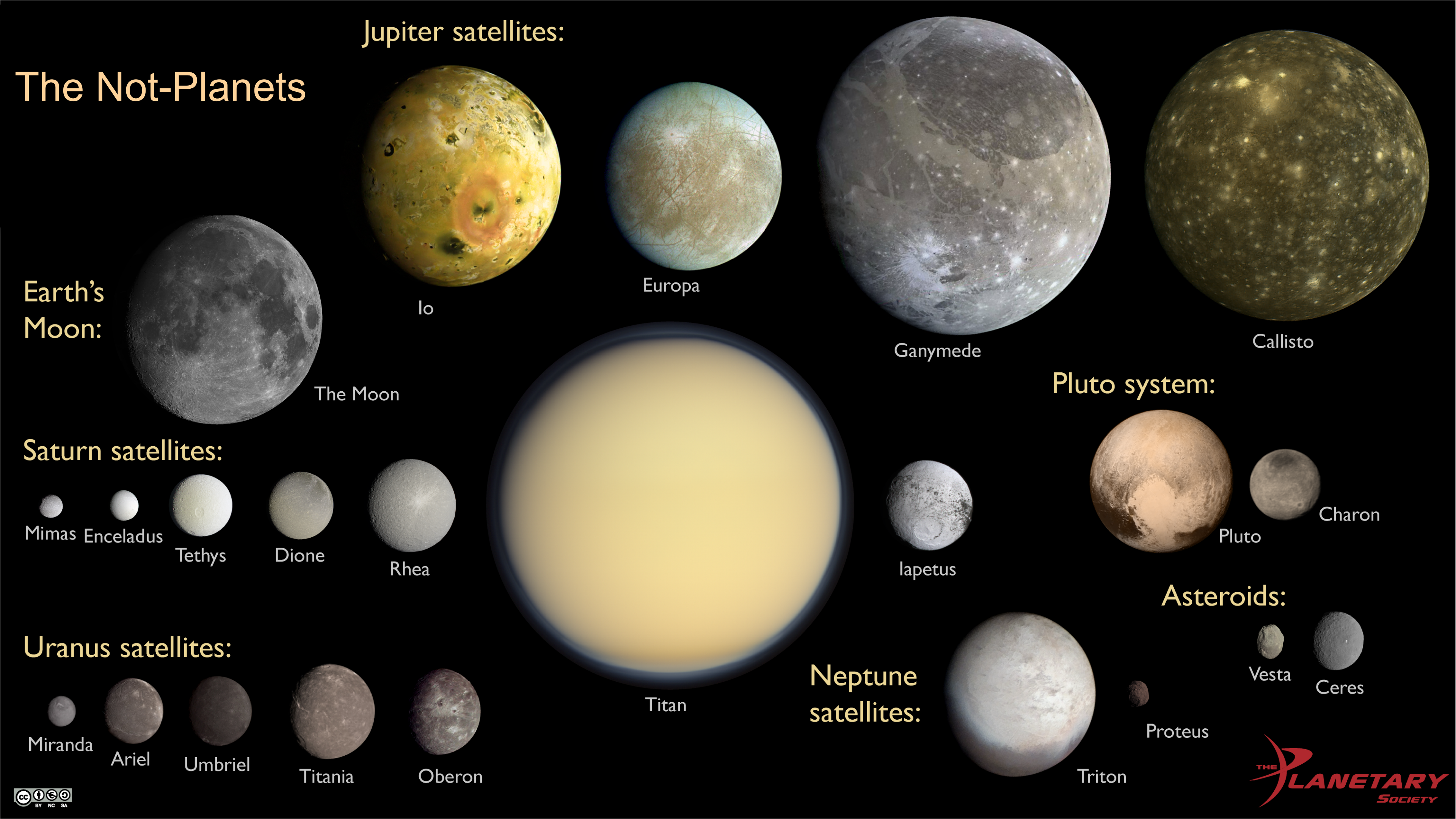
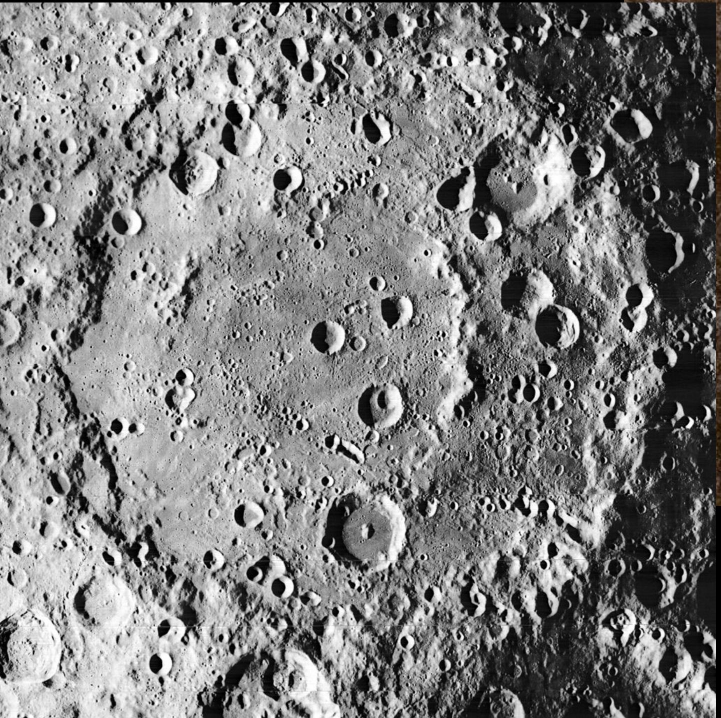
Geological Activity on Tidally-Heated Solar System Worlds

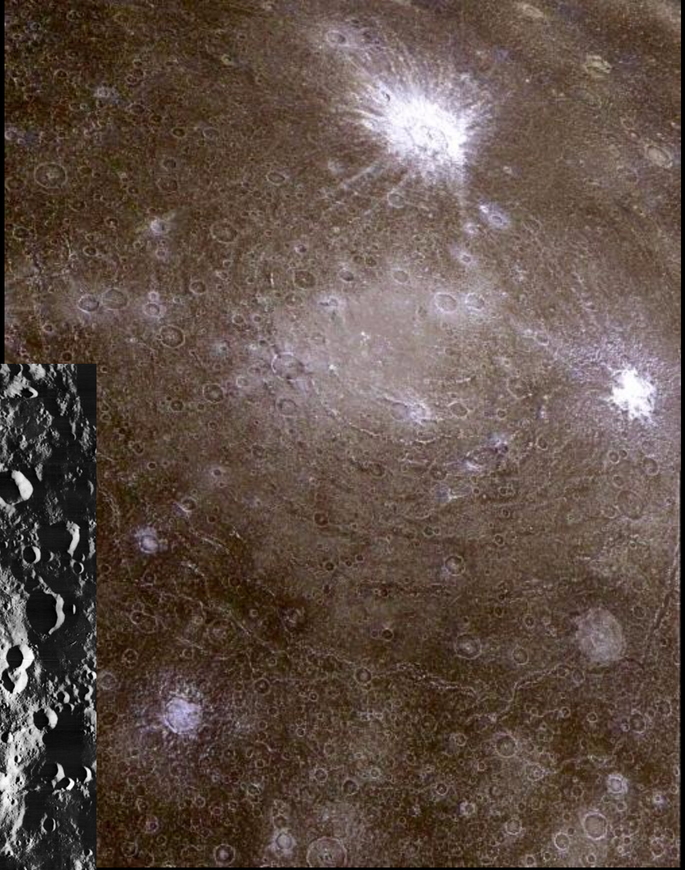
J. A. Rathbun (PSI, @LokiVolcano)

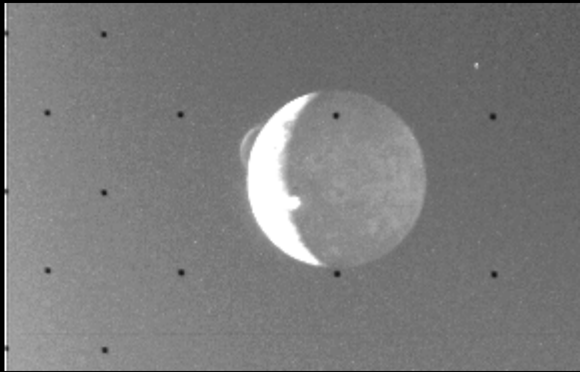

The Not-Planets
Jupiter satellites:
Io
Europa
Ganymede
Callisto
Earth's Moon:
The Moon
Titan
Pluto system:
Pluto
Charon
Saturn satellites:
Mimas
Enceladus
Tethys
Dione
Rhea
Iapetus
Asteroids:
Vesta
Ceres
Uranus satellites:
Miranda
Ariel
Umbriel
Titania
Oberon
Neptune satellites:
Triton
Proteus
THE PLANETARY SOCIETY
BY NC SA

Io

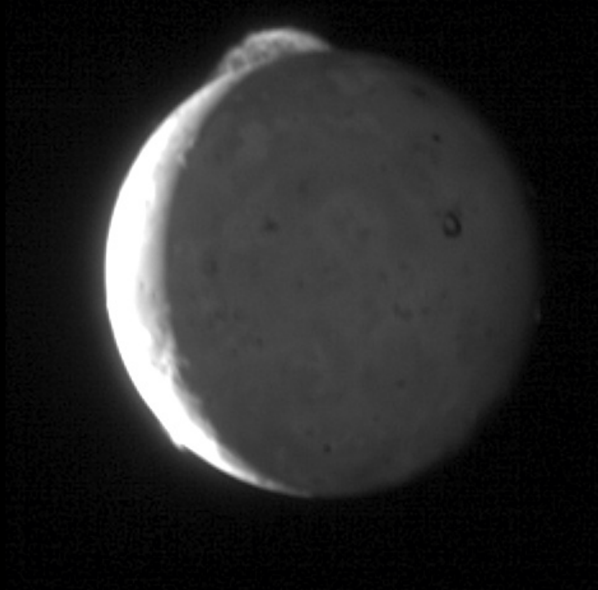
Expected:



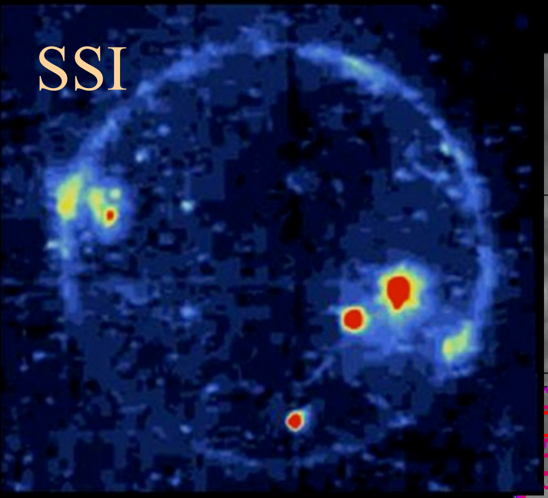


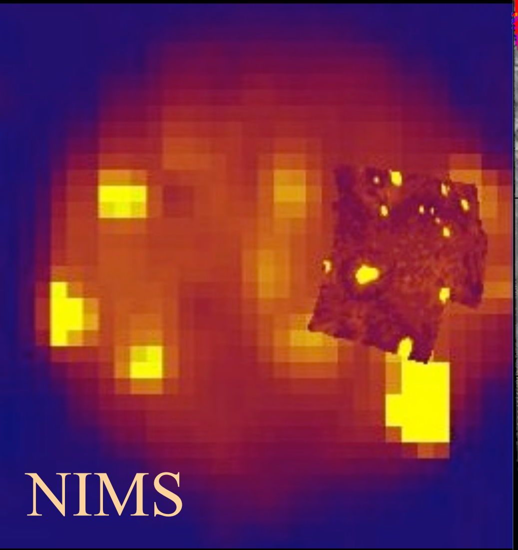


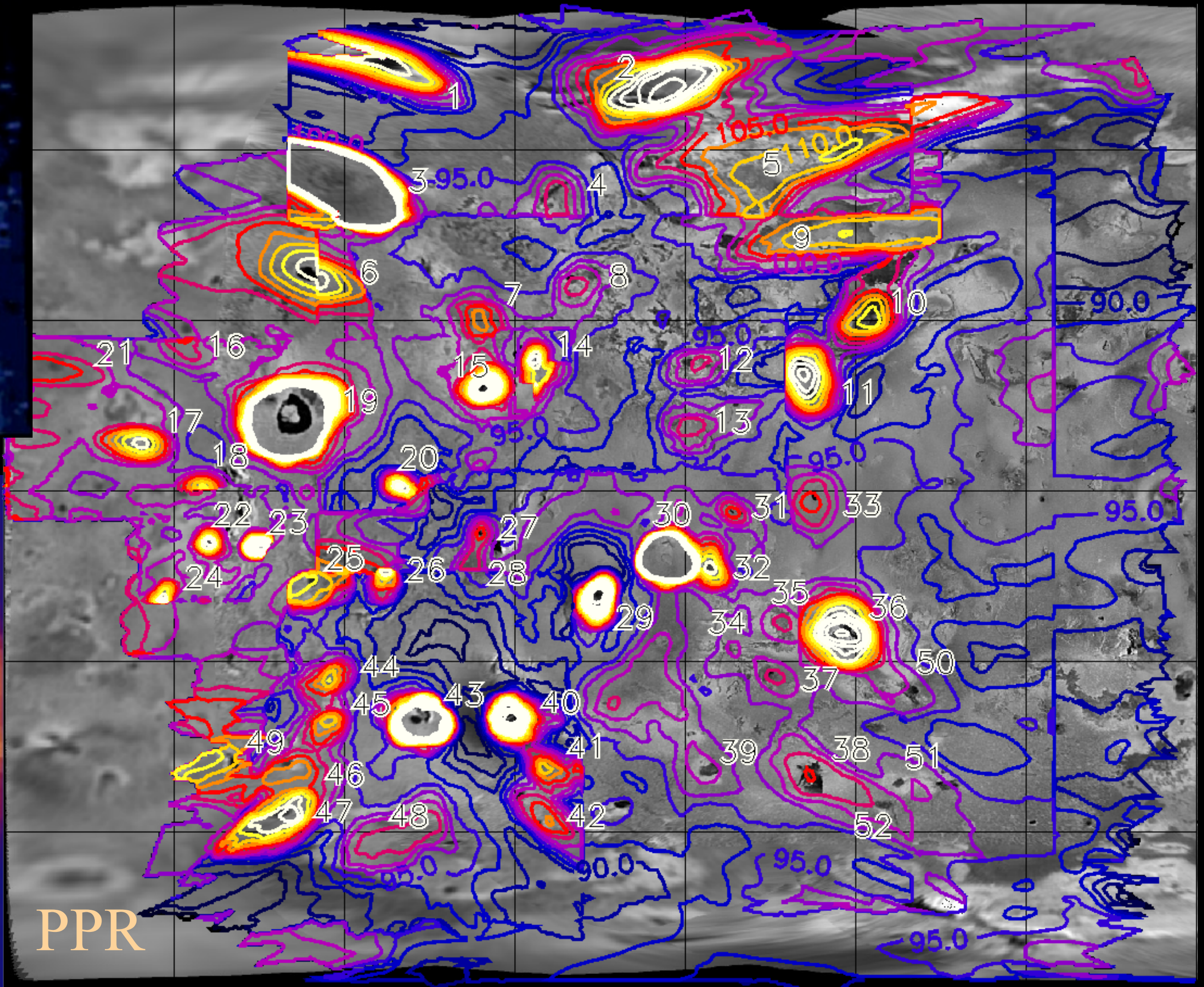
Observed:

