Gravity-based earthquake early warning :

Why do we need new instruments ? Which sensitivity is needed ?

Kévin Juhel (IPGP)

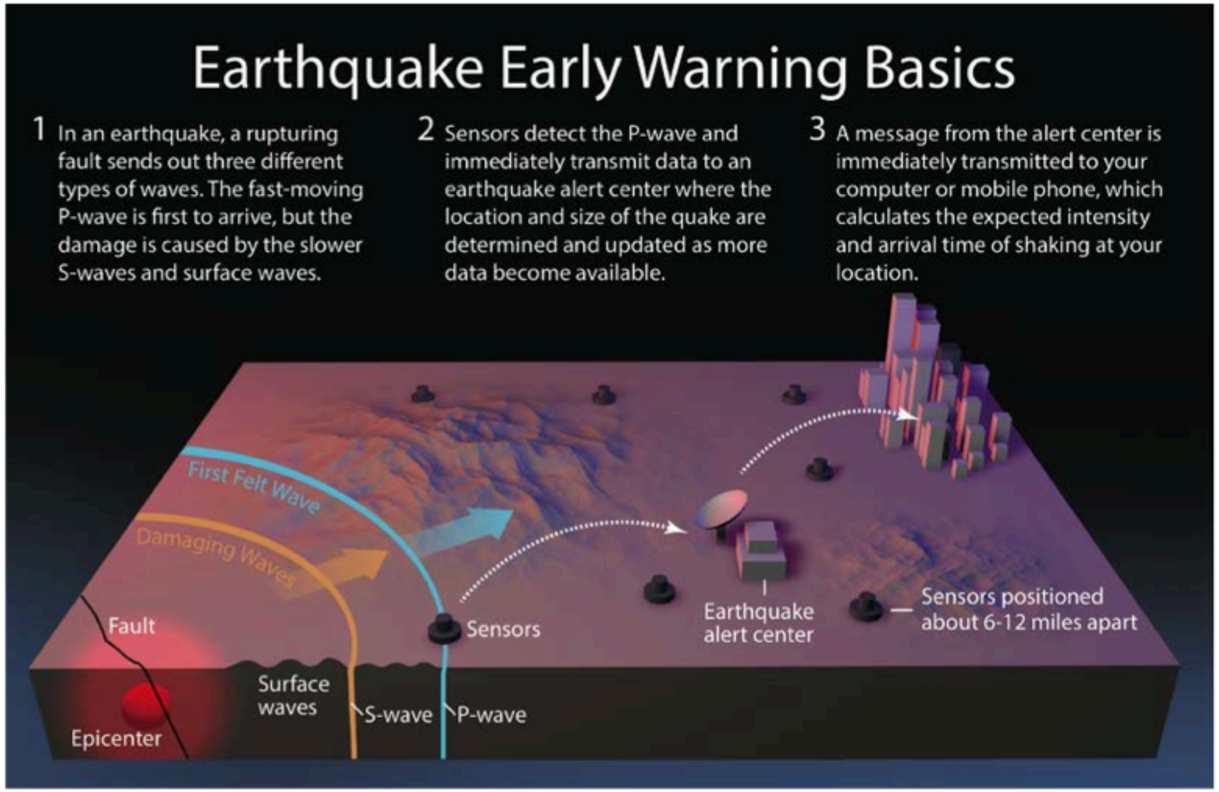
Jean Paul Ampuero (Caltech, Géoazur), Matteo Barsuglia (APC), Pascal Bernard (IPGP), Éric Chassande-Mottin (APC),

Jan Harms (INFN), Jean-Paul Montagner (IPGP), Martin Vallée (IPGP), Bernard Whiting (U. Florida)

Earthquake early warning basics

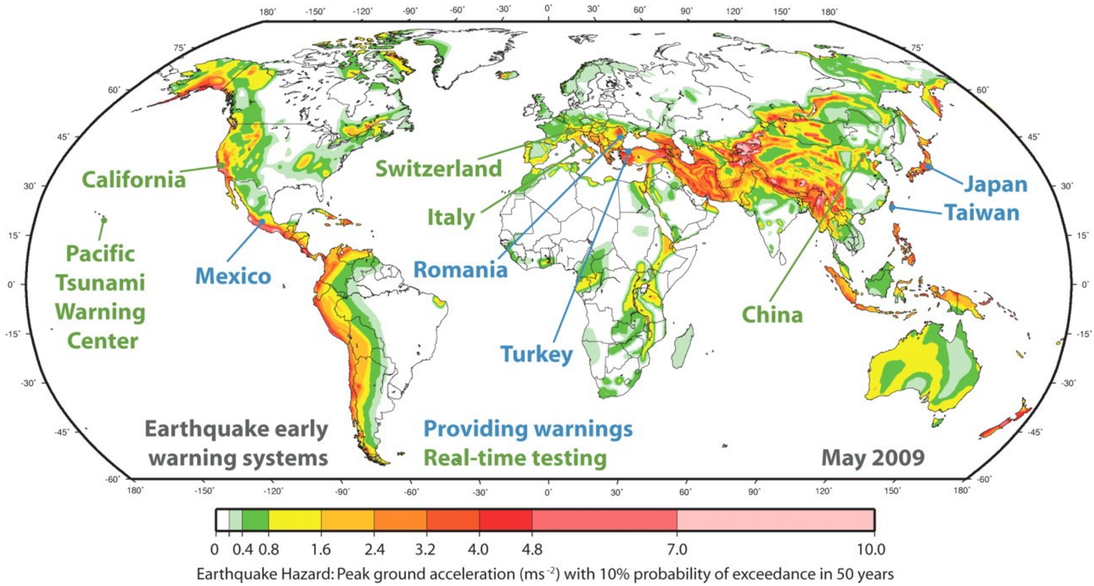
Early warning basics :

- Seismic networks + communications
- Aim : provide warning prior to significant ground shaking
- Velocity difference between (fast) P-waves and (damaging) S-waves



from https://earthquake.usgs.gov

Existing Earthquake Early Warning Systems (EEWS) :



[Allen, 2009]

Blind zone of conventional EEWS :

$$\text{radius} = \sqrt{\beta^2 \left(\sqrt{d^2 + z^2}/\alpha + \Delta t\right)^2 - z^2}$$

$$\begin{cases} \alpha,\ \beta & : \text{seismic waves velocity} \\ d & : \text{epicentral distance} \\ z & : \text{depth of the earthquake} \\ \Delta t & : \text{system delay} \end{cases}$$

[Kuyuk and Allen, 2013]

Early response of a ground-based seismometer

What is recorded by a seismometer :

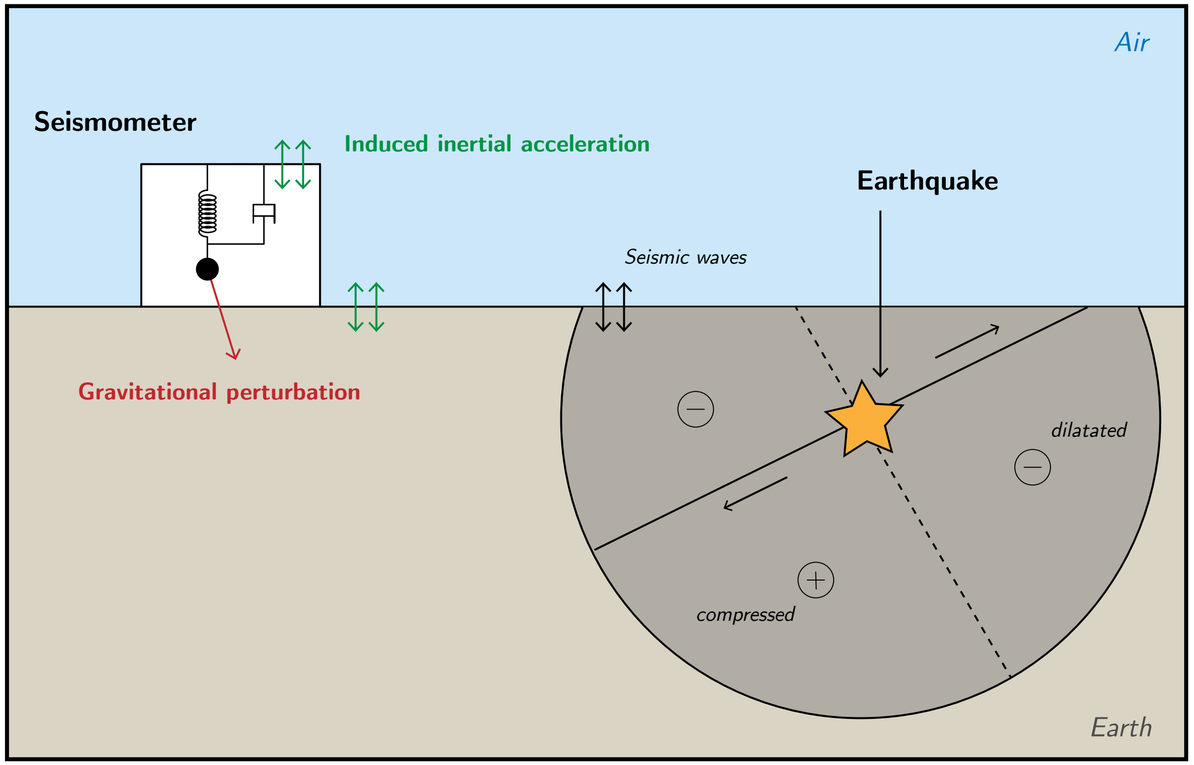
$$f_r = \ddot{s}_r + g_1^L = \ddot{s}_r + g_1^E + s \cdot \nabla g_0$$

[Dahlen and Tromp, 1998]

g_1 : gravitational perturbation

$\ddot{s}_r$: gravity-induced inertial acceleration

$s \cdot \nabla g_0$: coupling terms to the static gravity field



Early response of a ground-based seismometer

What is recorded by a seismometer :

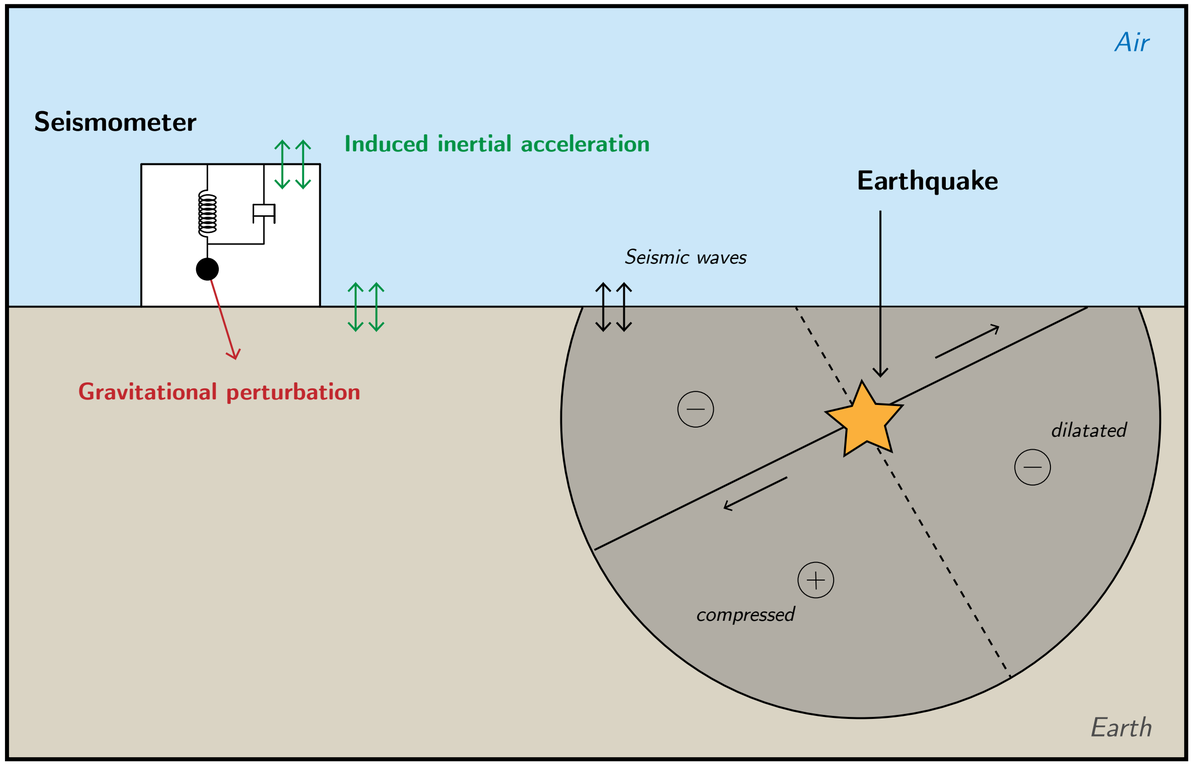
$$f_r = \ddot{s}_r + g_1^L = \ddot{s}_r + g_1^E + s \cdot \nabla g_0$$

[Dahlen and Tromp, 1998]

g_1 : gravitational perturbation

$\ddot{s}_r$: gravity-induced inertial acceleration

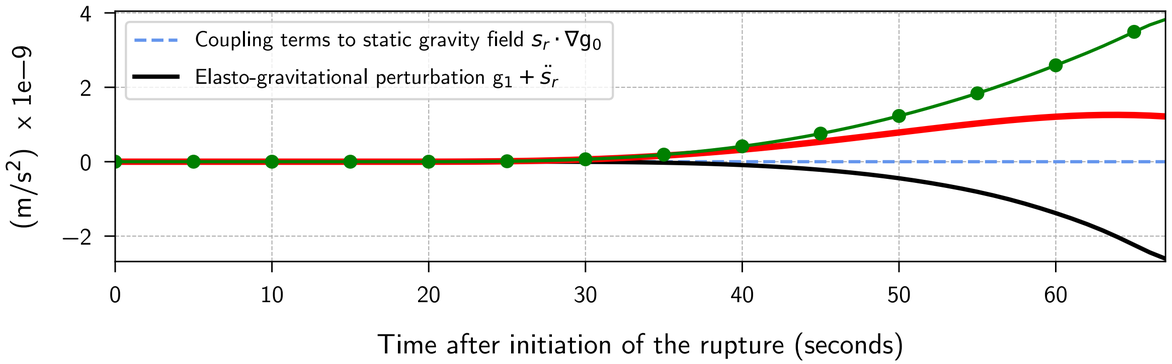
$s \cdot \nabla g_0$: coupling terms to the static gravity field



Detection of every > M6.5 earthquakes ?

