# The quest for life:
# Ocean worlds of the outer Solar system.


**Dr Wladimir Lyra**

California State University, Northridge

Jet Propulsion Laboratory


de Toledo High School, May 8th, 2017


www.zerenner.fot.br

# Quick Bio

*Wladimir Lyra*

**B.Sc. in Astronomy**, Federal University of Rio de Janeiro (UFRJ, **Brazil**), 1999-2003.

**Research Assistant** 2003-2004

Space Telescope Science Institute (*STScI*, Baltimore **MD**)
Cerro Tololo Interamerican Observatory (*CTIO*, La Serena – **Chile**)
European Southern Observatory (*ESO*, Munich – **Germany**)
Lisbon Observatory, **Portugal**.

**Ph.D. in Astronomy**, Uppsala University (Uppsala, **Sweden**), 2004-2009.

Nordic Institute for Theoretical Physics (*NORDITA*, Stockholm, **Sweden**)
Max-Planck Institute for Astronomy (*MPIA*, Heidelberg, **Germany**)

**Postdoctoral Researcher**

American Museum of Natural History (*AMNH*, New York **NY**), 2009-2011.
Jet Propulsion Laboratory (NASA-JPL/Caltech, Pasadena **CA**), 2011-2015.

**Stellar Astrophysics, Planetary Sciences**

Solar-type stars, extrasolar planets, star formation, *circumstellar disks and planet formation*.
Hydrodynamics, plasma physics, turbulence, life in the universe, *icy moons and Europa*.

Rio de Janeiro, Brazil

Rio de Janeiro, Brazil

La Serena, Chile

Rio de Janeiro, Brazil

La Serena, Chile

Munich, Germany

F

Rio de Janeiro, Brazil

La Serena, Chile

Lisbon, Portugal

Munich, Germany

Rio de Janeiro, Brazil

La Serena, Chile

Baltimore, USA

Lisbon, Portugal

Munich, Germany


Rio de Janeiro, Brazil


Uppsala, Sweden


La Serena, Chile


Baltimore, USA


Lisbon, Portugal


Munich, Germany

Rio de Janeiro, Brazil

Uppsala, Sweden

Stockholm, Sweden

La Serena, Chile

Baltimore, USA

Lisbon, Portugal

Munich, Germany

Heidelberg, Germany

Rio de Janeiro, Brazil

Uppsala, Sweden

Stockholm, Sweden

La Serena, Chile

Baltimore, USA

Lisbon, Portugal

Munich, Germany


New York, USA


Heidelberg, Germany


Rio de Janeiro, Brazil


Uppsala, Sweden


Stockholm, Sweden


La Serena, Chile


Baltimore, USA


Lisbon, Portugal


Munich, Germany

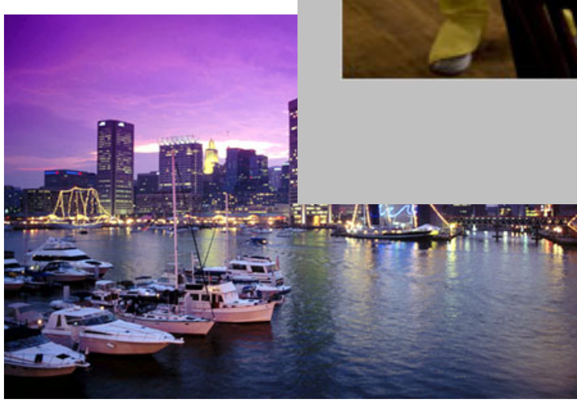
New Yor

Janeiro, Brazil

Uppsala,

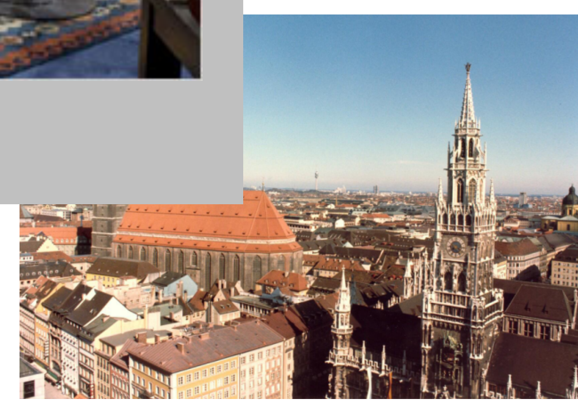
erena, Chile

Pasadena, CA



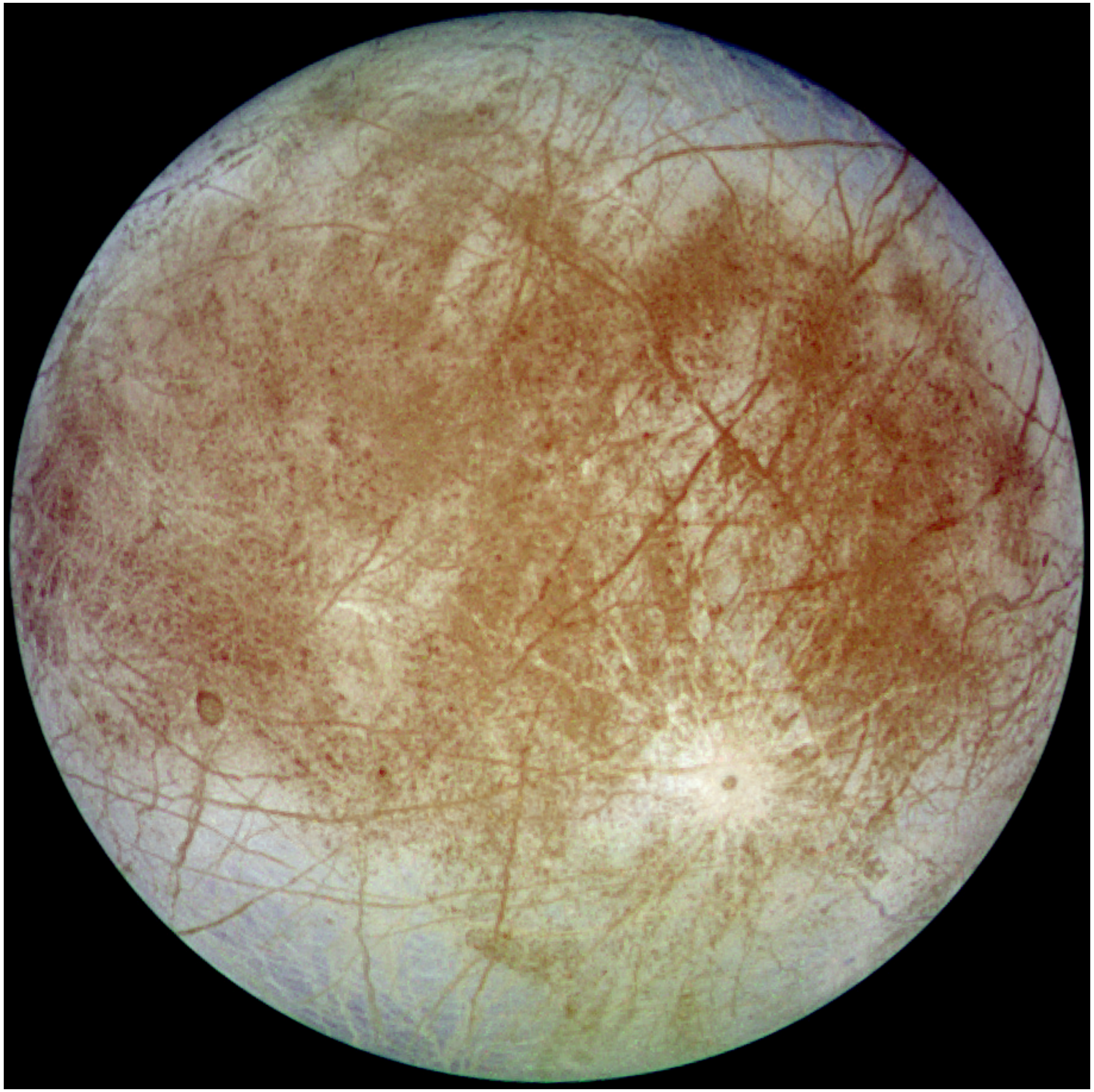
Baltimore, USA

Lisbon, Portugal



Munich, Germany

# Europa



# Volcanic Moons

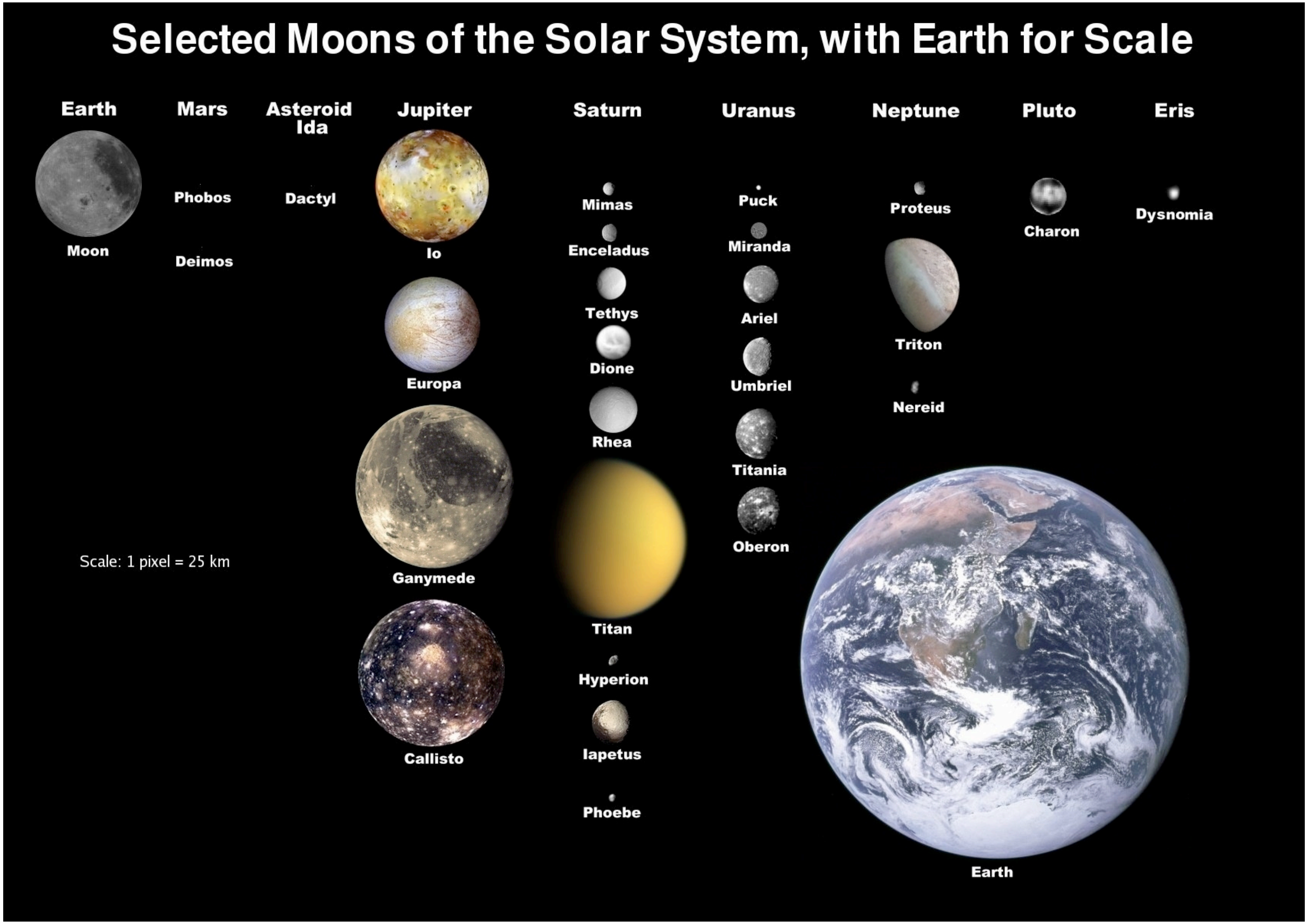
**Obi-Wan Kenobi and Darth Vader fight on the volcanic moon of Mustafar.**

Star Wars, Episode III, “Revenge of the Sith”

## Jupiter's family portrait

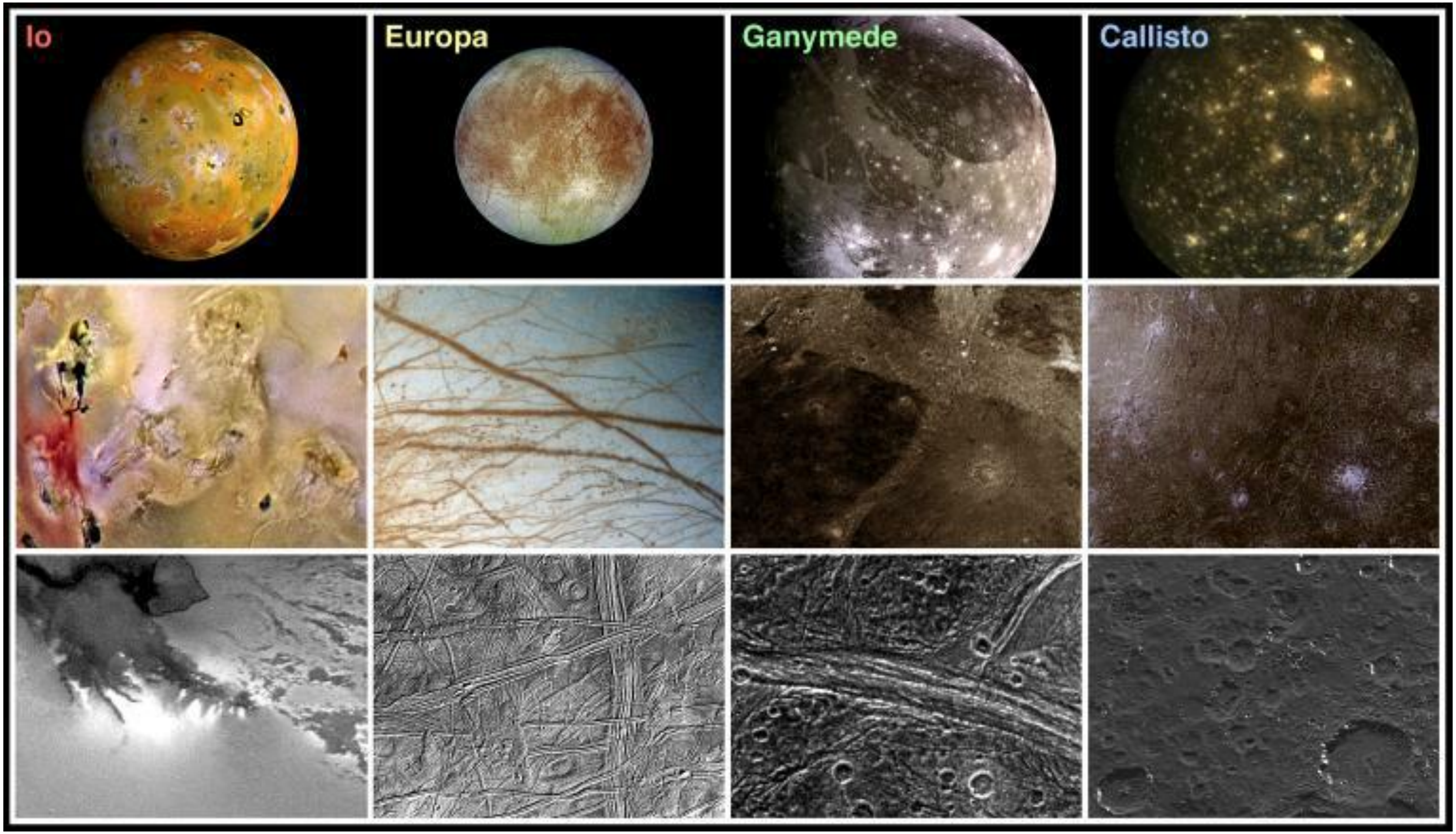
Io Europa Ganymede Callisto

# Moons of the Solar System



# Size Comparison

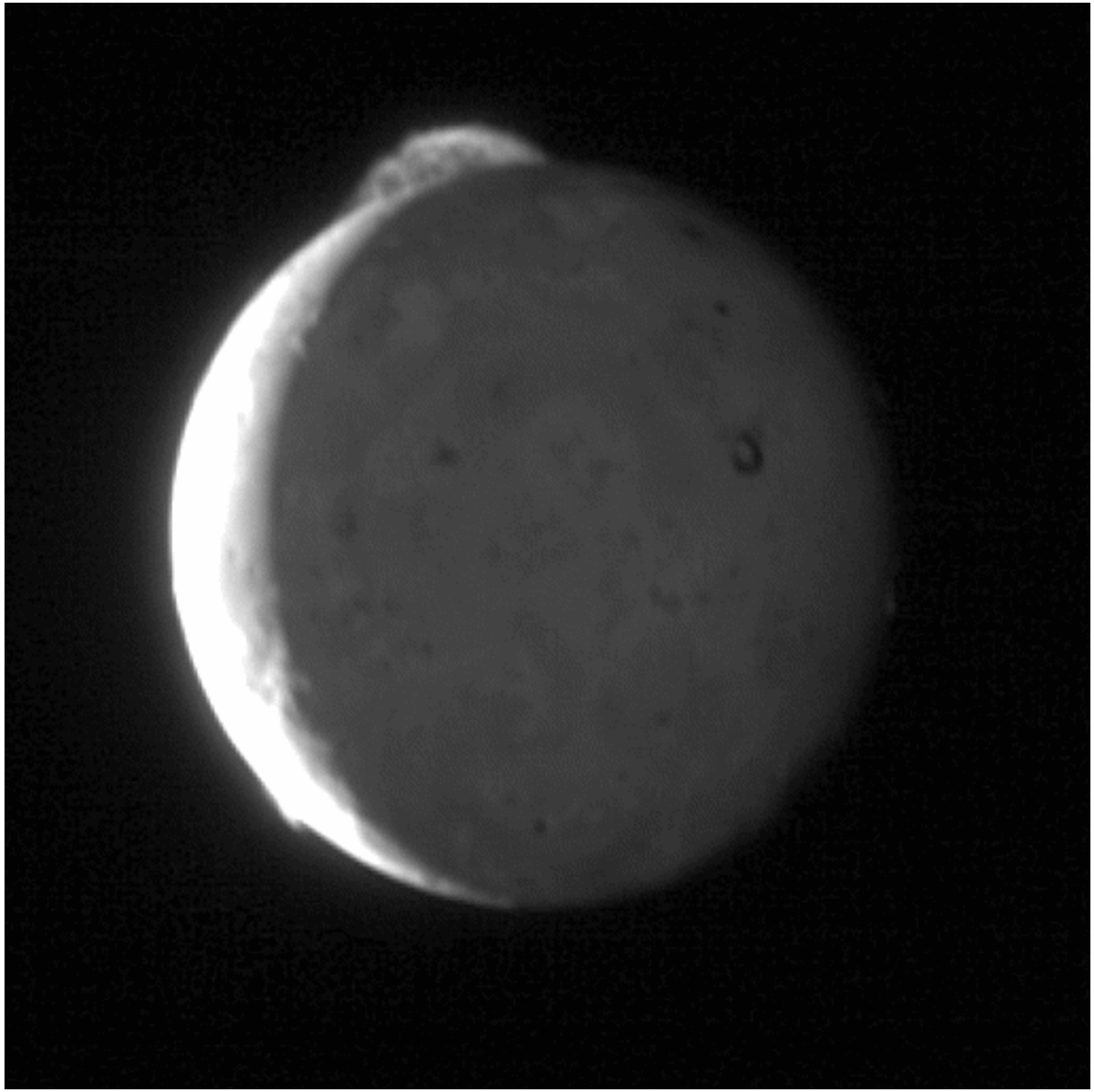
# Surfaces of the Galilean Satellites




← Young surfaces → Old surface

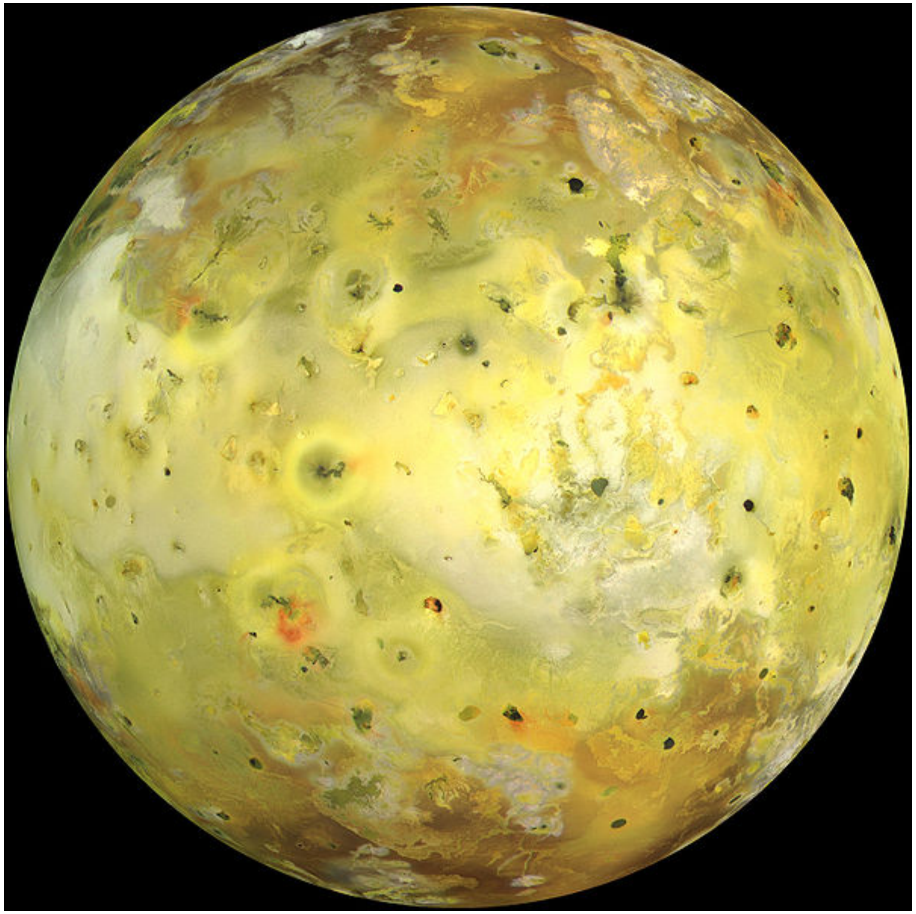
(Geologically Active)

# Io in action



# Io – Jupiter's Volcanic Moon

Nowhere else in the Solar System
do **volcanic processes**
so **dominate** everything we see as on **Io**



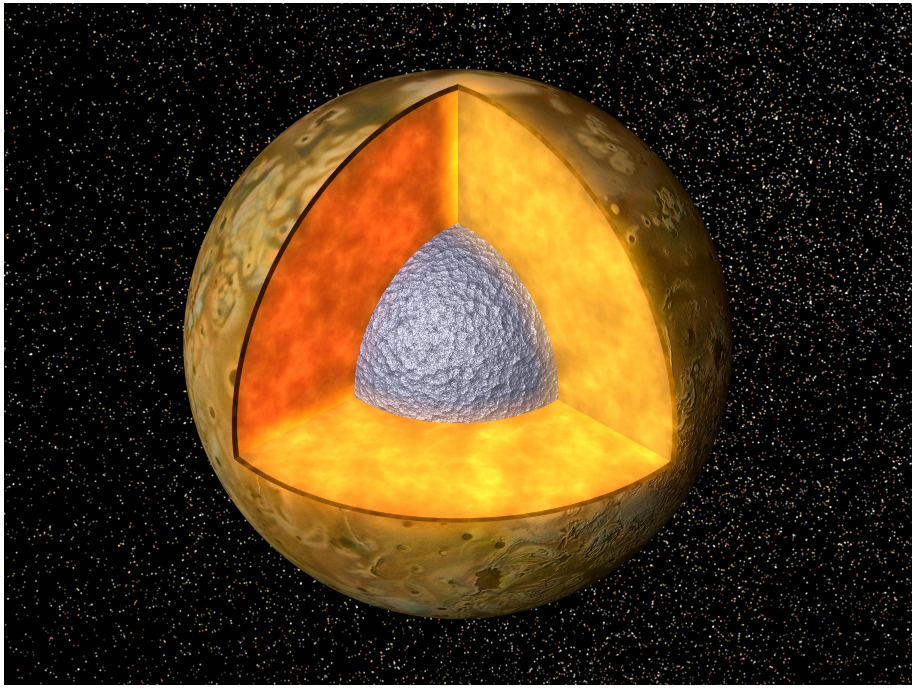
**100 times more volcanic than Earth!!**

Ground temperature: 110K

**Bright areas: Fresh sulfur frost**

**Yellow-Brown areas: older sulfur compounds**

# Io's interior



Thin silicate crust

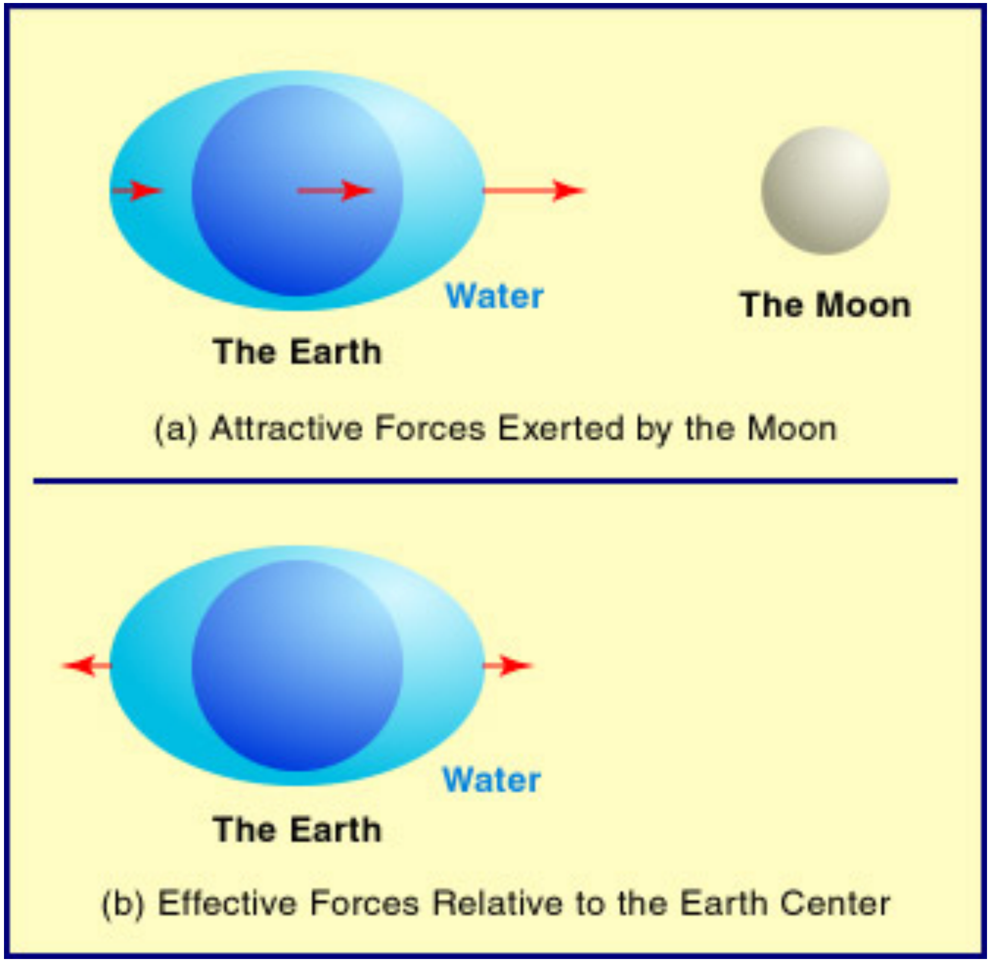
Molten silicate interior

Iron rich core

Io is roughly the size of the Moon.

How does such a small body retain such a hot interior?

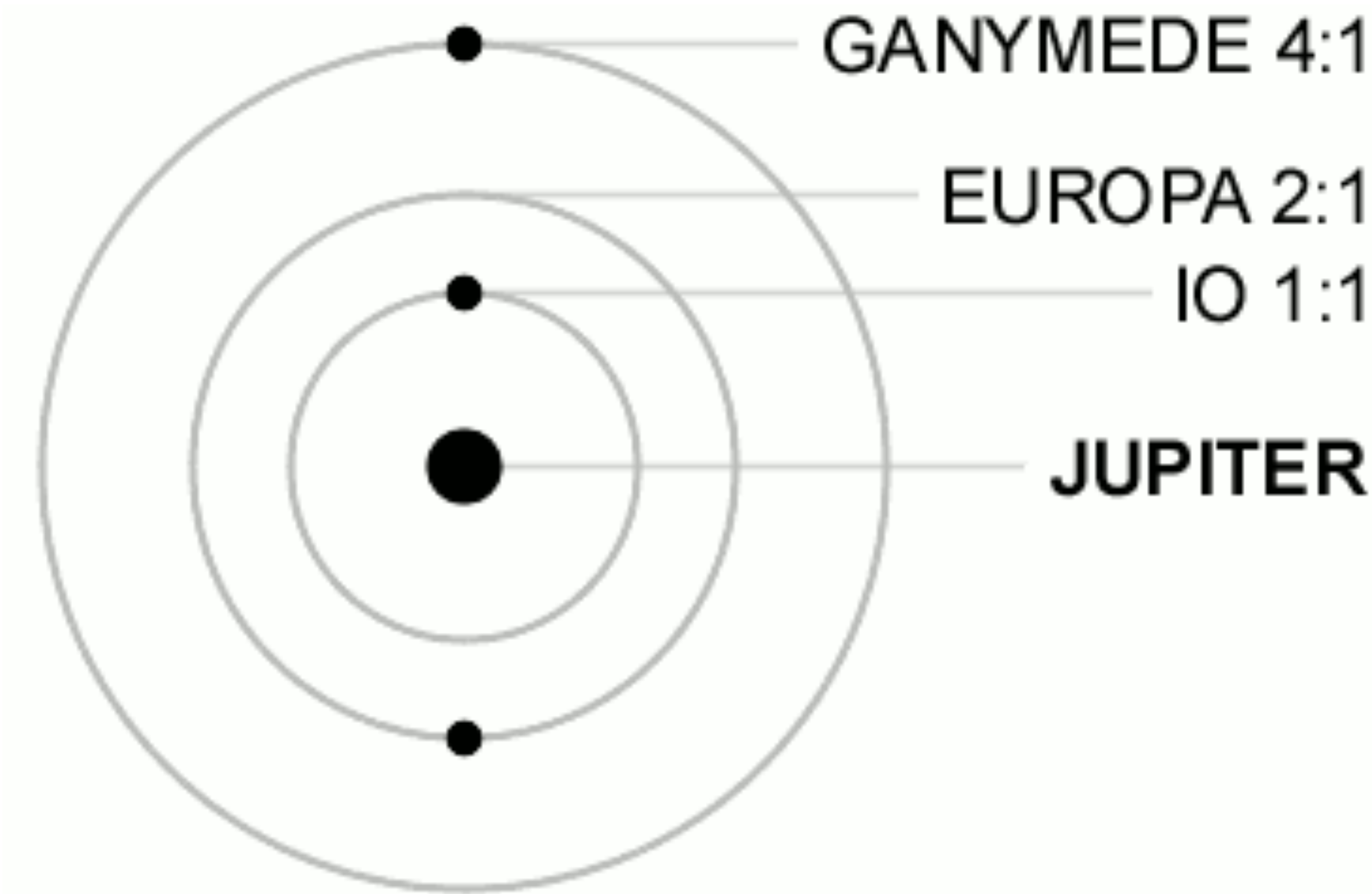
# Tides



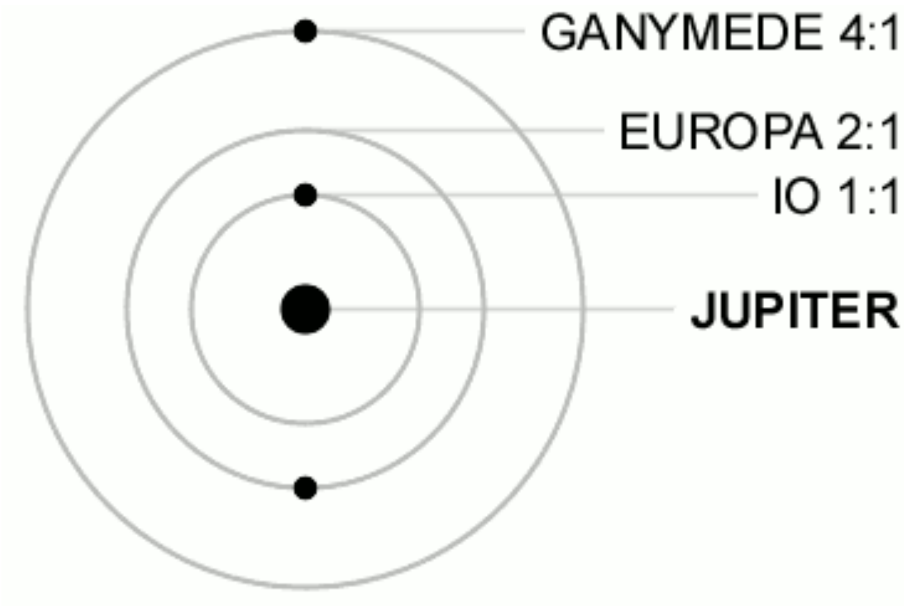

The side closer to the Moon experiences a greater pull than the side further out.

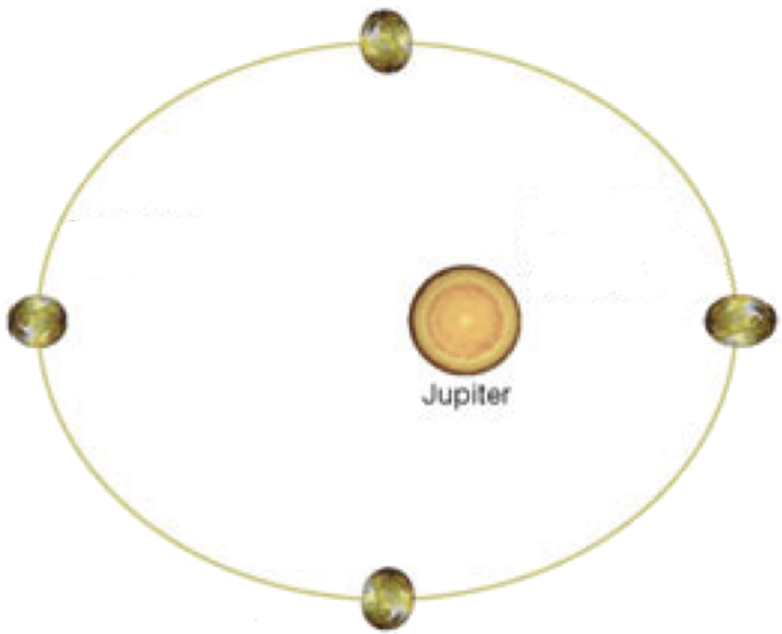
The effective result is a *differential* force we call **Tidal Force**.

