Pathways Towards Exomoons

Brief Outline

- Big thank-you to our 10 speakers (Kane, Hong, Perets, Dobos, Forgan, Kisiyakova, Lacy, Kipping, Haghighipour, Beaulieu)
- Exomoons are coming, we aim to build an interested community through our meeting
- 3 main topics: i) formation & evolution ii) habitability iii) detection
- We will post slides pending agreement from speakers at www.exomoon.org

~habitable zone

Foreman-Mackey+ 2014

$0.5R_\oplus$ moons stable

$0.5R_\oplus$ moons unstable

[Barnes & O'Brien 2002]

Gaseous-Rocky divide at $1.5R_\oplus$ [Rogers 2015]

Gaseous Planets

$\eta^{HZ}_{gassy} = 9.2^{+1.9}_{-1.7}$ %

≈5× more

Rocky Planets

$\eta^{HZ}_{rocky} = 1.7^{+2.6}_{-1.0}$ %

Planet size [Earth radii]

32.0
16.0
8.0
4.0
2.0
1.0
0.5

6.25
12.5
25
50
100
200
400

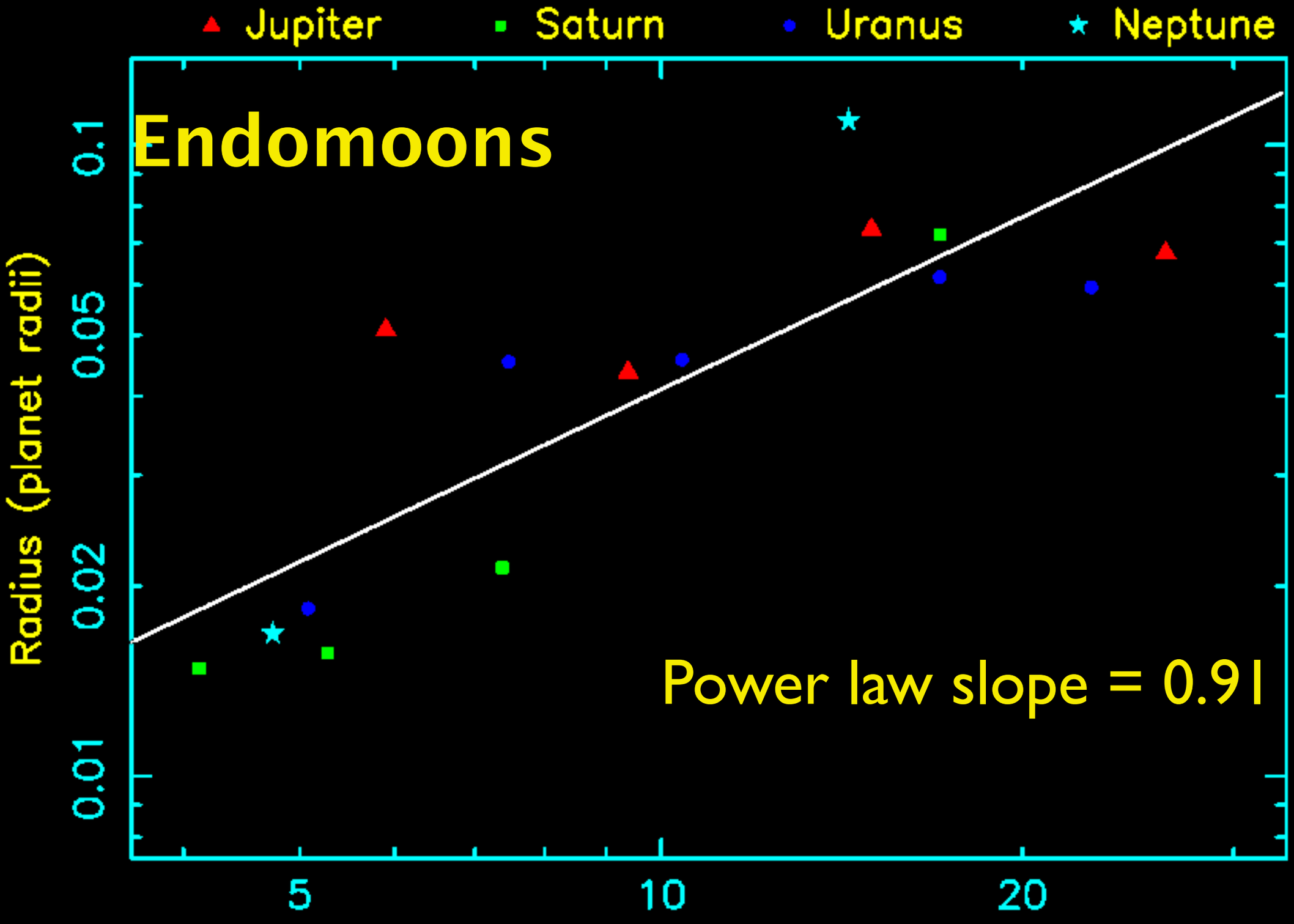
Orbital period [days]

Planet occurrence, η_{planet} [%]

3
2
1
0

FORMATION & EVOLUTION

***Kane**: Sol Sys Moons as Exoplanet Analogs*



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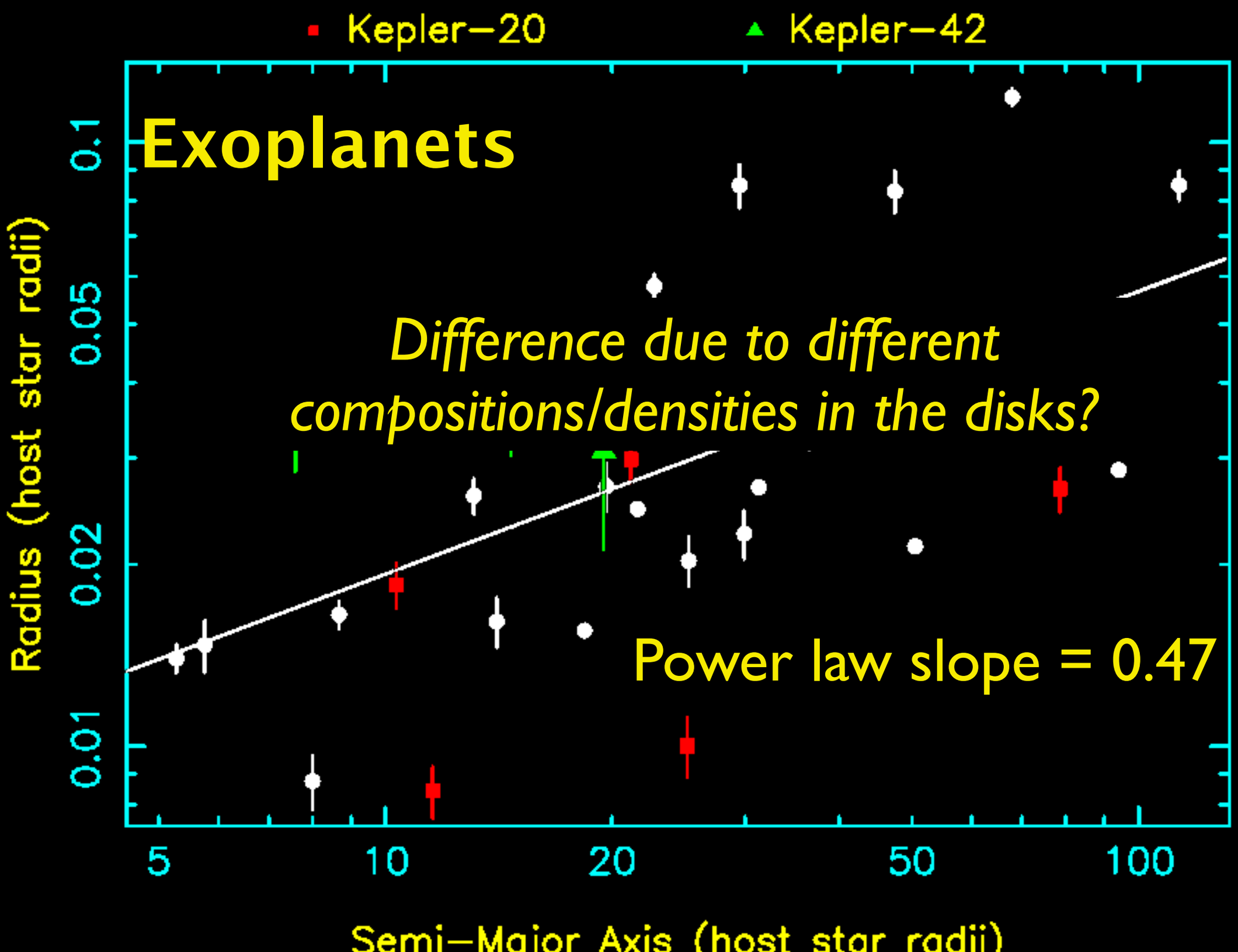

FORMATION & EVOLUTION

***Hong**: Exomoon Survivability after Close Planet-Planet Encounters*

- planet-planet scattering reproduces observed exoplanet eccentricity - will their moons survive?

