

# Astro-1 Honors 2020

## Class 5: In Situ Resource Utilization – Finding and extracting water and other volatiles on the Moon

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# OUR GOAL IS TO FIND WATER, MINERALS, AND VOLATILES. HOW?

The Moon may have substantial deposits of  $\text{H}_2\text{O}$ ,  $\text{NH}_3$  (ammonia),  $\text{CO}_2$ ,  $\text{H}_2\text{S}$  (hydrogen sulfide), and other volatiles in the PSRs at the poles.

How do we know this? Mainly from lunar orbiters and probes that were crashed into the surface intentionally, so that orbiters could study the plumes that were ejected.

## What do we mean by spectroscopy?

Methods:

- Molecular spectroscopy

- Thermal emission spectroscopy

- Raman spectroscopy

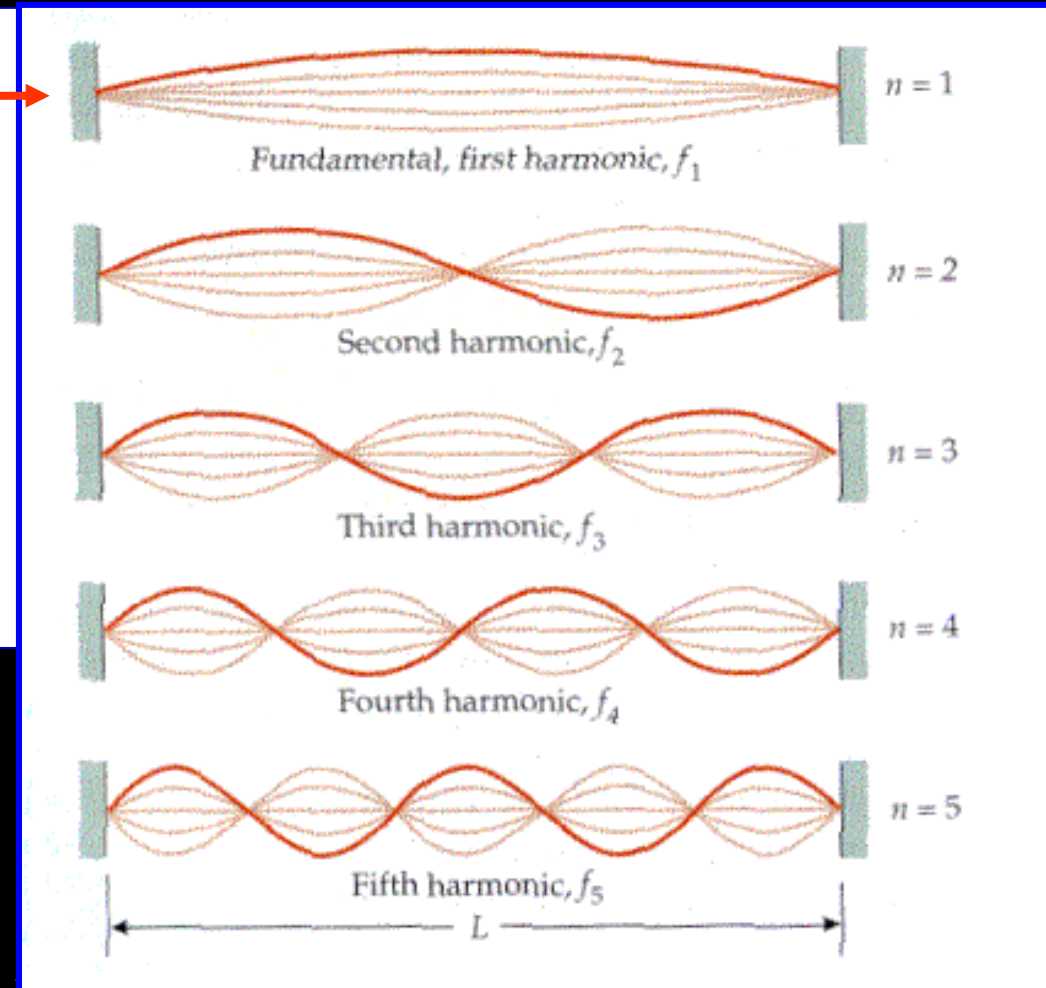
- UV reflection and absorption

- IR reflection and absorption

**When energy is put into a system – an atom, a molecule, a string, a wind instrument, a bridge, a planet, etc., the system oscillates in characteristic frequencies called NORMAL MODES.**

The fundamental frequency gives us the lowest tone we can hear for a particular length of string.

Multiples of the fundamental frequency produce higher tones.



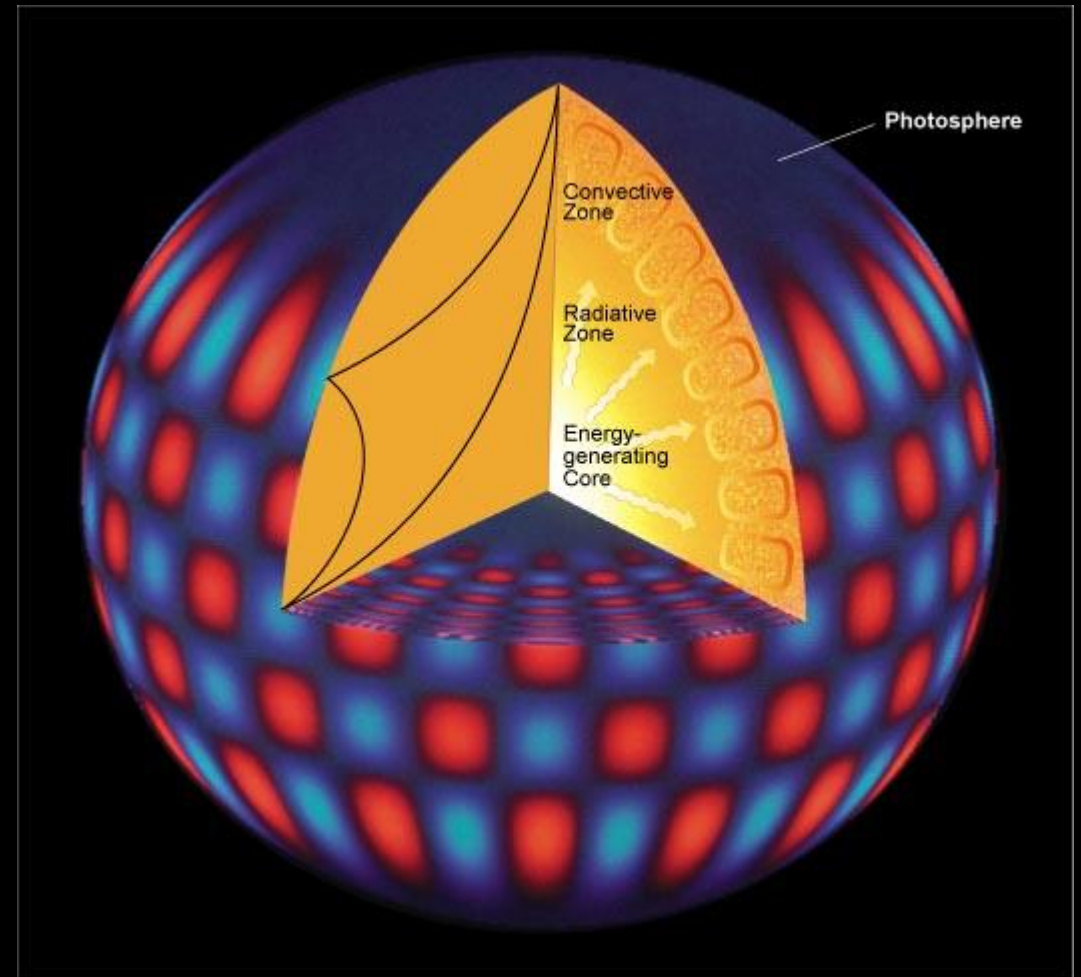
**If we can identify these characteristic frequencies, we can use this information to identify the substance.**

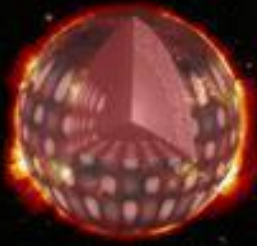


**Tacoma Narrows Bridge – wind set it vibrating in its normal modes until one day it collapsed.**

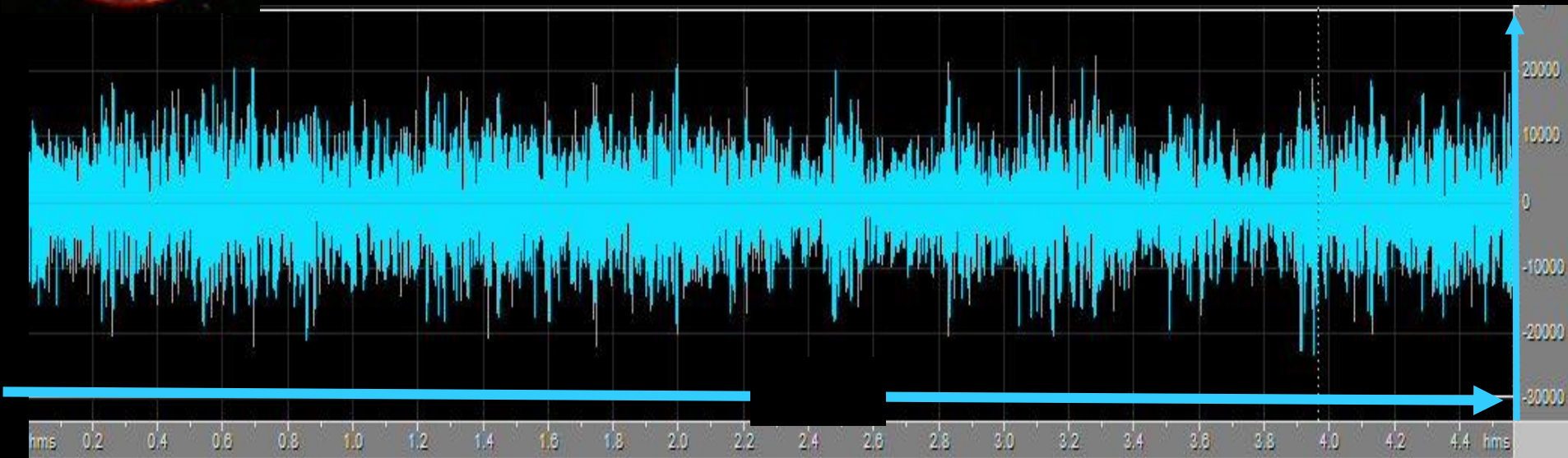
<https://www.youtube.com/watch?v=qbOjxPCfaFk>

**The Sun vibrates in normal modes**



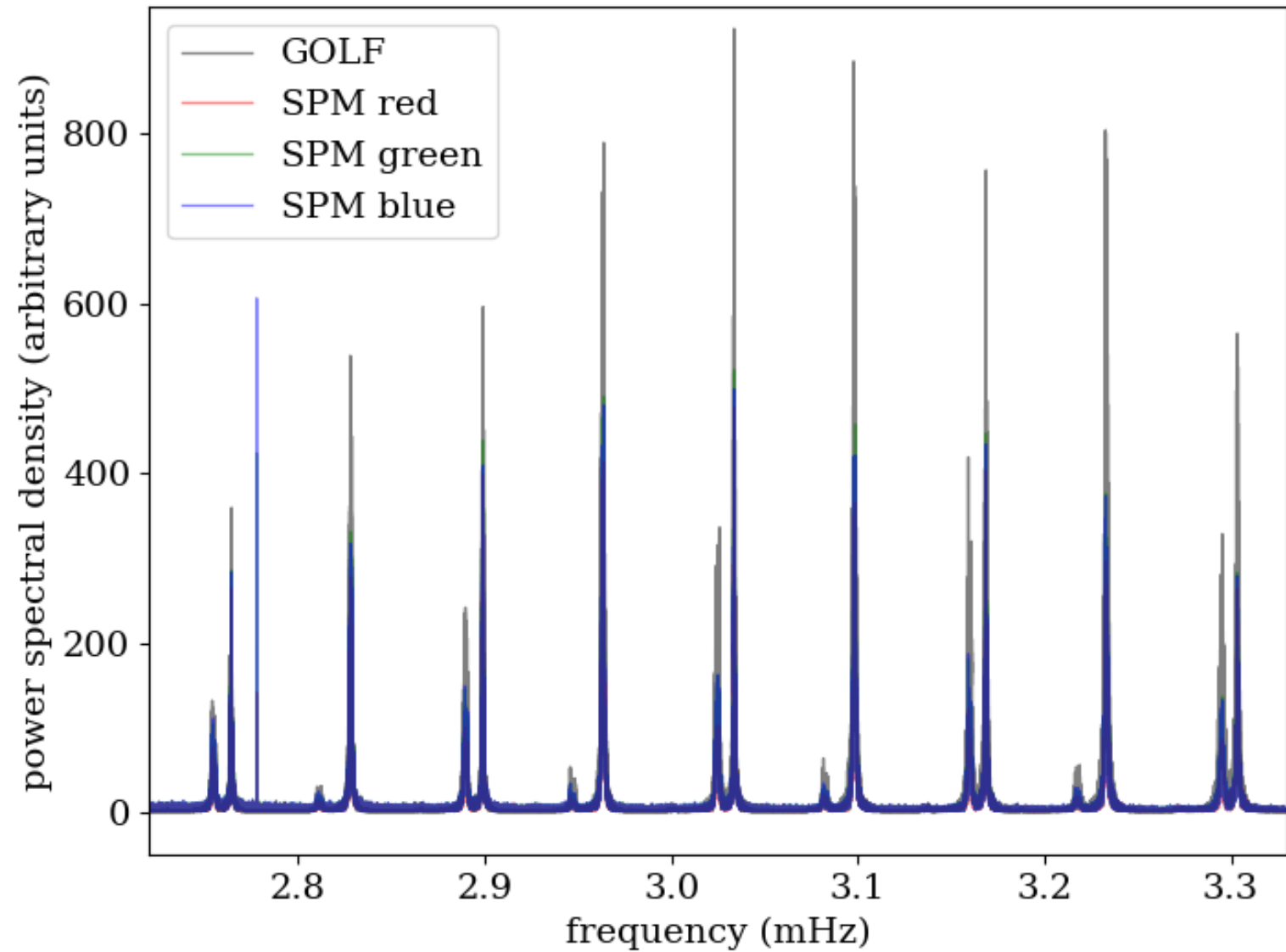


Here is the sound of pressure waves sloshing around inside the Sun, recorded by the BiSON group in Birmingham, UK, <http://bison.ph.bham.ac.uk/>, compressed around 10,000 times to the range of human hearing.

