warning system

PEGSNet : the training database

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

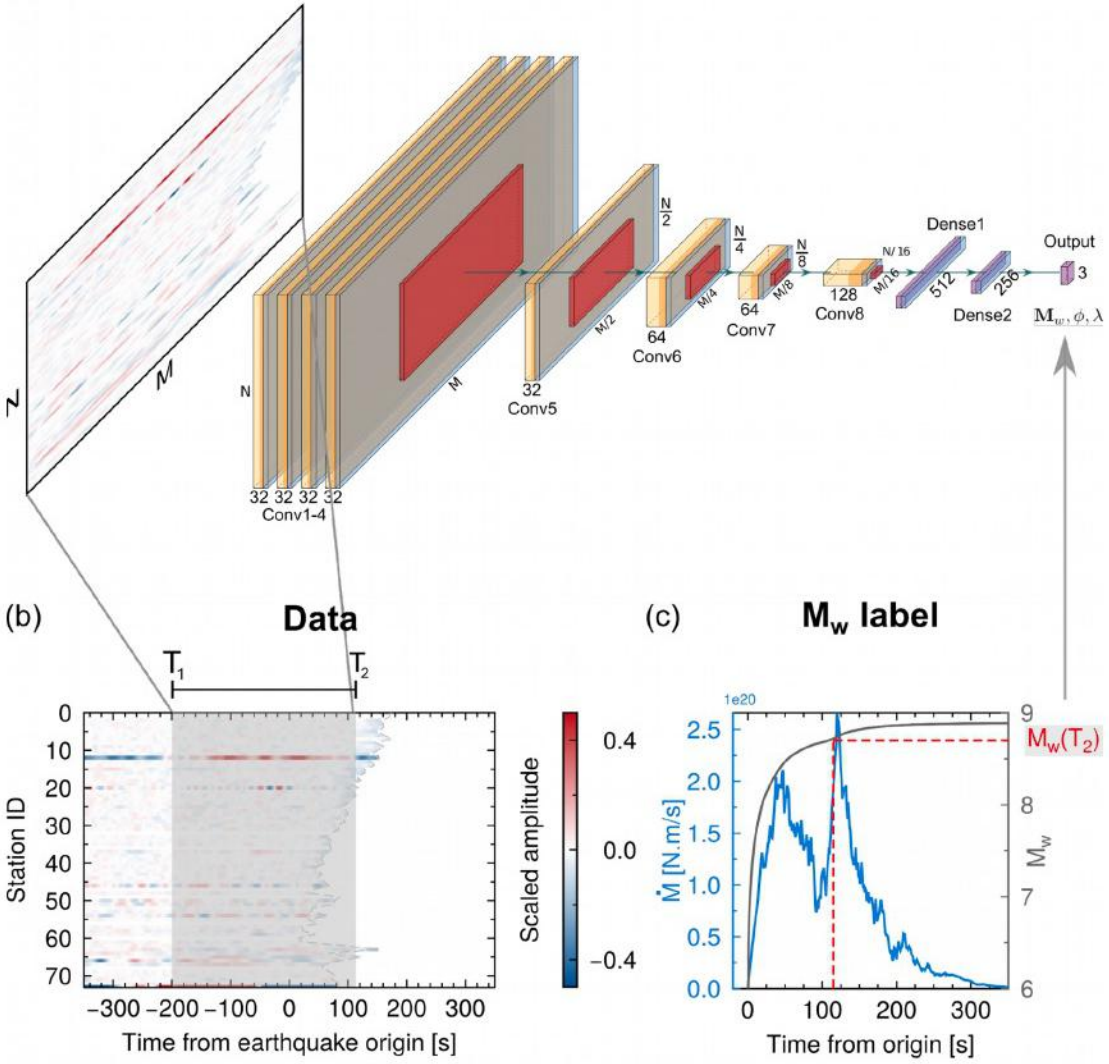


- Real noise added to synthetic PEGS
- 500k synthetic earthquake sources
- Location, dip and strike from Slab2.0 *(Hayes et al. 2018)*
- M_w follows uniform distribution U *[5.5, 10.0]*
- STF empirical model *(Meier et al. 2017)*
- P-wave travel times assumed known

Licciardi, Bletery, Rouet-Leduc et al., *Nature*, 2022

PEGSNet : architecture and learning strategy

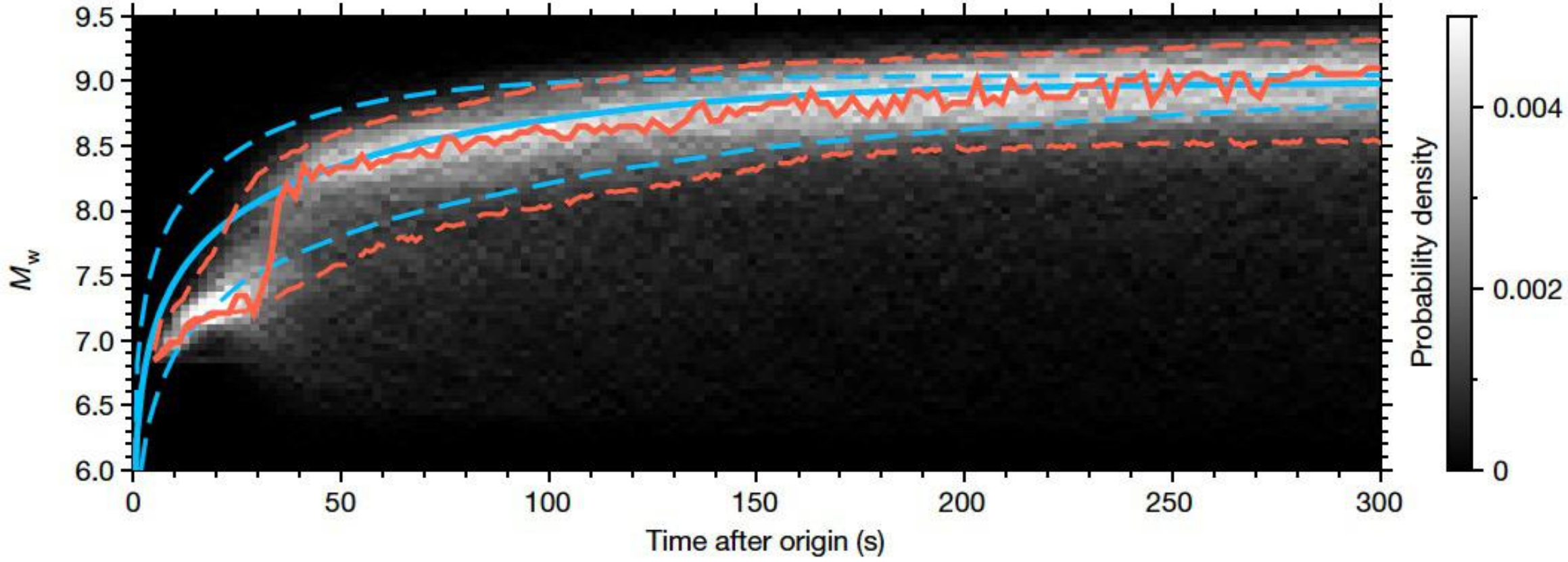
Architecture (Convolutional Neural Network)



- 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.

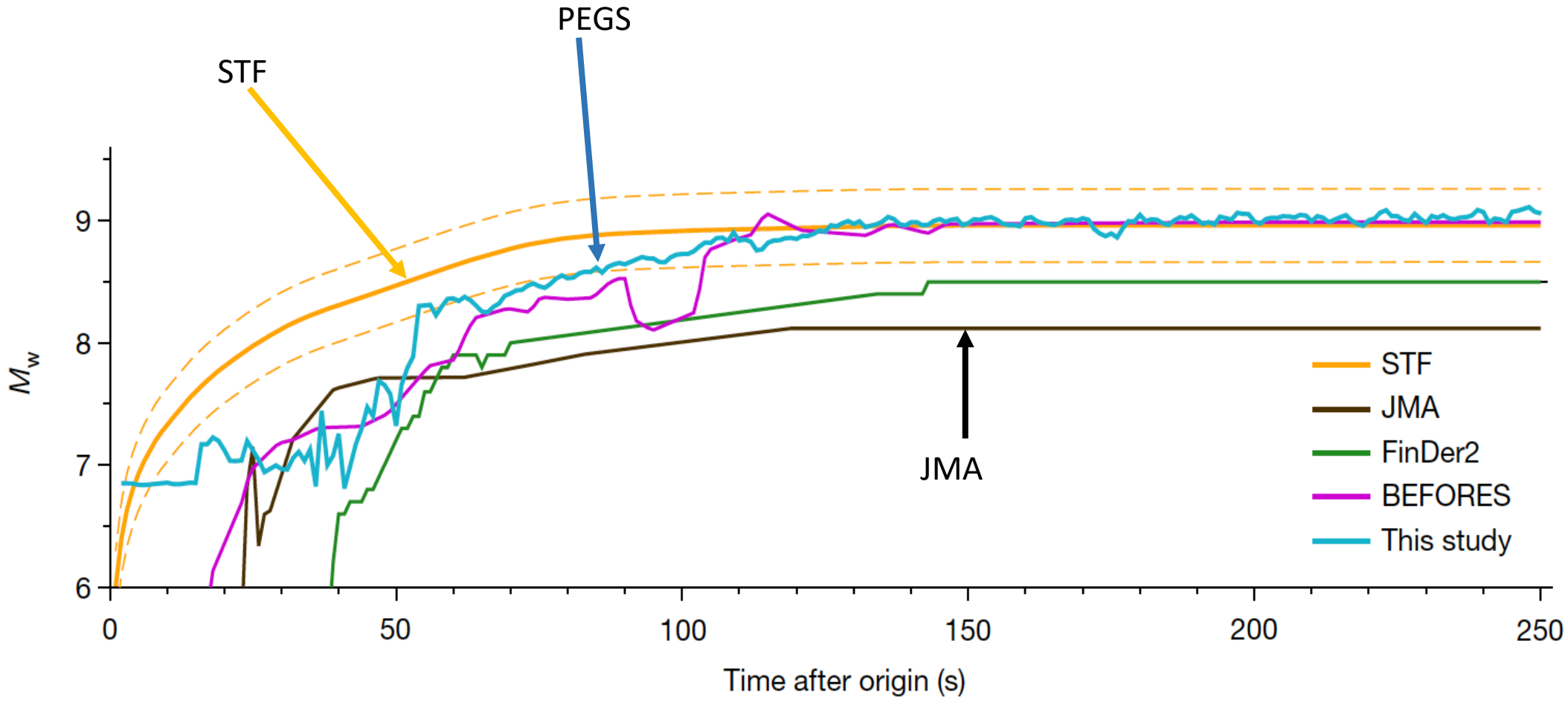
Licciardi, Bletery, Rouet-Leduc et al., *Nature*, 2022

