국가수리과학연구소 National Institute for Mathematical Sciences

UNIVERSITY OF CALGARY

μGICK Yemi Observatory
micro-Gravity Investigator in Canada-Korea

YeMiGO

-microgravity measurement for solid earth to gravitational-wave research-

John J. Oh (NIMS)

μGICK / ENIGMA Collaboration

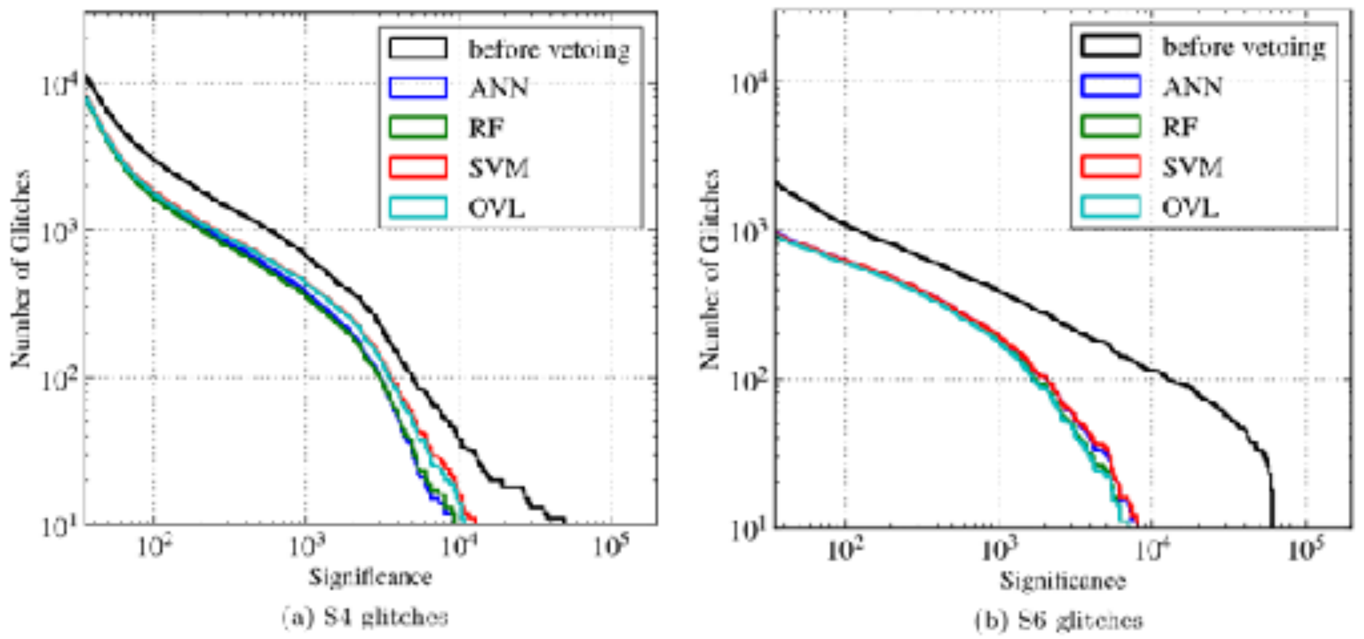
2025. 11. 22

Chonnam National University

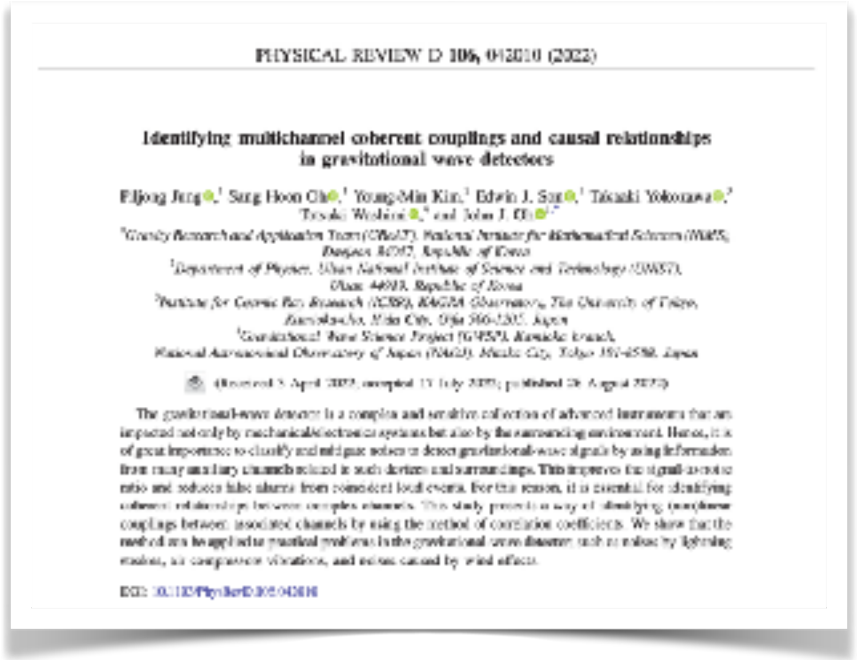
KSHEP Fall Meeting / NPA Joint Workshop

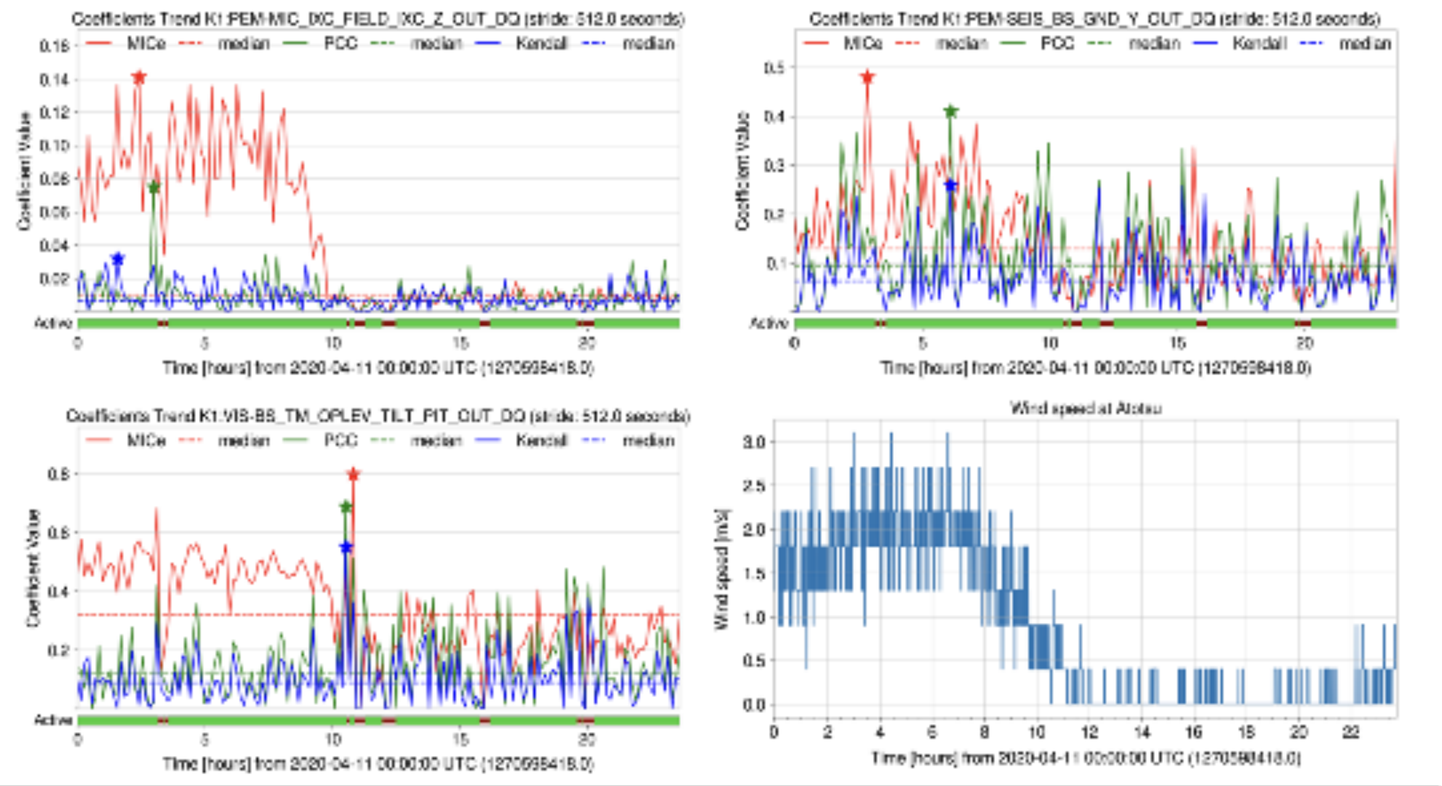
Motivation

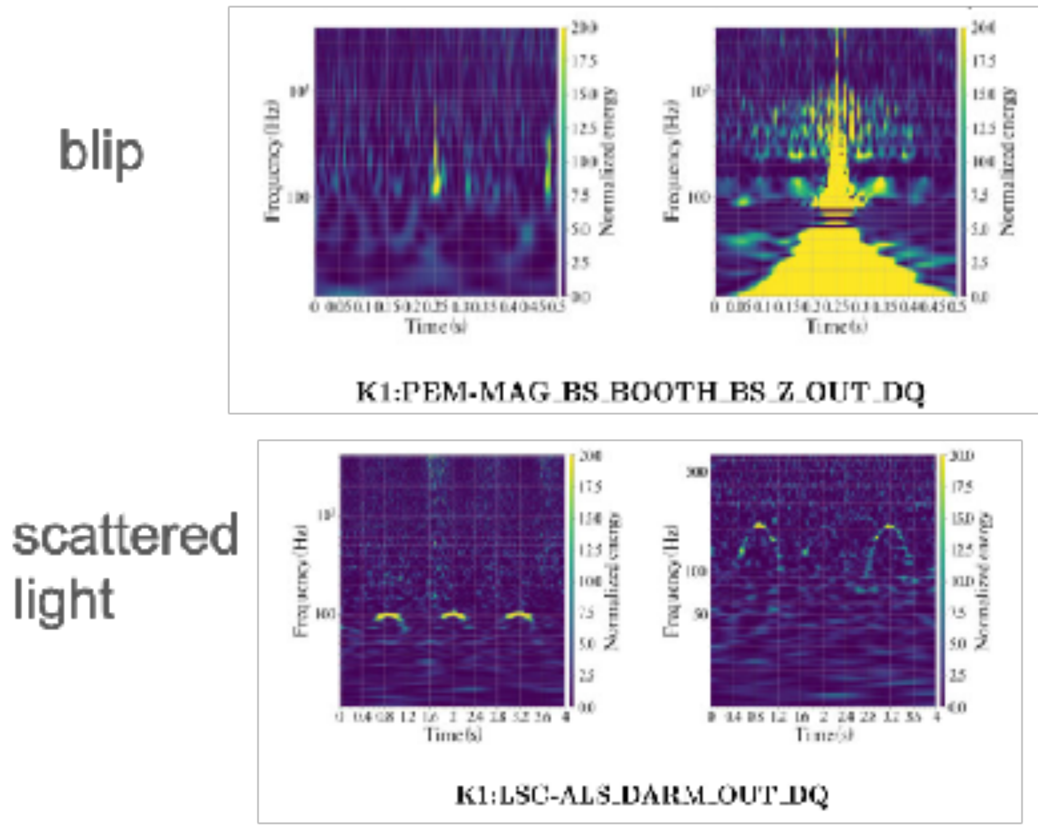
- After joining LSC (2009), we joined LSC-Detchar and KAGRA-Detchar groups:
  - NIMS: John J. Oh, Sang Hoon Oh, Edwin J. Son, Hwansun Kim
    * Piljong Jung, Byeol Kim (Internship)
  - Pusan Nat'l Univ.: Young-Min Kim (now in KASI)
- Detchar Project Topics:
  - Noise hunting tools
  - Noise analysis algorithms
  - DQ Shift
  - Machine learning based classification of noise
  - Trigger generation algorithm
- UNIST group joined the KAGRA Detchar from 201x:
  - Kyujin Kwak, Kihyun Jung




Application of machine learning algorithms to the study of noise artifacts in gravitational-wave data


PHYSICAL REVIEW D 106, 042010 (2022)
Identifying multichannel coherent couplings and causal relationships in gravitational wave detectors






PTEP
Identification of Noise-Associated Glitches in KAGRA O3GK with Hierarchical Veto

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Motivation

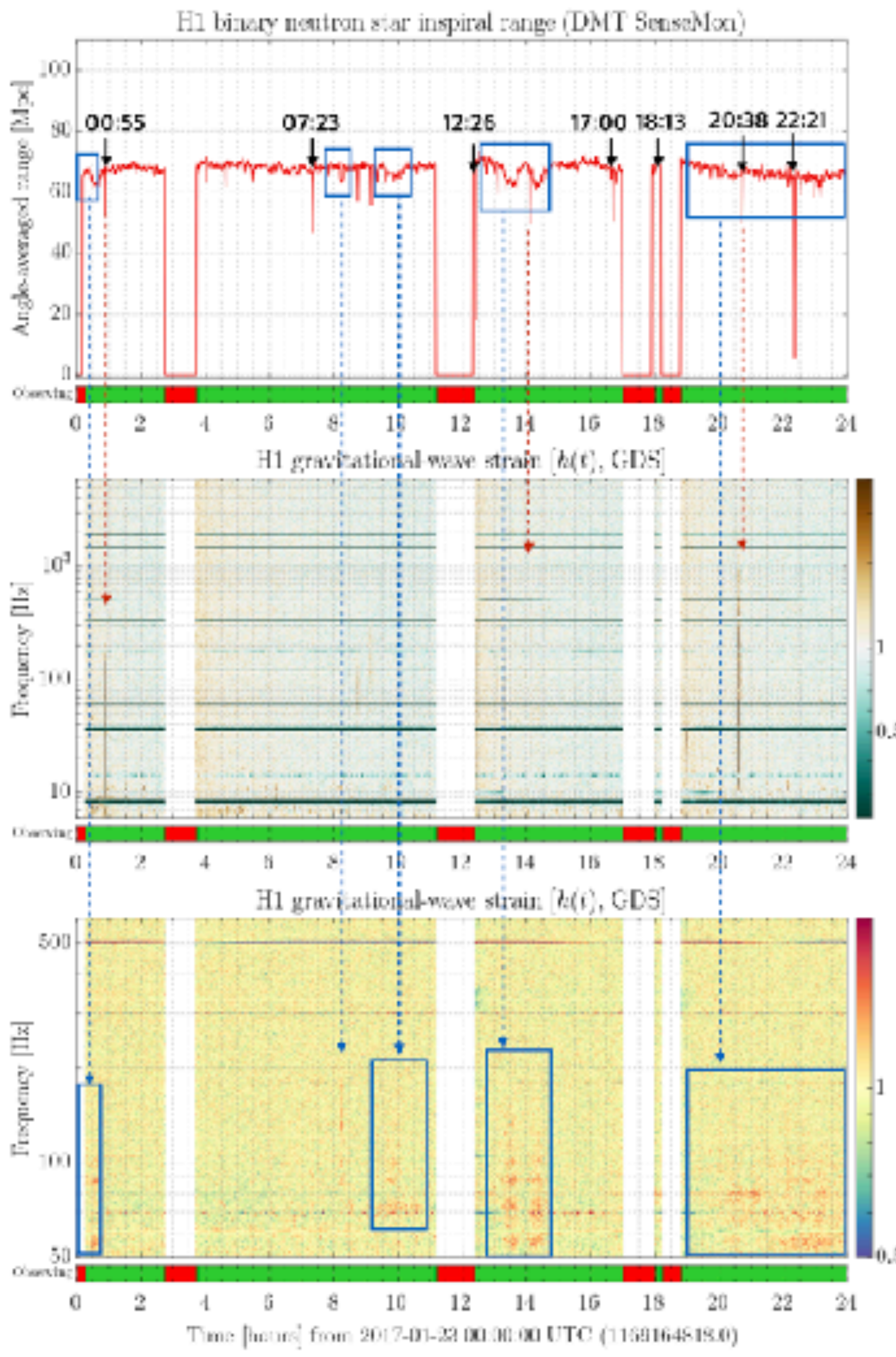
- **GW channel**, h(t)
- **200,000 auxiliary channels** – monitor 1) instrument behavior 2) environmental conditions

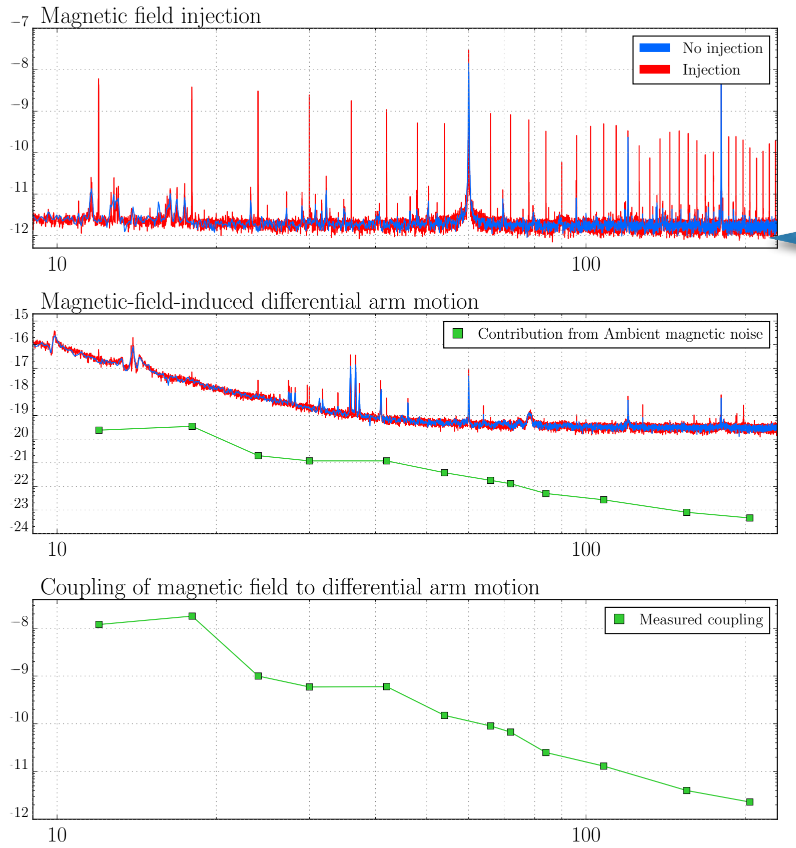
a) witness a broad spectrum of potential coupling mechanism

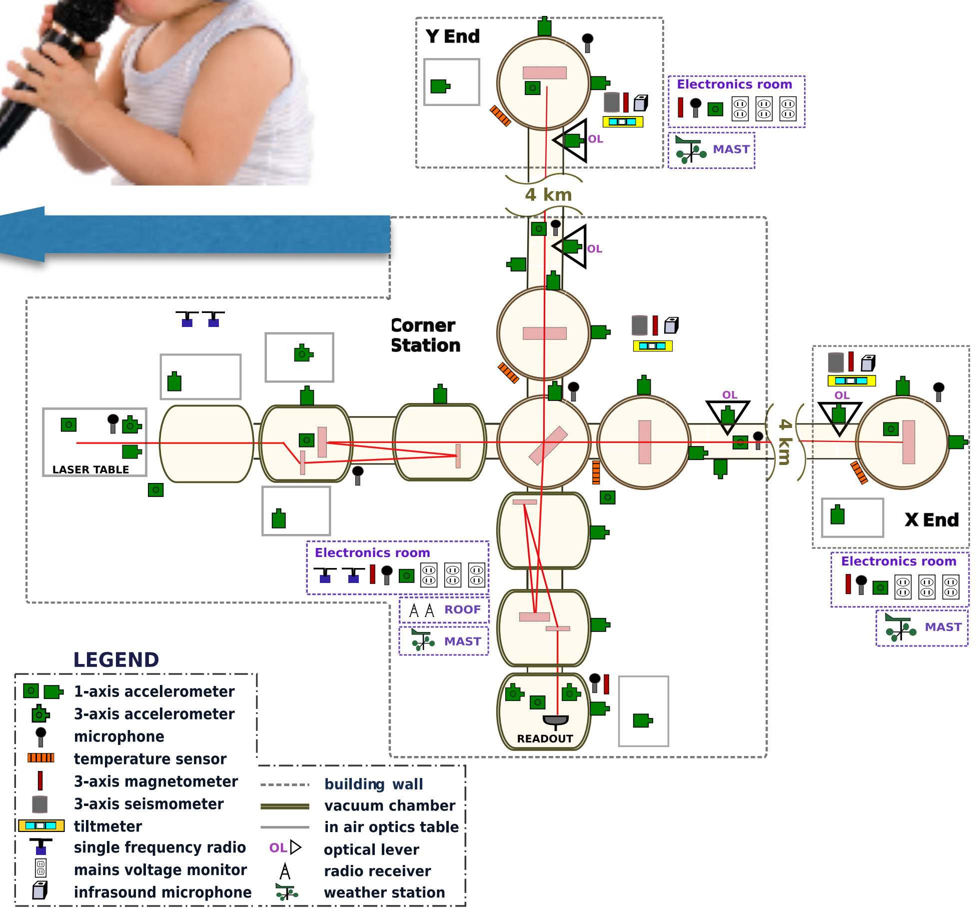
b) useful for diagnosing instrument faults and identifying noise correlation

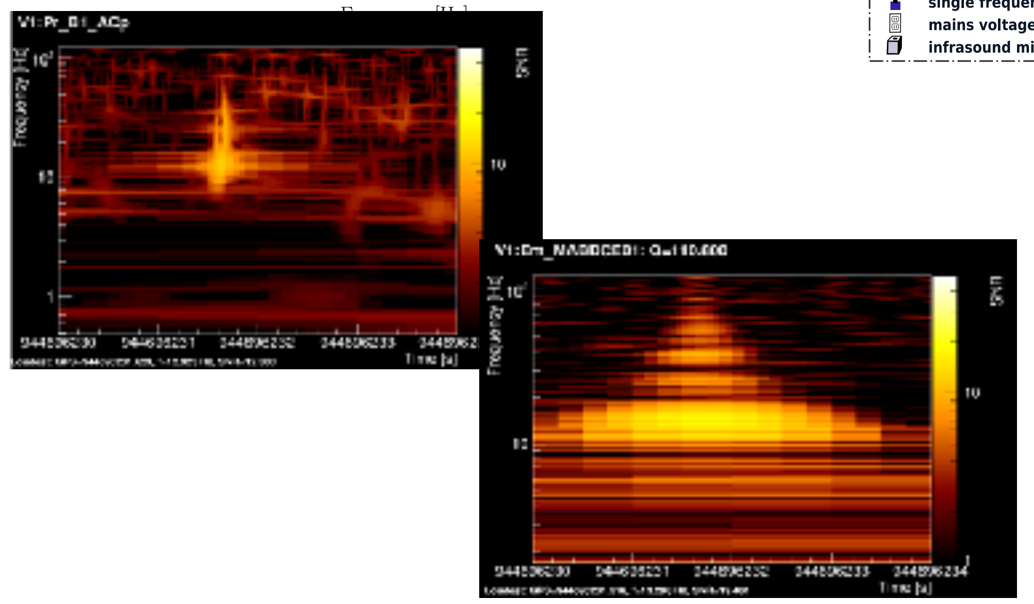
– **PEM (physical environment monitor)** : monitor the local surroundings for potential disturbance that may affect GW channel – ground motion, optical table motion, magnetic field variation, acoustic disturbance, cosmic ray showers

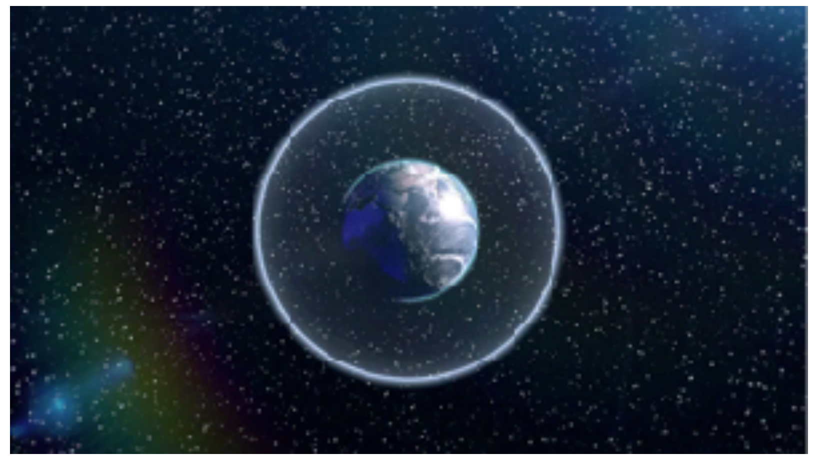
* injection studies – in order to know the relationship between PEM and GW channels (by intentional stimulus)

