Probing the subsurface of the two faces of Iapetus

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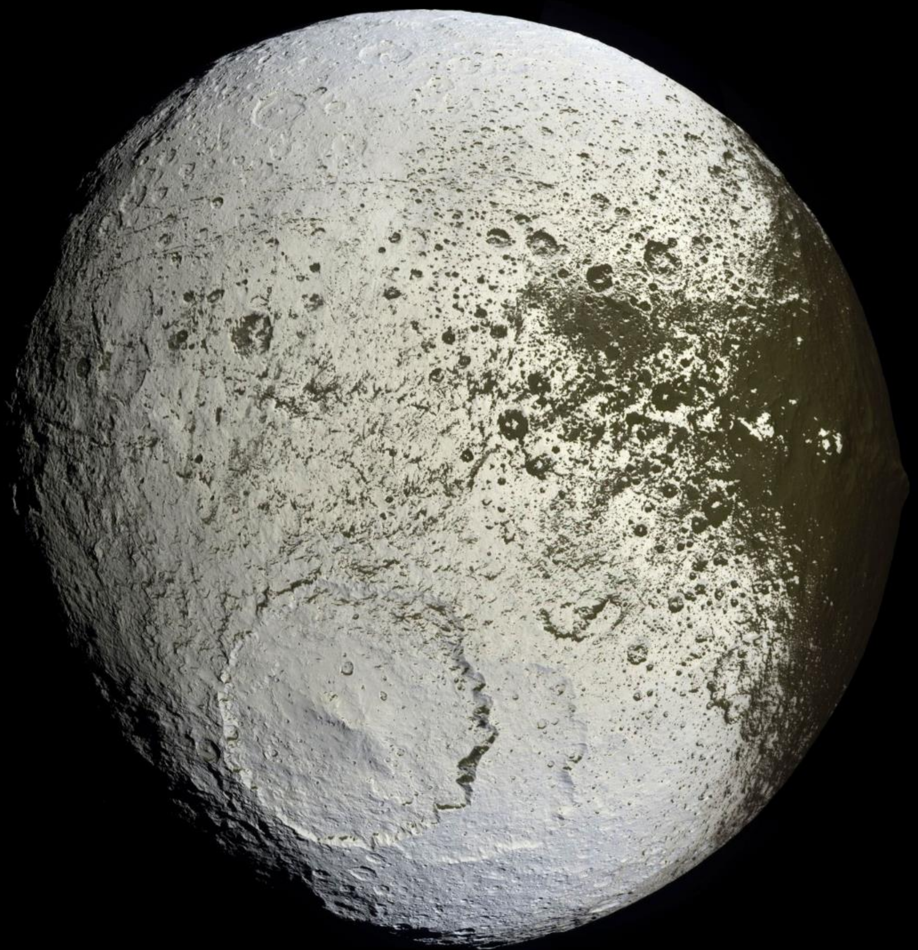
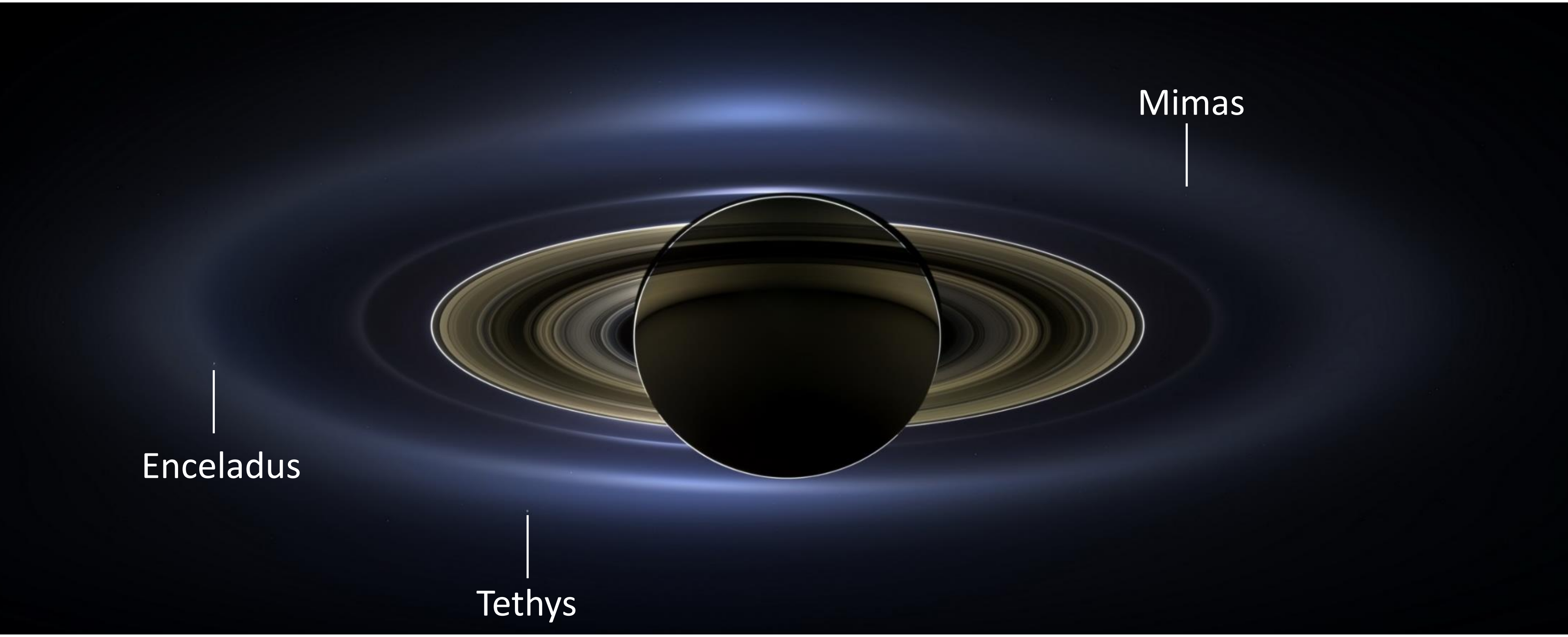
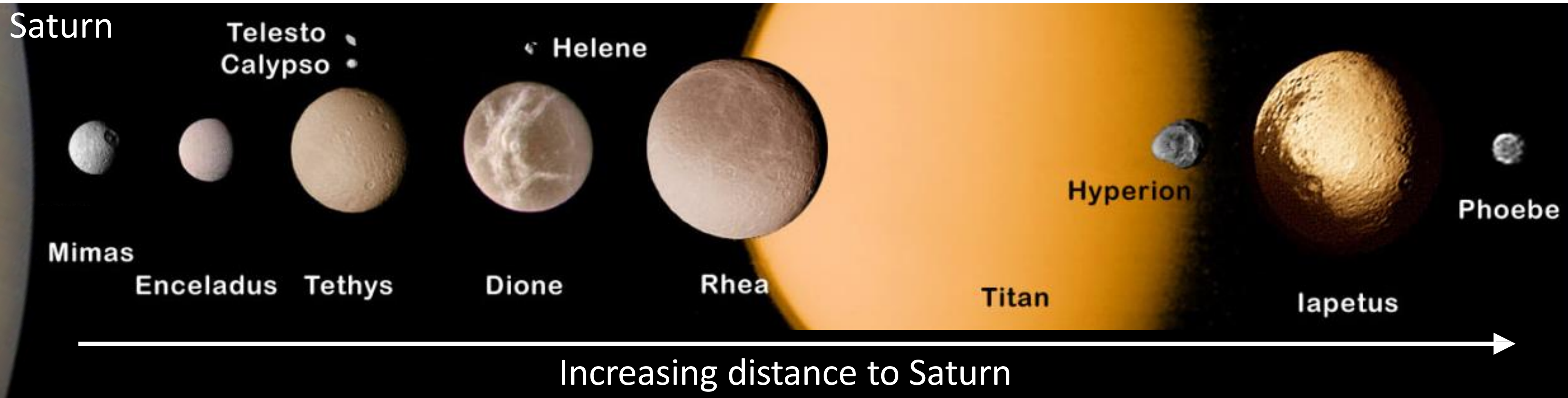


Context

Saturn’s icy moons





Data: IRAM, VLA, and Cassini Radar/radiometer

- Cassini 2.2 cm Radar/radiometry resolved and unresolved observations of Saturn's icy satellites

Ground-based observations:
- IRAM NIKA2 observations of Iapetus at 1.25 and 2 mm
- VLA resolved observations of Iapetus at 9, 13, 16, 20, and 23 mm
- ALMA resolved observations at 0.9, 1.3, and 3.1 mm?