Synthetic tests on M_w 9 earthquakes



Licciardi, Bletery, Rouet-Leduc et al., *Nature*, 2022

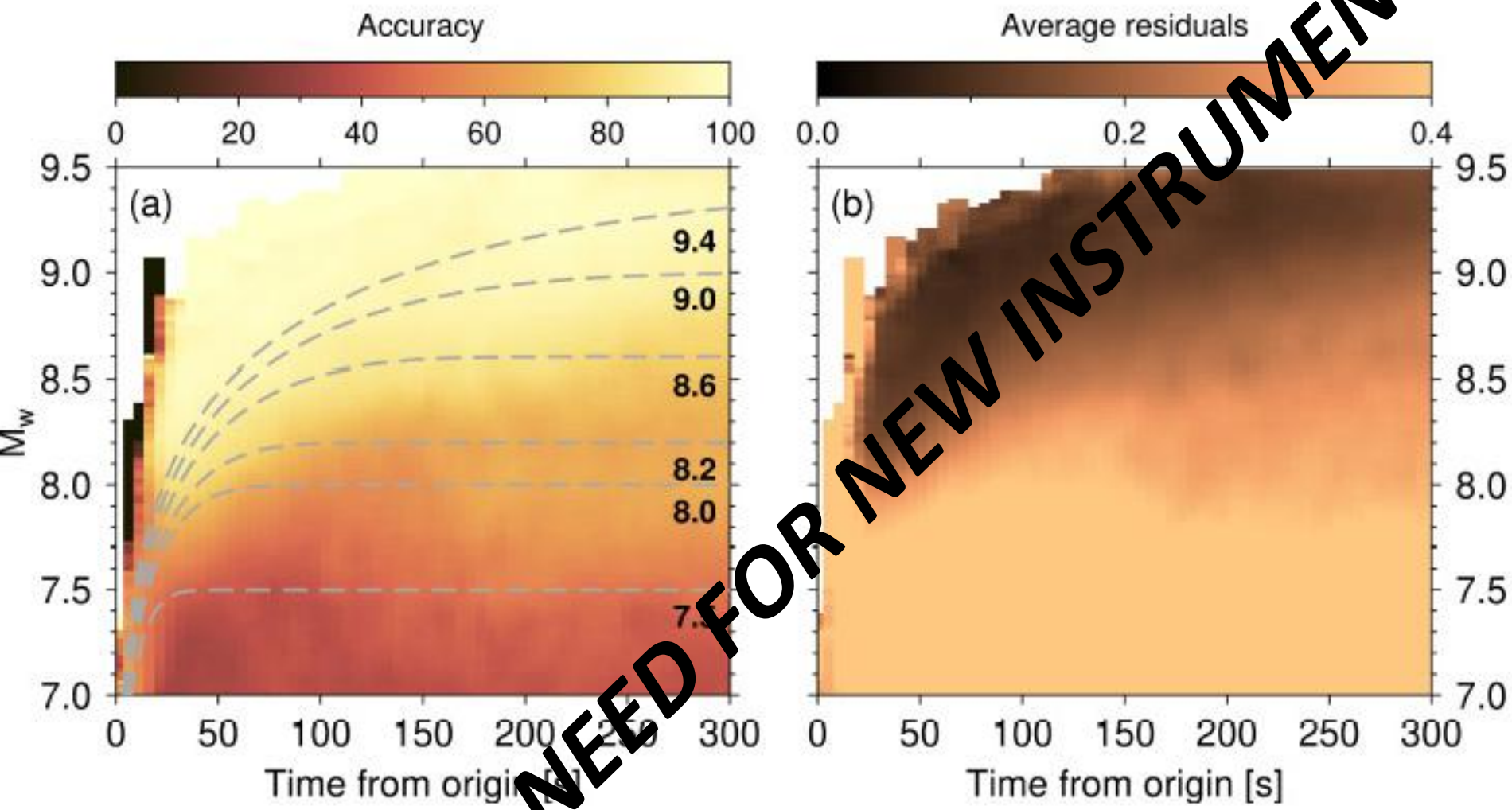
Performance on the Tohoku-Oki earthquake



Licciardi, Bletery, Rouet-Leduc et al., *Nature*, 2022

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

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



NEED FOR NEW INSTRUMENT

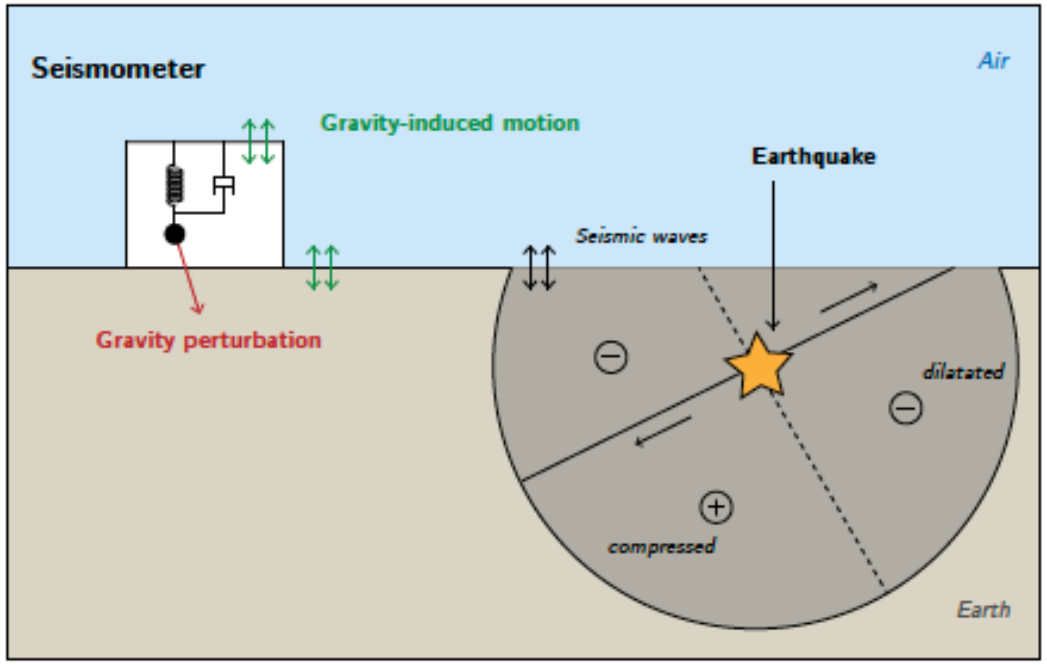
$M_w > 8.3$

- 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.

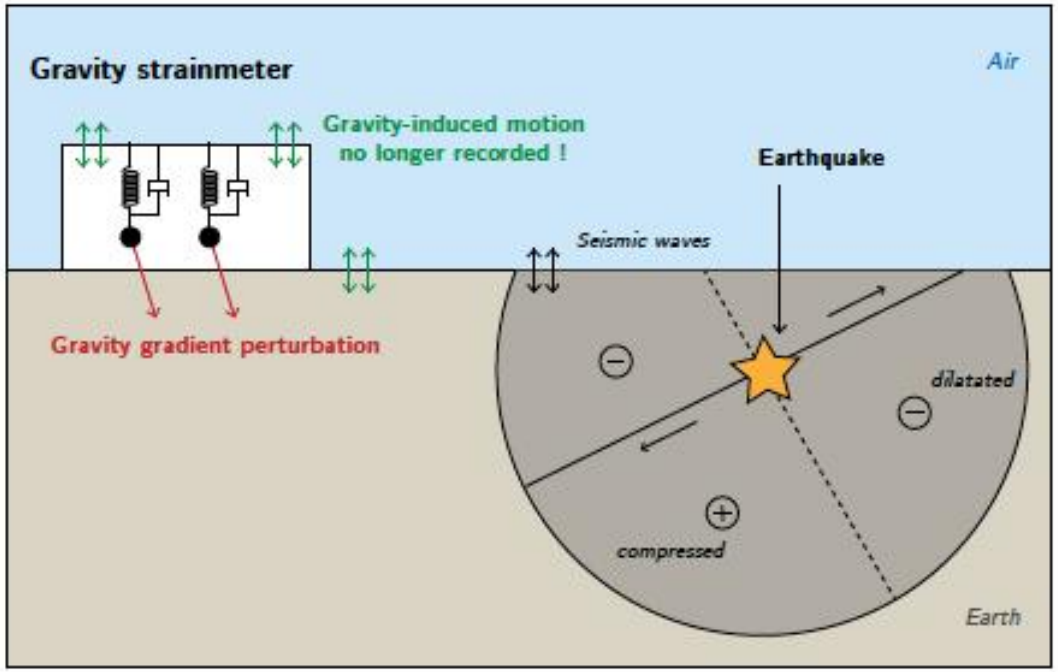
Licciardi, Bletery, Rouet-Leduc et al., *Nature*, 2022

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

<u>limitations</u> :

- background seismic noise
- compensation between δg and $\ddot{u}$

<u>differential measurement</u> :

- noise reduction
- $\ddot{u}$ no longer recorded

NEED FOR NEW INSTRUMENTS
(gradient of the gravity field $\boldsymbol{\nabla}\mathbf{g}$)

