

SEIS

The Seismic Environment of the Moon: Signal for Geophysics and Noise for astrophysics.....

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Co-Principal Investigator, Artemis 5 NASA South Pole Seismic Station

Co-Investigator, ChangE'7 CSA Lunar Seismograph

Co-investigator, LILA Lunar GW detector project

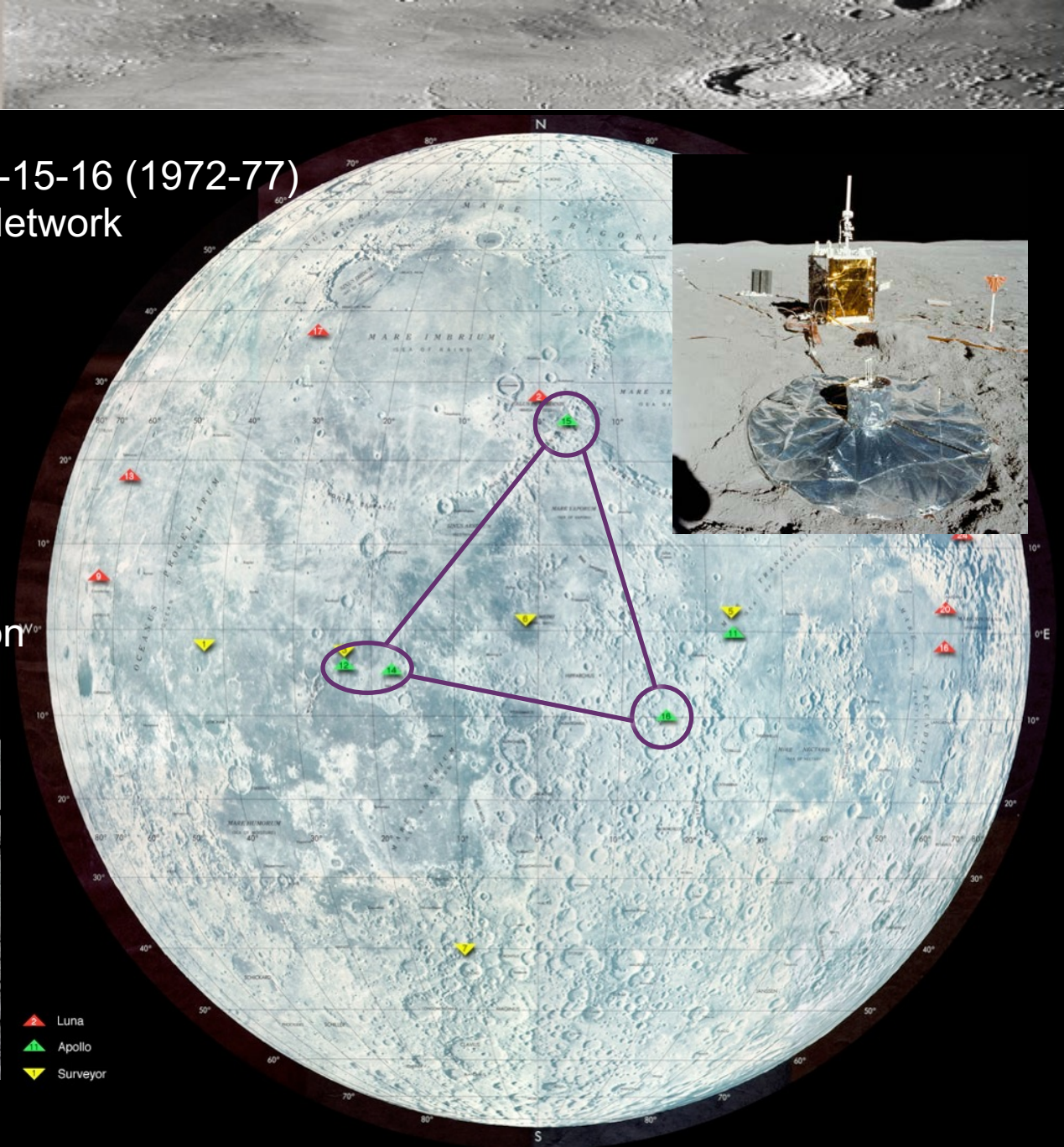
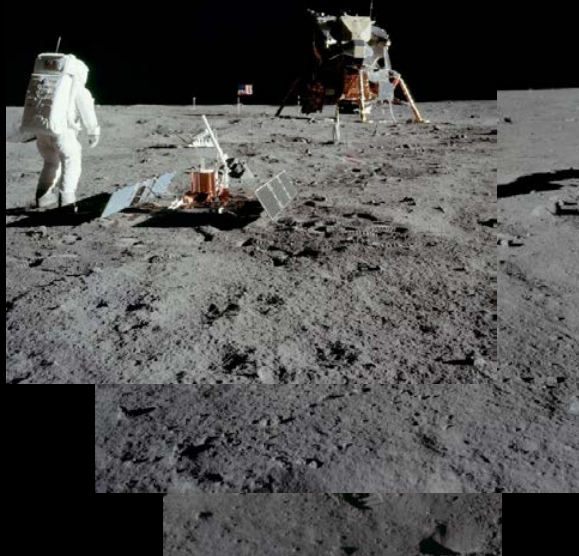
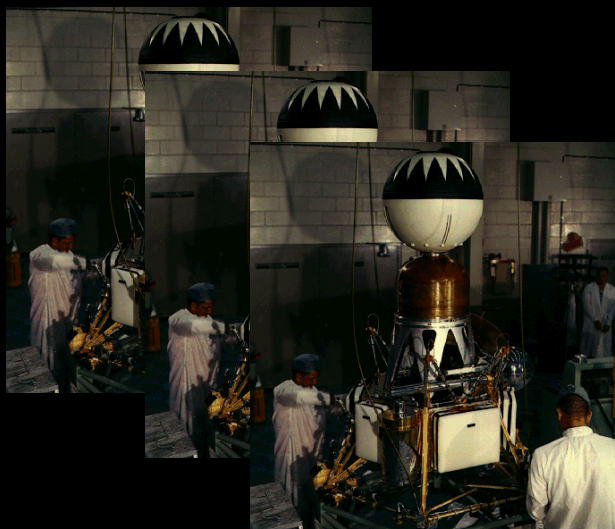
- Why Astrophysicists and Cosmologists want the Moon to be aseismic?
- Why planetologists want the Moon to be seismically active?
- What we know after the Apollo seismic experiment (and in general what we get from planetary seismology) ?
- What we do not know after the Apollo seismic experiment ?
 - Focus on the lunar seismic noise and seismic signals
- Selected Near future missions compared to Apollo
- What will NOT be made by near future mission and associated goals
- Noise challenge for very long period seismology
- Noise challenge for Gravitational wave

Moon seismology

Apollo 12-14-15-16 (1972-77)
First Lunar Network

Ranger 3-4-5 (1962)
First attempts to land seismometer

Apollo 11 (7/1969)
First Lunar single station



Moon GW detector : the first step of J.Weber

2512



Moon GW detector : theory in one slide....

SOURCE: « tidal » strain (L=2 in spherical harmonics) generated by the GW

$$\mathbf{f}_{tidal}(\mathbf{r}, t) = \frac{1}{2} \rho(r) r \hat{\mathbf{e}}_r \cdot \ddot{\mathbf{h}}(t),$$

- Only the normal modes with a L=2 component are excited
- for a Moon spherically model, only the multiplet with L=2 are excited
- in the real moon, other modes with L≠2 will be excited too, if coupled to a L=2 mode, but with much weaker amplitudes

$$T_U \equiv \sum_n \frac{f_g^2}{f_n^2 - f_g^2 + i f_n f_g / Q_n} \frac{U_n(r)}{R_P} \chi_n,$$

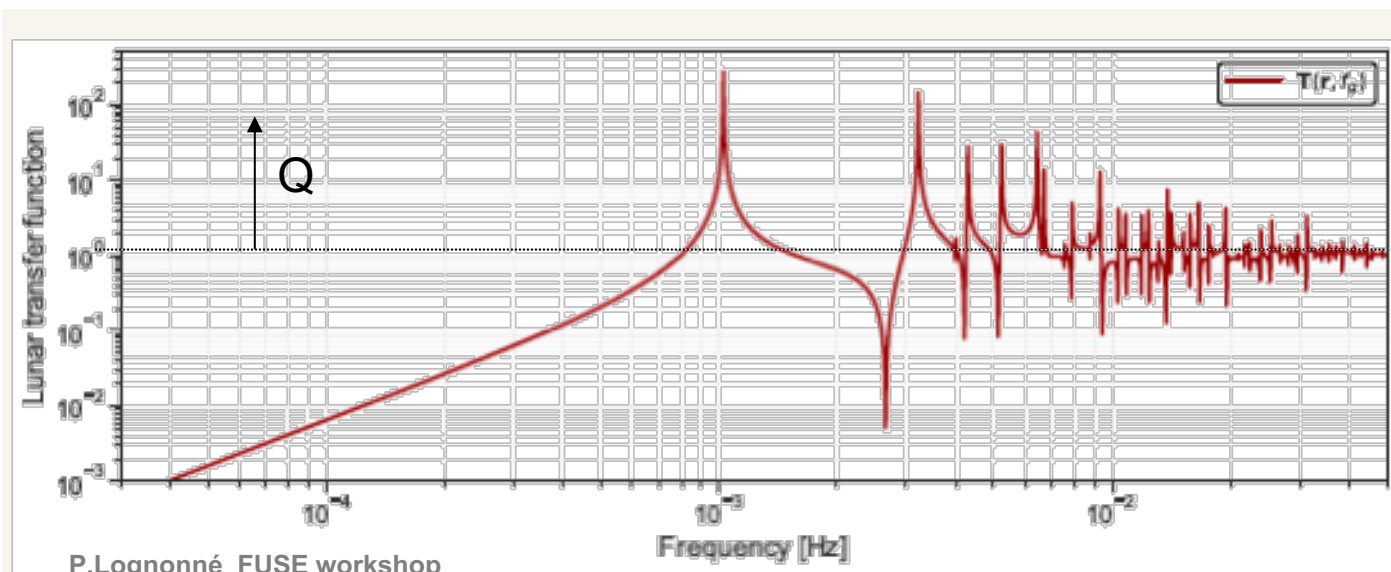
$$T_V \equiv \sum_n \frac{f_g^2}{f_n^2 - f_g^2 + i f_n f_g / Q_n} \frac{V_n(r)}{R_P} \chi_n,$$

The Moon responds elastically with its normal modes

$$\mathbf{s}(\mathbf{r}, t) = R_M h(t) \underbrace{\sum_{m, \alpha} f_m(e, \lambda, \nu) \mathcal{P}_m^\alpha(\theta, \phi) T^\alpha(\mathbf{r}, f_g)}_{T(\mathbf{r}, f_g): \text{ lunar response function}}.$$



- for the gravest modes, we have resonance and antiresonance
- for the modes at higher frequencies, frequency differences between modes are smaller, resonances are cancelled by the summation
- displacement is $\sim Q \cdot 1740 \text{ km} \cdot h \sim Q \times 1.74 \cdot 10^{-14} \text{ m}$ for $h=10^{-20}$



Moon GW detector : how to detect....

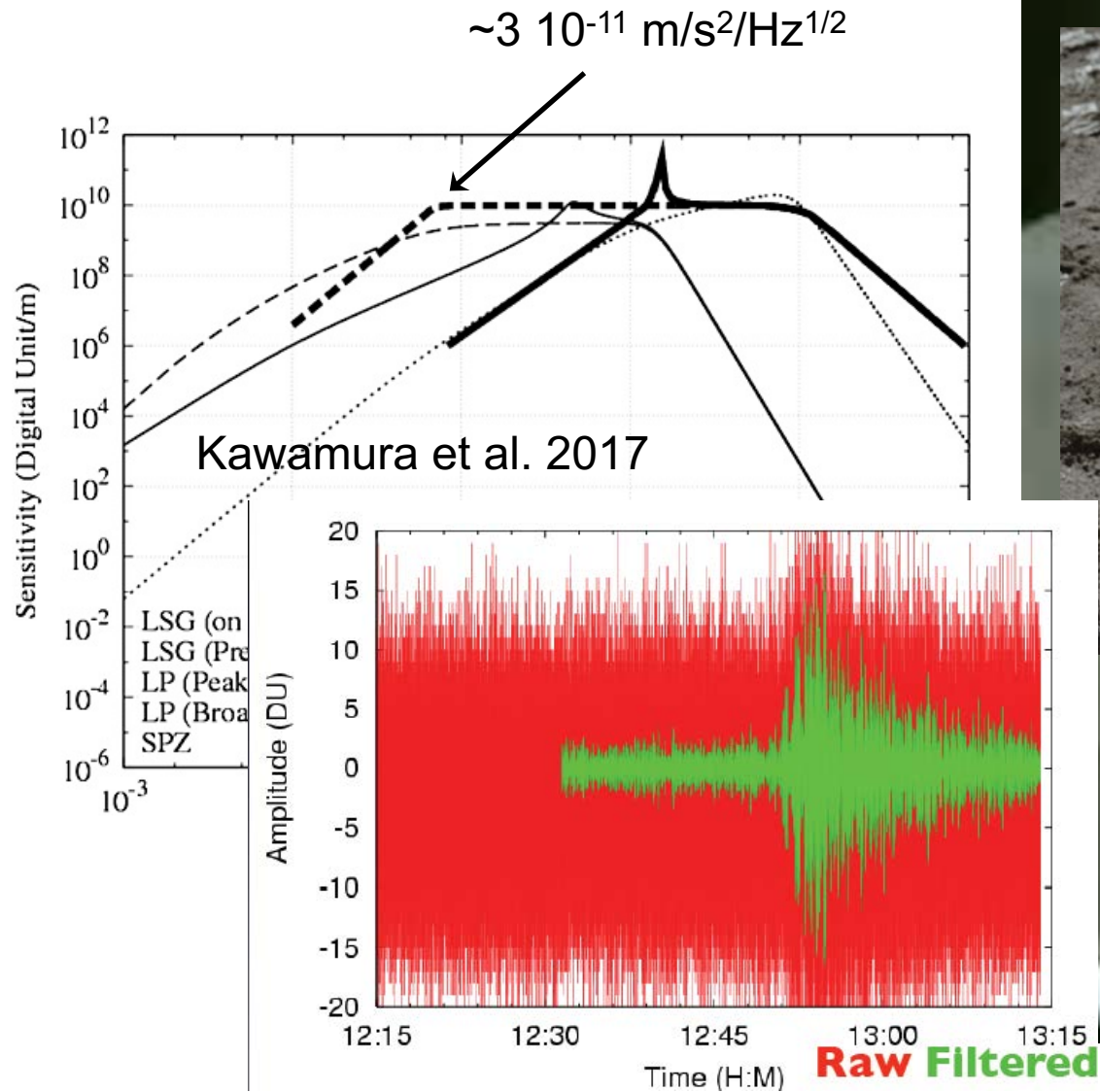
2F12

- These signals can be detected
 - By accelerometer with amplitude of about
 $\sim Q \cdot 1740 \text{ km} \cdot h \cdot (2\pi f)^2 \sim Q \times 6 \times 10^{-13} f^2 \text{ m/s}^2$ for $h=10^{-20}$
(multiplied by source and station factor ~ 1)

Apollo 17 Surface Gravimeter (PI J.Weber)

- By a strainmeter of length L with strain amplitude of about
 $\sim Q \cdot 1740 \text{ km} \cdot h \cdot L / 1740 \text{ km} \sim Q \times L \cdot h \sim Q \times 10^{-16}$ for $L=10 \text{ km}$ and $h=10^{-20}$
(multiplied by source and station factor ~ 1)

The first step: J.Weber, the Moon and the Lunar Surface Gravimeter



Moon GW detector : how to detect....

2F12

- These signals can be detected
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Ongoing European lead project LGWA (PI Jan Harms)

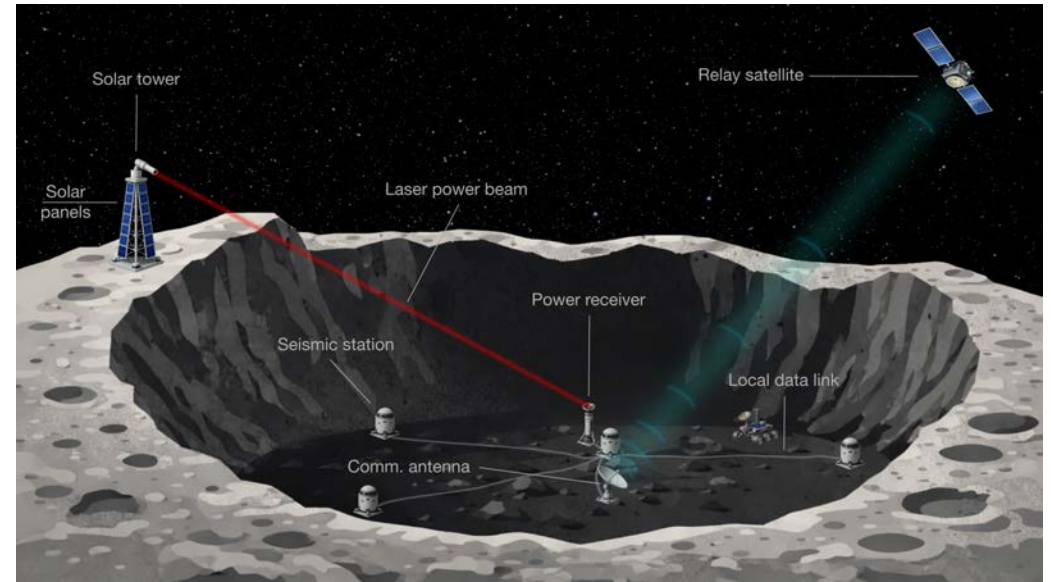
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Ongoing US lead project LILA (PI Karan Jani)

Moon GW detector : how to detect....

Ongoing project LGWA (PI Jan Harms). =>

- 3 very sensitive horizontal seismic stations in a permanently shadowed crater
- will use more stable temperature but will request either transmission of power or nuclear power
- the natural seismic noise of the Moon must be removed from the GW signal by the network signal processing
- precursor project: sound-check



<= Future project LILA (PI Karan Jani)

3 very sensitive strainmeter nodes on the rim of a large ~40 km crater

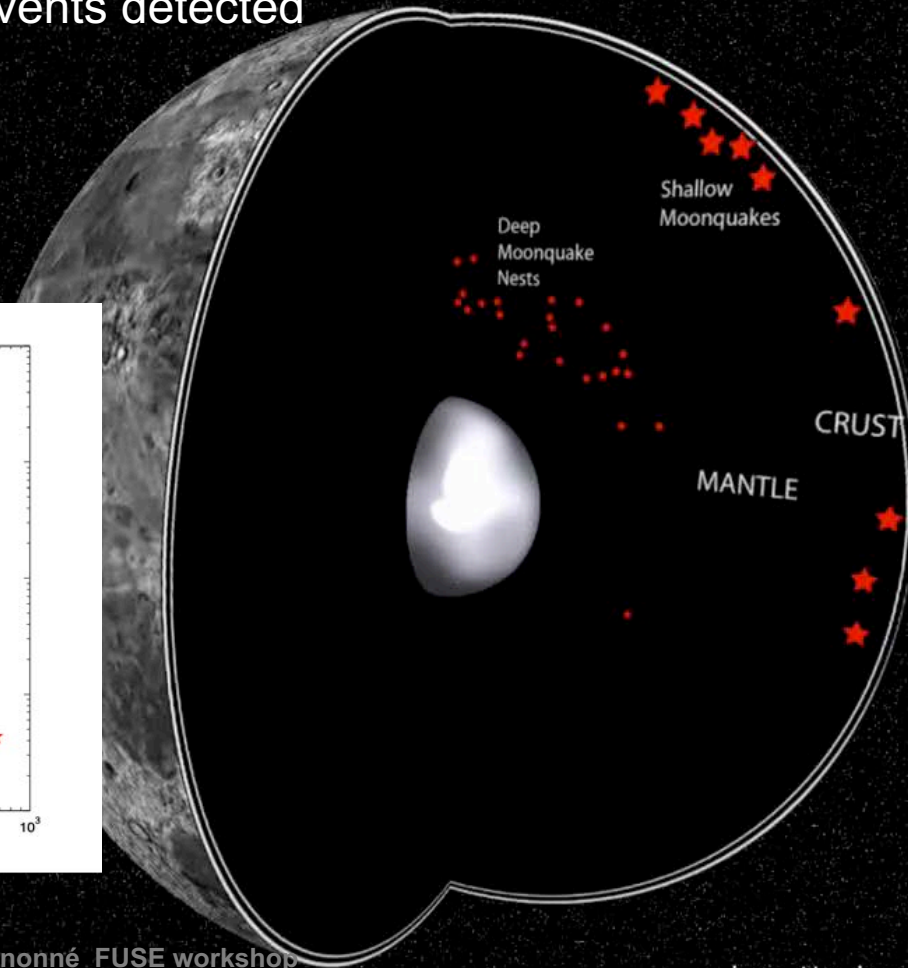
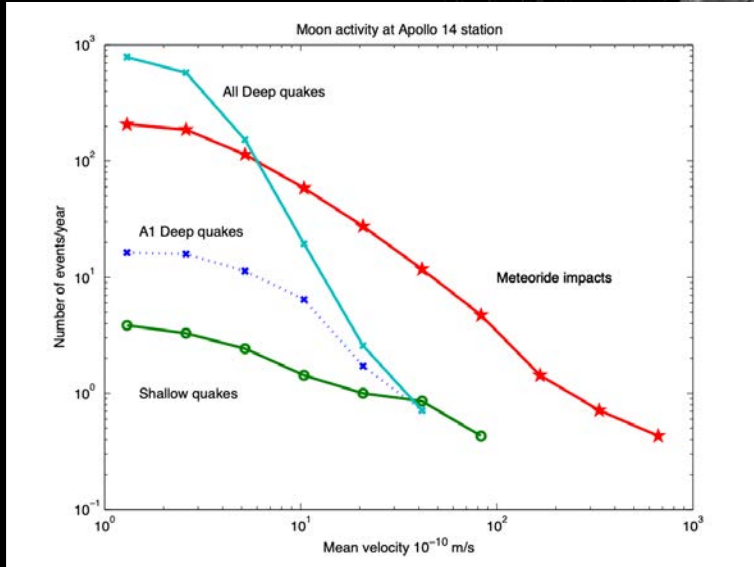
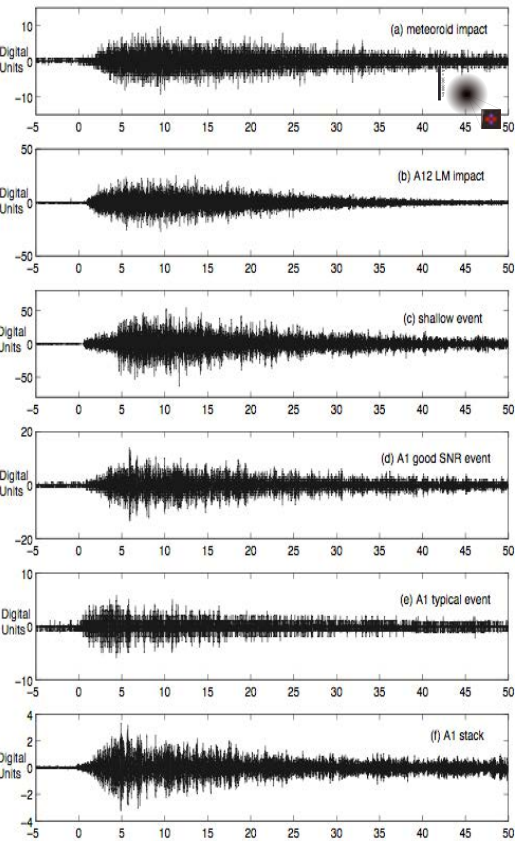
- can use solar panels but might be in an environment with more temperature variations
- the natural seismic noise of the Moon must be removed from the GW signal seismic attenuators and seismic decorrelation
- precursor project: iLILA

- Why Astrophysicists and Cosmologists want the Moon to be aseismic?
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Apollo network achievements

He atome

- **1969–1977**: Observational period
- **1972**: Full network operational
- 5 stations deployed, including 4 with long term network operation (5.5 yr)
- One gravimeter deployed for GW which failed to operate nominally
- More than 13000 events detected



Lognonné & Johnson,
2007, 2015

Moonquakes....

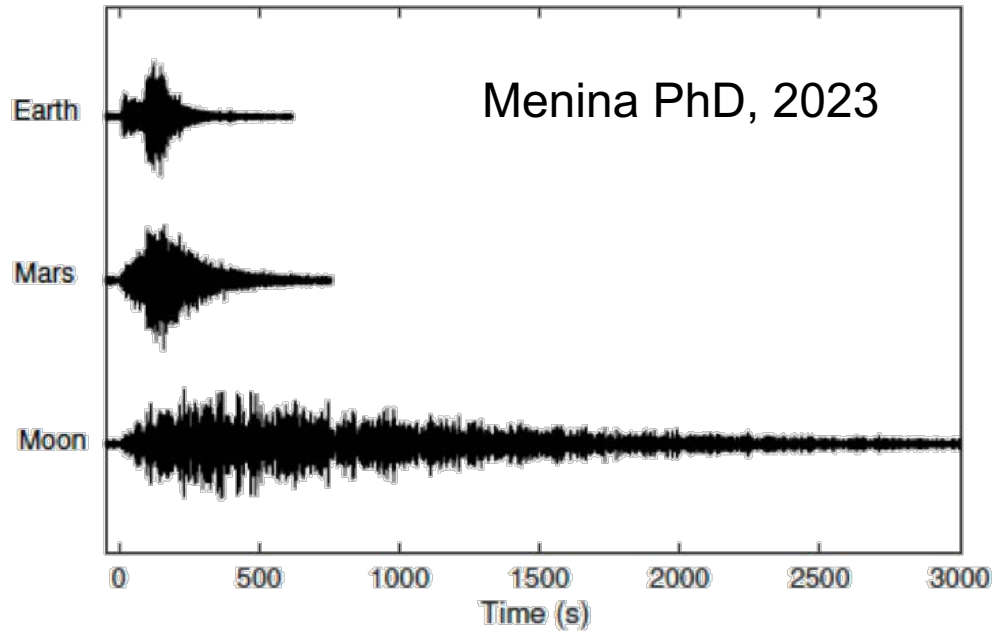


Figure 6.1: Seismograms comparison. (top) Earth regional event recorded on the Canadian shield. (middle) Martian VF event. (bottom) Lunar impact seismogram recorded by the Apollo 14 seismometer. The events are filtered around 7.5 Hz. $t = 0$ s refers to the the P-wave arrival time.

- Lunar propagation at long distance does not follow seismic wave equation as on Earth but is closed from diffusion theory
- Lunar events last hours, with a slow coda decay

- The decay depends on the path...

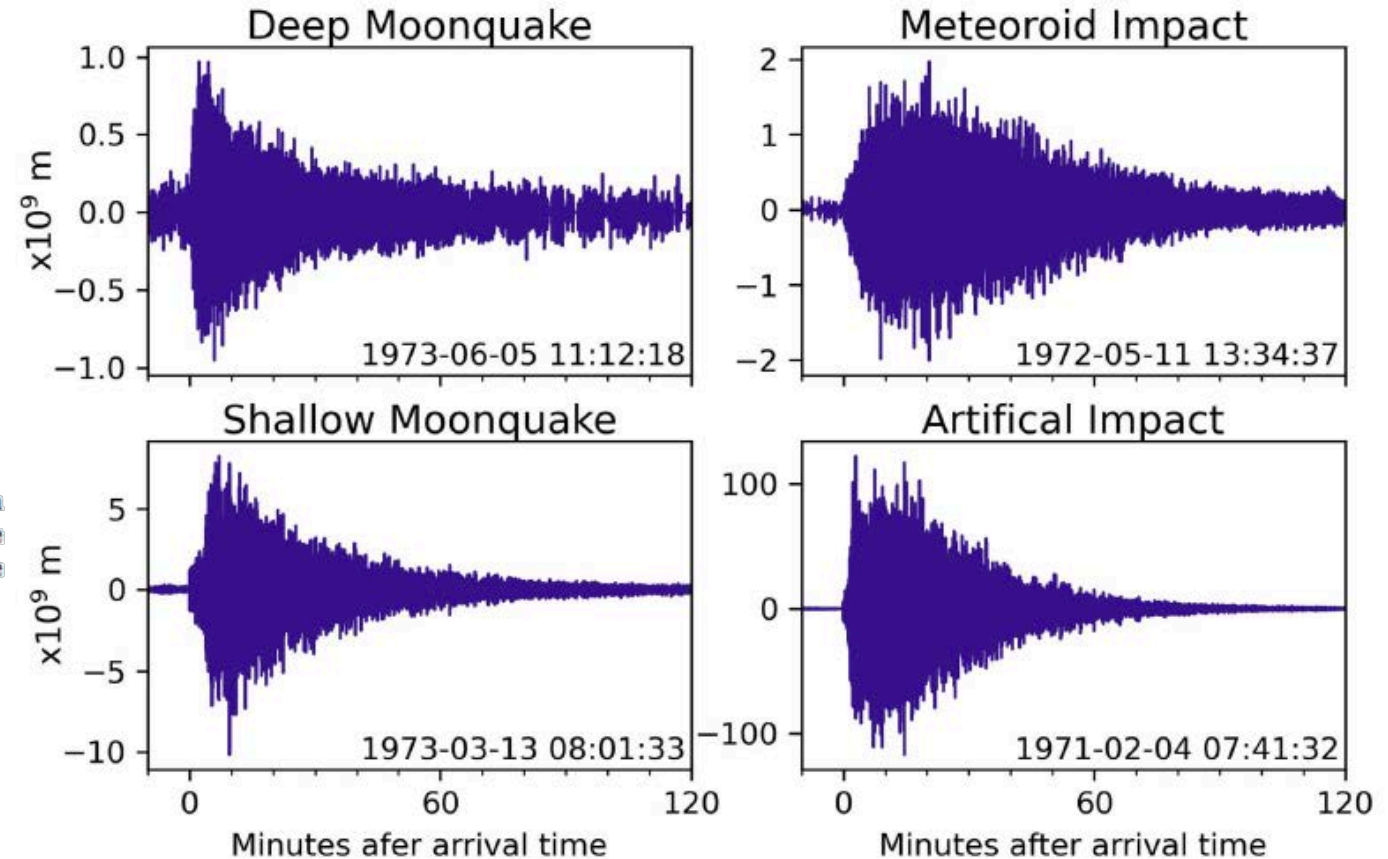
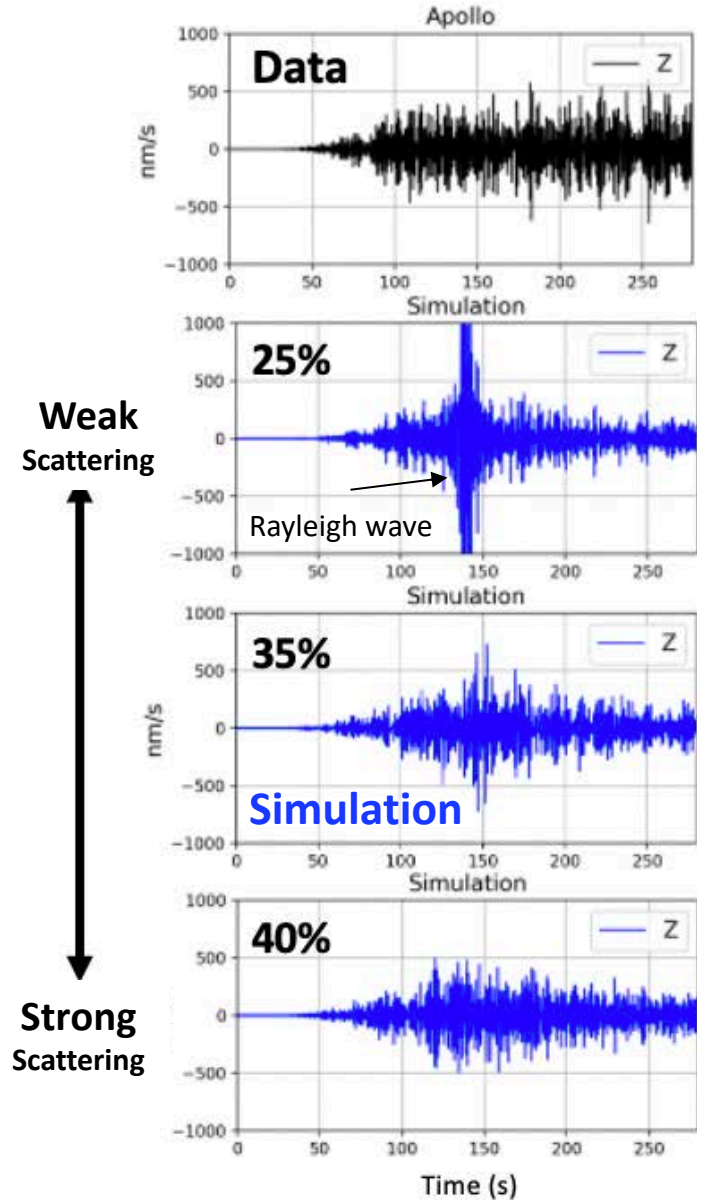
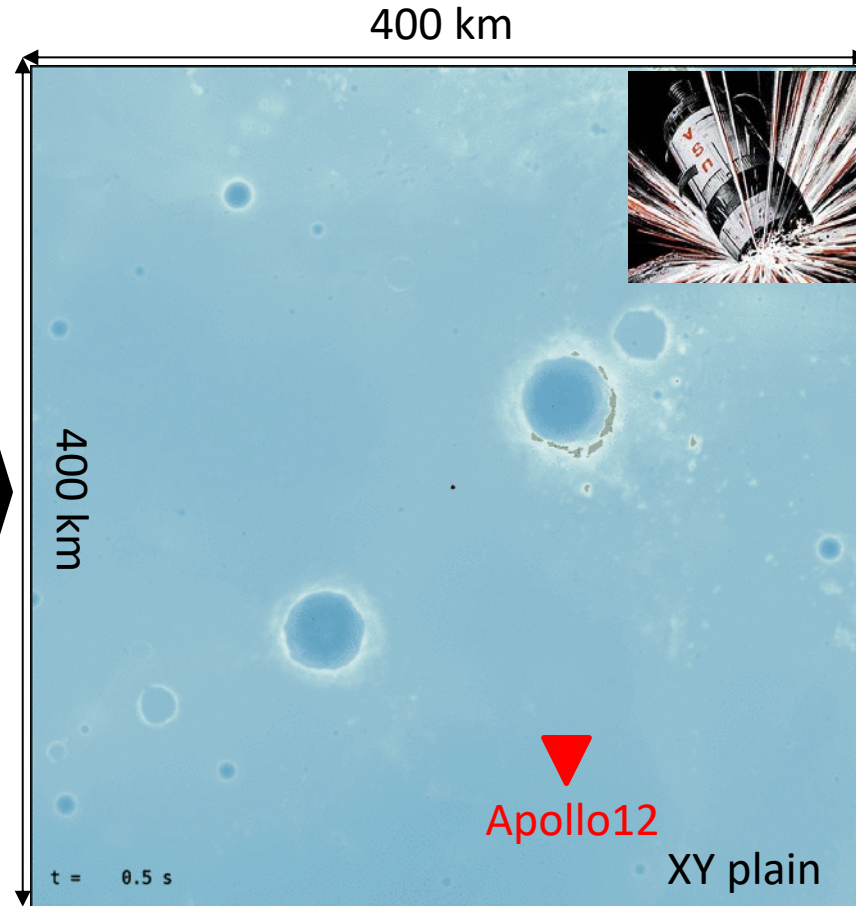
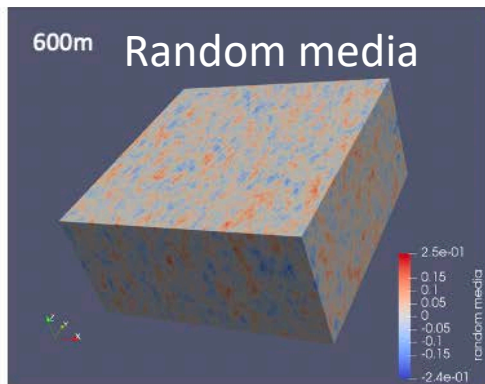
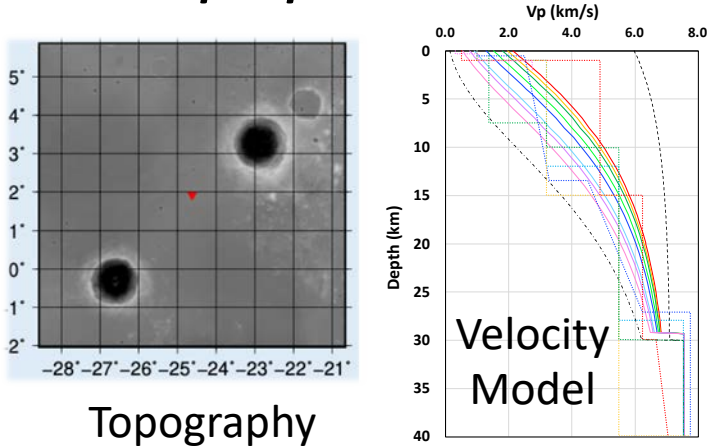


Figure 3. Examples of a deep moonquake, a meteoroid impact, a shallow moonquake, and an artificial impact. The events were recorded on seismic station S12 on the vertical component (MHZ). The timing for each event is in minutes and relative to the arrival time. The traces are displayed in displacement (in meters), with different scales for each event. The amplitude of the artificial impact signal exceeded the range of the instrument.

Seismic scattering : Modelling illustration on impact

10/27

Input parameters



Moonquakes propagation...

To first order, the envelop is following diffusion theory

$$\frac{\partial I(\mathbf{r}, t)}{\partial t} - cDV^2 I(\mathbf{r}, t) = - \left(\frac{1}{\tau^s} \right) I(\mathbf{r}, t) + S(\mathbf{r}, t)$$

And better theories must consider in that diffusion conversion between P and S

(Margerin, 2017):

$$\begin{aligned} (\partial_t + c^p \mathbf{n} \cdot \nabla) \rho^p(\mathbf{r}, \mathbf{n}, t) = & - \left(\frac{1}{\tau^p} + \frac{1}{t_i^p} \right) \rho^p(\mathbf{r}, \mathbf{n}, t) + \frac{1}{\tau^{pp}} \int_{4\pi} p^{pp}(\mathbf{n}, \mathbf{n}') \rho^p(\mathbf{r}, \mathbf{n}', t) d^2 \mathbf{n}' \\ & + \frac{1}{\tau^{sp}} \int_{4\pi} p^{sp}(\mathbf{n}, \mathbf{n}') \rho^s(\mathbf{r}, \mathbf{n}', t) d^2 \mathbf{n}' + S^p(\mathbf{r}, \mathbf{n}, t) \\ (\partial_t + c^s \mathbf{n} \cdot \nabla) \rho^s(\mathbf{r}, \mathbf{n}, t) = & - \left(\frac{1}{\tau^s} + \frac{1}{t_i^s} \right) \rho^s(\mathbf{r}, \mathbf{n}, t) + \frac{1}{\tau^{ps}} \int_{4\pi} p^{ps}(\mathbf{n}, \mathbf{n}') \rho^p(\mathbf{r}, \mathbf{n}', t) d^2 \mathbf{n}' \\ & + \frac{1}{\tau^{ss}} \int_{4\pi} p^{ss}(\mathbf{n}, \mathbf{n}') \rho^s(\mathbf{r}, \mathbf{n}', t) d^2 \mathbf{n}' + S^s(\mathbf{r}, \mathbf{n}, t) \end{aligned} \quad (5.1)$$

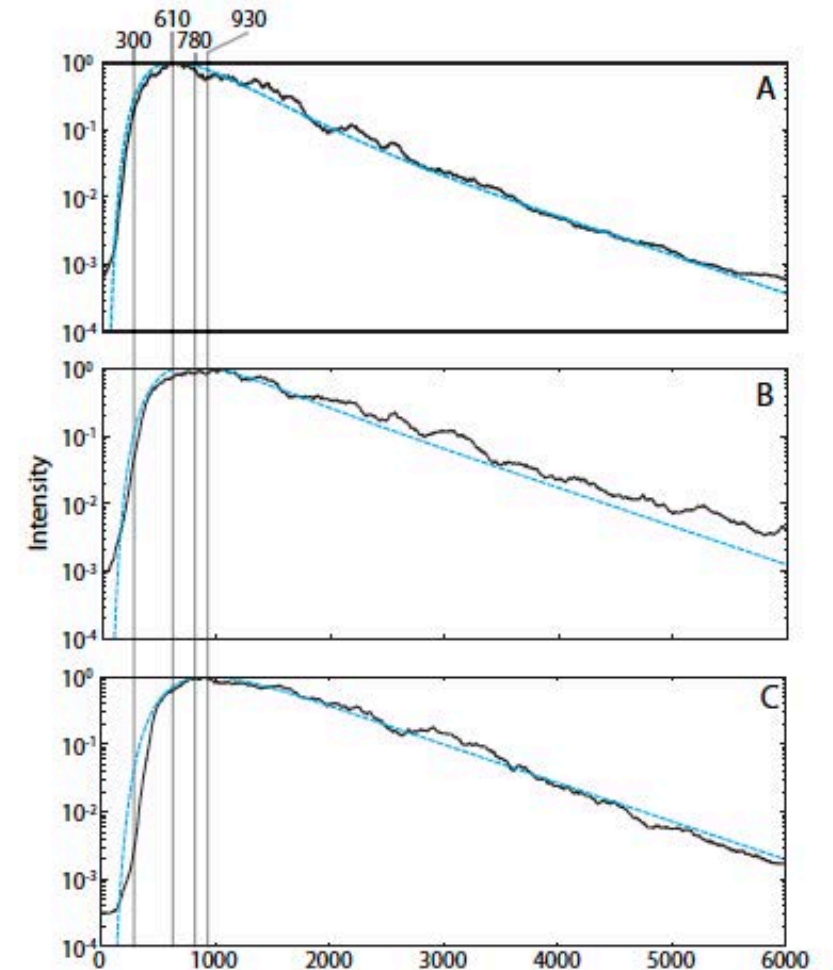
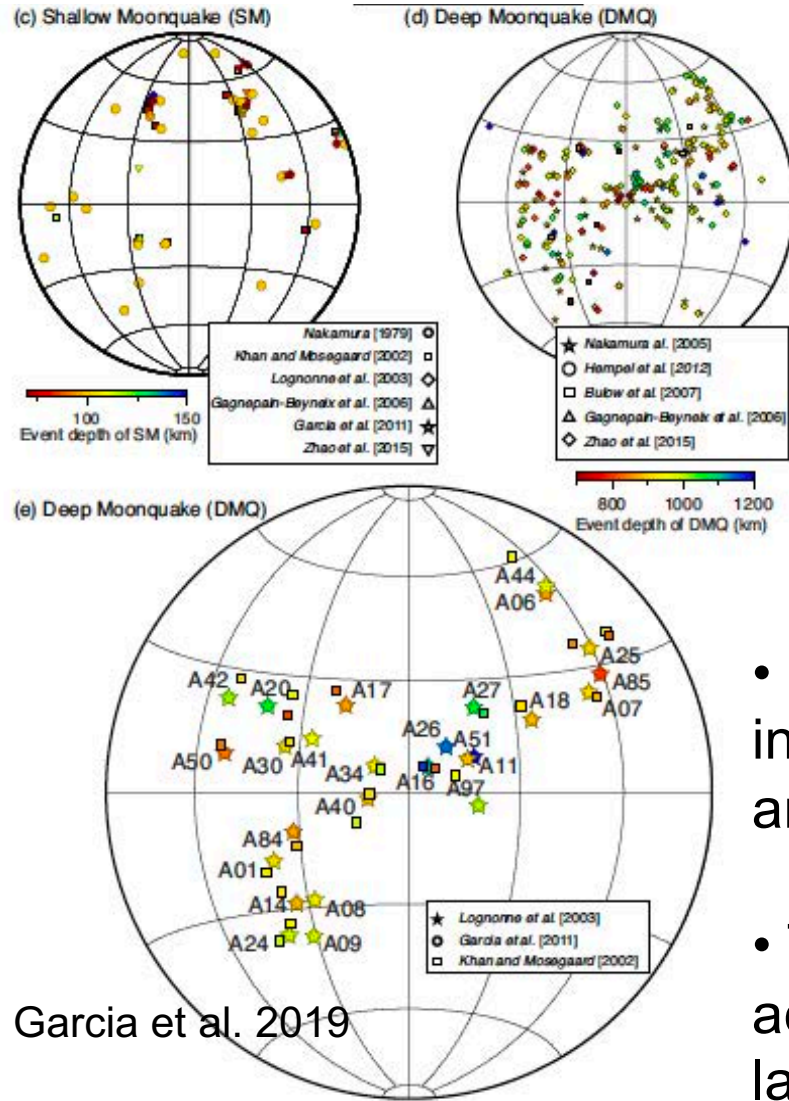


