Exoplanet Dynamics: What we know from Kepler

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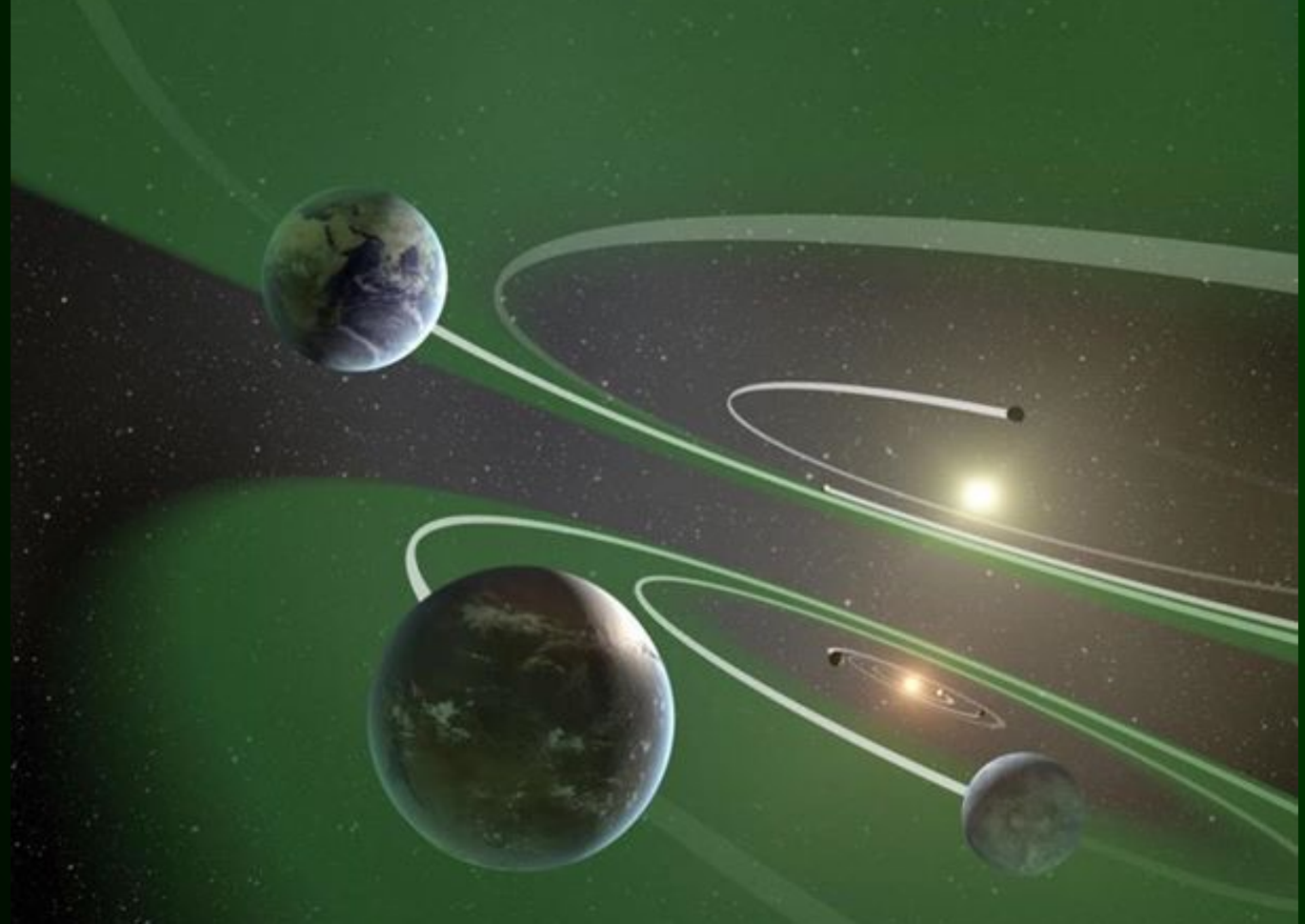
Friends of KITP, 17 March 2015



Thanks to Vikki Meadows, Josh Winn for slides

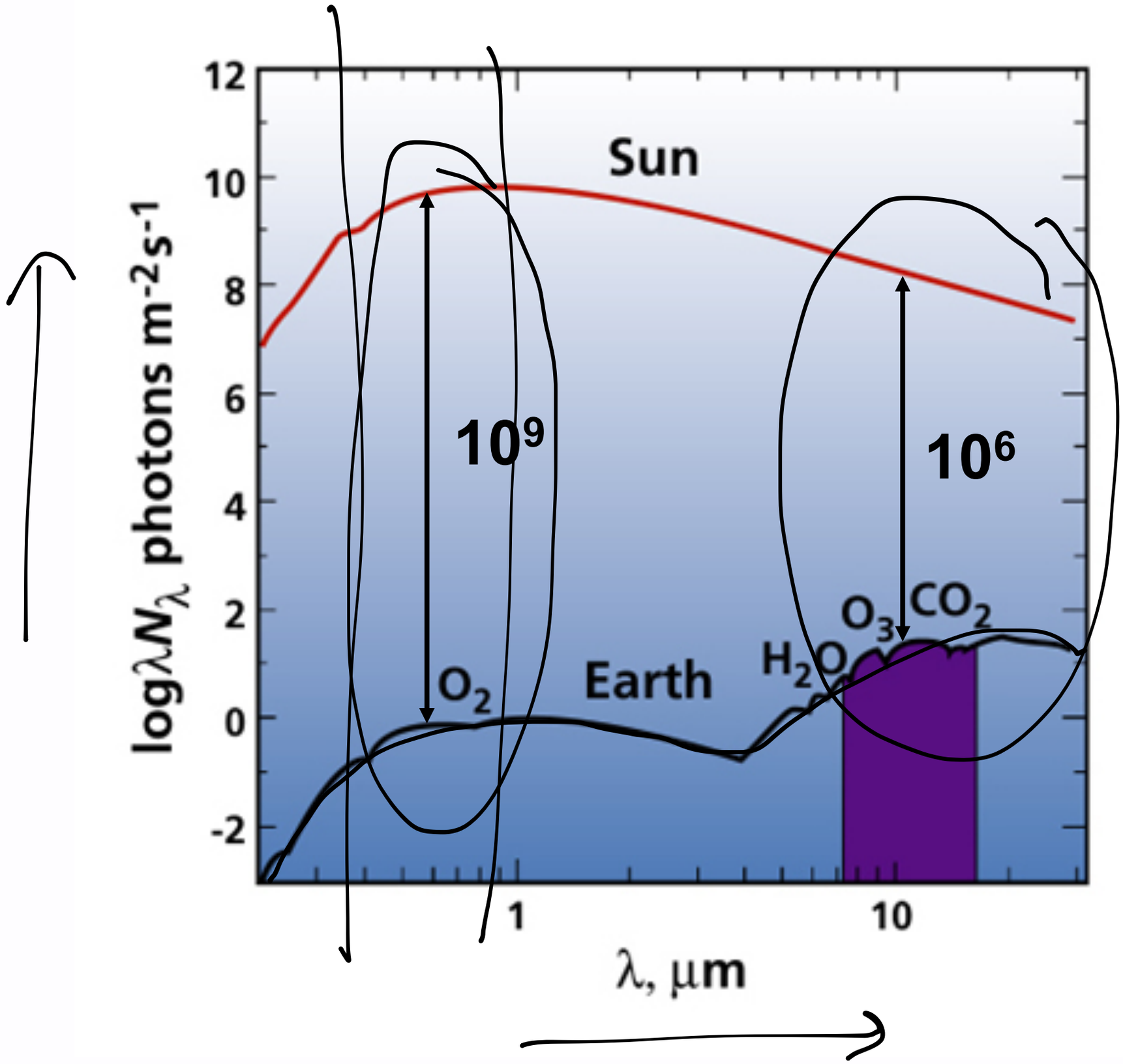
"There are countless suns and countless earths all rotating around their suns in exactly the same way as the seven planets of our system. We see only the suns because they are the largest bodies and are luminous, but their planets remain invisible to us because they are smaller and non-luminous. The countless worlds in the universe are no worse and no less inhabited than our Earth."