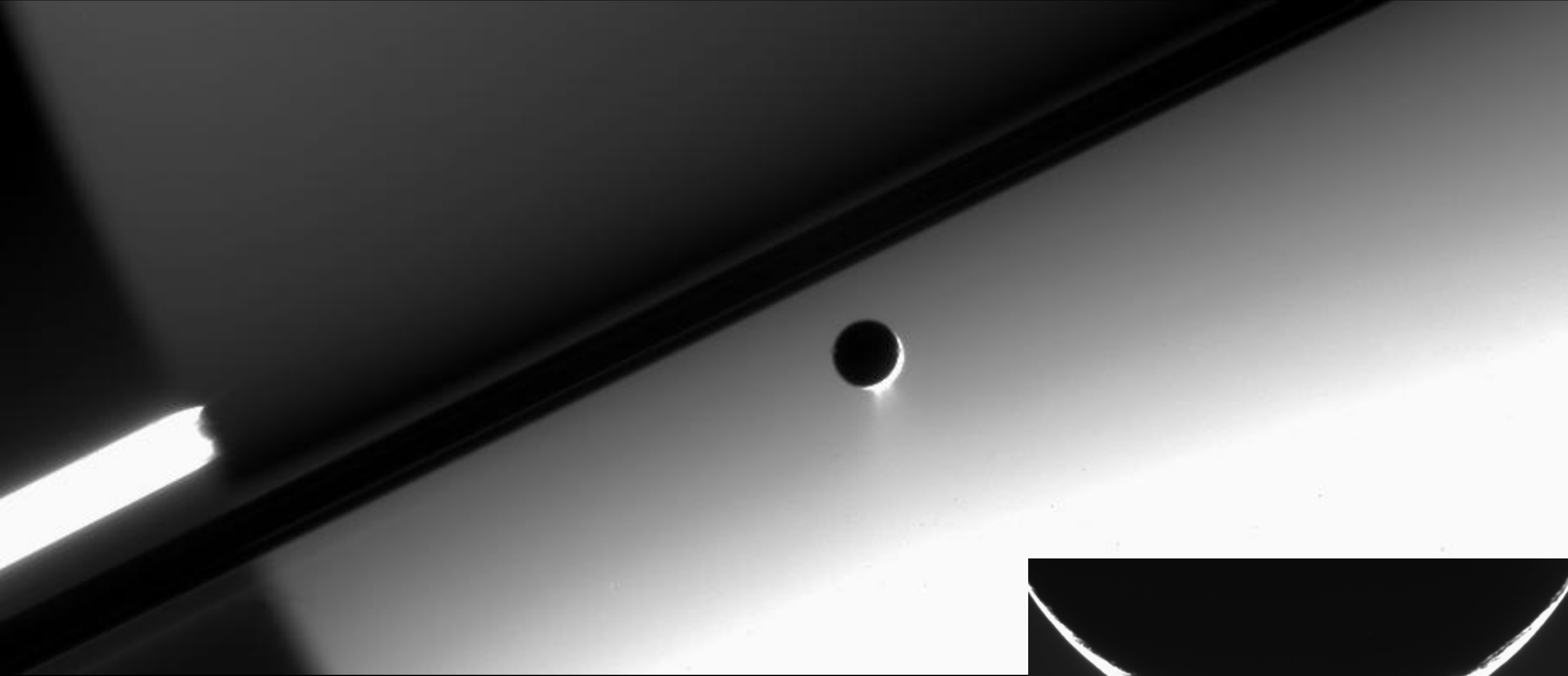


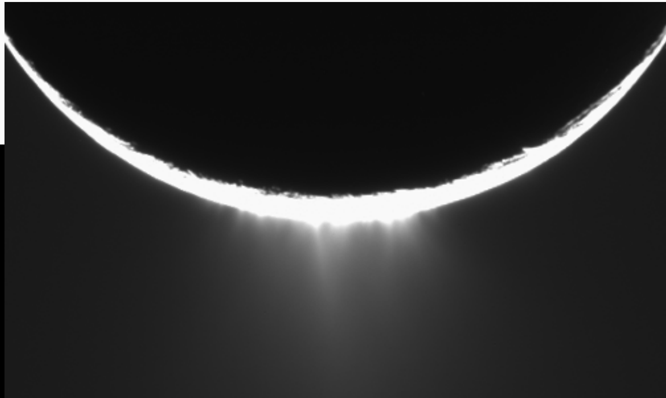
Io from Galileo



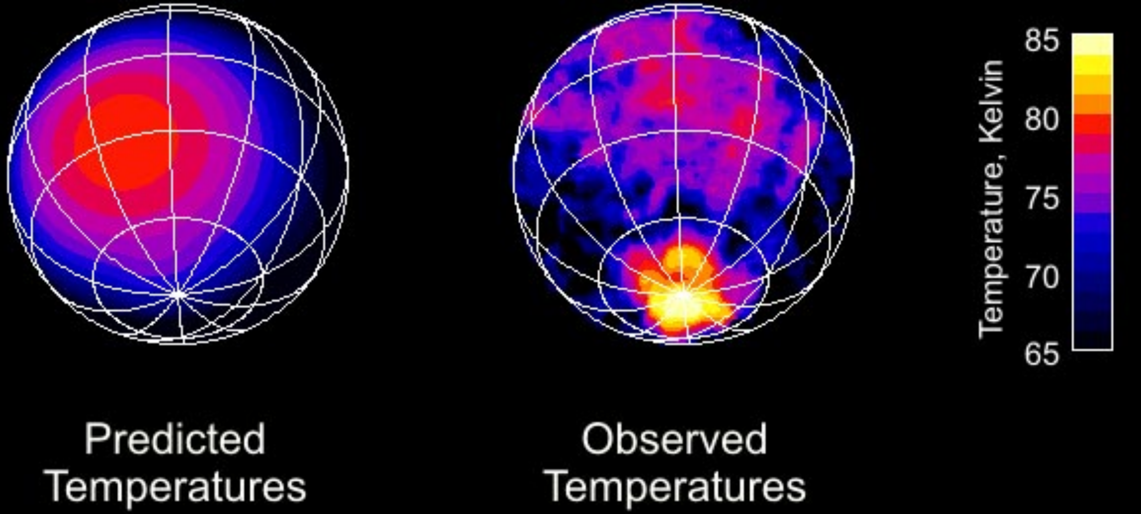






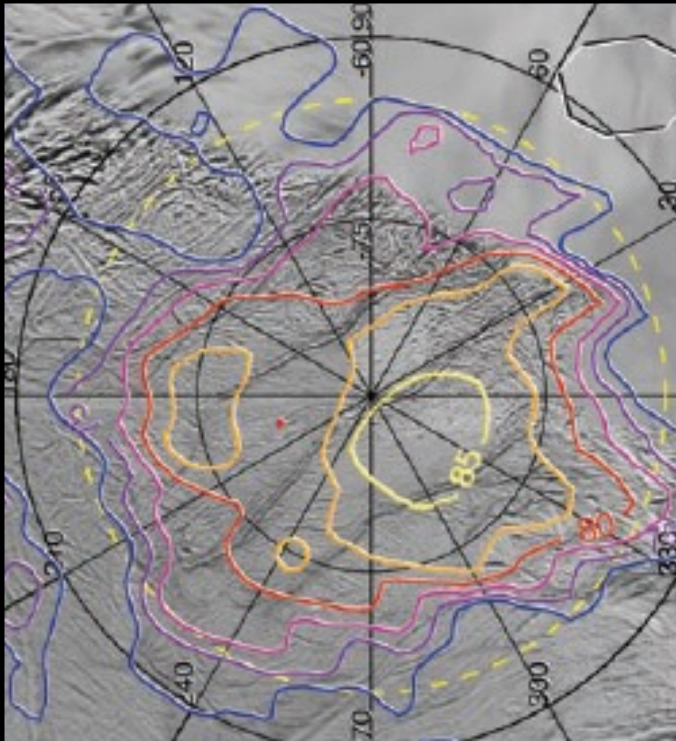


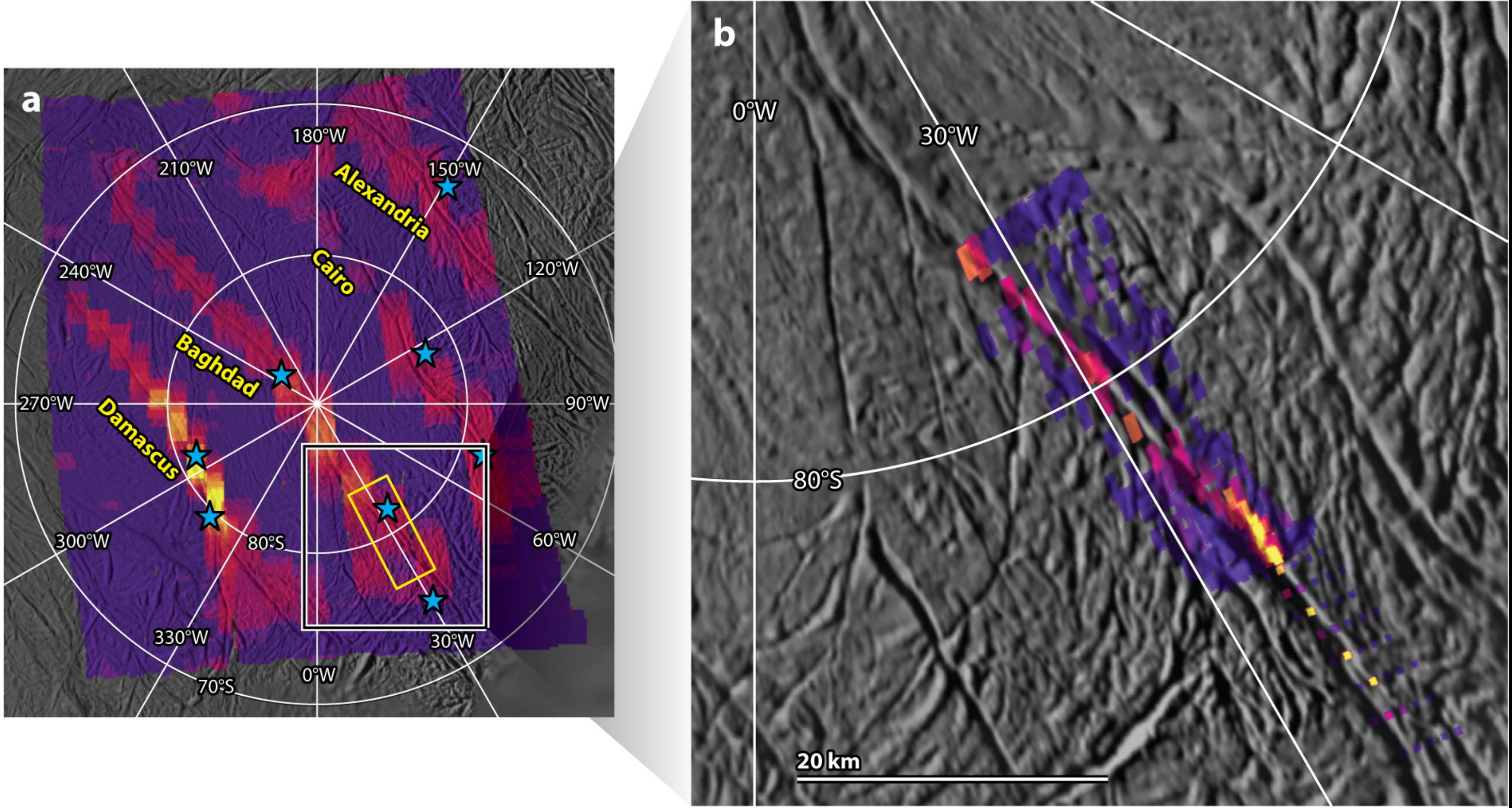
Enceladus - plumes



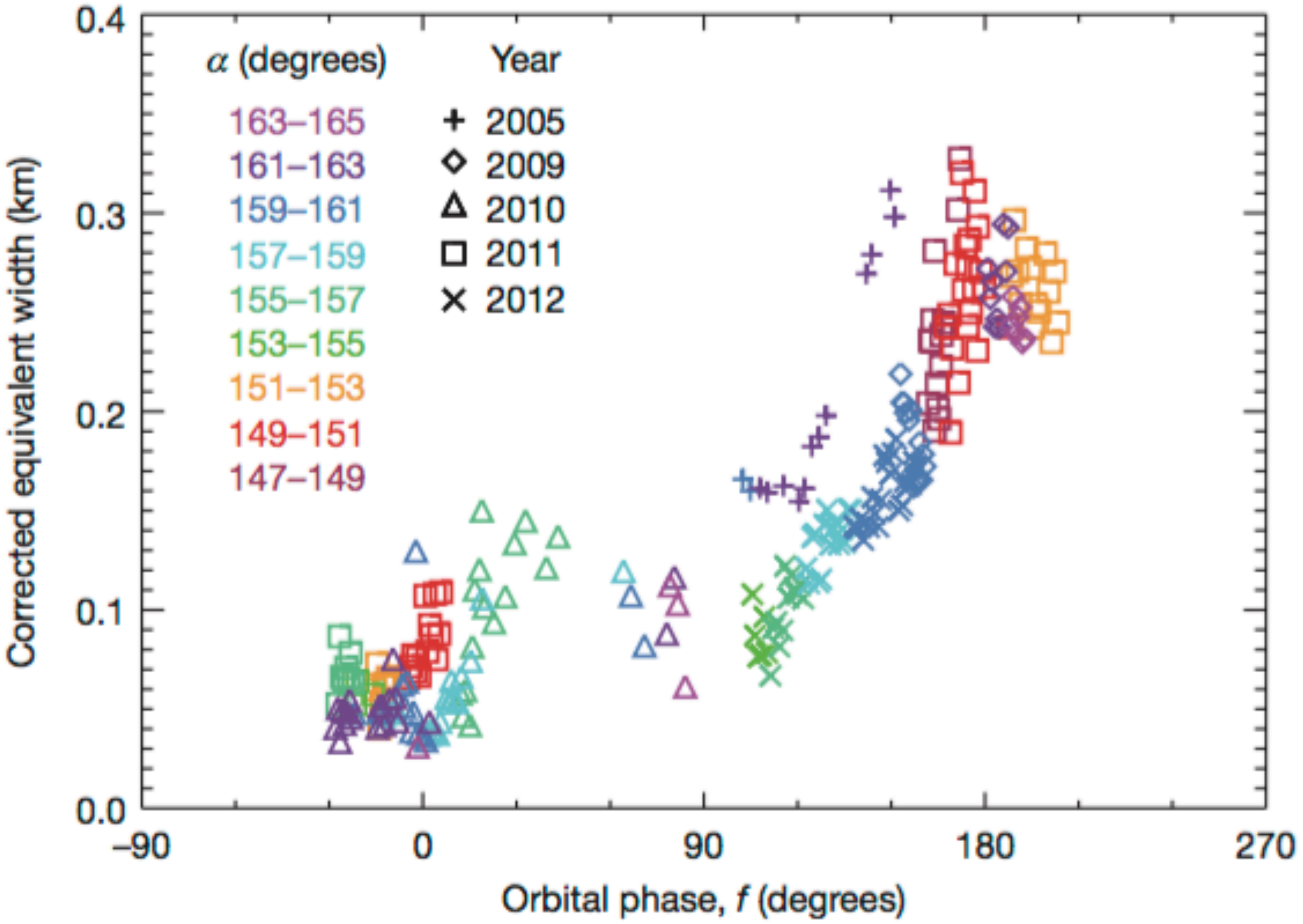
Endogenic activity at Enceladus’ South Pole

(Spencer et al., 2006)

