

# Effect of Space Weathering in Stimulating the Oxidation of Lunar Materials

## Part I: Fe Metal

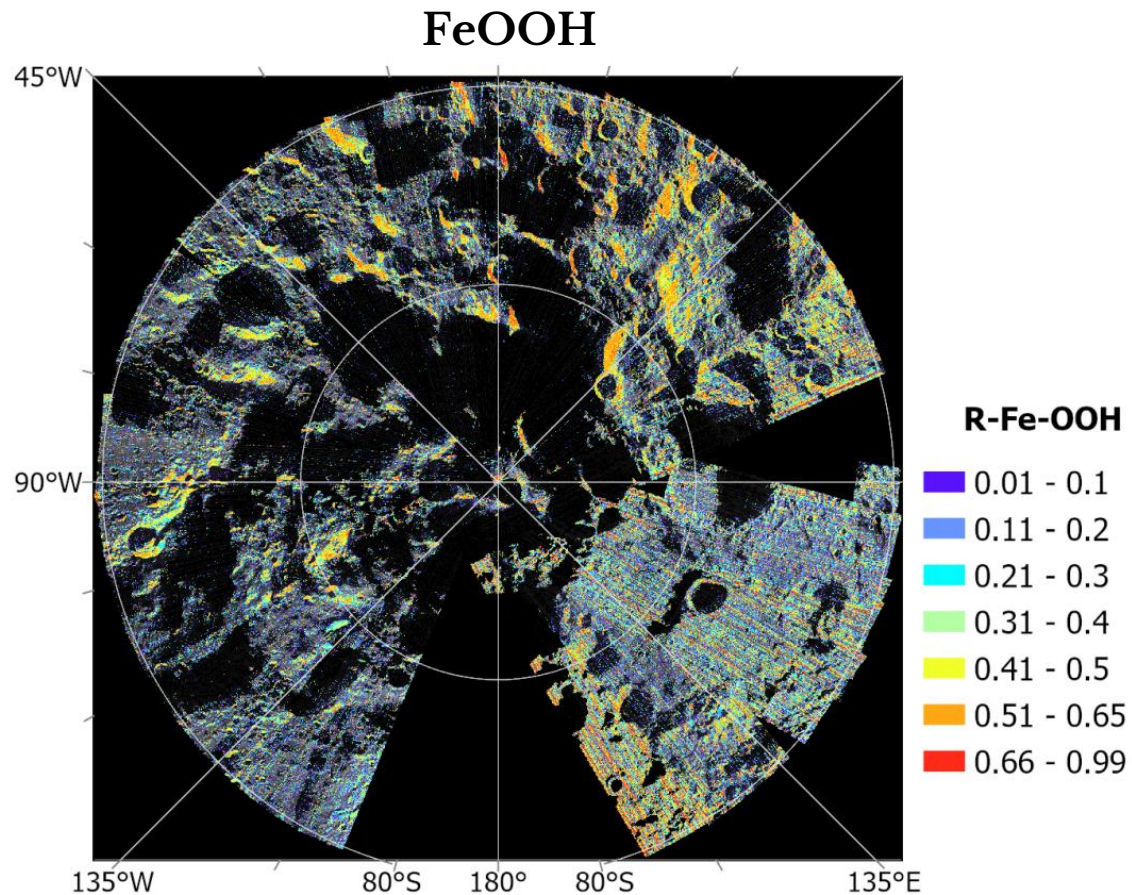
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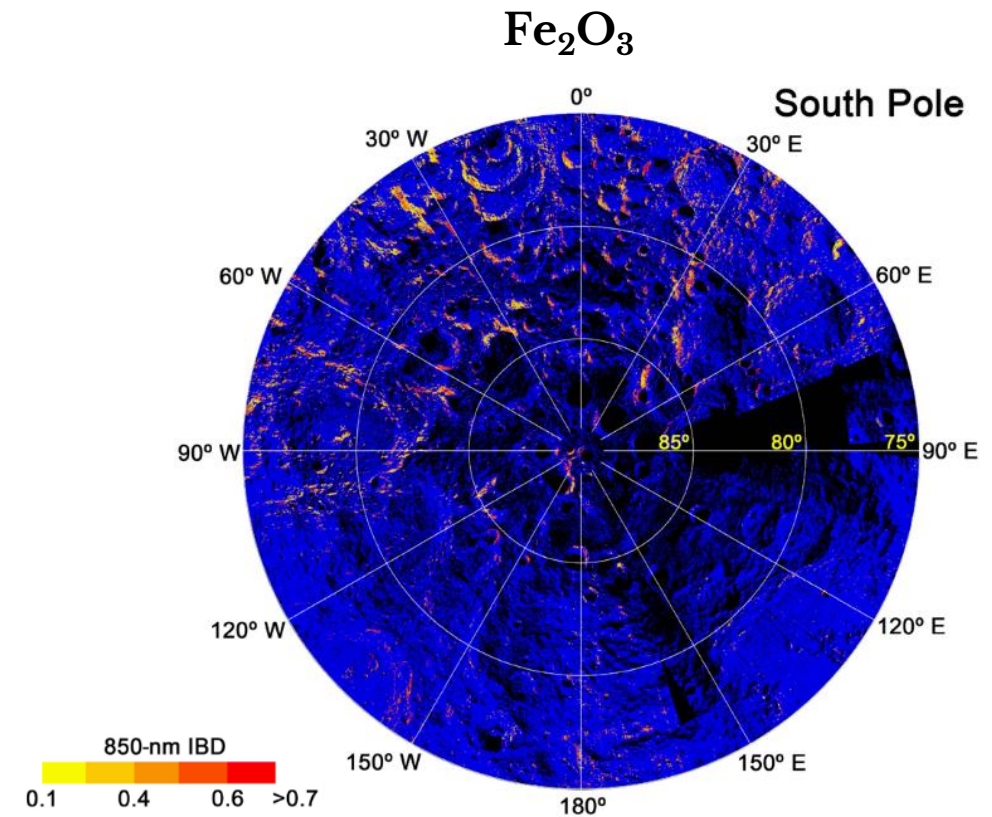
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# Introduction: M<sup>3</sup> data

