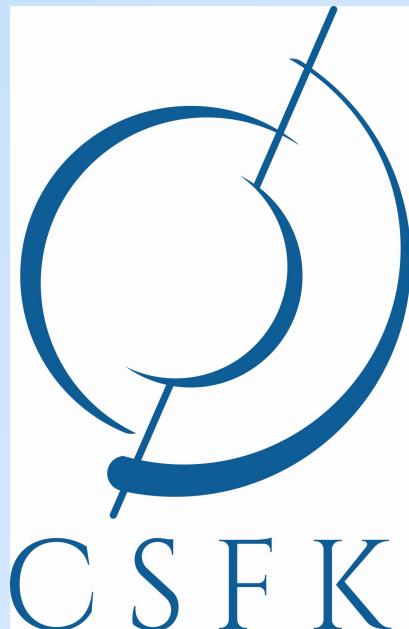


What Makes an Exomoon Habitable?



Vera Dobos
Konkoly Observatory
Hungarian Academy of Sciences
(MTA CSFK)
Budapest, Hungary



Missions to Habitable Worlds
28-29 October 2015 Budapest, Hungary

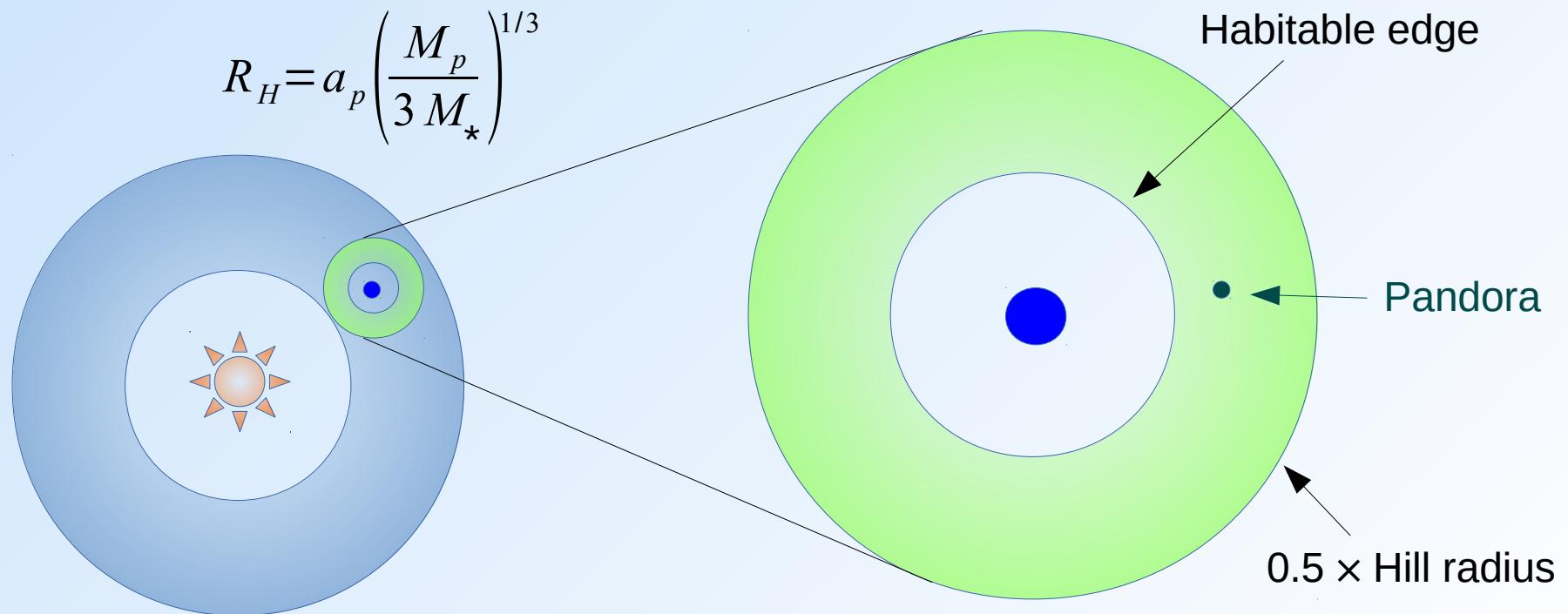
What makes Pandora habitable?



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)

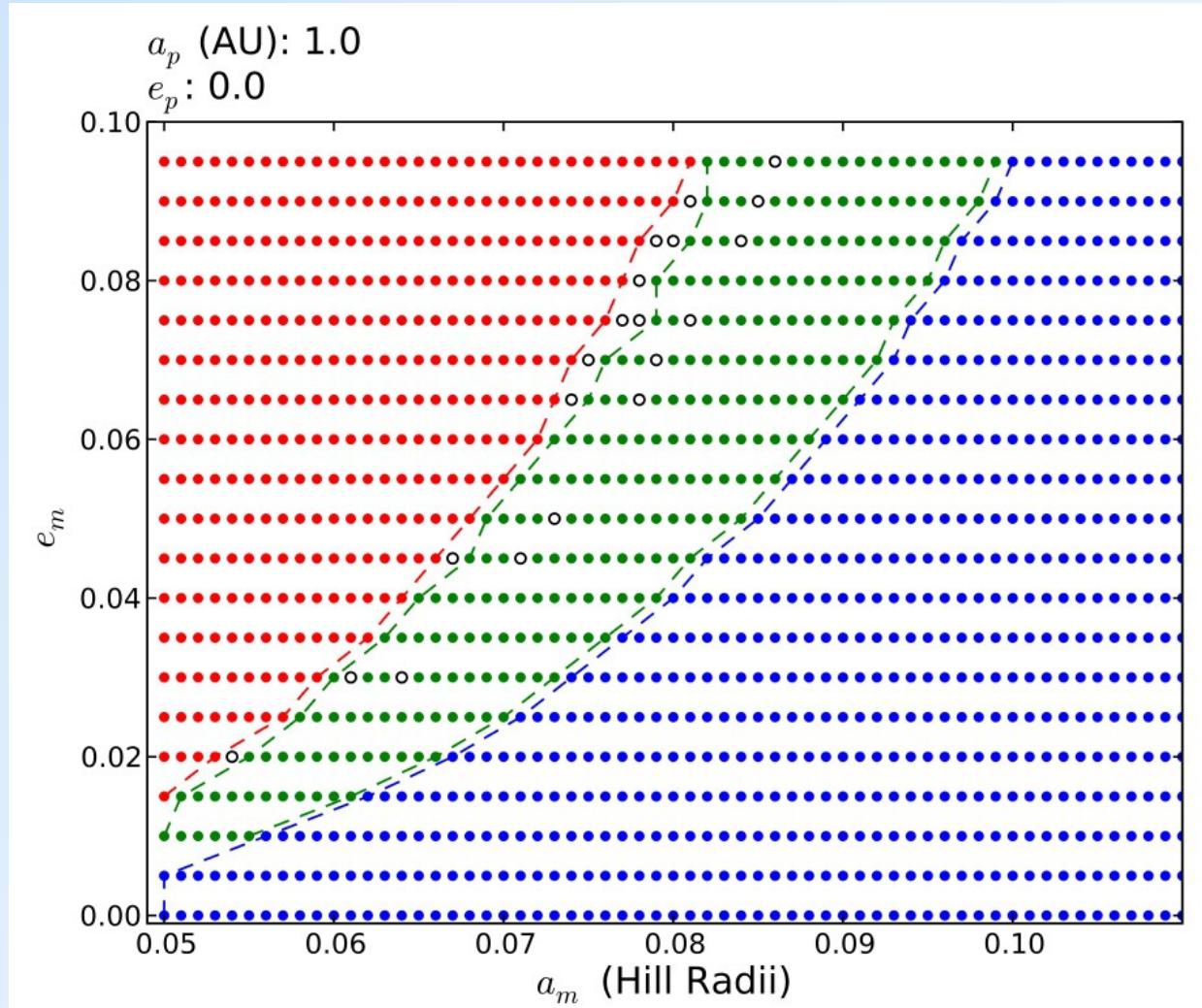


Outer limit: snowball Pandora

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

Eclipses
+
Ice-Albedo Feedback
=

2nd
Circumplanetary Edge!