→ Have night and day observations to study the surface's thermal properties
→ Build a microwave spectrum to understand the vertical structure of the surface

IRAM 30m telescope

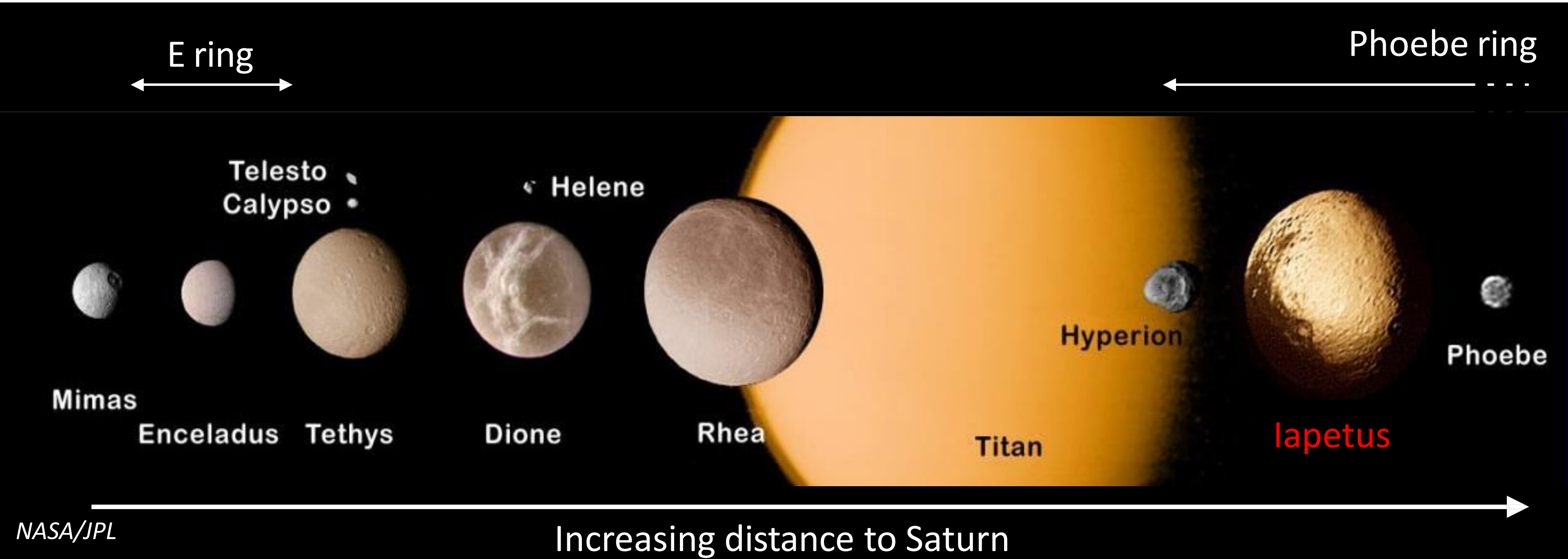
Cassini spacecraft

Image credit: NASA's eyes

Iapetus in the Saturn system

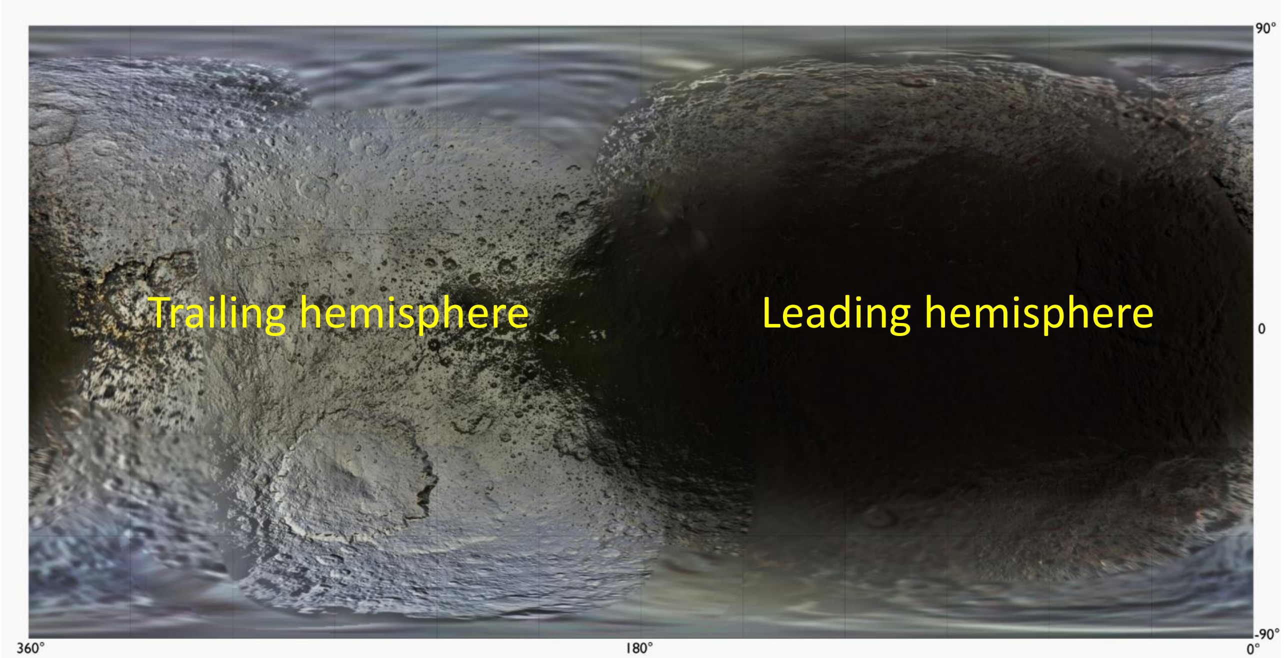
Iapetus:

- Diameter of 1470 km (Paris-Grenada + 100km)
- Heavily cratered → very old surface
- Density of 1.088 kg/m^3 → 70-80% water ice
- Largest albedo contrast in the solar system: trailing 10 times brighter
- Distance from Saturn 60R$_{Saturn}$ (8-9')→ within the Phoebe ring



Origin of the dichotomy

- Iapetus lies within the Phoebe ring, a wide and diffuse ring likely originating from the satellite Phoebe.
- The Phoebe ring is retrograde: its particles fall on Iapetus' leading side.
- The resulting albedo dichotomy causes large temperature differences between dark and bright regions.
- Ice sublimates from the dark regions and is deposited on the bright regions, enhancing the albedo difference.
- Runaway thermal migration of water ice (Spencer et al., 2010)



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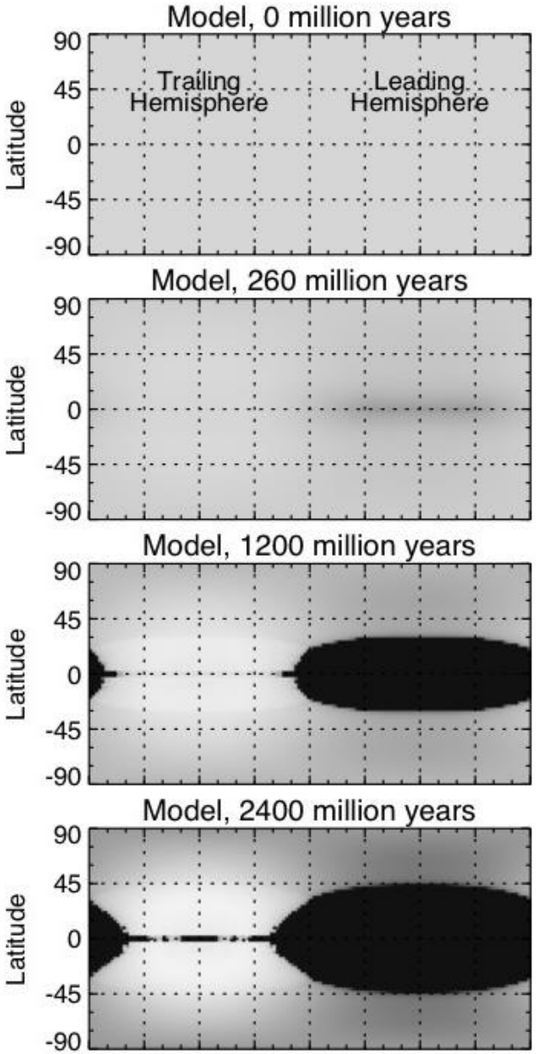


Spencer et al. (2010)

Subsurface properties from Radar

- Arecibo (12.6 cm) does not see the dichotomy (Black et al., 2004) but the Cassini Radar (2.2 cm) does (Ostro et al., 2006, 2010).

→ The dark layer is several decimeters deep, but <1m.