Unexpected occurrence of iron (hydr)oxides on the Moon (polar regions)

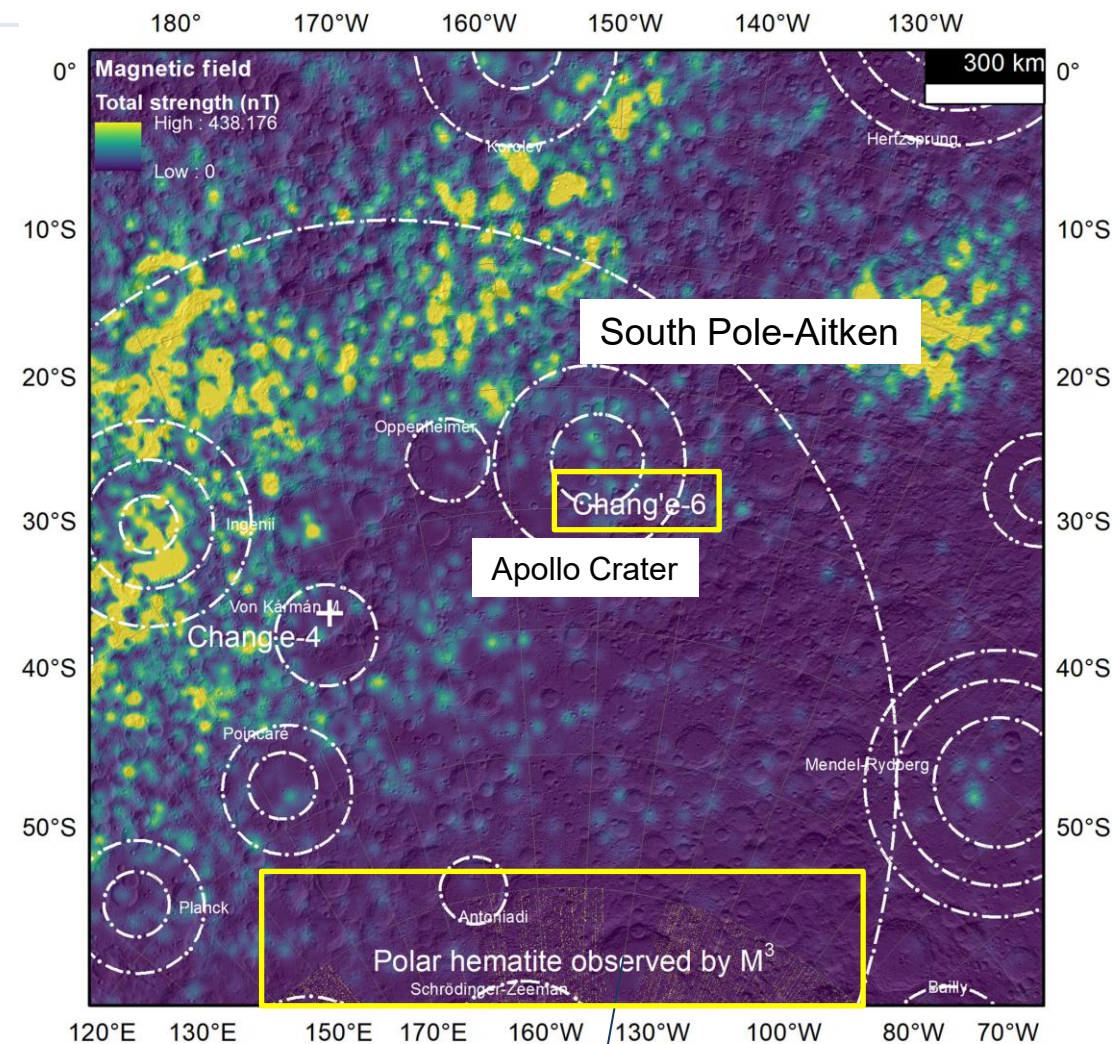
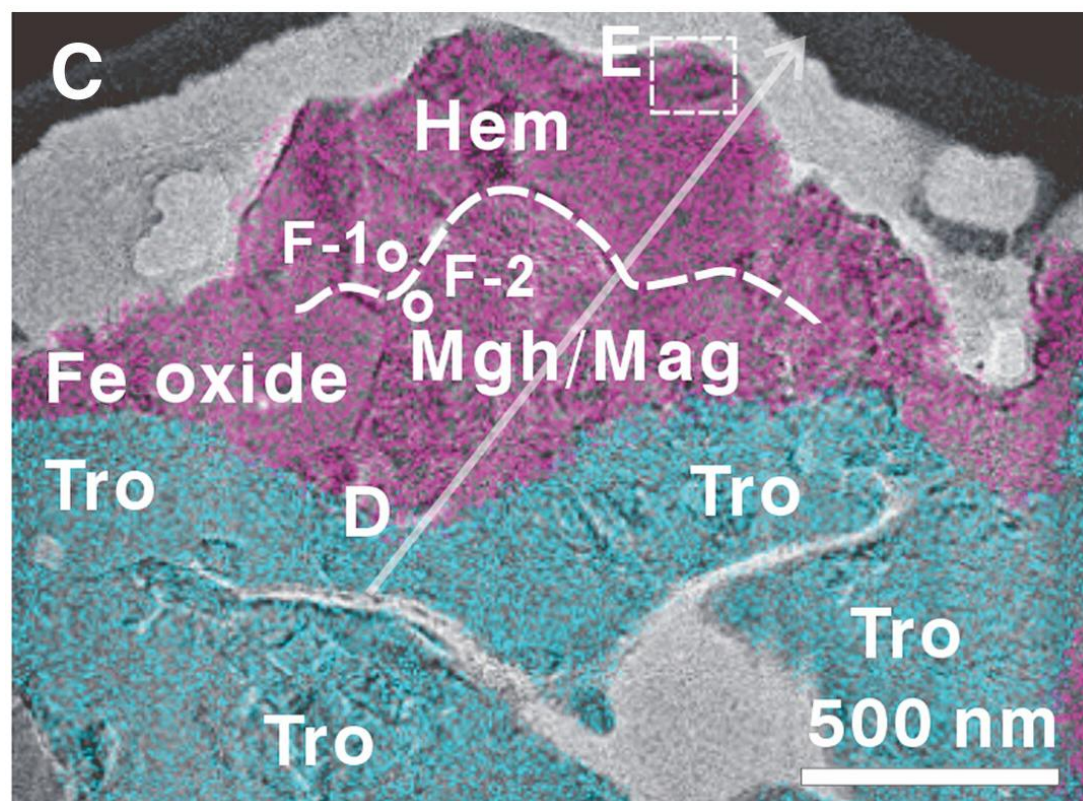


