


The Seismic Environment of the Moon: Geophysical Goals and Noise Challenges with Gravitational Waves

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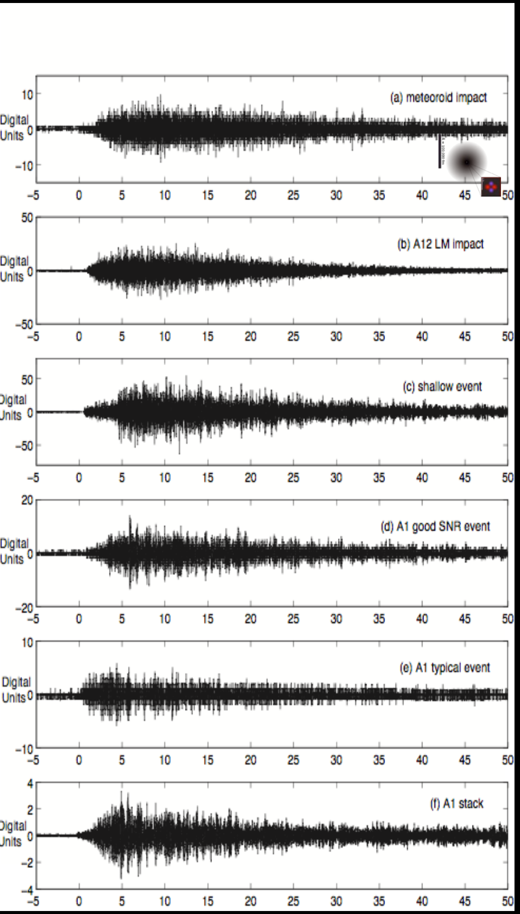
Outline of the presentation

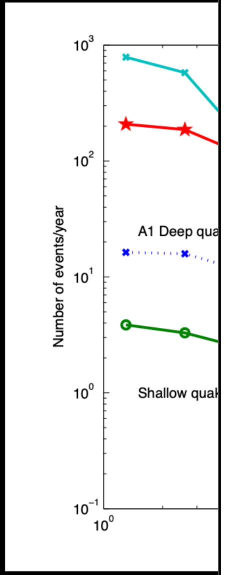
- What we know after the Apollo seismic experiment ?
- What we do not know after the Apollo seismic experiment ?
  - Focus on the lunar seismic noise and seismic signals
- Selected Near future missions compared to Apollo
- What will NOT be made by near future mission and associated goals
- Noise challenge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

Apollo network achievements



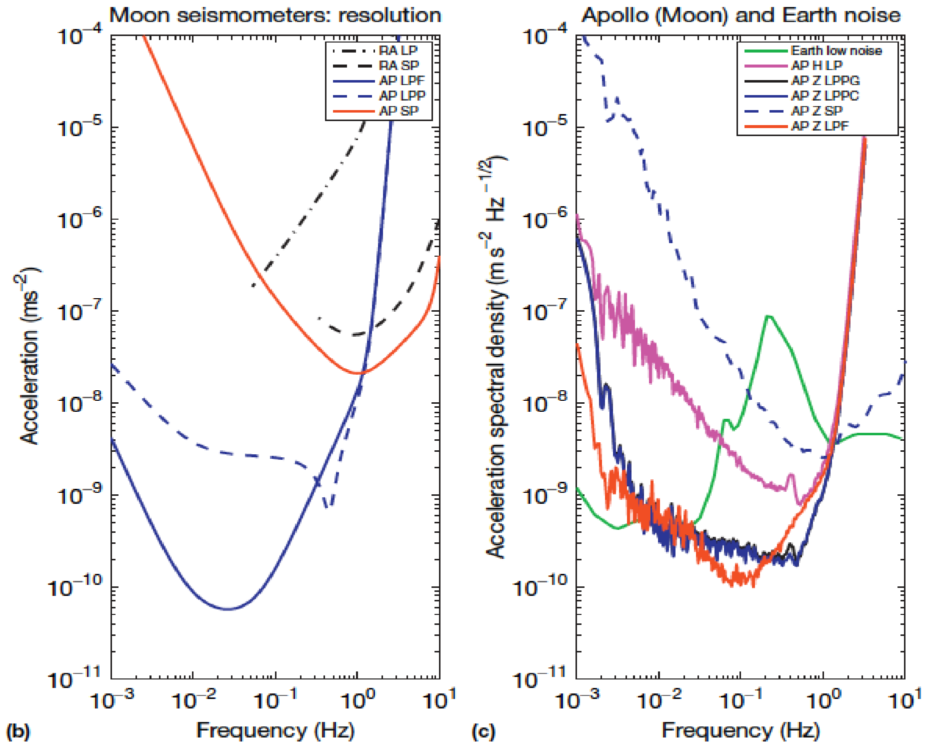
He atome

- **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 nominaly



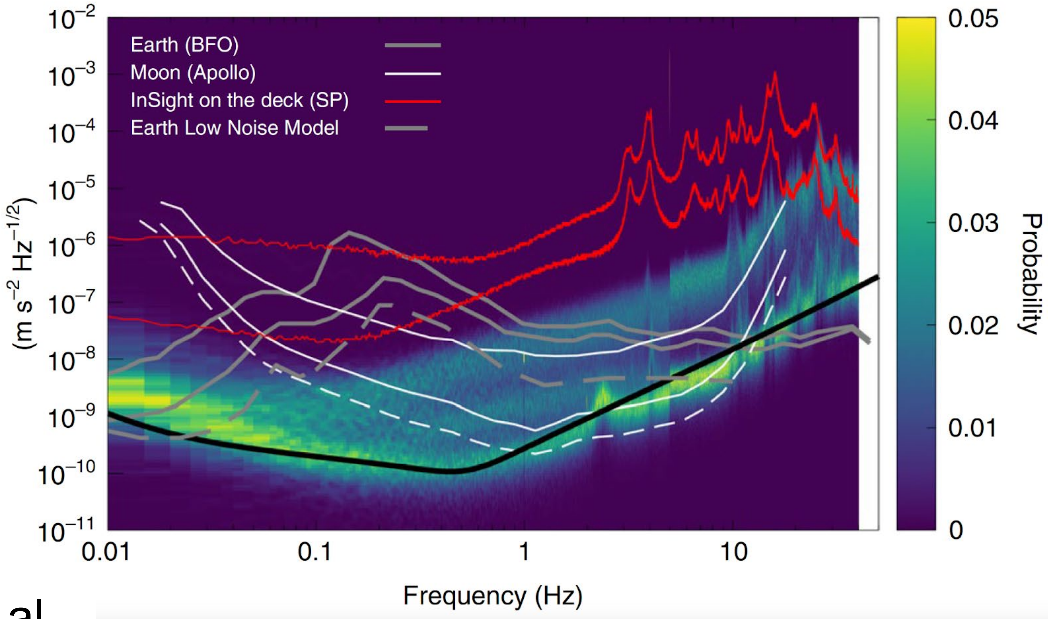
Lognonné & Johnson, 2007, 2015

What Apollo did not: seismic noise

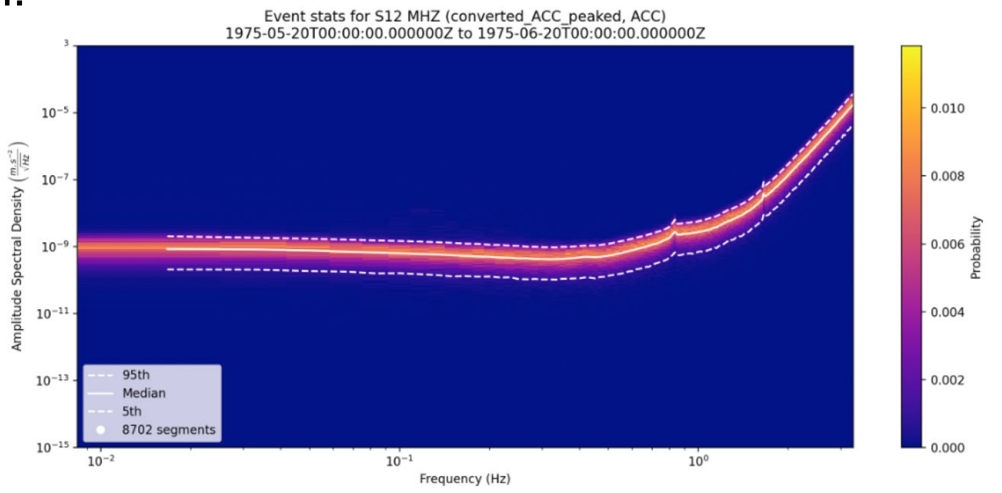


Lognonné & Johnson, 2015

Lognonné et al. 2020 (Mars)



Kawamura et al. 2025 (Moon)

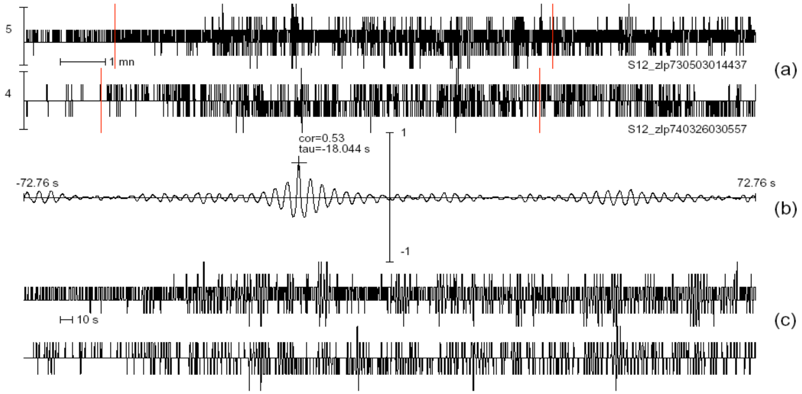


;ure 5 – Comparison of noise statistics before (a) and after (b) corrected by the transfer function, tak
2 MHZ as an example.

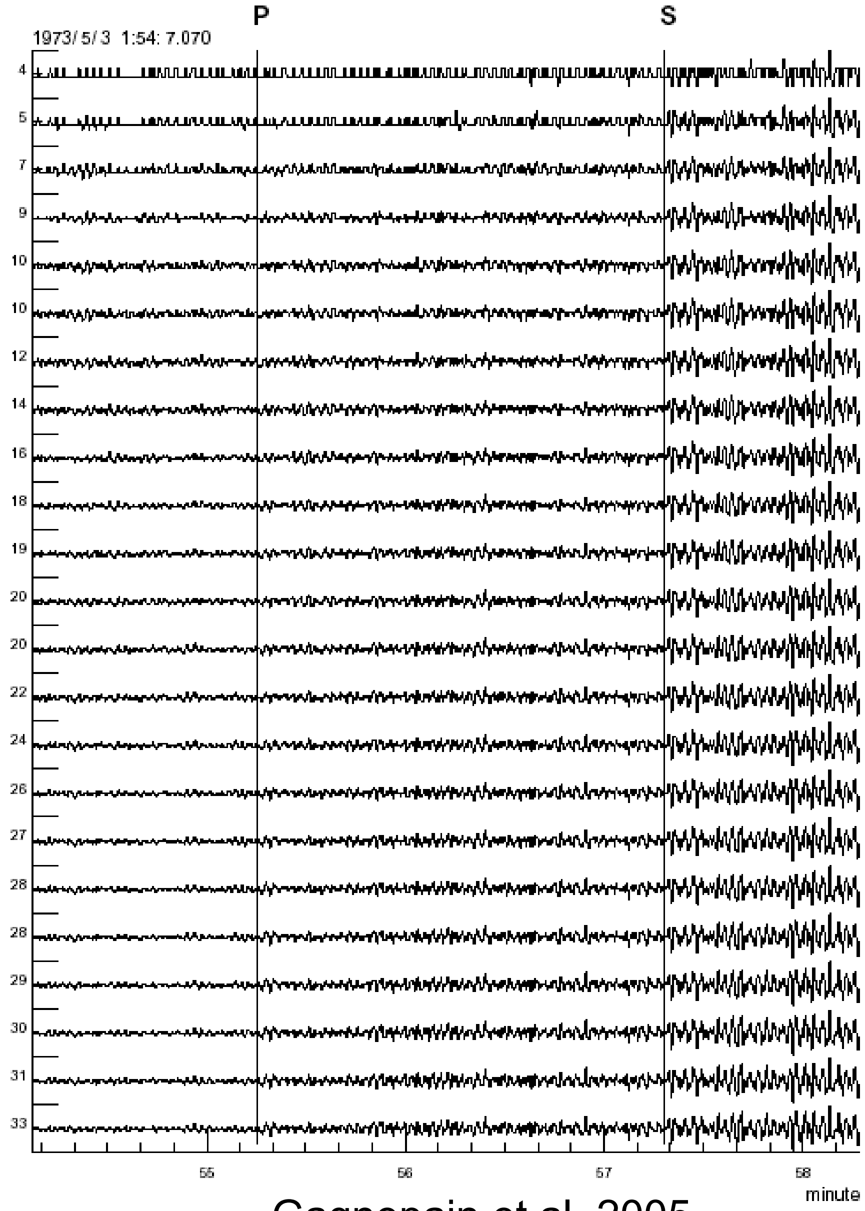
- The Apollo seismometer noise, when no quakes, is extremely stable and is just the sensor self noise
- Horizontal component likely see tilt noise
- Apollo did not constrained any lunar seismic noise apart the thermal moonquakes and instruments artefacts (glitches, spikes, etc).