Runaway Greenhouse

Habitable

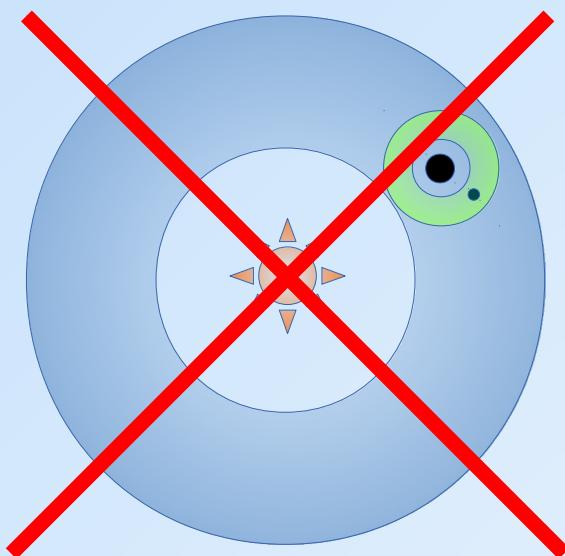
Snowball Moon

Transiently Habitable

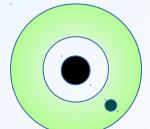
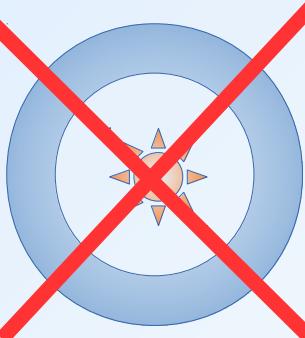
Forgan & Yotov (2014) MNRAS 441, 3513

Could Pandora be habitable...

... outside the circumstellar
habitable zone?



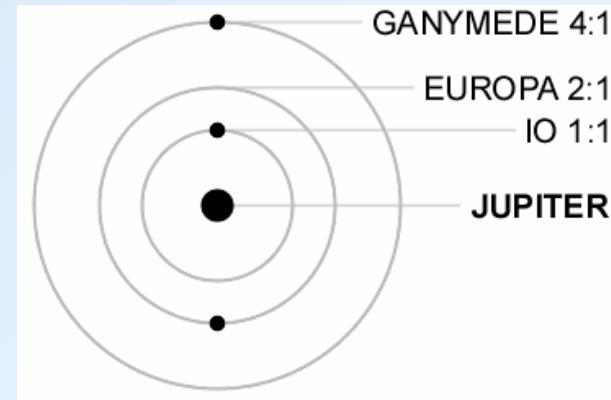
... or without a star?



Tidal Heating

- Inner heat

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

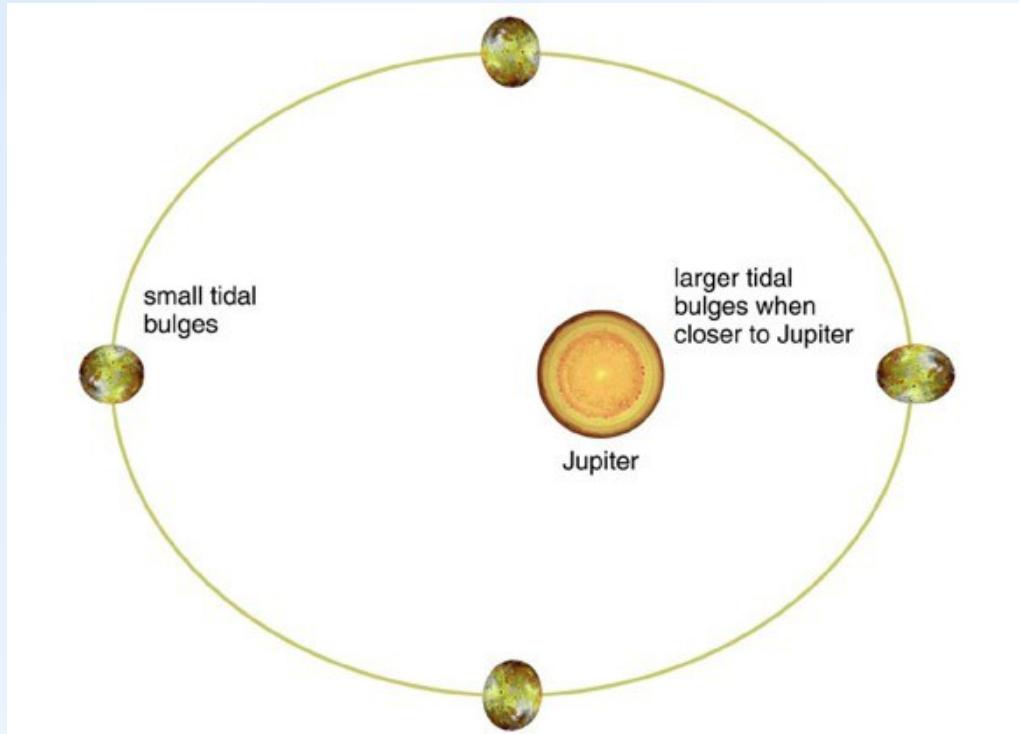


- Eccentricity is needed!

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

- 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

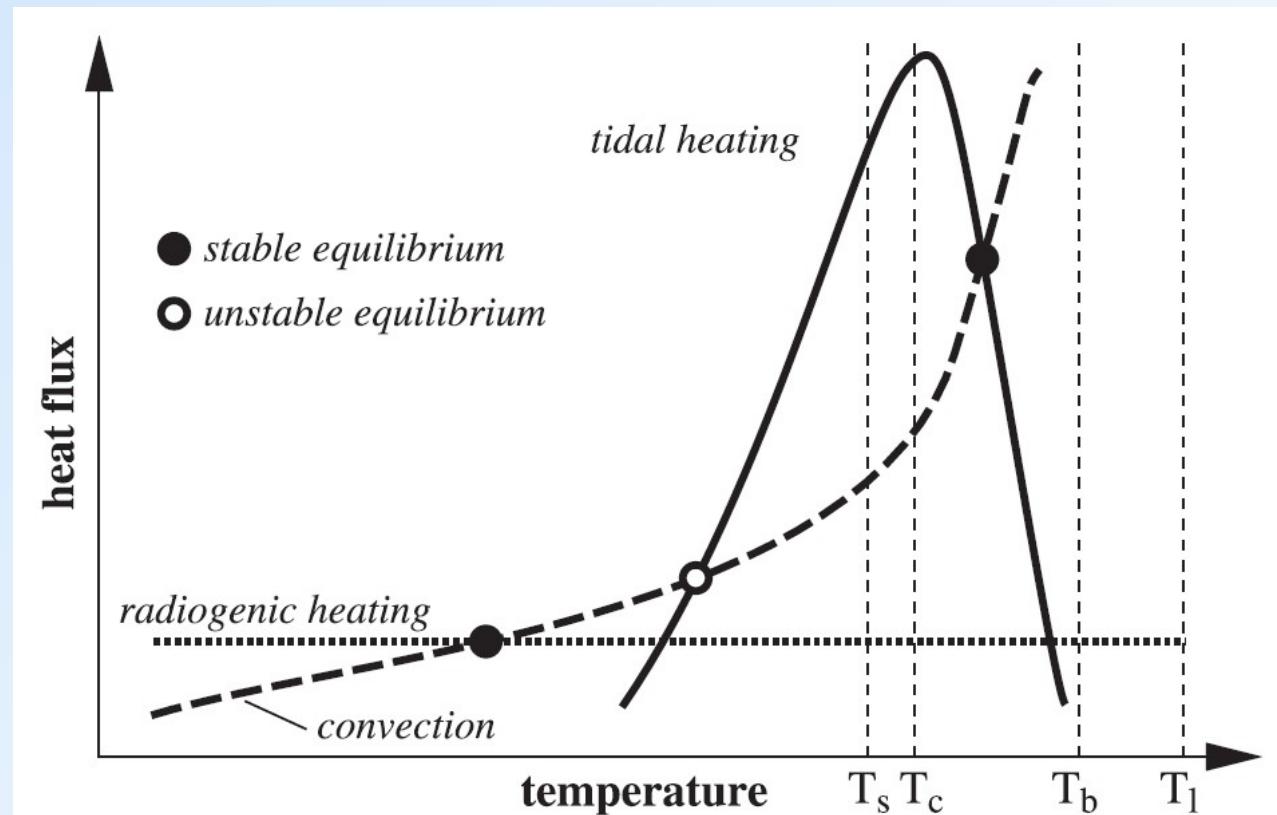
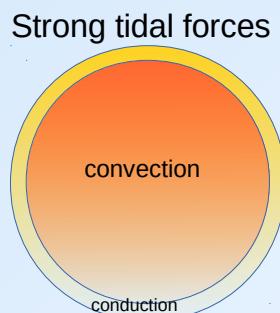
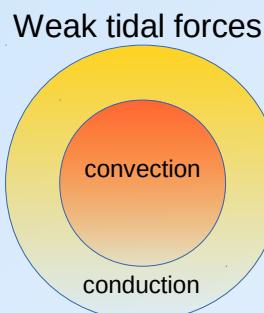
Giant planets: 10^4 – 10^5 order of magnitude

