The *Kepler* Mission: Overview and Results

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Kepler Mission Concept

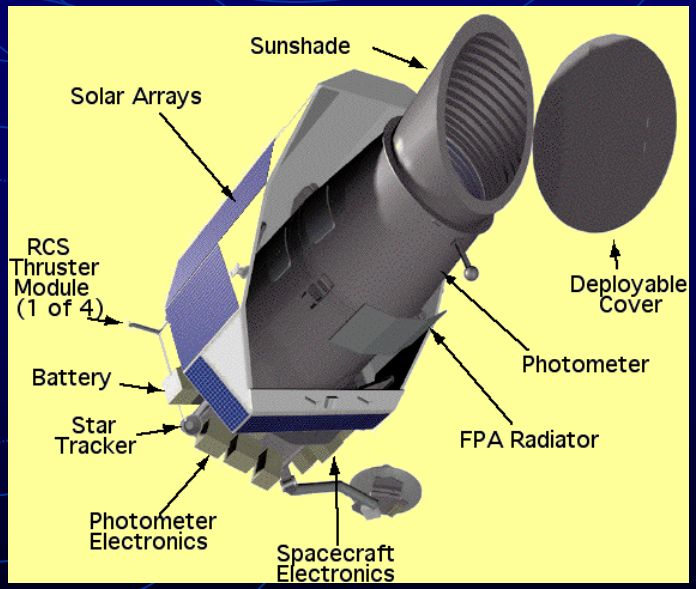
- Kepler is optimized to find Earth-like transiting planets
  - Radius down to 1 $R_\oplus$
  - Sun-like host stars
  - Orbits out to 1 AU (P ~ 1 year)
- Mission characteristics
  - Up to 170,000 pre-selected targets
  - Earth-trailing heliocentric orbit for stability
  - Stare at a single field for the entire mission

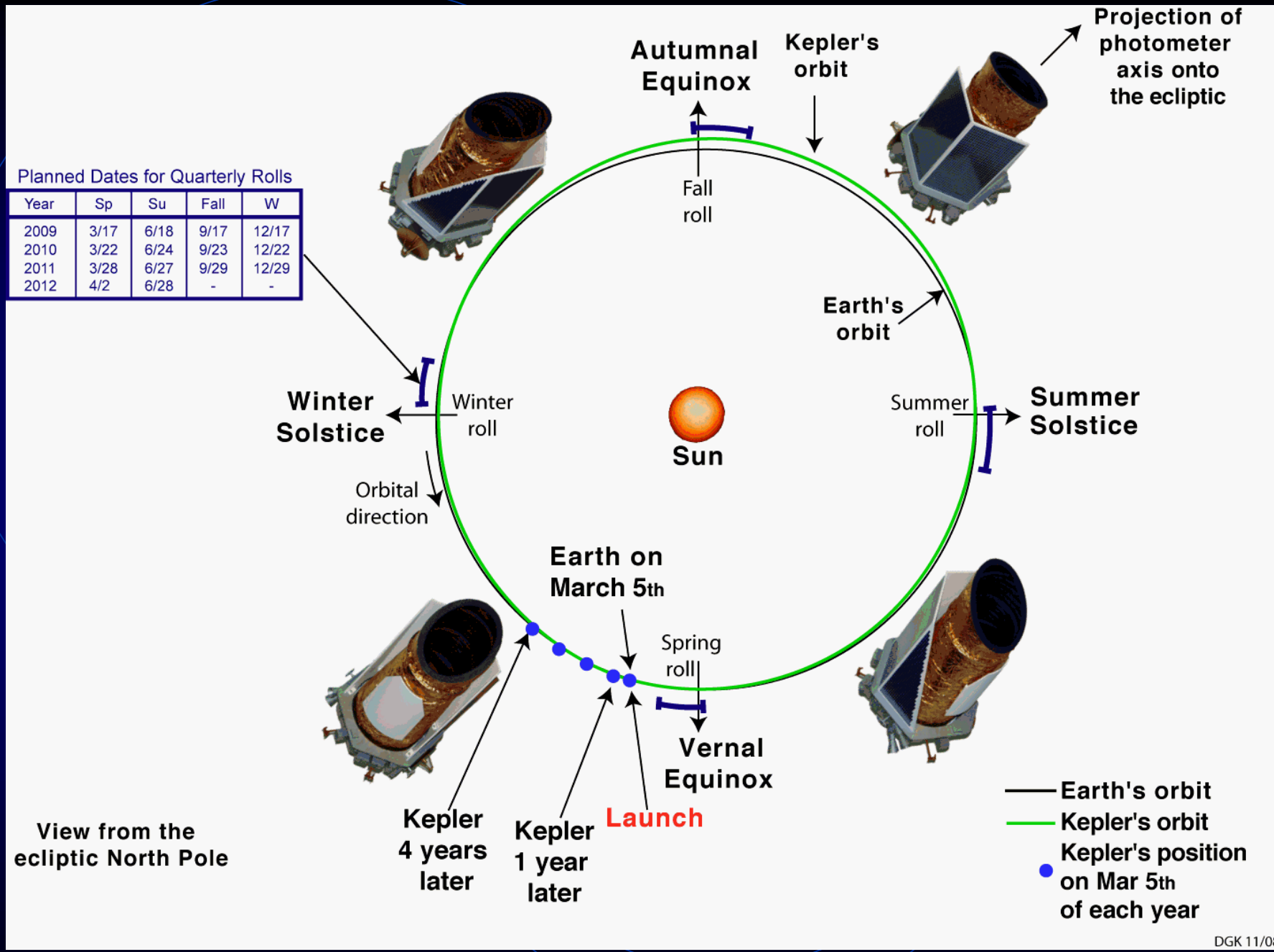
Science Questions Addressed

- What is the frequency of Earth-size planets in or near the Habitable Zone (HZ) of solar-like stars?
  - Are terrestrial planets common or rare?
- What are the distributions of sizes and semi-major axes?
- What are the frequency and orbital distributions of planets in multiple stellar systems?
- What are the distributions of the semi-major axis, albedo, size, mass, and density of short-period giant planets?
- How are these properties associated with stellar characteristics?