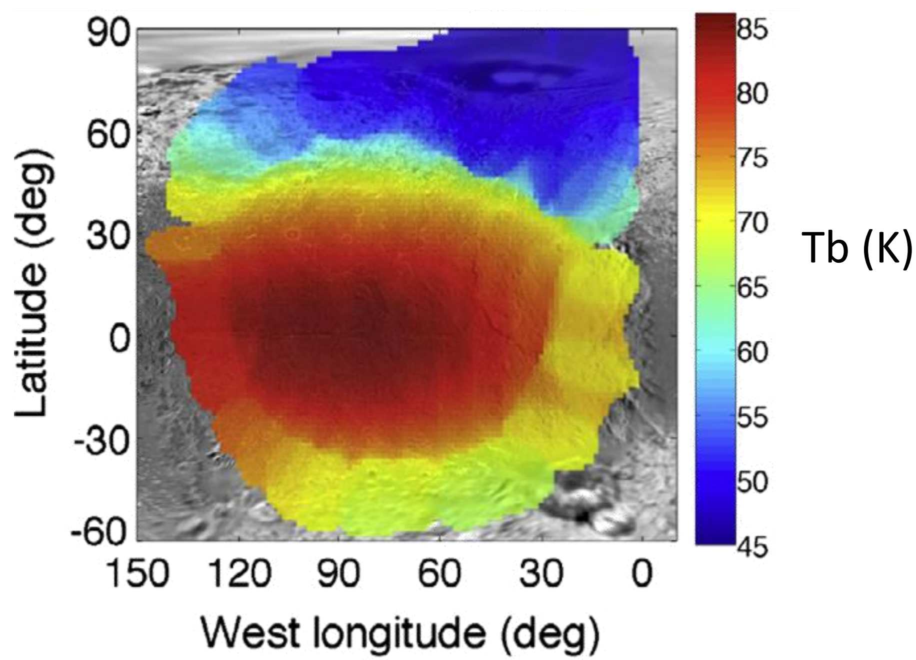
- Cassini radiometer (2.2 cm, larger penetration depths than the active Radar) detects the icy substrate under the dark layer (Le Gall et al., 2014); resolved data on the dark material indicate that:

→ It is very emissive: consistent with the material being sourced in the Phoebe ring.

- Cassini CIRS (17-1000 µm) finds thermal inertias of 6-25 MKS (Howett et al., 2010). Cassini radiometry finds >100MKS.

→ The subsurface is more compact.

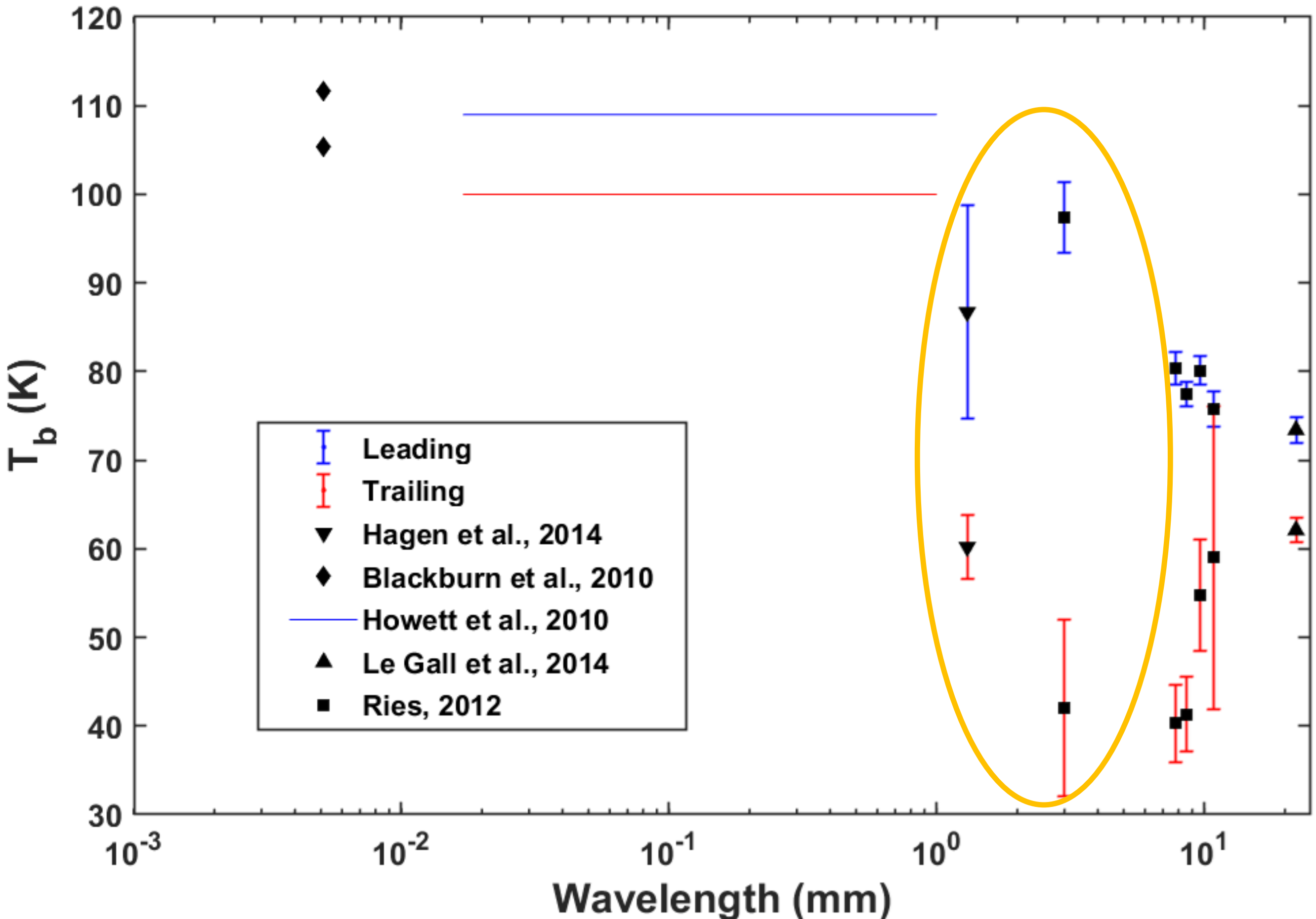
2 cm radiometry



Le Gall et al. (2014)

The need for more mm observations

- There is very little data between 1 and 4 mm
- The data available shows large variations in brightness temperature at these wavelengths
  - → More data is necessary to understand these variations
  - → NIKA2 can help!



Method

Expected fluxes

	1.2 mm fluxes (Jy)	2 mm fluxes (Jy)
Iapetus trailing (1.3 mm T_b from Hagen et al., 2014)	0.085	0.030
Iapetus leading (1.3 mm T_b from Hagen et al., 2014)	0.127	0.044
Titan	1.34	0.47
Saturn	1225	449

- Titan's fluxes are known within <5% uncertainty, and it is observed simultaneously as Iapetus (same elevation, same atmospheric conditions)

  → Calibrate on Titan.

- Saturn is 10 000 times brighter than Iapetus!

  → Detecting a faint source next to a very bright source is our biggest challenge.

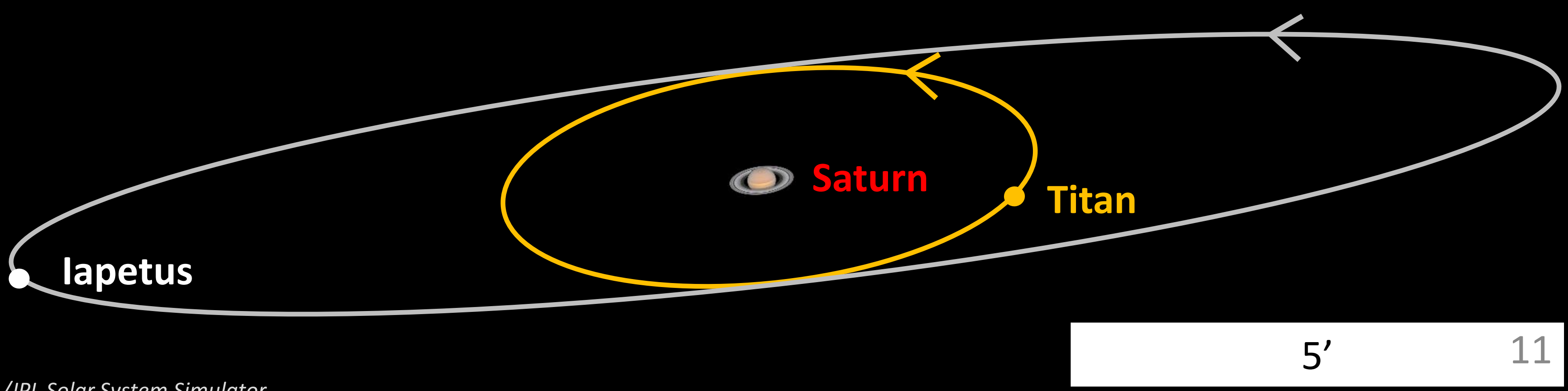
Satellite positions

- Titan (16 day orbital period) and Iapetus (79.3 day orbital period) will be most easily detectable at maximum elongation
- At maximum elongation, Iapetus shows either its leading or its trailing side to the Earth: so the highest flux contrasts will be measured at maximum elongation.

