From Lunar water exploration to astrophysics from the moon – MoMoTarO

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Photonics, space, lasers: designing the future society – vision 2040, Osaka EXPO, 2025 September 10
https://photonics-space-lasers.avcr.cz/ (10 min + 2 min)

Teruaki Enoto (Kyoto University & RIKEN, JP)

- X-ray astronomer studying high-energy **astrophysics** of neutron stars (pulsars)
  - Satellite projects: Suzaku, Astro-H (Hitomi), XRISM, NICER, NinjaSat …
- High-energy **atmospheric** physics of lightning and thunderstorms
  - Citizen science “Thundercloud Project” working with Nakazawa san et al.
- Czech-Japanese collaboration. Invited by Prof. Norbert Werner! Thanks!

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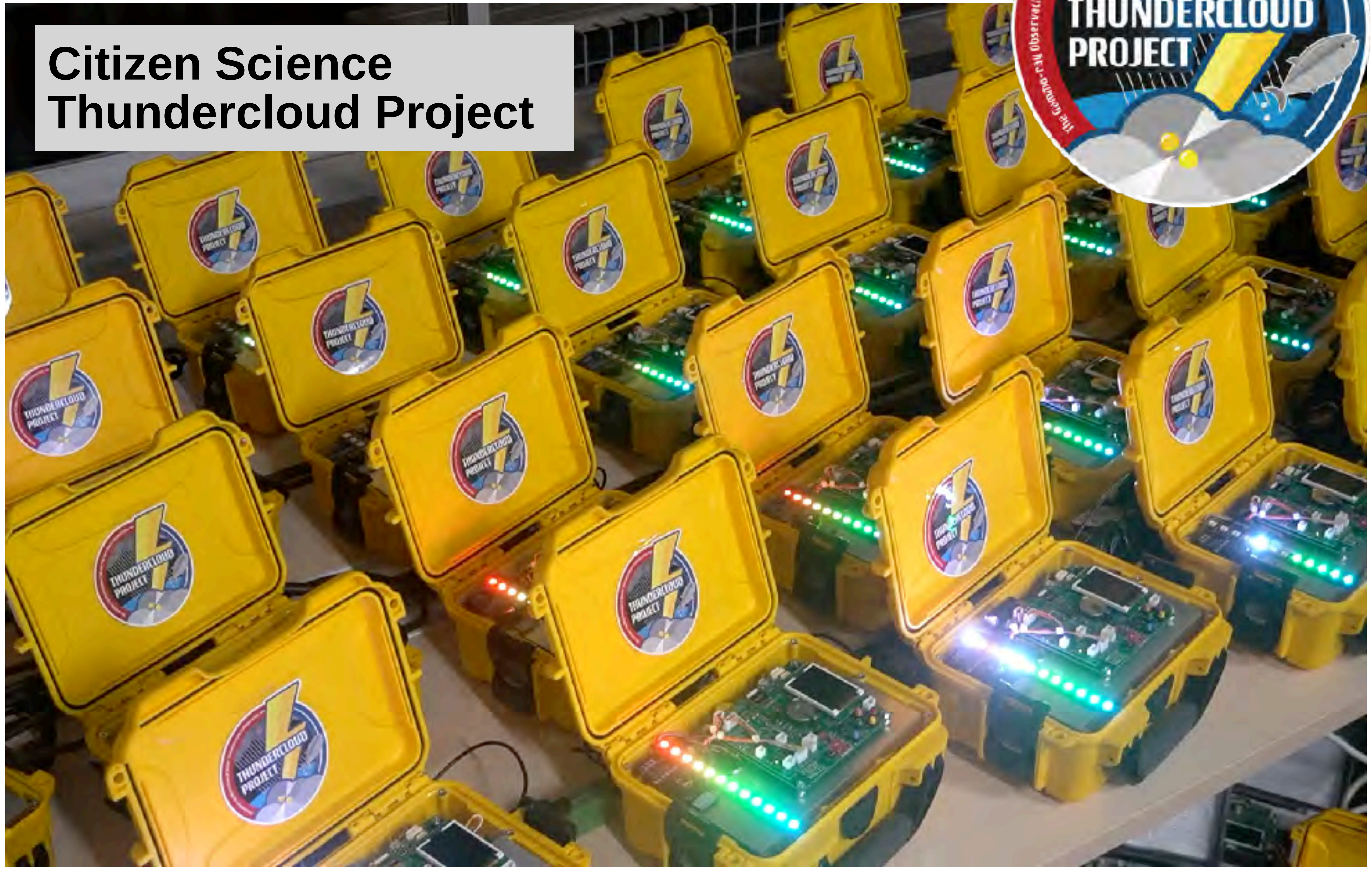
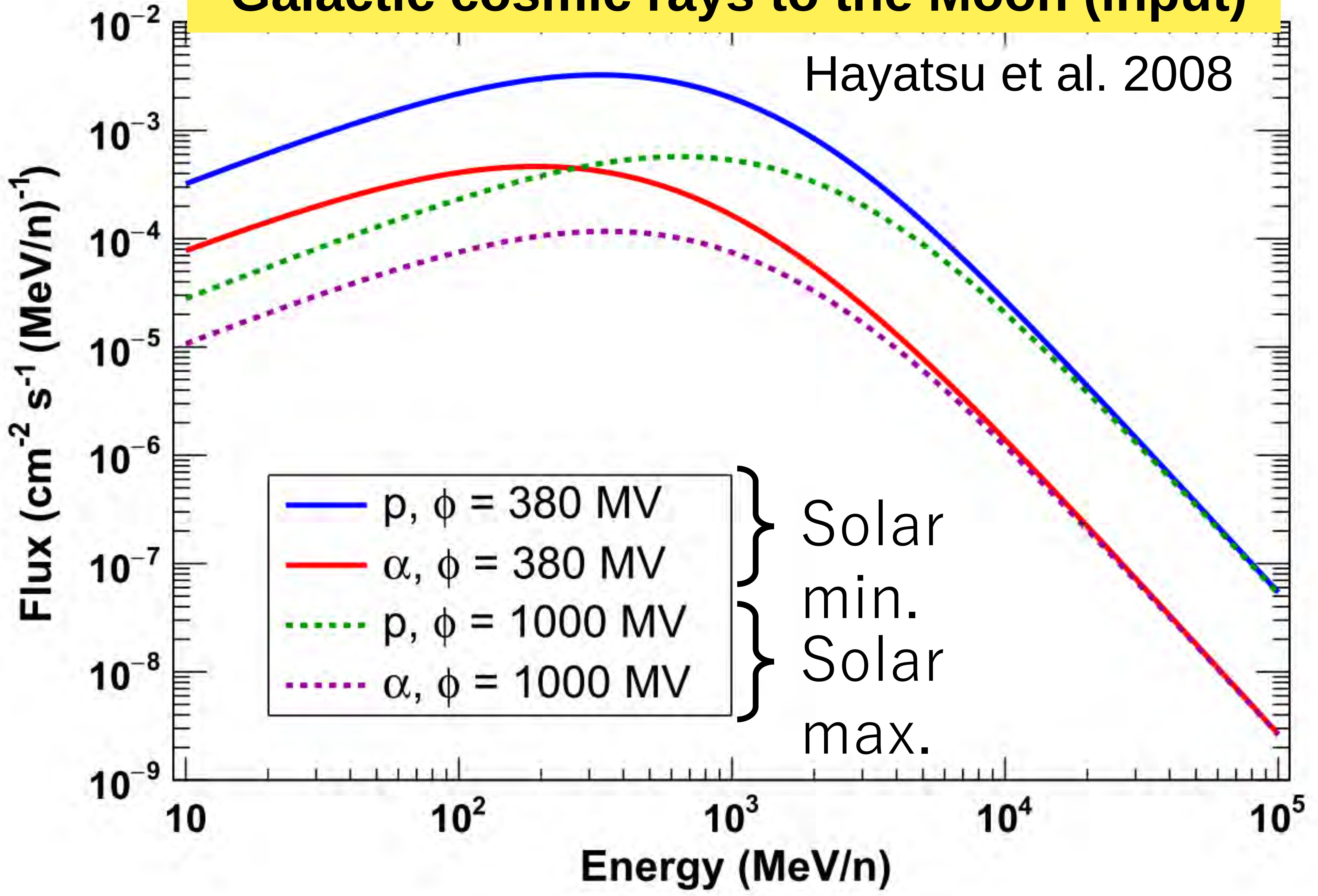


How to find lunar water resources using cosmic rays?