- **Viscoelastic models:**

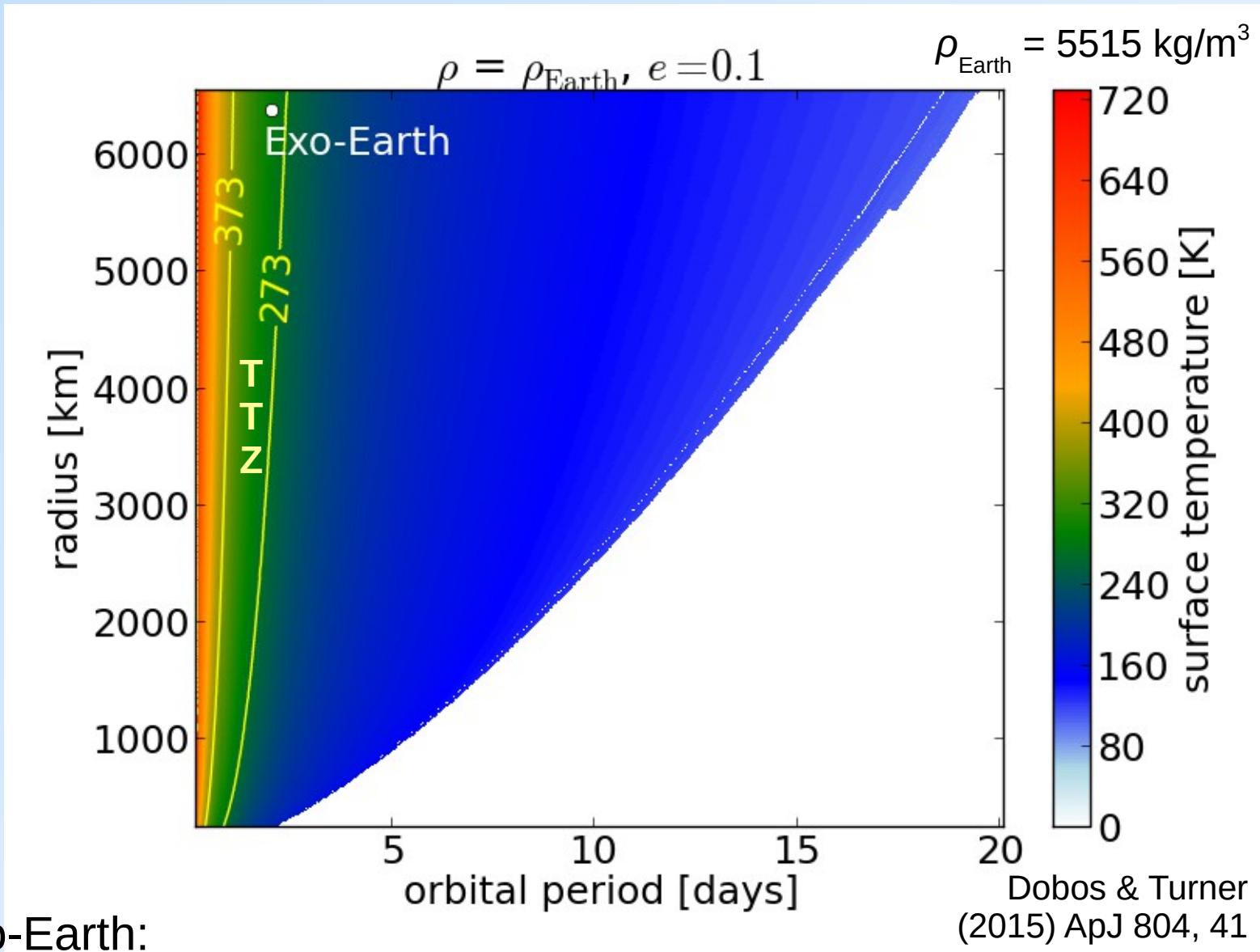
(Fischer & Spohn 1990, Moore 2003)

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

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



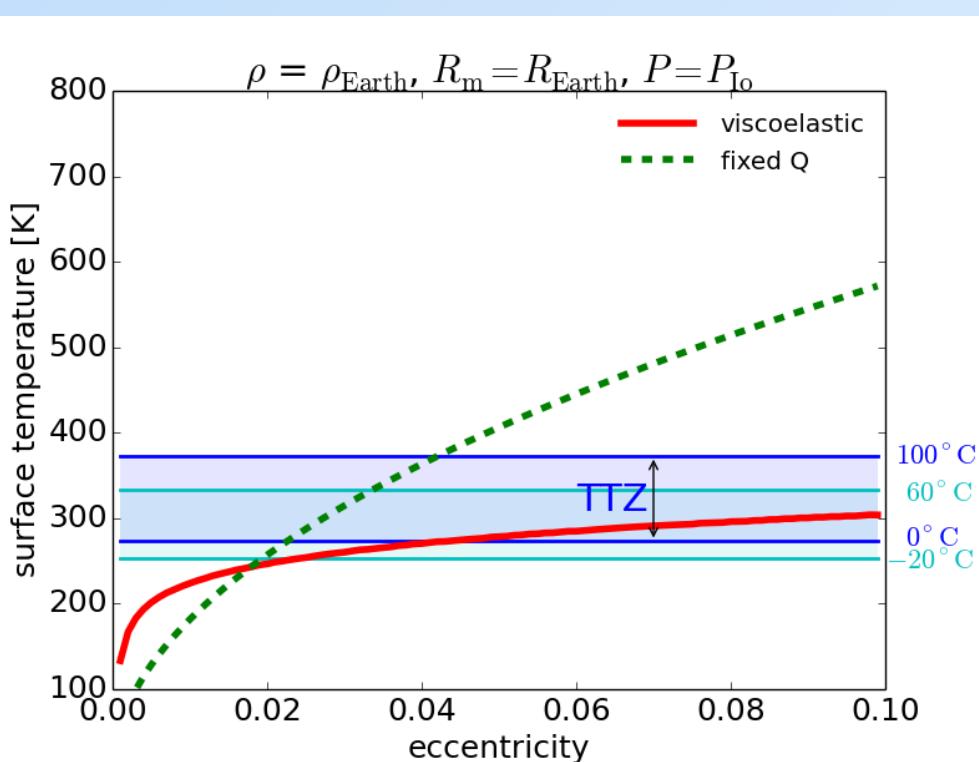
Tidal Temperate Zone (TTZ)



- Exo-Earth:

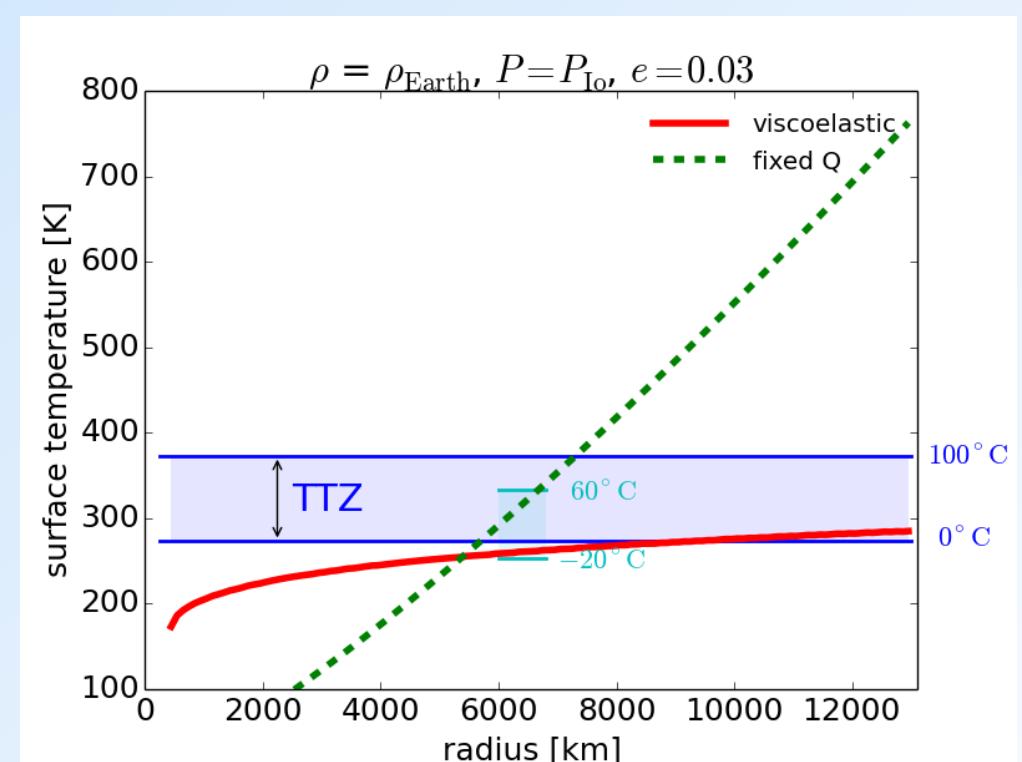
$R = R_{\text{Earth}}, T_s = 288\text{K}$ \rightarrow then $P = 2$ days ($e = 0.1$ fixed)

Comparison of models



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

60°C: eukaryotes, runaway greenhouse



Fixed Q: - for Earth
 $Q = 280$
 $\mu = 12 \cdot 10^{10} \text{ kg / (m s}^2\text{)}$

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

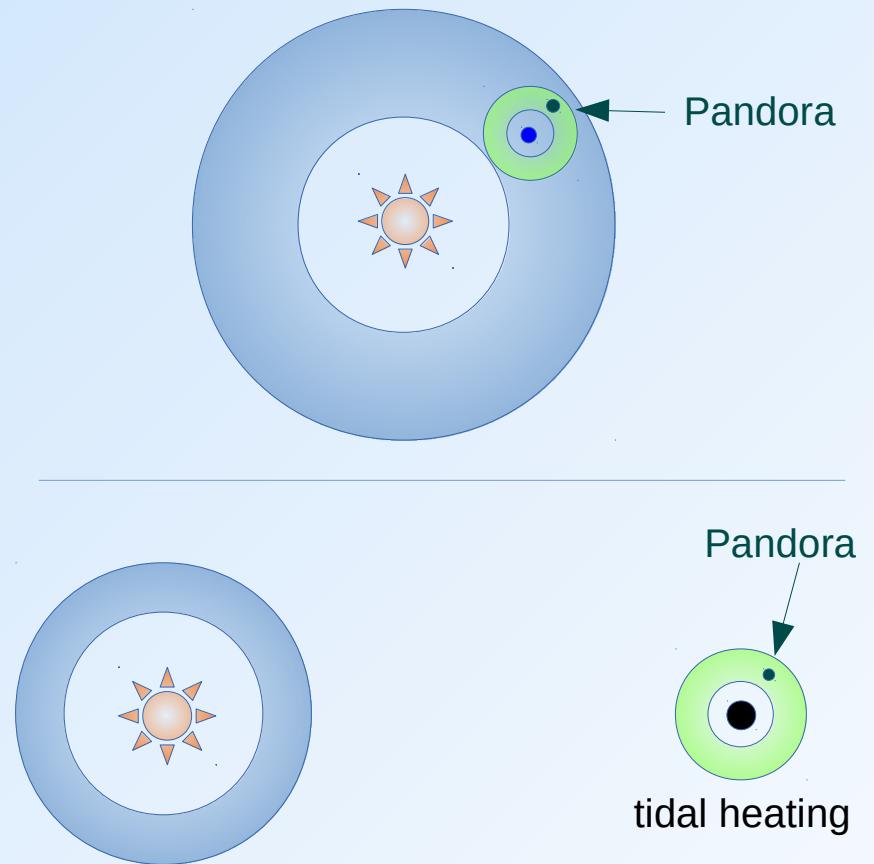
Dobos & Turner
(2015) ApJ 804, 41



Na'vi on Pandora
(from the movie Avatar)

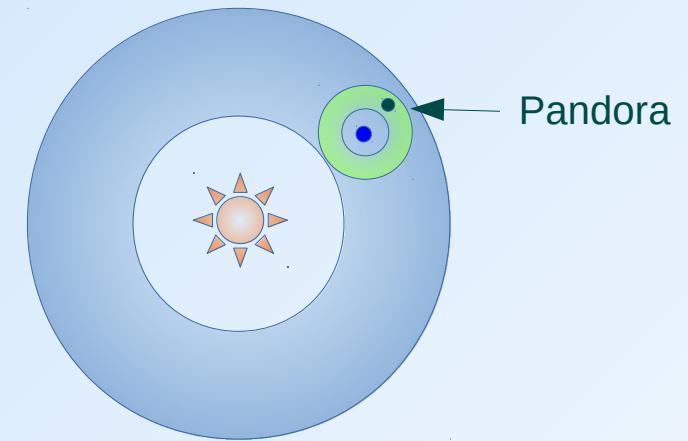


Na'vi on Pandora
(from the movie Avatar)





Na'vi on Pandora
(from the movie Avatar)