L. Sun et al., 2025



S. Li et al., 2020

# Iron oxides in Chang'e 6 sample



# Why do iron oxides form?



## Reduced condition

Overall lunar environment:  
1 log unit below the Iron-  
Wüstite buffer (IW-1).

**Should not form iron  
oxide**



## O<sup>+</sup> from Earth wind

S. Li et al., 2020 hypothesized  
liberated Fe<sup>2+</sup> by molecular  
water is oxidized by oxygen,  
forming goethite and hematite.

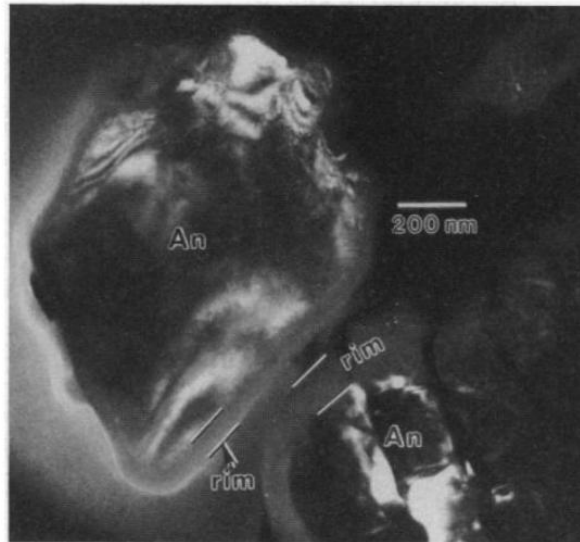


## Impact events

Y. Liu et al., 2025: Heat + O-  
rich plume can oxidize troilite  
(not limited to high latitudes)

# Our view: iron metal + O/H<sub>2</sub>O + electron impact

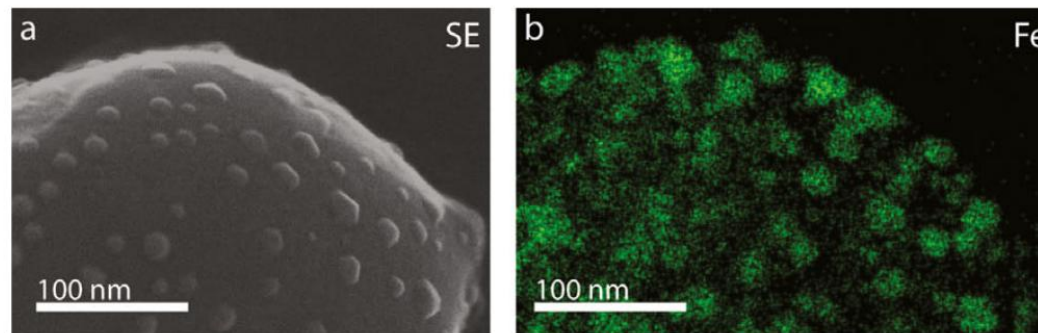
Fe<sup>0</sup> is present in lunar samples.



