Theoretical Investigations of Exomoons

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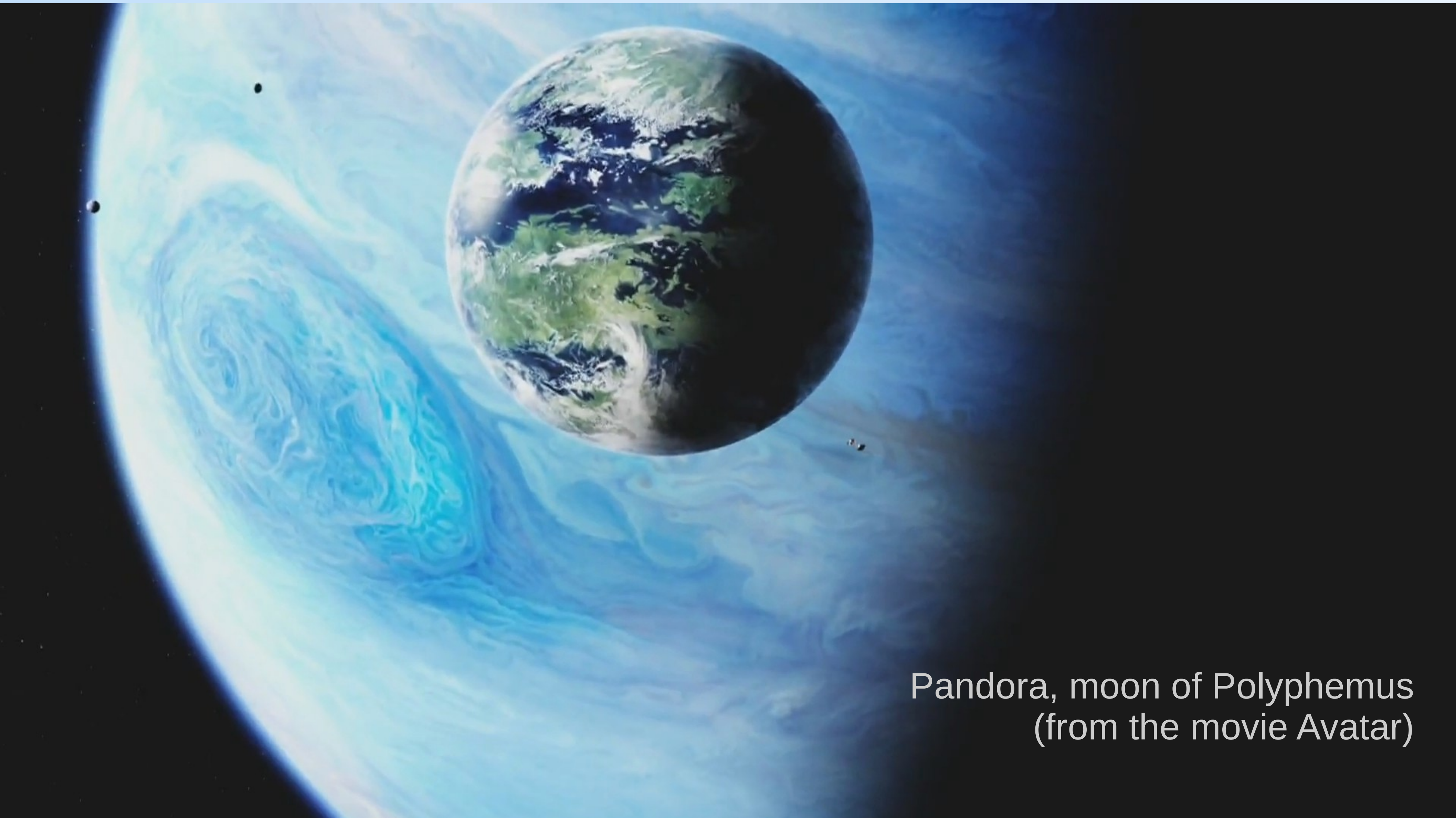
What makes Pandora habitable?

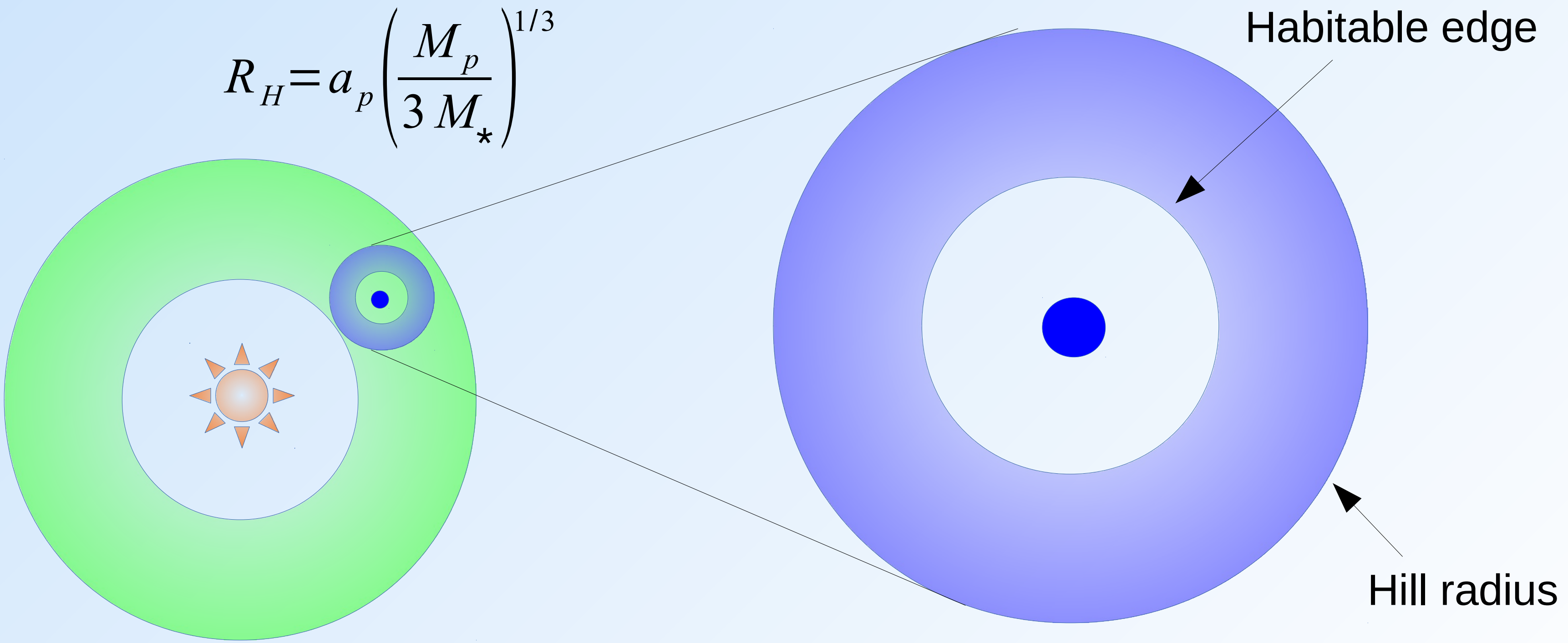


Pandora, moon of Polyphemus
(from the movie Avatar)

Circumplanetary habitability

- Range of habitable orbits around a planet in the IHZ
  - Habitable edge: the innermost orbit defined by the runaway greenhouse limit
  - Hill radius: farthest possible orbit around the planet (gravitational dominance)

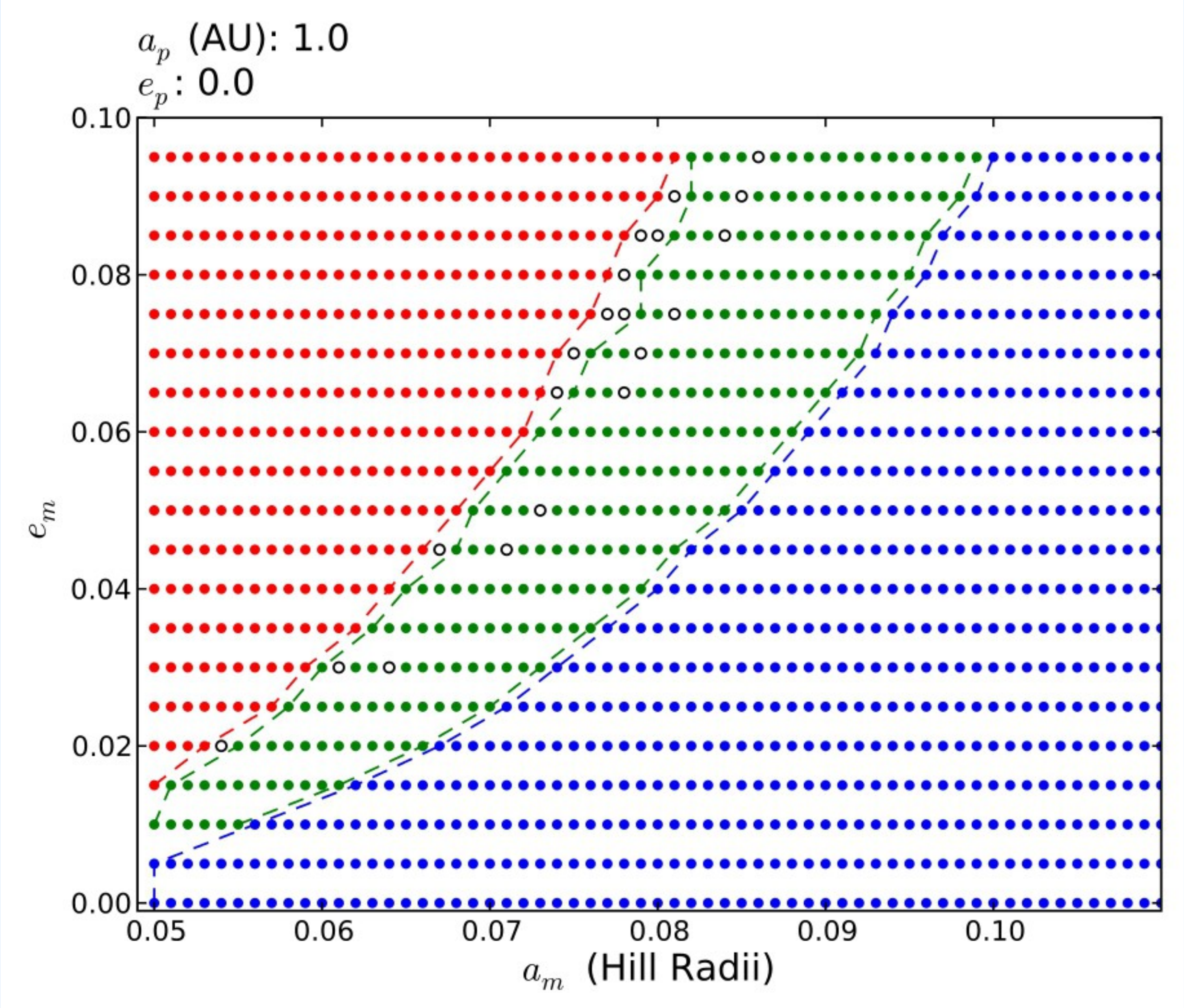
$$R_H = a_p \left(\frac{M_p}{3 M_*} \right)^{1/3}$$



Outer limit: snowball Pandora

1D Energy Balance Climate Models:
Stellar flux
+ planetary flux
+ tidal heating

Eclipses
+
Ice-Albedo Feedback
=
2nd Circumplanetary Edge!



