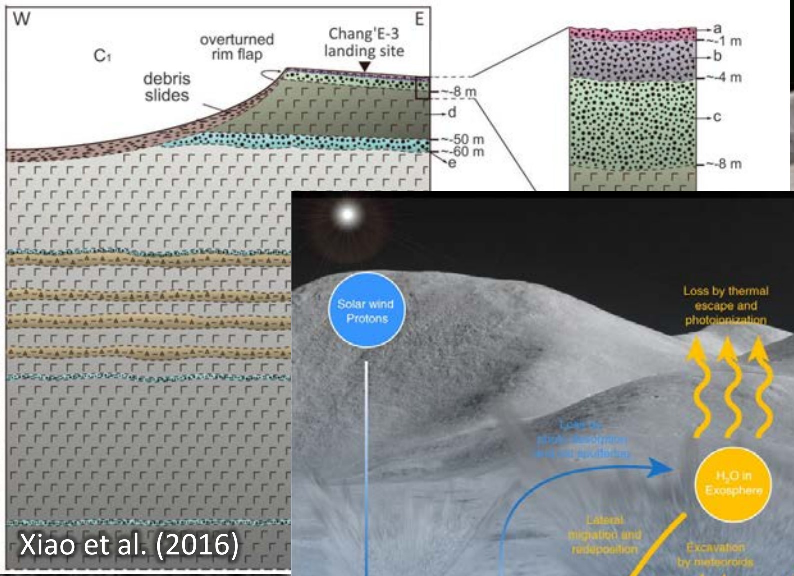
CSRI
Center for Space Resources and Innovation

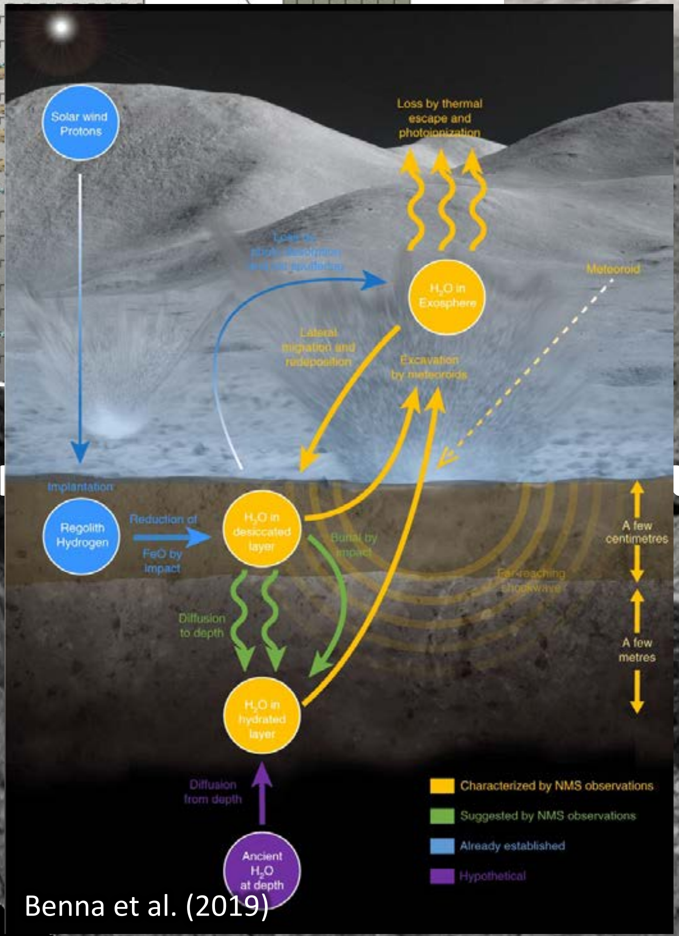
Dielectric Analyzer for Detecting Water and Metallic Mineral Resources

Makito Kobayashi, Hideaki Miyamoto, Airi Toida, and LDA Team

Importance of the subsurface for resource explorations

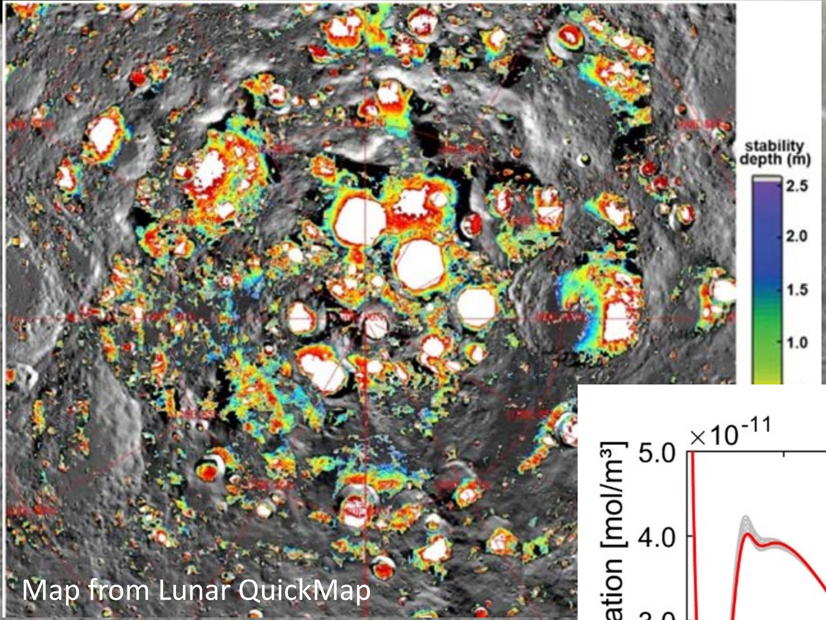


Xiao et al. (2016)

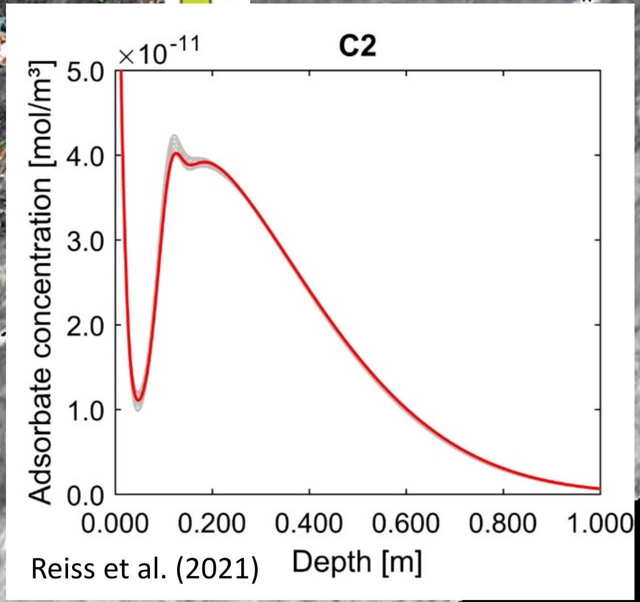


Benna et al. (2019)

Regolith reco… …ution.



