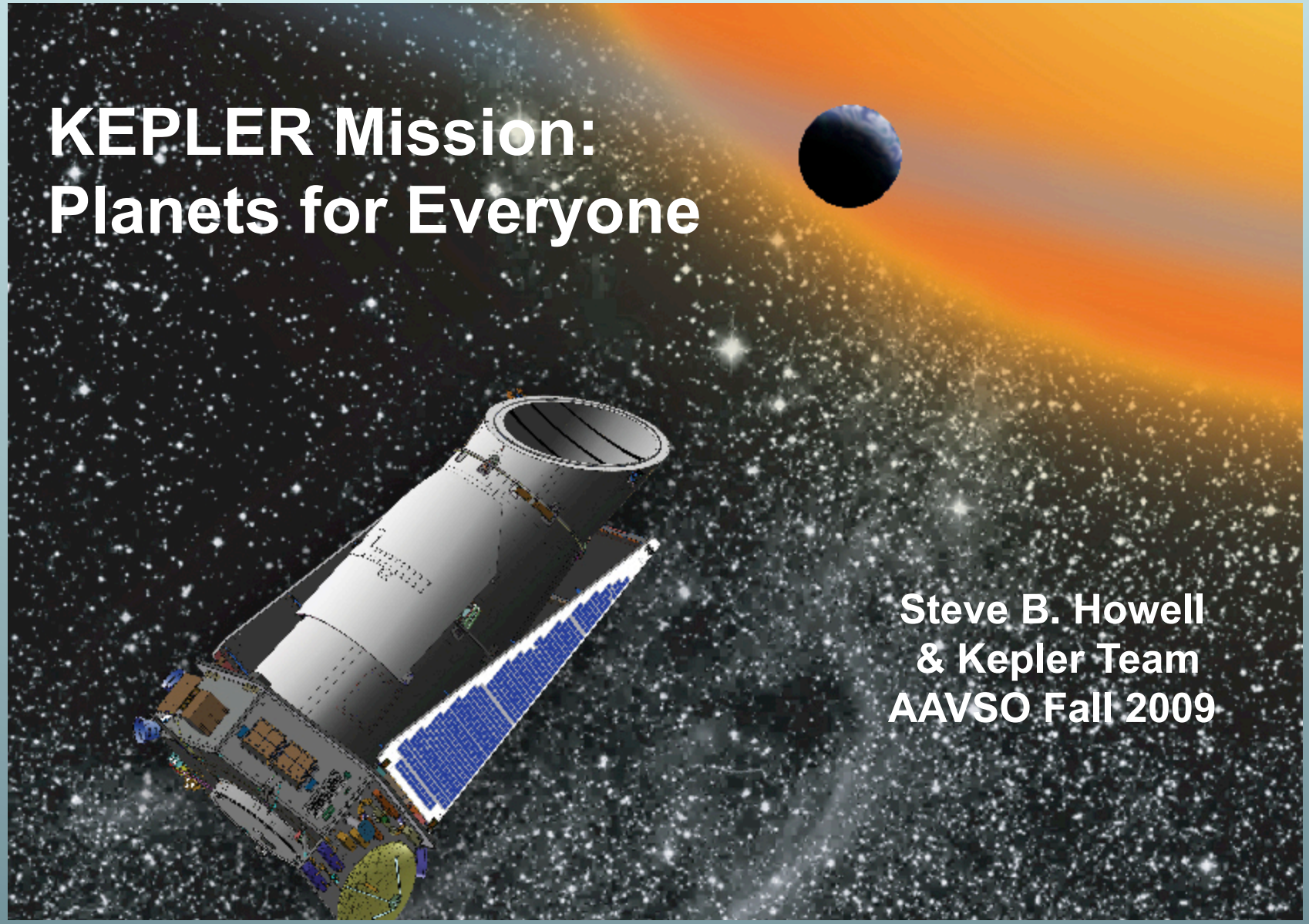


A Search for Earth-size Planets

Kepler Mission

Kepler
A Search for Earth-size Planets

The Kepler space telescope's primary goal is to use transit photometry to detect exo-planets like Earth:
Rocky and in the Habitable Zone of a solar-like star.

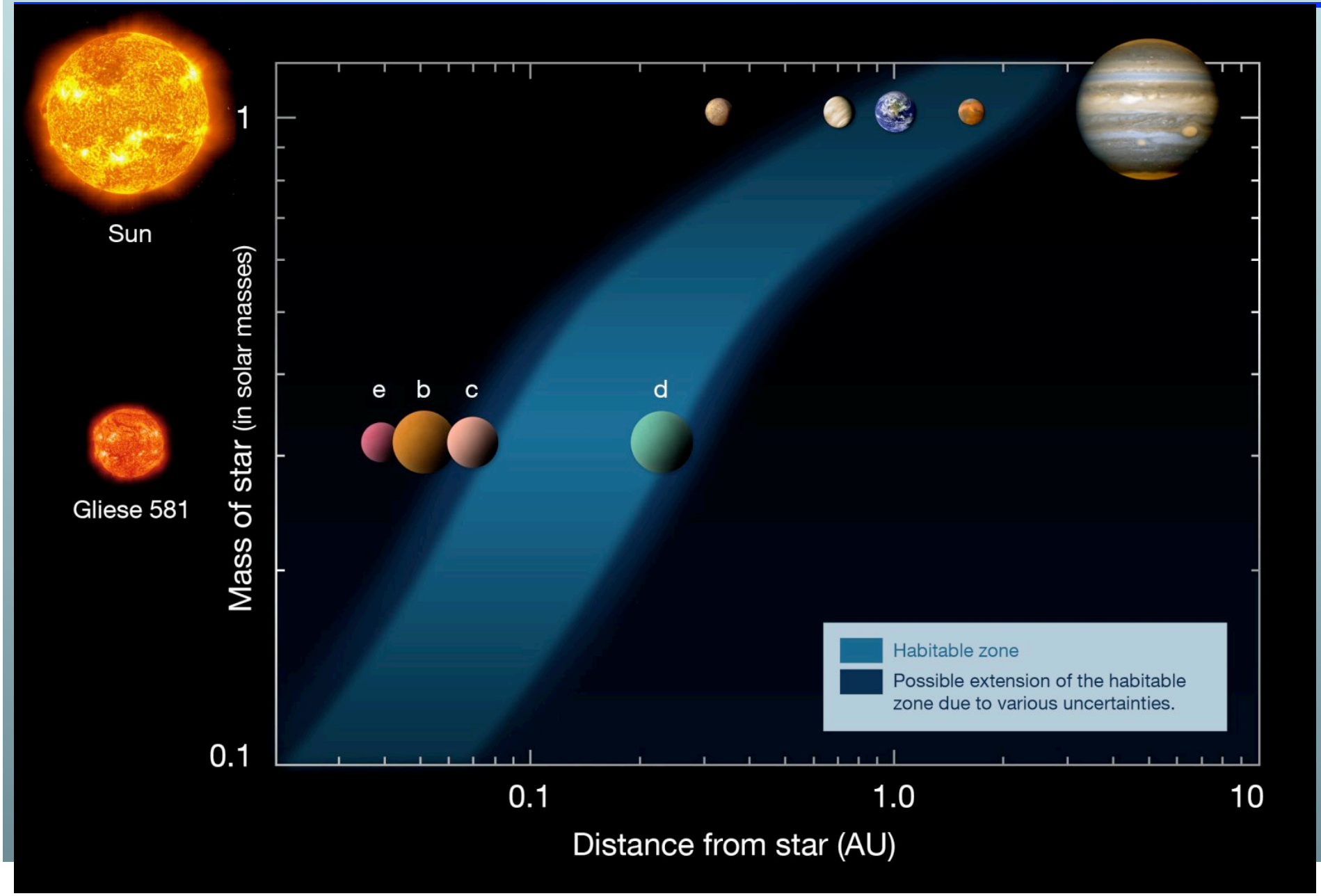
This mission is of great significance to our understanding of the universe and our place in it.