2 main limitations :

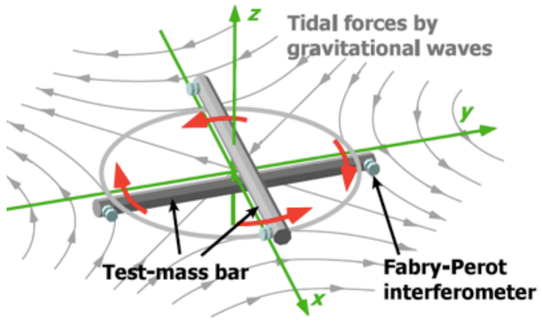
- ambiant seismic noise
- cancelling effect close to onset time



Gravity-based earthquake early warning system

Next generation of gravity strainmeters :

- Superconducting gravity gradiometers
- Atom interferometers
- Torsion bars antennas (e.g. TOBA)



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

- ~~ambiant seismic noise~~
- ~~cancelling effect close to onset time~~

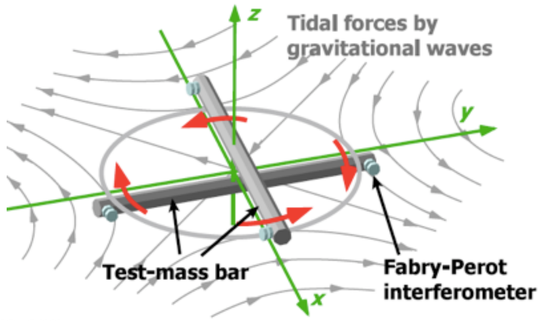
↓

- noise reduction
- differential measurement

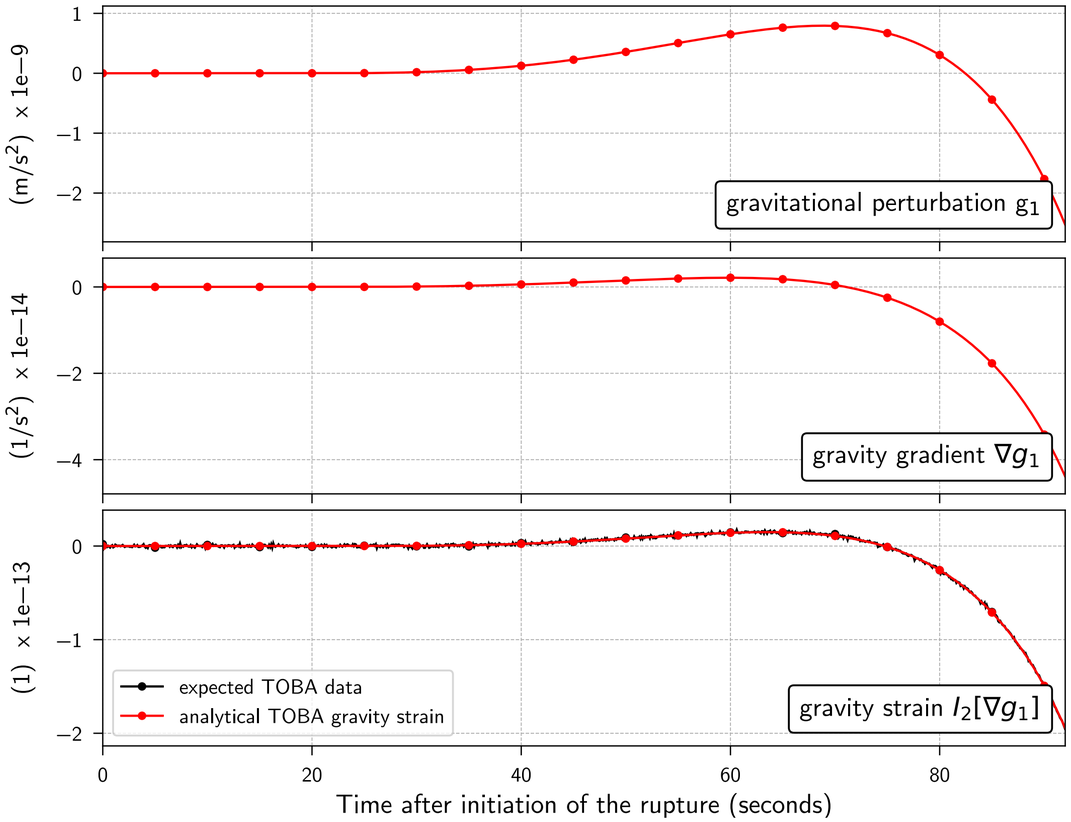
Gravity-based earthquake early warning system

Next generation of gravity strainmeters :

- Superconducting gravity gradiometers
- Atom interferometers
- Torsion bars antennas (e.g. TOBA)

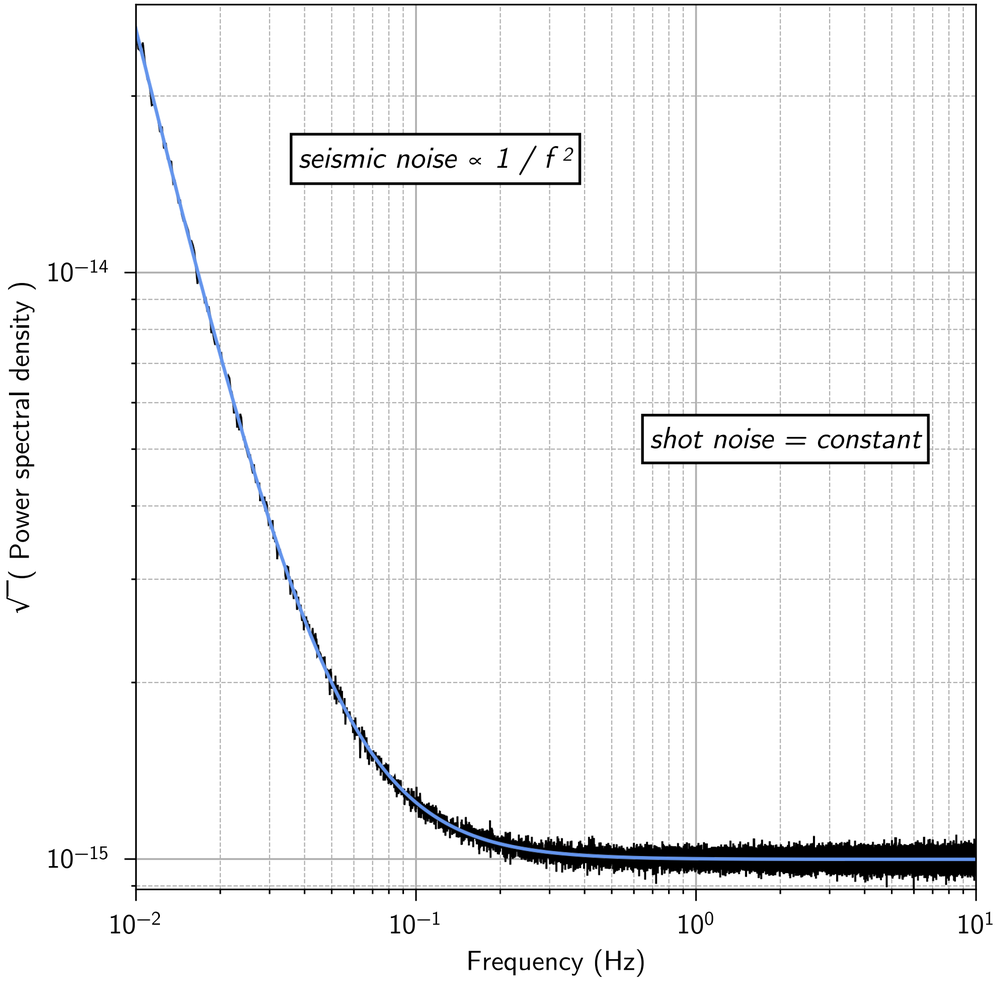


from http://www.gw-indigo.org



[Harms, 2016]

Detector sensitivity model :

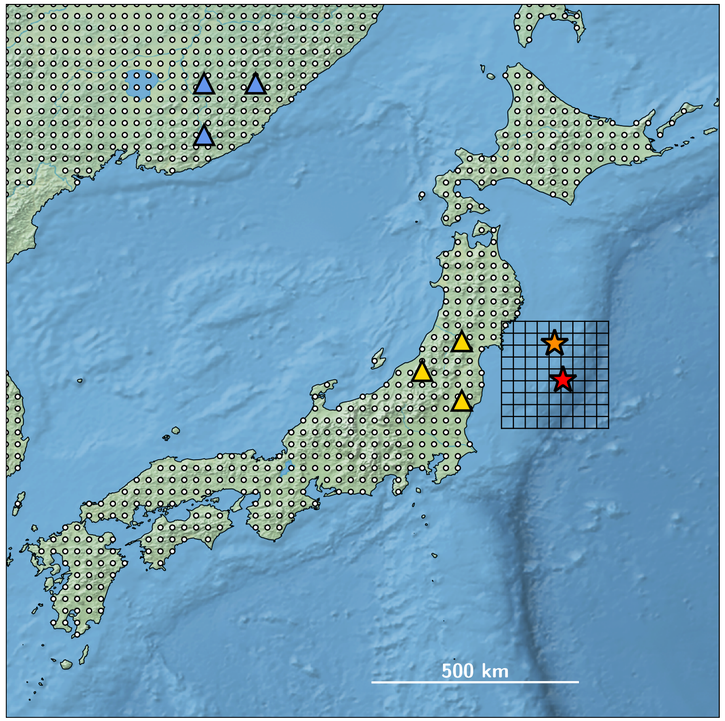


Future « recorded » data :

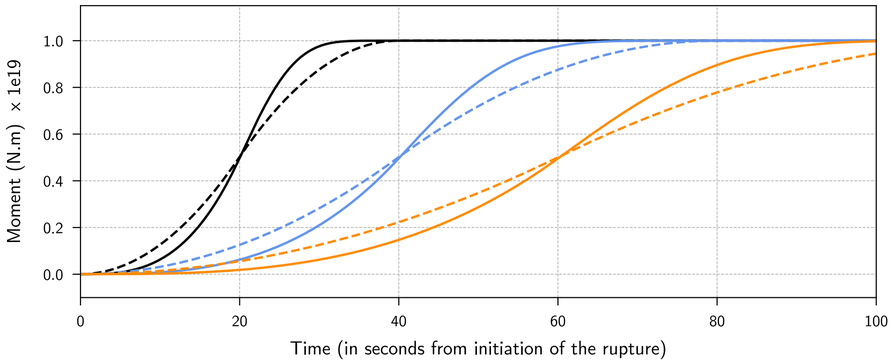
analytical gravity strain perturbation + expected instrumental noise

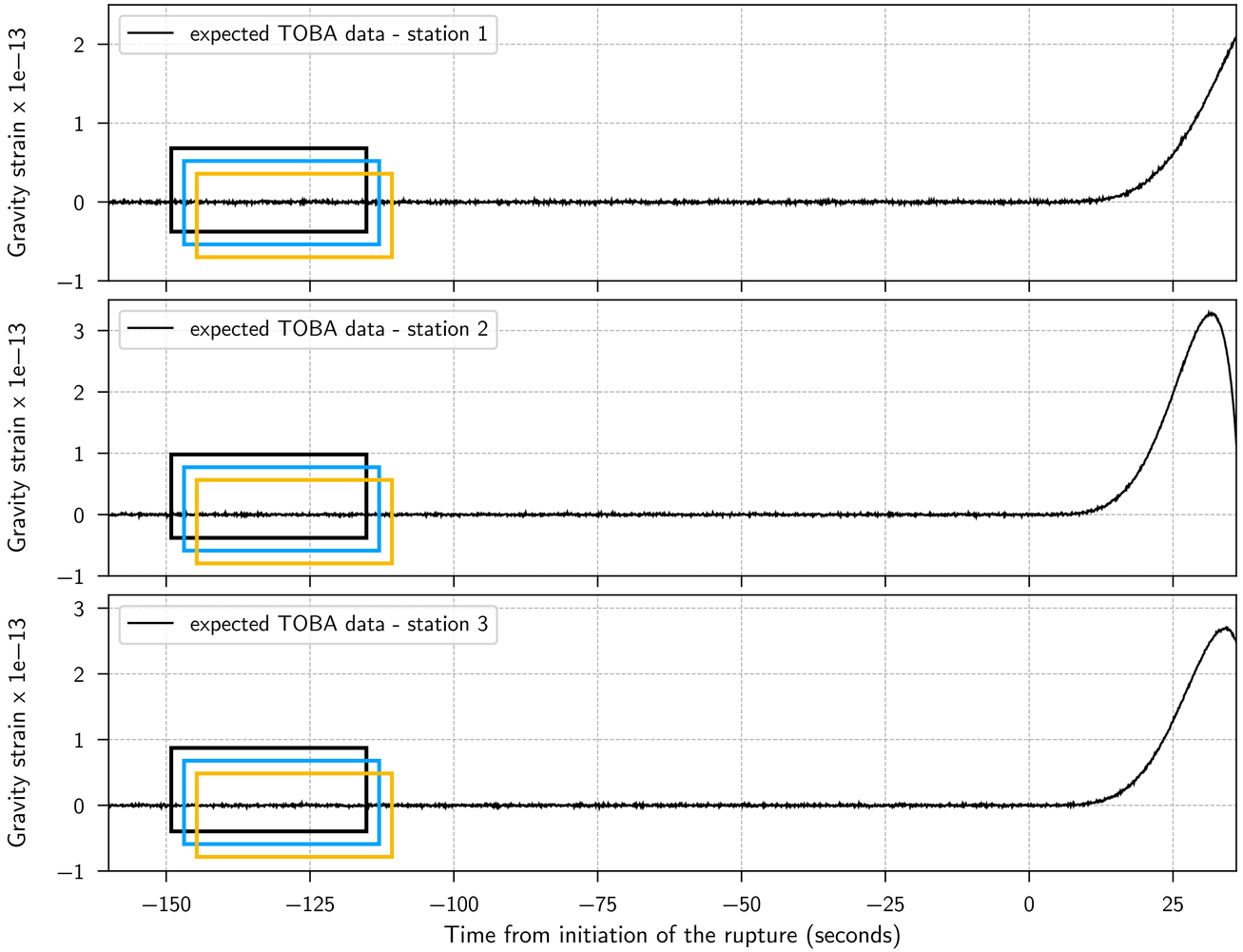
Likelihood of an earthquake rupture

Network configuration :



Source time function database :

