GEOS 22060/ GEOS 32060 / ASTR 45900

What makes a planet habitable?

Ice-covered oceans

Lecture 17 (make-up lecture)

Friday 28 February 2019

Ice-covered oceans

Persistent global ice cover:

DATA

PHYSICAL BASIS FOR LONG-TERM OCEAN STABILITY

ENERGETIC CONSTRAINTS ON BIOSPHERES

FUTURE TESTS AND TECHNIQUES

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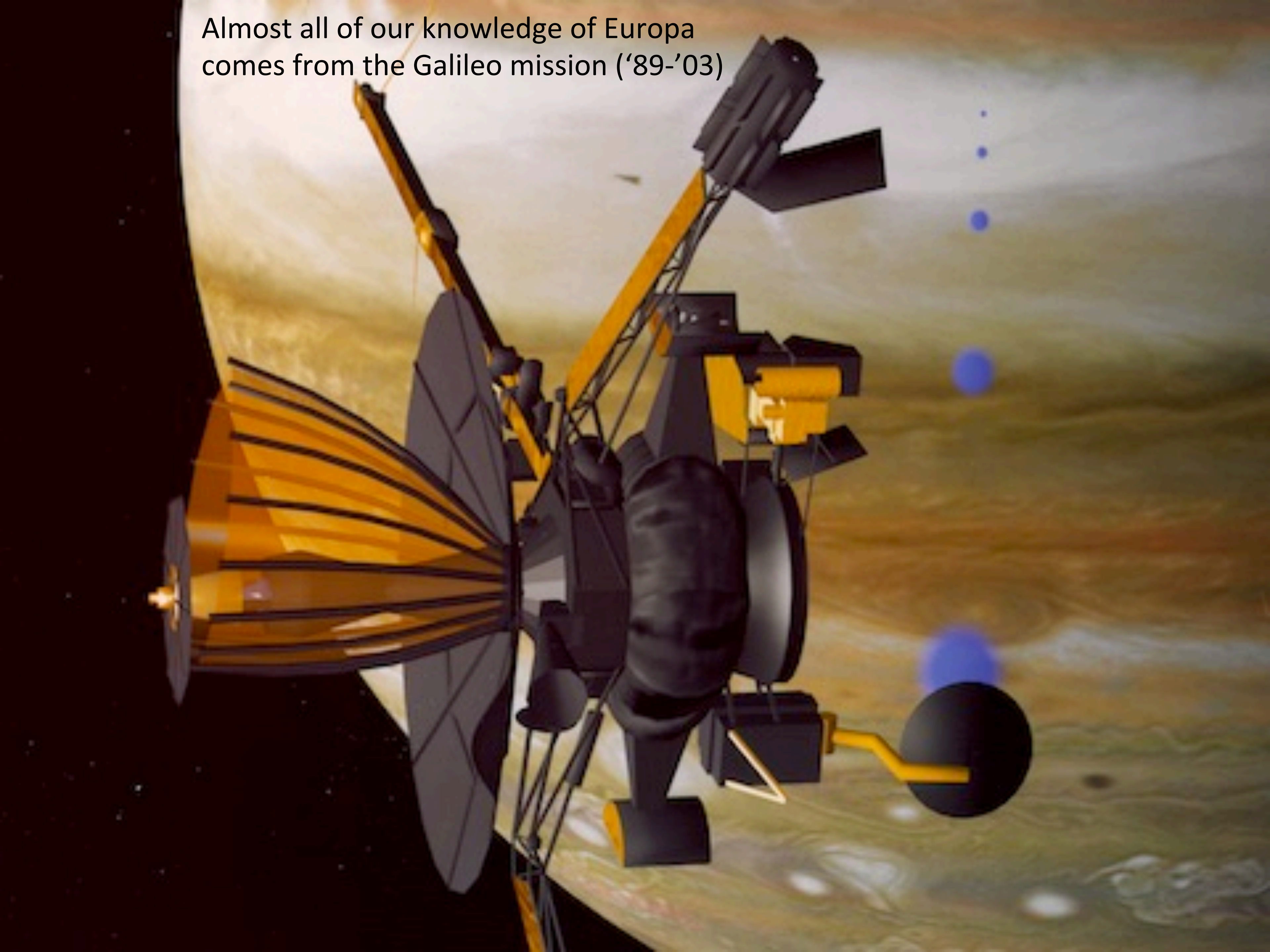
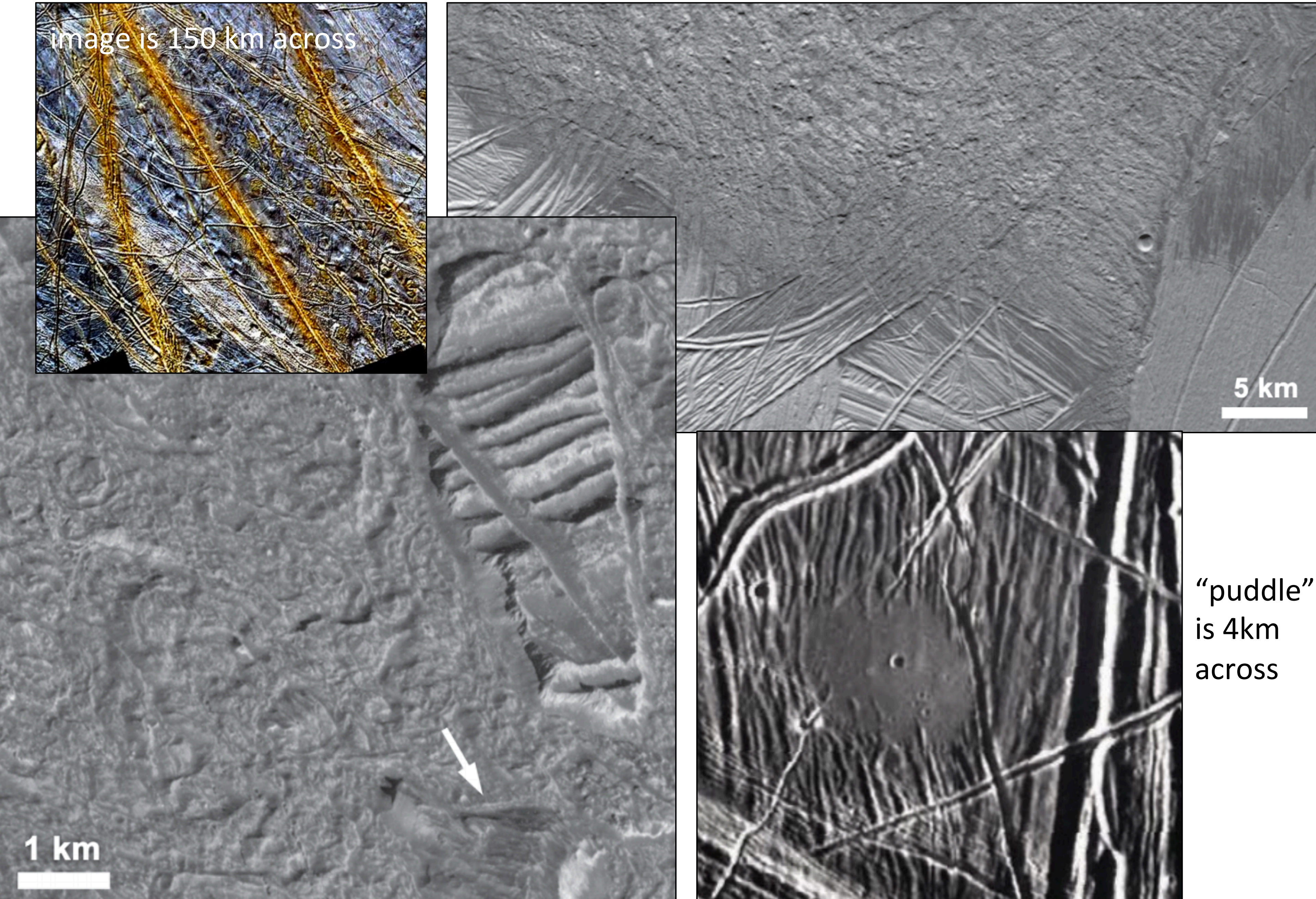
Almost all of our knowledge of Europa comes from the Galileo mission (‘89-’03)

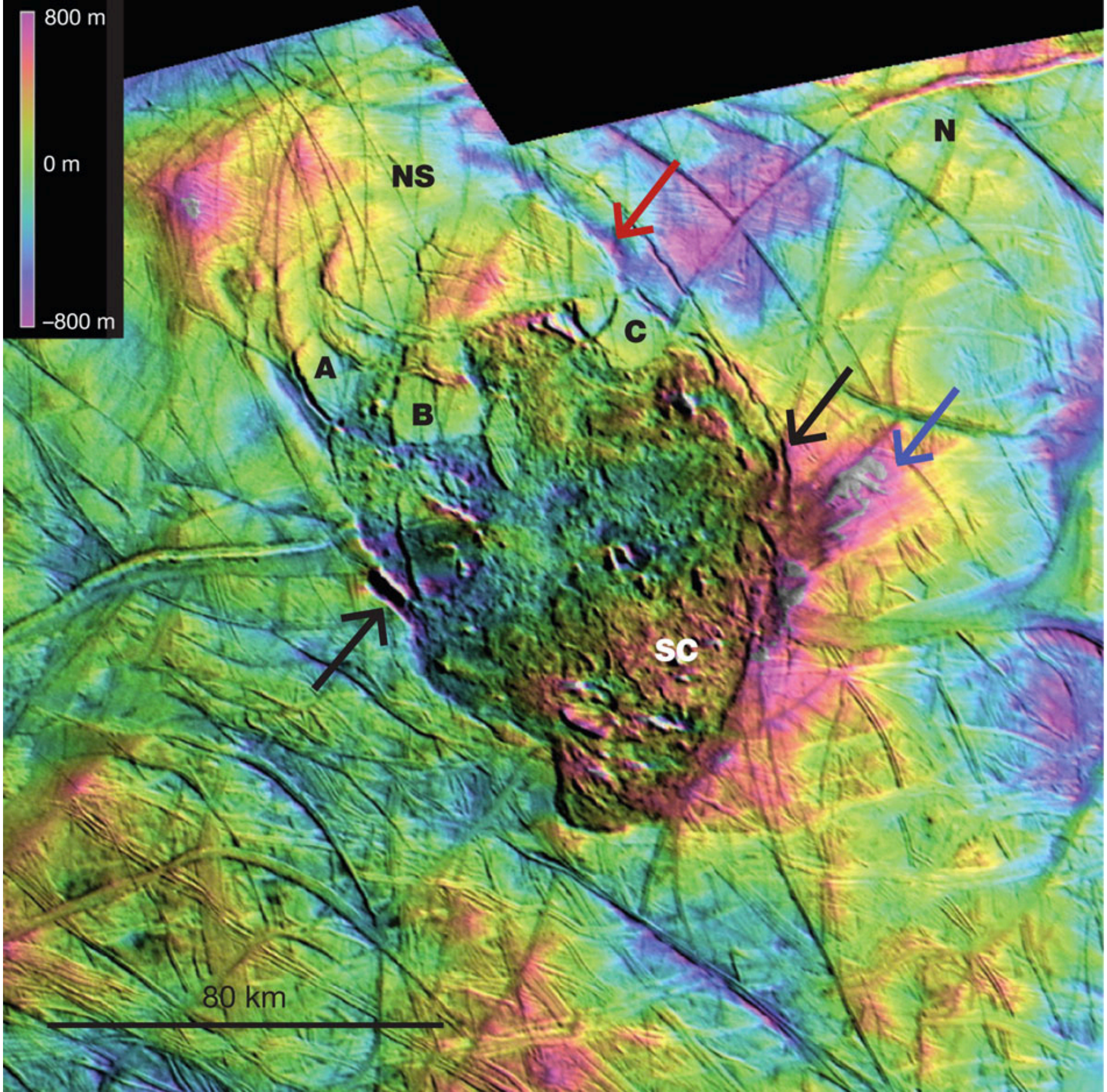


Multiple lines of geologic evidence for liquid water at or near the water-ice surface of the moon

