TransFormers for Ensuring Long-Term Operations in Lunar Extreme Environments

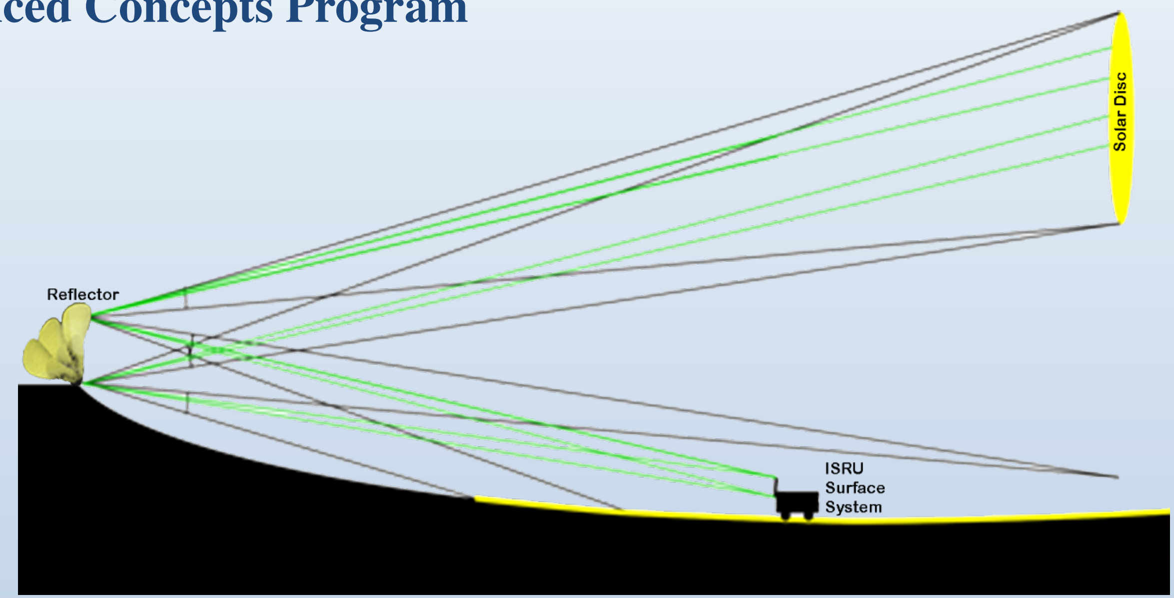
Ensuring Long-Term Operations in Regions of Darkness and Low Temperatures

NASA Innovative Advanced Concepts Program
NIAC Phase II Study

James Mantovani[1]

Adrian Stoica (PI) [2],
Brian Wilcox[2],
Leon Alkalai[2],
Michael Ingham[2],
Marco Quadrelli[2],
Leslie Tamppari[2],
and Karl Mitchell[2]

[1]NASA Kennedy Space Center
[2]Jet Propulsion Laboratory



SWAMP WORKS
NASA KENNEDY SPACE CENTER

Jet Propulsion Laboratory
California Institute of Technology

Space Resources Roundtable

Planetary & Terrestrial Mining Sciences Symposium

June 7 - 9, 2016 Golden, CO

Can the Moon become a cost-effective base to develop ISRU capabilities to extend human presence from beyond low-Earth orbit to Mars and the asteroids?

C. Miller et al. (2015). ”Economic Assessment and Systems Analysis of an Evolvable Lunar Architecture that Leverages Commercial Space Capabilities and Public-Private-Partnerships”
http://science.ksc.nasa.gov/shuttle/nexgen/Nexgen_Downloads/NexGen_ELA_Report_FINAL.pdf

TransFormers for Extreme Environments - Concept

TransFormers are a new class of robotic space systems that use shape/function transformation/change to project energy - *inducing a favorable micro-environment at the locale where exploration takes place* - e.g. robots exploring permanently shadowed craters, allowing them survive the extreme cold and darkness.

TransFormers add a new perspective to surviving Extreme Environments:
Instead of *coping with the environment*, *change the environment*

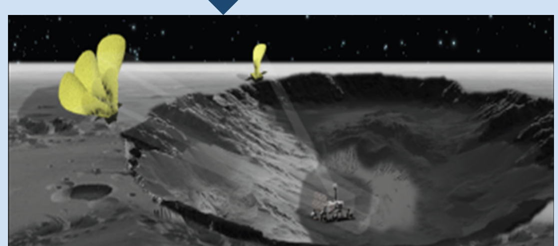
Sunny ?

Yes

Make a survivable micro-environment, bringing in remote resources

No

RTG



No direct Sun, then bring in the Sunlight

Use *local resources* (on-platform energy generation/storage)

NIAC Study Phase I and II
Assess TransFormer (TF) powered exploration and ISRU at Shackleton Crater (SC)

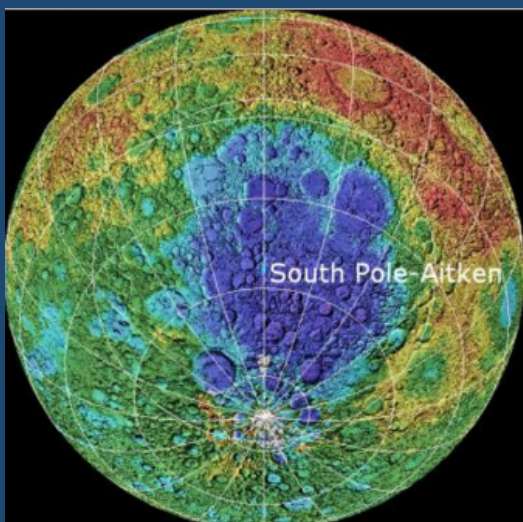
Can we supply enough solar power continuously, anytime, anywhere around SC, inside and outside?

- *Prospect and excavate regolith inside the crater*
- *Explore the crater*
- *Power multiple robots (without the need for RTG's)*
- *In-Situ Resource Utilization (ISRU) production of water, fuel*
- *Human base*

Assess a continuous and permanently powered infrastructure at the South Pole to provide power/heat, for NASA and partners

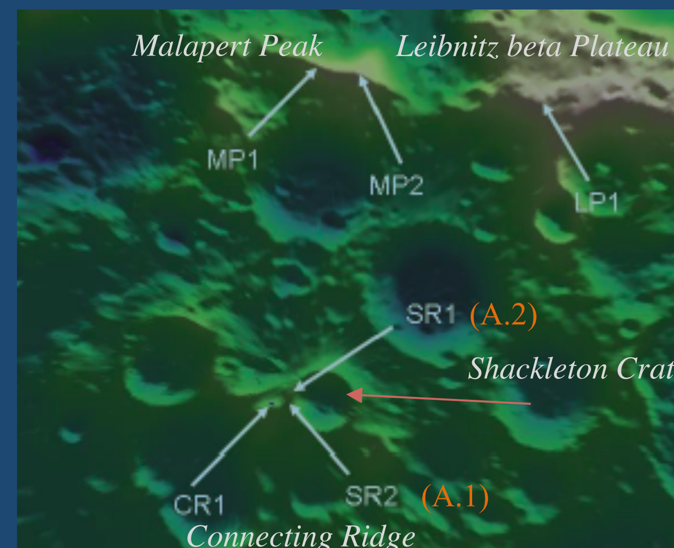
The Moon –
Potential spaceport with its own fuel production

The South Pole of the Moon is the premier location for a permanent base and obtaining water, hydrogen and oxygen … AND having *almost* permanent solar power available.



Region of interest #1

Shackleton Crater/Rim



Six principal Regions of Interest (ESA)

What is delaying us?

The Extreme Environment - no source of energy when sunlight is not available - cold, permanently shaded inside the crater

Address EE and Power issues

Phase 1 - *Transform Extreme Environments (EE) into a mild environment near assets*

Can we find an *affordable* solution (non-nuclear):

- Use reflectors to provide solar energy to areas of interest (transform the EE locally)
- Compact folded and deploy to large aperture (TransFormers)

Yes we can! *Whenever there is sun, we can reflect solar energy to power rovers up to 10km* with some limitations:

- No location near SC is permanently illuminated, so rovers need to survive ~ 60 hours of dark (hibernation, batteries, etc)
- We cannot focus the sunlight beam only on the rover solar panels when at 10km – will illuminate larger area

The flip side: for a wider illumination area we can power ***multiple robots*** *simultaneously*, including *small rovers* (that can't carry RTG).

Provide enough power - continuous/permanent for exploration and ISRU

Phase 2 - *Can we supply enough solar power continuously, anytime, anywhere around SC, inside and outside?*

- *Explore/excavate in the crater*
- *Travel around*
- *Use multiple robots, no need for RTG each*
- *In-Situ Resource Utilization production of fuel, water*
- *Human Base*

It means that one can establish a permanent continuous power infrastructure at the South Pole that can provide power/heat to anyone's equipment*, so they don't have to handle power and thermal issues

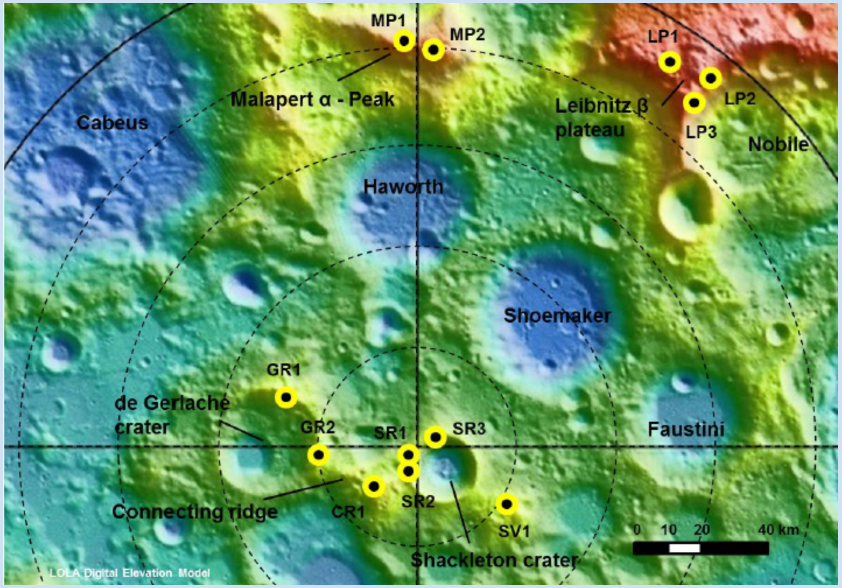
**Attracting potential customers to an airport/spaceport is a good idea*

Goal: To power exploration and ISRU missions at Shackleton Crater

TFs at the South Pole of the Moon

The rim of the Shackleton crater (SC) at lunar south pole is illuminated most of the time, while the floor is permanently shaded, and may harbor water in the icy regolith; SC candidate for a lunar outpost

Placed on the rim of SC, TFs would reflect solar energy onto robots operating in the dark cold crater.



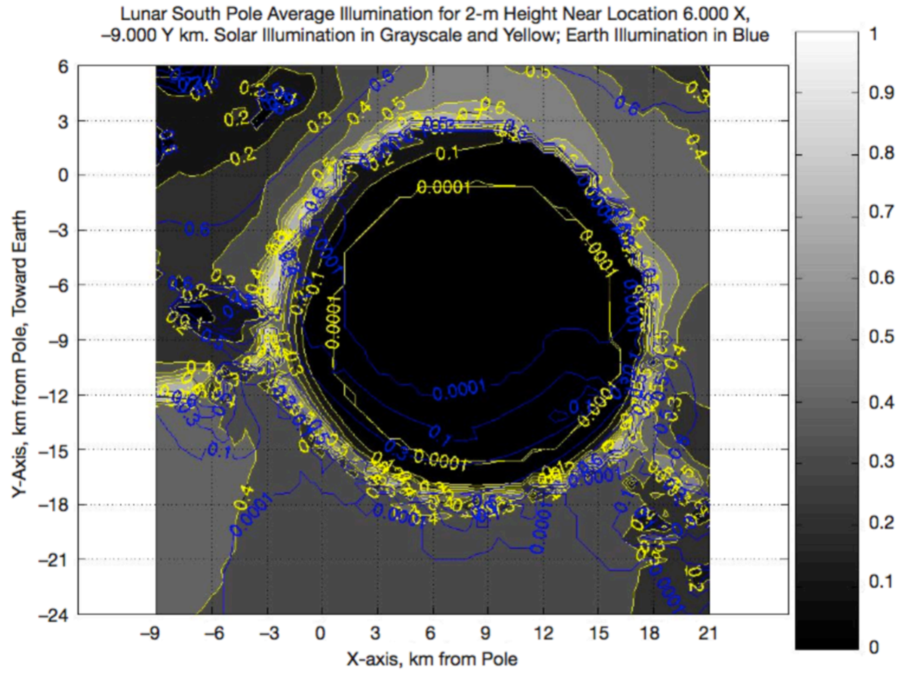


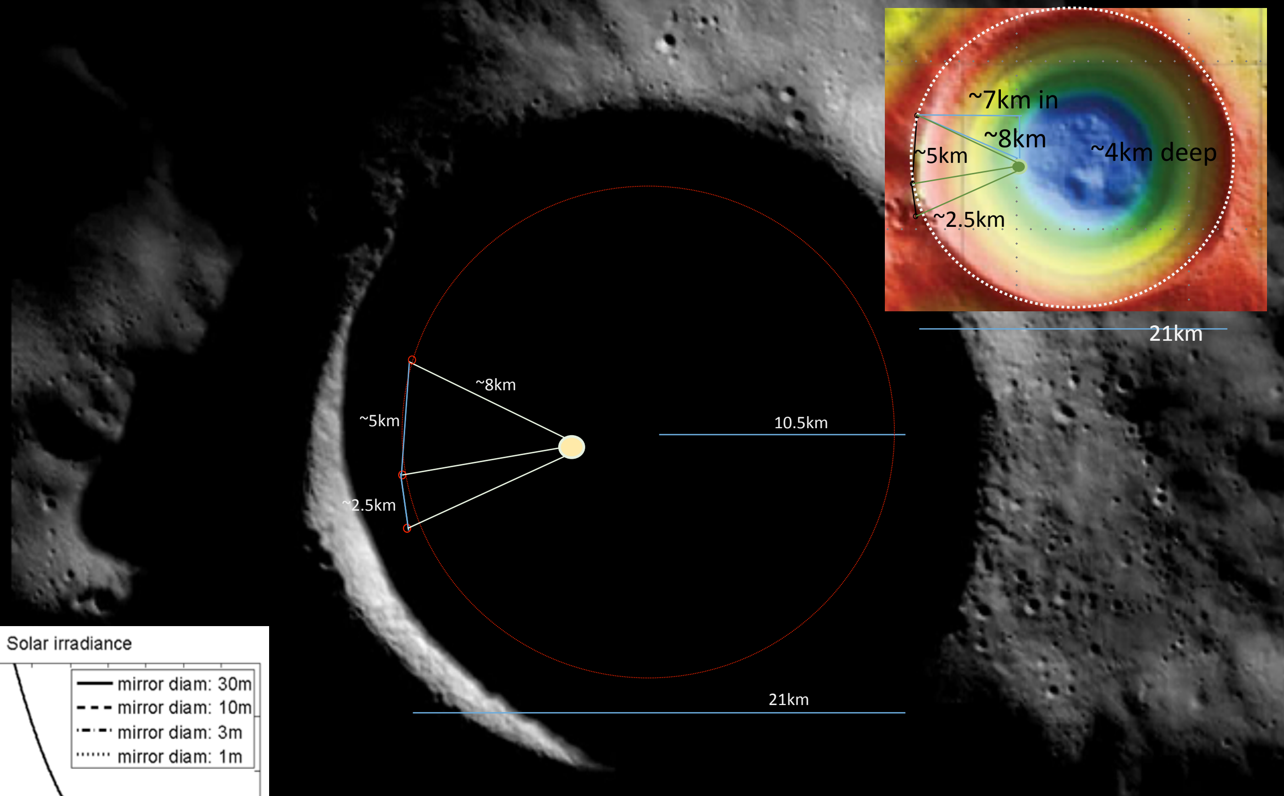
Figure 16. Shackleton Crater yearly average illumination, coarse resolution.

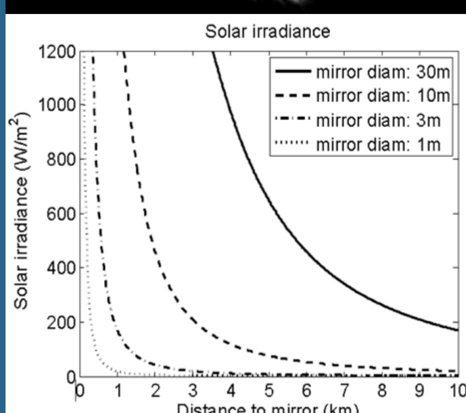
The sites A1, A2, and B1 have the highest multiyear average solar illumination for the lunar south pole sites The most lit area on the Shackleton rim, A1, sees 100% of the solar disk 86.3% of the time

- Longest period of continuous (total) darkness is 2.46 days
- Longest period of partial darkness (<100% solar illumination) is 5.5 days

TFs could rise tens of meters above the ground, for increased illumination

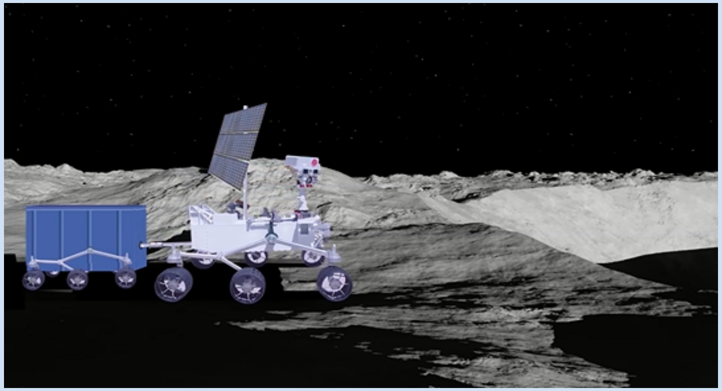
3 Point Infrastructure ensures permanent illumination at Shackleton Crater



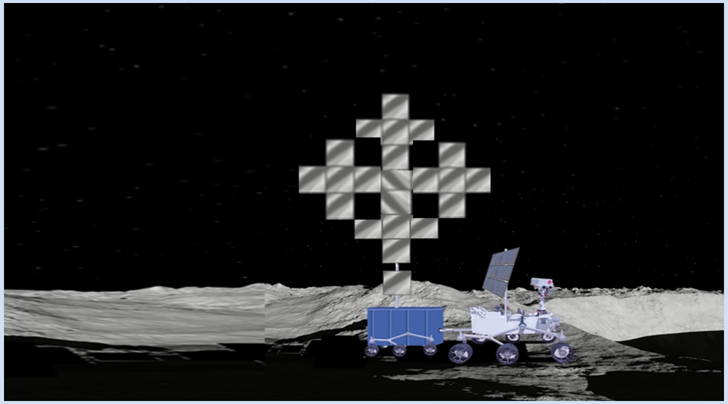


Phase I

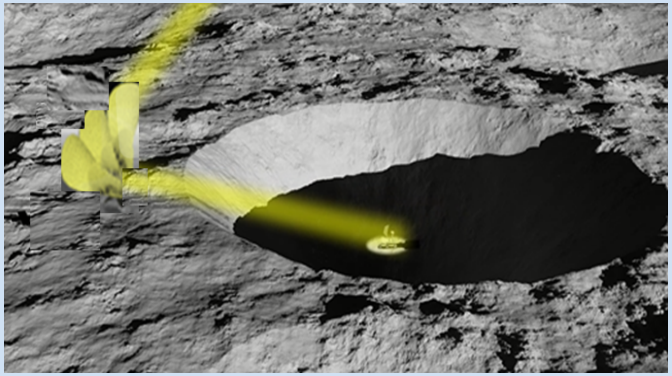
Mission Scenario: Shackleton Crater Exploration



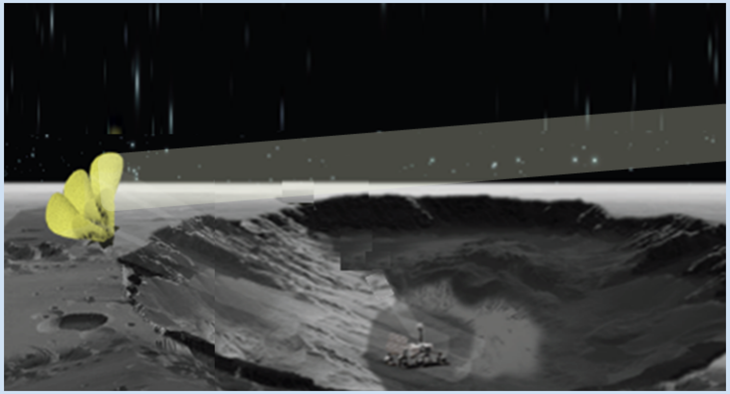
A rover transports a compactly folded TF away from a lander, and approaches the rim.



The TF unfolds to reflect sunlight into the crater—it is placed at a location that provides line-of-sight coverage of the planned ER path, and, under its own actuation, adjusts its position/posture for improved stability, A crosslet origami unfolding is depicted.



The ER starts its descent into the crater. The TF continuously tracks the ER, lighting its path with reflected sunlight. As the ER reaches areas with ambient temperatures below 100K, it is powered and warmed by the TF projected energy.

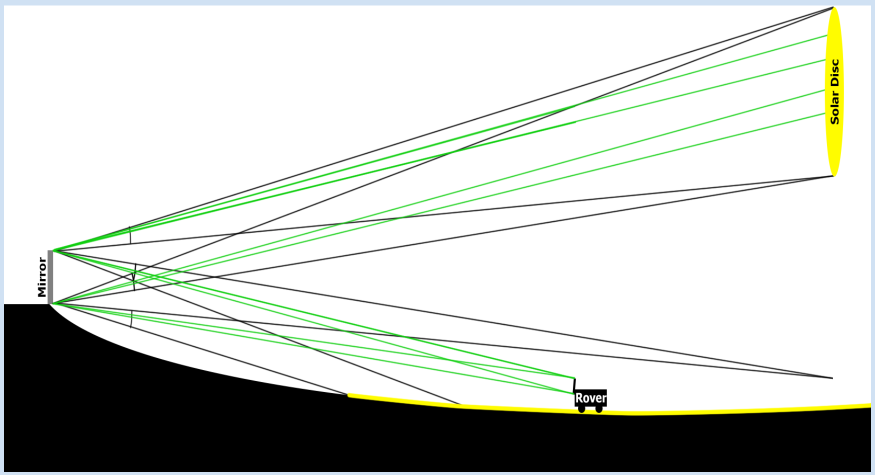


The TF continuously adapts its reflector shape, precisely tracking the moving ER, pointing the reflected energy onto its solar arrays, and controlling the beam as required for the ER to examine its surroundings and to take

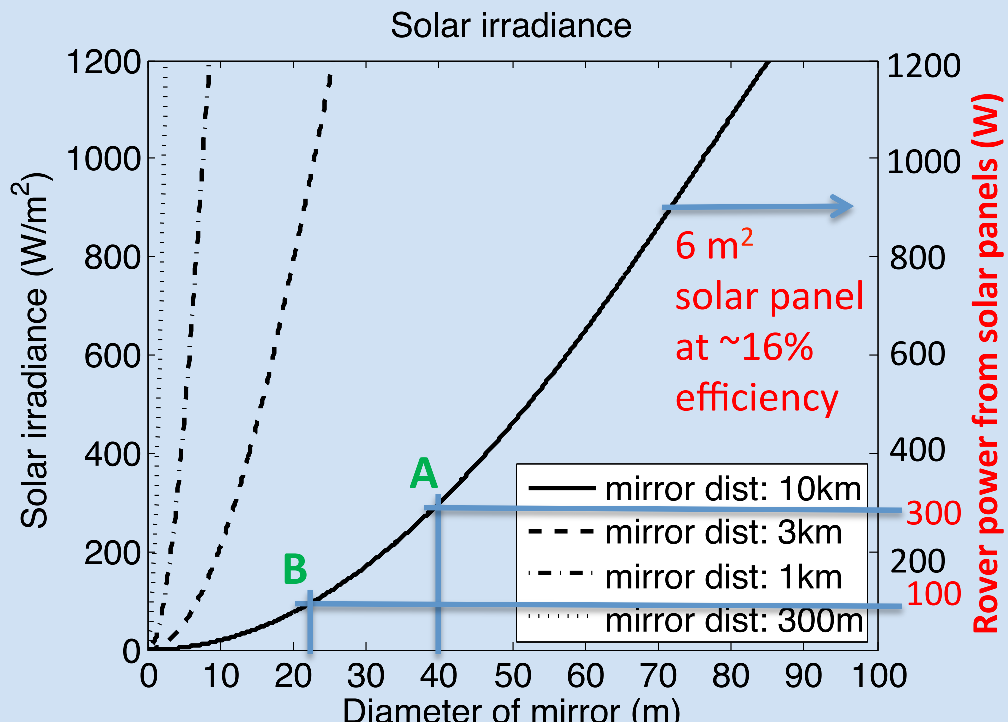
Phase I

Size of needed TF reflective surfaces

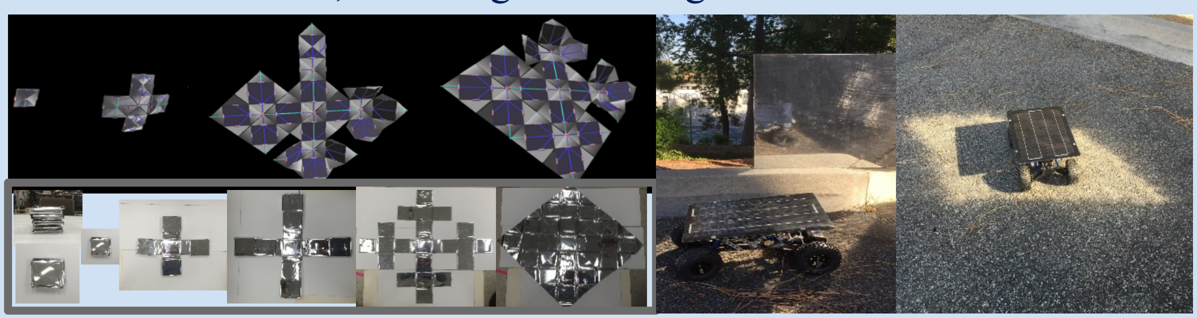
TFs on the rim can power/warm rovers inside the 10km radius SC; a 40 m diameter TF ($1256 m^2$) is needed to provide ~300 W/m^2 of power at 10 km (enough for an MSL-class rover with ~6 m^2 solar panels). 100W (MER-level power) provided by a 25m diameter TF

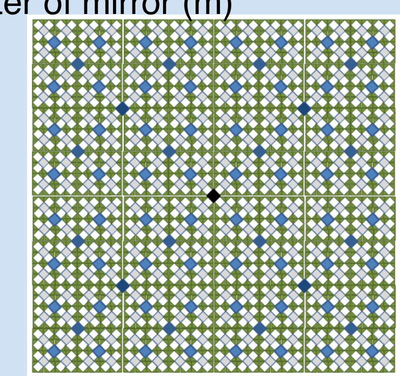


Packing Large Reflectors In Small Packages



A 40 m diameter TF, 0.1 to 1 mm thin, could be packed within ~1 m^3; and weight ~100 kg …





Developed new origami-folding techniques: Crosslet origami

Phase I

Thermal Aspects

Rover thermal design not an issue

Design mechanisms and structure for cold operations

- Nighttime T down around -200° C; Drive & steering motors unheated

Battery and reflector size needs

• *Assuming periods of total darkness up to 60 hours (2.5 days) battery capacity for survival heating would need to be as shown in the table below*

Rover Mass	Thermal Power Req.	Energy Req.	Battery Capacity (70% max DOD)	Approx battery mass*	Rover surface area (m^2)	Reflector area (m^2)
10 kg	13 W	780 W-hr	1115 W-hr	11.2 kg	1	0.2
200 kg	30 W	1800 W-hr	2572 W-hr	25.7 kg	3	1
1000 kg	100 W	6000 W-hr	8751 W-hr	87.5 kg	10	4

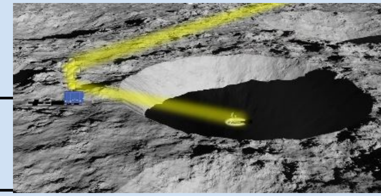
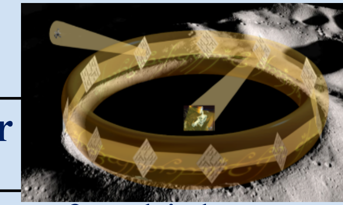
• Note that battery mass unrealistic for 10 kg rover.

Illumination of terrain

Illumination will not sublimate icy water;
An oasis could be illuminated in proximity of deposits (could be covered by a PV blanket);
Rovers would recharge in oasis and make incursions of hours in neighboring cold regions for prospecting and returning regolith.

Phase I

Comparison with MMRTG Power

MMRTG 	**TF1** 	**TF2: Ring of Power** 
Allows single flight system (comm sat may be required)	Requires coordination of two independent autonomous systems	Requires coordination of multiple independent autonomous systems
Allows unconstrained landing directly in crater	Simplest variants require rover to descend crater wall; or, e.g. precise landing at illuminated point	Allows unconstrained landing directly in crater in illuminated oases
Limited Plutonium supply	Unlimited solar resource (interrupts)	Unlimited solar resource (continuous)
Straightforward operation, tolerant of faults and comm outages	Relatively complex operation and interactions: Sun and rover must be continuously tracked; Rover must survive periodic outages	Requires relatively complex operation and interactions: Sun and rover must be continuously tracked; No outages
Requires relay satellite	Enables comm relay	Enables comm relay
Plenty of excess heat, but lighting requires electrical power. Provides ~110 W electrical (continuous). Must reject ~1900 W waste heat	Provides area lighting, direct heating Rover power can be sized to need. Can support large or small rover (but not Sojourner small)	Provides area lighting, direct heating Rover power can be sized to need. Can support large or small rover; can support many rovers at once;
Mass ~**45 kg** per unit; implies large rover. Cost: ~ **$45M**/MMRTG + launch	Rover can be small / several Can be used for multiple missions	Rover can be small; can be large and many; multiple missions, continuous operations

At 80% efficiency, the power reflected by the 1256 m2 surface is 1.2 MW; a single TF can power 100s of MSL-class rovers at once, over the illuminated area, including robots too small to carry RTGs, swarms for prospecting and returning regolith.