- Giordano Bruno (1584)

Significance of Extrasolar Planets

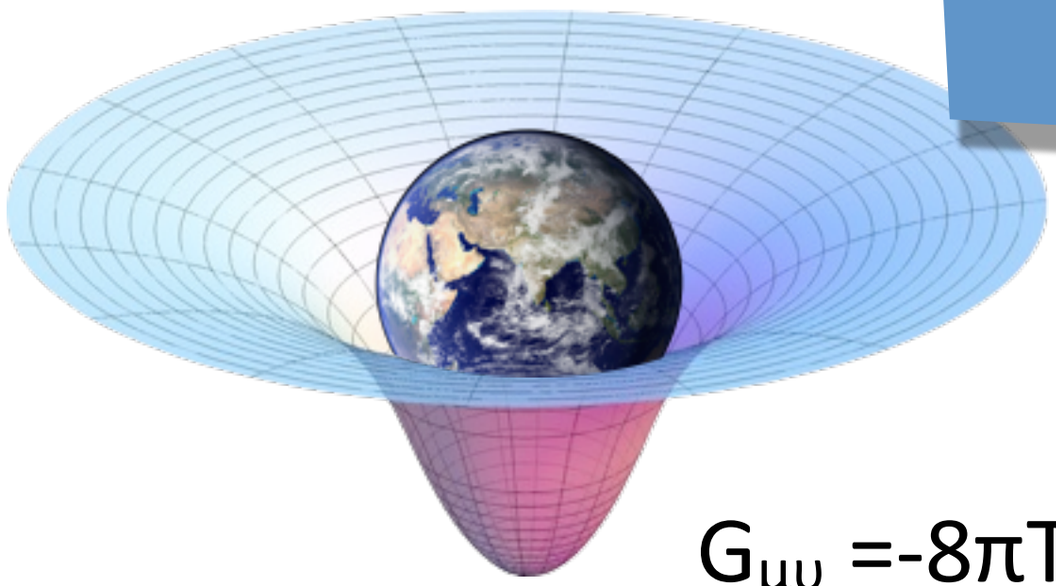
- New examples of different types of planets.
- Clues for how planets form.
- How special/common is our Earth?
- Start of search for life beyond the solar system.

Finding planets is ***hard***

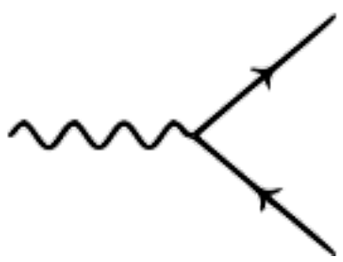


Gravitational interaction

Electromagnetic interaction



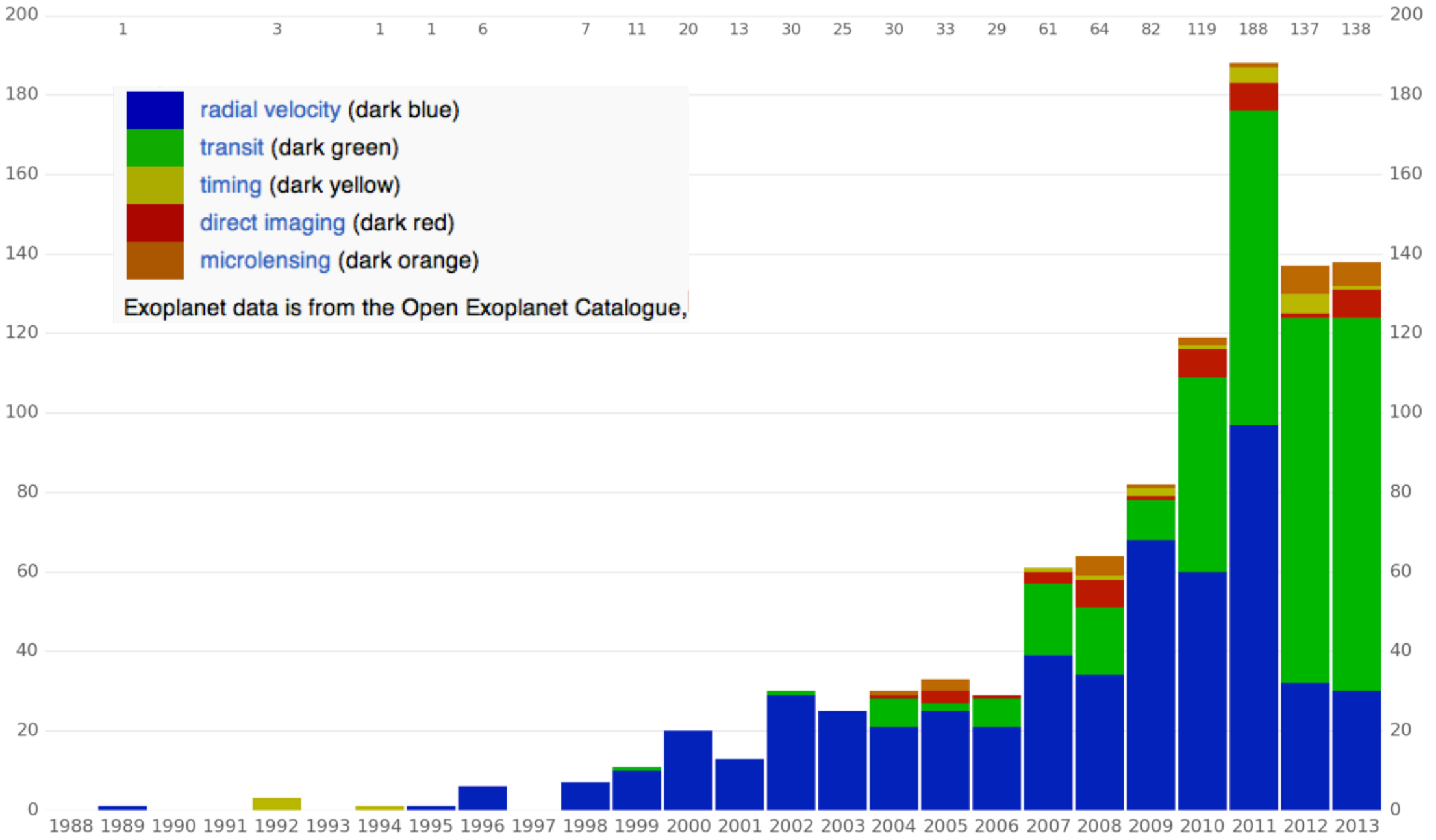
$G_{\mu\upsilon} = -8\pi T_{\mu\upsilon}$



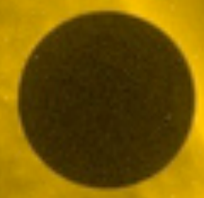
- Radial velocity
- Astrometry
- Microlensing
- Timing

