Review of Kepler Science & Prospects for the Future

Eric B. Ford (UF)
Kepler Participating Scientist
Member of Kepler Exoplanet Council

6th Meeting of NASA's ExoPAG
Exoplanet Exploration Program Analysis Group
in association with the 44th AAS DPS Meeting
October 14, 2012

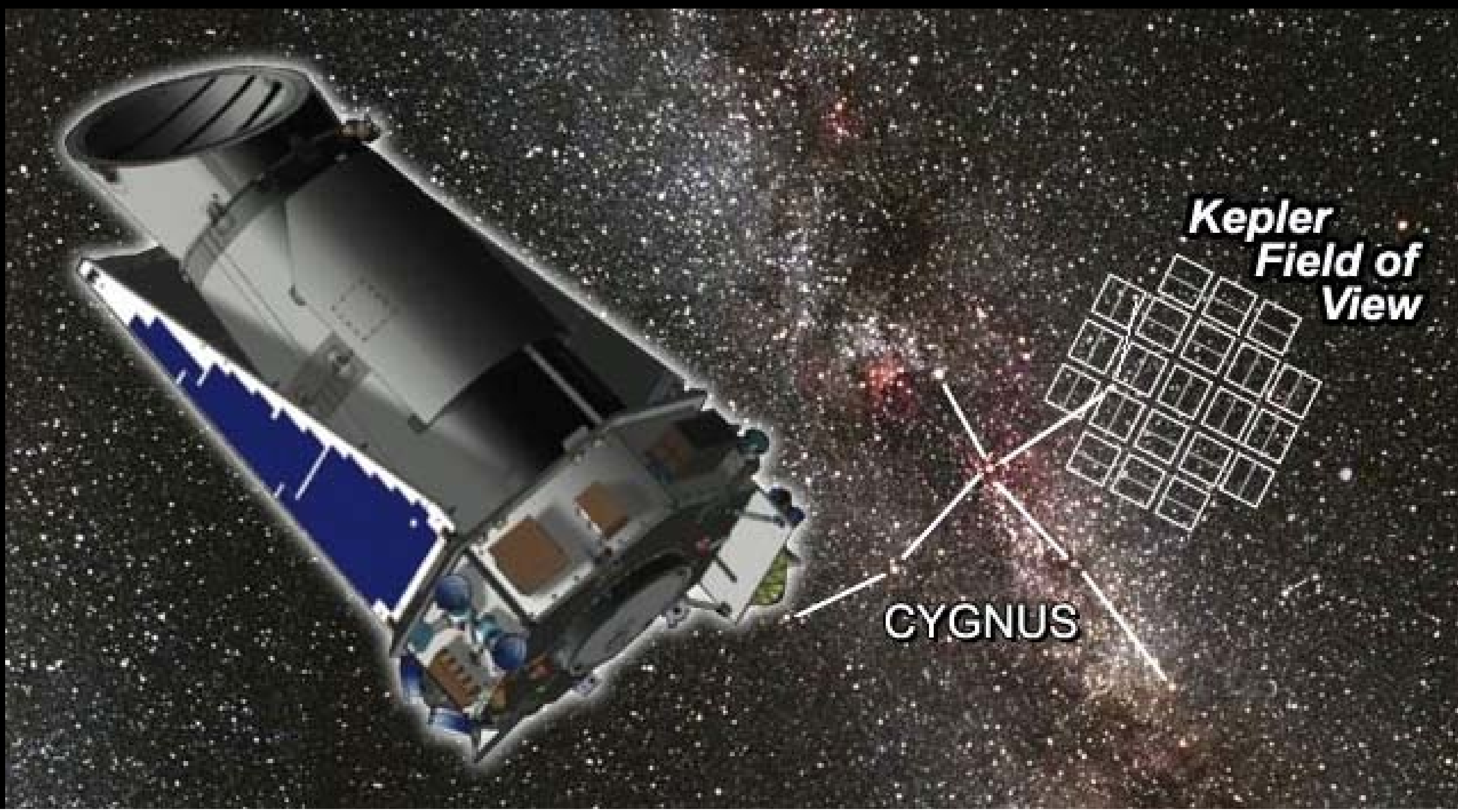
NASA

Outline

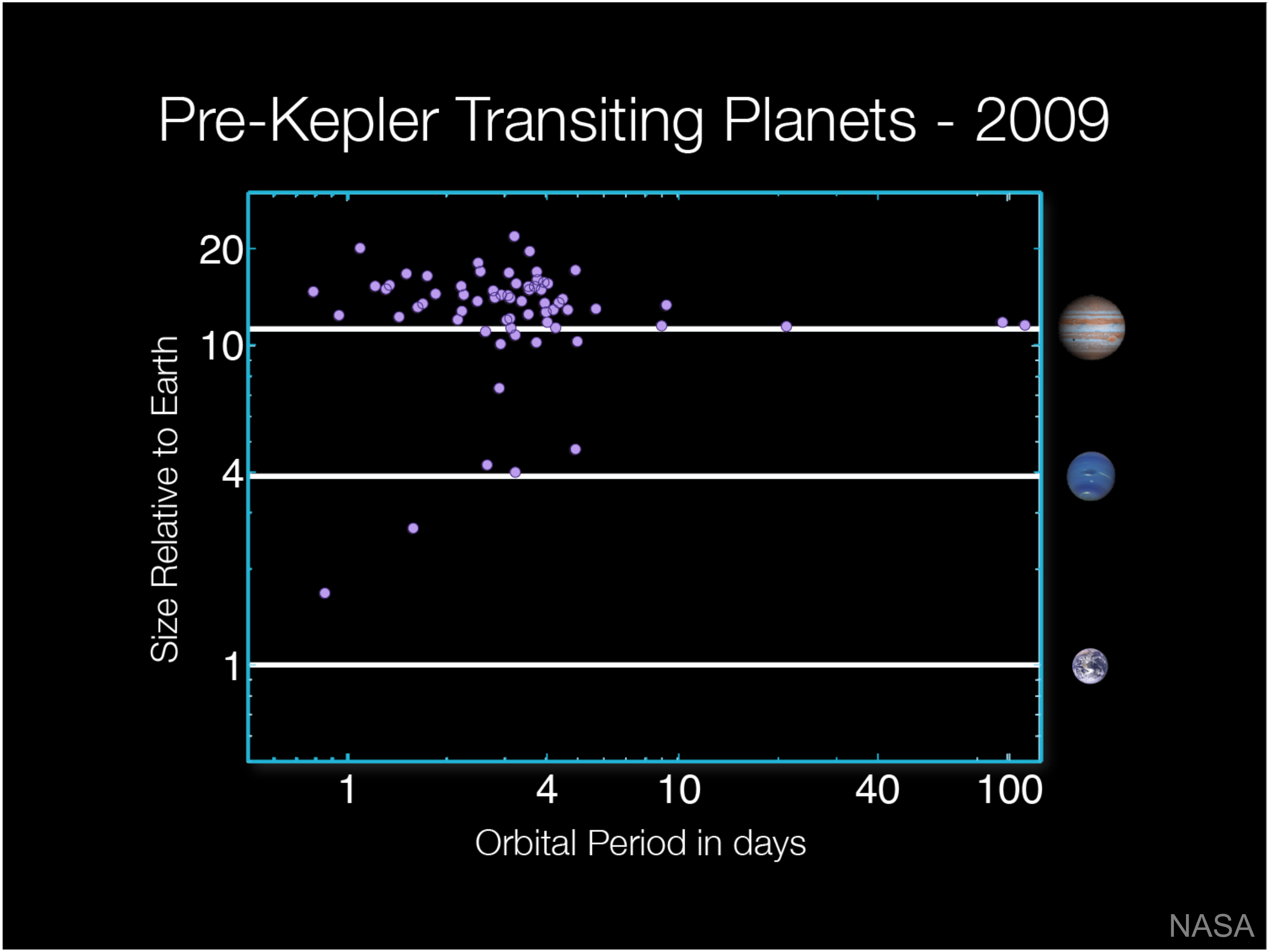
- Review of *Kepler* Exoplanet Results
- Future *Kepler* Exoplanet Science
- Needs to Extract *Kepler* Science
- Lessons Learned

NASA's Kepler Mission

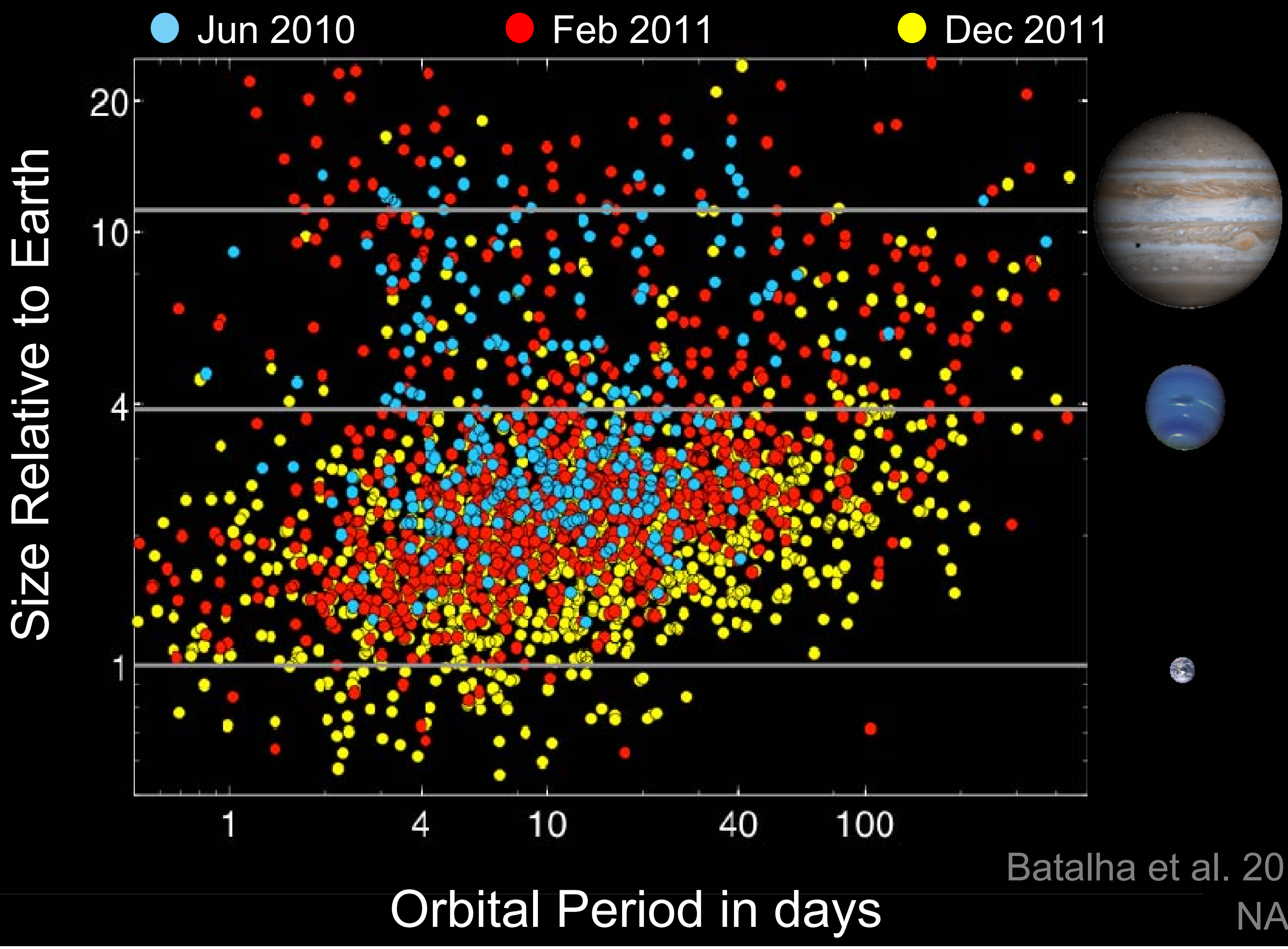
- Photometry of >190,000 stars
- Looking for Earth-like planets in transit
- 50μmag in 6 hours; 30 minute cadence
- All data public as of Oct 28, 2012



NASA


Pre-Kepler Transiting Planets - 2009
Size Relative to Earth
20
10
4
1
1
4
10
40
100
Orbital Period in days
NASA