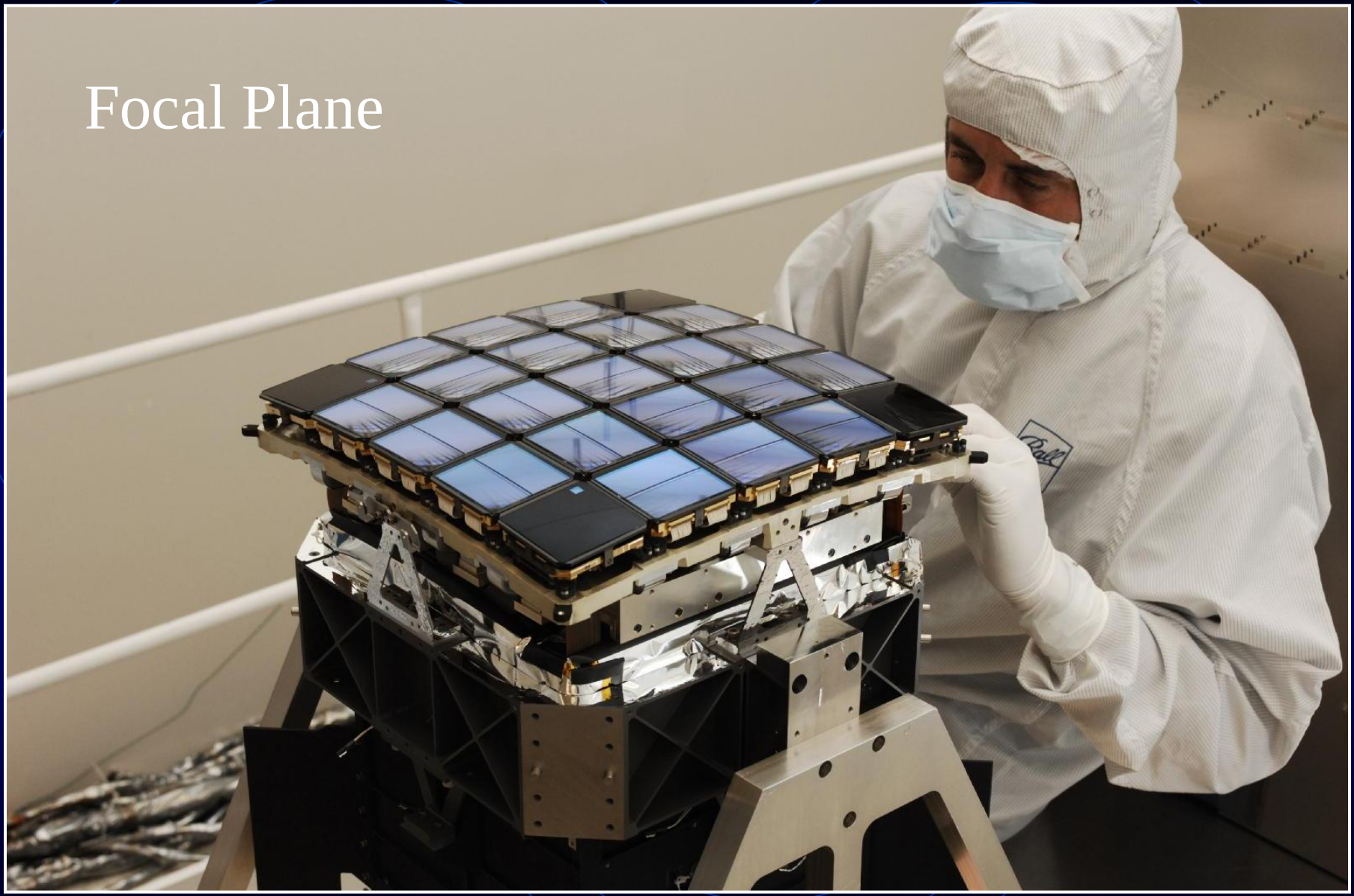
Spacecraft/Instrument Specifications

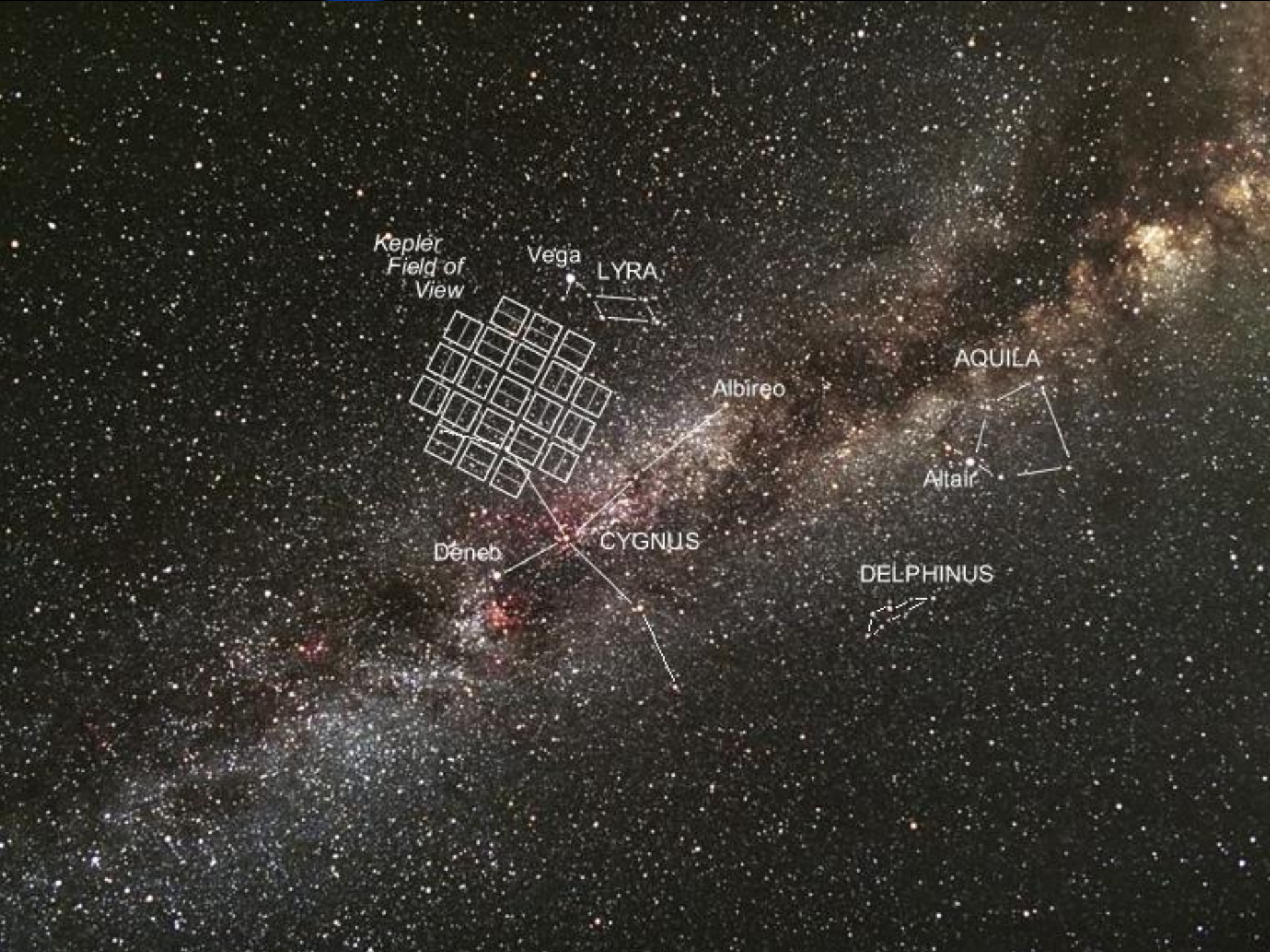
- 1.4m Schmidt primary, 0.95m effective aperture, total weight of 1039 kg
- 115 square degree field of view
- Focal plane has 42 CCDs (27 μm pixels), 2200×1204 pixels each; largest focal planet for a NASA flight mission (94.6 million science pixels)
- Scale = 3.98" per pixel
- 30-minute cadence for up to 170,000 stars, 1-minute cadence for up to 512 stars (asteroseismology)
- Designed to reach a final photometric precision of 20 ppm, sufficient to detect an Earth-size planet around a V = 12 mag G2V star at a 4σ confidence level in a total of 6.5 hours of integration
- Passband 420–900 nm
- Observes continuously for 3.5 years, with a spacecraft roll every three months

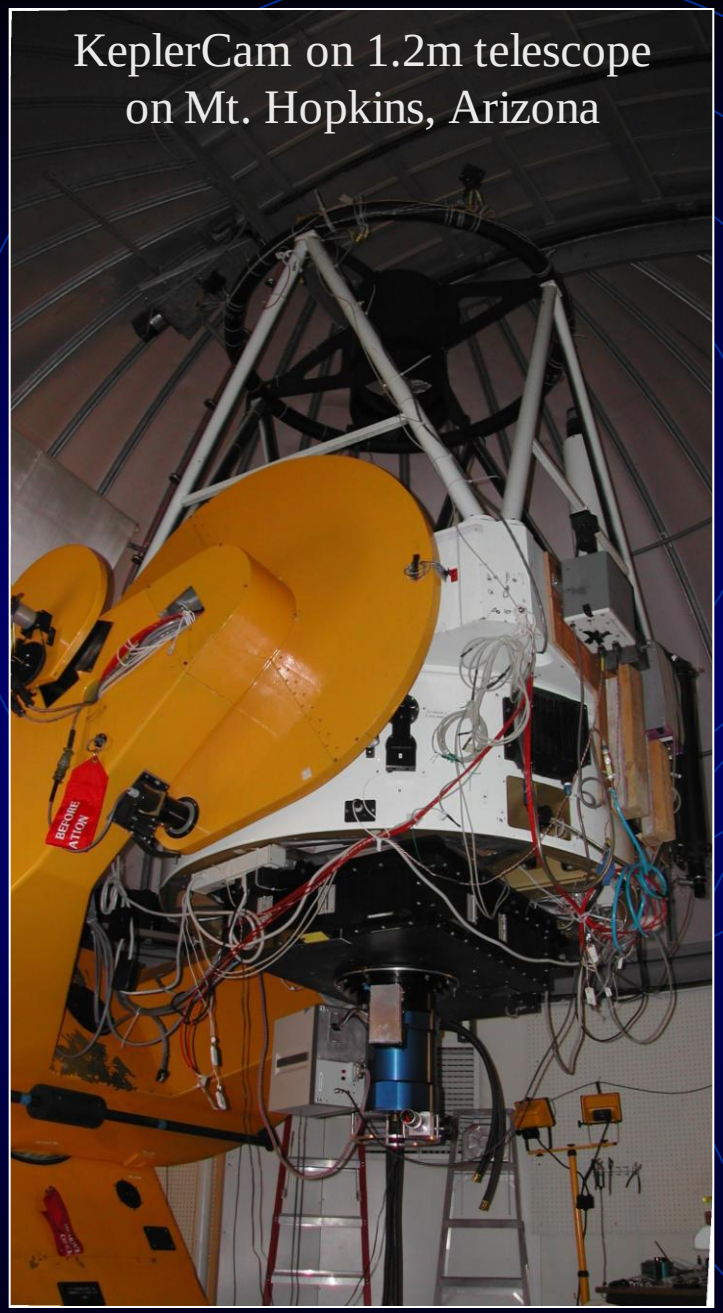



Planned Dates for Quarterly Rolls
Year Sp Su Fall W
2009 3/17 6/18 9/17 12/17
2010 3/22 6/24 9/23 12/22
2011 3/28 6/27 9/29 12/29
2012 4/2 6/28 - -
Autumnal Equinox
Kepler's orbit
Projection of photometer axis onto the ecliptic
Fall roll
Earth's orbit
Winter Solstice
Winter roll
Sun
Summer roll
Summer Solstice
Orbital direction
Earth on March 5th
Spring roll
Vernal Equinox
Kepler 4 years later
Kepler 1 year later
Launch
View from the ecliptic North Pole
Earth's orbit
Kepler's orbit
Kepler's position on Mar 5th of each year
DGK 11/08

