Prompt gravity signal

induced by the 2011 Tohoku-oki earthquake

recorded by superconducting gravimeter and broadband F-net stations

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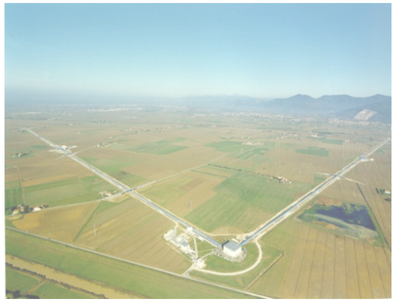
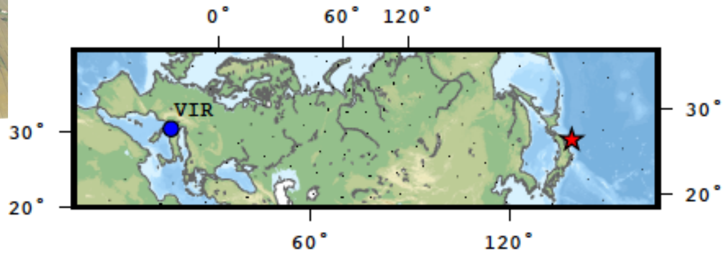
Outline: The story and the approach

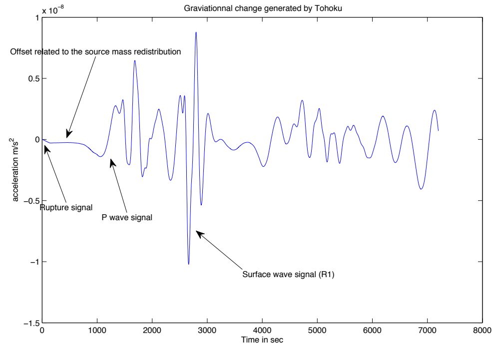
- **Motivation**

VIRGO
(*Gravitational wave Interferometer*)



normal mode calculation

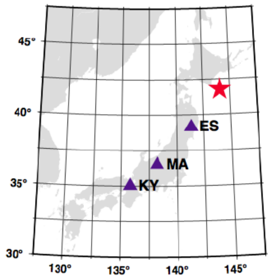


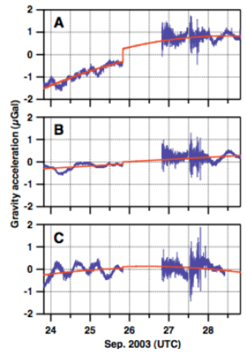


- **Search for gravity data**

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)



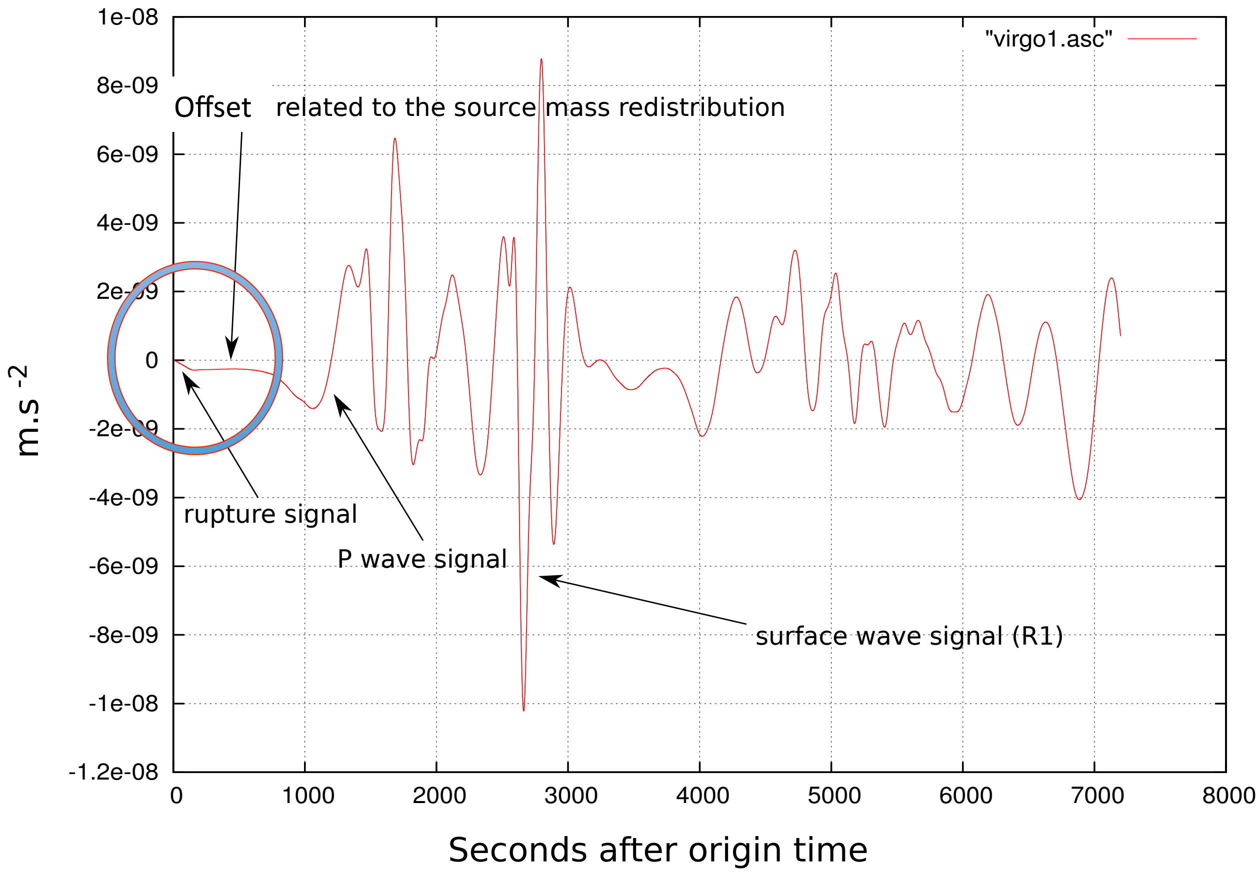


- The choice of Kamioka SG data

- **Search for a** prompt gravity signal
- **Statistical tests**
- Broadband F-Net data
- **Perspectives and ongoing projects**

Motivation
NORMAL MODE THEORY

Simulated gravitational change at the Virgo site . Source: Tohoku
Z component low-pass filtered at 100s



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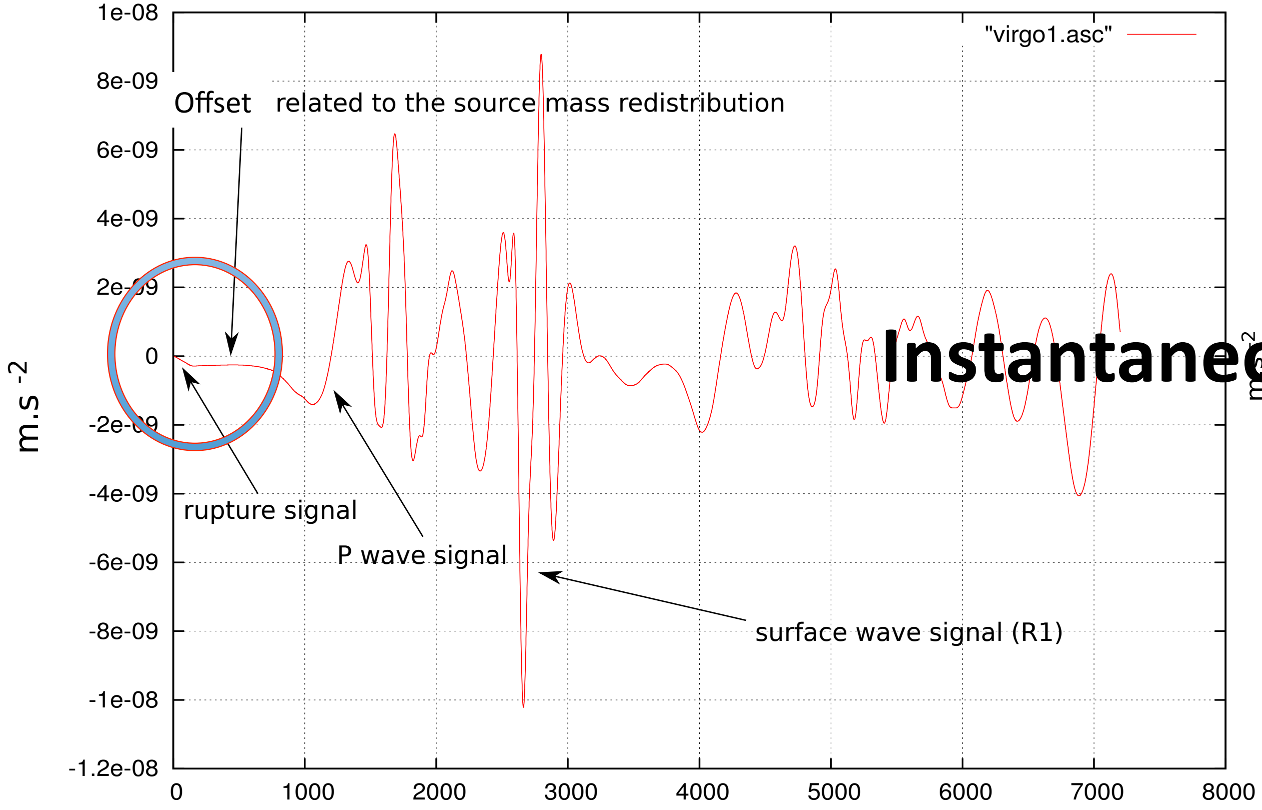
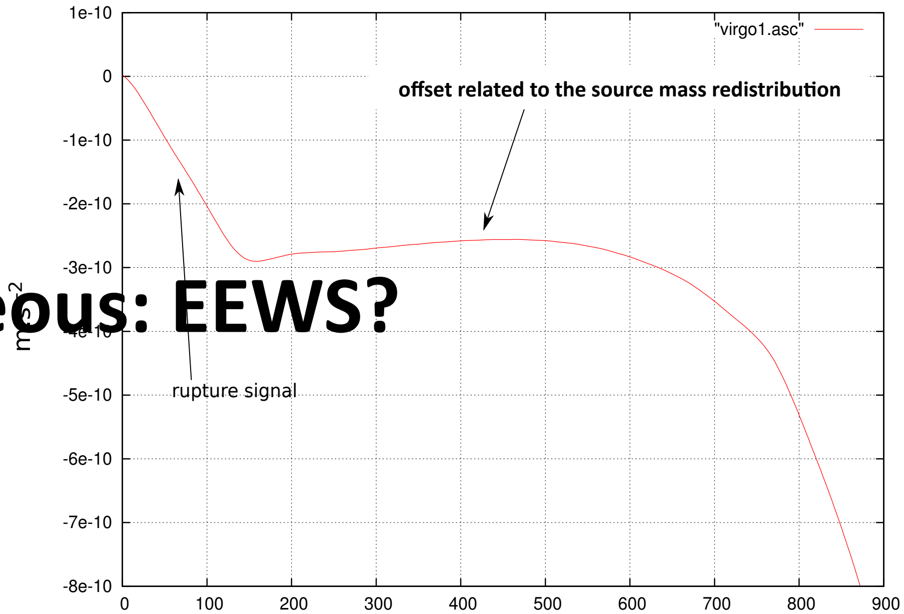