Sub-Hz gravitational –wave detection

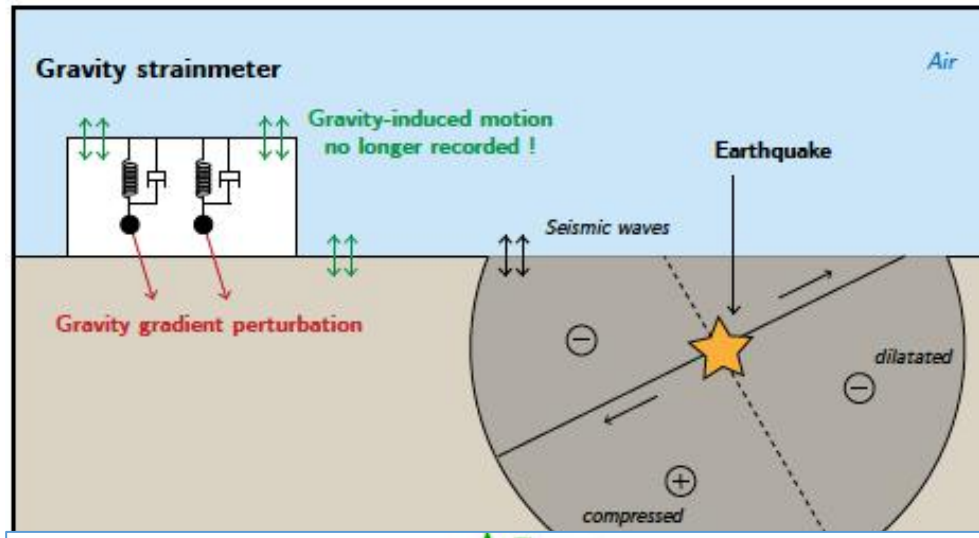
1) Superconducting gradiometers

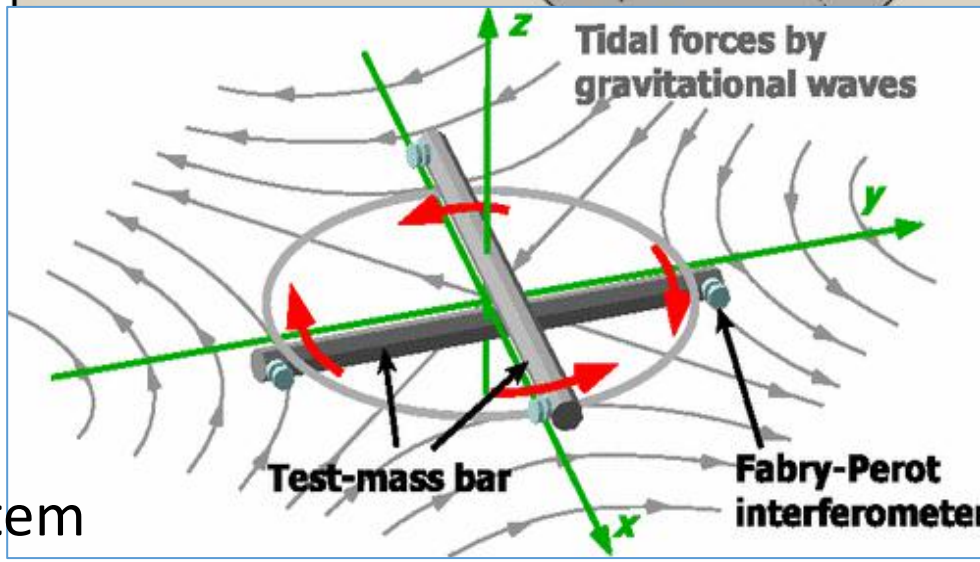
2) Atom interferometers

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

PEGASEWS detector

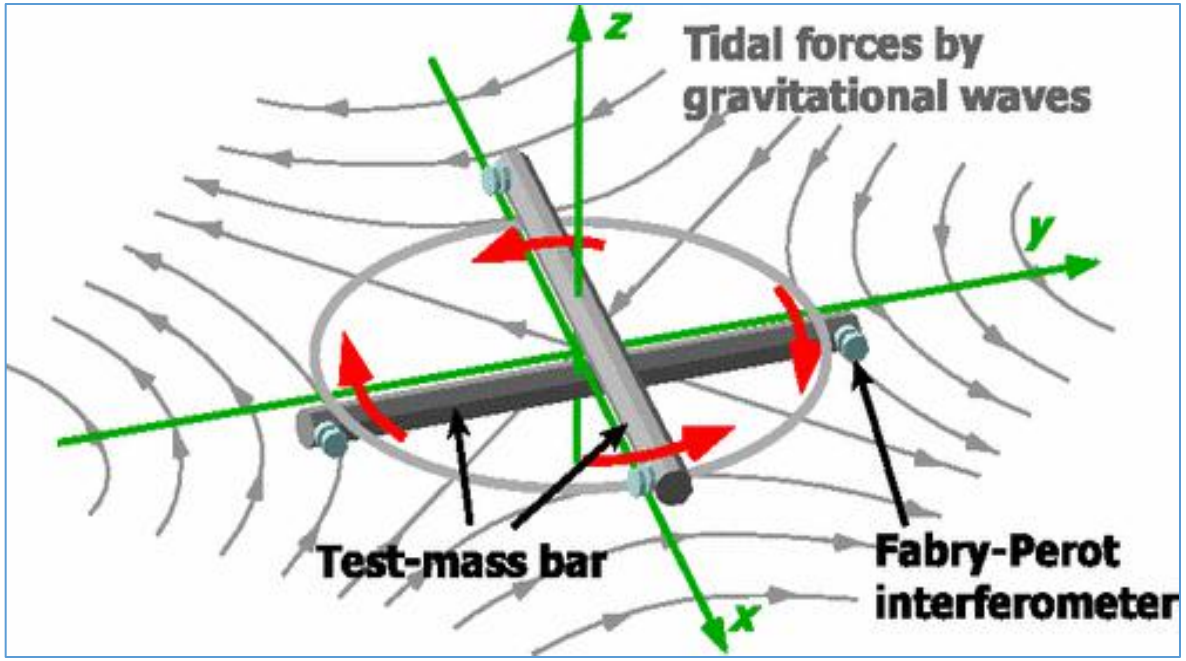
Prompt Earthquake Gravity Anomalies- Early Warning System





Barsuglia et al. 2018

Gravitational wave detectors: TOBA

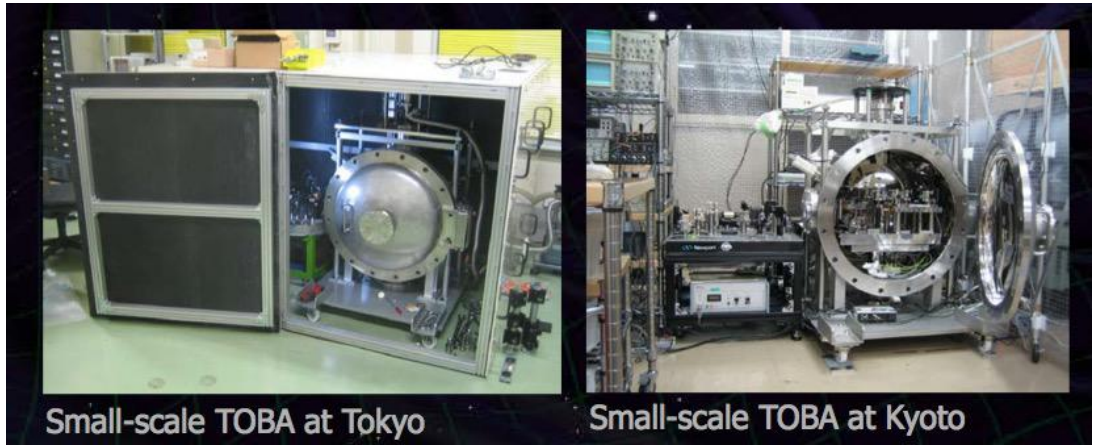


TOBA concept (torsion-bar antenna)-
University of Tokyo
Ando et al (2010)

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}

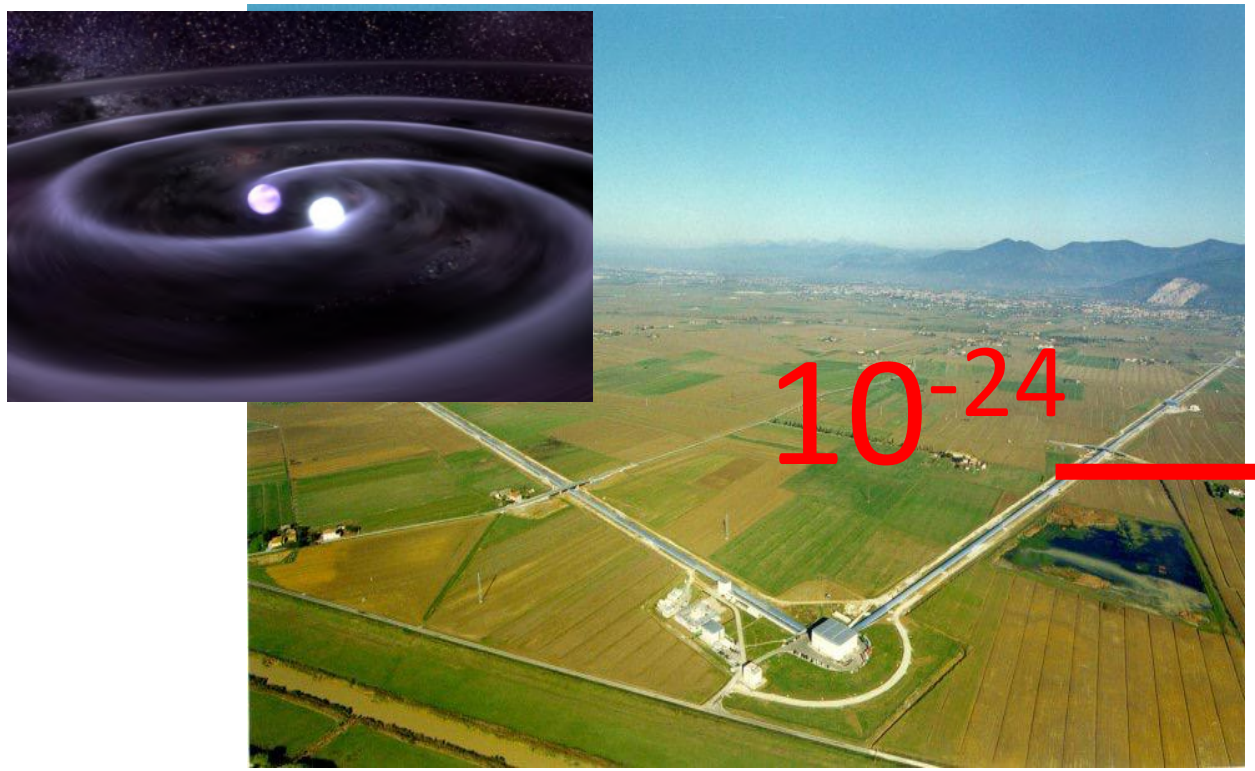
=> goal **PEGASEWS** 10^{-15} √Hz

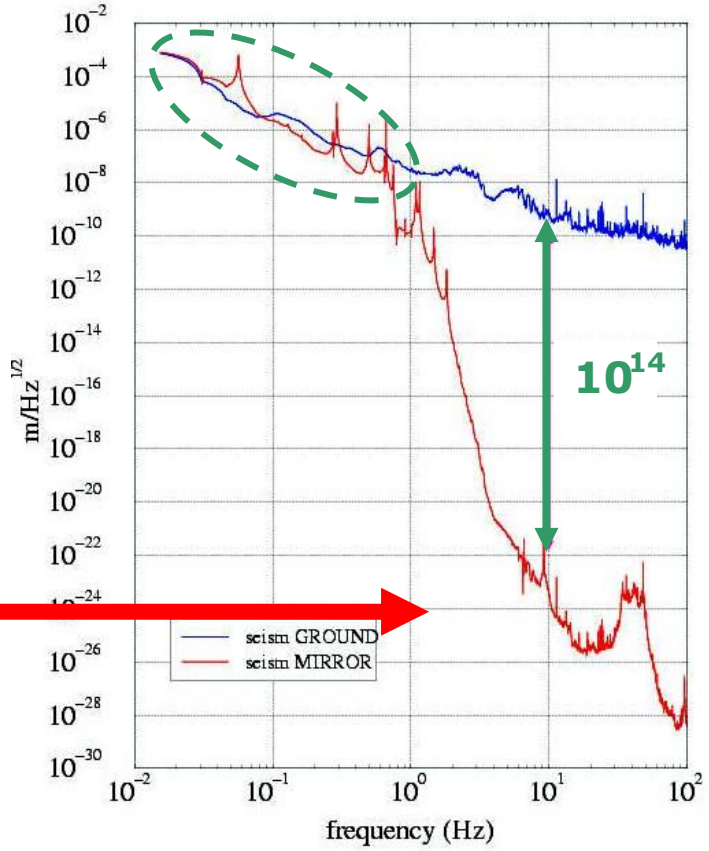


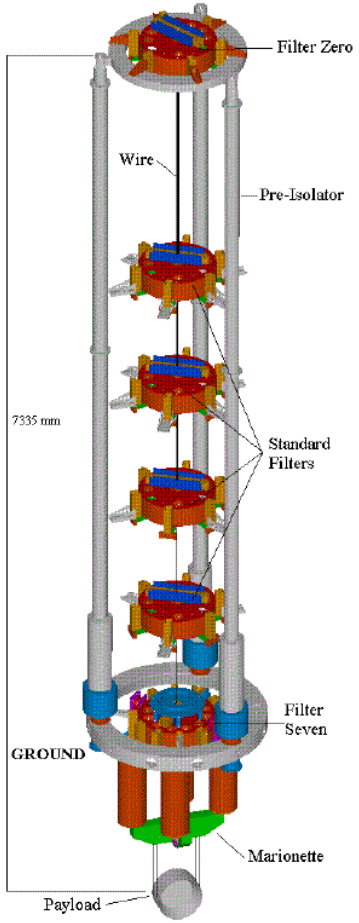
Barsuglia et al. 2018

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

VIRGO (Italian – French Gravitational wave detector)