Summary of main findings

- Highest return on investment for science and in preparation for preparing resources for inter-planetary travel by ISRU comes from TF missions at the lunar South Pole.
- A 40-m diameter (~1200 m^2 surface) TF is needed to project 300 W/m^2 10 km into SC, sufficient for MSL level (~300 W electric power from 6 m^2 solar panels at 16% efficiency).
- The component technologies for implementing a 1200 m^2 autonomous TF are at TRL 3 and higher. Integration is between TRL 1 and 2.
- A 1200-m^2 surface could be packed within 1 m^3, and could weigh less than 100 kg. The study offers promise that needed functionality can be packed in sub-mm layer, and large surfaces can be compactly packed and unpacked, for example, in origami style.
- The RTG mass prevents its use by MER or smaller rovers. TF cost is projected to be lower than RTGs (~$45M); multiple rovers, and multiple missions require no additional cost. *This was a valuable observation, which justifies further study - to evaluate its risks and potentials*.
- Short-term (hours) illumination of regions containing volatiles, appears not to lead to sublimation. Alternatives to further explore how to protect the icy deposits need be explored.
- *TFs show considerable advantages for successive/ diverse missions in the same region, and for simultaneous powering of multiple platforms, enabling new classes of missions at relatively close, yet now inaccessible places of interest*.

The vision we propose to bring to develop

- *Imagine an oasis of warm sunlight surrounded by a desert of freezing cold darkness. Robots inside the oasis perform scientific lab analyses and process icy regolith brought from excavations in the neighboring darkness.*
- *This oasis, about the size of a football field, lies in a valley about twice the size of Washington DC, surrounded by peaks the size of Mount Rainier. From its low angle on the horizon, the sun's rays never shine over the peaks into the valley, until heliostats unfold on these peaks and redirect the rays down to form the oasis of sunlight. This place becomes a large science laboratory and the largest off-Earth producer of liquid hydrogen and liquid oxygen for fueling inter-planetary trips.*
- *This is the Shackleton crater at the lunar South Pole and TransFormers are the heliostats projecting sunlight onto the oasis.*

Objectives

- The first objective is to advance the TF concept in the context of a lunar mission at Shackleton crater, to power, heat and illuminate robotic operations inside SC to prospect/excavate lunar volatiles in icy regolith, and to perform in-situ resource utilization (ISRU) of icy regolith in order to extract water, hydrogen, and oxygen.

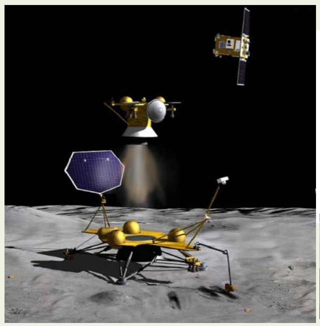
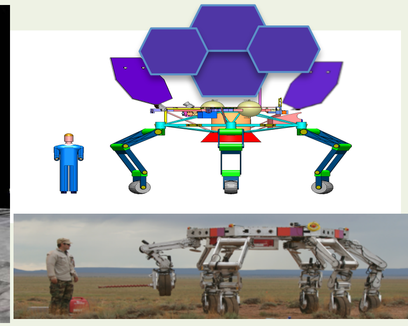
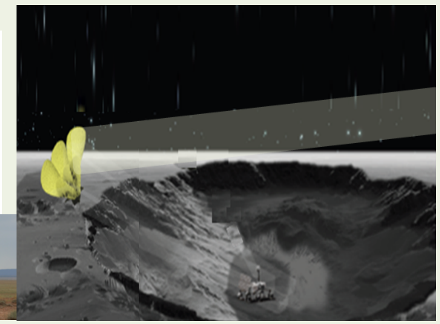
- The second objective is to advance the feasibility of TFs by performing a point design of a scalable TF that packs in a cube of less than 1m on the side, weights 10–100 kg, unfolds to over 1,000 m^2 of thin (0.1 to 1 mm) reflective surface with over 95% long-term reflectivity and is robust to dust obscuration.

Phase II

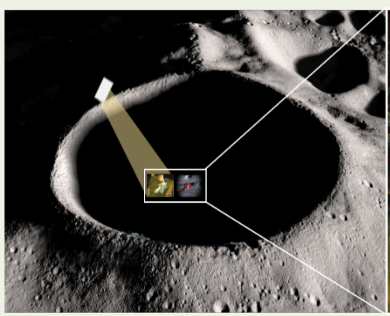
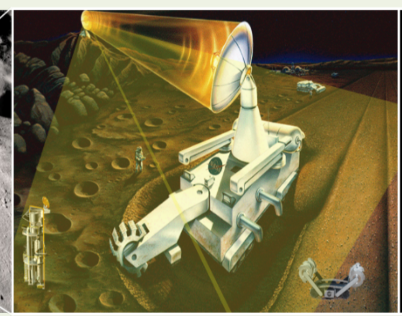
Main Tasks

1. Mission analysis using TF to power/heat/illuminate **robotic operations** inside SC for

   a) prospecting lunar volatiles in icy regolith,

b) processing/ISRU of icy regolith to extract water, hydrogen and oxygen.


2. Technology for unfolding of TF from compact (MER-size) volume, to a large vertical surface (>1000 m^2) (how do we make affordable TFs?)

Our target: A 40m diameter TF (~1256 m^2 surface) - 1mm thin in 1.2m^3

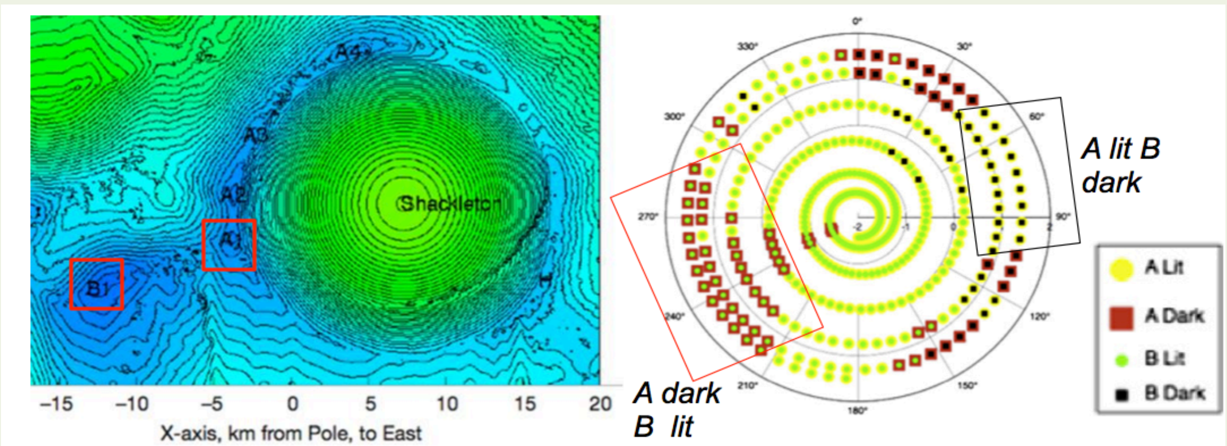
Phase II

Main Tasks (continued)

New idea

3. Design a solar power infrastructure at the lunar South Pole, providing *continuous illumination inside/around crater*, using properly placed TFs

We knew that Points A1 and/or B1 are illuminated for over 8 continuous months and greater than ~94% of the time overall.

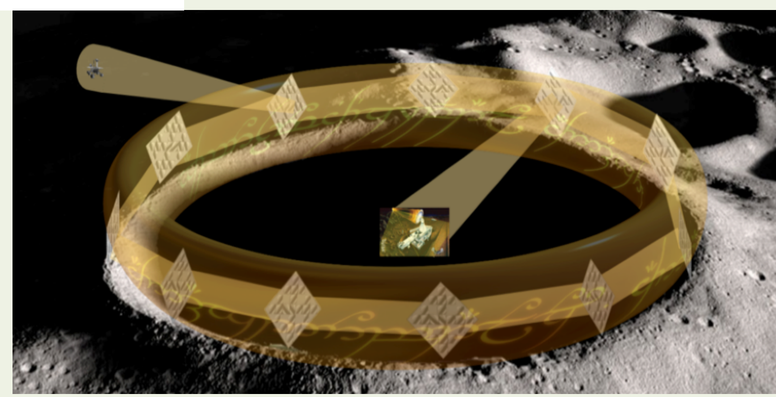


Bussey et al

Placing multiple TFs on circular ring on the rim, one may be able to achieve **continuous illumination** within the ring, and reflect it where needed.

This opens the possibility to develop a Continuous Solar Power Infrastructure at the South Pole.

Disposed in circle around SC and reflecting from one to another, this 'ring' would power robots, equipment and human outposts, for NASA and other.



Science: Lunar Polar Volatiles Explorer

A New Frontiers class mission, but not in the current Decadal Survey roadmap.

1. What is the lateral and vertical distribution of the volatile deposits?
2. What is the chemical composition and variability of polar volatiles?
3. What is the isotopic composition of the volatiles?
4. What is the physical form of the volatiles?
5. What is the rate of the current volatile deposition?

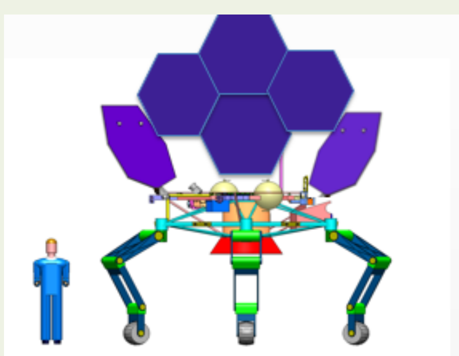
Three different designs that were extremely sensitive to power. Major goals were not met on New Frontiers budget using non-ASRG solutions (MMRTG solutions not studied).

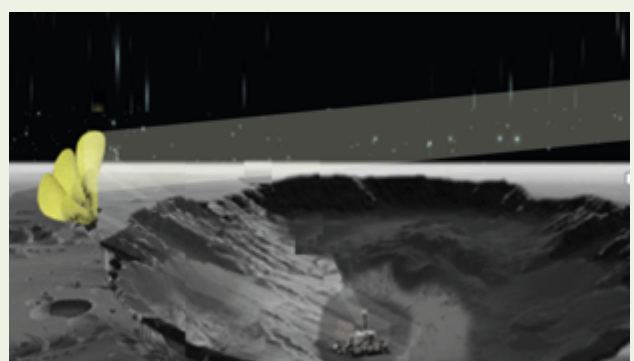
Major challenge: <<100 K temperature. No insolation.

Phase II

Prospecting Rovers Rim/Floor SC

- Level One Science Requirements: (L1) The scientific payload shall measure water ice at concentrations of 10 to ~1000 ppm and OH and molecular water in minerals at sensitivities of 5 percent by weight. (L2)The mission shall be capable of detecting water in the subsurface to a min depth of 2 m.
- The average average power consumption of ATHLETE peaks at 360m/hr – 500 Watt peak Distance travelled during day: 200 meters;
- The size of the solar array for the Rim Athlete is **3 $m^{2.}$** The ATHLETE on the SC floor at 10 km from TF receives ~$1/4^{th}$ of the solar intensity through reflection; thus the rover panels need to be min **12 m^2** we will consider an additional panel; **15 m^2 solar array.**
- The study will determine rover needs to perform a survey of the crater floor and what requirements this imposes on TFs. We will consider methods of beam control.





Resource Prospector

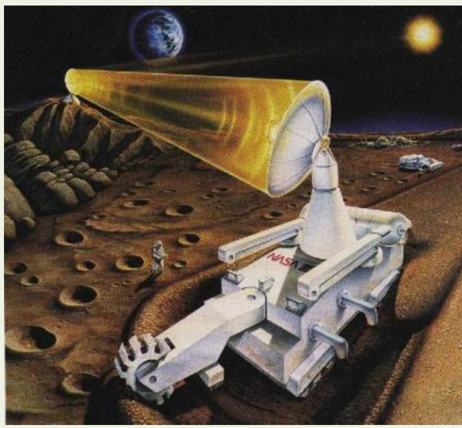
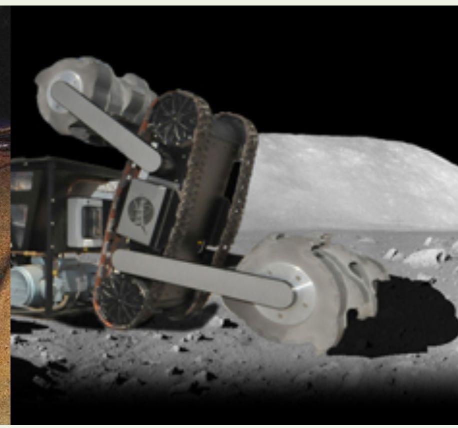
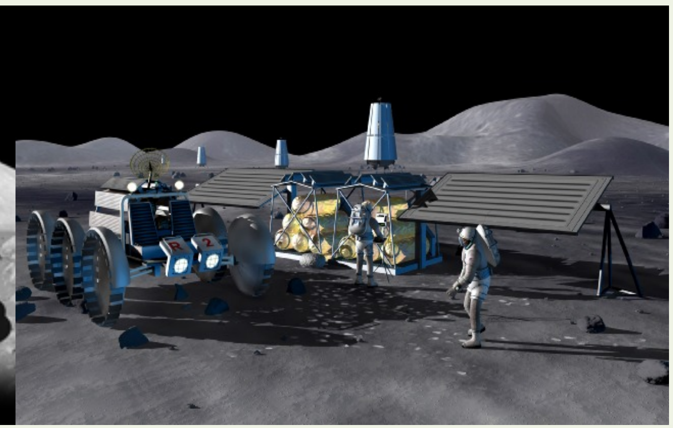
In-Situ Resource Utilization

ISRU systems will require continuous power to survive temperature extremes on planetary surfaces and to produce commodities such as water and oxygen from regolith.

- Water
- He-3
- Other volatiles….
- Permanently dark skies for astronomy

In-Situ Resource Utilization

- **Warming prospecting rovers, regolith excavators, rovers for construction and civil engineering (landing pads and berms), regolith processing plants, and commodity storage tanks…**
- **The reactors will also need electrical power to heat cold regolith to an elevated temperature before it can be processed effectively; the TF could provide at least in part the needed thermal energy.**

- **As an estimate ~100 kW of total power could be sufficient to maintain power to excavators, prospecting rovers and for ISRU processing depending on what the daily mass requirement is for excavated regolith or for oxygen production..**
- **Depending on the ISRU process, elevated temperature would be ~1000°C for chemical reactions that extract oxygen from mineral oxides, or 300–400°C to evolve water from hydrated minerals by thermal heating. A batch size of 100 kg of regolith might have to be processed each time.**

Task 2.1: TF Design and Fabrication

2.1.1 Design/fabrication an actuated/unfolding TF unit (1250 m^2)

2.1.2 Unfolding from Compact Package

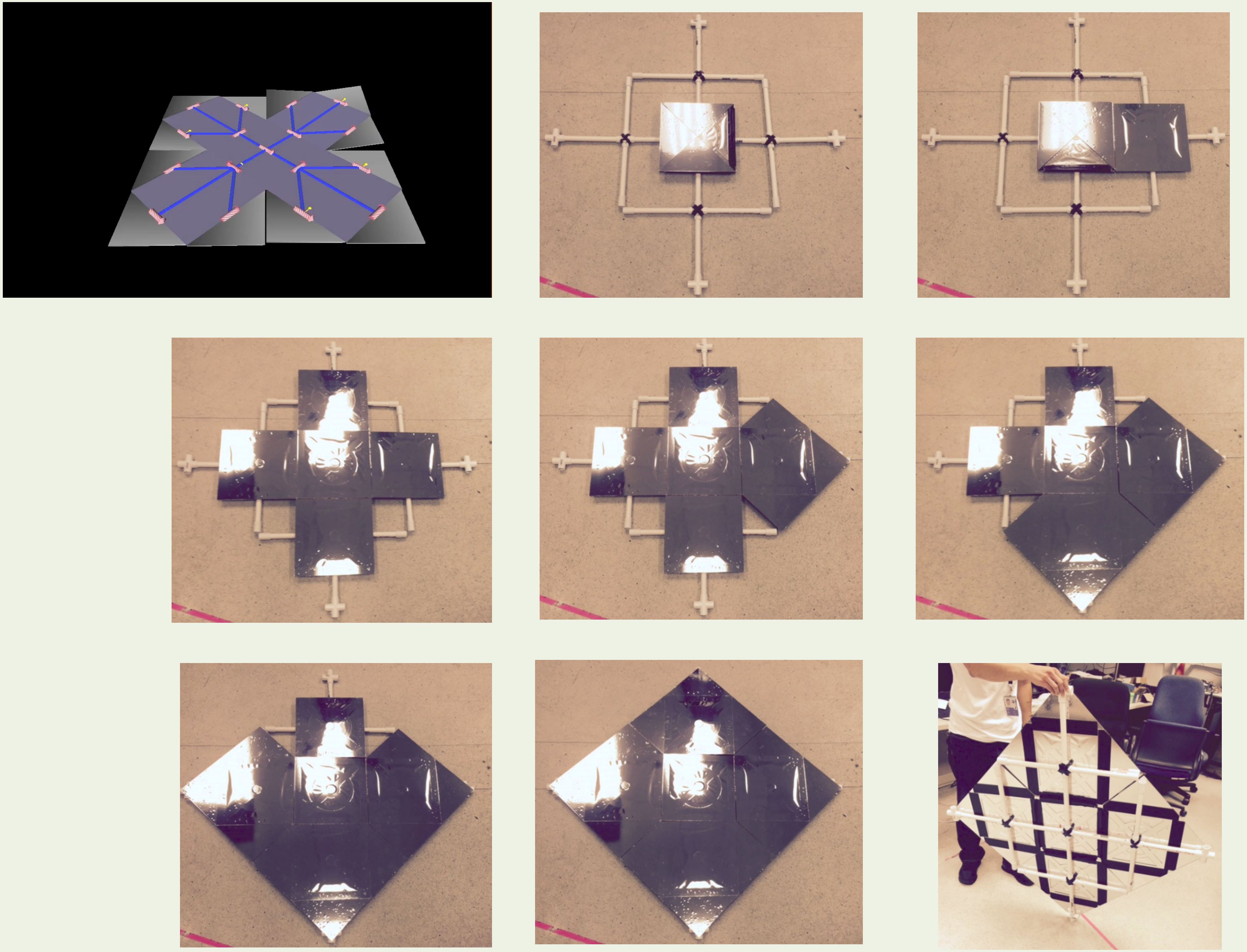
2.1.3 Actuation Design

2.1.4 Reflective Materials

2.1.5 Pointing, Control of directional Projection, Autonomous Operation

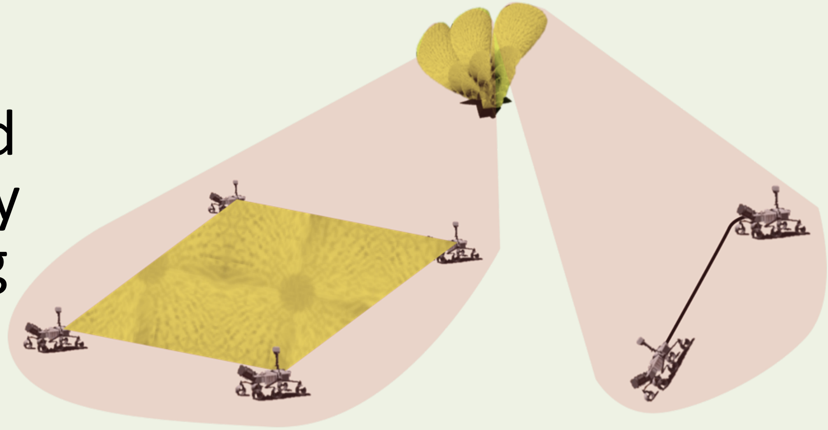
2.1.6 Dust Mitigation

Phase II

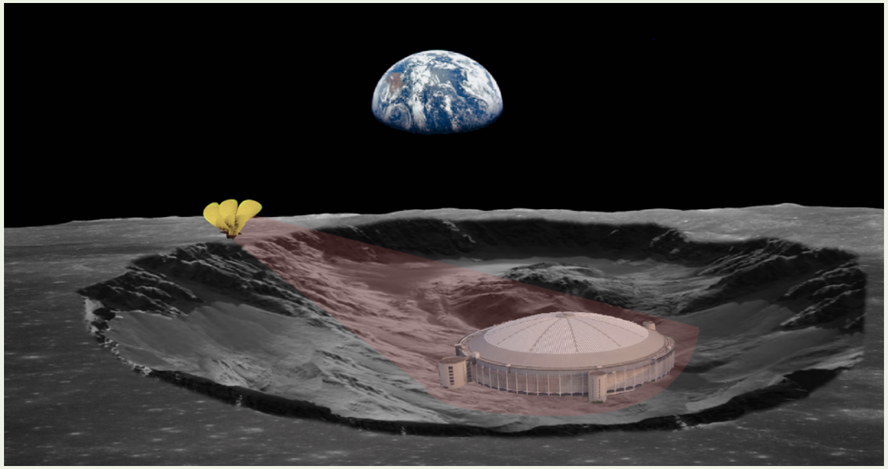


Oasis Operations for Environmental Protection

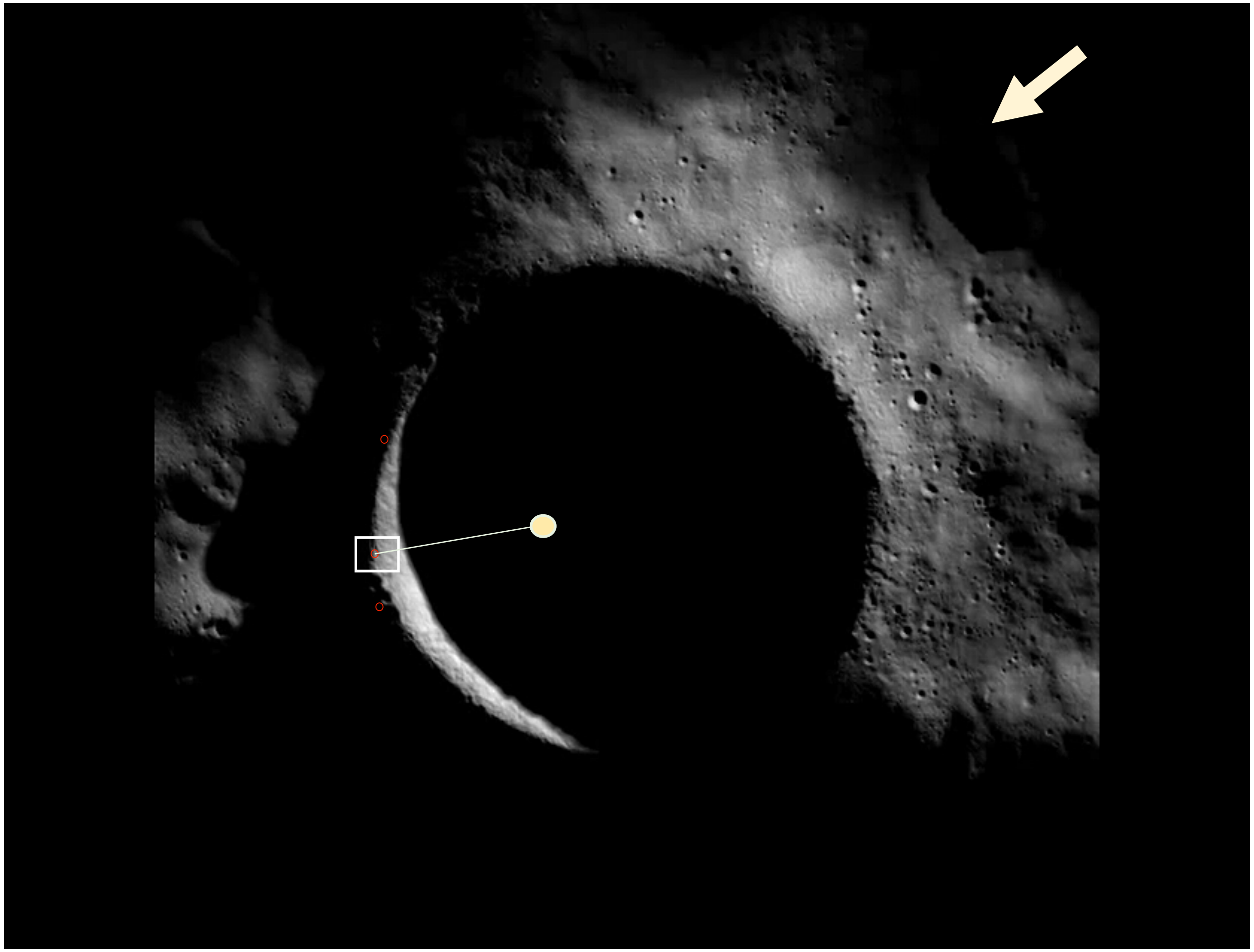
Study how to power multiple robots and equipment in an oasis, a delimited area that is illuminated and heated, away from and nearby the main excavation and processing area.

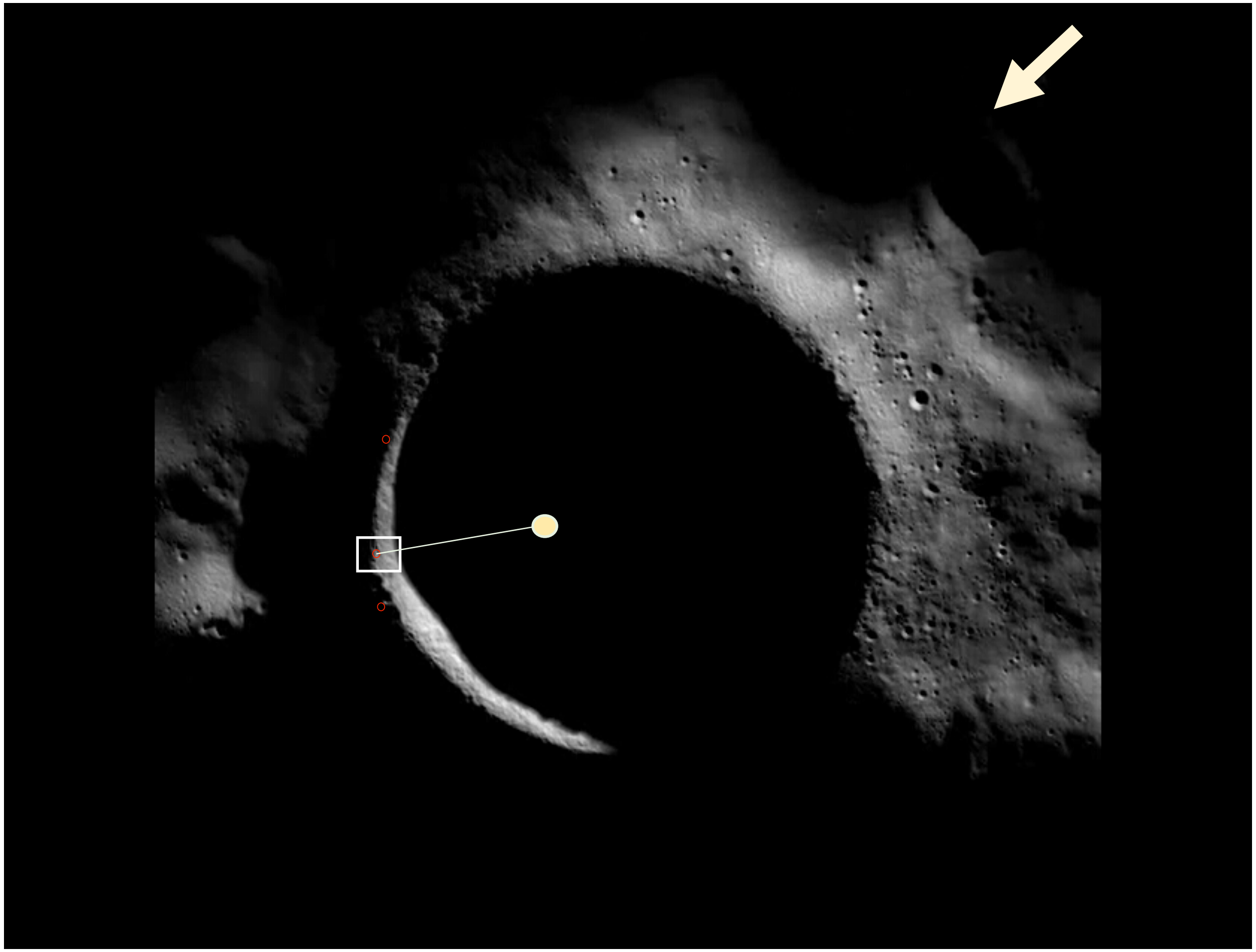


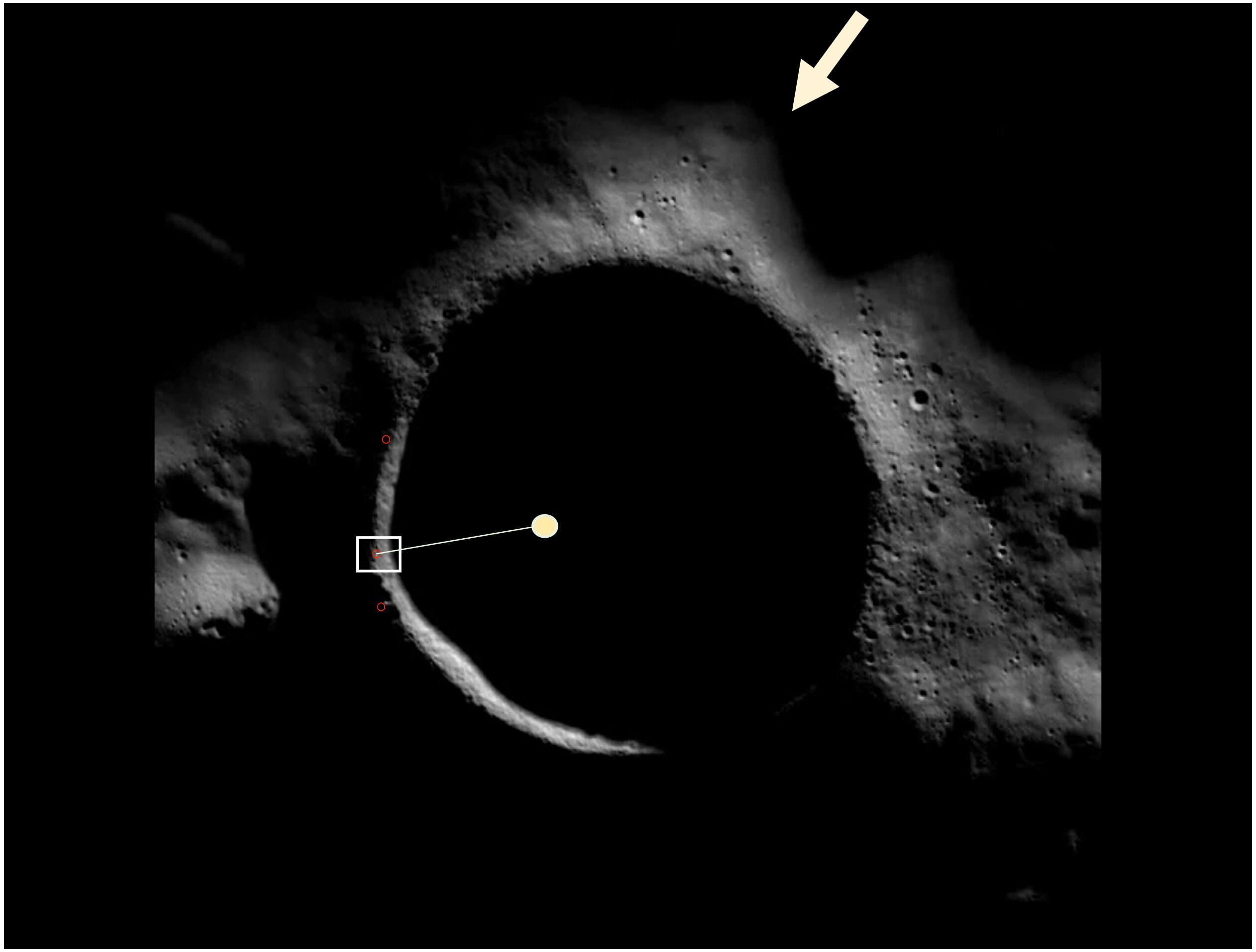
Will determine the operation of multiple robots in the oasis, with a combination of solar panels on each, and a general area for energy conversion, which will be used for recharging of batteries..