Map from Lunar QuickMap

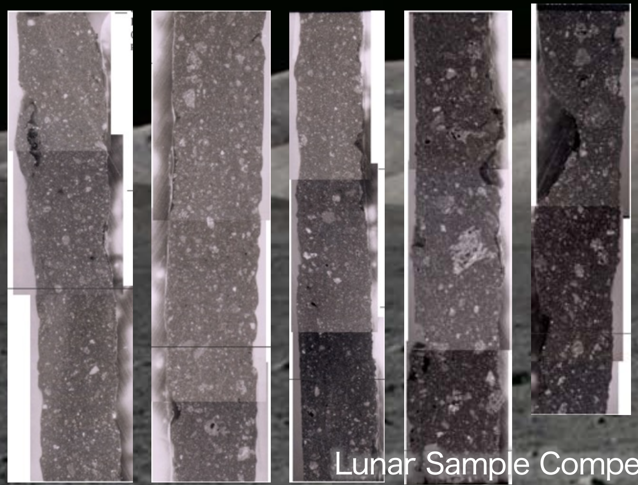


Reiss et al. (2021)

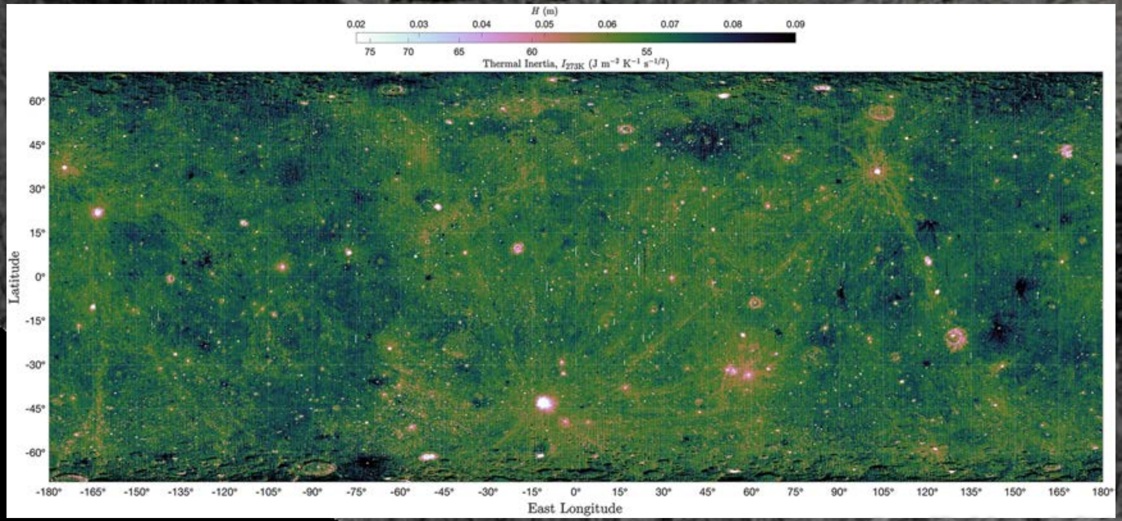
At a certain depth, water-ice can stably exist.

Low temperature regolith can trap water molecules.

Difficulties to obtain the subsurface information

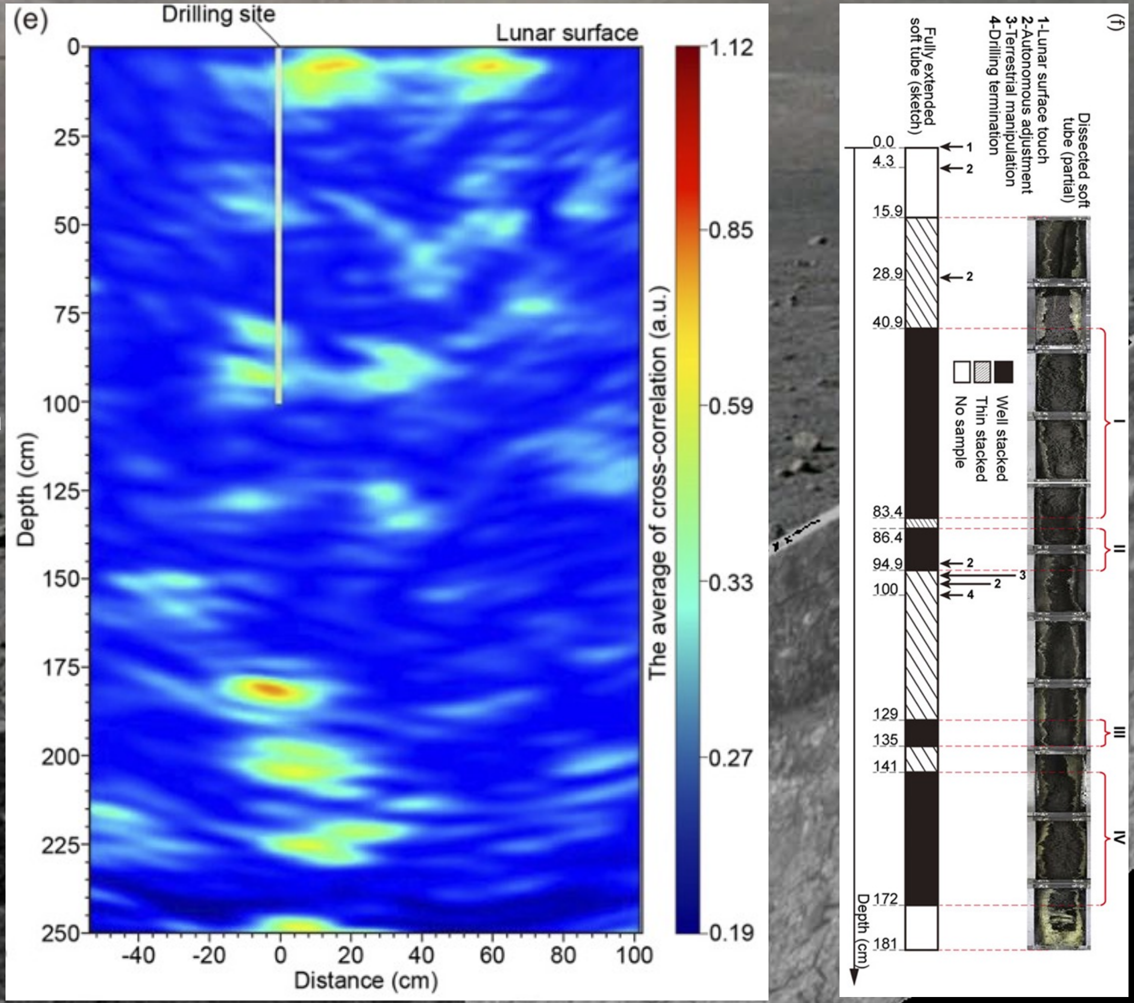


Heterogeneity of Apollo's core samples on the centimeter to millimeter scale



Bandfield et al. (2011)

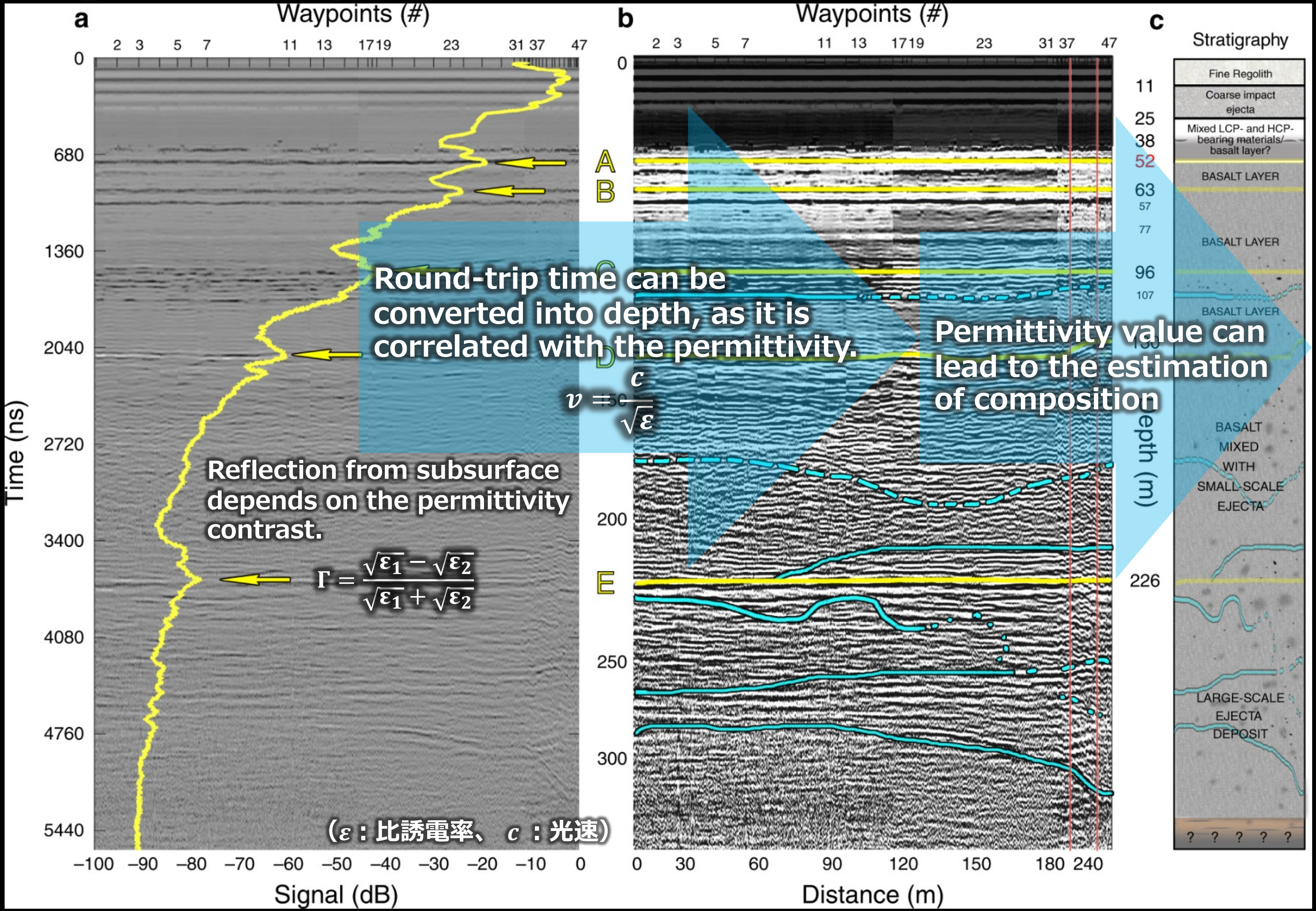
Significant variation of the thermal inertia even on the very shallow subsurface (< a few cm)