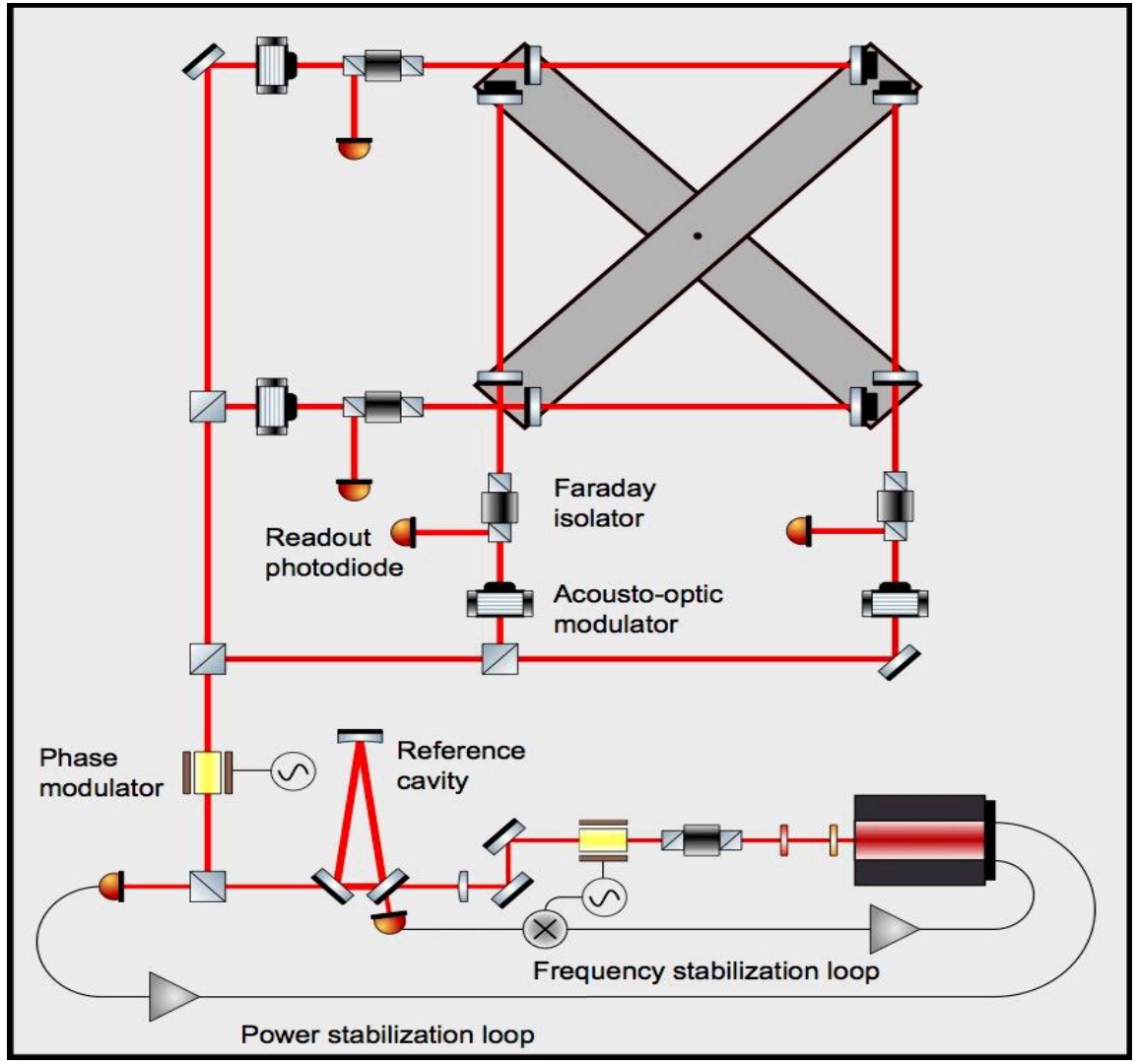




Seismic wall at f>1 Hz

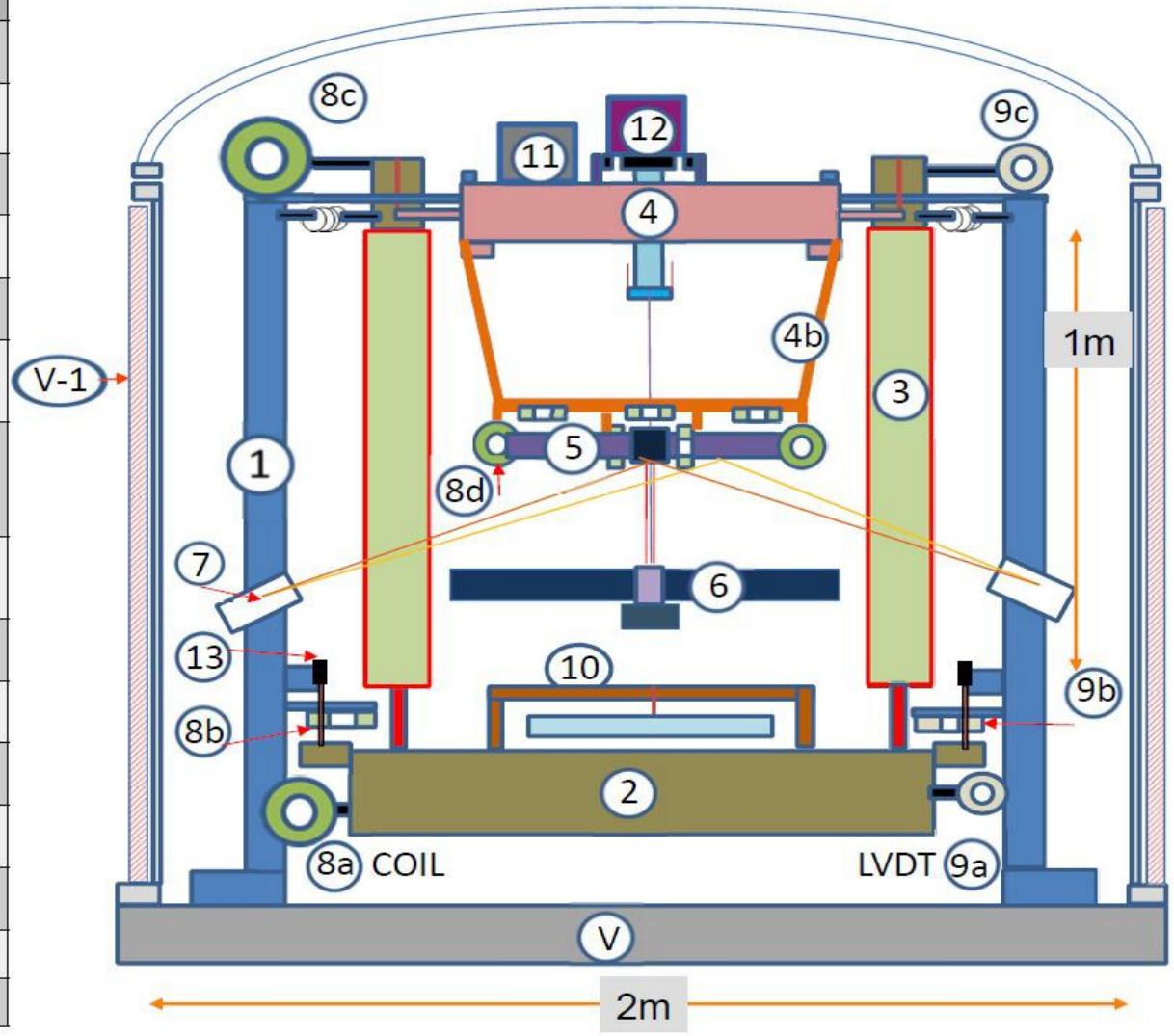
Read-out system of PEGASEWS: APC

4 Fabry-Perot cavities



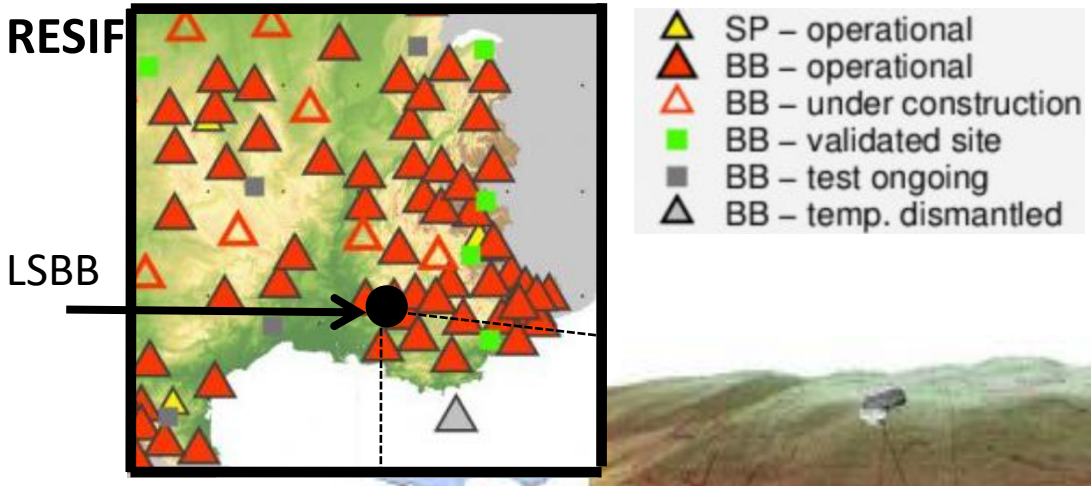
Conceptual scheme of the vibration isolation to be developed for PEGASEWS: INFN