# Orbital Clockwork



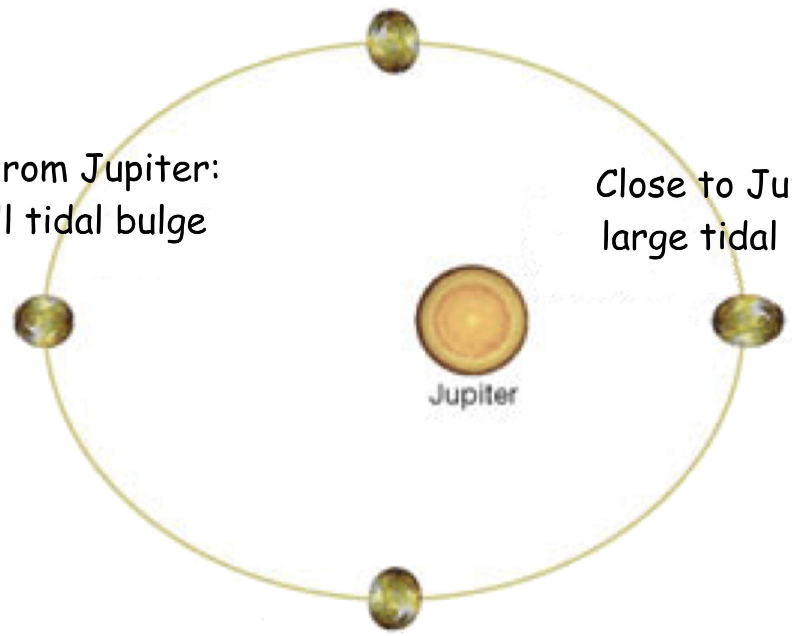
# Swinging Moons




Periodic tug of Europa makes
Io's orbit slightly elliptic
(e ~ 0.004)

# Tidal Heating



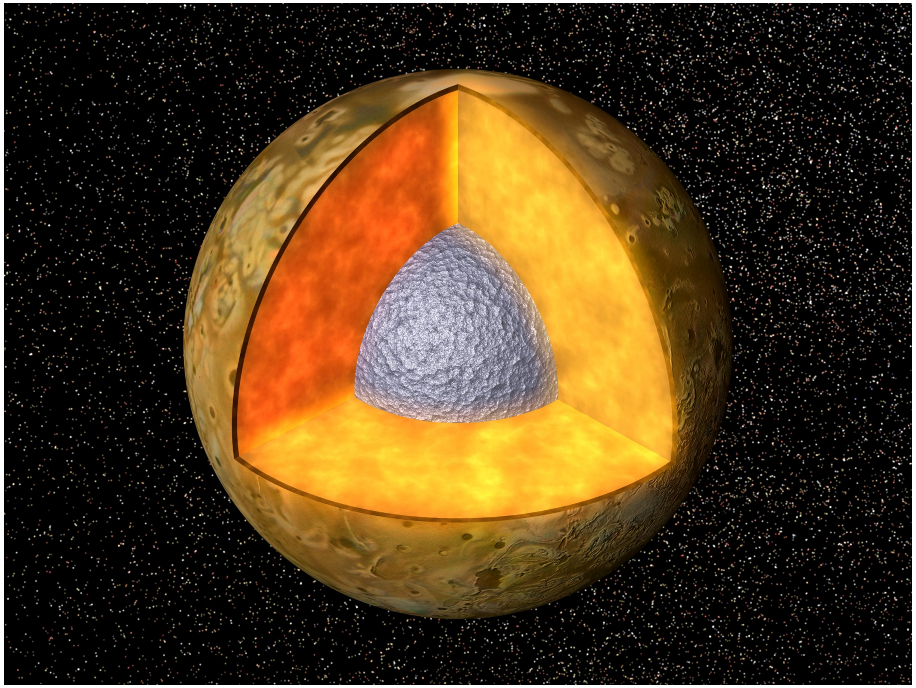

**Difference in tidal bulge**

from closest to farthest from Jupiter:

**100 m (~300 ft)**

**MASSIVE FRICTION!!!**

# Tidal heating
## keeps Io's interior molten

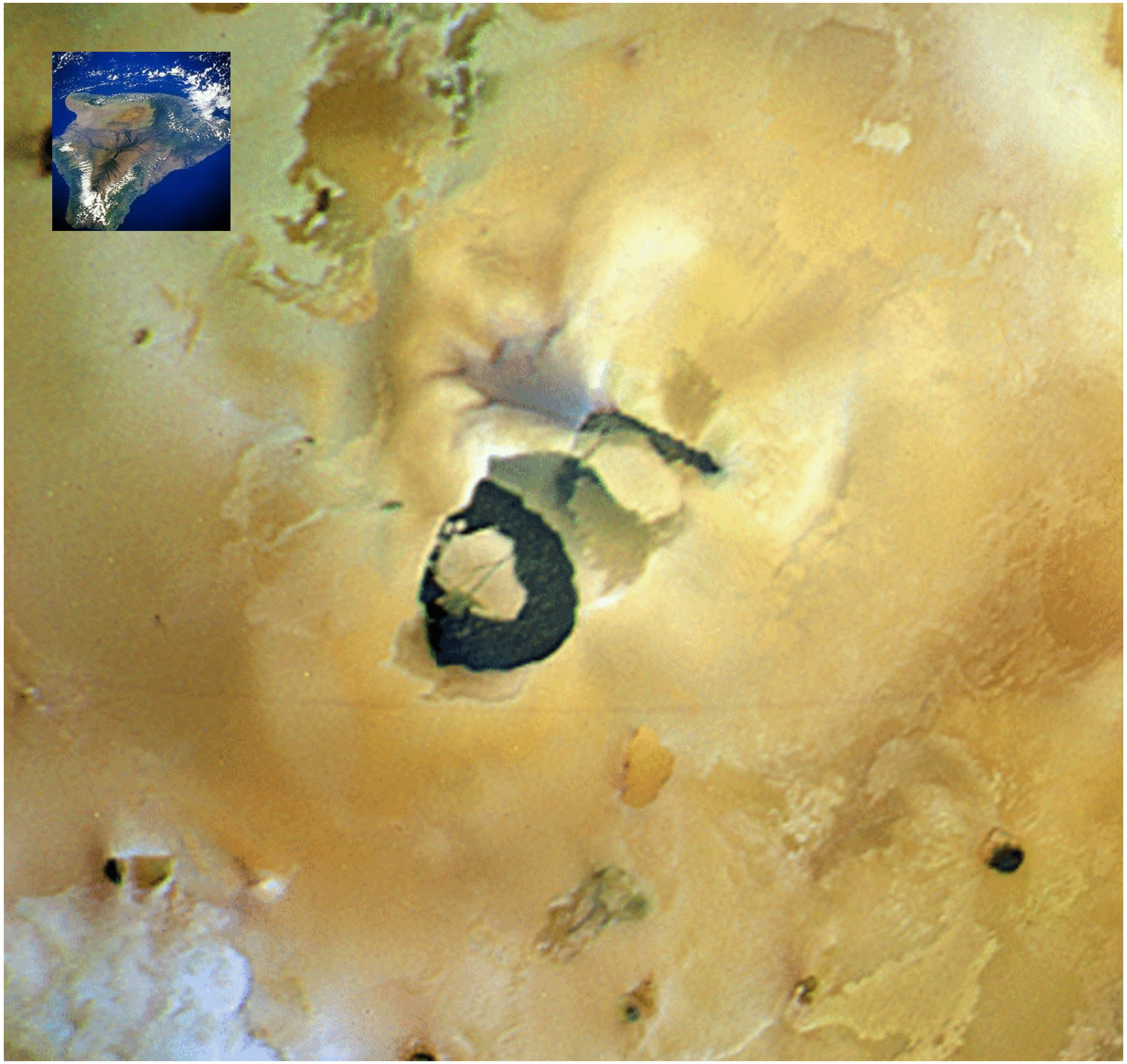


Thin silicate crust

**Molten silicate interior**

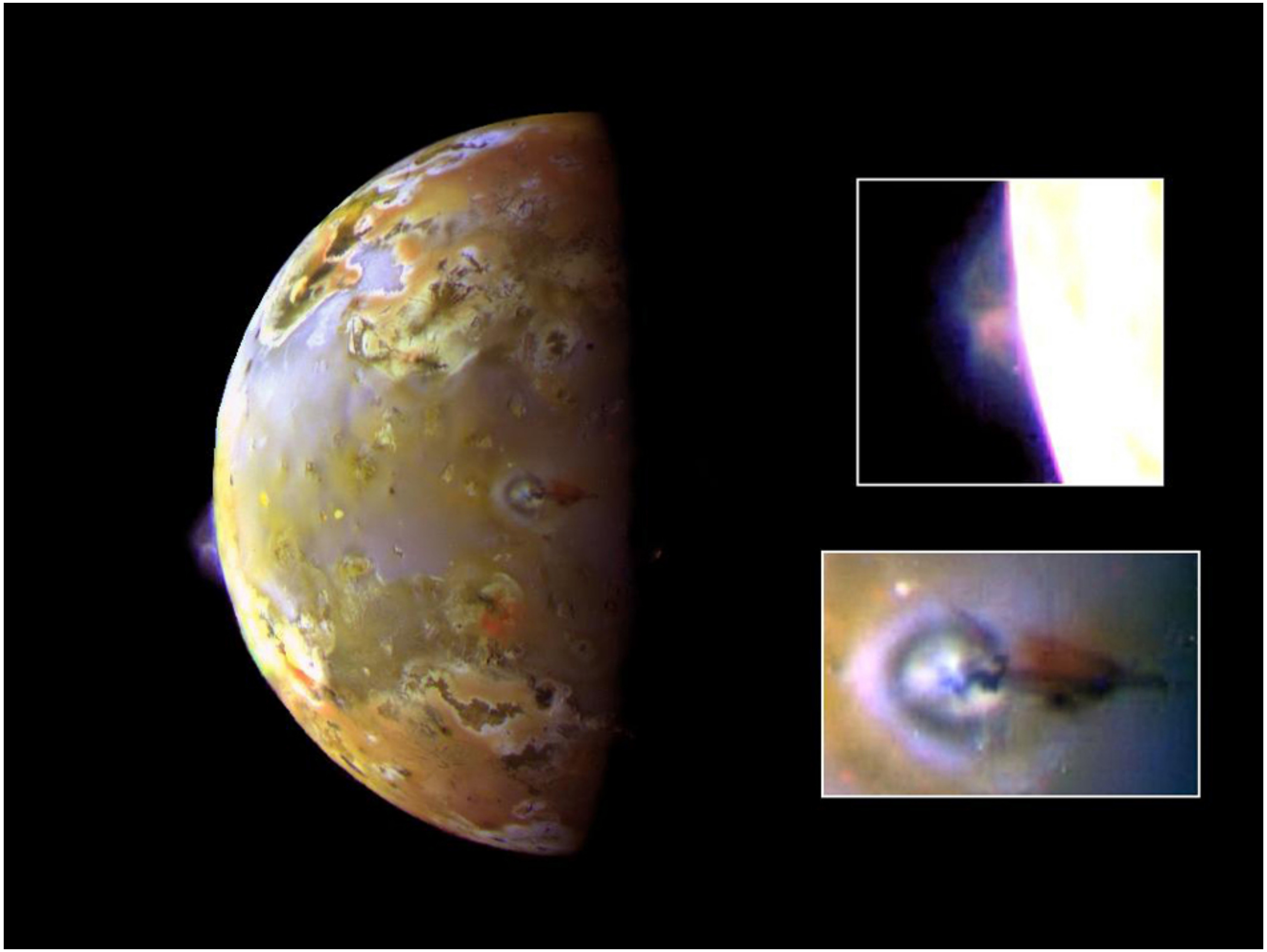
Iron rich core

# Io's Volcanoes

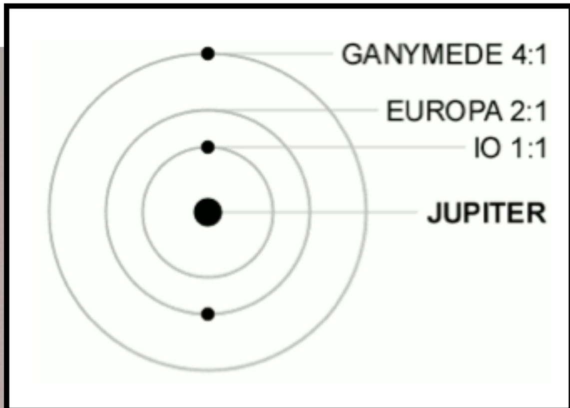


Loki

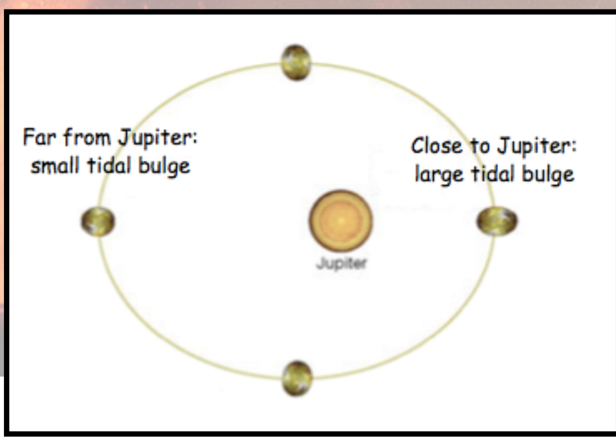
# Active plumes



# Tidal Heating: Summary

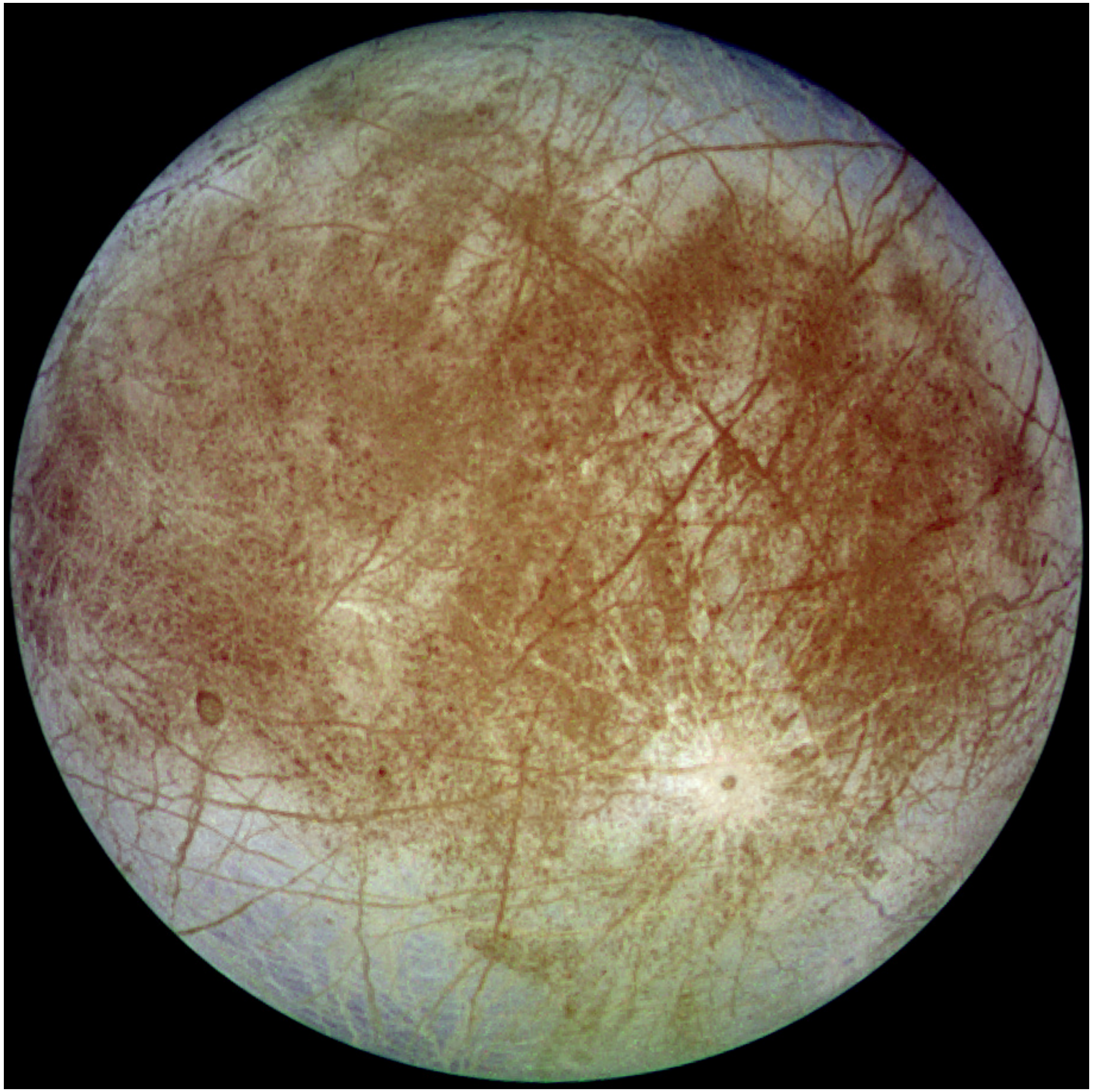



Periodic pull of outer moons keeps Io's orbit elliptic

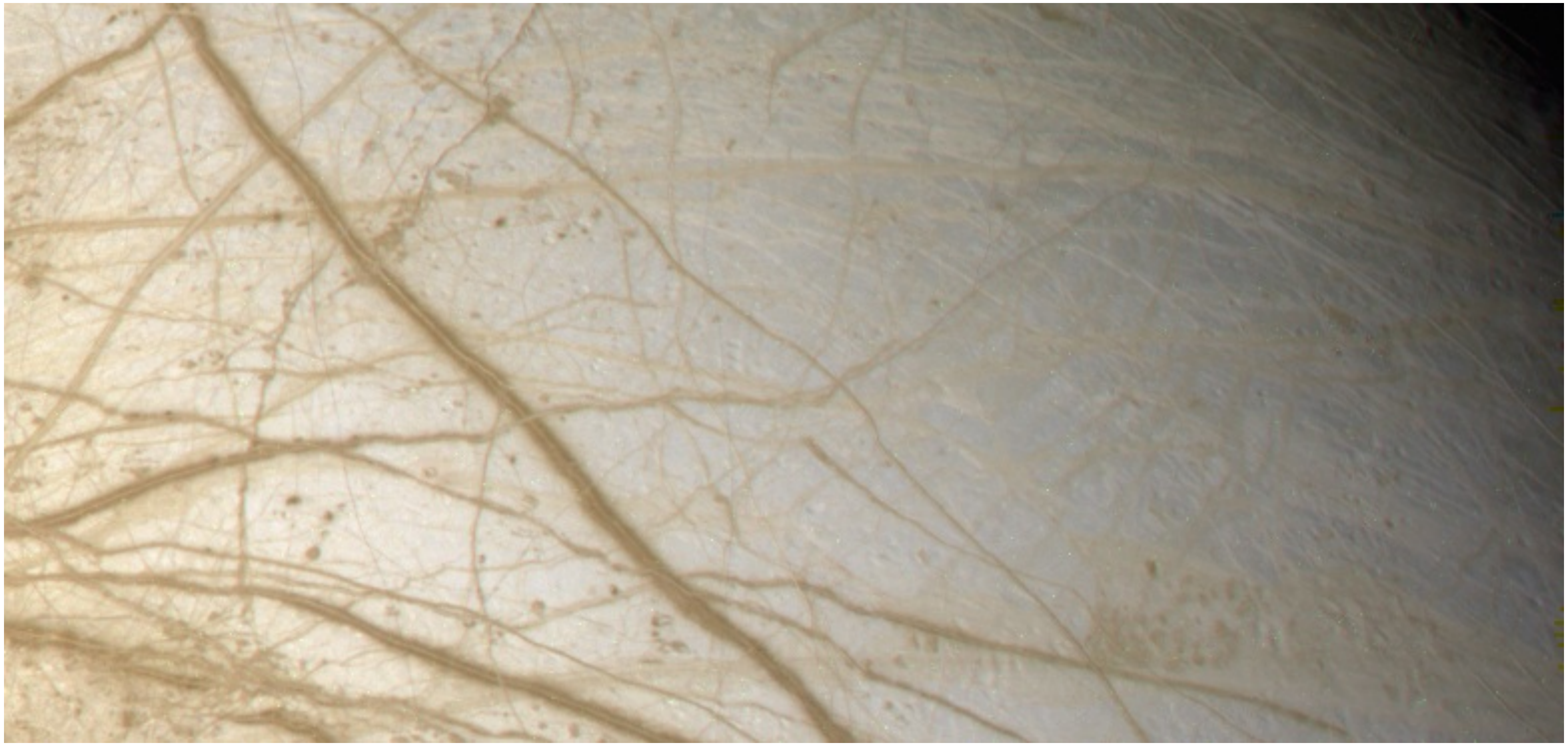



Varying tidal bulge in elliptic orbit generates energy through friction

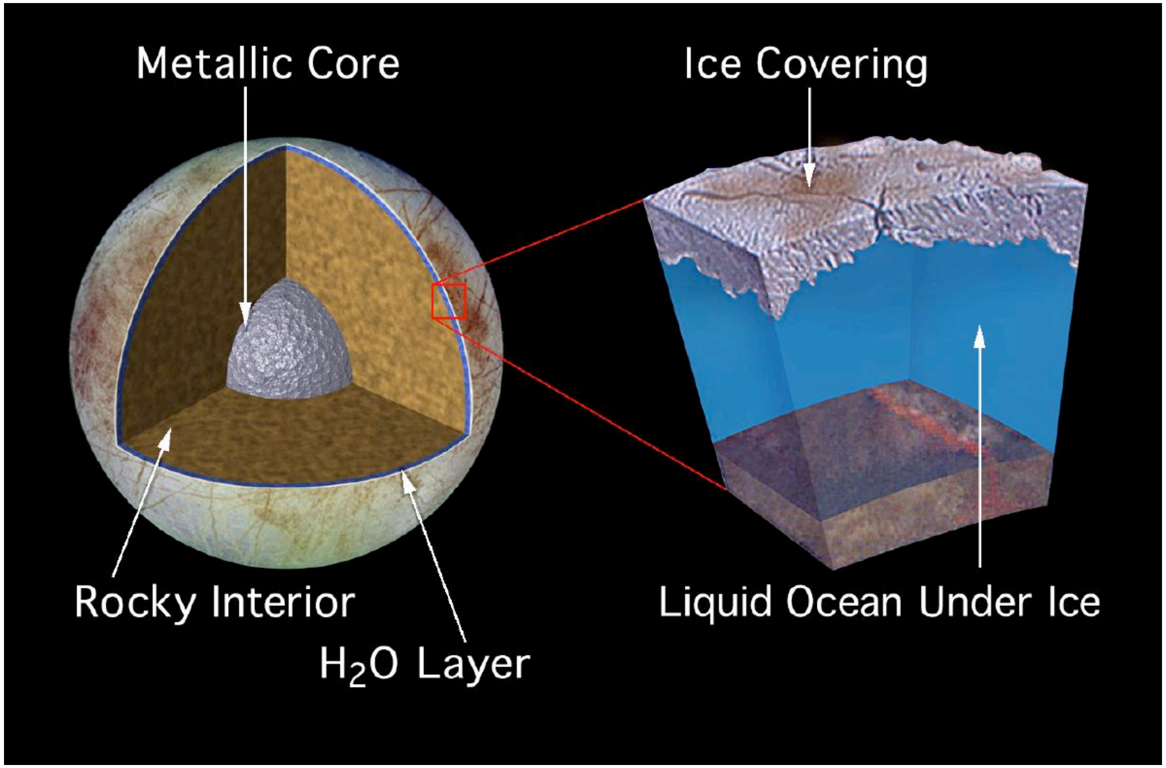
# Europa

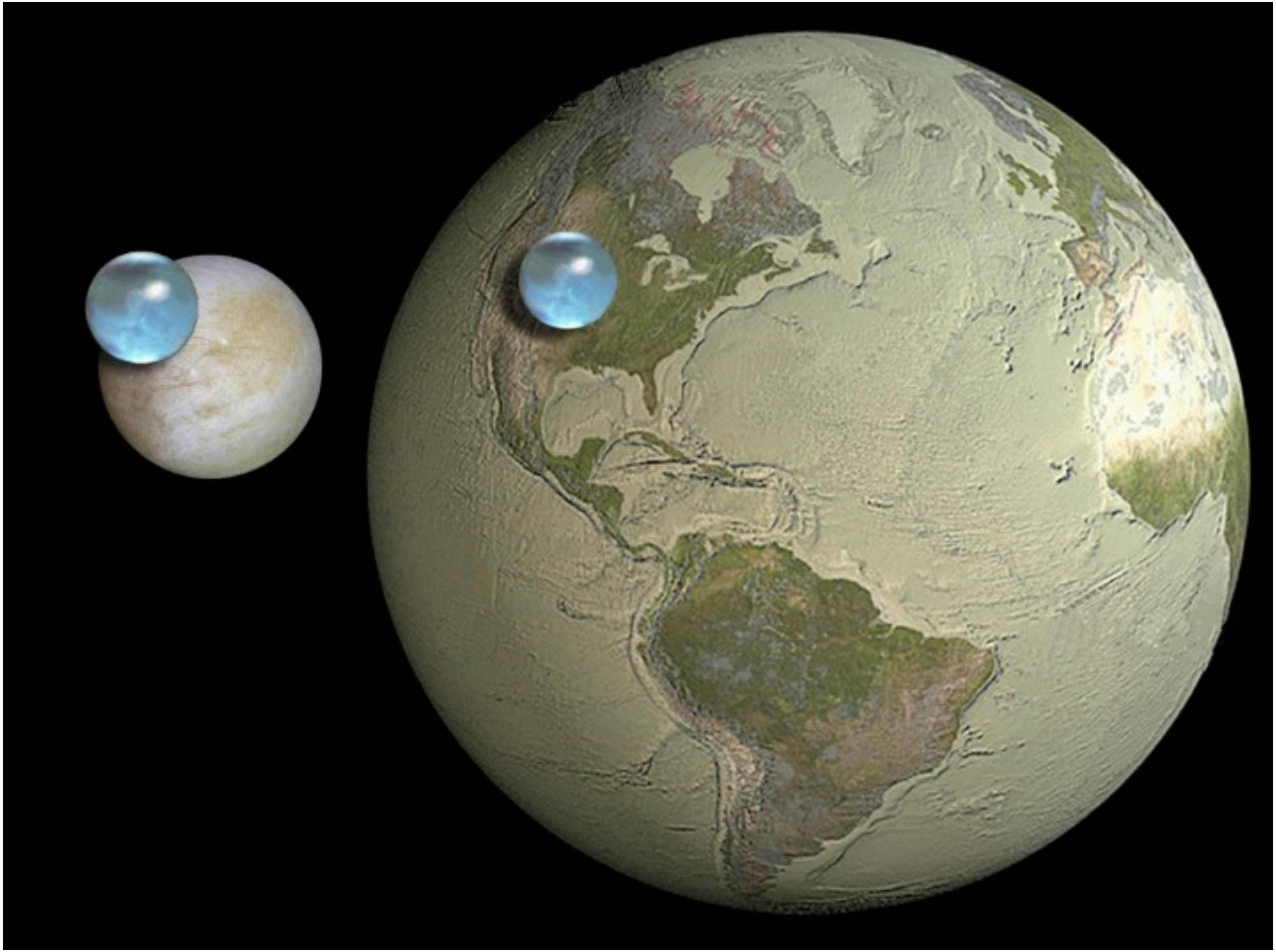


# Ice Tectonics

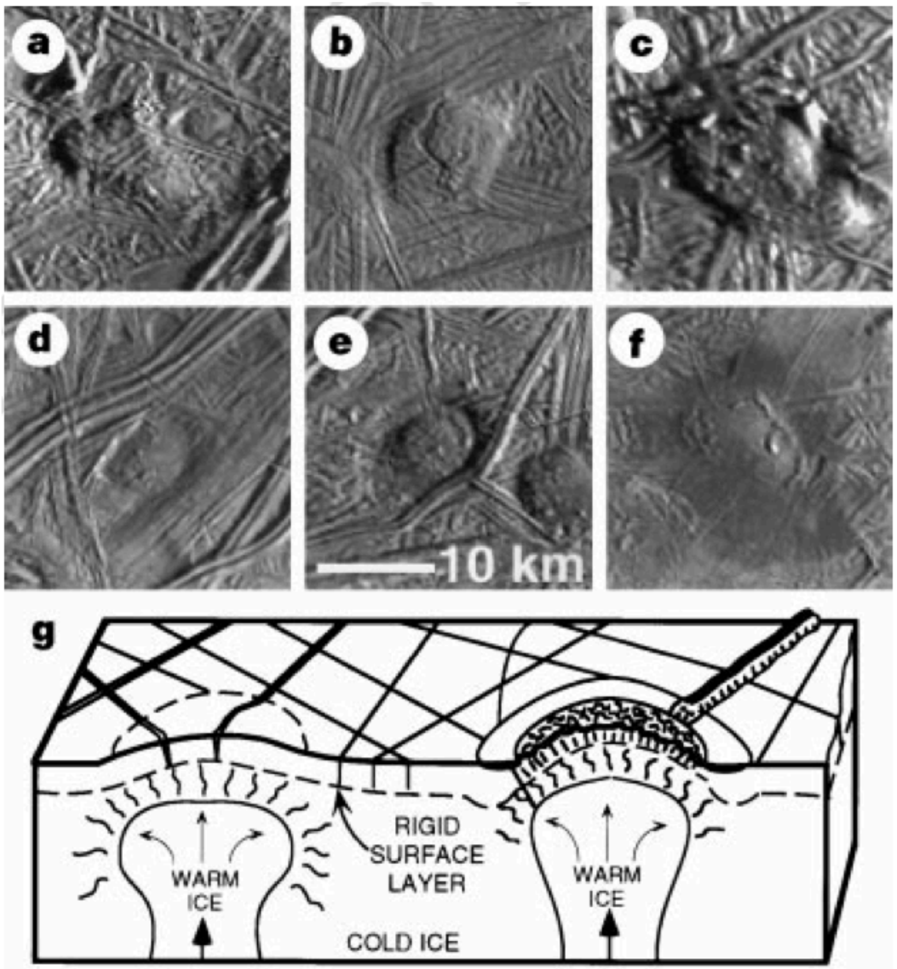


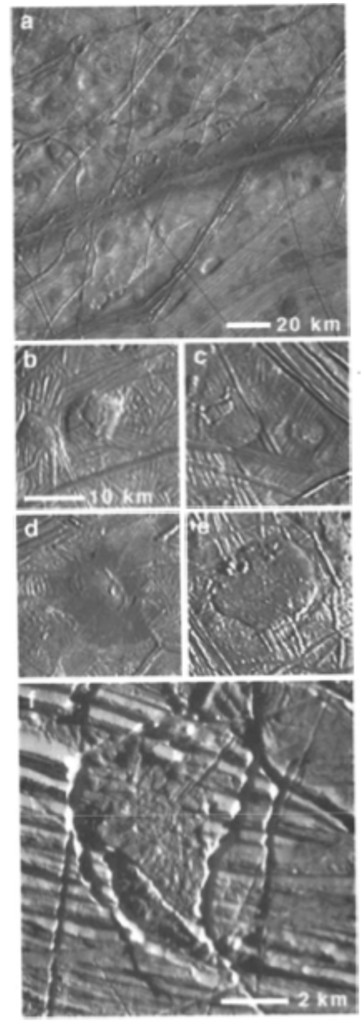
# Europa has less tidal heating

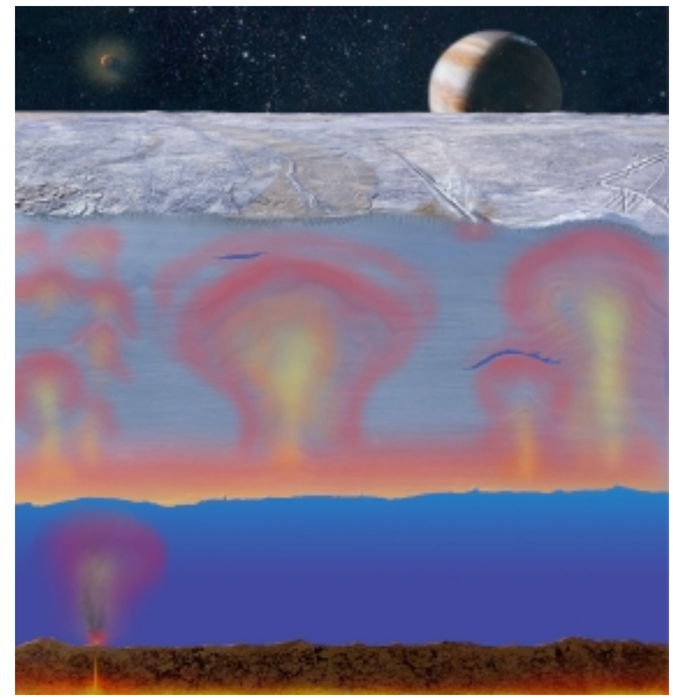




# Evidence for Convection



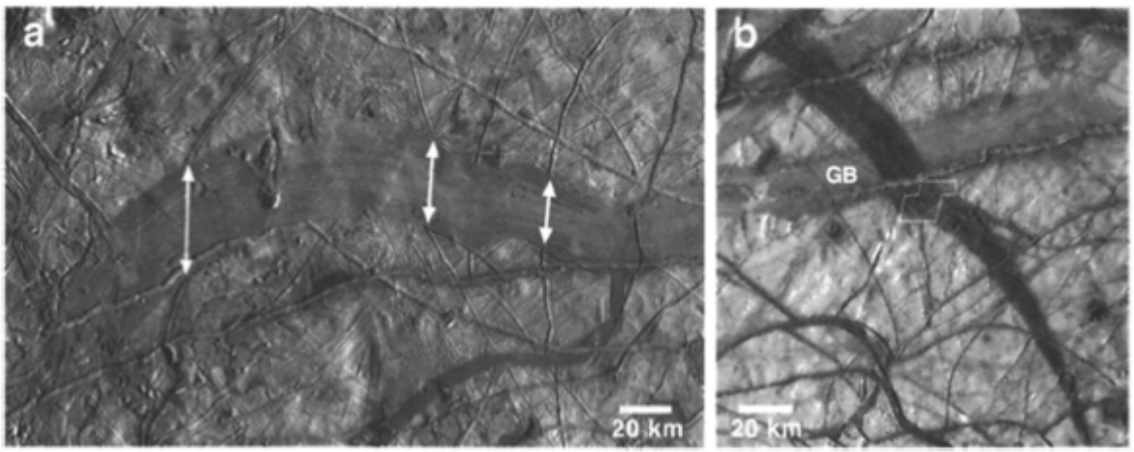



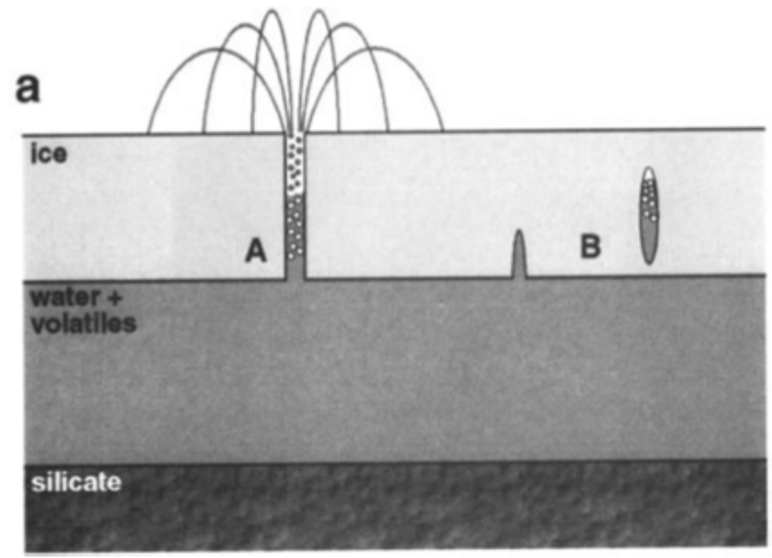
Ice diapirism

(Pappalardo et al. 1998, Nature, 391, 22

Pappalardo et al. Journal of Geophysical Research, 1999, 104, 24015)