Zhang et al. (2023)

Existence of high-density materials (e.g., boulder)

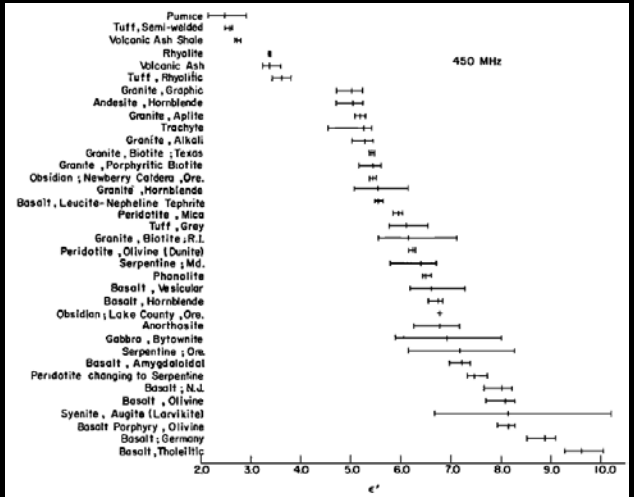
Electromagnetic exploration can obtain subsurface information



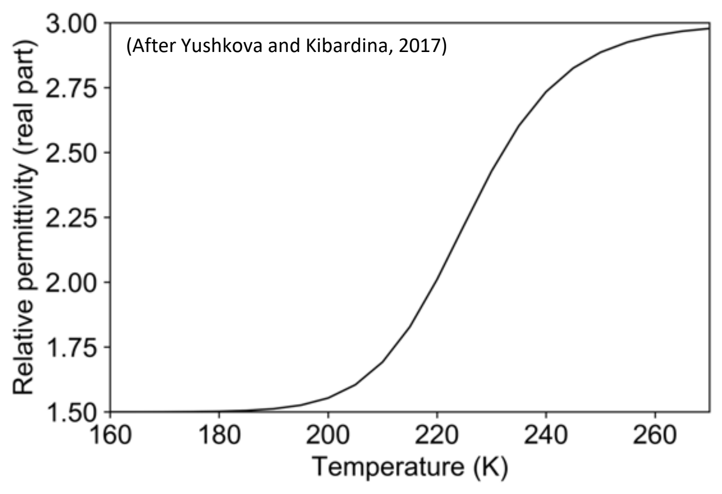
A precise understanding of permittivity is key to obtaining subsurface information