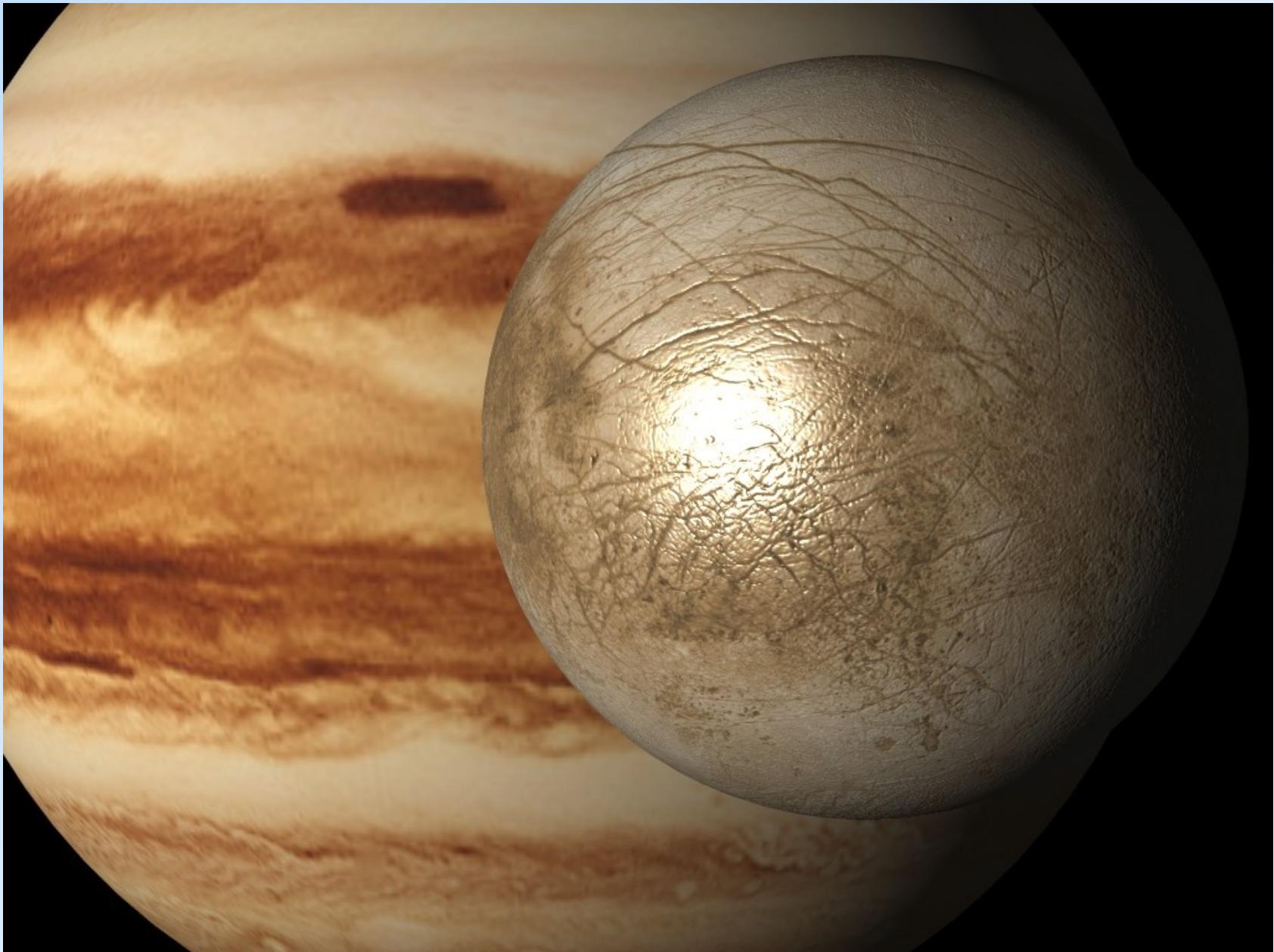


Octopus-like alien
on Europa

(from the movie
Europa Report)



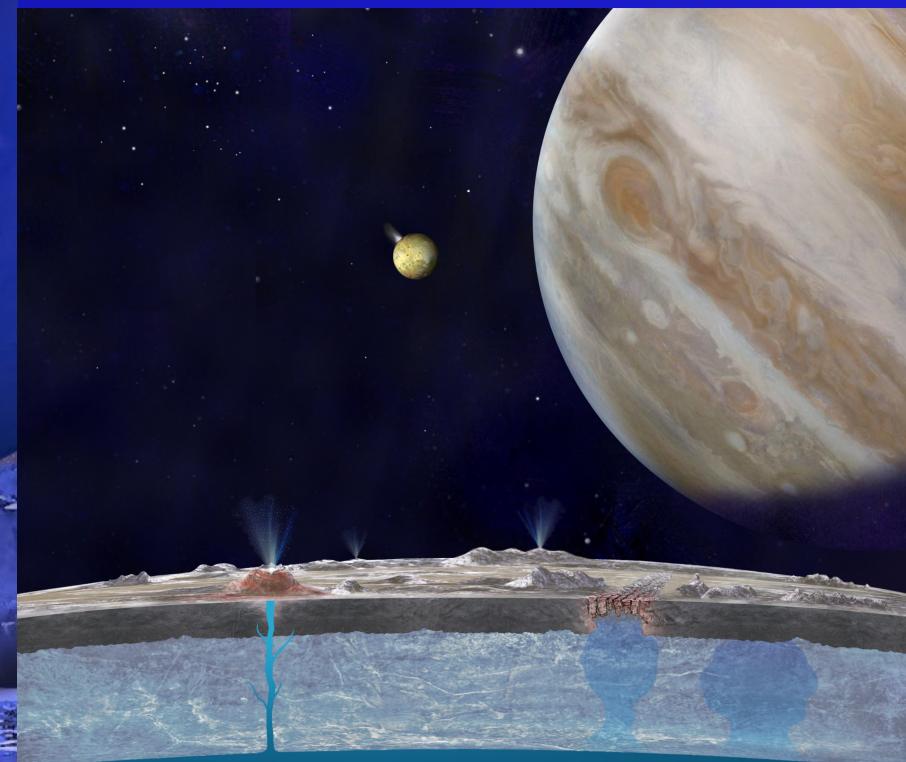
What makes Europa habitable?





NASA/ESA/K. Retherford, SwRI

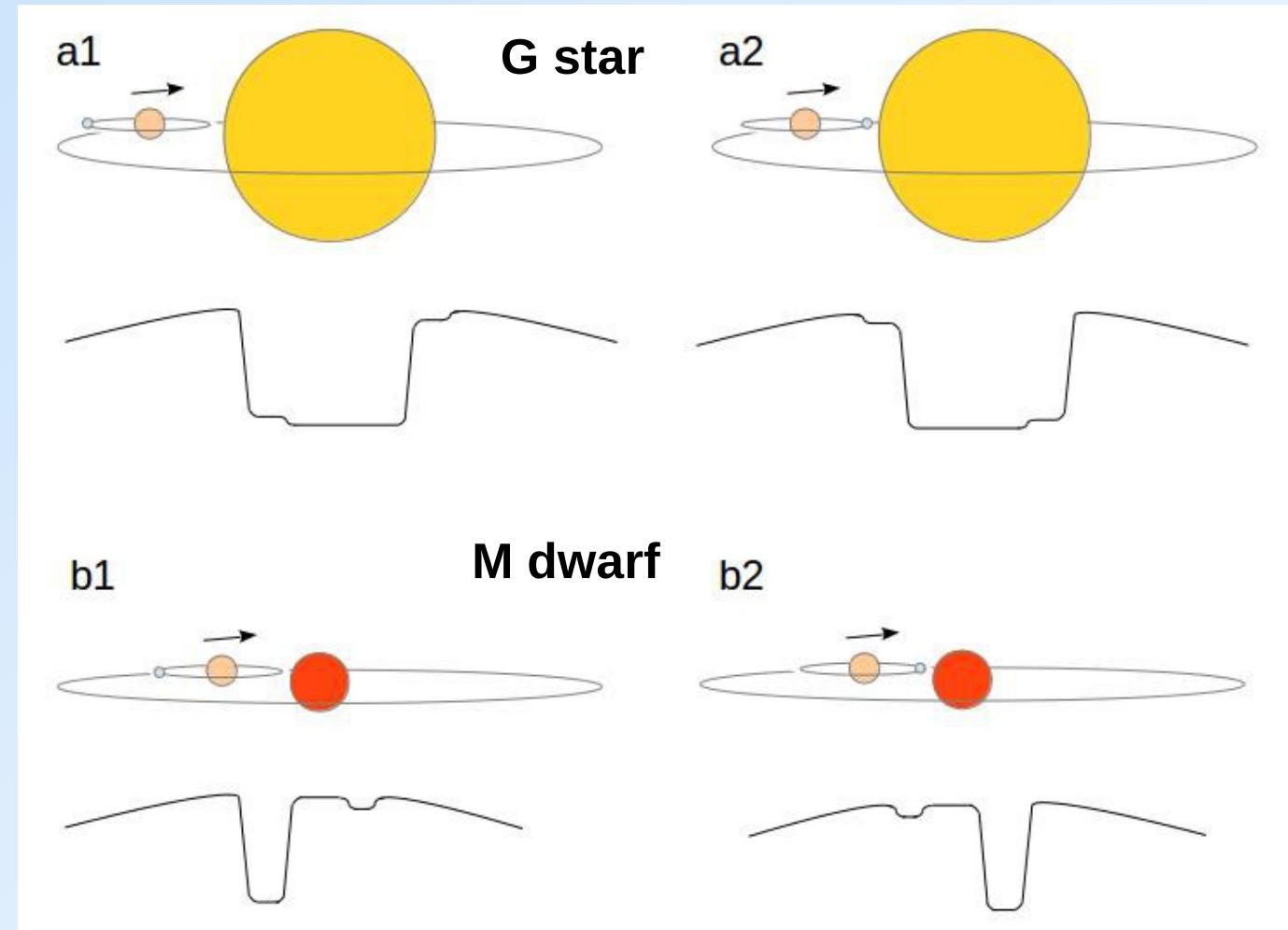
Europa



NASA/Caltech

Albedo estimation of icy moons

Occultation light
curve
(not transit!)