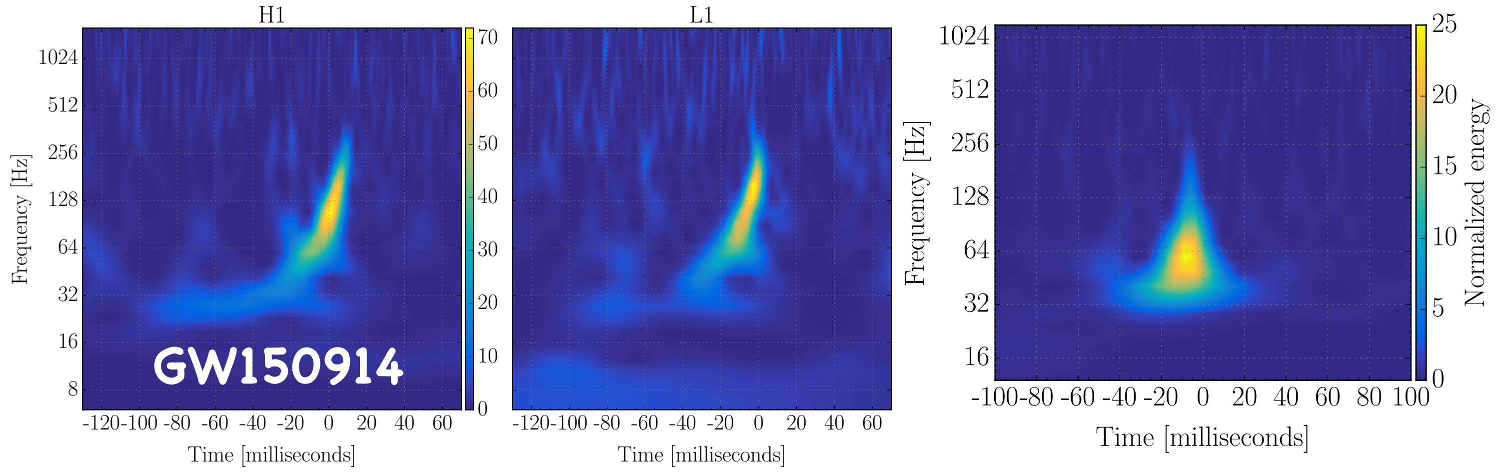


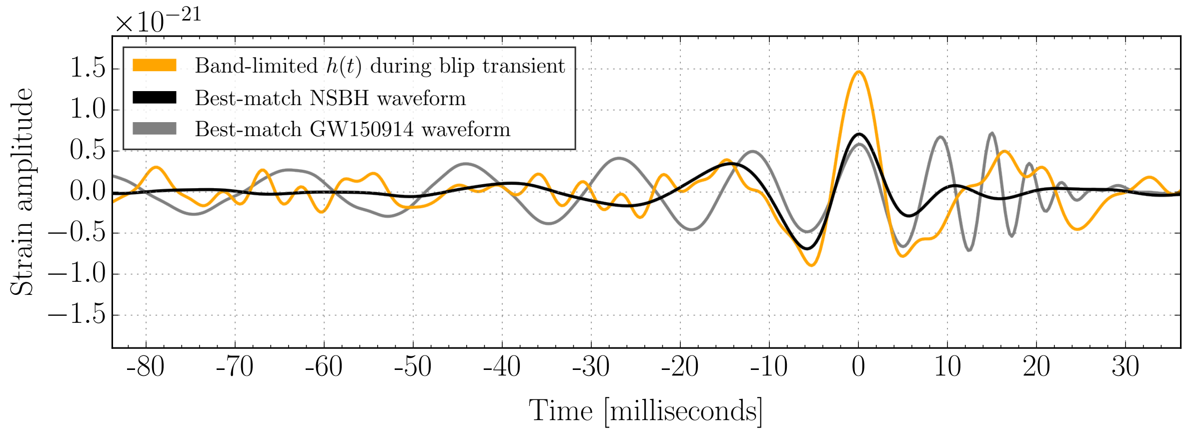












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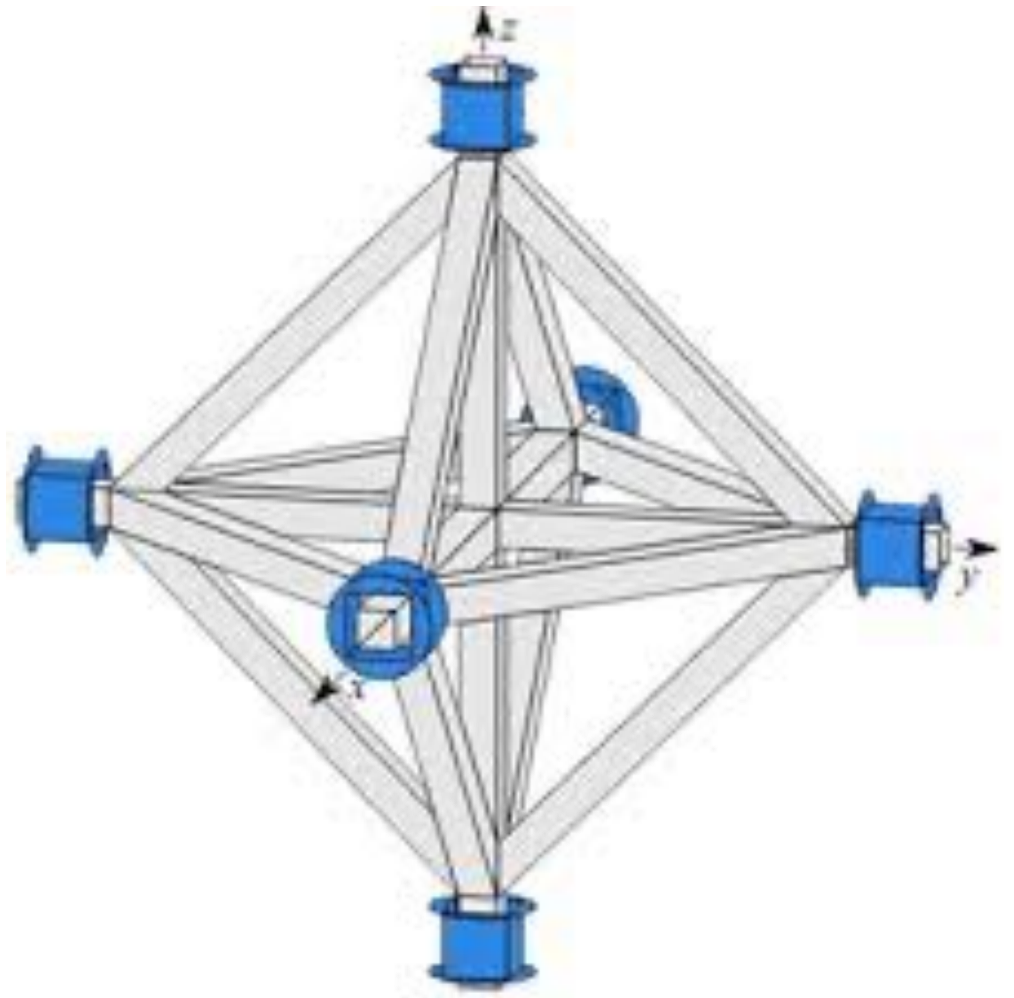
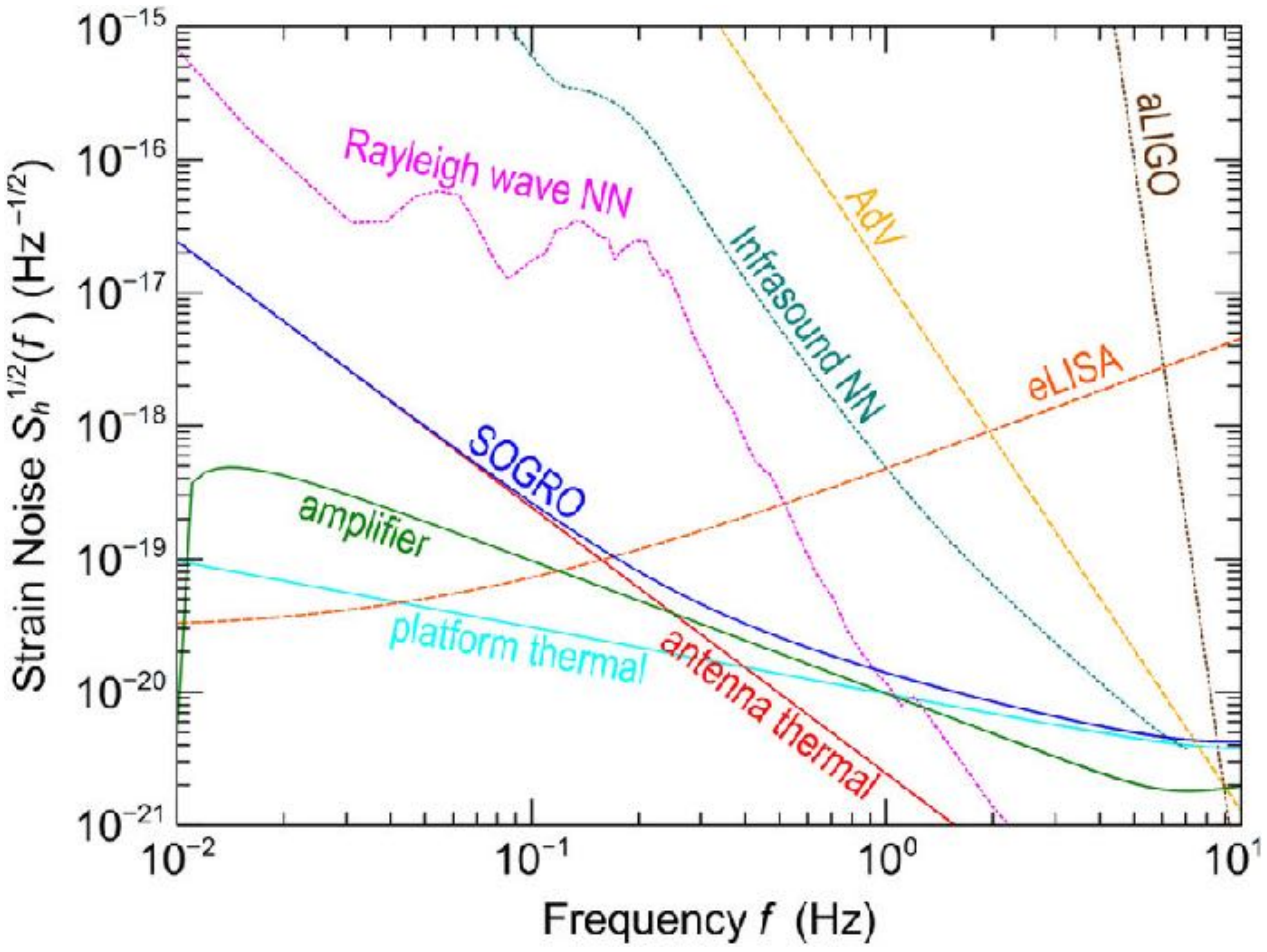
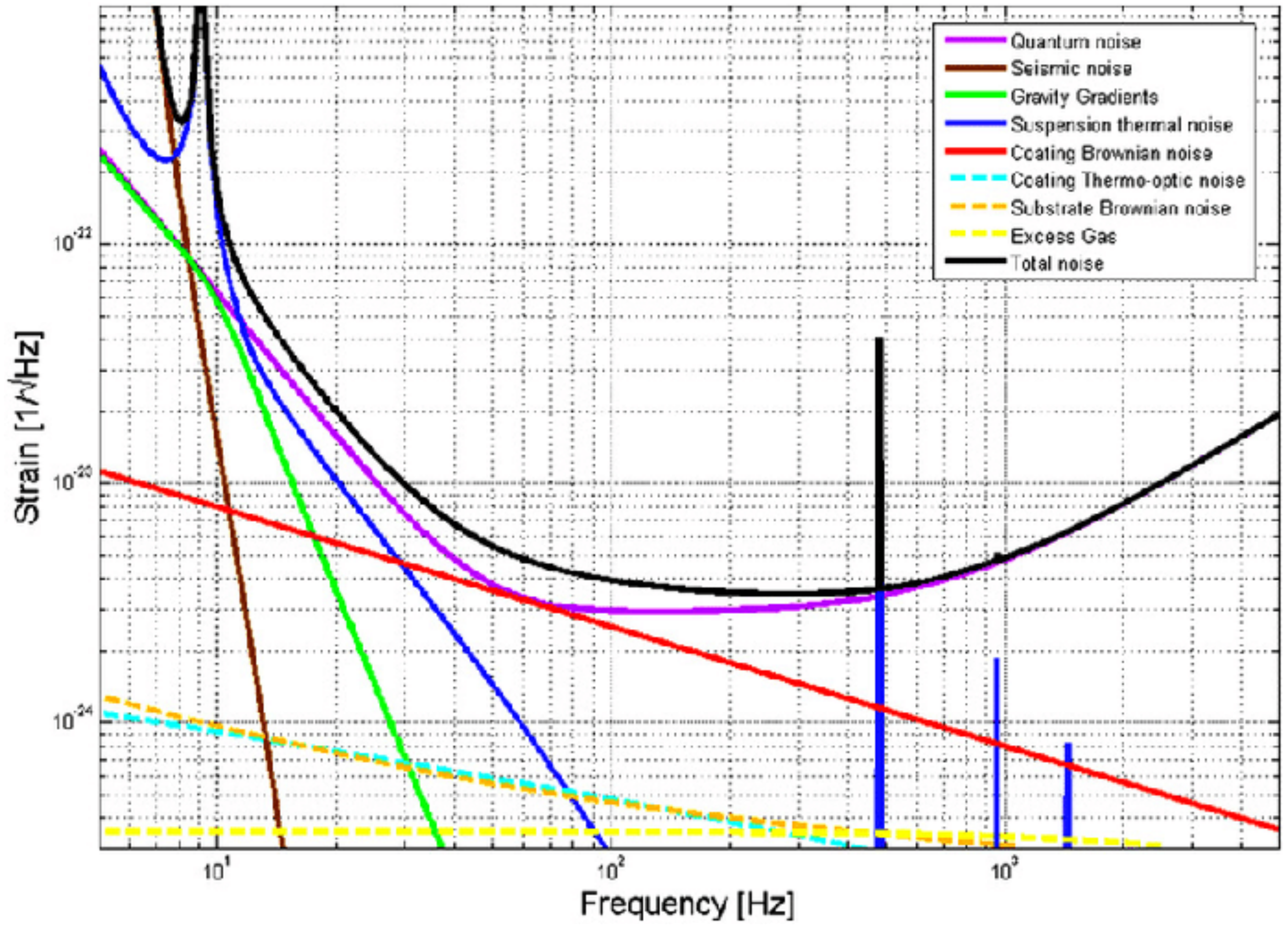
Motivation

- Seismic noises
- Newtonian noises

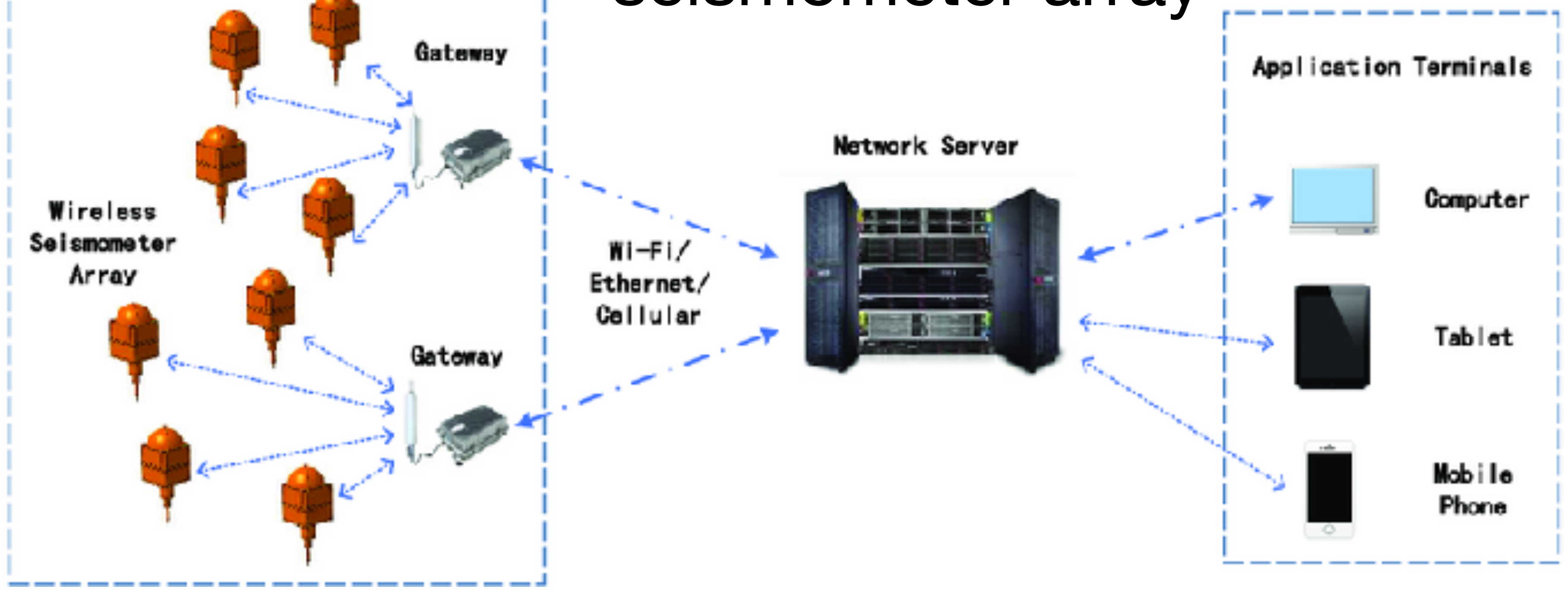


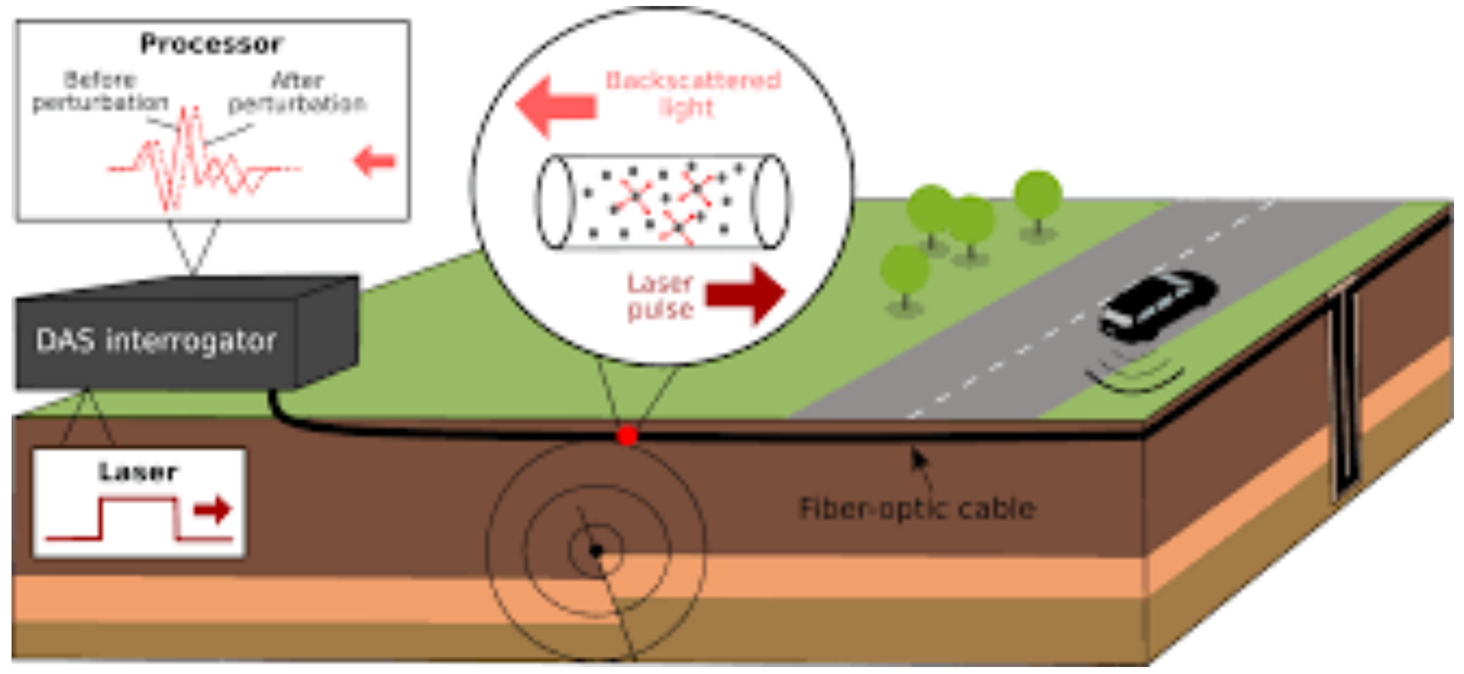




measuring gravity

seismometer array





DAS (Distributed Acoustic Sensing)

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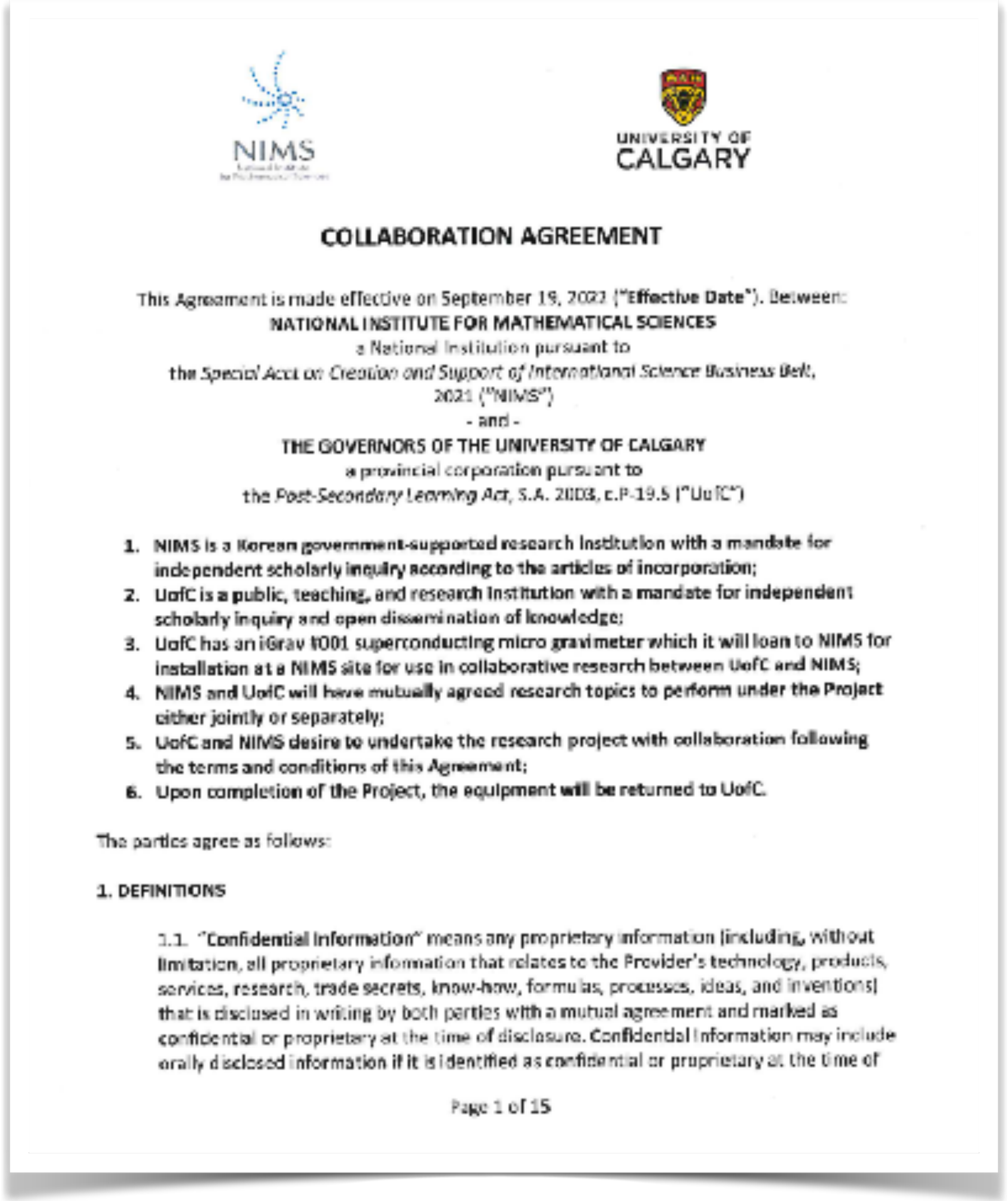
μGICK Project



NIMS

UNIVERSITY OF CALGARY

COLLABORATION AGREEMENT

This Agreement is made effective on September 19, 2022 ("Effective Date"). Between:
NATIONAL INSTITUTE FOR MATHEMATICAL SCIENCES
a National Institution pursuant to
the *Special Act on Creation and Support of International Science Business Belt*, 2021 ("NIMS")
- and -
THE GOVERNORS OF THE UNIVERSITY OF CALGARY
a provincial corporation pursuant to
the *Post-Secondary Learning Act*, S.A. 2003, c.P-19.5 ("UofC")

1. NIMS is a Korean government-supported research institution with a mandate for independent scholarly inquiry according to the articles of incorporation;
2. UofC is a public, teaching, and research institution with a mandate for independent scholarly inquiry and open dissemination of knowledge;
3. UofC has an iGrav #001 superconducting micro gravimeter which it will loan to NIMS for installation at a NIMS site for use in collaborative research between UofC and NIMS;
4. NIMS and UofC will have mutually agreed research topics to perform under the Project either jointly or separately;
5. UofC and NIMS desire to undertake the research project with collaboration following the terms and conditions of this Agreement;
6. Upon completion of the Project, the equipment will be returned to UofC.

The parties agree as follows:

1. DEFINITIONS

1.1. "Confidential Information" means any proprietary information (including, without limitation, all proprietary information that relates to the Provider's technology, products, services, research, trade secrets, know-how, formulas, processes, ideas, and inventions) that is disclosed in writing by both parties with a mutual agreement and marked as confidential or proprietary at the time of disclosure. Confidential Information may include orally disclosed information if it is identified as confidential or proprietary at the time of

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Yemilab-Proposal-2022-

Letter of Intent

Title: Study of Micro-Gravity Signals using Superconducting Gravimeter (iGRAV)

Name, Institution: National Institute for Mathematical Sciences (Address: 70 Yuseongdaero 1689beon-gil, Yuseong-gu, Daejeon, Korea)

Abstract:

We propose to install and operate the superconducting gravimeter, iGrav in YemiLab, and to measure the gravity change induced by various seismic activities including earthquake ruptures. Apart from static gravity changes generated by mass redistribution induced by earthquakes, transient gravity signals in principle are expected at all distances during the earthquake ruptures before the arrival of seismic waves. However, the seismic noise background often limits the ability to detect such transient gravity signals. It is required to operate the iGrav in a low-noise environment. An underground facility such as YemiLab can provide excellent low-noise conditions to maximize the chance to detect the transient gravity.
In addition, measurement of the gravity fields underground can provide very important information to model the gravity noise and reduce it for the future underground gravitational wave detector such as the Einstein Telescope. The proposed experiment includes 1) background microgravity which is induced by various seismic activities around YemiLab 2) monitoring microgravity signals pre-, co-, and post-seismic activities 3) measurement of elasto-gravity signals excited by earthquakes. After successful installation, we start calibration of the iGrav using an absolute gravimeter in late September 2022. From October to November 2022, engineering operations will be carried out in order to obtain initial data to determine environmental correction. Then we will conduct continuous gravity measurements from Dec 2022 to the End of 2025 with minimal intervention for maintenance purposes.

- The GReAT has focused on the EED using Superconducting Gravimetry & Gradiometry
- 2021. 11. 13 - Prof. Jeong Woo Kim's invitation: Micro-gravity lecture
- 2022. Feb. Discussion with Prof. JWK for installation of iGRAV in Korea
- 2022. Mar. Yemi Underground Lab Seriously considered
- 2022. May - IBS presentation for CUP-Yemilab application
- 2022. Jun. - IBS Application approved
- 2022. Aug. - Construction started / 2022. Sep. - Construction finished
- 2022. Sep. 26 - MoU btw NIMS-Univ. of Calgary signed
- 2022. Sep. 30-Oct.3 - iGrav shipped (from Calgary to Yemi)
- 2022. Oct. 4 - 16 - iGrav installation
- 2022. Oct. 27 - Inauguration ceremony of YeMiGO (Yemi Micro-Gravity Observatory)
- 2022. Oct. 16 - Nov. 15 - Engineering Run
- 2022. Nov. 16 - GNSS installed / Official Observation Run Started

μGICK Project

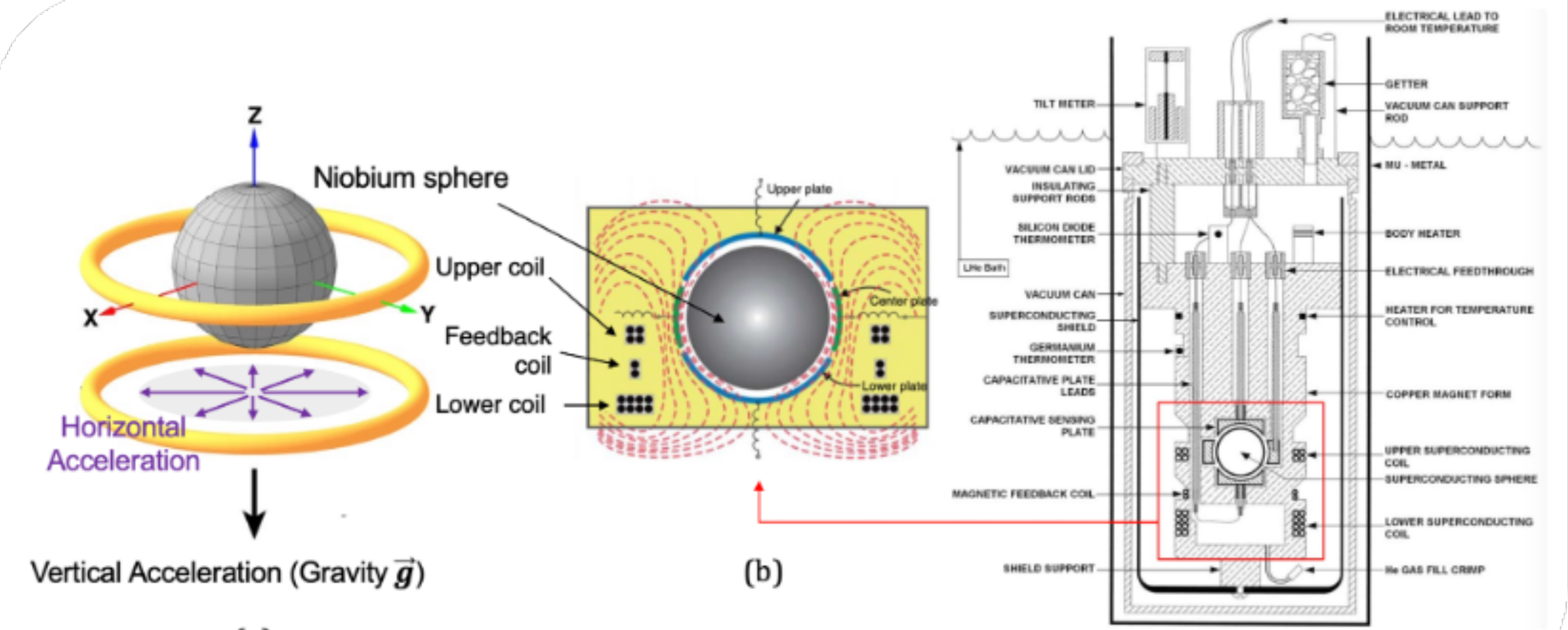
SG: Superconducting Gravimeter

Measuring relative gravity using magnetic levitation of superconducting material (Nb) in 4.2K

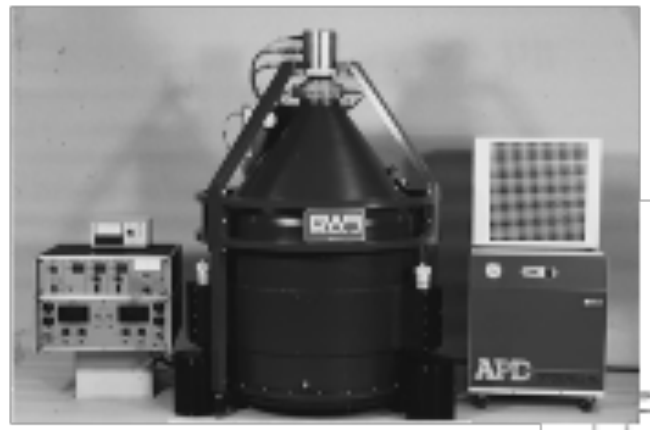
- 1 nano Gal - precision
- 0.5 micro Gal drift / month
- very stable
- steady for long duration measurement

Need a reference to convert gravity unit:

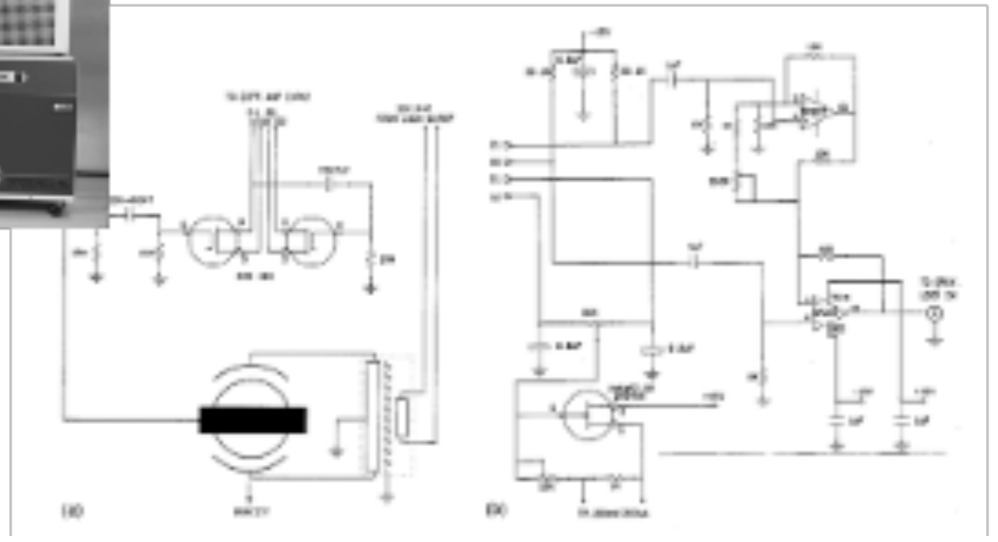
- Theoretical Earth-tide
- Absolute measurement of G (FG-5, A10 etc)
- Calibrated relative gravimeter by AG
- Scale factor : microGal/V



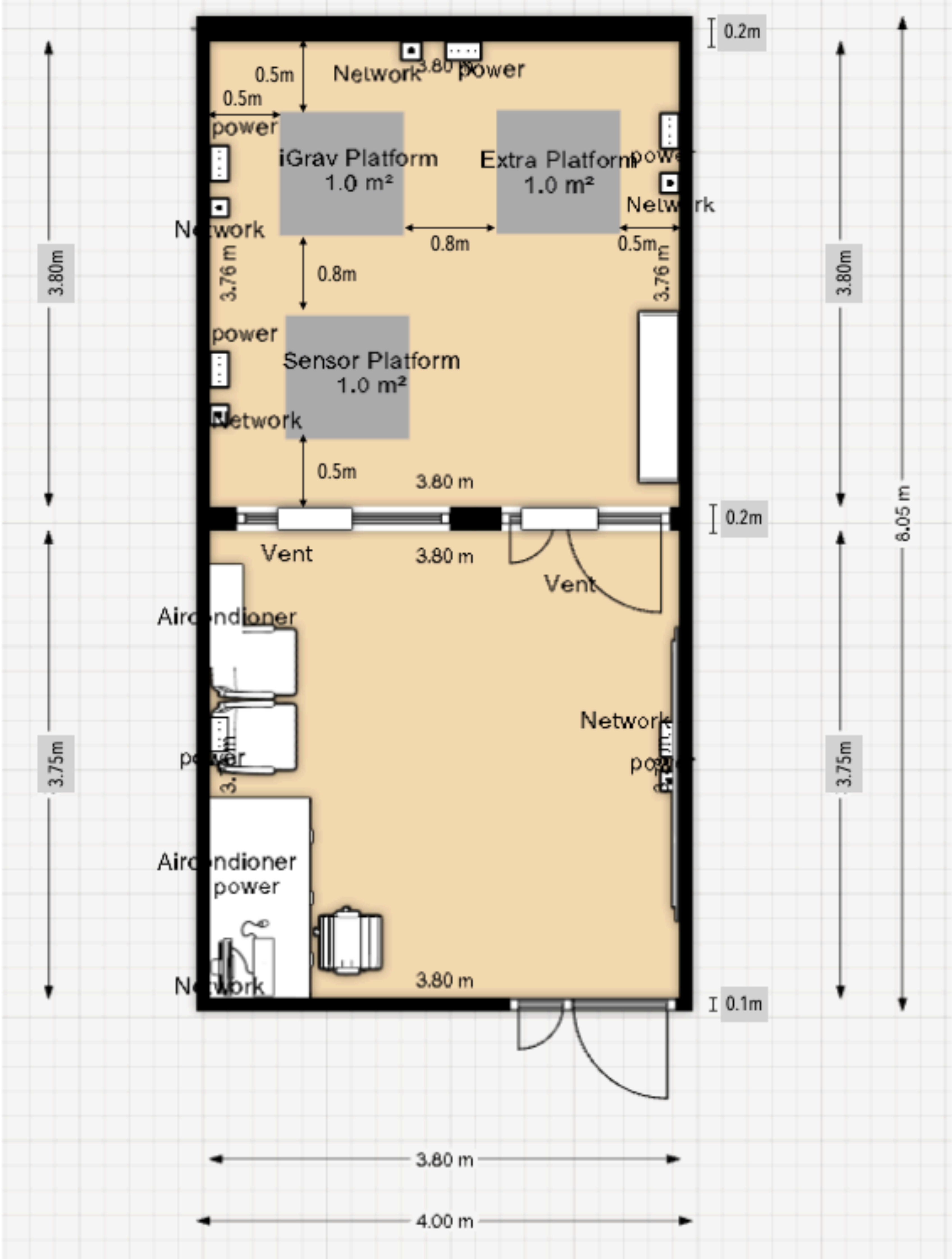
(a) (b) (c)



John M. Goodkind
(Univ. of California, San Diego)



Construction



- **Design: Two Rooms in a Lab - Sensor room / Control room**
- **Sensor room: three platforms for iGrav and other sensors**
- **Control room: monitoring, DAS server, UPS, other materials, etc**

Construction

- **Three platforms are designed: two are connected to the bedrock while the rest is not for the comparison reason**
- **An isolated booth was built to control the temperature and dust in the tunnel**
- **Typical temp: 26-33$^{\circ}C$ and humid: 30-50%**
- **Compressor room: all compressors are maintained in a room with ventilation and air-conditioning systems**

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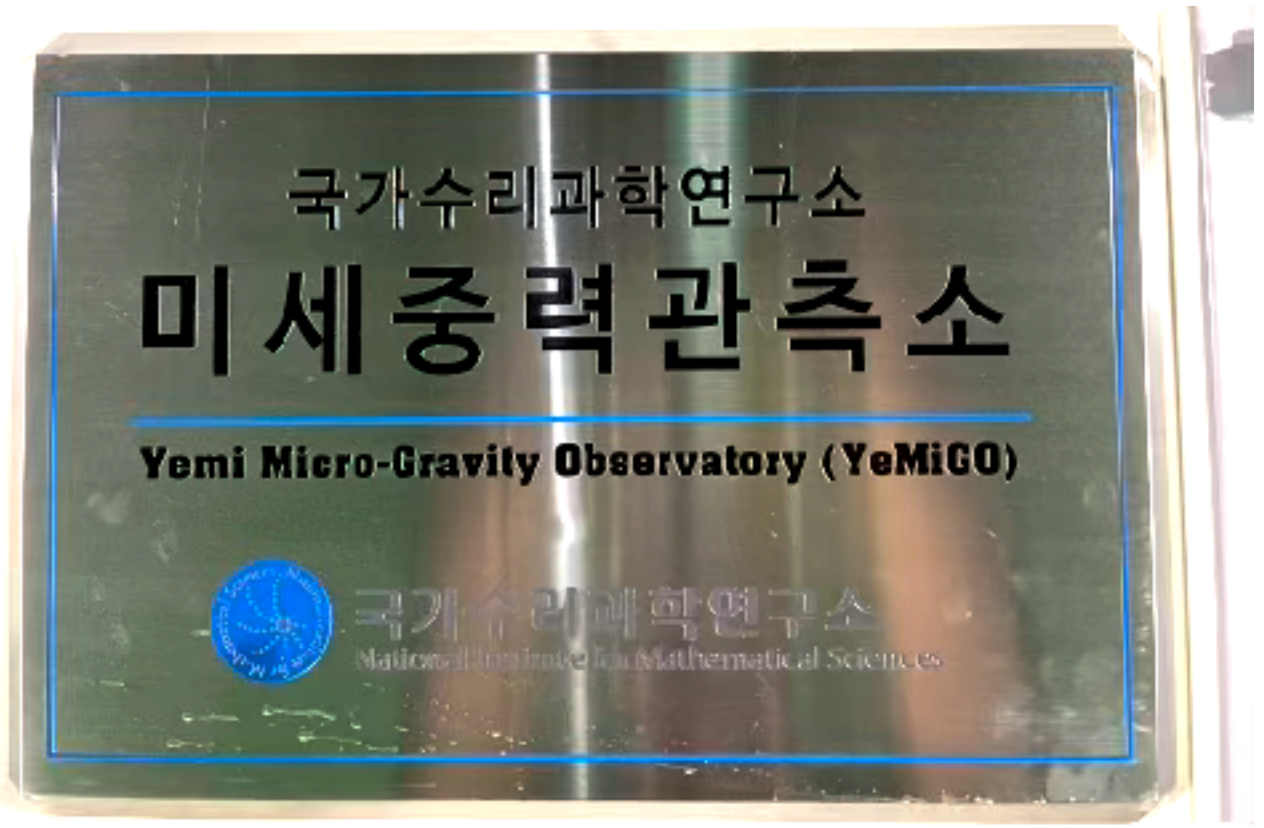
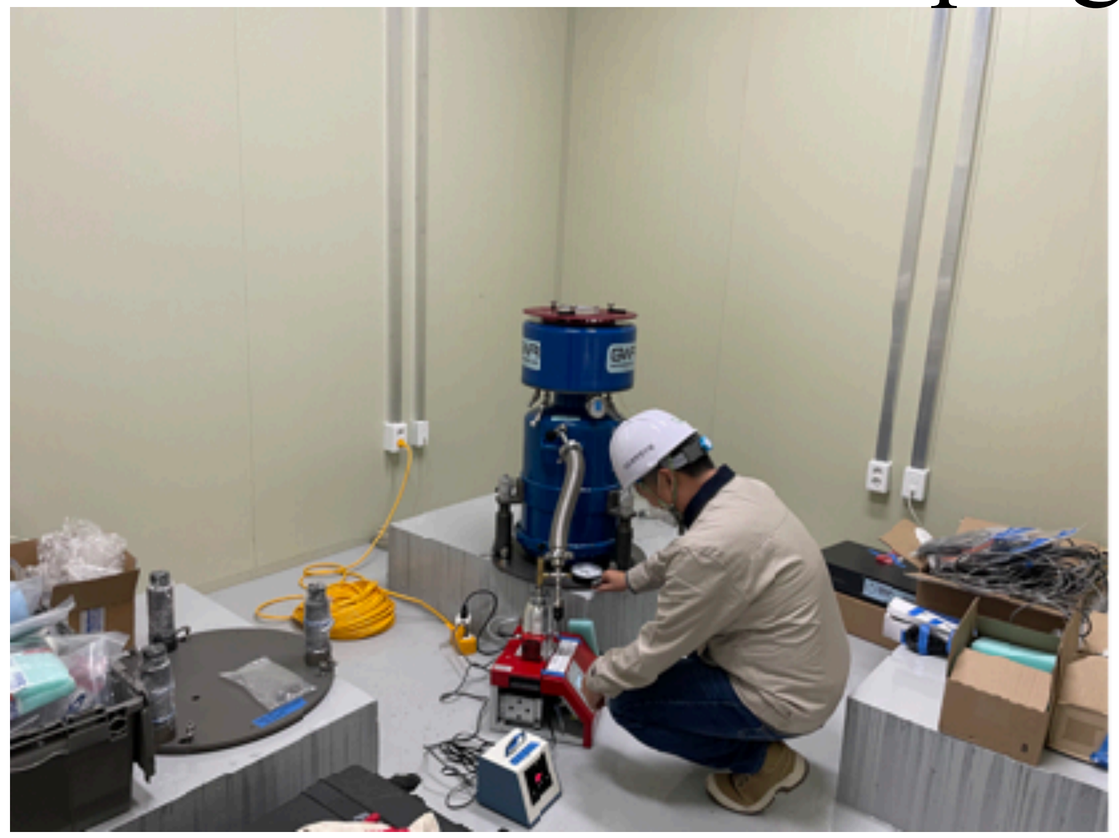
YeMiGO: Installation & Construction (2022.10-11)

