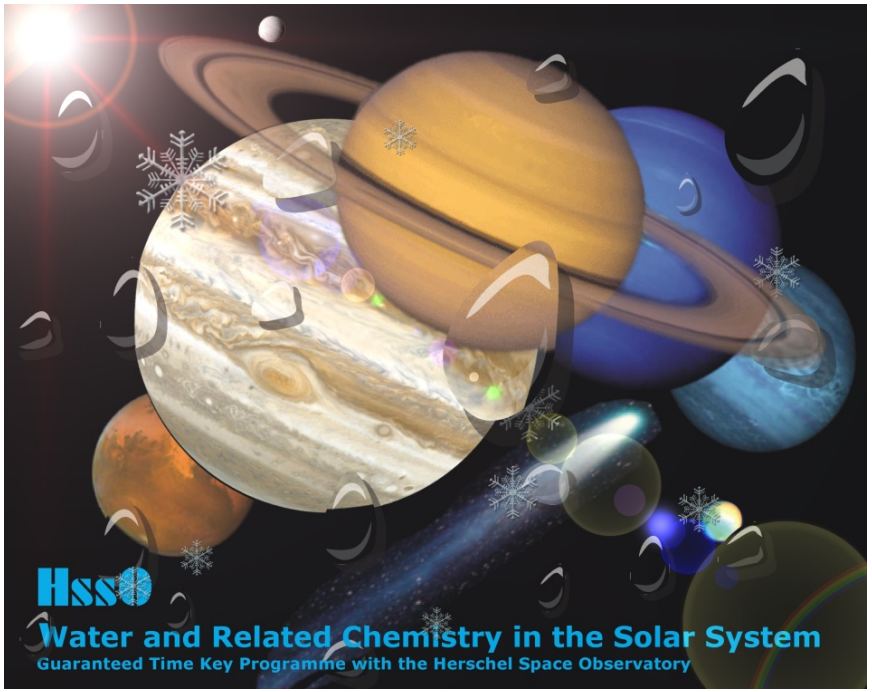
Detection and Characterisation of Ganymede's and Callisto's Water Atmospheres



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Submm wave sounding of sources and sinks of water vapour in the surface-bounded atmosphere of Europa.

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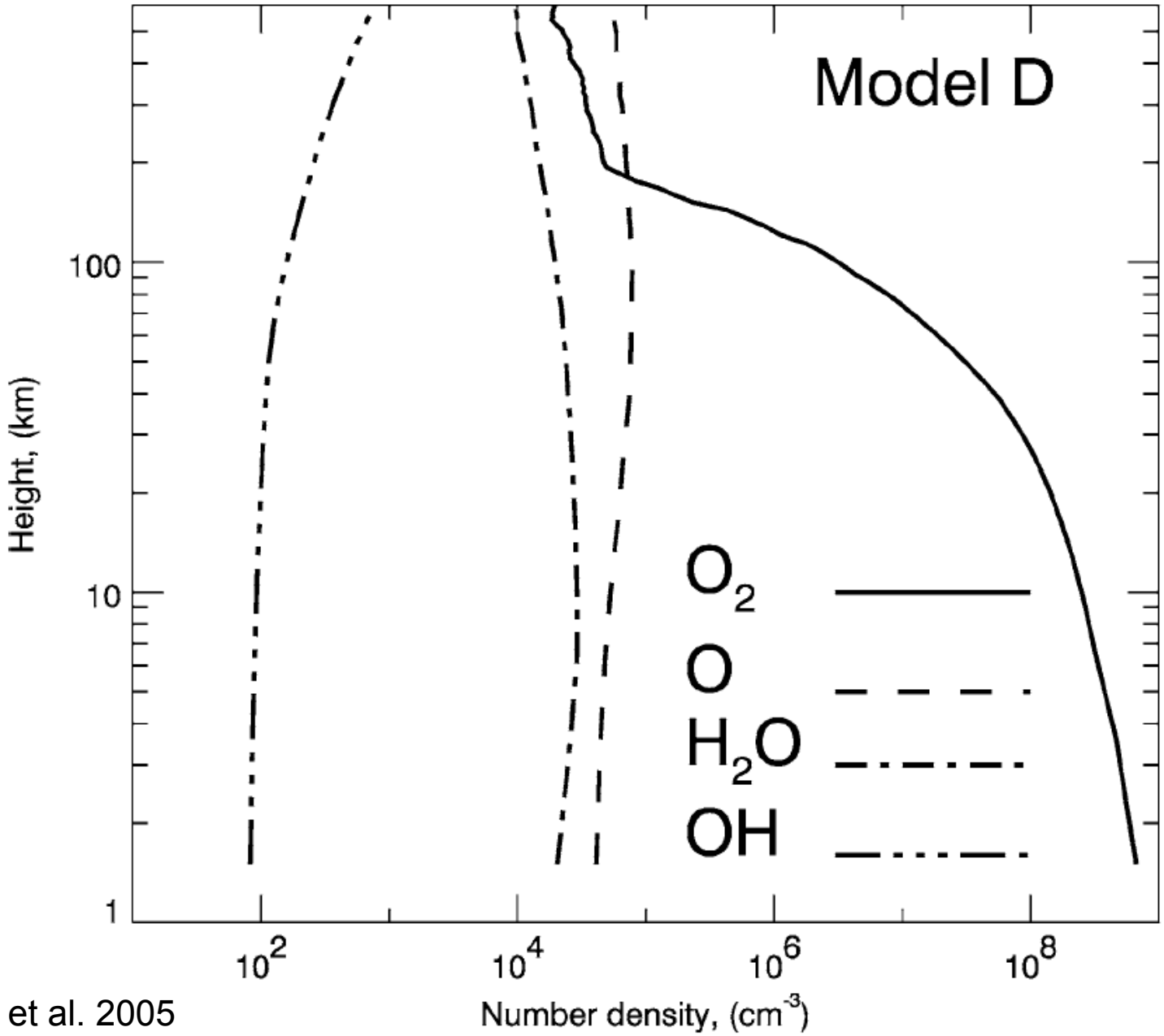
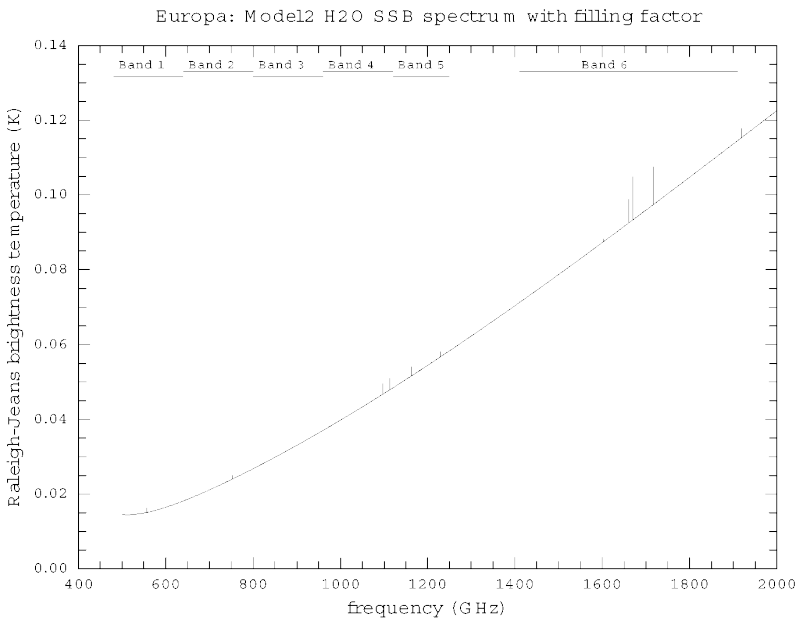
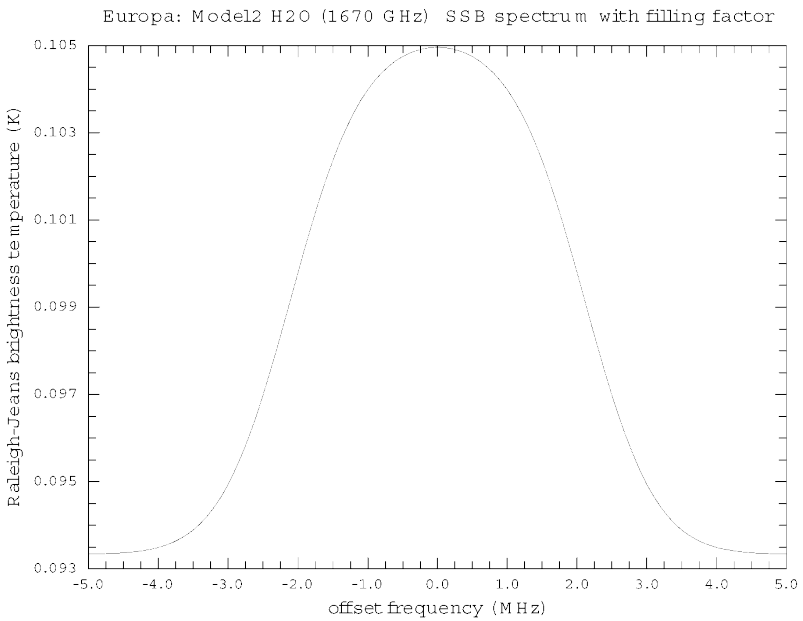
The atmosphere of Europa is produced mainly from irradiation of its exposed outer surface by magnetospheric plasma and UV photons. Its main component, molecular oxygen has been indirectly observed by the HST (Hall et al., ApJ, 499, 475, 1998). High spatially resolved observations along with 3-d model calculations of the atmosphere are a key to determining the rate of surface chemical modification on Europa from irradiation effects. Irradiation is the dominant surface alteration process on outer Solar System bodies including those in the Kuiper belt and the Oort cloud (e.g. Shematovich et al. 2005). Oxidant production by irradiation also provides a possible pathway for support of life within Europa's putative subsurface ocean. The atmospheric composition of Europa is determined by both the water and oxygen photochemistry in the near-surface region, escape of suprathermal oxygen and water into the jovian system, and the exchange of radiolytic water products with the porous regolith. Water vapour is transformed into its gaseous state by sputtering processes and sublimation. Generally the water sublimation rate should be extremely low, resulting from the average surface temperature of only 106 K which implies a sublimation rate of about 10^7 cm^{-2} s^{-1}. However around the dayside equator temperatures of 132 K and higher appear, leading to an increase of the sublimation rate of at least 4 orders of magnitudes, meaning that sublimation could be a major water vapour production process. Recent Cassini images of Enceladus suggest that cryovolcanic activity should be considered as another possible source of water vapour. "Boiling" water which may also exist due to thermal flexing and cracks in the surface will result in a highly increased supply of water vapour to the atmosphere and thus source regions will be easily detectable. Newest model calculations in preparation of the Herschel Space Observatory solar system science program provided the amazing result that water in Europa's surface-bound atmosphere might be detected by one of its experiments, the Heterodyne Instrument for the Far Infrared, HIFI.

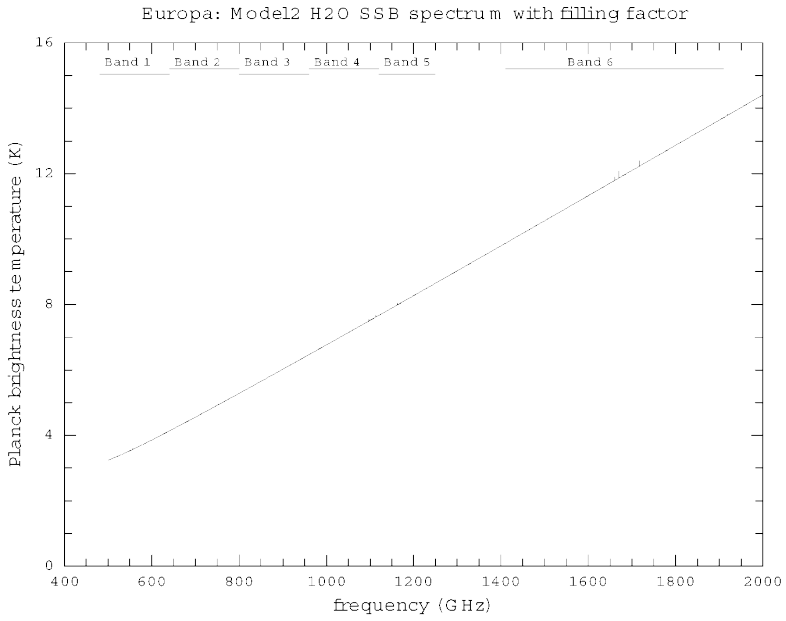
Future Mission to Europa and the Jovian System, CNES, Paris 12-13 December 2005