- Transit
- Secondary eclipse
- Imaging

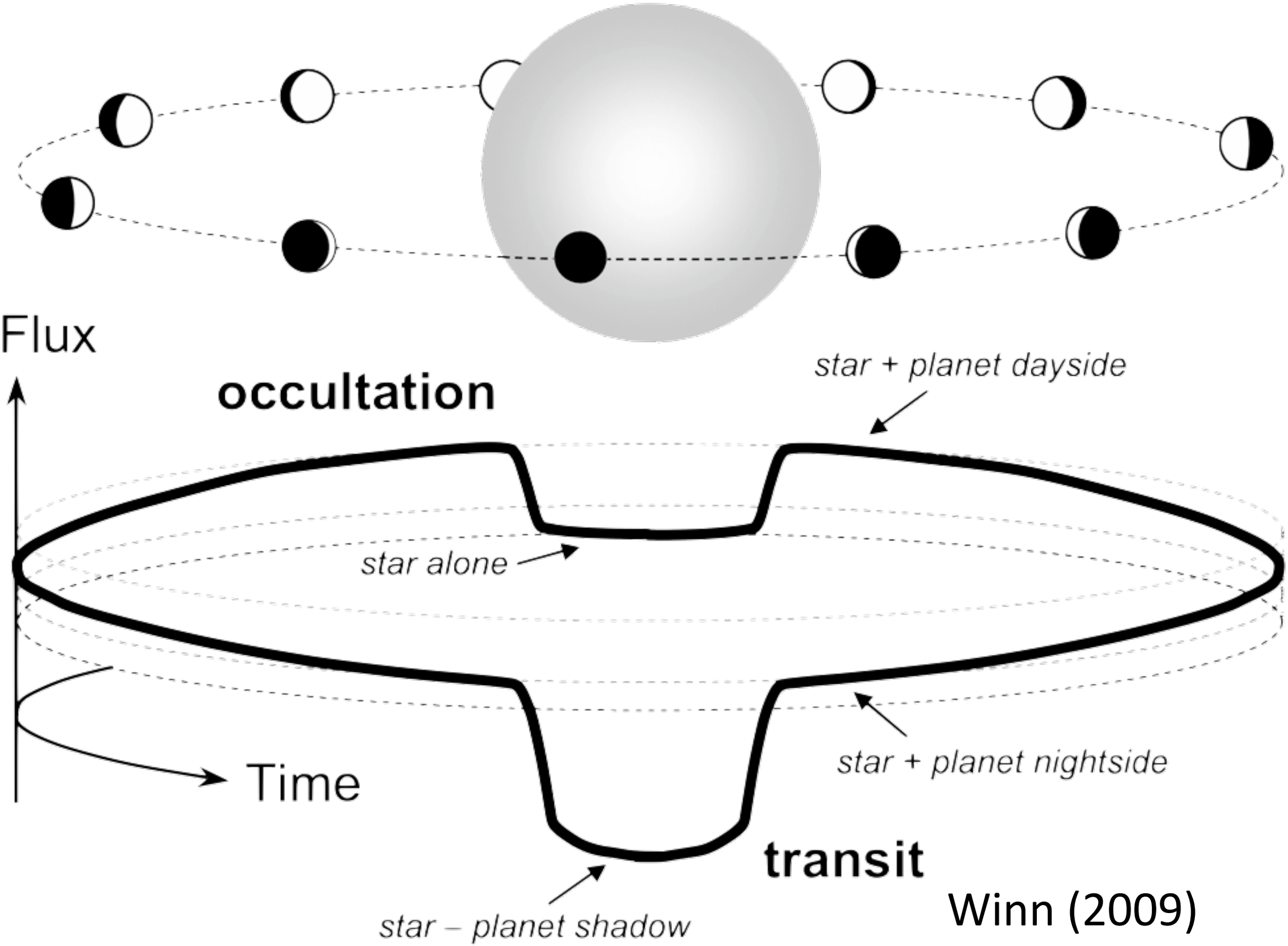
Growth of exoplanet discoveries



Transit of Venus

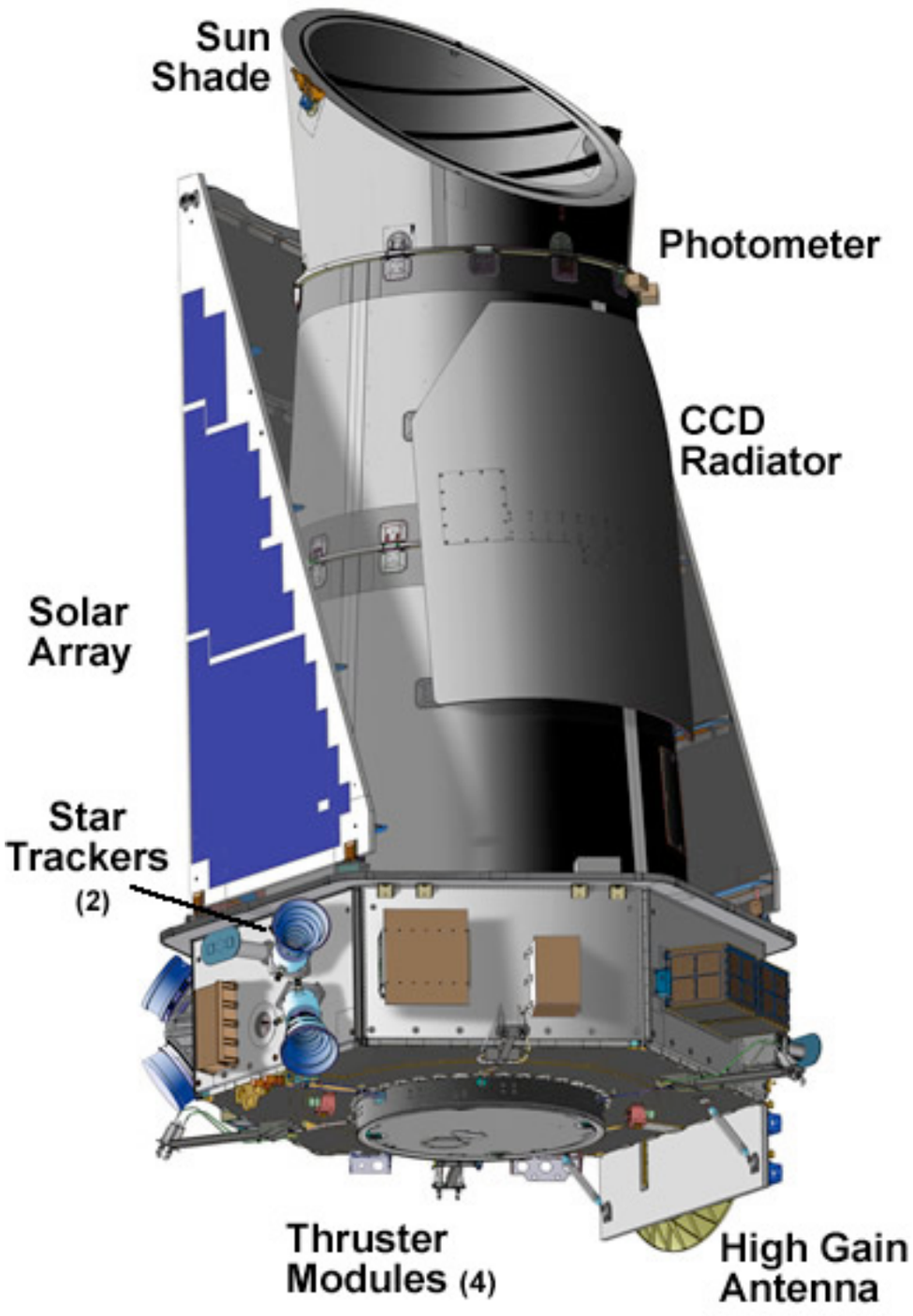


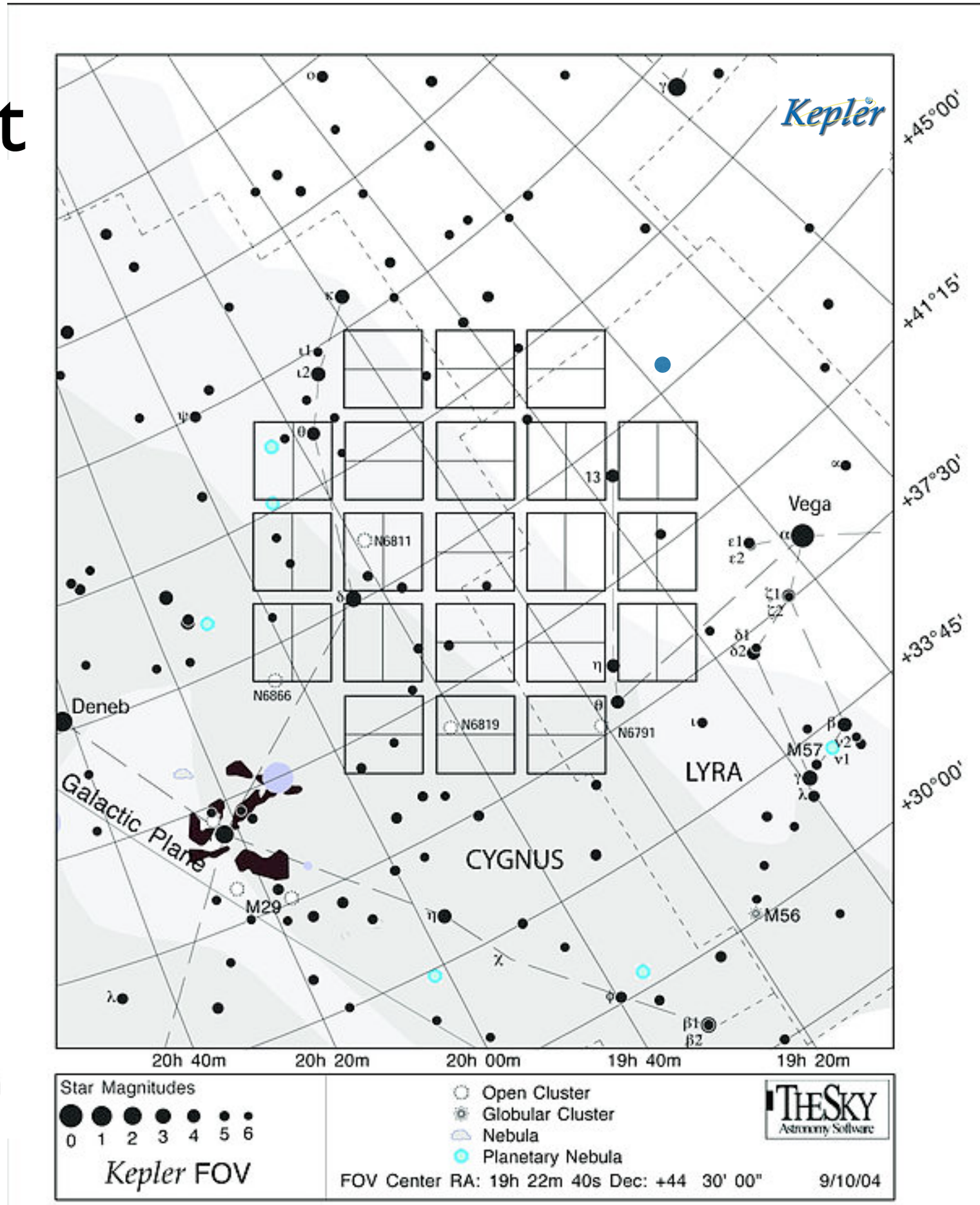
Text


Flux
occultation
star + planet dayside
star alone
star + planet nightside
Time
transit
star – planet shadow

