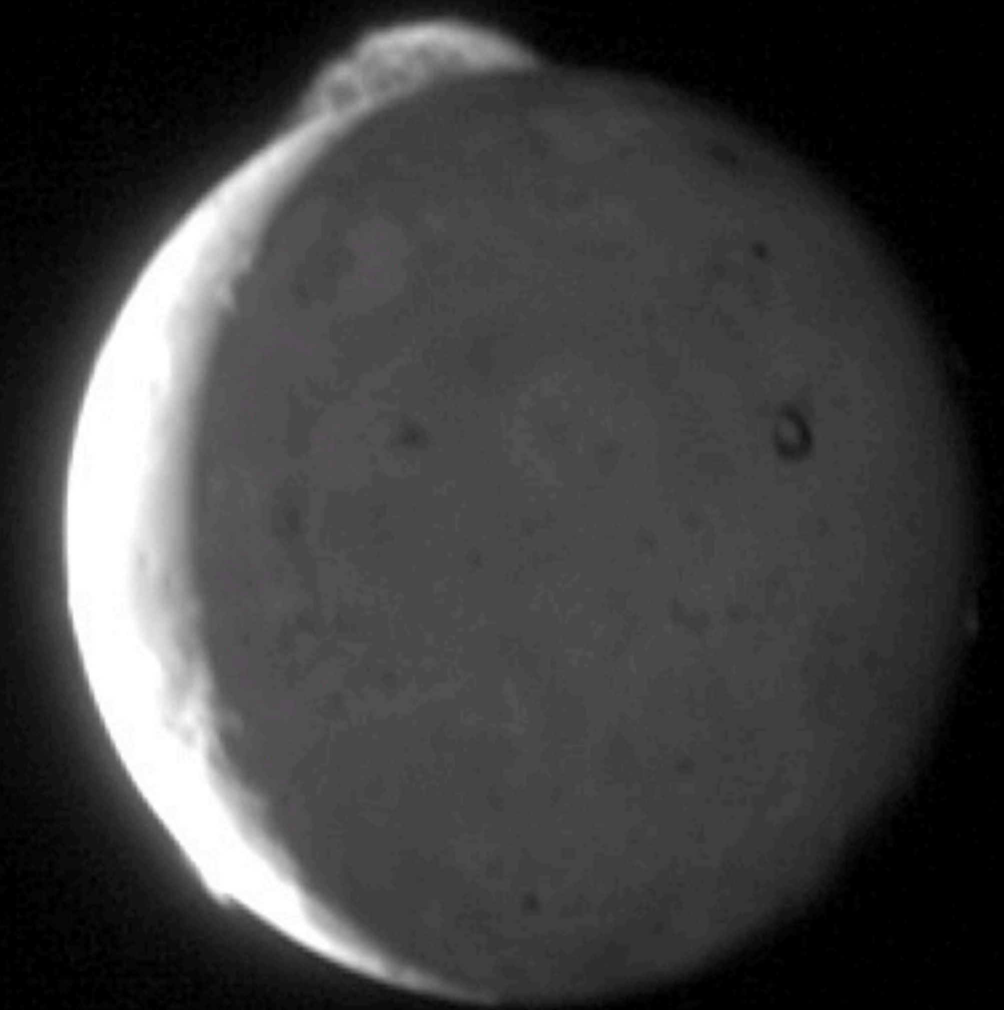
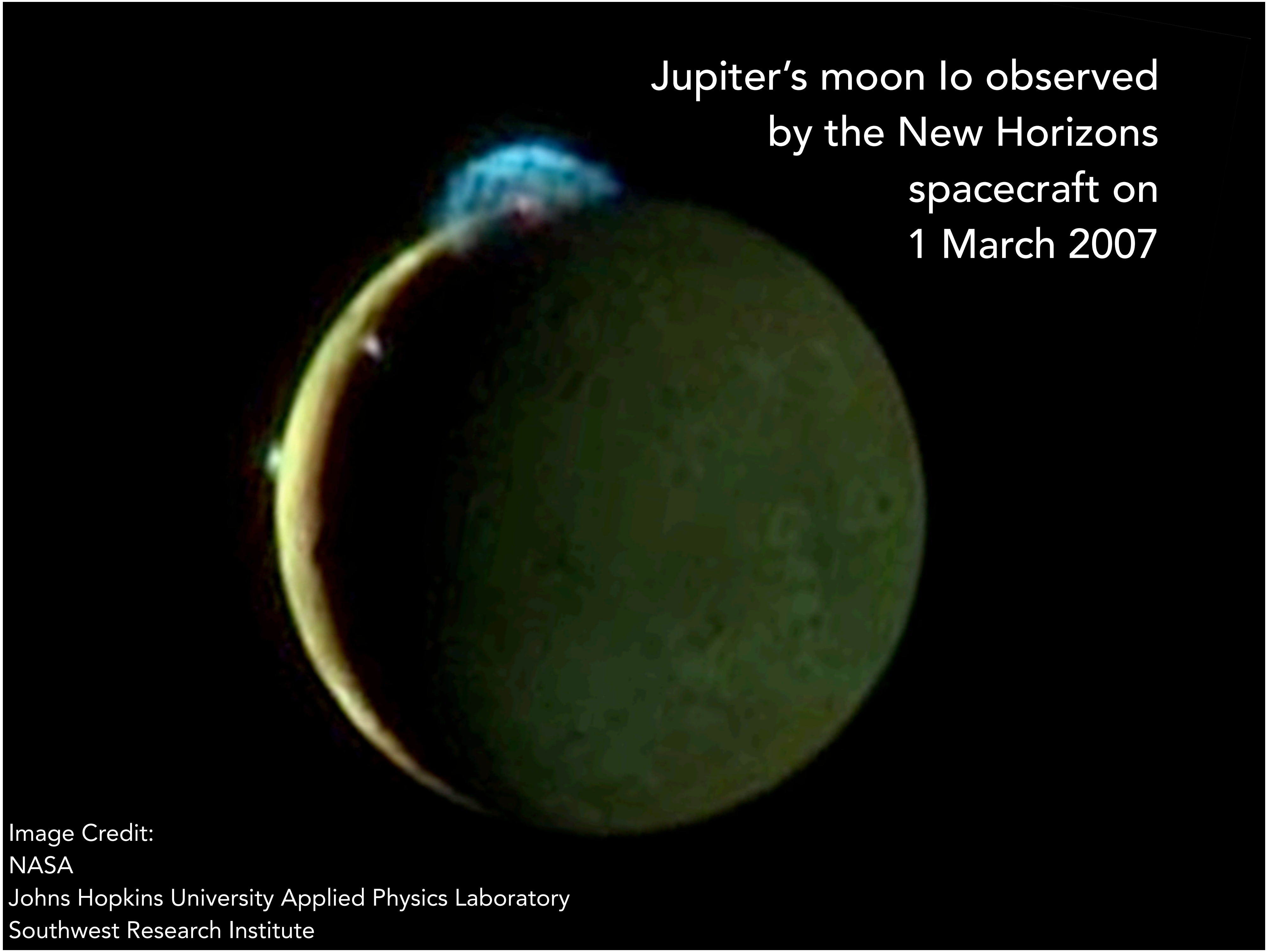
The Perils and Merits of Living with Tidal Heating



Dr. René Heller
Max Planck Institute for Solar System Research, Göttingen


Jupiter's moon Io observed
by the New Horizons
spacecraft on
1 March 2007
Image Credit:
NASA
Johns Hopkins University Applied Physics Laboratory
Southwest Research Institute

Heating from the Outside
On Earth

- Earth receives 1360 W/m^2 of power from the Sun.
- It absorbs 70% of this light. Its albedo is α = 30% = 0.3.
- As the Earth rotates, it distributes the absorbed energy (f=1/4).
- The global average flux on Earth is

  F = 1360 W/m^2 × 0.7 × 1/4 = **<u>238 W/m^2</u>**.

Heating from the Outside

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  $F = 1360\ W/m^2 \times 0.7 \times 1/4 = \underline{\mathbf{238\ W/m^2}}$.
- Stefan-Boltzmann equation*

  $T = (F / \sigma_{SB})^{1/4} = 254\ K = \underline{\mathbf{-18.6°C}}$.

In fact, the average surface temperature is +15°C due to the atmospheric greenhouse effect.

* Josef Stefan (1879) in Sitzungsberichte der Mathematisch-Naturwissenschaftlichen Classe der Kaiserlichen Akademie der Wissenschaften

René Heller

Heating from the Outside

On Venus

- Venus receives 1360 W/m^2 × (1 AU / 0.72 AU)^2 = 2600 W/m^2.
- It absorbs 23% of this light. Its albedo is α = 77% = 0.77.
- Venus rotates slowly, its heat distribution is less efficient (f=1/2).
- The global average flux on Venus is

  F = 2600 W/m^2 × 0.23 × 1/2 = **299 W/m^2**.
- Stefan-Boltzmann equation*

  $T = (F / \sigma_{SB})^{1/4}$ = 218 K = **–4°C**.

In fact, the average surface temperature is +464°C due to the atmospheric greenhouse effect.

* Josef Stefan (1879) in Sitzungsberichte der Mathematisch-Naturwissenschaftlichen Classe der Kaiserlichen Akademie der Wissenschaften

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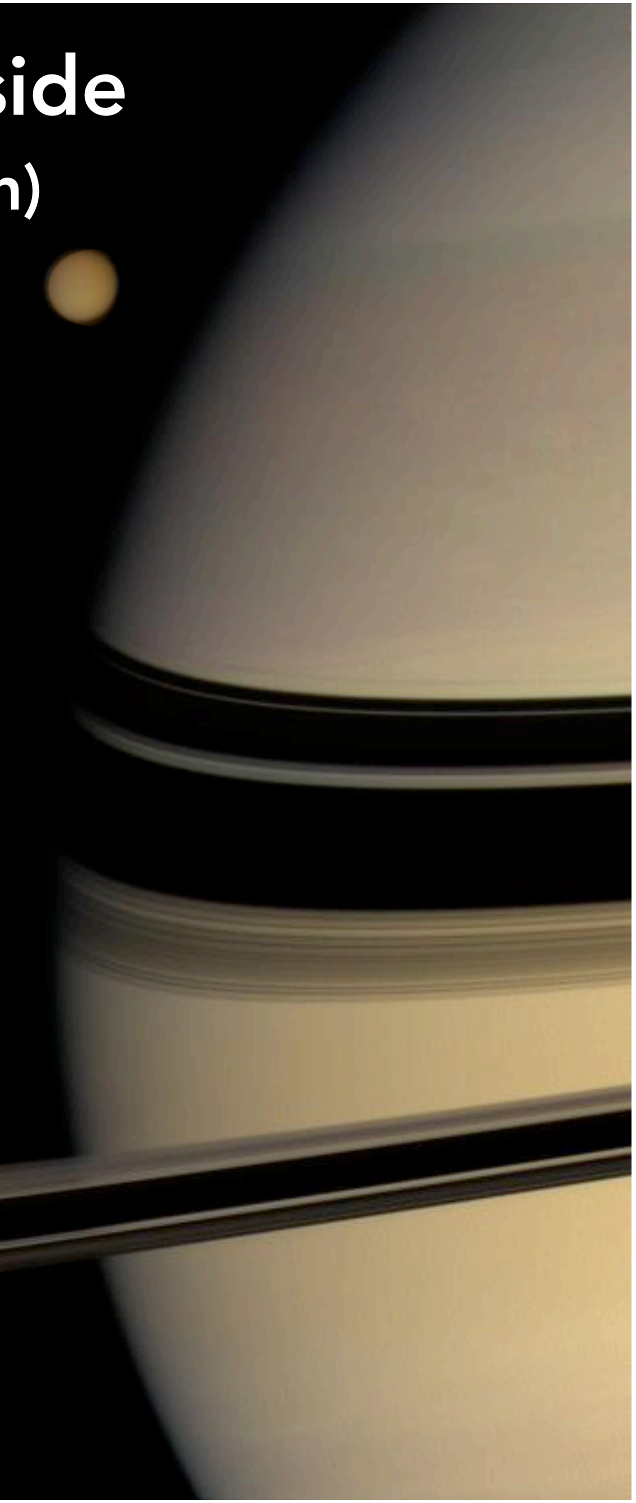
Heating from the Outside

On Titan (Orbiting Saturn)

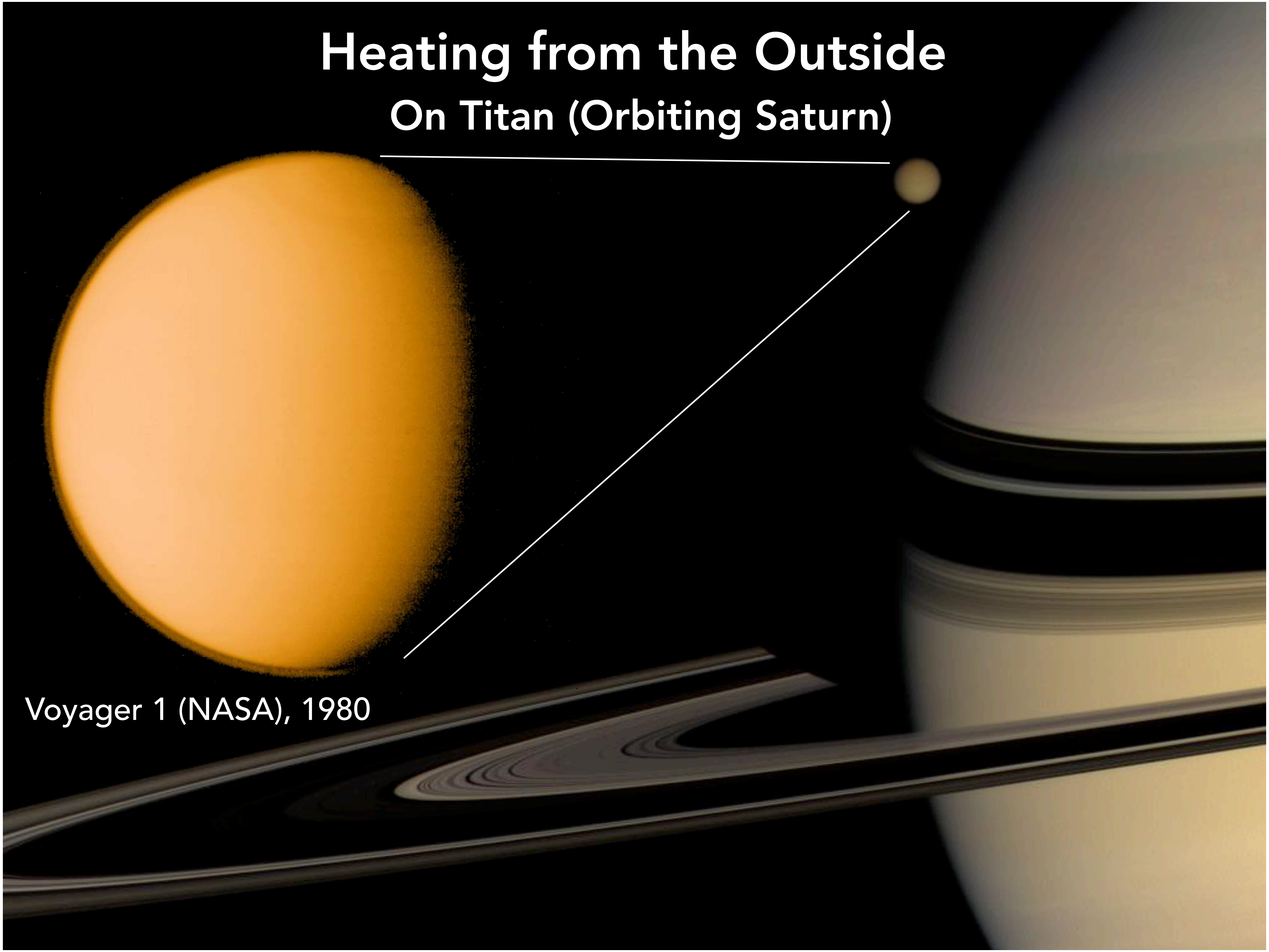
- Titan receives 1360 W/m^2 × (1 AU / 9.6 AU)^2
  = 15 W/m^2.

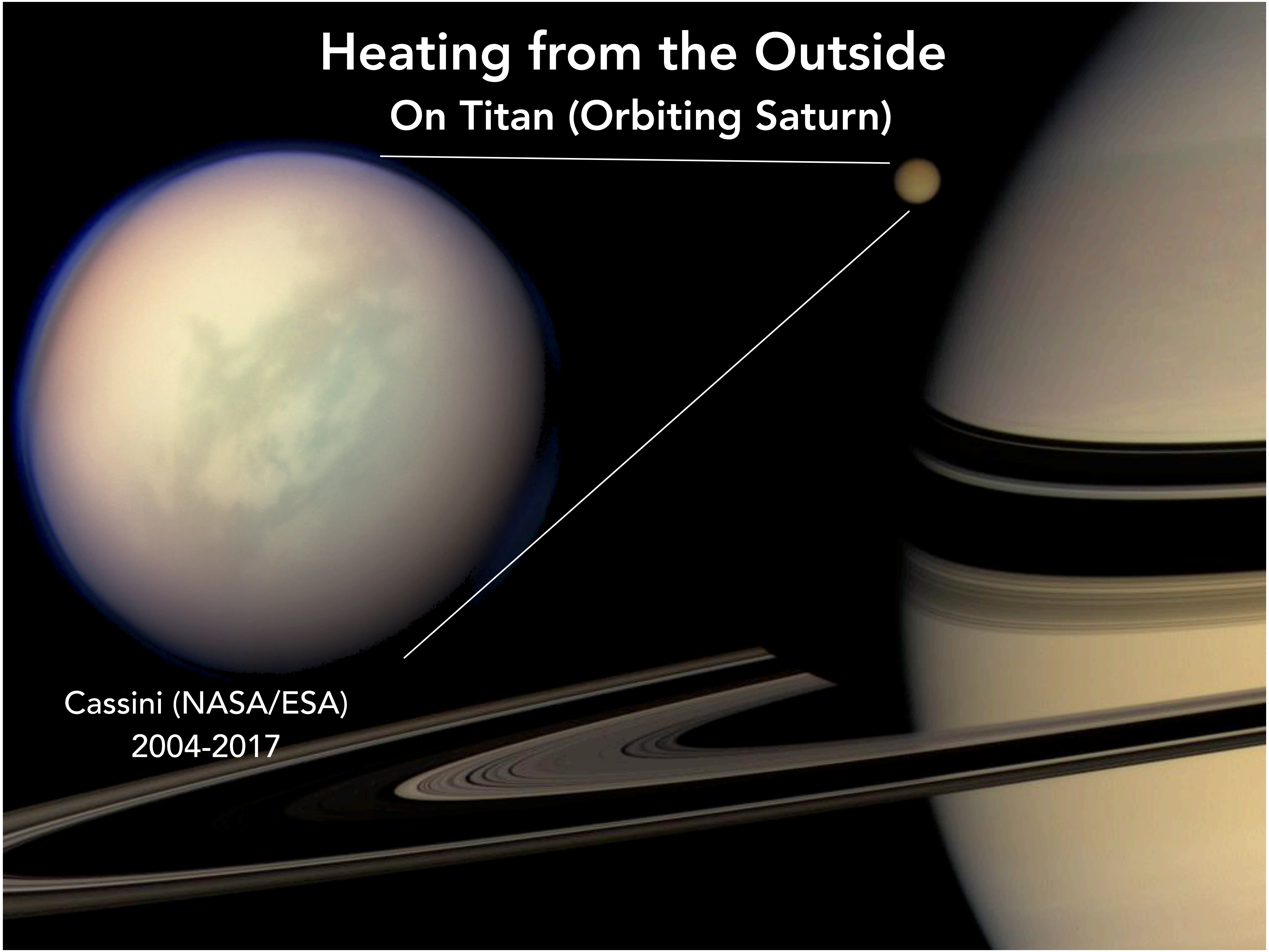
- The global average flux on Titan is
  F = 15 W/m^2 × 0.78 × 1/4 = <u>3 W/m^2</u>.

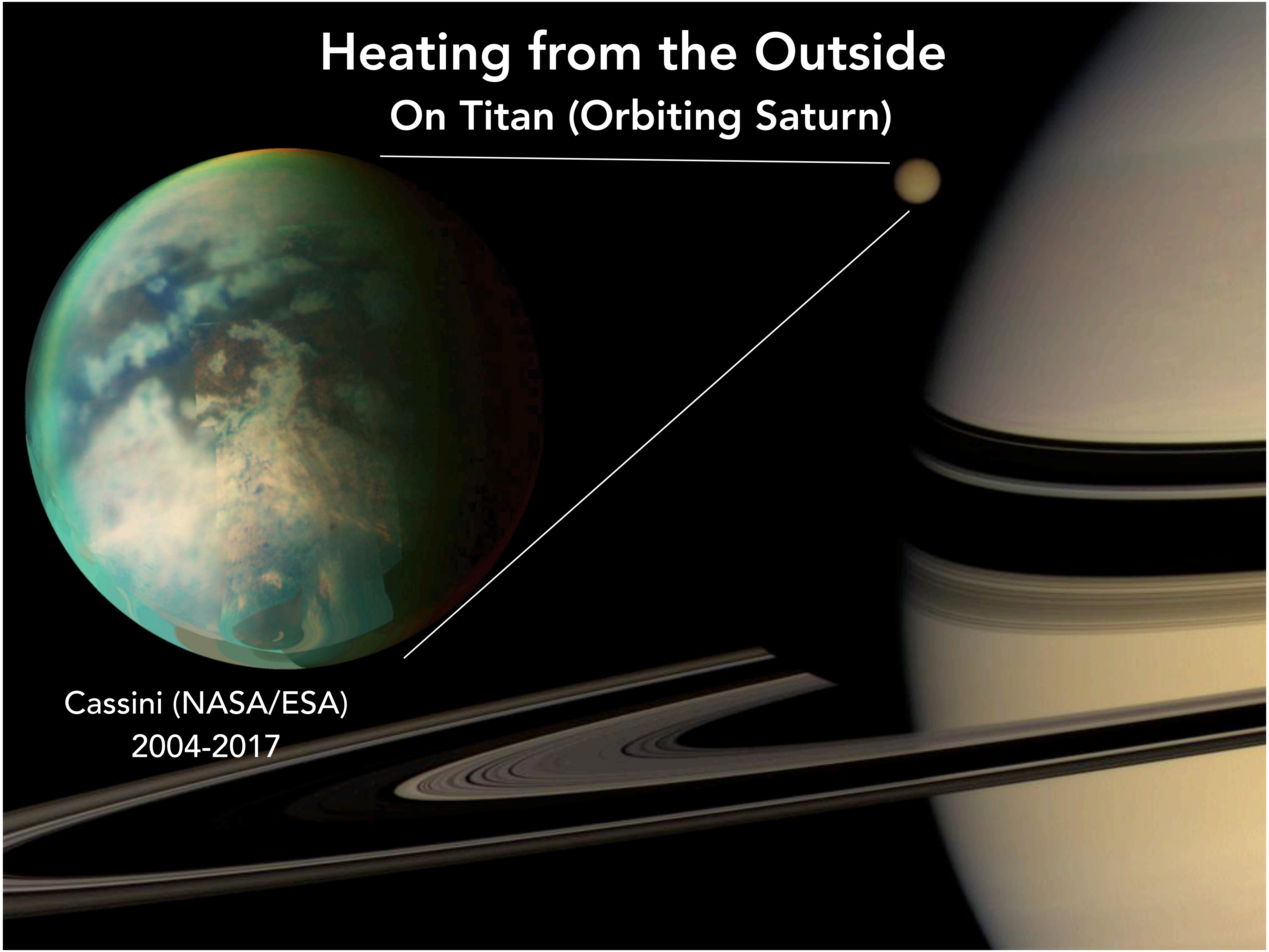
- Stefan-Boltzmann equation*
  $T = (F / \sigma_{SB})^{1/4}$ = 84 K = <u>–189°C</u>.