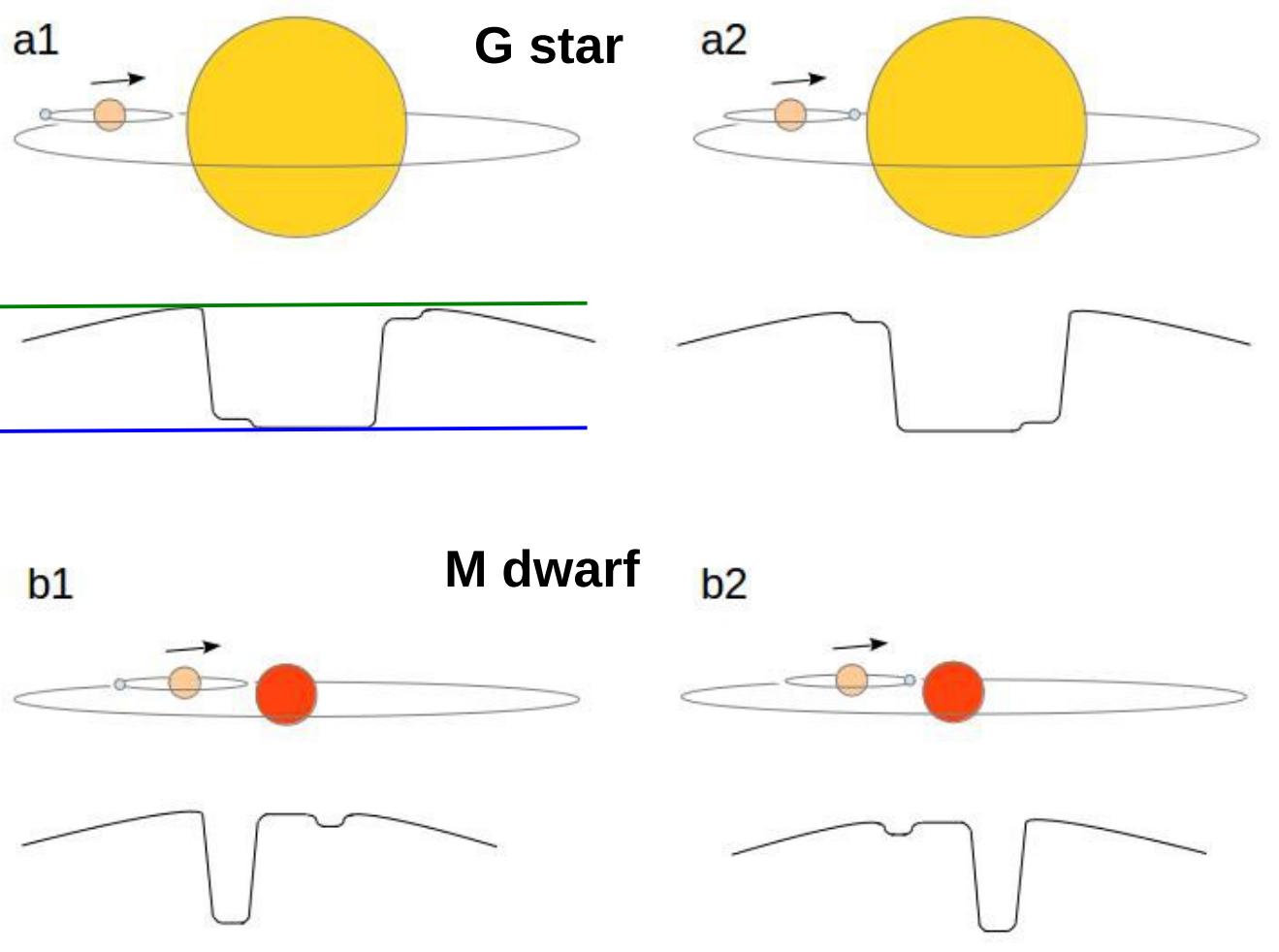


Albedo estimation of icy moons

Occultation light
curve

Stellar + planetary
+ moon flux

Stellar flux



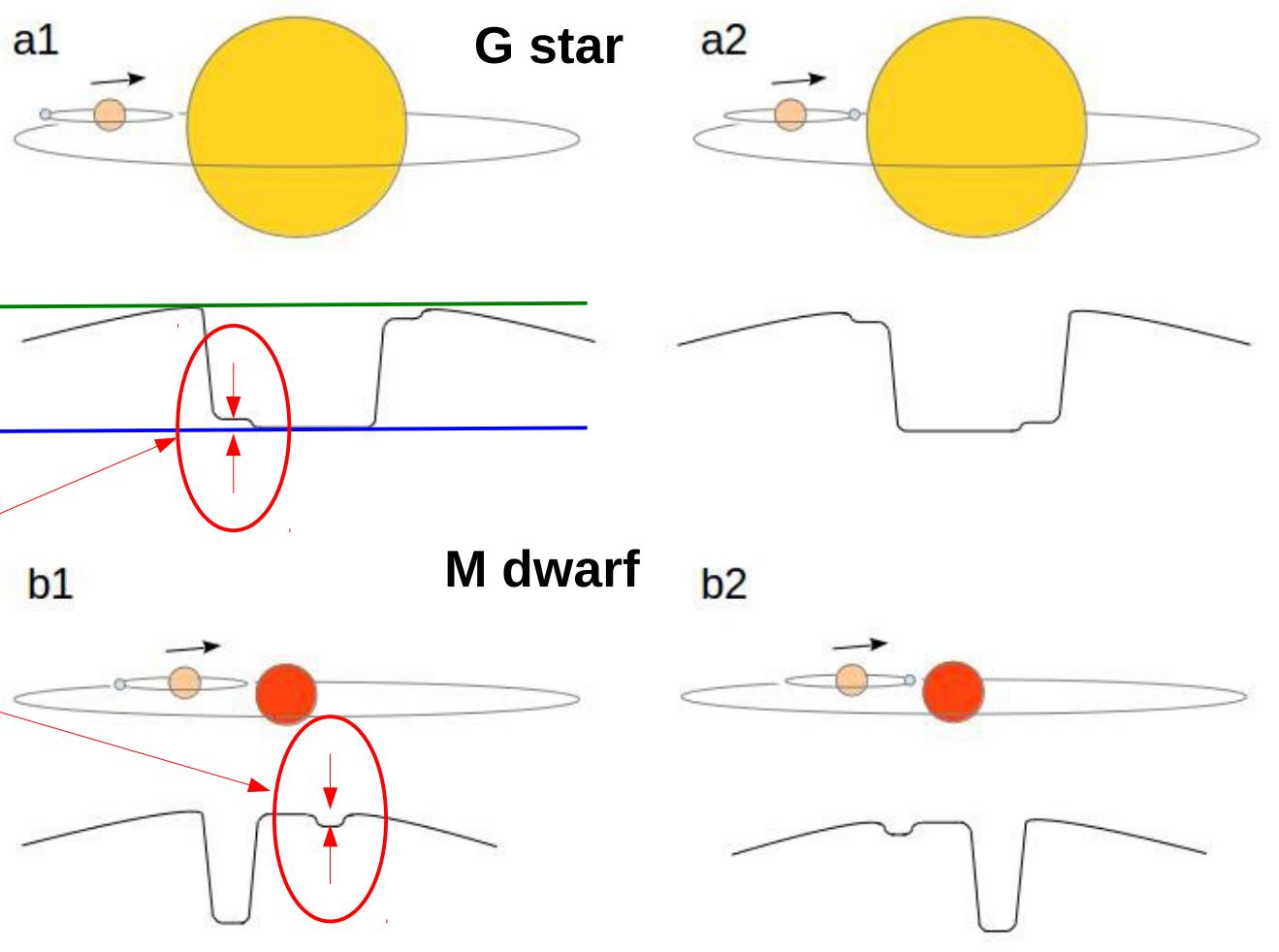
Albedo estimation of icy moons

Occultation light curve

Stellar + planetary
+ moon flux

Stellar flux

Moon's contribution
to the flux
(reflected light)



