Quantitative evaluation of the lunar scattering environment and constructive proposals for future seismic explorations

三次元地震波伝搬シミュレーションによる月地殻散乱特性評価と将来月震探査への提案

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Abstract

The internal structure of the Moon holds essential information for clarifying how it formed and evolved until today. In general, the retrievable constraints vary depending on the scale to which we pay attention. For example, the bulk composition and the global physical structure provides us with a strong constraint on the thermal environment at the initial stage of the formation, and the subsurface structure (top several tens of kilometers) enables us to infer the subsequent geological evolution (such as volcanism, metamorphism) and/or the impact history. Thereby, it is important to reveal the inner structure in various scales for better understanding of the history of the Moon.

The direct exploration of the lunar interior using seismic waves started in 1969 accompanied by the Apollo missions (e.g. [1]). A seismic network constructed on the nearside of the Moon brought us more than 12,000 seismic events, allowing us to estimate its internal structure (e.g. [2]). Even though the Apollo lunar seismic data has been investigated over the past 50 years, the lunar interior remains uncertain, and we are still far from giving a critical constraint on the formation process and/or subsequent evolution (see [3] Garcia et al. for the recent review). One of the most serious problems in lunar seismology is "seismic scattering" due to the intense heterogeneous structure, so-called "megaregolith". The strongly scattered signals prevent us from precisely identifying the seismic phases (e.g., P, S), leading to the large uncertainty of a resultant 1D structure model. Although various studies attempted to constrain the scattering properties of the megaregolith using the radiative transfer theory (e.g., [4] [5]), the structure is left uncertain. In this study, we estimate the scattering structure more directly by employing full 3D seismic wave propagation simulation (namely, taking into account the free surface and the spatial variation of elastic parameters). While this is the most straightforward way, it requires a vast amount of computational resources, which kept us from performing this kind of simulation. However, the recent progress in computational technology (i.e., super-computer) makes it possible to conduct such an expensive simulation, allowing us to apply this method to lunar seismology.

Significant progress is that we realized a stable computation up to 2 Hz, which completely covers the frequency range of the Apollo observation with the long-period seismometer. This enabled us to perform a direct comparison between the data and synthetics at the same frequency for the first time. Through the forward modeling of lunar seismic waves, we succeeded in reproducing the Apollo seismic data, resulting in the quantitative evaluation of scattering properties at the Apollo 12 landing site. This not only brought us a concrete view of the subsurface heterogeneity of the Moon but also open a way to the comparative planetology with respect to "scattering environment".

In the presentation, we give a general summary of planetary seismology, followed by the forward modeling of lunar seismic waves and the quantitative comparison of scattering environment between the Earth, the Moon, and Mars. Then, we discuss how our results can contribute to future mission designs. In the end, the spillover effect to other planets is presented.

References

[1] Latham et al. (1969), *Science*, 165, 3890. [2] Nakamura et al. (1982), *Proc. Lunar Planet. Sci. Conf.*, 13th, A117-A123. [3] Garcia et al. (2019), *Space Sci. Rev*., 215:50. [4] Dainty and Toksoz (1981), *Phys. Earth Planet. Int.*, 26, 250-260. [5] Gillet et al. (2017), *Phys. Earth Planet. Int.,*262, 28-40.

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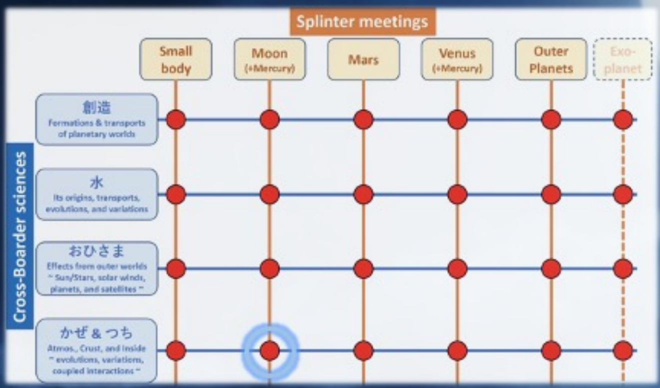