Voyager 1 (NASA), 1980


Heating from the Outside
On Titan (Orbiting Saturn)
Voyager 1 (NASA), 1980


Heating from the Outside
On Titan (Orbiting Saturn)
Cassini (NASA/ESA)
2004-2017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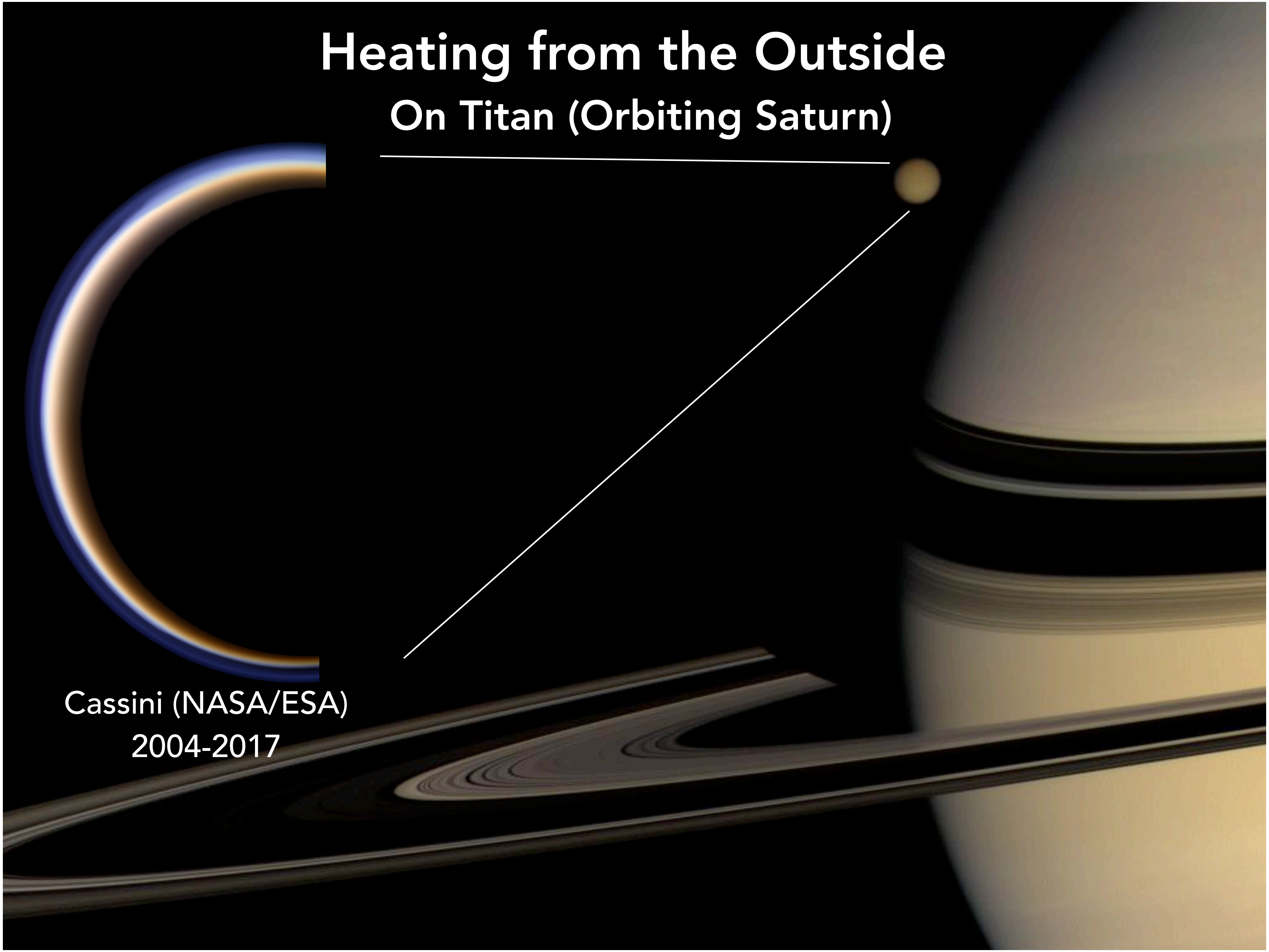
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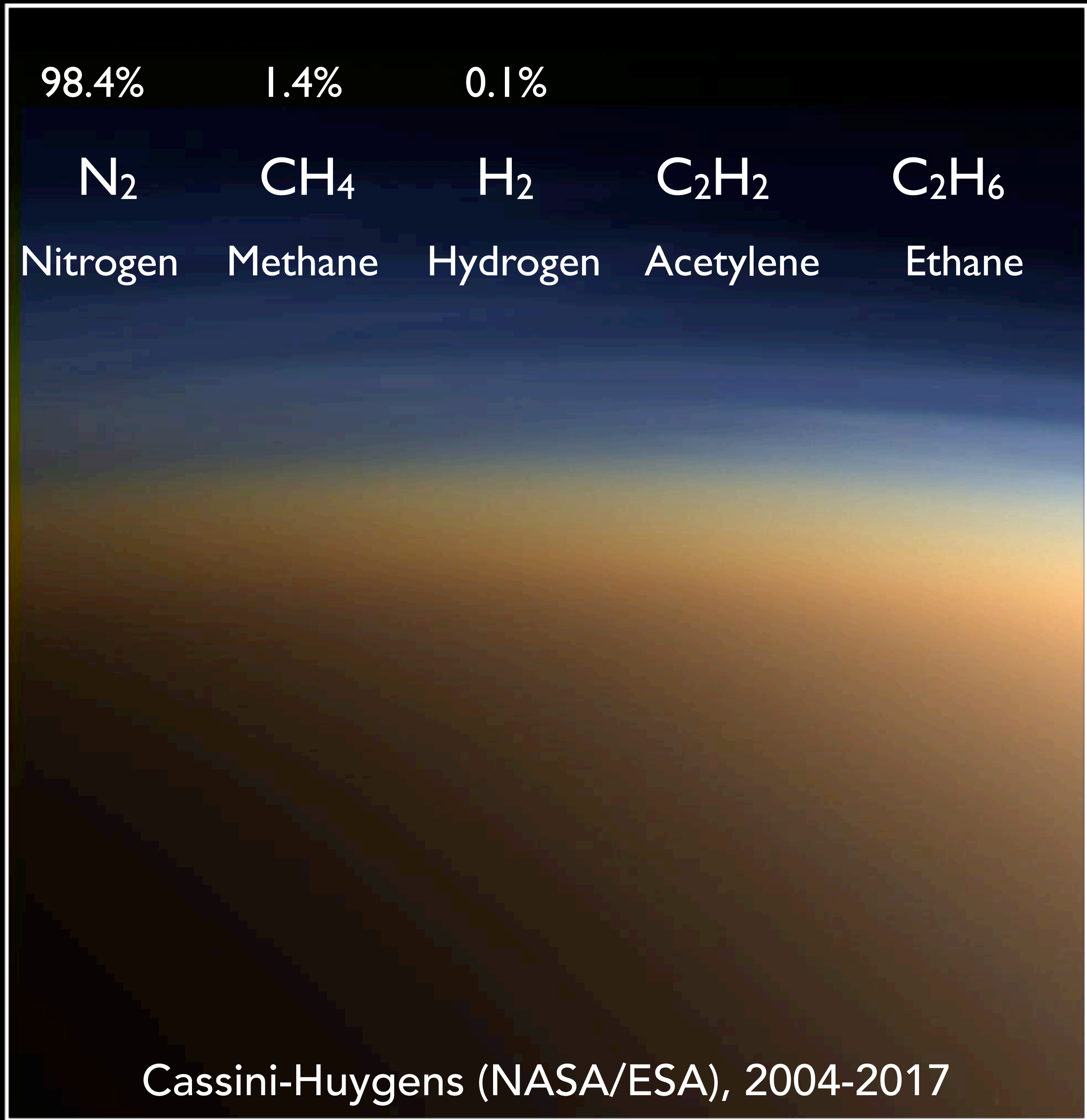
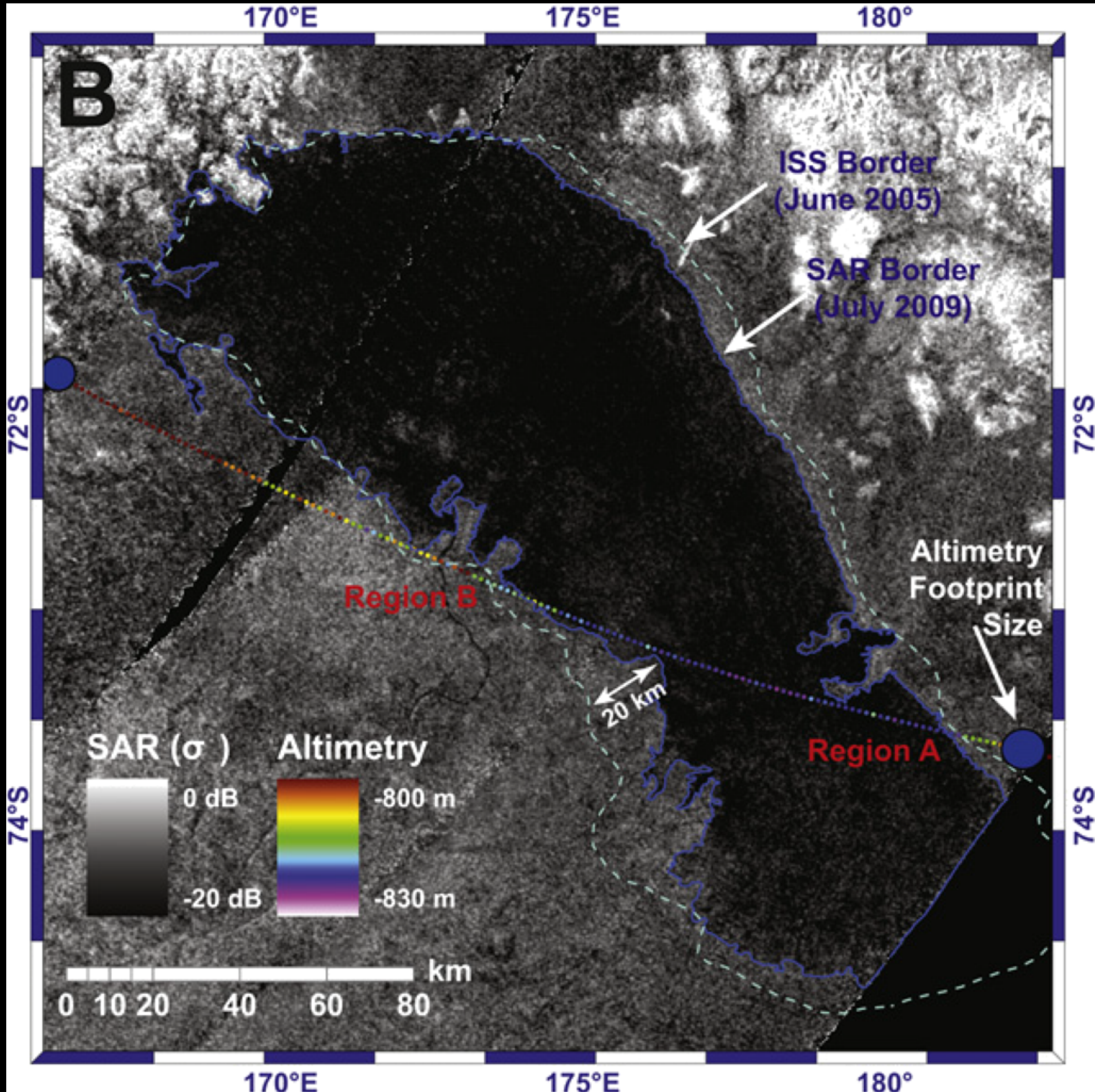
Heating from the Outside



Heating from the Outside

On Titan (Orbiting Saturn)



Cassini-Huygens (NASA/ESA), 2004-2017

Heating from the Outside

On Titan (Orbiting Saturn)

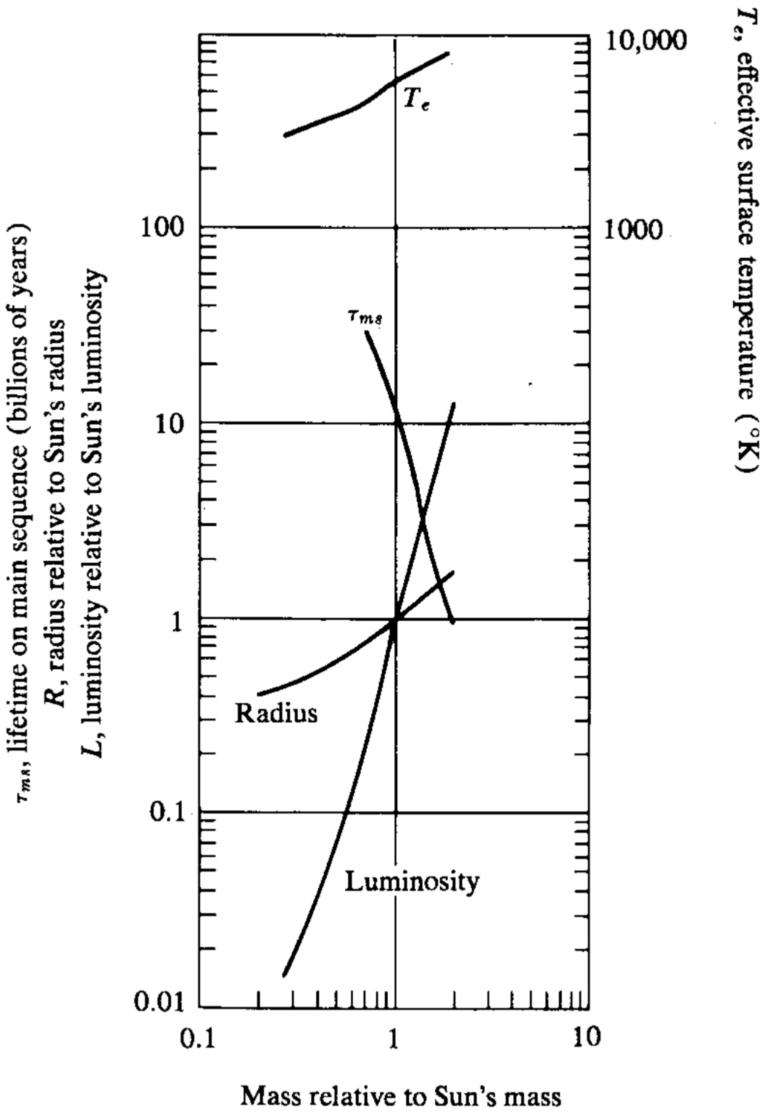
$T = (F / \sigma_{SB})^{1/4}$ = 84 K = <u>–189°C</u>.

Huygens measured 94K = -179°C. There is +10°C of greenhouse warming

Huygens lander (ESA), 2004

Heating from the Outside

Habitable Zones Around Stars



Dole (1964, *Habitable planets for man*)

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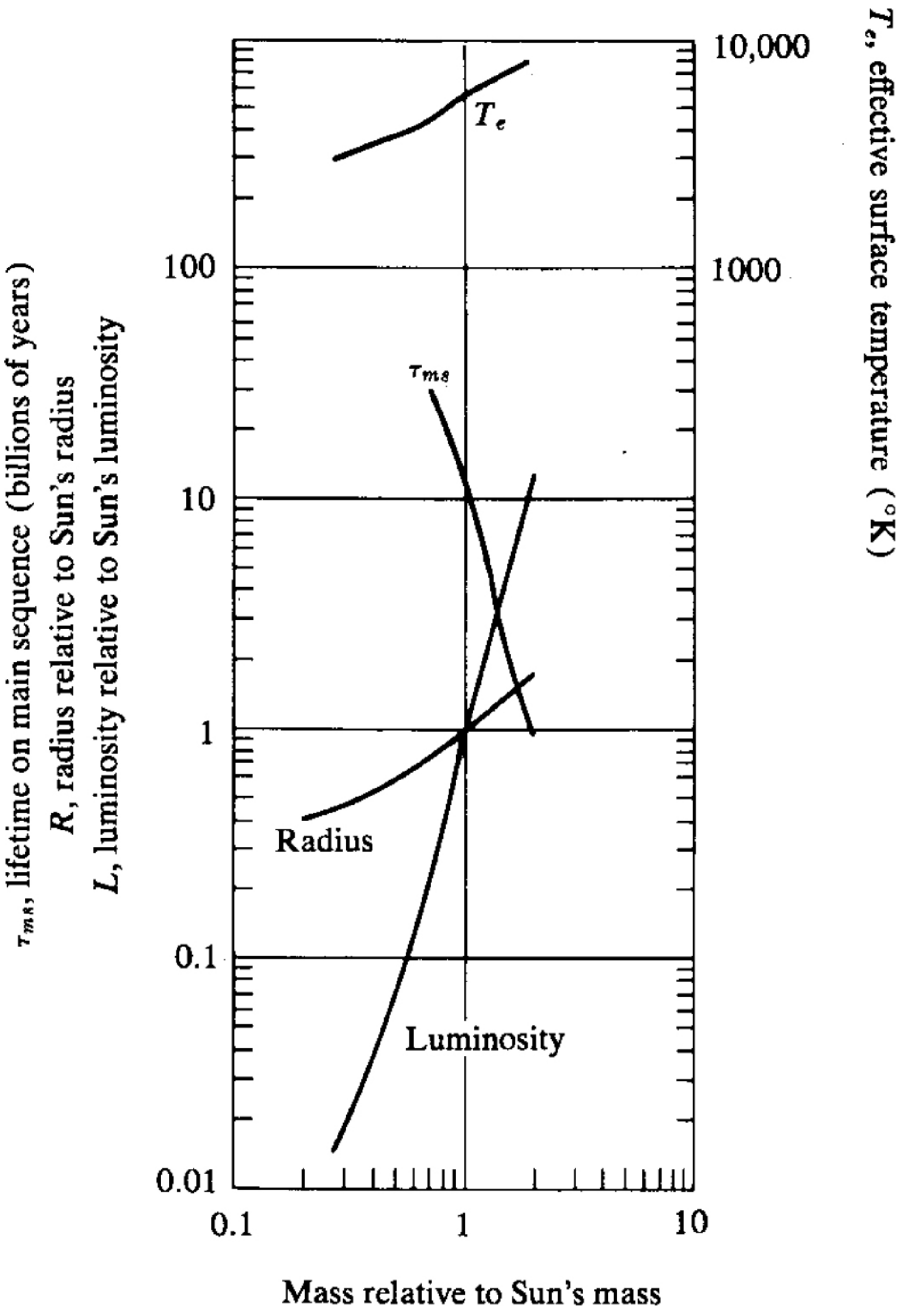
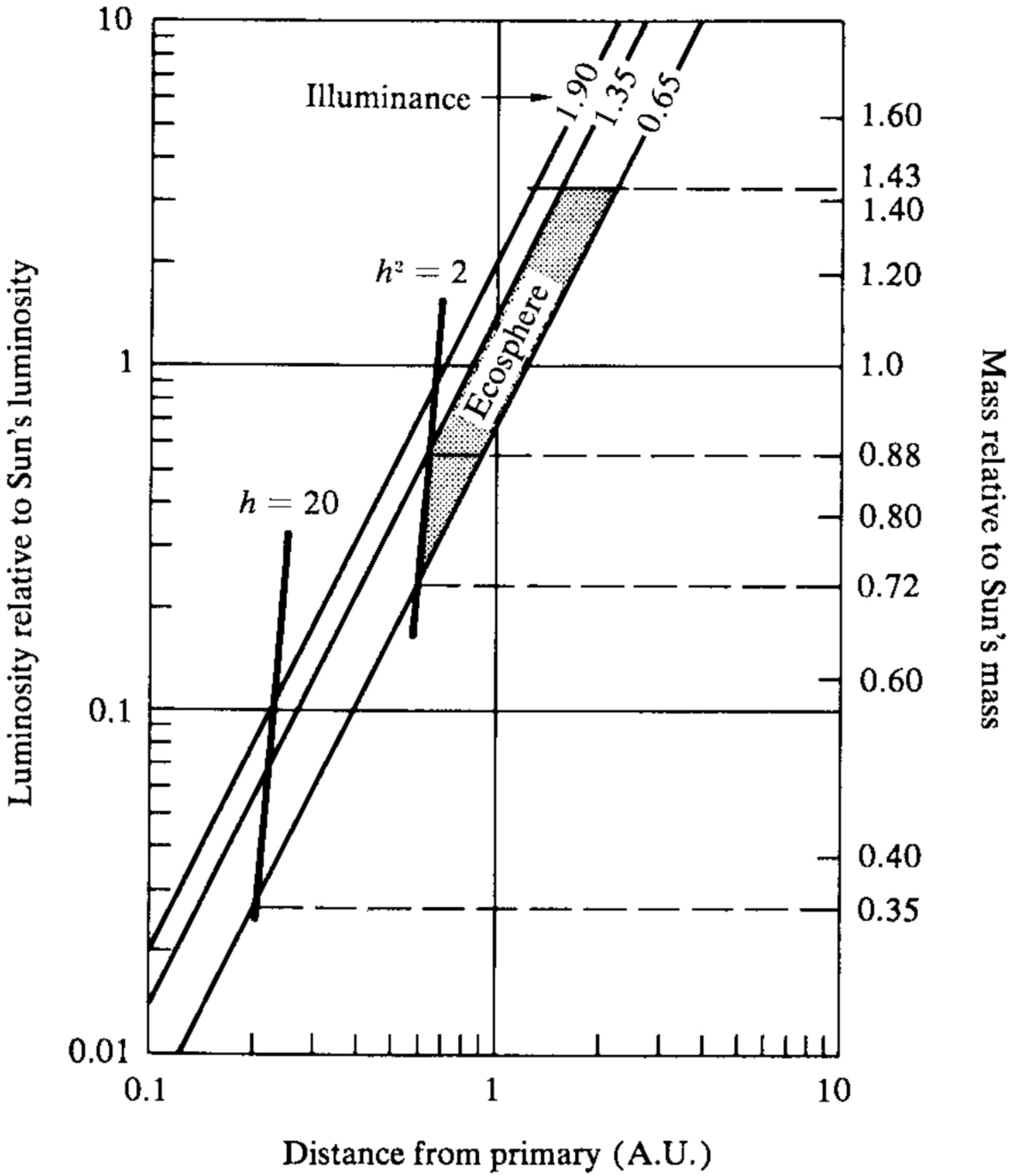
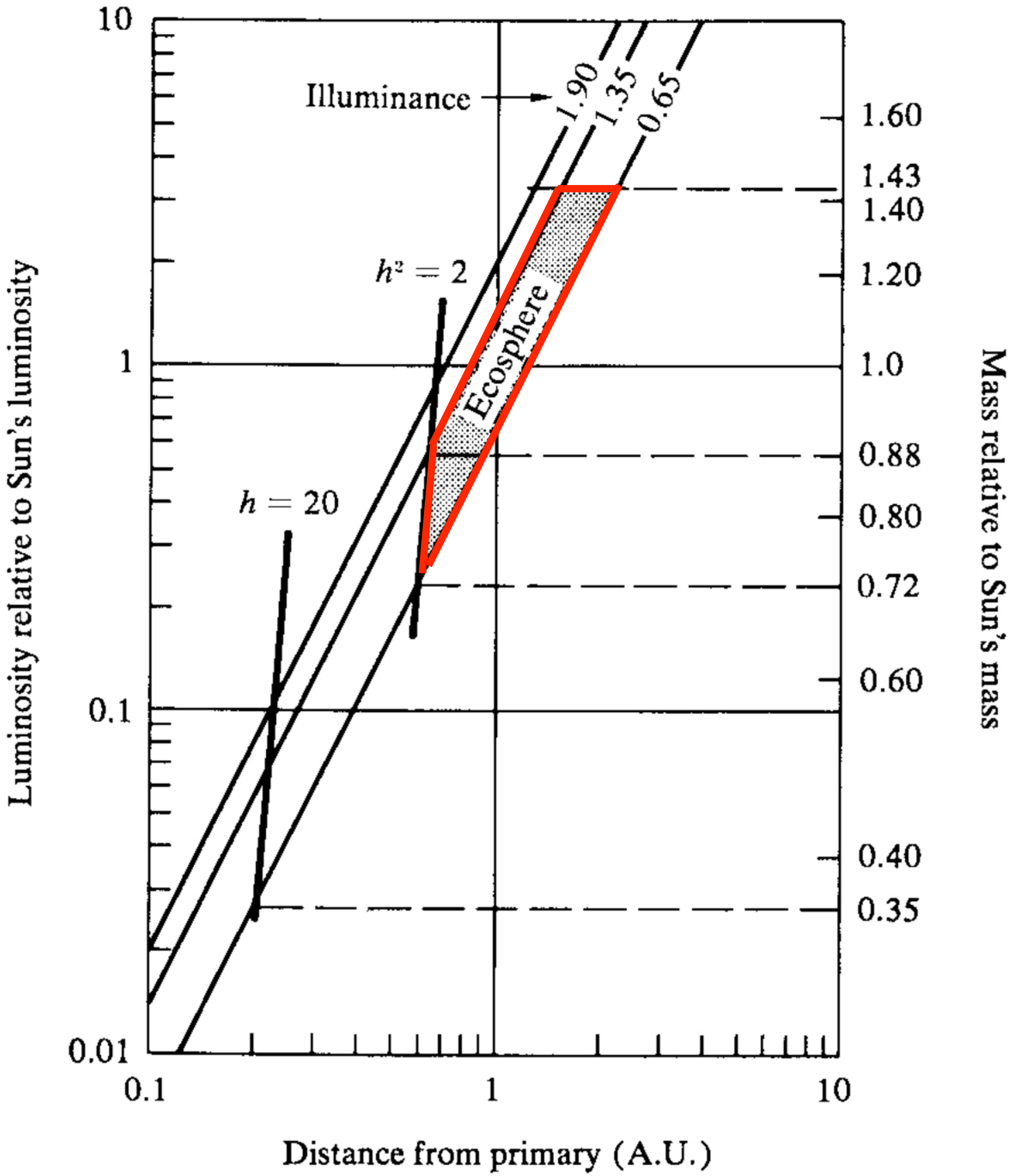