# Evidence for Convection

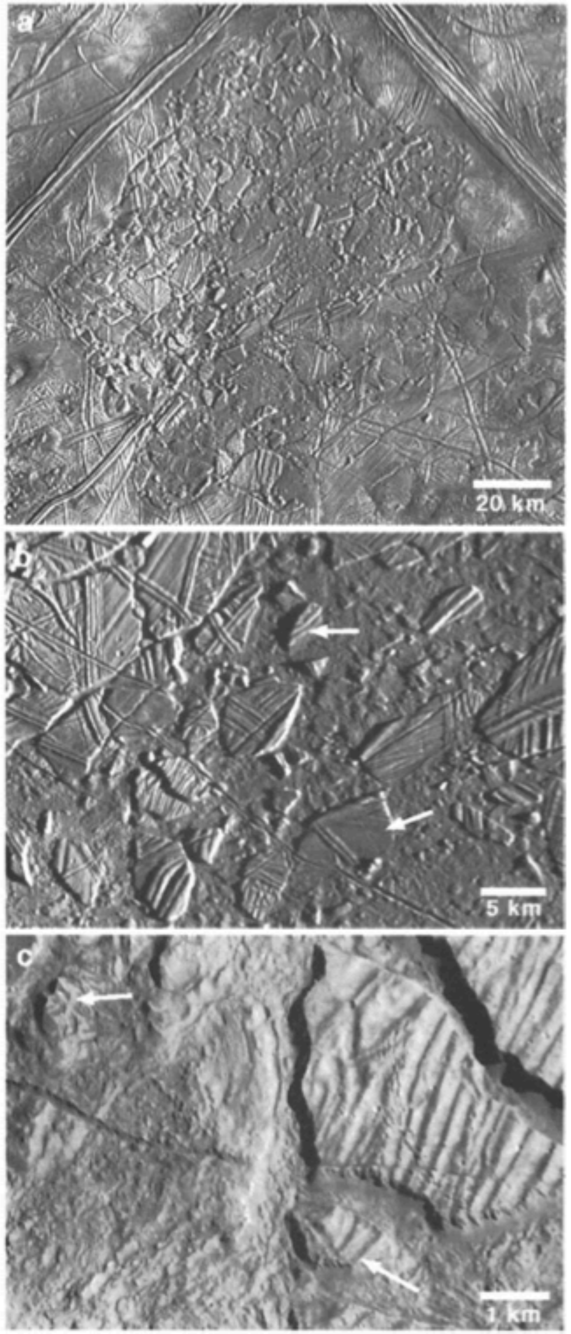


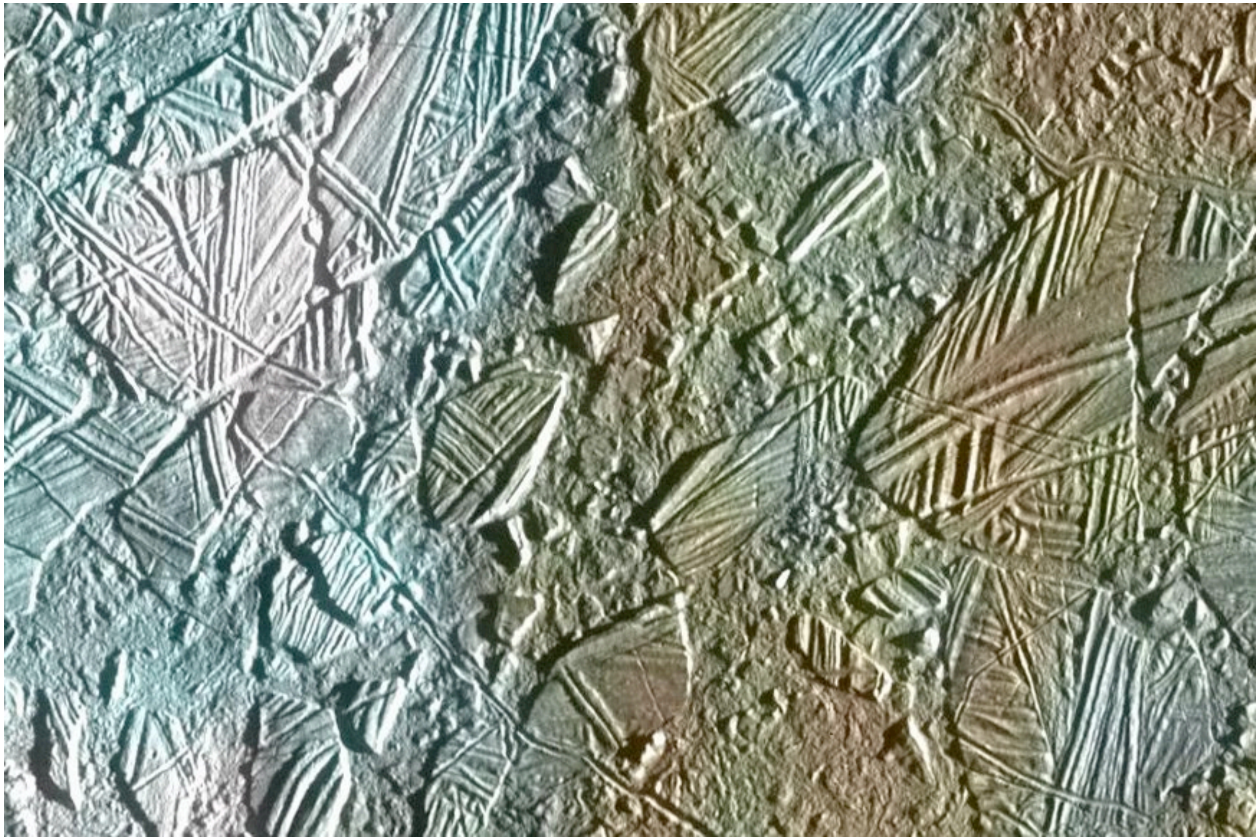




“Pull-apart” bands

(Tectonic faults, like mid-ocean ridges)

# Evidence for Convection



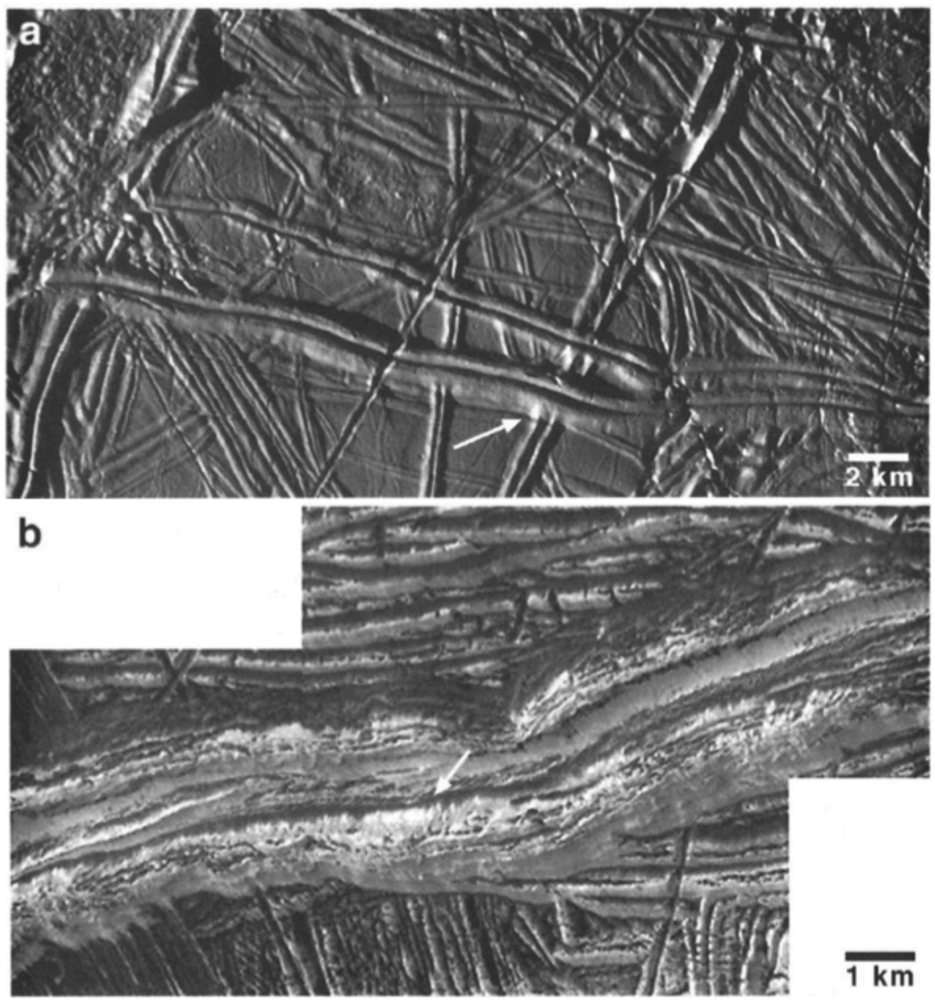



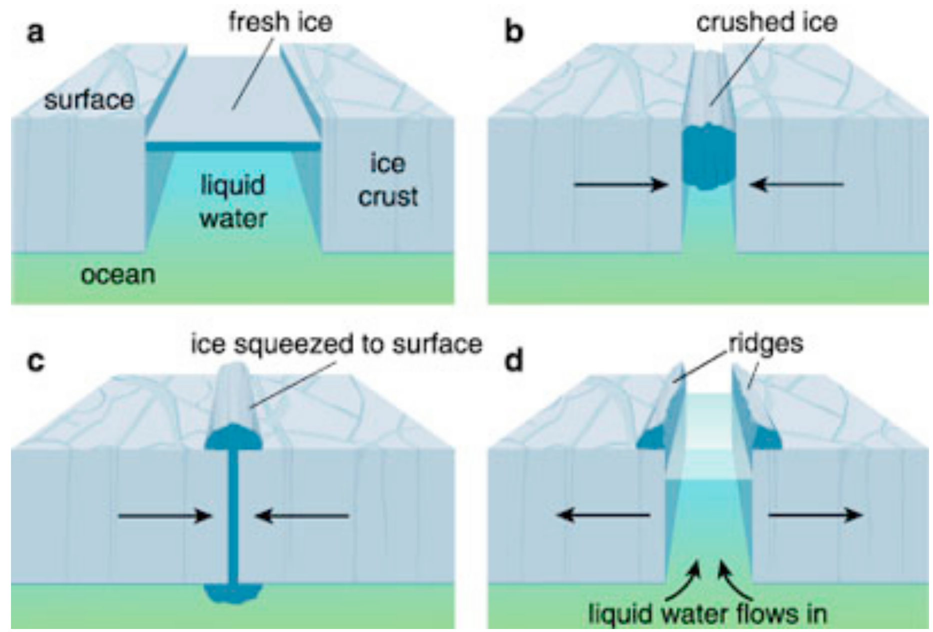
Chaos regions

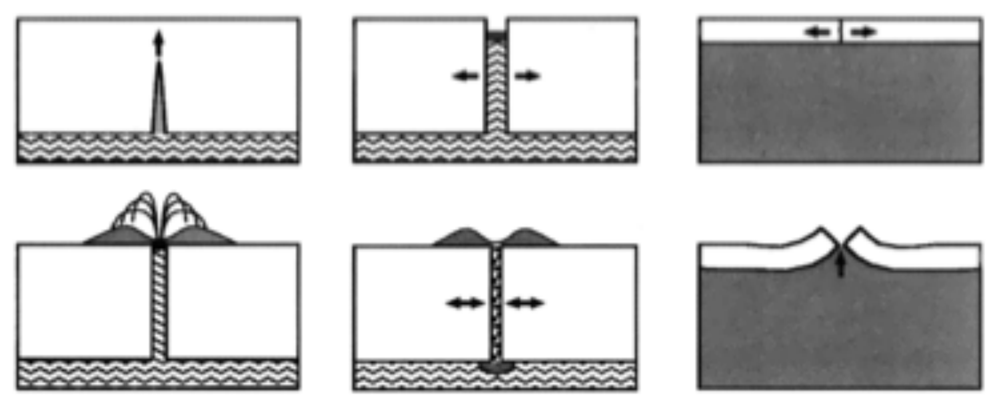
(large areas of melt that refroze)

# Evidence for Convection

Ridges



# Evaporites



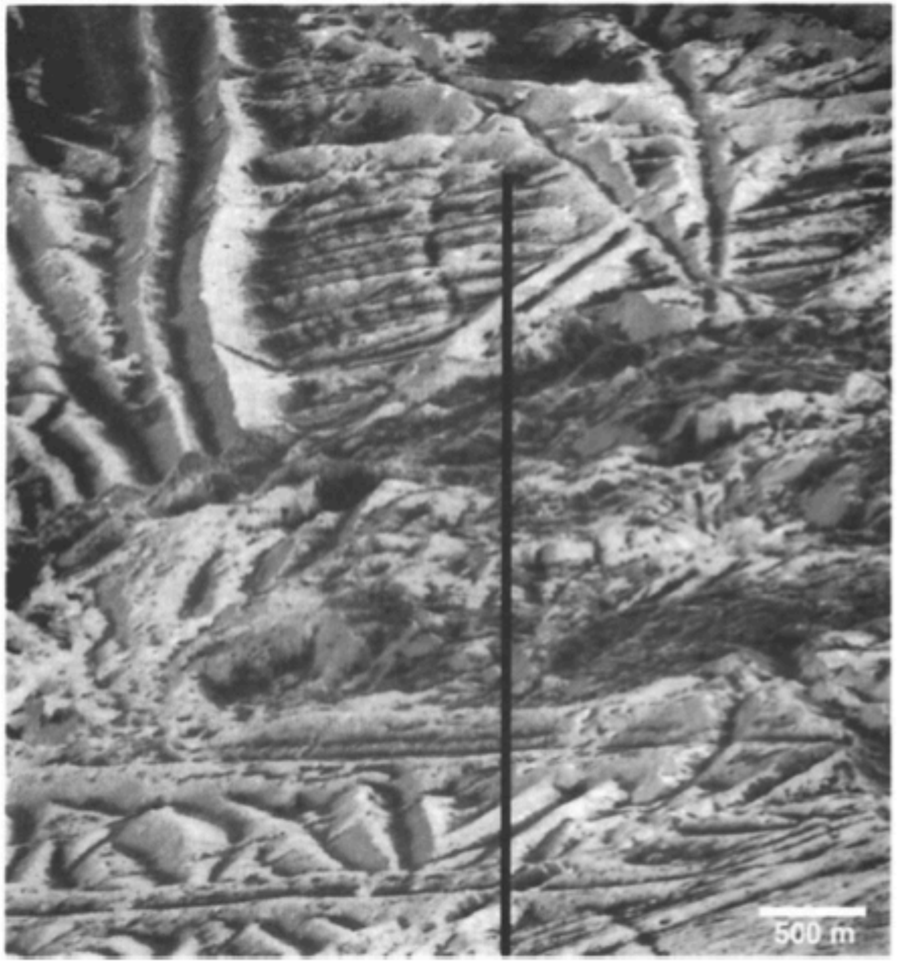



**Figure 14.** Bright and dark materials seen at the highest Galileo resolution. This oblique-looking view is the highest resolution image of Galileo's orbital tour, with ~6 m/pxl horizontal scale. Topography is the chief control on the albedo patterns. Bright material generally correlates with higher topography, and dark material occupies topographic lows. Segregation of surface materials into bright (icy) and dark (non-ice) patches is suggestive of sublimation-driven thermal segregation, which acts on very short timescales and can dominate over sputtering in Europa's equatorial region [*Spencer*, 1987]. Warmer temperatures there and down-slope movement of non-ice materials may initially act to concentrate dark materials in topographic lows. There is no direct evidence seen for venting of bright frosts from ridges or cracks. North is to the right, and the scene is illuminated from the east-northeast (lower right). Galileo observation 12ESMOTTLE01.

# Non-synchronous rotation

Geissler et al. 1998

## Evidence for non-synchronous rotation of Europa


**P. E. Geissler[*], R. Greenberg[*], G. Hoppa[*], P. Helfenstein[†], A. McEwen[*], R. Pappalardo[‡], R. Tufts[*], M. Ockert-Bell[†], R. Sullivan[‖], R. Greeley[‖], M. J. S. Belton[§], T. Denk[¶], B. Clark[†], J. Burns[†], J. Veverka[†] & the Galileo Imaging Team**

* *Lunar and Planetary Laboratory, University of Arizona, Tucson, Arizona 85712, USA*

† *Laboratory for Planetary Science, Cornell University, Ithaca, New York 14853, USA*

‡ *Department of Geological Sciences, Box 1846, Brown University, Providence, Rhode Island 02912, USA*

§ *National Optical Astronomy Observatories, PO Box 26732, Tucson, Arizona 85726, USA*

‖ *Department of Geology, Arizona State University, Box 871404, Tempe, Arizona 85287, USA*

¶ *DLR, Institute for Planetary Exploration, Rudower Chaussee 5, 12489 Berlin, Germany*



**Non-synchronous rotation of Europa was predicted on theoretical grounds[1], by considering the orbitally averaged torque exerted by Jupiter on the satellite's tidal bulges. If Europa's orbit were circular, or the satellite were comprised of a frictionless fluid without tidal dissipation, this torque would average to zero. However, Europa has a small forced eccentricity $e \approx 0.01$ (ref. 2), generated by its dynamical interaction with Io and Ganymede, which should cause the equilibrium spin rate of the satellite to be slightly faster than synchronous. Recent gravity data[3] suggest that there may be a permanent asymmetry in Europa's interior mass distribution which is large enough to offset the tidal torque; hence, if non-synchronous rotation is observed, the surface is probably decoupled from the interior by a subsurface layer of liquid[4] or ductile ice[1]. Non-synchronous rotation was invoked to explain Europa's global system of lineaments and an equatorial region of rifting seen in Voyager images[5,6]. Here we report an analysis of the orientation and distribution of these surface features, based on initial observations made by the Galileo spacecraft. We find evidence that Europa spins faster than the synchronous rate (or did so in the past), consistent with the possibility of a global subsurface ocean.**


hemisphere, centred at 45° N, 221° W. False-colour composites made up from these images show at least three distinct classes of linear features on Europa's surface (Fig. 1). These features may represent different stages of development of tectonic lineaments on Europa. Their distributions are shown in Fig. 2, derived from photogeological and spectral mapping (supervised classification) of the photometrically corrected four-colour data. Bands with spectral reflectance similar to the bright wedge (Fig. 2a) make up the stratigraphically oldest lineaments and generally have south-west–northeast trends. The intermediate-aged triple-bands (Fig. 2b) trend roughly east–west, with the younger of the two

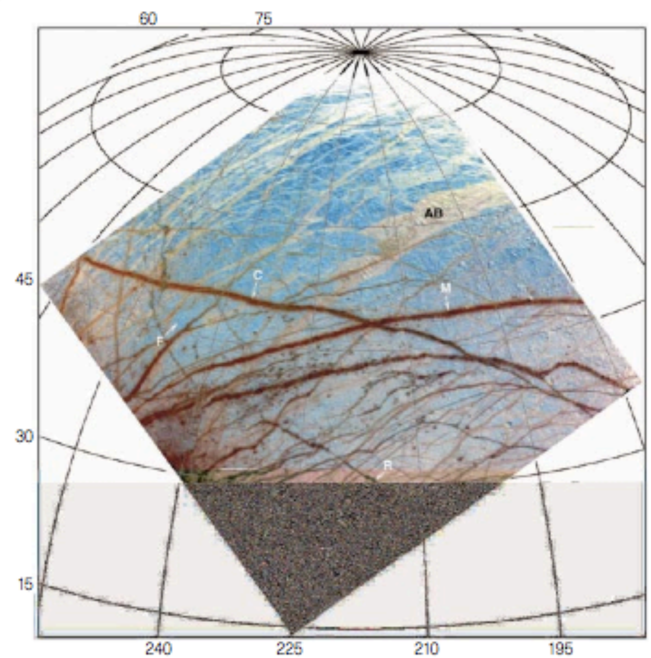
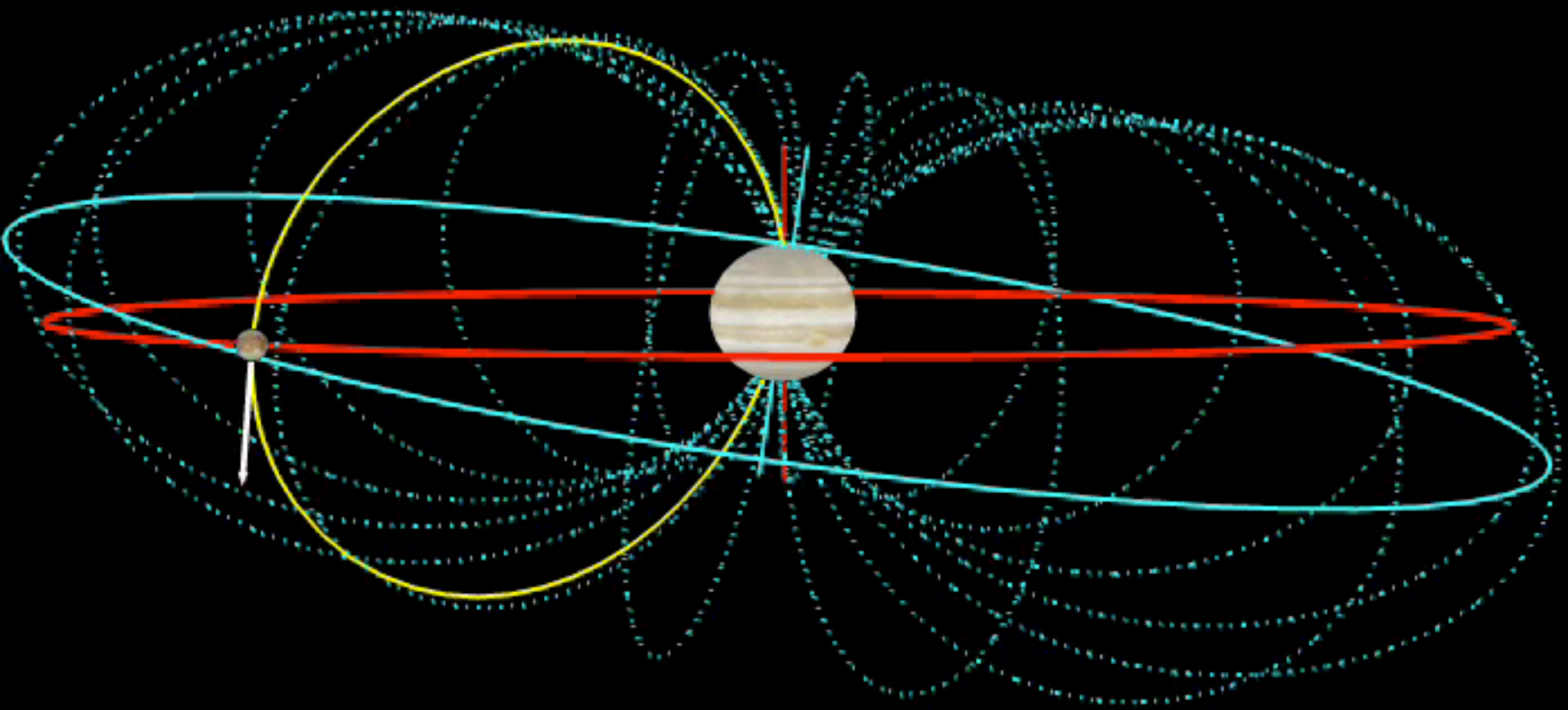



**Figure 1** False-colour composite of northern high-latitude region of Europa, produced from images images taken through the 968-nm, 756-nm and green filters. Overlaid is a grid showing location in degrees North latitude and West longitude. The most prominent linear features are the dark triple-bands such as Cadmus Linea and Minos Linea. The triple-bands overprint many older lineaments which are intermediate in colour between the triple-bands and the



# Induced magnetic field

## Induced magnetic fields as evidence for subsurface oceans in Europa and Callisto

**K. K. Khurana*, M. G. Kivelson*†, D. J. Stevenson‡, G. Schubert*†, C. T. Russell*†, R. J. Walker* & C. Polanskey§**

** Institute of Geophysics and Planetary Physics, † Department of Earth and Space Sciences, University of California, Los Angeles, California 90095, USA*
*‡ Division of Geological and Planetary Sciences, California Institute of Technology, Pasadena, California 91125, USA*
*§ The Jet Propulsion Laboratory, 4800 Oak Grove Road, Pasadena, California 91109, USA*

**The Galileo spacecraft has been orbiting Jupiter since 7 December 1995, and encounters one of the four galilean satellites—Io, Europa, Ganymede and Callisto—on each orbit. Initial results from the spacecraft's magnetometer[1,2] have indicated that neither Europa nor Callisto have an appreciable internal magnetic field, in contrast to Ganymede[3] and possibly Io[4]. Here we report perturbations of the external magnetic fields (associated with Jupiter's inner magnetosphere) in the vicinity of both Europa and Callisto. We interpret these perturbations as arising from induced magnetic fields, generated by the moons in response to the periodically varying plasma environment. Electromagnetic induction requires eddy currents to flow within the moons, and our calculations show that the most probable explanation is that there are layers of significant electrical conductivity just beneath the surfaces of both moons. We argue that these conducting layers may best be explained by the presence of salty liquid-water oceans, for which there is already indirect geological evidence[5,6] in the case of Europa.**

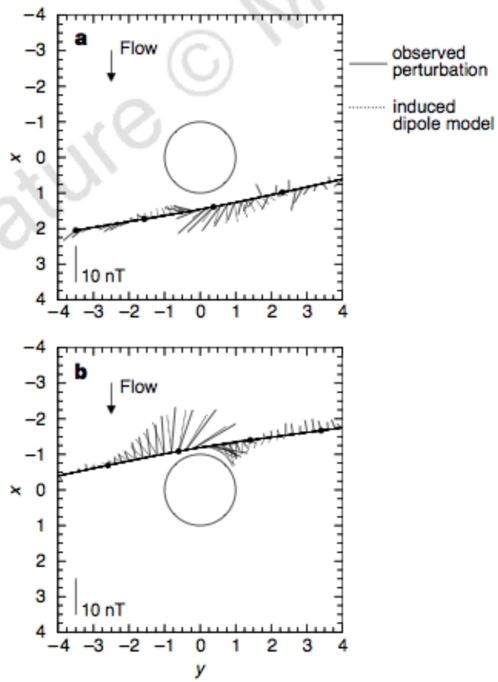
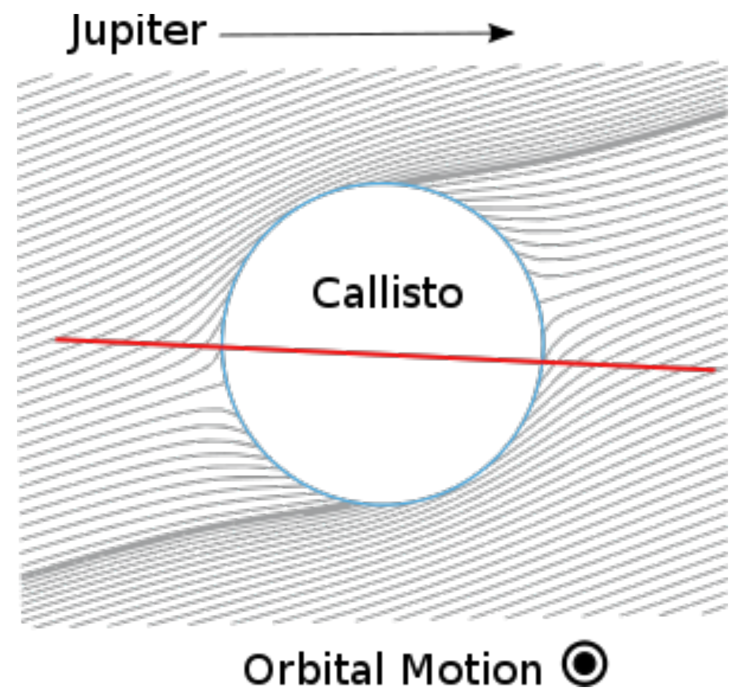
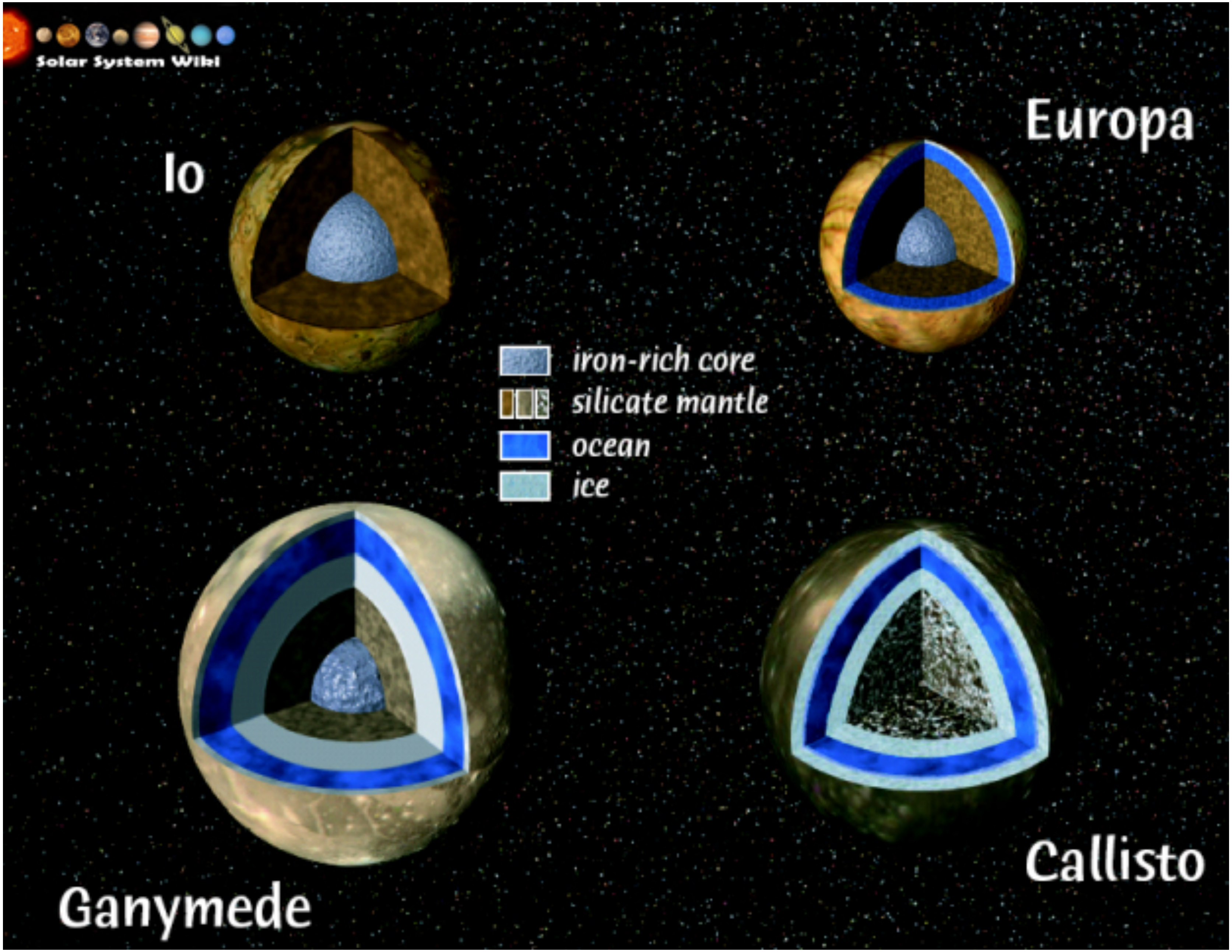


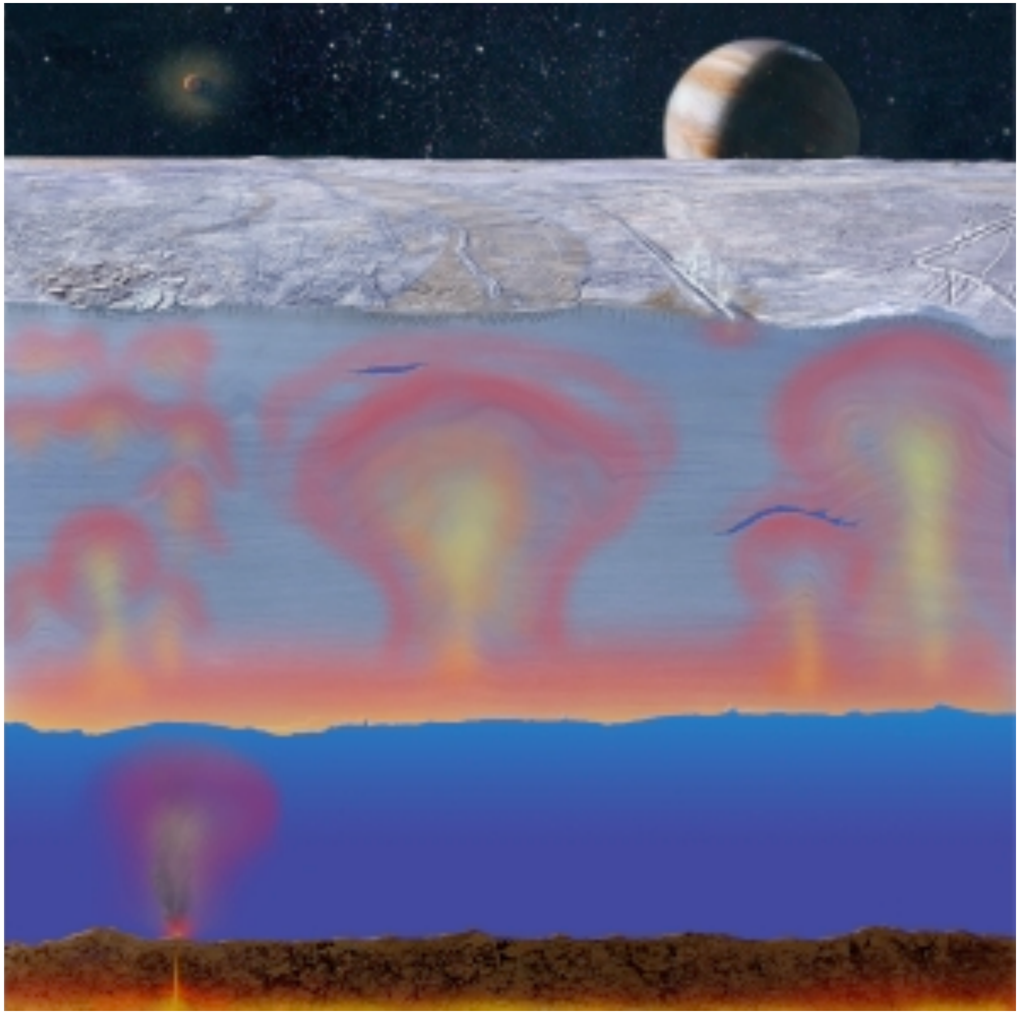

**Figure 3** Magnetic field observations from the C3 and C9 passes. **a**, The magnetic field perturbations (vectors drawn with solid lines) and the modelled induction field (vectors shown dotted) along the trajectory of the C3 encounter in the *x*–*y* plane. **b**, The magnetic field perturbations and the modelled induction field for the C9 encounter. The distance scale is in units of $R_C$ ($1R_C$ = radius of Callisto = 2,409 km).