Kepler will obtain a statistically valid result by monitoring > 100,000 stars within a 100 sq. deg region of the sky.

The Habitable Zone

Mayor et al., 2009

Kepler
A Search for Earth-size Planets



EXTRA-SOLAR PLANETS – A Review

Kepler
A Search for Earth-size Planets

What is an Exo-planet?

A planet that orbits a star other than our Sun.

The upper planet mass –the planet-star (brown dwarf) boundary - is fuzzy, but roughly a body orbiting a star with a mass ~13-15 Jupiter masses or less is considered a planet.

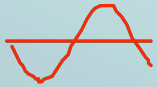
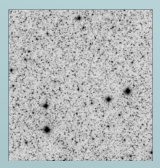
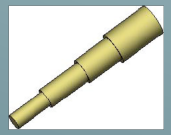
Late-type red dwarfs, brown dwarfs, and Jupiters are all ~equal in radius

What is a Pirates Favorite Planet?

MARRRRRRRRRRRRRRs!

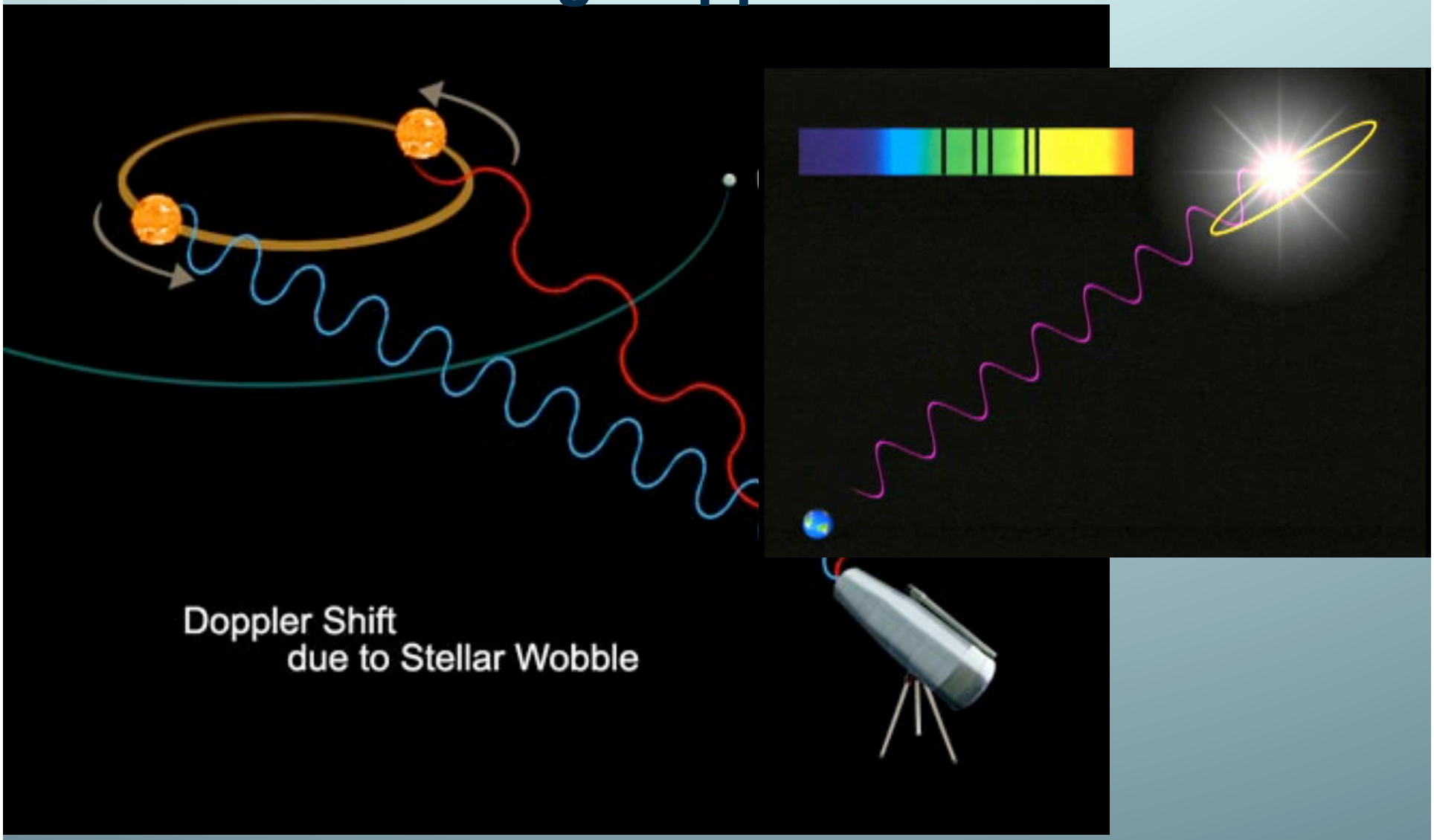
TECHNIQUES FOR FINDING EXO-PLANETS

Kepler
A Search for Earth-size Planets

Method	Yield	Mass Limit	Status
 Pulsar Timing	m/M ; τ	Lunar	Successful
 Radial Velocity	$m \sin i$; τ	Uranus	Successful
 Astrometry	m ; τ ; D_S ; a		
Ground: Telescope		Jupiter	Ongoing
Ground: Interferometer		<Jupiter	In development
Space: Interferometer		Uranus	Planned
 Transit Photometry	A ; τ ; $\sin i=1$		
Ground		Saturn	HD209458, OGLE TR-56?
Space		Earth	CoRoT, Kepler
 Reflection Photometry:	*albedo*A* ; τ		
Space		Saturn	Planned *Kepler*
 Microlensing:	f(m,M,r,D_S,D_L)		
Ground		sub-Uranus	On-going
 Direct Imaging	*albedo*A* ; τ ; D_S ; a ; M		
Ground		Saturn	Being studied
Space		Earth	Being studied?