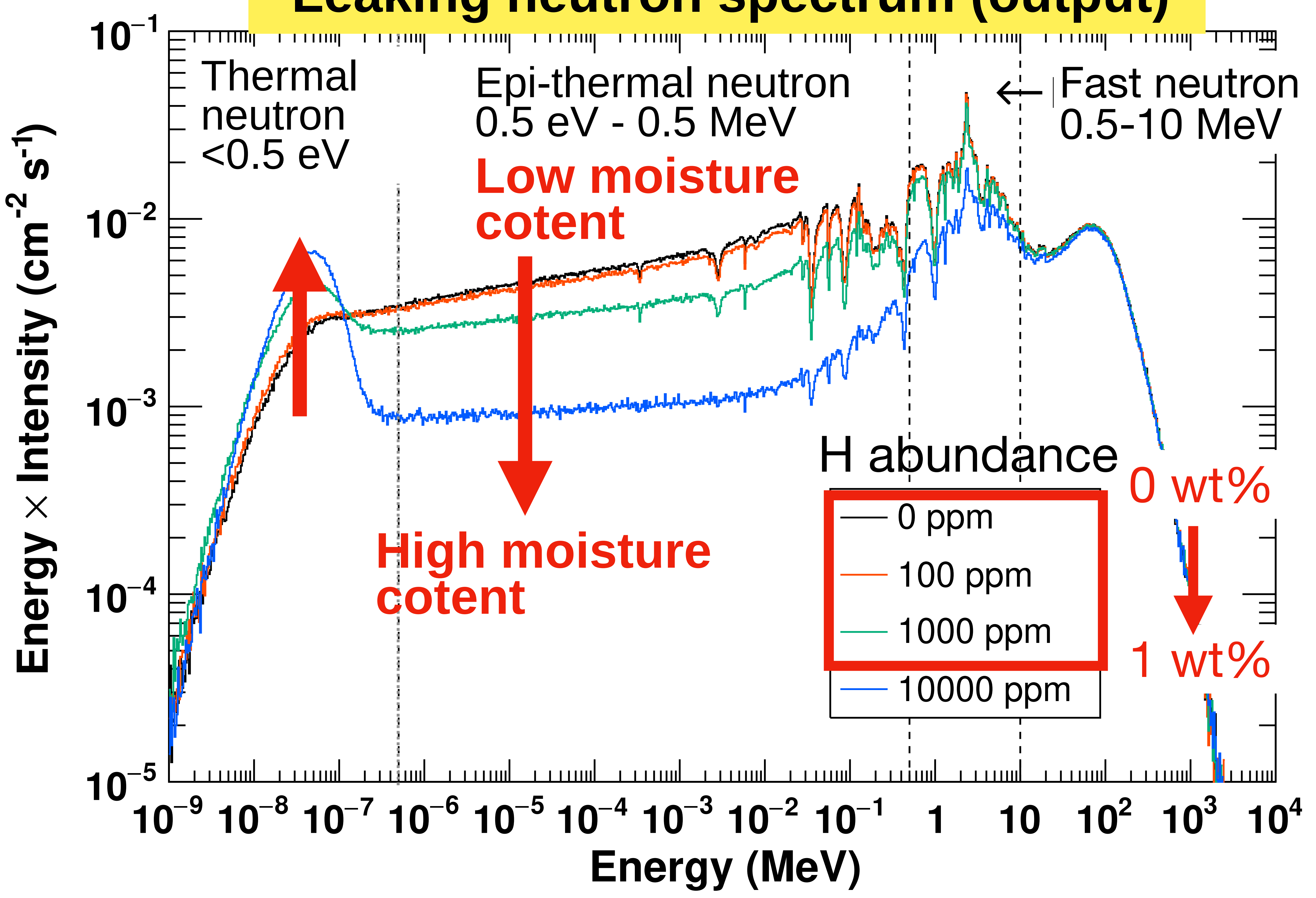

How to find lunar water resources using cosmic rays?
Moon Moisture Targeting Observatory
onboard the ISS
MoMo
TarO
Moon Moisture Targeting Observatory (MoMoTarO)
Galactic cosmic rays colliding with the lunar surface produce fast neutrons, which leak out as low-energy (epi-)thermal neutrons via proton (water) scattering.
• Lunar rover missions will locate subsurface water in a non-contact way via neutron monitors.
Lunar rover
MoMoTarO
Galactic cosmic rays (Proton)
Thermal neutron
Fast neutron
Gamma rays
Water (proton)
Nuclear reactions
Neutron capture

Simulated cosmic-ray induced neutron spectrum

Galactic cosmic rays to the Moon (input)



Leaking neutron spectrum (output)