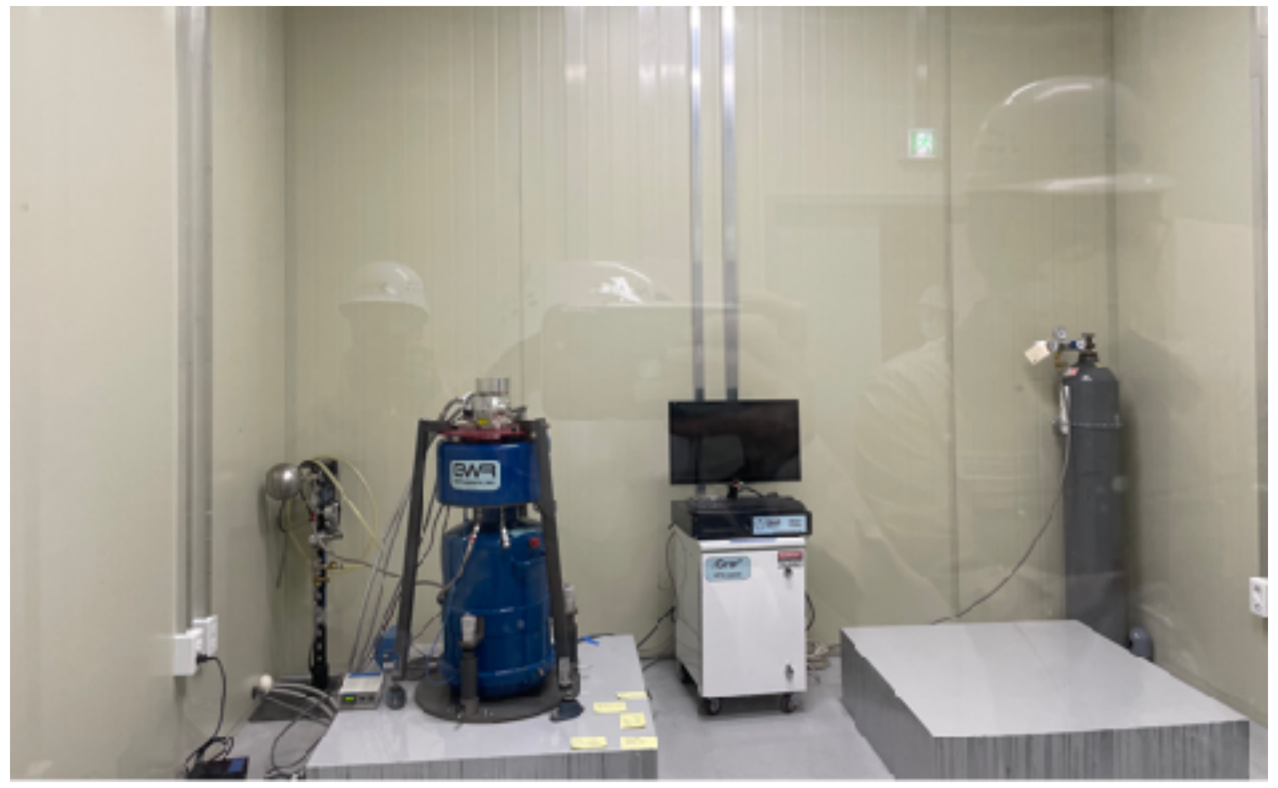


NIMS inauguration (2022.11)

Dewar Vacuum Pumping

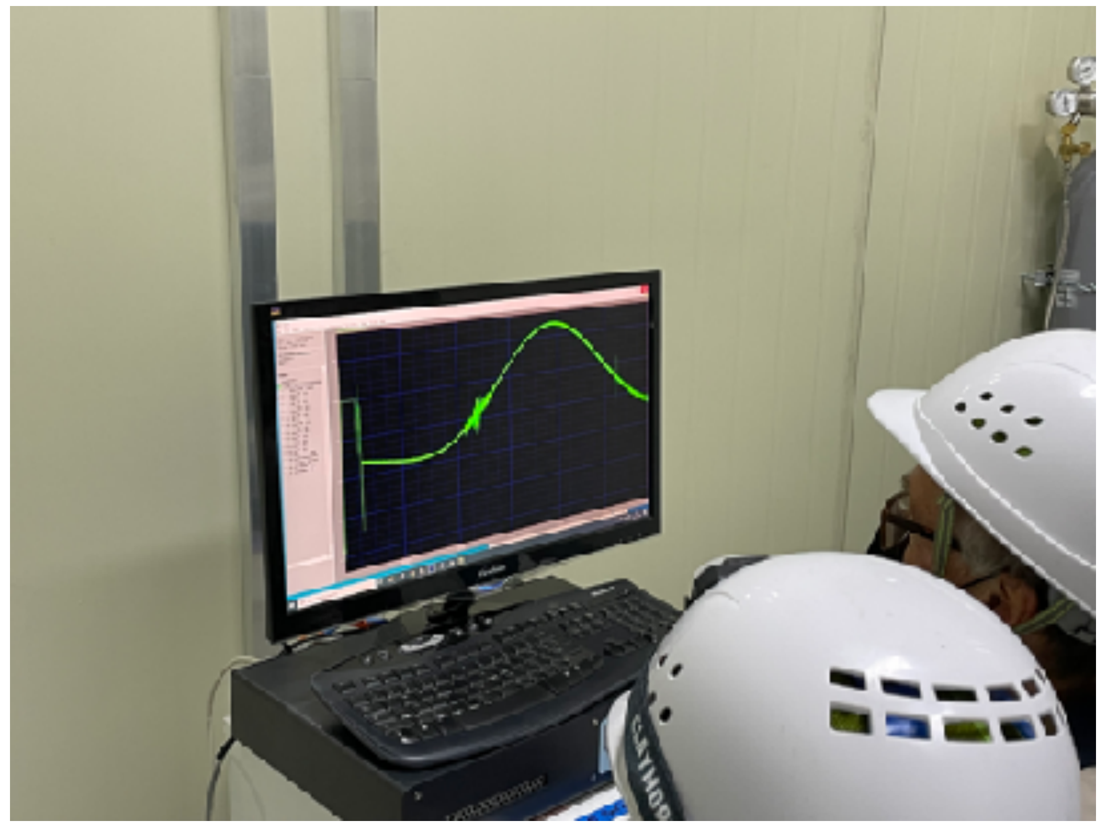


LHe supply

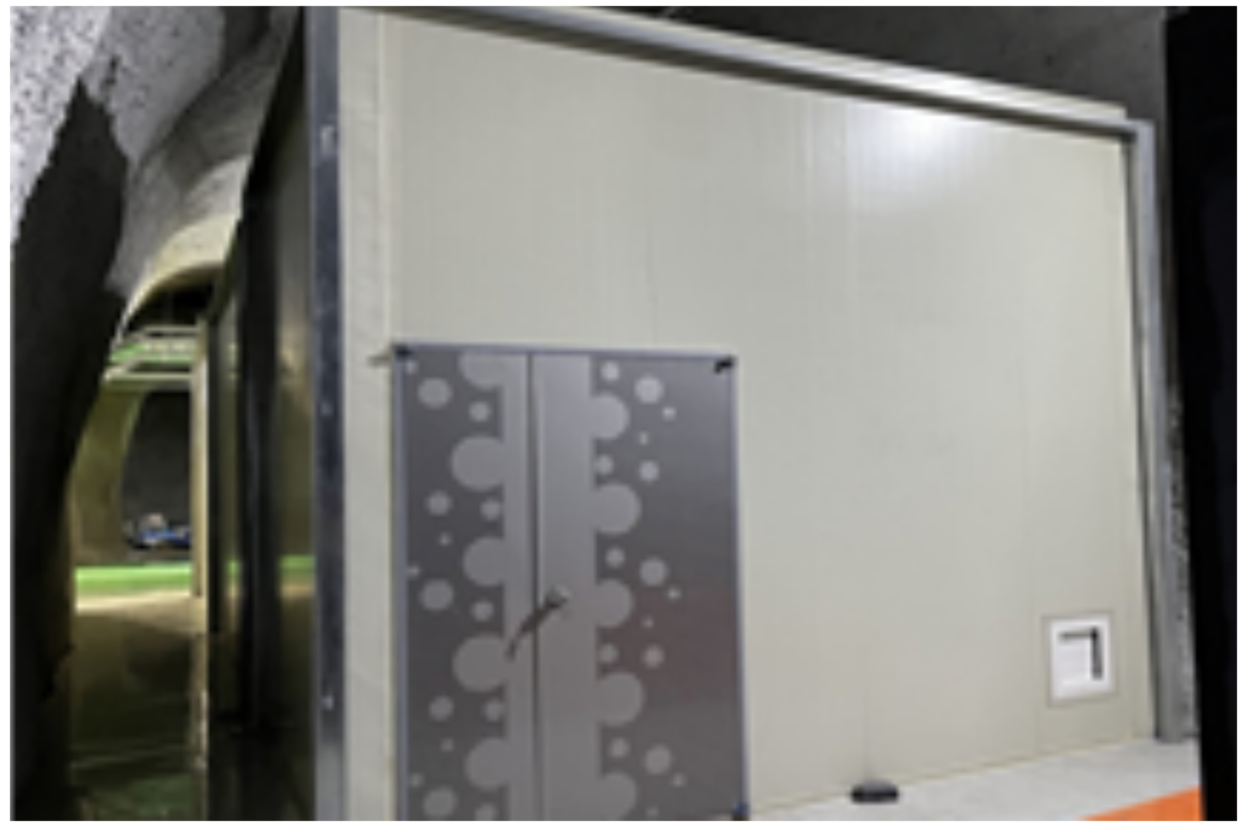


Operation Starts (2022.11.16)

Nitrogen Liquify



1st Tide signal



2nd Lab building
for compressor

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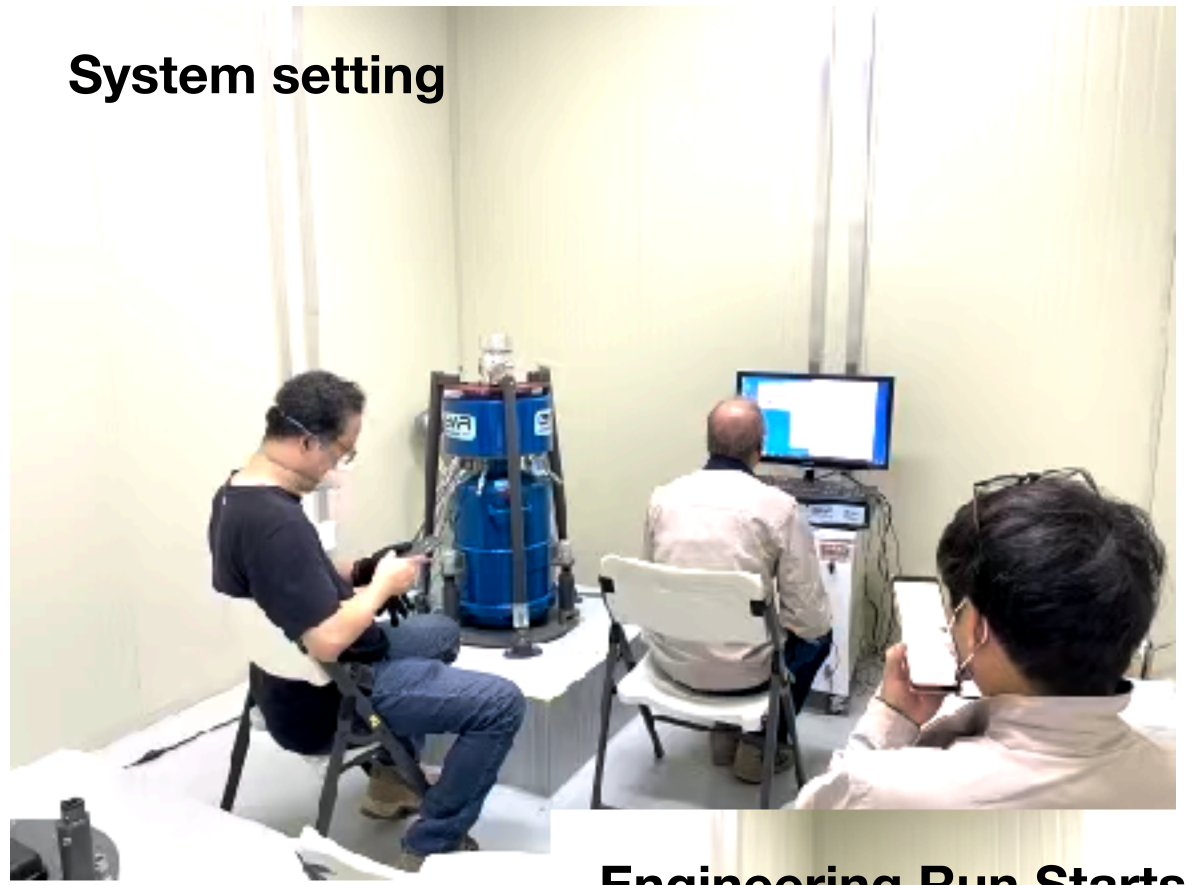
Installation & Engineering Run

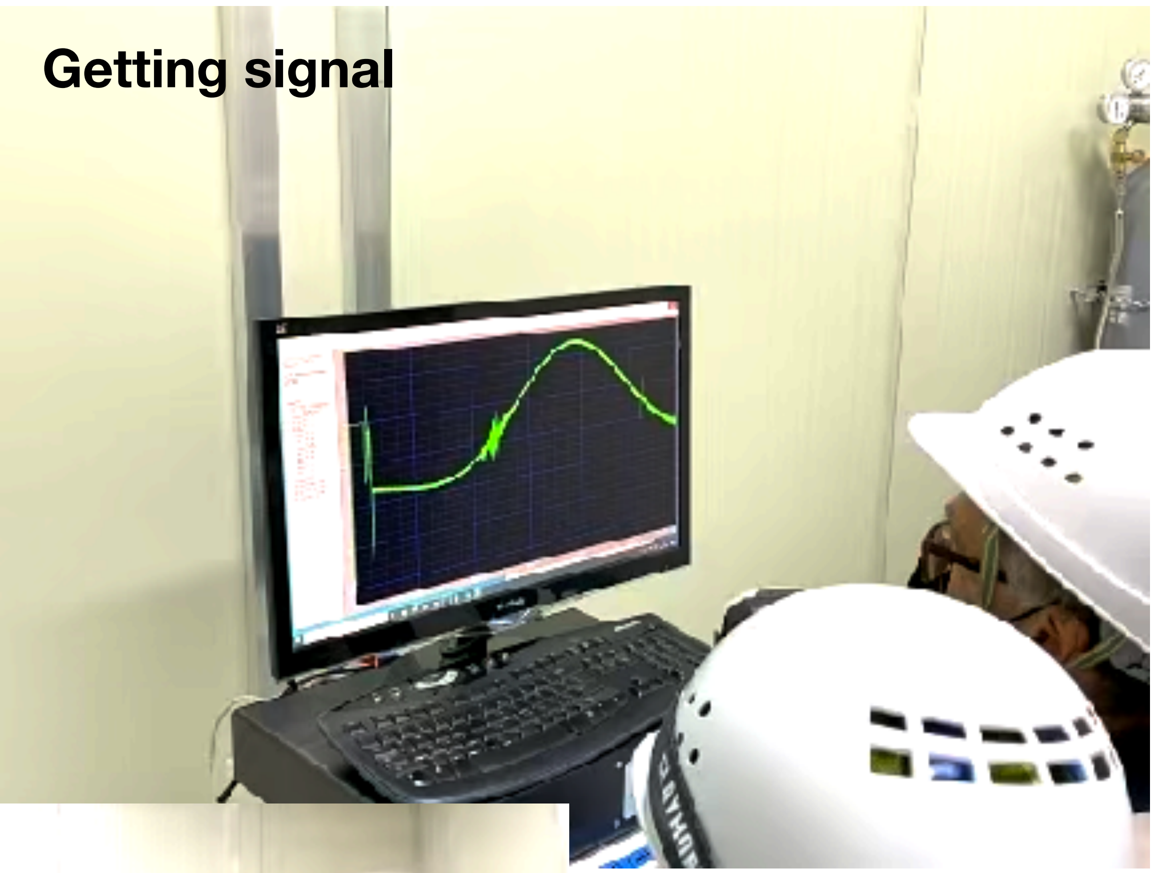
GNSS system installed

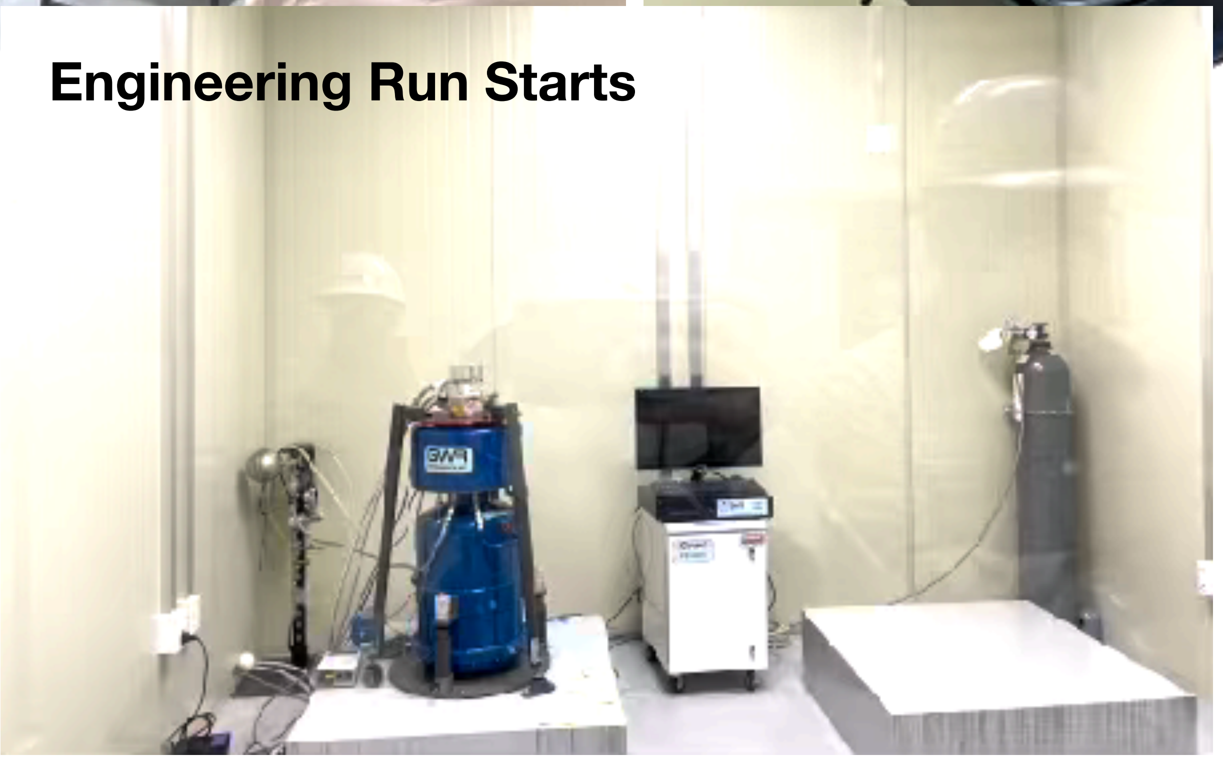
- All installations have been completed excluding the GNSS antenna signal
- The GNSS system was installed on 16th Nov. 2022
- GPS antenna has been installed near the 2nd vertical shaft - optical cable was provided by IBS-CUP, RF converter used to get a signal to iGRAV system

Installation & Engineering Run

- iGRAV installation: 2022.10.4-10.16
- Engineering Run: 2022. 10. 16 - 2022. 11. 15
- No timestamp: GNSS not installed yet


System setting

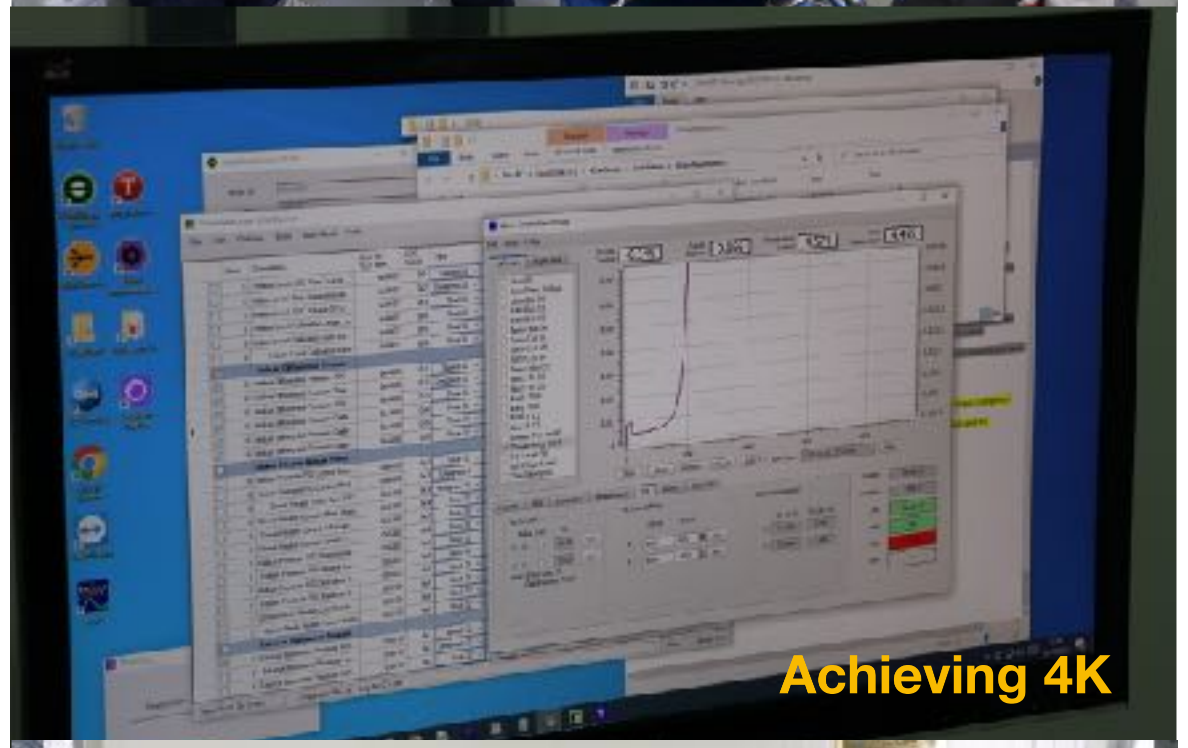

Getting signal


Engineering Run Starts


Vacuum pumping


LHe Cooling


Nitrogen Cooling

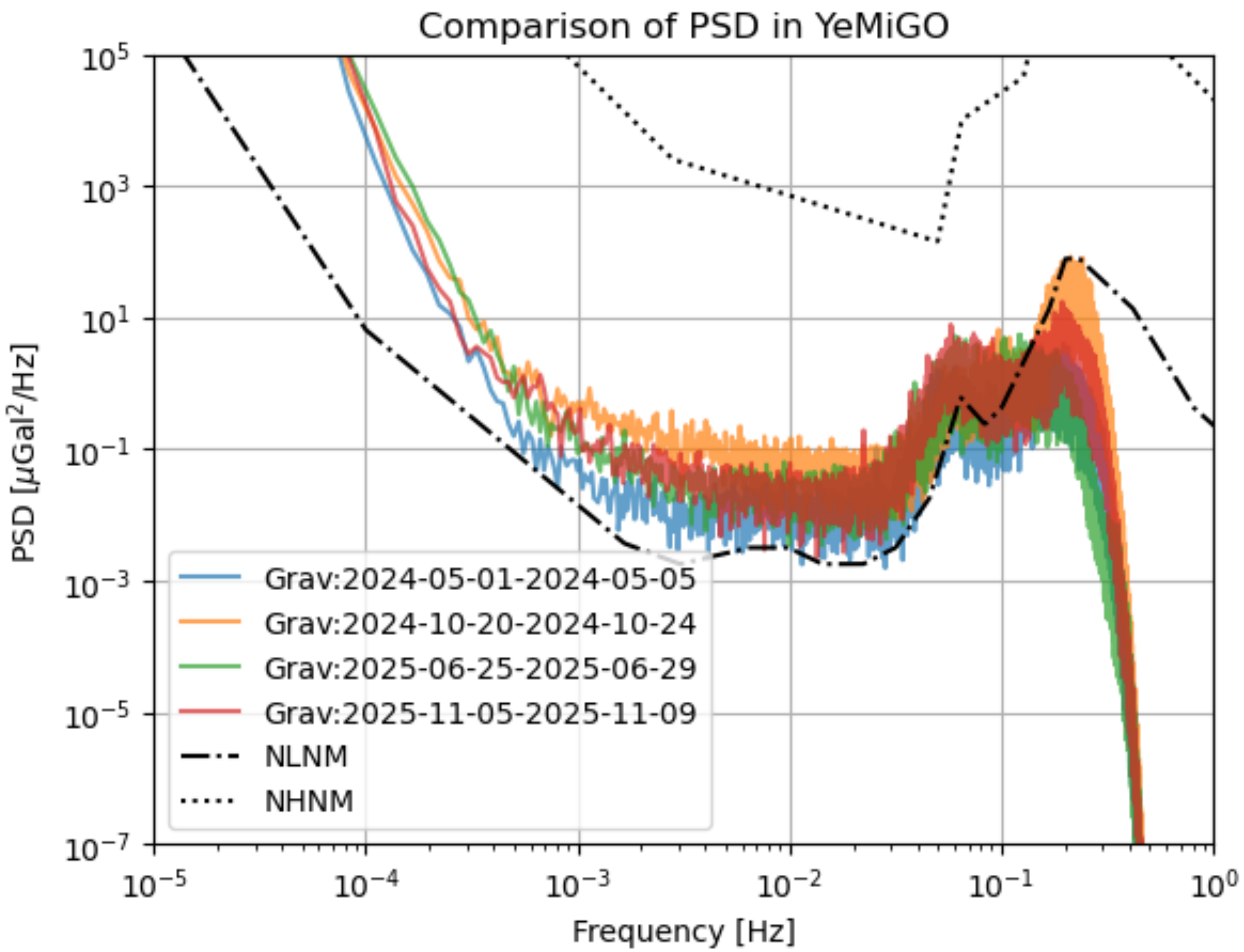

Achieving 4K


Installing Compressor Box


NIMS inauguration ceremony: Oct 27 2022

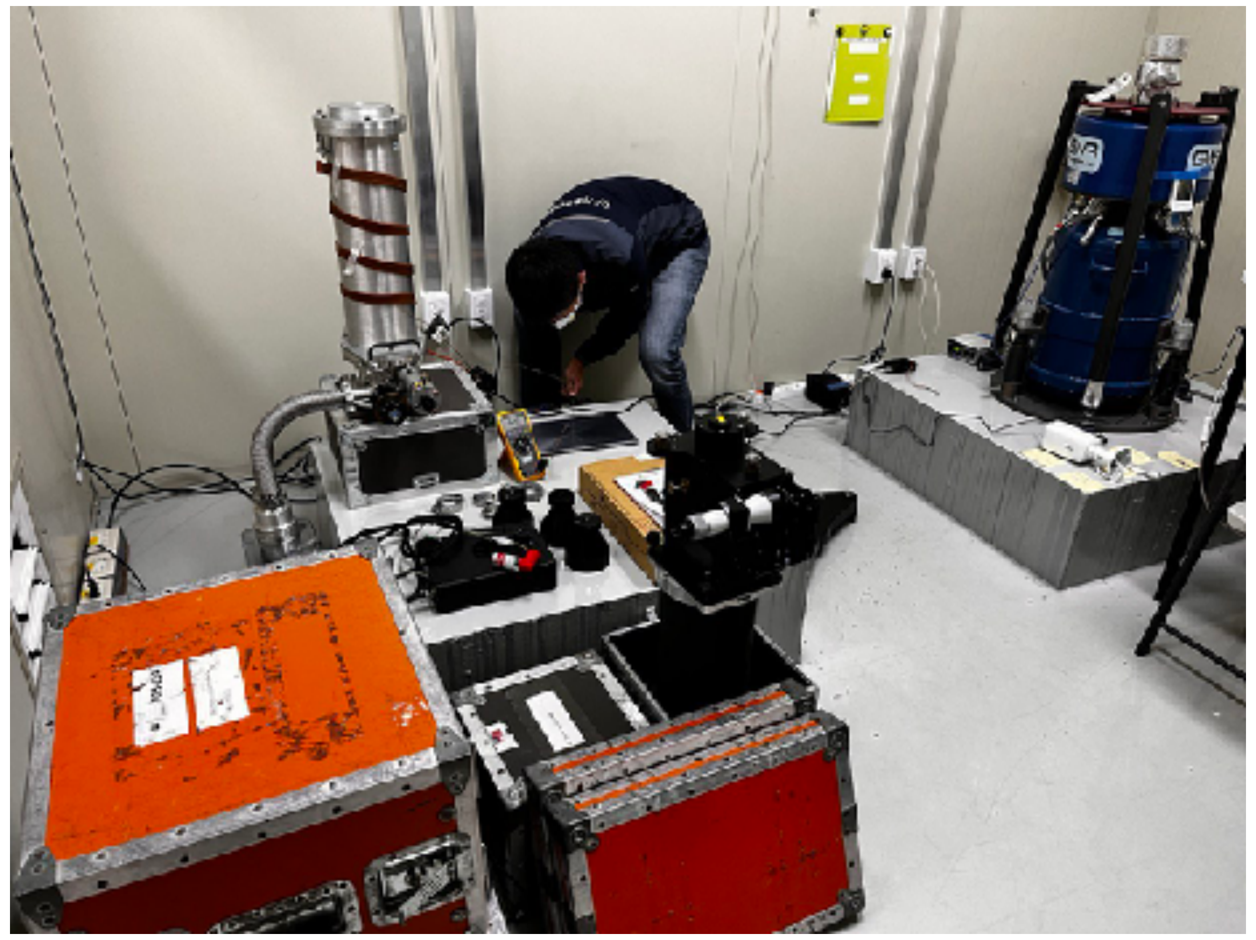
YeMiGO Status

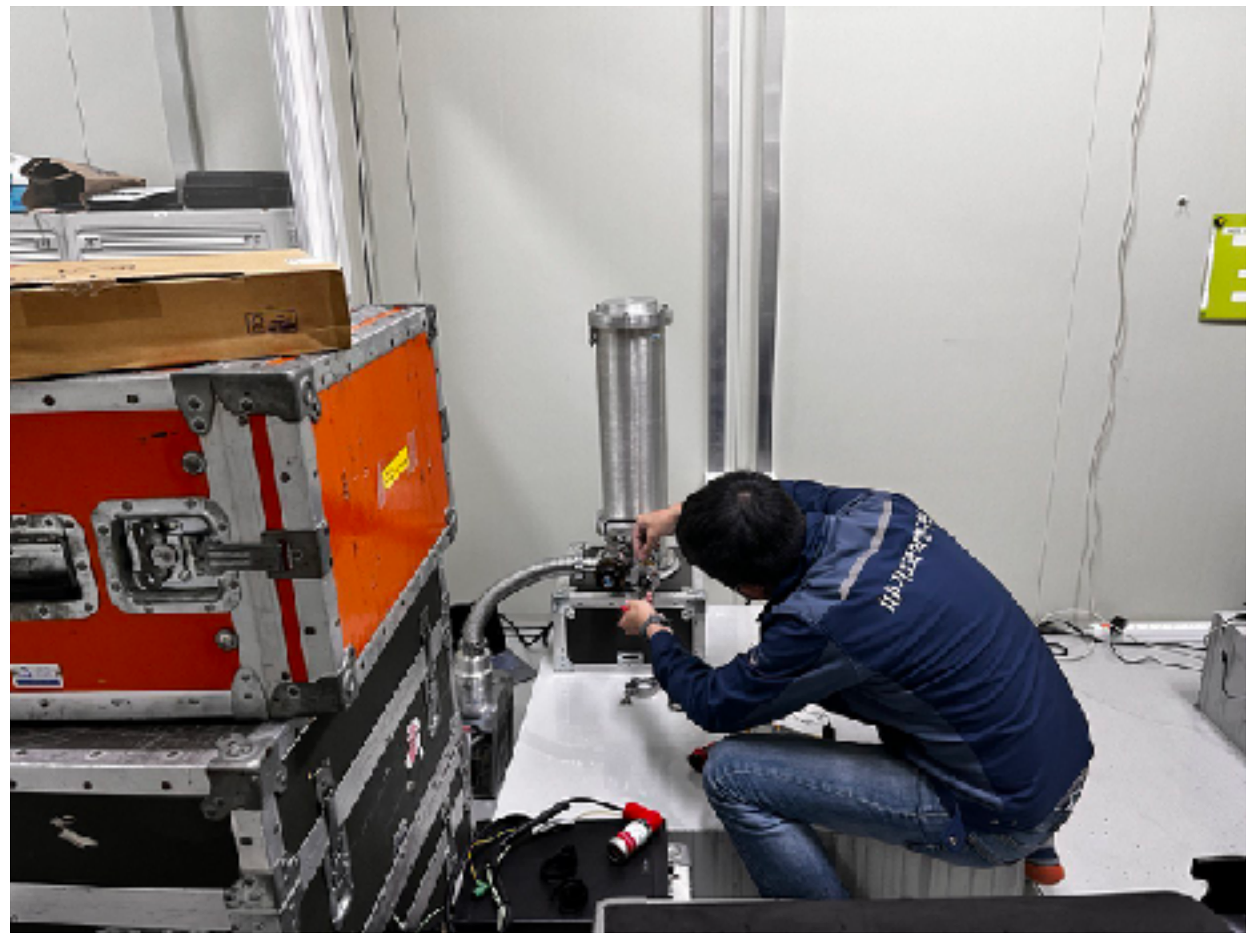
- Observation Run(ORP1): 2022. 11. 16 - 2024. 6. 25
  - OR1: 579days - Duty cycle: 98.65%
  - No data: 2022. 10. 19 - 2022. 10. 25 (Due to the malfunction of the coldhead and the DAS system, data taking is stopped)
- Engineering Run@Phase 2 (ERP2): 2025. 8. 30 - present
  - Due to malfunctioning of the system, iGrav was reinstalled (August 2025)
  - 1/f noise in 10^{-4} ~ 10^{-2} band
  - Decreased so far