Forgan & Yotov (2014) MNRAS 441, 3513

Runaway Greenhouse

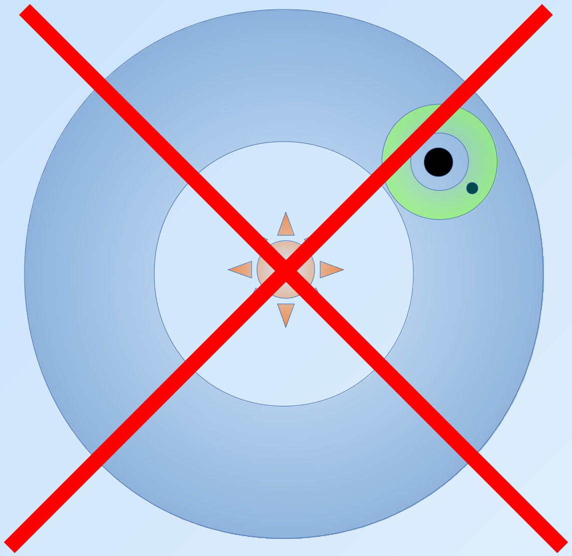
Snowball Moon

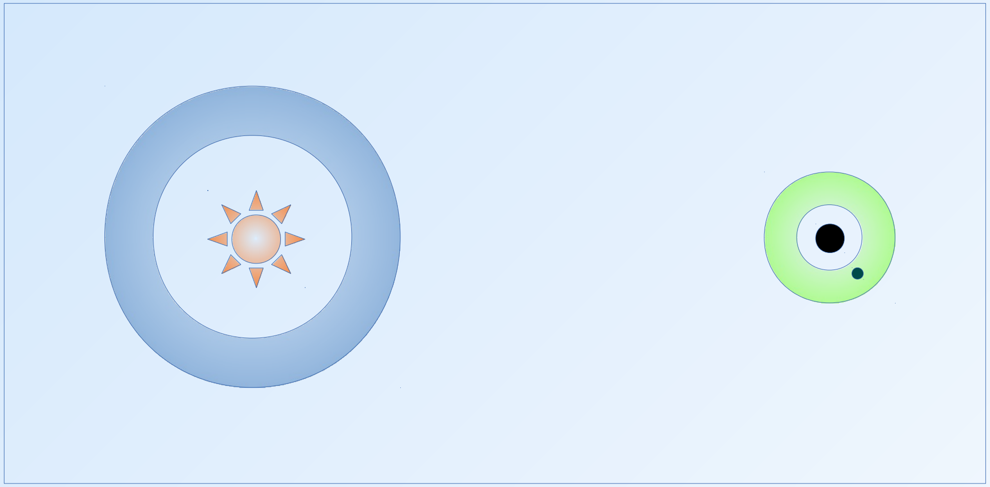
Habitable

Transiently Habitable

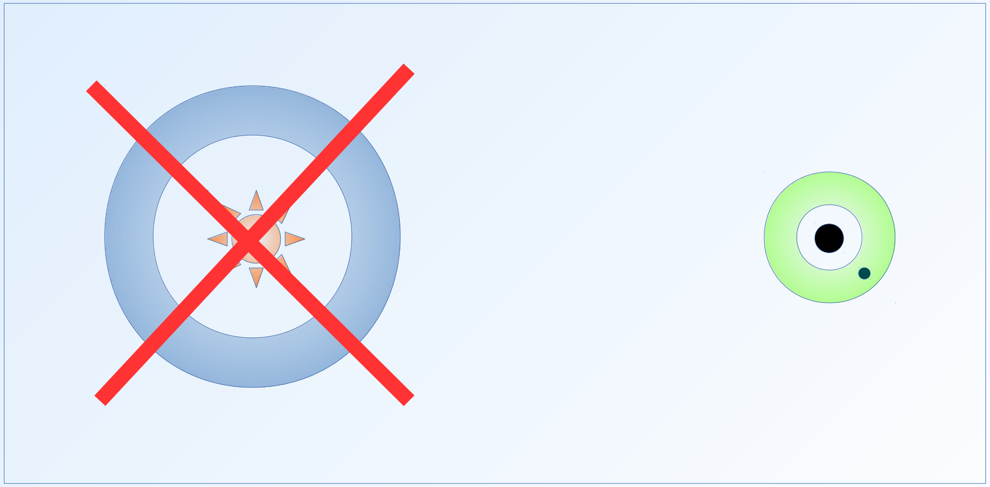
Could Pandora be habitable...

... outside the circumstellar habitable zone?



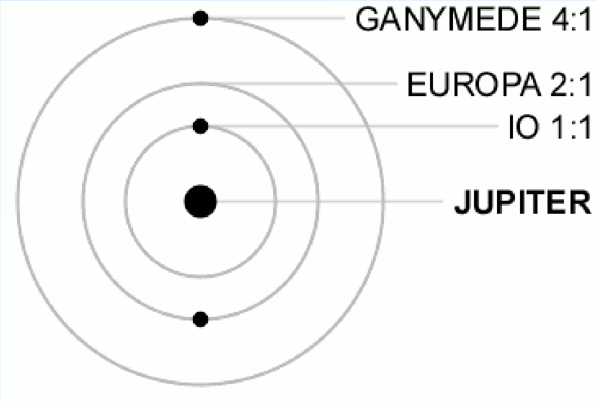


... or without a star?



Tidal Heating

- Inner heat
  - Gravitational forces, deformation
  - Inner friction → heat dissipation
  - If perfectly elastic: immediate deformation
  - Else: Time lag
  - Dissipation depends on internal structure

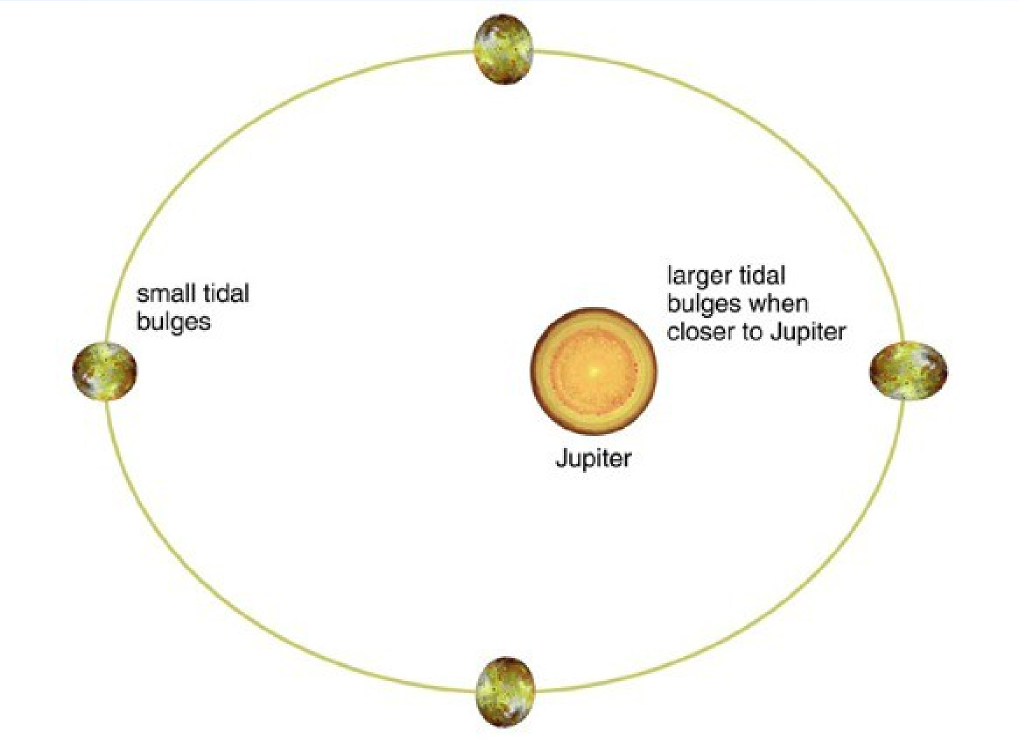


- Eccentricity is needed!

$$\dot{E} = \frac{21}{2} \frac{R^5 n^5 e^2}{G} \frac{k_2}{Q}$$

  - MMR maintain tidal forces

- Can maintain suitable temperature for liquid water for several Gyrs



Models

- **Fixed Q models:** (e.g. Peters & Turner, 2013, ApJ 769, 98)

$$L_{tidal} = \frac{42\pi G^{5/2}}{19} \frac{R^7 \rho^2 M_p^{5/2}}{\mu Q} \frac{e^2}{a^{15/2}}$$

μ: rigidity

Q: dissipation factor

Rocky planets, moons: 1 – 100

Giant planets: 10^4 – 10^5 order of magnitude

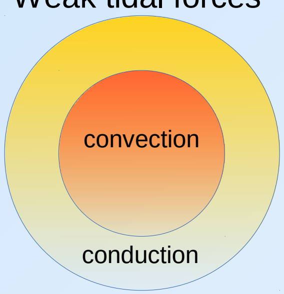
- **Viscoelastic models:**

  (Fischer & Spohn 1990, Moore 2003)

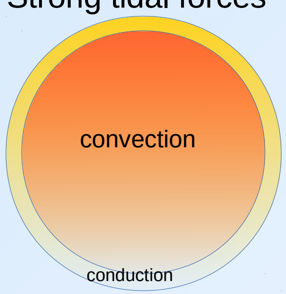
  - $\eta(T)$, $M(T)$
  - Tidal heat rate:

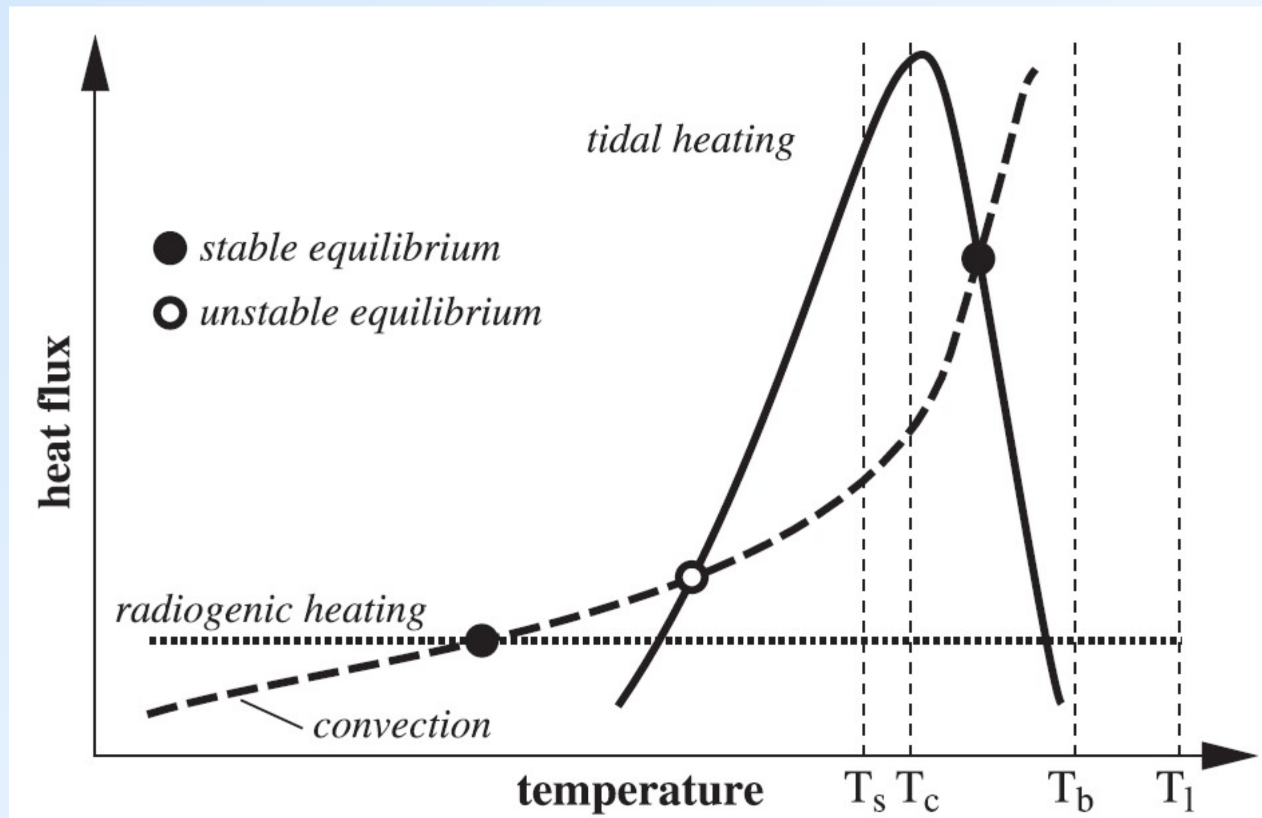
$$\dot{E} = \frac{-21}{2} \frac{R^5 n^5 e^2}{G} \operatorname{Im}(k_2)$$