What Apollo did : Discovering the DMQs nest

- example of two quakes (in 1973 and in 1974) from the same deep focus and their cross-correlation
- cross-correlation provides the time shift necessary to align the arrival times

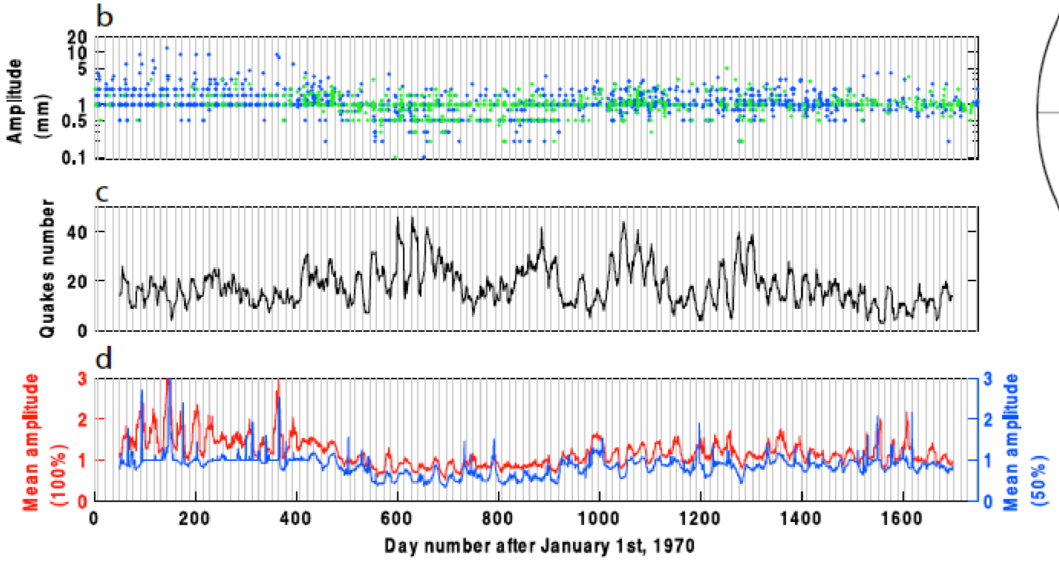


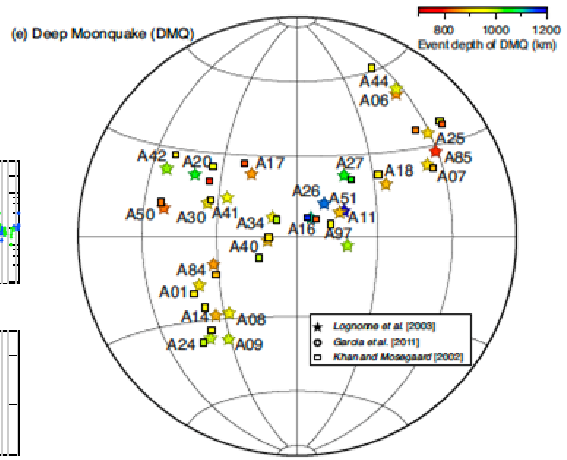
Stack of one DMQ nest



Gagnepain et al. 2005

Activity of one DMQ nest (Lognonné & Johnson 2015)

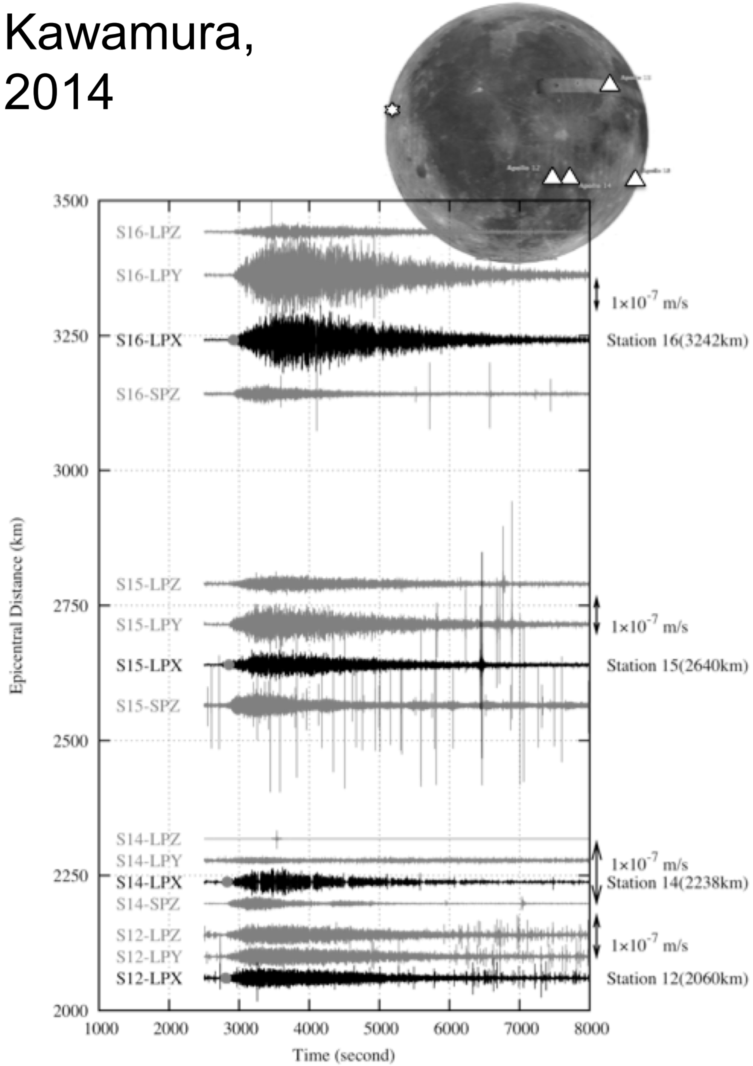




Location of the DMQ nests (Garcia et al. 2019)

Impacts by Apollo

Lognonné and Kawamura, 2014



- About 1700 impacts detected by the network and signals last for hours
- detection rate are about 100 impacts /year on the LP instrument down to resolution of about 1 Apollo DU. These rates are those predicted from Earth-Moon impact rates (Brown et al., 2022, Lognonné et al. 2009)
- Some of the rare natural impacts were very large (m > 10t)
- Only artificial impacts have been associated to crater and have known position
- A lot of science analysis can today be made with 1 Apollo DU unit…

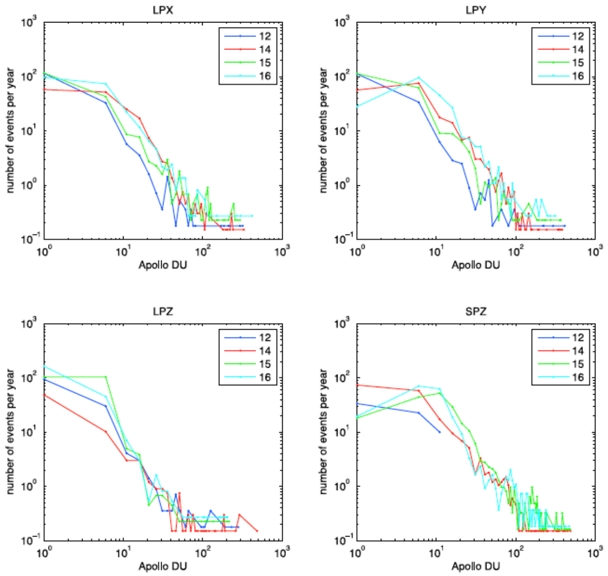


Figure 2. Number of impacts per year in peaked response mode with a given peak-to-peak amplitude (in Apollo DU) on the LP channels of all four stations. The SP statistics are shown for comparison; note that the SP component of station 12 failed early into the experiment.

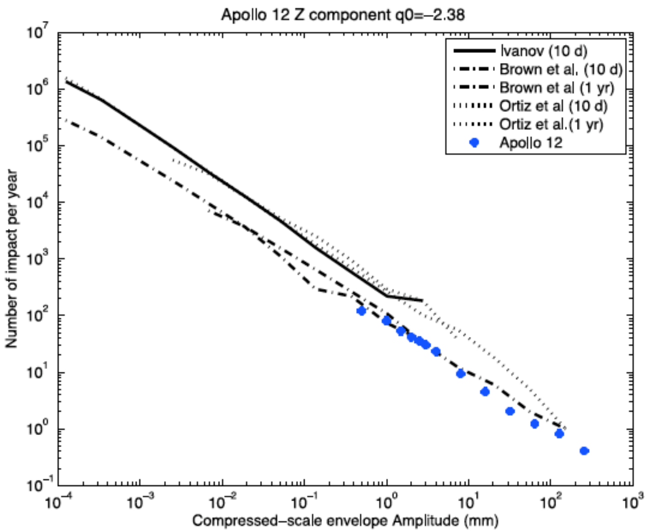
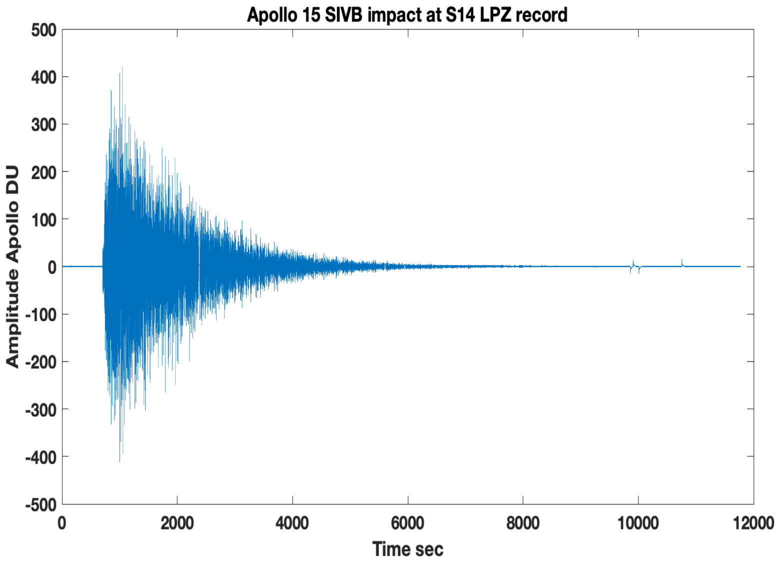


Figure 16. Number of impacts per year with a given amplitude modeled at station 12 using impact statistics derived from the Ivanov (solid line), Ortiz (dotted line), and Brown (dashed-dotted line) models. For comparison with the Apollo catalog information (circles), we report the compressed-scale envelope 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.

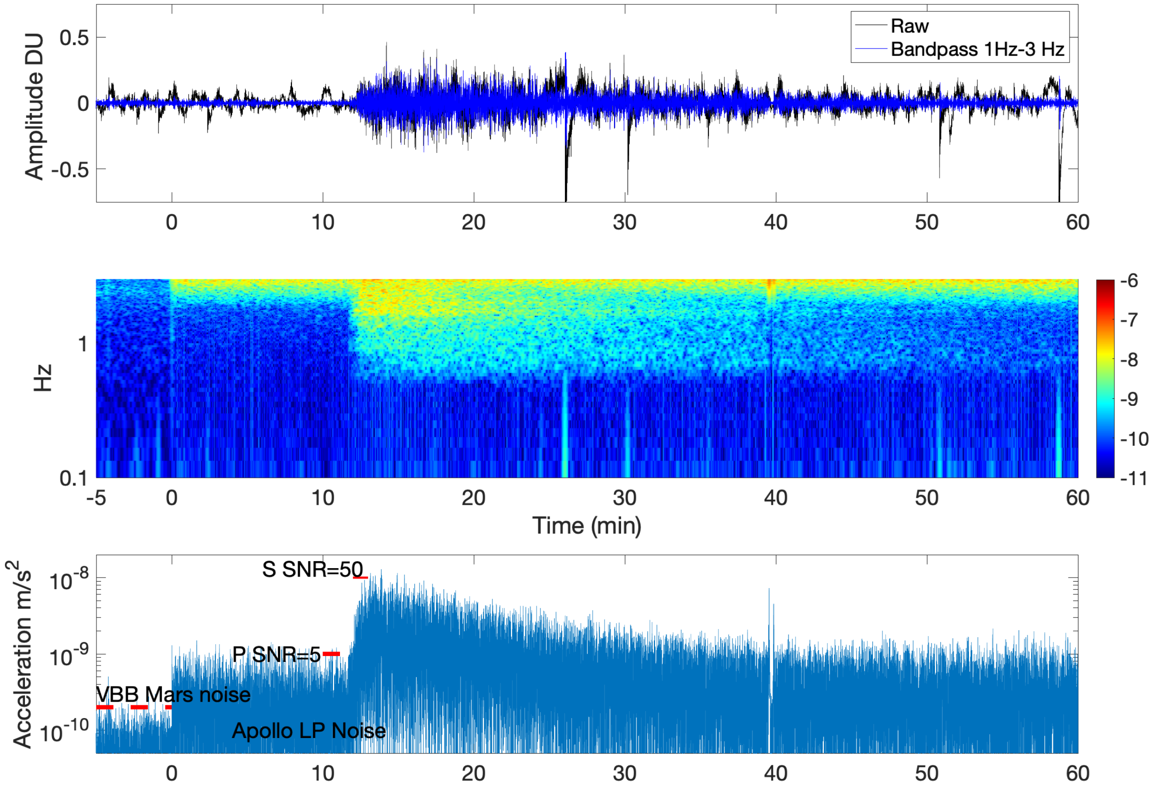
Lognonné et al, 2009

Impacts with modern seismometers

Apollo Record

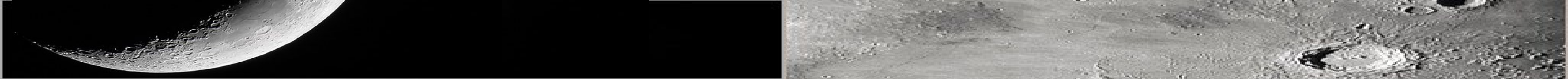


Modern Record (with InSight VBB noise)



- One of the best recorded impact (SIVB Impact) at 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
  - Correct the cutoff (1.5 Hz for SIVB, 6.2 Hz for the 1 kg impact) assuming an ω^3 source model

- The VBBZ self noise on CP12/FSS is 2 times smaller
- Roughly, the 1 DU impacts of Apollo will provide SNR ~10 for P and SNR ~100 for the S.