→ Strong timing constraints for the observations: both Titan and Iapetus must be near maximum elongation.

→ Make large maps including Iapetus, Titan, and Saturn at the same time, and centered on Saturn to avoid beam distortions.

Satellite positions on March 20, 2019, as seen from Earth (Saturn is to scale)



NASA/JPL Solar System Simulator

NIKA2 Iapetus observations

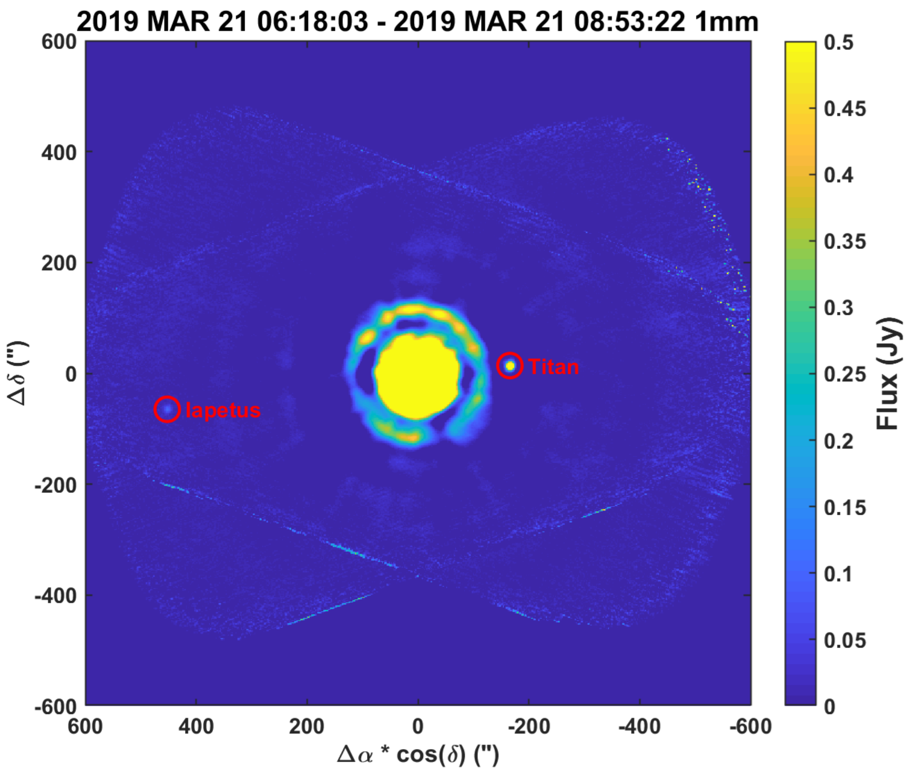
Date	Elevation	Tau	Latitude (°N)	Longitude (°E)	Angular distance to Saturn (")	Observed side
23 May 2018	27.6-30.7	0.28	11.2	-180	95	Mixed
27 May 2018	28.7-30.4	0.56	11.3	-161	212	Mixed
28 May 2018	22.2-30.7	0.21	11.3	-157	250	Mixed
29 May 2018	21.5-30.7	0.20	11.3	-152	291	Mixed
14 Feb 2019	27.4-31.0	0.13	9.5	-55	432	Leading
15 Feb 2019	28.1-30.9	0.21	9.5	-50	412	Leading
12 Mar 2019	29.7-31.3	0.10	8.9	61	412	Trailing
20 Mar 2019	20.2-31.3	0.13	8.8	96	495	Trailing
21 Mar 2019	28.5-31.3	0.17	8.8	101	491	Trailing

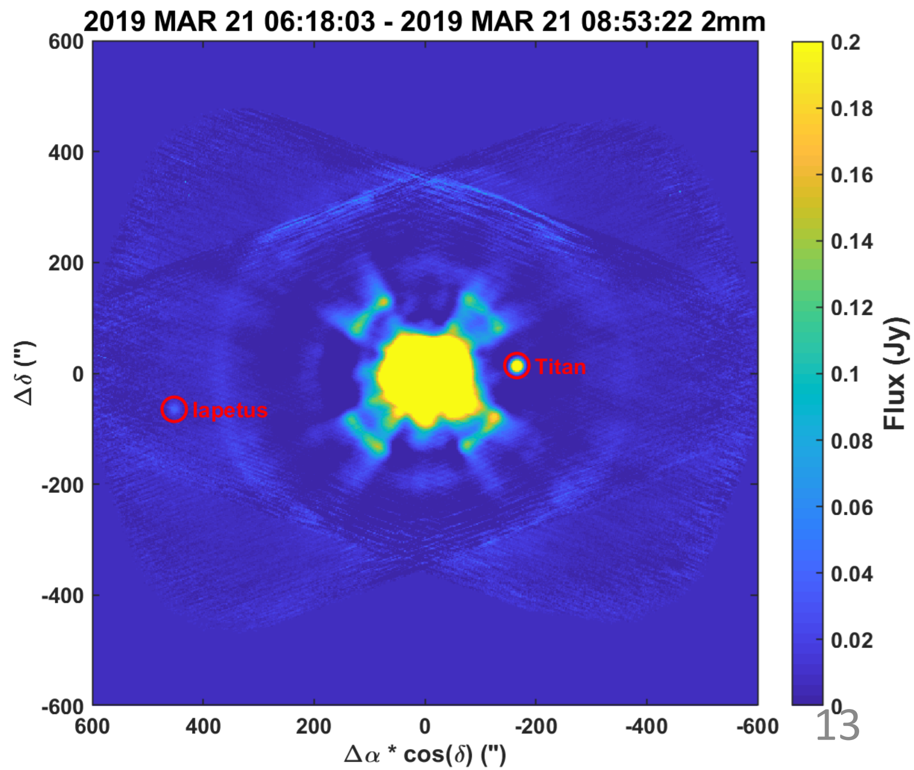
→ May 23 (Iapetus too close to Saturn) and 27 (tau too high): data not usable
→ Both leading and trailing sides observed with good atmospheric conditions
→ Relatively low elevation

First method: integrate the data

If Titan and Iapetus are far enough from Saturn and are not in a local peak of the beam pattern, then we can simply measure the flux on Titan and Iapetus.

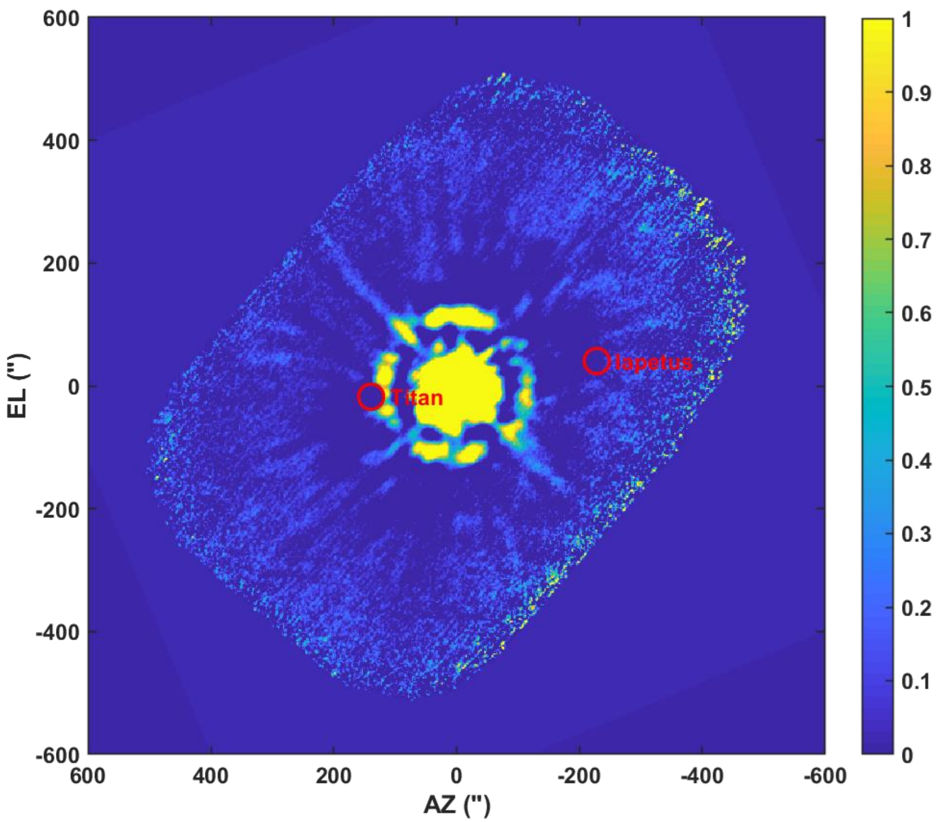
→ Good initial guess, but in reality there are small local peaks out to ~6’





