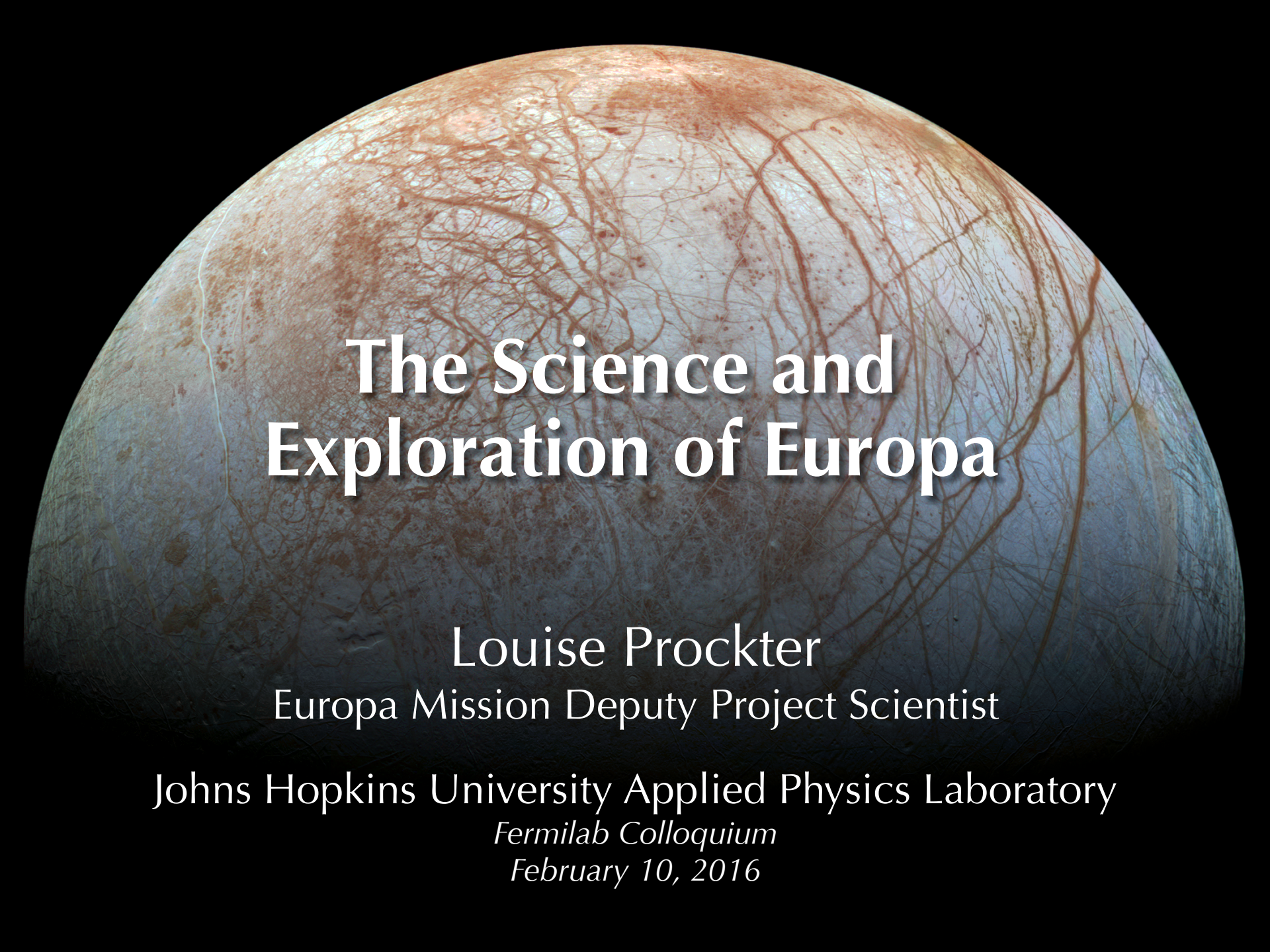


The Science and Exploration of Europa

Louise Prockter

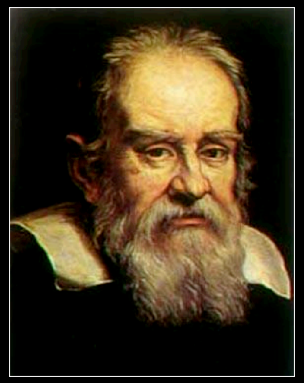
Europa Mission Deputy Project Scientist

Johns Hopkins University Applied Physics Laboratory

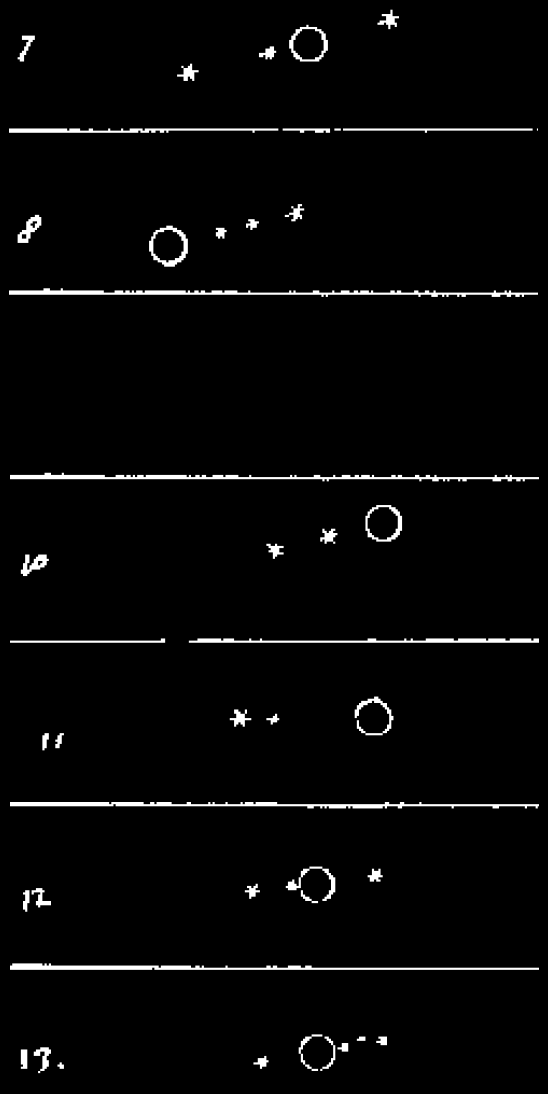
Fermilab Colloquium

February 10, 2016

Discovery of Jupiter's moons: January 1610

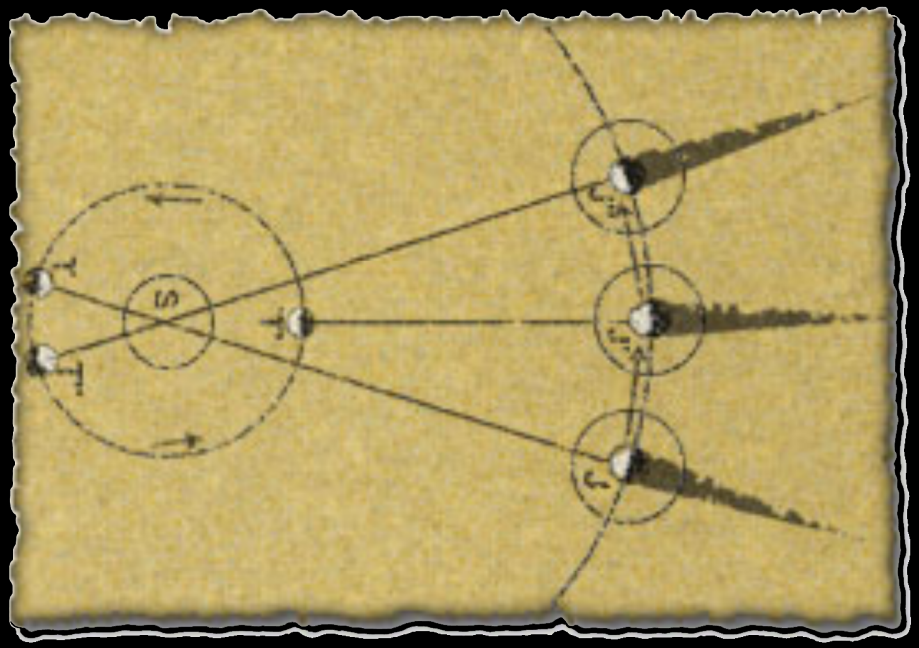


Galileo's sketches



Observations in the pre-space age

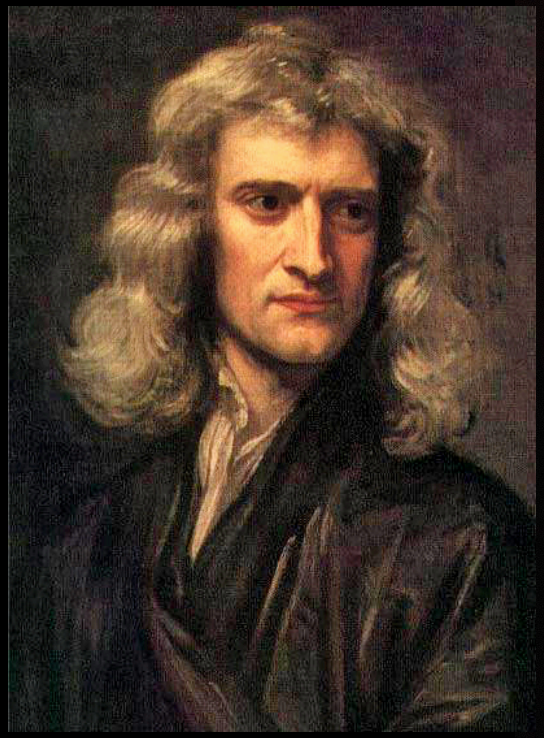
- 1675 Danish astronomer Ole Roemer estimates the speed of light by observing eclipses of the large Jovian moons

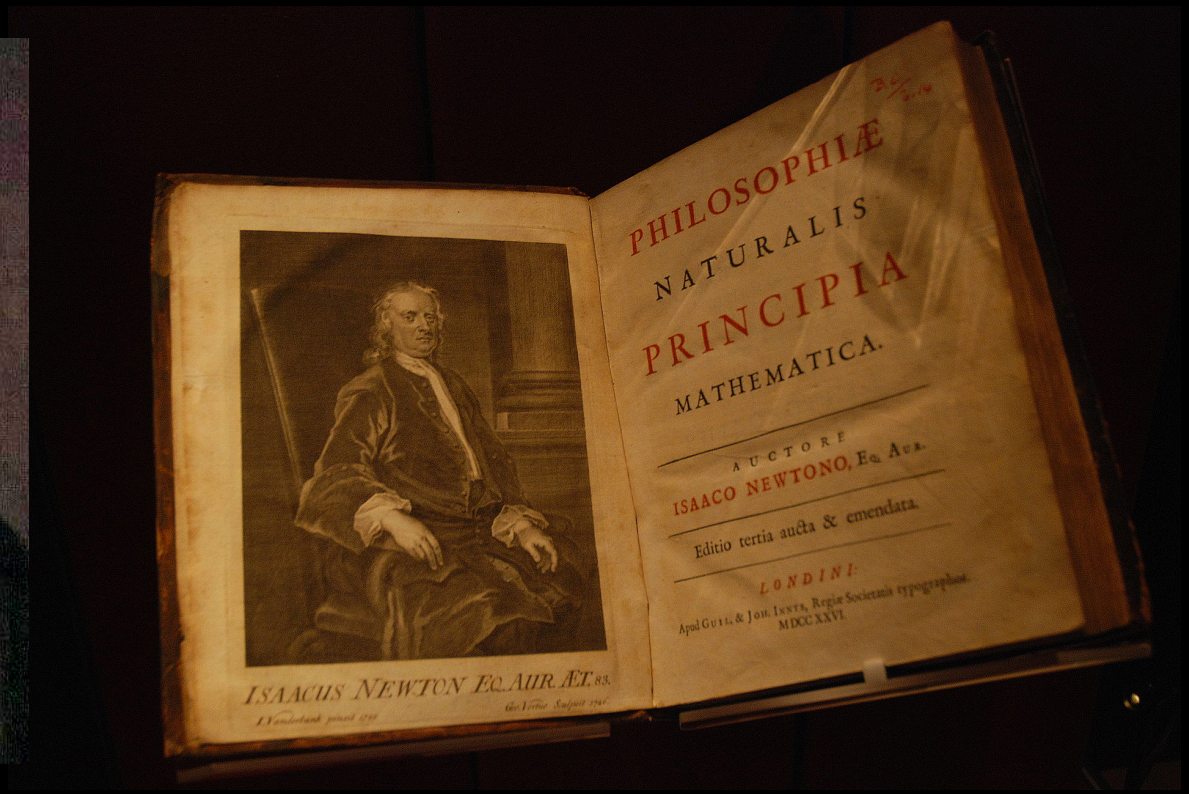


Roemer's drawing of Io's Jupiter eclipse

Observations in the pre-space age

- 1675 Danish astronomer Ole Roemer estimates the speed of light by observing eclipses of the large Jovian moons
- 1726 Isaac Newton publishes mass estimate of Jupiter using motions of the four large moons





Observations in the pre-space age

- 1675 Danish astronomer Ole Roemer estimates the speed of light by observing eclipses of the large Jovian moons
- 1726 Isaac Newton publishes mass estimate of Jupiter using motions of the four large moons
- 1805 Pierre Laplace deduces the mass of Europa to within 10% of the modern value and identifies orbital resonances among the moons

MÉCANIQUE CÉLESTE.

BY THE

MARQUIS DE LA PLACE,

TRANSLATED, WITH A COMMENTARY,

BY

NATHANIEL BOWDITCH, LL.D.

VOLUME I.

BOSTON:

PRINTED AND PUBLISHED BY HILLIARD, GRAY, LITTLE, AND WILKINS.

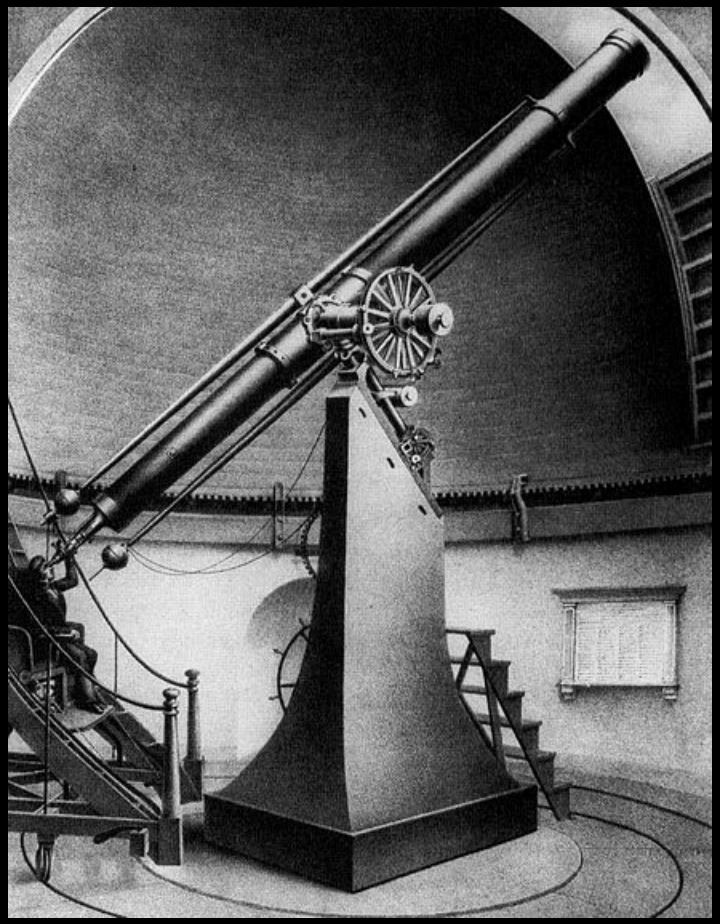
MDCCCXXIX.

Observations in the pre-space age

- 1675 Danish astronomer Ole Roemer estimates the speed of light by observing eclipses of the large Jovian moons
- 1726 Isaac Newton publishes mass estimate of Jupiter using motions of the four large moons
- 1805 Pierre Laplace deduces the mass of Europa to within 10% of the modern value and identifies orbital resonances among the moons
- 1859 Pietro Secchi estimates Europa's diameter, 6% larger than modern value

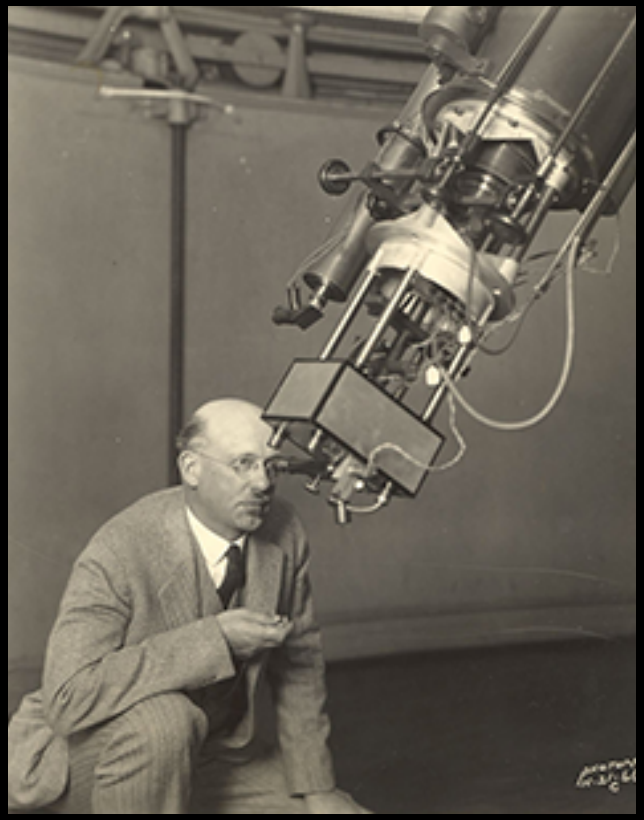
Observations in the pre-space age

- 1879 Pickering produces first accurate photometry measurements of Europa, and in 1908 suggests Europa is a low-density body with a bright surface



Observations in the pre-space age

- 1879 Pickering produces first accurate photometry measurements of Europa, and in 1908 suggests Europa is a low-density body with a bright surface
- 1927 Stebbins shows that Europa is in synchronous rotation and that the leading and trailing hemispheres had an asymmetry

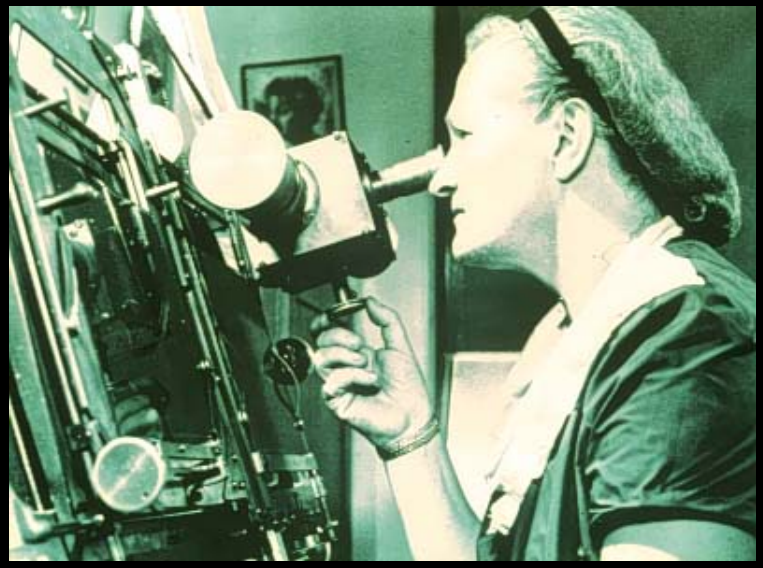


Observations in the pre-space age

- 1879 Pickering produces first accurate photometry measurements of Europa, and in 1908 suggests Europa is a low-density body with a bright surface
- 1927 Stebbins shows that Europa is in synchronous rotation and that the leading and trailing hemispheres had an asymmetry
- 1952 Urey speculates that the outer solar system is filled with water ice, and that the water of the Jovian moons must be at or near their surfaces. He even suggests water flows might occur instead of terrestrial lava flows

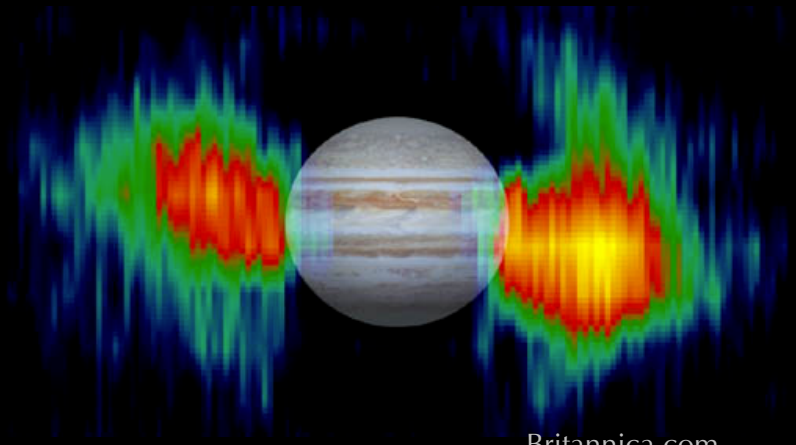
Observations in the pre-space age

- 1879 Pickering produces first accurate photometry measurements of Europa, and in 1908 suggests Europa is a low-density body with a bright surface
- 1927 Stebbins shows that Europa is in synchronous rotation and that the leading and trailing hemispheres had an asymmetry
- 1952 Urey speculates that the outer solar system is filled with water ice, and that the water of the Jovian moons must be at or near their surfaces. He even suggests water flows might occur instead of terrestrial lava flows
- 1956 Payne-Gaposchkin publishes that Europa has a negligible atmosphere



Observations in the pre-space age

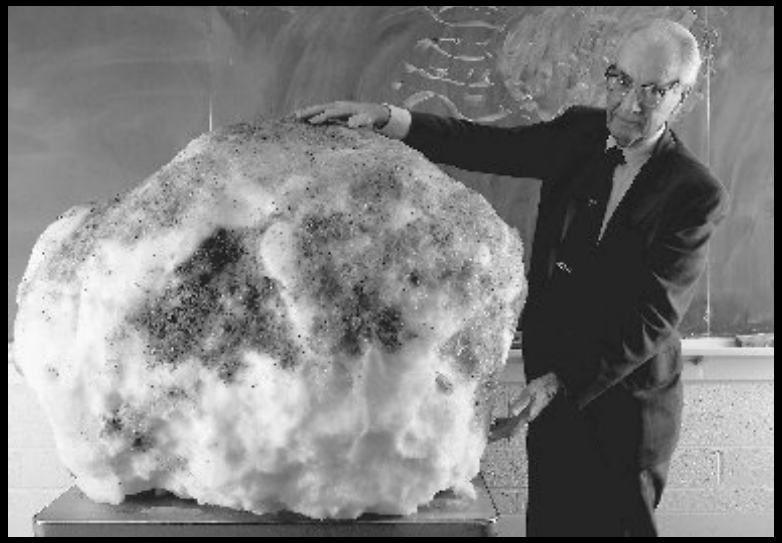
- 1879 Pickering produces first accurate photometry measurements of Europa, and in 1908 suggests Europa is a low-density body with a bright surface
- 1927 Stebbins shows that Europa is in synchronous rotation and that the leading and trailing hemispheres had an asymmetry
- 1952 Urey speculates that the outer solar system is filled with water ice, and that the water of the Jovian moons must be at or near their surfaces. He even suggests water flows might occur instead of terrestrial lava flows
- 1956 Payne-Gaposchkin publishes that Europa has a negligible atmosphere
- 1950's Jupiter is recognized as having a substantial magnetic field containing extensive energetic plasma