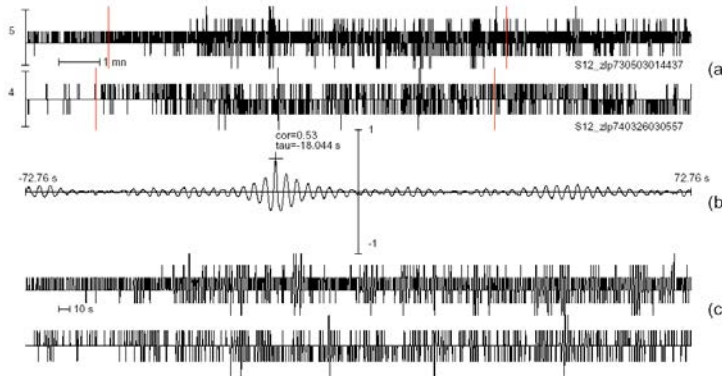
Figure 2.13: Synthetic (blue) and observed (black) energetic envelopes of lunar seismic events located at: (A) 15.6°, (B) 38.5° and (C) 60.9°. 610 s, 780 s and 930 s refer to the arrival time of the maximum at A, B and C, respectively. (From (Gillet et al., 2017))

Moonquakes

- About 12000 DMQs and ~30 Shallow moonquakes

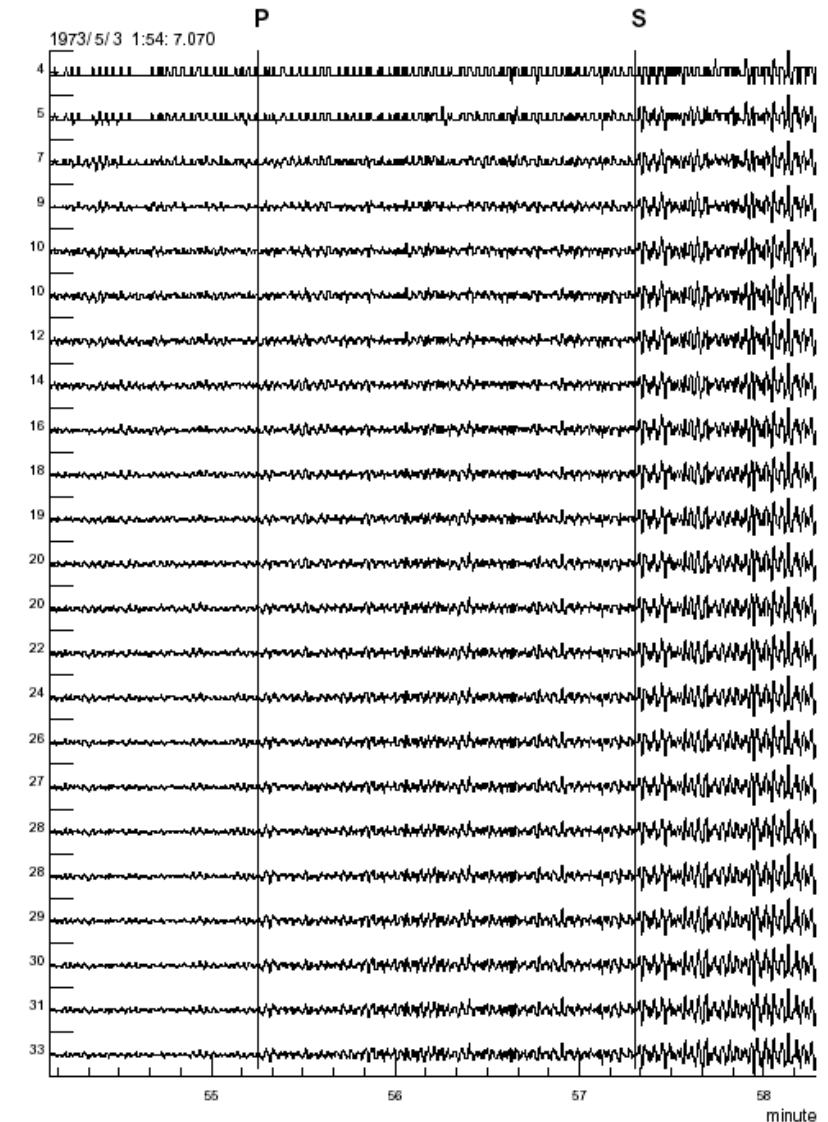


Garcia et al. 2019



- example of quakes (in 1973 and in 1974) from the same deep focus and their cross-correlation

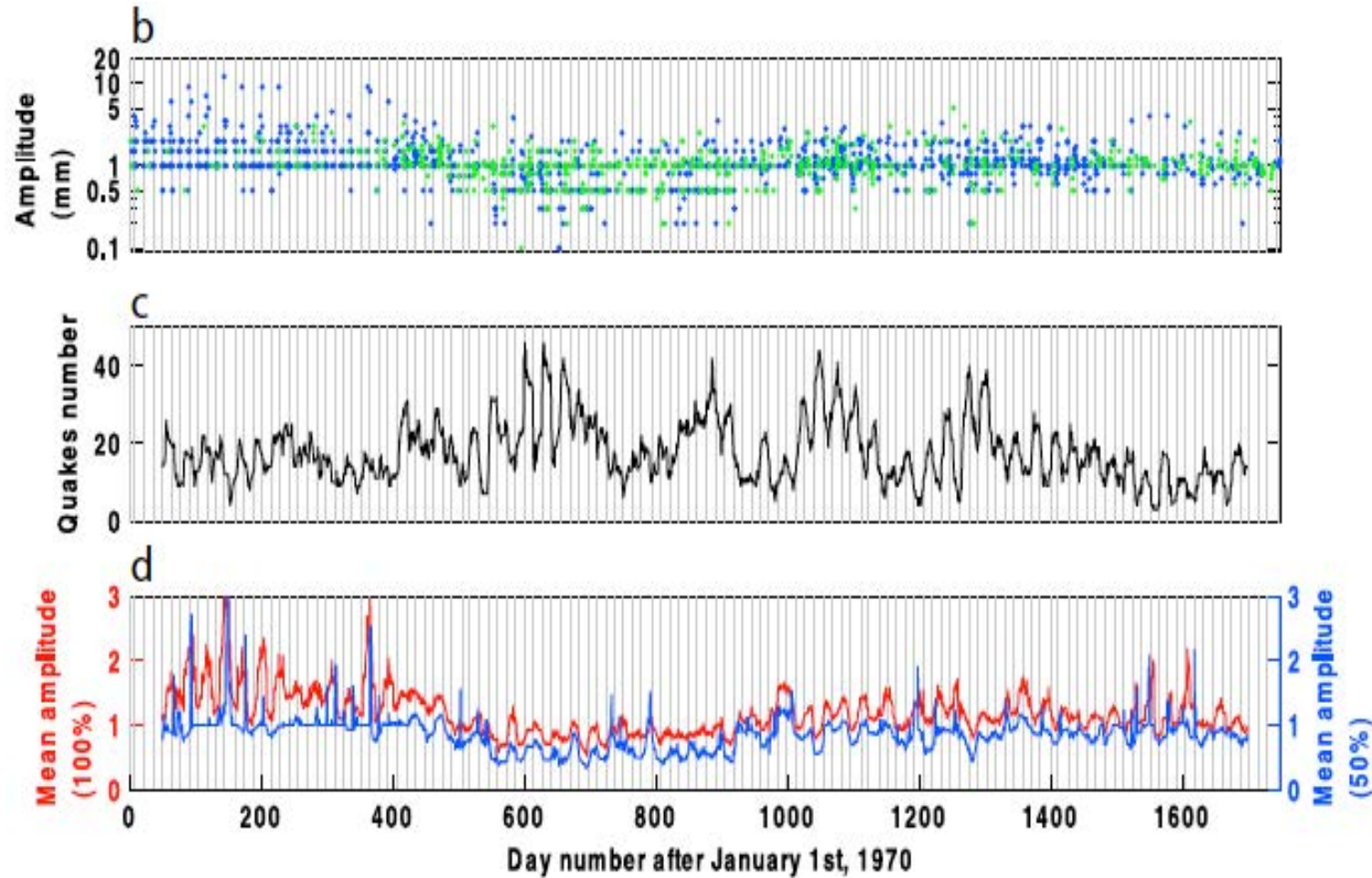
- These deep focus will likely be active when future missions will land, enabling virtual « network » analysis with Apollo



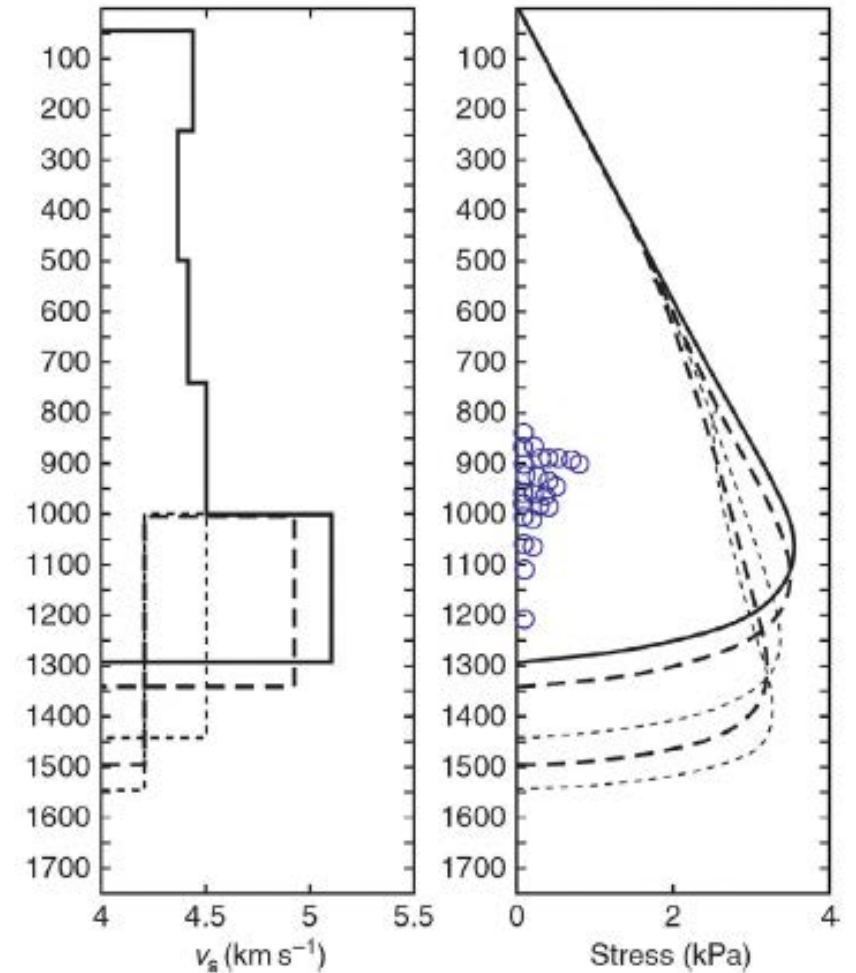
Beyneix et al. 2006

What Apollo did : Discovering the DMQs nest

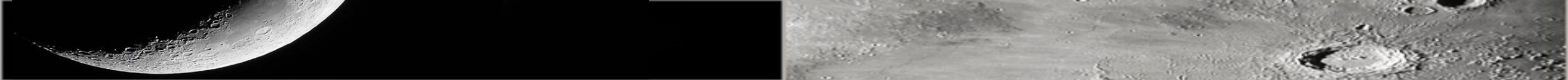
Activity of one DMQ nest
(Lognonné & Johnson 2015)



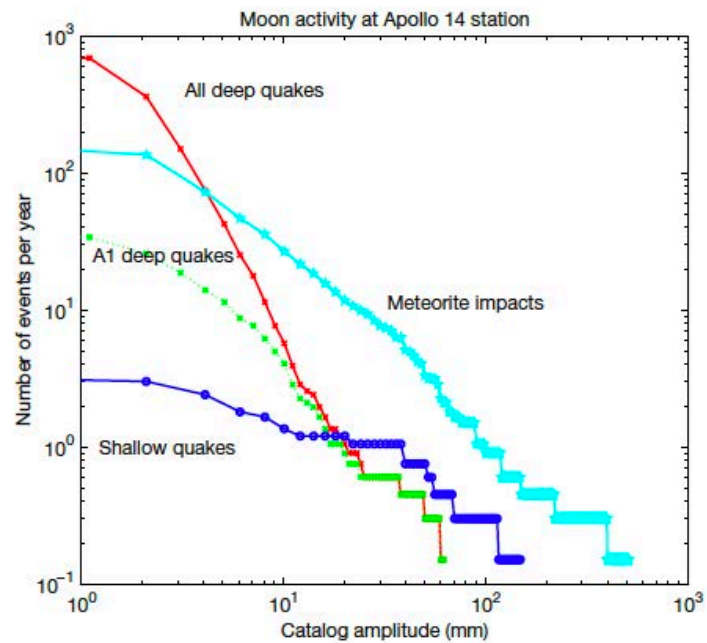
Beyneix et al. (2006): liquid core



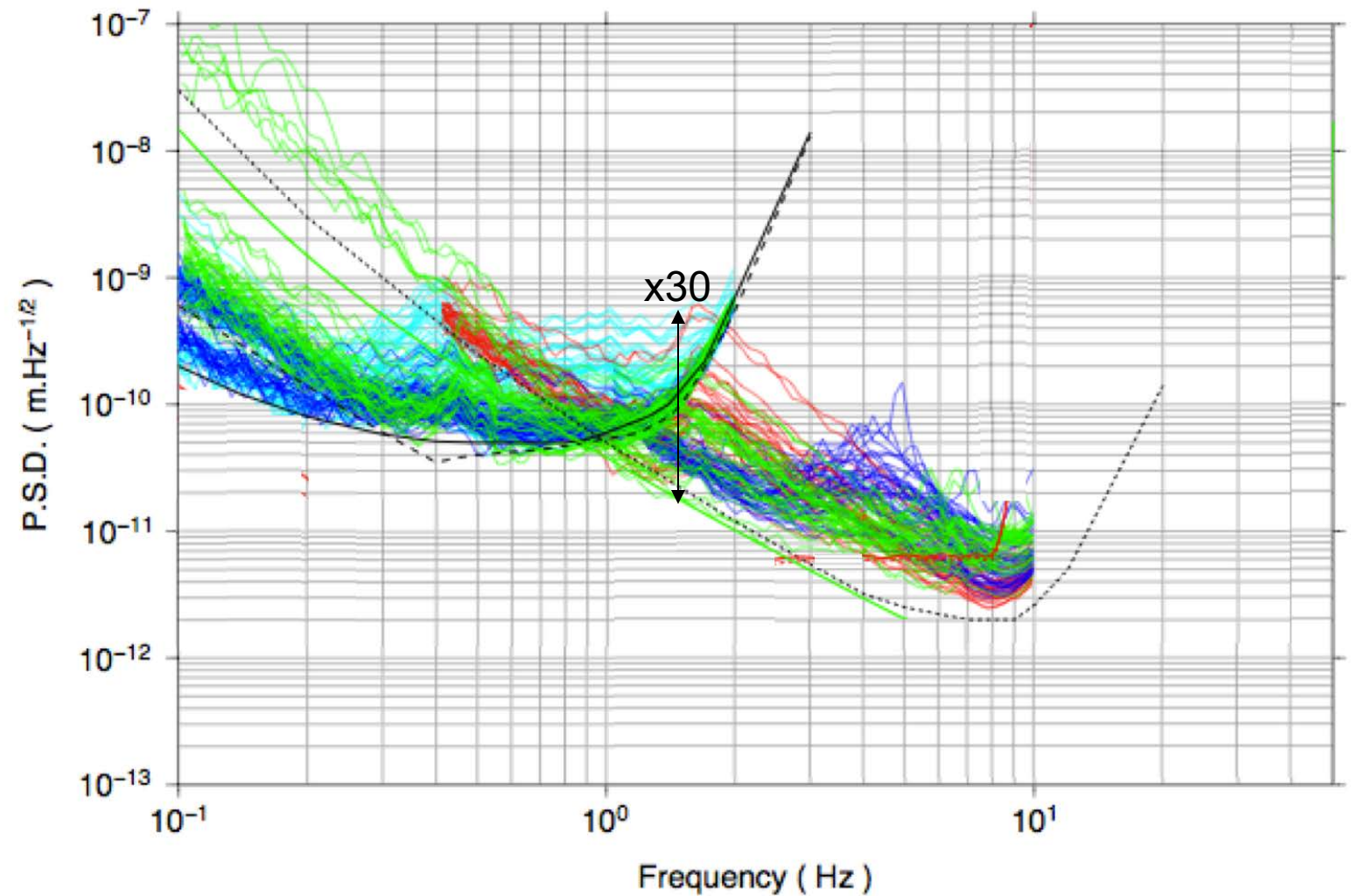
Tidal stresses and DMQ depth
(Lognonné & Johnson 2015)



The Apollo DMQ collection (from DMQ seismograms collection, spectra of 1800 sec)



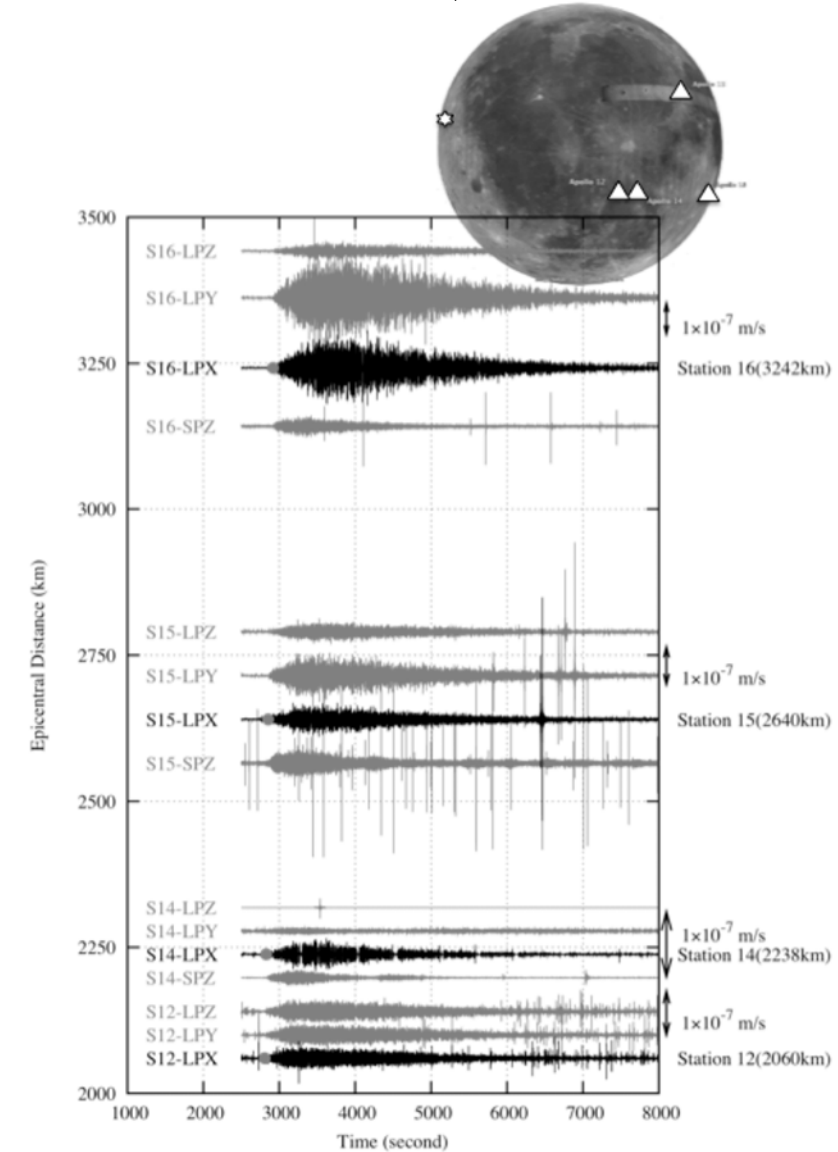
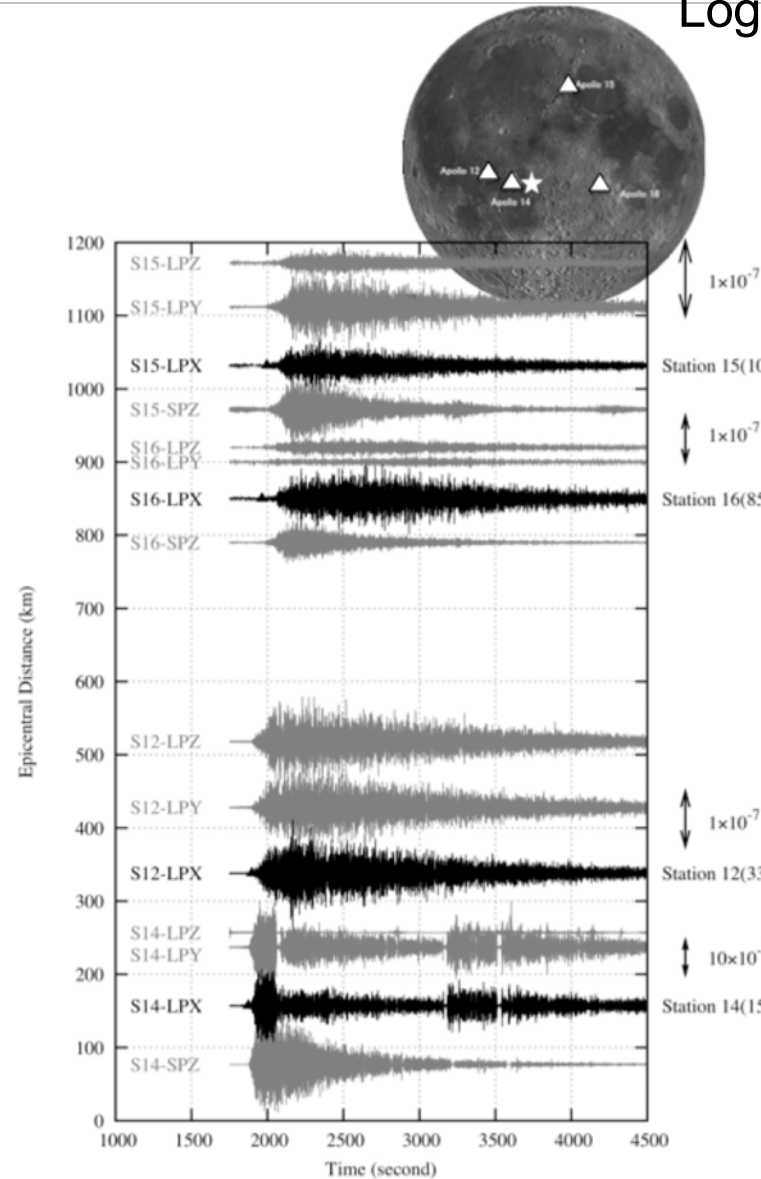
$X30 \times 2 = 60$ (peak to peak)



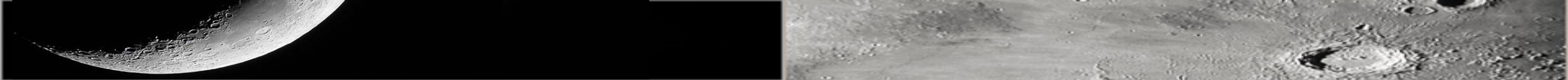
Impacts

- About 1700 impact detected including artificial impacts with known impact time and location
- Located only for ~10 artificial impacts
- provided a large part of the informations on the crustal structure

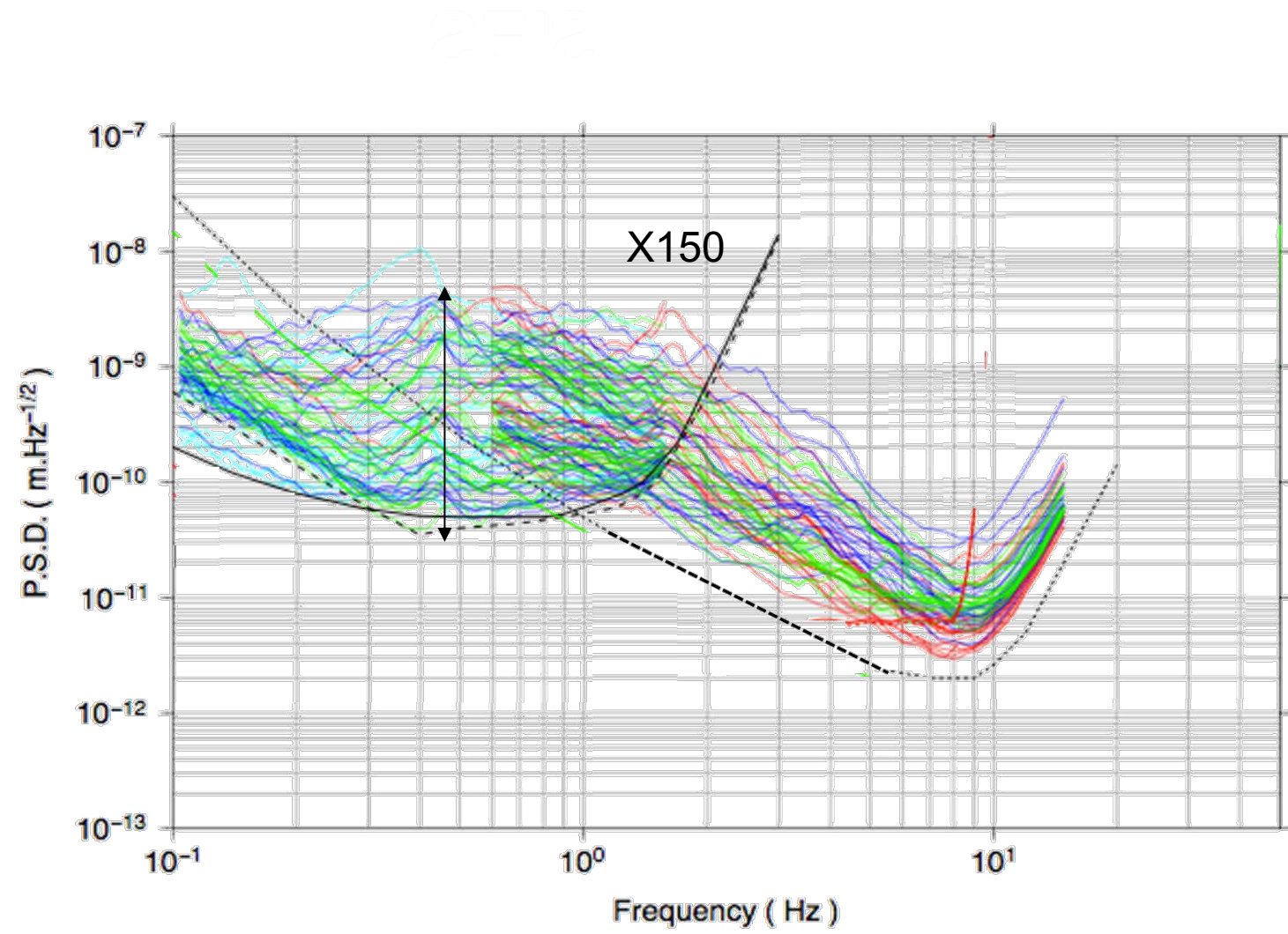
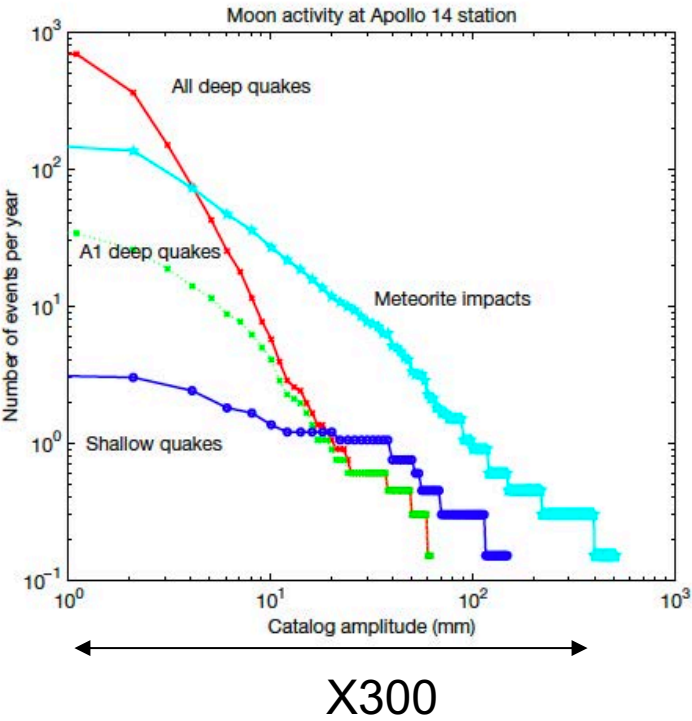
Lognonné and Kawamura, 2014



P.Lognonné FUSE workshop



Example on Apollo Impact collection



impacts frequency

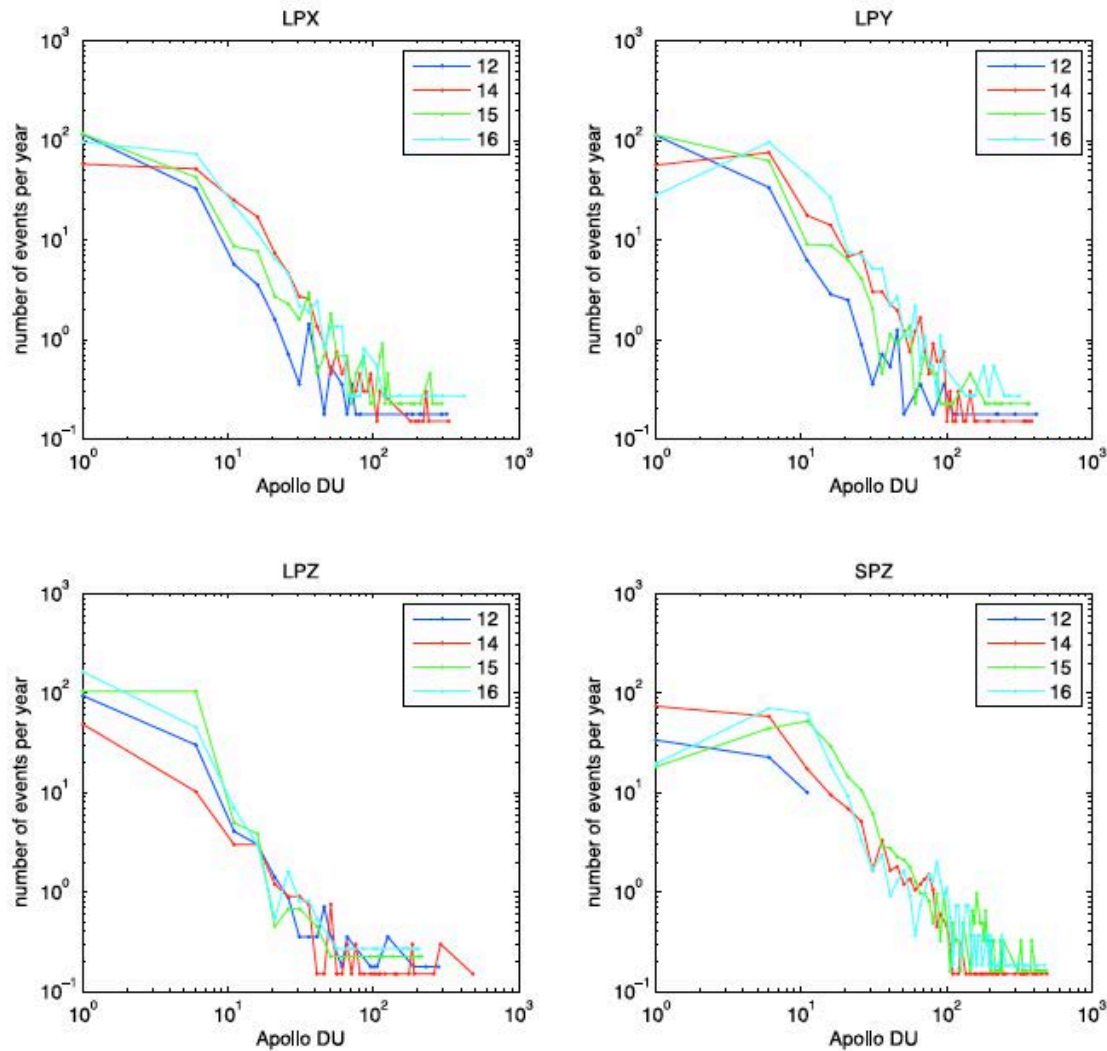


Figure 2. Number of impacts per year in peaked response mode with a given peak-to-peak amplitude (in Apollo DU) on the LP channels of all four stations. The SP statistics are shown for comparison; note that the SP component of station 12 failed early into the experiment.

- The Apollo detection rate are about 100 impacts /year on the LP instrument with the resolution of about 1 Apollo DU

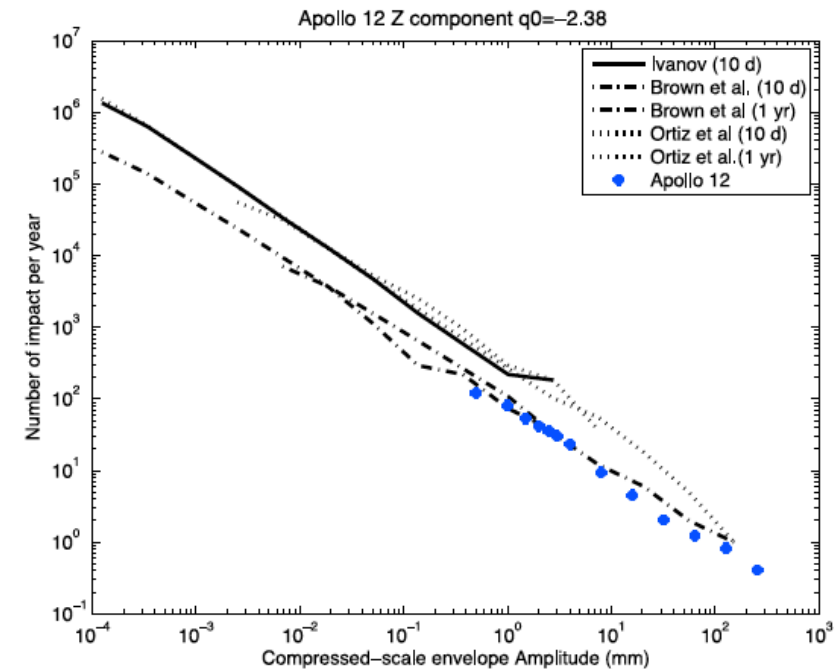
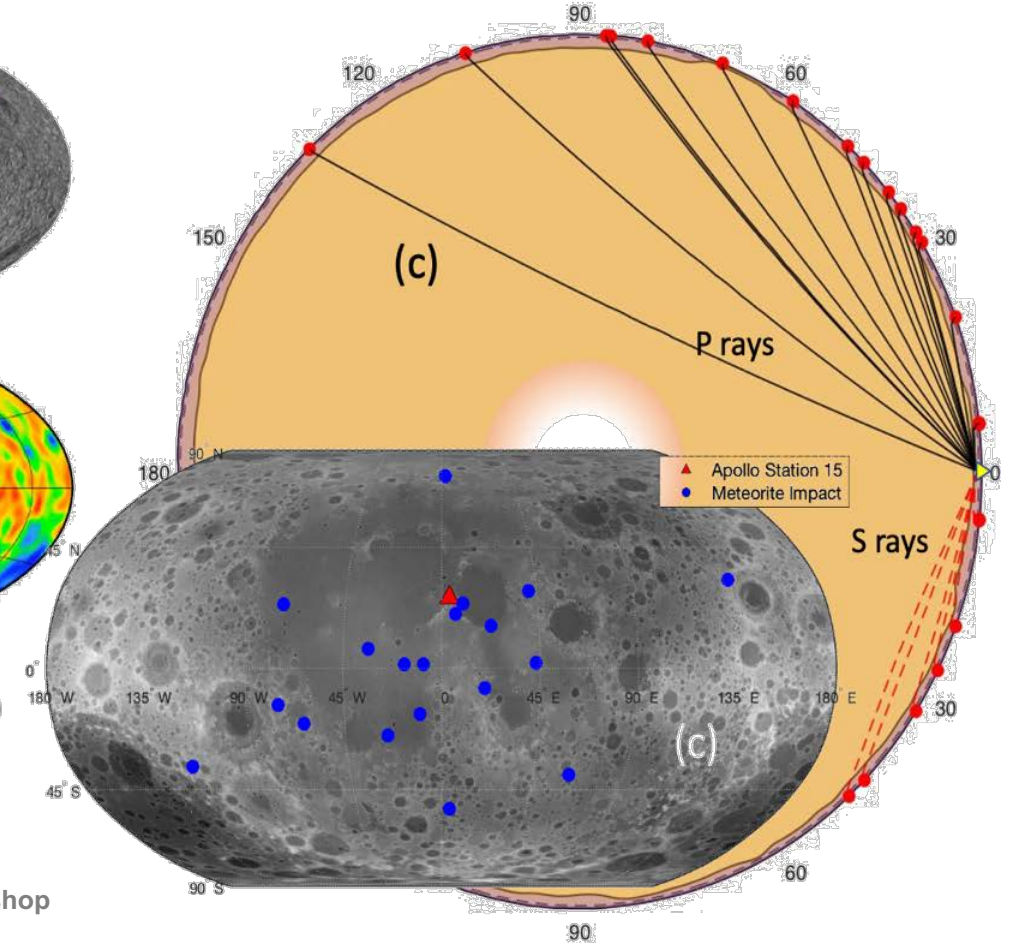
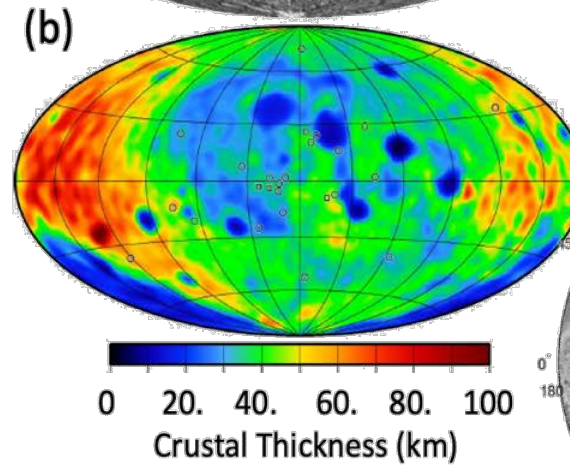
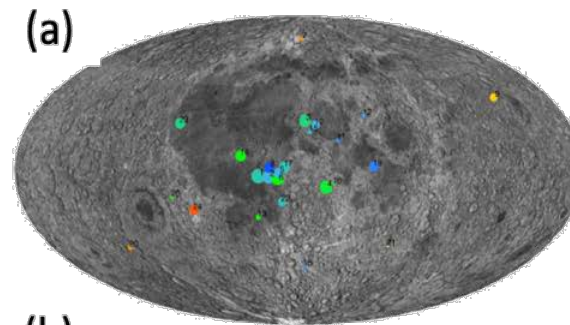
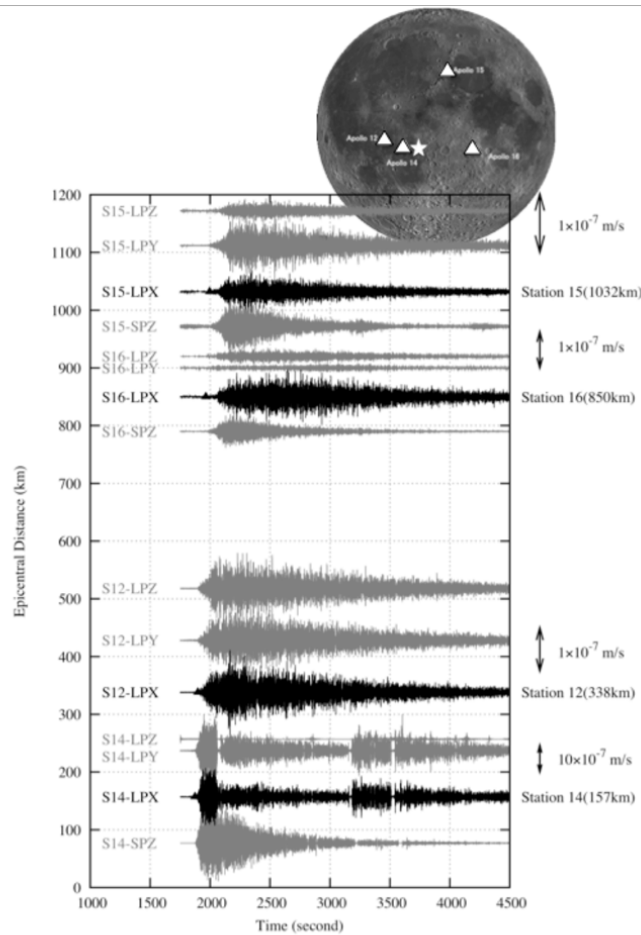


Figure 16. Number of impacts per year with a given amplitude modeled at station 12 using impact statistics derived from the Ivanov (solid line), Ortiz (dotted line), and Brown (dashed-dotted line) models. For comparison with the Apollo catalog information (circles), we report the compressed-scale envelope amplitude estimated from our synthetics. For the Brown and Ortiz impact models, the line segment on the left is for the 10 day simulation and corresponds to small impacts while the one on the right is for the 1 year simulation, corresponding to large impacts.