Focal Plane

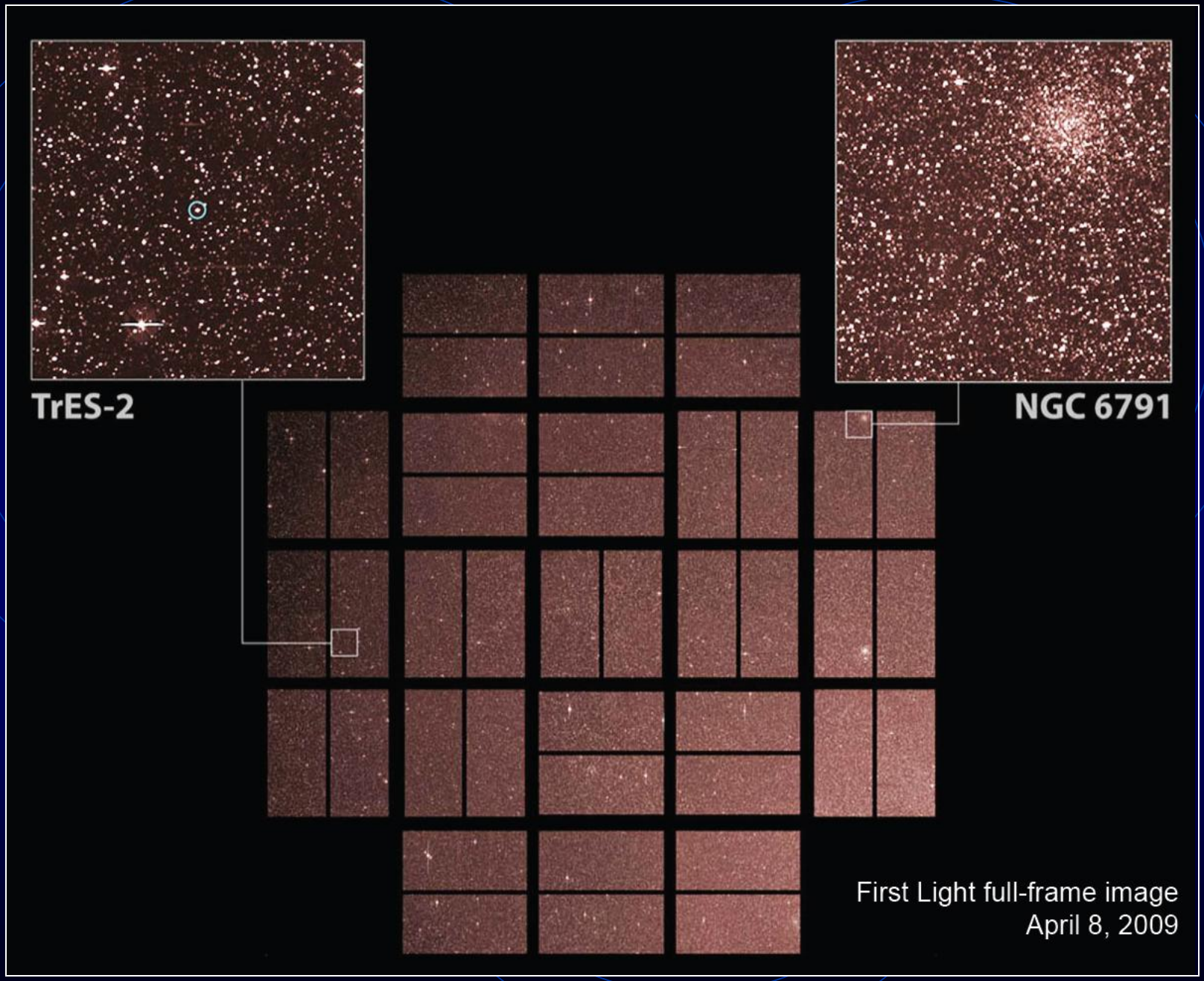



Kepler
Field of
View
Vega
LYRA
Albireo
AQUILA
Altair
Deneb
CYGNUS
DELPHINUS



Kepler Input Catalog

- *Kepler* observes from a pre-selected list of objects
- New Sloan *griz*+D51 photometry of ~13 million stars with KeplerCam; 2MASS JHK_s also available; overall precision ~ 0.02 mag
- Photometric estimates of $T_{\rm eff}$, log g, [Fe/H], and reddening for all stars
- Reliable dwarf/giant separation
- Giant stars and early-type stars are de-emphasized: mostly FGKM stars
- Final list of potential targets has ~170,000 stars


TrES-2
NGC 6791
First Light full-frame image
April 8, 2009




FIES on NOT 100"

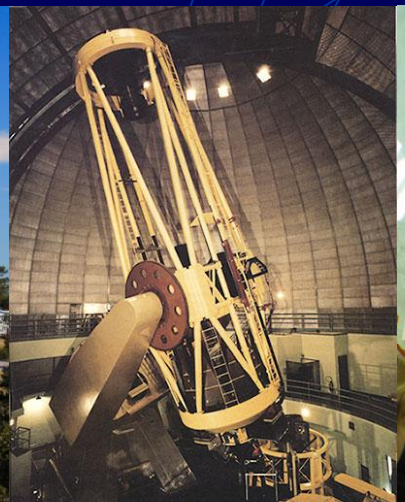
TRES on FLWO 60"

Reconnaissance Spectroscopy

For better classification of T_{eff}, log g, [Fe/H], v sin i, and for RV

Hamilton on Lick 120"

Coudé on McDonald 107"

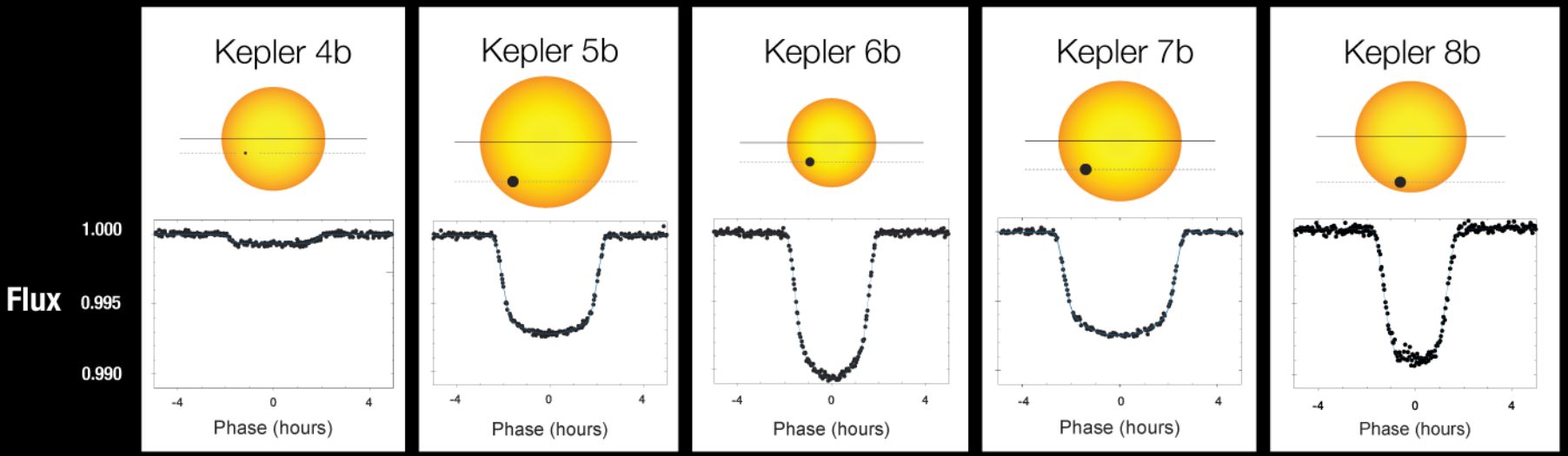
Validation of *Kepler* Candidates

- S/N ratio > 7 to rule out statistical fluctuations
- Three or more transits to confirm orbital periodicity
- Light curve depth, shape, and duration must be right
- Analysis of centroid motion to rule out blends
- Radial velocity measurements
  - Medium precision to rule out stellar companions
  - High precision to measure mass of super-Earths and giant planets
  - R-M effect to confirm orbiting planet, when possible
- High spatial resolution imaging (AO/speckle) to identify extremely close background stars; then look for variability of background stars
- Check for color-dependent transit depth (*Spitzer* observations)
- Model *Kepler* light curves directly as blends ("BLENDER")

Data Collection and First Discoveries

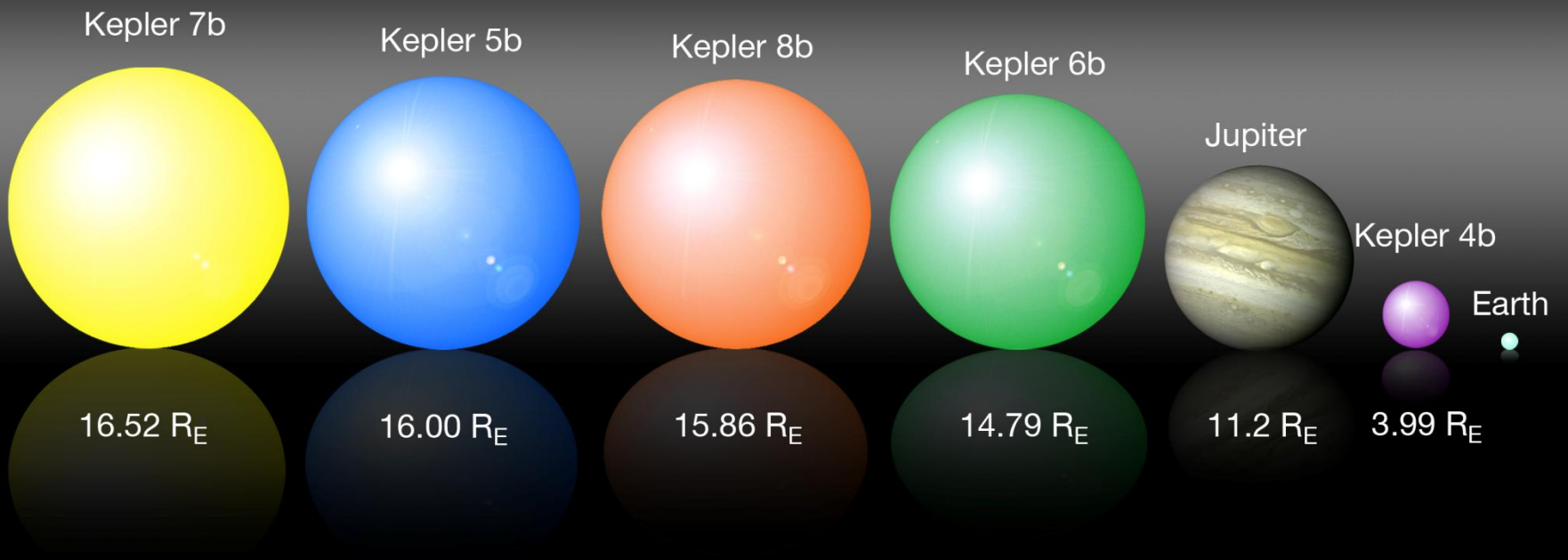
- Three transiting planets previously known in the *Kepler* field: TrES-2b, HAT-P-7b, HAT-P-11b
- Commissioning period = 9.7 days (Q0); only brightest 53,000 stars observed
- First (short) quarter = 33.5 days (Q1), 153,000 stars observed. Subsequent quarters of 90 days
- Five Jupiter- and Neptune-size planets discovered in Q0+Q1: Kepler-4b to Kepler-8b; many more candidates found but not yet confirmed