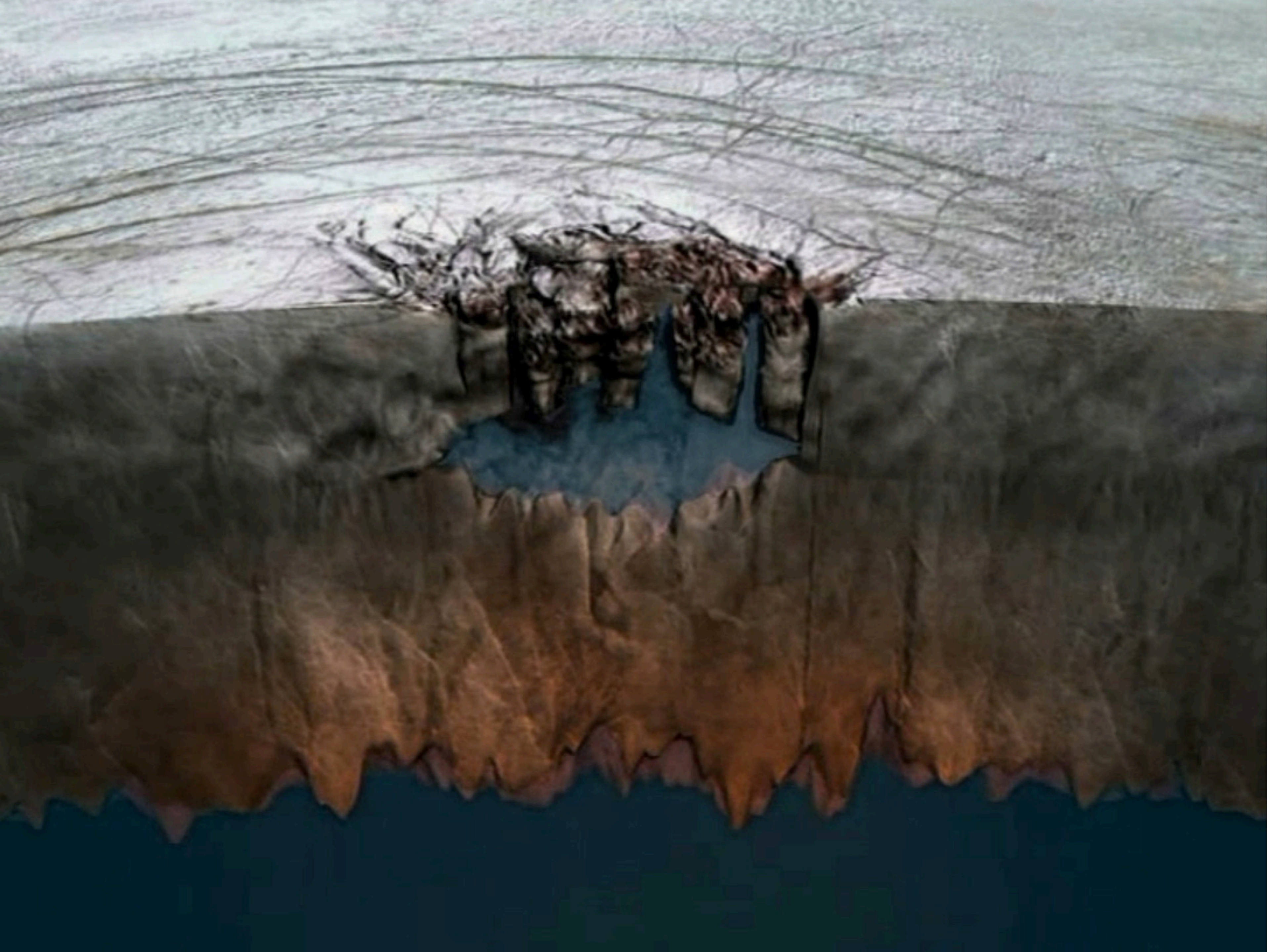


“puddle” is 4km across

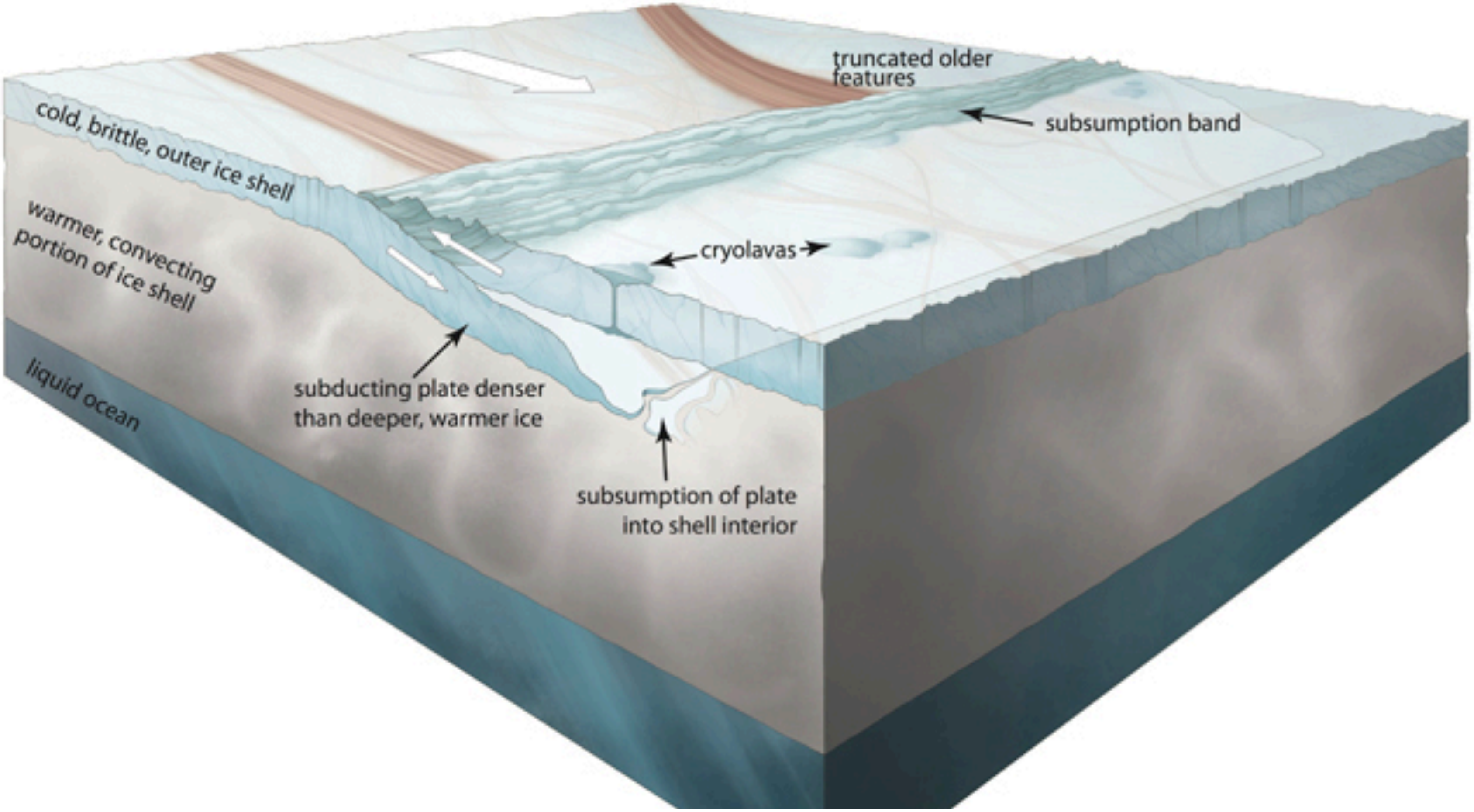
Thera Macula



Schmidt et al. Nature 2011

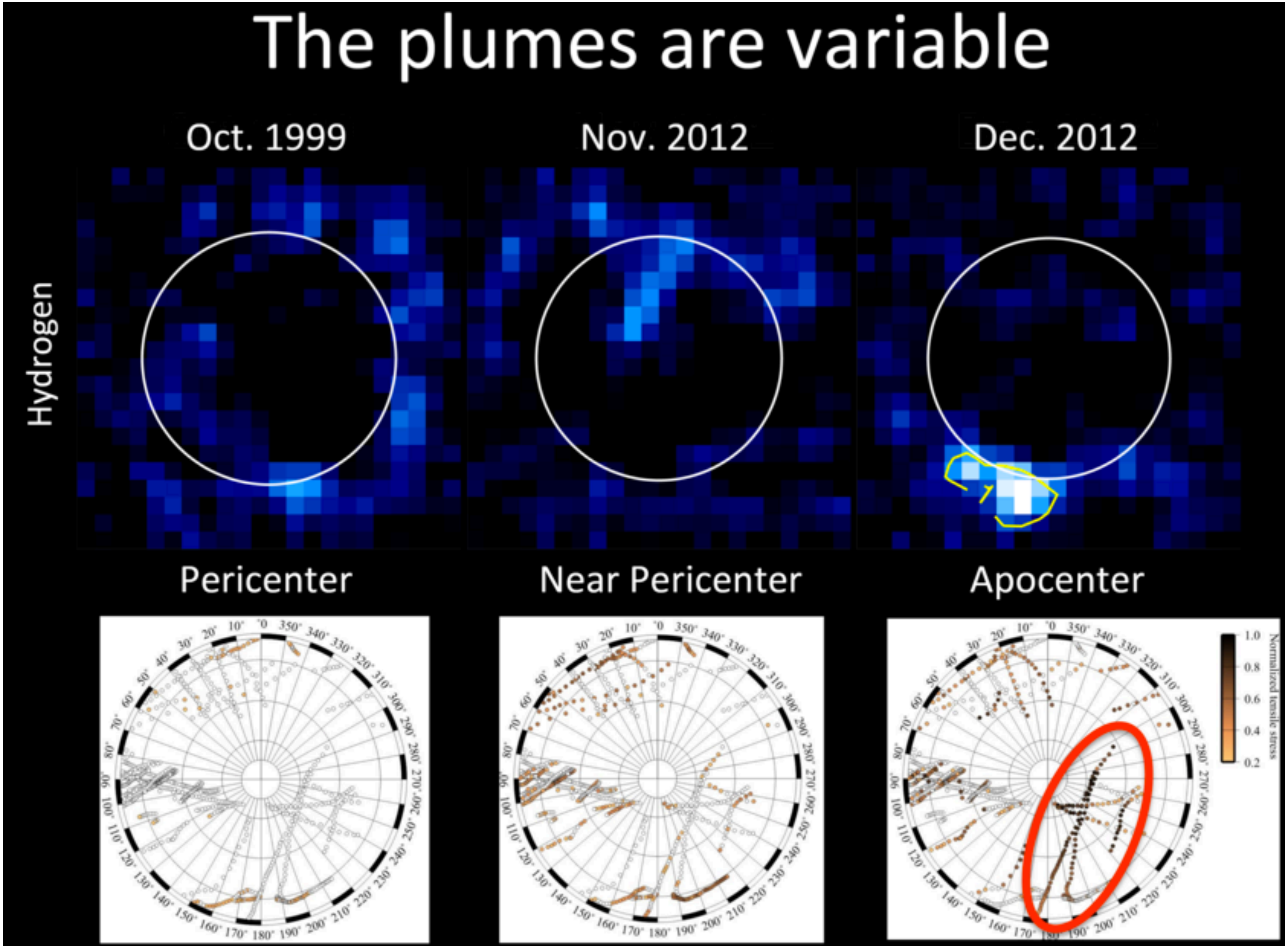


Controversial claims of plate tectonics on Enceladus



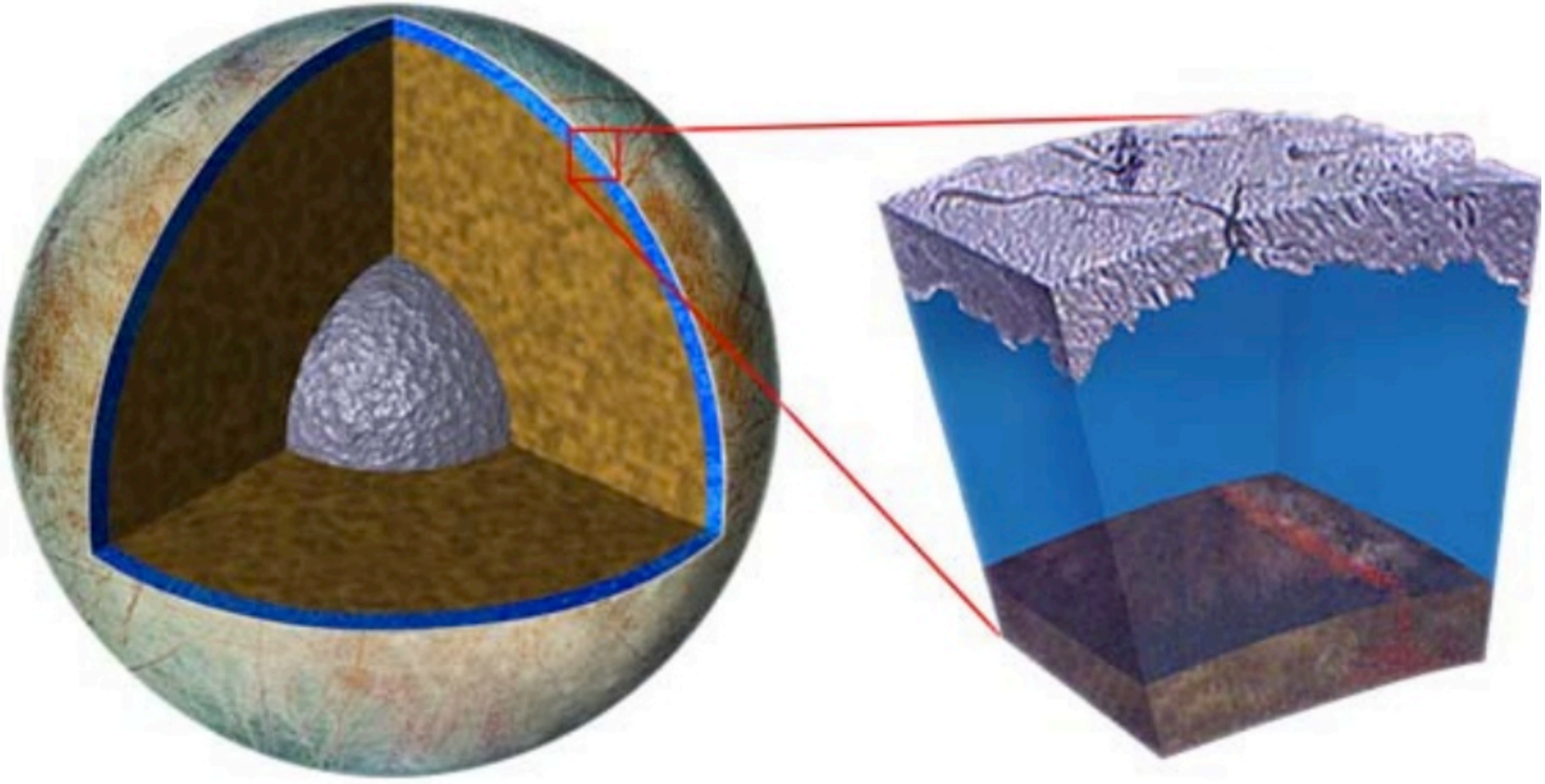
Kattenhorn et al. Nature 2014

Candidate cryovolcanic (water vapor) plumes detected by HST



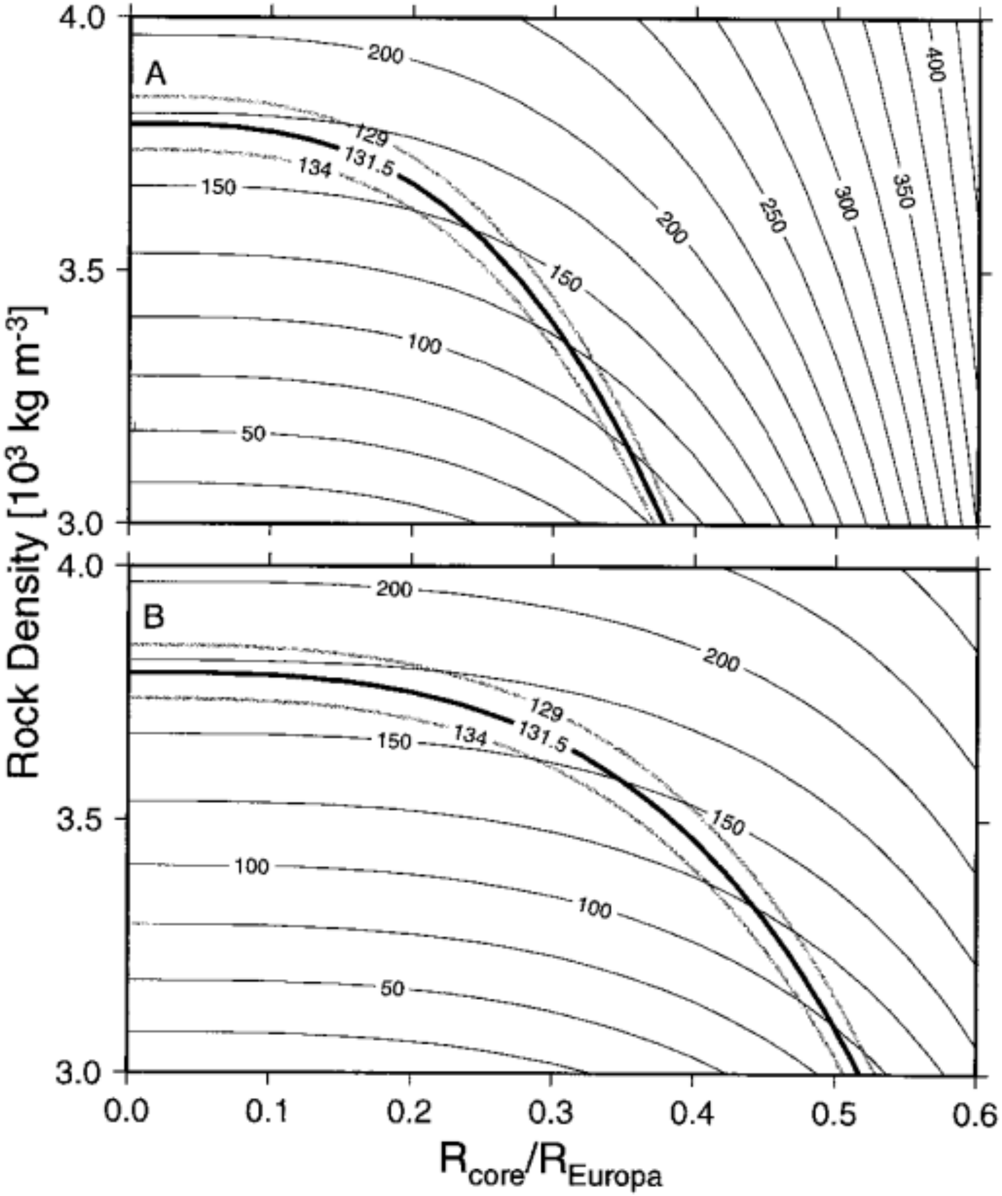
Roth et al. Science 2014

Europa is differentiated in to a H_2O layer, rock mantle, and metal core. The ice above the ocean is at least 1 km thick (best estimate 30 km thick)



Gravity data constrain Europa’s ocean thickness

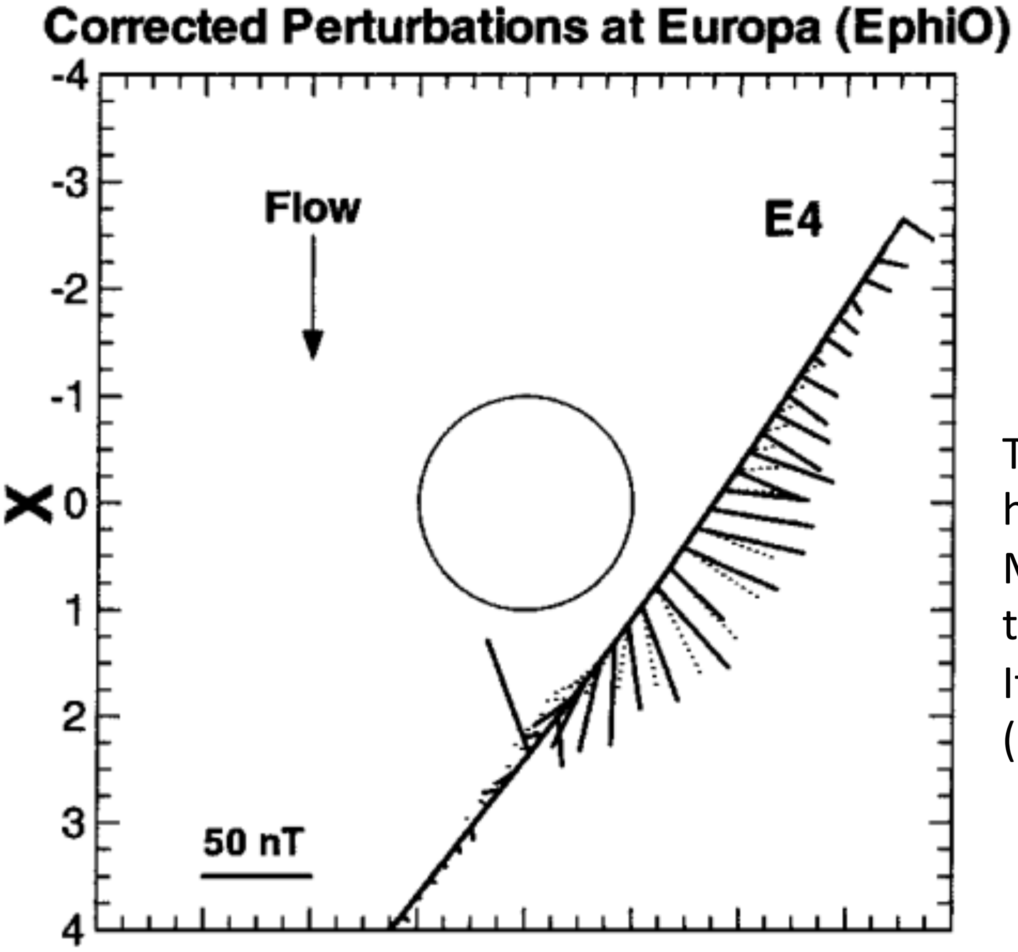
Fig. 2. Details of the intersection of the model surface of Fig. 1 with the horizontal outer shell density = 1050 kg m^{-3} plane. Europa three-layer models having an ice density (outer shell density) of 1050 kg m^{-3} are shown for an Fe core (**A**) and an Fe-FeS core (**B**). The solid curve labeled 131.5 ($\times 10^{-6}$) defines models constrained by Europa’s mean density and the indicated values of C_{22} used in constructing the model surfaces in Fig. 1. The curves designated 129 and 134 ($\times 10^{-6}$) delineate models with the $\pm 1\sigma$ values of C_{22}. The numbers within the curves denote the outer shell thickness (in kilometers).



C_{22} = gravitational anomaly associated with tidal elongation towards and away from Jupiter

Anderson et al. Science 1998

Magnetic data require a conducting fluid inside Europa; most likely a salty ocean.



This technique works because Jupiter
has an inclined magnetic field (10 degrees).
Magnetic field strength varies from 400 nT
to 500 nT every 5 hours.
It does not work at Saturn
(axially aligned magnetic field).

Solid lines: data
Dashed lines: induced-dipole model

Khuruna et al., Astrobiology 2002

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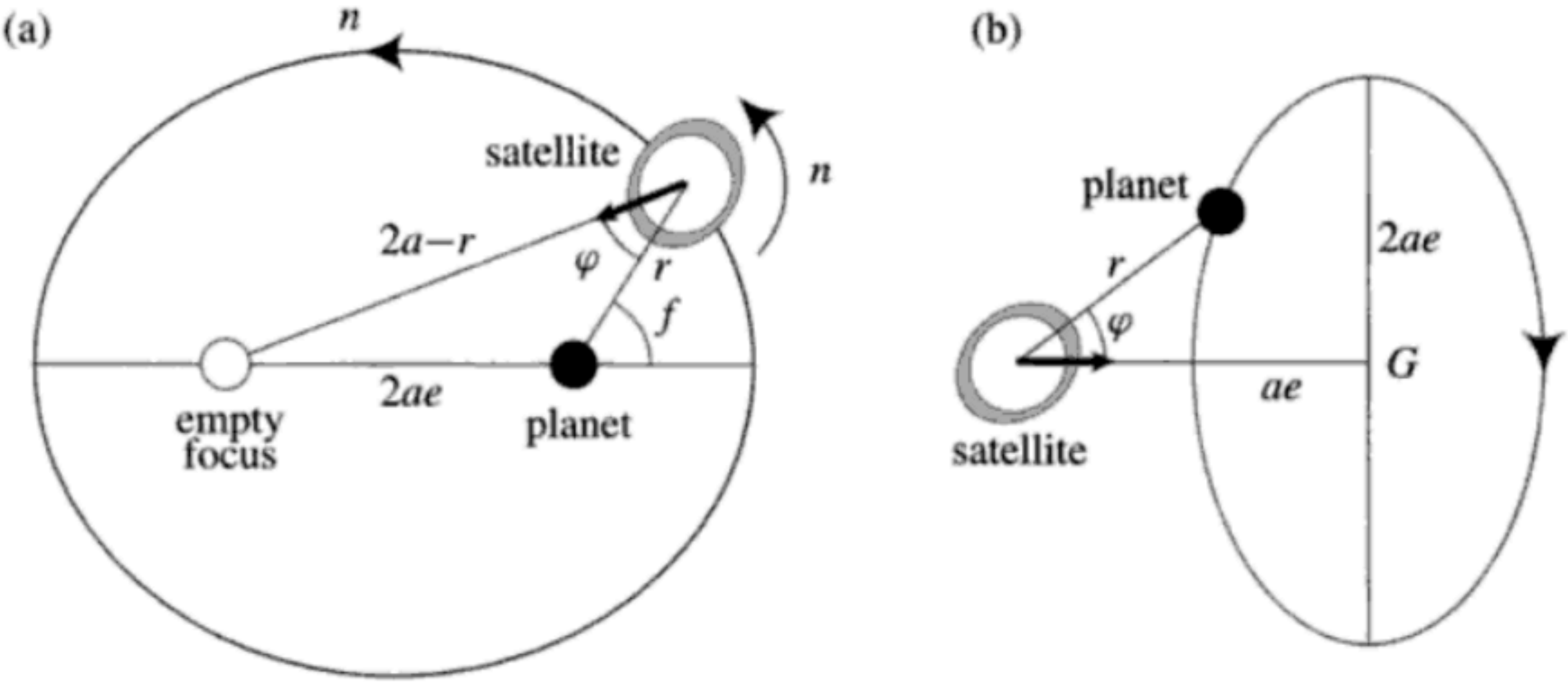


Fig. 4.13. (a) The path of a satellite in an elliptical orbit in the frame centred on the planet. The satellite keeps one face (marked by an arrow) pointed toward the empty focus of its orbit. (b) The path of the planet in a frame centred on and rotating with the satellite. For small values of e the planet moves about its guiding centre, G, on an ellipse with semi-major and semi-minor axes in the ratio 2:1.

Murray & Dermott 1999

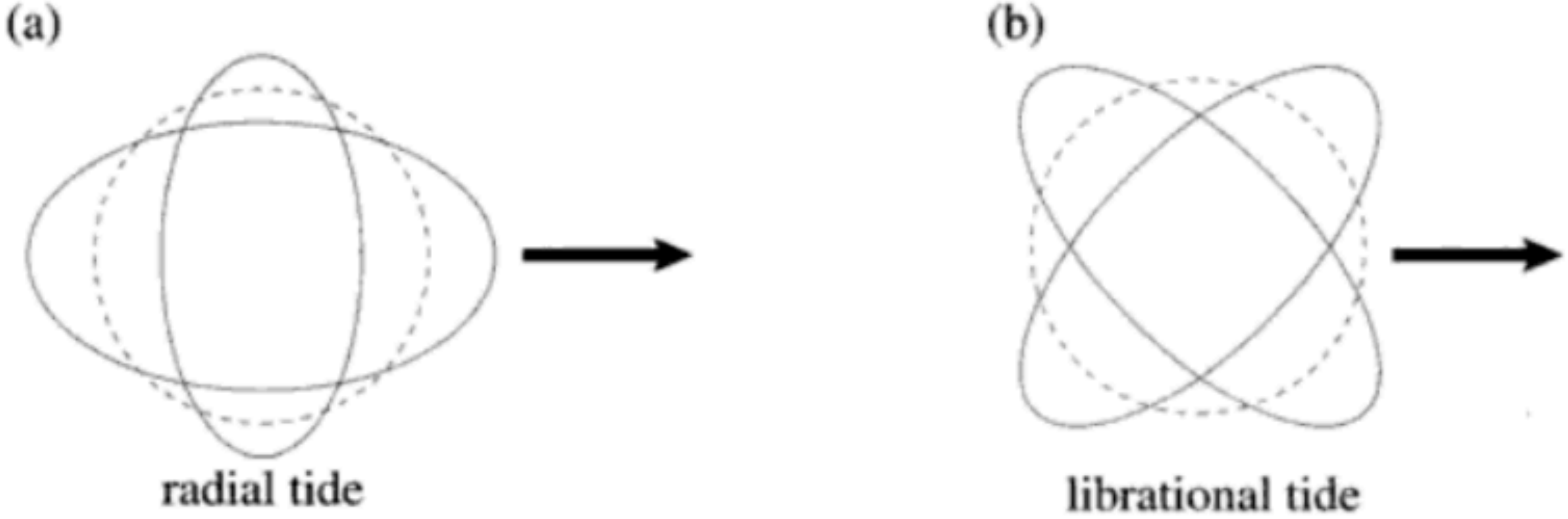
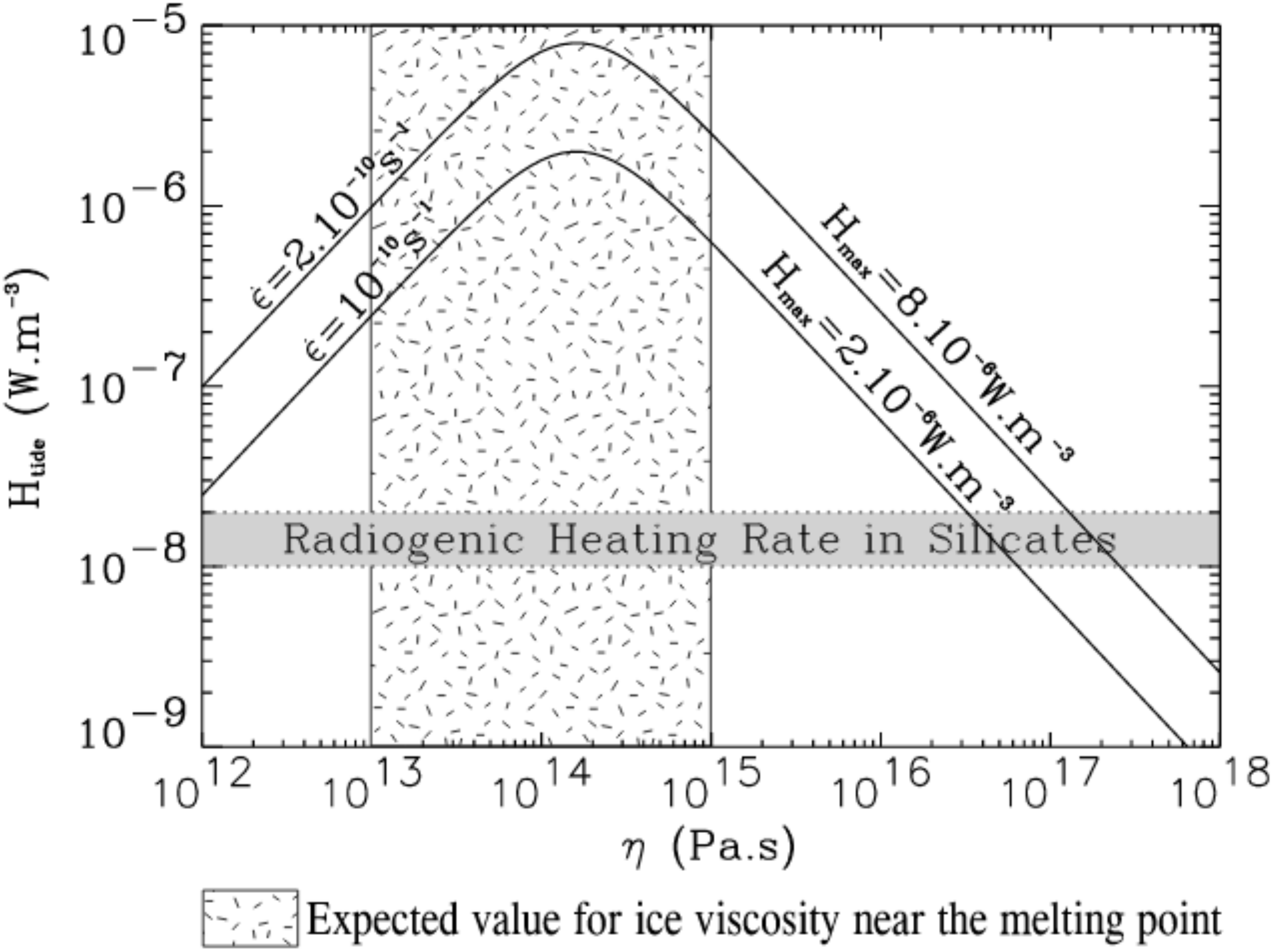


Fig. 4.15. The orientation of the equipotential curves in the equatorial plane ($\theta = \pi/2$) for the extremes of the (a) radial tide and (b) librational tide induced in a satellite due to its orbital eccentricity. In each case the arrows mark the direction of the planet.

Tidal dissipation occurs in the silicate mantle, the ocean, and the ice shell.
It is currently thought that dissipation in the ice shell is the most important
(sustaining the ocean – warm insulation)



Tobie et al. JGR-Planets 2003

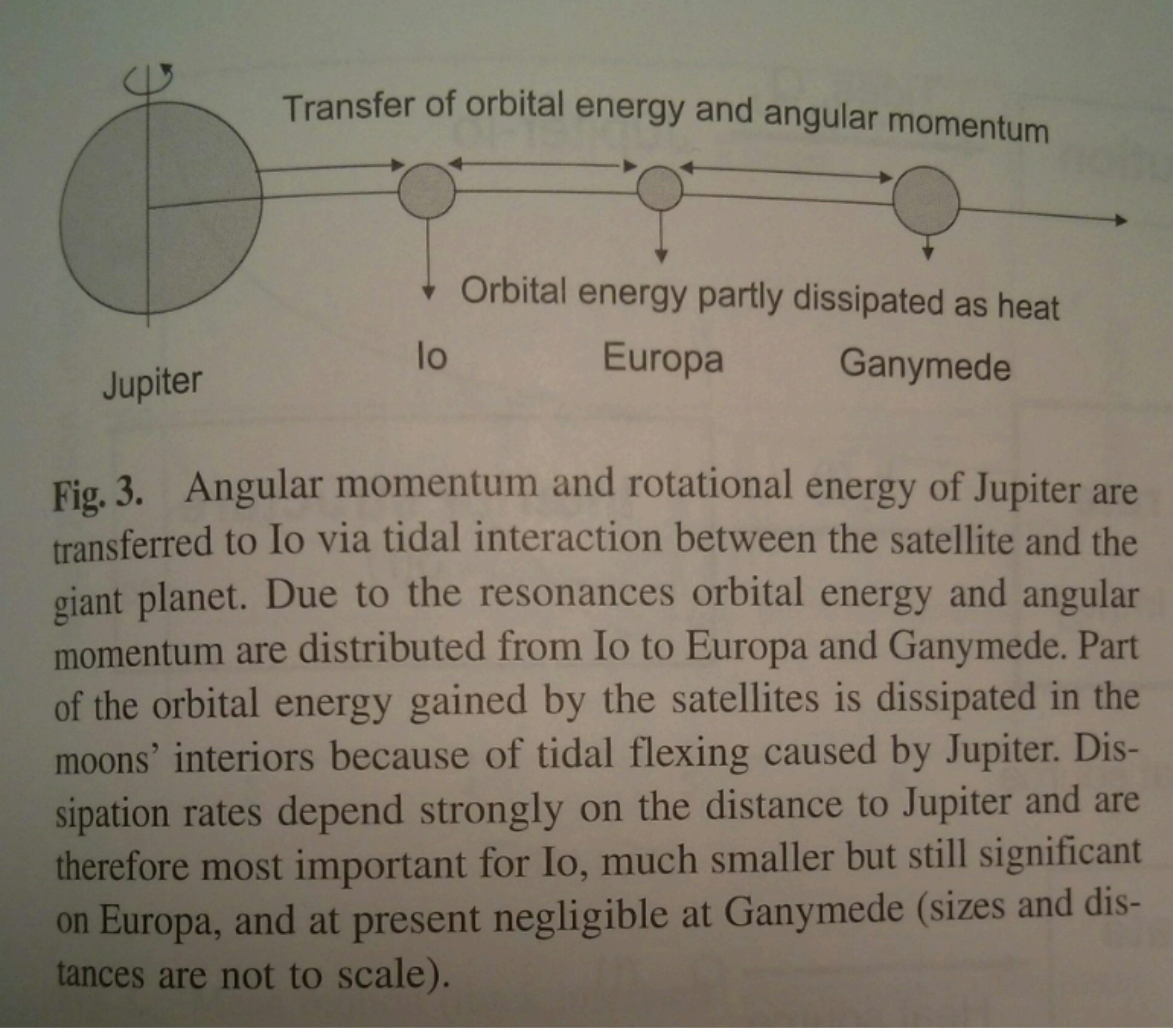


Fig. 3. Angular momentum and rotational energy of Jupiter are transferred to Io via tidal interaction between the satellite and the giant planet. Due to the resonances orbital energy and angular momentum are distributed from Io to Europa and Ganymede. Part of the orbital energy gained by the satellites is dissipated in the moons' interiors because of tidal flexing caused by Jupiter. Dissipation rates depend strongly on the distance to Jupiter and are therefore most important for Io, much smaller but still significant on Europa, and at present negligible at Ganymede (sizes and distances are not to scale).