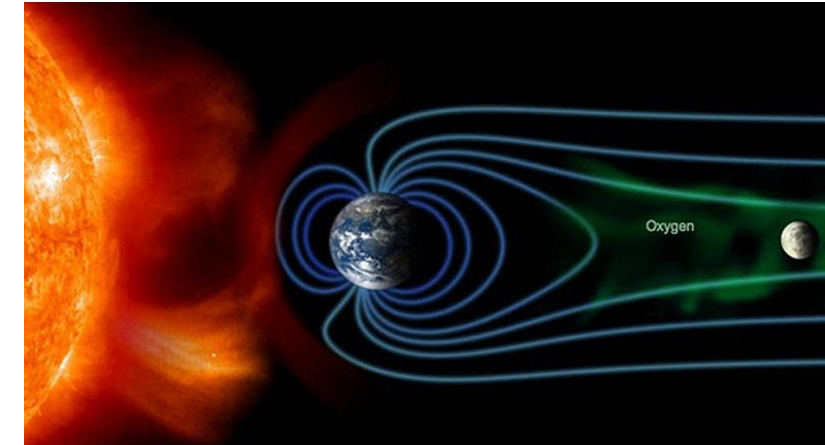
**Fig. 1.** Dark-field TEM image of anorthite (An) grains with amorphous rims from soil sample 61181. The rim on the grain in the lower right corner of the figure contains small (~5 nm) bright inclusions that are probably **Fe metal**.

Keller and McKay, 1993

Simulated space weathering can form nanophase Fe<sup>0</sup> (npFe<sup>0</sup>) on the surface of lunar soil grains.



Thompson et al., 2017



Credit: Osaka Univ.

+  
O and H<sub>2</sub>O in the lunar  
exosphere  
Vorburger et al., 2014,  
Reiss, 2024

+  
Solar wind → continuous  
electron impact

# Methodology: vacuum chamber with EEI + laser

Vacuum chamber: down to 0.1 mbar, Ar filled to 3 mb

Energetic Electron impact (EEI):  $\sim 275$  eV, flux= $10^{19}$  s<sup>-1</sup> m<sup>-2</sup>

Laser power density= $1.6 \times 10^8$  W/m<sup>2</sup>

Calculating residual oxygen in the chamber:

- Based on leak rate and 3 purges:  $2 \times 10^{-6}$  mbar
- Based on O<sub>I</sub>\* emission line in plasma:  $7 \times 10^{-3}$  mbar

(O<sub>I</sub>\* emission line caused by breakdown of residual O<sub>2</sub> and H<sub>2</sub>O)



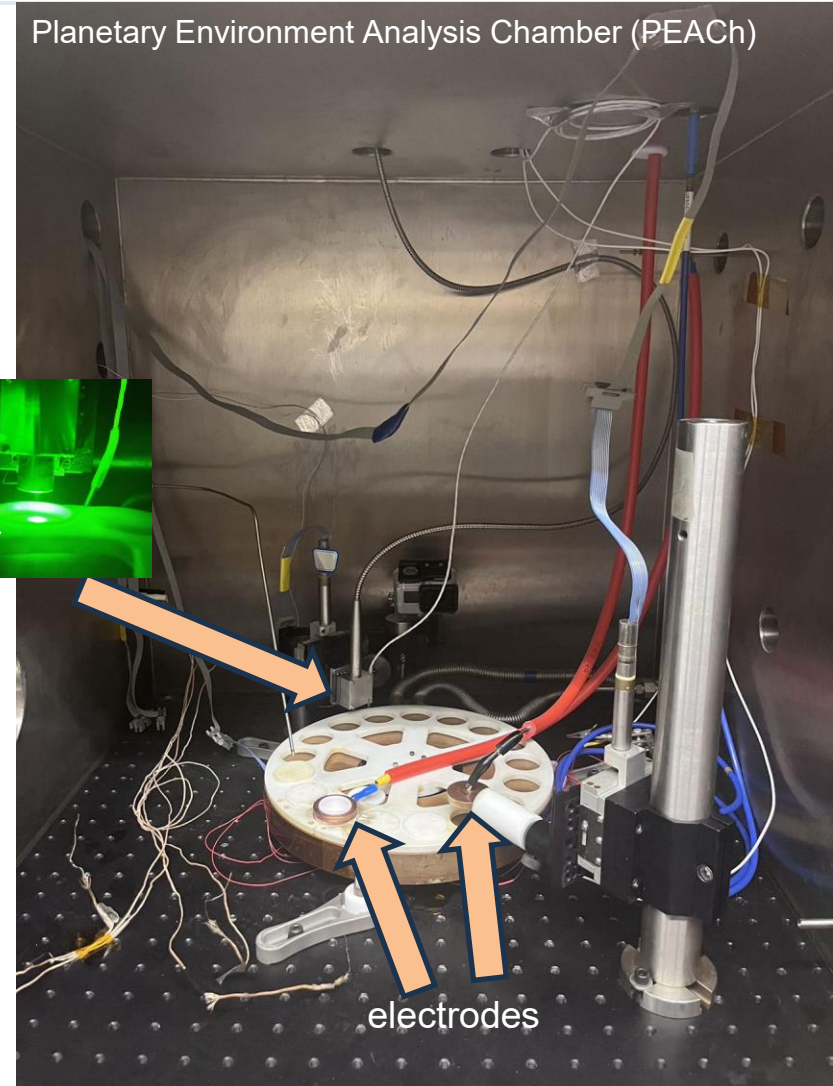
Sample: 1 g Fe powder <150  $\mu$ m



EEI (in between electrodes)