Britannica.com

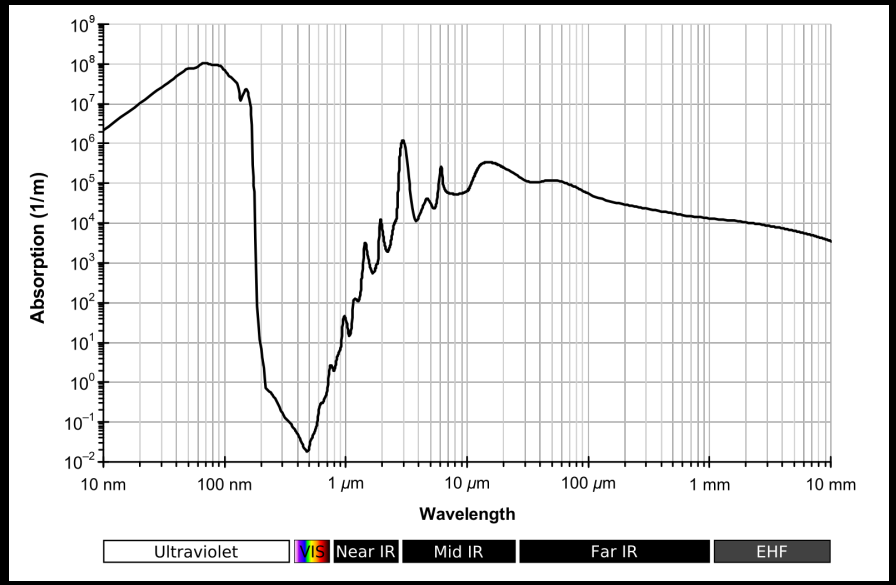
Other ground-based telescopic observations

- 1963 Whipple writes that Europa's surface must be at least partially covered with some H_2O ice and other frozen gases



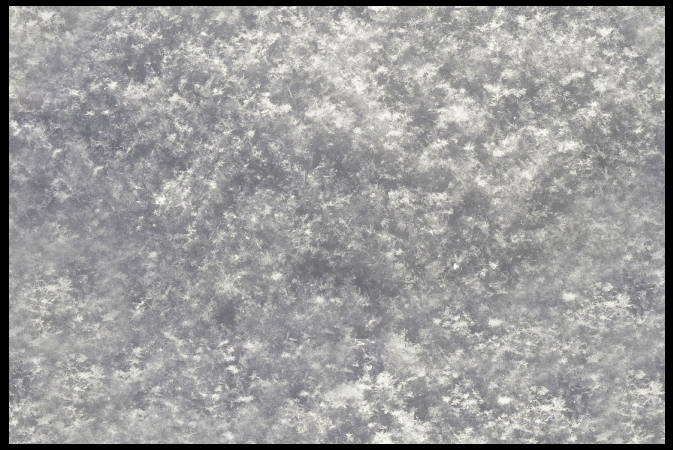
Other ground-based telescopic observations

- 1963 Whipple writes that Europa's surface must be at least partially covered with some H_2O ice and other frozen gases
- Early 1970's: Color and infrared measurements yield direct temperatures of Europa and information of surface composition
  - 1972 Pilcher concludes that Europa's surface is 50-100% water ice
  - 1974 Morrison suggested variations in Europa's reflectance could be due to exogenic effects due to interactions with the Jovian magnetosphere

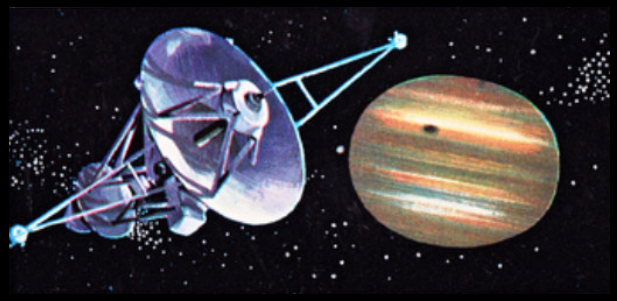


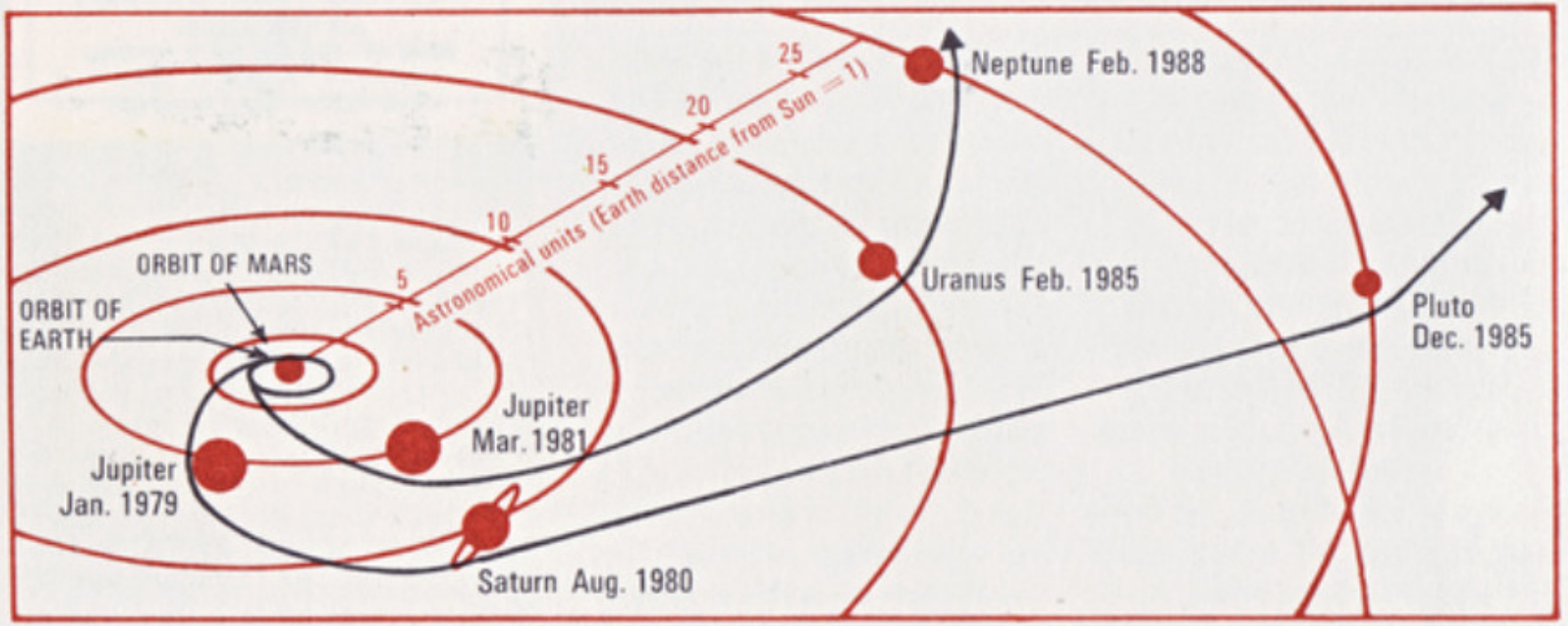
Other ground-based telescopic observations

- 1963 Whipple writes that Europa's surface must be at least partially covered with some H_2O ice and other frozen gases
- Early 1970's: Color and infrared measurements yield direct temperatures of Europa and information of surface composition
  - 1972 Pilcher concludes that Europa's surface is 50-100% water ice
  - 1974 Morrison suggested variations in Europa's reflectance could be due to exogenic effects due to interactions with the Jovian magnetosphere
- 1965 and 1975 Low and Murray find brightness temperature for Europa of 120K
- 1972, 1973 Morrison and Cruikshank determine Europa's thermal inertia, finding it has a low-conductivity, porous surface material

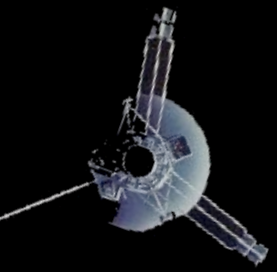


The Grand Tour

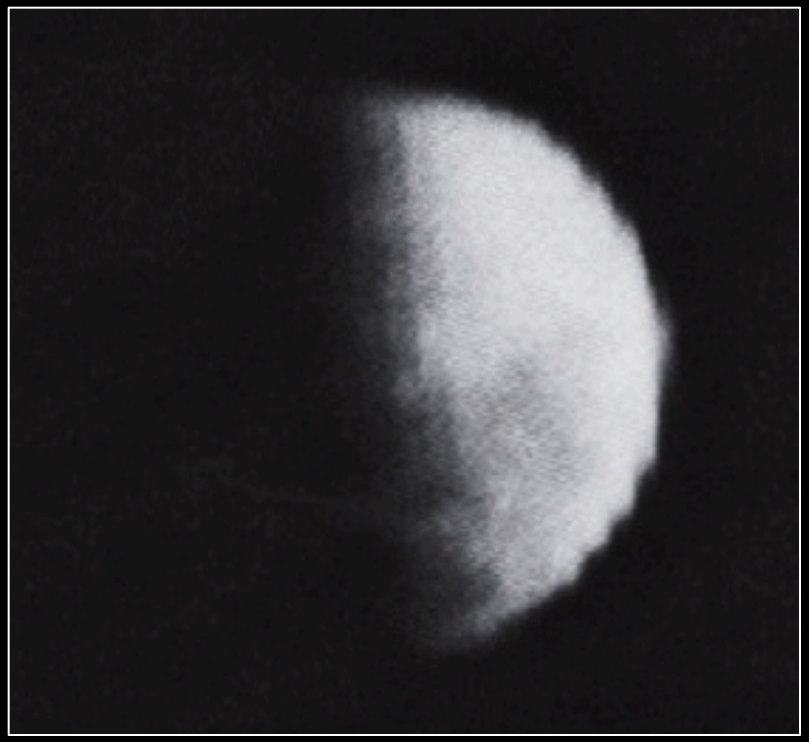




47. The exact layout of the spacecraft is not yet finalised, the card illustration showing one possible configuration. In multi-planet reconnaissance, the less time taken, the greater the chance of success, for it is easier to make a spacecraft operate reliably for nine years than 18 years. A similar conjunction of the outer planets will not recur for over 170 years. Two possible missions are shown, with the trajectories and the planets' fly-by dates.



Pioneer 10 views Europa (1973)



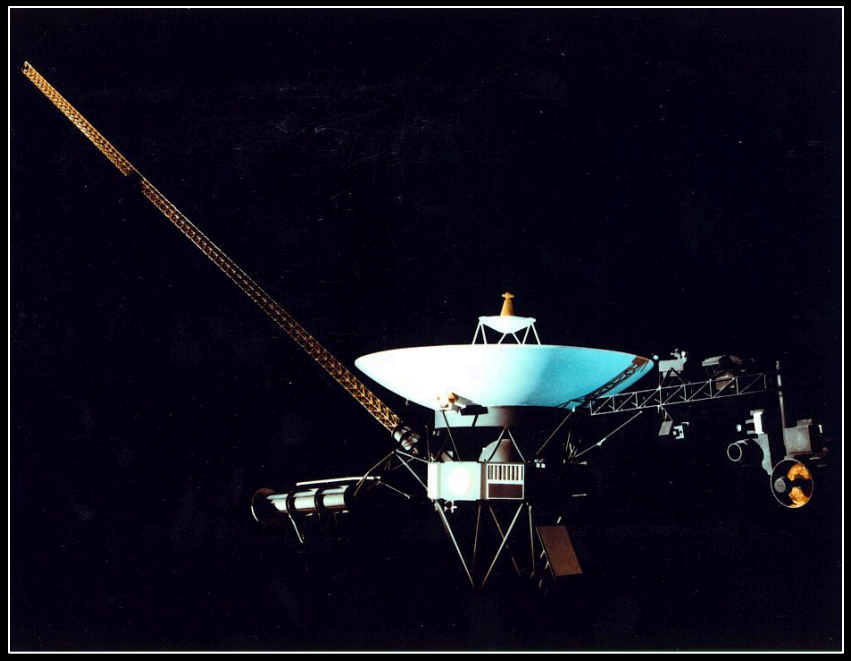
- Scan by imaging photopolarimeter
- Dec. 3, 1973, ~200 km/pixel

Voyager 1

Launched 5 Sep 1977

Closest approach to Jupiter Mar 5, 1979

Voyager 2

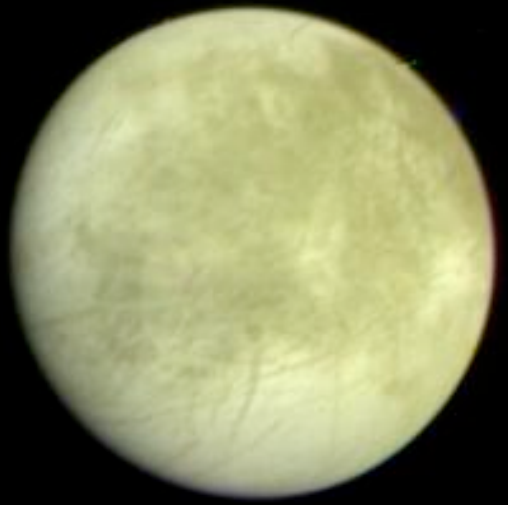


Launched 20 Aug 1977

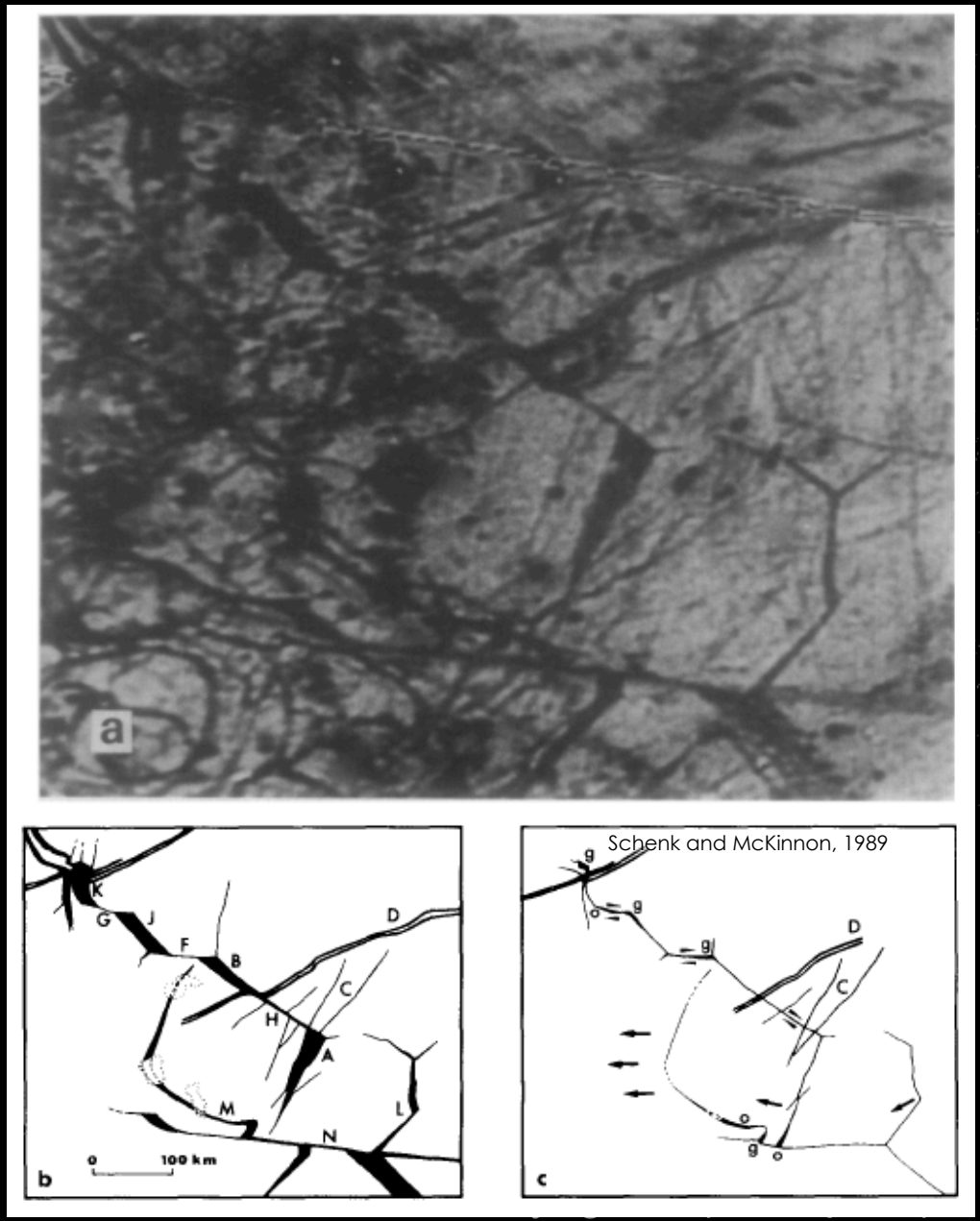
Acquired color imaging of Europa July 9, 1979

Voyager science results

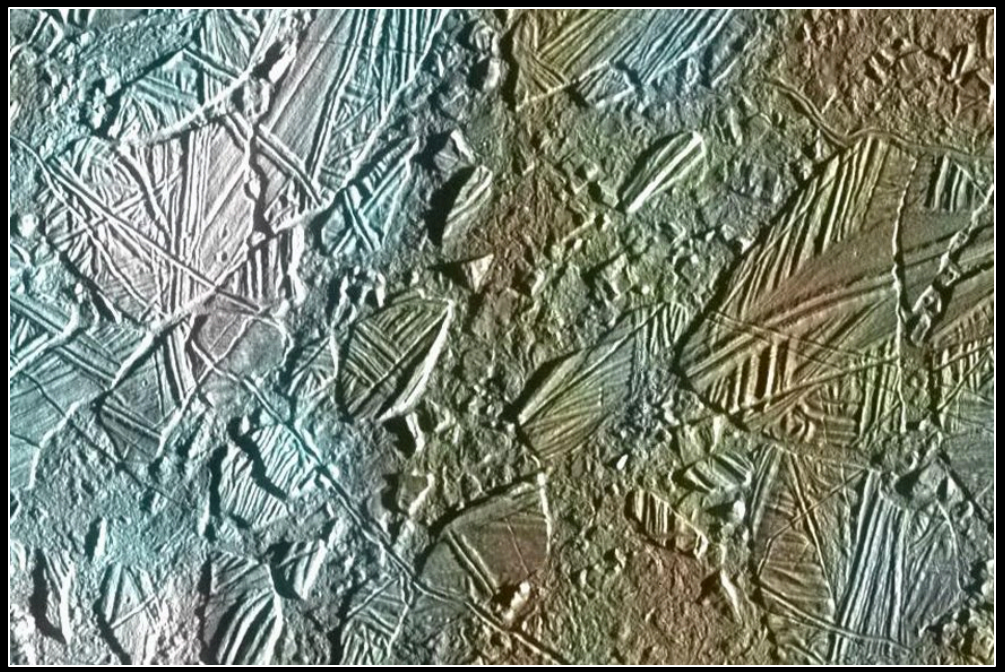
- Diameters of large satellites
- Few large impact craters
  - young surface or “relaxation”?
- Mottled terrain
  - internal activity or only impacts?
- Bright, lineated plains
  - crustal mobility
- Characterized Jovian magnetosphere and plasma environment



Voyager 1 (20 km/pixel)



Galileo

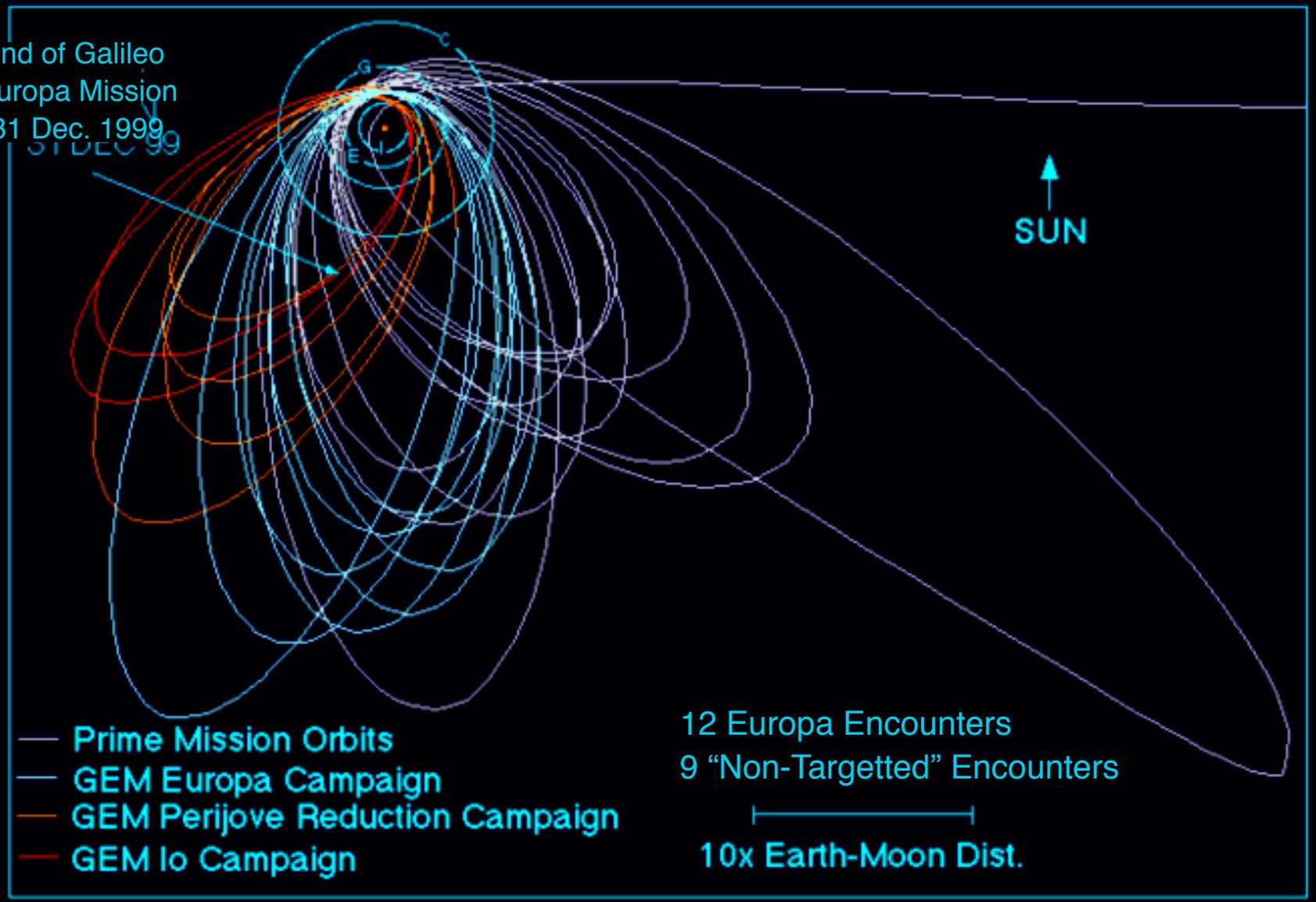


Deployed from Space Shuttle Oct 1989

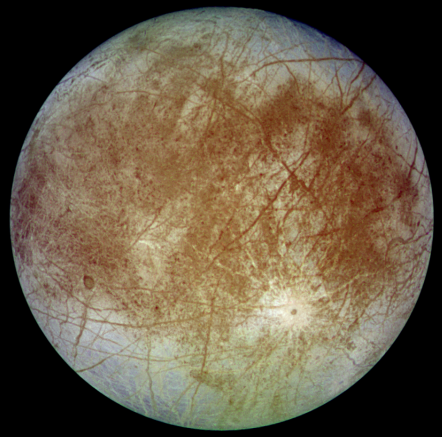
Probe deployed 7 Dec 1995

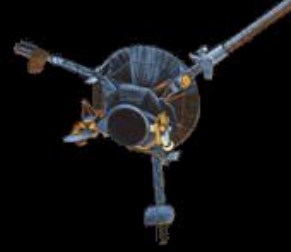
End of mission 21 Dec 2003

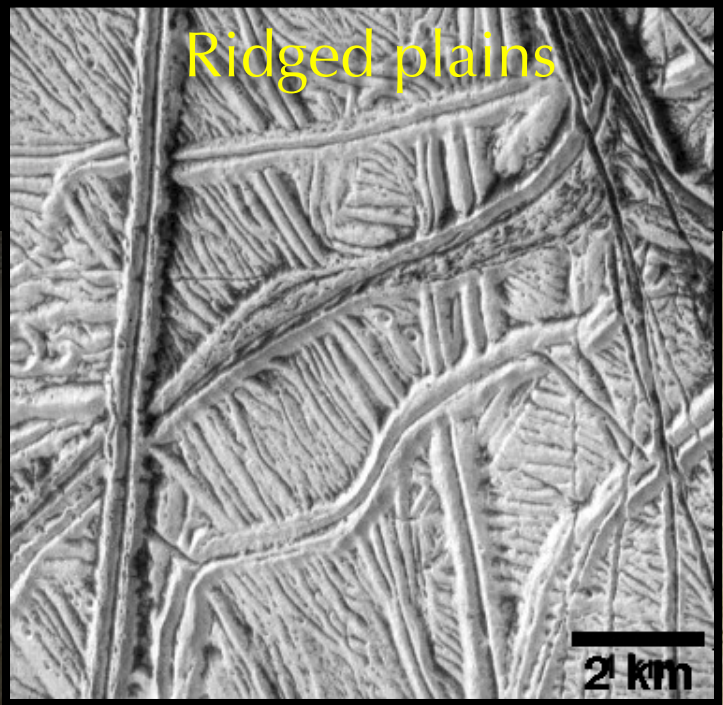
Galileo Europa Mission (GEM) and Prime Mission Tours