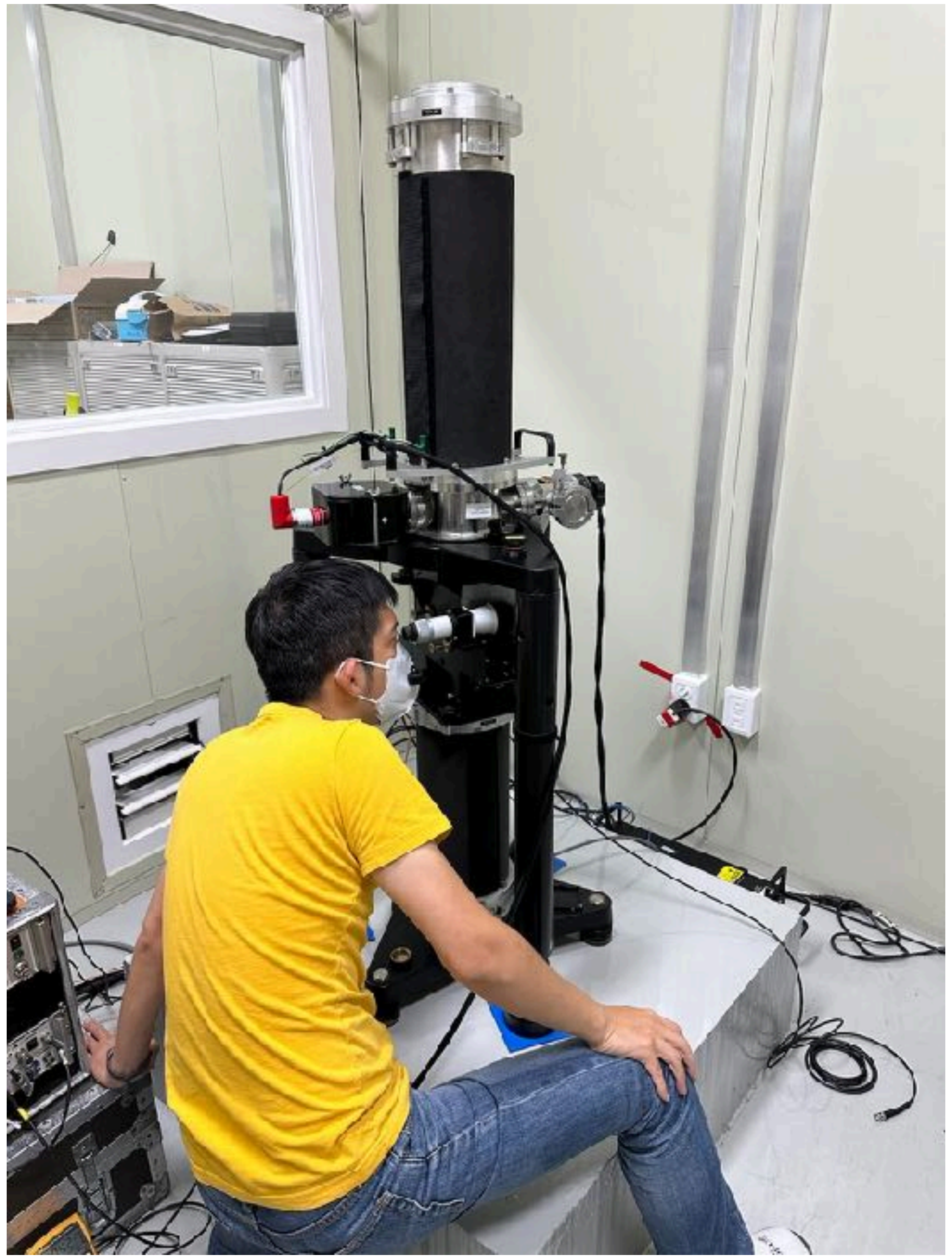


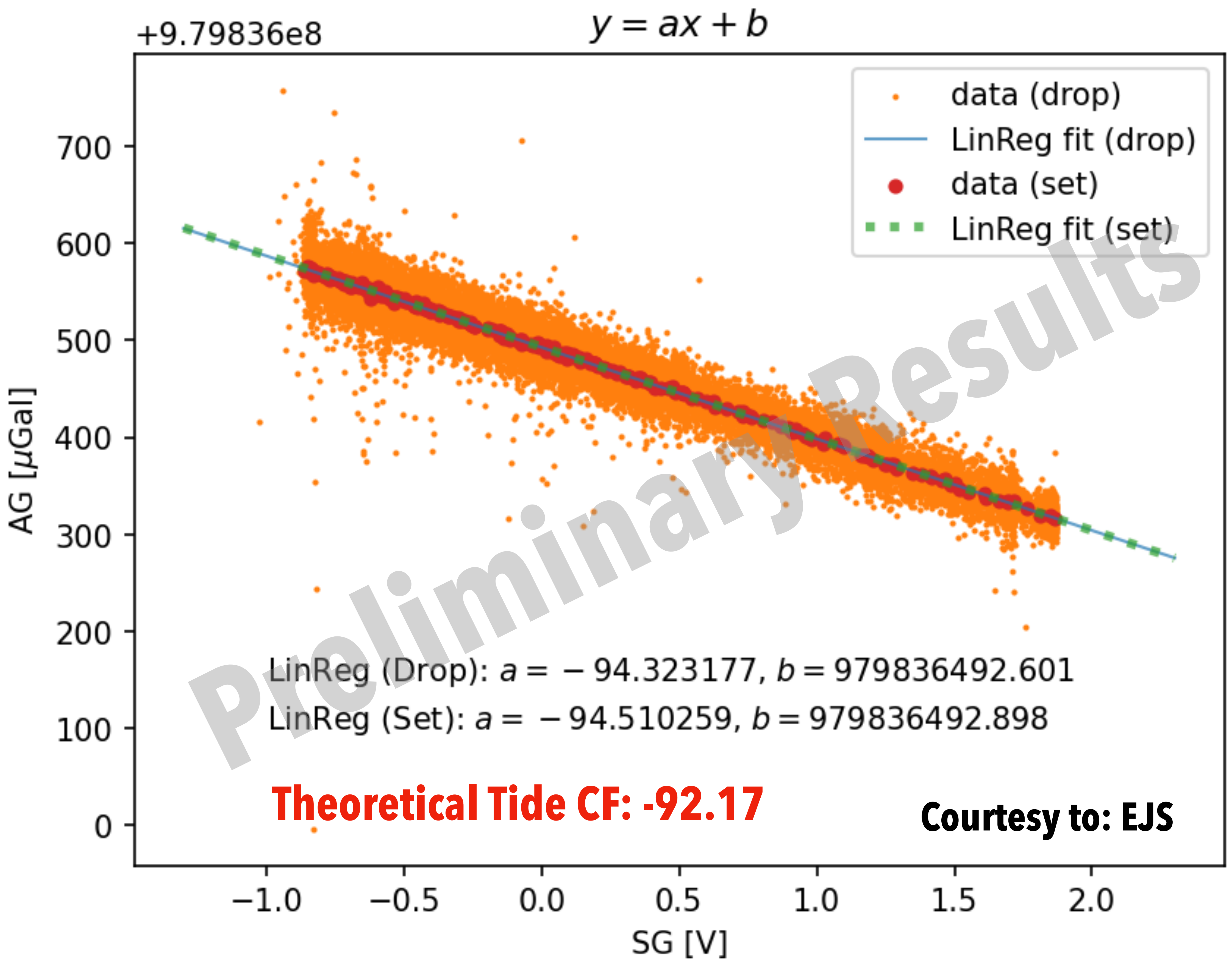
Absolute Gravity Measurement Campaign

- For calibration factor of iGrav (2023.11.9-2023.11.14)
- Thanks to: Prof. Hwang, Cheng, and Nicky Hsieh (ITRI)









Correction & Calibration for Residual Gravity

$$g_{Obs} = g_{Tide} + g_{Ol} + g_{Pol} + g_{Atm} + g_{Hyd} + g_{Dis} + g_{Res}$$

g_{Tide} Earth Tides ~few hundred μGal

g_{Pl} Polar Motion ~1 – 3 μGal

g_{Ol} Ocean Loading ~0.1~10 μGal

g_{Atm} Atmospheric Pressure ~1~50 μGal

g_{Hyd} Hydrology

g_{Dis} Ground Vertical Displacement

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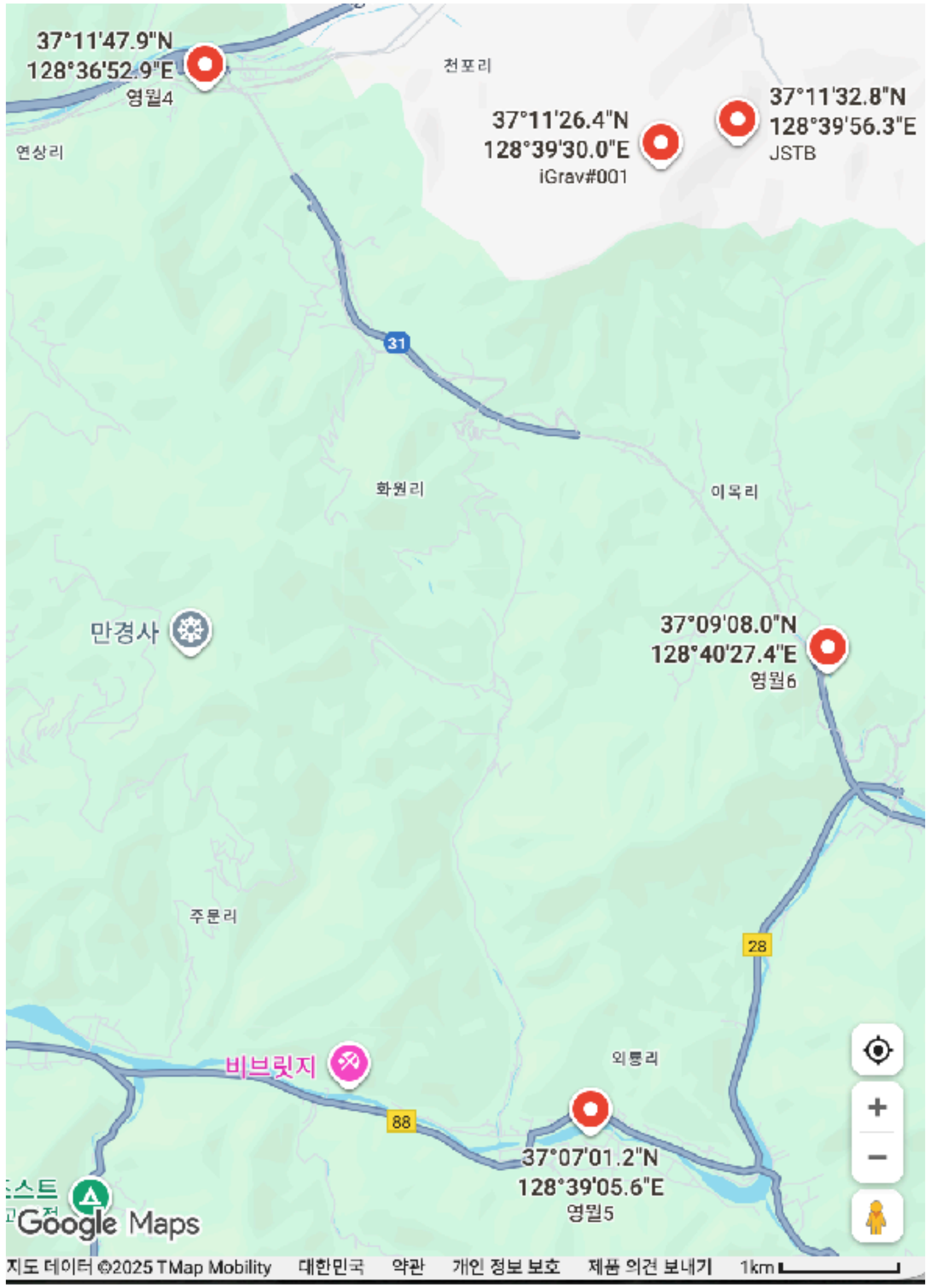

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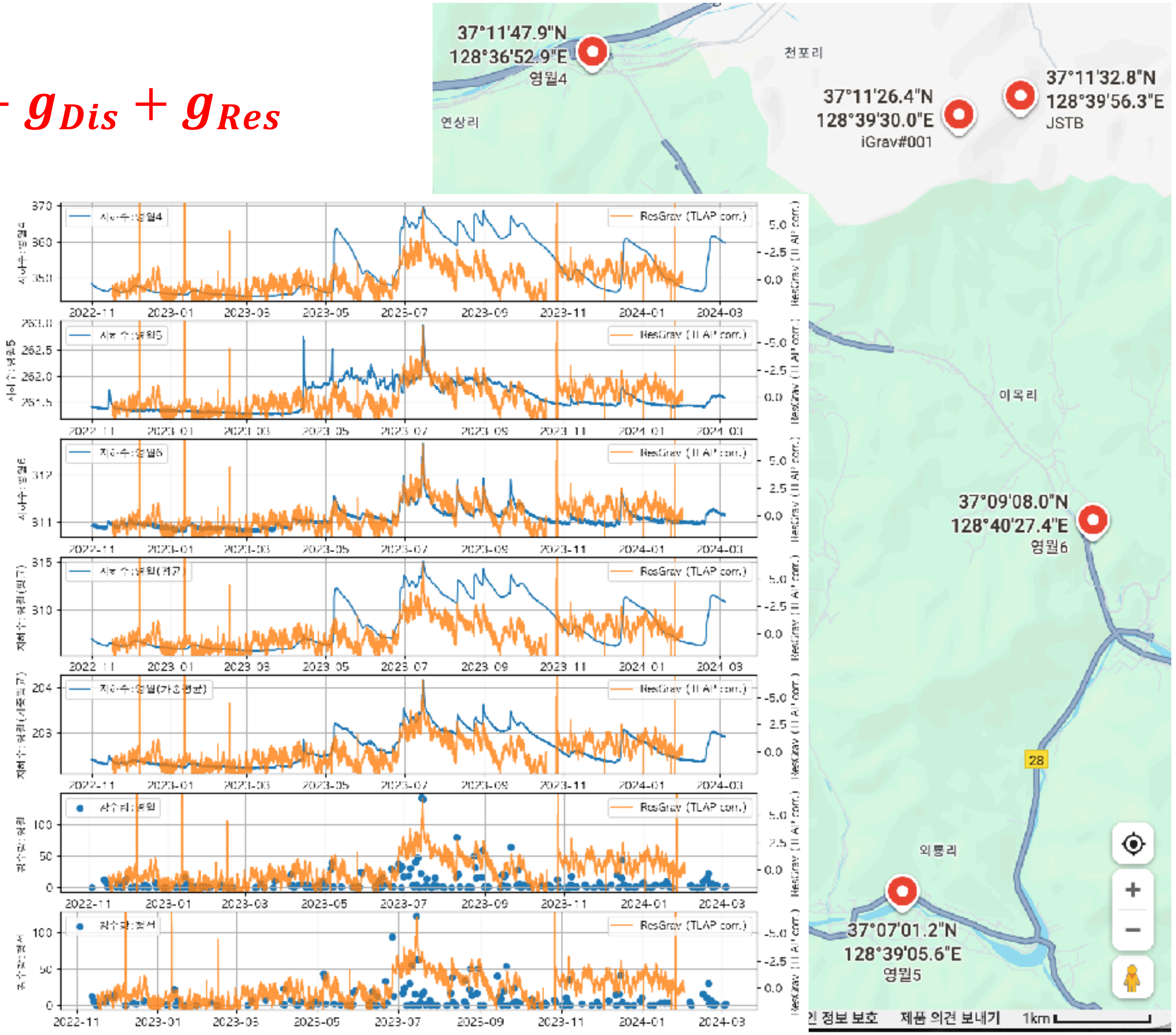

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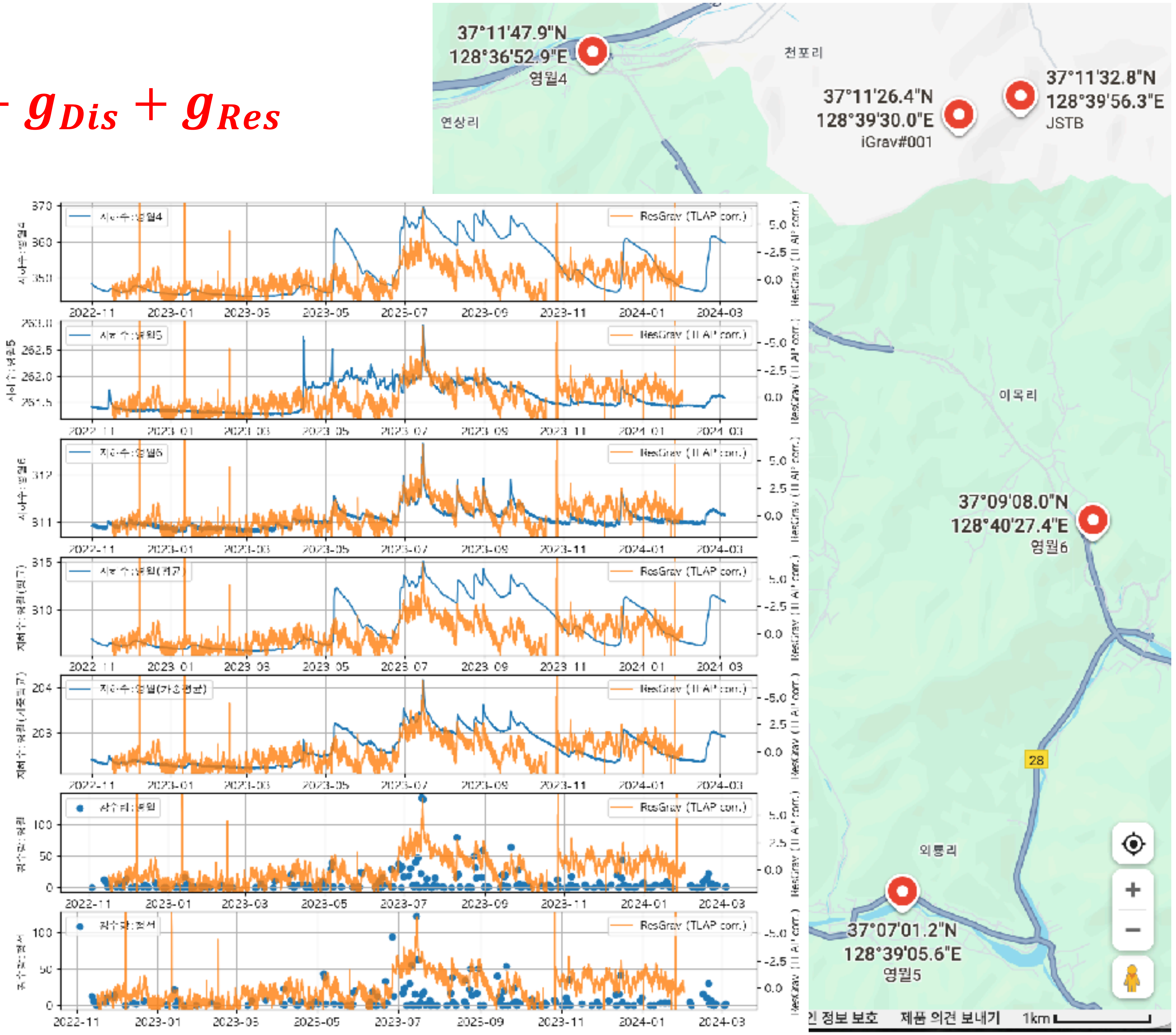

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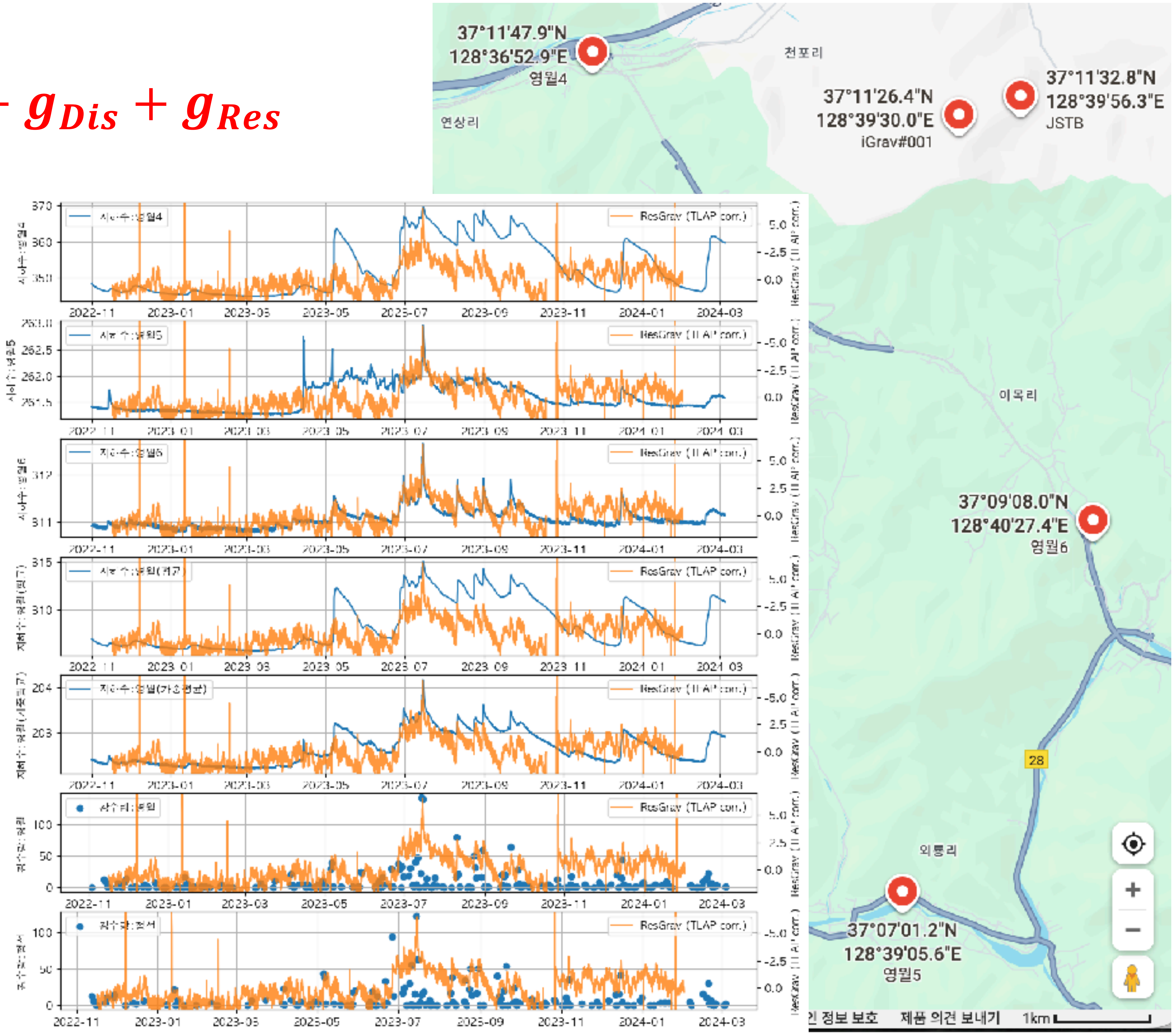

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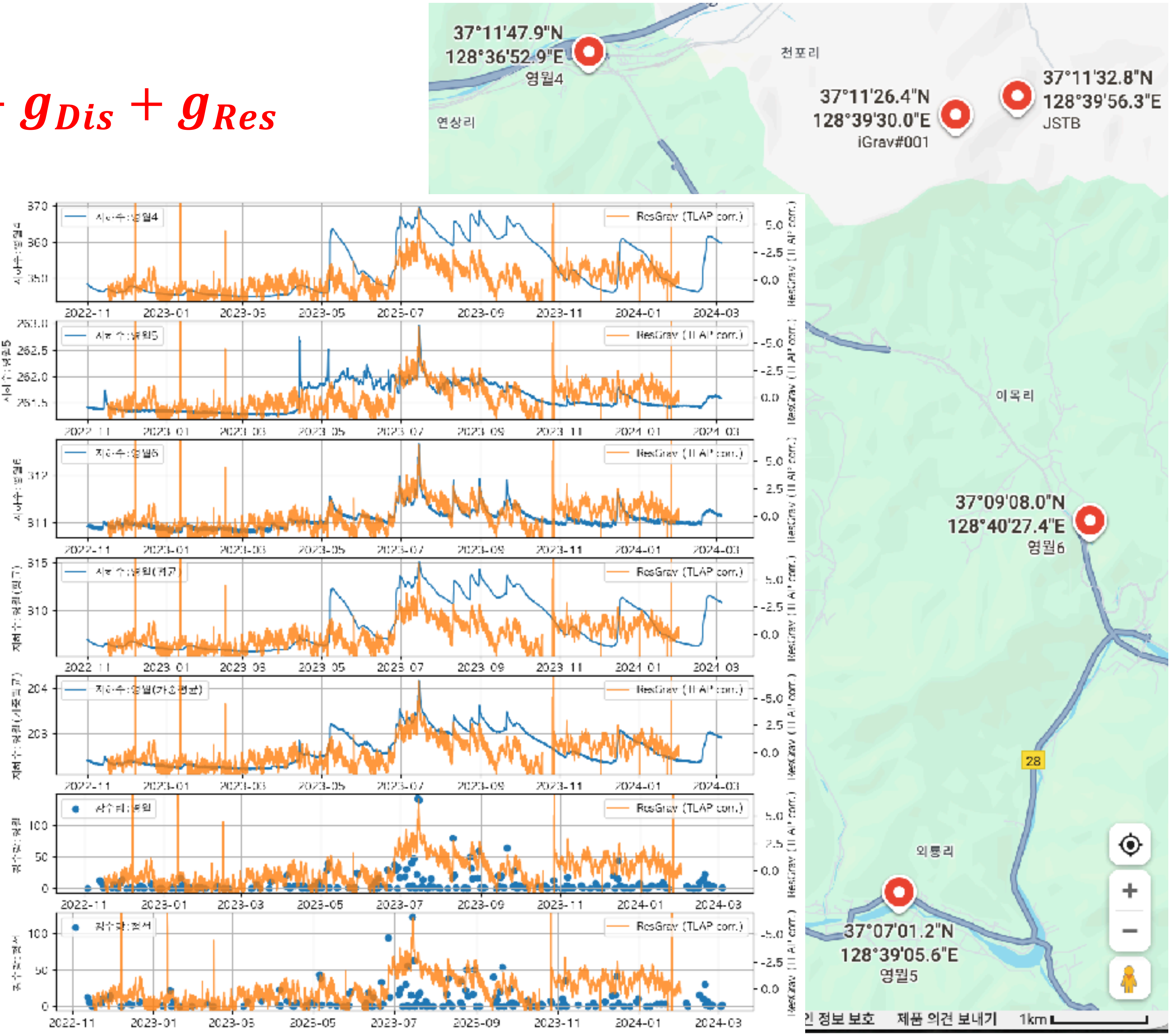
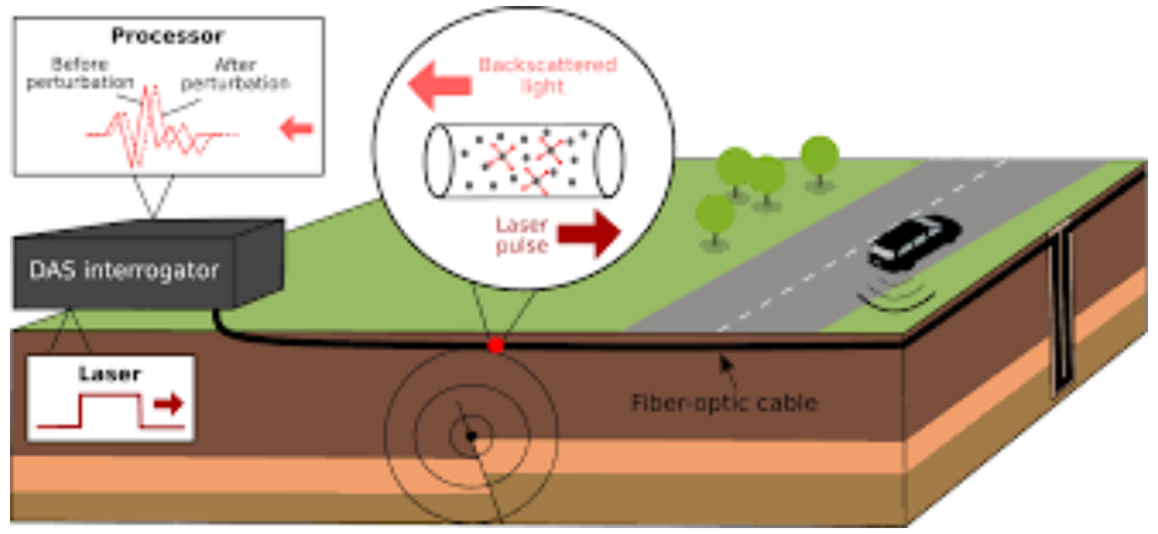
- ✔ g_{Tide} Earth Tides ~few hundred μGal
- ✔ g_{Pl} Polar Motion ~1 – 3 μGal
- ✔ g_{Ol} Ocean Loading ~0.1~10 μGal
- ✔ g_{Atm} Atmospheric Pressure ~1~50 μGal
- 🤔 g_{Hyd} Hydrology
- 🤔 g_{Dis} Ground Vertical Displacement





DAS (Distributed Acoustic Sensing)