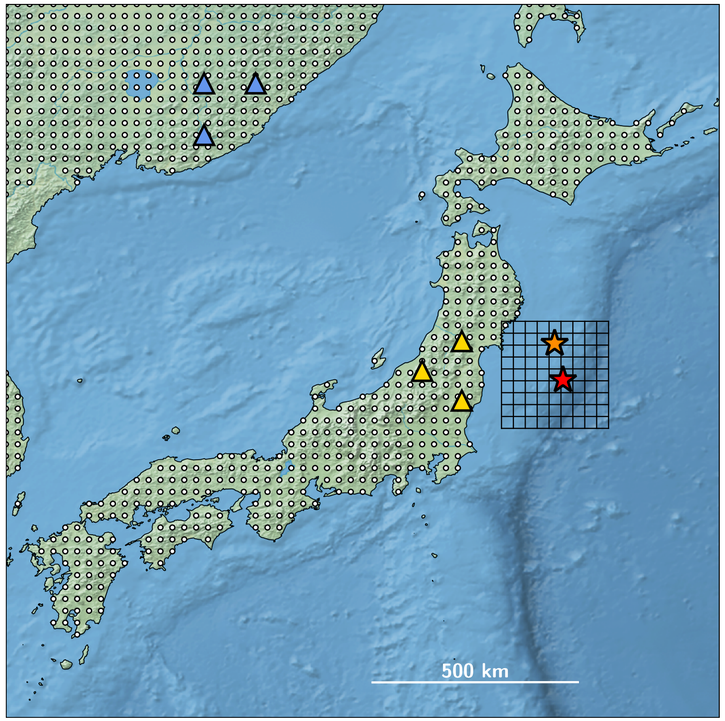




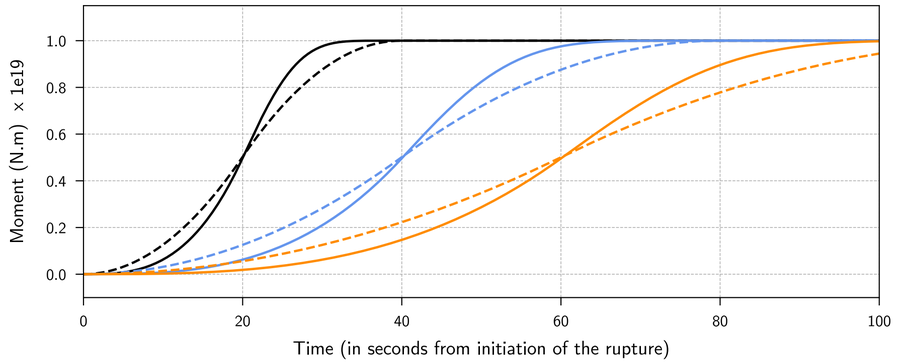
« Real-time » estimation of the likelihood of an earthquake rupture

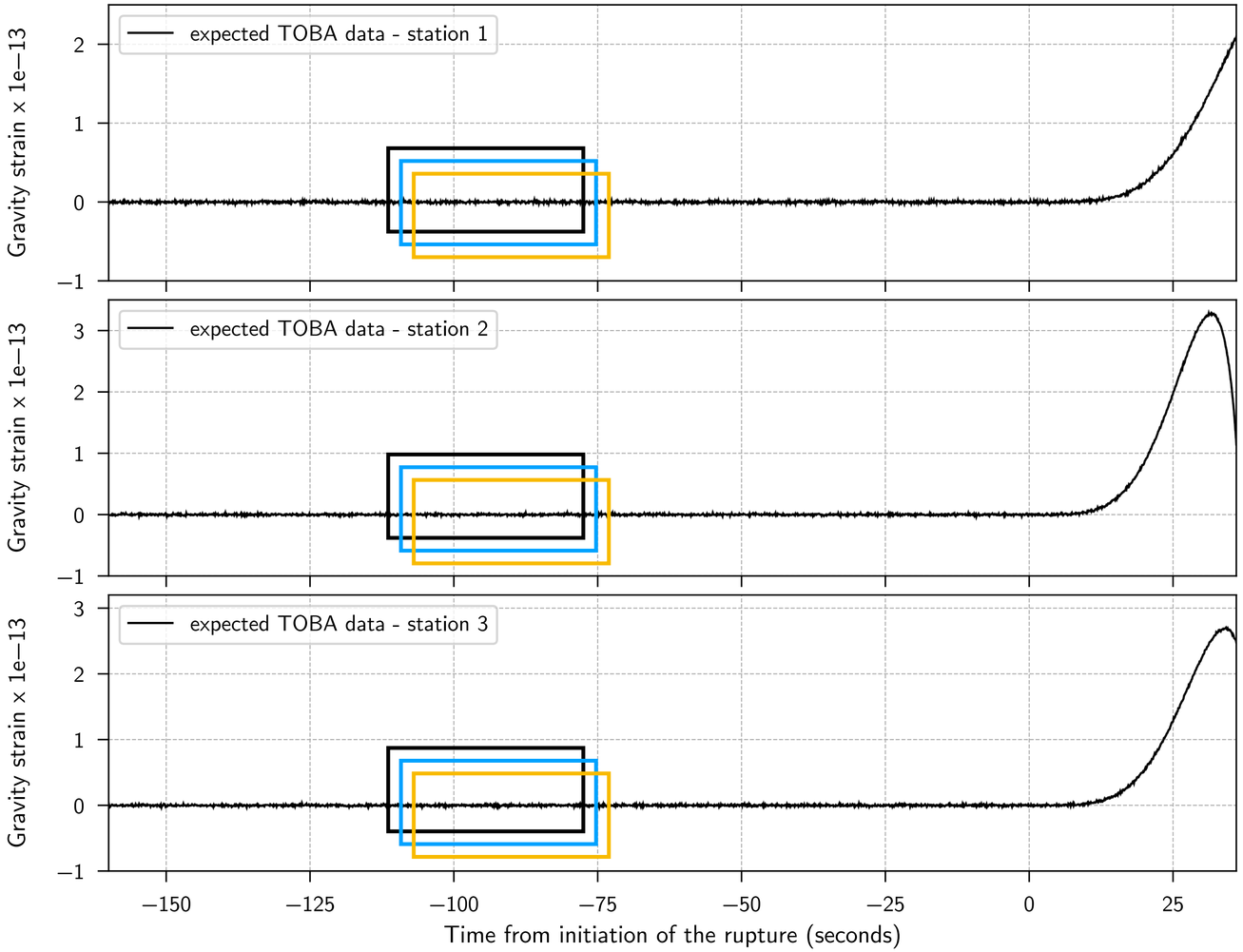
Likelihood of an earthquake rupture

Network configuration :



Source time function database :

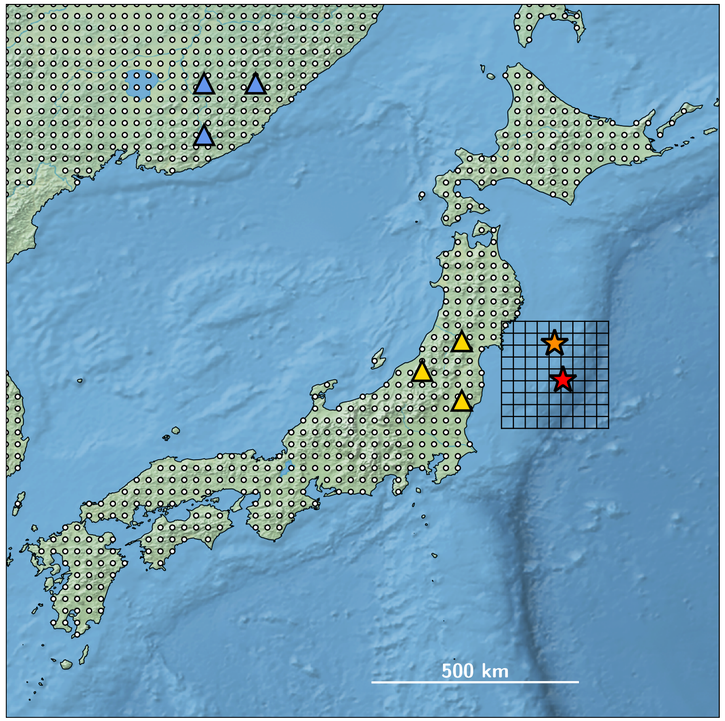




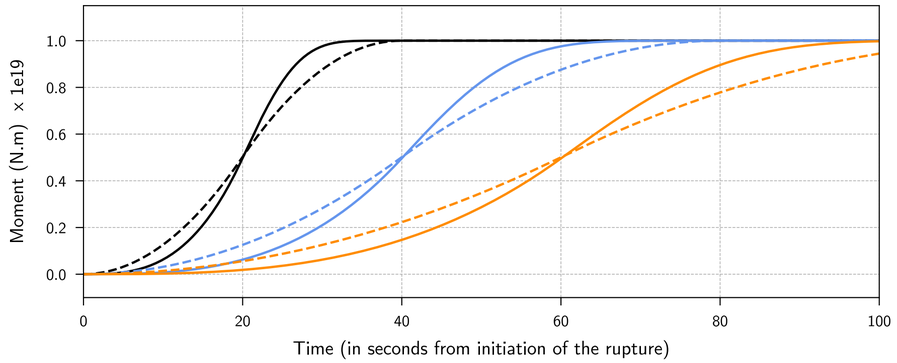
« Real-time » estimation of the likelihood of an earthquake rupture

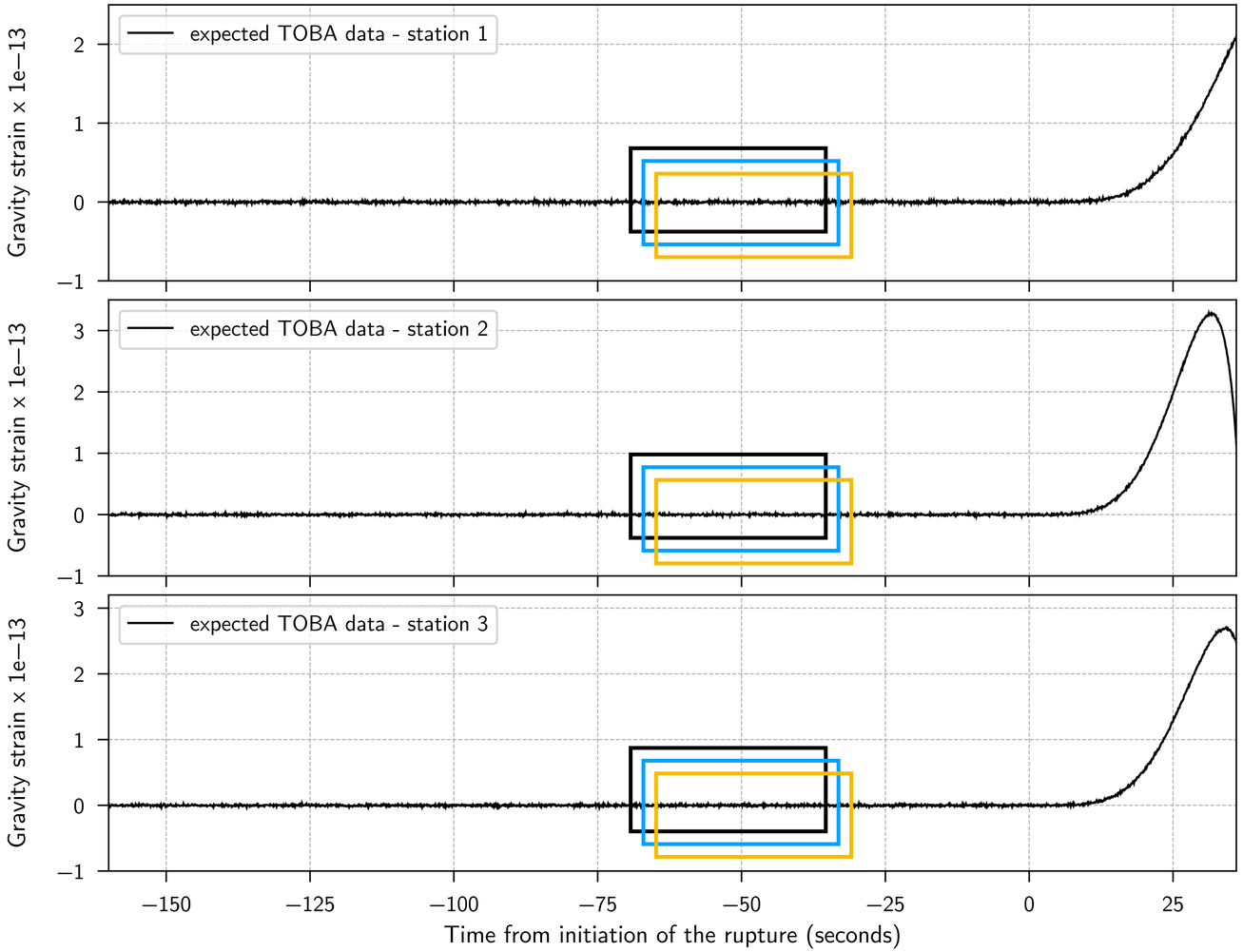
Likelihood of an earthquake rupture

Network configuration :



Source time function database :

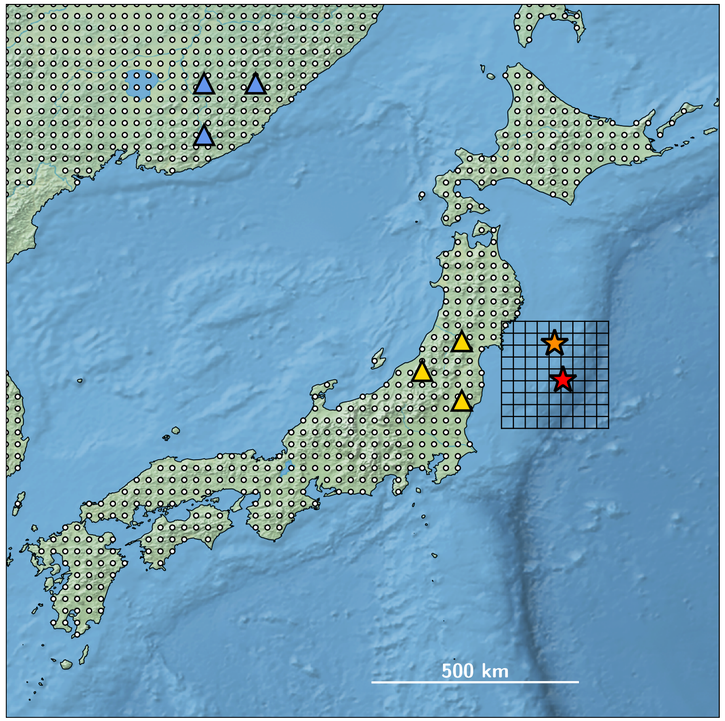




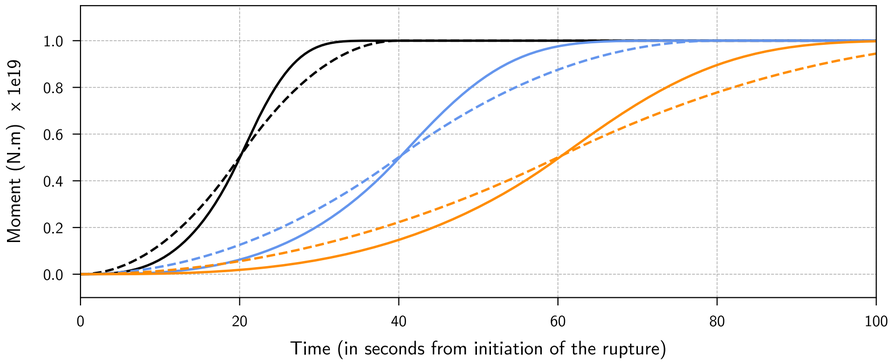
« Real-time » estimation of the likelihood of an earthquake rupture