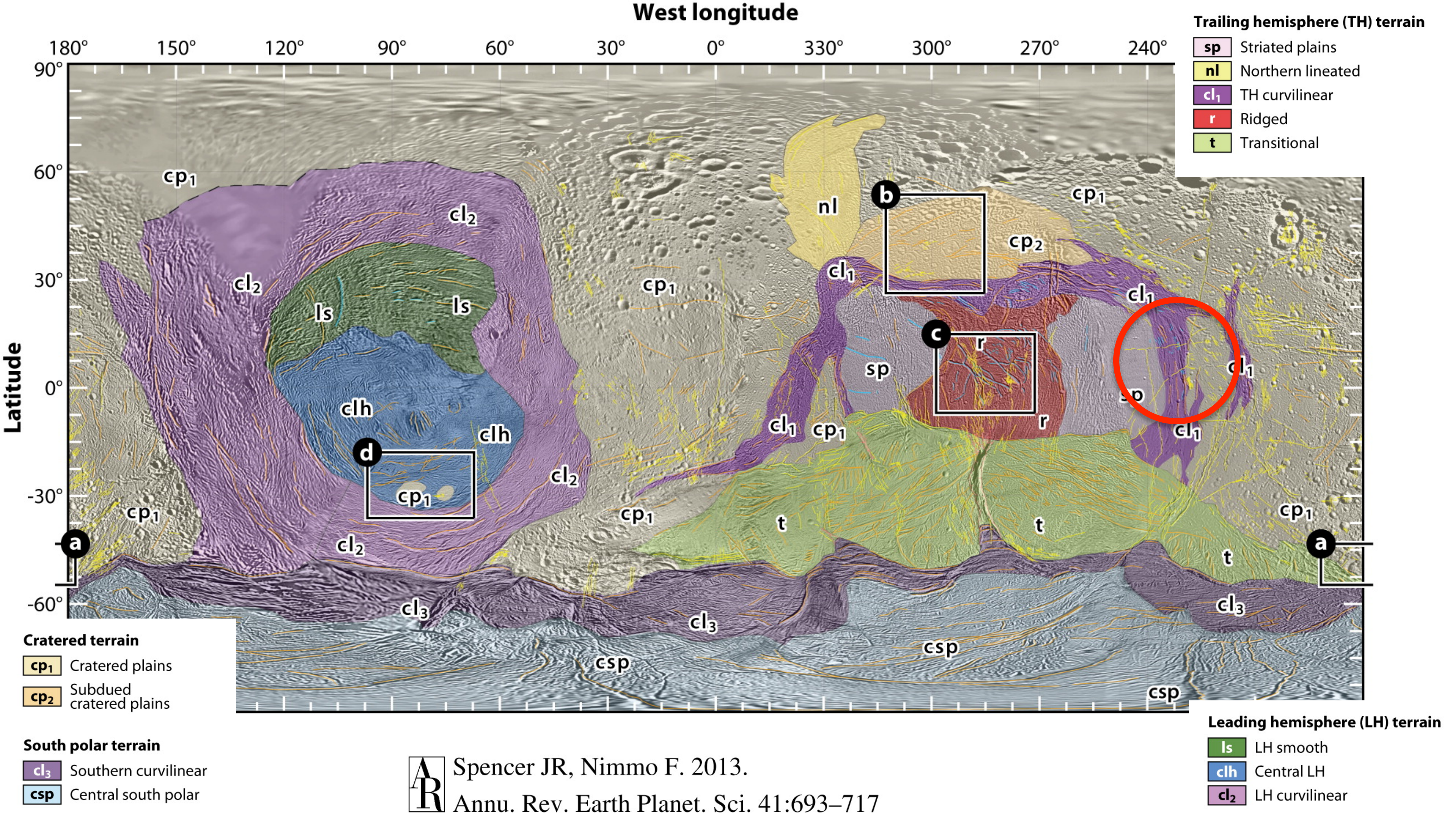




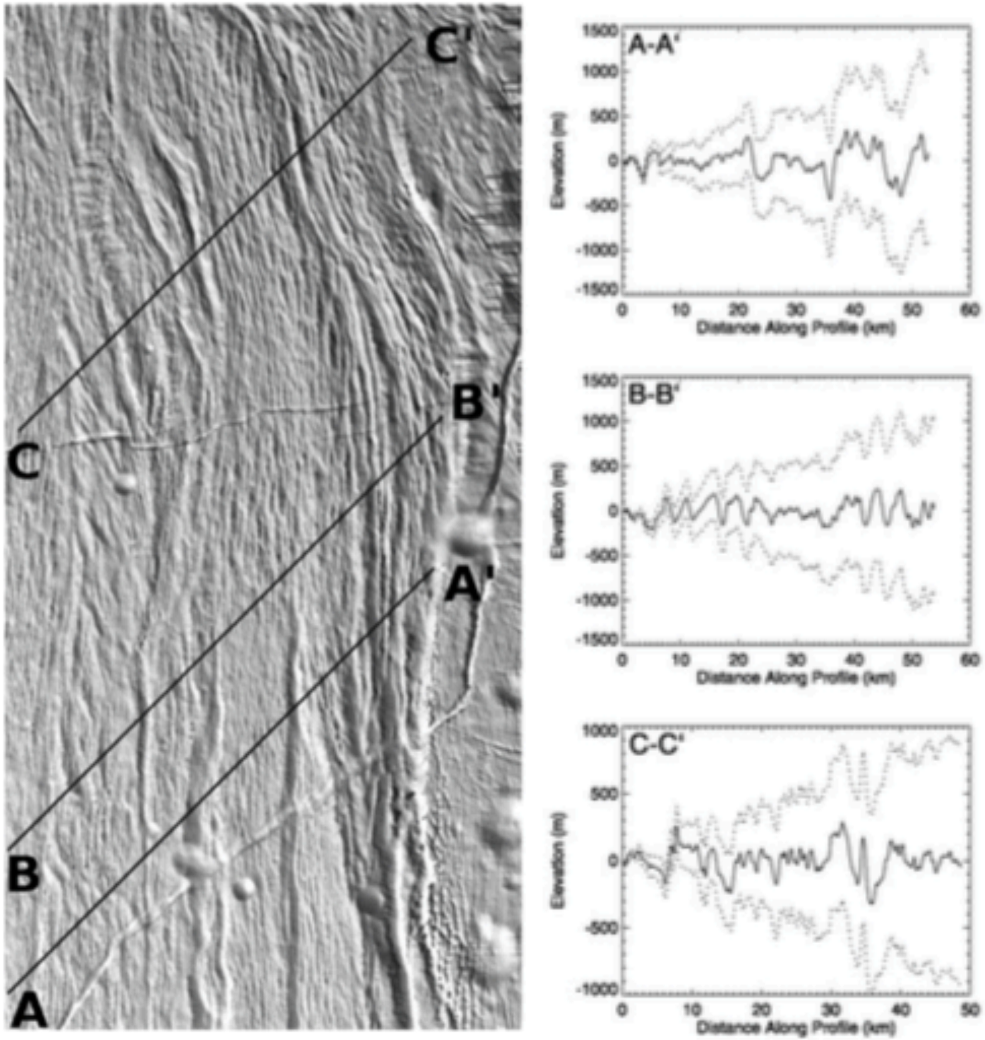
Spencer JR, Nimmo F. 2013.
Annu. Rev. Earth Planet. Sci. 41:693–717



Correlation between plume activity and tidal stress (Hedman et al., 2013)



Spencer JR, Nimmo F. 2013.
Annu. Rev. Earth Planet. Sci. 41:693–717



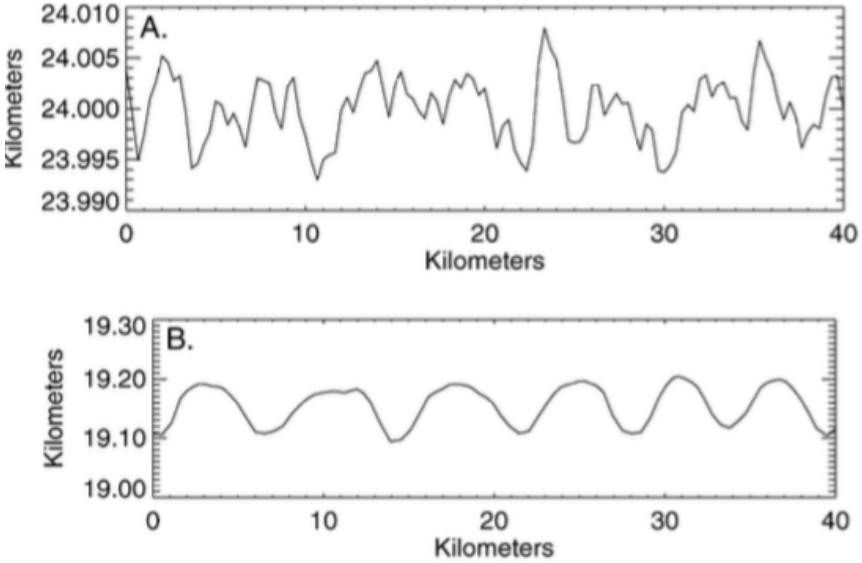
Diyar Planitia Ridges

λ=3-4 km; A=100-400 m

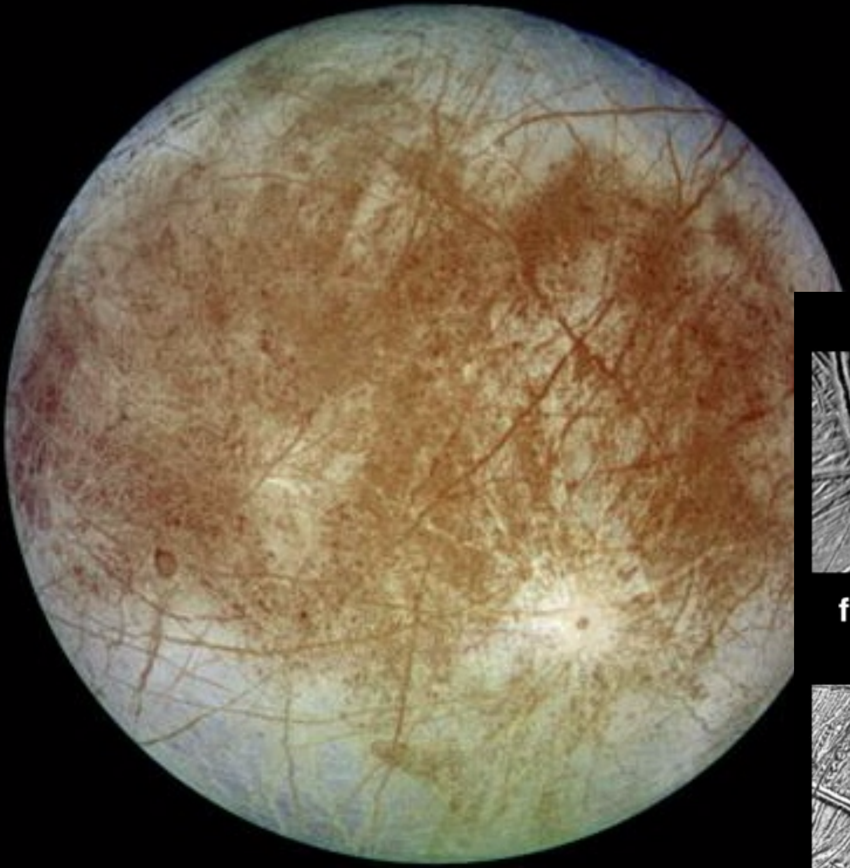
Heat flow 110-220 mWm^{-2}

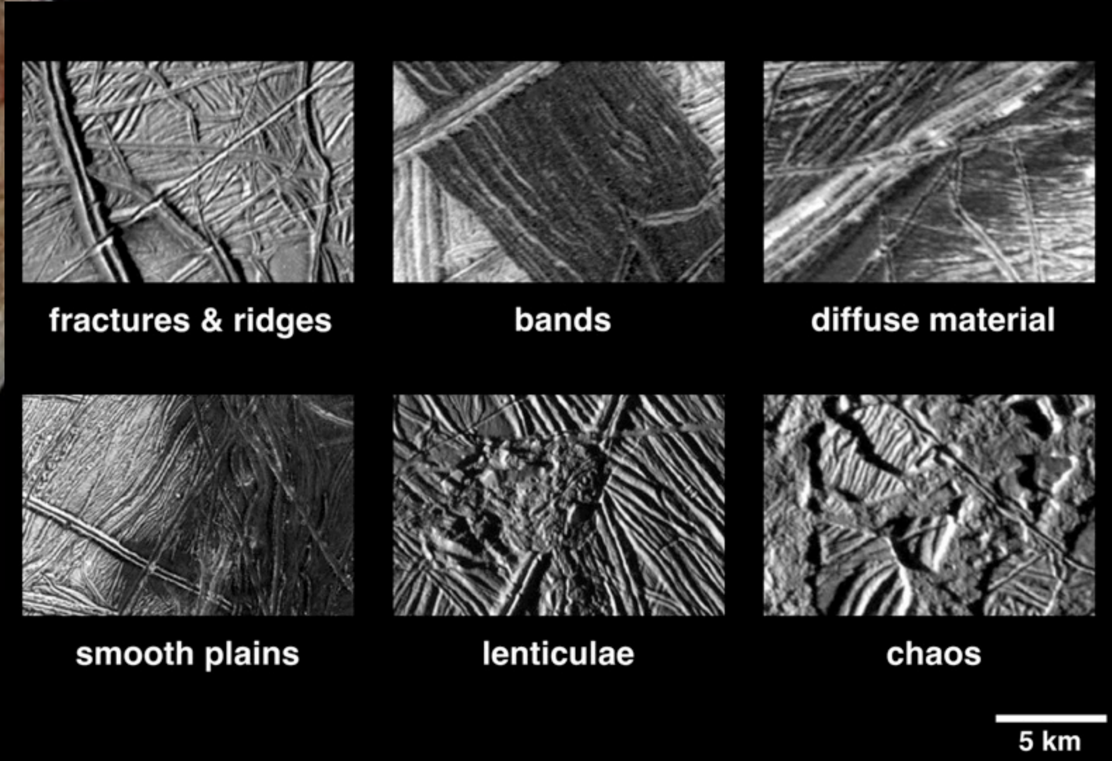
Elastic thickness 0.4-1.4 km

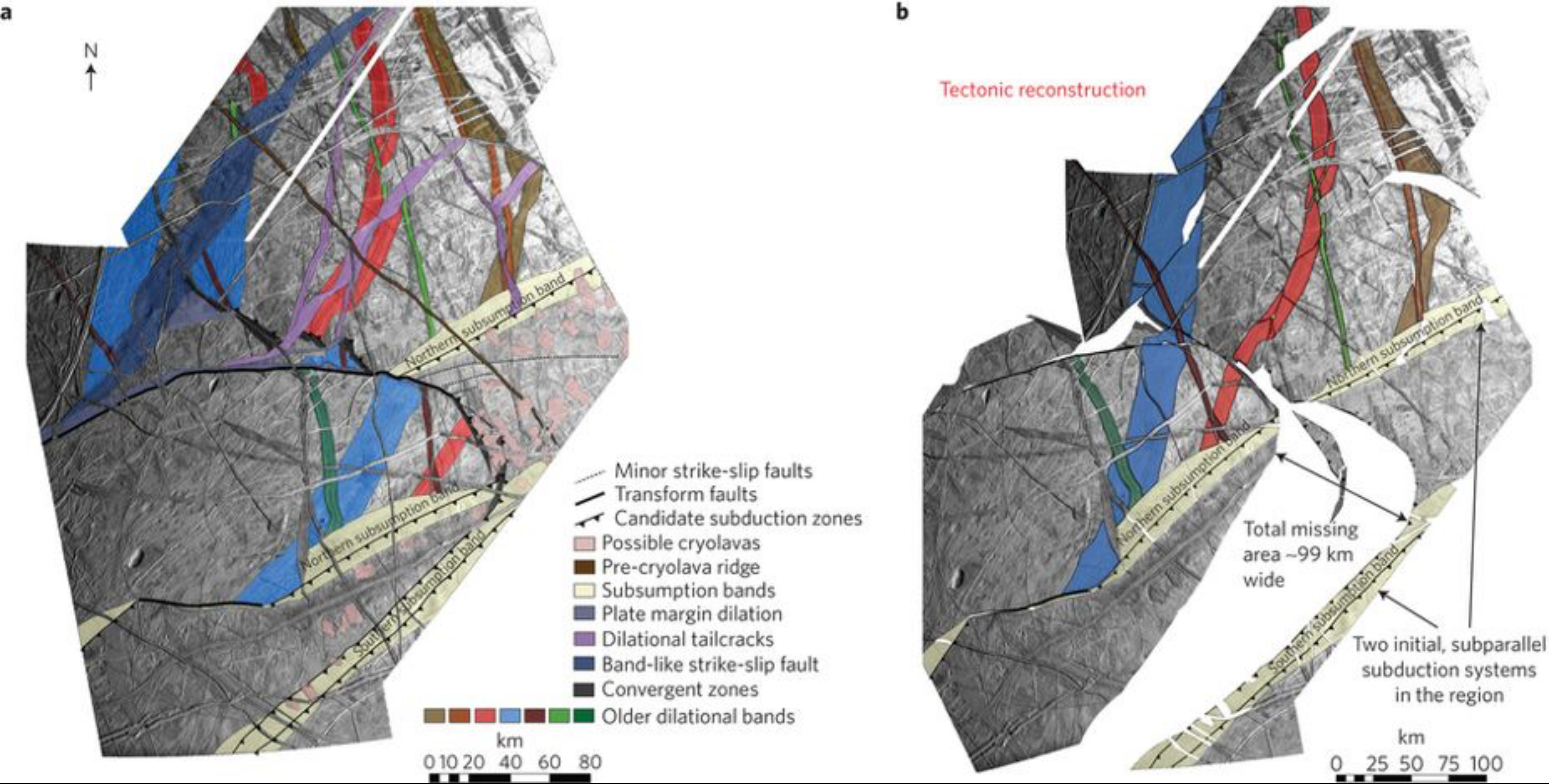
Bland, et al. (2007)