$\Delta \approx 90°$ (≈10 000km)

Simulated gravitational change at the Virgo site . Source: Tohoku
Z component

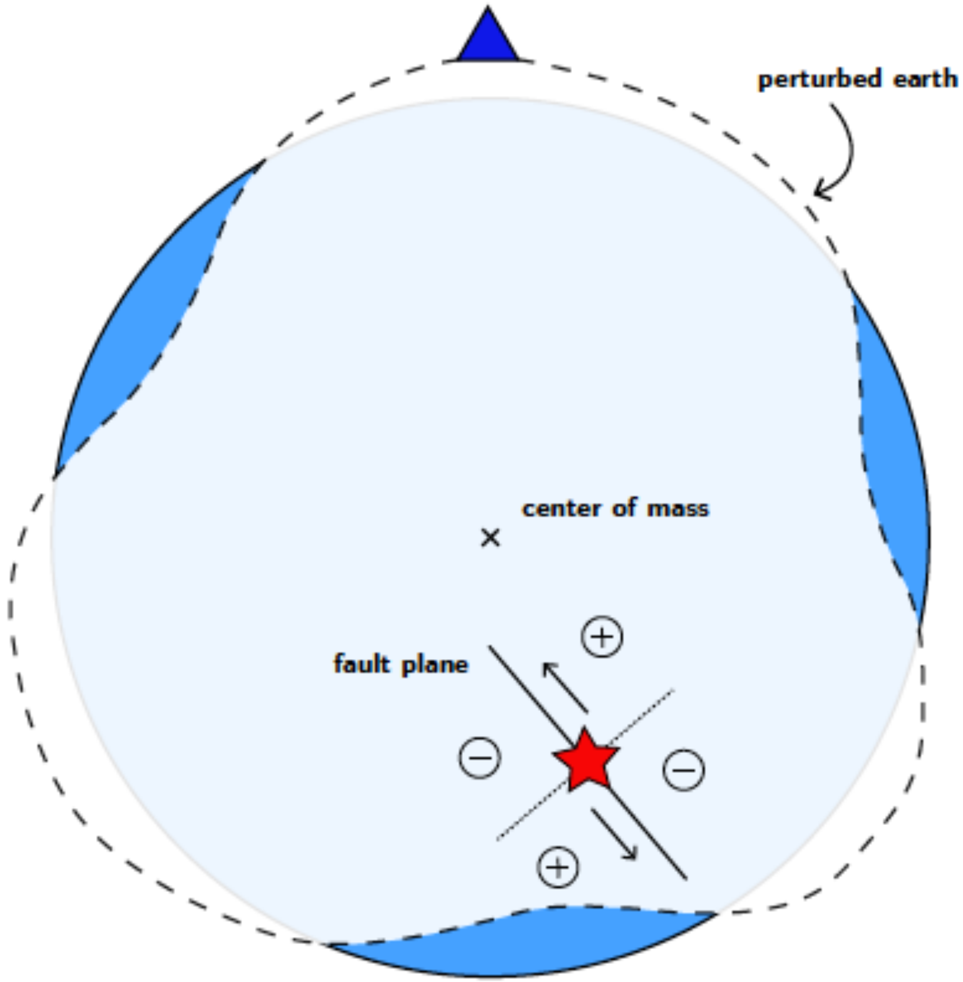


Instantaneous: EEWS?

Gravity perturbations induced by earthquakes

Two basic effects:
-Mass redistribution $-\nabla(\rho_0 \mathbf{u})$
-Free air gravity anomaly
(perturbation of the Earth surface)

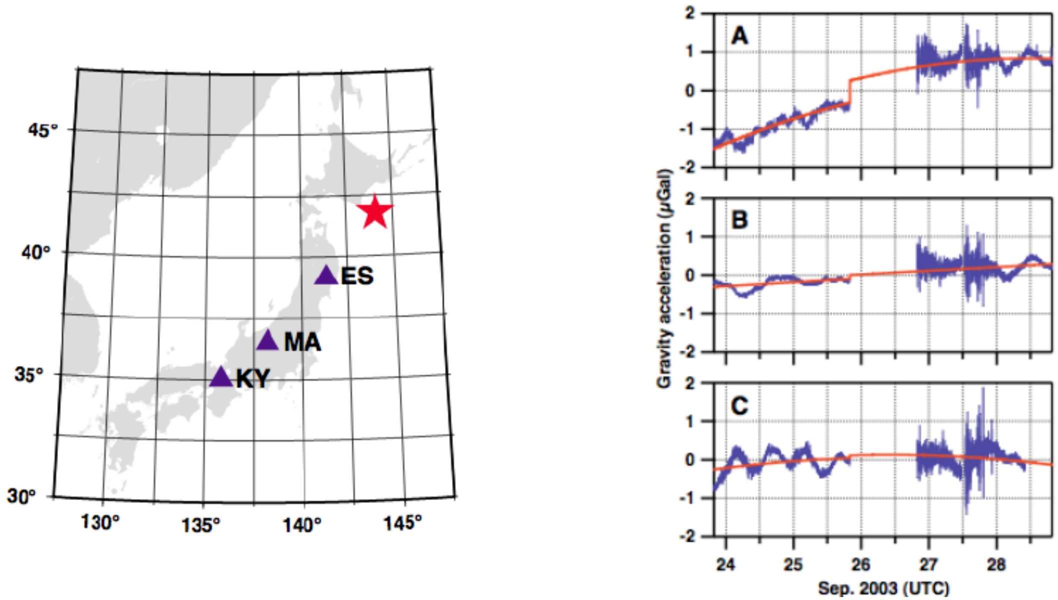
Theoretical Approach
-direct numerical calculations:
(Harms et al., GJI, 2015, 2016)
-Normal mode Theory (Juhel et al., 2017)



Static gravity changes induced by earthquakes measured

- Ground-based stations: Superconducting gravimeters after large earthquakes

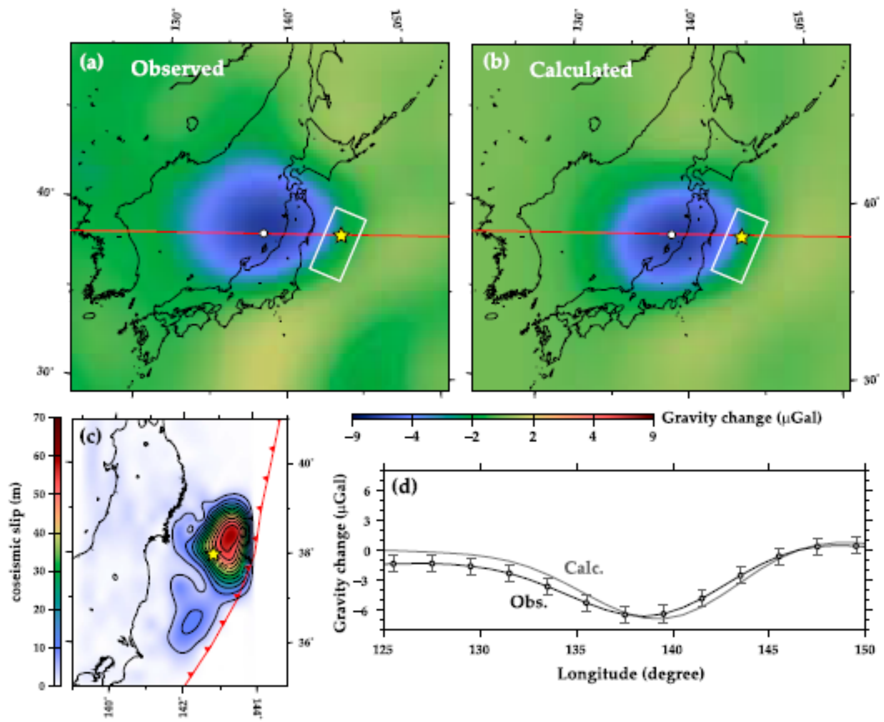
(2003 M=8.0 Tokachi-oki earthquake)