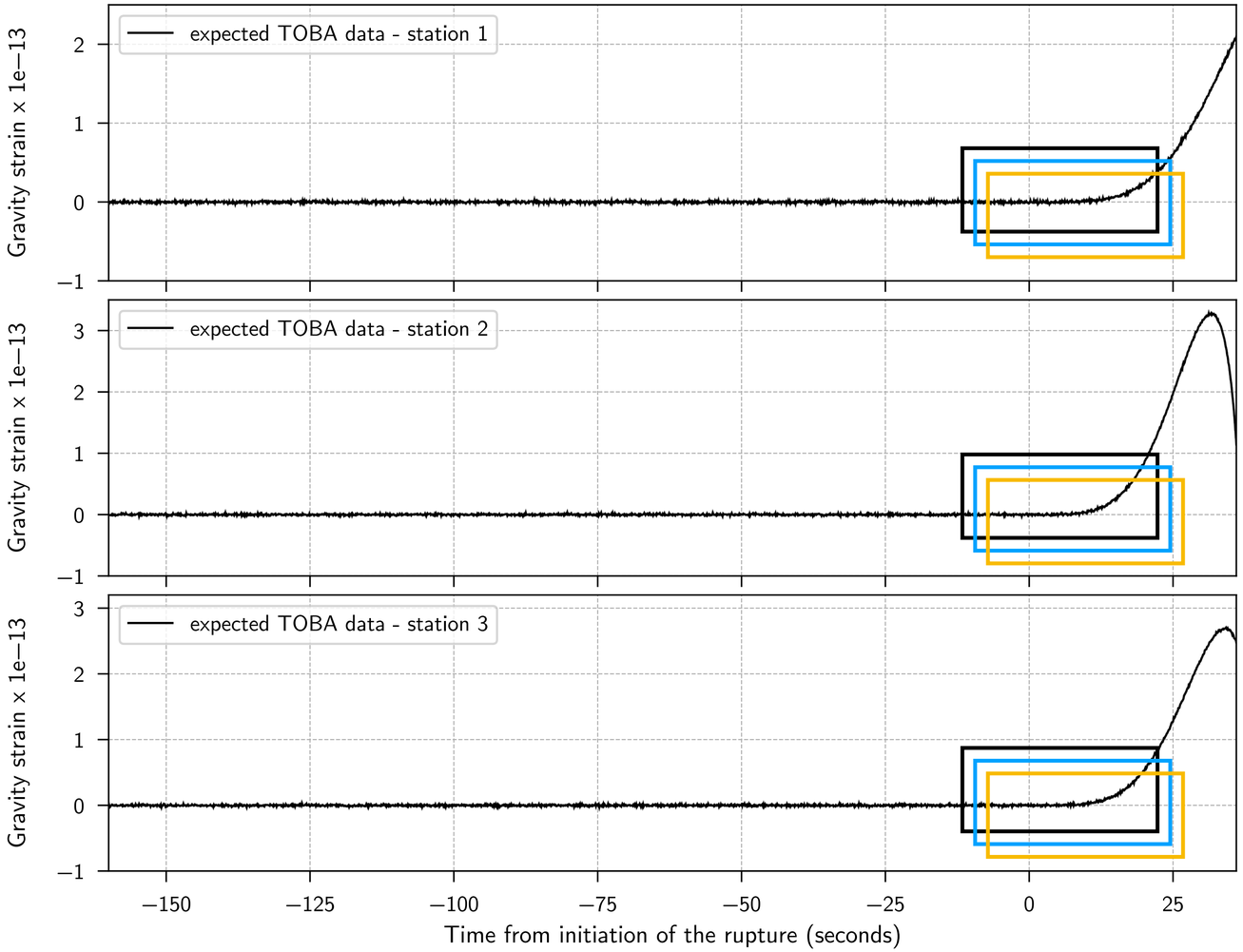
Likelihood of an earthquake rupture

Network configuration :



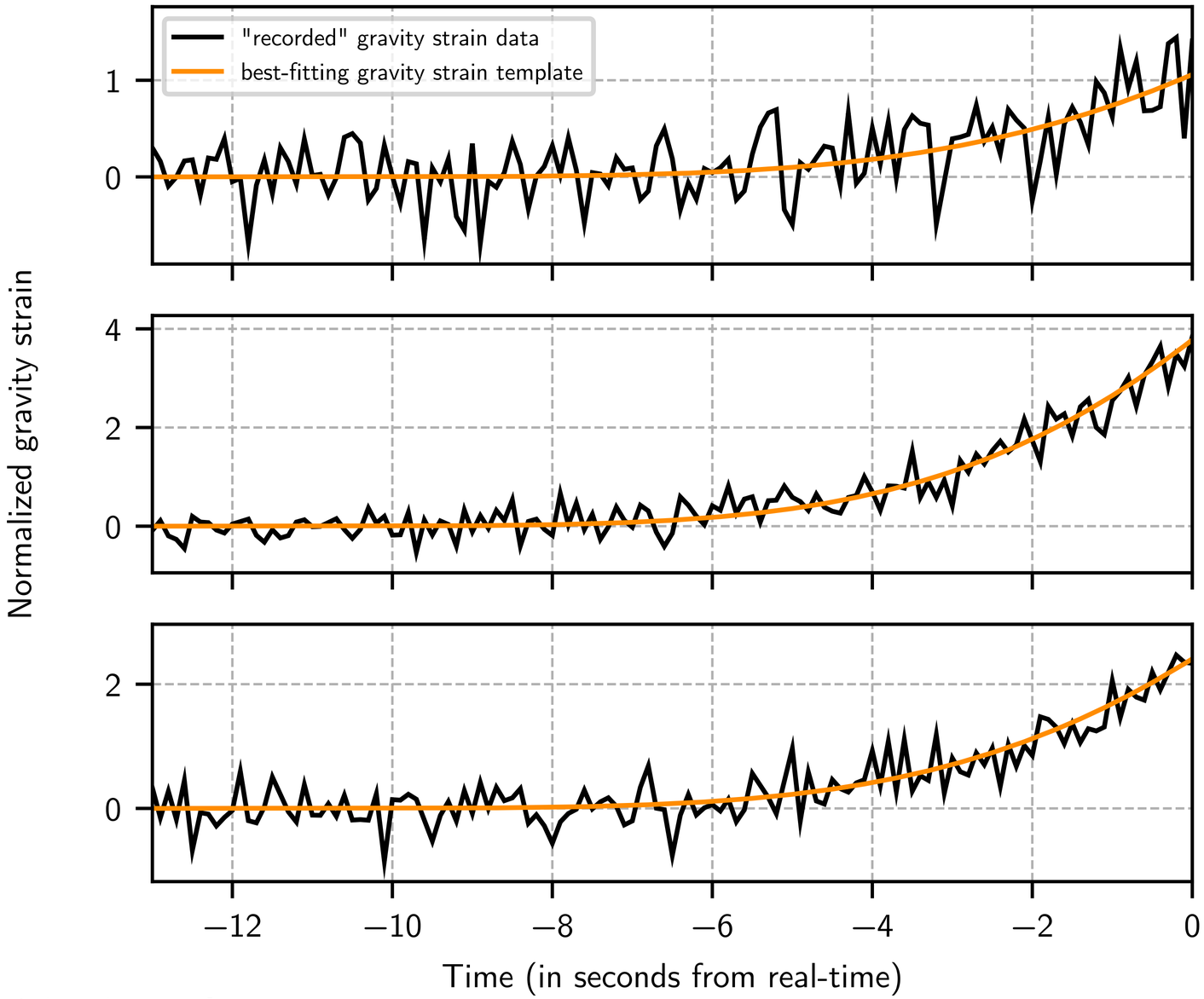
Source time function database :

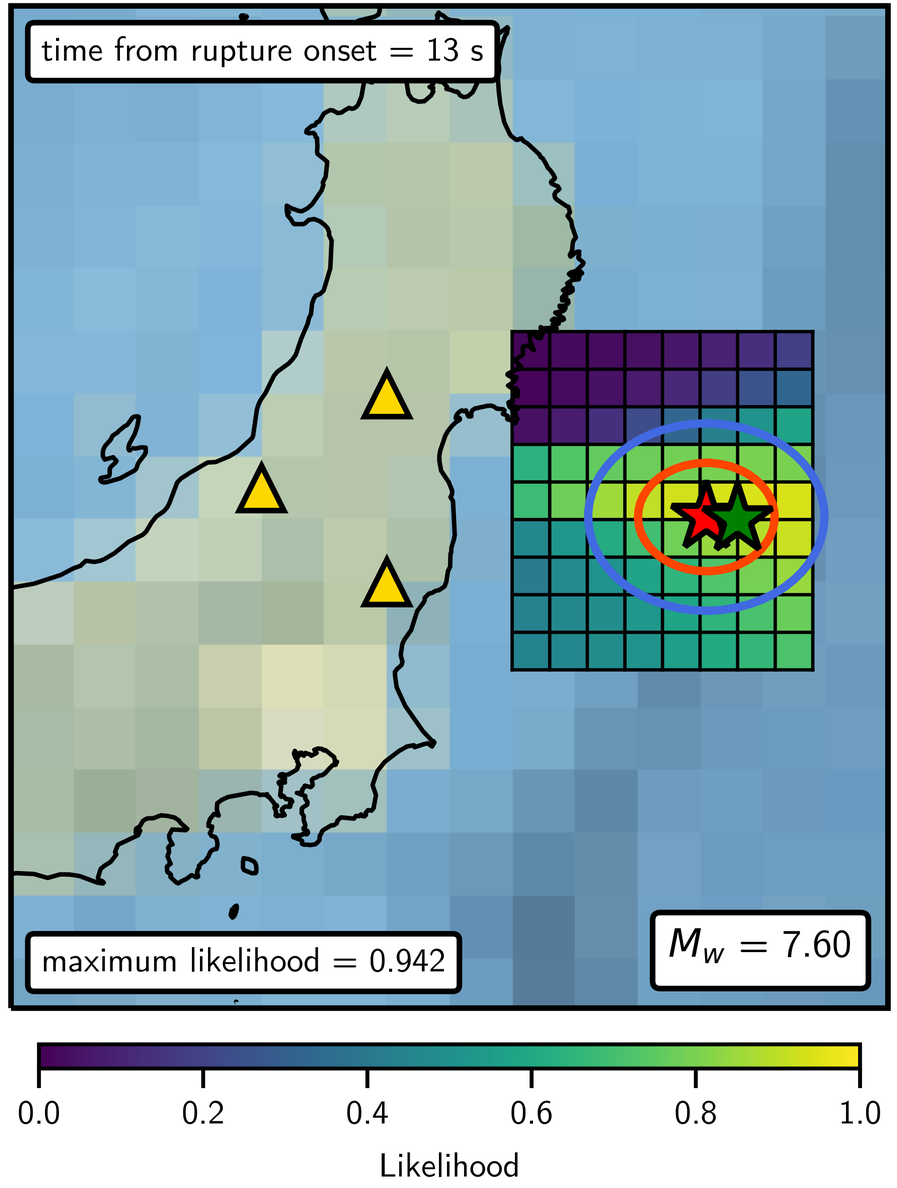




« Real-time » estimation of the likelihood of an earthquake rupture

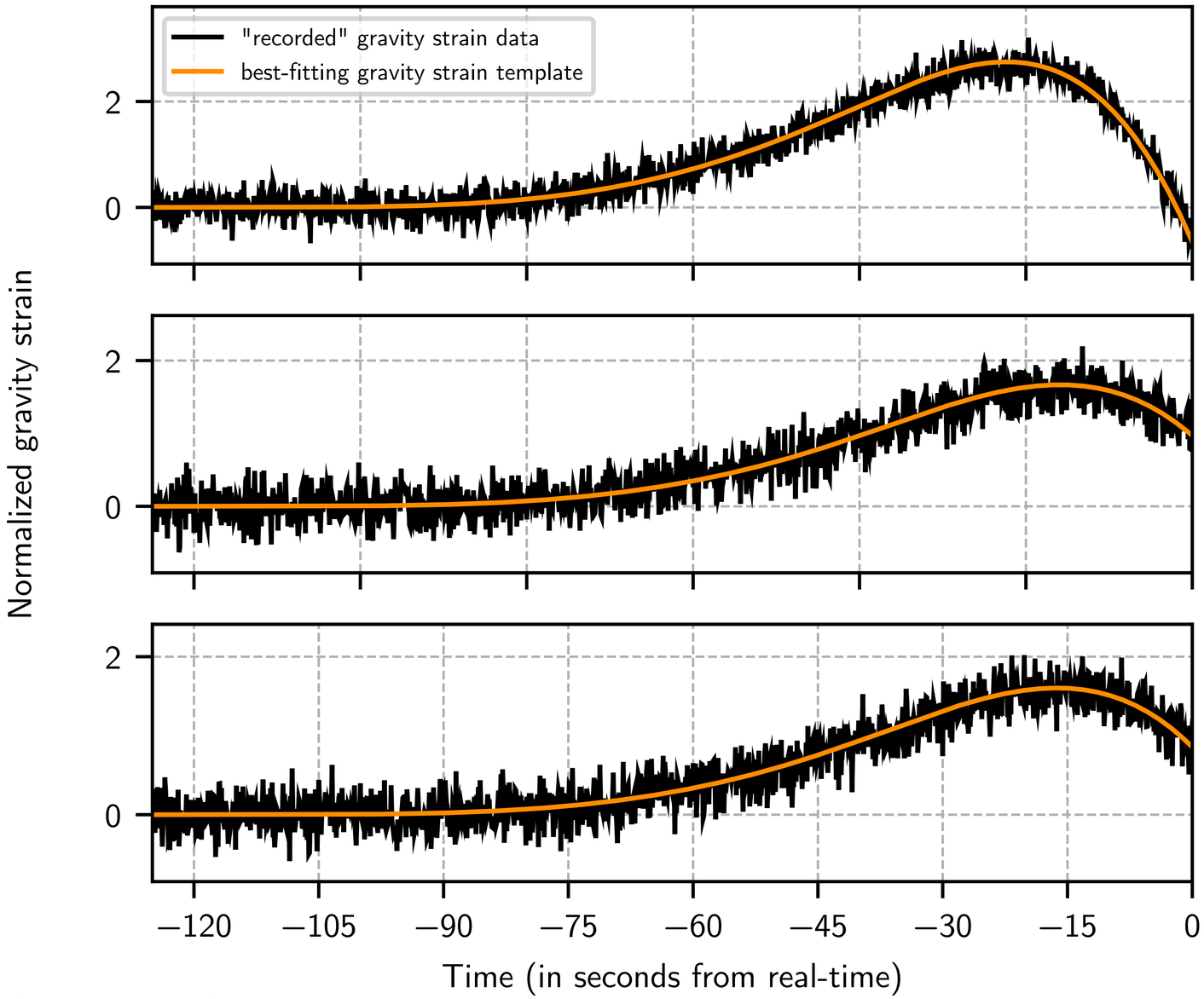
M9.1 Tohoku earthquake - Early detection