Kepler's Planet Candidates as of Dec 2011



Batalha et al. 2012
NASA

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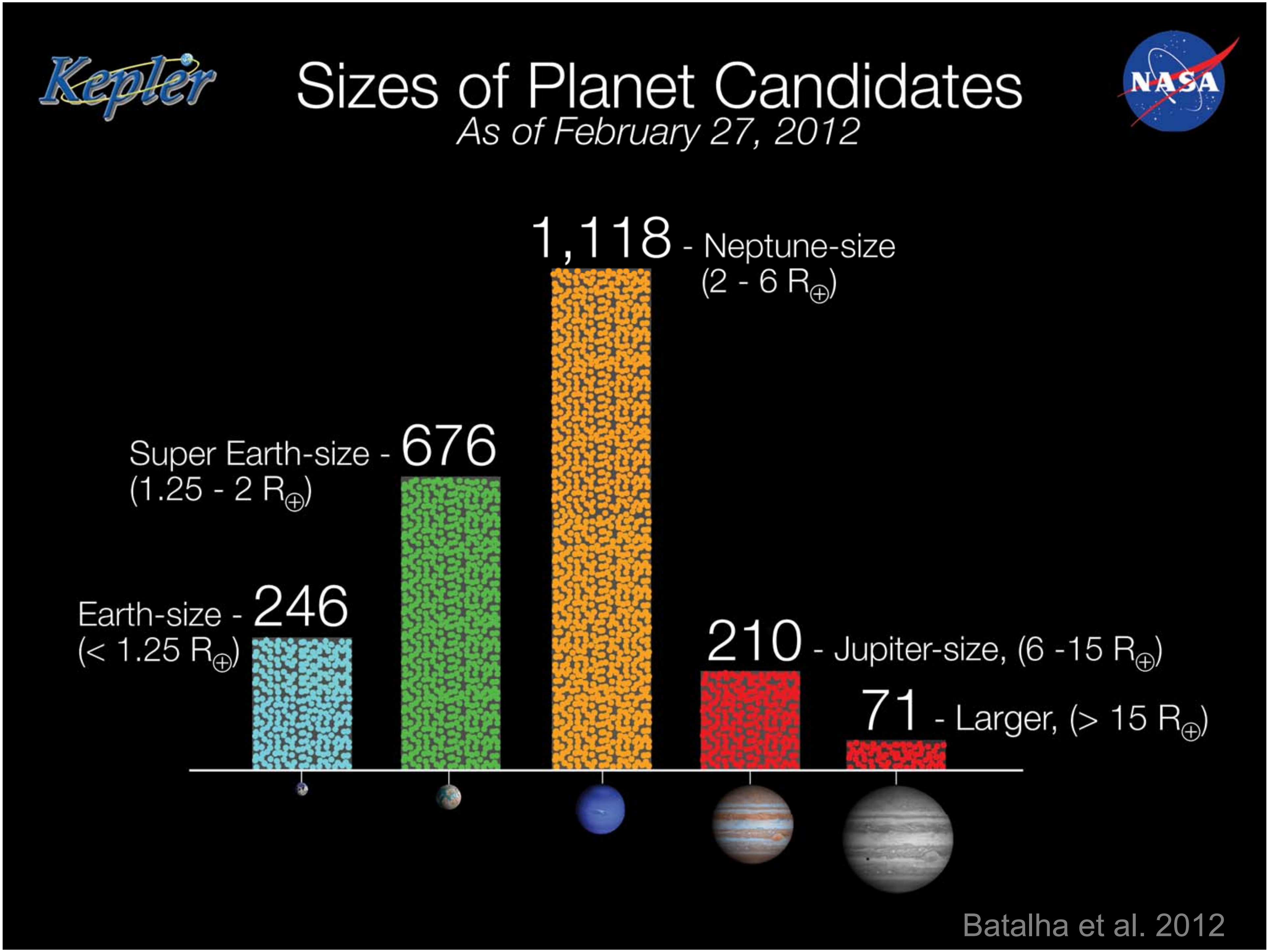
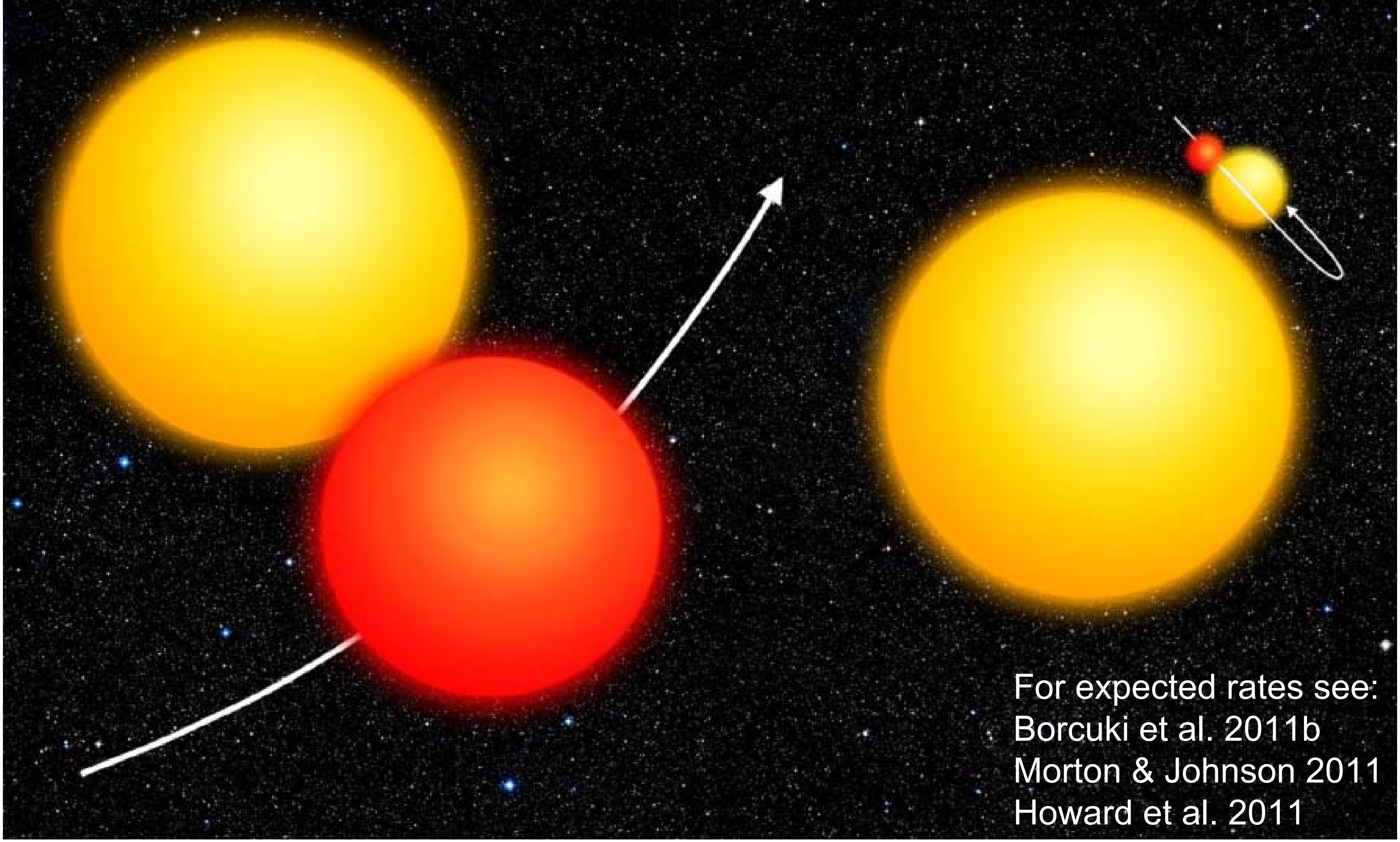

Kepler
Sizes of Planet Candidates
As of February 27, 2012
NASA
1,118 - Neptune-size
(2 - 6 R⊕)
Super Earth-size - 676
(1.25 - 2 R⊕)
Earth-size - 246
(< 1.25 R⊕)
210 - Jupiter-size, (6 -15 R⊕)
71 - Larger, (> 15 R⊕)
Batalha et al. 2012

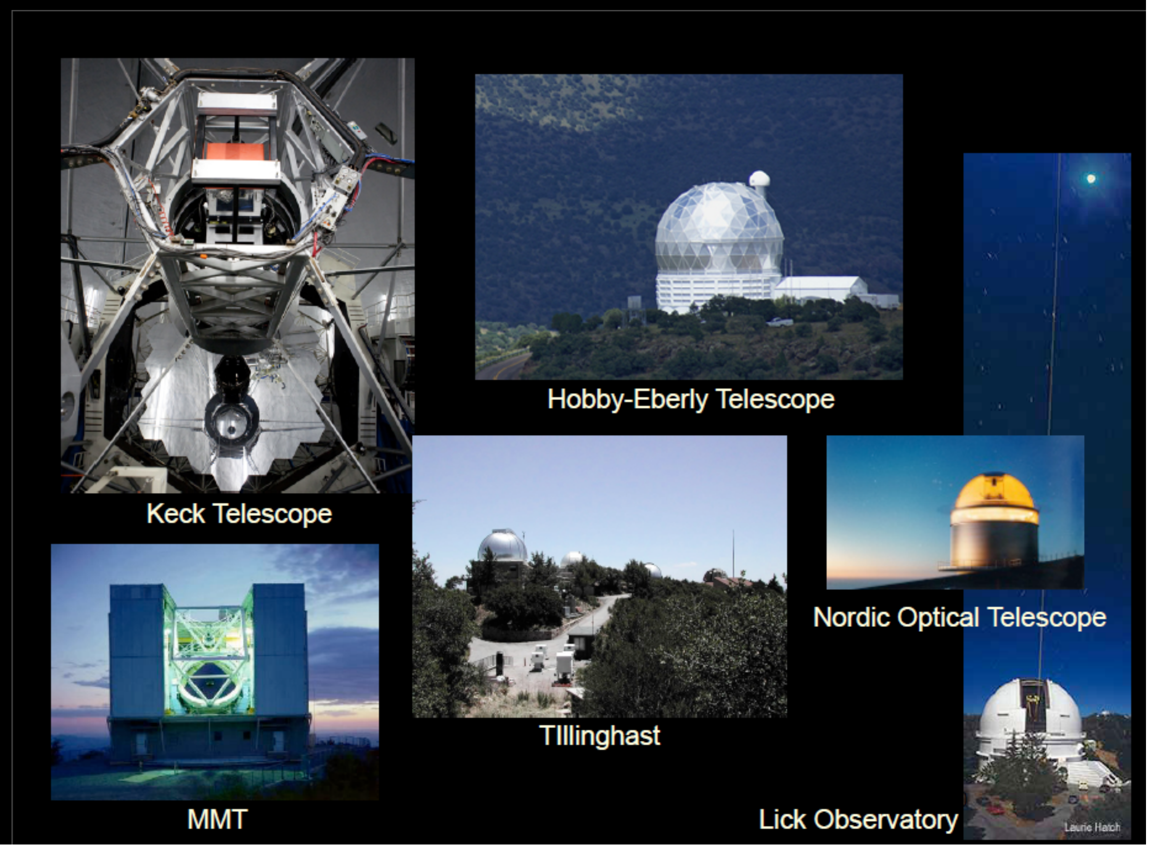
Possible False Positives



For expected rates see:
Borcuki et al. 2011b
Morton & Johnson 2011
Howard et al. 2011

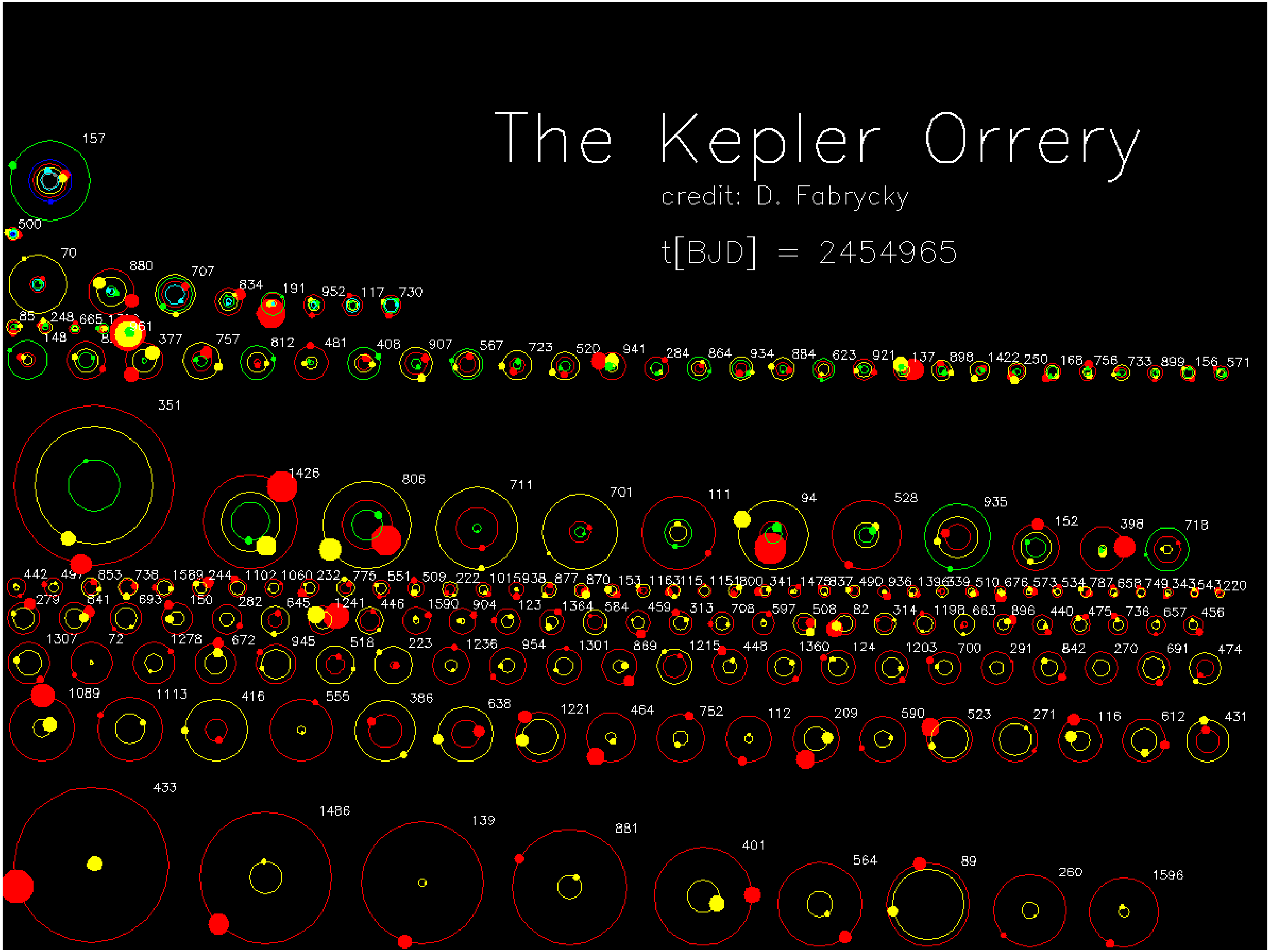
Follow-Up Observation Program

- Imaging (Standard, AO, Speckle, HST)
  - Removes confusion due to crowding
- Spectroscopy
  - Low-Res removes some false positives (e.g., binaries)
  - High-Res can measure mass of some planets
  - Upper limit to RV for small planets
- Transit Observations
  - Test for triples
- Combining FOP & Kepler data
  - Light curves
  - Centroid motion
  - Occultations
  - Transit Timing