Imanishi et al. (Science, 2004)

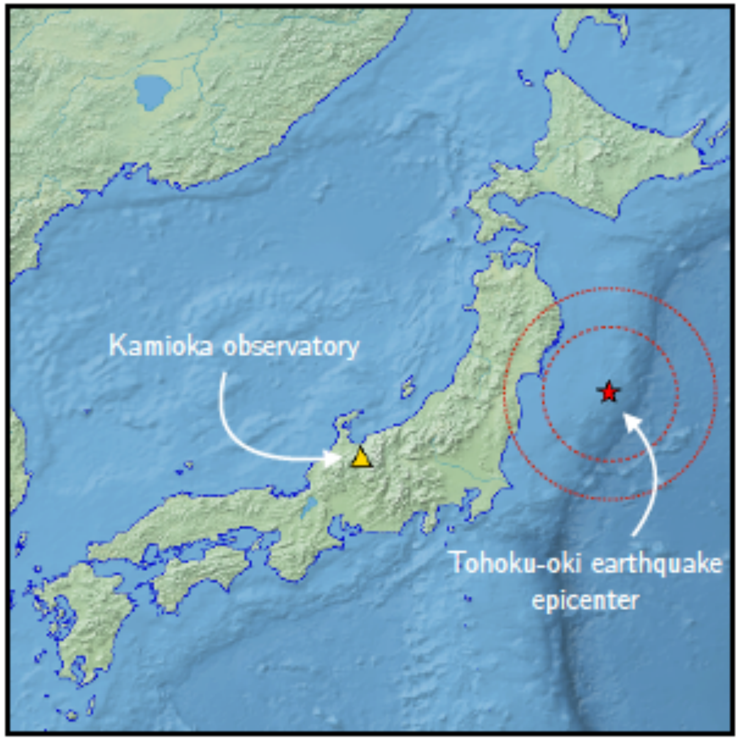
- GRACE / GOCE satellites

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



Matsuo and Heki (2011)

The choice of Kamioka SG 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)

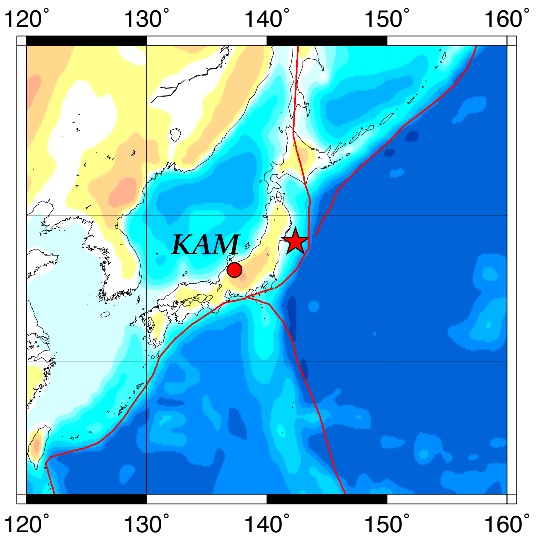
- Superconducting gravimeters are so far the best instruments measuring the Earth gravity field

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

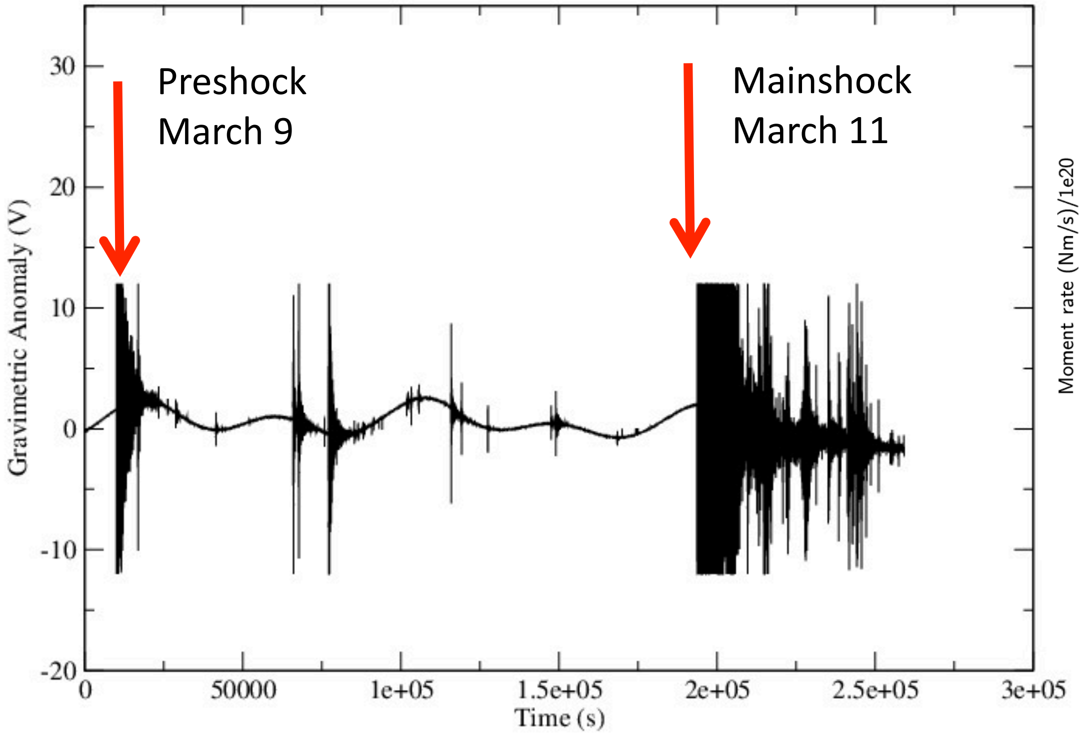
- Continuous data recording at 1sps (1Hz), on contrast with other SG instruments (1spm ≈ 0.0167Hz)

- Data easily accessible (thanks to Dr. Tamiura)

Transient gravity changes induced by earthquakes?

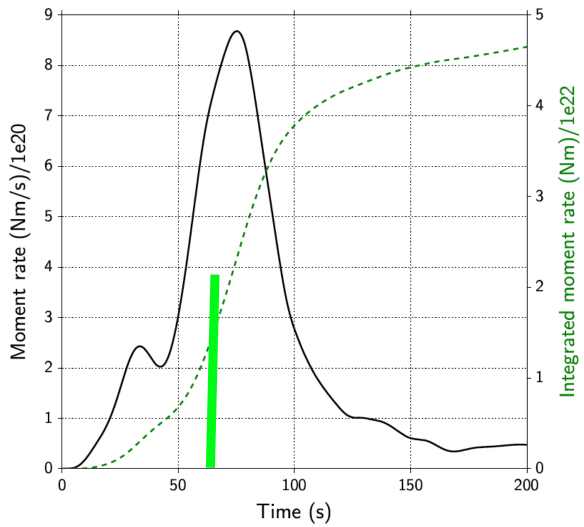


SG data at Kamioka Observatory
≈500 km from the Tohoku epicenter



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

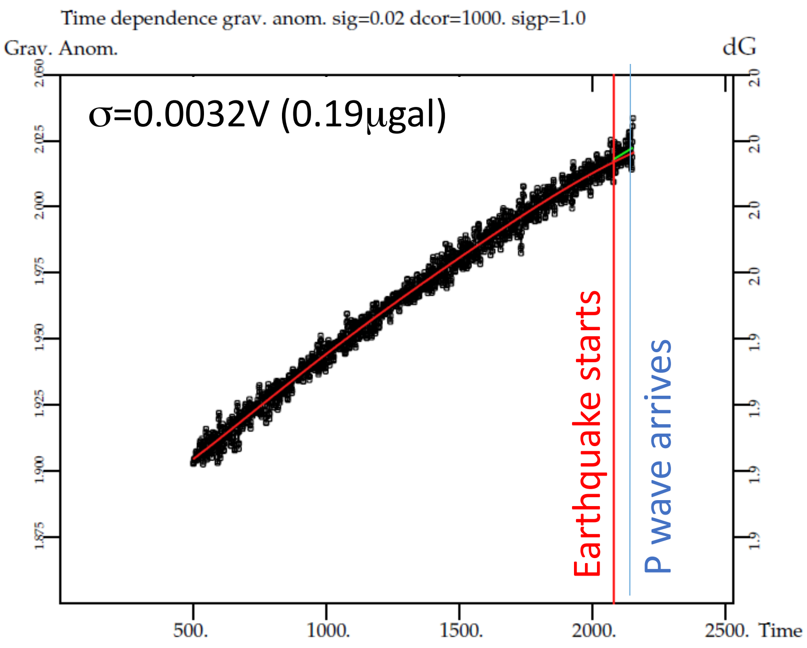
P-waves arrive
68s after t_{eq}



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

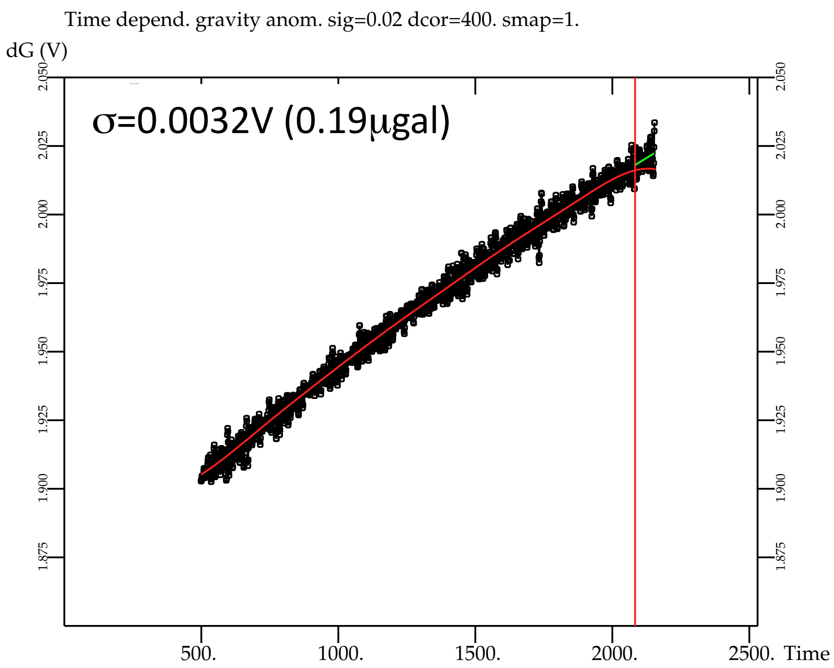
Superconducting gravimeter data during the March 11th 2011 Tohoku earthquake