Crust inversion and impacts from Apollo 15

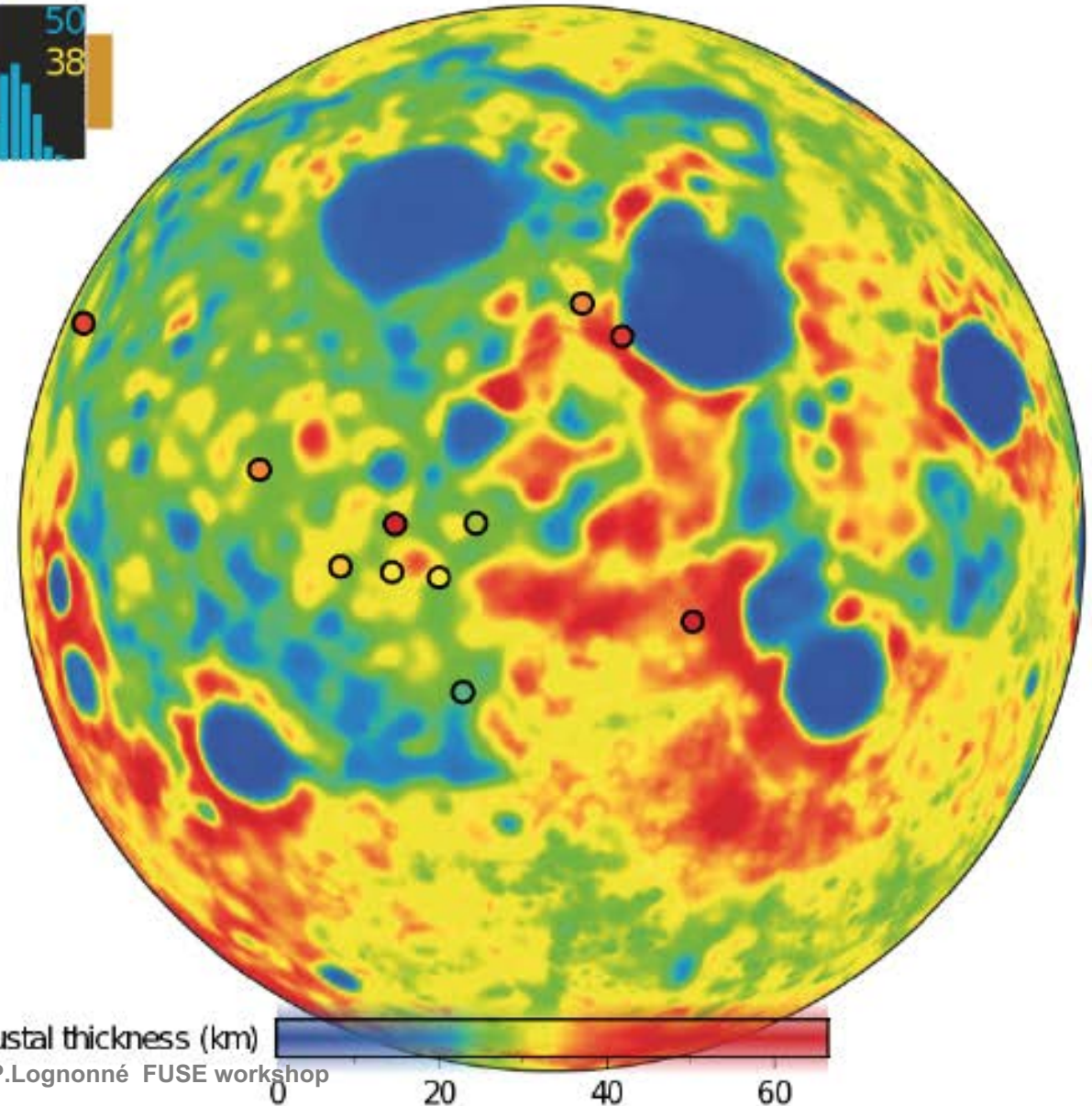
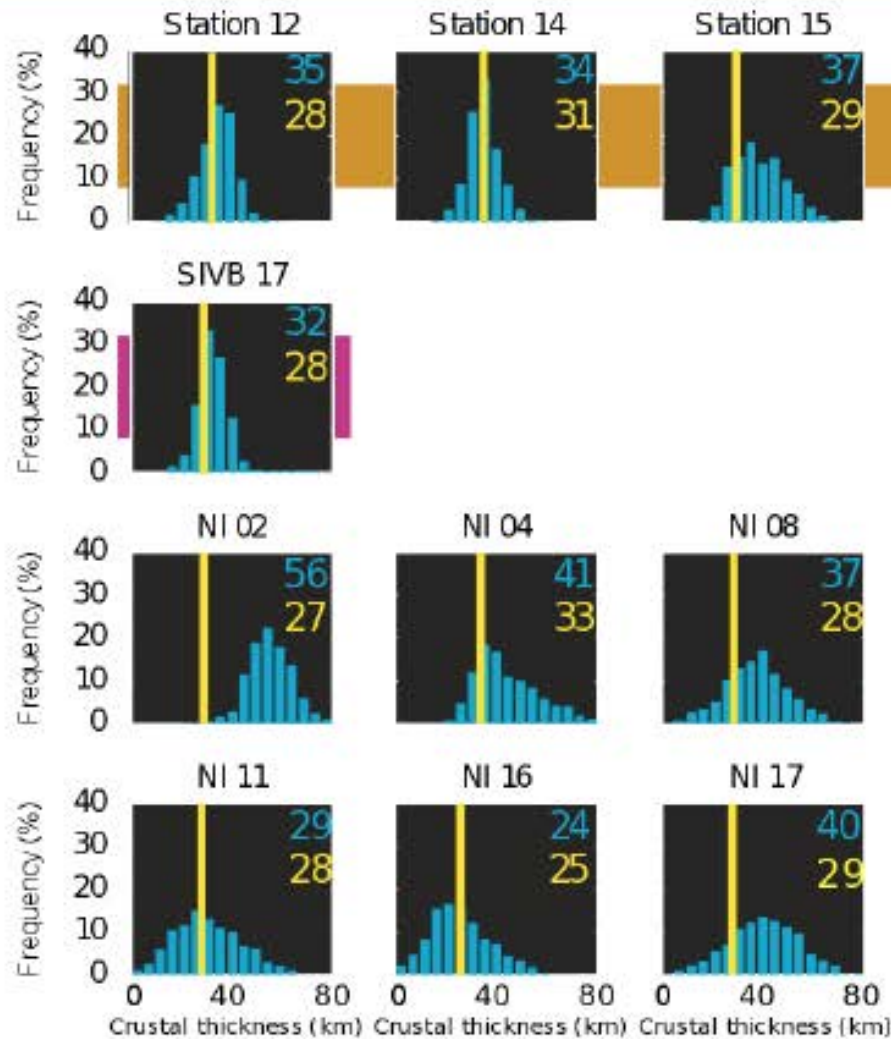
- Only Impacts with known or well inverted location can be used.
 - Only the artificial impacts meet that condition
- Natural, due to scattering, have a poor S arrival time determination and large location errors



Zhang et al. 2025

P. Lognonné FUSE workshop

Example 1: Anchoring the crustal thickness of the Moon



GRAIL data - Model 1 → 34 km crustal thickness

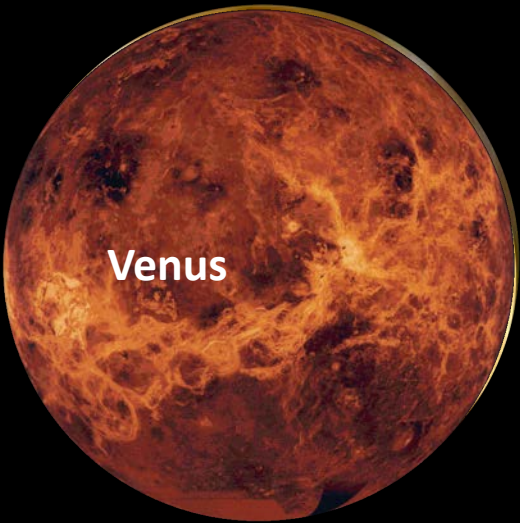
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Courtesy M.Drilleau, J.F.Blanchette-Guertin

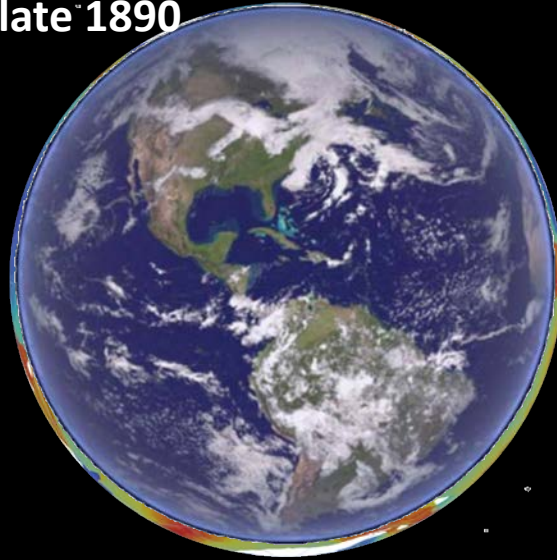
Various past and ongoing projects

Many dense Earth seismic networks since late 1890

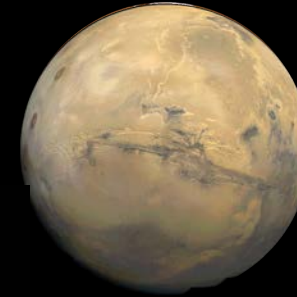
After almost 140 years of seismology since von Reubeur-Pasch with seismograph record...



Venus



Moon



Mars

Single stations:
Viking 1-2 1976

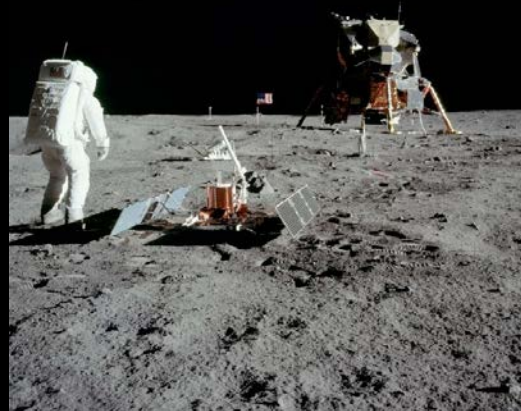


Icy Moons

Single stations:
Ranger 3-4 (1962)



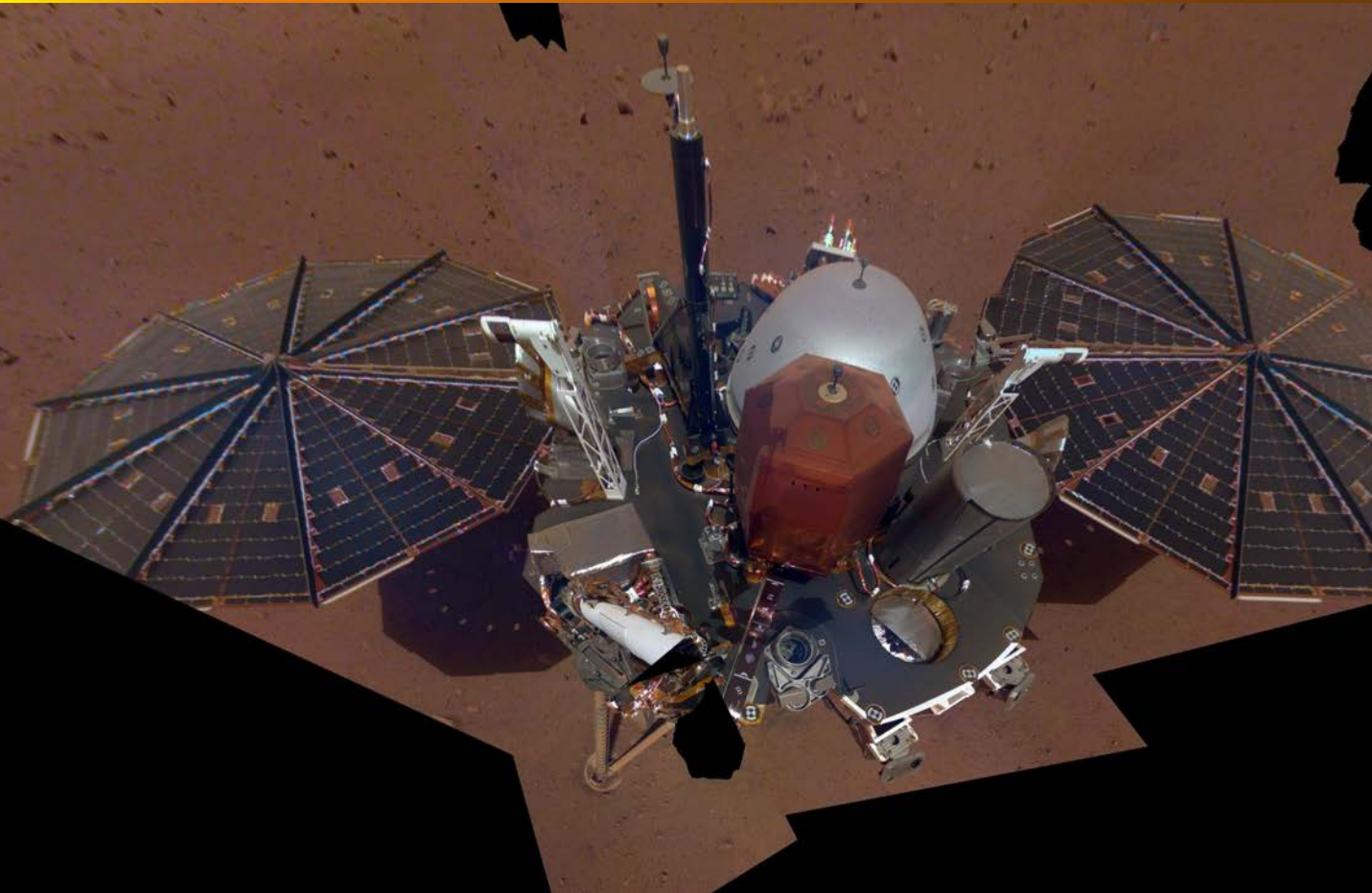
Network:
Apollo 11-
12-14-
15-16-17
1969-> 1977



InSight
2018-2022

InSight : an international seismic discovery of Mars

Banerdt et al. 2020



Instrument Deployment System (IDS)



- Instrument Deployment Arm (IDA)
- Instrument Deployment Camera (IDC)
- Instrument Context Camera (ICC)



Rotation and Interior Structure Experiment (RISE)



Laser Retroreflector for inSight (LaRIL)

Heat Flow and Physical Properties Package (HP³)



Auxiliary Payload Sensor Suite (APSS)

- Magnetometer (IFG)
- Microbarometer
- Wind sensor (TWINS)



Seismic Experiment for Interior Structure (SEIS)

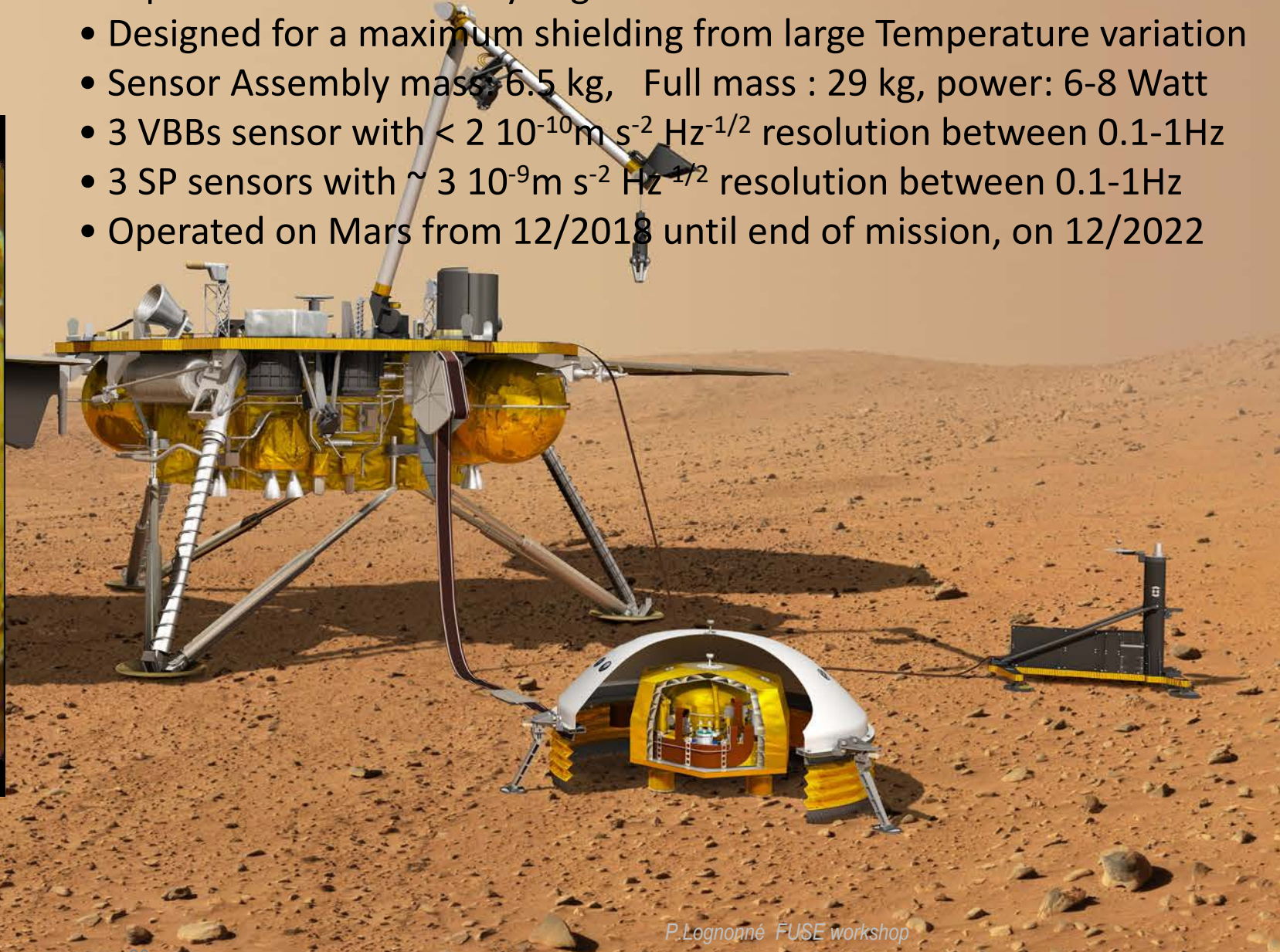
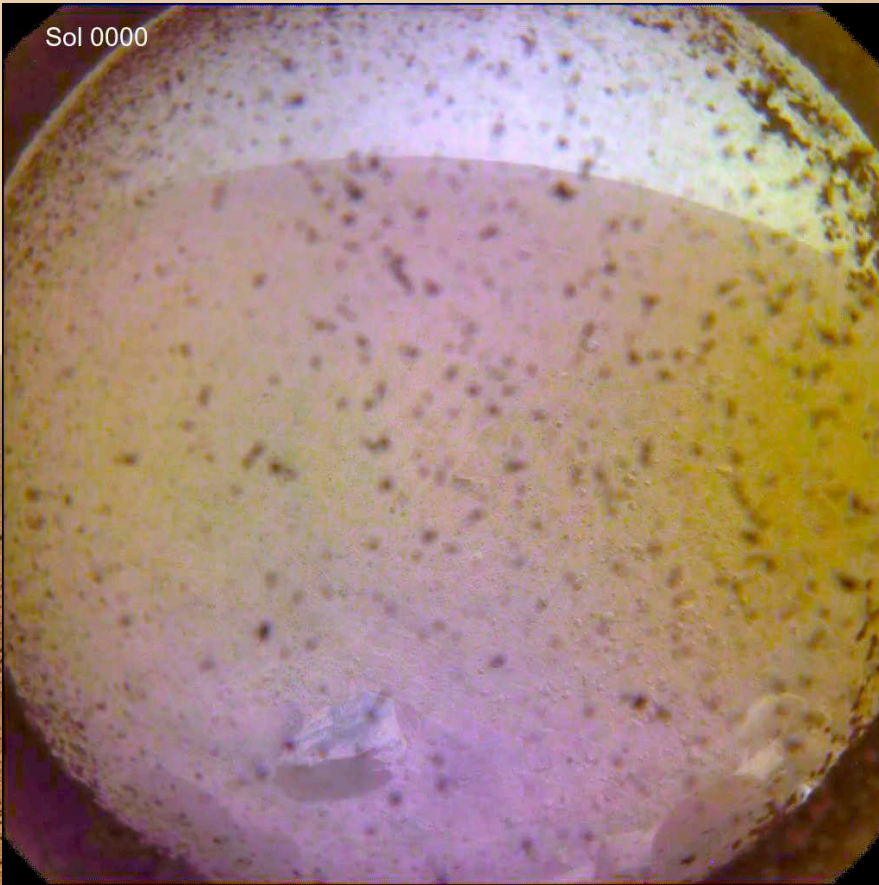


- InSight was the first geophysical observatory deployed on Mars, with a suite of instruments comparable to those deployed on the Moon by the Apollo Lunar Surface Packages (plus atmospheric sensors...)
- InSight landed on Mars on November, 26, 2018 and operated until mid december 2022

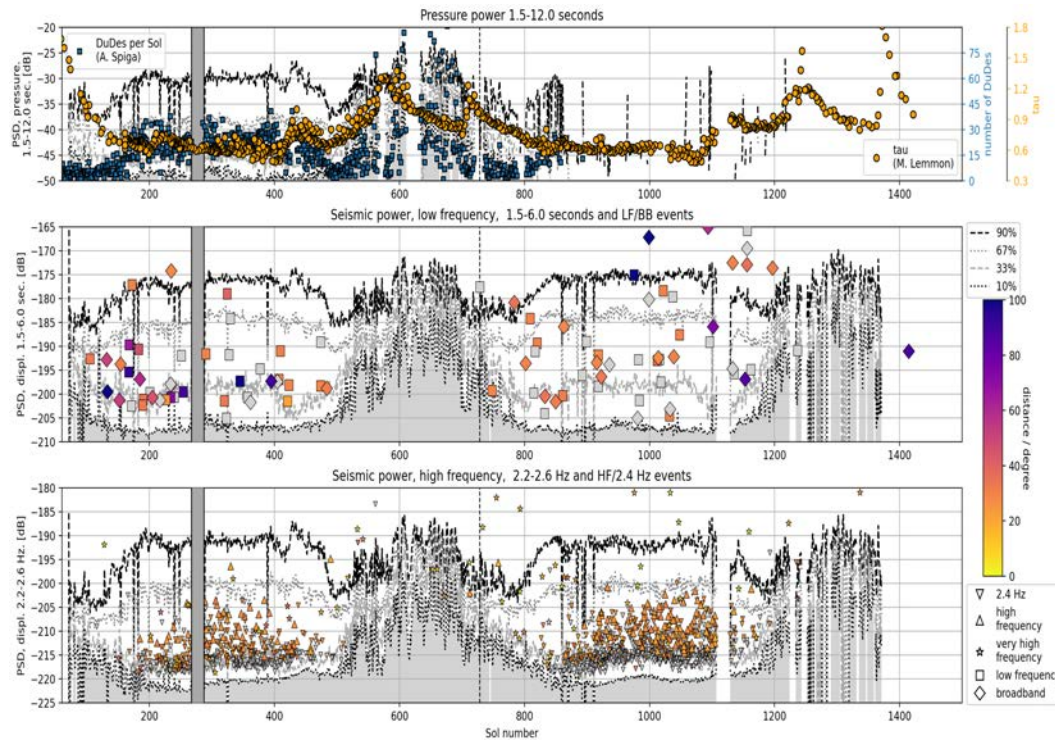
SEIS on the field

SEIS installation seen by the pan cam of InSight

- Experiment described by Lognonné et al. 2019
- Designed for a maximum shielding from large Temperature variation
- Sensor Assembly mass: 6.5 kg, Full mass : 29 kg, power: 6-8 Watt
- 3 VBBs sensor with $< 2 \cdot 10^{-10} \text{ m s}^{-2} \text{ Hz}^{-1/2}$ resolution between 0.1-1Hz
- 3 SP sensors with $\sim 3 \cdot 10^{-9} \text{ m s}^{-2} \text{ Hz}^{-1/2}$ resolution between 0.1-1Hz
- Operated on Mars from 12/2018 until end of mission, on 12/2022

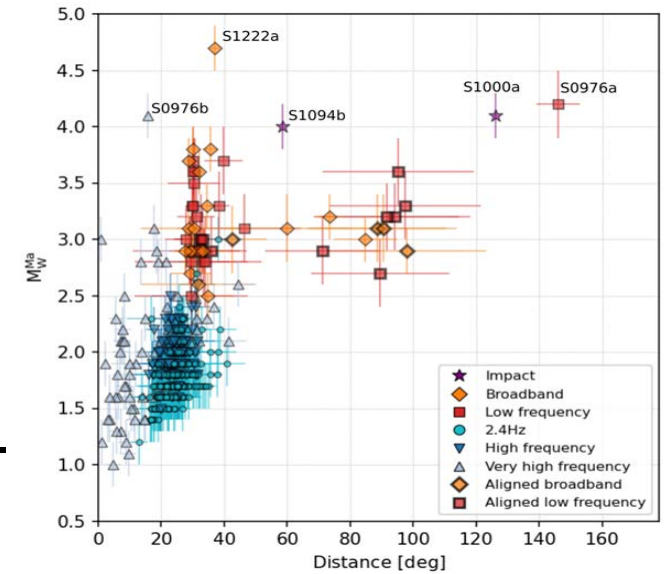


- More than 1300 events including ~100 with large low frequency (< 1 Hz) amplitudes
- Less than 20 however with clear back-azimuth (quality A) and therefore located



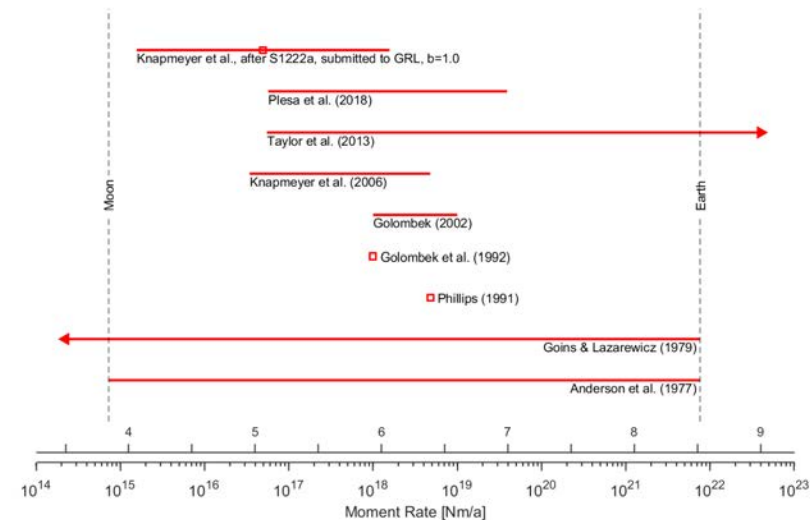
MQS, Clinton et al. 2023

- A seismicity putting Mars between Earth and Moon, but much closer than the Moon than proposed prior InSight (Banerdt et al., 2020, Knapmeyer et al. 2022)

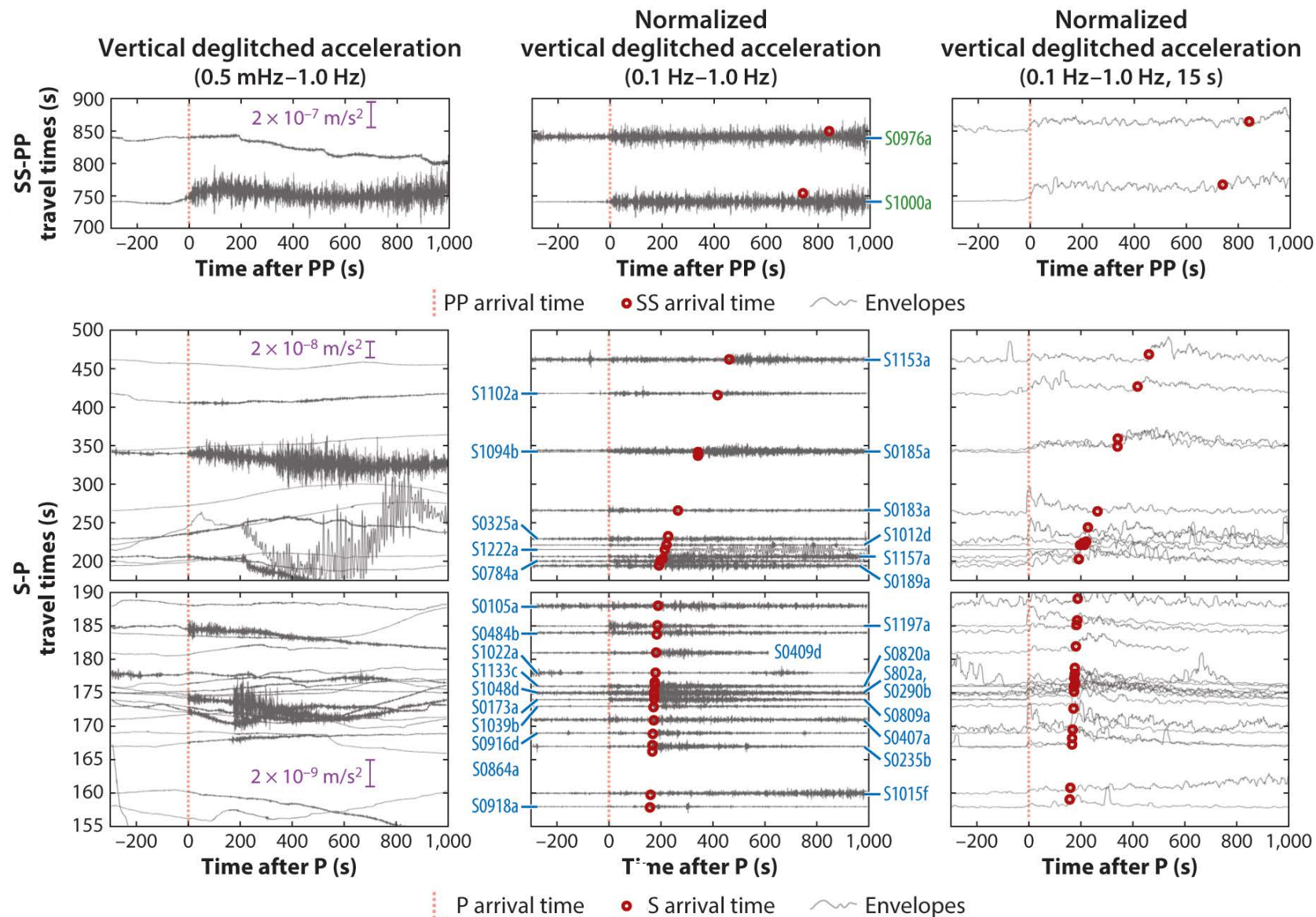


Knapmeyer et al. 2022

Clinton et al. 2023

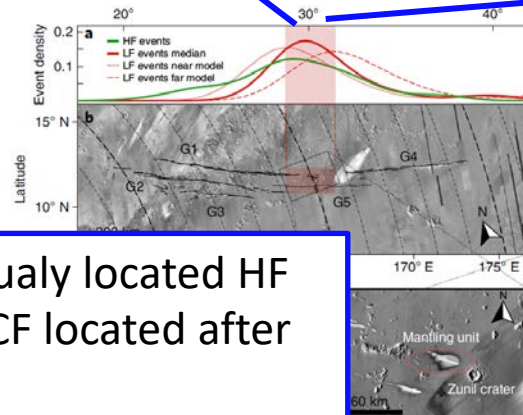
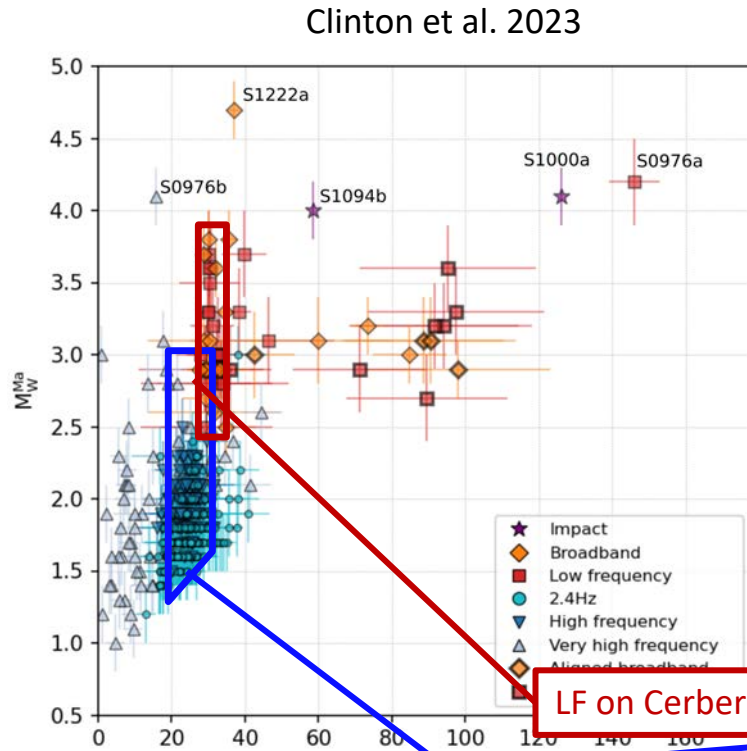


Marsquakes and Impacts : waveforms collections

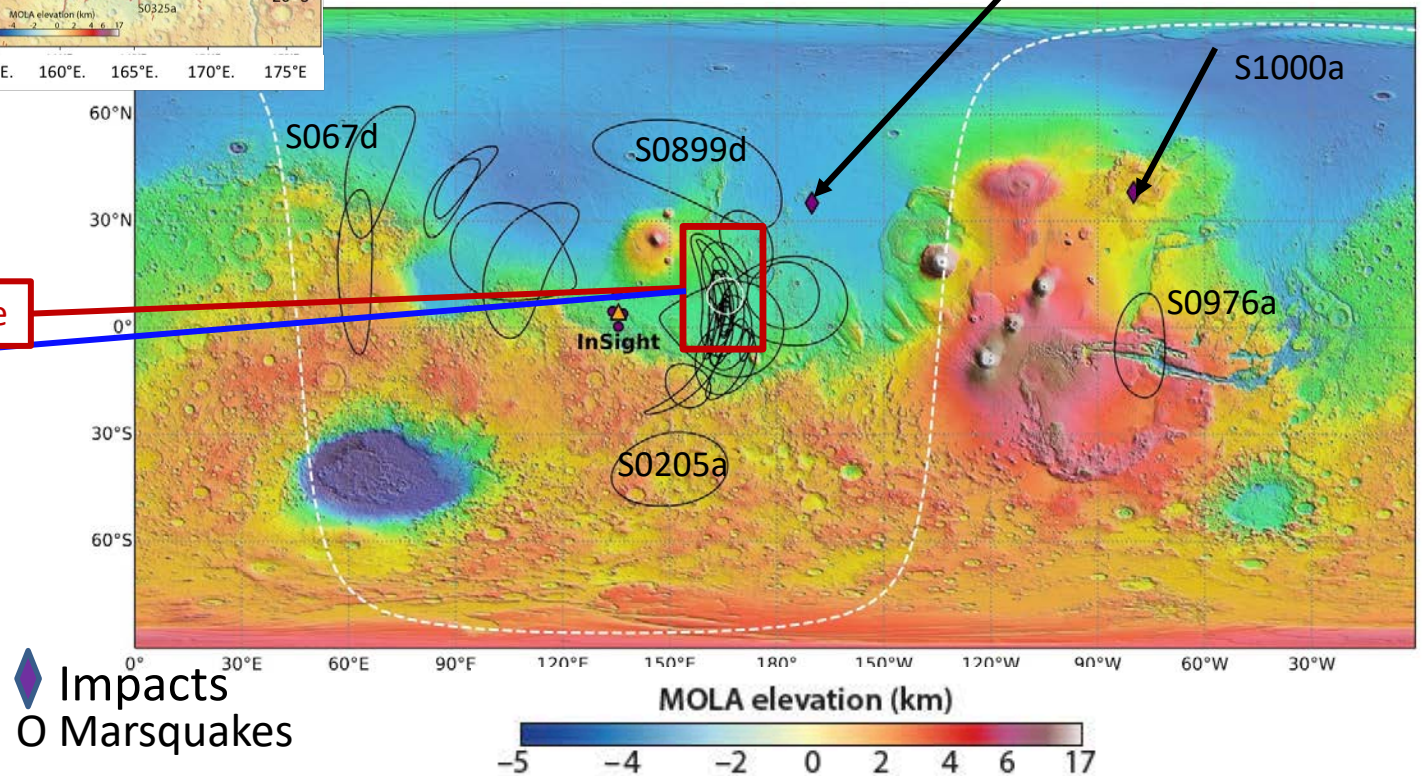
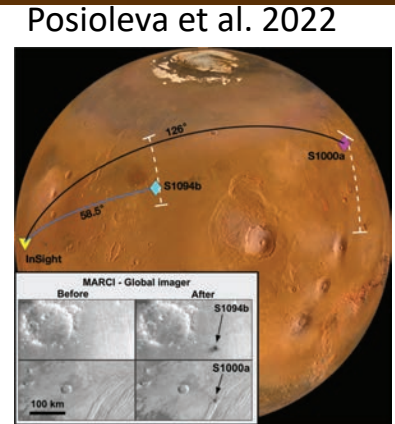
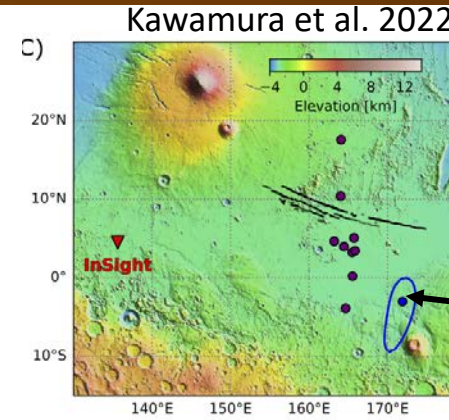
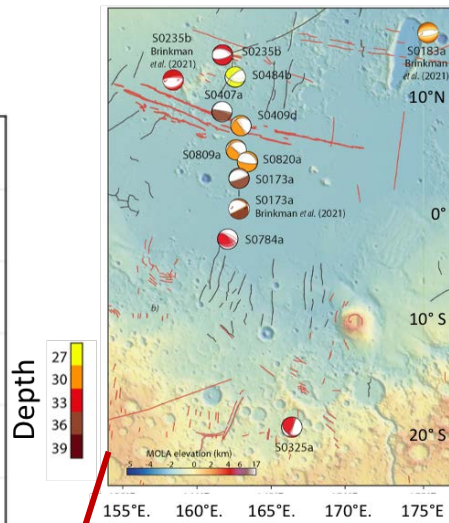


Lognonné P, et al. 2023.
Annu. Rev. Earth. Planet. Sci. 51: in press

Marsquakes and Impacts collection: location and seismicity map

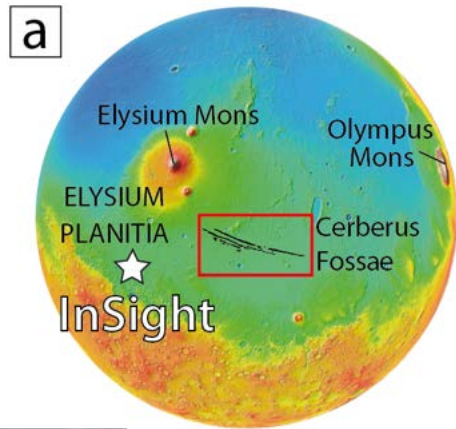


Non individually located HF events but CF located after alignment

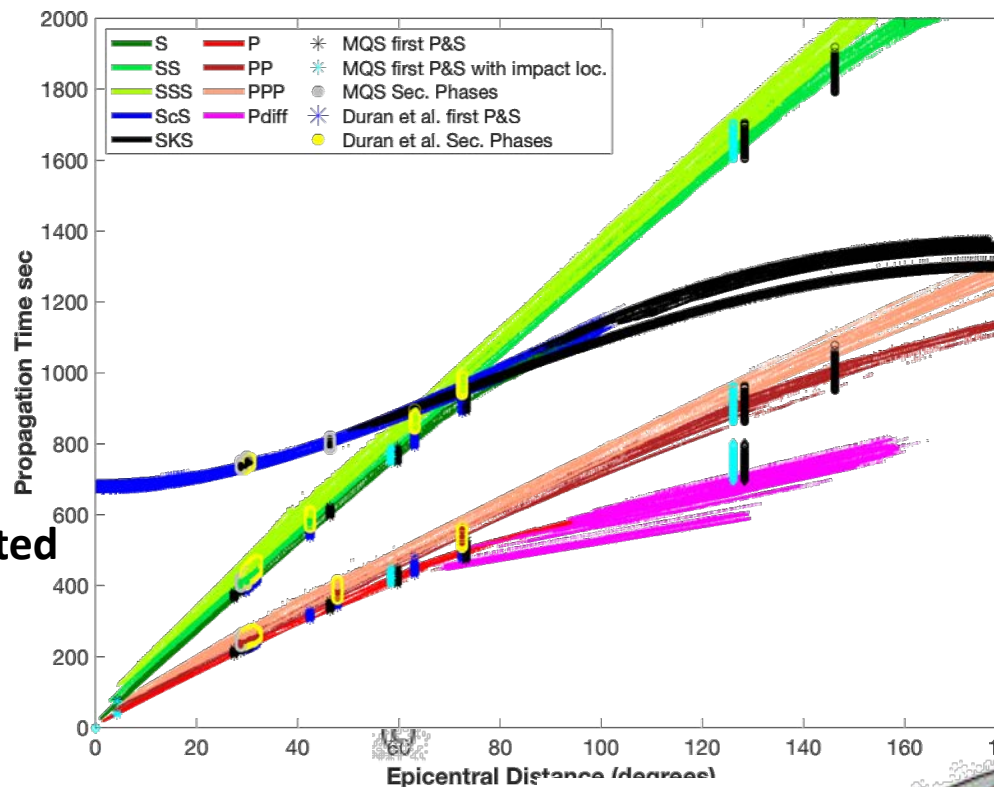


After Zenhäusern et al., 2022

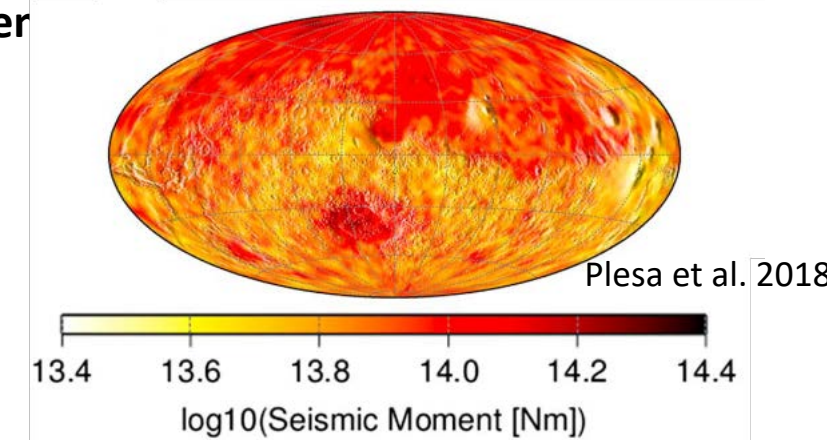
Marsquakes and Impacts collection: travel times



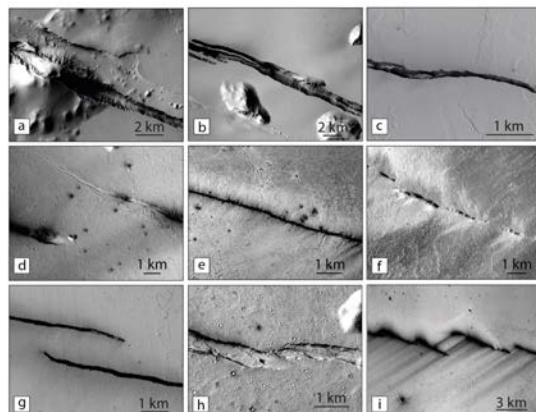
Expected: Nearby located impacts (D < 300 km)



Expected: Globally distributed teleseismic events

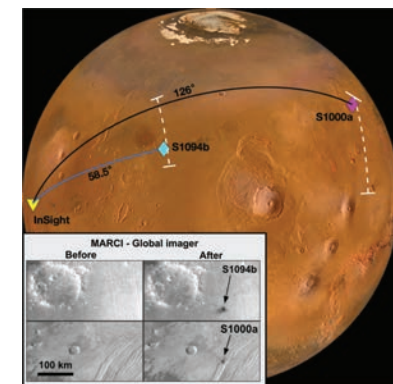
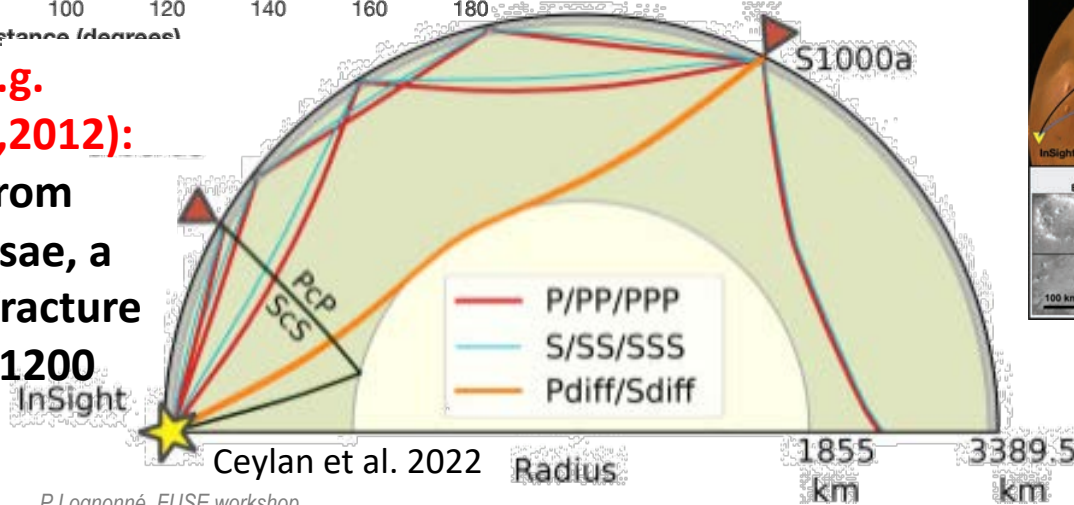