Extensometers

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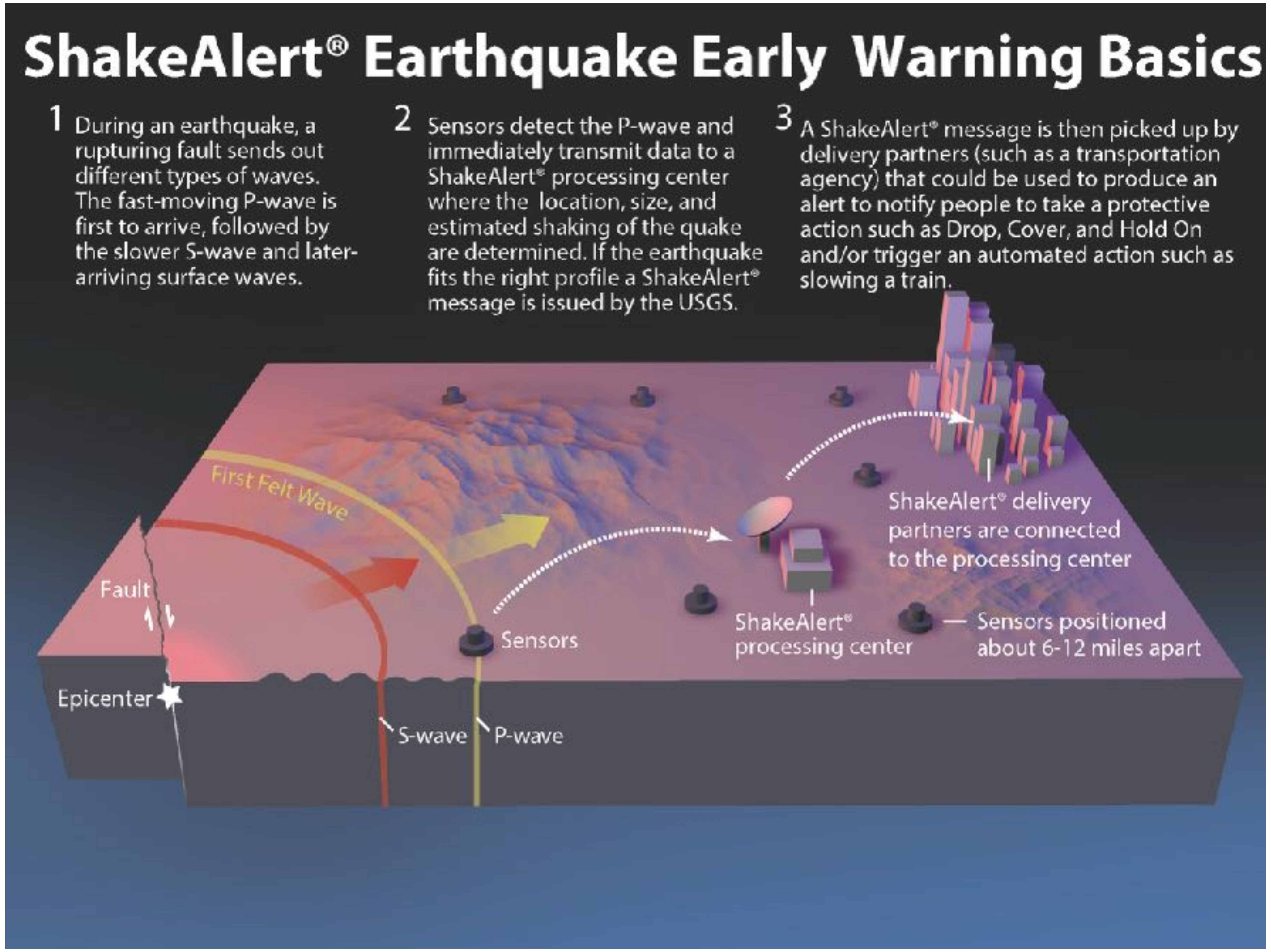
Science Case with YeMiGO

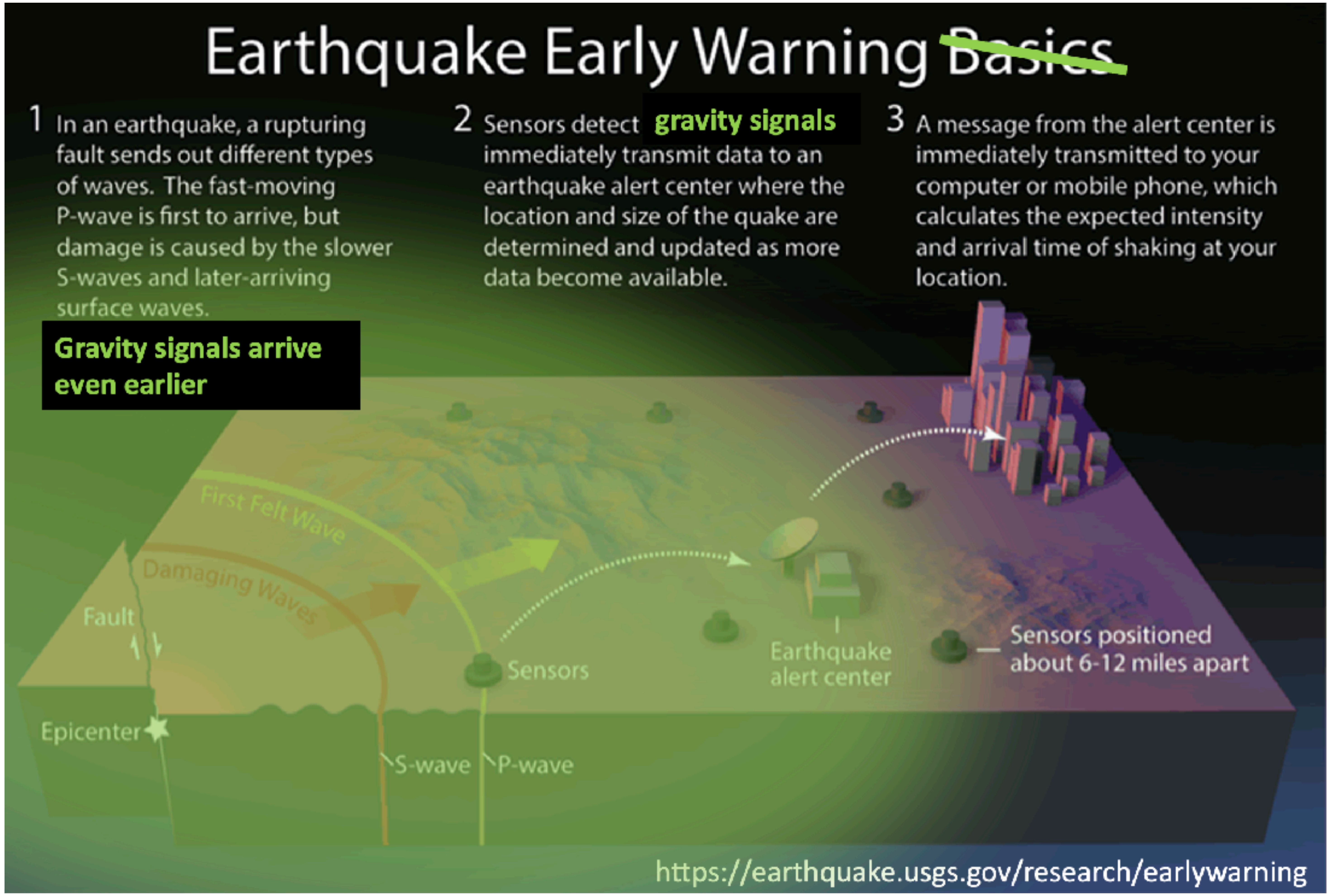
YeMiGO is the Micro-Gravity Observatory at Yemilab, located 1,008 meters beneath Mt. Yemi and 125 meters below mean sea level, and hosts the world's deepest installation of a micro-gravity sensor.

Gravity-based EQ Detection



PEGS - Gravity Change from EQ

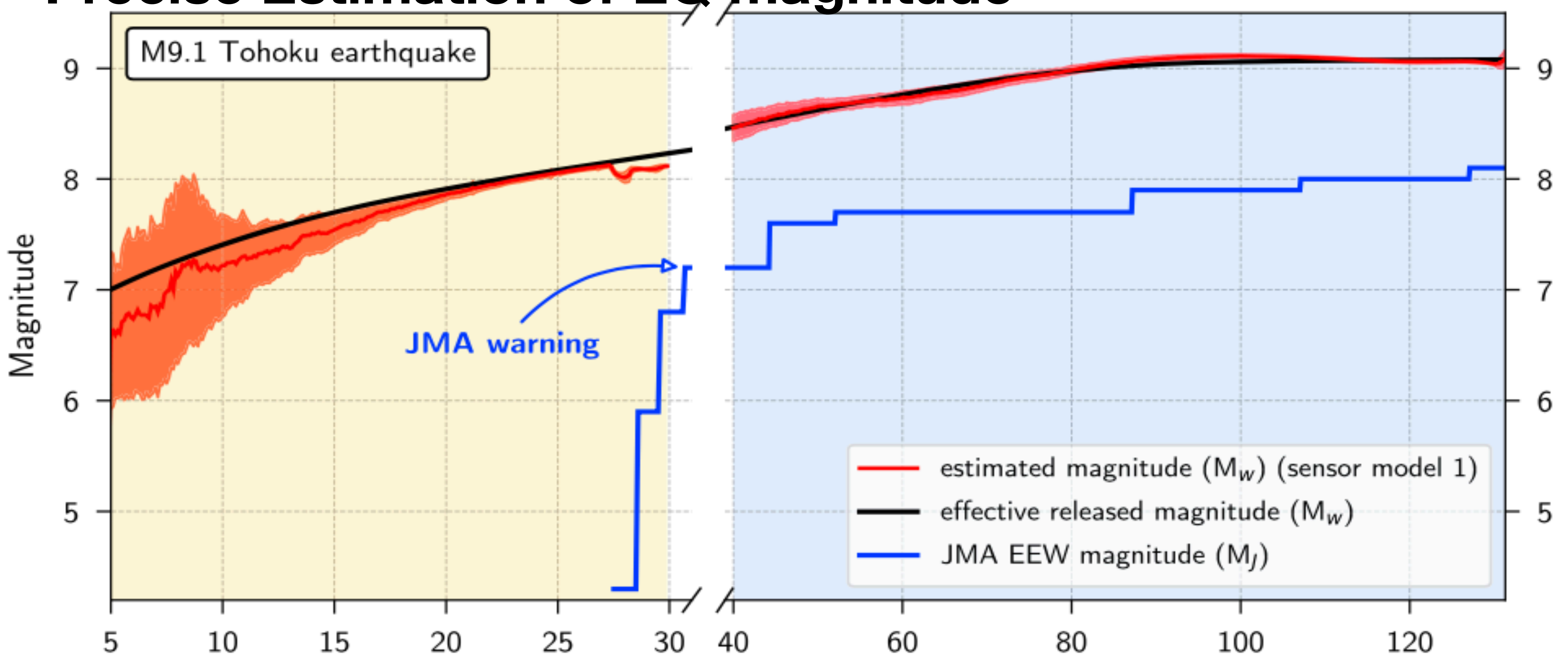
- **New Paradigm for EEW**

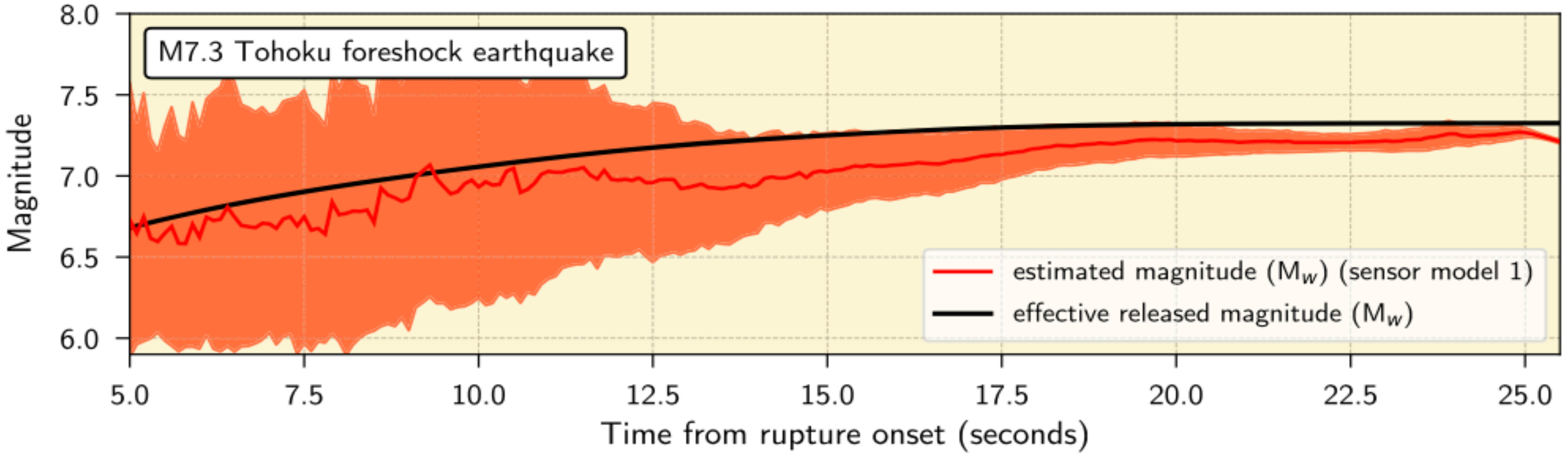


PEGS - Gravity Change from EQ

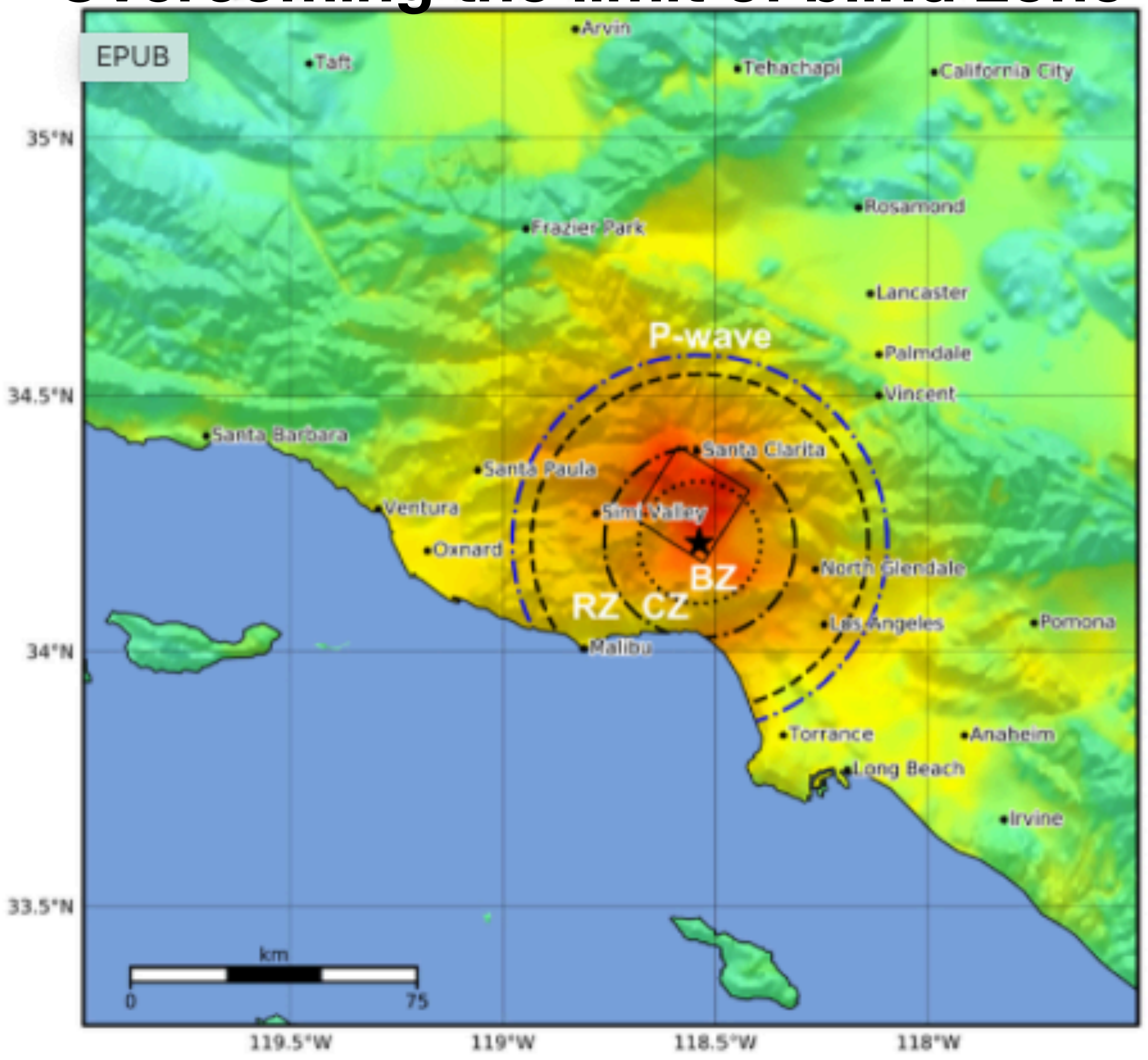
- **New Paradigm for EEW**

Precise Estimation of EQ magnitude





Overcoming the limit of blind zone



SHAKING	Not felt	Weak	Light	Moderate	Strong	Very strong	Severe	Violent	Extreme
DAMAGE	None	None	None	Very light	Light	Moderate	Moderate/heavy	Heavy	Very heavy
PGA(%g)	<0.05	0.3	2.76	6.2	11.5	21.5	40.1	74.7	>139
PGV(cm/s)	<0.02	0.13	1.41	4.65	9.64	20	41.4	85.8	>178
INTENSITY	I	II-III	IV	V	VI	VII	VIII	IX	X+

Scale based on Worden et al. (2012) Version 1: Processed 2018-11-28T21:10:02Z

△ Seismic Instrument ○ Macroseismic Observation ★ Epicenter ▭ Rupture

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PEGS - Gravity Change from EQ

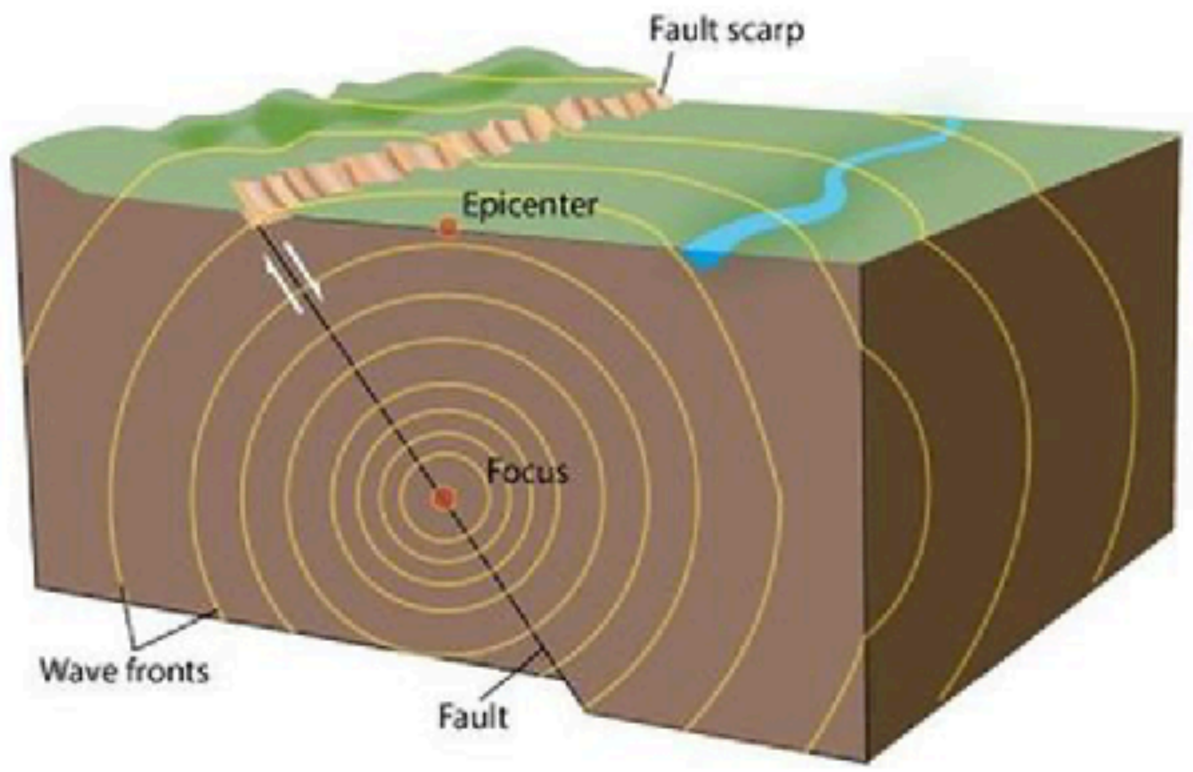
Dynamic gravity changes induced by earthquakes: basic concept

Earthquake **slip** → Direct propagation of gravity change (speed of light)

Static + **transient deformation** (seismic waves)

Density perturbations: P waves

+ deformation of material interfaces (e.g. free surface)



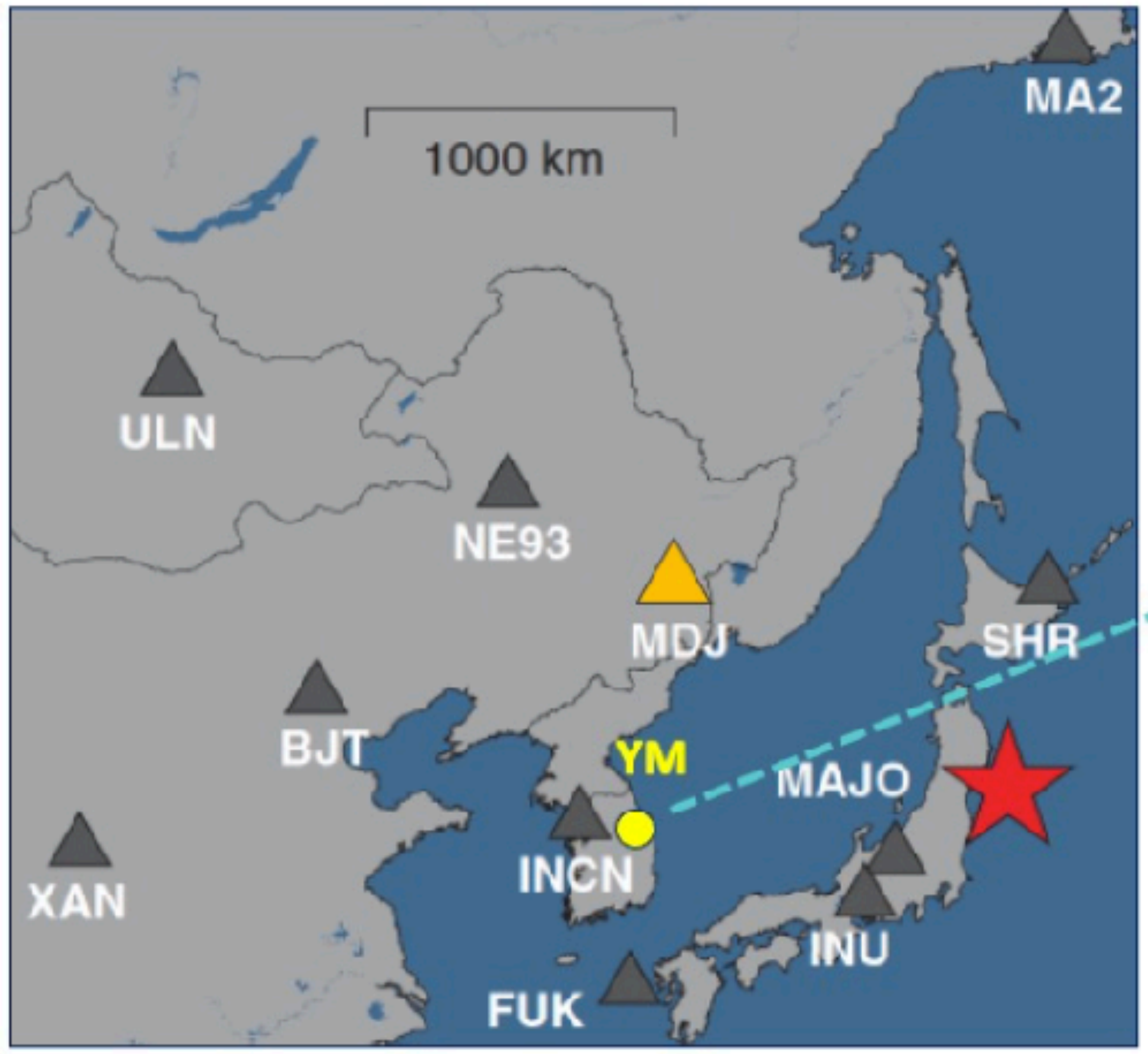
Perturbations of gravity field

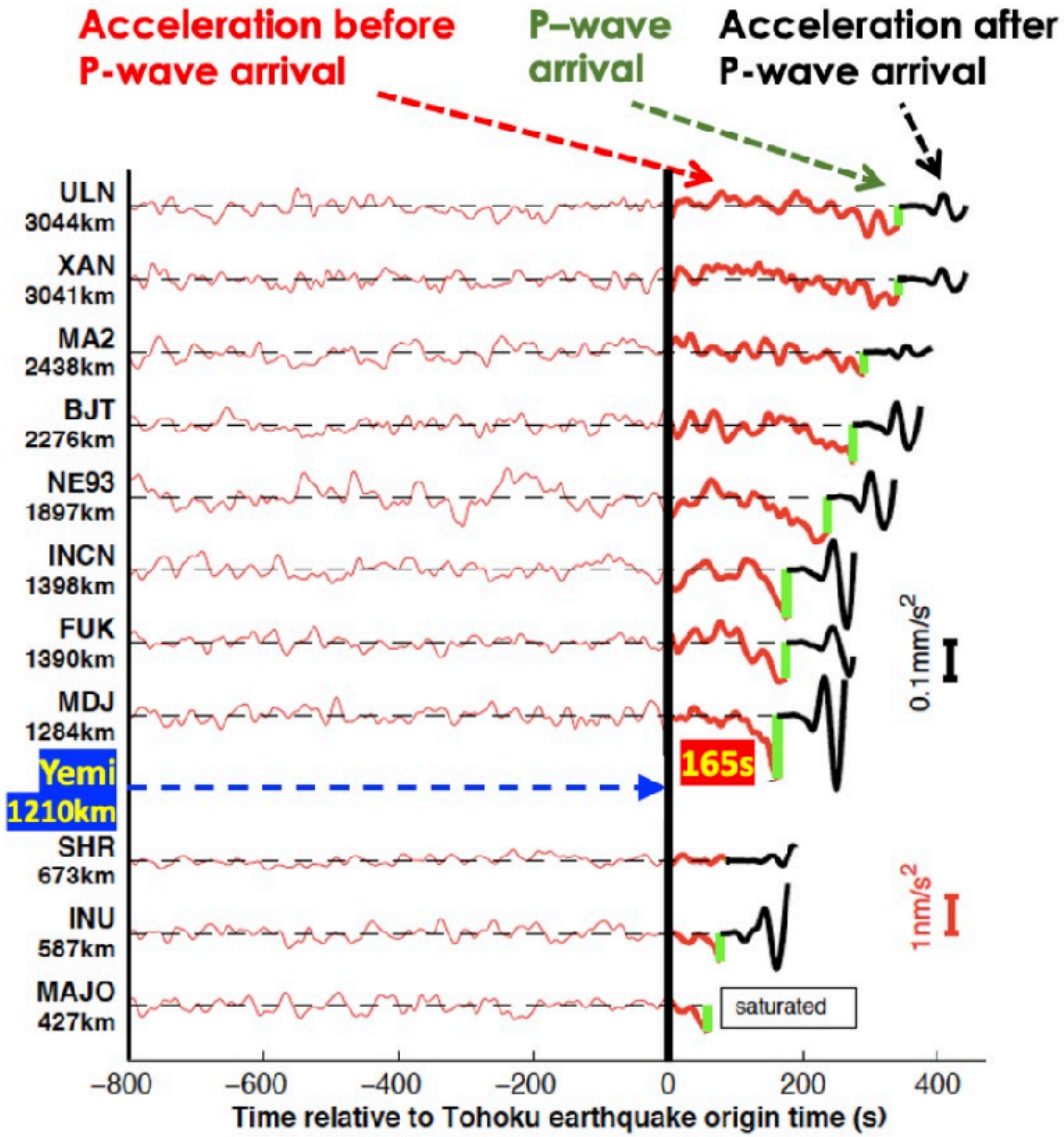
long-range and instantaneous (speed of light)

PEGS

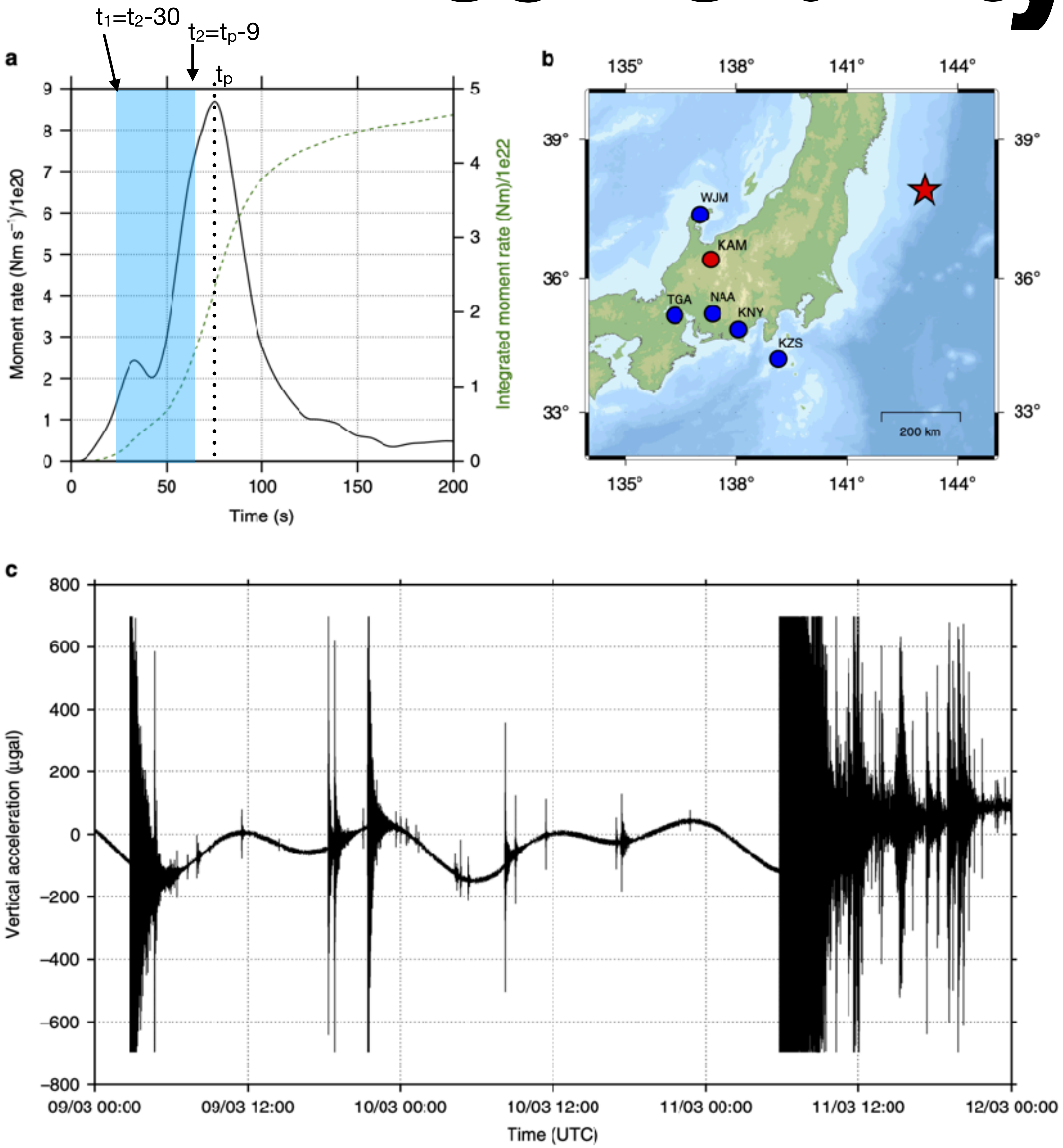
PEGS - Gravity Change from EQ

Vallée et al. " Observations and modeling of the elastogravity signals preceding direct seismic waves", Science, 358, 1164–1168, 2017

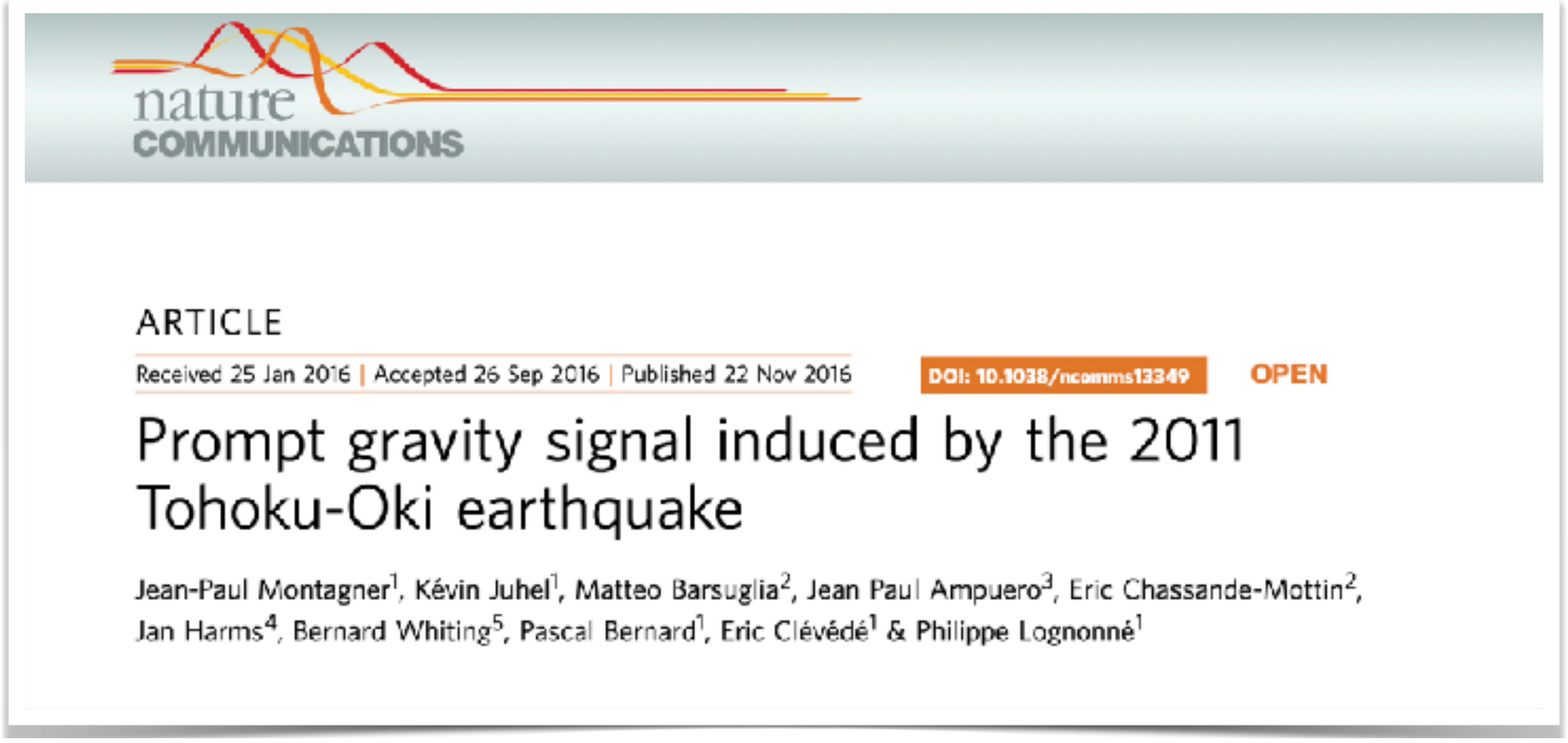




PEGS - Gravity Change from EQ



PEGS - SG data + F-net (Tohoku 2011)