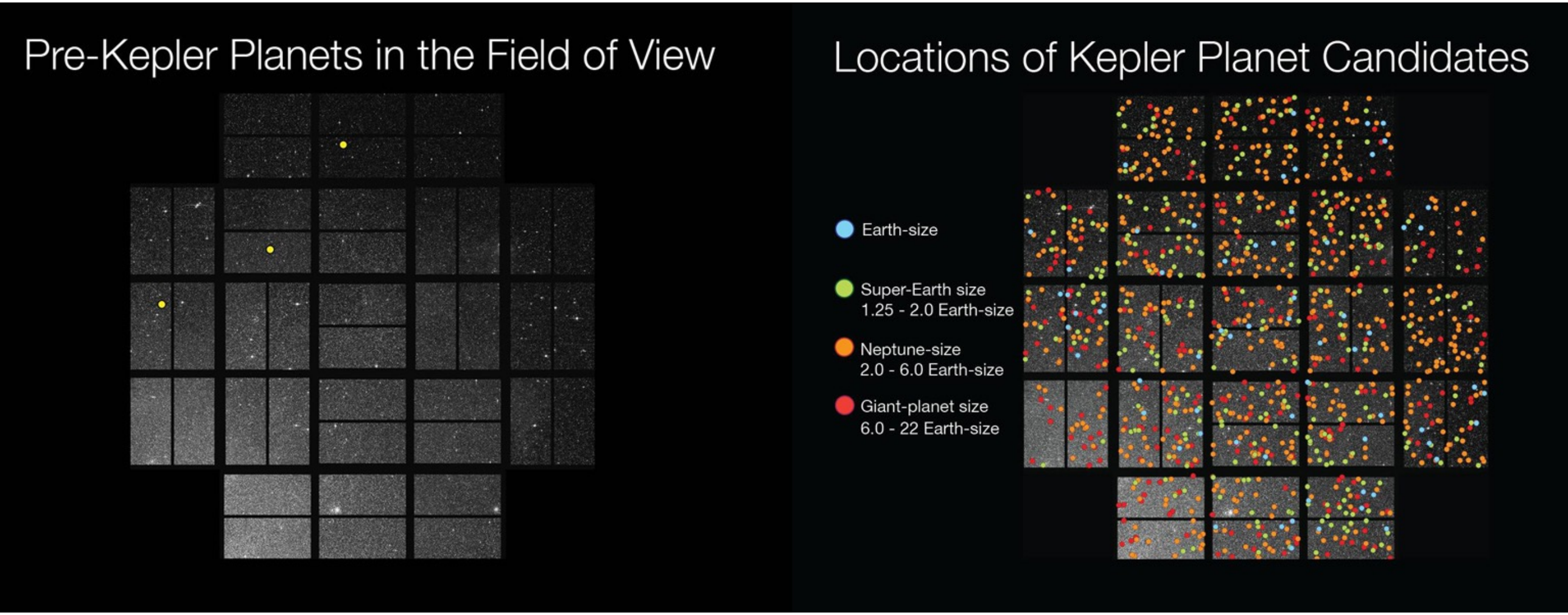
Winn (2009)