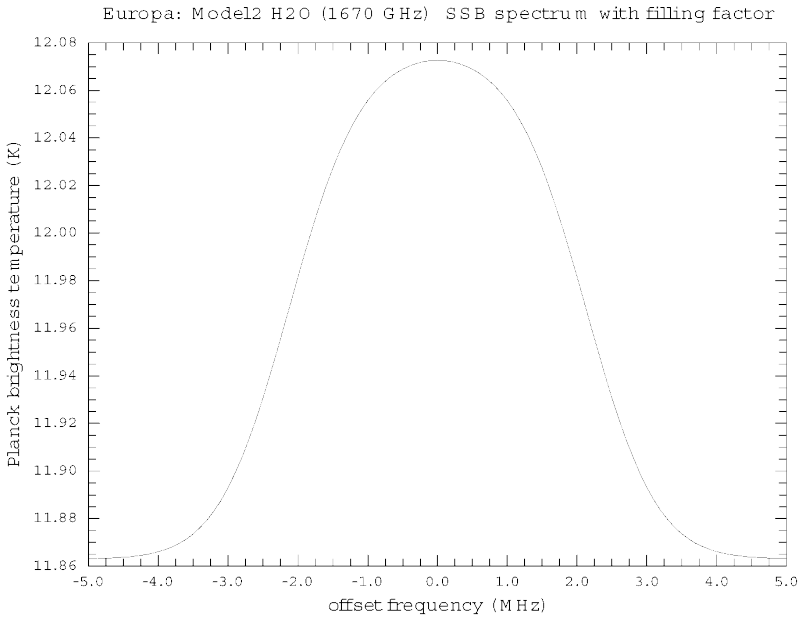


Shematovic et al. 2005


Europa: Model2 H2O SSB spectrum with filling factor
Band 1
Band 2
Band 3
Band 4
Band 5
Band 6
Raleigh-Jeans brightness temperature (K)
frequency (GHz)


Europa: Model2 H2O (1670 GHz) SSB spectrum with filling factor
Raleigh-Jeans brightness temperature (K)
offset frequency (MHz)


Europa: Model2 H2O SSB spectrum with filling factor
Band 1
Band 2
Band 3
Band 4
Band 5
Band 6
Planck brightness temperature (K)
frequency (GHz)

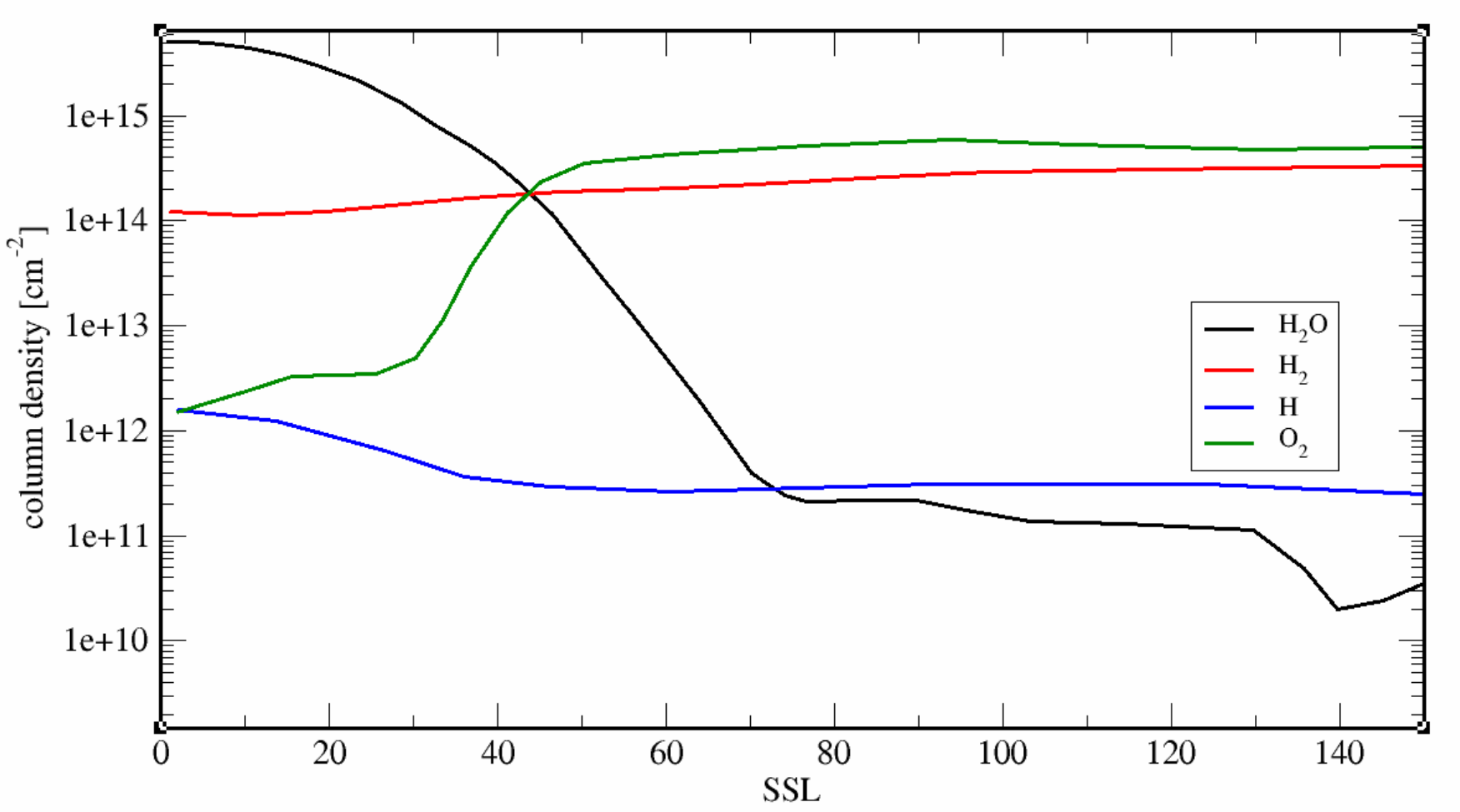

Europa: Model2 H2O (1670 GHz) SSB spectrum with filling factor
Planck brightness temperature (K)
offset frequency (MHz)

Water atmosphere detectable by HIFI?

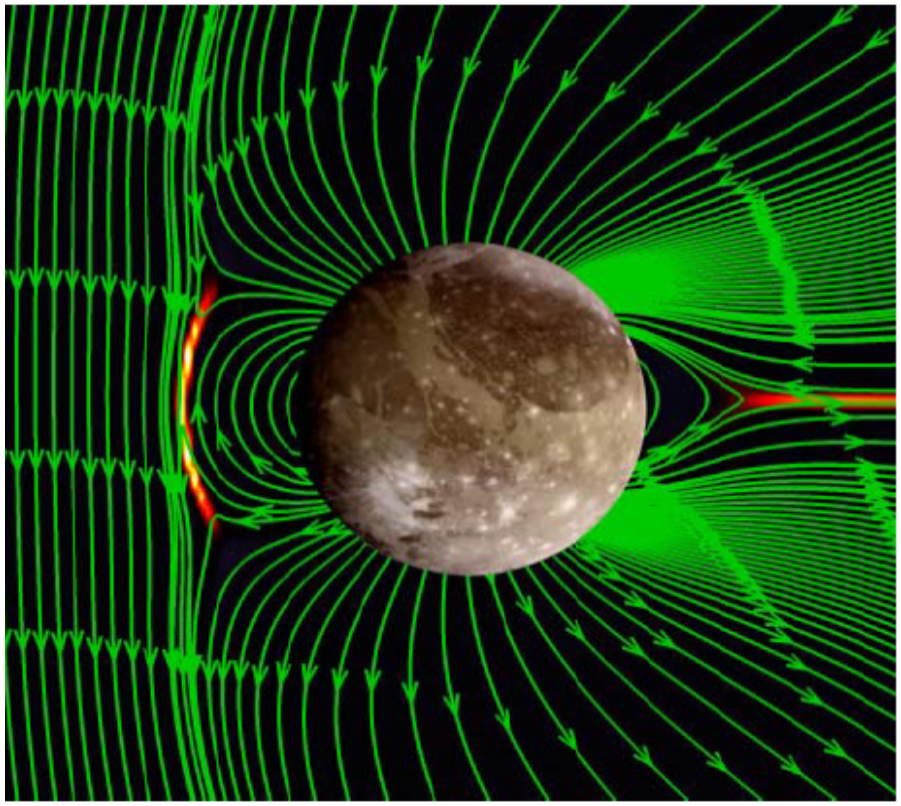
- In principle yes, but 10 mK line amplitude would make observation too expensive for HssO
- Rough estimations on Ganymede and Callisto suggested detectability of water atmosphere as well, because lower albedo than Europa => higher surface temperatures (E: 0.68/134; G: 0.44/152; C: 0.19/165), higher sublimation rates.
- Ceres with ~ 1000 km diameter may work also, because of its smaller distance (2.5 – 2.9 AU vs 5 AU of Galilean Satellites).

But since we did not have reasonable models for any of this objects it was too risky to include any of these obs. into the KP.

2007: Marconi model on Ganymede



Ganymede in the Jovian System:



Observations indicate that Ganymede has a significant O_2 atmosphere, probably a subsurface ocean, and is the only satellite with its own magnetosphere.

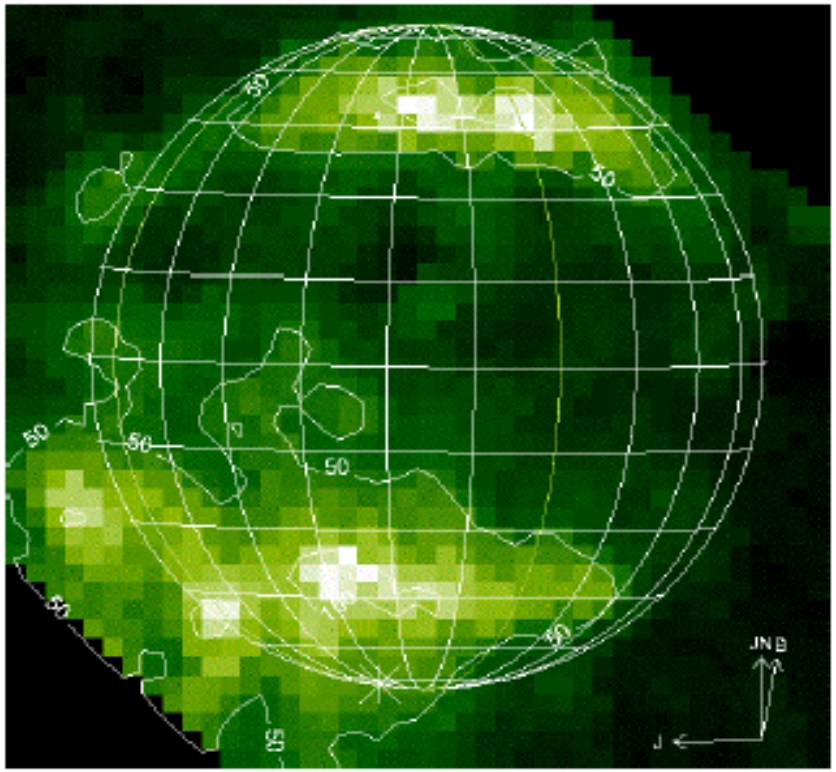
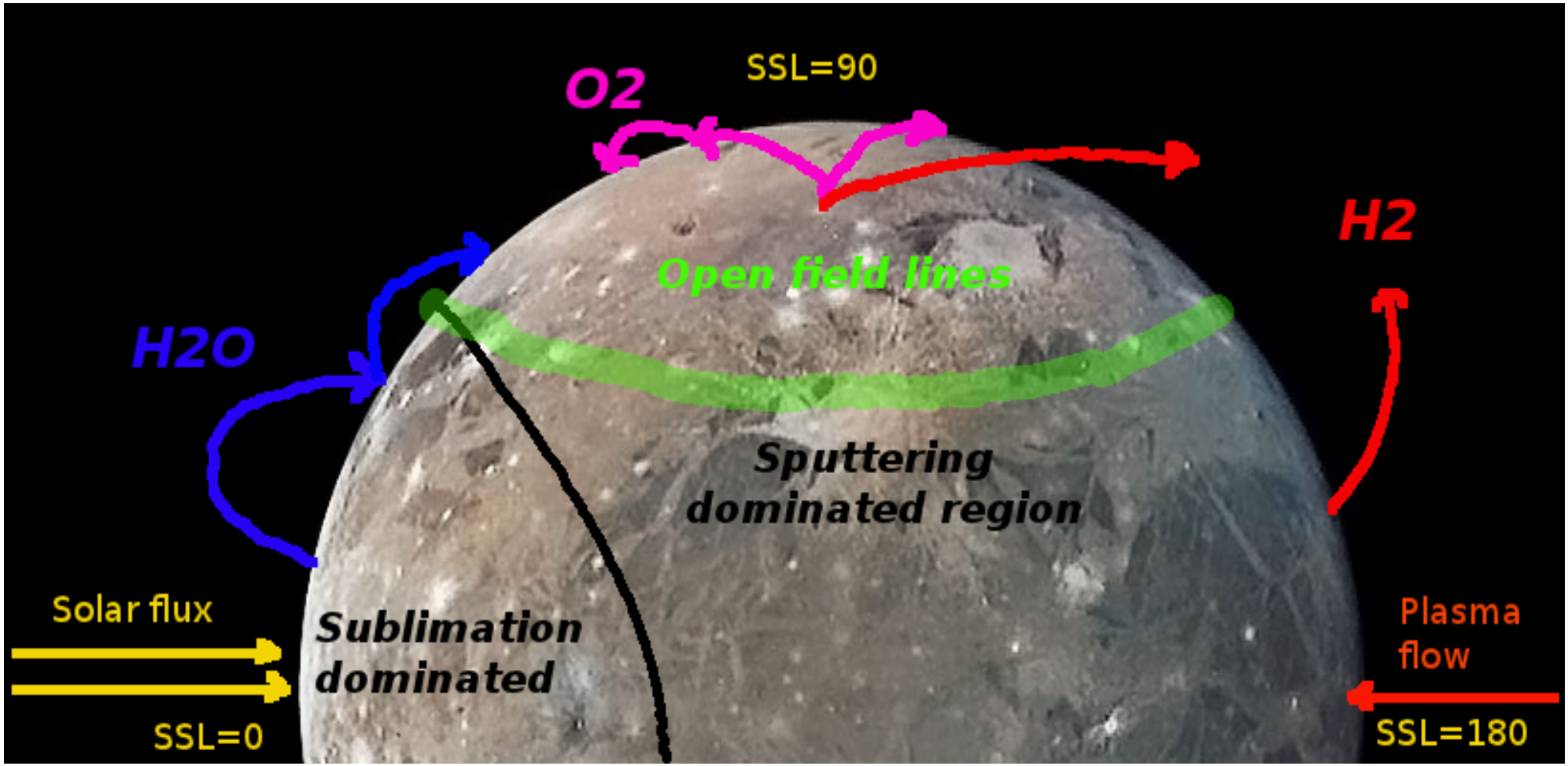


Figure 19.12. Ganymede auroral emission from oxygen (OI 1356 Å) observed with HST.