- moon survival vs planet observables: semi-major axis, ecc, inc, mass => can predict moon survival rates and place upper bounds on moon semi-major axis

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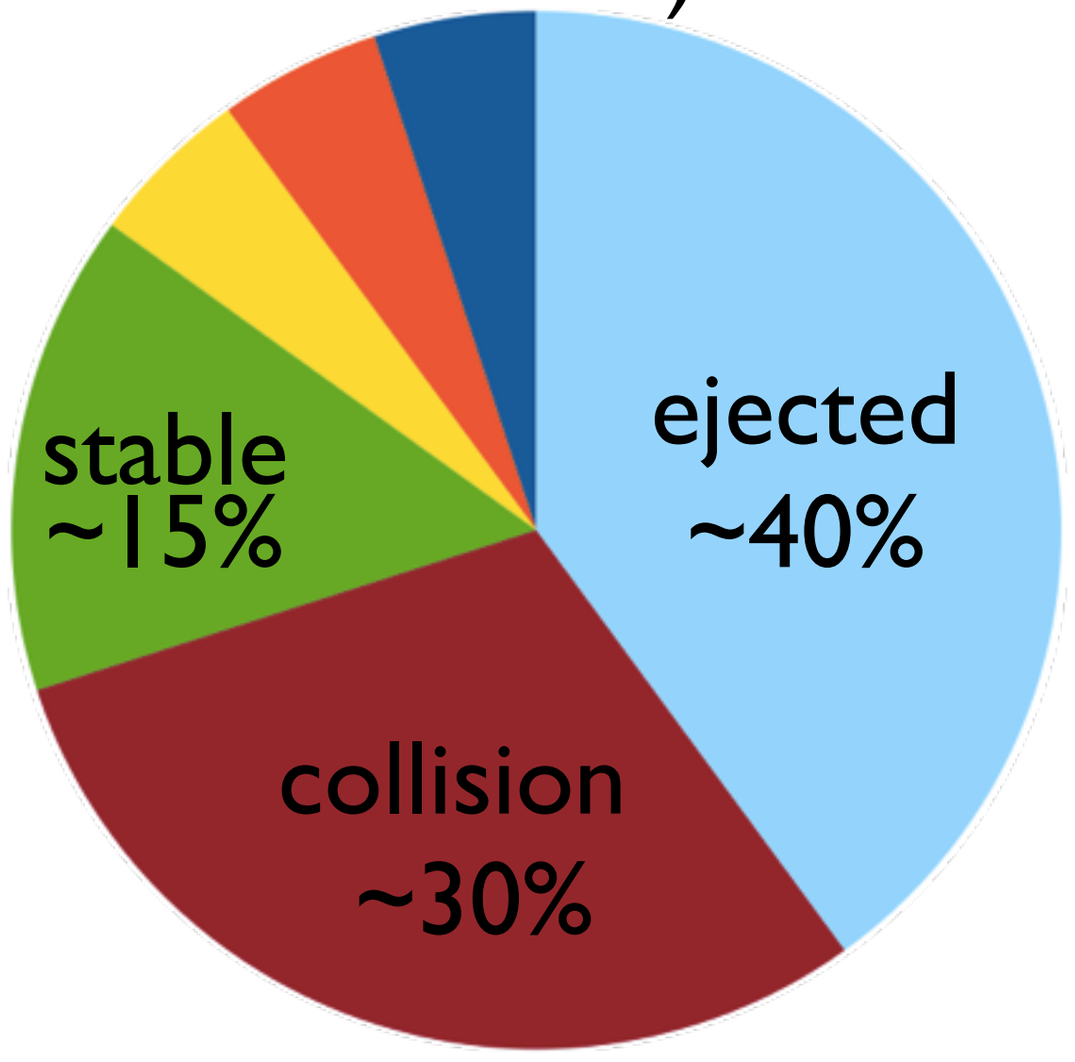
- moon survival vs planet observables: semi-major axis, ecc, inc, mass => can predict moon survival rates and place upper bounds on moon semi-major axis
- favourable conditions for survival: low inc & ecc, less migration, attached to massive planets and less frequent/more distant planet-planet encounters

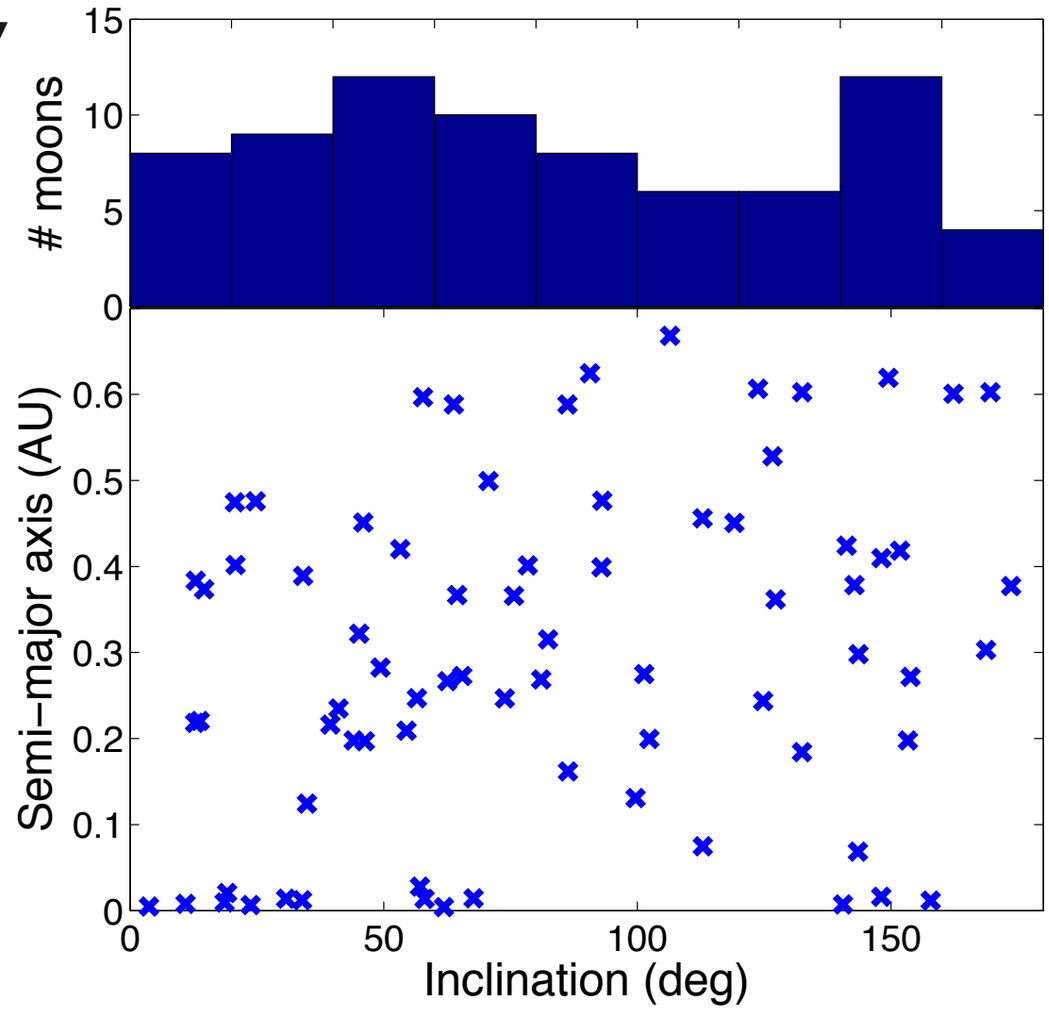
other cases (e.g. astrocentric orbit)



FORMATION & EVOLUTION

***Perets**: Formation & Evolution of (Exo)moons*

- Solar system moons of the gas-giants, (including retrograde small moons), may have all formed through in-situ formation
  - **Capture scenarios might not be needed**

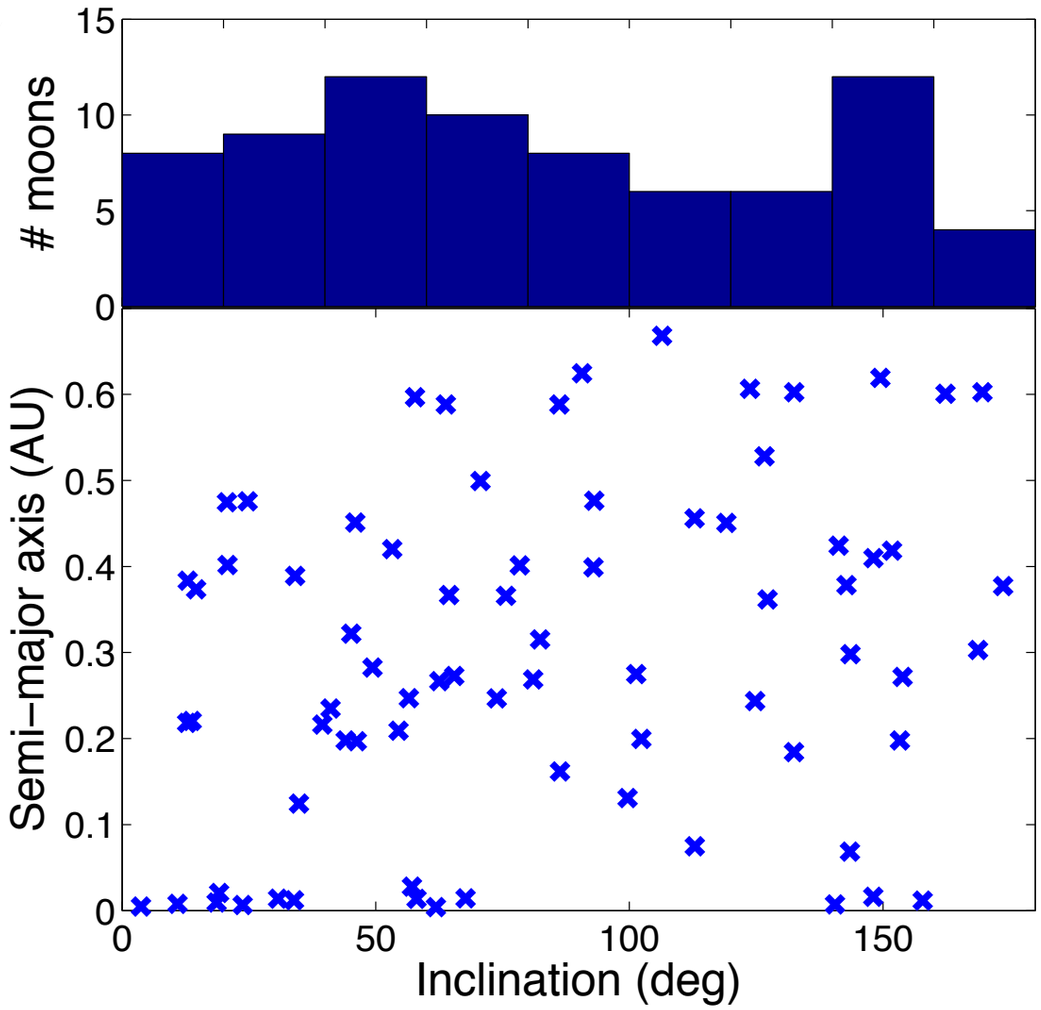


Inclined moons formed as regular satellites + moon-moon scattering

FORMATION & EVOLUTION

***Perets**: Formation & Evolution of (Exo)moons*

- Solar system moons of the gas-giants, (including retrograde small moons), may have all formed through in-situ formation
  – Capture scenarios might not be needed
- Large Mars-size moons can form in more massive circumplanetary disk, which would suggest the possibility of large exomoons around more massive planets
- Moons of migrating planets are less likely to survive, even in the inner regions