Associated parameters with permittivity

Materials

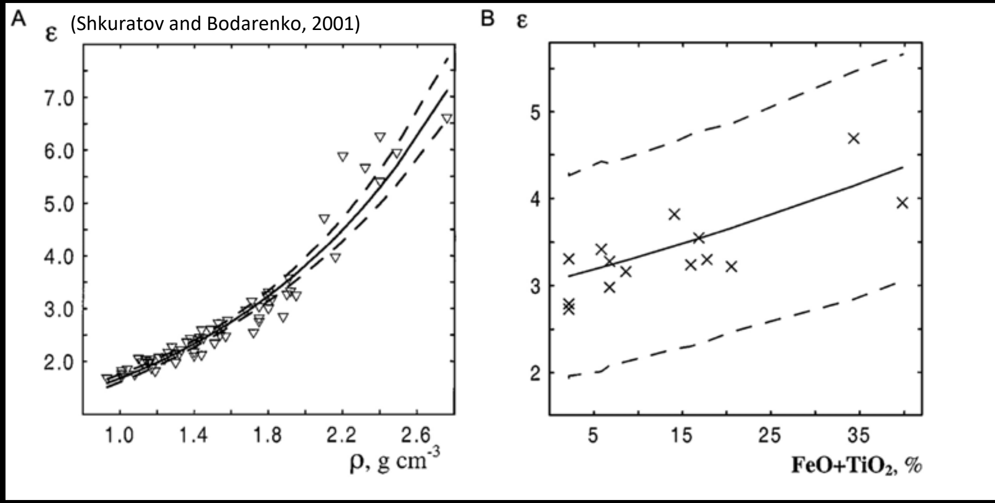


Temperature



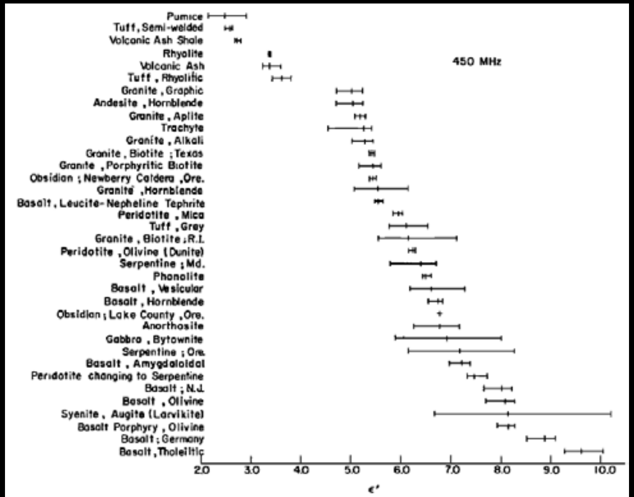
Packing density

Chemical composition

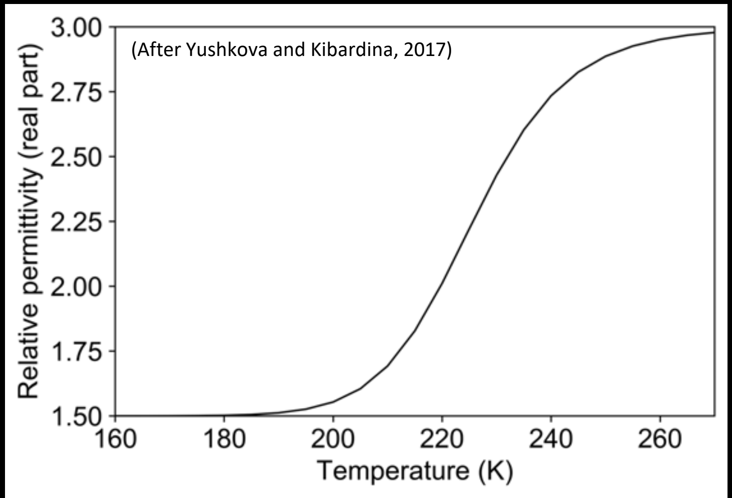


Useful parameters for detecting/quantifying variable resources

Materials

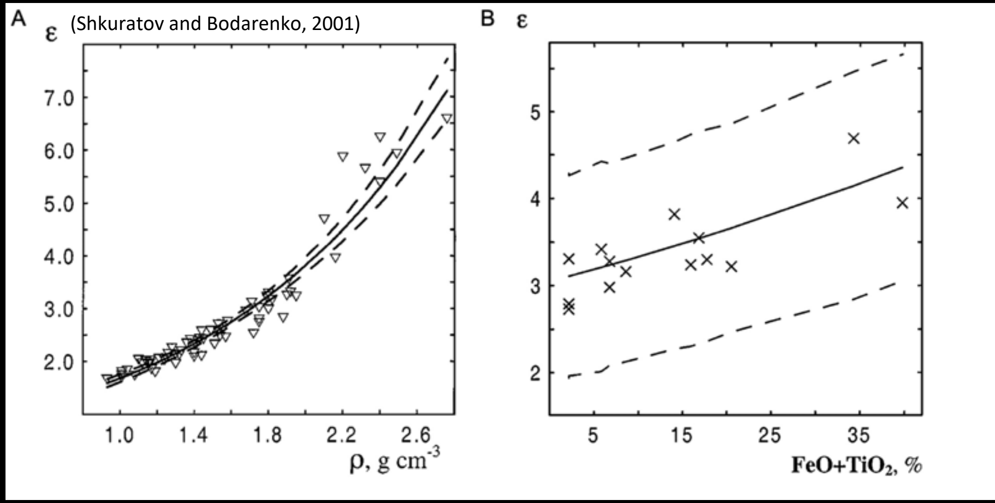


Temperature

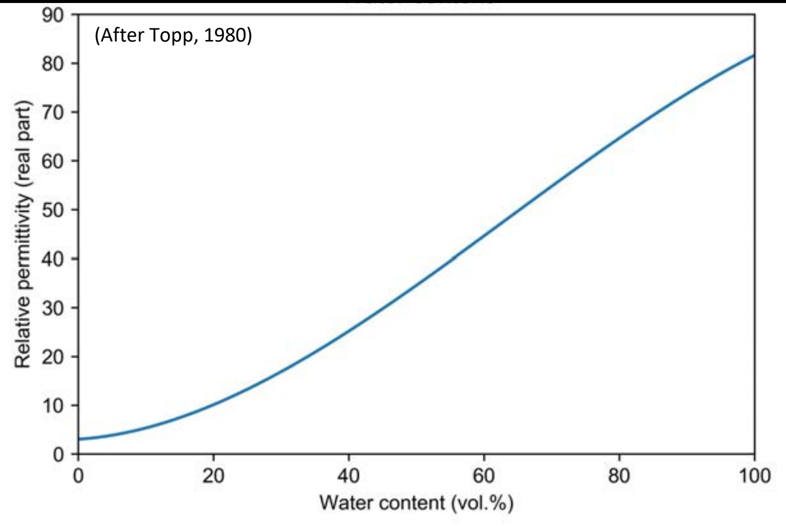


Packing density

Chemical composition



Easiest: Liquid water



Water-ice/rock fraction

$$\varepsilon_{(T=T_1)}^{\frac{1}{3}} = f_{rock}\varepsilon_{rock(T=T_1)}^{\frac{1}{3}} + f_{ice}\varepsilon_{ice}^{\frac{1}{3}} + (1 - f_{rock} - f_{ice})\varepsilon_{air}^{\frac{1}{3}}$$

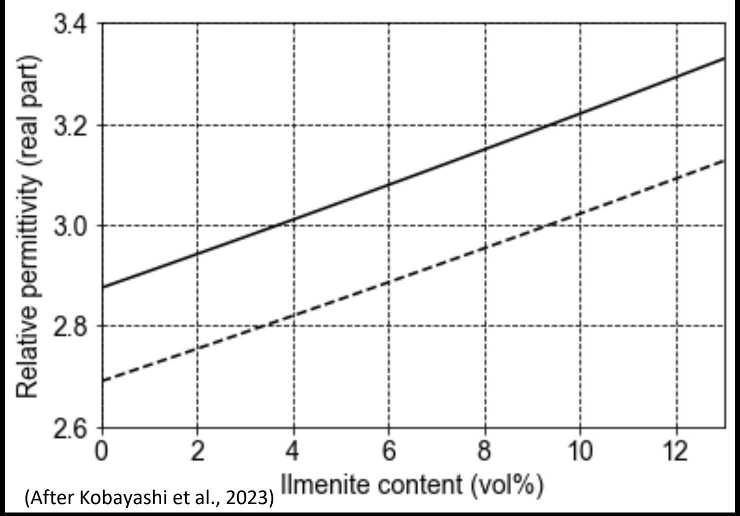
$$\varepsilon_{(T=T_2)}^{\frac{1}{3}} = f_{rock}\varepsilon_{rock(T=T_2)}^{\frac{1}{3}} + f_{ice}\varepsilon_{ice}^{\frac{1}{3}} + (1 - f_{rock} - f_{ice})\varepsilon_{air}^{\frac{1}{3}}$$

($\varepsilon_{(T=T_i)}$: permittivity of lunar regolith at temperature $T_{i,}$
$\varepsilon_{rock(T=T_i)}$: permittivity of lunar simulant at temperature)

$$\varepsilon_{(T=T_1)}^{\frac{1}{3}} - \varepsilon_{(T=T_2)}^{\frac{1}{3}} = f_{rock}(\varepsilon_{rock(T=T1)}^{\frac{1}{3}} - \varepsilon_{rock(T=T2)}^{\frac{1}{3}})$$

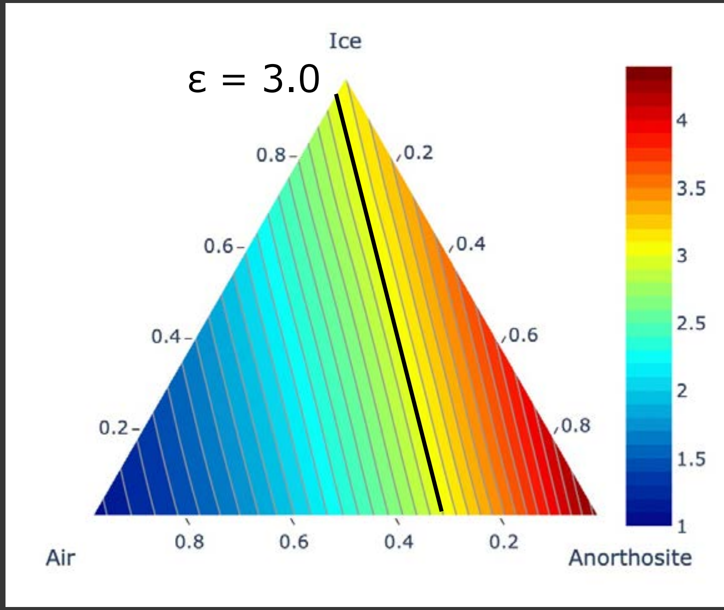
Accuracy: ~1 wt%

Metal resources



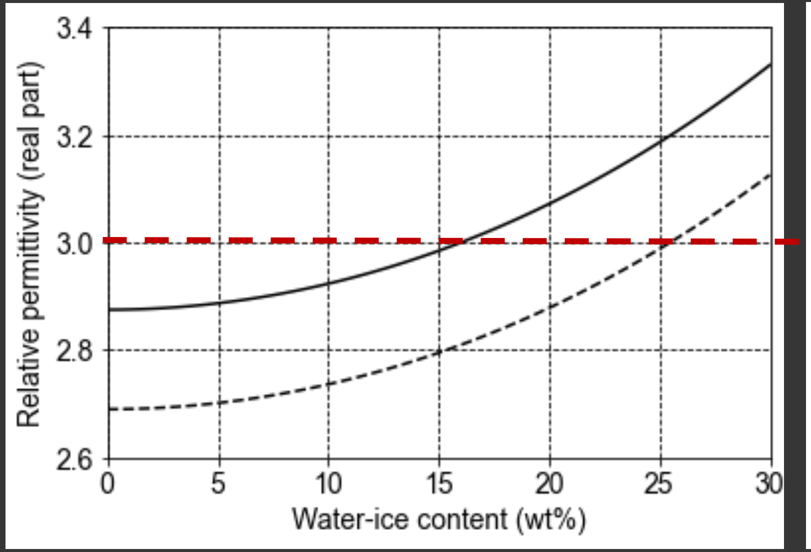
Be careful to obtain the information from permittivity