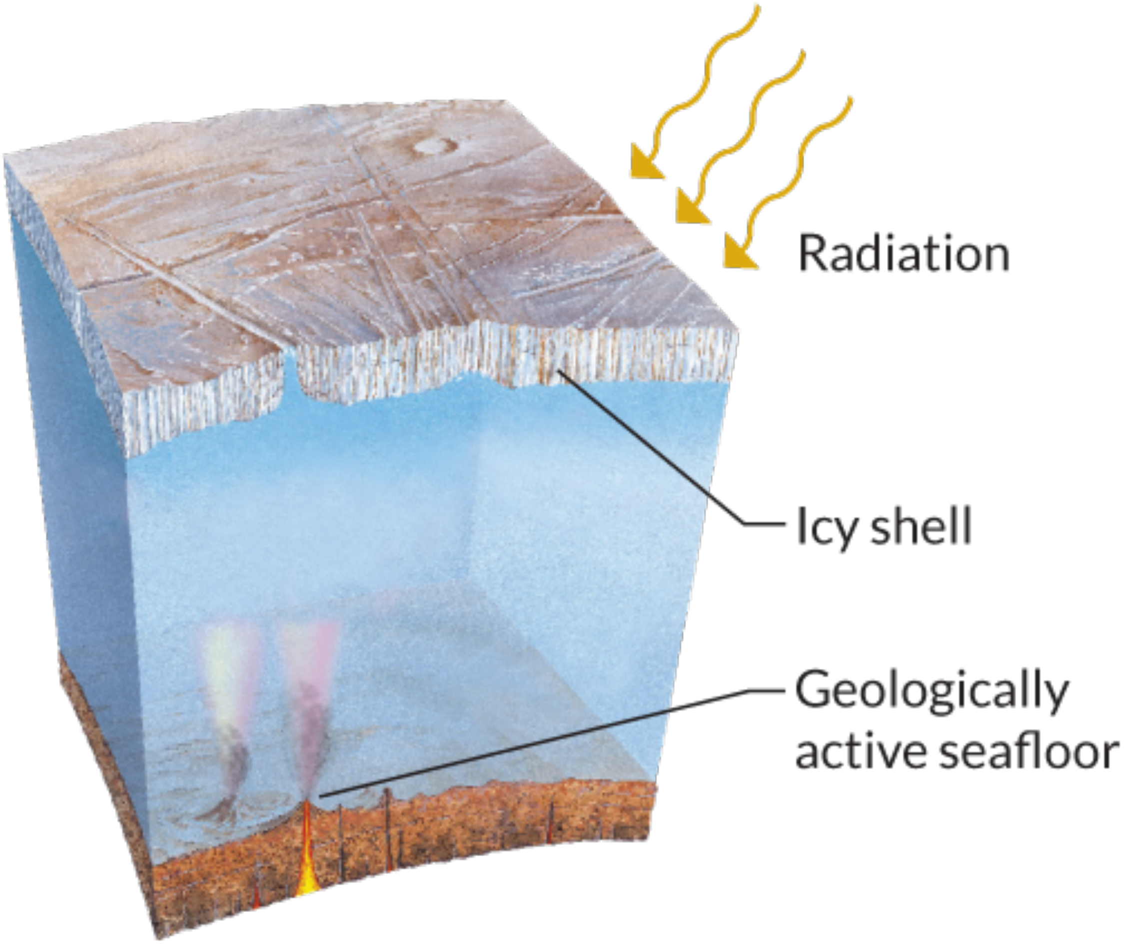


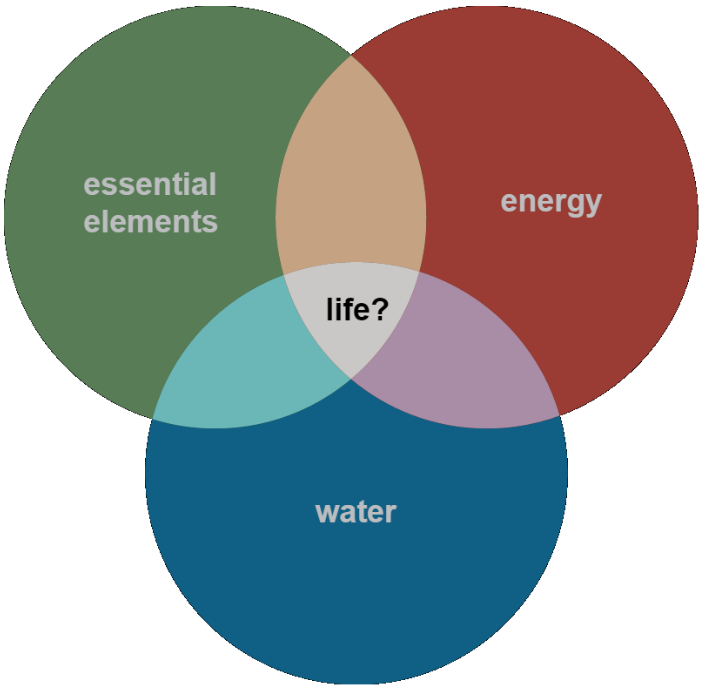
Solar System Wiki
Io
Europa
iron-rich core
silicate mantle
ocean
ice
Ganymede
Callisto

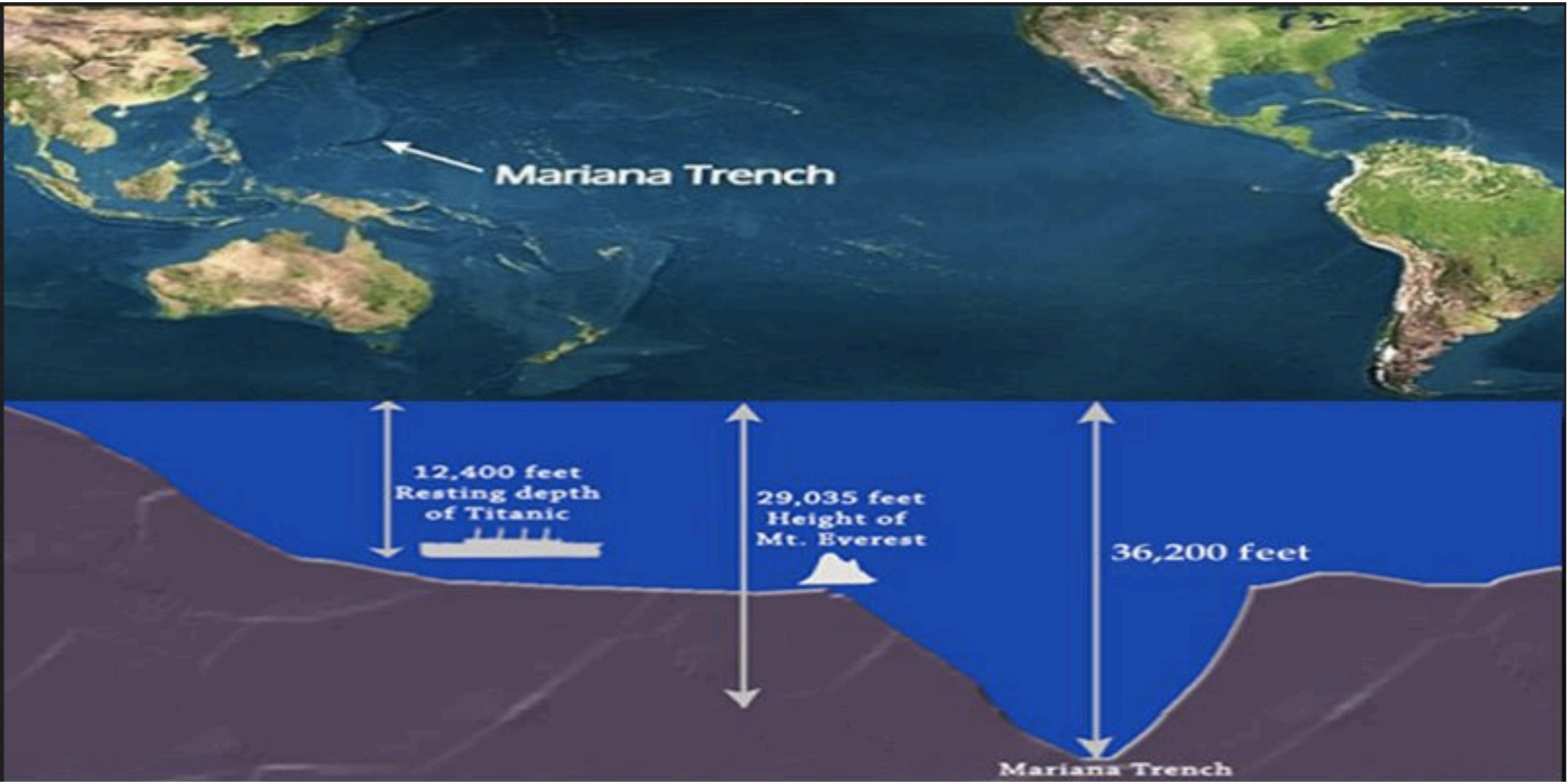
# Ice Convection

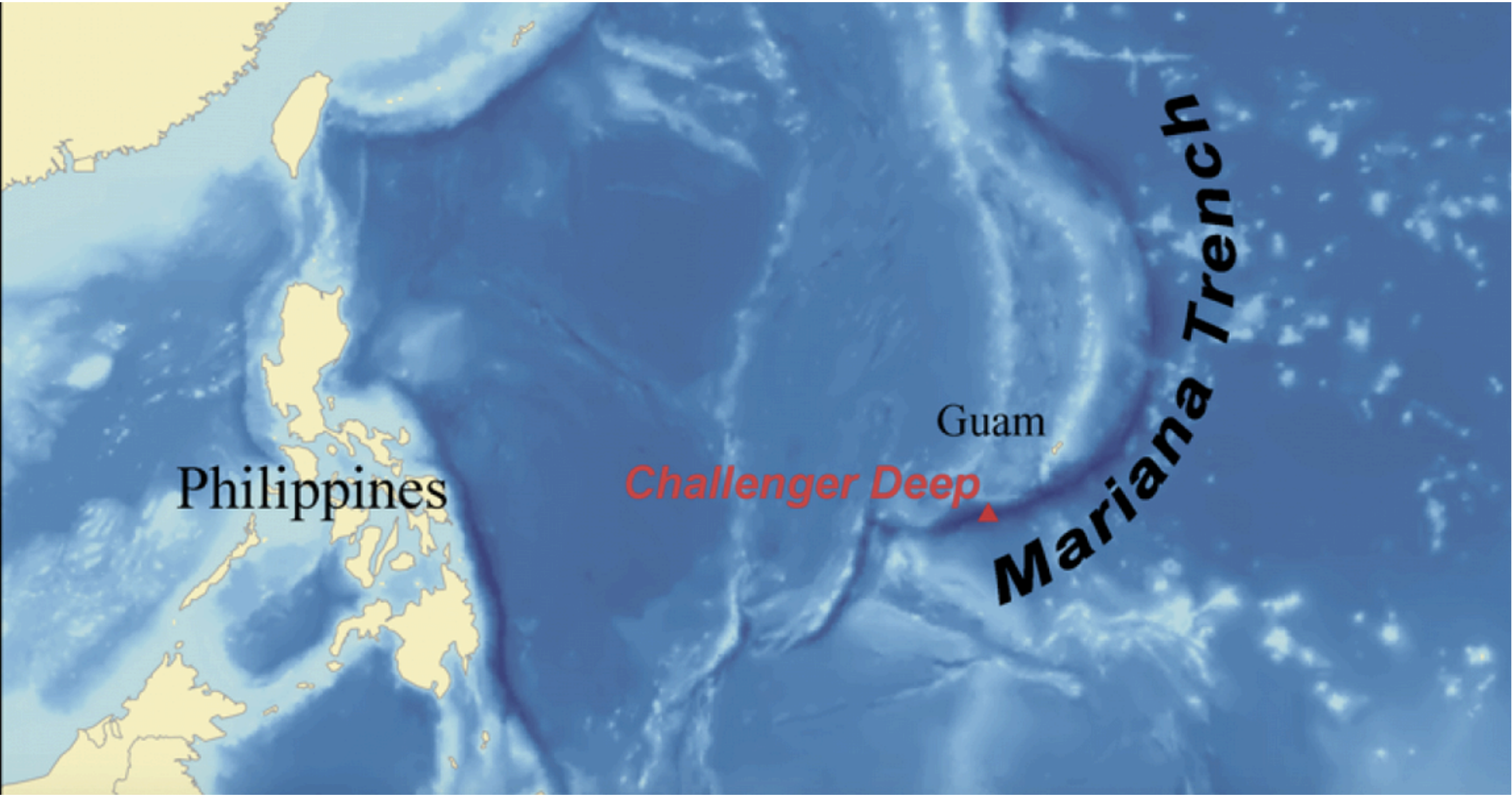


# Life?


Radiation
Icy shell
Geologically
active seafloor


essential
elements
energy
life?
water


Mariana Trench
12,400 feet
Resting depth
of Titanic
29,035 feet
Height of
Mt. Everest
36,200 feet
Mariana Trench


Mariana Trench
Guam
Philippines
Challenger Deep


Challenger Deep: 11,156 m


2
3
4


Sirena Deep: 10,700 m

# Serpentinization

(hydration of olivine)

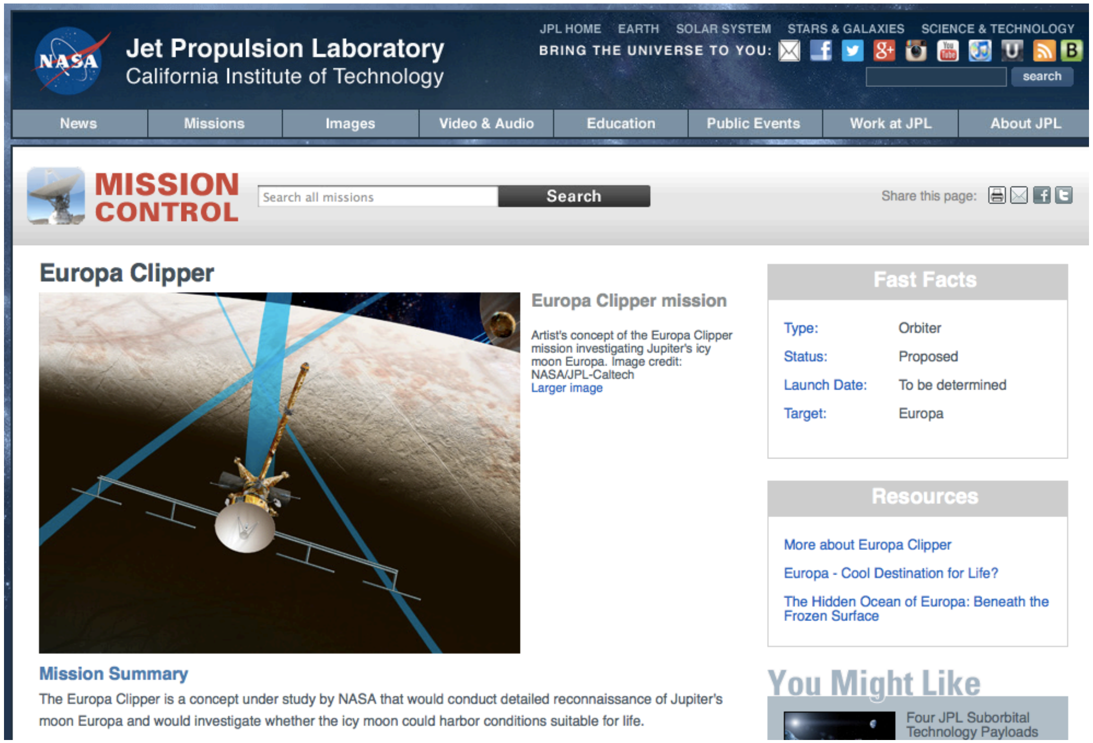
Olivine + $H_2O$ → Serpentine

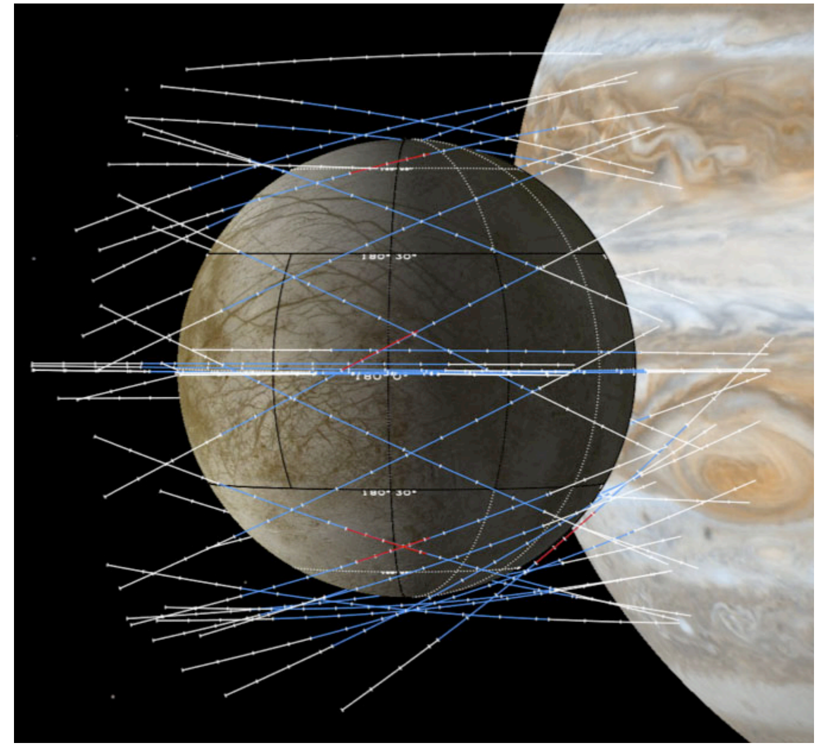
(+ HEAT and Large VOLUME Increase
With high pH and highly reducing conditions)

**Olivine (Peridotite)**

**Serpentinite**

# Europa Clipper



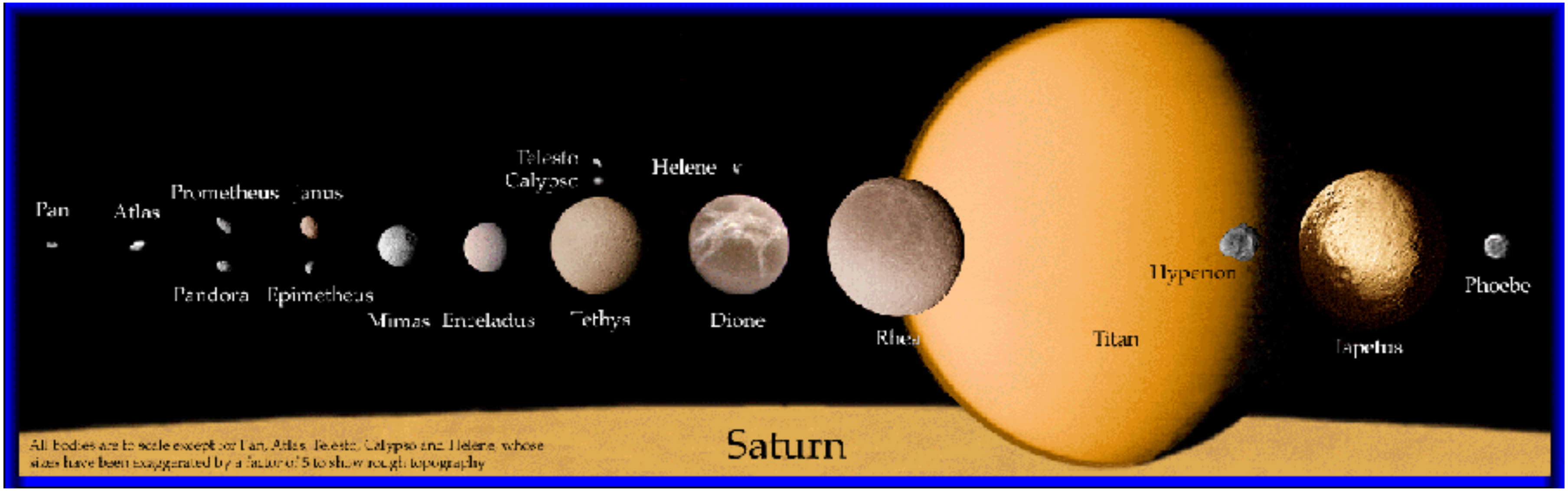
Reconnaissance: 45 flybys, as low as 25km

Radar to determine ice's thickness

High resolution camera

Identify future landing sites

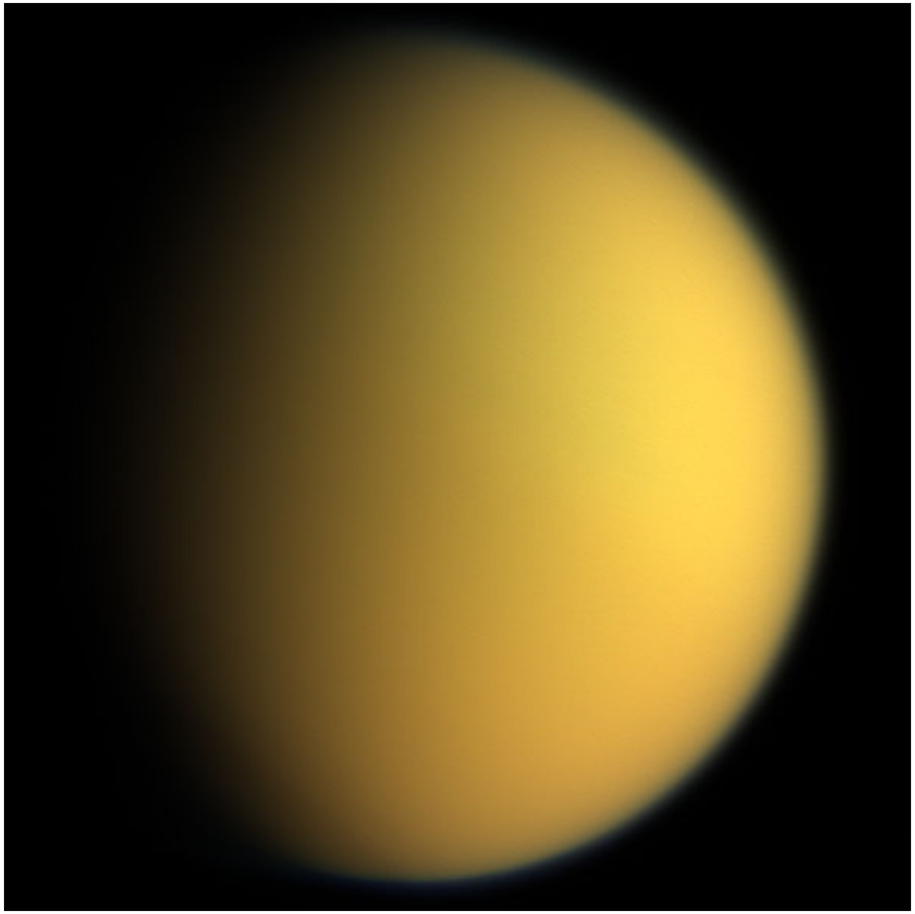
# Saturn's Giant Moon




Second in size only to Ganymede, **Titan** is bigger than Mercury

The only satellite with a considerable atmosphere

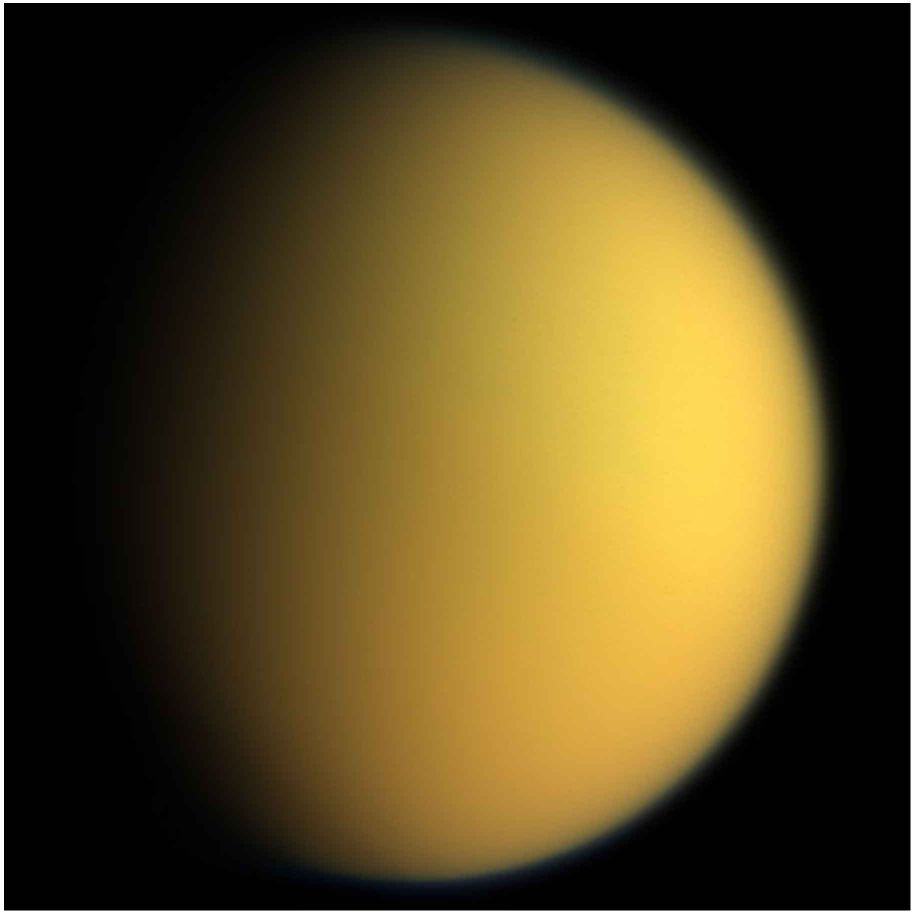
# Titan



Atmosphere!

100% covered in opaque orange haze
No view of the surface

# Titan



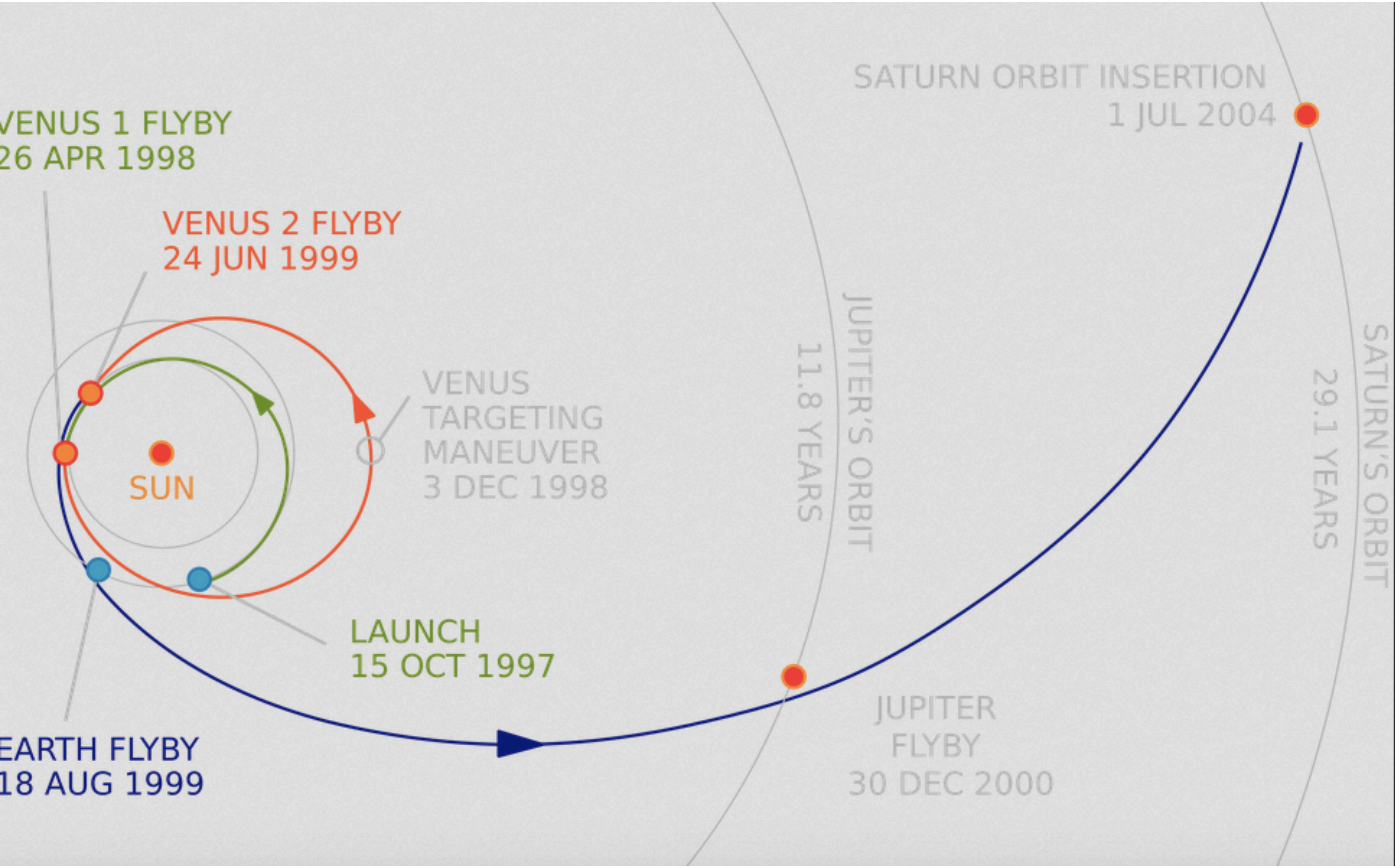
Methane triple point
~90K

Titan's mean temperature

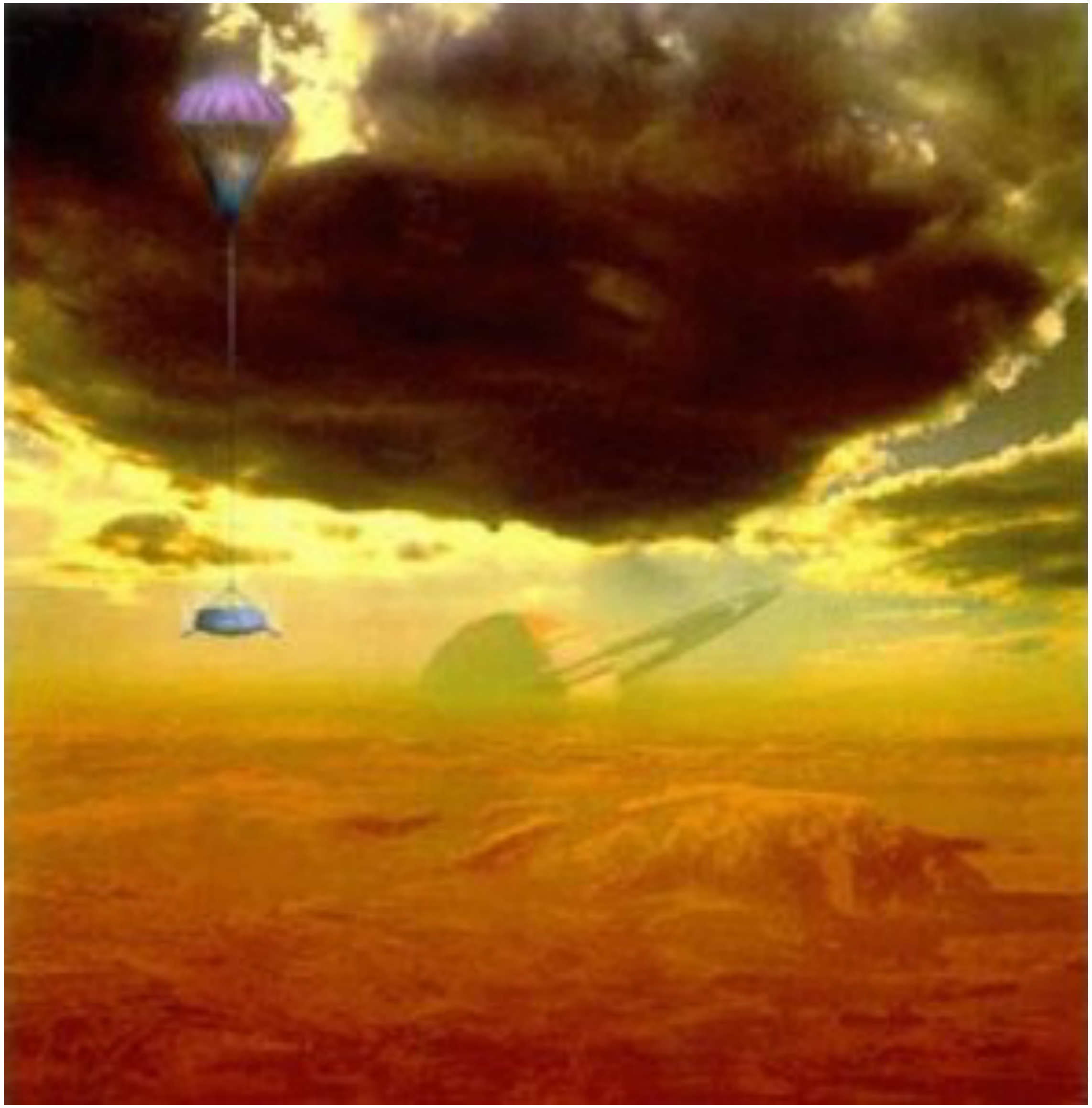
~93K

Methane in Titan should be like water on Earth!

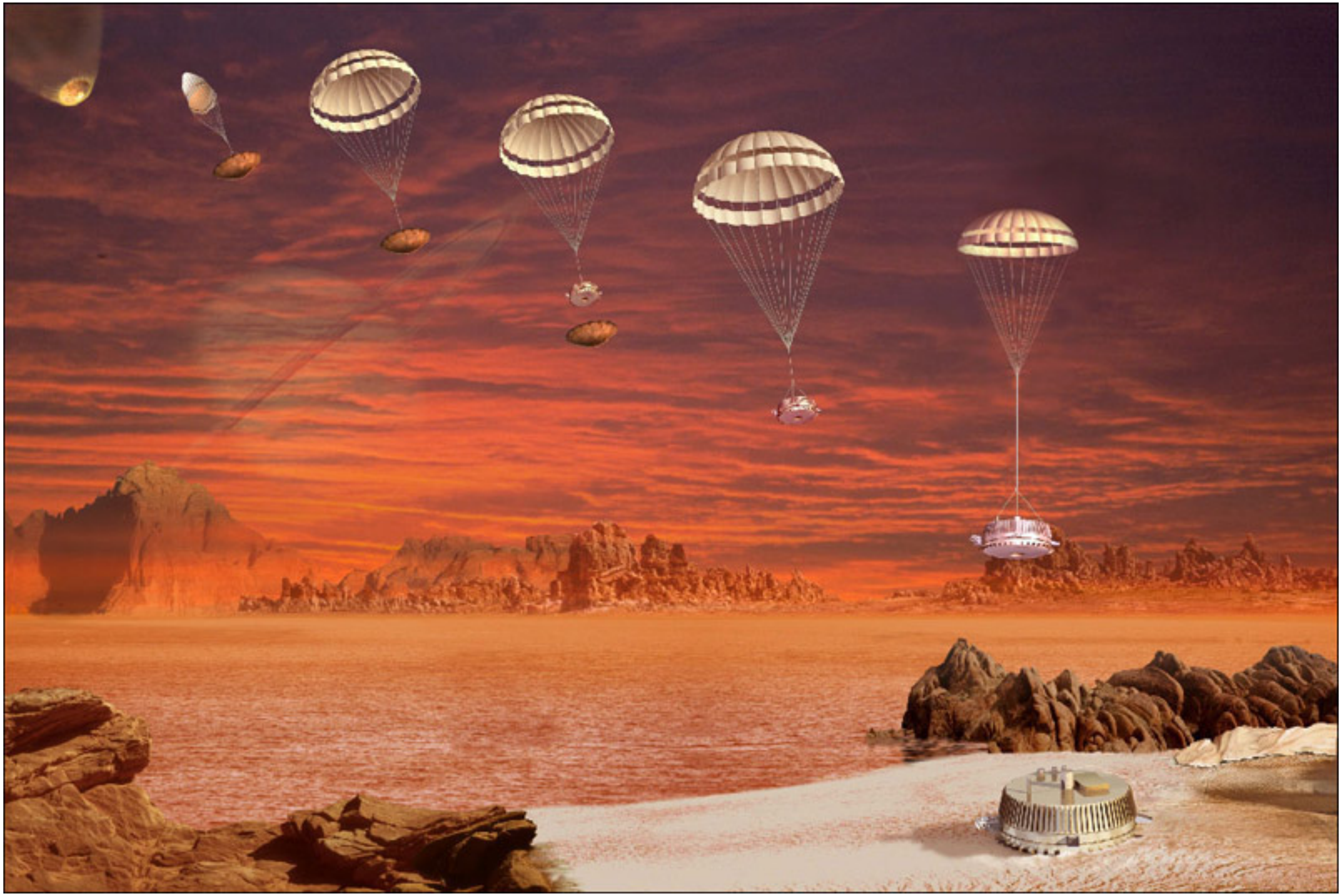
Presence of liquid hydrocarbons highly likely.