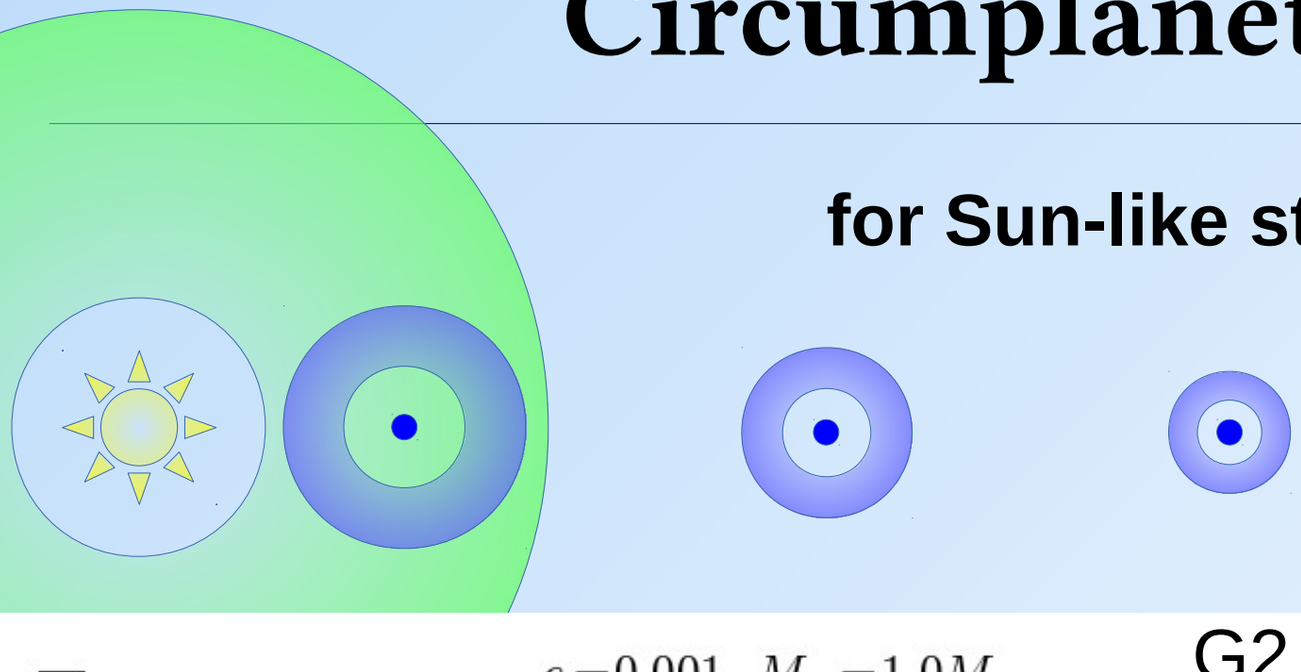
Inclined moons formed as regular satellites + moon-moon scattering