Anorthositic regolith containing water-ice

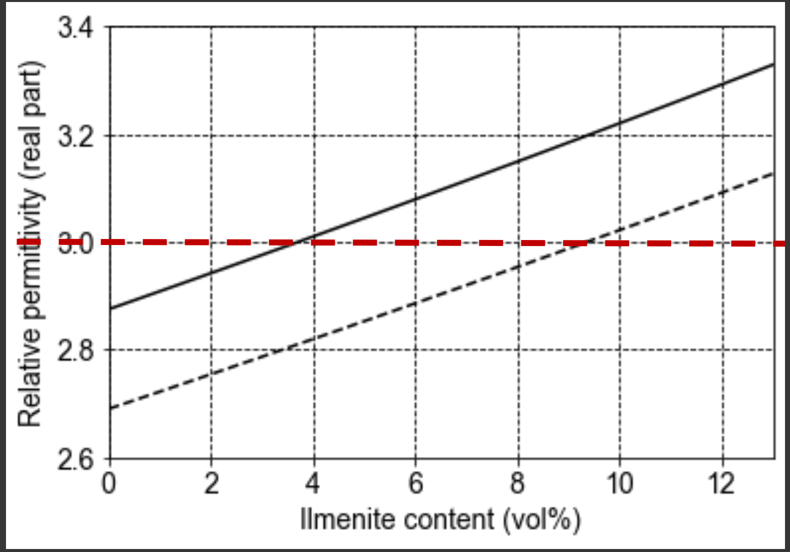


A permittivity value cannot decide the fraction of rock-ice-void.

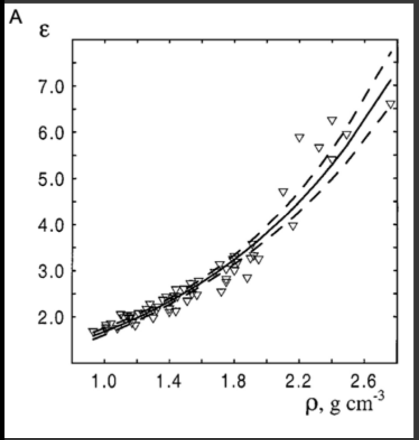
Mixture of regolith and water-ice



Mixture of regolith and ilmenite



Even if the porosity is determined, it is impossible to distinguish whether the effects are due to the presence of water ice or the presence of high dielectric materials, such as ilmenite.



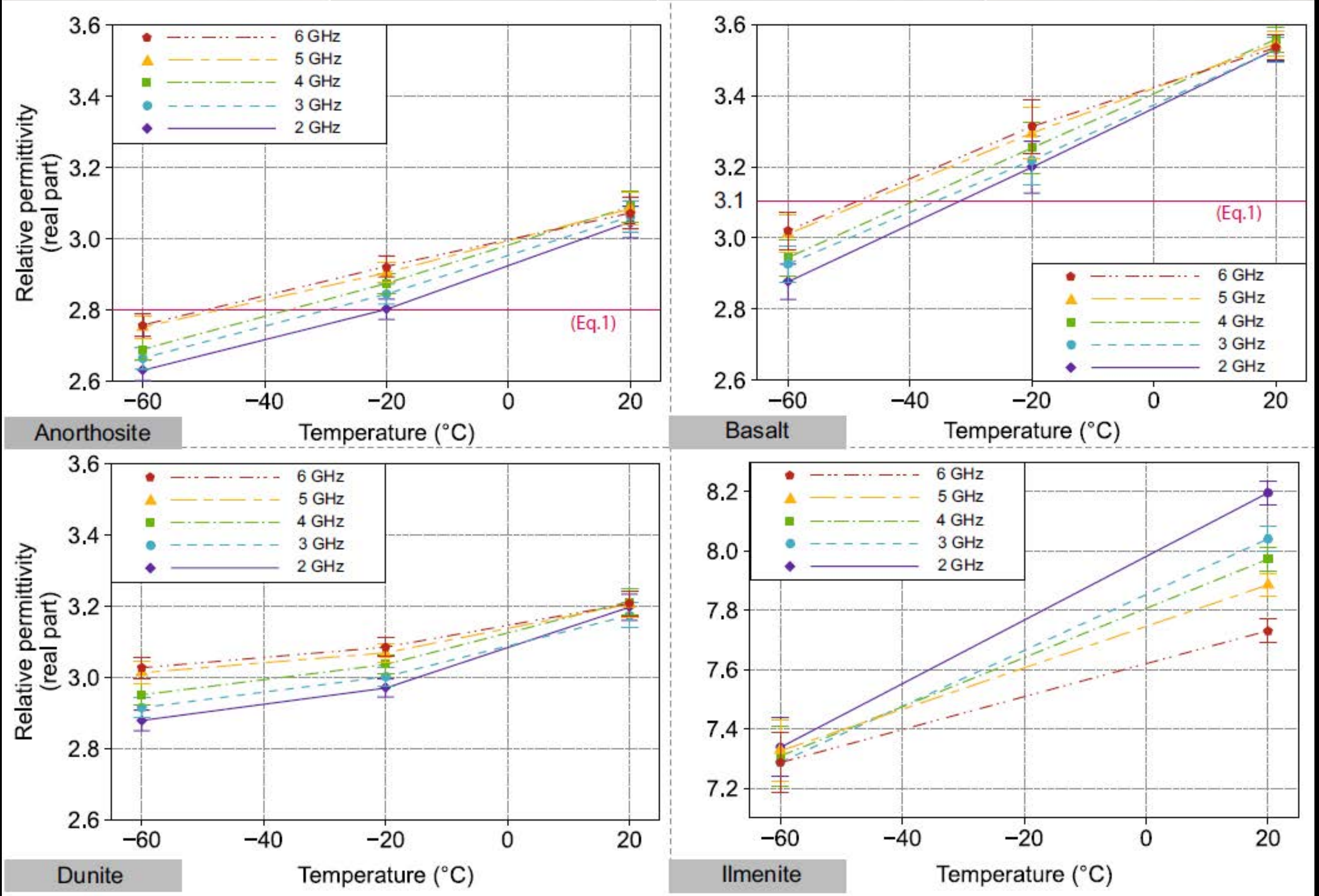
Uncertainty of bulk density dependency

Shkuratov and Bodarenko (2001)

Complied data with inconsistent composition, measurement environment, and frequency is treated as if it were accurate.

For the detection of water-ice, additional, more precise analytical strategy is essential.

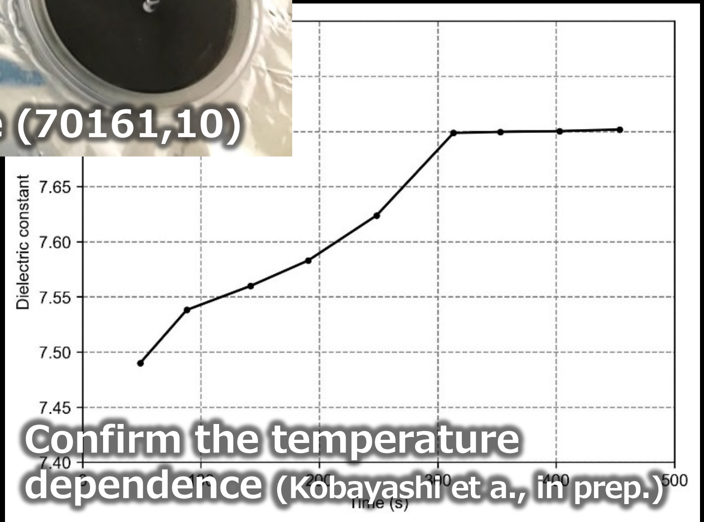
Findings: Importance of temperature dependency (Kobayashi et al., 2023)



Developed lunar regolith simulant
（Anorthosite, Basalt, Dunite, Ilmenite）

Permittivity can vary 6-18% at -60℃ to +20℃, depending on materials
→Suggesting that temperature-dependent permittivity change is not uniform in different composition regolith.