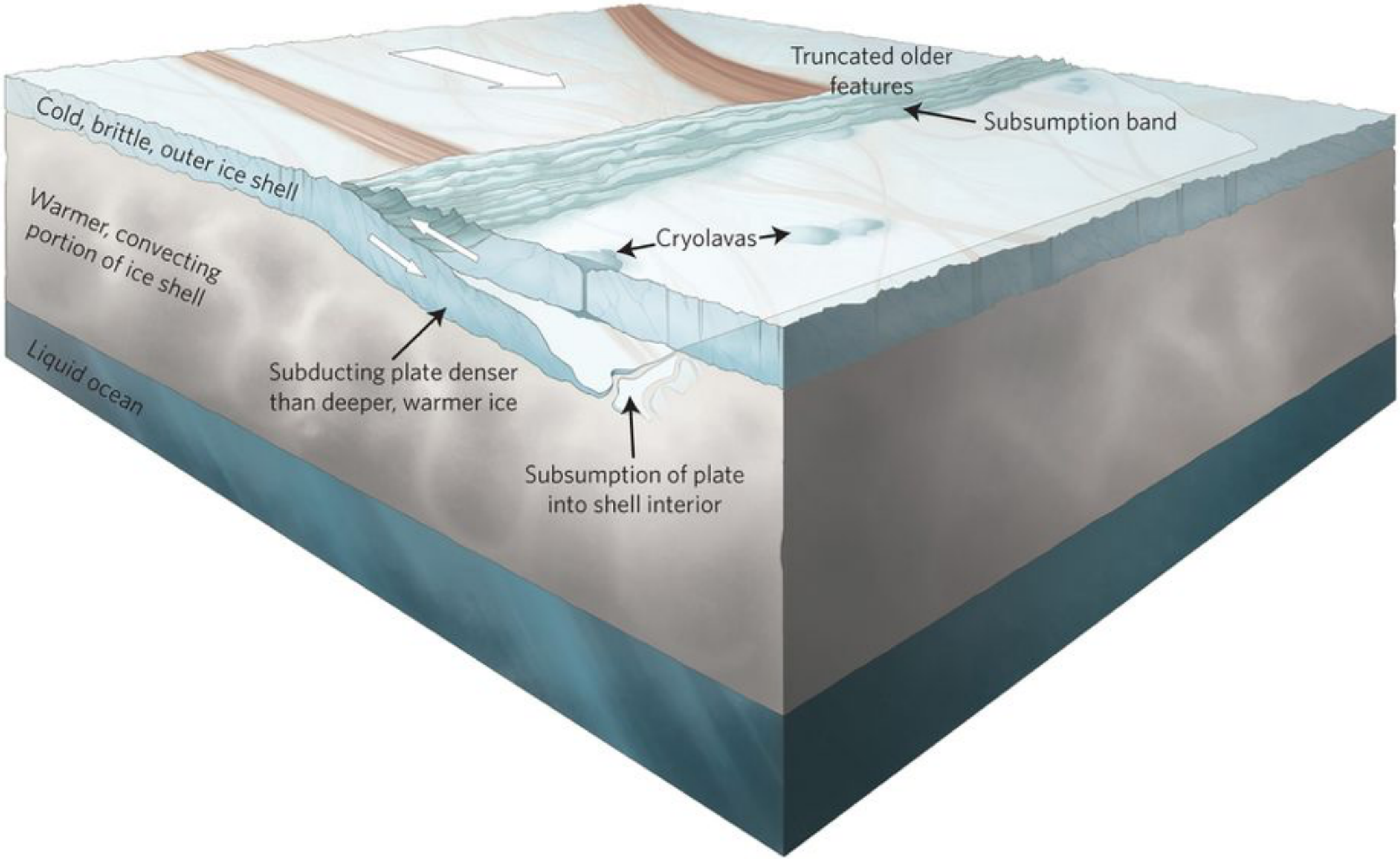
Europa



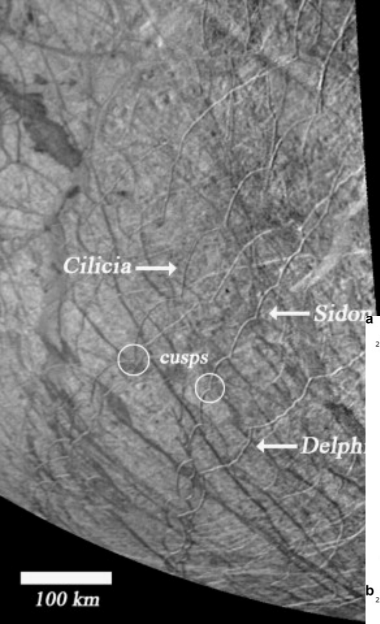

fractures & ridges
bands
diffuse material
smooth plains
lenticulae
chaos
5 km

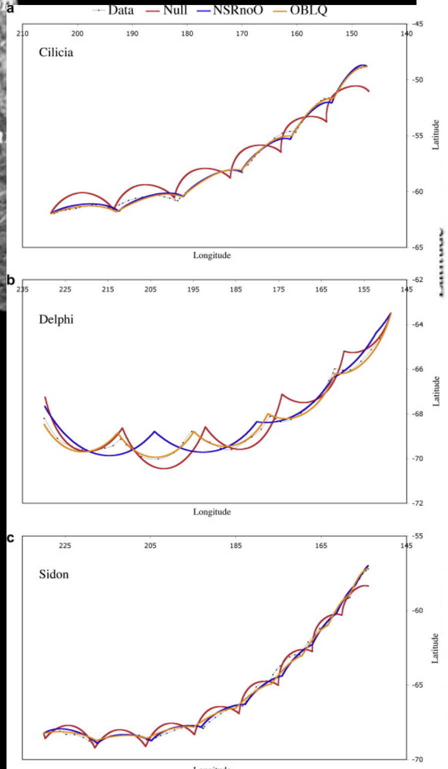


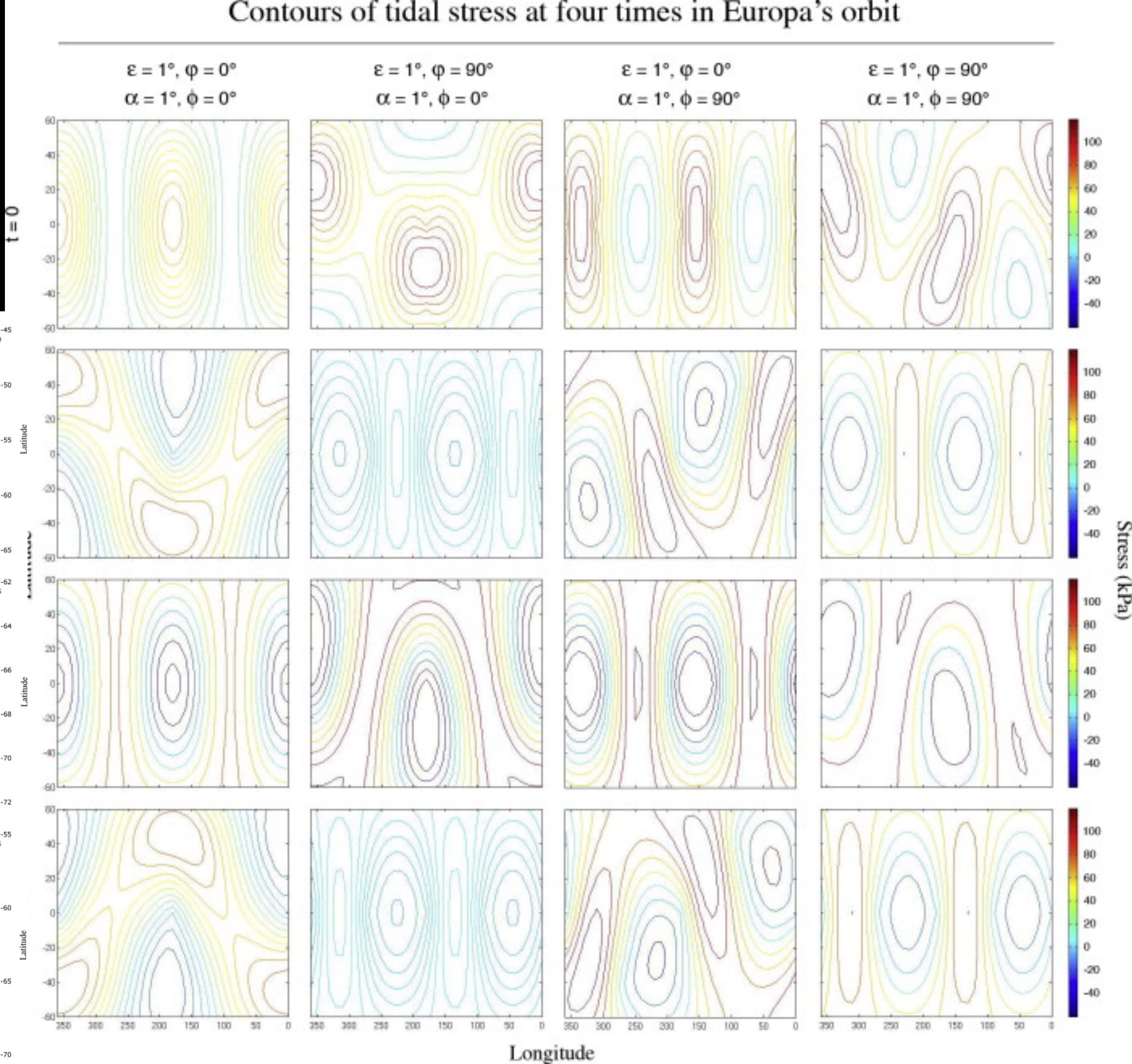
a
N
Northern subsumption band
Northern subsumption band
Southern subsumption band
Minor strike-slip faults
Transform faults
Candidate subduction zones
Possible cryolavas
Pre-cryolava ridge
Subsumption bands
Plate margin dilation
Dilational tailcracks
Band-like strike-slip fault
Convergent zones
Older dilational bands
km
0 10 20 40 60 80
b
Tectonic reconstruction
Northern subsumption band
Northern subsumption band
Northern subsumption band
Southern subsumption band
Total missing area ~99 km wide
Two initial, subparallel subduction systems in the region
km
0 25 50 75 100



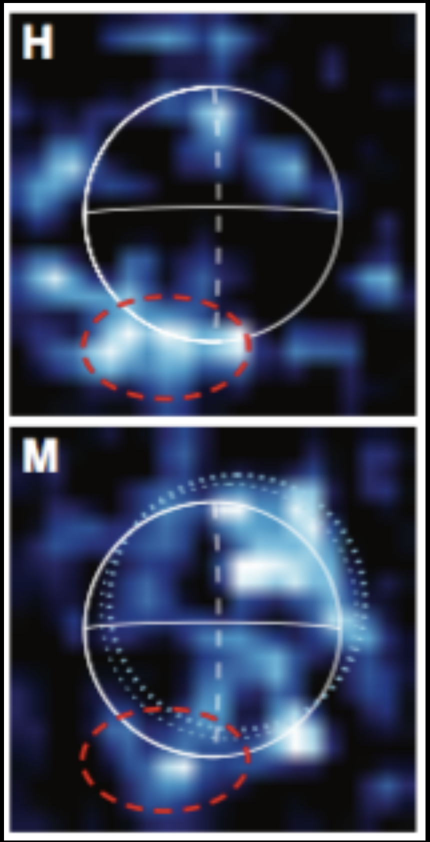
Truncated older features
Subsumption band
Cold, brittle, outer ice shell
Warmer, convecting portion of ice shell
Cryolavas
Liquid ocean
Subducting plate denser than deeper, warmer ice
Subsumption of plate into shell interior

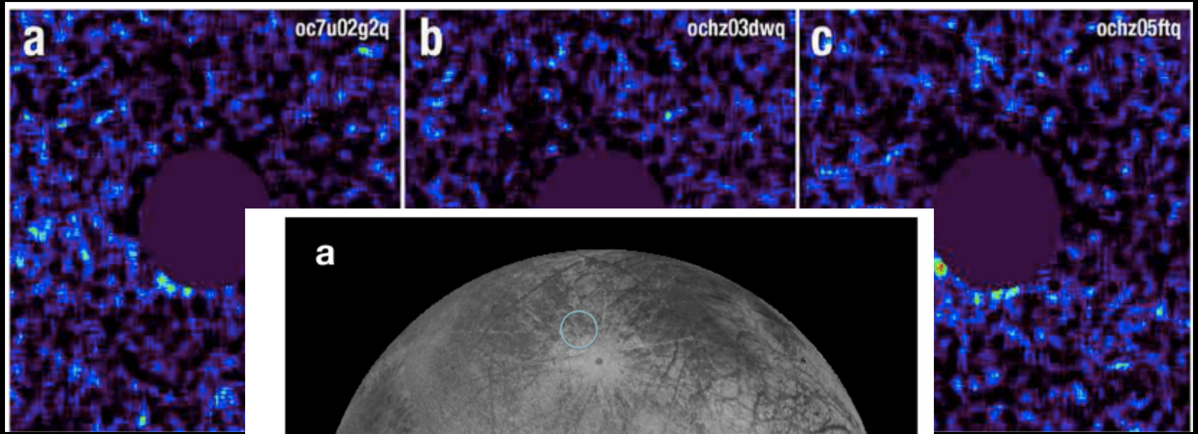

Cilicia
Sidon
cusps
Delphi
100 km

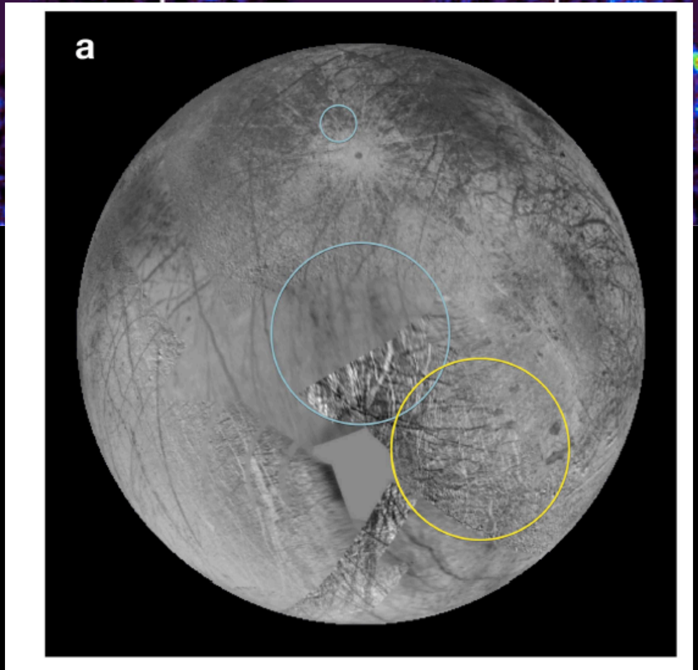

Data
Null
NSRnoO
OBLQ
a
Cilicia
b
Delphi
c
Sidon
Longitude
Latitude


Contours of tidal stress at four times in Europa's orbit
ε = 1°, φ = 0°
α = 1°, ϕ = 0°
ε = 1°, φ = 90°
α = 1°, ϕ = 0°
ε = 1°, φ = 0°
α = 1°, ϕ = 90°
ε = 1°, φ = 90°
α = 1°, ϕ = 90°
t = 0
Stress (kPa)
Longitude

HST observations of putative plumes

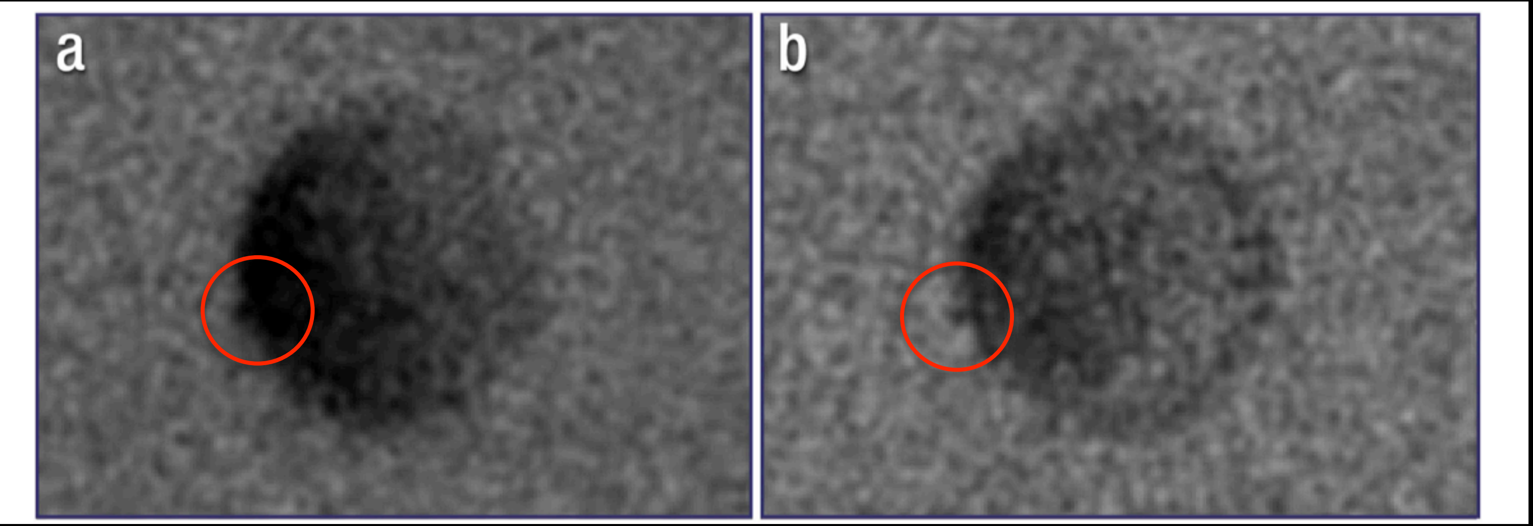






Sparks, et al. Findings

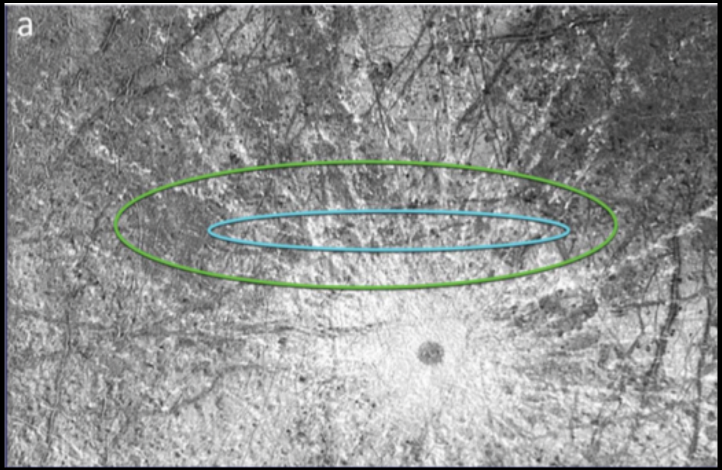
2014 March 17 (Paper 1) 2016 February 22 (Paper 2)

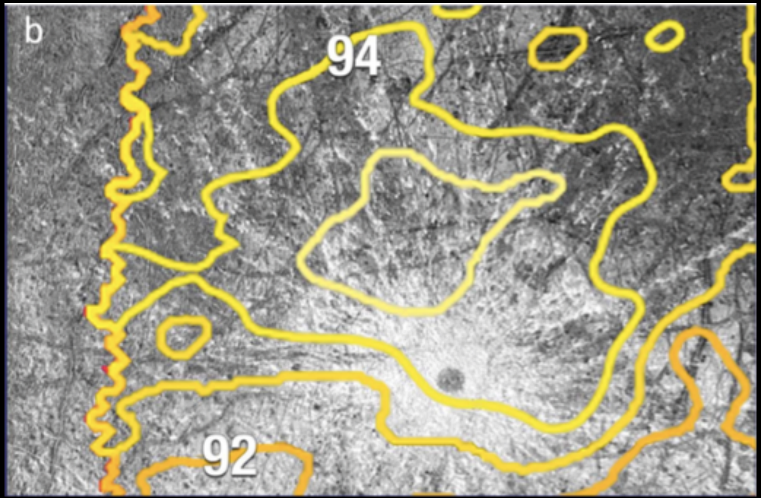


A second event at the same location as previous detection !!