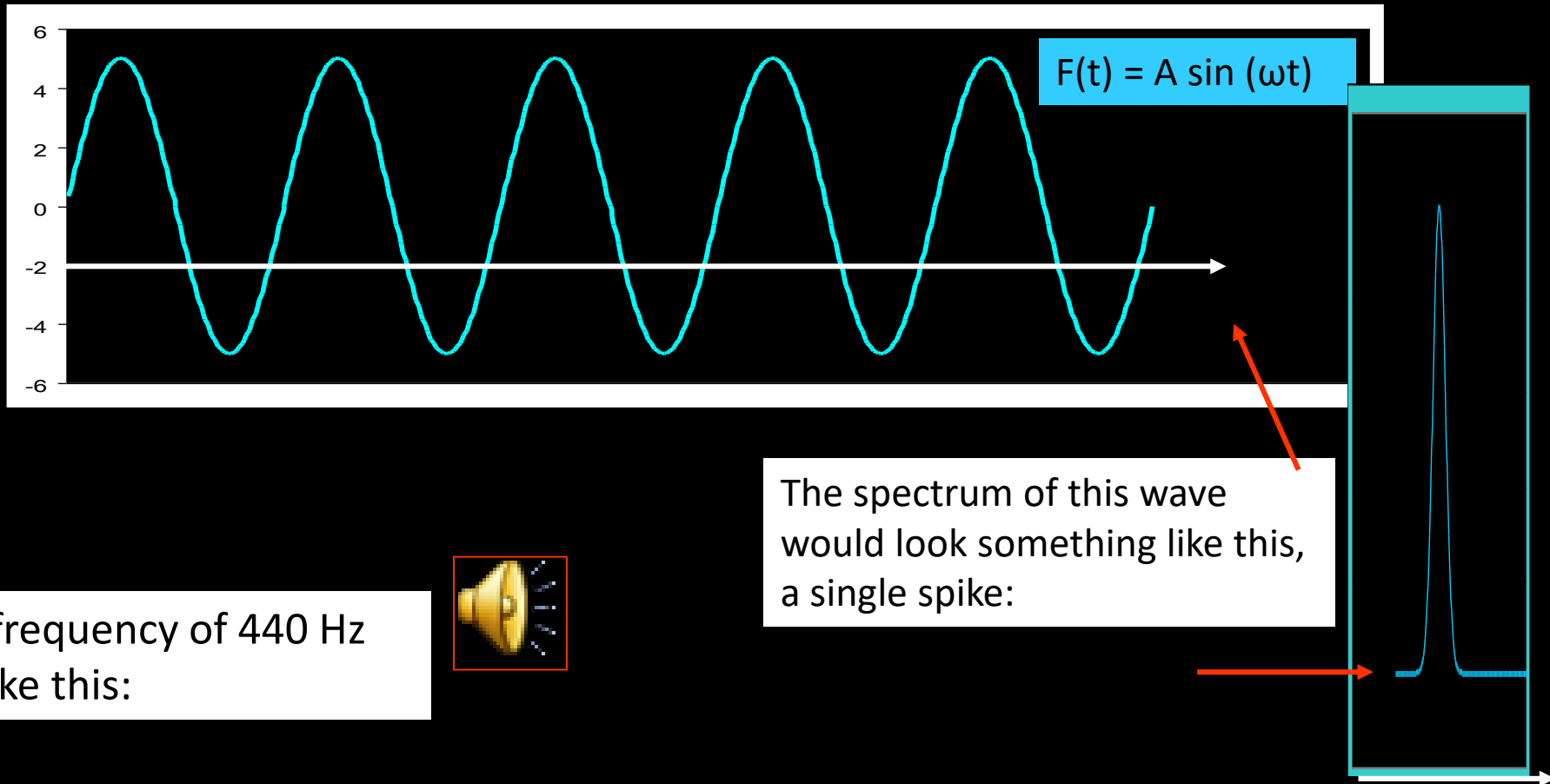


## Spectrum of sound waves in the Sun

Frequencies are in milliHertz, around 10,000 times below audible frequencies for human ears.



The simplest mathematical representation of a wave  $F(t) = A \sin(\omega t)$  represents a periodic displacement of some medium with amplitude "A" and angular frequency  $\omega$ . The simplest wave form looks something like this:



A single frequency of 440 Hz sounds like this:

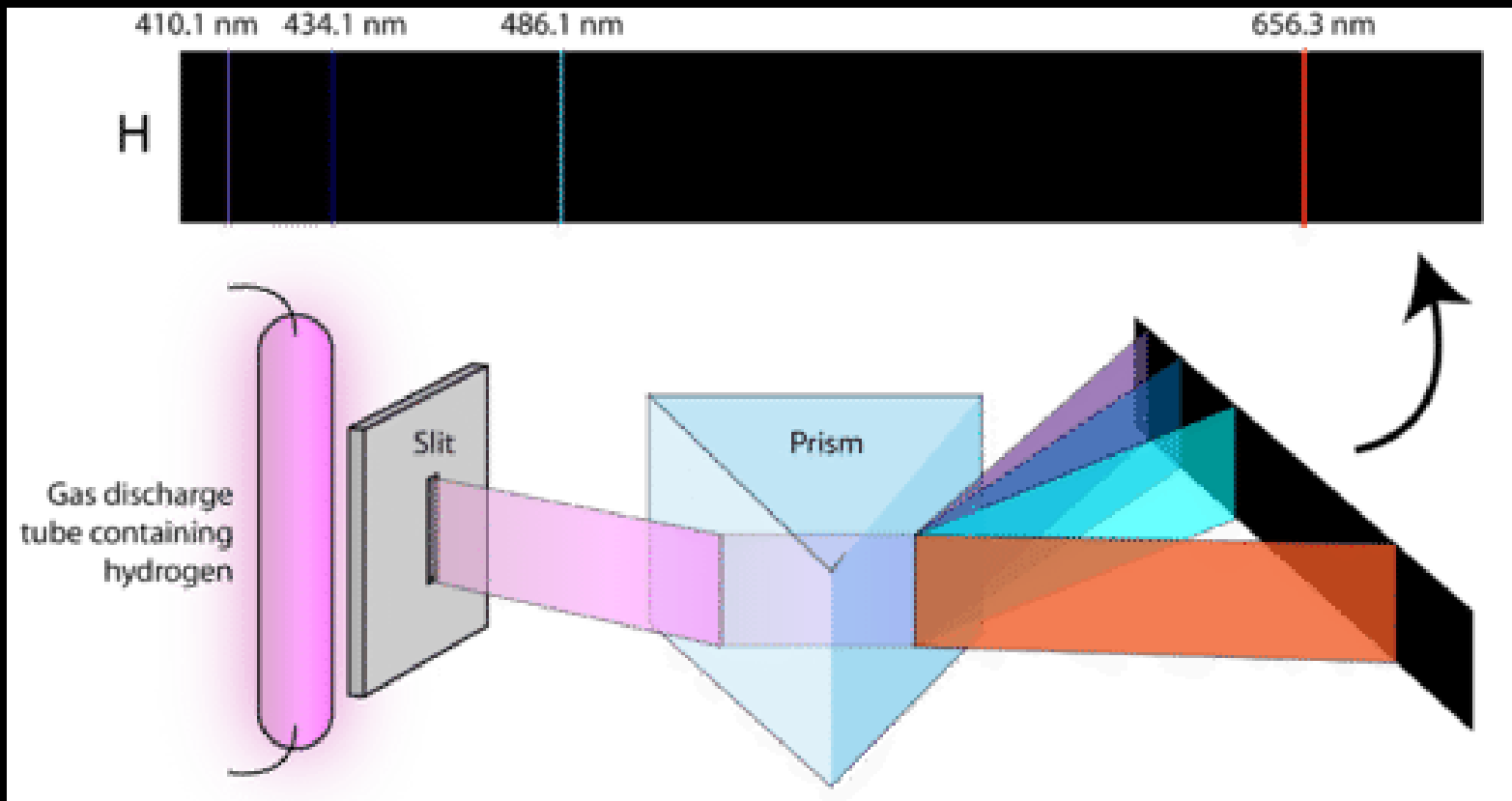


The spectrum of this wave would look something like this, a single spike:

# Atomic spectra

A spectrum of vibrations is produced when energy falling on an atom causes the electrons to oscillate in characteristic frequencies, called **NORMAL MODES**, and absorb, transmit, or emit energy at precise wavelengths/frequencies that are characteristic of that substance.

Thus a spectrum is like a 'fingerprint' of a substance.

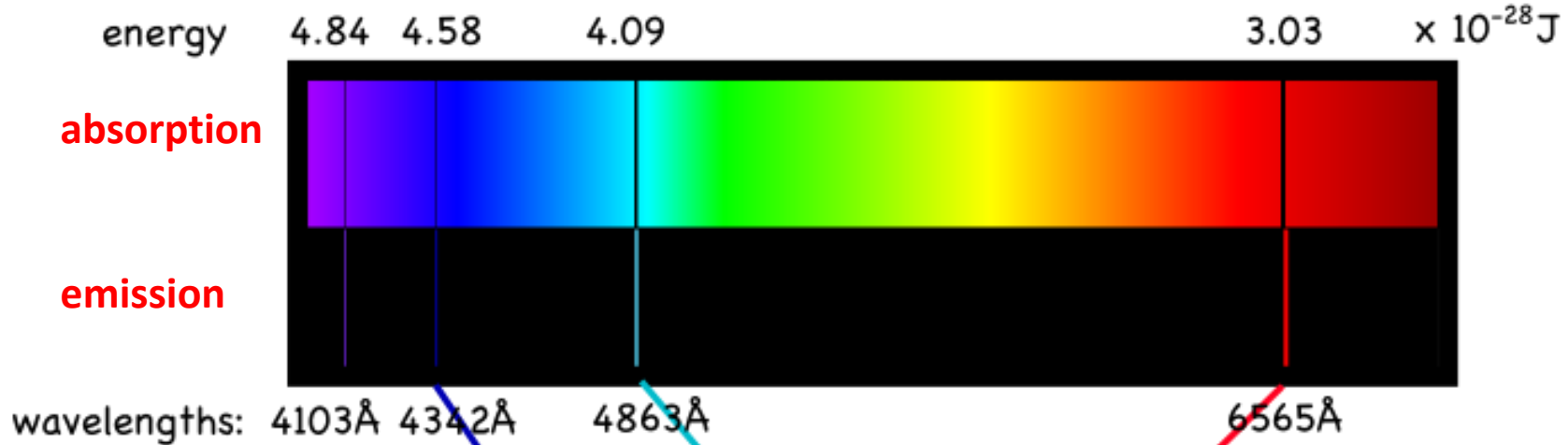


You have seen this phenomenon for the hydrogen emission spectrum class.

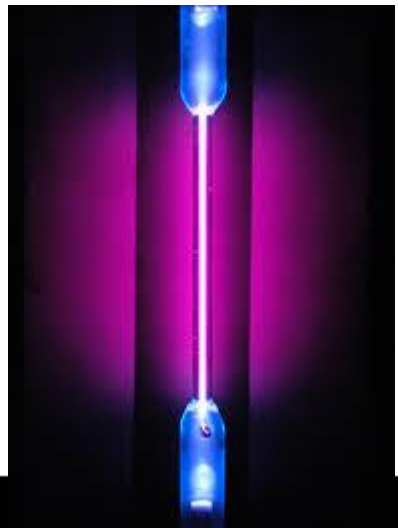
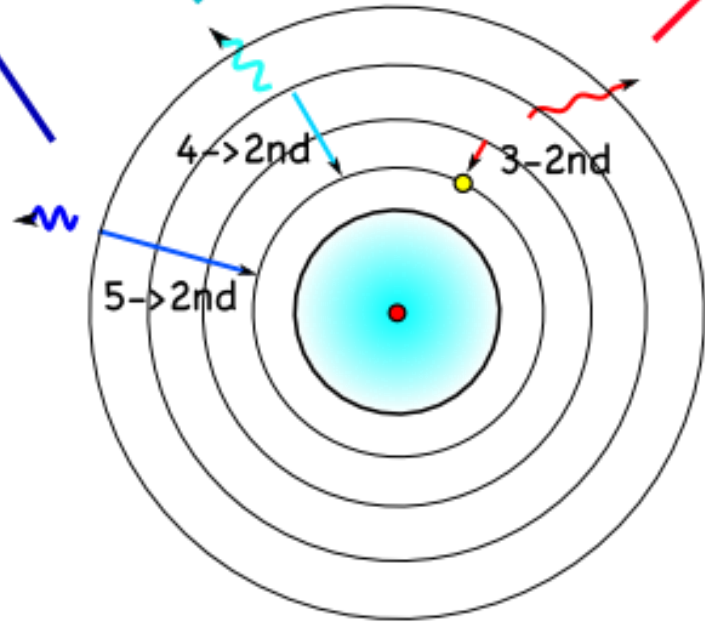


# Hydrogen spectrum for visible light

$$E = hf$$



H-atom absorbs energy in 'just the right' amounts so that electrons oscillate between their rest energy level and higher energy levels. The total color is magenta (pinkish-purplish). When the light is seen through a diffraction grating, the individual colors are visible.