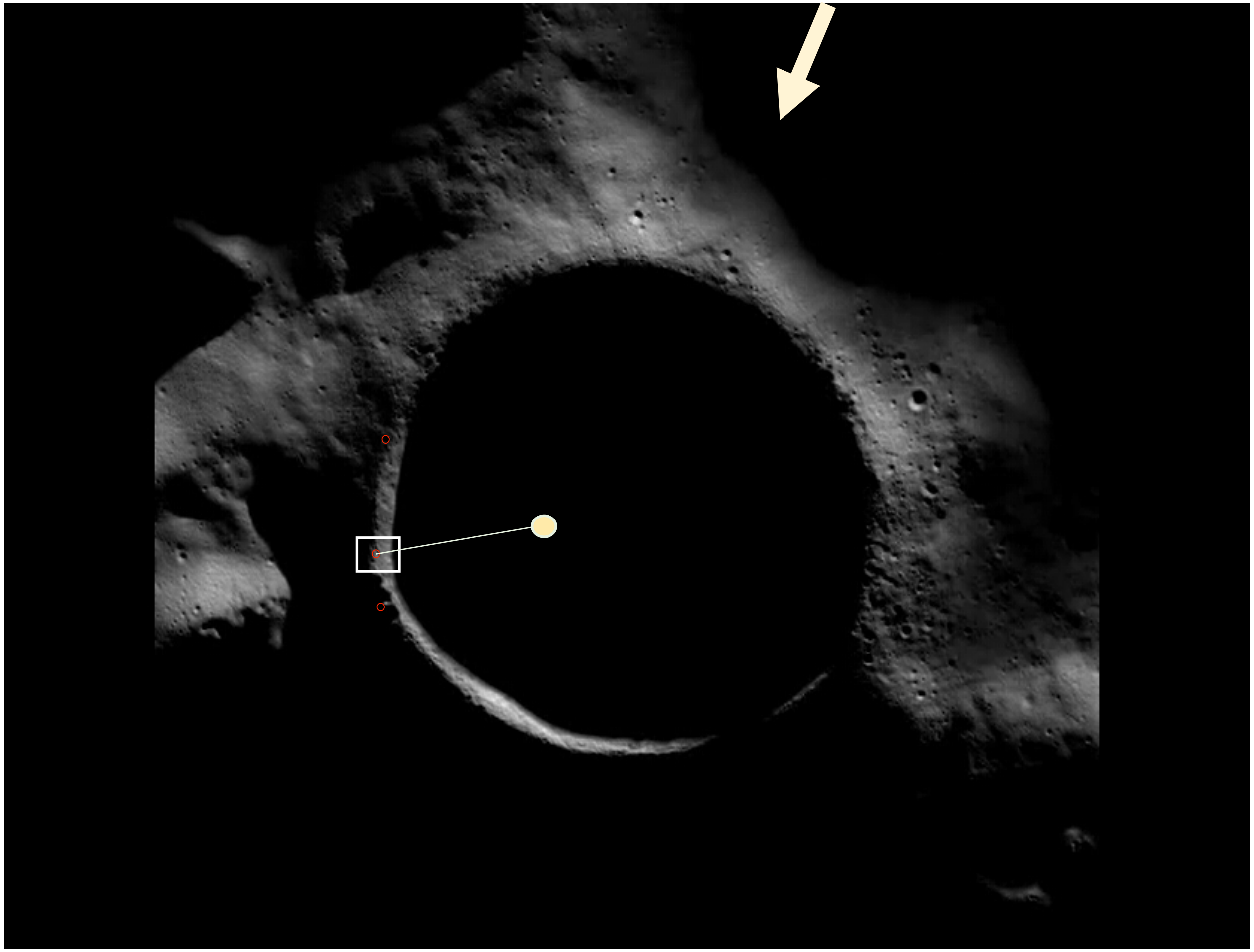


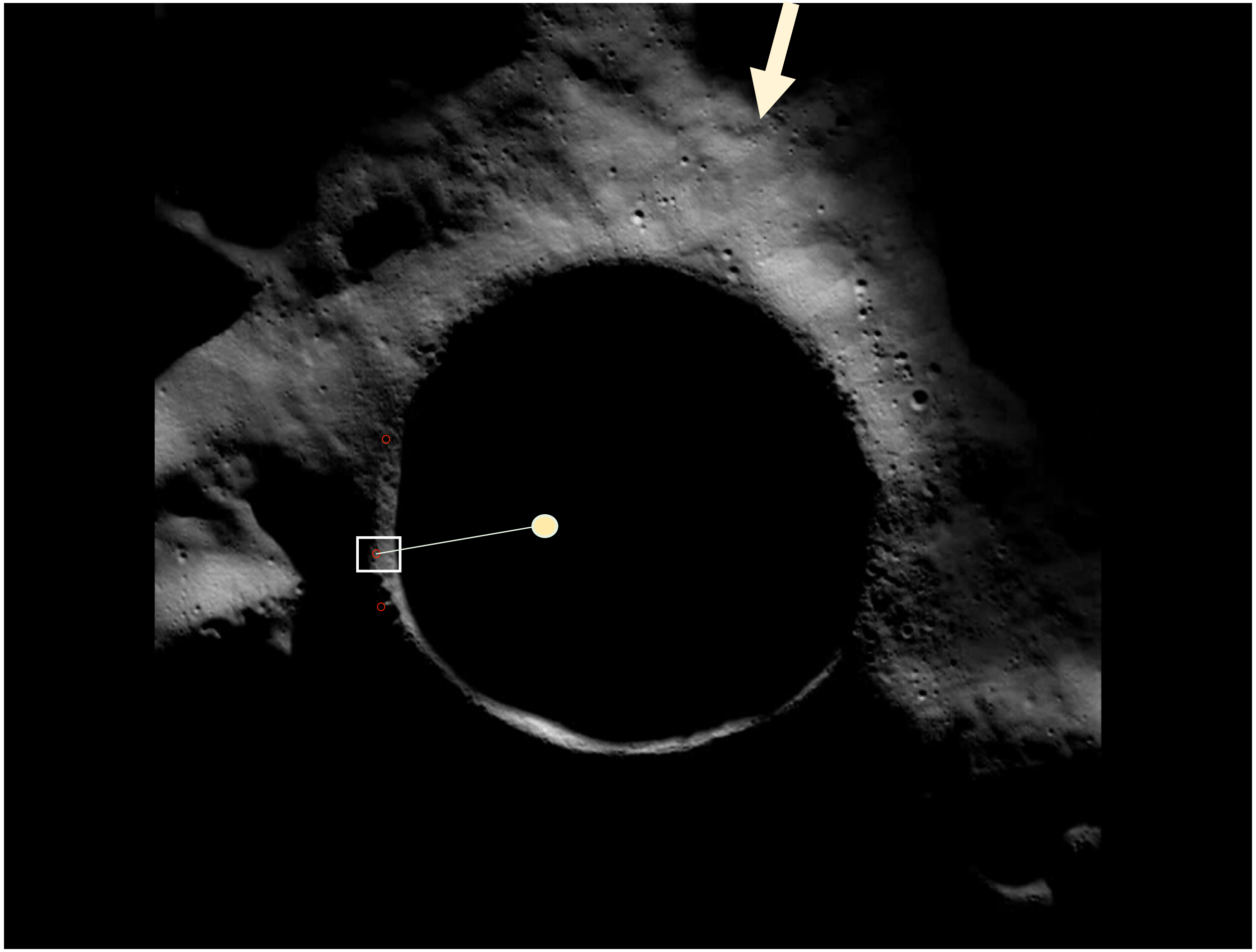
Questions?