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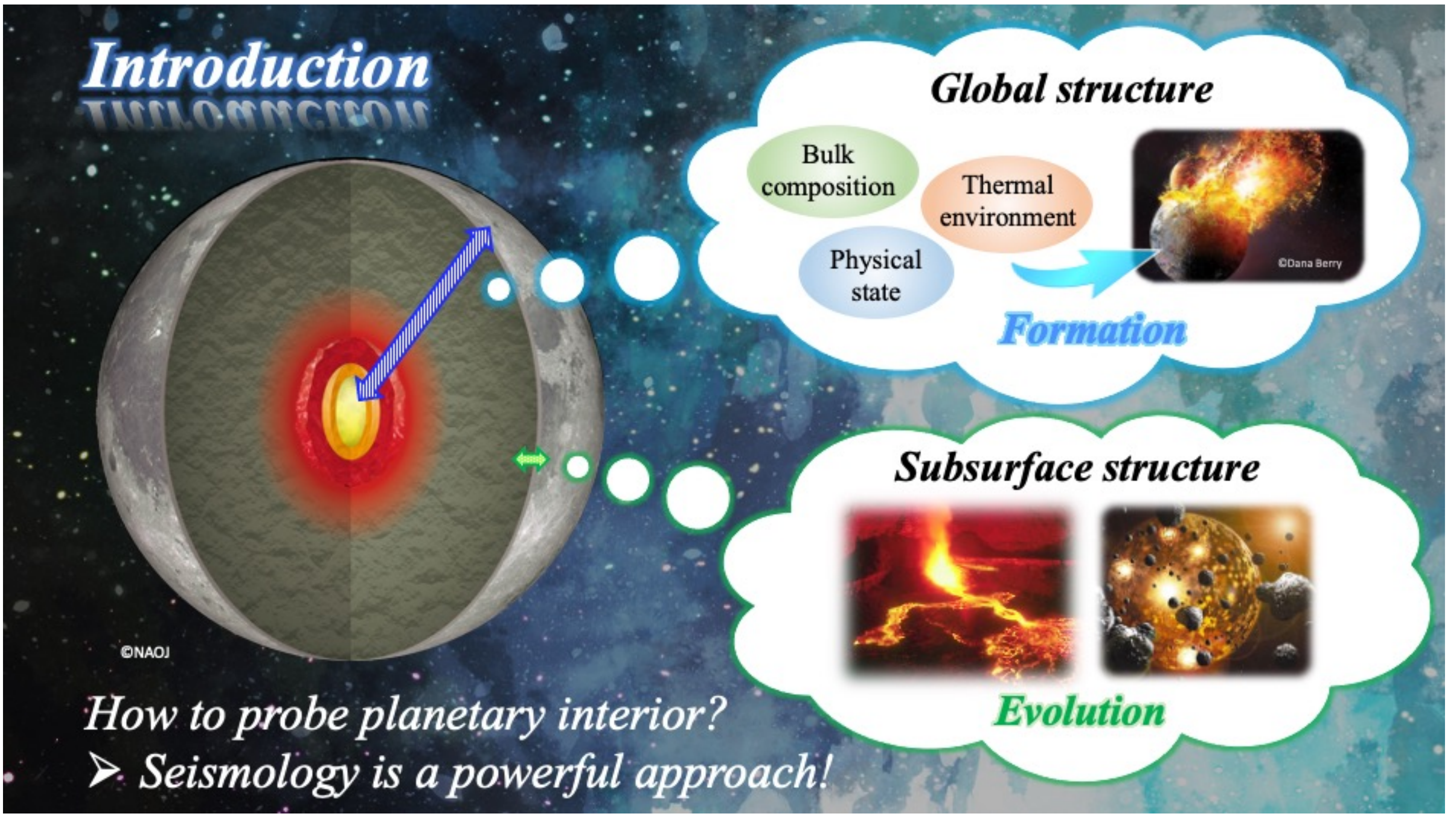
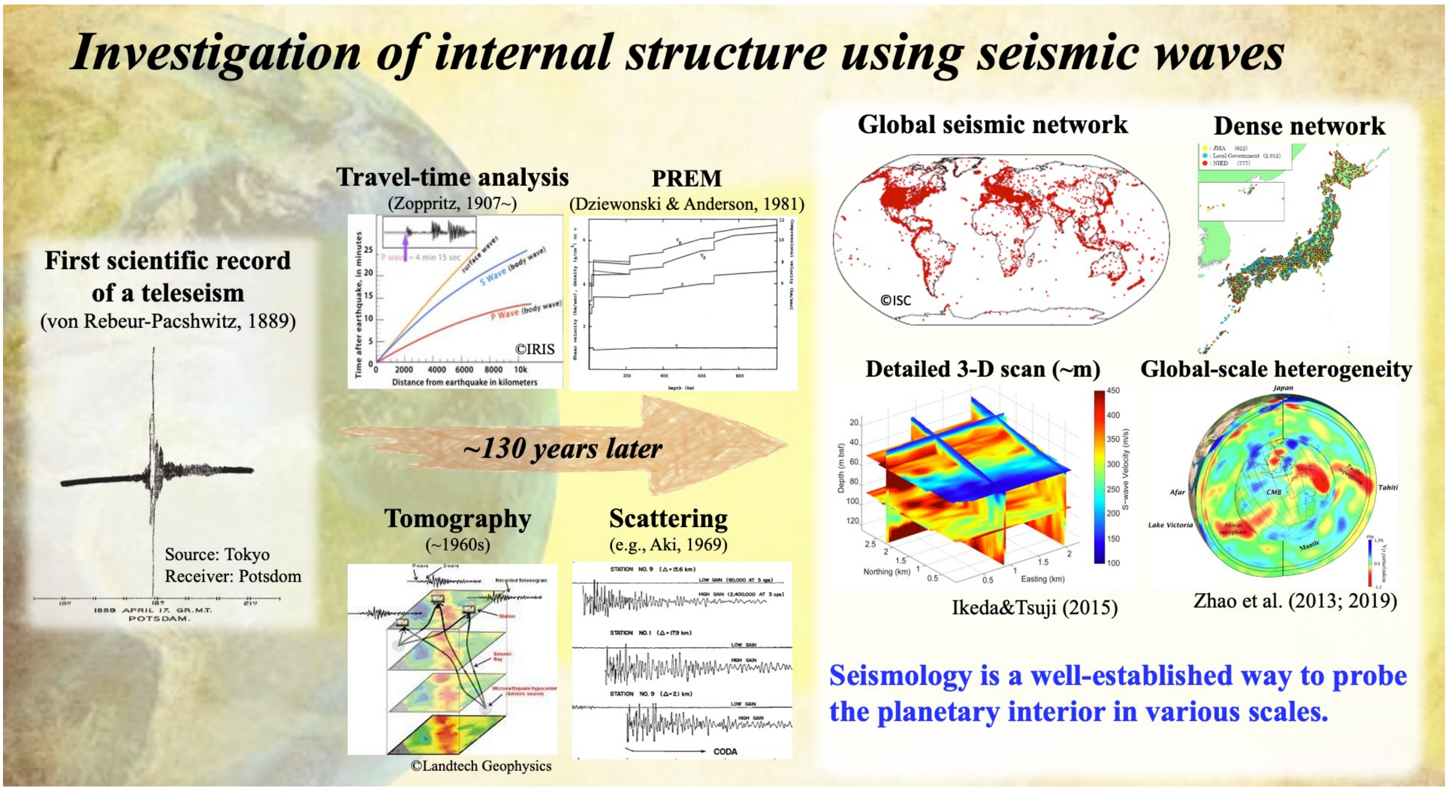
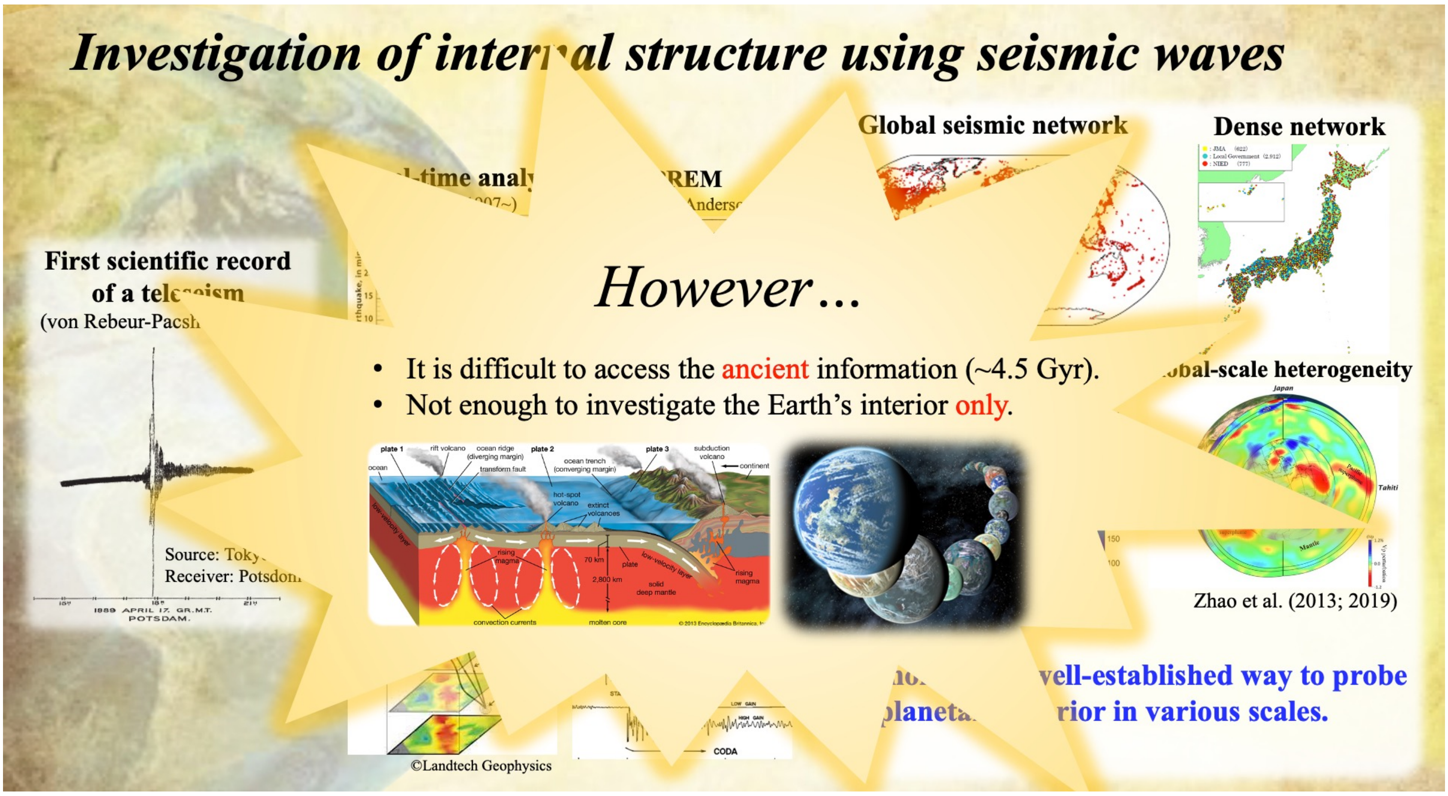
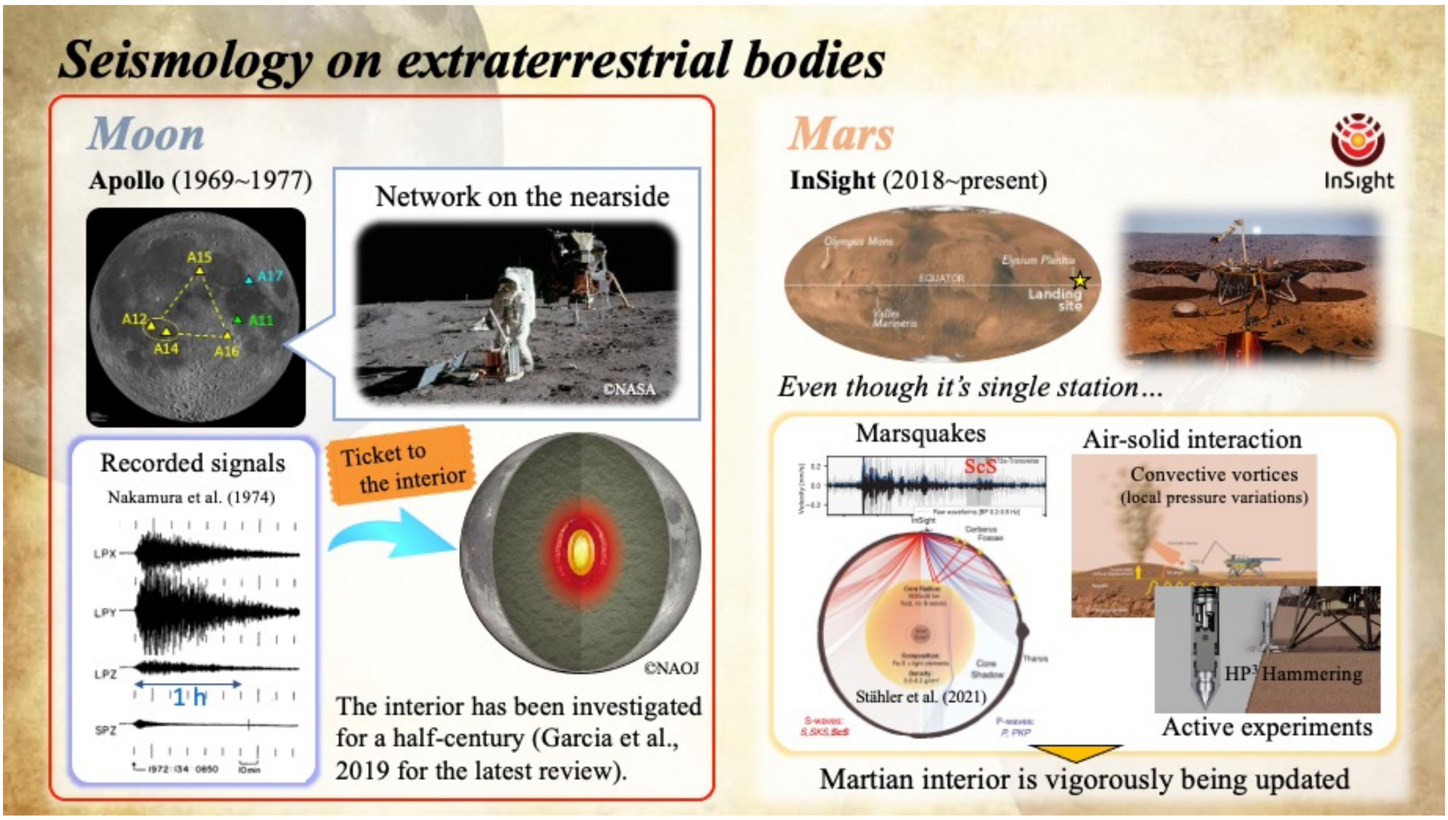
Contents