Weak tidal forces



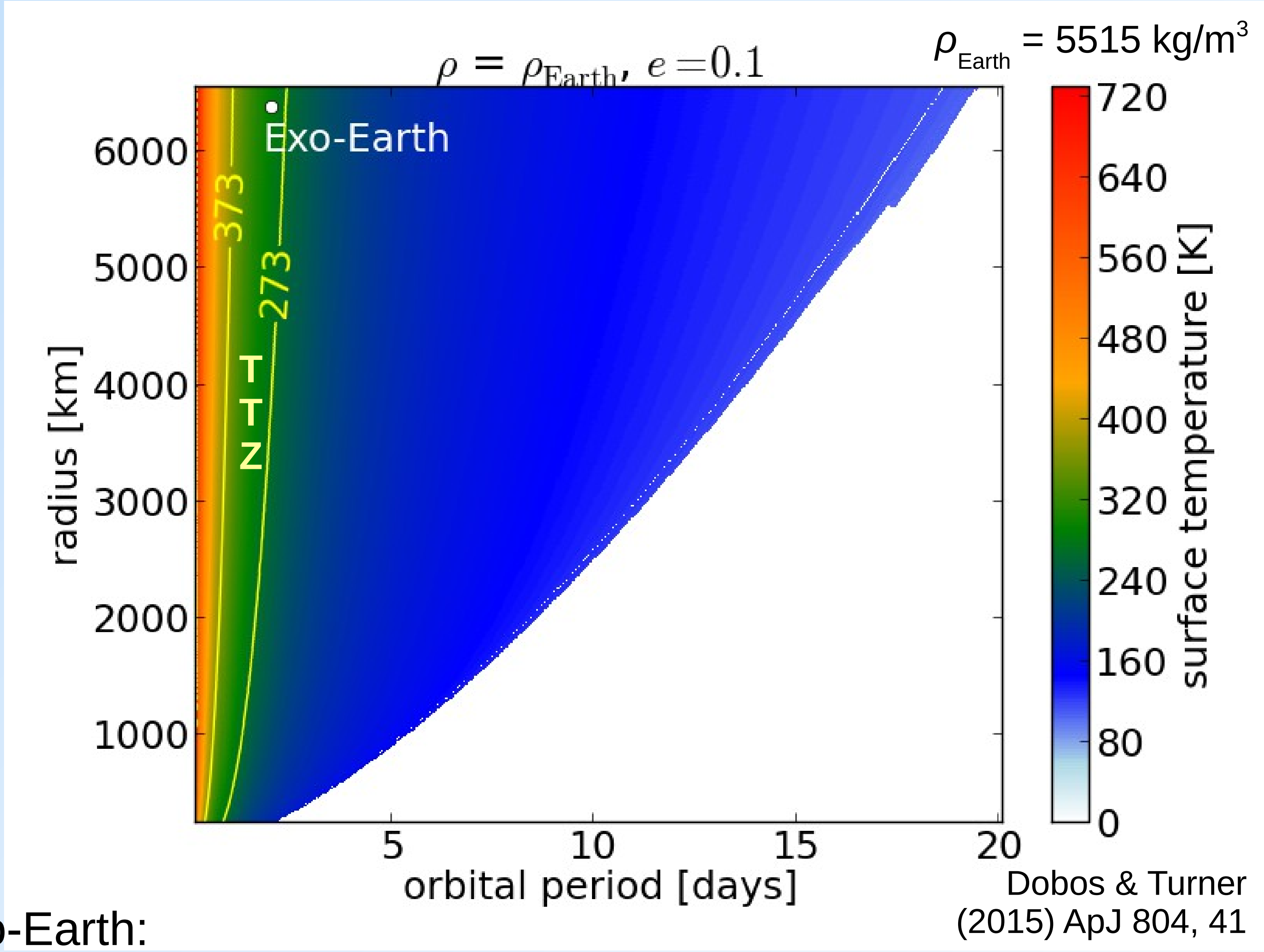
Strong tidal forces





Moore (2003) Journal of Geophysical Research (Planets), 108, 5096

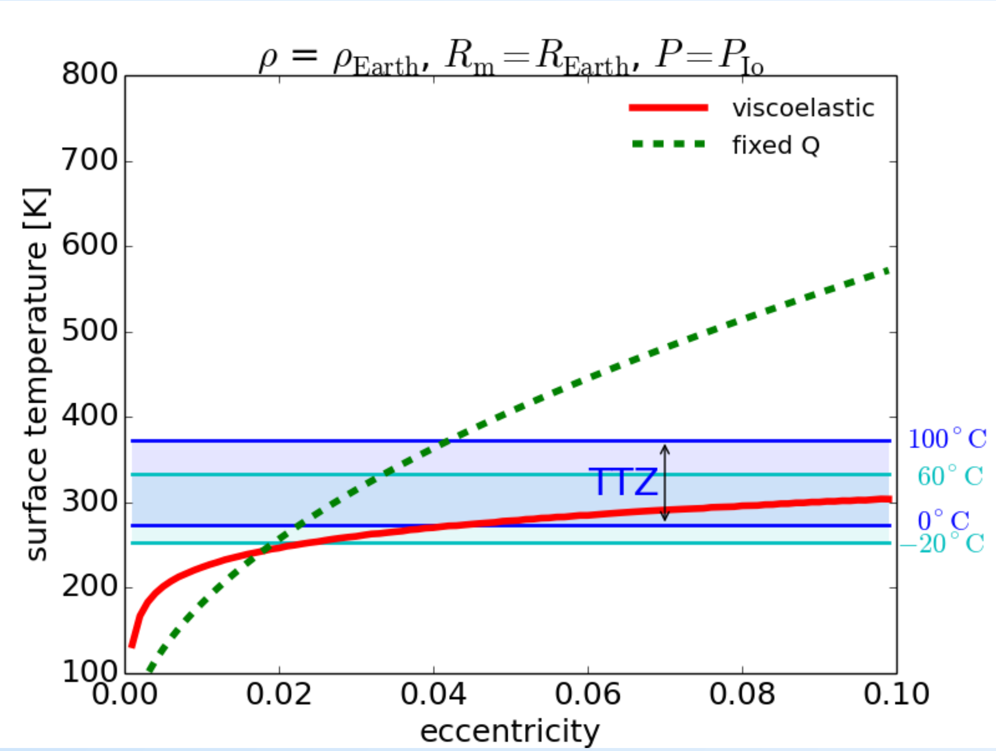
Tidal Temperate Zone (TTZ)

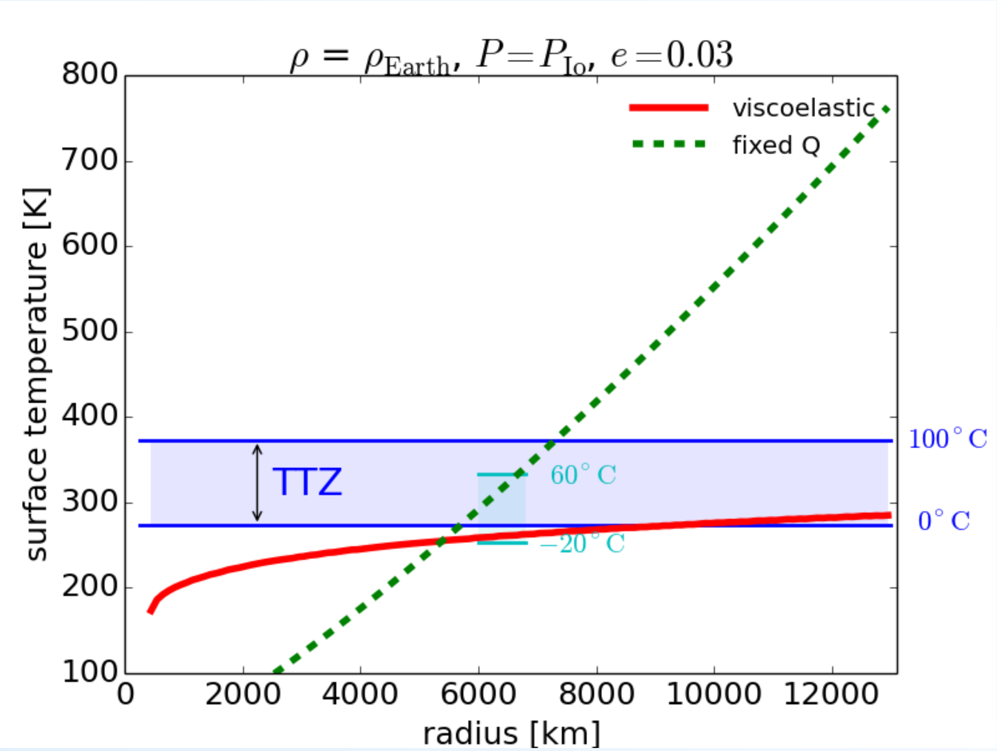


- Exo-Earth:

  $R = R_{Earth}$, T_s = 288K → then P = 2 days (e = 0.1 fixed)

Comparison of models





Dobos & Turner (2015) ApJ 804, 41

-20°C: limit of microbial activity in salty solutions

60°C: eukaryotes, runaway greenhouse

Fixed Q: - for Earth $Q = 280$

$\mu = 12 \cdot 10^{10}$ kg / (m s^2)

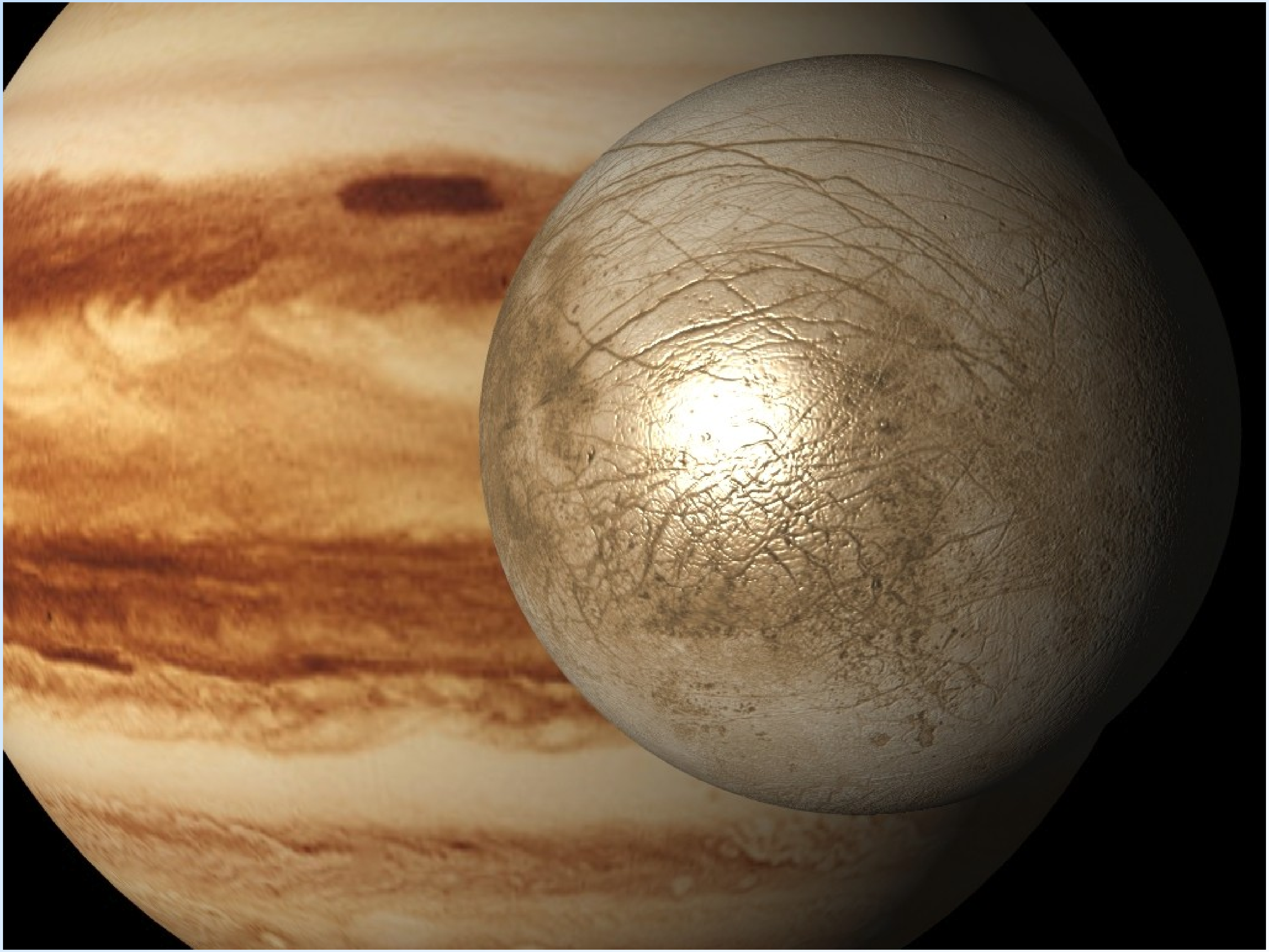
(Peters & Turner, 2013, ApJ 769, 98)