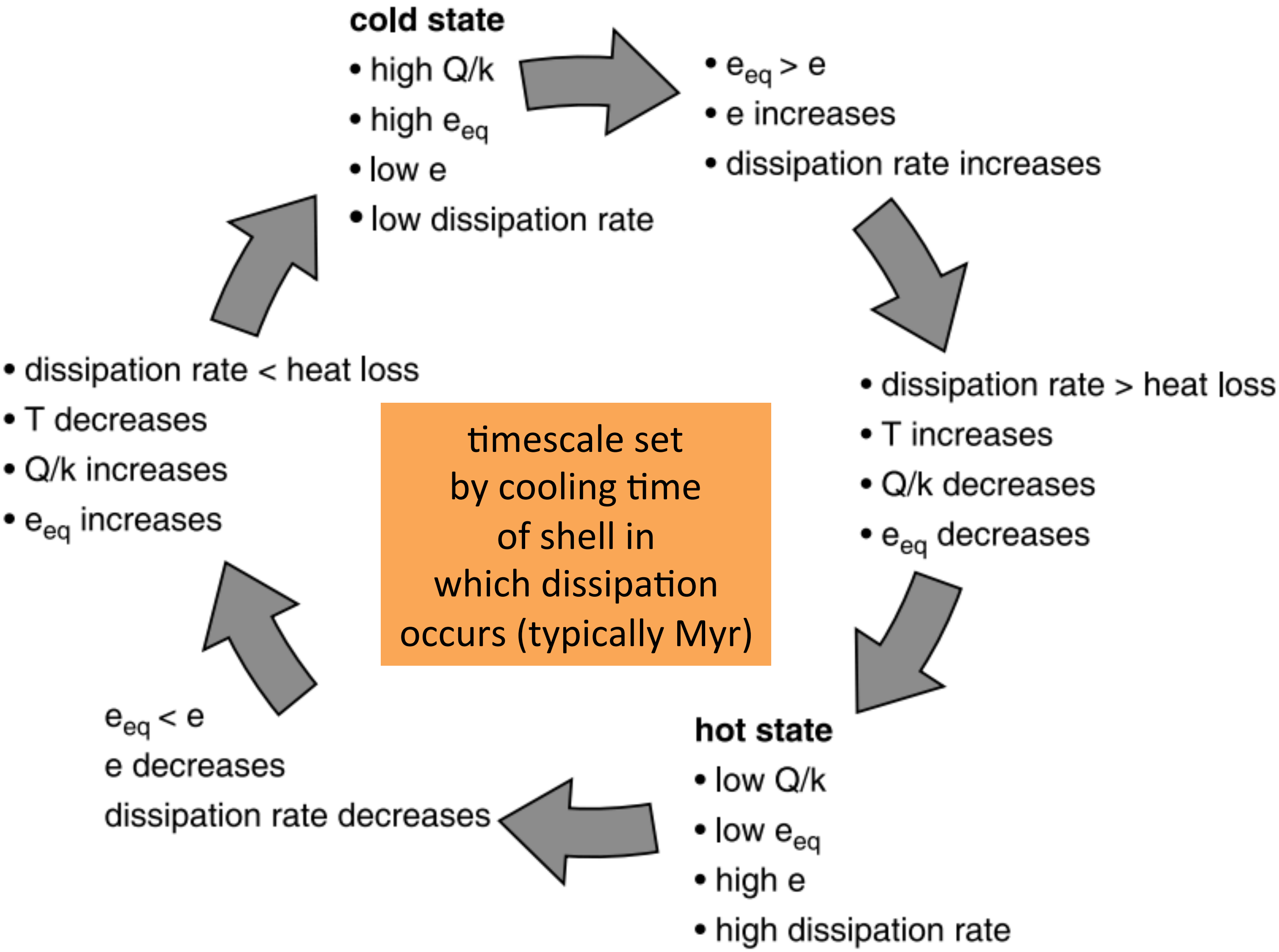
Io: 100x more volcanically active than Earth

Europa: Ice-covered, internal water ocean

Ganymede: Ice-covered, internal water oceans

Schubert et al., 'Interior of Europa,' in the Europa Book, U. Arizona Press, 2009

Link between tidal dissipation and internal temperature allows oscillations in internal temperature



cold state

- high Q/k
- high e_{eq}
- low e
- low dissipation rate

- $e_{eq} > e$
- e increases
- dissipation rate increases

- dissipation rate > heat loss
- T increases
- Q/k decreases
- e_{eq} decreases

hot state

- low Q/k
- low e_{eq}
- high e
- high dissipation rate

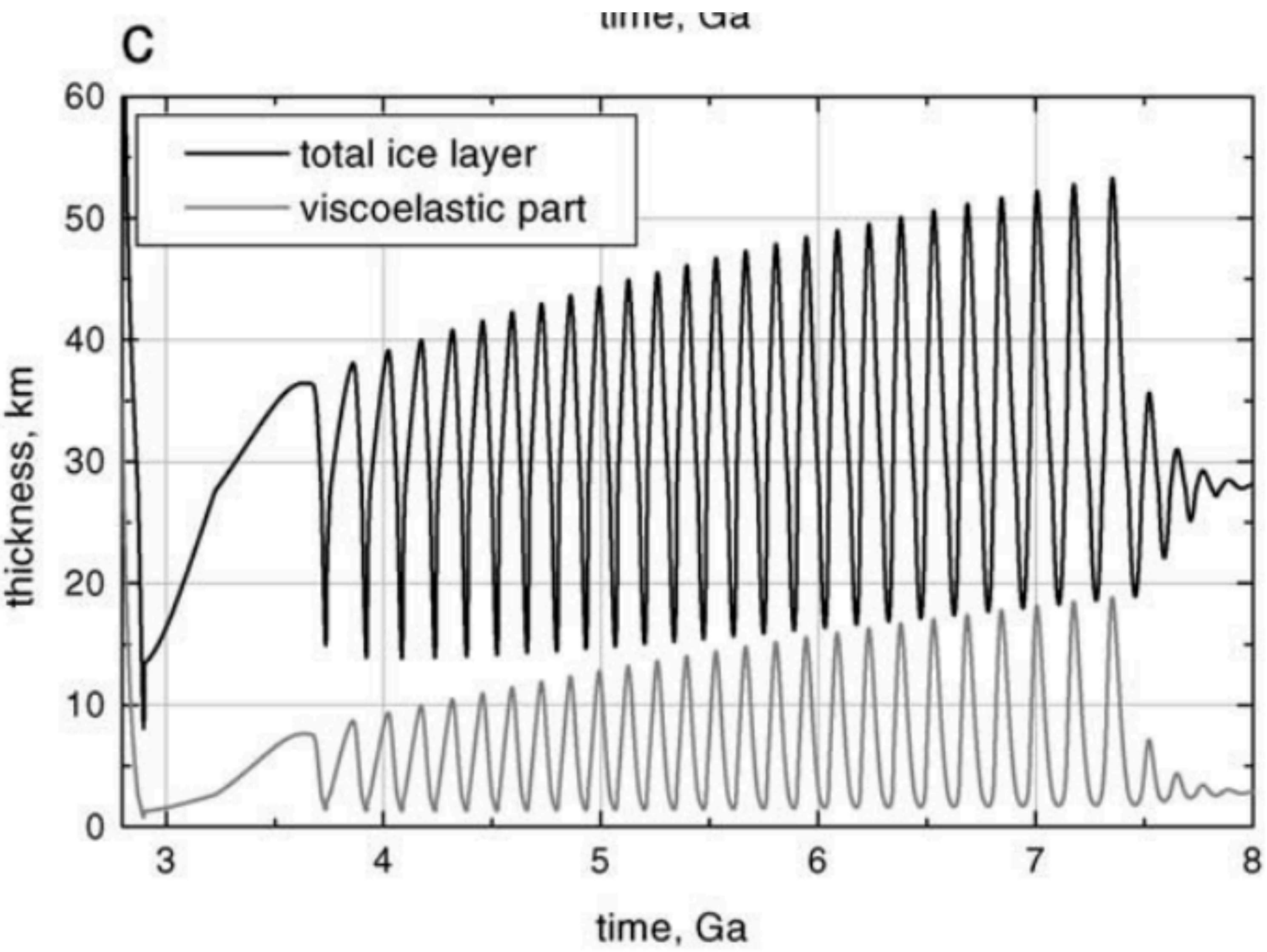
$e_{eq} < e$
e decreases
dissipation rate decreases

- dissipation rate < heat loss
- T decreases
- Q/k increases
- e_{eq} increases

timescale set
by cooling time
of shell in
which dissipation
occurs (typically Myr)

Schubert et al. Space Science Reviews 2010

One possible solution for coupled Europa-Io orbital-thermal evolution: illustrative only



Hussmann & Spohn, Icarus, 2004

These feedbacks are common, and many mid-sized icy objects likely maintain H2O oceans

Red boxes show worlds for which there is direct evidence for a sub-ice H2O ocean

Most of the habitable volume in the Solar System is likely water in sub-ice oceans

Ammonia antifreeze is important at Saturn's orbit and beyond.

This graphic is from 2010. There is now evidence (libration) that Mimas also has a global ocean.

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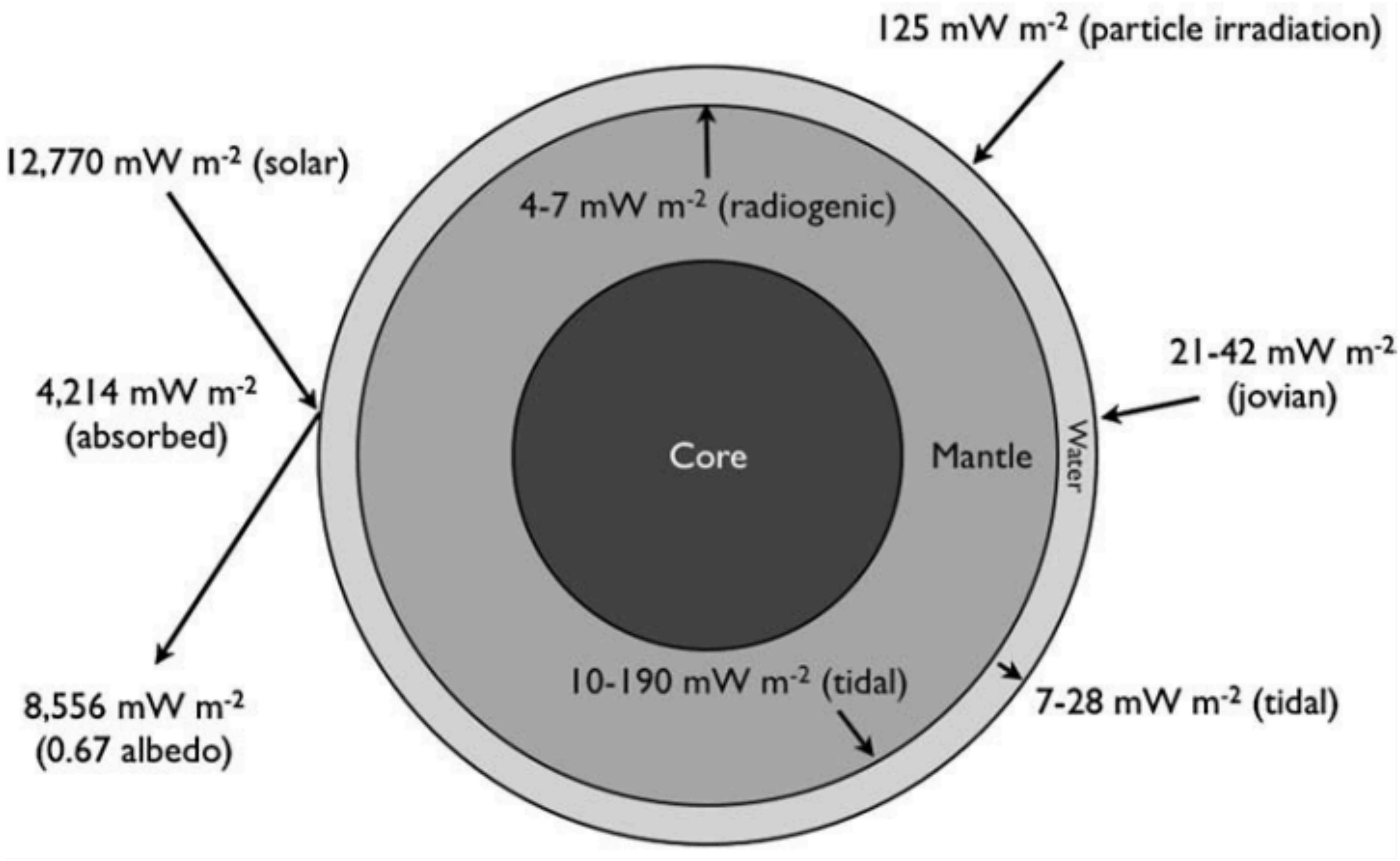
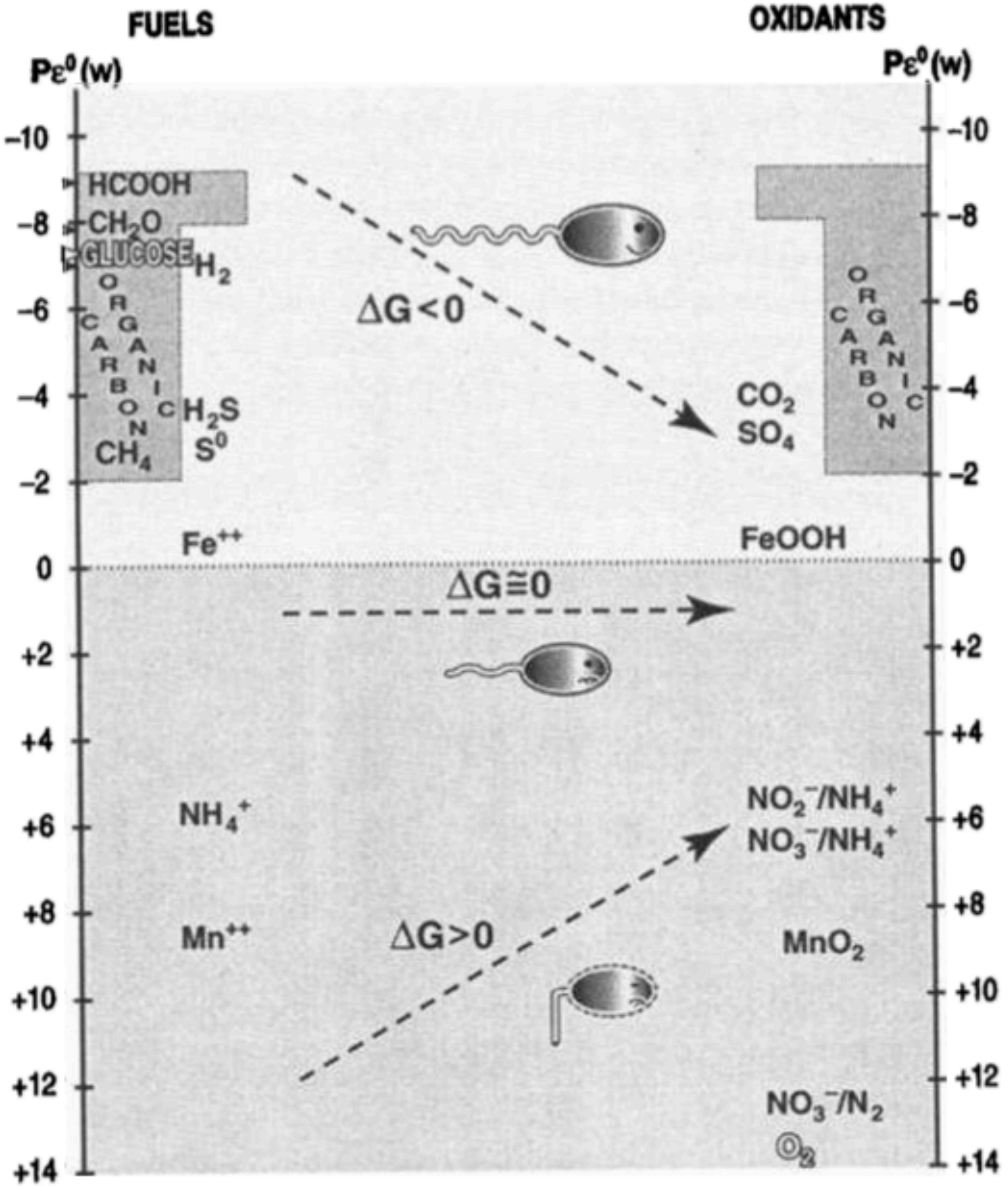
Energy budget of Europa's ocean



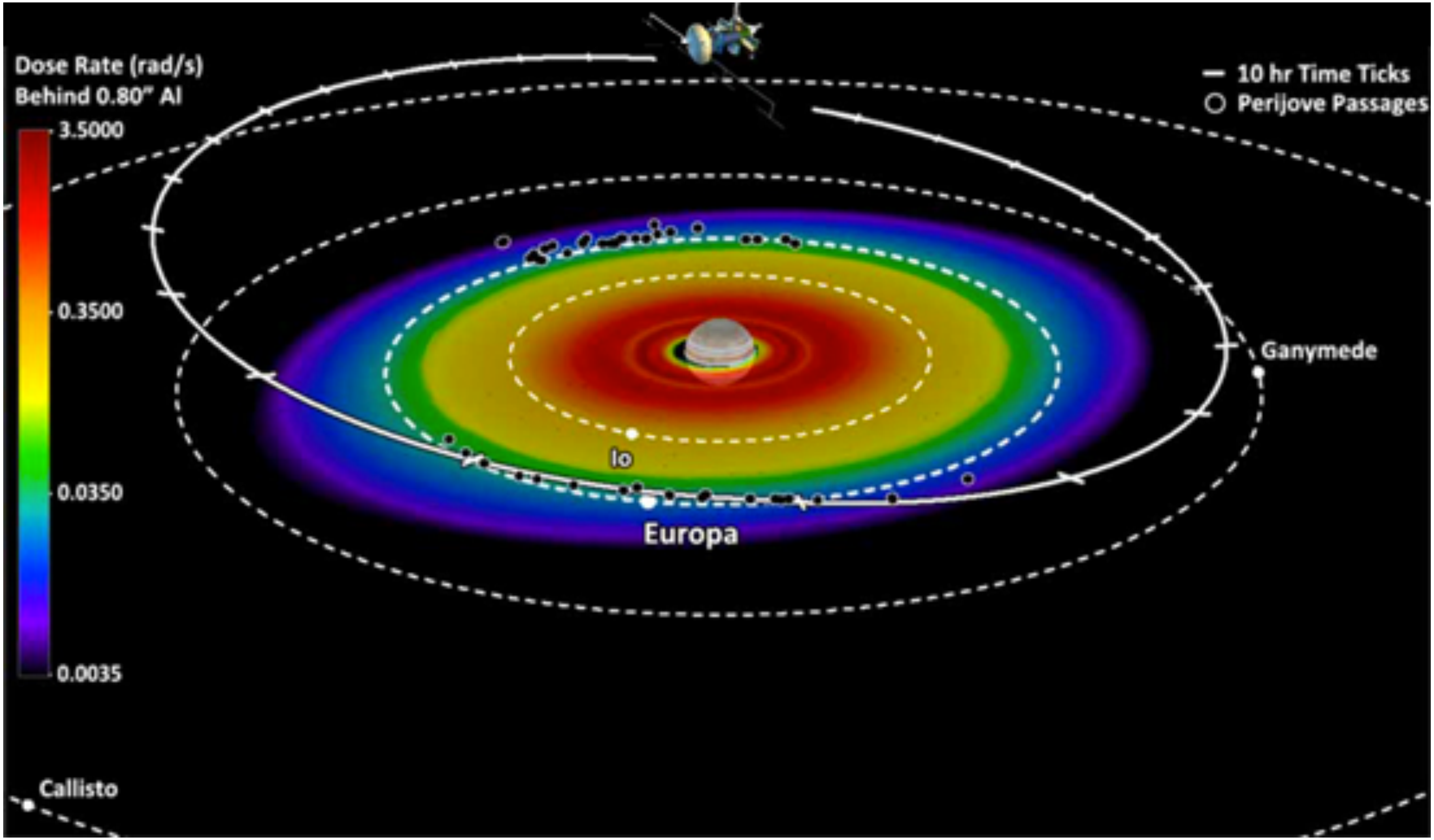
Hand et al. 2007



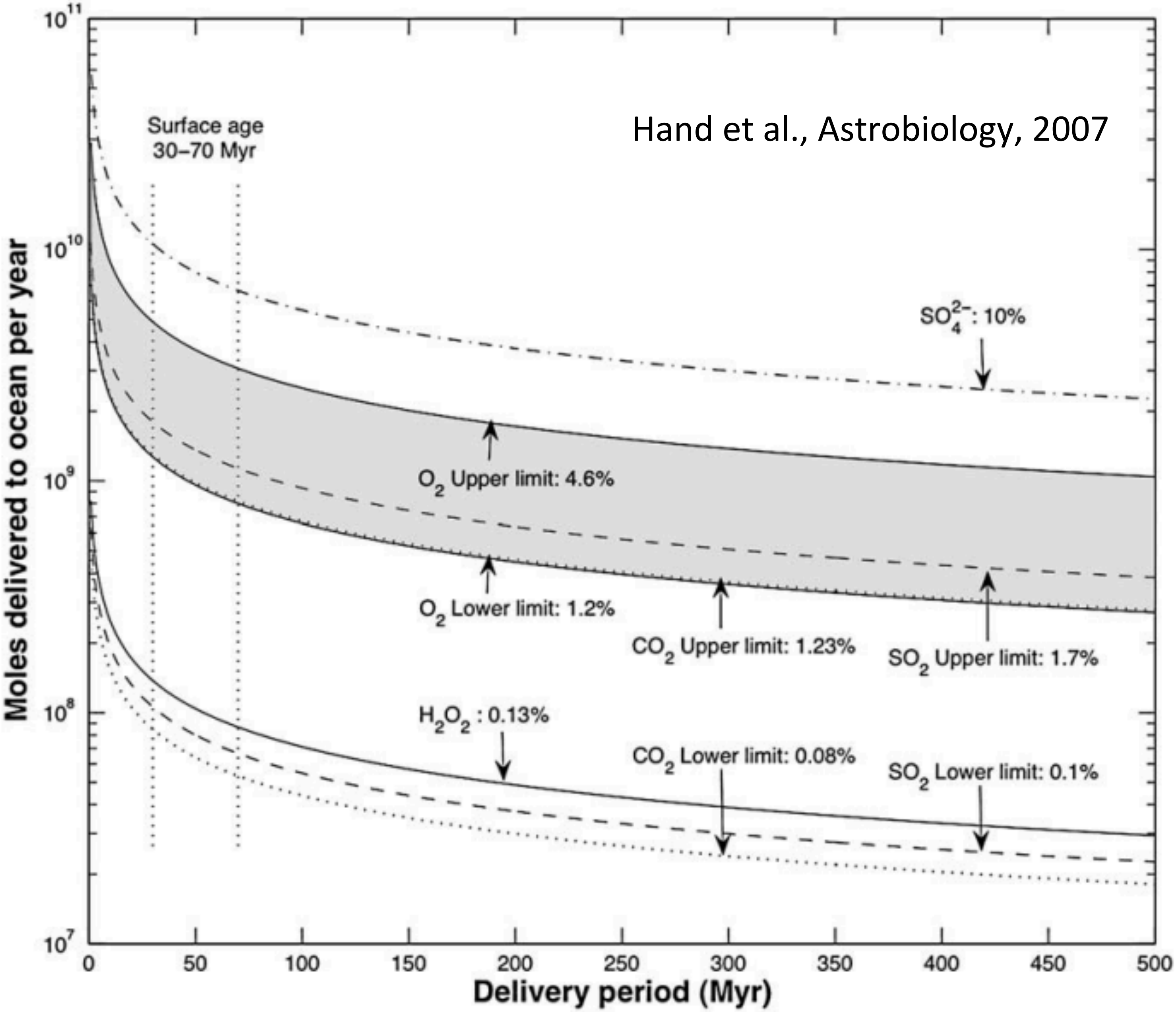
Thermodynamics: The Chemical Fuels and Oxidants of Life