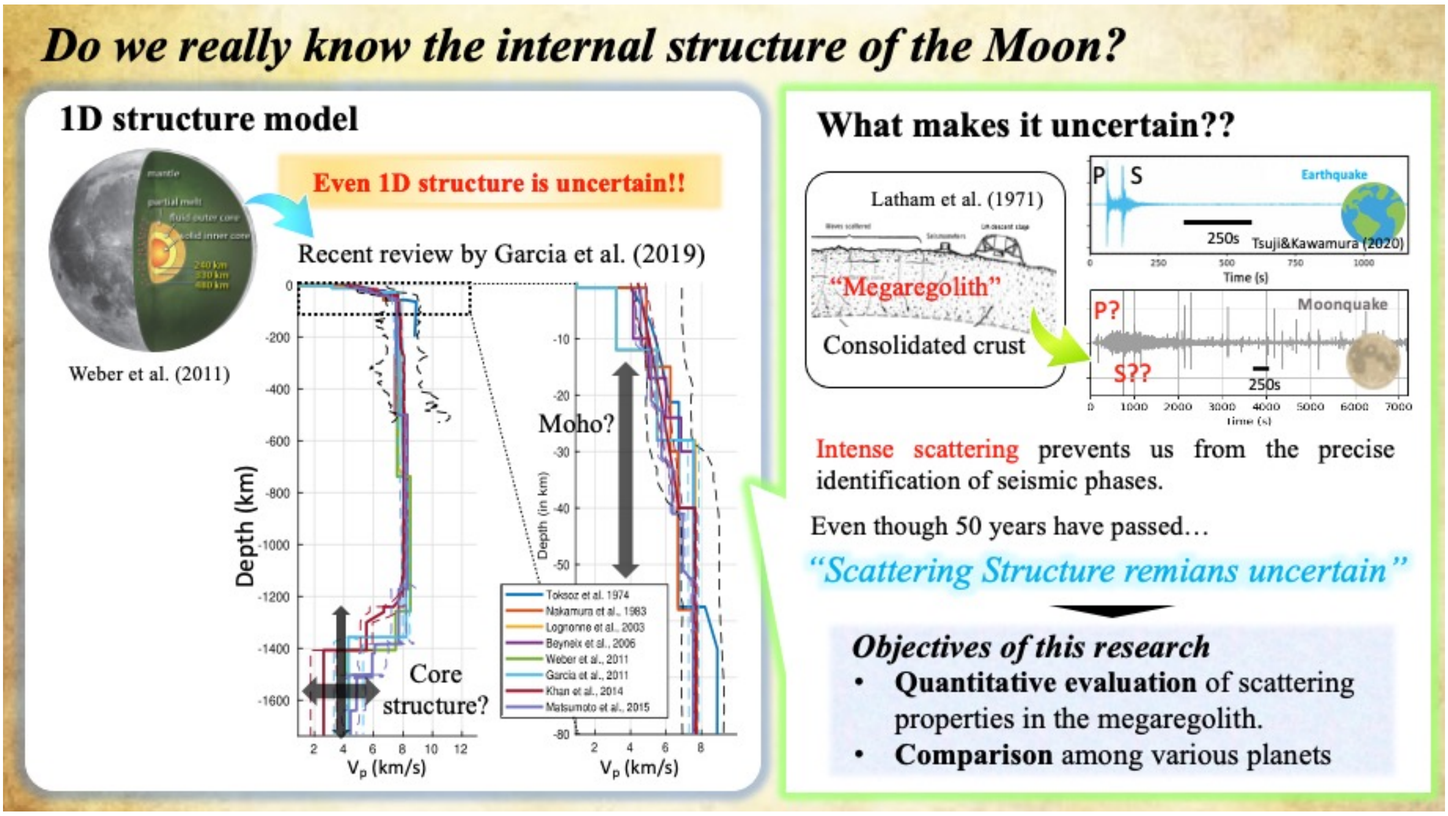

Introduction
Global structure
Bulk composition
Thermal environment
Physical state
©Dana Berry
Formation
Subsurface structure
Evolution
©NAOJ
How to probe planetary interior?
➢ Seismology is a powerful approach!