SATURN ORBIT INSERTION
1 JUL 2004
VENUS 1 FLYBY
26 APR 1998
VENUS 2 FLYBY
24 JUN 1999
VENUS
TARGETING
MANEUVER
3 DEC 1998
SUN
11.8 YEARS
JUPITER'S ORBIT
29.1 YEARS
SATURN'S ORBIT
LAUNCH
15 OCT 1997
JUPITER
FLYBY
30 DEC 2000
EARTH FLYBY
18 AUG 1999

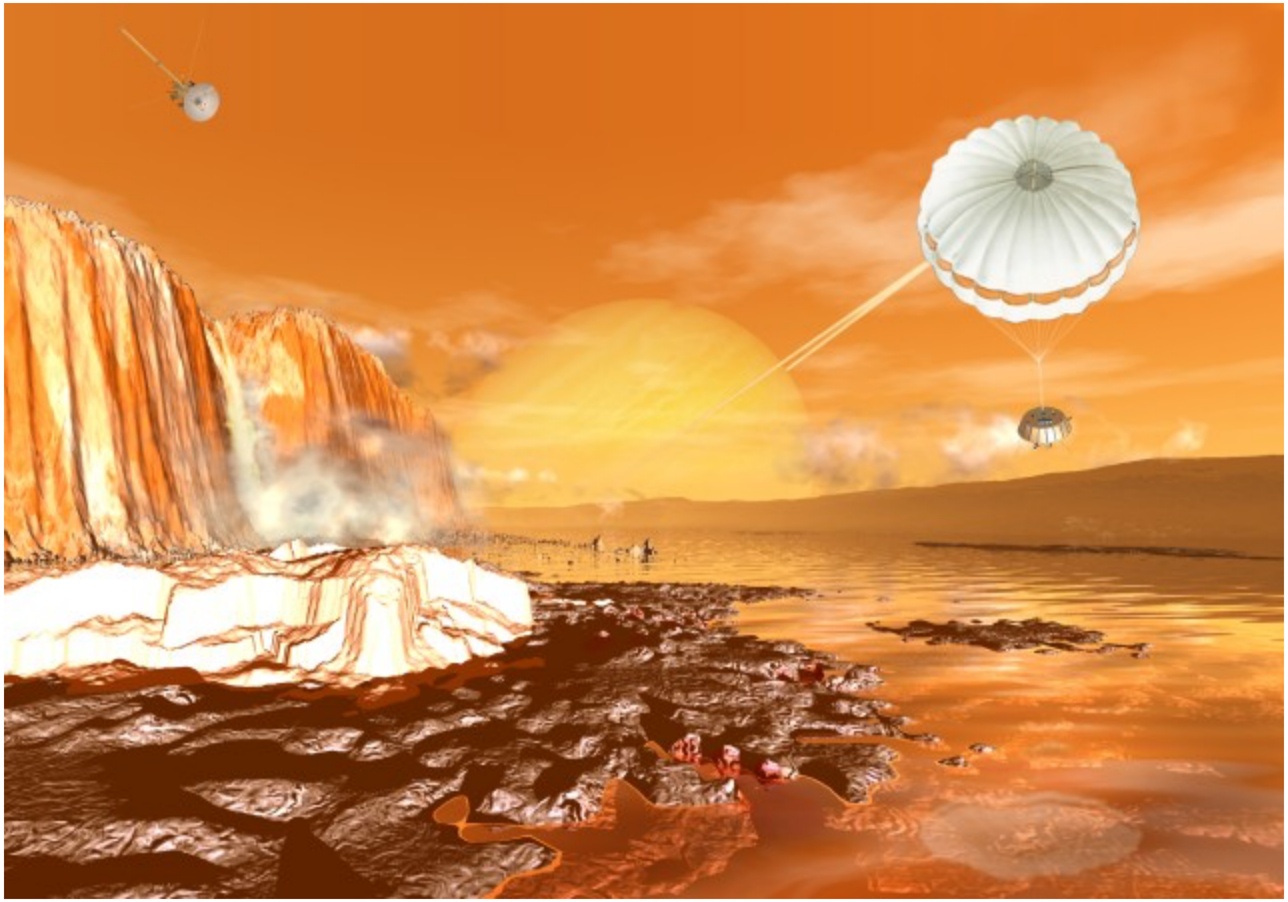
# Pre-Cassini speculations



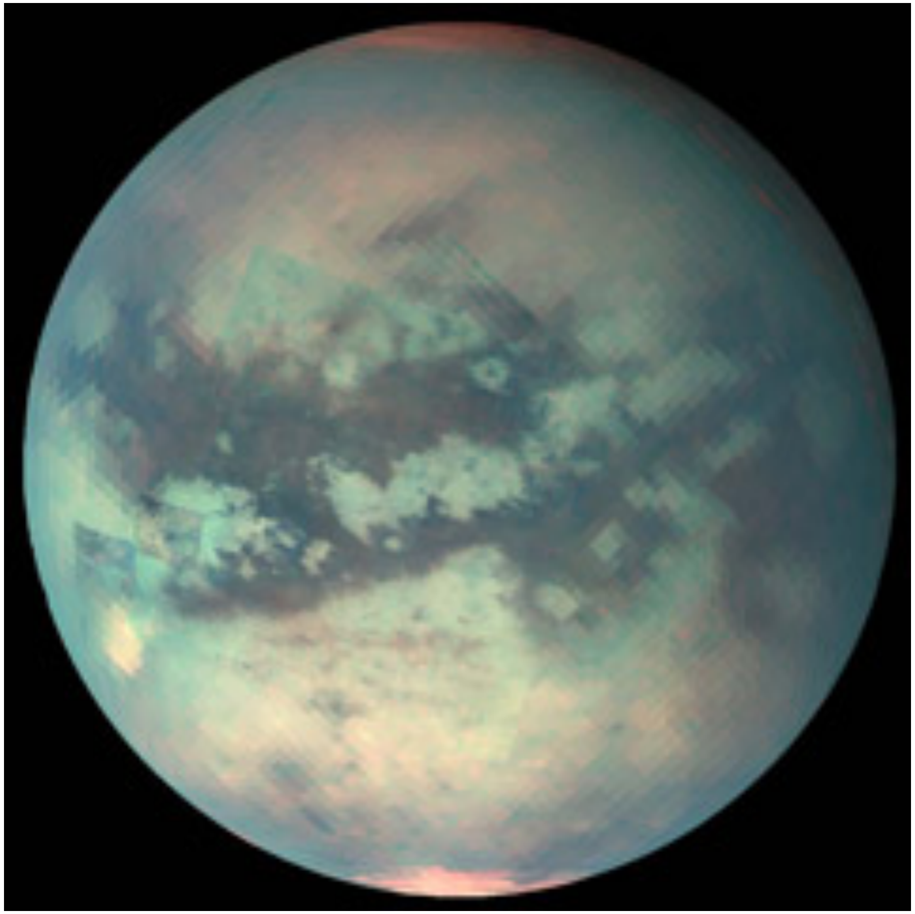
# Pre-Cassini speculations



# Pre-Cassini speculations

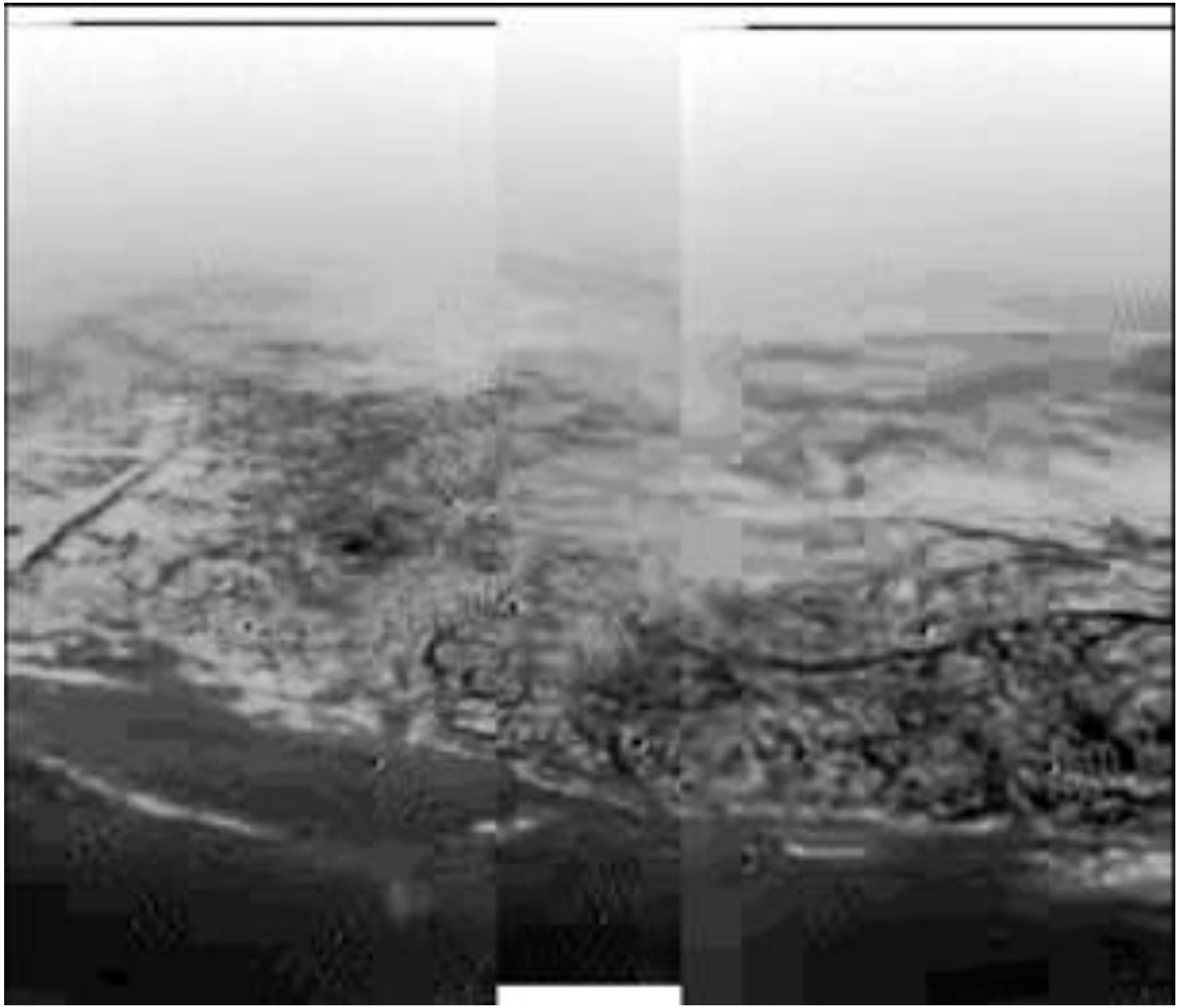


# Titan



Radar image by Cassini

# Huygens descent



# Huygens descent

# Huygens landing site

# Huygens landing site

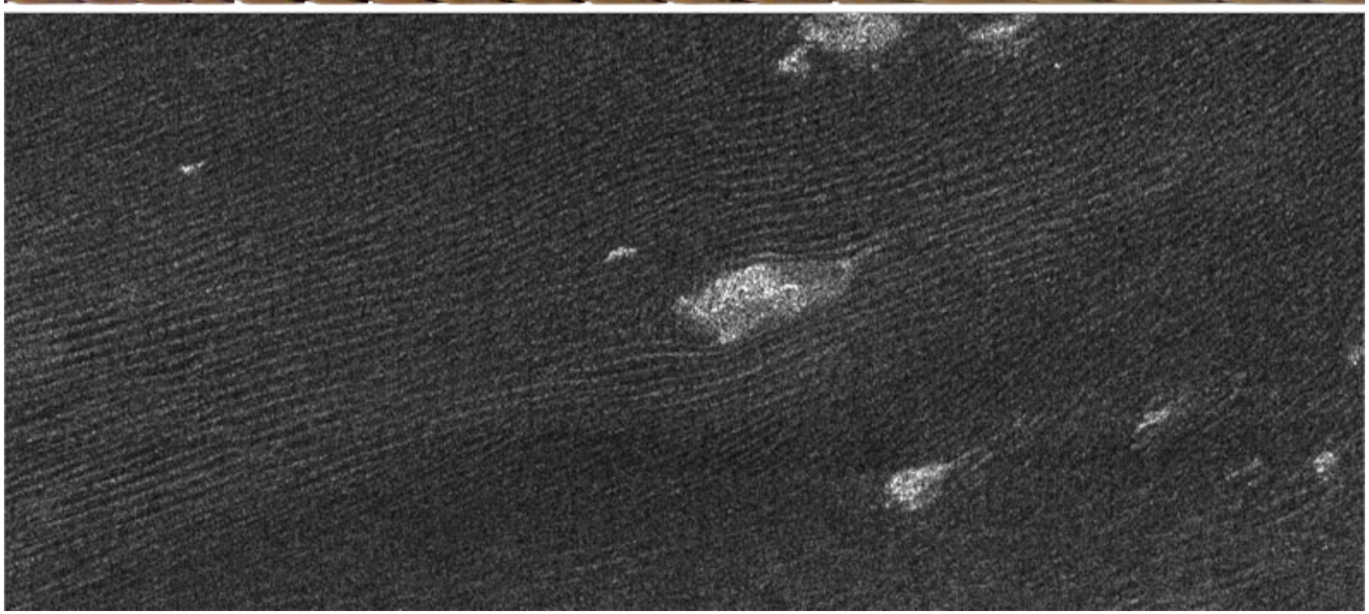
# Huygens landing site

Titan　　　　Earth

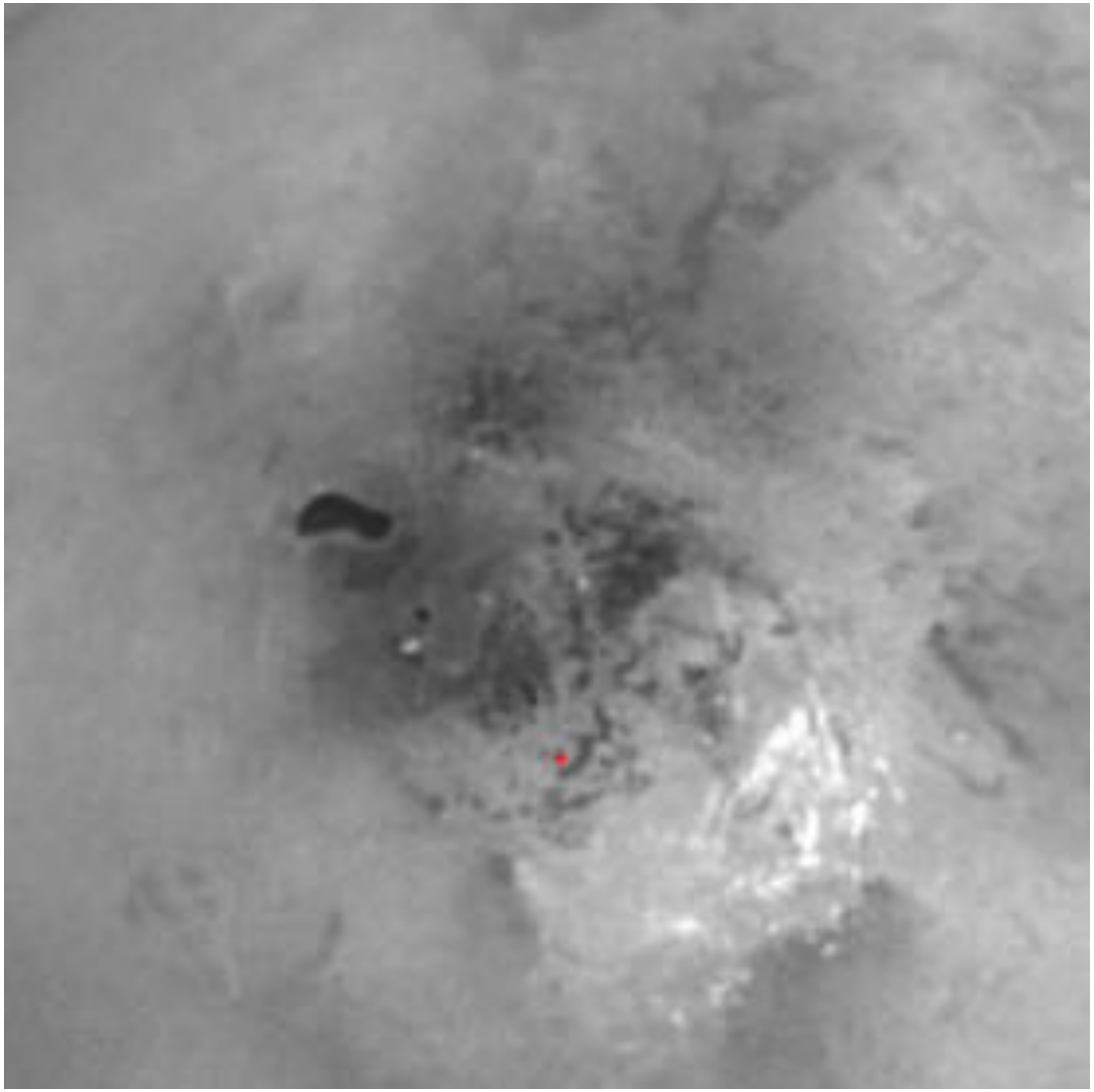
# Titan Dunes

Earth

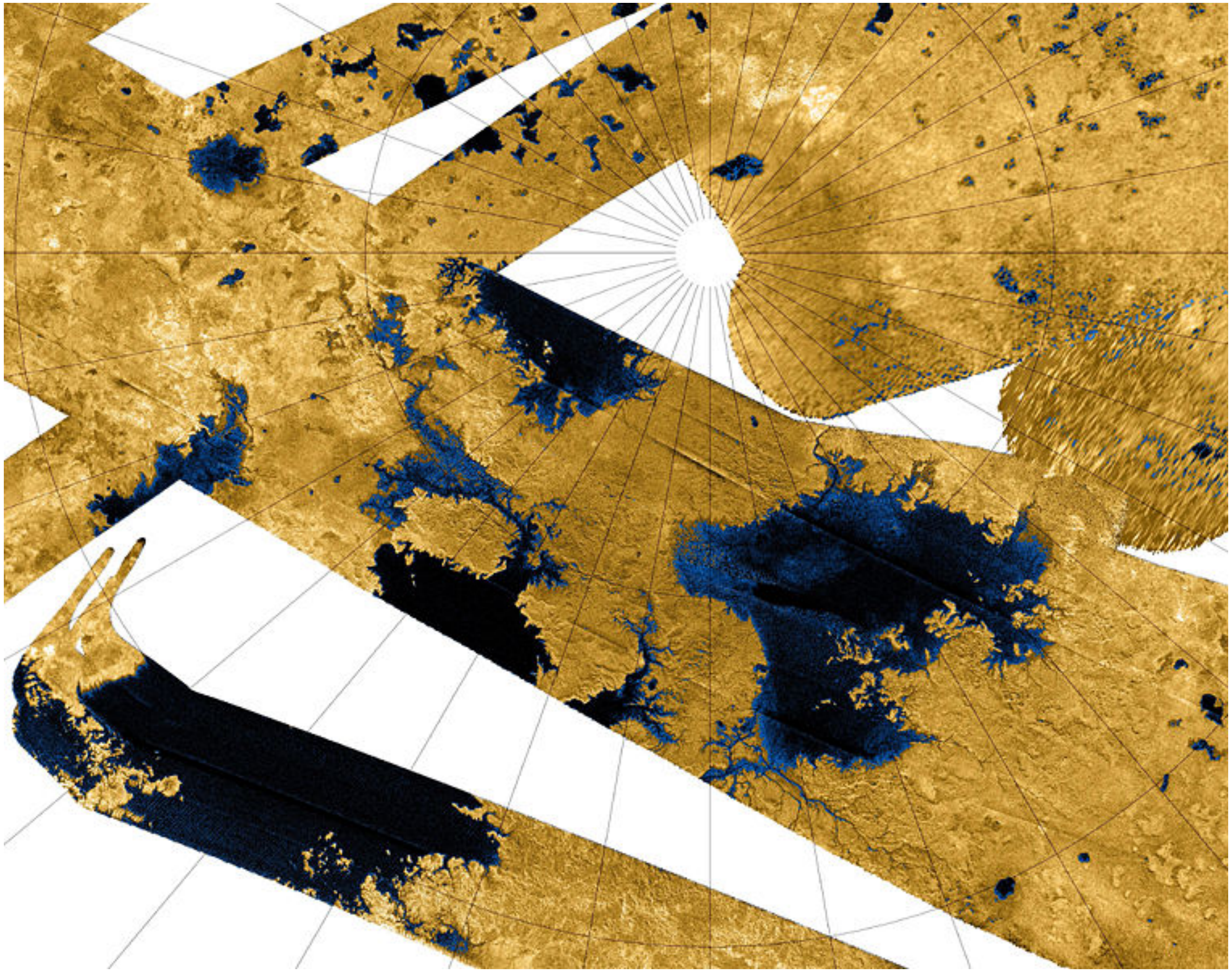
Titan



# A little lake near the South Pole

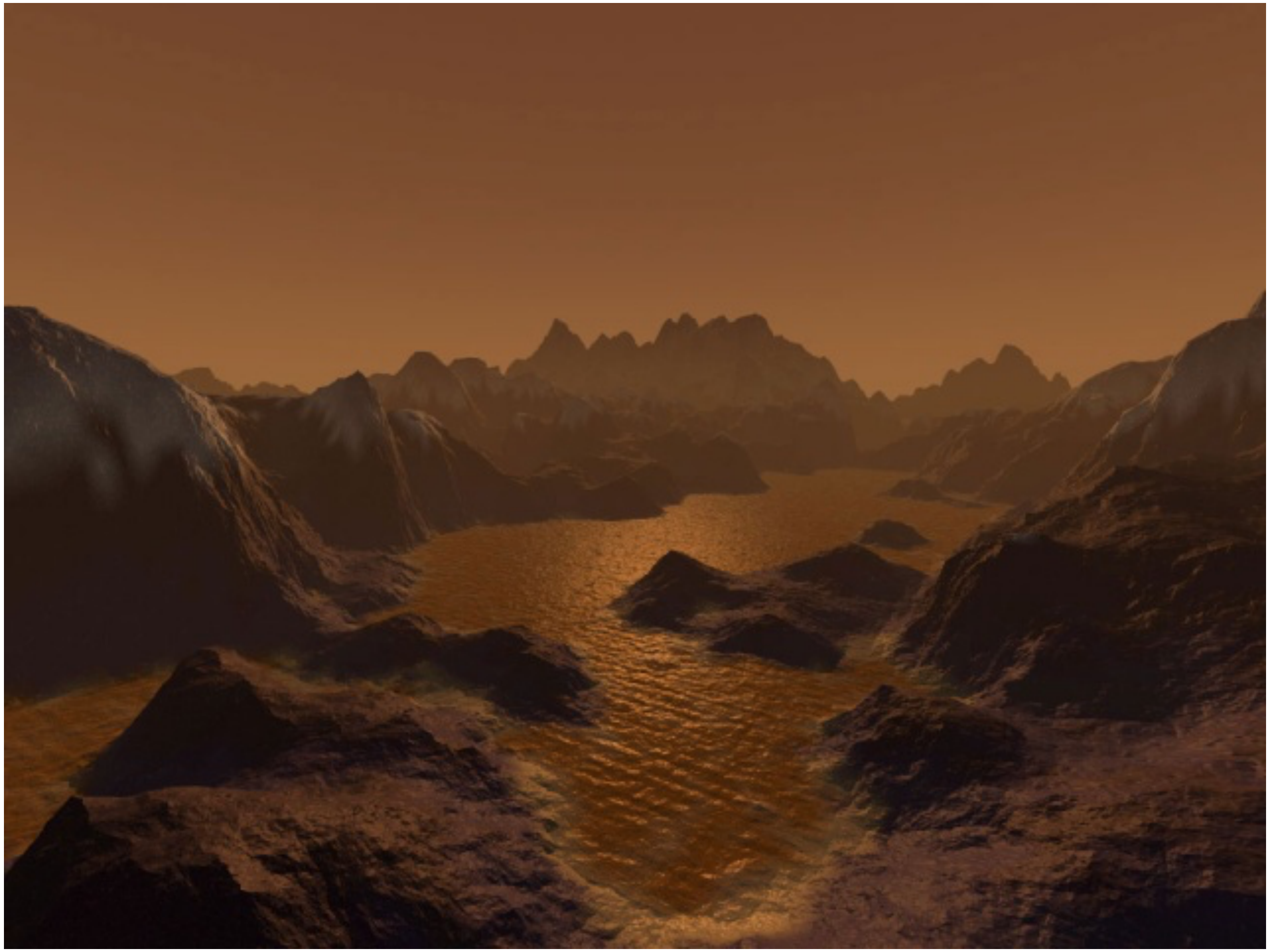


# Lakes at last!

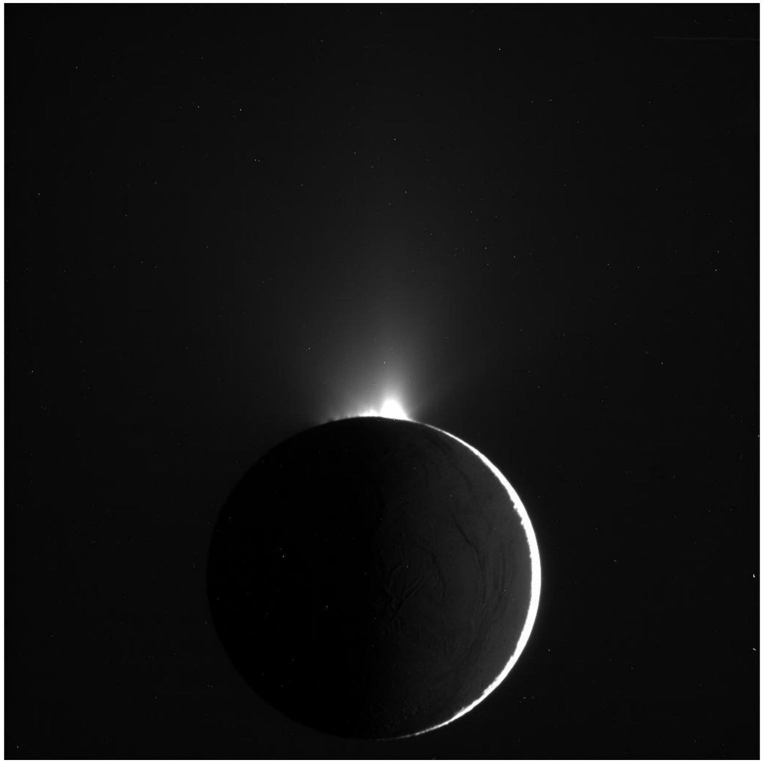


# Lakes at last!

# Lakes of Titan

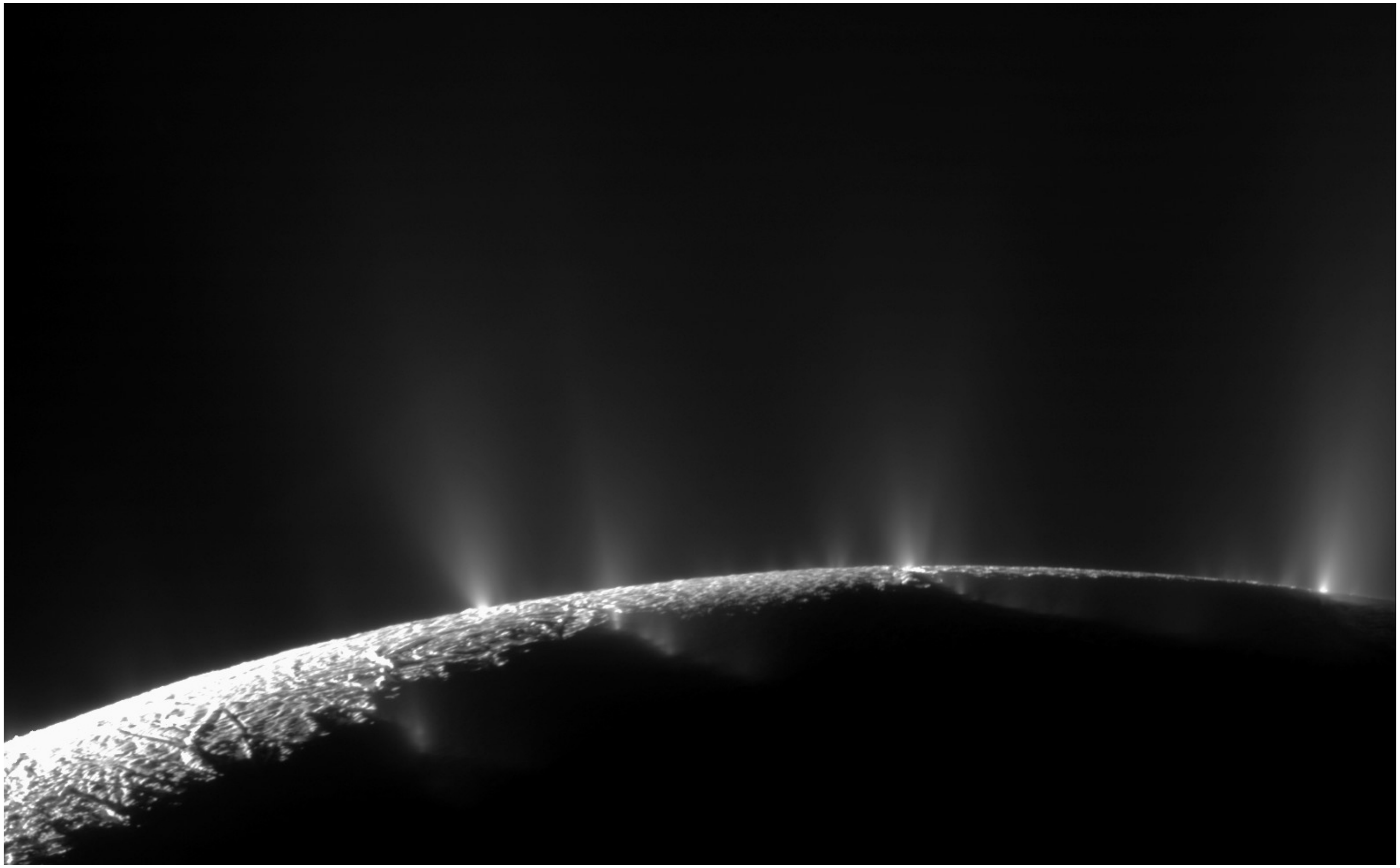


# Enceladus



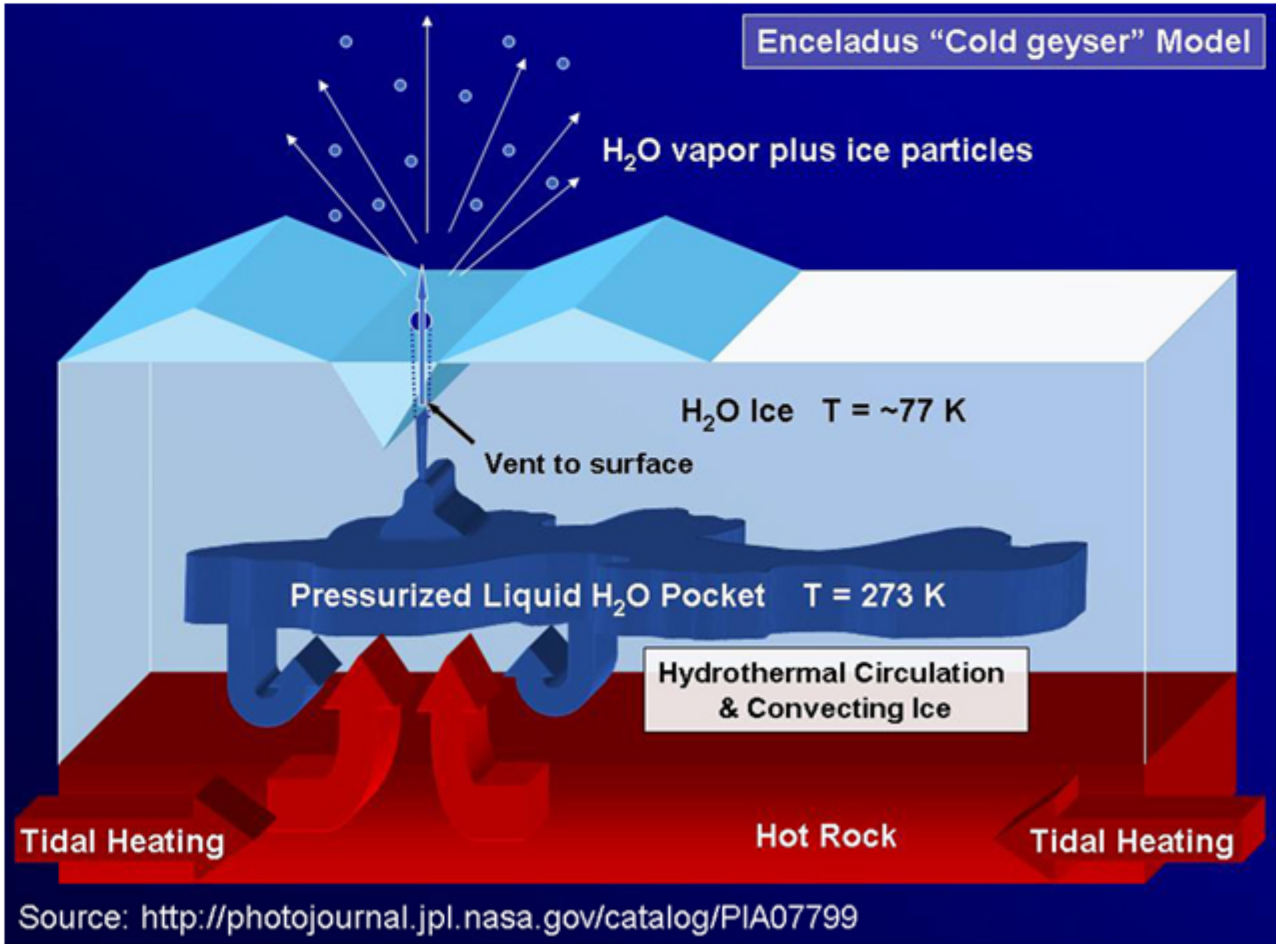
Plumes imaged by Cassini

# Enceladus



Close up of the plumes

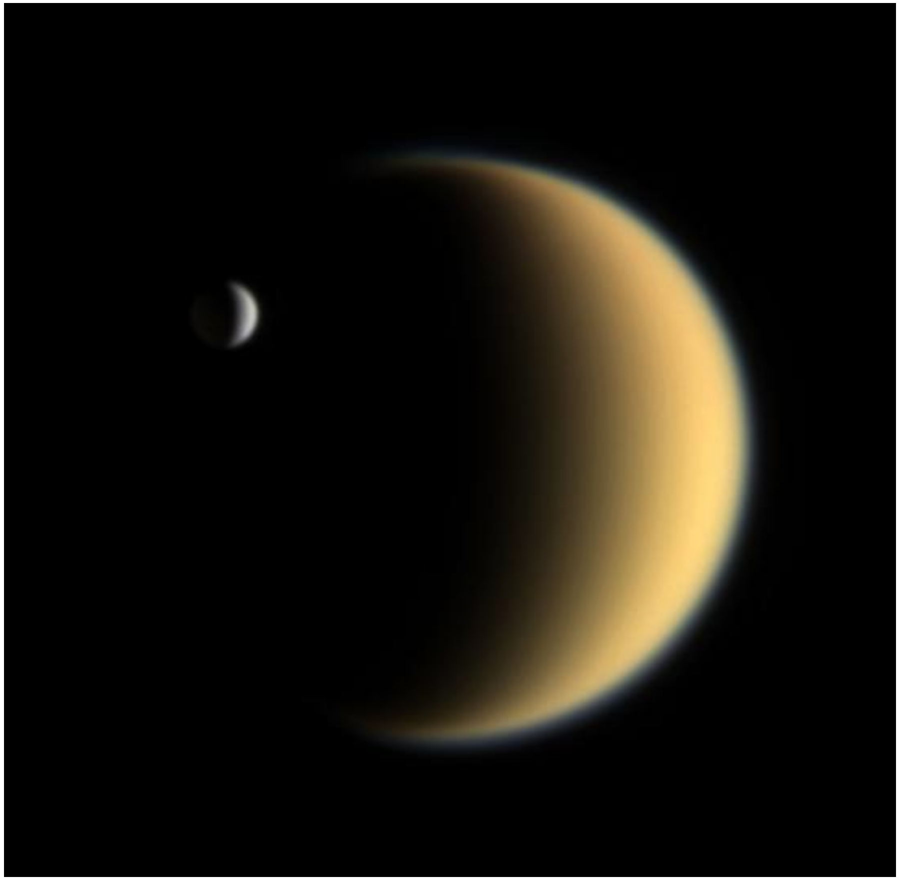
# Enceladus



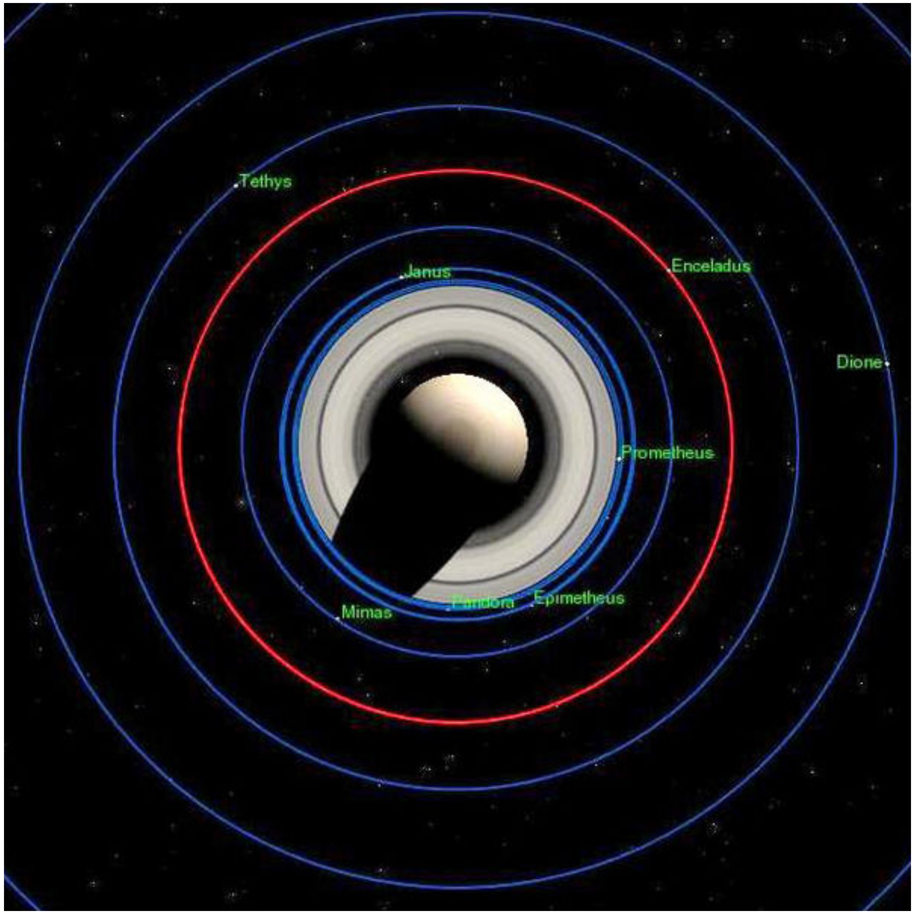
Enceladus "Cold geyser" Model
H2O vapor plus ice particles
H2O Ice T = ~77 K
Vent to surface
Pressurized Liquid H2O Pocket T = 273 K
Hydrothermal Circulation & Convecting Ice
Tidal Heating
Hot Rock
Tidal Heating
Source: http://photojournal.jpl.nasa.gov/catalog/PIA07799