Images of Ganymede's OI 135.6 nm emission for HST orbits on 1998 October 30 (*Feldman et al., 2000*).

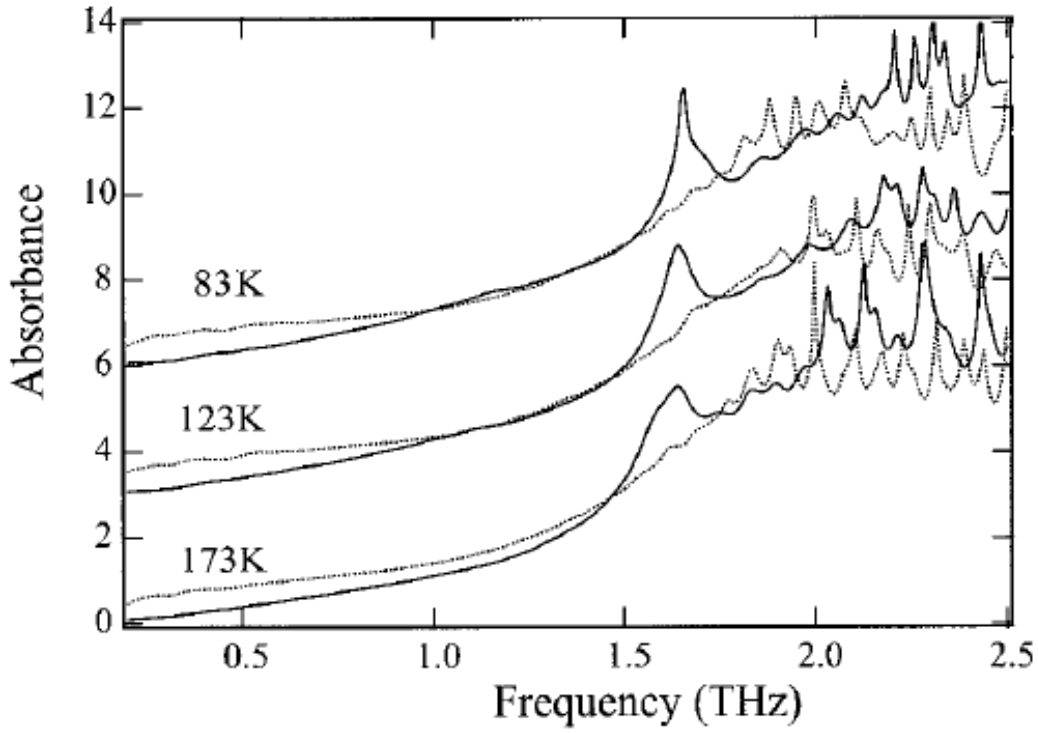
Schematic picture of processes creating the Ganymede atmosphere



Ganymede's water atmosphere

- Production processes of water are sputtering of heavy ions and electrons from the Jupiter co-rotating plasma and sublimation. The sublimation dominates 45 deg around the sub-solar point and while sputtering elsewhere. Sublimation produces a 3 orders of magnitude higher water vapour density than sputtering.
- Sublimation rates depend on types of ices: crystalline vs amorphous, impurities by different minerals/salts, ice-regolith mixtures
- These parameters have been constrained by THz time domain spectroscopy in the lab

Distilled water (dotted) and NaCl added.

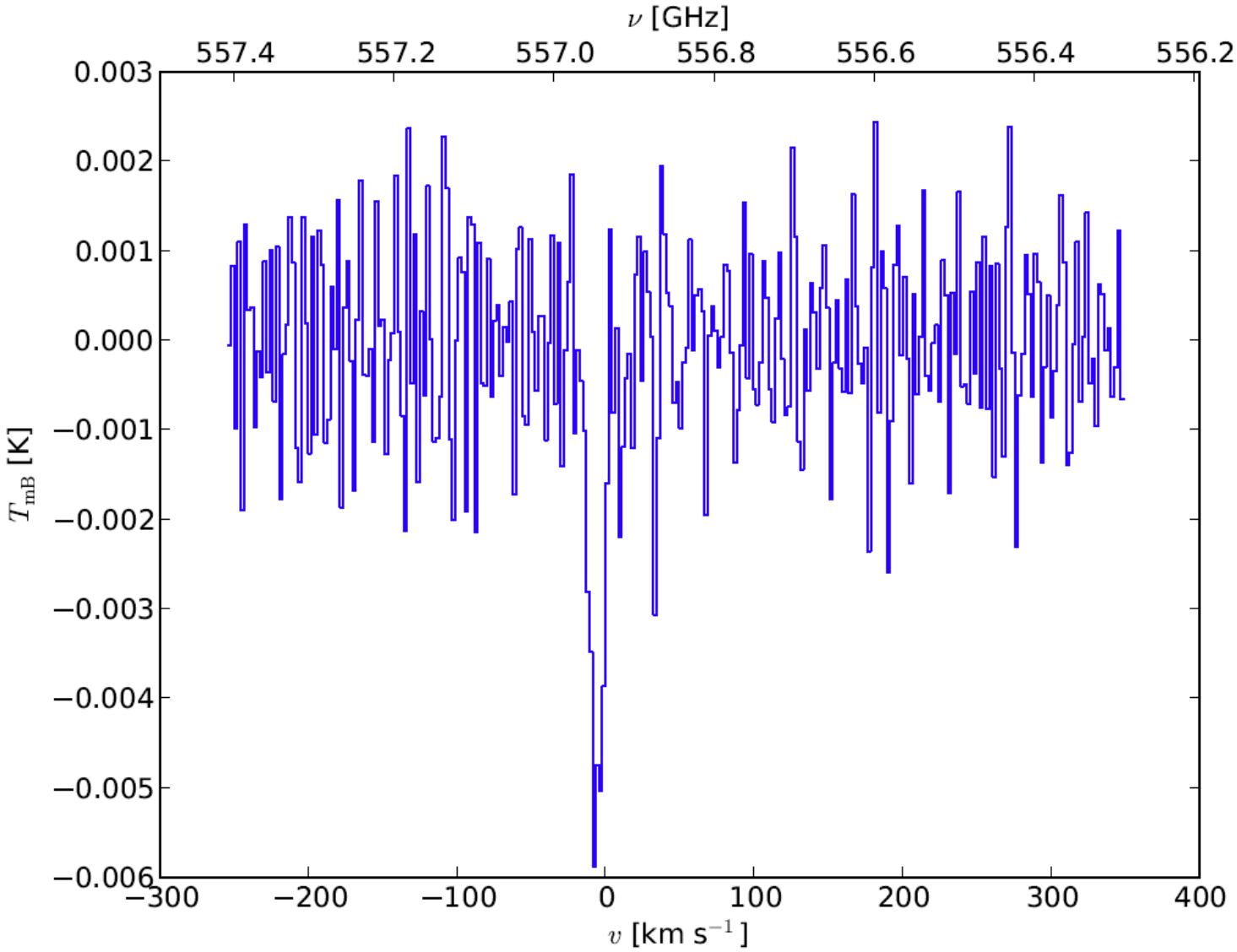


Rungsawang, 2007: different alkali chlorides and ices can be identified in the FIR

OT 1 proposal on Galilean satellites

- Idea:
  - detect water lines of all four satellites
  - Measure surface spectra with PACS and SPIRE in order to characterise the ices on their sublimation capabilities.
- HIFI integration times 15 h/moon.
- PACS/SPIRE about 5 h/moon
- Proposal not successful (“detections unlikely”)

HssO: 4 h spare time on Ganymede/557 GHz



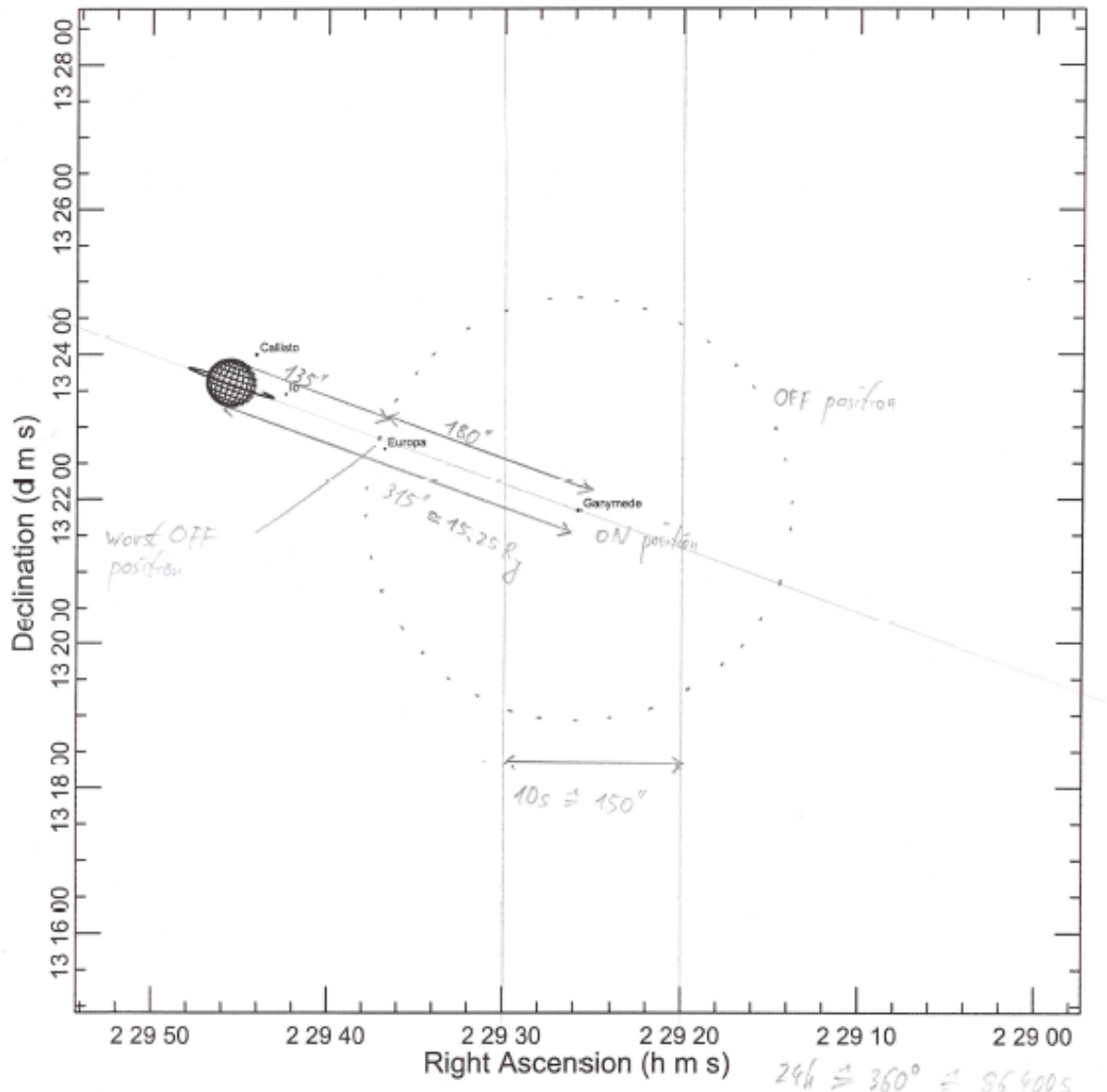
Detection! But what?

- Problem: line not exactly at rest frequency of Ganymede. Zooming in shows that the line is much wider than expected.

- Observation was performed in dual beam switch mode.

- What went wrong?