Na'vi on Pandora
(from the movie Avatar)

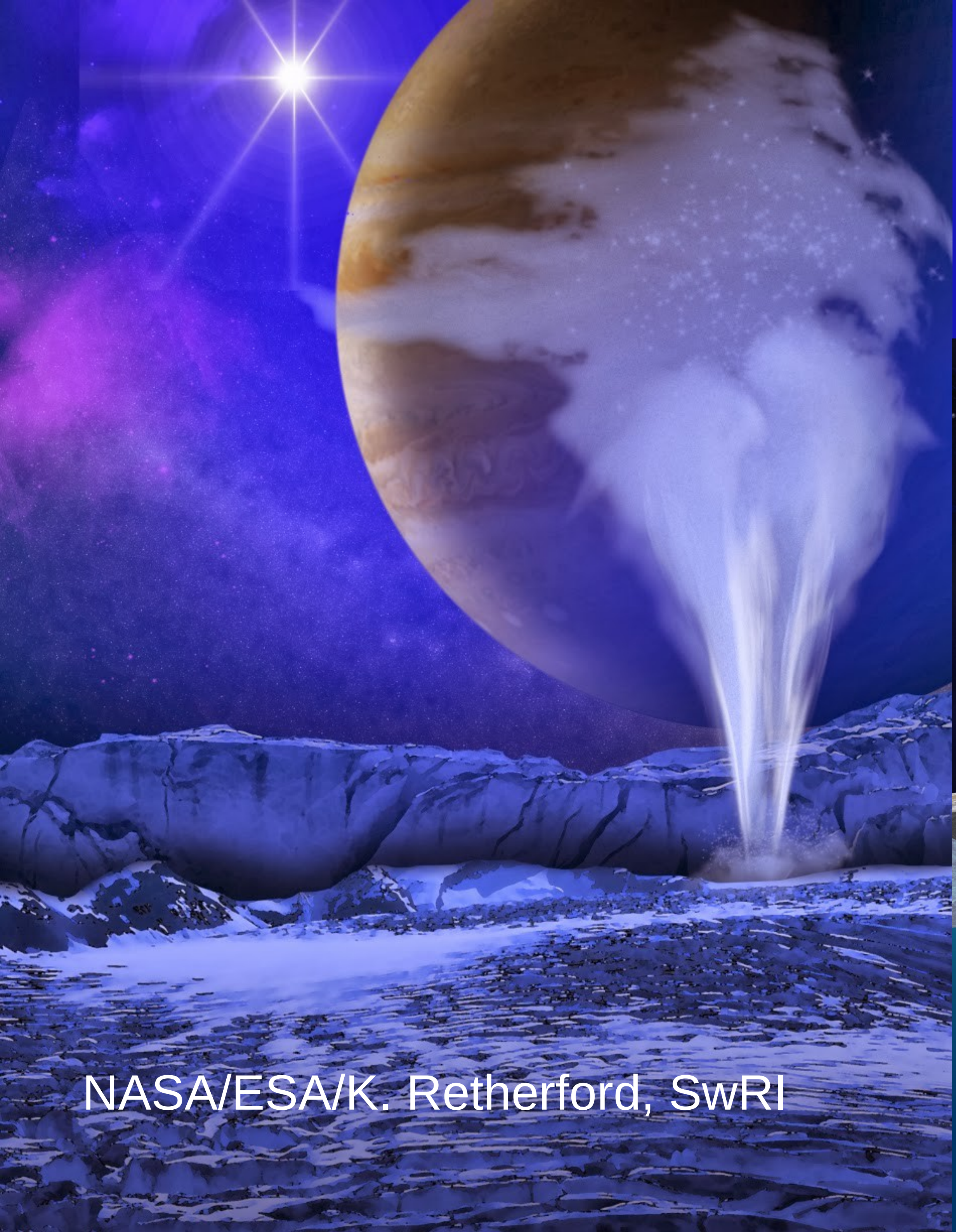
Na'vi on Pandora
(from the movie Avatar)

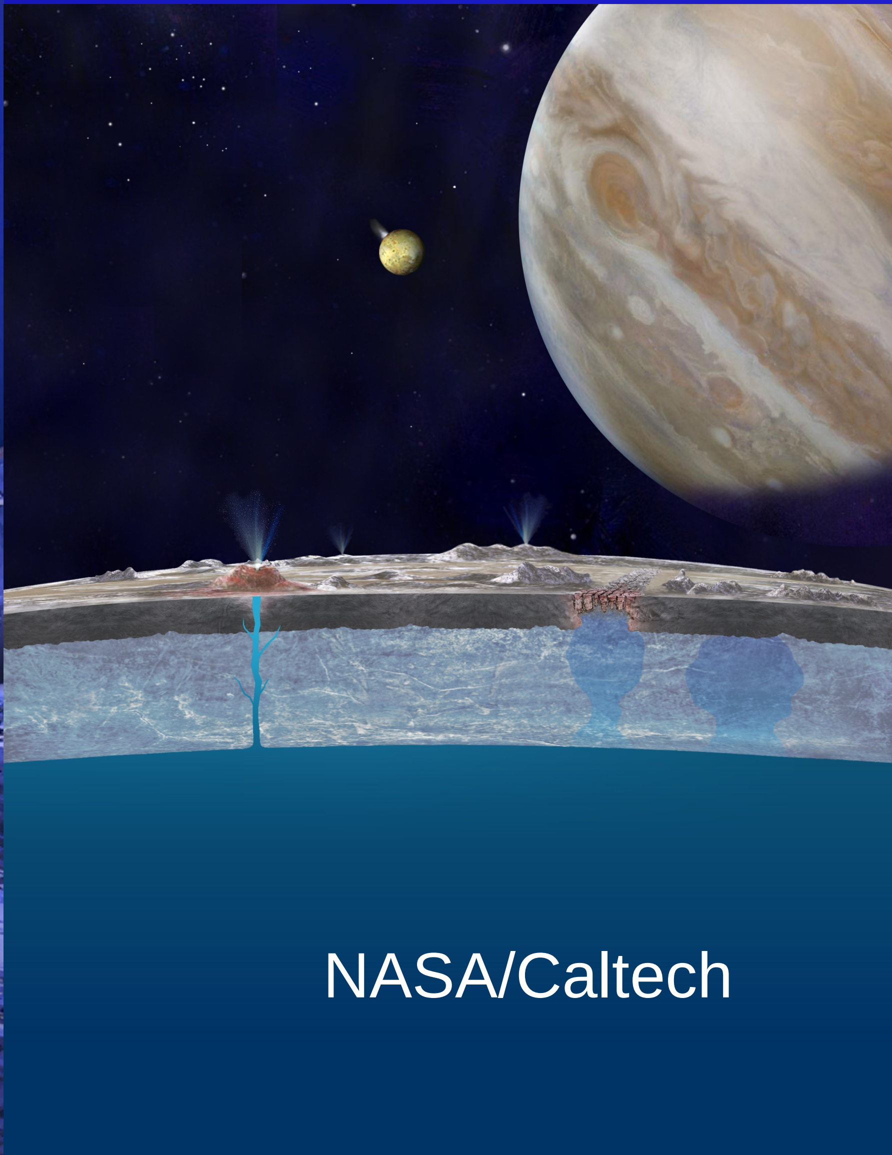
Octopus-like alien on Europa
(from the movie Europa Report)

What makes Europa habitable?



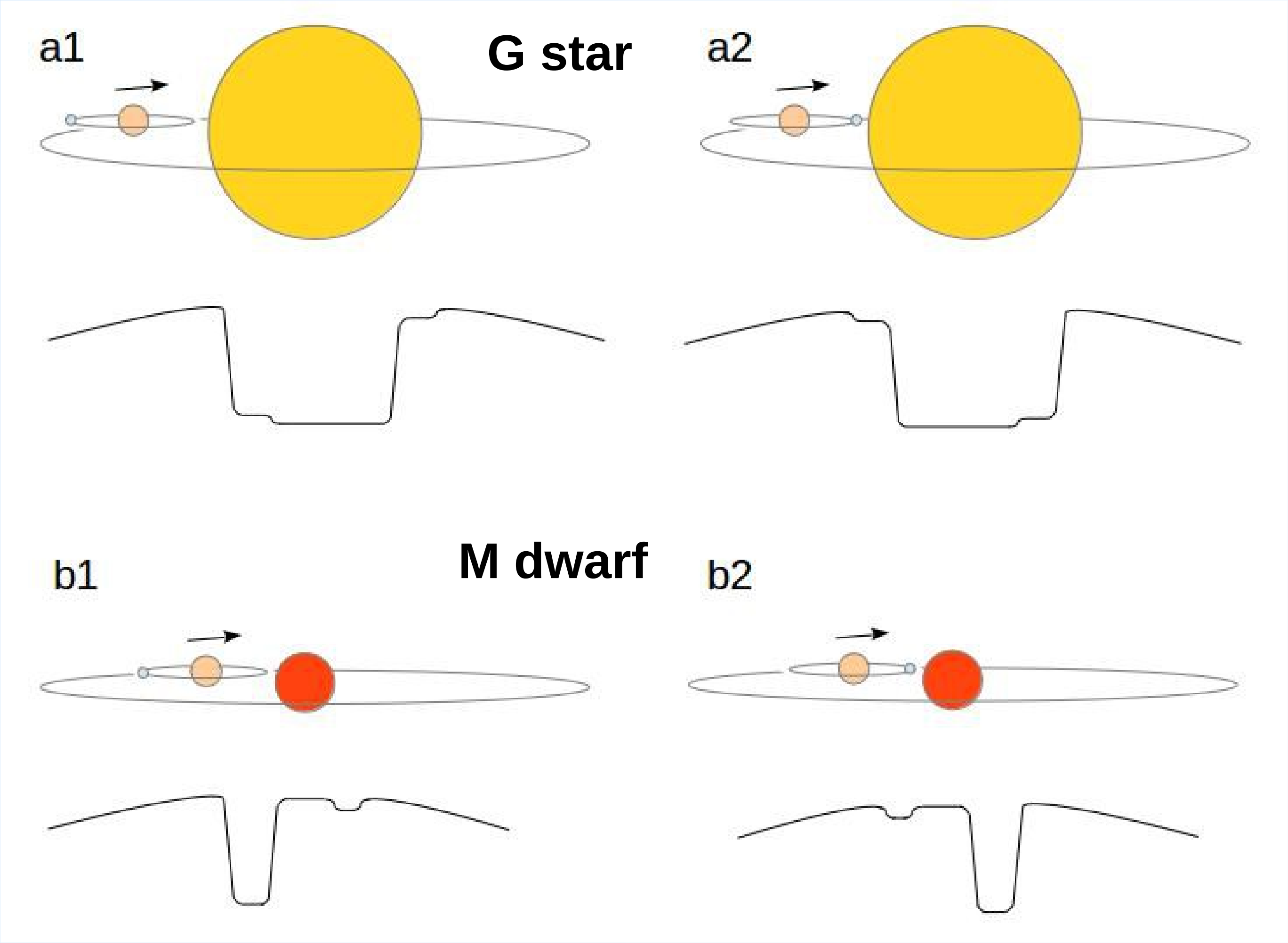
Europa





Albedo estimation of icy moons

Occultation light curve
(not transit!)