Second method: map then subtract Saturn's contribution

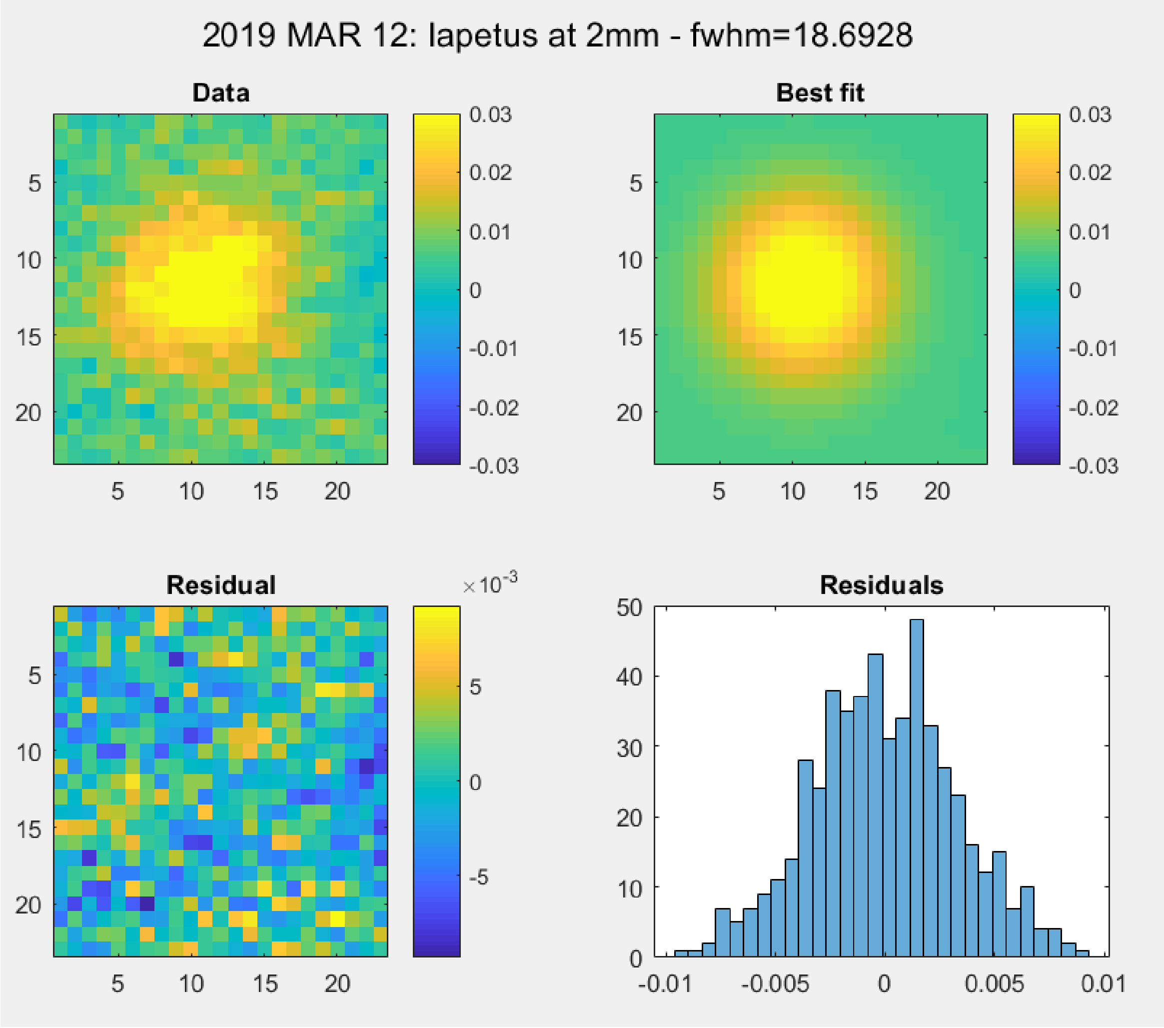
- Beam orientation is fixed in az el
- Individual scans are averaged in AZ, EL coordinates, after masking Iapetus and Titan
  → Obtain the Saturn contribution
- Convert to ra-dec, and subtract from each scan
- Can then average the scans and compute the Titan and Iapetus flux.



Satellite flux

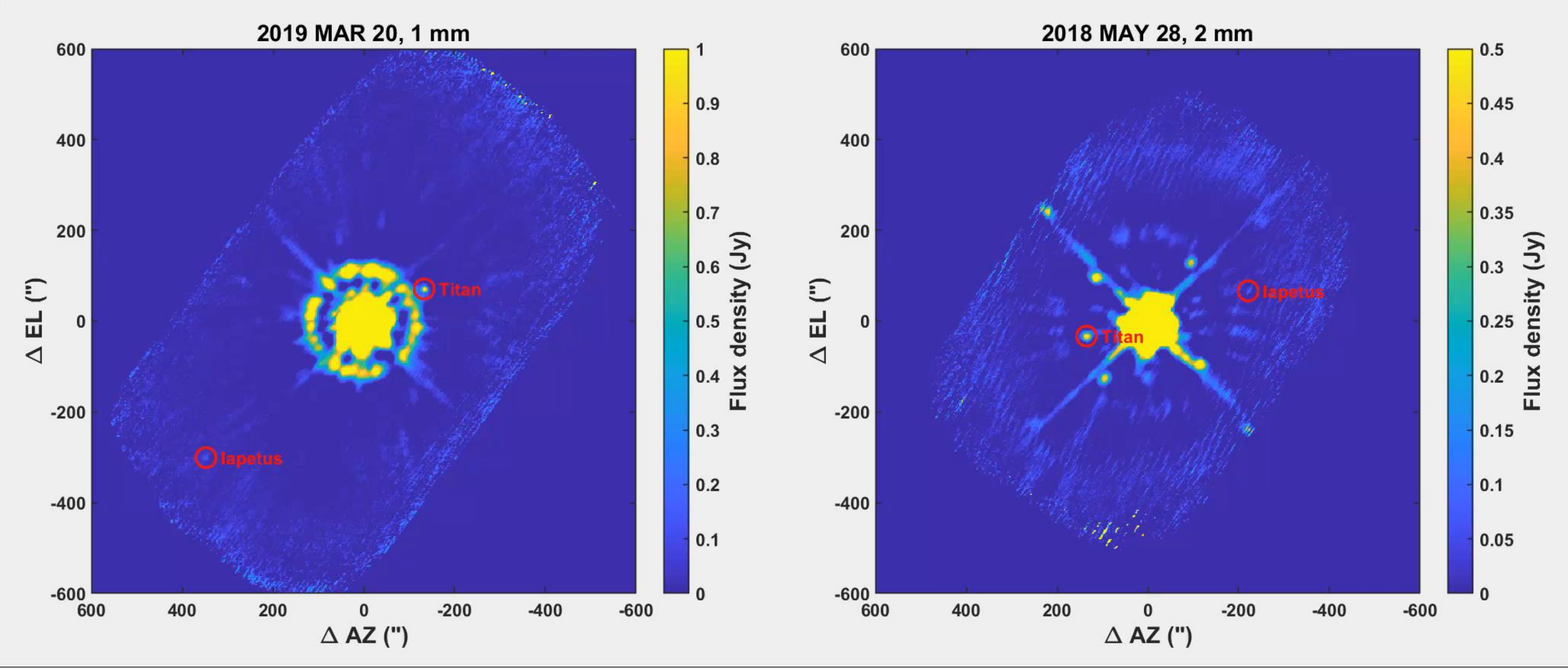
For both methods, the satellite flux is calculated by:

- Selecting a small region around the moon (small enough to exclude background fluctuations)
- Fitting a circular Gaussian, with FWHM=11-13.1” at 1.2 mm and 17.5-19.6” at 2mm (nominal fwhm, allowing for up to 2” larger in case of defocusing).
- Also fitting a tilted plane in the background, in case the background is not flat.