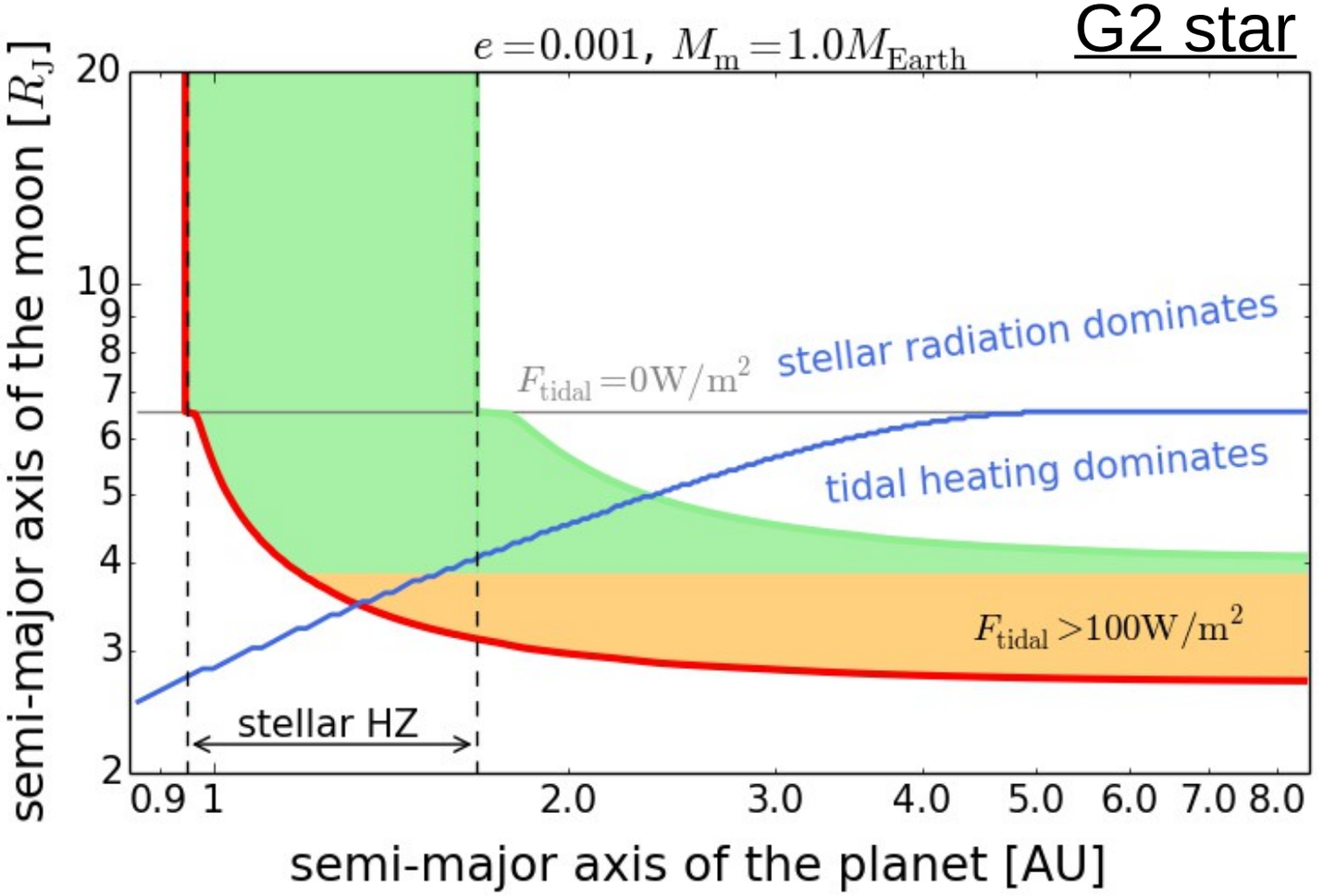
EXOMOON HABITABILITY

Dobos: *Viscoelastic Tidally Heated Exomoons*

Circumplanetary HZ

for Sun-like stars





Stellar irradiation
+
tidal heating

Jupiter-like planet
+
Earth-like moon

Outer limit: maximum greenhouse

Inner limit: runaway greenhouse

Dobos et al. (2015), *in preparation*

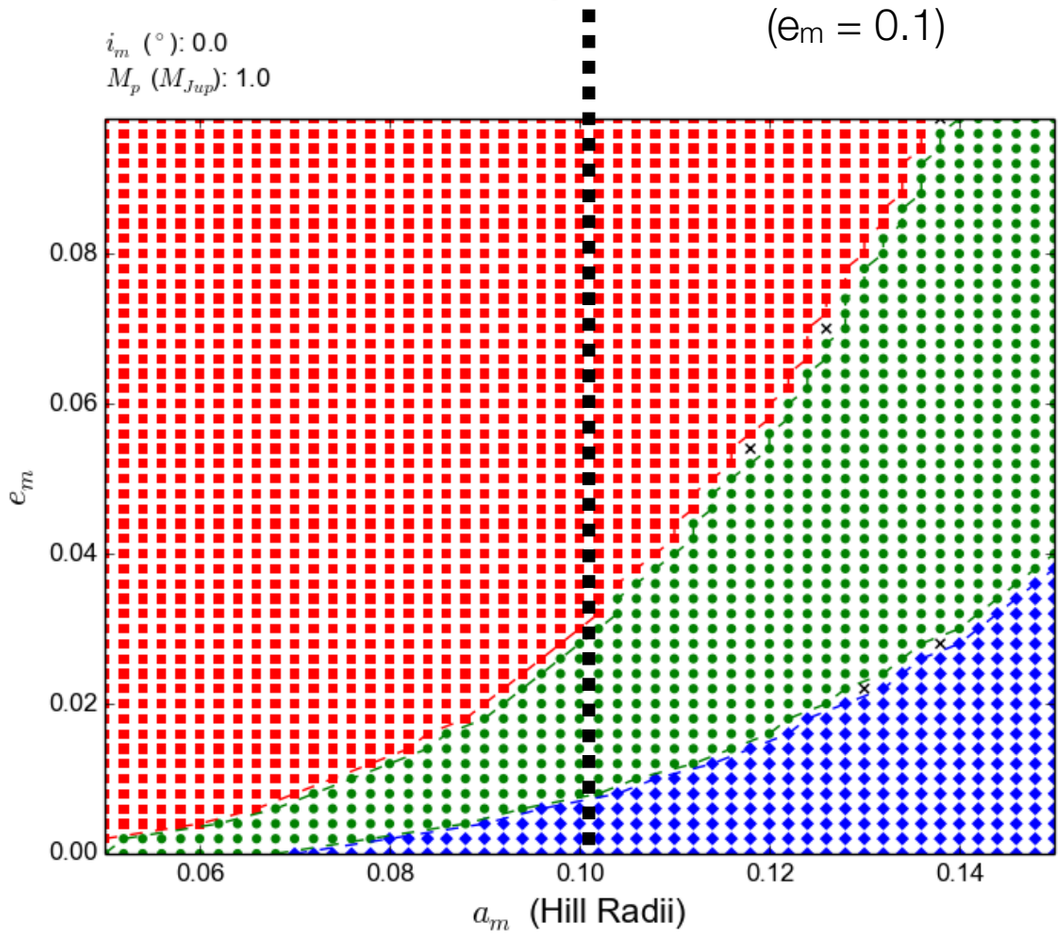
EXOMOON HABITABILITY

Forgan: *Climate Models of Earthlike Exomoons*

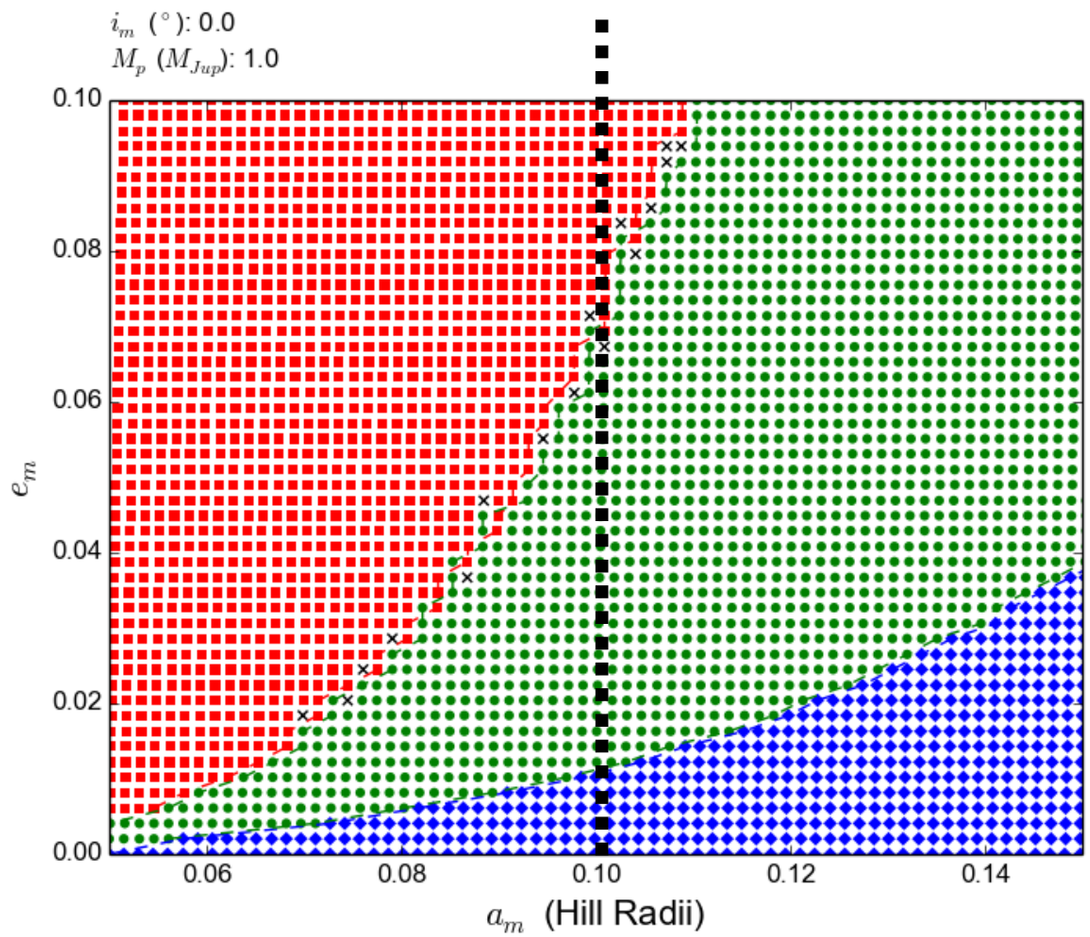
University of St Andrews

Forgan and Kipping (2013), Forgan and Yotov (2014), Forgan, Dobos and Turner (in prep).

Forgan & Yotov (2014) outer edge of HZ
(e_m = 0.1)



CS cycle
Fixed-Q tidal Heating



CS cycle
Viscoelastic tidal Heating

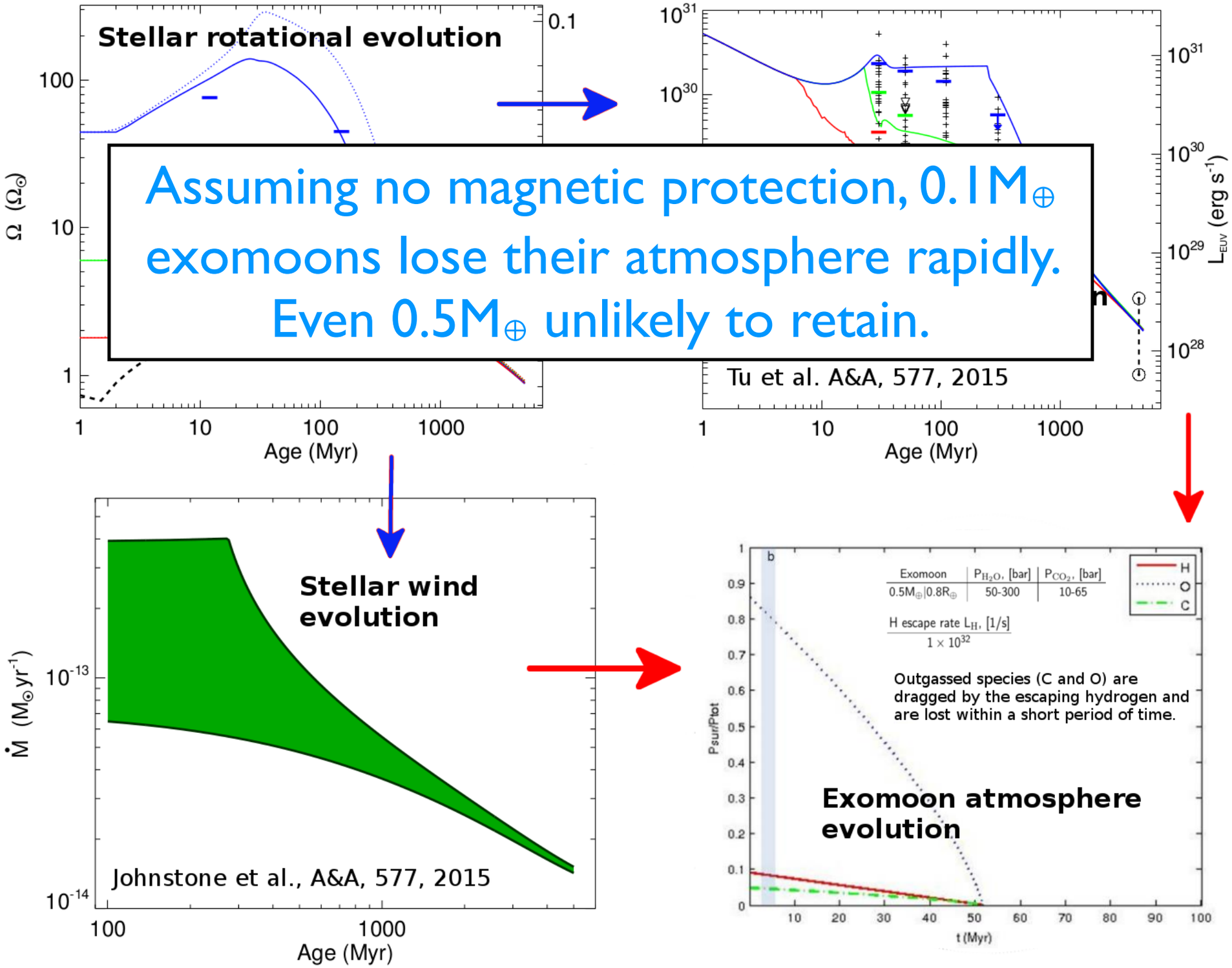
- Exomoon HZ are complex and multimodal
- Circumplanetary HZs have an inner and an outer edge
- This is due to a combination of eclipses and ice albedo feedback