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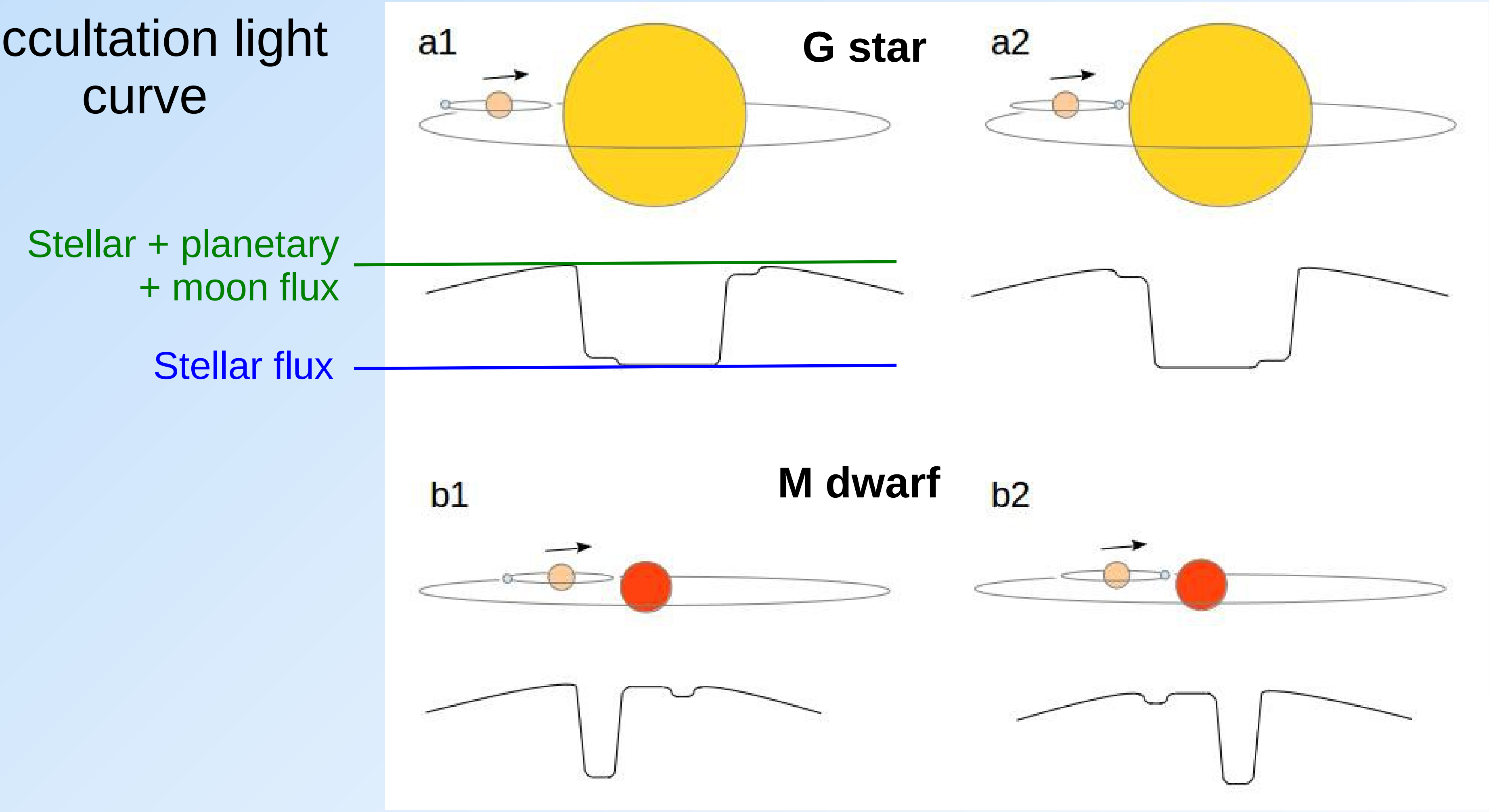


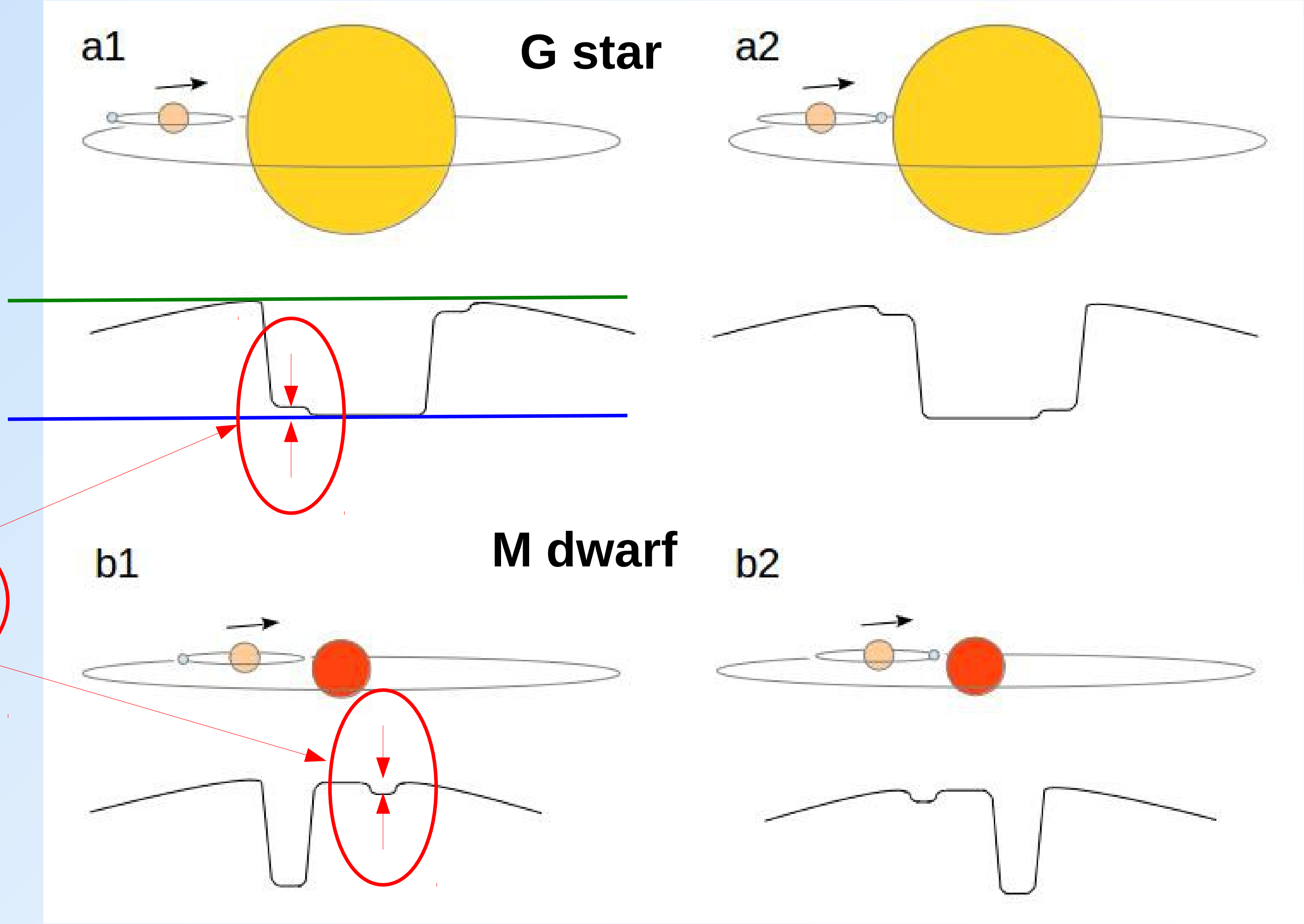
Albedo estimation of icy moons

Occultation light curve

Stellar + planetary + moon flux

Stellar flux

Moon's contribution to the flux (reflected light)



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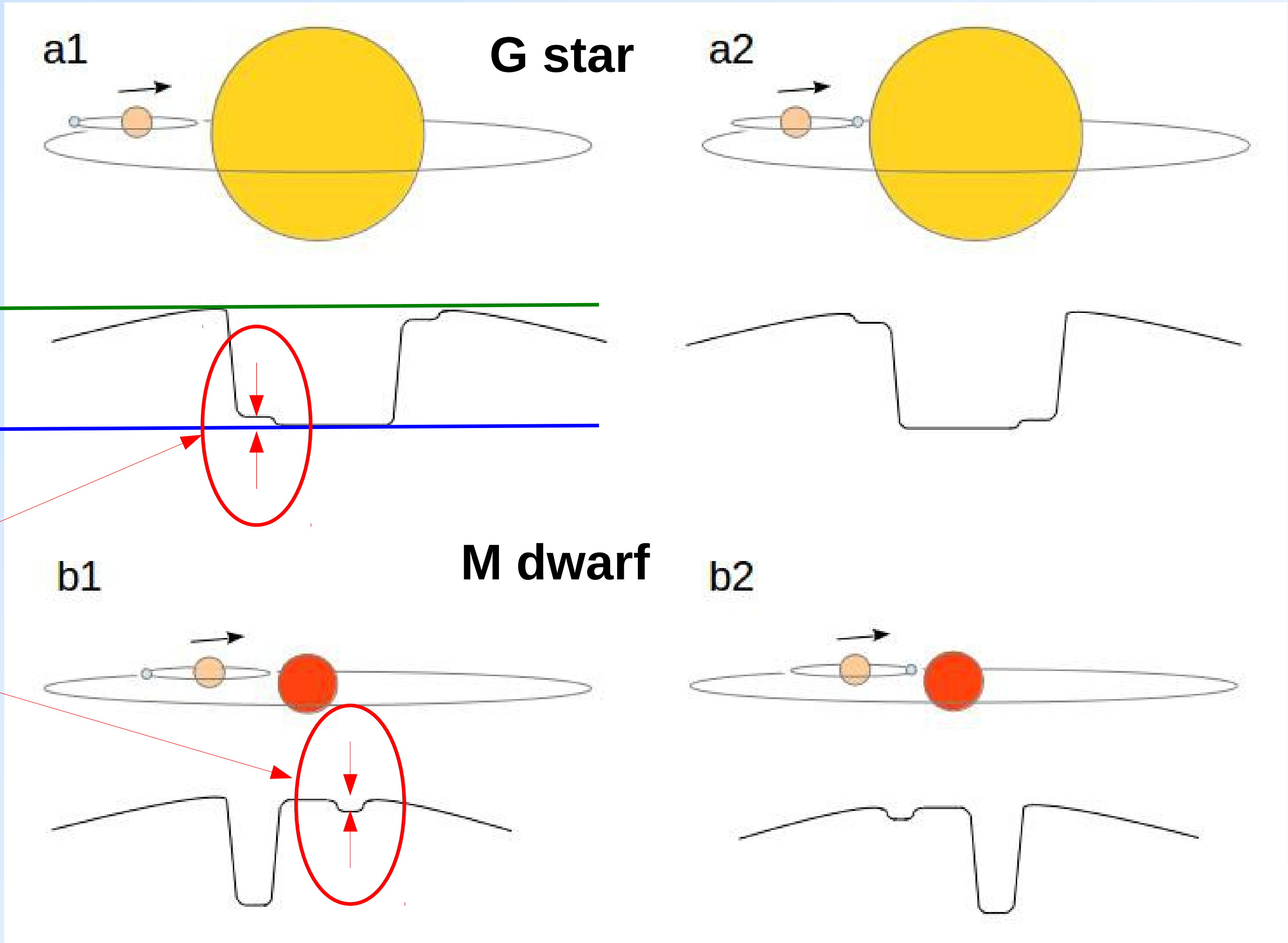
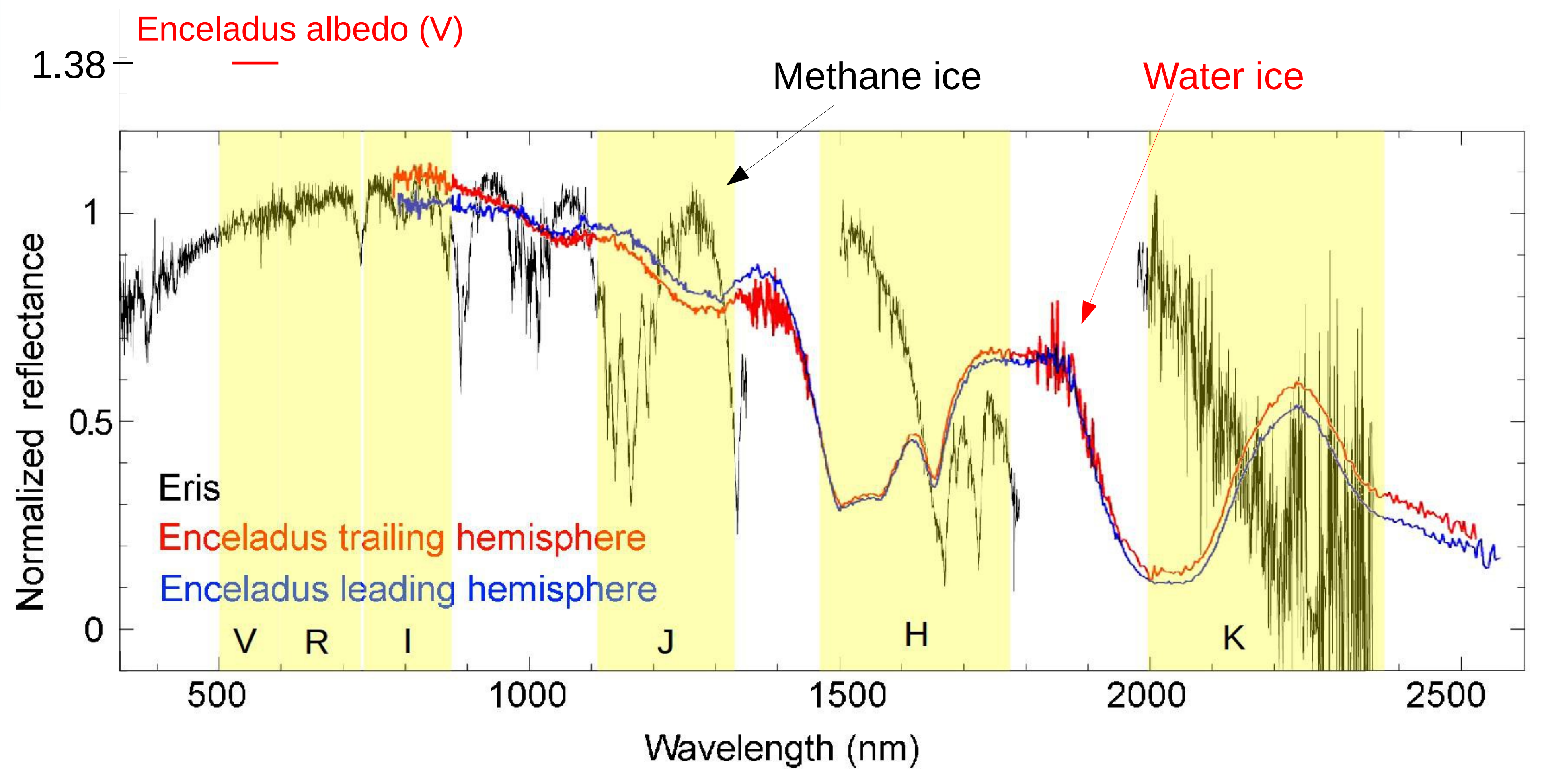