# Enceladus

Enceladus and Titan



# Tidal Heating!




2:1 resonance with Dione
keeps Enceladus' orbit eccentric
(e ~ 0.004)

# Can shocks from high-mass planets explain infrared emission in protoplanetary disks?


## Wladimir Lyra

California State University Northridge (CSUN)
*Tenure-Track Professor*

Jet Propulsion Laboratory (NASA-JPL)
*Research Associate*

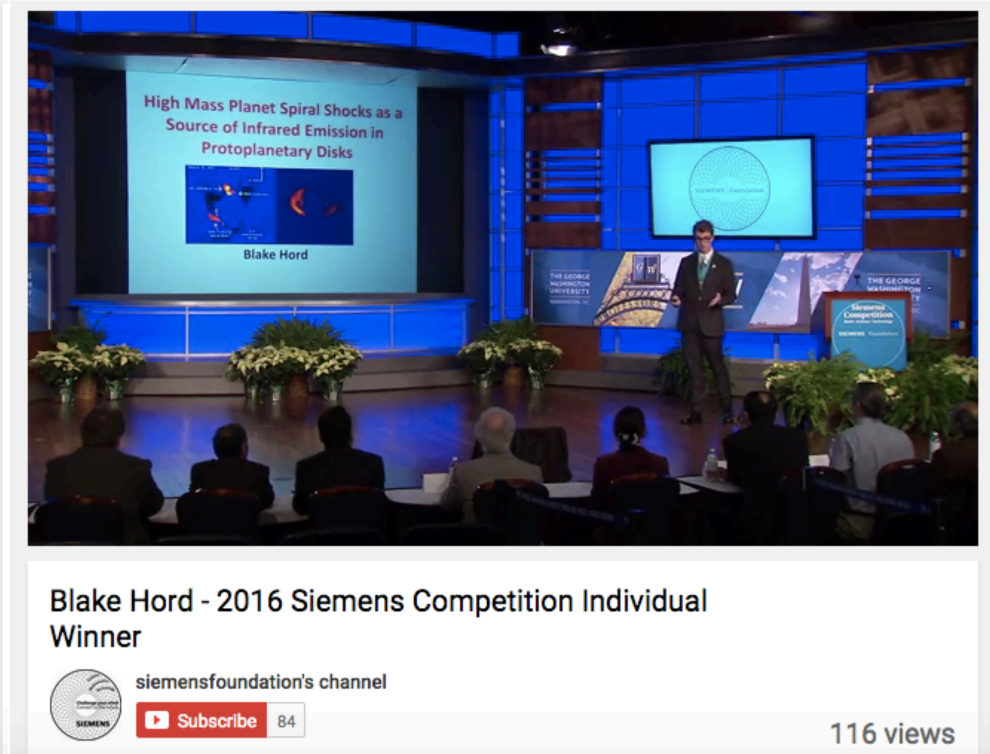
Observatorio do Valongo (OV UFRJ, Brazil)
*Friend of the department*

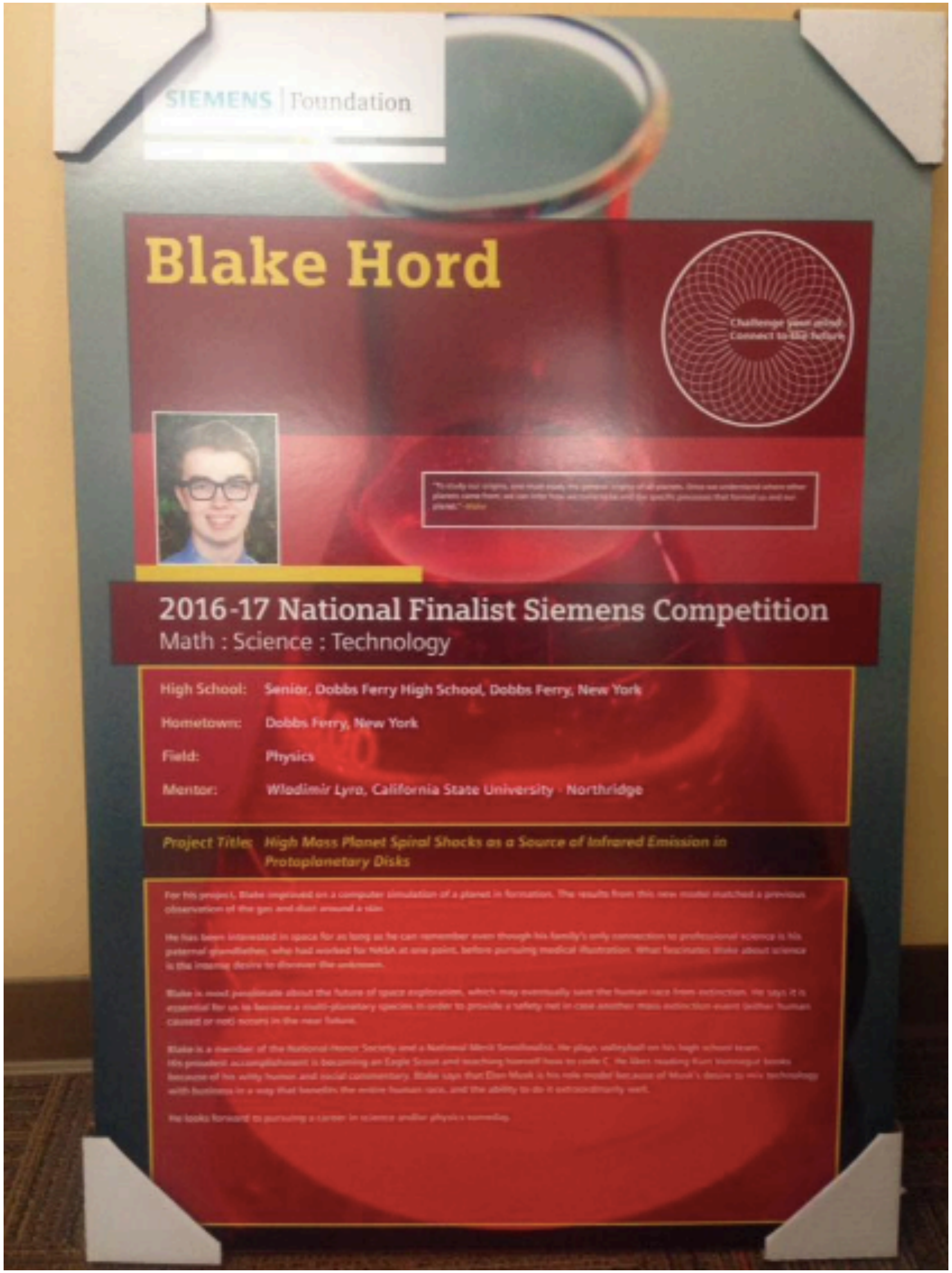
Collaborators

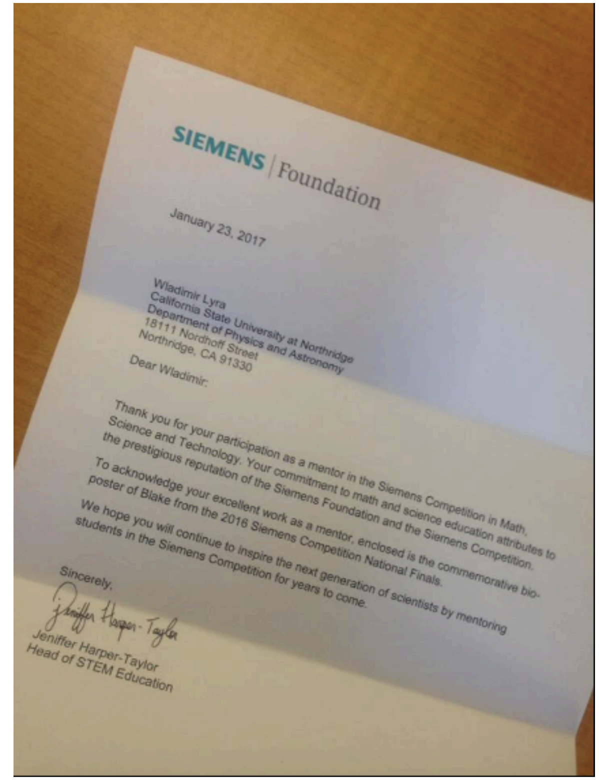
Aaron Boley (Vancouver), Kees Dullemond (Heidelberg), Mario Flock (JPL),
***Blake Hord (Dobbs Ferry High School, NY)***, Anders Johansen (Lund),
Mordecai Mac Low (AMNH), Satoshi Okuzumi (JPL), ***Alex Richert (PSU),*** Neal Turner (JPL).

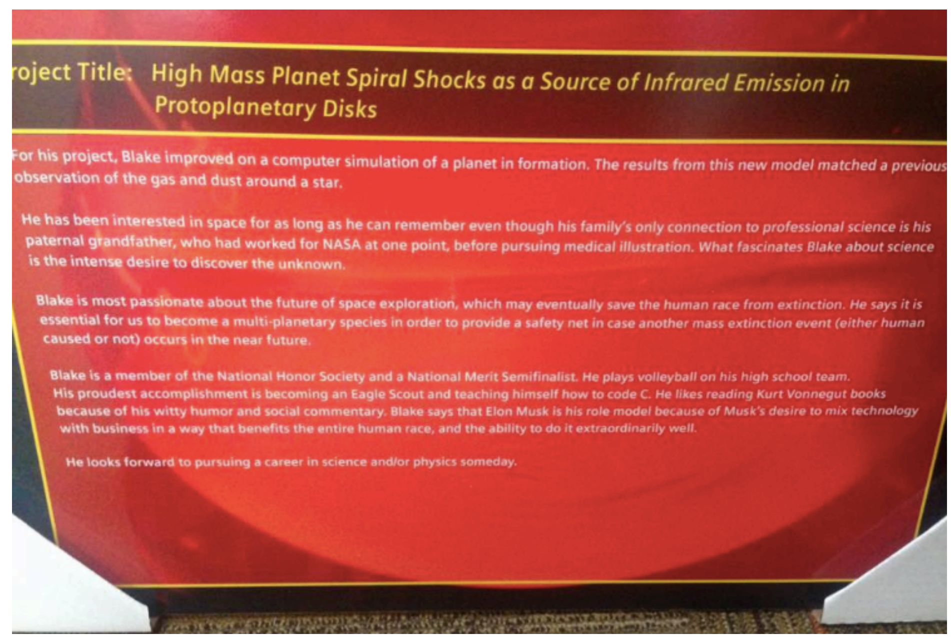

LARIM, Cartagena de Indias, Colombia, Oct $6^{th}$, 2016

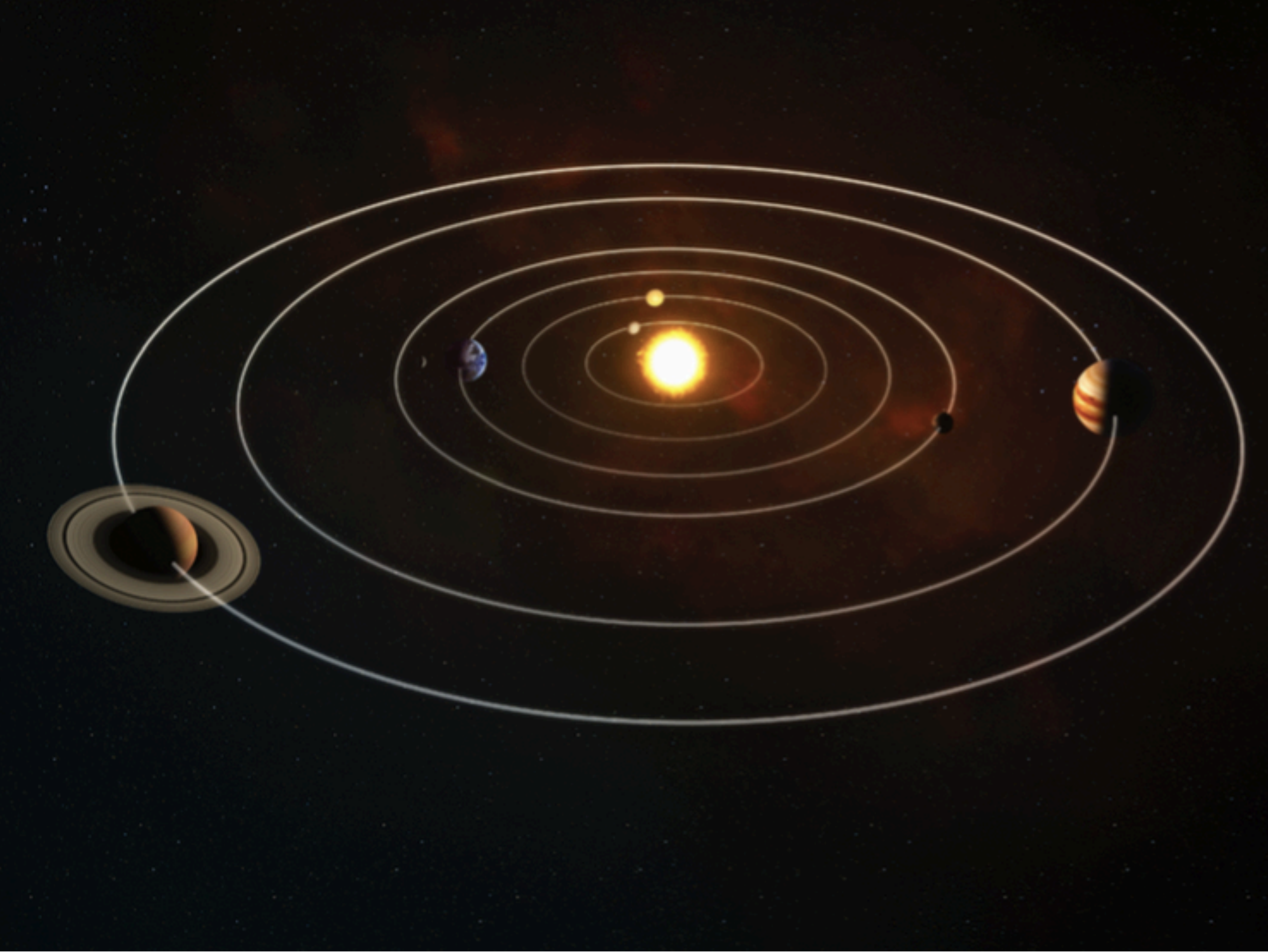
## ***Blake Hord*** *(Dobbs Ferry High School, NY)*

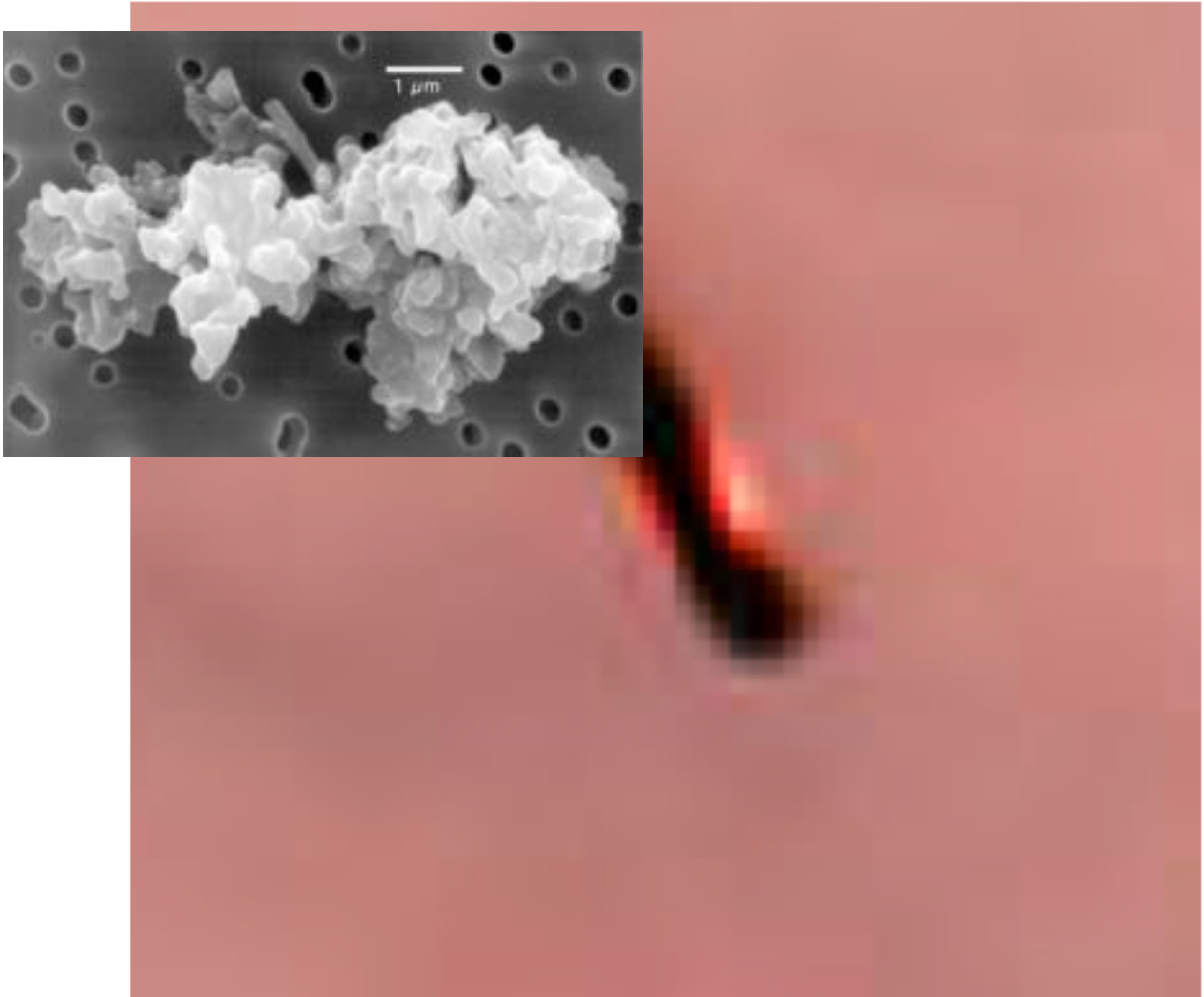

SIEMENS | Foundation
Blake Hord
2016-17 National Finalist Siemens Competition
Math : Science : Technology
High School: Senior, Dobbs Ferry High School, Dobbs Ferry, New York
Hometown: Dobbs Ferry, New York
Field: Physics
Mentor: Wlodimir Lyra, California State University - Northridge
Project Title: High Mass Planet Spiral Shocks as a Source of Infrared Emission in Protoplanetary Disks


SIEMENS | Foundation
January 23, 2017
Wladimir Lyra
California State University at Northridge
Department of Physics and Astronomy
18111 Nordhoff Street
Northridge, CA 91330
Dear Wladimir:
Thank you for your participation as a mentor in the Siemens Competition in Math, Science and Technology. Your commitment to math and science education attributes to the prestigious reputation of the Siemens Foundation and the Siemens Competition.
To acknowledge your excellent work as a mentor, enclosed is the commemorative bio-poster of Blake from the 2016 Siemens Competition National Finals.
We hope you will continue to inspire the next generation of scientists by mentoring students in the Siemens Competition for years to come.
Sincerely,
Jeniffer Harper-Taylor
Head of STEM Education

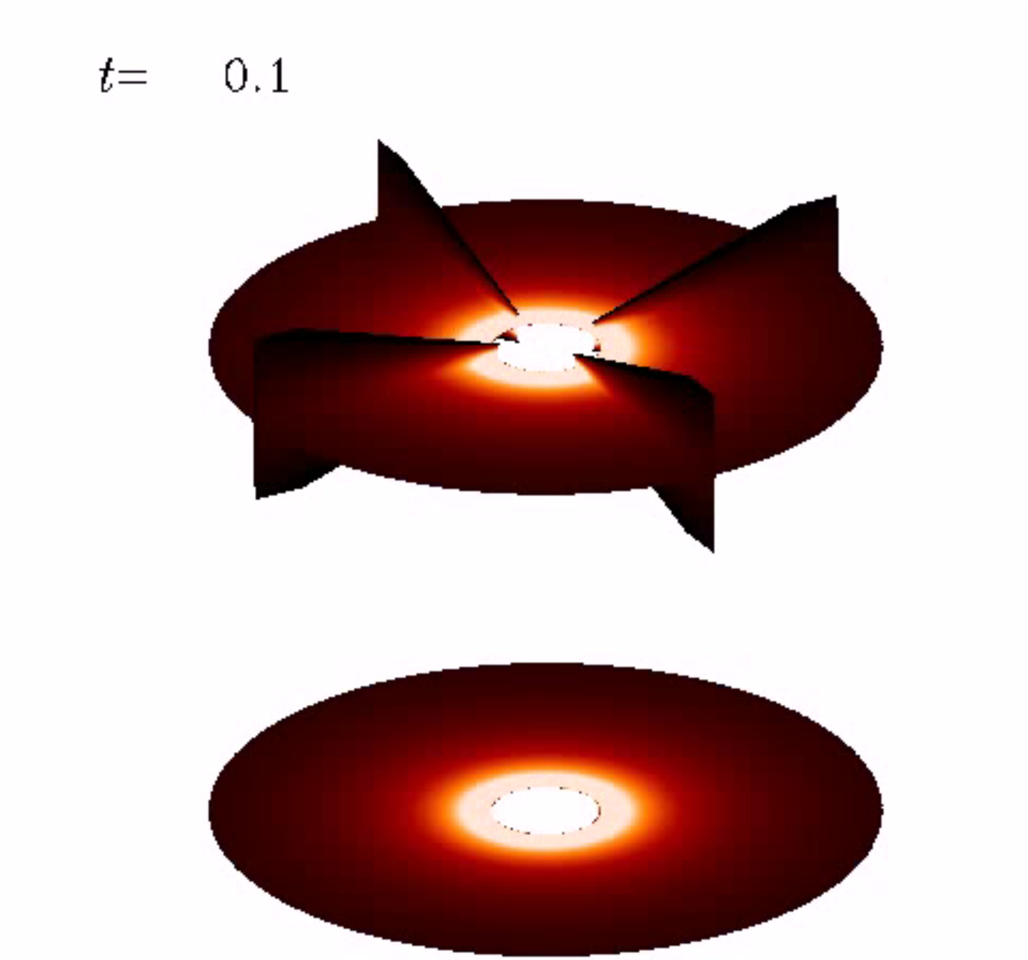

roject Title: High Mass Planet Spiral Shocks as a Source of Infrared Emission in Protoplanetary Disks
For his project, Blake improved on a computer simulation of a planet in formation. The results from this new model matched a previous observation of the gas and dust around a star.
He has been interested in space for as long as he can remember even though his family's only connection to professional science is his paternal grandfather, who had worked for NASA at one point, before pursuing medical illustration. What fascinates Blake about science is the intense desire to discover the unknown.
Blake is most passionate about the future of space exploration, which may eventually save the human race from extinction. He says it is essential for us to become a multi-planetary species in order to provide a safety net in case another mass extinction event (either human caused or not) occurs in the near future.
Blake is a member of the National Honor Society and a National Merit Semifinalist. He plays volleyball on his high school team. His proudest accomplishment is becoming an Eagle Scout and teaching himself how to code C. He likes reading Kurt Vonnegut books because of his witty humor and social commentary. Blake says that Elon Musk is his role model because of Musk's desire to mix technology with business in a way that benefits the entire human race, and the ability to do it extraordinarily well.
He looks forward to pursuing a career in science and/or physics someday.



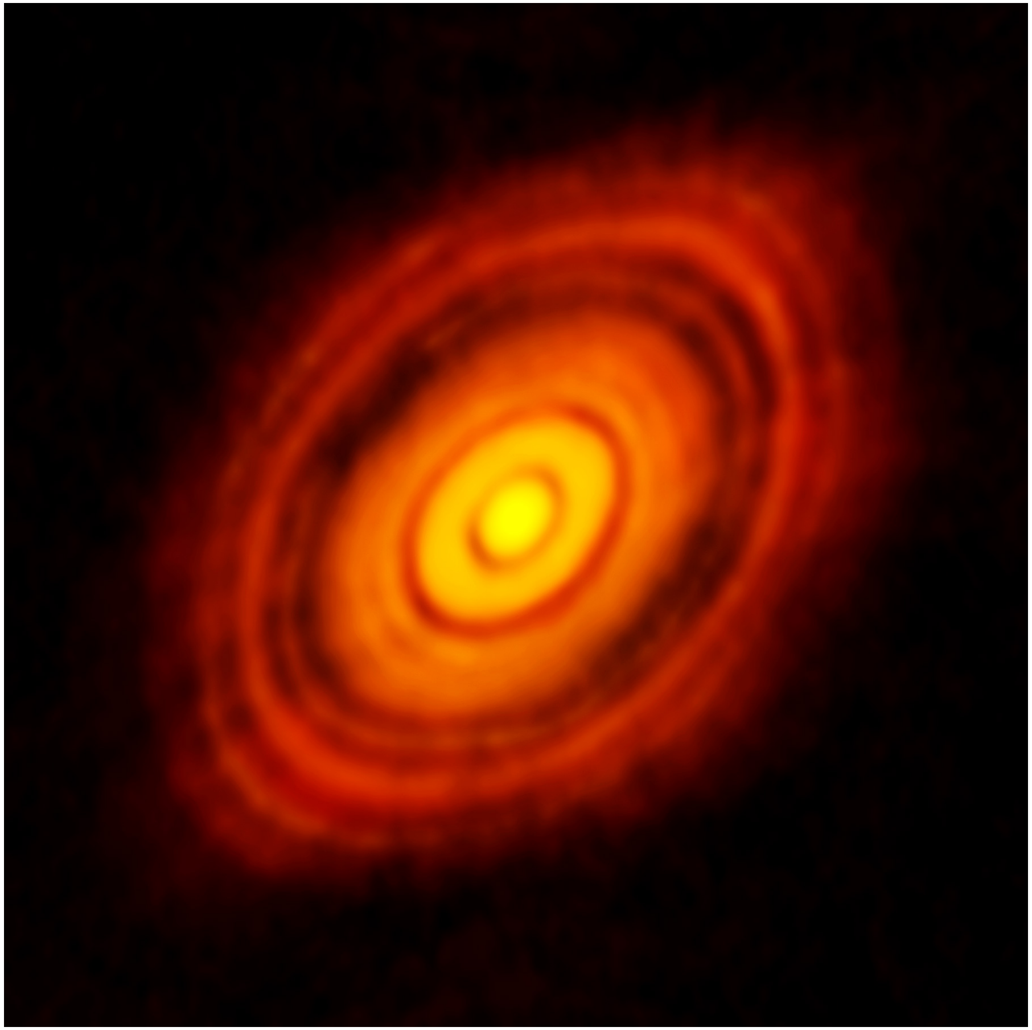

Betelgeuse
Bellatrix
Orion's Belt
Orion Nebula
Rigel
Saiph


1 μm

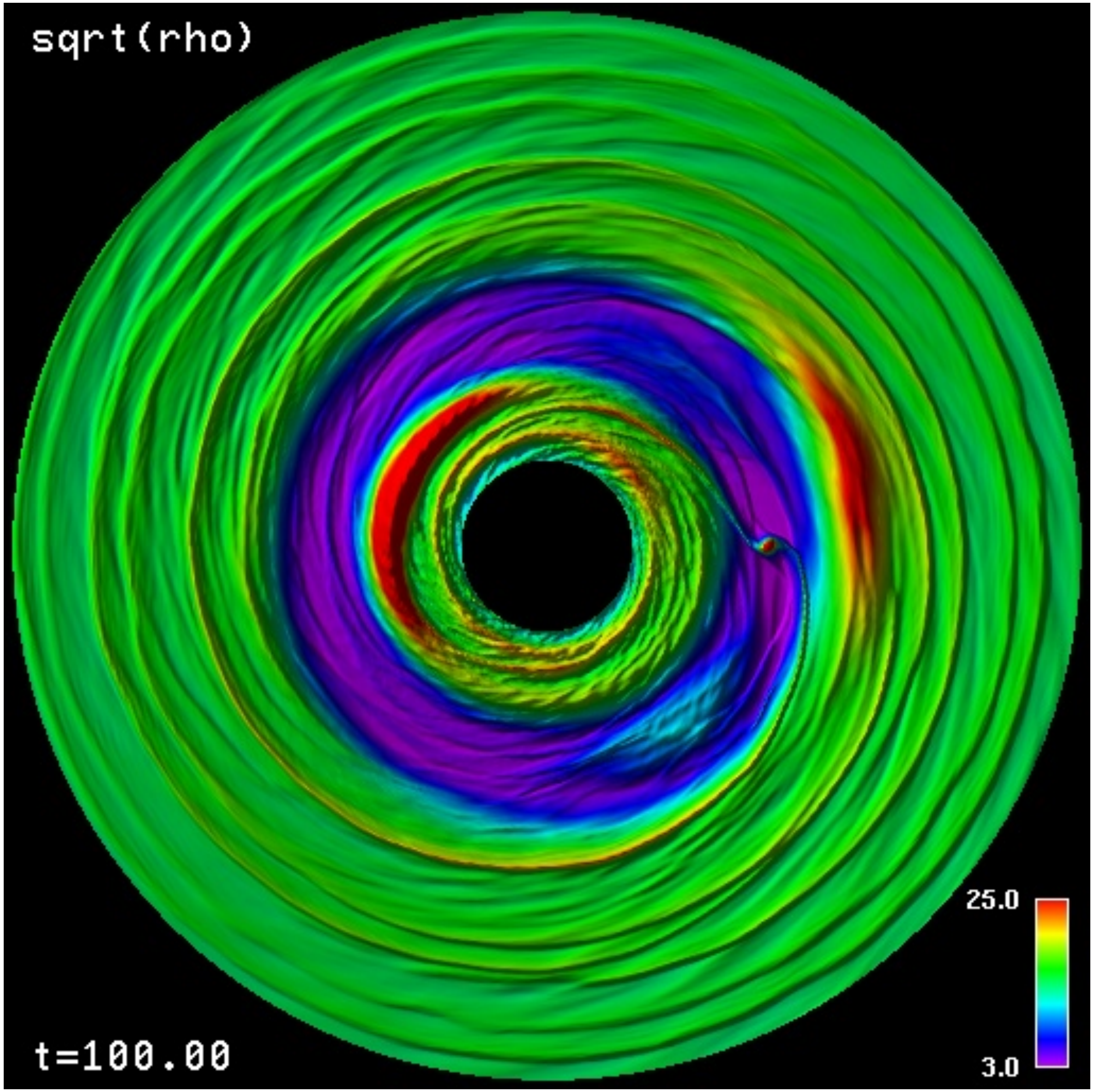
**Planet-Disk Interaction**




**Observation: HL Tau**

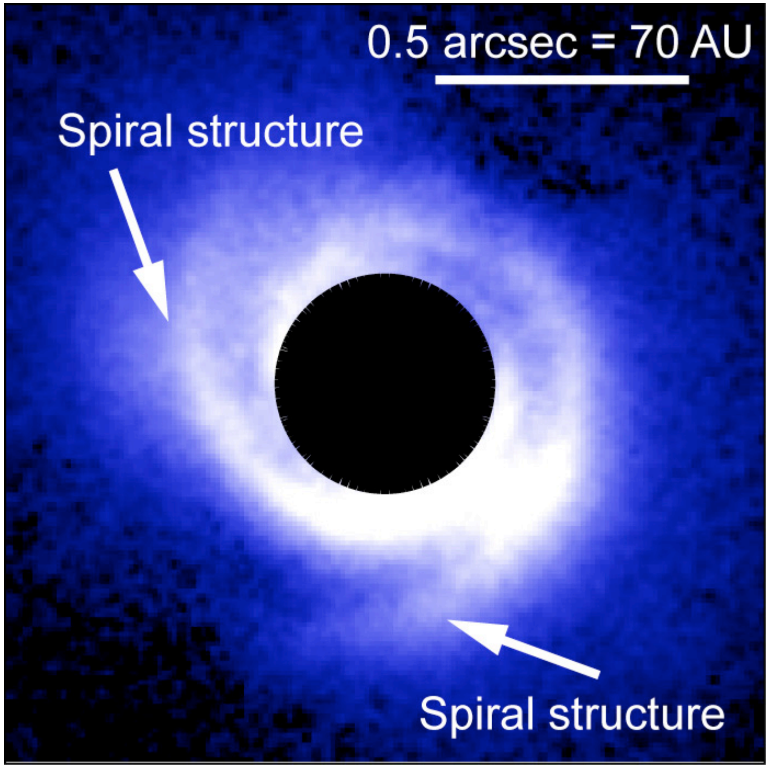


# Planet-disk interaction: gaps, spirals, and vortices.



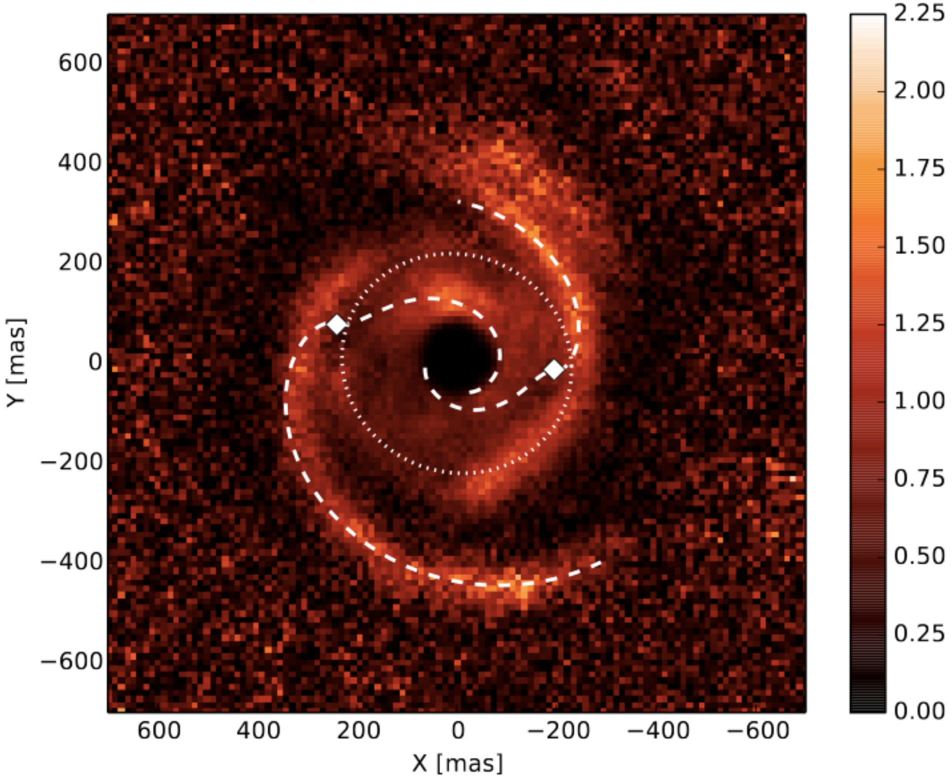
# Observational Evidence: Spirals

SAO 206462



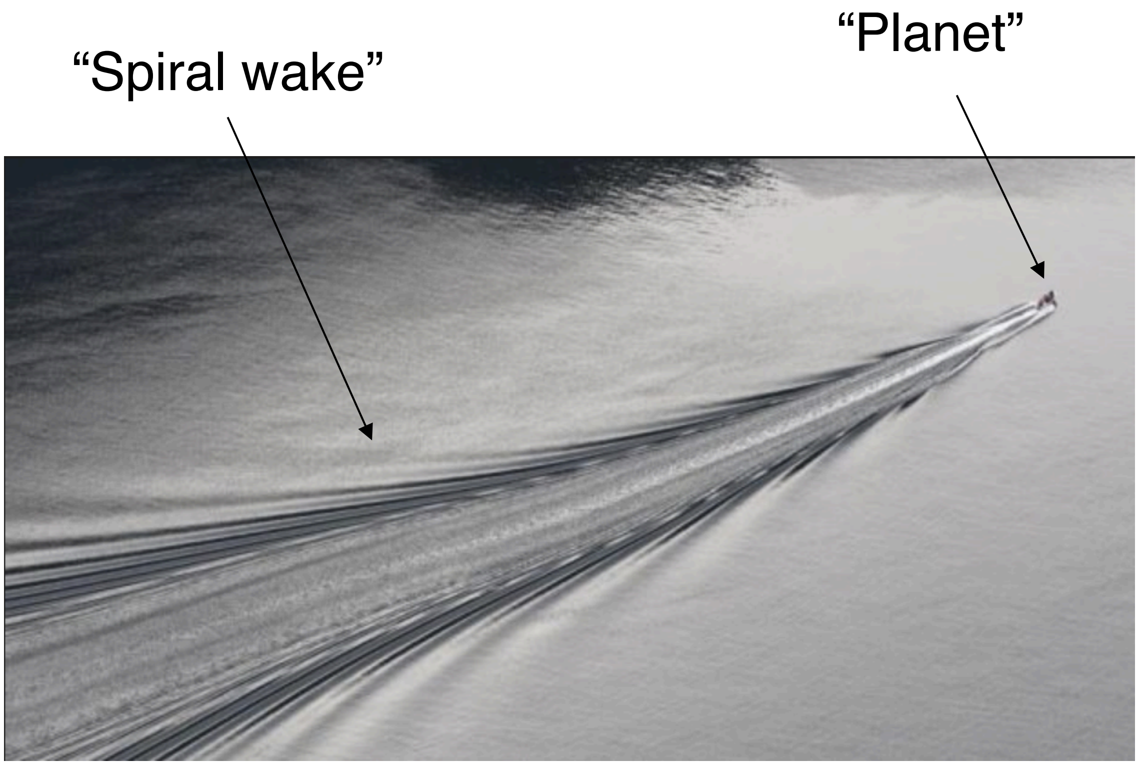

Muto et al. (2012)