Transit Light Curves

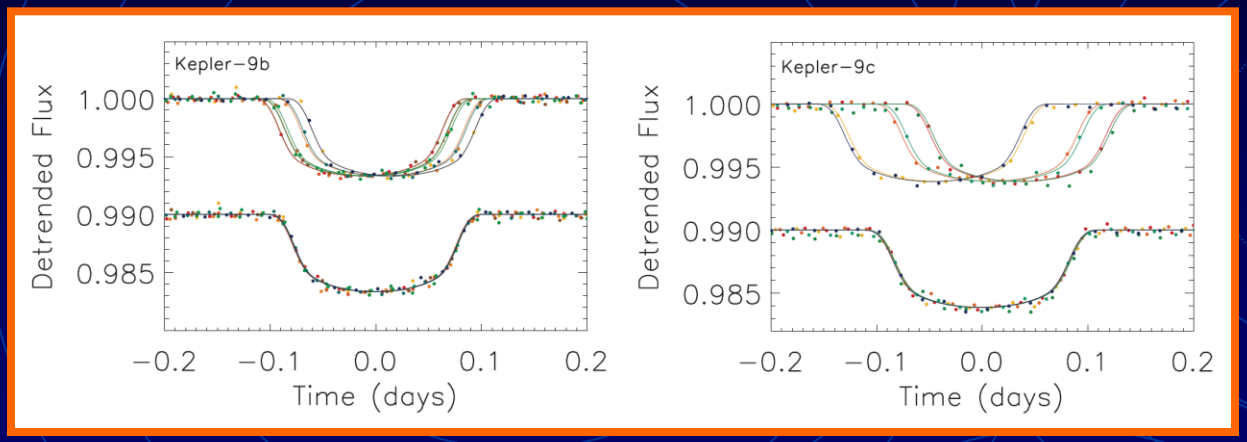


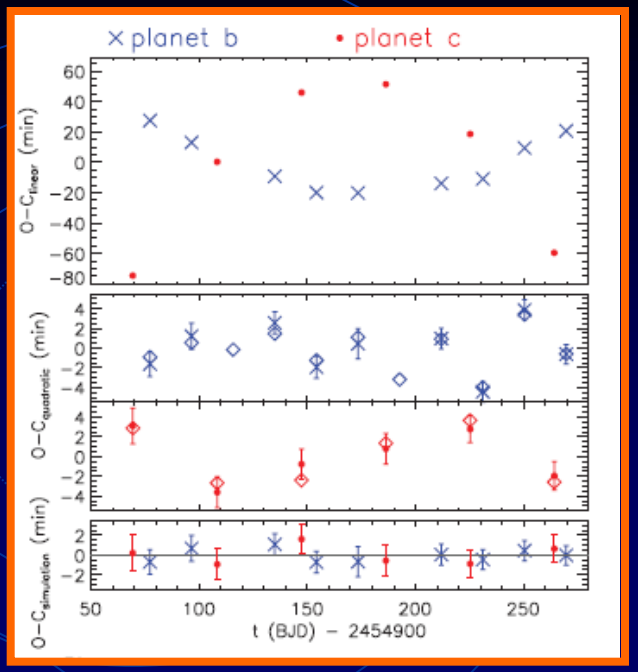
Orbital Period (days)	3.2 days	3.5 days	3.2 days	4.9 days	3.5 days

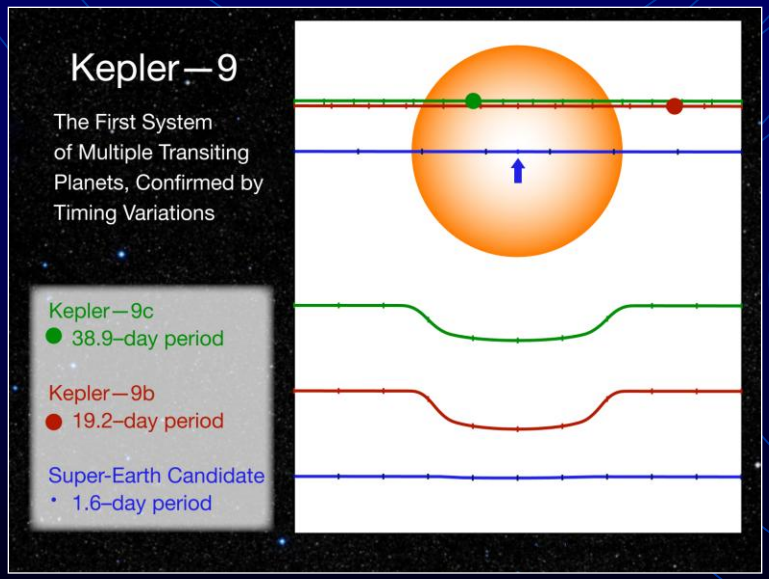
Planet Size

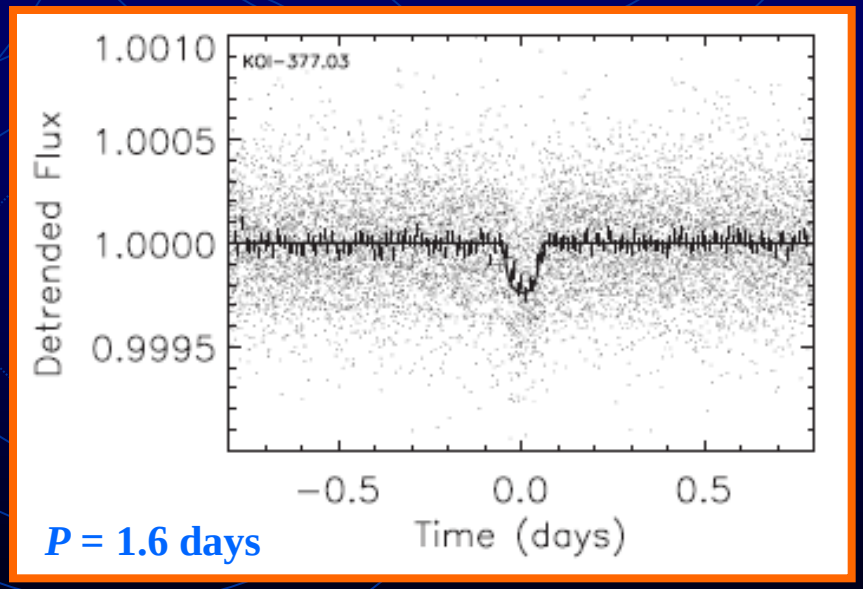

Kepler 7b
Kepler 5b
Kepler 8b
Kepler 6b
Jupiter
Kepler 4b
Earth
16.52 R_E
16.00 R_E
15.86 R_E
14.79 R_E
11.2 R_E
3.99 R_E