Not expected: Very large impacts (D > 100m) at teleseismic distances



Perrin et al. 2022

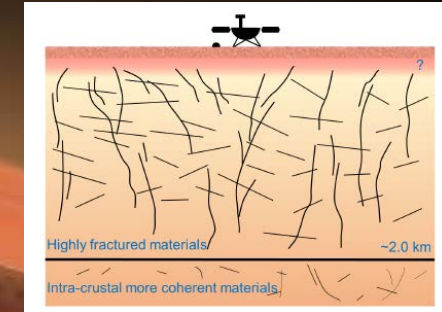
Suggested (e.g. Roberts et al, 2012): Marsquake from Cerberus Fossae, a giant active fracture network of ~1200 km



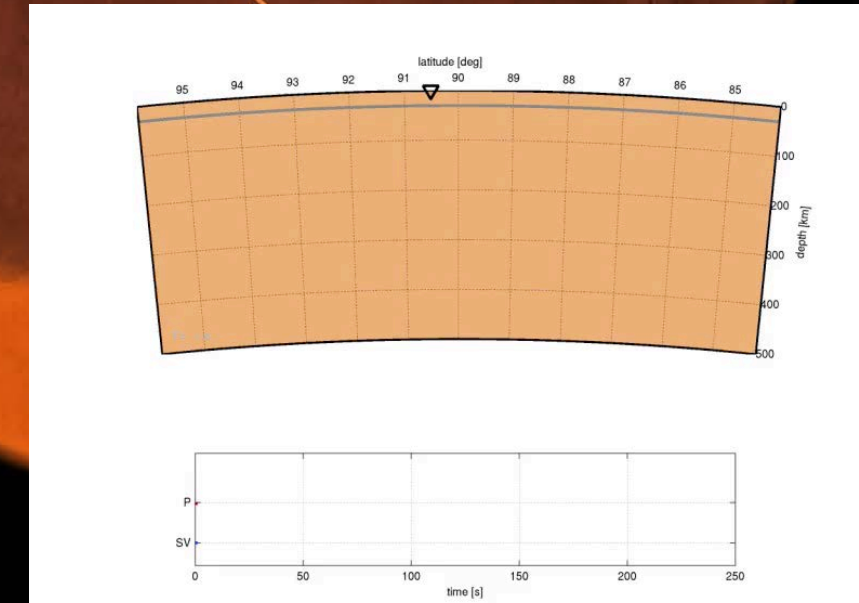
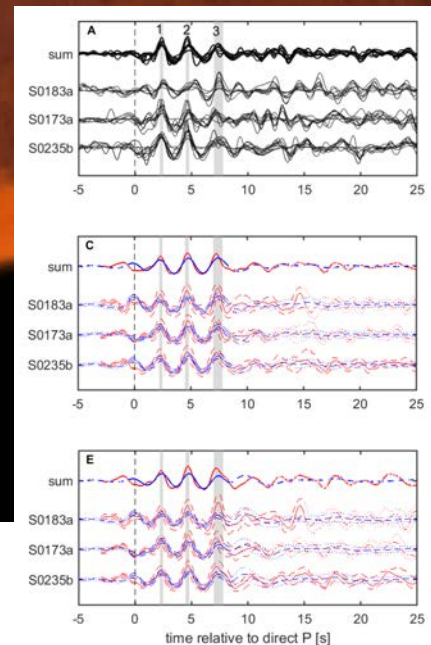
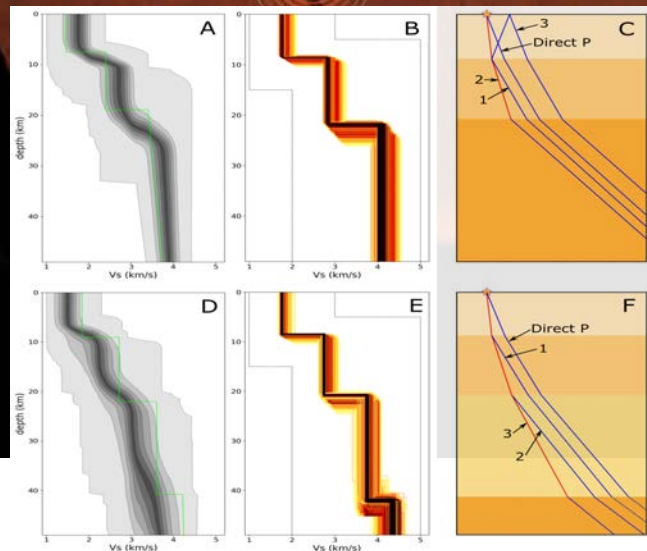
Posioleva et al. 2022

Crust layering and crustal thickness below InSight

- A first layer of 8-11 km with high porosity (20%)
Exclude ice-saturation and must be dry (Manga & Wright, 2021)
Possible anisotropy associated to gas-filled fractures (Li et al., 2022)
- A second discontinuity at ~20km observed from RF (Knapmeyer et al 2020)
Confirmation by Z noise auto-correlation (Deng & Levander, 2020, Compaire et al. 2021, Schimmel et al. 2021)
- A third weaker discontinuity at about 40 km, confirmed by other analysis (Duran et al., 2022, Kim et al., 2021, Joshi et al. 2022)
- Likely the Martian crust-mantle boundary



New with S1222a (Shi et al., 2022)

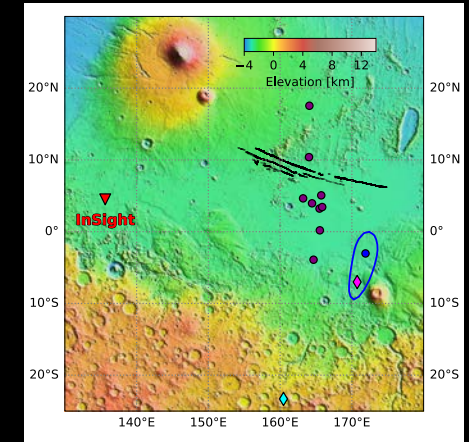


Lognonné et al. (2020); Knapmeyer-Endrun et al. (2021); Li et al. (2022)

Deeper crustal layering with S1222a surface waves

- First observation of Rayleigh and Love surface wave on R1 and first observations of Multiple orbit waves (Beghein et al , Kawamura et al., Li et al., Panning et al. 2022, Xu et al 2023)
- Apparent anisotropy observed between SH and SV, possibly related to deep crust layering (Xu et al, 2023)

Xu et al. (2023)



- MQS, Kawamura et al. 2022
- ◆ R1R2R3, Panning et al. 2022

S1222a MQS ID

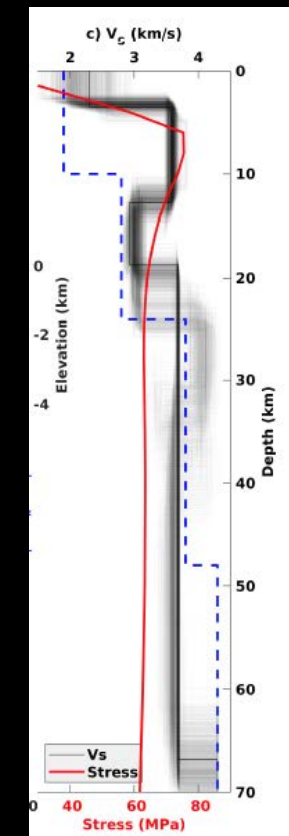
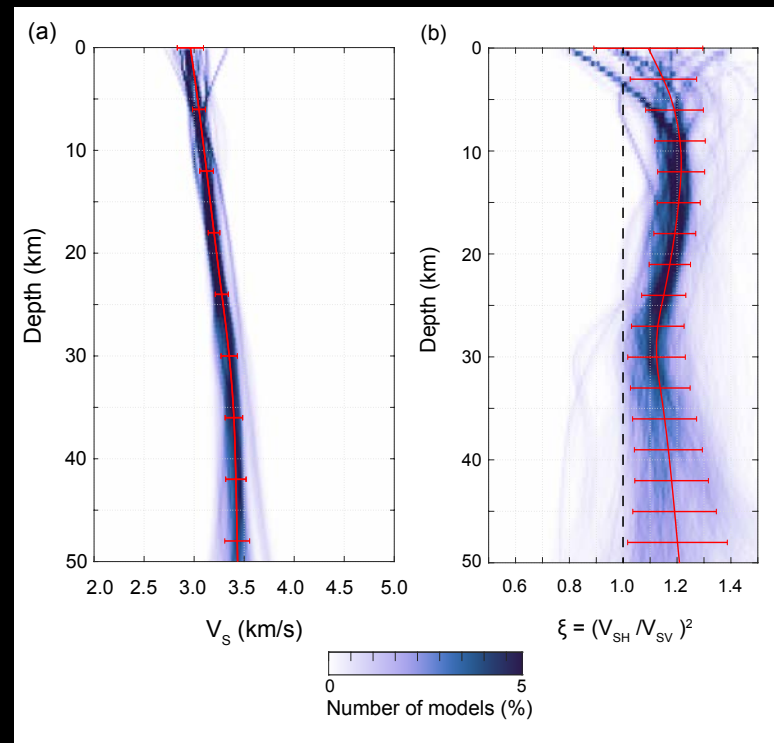
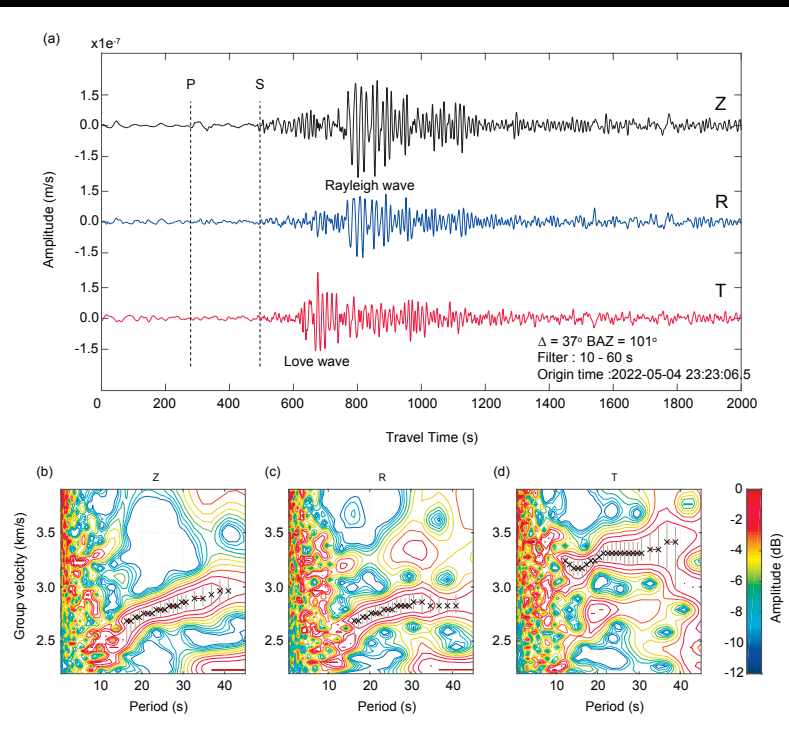
May, 4, 2022

$M_w \sim 4.7$

$\Delta = 37^\circ$ (2190 km)

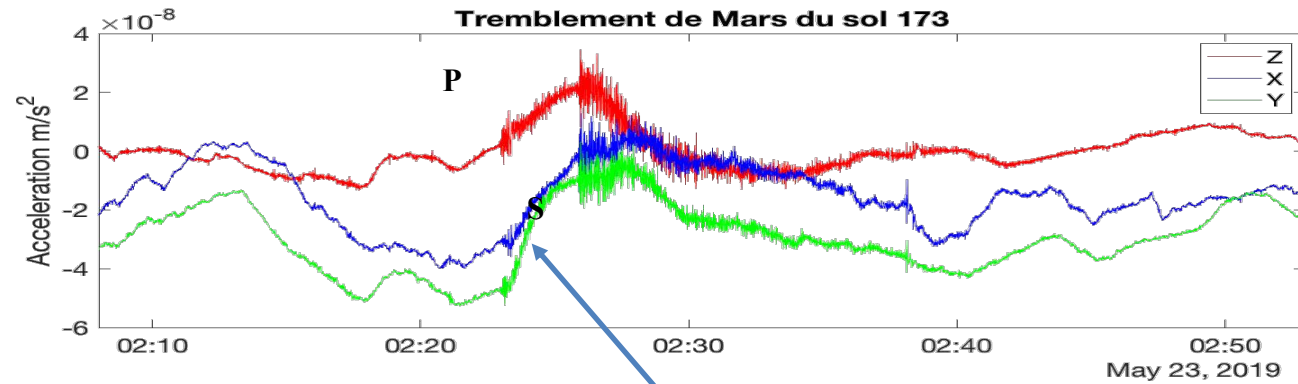
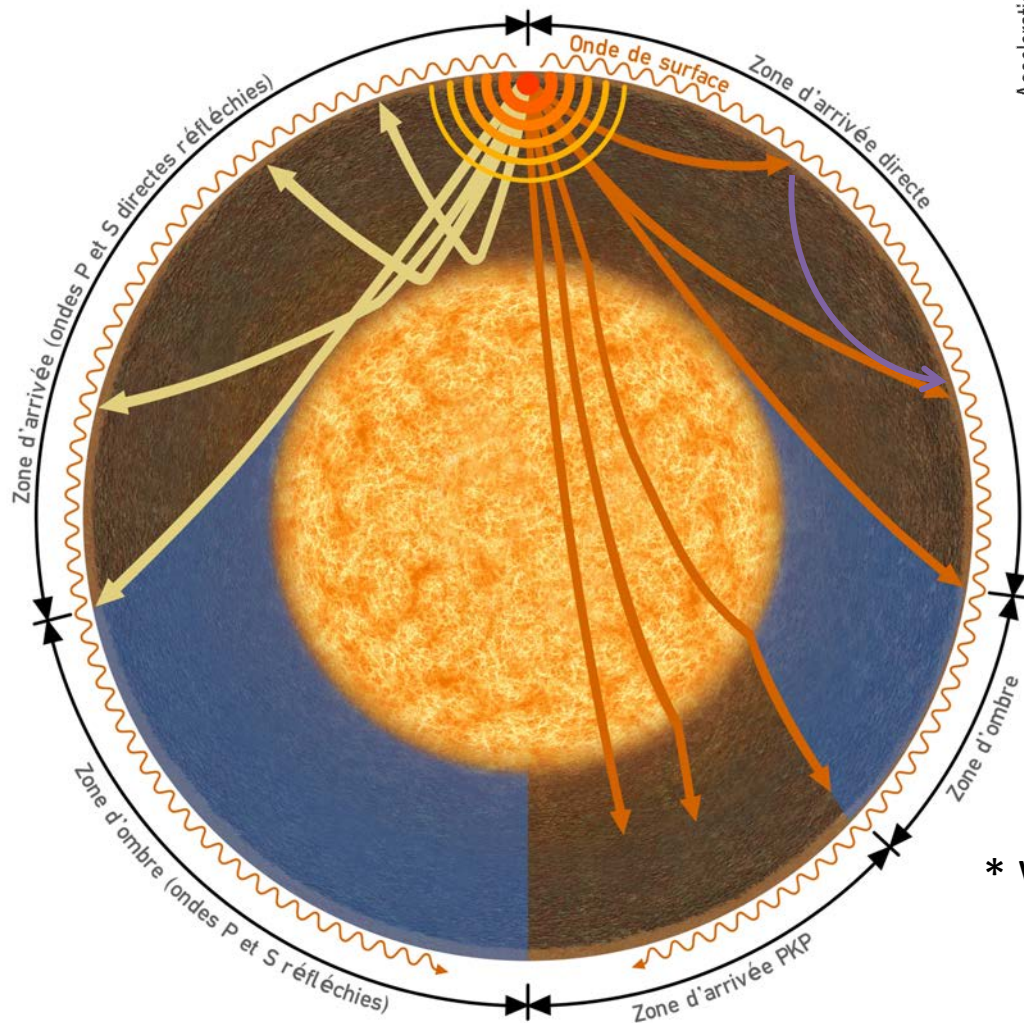
Loc: $3^\circ\text{S } 172^\circ\text{E}$

Beghein et al. (2022)



Mantle structure with one station: Multiple (SS+,PP+) travel times

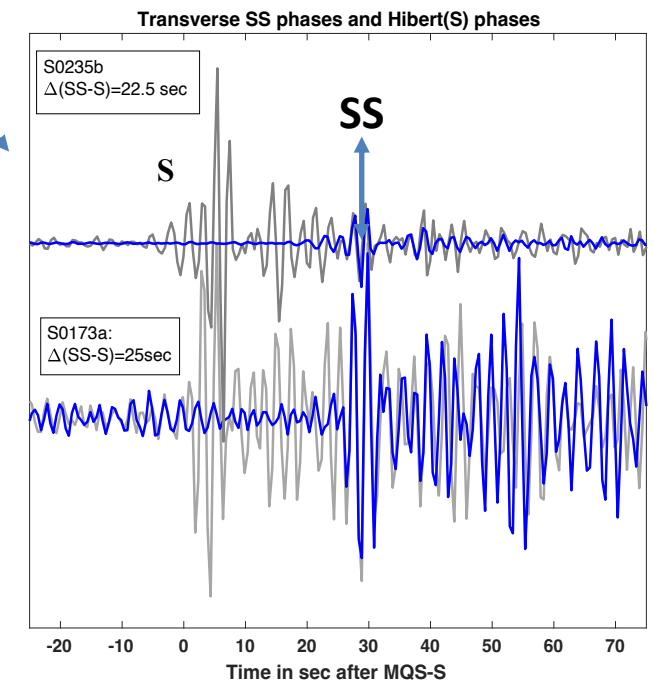
Example S0173 Marsquake (M ~3.7)



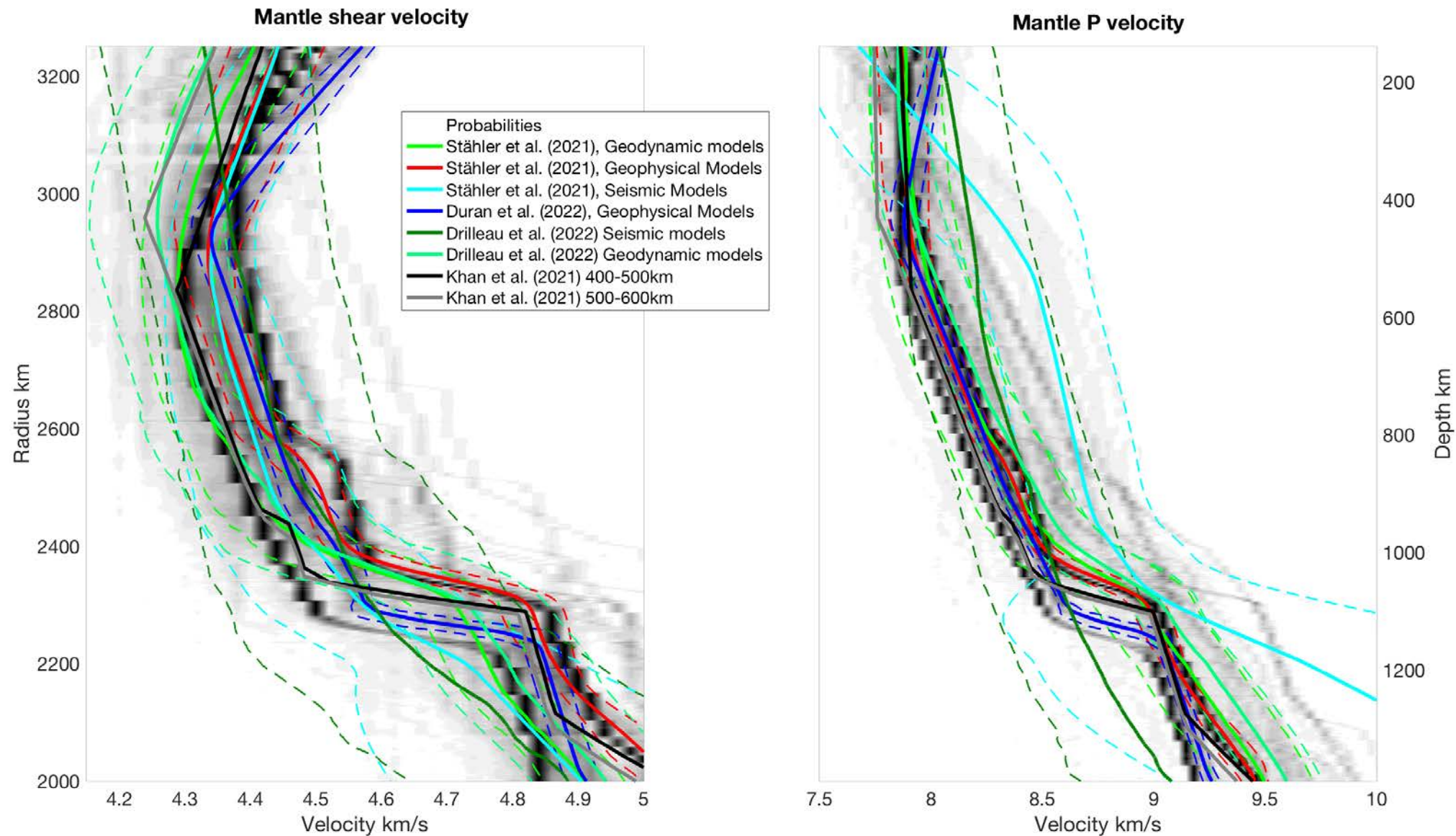
Now 2nd generation with 2x more quakes and data

Reference	MQ	PP & PPP	SS & SSS	ScS
Khan et al. 2021	8	8	11	0
Stähler et al. 2021	9	9	11	6
Duran et al. 2022 *	14	15	18	3
Drilleau et al. 2022*	17	30	29	10

* With additional depth phases



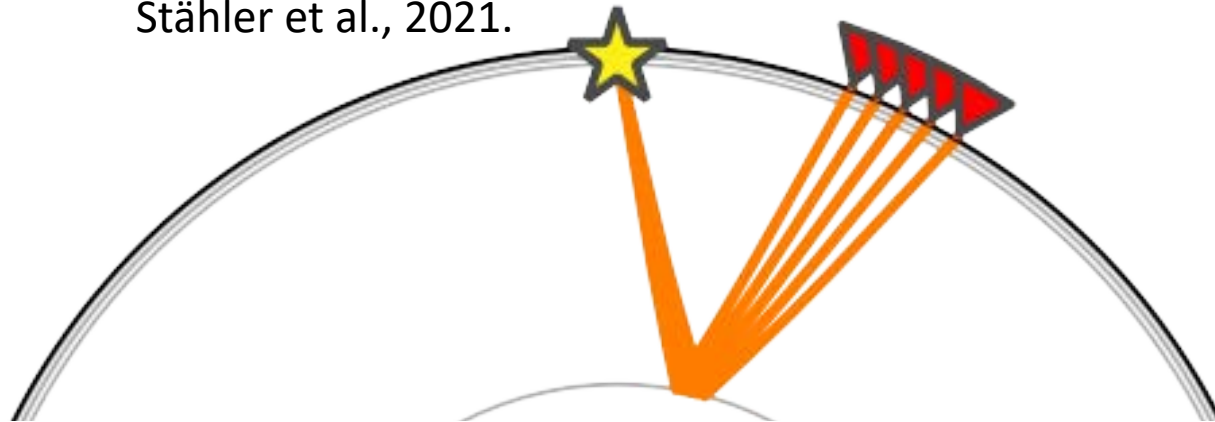
Example of SS Waveform matching from Khan et al. 2021



Seismic detection of the Martian core

ScS

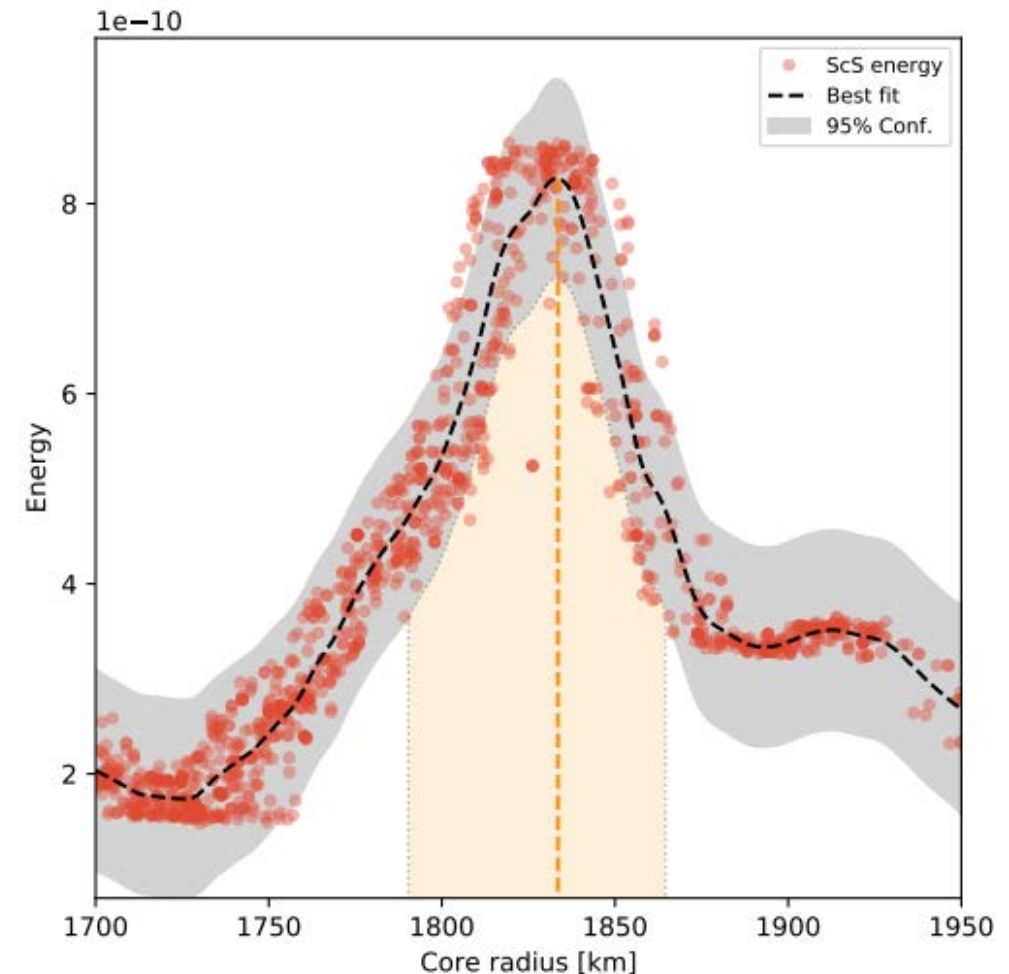
Stähler et al., 2021.



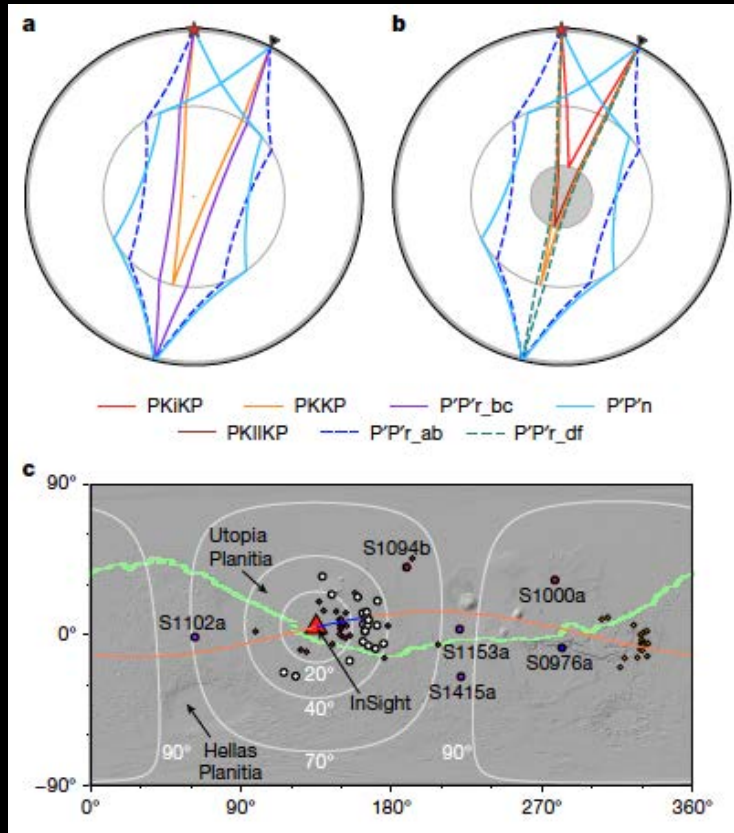
- Stack signal of multiple marsquakes at predicted ScS time for different models
- 6 quakes used (magnitude 3 to 3.7)

Solid/liquid interface (core) radius: 1830 ± 40 km

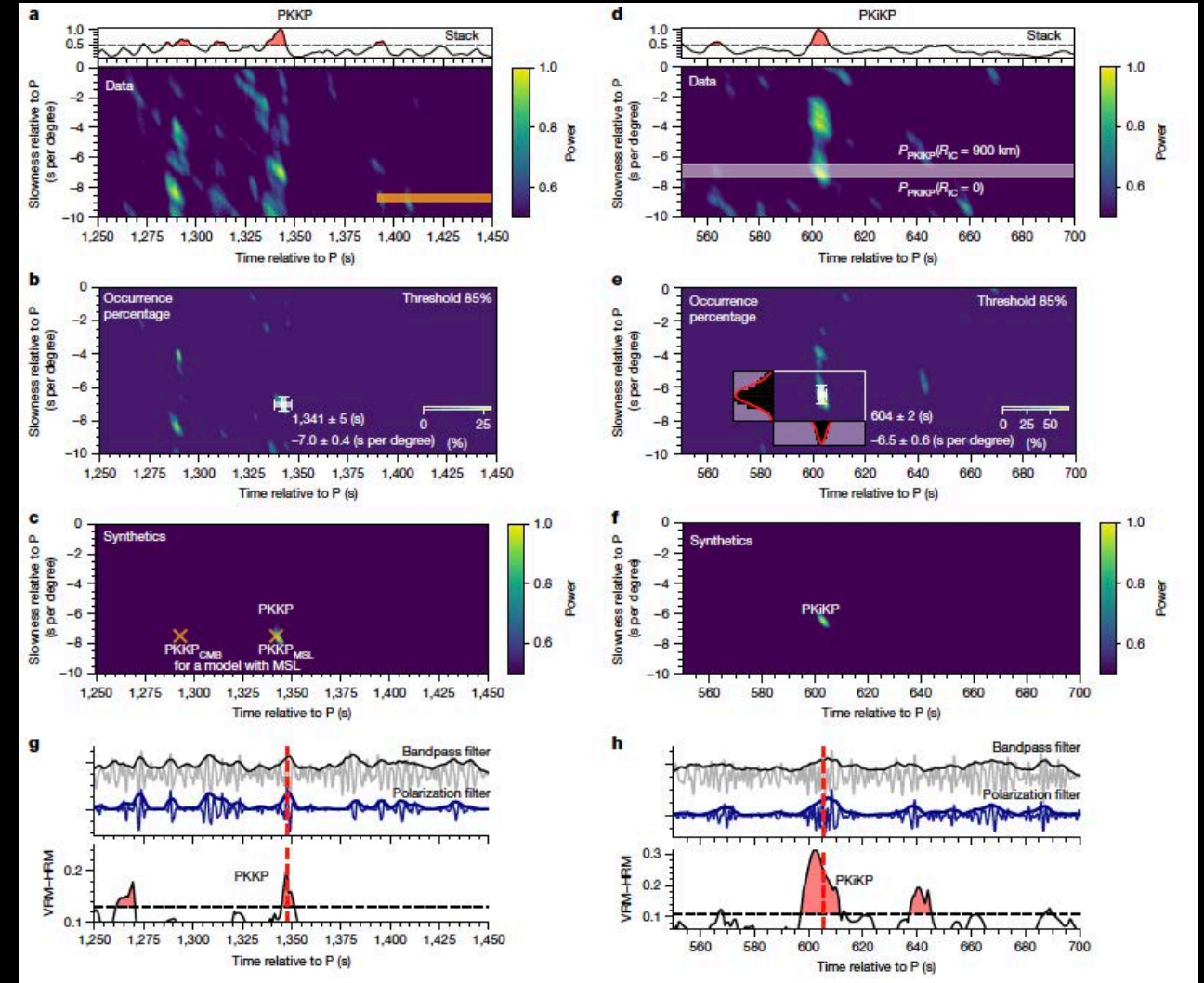
Observation confirmed recently by Wang & Tkalčić, 2022



Stähler et al., 2021.



- An inner core of ~ 600 km might generate these phases, assuming phases to be mostly from 1D layering
- This request an FeO inner core to cristalyze and be stable, which is not still considered as unlikely by the community



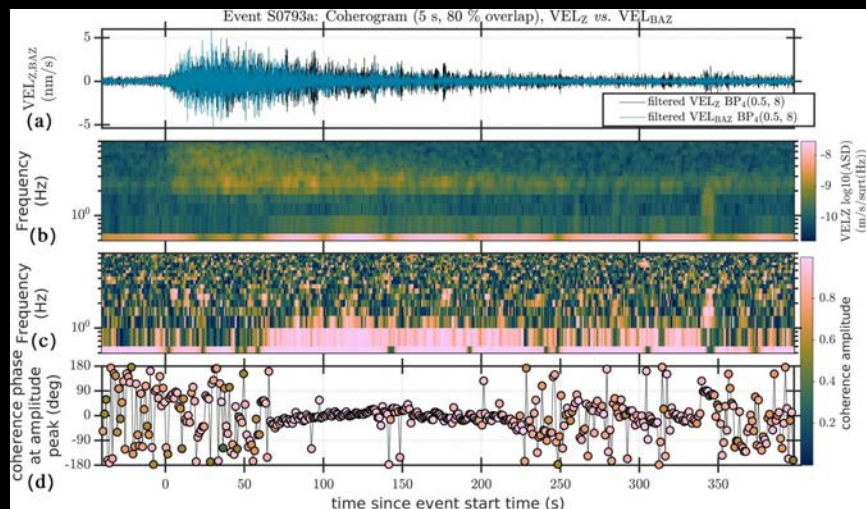
Bi et al. 2025, Nature

P.Lognonné FUSE workshop

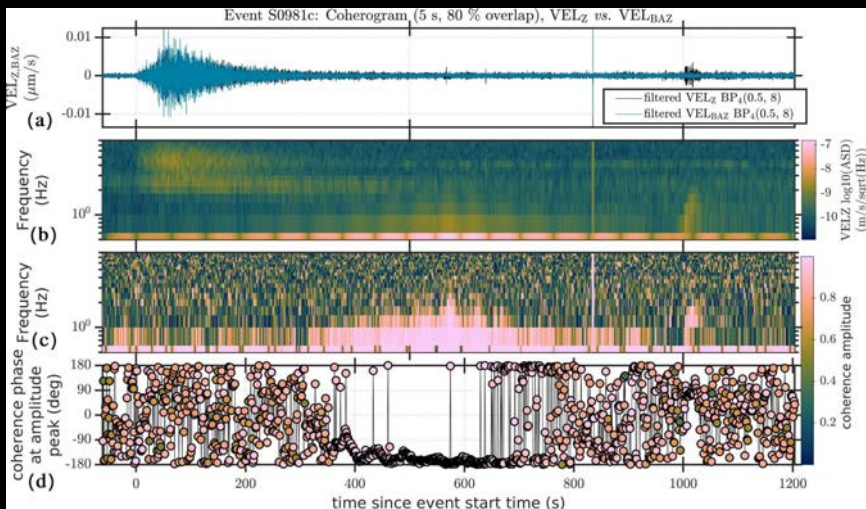
Small and close ...Impacts



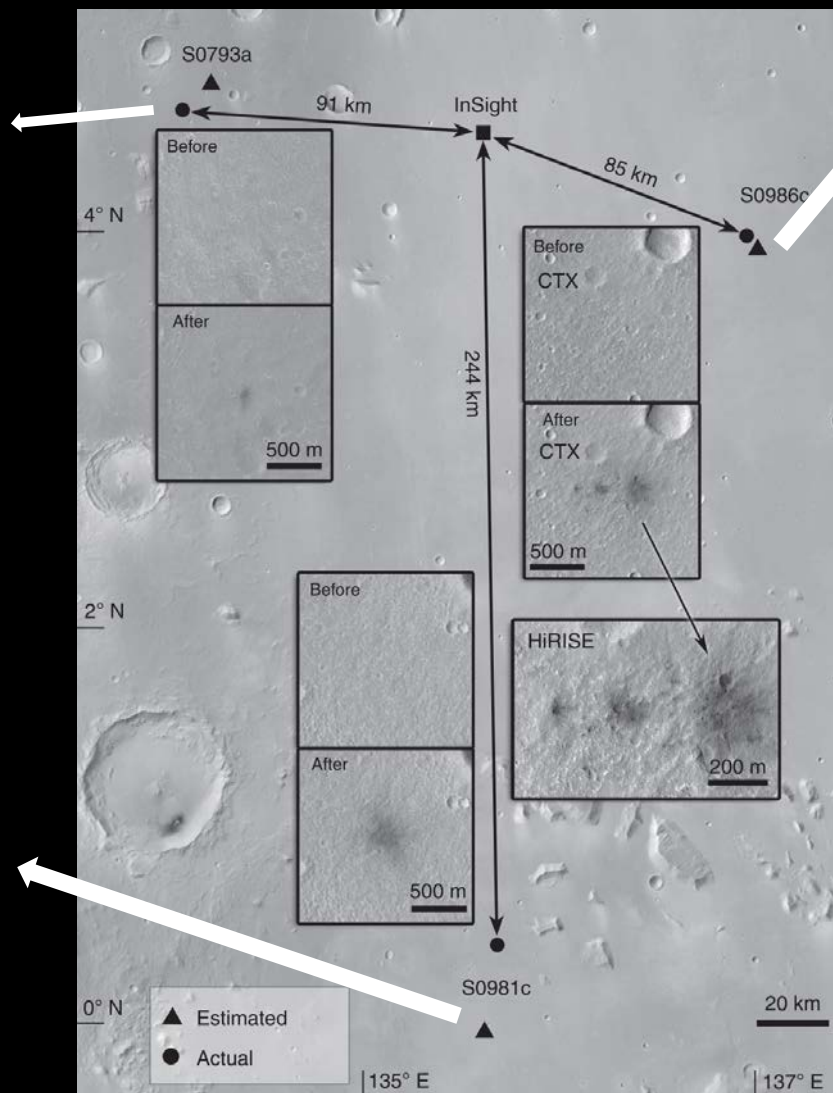
• Other nearby impacts....