Kepler spacecraft



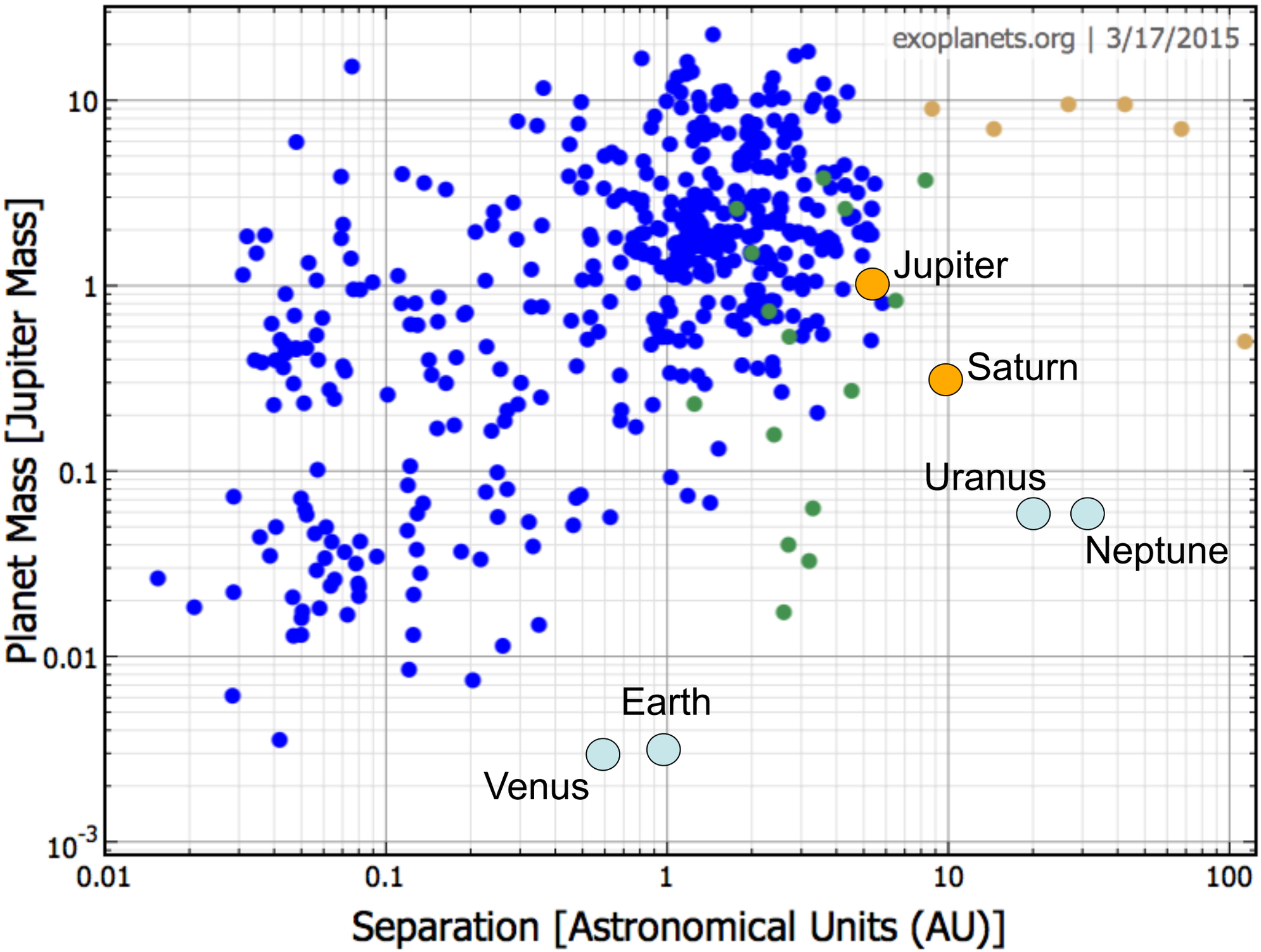


Kepler discoveries



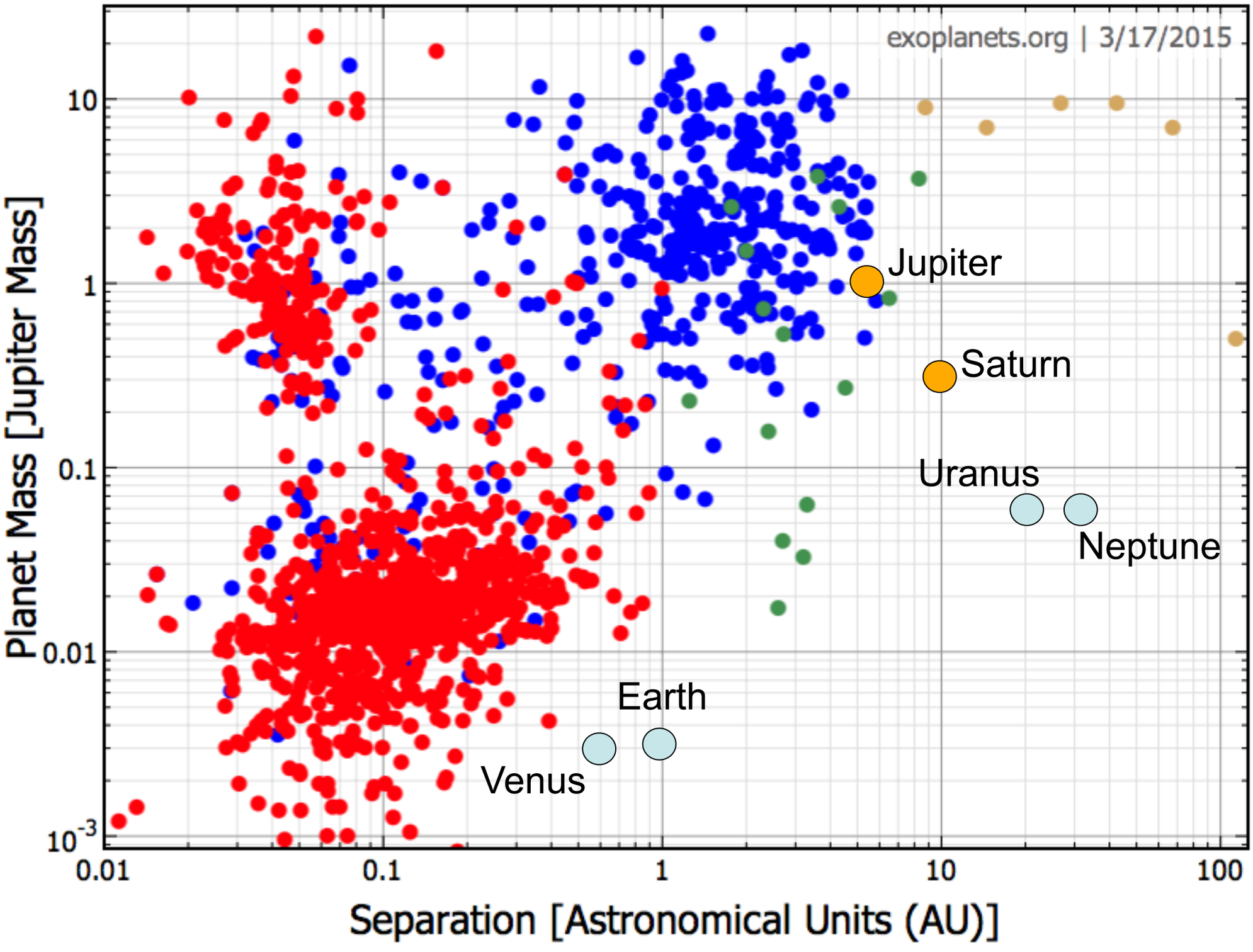
(Out of date!)

Planetary architectures



1500 confirmed planets as of March 17, 2015

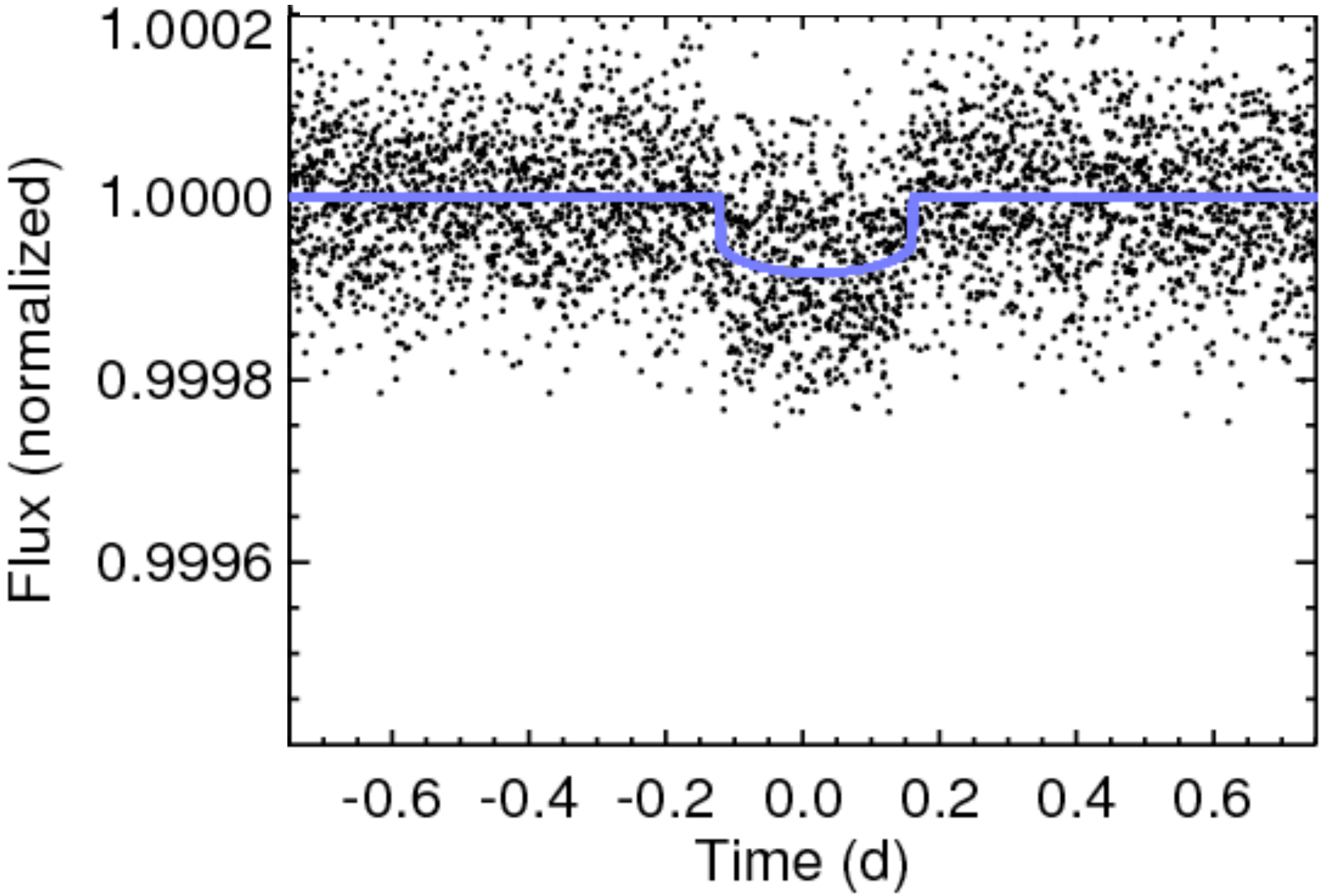
Planetary architectures



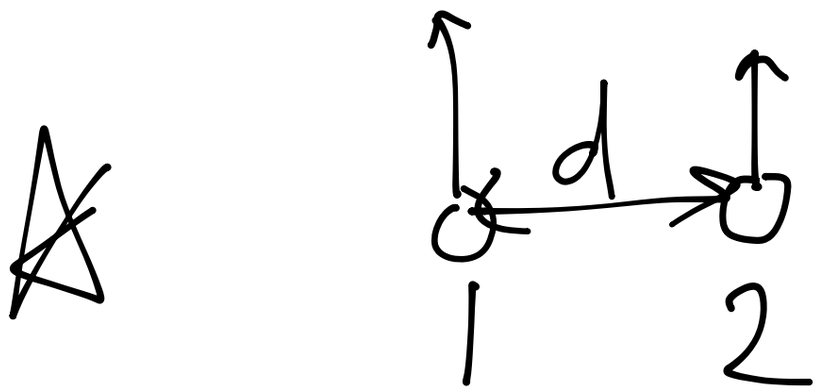
1500 confirmed planets as of March 17, 2015

Survey of 150,000 stars from 2009-present

Example folded transit light curve:



Measuring mass with transit timing: what are super-Earths/mini-Neptunes made of?