T_e, effective surface temperature (°K)
10,000
1000
T_e
τ_{ms}
Radius
Luminosity
τ_{ms}, lifetime on main sequence (billions of years)
R, radius relative to Sun's radius
L, luminosity relative to Sun's luminosity
100
10
1
0.1
0.01
0.1
1
10
Mass relative to Sun's mass

Dole (1964)



Luminosity relative to Sun's luminosity
Illuminance
1.90
1.35
0.65
$h^2 = 2$
$h = 20$
Ecosphere
10
1
0.1
0.01
0.1
1
10
Distance from primary (A.U.)
1.60
1.43
1.40
1.20
1.0
0.88
0.80
0.72
0.60
0.40
0.35
Mass relative to Sun's mass

Dole (1964)



Dole (1964)

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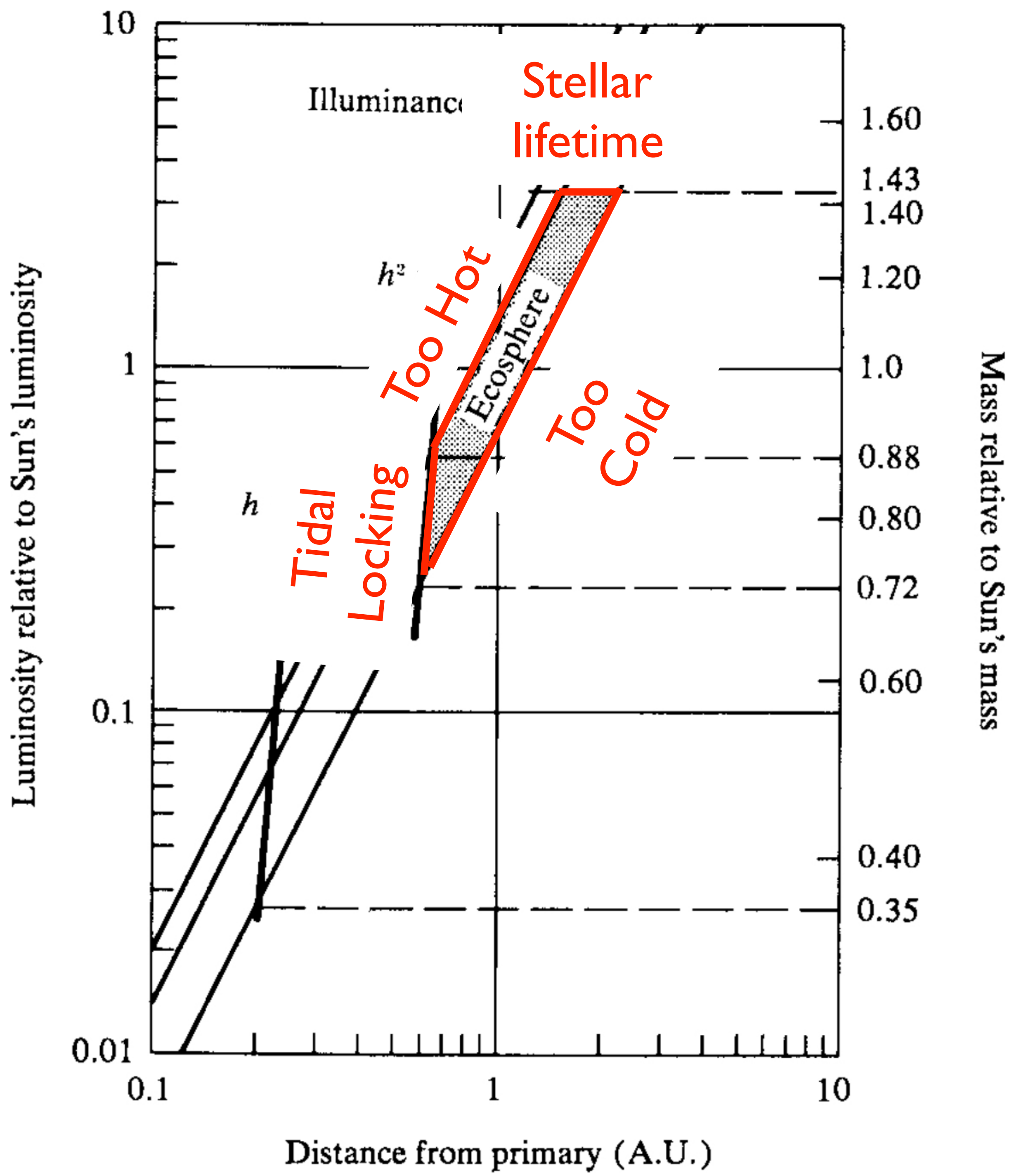

Dole (1964)

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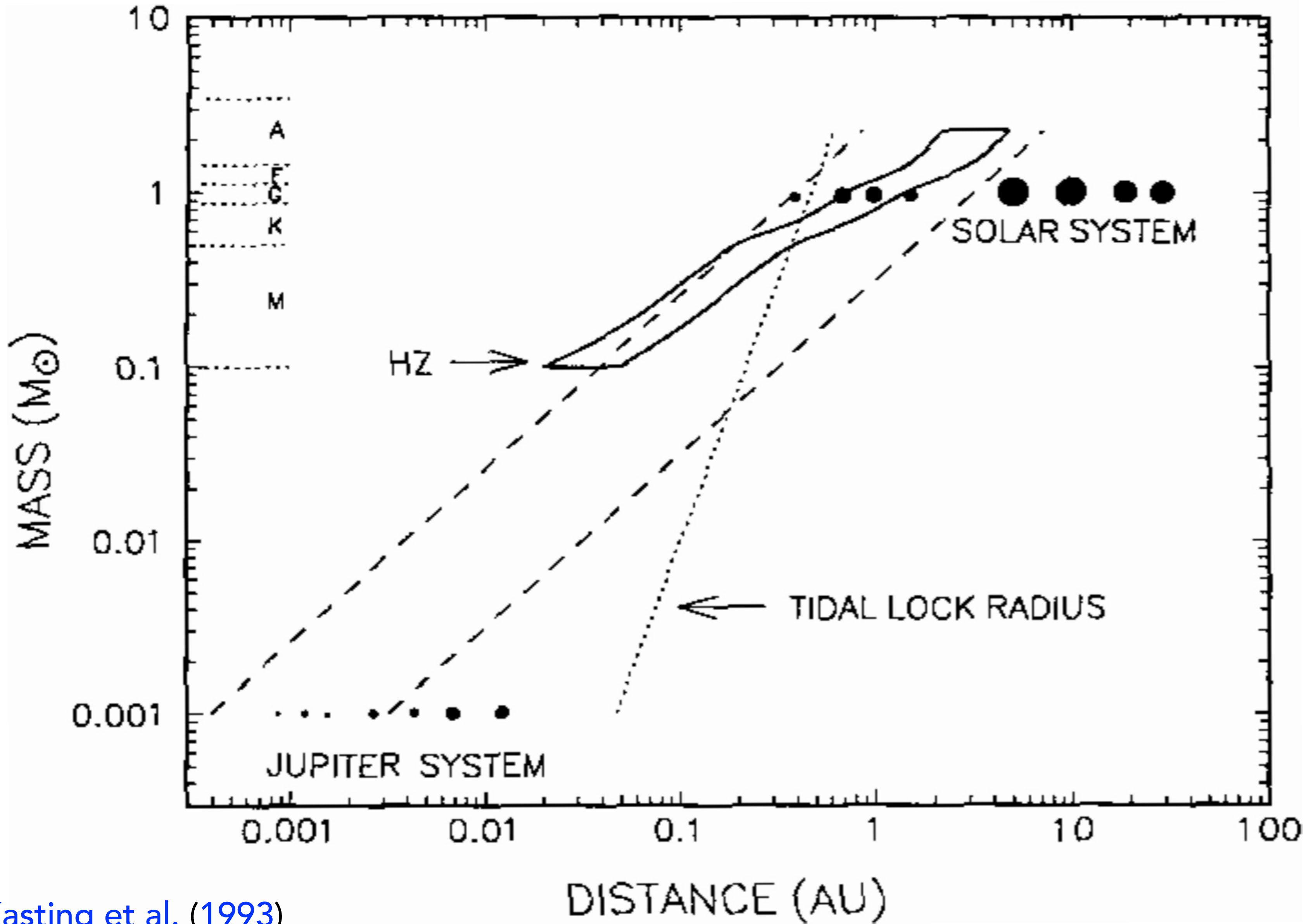
Heating from the Outside

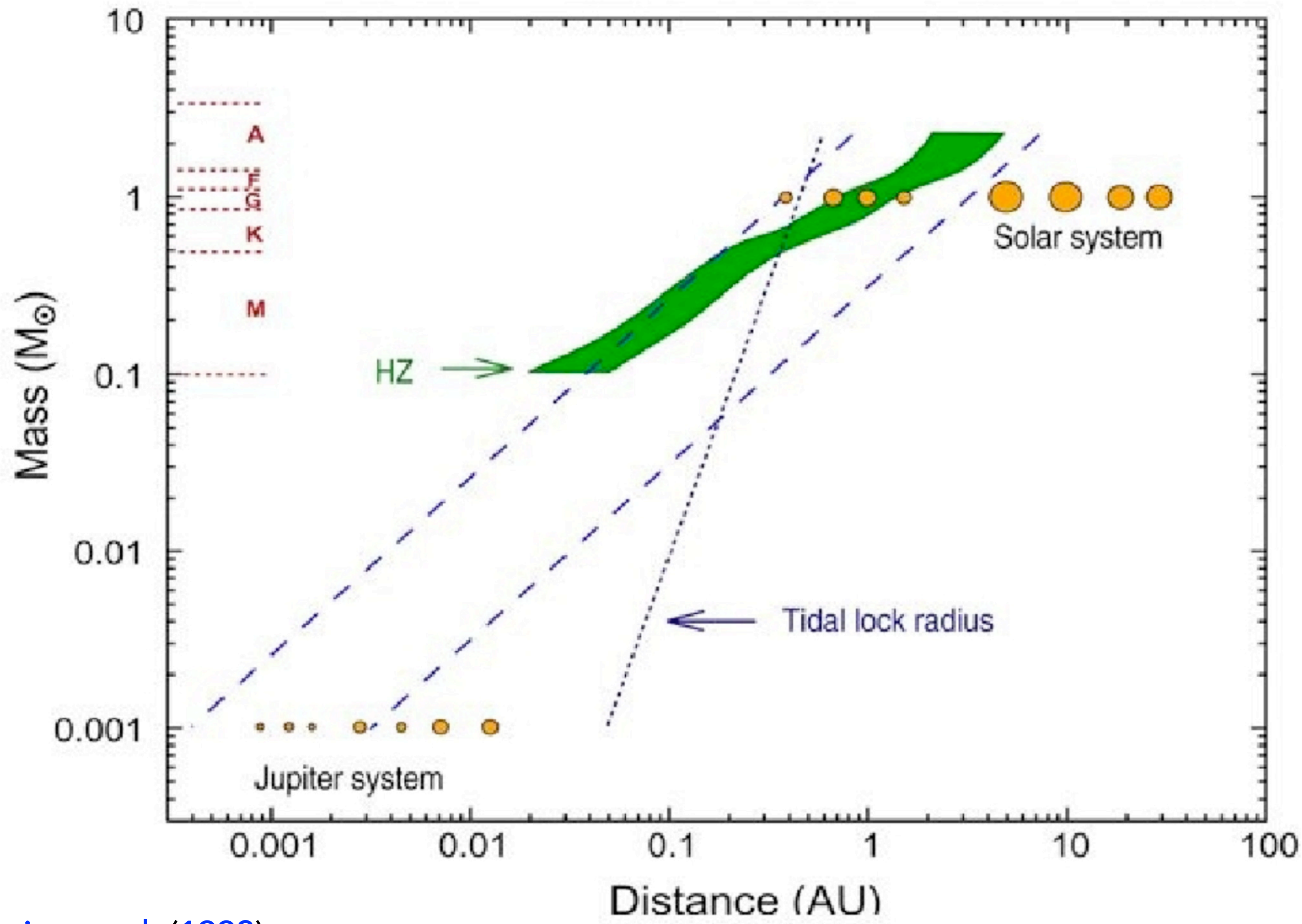
Habitable Zones Around Stars



Kasting et al. (1993)

Heating from the Outside

Habitable Zones Around Stars



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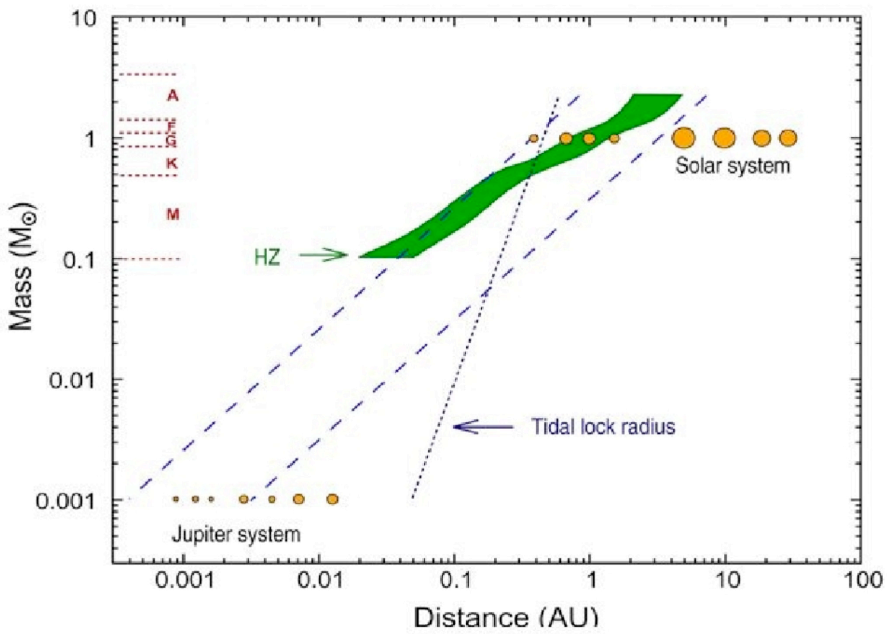


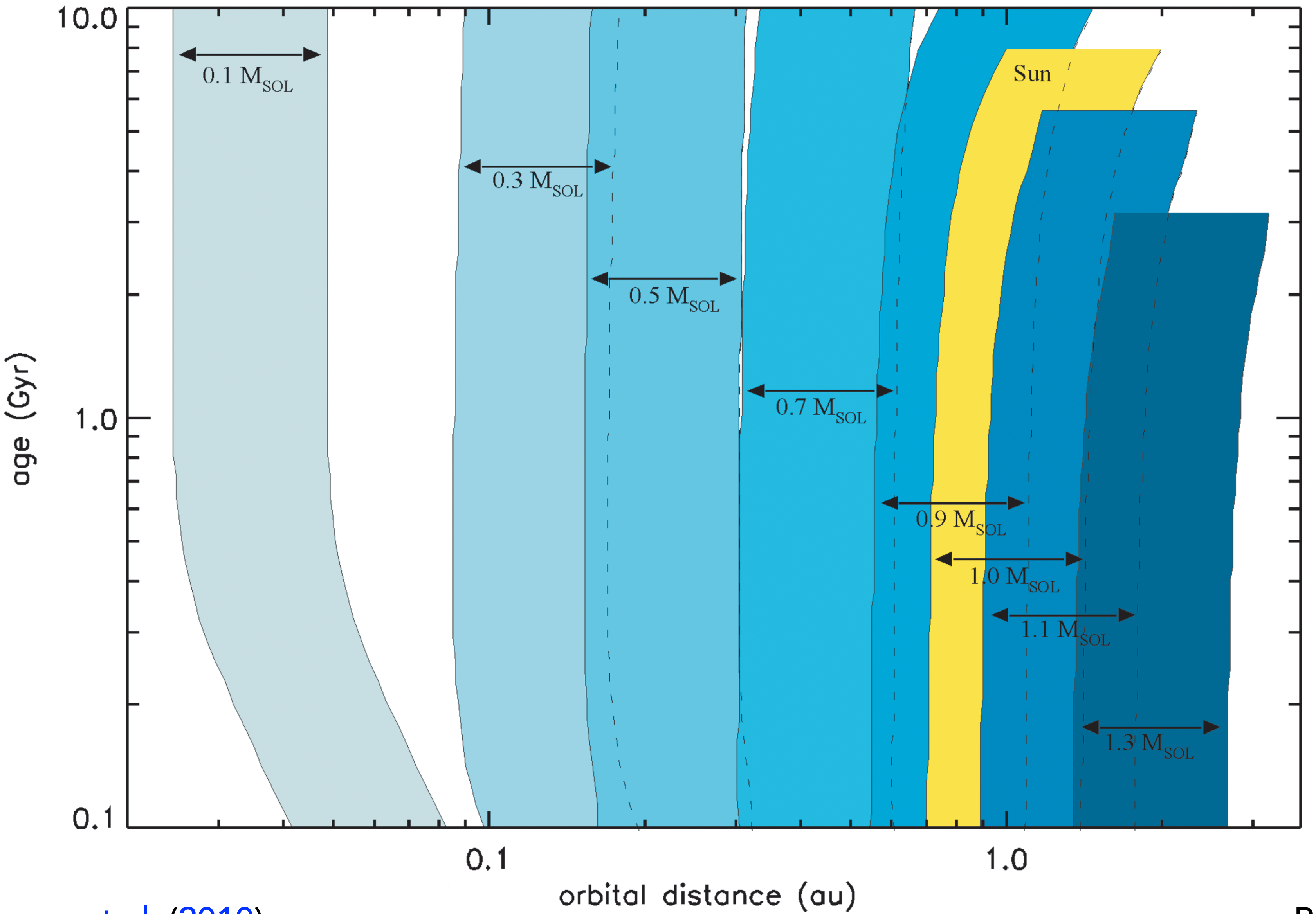
- Inner HZ boundary:
  runaway greenhouse effect