Problem: the changing beam

- Orientation of the scan
- Time of day
- Elevation
  → We can never perfectly subtract the beam pattern…

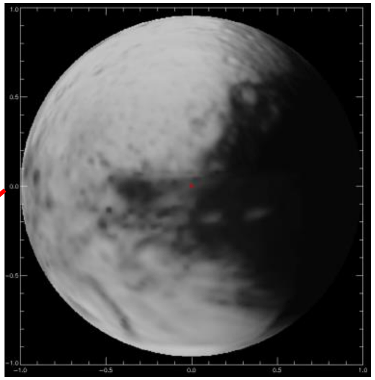


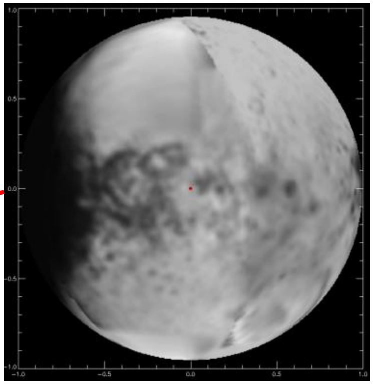
Preliminary results

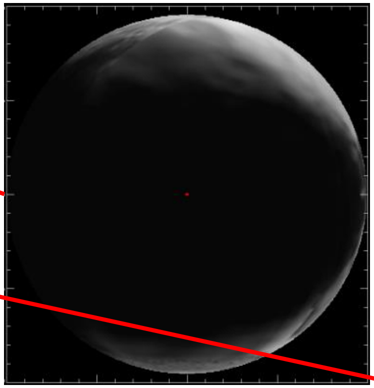
Using a first daily reduction of the data

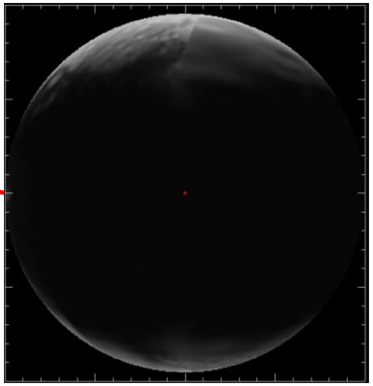
It seems only a few (4-6) scans were included.

Date	Longitude (°E)	1.2-mm T_b (K)	2.0-mm T_b (K)
28 May 2018	203	64±6	60±2
29 May 2018	208	60±5	58±2
14 Feb 2019	305	62±9	52±2
15 Feb 2019	310	65±9	59±2
12 Mar 2019	61	75±5	84±2
20 Mar 2019	96	71±7	76±2
21 Mar 2019	101	73±6	81±2





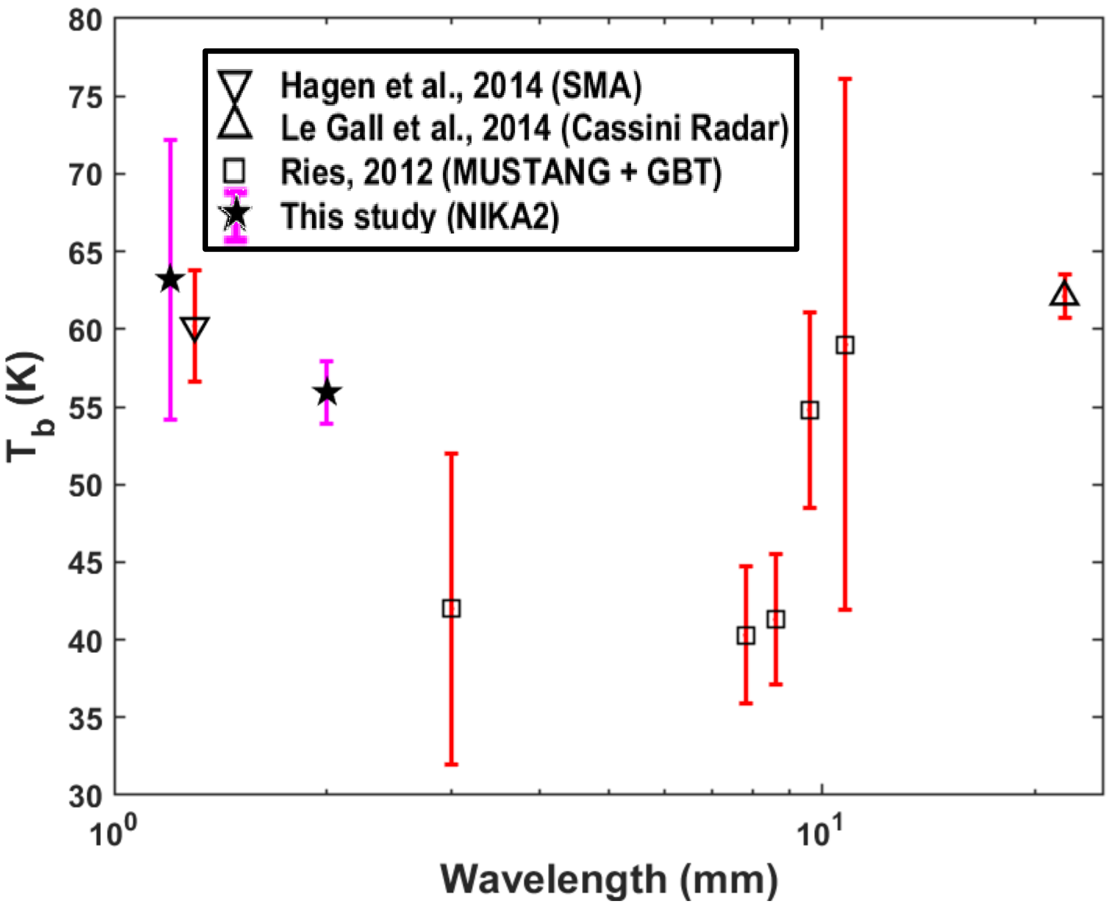




→ The leading side is brighter at 1.2 and 2 mm (as expected)

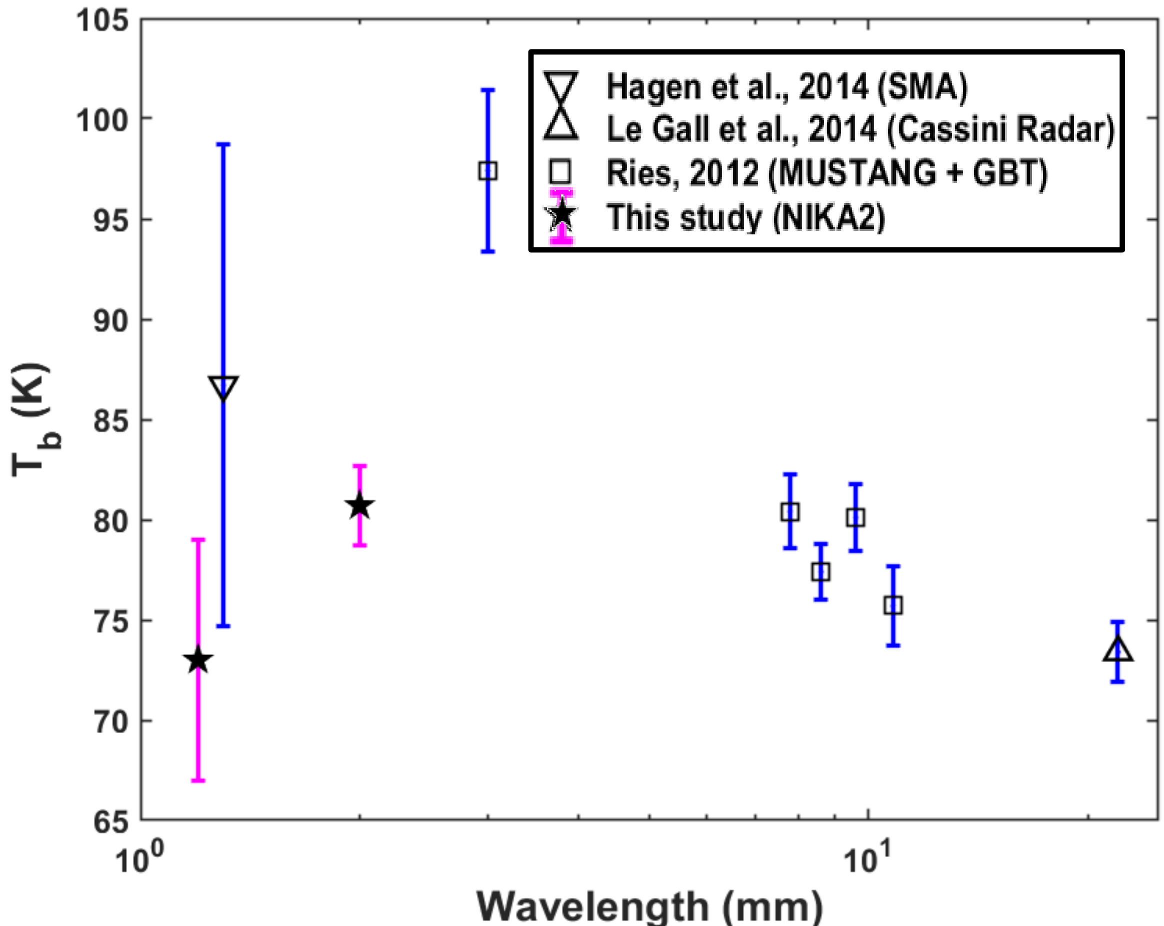
Preliminary interpretation: trailing

- Consistent with other mm observations
- Large absorption feature centered around ~4 mm
  - → Consistent with diffuse scattering by mm-sized ice particles (Ries, 2012)
  - → Future work using all data: constrain the particle size using the Microwave Emission Model for Layered Snowpacks (MEMLS; Wiesmann and Mätzler, 1998)