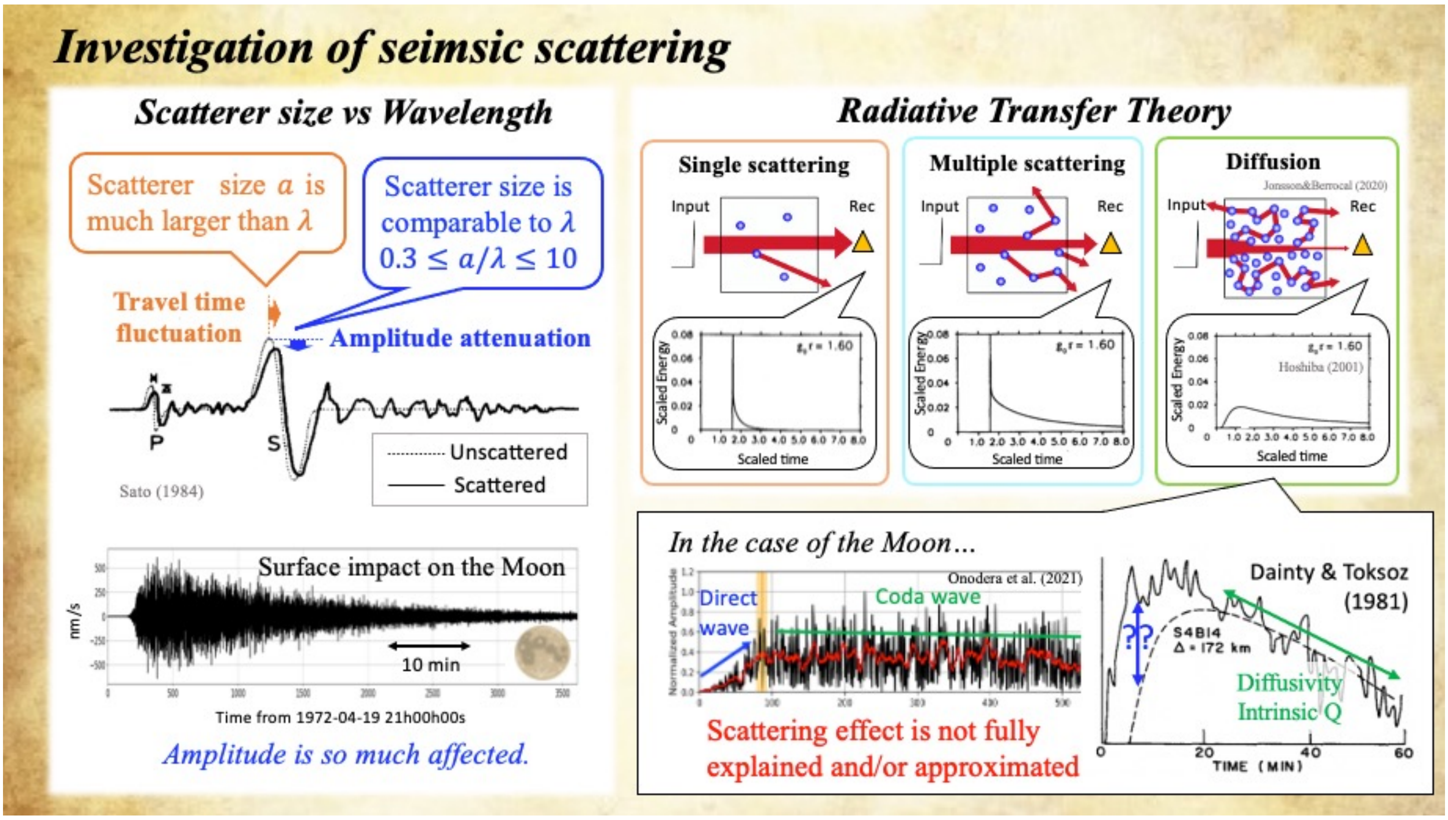

Investigation of internal structure using seismic waves
First scientific record of a teleseism
(von Rebeur-Pacshwitz, 1889)
Source: Tokyo
Receiver: Potsdom
1889 APRIL 17. GR.M.T. POTSDAM.
Travel-time analysis
(Zoppritz, 1907~)
Time after earthquake, in minutes
Distance from earthquake in kilometers
©IRIS
PREM
(Dziewonski & Anderson, 1981)
~130 years later
Tomography
(~1960s)
©Landtech Geophysics
Scattering
(e.g., Aki, 1969)
CODA
Global seismic network
©ISC
Dense network
Detailed 3-D scan (~m)
Ikeda&Tsuji (2015)
Global-scale heterogeneity
Zhao et al. (2013; 2019)
Seismology is a well-established way to probe the planetary interior in various scales.

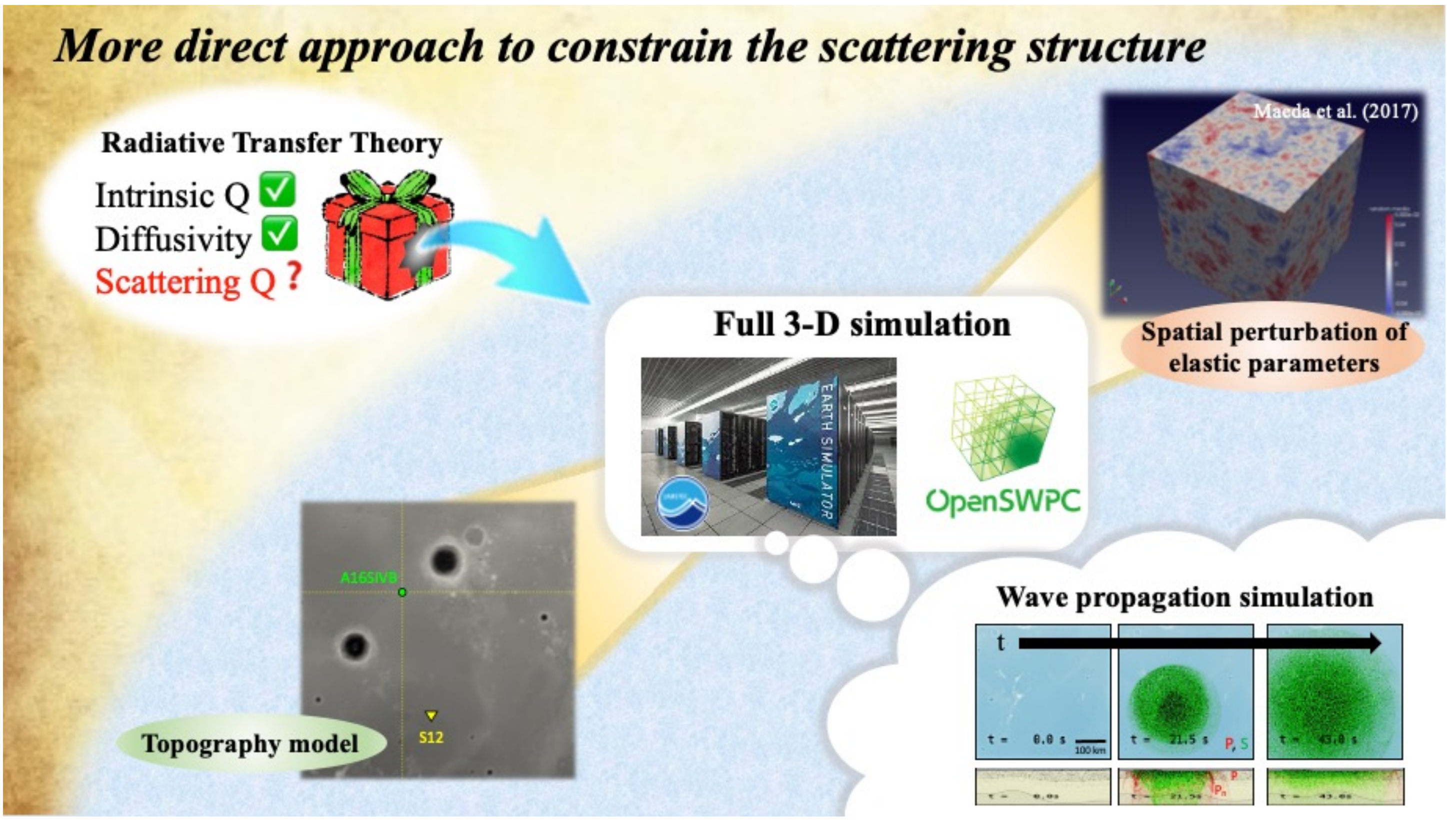

Investigation of internal structure using seismic waves
Global seismic network
Dense network
First scientific record
of a teleseism
(von Rebeur-Pacsh
Source: Toky
Receiver: Potsdam
However…
It is difficult to access the ancient information (~4.5 Gyr).
Not enough to investigate the Earth's interior only.
Zhao et al. (2013; 2019)
©Landtech Geophysics
CODA