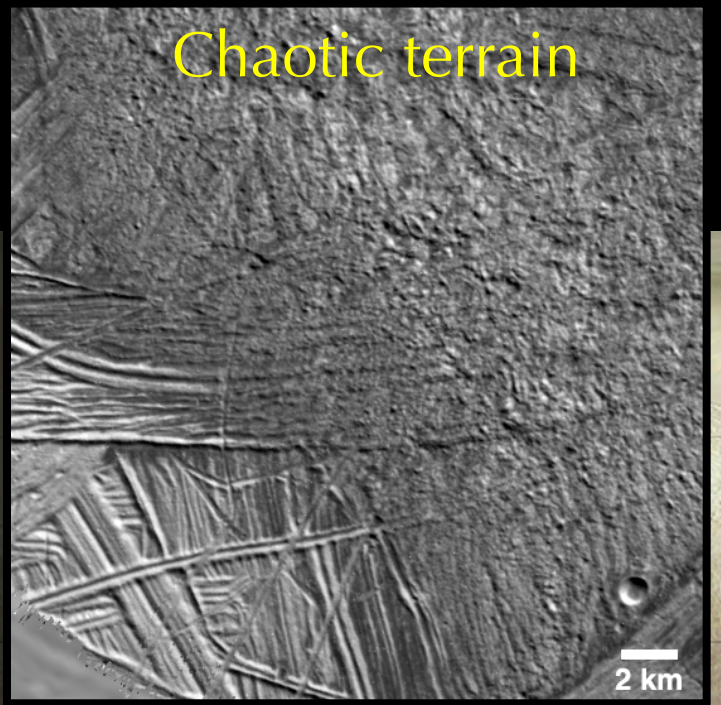


Galileo's views of Europa's surface

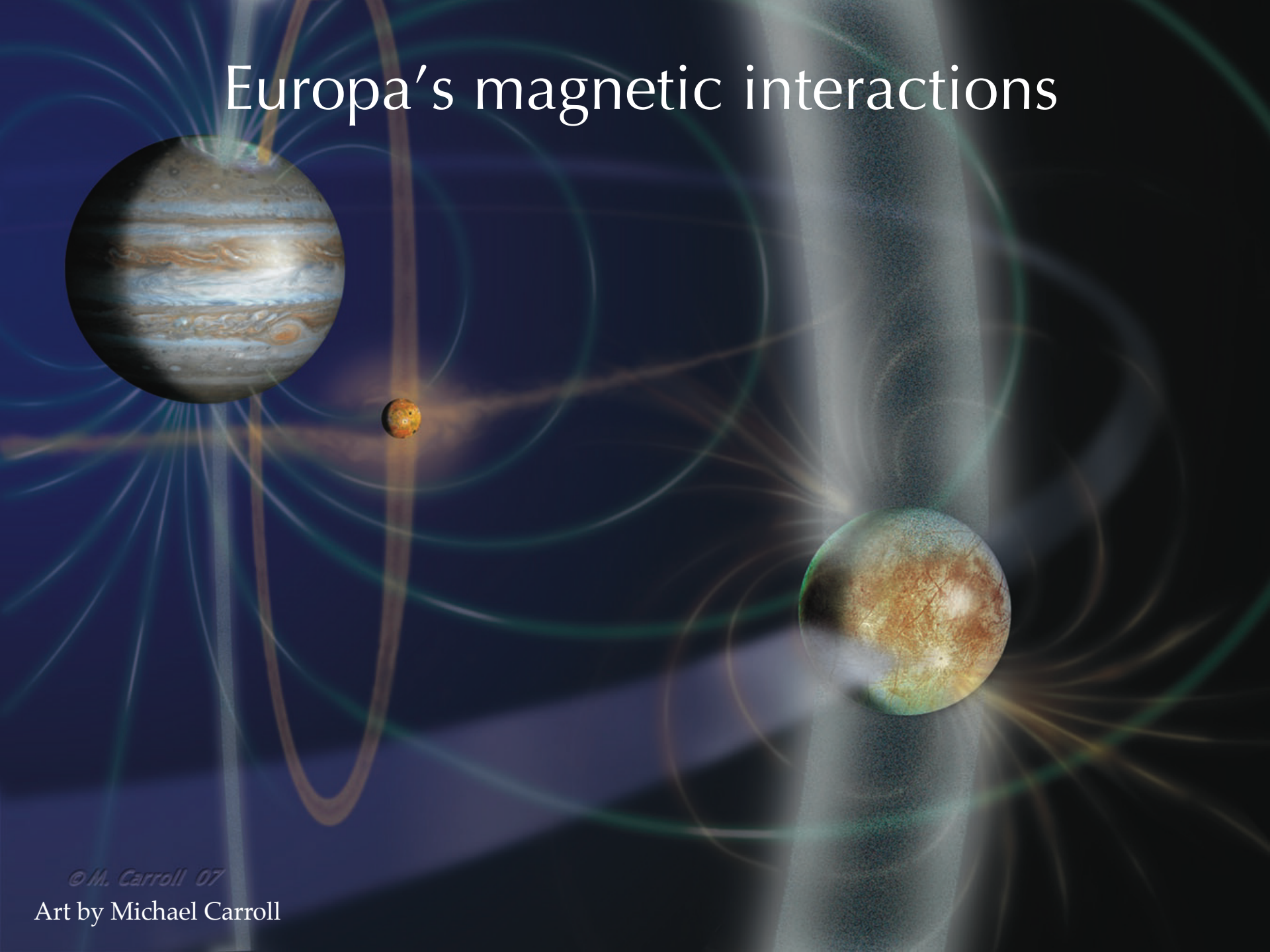






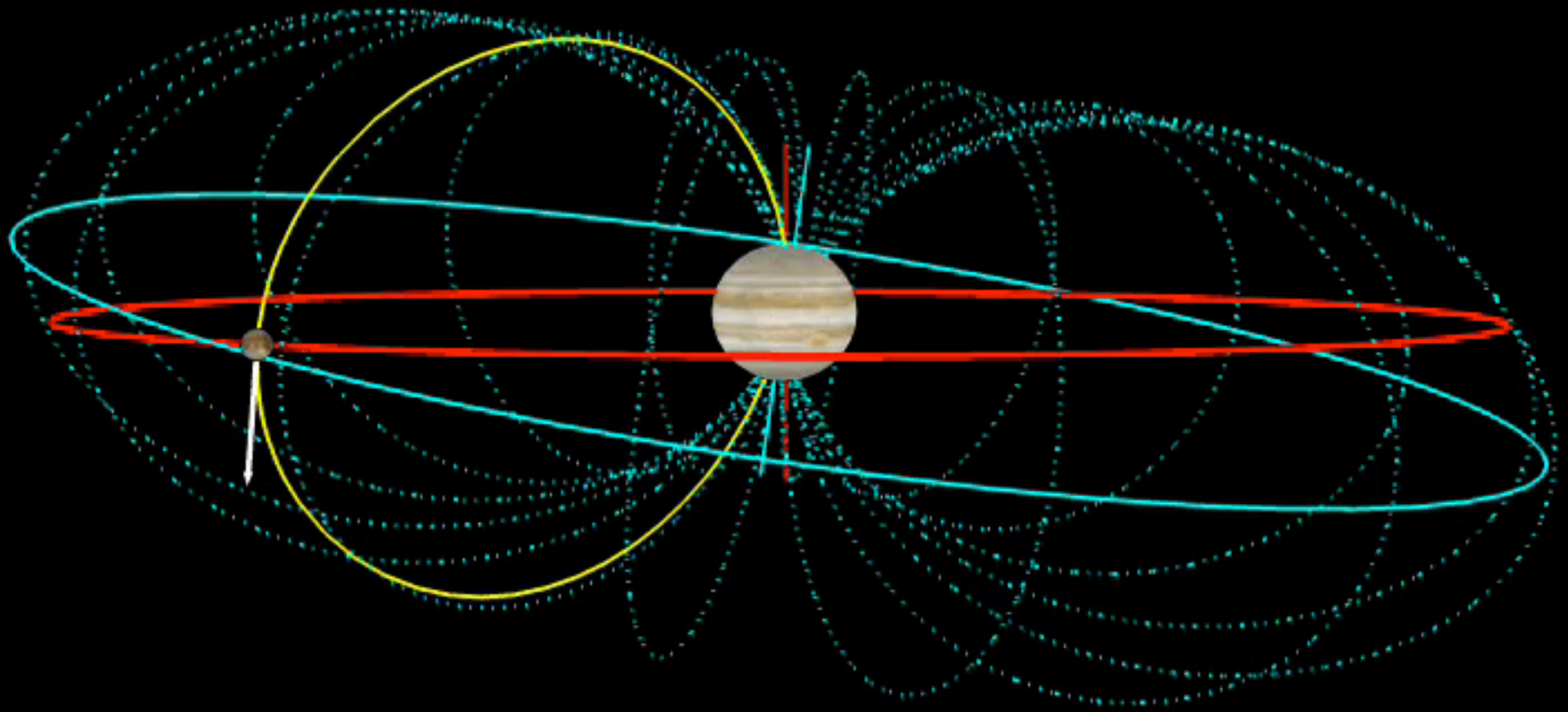


Europa's magnetic interactions



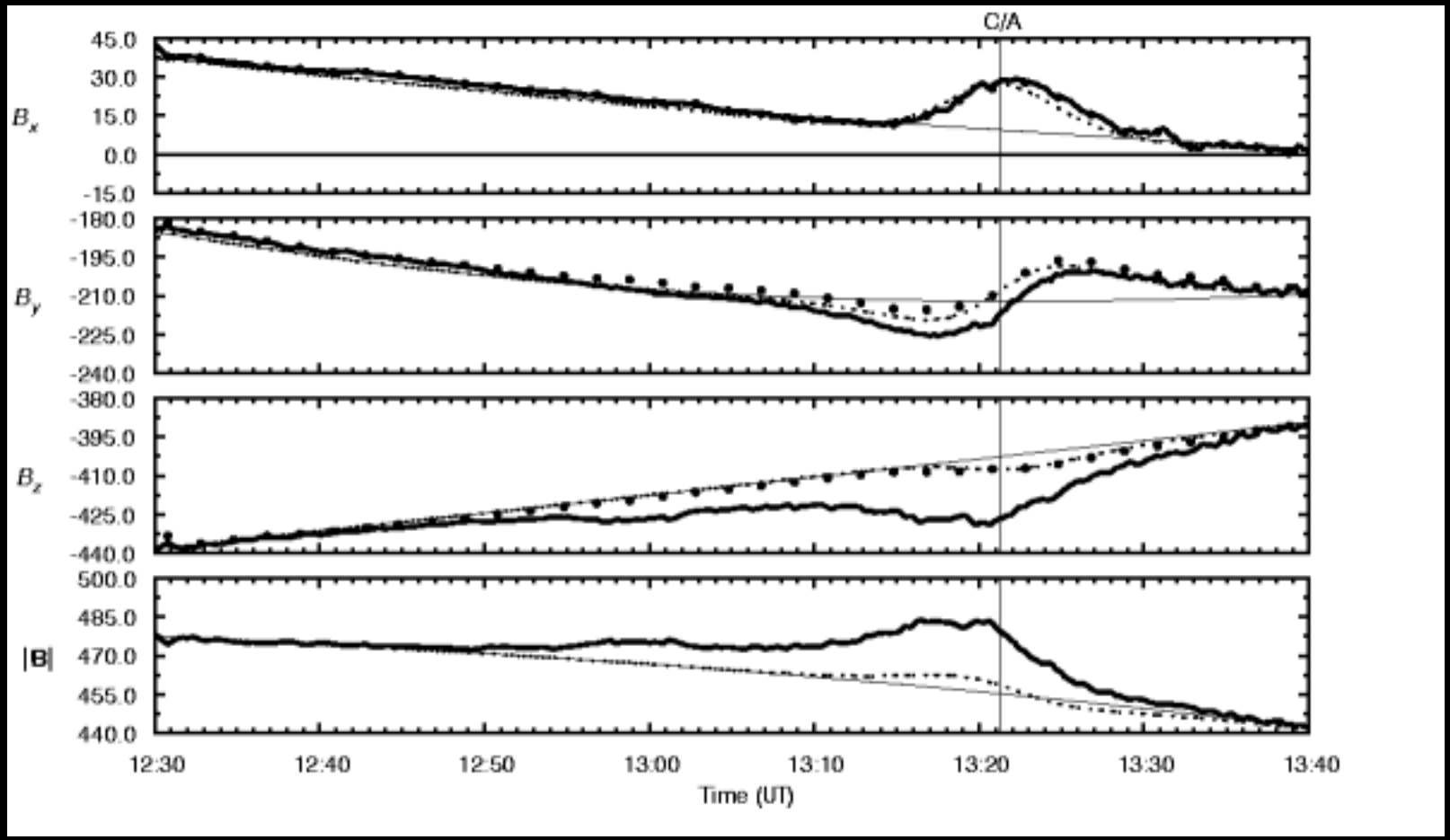
Art by Michael Carroll

Interaction of Europa with Jupiter's magnetic field



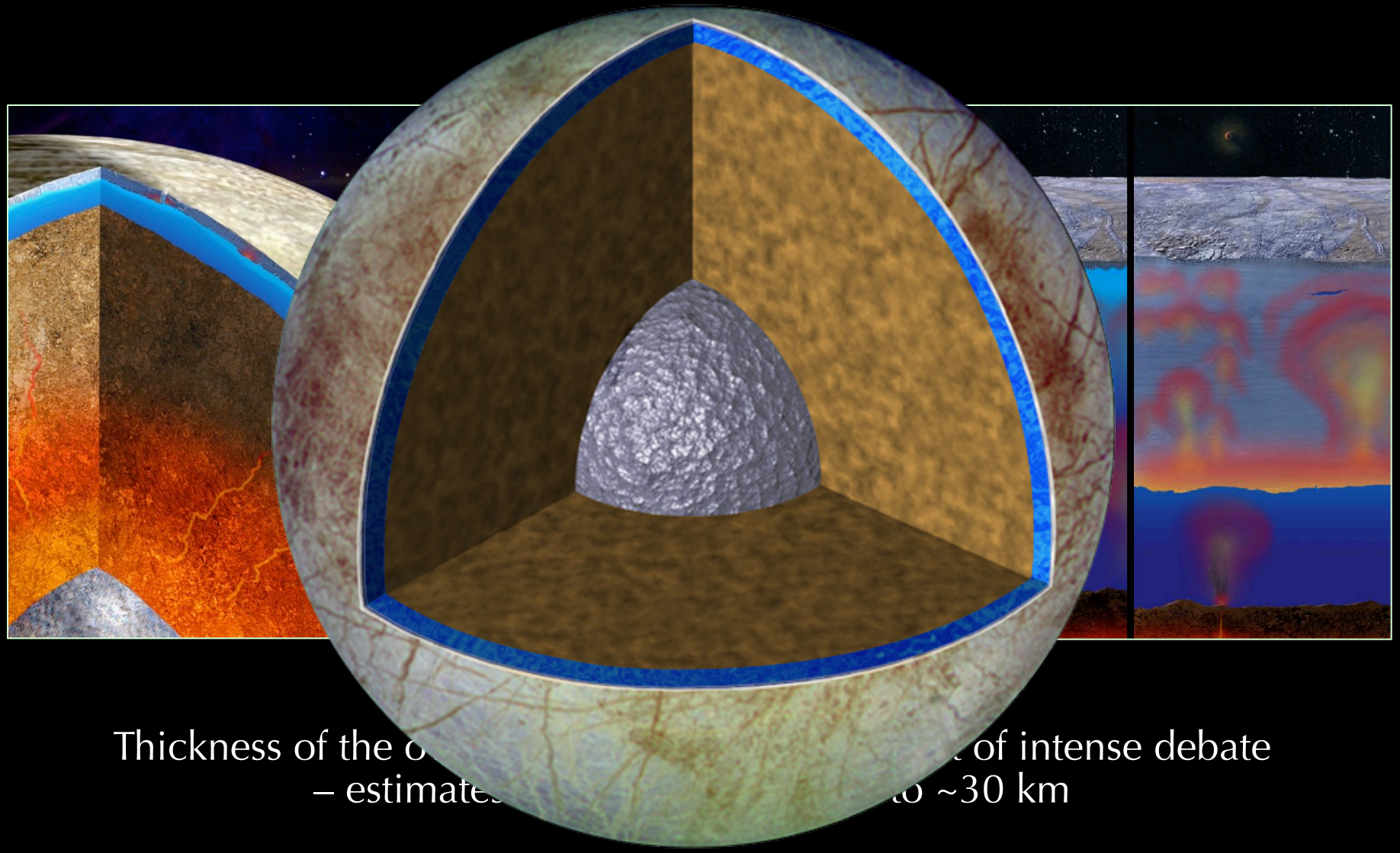
Jet

Europa's magnetic signature



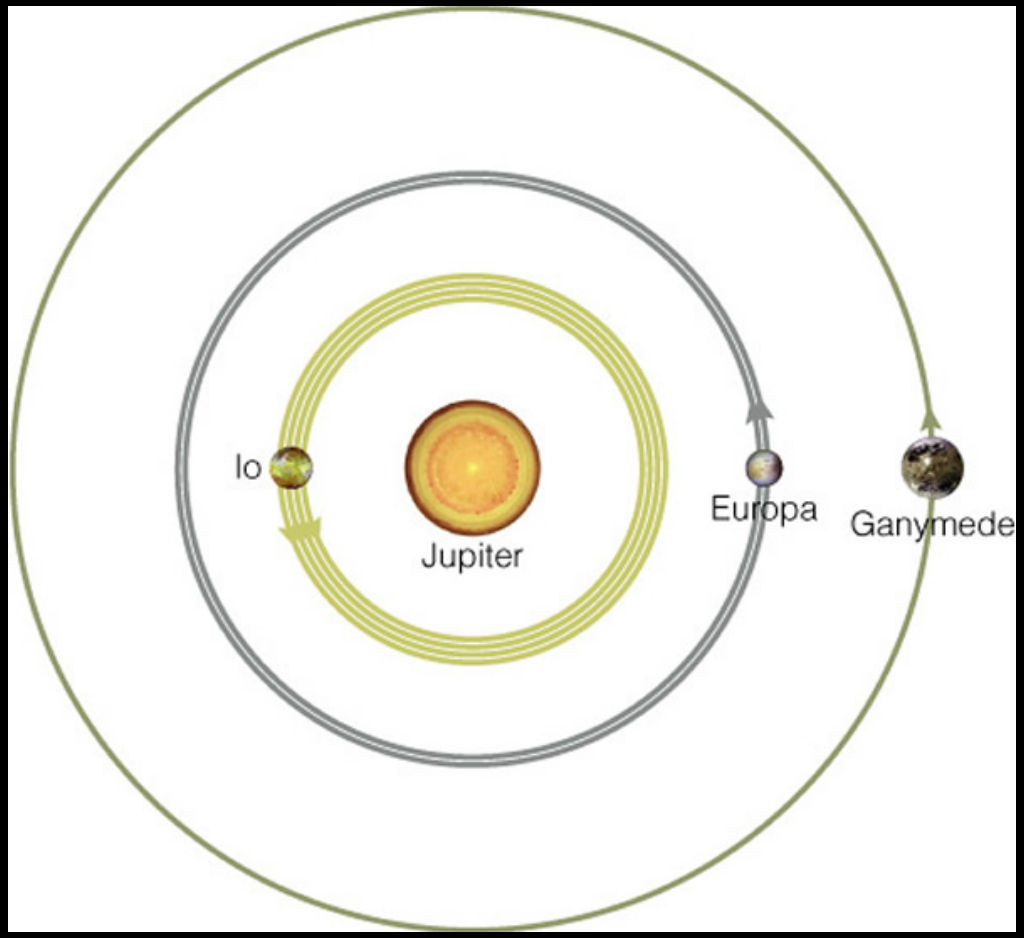
After Khurana et al., 1998

Magnetometer evidence indicates the presence of a ~100 km thick subsurface salty liquid water ocean at Europa