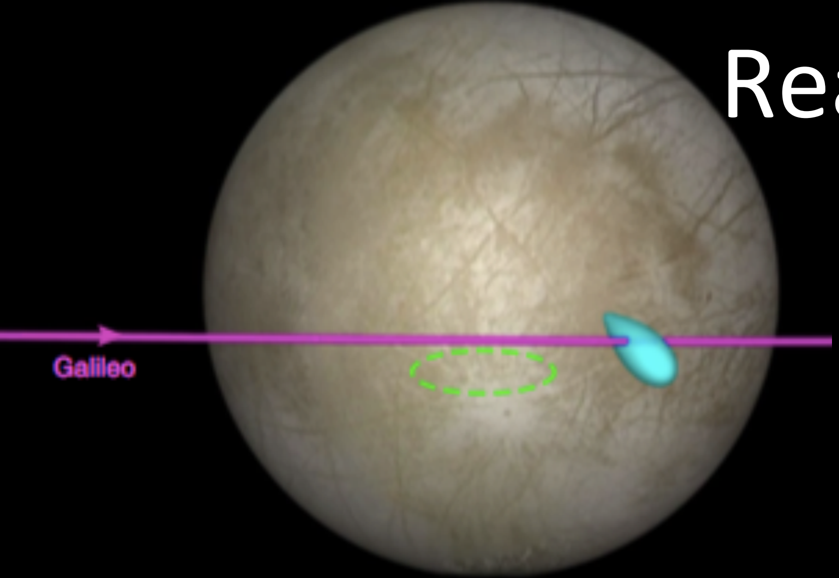
Comparison with PPR observations

- PPR nighttime thermal anomaly in same location (E17, open filter)

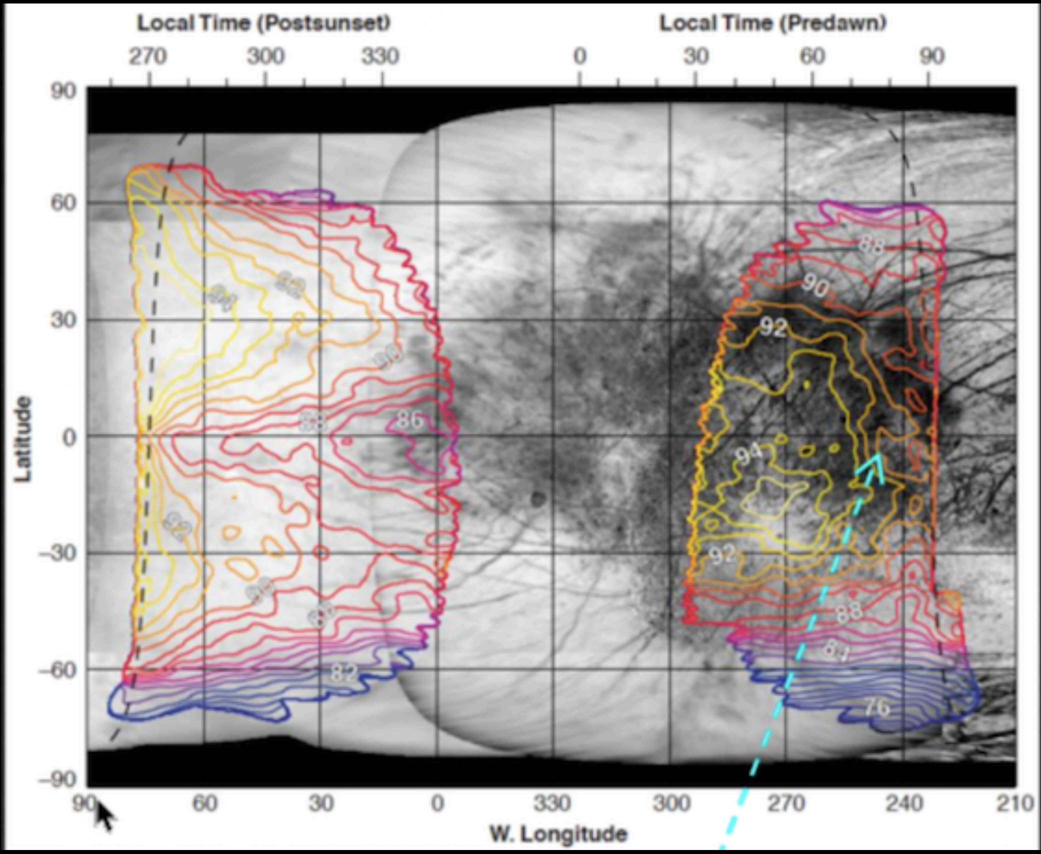




Reanalysis of Galileo data

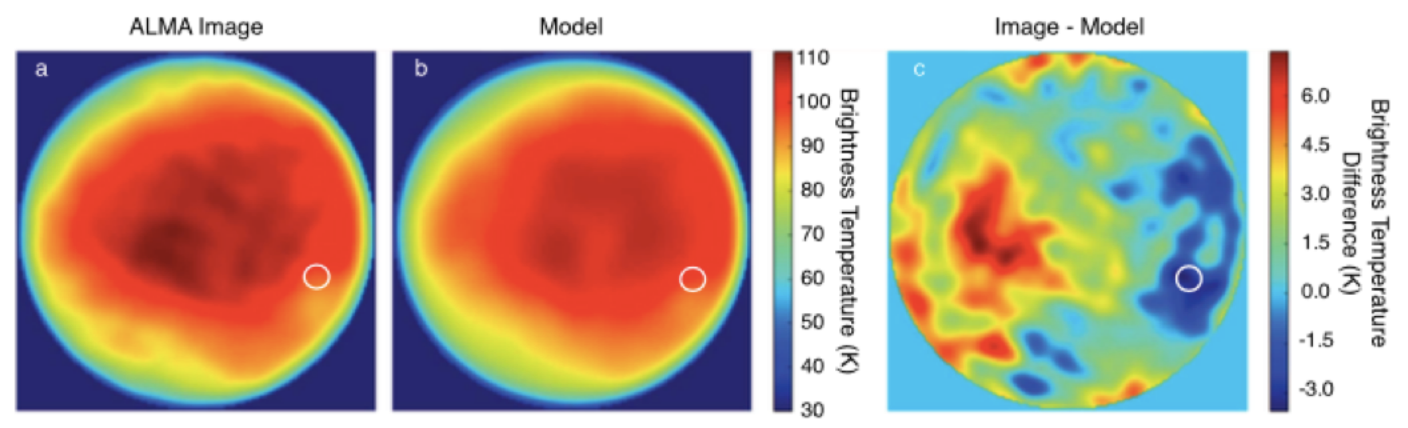


- Jia et al., 2018 found location is ~1000 km NE of Sparks plume location



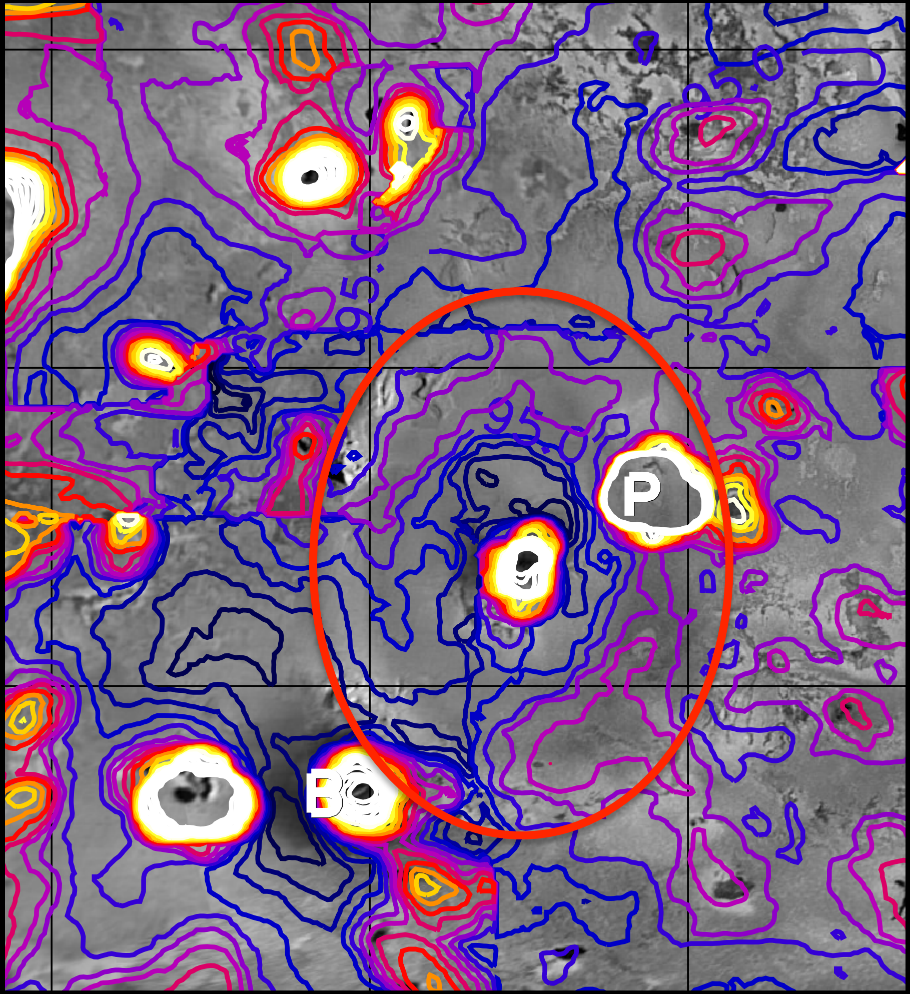
Europa plumes/hotspot?

- Thermal model fits to best thermal data available (including ground-based) do NOT require endogenic heating
  - PPR nighttime thermal anomaly in Sparks location is cold during the daytime (Trumbo et al. 2017) → thermal inertia anomaly



Plume?

- Nighttime temperatures of Io's Pele plume deposit higher than background
  - Different material
- Suggests higher thermal inertia in plume fallout
- No thermal inertia anomaly in the Jia location

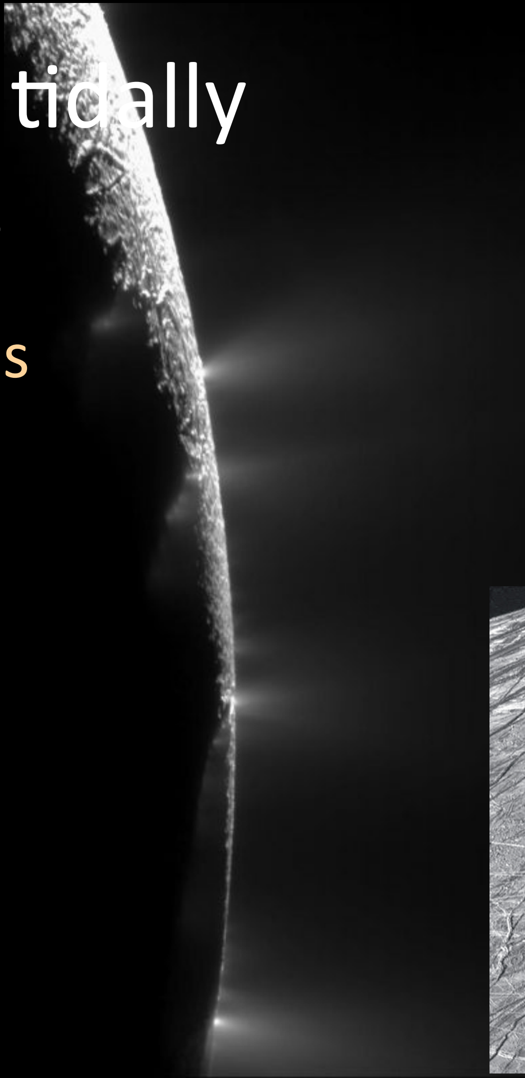


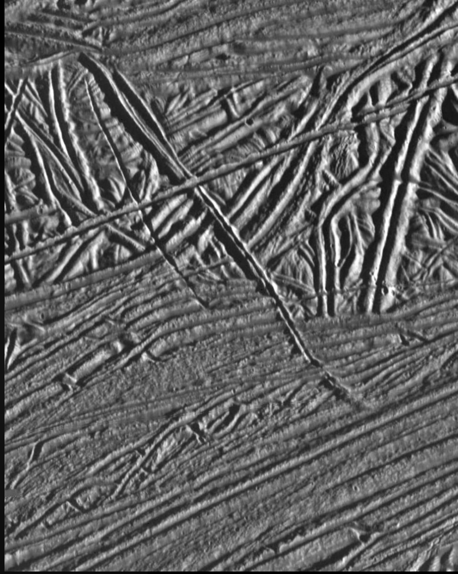
Could a hotspot be hiding? (Rathbun, in prep.)

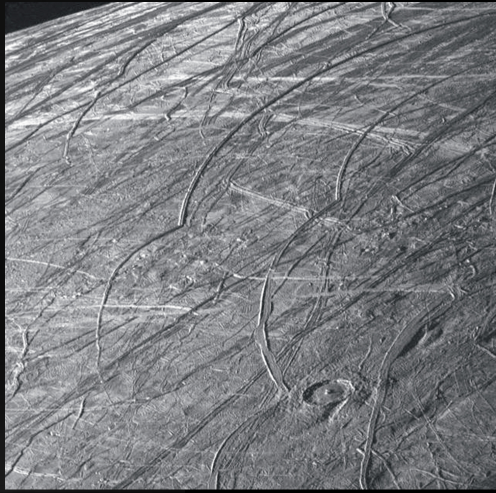
	Radius (km)	**Area (km^2)**	Temperature (K)	Brightness
ALMA observation at 1.3 mm, Brightness in W/m/str				
Background fov	156	2.4×10^4	120 (emis corr.)	0.8
Model Hotspot	10	100	200	6×10^{-3}
PPR nighttime observation in open filter, Brightness in GW				
Background fov	45	2.0×10^3	95	9.2
Model Hotspot	10	100	170	4.7
Model "tigerstripe"	120 km long	86	133	1.5
PPR detection limits			2-5 GW	

Geologic features on tidally heated worlds

- Thermal (endogenic) sources
- Plumes
- Ridges, bands
- Cycloids
- Volcanic flows
- Cryovolcanic flows?