SG data at Kamioka Observatory
≈500 km from the Tohoku epicenter
1 Hz sampling



Δ_{cor}= 1000s

Gravity perturbation V/ -58 μgal



Δ_{cor}= 400s

Superconducting gravimeter data during the March 11th 2011 Tohoku earthquake

SG data at Kamioka Observatory
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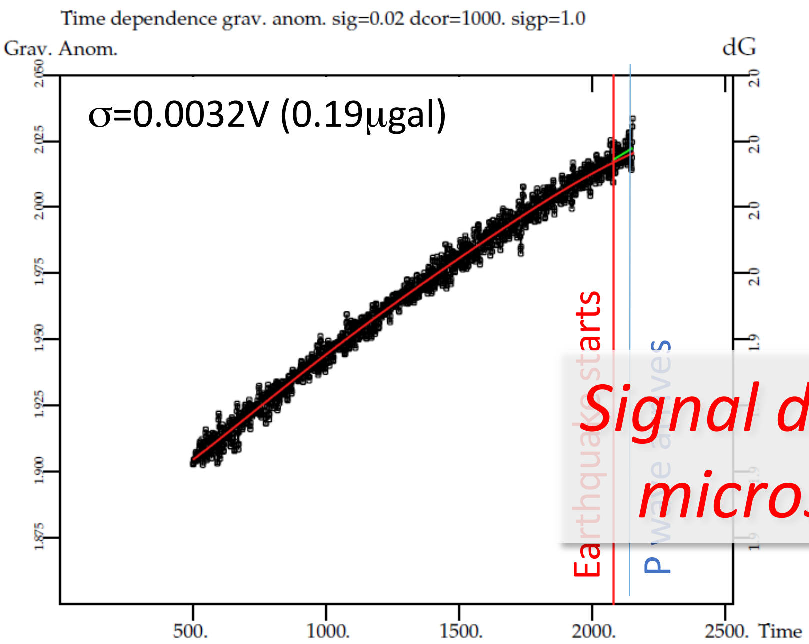

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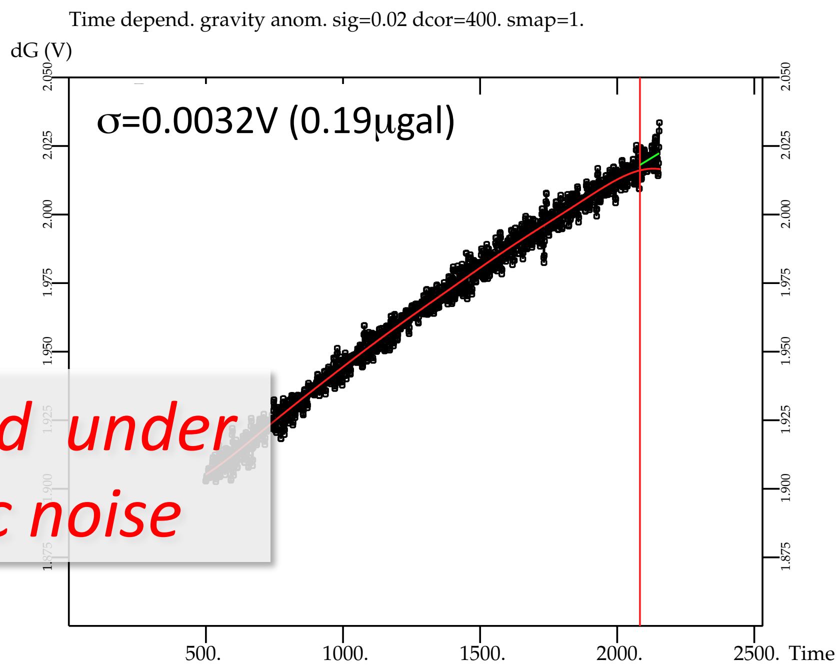
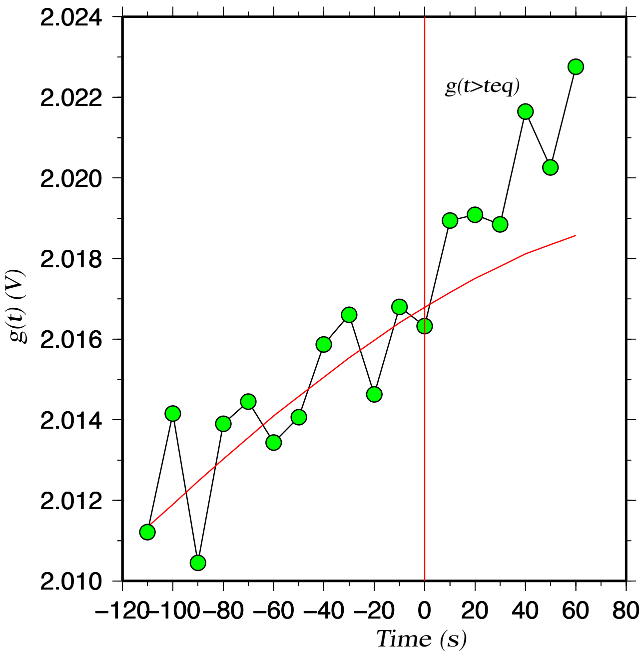