$A_g = (y_2 - y_1)\,(d / R_m)^2$

geometric albedo

Which photometric band?



Spectra from: Verbiscer et al. (2006) Icarus 182, 211
and Alvarez-Candal (2011) A&A 532, A130

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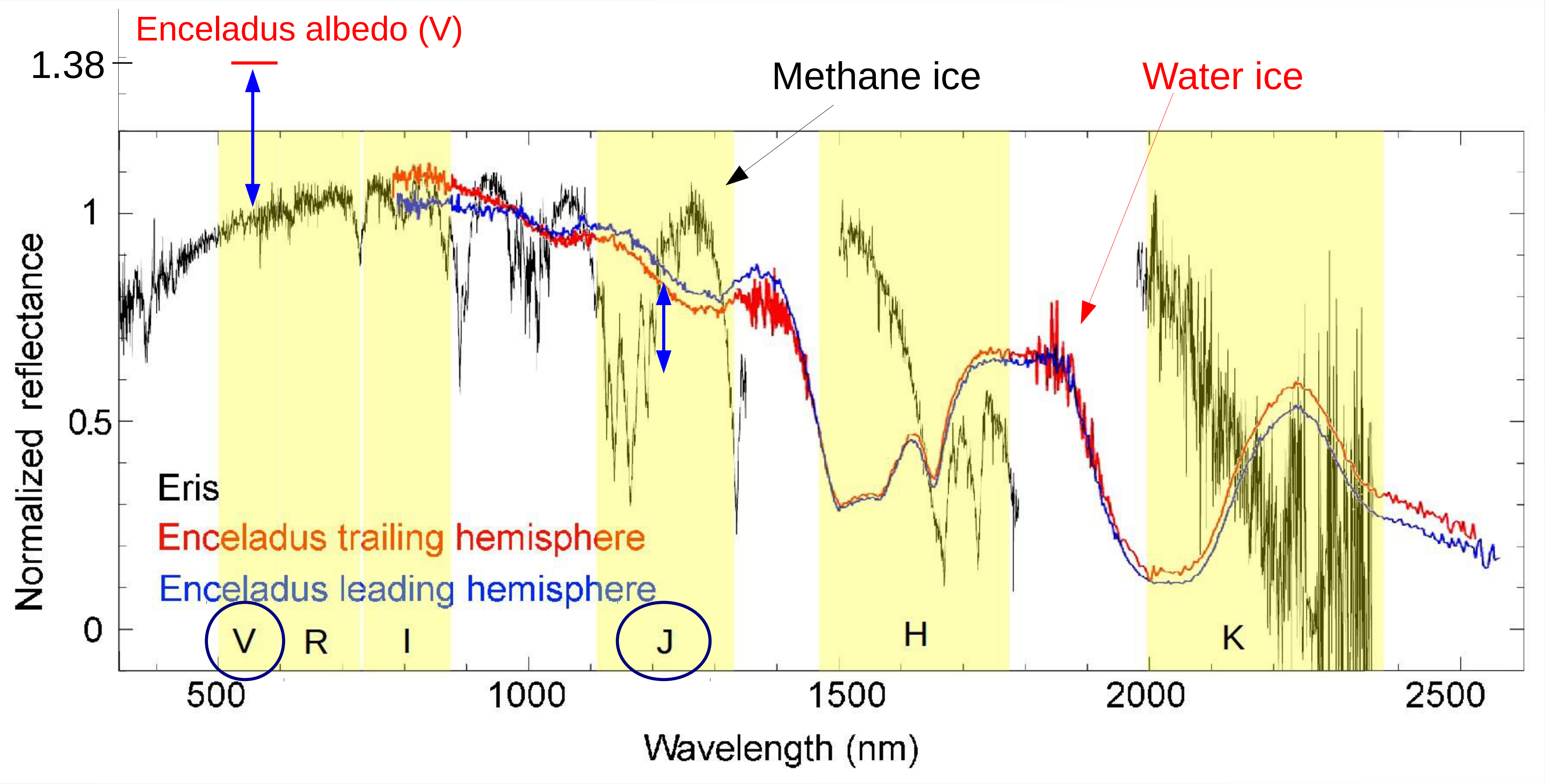
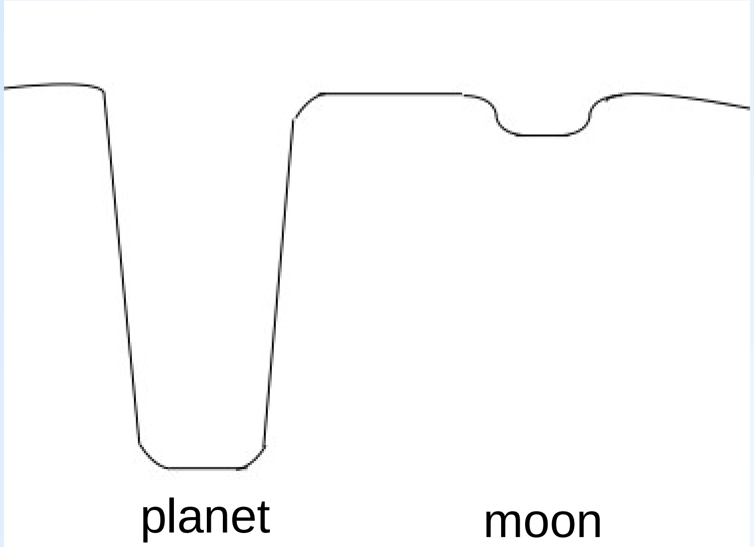


CHEOPS, PLATO 2.0: V, R
JWST: I, J, H, K

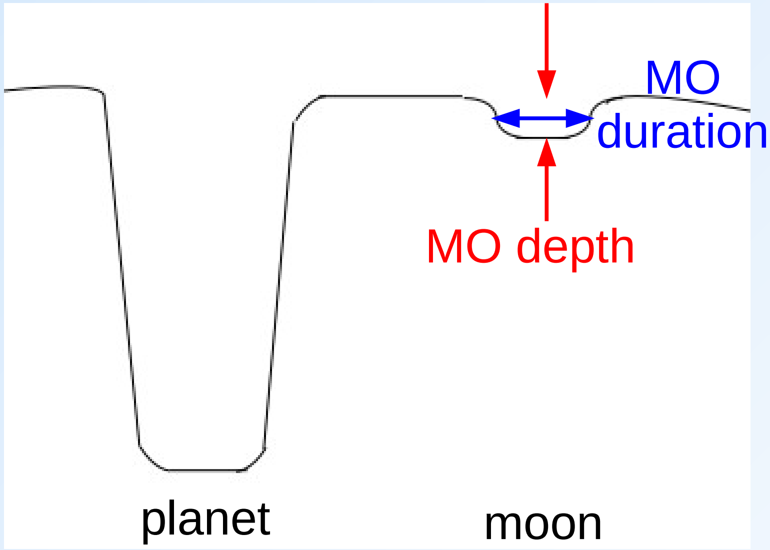
Spectra from: Verbiscer et al. (2006) Icarus 182, 211 and Alvarez-Candal (2011) A&A 532, A130

Observability



Observability

MO: moon occultation



Observability

Large icy moon: 2.5 R_{Earth}, water ice (~5 M_{earth})