moon occultation
depth

Albedo estimation of icy moons

Occultation light curve

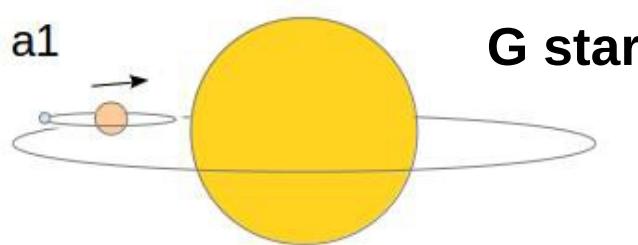
Stellar + planetary
+ moon flux

Stellar flux

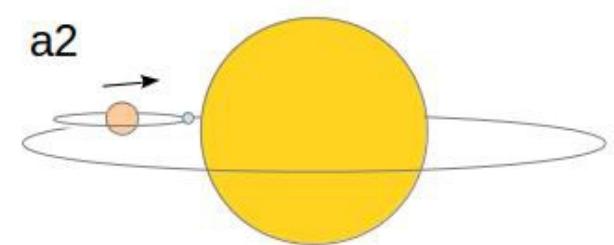
Moon's contribution
to the flux
(reflected light)

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

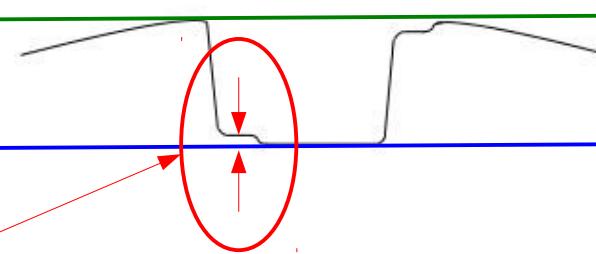
geometric albedo



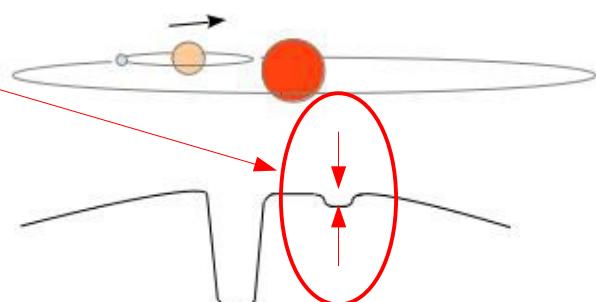
G star



a2

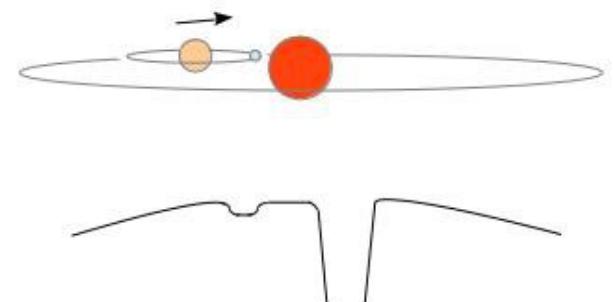


b1



M dwarf

b2



moon occultation
depth

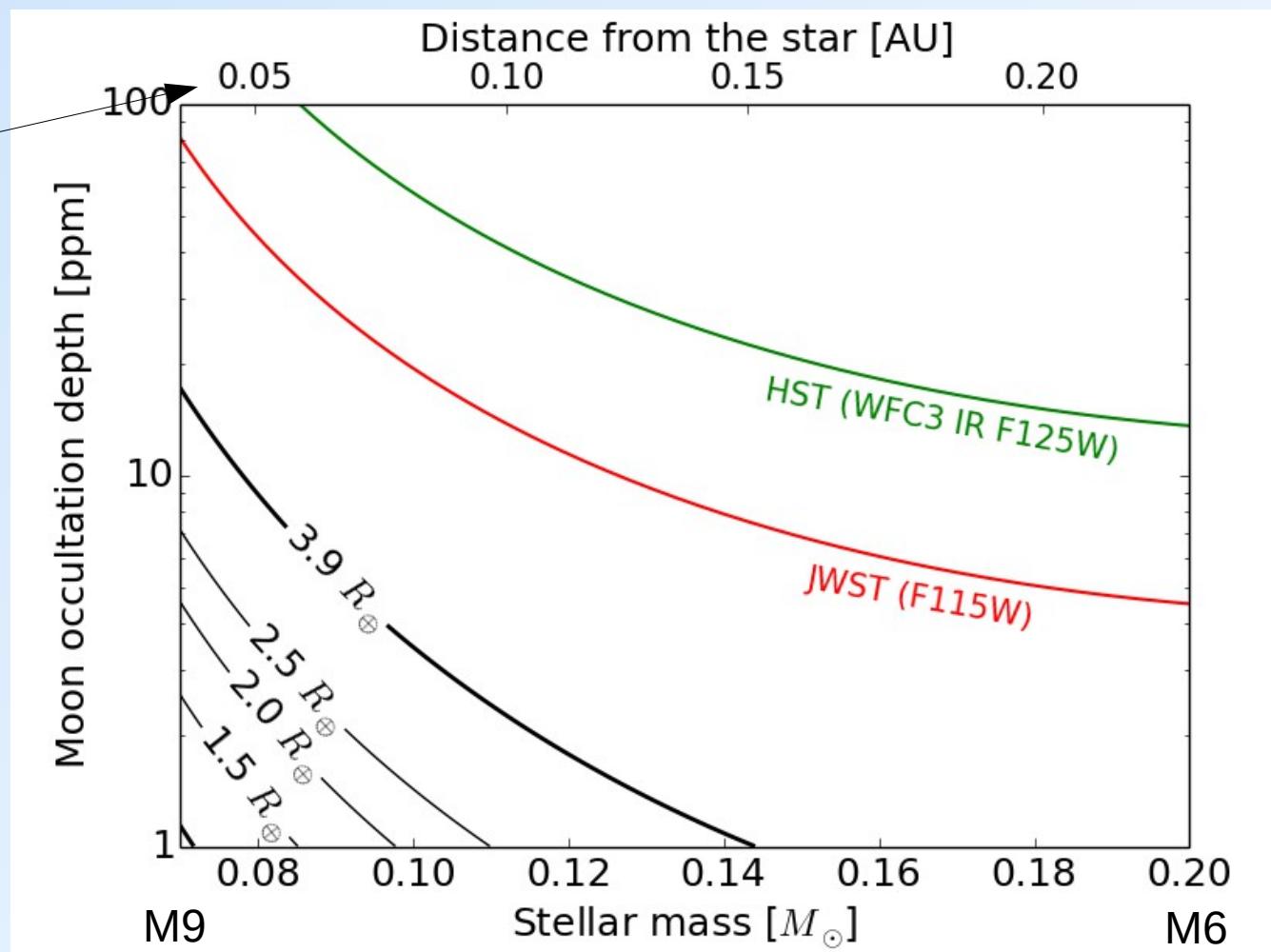
Observability

Large icy moon: if $2.5 R_{\text{Earth}}$  $\sim 5 M_{\text{Earth}}$

Neptune-mass planet

J phot. band ($A_g = 0.84$)