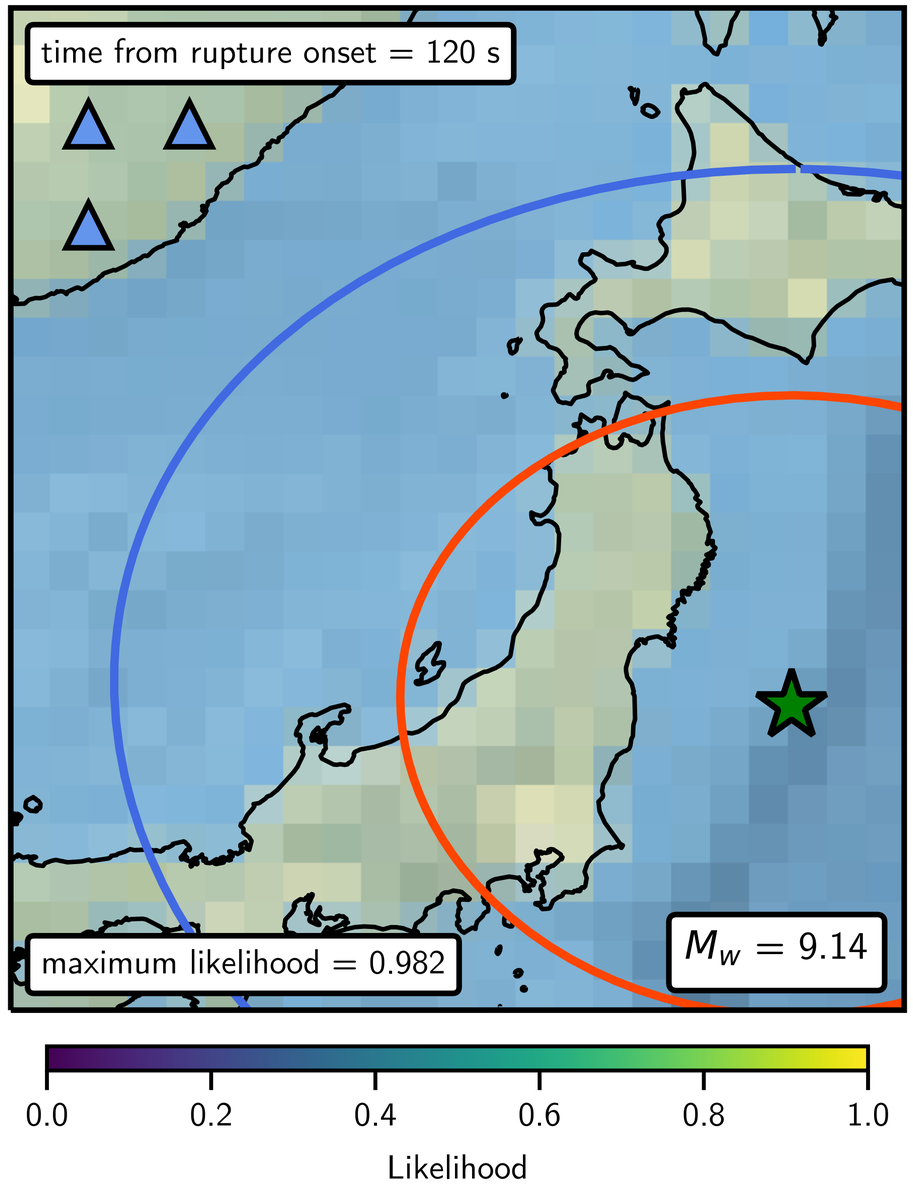




[Juhel et al, in prep]

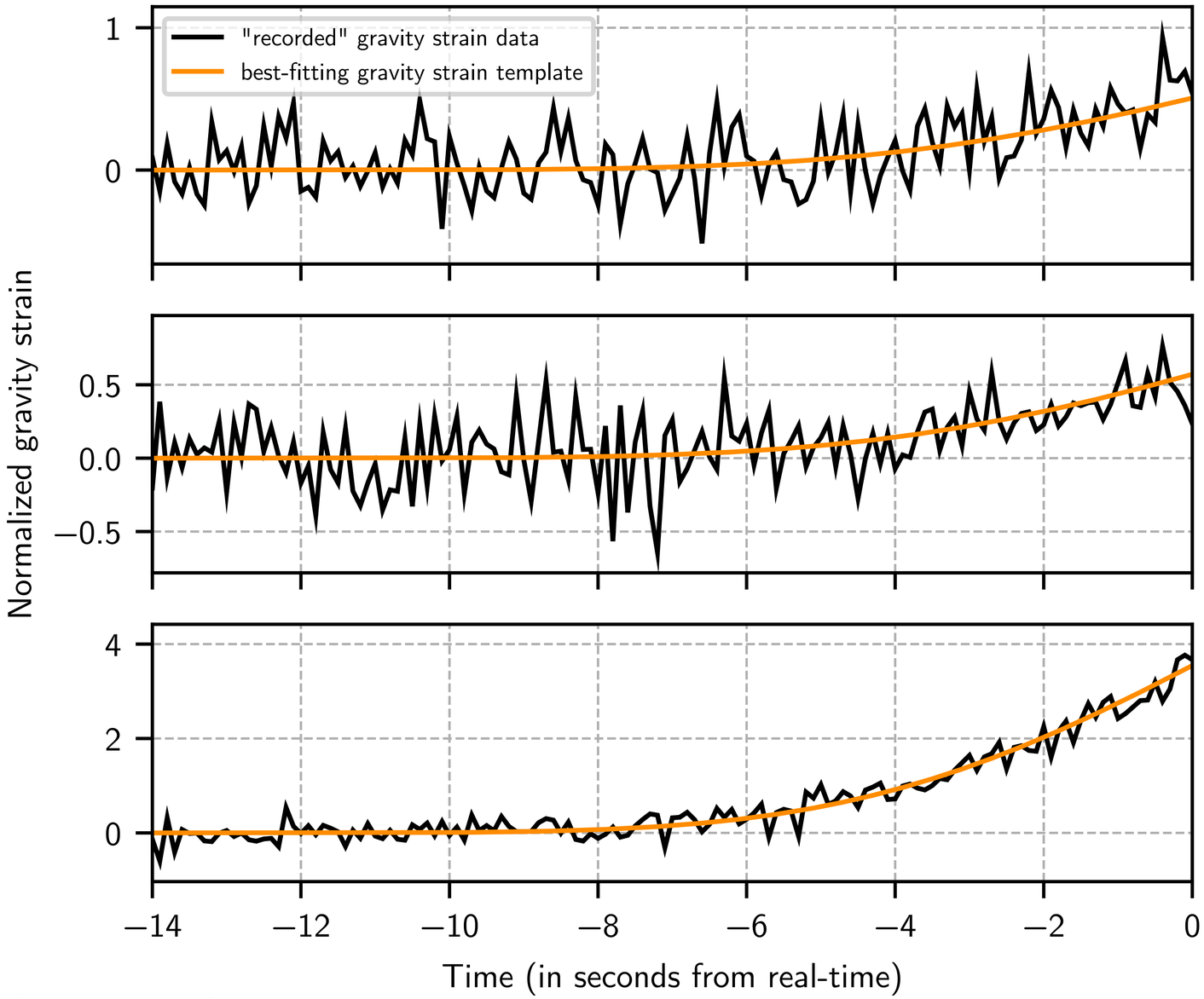
M9.1 Tohoku earthquake - Early estimation of the magnitude

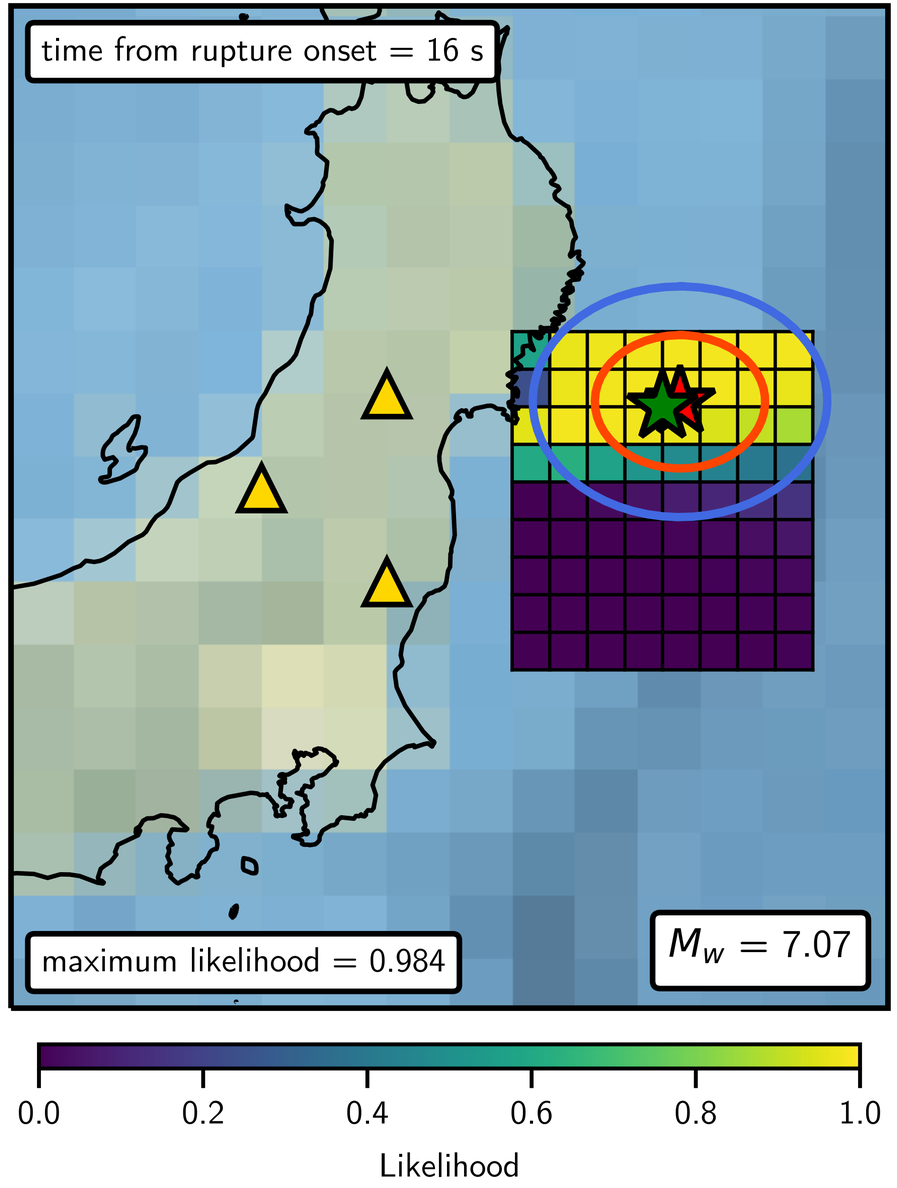




[Juhel et al, in prep]