Thickness of the o of intense debate
– estimate ~30 km

The Laplace resonance

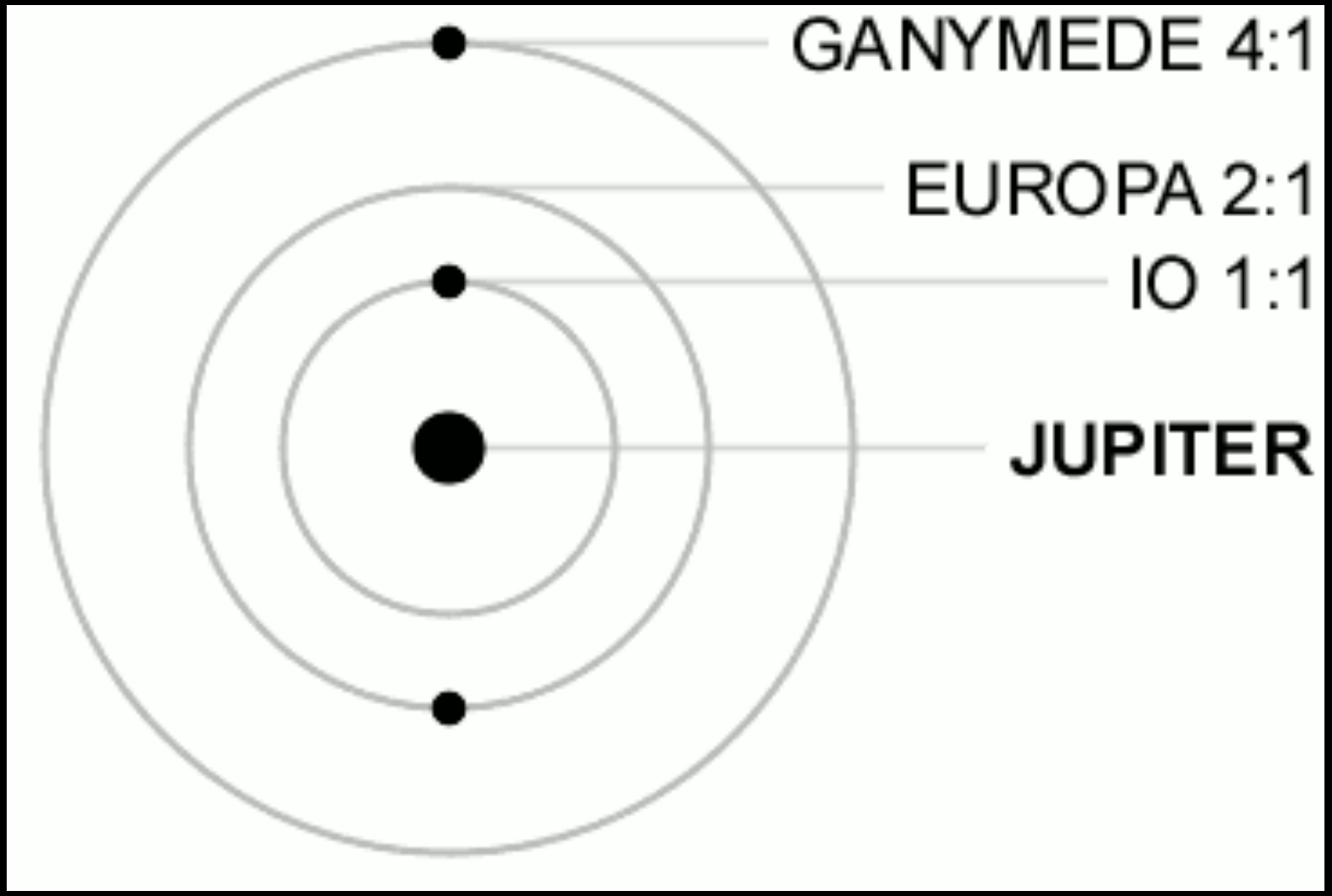


Ganymede 7.2 days

Europa 3.6 days

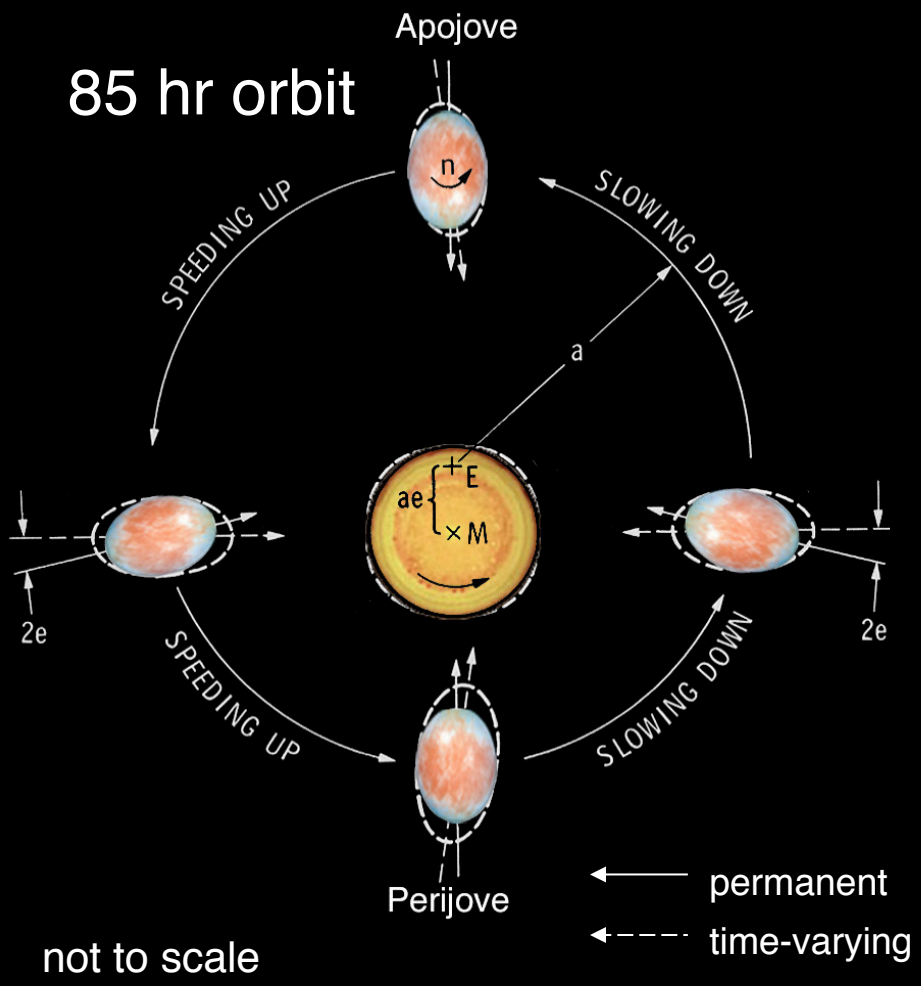
Io 1.8 days

The Laplace resonance



Resonance of inner 3 Galilean satellites keeps their orbits eccentric

Eccentric orbit: Tidal heating

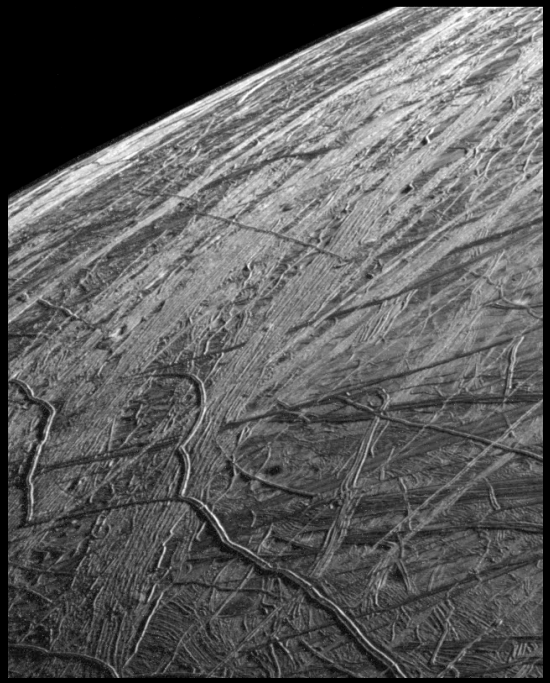


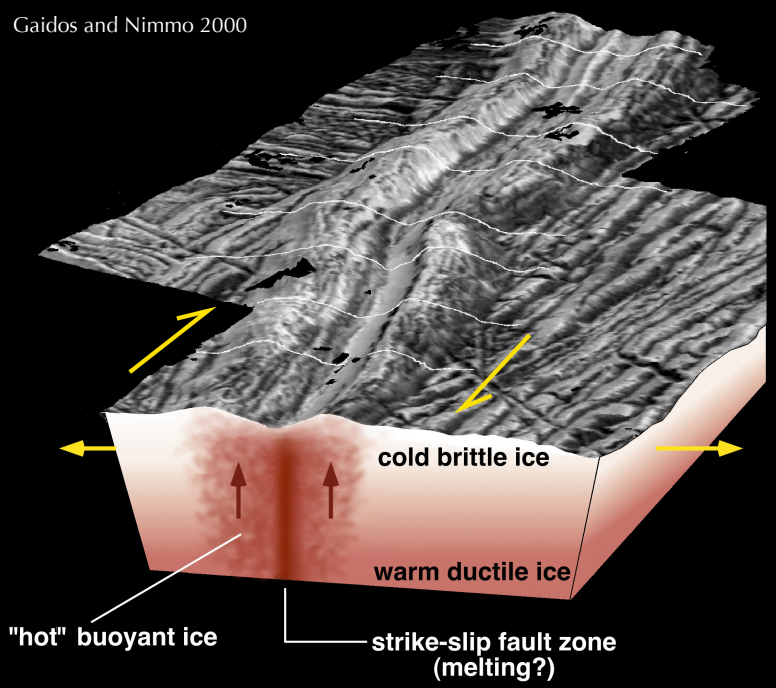
Squeezing heats up warm ice (or rock): tidal heating!

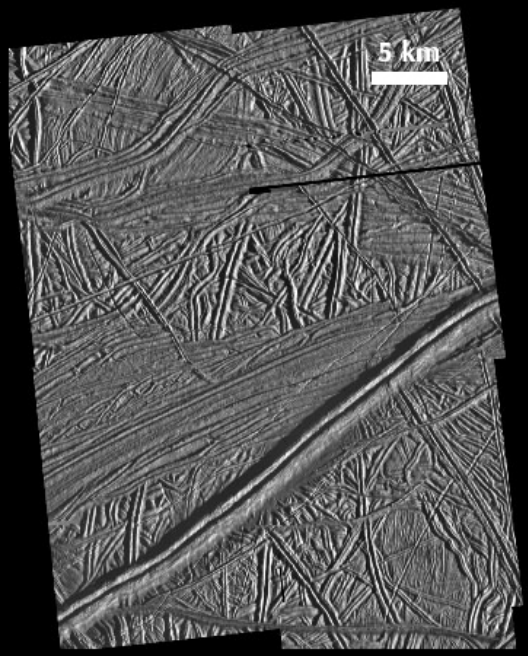
Europa's tectonics

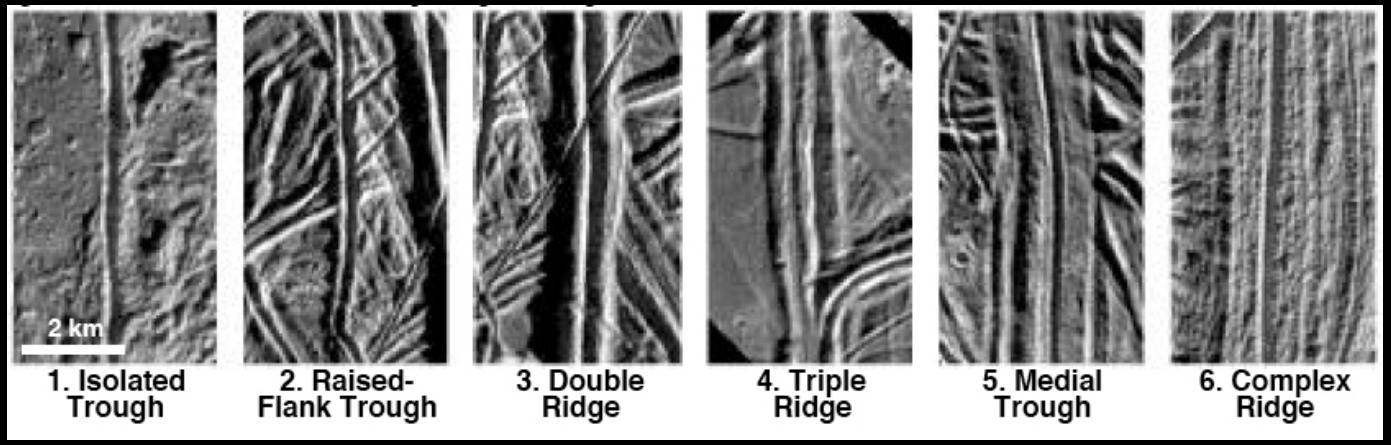
Mosaic by Ryan Sicilia

Ridges



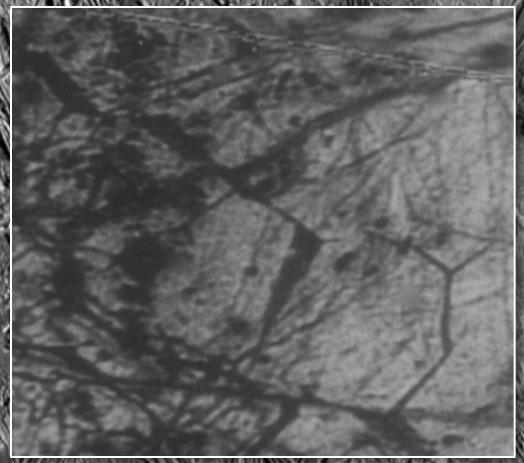


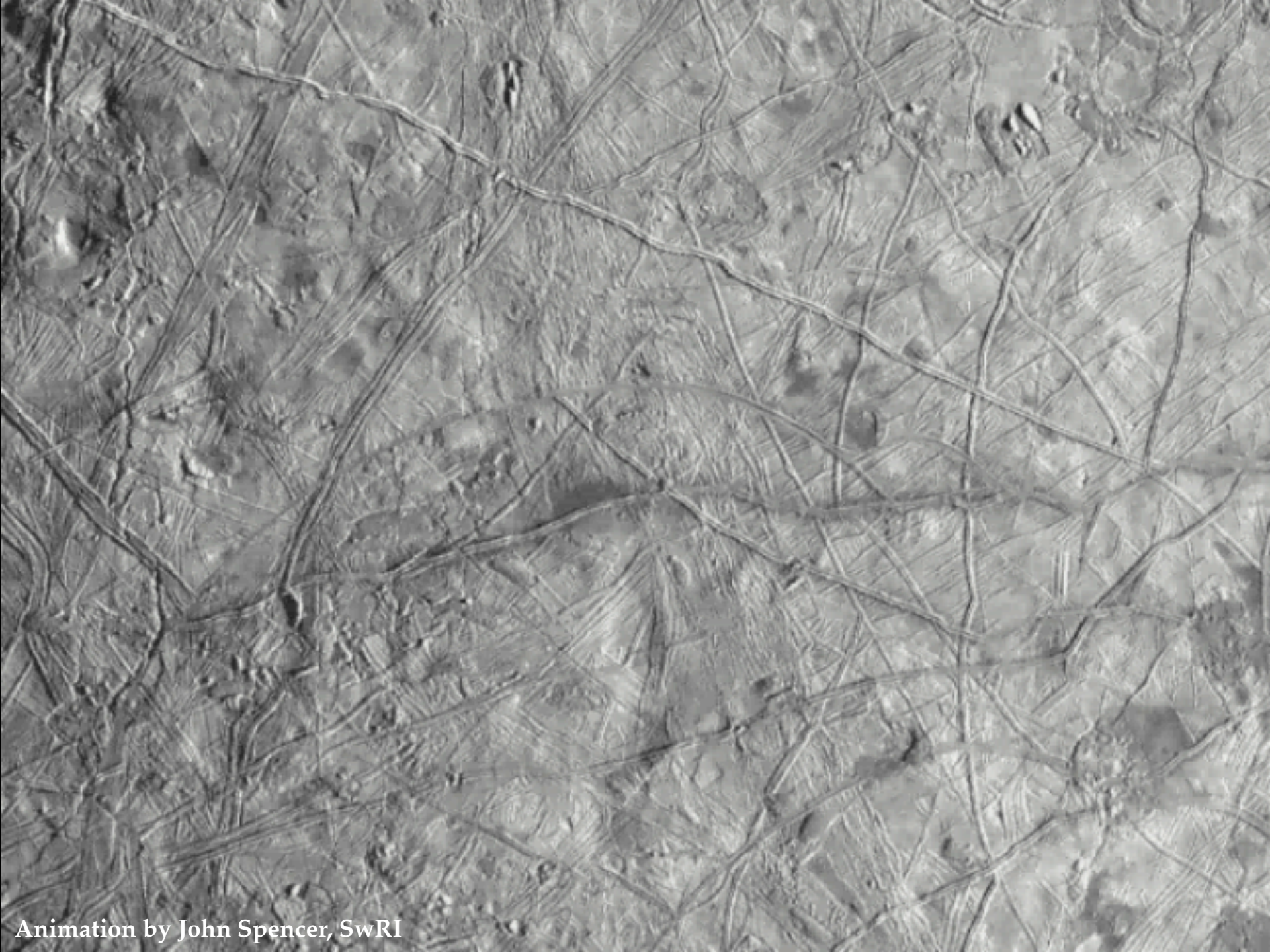




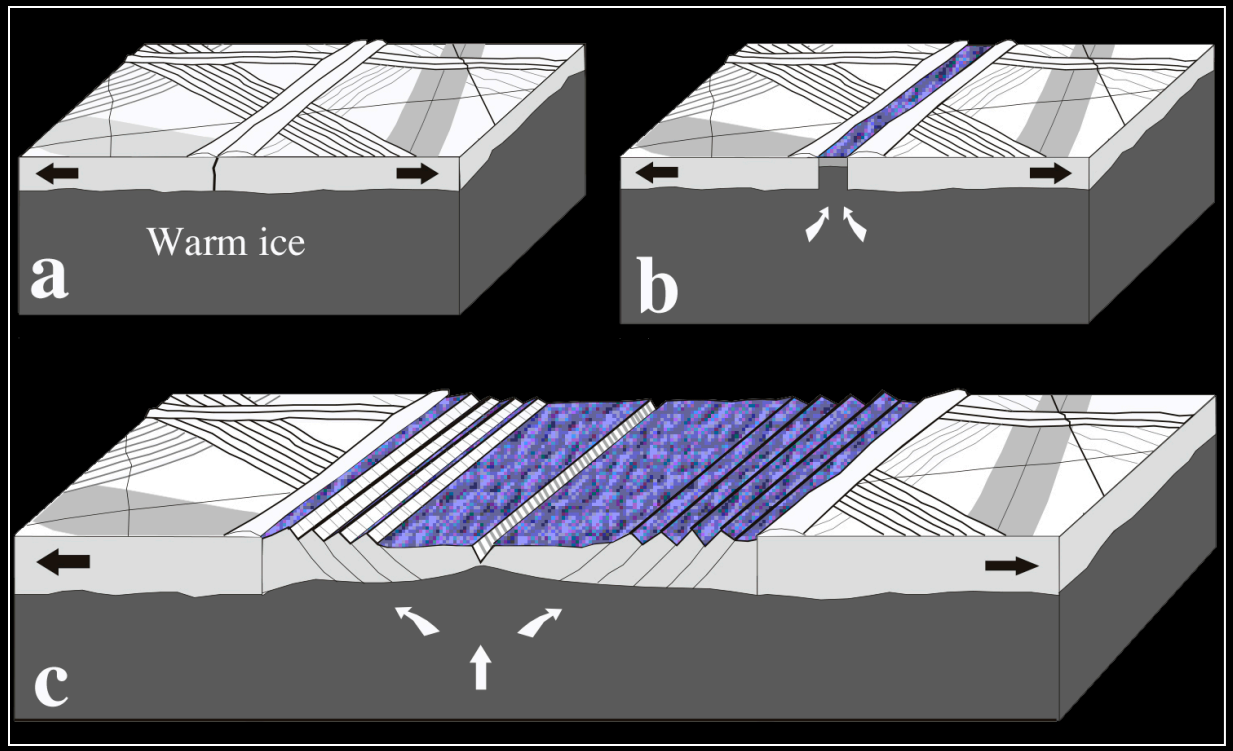
Greenberg et al., 1998; Pappalardo et al., 1998

Pull-apart bands

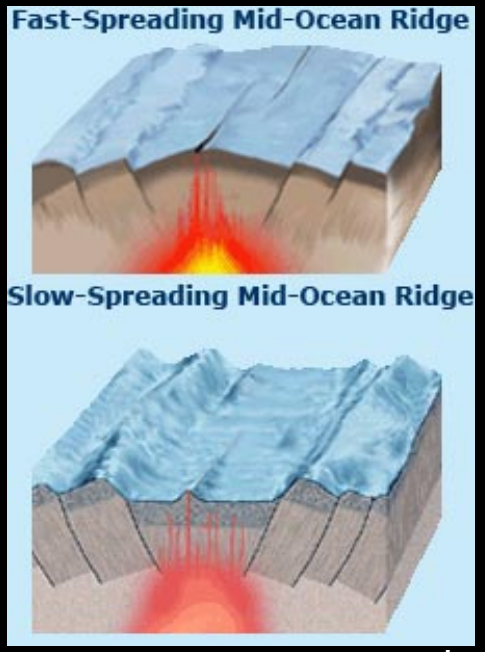



Animation by John Spencer, SwRI

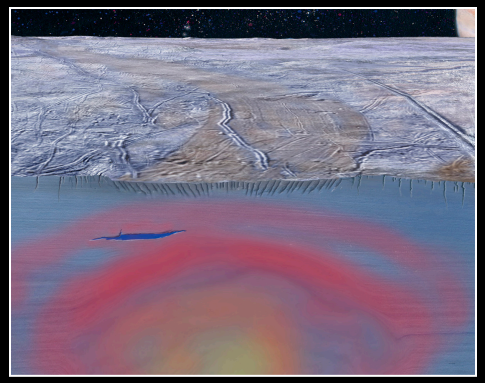
“Seafloor-spreading” model of band formation



Prockter et al., 2002



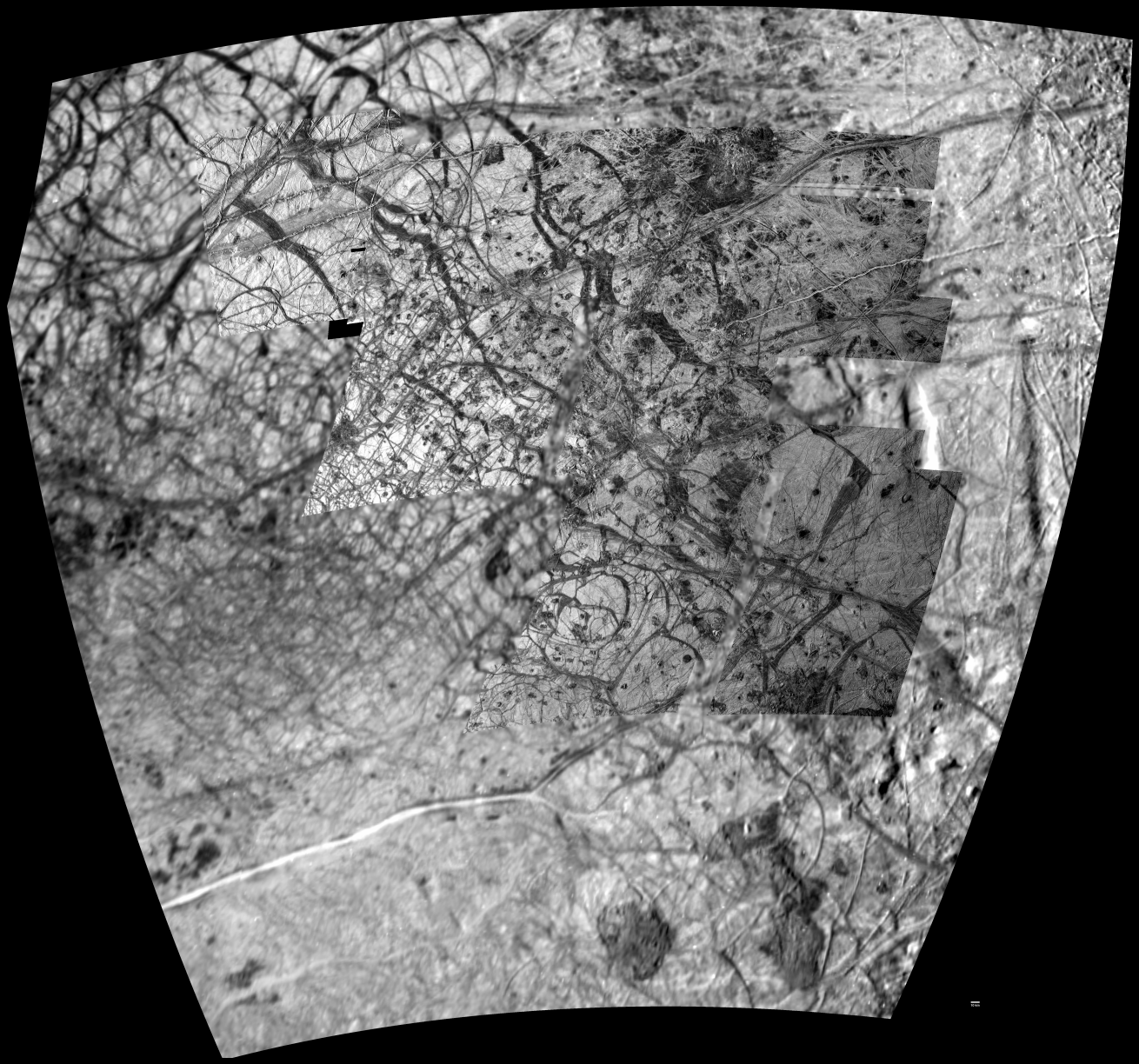
Earth



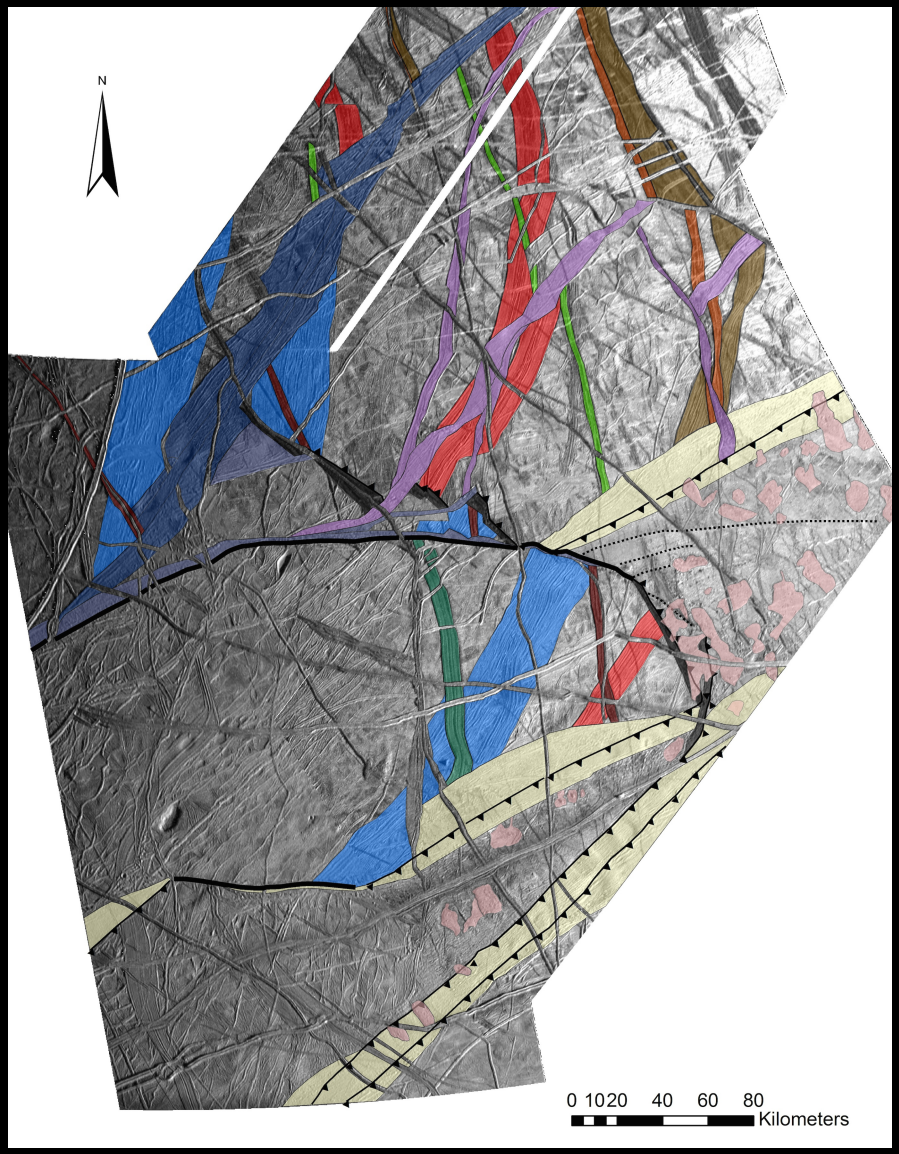
Europa?