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- What we do not know after the Apollo seismic experiment ?
  - Focus on the lunar seismic noise
- Selected Near future missions compared to Apollo
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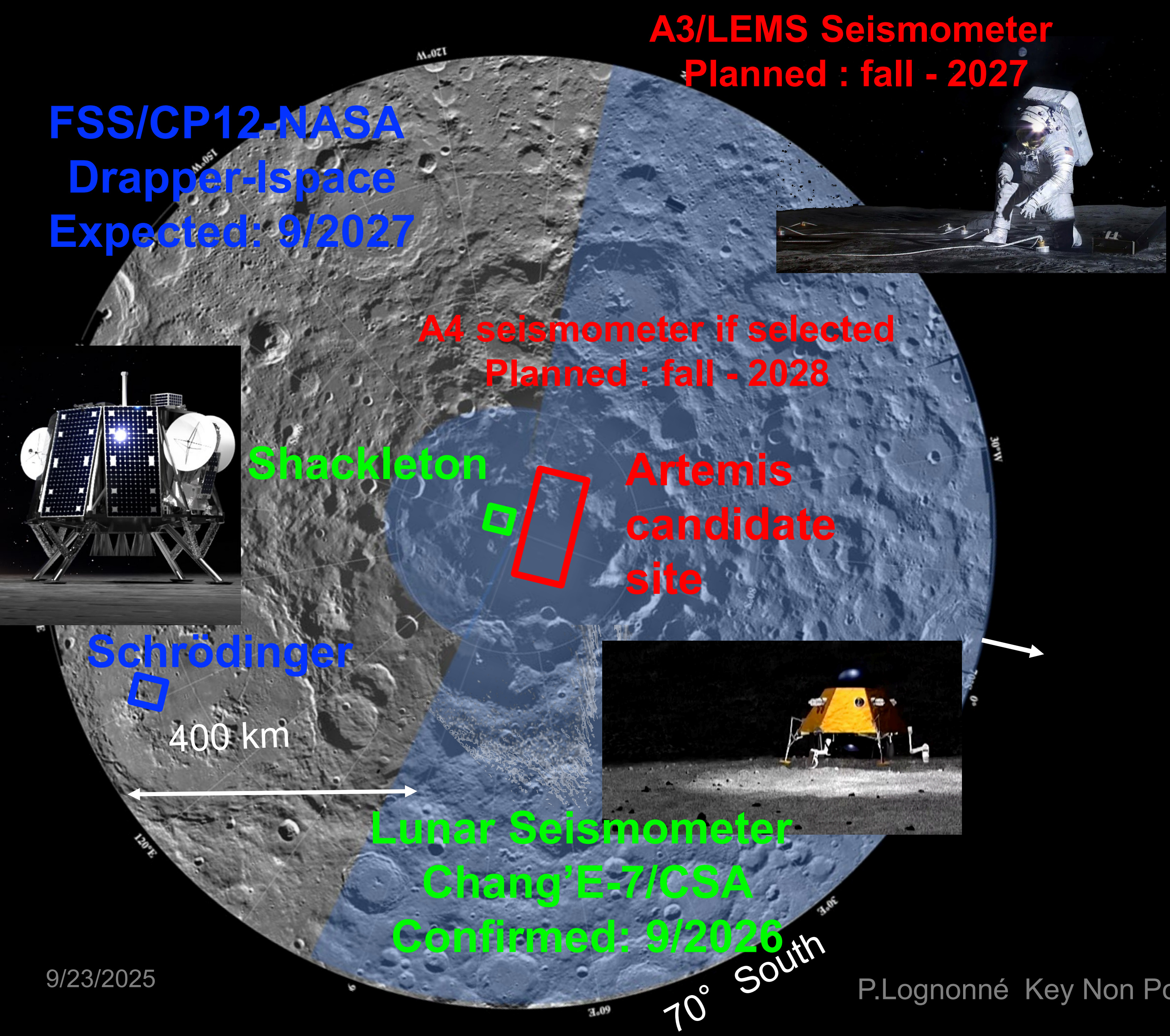
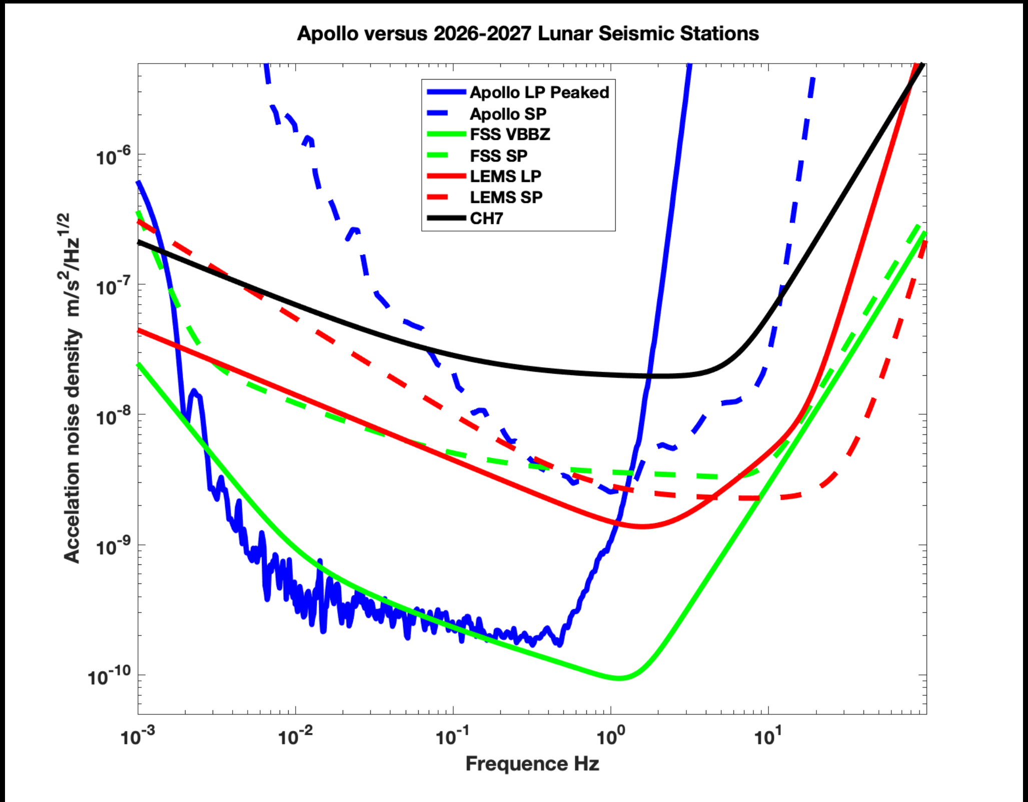
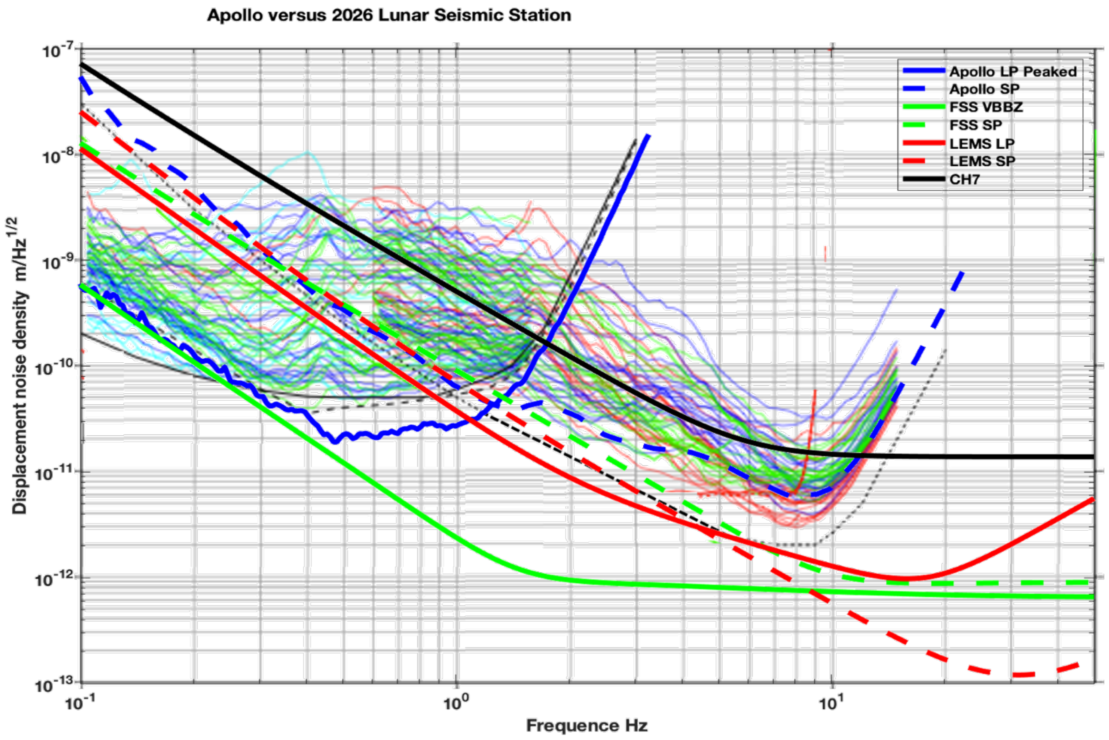
- Noise challenge for very long period seismology
- Noise challenge for Gravitational waves