K. Nealson
JGR Planets
1997

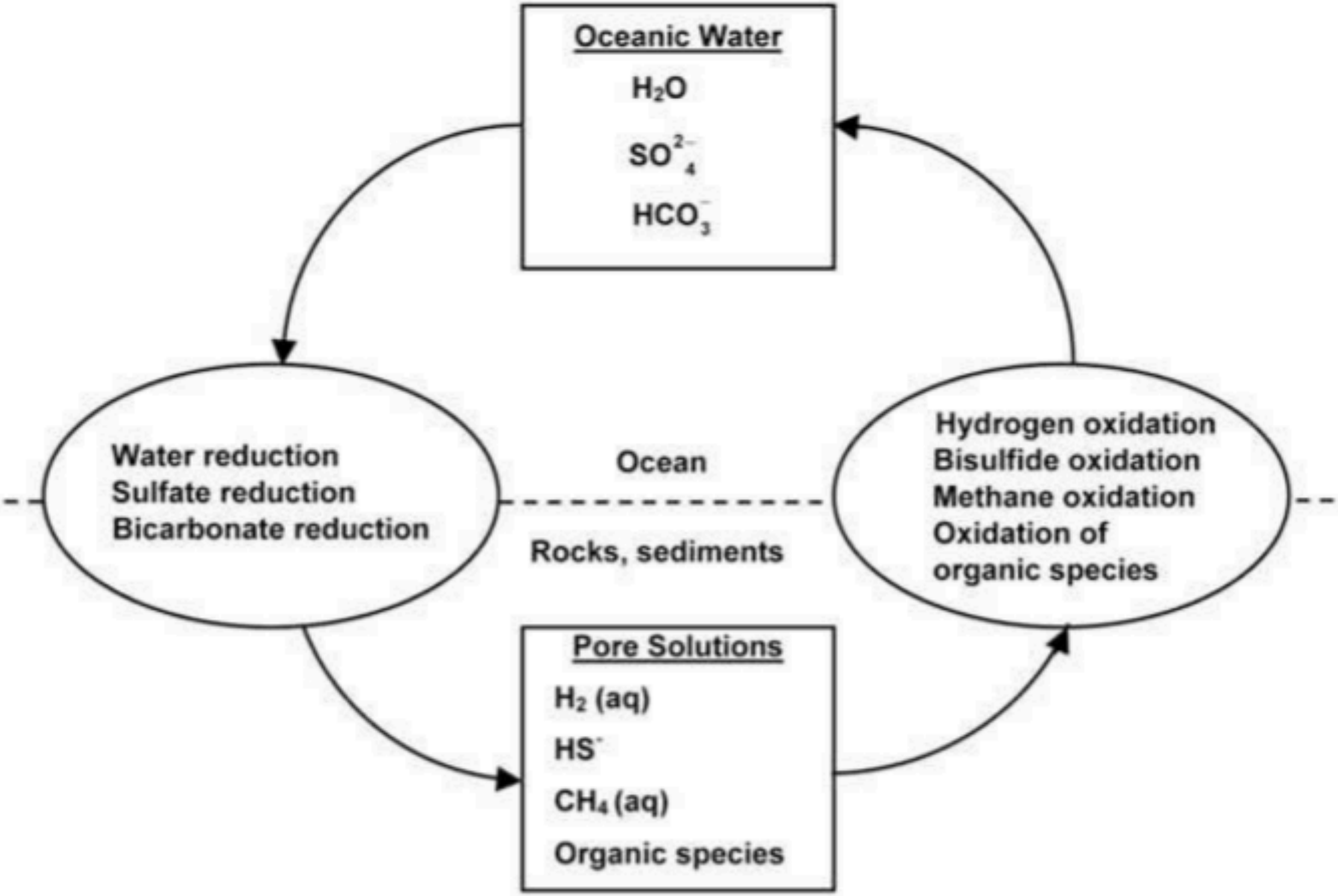
Giant-planet magnetic fields entrain charged particles which bombard the trailing hemispheres of moons → radiolytic chemistry



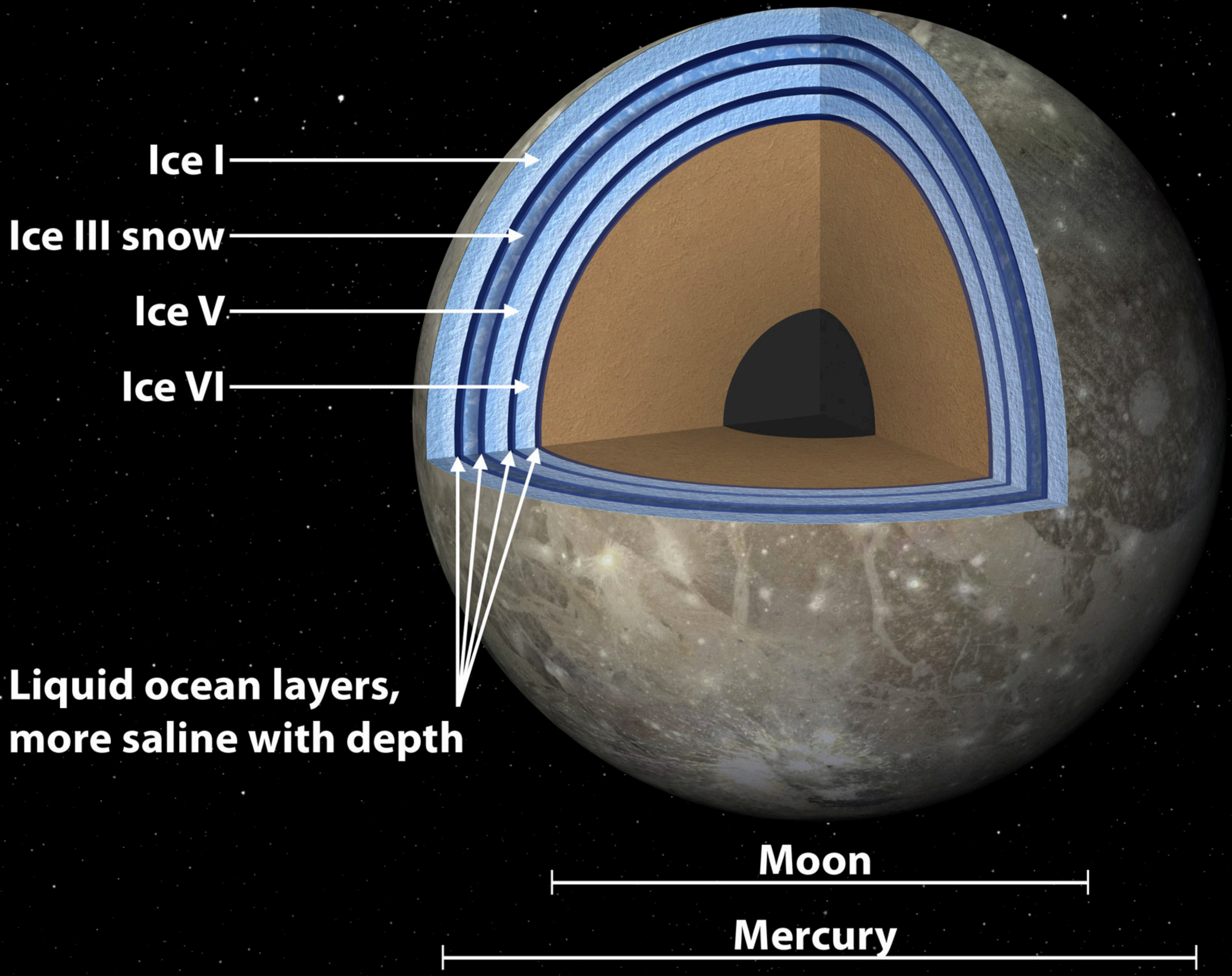
An oxygen-rich Europa ocean, supplied by recycling of radiolytically-processed material from the surface?



Hand et al., Astrobiology, 2007


Oceanic Water
H_2O
SO_4^{2-}
HCO_3^-
Water reduction
Sulfate reduction
Bicarbonate reduction
Ocean
Rocks, sediments
Hydrogen oxidation
Bisulfide oxidation
Methane oxidation
Oxidation of organic species
Pore Solutions
H_2 (aq)
HS^-
CH_4 (aq)
Organic species

Ganymede



Ice I

Ice III snow

Ice V

Ice VI

Liquid ocean layers, more saline with depth

Moon

Mercury

Ice-covered oceans

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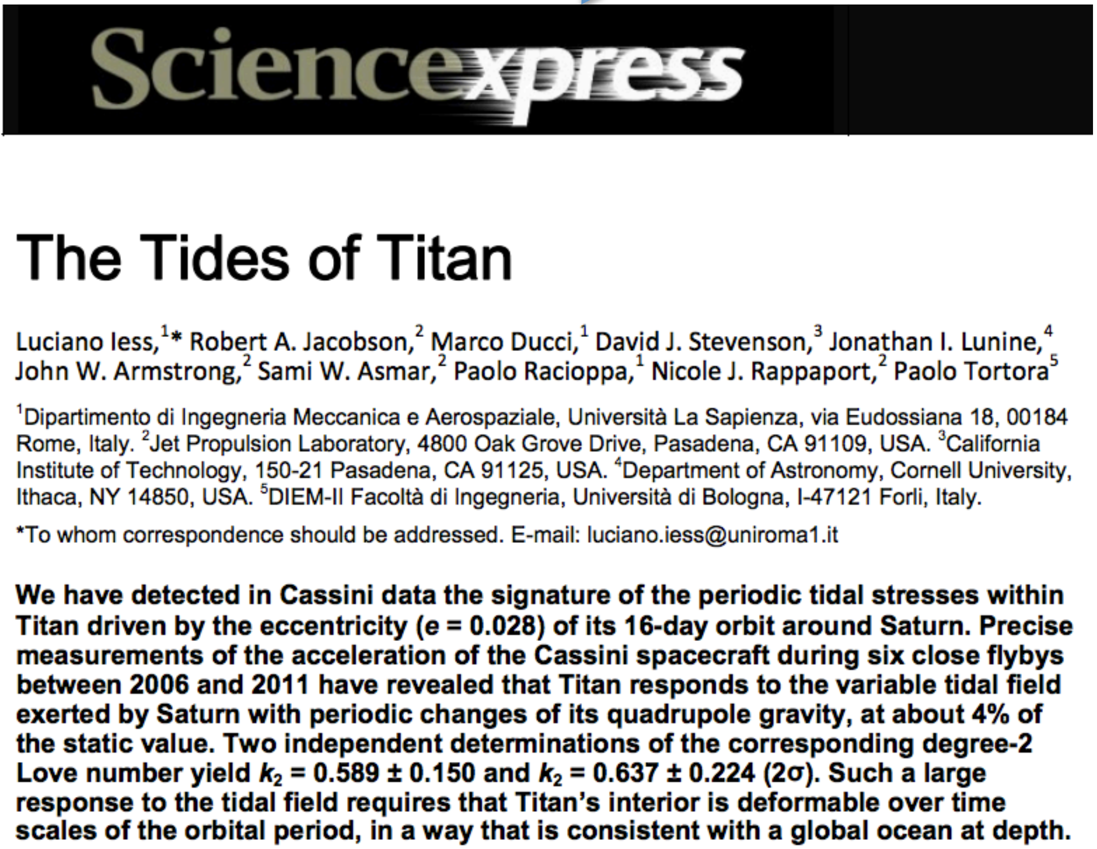
How to confirm a global sub-ice ocean exists: decoupling of ice shell from deep interior by ocean increases the amplitude of gravity tides and/or physical libration



Sciencexpress

The Tides of Titan

Luciano Iess,[1]* Robert A. Jacobson,[2] Marco Ducci,[1] David J. Stevenson,[3] Jonathan I. Lunine,[4] John W. Armstrong,[2] Sami W. Asmar,[2] Paolo Racioppa,[1] Nicole J. Rappaport,[2] Paolo Tortora[5]

[1]Dipartimento di Ingegneria Meccanica e Aerospaziale, Università La Sapienza, via Eudossiana 18, 00184 Rome, Italy. [2]Jet Propulsion Laboratory, 4800 Oak Grove Drive, Pasadena, CA 91109, USA. [3]California Institute of Technology, 150-21 Pasadena, CA 91125, USA. [4]Department of Astronomy, Cornell University, Ithaca, NY 14850, USA. [5]DIEM-II Facoltà di Ingegneria, Università di Bologna, I-47121 Forlì, Italy.

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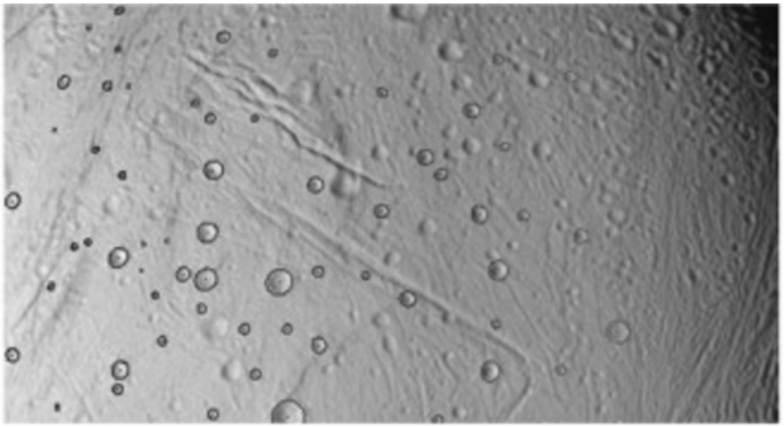
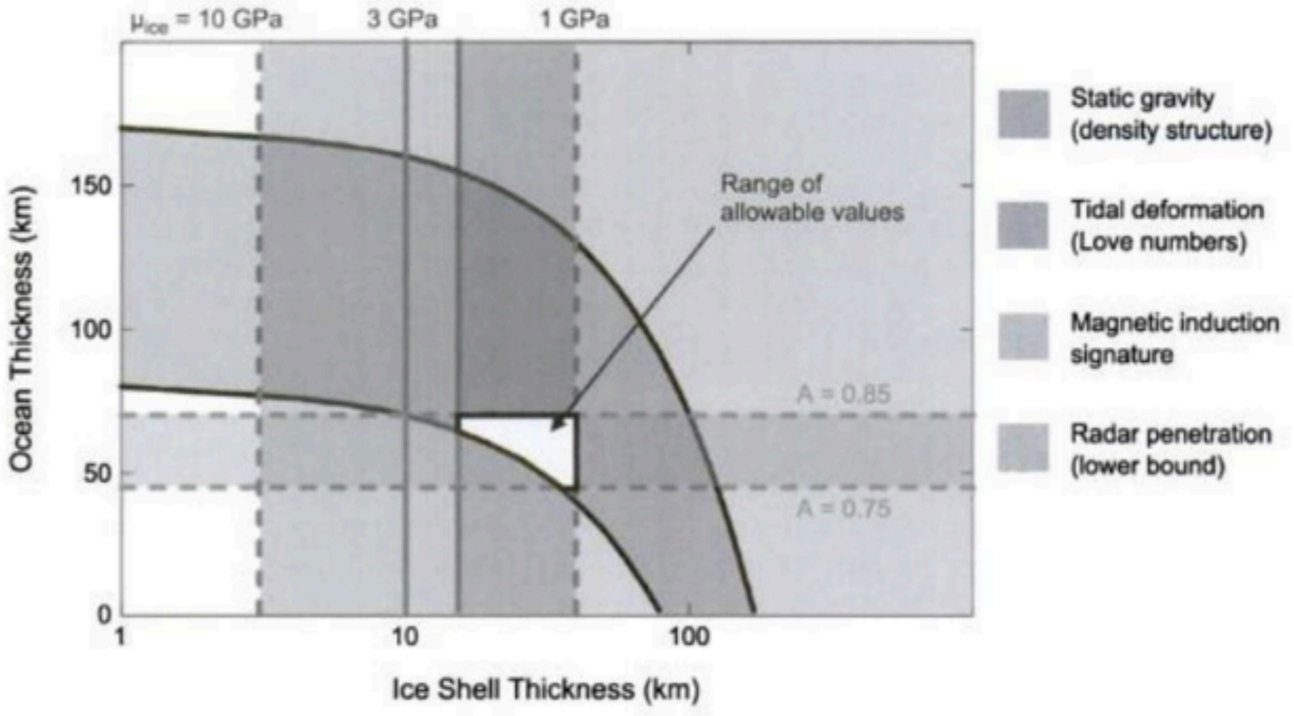
We have detected in Cassini data the signature of the periodic tidal stresses within Titan driven by the eccentricity (e = 0.028) of its 16-day orbit around Saturn. Precise measurements of the acceleration of the Cassini spacecraft during six close flybys between 2006 and 2011 have revealed that Titan responds to the variable tidal field exerted by Saturn with periodic changes of its quadrupole gravity, at about 4% of the static value. Two independent determinations of the corresponding degree-2 Love number yield $k_2 = 0.589 \pm 0.150$ and $k_2 = 0.637 \pm 0.224$ (2σ). Such a large response to the tidal field requires that Titan's interior is deformable over time scales of the orbital period, in a way that is consistent with a global ocean at depth.

Thomas et al. Icarus 2016



Measuring the thickness of the ice shell



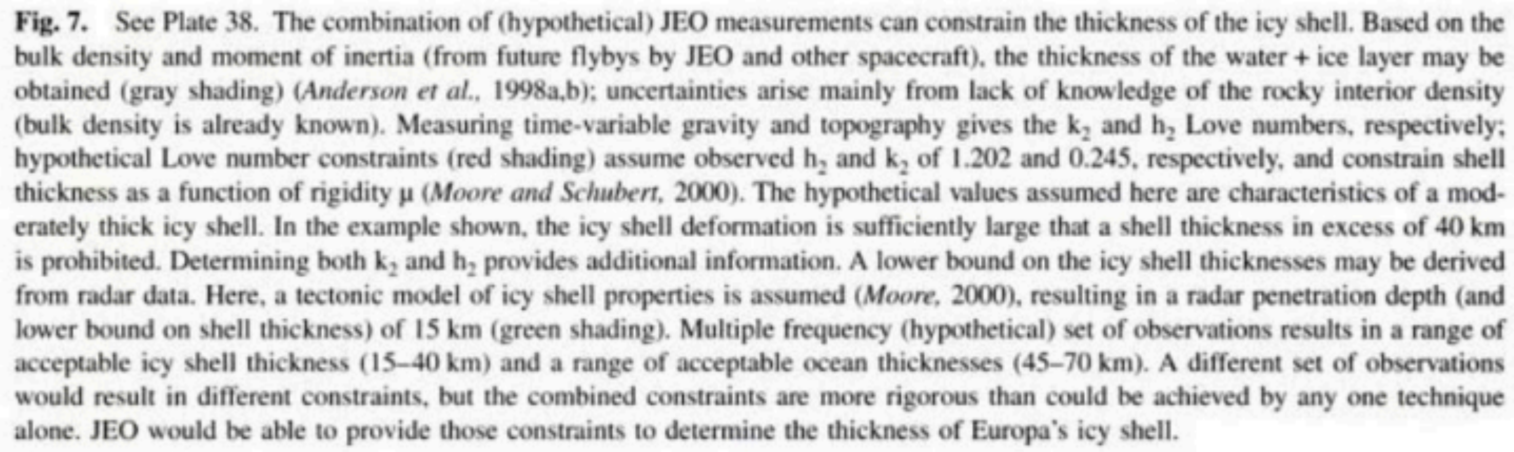
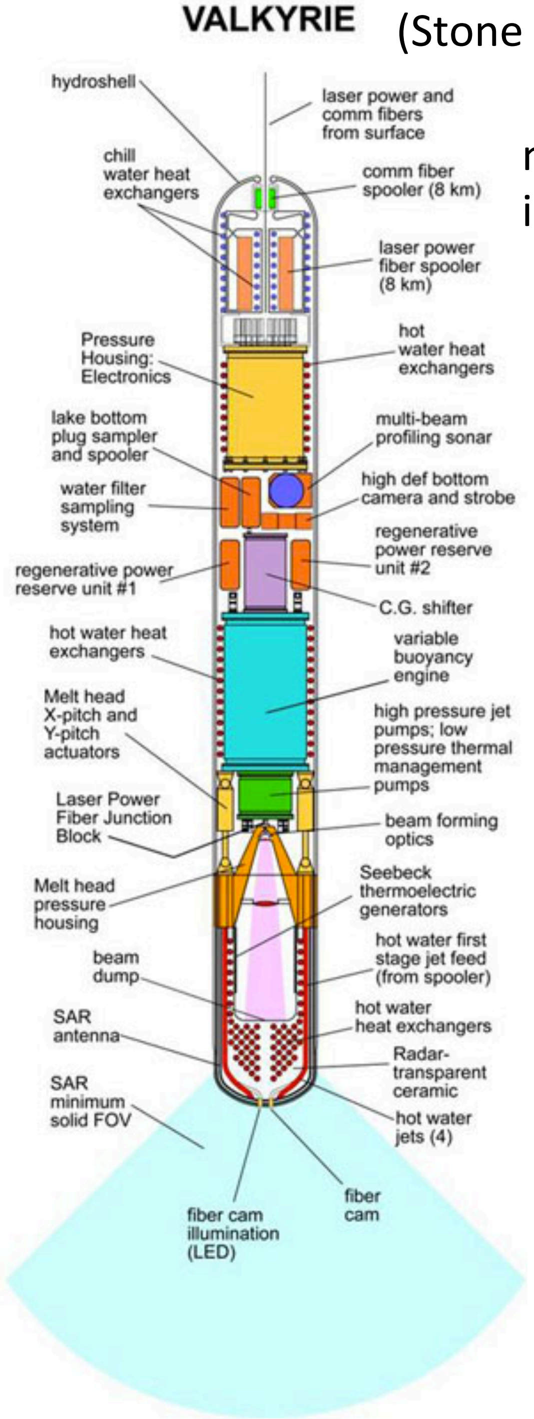


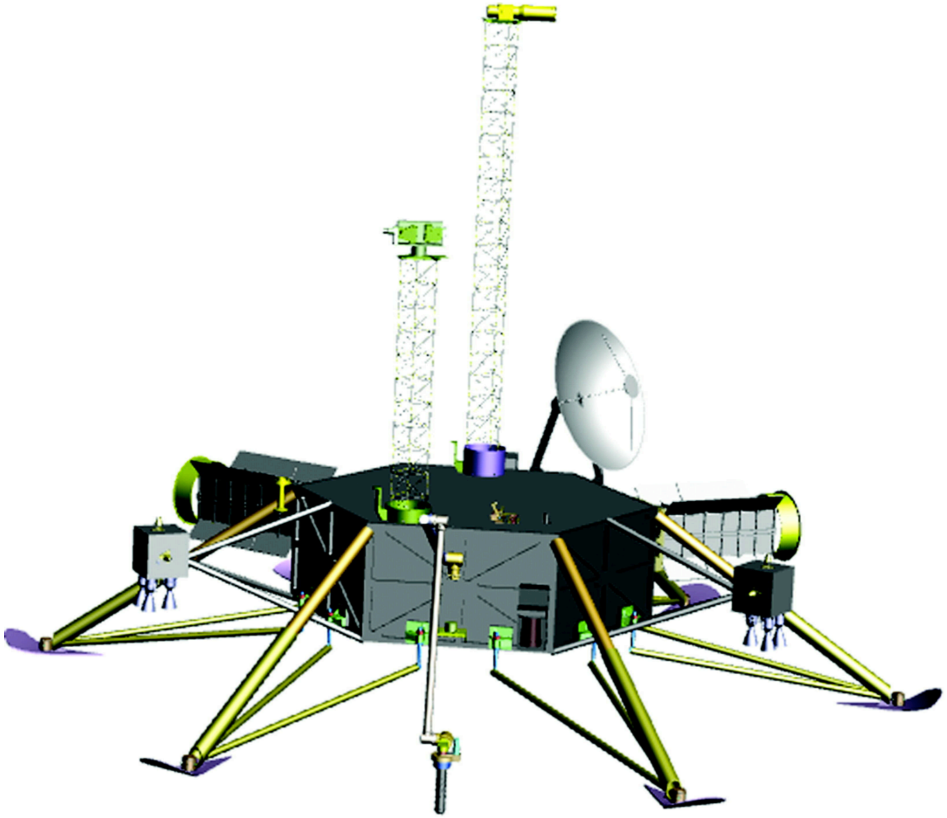
Fig. 7. See Plate 38. The combination of (hypothetical) JEO measurements can constrain the thickness of the icy shell. Based on the bulk density and moment of inertia (from future flybys by JEO and other spacecraft), the thickness of the water + ice layer may be obtained (gray shading) (*Anderson et al.*, 1998a,b); uncertainties arise mainly from lack of knowledge of the rocky interior density (bulk density is already known). Measuring time-variable gravity and topography gives the k_2 and h_2 Love numbers, respectively; hypothetical Love number constraints (red shading) assume observed h_2 and k_2 of 1.202 and 0.245, respectively, and constrain shell thickness as a function of rigidity μ (*Moore and Schubert*, 2000). The hypothetical values assumed here are characteristics of a moderately thick icy shell. In the example shown, the icy shell deformation is sufficiently large that a shell thickness in excess of 40 km is prohibited. Determining both k_2 and h_2 provides additional information. A lower bound on the icy shell thicknesses may be derived from radar data. Here, a tectonic model of icy shell properties is assumed (*Moore*, 2000), resulting in a radar penetration depth (and lower bound on shell thickness) of 15 km (green shading). Multiple frequency (hypothetical) set of observations results in a range of acceptable icy shell thickness (15–40 km) and a range of acceptable ocean thicknesses (45–70 km). A different set of observations would result in different constraints, but the combined constraints are more rigorous than could be achieved by any one technique alone. JEO would be able to provide those constraints to determine the thickness of Europa's icy shell.