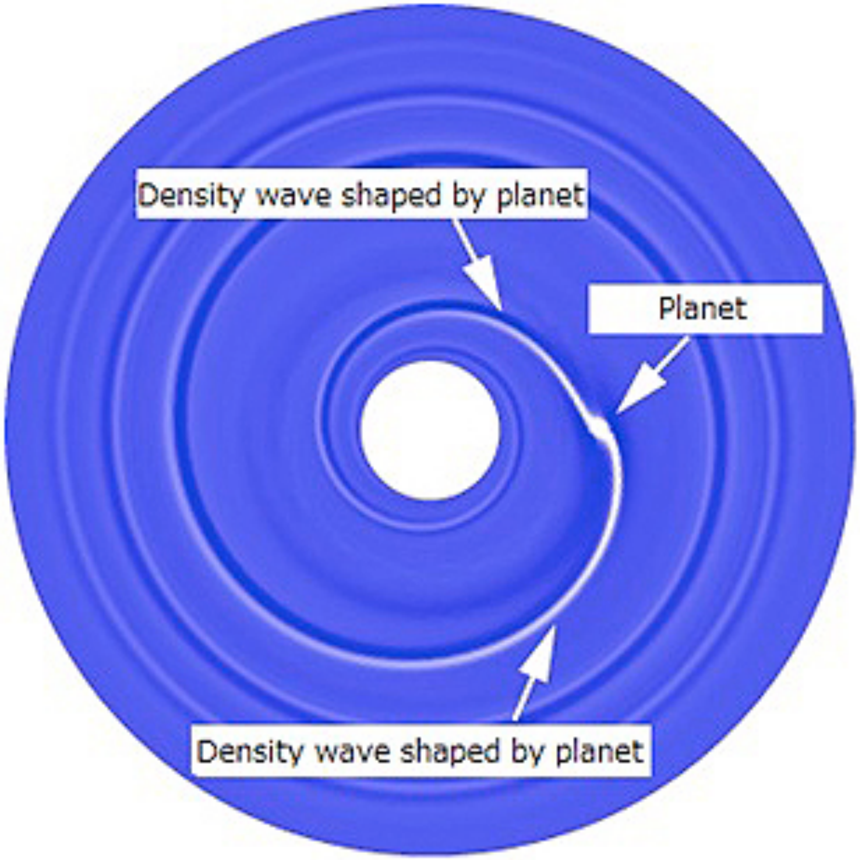
MWC 748




Benisty et al. (2015)

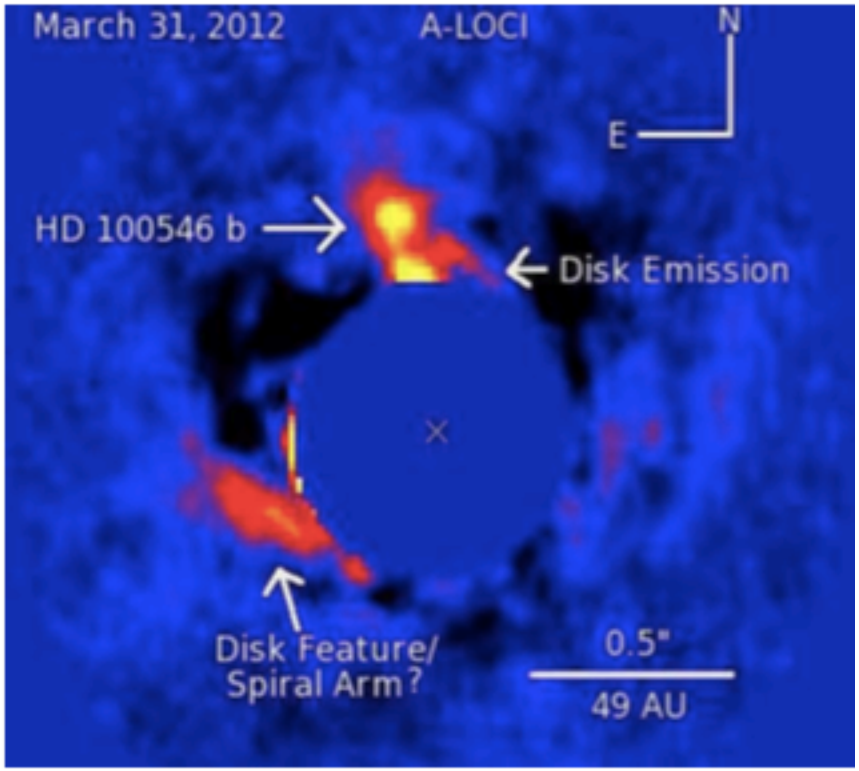
# Planet spirals



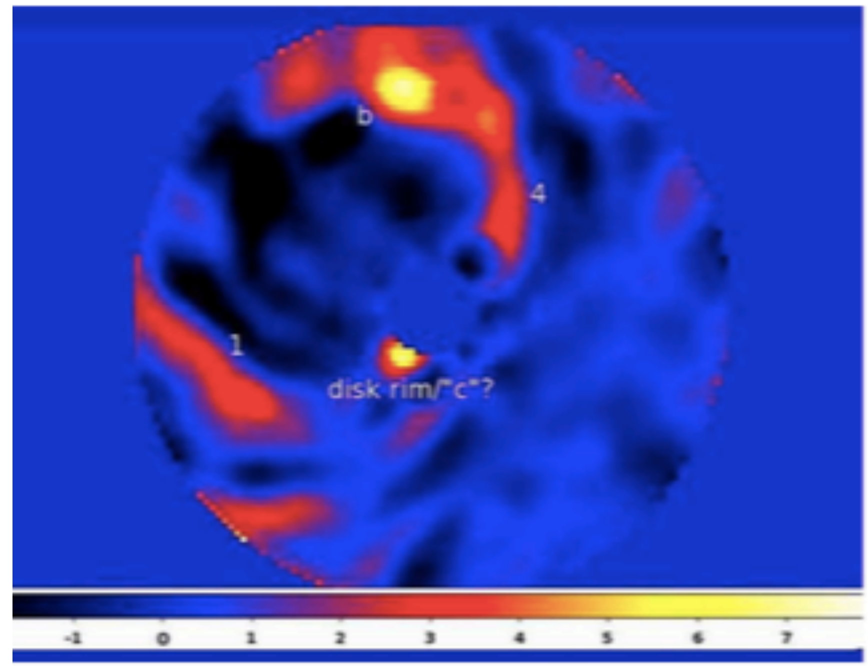



# The strange case of HD 100546

L band (~3.5 μm)

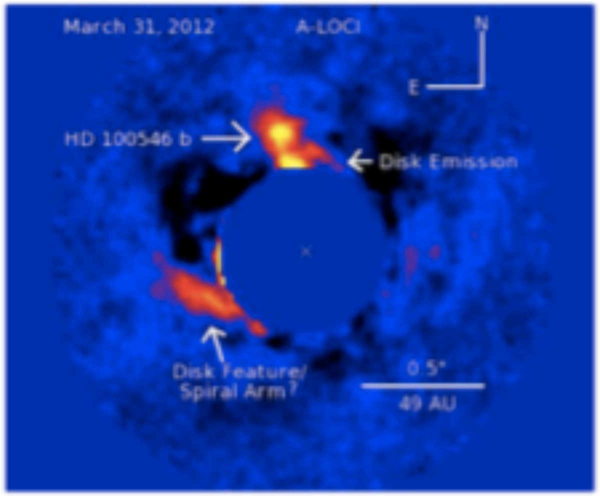



H band (~1.6 μm)

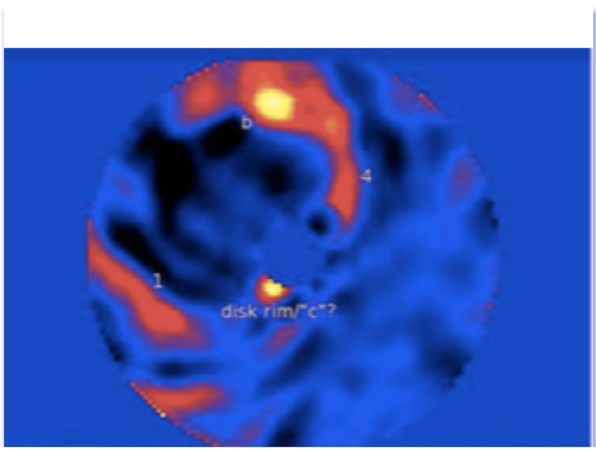



Currie et al. (2014), Currie et al. (2015)

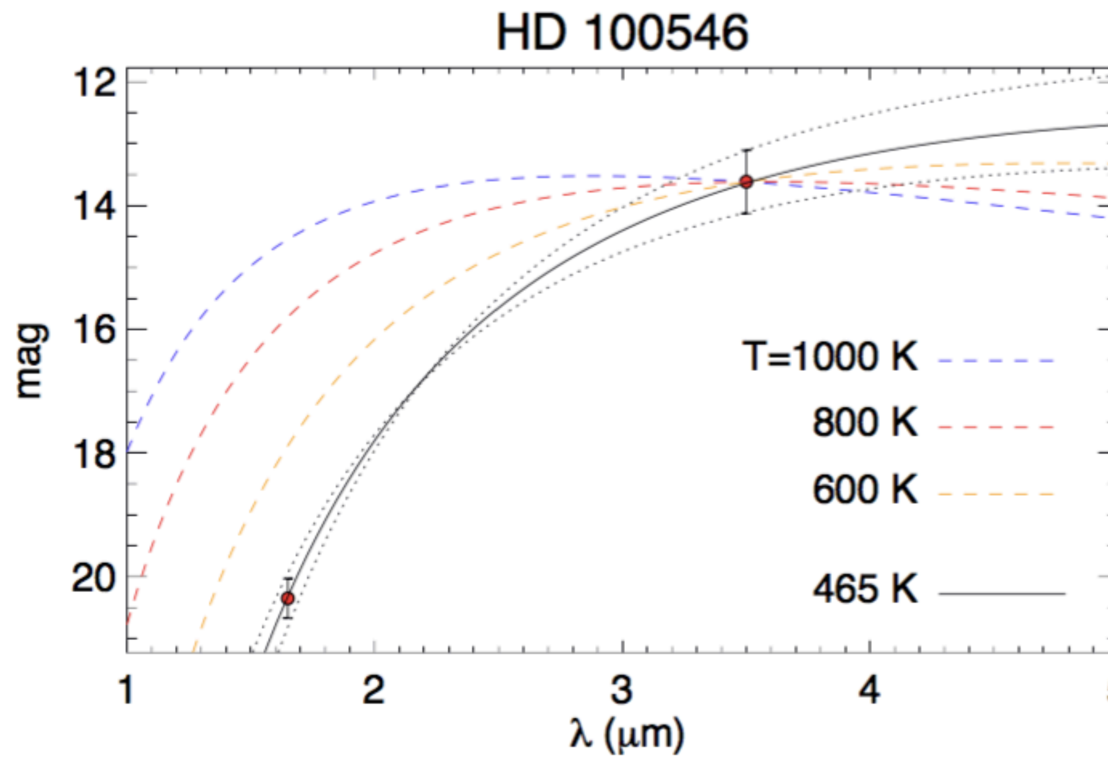
# Pinning down the temperature




L band

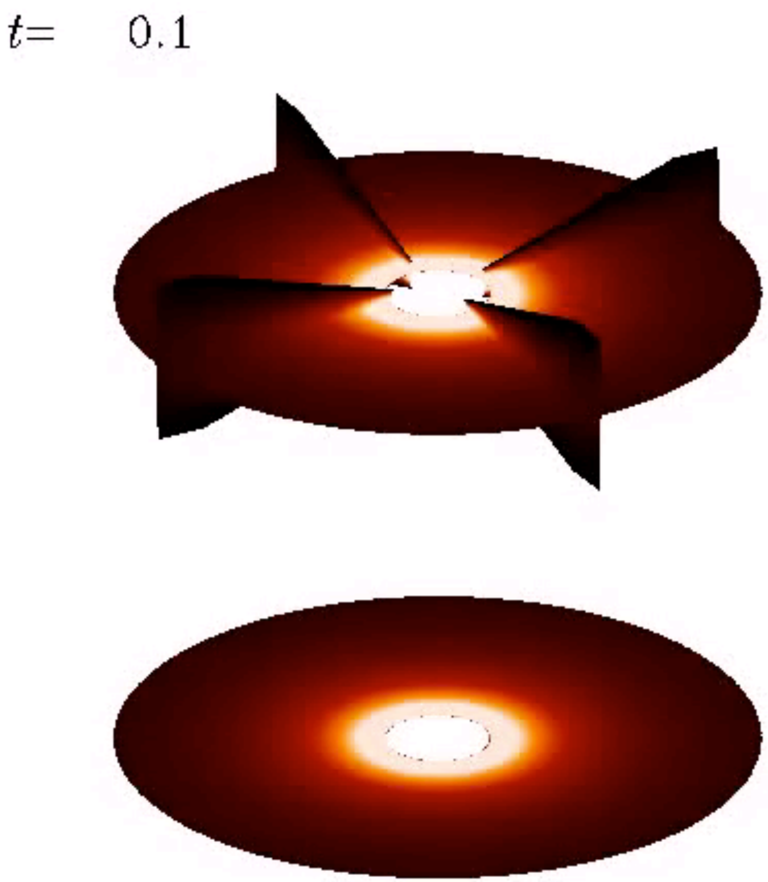


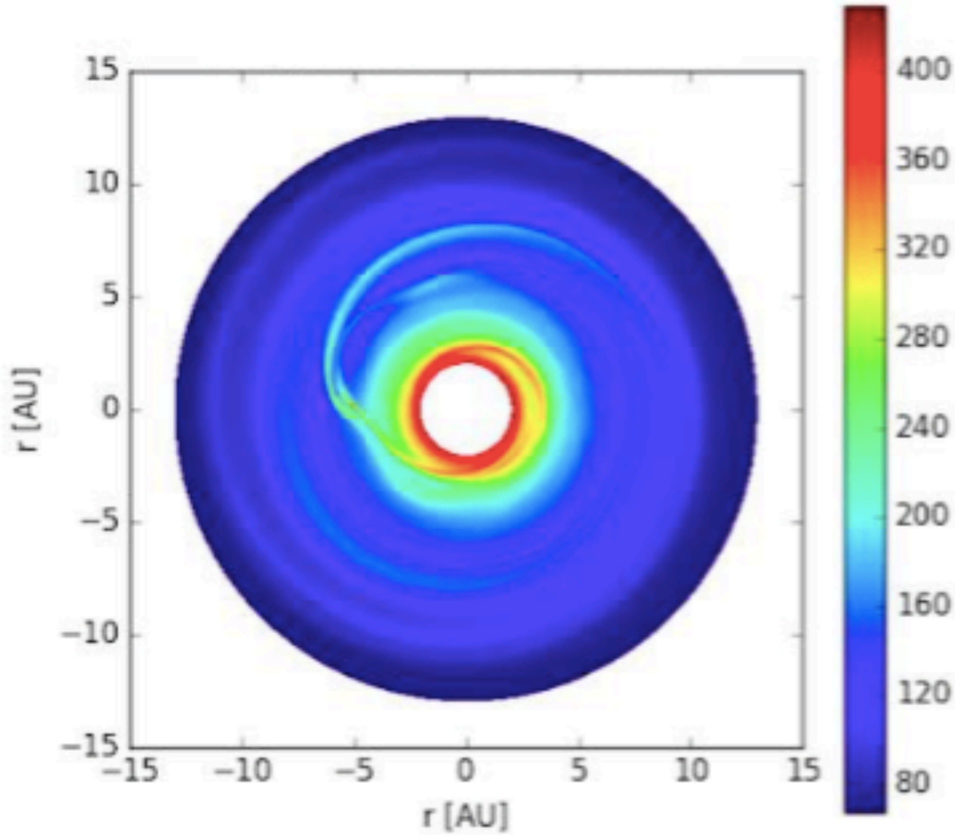

H band




Lyra et al. (2016)

# Supersonic Wakes of High Mass Planets



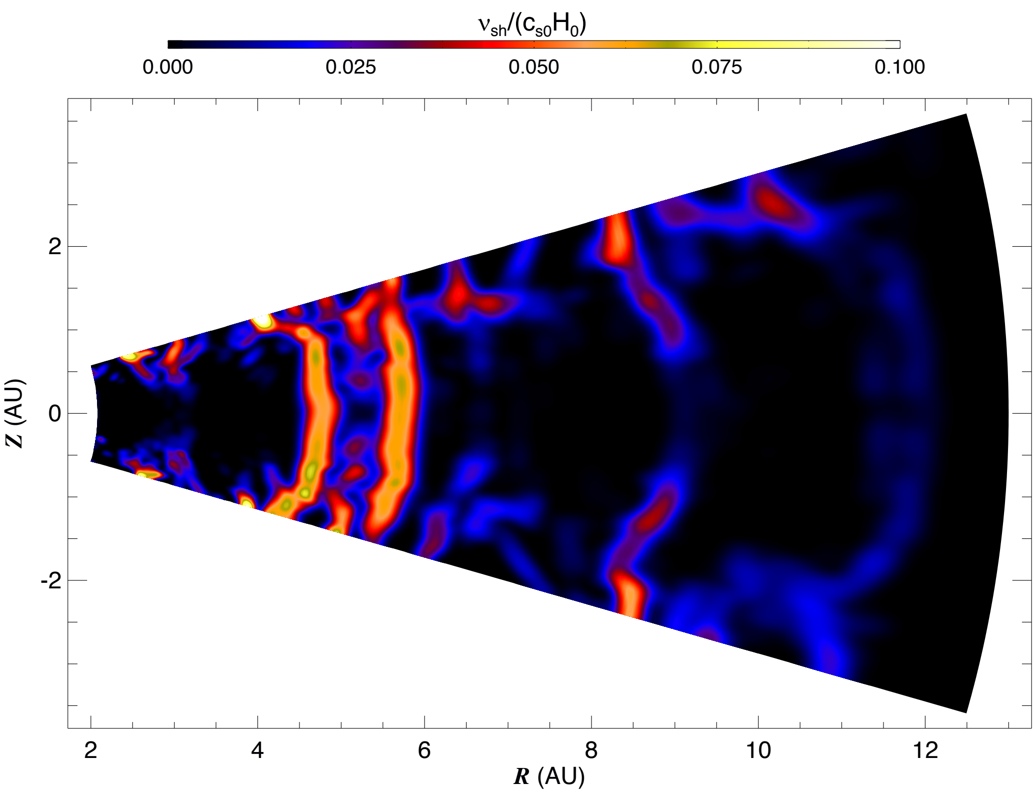




Temperature - **5M$_J$**

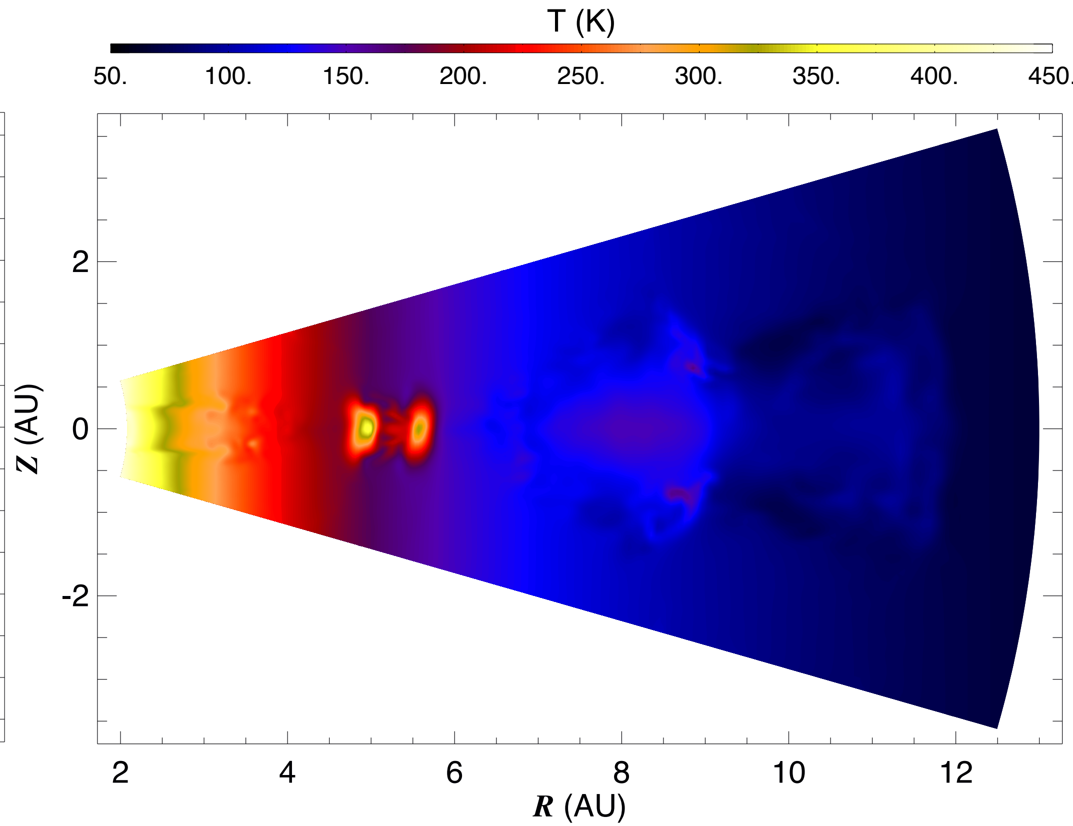
Lyra et al. (2016)

# Shock bores

## Shocks (velocity convergence)



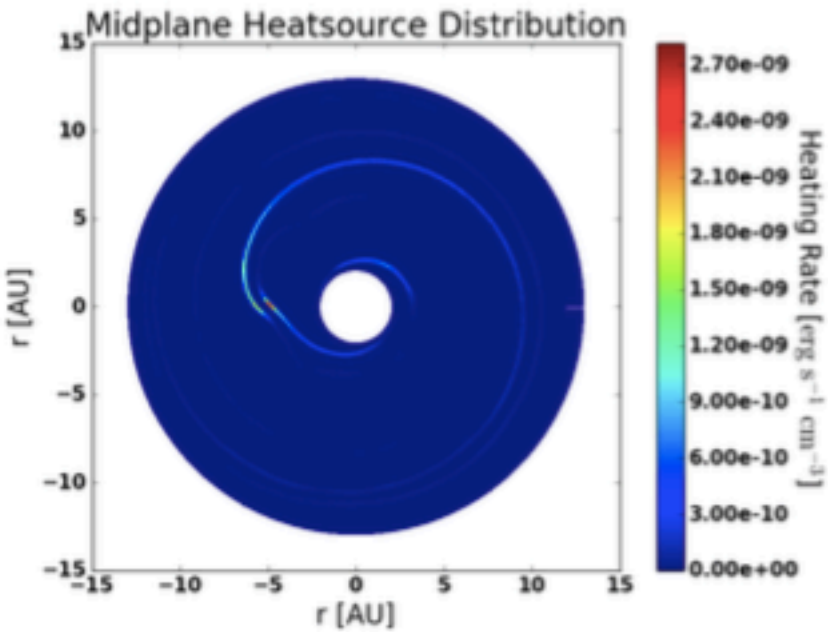

## Temperature

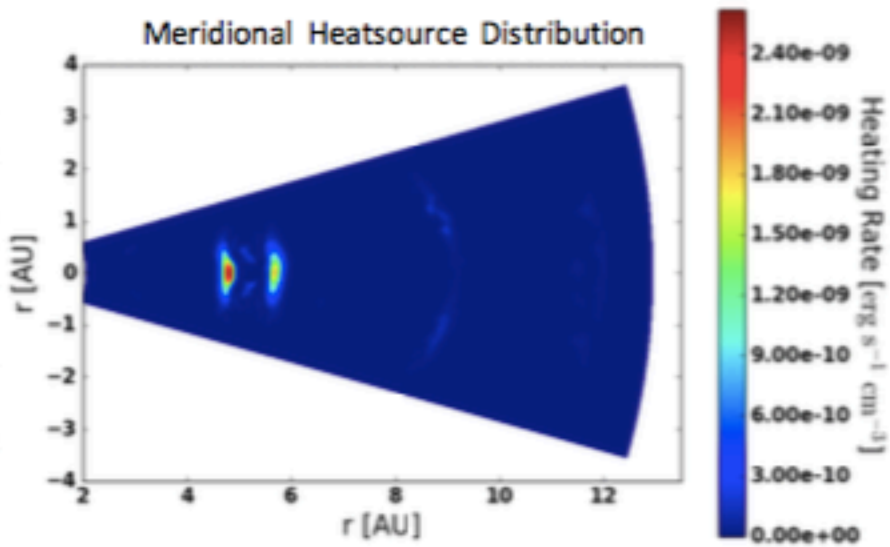



Lyra et al. (2016)

# RADMC-3D
(Dullemond 2012)

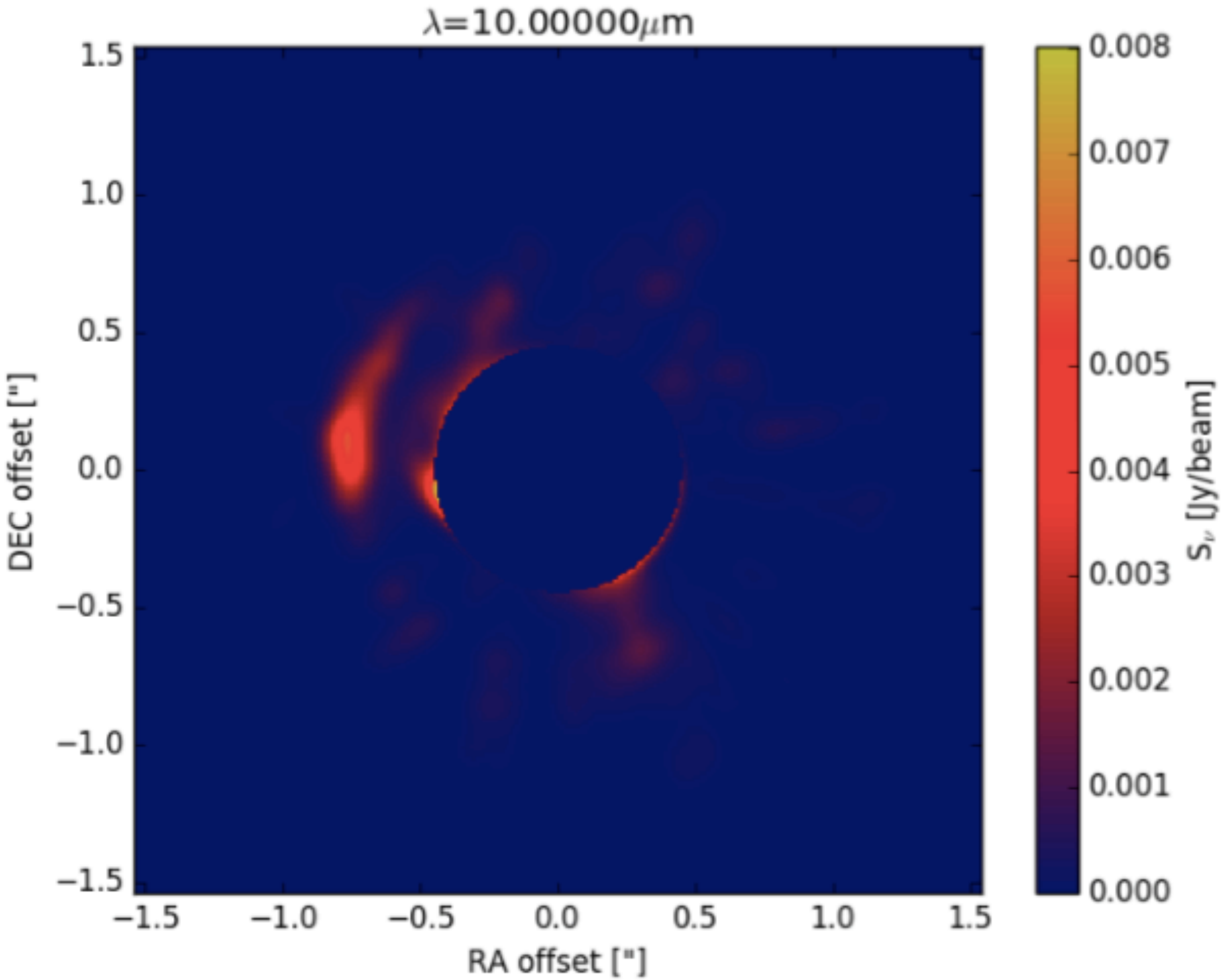
## Radiative Transfer - **Shock heating**



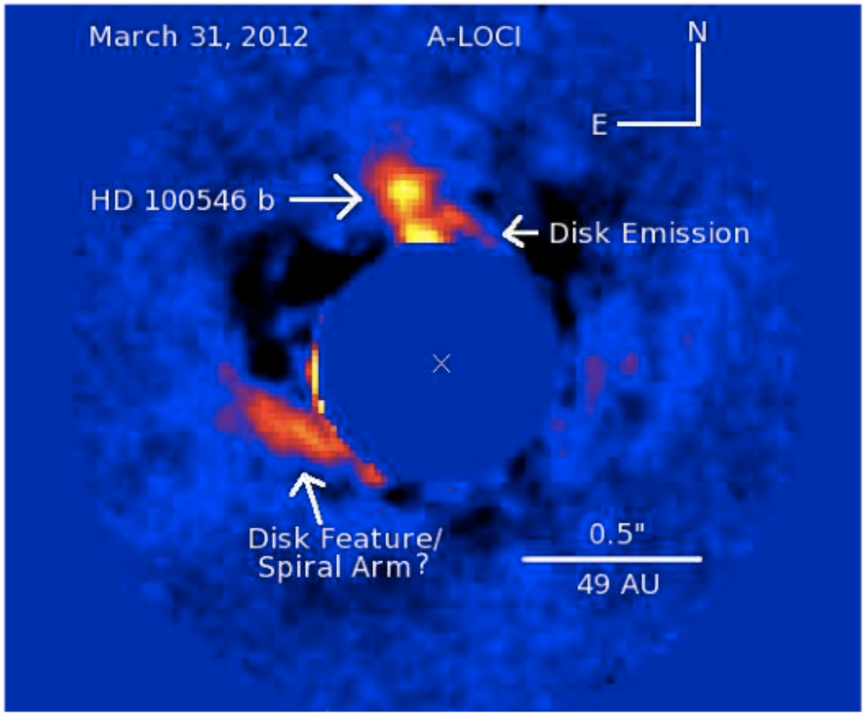

Hord et al. (2017, in prep)

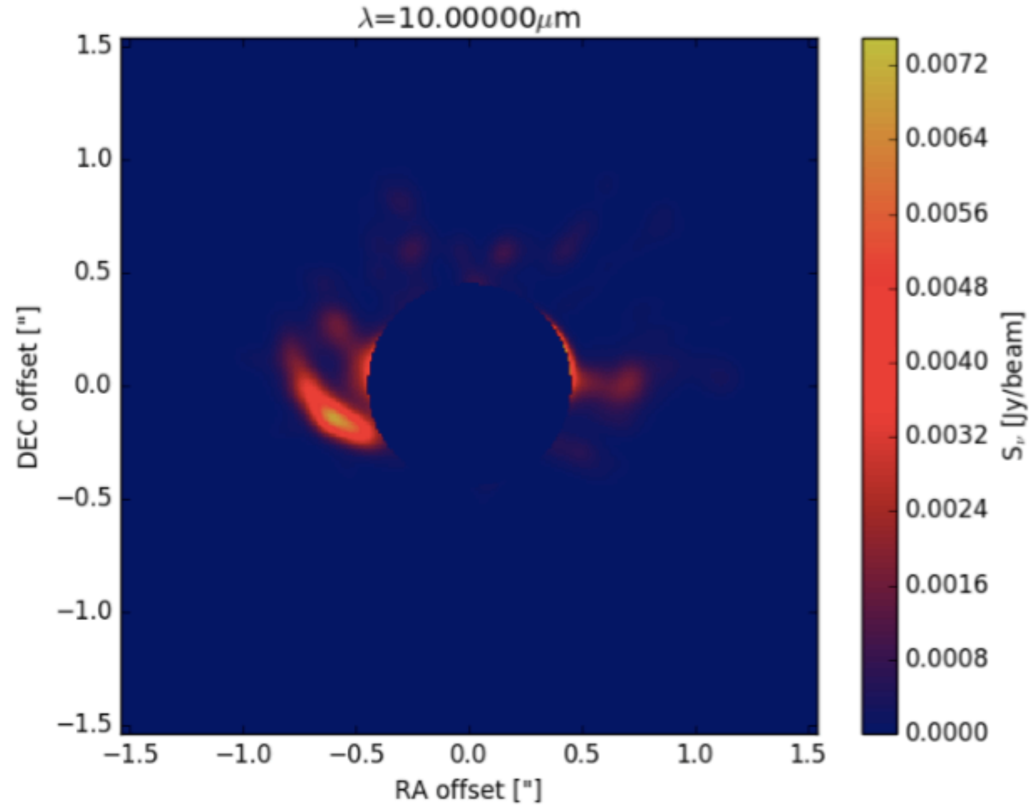
# Synthetic image




Hord et al. (2017)