- Outer HZ boundary:
  maximum CO_2 greenhouse effect

Kasting et al. (1993)

Heating from the Outside

Habitable Zones Around Stars



Lammer et al. (2010)

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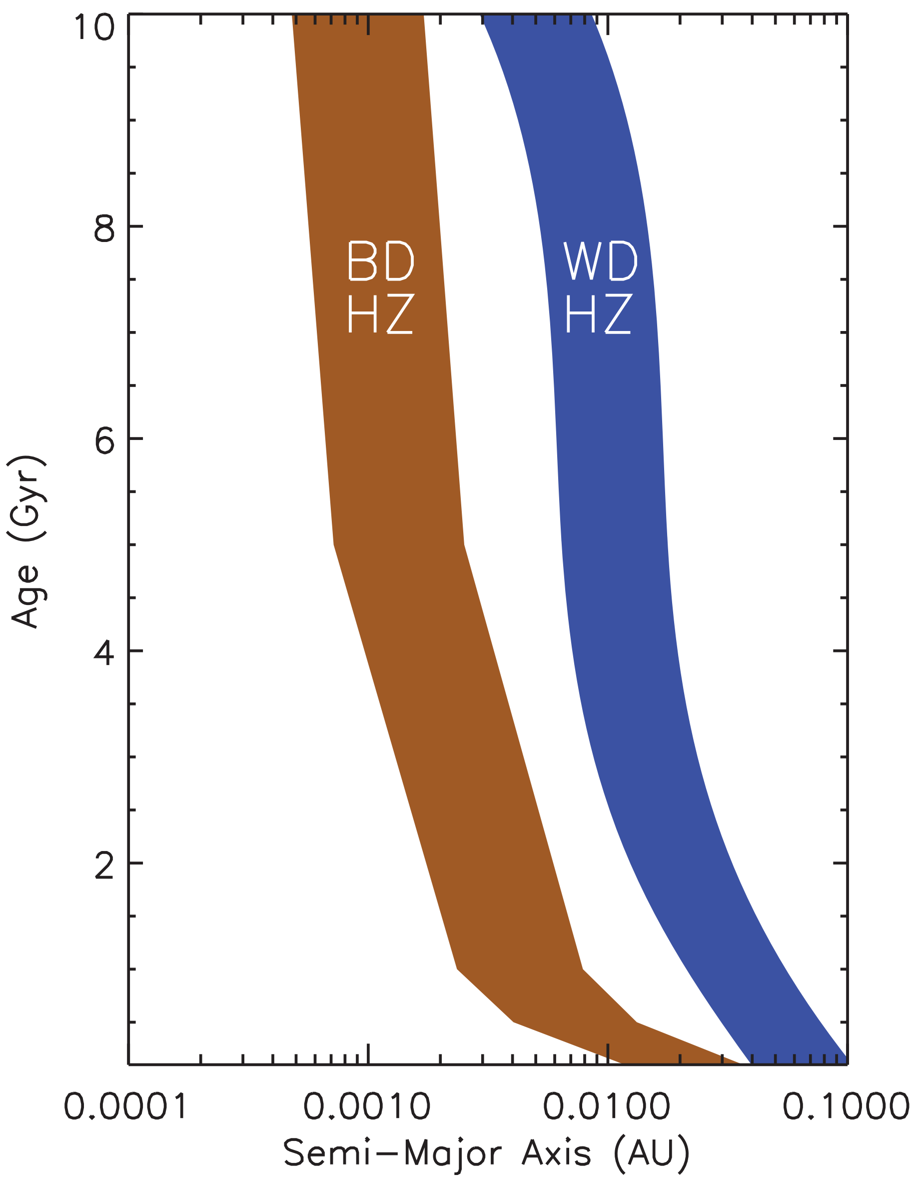
Heating from the Outside

Habitable Zones Around Stars



Barnes & Heller (2013)

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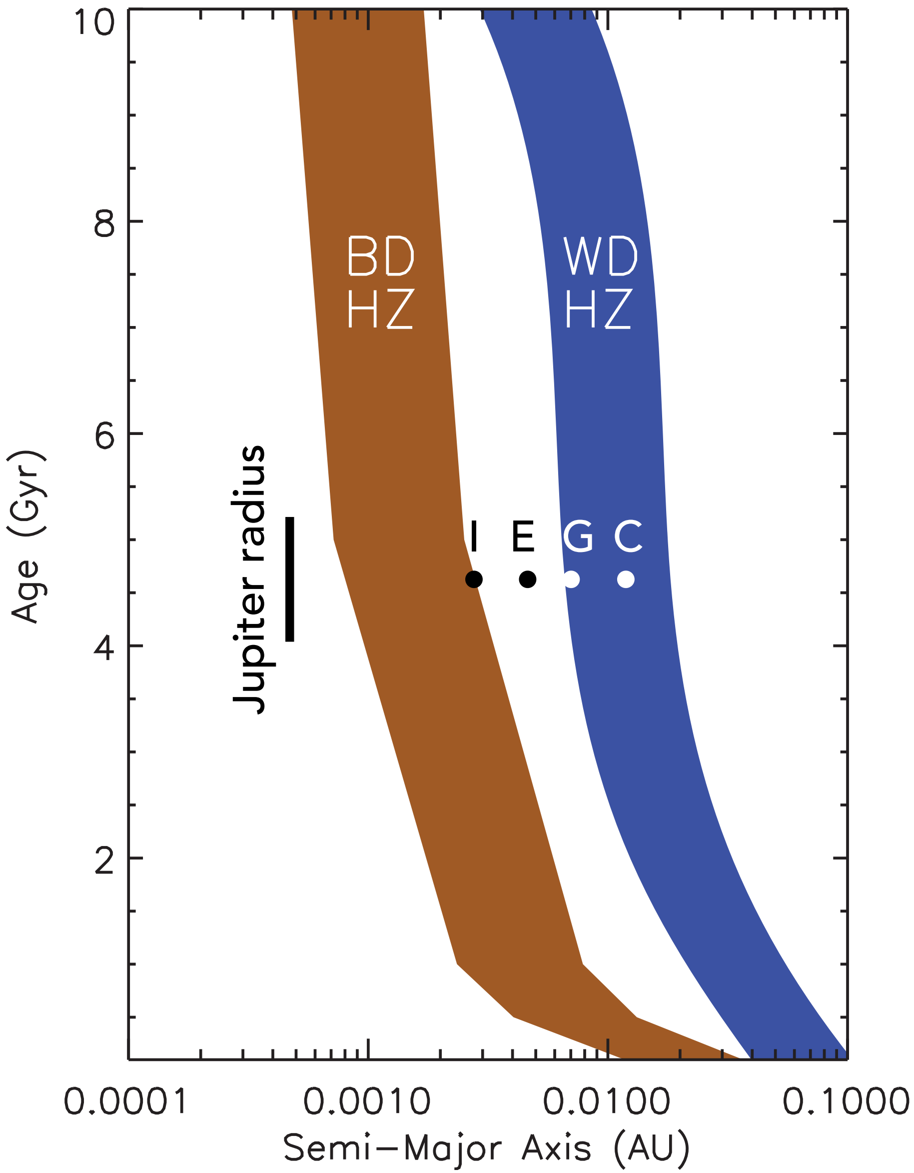
Heating from the Outside

Habitable Zones Around Stars



Barnes & Heller (2013)

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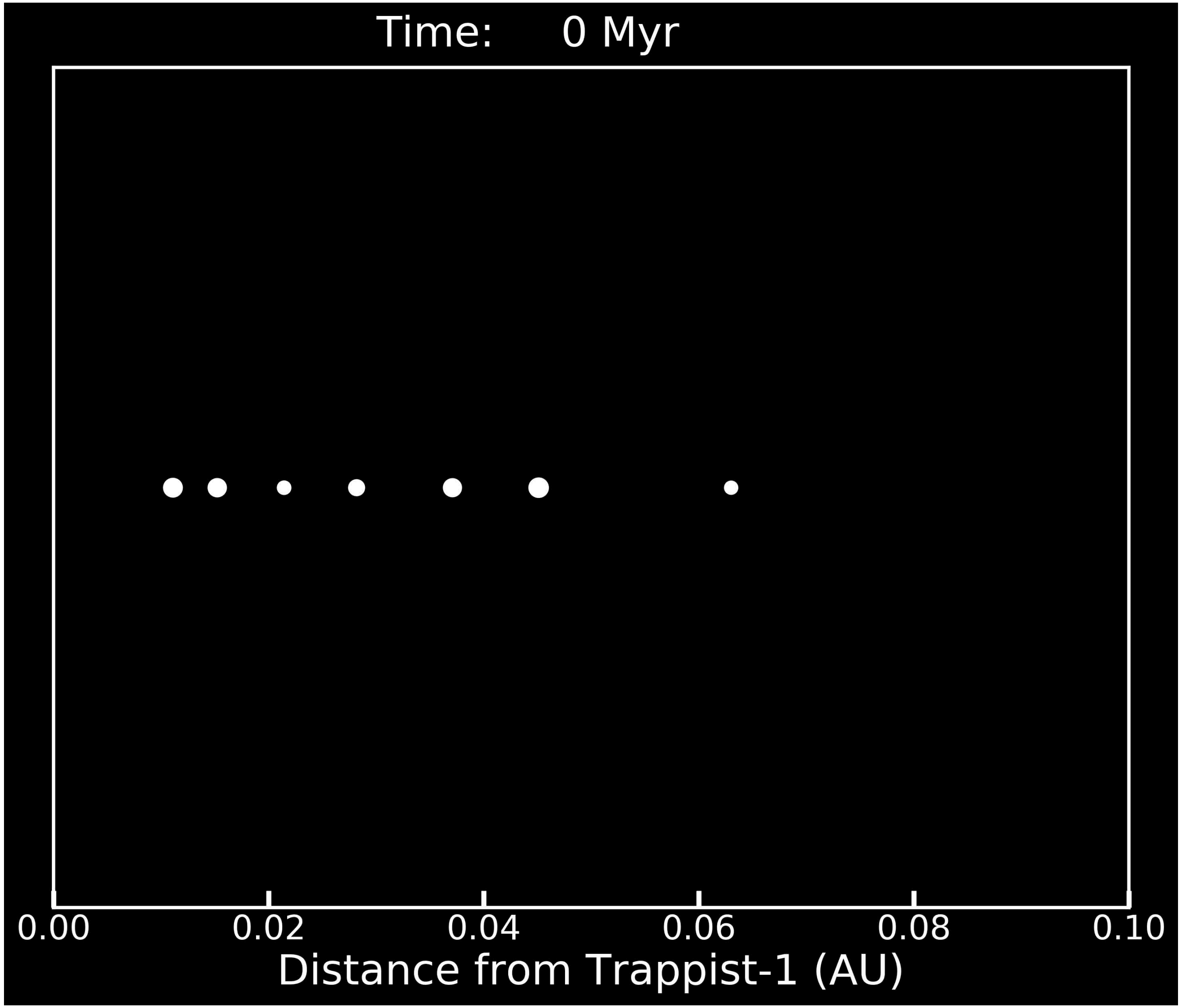
Heating from the Outside

Habitable Zones Around Stars

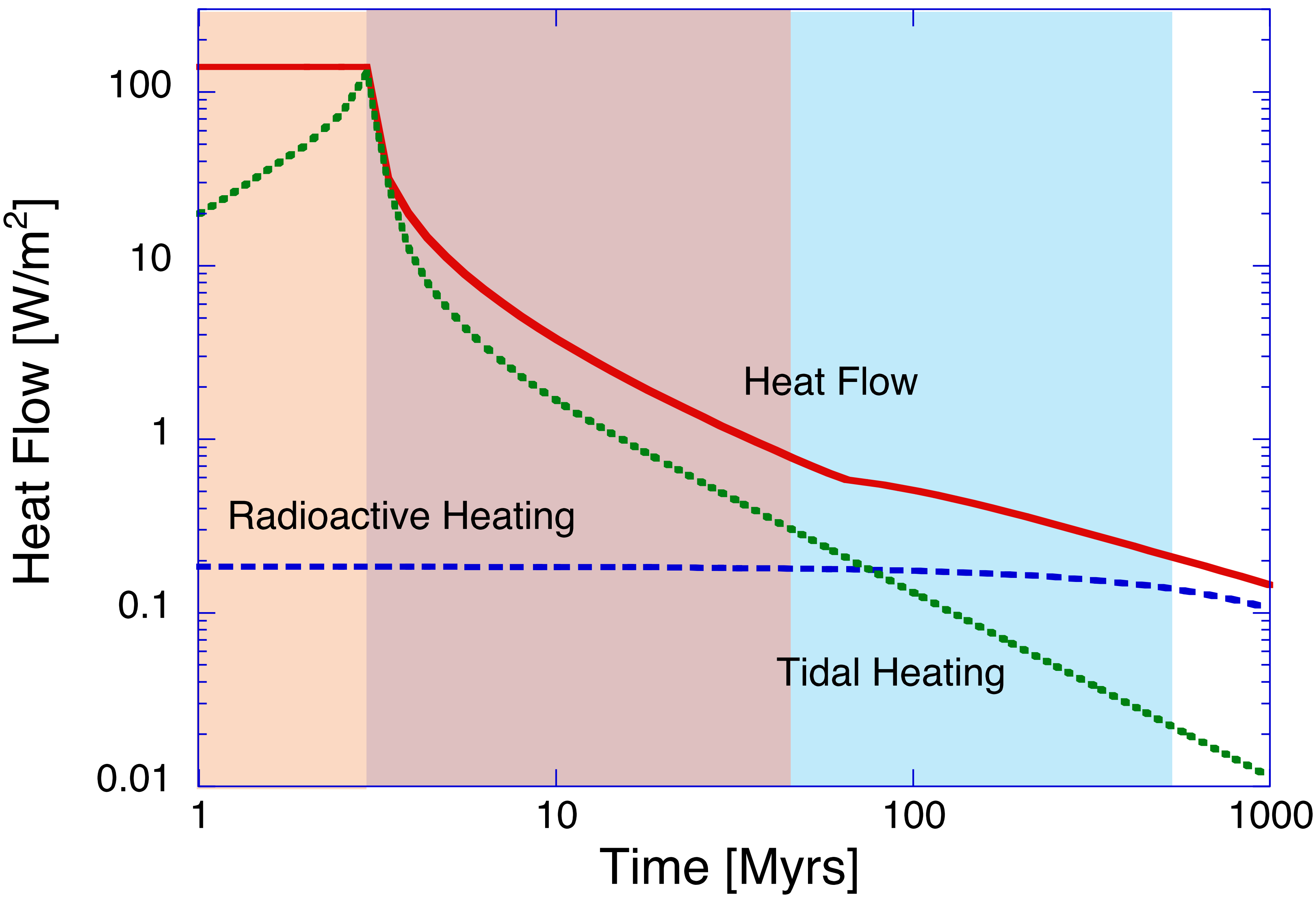


TRAPPIST-1:

- ultra-cool red dwarf
- 40 ly away, ~7.6 Gyr old
- 7 transiting planets (Gillon+ 2015; Delrez+ 2018)
- all planets roughly Earth-sized

Video credit: Rory Barnes (using stellar evolution tracks: Baraffe+ 2016; HZ limits: Kopparapu+ 2013)

Heating from the Inside



Zahnle et al. (2007)

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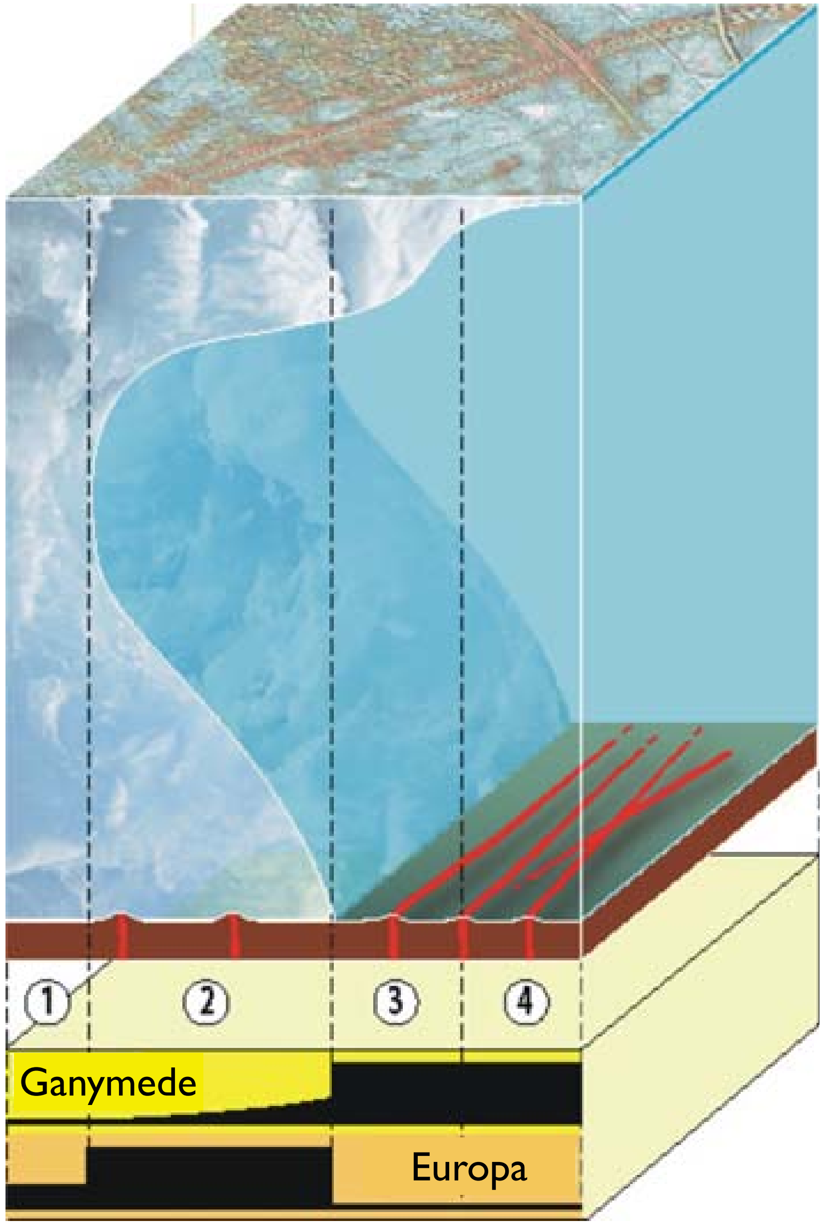
Heating from the Inside



Lammer et al. (2009)

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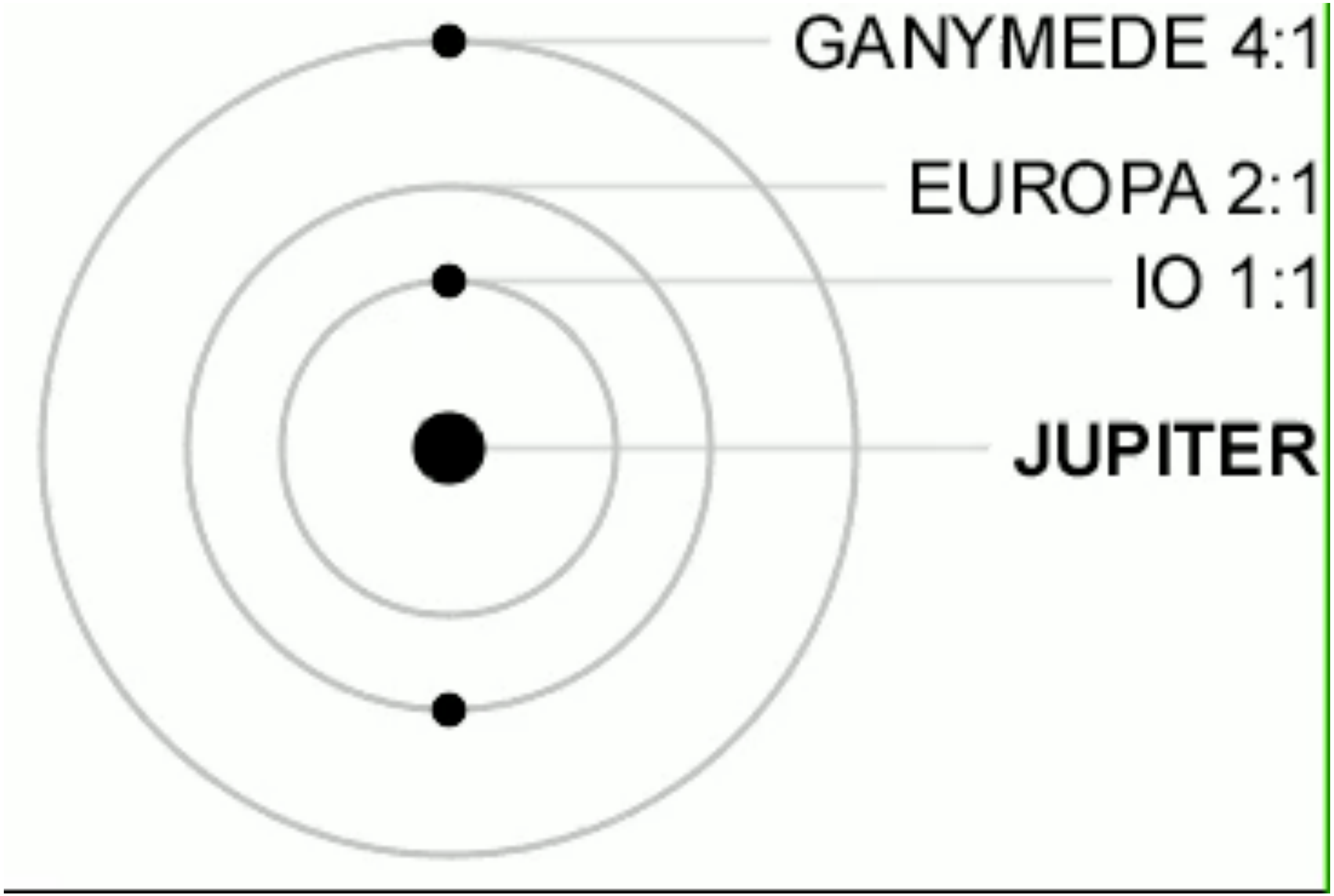
Heating from the Inside