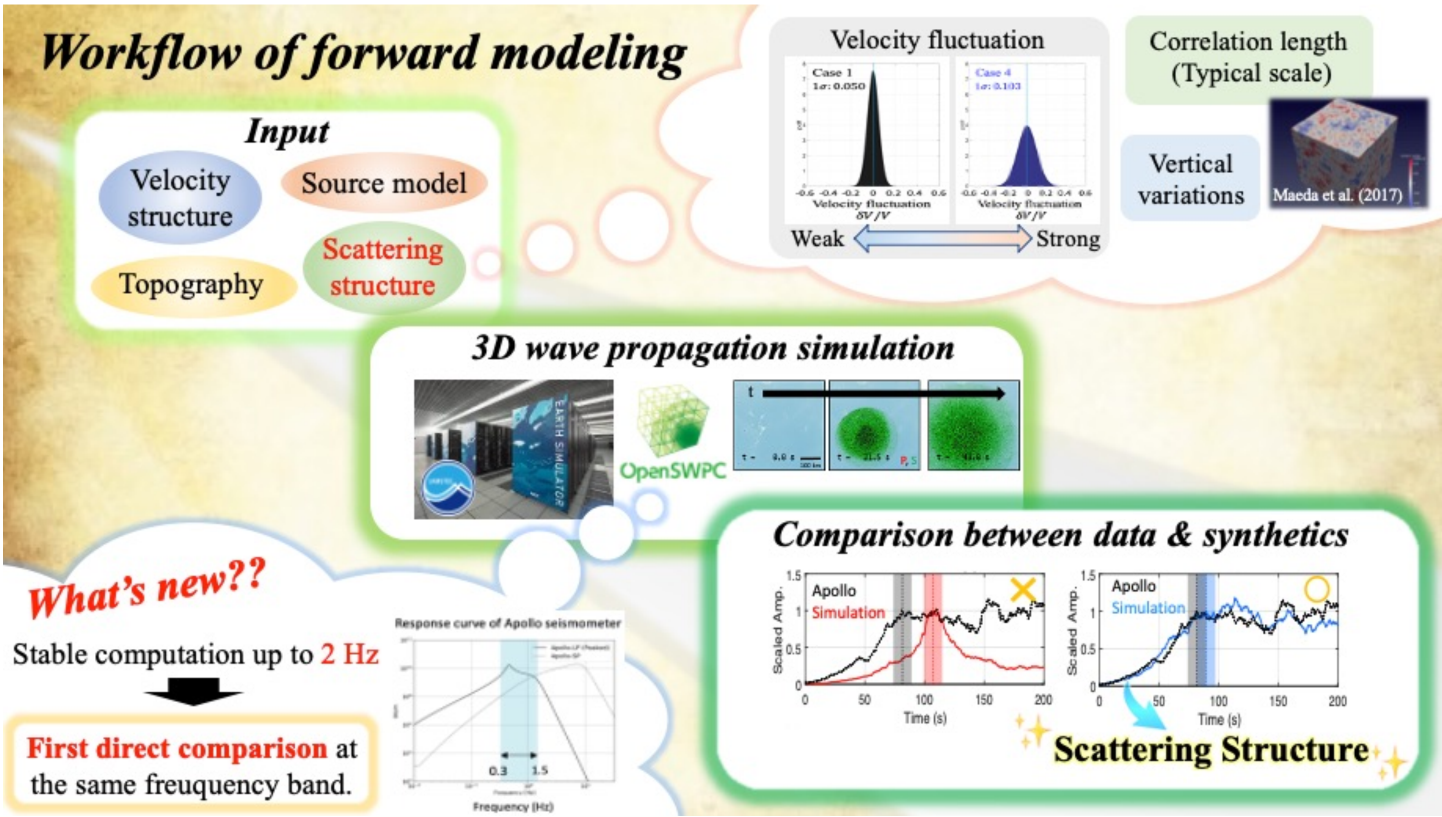

Seismology on extraterrestrial bodies
Moon
Apollo (1969~1977)
Network on the nearside
©NASA
A15
A17
A12
A11
A14
A16
Recorded signals
Nakamura et al. (1974)
LPX
LPY
LPZ
SPZ
1 h
Ticket to
the interior
©NAOJ
The interior has been investigated
for a half-century (Garcia et al.,
2019 for the latest review).
Mars
InSight (2018~present)
InSight
Olympus Mons
Elysium Planitia
EQUATOR
Landing site
Valles Marineris
Even though it's single station…
Marsquakes
ScS
Stähler et al. (2021)
Air-solid interaction
Convective vortices
(local pressure variations)
HP³ Hammering
Active experiments
Martian interior is vigorously being updated

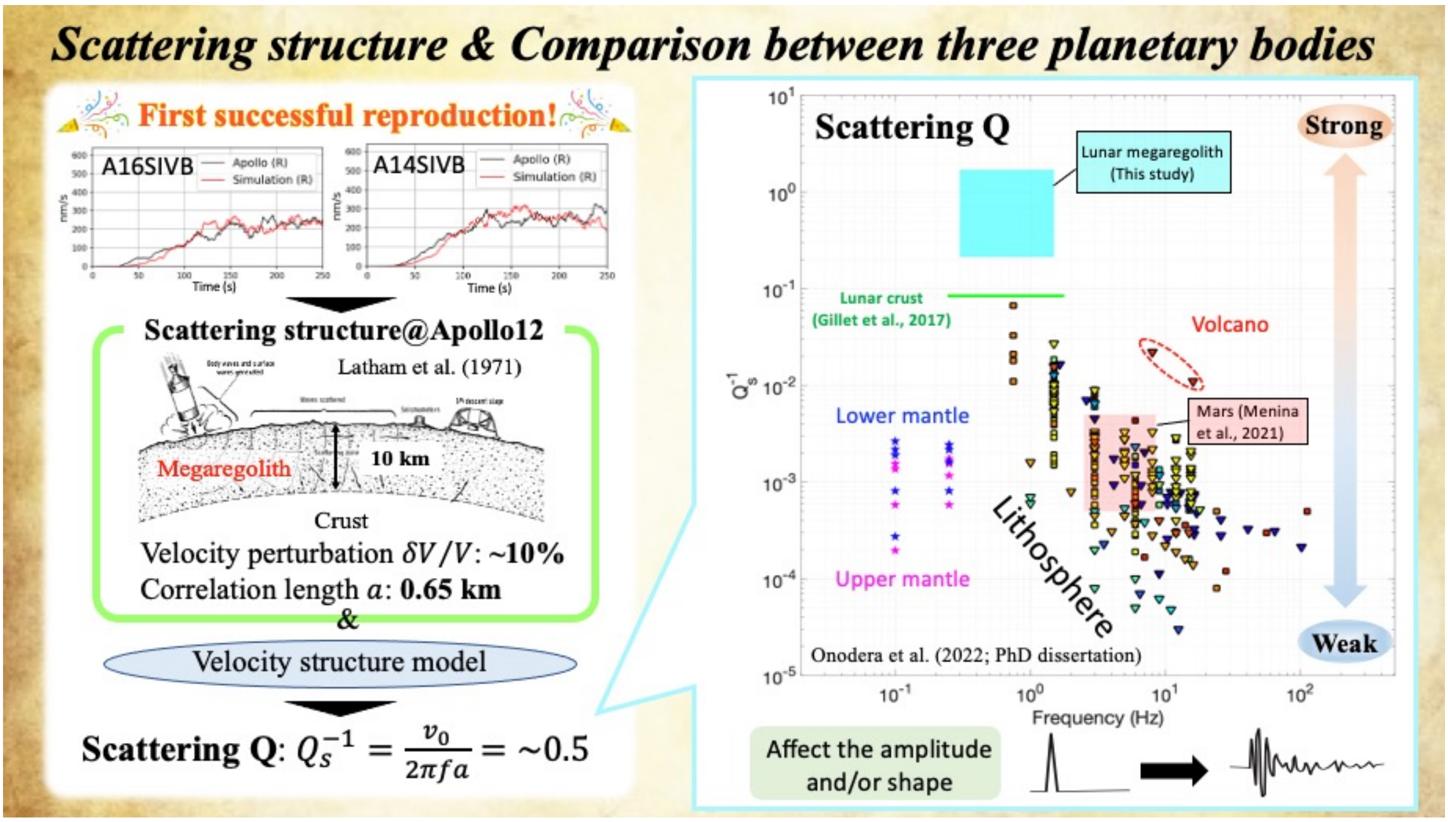

Contents
Introduction
Scattering structure of the Moon
Proposals for future explorations
Summary