Jupiter Viewer Results



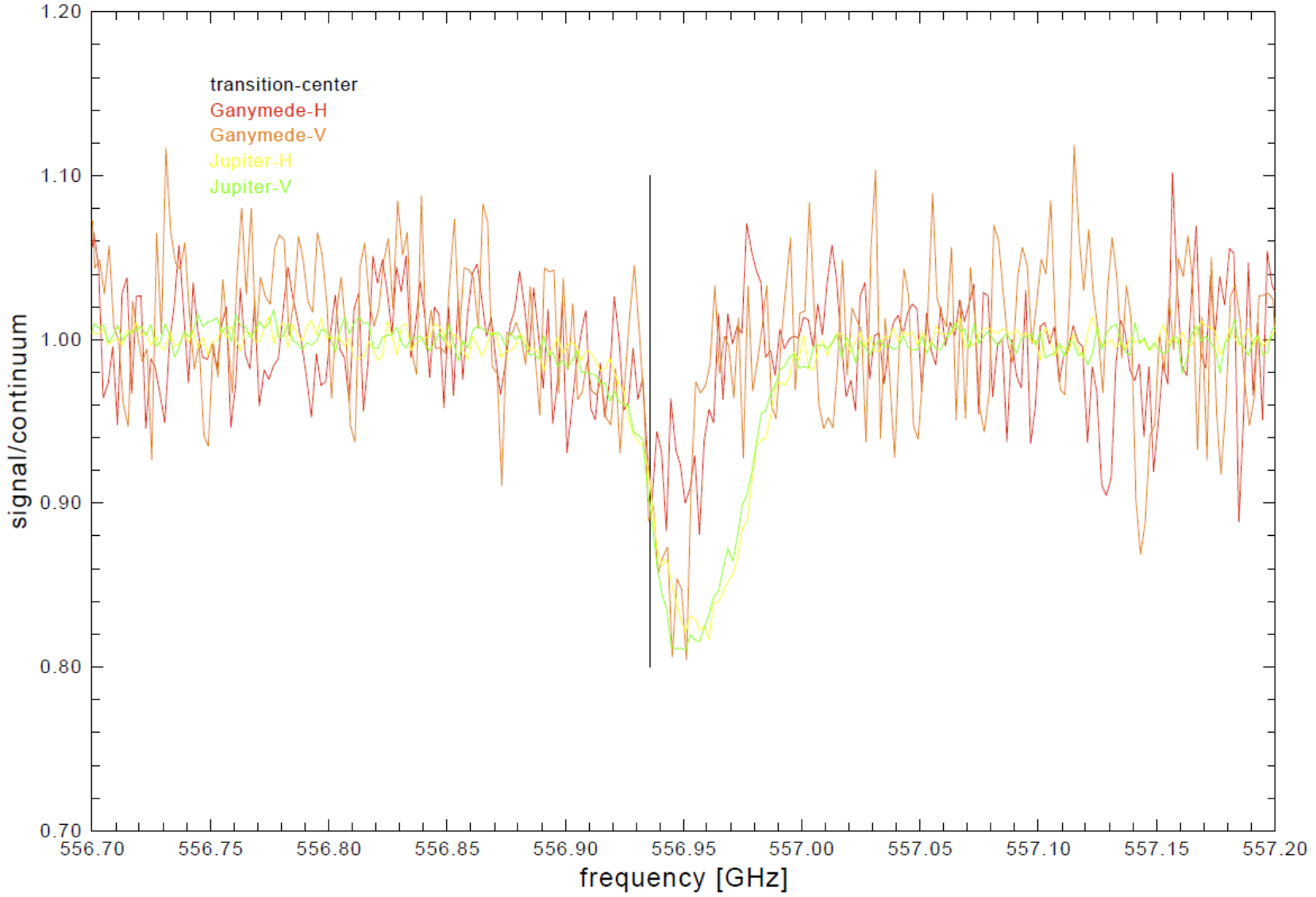
Time (UTC): 2011-08-08T14:38:00Z
Ephemeris: JUP204 + JUP230 + DE421
Viewpoint: Earth's center
Moon selection: Io-Callisto
Ring selection: Main

24h ≙ 360° ≙ 86400s

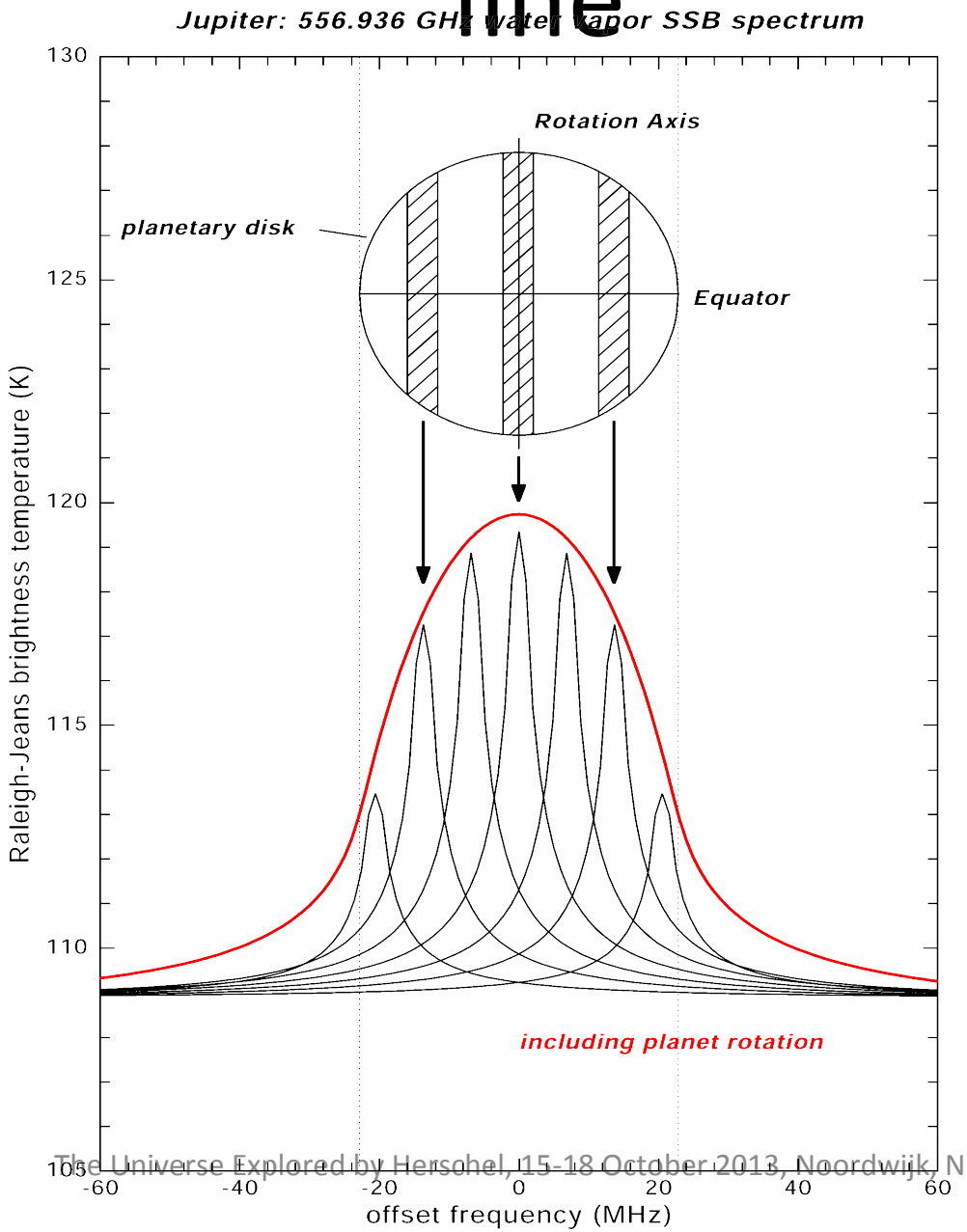
86400s ≙ 360 · 3600"

1s ≙ 15"

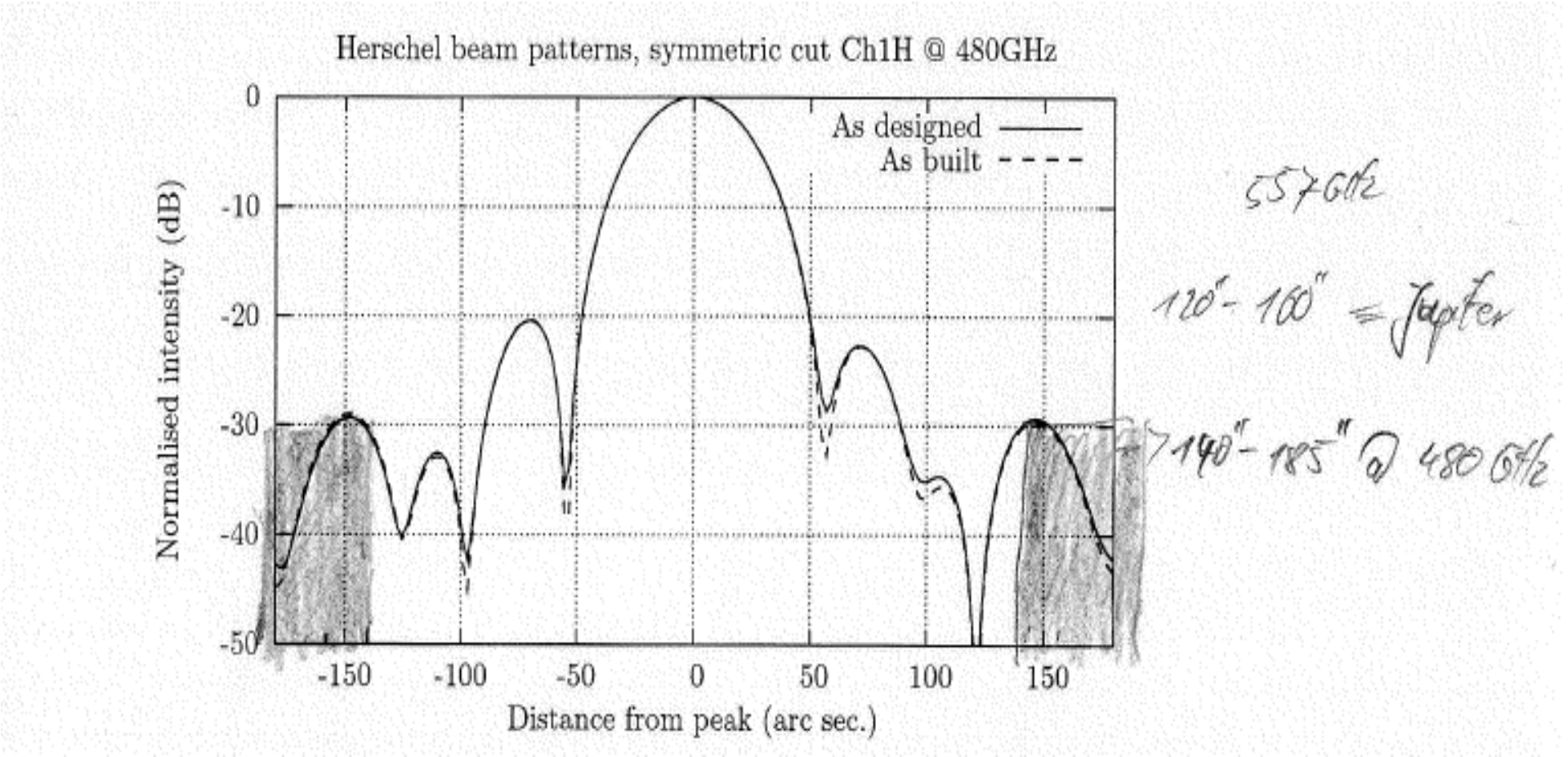
Jupiter water line contamination?



Rotational broadening of water line



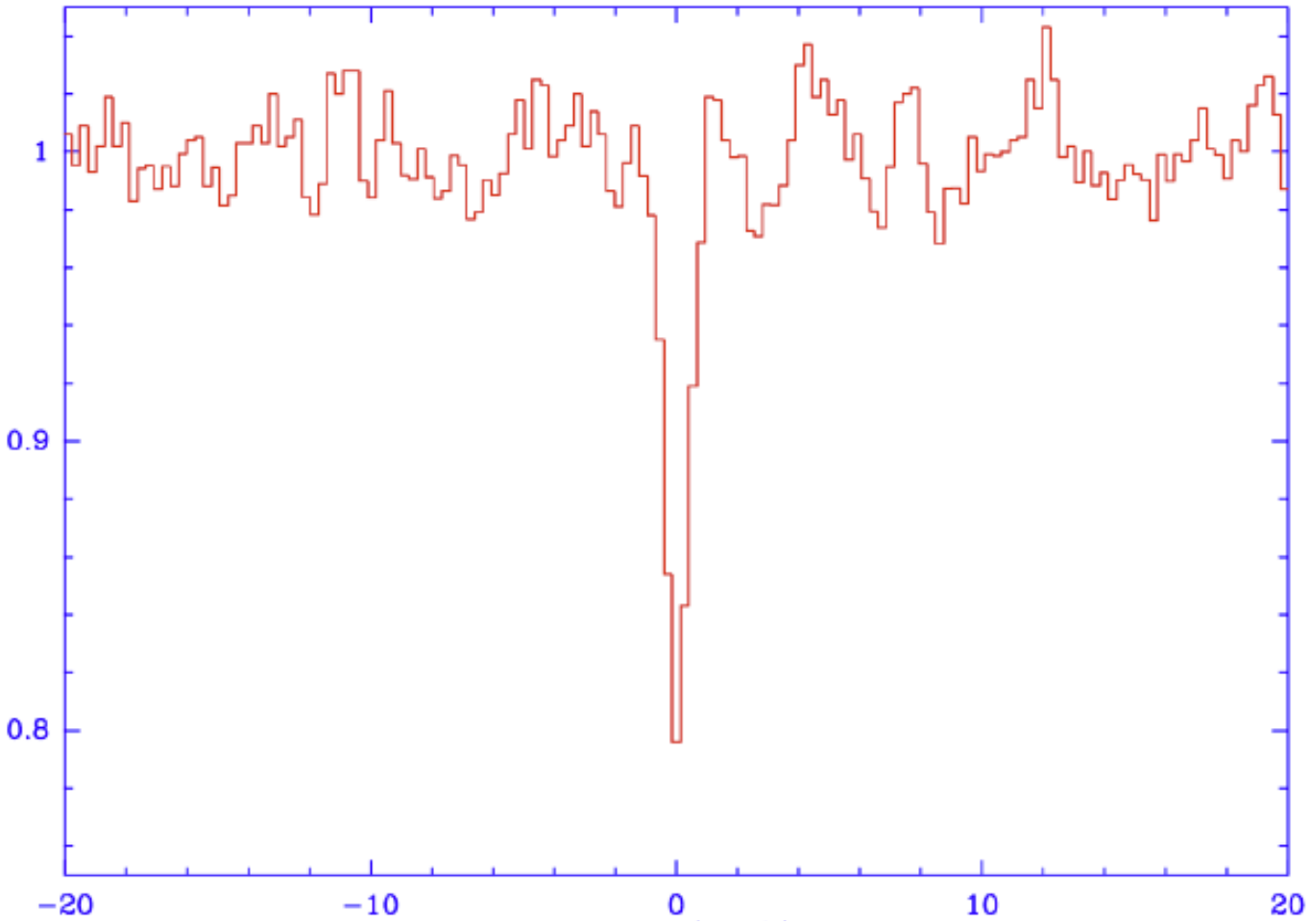
Second sidelobe of Herschel beam hits Jupiter
Sidelobs widths half of main lobe widths, therefore only half of Jupiter covered
Detected line widths fits with Jupiter position
No detection of Ganymede water!!!