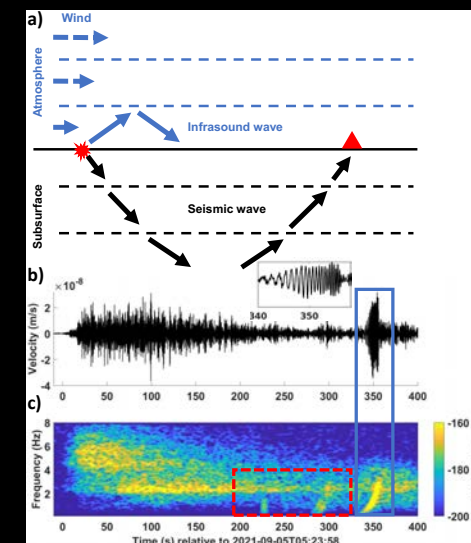
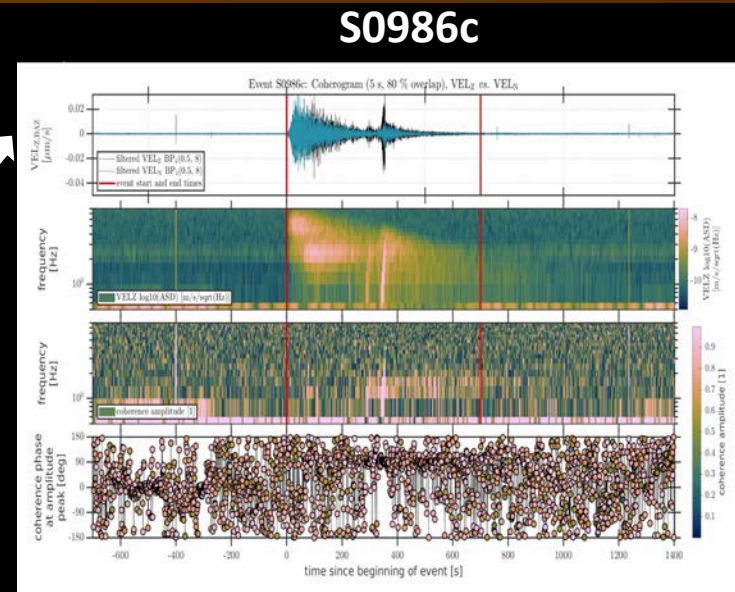
S0793a



S0981c

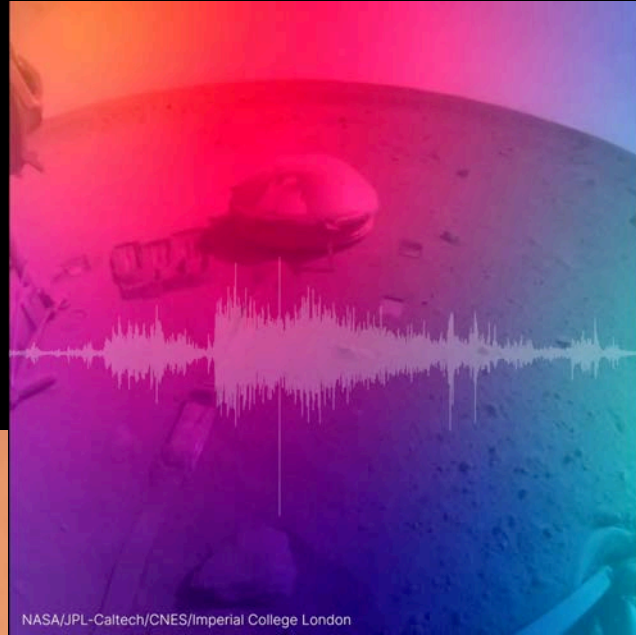


Garcia et al. 2022

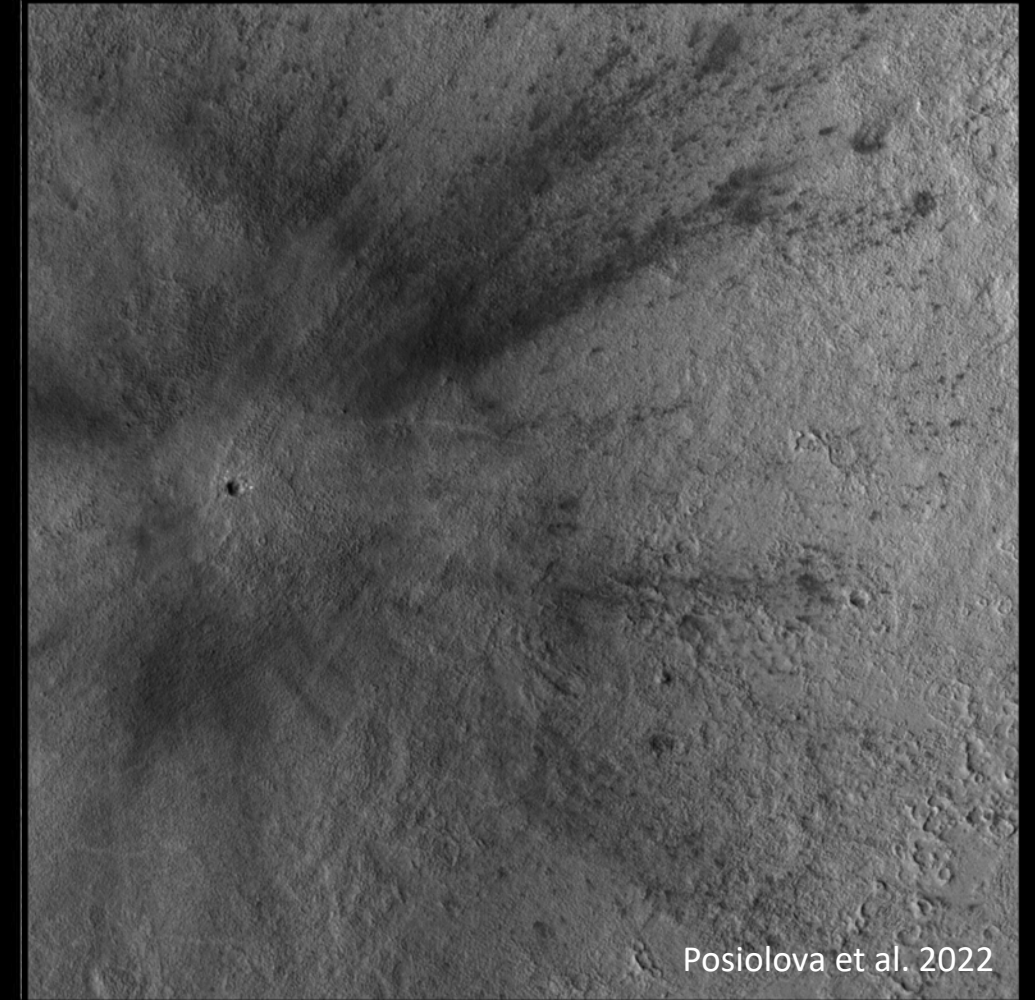


Large ...Impacts... on 24/12/2021

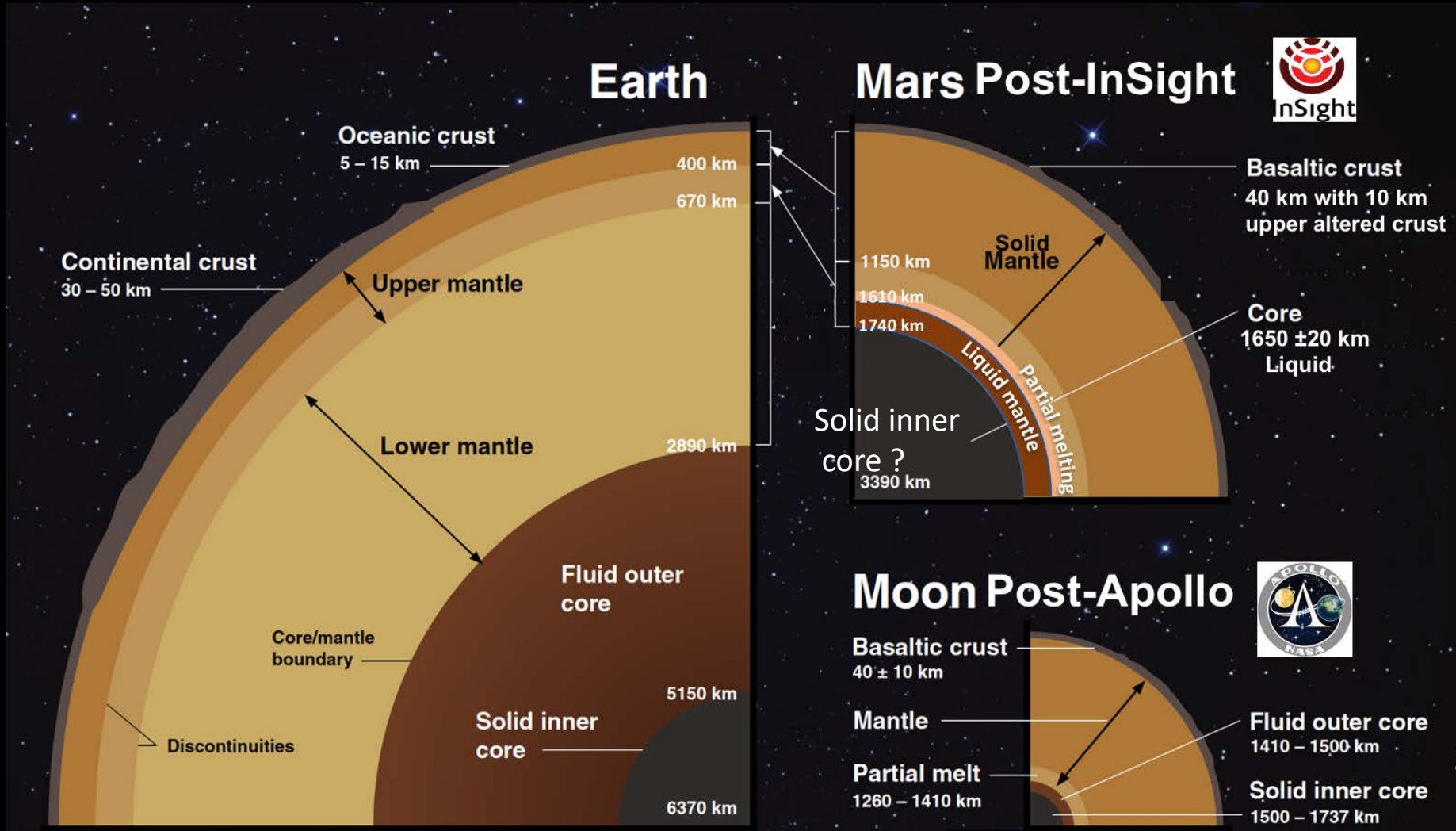
On Mars... SEIS
signal detection



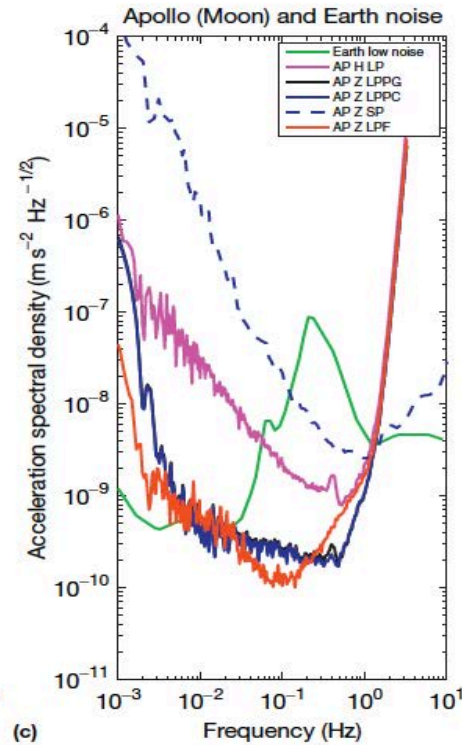
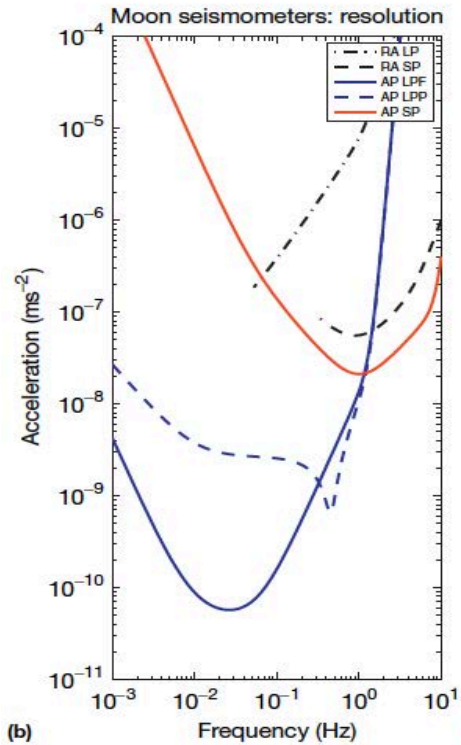
Above Mars... MRO post-impact imaging



Internal structure of Mars and the Moon from Seismology



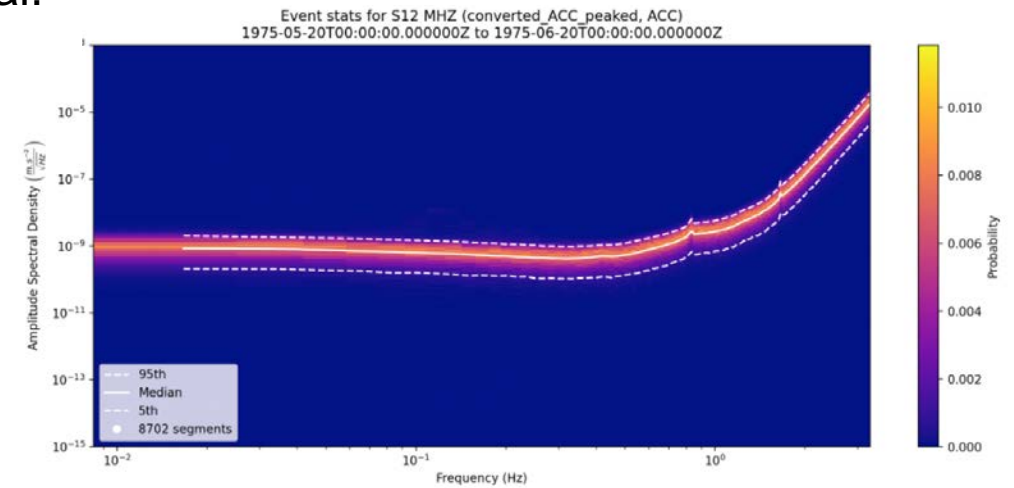
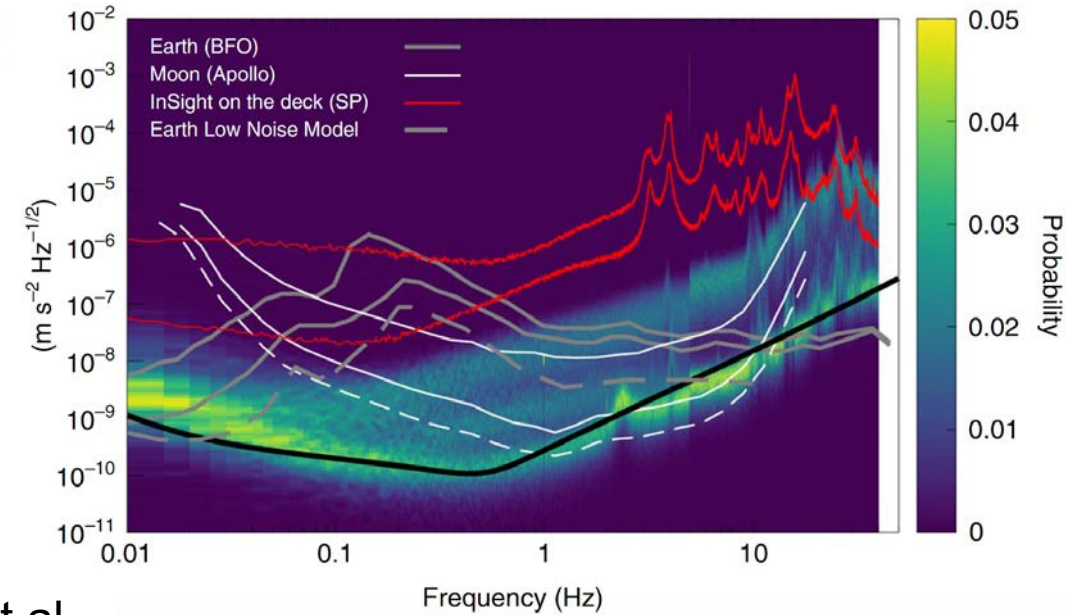
What Apollo did not: seismic noise



Lognonné et al.
2020 (Mars)

Lognonné
& Johnson,
2015

Kawamura et al.
2025 (Moon)



- The Apollo seismometer noise, when no quakes, is extremely stable and is just the sensor self noise
- Horizontal component likely see tilt noise
- Apollo did not constrained any lunar seismic noise apart the thermal moonquakes and instruments artefacts (glitches, spikes, etc).

Determining the flux of seismic signal below Apollo level

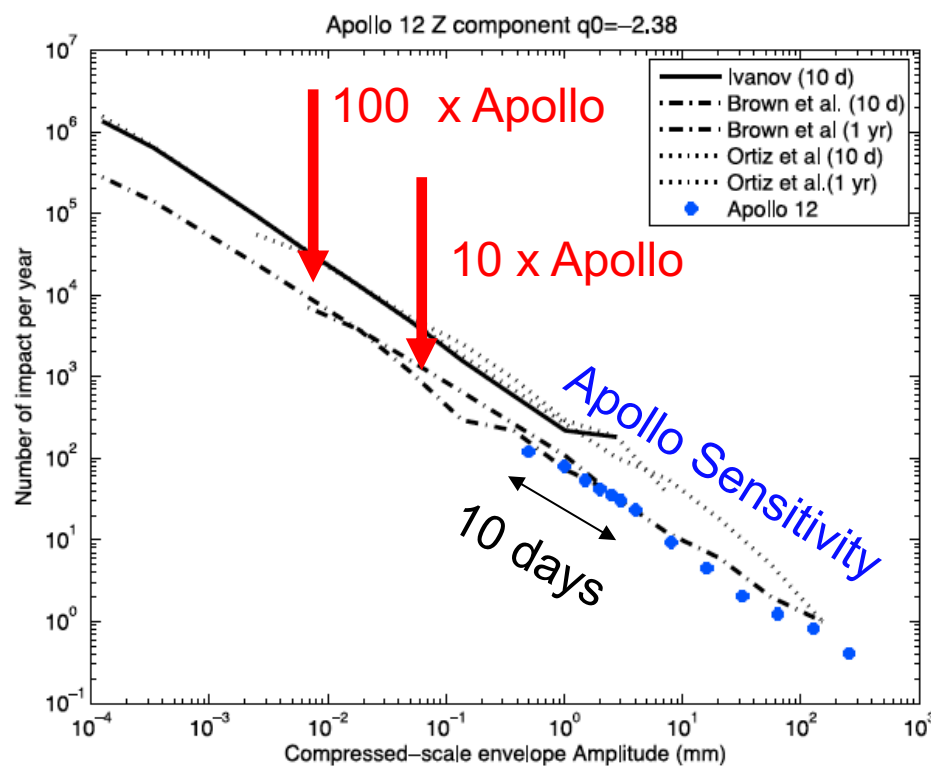
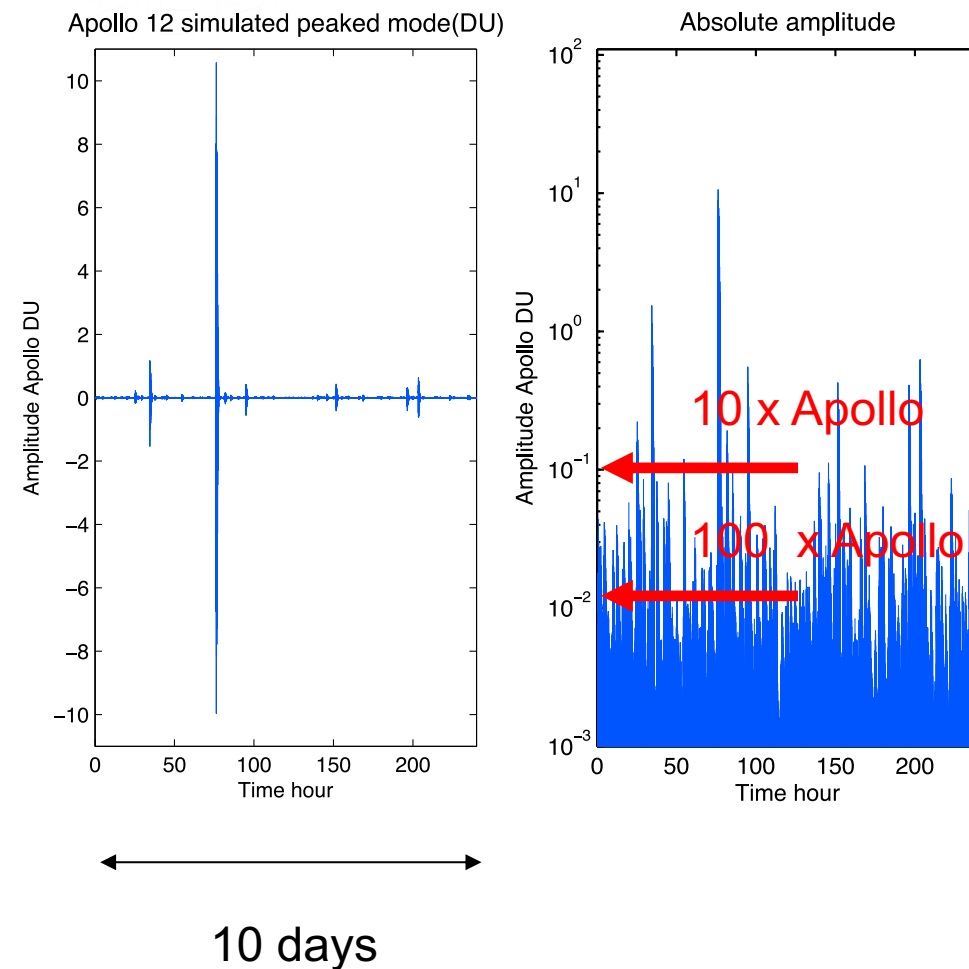
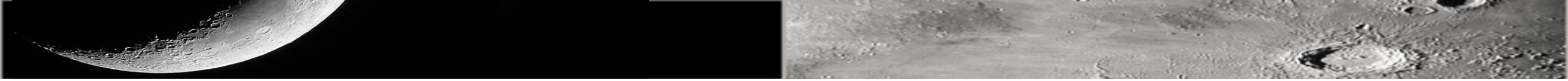


Figure 16. Number of impacts per year with a given amplitude modeled at station 12 using impact statistics derived from the Ivanov (solid line), Ortiz (dotted line), and Brown (dashed-dotted line) models. For comparison with the Apollo catalog information (circles), we report the compressed-scale envelope amplitude estimated from our synthetics. For the Brown and Ortiz impact models, the line segment on the left is for the 10 day simulation and corresponds to small impacts while the one on the right is for the 1 year simulation, corresponding to large impacts.





2512

- What we know after the Apollo seismic experiment ?
- What we do not know after the Apollo seismic experiment ?
 - Focus on the lunar seismic noise
- Selected Near future missions compared to Apollo
- What will NOT be made by near future mission and associated goals
- Noise challenge for very long period seismology
- Noise challenge for Gravitational waves

2026-2030:

Return of seismology on the Moon

A3/LEMS Seismometer
Announced : fall - 2028



Spider

Blue Ghost 2
2027

TBD Farside



Shackleton



Artemis
candidate
site



A4/SPSS seismometer
1 yr after A3



Schrödinger



400 km

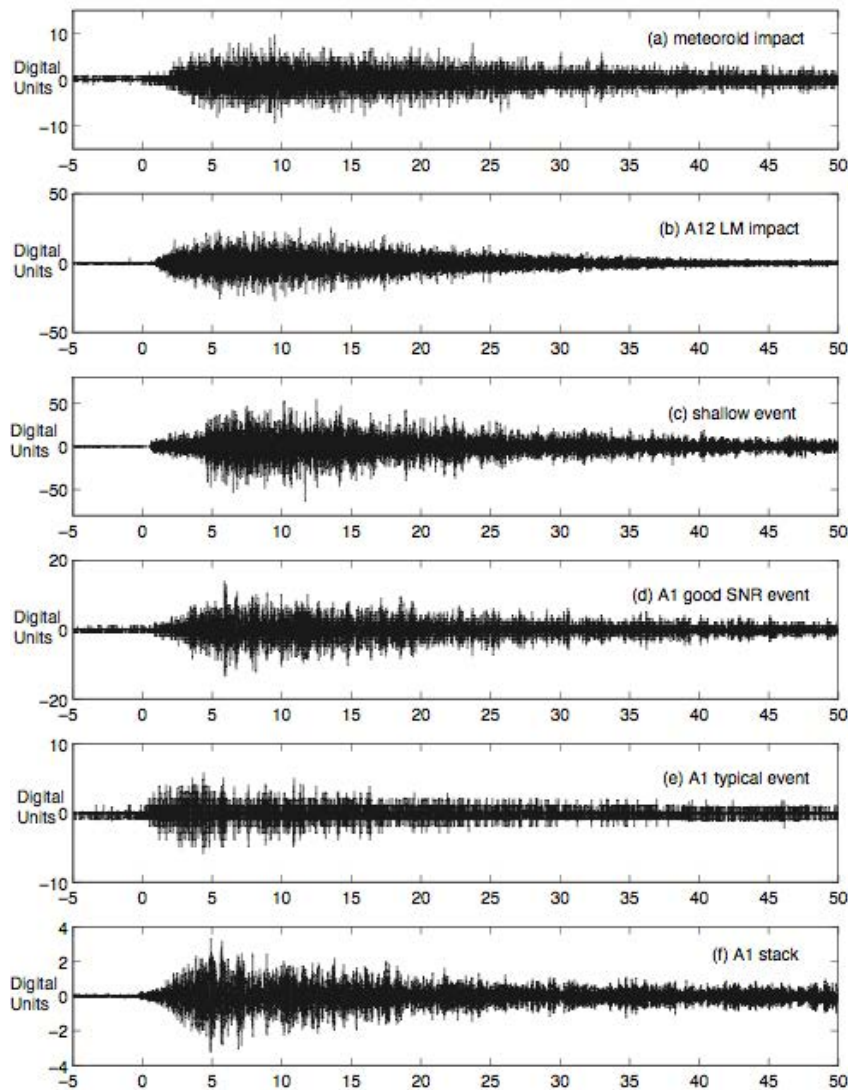
FSS/CP12-NASA
Draper-Ispac
Expected: 2030



Lunar Seismometer
Chang'E-7/CSA
Expected: 3/2027

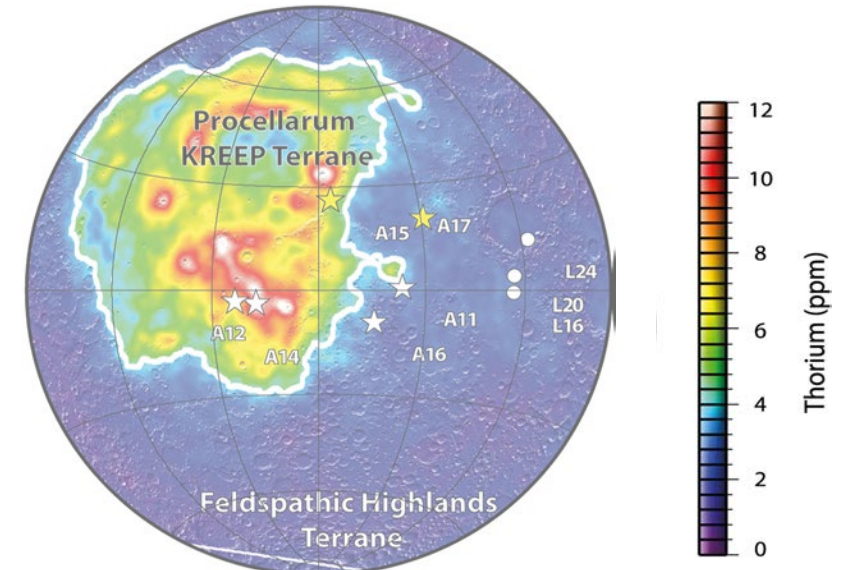


Why lunar seismology after Apollo (1/2) ?



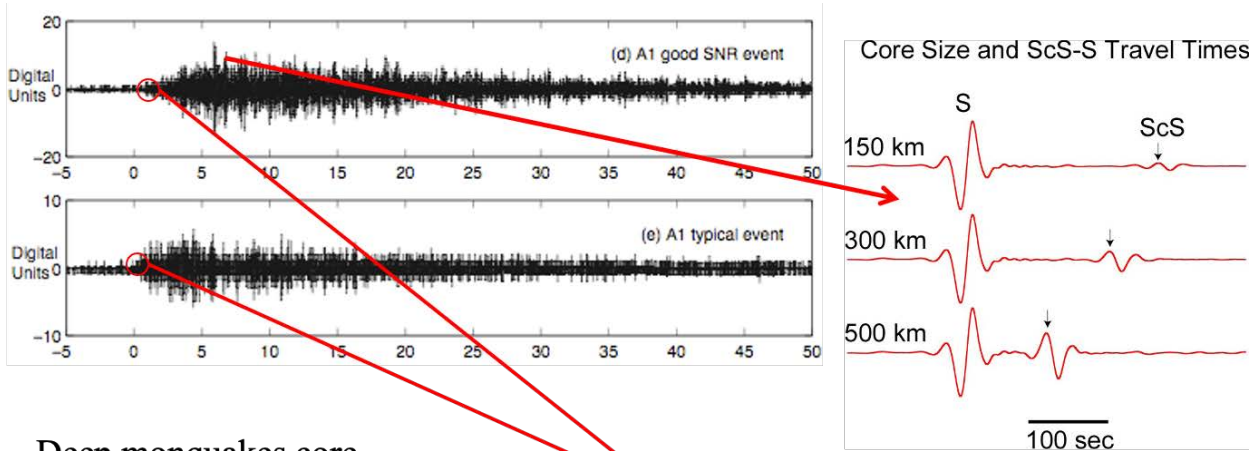
- The Apollo data set has been used to determine first models of the lunar interior and to determine the present day flux of meteorites
- Many Science questions remain on deep interior, especially on:
 - The deep interior, including melting at the base of the mantle, inner core and outer core structure
 - The mantle structure away from the Apollo landing areas, i.e. PKT terrane
 - The seismicity of the South pole, where one of the largest quake was observed
 - The seismicity of the far side, where little DMQs were observed
 - Lateral variations

- These questions are also linked to the Earth-Moon formation and evolution, including habitability

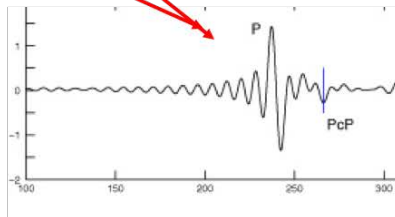


Why going back with more sensitive instrument than Apollo ?

Getting smaller seismic phases



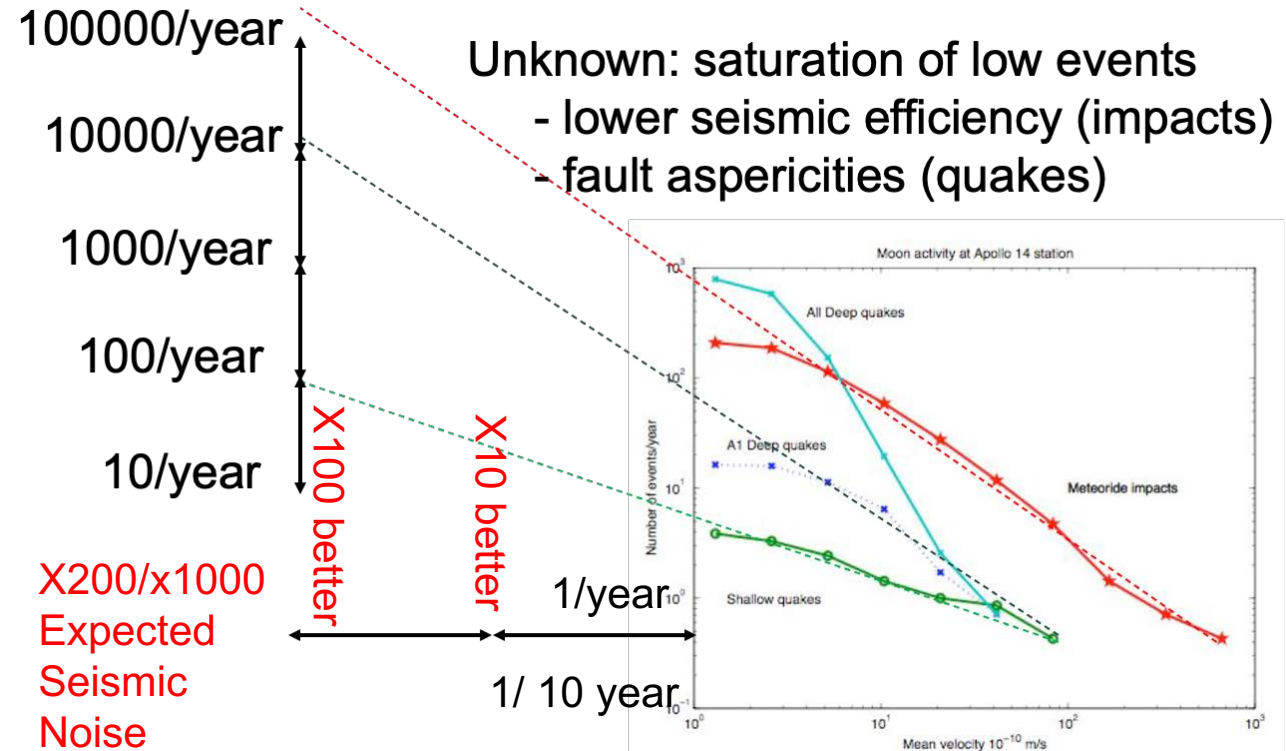
Deep monquakes core phases will have amplitudes typically 1/10 Apollo DU
Might be detected with stacks by VBB with LSBs 1/100 Apollo and noise of 1/10 Apollo



Takeuchi et al.

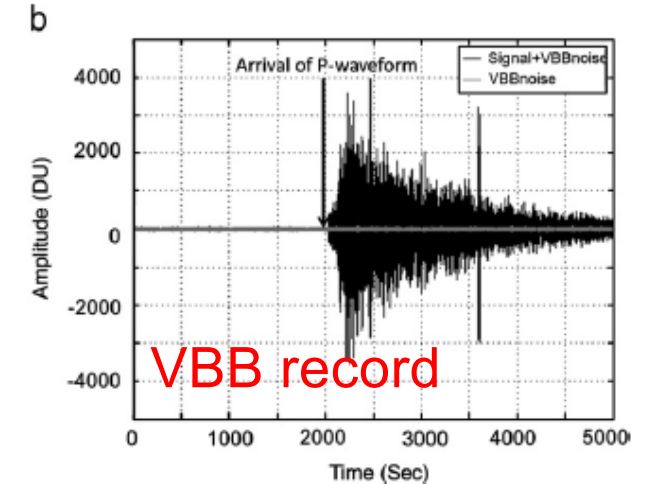
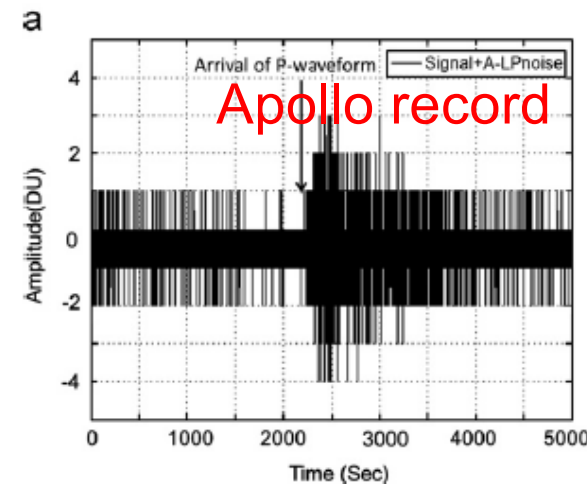
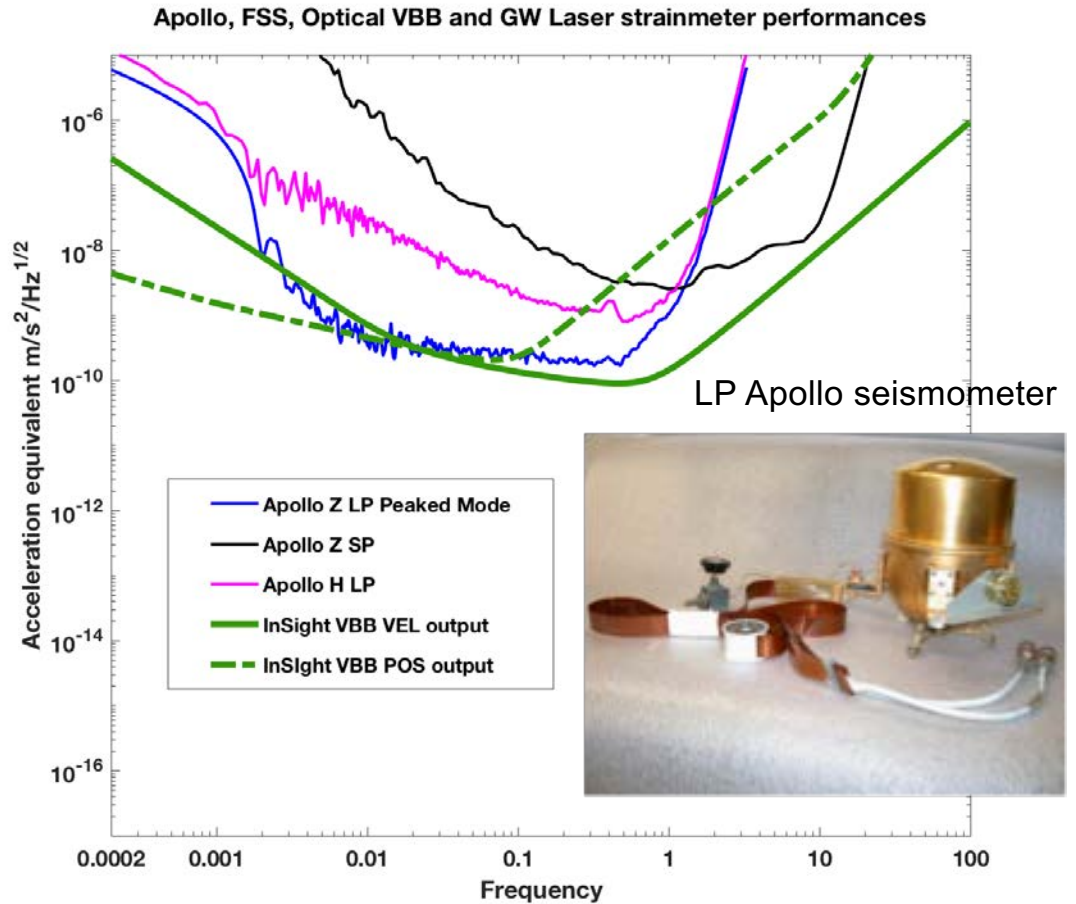
Weber et al.

Getting more frequent events

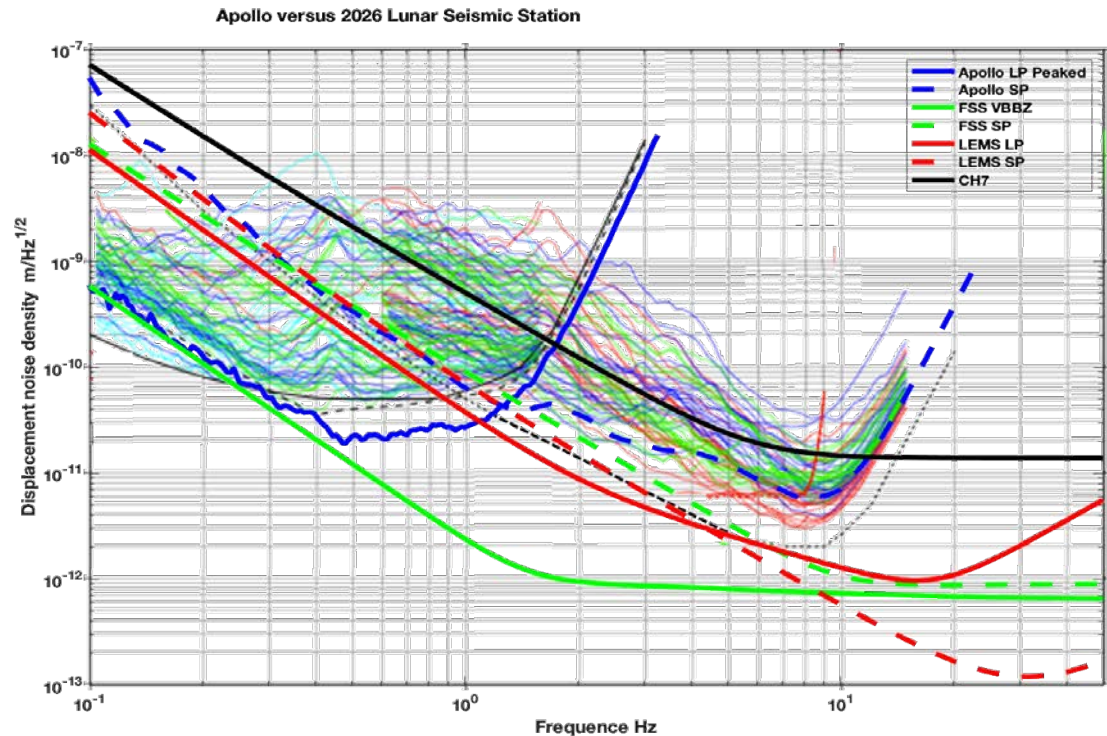


Very Broad band seismology revolution

- Although being a wonderful instrument at its time, the Apollo seismometers were not resolving their noise and had a 10 bits A/D
 - This prevented the observation, on single records, of any secondary phases, as well as any long period observations of deep phases or surface waves.
 - Most of the Apollo analysis and interior models were made with travel times of P and S only
- VBB capabilities for full waveform recording are illustrated by the success of InSight VBB for Mars !

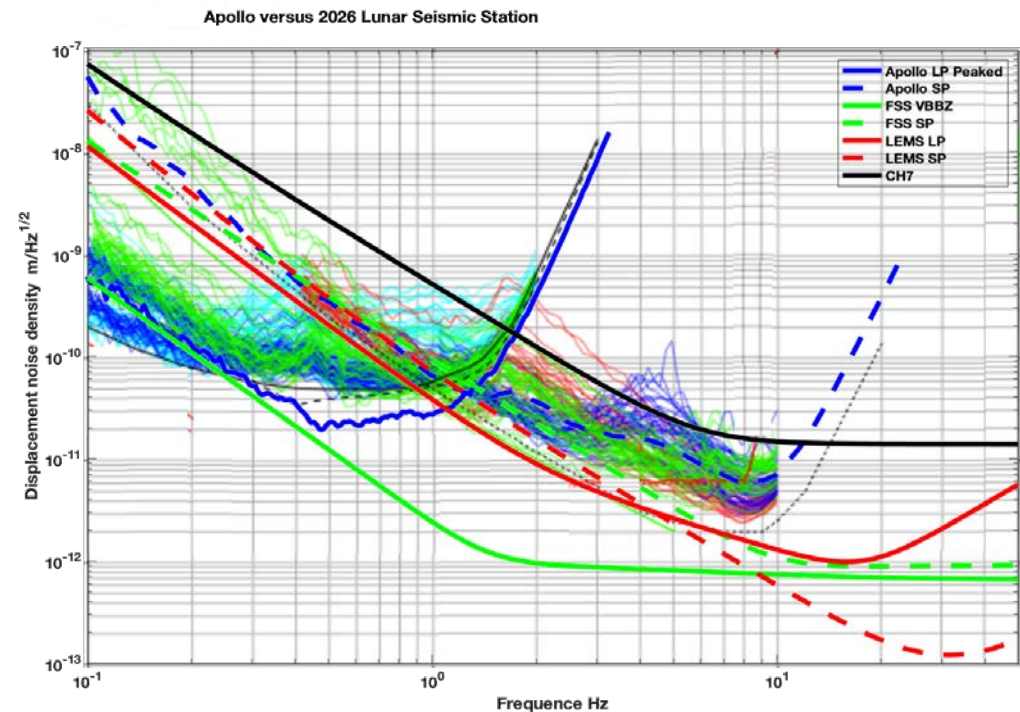


Expected detection improvement compared to Apollo



Apollo detected Impacts versus New seismometers performances

- Large improvement in the 0.3-10 Hz bandwidth with VBBZ/FSS
- Large improvement above 10 Hz with the LEMS-SP/A3
- LEMS-LP comparable to Apollo LP, CH7-LS comparable to Apollo SP (with much better acquisition)
- No improvement at long period (< 0.1 Hz)



Apollo detected DMQs versus New seismometers performances

Small high frequency impacts

- Small impacts were well observed by Apollo SP (Duennebier et al. 1974)

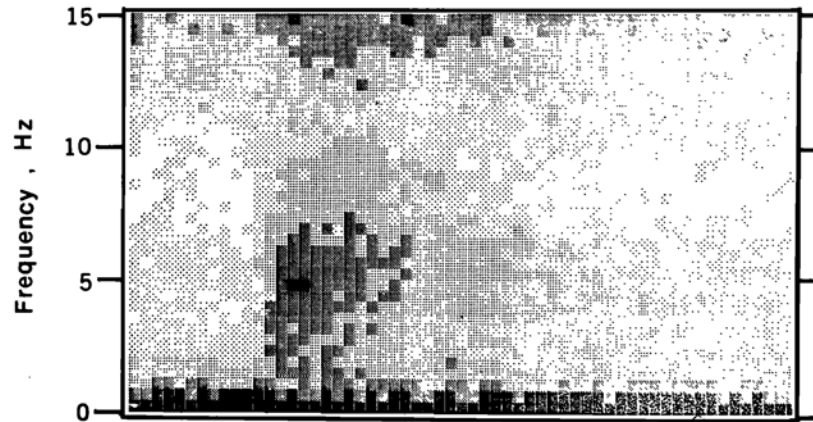
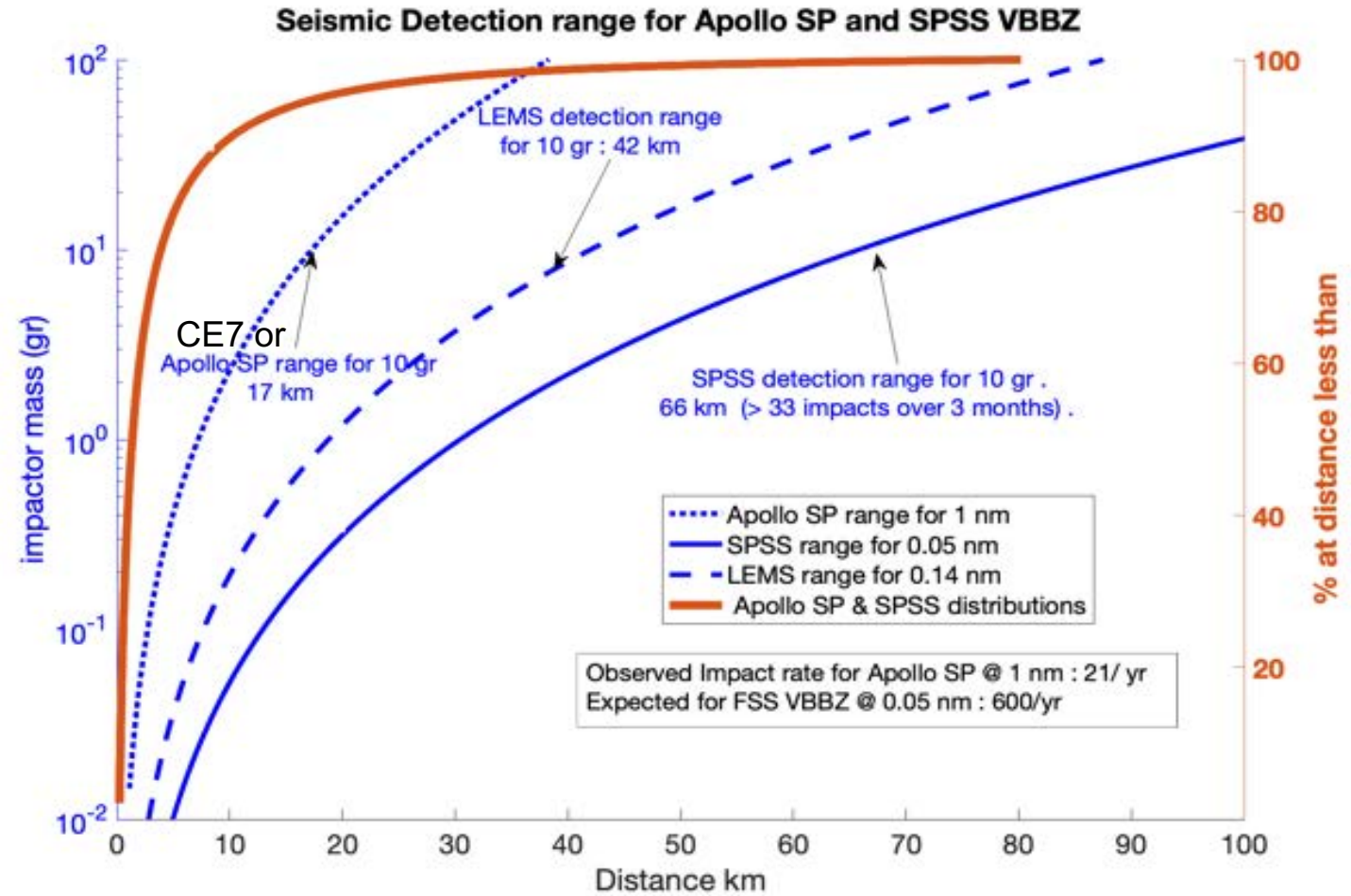
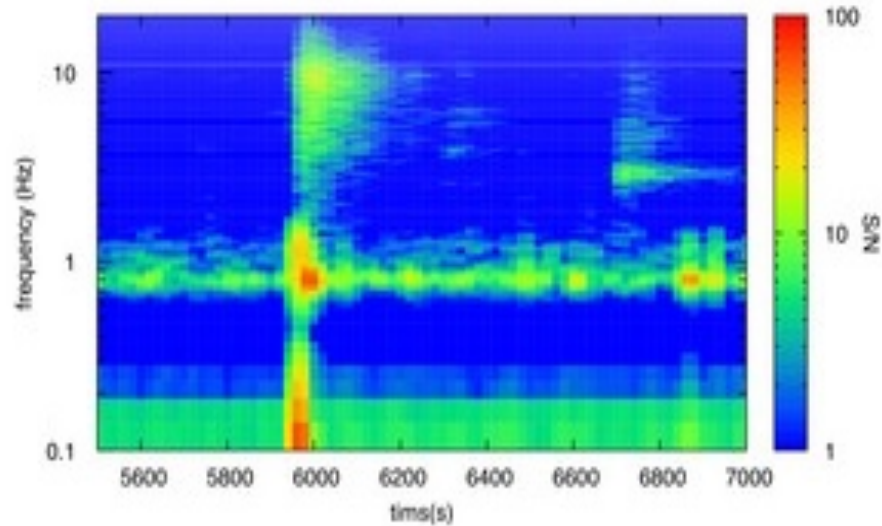
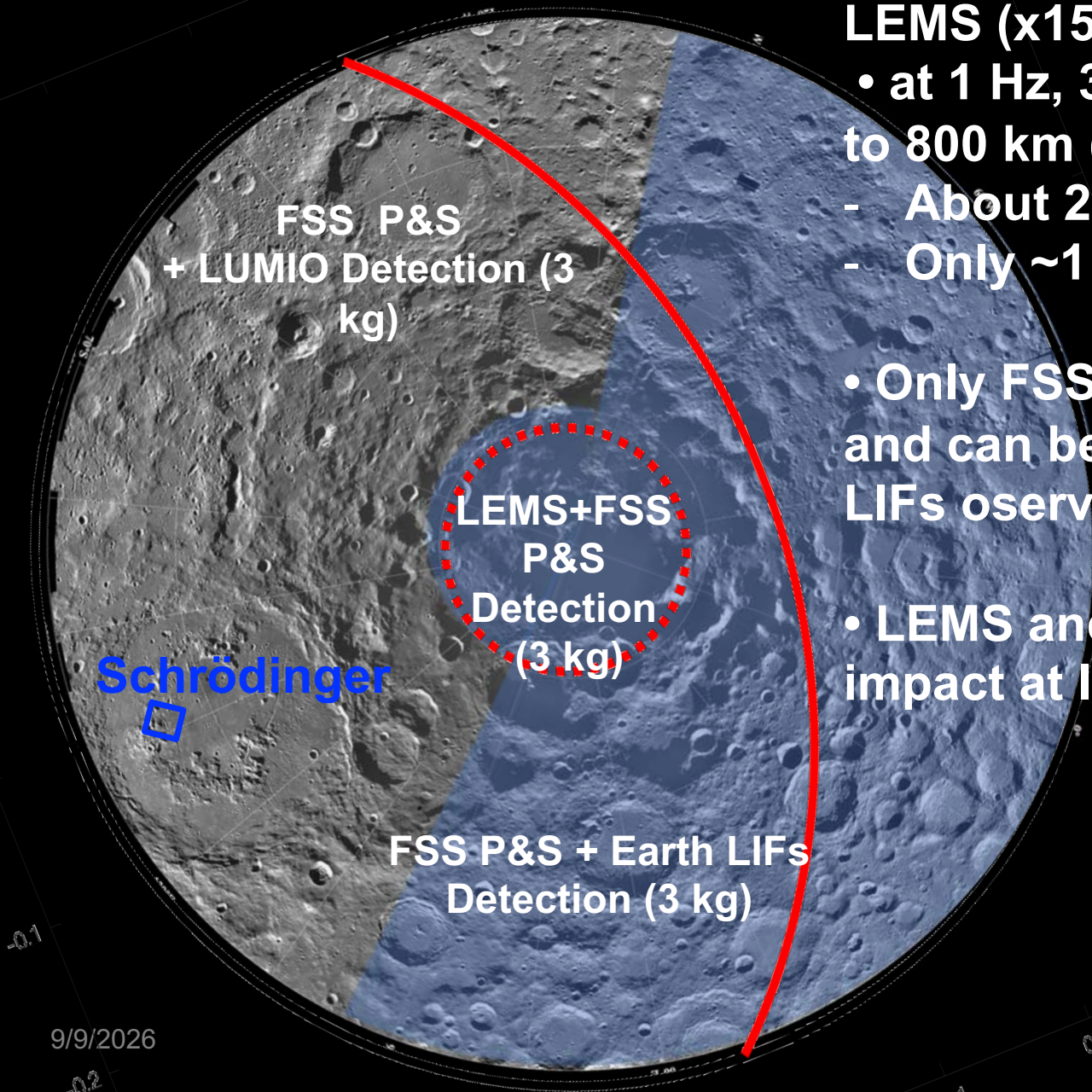


Fig. 1d. Frequency domain recordings for a thermal moonquake event for comparison with the above events. See companion paper [Duennebier and Sutton, 1974].