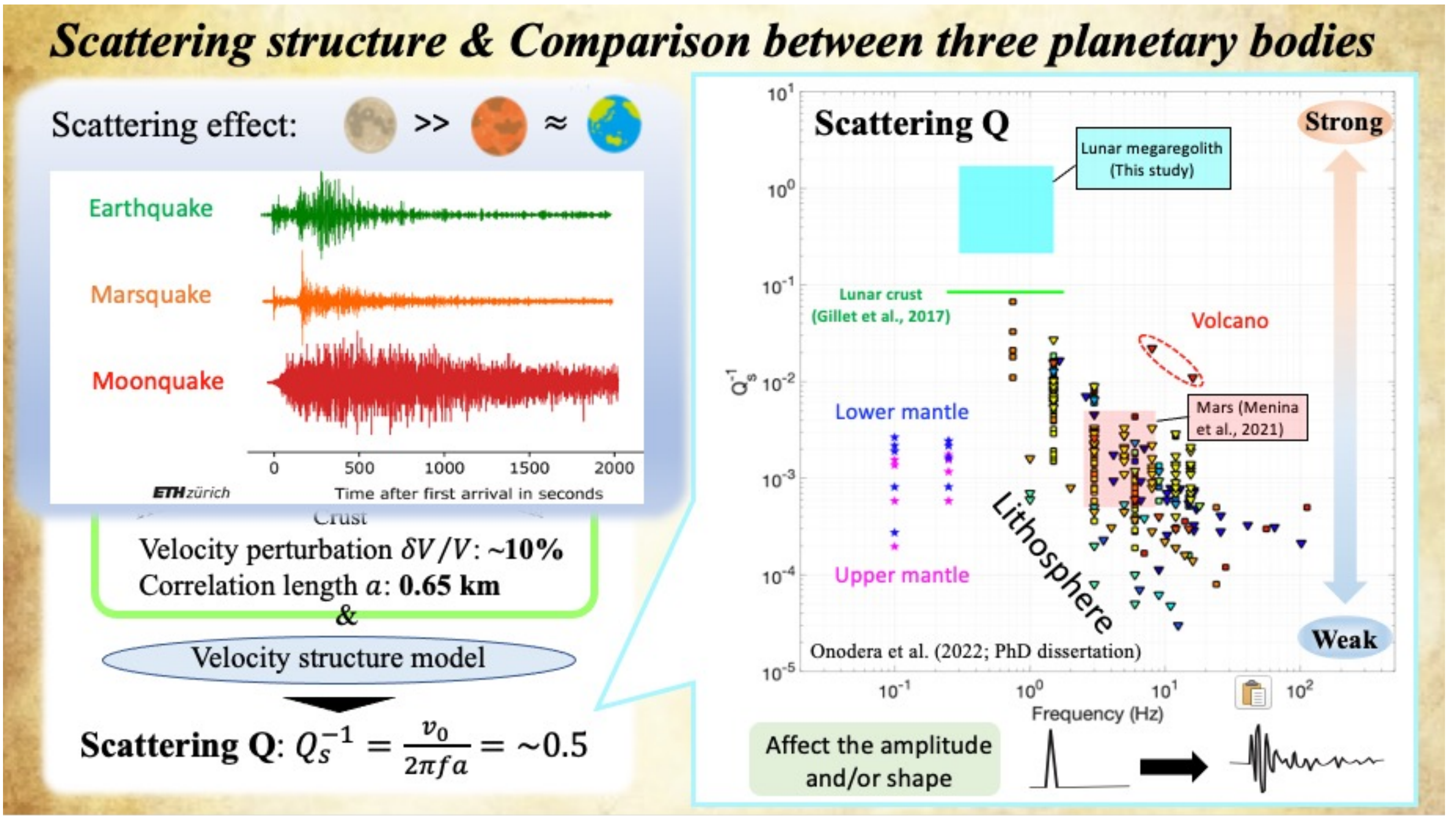

Do we really know the internal structure of the Moon?
1D structure model
Even 1D structure is uncertain!!
Recent review by Garcia et al. (2019)
Weber et al. (2011)
Depth (km)
Moho?
Core structure?
Toksoz et al. 1974
Nakamura et al., 1983
Lognonne et al., 2003
Beyneix et al., 2006
Weber et al., 2011
Garcia et al., 2011
Khan et al., 2014
Matsumoto et al., 2015
Depth (in km)
V_p (km/s)
V_p (km/s)
What makes it uncertain??
Latham et al. (1971)
"Megaregolith"
Consolidated crust
P
S
Earthquake
250s
Tsuji&Kawamura (2020)
Time (s)
P?
S??
Moonquake
250s
Intense scattering prevents us from the precise identification of seismic phases.
Even though 50 years have passed…
"Scattering Structure remians uncertain"
Objectives of this research
Quantitative evaluation of scattering properties in the megaregolith.
Comparison among various planets


Investigation of seimsic scattering
Scatterer size vs Wavelength
Scatterer size a is much larger than λ
Scatterer size is comparable to λ 0.3 ≤ a/λ ≤ 10
Travel time fluctuation
Amplitude attenuation
P
S
Unscattered
Scattered
Sato (1984)
Surface impact on the Moon
nm/s
10 min
Time from 1972-04-19 21h00h00s
Amplitude is so much affected.
Radiative Transfer Theory
Single scattering
Multiple scattering
Diffusion
Input
Rec
Jonsson&Berrocal (2020)
Scaled Energy
Scaled time
Hoshiba (2001)
In the case of the Moon…
Onodera et al. (2021)
Direct wave
Coda wave
Scattering effect is not fully explained and/or approximated
Dainty & Toksoz (1981)
S4B14
Δ = 172 km
Diffusivity
Intrinsic Q
TIME (MIN)


More direct approach to constrain the scattering structure
Radiative Transfer Theory
Intrinsic Q
Diffusivity
Scattering Q ?
Full 3-D simulation
EARTH SIMULATOR
OpenSWPC
Maeda et al. (2017)
Spatial perturbation of elastic parameters
A16SIVB
S12
Topography model
Wave propagation simulation
t


Workflow of forward modeling
Input
Velocity structure
Source model
Topography
Scattering structure
Velocity fluctuation
Case 1
1σ: 0.050
Case 4
1σ: 0.103
Velocity fluctuation δV/V
Weak
Strong
Correlation length (Typical scale)
Vertical variations
Maeda et al. (2017)
3D wave propagation simulation
OpenSWPC
What's new??
Stable computation up to 2 Hz
First direct comparison at the same freuquency band.
Response curve of Apollo seismometer
0.3
1.5
Frequency (Hz)
Comparison between data & synthetics
Apollo
Simulation
Scaled Amp.
Time (s)
Scattering Structure


Scattering structure & Comparison between three planetary bodies
First successful reproduction!
A16SIVB
A14SIVB
Apollo (R)
Simulation (R)
nm/s
Time (s)
Scattering structure@Apollo12
Latham et al. (1971)
Megaregolith
10 km
Crust
Velocity perturbation δV/V: ~10%
Correlation length a: 0.65 km
&
Velocity structure model
Scattering Q: $Q_s^{-1} = \frac{v_0}{2\pi f a} = \sim 0.5$
Scattering Q
Strong
Weak
Lunar megaregolith (This study)
Lunar crust (Gillet et al., 2017)
Volcano
Mars (Menina et al., 2021)
Lower mantle
Upper mantle
Lithosphere
Onodera et al. (2022; PhD dissertation)
Frequency (Hz)
Affect the amplitude and/or shape