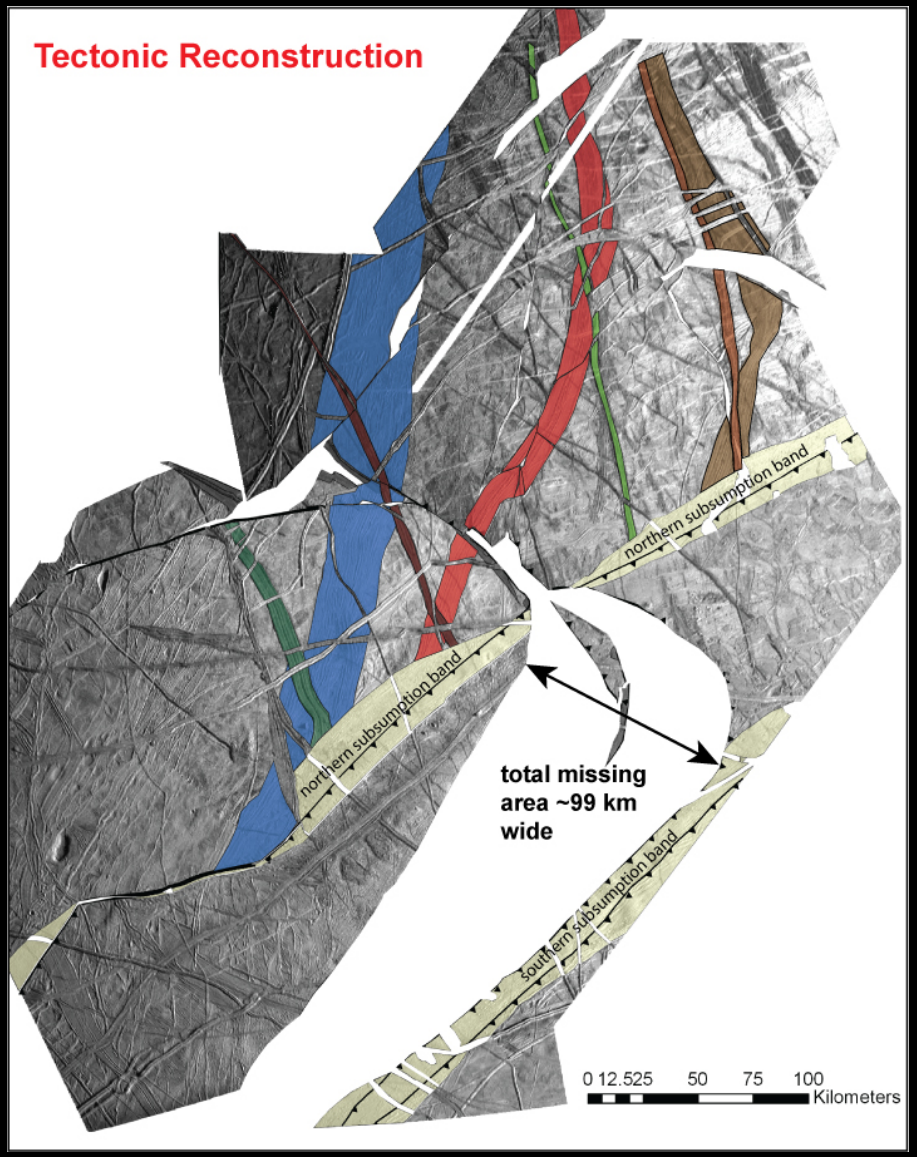
Similar mechanism to terrestrial mid-ocean ridges

Lots of extension – where's the contraction?



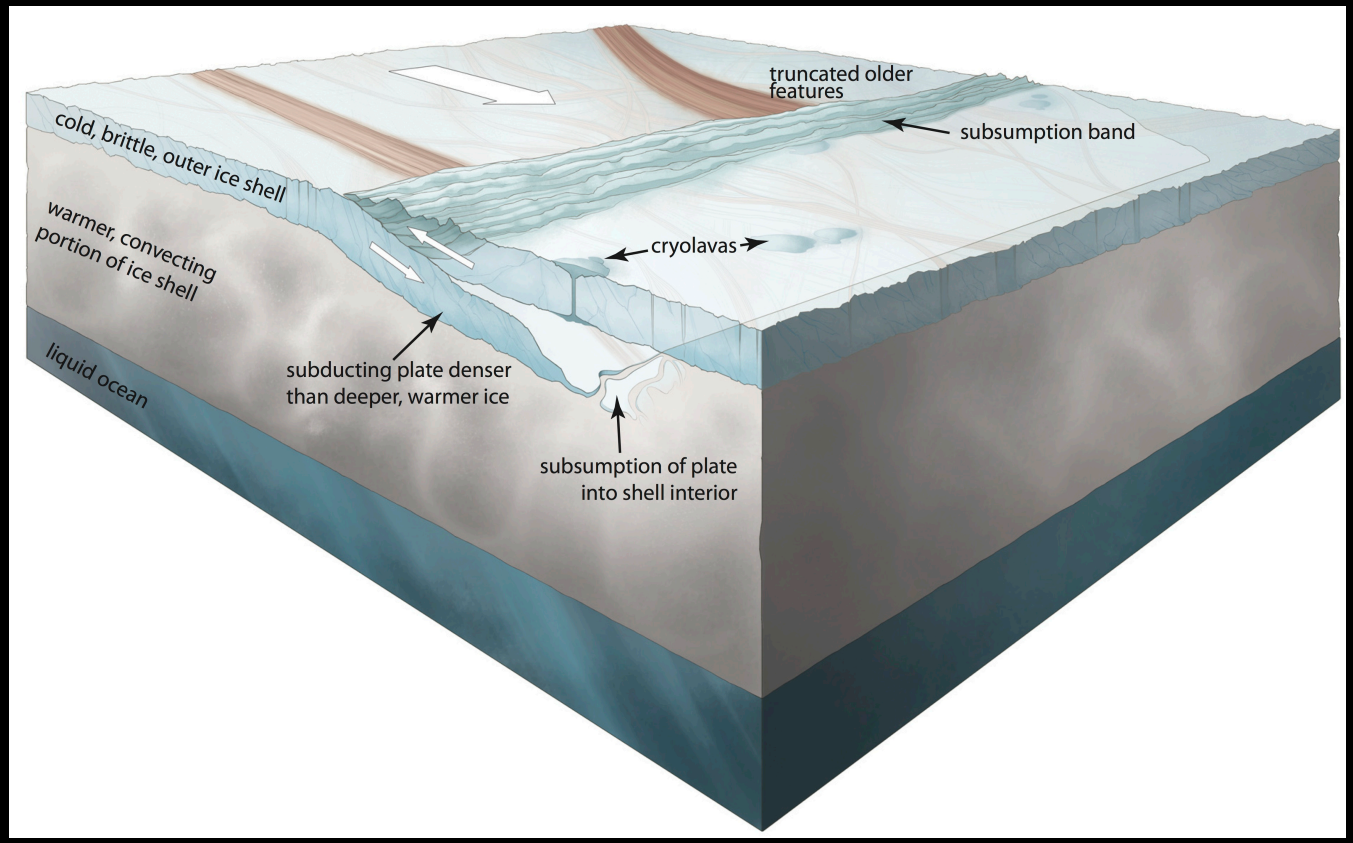
Subduction on Europa





Kattenhorn and Prockter, 2014

Subduction on Europa



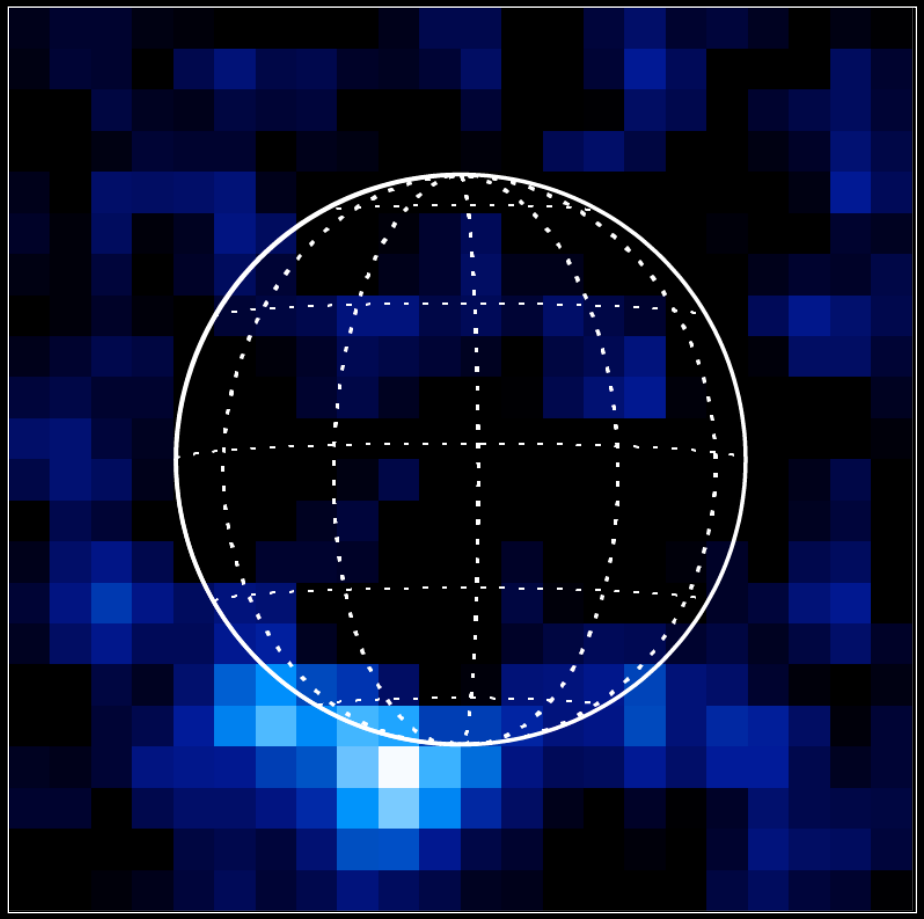
Kattenhorn and Prockter, 2014

If Europa's surface is undergoing spreading and subduction,
it is the only other body in the Solar System beside Earth which has plate tectonics

Europa's volcanism

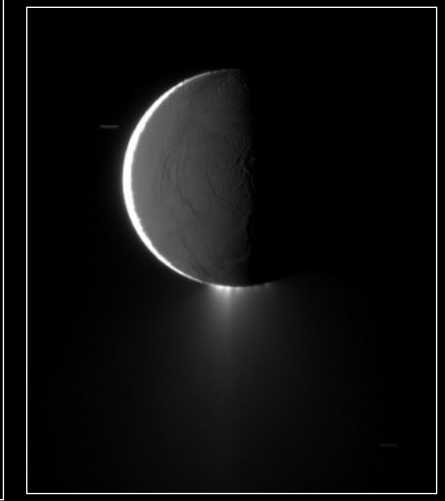
Mosaic by Ryan Sicilia

Possible plumes of water



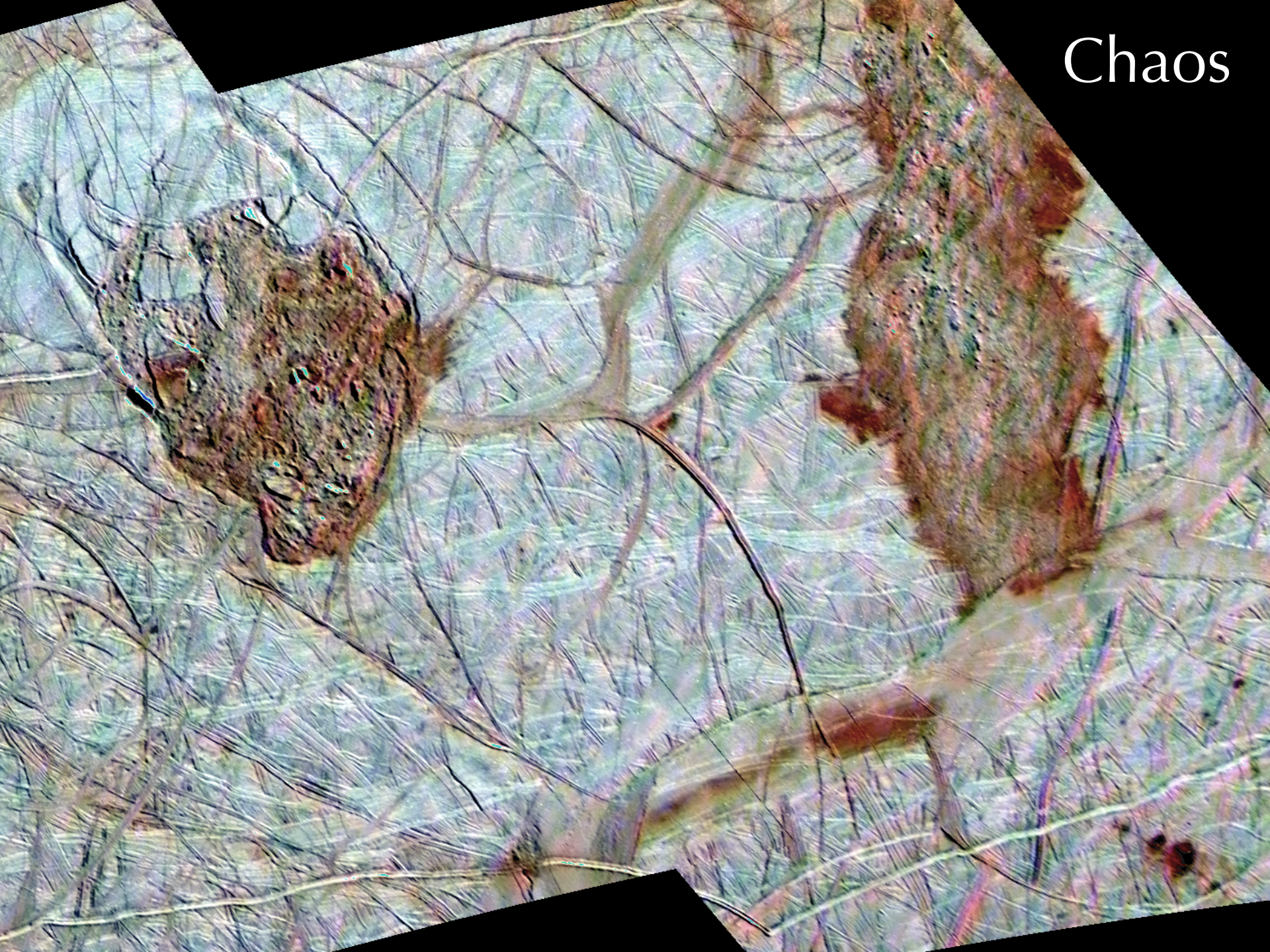
NASA/L. Roth

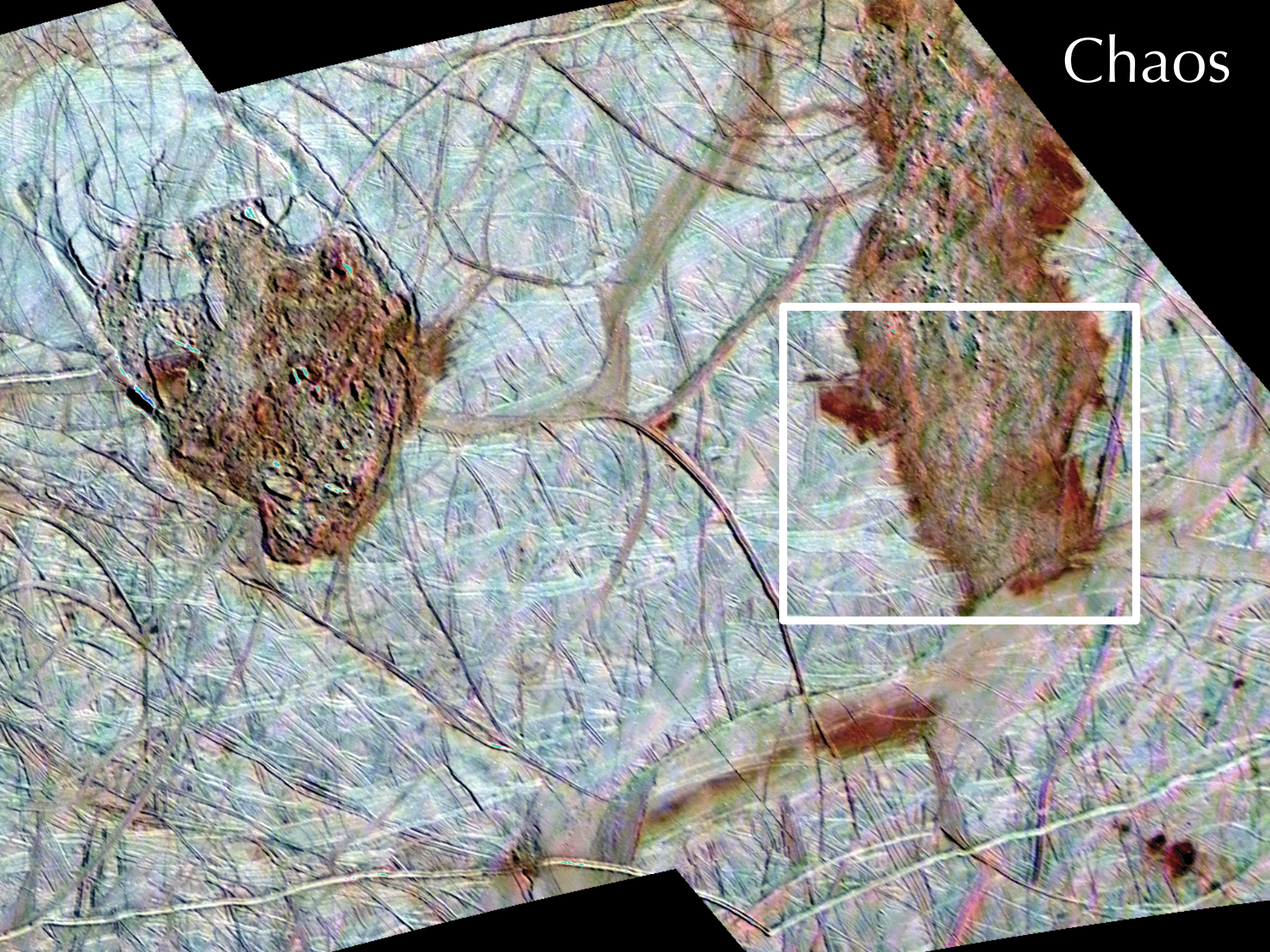
- Recent Hubble observations of Hydrogen and Oxygen ions concentrated near Europa's south pole (Roth et al., 2014)
- Interpreted as plumes of water vapor ~200 km high