Highlights from 2 Years Ago

Kepler-9 b-d Kepler-10b Kepler-11 b-g


The Kepler Orrery
credit: D. Fabrycky
t[BJD] = 2454965

Systems w/ Multiple Transiting Planets

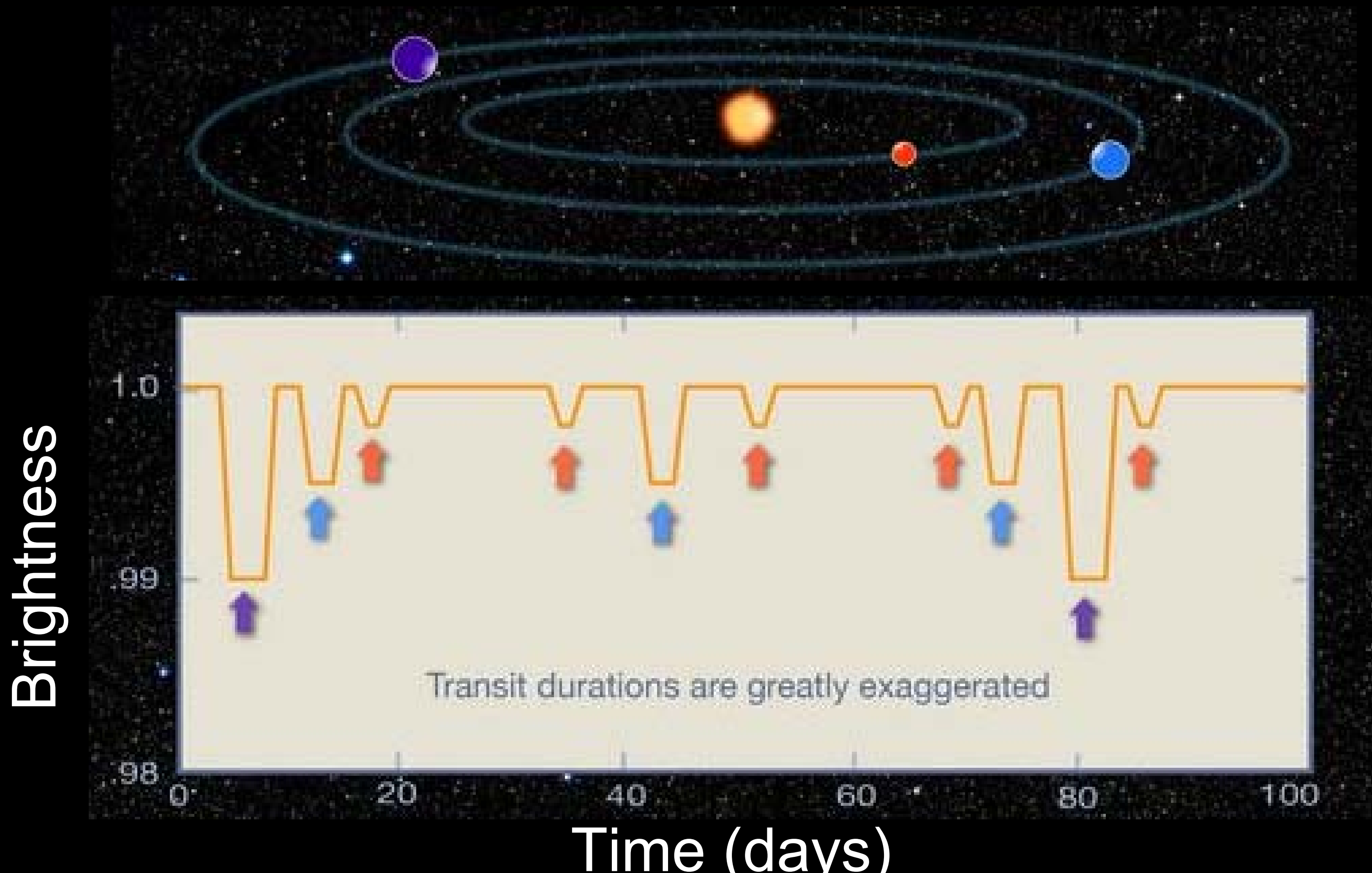
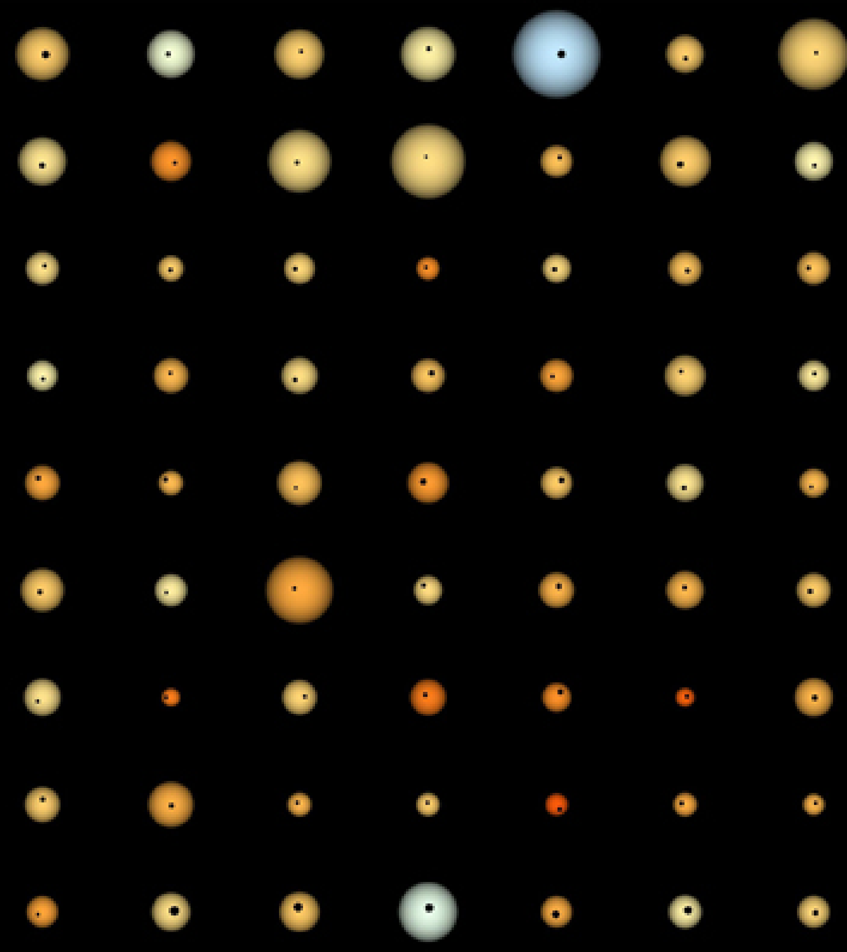


Image credit: NASA Ames/Kepler

[redacted]

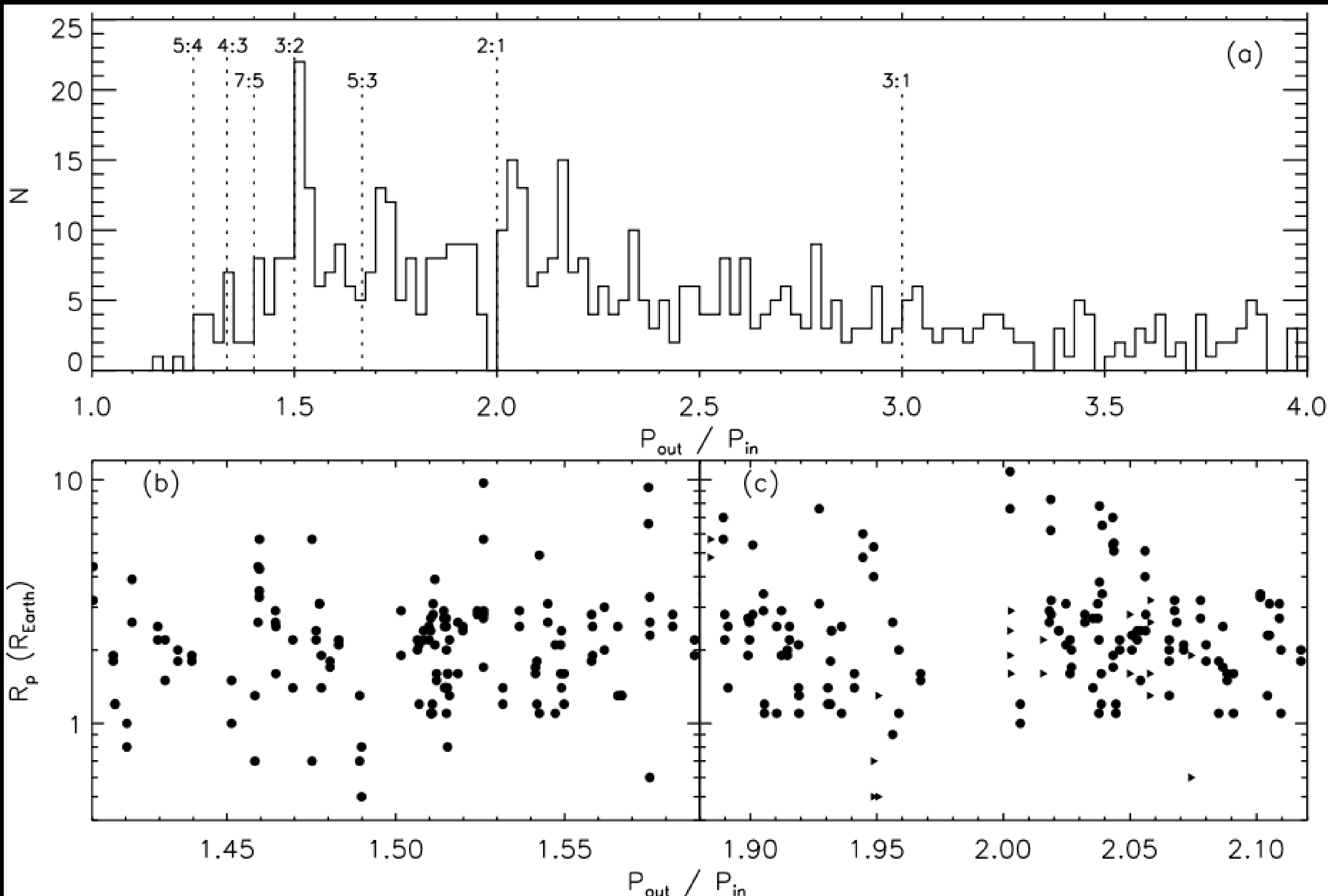
Hot Jupiters are Lonely

- 63 Hot Jupiters
- No other transiting planets
- No TTV signals
- Consistent with eccentricity excitation followed by tidal circularization



(Steffen et al. 2012 PNAS;
but see Szabo et al. arxiv)

Kepler's Near Resonant Systems



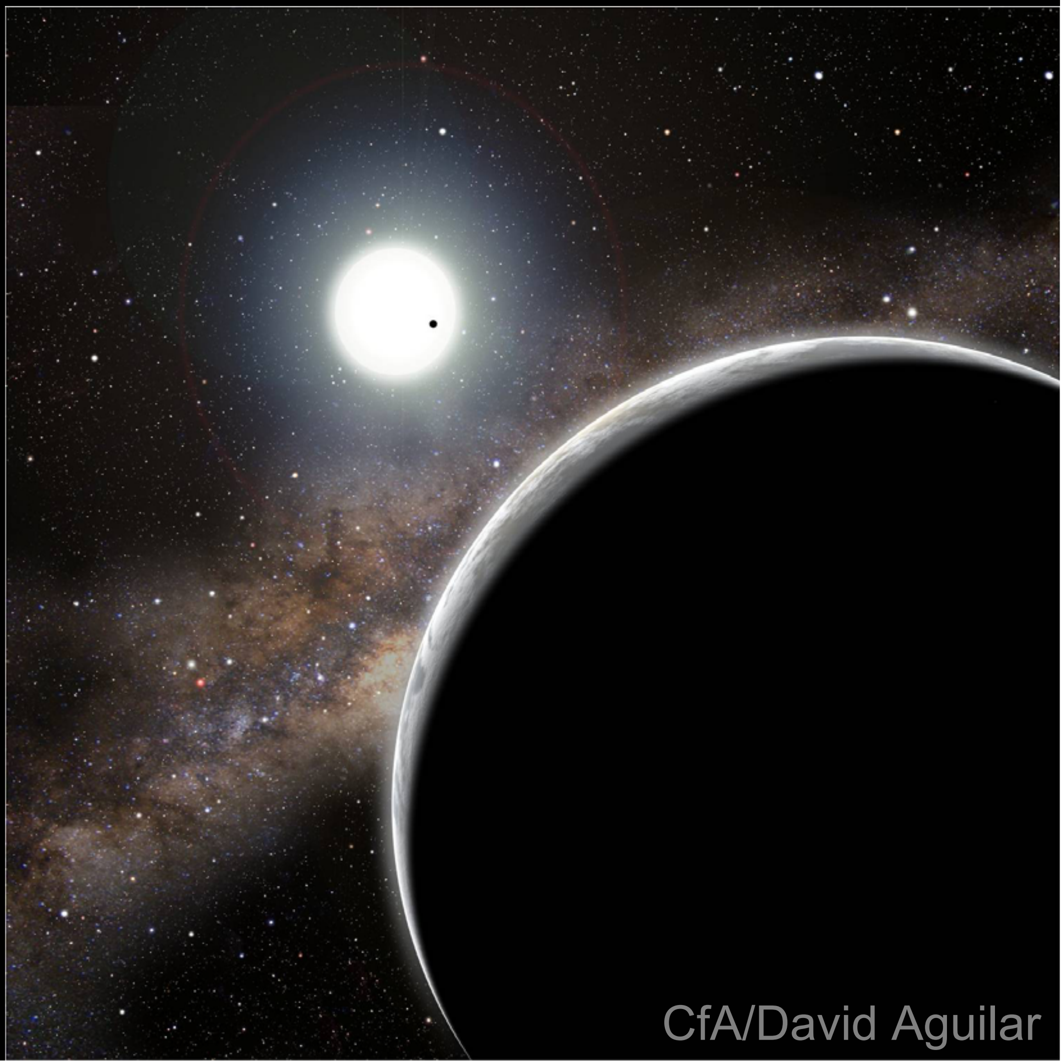
Fabrycky et al. 2012

Kepler's Multiple Planet Systems

Holman+ 2011; Batalha+ 2010; Torres+ 2010; Lissauer+ 2011; Cochran+ 2011; Ford+ 2012; Steffen+ 2012ab; Fabrycky+ 2012; Fressin+ 2012; Muirhead+ 2012; Nesvorny+ 2012; Xie 2012; Orosz+ 2012