Kepler-9: Transit Timing Variations

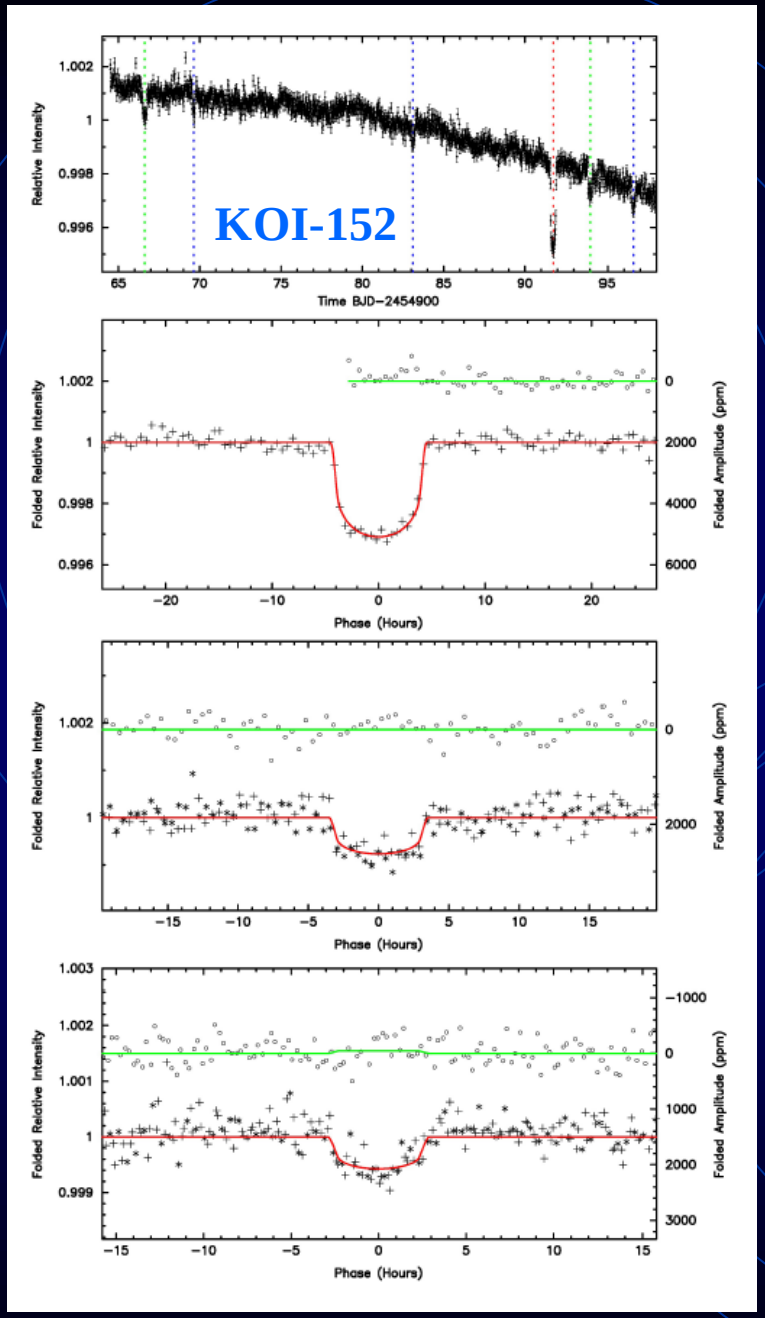


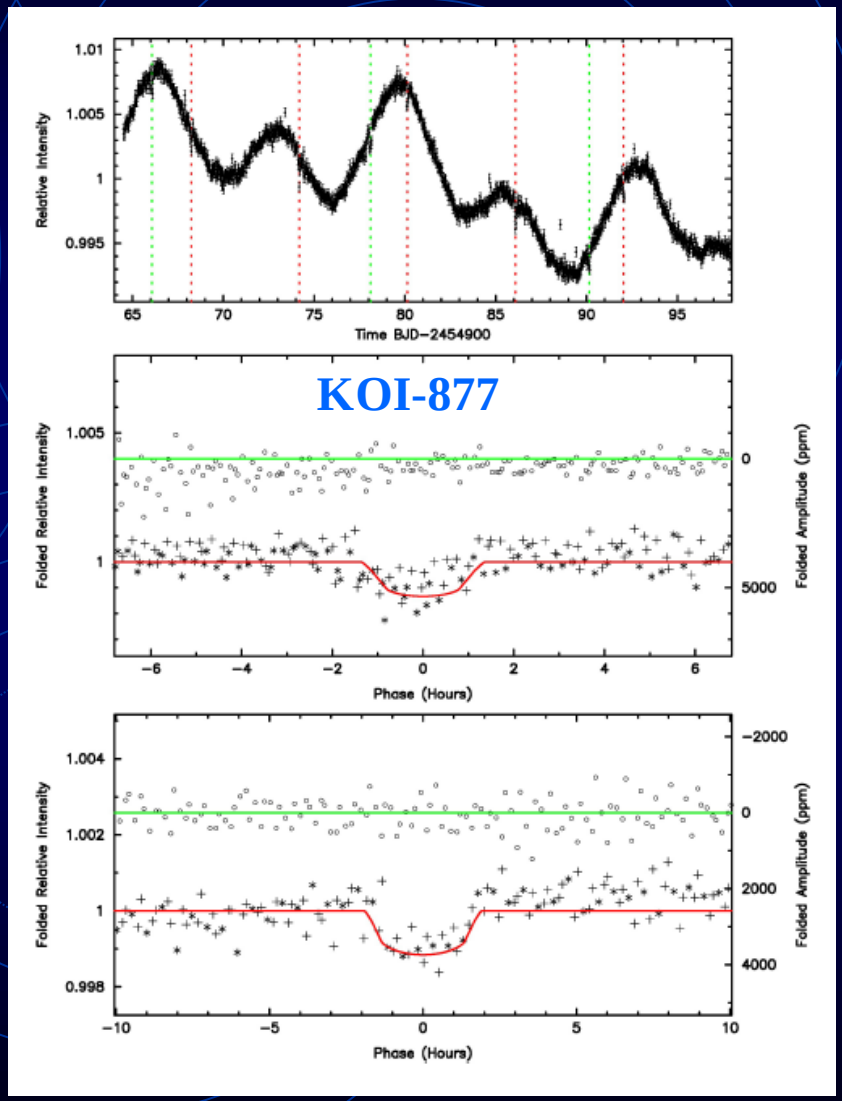




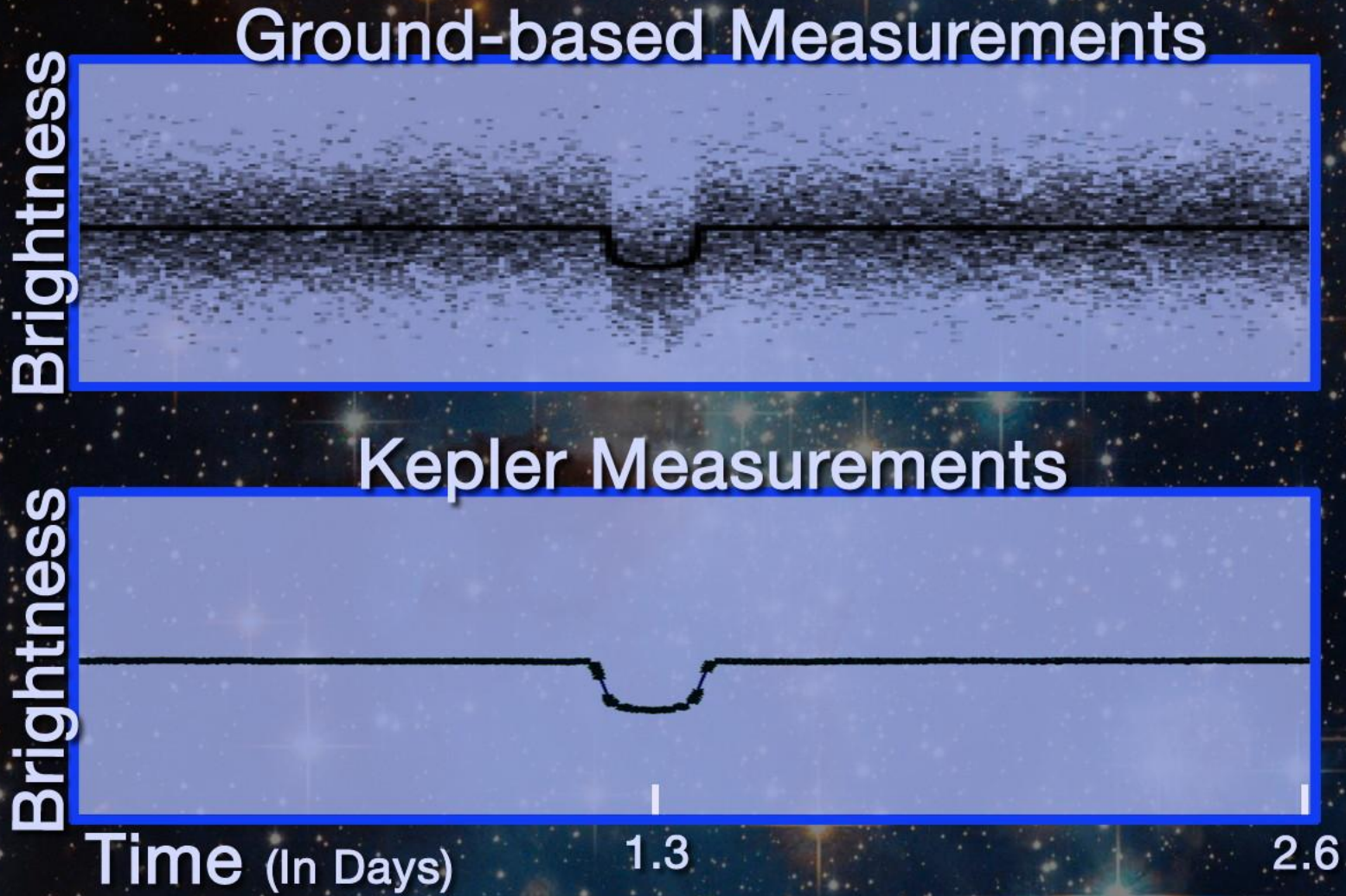


Multiple Transiting Exoplanet Candidates (Steffen et al. 2010)