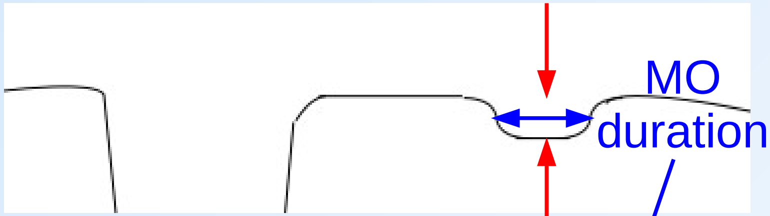
Neptune-mass planet

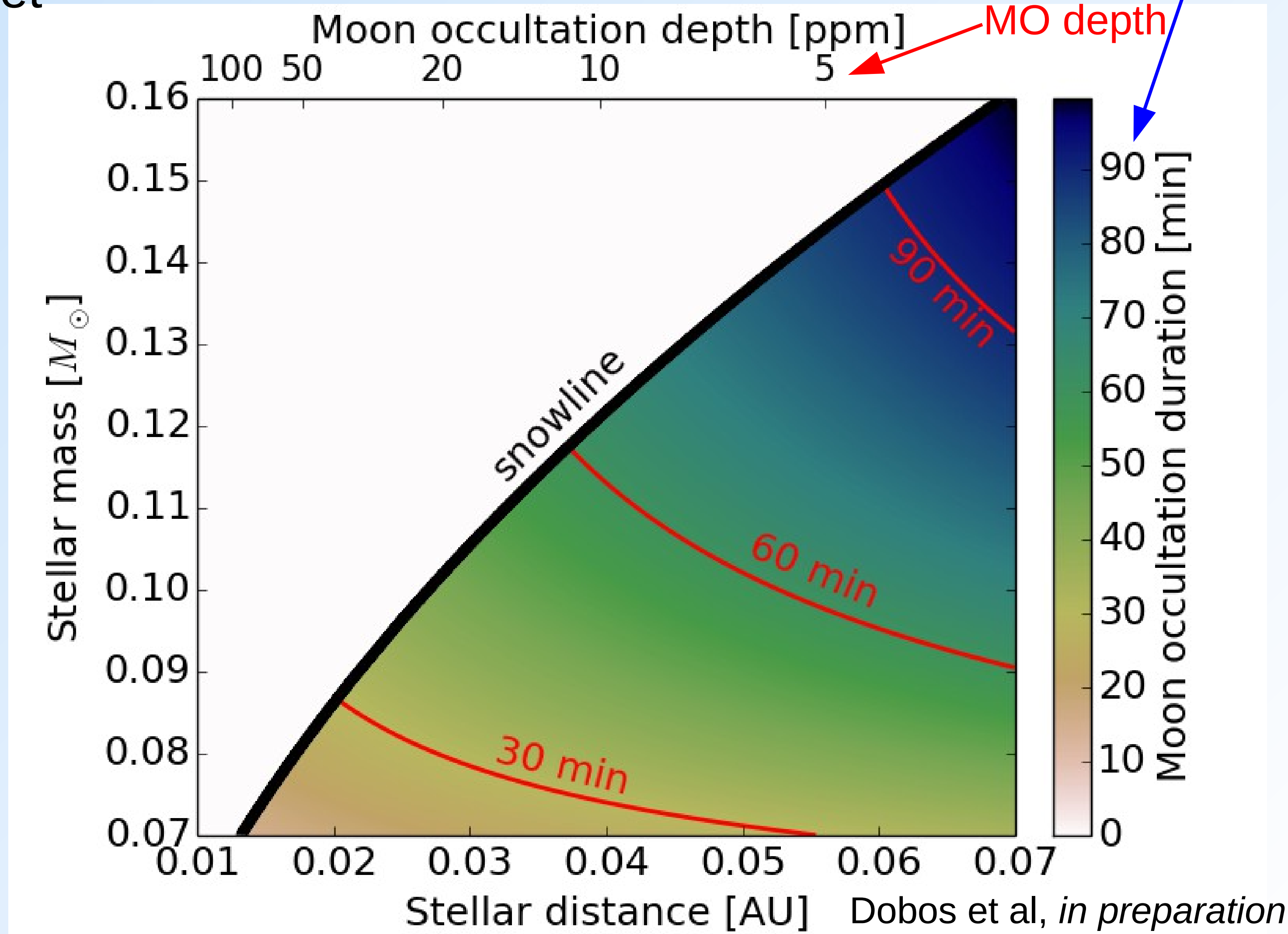
MO: moon occultation

Small stars:
snowline closer

Longer MO duration:
better photometric precision

Larger MO depth:
easier detection





Dobos et al, *in preparation*

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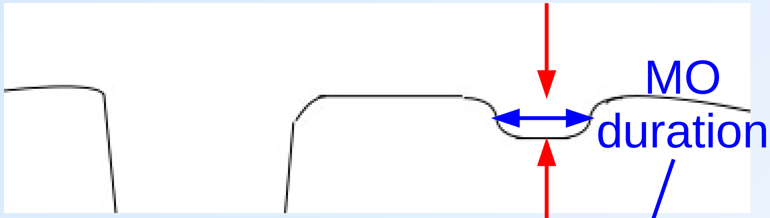

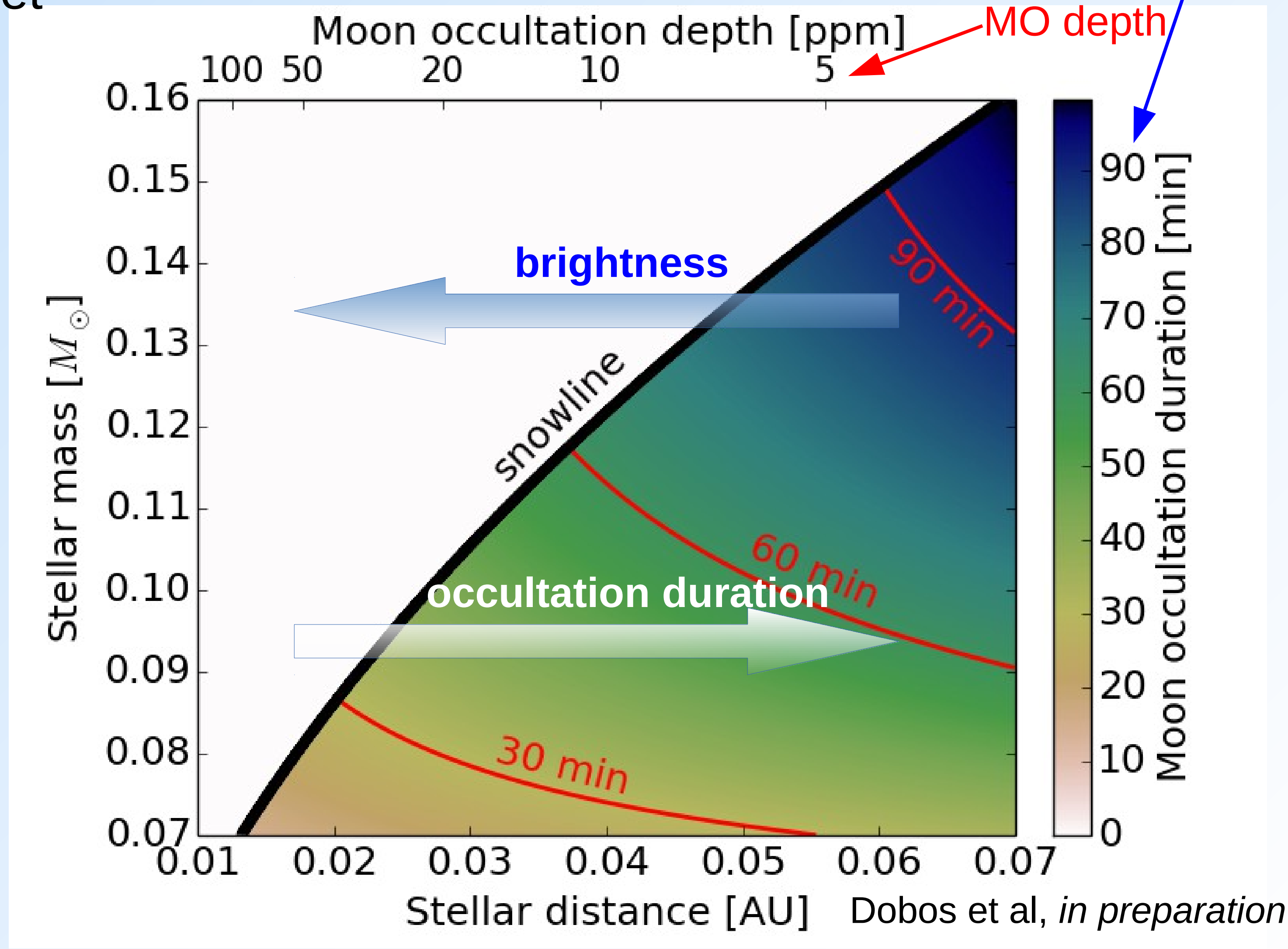

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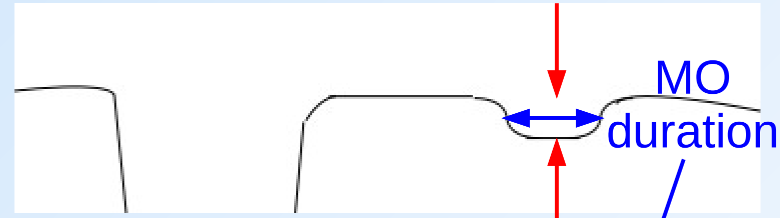
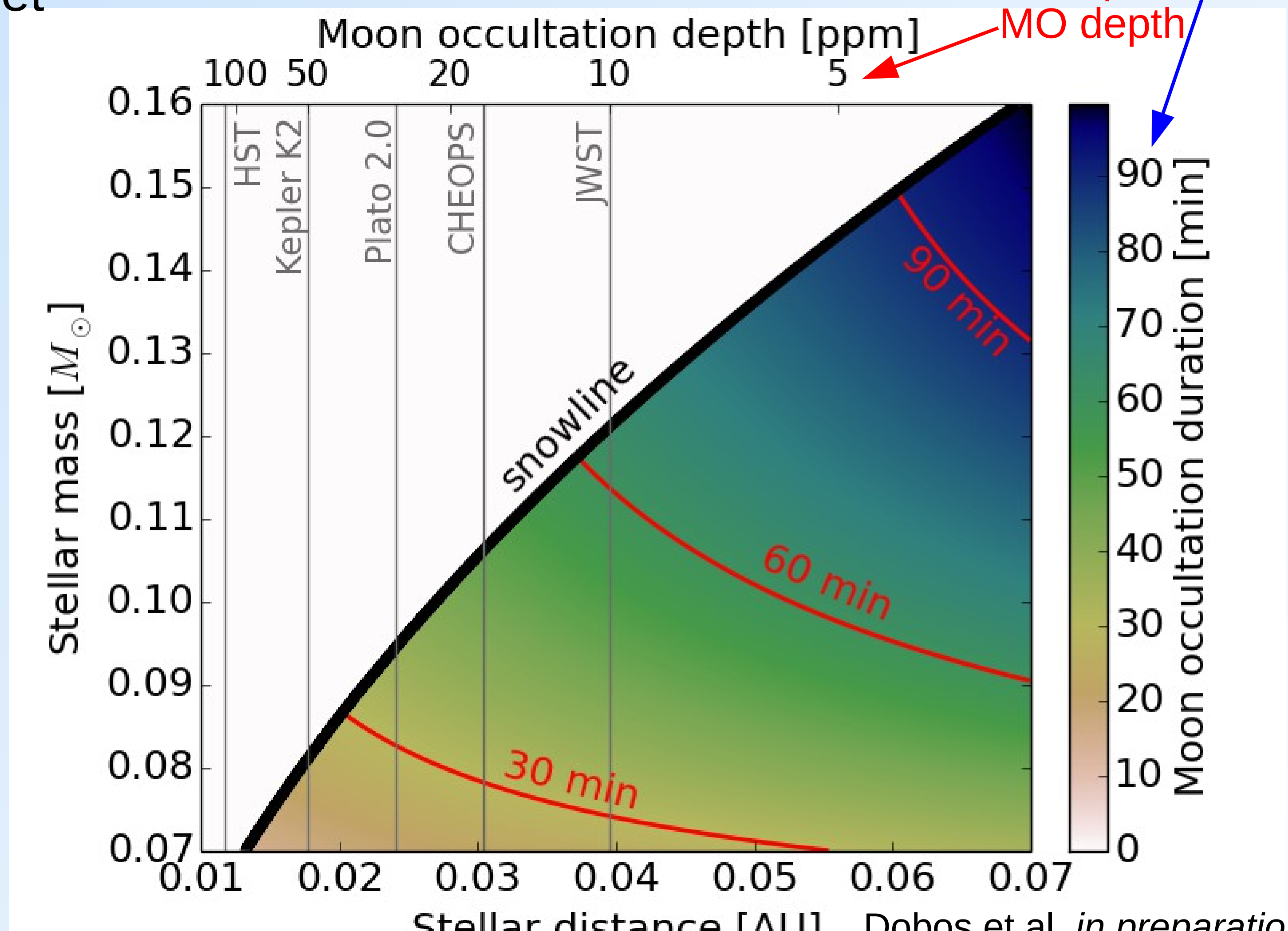
Expected noise levels:

JWST:
~10–20 ppm / several hrs

CHEOPS:
~20 ppm / several hrs

Plato 2.0:
~27 ppm / 1 hr





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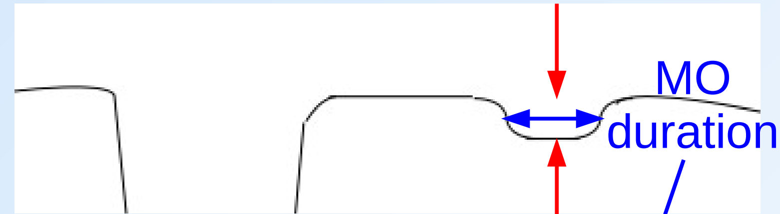