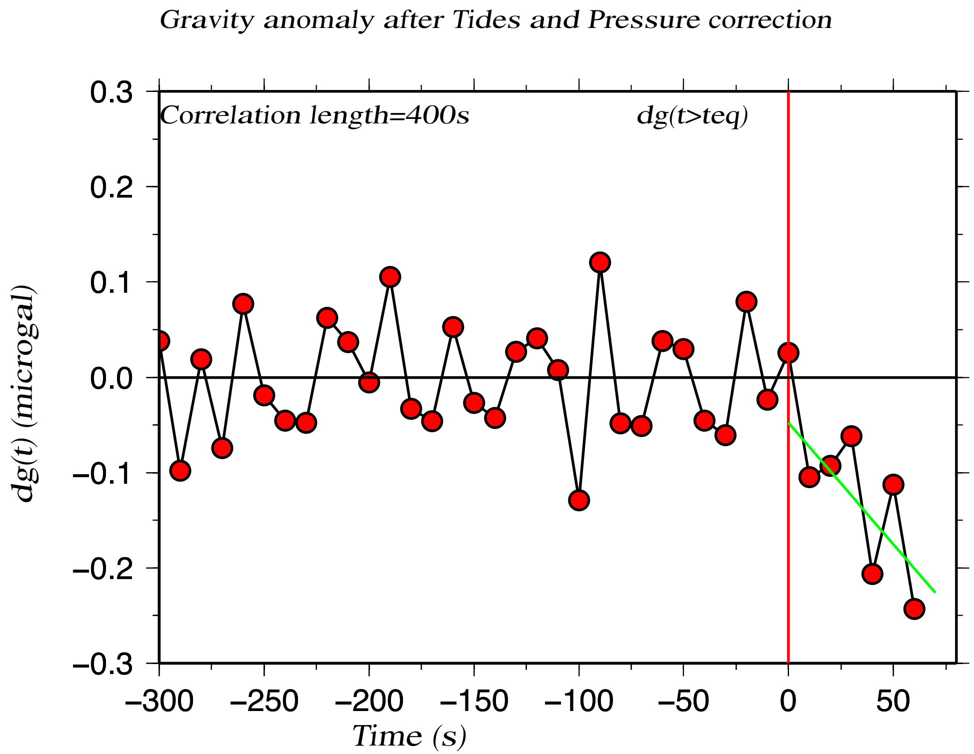
Δ_{cor}= 400s

Signal drowned under microseismic noise

Uncorrected decimated data



Corrections from Tides and pressure variations



Statistical Tests: Blind Test

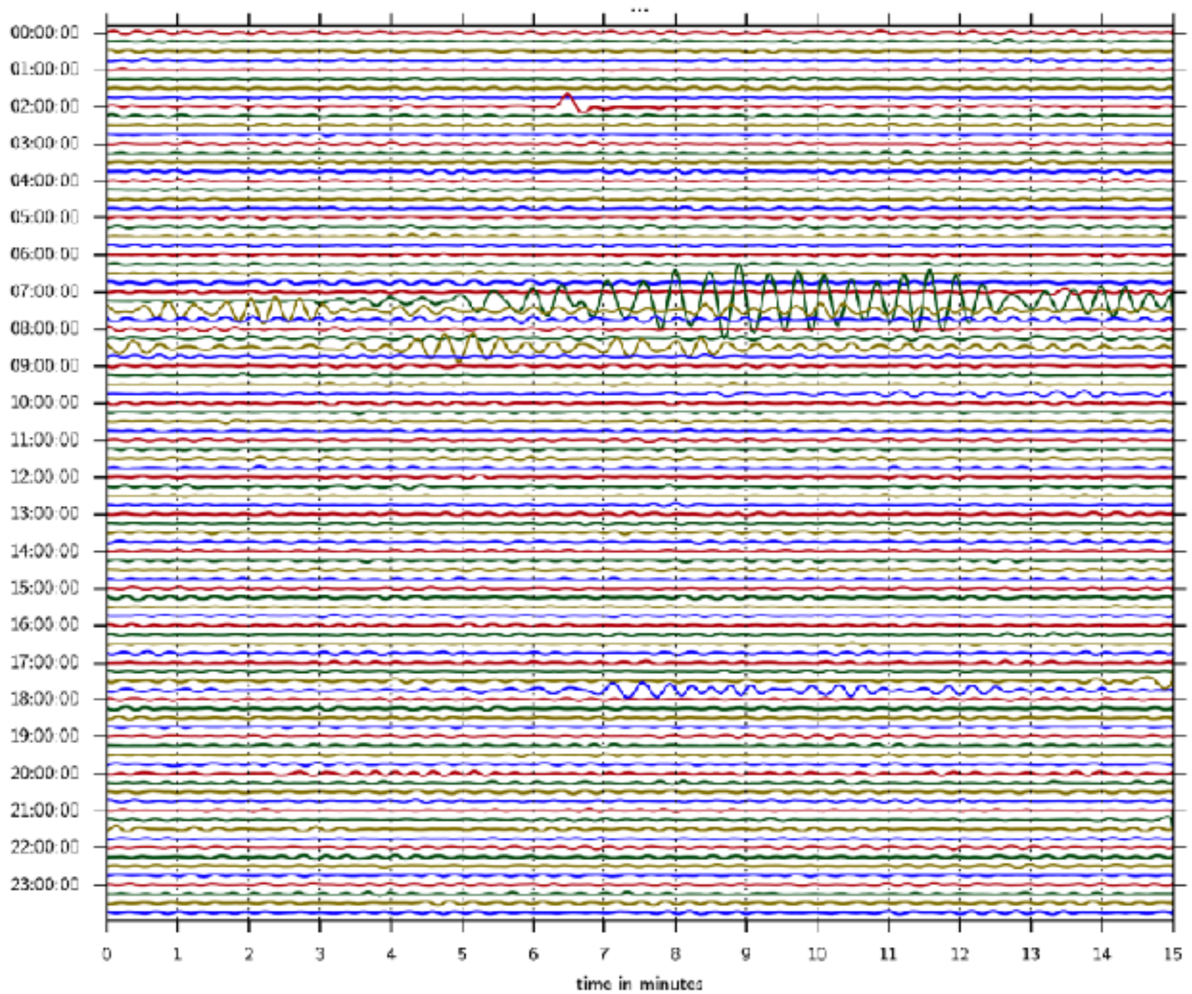
Polynomial Curve Fitting Analysis

Kamioka Observatory

Tohoku Earthquake (11/03/2011)

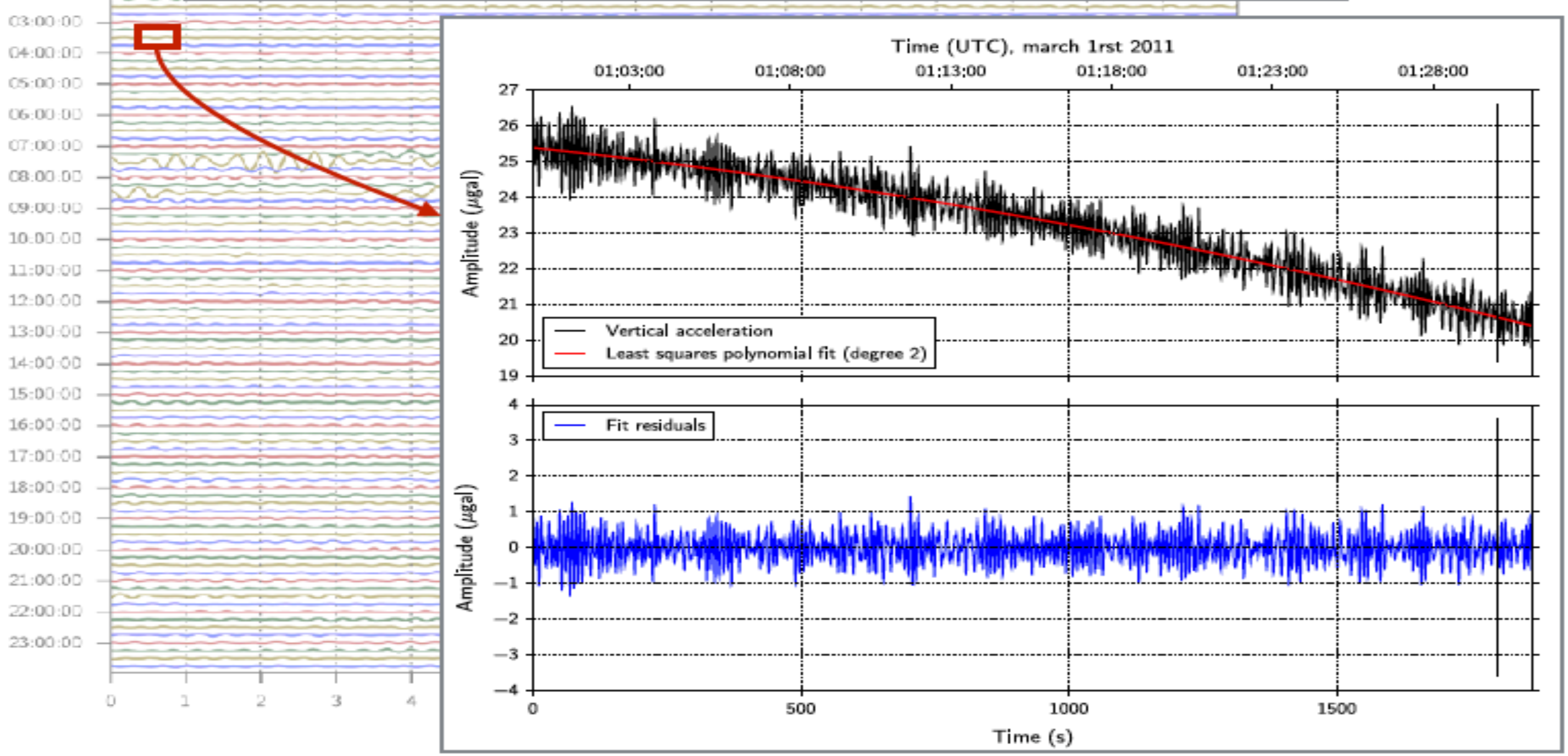
'Blind' Statistical detection procedure

We tune our detection procedure on 60 days of background data

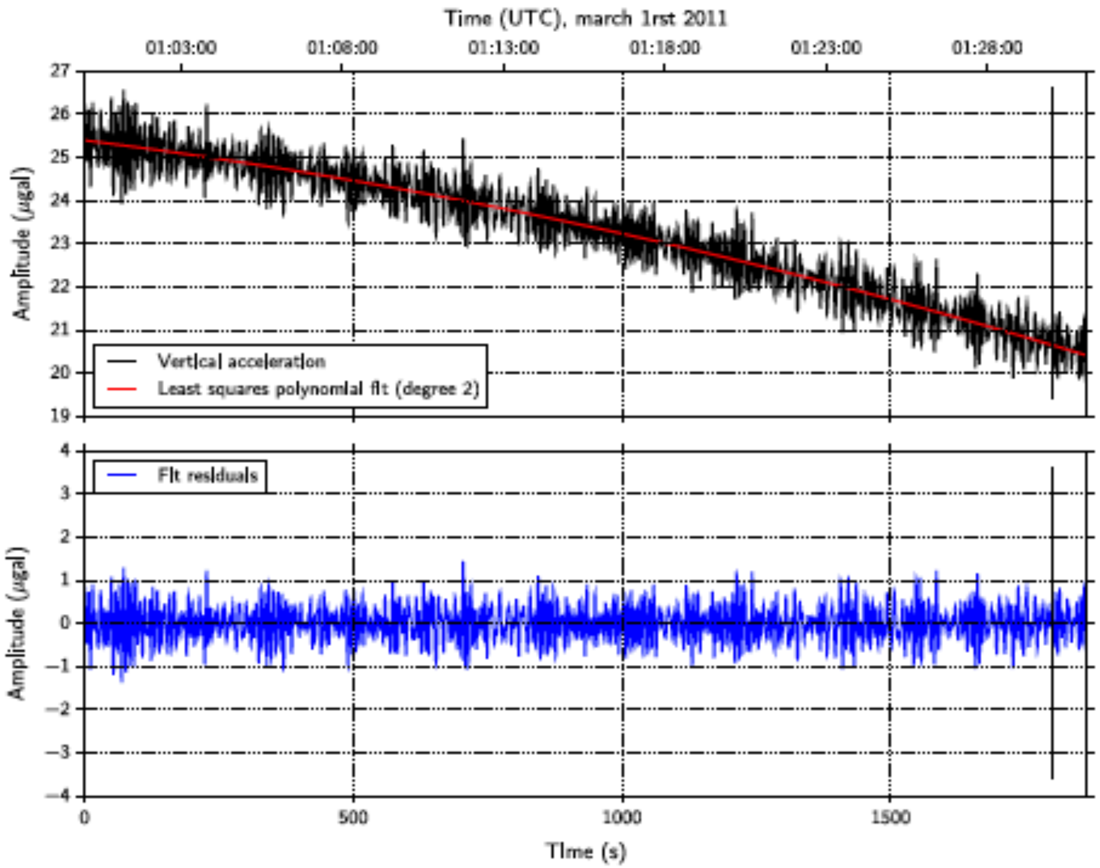


’Blind’ Statistical detection procedure

- Least squares polynomial fitting of the long trend - depends on *duration* T and *degree* d
- Extrapolation of the fitting polynomials, for 65 seconds after t_{end}
- Computation of the residuals *res(t)*