- Much superior performance VBBZ compared to LEMS (x15 at 1 Hz) and CH7 (x 210)
- at 1 Hz, 3 kg impacts at 24 km/s can be detected up to 800 km (VBBZ) compared to 135 km for LEMS
 - About 25 per year expected for FSS
 - Only ~1 per year for LEMS
- Only FSS can be seen as a « global » network station and can be linked to south hemisphere LUMIO-Ground LIFs observatories
- LEMS and CH7 will be mostly sensitive to the regional impact at less than 100 km of distance

How better than Apollo can FSS/SPSS detect Impact ?

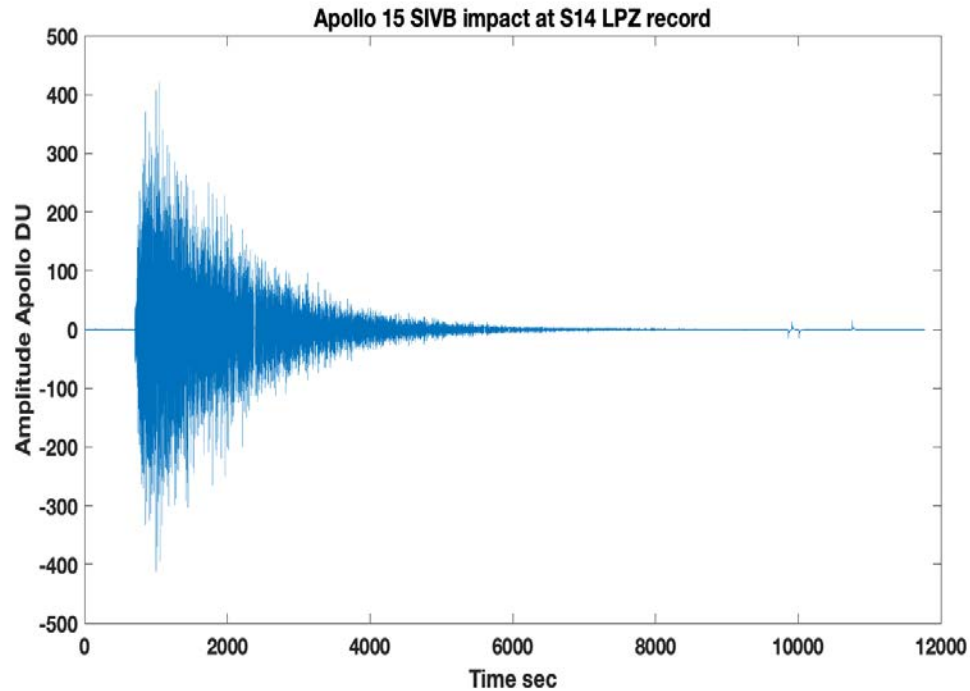
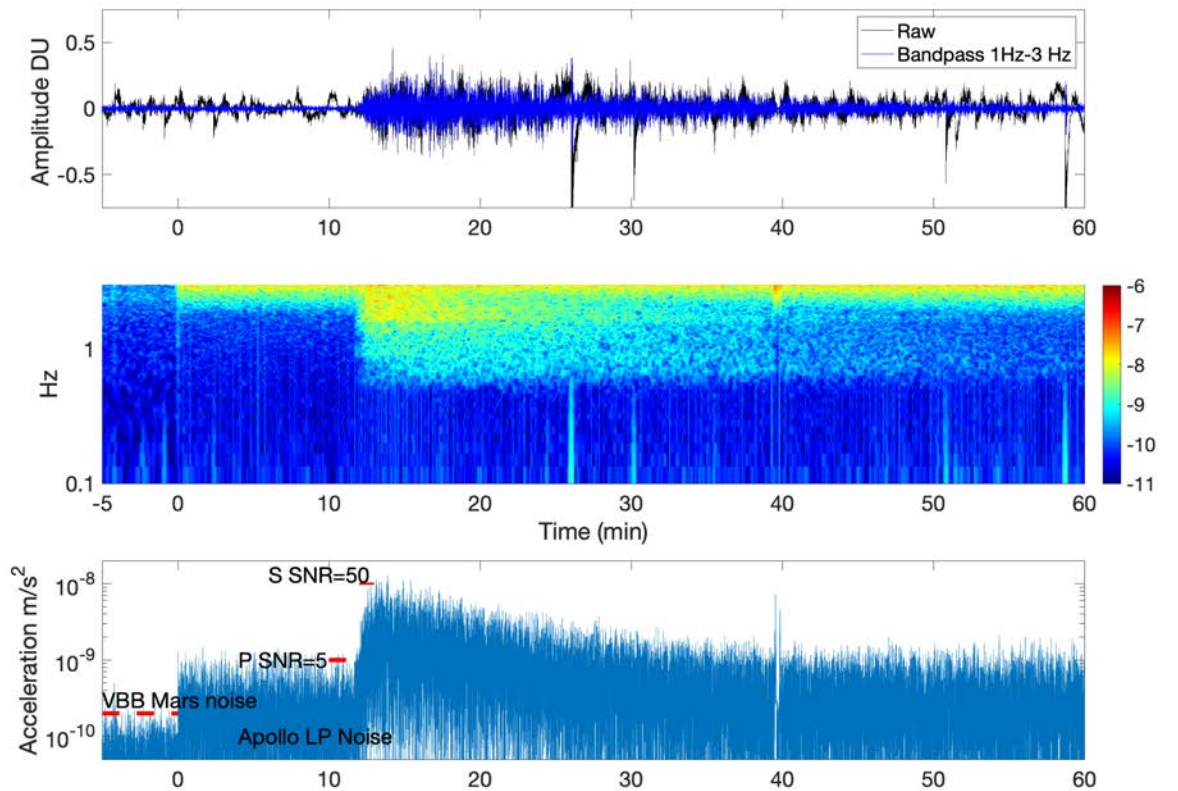
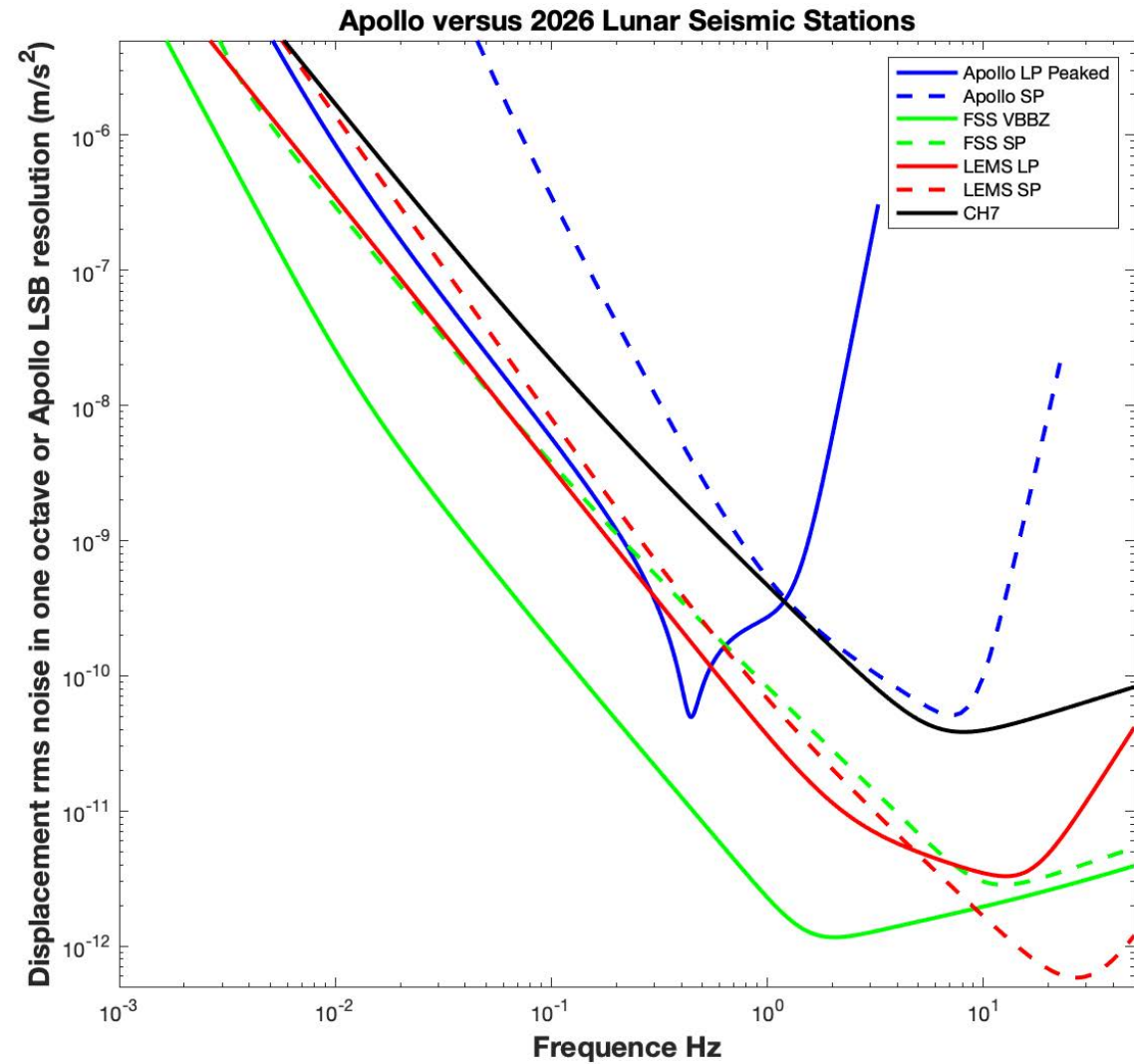
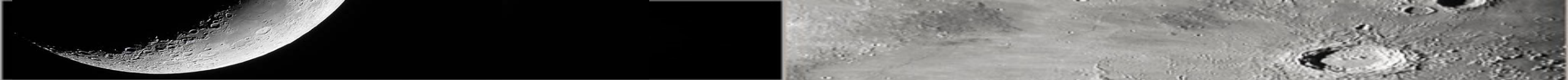


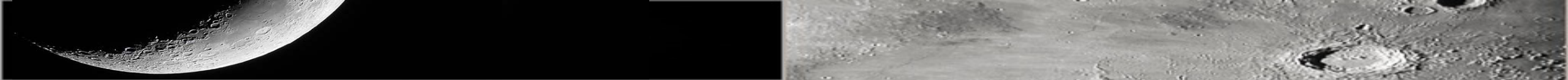
Table 1
Artificial impacts (data are taken from Tókosz et al. (1974))

Impact	Date	Lat.	Long.	Impact velocity (km/s)	Mass (kg)	Distance from stations (km)				Kinetic energy (erg)	mv (kg m/s)
						S12	S14	S15	S16		
12LM	20.1.69	39.4S	21.20W	1.68	2383	73	-	-	-	3.36×10^{16}	0.4×10^7
13S4	15.04.70	27.5S	27.86W	2.58	13925	135	-	-	-	4.63×10^{17}	3.59×10^7
14S4	04.02.71	8.09S	26.02W	2.54	14016	172	-	-	-	4.52×10^{17}	3.56×10^7
14LM	07.02.71	3.42S	19.67W	1.68	2303	114	67	-	-	3.35×10^{16}	0.39×10^7
15S4	29.07.71	15.1S	11.81W	2.58	13852	355	184	-	-	4.61×10^{17}	3.57×10^7
15LM	03.08.71	26.36N	0.25E	1.70	2385	1130	1048	93	-	3.44×10^{16}	0.41×10^7
16S4	19.04.72	13.0N	23.80W	?	?	132	243	1099	-	?	?
17S4	10.12.72	42.1S	12.31W	2.56	14487	338	157	1032	850	4.71×10^{17}	3.69×10^7
17LM	15.12.72	19.96N	30.50E	1.67	2260	1750	1598	770	985	3.15×10^{16}	0.38×10^7

- Take one of the best recorded impact (SIVB Impact)
- Distance = 184 km
- Divide the amplitude to the impulse of a 1 kg meteorid impacting at 20 km/s (roughly 1100) , so we are at about 1 DU peak-to-peak
- Brown statistics suggests 1300 impacts/yr on the Moon with mass > 1 kg, and the 184 km circle surface is 0.28% of the Moon, so we might have only 3 impacts per year...
- Correct the cutoff (1.5 Hz for SIVB, 6.2 Hz for the 1 kg impact) assuming an ω^3 source model
- This will boost the signal in the 1-3 Hz bandwidth where FSS-VBBZ are improving at best Apollo



- Roughly, the 1 DU impacts of Apollo will provide SNR ~ 10 for P and SNR ~ 100 for S

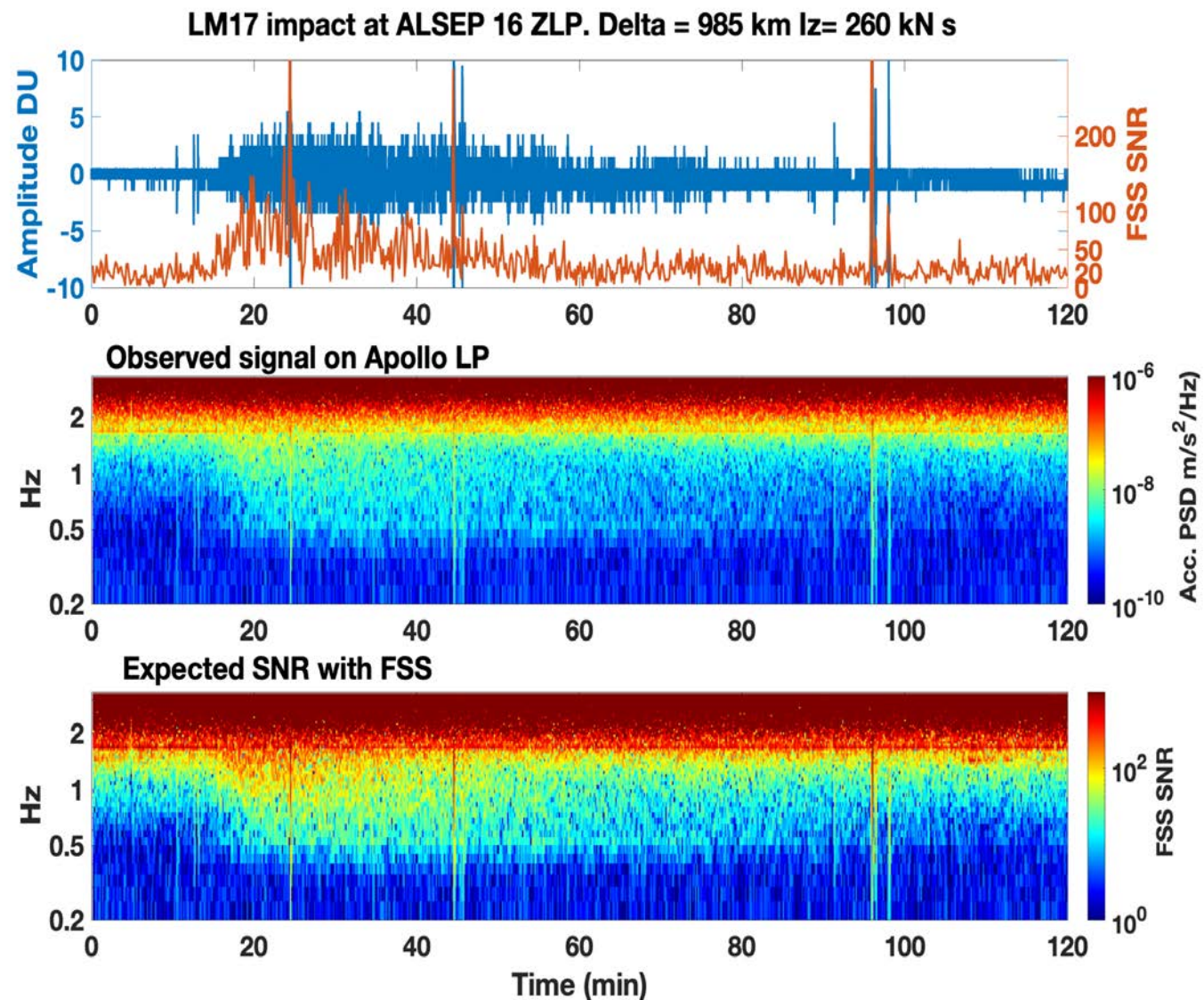
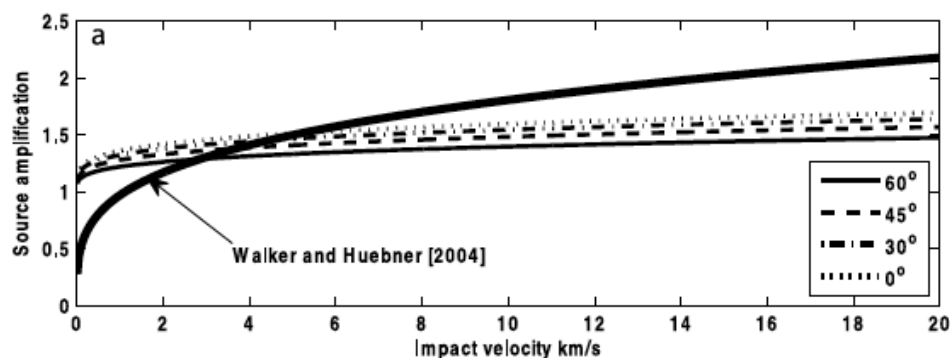


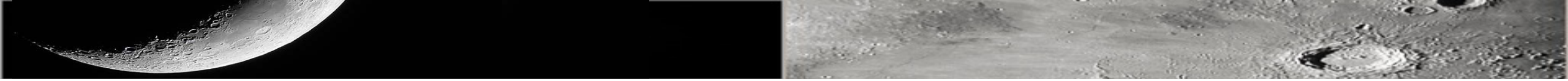
Other example: LEM Impact at 985 km

$260 \text{ kNs impulse} / 20 \text{ km/s} = 13 \text{ kg}$ (without ejecta)

$260 \text{ kNs impulse} / 20 \text{ km/s} = 8.5 \text{ kg}$ (with ejecta)

- still with SNR = 10 for P
- impact of 4.25 kg will have a SNR of ~5

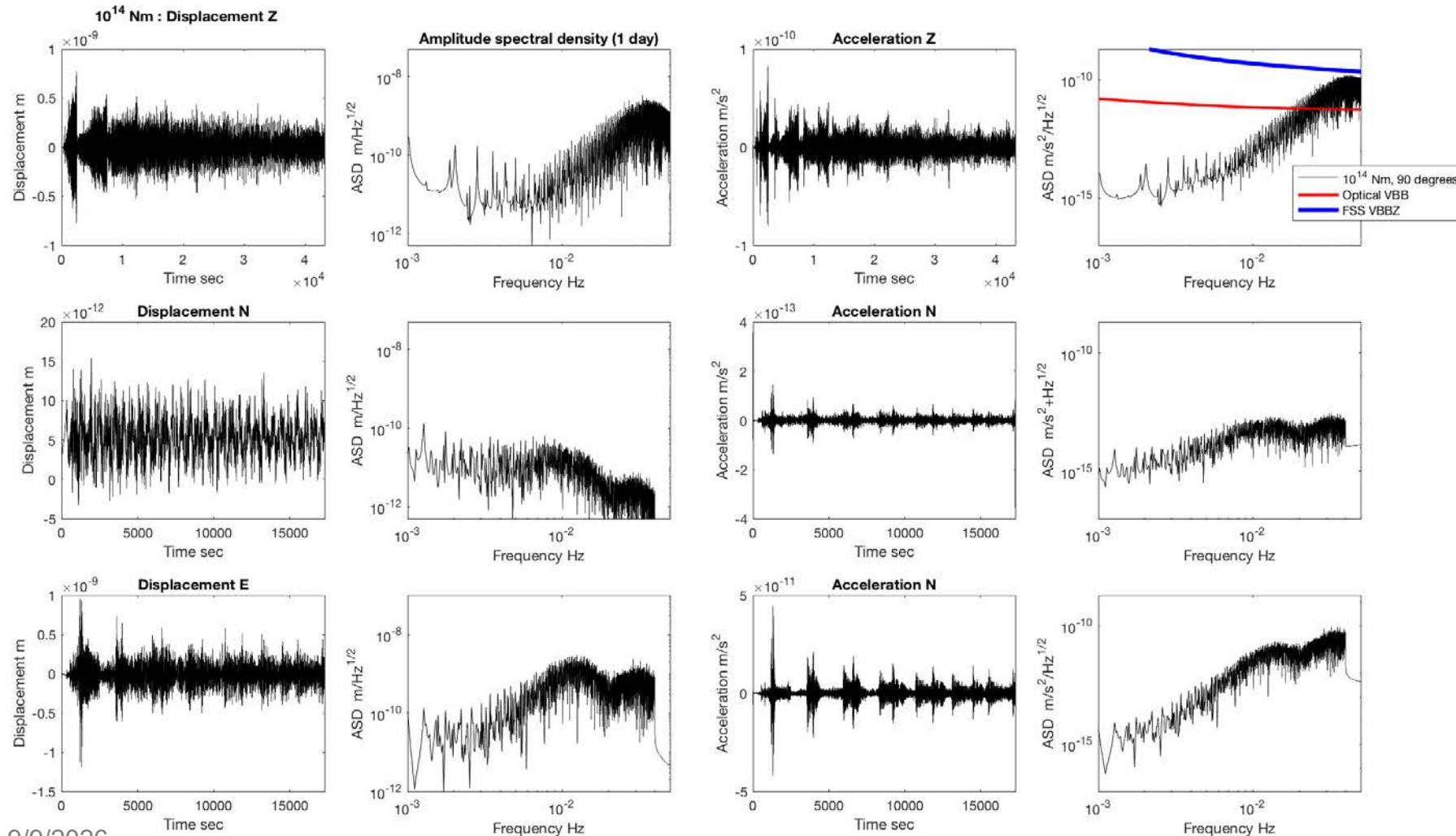




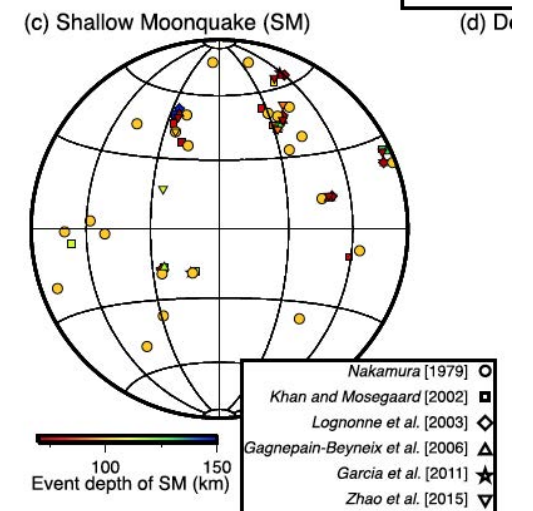
- What we know after the Apollo seismic experiment ?
- What we do not know after the Apollo seismic experiment ?
 - Focus on the lunar seismic noise
- Selected Near future missions compared to Apollo
- What will NOT be made by near future mission and associated goals
 - Global scale, requesting non long lived polar stations
 - Long period seismology, including normal modes
- Noise challenge for very long period seismology
- Noise challenge for Gravitational waves

What FSS will not do: Exploring long period seismic signals

Shallow moonquake: 10^{14} Nm, 30 km prof, 90°



Seismic Moment Nm	Number
$2.5 \cdot 10^{13}$	18
$5 \cdot 10^{13}$	13
10^{14}	9
$2 \cdot 10^{14}$	6
$4 \cdot 10^{14}$	3

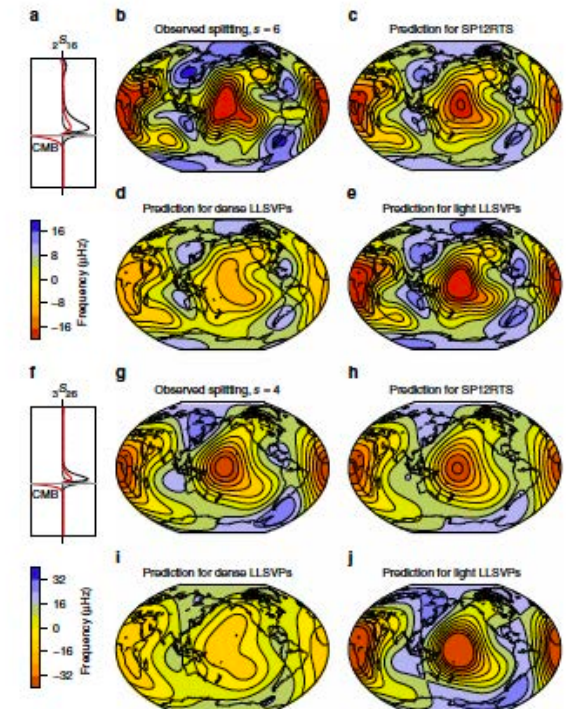
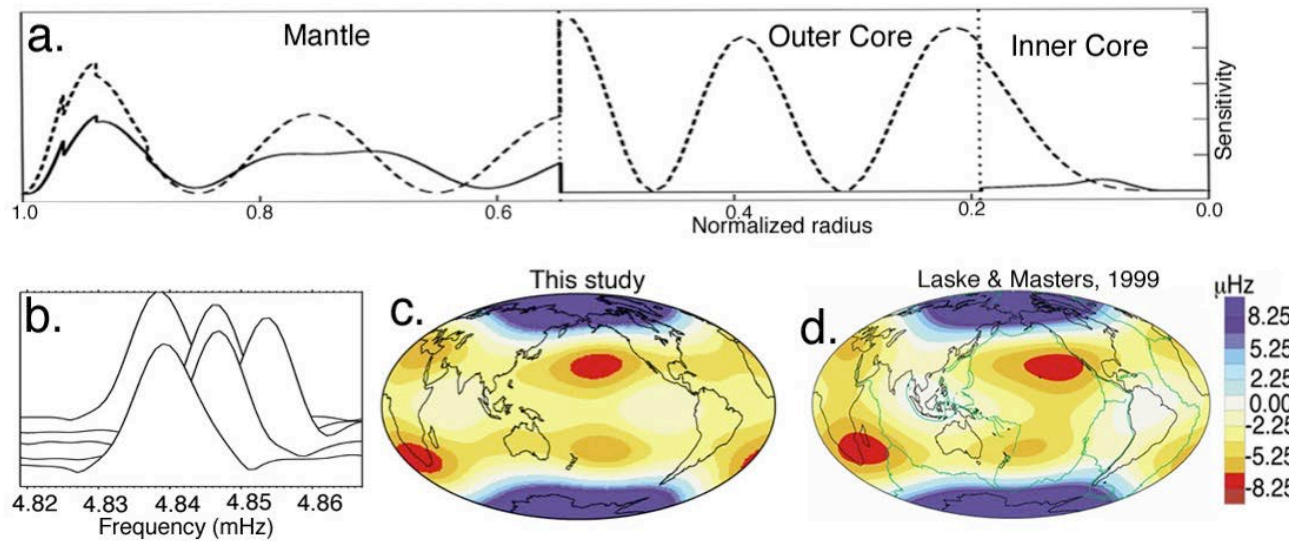


Why Normal modes?

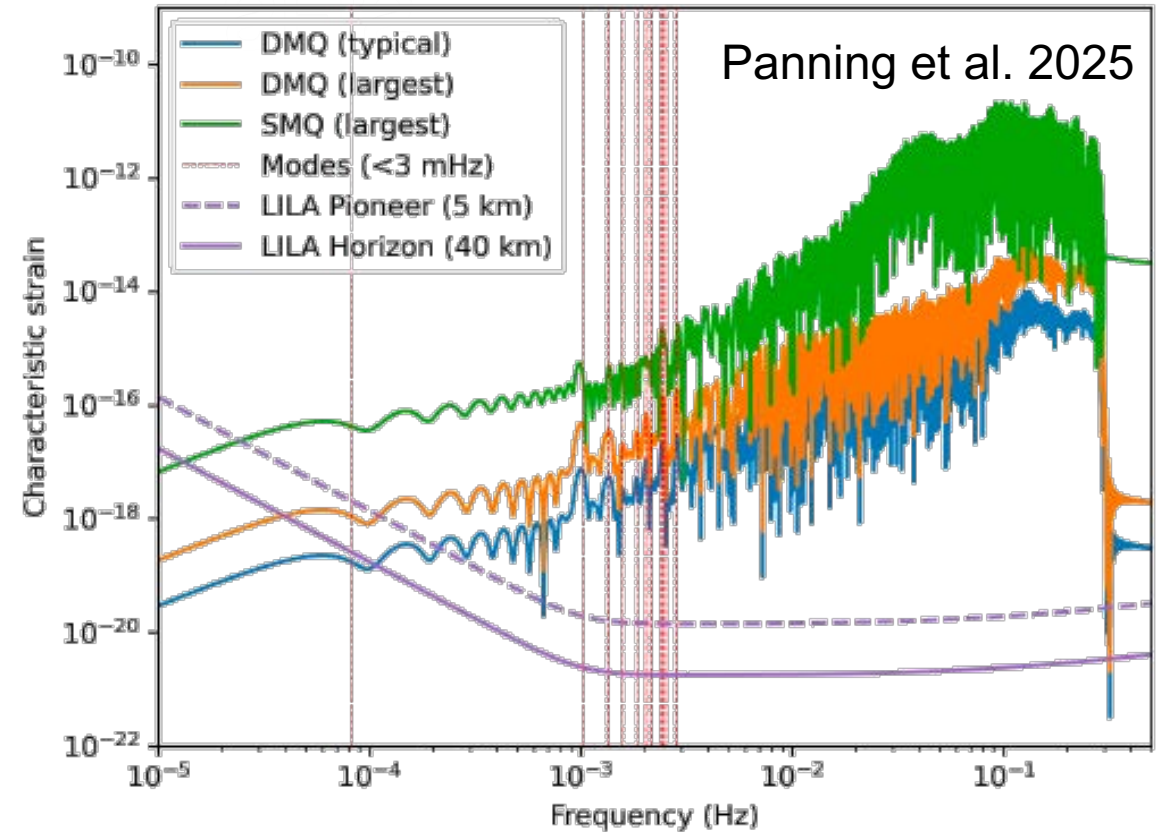
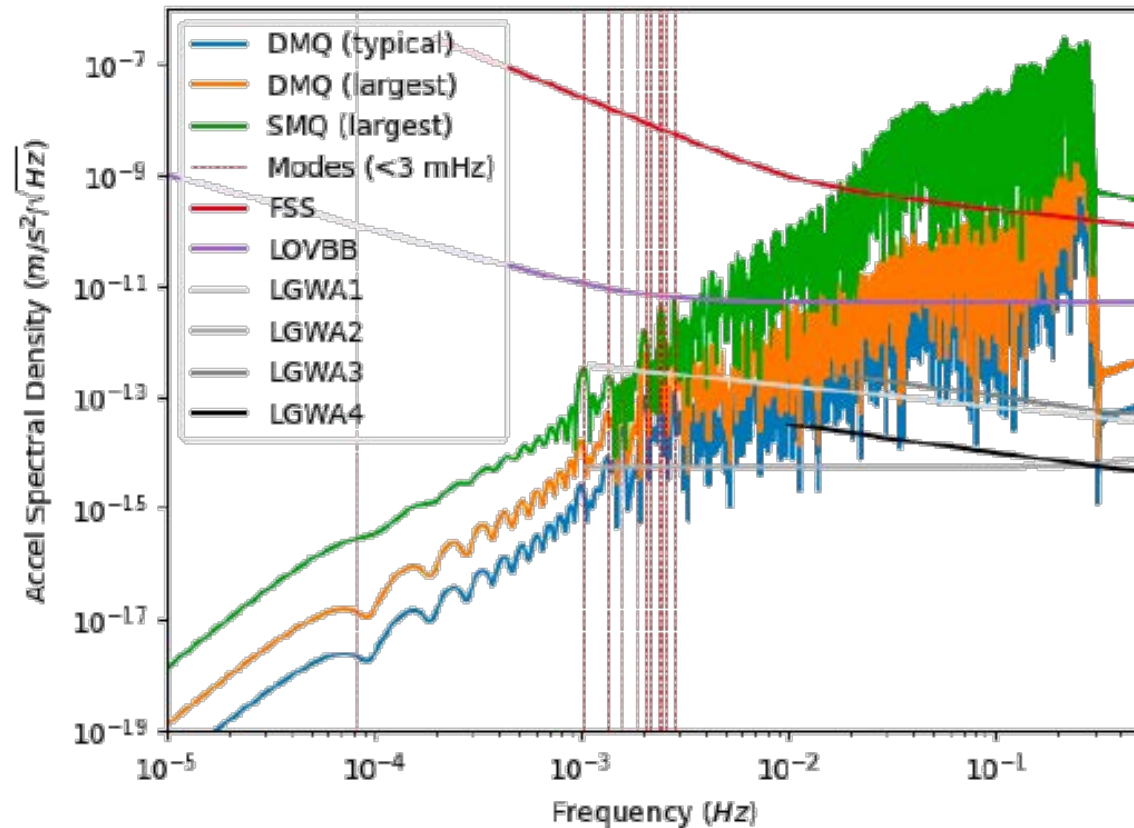
- Normal modes excited by large earthquakes provide the best 1D model (e.g. PREM, Dziewonski and Anderson, 1981) and can also infer the 3D deep to very deep structure of the Earth
- This is made by measuring the splitting of these normal modes and request several pairs of source-stations with known locations
- This can be made by a single instrument measuring several located sources (e.g. DMQs on the Moon) or several stations measuring a few quakes (e.g. Large Earthquakes with Earth VBB Network)

Koelemeijer et al. 2017

Courtesy Tkalčić et al. 2025

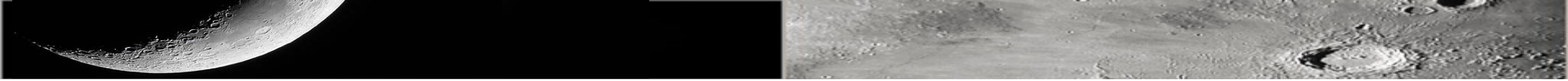


Normal modes on the Moon: instrument challenge



Panning et al. 2025

- FSS-VBBZ (TRL9) might capture Surface waves down to 0.05 Hz if surviving several years
- LOVBB (TRL5) might capture Mantle Normal modes down to 5 mHz if long term monitoring
- LGWA inertial sensors (Ajith et al., 2024) might detect below 5 mHz but with too modest SNR
- Only strainmeters (LILA, LBI-GND) provide high SNR modes observations down to ${}_0S_2$ and even ${}_1S_1$



2512

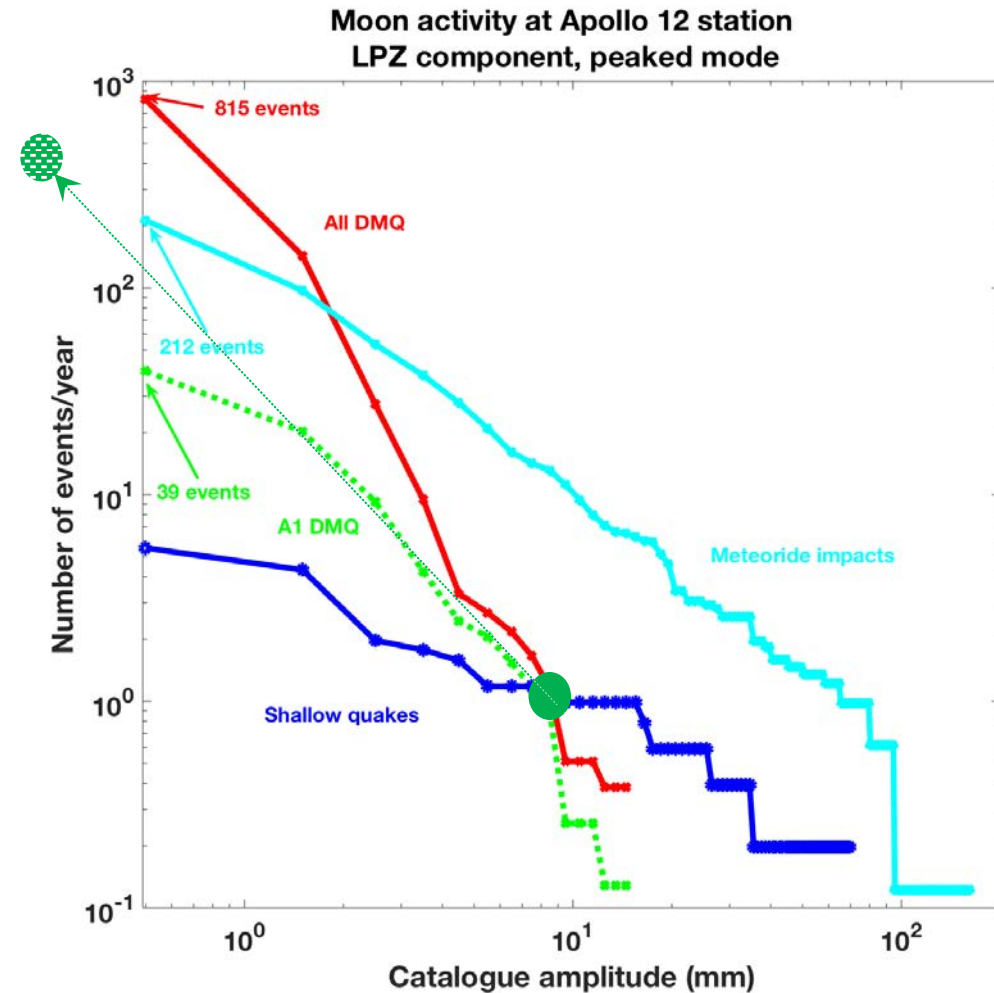
- What we know after the Apollo seismic experiment ?
- What we do not know after the Apollo seismic experiment ?
 - Focus on the lunar seismic noise
- Selected Near future missions compared to Apollo
- What will NOT be made by near future mission and associated goals
- **Noise challenge for very long period seismology**
- Noise challenge for Gravitational waves

Normal modes on the Moon: targeting DMQs

Example

- A1: 29/10/1975
 6.8×10^{13} Nm (Kawamura et al. 2017)
 7.4×10^{13} Nm (Goins et al. 1981)
Largest A1 $\sim 10^{14}$ Nm
Smallest A1 Apollo A1 $\sim 5 \cdot 10^{12}$ Nm
Daily if extrapolated ● $\sim 2 \cdot 10^{12}$ Nm

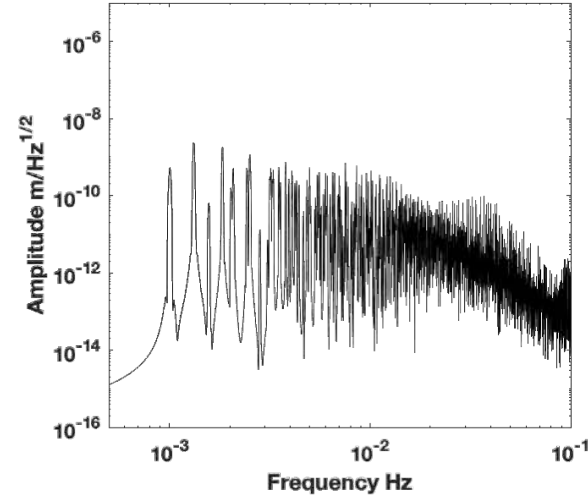
- Further Assumptions:
A1 detected at South Pole
800 km depth
Strike/dip/rake mechanism
 $45^\circ / 45^\circ / 45^\circ$