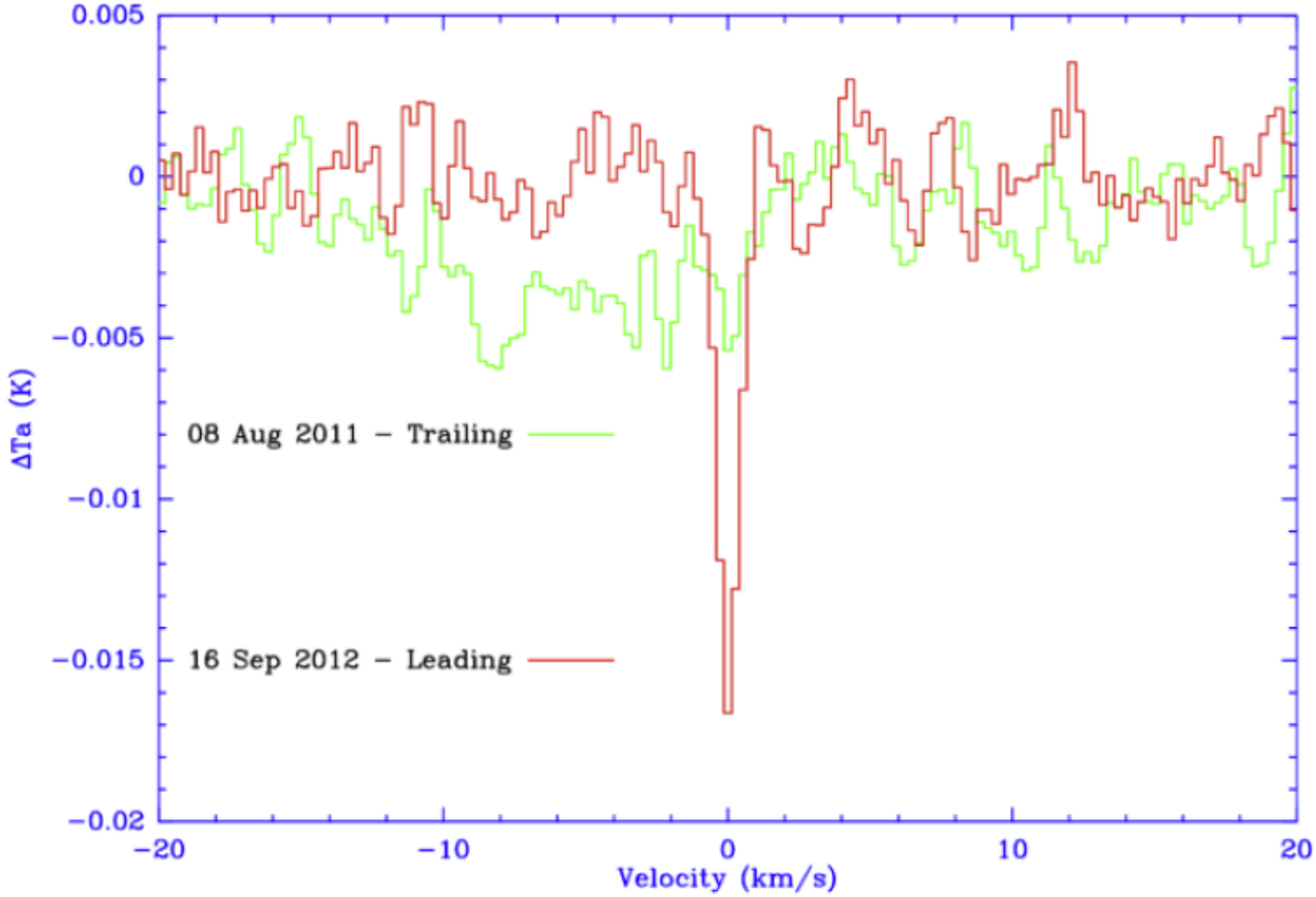
Is there any line hidden from Ganymede?

- Extensive effort to re-calibrate the data
- Tried out beam switch rather than dual beam
- Result: no line found
- No water out there? Were the reviewers right?
- After long discussions within the team: we try it again with frequency switch using the last remaining GT. There must be a water atmosphere! It would have great impacts on …

Finally really detected on 16 Sep 2012!



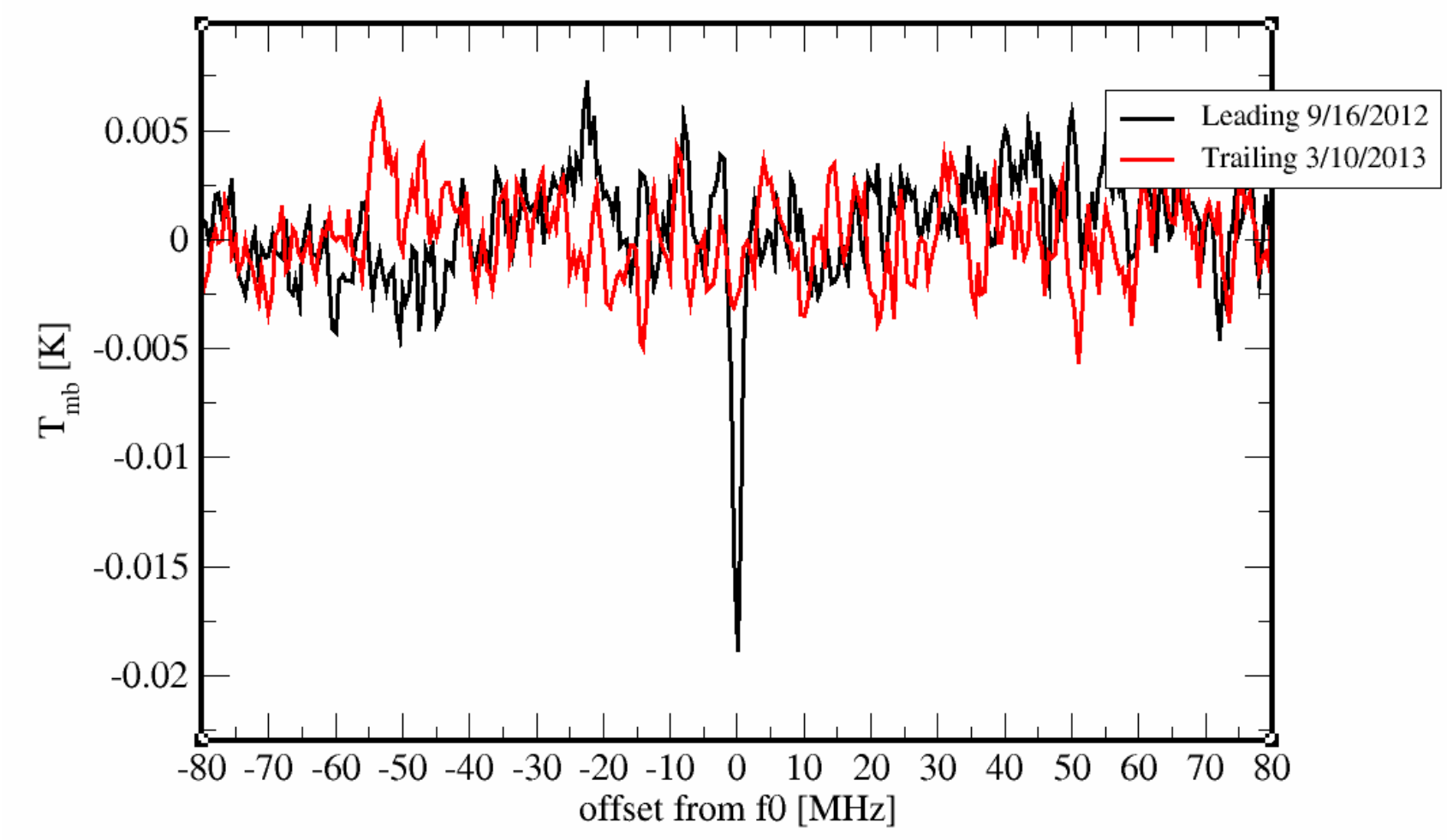
Comparison of the observations



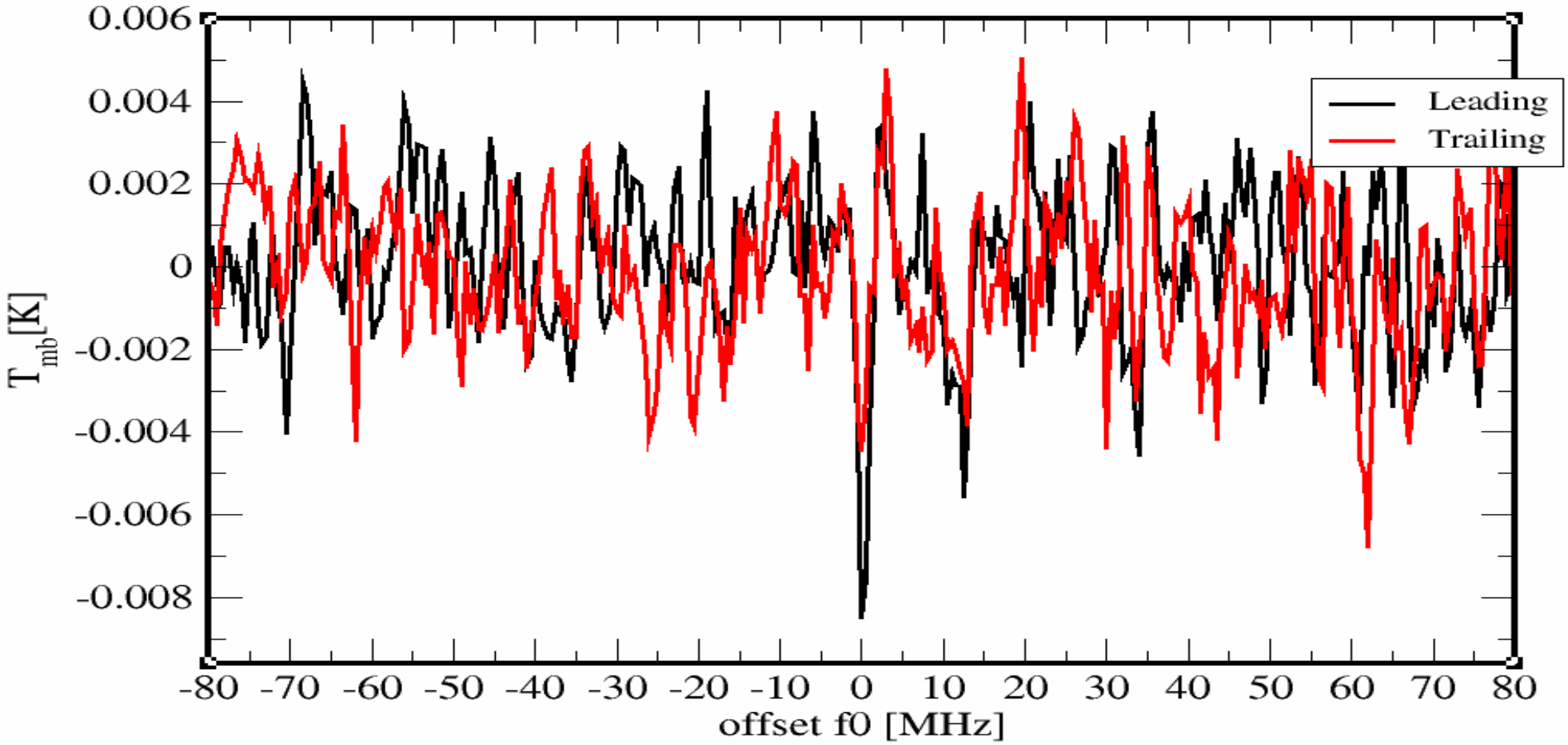
Is there a leading/trailing side asymmetry?

- Since sublimation is the dominant production mechanism there should be only a small asymmetry.
- We need a confirmation: DDT proposal: trailing side Ganymede and leading/trailing side Callisto
- Proposal successful!