Apollo sample (70161,10)



Confirm the temperature dependence (Kobayashi et a., in prep.)

Findings: Different temperature dependency of rock and ice

While rock has temp. dependence, water-ice does not (@UHF band)

Permittivity mixing model of the regolith with water-ice at different temp.

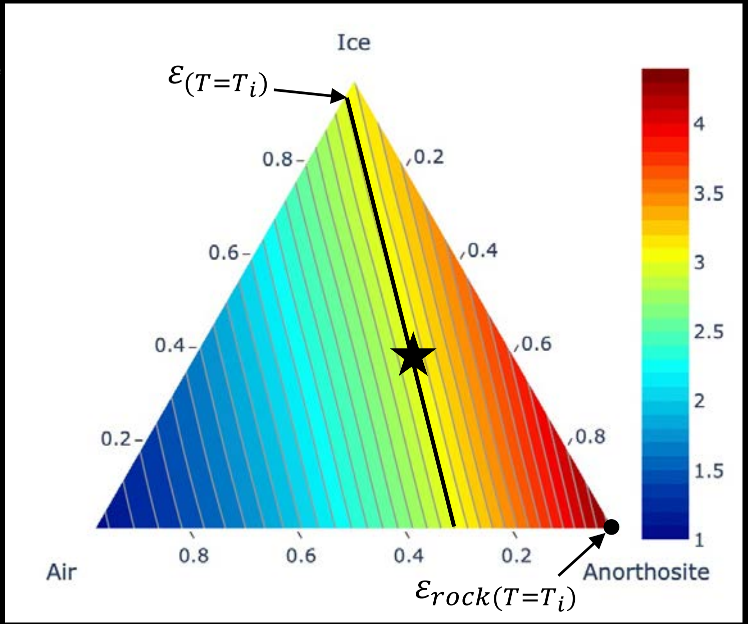
$$\varepsilon_{(T=T_1)}^{\frac{1}{3}} = f_{rock}\varepsilon_{rock(T=T_1)}^{\frac{1}{3}} + f_{ice}\varepsilon_{ice}^{\frac{1}{3}} + (1 - f_{rock} - f_{ice})\varepsilon_{air}^{\frac{1}{3}}$$

$$\varepsilon_{(T=T_2)}^{\frac{1}{3}} = f_{rock}\varepsilon_{rock(T=T_2)}^{\frac{1}{3}} + f_{ice}\varepsilon_{ice}^{\frac{1}{3}} + (1 - f_{rock} - f_{ice})\varepsilon_{air}^{\frac{1}{3}}$$

$\varepsilon_{(T=T_i)}$: In-situ permittivity of lunar regolith with the porosity of $(1 - f_{rock})$ at temperature
$\varepsilon_{rock(T=T_i)}$: True permittivity of lunar regolith without the porosity at temperature T_i
f_{ice}: Volume fraction of water-ice in regolith

$$\Rightarrow \varepsilon_{(T=T_1)}^{\frac{1}{3}} - \varepsilon_{(T=T_2)}^{\frac{1}{3}} = f_{rock}(\varepsilon_{rock(T=T1)}^{\frac{1}{3}} - \varepsilon_{rock(T=T2)}^{\frac{1}{3}})$$

(Miyamoto et al. *in revision*; Kobayashi et al., *2023*)



In-situ and laboratory permittivity measurement at different temp. can determine the porosity, rock fraction, and water-ice content (★)

Accuracy

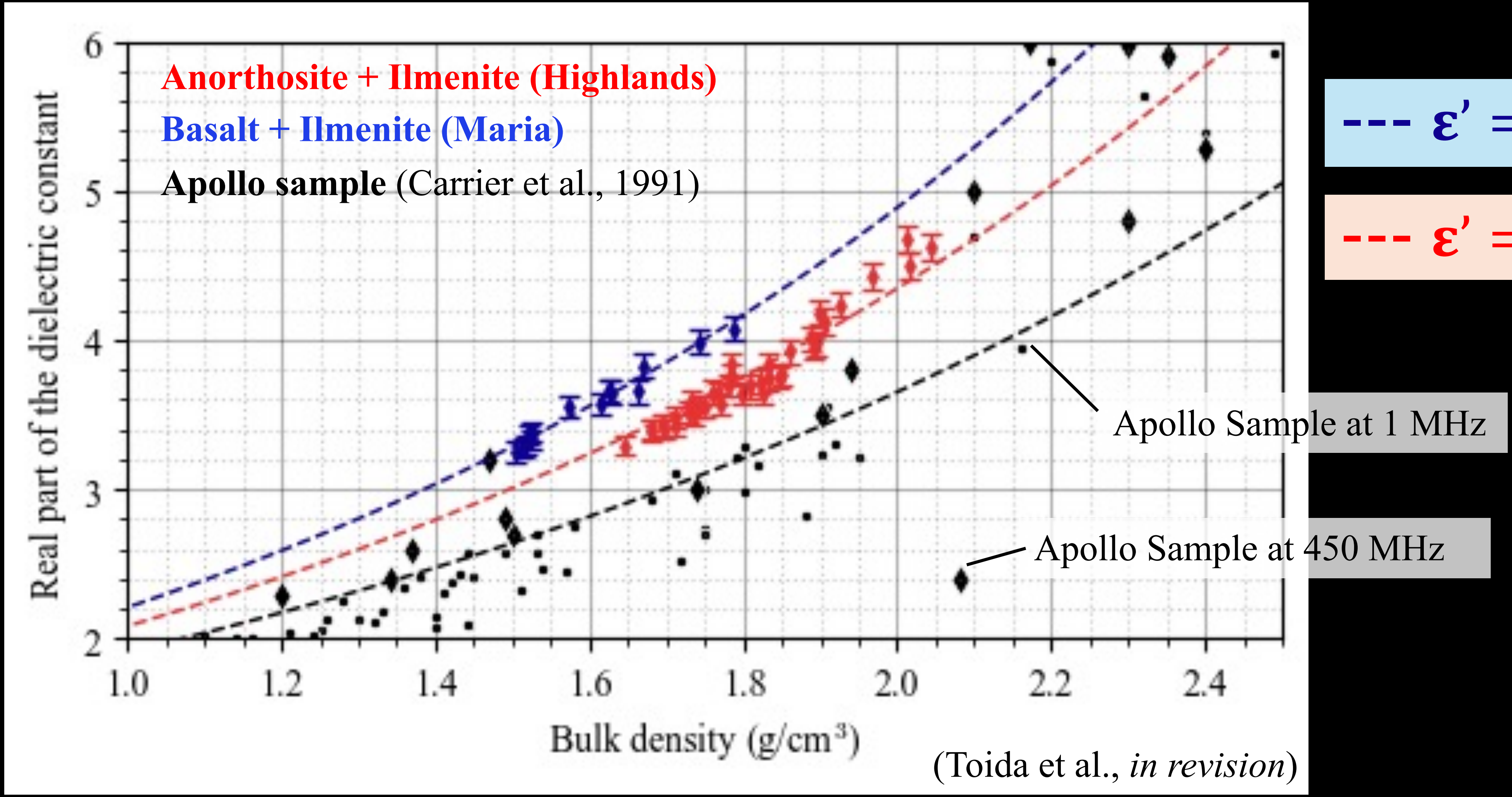
$$f_{rock} = \frac{\varepsilon_{rock(T=T1)}^{\frac{1}{3}} - \varepsilon_{rock(T=T2)}^{\frac{1}{3}}}{\varepsilon_{(T=T1)}^{\frac{1}{3}} - \varepsilon_{(T=T2)}^{\frac{1}{3}}}$$

Assume that the chemical composition
・If we get the return samples and measure their permittivity in laboratory, $\varepsilon_{rock(T=T_i)}$ can be determined in the accuracy of 1.0%.