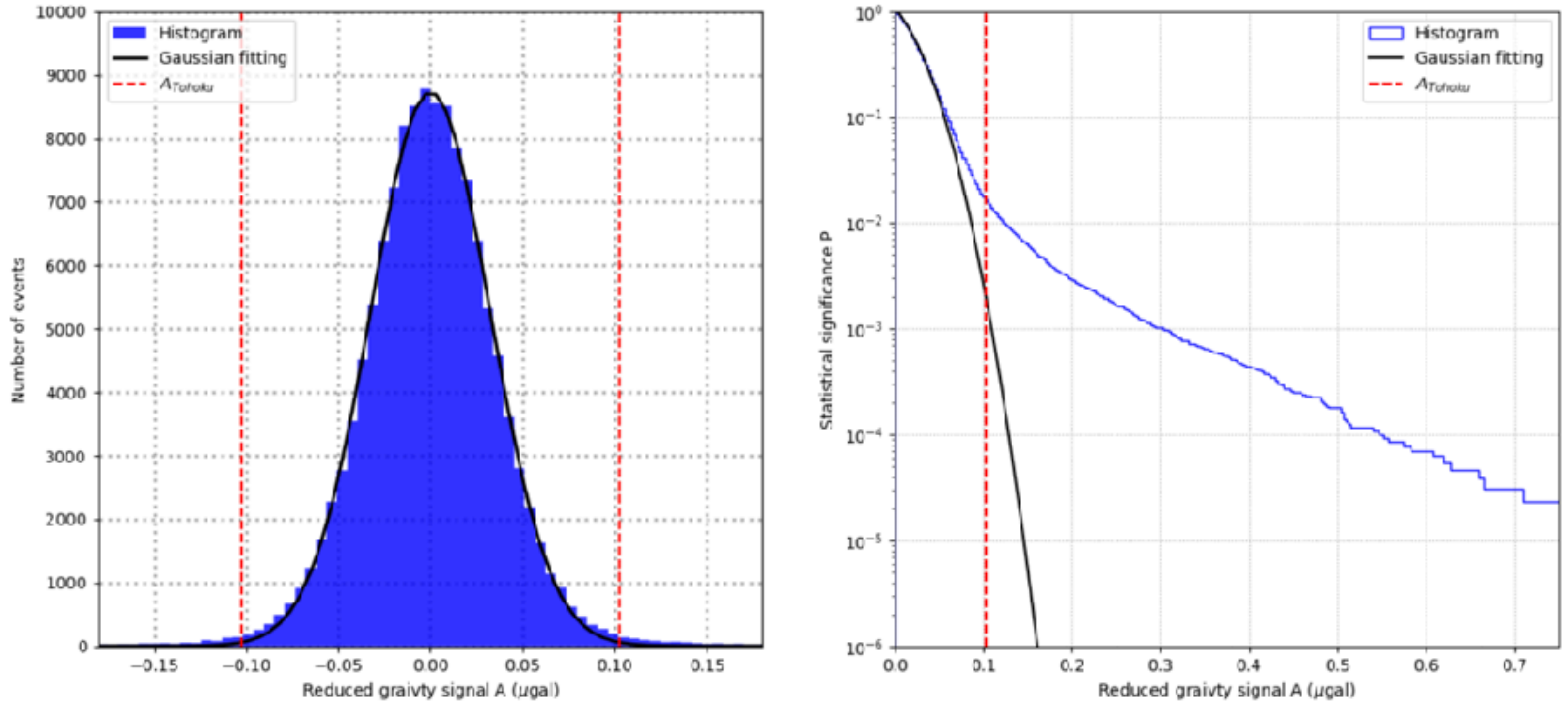

nature COMMUNICATIONS

ARTICLE

Received 25 Jan 2016 | Accepted 26 Sep 2016 | Published 22 Nov 2016 DOI: 10.1038/ncomms13349 OPEN

Prompt gravity signal induced by the 2011 Tohoku-Oki earthquake

Jean-Paul Montagner[1], Kévin Juhel[1], Matteo Barsuglia[2], Jean Paul Ampuero[3], Eric Chassande-Mottin[2], Jan Harms[4], Bernard Whiting[5], Pascal Bernard[1], Eric Clévédé[1] & Philippe Lognonné[1]



Rejected with 98.4% significance level

A_{tohoku} might be came from other things

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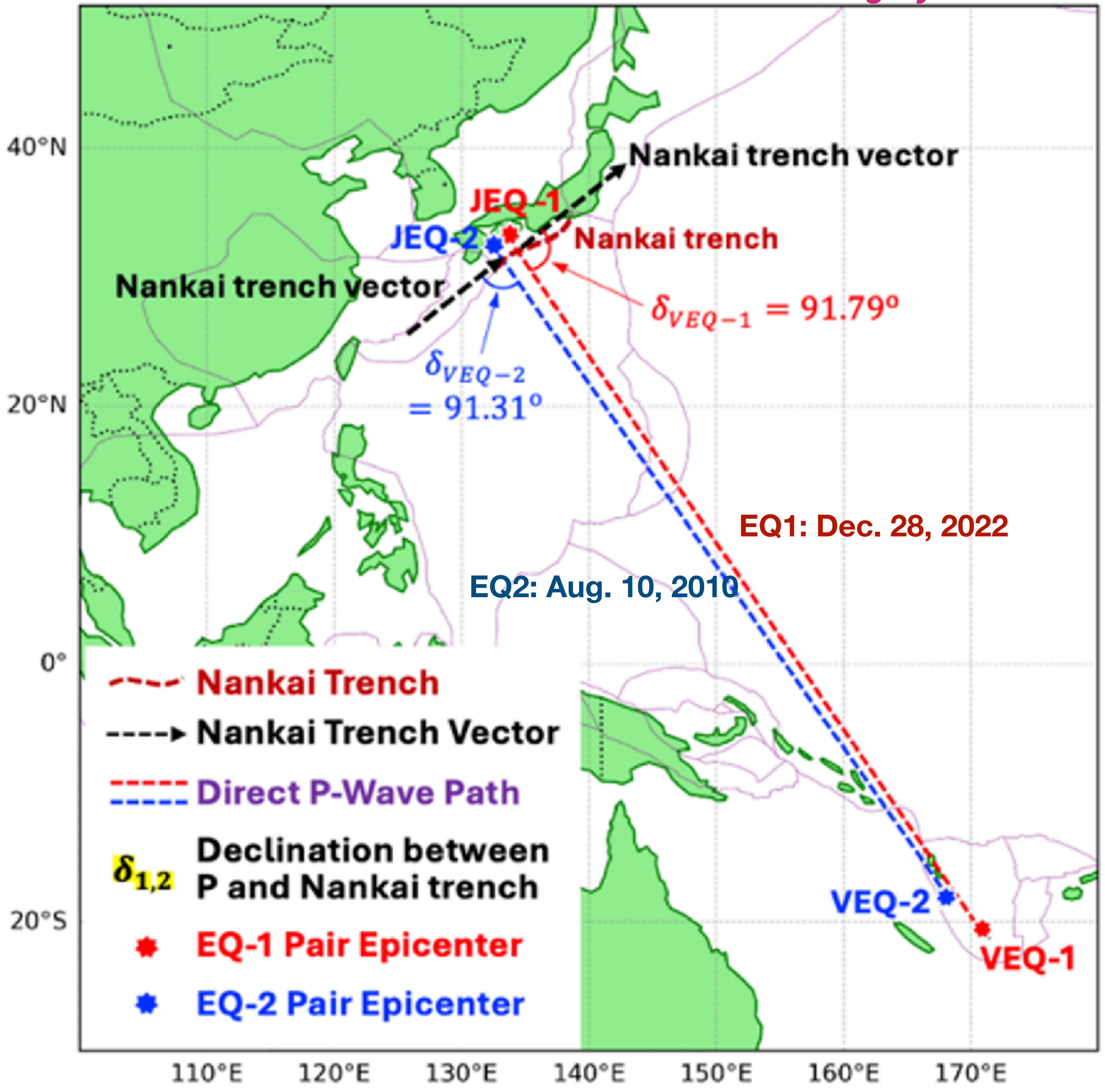
Induced EQ by EQ

In collaboration with U of Calgary and NIMS

- EQ: drastic fault slip - moving plates and its accumulated stresses
- EQ can be also induced (triggered) by another nearby EQs
- Typically, induced EQ was caused by S-waves from other EQs.
- Two counter examples induced by P-waves from distant EQs with a special geometrical structure (refracted/reflected conversion to S-wave modes)

  Ex1) 2022, Dec. 28 (YeMiGO data)/ VEQ1 M6.1 –– (12min later) –– JEQ1 M4.3 (Nankai)

  Ex2) 2010, Aug. 10 (Kaimoka data)/ VEQ2 M4.7 –– (12min later) –- JEQ2 M4.0 (Nankai)
- **The common geometrical structure:** the wave-front of seismic waves is almost perpendicular to the Nankai trench vector.
- So, the 1st arrival P-waves can be converted to S-wave mode with a certain refraction and reflection, then the accumulated stresses can be triggered to the Nankai EQs.



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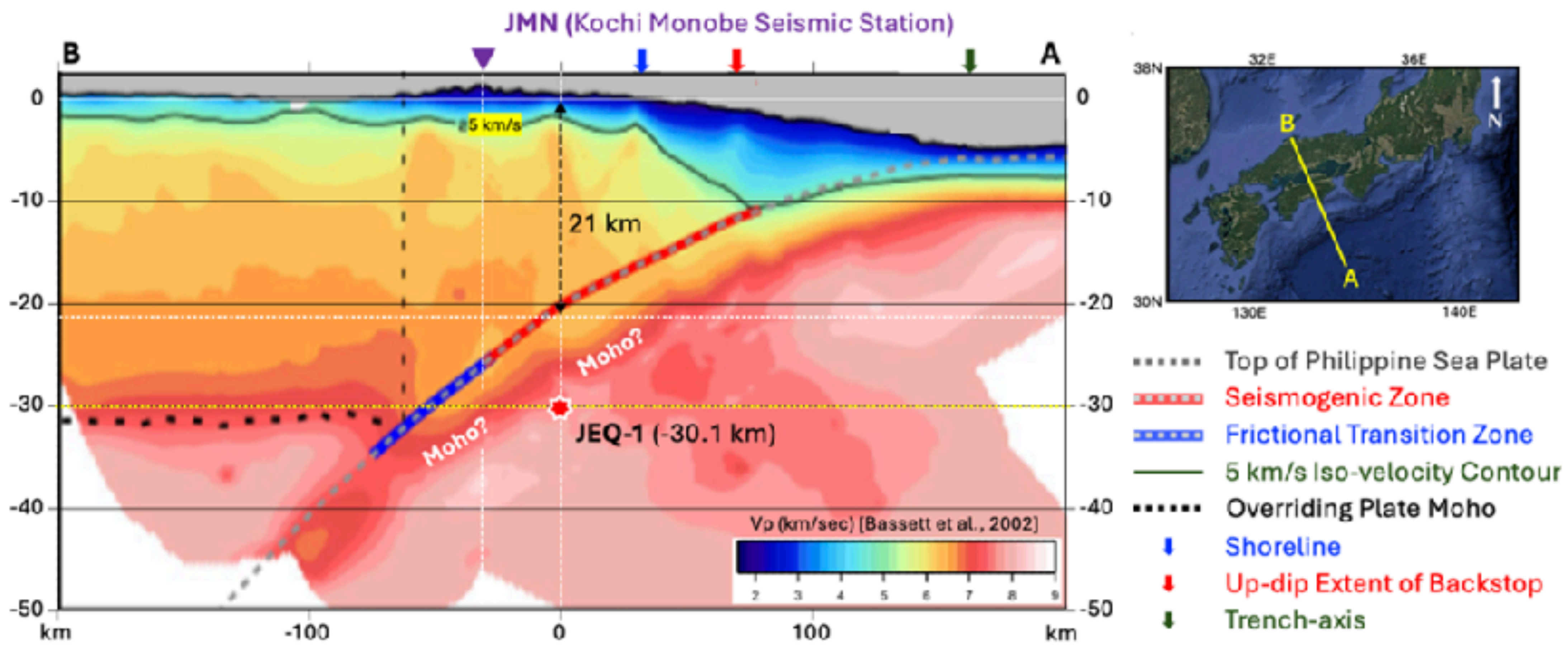
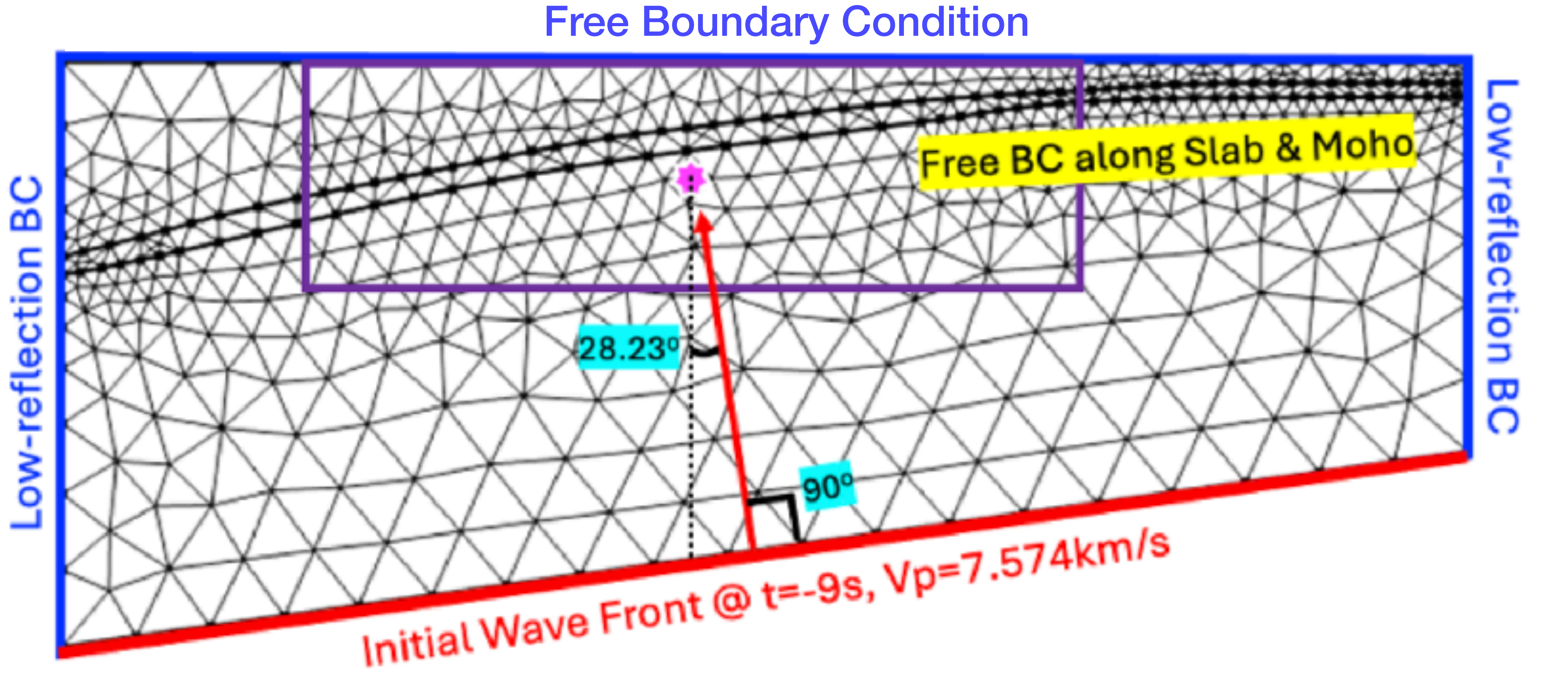
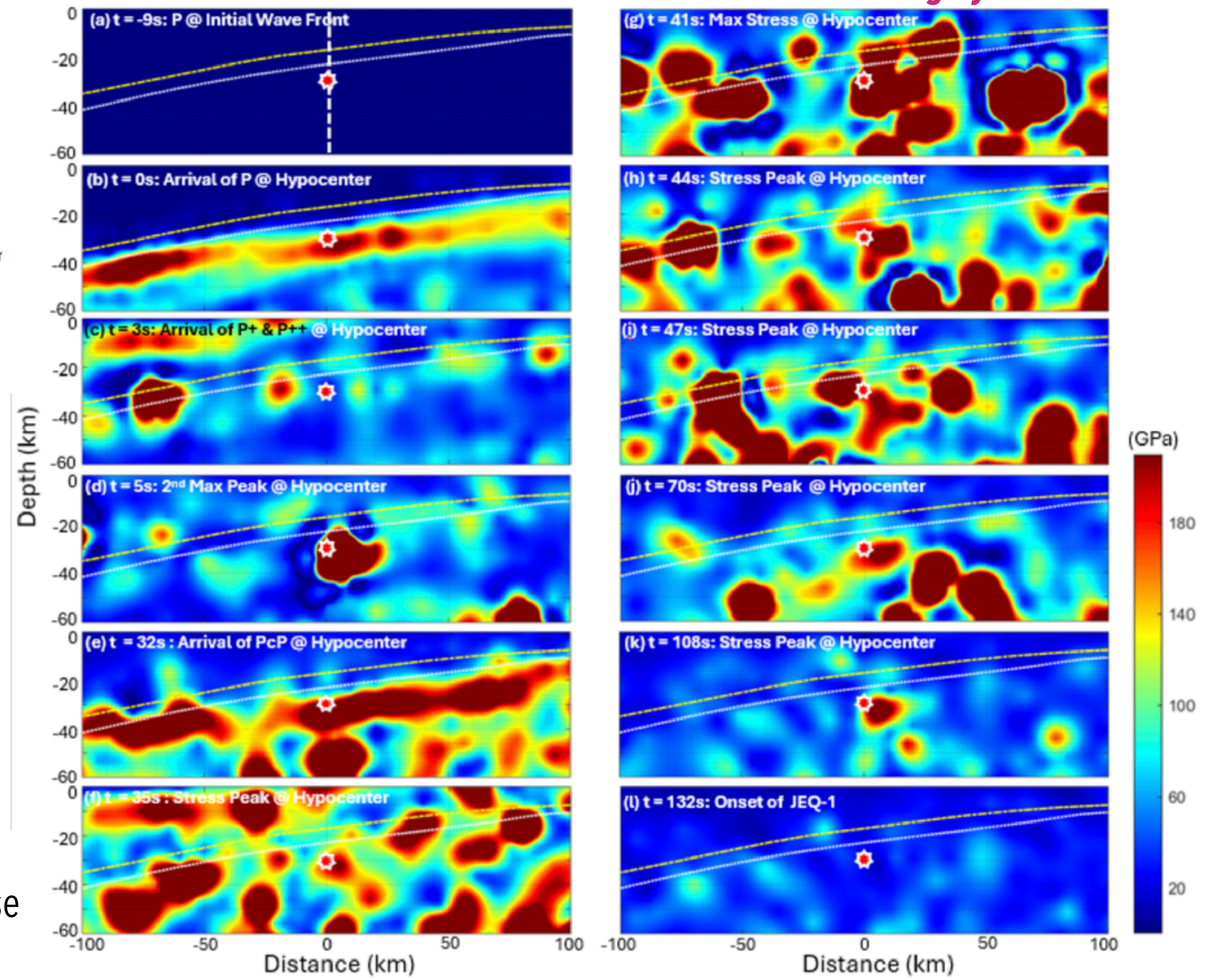
Induced EQ by EQ

In collaboration with U of Calgary and NIMS



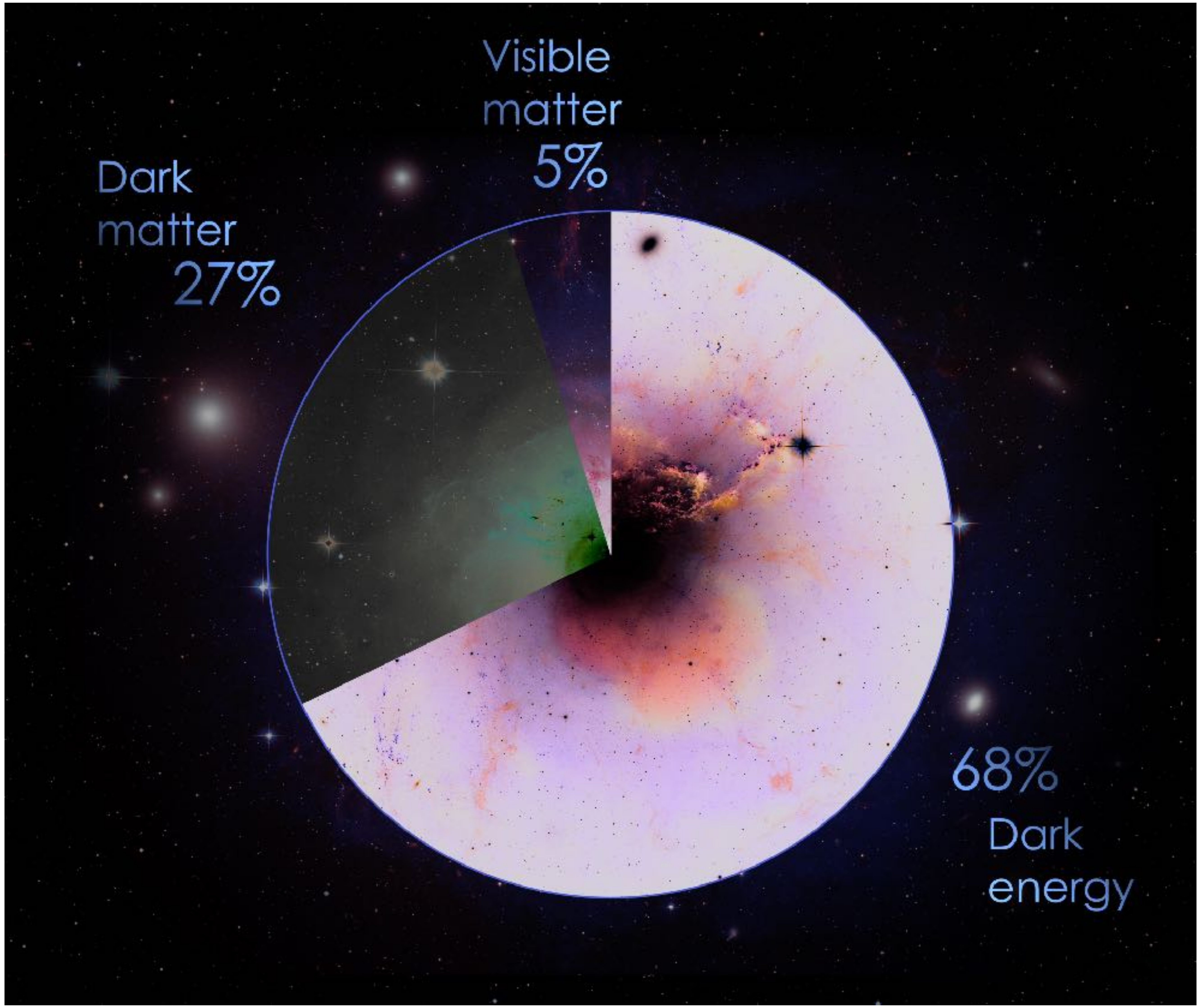
Vp profile along the white line in the top right map (along -50km) [modified from Bassett et al., 2002]





The refraction and reflection in the mantle and moho-surface with different material properties of elastic media can increase the stress near the EQ epicenter.

Dark Matter Clumps Search using SGs



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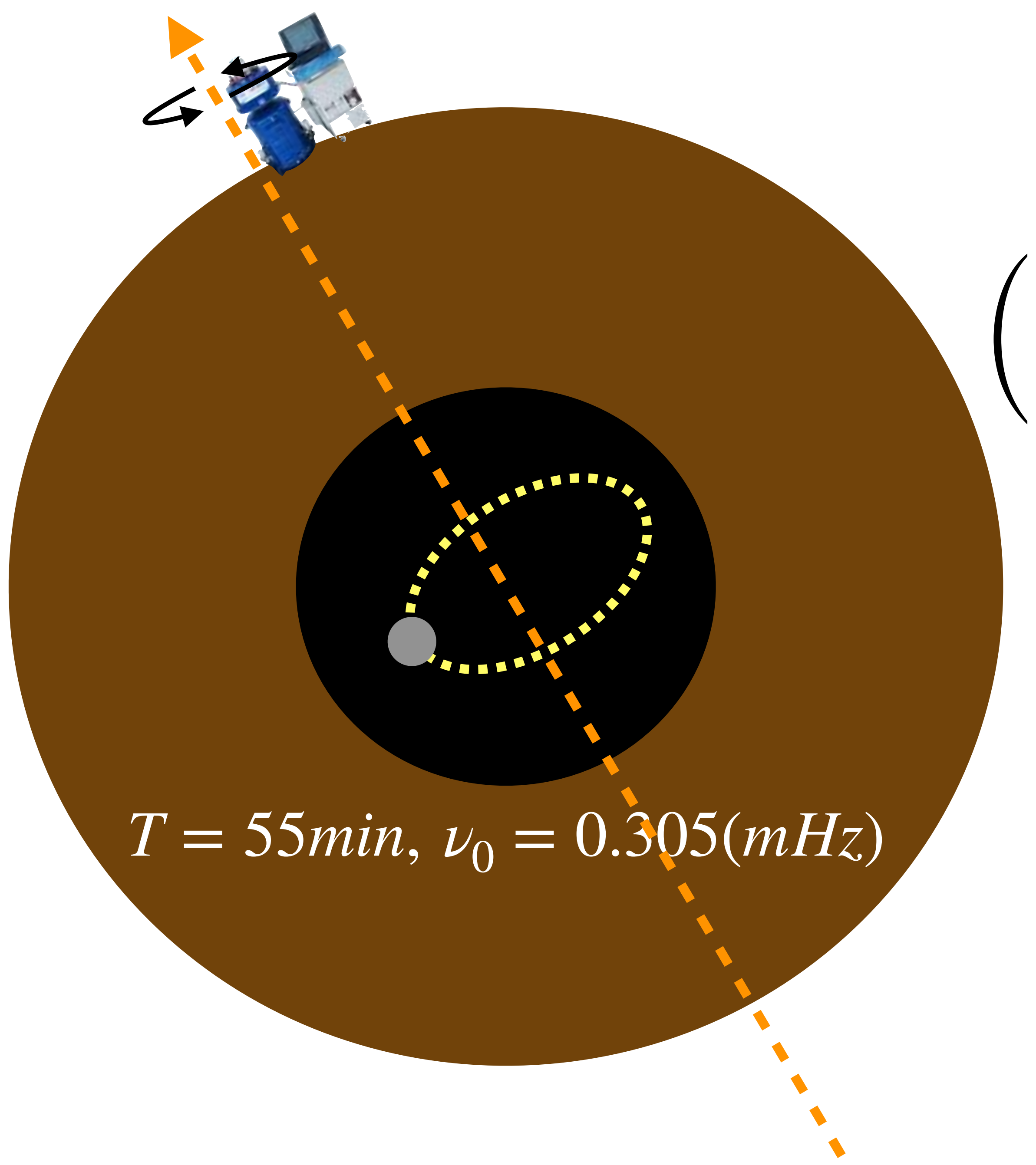
Dark Matter Clumps (DMC) in the Solar System

- **DMC (Dark matter clumps) in the Solar System**
  - C. J. Horowitz and R. Widmer-Schnidrig, PRL 124, 051102 (2020)
  - M. Cuadrat-Grzybowski et al., arXiv: 2403.14397 [astro-ph.CO]
- If DM exists, there might be two possibilities: DMC captured by the Earth's gravity or passed by the Earth with a certain orbital motions

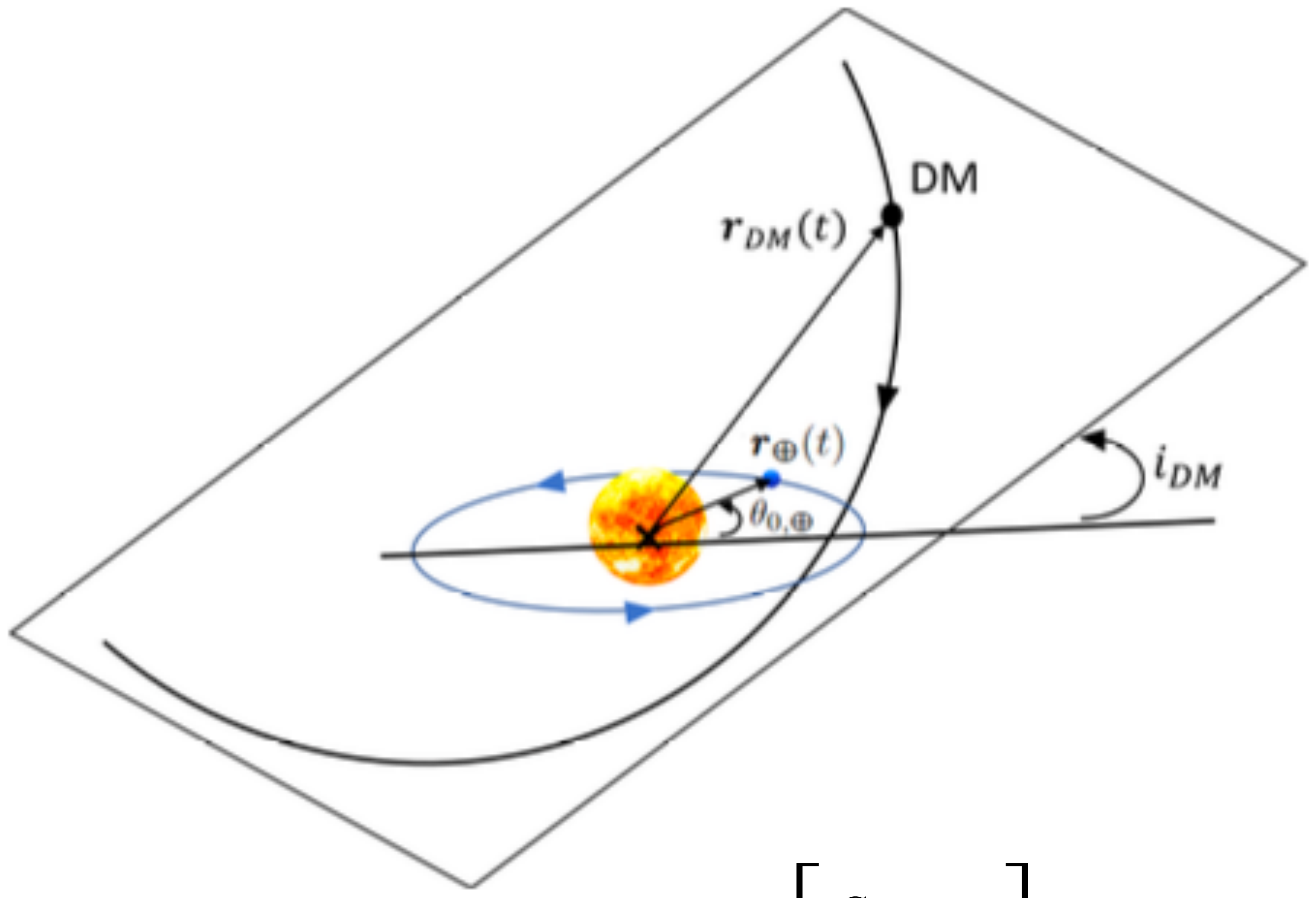


$$\left(\frac{m_D a}{M_E R_E}\right) = \frac{\Delta g(t)}{g\left(2+\frac{\rho_c}{\rho_E}\right)\Delta(t)} < \frac{\Delta g(0.3mHz)}{g(2+13.1/5.51)F(\Theta_L)}$$

$$m_D^{BFO} < 1.259\times10^{-12}M_E = 3.781\times10^{-18}M_\odot$$

$$m_D^{YeMiGO} < 1.257\times10^{-12}M_E = 3.775\times10^{-18}M_\odot$$

assuming $a = 0.1R_E$



$$\left|\frac{\delta g}{g}\right| = \left|\frac{\delta F_G}{F_G}\right| = \left[\frac{\frac{Gm_{DM}m_s}{R^2}}{\frac{GM_\oplus m_s}{r^2_{\oplus/s}}}\right] = \frac{m_{DM}}{M_\oplus}\left(\frac{r_{\oplus/s}}{R}\right)^2$$

$$\delta F_G = -\frac{Gm_{DM}m_s}{(R-r_{\oplus/s})^2} \sim -\frac{Gm_{DM}m_s}{R^2}$$

$$F_G = -\frac{GM_\oplus m_s}{r^2_{\oplus/s}}$$

Dark Matter Search using SGs

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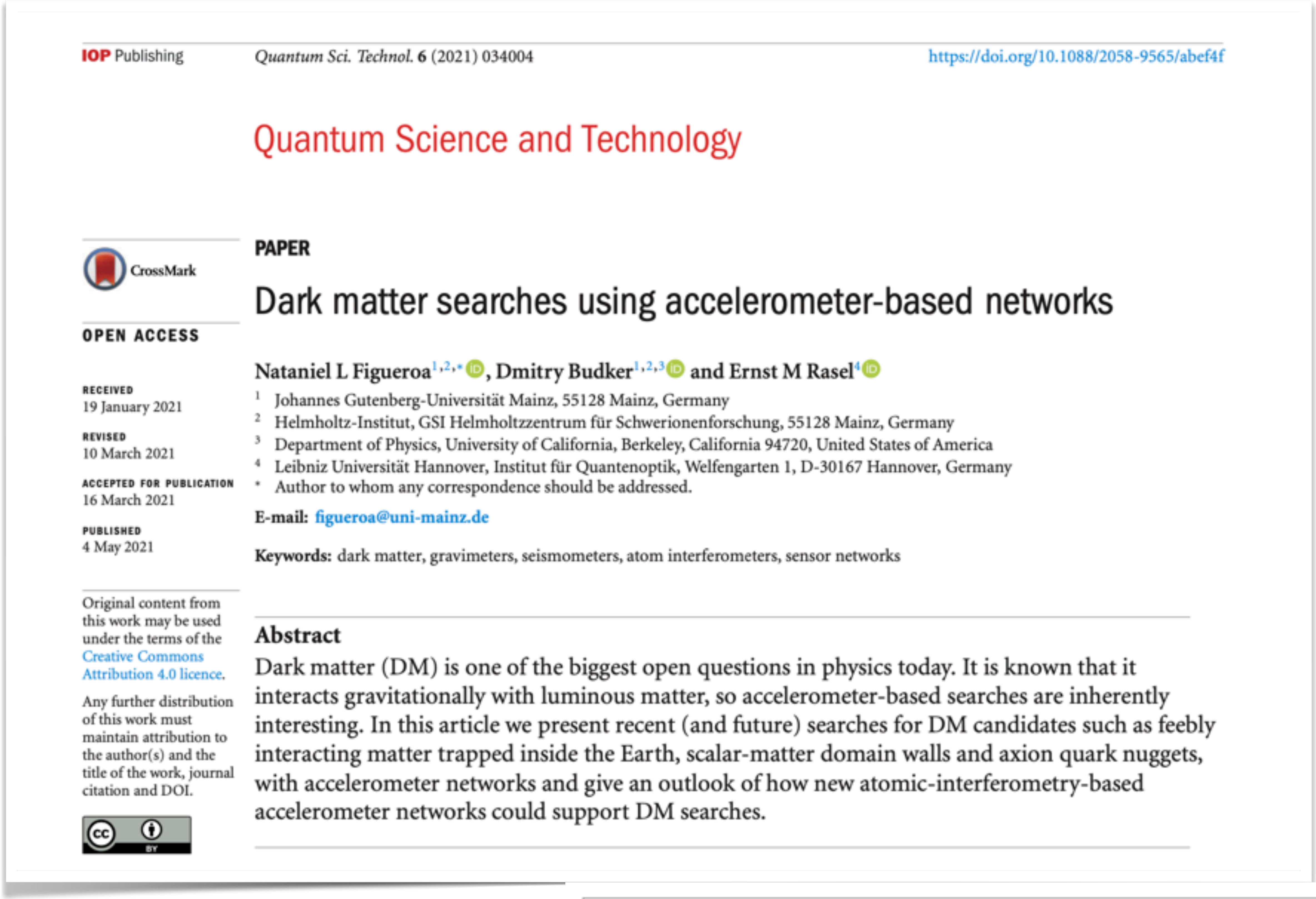

IOP Publishing Quantum Sci. Technol. 6 (2021) 034004 https://doi.org/10.1088/2058-9565/abef4f

Quantum Science and Technology

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PAPER

Dark matter searches using accelerometer-based networks

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2 Helmholtz-Institut, GSI Helmholtzzentrum für Schwerionenforschung, 55128 Mainz, Germany
3 Department of Physics, University of California, Berkeley, California 94720, United States of America
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Keywords: dark matter, gravimeters, seismometers, atom interferometers, sensor networks

Abstract

Dark matter (DM) is one of the biggest open questions in physics today. It is known that it interacts gravitationally with luminous matter, so accelerometer-based searches are inherently interesting. In this article we present recent (and future) searches for DM candidates such as feebly interacting matter trapped inside the Earth, scalar-matter domain walls and axion quark nuggets, with accelerometer networks and give an outlook of how new atomic-interferometry-based accelerometer networks could support DM searches.