Scattering structure & Comparison between three planetary bodies
Scattering effect: >> ≈
Earthquake
Marsquake
Moonquake
0 500 1000 1500 2000
Time after first arrival in seconds
ETH zürich
Crust
Velocity perturbation δV/V: ~10%
Correlation length a: 0.65 km
&
Velocity structure model
Scattering Q: $Q_s^{-1} = \frac{v_0}{2\pi f a} = \sim 0.5$
Scattering Q
Lunar megaregolith (This study)
Strong
Weak
Lunar crust (Gillet et al., 2017)
Volcano
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Frequency (Hz)
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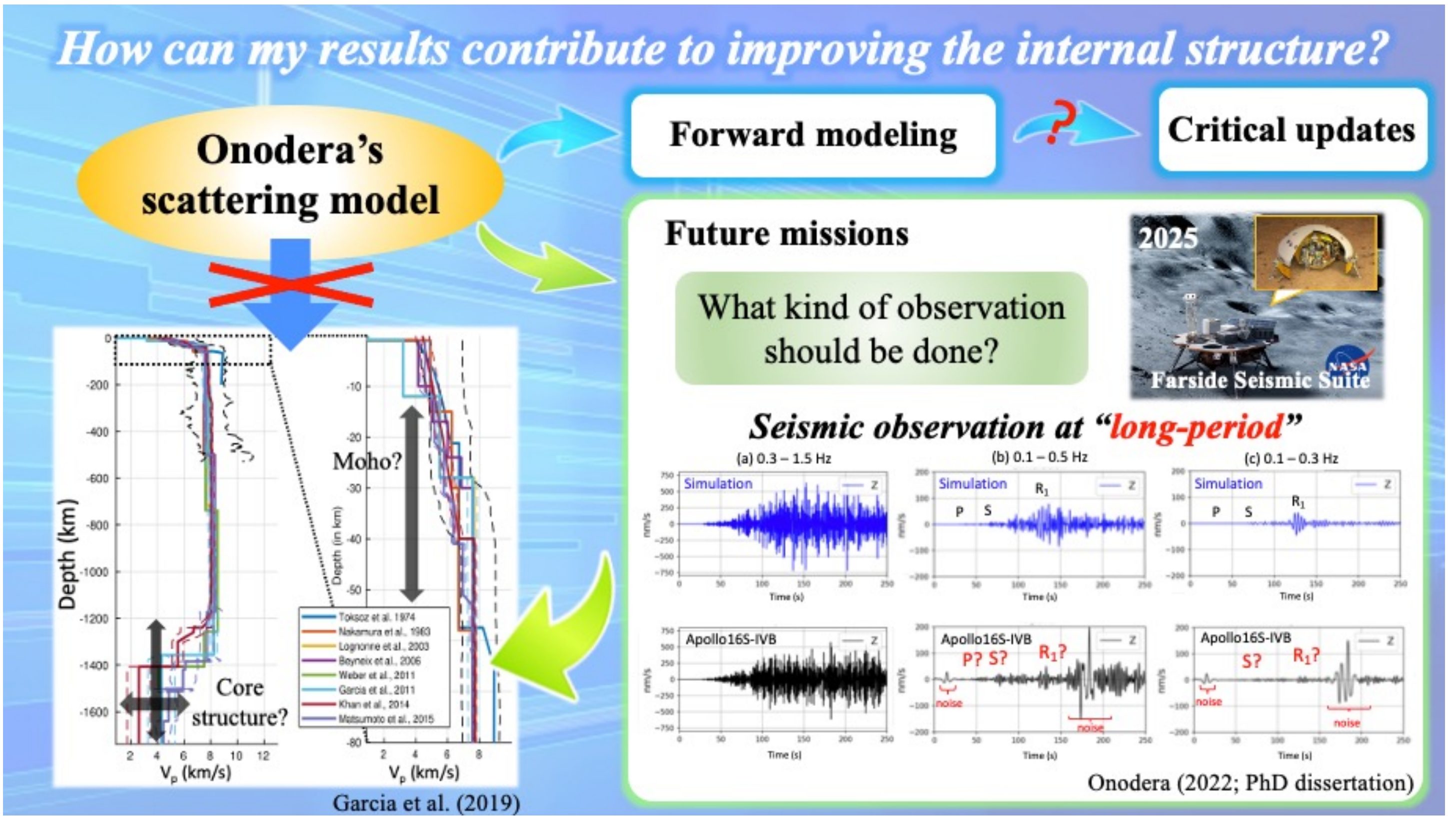
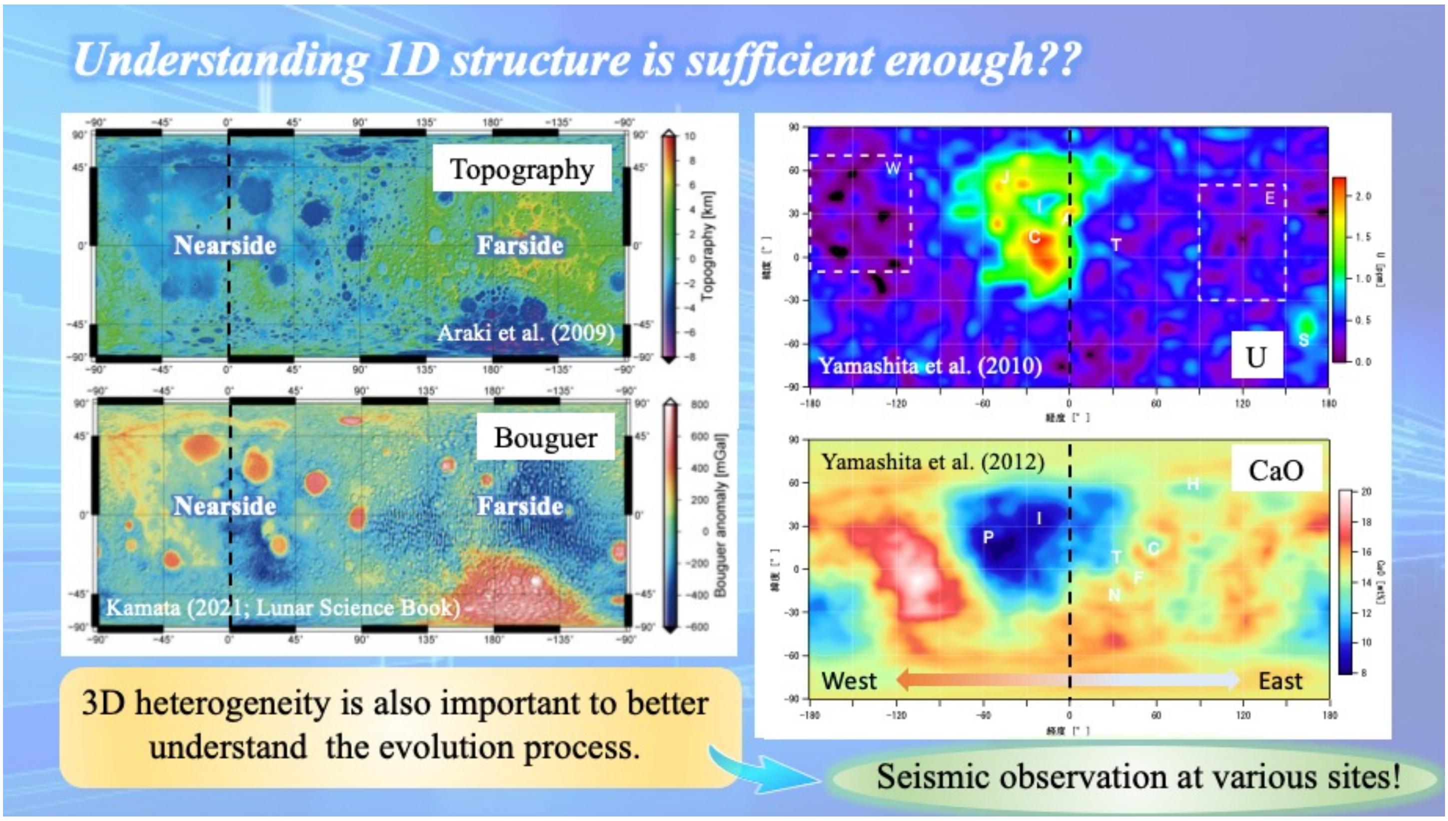
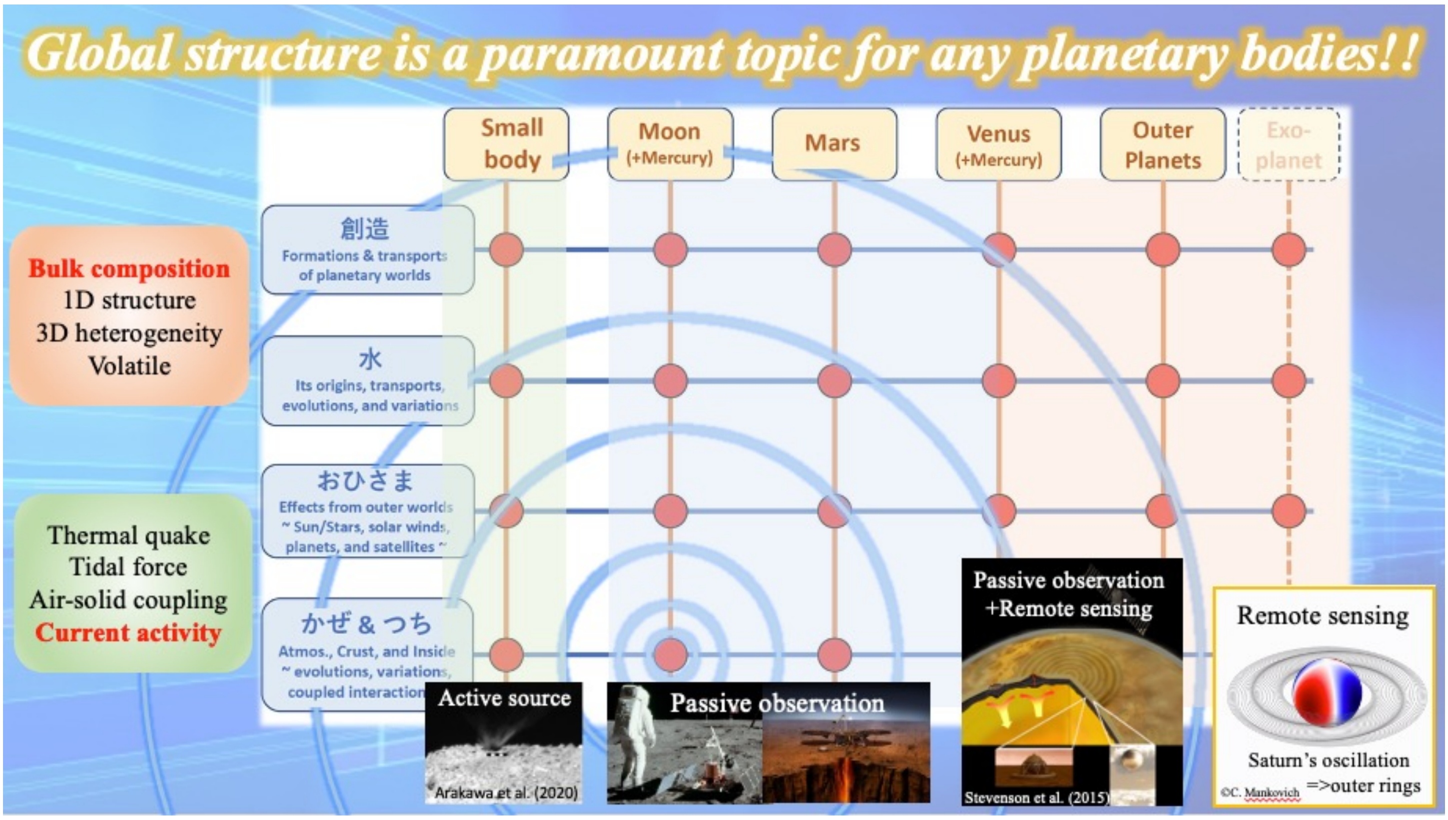
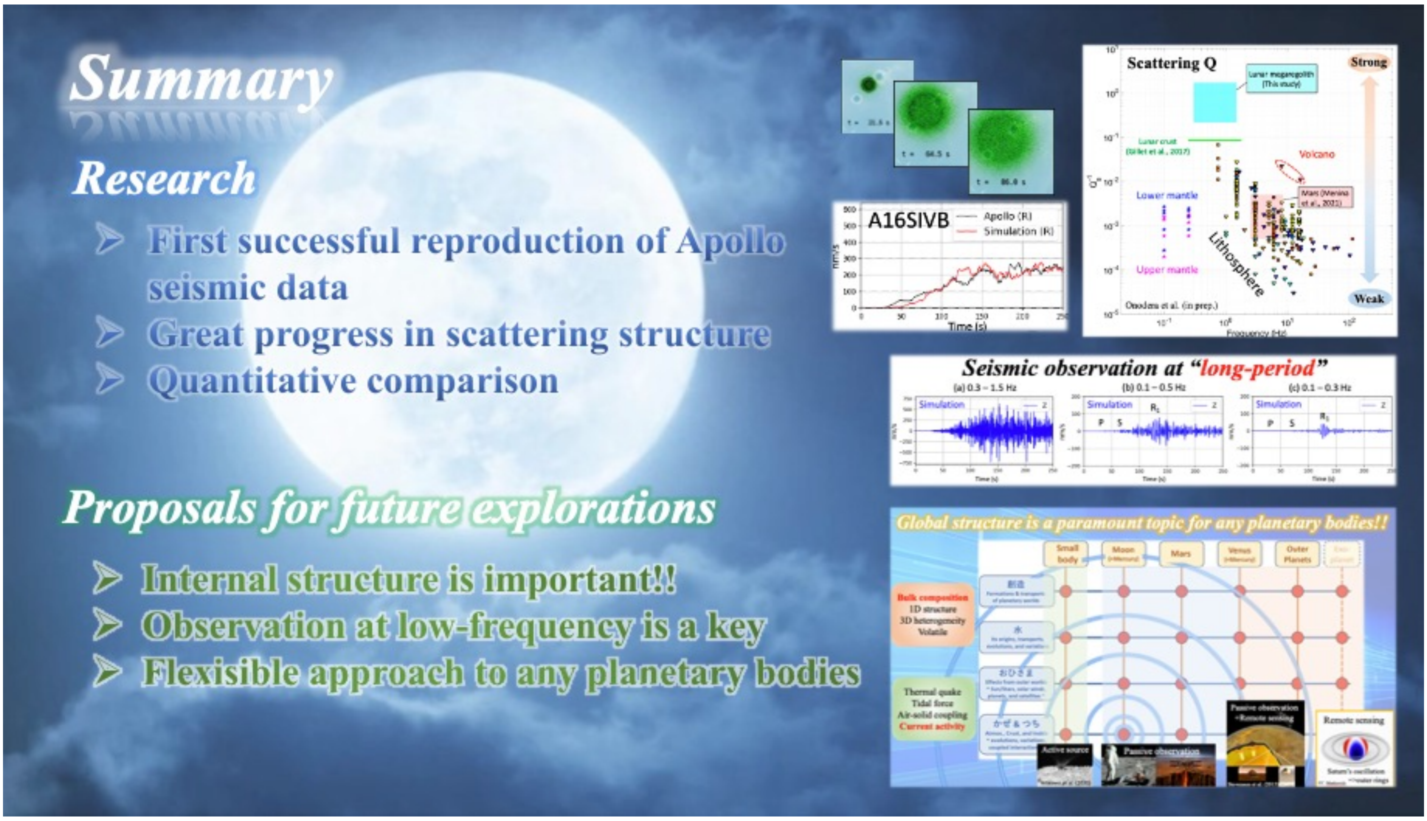