Laser



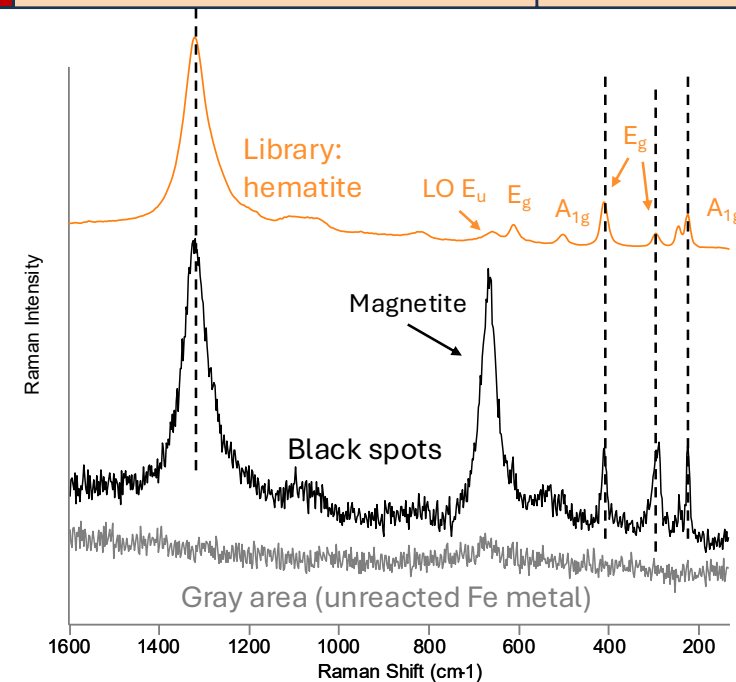
electrodes

# Key findings: oxidation of Fe

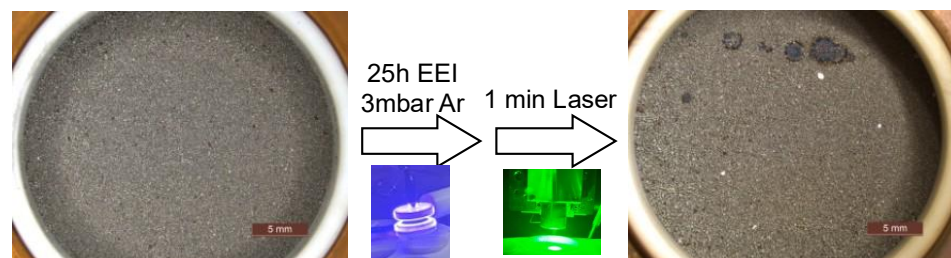
EEL only  
in Ar



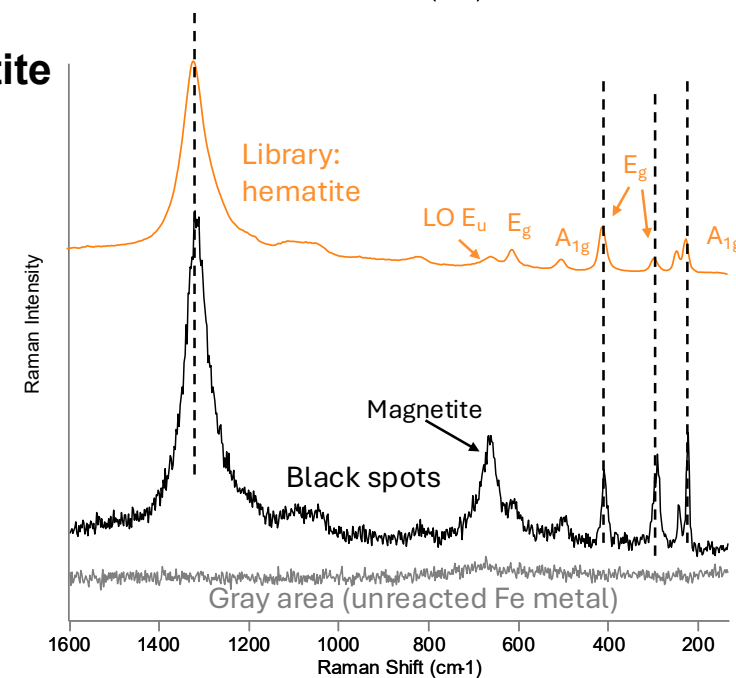
EEL only  
in Ar



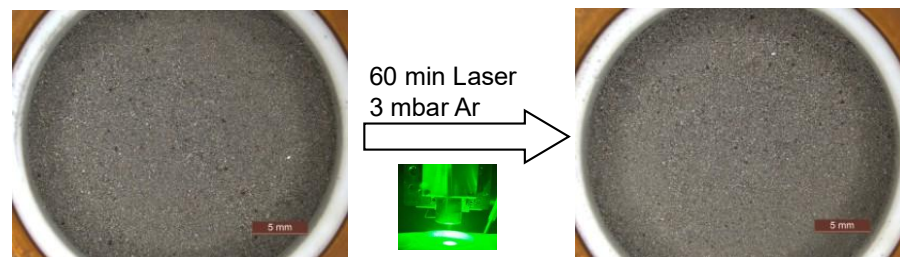
EEL+laser  
in Ar



Raman spectra of  
black spots are  
hematite + magnetite

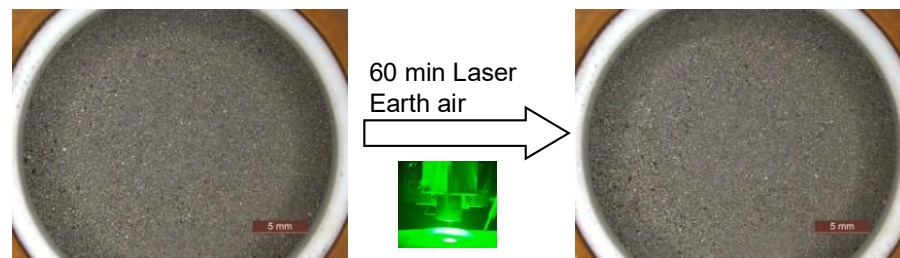


Laser only  
in Ar



EEL+laser  
in Ar

Laser only  
in air

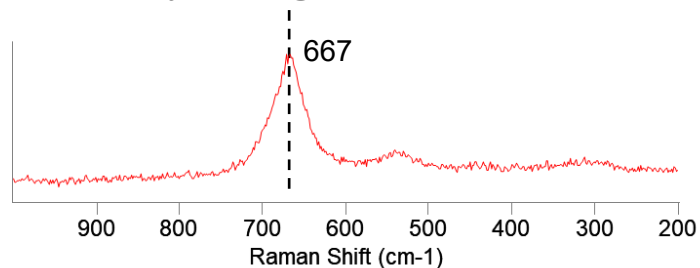