2026-2030: Return of seismology on the Moon

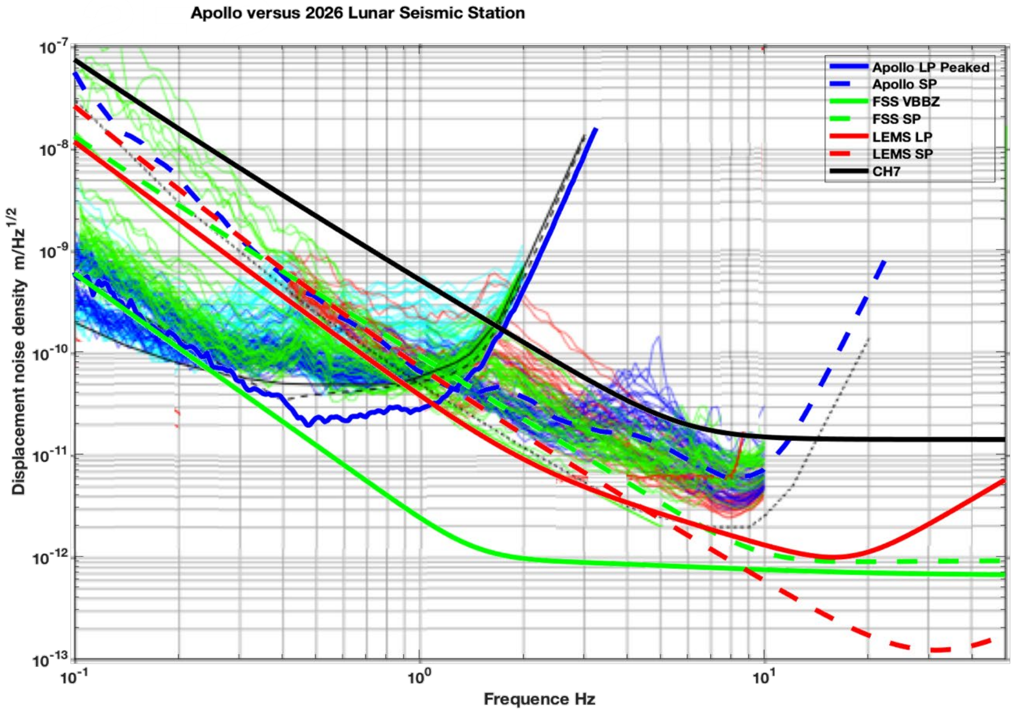




Expected detection improvement compared to Apollo

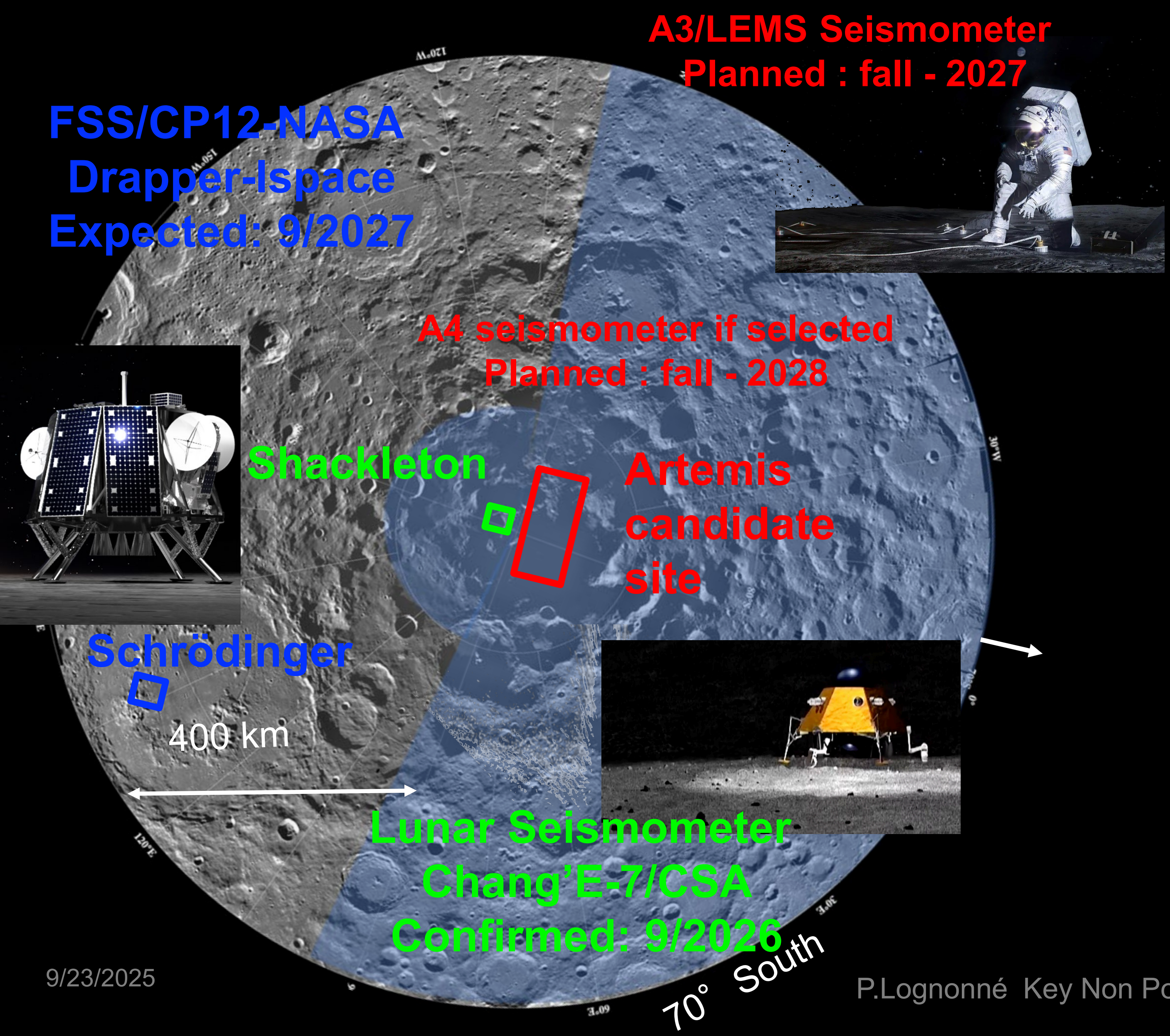


Apollo detected Impacts versus New seismometers performances



Apollo detected DMQs versus New seismometers performances

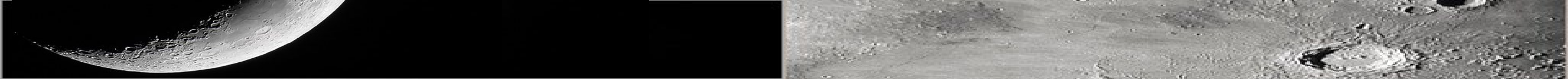
- Large improvement in the 0.3-10 Hz bandwidth with VBBZ/FSS
- Large improvement above 10 Hz with the LEMS-SP/A3
- LEMS-LP comparable to Apollo LP, CH7-LS comparable to Apollo SP (with much better acquision)
- No improvement at long period (< 0.1 Hz)



- ***Only one station with much better performance than Apollo above 0.1 Hz***
- ***None with better to much better performances below 0.1 Hz***
- ***No Network strategy but might generate a network***
- ***Will focus on the South polar areas, possibly South hemisphere and will miss global scale view***

ADDING STATIONS AWAY FROM SOUTH POLE IS A NEAR TERM PRIORITY

ANY FUTURE MISSION MUST PROVIDE A GLOBAL VIEW WITH CONSTRAIN ON 3D STRUCTURE AND BETTER SENSITIVITY



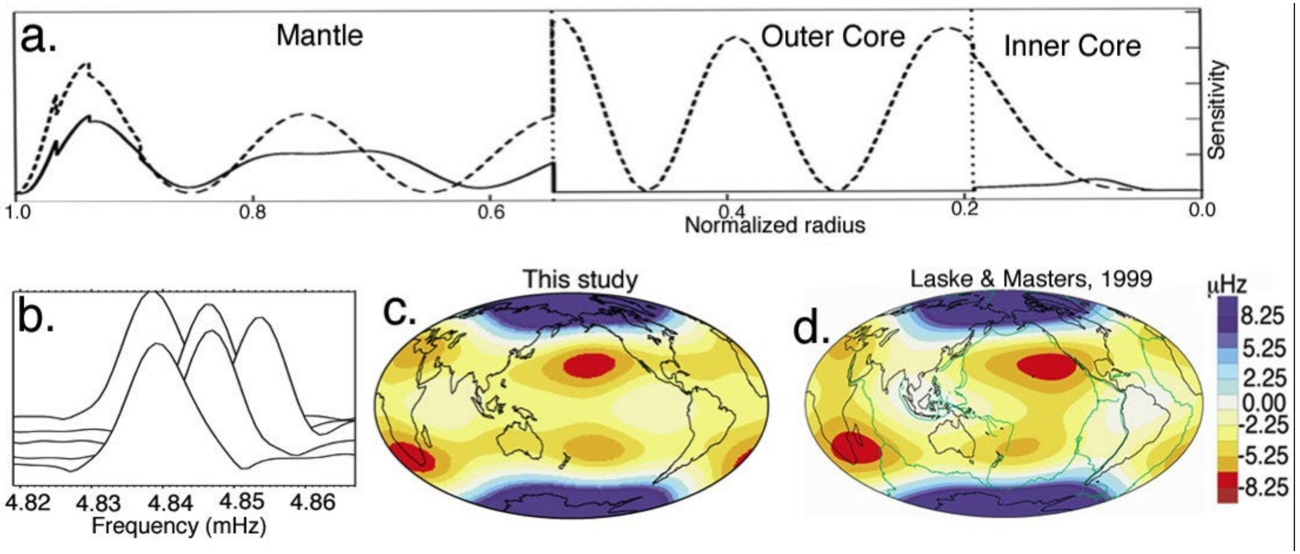
- What we know after the Apollo seismic experiment ?
- What we do not know after the Apollo seismic experiment ?
  - Focus on the lunar seismic noise
- Selected Near future missions compared to Apollo
- What will NOT be made by near future mission and associated goals
  - Global scale, requesting non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

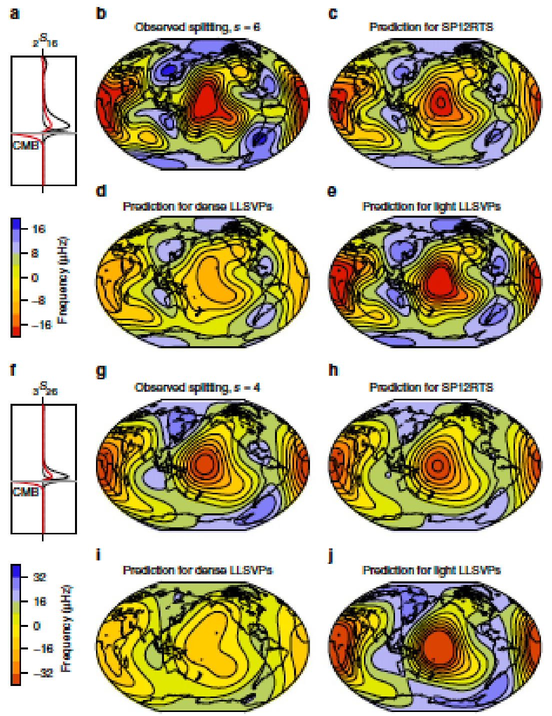
Why Normal modes?

- Normal modes exited 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)