How can my results contribute to improving the internal structure?
Onodera's scattering model
Forward modeling
?
Critical updates
Future missions
What kind of observation should be done?
2025
Farside Seismic Suite
Seismic observation at "long-period"
(a) 0.3 – 1.5 Hz
(b) 0.1 – 0.5 Hz
(c) 0.1 – 0.3 Hz
Simulation
Apollo16S-IVB
P? S?
S?
noise
Time (s)
Depth (km)
Moho?
Core structure?
Toksoz et al. 1974
Nakamura et al., 1983
Lognonne et al., 2003
Beyneix et al., 2006
Weber et al., 2011
Garcia et al., 2011
Khan et al., 2014
Matsumoto et al., 2015
Garcia et al. (2019)
Onodera (2022; PhD dissertation)


Understanding 1D structure is sufficient enough??
Topography
Nearside
Farside
Araki et al. (2009)
Topography [km]
Bouguer
Kamata (2021; Lunar Science Book)
Bouguer anomaly [mGal]
Yamashita et al. (2010)
U
Yamashita et al. (2012)
CaO
West
East
3D heterogeneity is also important to better understand the evolution process.
Seismic observation at various sites!


Global structure is a paramount topic for any planetary bodies!!
Small body
Moon (+Mercury)
Mars
Venus (+Mercury)
Outer Planets
Exo-planet
Bulk composition
1D structure
3D heterogeneity
Volatile
Thermal quake
Tidal force
Air-solid coupling
Current activity
創造
Formations & transports of planetary worlds
水
Its origins, transports, evolutions, and variations
おひさま
Effects from outer worlds ~ Sun/Stars, solar winds, planets, and satellites ~
かぜ & つち
Atmos., Crust, and Inside ~ evolutions, variations, coupled interaction
Active source
Arakawa et al. (2020)
Passive observation
Passive observation +Remote sensing
Stevenson et al. (2015)
Remote sensing
Saturn's oscillation =>outer rings
©C. Mankovich


Summary
Research
First successful reproduction of Apollo seismic data
Great progress in scattering structure
Quantitative comparison
Proposals for future explorations
Internal structure is important!!
Observation at low-frequency is a key
Flexible approach to any planetary bodies
A16SIVB
Apollo (R)
Simulation (R)
Time (s)
Scattering Q
Strong
Weak
Volcano
Lower mantle
Upper mantle
Lithosphere
Onodera et al. (in prep.)
Seismic observation at "long-period"
Global structure is a paramount topic for any planetary bodies!!