**Analogy: Represent the Hydrogen visible spectrum with SOUND. For each wavelength, calculate the frequency. Then we map each frequency to a sound within the range of human hearing.**

$$c = \lambda f$$

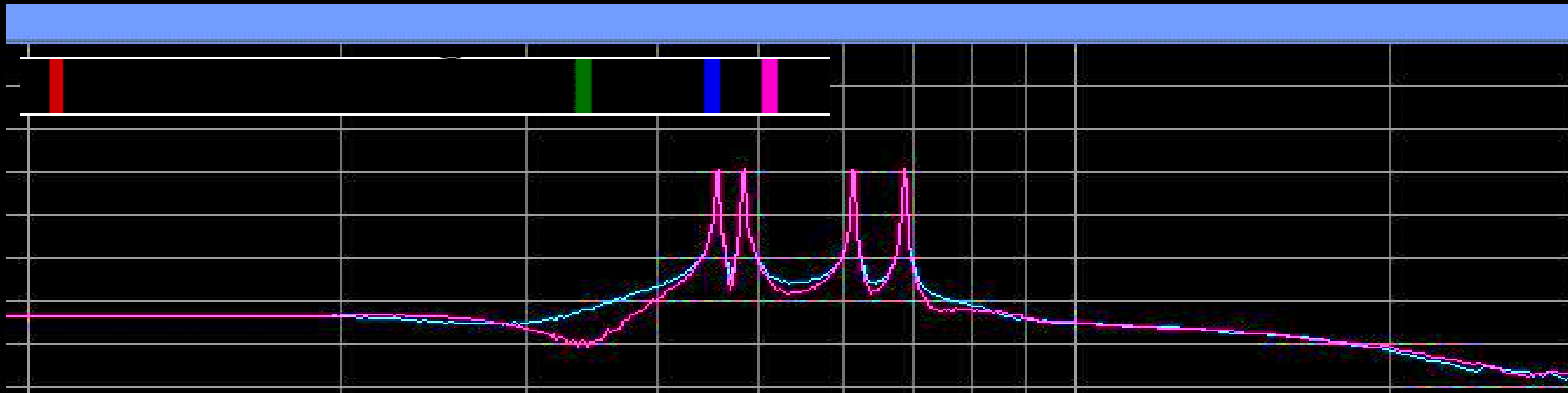
**For all light waves, speed is constant =  $3.0 \times 10^8$  m/sec**  
 **$f = c/\lambda$**

Spectral line	H- $\alpha$	H- $\beta$	H- $\gamma$	H- $\delta$
Wavelength	656 nm	486 nm	434 nm	410 nm
Frequency	$4.57 \times 10^{14}$ Hz	$6.17 \times 10^{14}$ Hz	$6.91 \times 10^{14}$ Hz	$7.32 \times 10^{14}$ Hz
Assigned tone	457 Hz	617 Hz	691 Hz	732 Hz

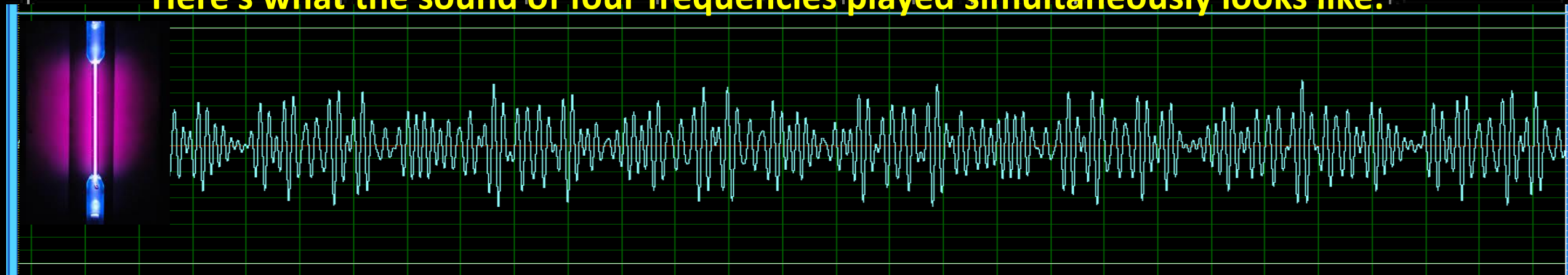
**Here is the 'sound' of excited hydrogen – the combination of four visible frequencies.**



Here's the *spectrum* of the Hydrogen Balmer series represented in sound – four peaks for each of the four frequencies: 457 Hz, 617 Hz, 691 Hz, and 732 Hz

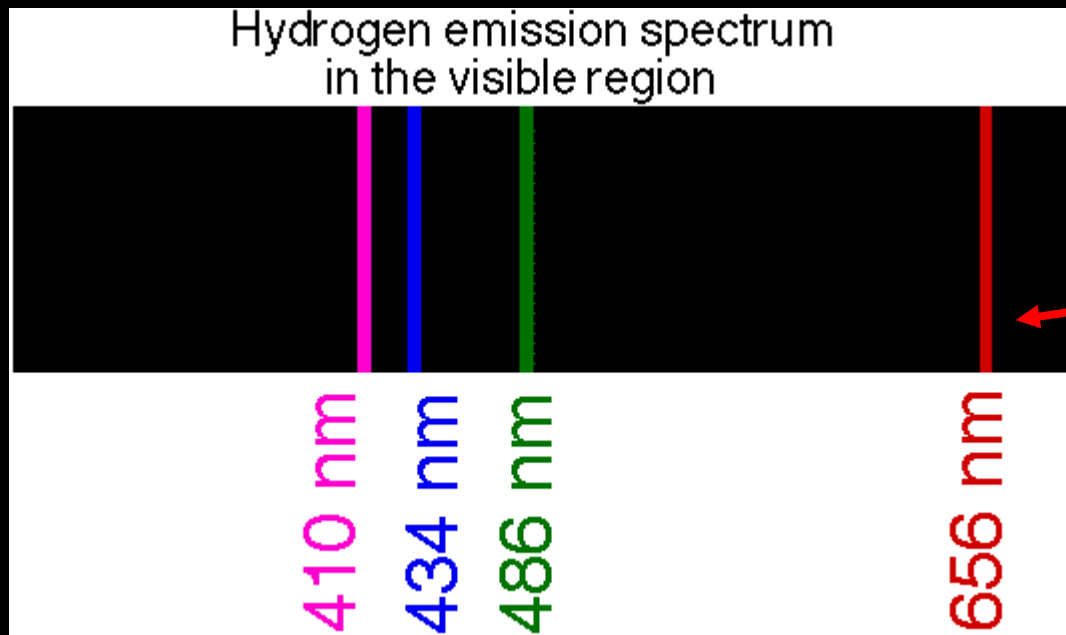
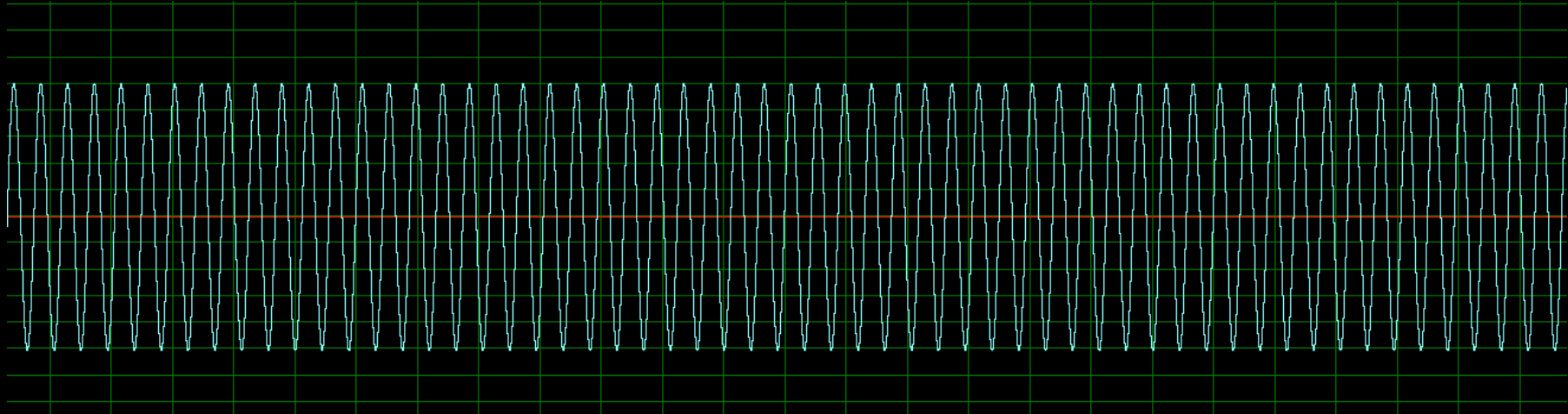


Here's what the sound of four frequencies played simultaneously looks like:

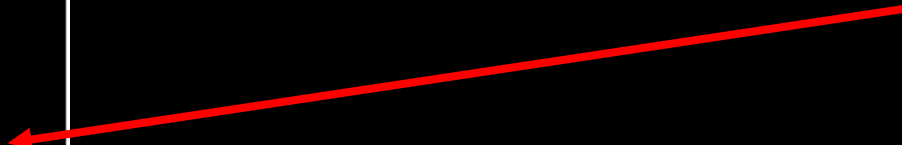




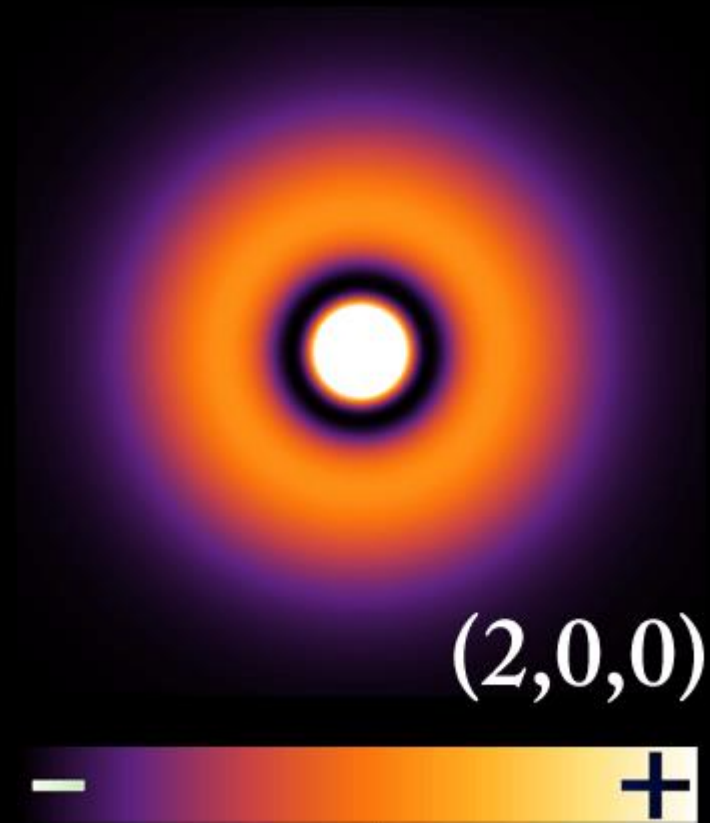
Here is the 'sound' of just the H- $\alpha$  line at 656 nm or 457 Hz



corresponding to just the H- $\alpha$  (red) line.



Here's a visualization of the normal modes of a hydrogen atom. The electron is excited by an input of energy of 'just the right amount' to make it jump to higher energy levels. The energy states of the electron in a hydrogen atom are visualized as 'orbitals' of different shapes. Every time the electrons go from a higher to a lower energy state, they emit photons that are of an energy that exactly matches the difference in energy levels.



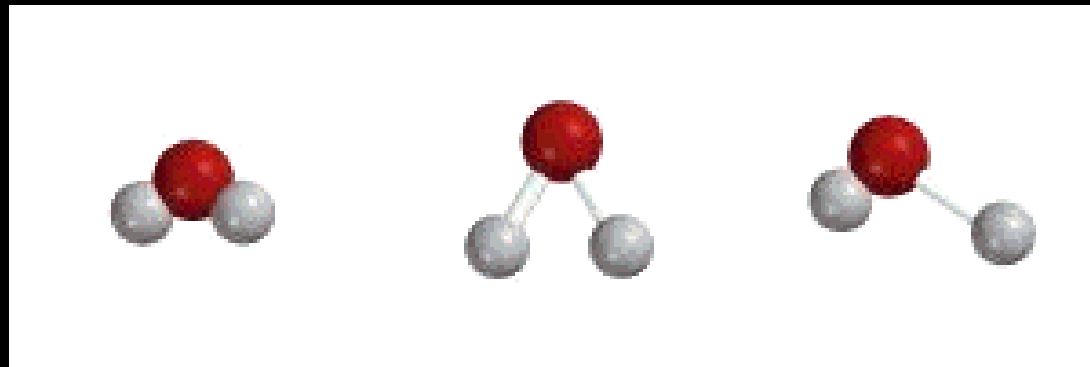
**Molecules produce absorption and emission spectra when excited so as to vibrate in their normal modes.**

**Normal modes for molecules in solids are vibrations.**

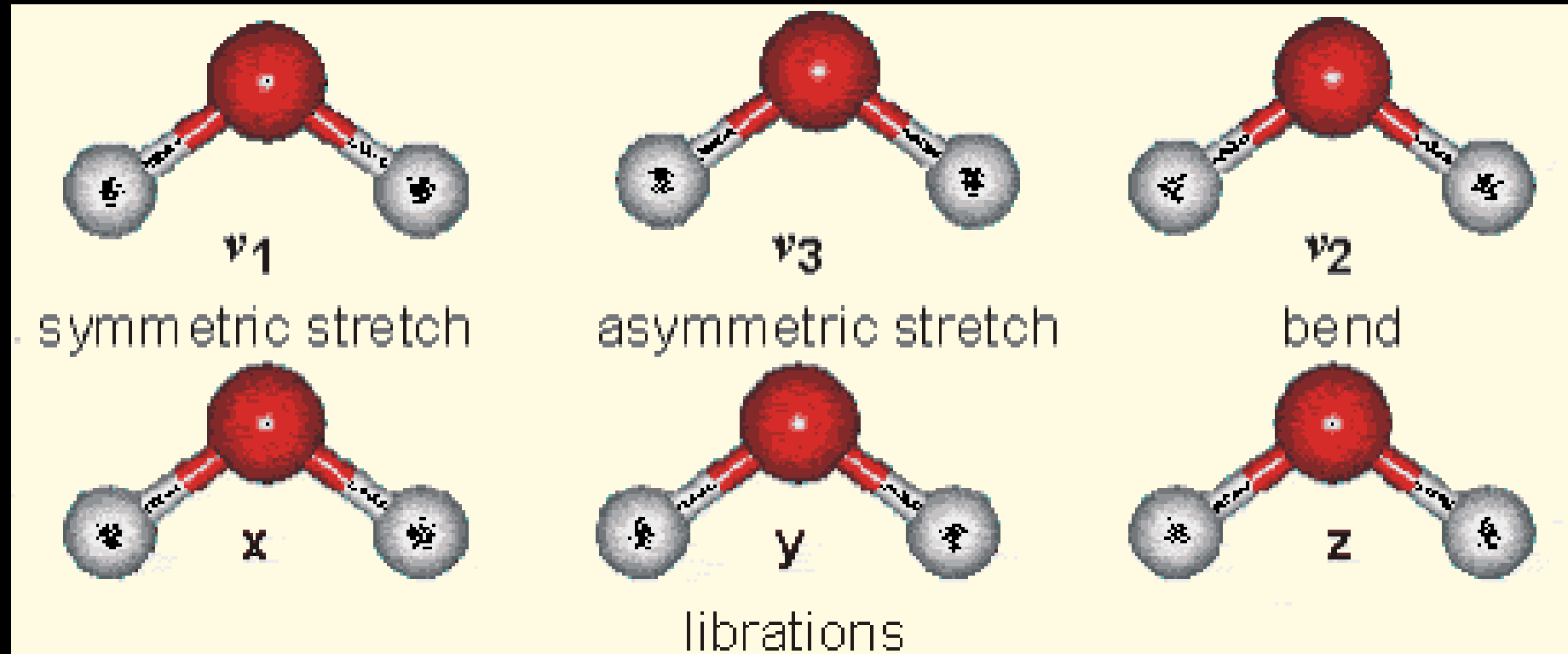
**Normal modes for molecules in liquids include vibrations, rotations, and librations.**