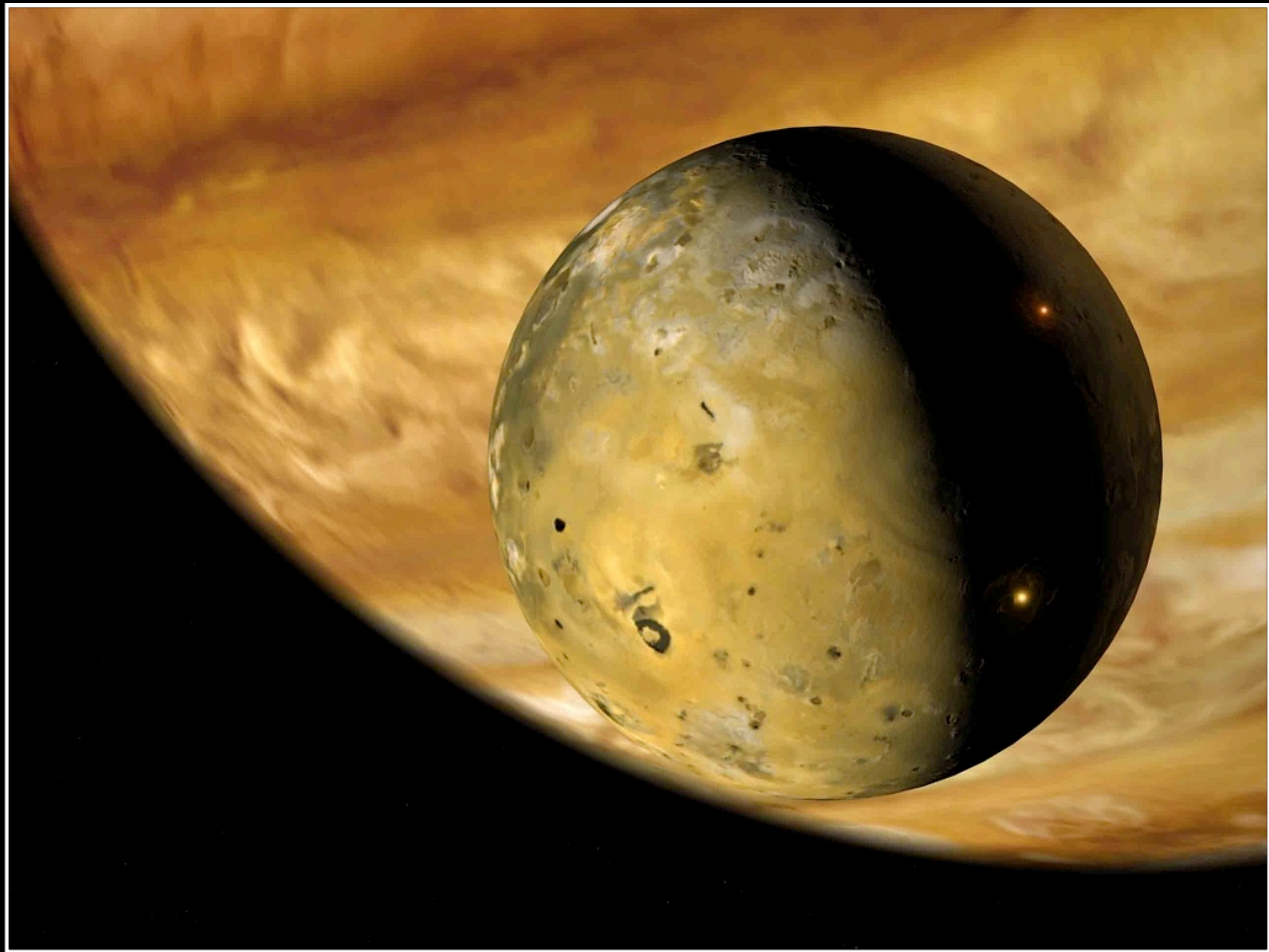
The Galilean Moons



NASA/JPL

Evidence of Tidal Heating in the Solar System

Io orbiting Jupiter



Galileo (NASA), 1995-2003

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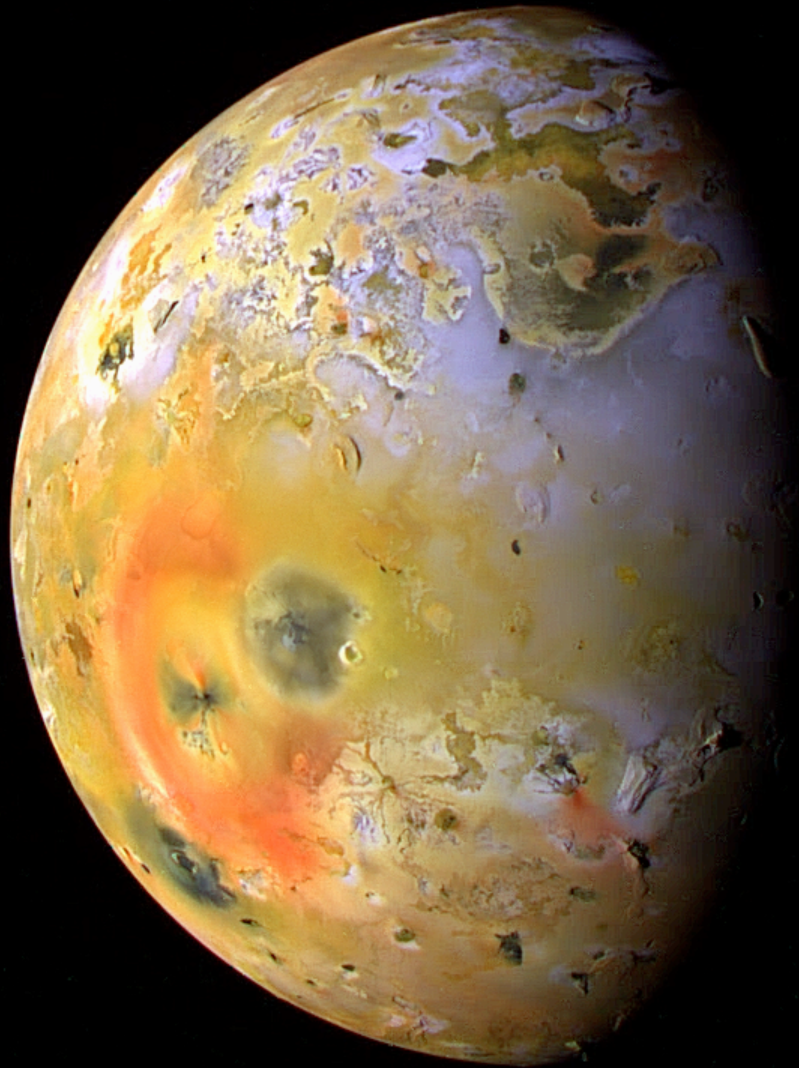

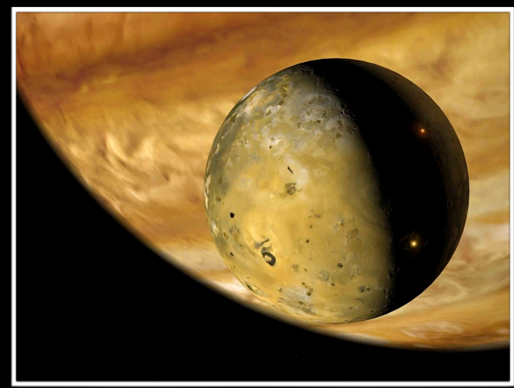

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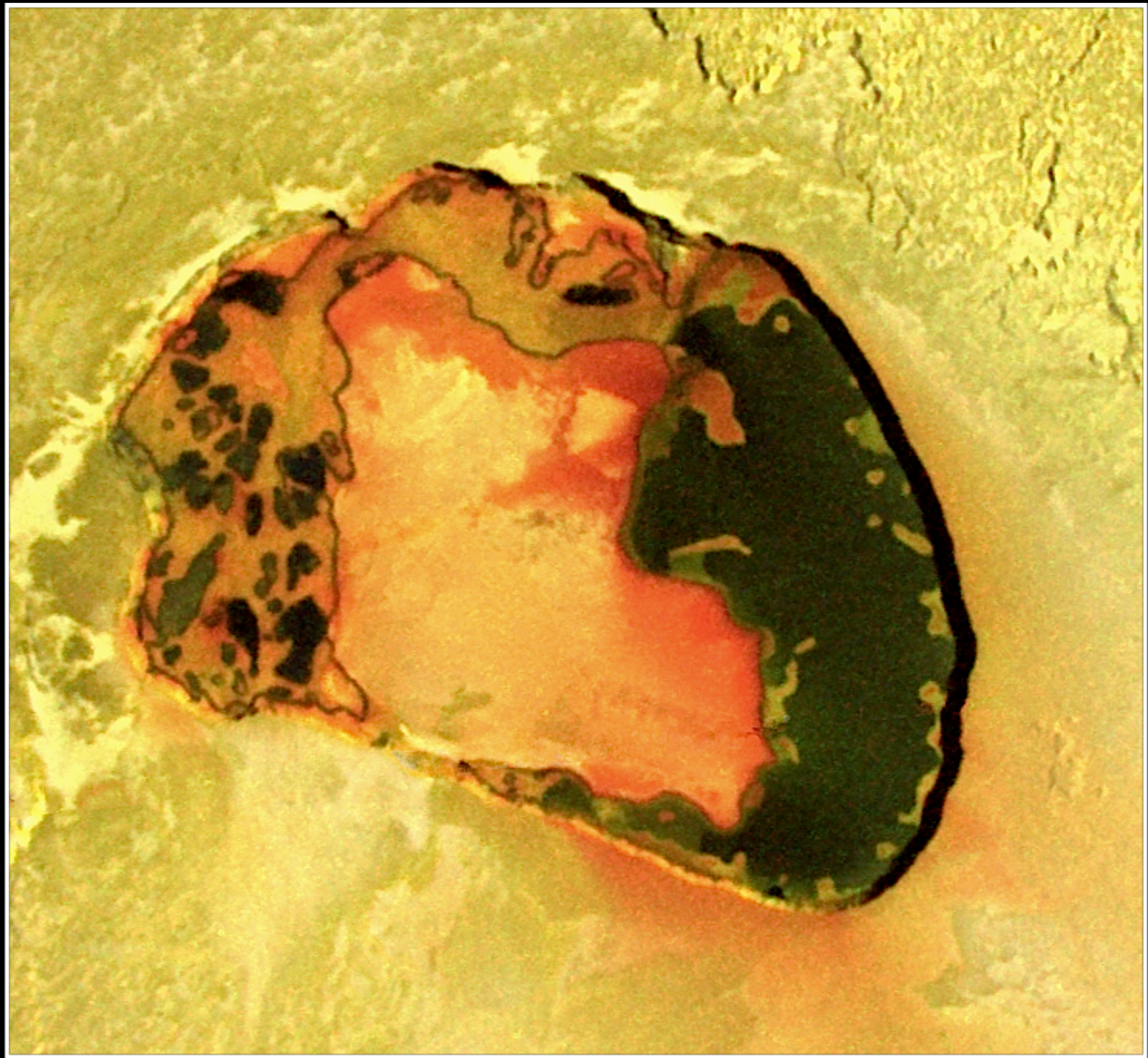
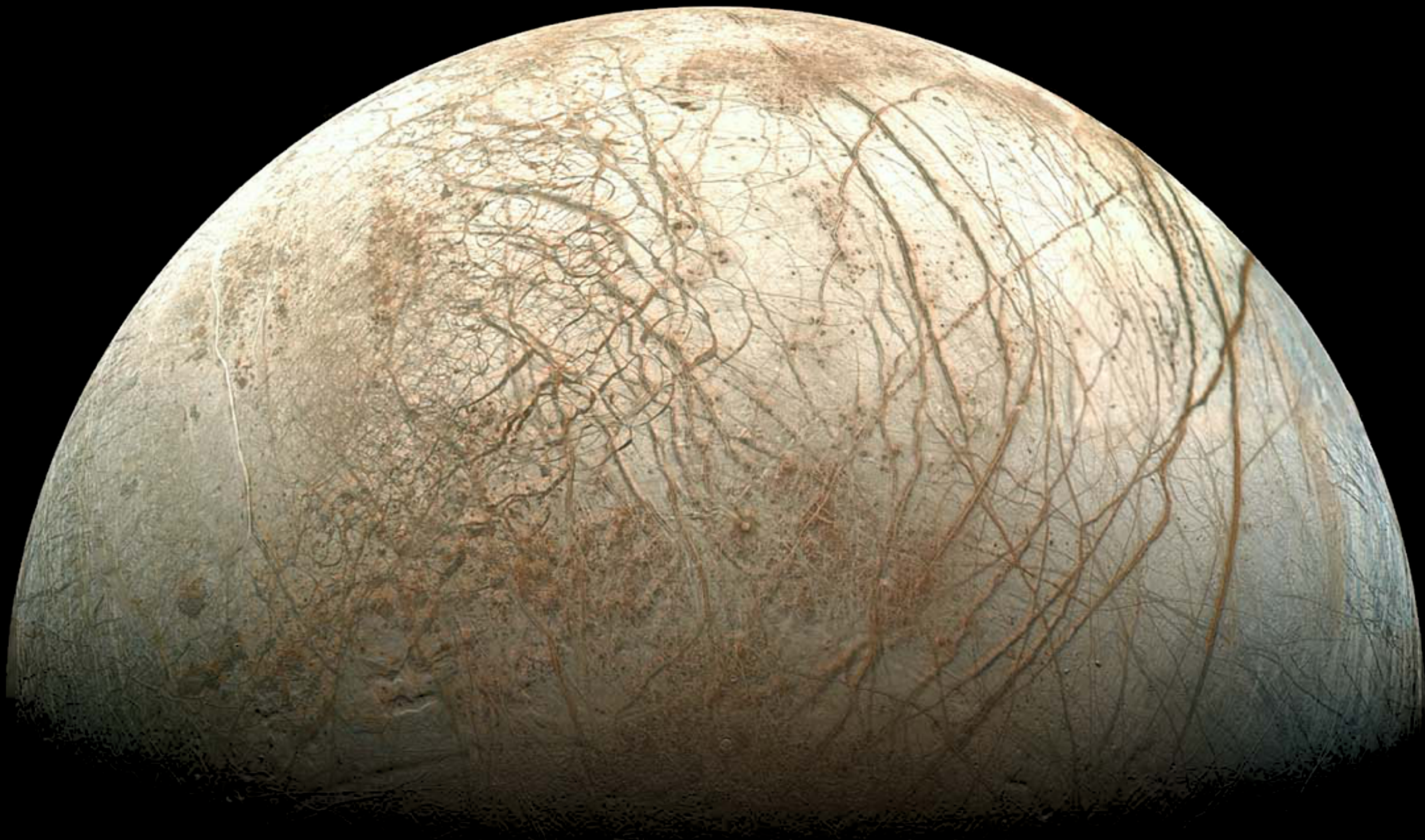


Galileo (NASA), 1995-2003

Evidence of Tidal Heating in the Solar System

Europa orbiting Jupiter



Galileo (NASA), 1995-2003

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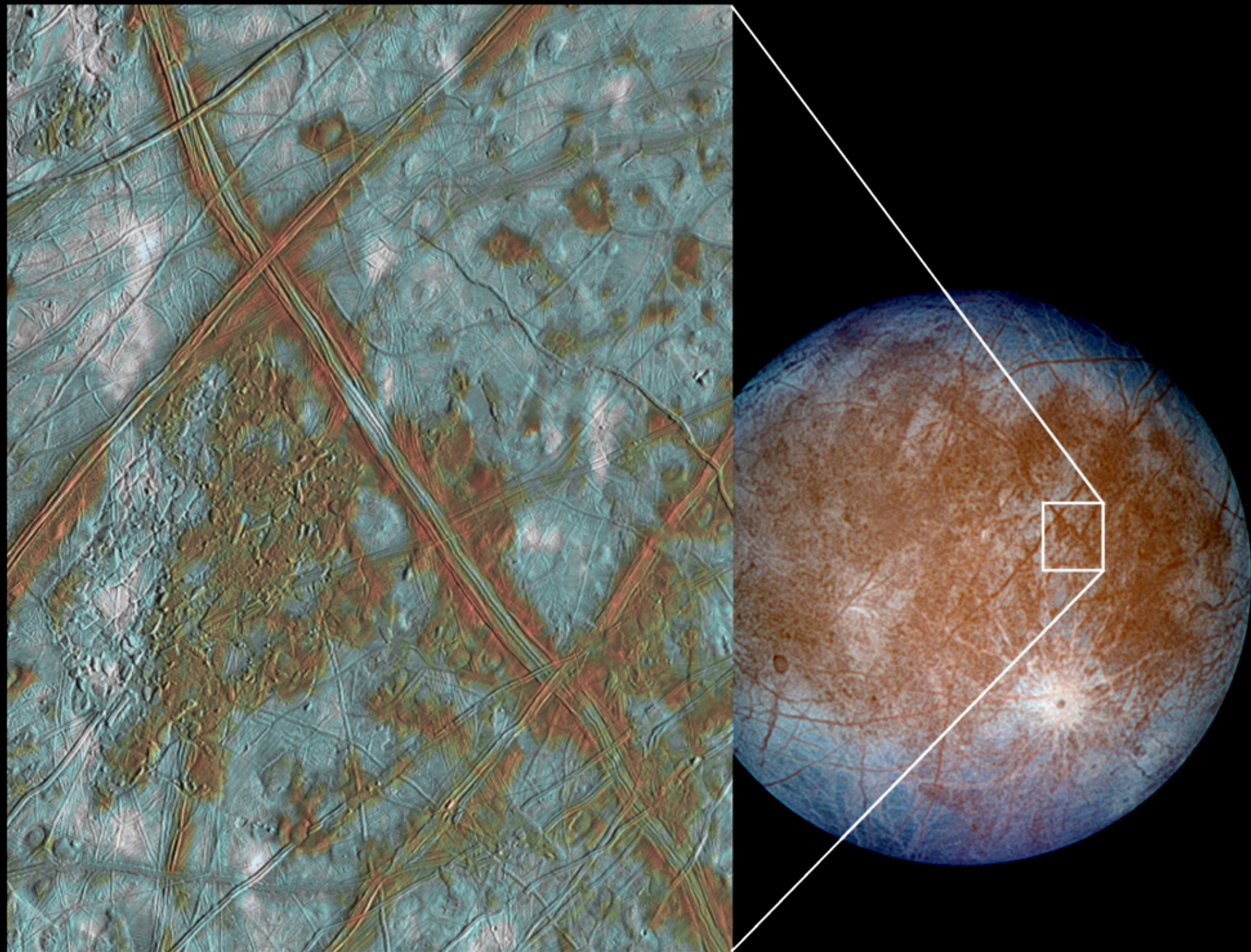

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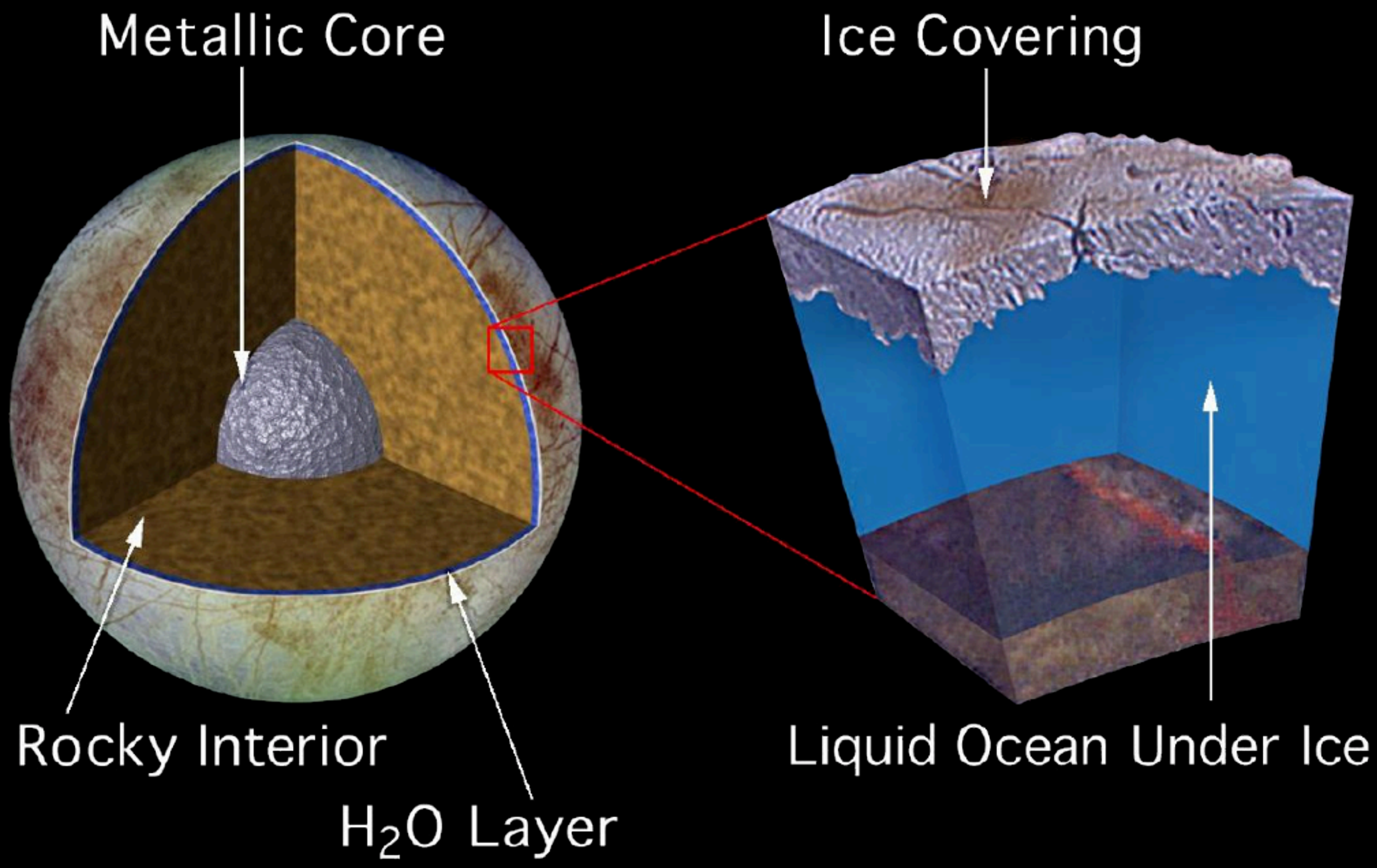