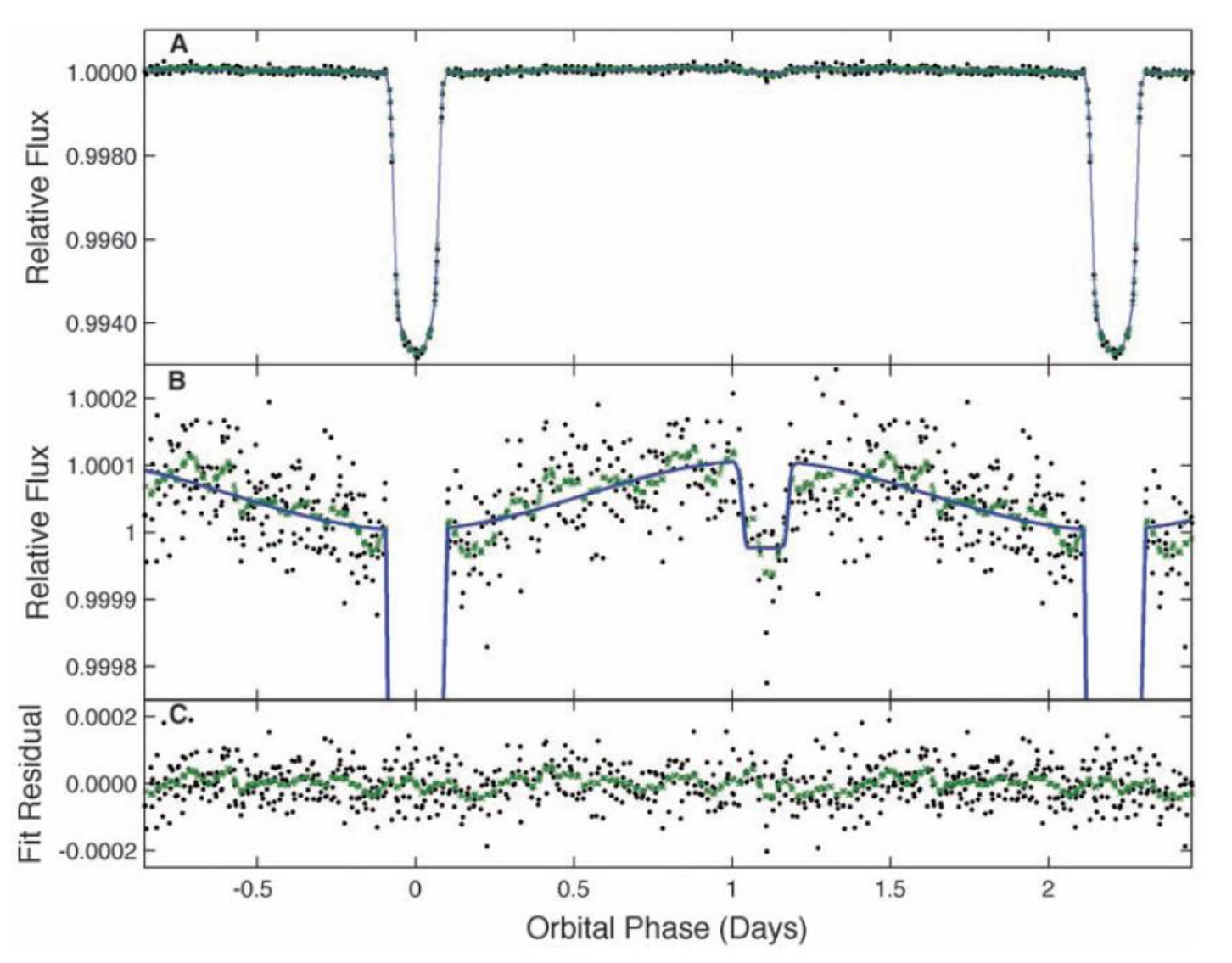




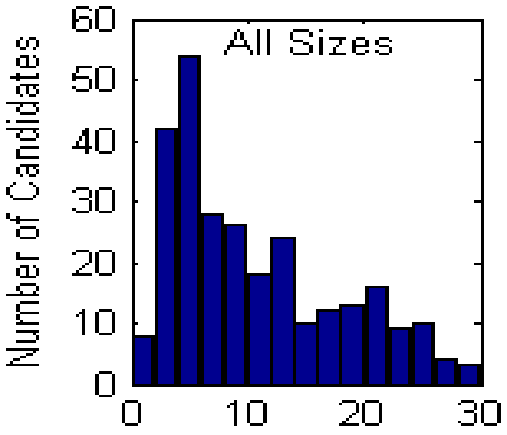
HAT-P-7 Light Curves

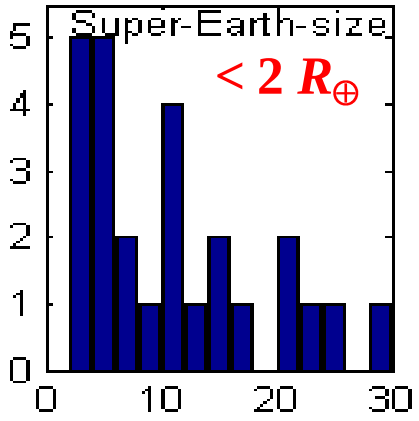


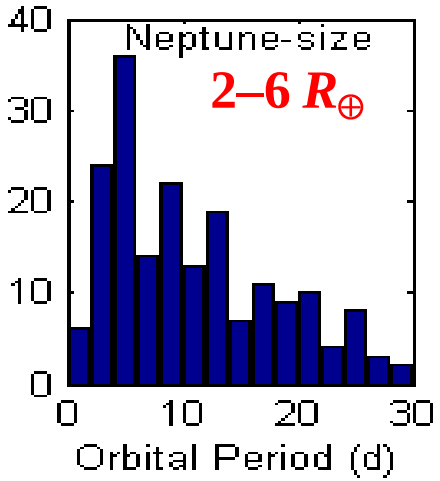
HAT-P-7b: Phase Function and Occultation

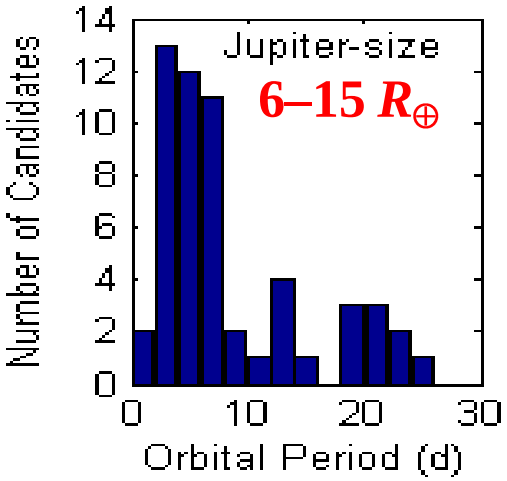


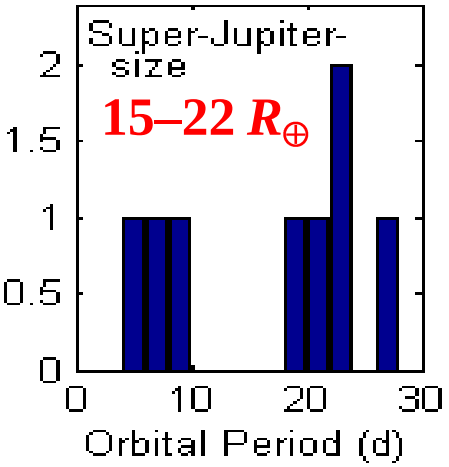
Statistics of Planet Candidate Sizes







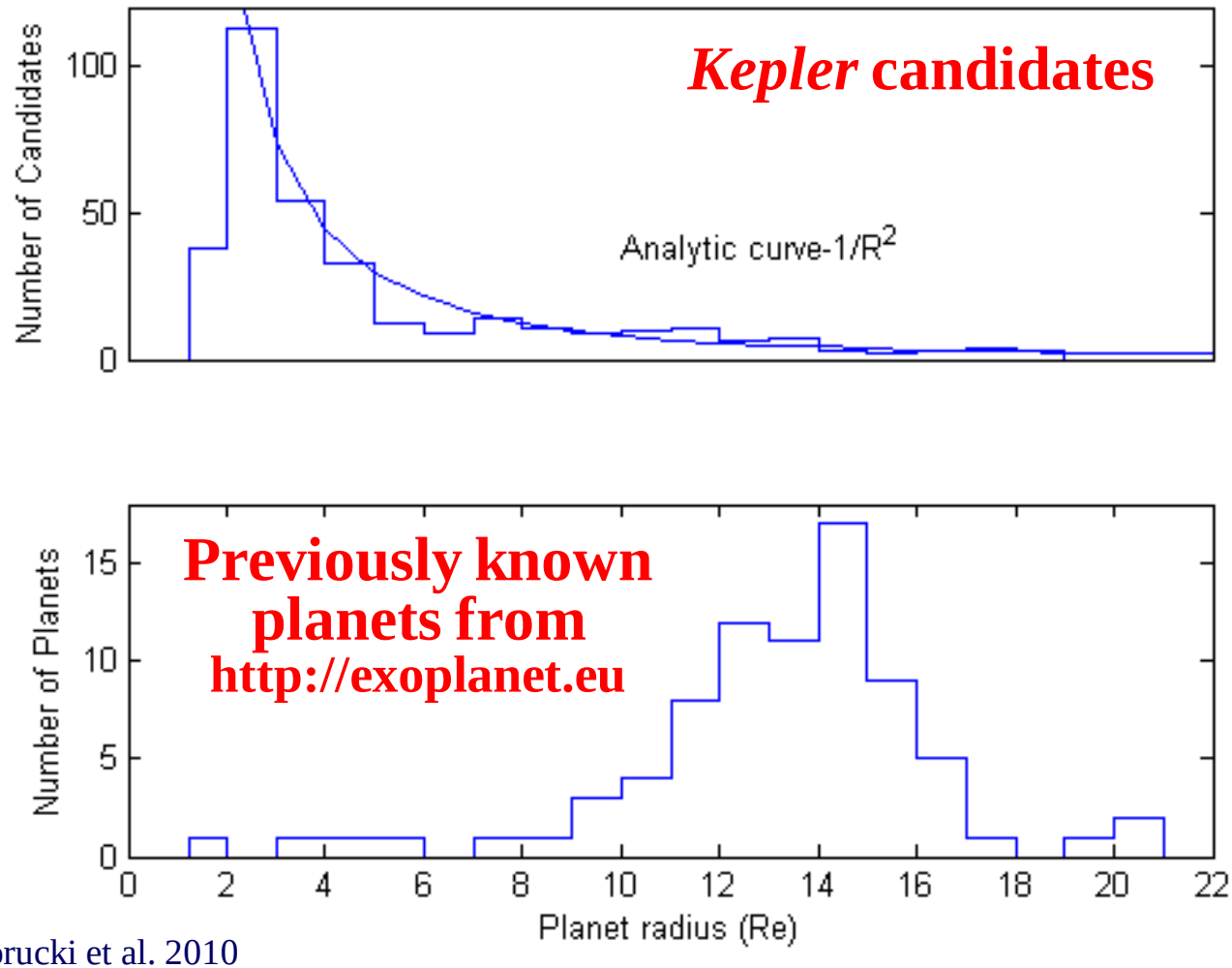




First *Kepler* data release: June 15, 2010 (Borucki et al. 2010)