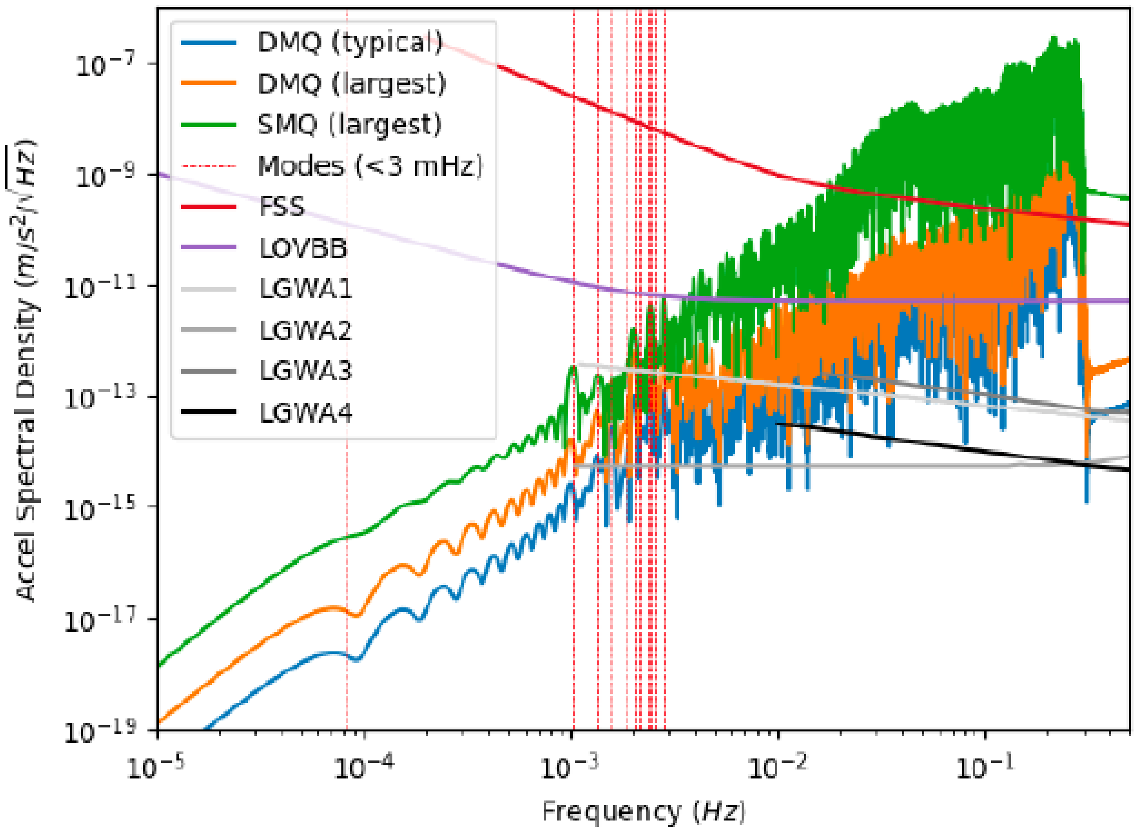
Koelemeijer et al. 2017

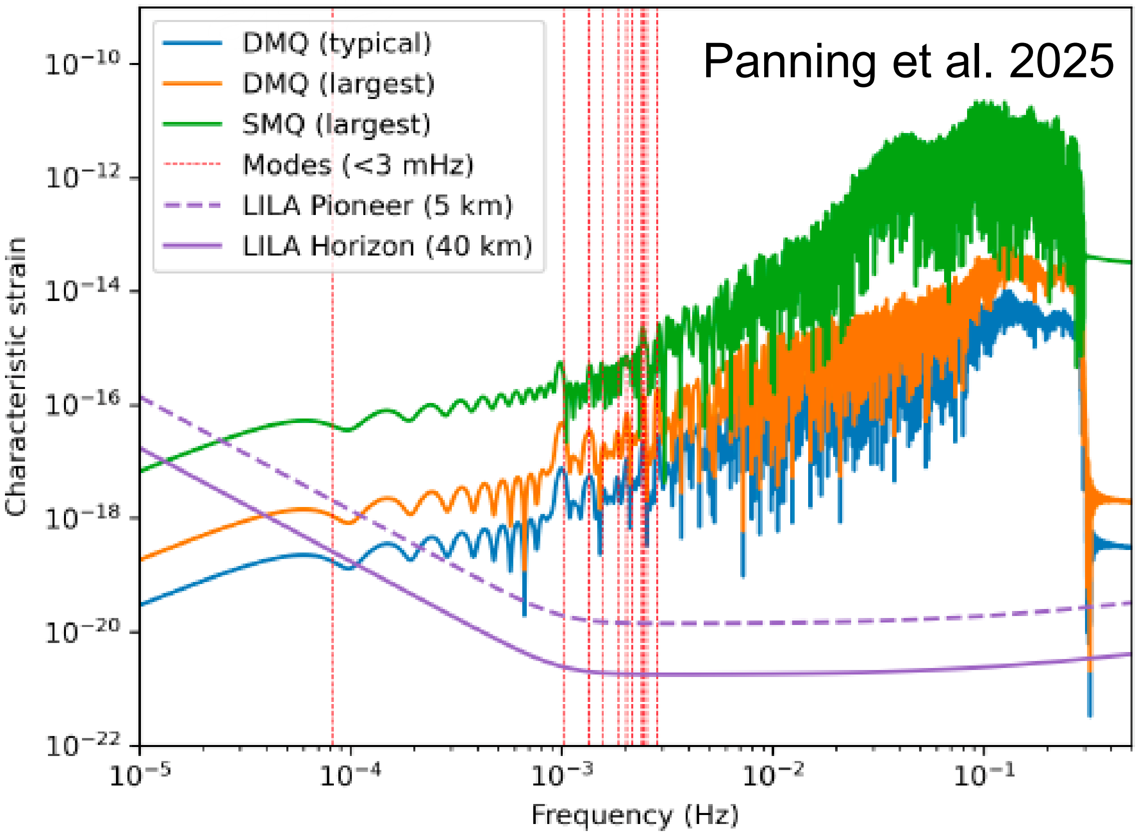
Courtesy Tkalčić et al. 2025



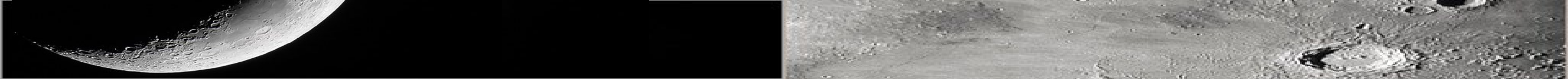


Normal modes on the Moon: instrument challenge





- 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 ${}_1S_1$



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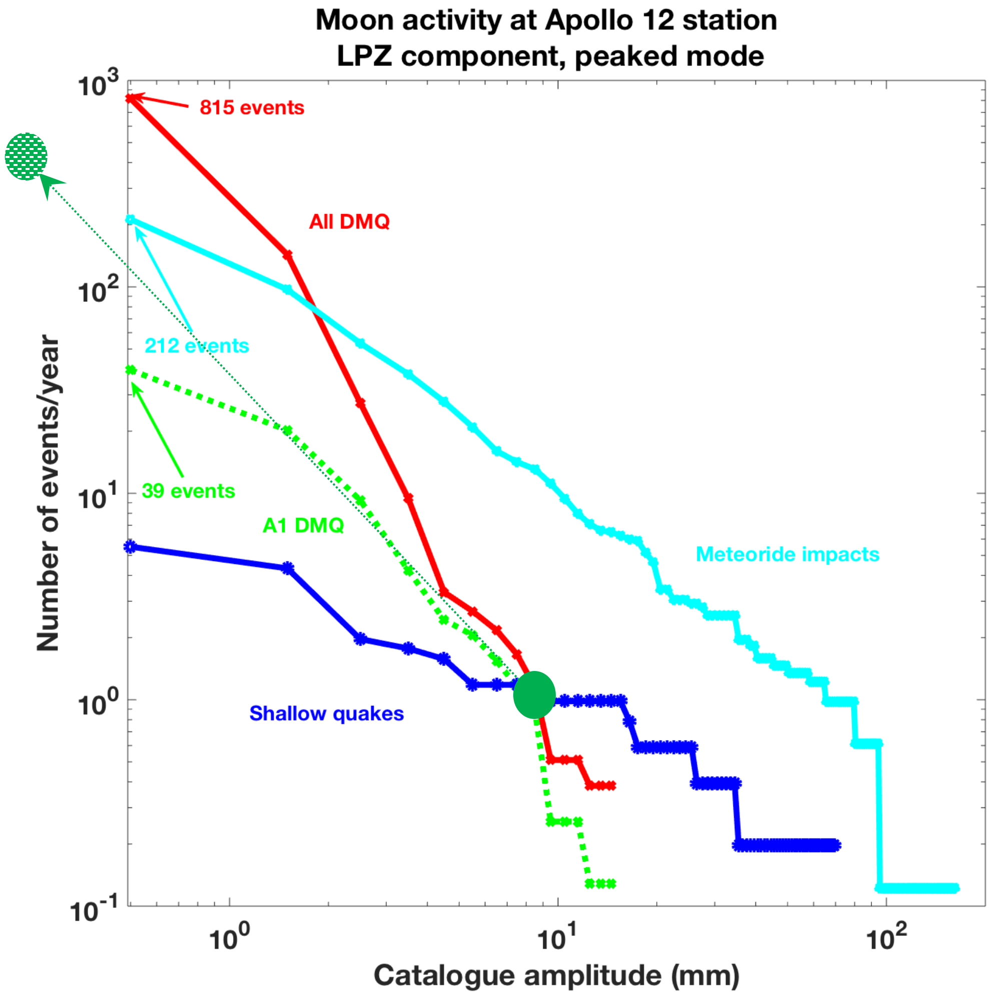
Normal modes on the Moon: targeting DMQs

Example

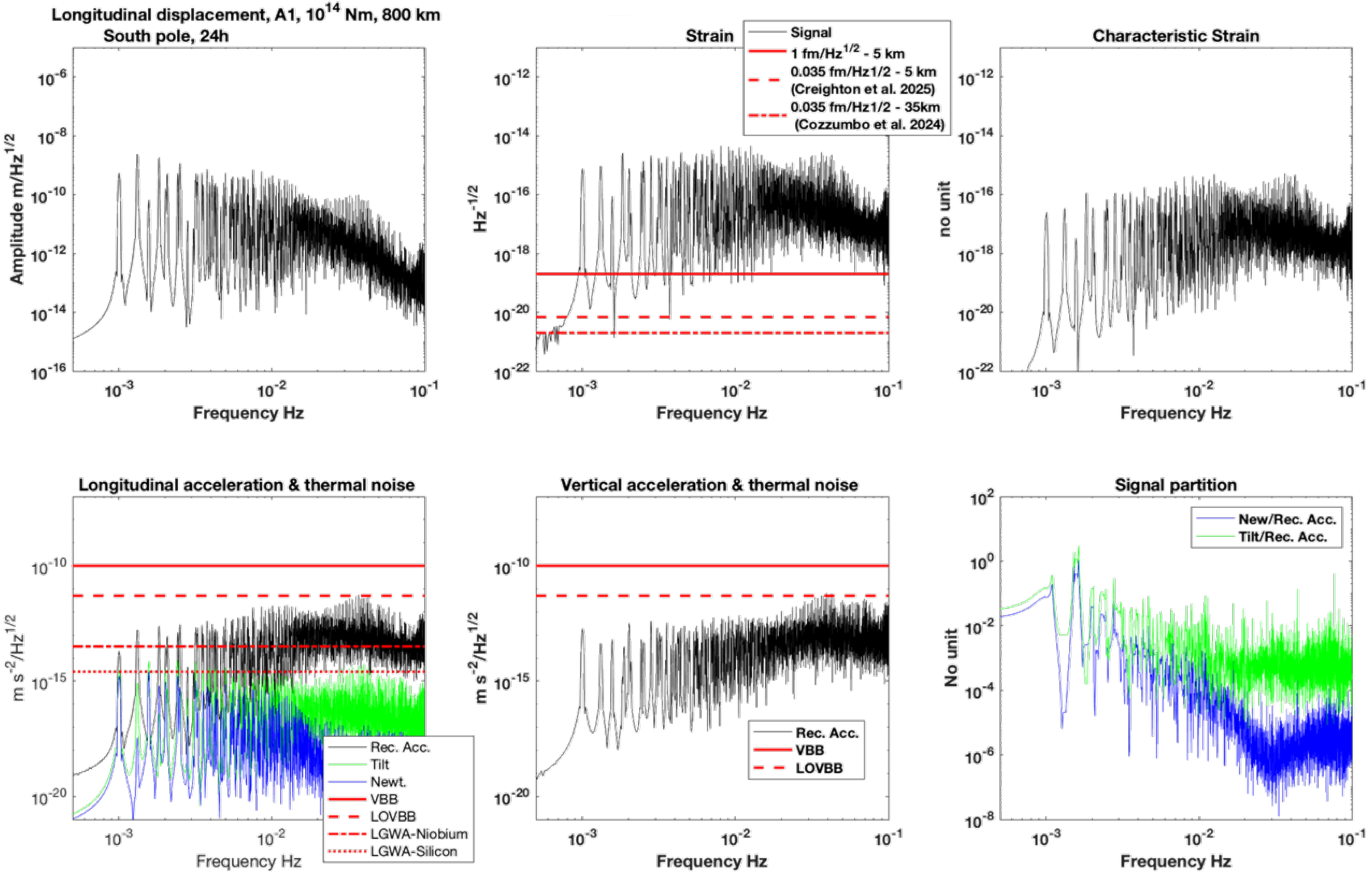
- A1: 29/10/1975
  - 6.8x10^{13} Nm (Kawamura et al. 2017)
  - 7.4x10^{13} Nm (Goins et al. 1981)
  - Largest A1 ~ 10^{14} Nm
  - Smallest A1 Apollo A1 ~ 5 10^{12} Nm
  - Daily if extrapolated ~ 2 10^{12} Nm



- Further Assumptions:
  - A1 detected at South Pole
  - 800 km depth
  - Strike/dip/rake mecanism
  - 45° /45° /45°

Normal modes on the Moon: Largest DMQs

- Source Challenges:
  - Several effects are expected to reduce the Normal modes signals
  - Focal mecanism
  - 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

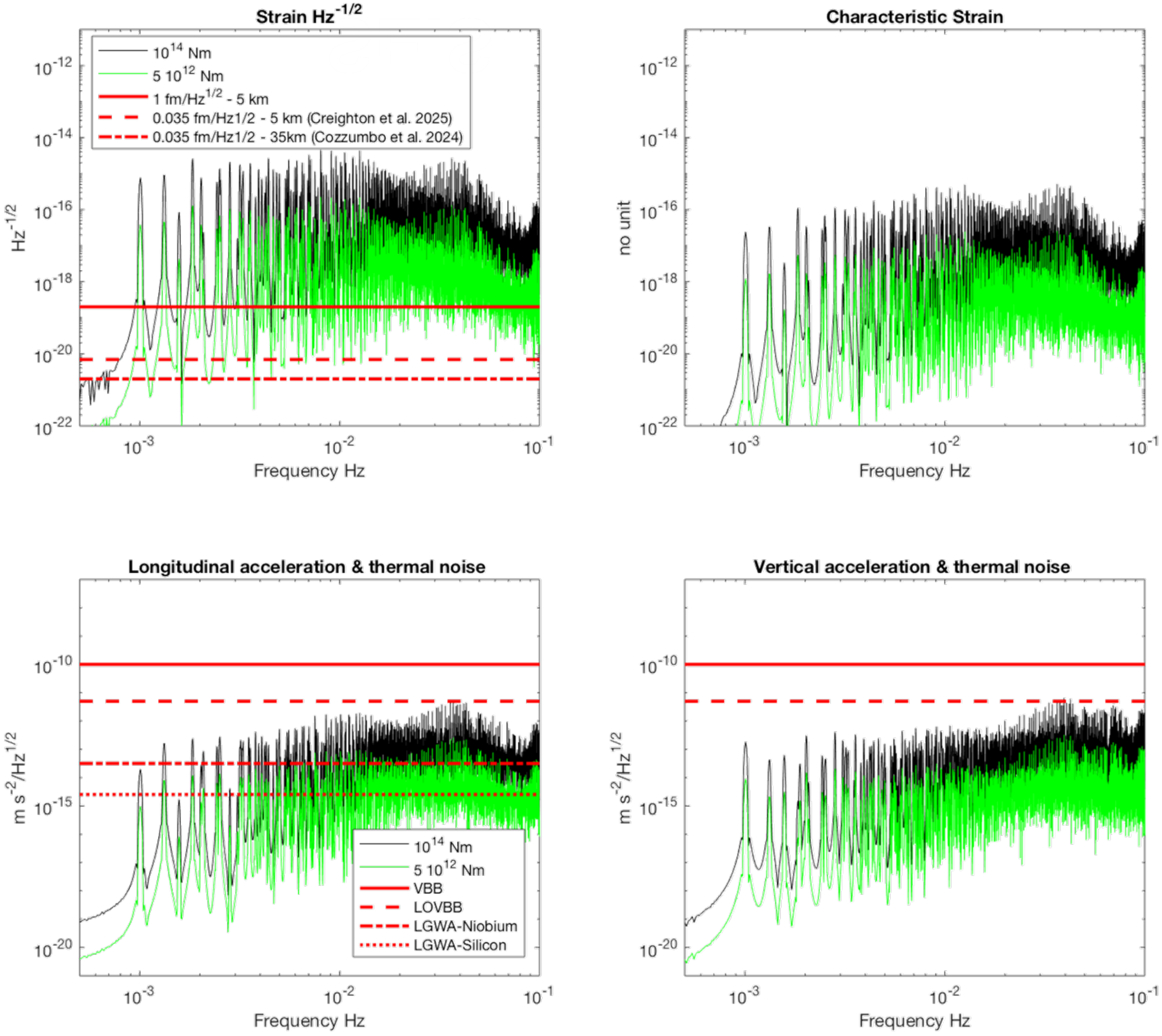


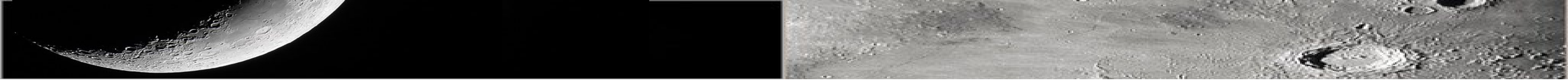
Normal modes on the Moon: small DMQs

- 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 10^{12} Nm

- Only strainmeters with better than 2 10^{-19} $Hz^{-1/2}$ sensitivity can achieve this goal
- Need a crater to minimize near surface dust effects and with the requested diameter for strainmeter arms