Landing and recovering ocean materials

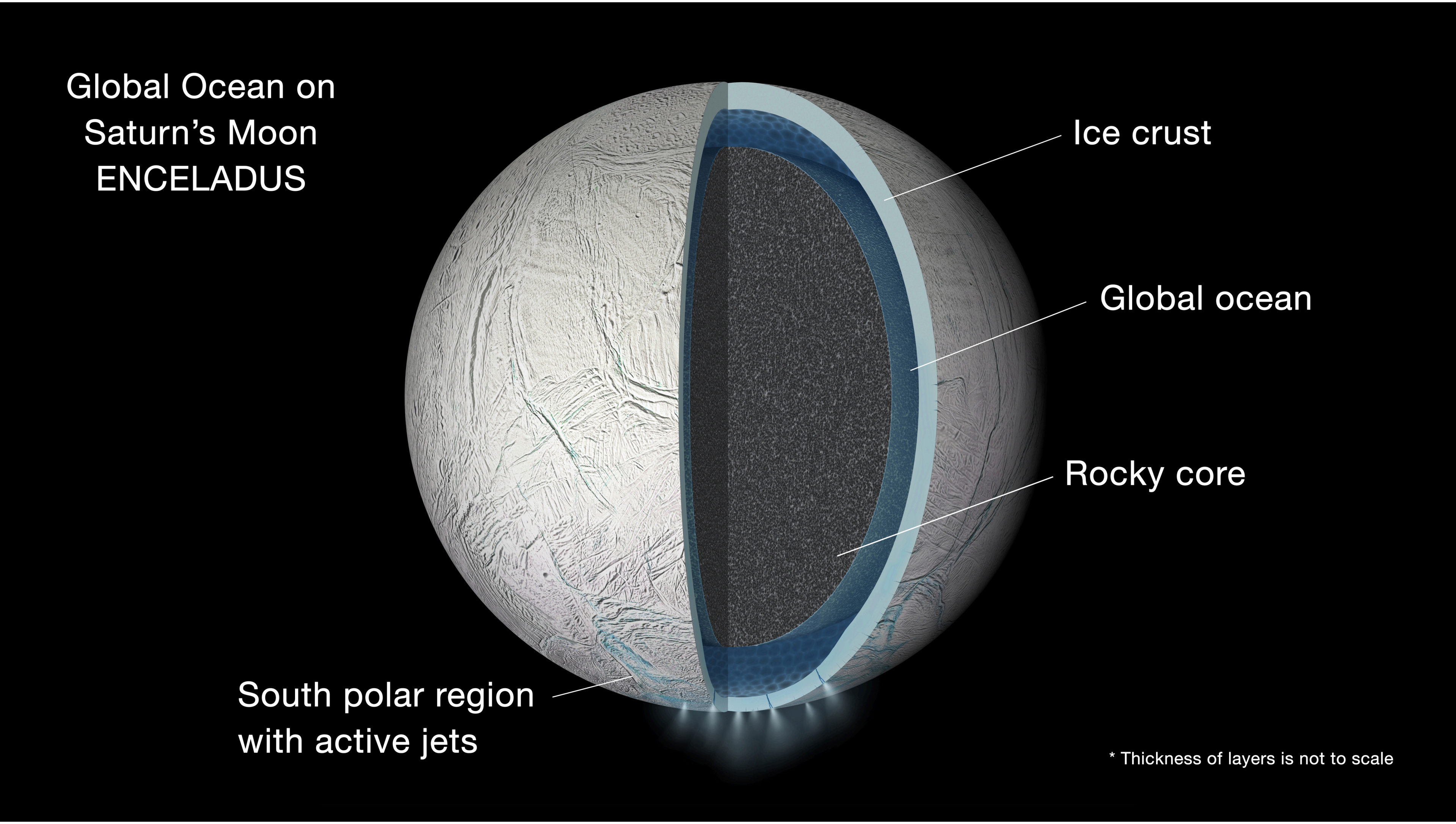


(Stone Aerospace)

nuclear reactor
is required



A shortcut: sample material from the cryovolcanic plumes of Saturn’s moon Enceladus



NASA/JPL

The ‘tiger stripes’ that launch Enceladus’ geysers are gateways to a global ocean

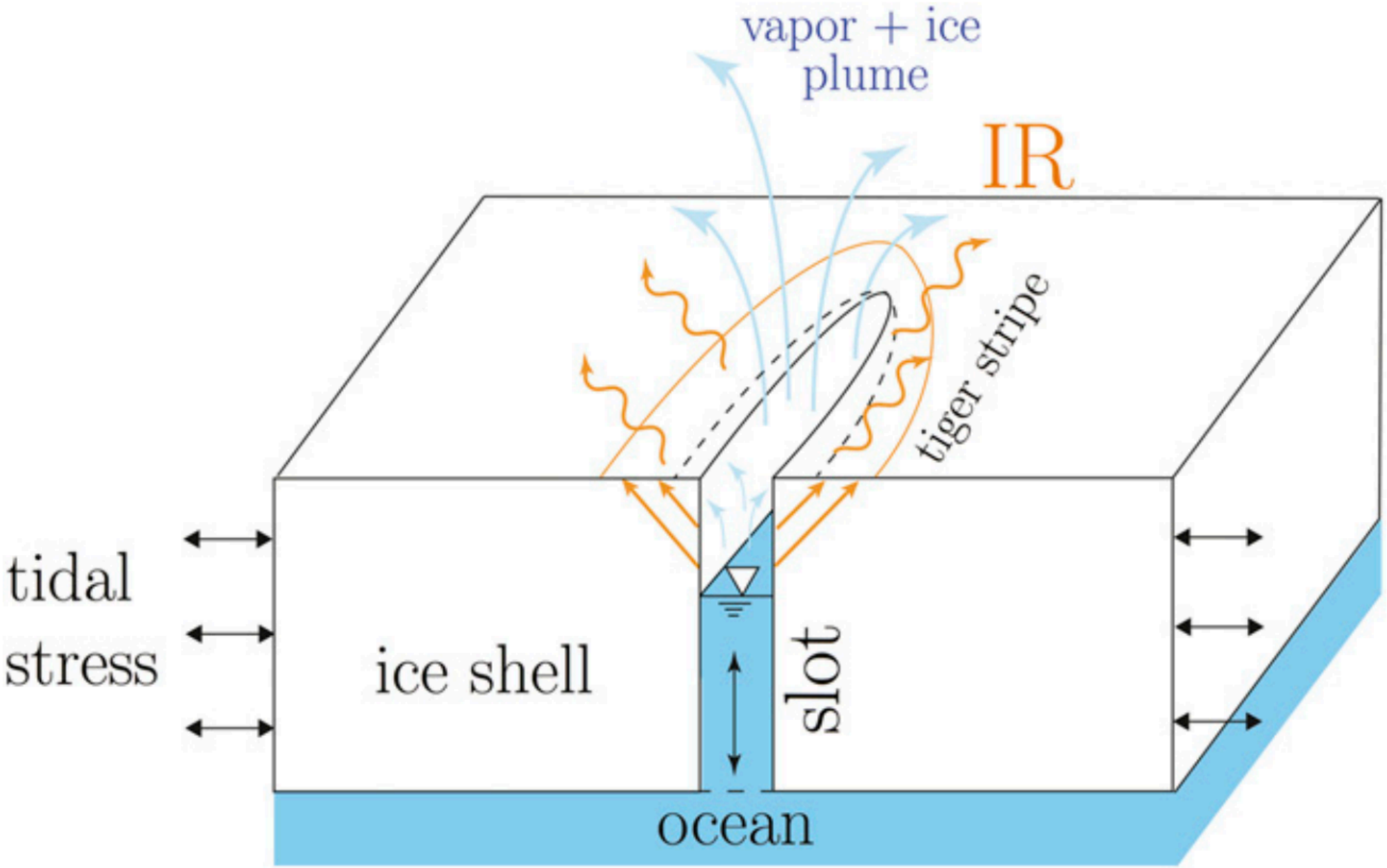
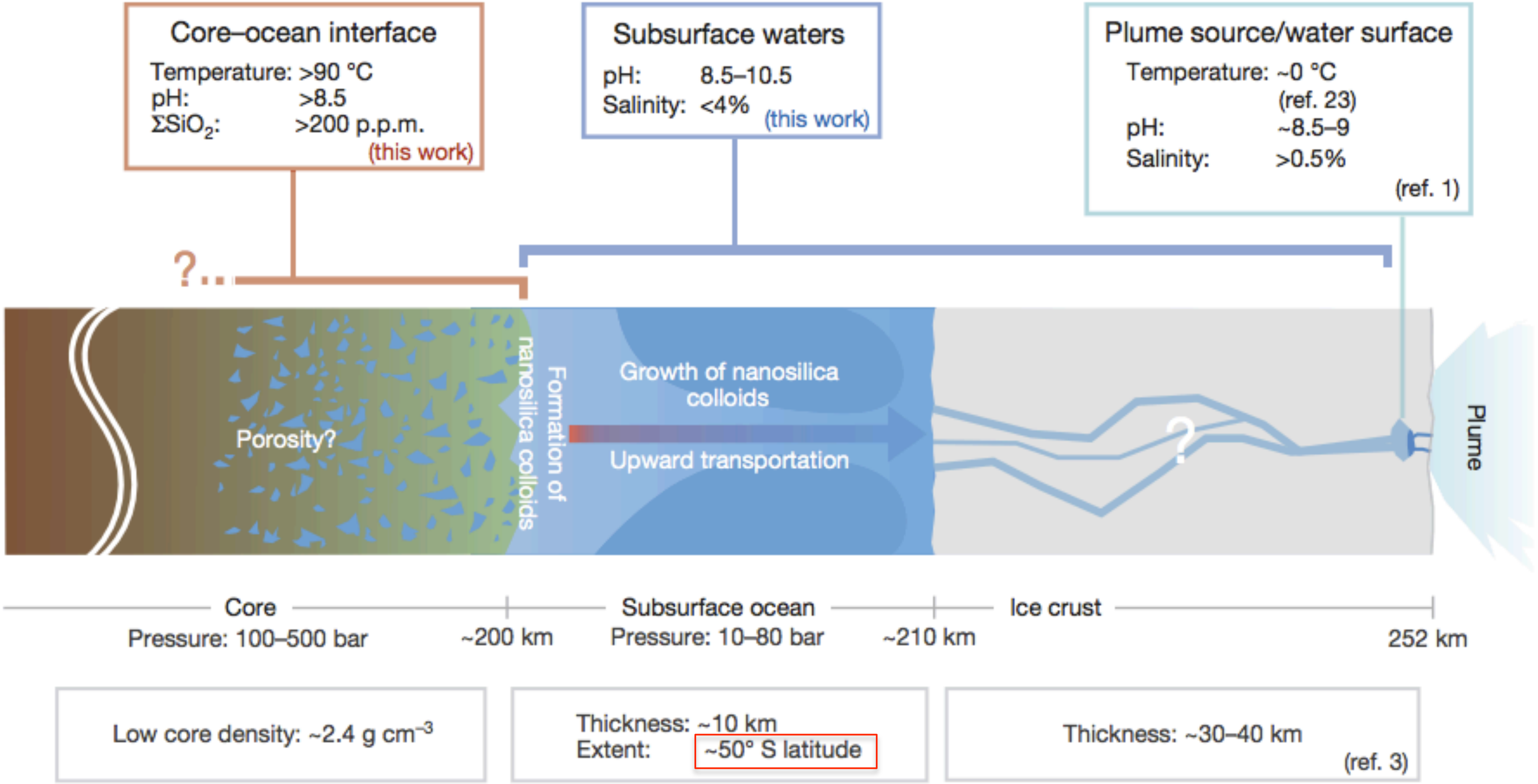


Fig. 1. The erupted flux from Enceladus (blue arrows) varies on diurnal timescales, which we attribute to daily flexing (dashed lines) of the source fissures by Saturn tidal stresses (horizontal arrows). Such flexing would also drive vertical flow in slots underneath the source fissures (vertical black arrow), which through viscous dissipation generates heat. This heat helps to maintain the slots against freezeout despite strong evaporitic cooling by vapor escaping from the water table (downward-pointing triangle). The vapor ultimately provides heat (via condensation) for the envelope of warm surface material bracketing the tiger stripes (orange arrows; “IR” corresponds to infrared cooling from this warm material).

Kite & Rubin PNAS 2016

Hydrothermal vents were active at the Enceladus seafloor geologically recently (inference: probably active today also)



Core–ocean interface
Temperature: >90 °C
pH: >8.5
ΣSiO_2: >200 p.p.m.
(this work)

Subsurface waters
pH: 8.5–10.5
Salinity: <4%
(this work)

Plume source/water surface
Temperature: ~0 °C (ref. 23)
pH: ~8.5–9
Salinity: >0.5%
(ref. 1)

Low core density: ~2.4 g cm^{-3}

Thickness: ~10 km
Extent: ~50° S latitude

Thickness: ~30–40 km (ref. 3)

not correct – now known to be global

Hsu et al. Nature 2015

Energy is available for life on Enceladus

$$CO_2(aq) + 4H_2(aq) \rightarrow CH_4(aq) + 2H_2O(l)$$

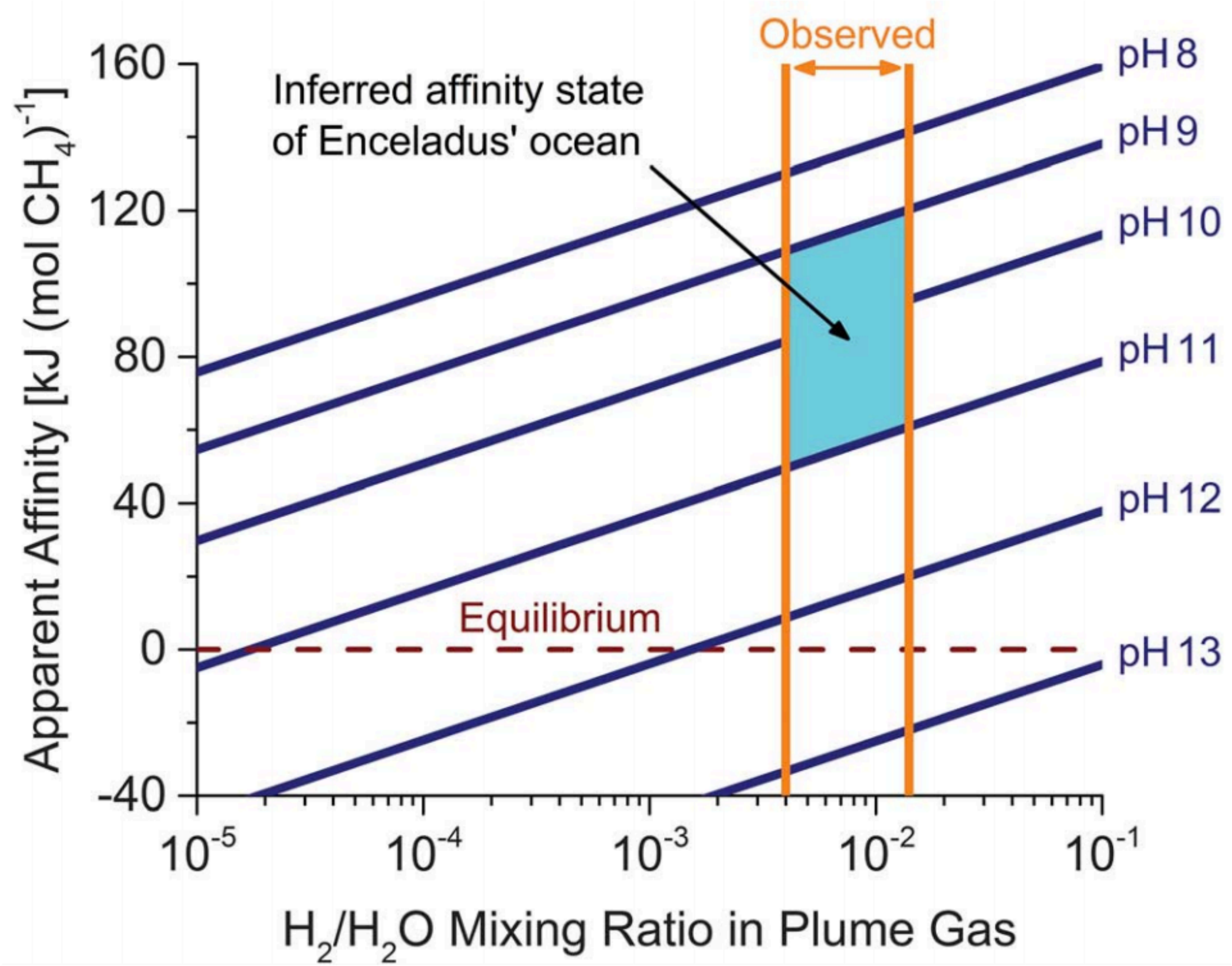
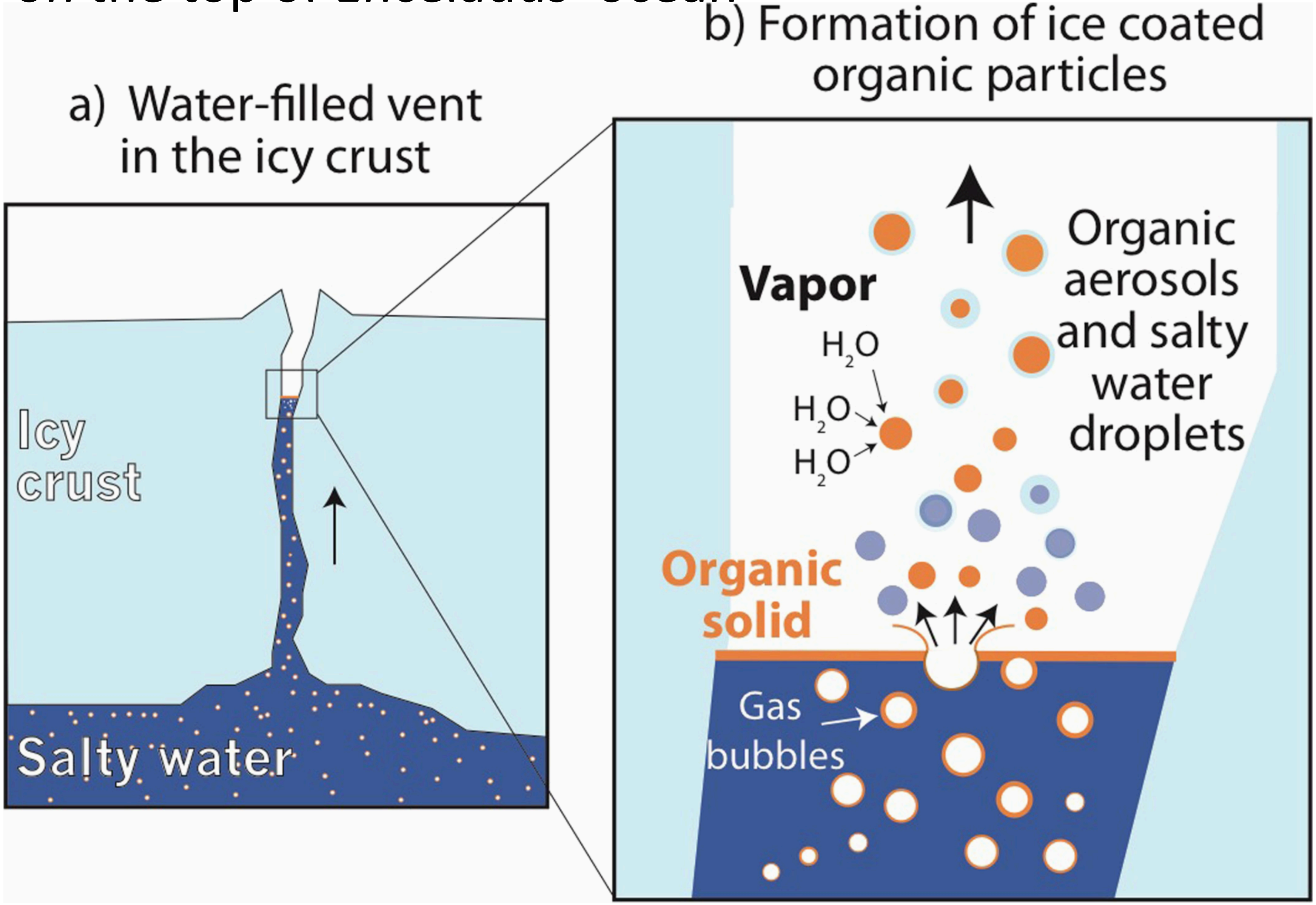


Fig. 4. Apparent chemical affinity for hydrogenotrophic methanogenesis in the ocean of Enceladus (273 K, 1 bar). The orange lines bracket the observed range in the mixing ratio of H_2 in the plume gas (Table 1). The dark blue lines are contours of constant ocean pH, a key model parameter. The cyan region indicates affinities for a pH range that may provide the greatest consistency between the results of (*13*, *15*, *25*). The dashed burgundy line designates chemical equilibrium, where no energy would be available from methanogenesis. These nominal model results are based on $CH_4/CO_2 = 0.4$ (Table 1), a chlorinity of 0.1 molal, and 0.03 molal total dissolved carbonate (*25*). Reported ranges in these parameters propagate to give an uncertainty in the computed affinities of ~10 kJ (mol CH_4)$^{-1}$.

Waite et al. Nature 2017

Complex organic molecules are being launched into space from a scum layer on the top of Enceladus' ocean



Extended Data Fig. 12 | Schematic on the formation of organic condensation cores from a refractory organic film. a, Ascending gas bubbles in the ocean[25] efficiently transport organic material[30] into water-filled cracks in the south polar ice crust. **b**, Organics ultimately concentrate in a thin organic layer (orange) on top of the water table, located inside the icy vents. When gas bubbles burst, they form aerosols made of insoluble organic material that later serve as efficient condensation cores for the production of an icy crust from water vapour, thereby forming HMOC-type particles. In parallel, larger, pure salt-water droplets form (blue), which freeze and are later detected by the CDA as salt-rich type-3 ice particles in the plume[8,9].

Postberg et al Nature 2018

Key points from today’s lecture

- evidence for global sub-ice oceans in the outer Solar System;
- the “ideal” sub-ice ocean for biology (and ways in which Europa, Ganymede and Enceladus deviate from that ideal).

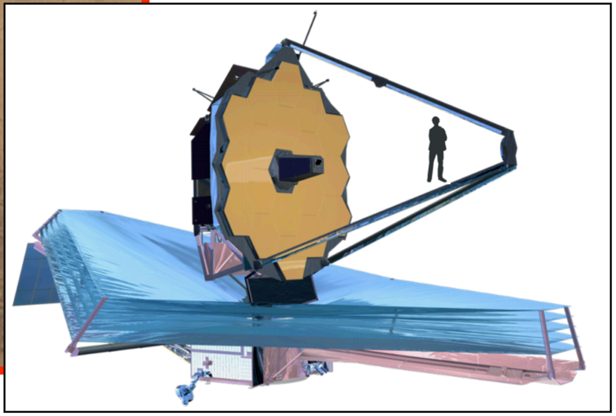
Is Earth a fluke, or are habitable climates common?

Habitable planets = subset of habitable-zone Earth-radius planets

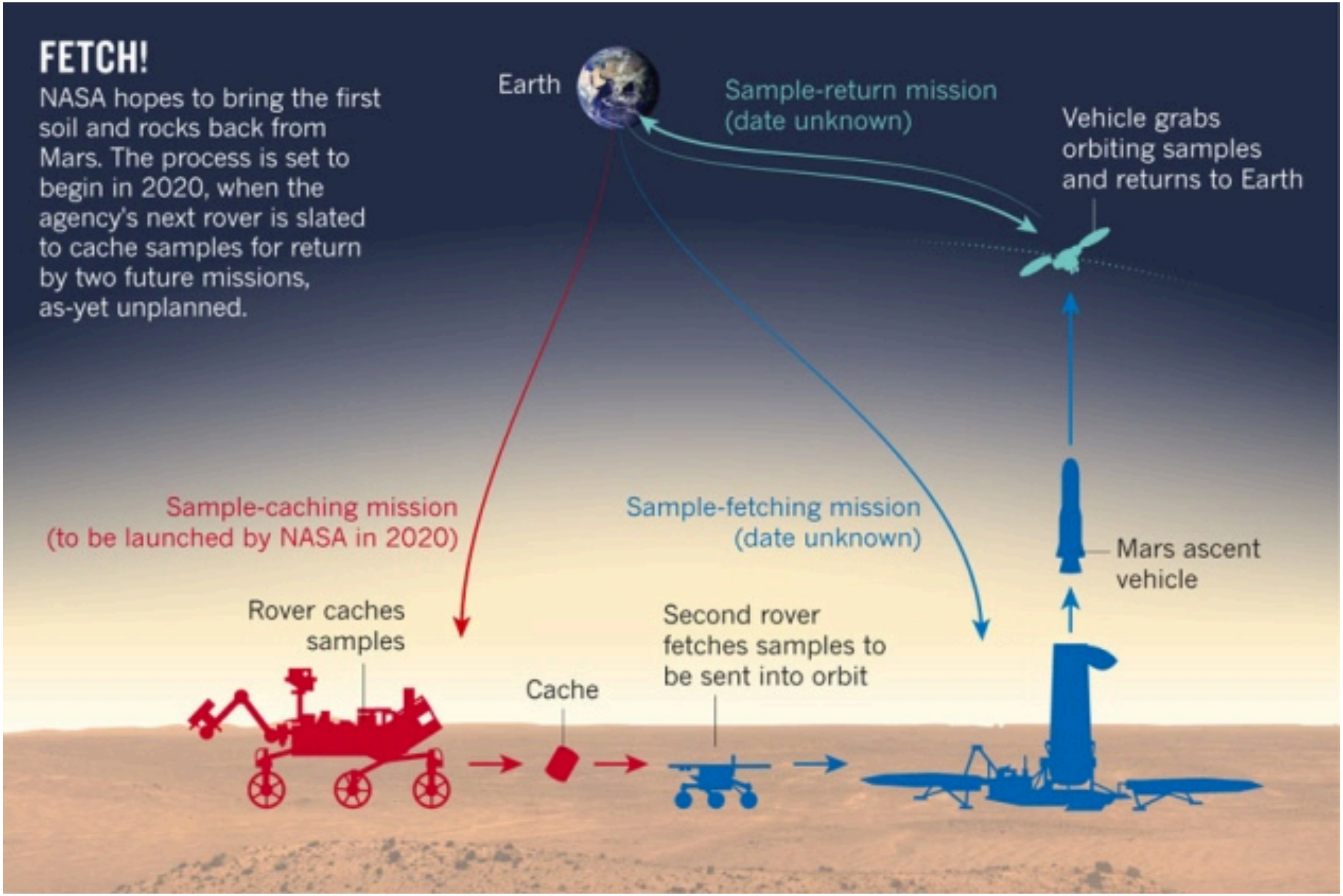
Yorkshire Coast, Earth
Toarcian OAE

Mars is the only planet known to record a major habitability transition in its sediments

Gale Crater, Mars
Habitability transition



Future large segmented telescopes
Exoplanet spectroscopy



FETCH!