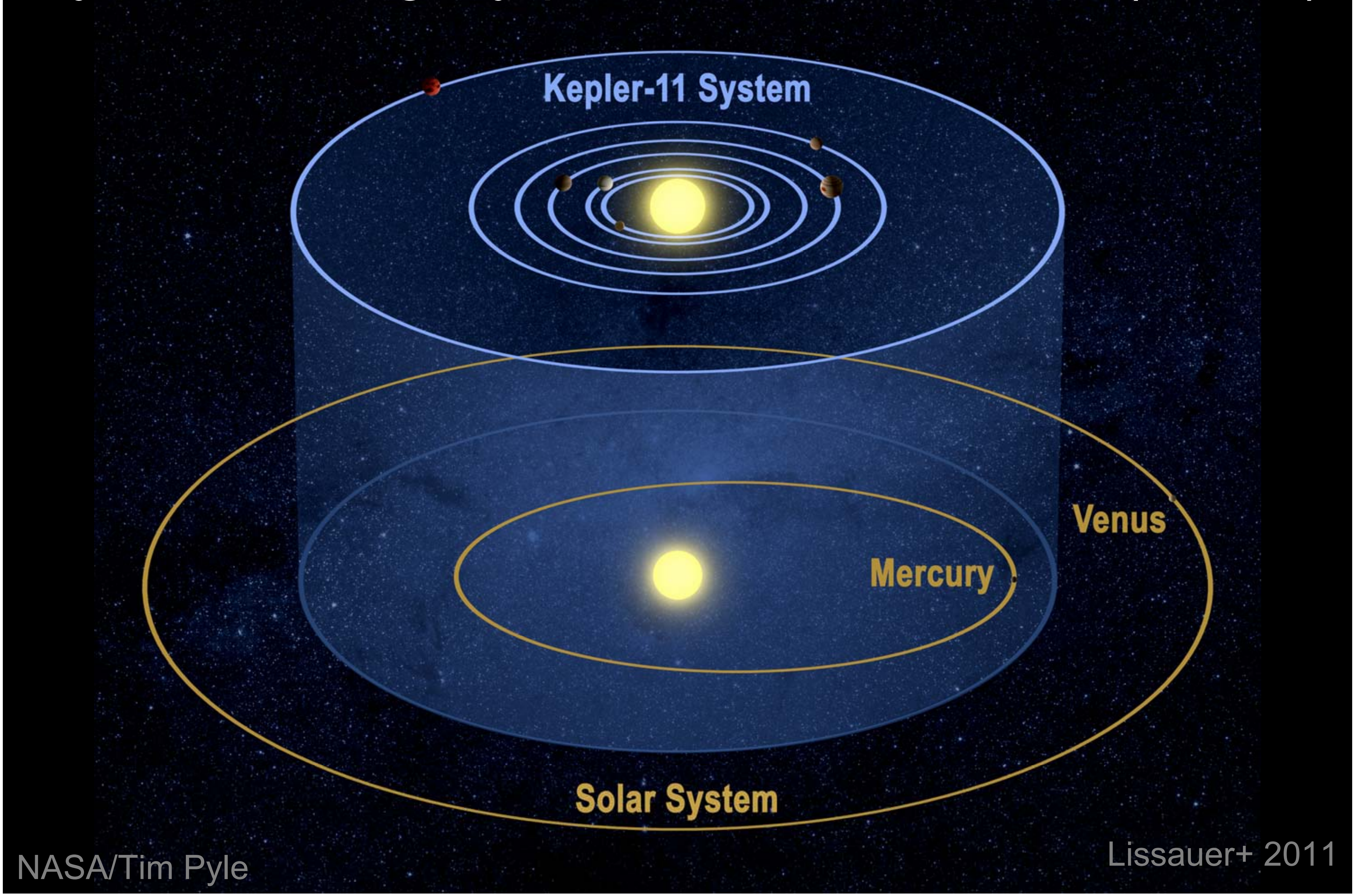
Non-Transiting Planets

- Kepler-19c
- Kepler-46c
- Probably dozens more in TTV catalogs
- Important for disentangling distributions for inclination & multiplicity



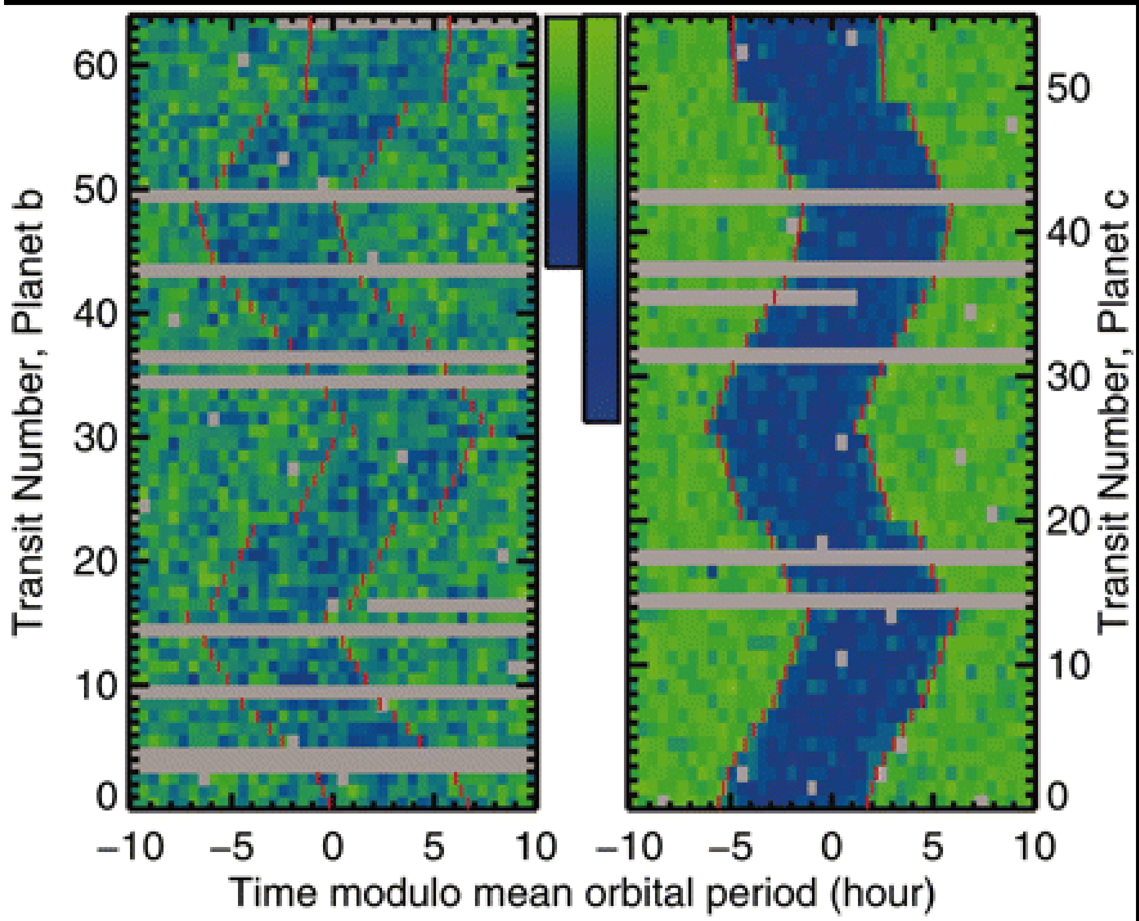
Ballard et al. 2011
Nesvory et al. 2012
Ford et al. 2012

Systems of Tightly-packed Inner Planets (STIPs)



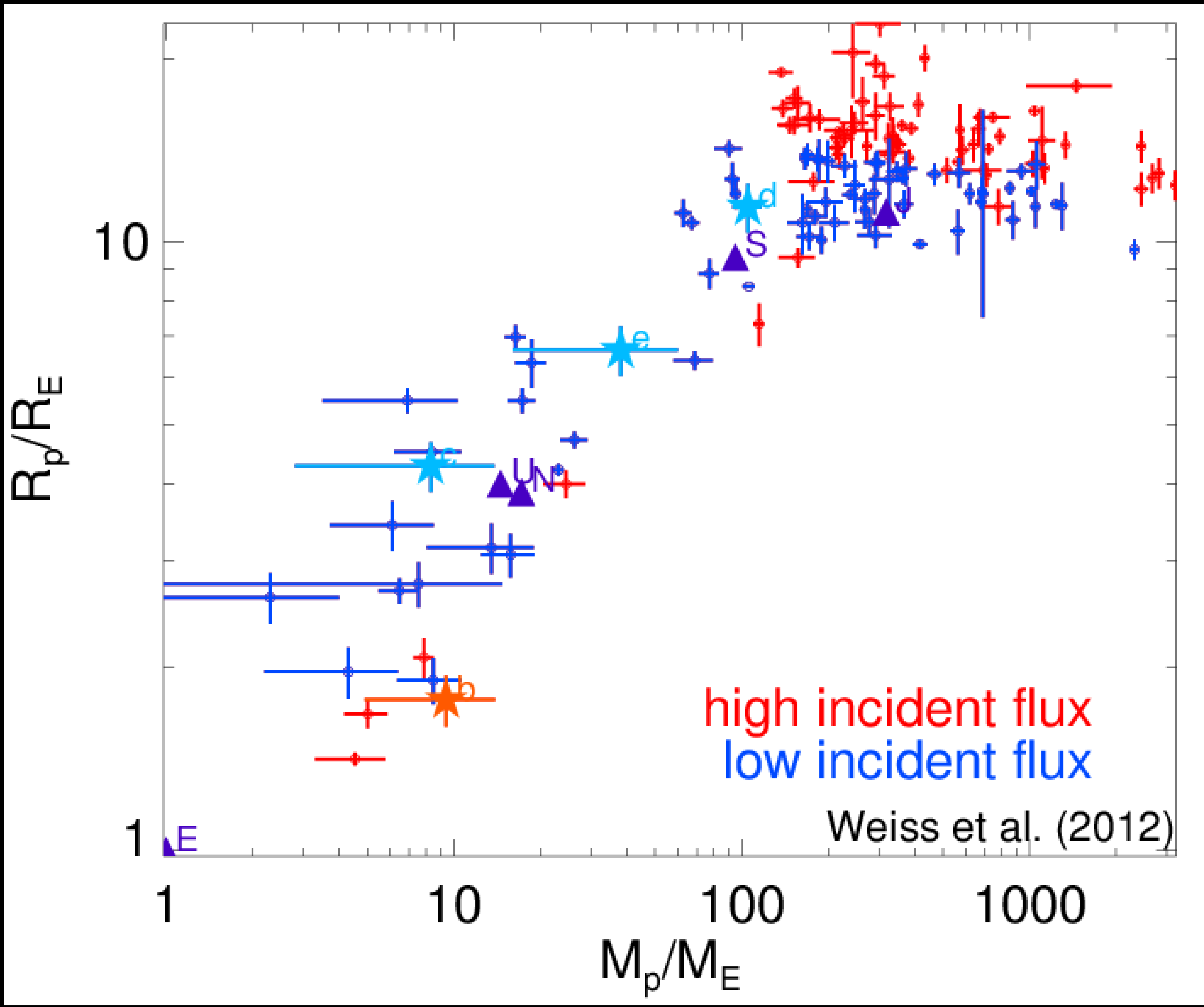
TTVs Characterize Planet Masses for Rapidly Interacting Systems

Kepler-36b&c: Chaotic due to 29:34 and 6:7 MMRs!