Small stars:
snowline closer



Observability

Large icy moon: if $2.5 R_{\text{Earth}}$  $\sim 5 M_{\text{Earth}}$

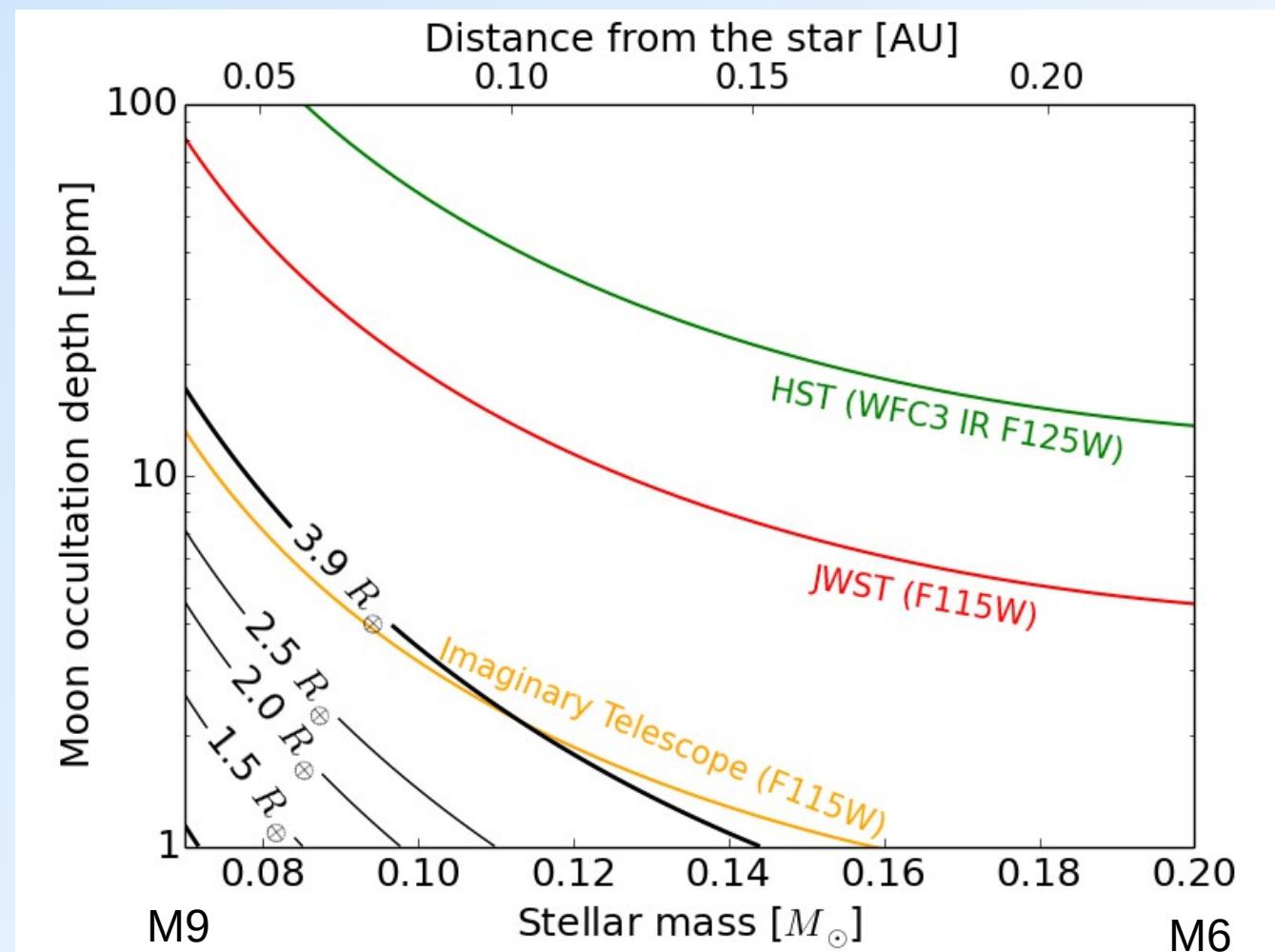
Neptune-mass planet

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Small stars:
snowline closer

5σ detection

Imaginary Telescope: 40 m



Observability

Large icy moon: if $2.5 R_{\text{Earth}}$  $\sim 5 M_{\text{Earth}}$

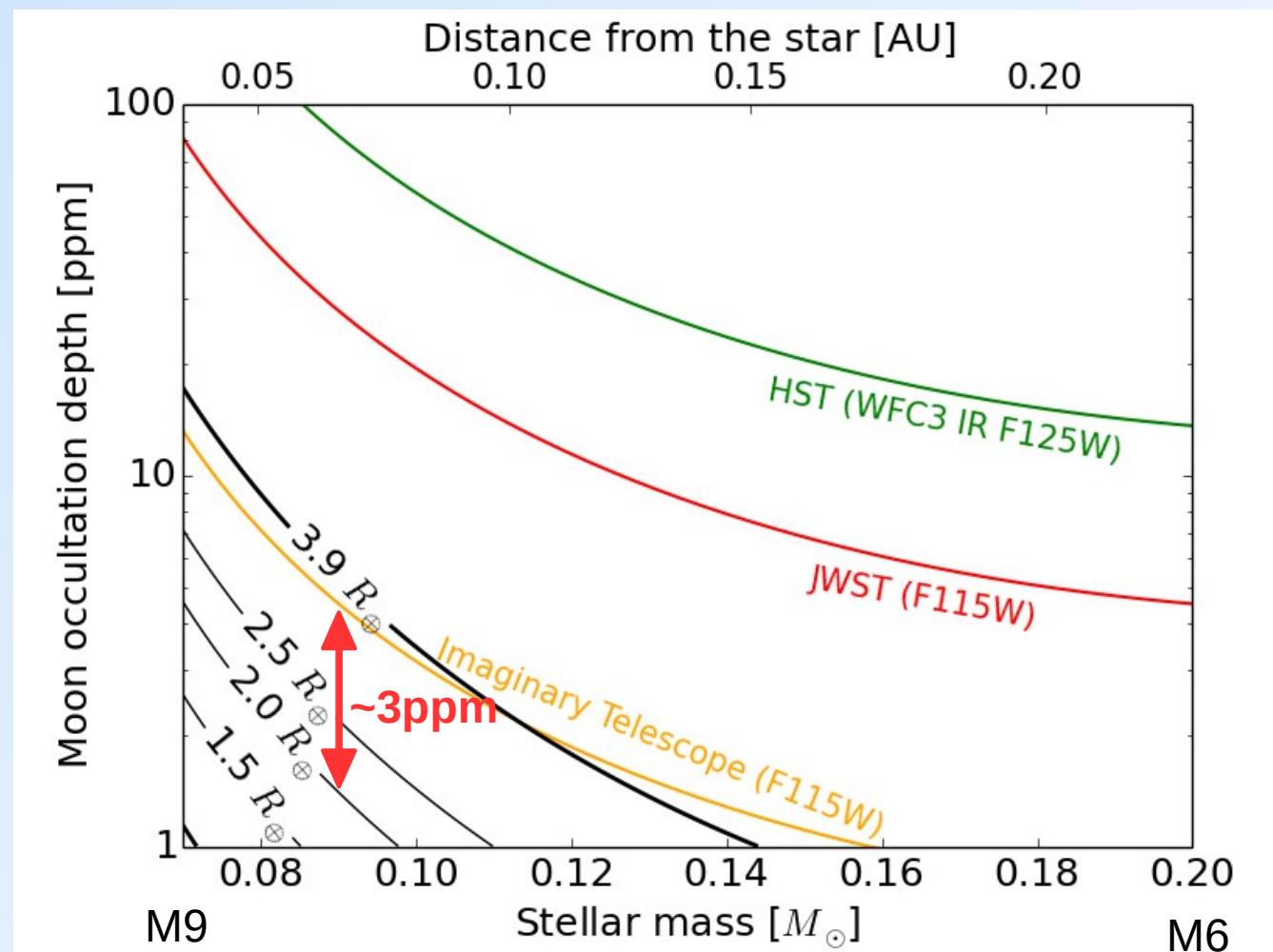
Neptune-mass planet

J phot. band ($A_g = 0.84$)

Small stars:
snowline closer

5σ detection

Imaginary Telescope: 40 m



Thank you

Collaborators:

- Edwin L. Turner
- Ákos Kereszturi
- Zsolt Keszthelyi
- András Pál
- László L. Kiss