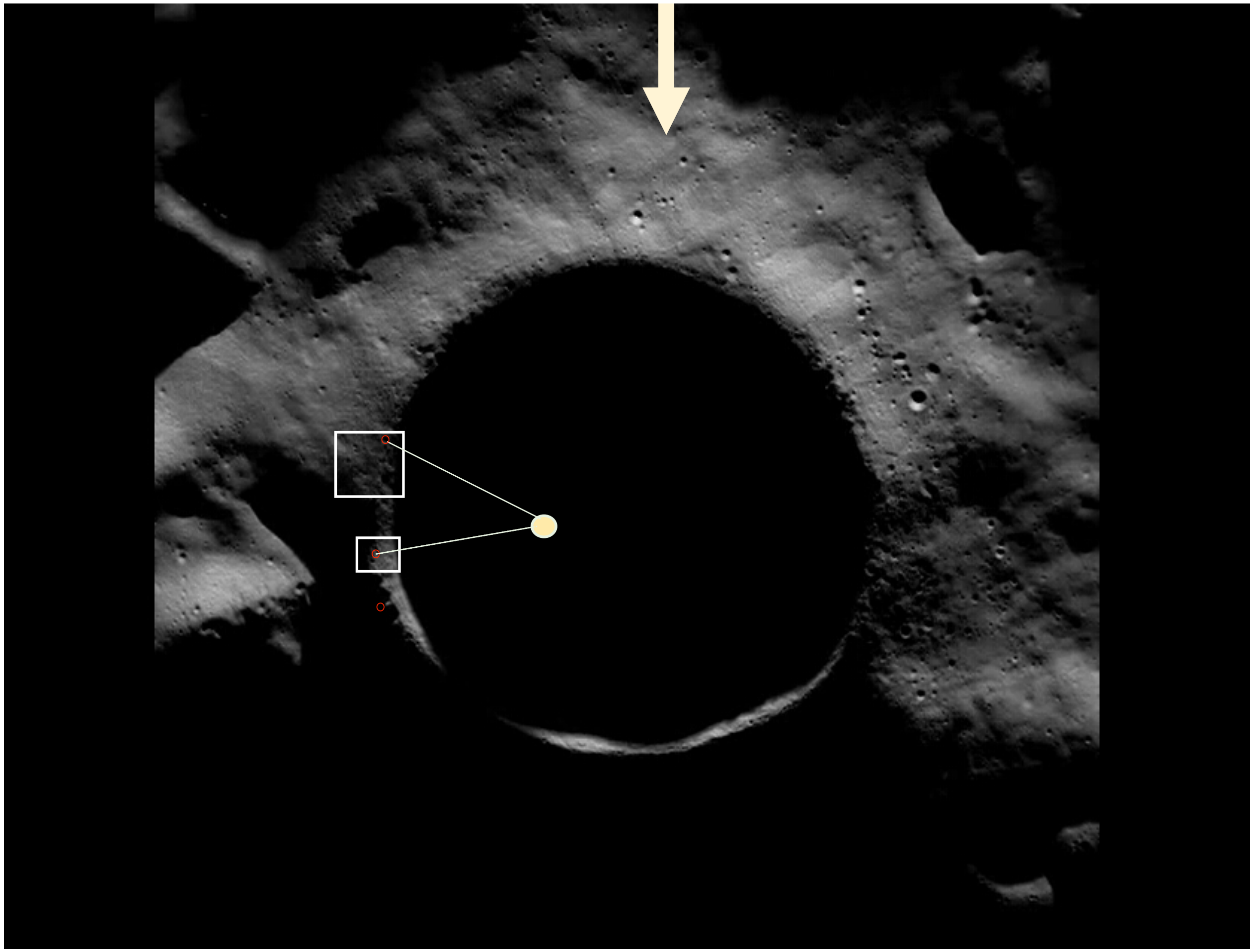


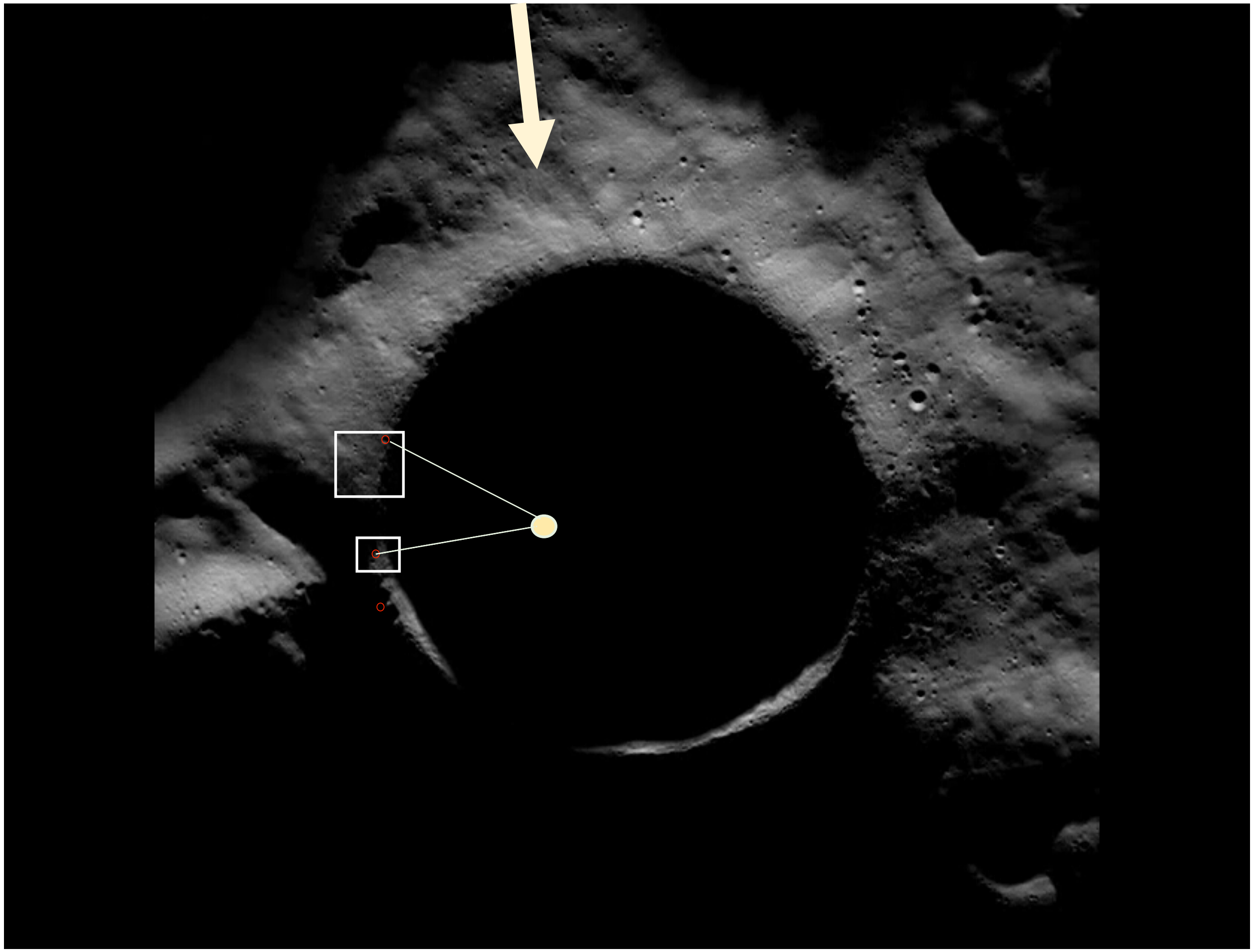


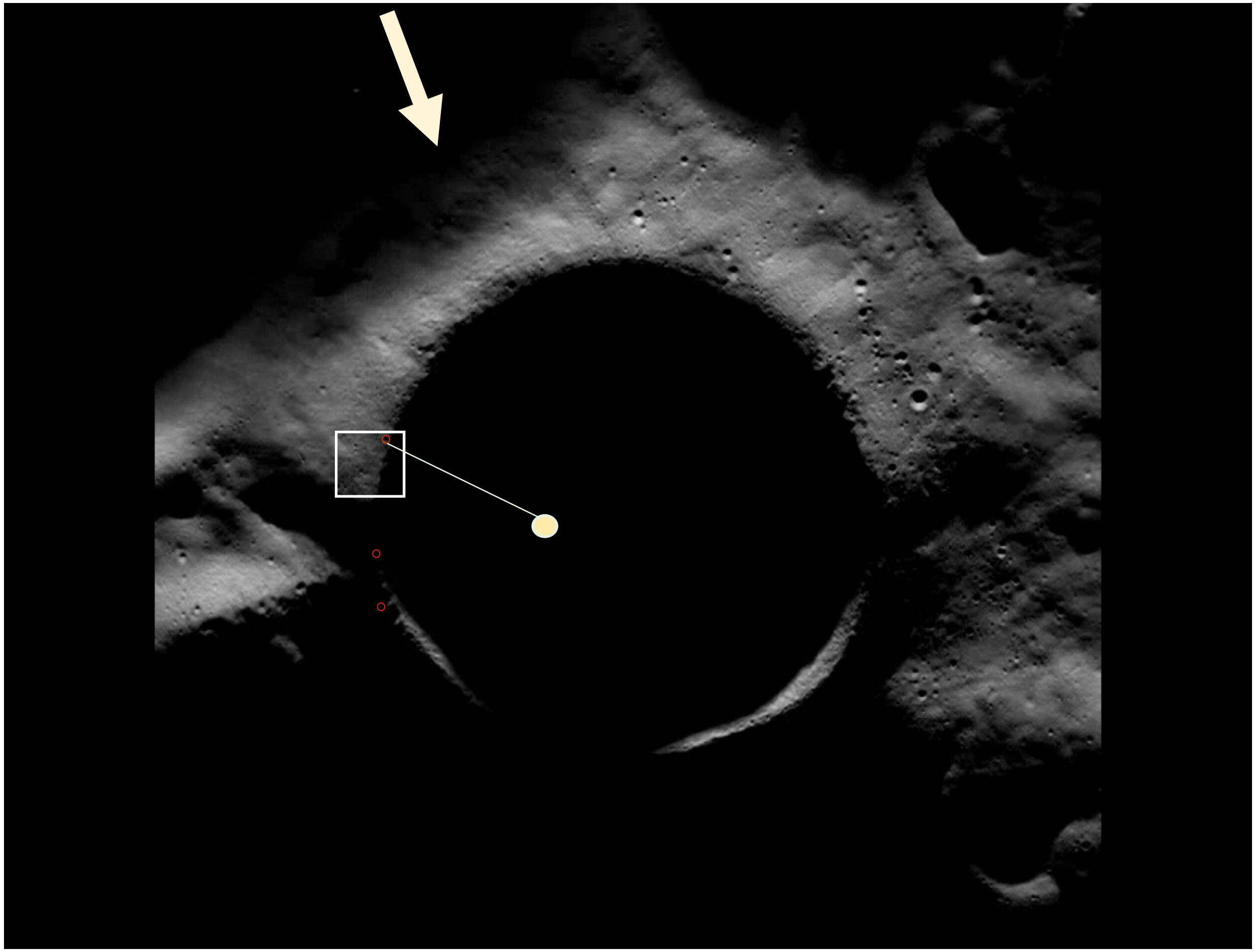


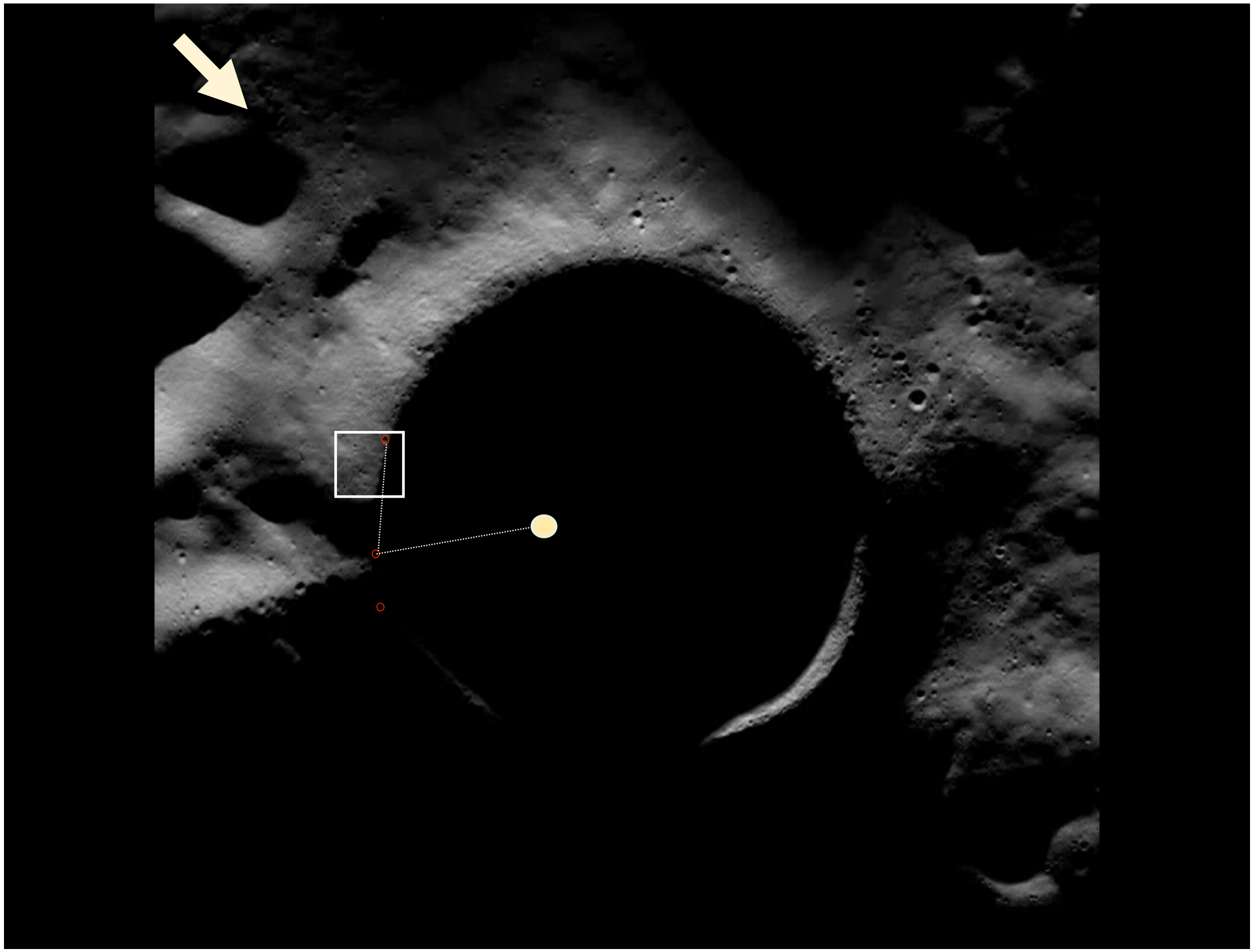


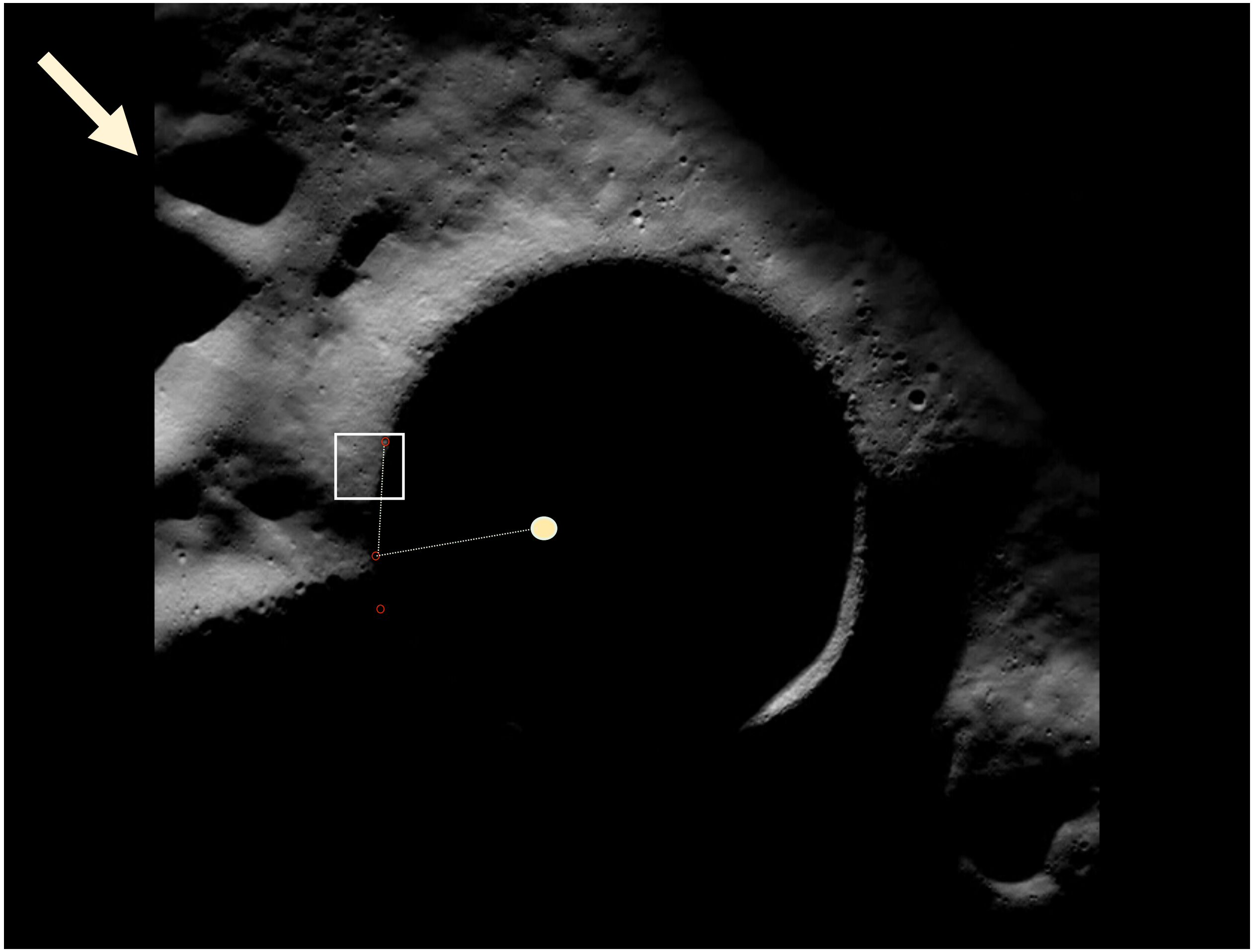


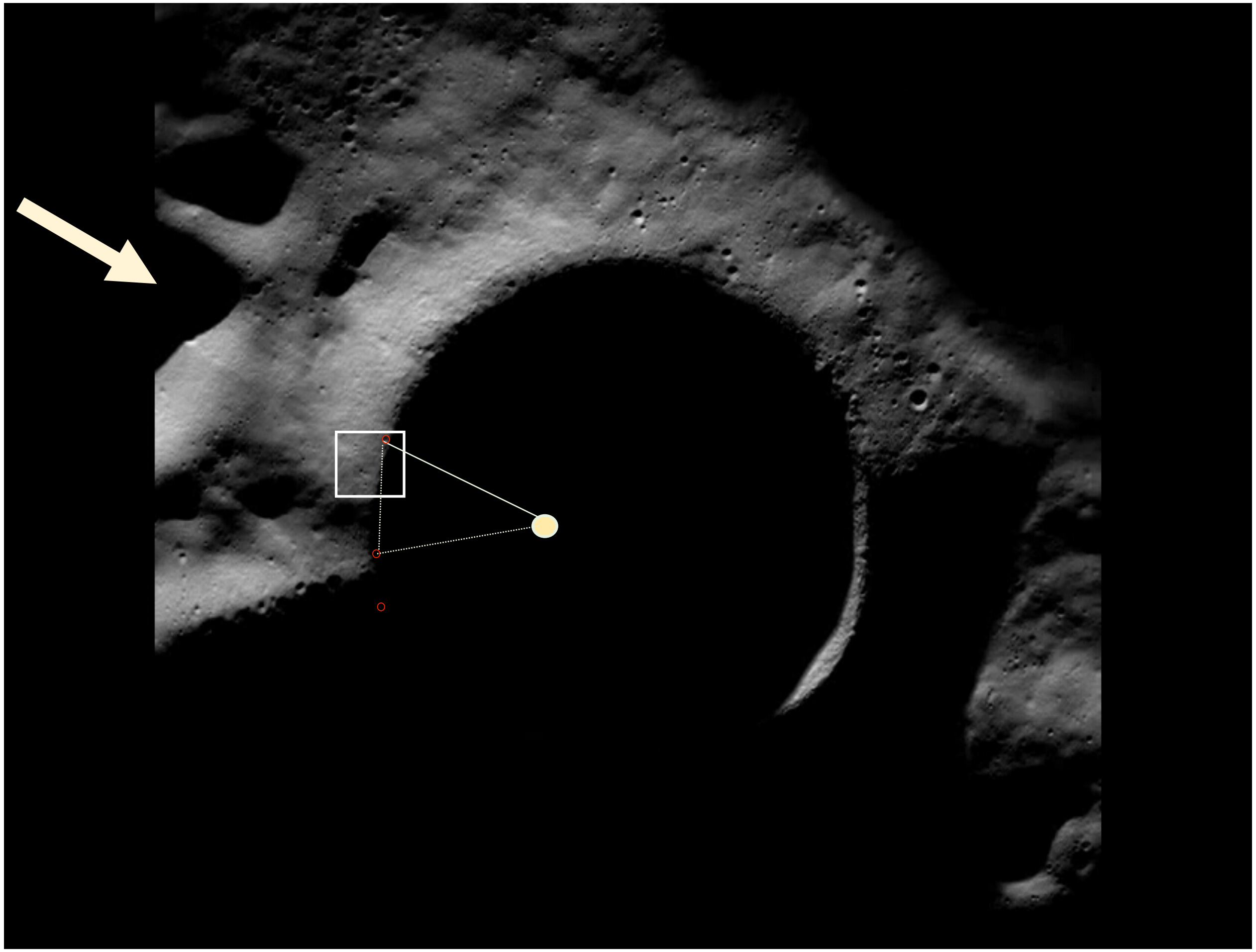


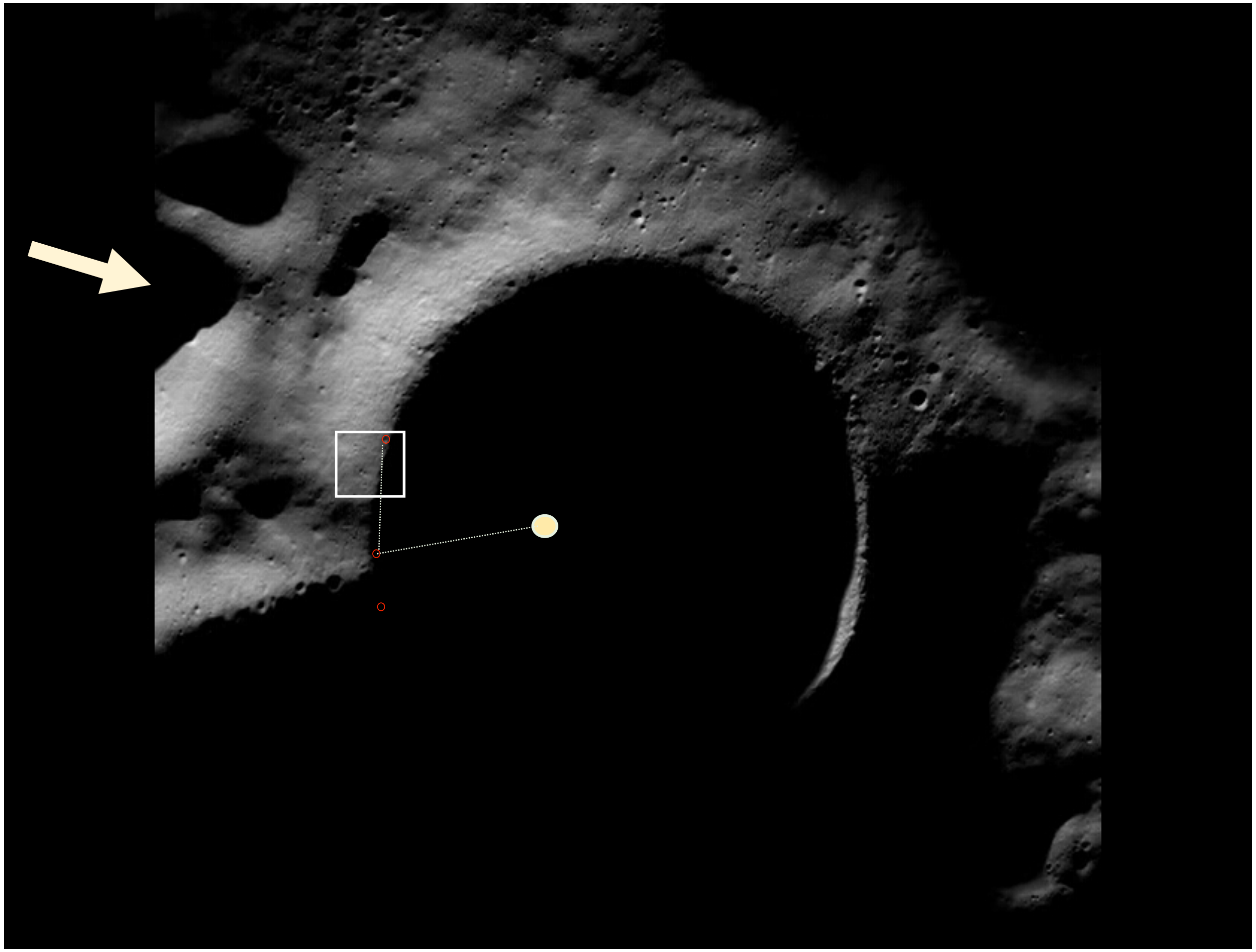


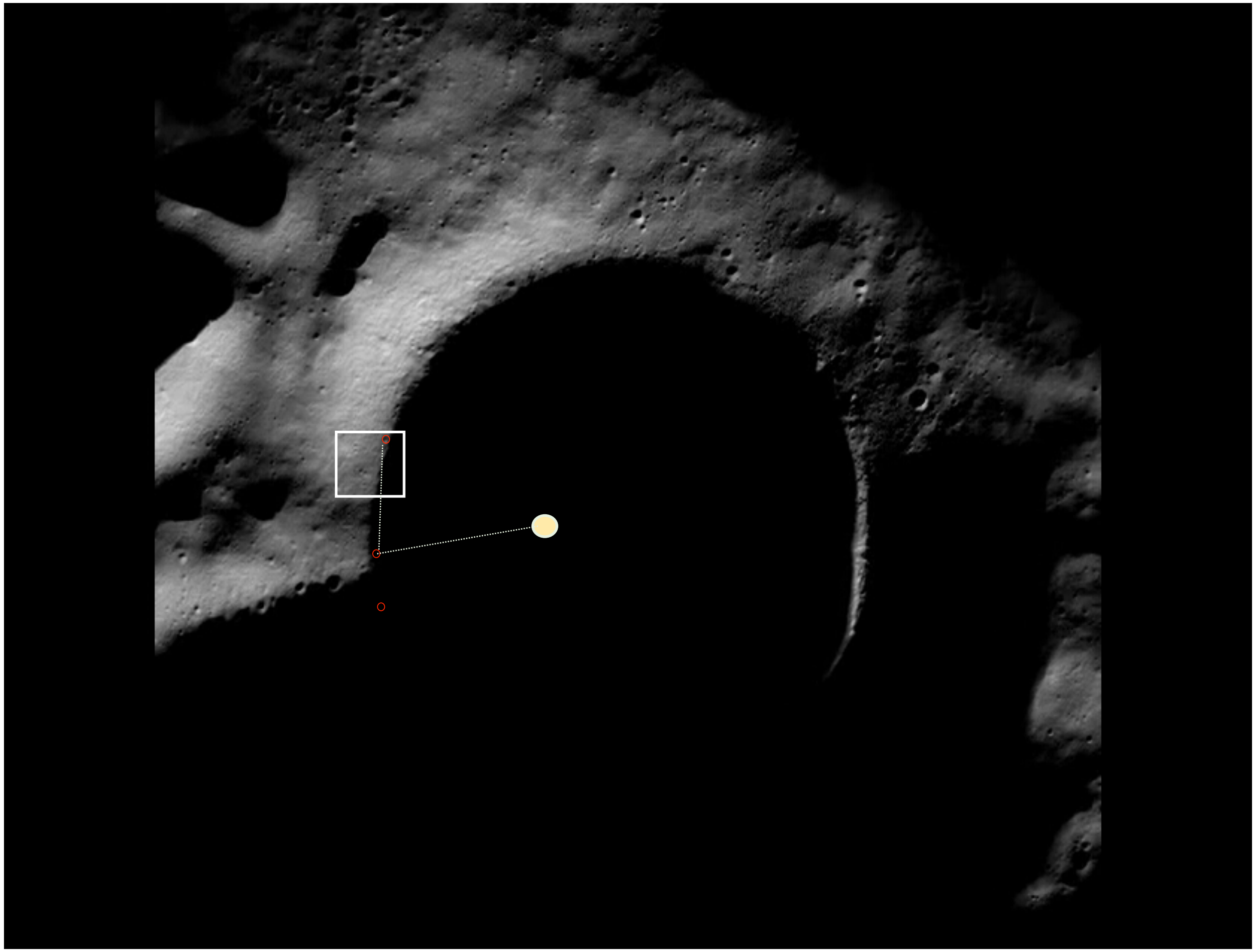


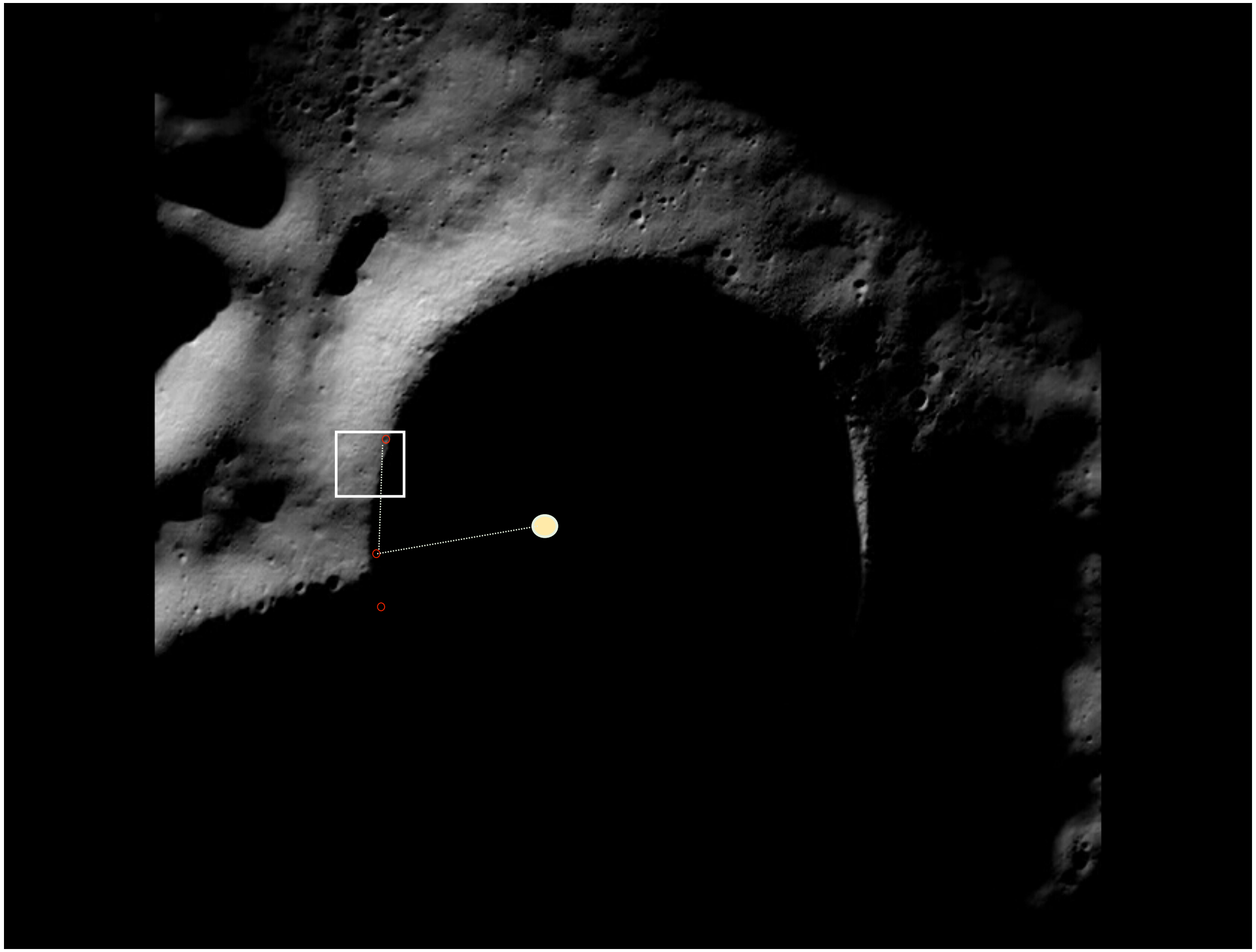


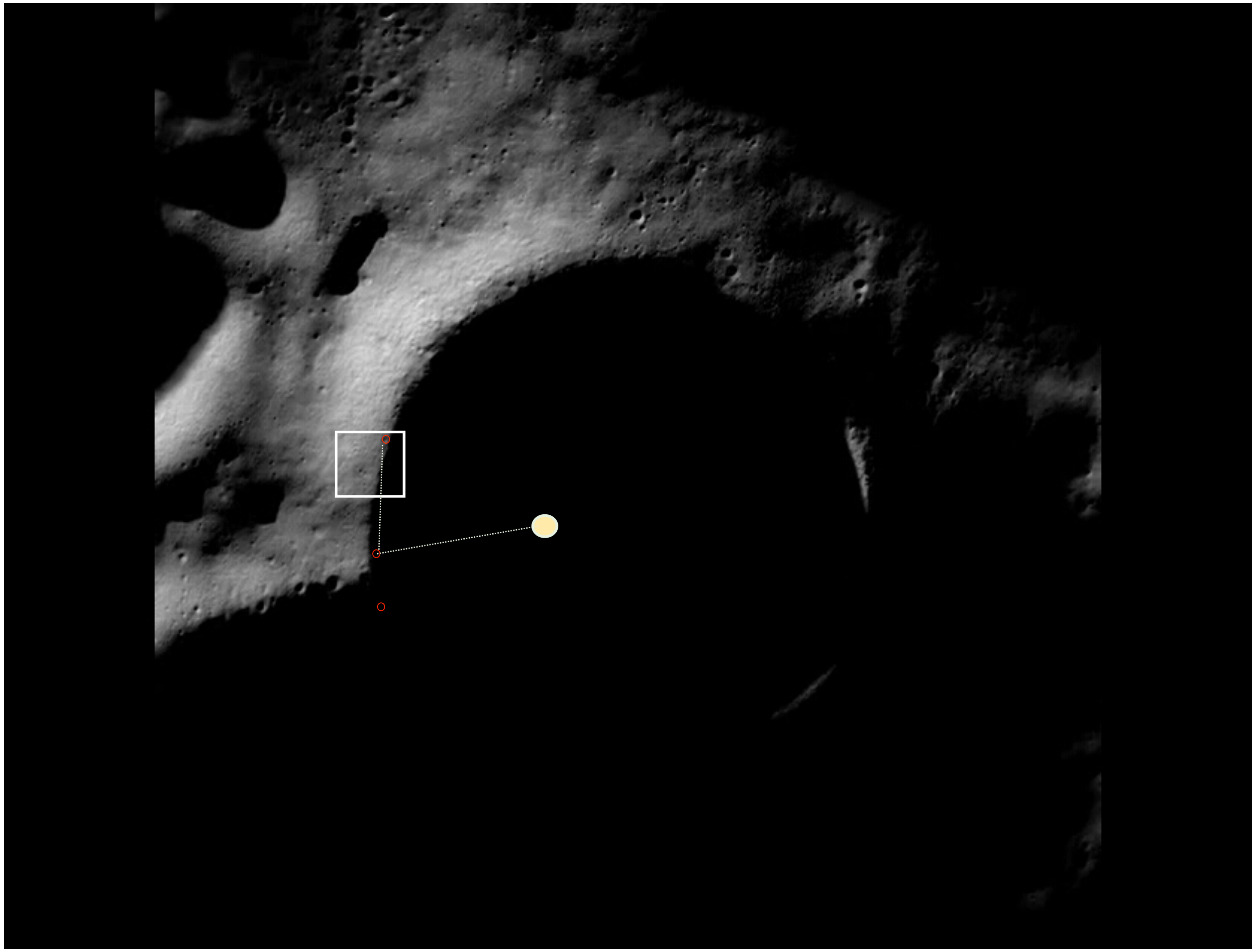