# Observation vs Synthetic Image

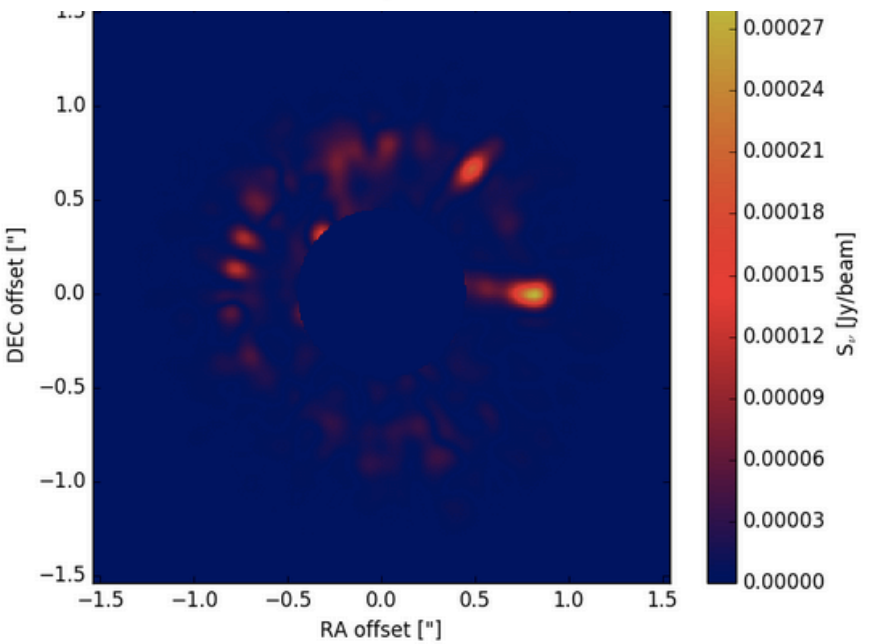


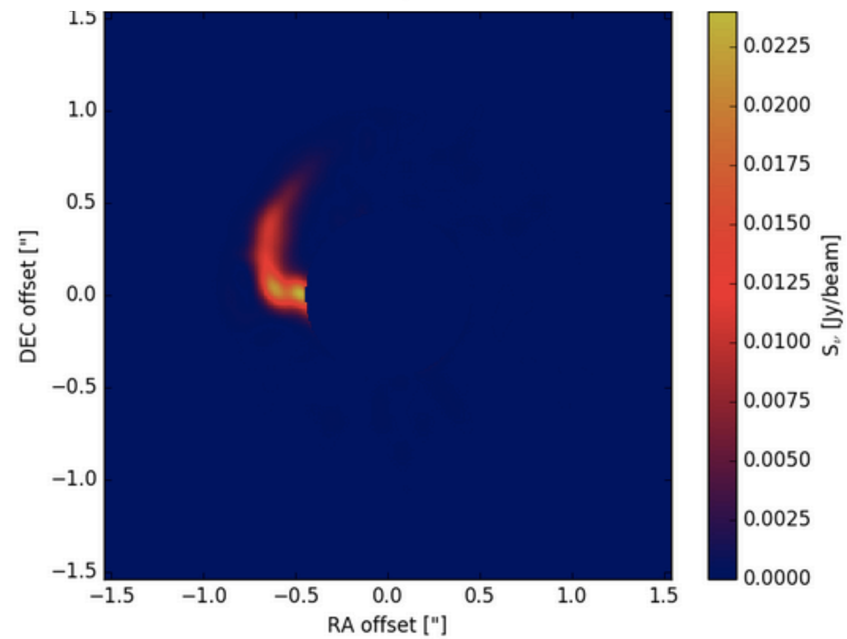

Hord et al. (2017)

# Effect of shocks alone

1 μm

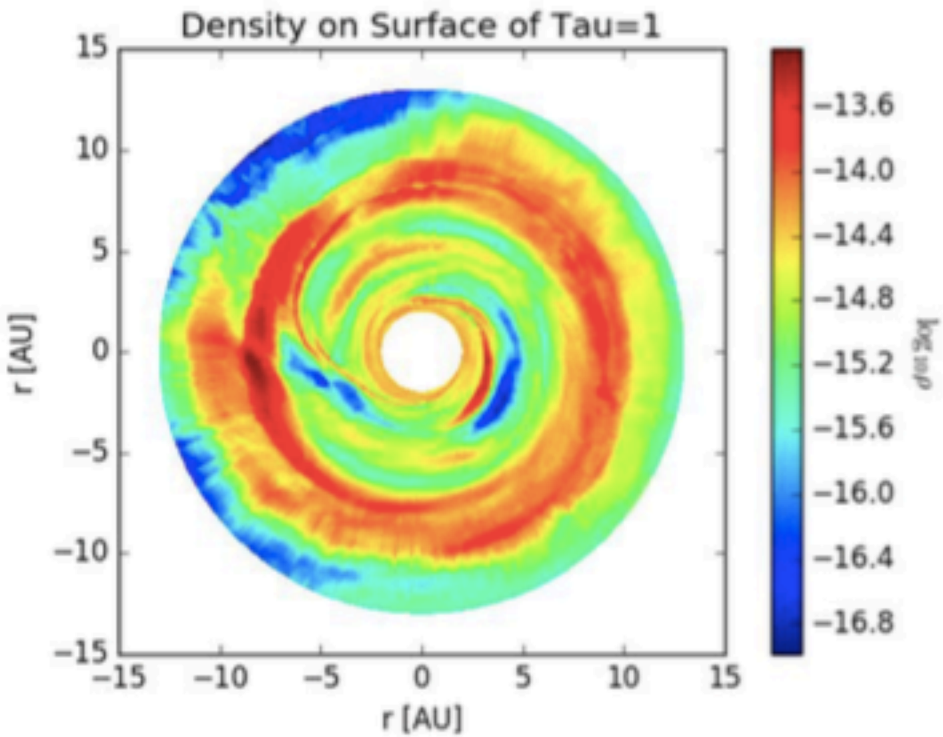



10 μm

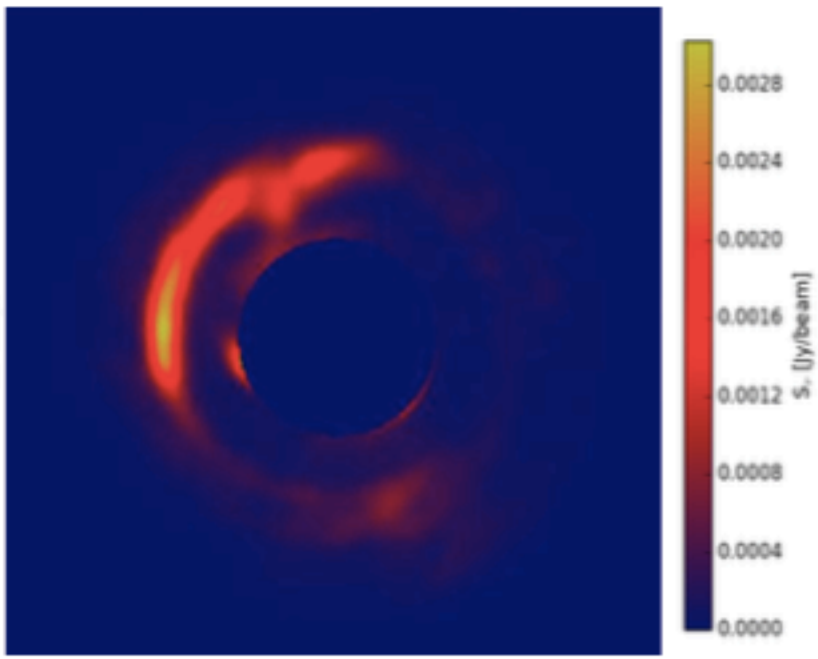



Hord et al. (2017)

# Scattering in Image




Light scattered off **gap outer edge**



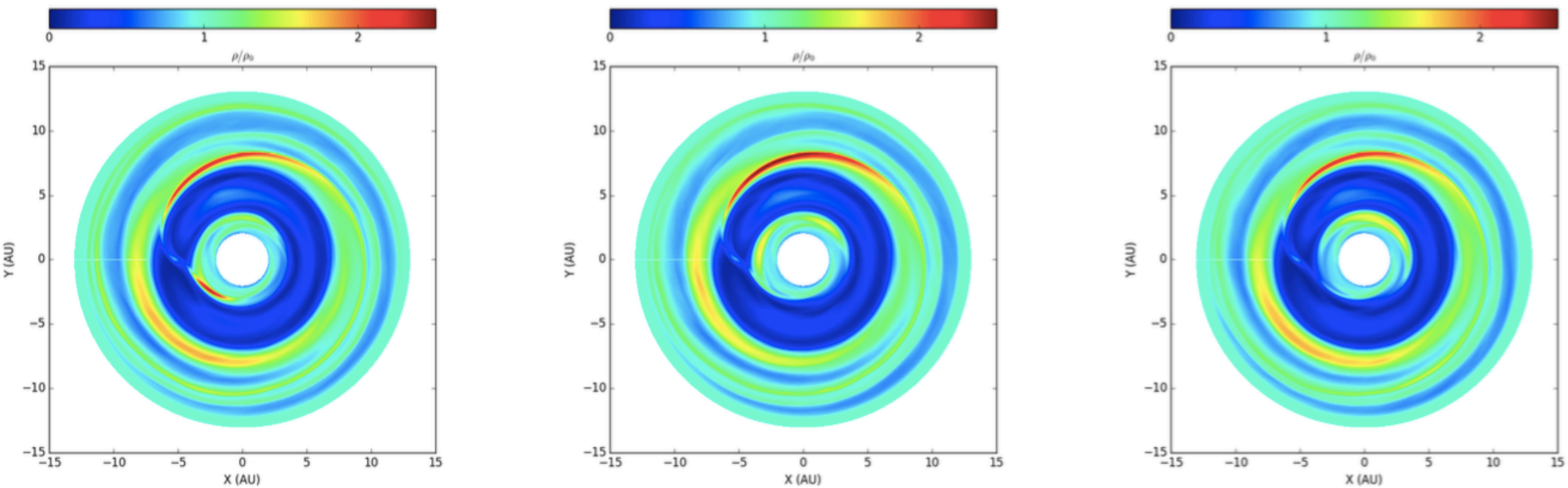

"Bird's eye view" synthetic image

Hord et al. (2017)

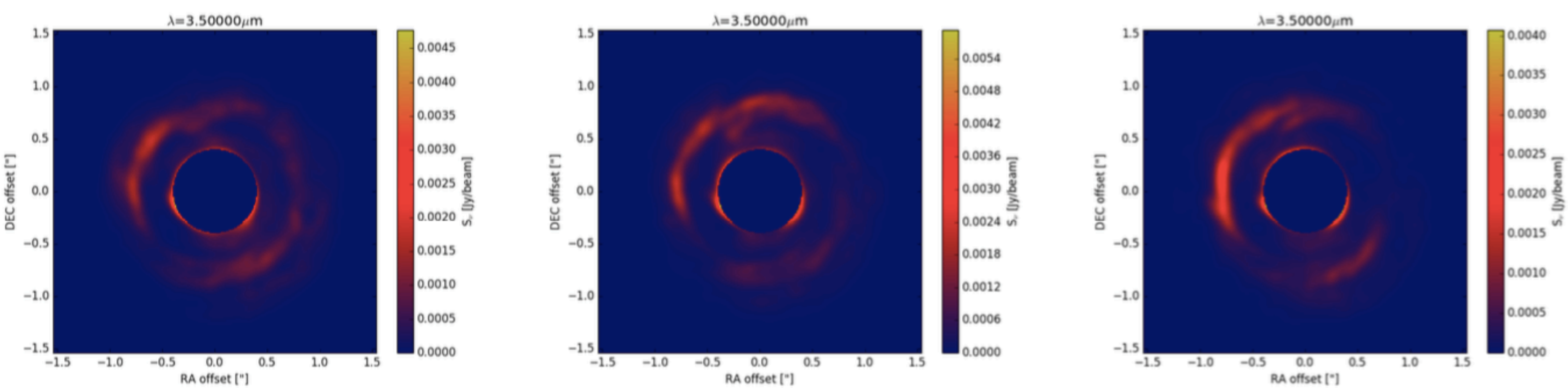
# The vortex raises the scale height

T = 39 orbits | T = 40 orbits | T = 41 orbits

## Density

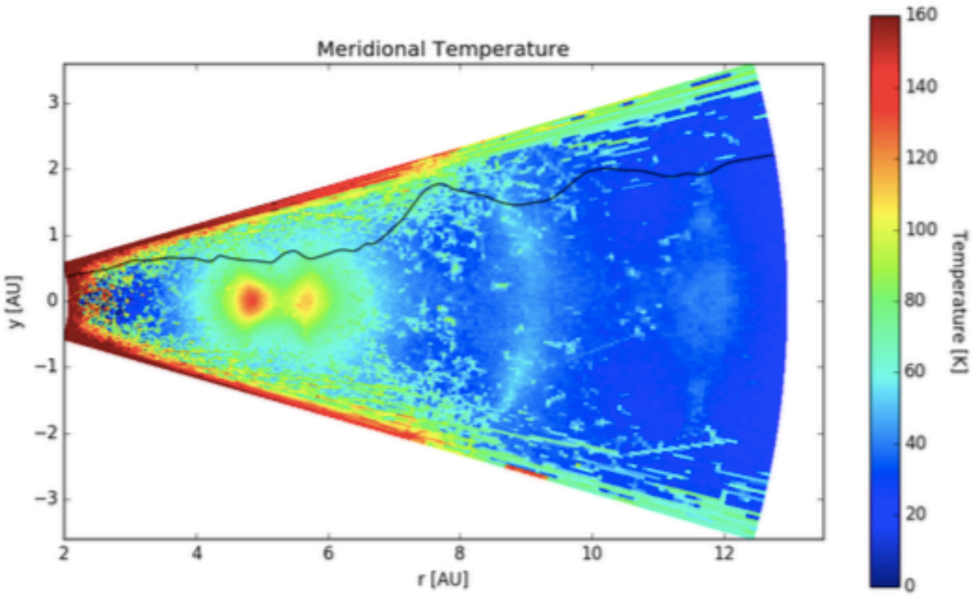



## Intensity

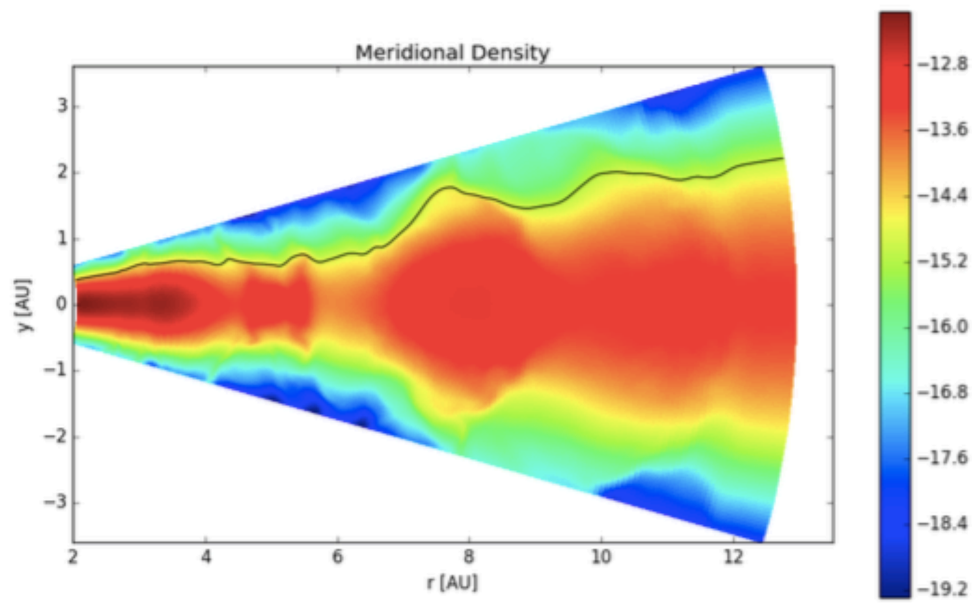


# A puffed-up outer gap

Temperature

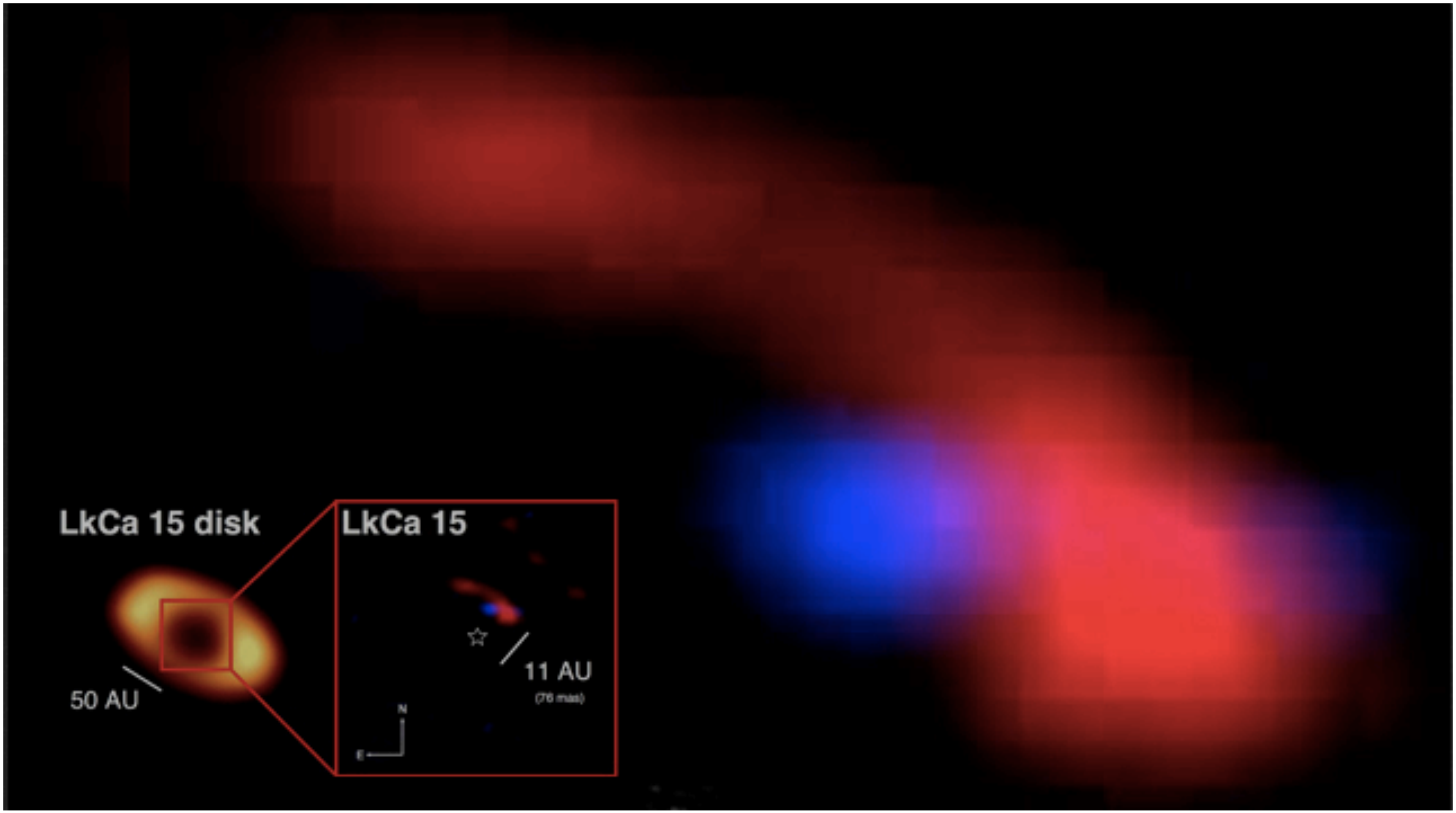



Density



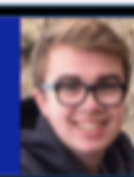

Hord et al. (2017)

# LkCa 15



# High Mass Planet Shocks as a Source of Infrared Emission in Protoplanetary Disks

Blake Hord[1,2,3], Wladimir Lyra[2,3], Neal J. Turner[3], Mario Flock[3]
[1]Dobbs Ferry High School [2]California State University Northridge [3]Jet Propulsion Laboratory



## Background

- Infrared feature around HD 100546 (Currie et al. 2014)
- Could be explained by spiral shock from high mass planet? – modeled by Lyra et al. (2016) using Pencil Code
- Hydrodynamic model of Lyra et al. (2016) used on-the-fly newton cooling function, surface temperatures inaccurate
- What would the observational signatures of the high mass planet modeled by Lyra et al. (2016) be with more realistic cooling?

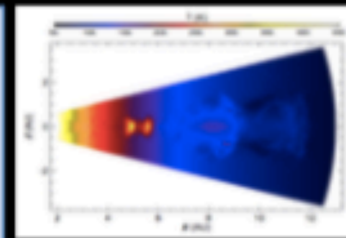


Figure 1: meridional temperature output from Lyra et al. (2016). Hot shock lobes on each side of planet at 5 AU

## Methods

- Took last snapshot of Lyra et al. (2016)
- RADMC-3D dust radiative transfer simulations performed with heat source function (Dullemond 2012)
- Wavelength-dependent opacities taken from Preibisch et al. (1993) (Figure 3)
- Shock heating rate used as heating rate input (Figure 2)
- Thermal Monte Carlo simulations run for $10^8$ photons
- Synthetic images made with ray-tracing function with resulting temperature

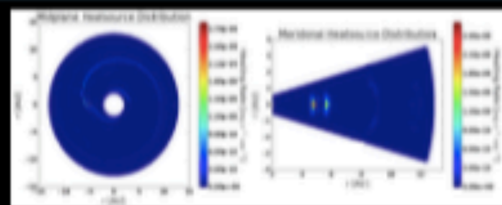


**Figure 2: midplane and meridional shock heating rate input into RADMC-3D. Follows spiral pattern and is collected around shock bores noted in Lyra et al (2016)**

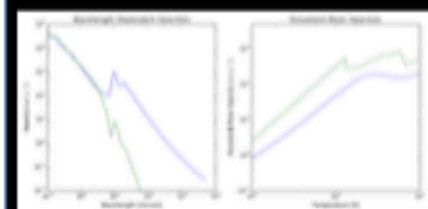


**Figure 3: wavelength-dependent opacities (Preibisch et al. 1993) and Rosseland Mean opacities calculated to match (Bell et al. 1997)**

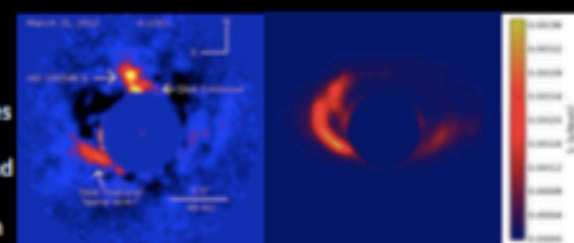


**Figure 4: Comparison between observation of HD 100546 at 3.5 microns (left, Currie et al. 2014) and synthetic image created by RADMC-3D (right) with the same inclination and position angles (50 and 138 degrees).**

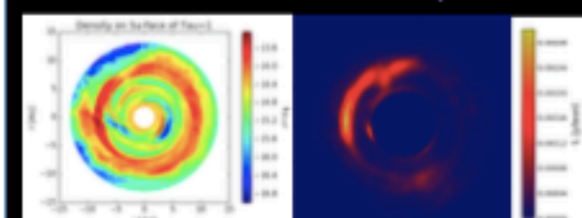


**Figure 5: Density on surface of optical depth 1 for 3.5 microns (left) and image with 0 degree inclination and position angle (right). Bright arm may not be caused by scattering off gap edge, but weak intensity ring may.**

## Results

- 5 AU around T Tauri star roughly equivalent to 50 AU around Herbig Ae star HD 100546
- Synthetic image at 3.5 microns to match L' band of Currie et al. (2014) (Figure 4)
- Spiral emission matches morphology
- Other observations in disk are from scattering of light, due to the gap outer edge (Figure 5)
- Second planet around HD 100546 may change density distribution so such scattering may not be prevalent

## Conclusions

- High Mass planets may be source of infrared emission spiral feature around HD 100546
- Future study of LkCa 15 system to provide more evidence for emission
- RADMC-3D does not take into account the time-dependence of the system

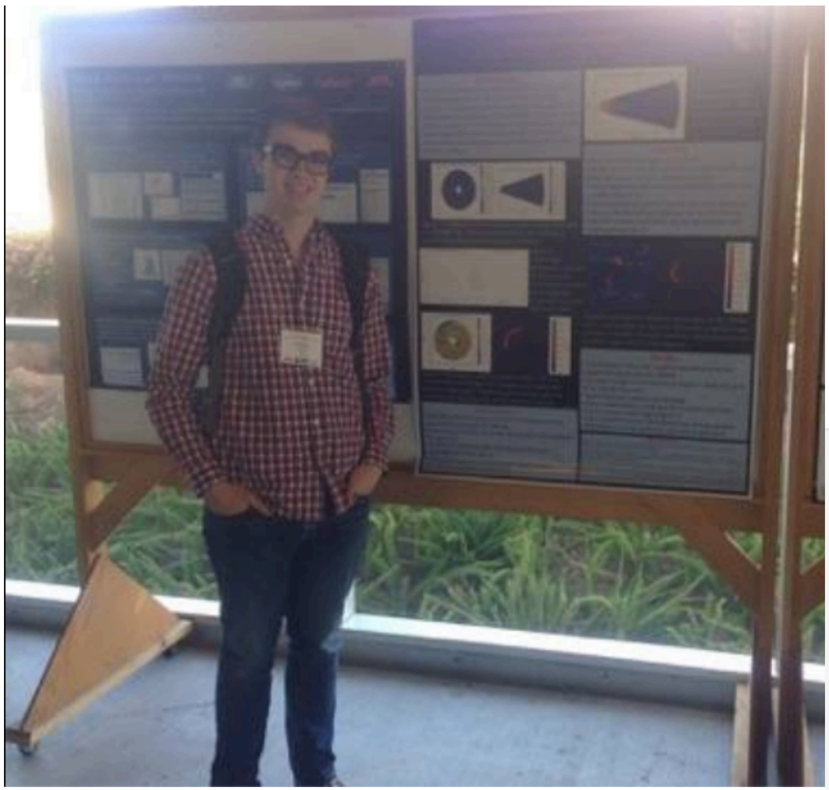
## Bibliography

Bell, K. R., Cassen, P. M., Klahr, H. H., & Henning, T. (1997). The structure and appearance of protostellar accretion disks: Limits on disk flaring. The Astrophysical Journal, 486(1), 372.

Currie, T., Muto, T., Kudo, T., Honda, M., Brandt, T. D., Grady, C., ... & McElwain, M. W. (2014). Recovery of the candidate protoplanet HD 100546 b with Gemini/NICI and detection of additional (planet-induced?) disk structure at small separations. The Astrophysical Journal Letters, 796(2), L30.

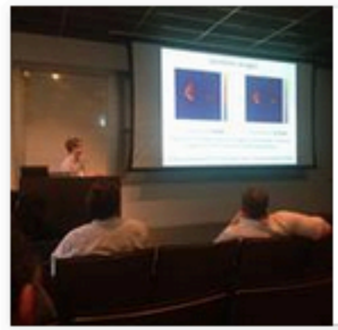
Dullemond, C. P. (2012). RADMC-3D: A multi-purpose radiative transfer tool. Astrophysics Source Code Library, 1, 02015.

## ***Blake Hord*** *(Dobbs Ferry High School, NY)*



**Wladimir Lyra**
September 22 at 12:32pm · Twitter

Blake Hord, my high-school intern, presenting the summer research he did at #csun. #ExSoCal 2016. https://t.co/JypTSoiSte



**Wladimir Lyra (@wladlyra) posted a photo on Twitter**

Get the whole picture - and other photos from Wladimir Lyra

PIC.TWITTER.COM/JYPTSOISTE | BY WLADIMIR LYRA

Like Comment Share

Paul Ries, John Tumminia and 15 others

**Blake Hord** It was an honor and a pleasure!
Unlike · Reply · 3 · September 22 at 10:42pm

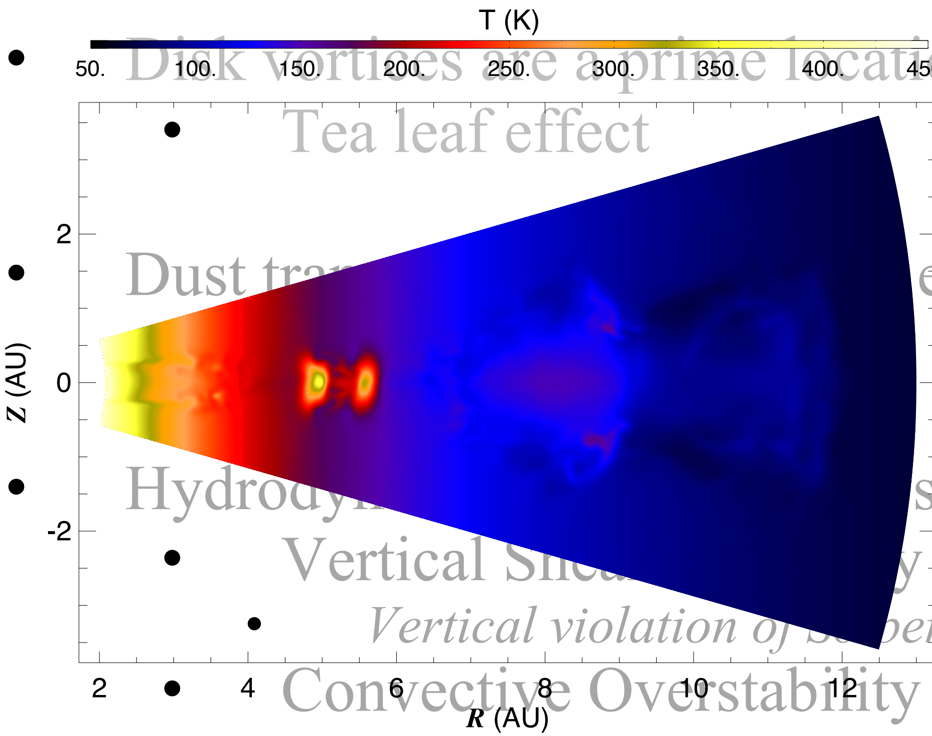
**Konstantin Batygin** It was a great talk!
Unlike · Reply · 3 · September 23 at 7:41am

**Jessie Christiansen** It was a very clear, professional, composed talk. For a grad student! Let alone a high school student. Well done.
Unlike · Reply · 1 · September 23 at 6:07pm

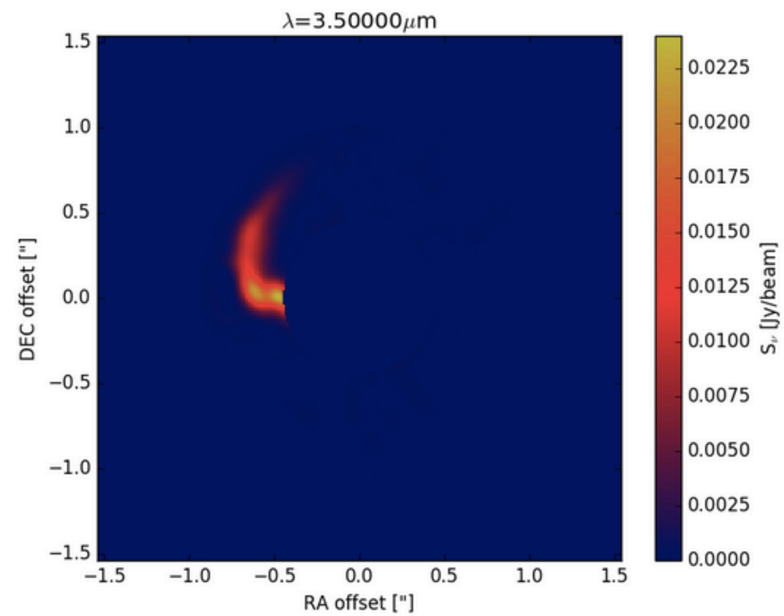
**Wladimir Lyra** Keep an eye on him, folks. This kid will go far. 🙂
Like · Reply · September 25 at 12:56am · Edited

# Conclusions

- Disk vortices are a prime location for planet formation
  - Tea leaf effect




- Dust tra… equilibr…
- Hydrody… s planet…
  - Vertical Shea… y
    - *Vertical violation of … berg-Hoila…*
  - Convective Overstability
    - *Amplification of epicyclic motion by buoyancy*
  - Zombie Vortex Instability
    - *Resonance between epicyclic and buyoancy frequency*

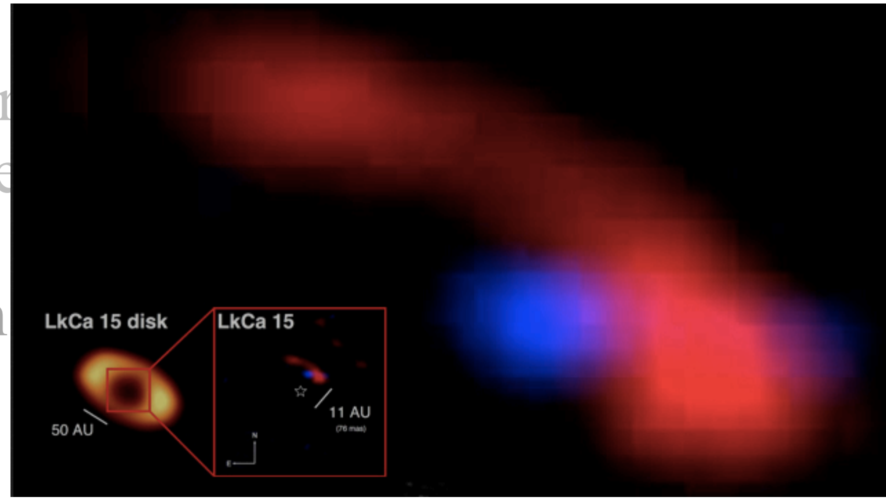


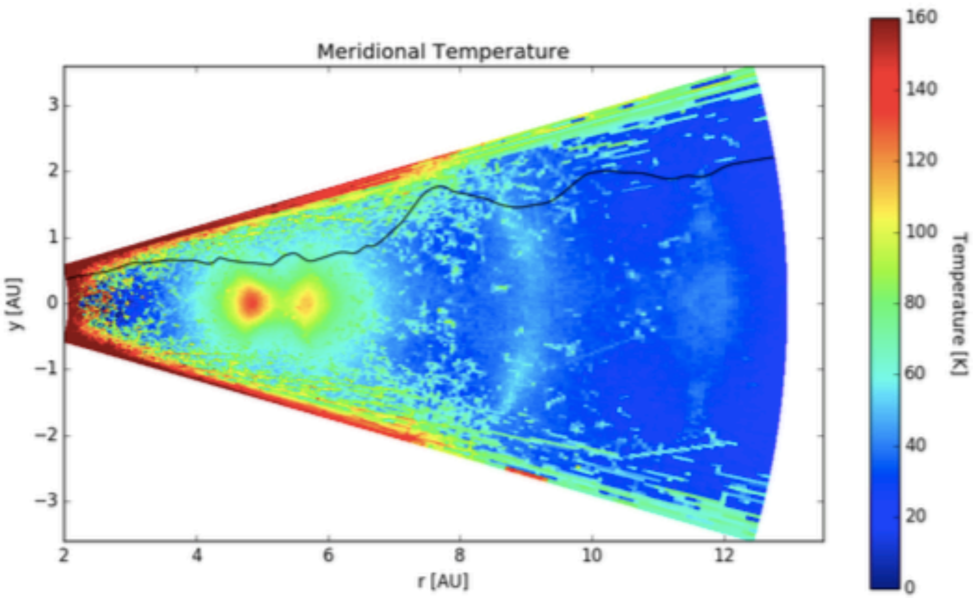

- Hot lobes next to high mass planets at high resolution

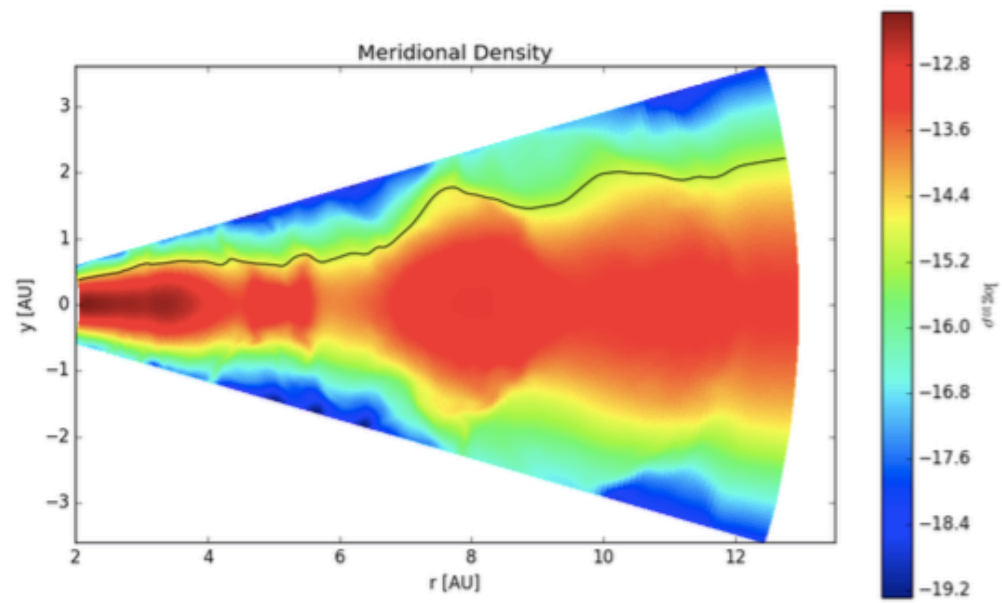
- Planets puff up their outer gap edges – visible in scattered light

# Conclusions

- Disk vortices ar ... ation
  - Tea leaf e ...
- Dust trapped in ... s the observations




- Planets puff up their outer gap edges – visible in scattered light