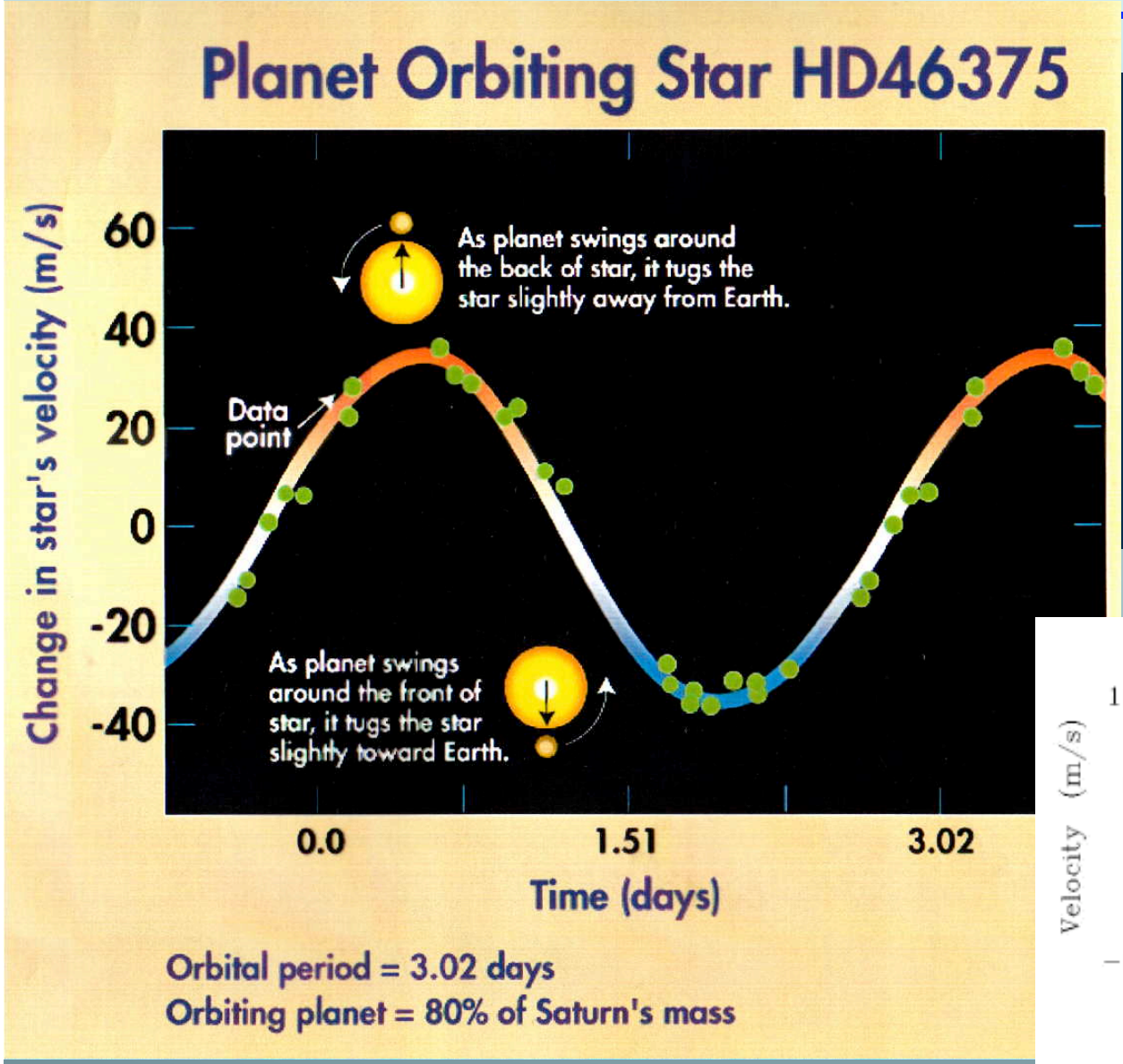
How to Detect Planets using Doppler Shift