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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


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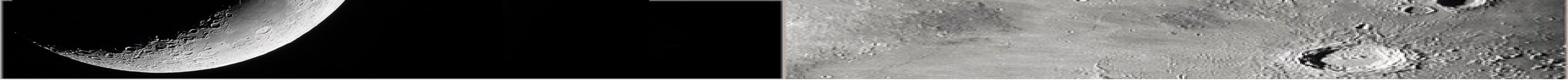
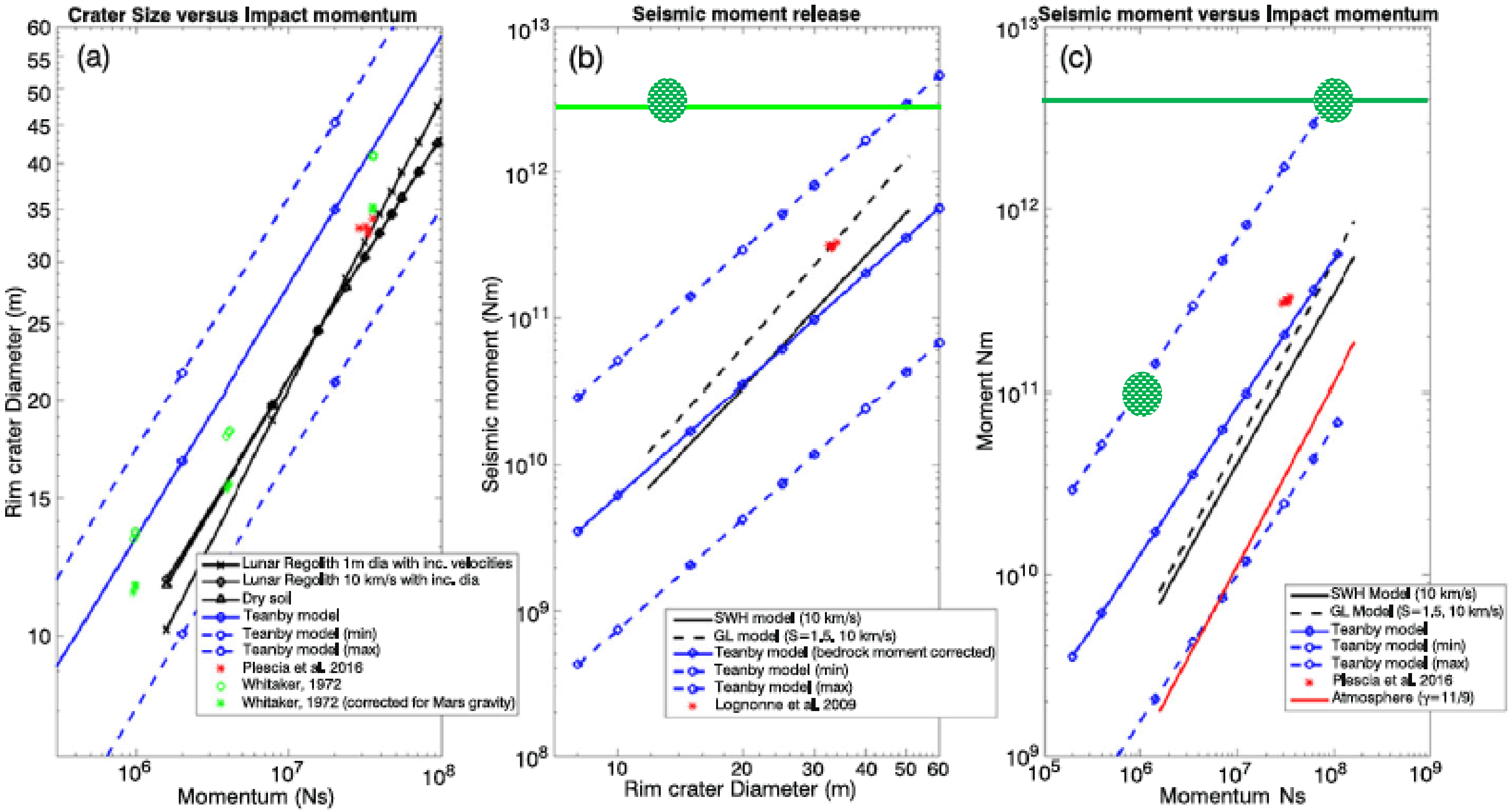
- Micro-seismic noise from meteorite hum (Lognonné et al. 2009)
- Micro-seismic noise from repeating DMQs
- Micro -seismic noise from Thermal Moonquakes and anthropogenic lunar activities
  - High frequency sources (f>1 Hz) and shall be far (>10 km) from future nbasis if any
- Ground noise from Solar 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 ~ 2 10^{12} Nm

as the same seismic moment of a very rare impact (~1/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



Daubar et al., 2017

All statistics with Brown et al. 2002 with upper limit

Seismic Impact Hum: deci-herz

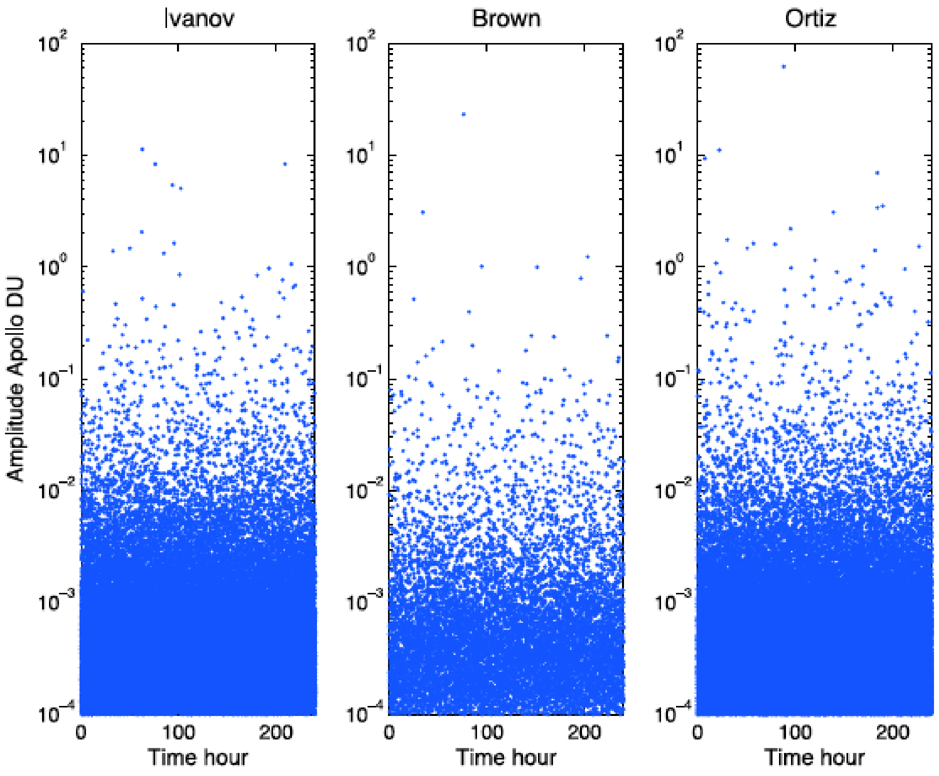


Figure 14. Simulated impact amplitudes. Each point provides the maximum envelope amplitude of a single simulated impact "recorded" at the station 12 location. From left to right are the simulations for the Ivanov, Brown, and Ortiz models, respectively. Each simulation spans 10 days.

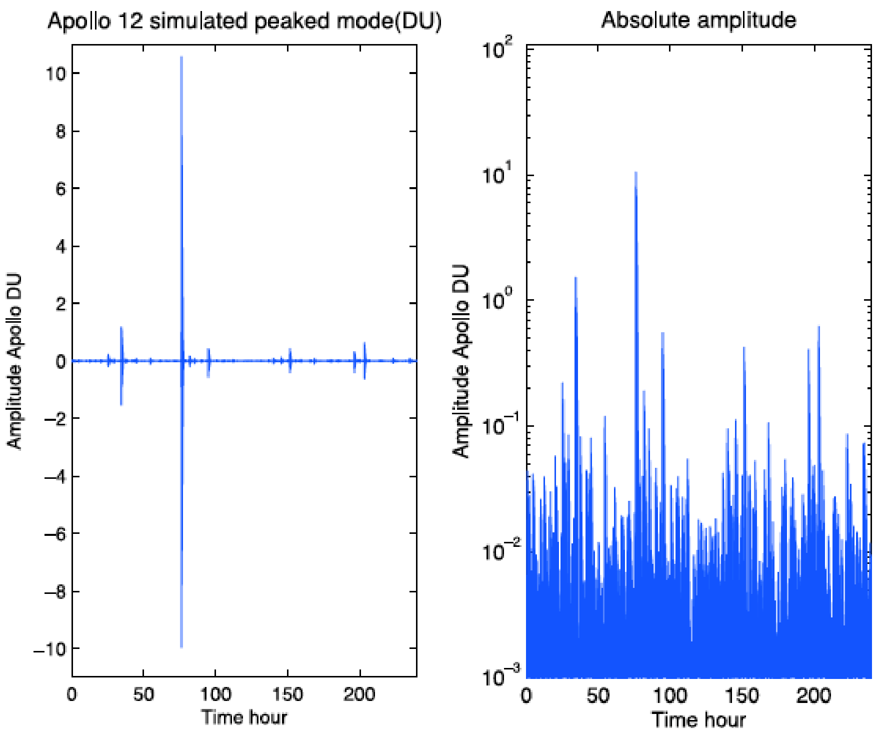
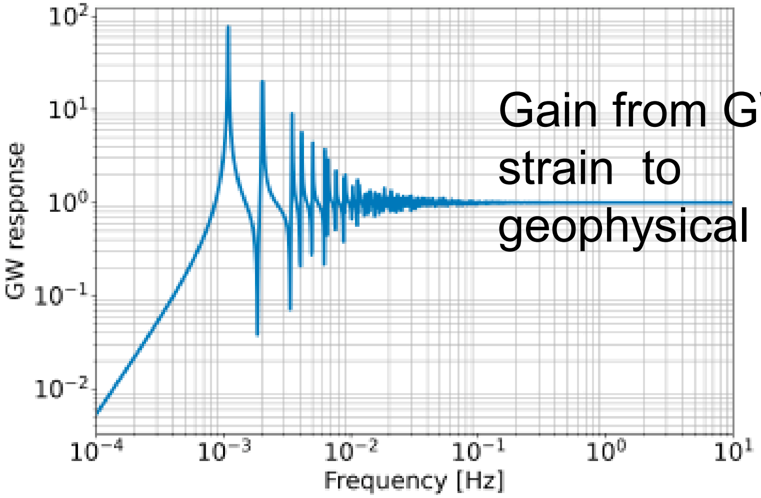


Figure 15. Composite waveform for impacts simulated using the Brown model. The duration of each waveform (corresponding to an individual impact) summed is 1 h, while the plot shows 10 days of signal. (left) The computed seismogram in Apollo DU. (right) The absolute value of the seismogram, on a logarithmic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

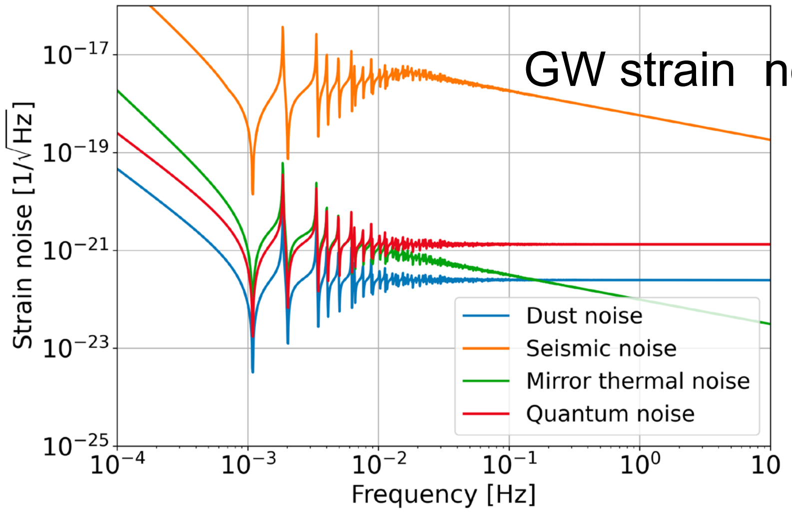
- A reasonable estimation of the Hum at 0.5 sec can be estimated to about 10^{-2} Apollo DU, which provides about 5 x 10^{-13} m rms , wich means 5 10^{-12} m/s^2 rms