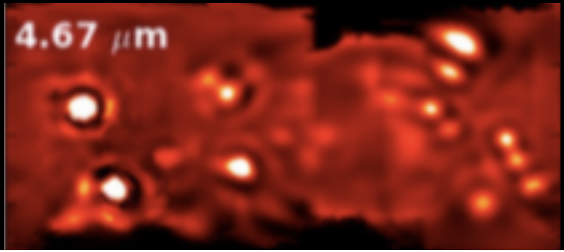


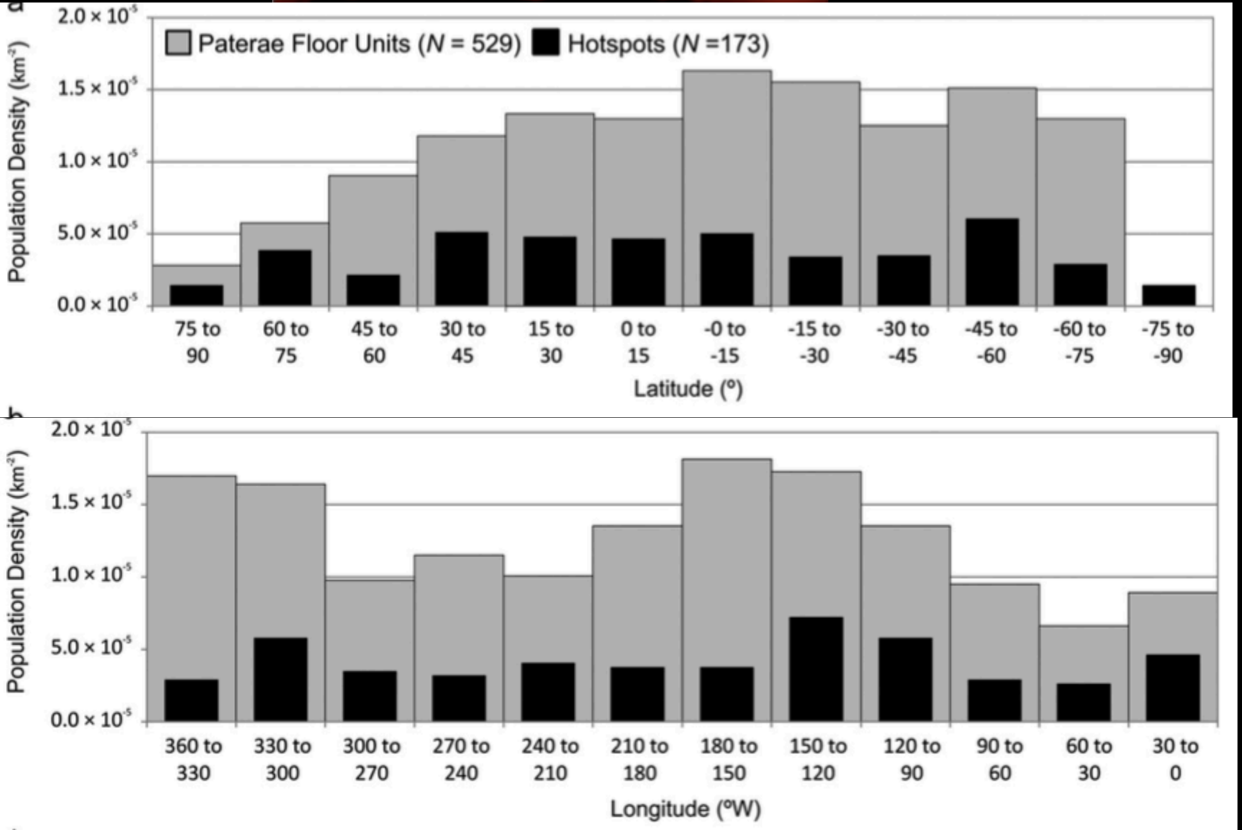




Q2: How do tides influence global heat flow and its variations (spatial and temporal), and how does this heat translate into specific geologic processes?

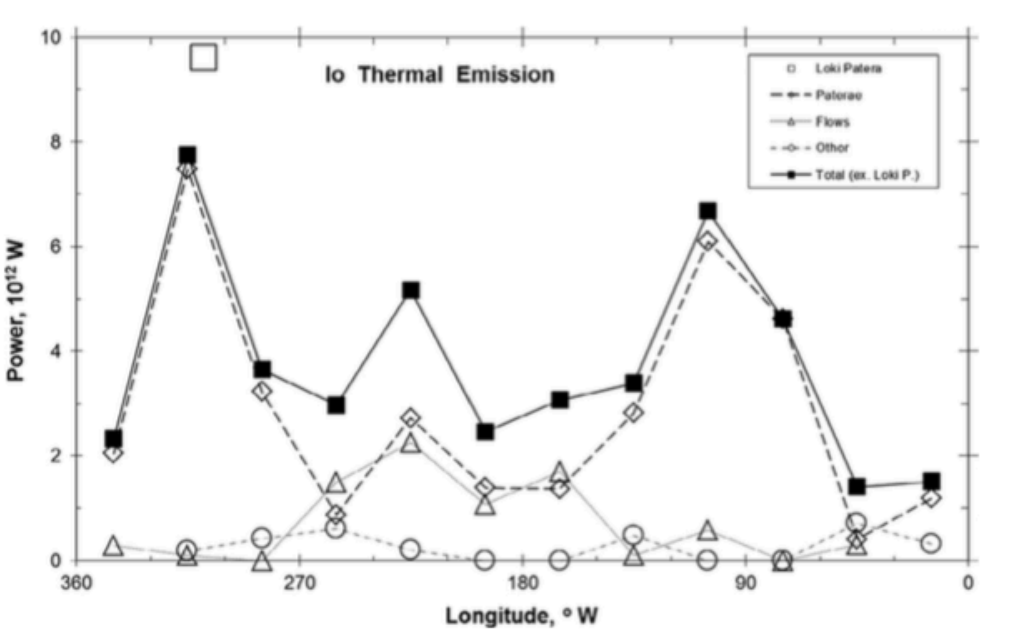
Back to Io: clearest signature of tidal heating

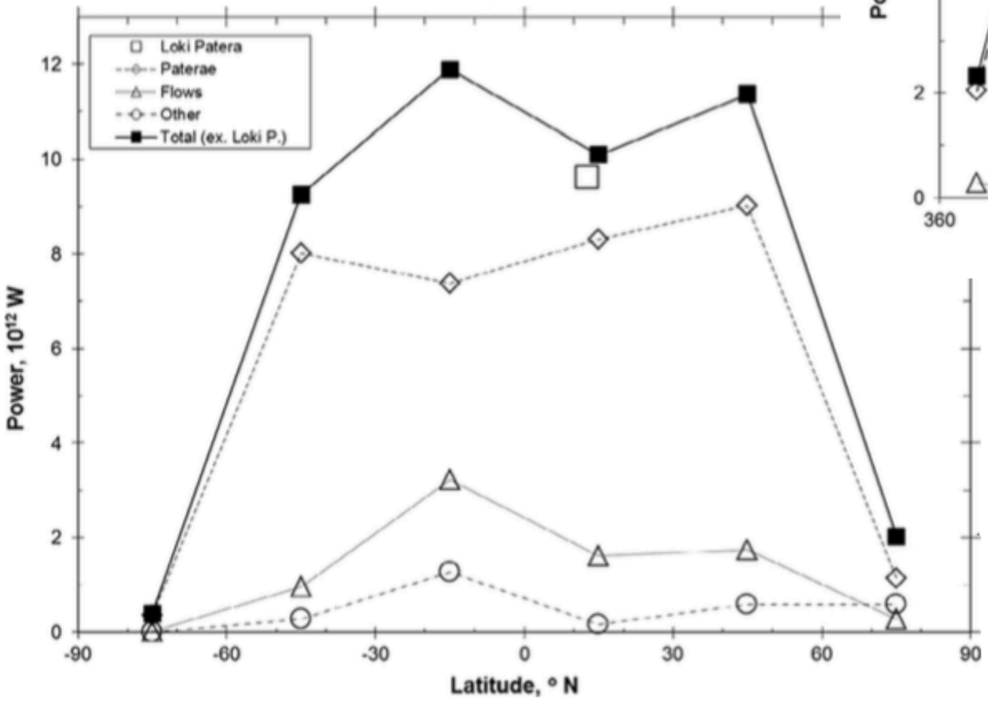




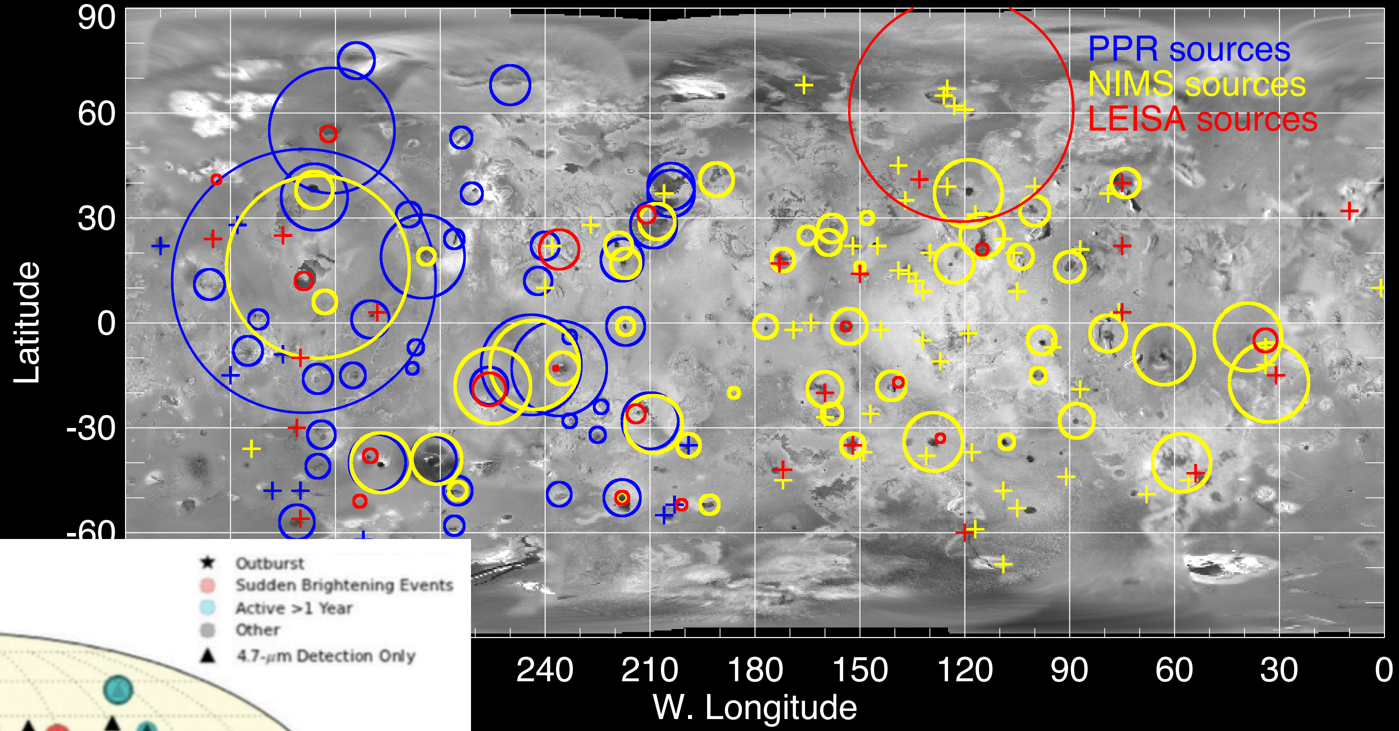
Assume distribution of volcanoes or volcanic output mimics heat flow