**Normal modes for molecules in gases also include translations.**

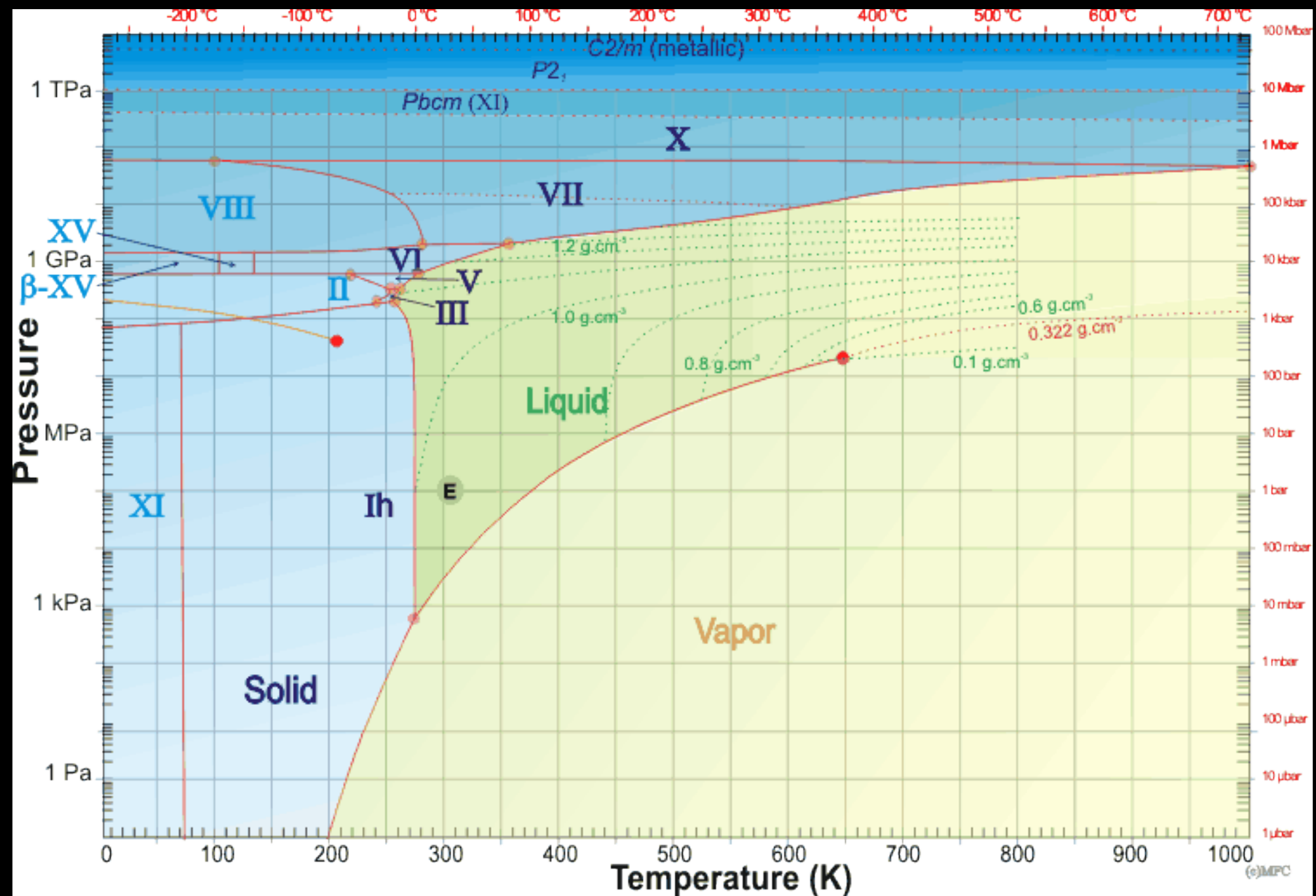
**For water,  $\text{H}_2\text{O}$ , the main “springs” that is doing the vibrating are the O-H bonds.**



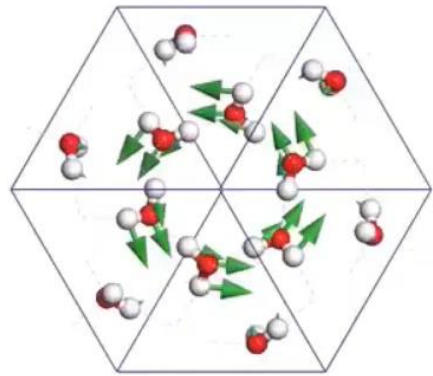
Water absorbs over a wide range of electromagnetic radiation with rotational transitions and intermolecular vibrations responsible for absorption in the microwave ( $\approx 1 \text{ mm} - 10 \text{ cm}$  wavelength) and far-infrared ( $\approx 10 \text{ }\mu\text{m} - 1 \text{ mm}$ ), intramolecular vibrational transitions in the infrared ( $\approx 1 \text{ }\mu - 10 \text{ }\mu$ ) and electronic transitions occurring in the ultraviolet region ( $< 200 \text{ nm}$ ).



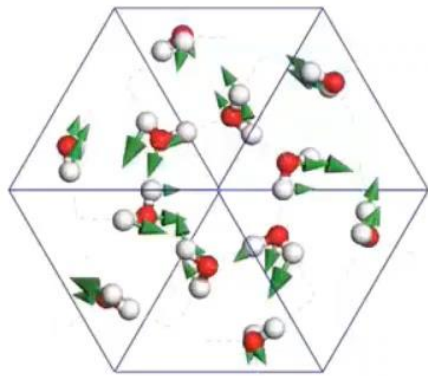
[http://www1.lsbu.ac.uk/water/water\\_vibrational\\_spectrum.html](http://www1.lsbu.ac.uk/water/water_vibrational_spectrum.html)



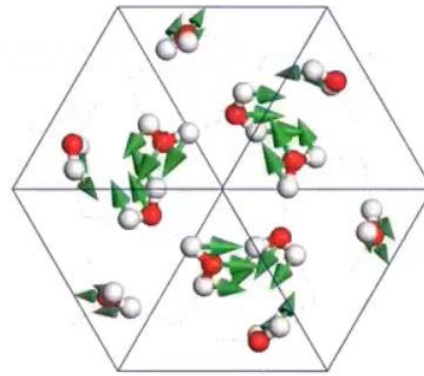




Cluster vibration



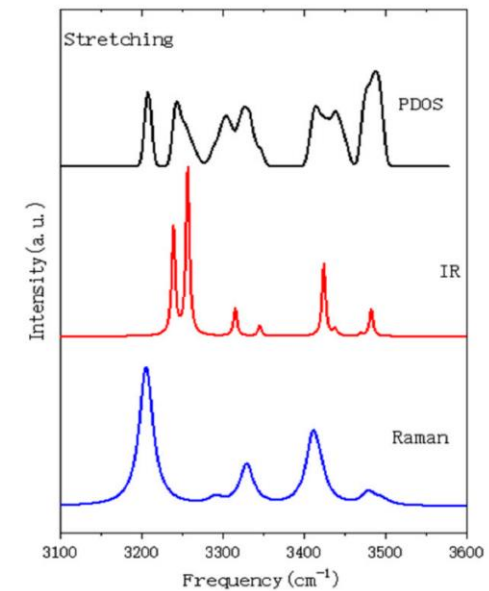
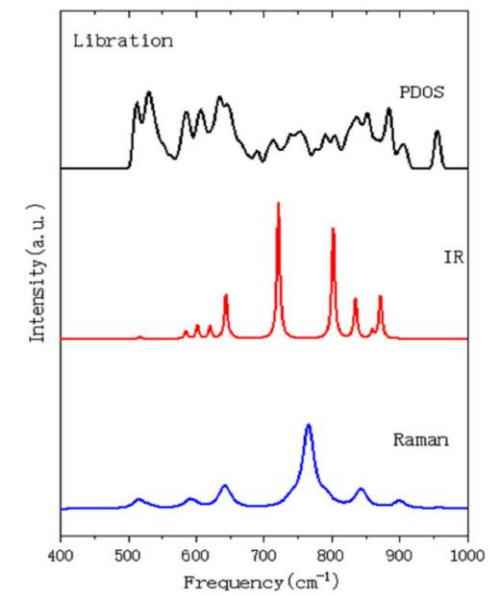
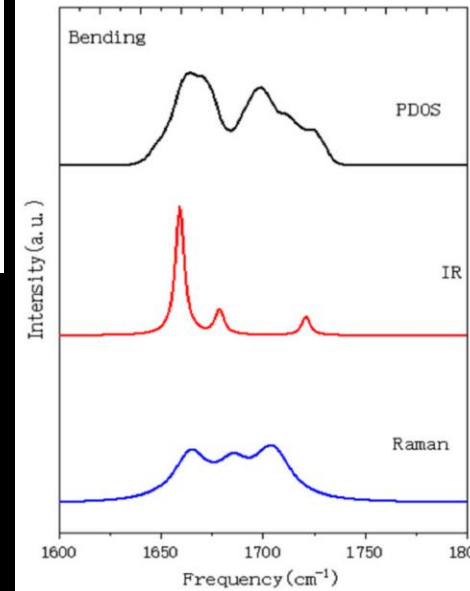
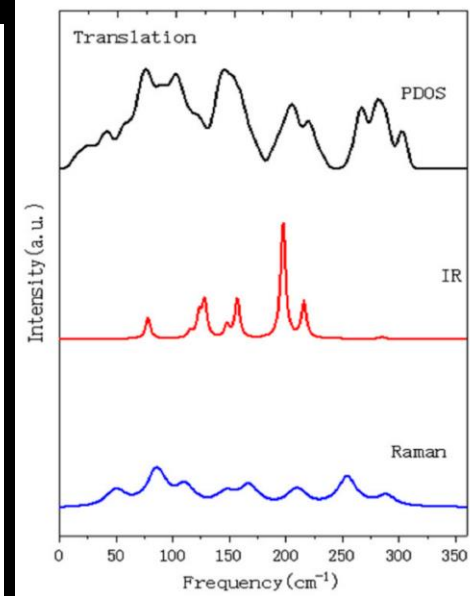
Two-bond mode



Four-bond mode

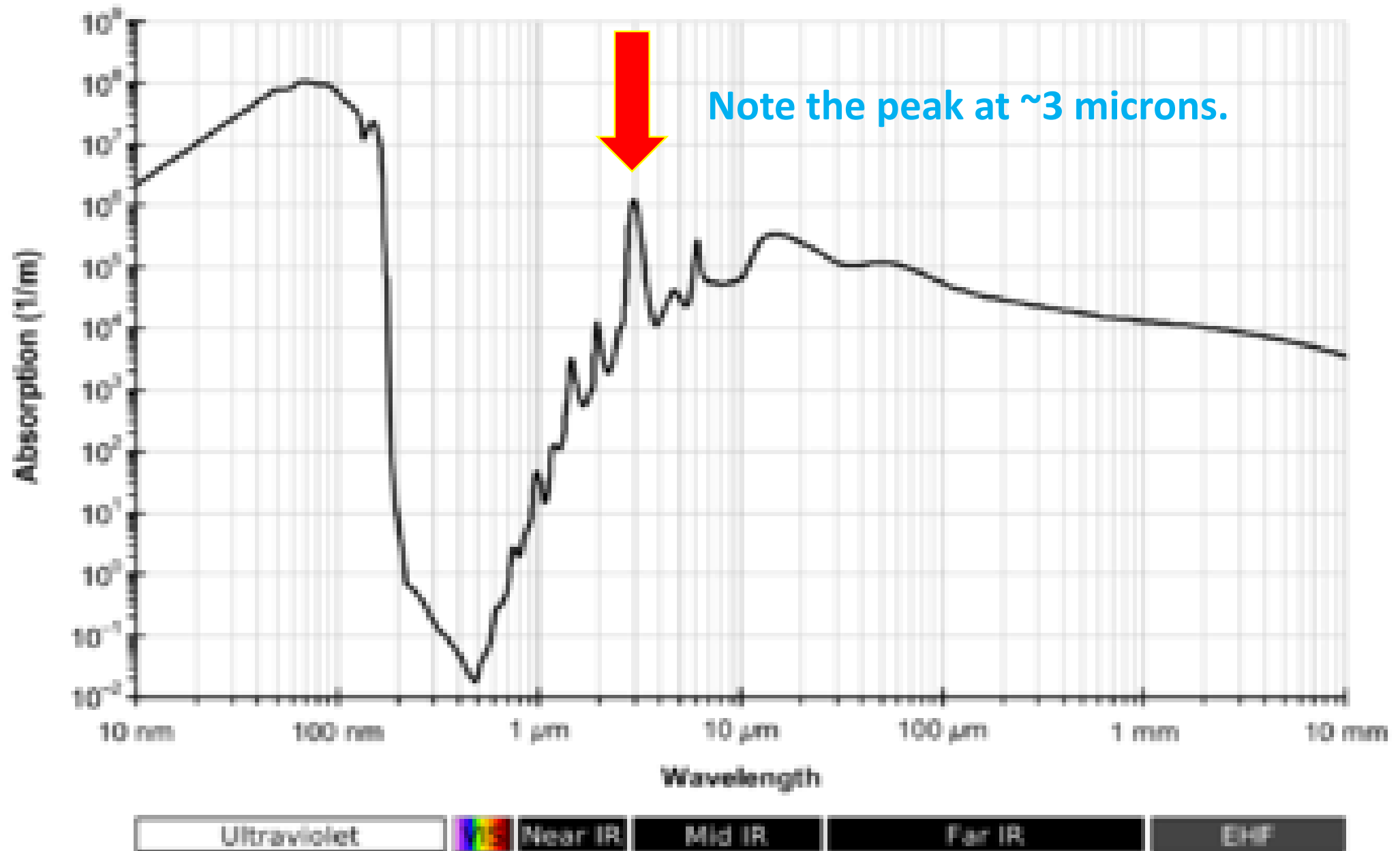
## DFT Investigations of the Vibrational Spectra and Translational Modes of Ice II