(see details in Lognonné et al. 2009)

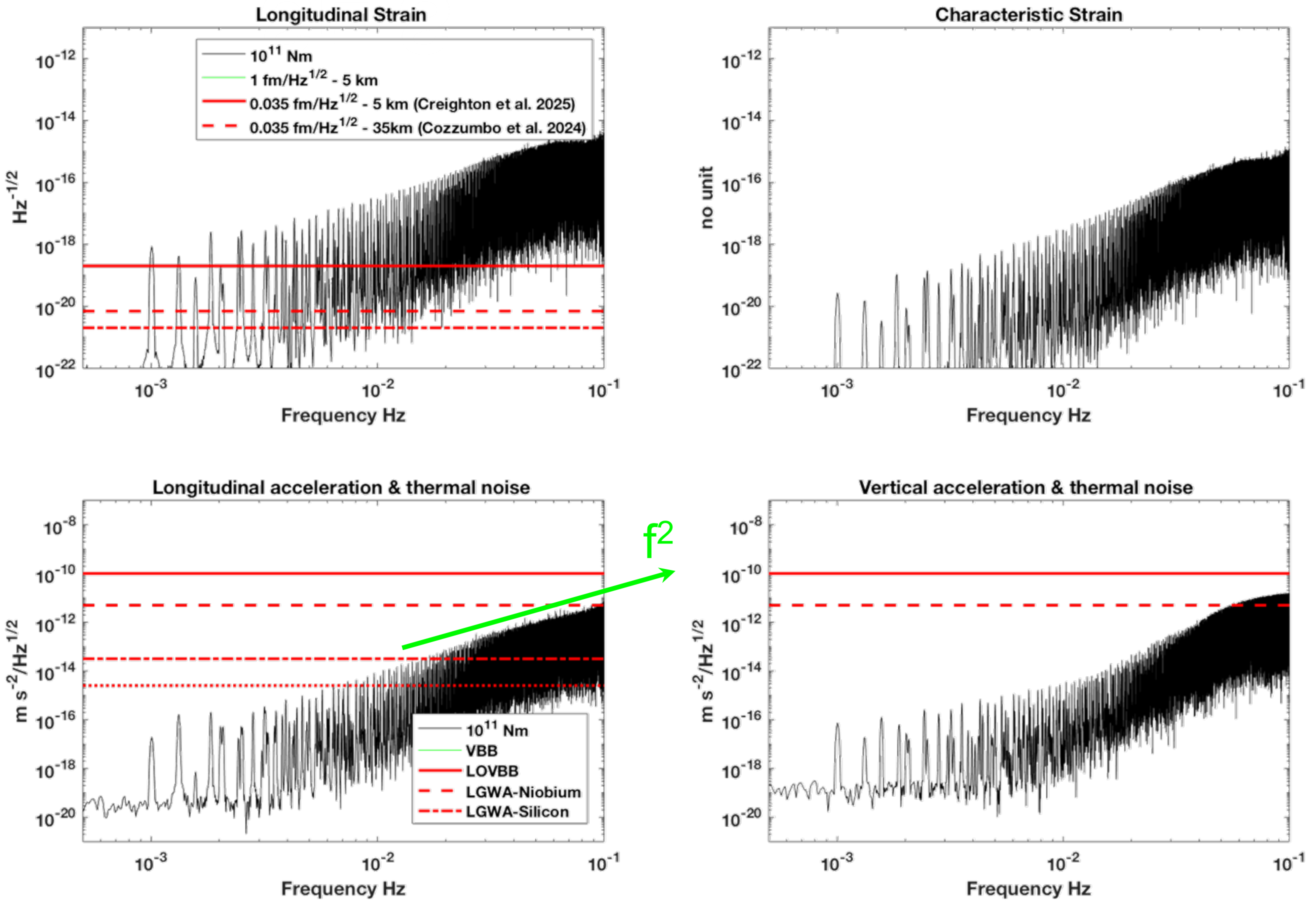
Seismic Impact Hum: long period



Gain from GW strain to geophysical strain



GW strain noise



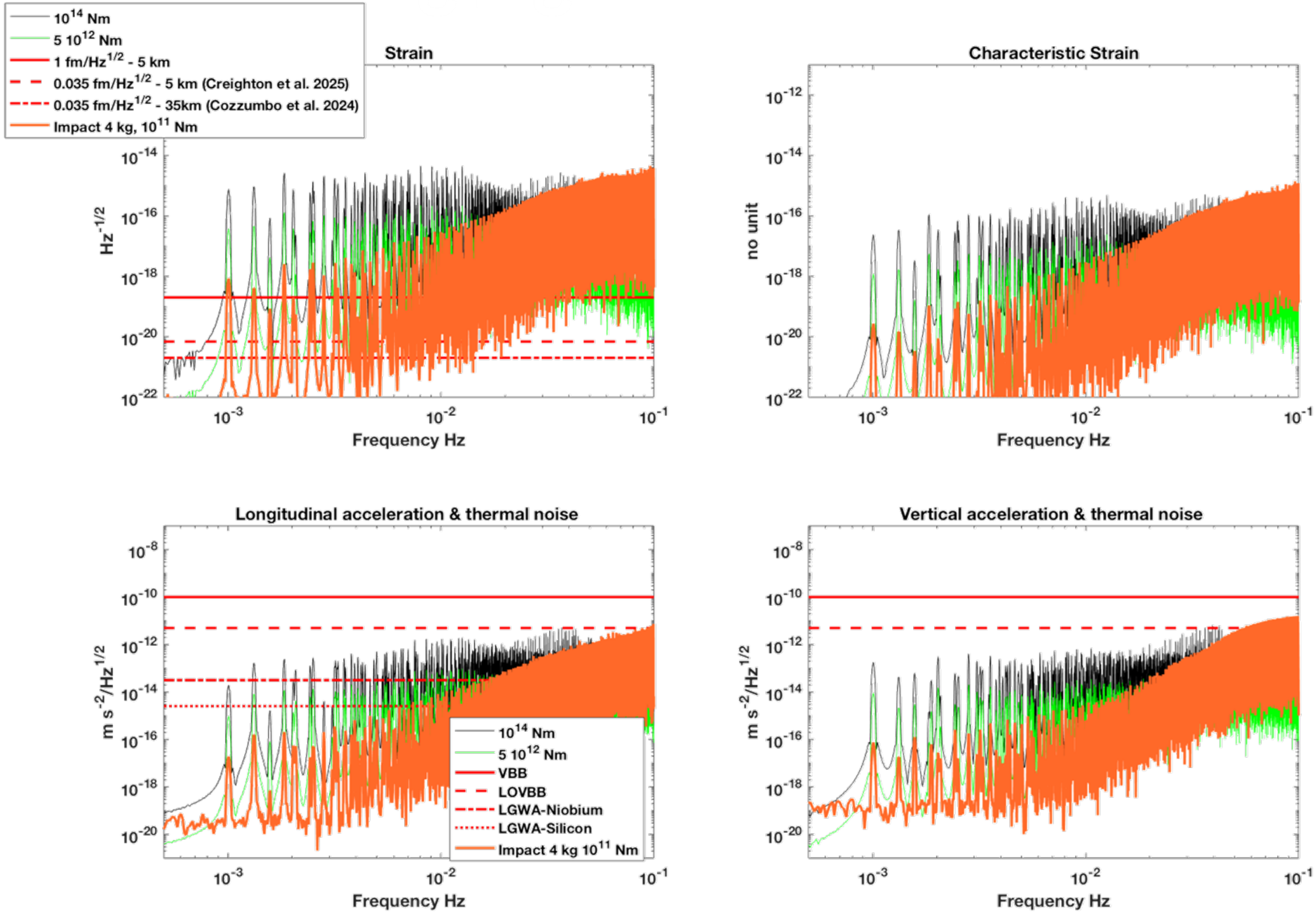
Normal modes: impact at 72° , 4kg, 10^{11} Nm, 5 10^{-18} Hz$^{-1/2}$@ 100 sec

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

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

Seismic Impact Hum versus Normal modes

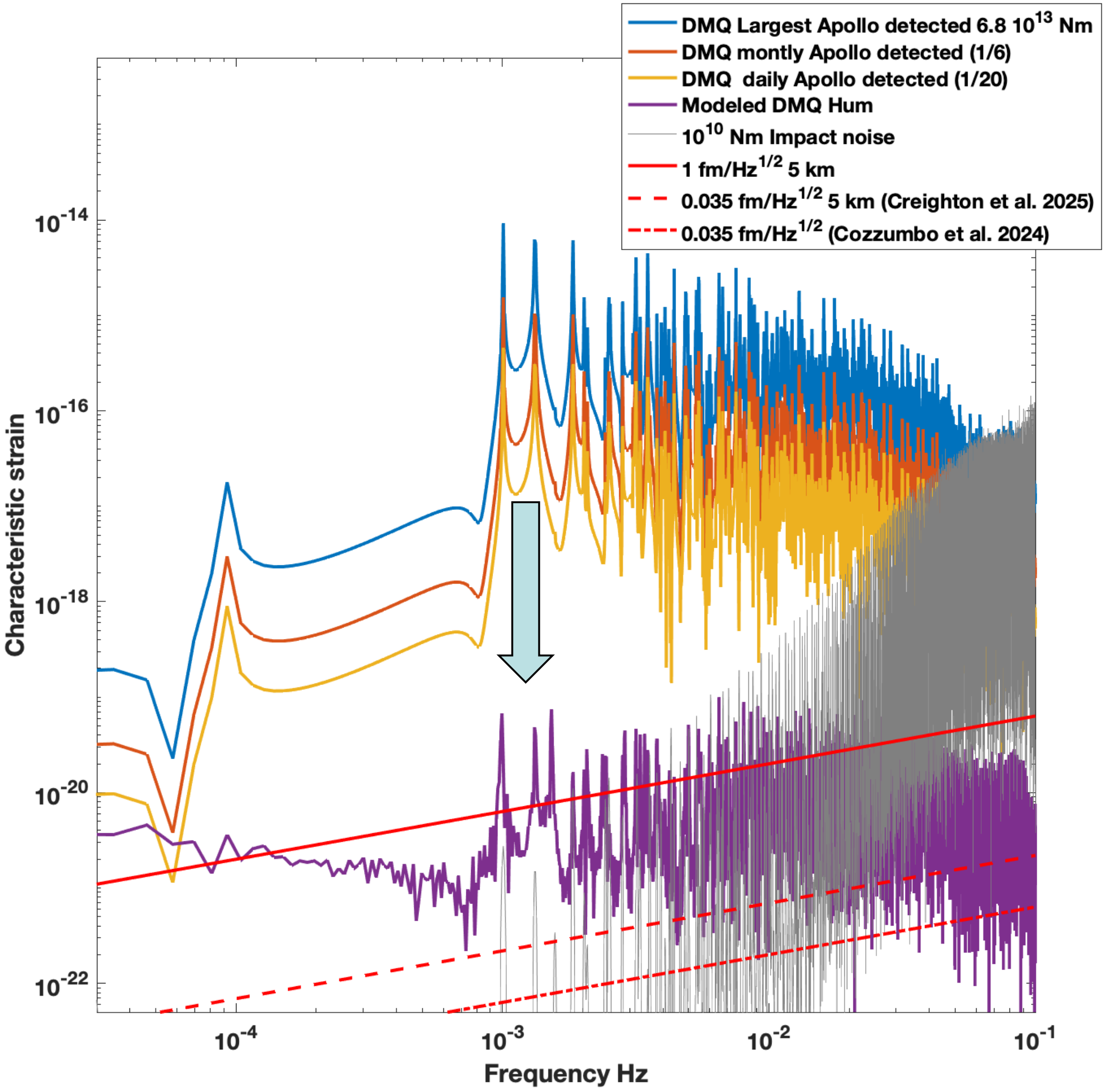
- The seismic impact hum rises as f^2
- This model is likely overestimating by 10-100 due to:
  - The upper limit used for impacts Moment/impulse
  - the 1D model with scattering
  - the single impact model and distance
- Scattering effects are likely larger on the impacts than on DMQ
- This nevertheless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



DMQ Hum versus Impact Hum

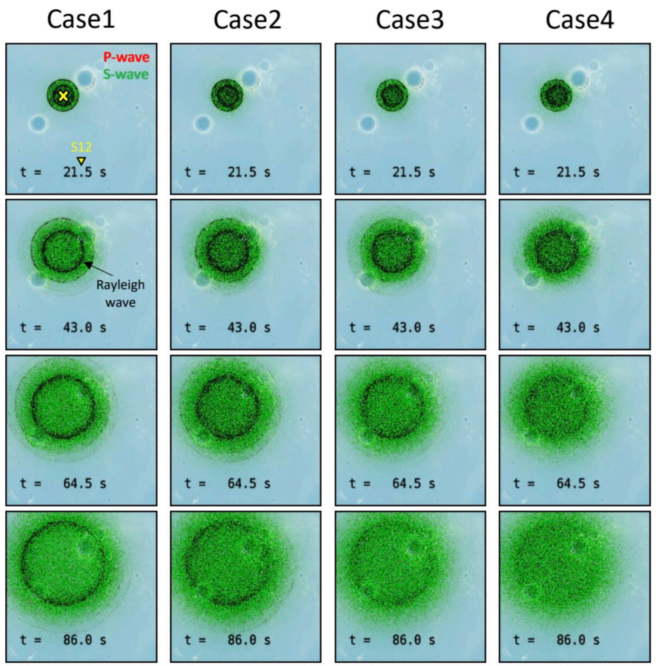
- By using the frequency magnitude law of DMQ and assuming it can be extrapolated below the minimum of Apollo (assume no locking asperity..), we can extrapolate **a DMQ Hum** made by the superposition of several DMQs occurring at different times below the resolution of Apollo
- **This DMS Hum** might 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.