Preliminary interpretation: leading

- Consistent with other mm observations
- There is a very steep slope from 1 to 3 mm (if the 3 mm point is correct)
  → Indicative that the subsurface properties change very quickly with depth? Layers sensed at 1 mm may be less emissive (higher porosity and/or more volatiles) than at 2 and 3 mm.



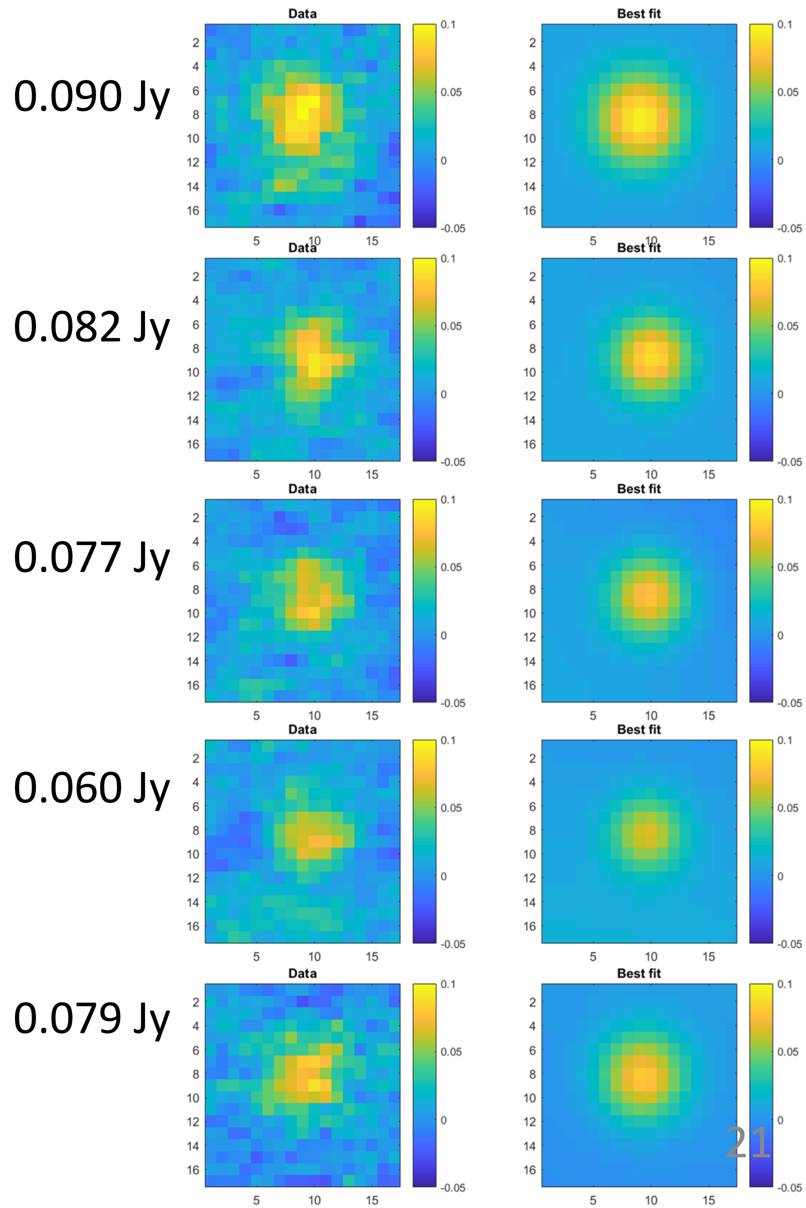
Problems when looking at all the data

The fluxes (and therefore the T_b) vary a lot within one day, and from day to day.

- This is more than just noise or an offset in the whole image (the flux on Titan is stable during these scans).
- Probably the position of Iapetus within the beam varies (On a bump or a hole in the beam).
  Indeed, the amplitude of faint features in the beam changes with time, so we can never subtract it perfectly.
- On some days this also happens with Titan, affecting our calibration.

→ This problem needs detailed work, looking at each scan individually, to determine accurately the flux from Iapetus.

Example: Feb 14 2019

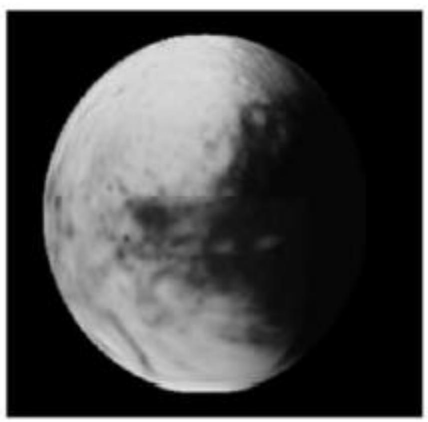


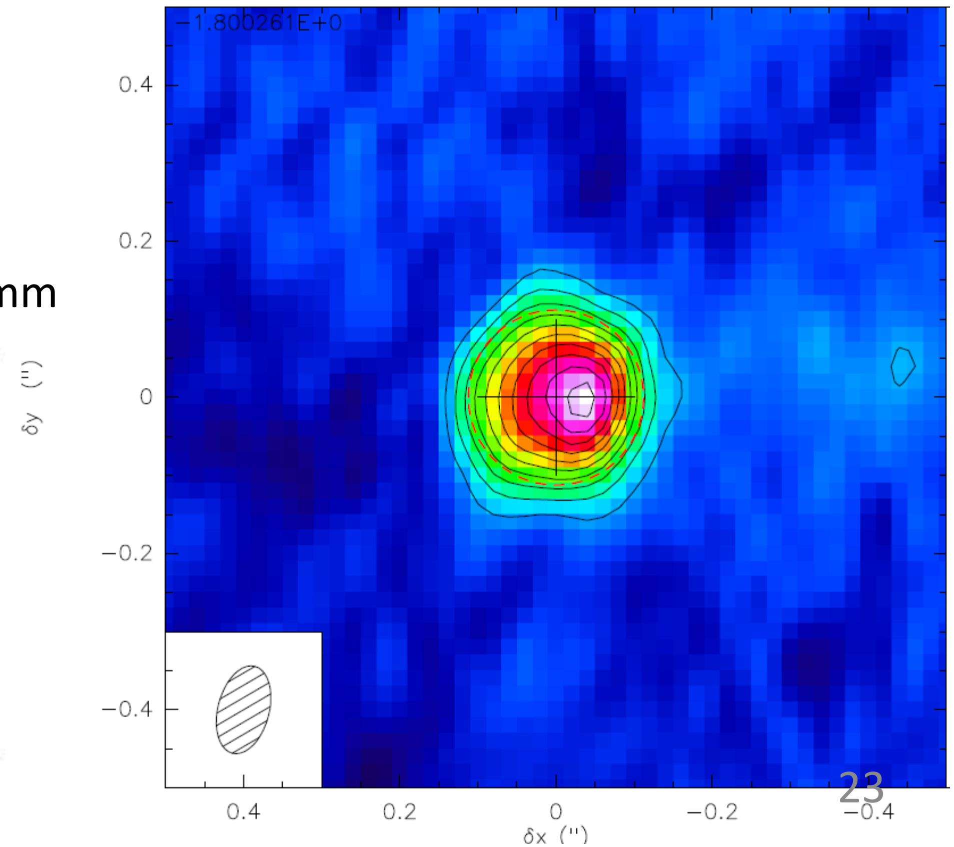
Complementary VLA observation

VLA (May 2018)