We define the reduced gravity signal $\boldsymbol{A}$ as :



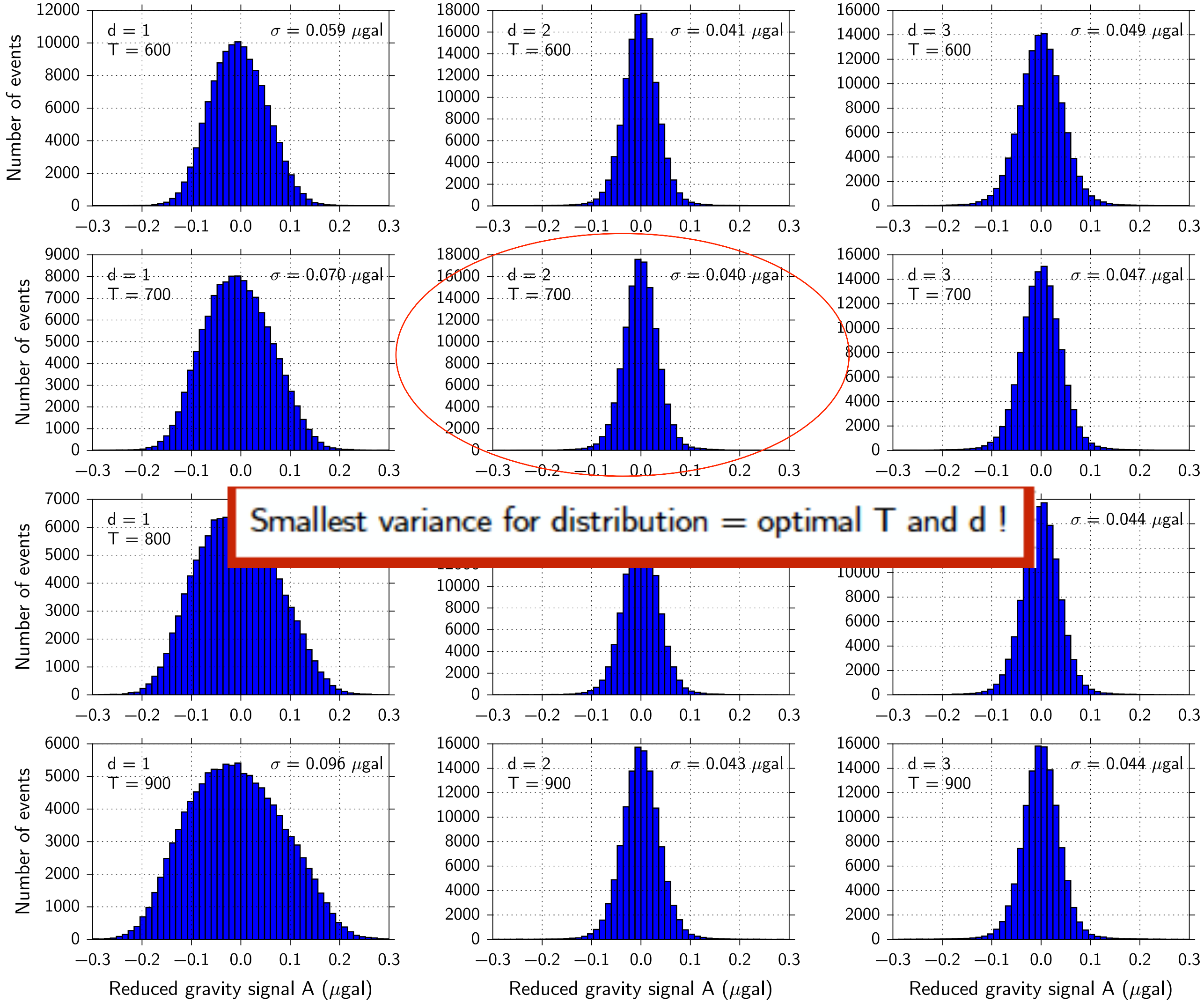
$$\mathcal{A} = \frac{1}{(t_2 - t_1)} \int_{t_1}^{t_2} res(t)\, dt$$

with $t_1 = t_{end} + 35s$,

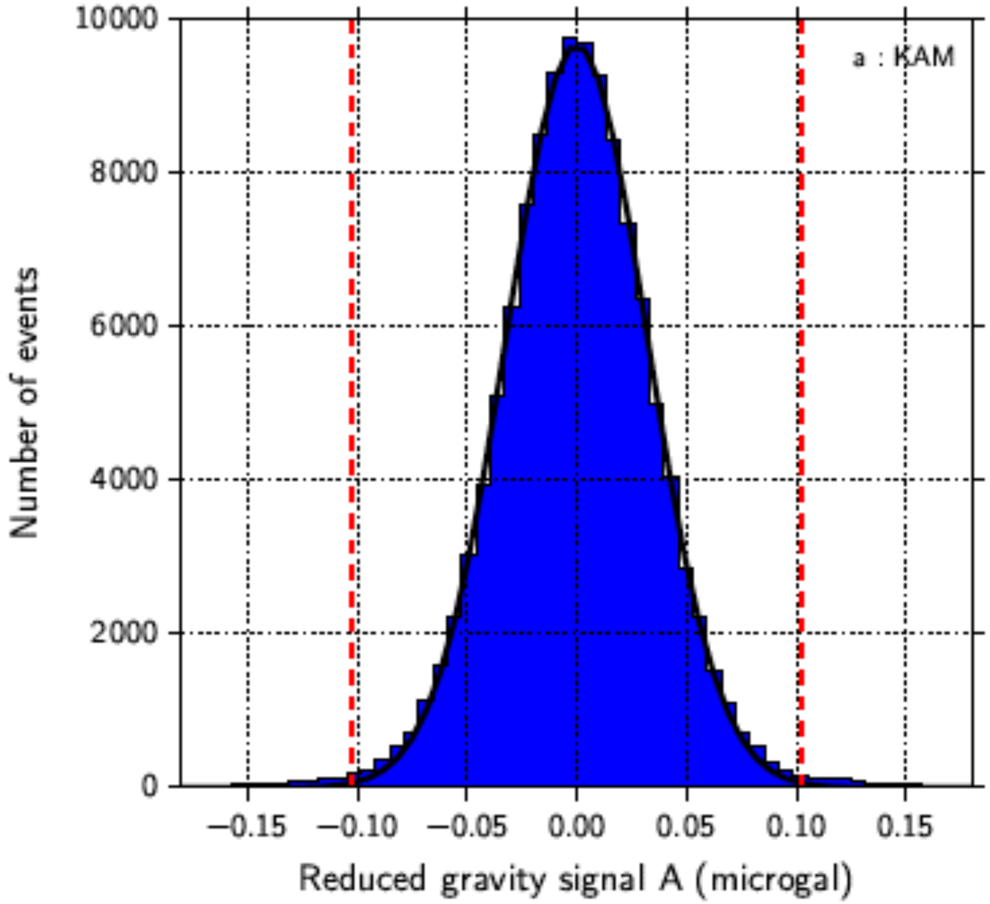
and $t_2 = t_{end} + 65s$

We got one $\boldsymbol{A}$ per window → distributions of A, for given duration $\boldsymbol{T}$ and degree $\boldsymbol{d}$

We got one ***A*** per window → distributions of A, for given duration ***T*** and degree ***d***



Smallest variance for distribution = optimal T and d !



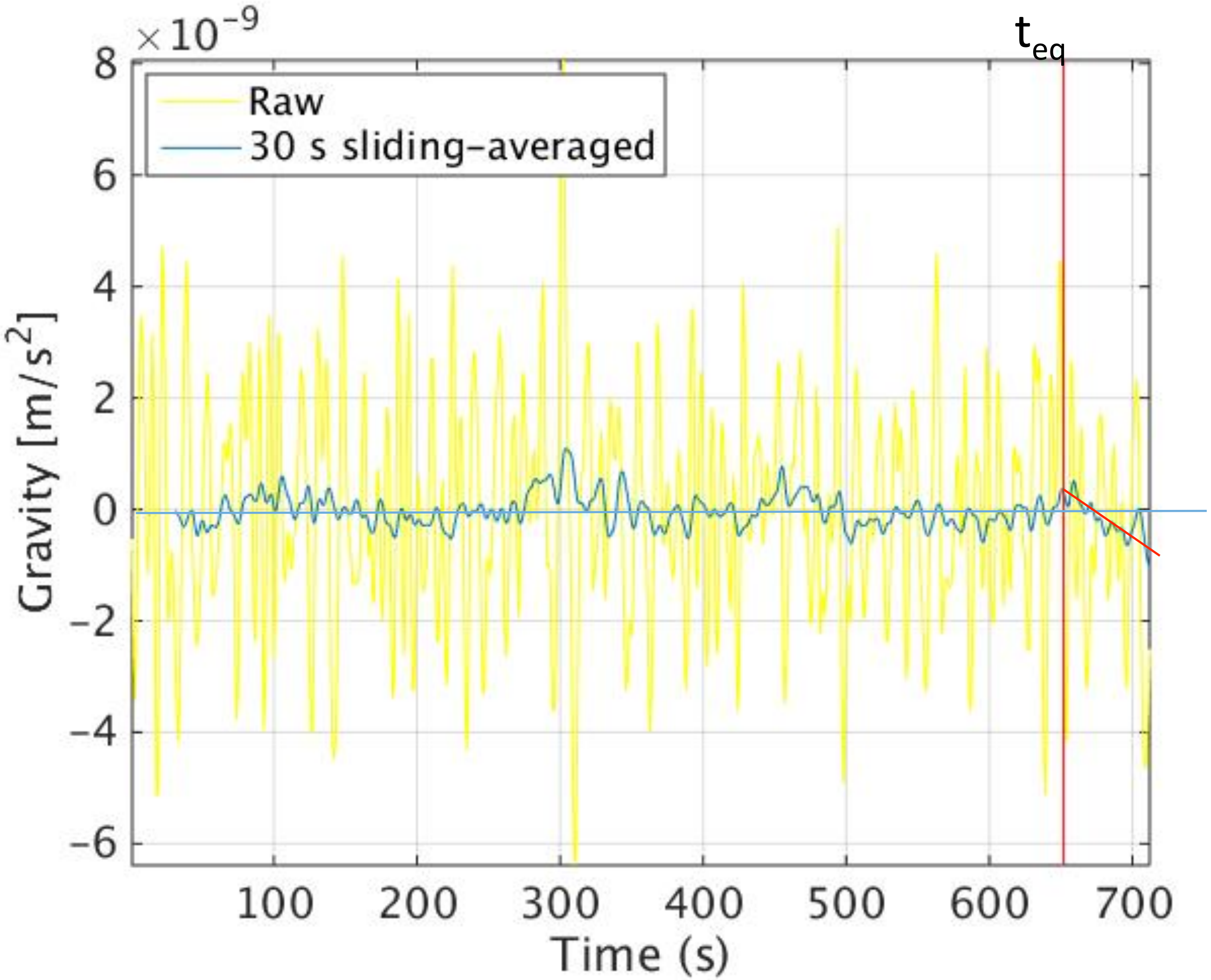
Not Gaussian distribution: Many outliers