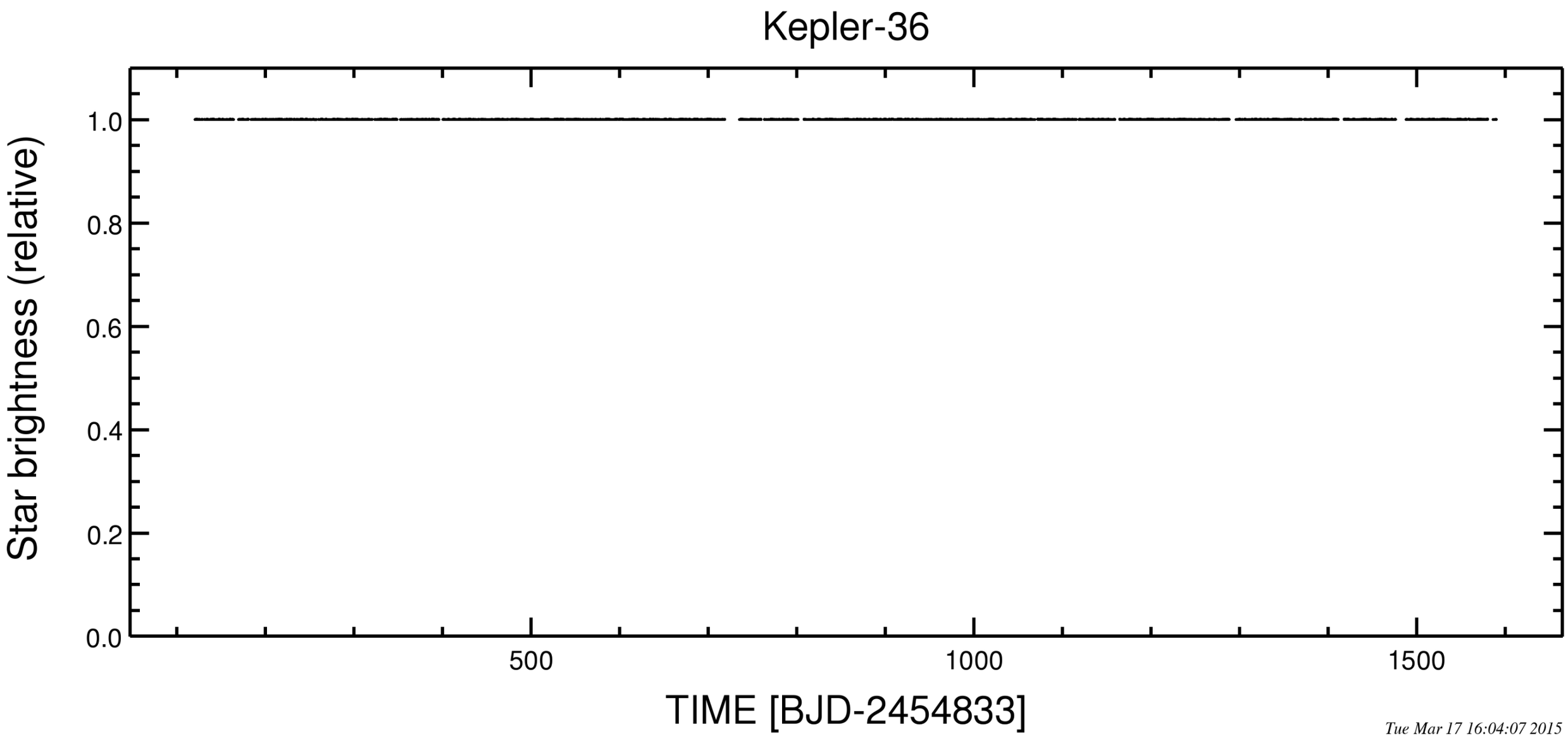


$$F_1 = m_1 a_1$$

$$F_1 = \frac{G m_1 m_2}{d^2}$$

$$\Rightarrow \quad a_1 = \frac{G m_2}{d^2}$$

Kepler-36c: a quasi-periodic Neptune



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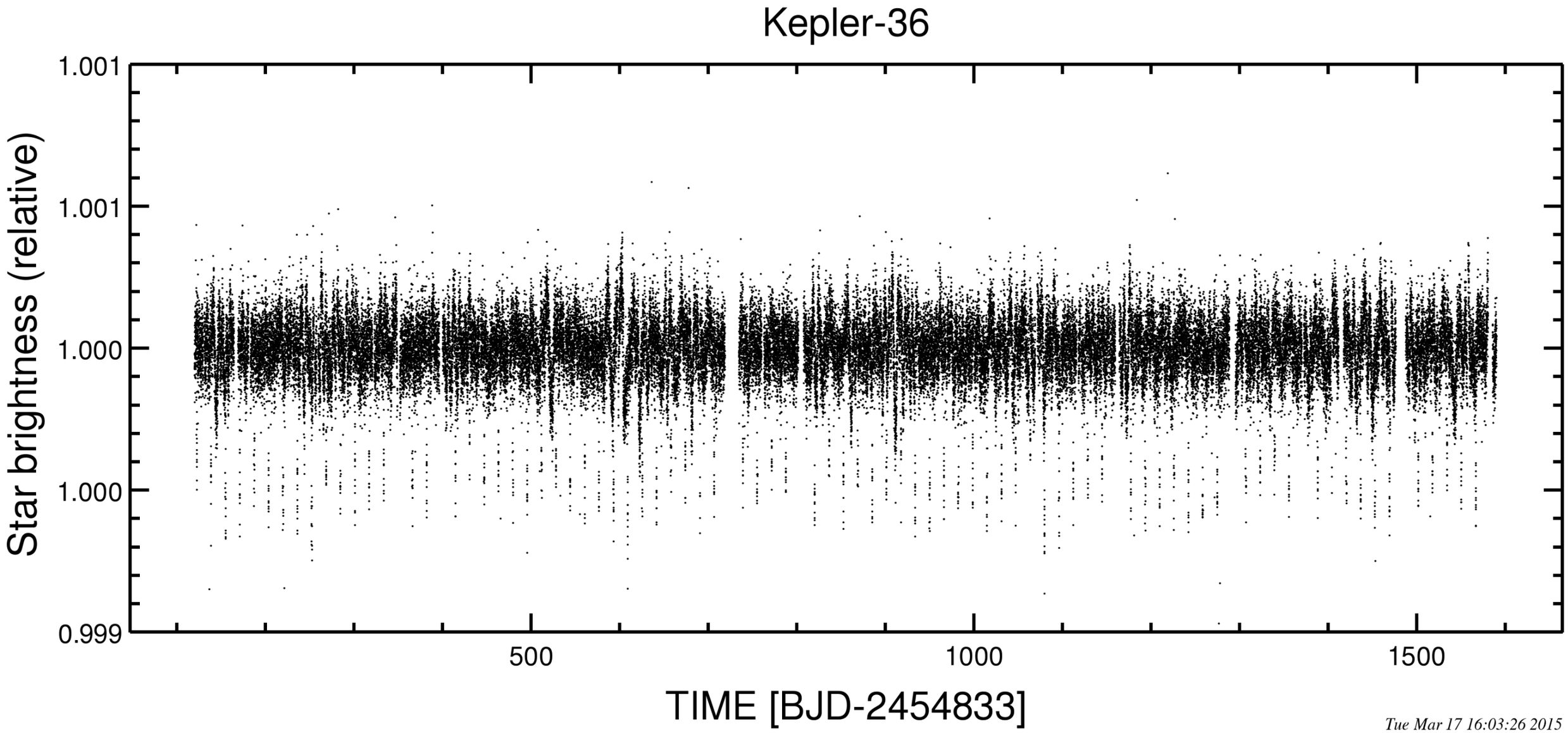