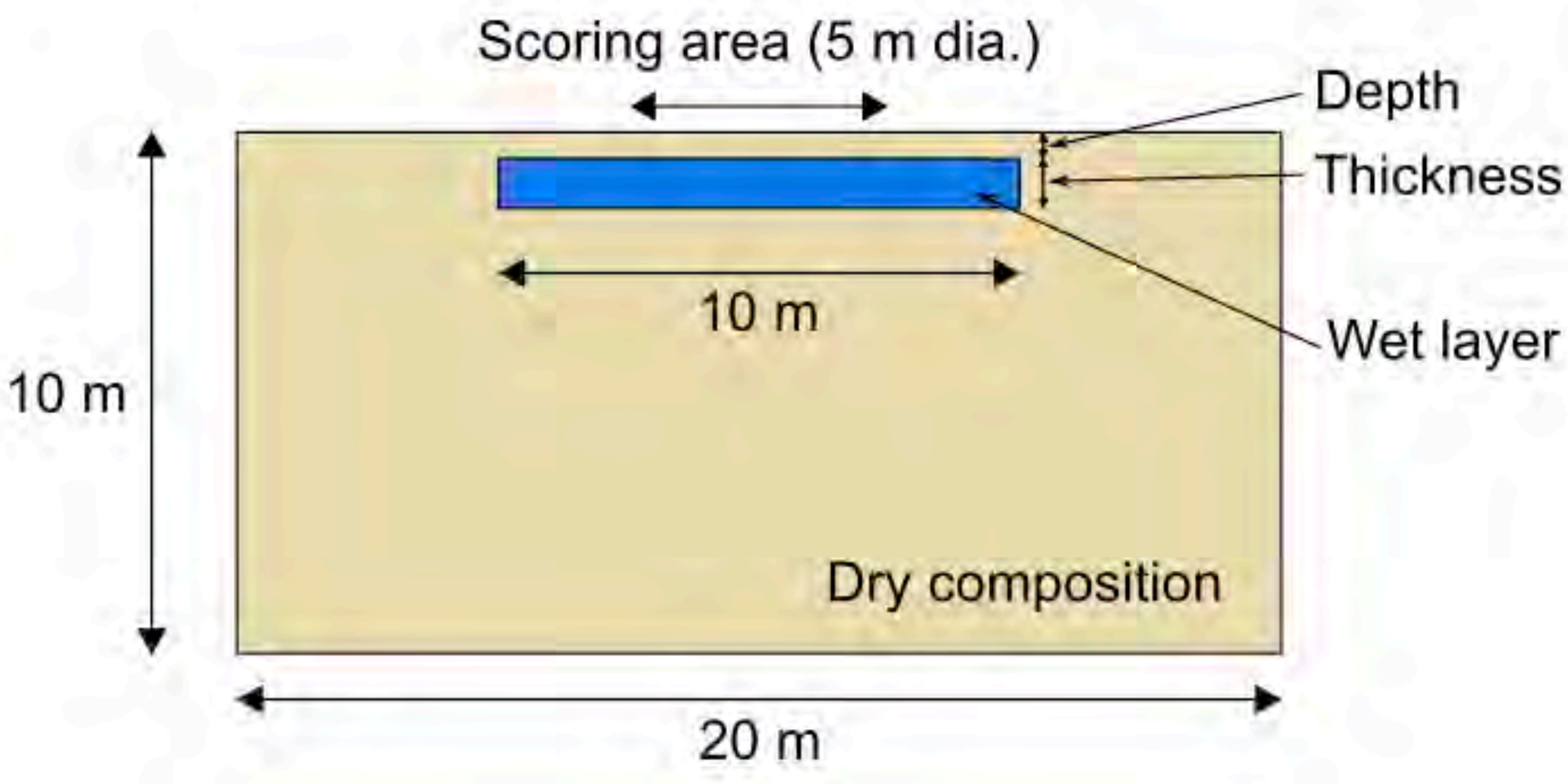


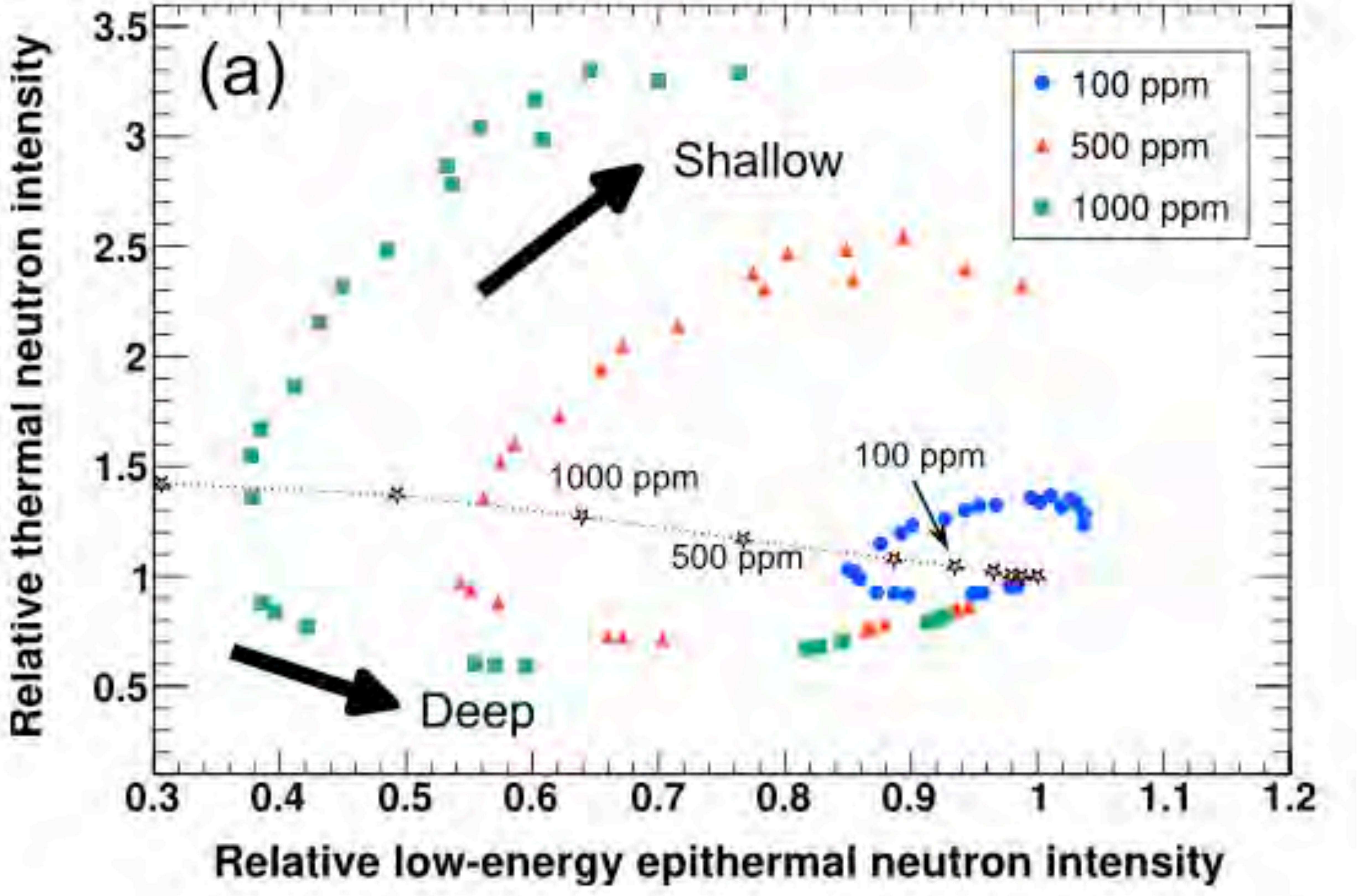
- We performed Geant4 Monte Carlo particle simulations to evaluate lunar surface neutrons induced by galactic cosmic rays at several situations of subsurface water.
- Combined measurements of thermal, epithermal, and fast neutrons can be used to estimate the thickness, depth, and moisture content of water resources under the surface.

Kusano, Nagaoka, Enoto, et al., Planetary and Space Science (2024)

see also Feldman et al. (1998), Lawrence et al. (2006), Sanin et al. (2017)