NASA hopes to bring the first soil and rocks back from Mars. The process is set to begin in 2020, when the agency's next rover is slated to cache samples for return by two future missions, as-yet unplanned.

Exoplanet habitability

HABITABLE-ZONE 1-2 EARTH RADIUS PLANETS ARE NUMEROUS

HABITABLE-ZONE 1-2 EARTH RADIUS PLANETS ARE LIKELY DIVERSE COMPOSITIONALLY

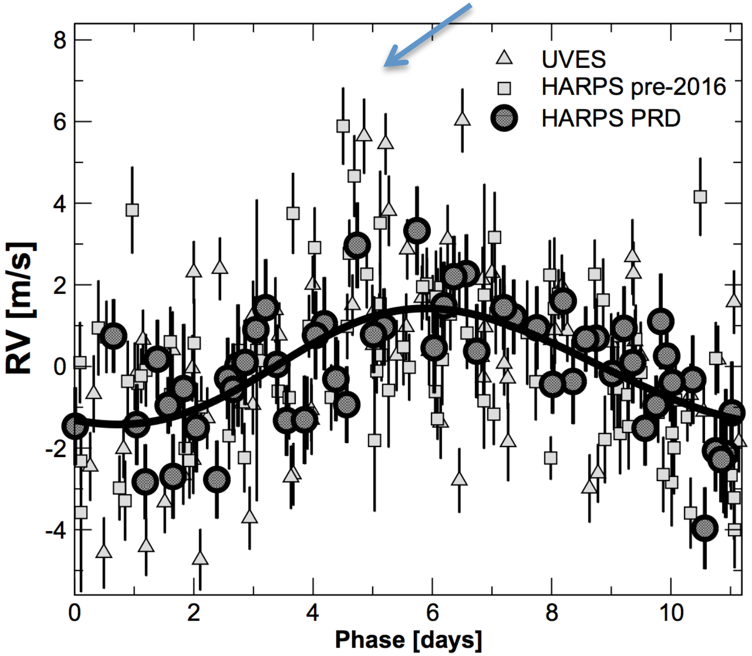
- MG/SI/FE
- WATER
- CARBON

THE M-STAR OPPORTUNITY

- PROBLEMS FOR HABITABILITY FOR PLANETS ORBITING M-STARS

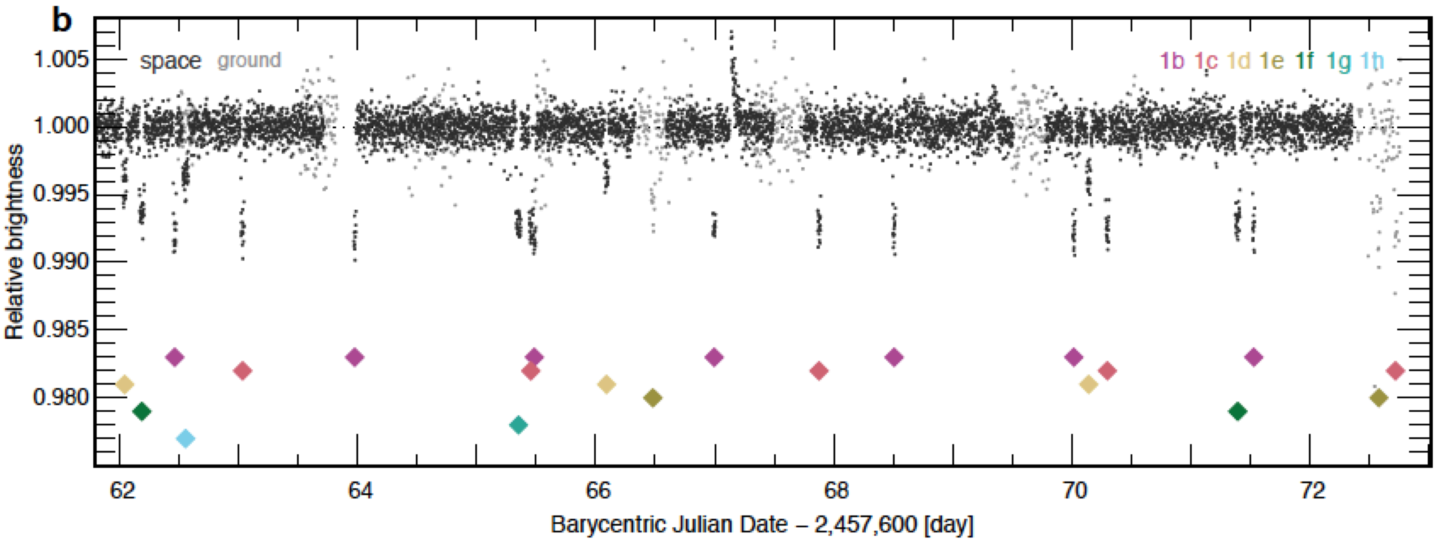
FUTURE MISSIONS

Exoplanets are detected mainly through radial velocity measurements and transits



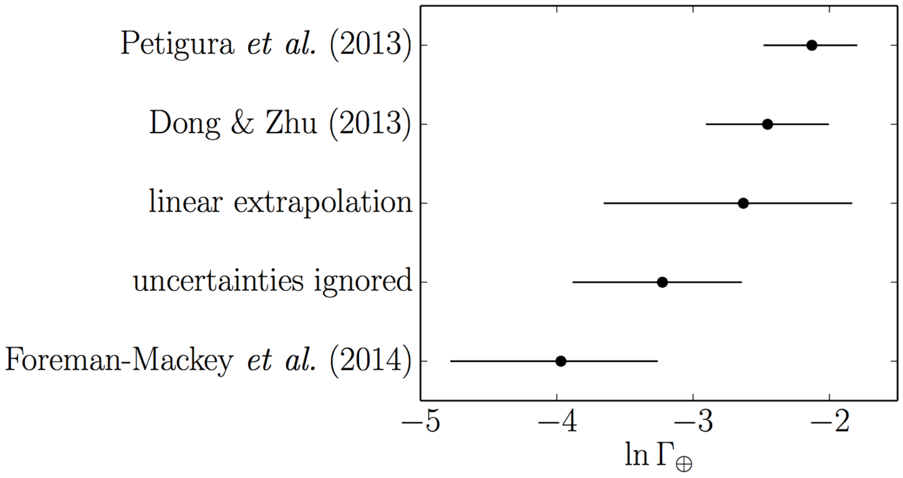
Proxima Centauri b
Anglada-Escudé et al. 2016

TRAPPIST-1 (Gillon et al. 2016)



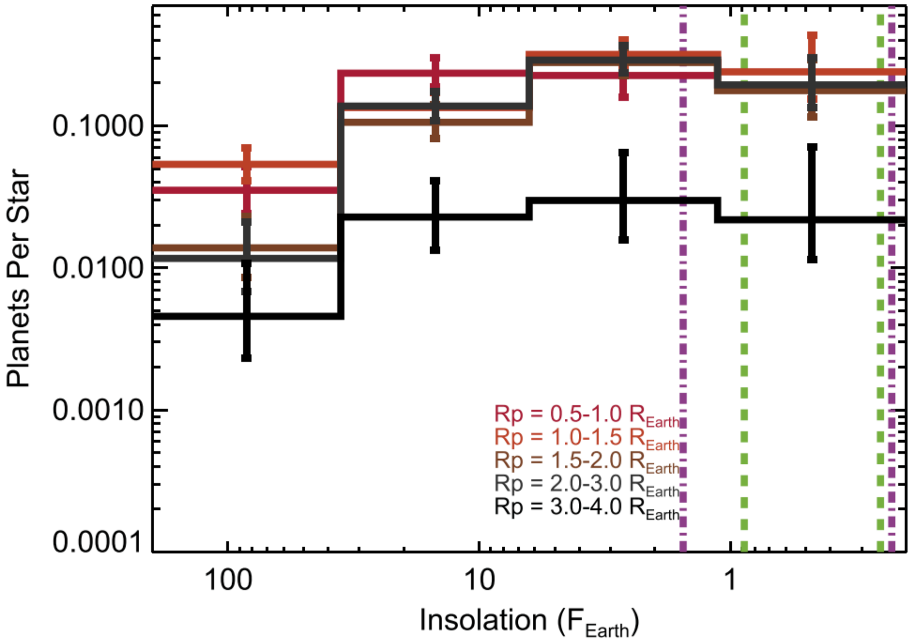
HABITABLE-ZONE 1-2 EARTH RADIUS PLANETS ARE NUMEROUS

Sunlike (FGK) stars:



$$\Gamma_\oplus = \left.\frac{\mathrm{d}N}{\mathrm{d}\ln P\ \mathrm{d}\ln R}\right|_{R=R_\oplus,\,P=P_\oplus}$$

Red dwarf (M) stars:

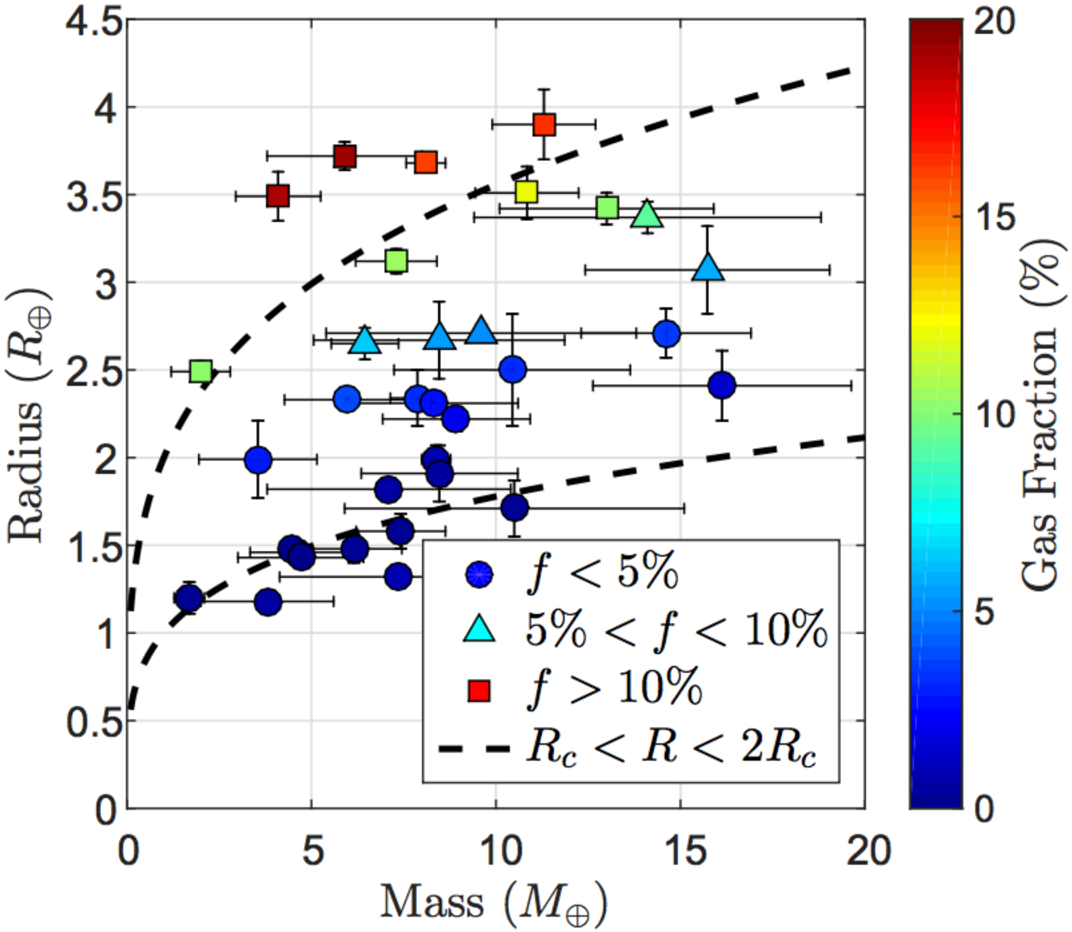


Dressing & Charbonneau ApJ 2015

HABITABLE-ZONE 1-2 EARTH RADIUS PLANETS ARE LIKELY DIVERSE COMPOSITIONALLY

- HYDROGEN
- MG/SI/FE
- WATER
- CARBON

HABITABLE-ZONE 1-2 EARTH RADIUS PLANETS ARE LIKELY DIVERSE COMPOSITIONALLY
- HYDROGEN

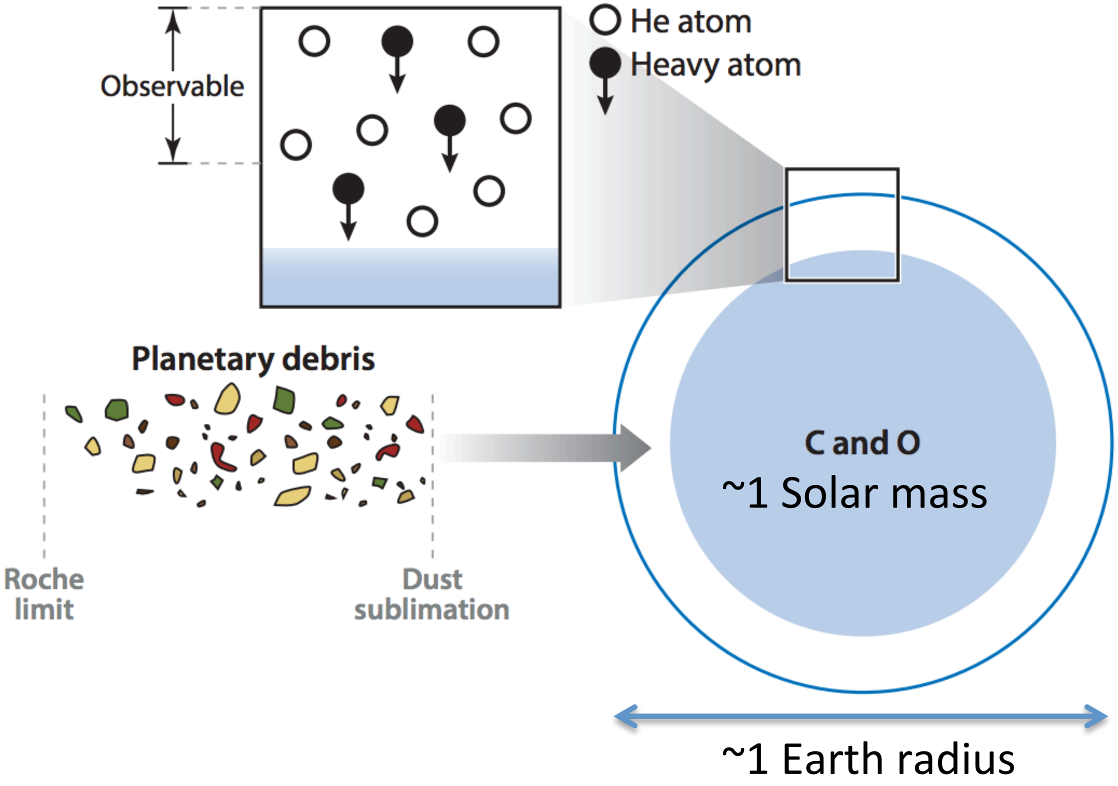


Ginzberg et al.
ApJ 2016

FIG. 2.— Observed super-Earth population (see text for details) from Weiss & Marcy (2014). The planets are grouped according to their gas mass fraction f, estimated by Equation (38), with low-density planets marked by triangles ($5\% < f < 10\%$) or squares ($f > 10\%$). The planet markers are also color-coded according to f. The two dashed black lines mark the radius of the rocky core $R_c(M_c)$ and $2R_c(M_c)$. Planets with substantial atmospheres are expected to be found roughly between the two lines.

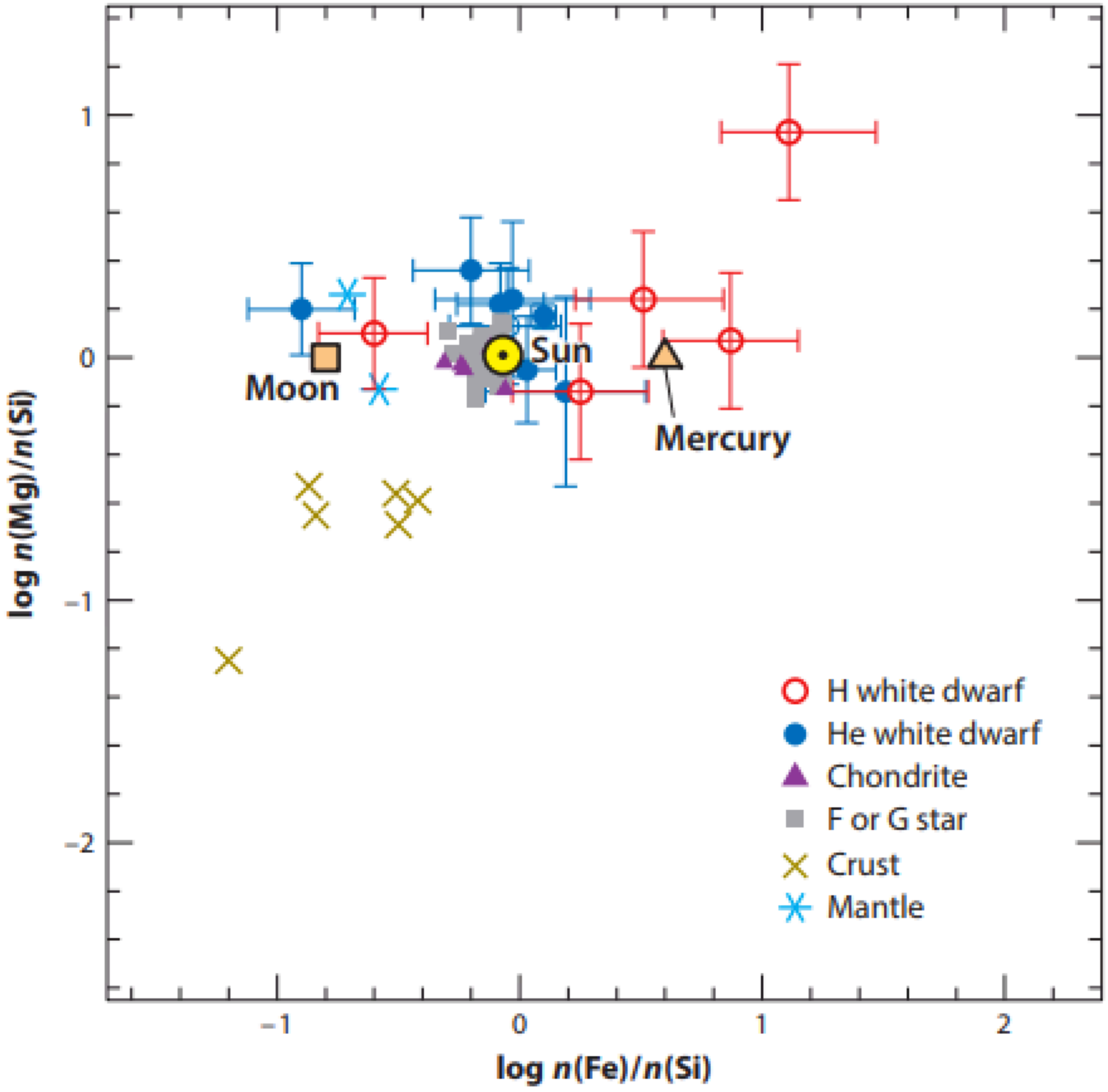
HABITABLE-ZONE 1-2 EARTH RADIUS PLANETS ARE LIKELY DIVERSE COMPOSITIONALLY

- MG/SI, MG/FE, e.t.c.



Constrained mainly by compositions of white dwarfs that are accreting material fderived from tidally shredded planets.

Jura & Young, 'Extrasolar cosmochemistry,' Annual Reviews, 2014



Jura & Young, ‘Extrasolar cosmochemistry,’ Annual Reviews, 2014

HABITABLE-ZONE 1-2 EARTH RADIUS PLANETS ARE LIKELY DIVERSE COMPOSITIONALLY

- WATER

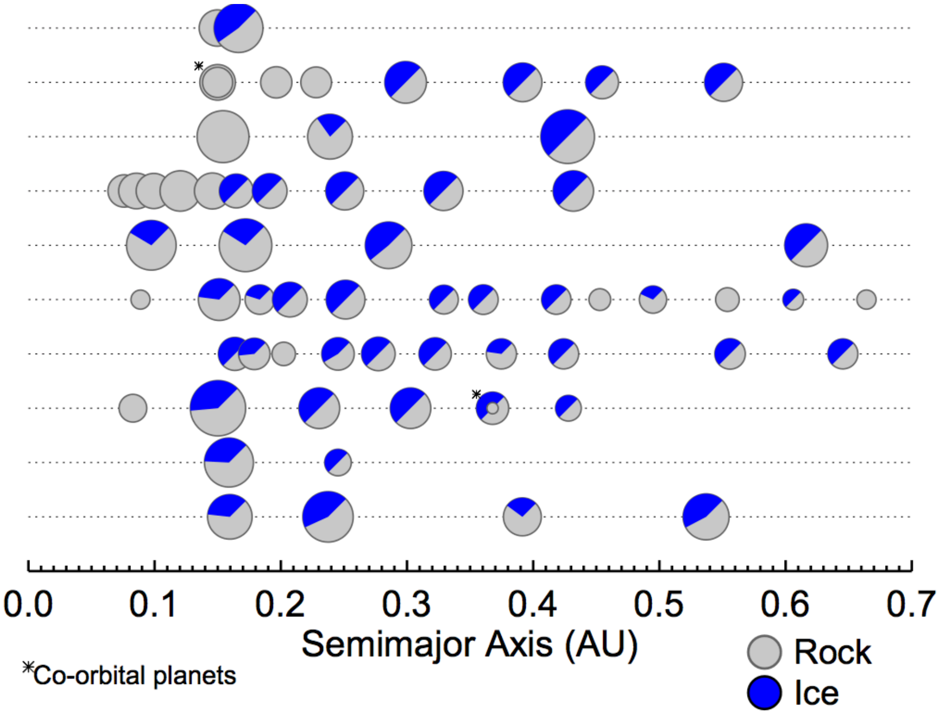
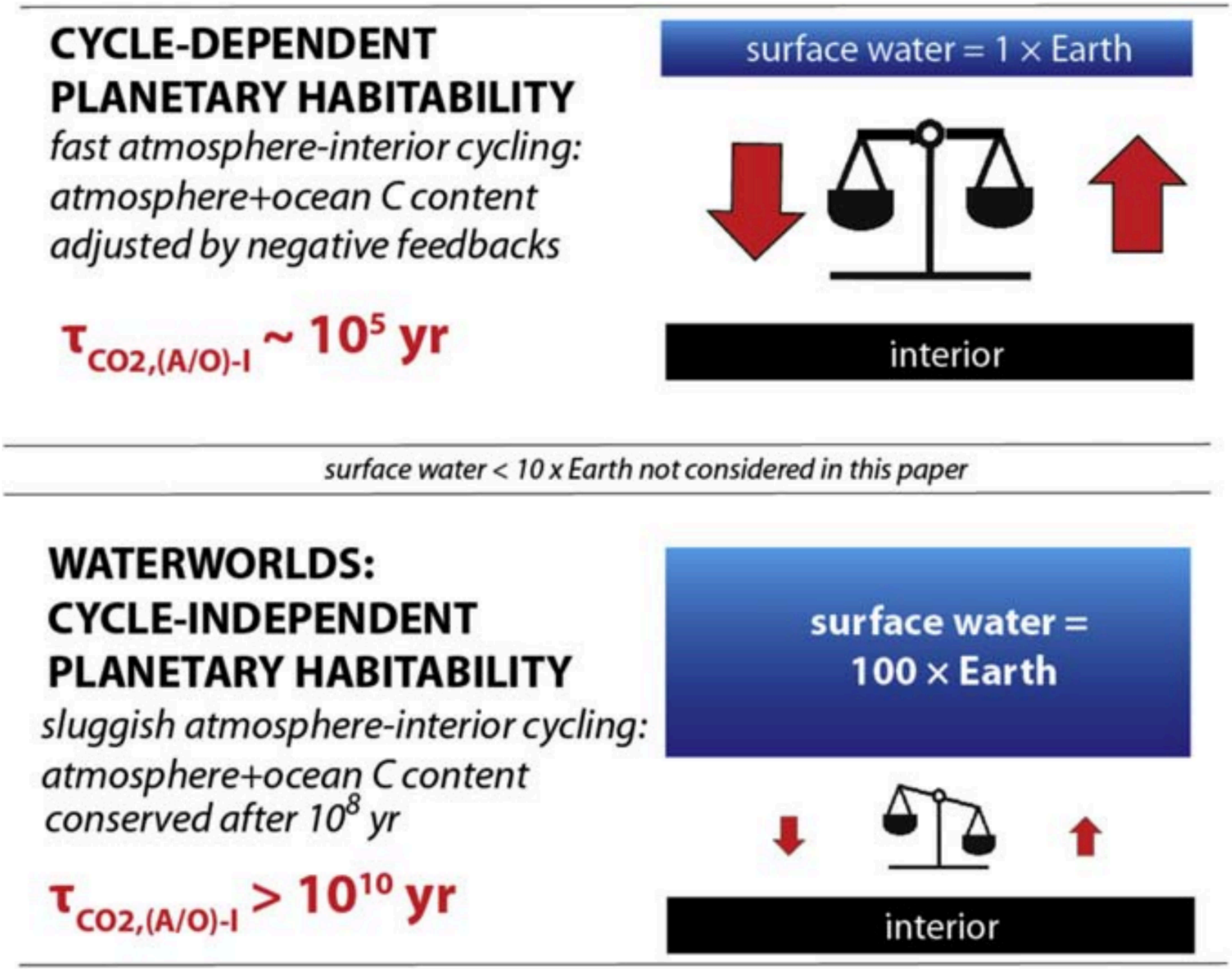


Figure 3. Final configuration of ten simulations illustrating the range of outcomes. Each planet's colors represent its rough composition: grey indicates rock and blue represents ice. Embryos that started past 5 AU started as 50-50 rock-ice mixtures and those from inside 5 AU were purely rocky. We do not account for various water loss processes and so the ice contents of simulated planets are certainly overestimates. The sizes of planets are scaled to their mass$^{1/3}$. The Kepler-36 analog system from Section 3 is at the top. Two co-orbital systems are marked with an asterisk.