Enceladus plumes

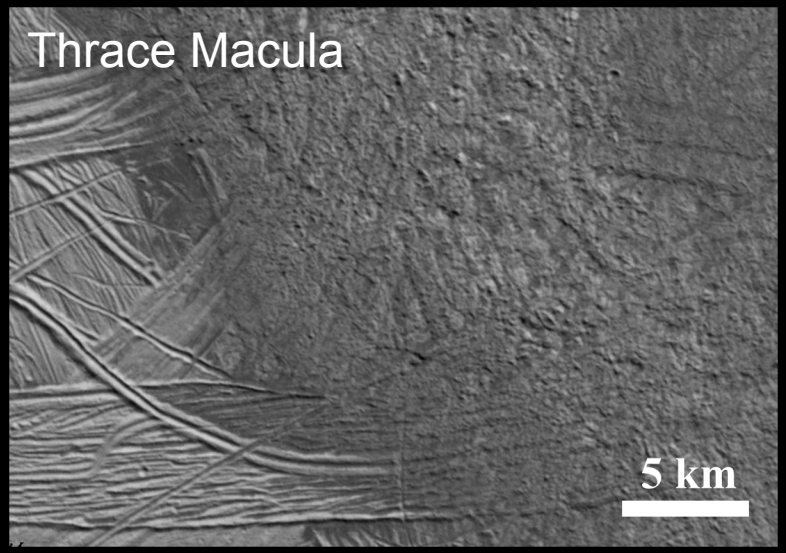
NASA/ESA/K. Retherford/SWRI

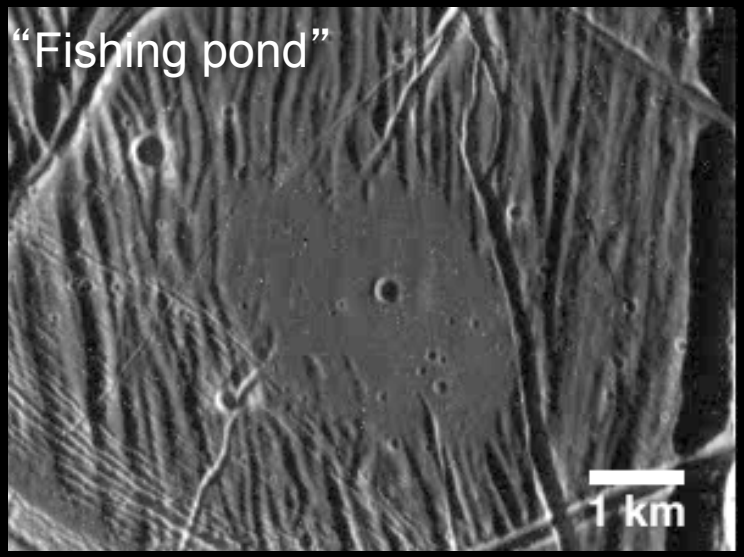

Chaos

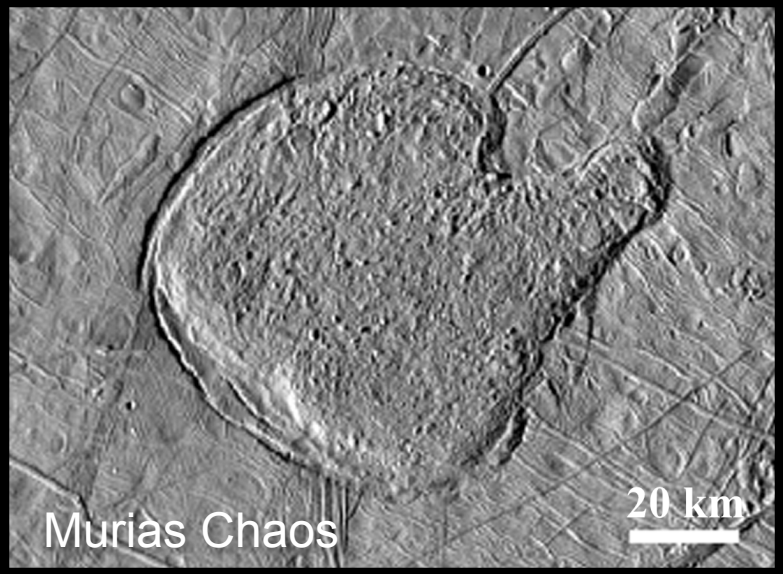

Chaos

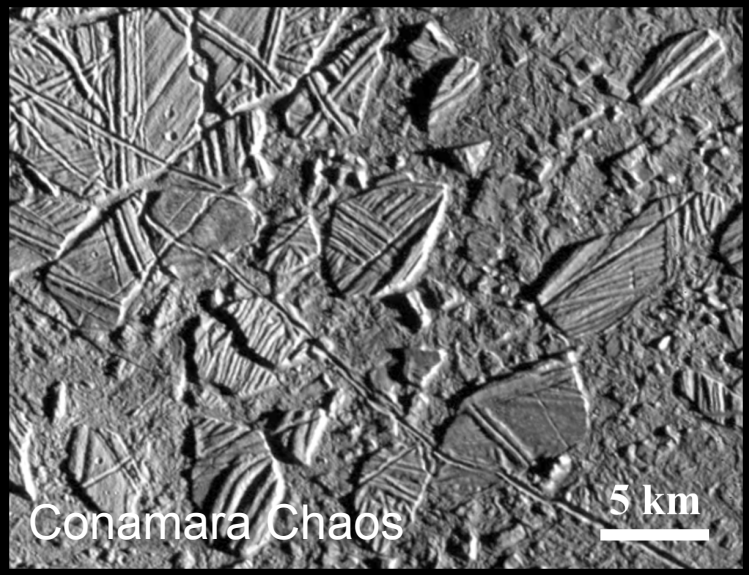

Thrace Macula
10 km

Chaos morphology

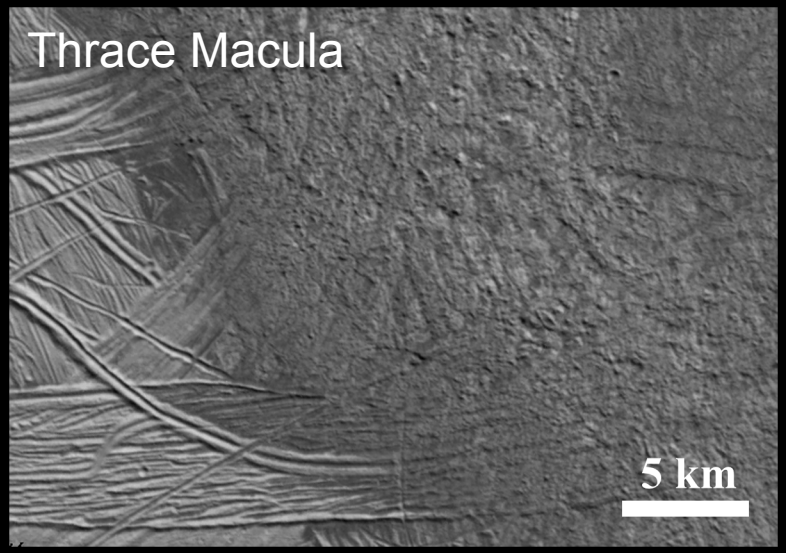


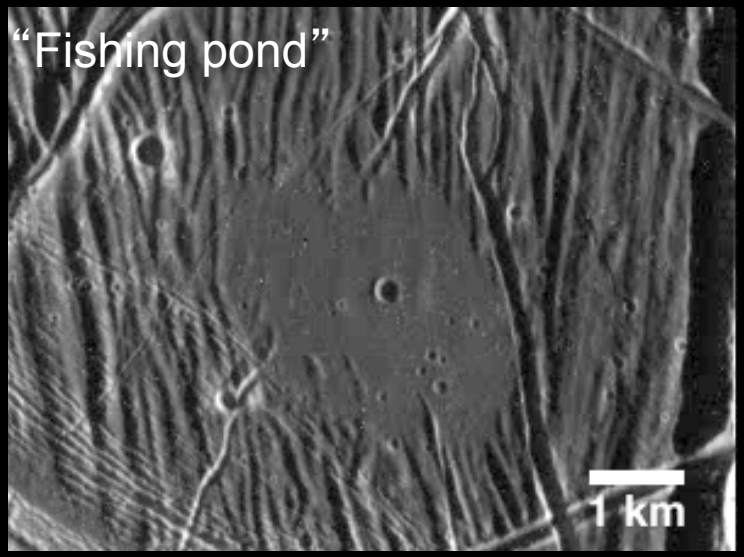


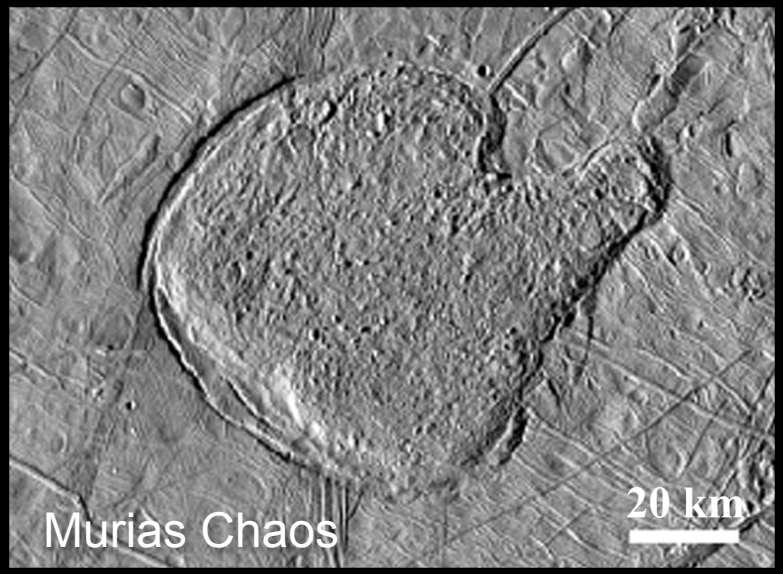


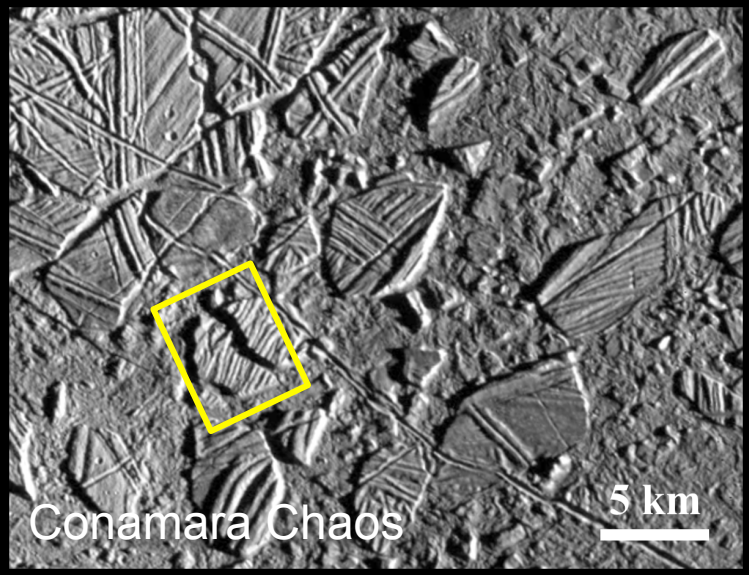


Chaos morphology



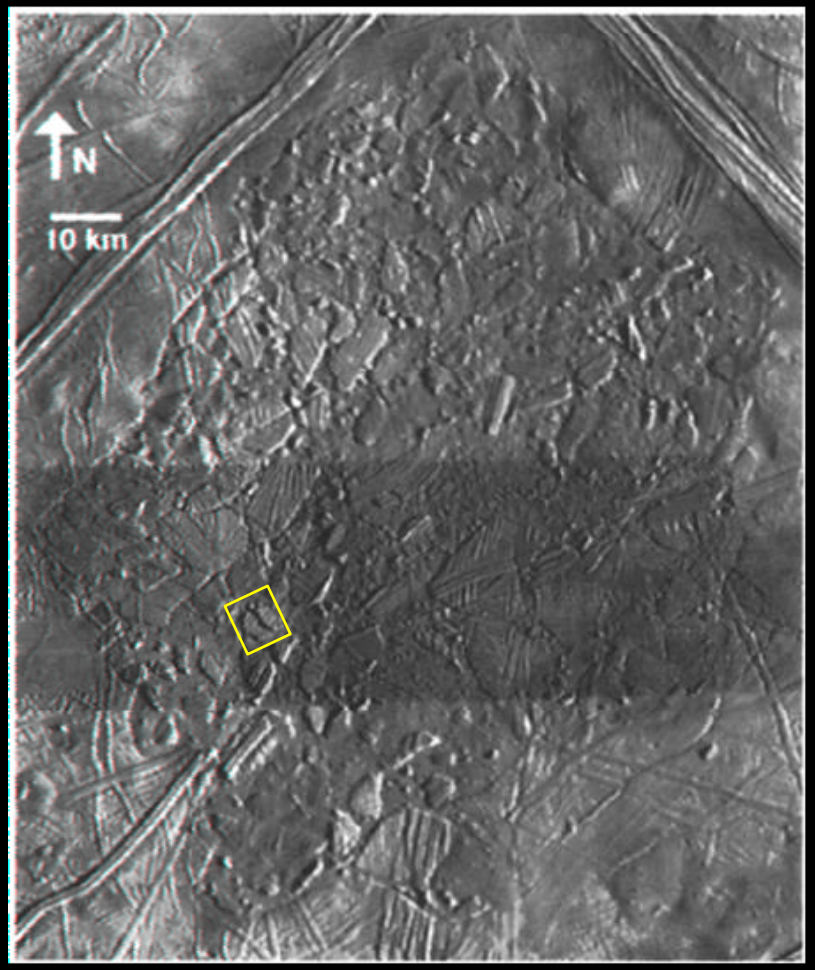


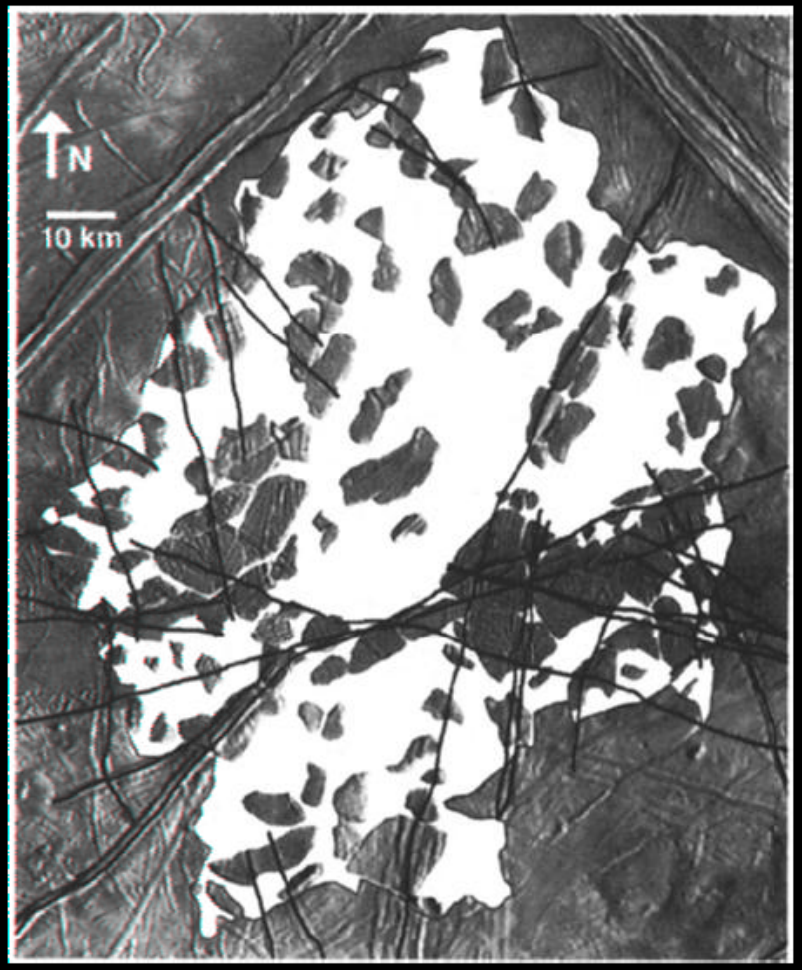





Fermilab
Tevatron
tunnel
500 m

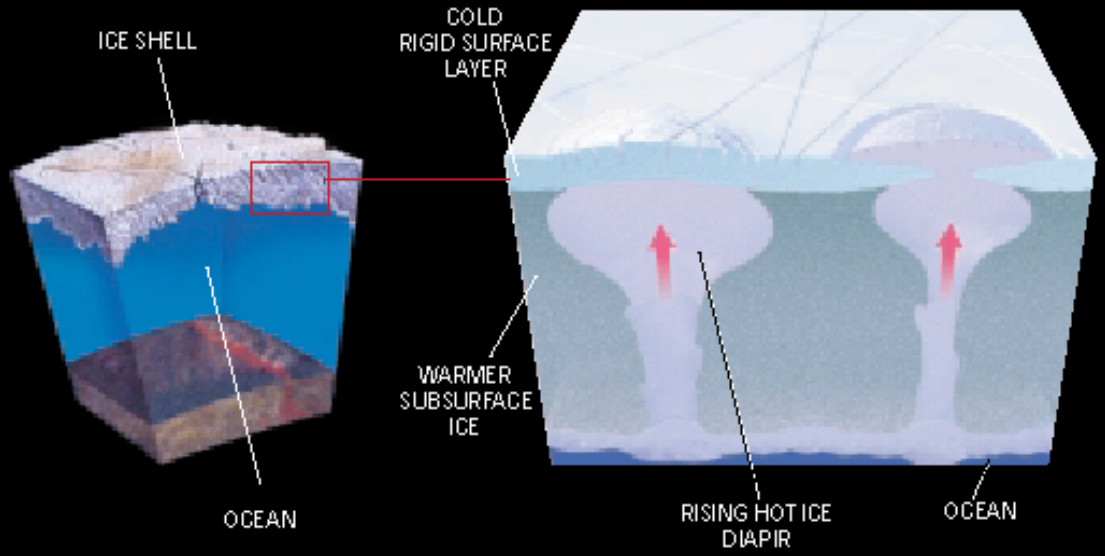
Conamara Chaos



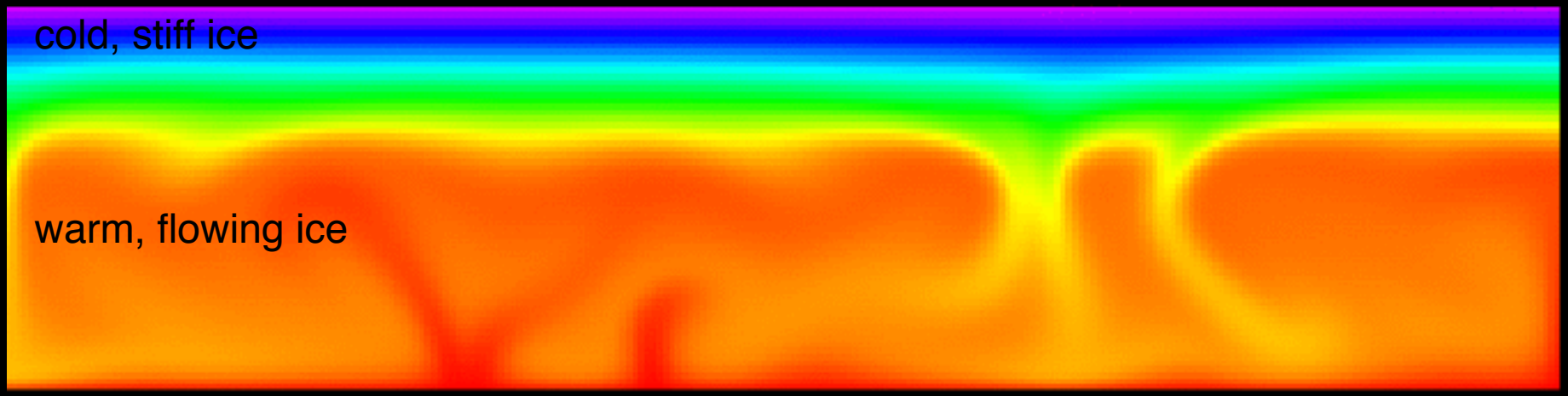


Spaun et al., 1998

Icy lava lamp?



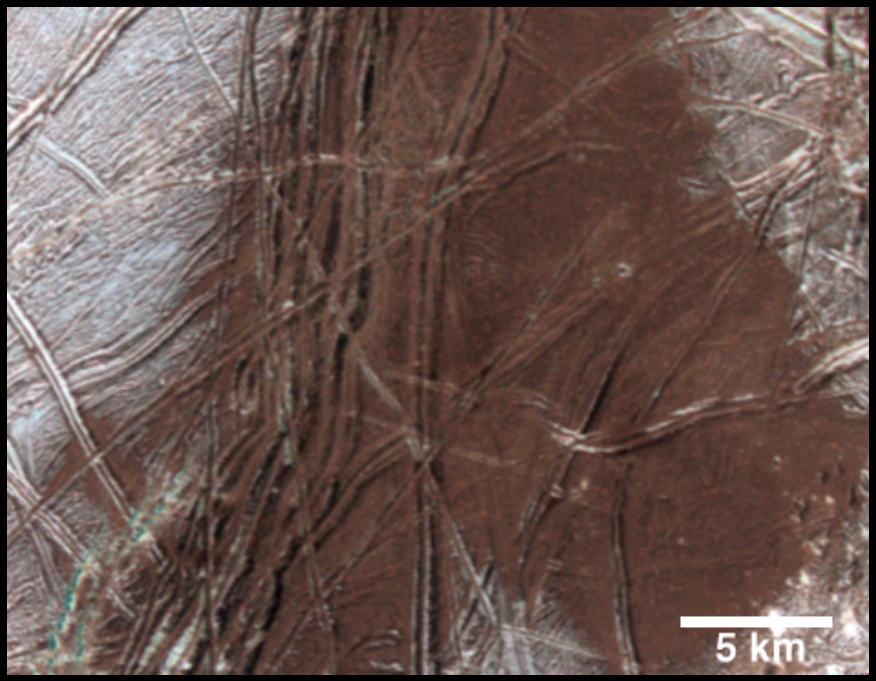
T = 100 K

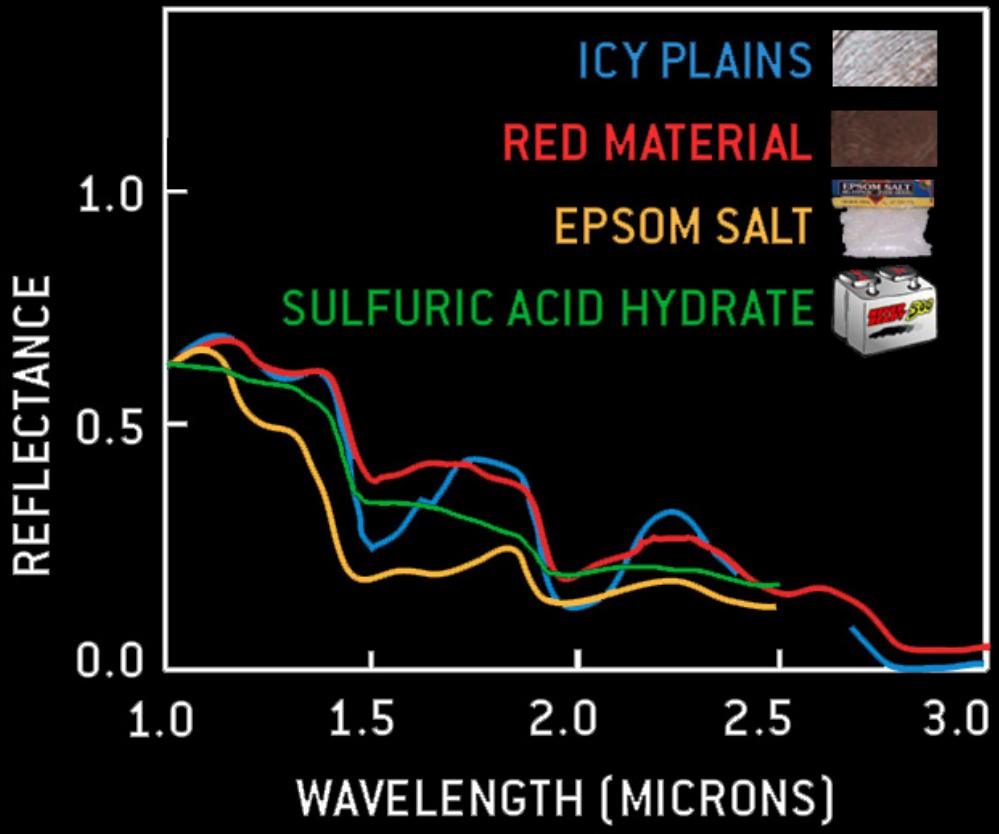


T = 270 K

[*courtesy A. Barr*]

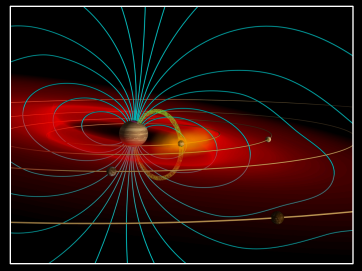
Surface composition

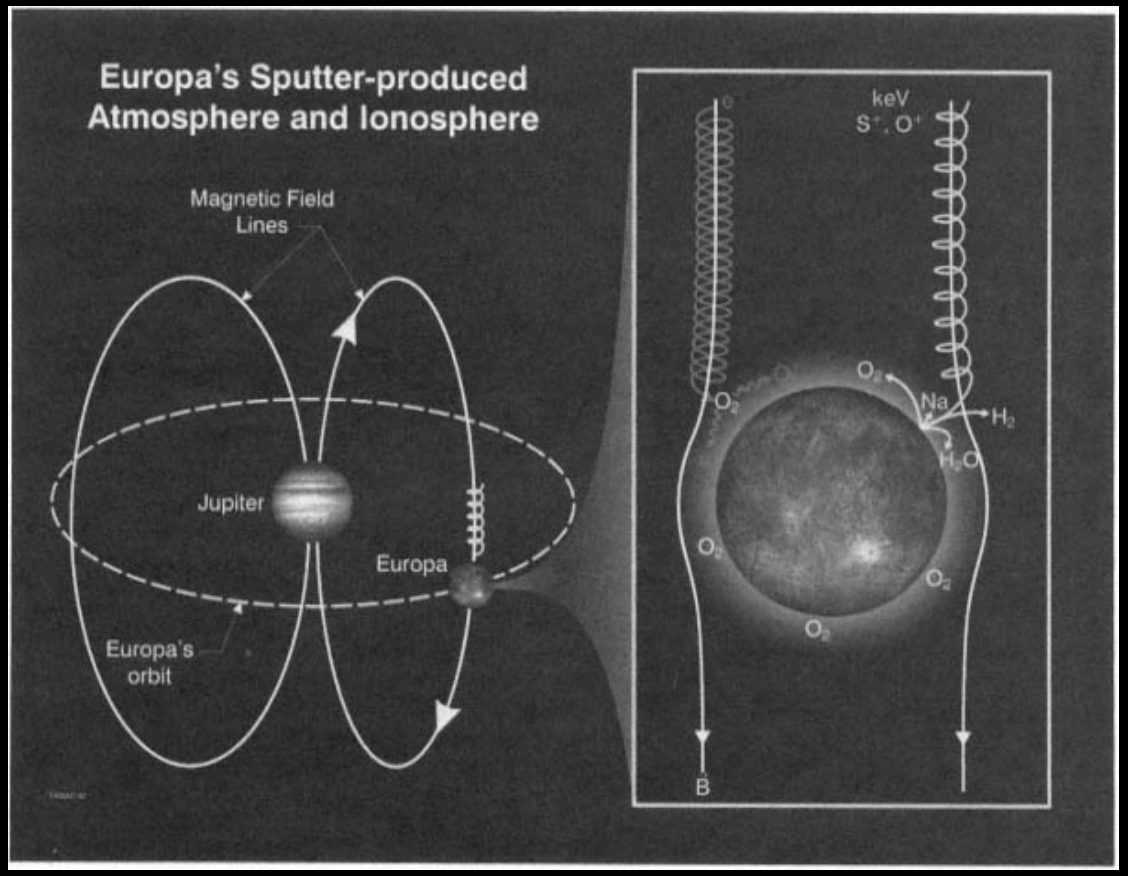




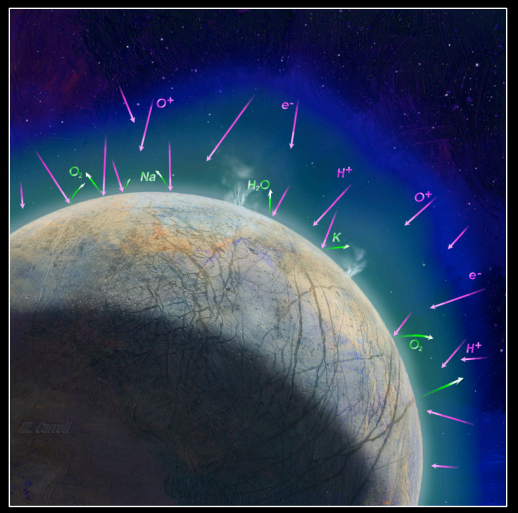
Infrared spectral fingerprint suggests sulfur-containing hydrates
Sulfur might explain Europa's ruddy visible color