Simulated cosmic-ray induced neutron spectrum





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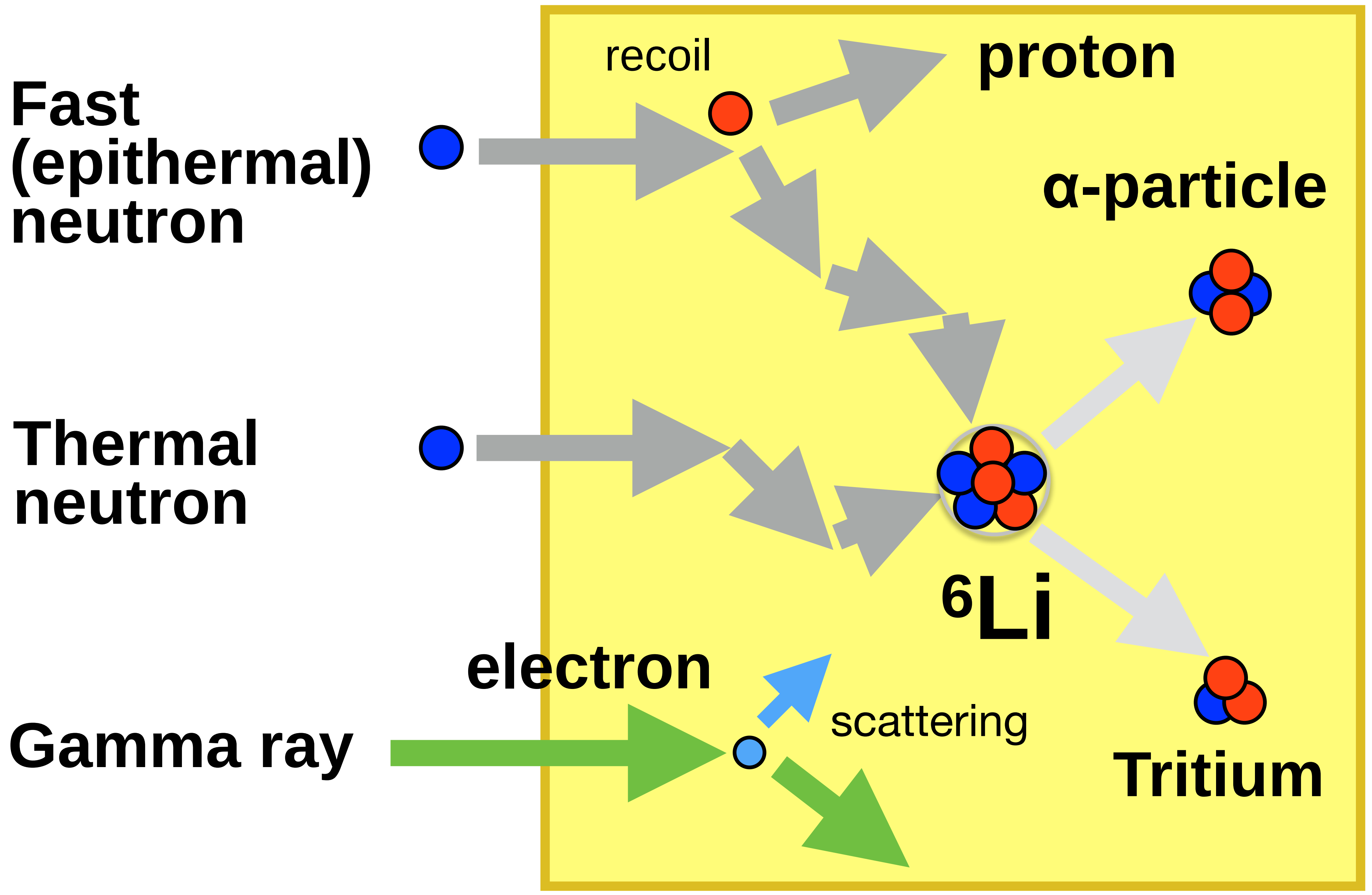
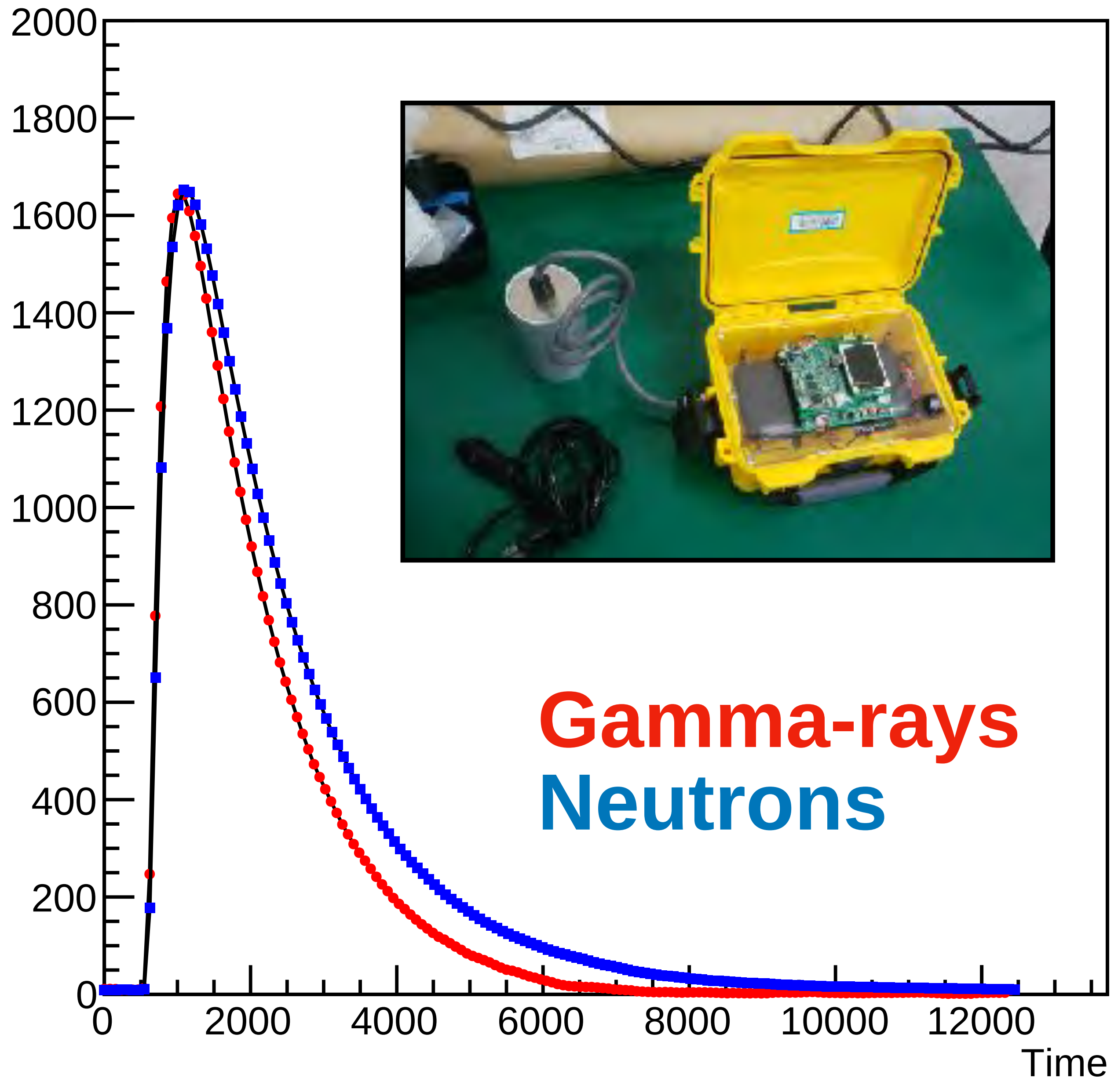
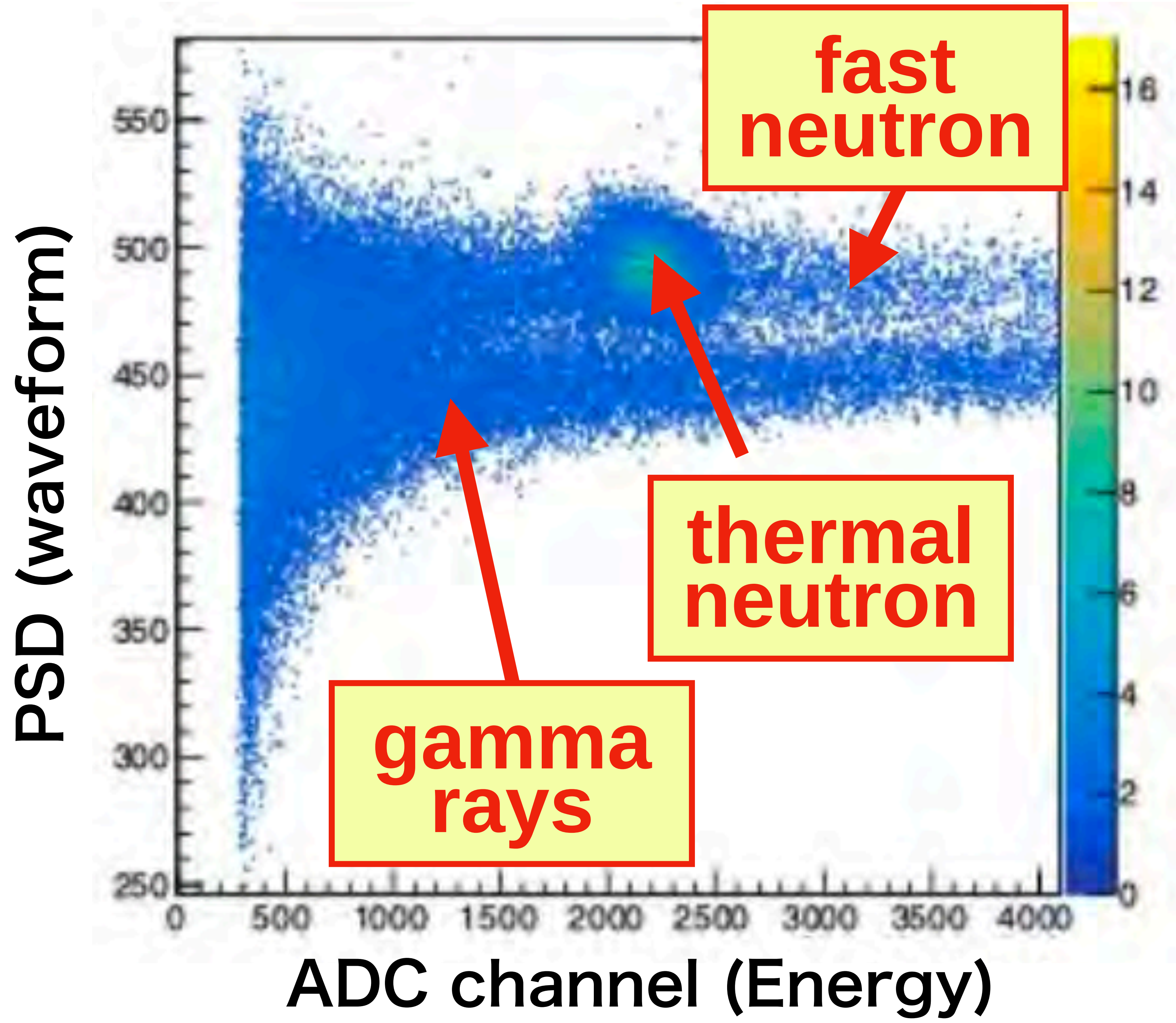
Developments of the scintillator-based MoMoTarO

- Helium gas detectors are popular for neutron measurements, but recently expensive.
- We employed lithium-doped plastic scintillators and multi-pixel photodetectors (SiPM), which are less expensive, resistant to vibration, compact and power-saving.
- Thanks to the pulse waveform difference, we can utilize Pulse Shape Discrimination (PSD) technique to discriminate thermal, fast neutrons and gamma rays, which provide high S/N ratio with excluding background gamma-ray events. (Note. gamma rays can be also used to know composition of the lunar soil).