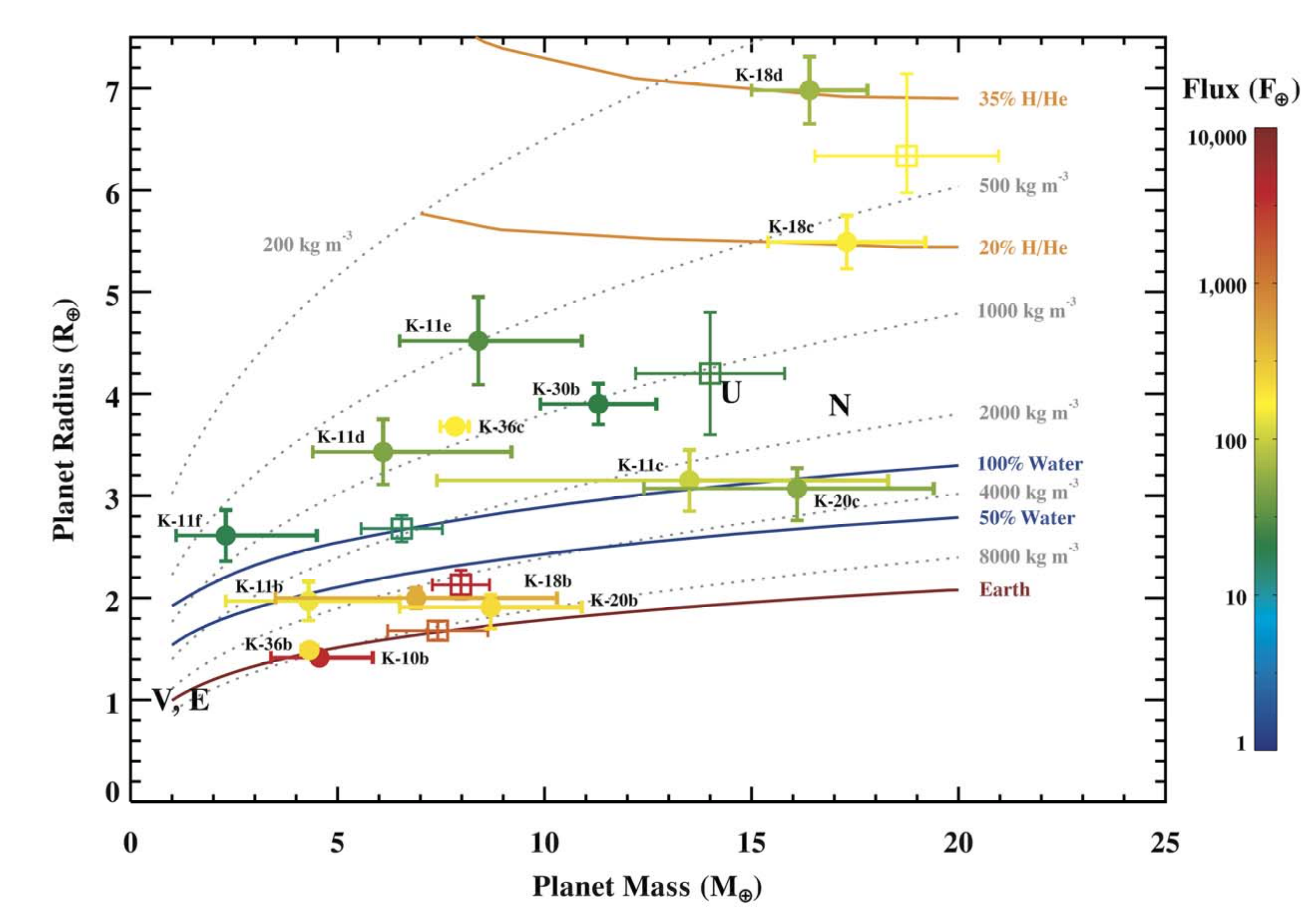


Carter et al. 2012; Deck et al. 2012

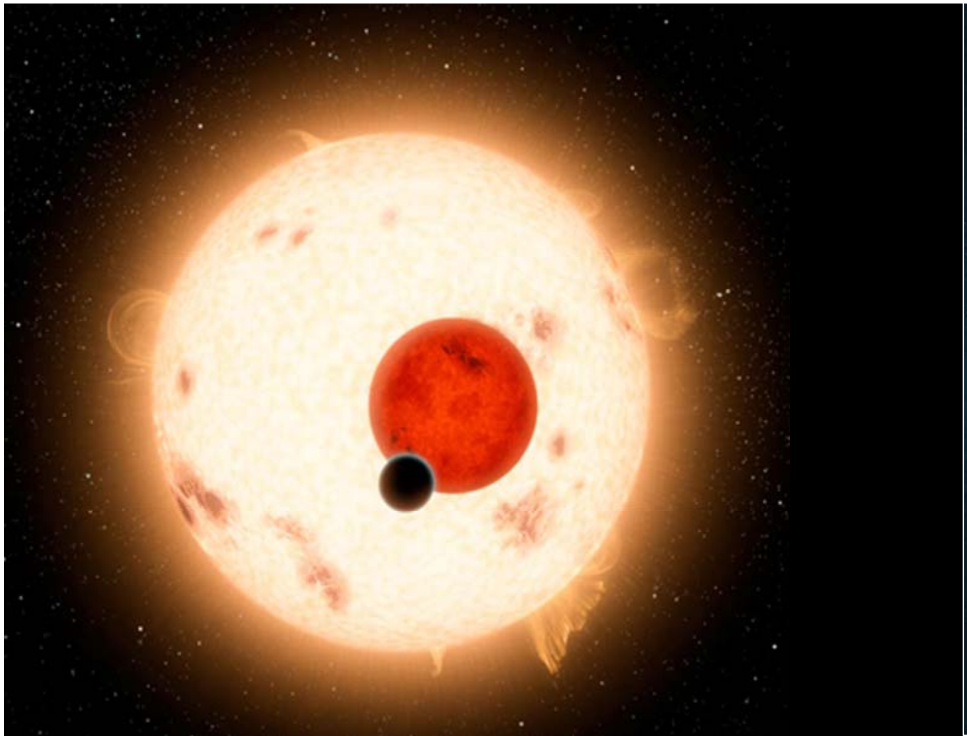
Exoplanet Mass-Radius Relation

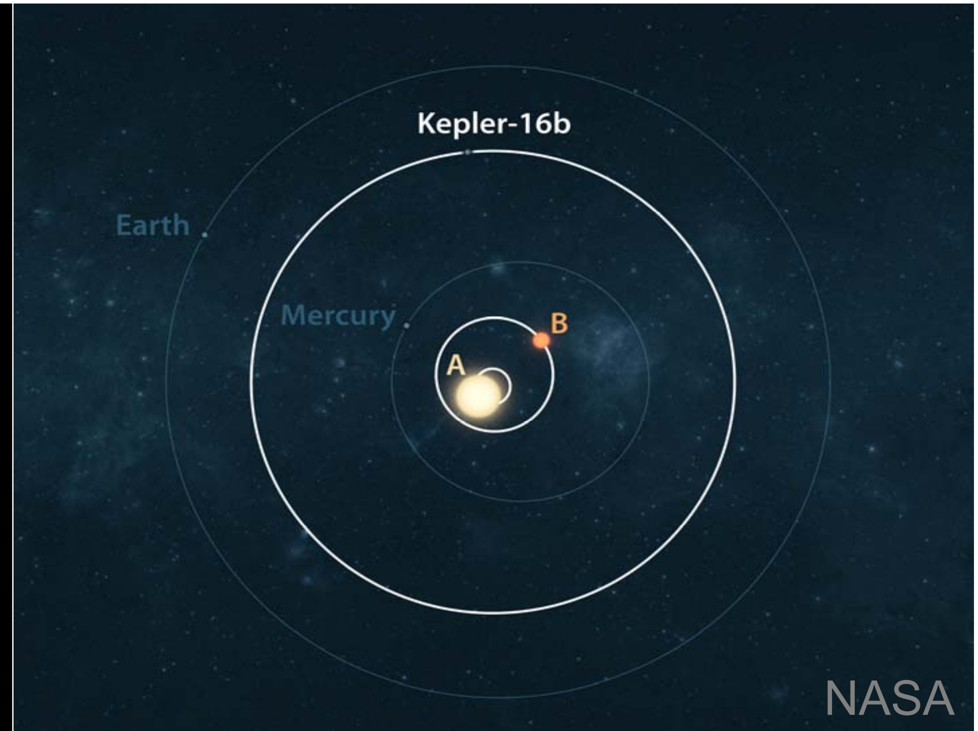


Super-Earths or Mini-Neptunes?