Kepler
A Search for Earth-size Planets

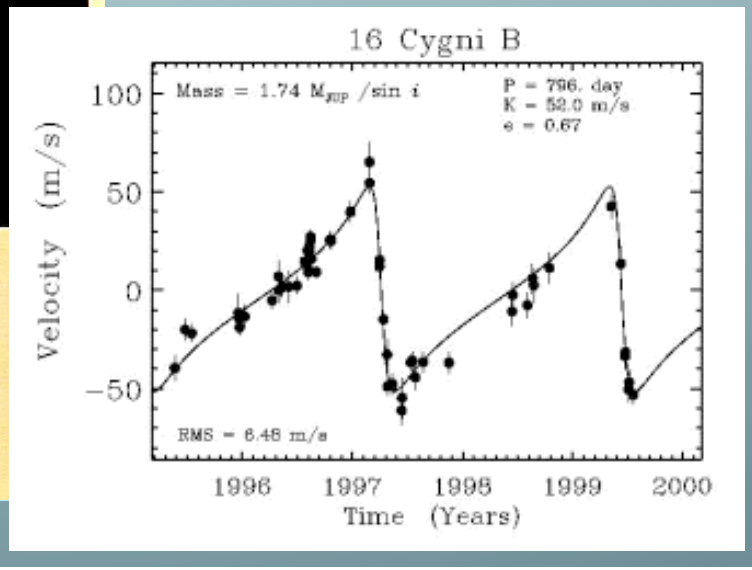


Doppler shift planet discovery

Kepler
A Search for Earth-size Planets

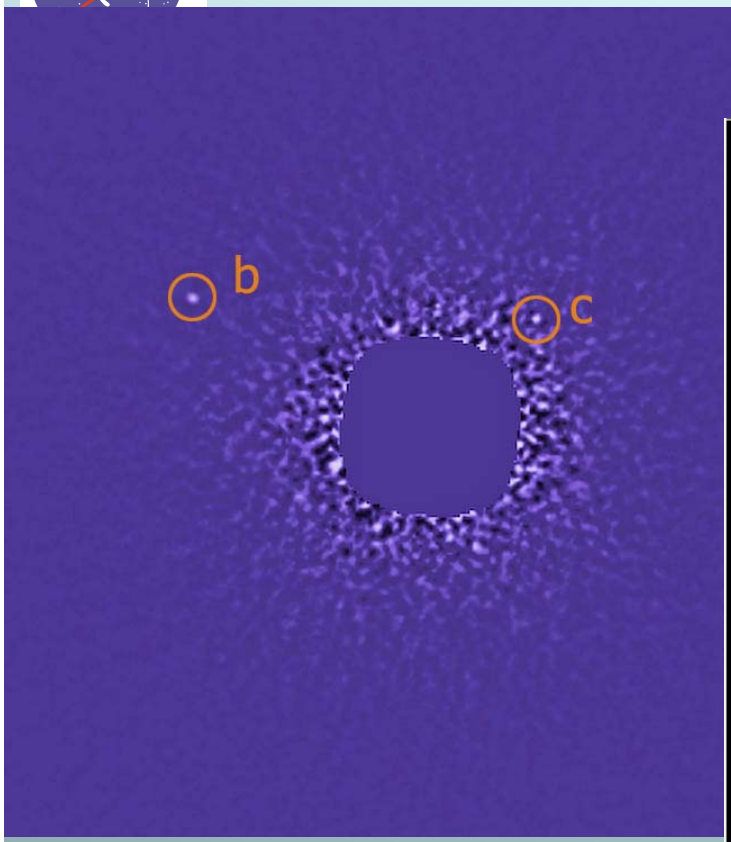


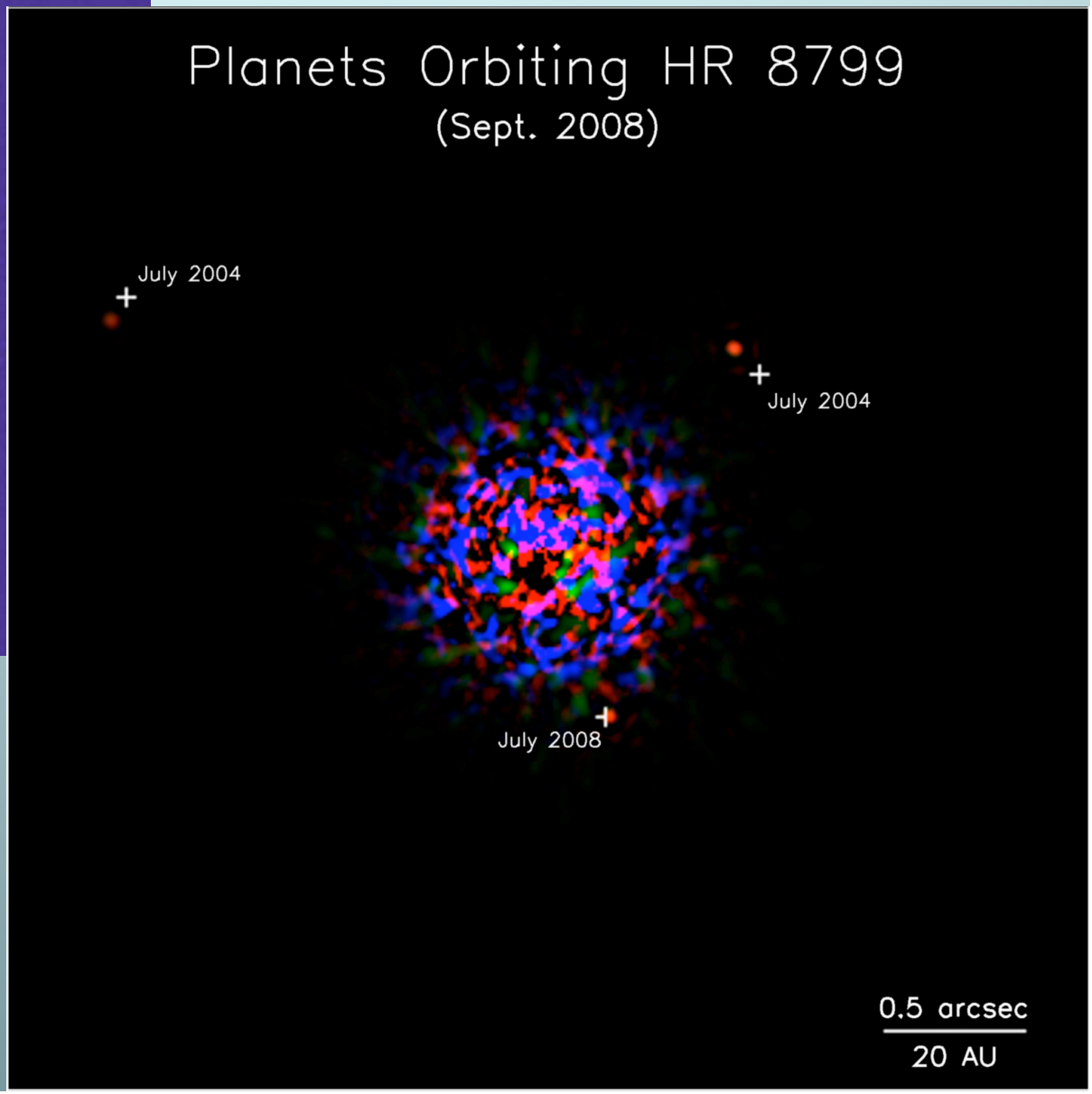
The "wobble" method gets the orbital period, semi-major axis, and a lower limit on the mass of the planet. RVs have detected down to 7 Earth-mass planets very close in, (but favors gas giant planets).



Direct Imaging !