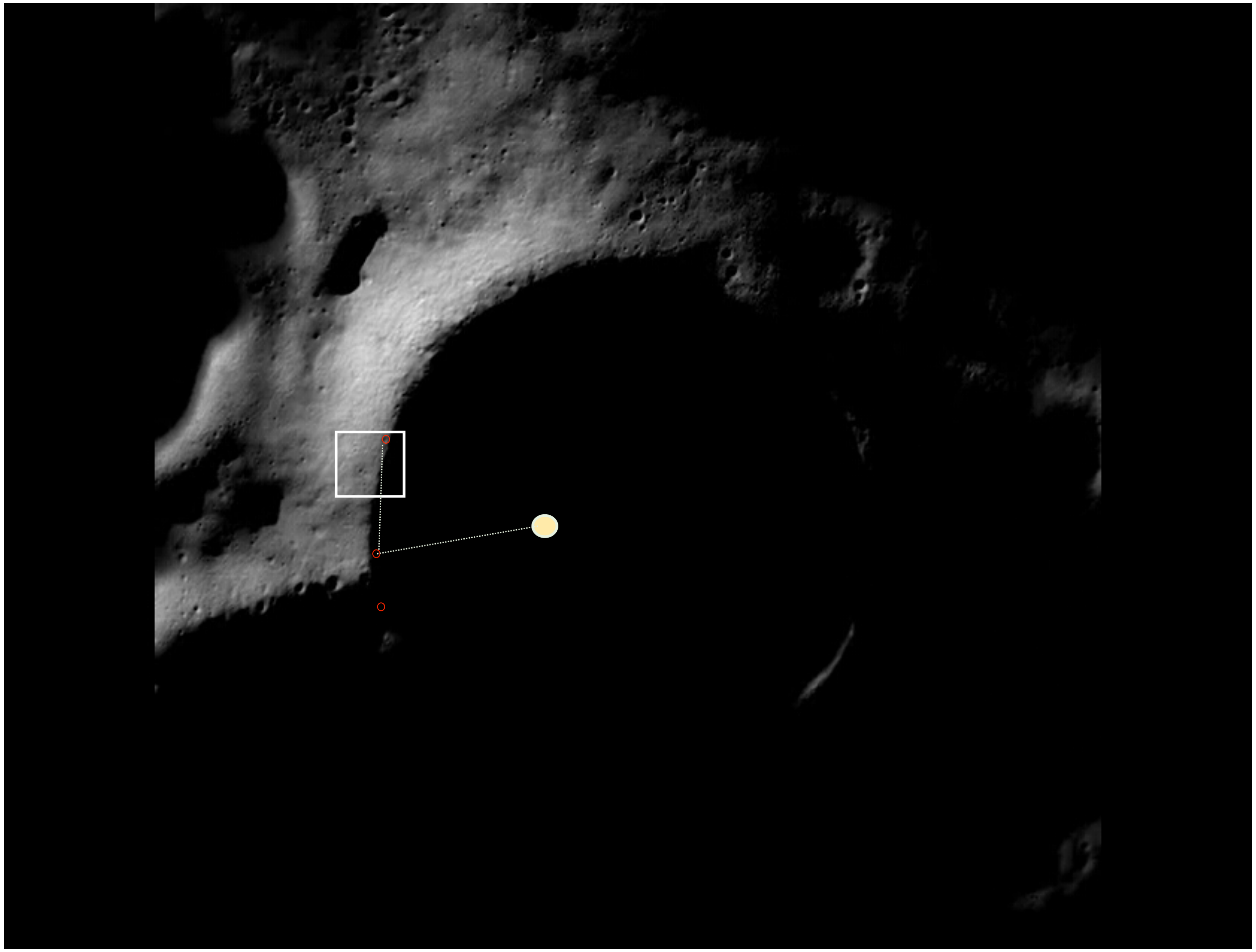


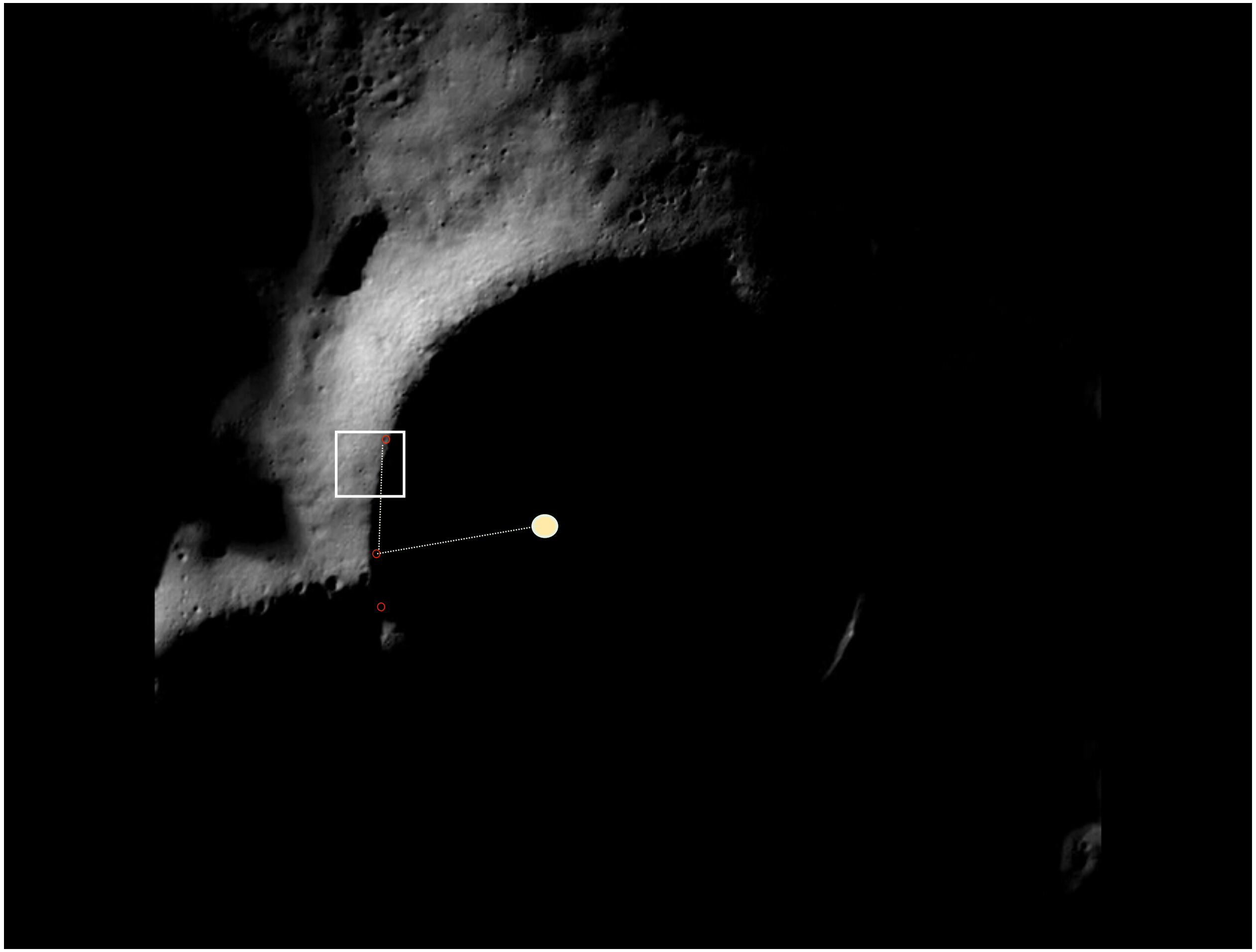


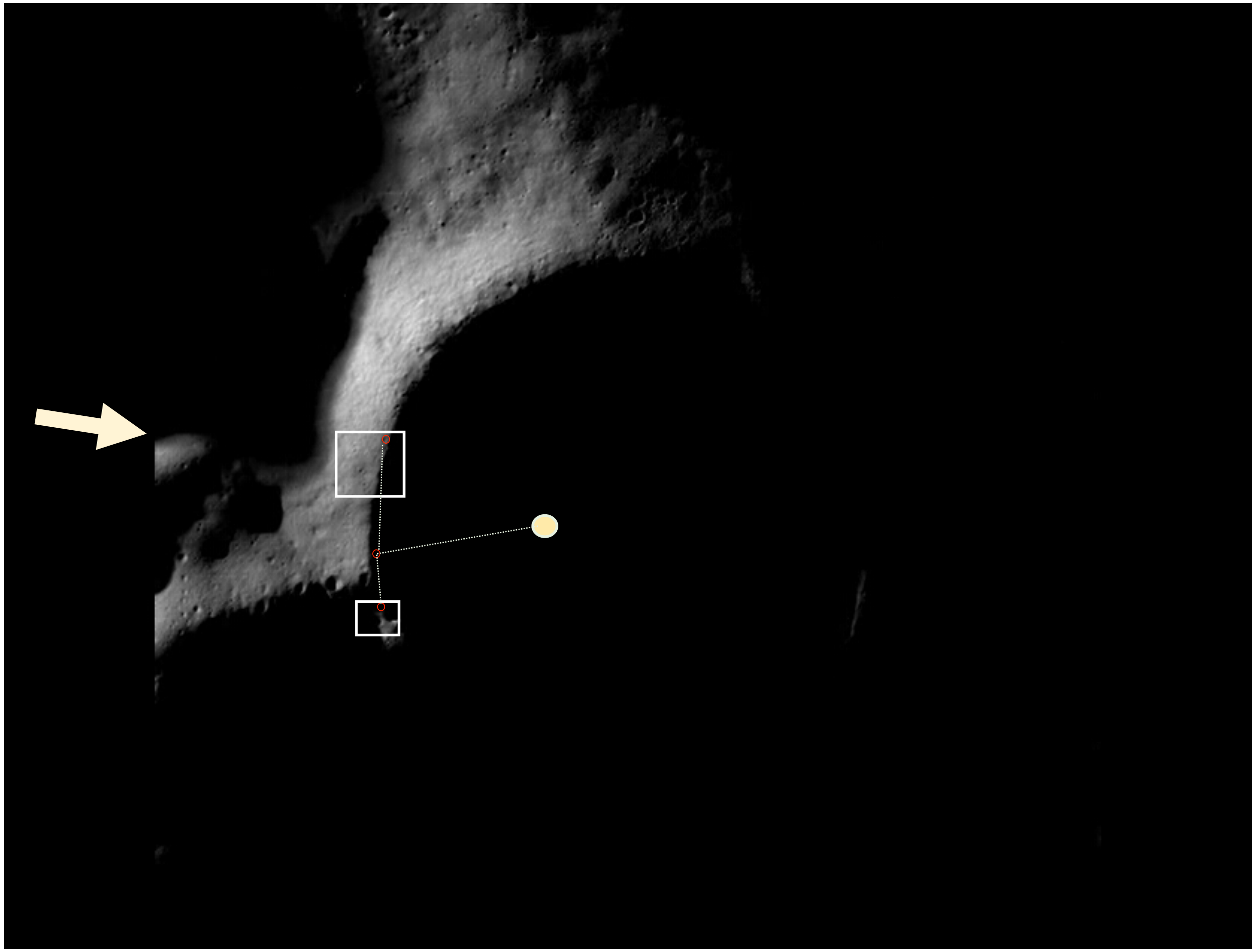


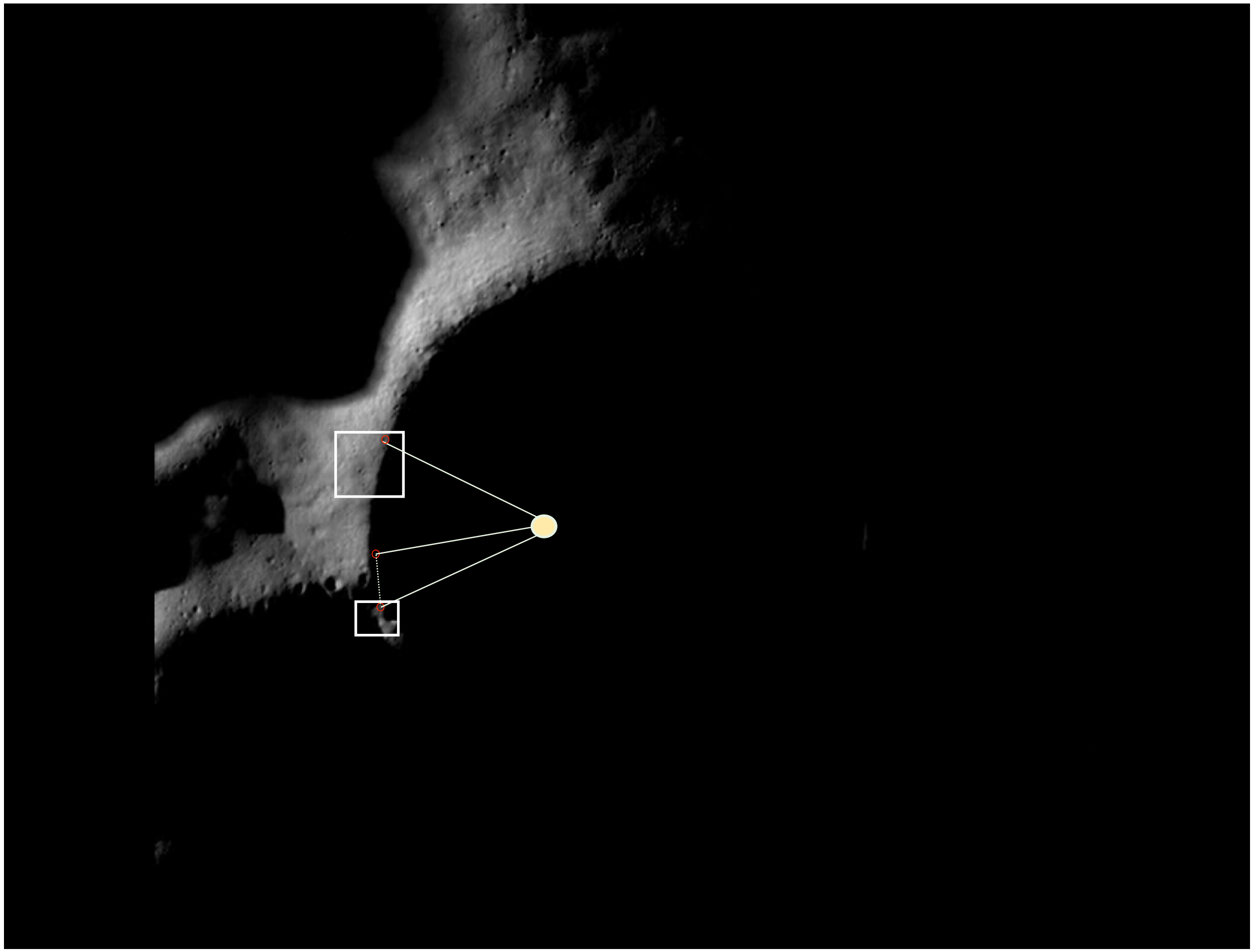


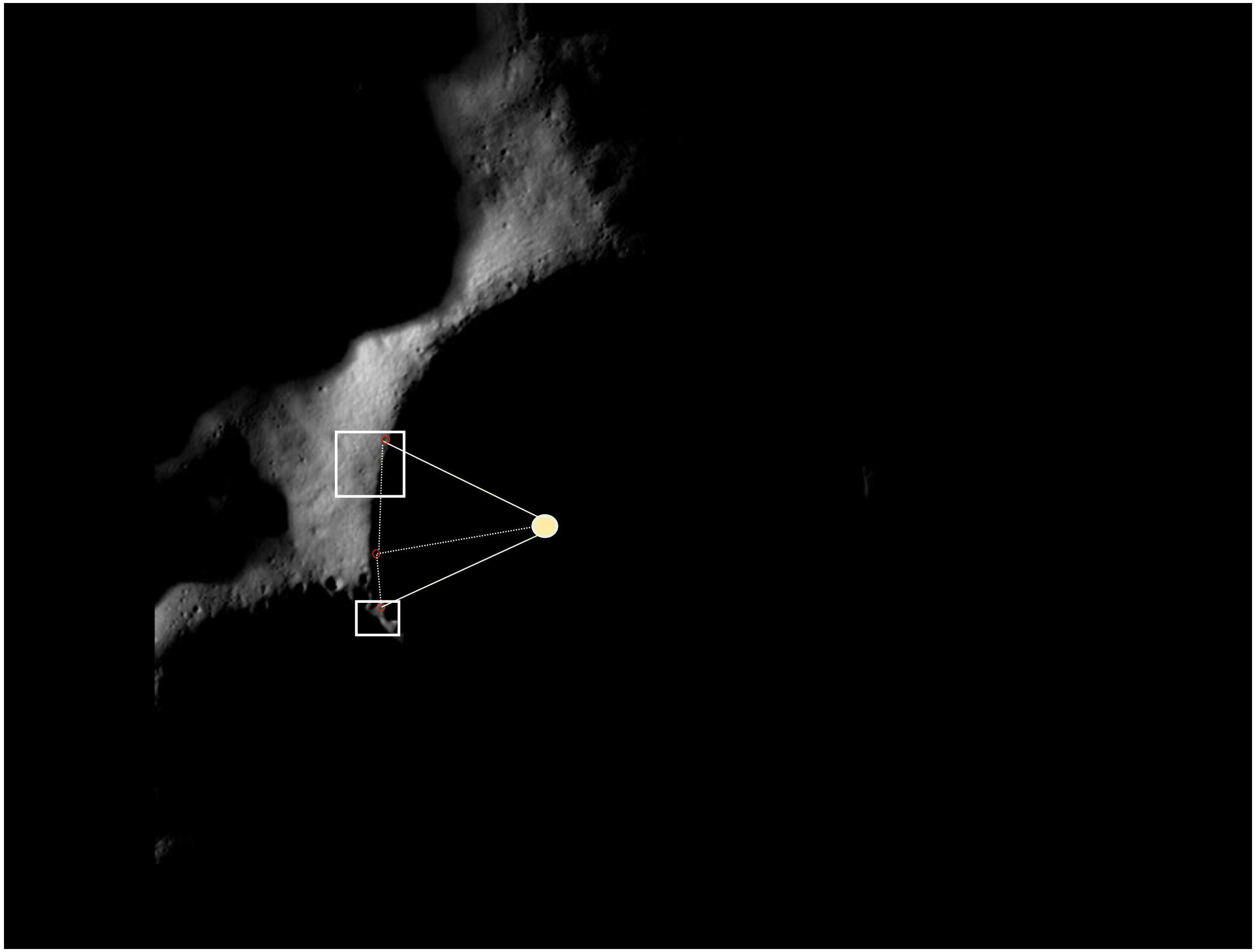


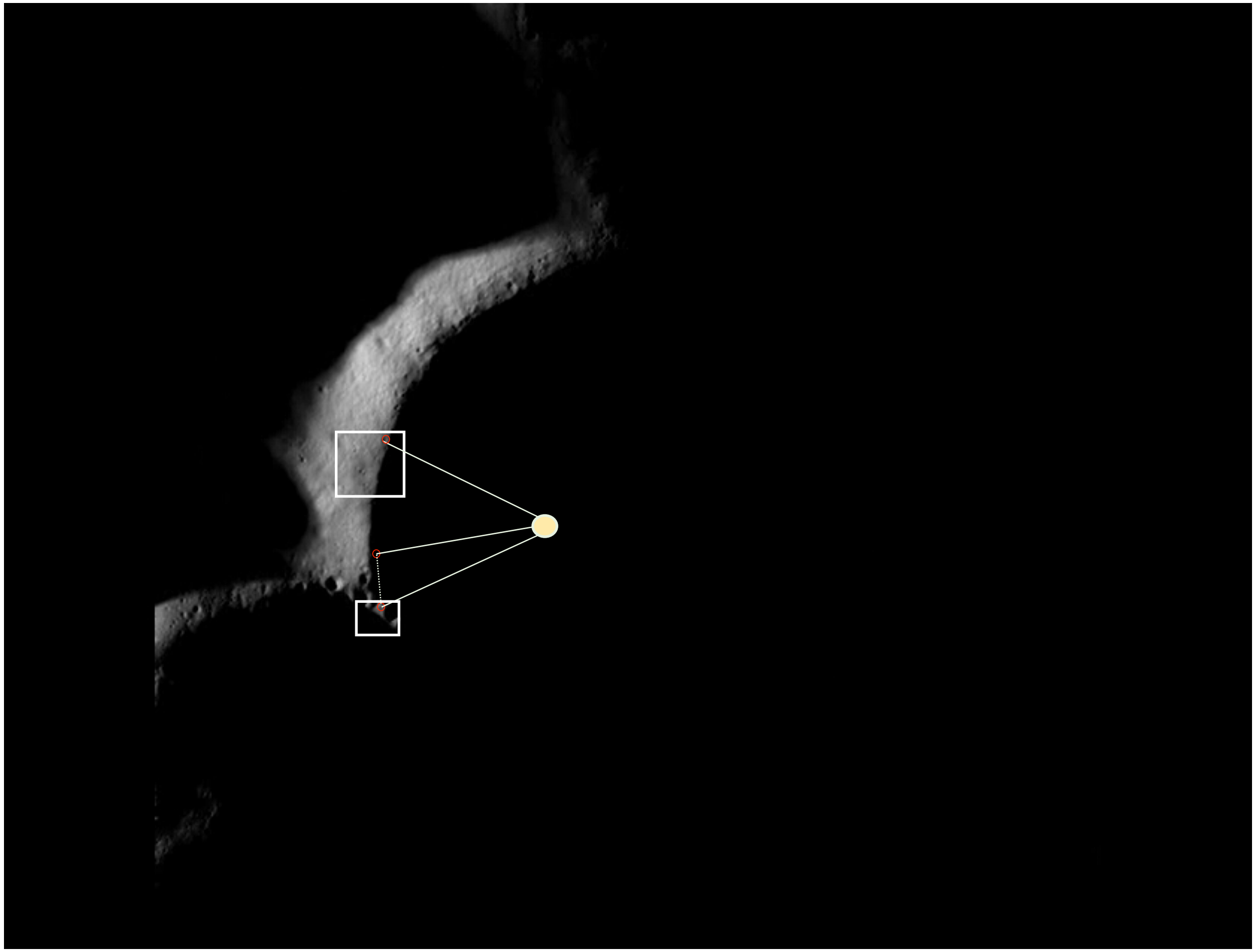


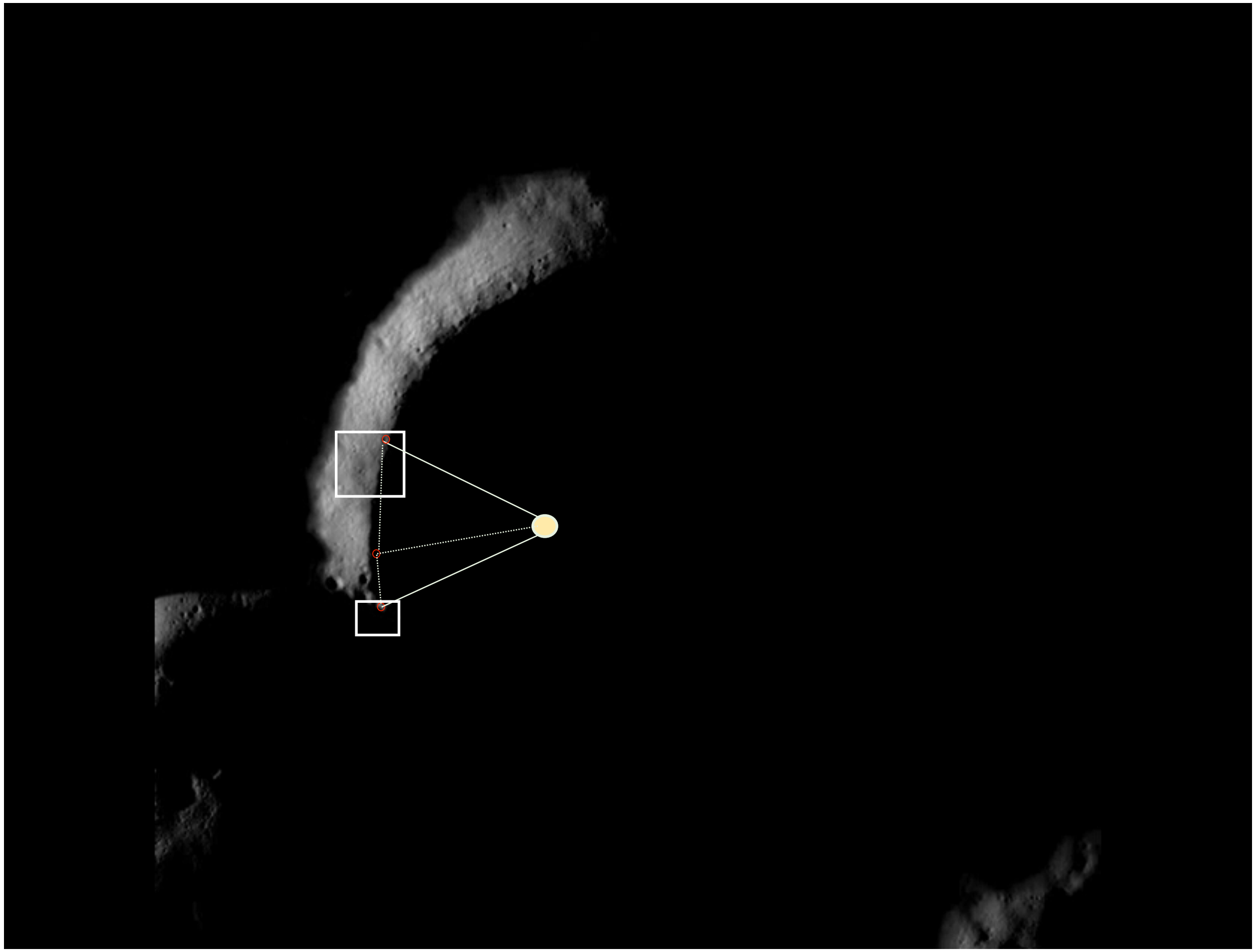


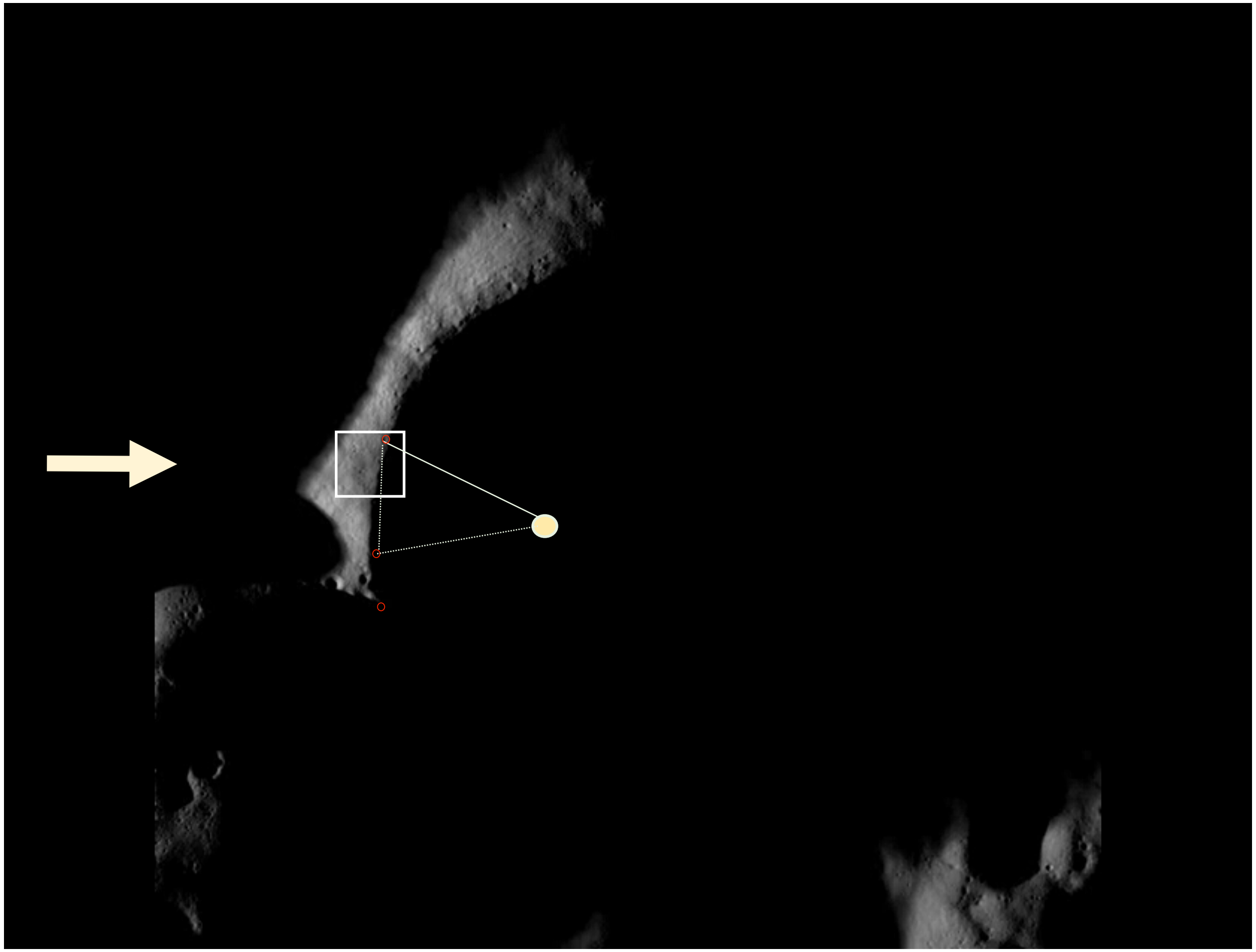


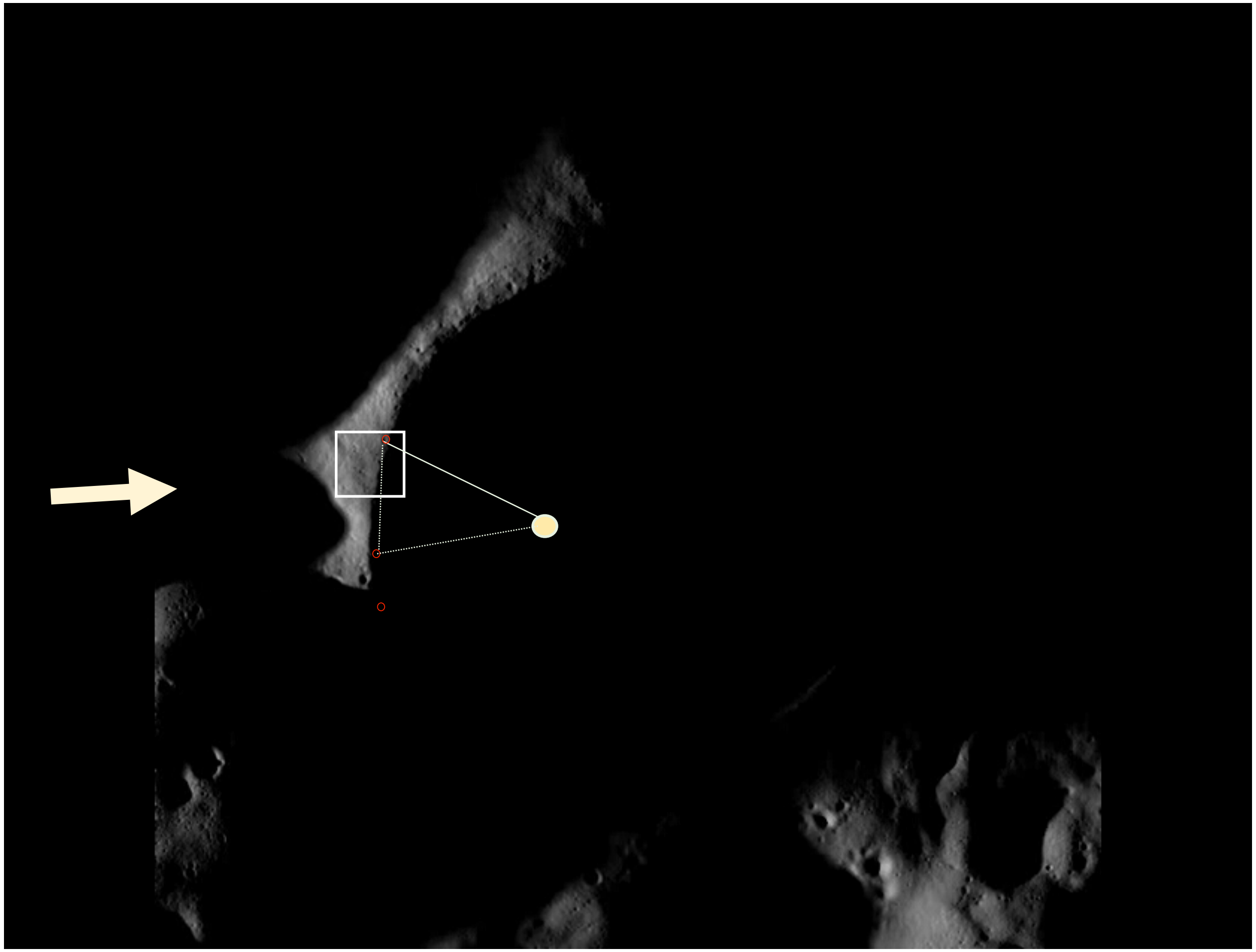