Physical processes of the scintillator





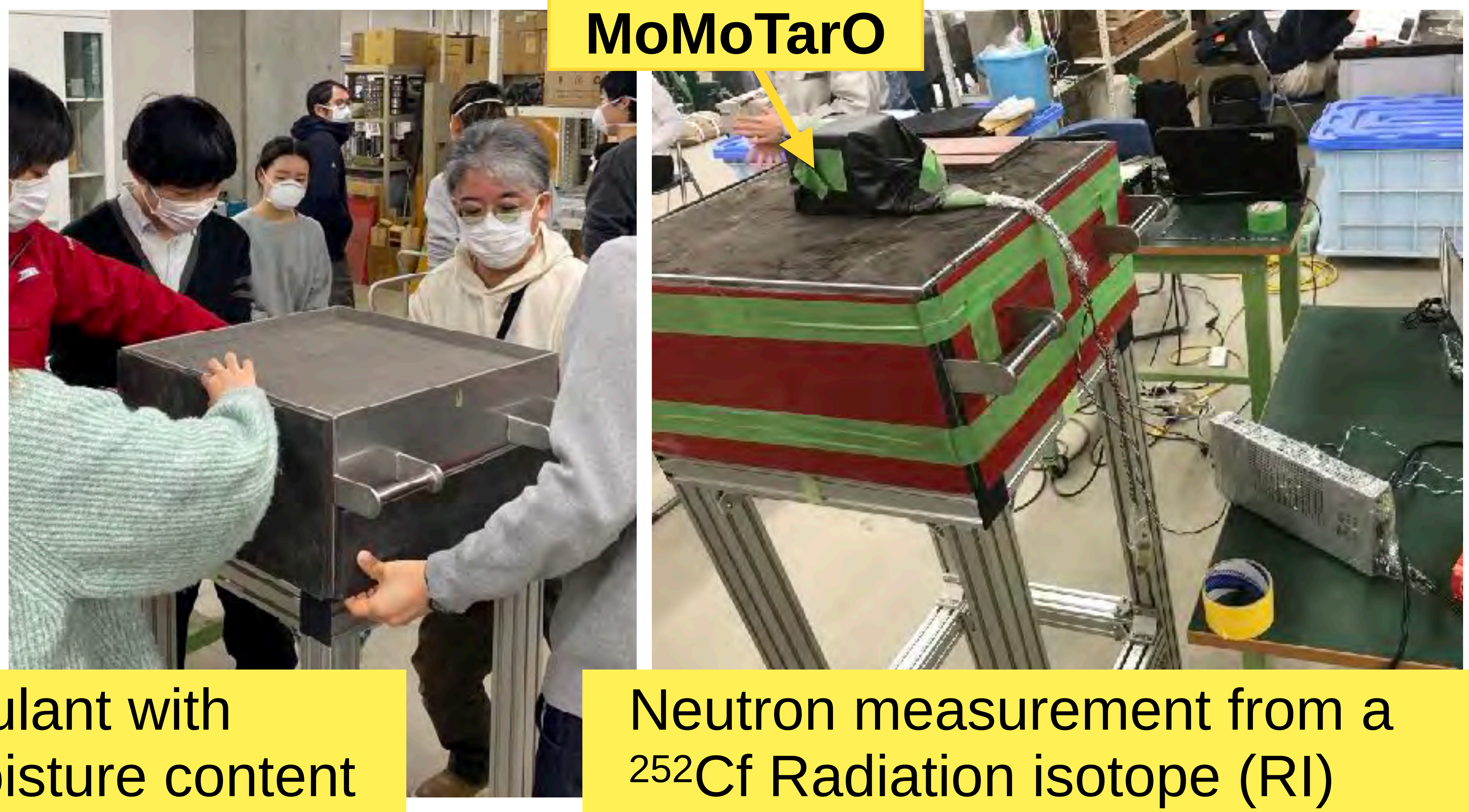


Lunar simulant experiment at low-water content

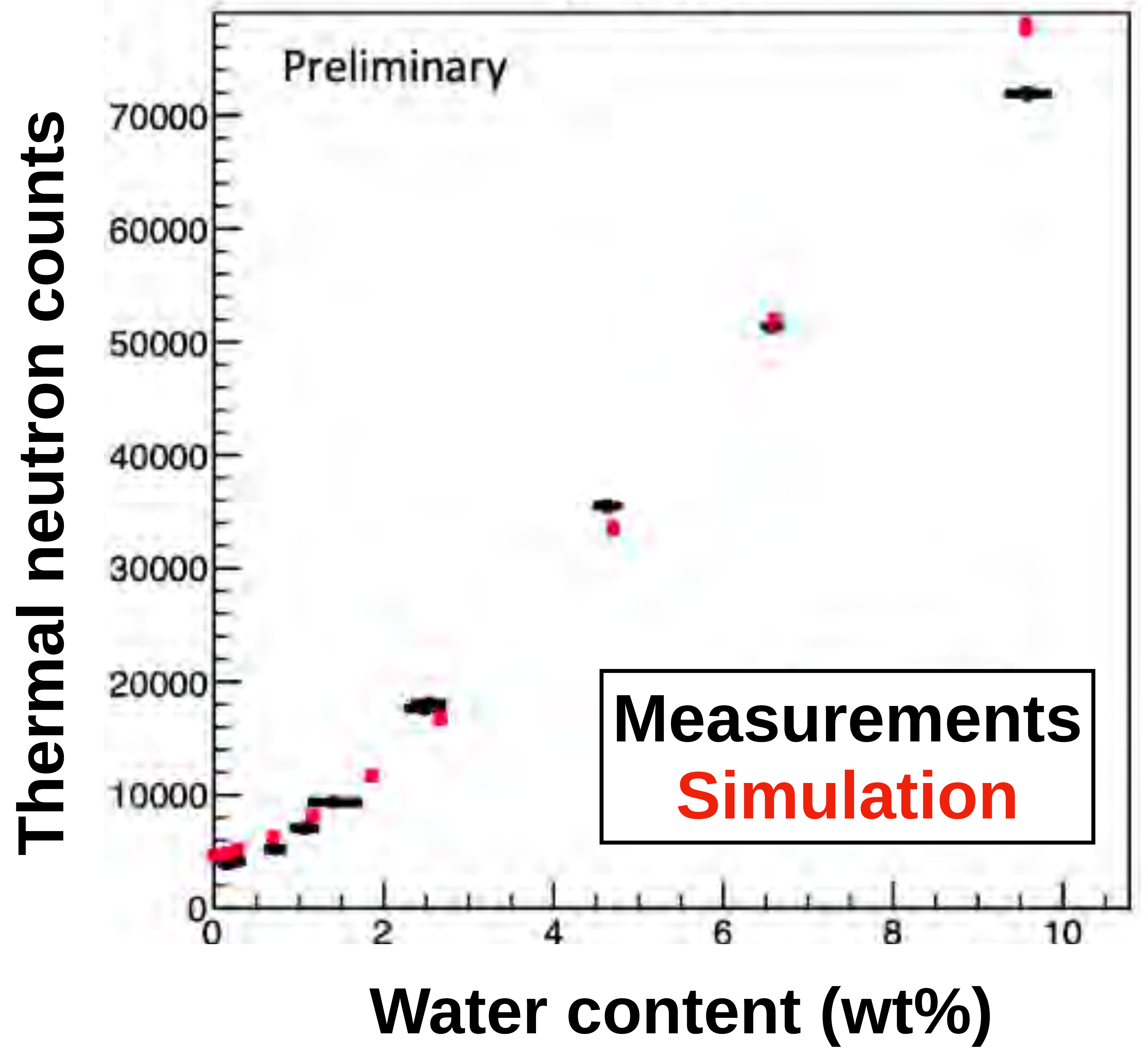
- In collaboration with civil engineering experts, we have established a method for controlling extremely low water content (<1% by weight) of lunar regolith simulant (FJS-1).
- We have verified that the lunar water content can be measured non-contactly down to 1% or less using the MoMoTarO, and the results are consistent with our Geant4 simulation result.
- By further using epithermal neutrons, we expect to achieve the measurement of extremely low water content level at <~0.5%.