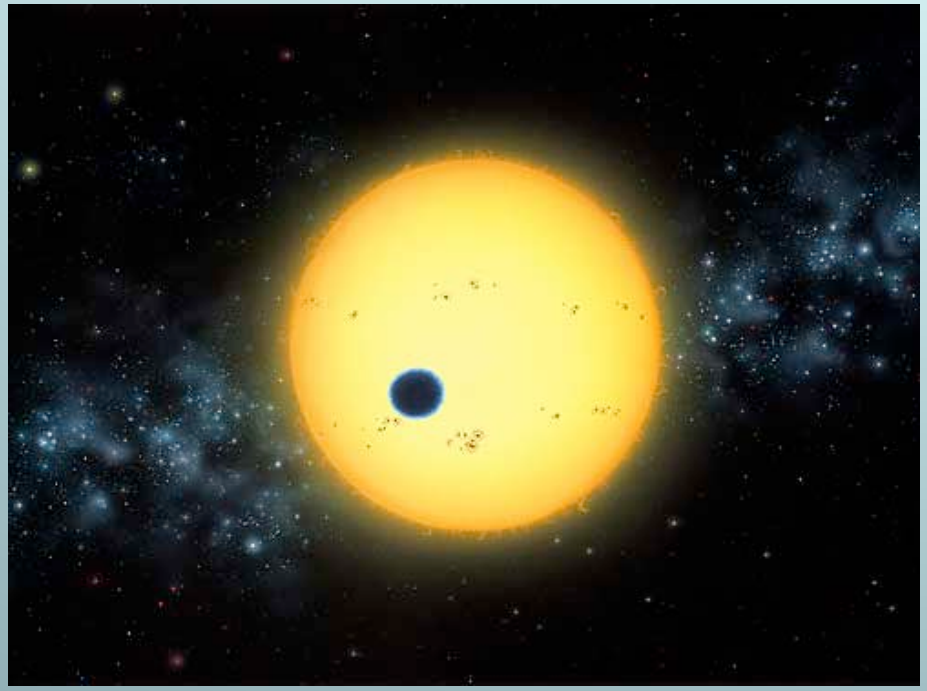
Kepler
A Search for Earth-size Planets

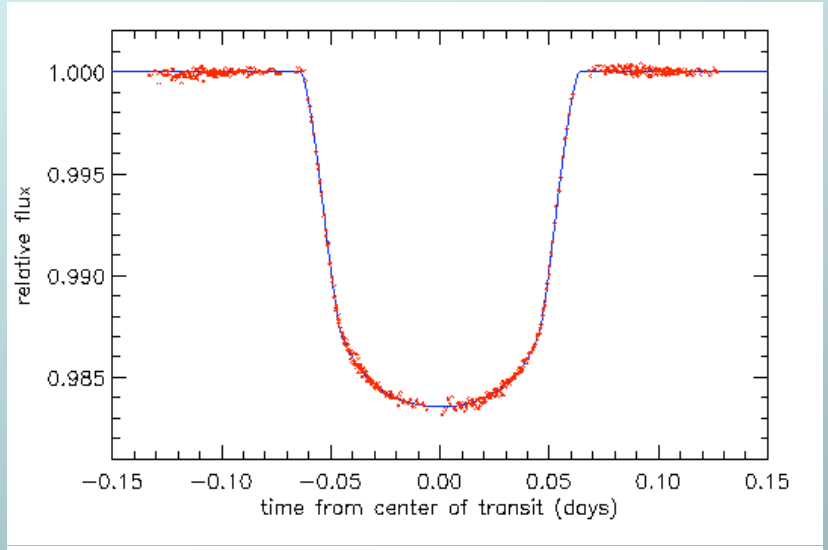




Kepler will use the Transit Method

Kepler
A Search for Earth-size Planets





HST measurement of HD209458

Transits tell us: Planet radius, orbit size, & density

Likelihood of transit is governed by orbital plane geometry. About 10% for very close-in large planets while only ~0.5% for true-Earth analogs. Short orbital periods and larger planets are favored.

CURRENT EXO-PLANET SURVEYS

Kepler
A Search for Earth-size Planets

- 82 Ground-based exo-planet surveys are underway
  - Doppler, transit, imaging, astrometry
- 21 space missions: 5 are current, remaining planned
  - Current dedicated missions use transits
- Dedicated Planet Missions w/ ability to find Earths

CoRoT (CNES)

Kepler (NASA)

- Useful Planet Finders/Follow-up Missions

MOST (Canada)

HST (photometry, astrometry)

Spitzer Space telescope (thermal imaging)

EXTRA-SOLAR PLANETS

Kepler
A Search for Earth-size Planets

What have we found so far? (Pre-Kepler, November 1, 2009)