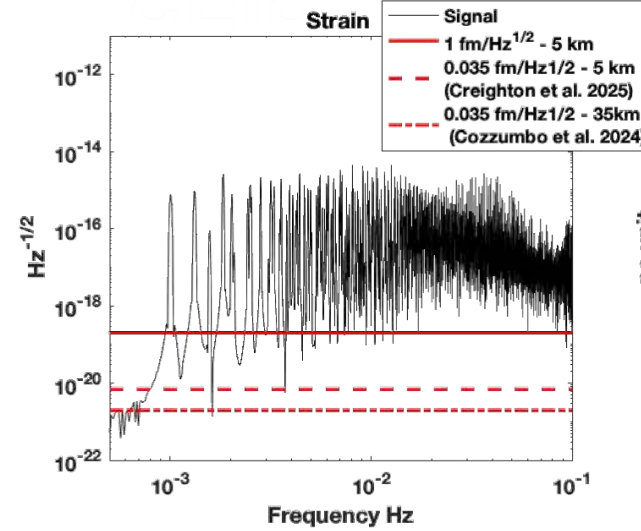
Normal modes on the Moon: Largest DMQs

- Source Challenges:
 - Several effects are expected to reduce the Normal modes signals
 - Focal mechanism
 - Larger attenuation in the deep interior
 - Lateral variations and associated splitting
 - Other DMQ sources are less active than A1
- Instrument challenge:
 - Tilt sensitivity for accelerometers

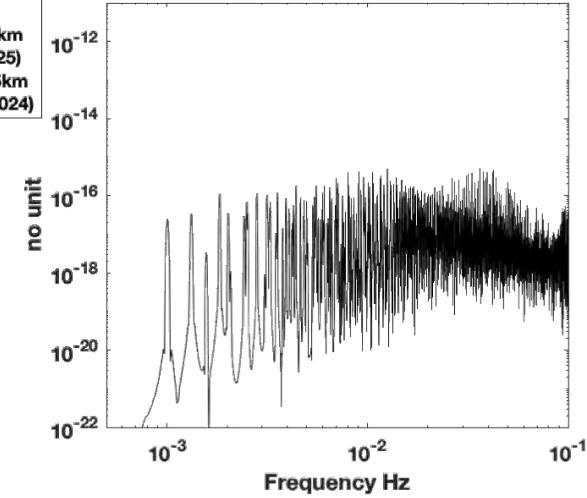
Longitudinal displacement, A1, 10^{14} Nm, 800 km
South pole, 24h



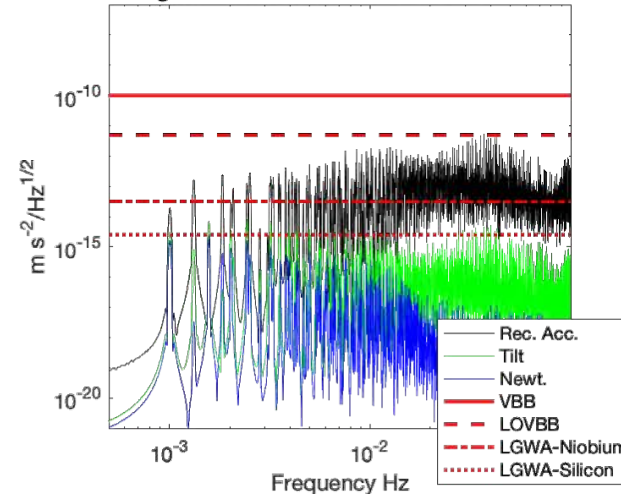
Strain



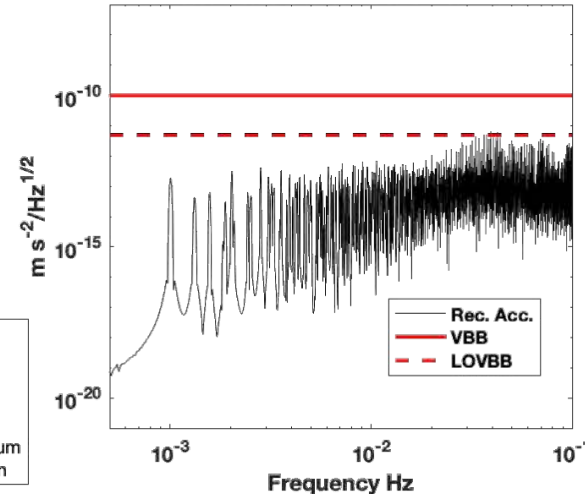
Characteristic Strain



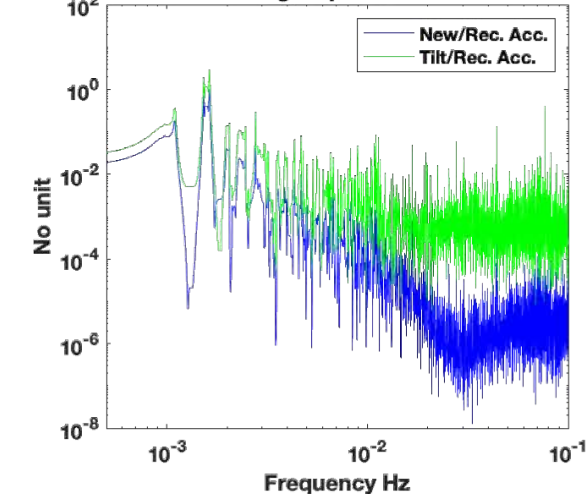
Longitudinal acceleration & thermal noise



Vertical acceleration & thermal noise

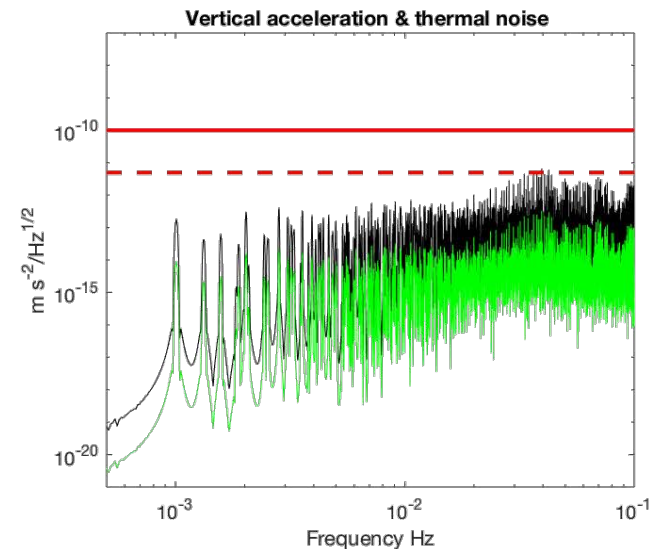
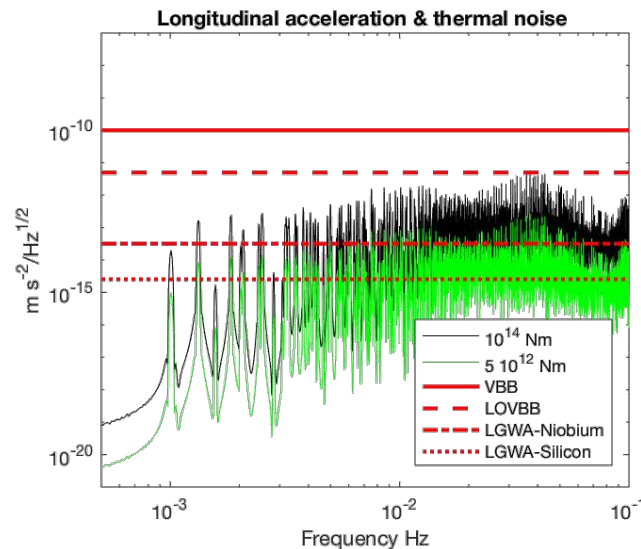
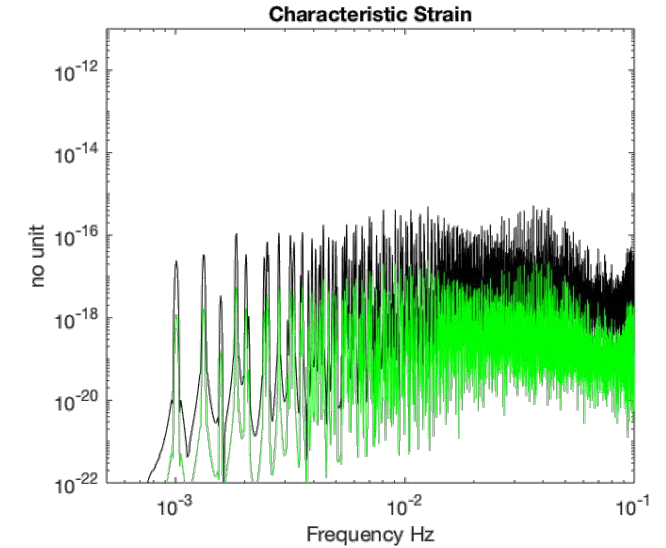
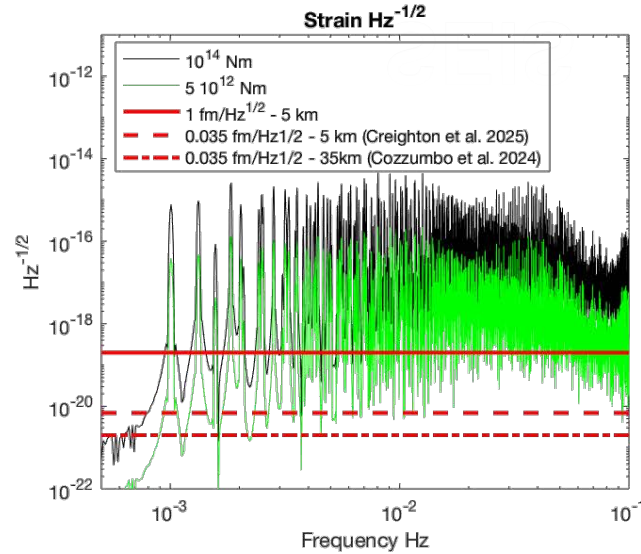


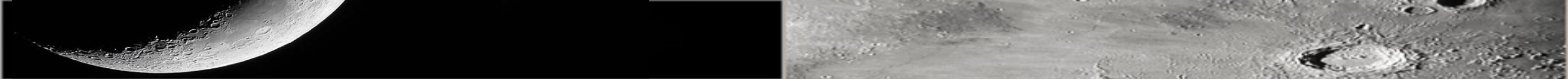
Signal partition



Normal modes on the Moon: small DMQs

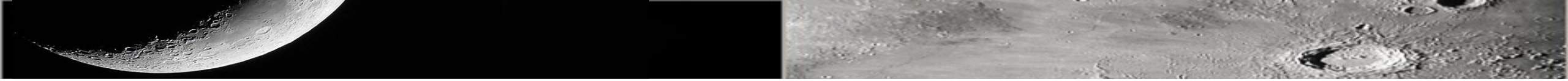
- The measurement of the normal modes excited by the weakest Apollo DMQ nest will provide several tens of splitting functions, enabling to determine the « fine structure » of the 3D deep lunar interior
- This will request the detection of normal modes from all Apollo DMQs nests...and DMQs down to $5 \cdot 10^{12}$ Nm
- Only strainmeters with better than $2 \cdot 10^{-19} \text{ Hz}^{-1/2}$ sensitivity can achieve this goal
- Need a crater to minimize near surface dust effects and with the requested diameter for strainmeter arms





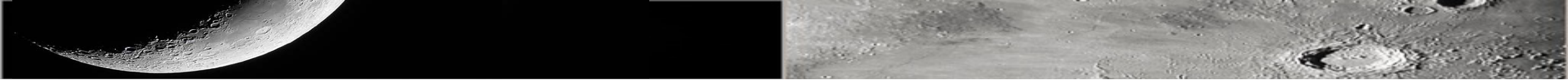
2512

- What we know after the Apollo seismic experiment ?
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 - Focus on the lunar seismic noise
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- What will NOT be made by near future mission and associated goals
- Noise challenge for very long period seismology
- **Noise challenge for Gravitational waves**



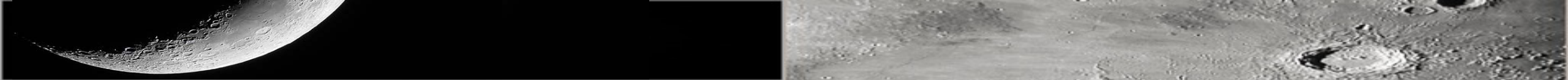
How low can we predict and possibly reduce the lunar seismic and environmental noise to level compatible with GW detection?

- Micro-seismic noise from meteorite hum (Lognonné et al. 2009)
- Micro-seismic noise from repeating DMQs
- Micro -seismic noise from Thermal Moonquakes and anthropogenic lunar activities
- Ground noise from Solar constant time fluctuation
- Gravitation noise from Earth
- Radiation, dust, magnetic field, etc affecting directly the strainmeters or accelerometers



How low can we predict and possibly reduce the lunar seismic and environmental noise to level compatible with GW detection ?

- Micro-seismic noise from meteorite hum (Lognonné et al. 2009)
- Micro-seismic noise from repeating DMQs
- Micro -seismic noise from Thermal Moonquakes and anthropogenic lunar activities
 - High frequency sources ($f > 1$ Hz) and shall be far (> 10 km) from future nbasis if any
- Ground noise from Solar constant time fluctuation
 - Proportional to T, including in PSR (due to reflected light), and will request MLI blanket ground shielding around instrument
- Gravitation noise from Earth
- Radiation, dust, magnetic field, etc affecting directly the strainmeters or accelerometers



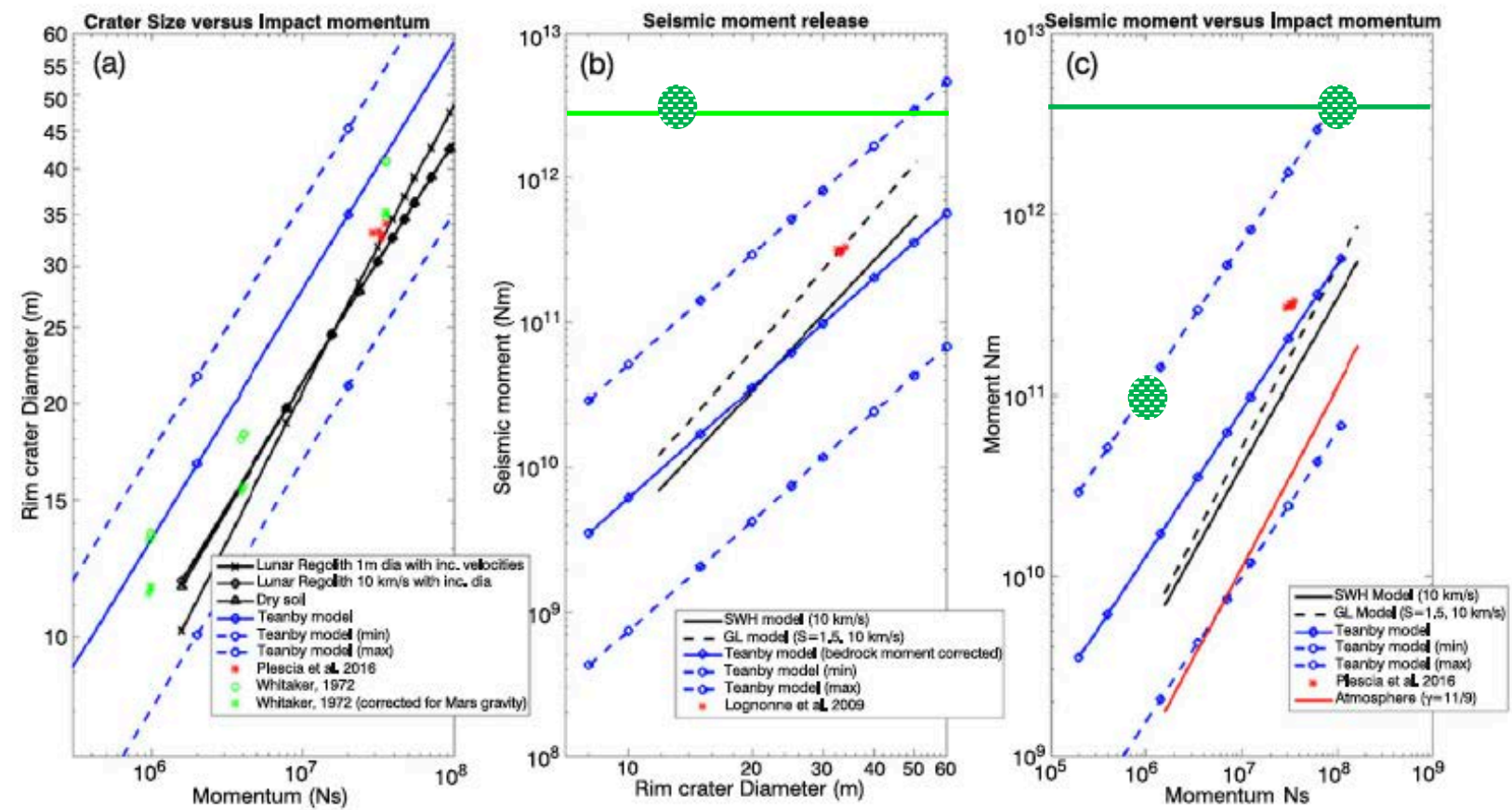
● Daily DMQ $\sim 2 \cdot 10^{12}$ Nm

as the same seismic moment of a very rare impact ($\sim 1/\text{yr}$, 10^8 Ns impulse, 50 m class diameter, upper limit) corresponding to mass of about 2.5 tons (assuming ejecta amplification ~ 2)

The daily largest impact has a mass of about 4 kg and a moment of about 10^{11} Nm

All statistics with Brown et al. 2002 with upper limit

9/9/2026



Daubar et al., 2017

Seismic Impact Hum: deci-herz

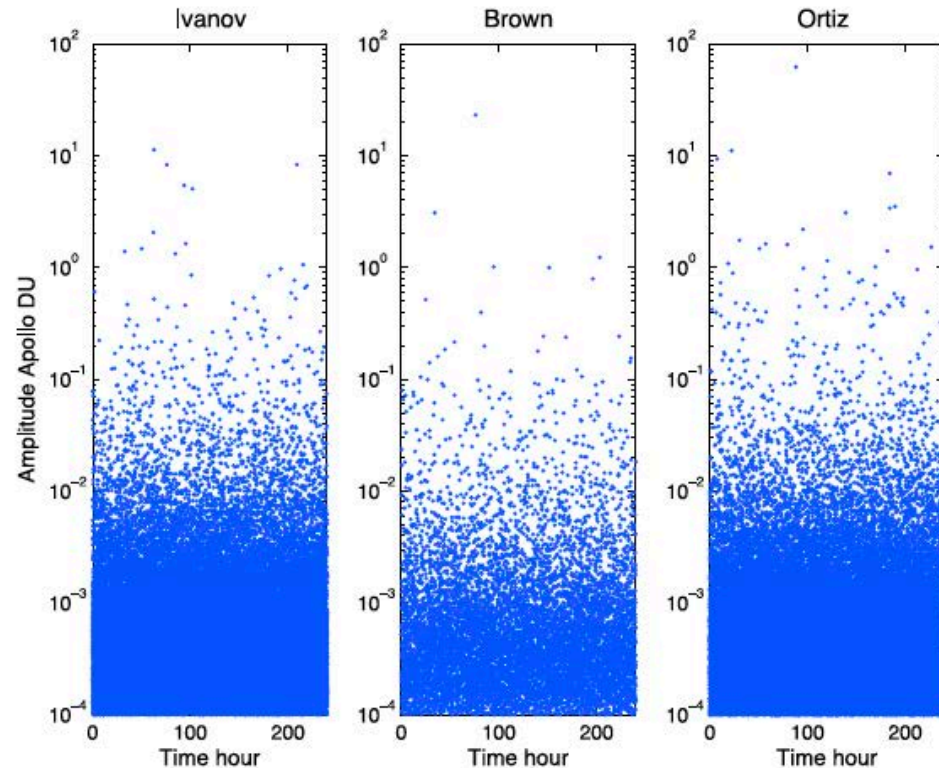


Figure 14. Simulated impact amplitudes. Each point provides the maximum envelope amplitude of a single simulated impact “recorded” at the station 12 location. From left to right are the simulations for the Ivanov, Brown, and Ortiz models, respectively. Each simulation spans 10 days.

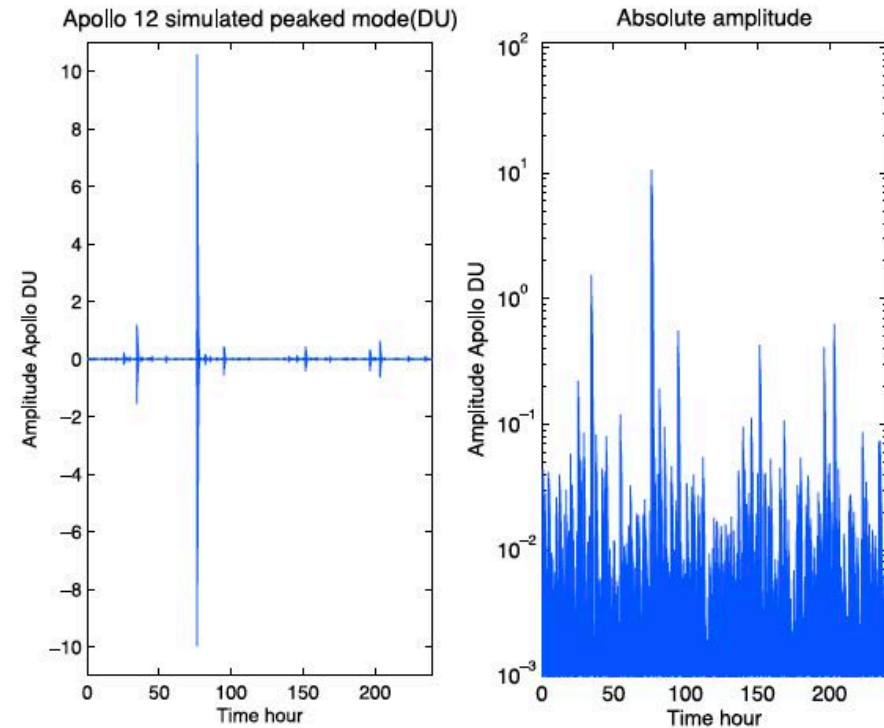
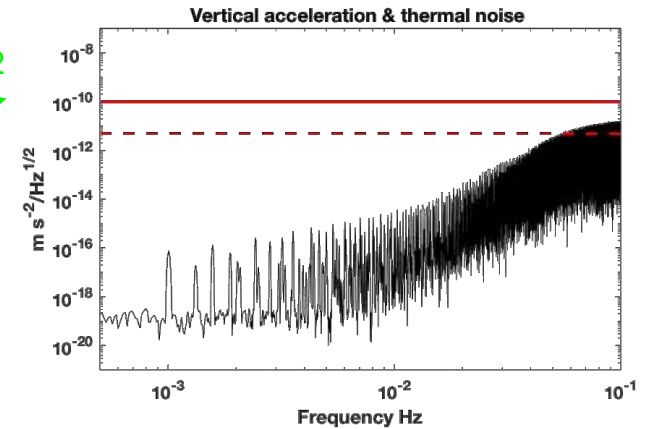
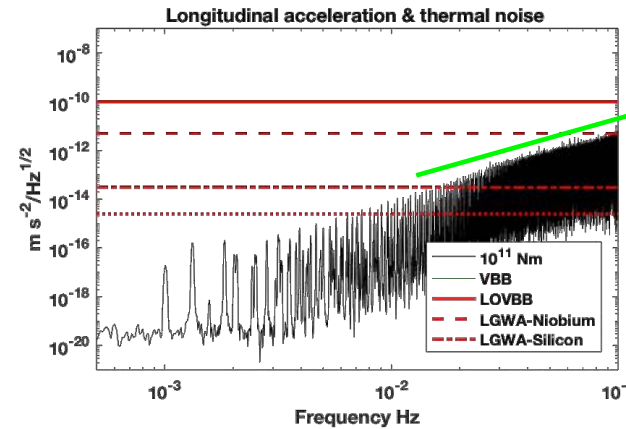
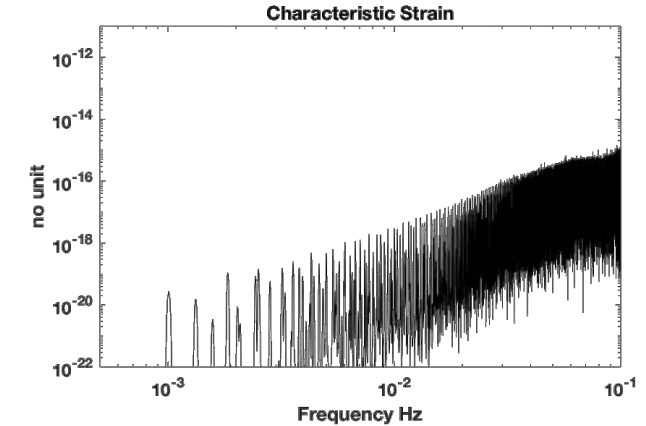
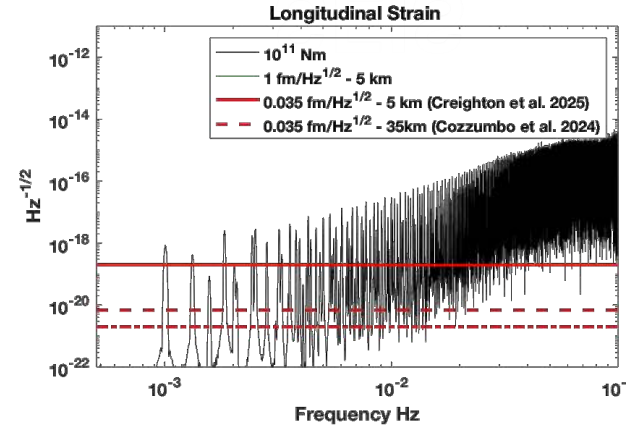
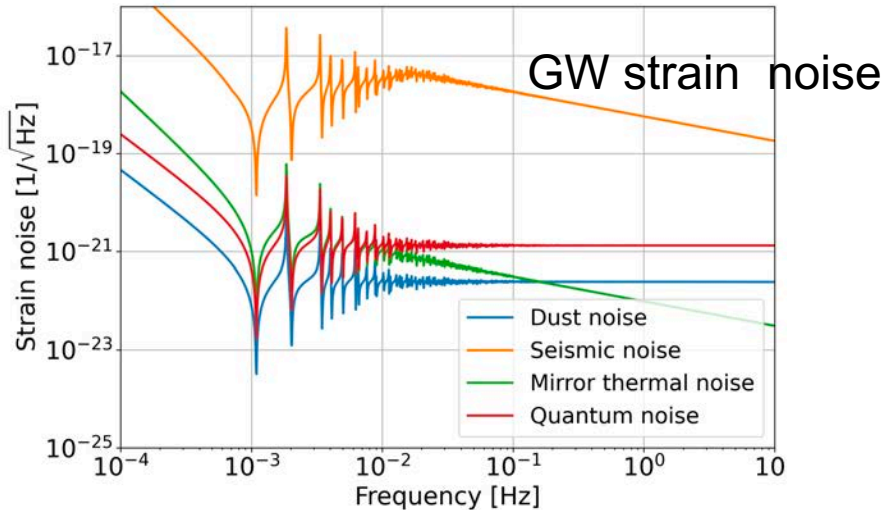
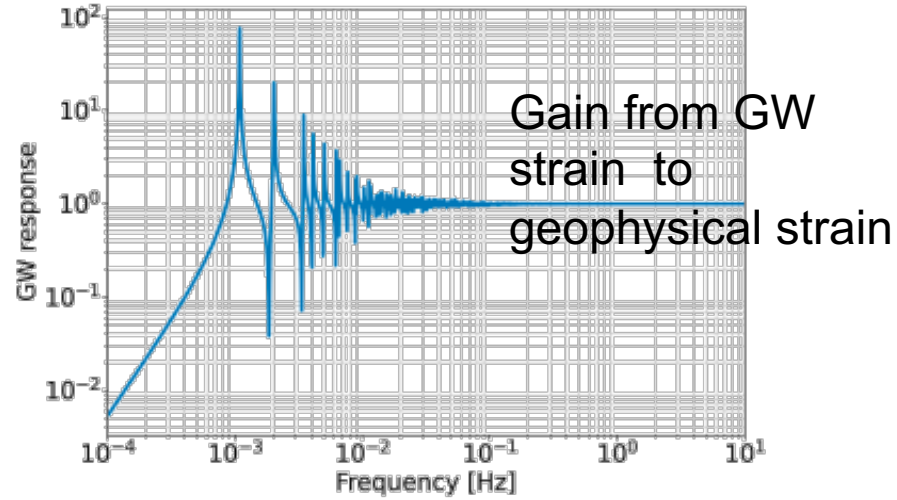


Figure 15. Composite waveform for impacts simulated using the Brown model. The duration of each waveform (corresponding to an individual impact) summed is 1 h, while the plot shows 10 days of signal. (left) The computed seismogram in Apollo DU. (right) The absolute value of the seismogram, on a logarithmic scale.

- A reasonable estimation of the Hum at 0.5 sec can be estimated to about 10^{-2} Apollo DU, which provides about 5×10^{-13} m rms , wich means 5×10^{-12} m/s² rms
(see details in Lognonné et al. 2009)

Seismic Impact Hum: long period



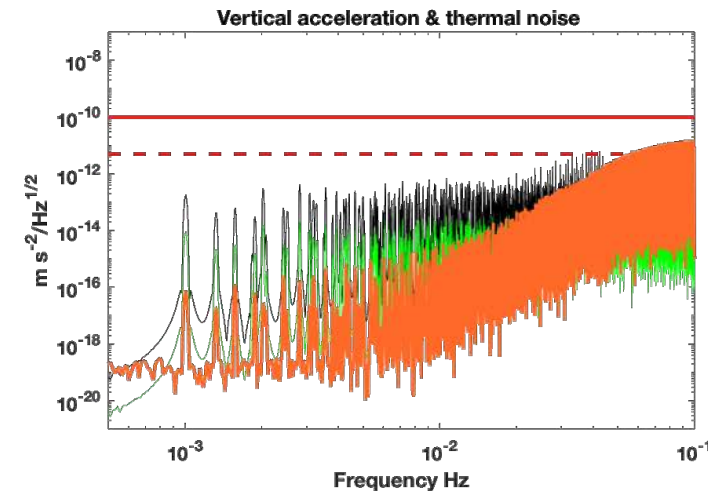
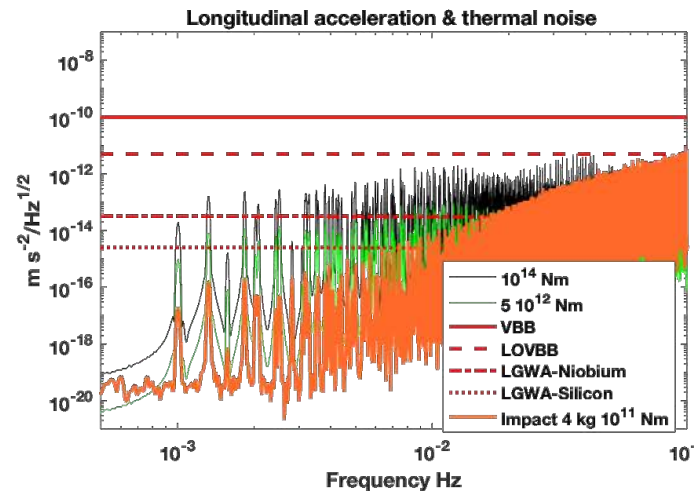
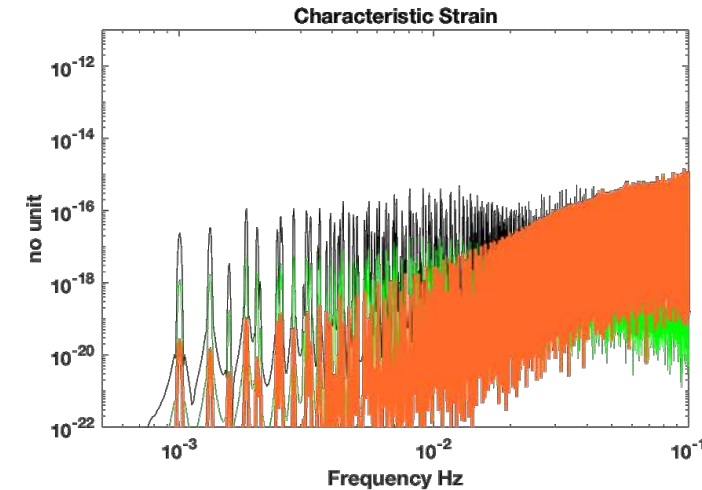
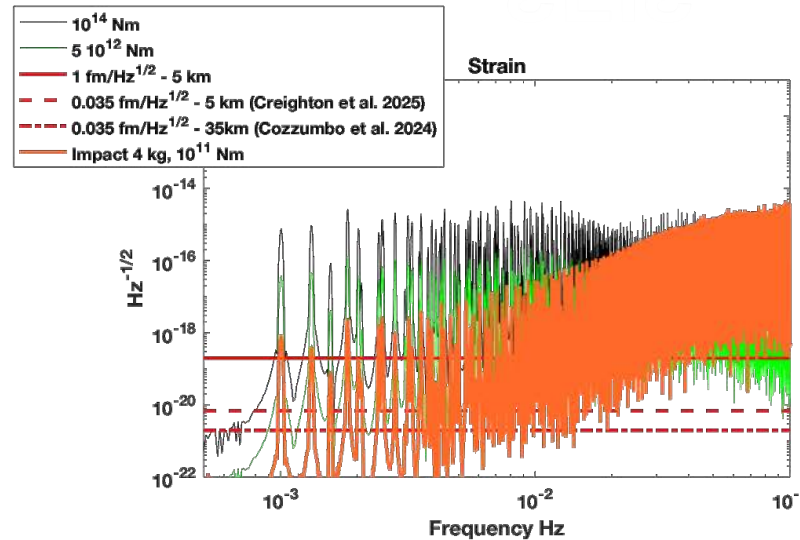
Normal modes: impact at 72° , 4kg, 10^{11} Nm, $5 \cdot 10^{-18} \text{ Hz}^{-1/2}$ @ 100 sec

(Only one impact. Hum to be estimated, but we are comparable to Lognonné et al. 2009)

Cozzumbo et al. 2024. (Seismic Noise $5 \cdot 10^{-18} \text{ Hz}^{-1/2}$ @ 100 sec) (Only impact noise and furthermore the seismic noise is also amplified by modes)

Seismic Impact Hum versus Normal modes

- The seismic impact hum rises as f^2
- This model is likely overestimating by 10-100 due to:
 - The upper limit used for impacts Moment/impulse
 - the 1D model with scattering
 - the single impact model and distance
- Scattering effects are likely larger on the impacts than on DMQ
- This nevertheless suggests that a rising impact seismic noise might be present
- Noise cancellation is likely requested when reaching deci-hertz for GW detectors while it might not so much affect Normal modes below 0.01 Hz

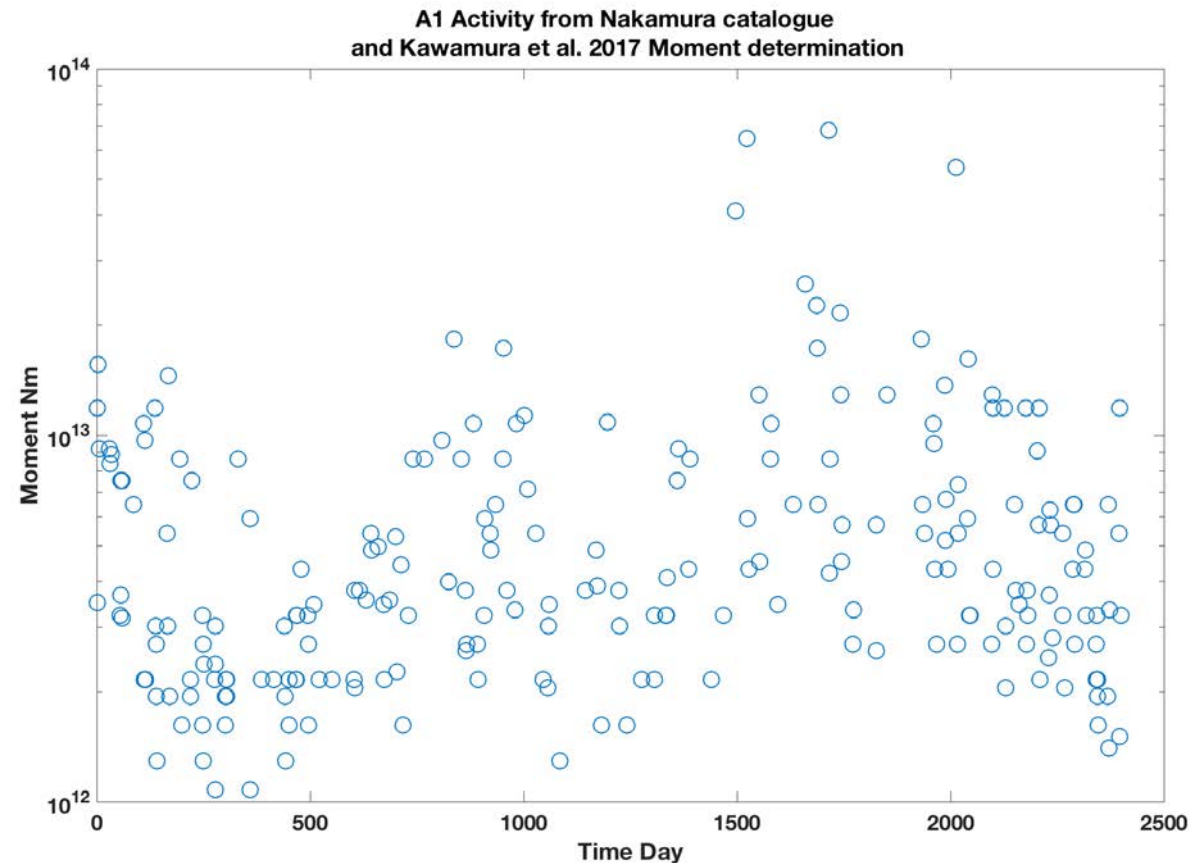


DMQ hum

- DMQ were closer from Apollo limitation, most of them being detected with signals of a few bits on Apollo
- Smaller DMQs might exist and they will contribute to a second source of hum with subvertical incidence angle

$M_s=3.7$

$M_s=2.4$



DMQ hum... extrapolating down

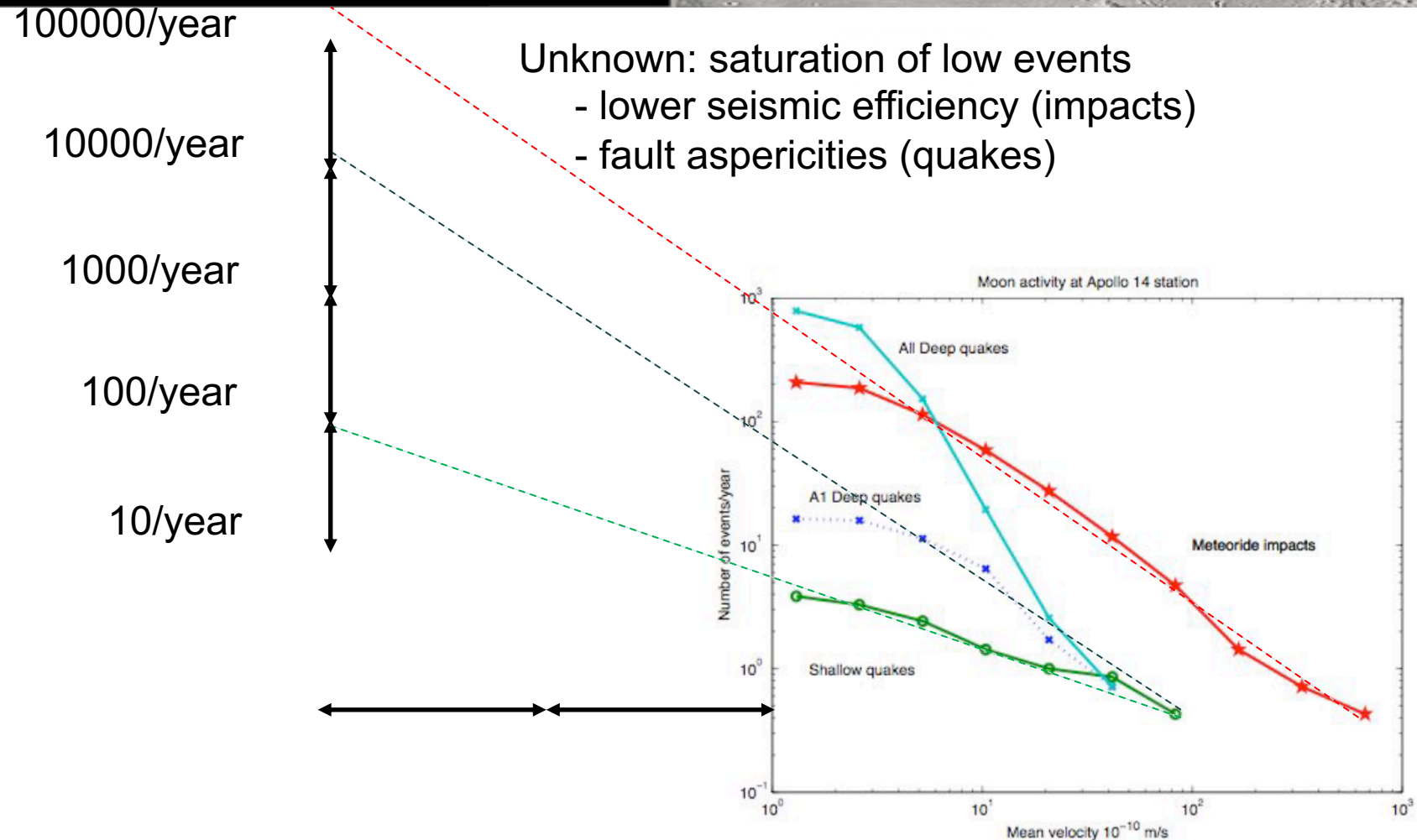
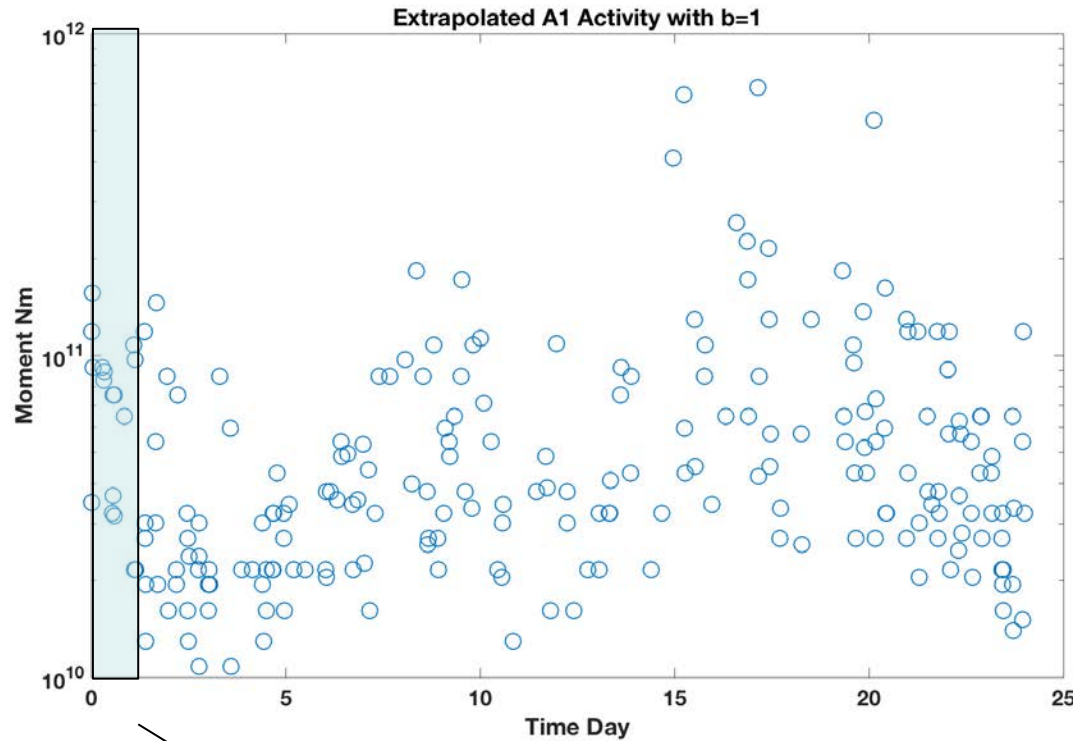