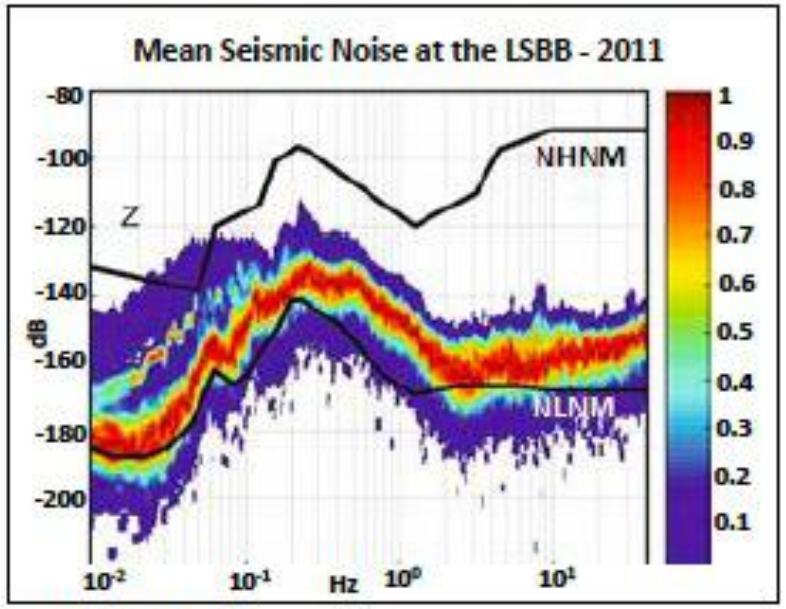
ID	LEGENDA
V	Vacuum Chamber
V-1	Thermal Insulation
1	Safety-Frame
2	Inertial Platform
3	Inverted Pendulum
4, 4b	Suspension Top-Stage
5	Suspension Steering Stage (Marionette)
6	Double Torsion Bar
7	Optical-Lever
8	Coil-Actuators
9	Coil-LVDT
10	Tiltmeter
11	Hor-Accelerometer
12	Vert-Accelerometer
13	PZT-Actuator



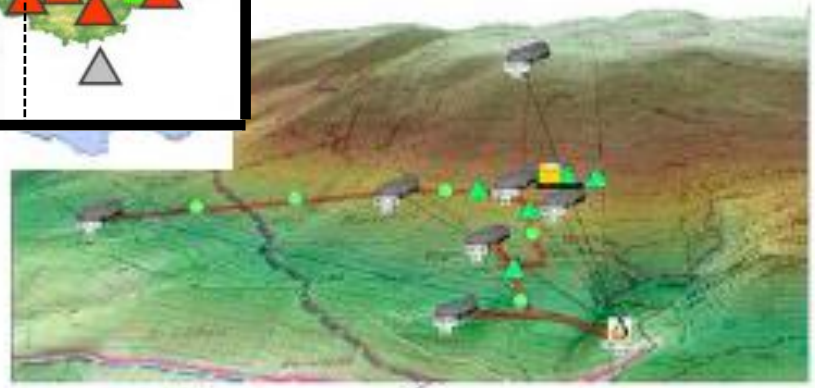
RUSTREL, LSBB

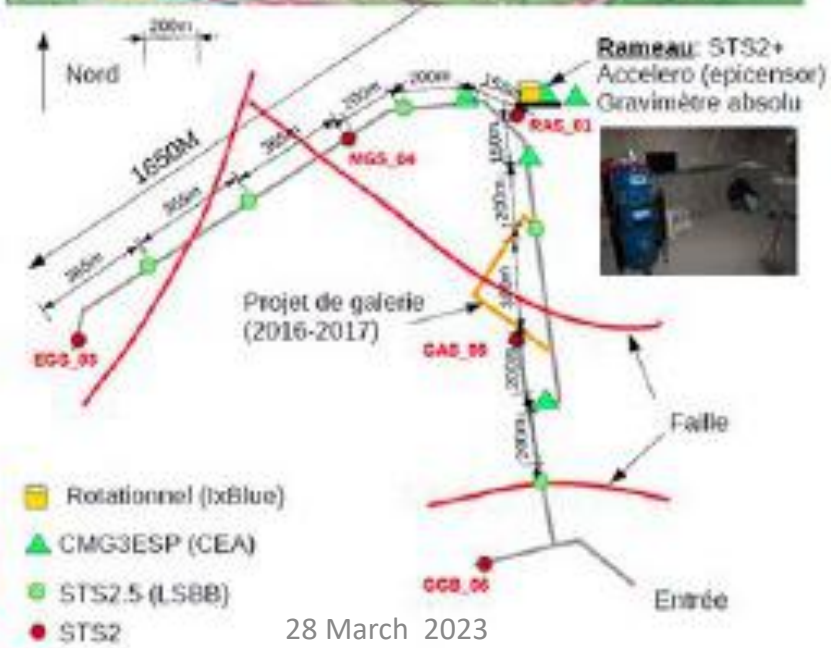
(Laboratoire Souterrain Bas Bruit)
CNRS/Nice:
Stéphane Gaffet





From https://lsbb.eu





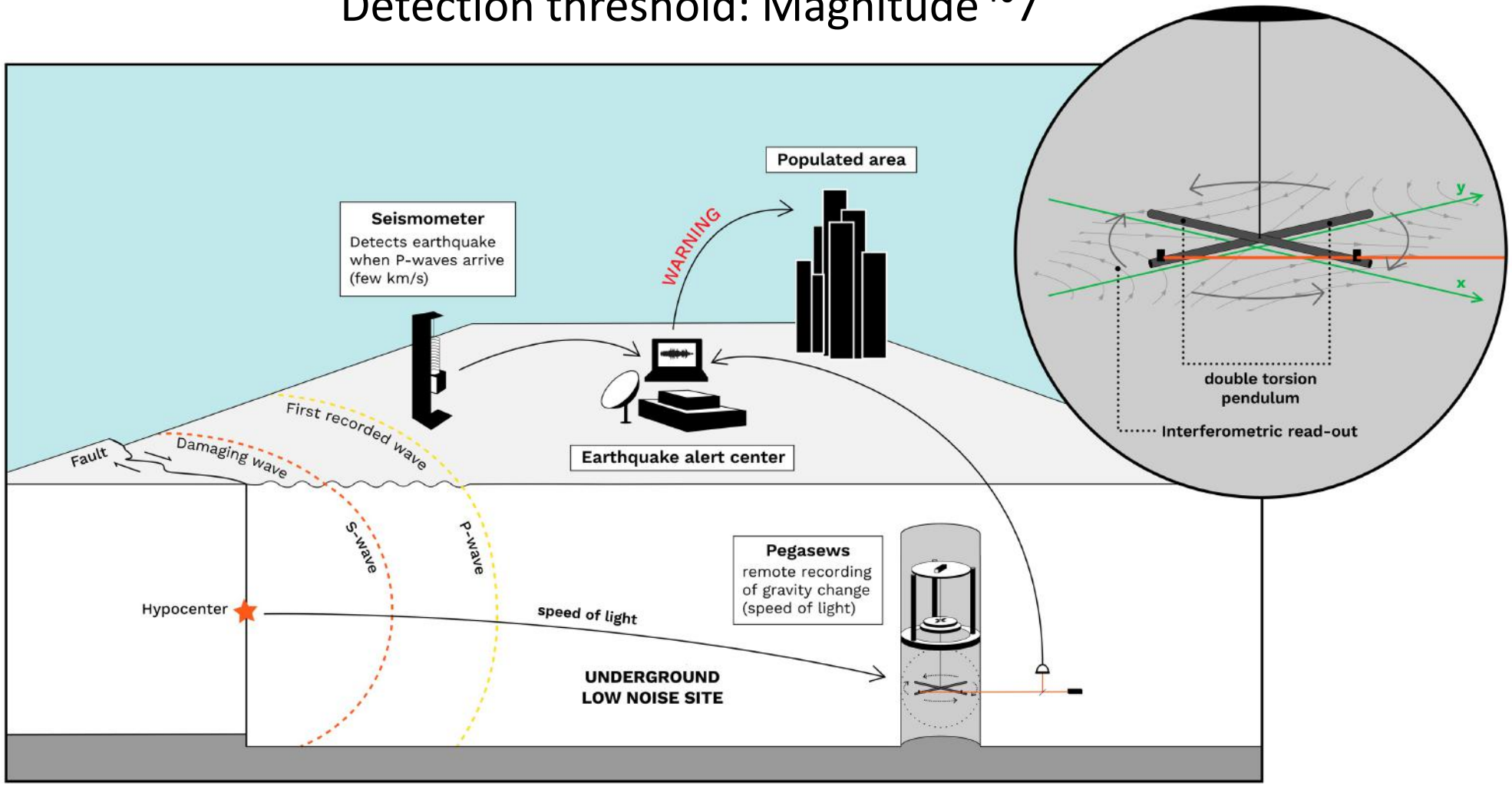
NEWTONIAN SEISMIC NOISE

3D- seismic networks
VBB- seismic sensors
Tiltmeters
Microbarometers
Rotational Sensors ?

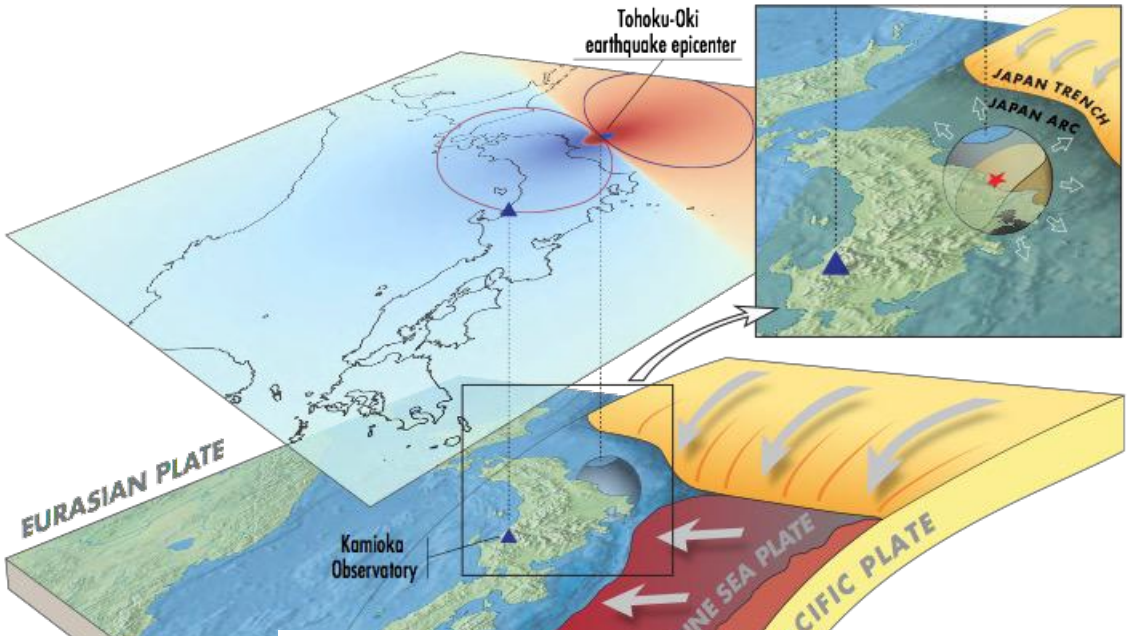
IPGP: Eléonore Stutzmann,
El-Madani Aissaoui,
Claudio Satriano
ENS: Frédéric Boudin
ESEO: Guy Plantier