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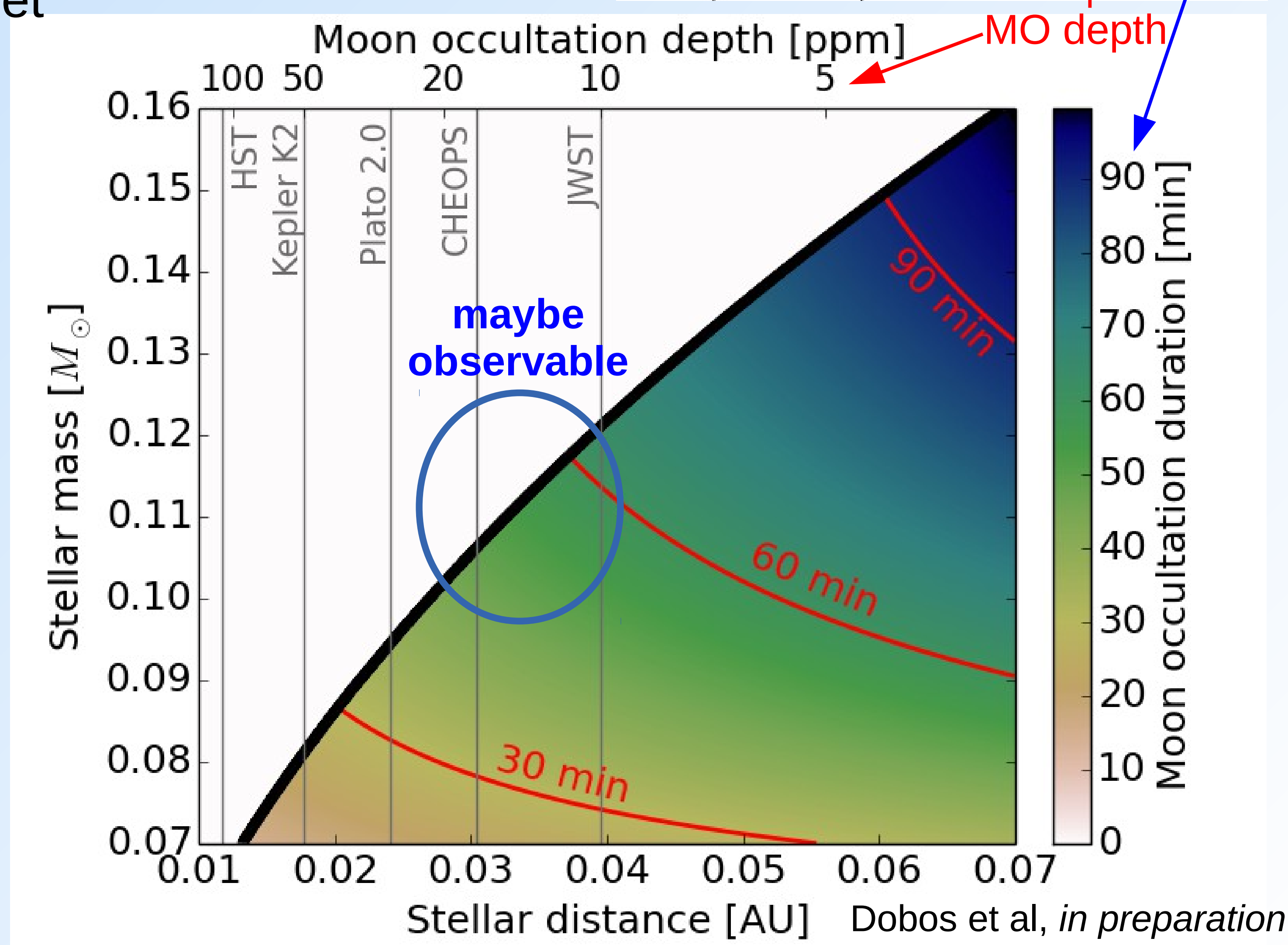
Repeated observations:

↓

albedo estimation is possible



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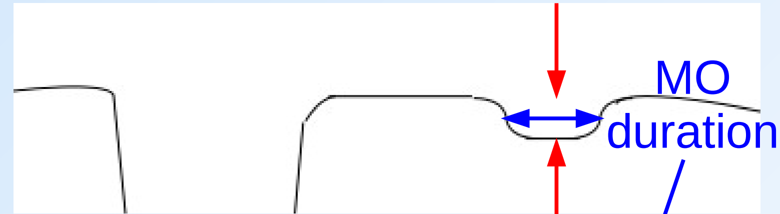

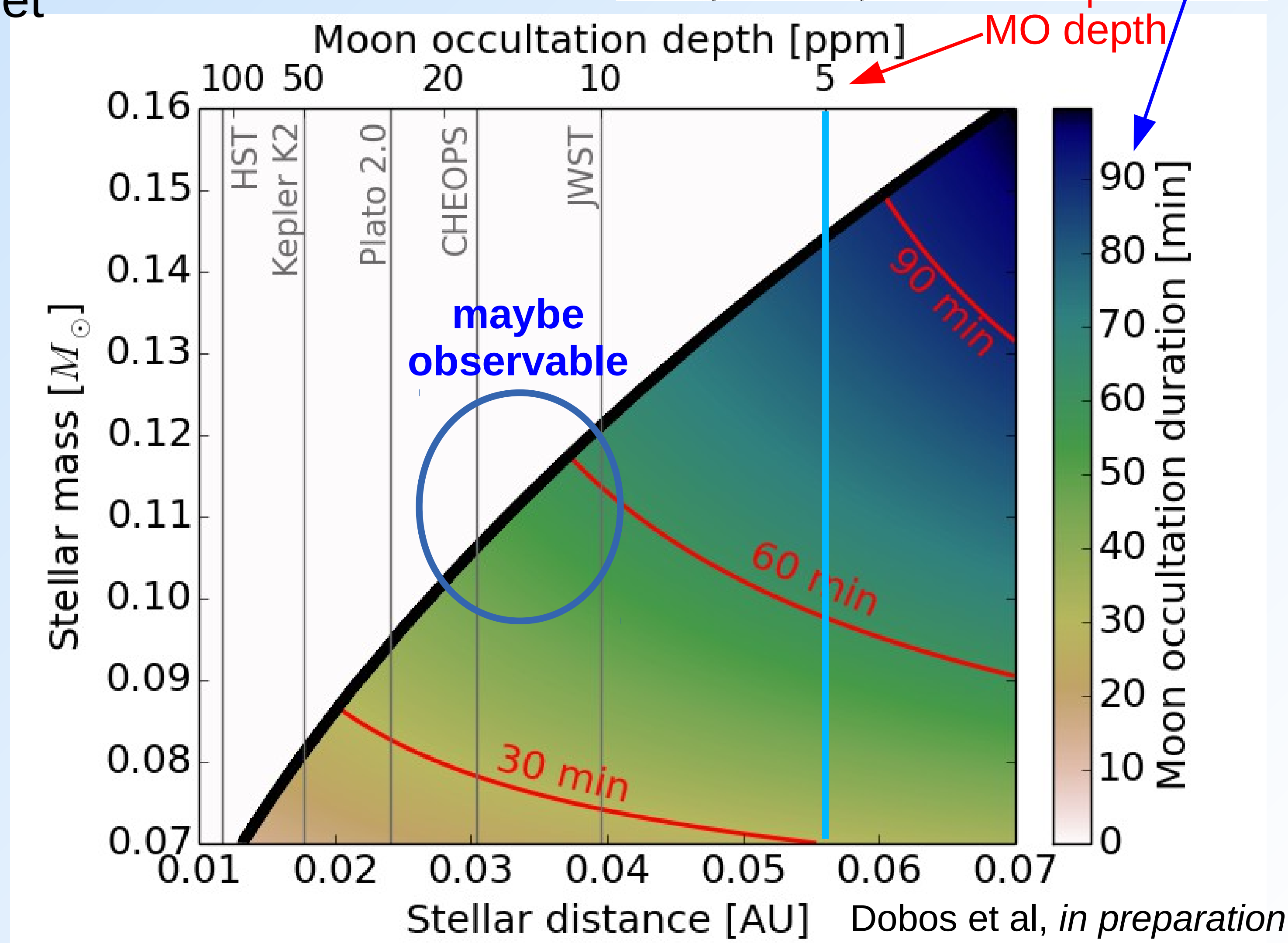

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Neptune-mass planet

MO: moon occultation

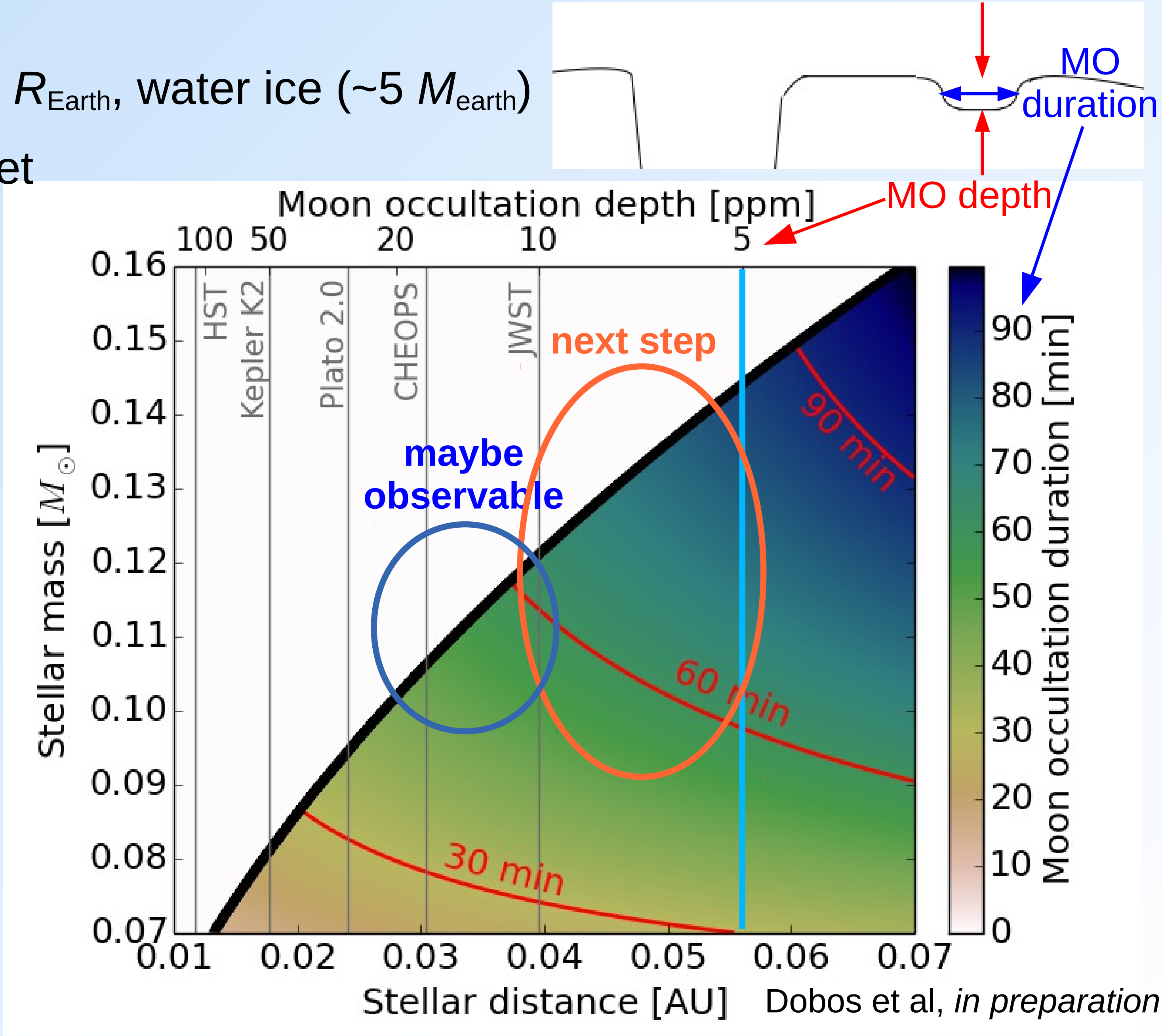
5 ppm means:
successful observation of...

...moons farther from the star

...moons around larger stars

...smaller moons

...less icy moons



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Thank you