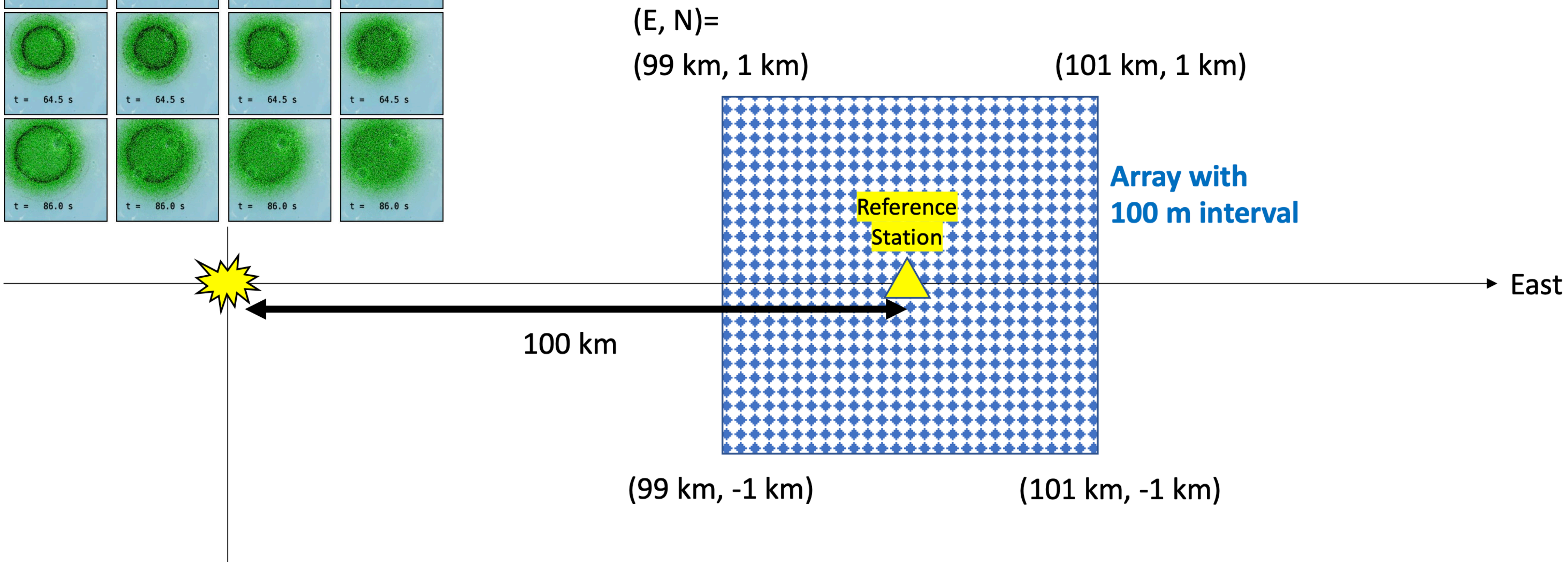
Noise cancellation in the deciHerz

Simulation …



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

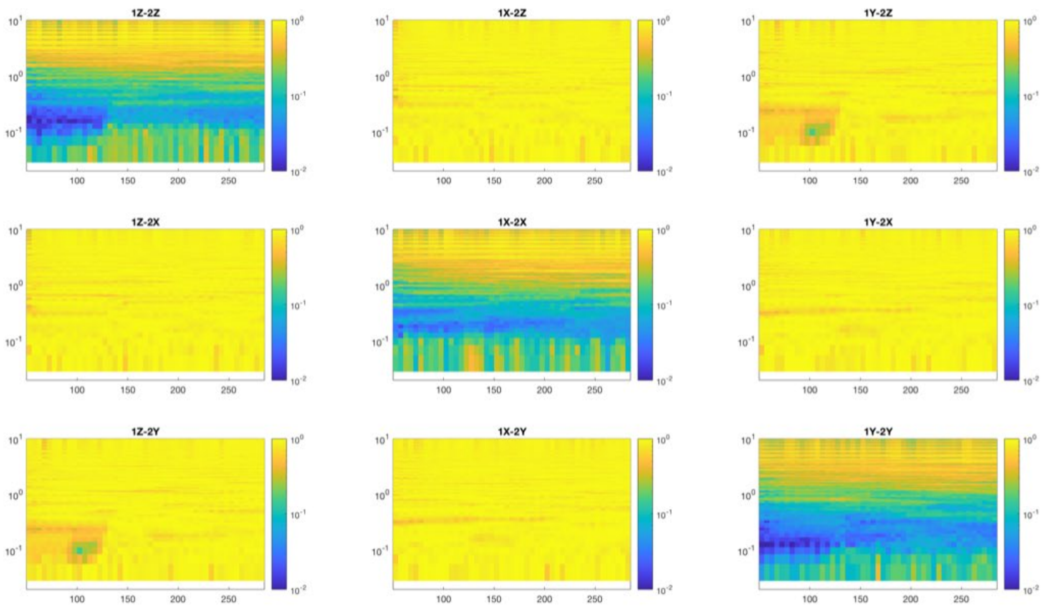
Question: Can we use close stations for removing any coherent seismic noise on the Moon ?



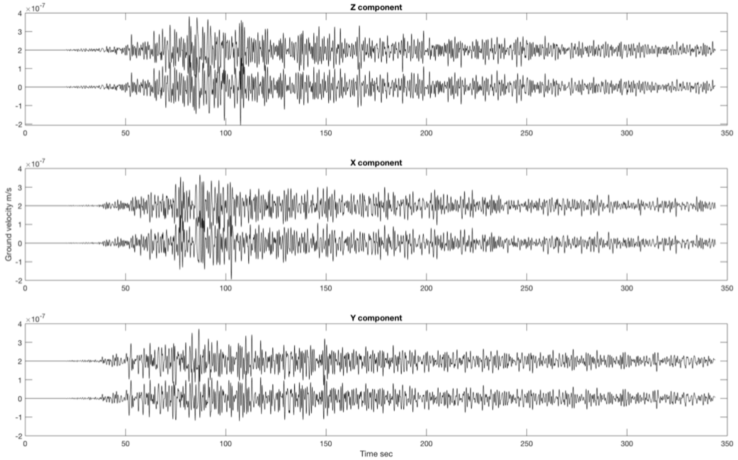
Onodera et al. 2023

Noise cancellation in the deciHerz

- The coherency is lost very rapidly in about 100m
- Numerical tests suggest a very low efficient, of about 20 db when we are in the coda of the seismic waves
- 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.

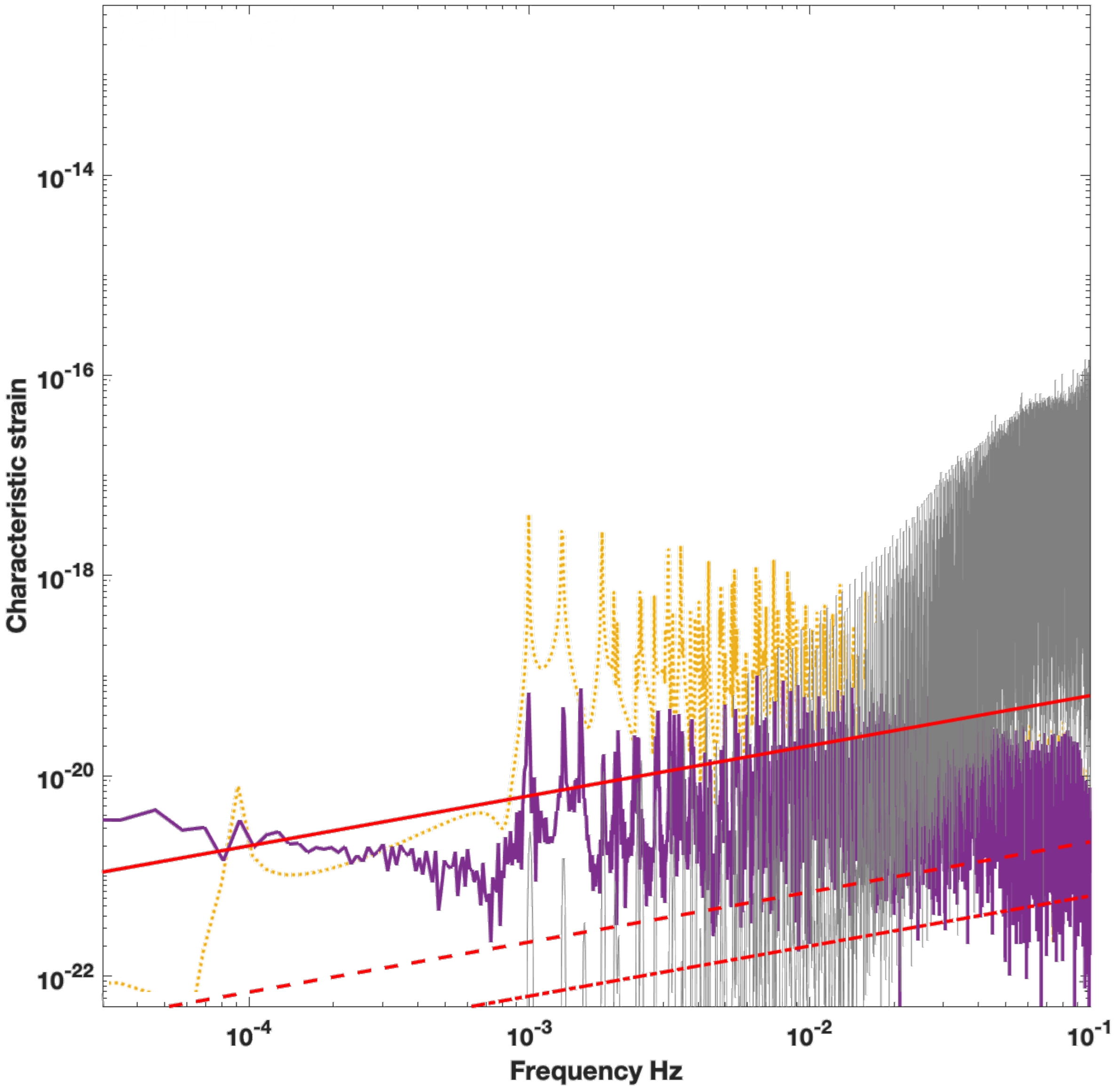


The color contour shows the relative amount of non coherent signal in the figure ($\sqrt{1-\gamma^2}$). We loose quickly the coherency in the signal for 2 separate stations.



My « best » estimate for 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-Herz, only damping + decorrelation seems good enough for decreasing the seismic noise.



Conclusion for Targeting 3D Deep Interior Lunar structure

- How can this science be accomplished on the Moon? Are there particular advantages to a non-polar lunar site?
  - **By measuring the Normal modes splitting excited by ALL Apollo detected DMQs nest with known locations**
  - **Yes, as we can select a crater matching the length of the strainmeter arms and deploy a new seismic stations away from the South Pole seismic network and explore new terranes.**
- What measurements are needed to accomplish the objective?
  - **2 Ground coupled strain measurements (E-W, N-S) made by a two arms strainmeter with sensitivity better than 1 fm/Hz$^{1/2}$ for 5 km baseline. None of the proposed lunar accelerometers meet the requirement.**
  - **Must be completed by ILN class Very broad band seismometers (0.01-50 Hz, 10^{-11} m/s^2/Hz$^{1/2}$ thermal noise)**
- Does this science require a specific site, multiple sites, or can it be done anywhere on the lunar surface?

  - To first order, this is site agnostic pending crater identification, but this shall be more than 10s km from future basis
- What will the site, or site type, need to ensure that the science objective can be accomplished (e.g. radio quiet, geological properties, other)?
  - **Young terrane to reduce the thickness of the ultra low velocity regolith layer (HF wave guide)**
- Is there a pathfinder to advance the scientific objective?

  - Any long lived seismic stations locating DMQs and improving knowledge on seismic noise
- How does a human onsite enable or improve the quality of the measurement(s)? (e.g., Judgement? Reaction? Adaptability?)
  - **Installation will be much easier with LTV and astronauts. Robotic installation will be very challenging with multiple landers**
- Are new capabilities and/or pre-placed assets necessary to ensure the human can do the measurement or collect the sample? If so, what?
  - **All technology seems available, even if no TRL6 instrument exists yet**