MoMoTarO CubeSat 1U Model

Prepare simulant with controlled moisture content



Neutron measurement from a ^{252}Cf Radiation isotope (RI)



Space verification on the ISS planned in 2026

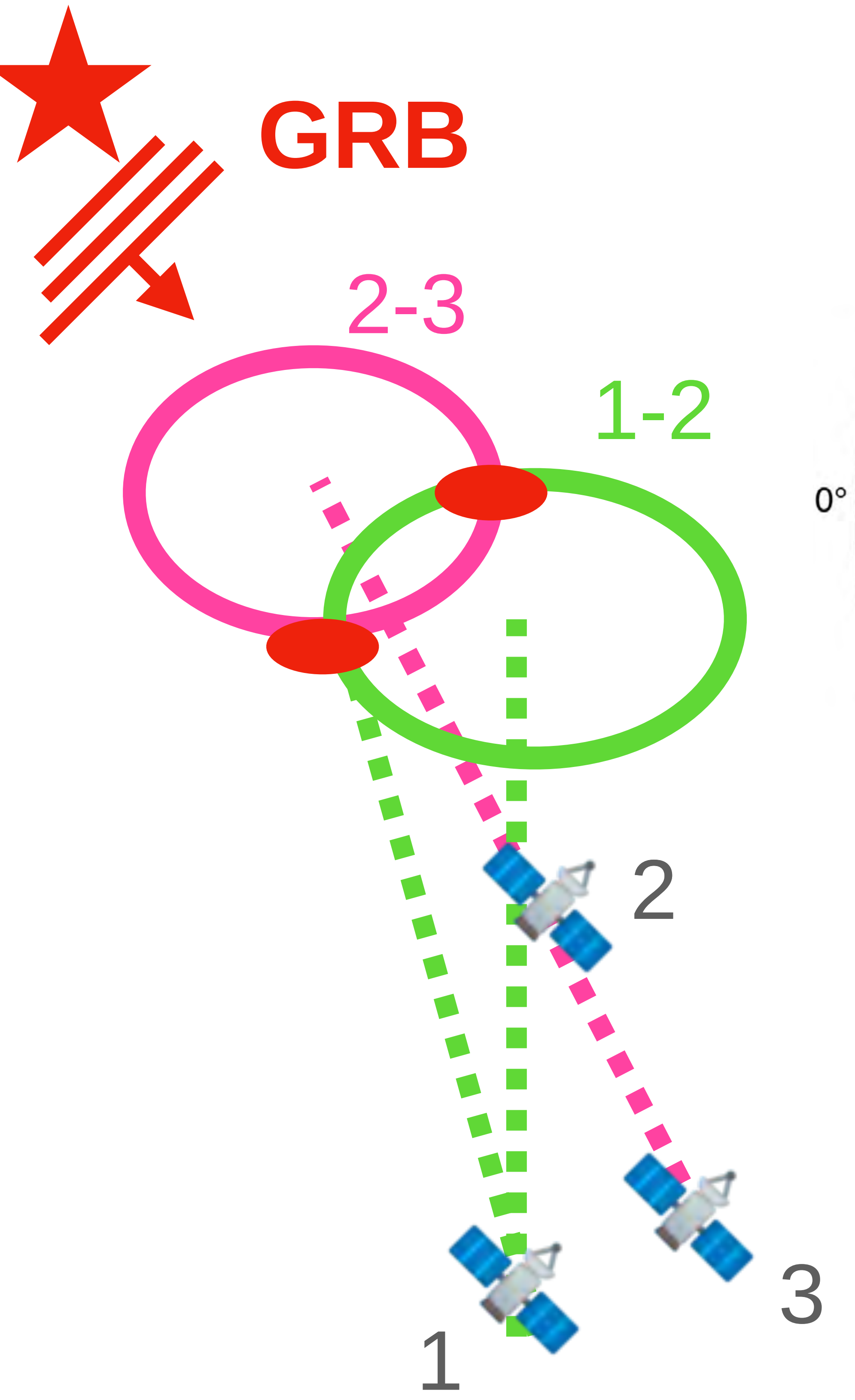
- Selected as a space project at the ISS in 2026 to install the MoMoTarO-ISS on the the Japanese exposed experiment module “Kibo” (i-SEEP/SpySE) for six months.
- MoMoTarO-ISS module is composed of 8 scintillator plates: total weight < 2 kg, size < CubeSat 2U (100x100x138 mm3), drive voltage 5 V, and total power < 3.5 W
- Currently conducting environmental testing on the ground with the aim of improving the Technical Readiness Level (TRL) in space verification supported by Space BD.
- We can also aim at measuring gamma-ray bursts, solar/albedo neutrons for science.

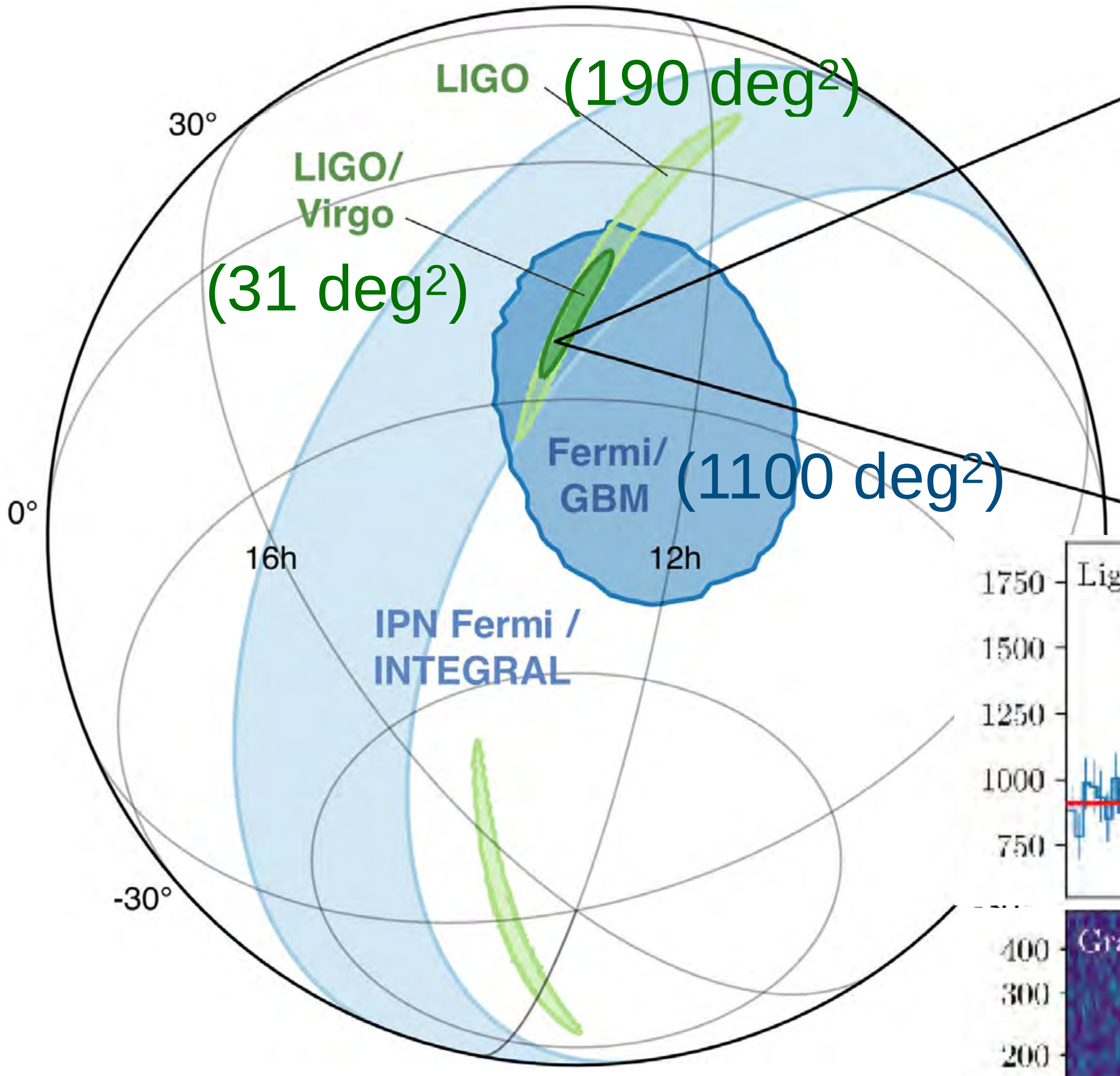
“Cislunar science” using the lunar exportation