EXOMOON HABITABILITY

***Kisiyakova**: Stability of Exomoon Atmospheres*

H. Lammer,
K.G.Kislyakova,
N.V. Erkaev,
I. Juvan,
P. Odert,
M. Güdel

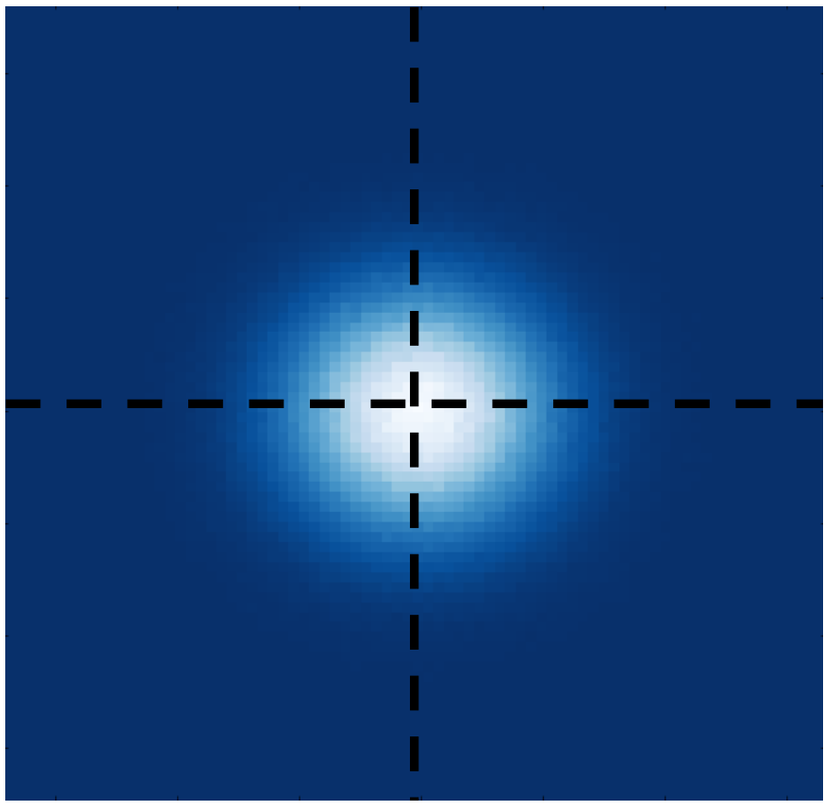
Summary of the study: Lammer et al., OLEB, 2014, **44**, 239



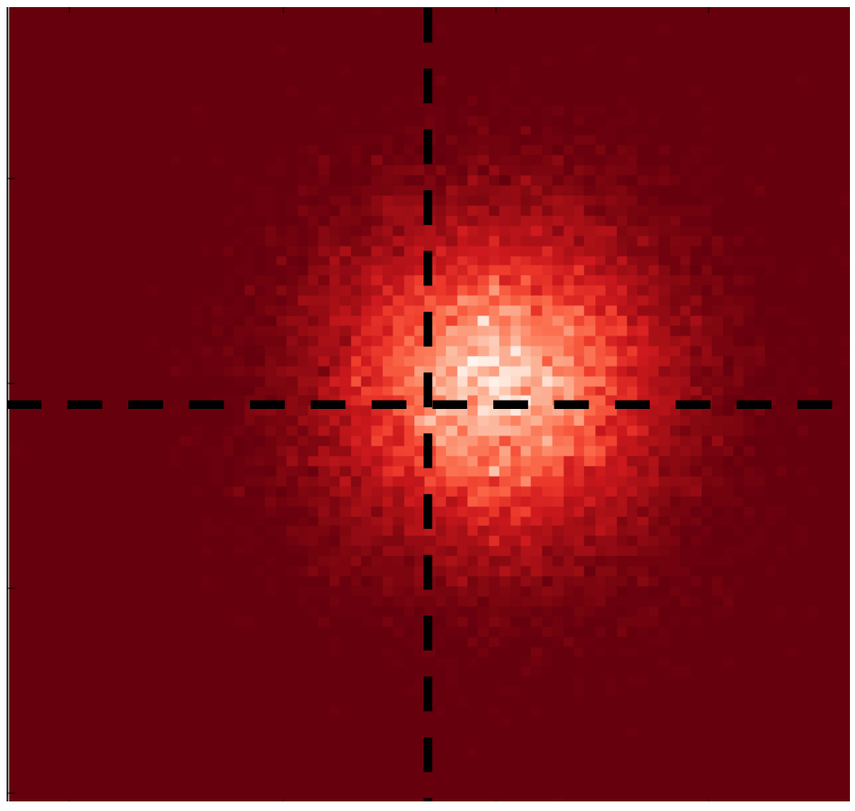
DETECTION OF EXOMOONS

***Lacy**: Spectroastrometric Detection of Exomoons*

Signal: $\left|Centroid(\lambda_{planet}) - Centroid(\lambda_{moon})\right|$



0.35um



2.69um

Earth-Moon around Alpha Centauri

(12m space telescope with perfect coronograph for 24h)

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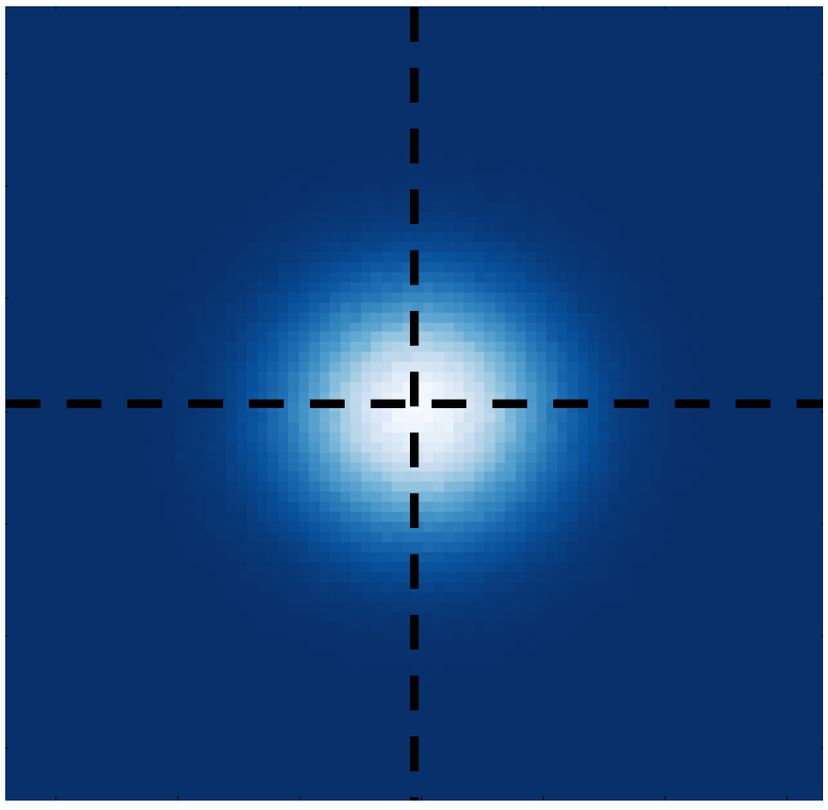

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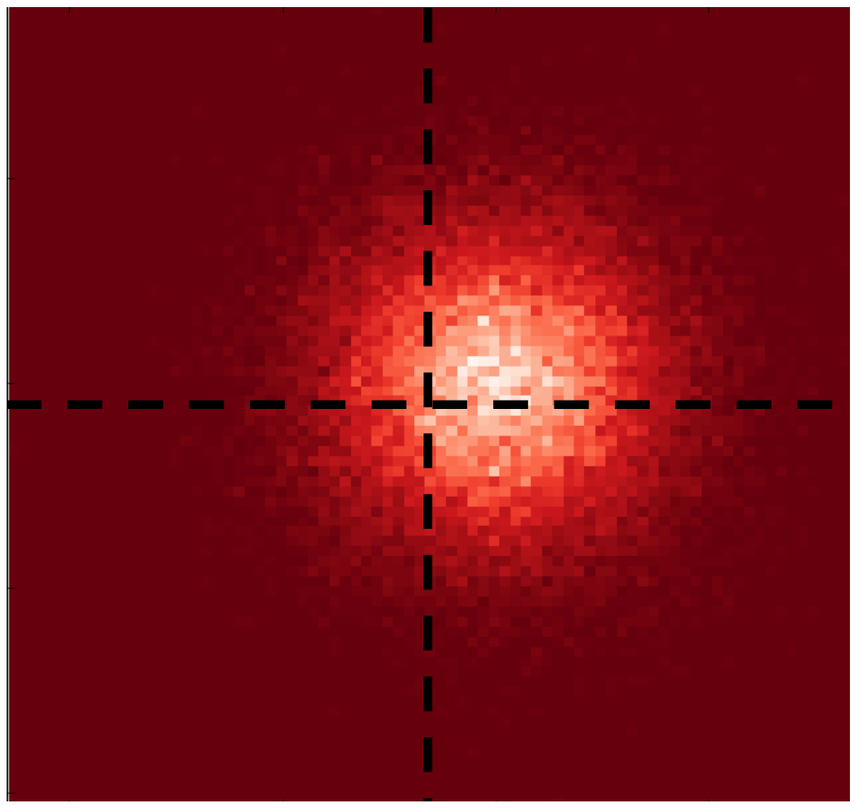

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DETECTION OF EXOMOONS

***Lacy**: Spectroastrometric Detection of Exomoons*

Potential targets:

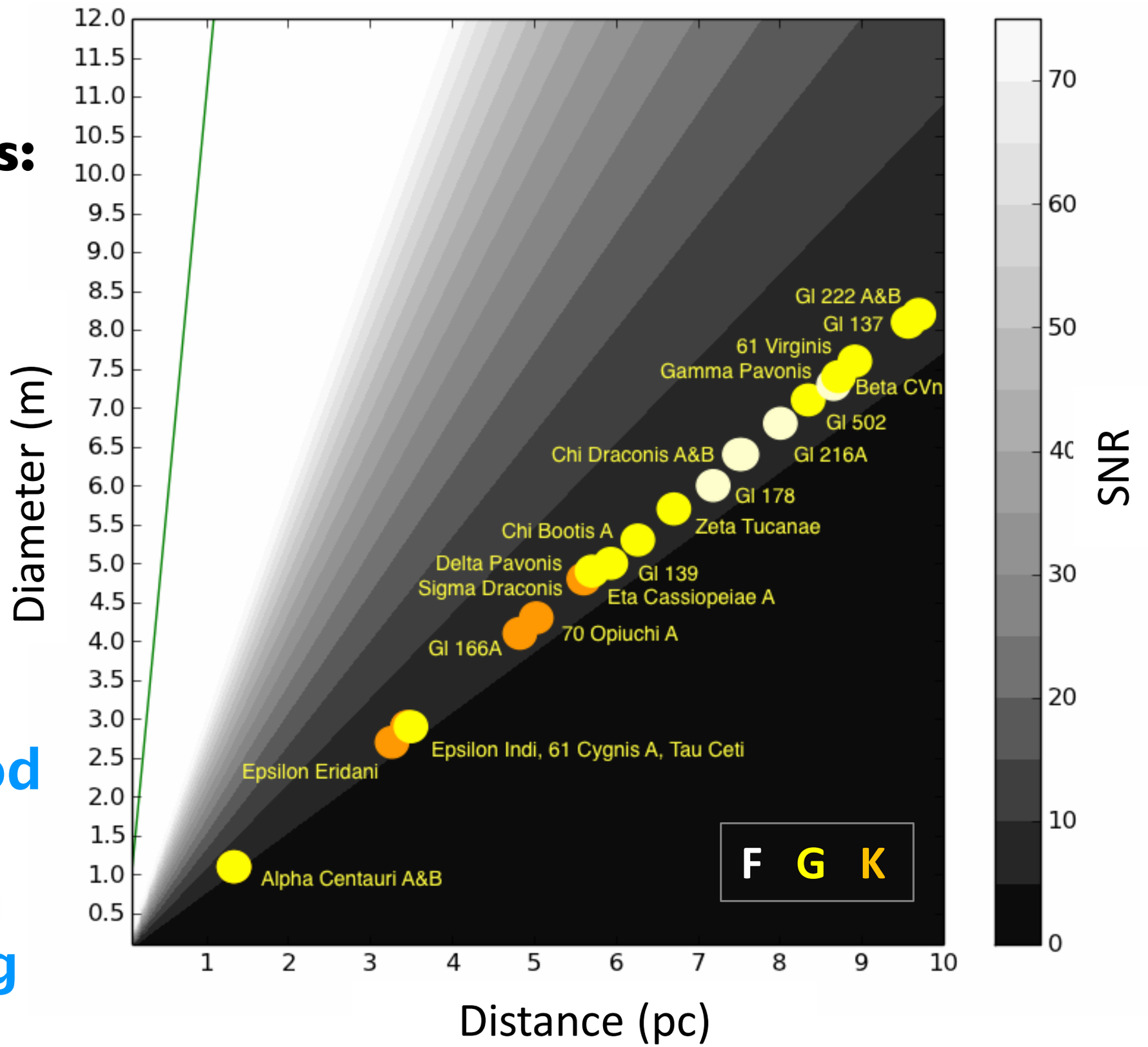
Earth–Moon

1 (Alpha Centauri)

Jupiter–Earth

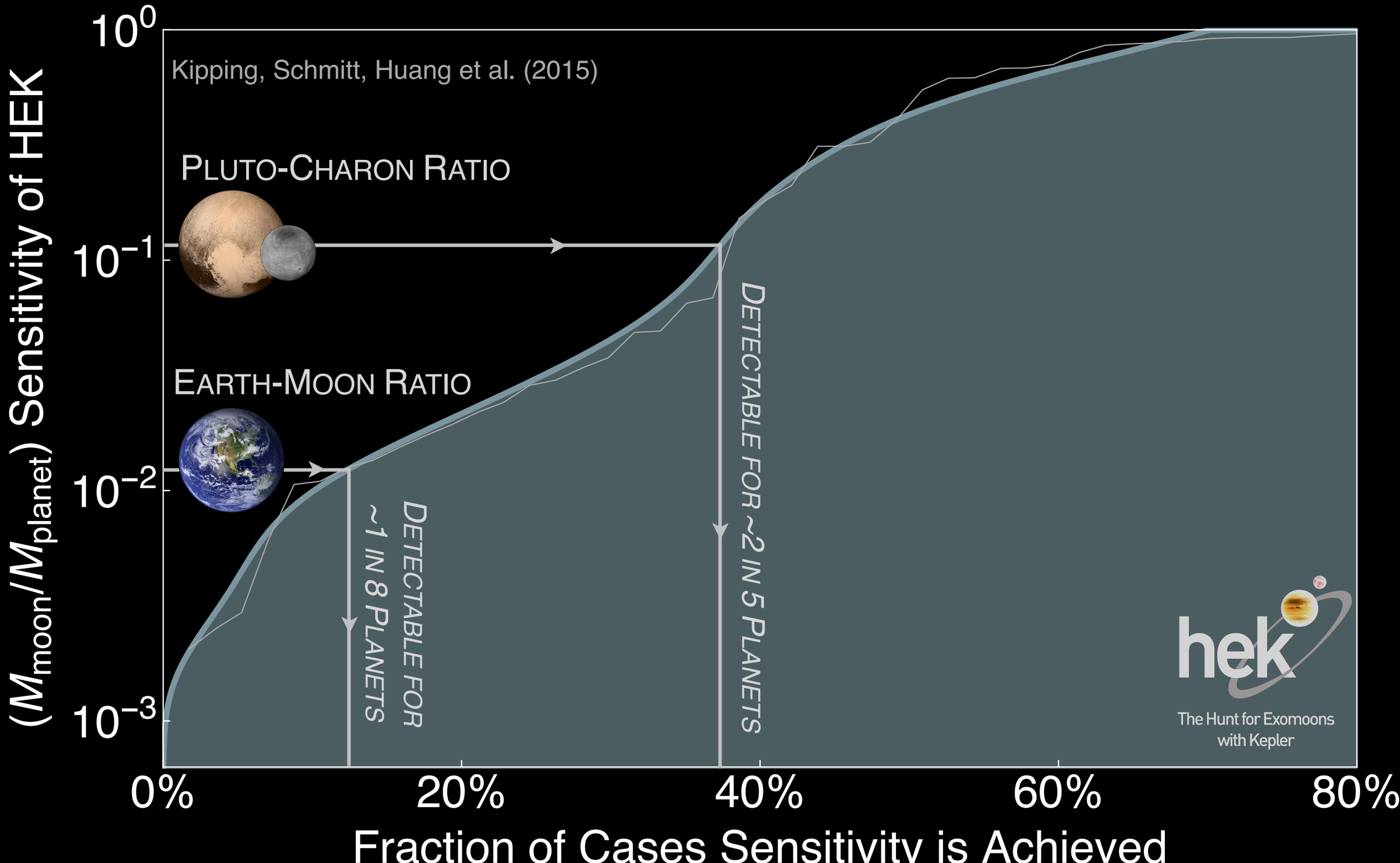
58 FGK stars

Not just a detection method but also a characterization method, yielding a moon spectra



DETECTION OF EXOMOONS

***Kipping**: The Hunt for Exomoons with Kepler (HEK) project*



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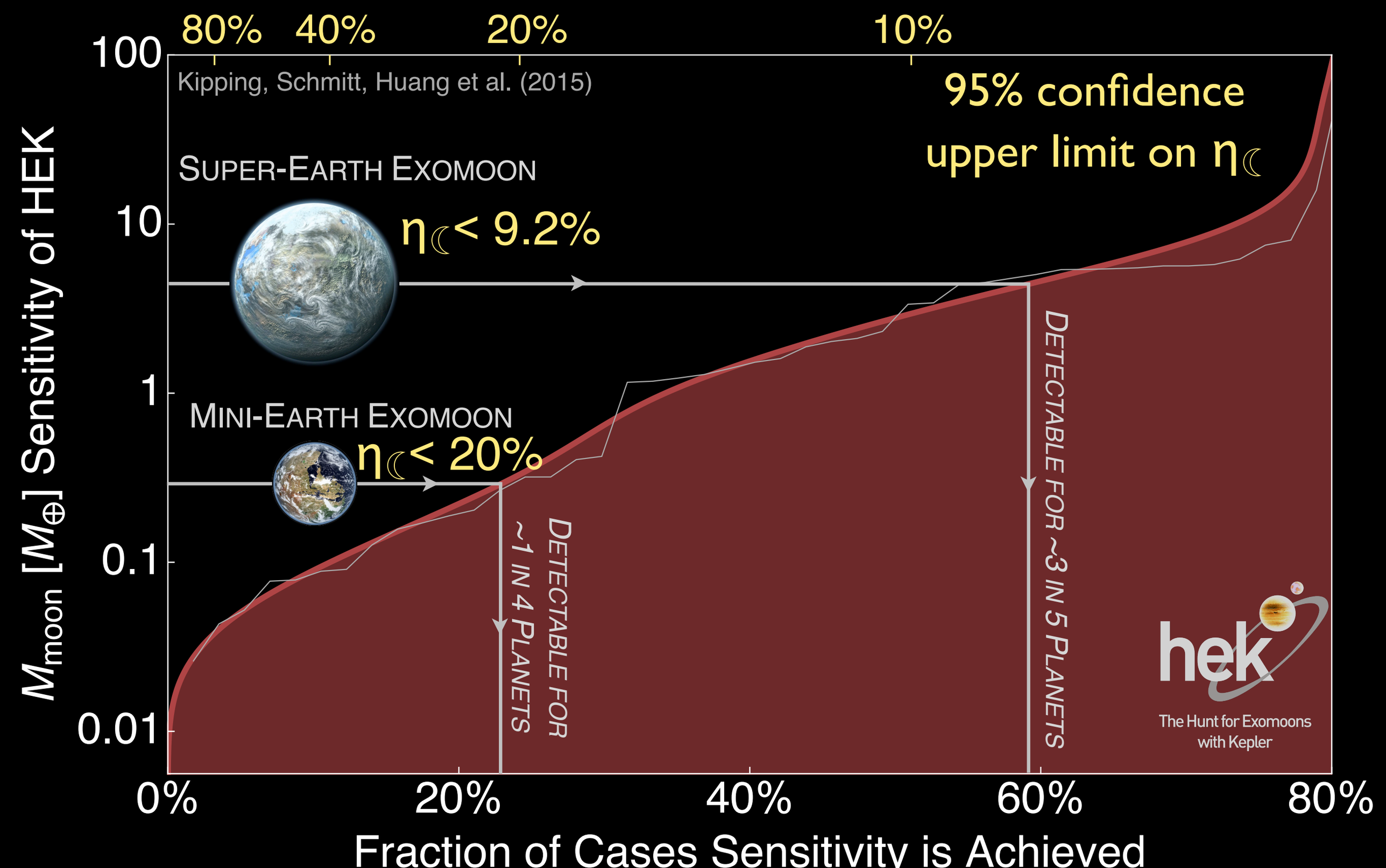