Radial velocity or astrometry

320 planetary systems 376 planets 38 multiple planets

Transiting planets

62 planetary systems 62 planets 3 multiple planets

Candidates detected by microlensing

8 planetary systems 9 planets 1 multiple planet

Candidates detected by imaging

9 planetary systems 11 planets 1 multiple planet

Candidates detected by timing

4 planetary systems 7 planets 2 multiple planets

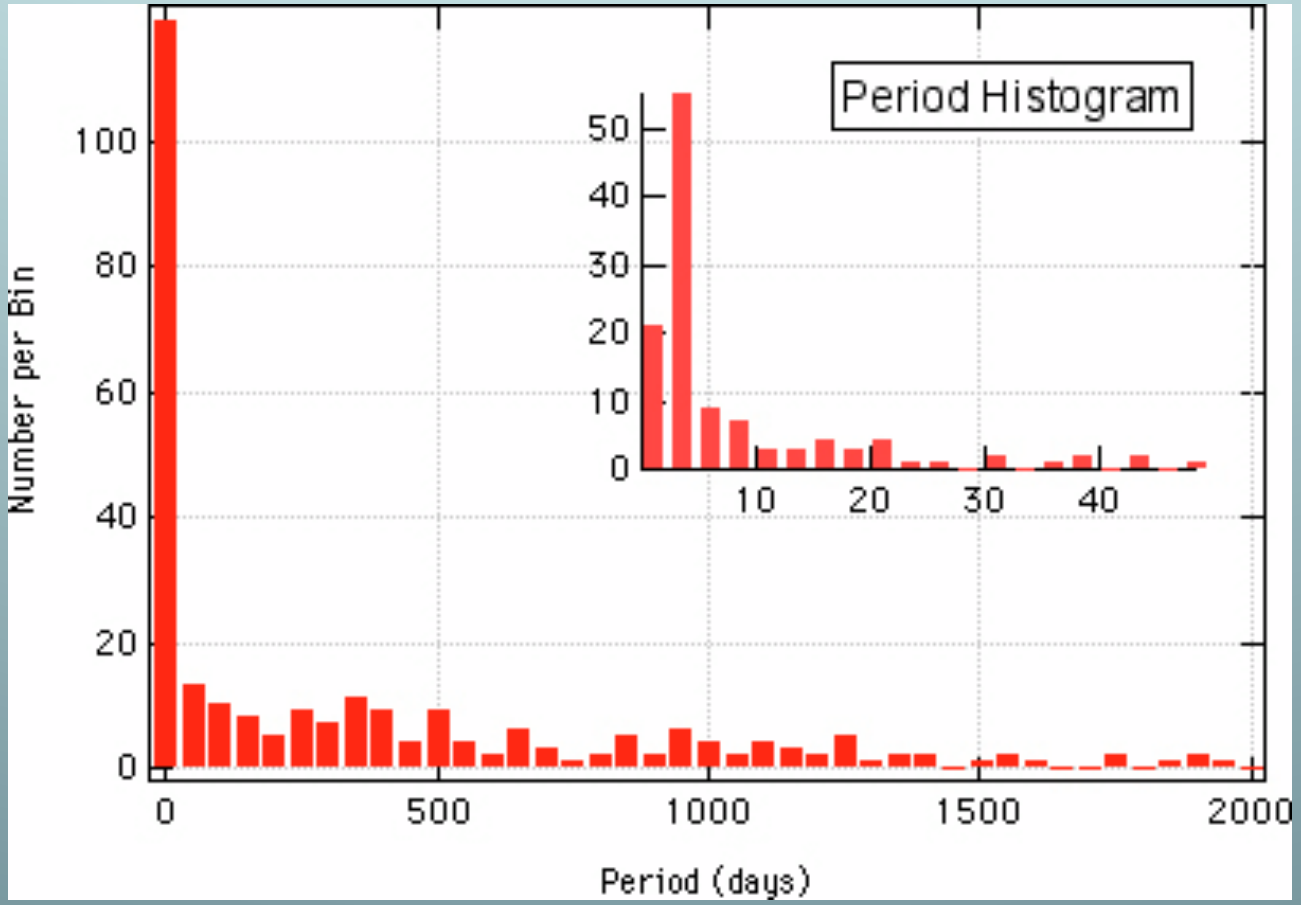
403 Total Exo-planets

EXTRA-SOLAR PLANETS

Kepler
A Search for Earth-size Planets

Characteristics:

Orbital Period (days) vs. Number of known Exo-Planets

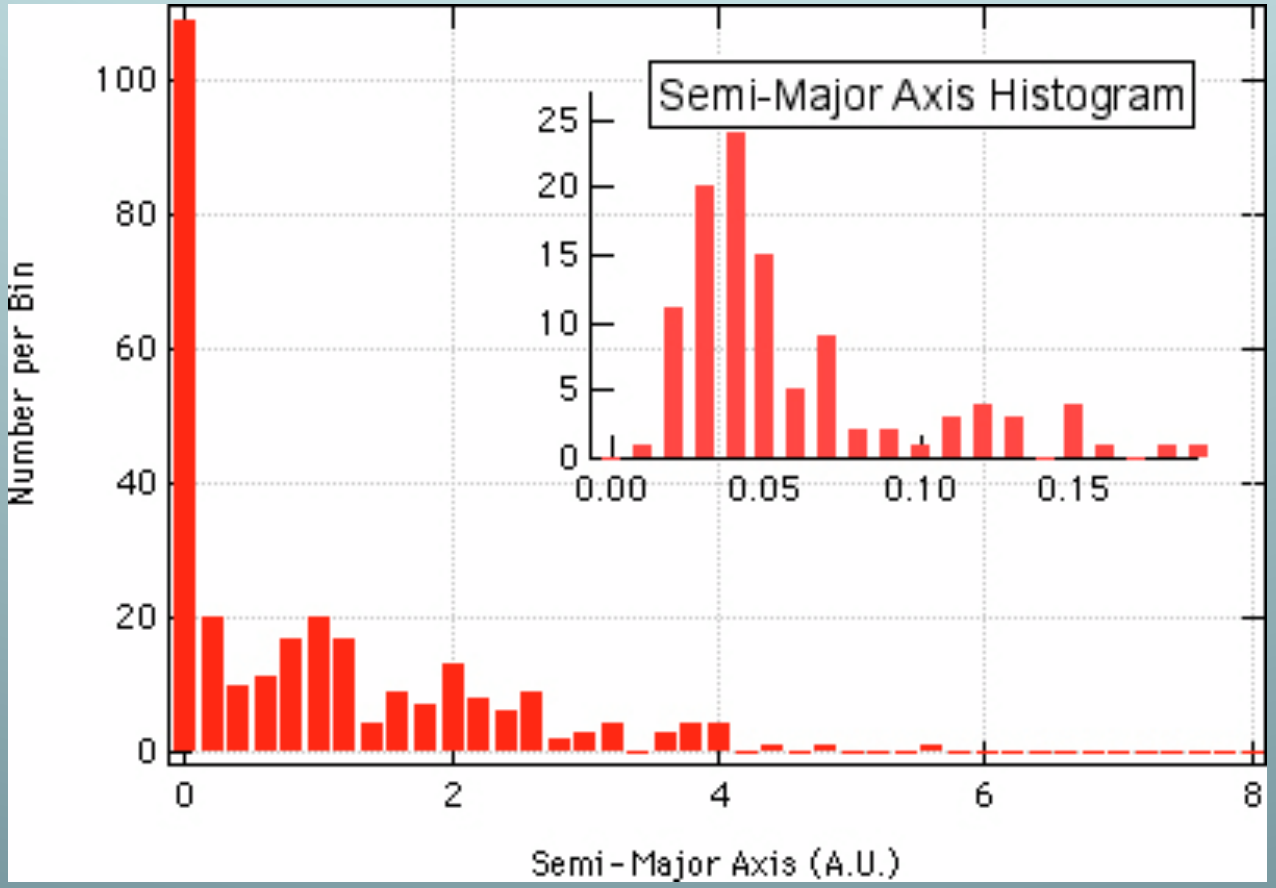


EXTRA-SOLAR PLANETS

Kepler
A Search for Earth-size Planets

Characteristics:

Semi-Major Axis (AU) vs. Number of known Exo-Planets

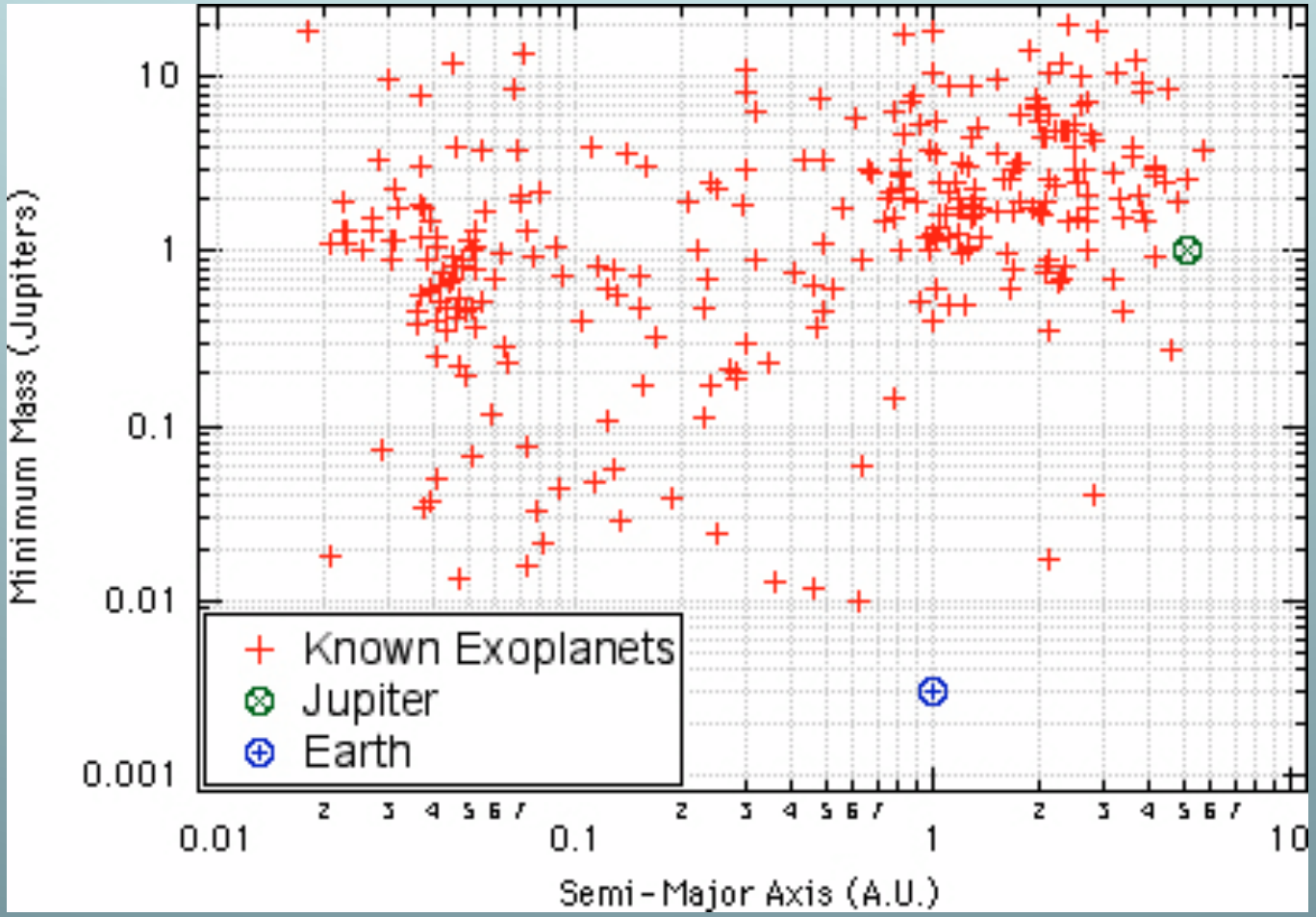


EXTRA-SOLAR PLANETS

Kepler
A Search for Earth-size Planets

Characteristics:

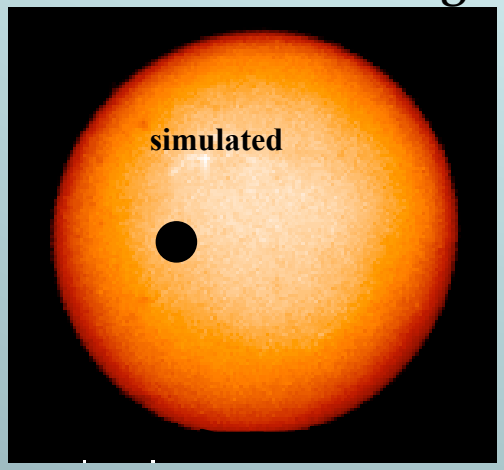
Mass vs. Semi-Major axis



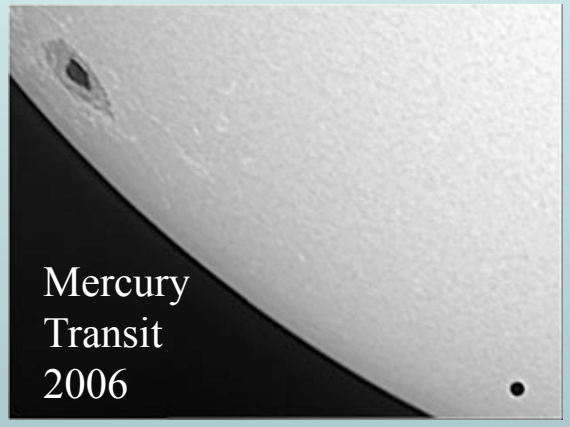
How to Detect Earth-Size Planets

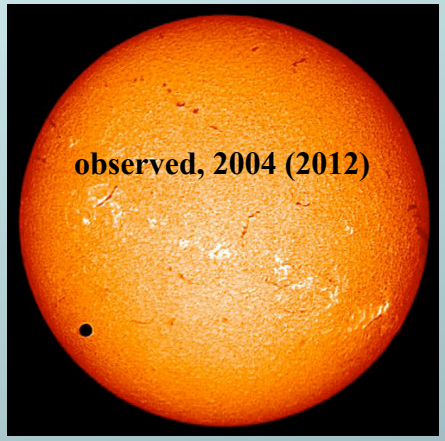
Kepler
A Search for Earth-size Planets

- The relative change in brightness is equal to the area ratio: A_{planet}/A_{star}



Jupiter:
1% area of the Sun (1/100)





Earth or Venus
0.01% area of the Sun (1/10,000)