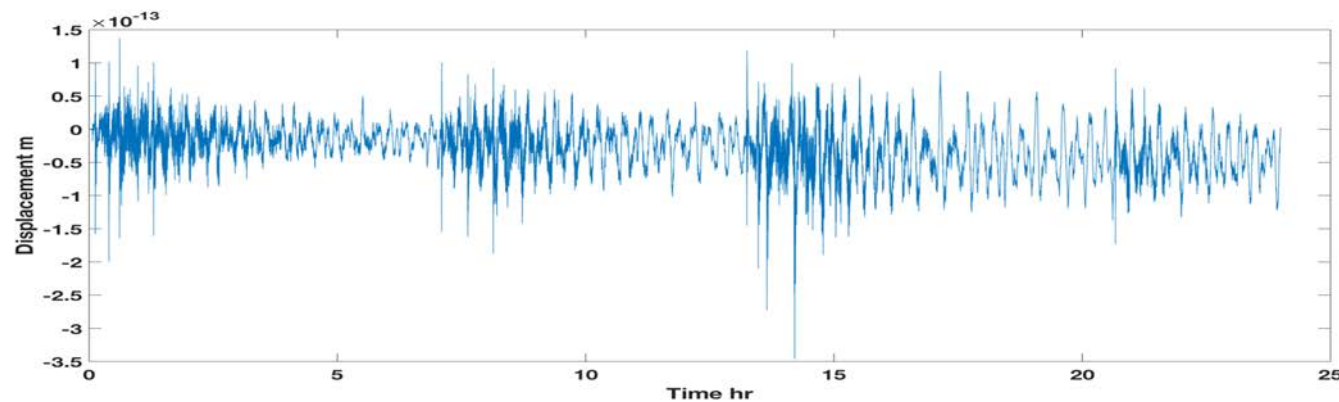
Figure 10: Number of events/year detected on the Apollo 14 station versus amplitude. Amplitudes are from the Nakamura (2004) catalogue and converted approximately as mean velocity, assuming a recording by the long-period horizontal component on the peaked mode and peaked frequency. Note the very high number of events detected, despite their very low amplitudes (See Figure 1 for seismometer sensitivity)

DMQ hum... extrapolating down



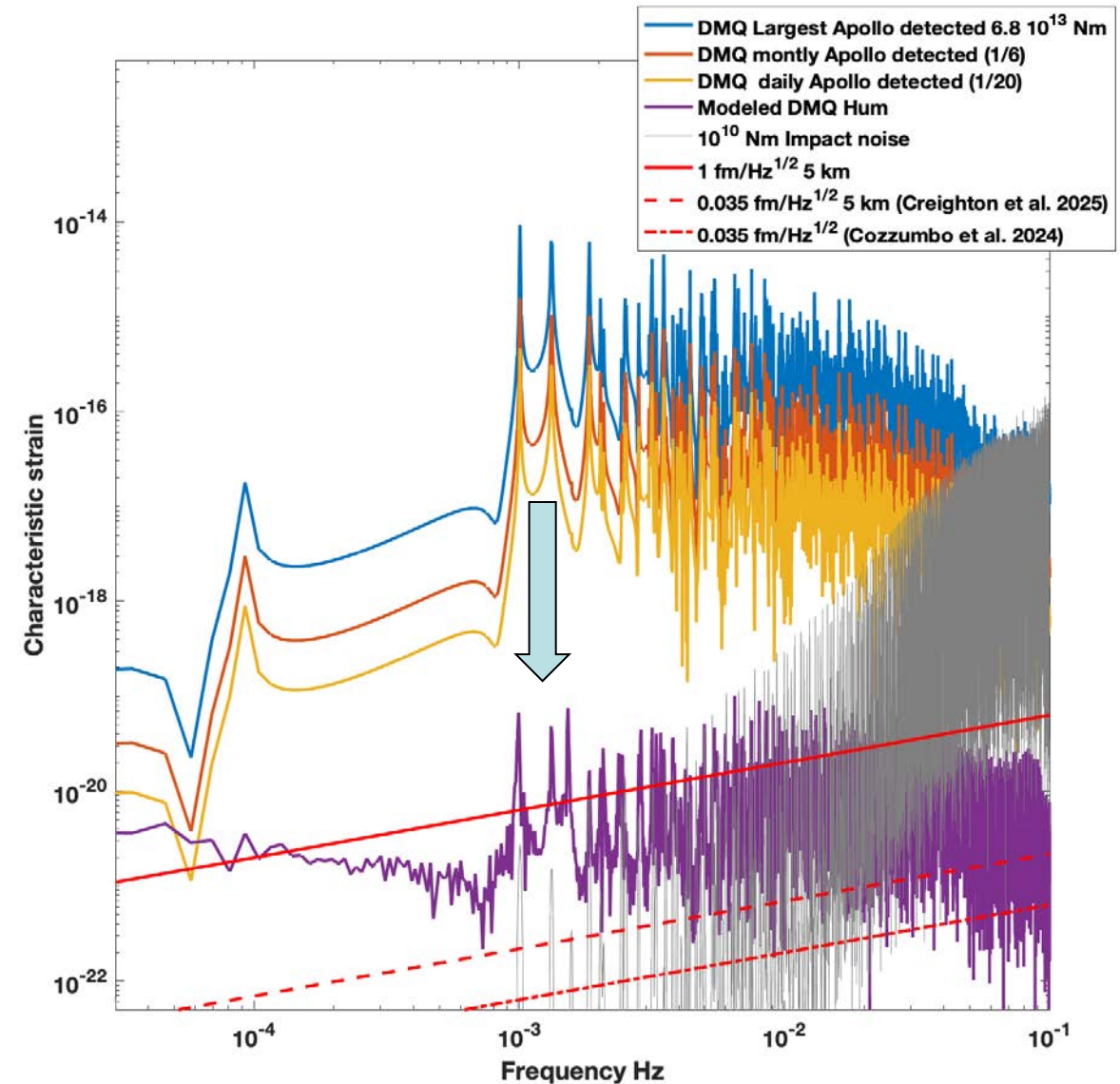
We simulate the small DMQs by accelerating the occurrence of the catalogue with a $b=1$ (1/100 for the time, 1/100 for the moment)

First day



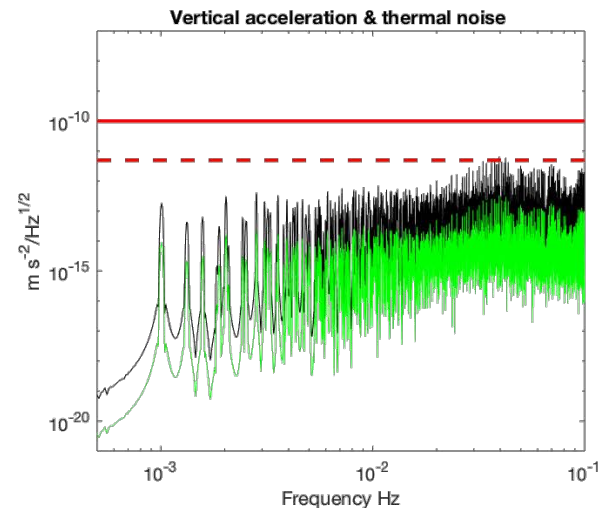
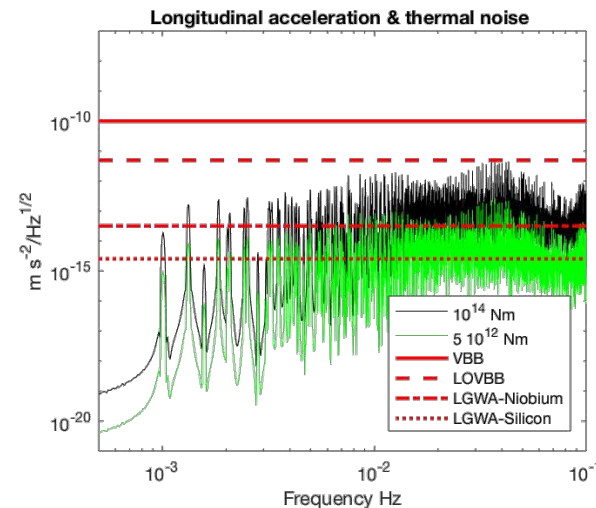
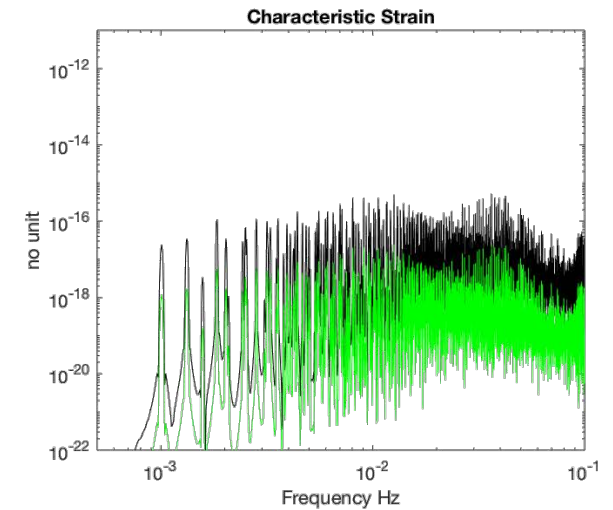
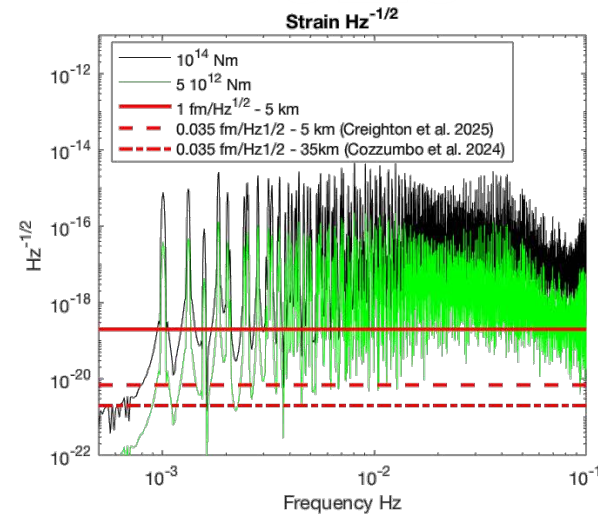
DMQ Hum versus Impact Hum

- By using the frequency magnitude law of DMQ and assuming it can be extrapolated below the minimum of Apollo (assume no locking asperity..), we can extrapolate **a DMQ Hum** made by the superposition of several DMQs occurring at different times below the resolution of Apollo
 - **This DMS Hum** might be a noise source compared to single DMQs (**Yearly**, **Monthly**, **Daily**)
 - We compare this to the **Impact seismic hum** reduced by 10.
 - Conclusion; Grey and purple are two possible contribution of the lunar seismic noise
- (Larger DMQ can likely be removed with template matching by 100 (conservative) to 500 when both the strain (for the template) and the seismic signal (for the time) are recorded jointly by a strain-meter and a seismometer.



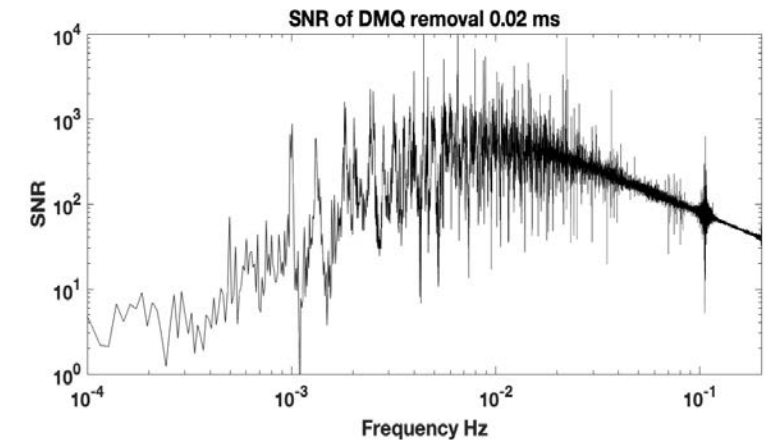
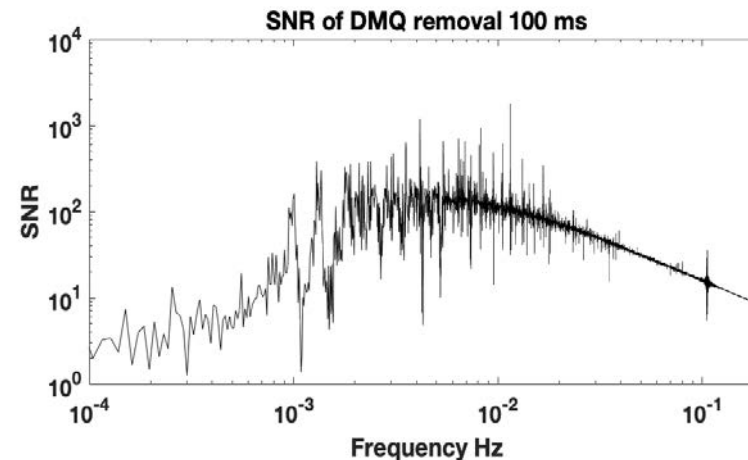
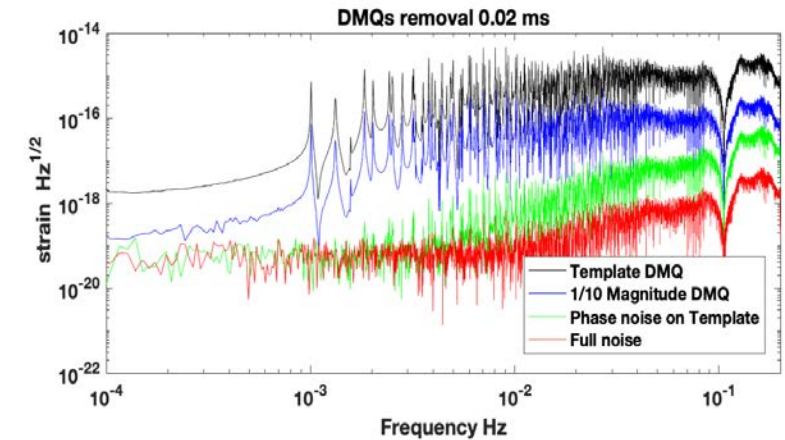
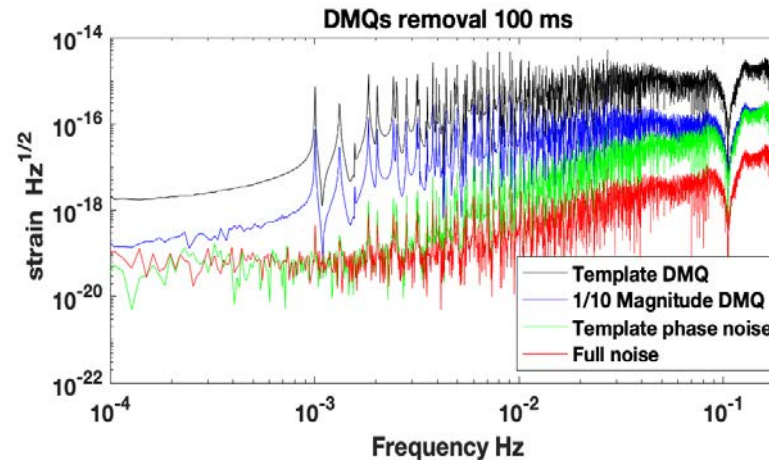
Seismic noise source #1: repeating DMQs

- Repeating DMQs will generate signals larger to much larger than the GW requirement
- We can expect for the daily DMQs burst of strain with amplitudes $\sim 10^{-18}$
- This seismic background can however be corrected with template matching techniques, assuming that:
 - (1) GW sensor do not saturate for the largest DMQs, which will provides the template
 - (2) The precise source time is known, which must request high sampling



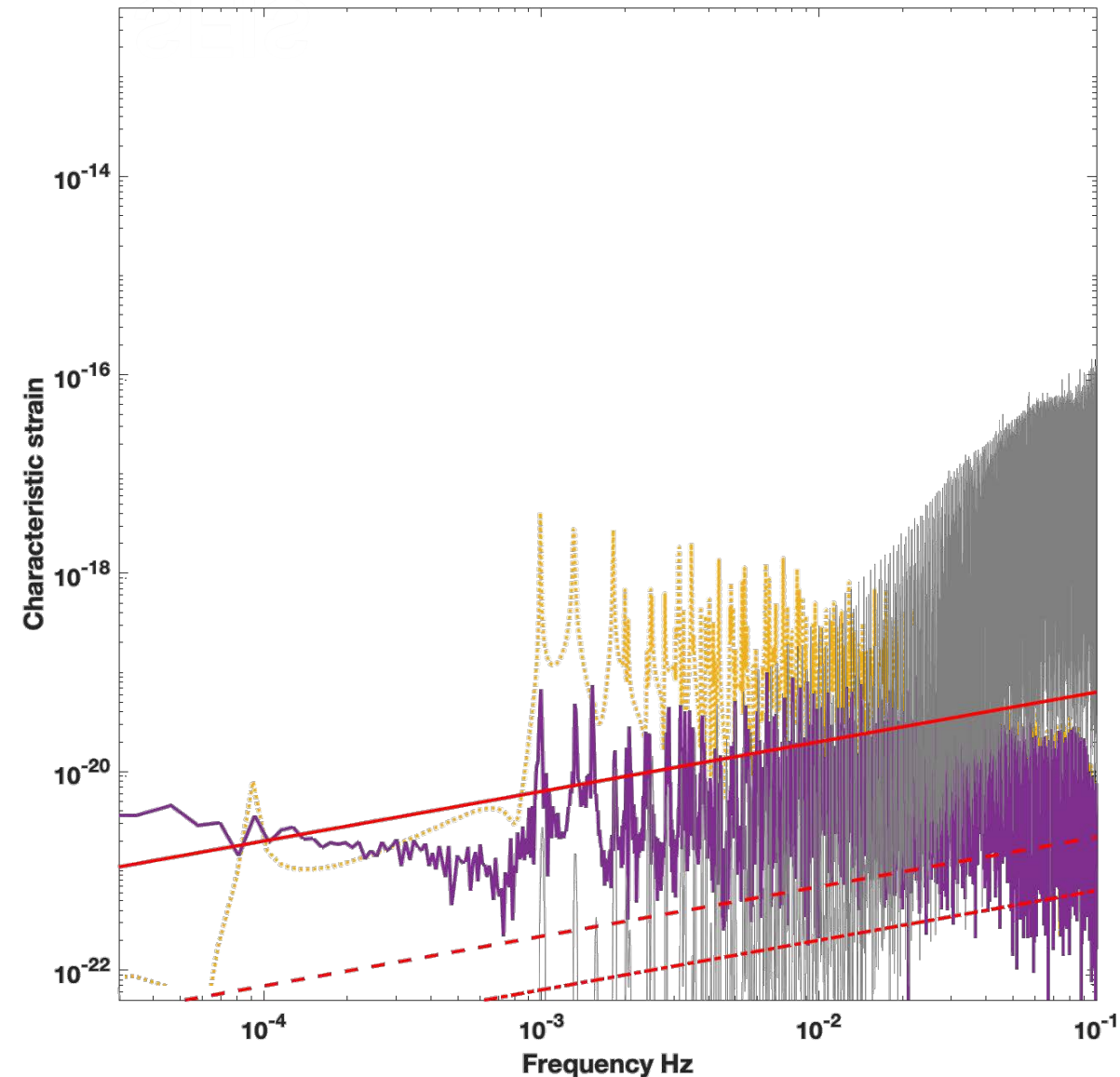
Seismic noise source #1: removing DMQs

- Typically, template removal will depend
 - (1) on the SNR of the largest DMQ of a given nest on the strainmeter, which will constrain the template fidelity
 - (2) on the timing of the source, which request the best high frequencies data, e.g. provided by a seismic sensor
 - (3) on the noise of the seismic sensor



My « best » estimate for seismic noise

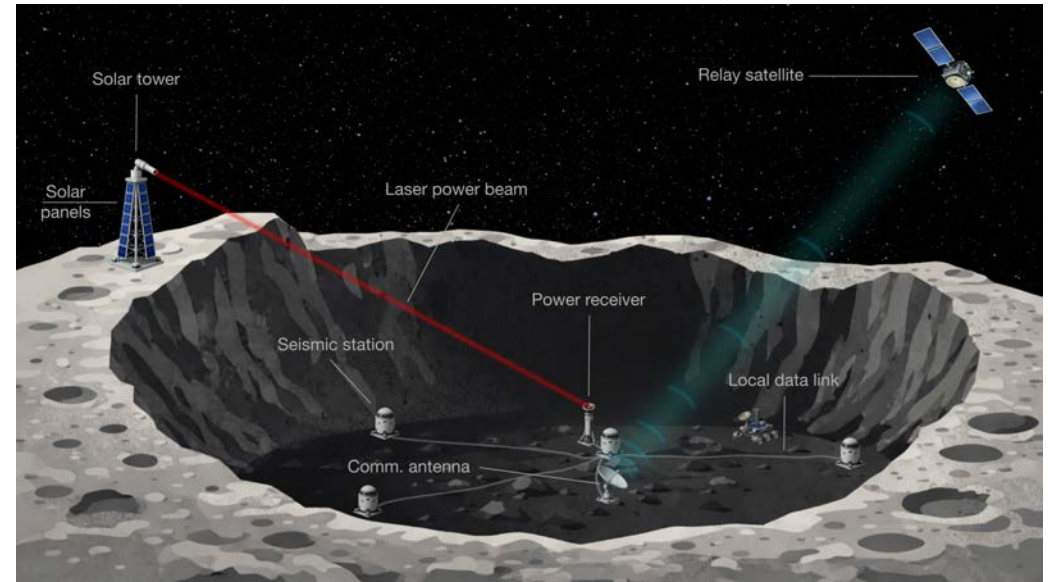
- Lunar seismic noise at long period is made by a **Hum from DMQ** and a **Hum from impacts**
- **Daily DMQs might be removed with template down to 40 db to their amplitude** . Larger DMQs might only be partially removed, leading to period with larger noise.
- **In the 0.1-10 mHz, this noise is comparable to a 1 fm/Hz^{1/2} – 5 km strainmeter requirement**
- All these estimations might be reduced significantly due to the intense scattering on the Moon
- This noise is compatible with the detection of Normal modes excited by DMQs, to a level compatible with splitting tomography of the deep lunar interior
- In the deci-Hertz (> 0.1 Hz) how to proceed?



Moon GW detector : how to detect....

Ongoing project LGWA (PI Jan Harms). =>

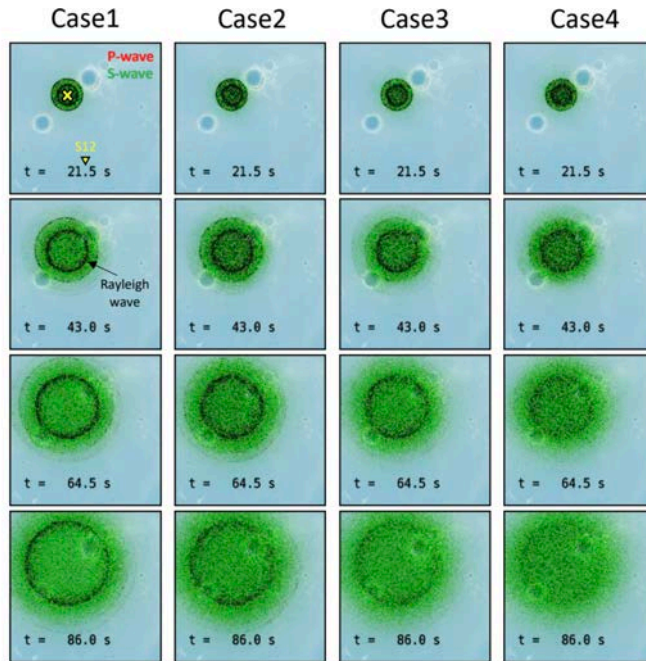
- 3 very sensitive horizontal seismic stations in a permanently shadowed crater
- will use more stable temperature but will request either transmission of power or nuclear power
- the natural seismic noise of the Moon must be removed from the GW signal by the network signal processing
- precursor project: sound-check



<= Future project LILA (PI Karan Jani)

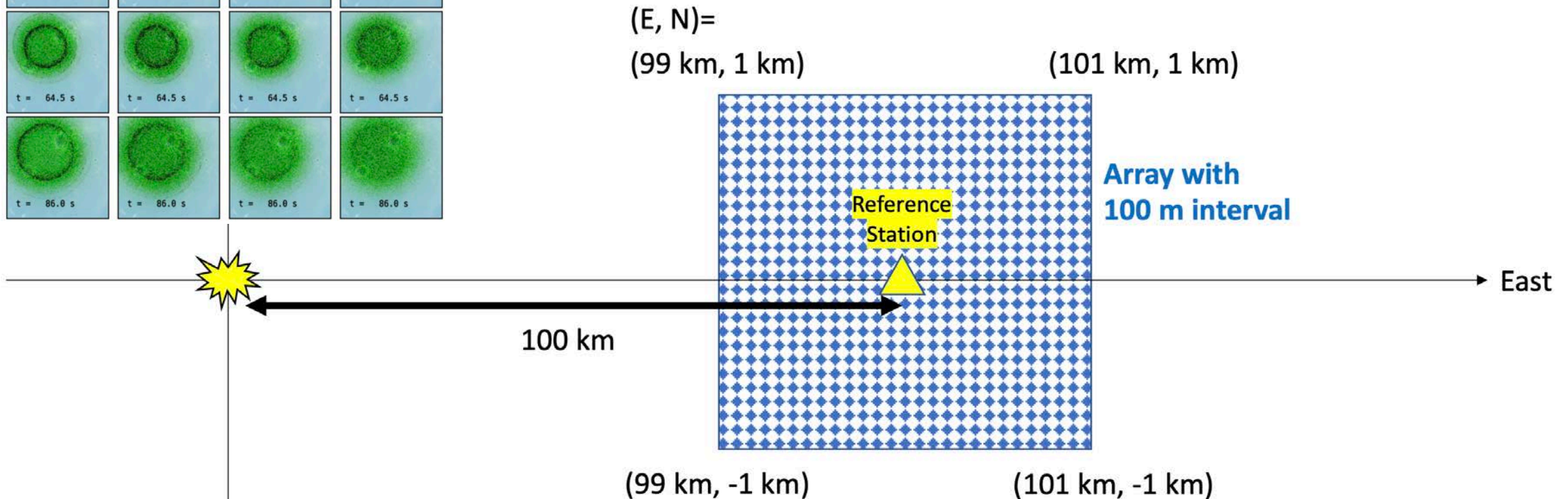
3 very sensitive strainmeter nodes on the rim of a large ~40 km crater

- can use solar panels but might be in an environment with more temperature variations
- the natural seismic noise of the Moon must be removed from the GW signal seismic attenuators and seismic decorrelation
- precursor project: iLILA



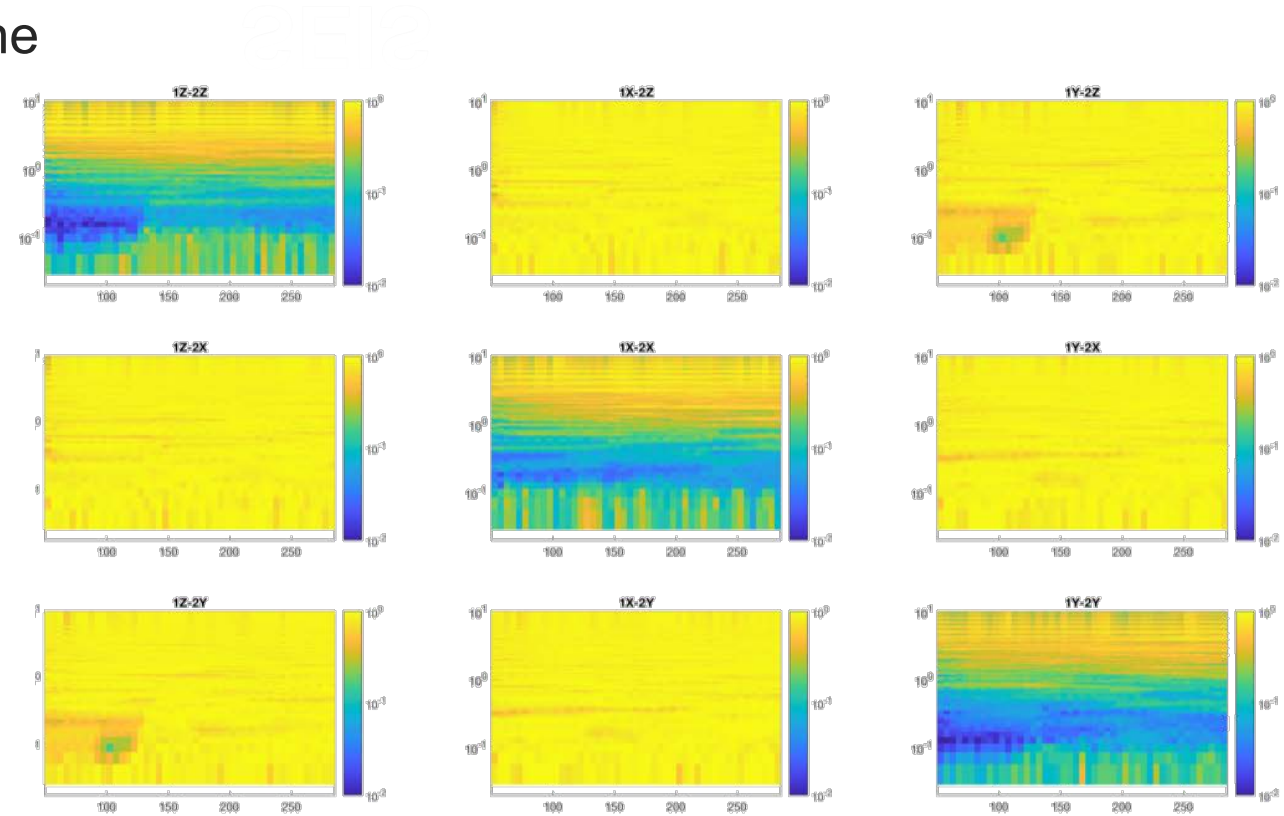
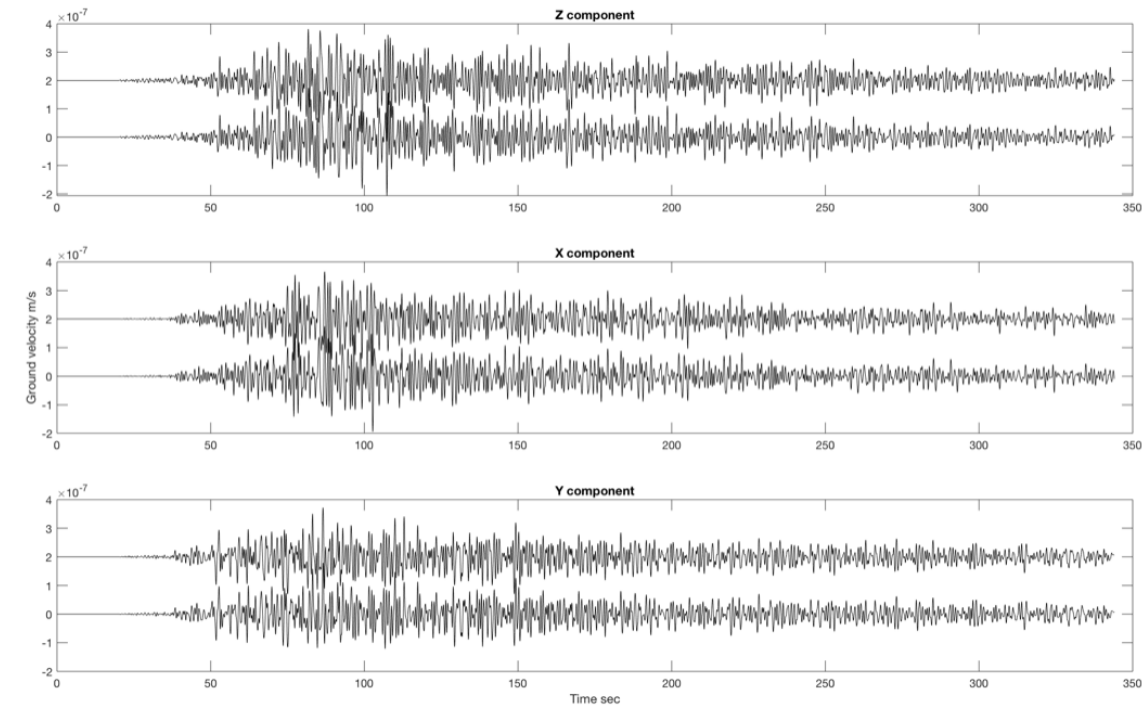
In contrary to the Earth, the seismic waves on the Moon are known to be in a strong diffusive regime .

Question: Can we use close stations for removing any coherent seismic noise on the Moon ?



Noise cancellation in the deciHerz

- We take 2 stations 100 m aways and compute the coherency between
- Numerical tests suggest a very low efficient, of about 20 db when we are in the coda of the seismic waves



The color contour shows the relative amount of non coherent signal in the figure ($\sqrt{1 - \gamma^2}$). We loose quickly the coherency in the signal between 2 stations.

Noise cancellation above 1 Hz

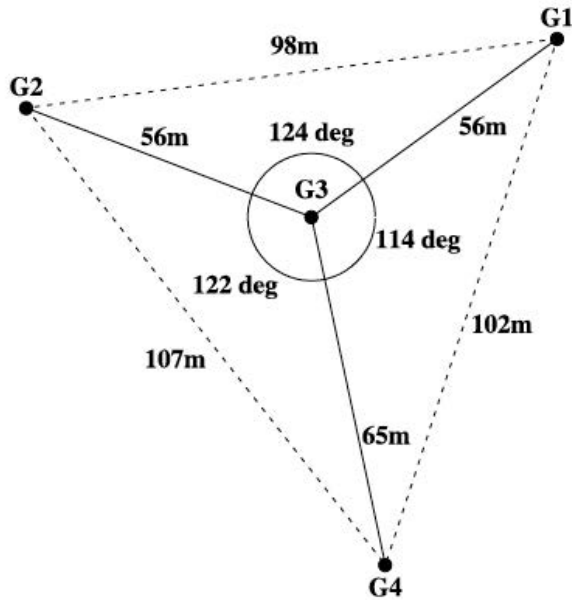


Figure 1. Geometry of the Apollo 17 LSPE geophone array.

- Noise correlation studied by Tanimoto (2008) between 4-10 Hz
- Correlation is lost after ~100 m
- Stations must be very close to achieve deci-hertz and can likely achieve only a poor seismic noise decorrelation
- This suggests that a damping + decorrelation with co-located sensor might be more efficient, as soon as the damping is better than 20-40 db.

98 m

65 m

102 m

65 m

107 m

65 m

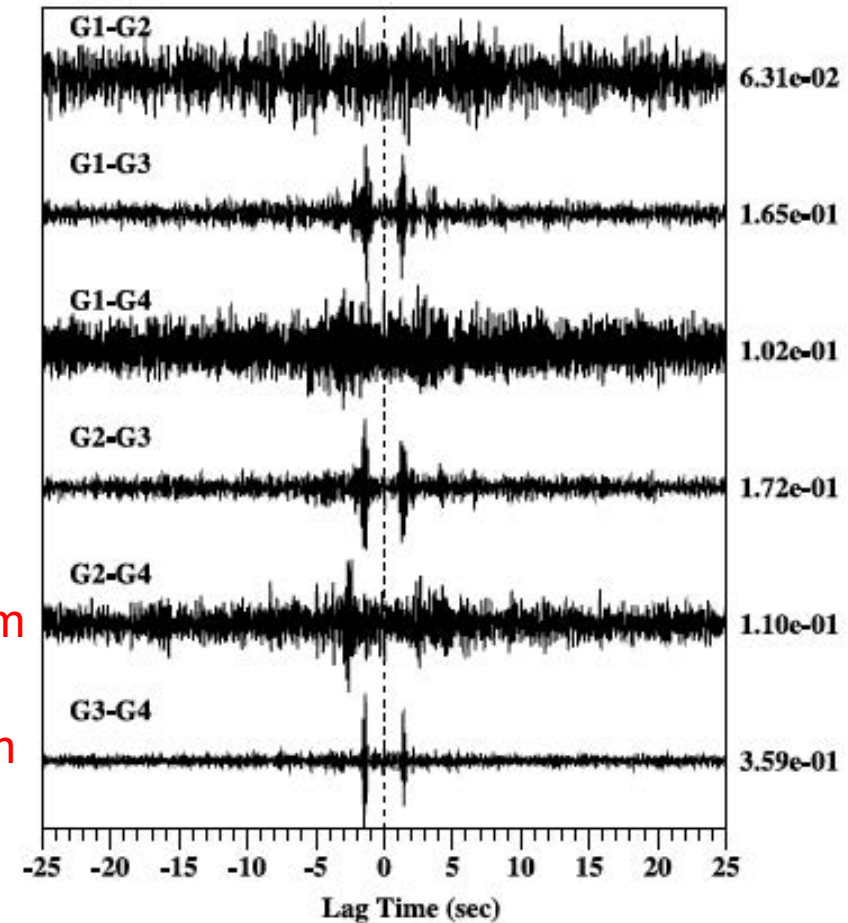


Figure 2. All six pairs of correlograms from the first day, 15 August 1976. The pairs that involve G3 show good SNR. Filter is flat between 4 and 10 Hz and tapered at both ends by cosine functions (1–4 and 10–13 Hz).

- This suggests that a damping + decorrelation with co-located sensor might be more efficient, as soon as the damping is better than 20-40 db.

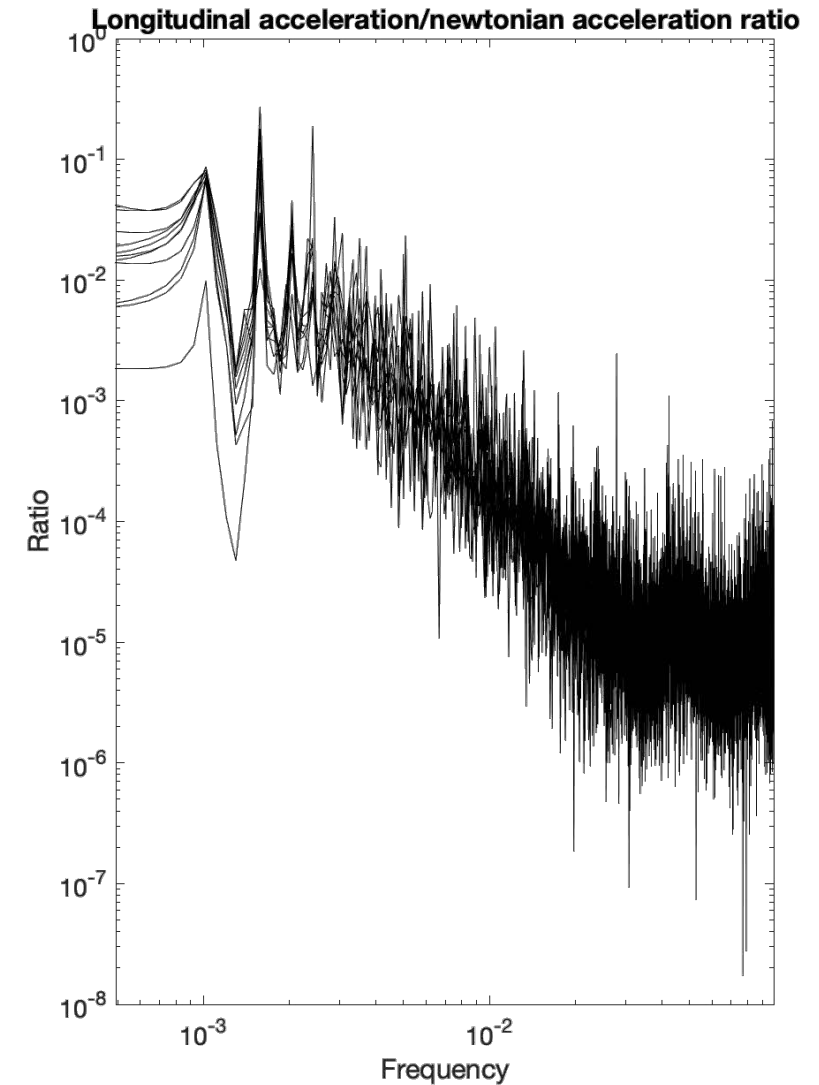
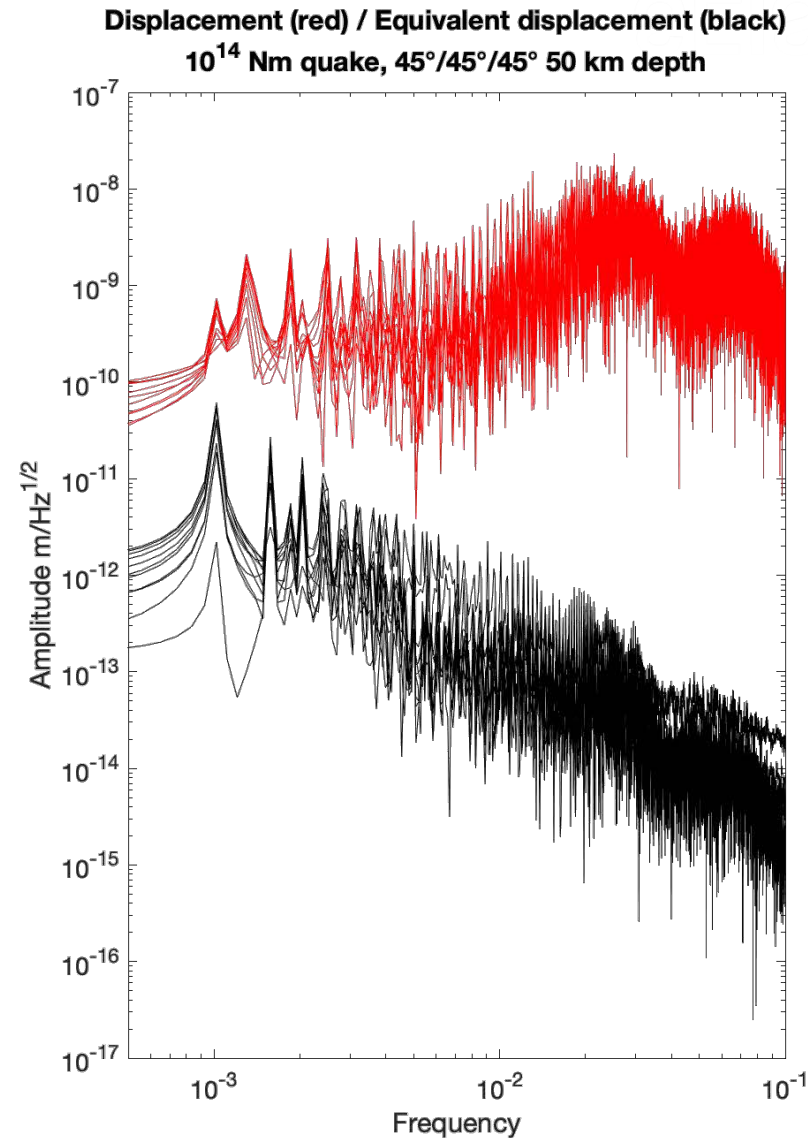


LILA Noise cancellation above 1 Hz

- LILA strategy is using several attenuation in series
 - LILA will have an attenuator like virgo with a few stages
 - The seismic noise from the measurement direction will be attenuated by A_{xx}
 - LILA has two strain measurement, one between the nodes/ground and one on free fall mirrors (the GW cavity)
 - The ground strain will be used to remove the attenuated coherent noise in the GW strain data
 - LILA baseline also additionnal Optical VBB sensors on each nodes
 - These sensors will be used to remove the cross-axis noises (noise from direction perpendicular to the GW strain direction) plus noise related to the difference of the attenuators
- Target is to attenuate all these seismic noise down to the level of the newtonian noise of seismic waves

Newtonian noise on the Moon

- Newtonian noise from synthetics
- $10^{-4}/10^{-5}$ of the seismic noise level at 0.1 Hz



Preliminary performances