M7.4 preshock earthquake - Early detection

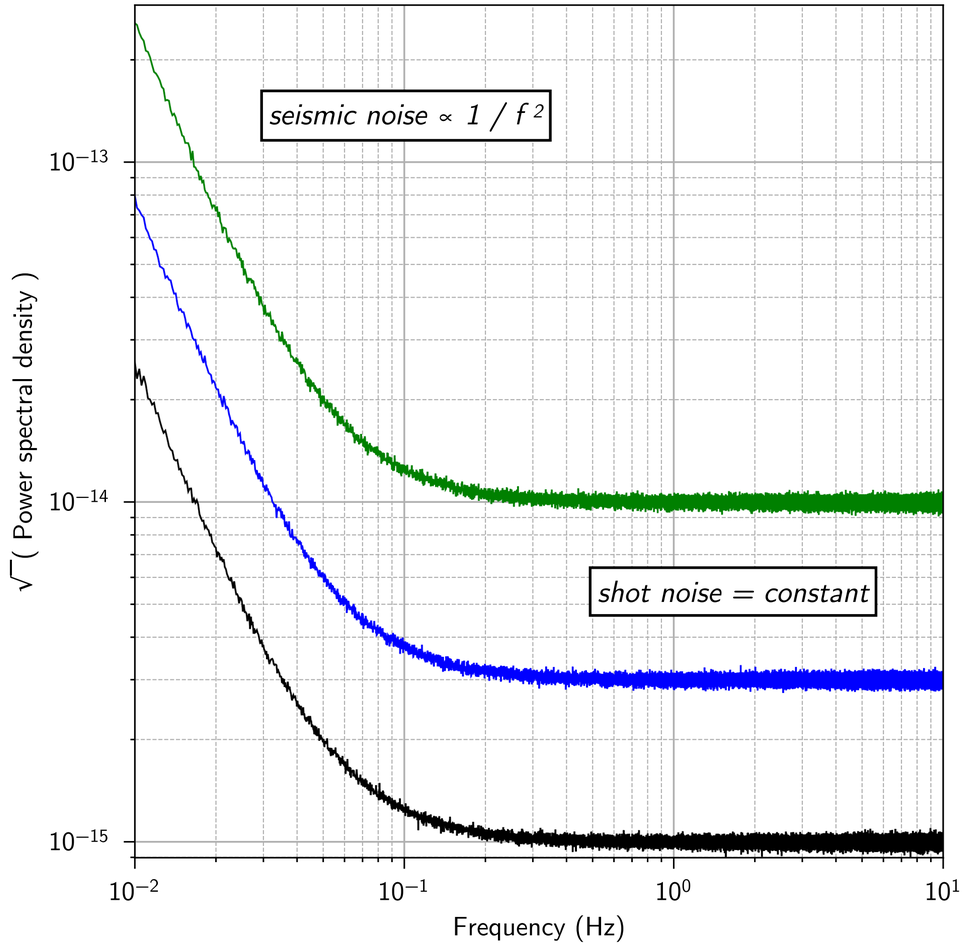




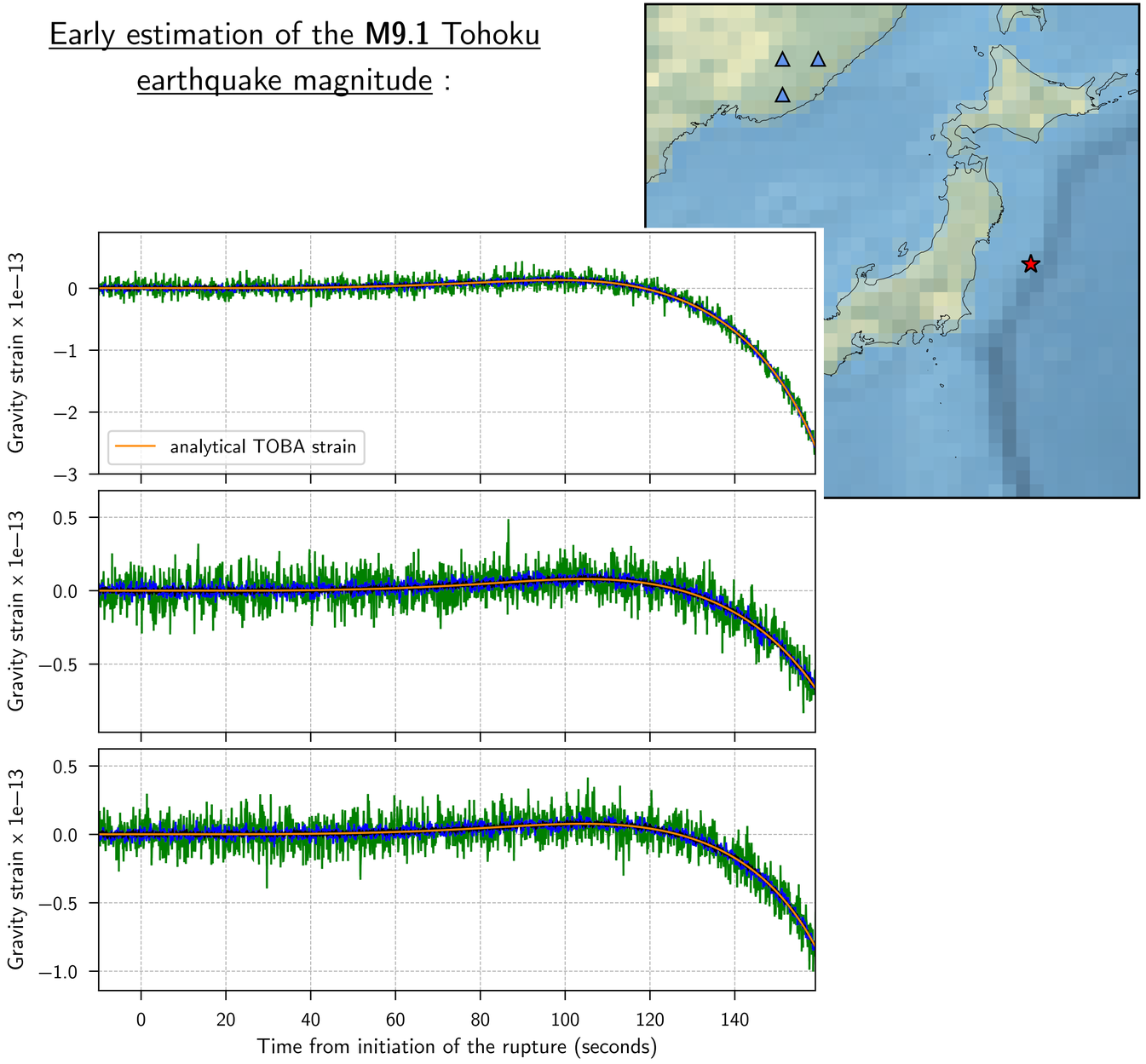
[Juhel et al, in prep]

Which sensitivity is needed ?

Detector sensitivity model :

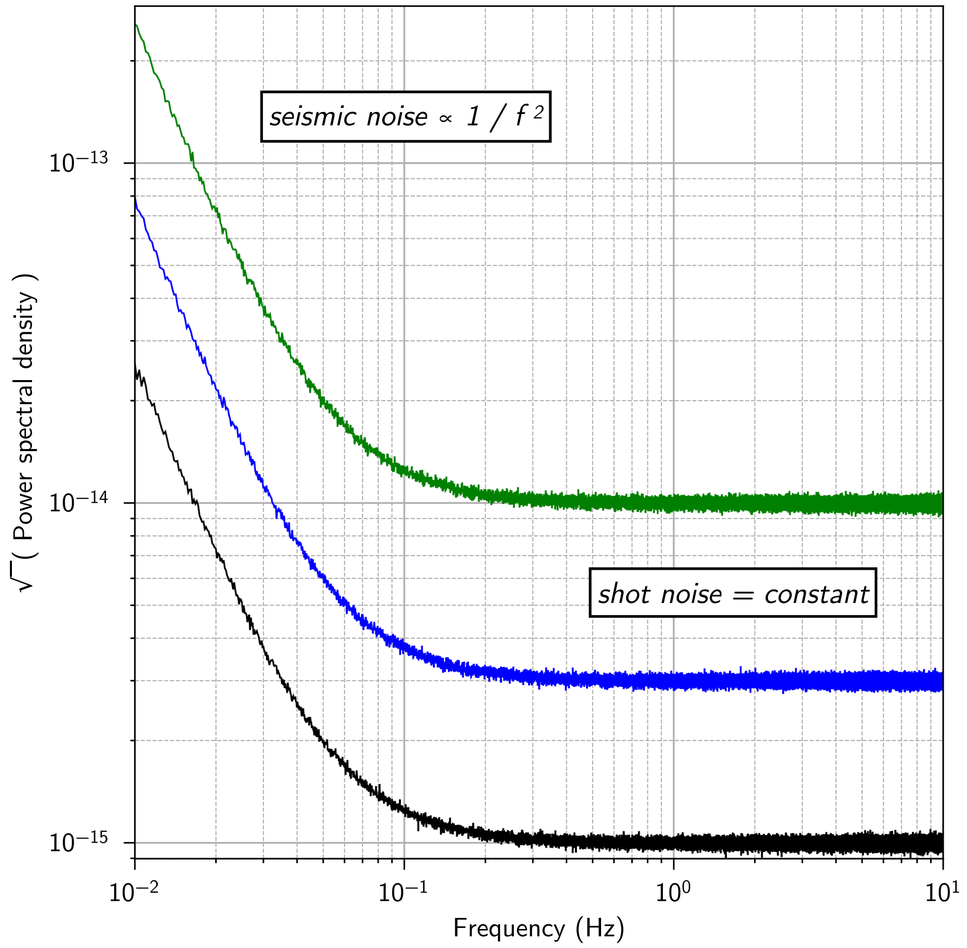


Early estimation of the **M9.1** Tohoku earthquake magnitude :

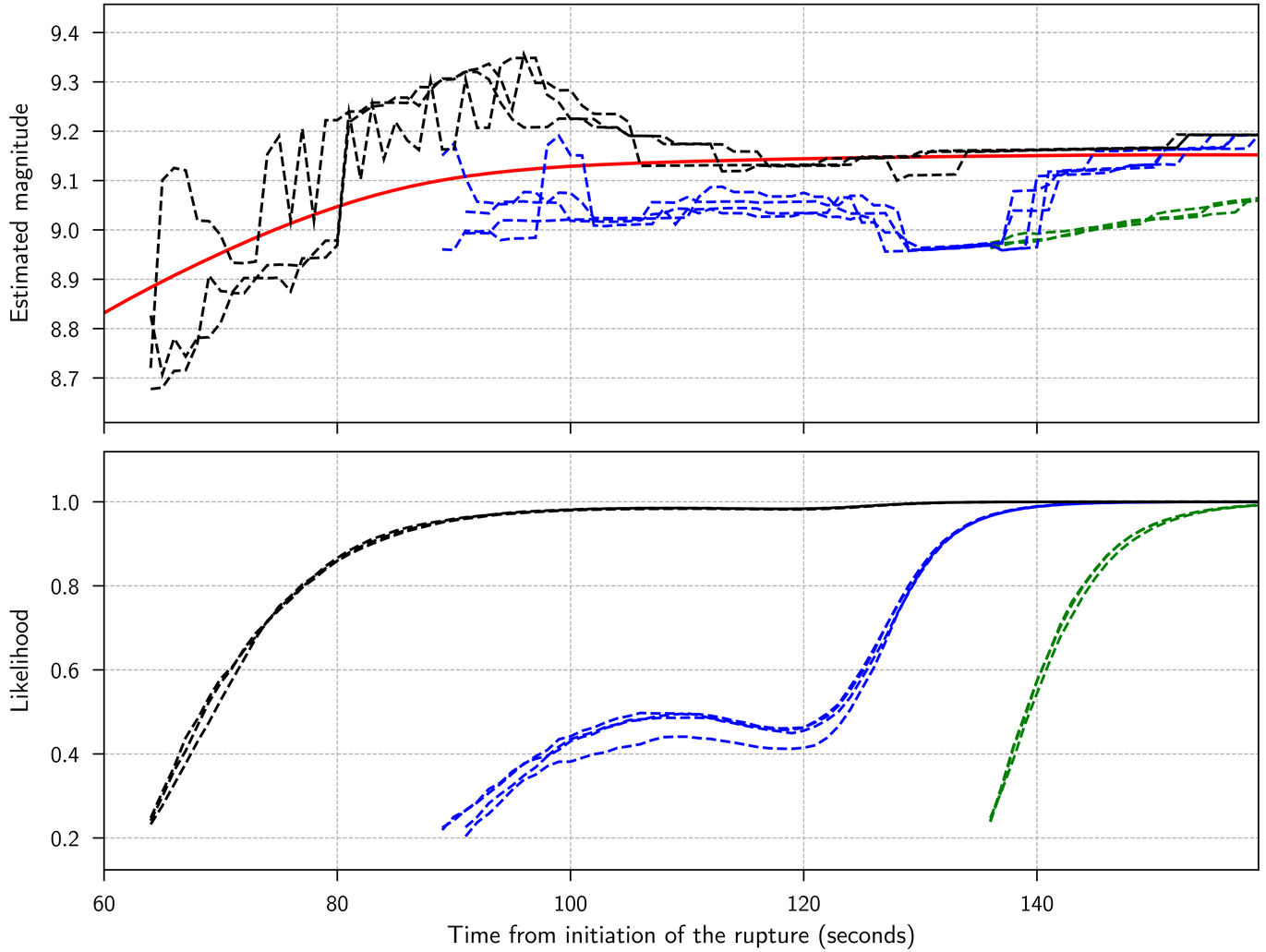


Which sensitivity is needed ?

Detector sensitivity model :



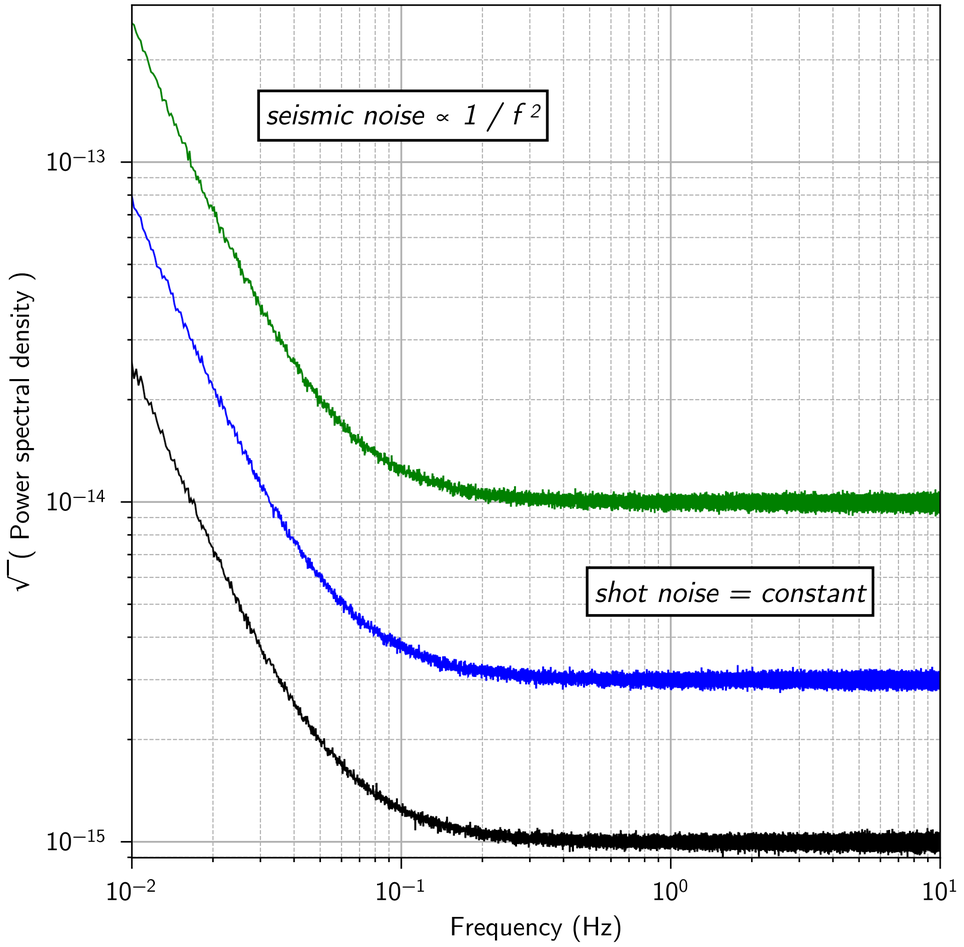
Early estimation of the **M9.1** Tohoku earthquake magnitude :