Statistical significance
p = probability for a signal to exceed A

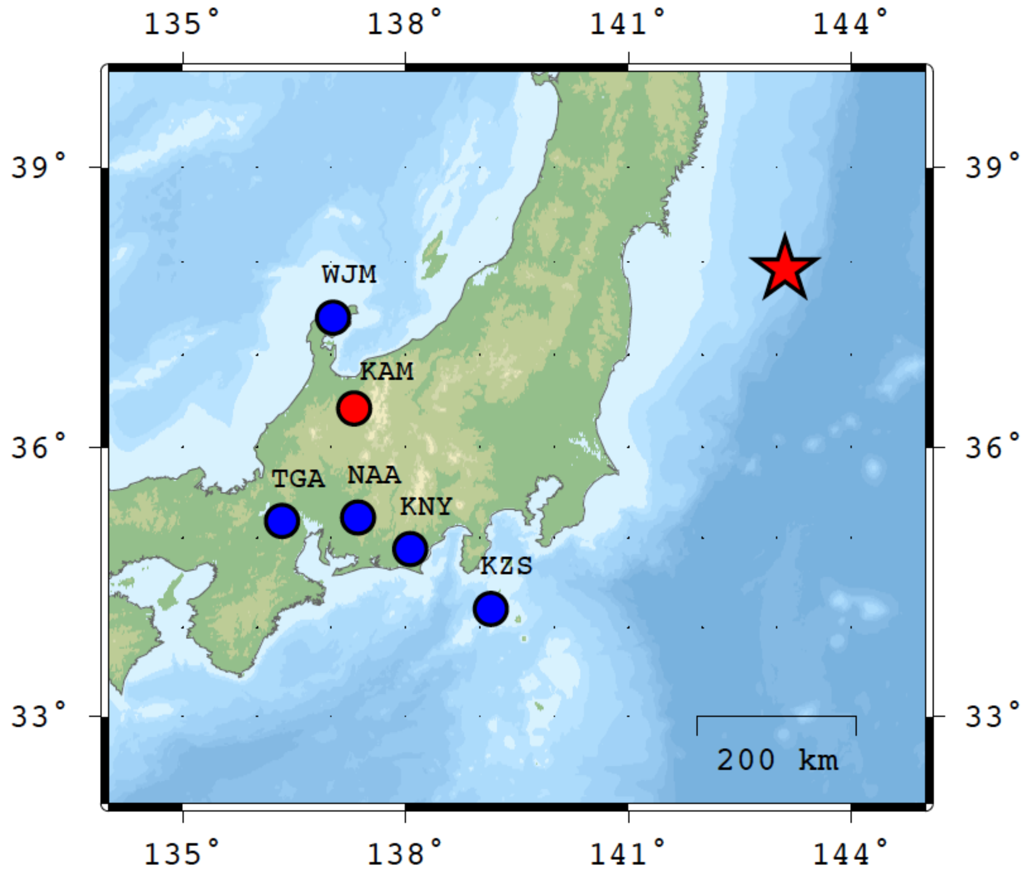
For the Kamioka station only :

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

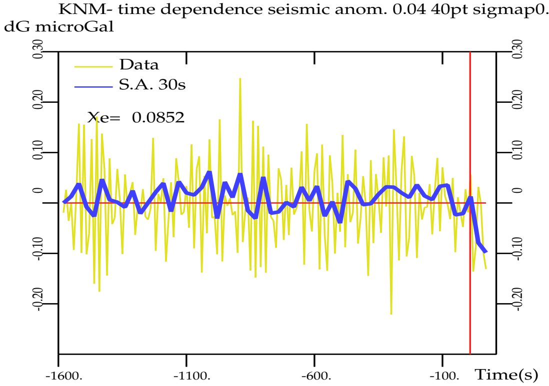
Time window before Tohoku earthquake:
L=690s, N=2, sliding average 30s



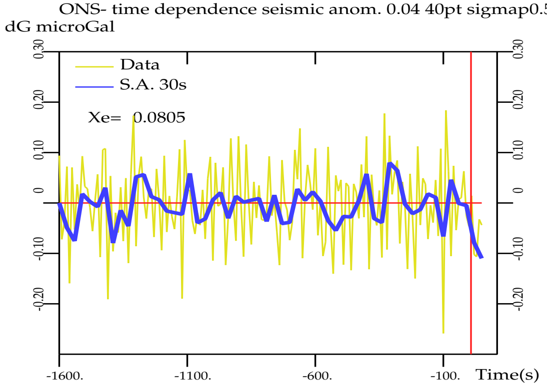
-Broadband Japanese network F-NET (STS1, STS2…)



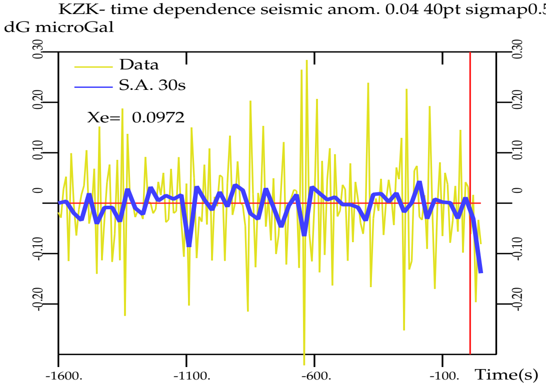
KNM- time dependence seismic anom. 0.04 40pt sigmap0.5



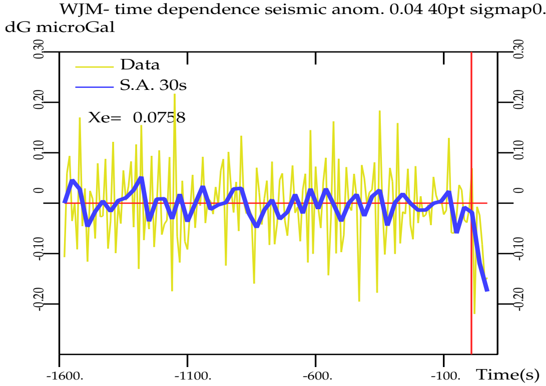
ONS- time dependence seismic anom. 0.04 40pt sigmap0.5



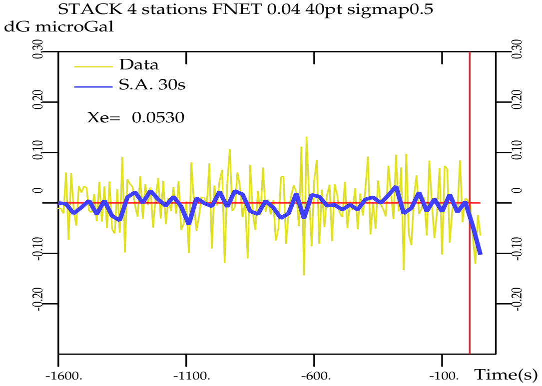
KZK- time dependence seismic anom. 0.04 40pt sigmap0.5