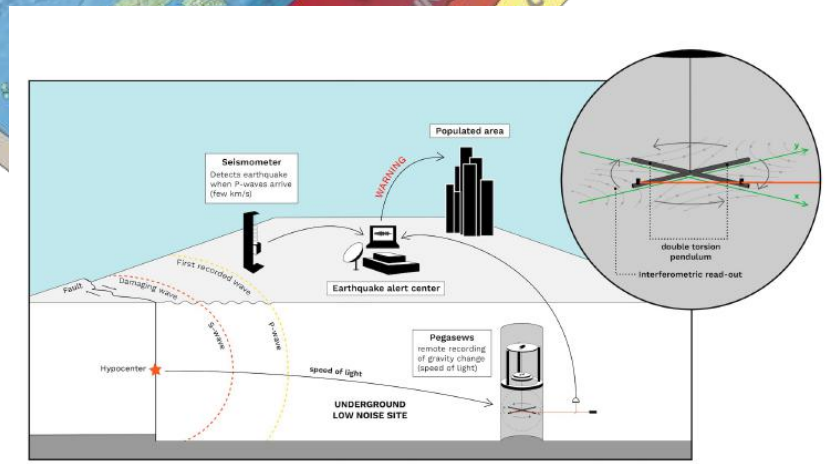
Other Site: Gran Sasso National Laboratory (LNGS)

Future EEWS based on PGS
PEGASEWS: Prompt Earthquake Gravity signAls: Seismic Early Warning System
Detection threshold: Magnitude ~7



Conclusions:
From Gravity field to Earthquake Early Warning Systems



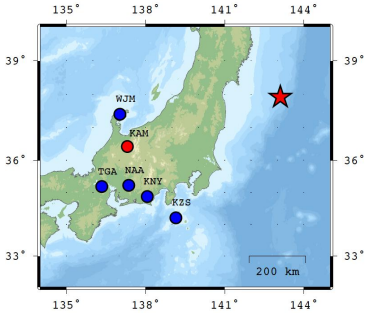


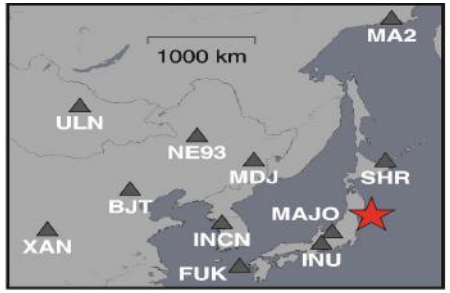
-Detection of a prompt gravity signal for Tohoku eq.: Very, very small $<10^{-9}$ m/s^2

-Detection at Kamioka (Superconducting gravimeter) ≈-0.1-0.2μGal at 500km (Montagner et al., 2016)

-In VBB stations in Japan and Eastern Asia (Vallée et al., 2017)

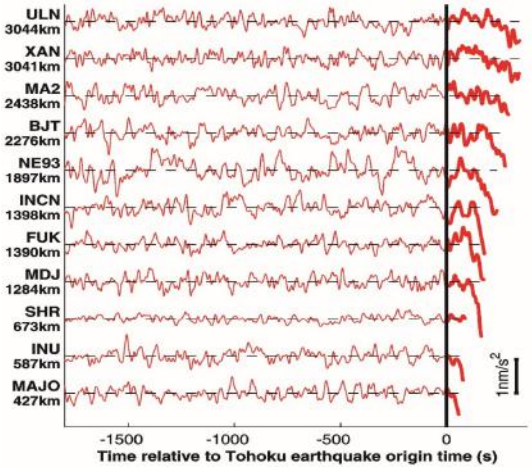
-For other earthquakes (Vallée & Juhel, 2019)





-EEWS: magnitude estimate

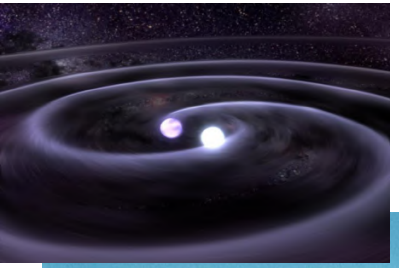
-Need for new gravity Instruments (TOBA, Atom Interferometers, superconducting gradiometers) In the frequency range 0.01-1Hz

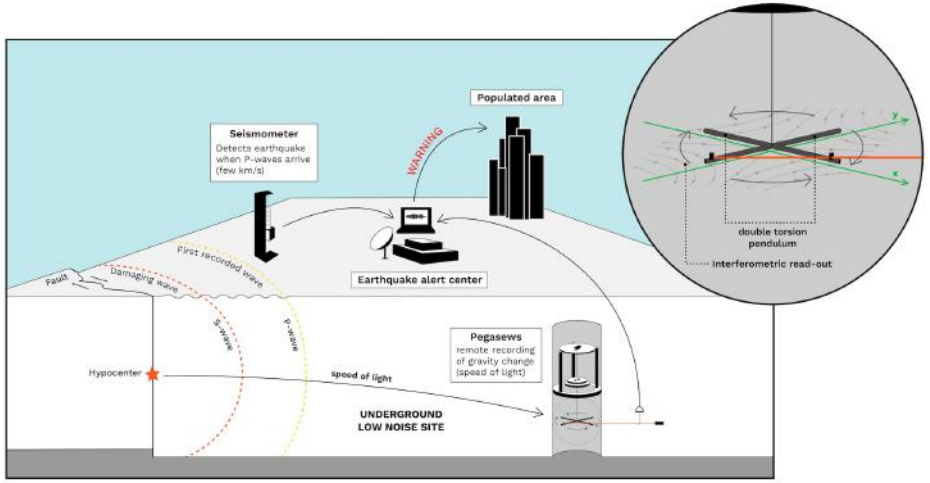


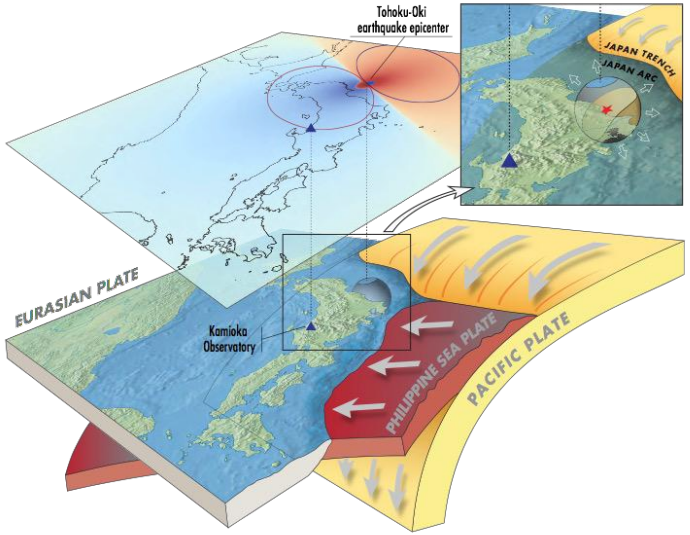
Conclusions

From gravitational waves to Earthquake Early Warning Systems to

Speed of light seismology



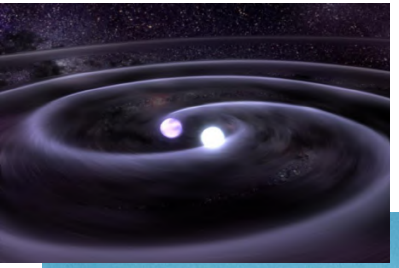




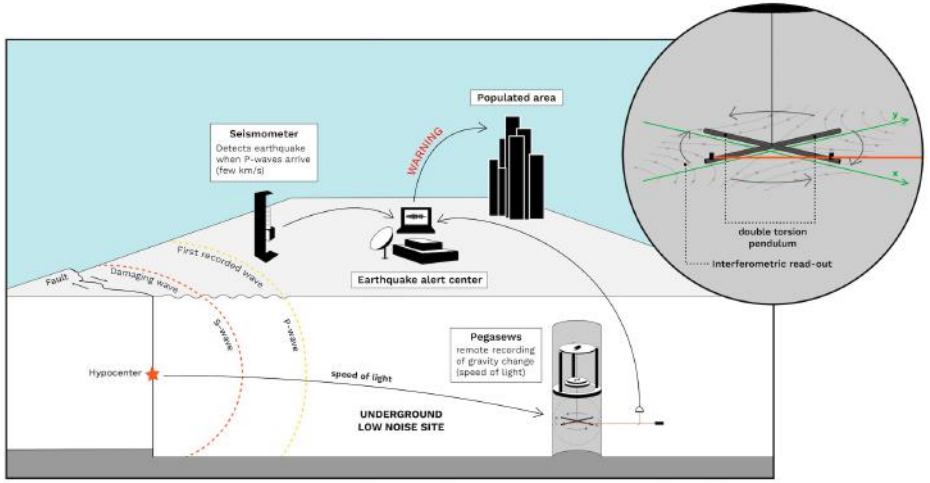
Conclusions

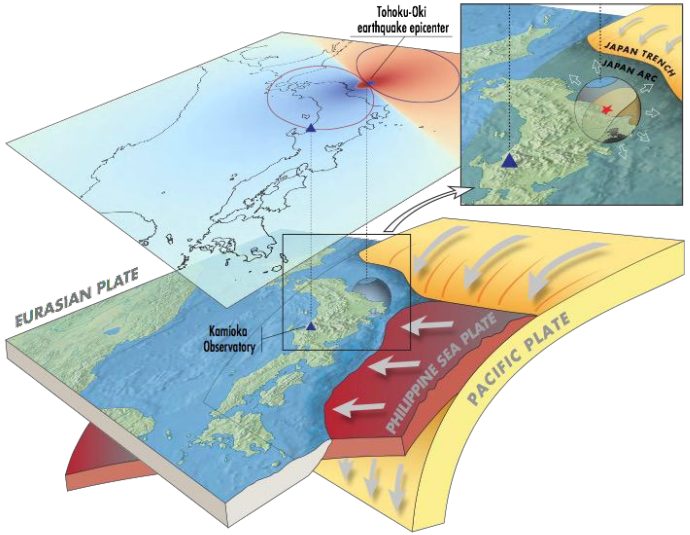
From gravitational waves to **Earthquake Early Warning Systems to**