<https://www.mdpi.com/1420-3049/24/17/3135/htm>



**Theoretical study of ice II – modeling normal modes of vibration and predicting the spectra that should be seen in different methods of spectroscopy.**

# Absorption spectrum for water

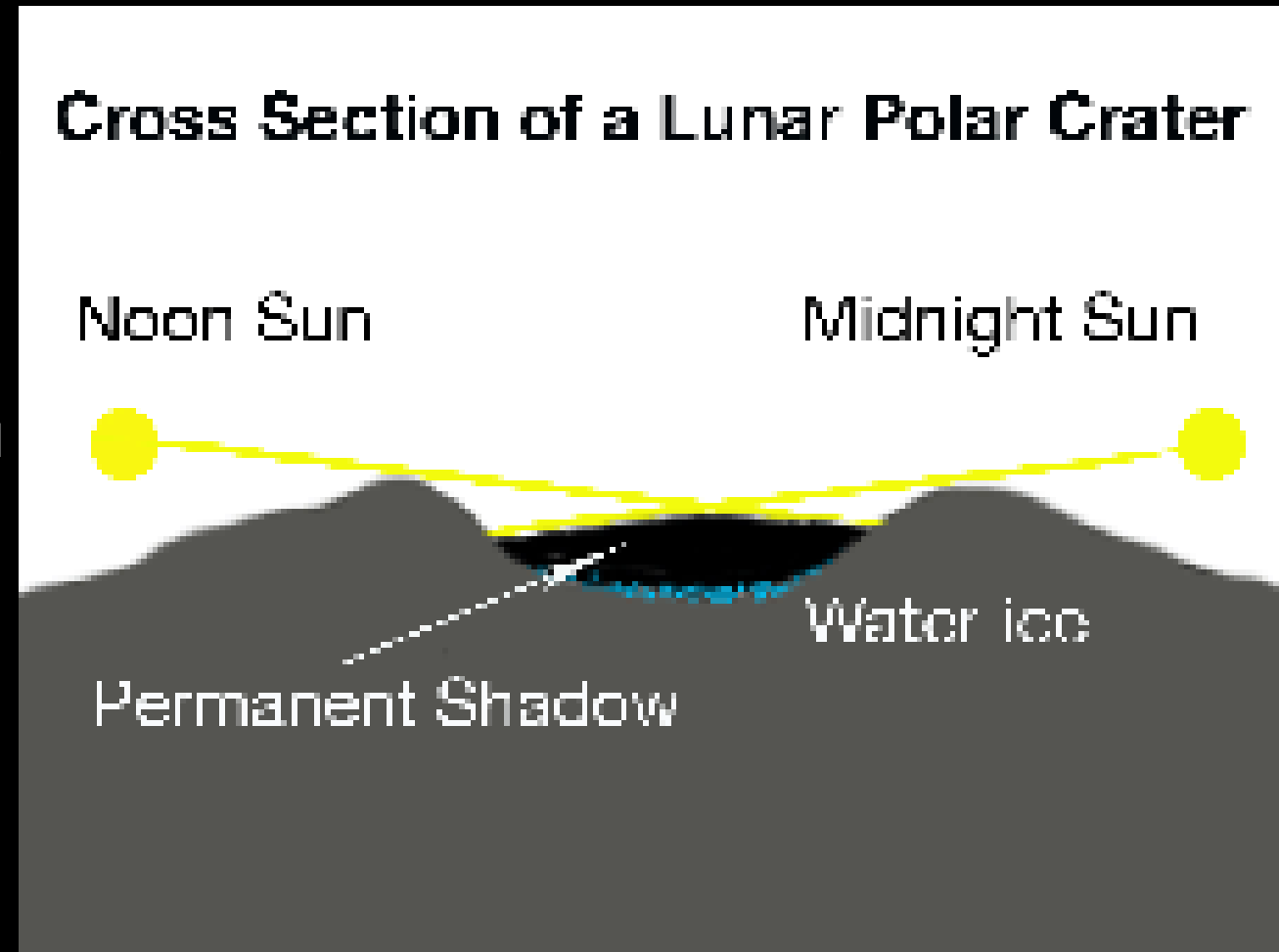


# OUR GOAL IS TO FIND WATER, MINERALS, AND VOLATILES. HOW?

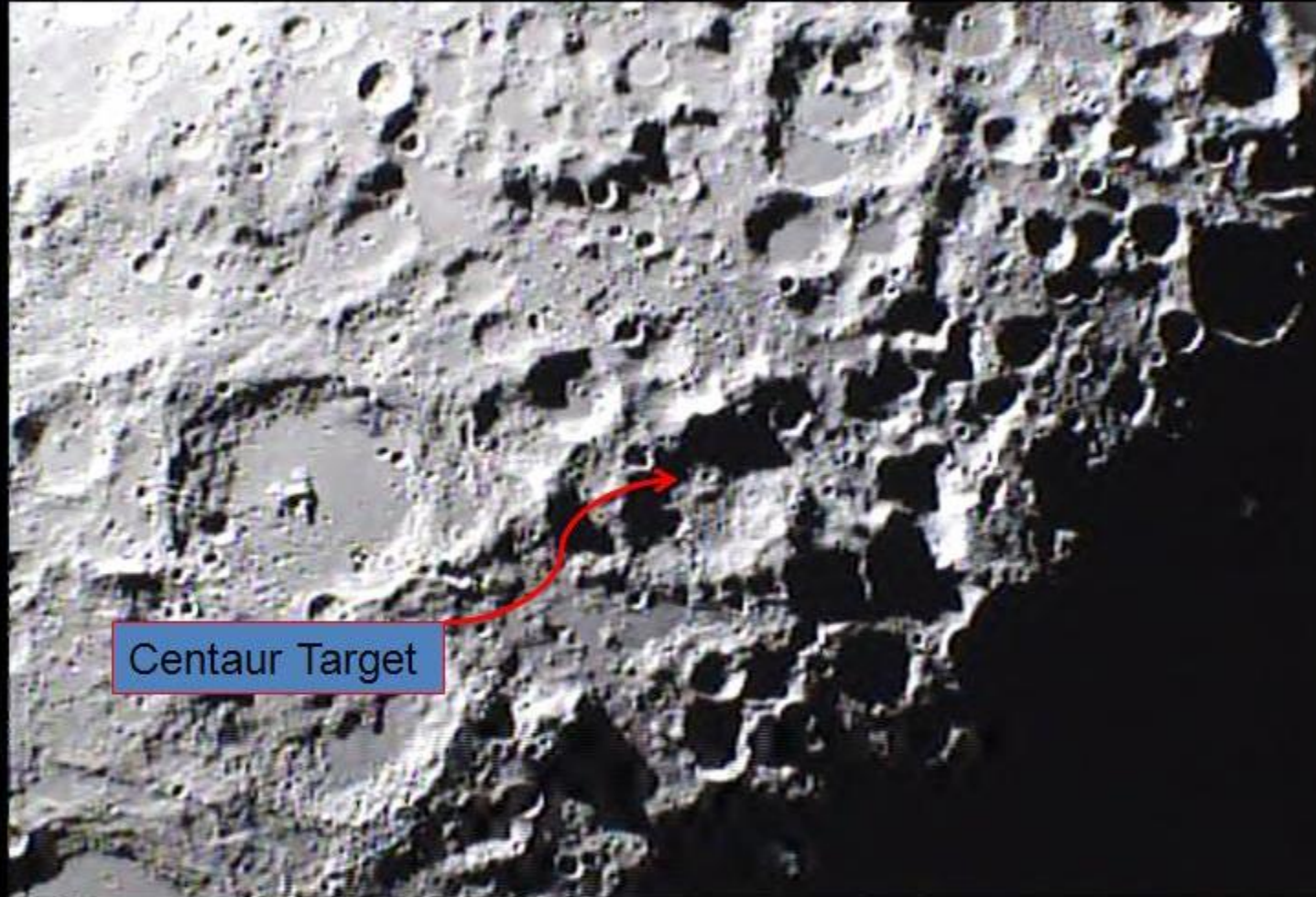
- **Orbiting spacecraft:** *active* multispectral reflectance measurements in the ultraviolet to near-infrared spectral range and/or *passive* multispectral emission measurements in the thermal infrared, for definitive detection and mapping of water and other volatiles within several micrometers of the surface
- **Impactor probes:** targeted, well characterized impacts to kinetically excavate the subsurface, observed from a separate Moon- or Earth-based platform in the ultraviolet to microwave spectral range to detect ice and vapor released at several distinct sites
- **Penetrator probes:** targeted, instrumented probes capable of detecting ices and quantifying their depth distribution at several distinct sites using neutron spectroscopy, mass spectroscopy, and/or tunable laser spectroscopy
- **Landers and rovers:** instrumented platforms with a drill or excavator, capable of measuring the composition and abundance of ices at the surface and subsurface within a relatively confined region of the Moon

Any light elements or compounds deposited on the lunar surface by possible out-gassing or comet fragments and meteorites are subject to direct exposure to the vacuum of space. Over the course of a lunar day, about 29 Earth days, all exposed surfaces of the moon are bathed in sunlight with daylight temperatures reaching up to 250° Fahrenheit (121° C.) Any ice exposed to sunlight for any length of time would turn into water vapor, break apart and be lost to space.

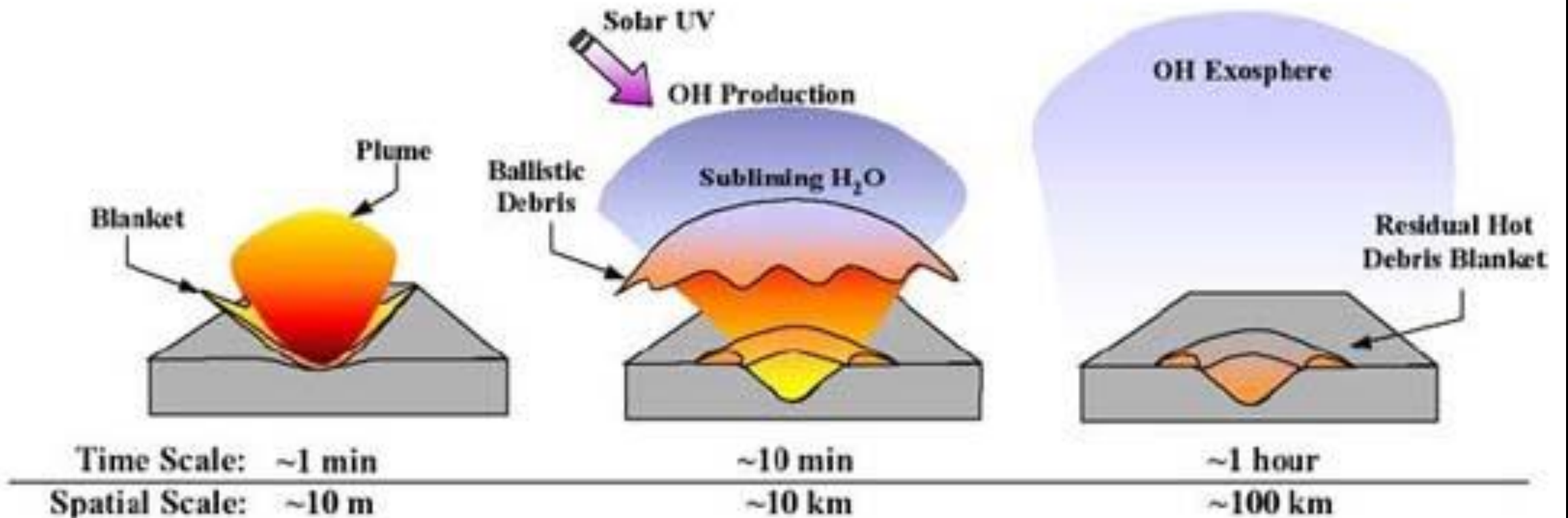
Water could only exist in areas of permanent shadow and those areas exist at the lunar poles. Some of these crater floors have not seen sunlight for possibly billions of years. Temperatures within these craters do not go above -280° F (-173° C) so they act as 'cold traps' where even light elements or compounds don't have enough energy to evaporate.



**Cabeus Crater, near South Pole, was the site of the LCROSS impact site, intended to observe water and volatiles in the ejecta plume.**



**LCROSS plume** <https://www.youtube.com/watch?v=ewW09godWVU>



# LCROSS

- Volatiles in LCROSS plume ejected from Cabeus Crater impact (9th Oct. 2009).
- Excavated top few metres of material at impact site (84.675°S, 311.275°E), deeper than neutron data represent ( $> \sim 0.7$  m).
- Mean H<sub>2</sub>O in plume detected as  $5.6 \pm 2.9$  % (155  $\pm$  12 kg).