# Aqueous alteration of Fe only forms magnetite

## Aqueous alteration experiment

50 mg Fe powder,  
1 ml water,  
1% oxygen in air  
Sealed container  
90 °C

Only magnetite seen



Start



10 days



20 days

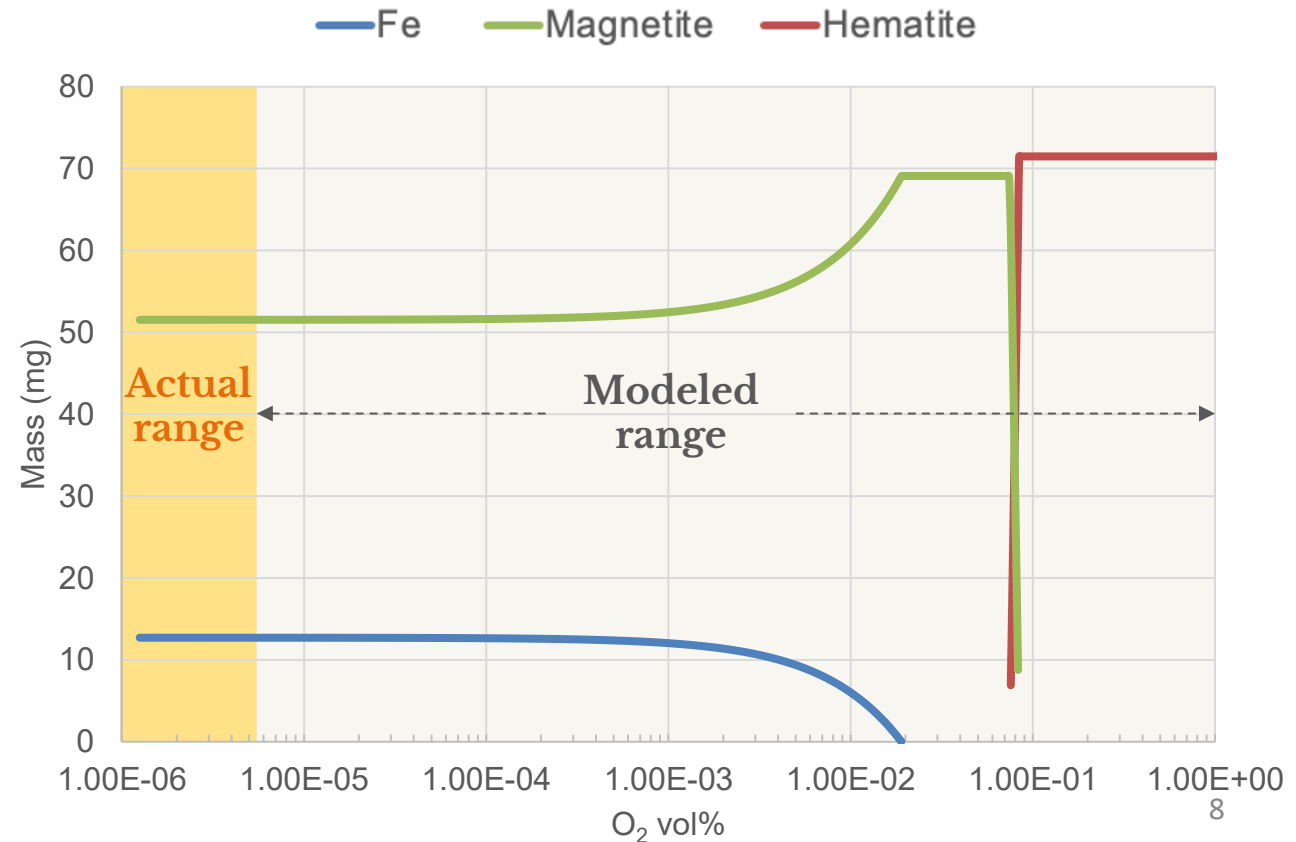


30 days

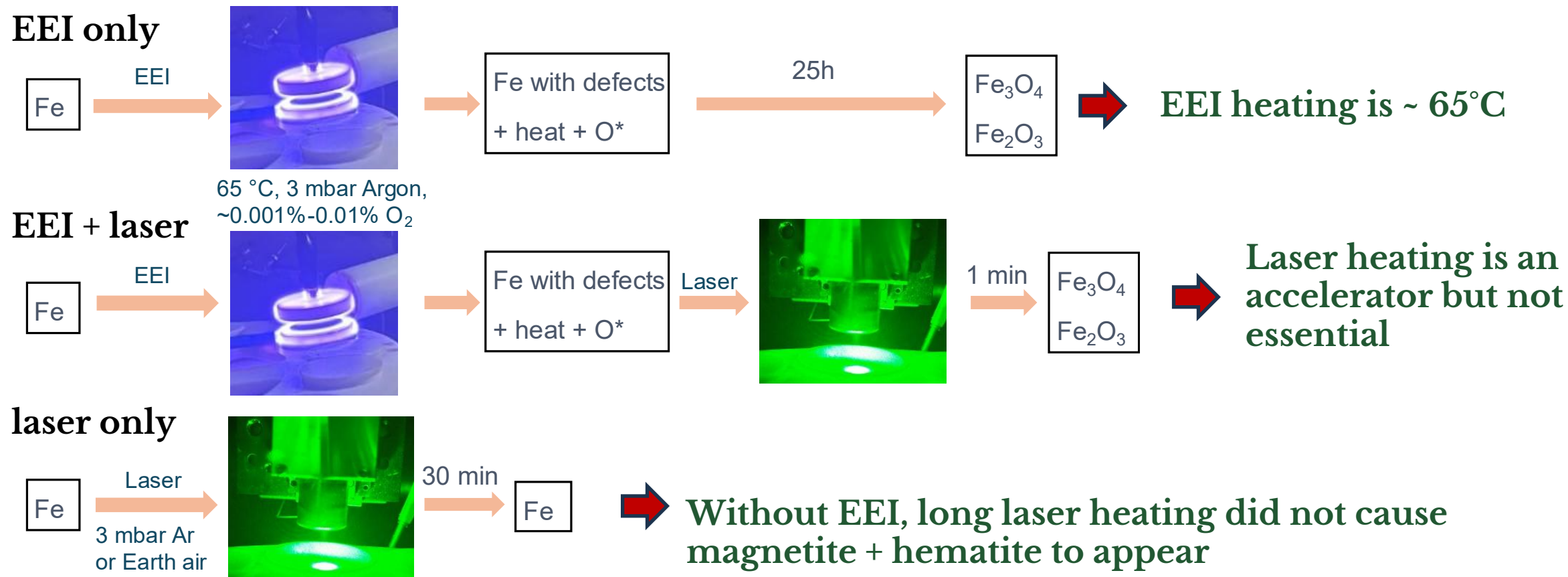


## Chemical modelling

1 g Fe powder, 20 ml water, how much O<sub>2</sub> inside our vacuum chamber



# EEI is the key in the abnormal formation of hematite



# EEI must have generated activated grain surface

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EEI might cause:

- Structural amorphization at the grain surface — (to test with TEM)
- Additional 100 nm size of Fe — (to test with SEM images)
- Unsatisfied bonds at the grain surface (or free radicals attached) — (to test with XPS)
- Frenkel defect (atom displacement)

# Conclusions



EEI (simulating space weathering) created reactive grain surface (e.g., defects in Fe structure), and when combined with heating, hematite can form even when  $O_2$  concentration is lower than chemical model predictions.