Speed of light seismology

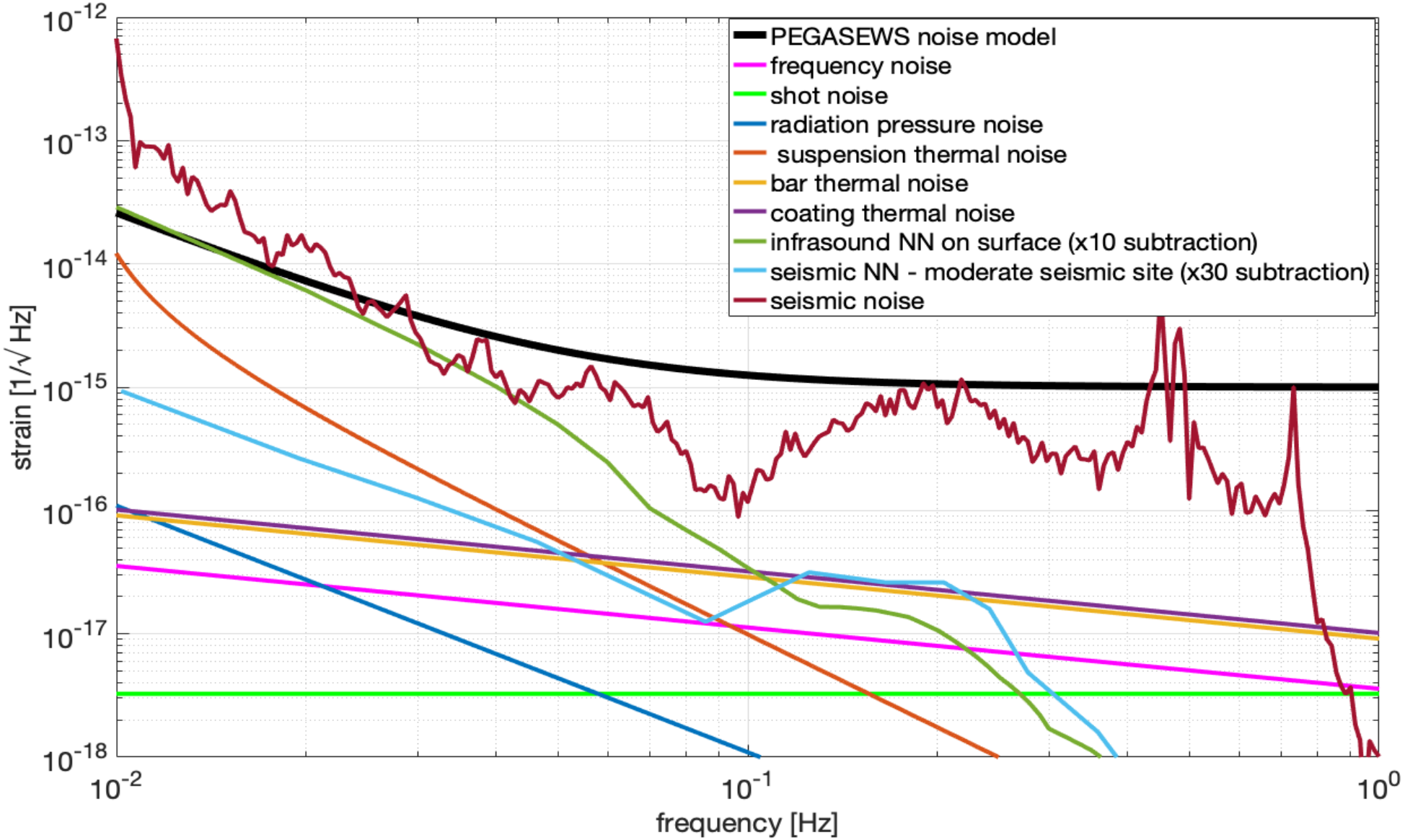


PEGASEWS project

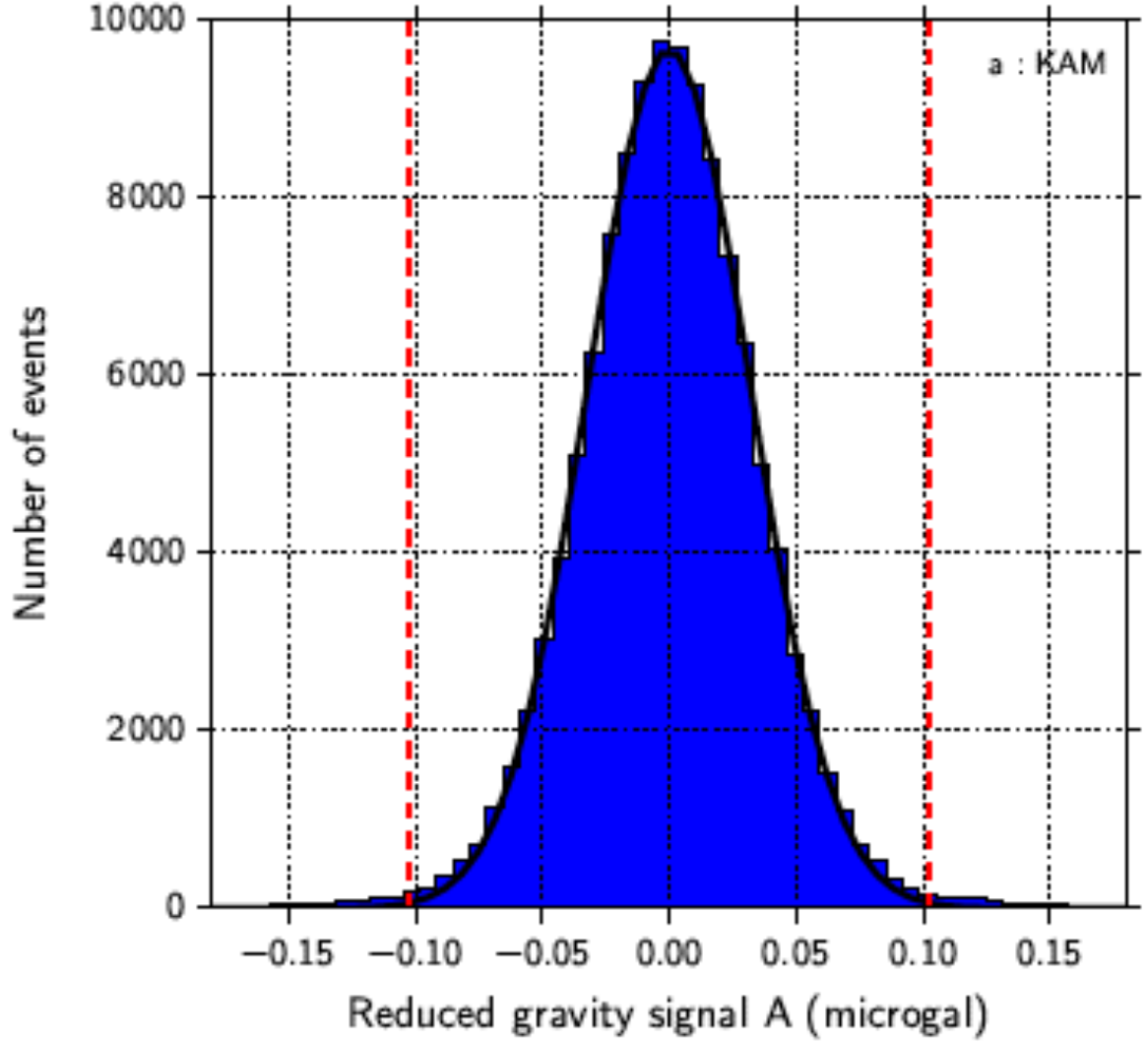


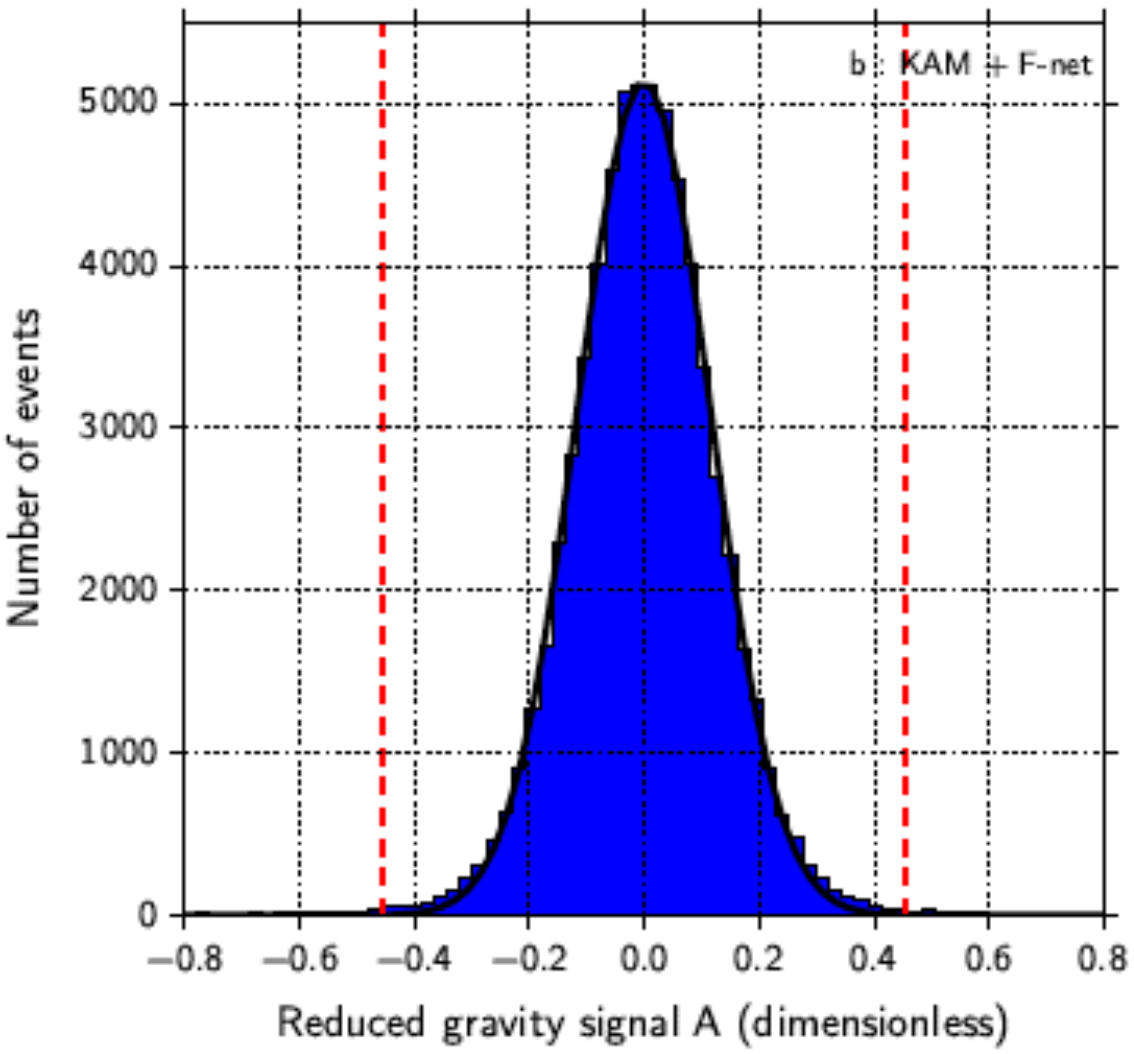


NOISE BUDGET



STATISTICAL ANALYSIS



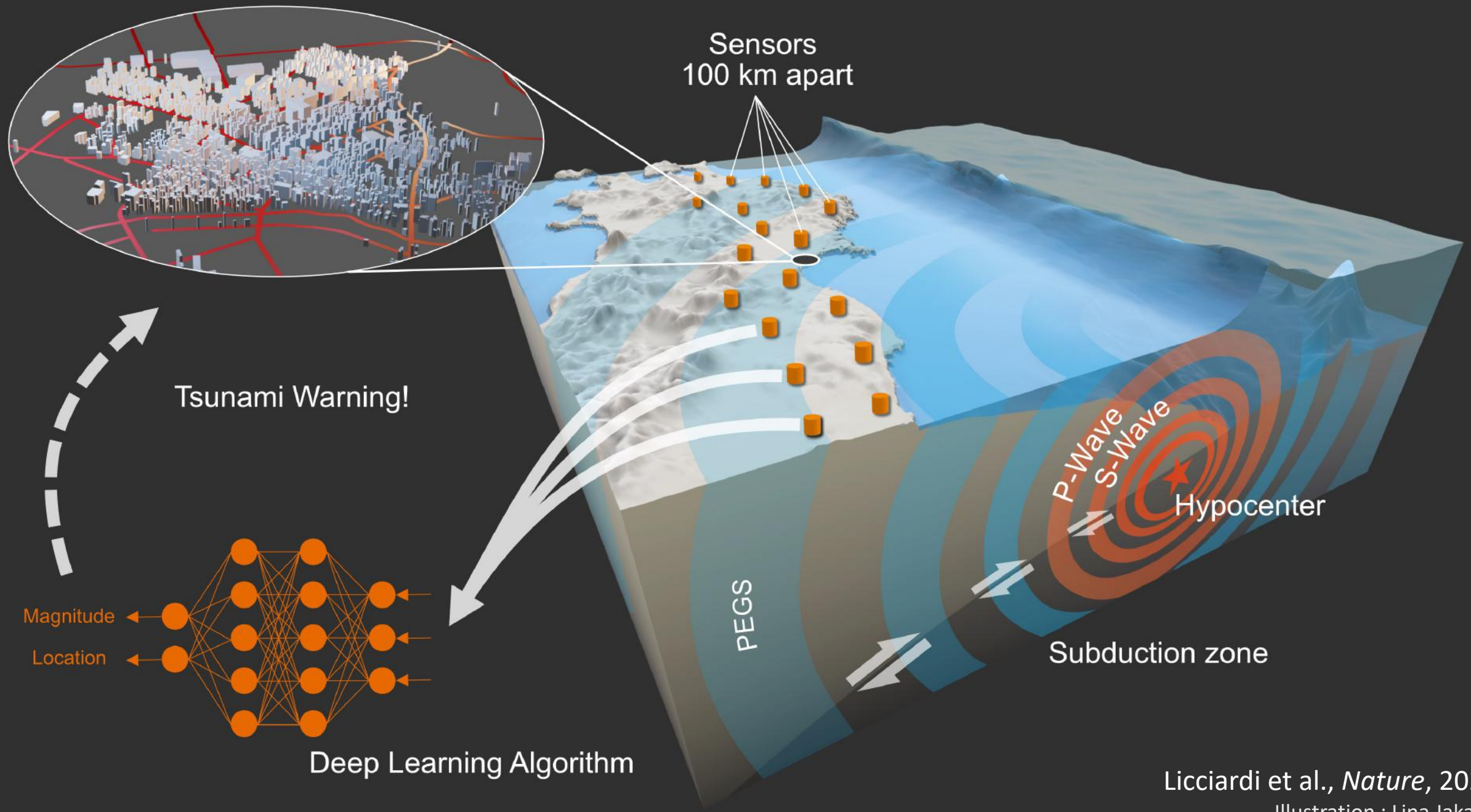


For the Kamioka station only :

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

For a stacked waveform :
Kamioka + 5 F-net

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

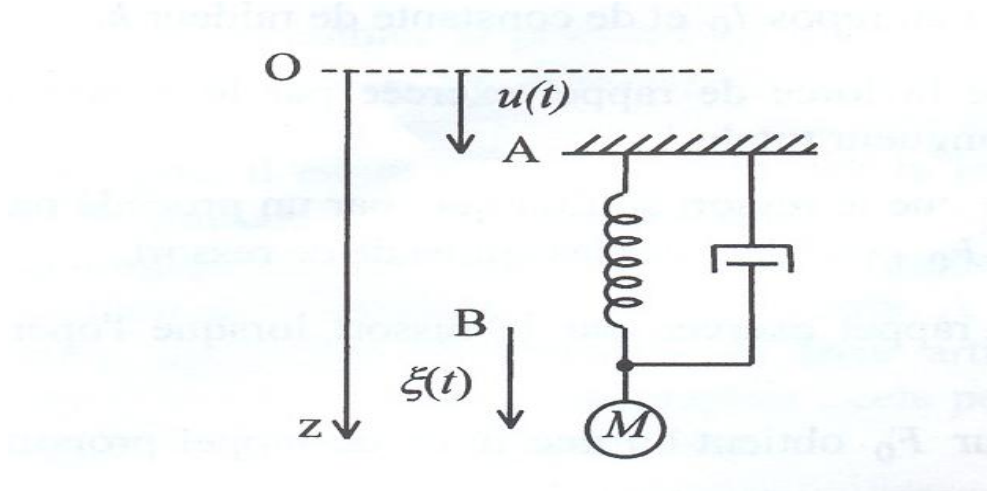


Licciardi et al., *Nature*, 2022

Illustration : Lina Jakaite

But what are exactly these signals that we observe ?

What do we expect to record with a ground-attached seismometer (or gravimeter) ?



Without gravitational changes, gravity only controls the equilibrium position of the mass, and we have :