See

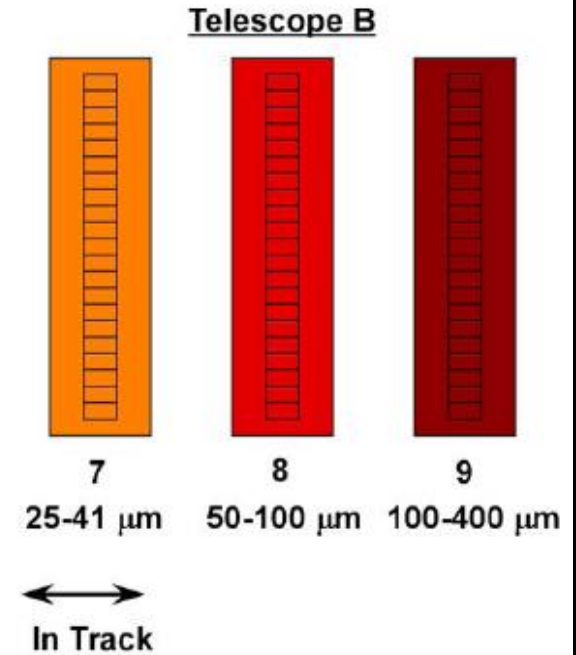
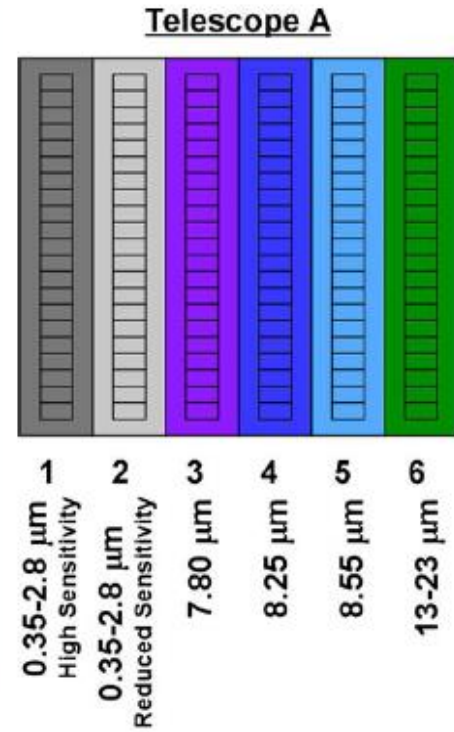
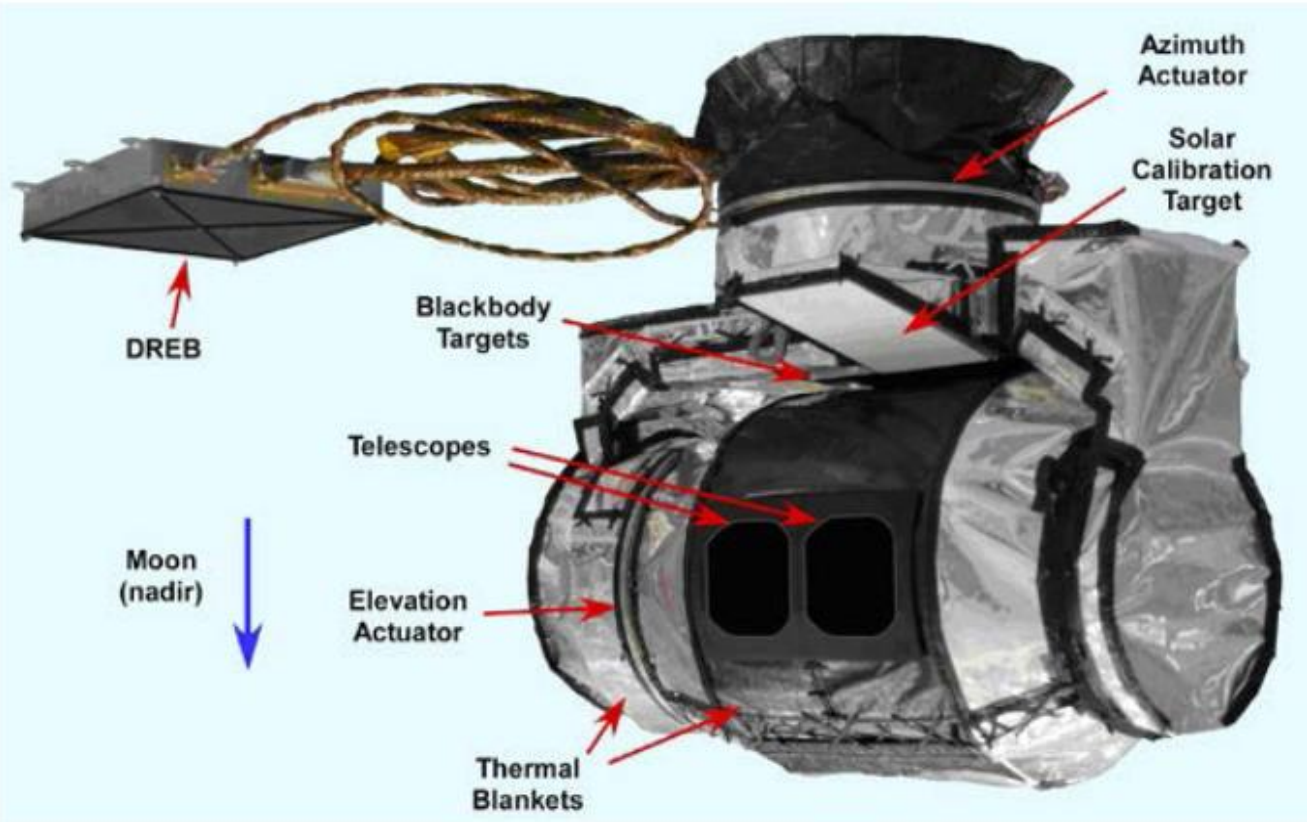
<https://www.youtube.com/watch?v=up1h-ziAK5E>

Compound	Molecules cm <sup>-2</sup>	% Relative to H <sub>2</sub> O(g)*
H <sub>2</sub> O	5.1(1.4)E19	100.00%
H <sub>2</sub> S	8.5(0.9)E18	16.75%
NH <sub>3</sub>	3.1(1.5)E18	6.03%
SO <sub>2</sub>	1.6(0.4)E18	3.19%
C <sub>2</sub> H <sub>4</sub>	1.6(1.7)E18	3.12%
CO <sub>2</sub>	1.1(1.0)E18	2.17%
CH <sub>3</sub> OH	7.8(42)E17	1.55%
CH <sub>4</sub>	3.3(3.0)E17	0.65%
OH	1.7(0.4)E16	0.03%