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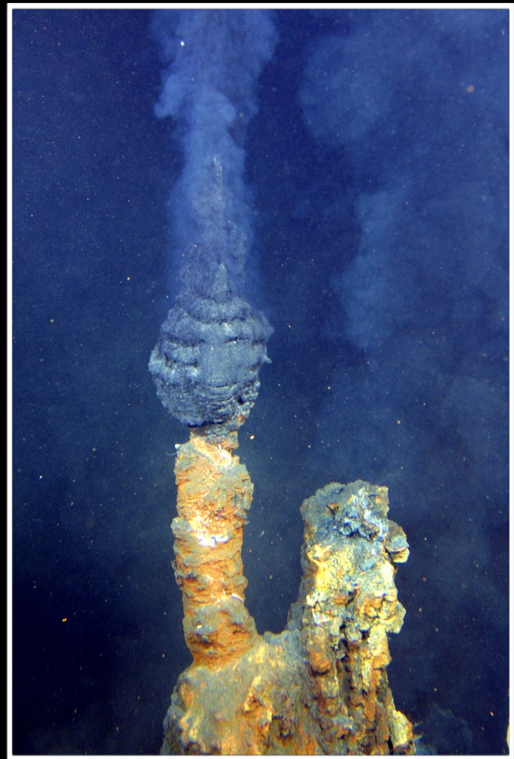
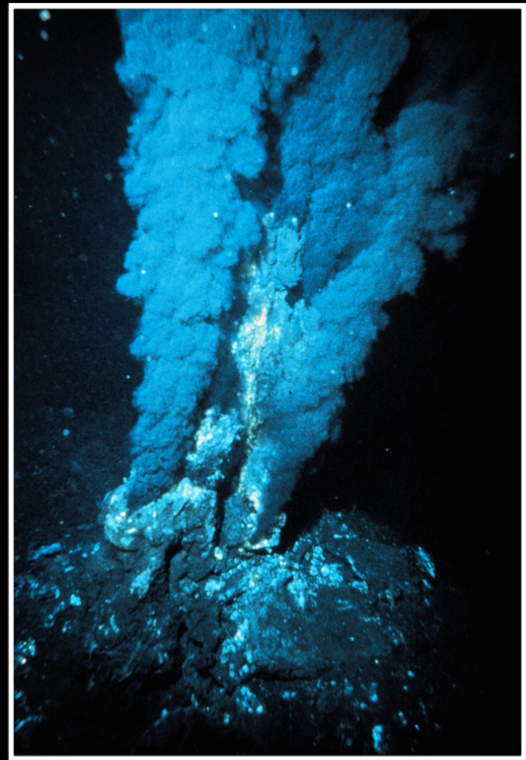
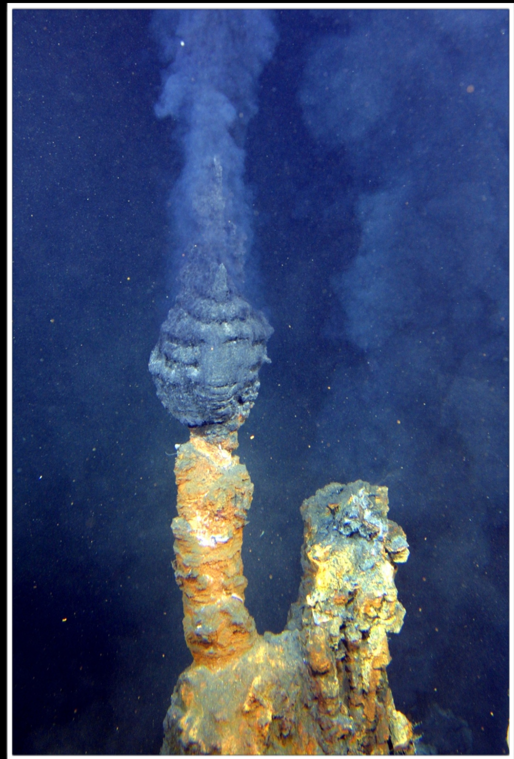


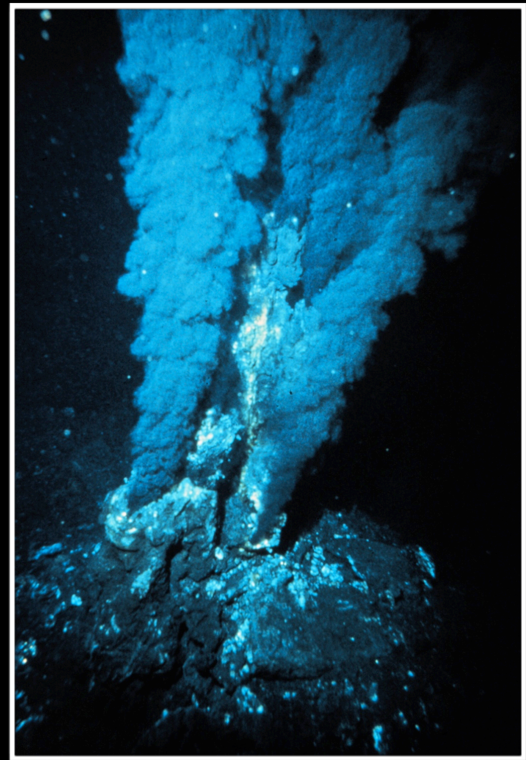


In 1977, “black smokers” have been found at the seafloor of the Pacific Ocean on Earth.

Evidence of Tidal Heating in the Solar System

Europa orbiting Jupiter

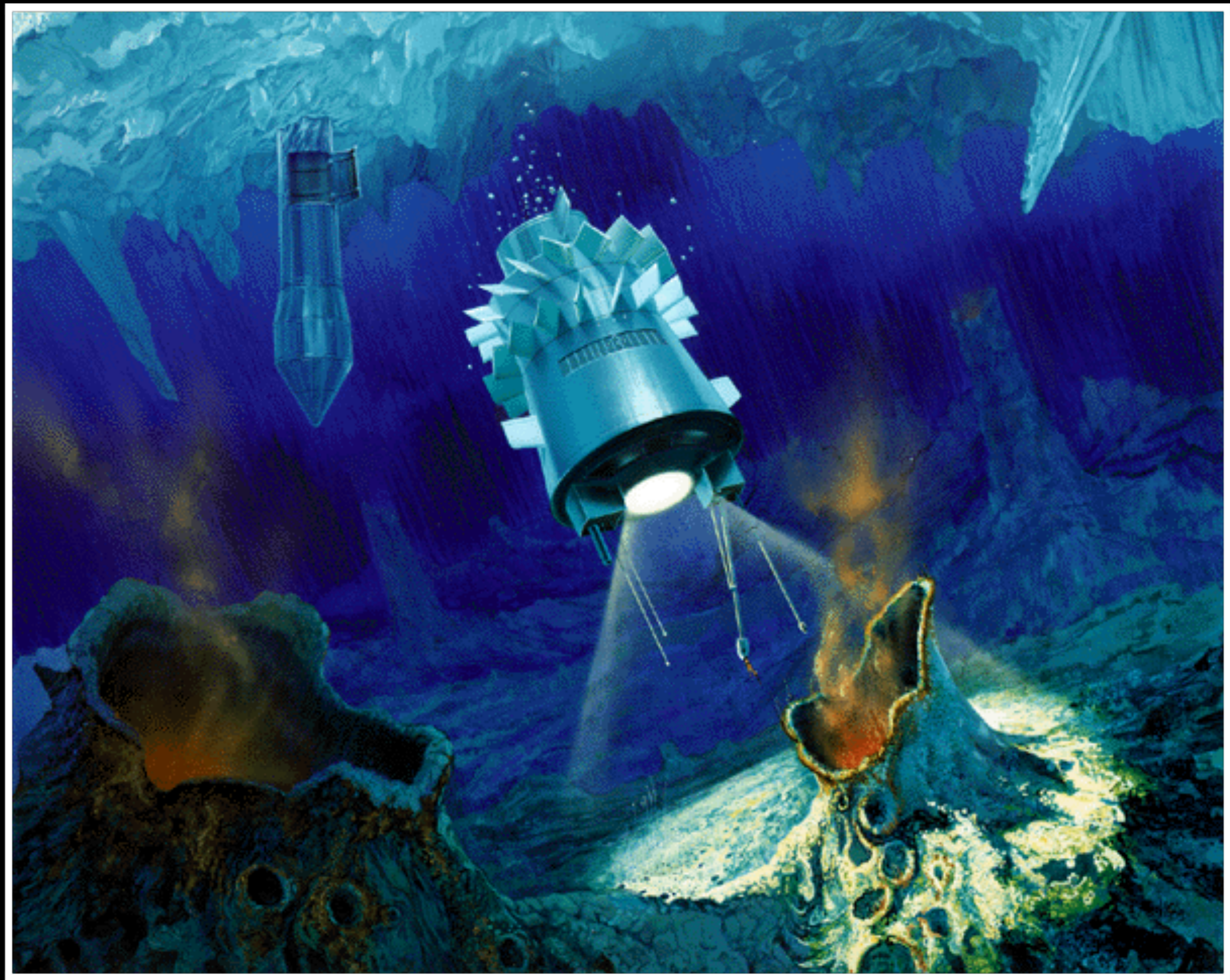




Uncoupled from the Sun as an energy source, a whole ecosystem exists in a depth of 3 km.

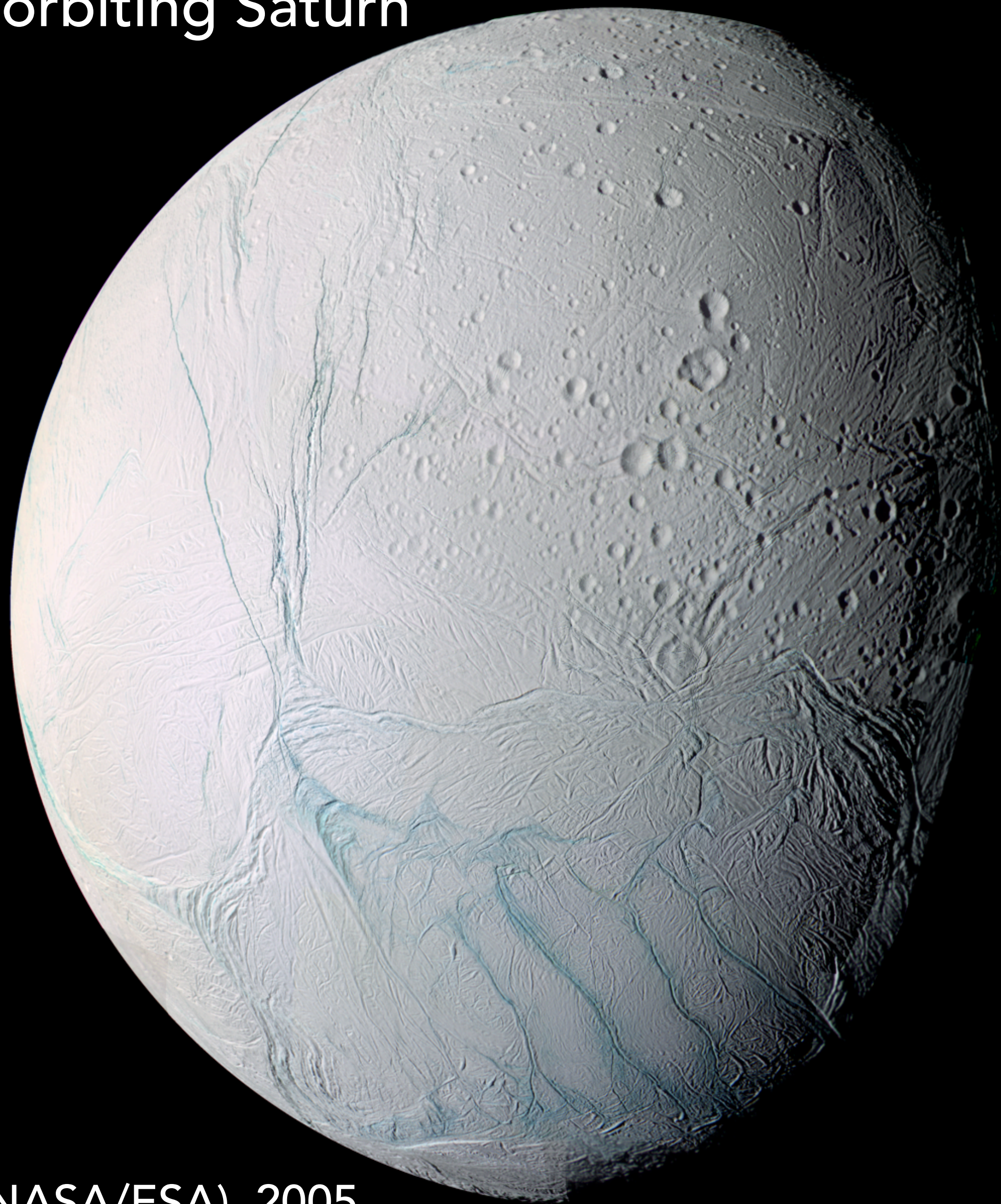
Evidence of Tidal Heating in the Solar System

Europa orbiting Jupiter



Evidence of Tidal Heating in the Solar System

Enceladus orbiting Saturn



Cassini-Huygens (NASA/ESA), 2005

Evidence of Tidal Heating in the Solar System

Enceladus orbiting Saturn

Evidence of Tidal Heating in the Solar System

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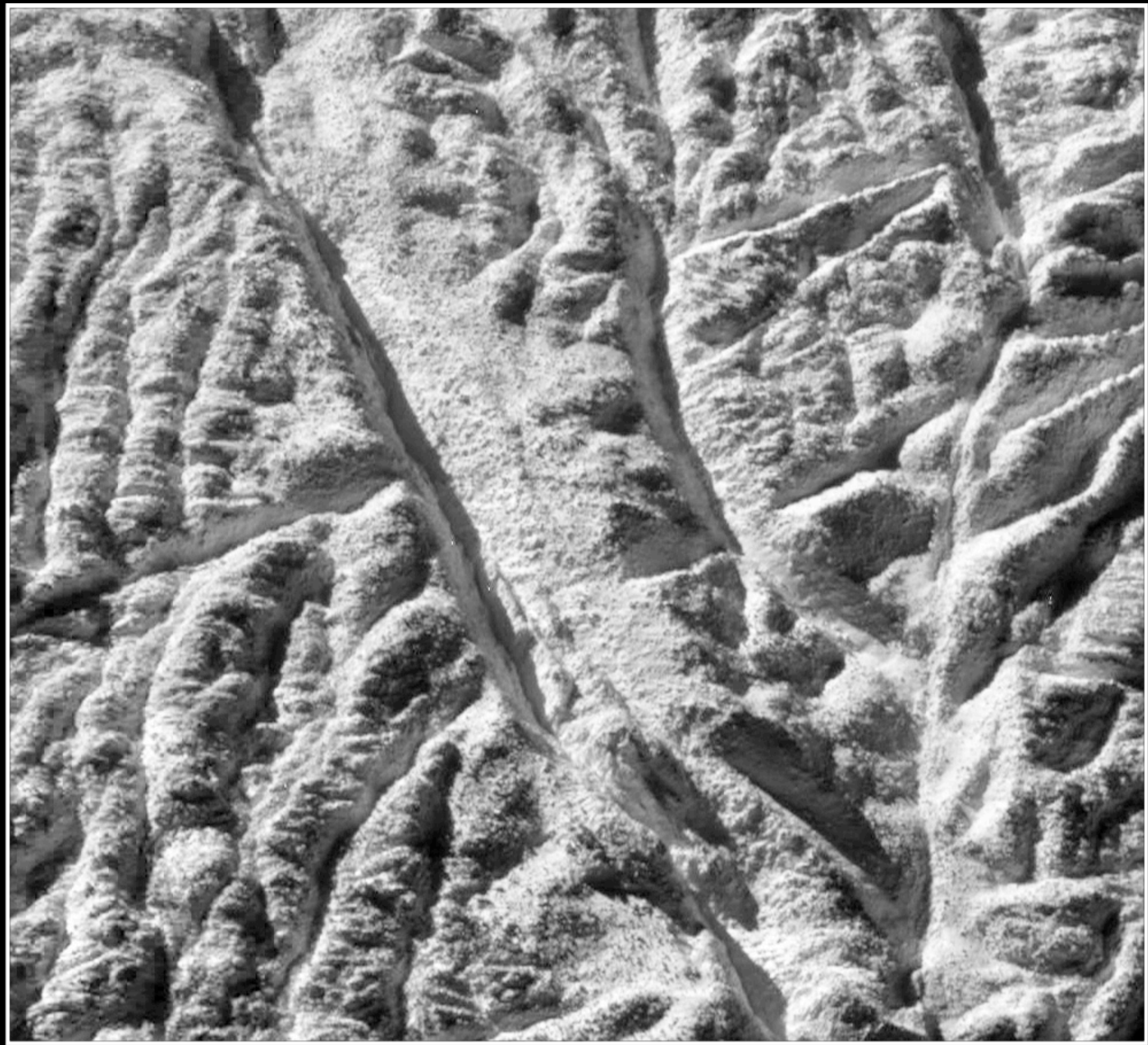
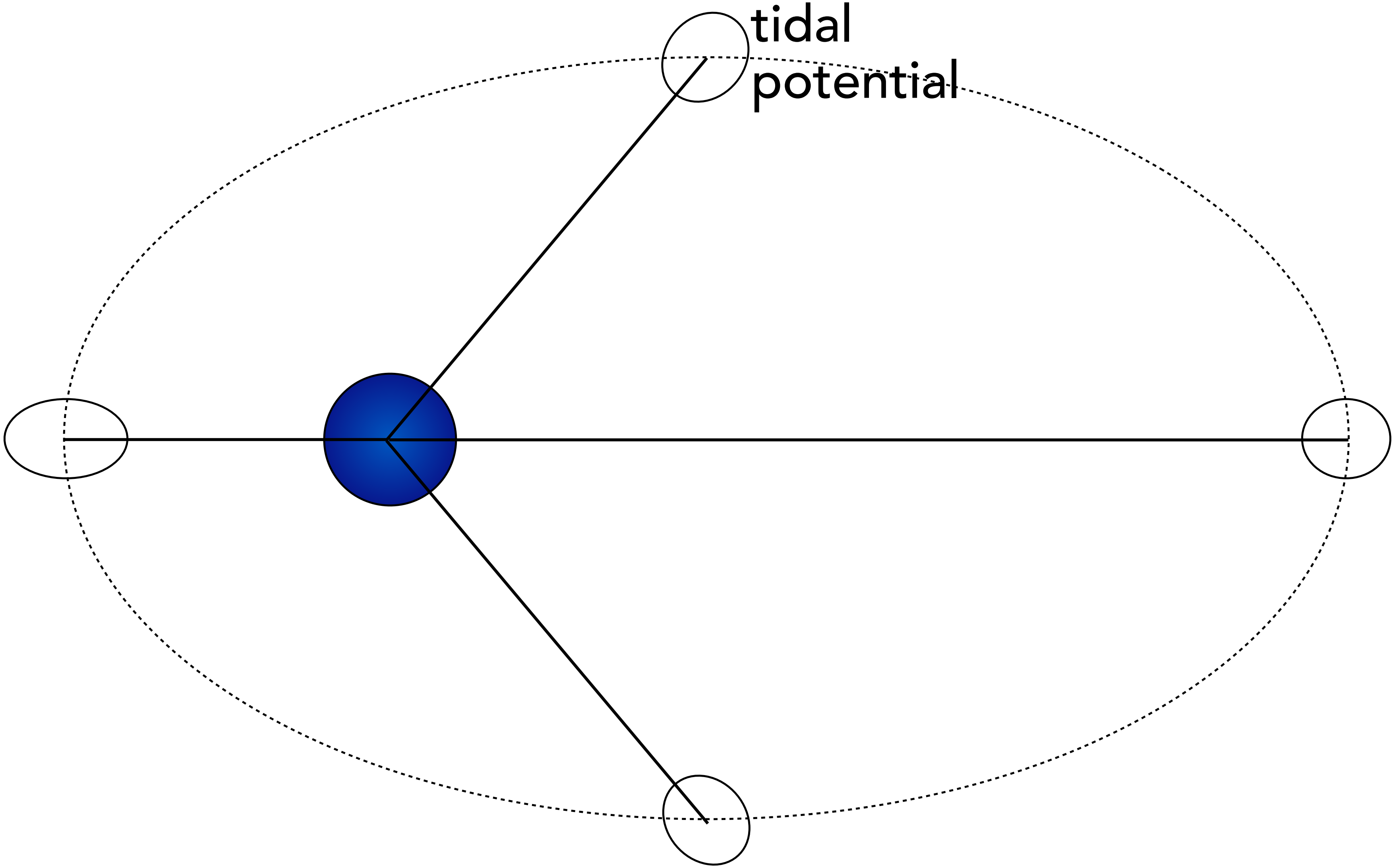


12 km

Cassini-Huygens (NASA/ESA), 2009

So where does the heating come from?