Raymond et al.
MNRAS Letters 2018

CYCLE-INDEPENDENT PLANETARY HABITABILITY ON EXOPLANET WATERWORLDS?



CYCLE-DEPENDENT PLANETARY HABITABILITY

fast atmosphere-interior cycling: atmosphere+ocean C content adjusted by negative feedbacks

$\tau_{CO2,(A/O)-I} \sim 10^5$ yr

surface water < 10 x Earth not considered in this paper

WATERWORLDS: CYCLE-INDEPENDENT PLANETARY HABITABILITY

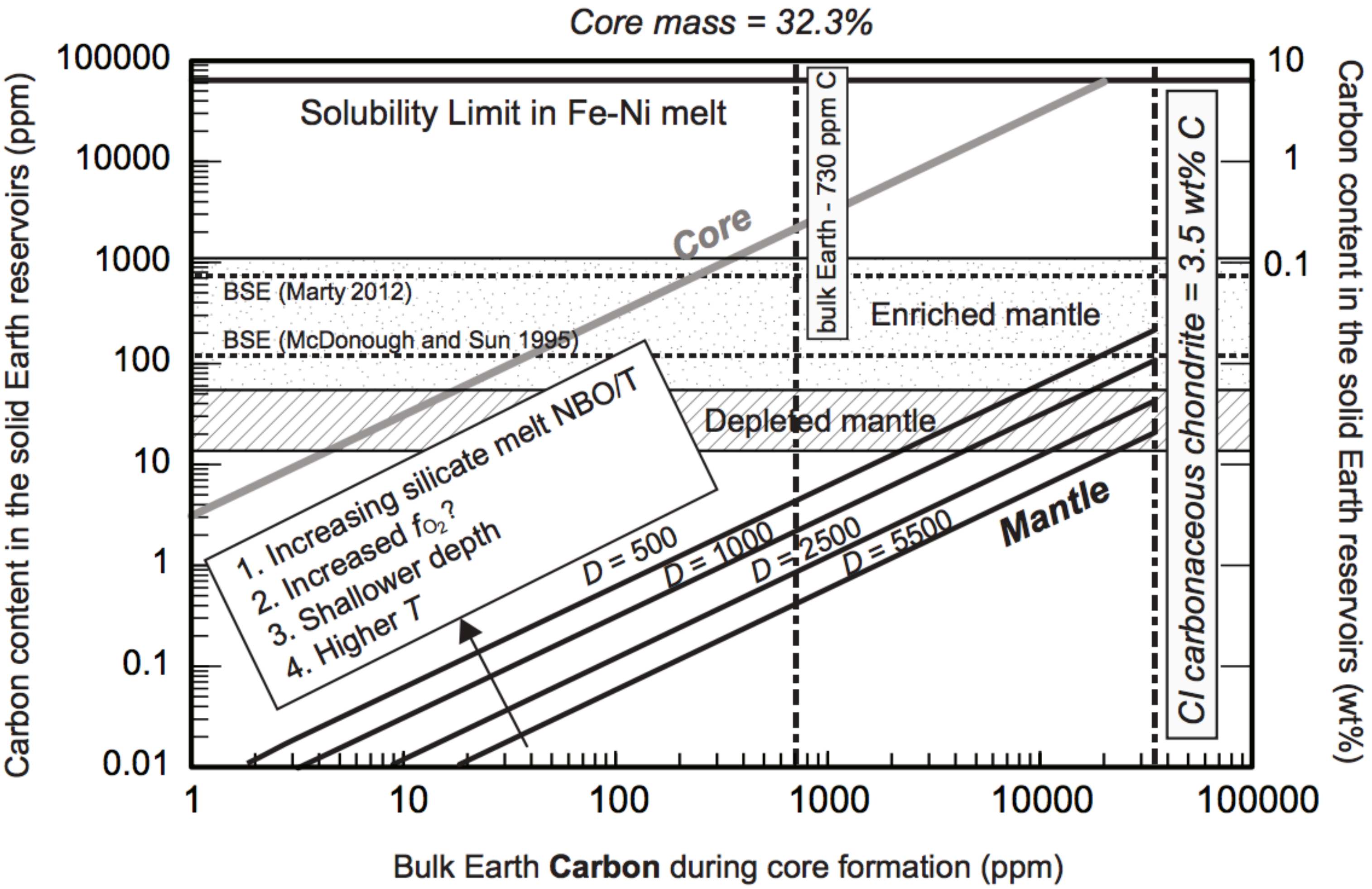
sluggish atmosphere-interior cycling: atmosphere+ocean C content conserved after 10^8 yr

$\tau_{CO2,(A/O)-I} > 10^{10}$ yr

Kite & Ford, ApJ 2018

HABITABLE-ZONE 1-2 EARTH RADIUS PLANETS ARE LIKELY DIVERSE COMPOSITIONALLY

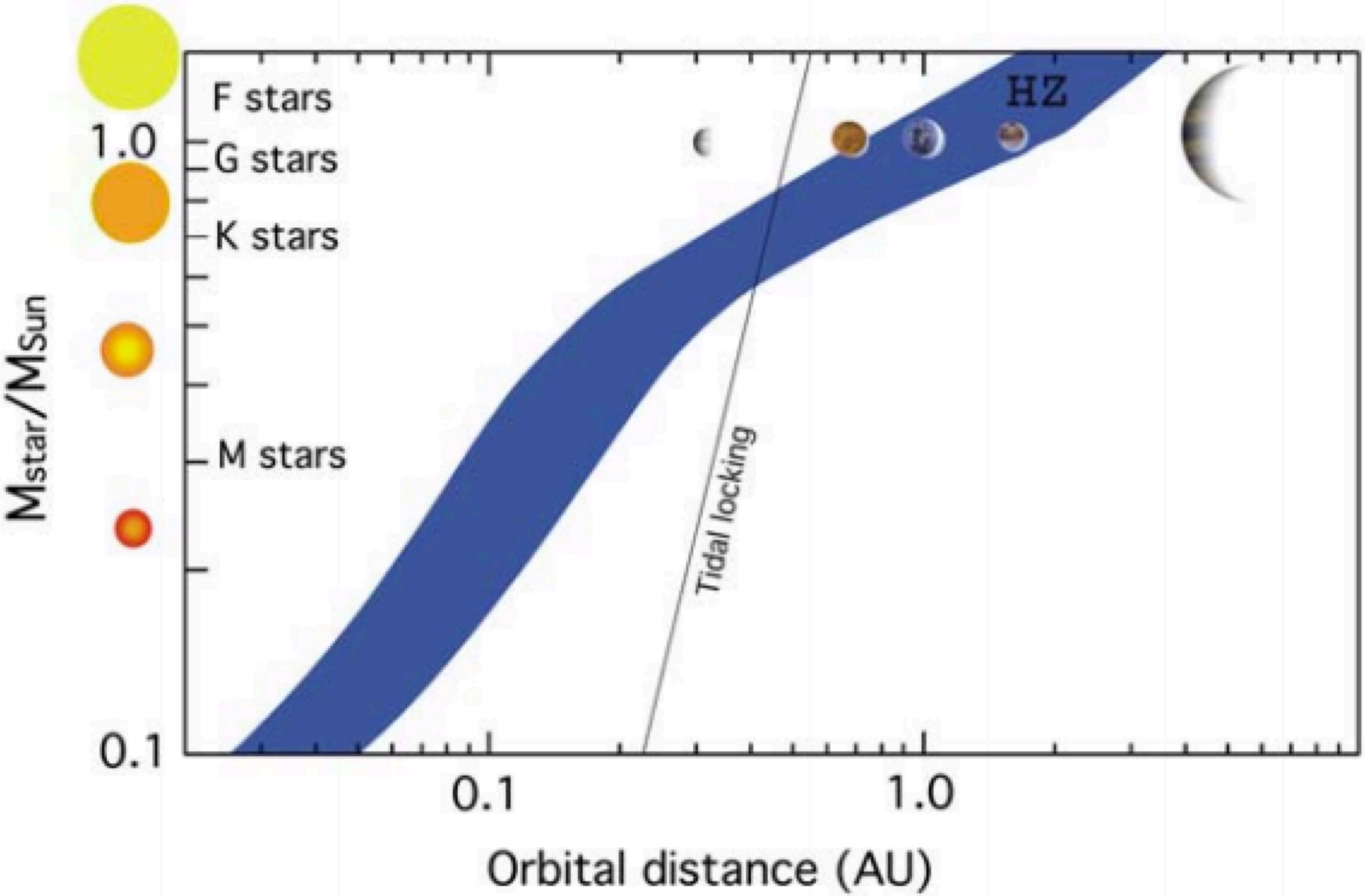
- CARBON

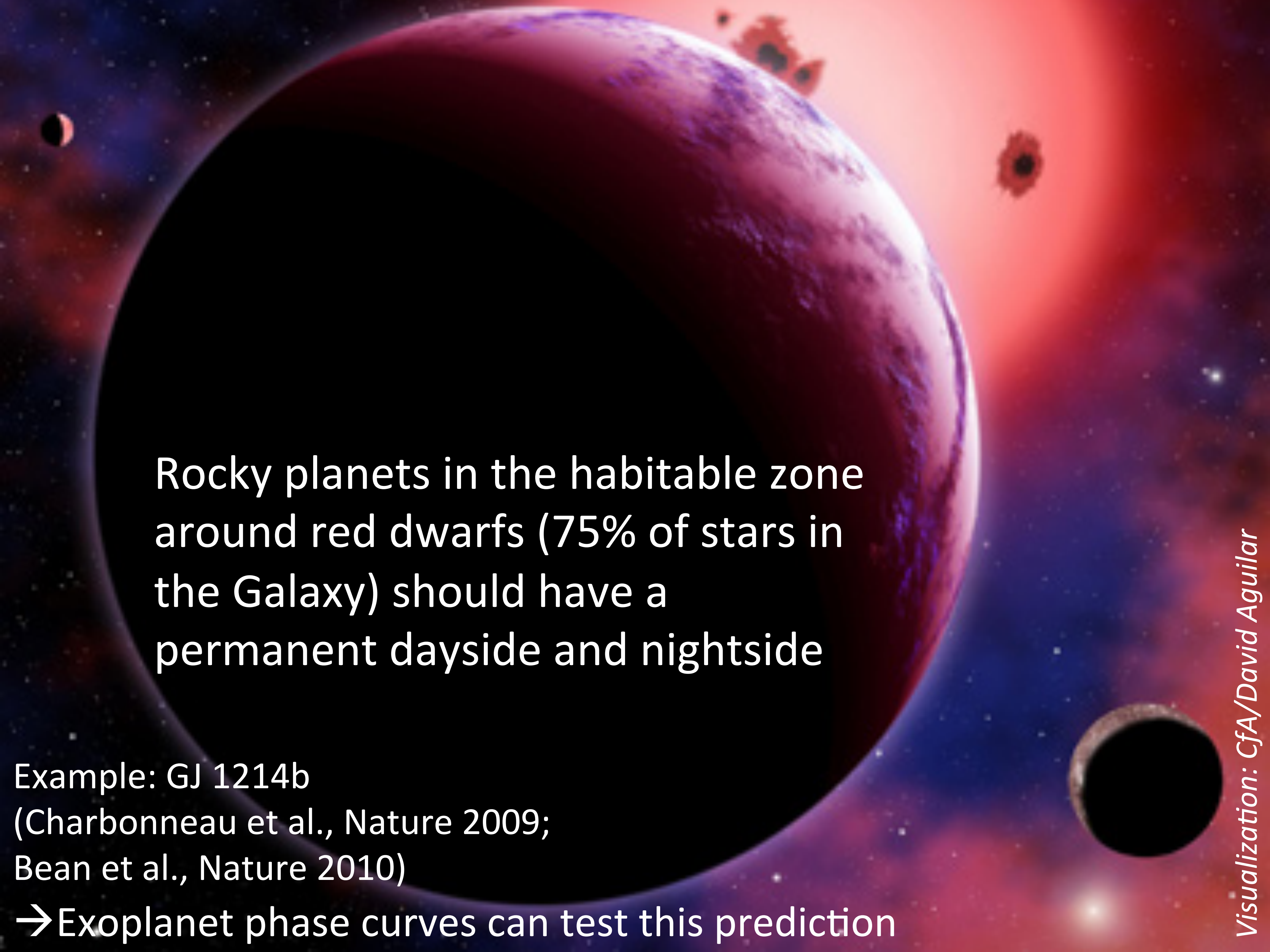


Dasgupta et al. 2013, Reviews in Mineralogy & Geochemistry

THE M-STAR OPPORTUNITY: RELATIVELY DEEPER AND MORE FREQUENT TRANSITS

→ EASIER TO DETECT & CHARACTERIZE



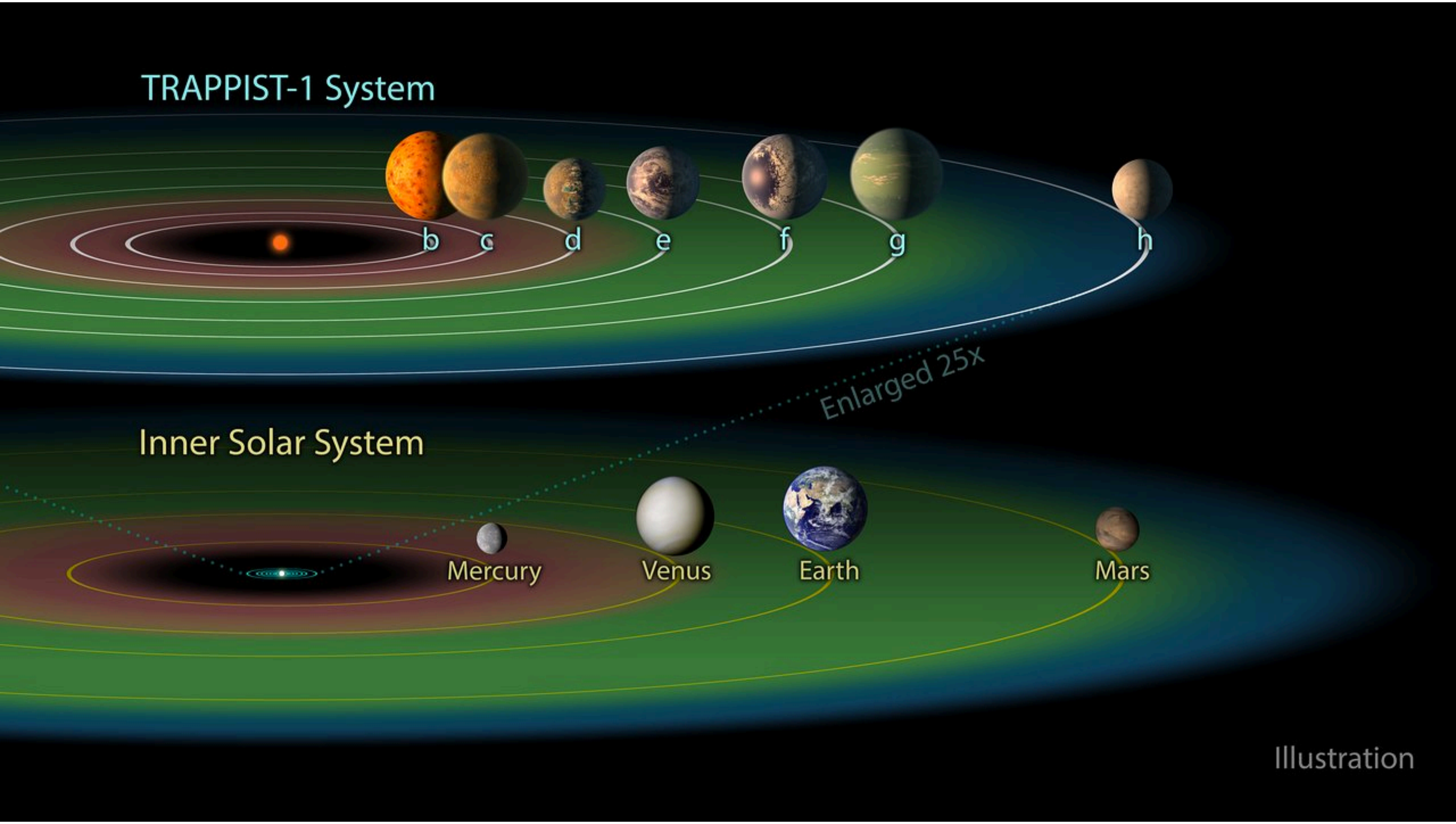


Rocky planets in the habitable zone around red dwarfs (75% of stars in the Galaxy) should have a permanent dayside and nightside

Example: GJ 1214b
(Charbonneau et al., Nature 2009;
Bean et al., Nature 2010)

→Exoplanet phase curves can test this prediction

Visualization: CfA/David Aguilar


TRAPPIST-1 System
b
c
d
e
f
g
h
Enlarged 25x
Inner Solar System
Mercury
Venus
Earth
Mars
Illustration

HIGH XUV FLUX SUSTAINED FOR LONG PERIOD FOR SMALL STARS

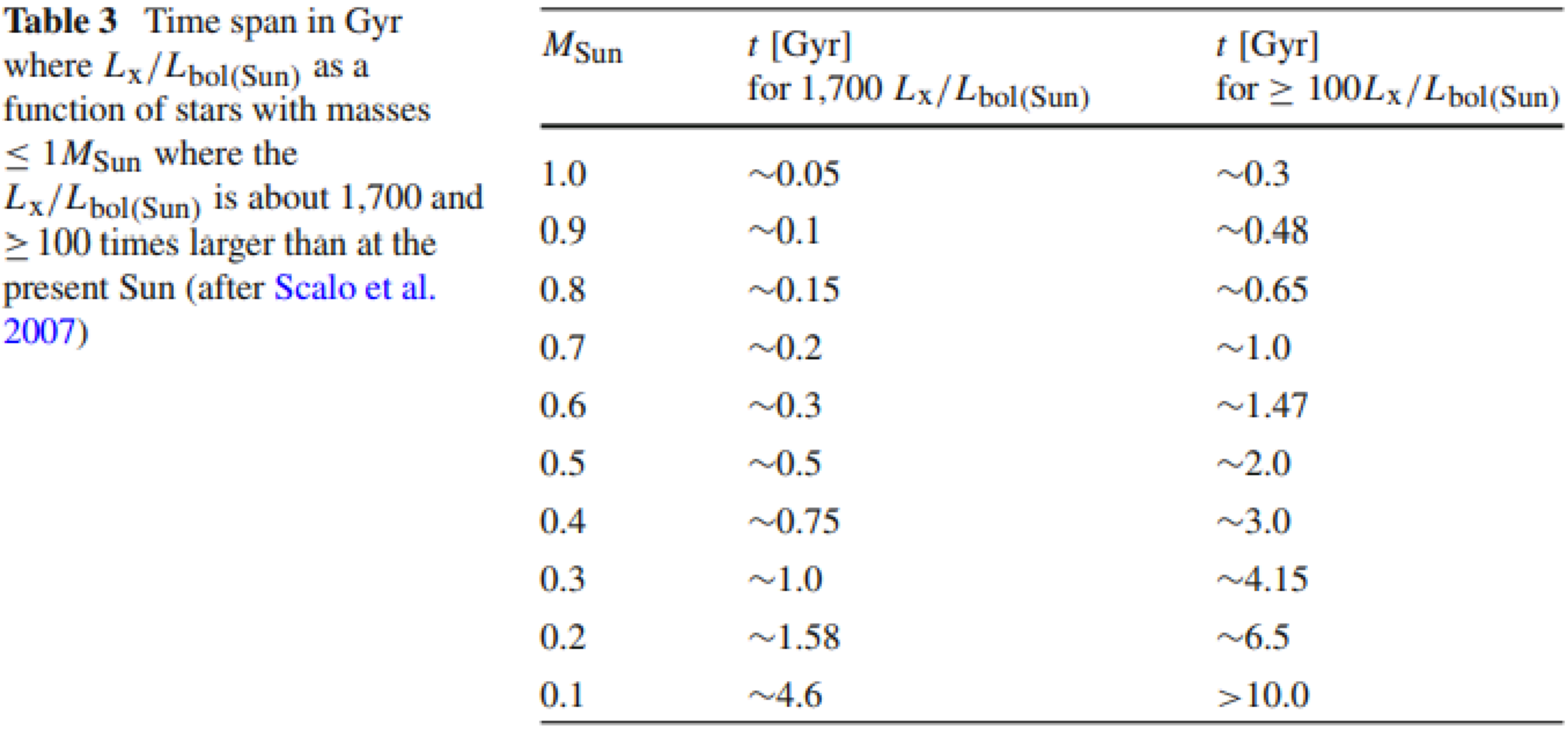
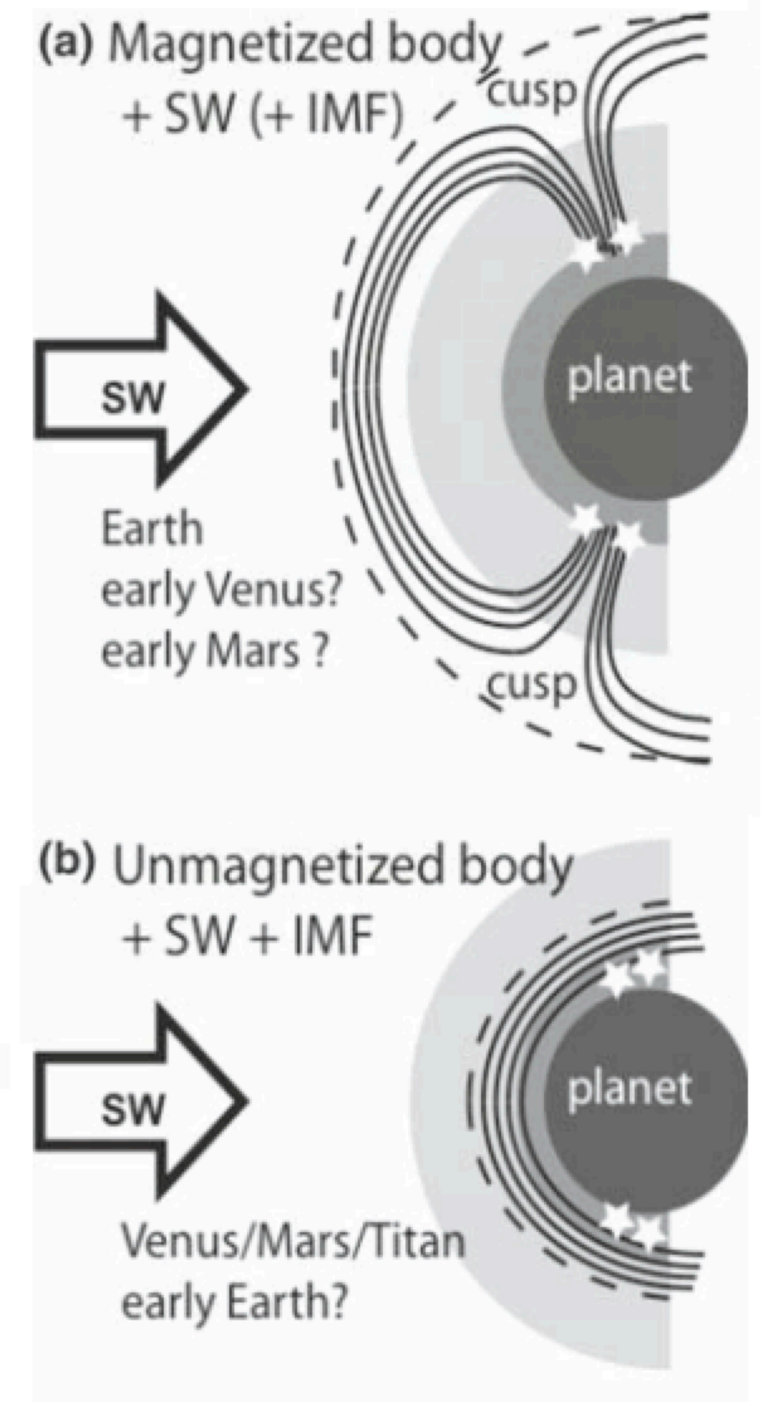


Table 3 Time span in Gyr where $L_x/L_{bol(Sun)}$ as a function of stars with masses $\leq 1 M_{Sun}$ where the $L_x/L_{bol(Sun)}$ is about 1,700 and ≥ 100 times larger than at the present Sun (after Scalo et al. 2007)