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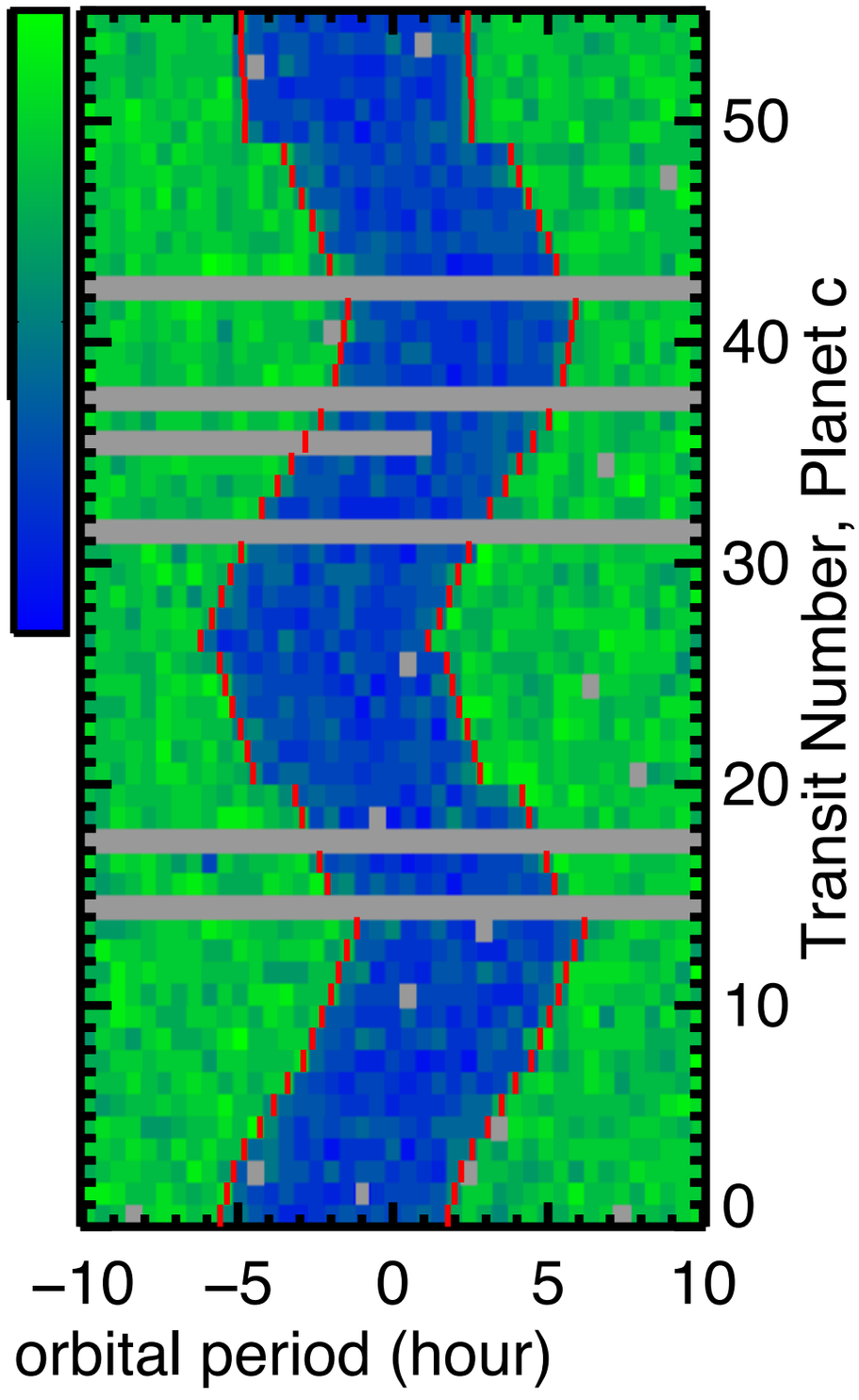
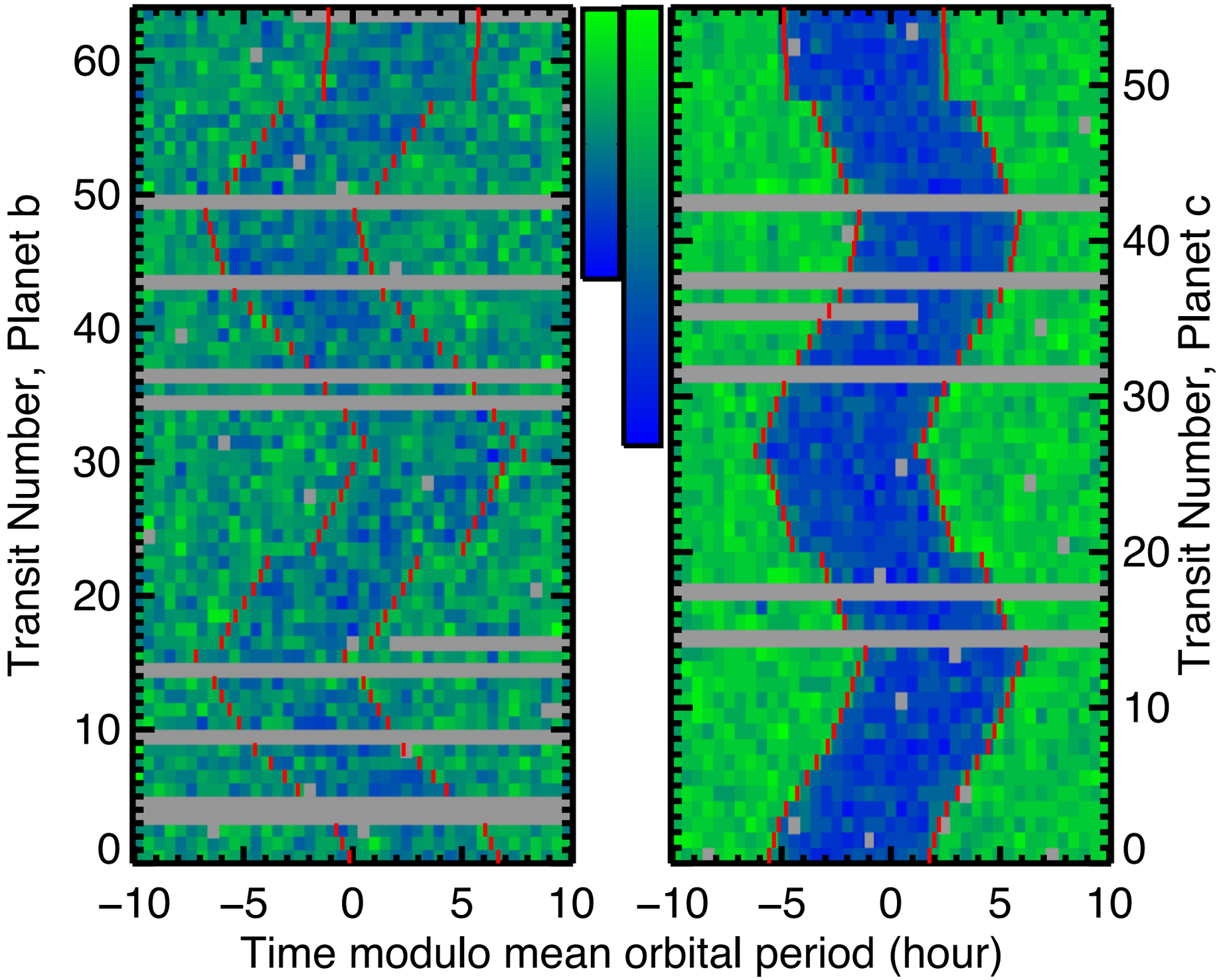
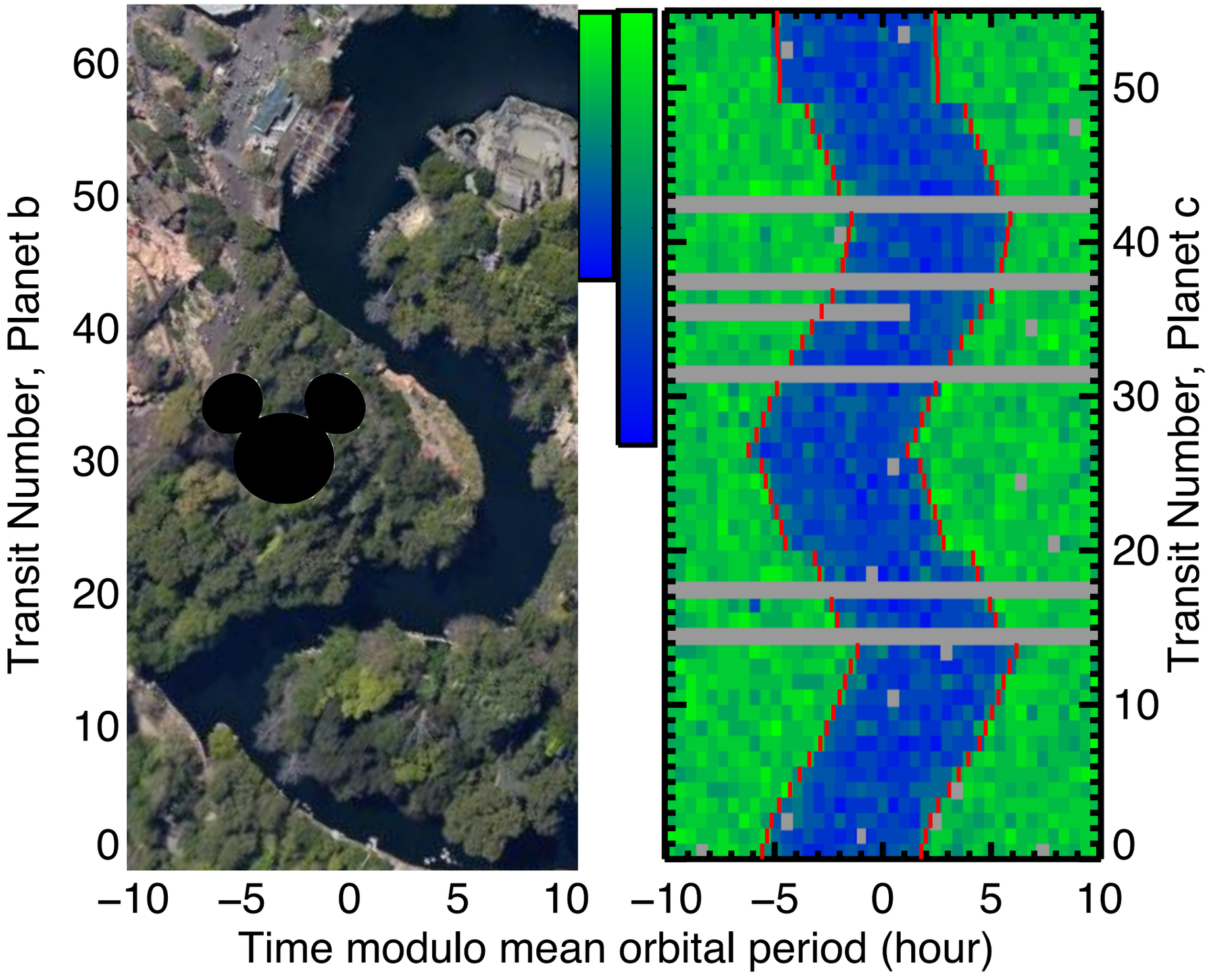