Hamilton, et al., 2013

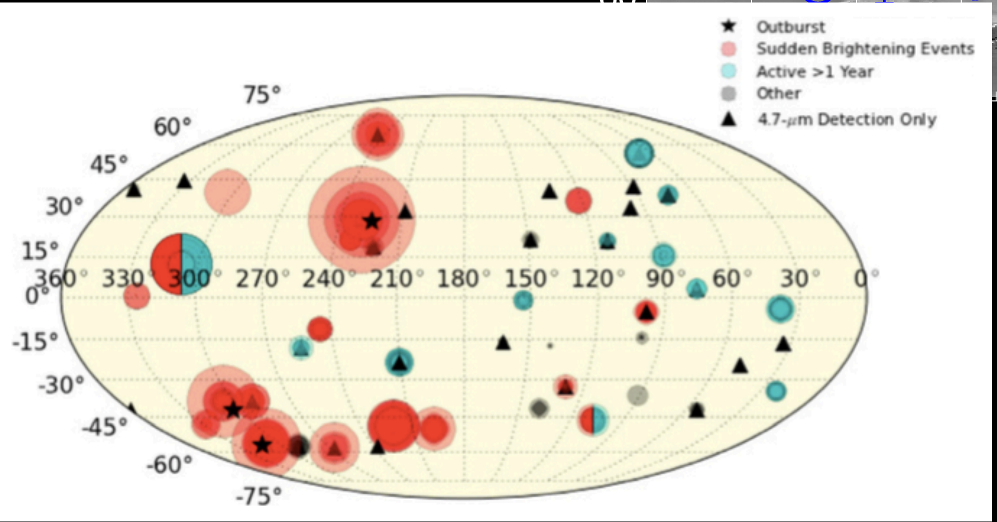




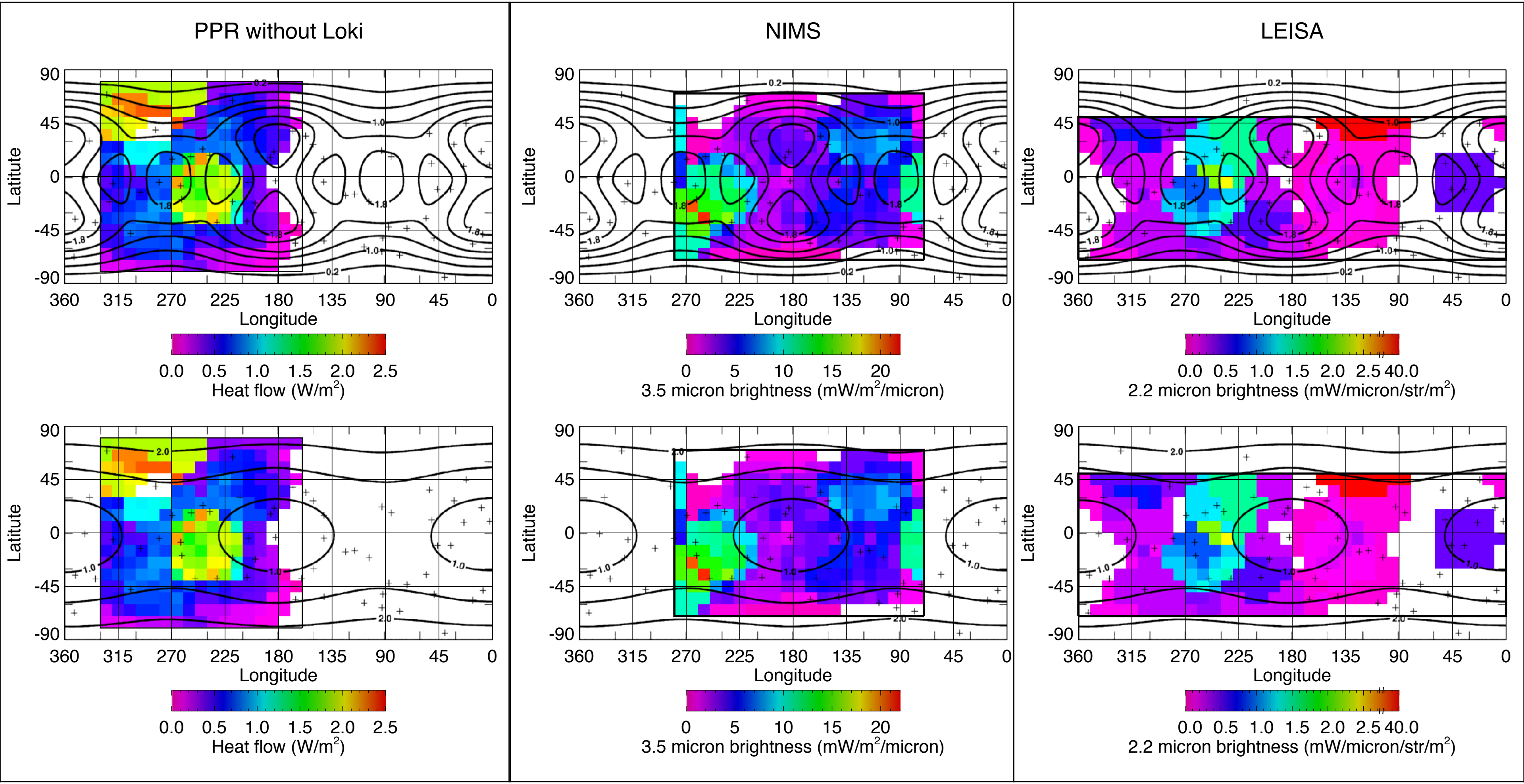
Veeder et al., 2015

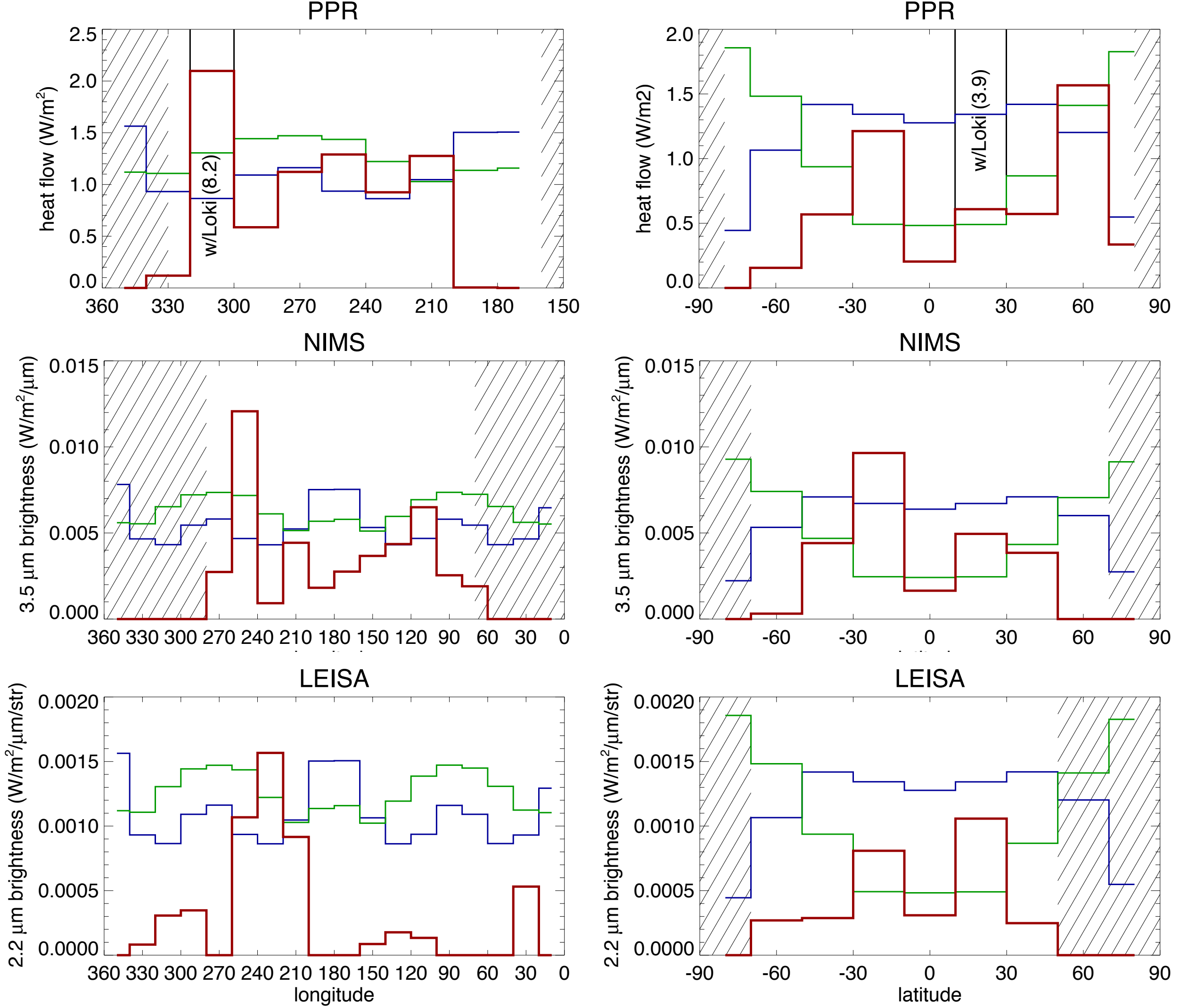


Rathbun et al., 2018

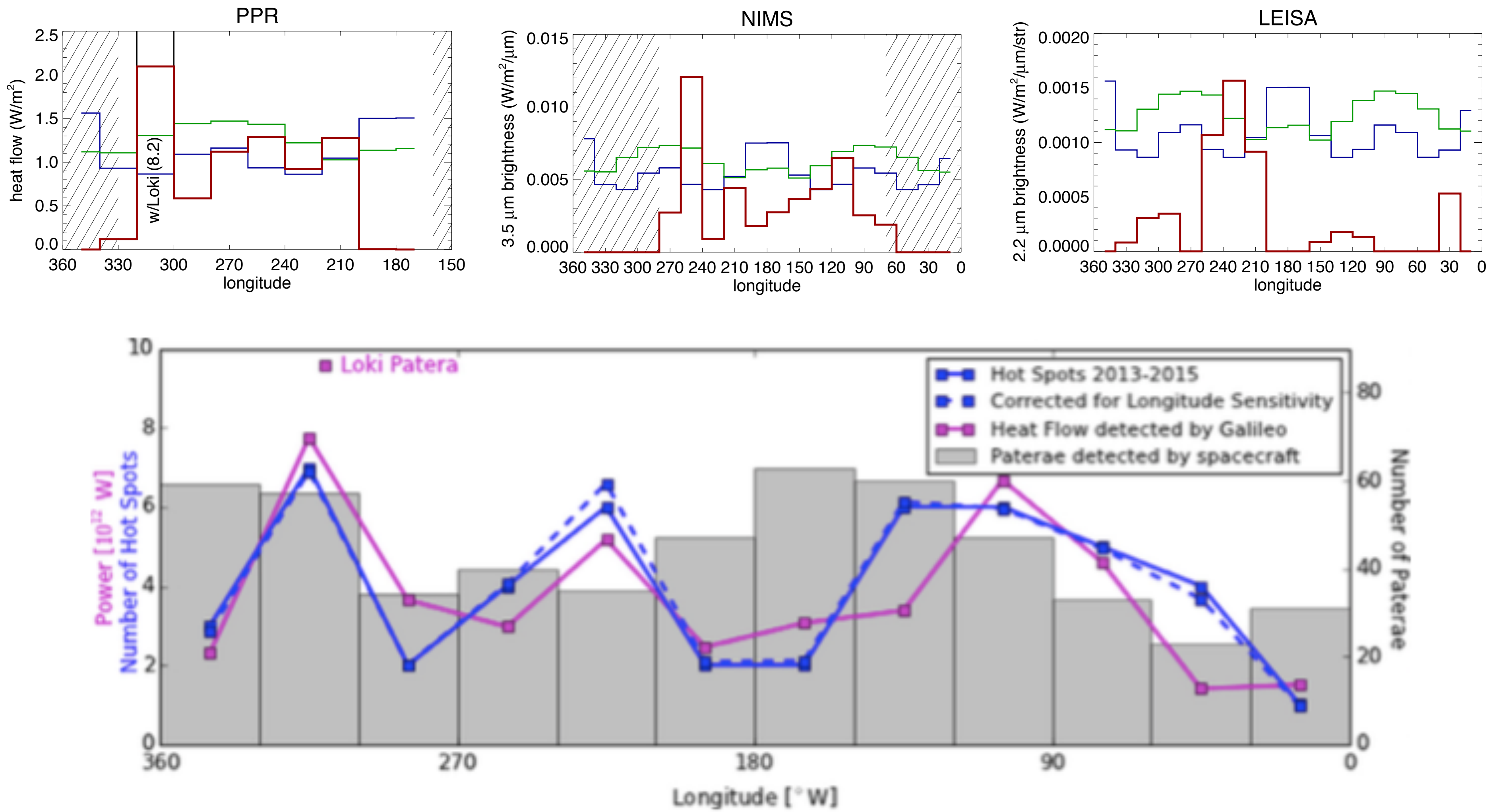


de Kleer and de Pater, 2016

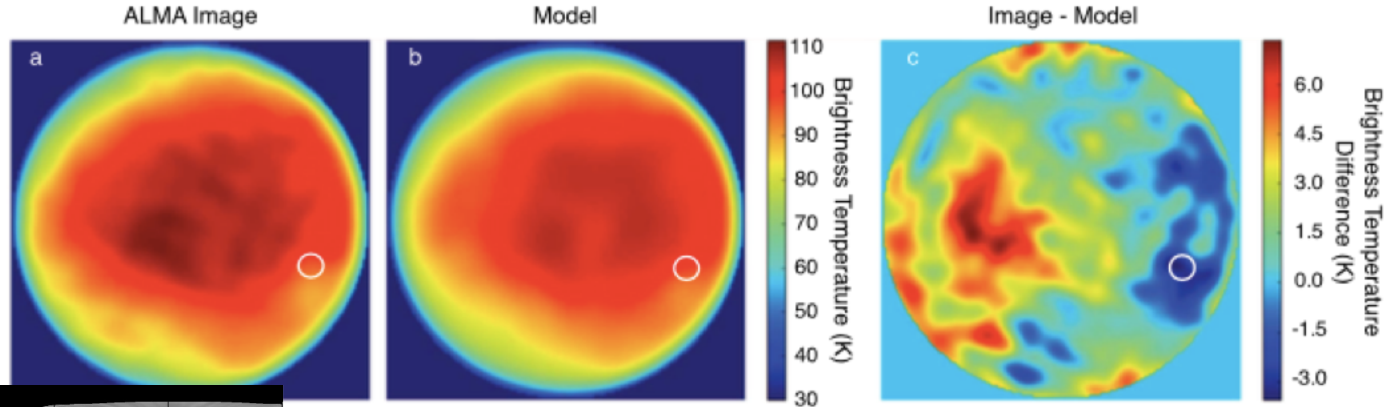

PPR without Loki
NIMS
LEISA
Latitude
Longitude
90 45 0 -45 -90
360 315 270 225 180 135 90 45 0
0.2
1.0
1.8
2.0
0.0 0.5 1.0 1.5 2.0 2.5
Heat flow (W/m²)
0 5 10 15 20
3.5 micron brightness (mW/m²/micron)
0.0 0.5 1.0 1.5 2.0 2.5 40.0
2.2 micron brightness (mW/micron/str/m²)

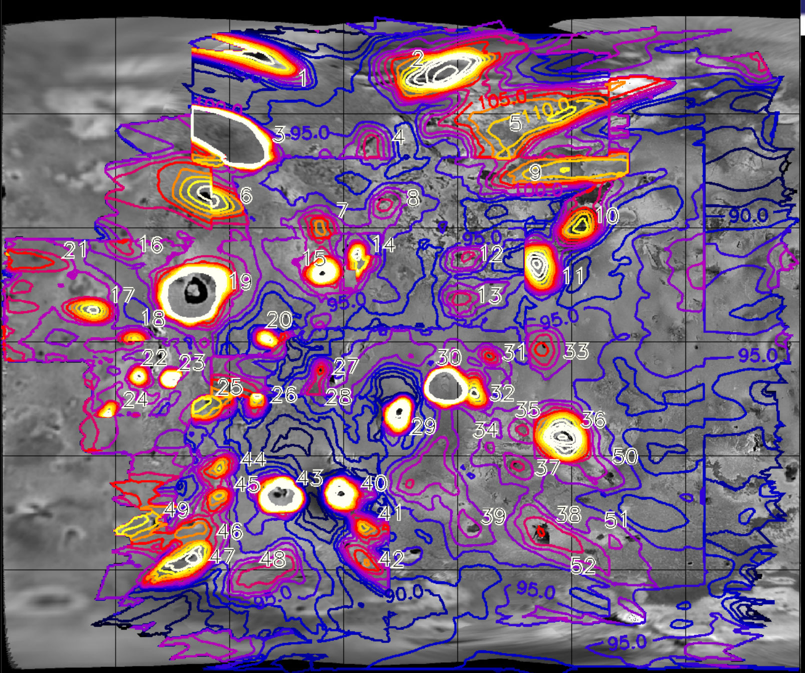


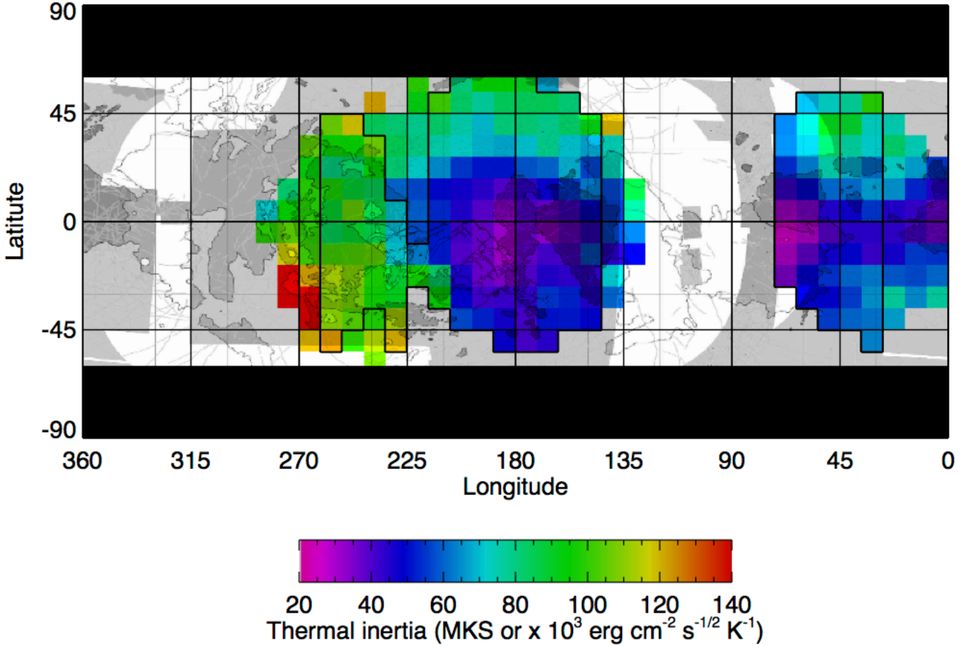
Biggest difference between end-member models is at high latitude, where there are substantial observational biases


PPR
heat flow (W/m^2)
w/Loki (8.2)
longitude
NIMS
3.5 μm brightness (W/m^2/μm)
longitude
LEISA
2.2 μm brightness (W/m^2/μm/str)
longitude
Loki Patera
Hot Spots 2013-2015
Corrected for Longitude Sensitivity
Heat Flow detected by Galileo
Paterae detected by spacecraft
Power [10^{12} W]
Number of Hot Spots
Number of Paterae
Longitude [° W]

Heat flow only







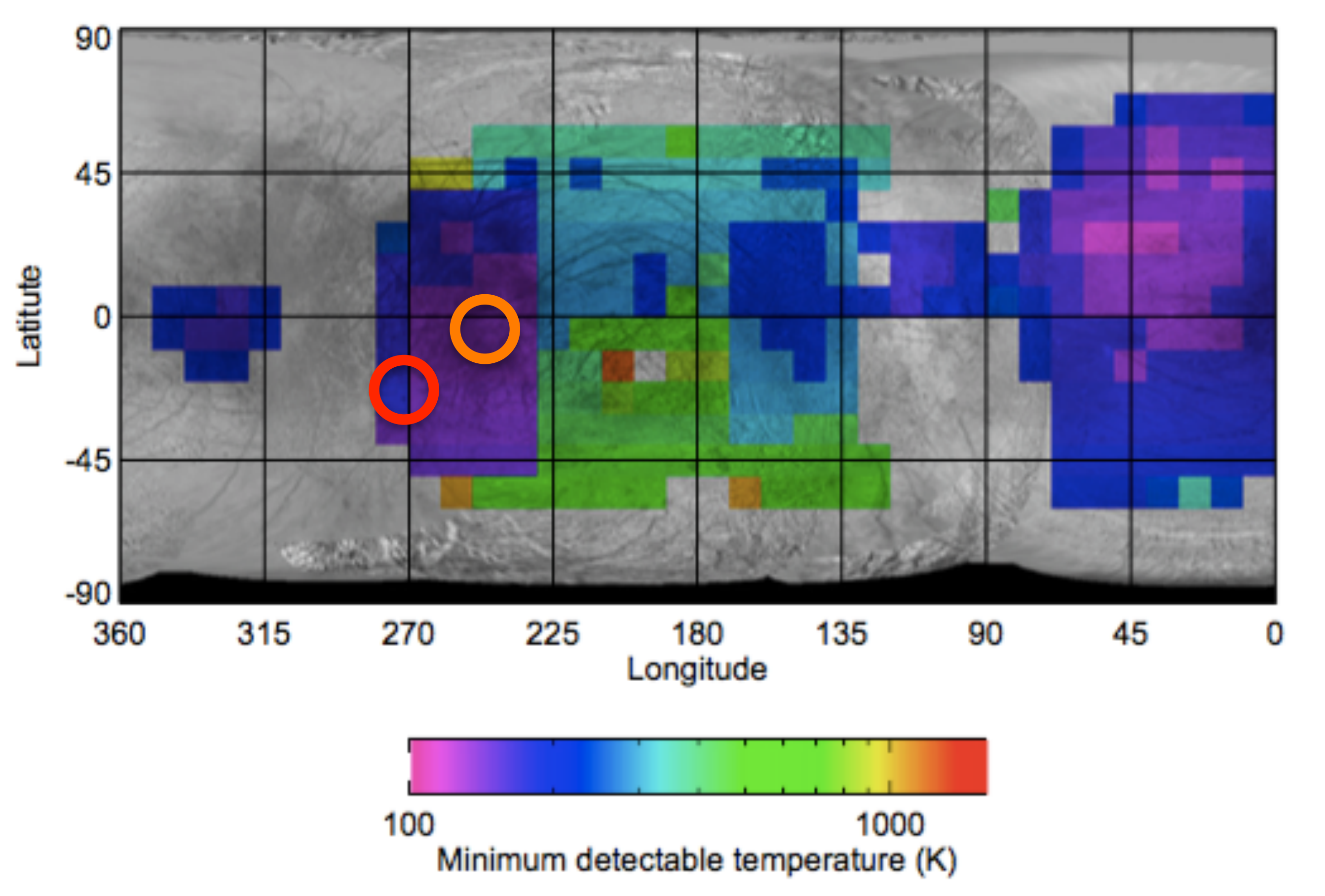
Discussion

- Measurements of Io's volcanic output and heat flow are getting better, but new observations would help
  - Combine ground-based and space-based thermal measurements?
- What observations are best to compare to model results?
  - On Io?
    - Largest tidal heating
    - Relatively easy to observe (spacecraft or ground-based) b/c close to Earth
  - On other Tidally heated worlds?
    - Heat flow?
    - Volcanic brightness?
    - Other?