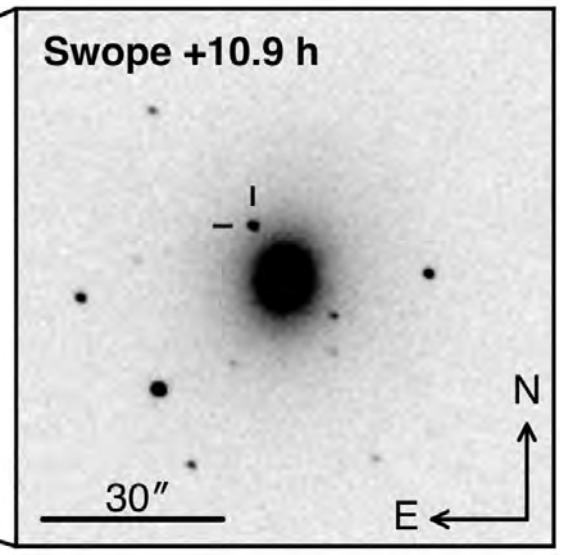
- We aim to deploy multiple MoMoTarO detectors on lunar rovers and the lunar orbiter. This radiation measurement network around the moon will be able to detect many gamma-ray bursts (GRBs).
- This will establish a new framework for "Cislunar science."

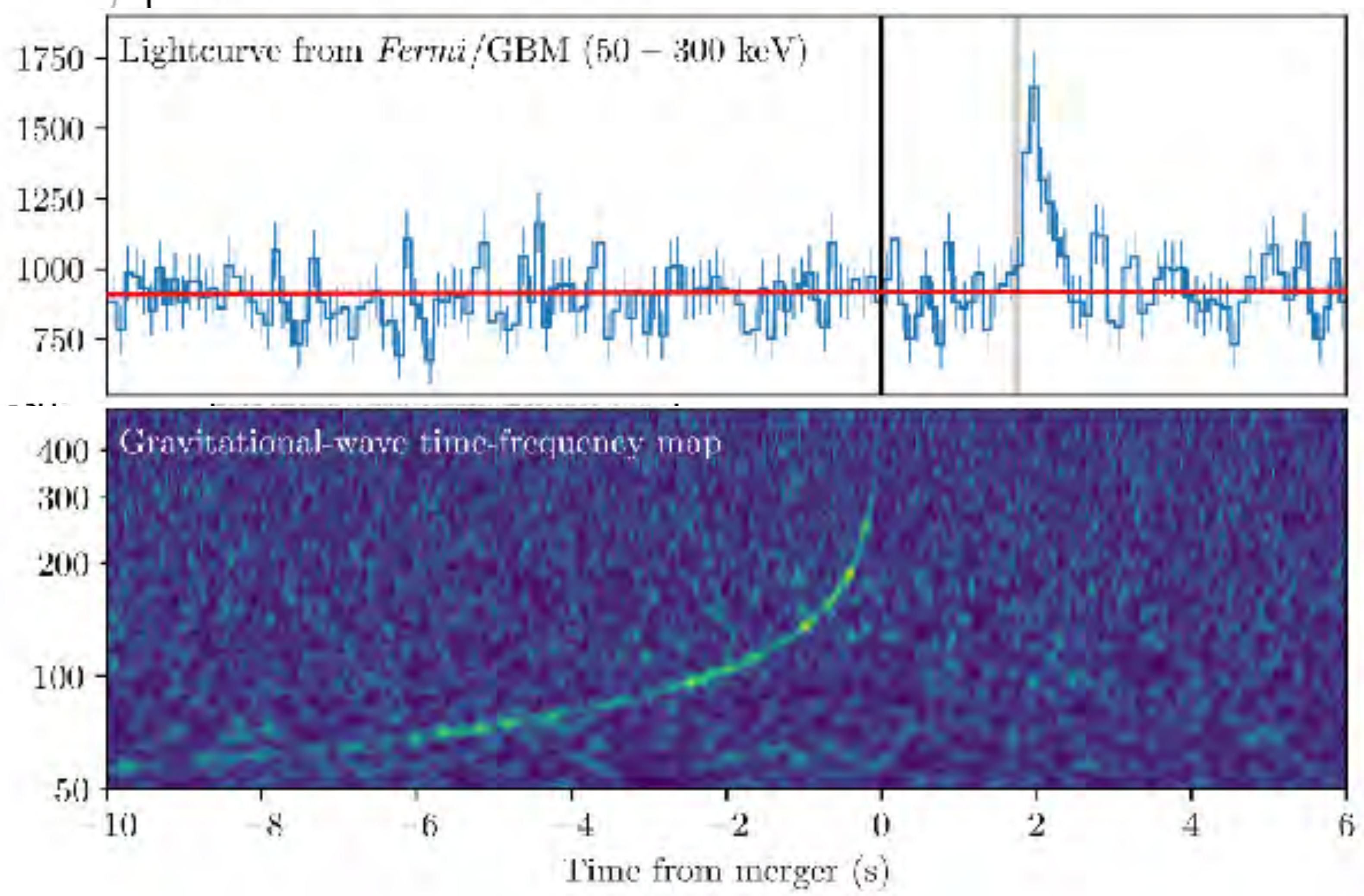
High-energy astro/particle physics on the Moon

- MoMoTarO is designed to detect gamma-ray bursts (GRB) on the Moon. Using the long distance between the Earth and the Moon, we want to precisely measure the arrival direction of GRBs using the principle of triangulation, as known as the InterPlanetary gamma-ray burst timing Network (IPN).
- If we can quickly measure the directions of short GRBs associated with gravitational waves, prompt follow-up observations of ground-based large optical/infrared telescopes can determine their host galaxies. We can contribute to gravitational wave cosmology.
- We are also aiming to measure the neutron lifetime using MoMoTarO series around the Moon.