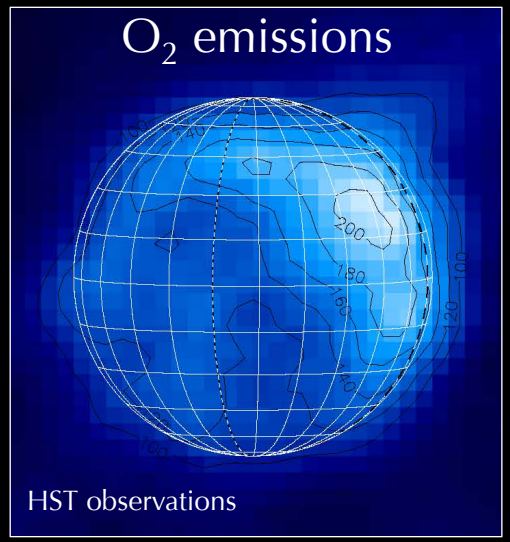
Europa's tenuous atmosphere





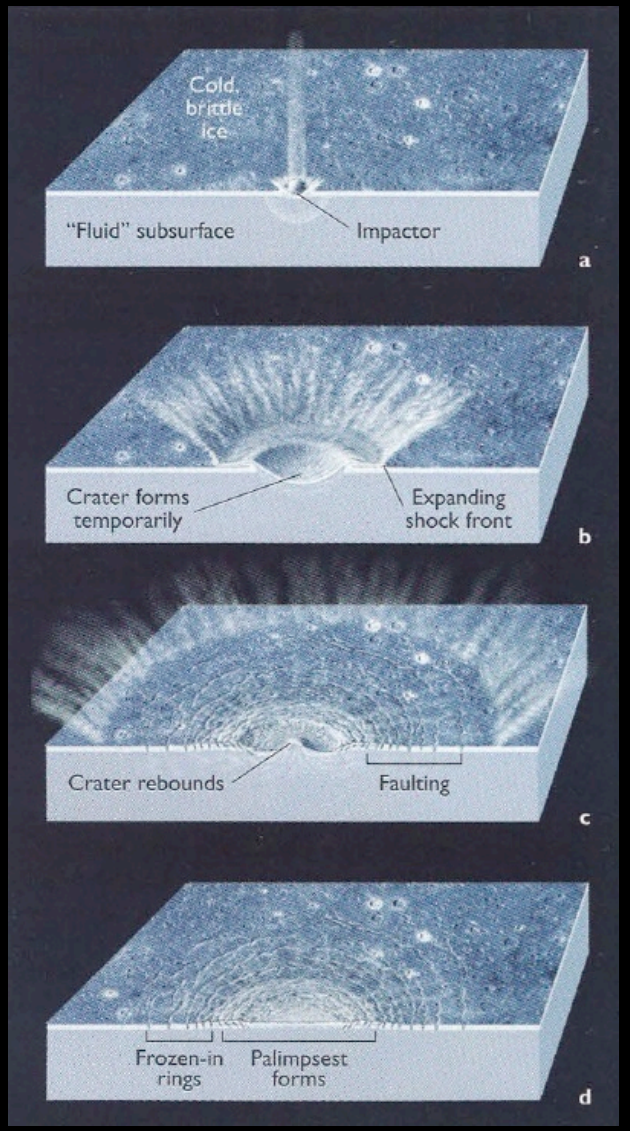
After Khurana et al., 1998





McGrath et al., 2004

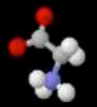
Large impacts



Few large impact craters: Suggests 40 - 90 Myr surface age
A couple of multi-ringed impacts penetrated 20 km thick ice

Europa: Ingredients for Life?

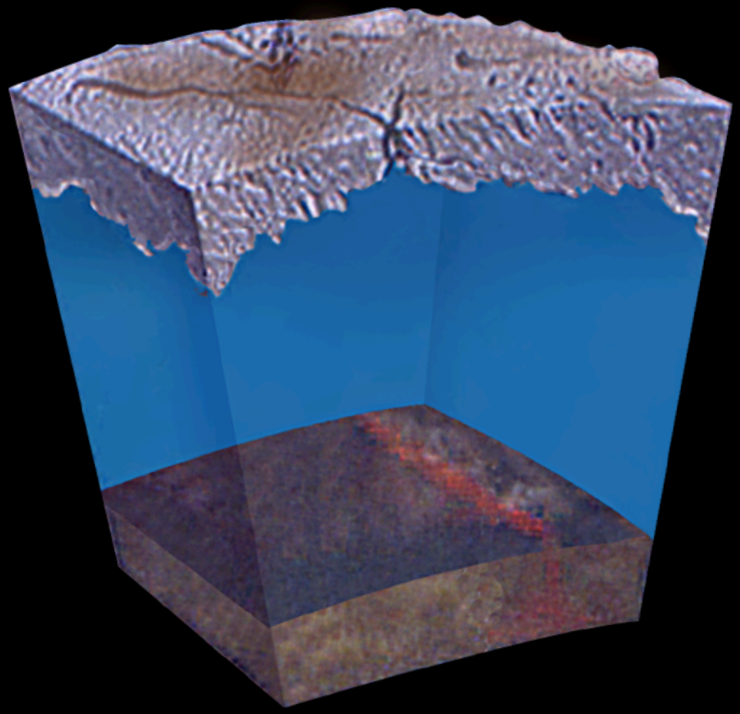
Water: *More than 2x all of Earth's oceans*

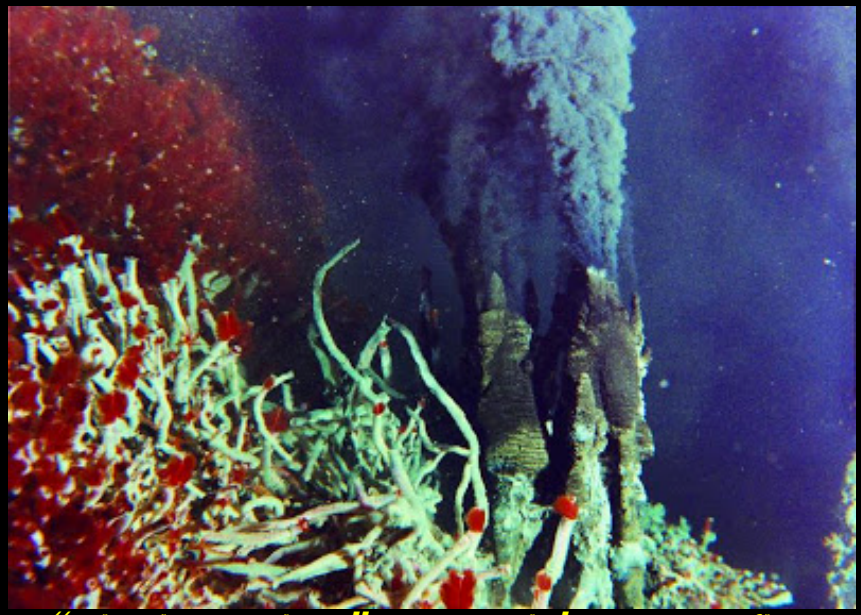


Essential elements: *From formation and impacts*

Chemical energy: *Potentially from above and below*

Stability: *Variable, but "simmering" for 4 billion years*



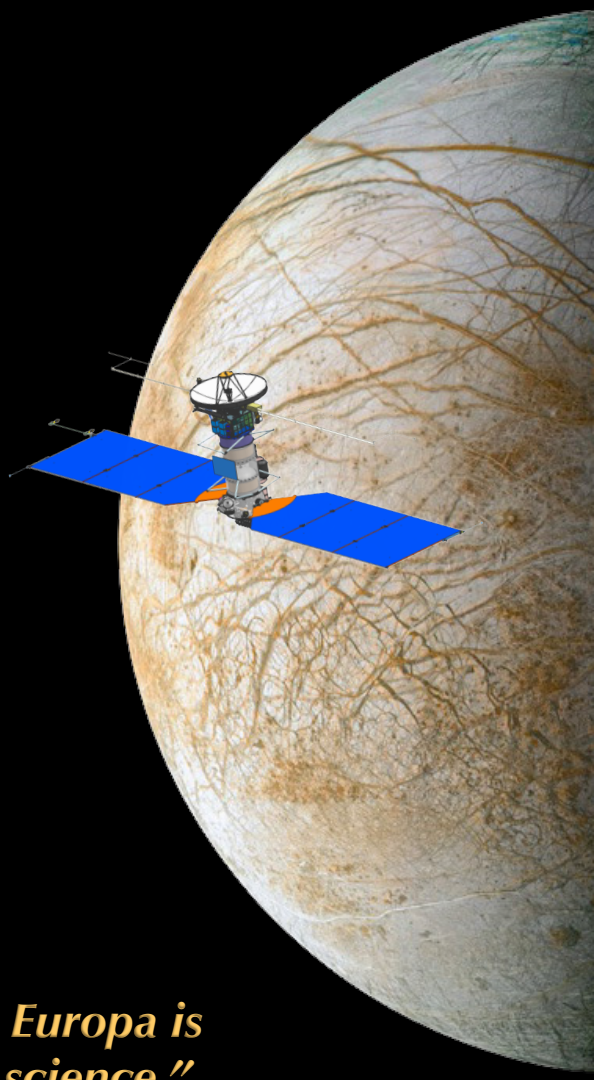


"Black smoker" on Earth's ocean floor

Source: Fisheries and Oceans, Canada

Future exploration of Europa

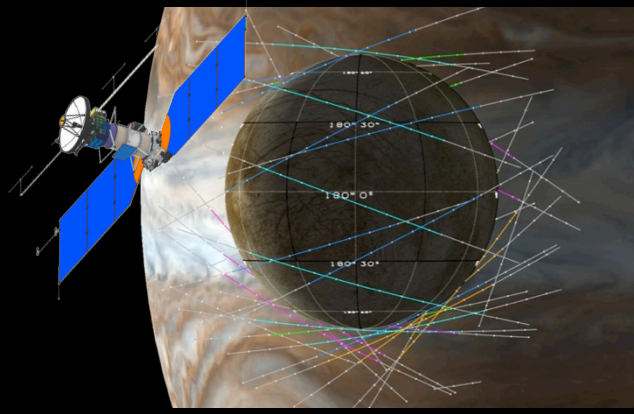
- Europa mission concepts have been studied by NASA for more than a decade
- Europa is one of the highest priority targets identified in the 2011 National Research Council's Planetary Decadal Survey
- In June 2015 NASA selected a $2B Europa multiple-flyby mission as its next outer planet flagship mission
- A comprehensive instrument payload was also selected around this time



"Because of (its) ocean's potential suitability for life, Europa is one of the most important targets in all of planetary science."

–2011 Planetary Decadal Survey

Europa multiple-flyby mission concept

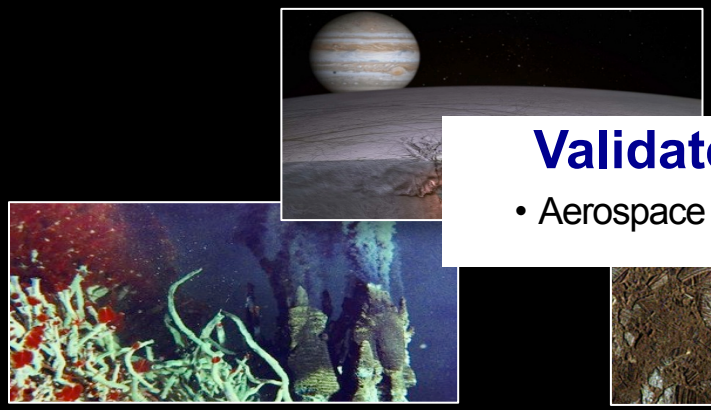


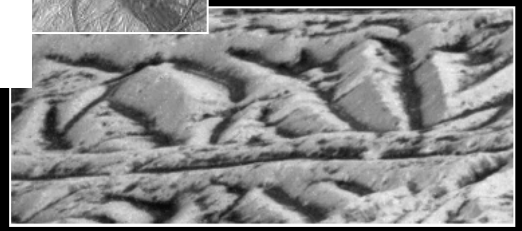
Jupiter-orbiting spacecraft which will carry out >45 flybys of Europa

- Launch: May 2022
- Arrive in Jupiter system: 2025 - 2028

Science Objectives

- **Ocean:** Existence, extent, salinity
- **Ice Shell:** Water within or beneath; nature of surface-ice-ocean exchange
- **Composition:** Key compounds; links to ocean composition
- **Geology:** Surface feature formation; sites of recent or current activity
- **Reconnaissance:** Surface characteristics at lander scale





Validated cost estimate

- Aerospace cost: $2.1B ($FY15, w/o LV)

Habitability: Ingredients for Life

Water

- Probable saltwater ocean, implied by surface geology and magnetic field
- Possible lakes within the ice shell, produced by local melting

Chemistry

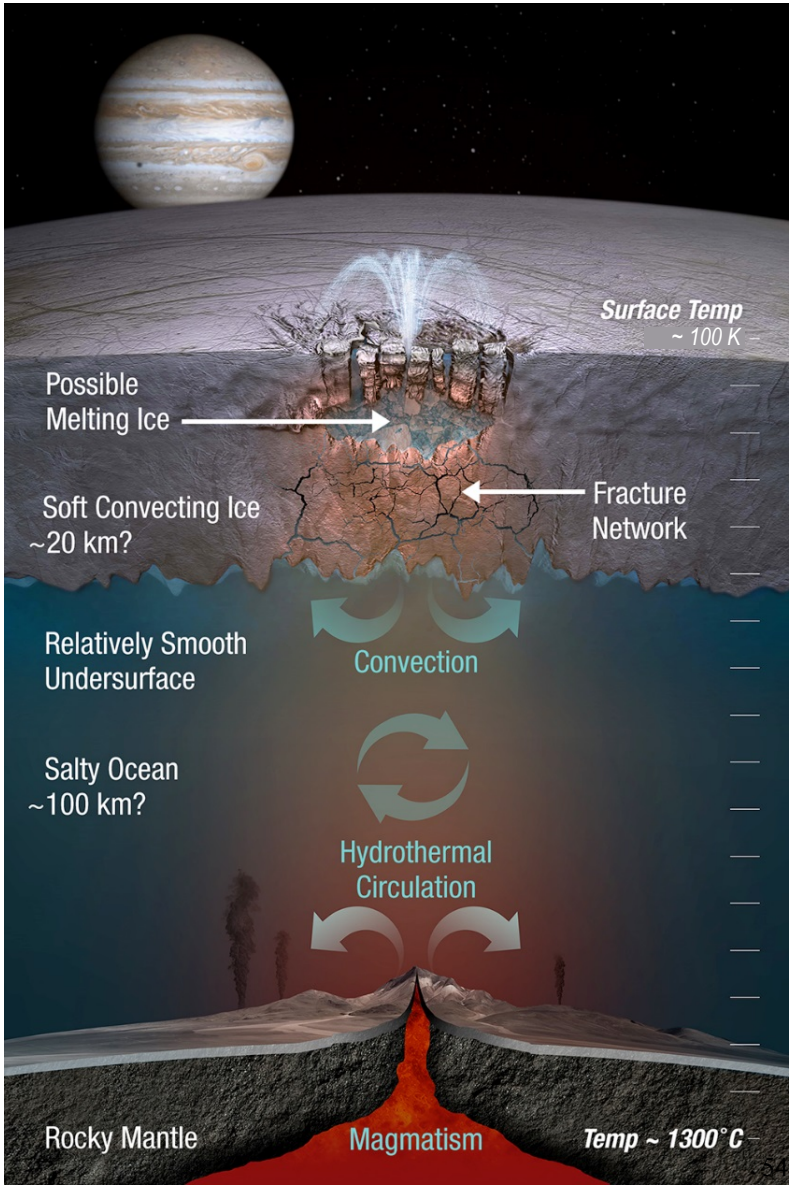
- Ocean in direct contact with mantle rock, promoting chemical leaching
- Dark red surface materials contain salts, probably from the ocean

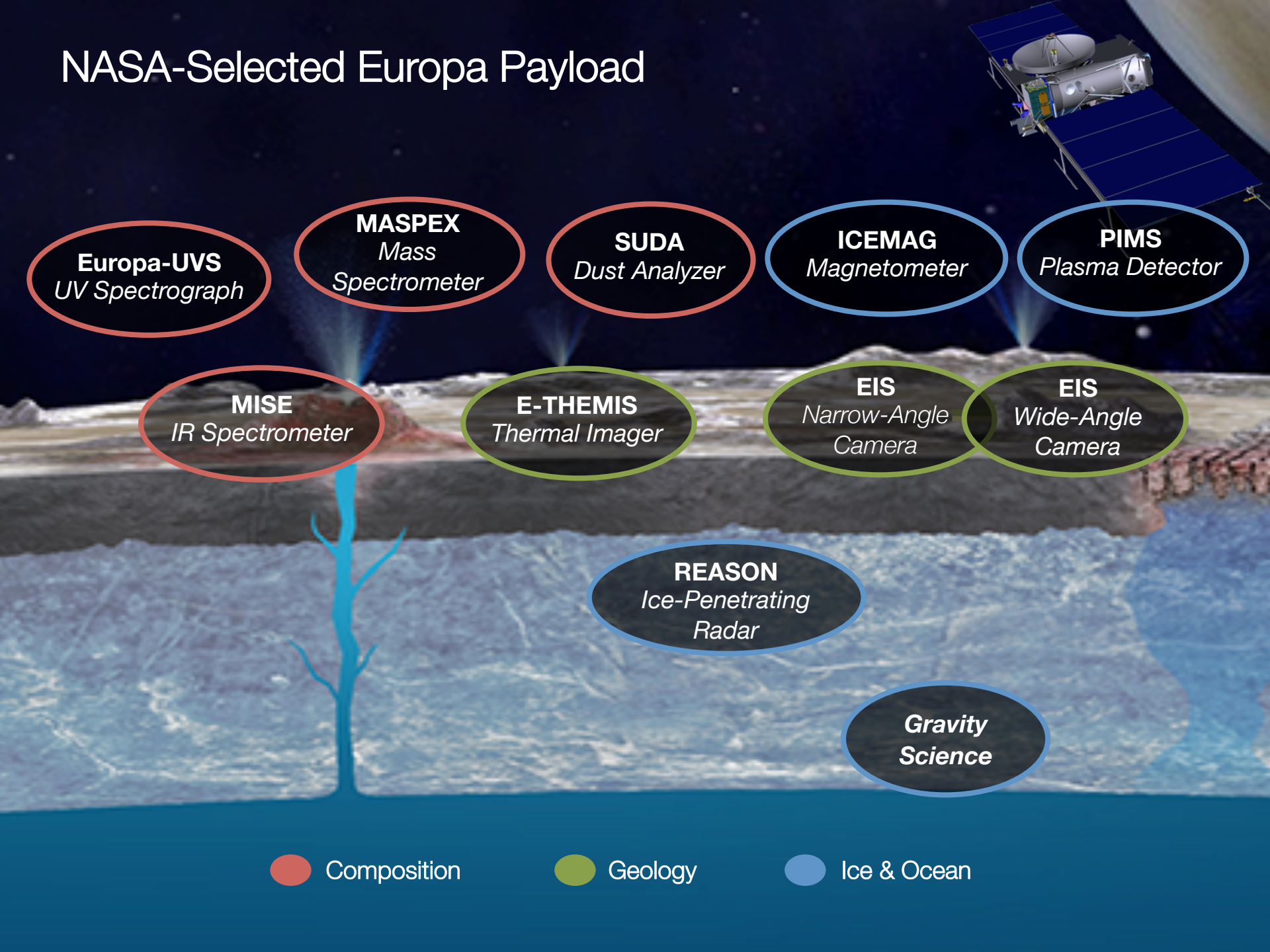
Energy

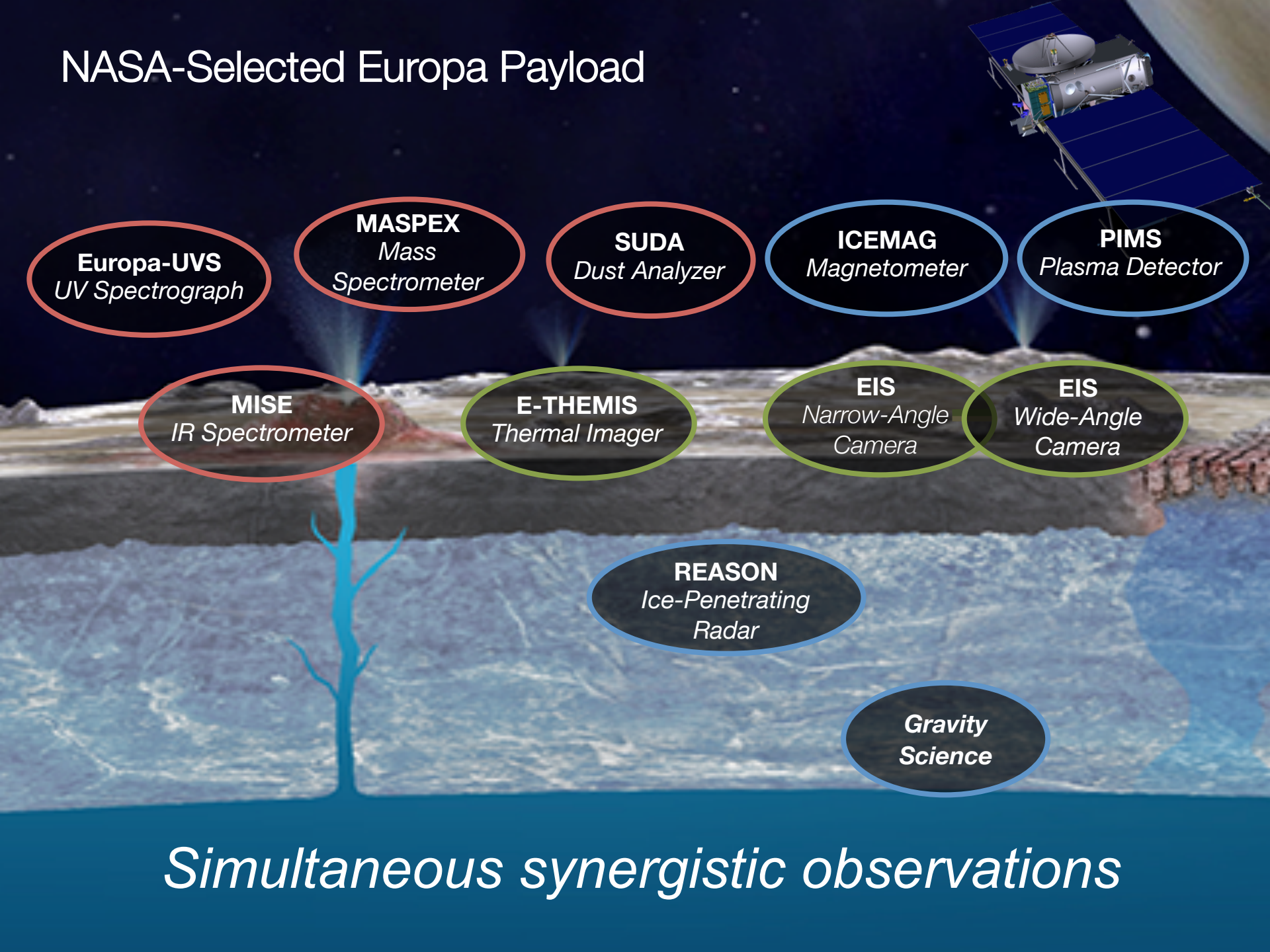
- Chemical energy could sustain life
- Surface irradiation creates oxidants
- Mantle rock-water reactions could create reductants

Geological activity "stirs the pot"