→The accuracy of rock fraction is about 4%
The accuracy of water-ice content is about **0.6 wt%**, assuming 40% porosity

In-situ measurement at different temperature is essential for quantifying the subsurface water-ice

Findings: $FeO+TiO_2$–permittivity correlation differs between matrix



--- $\varepsilon' = 2.21^{\rho_{bulk}}$

--- $\varepsilon' = 2.08^{\rho_{bulk}}$

Accurate interpretation of permittivity with knowledge of the target bulk composition enables more precise metallic resource exploration

Lunar Dielectric Analyzer (LDA)

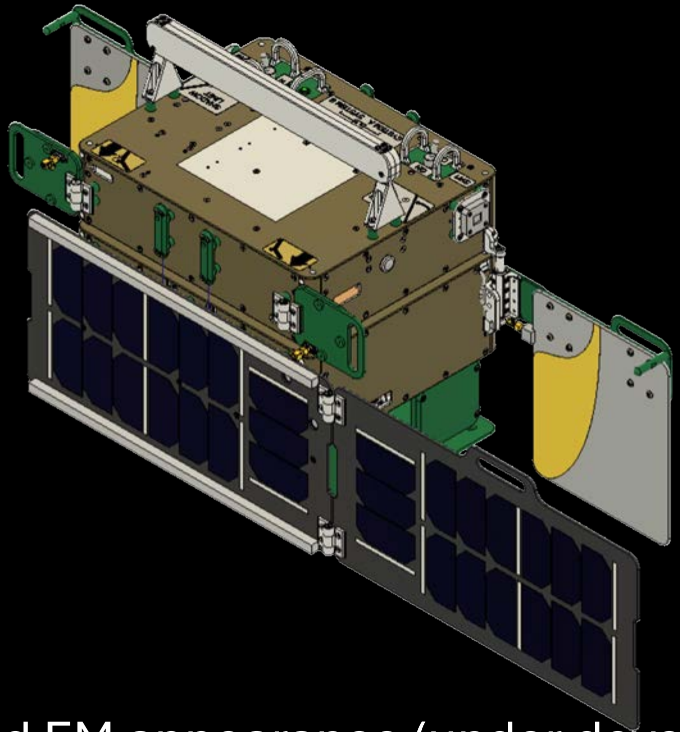
- LDA is a simple and robust instrument designed to measure the dielectric properties of the lunar surface and subsurface in situ for the first time. It will collect essential information about the subsurface structure without disturbing the regolith.

- LDA also aims to measure dielectric properties under varying temperatures caused by shadowing, which may enable the detection of volatile concentrations, if present.

-> Possibly, first lunar in-situ water-ice detection

- Furthermore, LDA is designed to survive the lunar night and conduct dielectric measurements after sunrise, allowing it to distinguish between volatiles originating from the HLS propulsion system and those naturally present in the lunar environment.

(Miyamoto et al. *in revision;* Kobayashi et al. *in revision*)



BBM and EM appearance (under development)

Overview of LDA science objectives

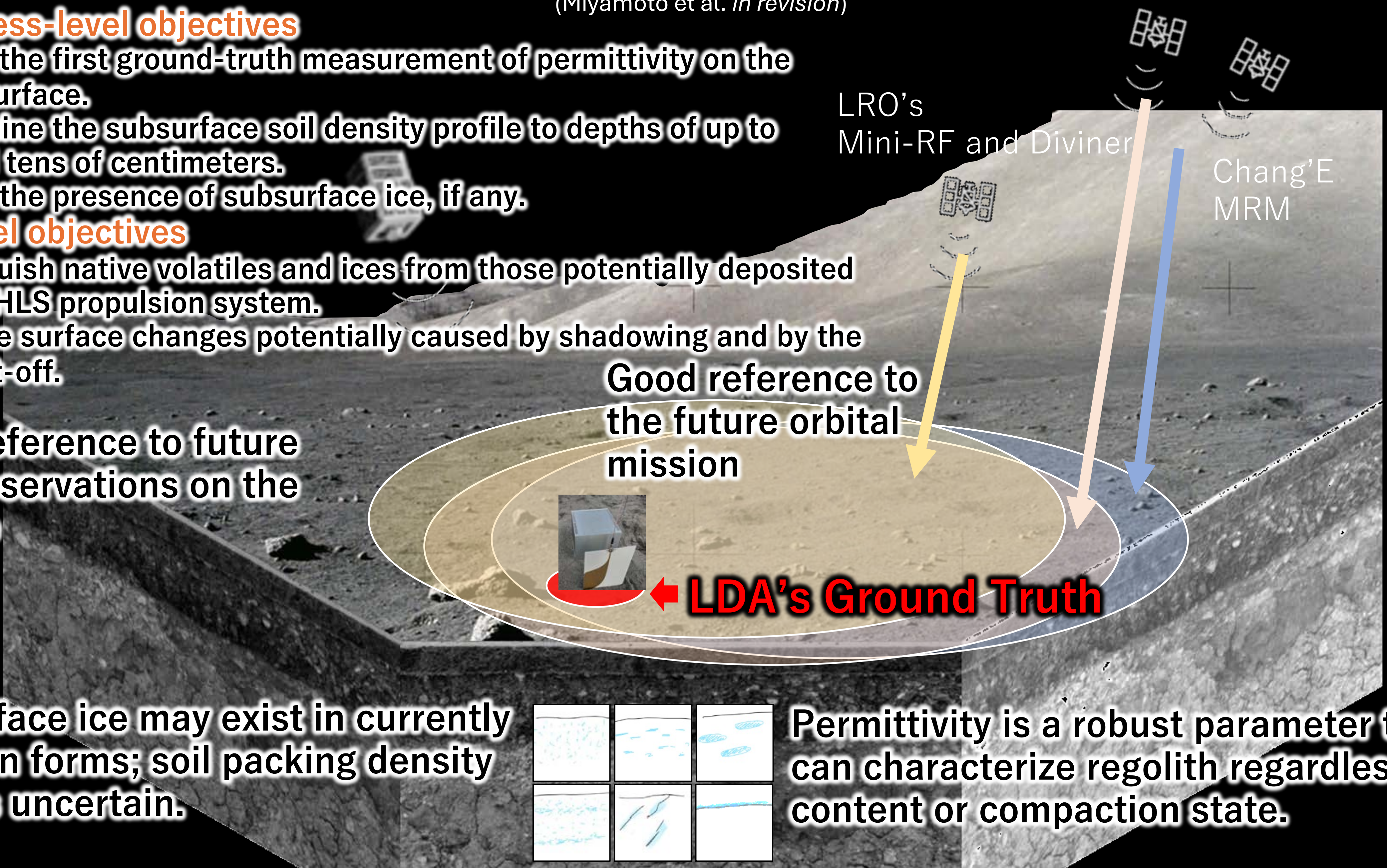
(Miyamoto et al. *in revision*)

Full success-level objectives

1. Obtain the first ground-truth measurement of permittivity on the lunar surface.
2. Determine the subsurface soil density profile to depths of up to several tens of centimeters.
3. Detect the presence of subsurface ice, if any.

Extra-level objectives

1. Distinguish native volatiles and ices from those potentially deposited by the HLS propulsion system.
2. Observe surface changes potentially caused by shadowing and by the HLS lift-off.