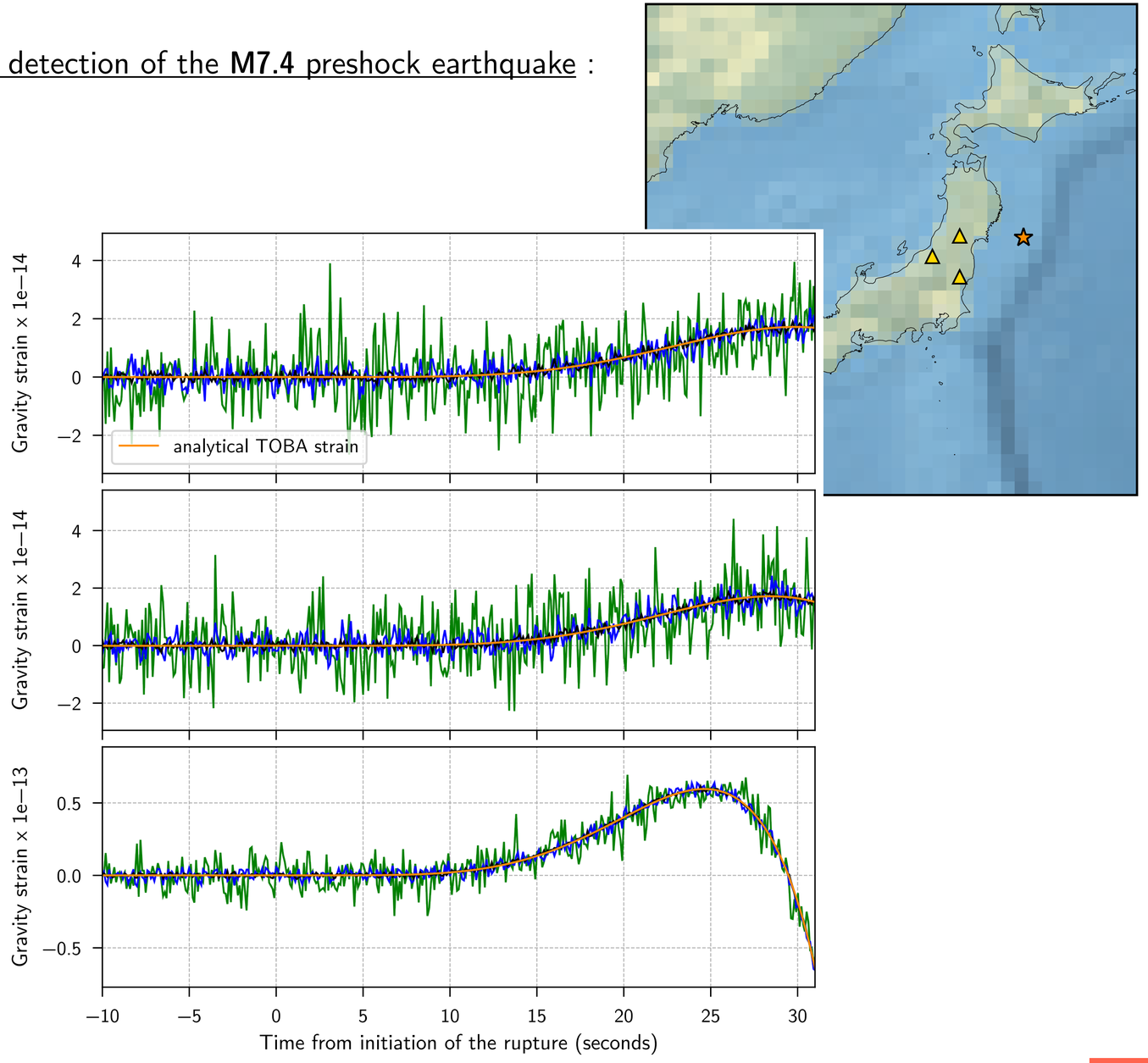
Sensitivity requirement : 10^{-15} for robust estimation

Which sensitivity is needed ?

Detector sensitivity model :

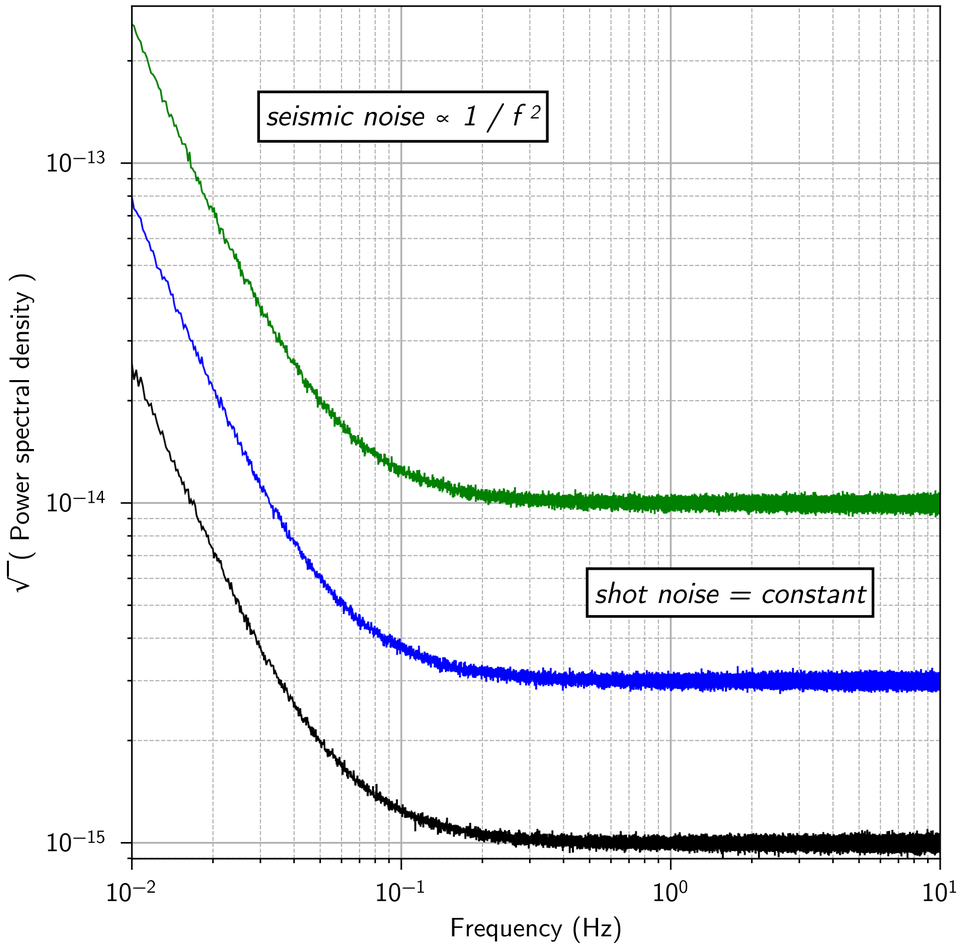


Early detection of the **M7.4** preshock earthquake :

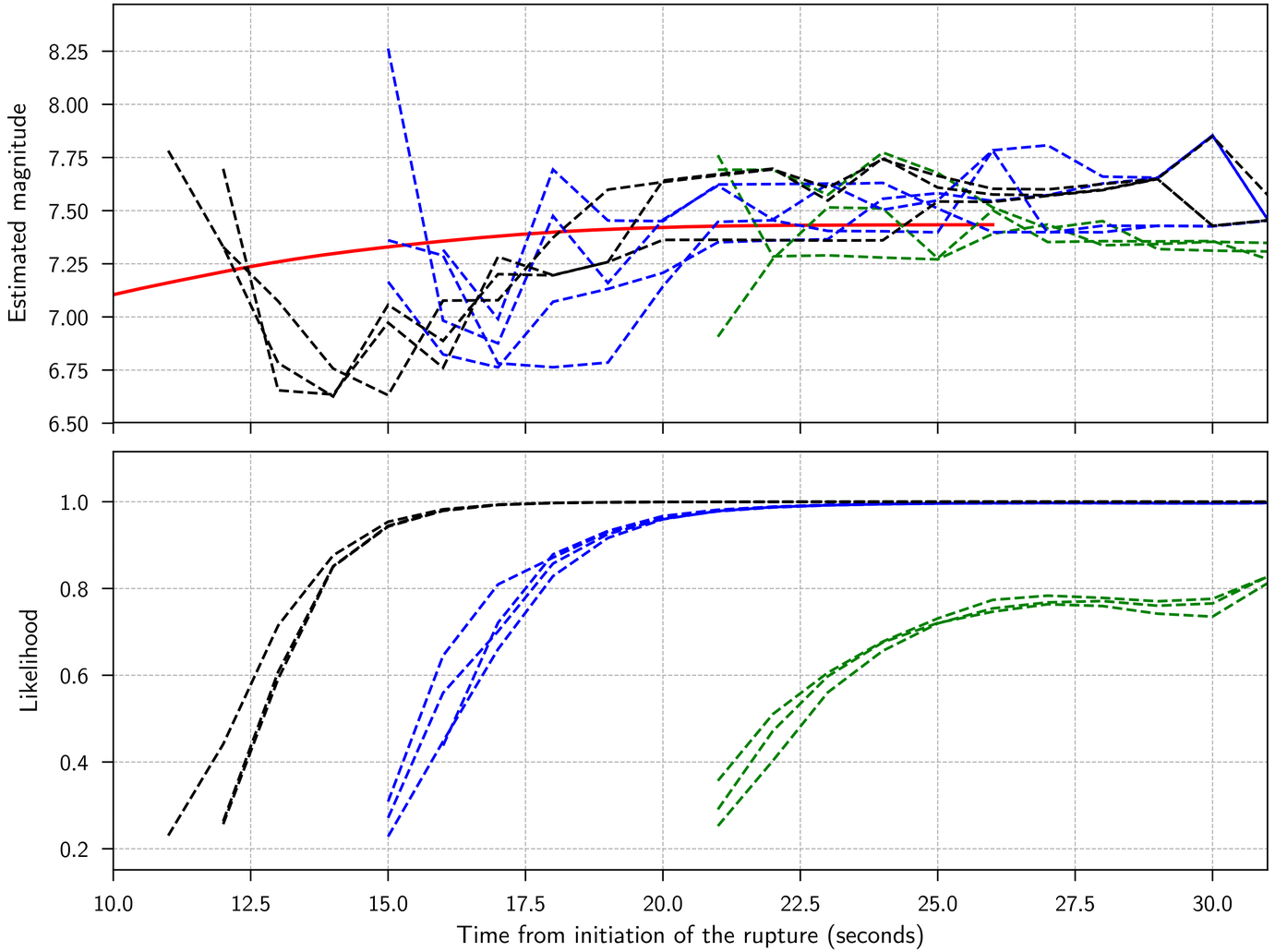


Which sensitivity is needed ?

Detector sensitivity model :



Early detection of the **M7.4** preshock earthquake :



Sensitivity requirement : 10^{-15} for fast detection

Conclusions / Perspectives

Early response to an earthquake rupture :

- Seismometer = gravity perturbation + gravity-induced inertial acceleration + noise

  Observed ! Motivation for instrumental developments to increase the range of magnitude where it can be observed

- Gravity strainmeter = gravity strain perturbation + expected instrumental noise

Gravity-based early warning :

- Next generation of instruments (sensitivity : 10^{-15})
- Early detection and magnitude estimation
- Complement of conventional EEWS based on seismic waves rapid detection : tsunami warning ?

Thank you for your attention !

Early response of a ground-based seismometer

What is recorded by a seismometer :

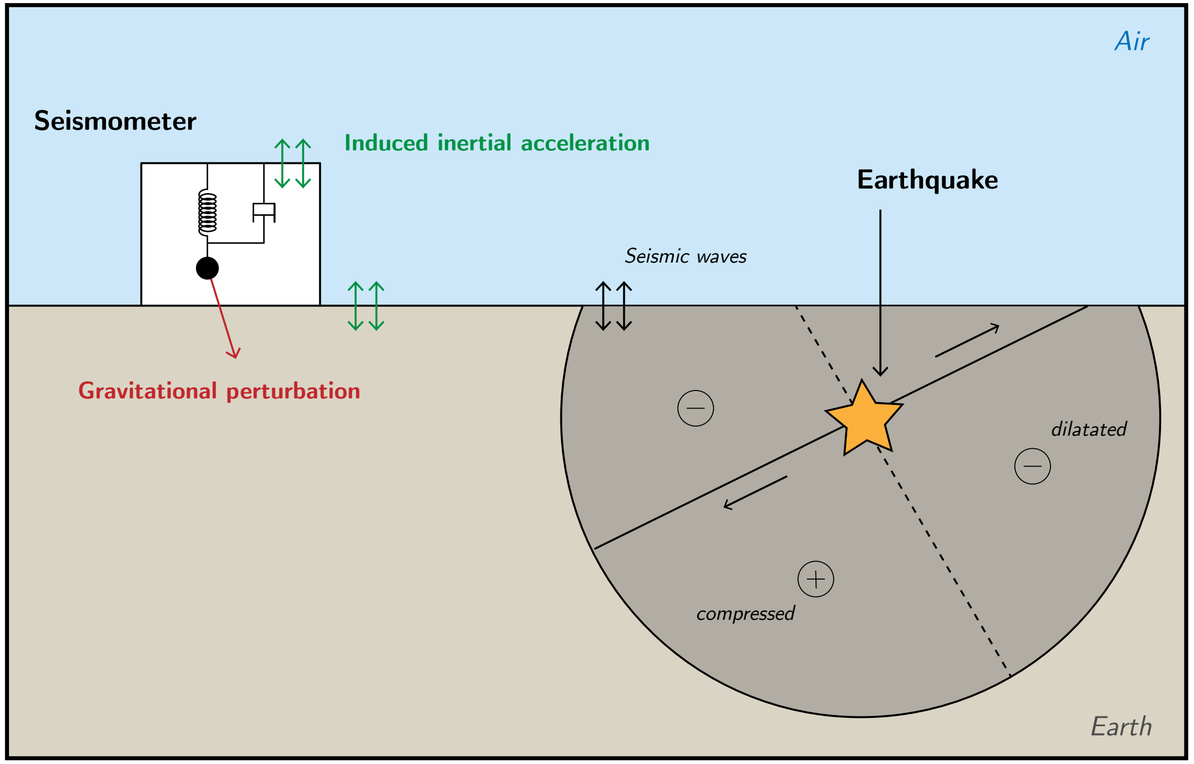
$$f_r = \ddot{s}_r + g_1^{L} = \ddot{s}_r + g_1^{E} + s \cdot \nabla g_0$$

[Dahlen and Tromp, 1998]

g_1 : gravitational perturbation

$\ddot{s}_r$: gravity-induced inertial acceleration

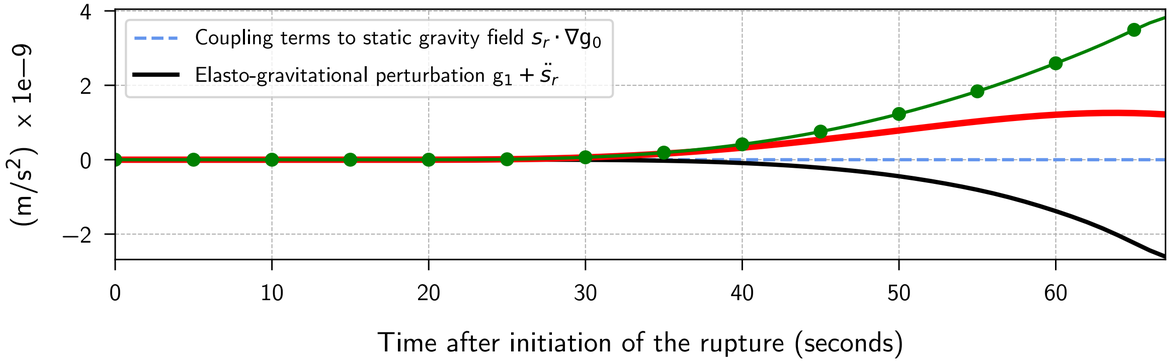
$s \cdot \nabla g_0$: coupling terms to the static gravity field