Colaprete et al. (2010), *Science*

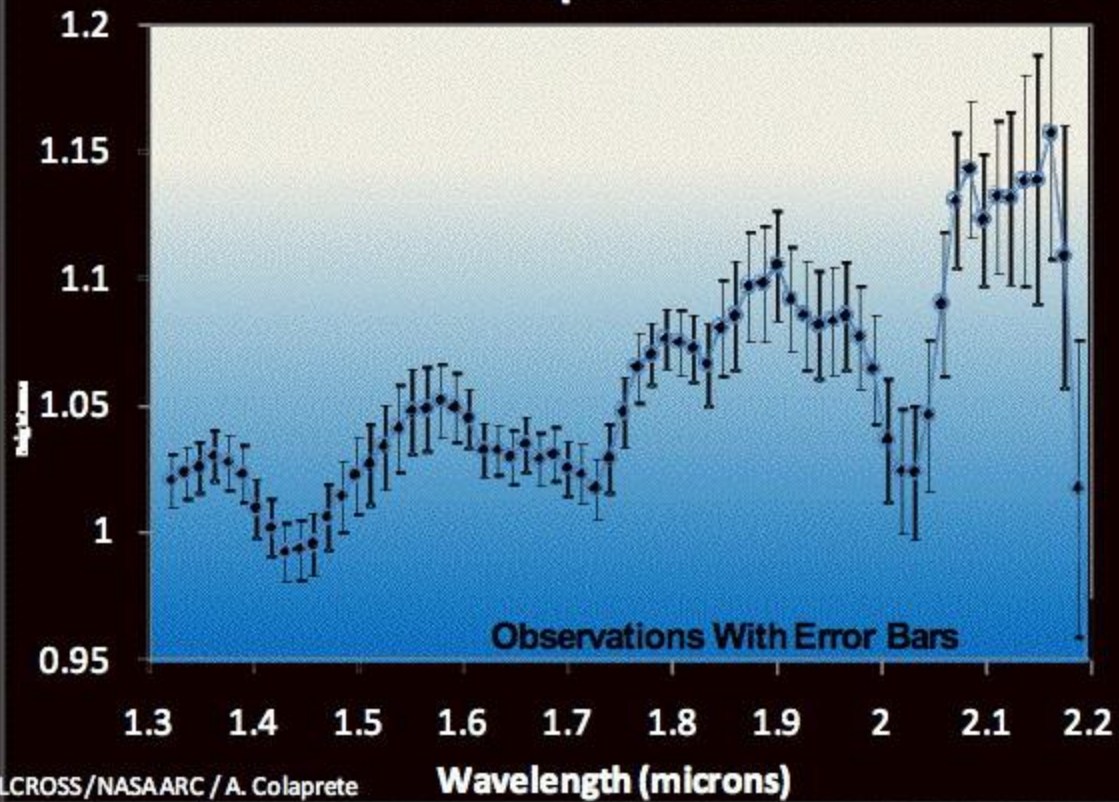
# LRO Diviner

## Multispectral camera observed LCROSS impact from lunar orbit

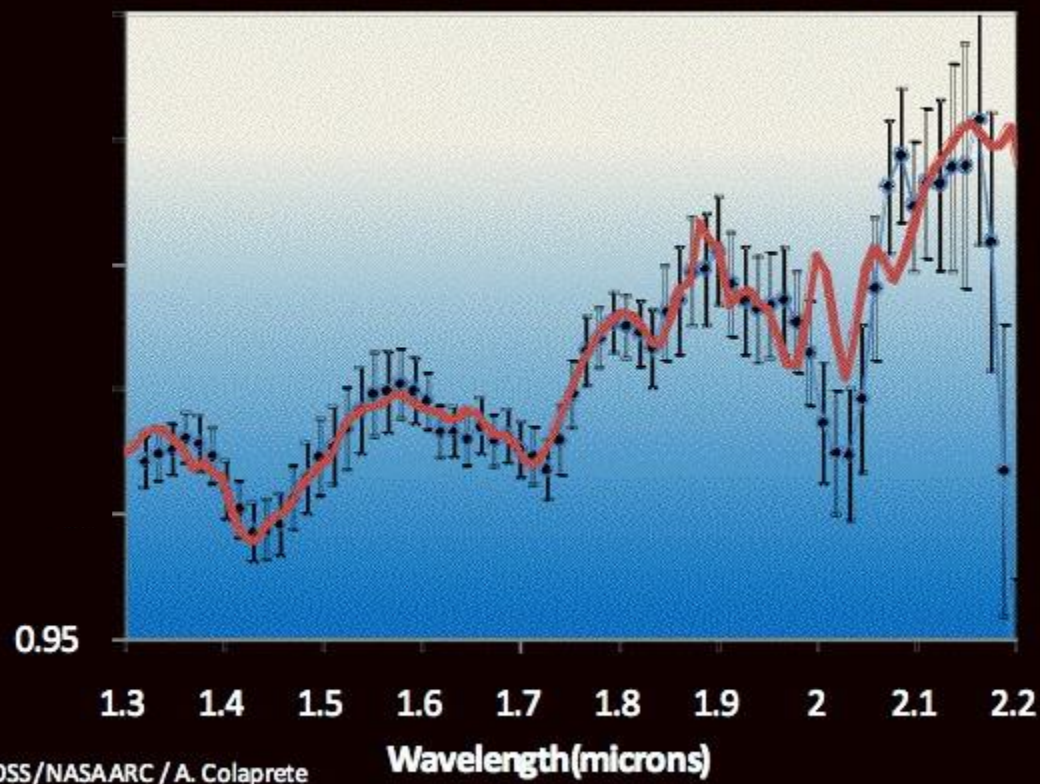


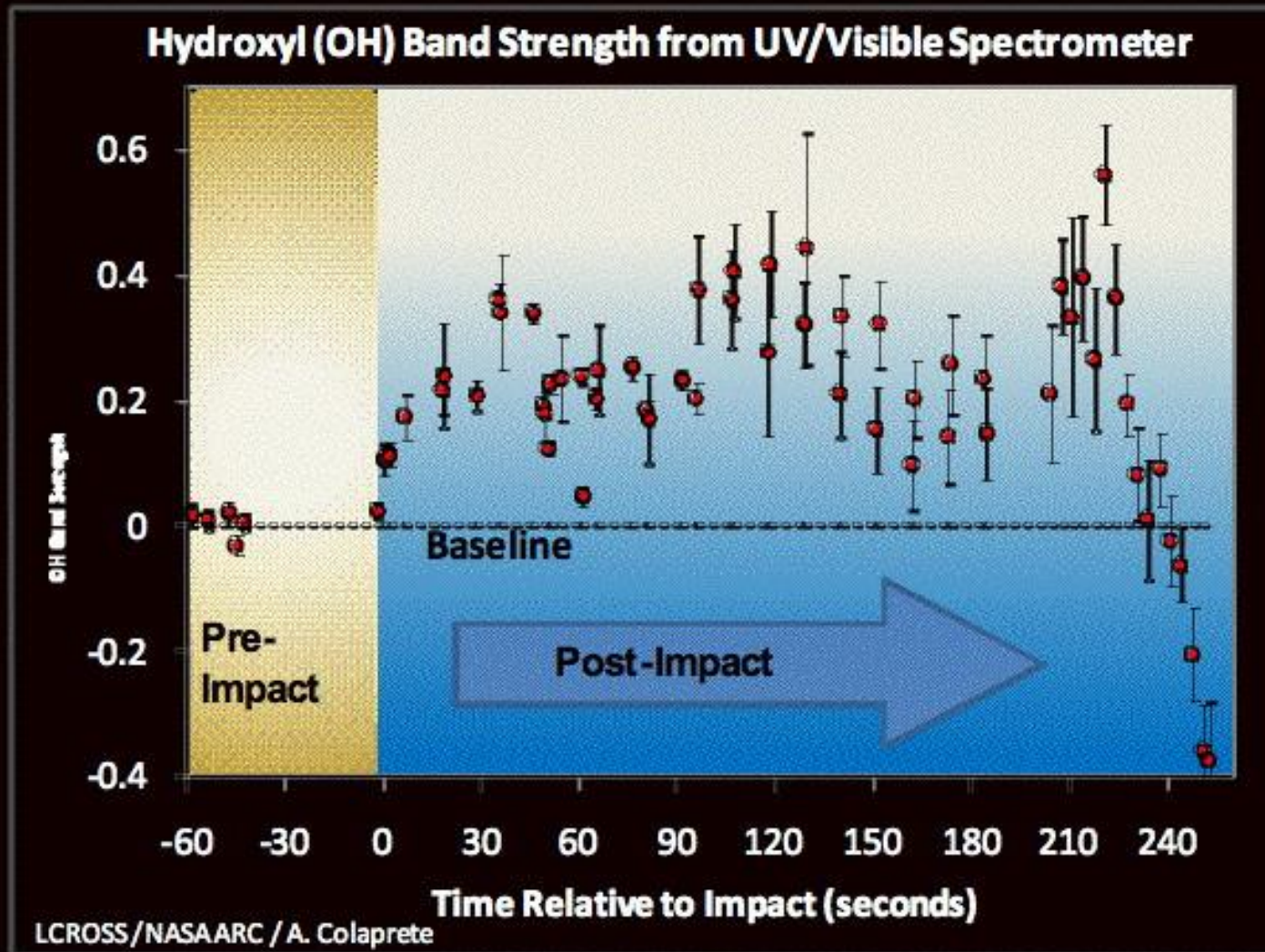


### LCROSS Near Infrared Spectrometer Observations

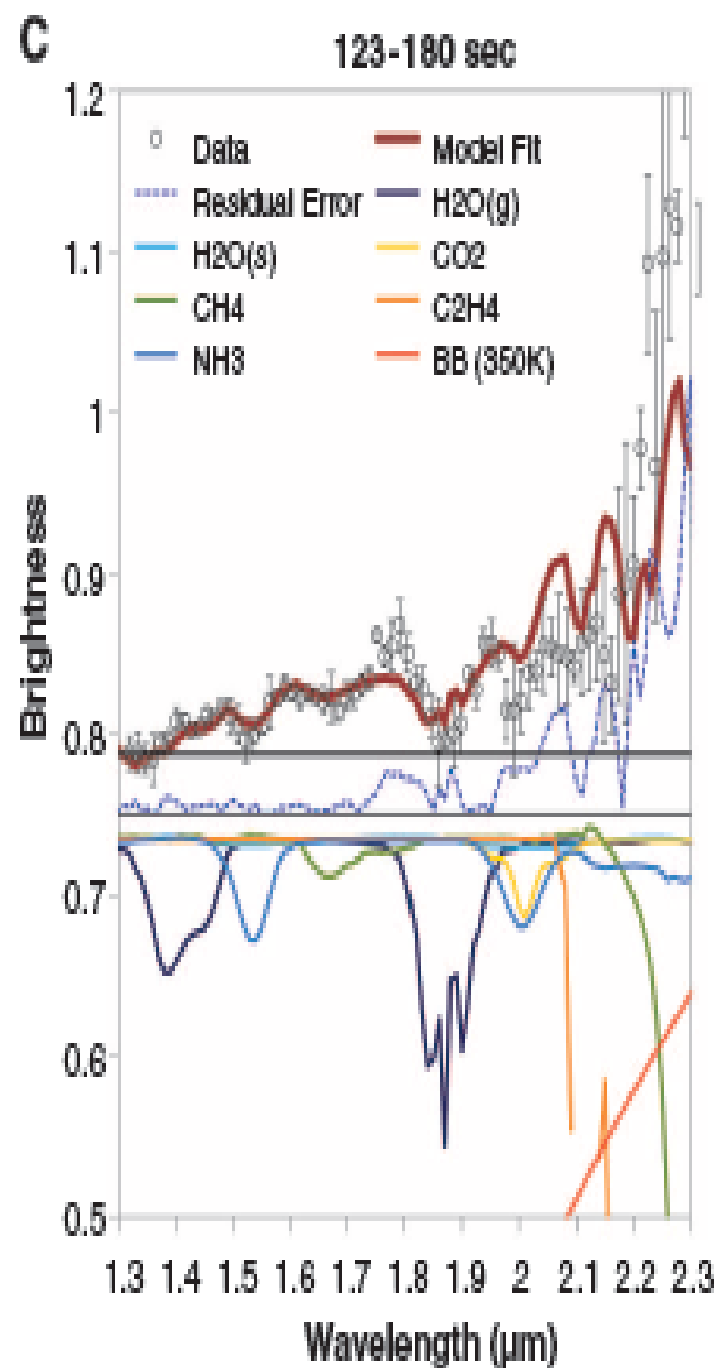
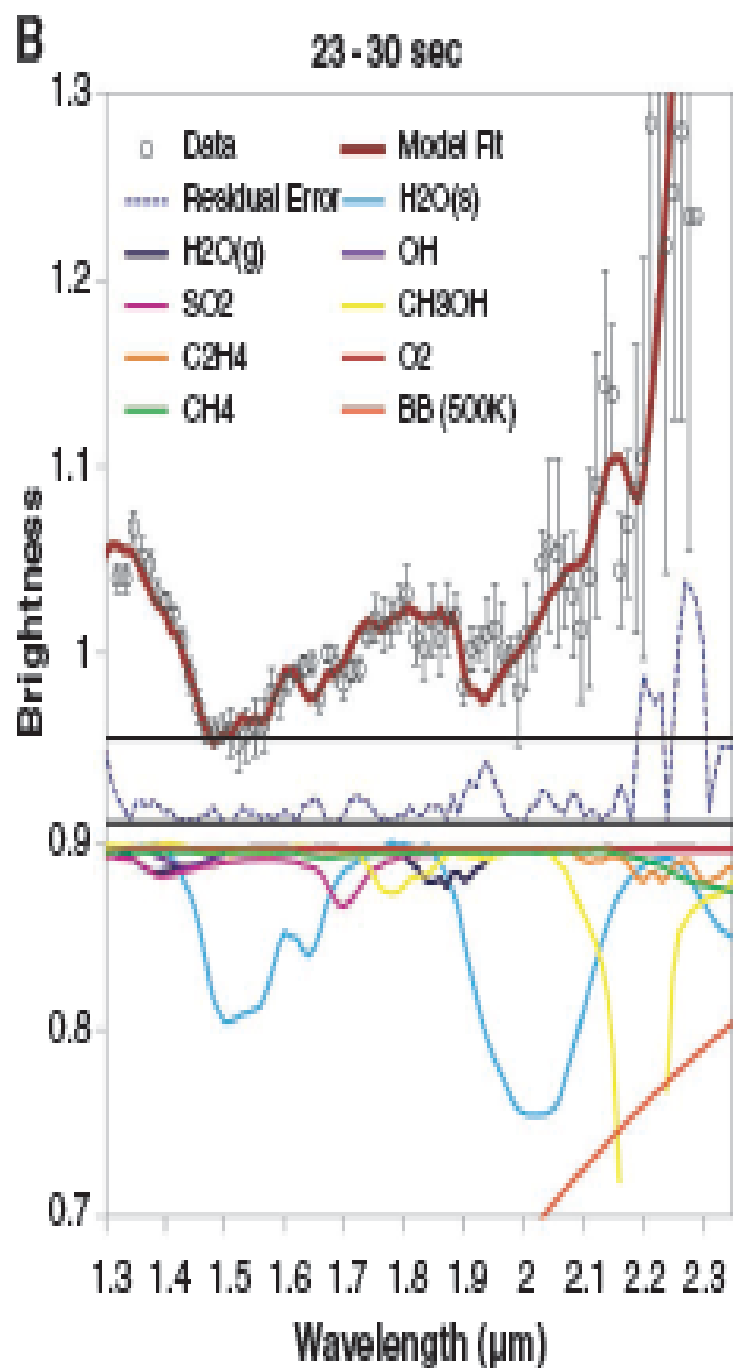
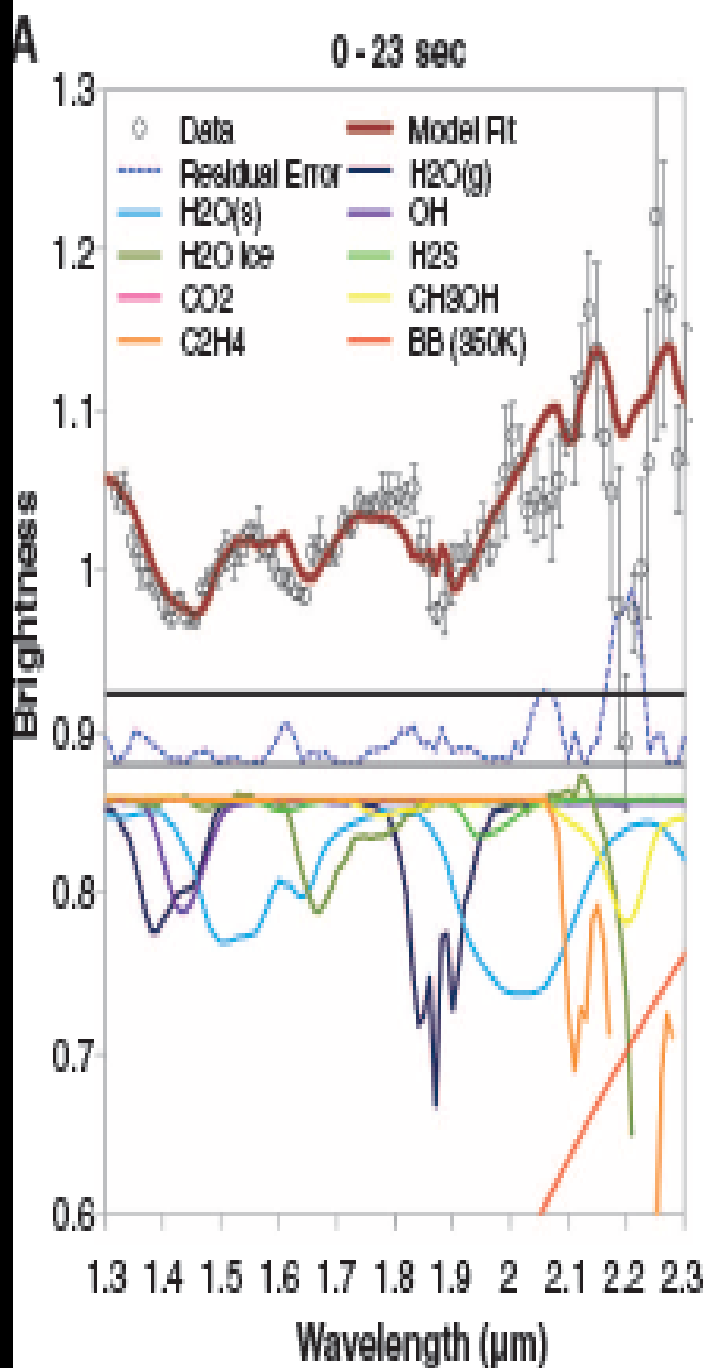


### LCROSS Observations with Model Fit





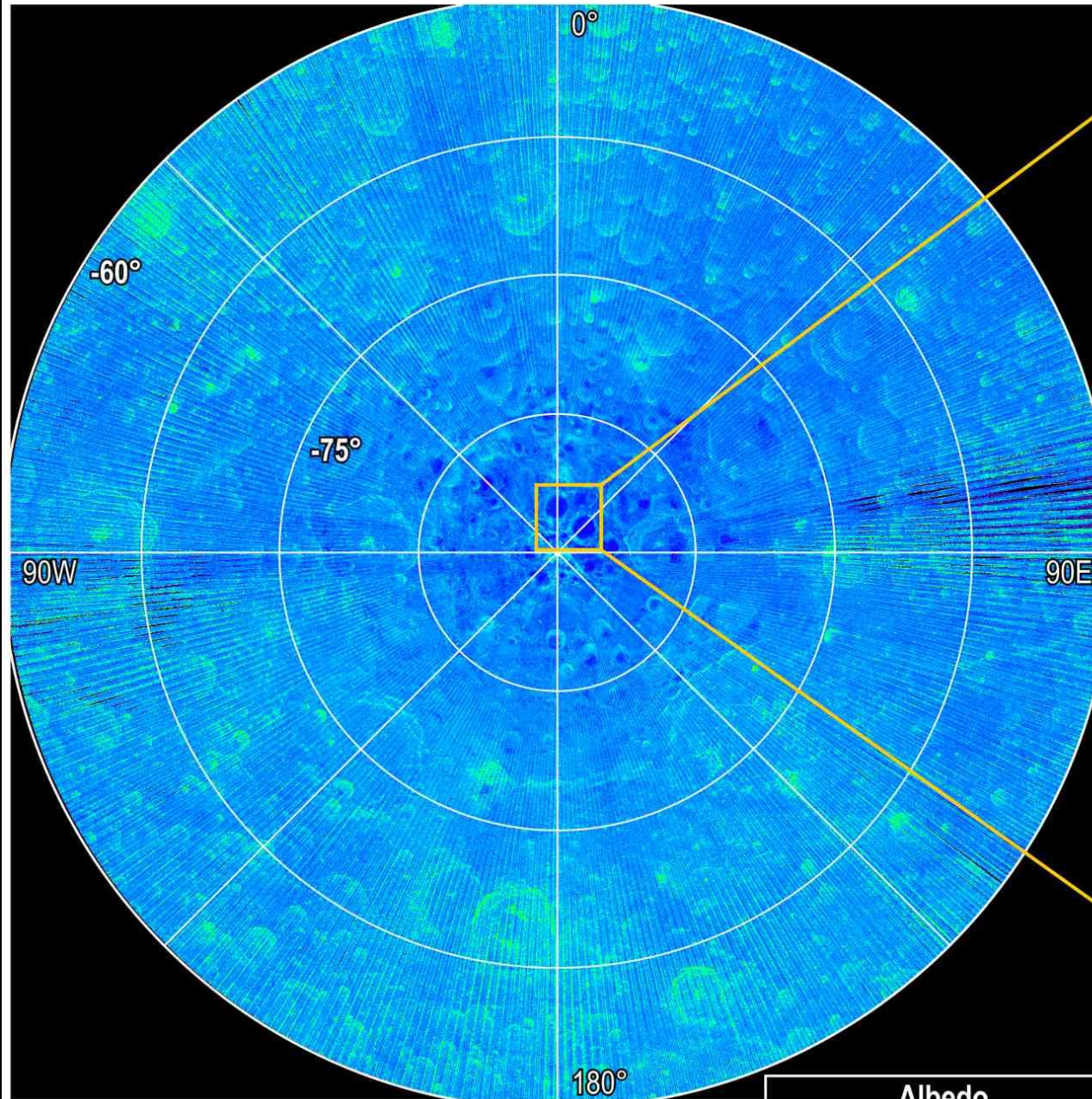
The OH emission lines strength plotted as a function of time. Before impact the line is flat (no OH). After impact the line strength grows and remains above the pre-impact baseline for several minutes.