Europa Flyby Mission will verify key* habitability *hypotheses

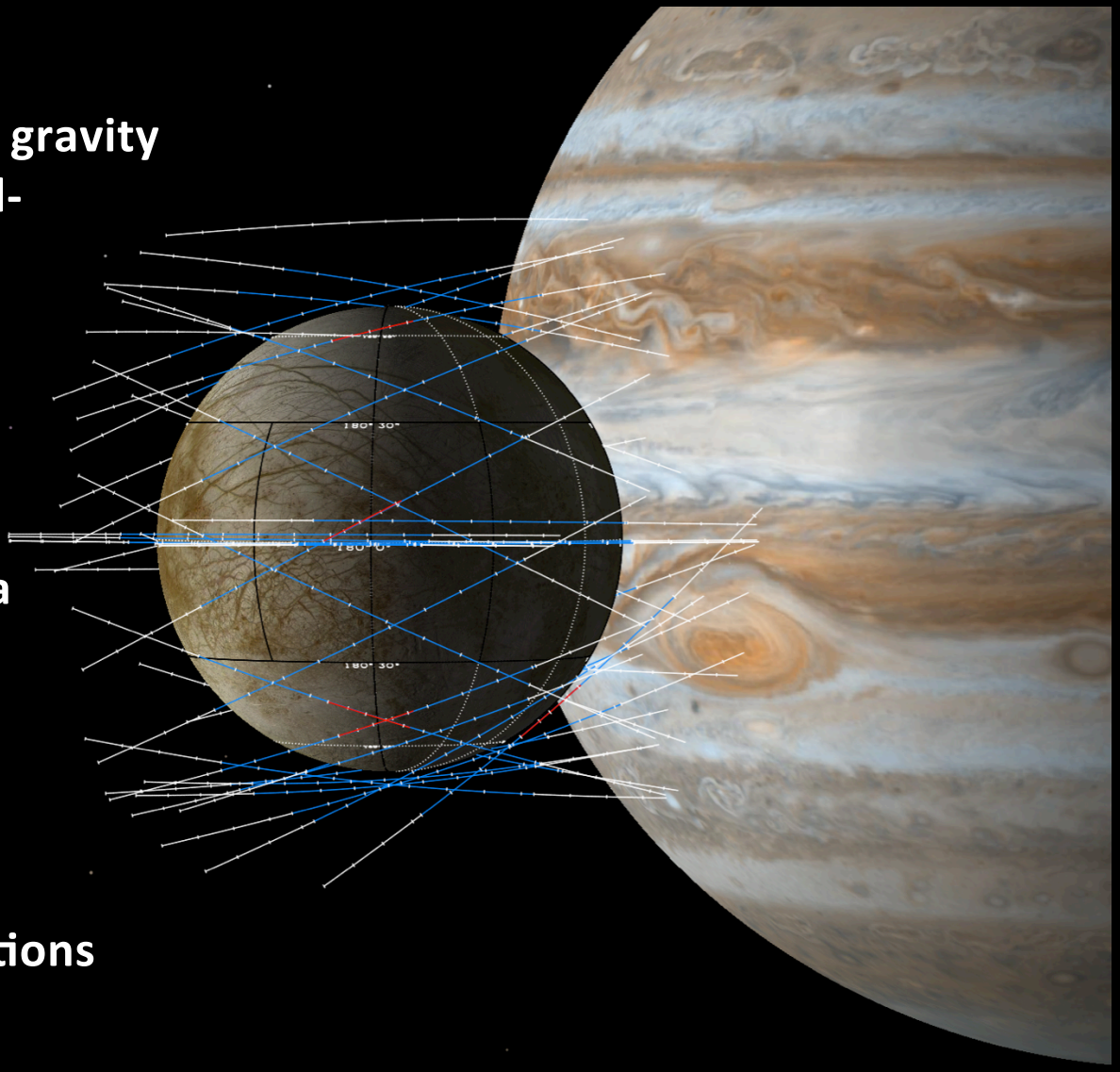



NASA-Selected Europa Payload
Europa-UVS
UV Spectrograph
MASPEX
Mass
Spectrometer
SUDA
Dust Analyzer
ICEMAG
Magnetometer
PIMS
Plasma Detector
MISE
IR Spectrometer
E-THEMIS
Thermal Imager
EIS
Narrow-Angle
Camera
EIS
Wide-Angle
Camera
REASON
Ice-Penetrating
Radar
Gravity
Science
Composition
Geology
Ice & Ocean

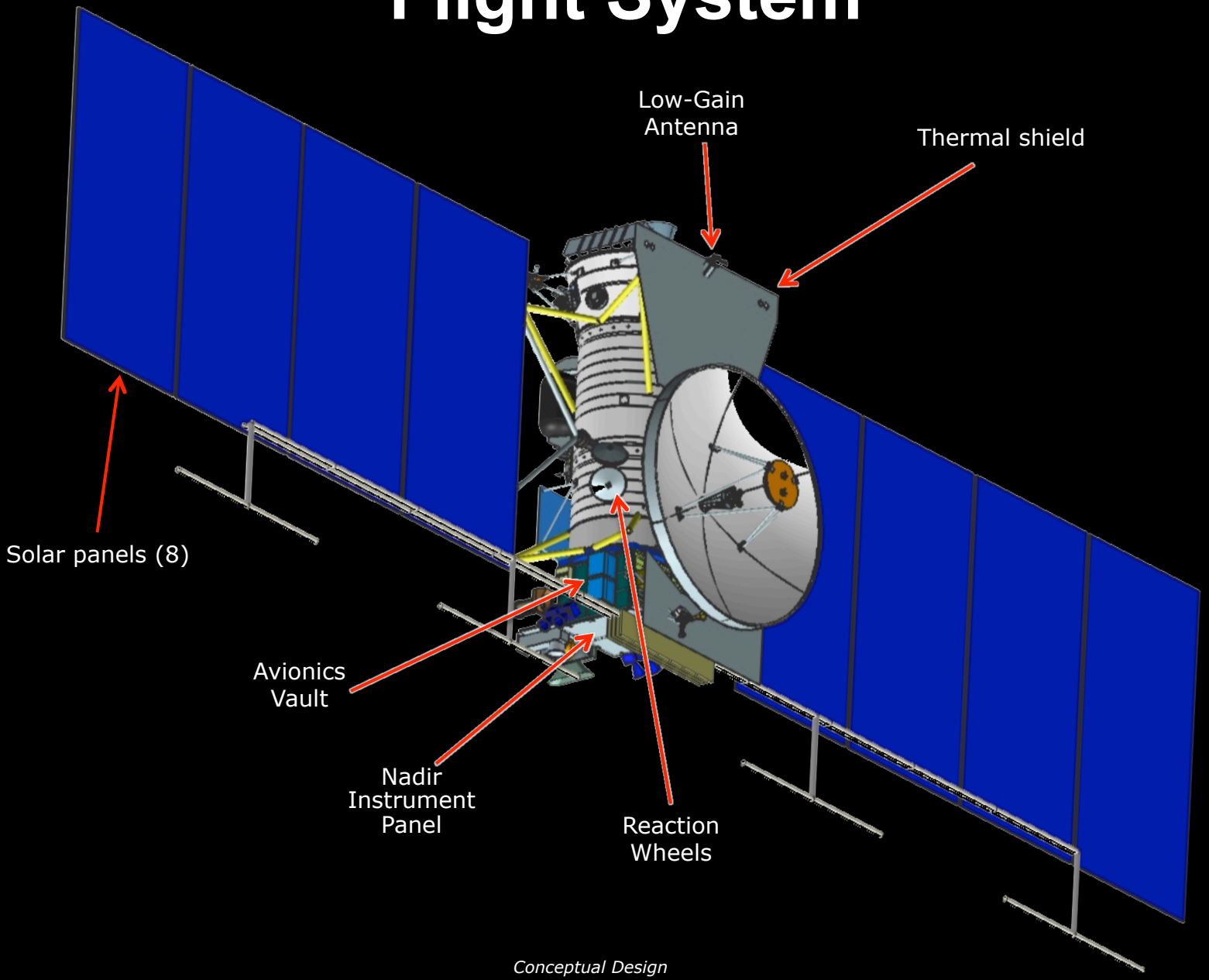

NASA-Selected Europa Payload
Europa-UVS
UV Spectrograph
MASPEX
Mass
Spectrometer
SUDA
Dust Analyzer
ICEMAG
Magnetometer
PIMS
Plasma Detector
MISE
IR Spectrometer
E-THEMIS
Thermal Imager
EIS
Narrow-Angle
Camera
EIS
Wide-Angle
Camera
REASON
Ice-Penetrating
Radar
Gravity
Science
Simultaneous synergistic observations

Mission Concept

- Utilize multiple satellite gravity assists to enable “global-regional coverage” of Europa while in orbit around Jupiter
- Current mission design consists of 45 low-altitude flybys of Europa in prime mission from Jupiter orbit over 3.5 yr
- Minimizes time in high-radiation environment
- Simple repetitive operations



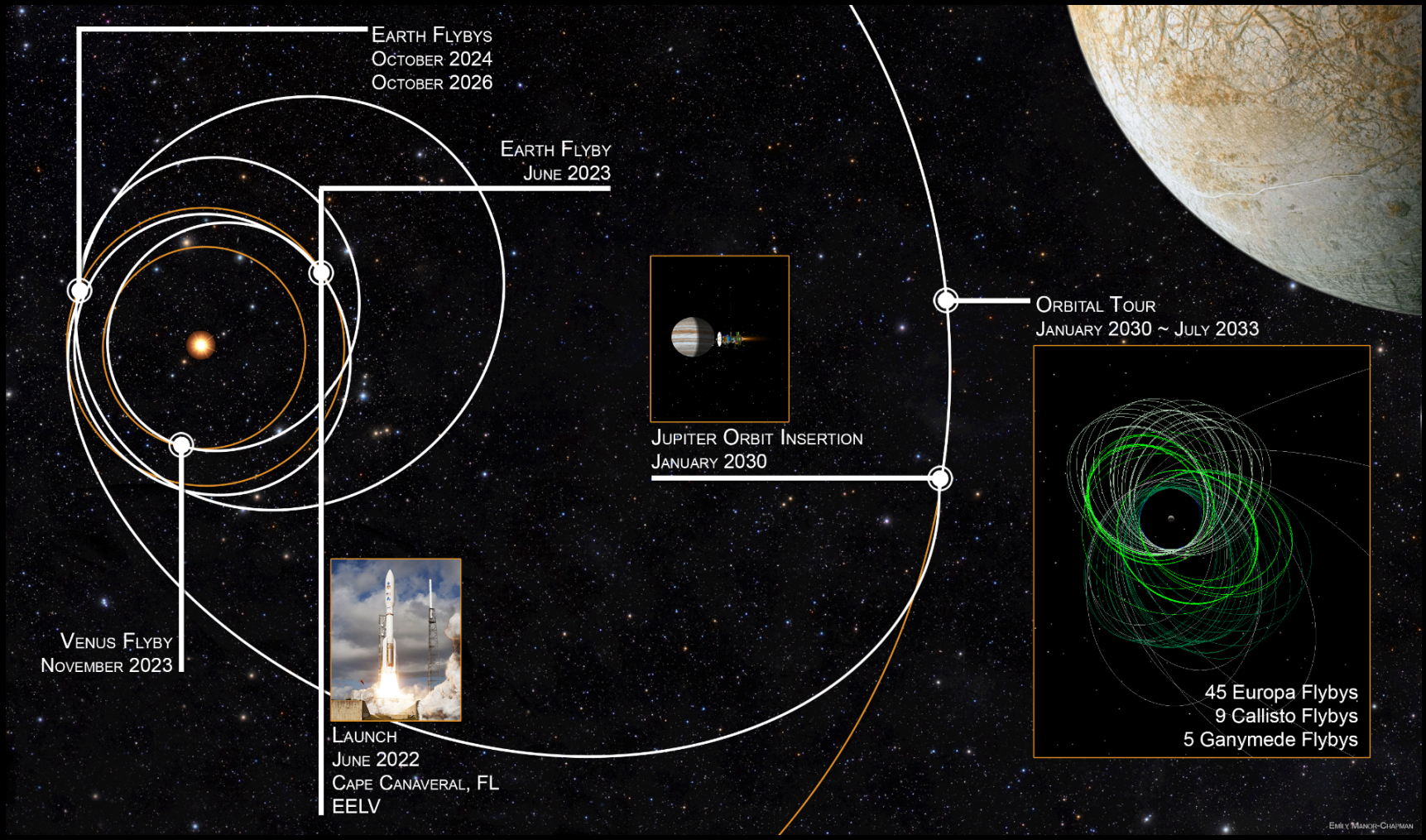
Flight System



Conceptual Design

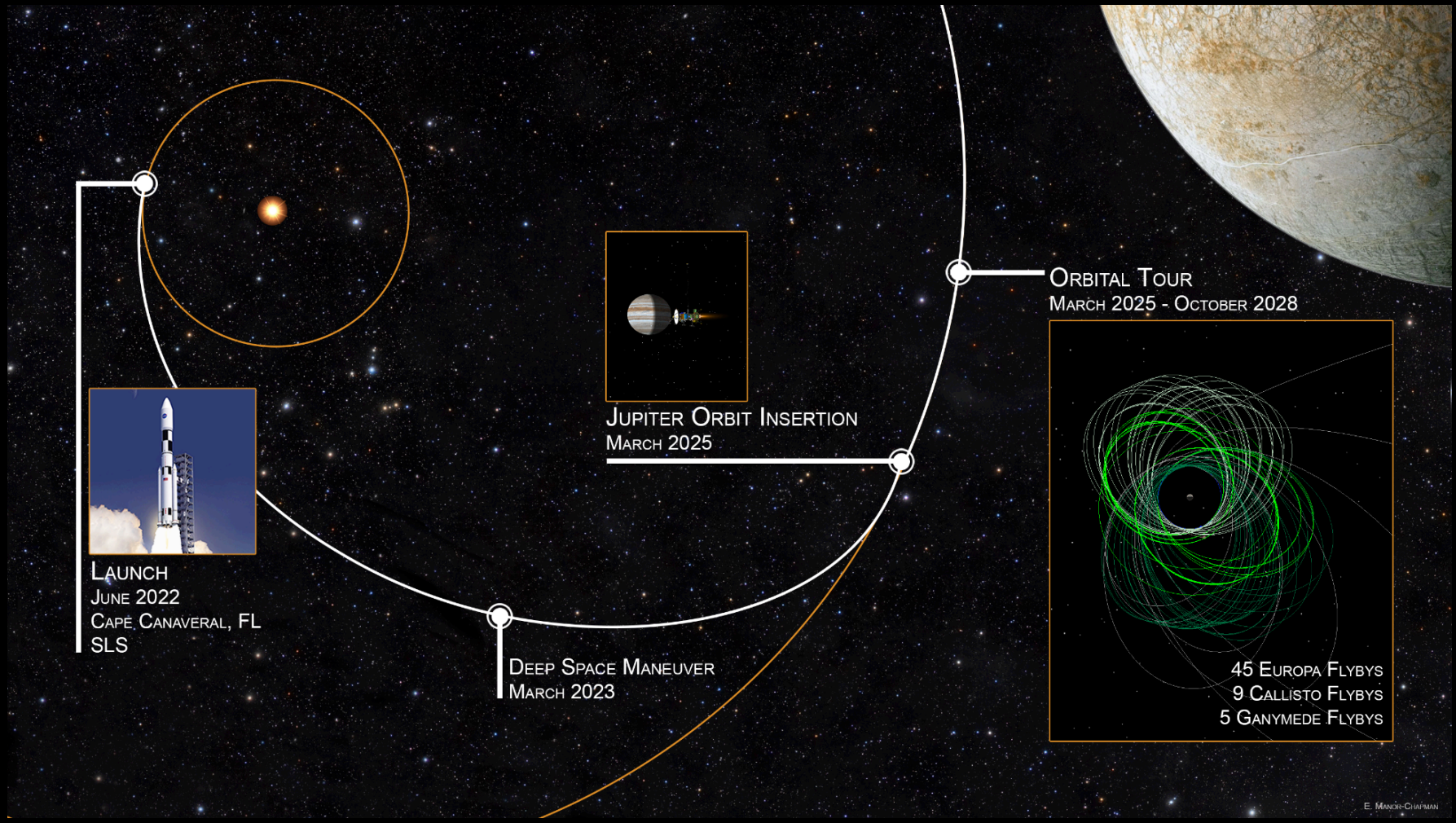
Pre-Decisional — For Planning and Discussion Purposes Only

Option A (EELV Launch): EVEEGA Trajectory and Jovian Tour



Transit to Jupiter → 7 years, 7 months

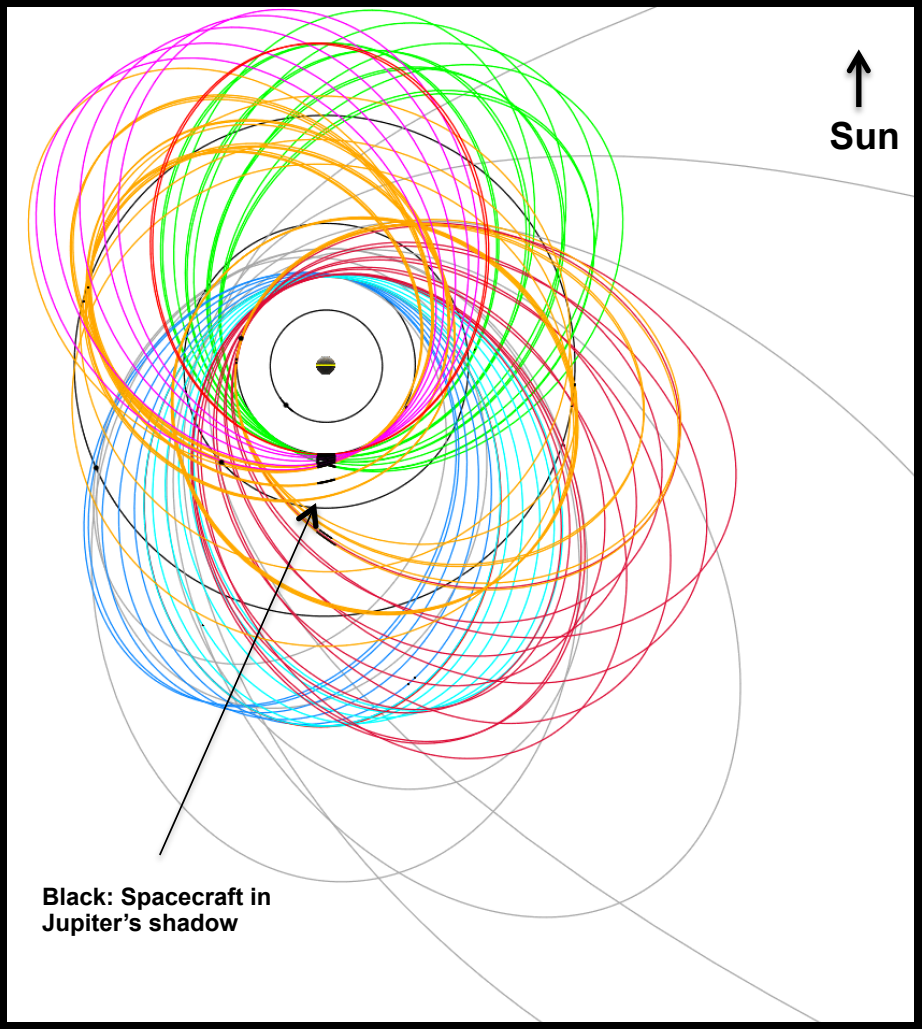
Option B (SLS Launch): Direct-to-Jupiter Trajectory & Jovian Tour



Transit to Jupiter → 2 years, 9 months

Jupiter Tour: 13F7-A21

Key Statistics	13F7-A21
Tour Duration	3.5 years
Number of Flybys: Europa Ganymede Callisto	 45 5 9
Time between Flybys: Maximum* Minimum Mean*	 57.2 days 5.5 days 18.9 days
Maximum Inclination	20.1°
Maximum Eclipse Duration	4.5 hours
Total Ionizing Dose** (TID)	2.8 Mrad
Deterministic ΔV (post-PRM)	164 m/s
Statistical ΔV (99%)	223 m/s
Total Mission ΔV	1596 m/s

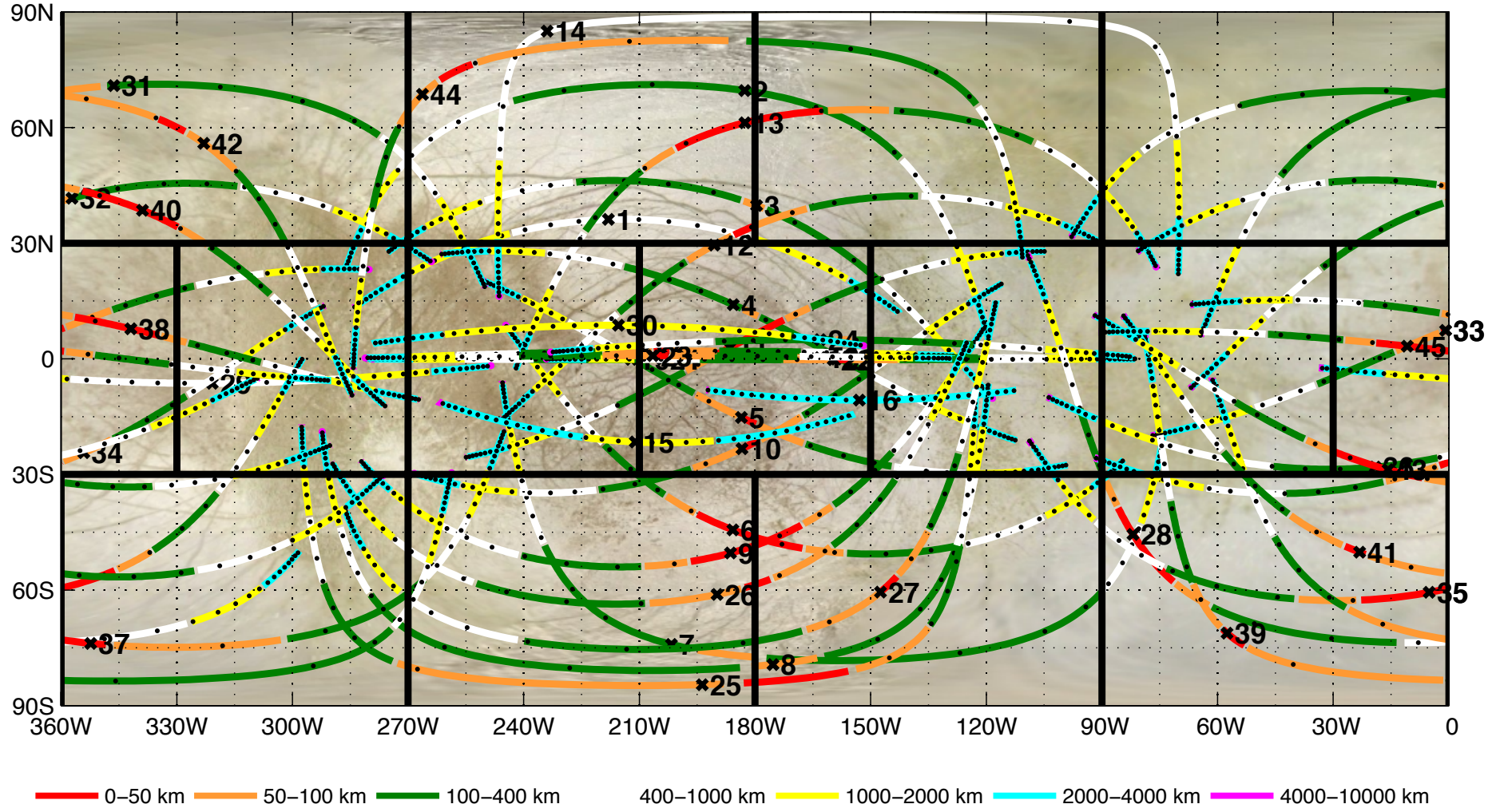


*Not including the 202-day capture orbit
**Si behind 100 mil Al, spherical shell (GIRE2)

Notional Flyby Timing

Comprehensive Surface Coverage

Ground tracks permit globally distributed regional coverage



- **Above 1,000 km: 2**
- **250 km to 750 km: 6**
- **80 km to 100 km: 9**
- **50 km: 18**
- **25 km: 10**

Summary

- Europa is a recently or currently active moon, of high significance as a potentially habitable world
- NASA has selected a multiple-flyby solar-powered mission to study Europa's habitability; earliest launch is 2022
  - The spacecraft will orbit Jupiter and will carry out ~45 globally distributed flybys of Europa to build up near-global coverage
  - A lander is also being studied by NASA as a possible add-on to the multiple-flyby mission
- We are very close to the next phase of Europa exploration!