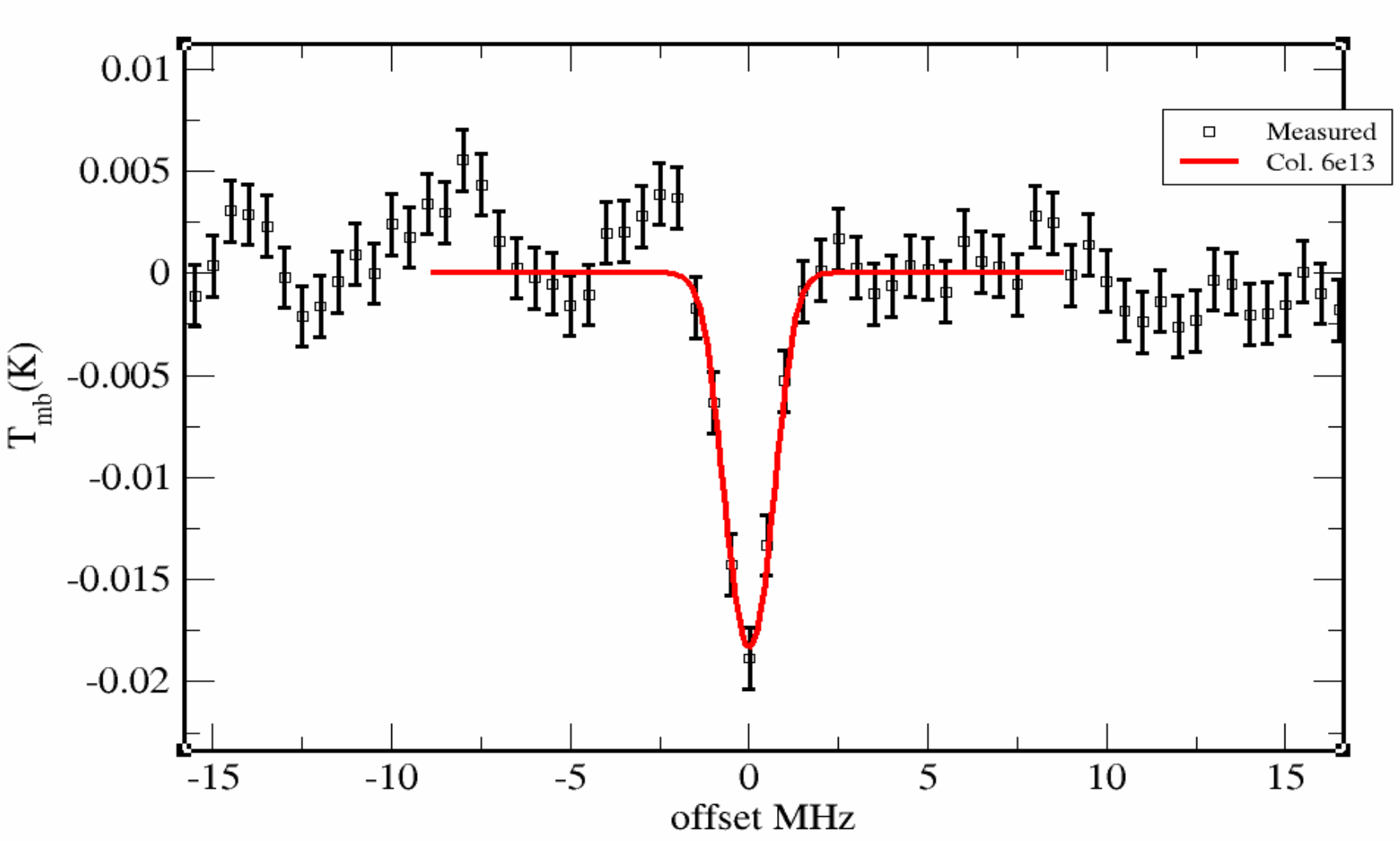
No water on trailing side confirmed!



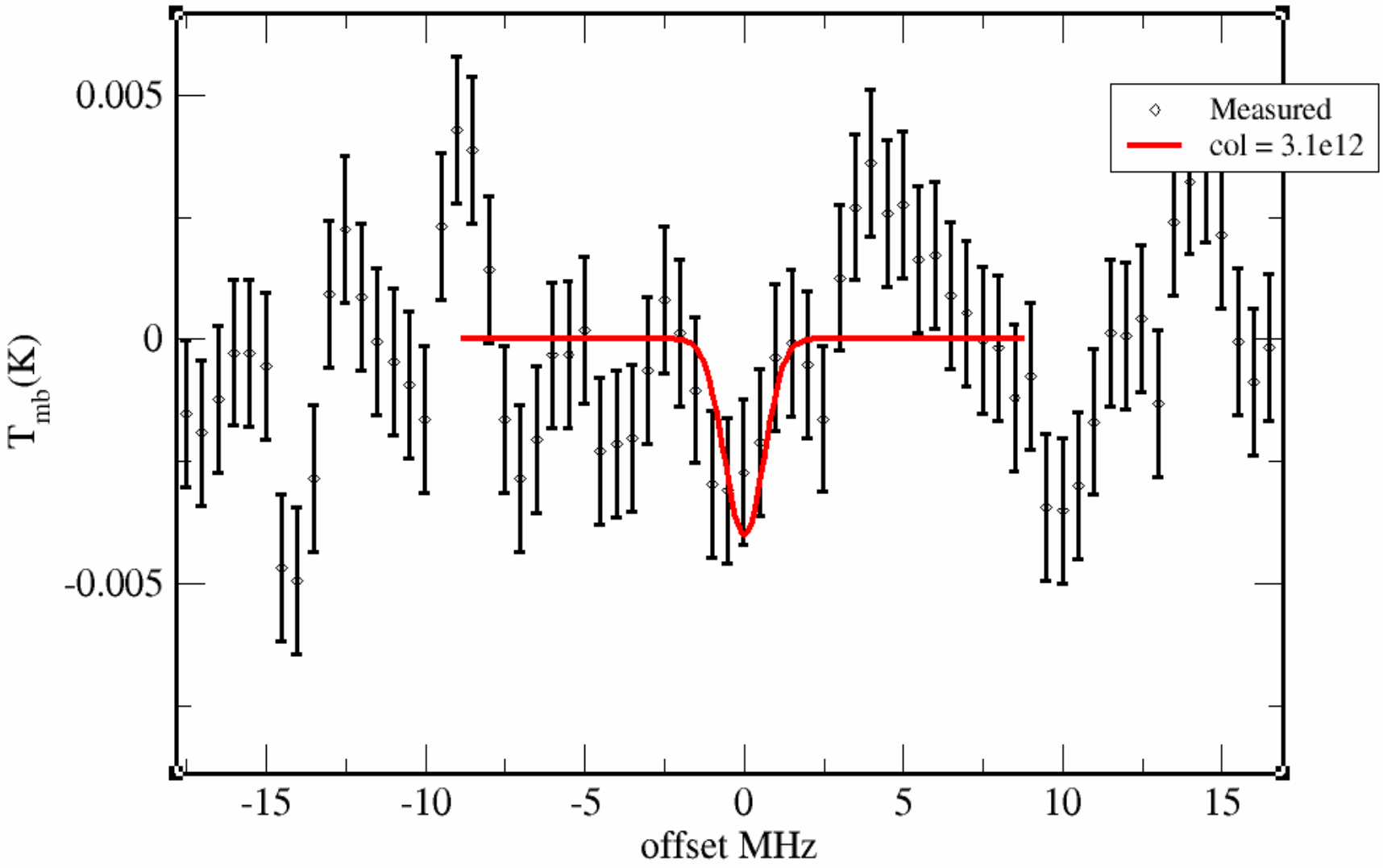
Same situation on Callisto!



Ganymede Leading hemisphere. Initial inversion yield column 6e13 cm-2 with 60% uncertainty.



Ganymede trailing hemisphere: Initial inversion yield a 2-sigma upper limit 3e12 cm-2 with 20% uncertainty.



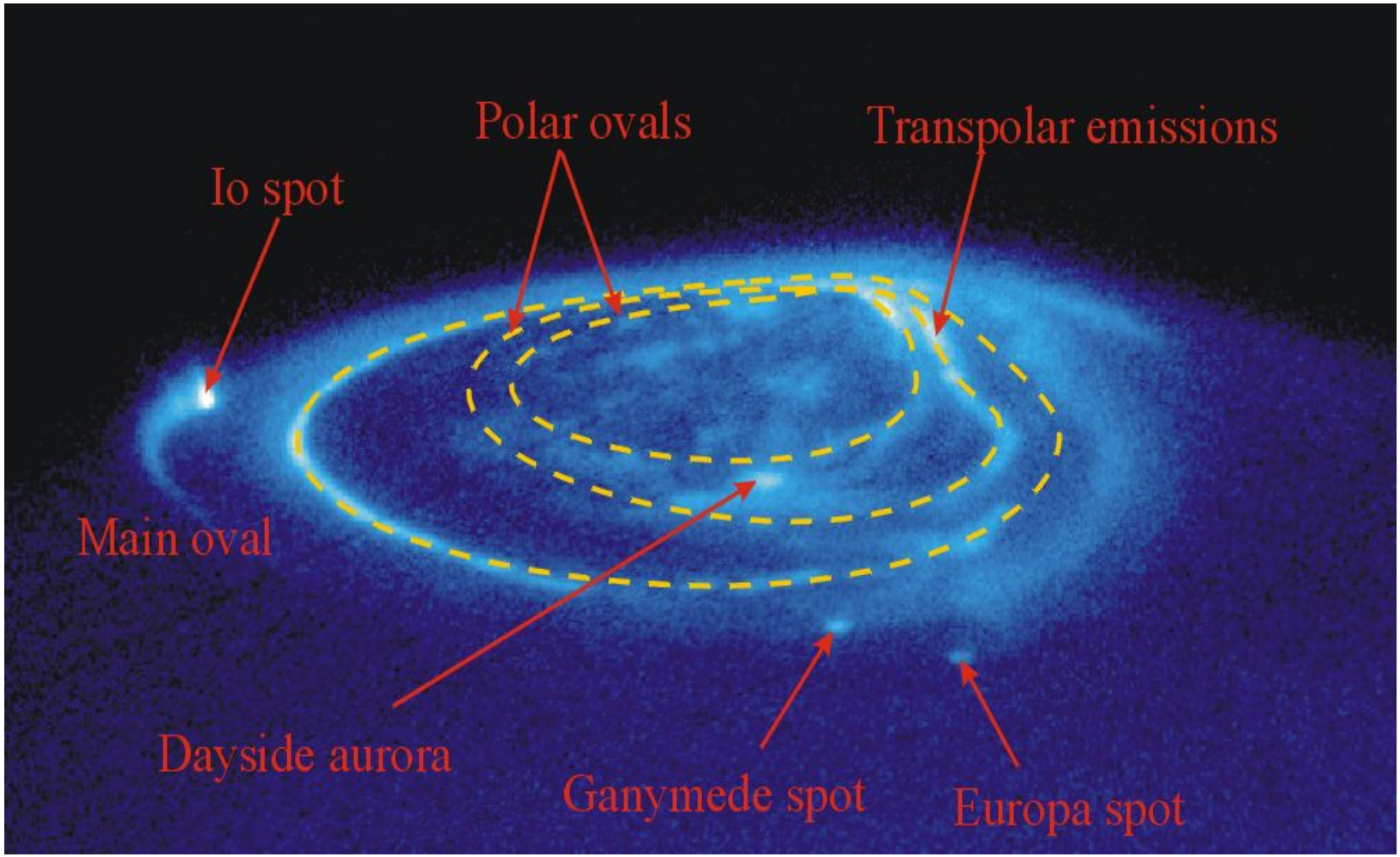
Ganymede and Callisto water atmospheres

- First detection of water in both atmospheres
- In both cases only a detection on the leading side.
- The L/T ratio in water vapour density is > 10 for Ganymede and ~3 for Callisto
- Unexpected finding and no easy explanation.
- We were lucky that by chance we observed the leading side of Ganymede.

Discussion

- In principle the finding points to sputtering as the main production process. However on Ganymede the sides we observed were shielded from sputtering by its magnetic field.
- The magnetosphere interaction of Callisto is negligible, sputtering as production process can be excluded (too far out).

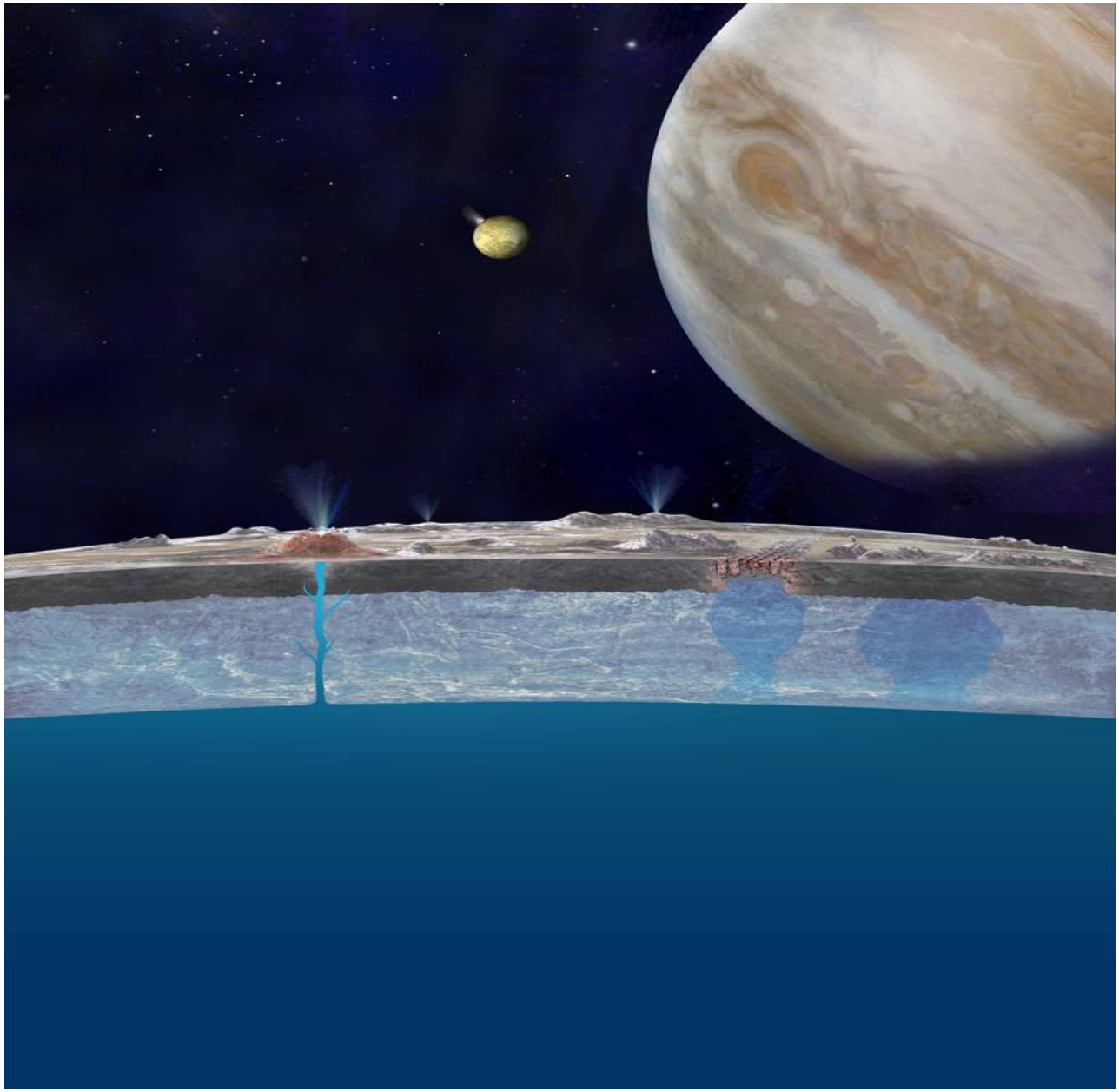
Jovian aurora → Callisto signature is missing → it orbits most of the time beyond the main Jupiter radiation belts. Smaller plasma density impacting the moon.