UV reflectivity map of lunar south pole measured by the LAMP instrument on LRO

Lyman- $\alpha$  line is the first spectral line in the UV spectrum of hydrogen

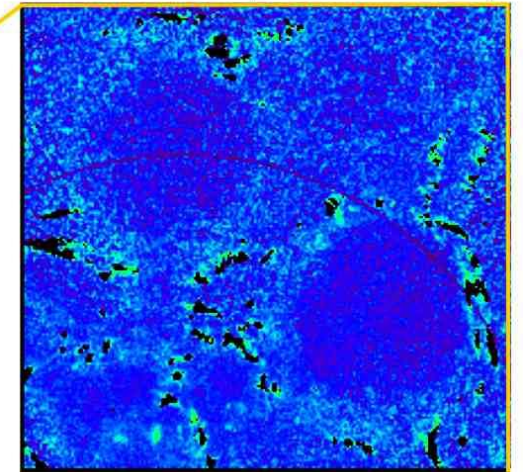
### South Pole Lyman- $\alpha$ Map



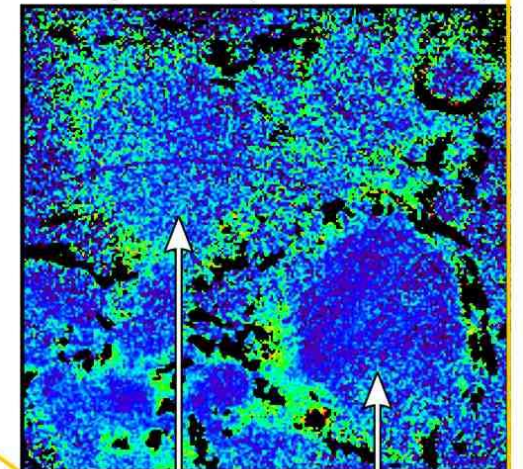
TA007636\_B



Surface Water Frost  
Shorter FUV (Frost Absorbs)



Longer FUV (Frost Reflects)



Haworth Crater:  
Brighter Longer FUV =>  
~1% Water Abundance

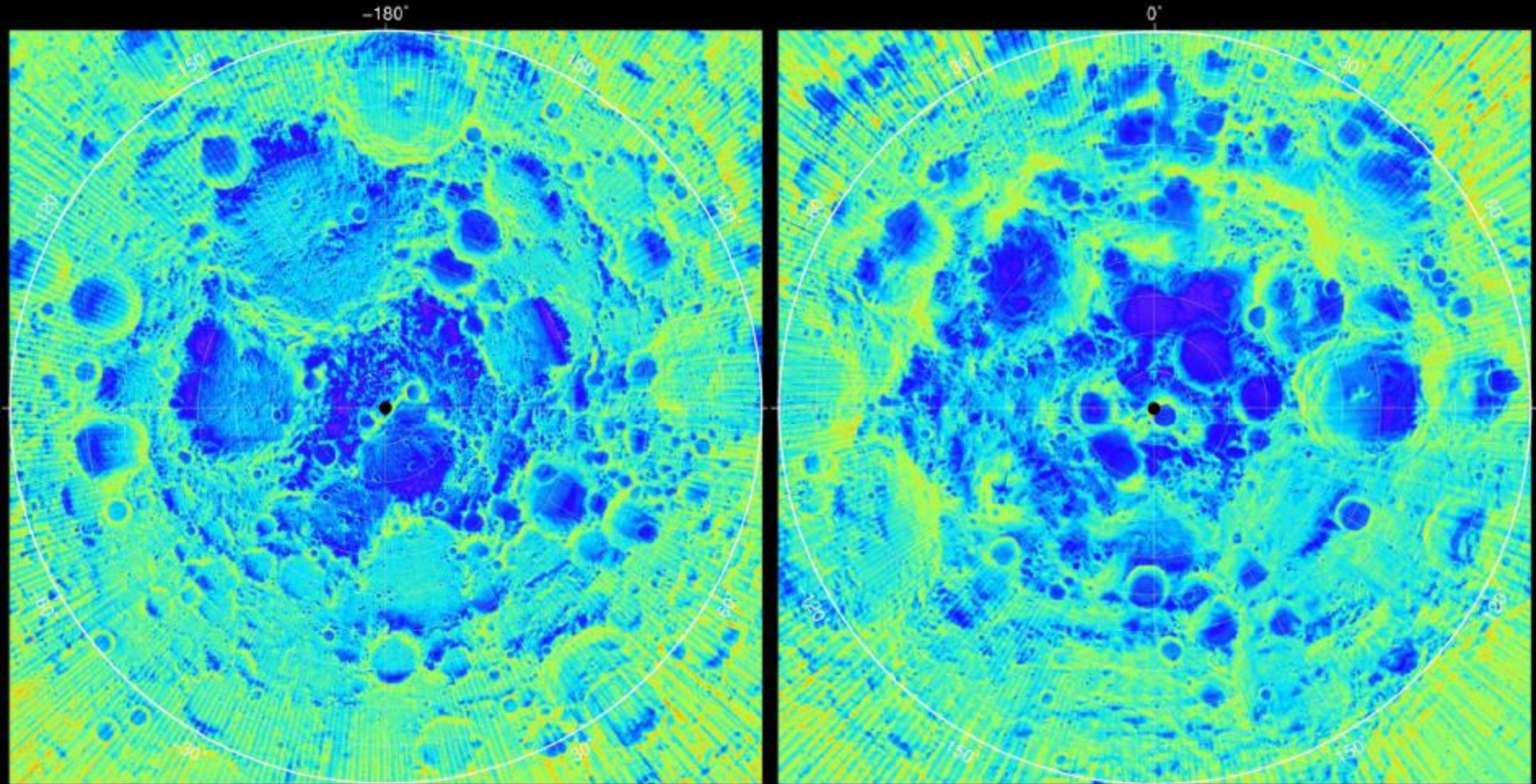
Shoemaker Crater:  
No Water Frost

# Diviner Observed Average Temperature

Reflectivity

North Pole

South Pole

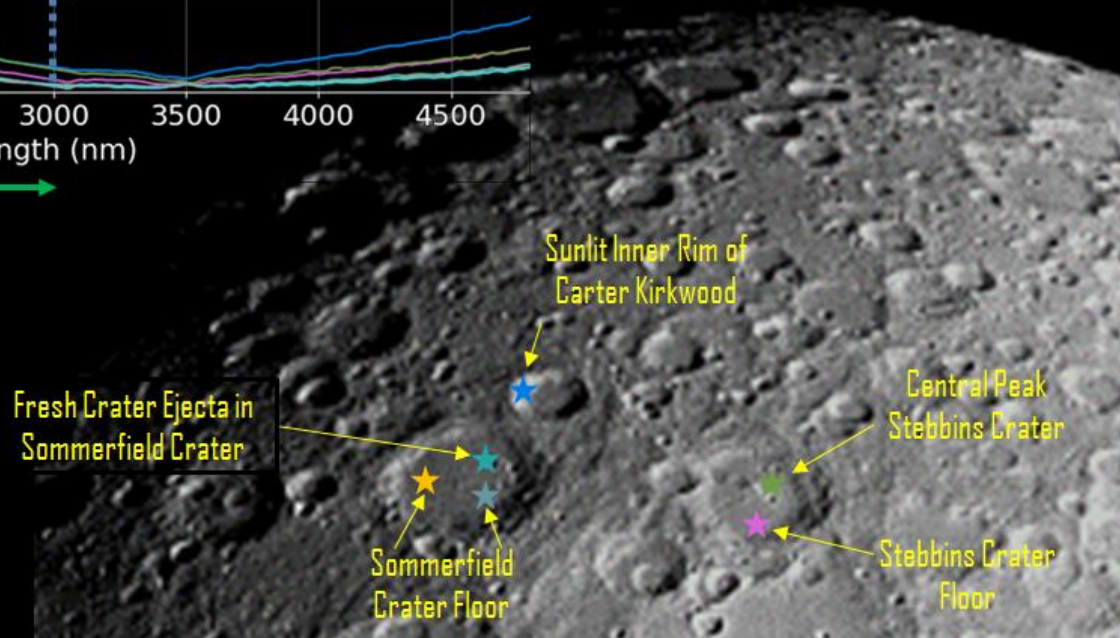
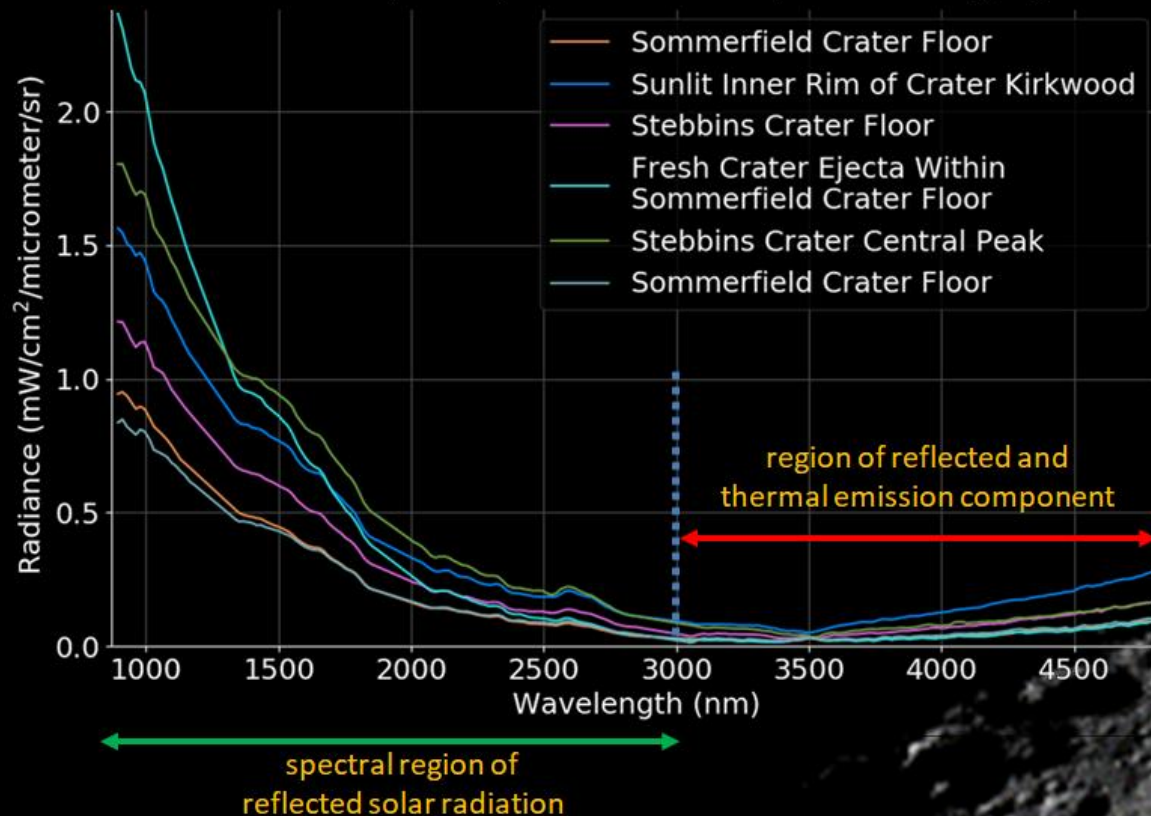


Average Bolometric Temperature



Average Bolometric Temperature

# Preliminary analysis of Chandrayaan-2 Imaging Infrared Spectrometer (IIRS) data



CHANDRAYAAN 2

## Results of various spectroscopic surveys, as reported in the KISS final report (see references in Canvas)

Shortwave-infrared spectroscopy has revealed an OH/H<sub>2</sub>O absorption band at high latitudes (>60° on both hemispheres) on the Moon, and, in one case, at both lunar terminators [Clark, 2009; Pieters et al., 2009; Sunshine et al., 2009], though it is

hydrocarbons, etc. The classic theory (WMB) envisioned exposed ice in large cold craters (cf. Vasavada et al., [1999]). Two variants of the classic storage geometry have been proposed: 1) the ice may be buried, and thus last at somewhat higher temperatures [Schorghofer, 2008; Paige et al., 2010], and 2) small shadows from large boulders and small craters near the poles may also act as cold traps resulting in a patchy distribution of ice with the resulting cumulative area being of comparable size to that of the large cold traps [Hayne et al., 2013a].

It remains unclear whether water ice in the PSRs could be exposed on the surface or only buried beneath the surface. If buried, it may have a layered structure, might be mixed with regolith by impact gardening, or distributed as impact ejecta. Some type of inhomogeneity can be expected in all cases.

**So: How do we look for water remotely?**

**By looking for reflection, emission, and absorption of H, OH, and H<sub>2</sub>O spectra according to what we understand of them by observation in the lab and modeling.**

**Why is water the signature of life?**



Liquid water is required for life to start<sup>c</sup> and for life to continue. No enzymes work in the absence of water molecules. No other liquid can replace water. We are very fortunate, therefore, that our planet is so well endowed. Water is a common material in the Universe, being found as widely dispersed gaseous molecules and as [amorphous ice](#) in tiny grains and much larger asteroids, comets and planets, but water needs particularly precise conditions to exist as a liquid as it does on Earth. It is most likely that this water arrived from multiple sources, such as comets and asteroids, somewhat after solid planet Earth was formed [[1015](#)].

Water possesses particular properties that cannot be found in other materials and that are required for life-giving processes (but see also [[1153](#)]). These properties are brought about by the [hydrogen-bonded environment](#) particularly evident in liquid water [[1423](#)]. Hydrogen bonds are roughly tetrahedrally and arranged such that when strongly formed the local clustering expands, decreasing the density. Such [low-density structuring](#) naturally occurs at low and supercooled temperatures and gives rise to many physical and chemical properties that evidence the [particular uniqueness of liquid water](#). If aqueous hydrogen bonds were actually somewhat stronger, then water would behave similar to a [glass](#), whereas if they were weaker then water would be a gas and only exist as a liquid at sub-zero temperatures.

[http://www1.lsbu.ac.uk/water/water\\_anomalies.html](http://www1.lsbu.ac.uk/water/water_anomalies.html)

## Consequences of changes in water's hydrogen bond strength

How much variation in water's hydrogen bond is acceptable for life to exist? A superficial examination gives the range of qualitative effects as indicated below.

Water hydrogen bond strength	Main consequence
No Hydrogen-bonding at all	No life
Hydrogen bonds slightly weaker	Life at lower temperatures
No change	Life as we know it
Hydrogen bonds slightly stronger	Life at higher temperatures
Hydrogen bonds very strong	No life

**If the hydrogen bonds in water were just a wee bit different, life as we know it would not exist**