DETECTION OF EXOMOONS

Hunt for Exomoons

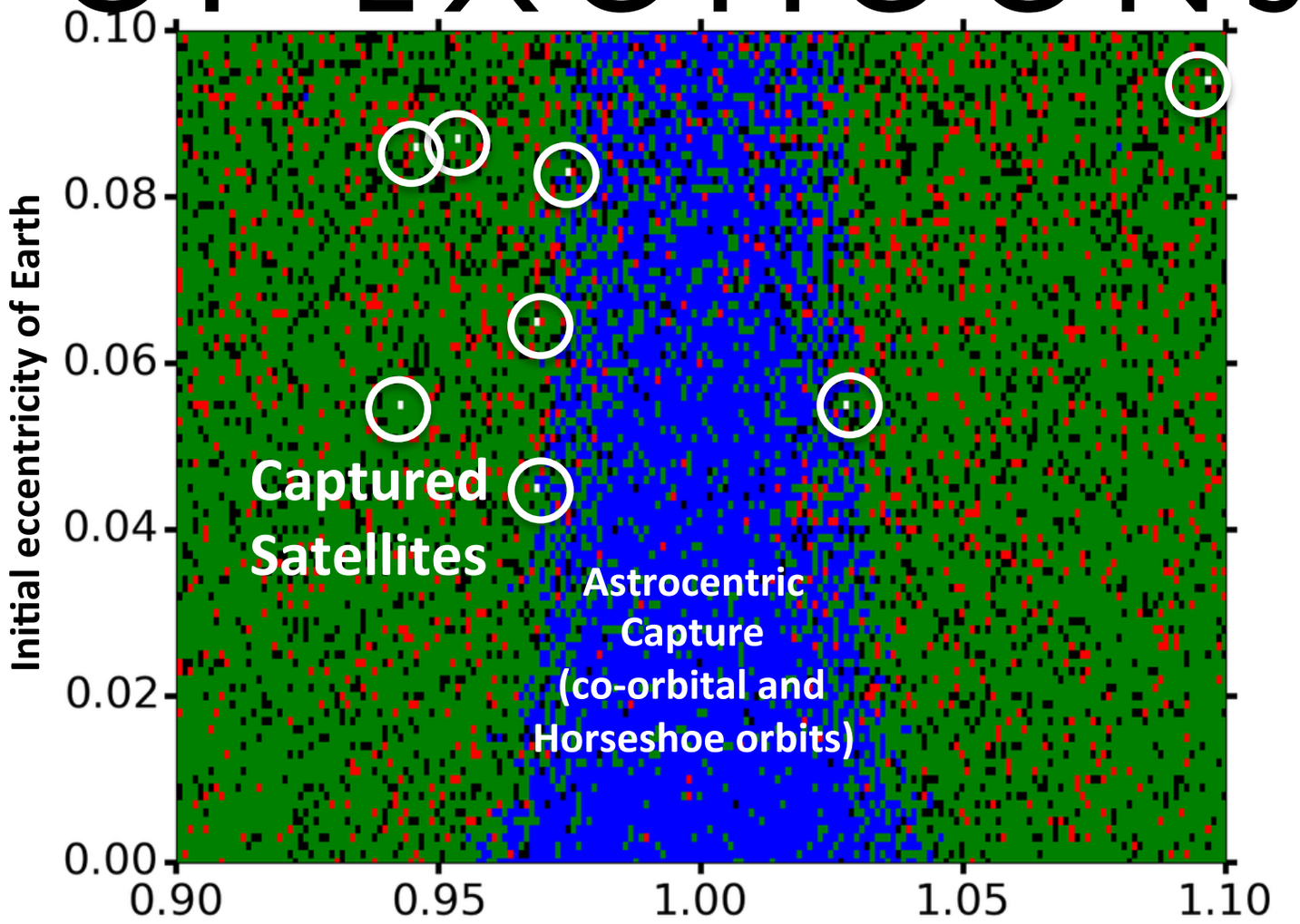
Formation, Evolution, and Detection

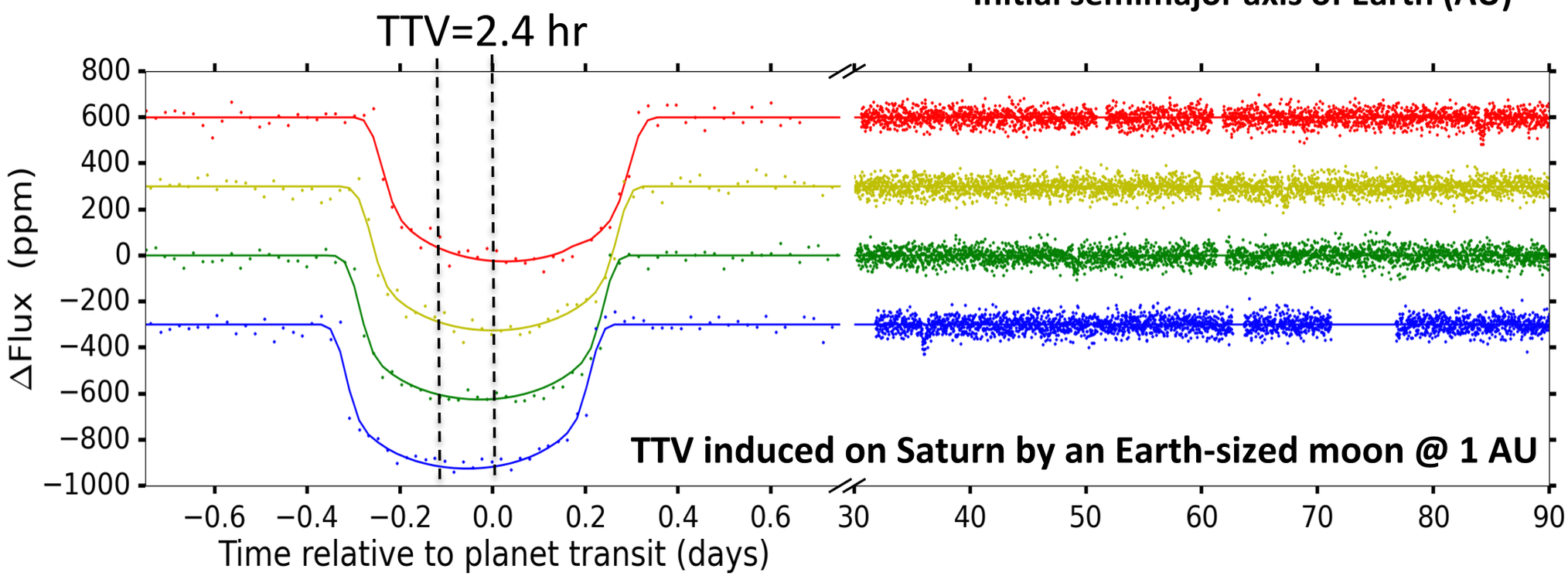
Nader Haghighipour (IfA, Hawaii)
Billy Quarles (NASA Ames)

Searching population of Kepler Neptune-sized Planet candidates for terrestrial-class satellites.

Constraining the search through formation process.

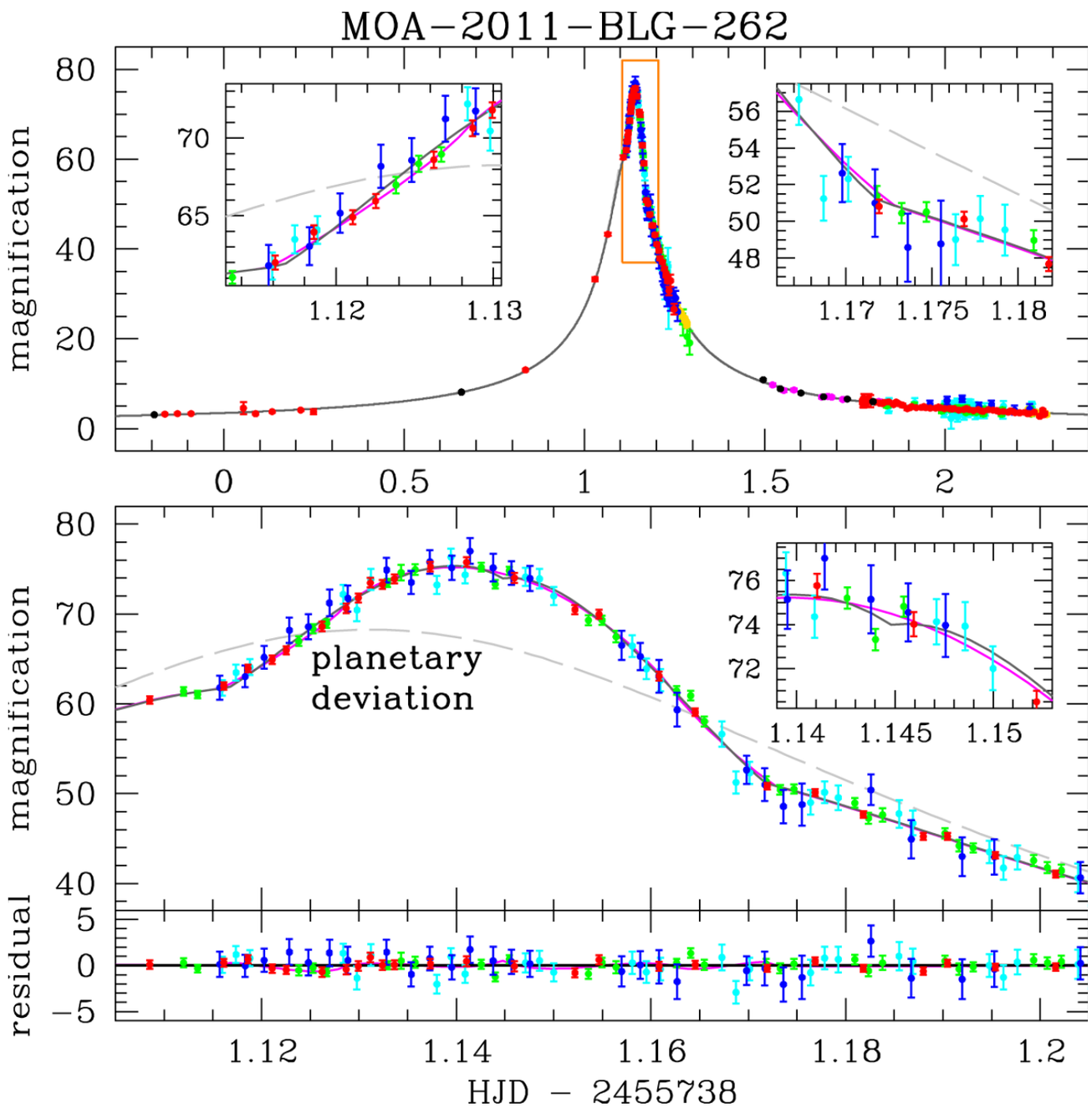
Use transit, TTV, and TDV to detect Exo-satellites.