Credit: NASA HST

Cryovolcanism like on Enceladus?

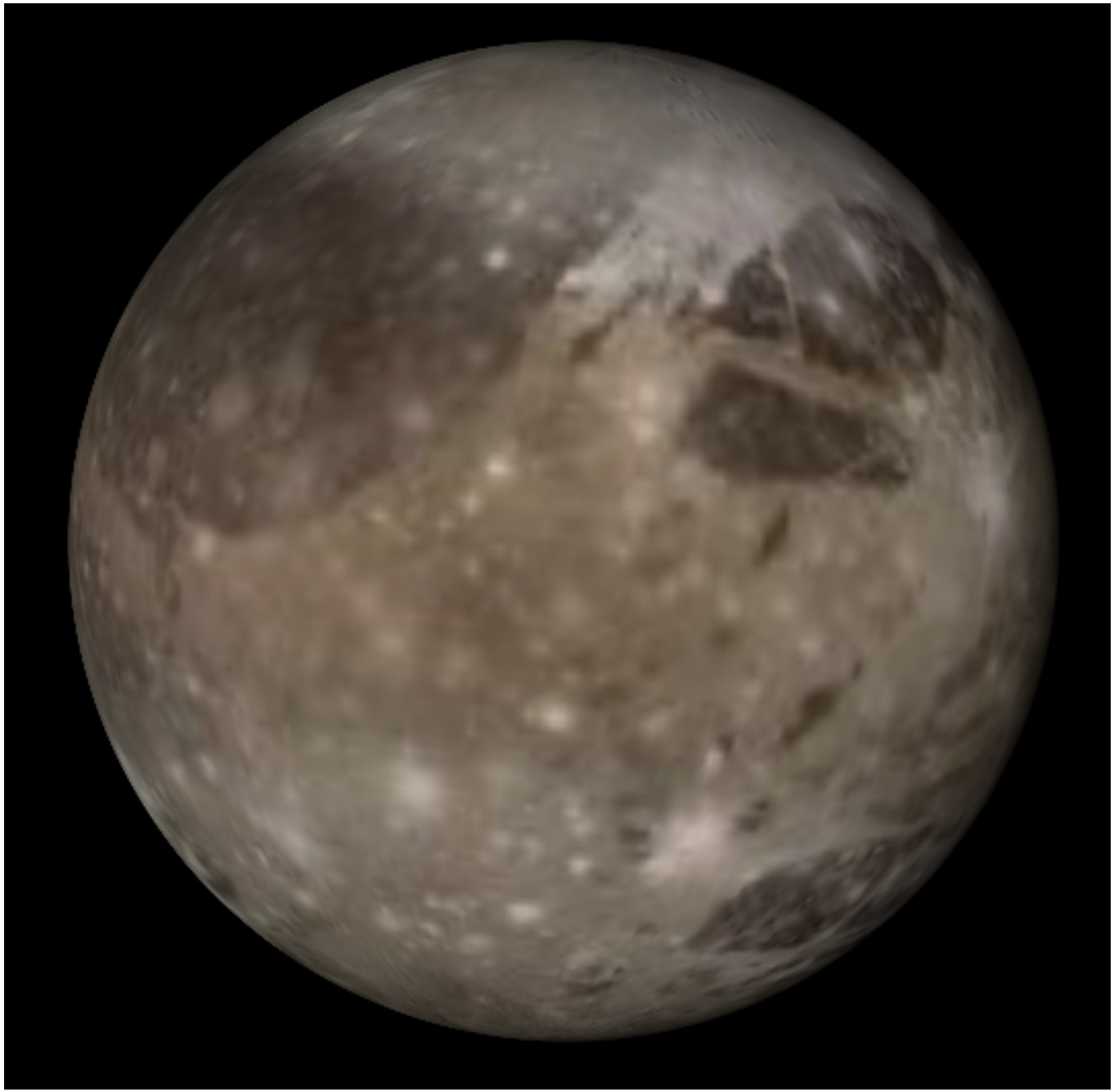
On leading sides
by chance?



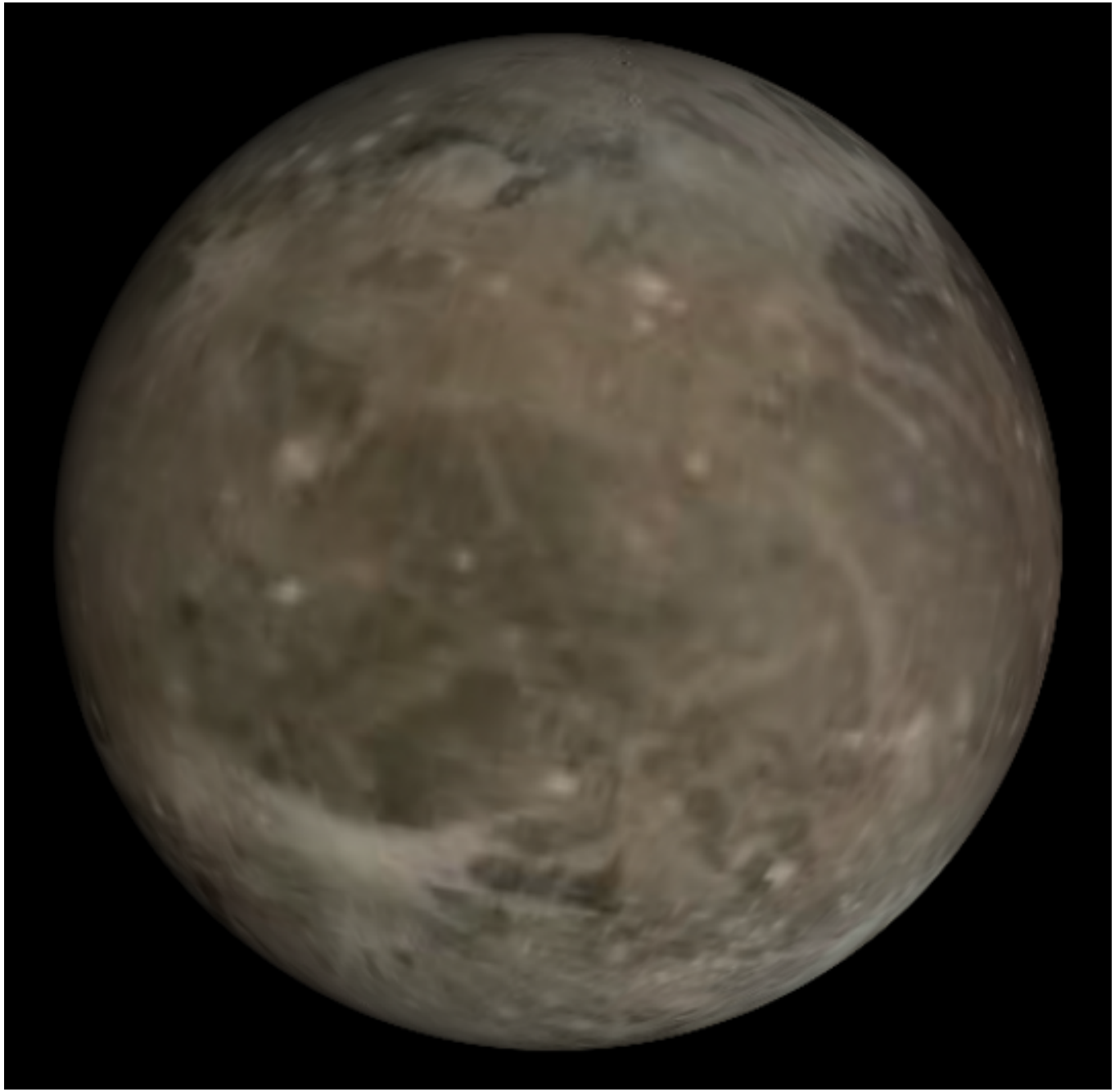
Why no sublimation on trailing sides?

- Callisto is rather dark. Water ice on the surface may have been largely depleted.
- Is there any good reason why on Ganymede only one hemisphere should be depleted in surface ice?
- Since sublimation is probably the main production process and locally rather limited, it is very important to investigate the exact location of the observation.

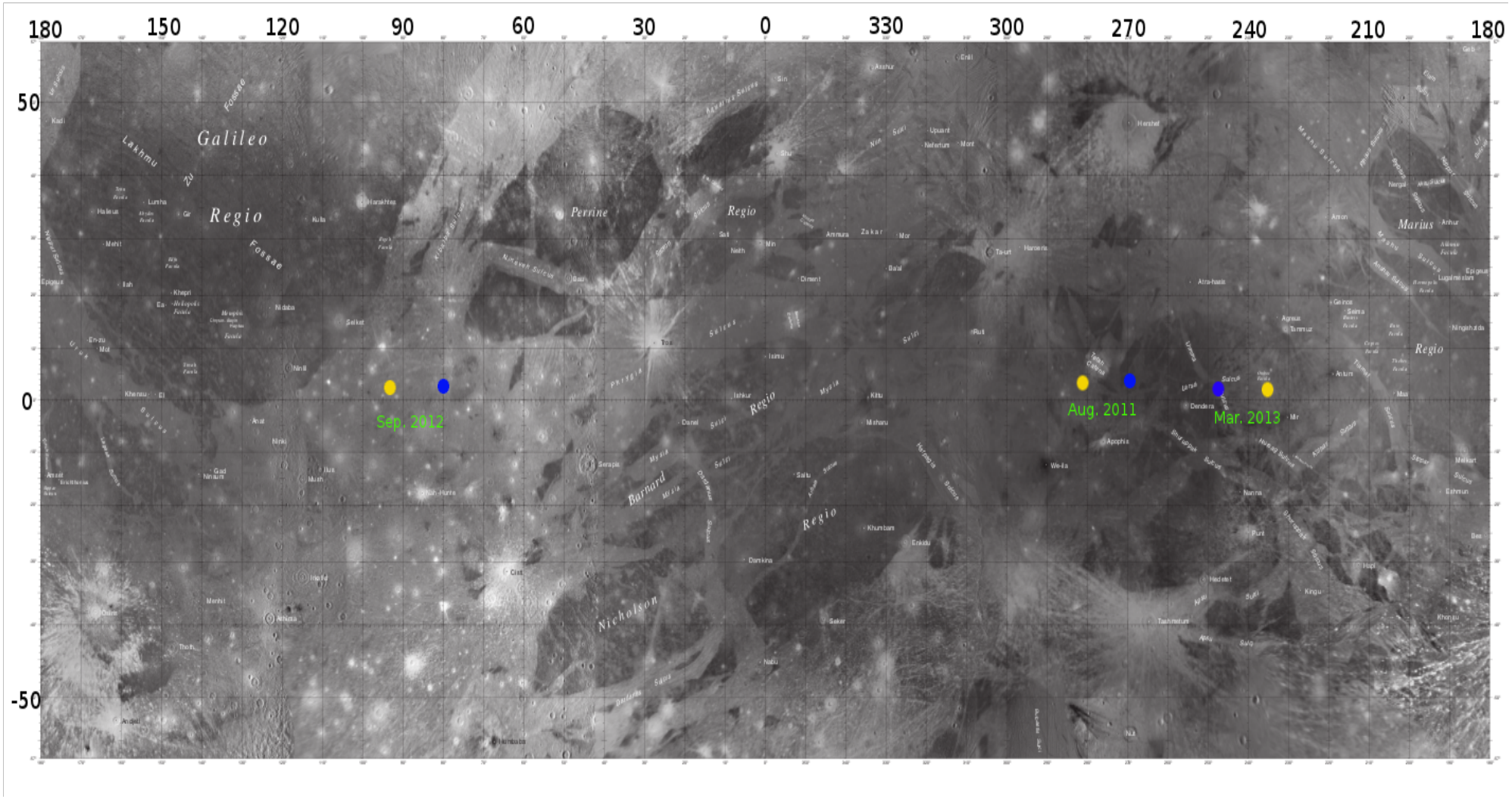
Leading hemisphere at the observation 16 September 2012