Back-up slides

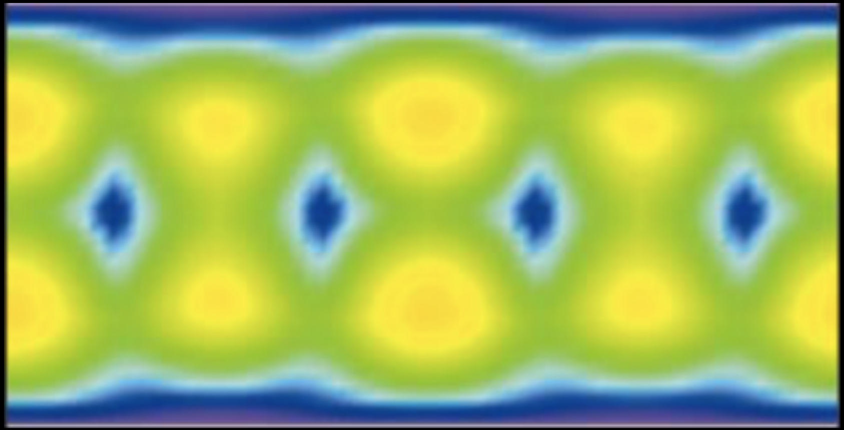
Hotspot limits from PPR data

- Rathbun et al. (2010)
- PPR would have detected a 100 km² hotspot if T > ~170 K (Sparks loc), ~140 K (Jia loc)



Io - conclusions

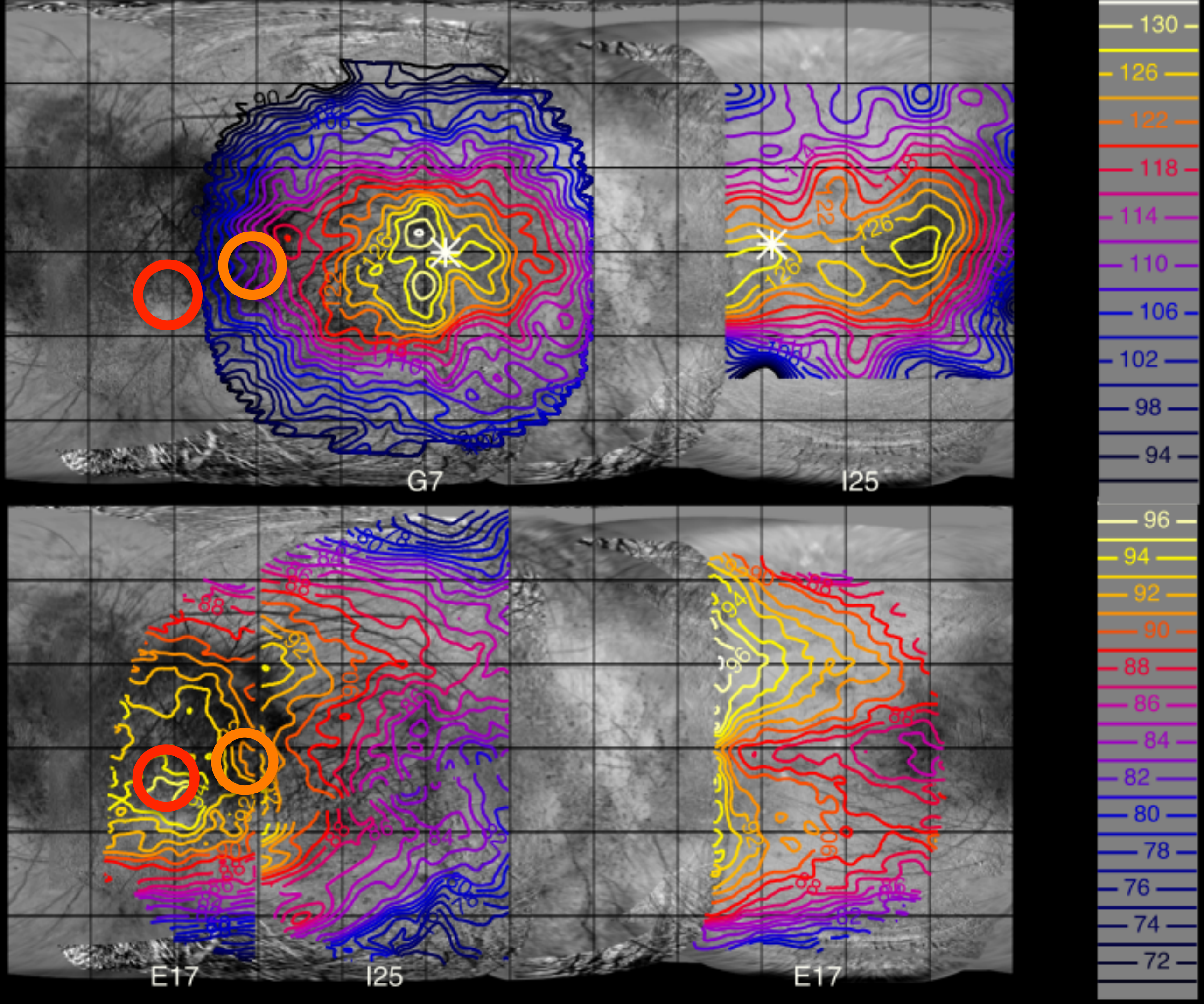
- Ignoring latitude variations, longitude variations are consistent with either mantle heating or asthenosperic with a 90 degree rotation
- Four-fold symmetry in longitude most consistent with combined heating case of Tackley et al. (2001)



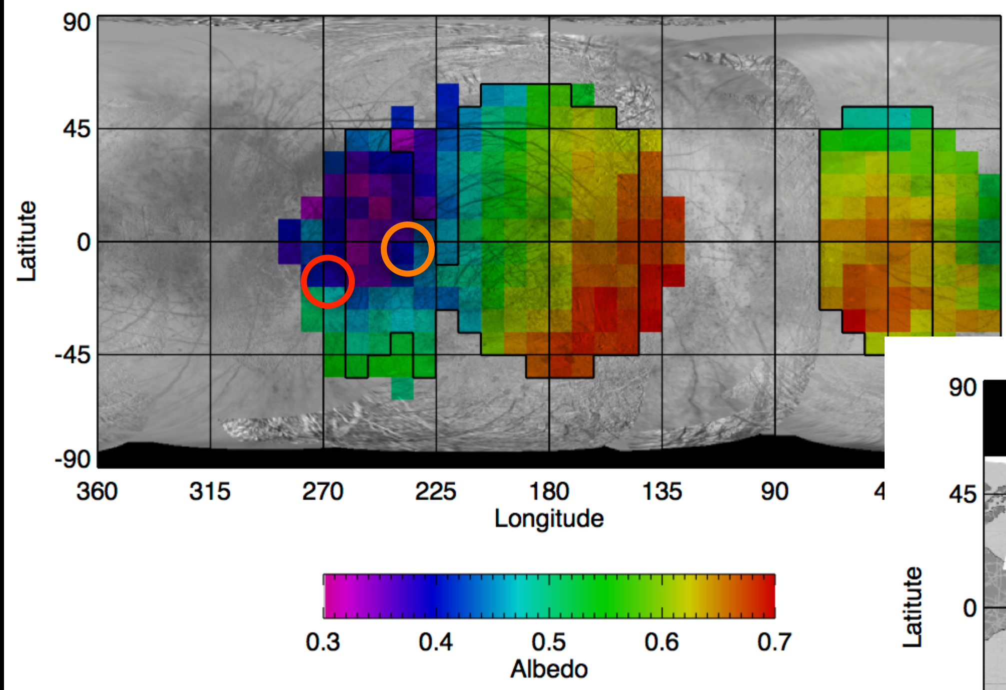
Best PPR

Daytime temperatures

Nighttime temperatures

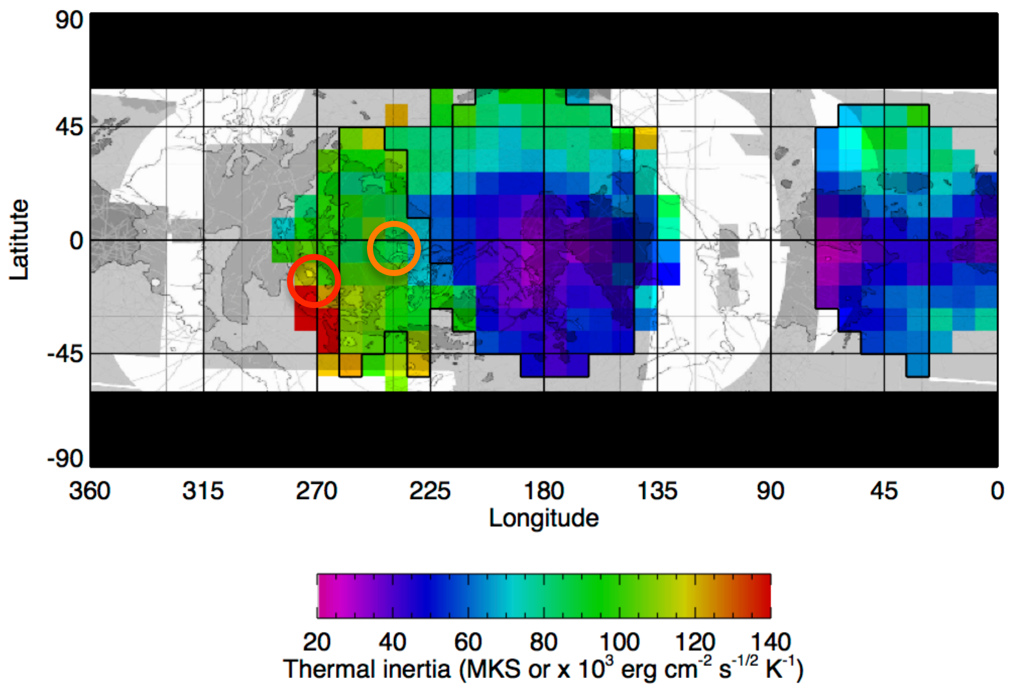


Albedo & thermal inertia



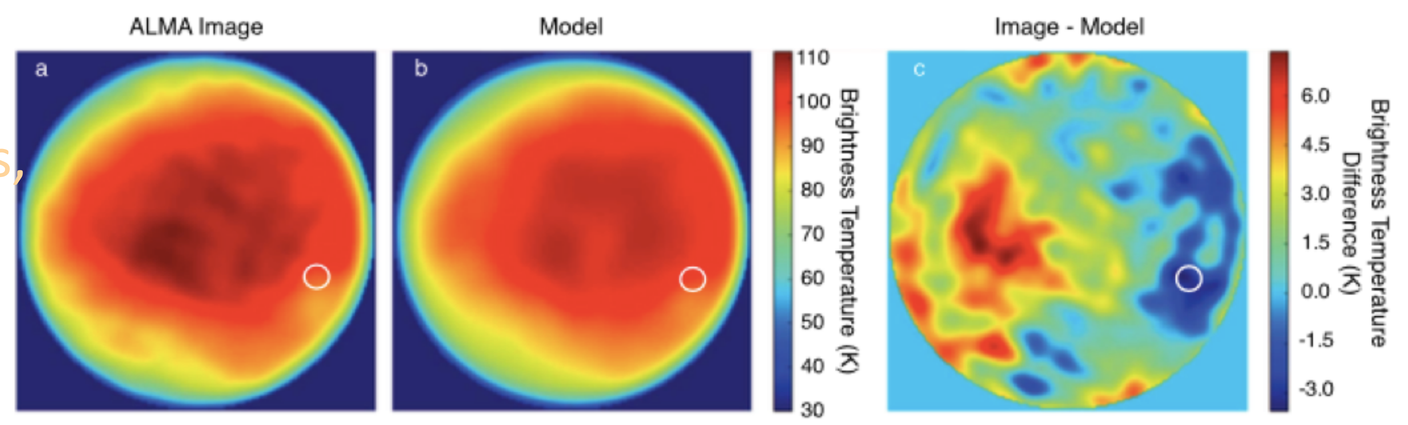
Rathbun and Spencer, 2014

- Jia location albedo ~ 0.4, thermal inertia ~ 100 mks



Sparks location – thermal model

- PPR observations at night and early-morning (3)
  - Early-morning in less sensitive filters: 27.5 (E6) & 35.5 μm
- No mid-day observations → bad thermal model
- Trumbo et al. (2017) – observed location in daytime using ALMA (1.3 mm)
  - Colder → thermal inertia > surroundings, NOT endogenic heating

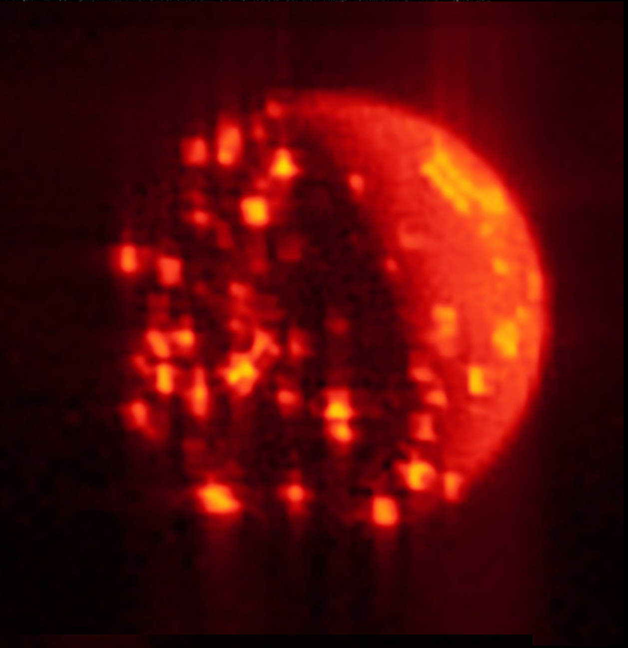


Conclusions – Sparks location

- Endogenic heating not necessary
- Higher measured thermal inertias near Pwyll are consistent with higher thermal inertias in plume fallout from Io’s Pele plume
- Would like to run similar models for nearby locations.
  - Trumbo et al. (2017) and Rathbun and Spencer (2014) found that thermal inertia anomaly extends beyond N. Pwyll and suggested it may be due to the Pwyll ejecta blanket
- Need data from E-THEMIS on Europa Clipper
  - Multiple wavelengths simultaneously
  - Higher spatial resolution

Conclusions – Jia location

- This area better observed by PPR than Sparks location
- Would have detected a hotspot as cool at 140 K if > 100 km2
  - Enceladus-style tiger-stripe heat source < detection limits
- Not located within PPR nighttime thermal anomaly
- Nothing in thermal data that suggests this location is special
  - Got good fit of thermal properties and they are similar across a broad region, so no property anomaly, either
- Seems too far from Sparks location (~1000 km) to be same plume source.



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Geological Activity on Tidally-Heated Solar System Worlds

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