Tidal Heating in Eccentric Orbits



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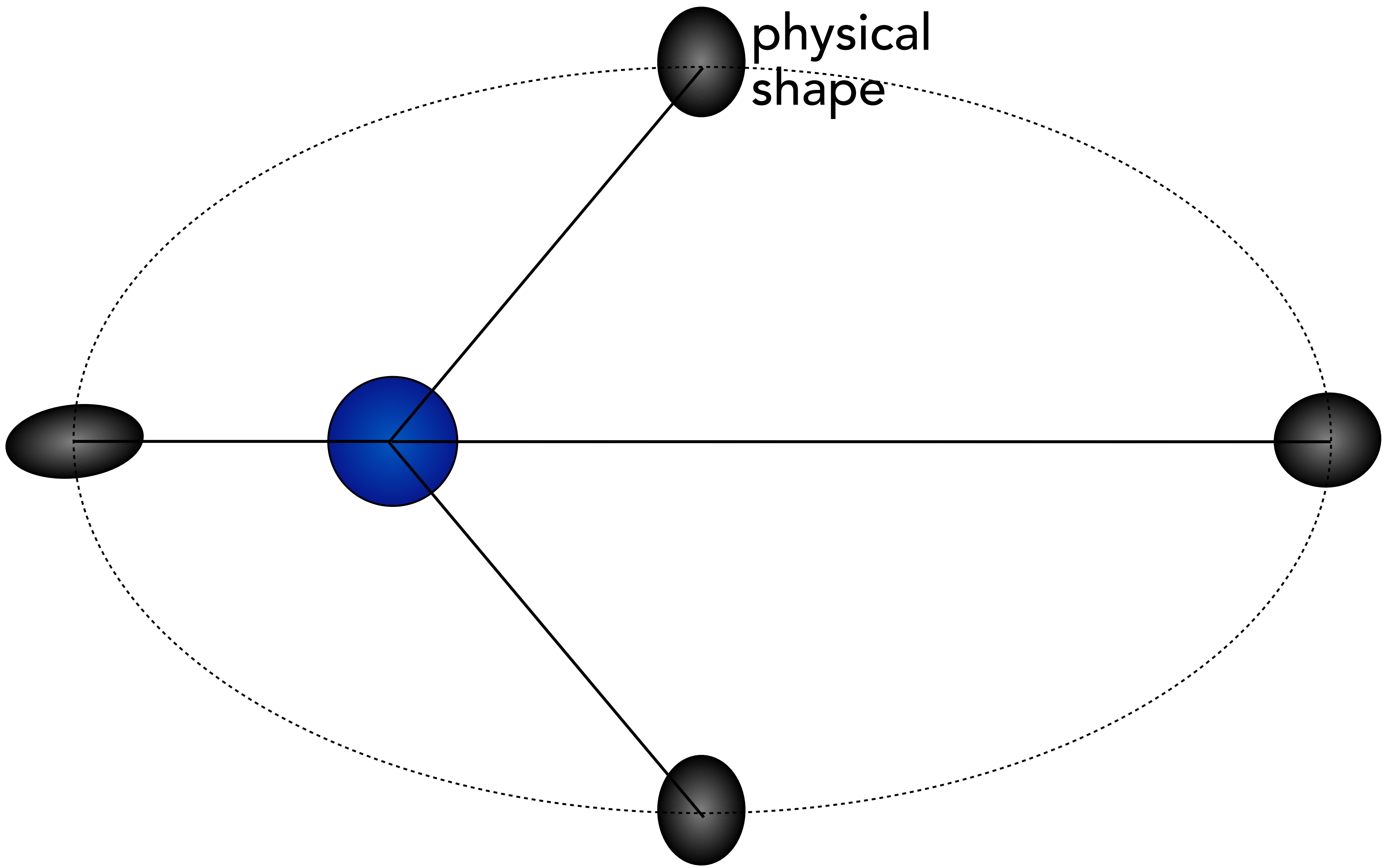
So where does the heating come from?

Tidal Heating in Eccentric Orbits



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So where does the heating come from?

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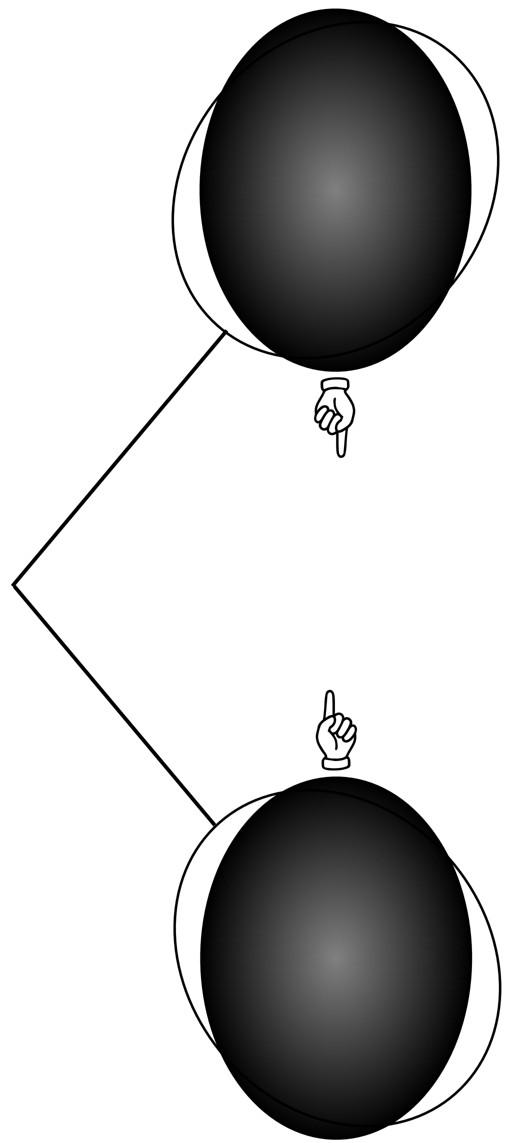

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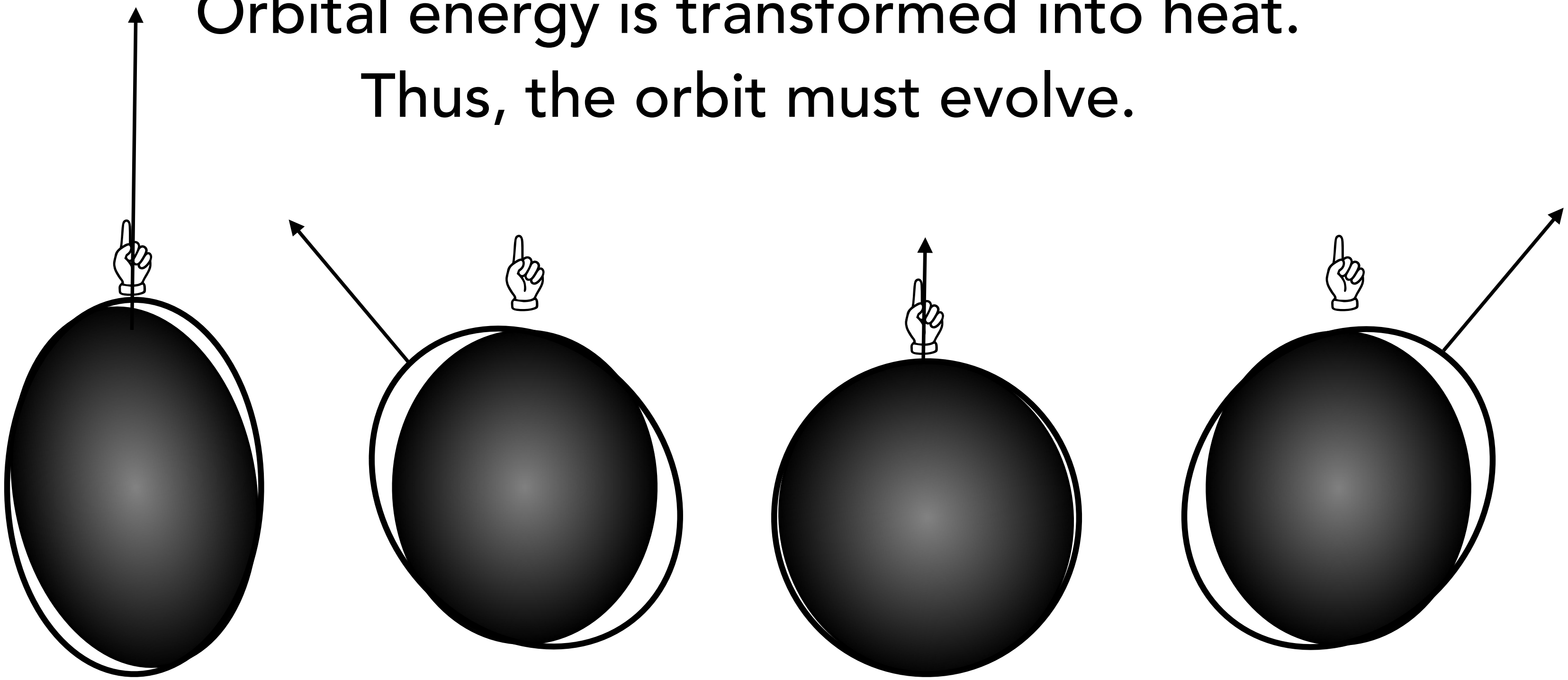
So where does the heating come from?

Tidal Heating in Eccentric Orbits

force ☝ standpoint

The moon is constantly being flexed.
Friction generates tidal heating.
Orbital energy is transformed into heat.
Thus, the orbit must evolve.



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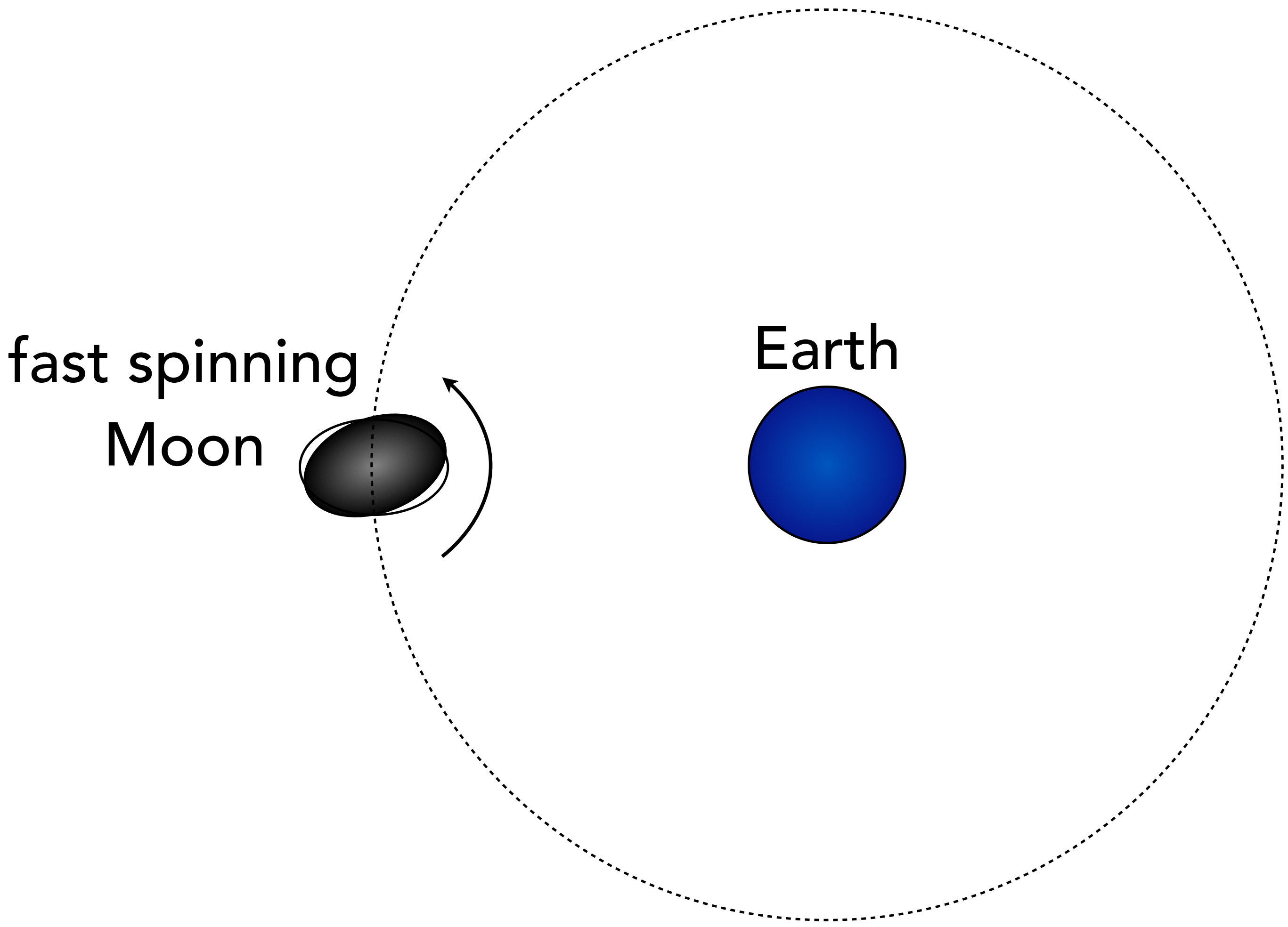
Orbital Evolution due to Tides

1. Rotational synchronization ("tidal locking"): $P_{\rm rot} = P_{\rm orb}$



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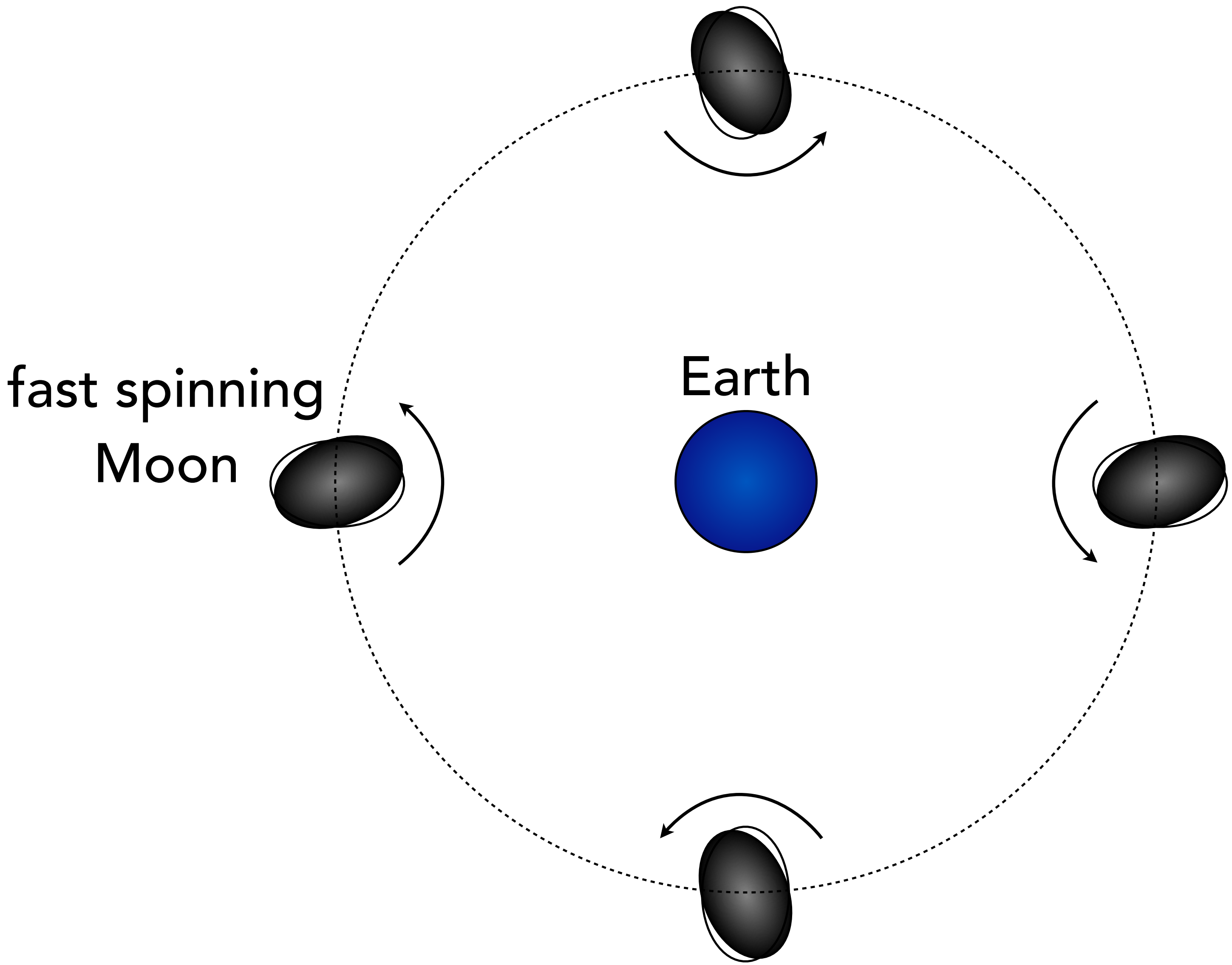

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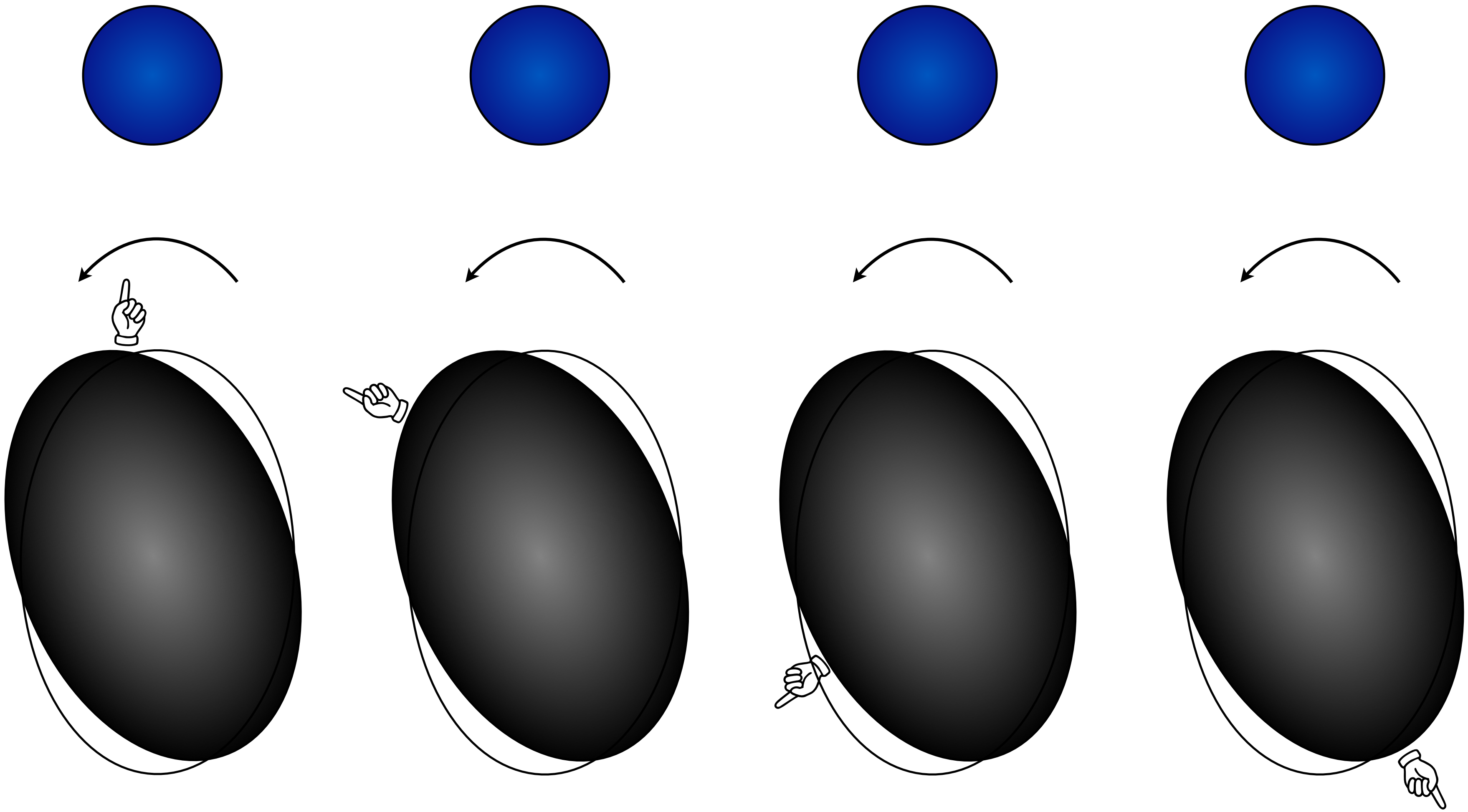

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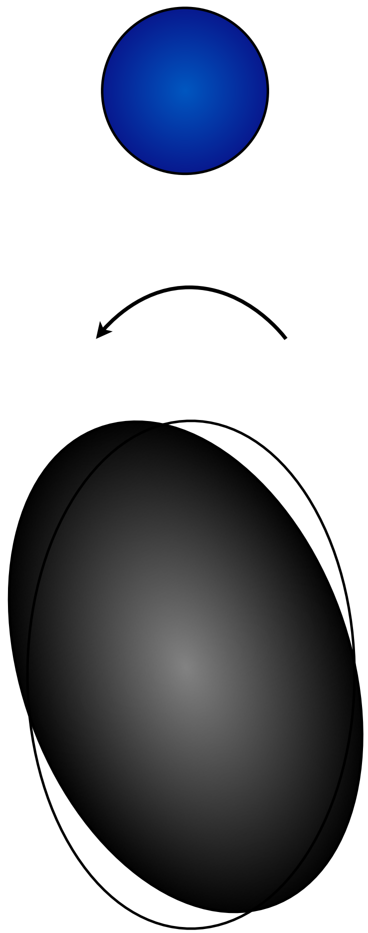
Orbital Evolution due to Tides

1. Rotational synchronization (“tidal locking”): $P_{rot} = P_{orb}$

The tidal potential acts to align the tidal bulge with the line connecting the Earth and the Moon.



The Moon’s rotation is being slowed down until its rotation is synchronous.

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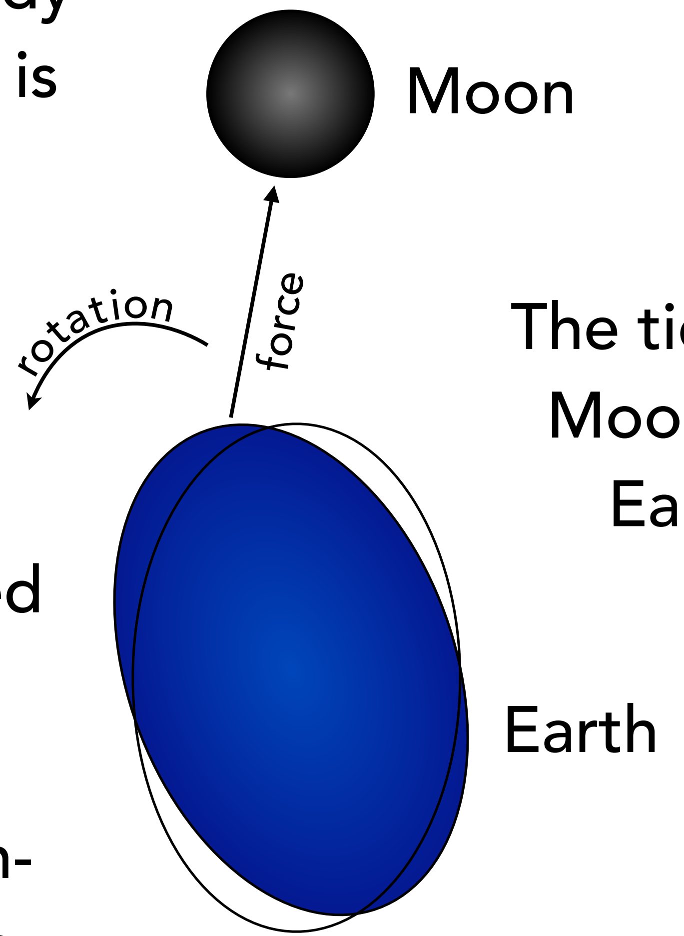
Tidal Locking of the Moon

Apollo 8 (NASA), Christmas Eve 1968

Orbital Evolution due to Tides

1. Rotational synchronization (“tidal locking”): $P_{rot} = P_{orb}$

While the Moon is already synchronous, the Earth is still spinning down.