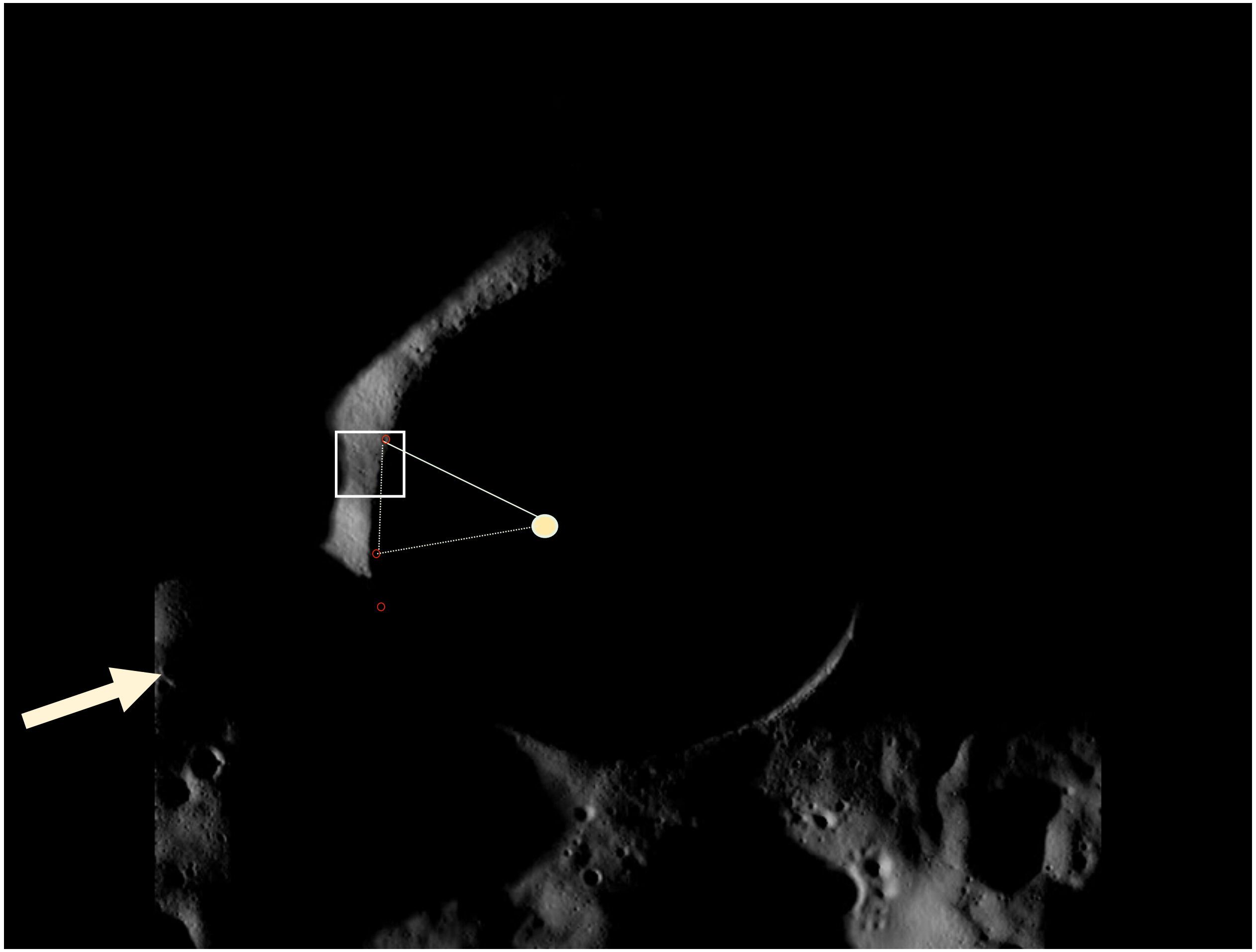


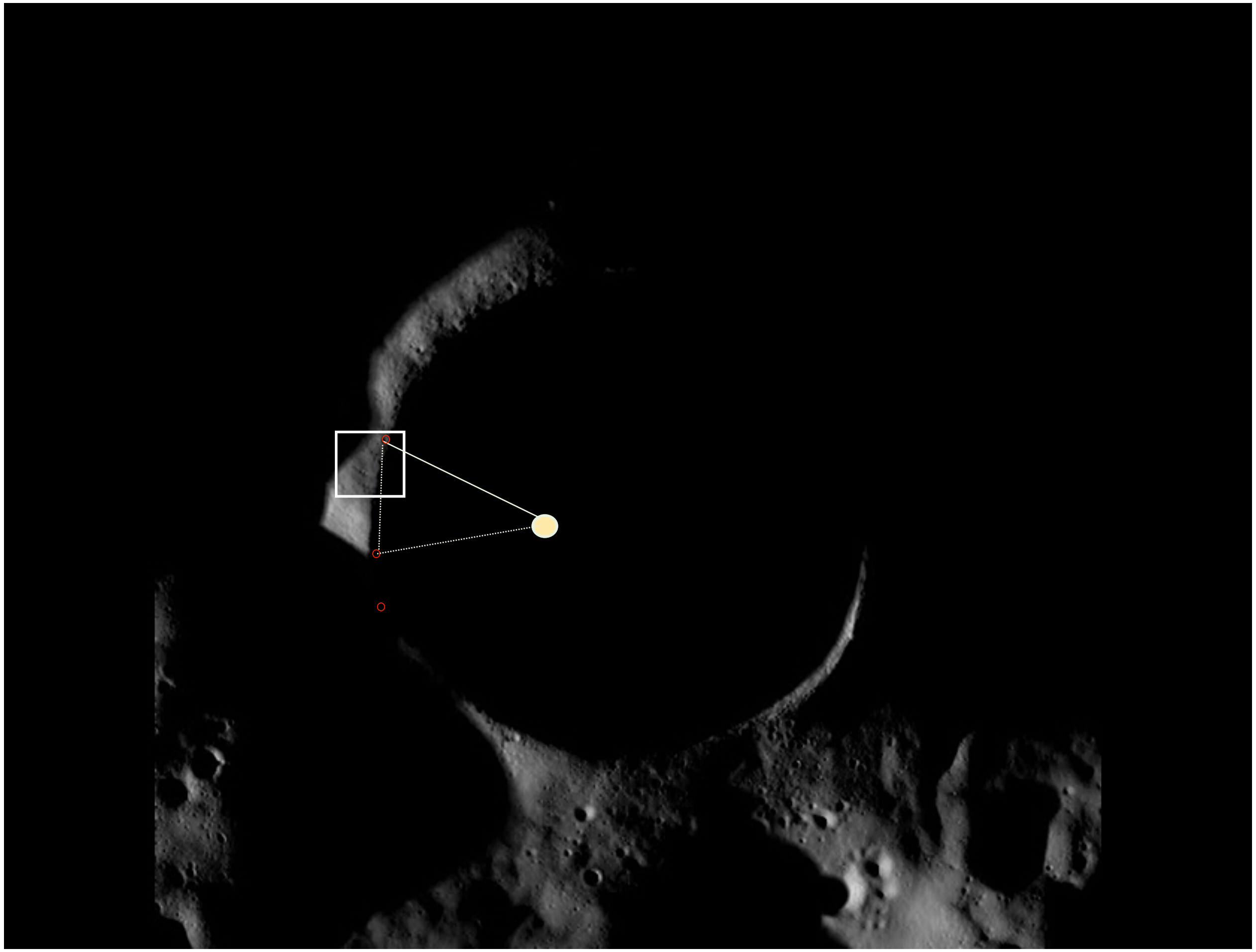


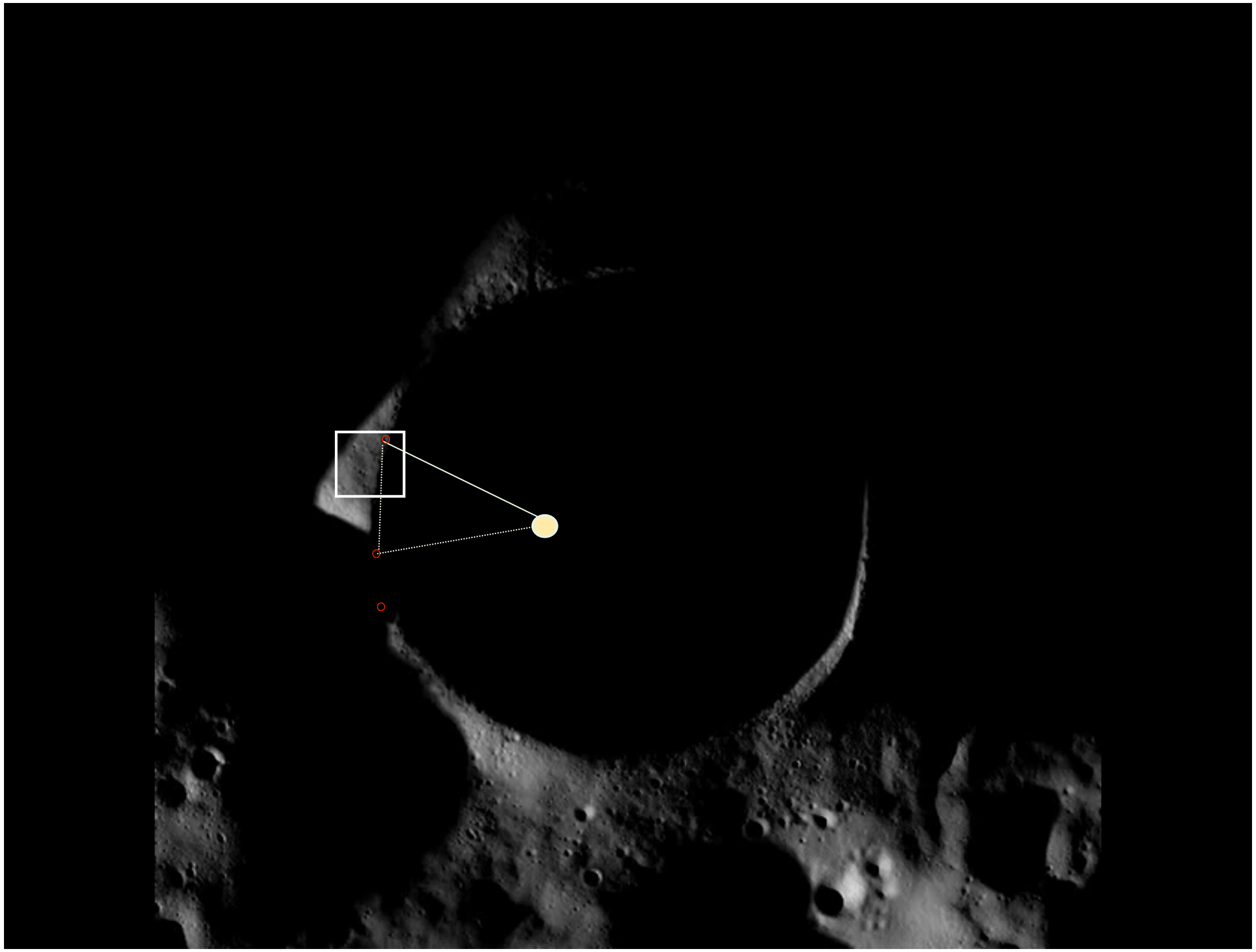


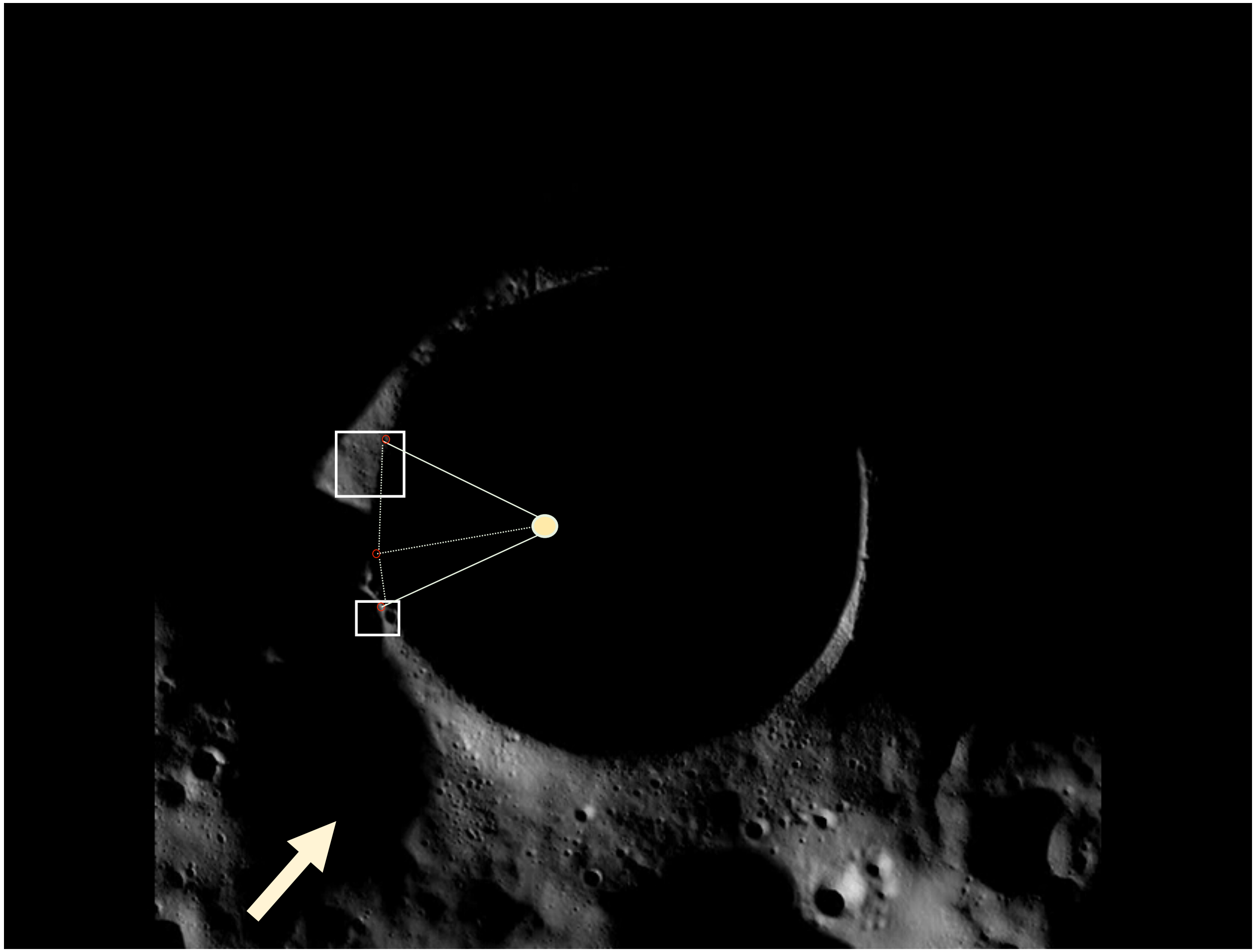


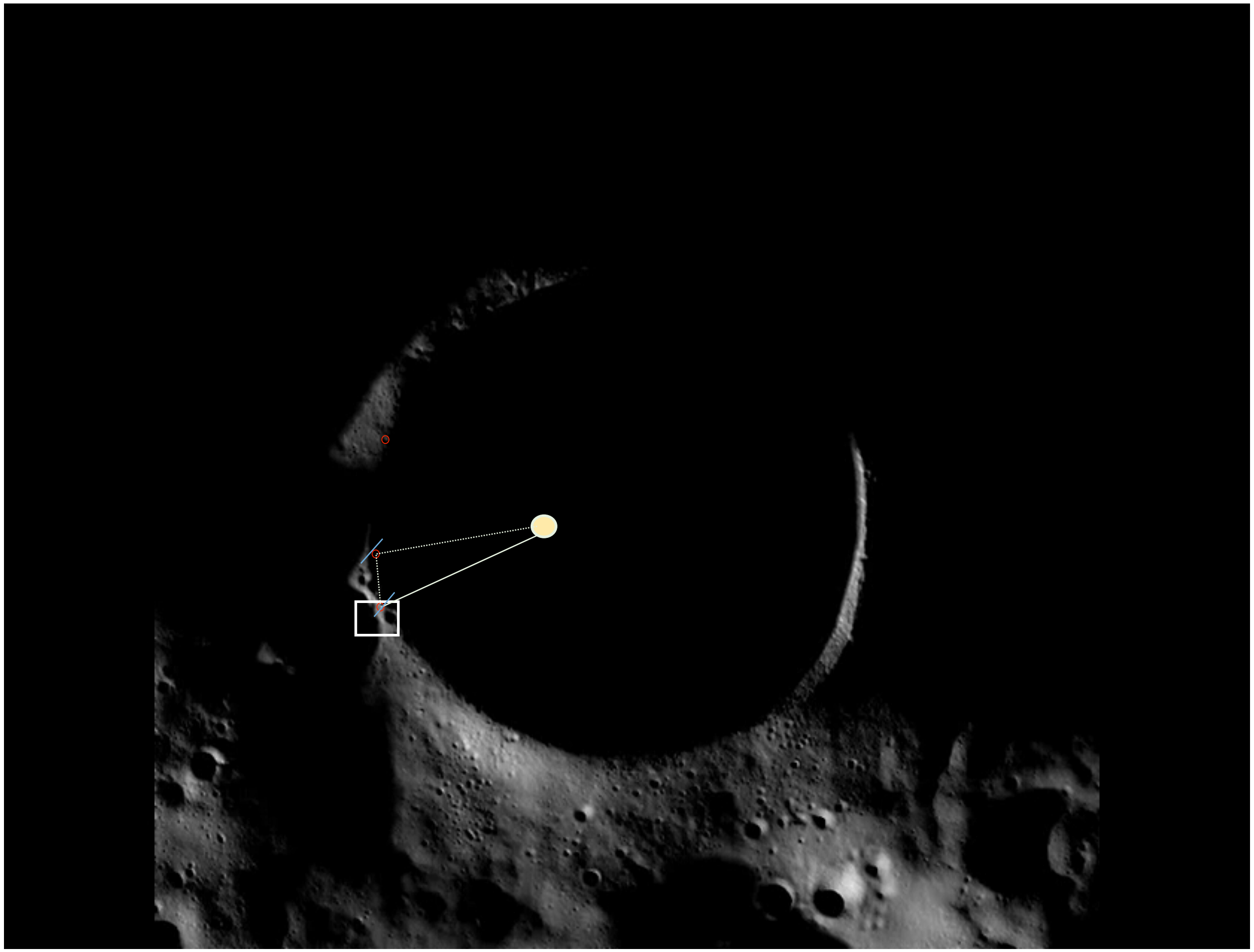


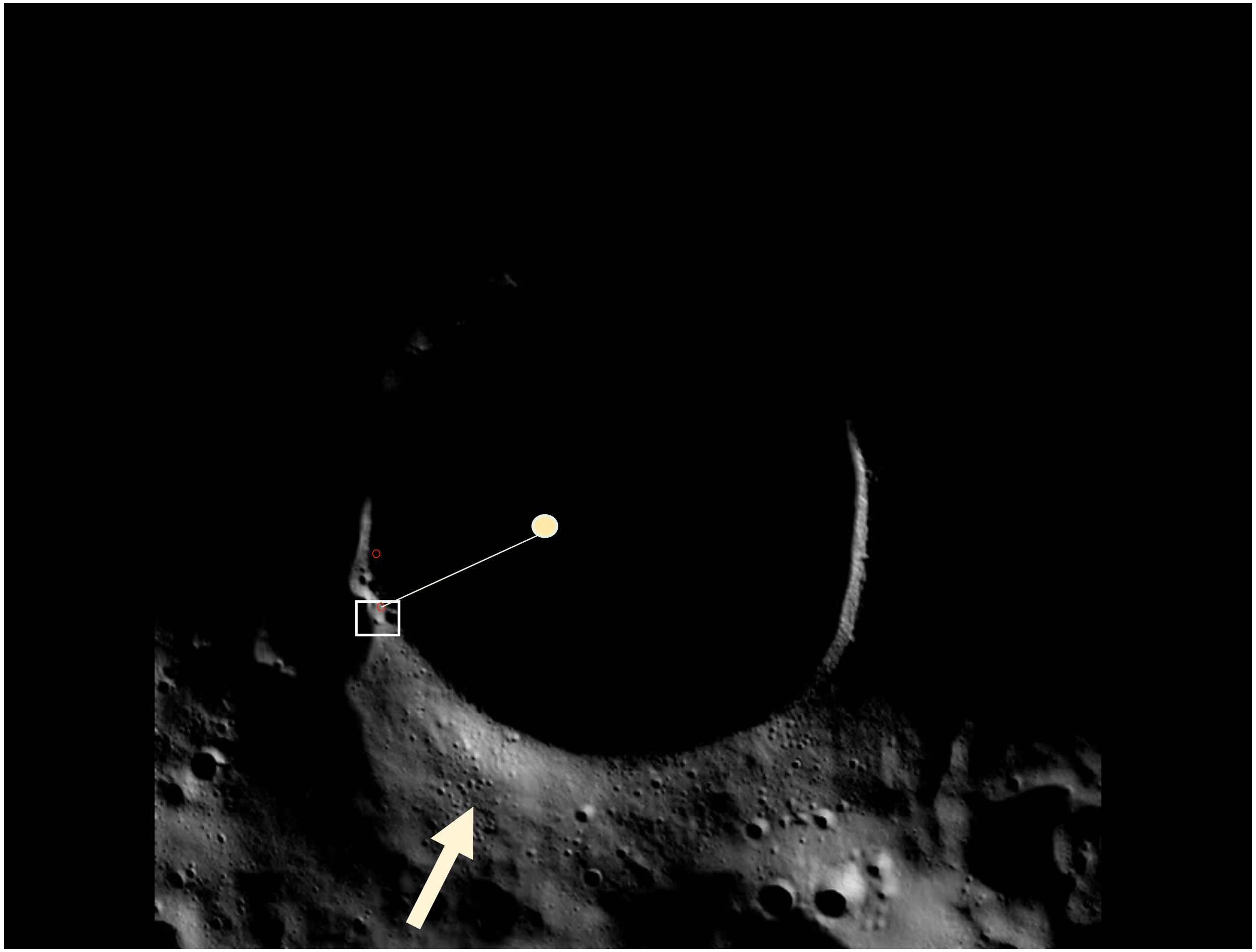


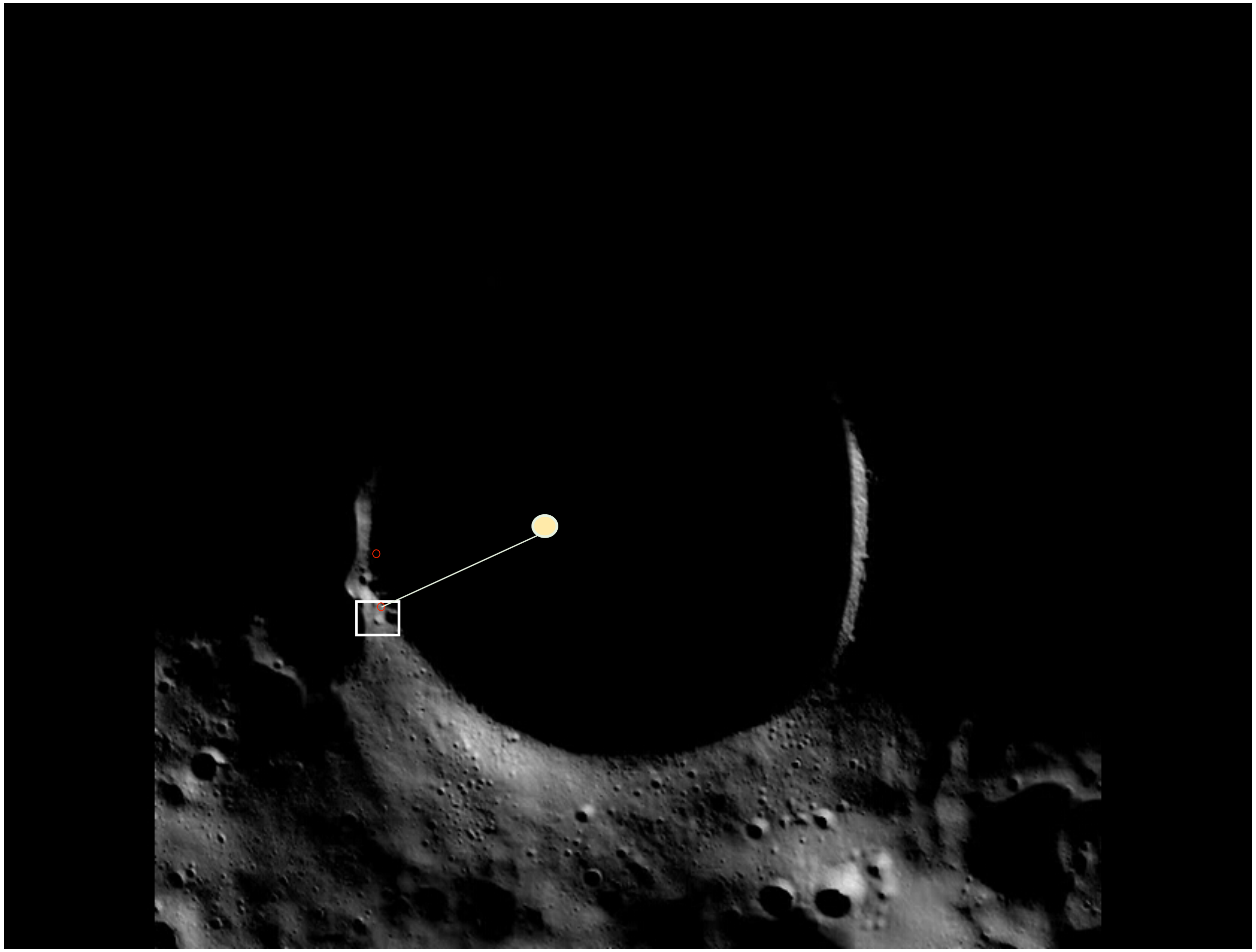


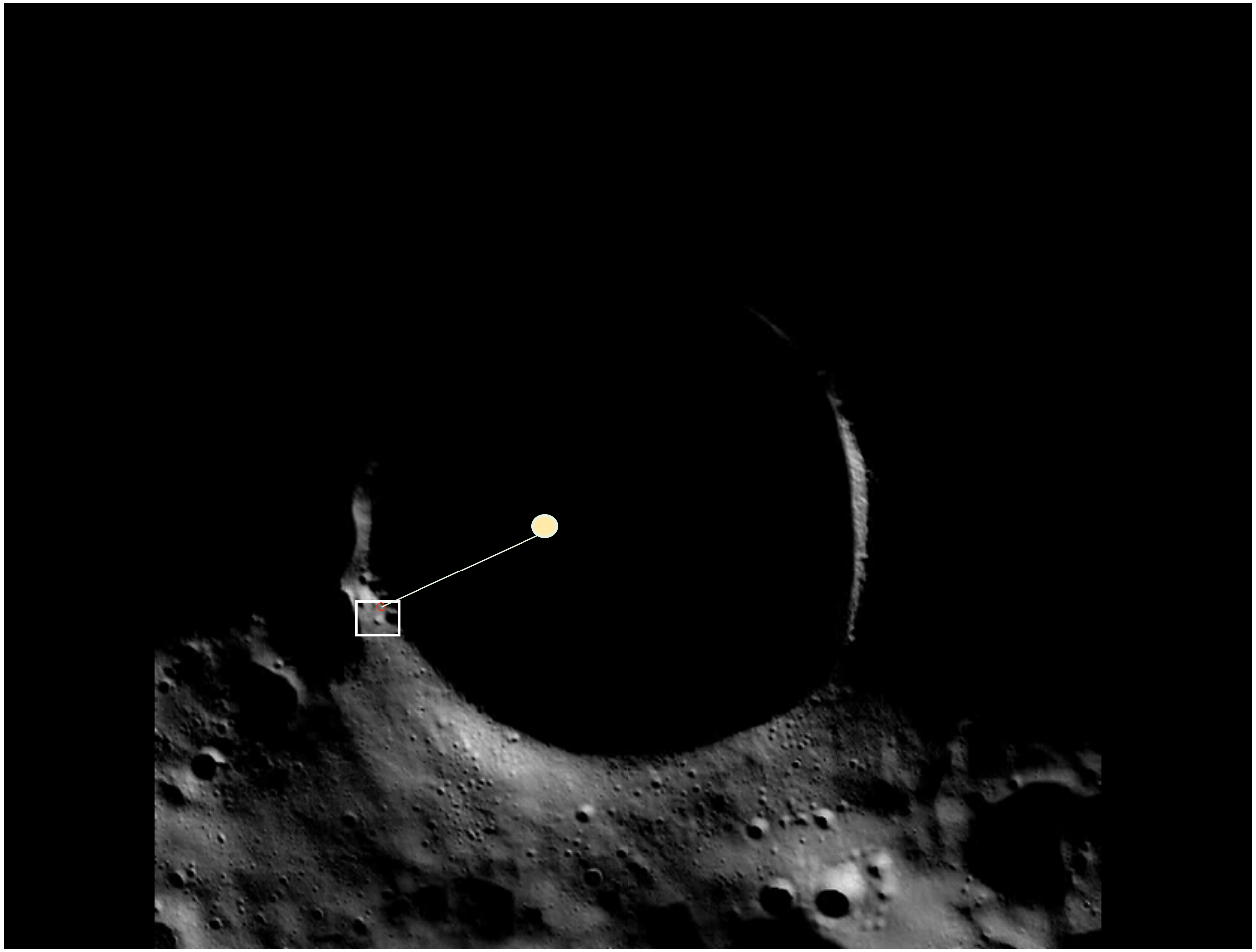


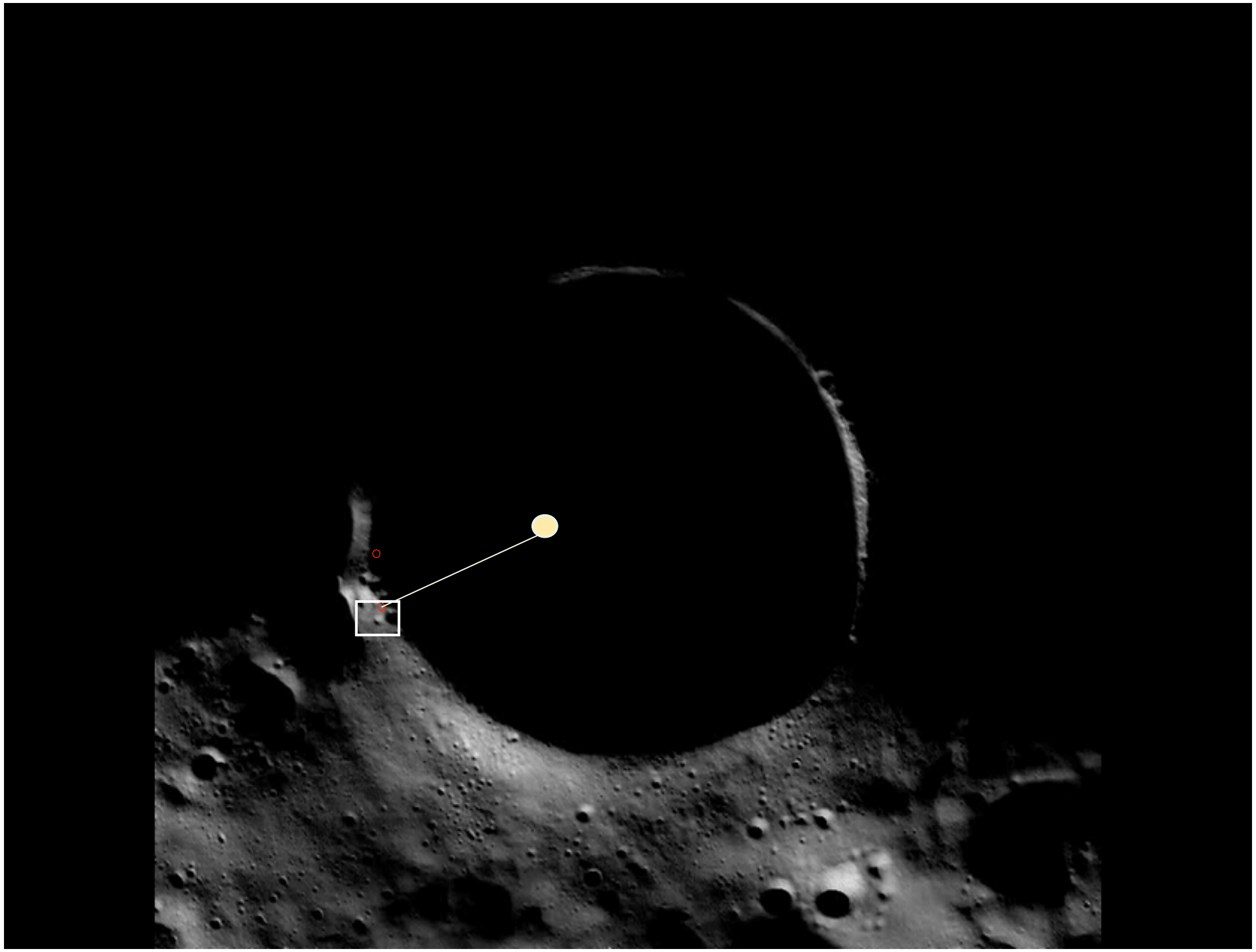


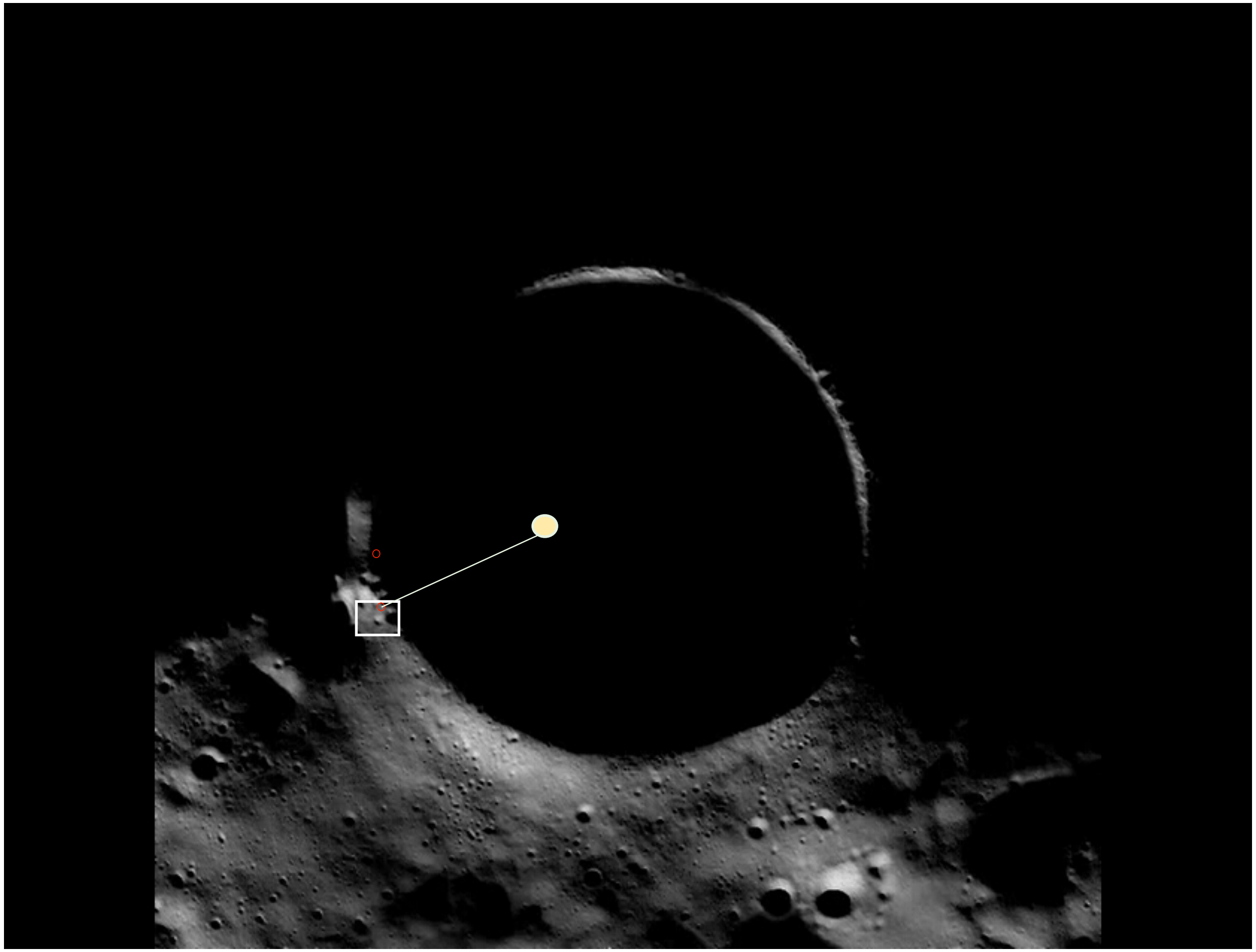