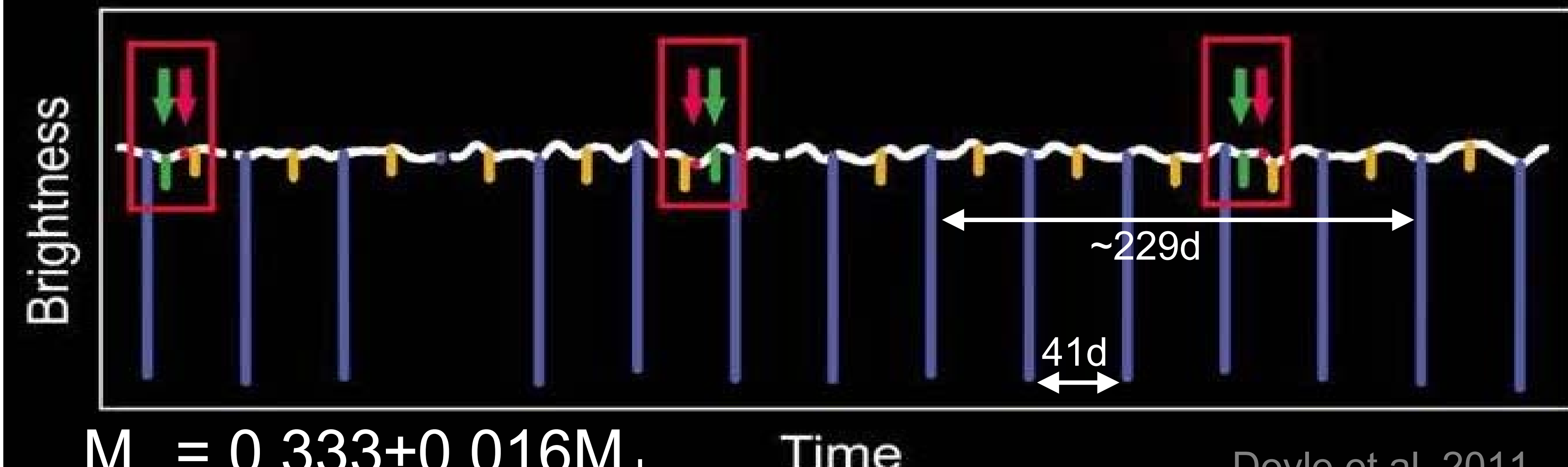


Eric Lopez



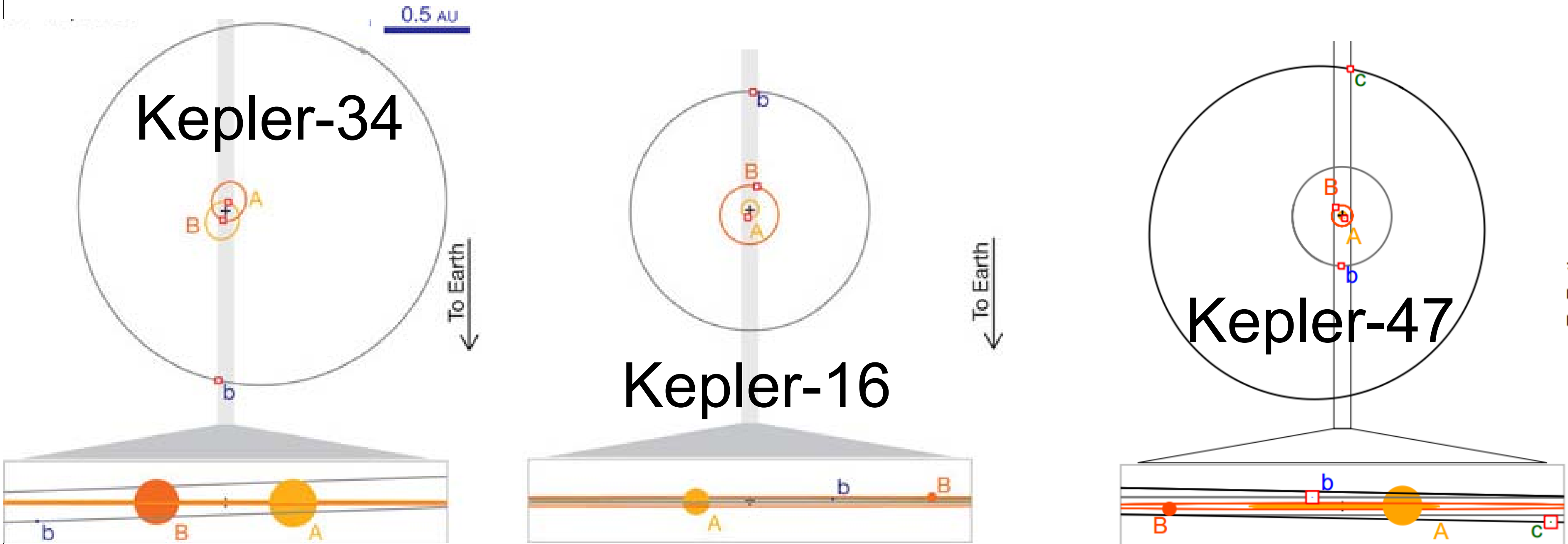


Circumbinary Planets

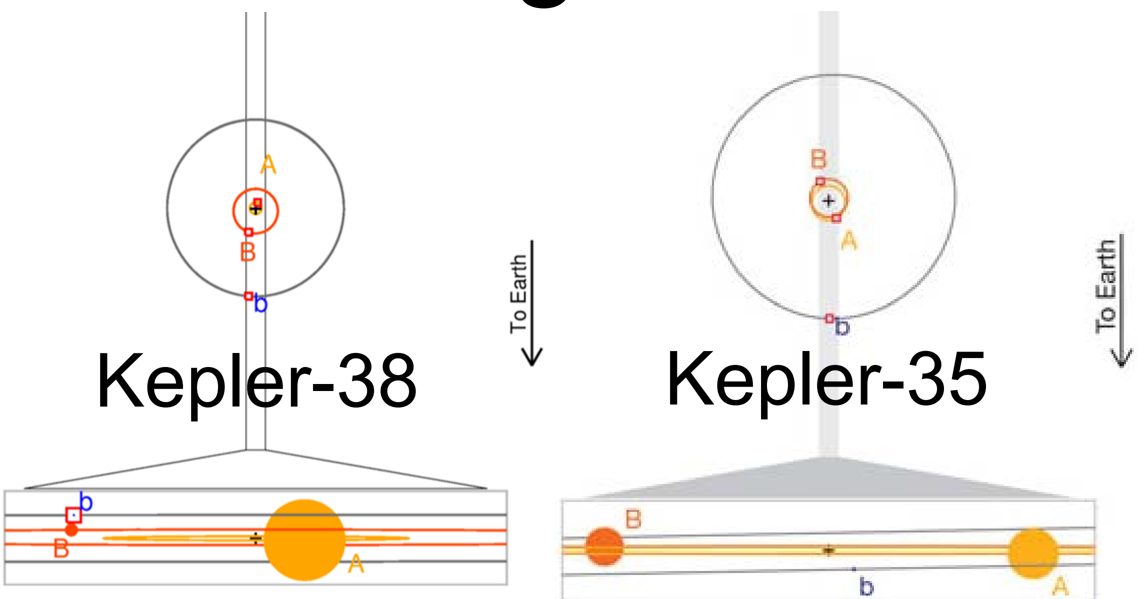


$M_p = 0.333 \pm 0.016 M_{Jup}$

Doyle et al. 2011

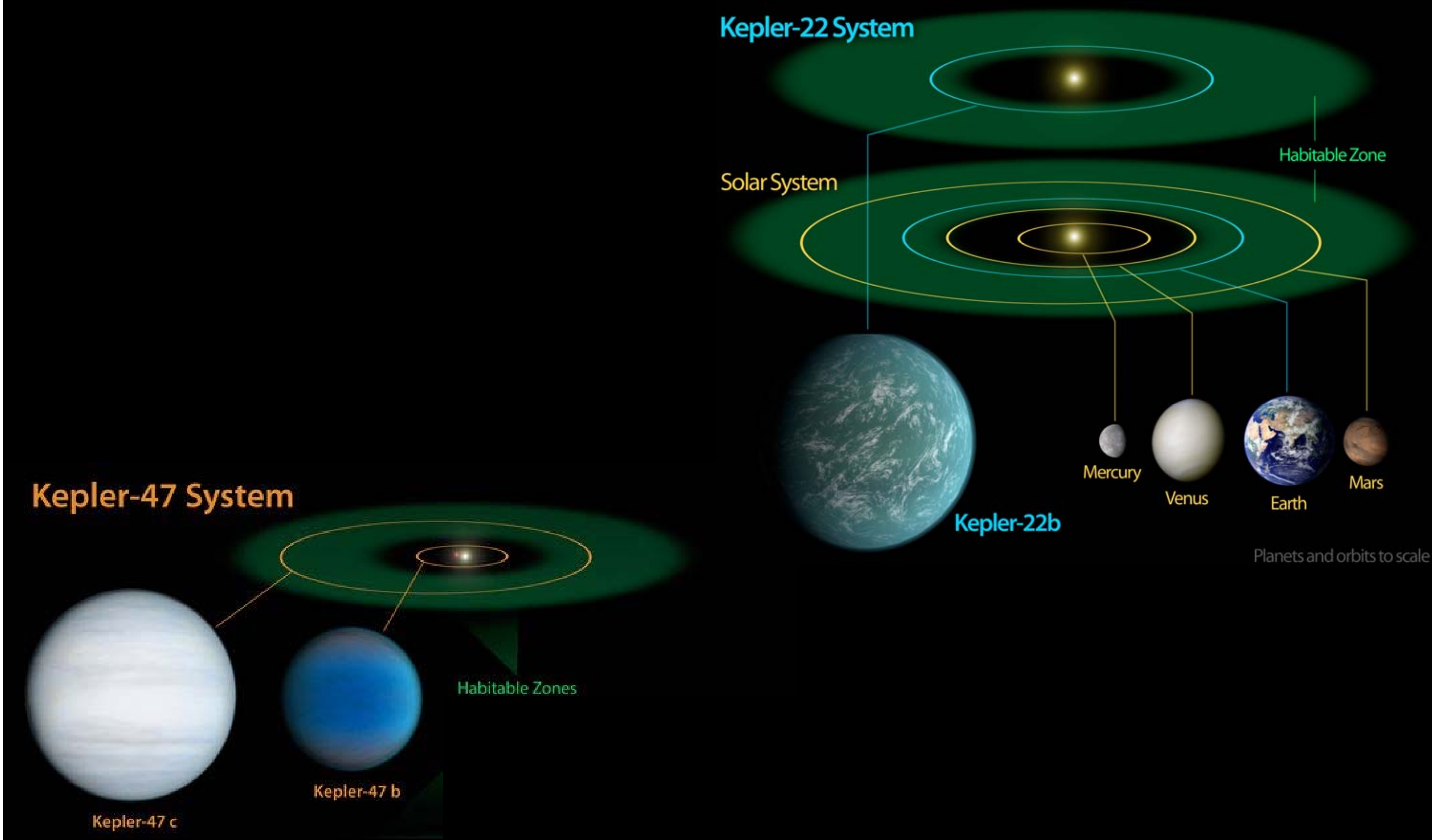


Transiting Circumbinary Planets



Doyle et al 2011
Winn et al. 2011
Welsh et al. 2012
Orosz et al. 2012ab

Transiting Planets in the HZ



Orosz et al. 2012 Image Credits: NASA Borucki et al. 2012

Future Kepler Science

NASA Senior Review recommended extending *Kepler* data collection from 3.5 years to 7.5 years

Purpose of Extended *Kepler* Mission

- Extend the Exoplanet Survey
  - Produce vetted catalogs of planet candidates
  - Including a sample of Earth-size candidates in/near HZ

- Enable the determination of η_{Earth}, the frequency of rocky planets in the habitable zone

- Support a limited Follow-up Program
  - Focus on planets with R_p<2.5 R_{Earth}
  - Improve planet radii (by improving stellar parameters)
  - Improve catalog reliability (e.g., high-resolution imaging)

- Build, maintain & support a legacy archive
- Support community observations & archival analysis
- Continue a robust EPO Program

Science in the Extended Mission

- Primary focus of extended mission:
  Measure η_{Earth}, the frequency of rocky planets in the HZ
- Kepler data will enable much more great science:

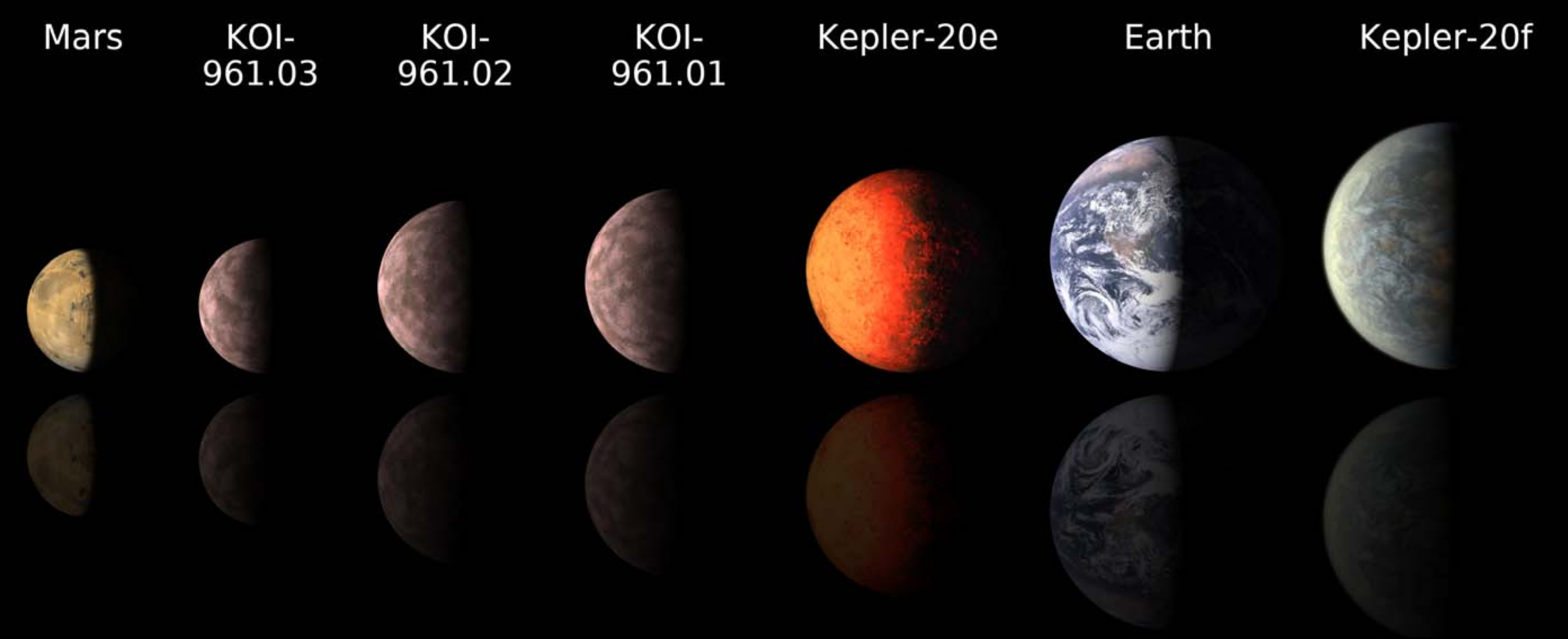
Exoplanets

- Larger Planets
- Short-period small planets
- Mass-Radius Relation
- RV Follow-up observations
- Transit Timing Variations
- Planetary Architectures
- Circumbinary Planets
- Correlations w/ Stellar properties

Astrophysics

- Eclipsing Binaries
- Astroseismology
- Variable Stars
- Stellar activity cycles
- Your idea here

Small Transiting Planets



NASA

Fressin+ 2012; Gautier+ 2012; Muirhead+ 2012

Future Prospects for TTVs

TTVs can confirm planets around:
• Faint stars
• Stars w/o RVs

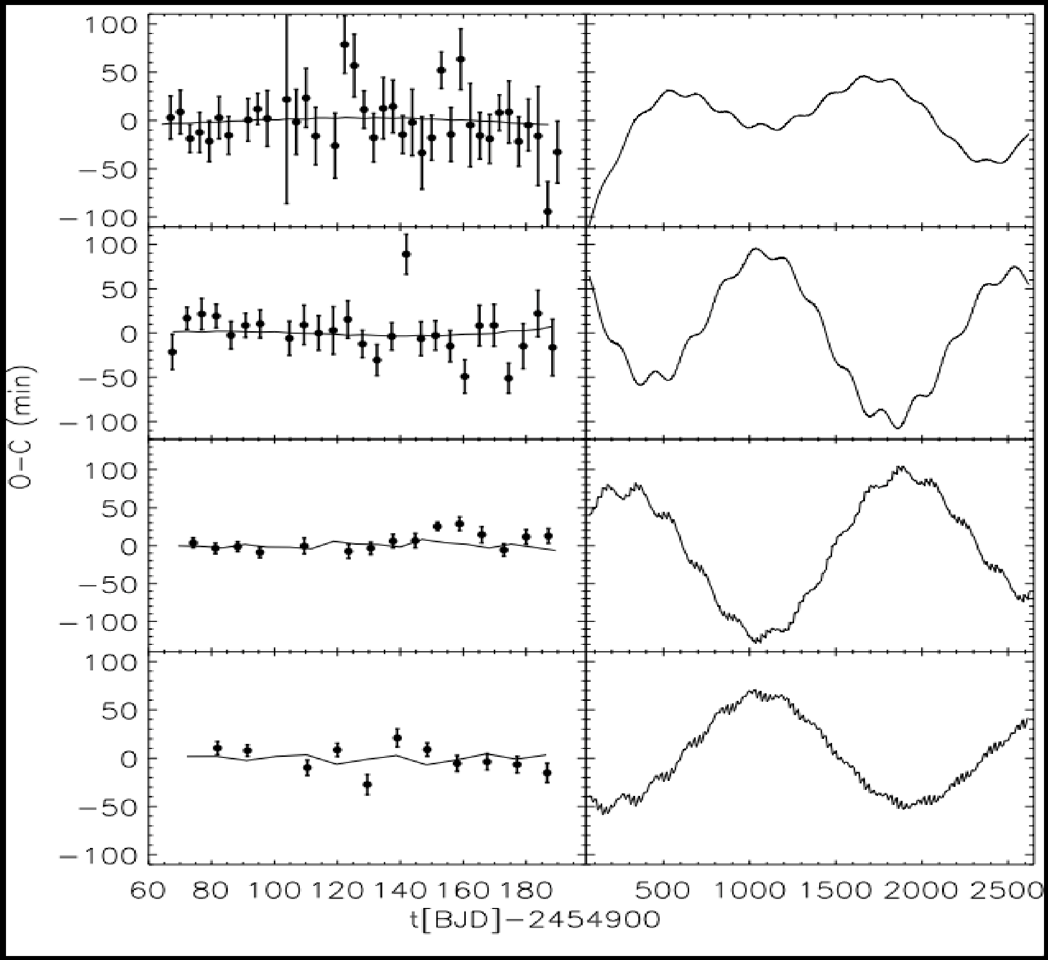
Expect to confirm & characterize many more planets via TTVs

Since typical TTV timescales ~ years
Extending time baseline TTVs offers:
• Masses for short-period planets
• Confirmation of closely spaced systems in HZ (w/ sensitivity increasing as ~$t^{5/2}$)

KOI 500

Observations (short-term)

Nominal Model (long-term)