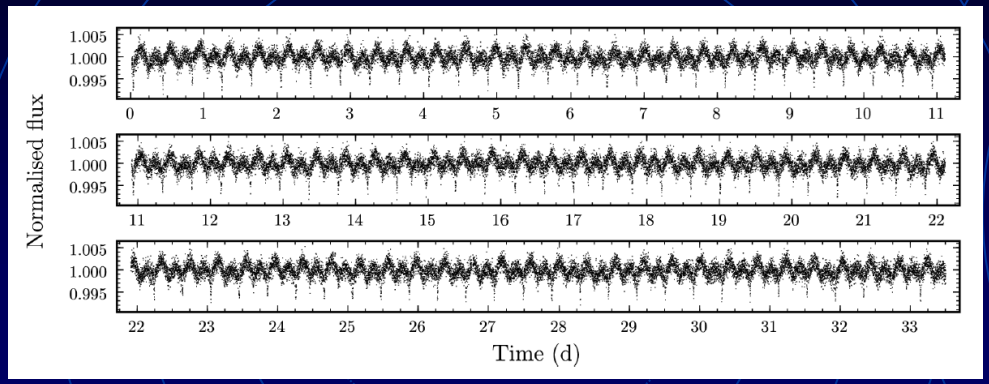
306 transiting planet candidates

Statistics of Sizes



Borucki et al. 2010

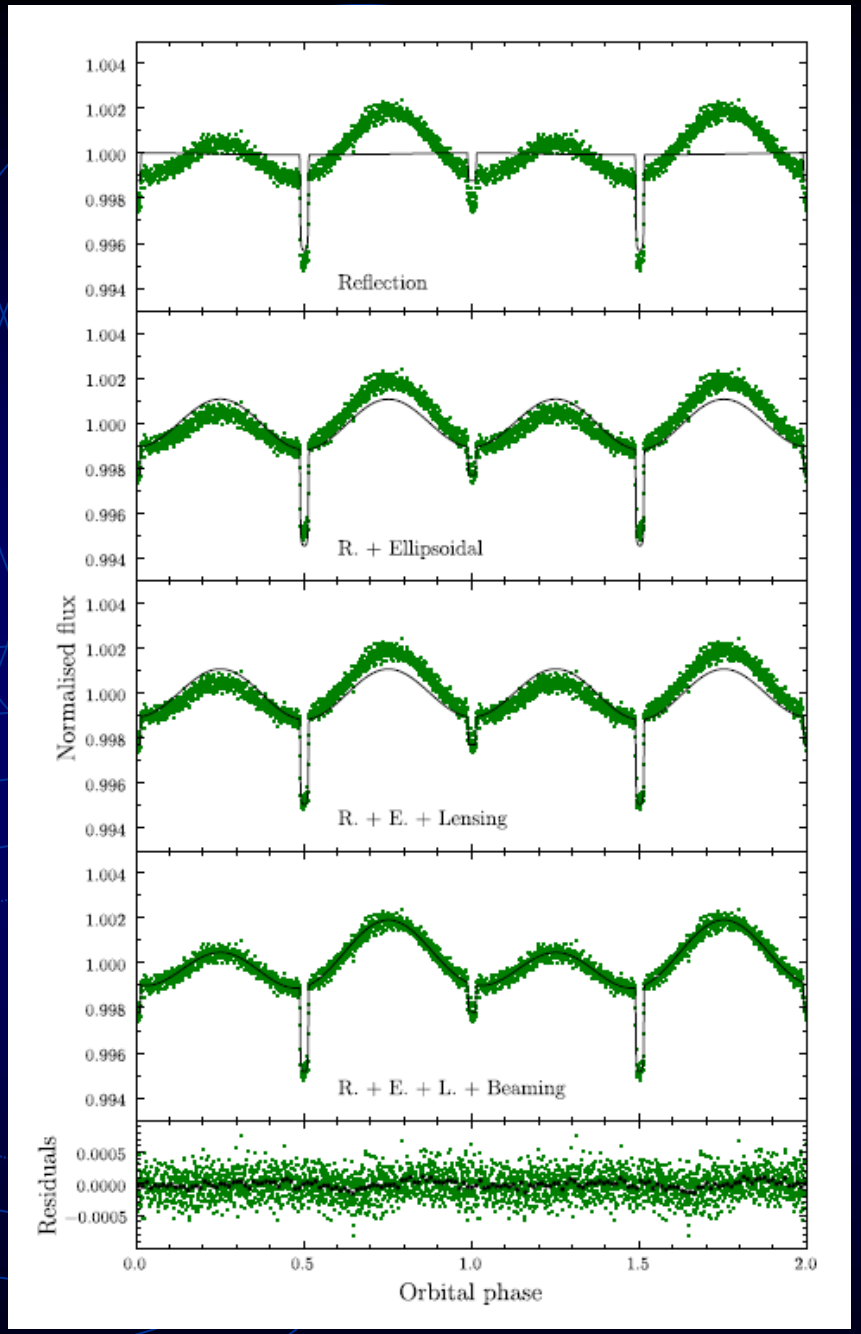
“Special Effects”



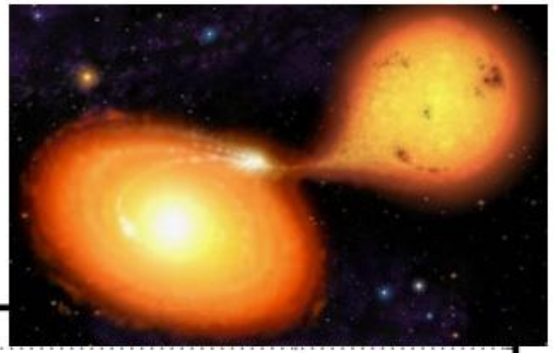
Kepler observations of the beaming binary KPD 1946+4340 (Bloemen et al. 2010)

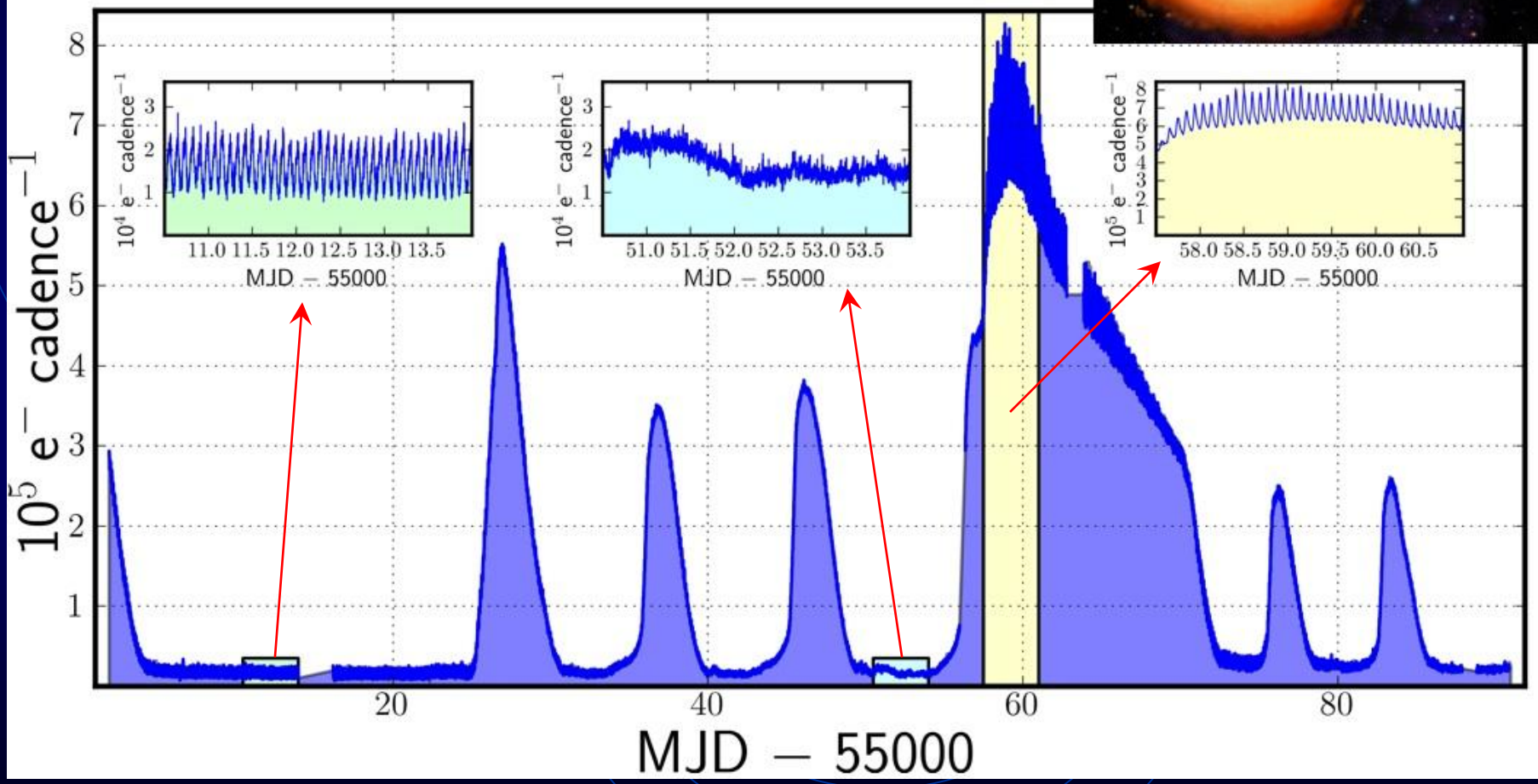
Eclipsing sdB+WD, P = 0.404 days

Doppler beaming is caused by the stars’ RV shifting the spectrum, modulating the photon emission rate and beaming the light somewhat in the direction of motion