The tidal torque of the Moon is slowing the Earth’s rotation.

While energy is dissipated as tidal heat, the total angular momentum is conserved. => The Earth-Moon distance increases.

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Orbital Evolution due to Tides

1. Rotational synchronization (“tidal locking”): $P_{\mathrm{rot}} = P_{\mathrm{orb}}$

2. Orbital circularization: $e = 0$

3. Spin-orbit alignment: $\psi = 0$

4. For $P_{\mathrm{rot}} < P_{\mathrm{orb}}$, the distance **in**creases (Earth-Moon system).
For $P_{\mathrm{rot}} > P_{\mathrm{orb}}$, the distance **de**creases (Phobos around Mars).

René Heller

Orbital Evolution due to Tides

of the Moon, while the semimajor axis of the lunar orbit exhibits a secular growth [*Lambeck*, 1980; *Burns*, 1986]

$$\frac{da}{dt} = f\, a^{-11/2} \qquad (1)$$

where

$$f = 3\frac{k}{Q}\frac{m}{M}R^5\mu^{1/2} \qquad (2)$$

is a function of the Moon's mass (m), the Earth's mass (M) and radius (R), an effective Earth+ocean tidal Love number (k) and dissipational quality factor (Q), as well as the combined gravitational mass of the Earth-Moon system

$$\mu = G(M+m)\,. \qquad (3)$$

If the factor f were a constant (but see below), then the orbital evolution proceeds in such a way that

$$A(t+\Delta t) = A(t) + \frac{13}{2}\, f\, \Delta t \qquad (4)$$

where

$$A = a^{13/2}. \qquad (5)$$

That is, the orbit evolves in such a way that the 13/2 power of the orbital size grows linearly in time. Note that this particular tidal evolution model implies a finite age for the lunar orbit. That is, at an earlier epoch

$$\Delta t_0 = -\left(\frac{2}{13}\right)\frac{a^{13/2}}{f} \qquad (6)$$

the predicted orbital radius collapses to zero.

The present size and rate of change of the lunar orbit are well constrained from laser range measurements to corner-cubes on the lunar surface, a time series now 30 years long [*Dickey et al.*, 1994]. The results are

$$a = 3.84402 \times 10^8 \text{ m} \qquad (7)$$

$$\frac{da}{dt} = (3.82 \pm 0.07) \times 10^{-2} \text{ m yr}^{-1} \qquad (8)$$

The rate (8) is consistent with other space-geodetic measurements—satellite altimetry and satellite perturbation analyses [*Ray*, 1994]—and with occultation measurements [*Morrison and Ward*, 1975]. The orbital evolution scaling parameter f thus has a current value of

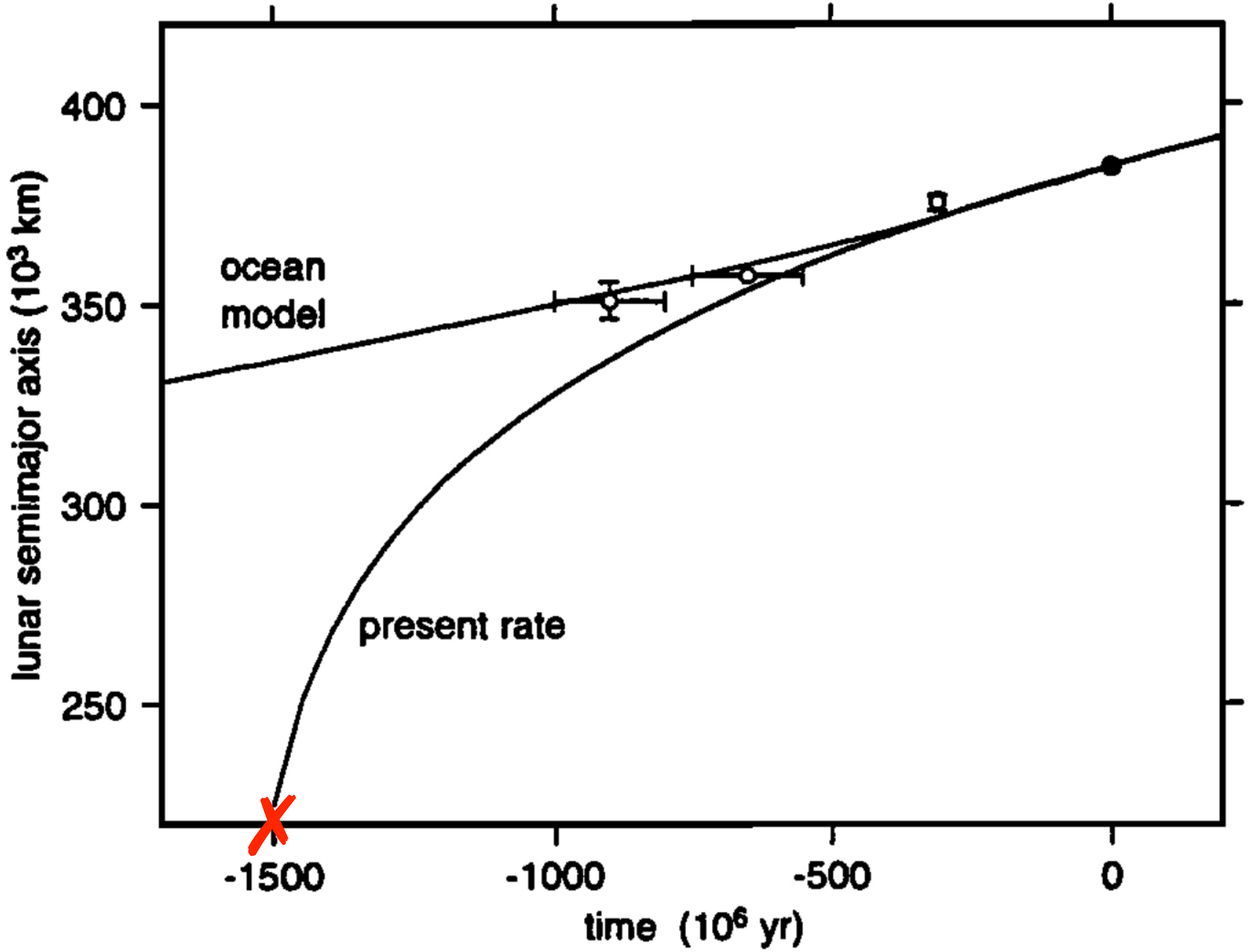
$$f = a^{11/2}\frac{da}{dt} \qquad (9)$$

$$= (6.29 \pm 0.12) \times 10^{45} \text{ m}^{13/2} \text{ yr}^{-1}$$

We can use analytical mathematical models and numerical simulations to compute the past orbital evolution of the Earth-Moon system.

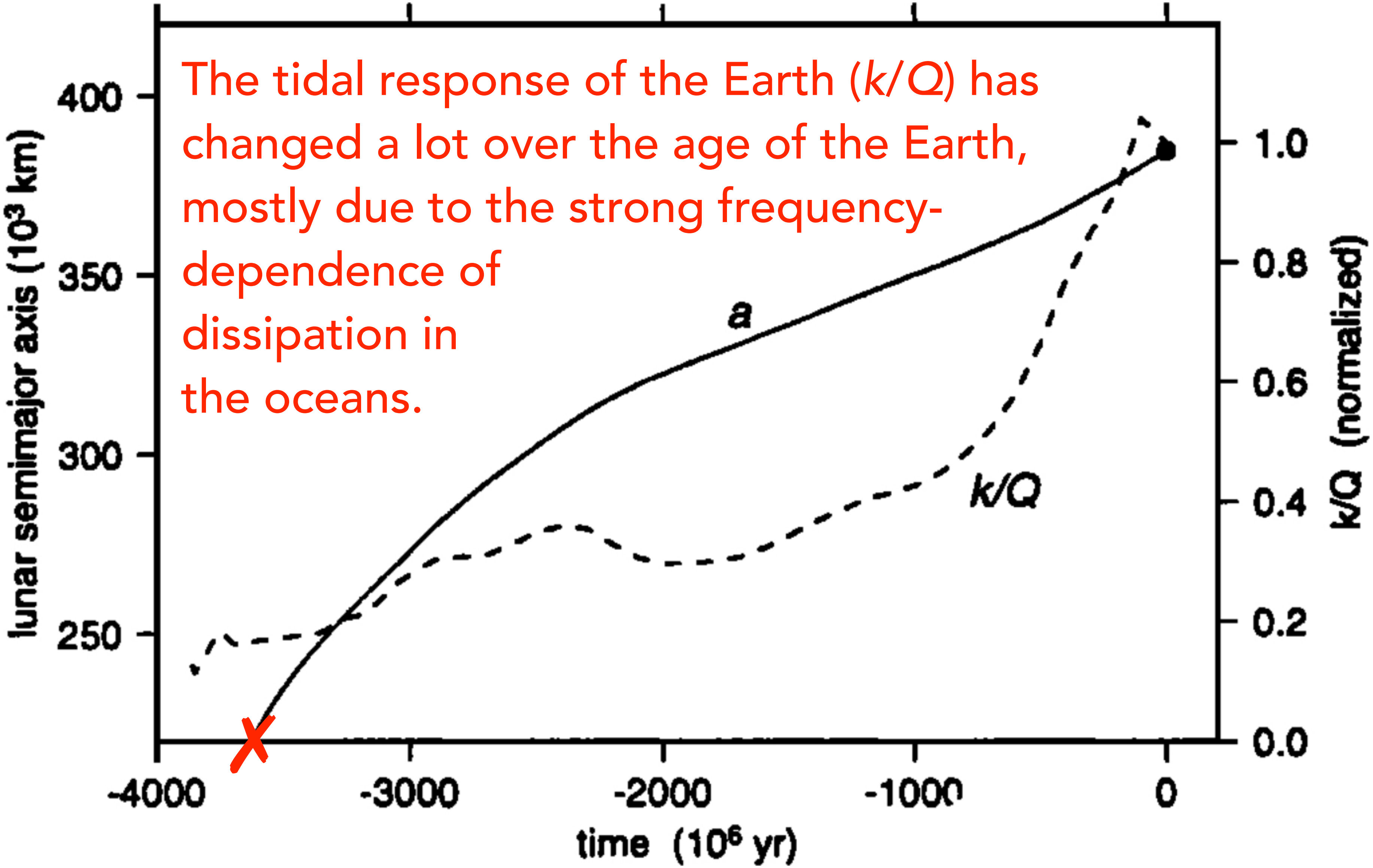
Bills & Ray (1999)

Orbital Evolution due to Tides



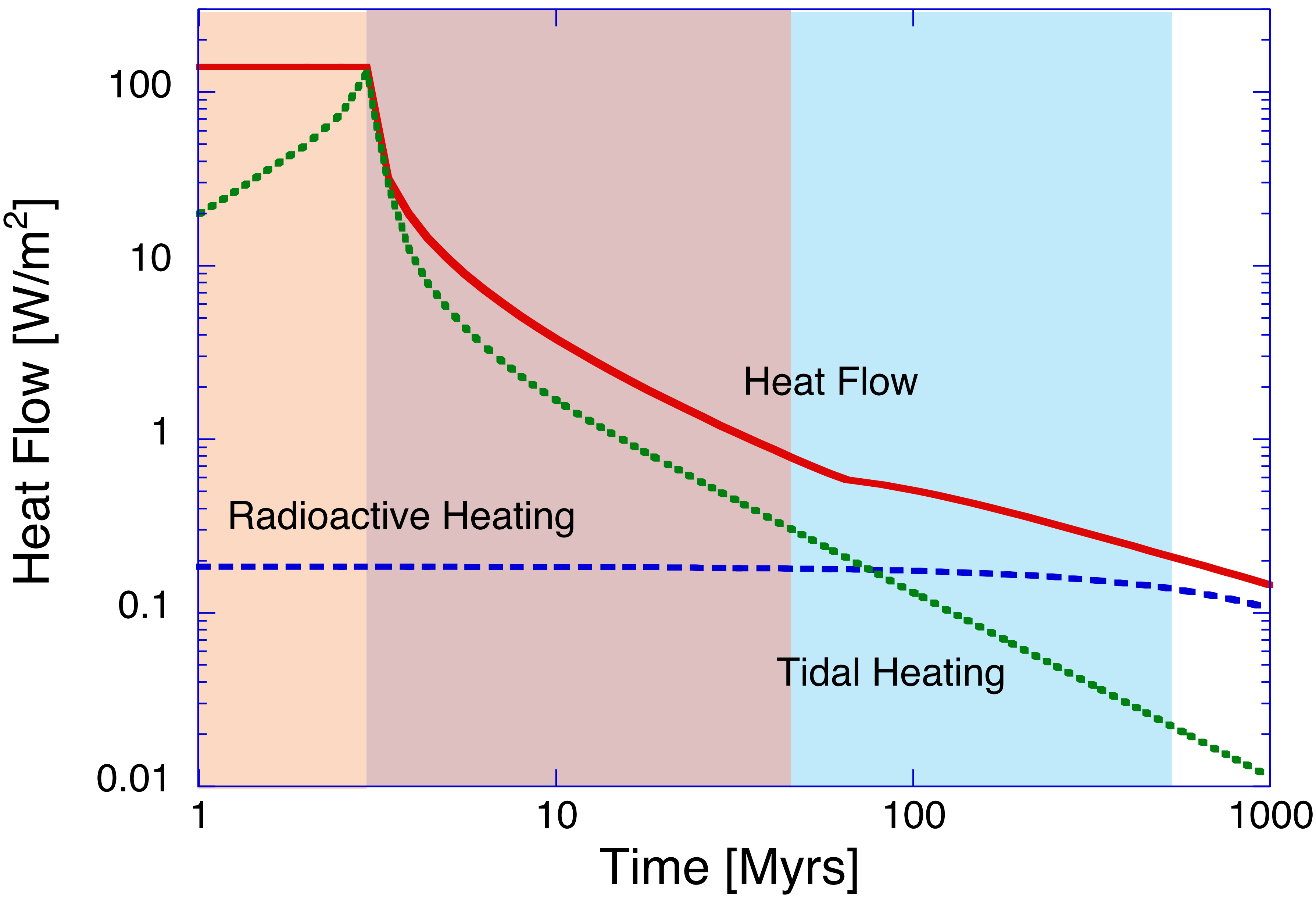
Bills & Ray (1999)

Orbital Evolution due to Tides



Bills & Ray (1999)

Heating from the Inside



Zahnle et al. (2007)

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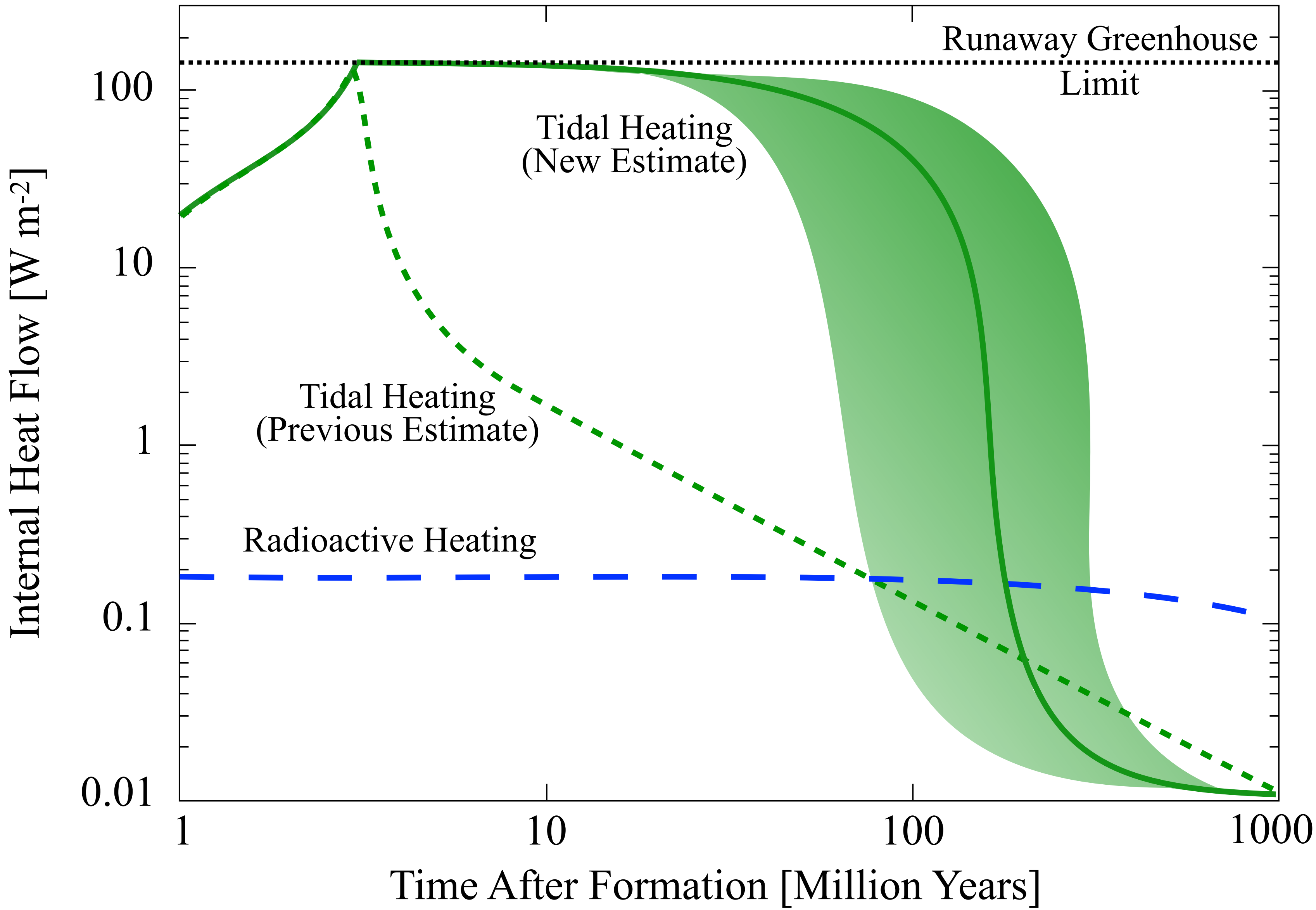
Heating from the Inside

The Faint-Young-Sun Paradox



Heller et al. (in prep.)

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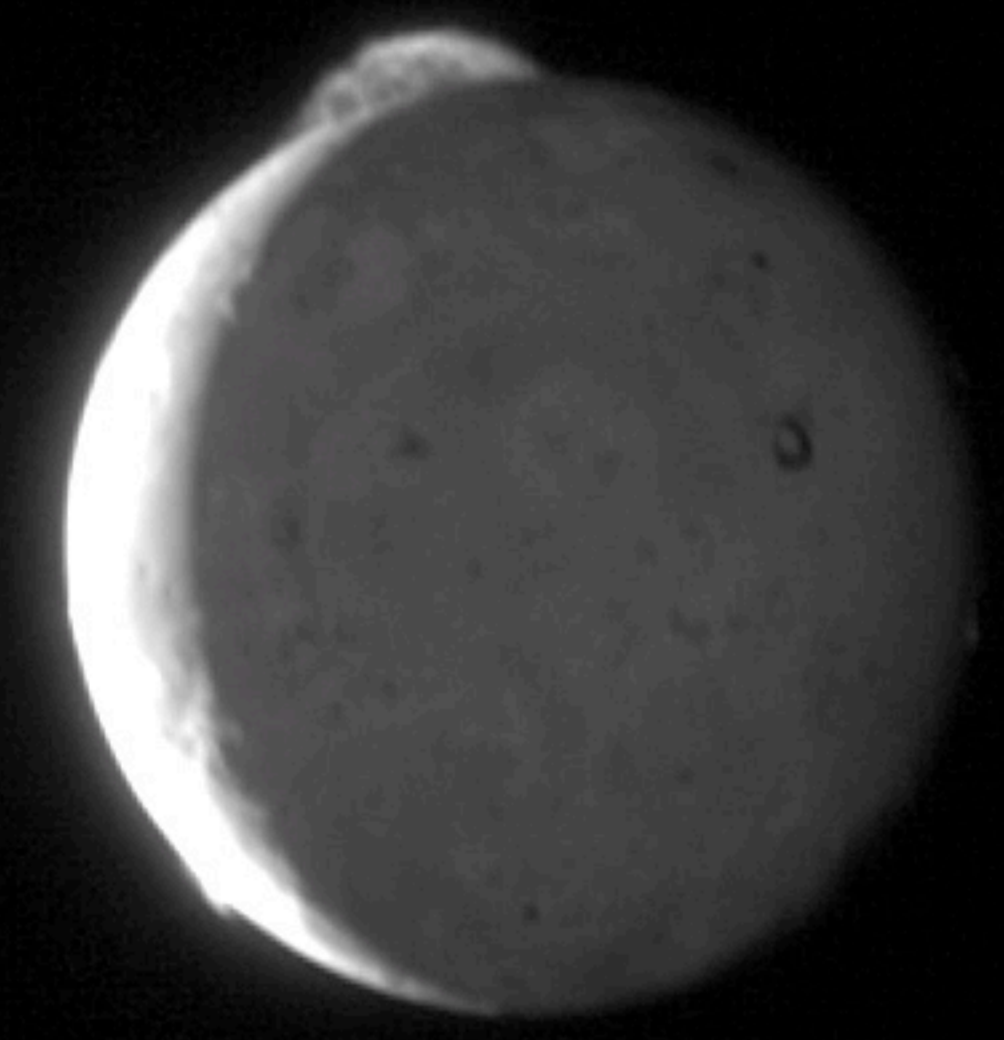
The Perils and Merits of Living with Tidal Heating



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