SGs: CDOs search

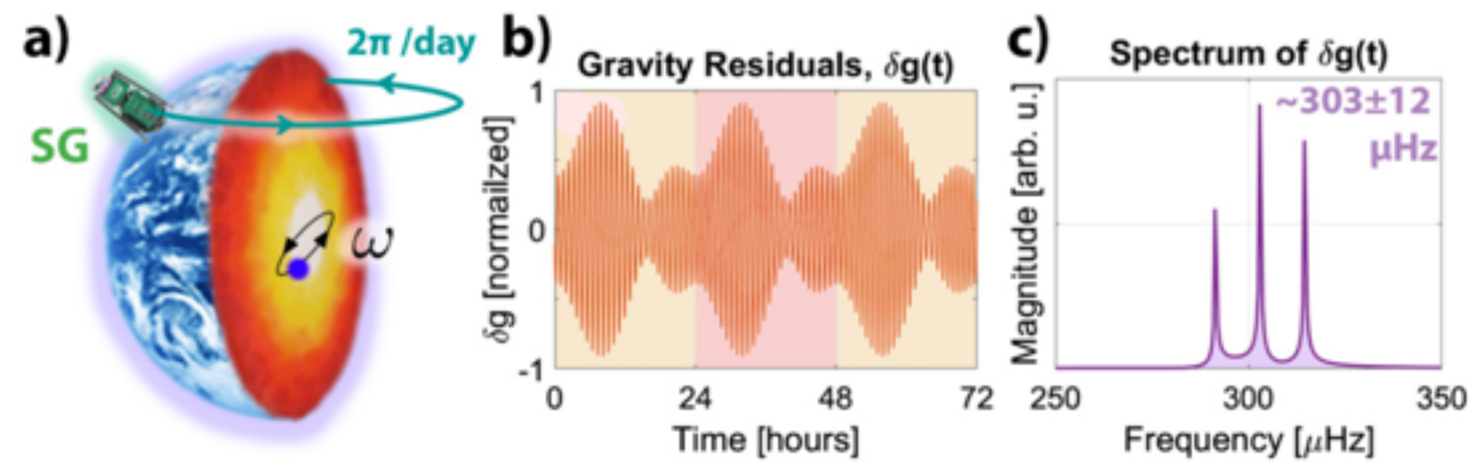

Figure 1. SG search scheme of section 2.1. The trajectories of a trapped CDO inside of Earth and of a SG station on the Earth's surface are shown in (a). The expected gravity residuals and their spectrum as measured by the the station are illustrated in (b) and (c) respectively. Note that the gravity residuals have a fast oscillation (the CDO frequency $\omega/2\pi \sim 303\ \mu$Hz), and a slow daily modulation due to the movement of the station. This gives the CDO spectrum sidebands at ± 1/day $\sim 11.6\ \mu$Hz [20]. The linewidths of the spectrum shown in (c) arise from considering a one-month-long window of data.

SGs: Domain-wall search

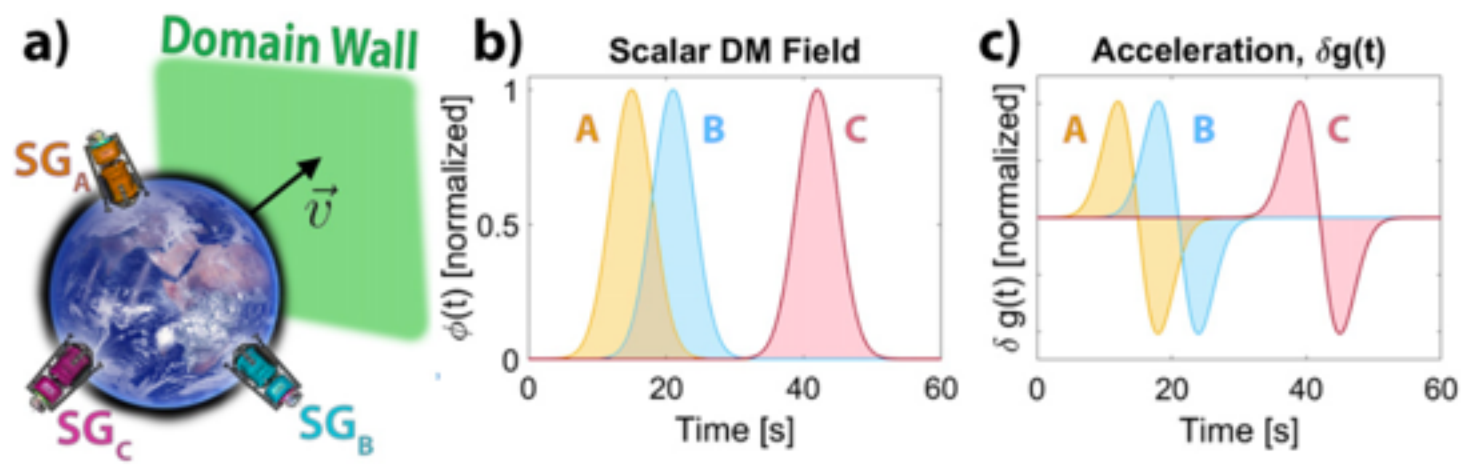

Figure 2. Domain wall acceleration signature, as explained in section 2.2. As Earth travels through a domain-wall (a), the scalar DM field will change at the SG stations (b). This will generate a transient acceleration (c). Note that the shape of the transient will depend on the width of the wall.

Atom interferometry sensor network

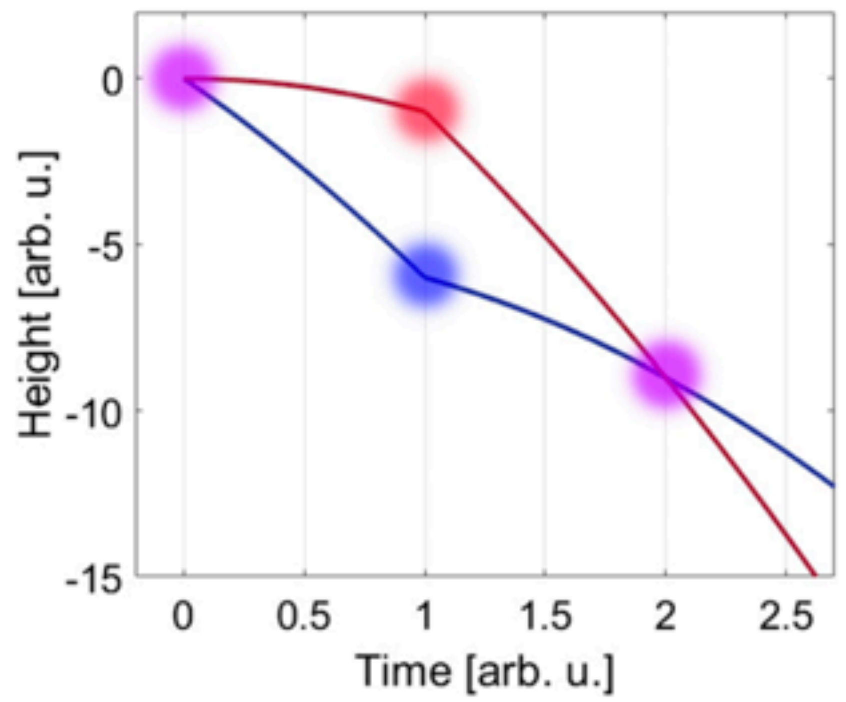

Figure 3. The principle of atomic interferometry. At $t = 0$, an optical pulse prepares an atomic wavepacket (purple cloud) into a superposition of states with different momenta, which separate spatially (red and blue clouds). An optical pulse at $t = 1$ swaps the momentum of the wavepackets. At $t = 2$ the wavepackets are recombined and the phase acquired between both arms of the interferometer is measured.

Axion antiquark nugget seismology

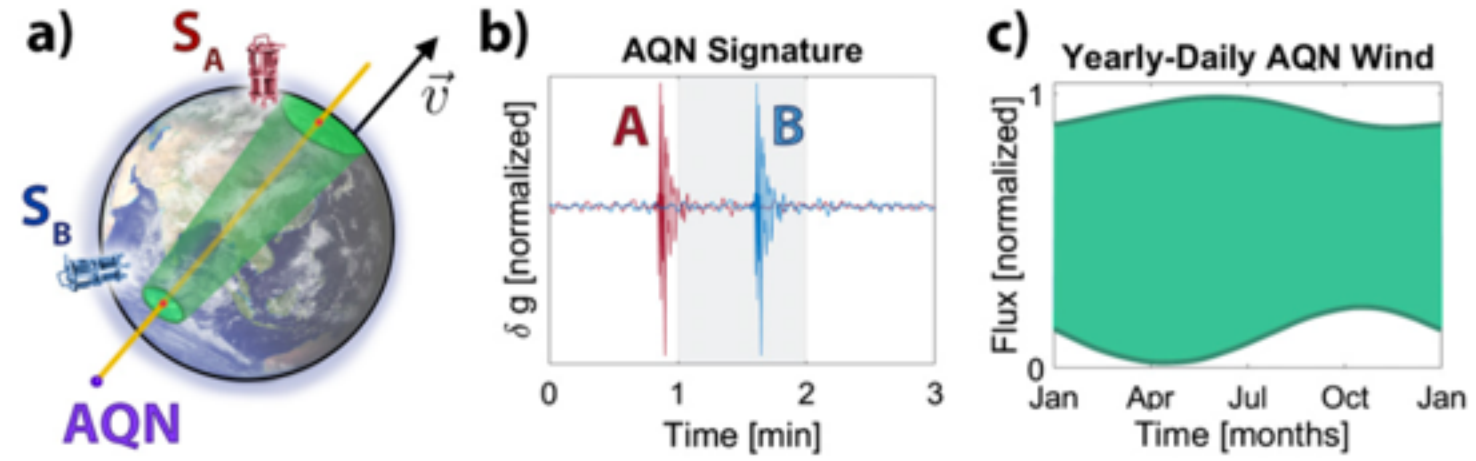

Figure 4. AQN search as explained in section 4. As an AQN travels supersonically through the Earth (a), it creates seismic waves that are detected by seismometer stations A and B (b), almost simultaneously. The frequency of such events will depend on the DM-wind direction and magnitude, which changes daily and yearly in a predictable fashion as shown in (c), which was calculated for Mainz (50.0° N, 8.2° E) for 2020–2021. Note that (c) corresponds to the time-varying component of the AQN wind, which oscillates daily between the minimum and maximum values shown, but these daily-oscillations are so fast that the plot looks solid.

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Dark Matter Search using SGs

Eur. Phys. J. D (2020) 74: 115
https://doi.org/10.1140/epjd/e2020-10069-8

THE EUROPEAN PHYSICAL JOURNAL D

Regular Article

A network of superconducting gravimeters as a detector of matter with feeble nongravitational coupling*

Wenxiang Hu[1], Matthew M. Lawson[2,3], Dmitry Budker[4,5], Nataniel L. Figueroa[4,a], Derek F. Jackson Kimball[6], Allen P. Mills Jr.[7], and Christian Voigt[8]

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Received 5 February 2020 / Received in final form 31 March 2020
Published online 11 June 2020

Abstract. Hidden matter that interacts only gravitationally would oscillate at characteristic frequencies when trapped inside of Earth. For small oscillations near the center of the Earth, these frequencies are around 300 μHz. Additionally, signatures at higher harmonics would appear because of the non-uniformity of Earth's density. In this work, we use data from a global network of gravimeters of the International Geodynamics and Earth Tide Service (IGETS) to look for these hypothetical trapped objects. We find no evidence for such objects with masses on the order of 10^{14} kg or greater with an oscillation amplitude of $0.1\,r_e$. It may be possible to improve the sensitivity of the search by several orders of magnitude via better understanding of the terrestrial noise sources and more advanced data analysis.

Eur. Phys. J. D (2020) 74: 61
https://doi.org/10.1140/epjd/e2020-100632-0

THE EUROPEAN PHYSICAL JOURNAL D

Regular Article

Constraining domain wall dark matter with a network of superconducting gravimeters and LIGO*

Rees L. McNally[a] and Tanya Zelevinsky

Department of Physics, Columbia University, 538 West 120th Street, New York, NY 10027-5255, USA

Received 13 December 2019 / Received in final form 13 January 2020
Published online 24 March 2020

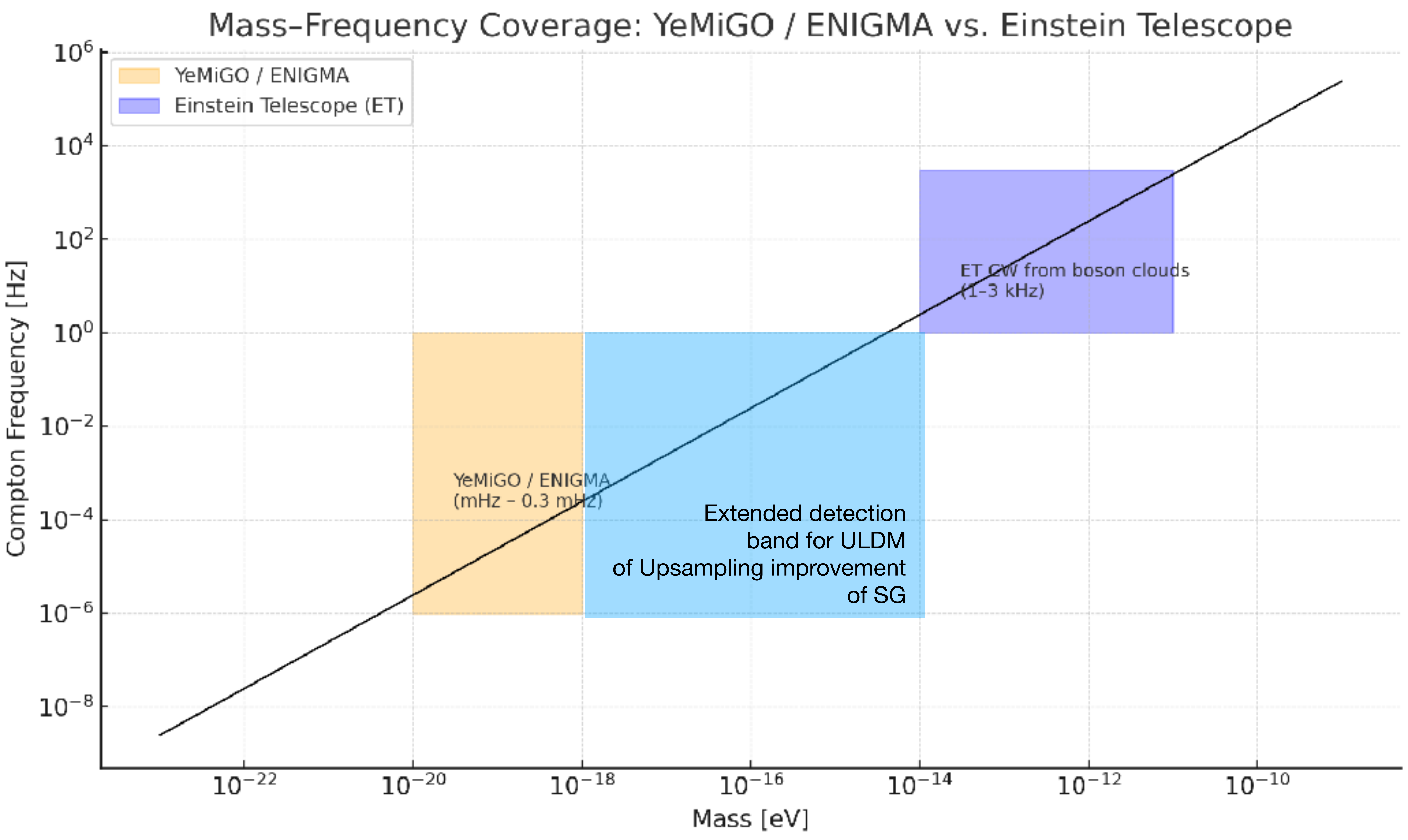
Abstract. There is strong astrophysical evidence that dark matter (DM) makes up some 27% of all mass in the universe. Yet, beyond gravitational interactions, little is known about its properties or how it may connect to the Standard Model. Multiple frameworks have been proposed, and precision measurements at low energy have proven useful to help restrict the parameter space for many of these models. One set of models predicts that DM is a scalar field that "clumps" into regions of high local density, rather than being uniformly distributed throughout the galaxy. If this DM field couples to a Standard Model field, its interaction with matter can be thought of as changing the effective values of fundamental constants. One generic consequence of time variation of fundamental constants (or their spatial variation as the Earth passes through regions of varying density) is the presence of an anomalous, composition-dependent acceleration. Here we show how this anomalous acceleration can be measured using superconducting accelerometers, and demonstrate that > 20 years of archival data from the International Geodynamics and Earth Tide Services (IGETS) network can be utilized to set new bounds on these models. Furthermore, we show how LIGO and other gravitational wave detectors can be used as exquisitely sensitive probes for narrow ranges of the parameter space. While limited to DM models that feature spatial gradients, these two techniques complement the networks of precision measurement devices already in use for direct detection and identification of dark matter.

Ultralight DM with SGs and ET

Ultralight DM search in collaboration with SGs and ET

the ultralight dark matter or dark boson clouds near the black hole accretion: the searching mission is included the Einstein Telescope science cases

- Compton frequency: $\nu_c = (mc^2)/h \approx 2.42 \times 10^{14}$
- Lower mass → longer period, higher field amplitude; higher mass → shorter period, lower amplitude.
- Detection "sweet spot" often in $m \sim 10^{-20}$ -10^{-18} eV range (periods from days to hours).
- Table examples:
  - 10^{-23} eV → ~13-year period; effectively static over experiments; hard to detect.
  - 10^{-21} eV → ~48-day period; μHz band; requires long-term stability.
  - 10^{-19} eV → ~11.5-hour period; sub-mHz; more cycles per day, smaller amplitude.
  - 10^{-18} eV → ~1.15-hour period; ~0.3 mHz; accessible to superconducting gravimeters.



ENIGMA Collaboration

East-Asian Network Initiative for Gravity Measurement Alliance

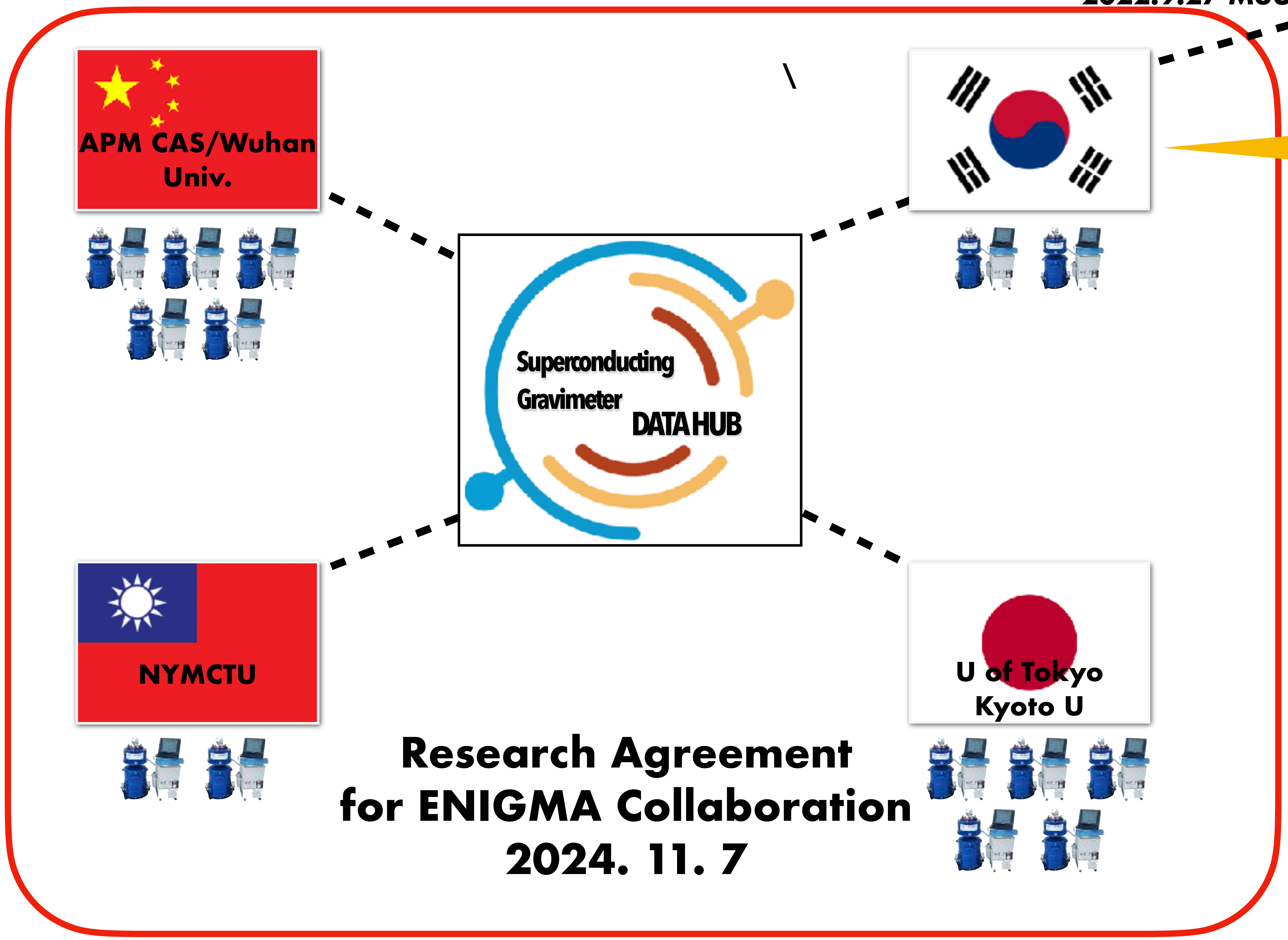
Korea: Sejong, Yemi (2)
China: Wuhan, Lijiang, Lhasa (3)
Taiwan: Tsinchu, Taipei (2)
Japan: Mizusawa (1)
Total: 8 SGs

- The multi-detector network has the advantage of getting N times SNR gain for Ns detectors.
- If each detector has enough distance from each other, then local noise reduction also has advantages, improving the data quality.

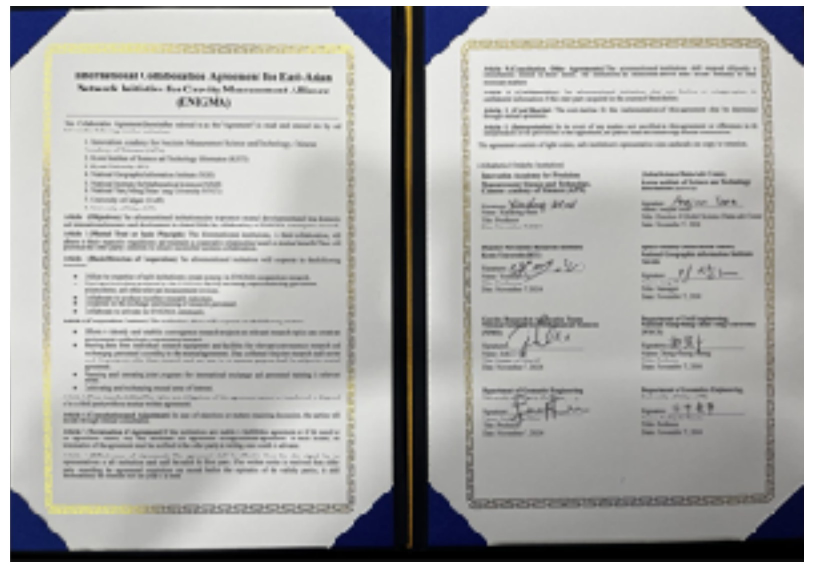
East-Asian Superconducting Gravimeter Network

- **Korea**
  - National Institute for Mathematical Sciences (NIMS)
  - National Geographic Information Institute (NGII)
  - Korea Institute of Science and Technology Information (KISTI)
- **Canada**
  - Univ. of Calgary
- **Taiwan**
  - National Yang-Ming Chao Tung Univ. (NYMCTU)
- **Japan**
  - Univ. of Tokyo
  - Disaster Prevention Research Institute (DPRI), Kyoto Univ.
- **China**
  - State Key Laboratory APM, Chinese Academy of Science

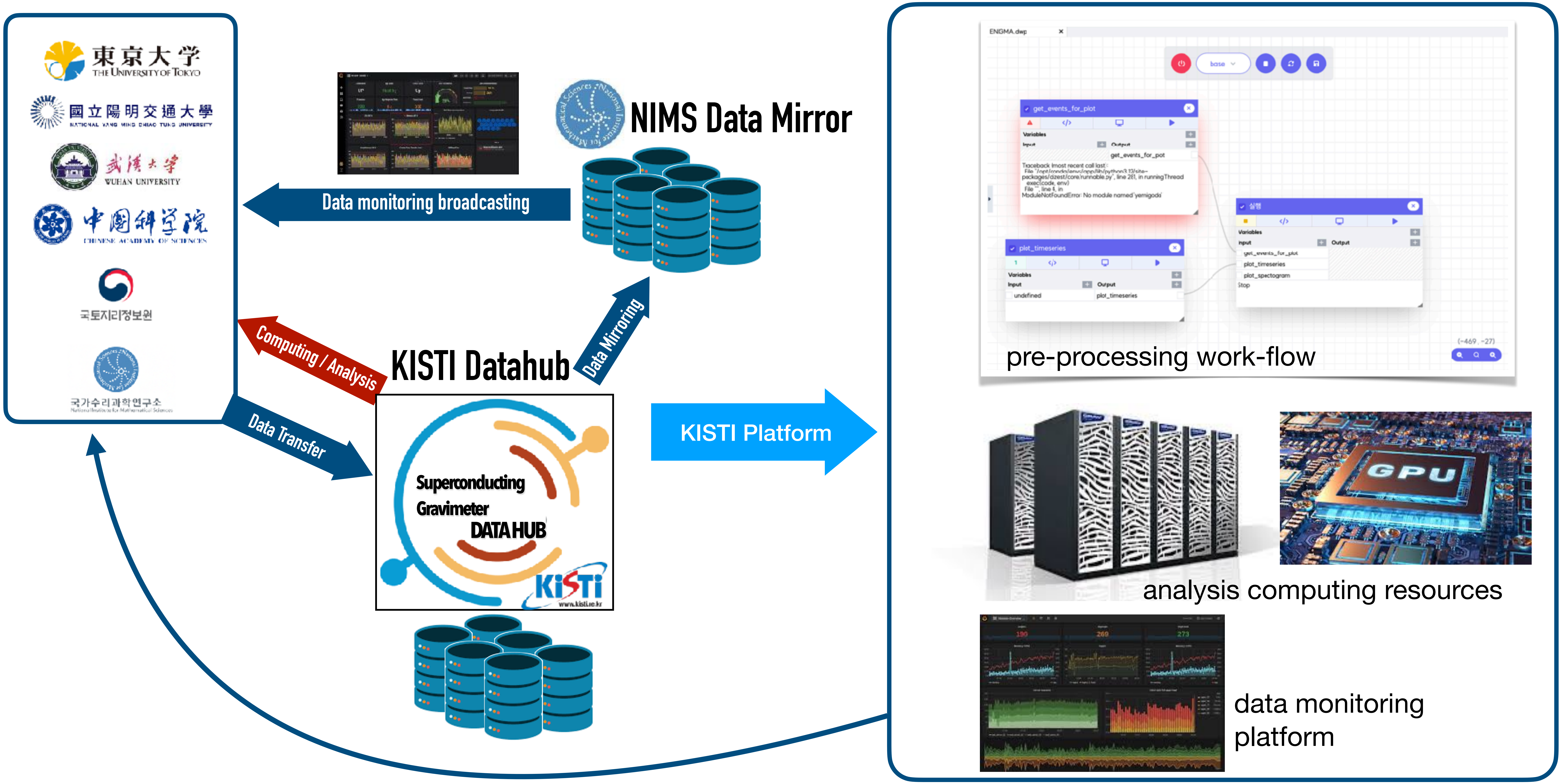
NIMS-UofC
2022.9.27 MoU



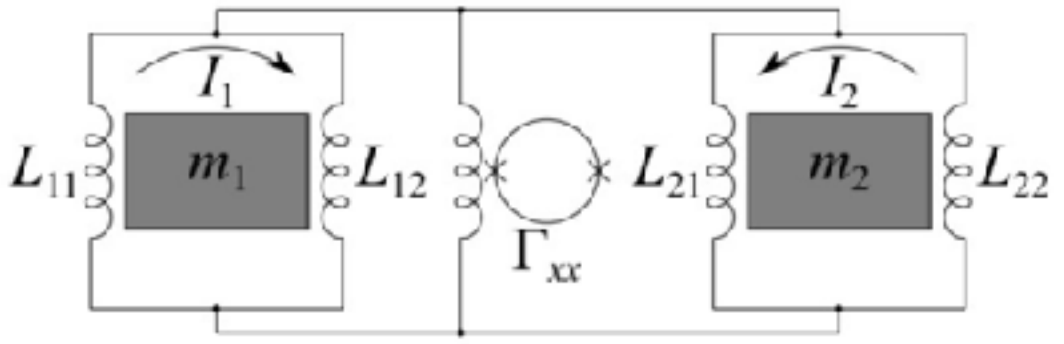
NGII-NIMS-KISTI Institutional MoU in preparation