M_{Sun}	t [Gyr] for 1,700 $L_x/L_{bol(Sun)}$	t [Gyr] for $\geq 100 L_x/L_{bol(Sun)}$
1.0	~0.05	~0.3
0.9	~0.1	~0.48
0.8	~0.15	~0.65
0.7	~0.2	~1.0
0.6	~0.3	~1.47
0.5	~0.5	~2.0
0.4	~0.75	~3.0
0.3	~1.0	~4.15
0.2	~1.58	~6.5
0.1	~4.6	>10.0

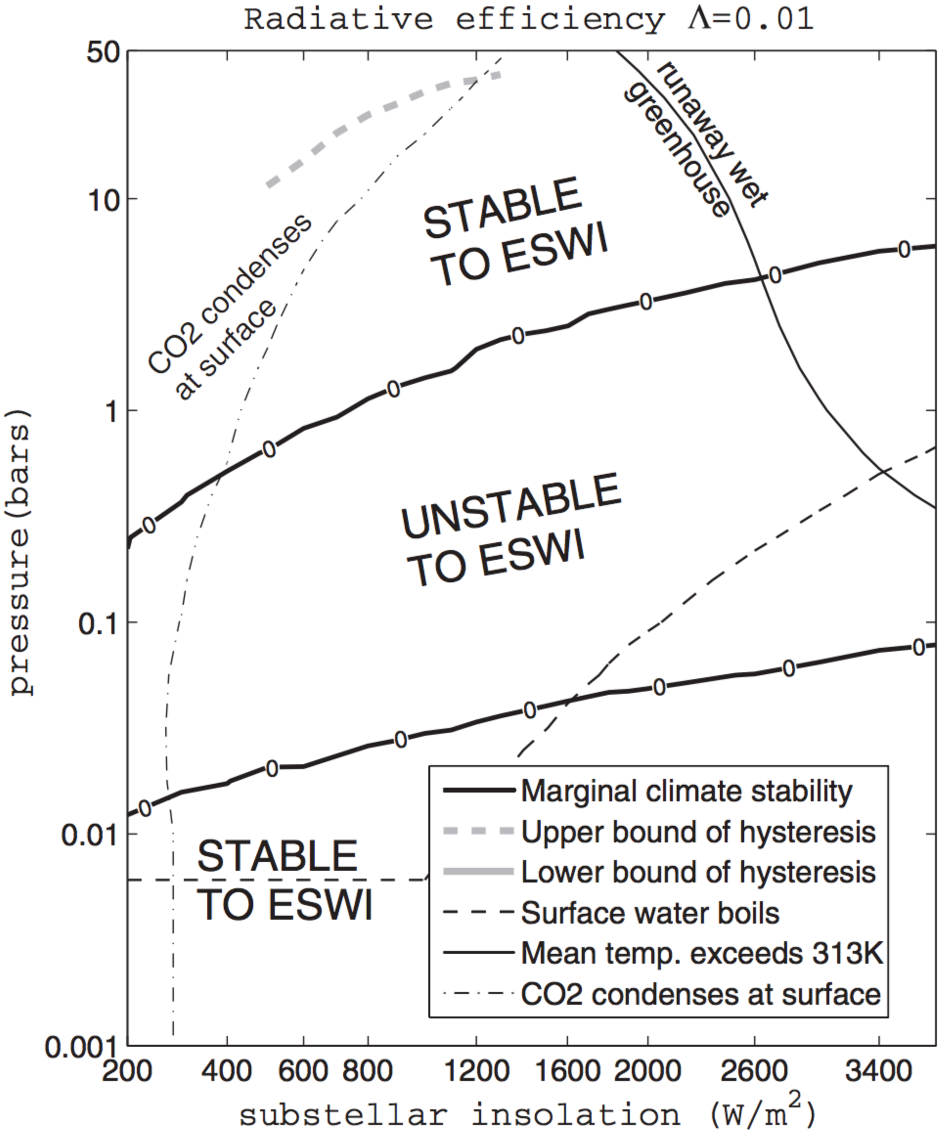
Lammer et al. 2009 Space Science Reviews

STRONGER STELLAR WIND → STRONGER NONTHERMAL ATMOSPHERIC ESCPAE



ADDITIONAL PROBLEMS FOR HABITABILITY FOR PLANETS ORBITING M-STARS

Enhanced Substellar Weathering Instability



Tarter et al. Astrobiology 2007

Kite et al. ApJ 2011

Exoplanet habitability

HABITABLE-ZONE 1-2 EARTH RADIUS PLANETS ARE NUMEROUS

HABITABLE-ZONE 1-2 EARTH RADIUS PLANETS ARE LIKELY DIVERSE COMPOSITIONALLY

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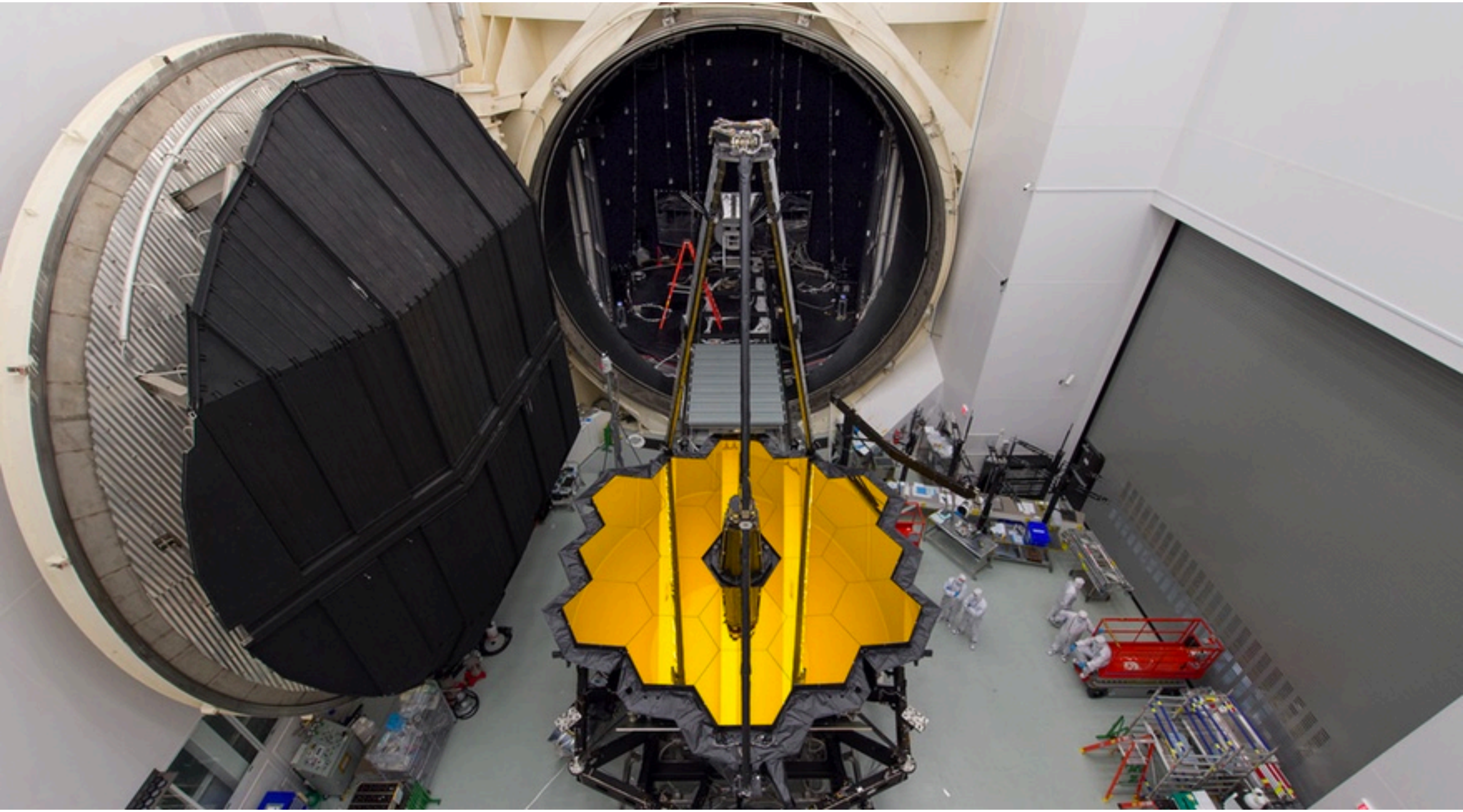
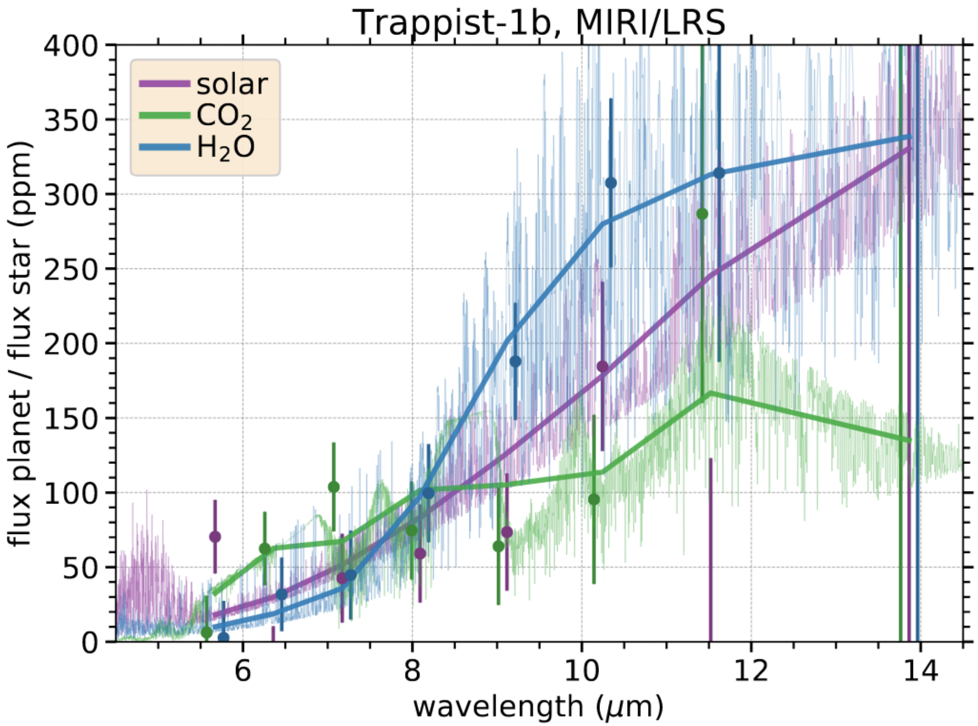
THE M-STAR OPPORTUNITY

- PROBLEMS FOR HABITABILITY FOR PLANETS ORBITING M-STARS

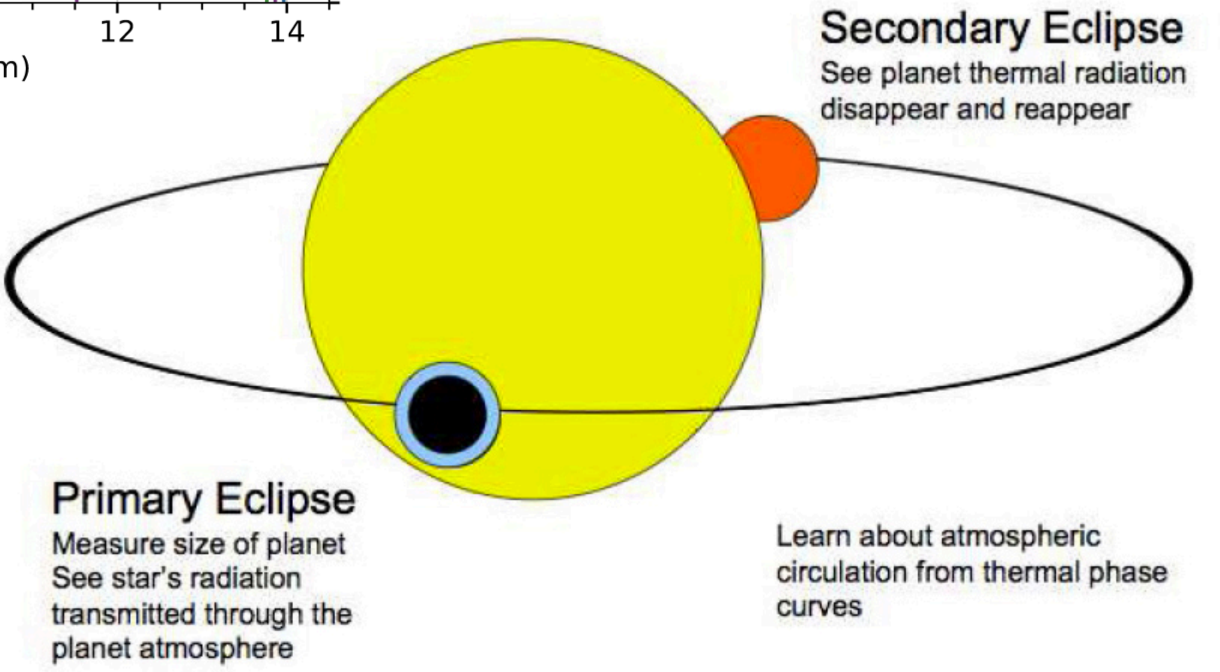
FUTURE MISSIONS



Simulated secondary eclipse spectra



Malik et al. in review



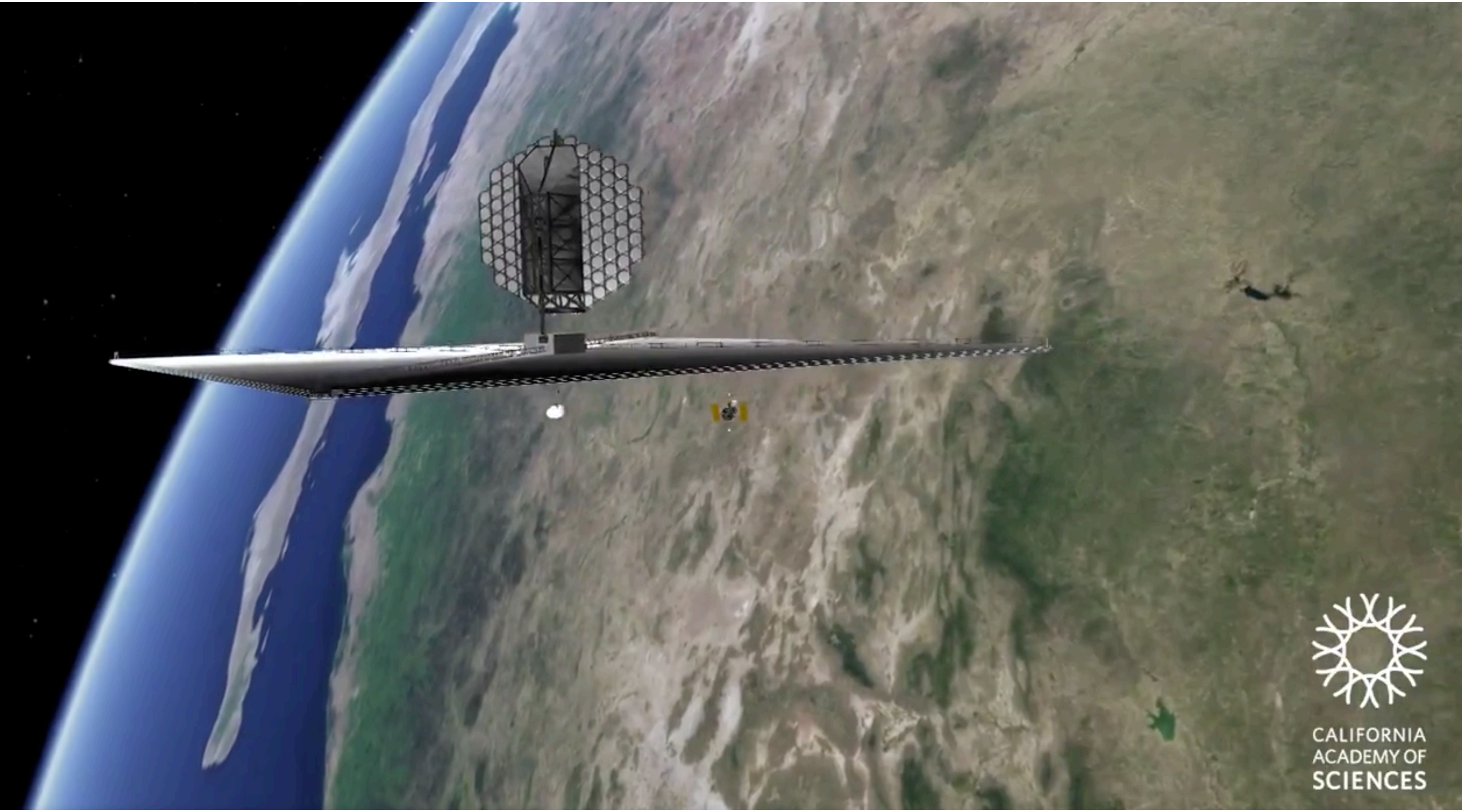
Secondary Eclipse

See planet thermal radiation disappear and reappear

Primary Eclipse

Measure size of planet
See star's radiation transmitted through the planet atmosphere

Learn about atmospheric circulation from thermal phase curves



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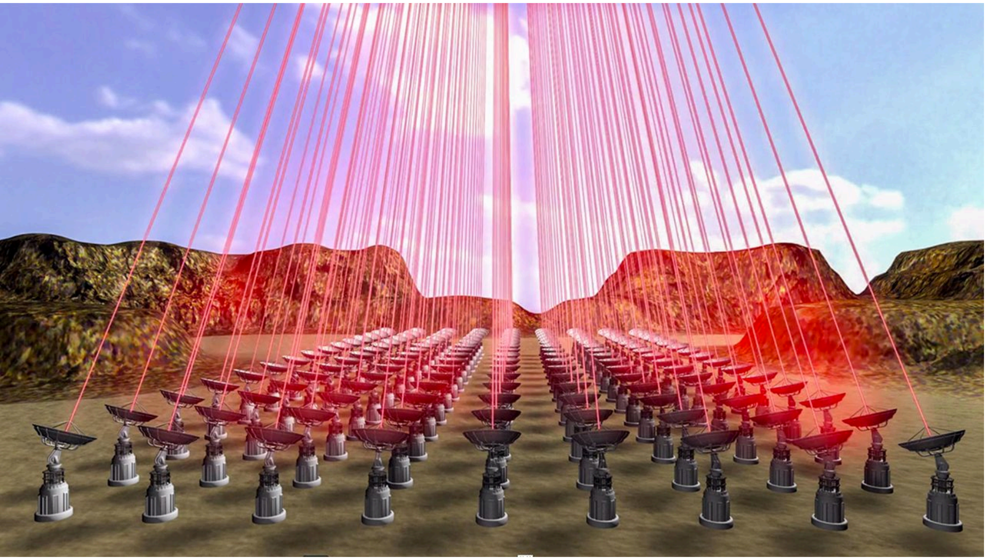
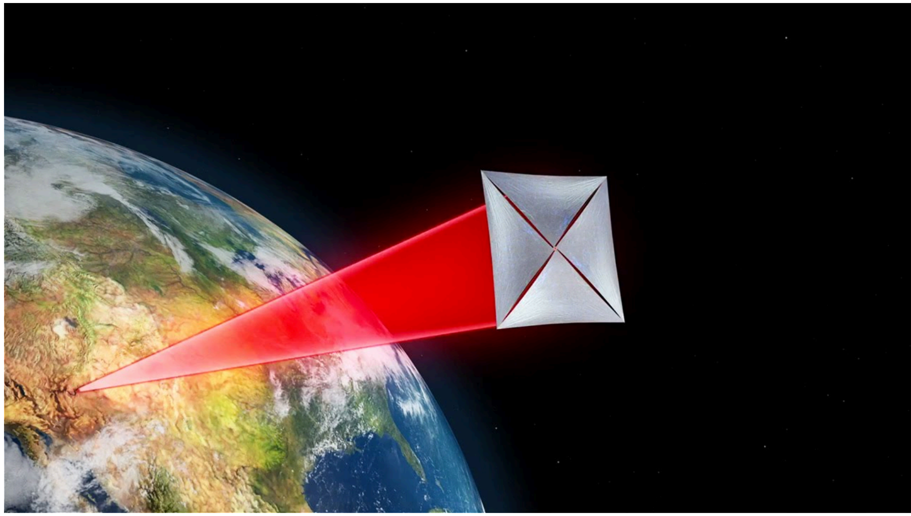
ACADEMY OF
SCIENCES

INTERSTELLAR MISSIONS?

- Current distance record: Voyager 1 @ 0.8 light-days
- No interstellar missions have been funded
- The technology for an interstellar mission does not currently exist
- Breakthrough Starshot is a philanthropically-funded technology development project for a laser-accelerated interstellar lightsail





50-70GW power, 0.1 gram payload, 5000g acceleration, 0.2c cruise speed

Exoplanet habitability

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HABITABLE-ZONE 1-2 EARTH RADIUS PLANETS ARE LIKELY DIVERSE COMPOSITIONALLY

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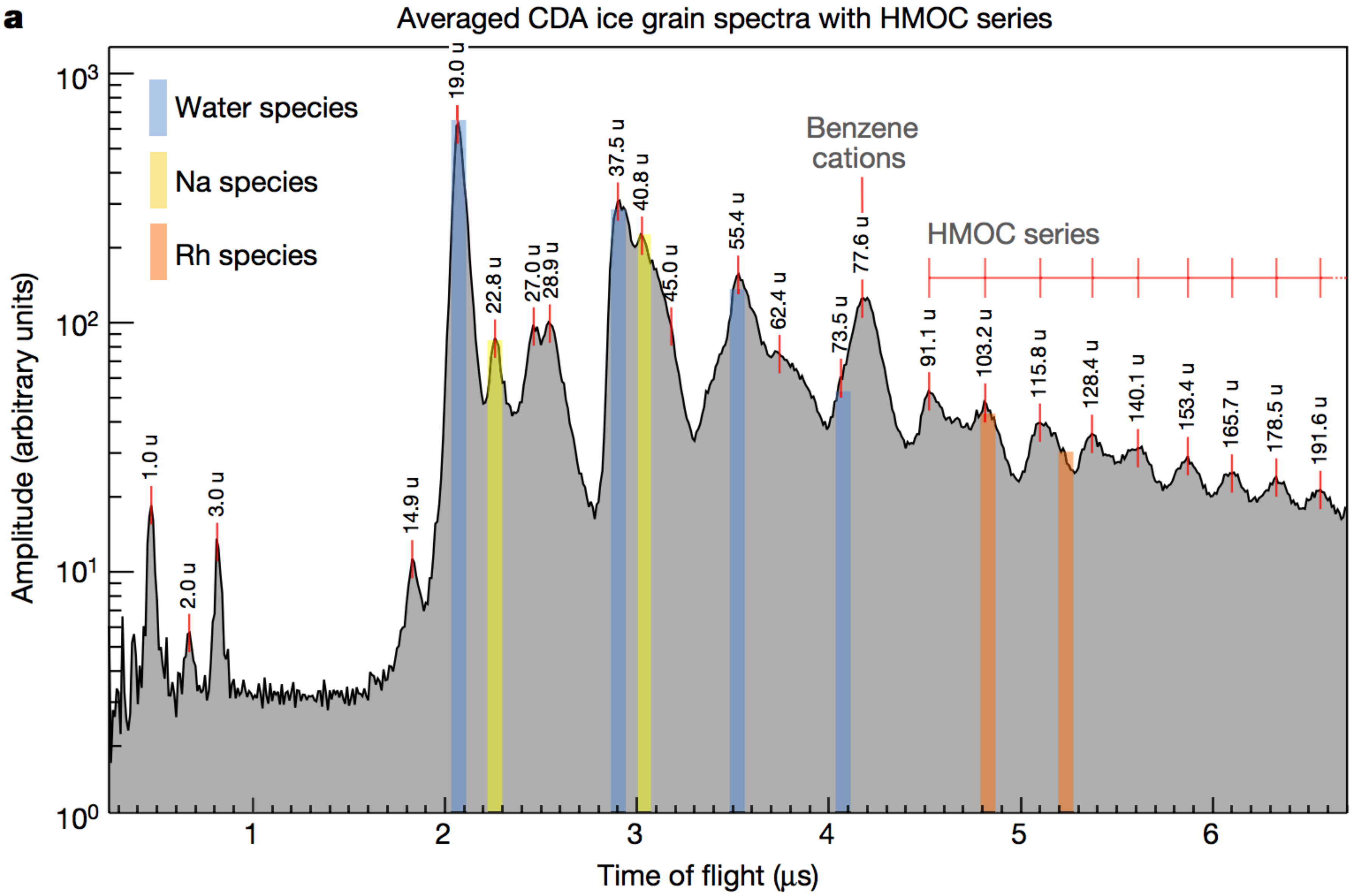
THE M-STAR OPPORTUNITY

- PROBLEMS FOR HABITABILITY FOR PLANETS ORBITING M-STARS

FUTURE MISSIONS


a
Averaged CDA ice grain spectra with HMOC series
Water species
Na species
Rh species
Benzene cations
HMOC series
1.0 u
2.0 u
3.0 u
14.9 u
19.0 u
22.8 u
27.0 u
28.9 u
37.5 u
40.8 u
45.0 u
55.4 u
62.4 u
73.5 u
77.6 u
91.1 u
103.2 u
115.8 u
128.4 u
140.1 u
153.4 u
165.7 u
178.5 u
191.6 u
Amplitude (arbitrary units)
10^3
10^2
10^1
10^0
Time of flight (µs)
1
2
3
4
5
6