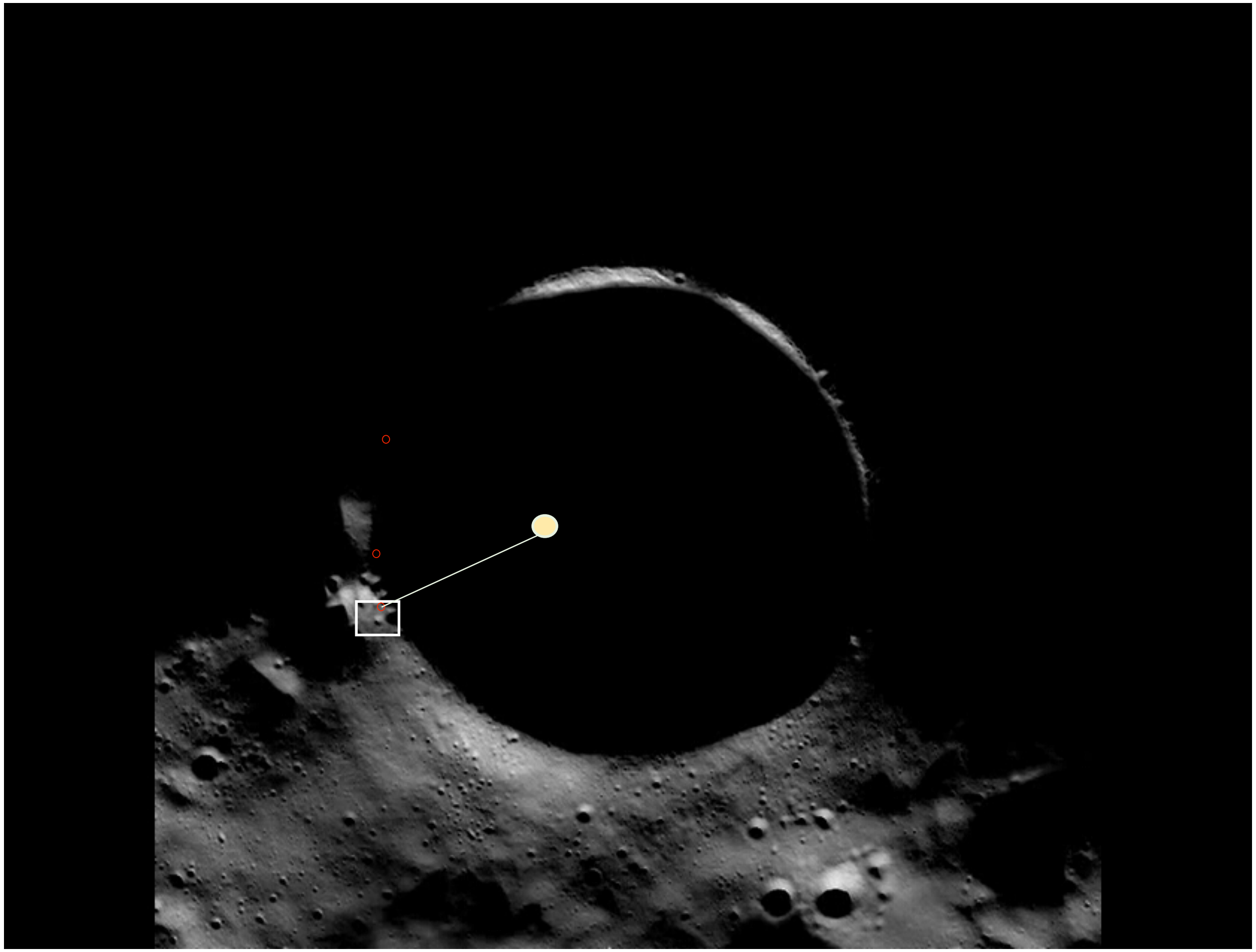


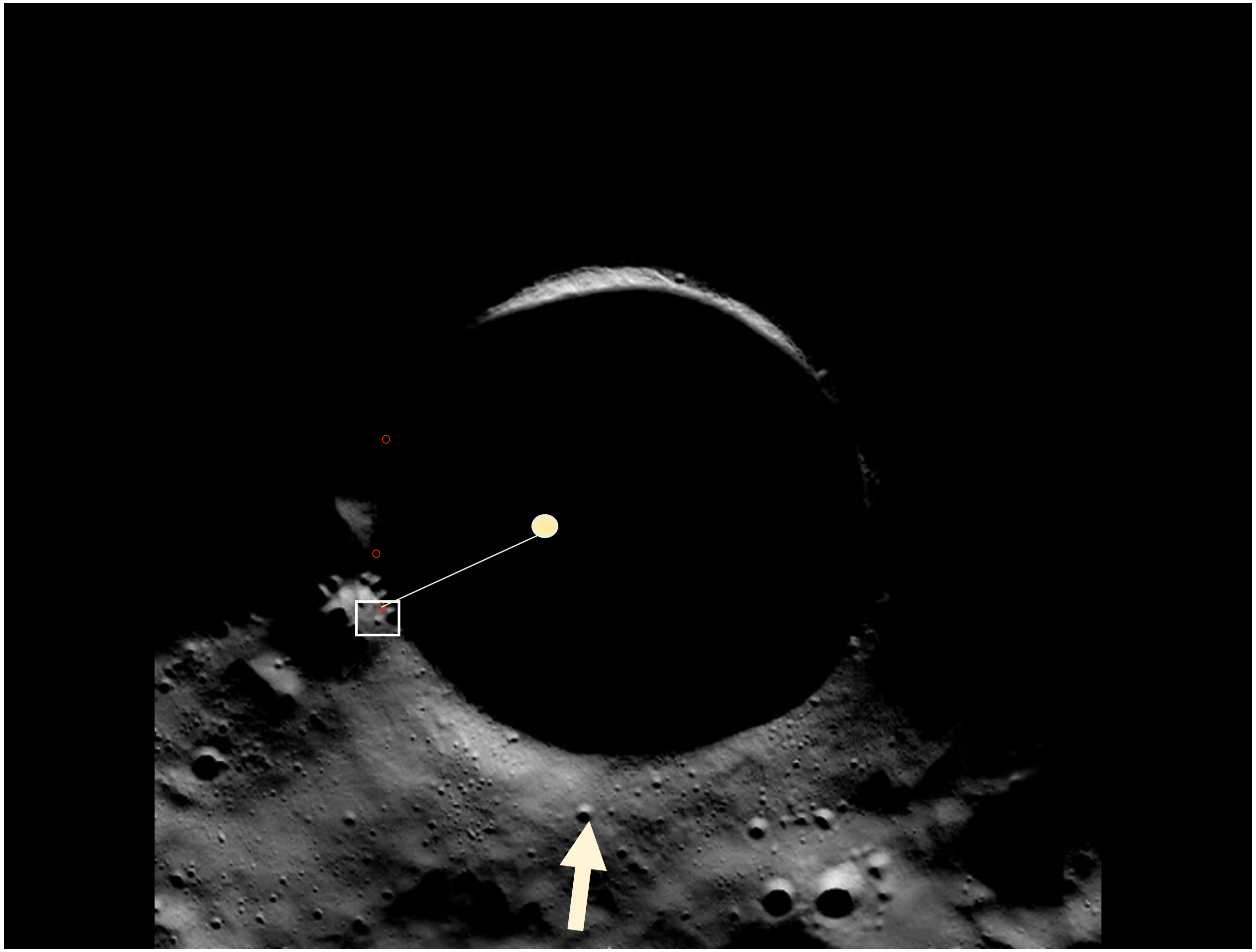


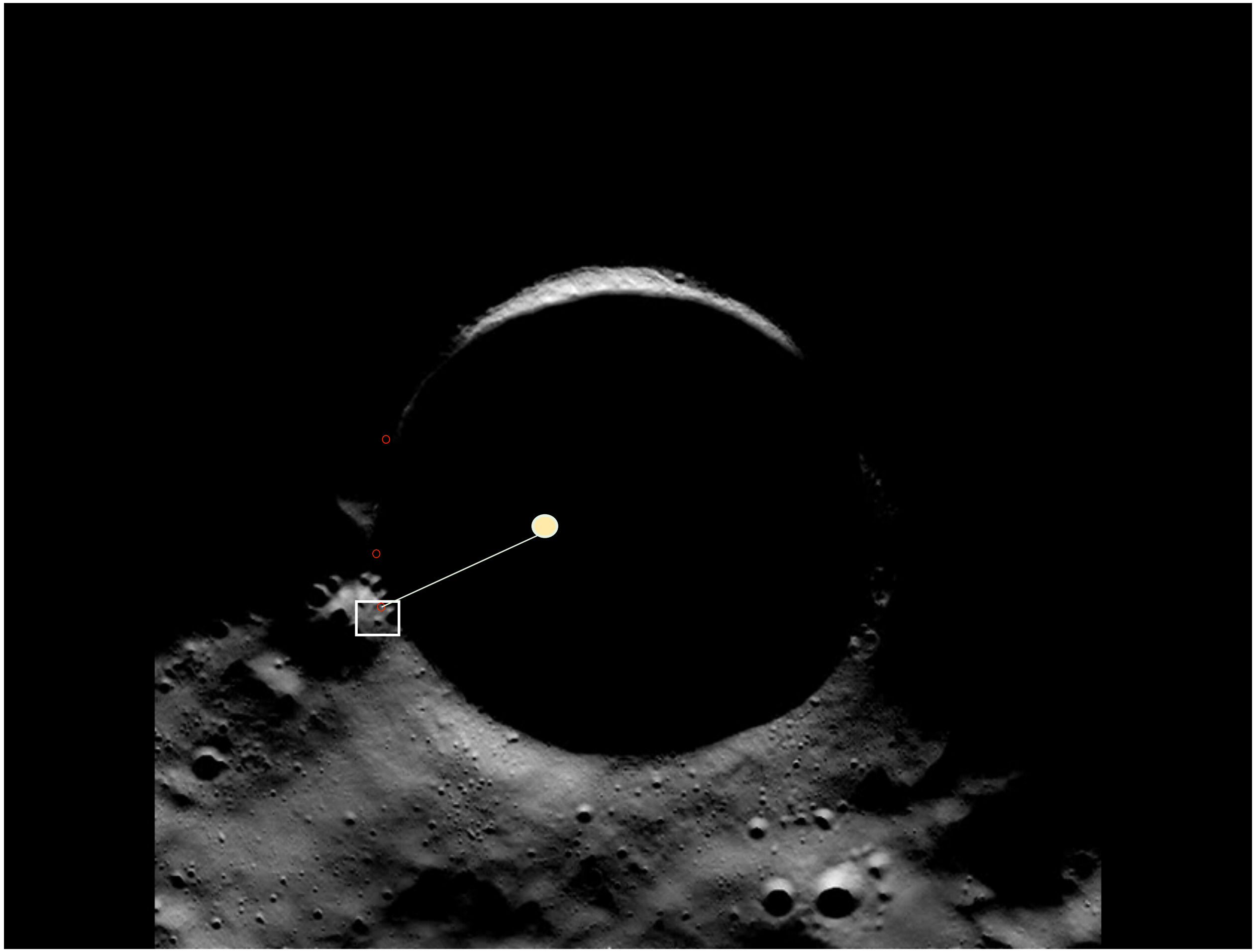


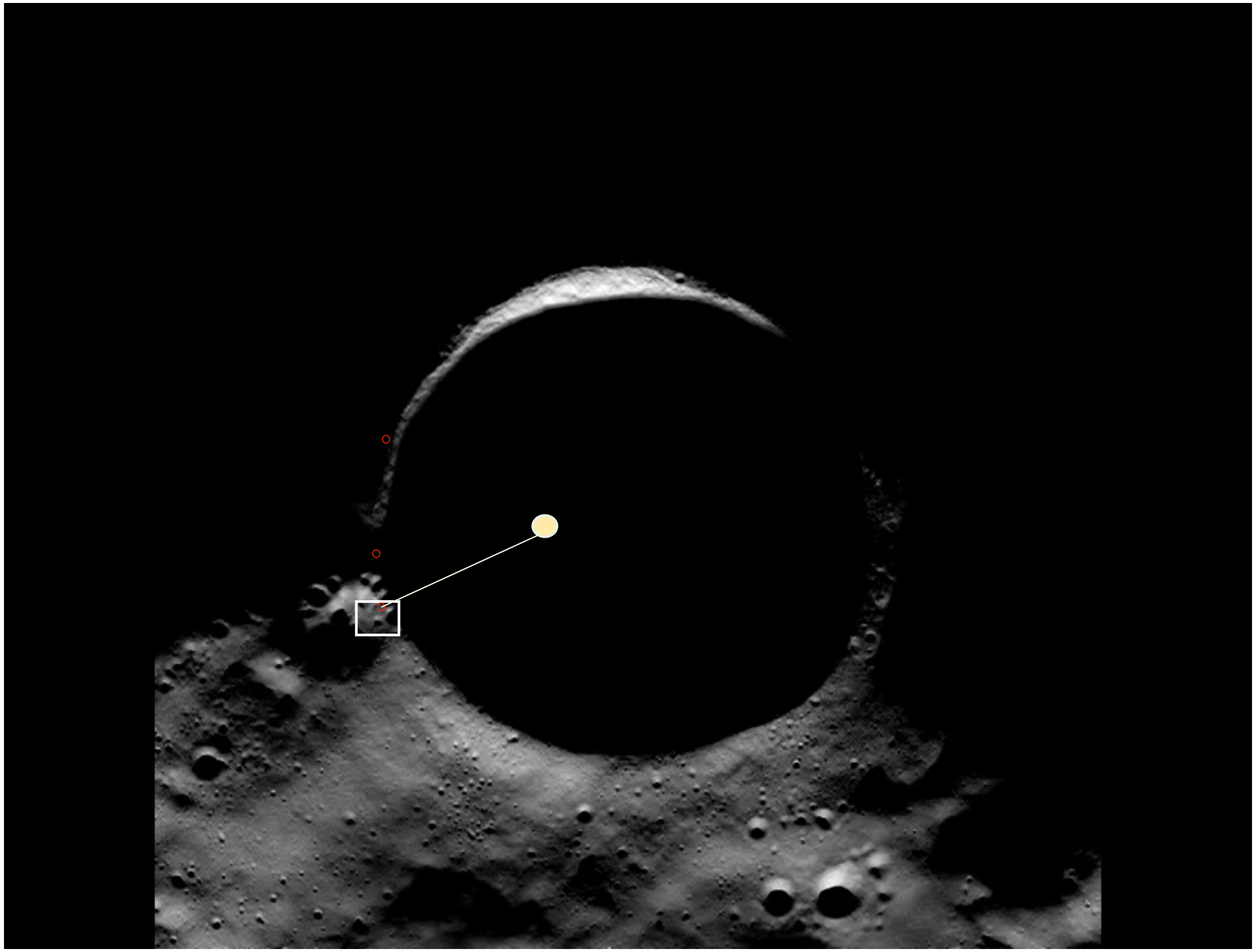


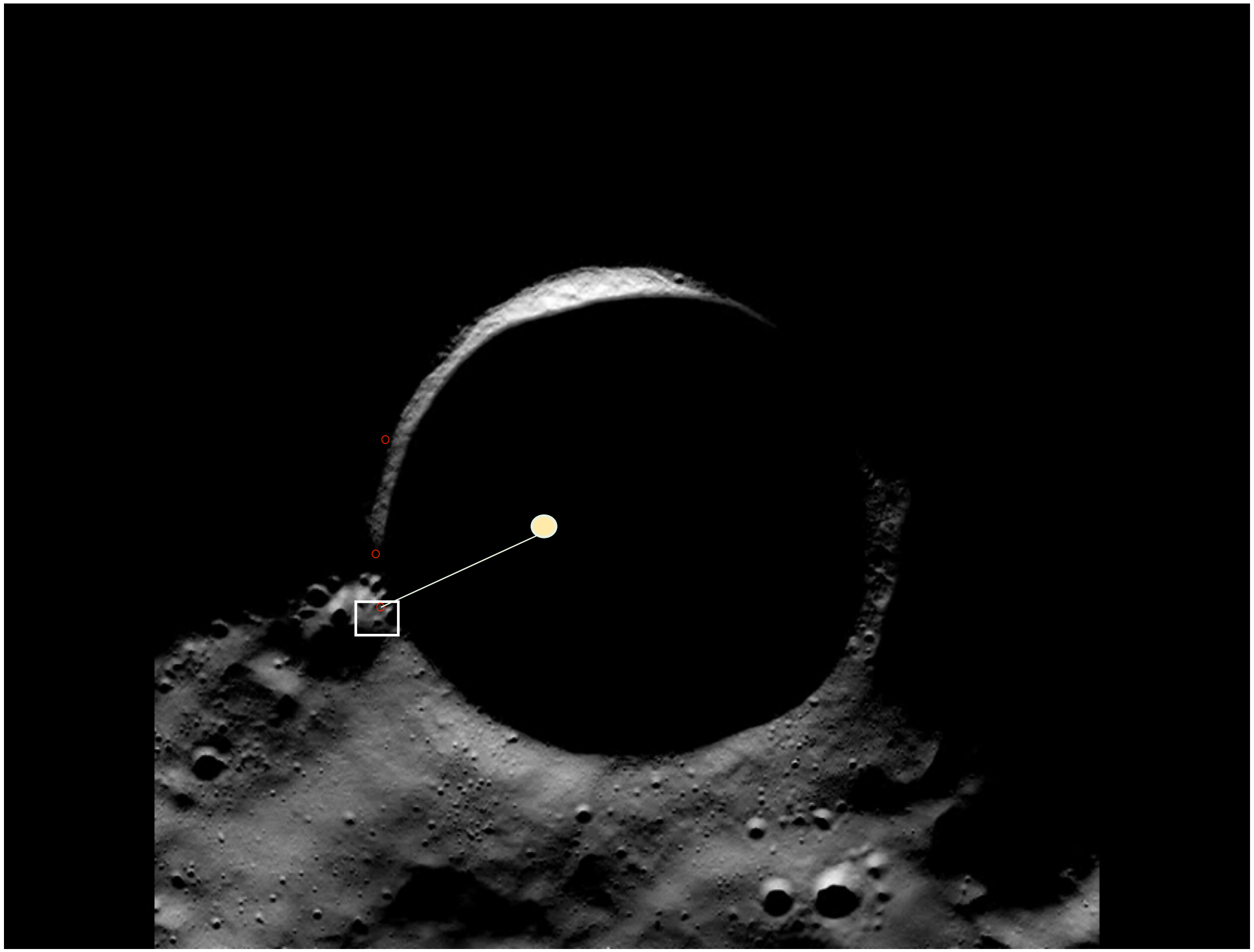


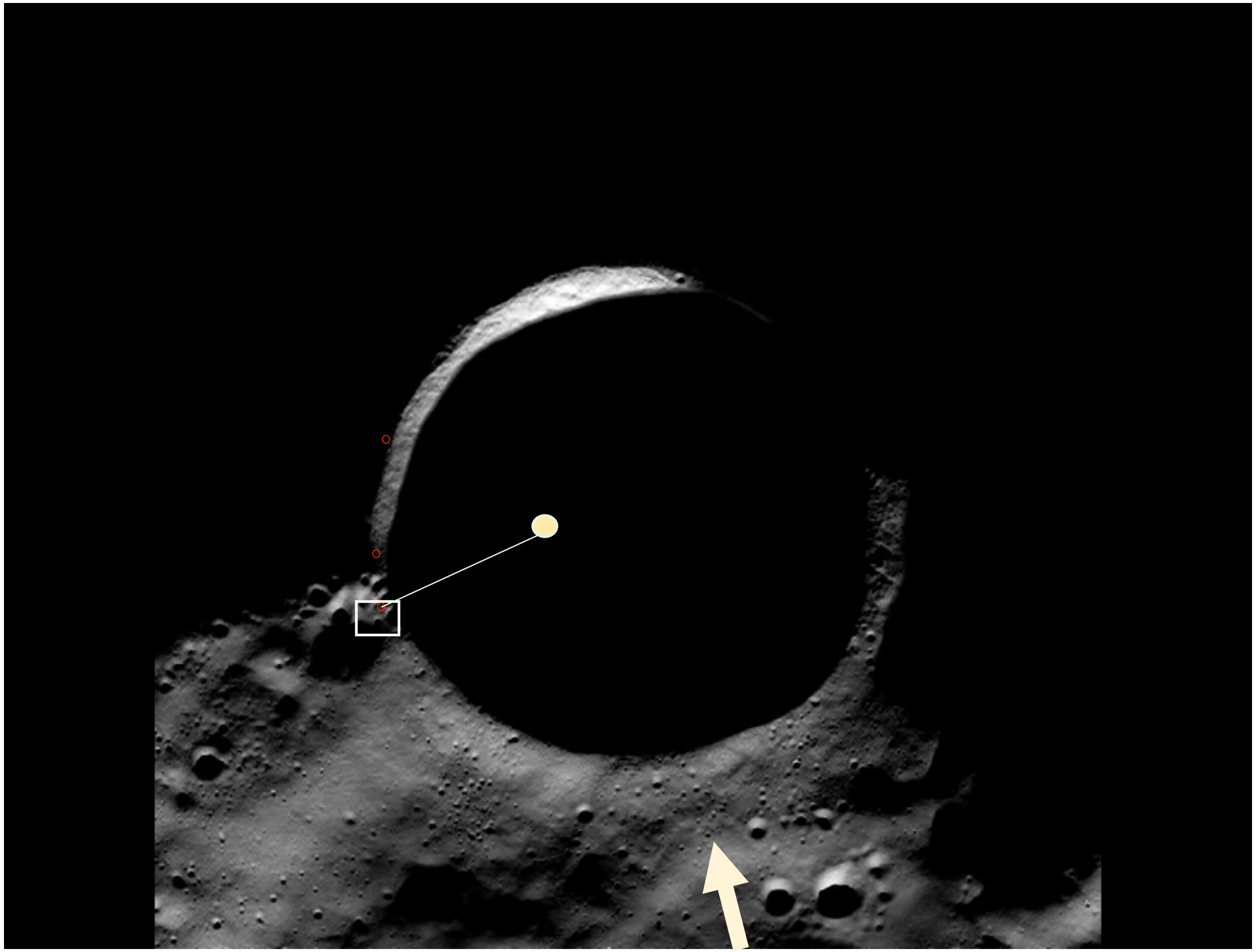


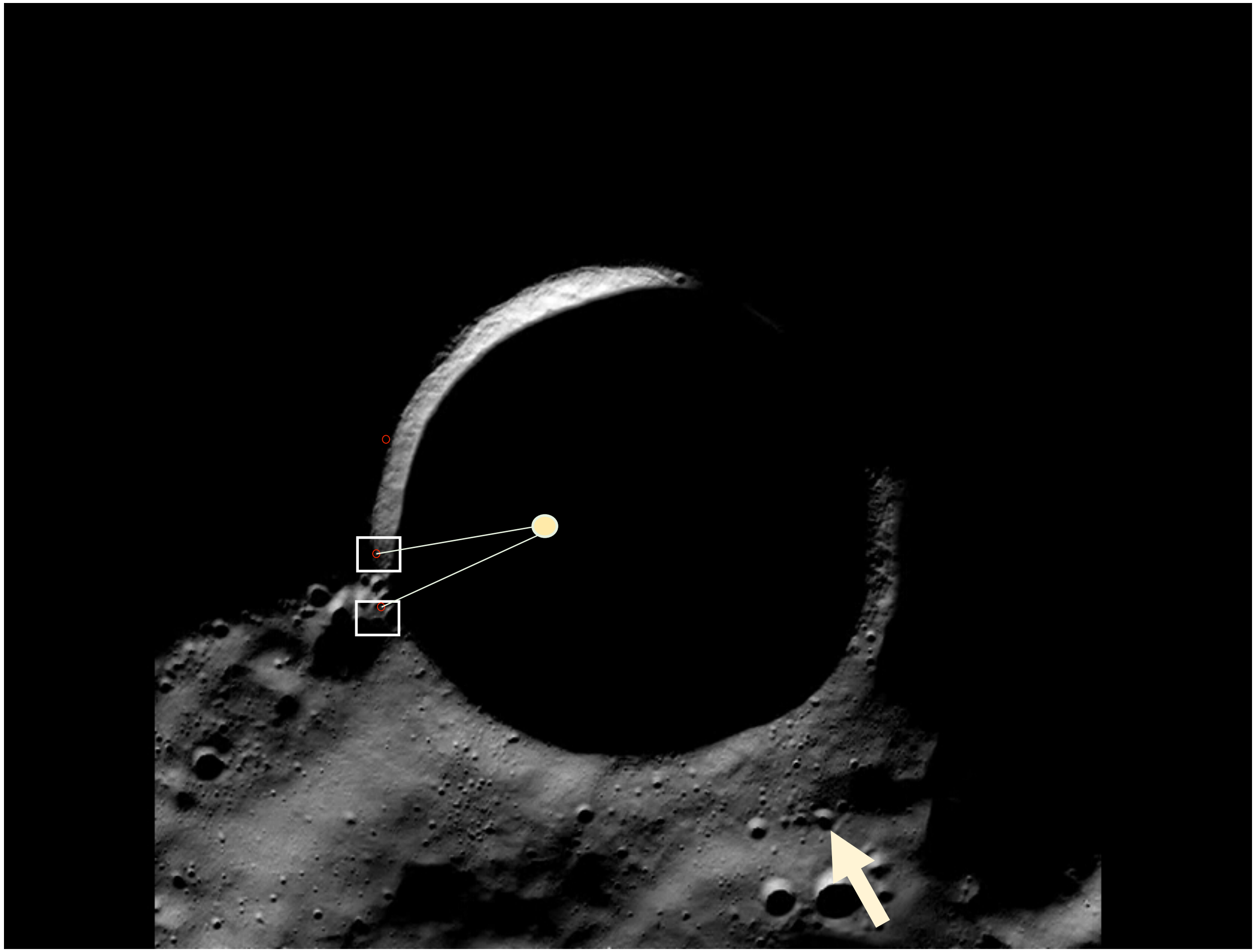


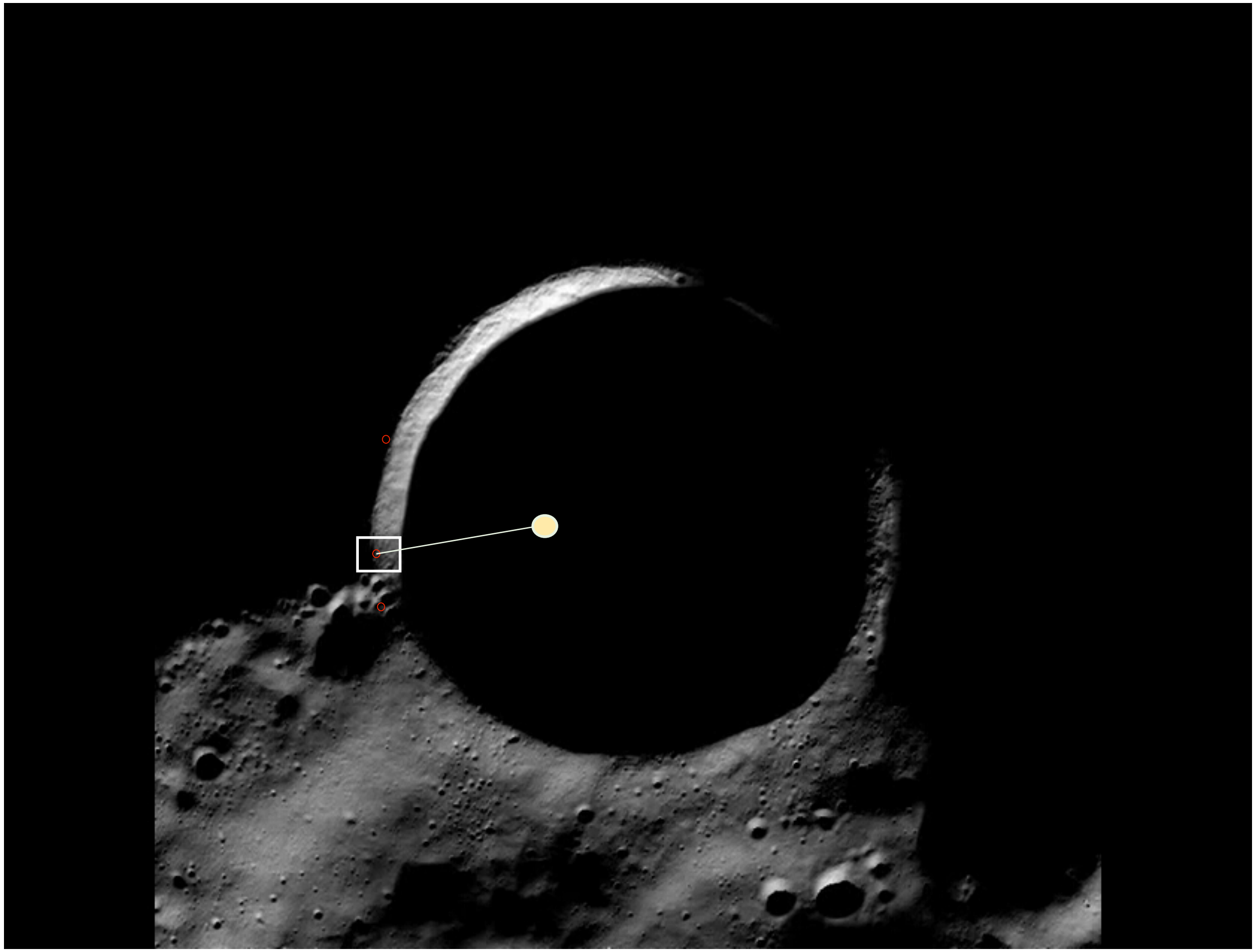


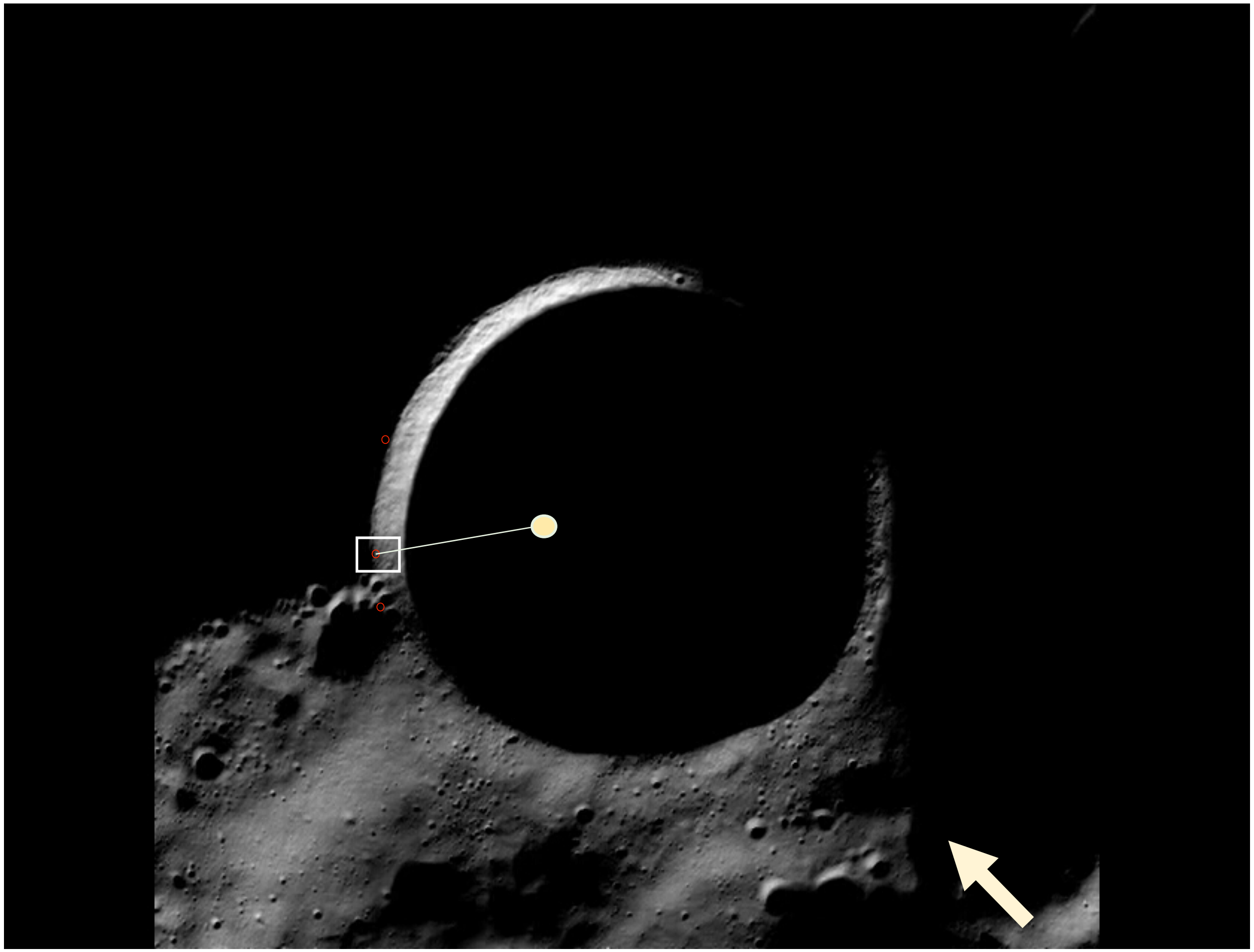