Ford et al. 2011

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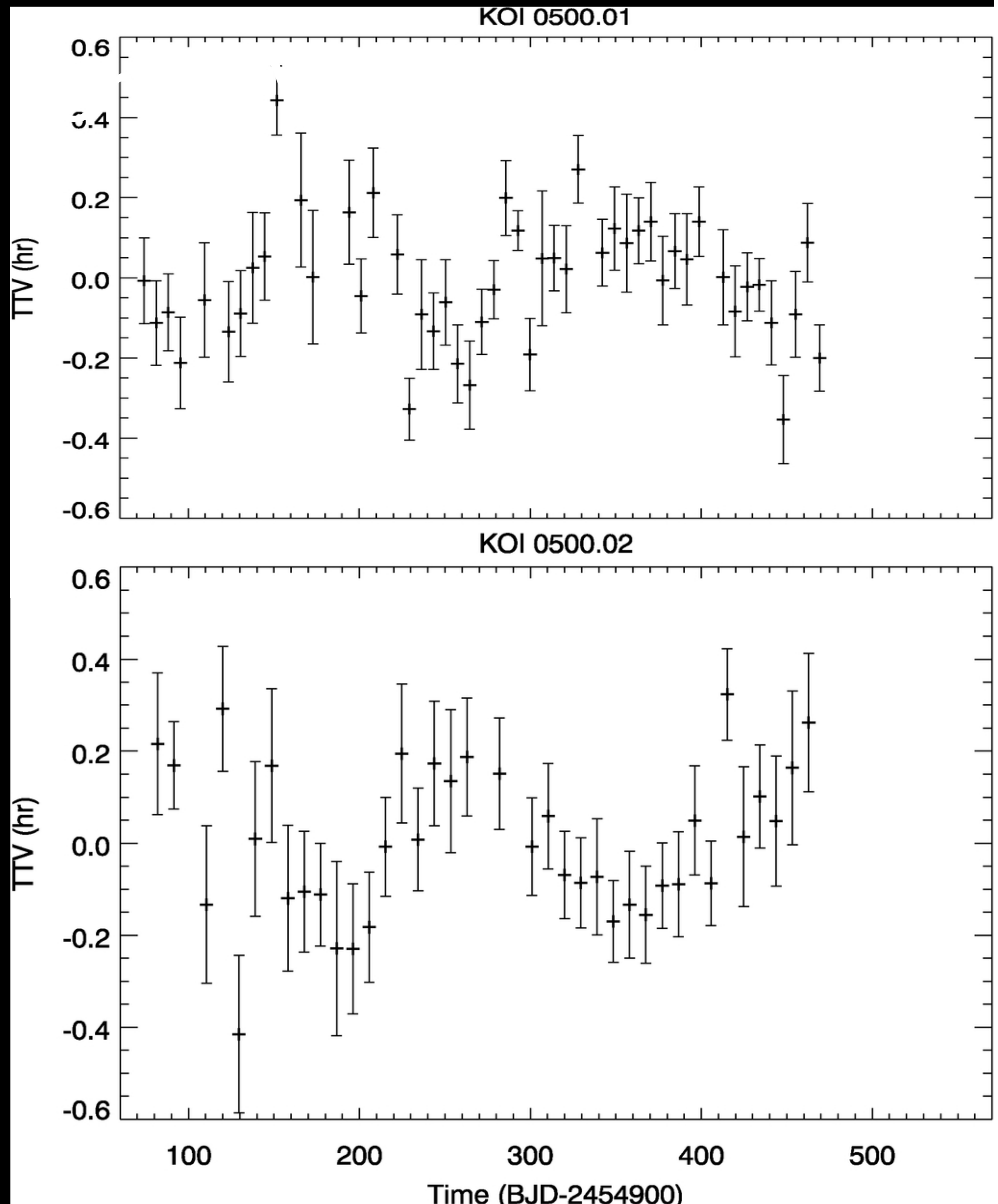
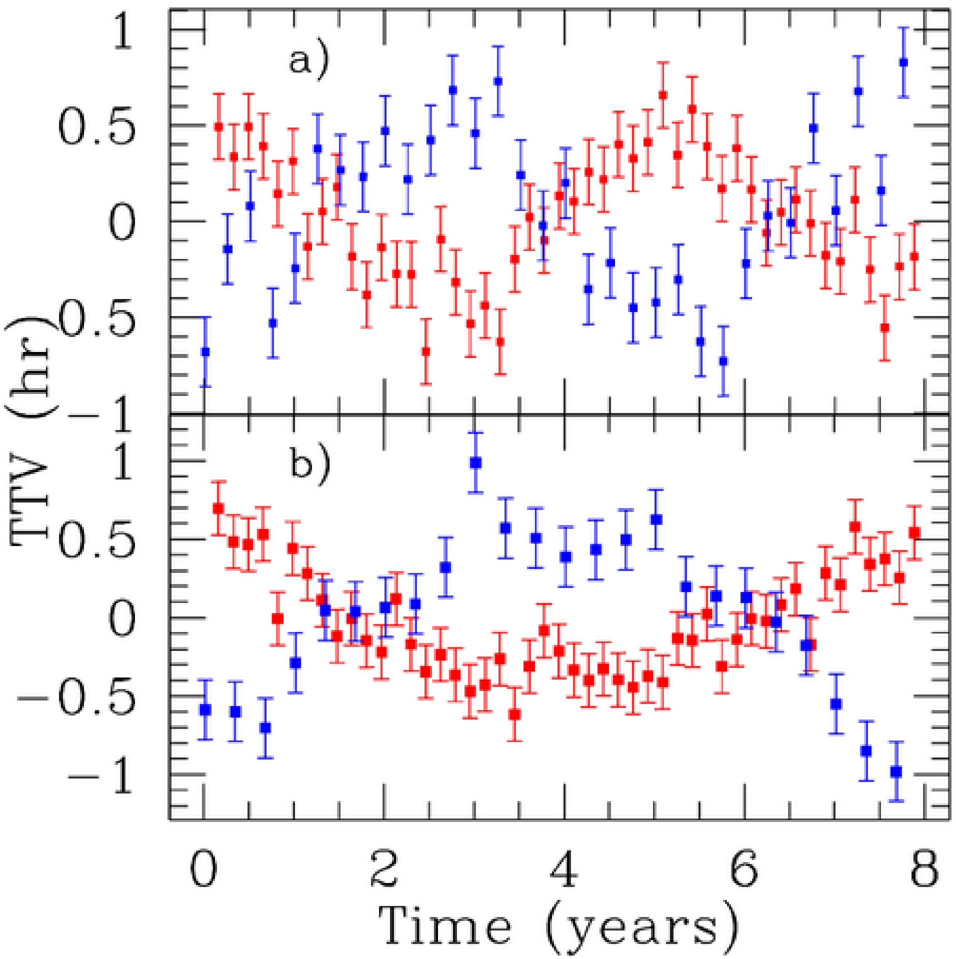
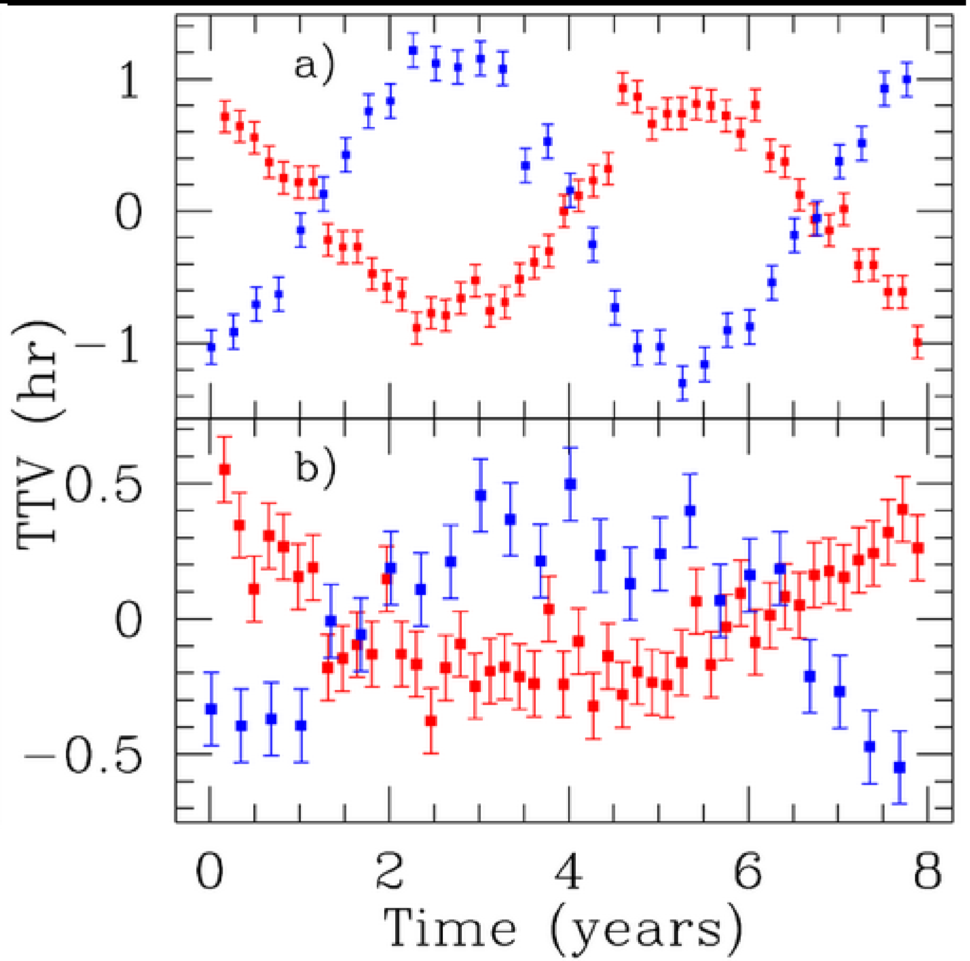


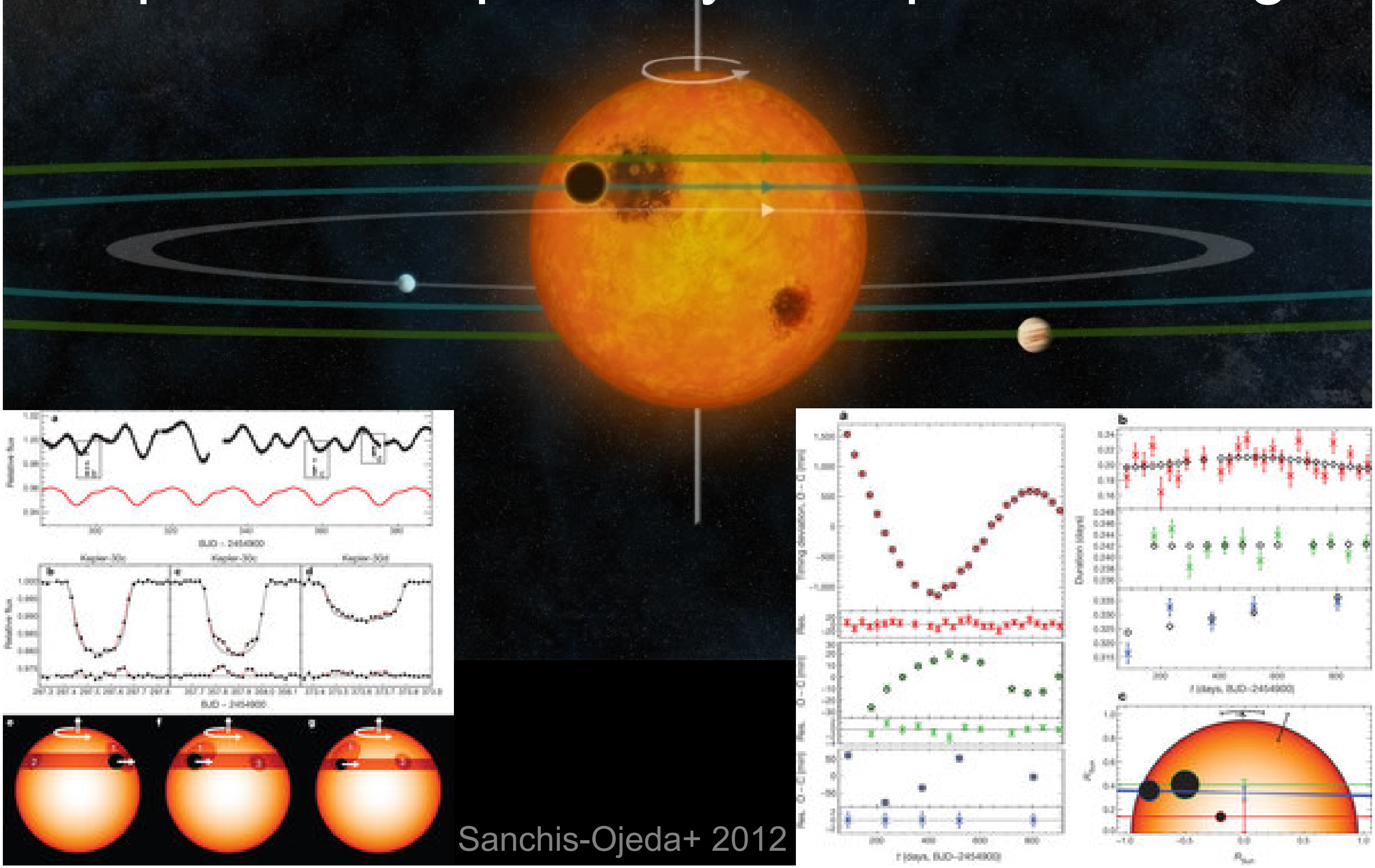
Ford et al. 2012; Xie 2012; Ragozzine et al. in prep

Future Prospects for Measuring Masses via TTVs



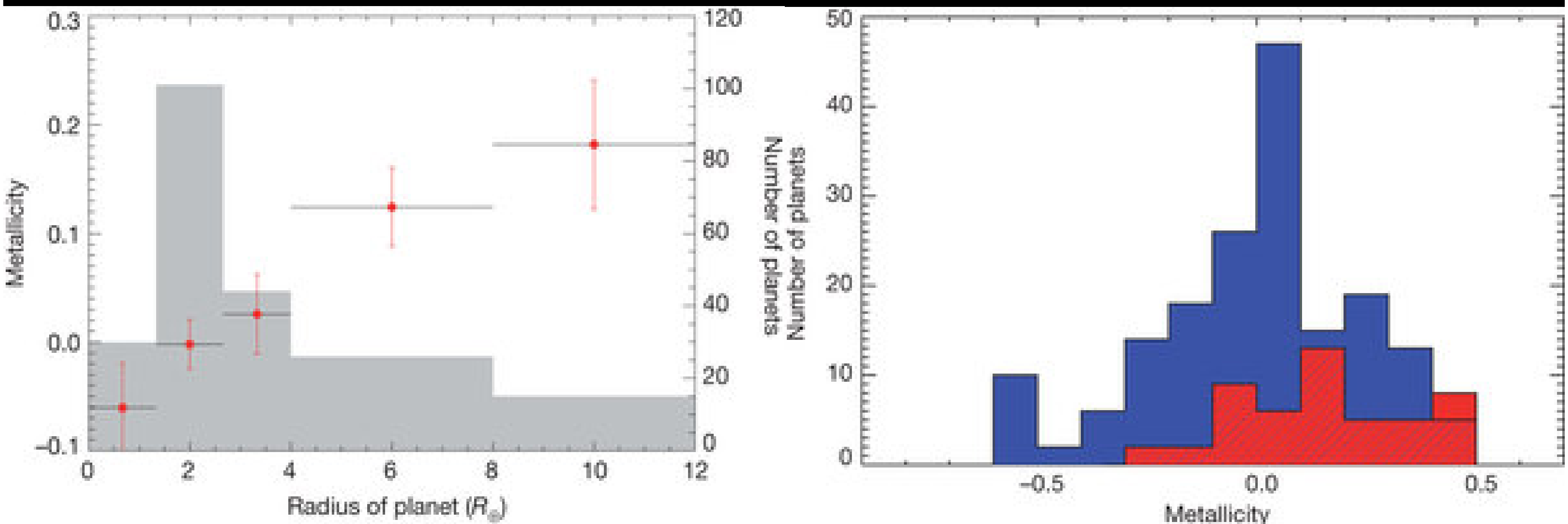


Kepler-30: Coplanarity via Spot Crossings



Sanchis-Ojeda+ 2012

Small Planets don't need Metal-Rich Stars



Buchave et al. 2011

What do we need to extract the best science from *Kepler?*

More Kepler Data (on the way),
More High-Value Planetary Systems (optimistic),
More Time/Brain Power (i.e., $$$),
More Follow-Up Observations (start planning now)

More *Kepler* Data

- Mission will continue observing stars:
  - With planet candidates &
  - Best targets for finding Earth-size planets in HZ
- Starting to consider whether some targets will be dropped during extended mission
- Increasing targets available to Guest Observer Program
  - 7,000 Long Cadence Targets
  - 96 Short Cadence Targets
  - Cycle 5 due Jan 18, 2013 (see http://keplerscience.arc.nasa.gov)

Improve Analysis of *Kepler* Data

- Good news: The *Kepler* pipeline keeps improving!
- Challenge: Specific science goals often benefit from specialized algorithms, e.g.
  - Photometry of saturated/faint/crowded target stars
  - Searching for circumbinary planets
  - Searching for planets with large TTVs
  - Measuring transit times of small planets
- Needs:
  - Funding for algorithm development & data analysis (e.g., ADAP)
  - Collaborate with Statisticians & Computer Scientists, e.g., “Modern Statistical and Computational for Analysis of Kepler Data” at SAMSI, June 10-28, 2013
  - Share tools via working groups and/or keplerscience.arc.nasa.gov

More Time & Brain Power

- NASA Funding Mechanisms
  - Origins of Solar Systems
  - Astrophysical Data Analysis Program (ADAP)
  - Participating Scientist Program (PSP)
  - Guest Observer Program
  - Others (e.g., Sagan fellowship programs)
- Work Efficiently: Join or take a leadership role in a working group
  - Benefit from experience of others
  - Coordinate research plans
  - Facilitate collaborations
  - Excellent opportunities for students/postdocs