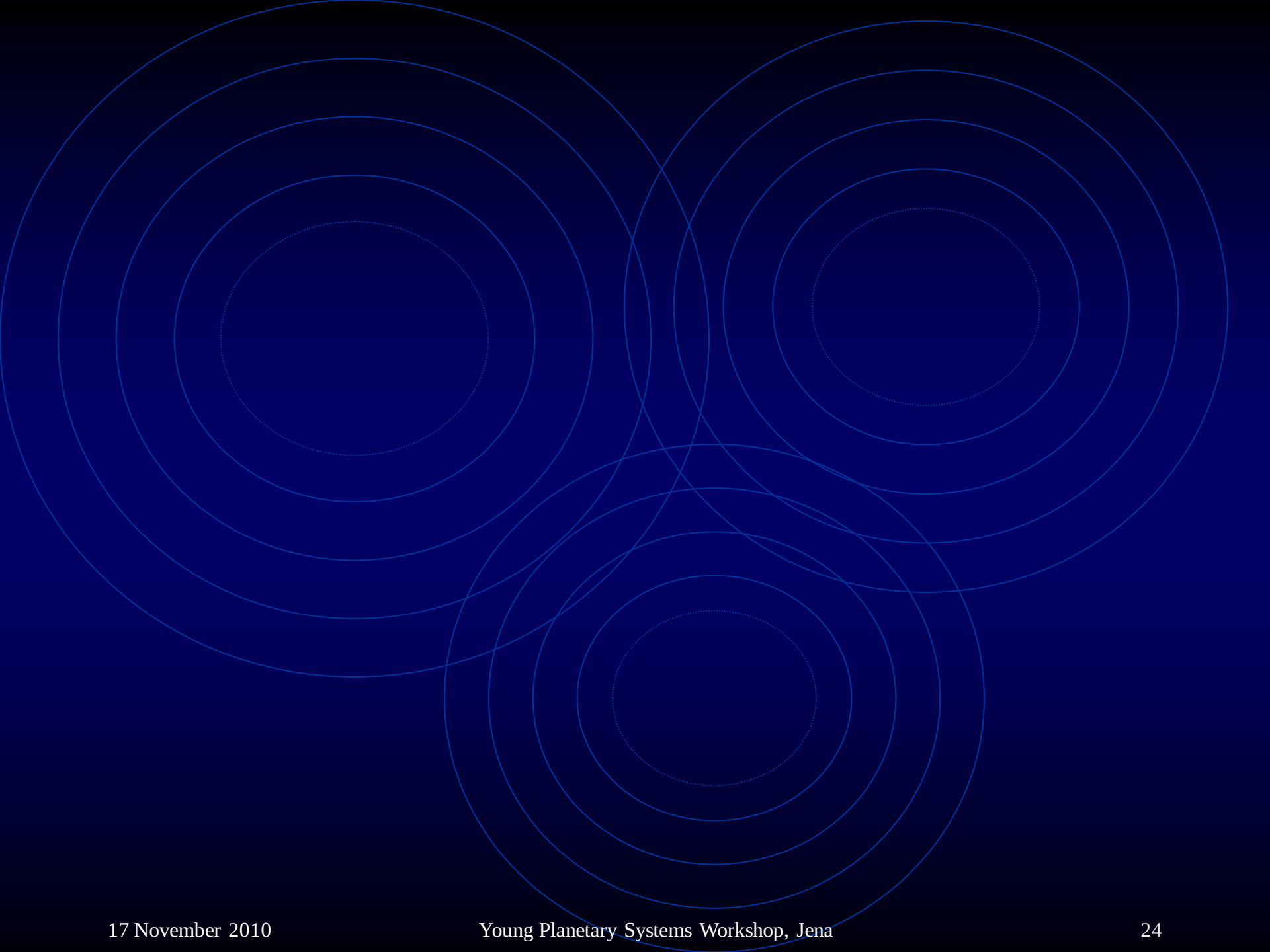
EXAMPLE: V344 LYR (DWARF NOVA)

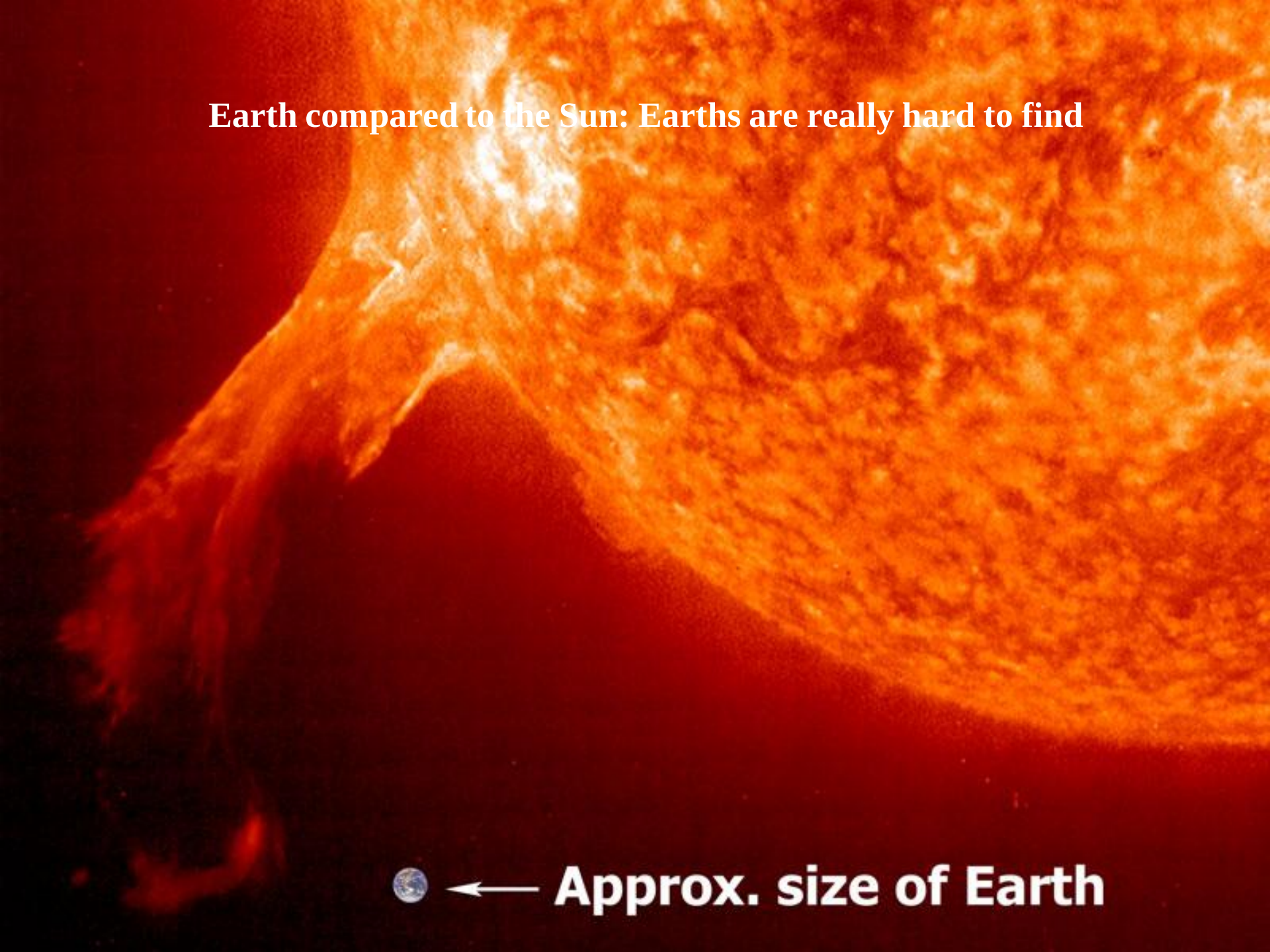




Final Remarks

- *Kepler* is on track to answer the key question of the frequency of Earth-size planets in the habitable zone of Sun-like stars
- Many planet candidates; bottleneck is the follow-up
- Expect amazing discoveries soon
- Lots of secondary science: stellar sizes and masses (binaries), stellar age and rotation rate (open clusters), stellar activity cycles, asteroseismology, star spots, flare stars, AGN
- New data release (Q2) scheduled for February 2011
- Guest Observer Program (Cycle 3 deadline is 2010 December 17th) for non-planet related investigations




Earth compared to the Sun: Earths are really hard to find
Approx. size of Earth