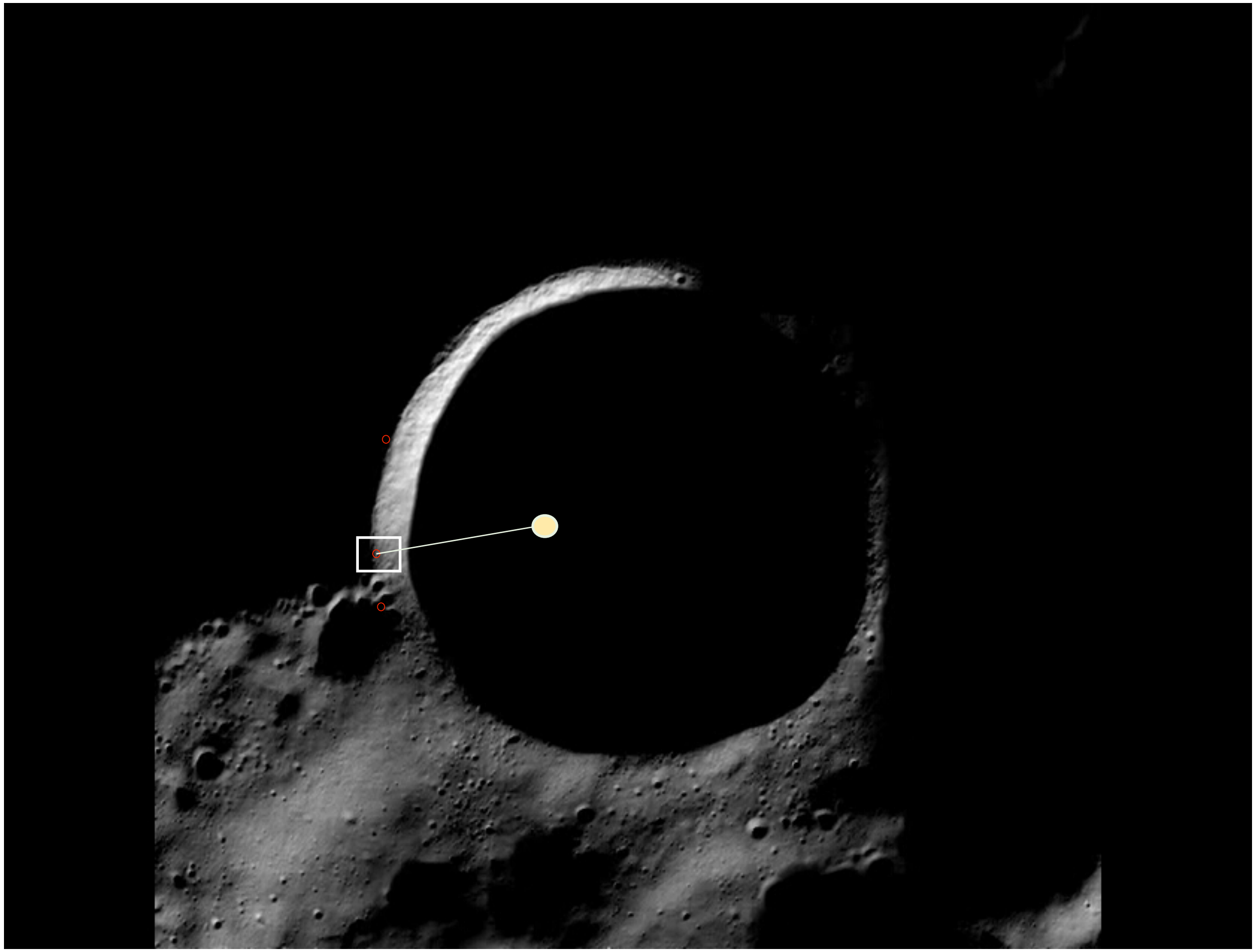


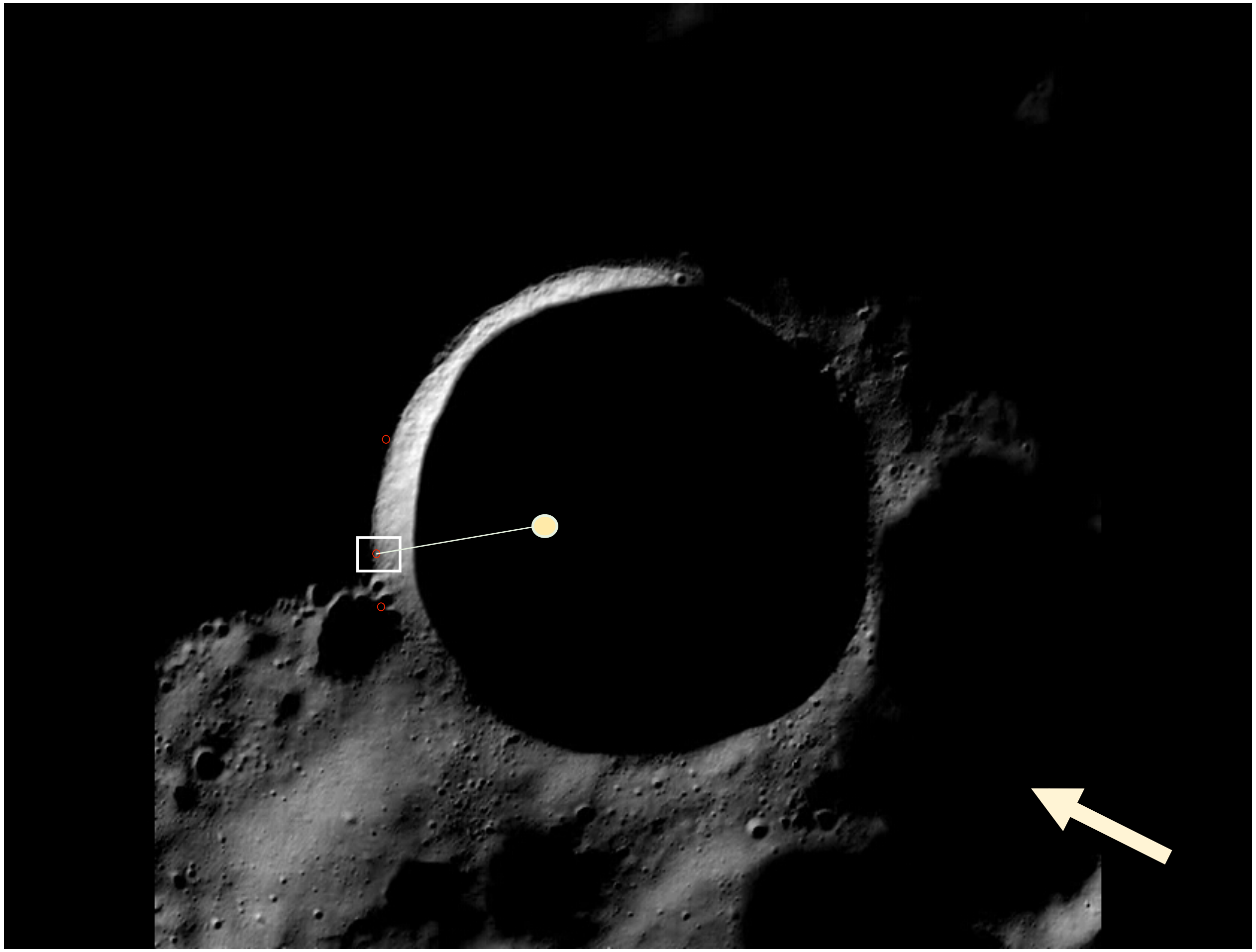


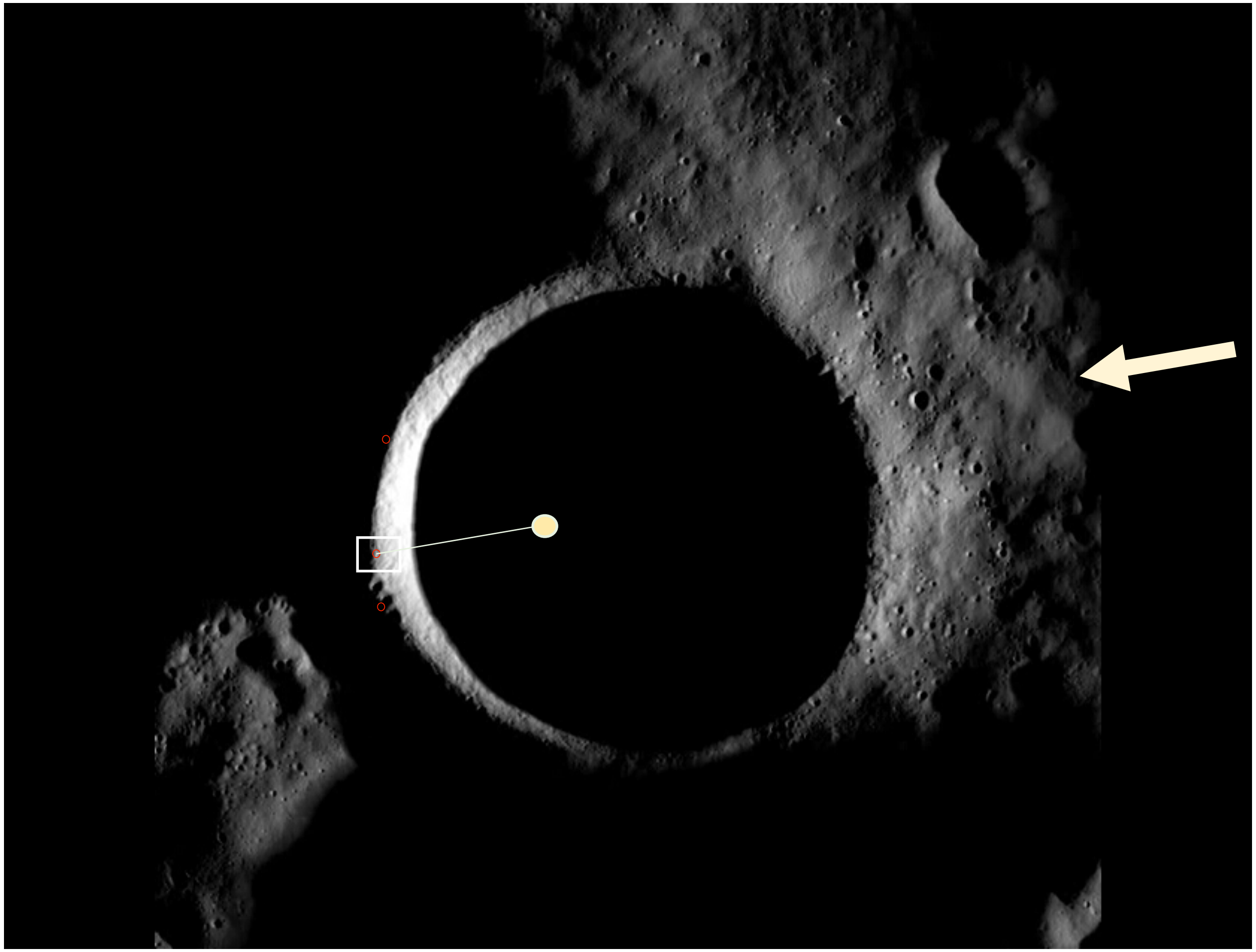


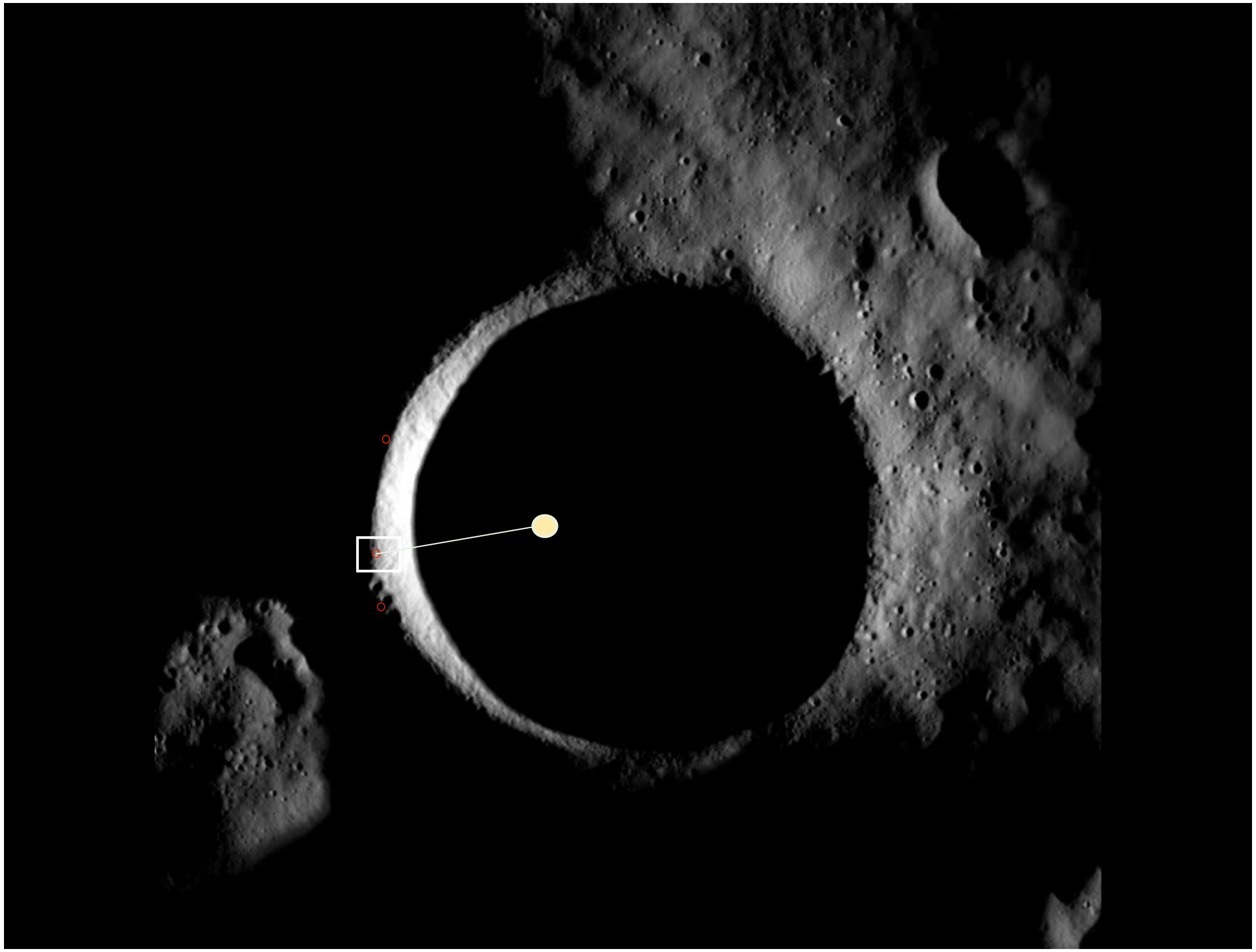


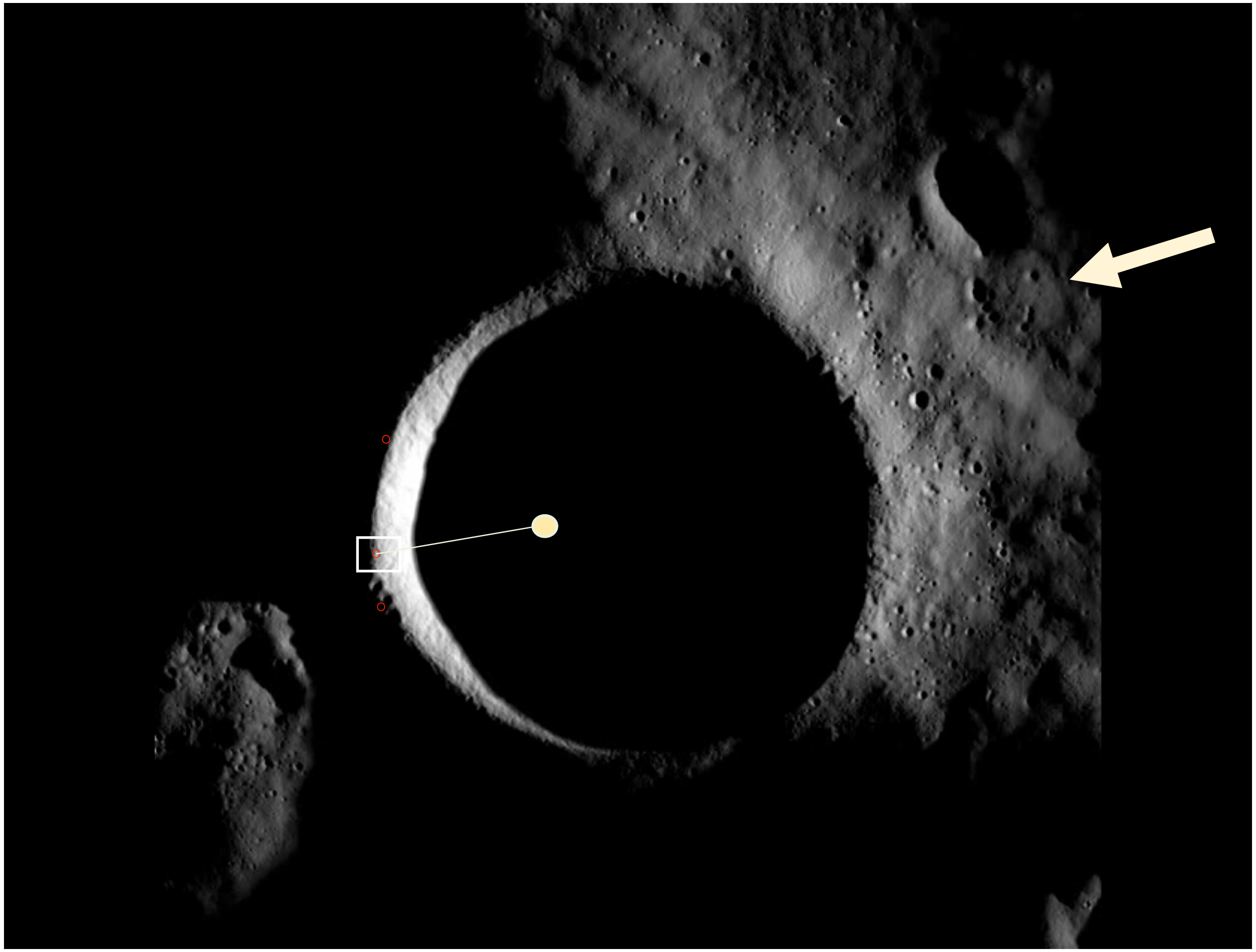


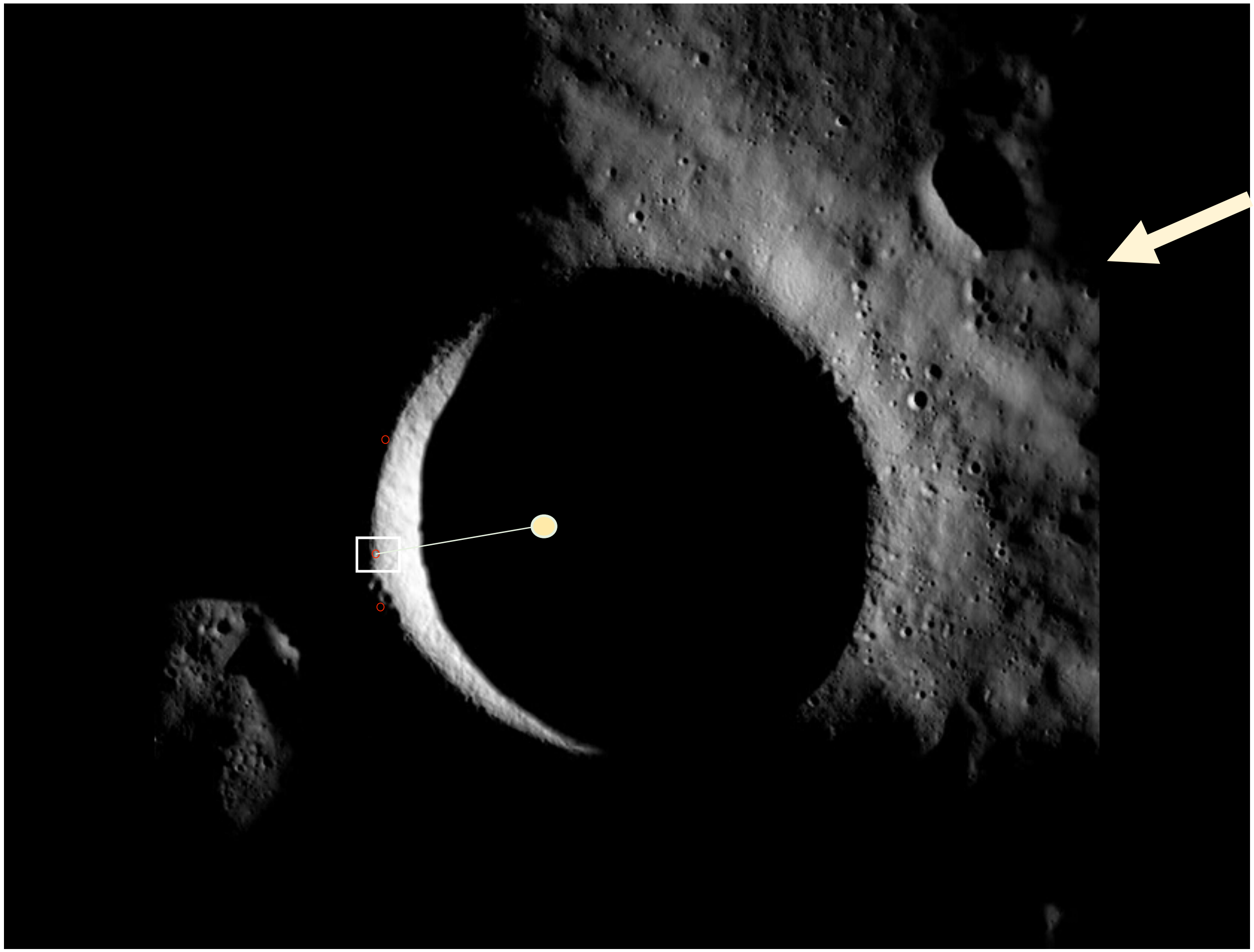


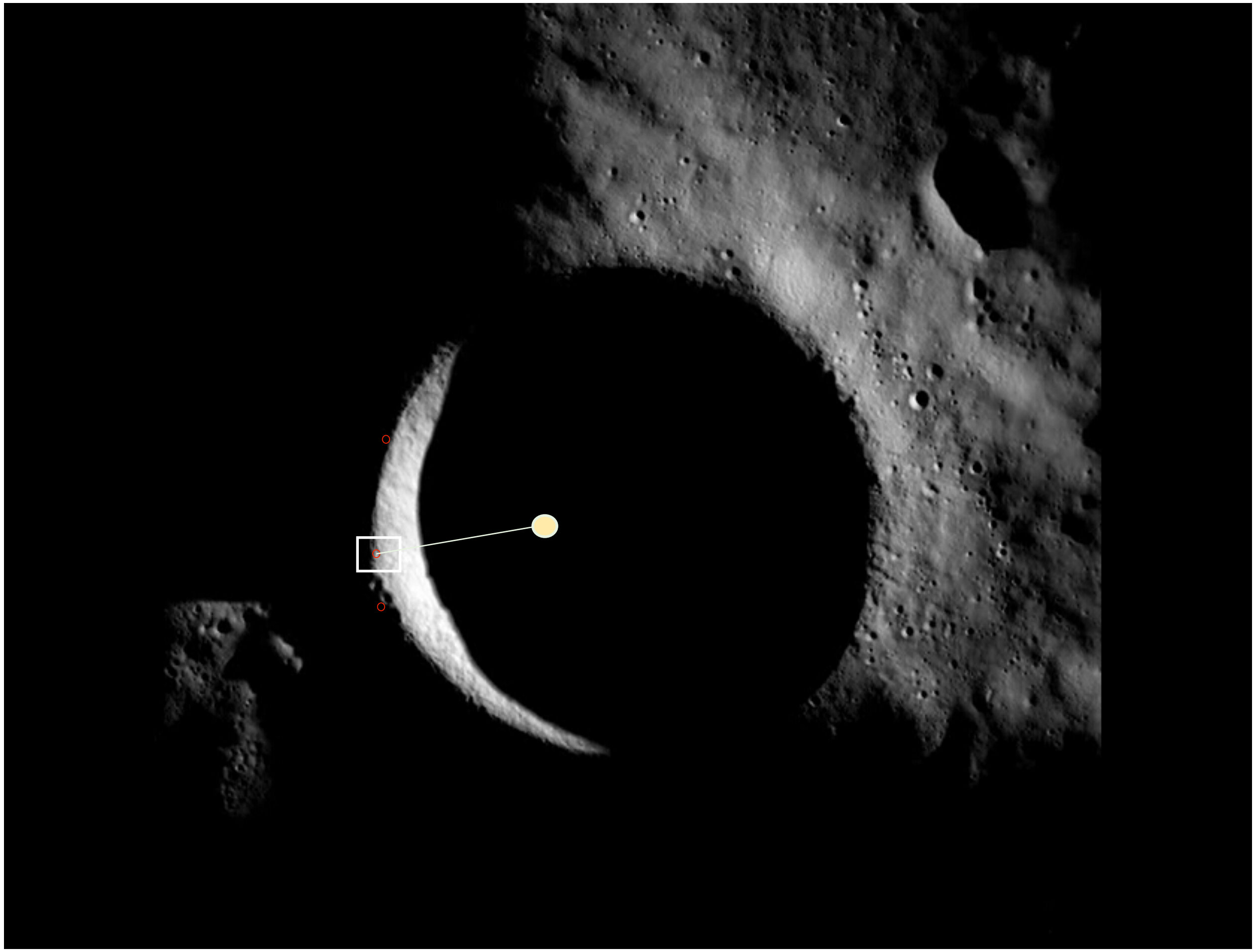


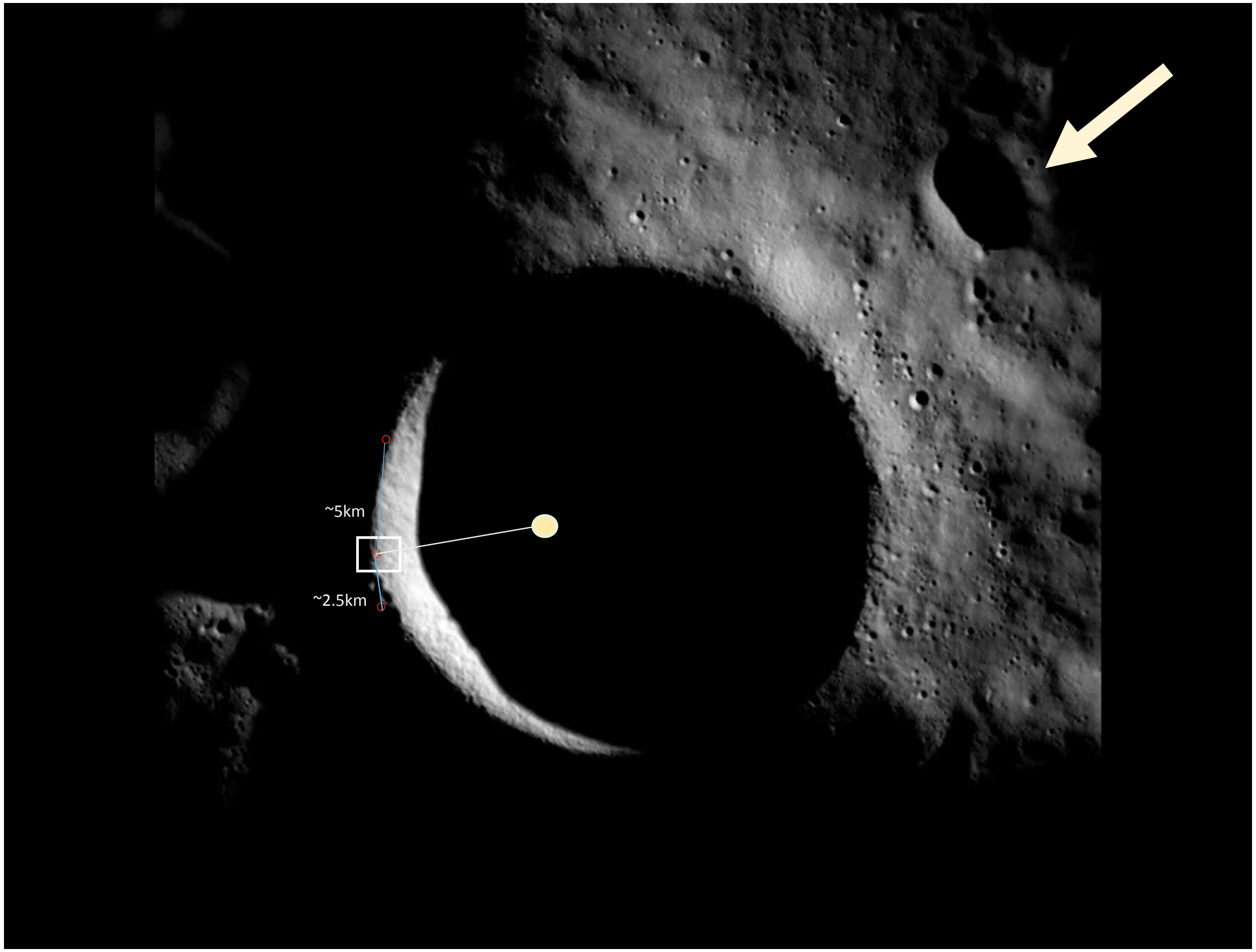











~5km
~2.5km

2 Point Infrastructure ensures permanent illumination outside SC