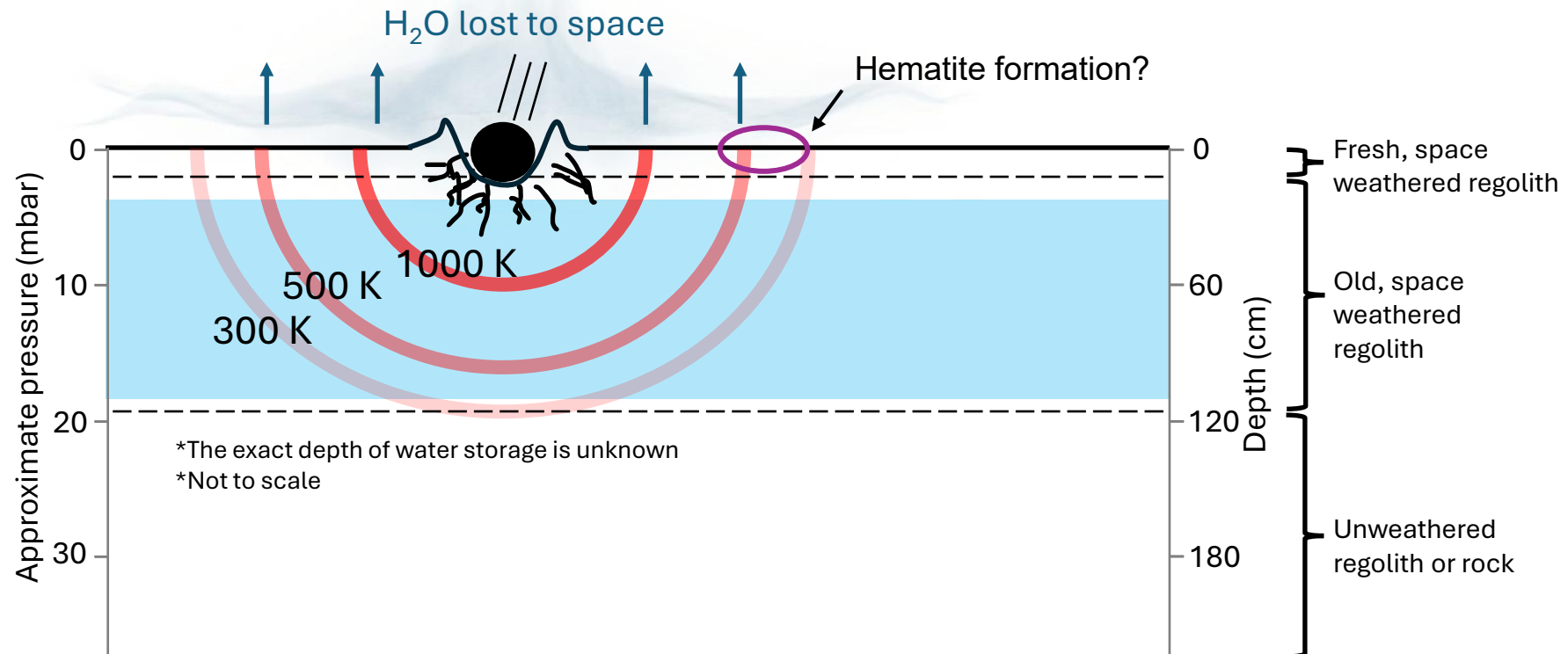
Considering the real lunar environment: electron impacted  $npFe^0$  can form hematite in the presence of water vapor (or O), impact events expedite this process. → More hematite in the polar regions.

This result does not conflict with other hypotheses. Our hypothesis might only partially contribute to hematite formation in actual lunar conditions.

Currently working with coarse Fe grains, will use  $npFe^0$  in the future.

# Next step experiments

- Next step-1: npFe<sup>0</sup> -bearing grains (space weathered), to see if hematite forms.
- Next step-2: Fe-bearing silicates, to see the structural changes and hematite formation



# Thank you

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# References

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- Li, S., Lucey, P. G., Fraeman, A. A., Poppe, A. R., Sun, V. Z., Hurley, D. M., & Schultz, P. H. (2020). Widespread hematite at high latitudes of the Moon. *Science Advances*, 6(36), eaba1940. <https://doi.org/10.1126/sciadv.aba1940>
- Sun, L., & Lucey, P. G. (2025). Detection of FeOOH in Lunar Polar Region Using Moon Mineralogy Mapper Data. *56th Lunar and Planetary Science Conference, LPI Contribution*, 3090, 1430. <https://ui.adsabs.harvard.edu/abs/2025LPICo3090.1430S/abstract>
- Liu, Y., Cao, H., Li, R., Chen, J., Yin, C., Jia, Z., Lu, X., Qiao, L., Fu, X., Liu, C., Li, C., Xin, Y., Lu, Y., Zeng, X., Liu, J., Li, Y., & Ling, Z. (2025). Discovery of crystalline Fe<sub>2</sub>O<sub>3</sub> in returned lunar soils. *Science Advances*, 11(46), eady5169. <https://doi.org/10.1126/sciadv.ady5169>
- Keller, L. P., & McKay, D. S. (1993). Discovery of Vapor Deposits in the Lunar Regolith. *Science*, 261(5126), 1305–1307. <https://doi.org/10.1126/science.261.5126.1305>
- Thompson, M. S., Zega, T. J., & Howe, J. Y. (2017). In situ experimental formation and growth of Fe nanoparticles and vesicles in lunar soil. *Meteoritics & Planetary Science*, 52(3), 413–427. <https://doi.org/10.1111/maps.12798>
- Vorburger, A., Wurz, P., Barabash, S., Wieser, M., Futaana, Y., Holmström, M., Bhardwaj, A., & Asamura, K. (2014). First direct observation of sputtered lunar oxygen. *Journal of Geophysical Research: Space Physics*, 119, 709–722. <https://doi.org/10.1002/2013ja019207>
- Reiss, P. (2024). Exploring the lunar water cycle. *Proceedings of the National Academy of Sciences*, 121. <https://doi.org/10.1073/pnas.2321065121>