Good reference to future GPR observations on the surface

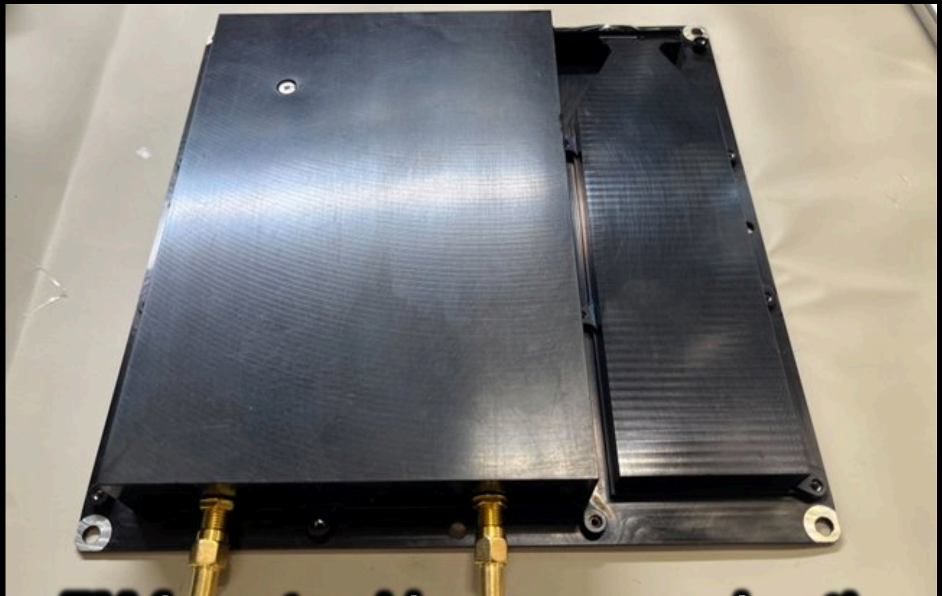
Subsurface ice may exist in currently unknown forms; soil packing density remains uncertain.

Permittivity is a robust parameter that can characterize regolith regardless of ice content or compaction state.


Linking Subsurface Exploration Strategies through Permittivity
LDA will measure the permittivity of the surface for the first time
by using a "resonator"
Good reference to the GPR of the LUPEX mission
Good reference to the future TSUKIMI mission (global dielectricity mapping)
LRO's Mini-RF and Diviner
Chandrayaan's Mini-SAR
Chang'E MRM
Good reference to previous electromagnetic observations
LDA's Ground Truth
Ice may exist in some form yet to be determined
Soil packing density is unknown
Permittivity is a robust way to describe soil with any type of ice and any packing density

Surface Dielectric Analyzer (SDA)

- SDA is an advanced version of LDA designed for spacecraft integration, providing a compact dielectric analyzer with a mass of only several hundred grams, or approximately 1 kg even when additional functions such as GPR capability are included.
- The flight model for asteroid resource exploration has already been developed, as part of the RANCH-integrated instrument reported in yesterday's presentation (Shimizu et al.), and is designed to operate on the surfaces of various celestial bodies, including the Moon, Mars, and asteroids.
- A new highly directive Vivaldi antenna sensor has been developed to enable efficient and lightweight subsurface/resource exploration; this sensor technology is currently patent pending.



FM for asteroid resource exploration

Developed antenna for LDA
(Patent pending; Sugihara et al. *submitted*)

Search for asteroids suitable for mining

In-situ measurement

$$\rho_{bd} = \frac{1}{\alpha}\left(\left[\frac{1+\sqrt{\frac{\widehat{\sigma_{OC}}}{g}\left(1-\frac{\mu_C}{\mu_{C,diff}}\right)}}{1-\sqrt{\frac{\widehat{\sigma_{OC}}}{g}\left(1-\frac{\mu_C}{\mu_{C,diff}}\right)}}\right]^{\frac{2}{3}} - 1\right)$$

ρ_{bd}: bulk density of the radar-probed material
$\widehat{\sigma_{OC}}$: OC radar albedo
g: backscatter gain
μ_C: circular polarization ratio,
$\mu_{C,diff}$: diffuse circular polarization ratio
$\varepsilon_{r,solid}$: dielectric constant of grain
ρ_{grain}: grain density
φ: porosity
ε … ric constant

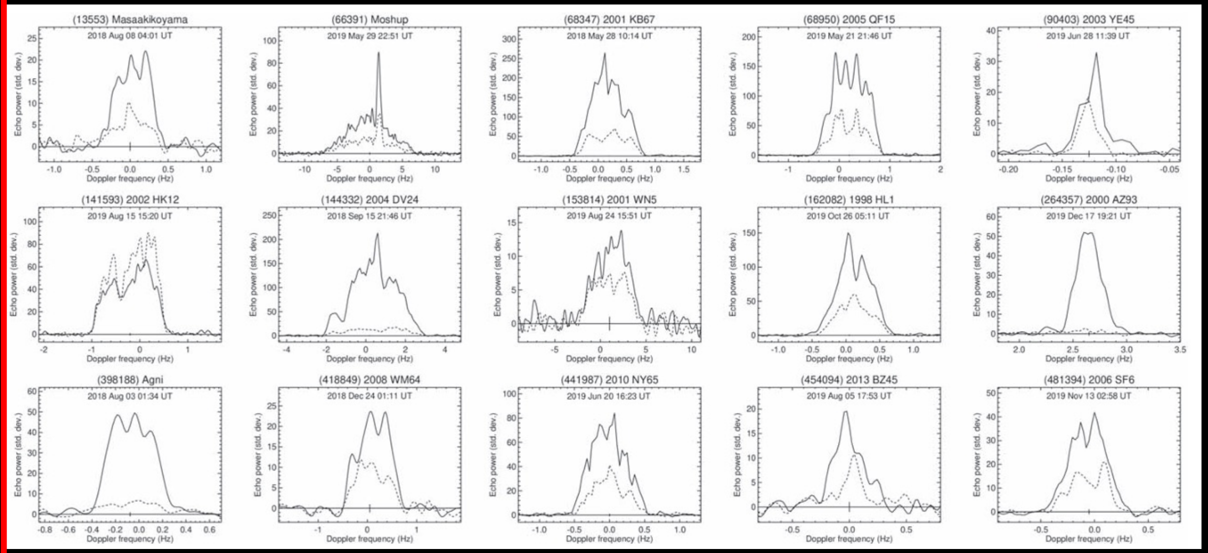
$$\alpha = \frac{\varepsilon_{r,solid}^{\frac{1}{3}} - 1}{\rho_{grain}}$$

$$\varepsilon_{measurement}^{\frac{1}{3}} = \ldots_{olid} \ldots + (1-\varphi)$$

SDA can determine this value!

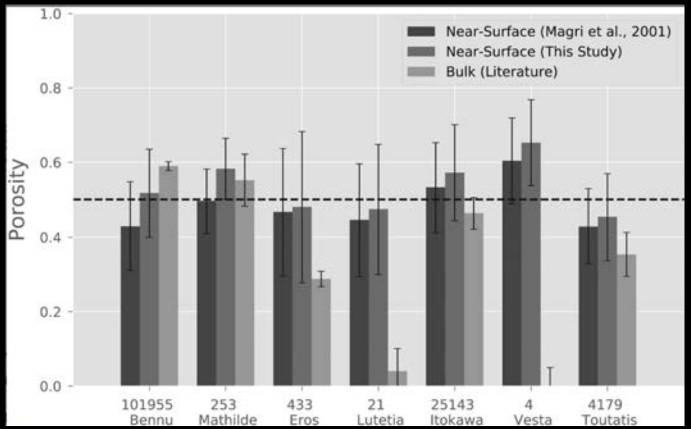
(Hickson et al., 2020)

Terrestrial telescope observations



(Virkki et al., 2022)

Index of easiness in mining



(Hickson et al., 2020)

Selection of mining methods

Conclusion & Summary

- **Permittivity** is one of the key parameter to obtain the information of water and metal resources.

- In-situ dielectric measurements combined with laboratory-based experimental results provide a practical framework for subsurface resource exploration and quantitative resource assessment on celestial bodies.

- **Lunar Dielectric Analyzer (LDA)** will be deployed during Artemis first landing mission to measure the permittivity at different temperatures. The objective is to obtain ground-truth data for electromagnetic explorations, as well as gain insights into the regolith structure and **water ice content of the subsurface**.

- **Surface Dielectric Analyzer (SDA)** is flight-ready and available for subsurface resource exploration on asteroids and other celestial bodies.