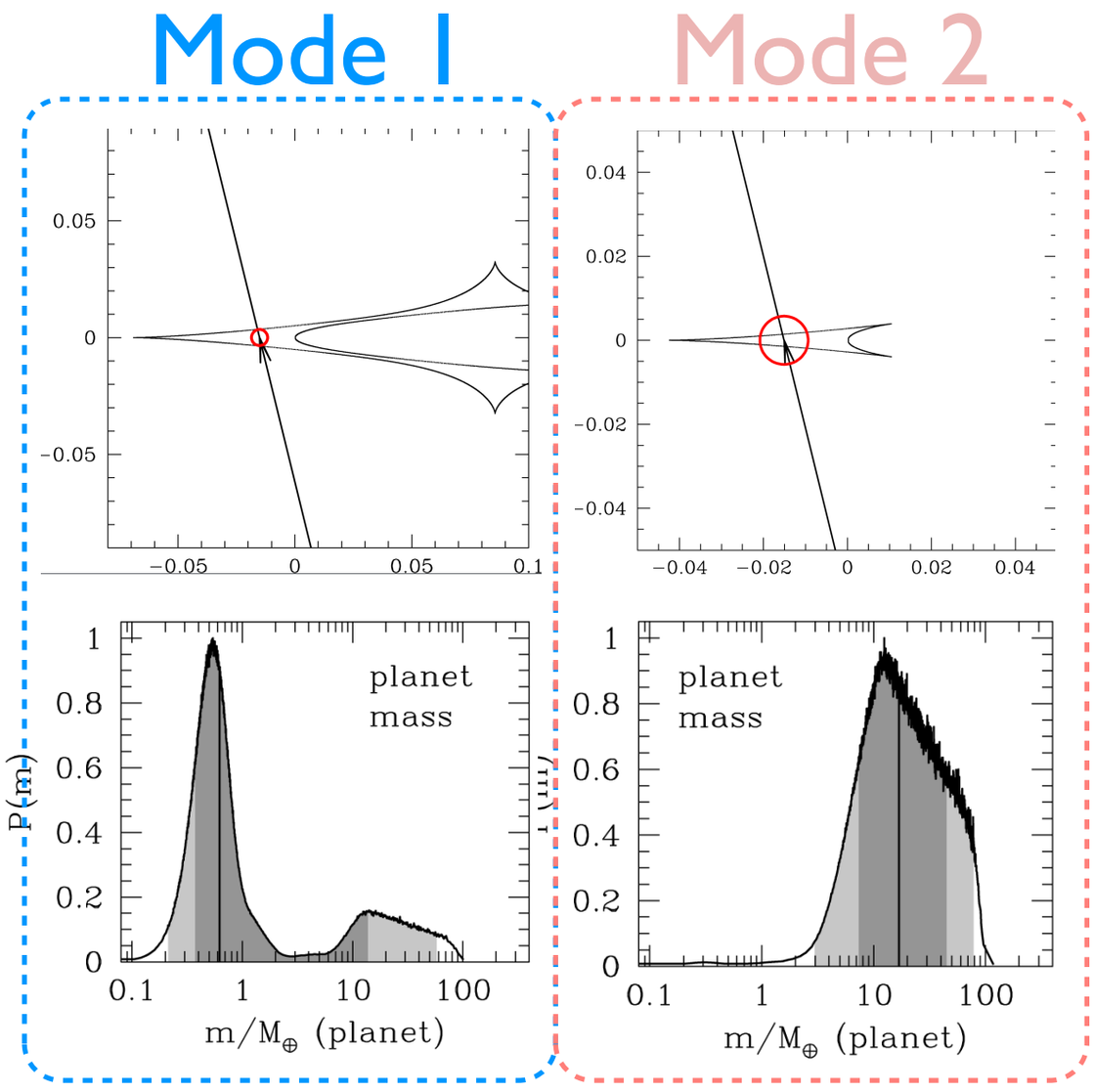




DETECTION OF EXOMOONS

Beaulieu: *A Microlensing Exomoon Candidate*





Mass-ratio = 5 10^{-4}

DETECTION OF EXOMOONS

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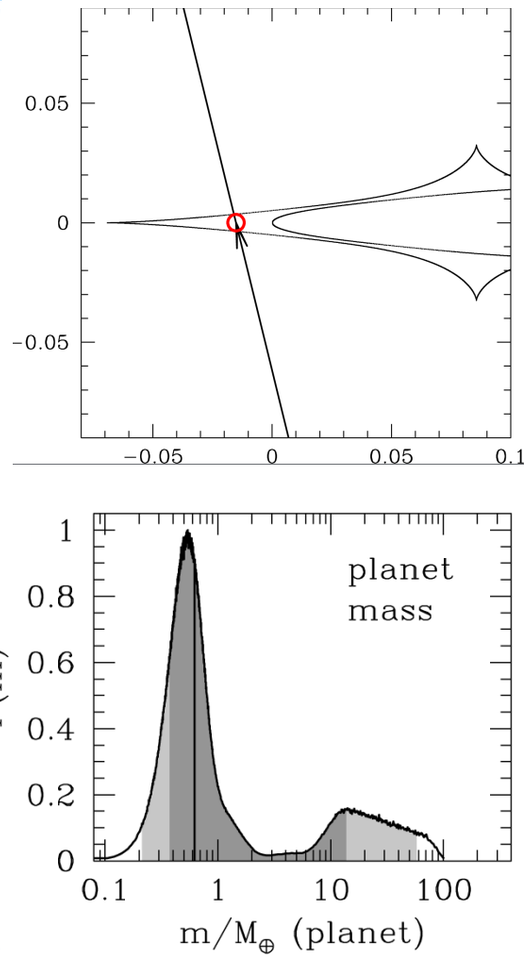
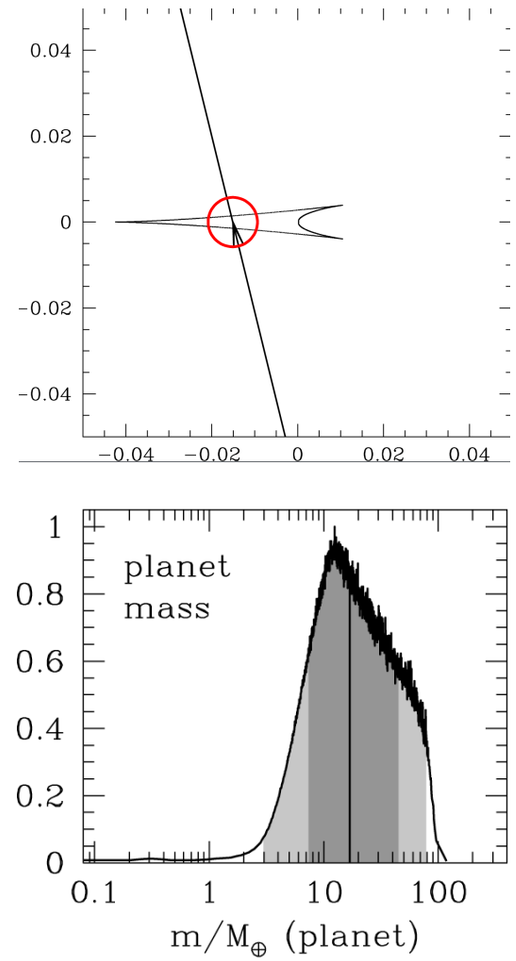
Mode 1



Free floating $5M_J$ Jupiter with a sub-Earth moon @ 500pc

Mode 2

Late M-dwarf with a sub-Neptune mass planet @ high velocity



No hope to distinguish with current data (if we'd had a parallax could have solved)

Mass-ratio = $5\ 10^{-4}$

Final Thoughts

- Is there a plausible pathway for the formation & evolution of big (Earth-like) moons?
- Planet migration/encounters are bad for moons
- Exomoons have complex, multi-dimensional "habitable-zones". Tides & atmospheric loss are major concerns.
- Is the current data on exomoons consistent with theoretical expectations?

Website: www.exomoon.org