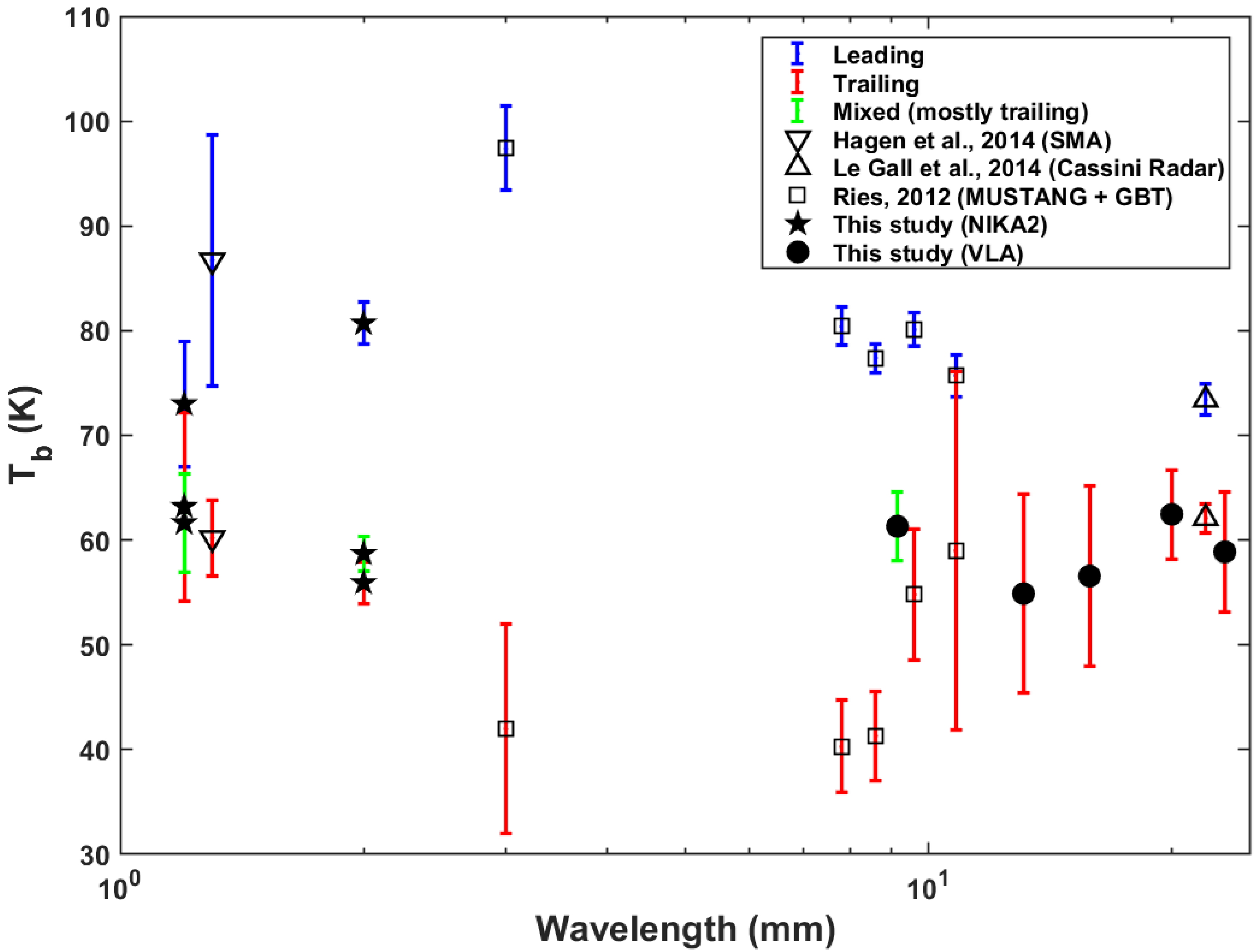
- Iapetus was observed with the VLA between at 9, 13, 16, 20, and 23 mm
- Observations on May 28 – June 3 (same as NIKA2 2018 data)
- Enough resolution to see that the leading side is brighter
- It is necessary to compare with a thermal model, to separate diurnal temperature fluctuations (warmer in late afternoon) from emissivity differences

28 May 2018: Iapetus at 9 mm





Iapetus spectra



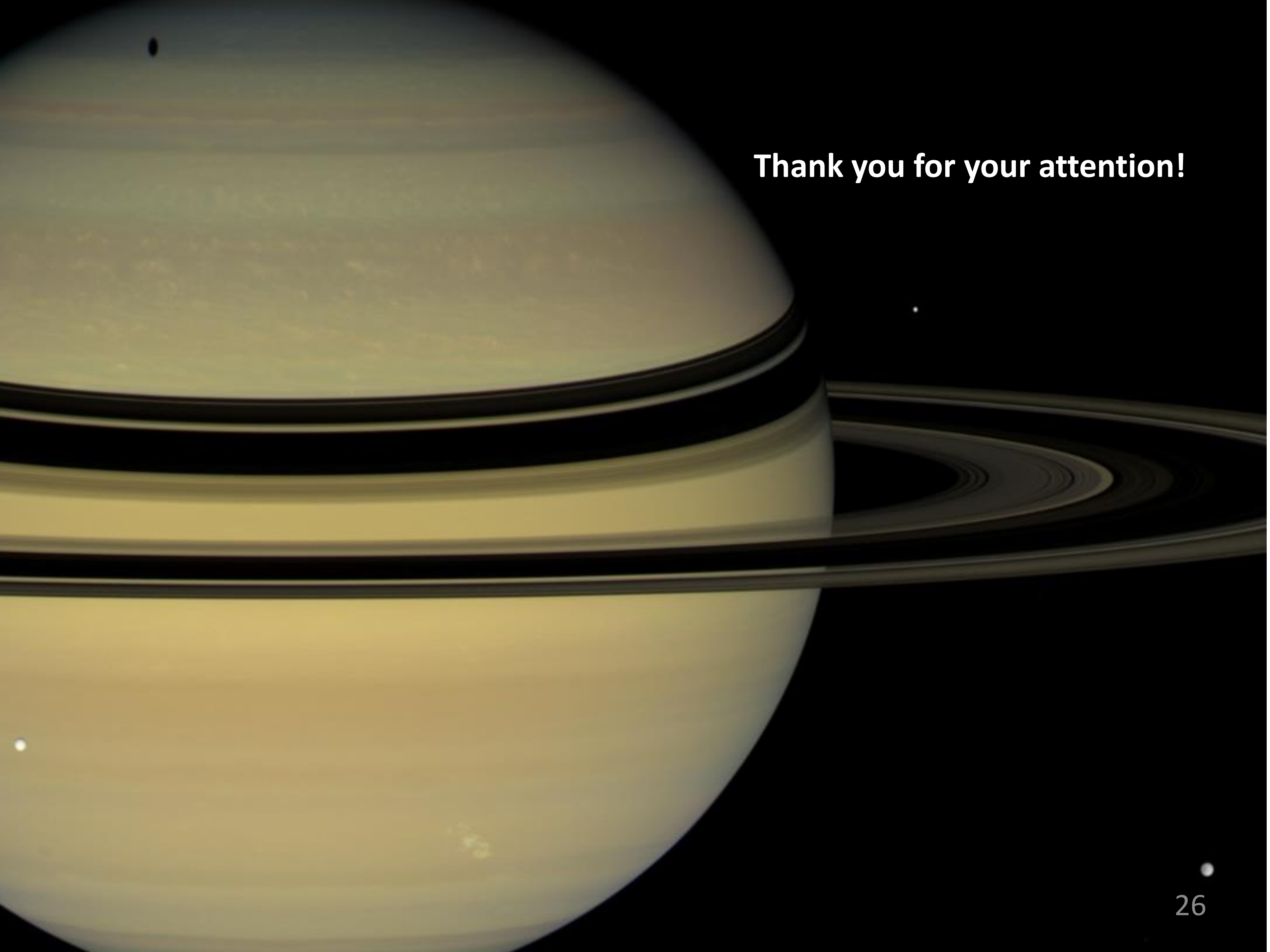
Conclusions and future work

Conclusions

- Accurately measuring the flux of a faint source near a bright source is challenging, especially given the variability of the beam pattern.
- Iapetus' leading is brighter than its trailing at 1.2 and 2 mm.
- A steep 1-3 mm T_b slope is possible on Iapetus' leading hemisphere, potentially indicating a change in compositional or structural properties at a depth of a few cm.

Future work

- Resolve the inconsistency in the data over a single day
- Use a thermal model to find the effective temperature, and thus extract the emissivity of the surface ($e = \frac{T_b}{T_{eff}}$)
- Use the MEMLS model to constrain grain size on the trailing side
- Obtain VLA data of the leading side, and of Phoebe for comparison
- Obtain ALMA data: resolved 0.9, 1.3, 3.1 mm observations of icy satellites (including Iapetus)



Thank you for your attention!