Kepler-36b,c: closest two orbiting planets



Carter, Agol et al. (2012)

Kepler-36b,c: closest two orbiting planets



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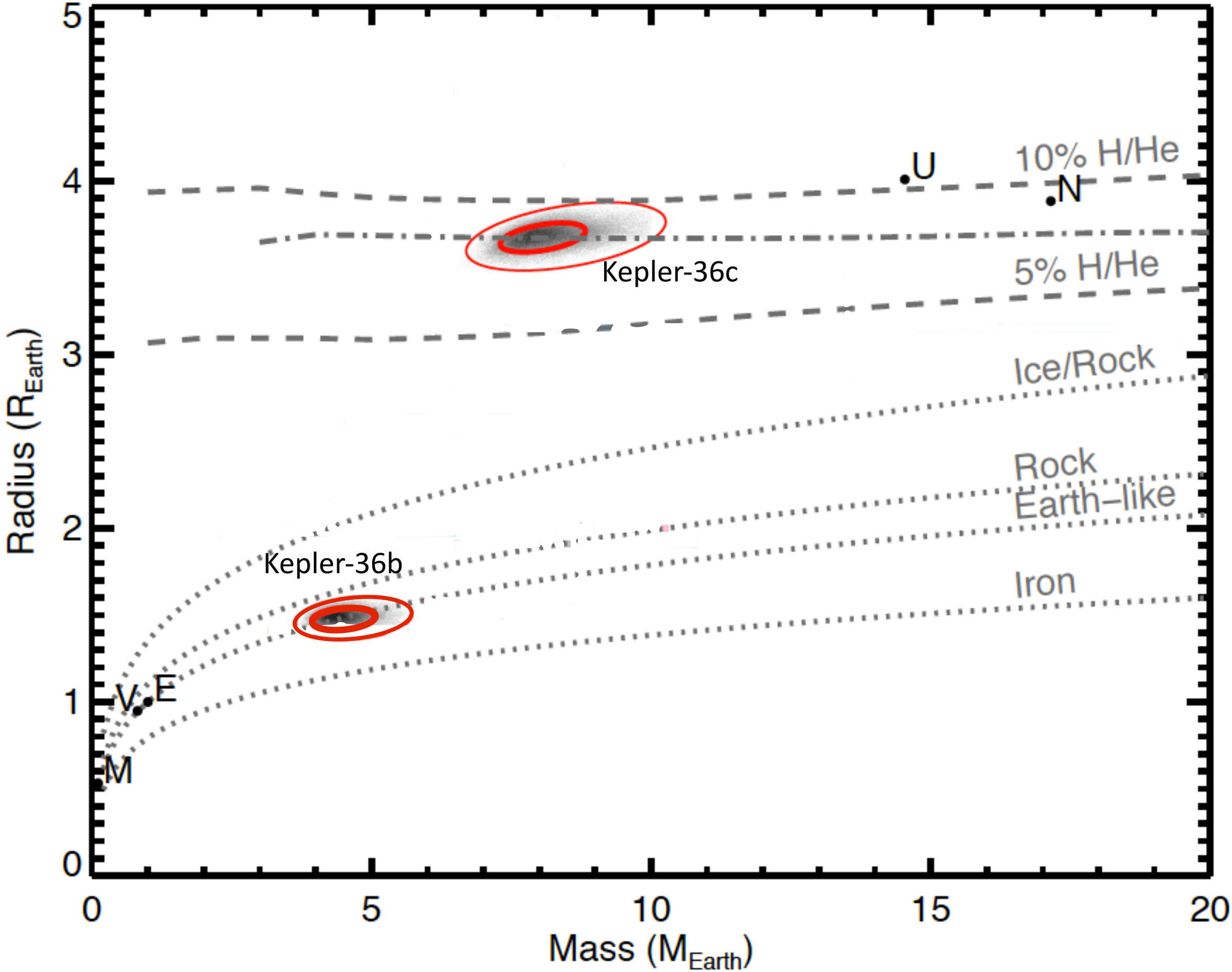
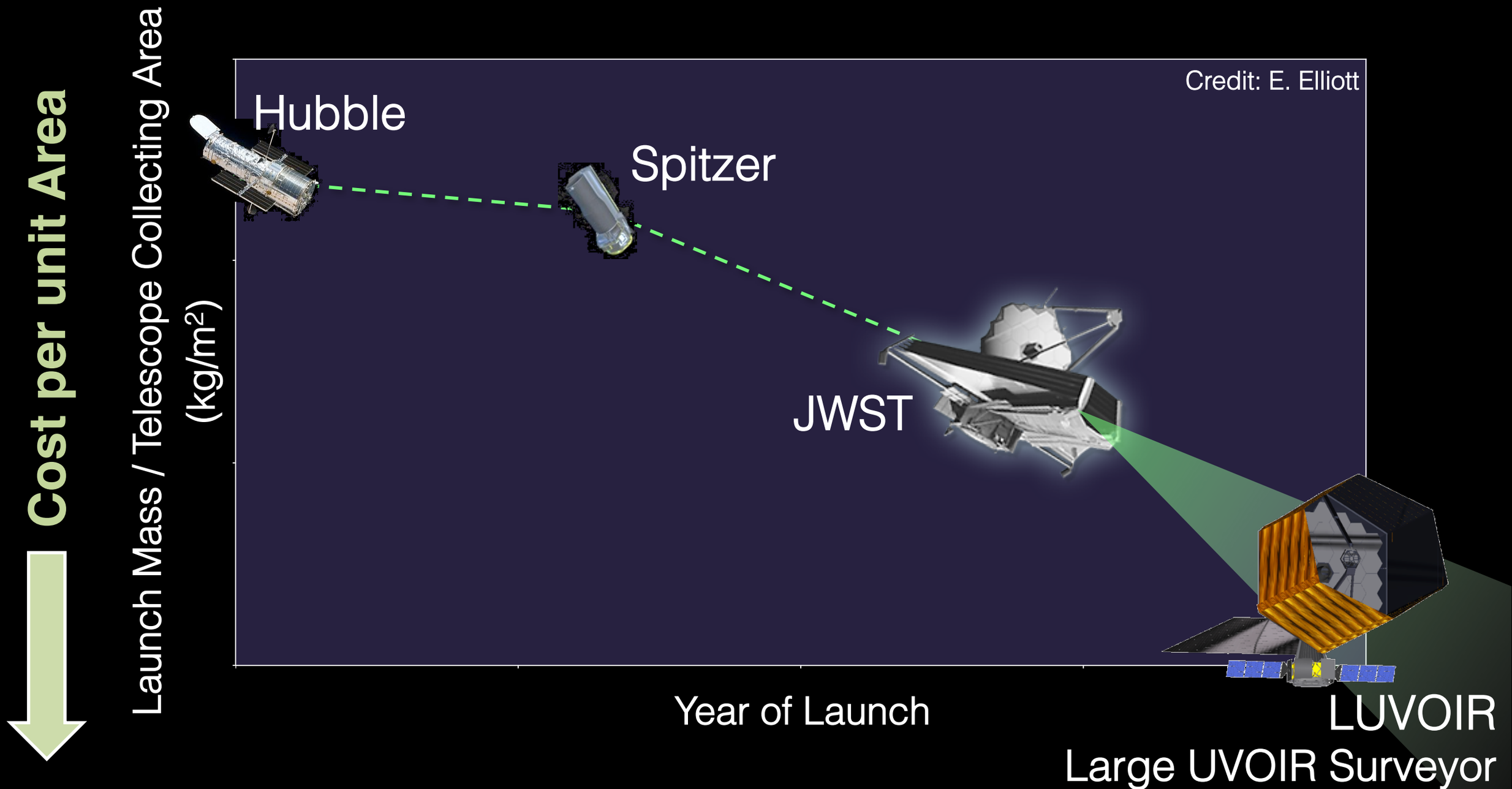

Radius (R_{Earth})
Mass (M_{Earth})
0
1
2
3
4
5
0
5
10
15
20
10% H/He
5% H/He
Ice/Rock
Rock
Earth–like
Iron
Kepler-36c
Kepler-36b
U
N
V
E
M

The Future

- More measurements of planet masses & radii from the Kepler data
- Ground-based: Keck, **LCOGT**, KOINet, Thirty-Meter Telescope (TMT)
- NASA planet missions: K2, Transiting Exoplanet Sky Survey (TESS), James Webb Space Telescope (JWST)
- Discovery/characterization of more ‘Earth-like’ planets

New Technology Changes the Cost Curve



Venus

Earth

Jupiter