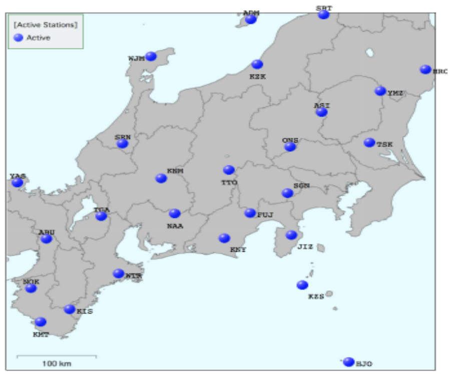


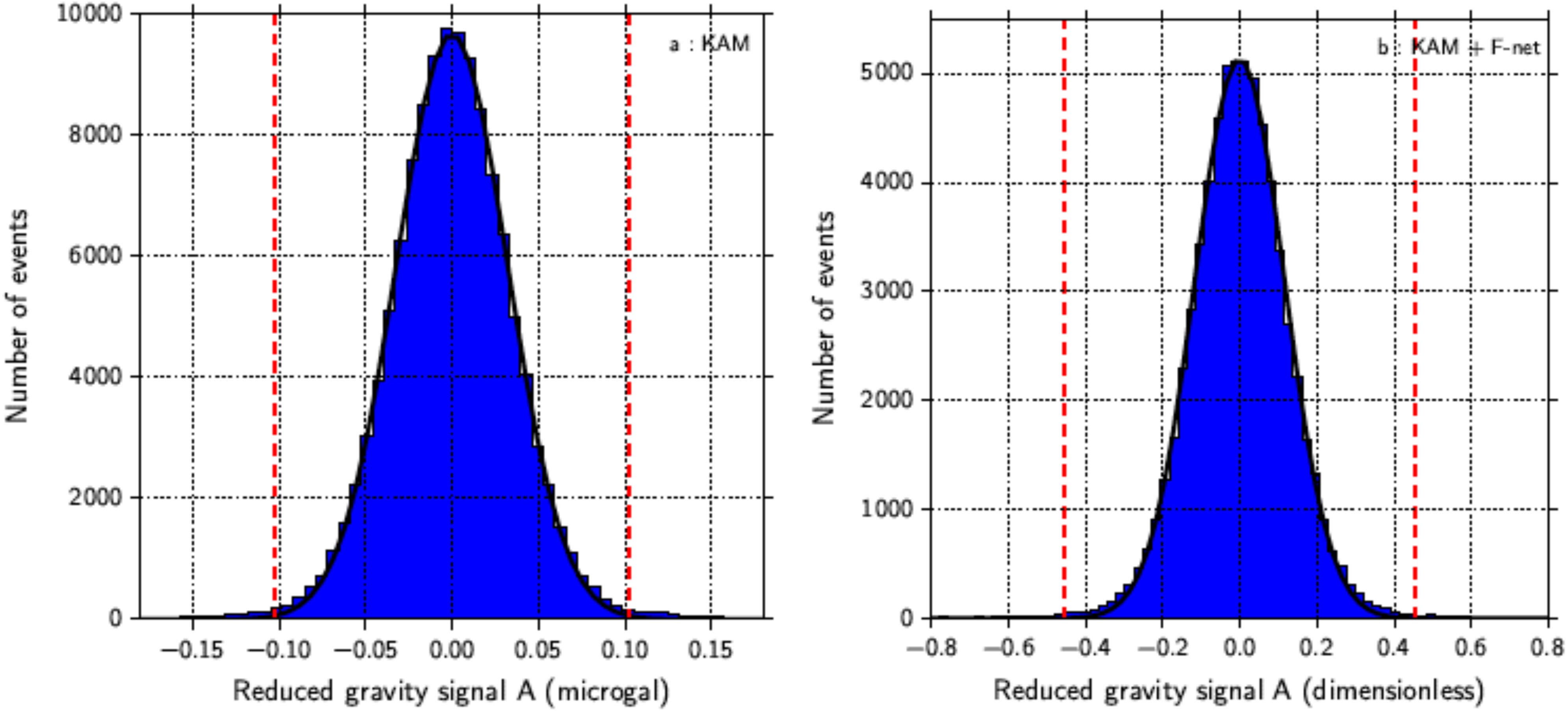
WJM- time dependence seismic anom. 0.04 40pt sigmap0.5



STACK 4 stations FNET 0.04 40pt sigmap0.5







For the Kamioka station only :

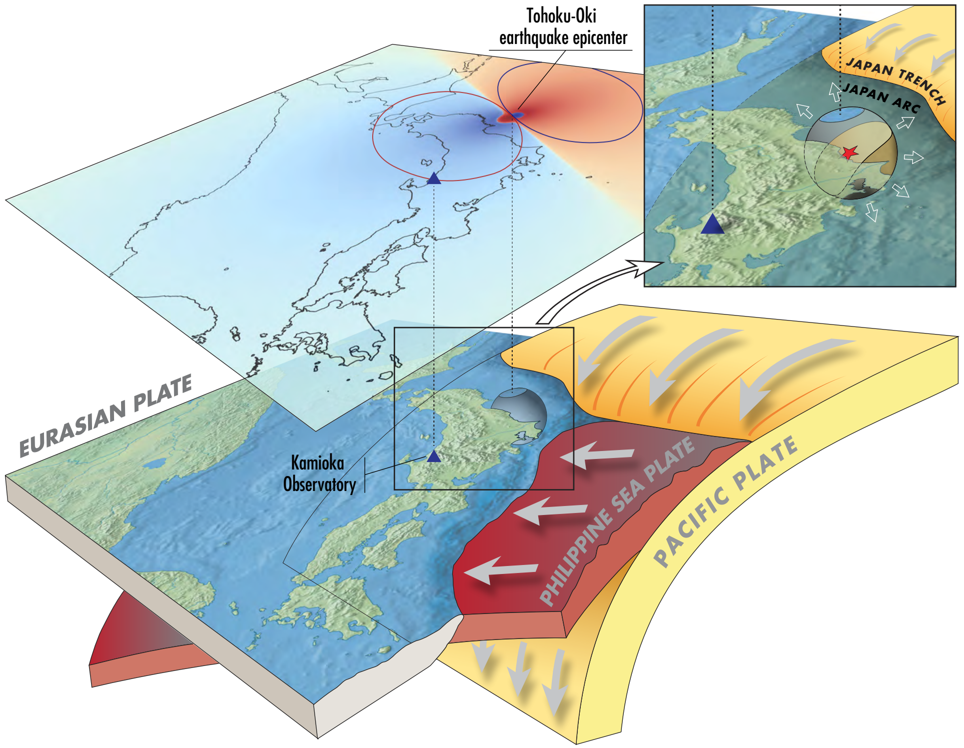
$p(A > A_{Tohoku}) = \mathbf{1.6\%}$

For a stacked waveform :
Kamioka + 5 F-net

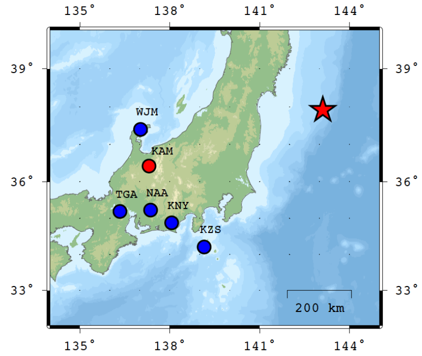
$p(A > A_{Tohoku}) = \mathbf{0.82\%}$

Conclusions:

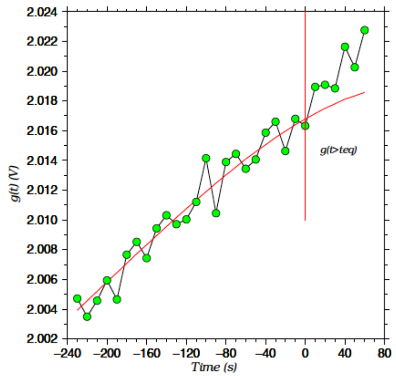
from Gravity field to **Earthquake Early Warning Systems**



-Detection of a prompt gravity signal
Very, very small



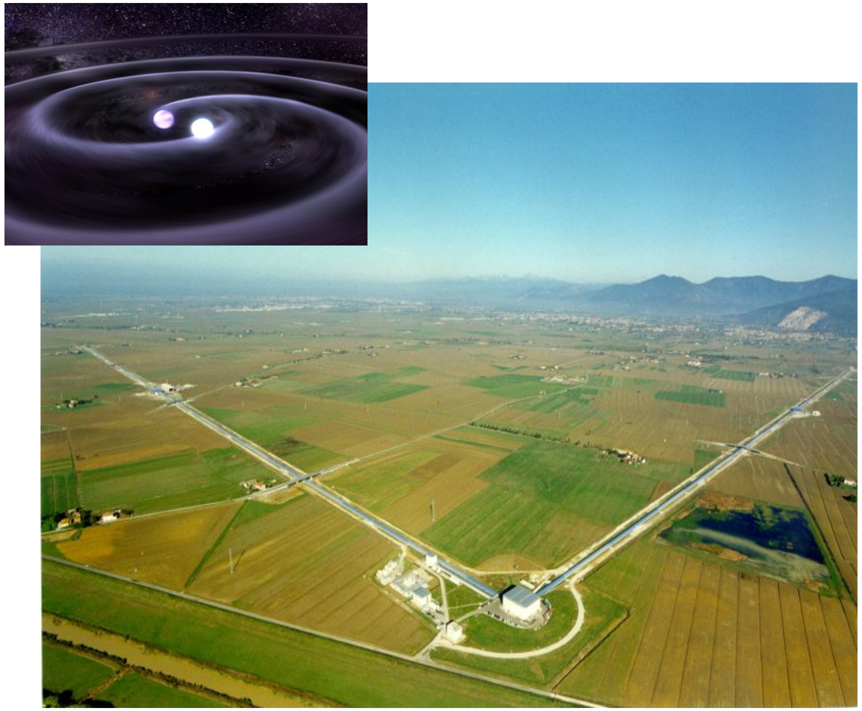
-Detection at Kamioka (Superconducting gravimeter)
≈-0.2-0.3μGal at 500km
Just above the detection threshold
- And in VBB Japanese stations



-Need for new gravity Instruments (TOBA, Atom interferometers, ...)

Conclusions:
from gravitational waves to **Earthquake Early Warning Systems**

Search and evidence for a gravity signal
associated with the Japan Tohoku-oki earthquake



THANK YOU
FOR YOUR
ATTENTION