$$\frac{d^2\xi}{dt^2} + \frac{D}{M}\frac{d\xi}{dt} + \frac{k}{M}\xi = -\frac{d^2u}{dt^2} \qquad (1)$$

With Δg, (1) is simply modified as :

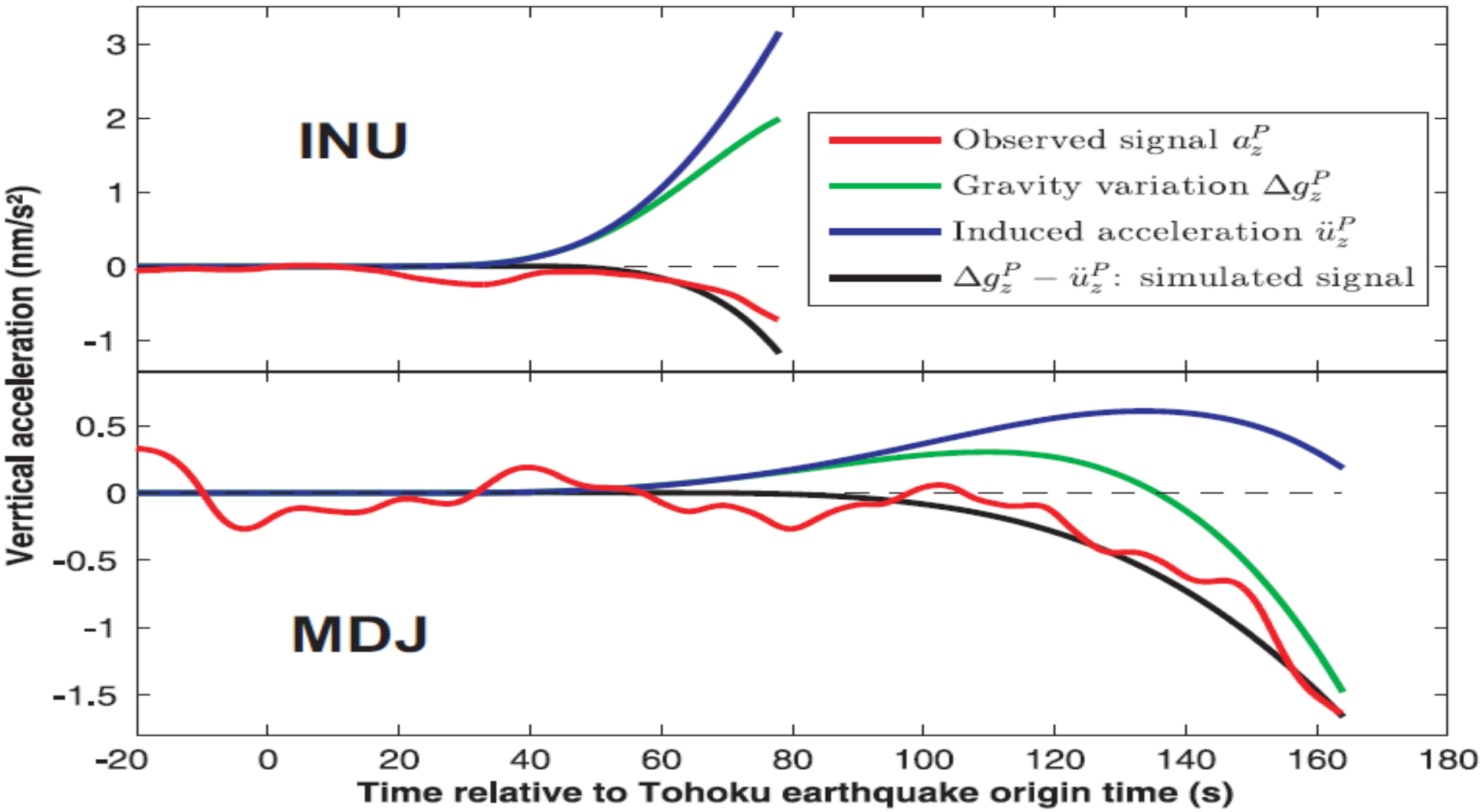
$$\frac{d^2\xi}{dt^2} + \frac{D}{M}\frac{d\xi}{dt} + \frac{k}{M}\xi = \Delta g - \frac{d^2u}{dt^2} \qquad (2)$$

A seismometer is therefore a **seismo-gravimeter, which records**, after correction from the instrumental response, **the difference between the ground acceleration and the gravitational perturbations**

How to model the difference between these two terms (Δg - $\ddot{u}$) ?

Courtesy of Martin Vallée

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., 2019

Reply to Tom Heaton: prompt gravity signal and inertial acceleration do not cancel