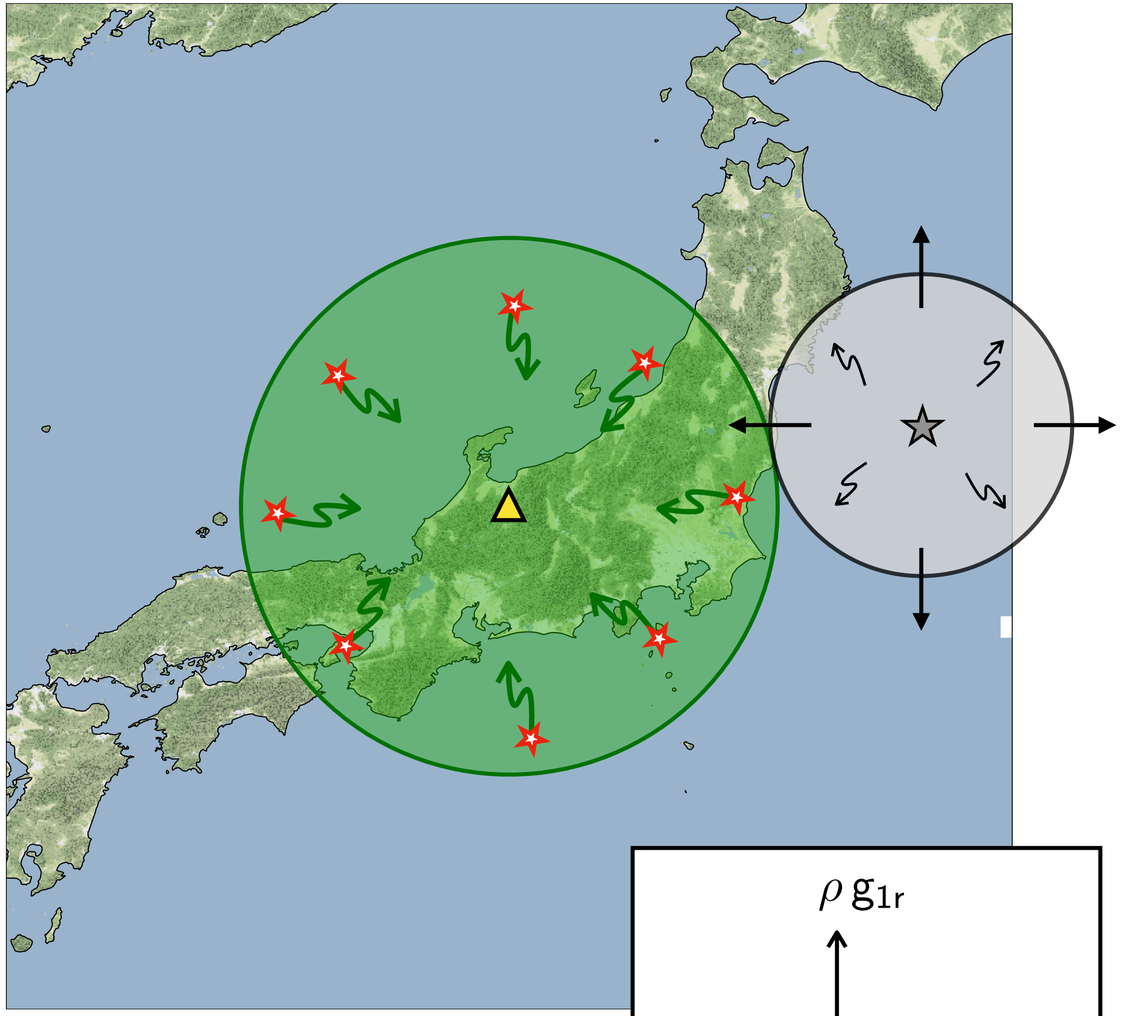
Detection of every > M6.5 earthquakes ?

2 main limitations :

- ambiant seismic noise
- cancelling effect close to onset time

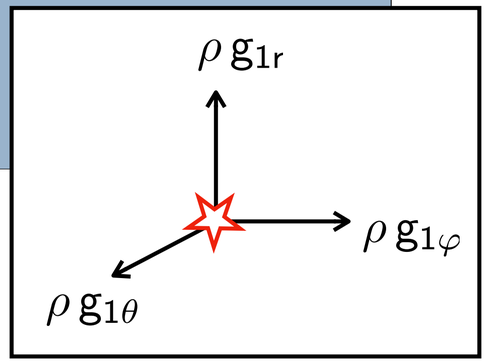


Gravity-induced inertial acceleration



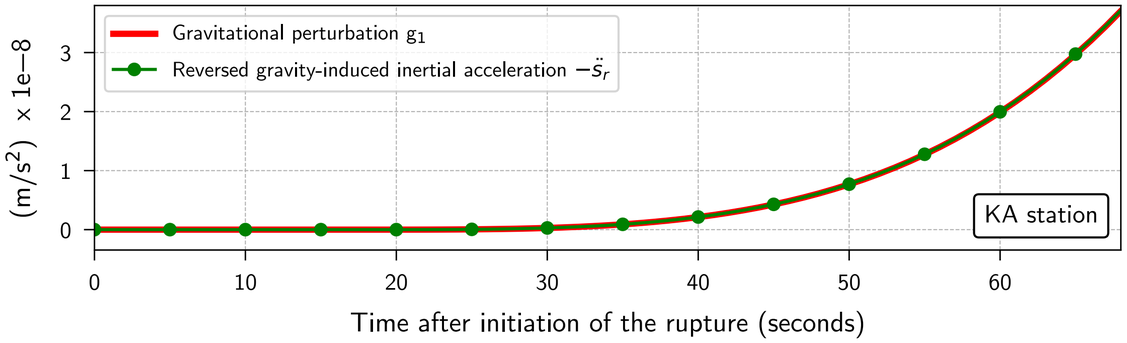
: seismic waves

: gravity-induced elastic waves

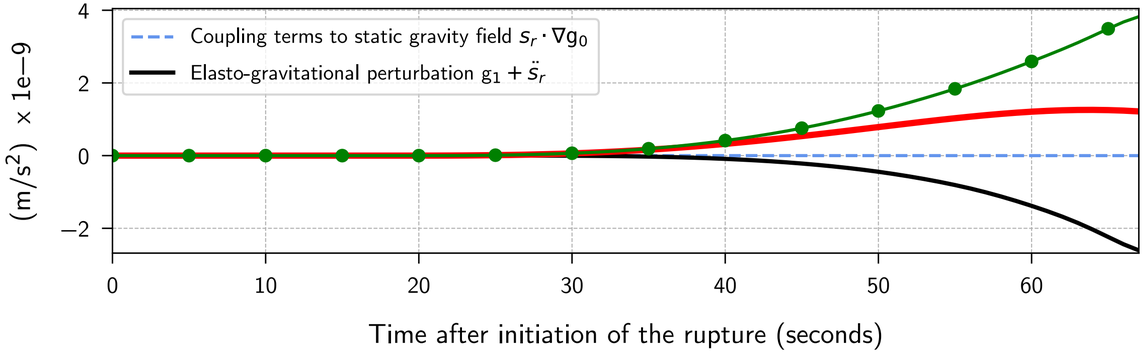


Gravity-induced elastic waves are summed into inertial acceleration

Convergence of the 2-step computation : cancellation of elasto-gravitational terms in **full-space geometry** [Vallée et al, 2017]



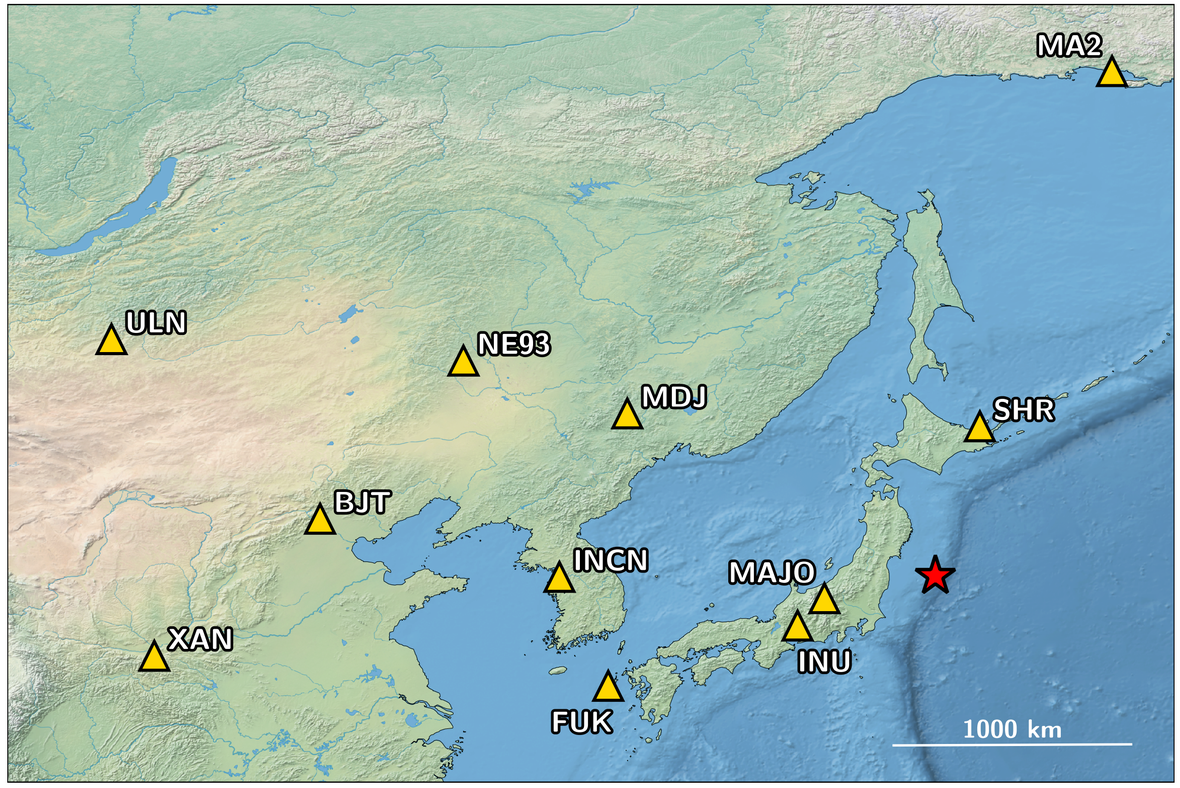
Computation of all elasto-gravitational terms in **PREM model** :

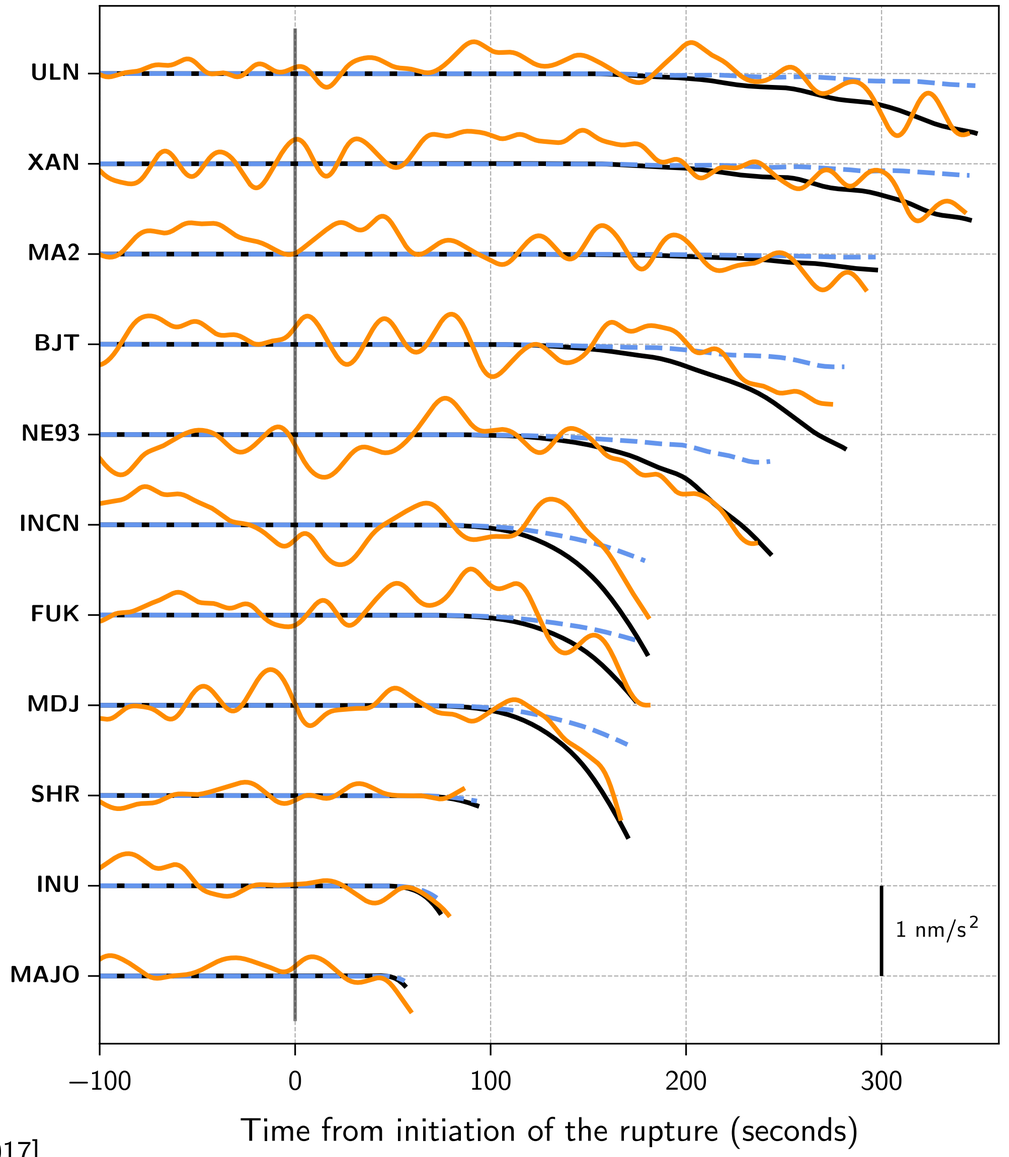


Observations and modeling of early elasto-gravity signals

Modeling of the elasto-gravitational perturbations :

- Data and synthetics systematically in good agreement
- Simulation of a M8.5 scenario : early estimation of a magnitude > M9





[Vallée et al, 2017]