ENIGMA Data Center

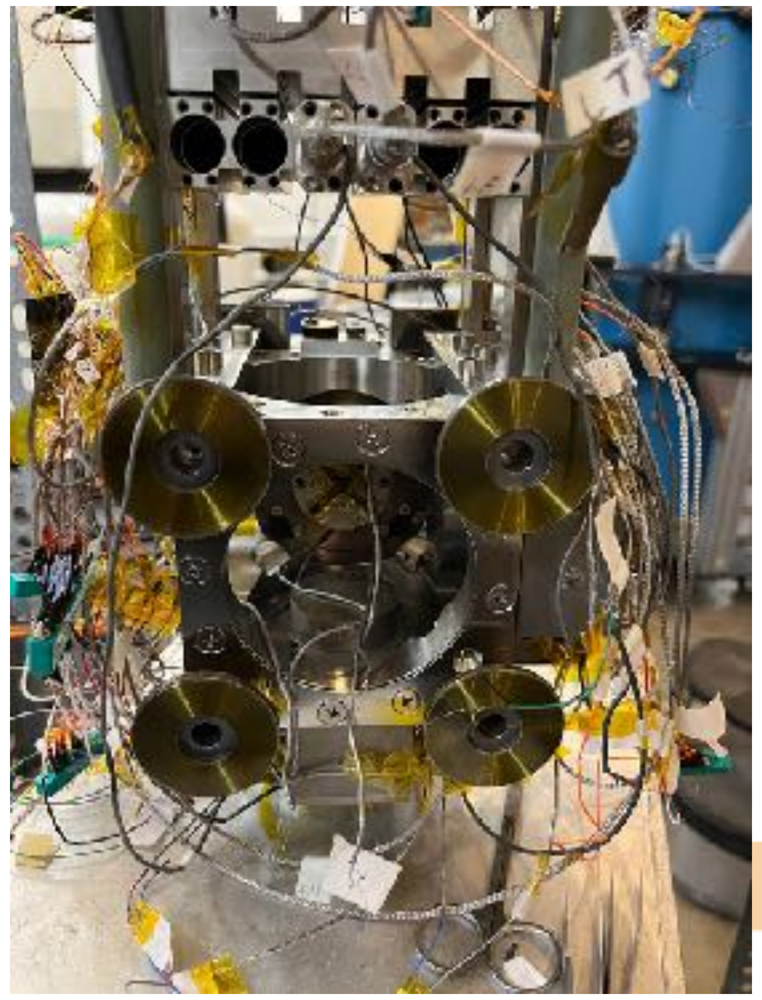
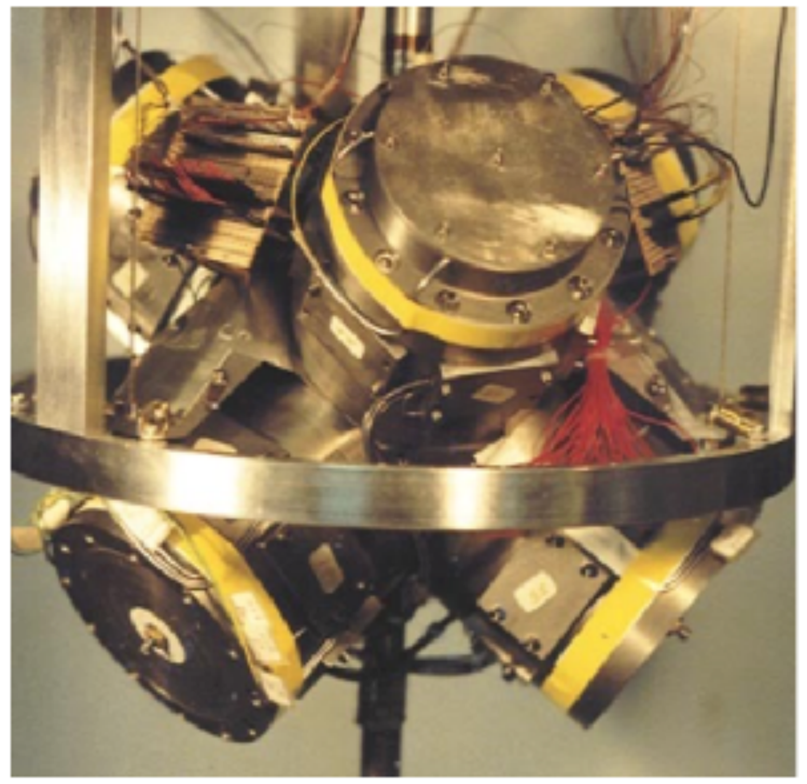


Development of SGG

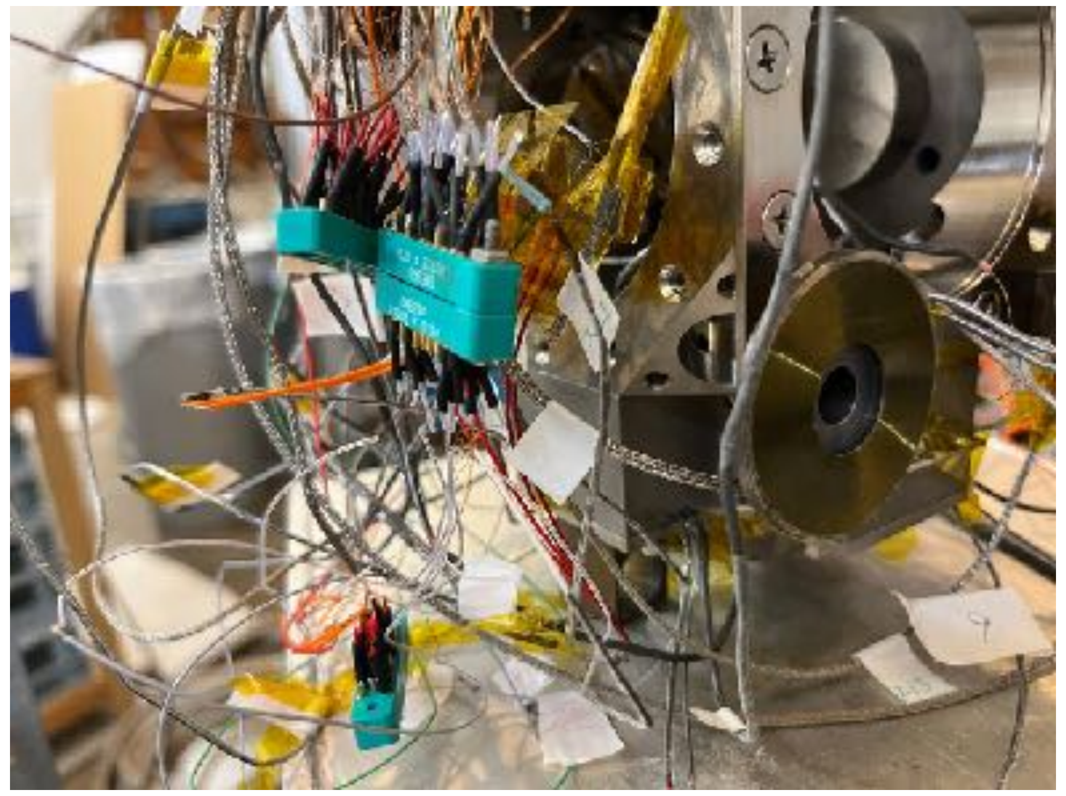
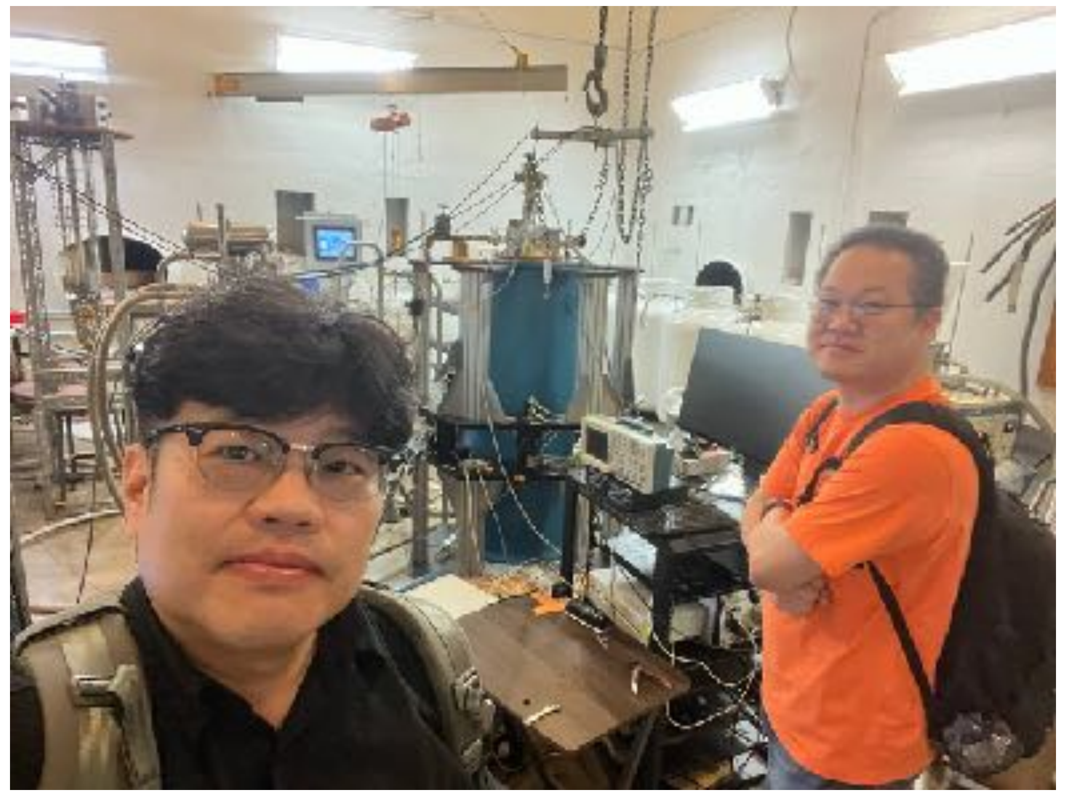


Superconducting Gravity Gradiometer:



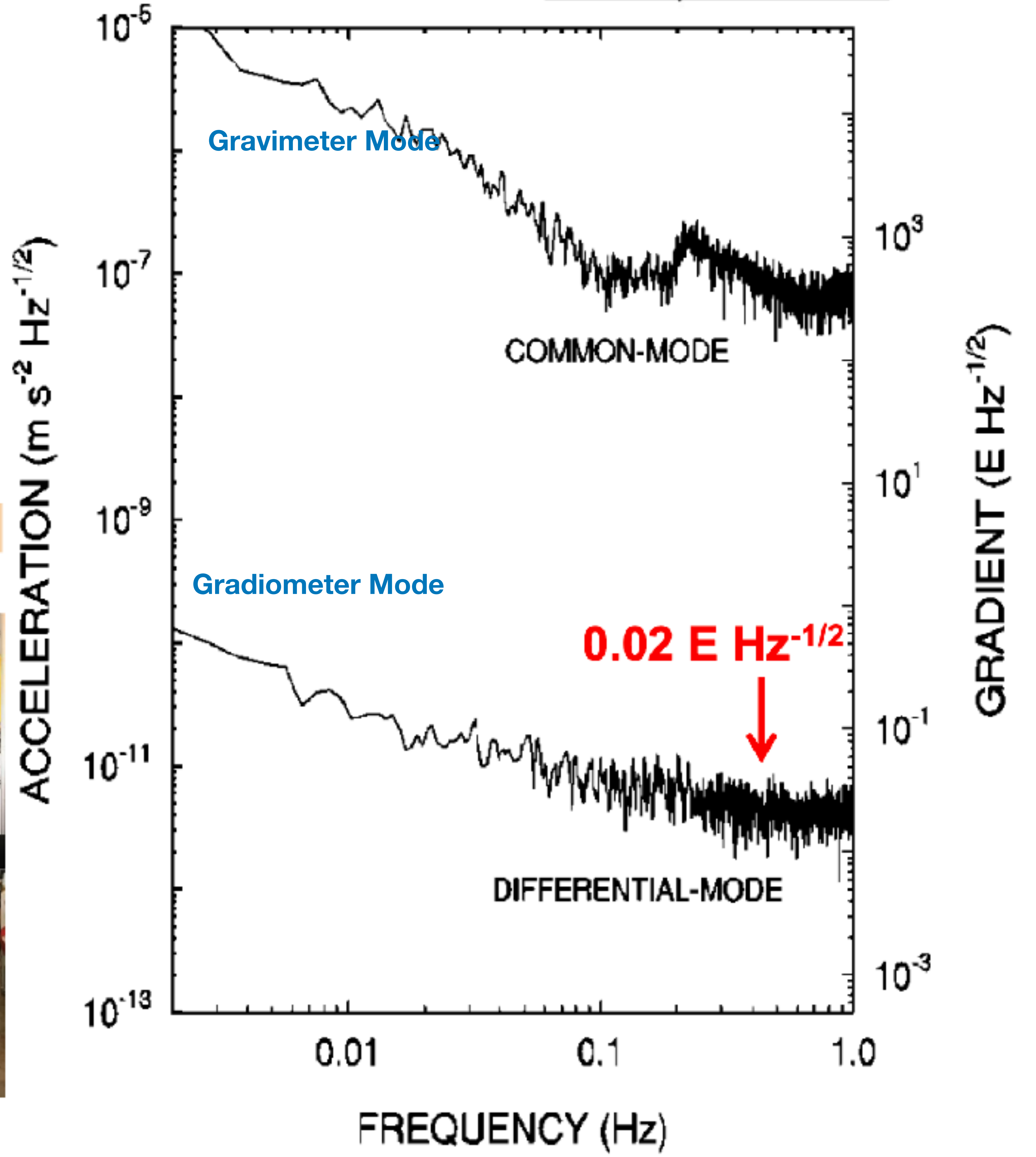



Moody *et al.*, *RSI* 73, 3957 (2002)

1-axis SGG Gravity sensor has been developed
by ADD & UMD for the submarine navigation (2019-2023)


3-axis mSOGRO (UMD)



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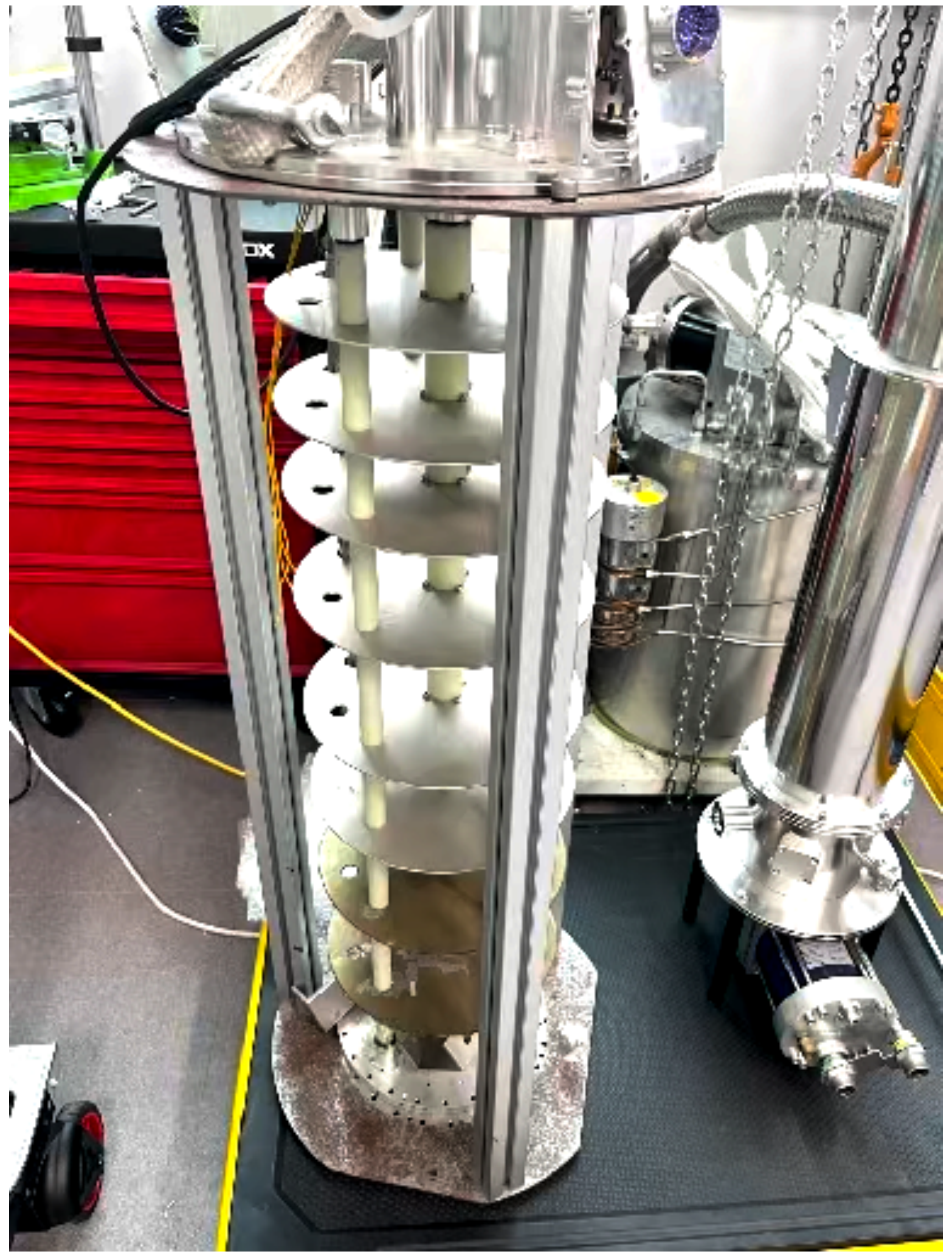
μGICK Yemi Observatory
micro-Gravity Investigator in Canada-Korea

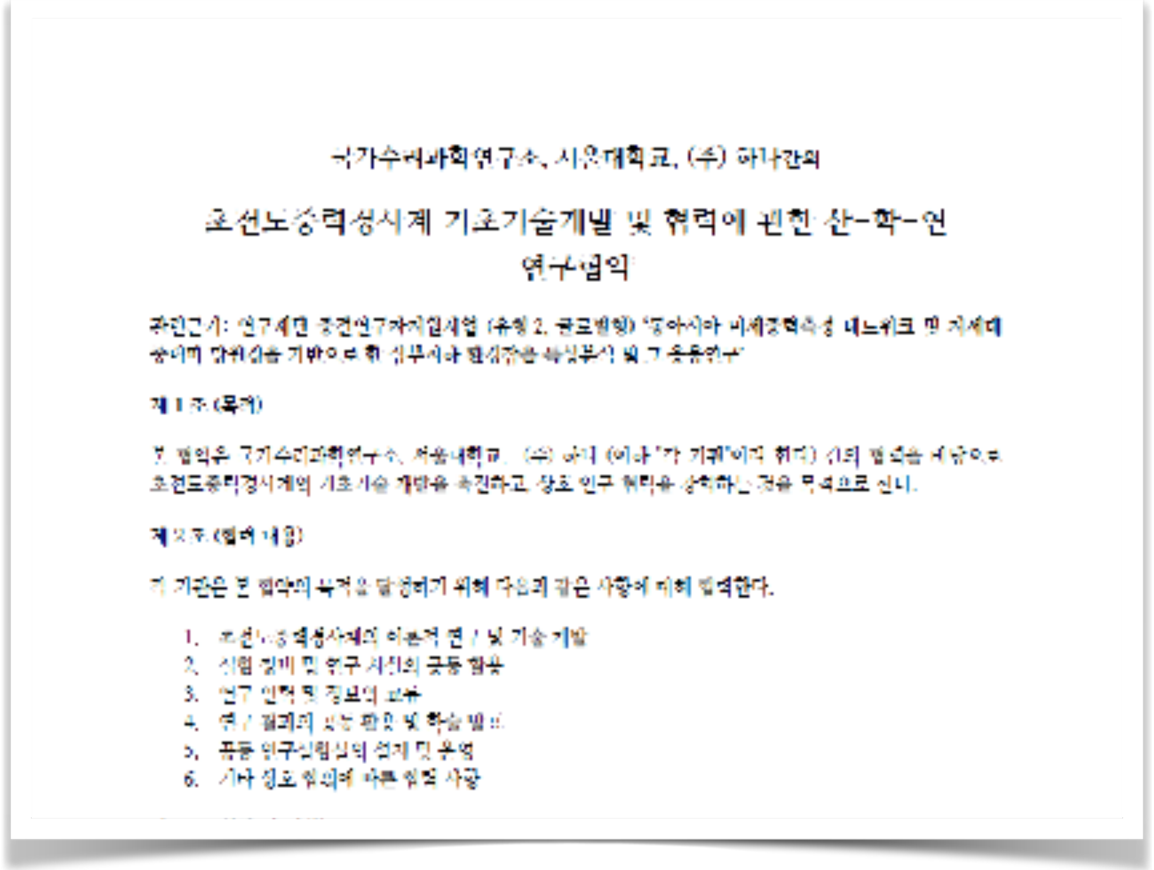
Development of SGG

Superconducting Gravity Gradiometer:



- 1st phase: LHe leak repair & Gravity signal test
  - achieve the 1/100 sensitivity of UMD M2
- 2nd phase: Cryocooler system design (LHe expensive & noncyclable)
  - long-term operation / deployment to YeMiGO
- DAPA & ADD approval (7.30) / Delivery to Hana (September)

In collaboration with NIMS-SNU-Hana Corp.

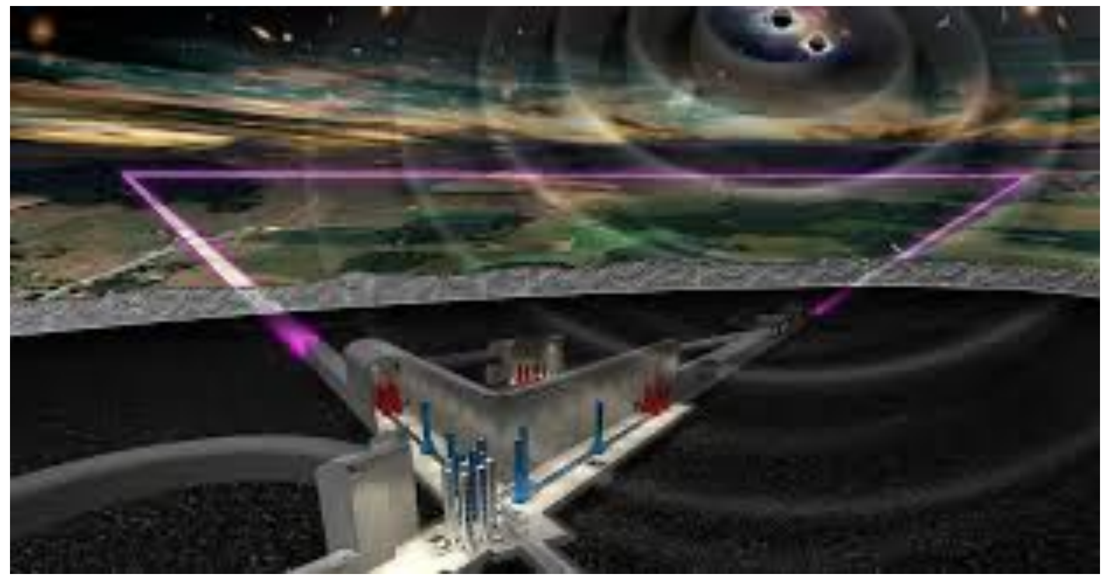

국가수리과학연구소, 서울대학교, (주) 하나간의

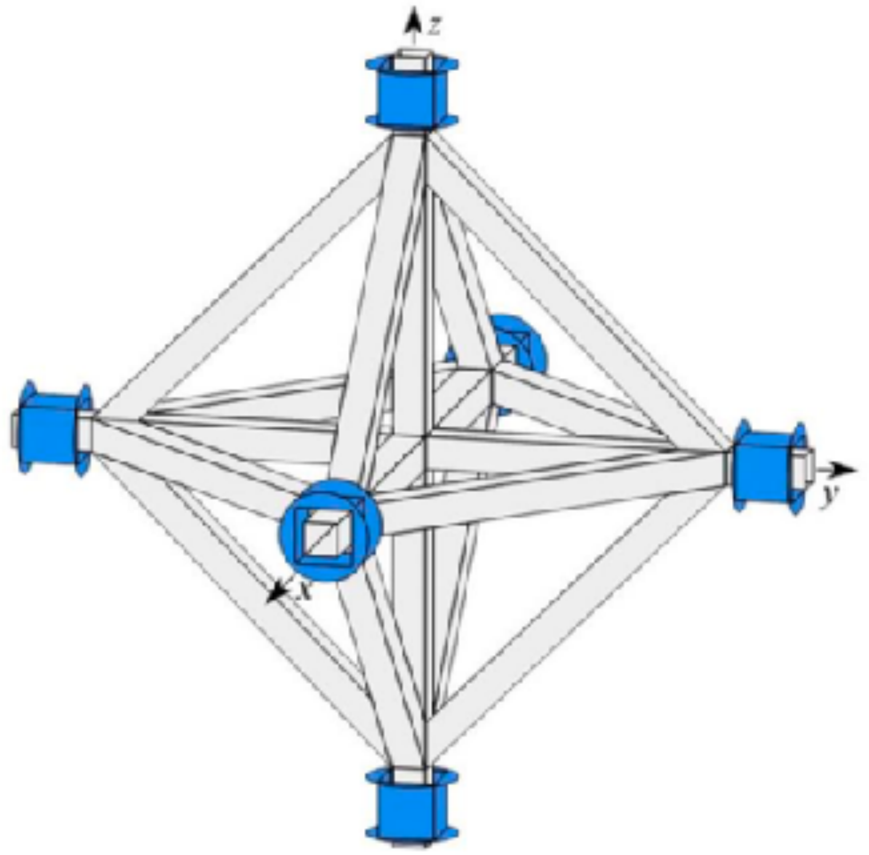
초전도중력경사계 기초기술개발 및 협력에 관한 산-학-연 연구협약

- Original target sensitivity: $0.1\,\mathrm{E\,Hz^{-1/2}} = 10^{-10}\,\mathrm{s^{-2}\,Hz^{-1/2}}$
  cf) Model 2 (Univ. of Maryland) - $0.001\,\mathrm{E\,Hz^{-1/2}} = 10^{-12}\,\mathrm{s^{-2}\,Hz^{-1/2}}$

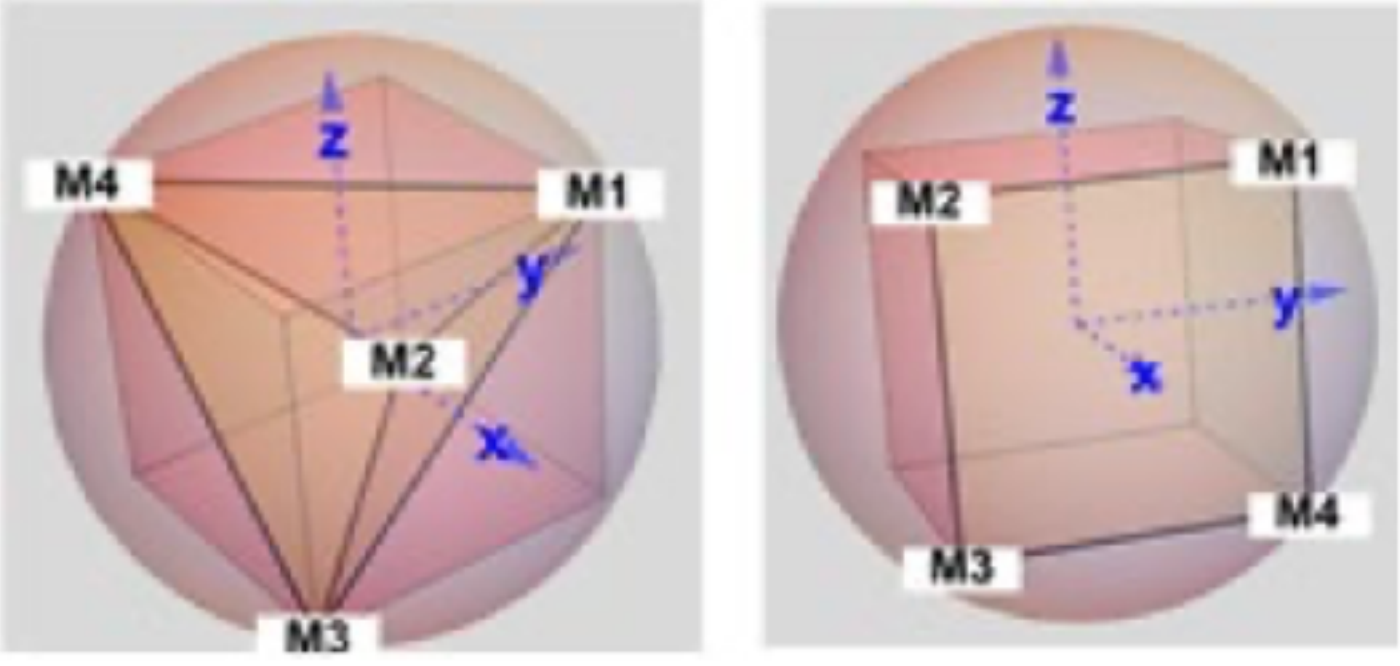
Application of SGG

SGG is a core technology of **SOGRO** - Superconducting Omnidirectional Gravitational Radiation Observatory
- much more challenging (almost impossible)



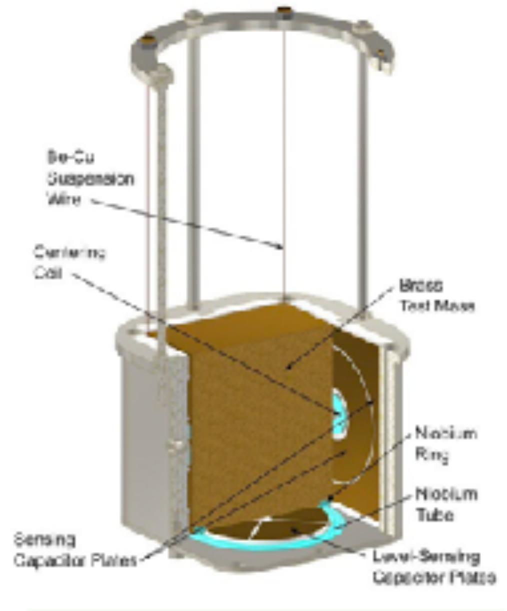


SGG can be used for constructing **Lunar Gravitational-Wave Observatory (European LGWA, LANGO-Lunar Accelerometer Network for Gravitational-wave Observatory)**

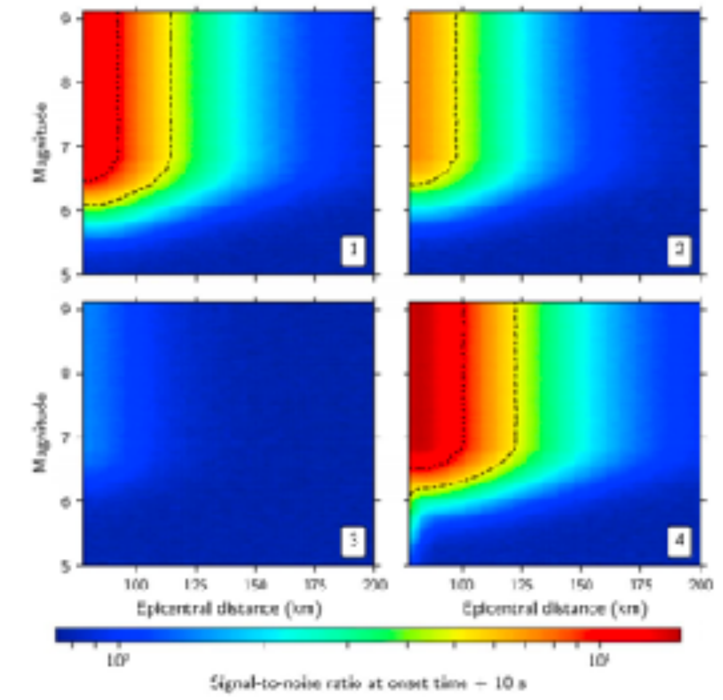


Tetrahedral configuration   Square configuration

SGG can be used for **low-frequency noise mitigation of the current / future ground-based GW telescope** (Einstein Telescope, Cosmic Explorer, A+, KAGRA+ etc)



A cut-away view of LANGO accelerometer



SGG will be a paradigm changing gravity sensor for the **Earthquake Early Warning**

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Collaborations

ENIGMA Collaboration

GReAT


John J. Oh

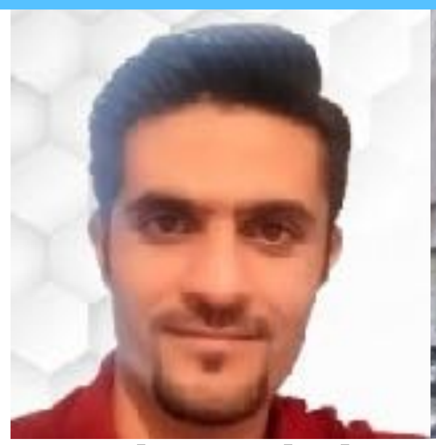

Edwin J. Son


Hwansun Kim


JeongCho Kim

μGICK collaboration


Jeong Woo Kim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Keun-Young Kim


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Thank you for your attention!