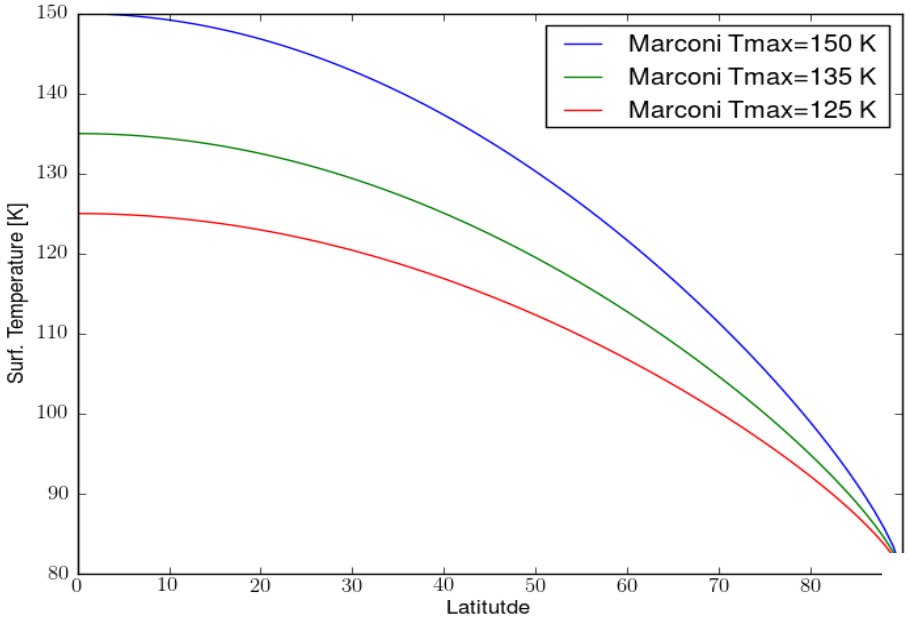
Trailing hemisphere at observation on 10 March 2013



Sub solar and sub Herschel points

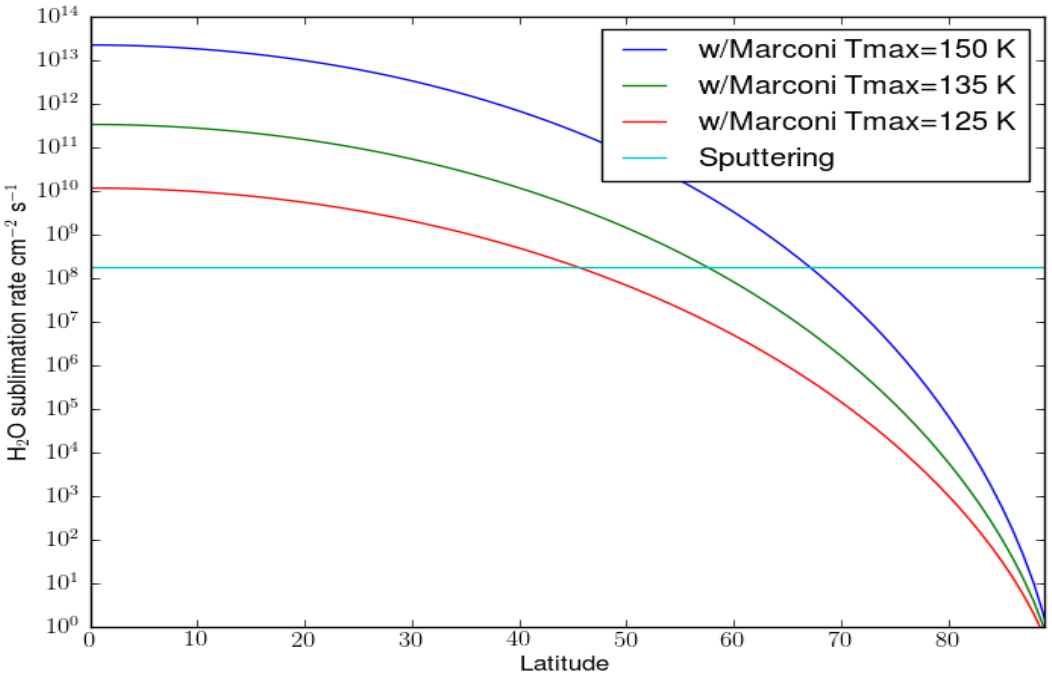


Sublimation flux – assuming different ice temperature



Temperature distribution

H2O Sublimation for the T assumed



Ganymede

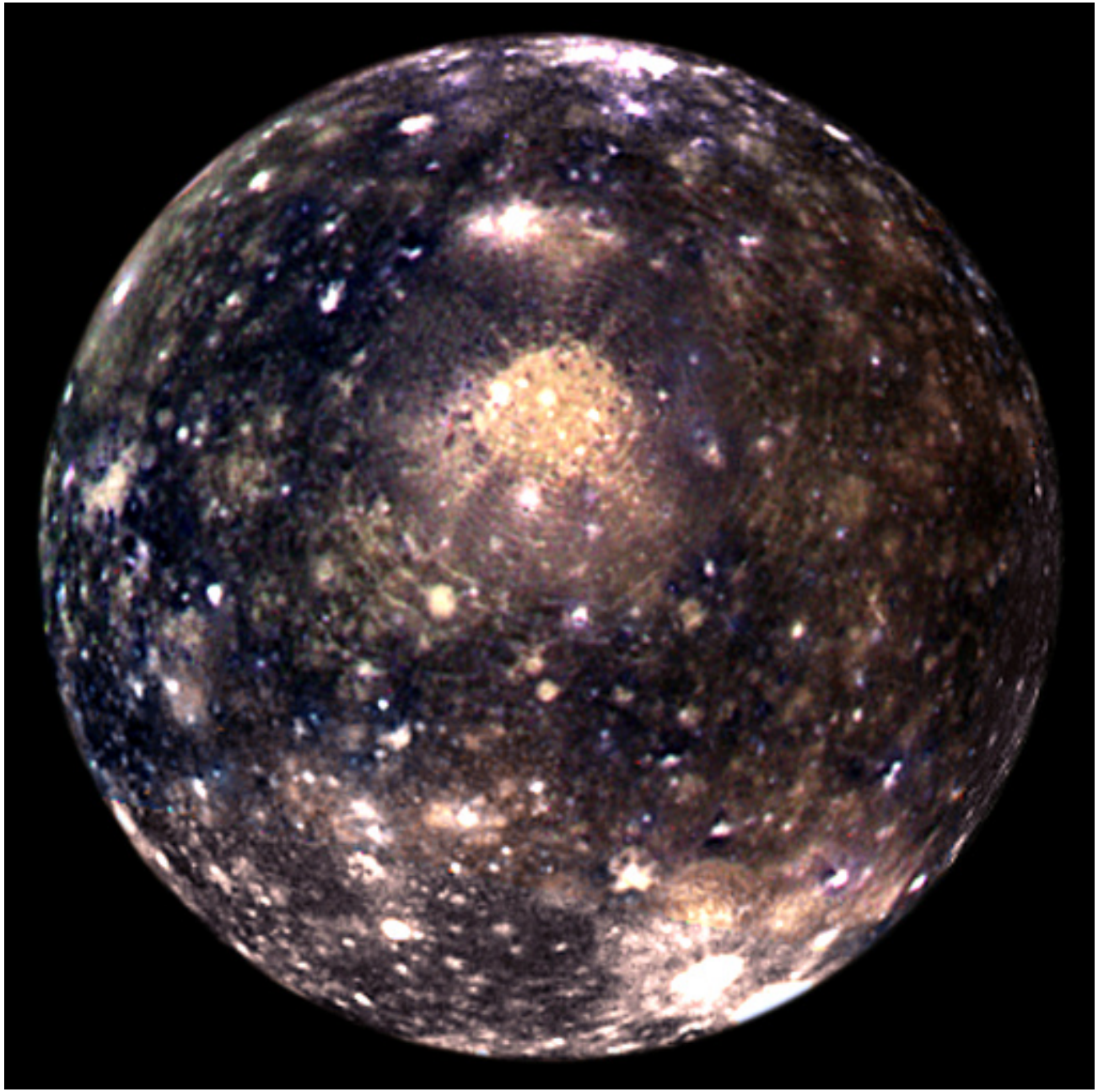
Trailing hemisphere darker than leading, albedo difference 15% (Spencer 1987)

Surface ice fraction:
65 % (bright) 35% (dark) rocky material (Papalardo 2004)

50 +- 15 % ice on trailing hemisphere and 65+-15 % on the leading (Polack 1978)

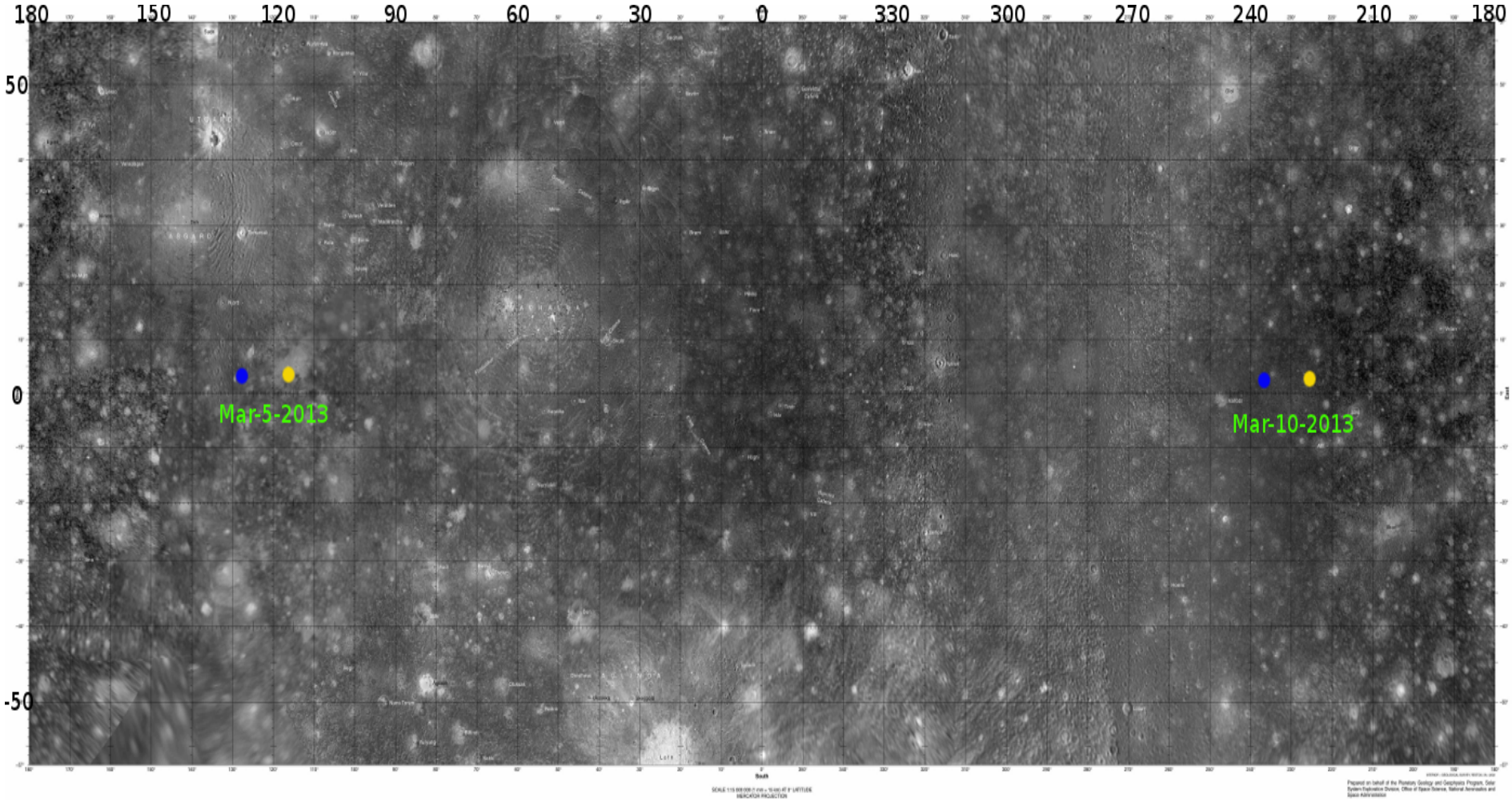
20-65 % ice on the surface (Pitcher 1972)

Properties of ice on both sides different?



Leading side of Callisto

Callisto surface map and where the center beam observations are located. Yellow=Sub-solar position. Blue=Sub Herschel. Leading hemisphere 90 deg lon.



Callisto

Leading hemisphere is darker than trailing ! (opposite to the other Galilean moons).

Albedo difference ~ 13% (Spencer 1987)

Mean ice fraction of the surface 10-50%, many regions completely ice-free (Showman 1999)

5-20 % surface ice fraction (Pitcher 1972)

5+-5 % surface ice fraction (Clark and McCord 1980)

Summary

- First detection of predicted water atmosphere of Ganymede and Callisto.
- Properties of atmospheres different from predictions and not easy to understand
- Detected strong asymmetry may be an expression of strong local variations of temperatures or ice properites.
- Cryovolcanism cannot be excluded as potential atmospheric source.