Increasing Community Involvement

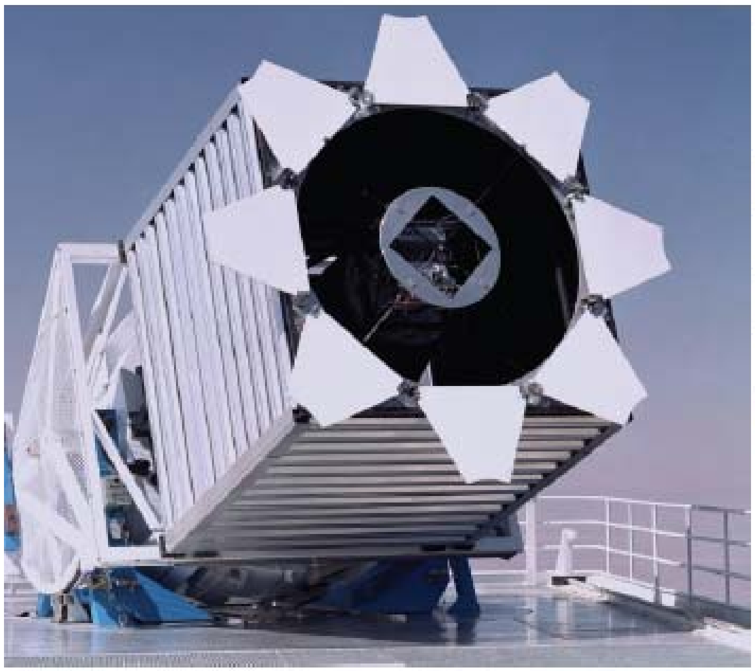
- Light curves will go public available as soon as processed via MAST (http://archive.stsci.edu/kepler/)
- More data products will become available via NASA Exoplanet Archive (http://exoplanetarchive.ipac.caltech.edu)
  - Transit search results, Transit diagnostics, Planet candidate catalogs
- Facilitating coordination & data sharing via *Kepler* Community Follow-Up Observing Program website (http://cfop.ipac.caltech.edu)
- Facilitating working groups (Contact: Natalie Batalha natalie.m.batalha@nasa.gov), including:
  - Star Properties
  - Transit Timing & Multi-body Systems
  - Eclipsing Binaries
  - Planet Populations?

Increasing Community Involvement

- Funding Opportunities
  - Origins of Solar Systems
  - Astrophysical Data Analysis Program (ADAP)
  - Participating Scientist Program (PSP)
  - Guest Observer Program
- Increasing targets for Guest Observer Program
  - 7,000 Long Cadence Targets
  - 96 Short Cadence Targets
  - Cycle 5 due Jan 18, 2013 (see http://keplerscience.arc.nasa.gov)
- Presence at DPS & other meetings
  - Science Talks & Posters (Mon & Tues, plenary & Tahoe room)
  - Joint *Kepler* & NExSci Booth

More Follow-Up Observations

- So many planet candidates, so little telescope time
  - Spectroscopy for stellar characterization
  - Low & High-precision RVs
  - High-resolution imaging
  - Complimentary transit observations
- Should observe stars w/o transiting planets to understand how planet host stars compare to full Kepler target list
- Encouraging community to use CFOP website:
  - Find data already available for targets you're studying
  - Share your data (or at least advertise it)
  - Coordinate your observations with others
  - Solicit observations of favorite object from the community
- Need community to "buy-in" to sharing data



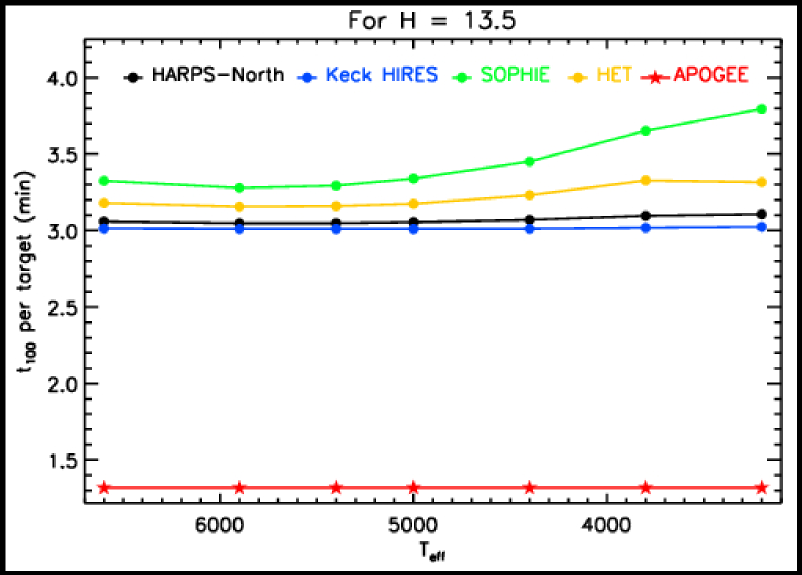
SDSS 2.5-meter telescope
at the Apache Point Observatory, NM
Image Credit: Sloan Digital Sky Survey

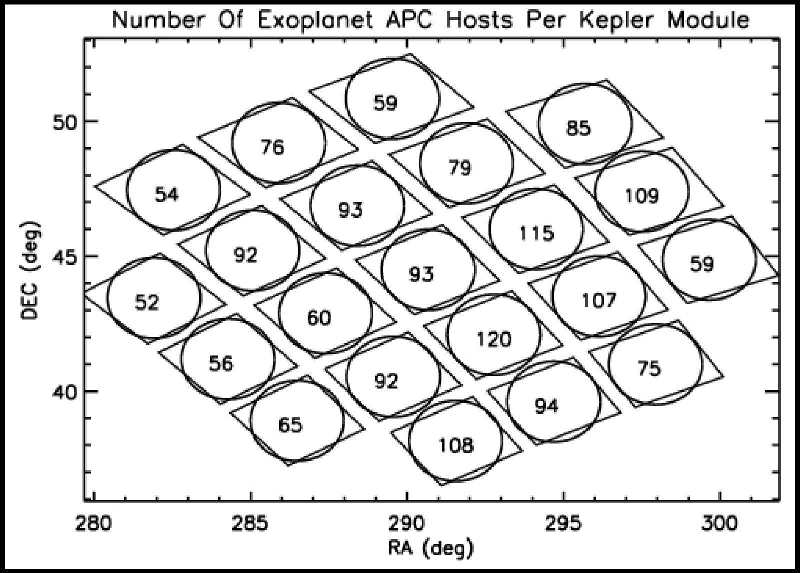
- High-S/N, high-resolution (R~22,500) spectroscopic survey H-band (1.5-1.7 micron)
- 100,000 stars in disk, bulge, halo
- ~10,000 targets in Kepler field, incl. ~2,000 dwarfs & subgiants V<11
- Chemical abundances to 0.1 dex precision
  - Molecular bands (OH, CN, CO)
  - α-elements (O,Mg, Si, S, Ca, Ti)
  - Iron-peak (Cr, V, Mn, Fe, Co, Ni)
  - ``Odd-Z" (Na, K, Al)
  - possibly even neutron capture

slide adapted from Courtney Epstein

APOGEE for Follow-Up of Kepler Planet Candidates

- RV precision of ~100m/s can recognize most false positives
- For 100m/s precision, APOGEE is ~2x as efficient as other facilities
- Frees Keck, HARPS-N, SOPHIE, HET to focus on high-precission for best planet candidates
- SDSS Field of View well matched with Kepler modules (95% of planet candidates using 1 APOGEE field/ Kepler module)
- Also measures 15 abundances & binarity for stars, both with and without transiting planets





(Fleming et al., submitted)

Steps to Measuring η_{Earth}

- Identify small planet candidates in/near HZ
  - Observe more transits, Improve data analysis algorithms
  - Understand pipeline completeness
- Characterize star properties (hosts & non-hosts)
  - Coordinated spectroscopic observing campaigns
- Confirm planets (or at least validate them)
- Establish that planets orbit target star & maximum dilution
  - Spectroscopy, high-contrast imaging, additional transit photometry
  - Detailed analysis of Kepler & FOP data
- Characterize planet masses & densities
  - For most cases will need to infer based on mass-radius relationship
- Characterize mass-radius relationship at small periods
  - RV observations (favorable stars, short-period planets)
  - Transit Timing Variations (favorable architectures)
- Understand selection effects/observational biases

Testing Planet Formation Theory

Orbital eccentricities, inclinations & multiplicity are three key probes of planet formation:

- Eccentricity distribution (+ stellar densities) → Transit duration distribution
- Inclination distribution + Frequency of multiple planet systems (+ Period distribution) → Frequency of multiply transiting systems
- Frequency of multiple planet systems + Eccentricity Distribution (+ Period distribution) → Distribution of TTV signatures

One complex inverse problem!

(Observables, Desired Distributions, Both)

Lessons Learned

Teamwork is Key!

Plan for Surprises

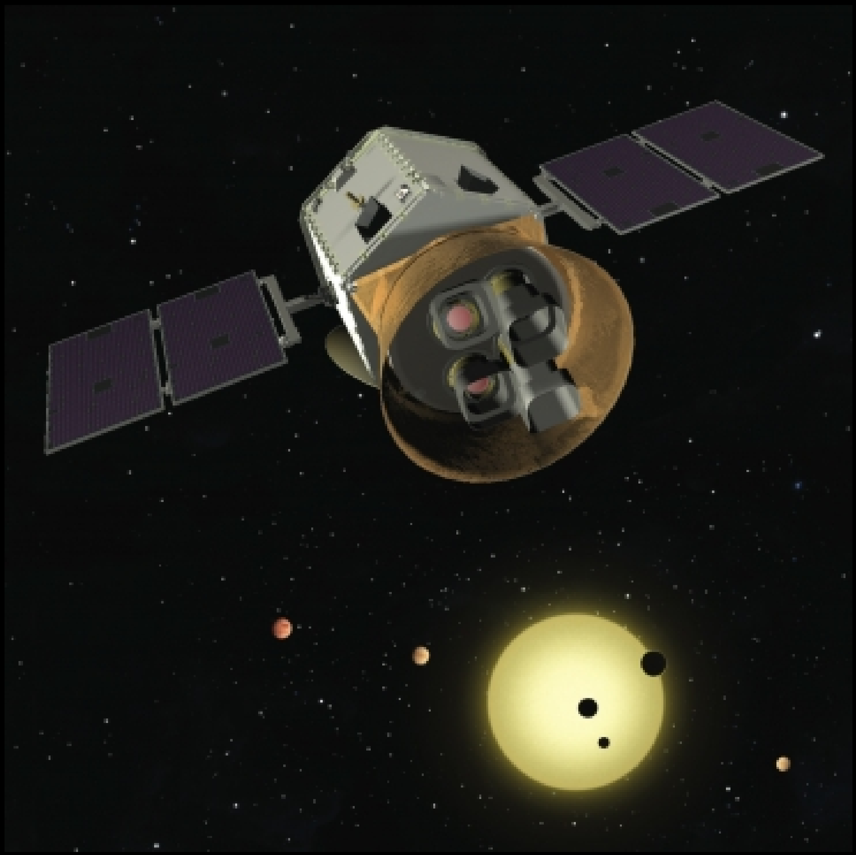
Lessons Learned

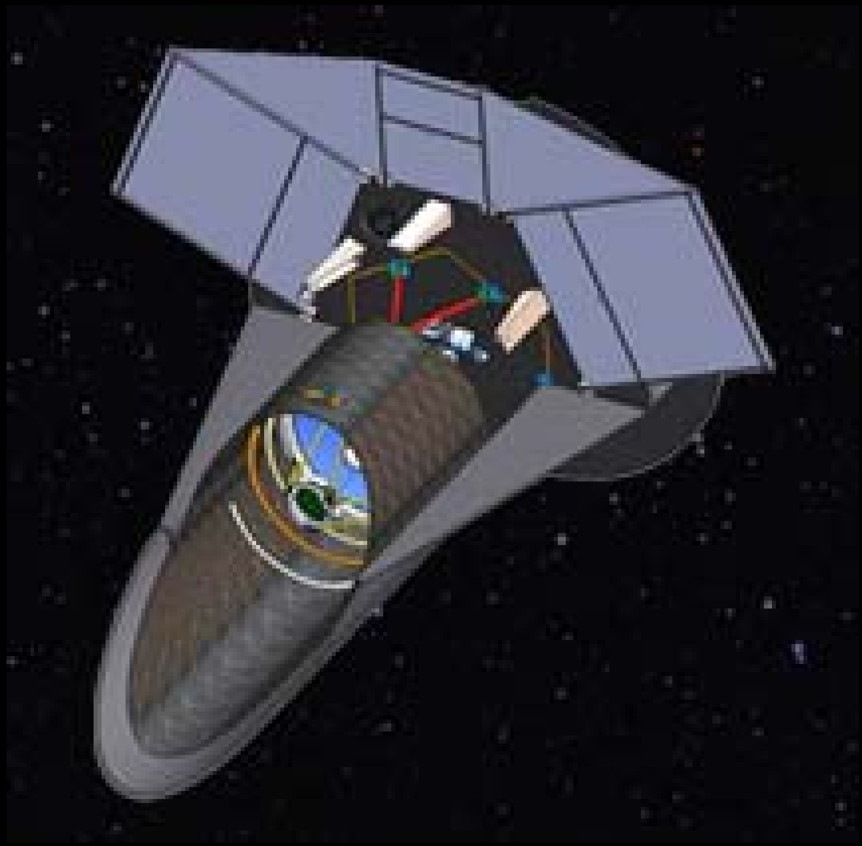
- Measuring η_{Earth} is a marathon, not a sprint
  - Too complex for a single analysis
  - Don’t try to do everything yourself
  - Report results in a way that can be combined with other observations/analyses
- Robust science requires
  - Understanding details of *Kepler* & follow-up data
  - Being on the lookout for rare objects
- Even a single planet confirmation has too many parts for one person to do it all.
  - Collaborate (hopefully via a working group)
  - People focus on papers that are likely to finish soon
  - Organize big projects into small papers

Lessons Learned

- Coordinate observations/analysis to avoid duplication & allocate resources wisely
- Lots of new possibilities thanks to Kepler's exquisite photometry & clever people
- Grad students or postdocs can pioneer a new sub-field of exoplanet science
- Plan for surprises & new ideas
- Learn to work probabilistically
  - Non-transiting planets
  - Some false positives (false positive rate is not 1 number)
  - Degenerate parameters

Future Space Missions





Questions