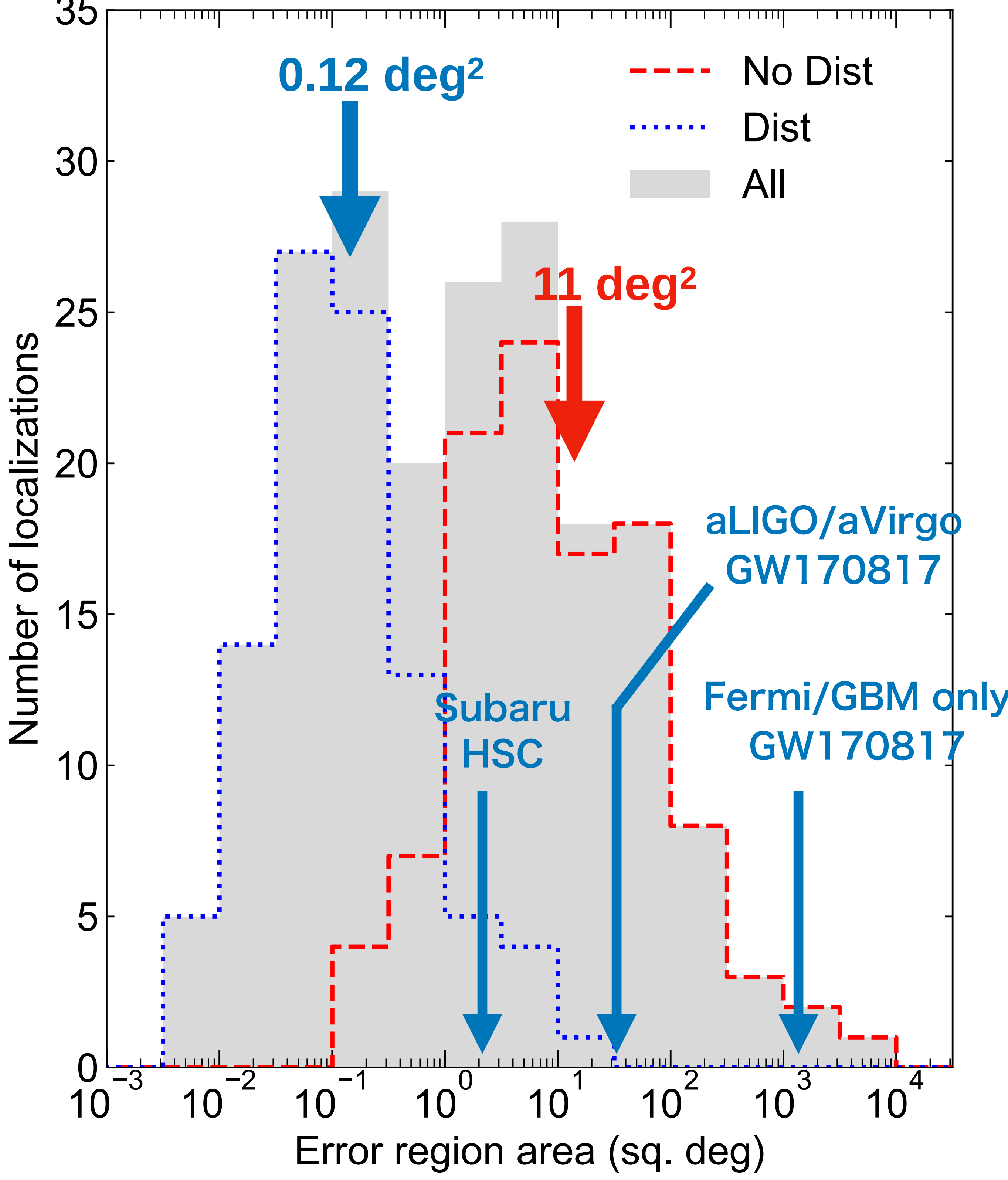




LIGO & Virgo Scientific Collaboration, ApJ (2017)

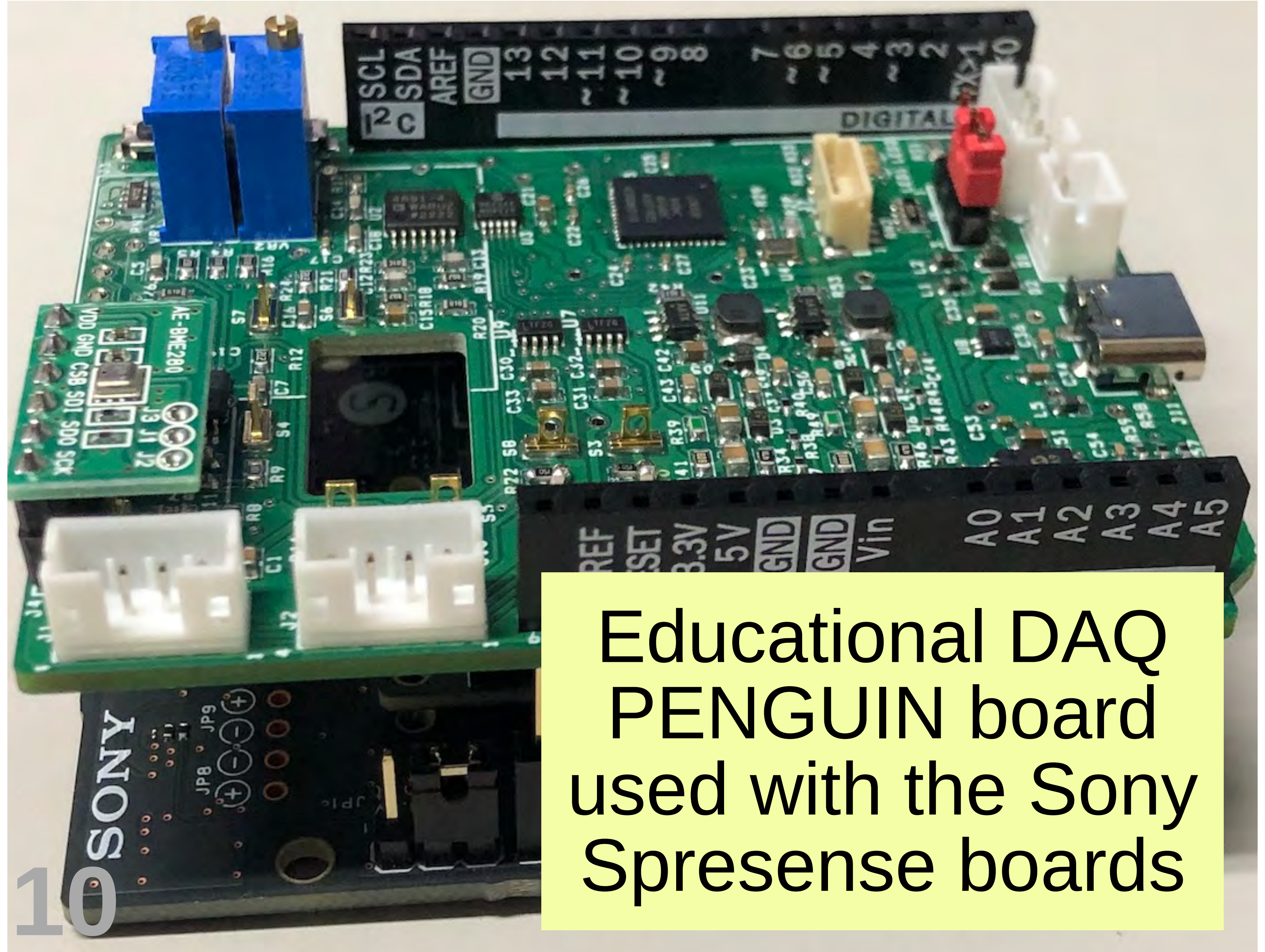
Example GW 170817
NS-NS merger

Sivinkin et al., ApJS (2022)



Education and outreach for next space generation

- Education of new generation for future space experiments is important for this long project: Developed new educational boards and small balloon experiments.
- Ph.D students of our team were awarded in two contests for small satellites by the proposal of lunar orbiter water resource exploration: Satellite design content in Japan (2022), and small sat conference in US (2023).
- Attracting wide interest of different players: e.g., visit and conversations with the two MEXT ministers (politicians), and outreach through academic crowdfunding.



Educational DAQ PENGUIN board used with the Sony Spresense boards

Small Sat Conference, 31st Annual Frank K. Redd Student Competition (2023 August 10)

Visit of the MEXT Minister (RIKEN, 2022 August, 31)

Academic crowdfunding for future cislunar science (until October 17)

だれもが月で研究できる時代へ

――アジャイル宇宙開発に挑戦！

月の水探しから、月を使った科学研究へ

Summary

- Moon Moisture Targeting Observatory (MoMoTarO) is a neutron and gamma-ray radiation monitor and means multidisciplinary collaboration for future lunar rovers payloads to search for water resources.
- We developed a new scintillator-based and multi-layer radiation detector to measure thermal, epithermal, and fast neutrons simultaneously with gamma rays (GRBs) using the pulse shaper discrimination technique.
- We established an on-ground examination method of low water-content lunar simulant and verified the capability of water-content measurement of MoMoTarOs supported by the Geant4 particle simulations.
- We will bring the MoMoTaro to the ISS in 2026 for the first space verification test, and hope to detect solar neutron events and GRBs, which will be performed around the Moon.

Czech-Japanese collaboration for the GRB IPN network?