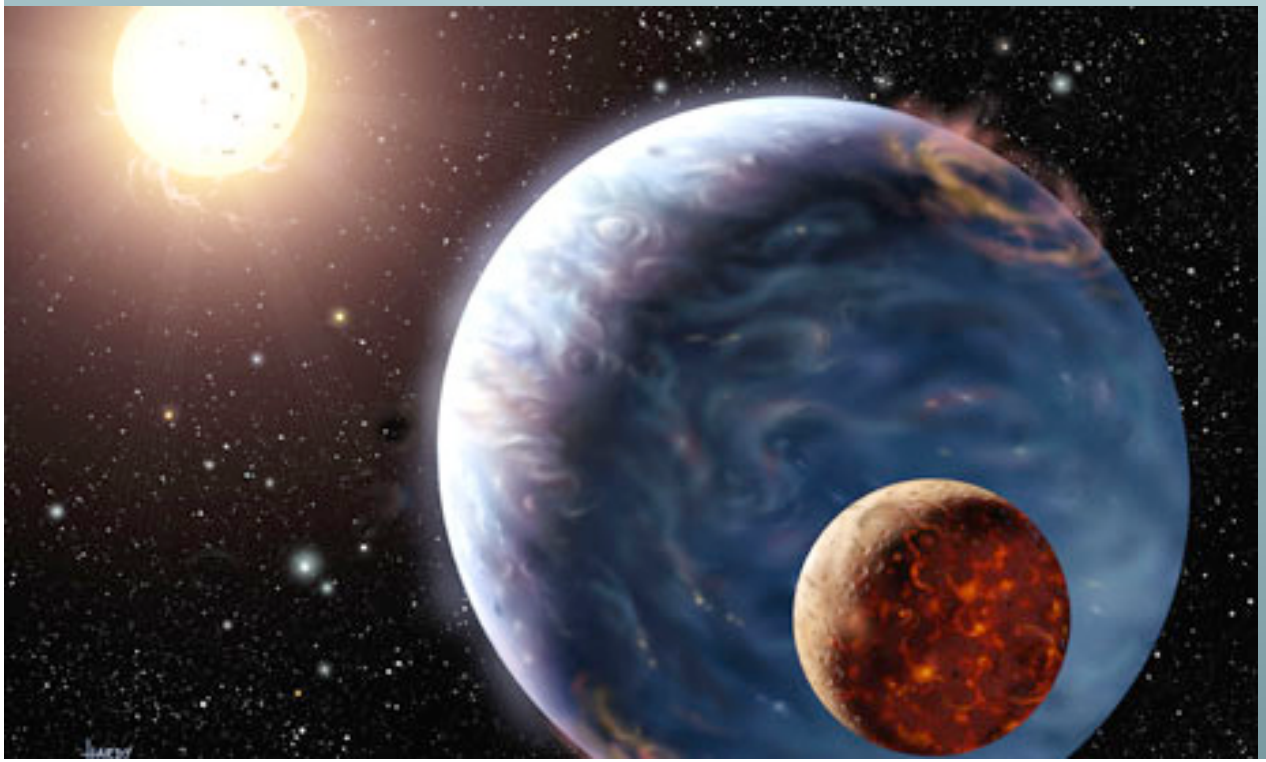
- To measure 0.01% must get above the Earth's atmosphere
- Allows continuous observation (no pesky Sun getting in the way, no Weather issues)
- Patience required:

  Must observe 3+ transits, with same brightness drop, duration and period: near 3 years to complete

KEPLER MISSION WILL ADDRESS

Kepler
A Search for Earth-size Planets

- **What is the frequency of Earth-size planets in or near the Habitable Zone (HZ) of solar-like stars?**
- **What are the frequency & orbital distributions of planets in star systems?**



- **What are the distributions of semi-major axes, albedo, size, and mass, of short-period planets?**

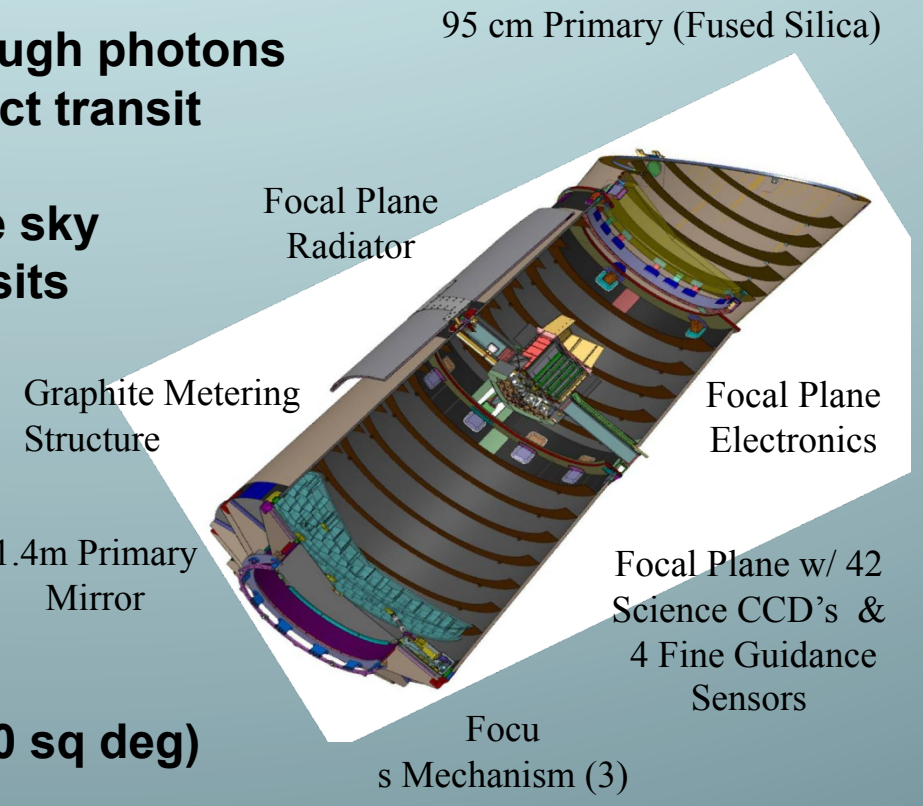
Kepler Mission

Kepler
A Search for Earth-size Planets

KEPLER: A Wide Field-of-View Photometer that Monitors 100,000+ Stars for 3.5 yrs with Enough Precision to Find Earth-size Planets in the Habitable Zone

Use transit photometry to detect Earth-size planets

- **0.95 meter aperture provides enough photons**
- **Observe for several years to detect transit patterns**
- **Monitor a single large area on the sky continuously to avoid missing transits**
- **Use heliocentric orbit**
- **Up to 170,000 targets at 30 min cadence & 512 at 1 min**



Get statistically valid results by monitoring; 100,000 stars

- **Wide Field-of-view telescope (100 sq deg)**
- **Large array of CCD detectors**

PREPARING FOR LAUNCH

Kepler
A Search for Earth-size Planets

- CCD Focal Plane being assembled

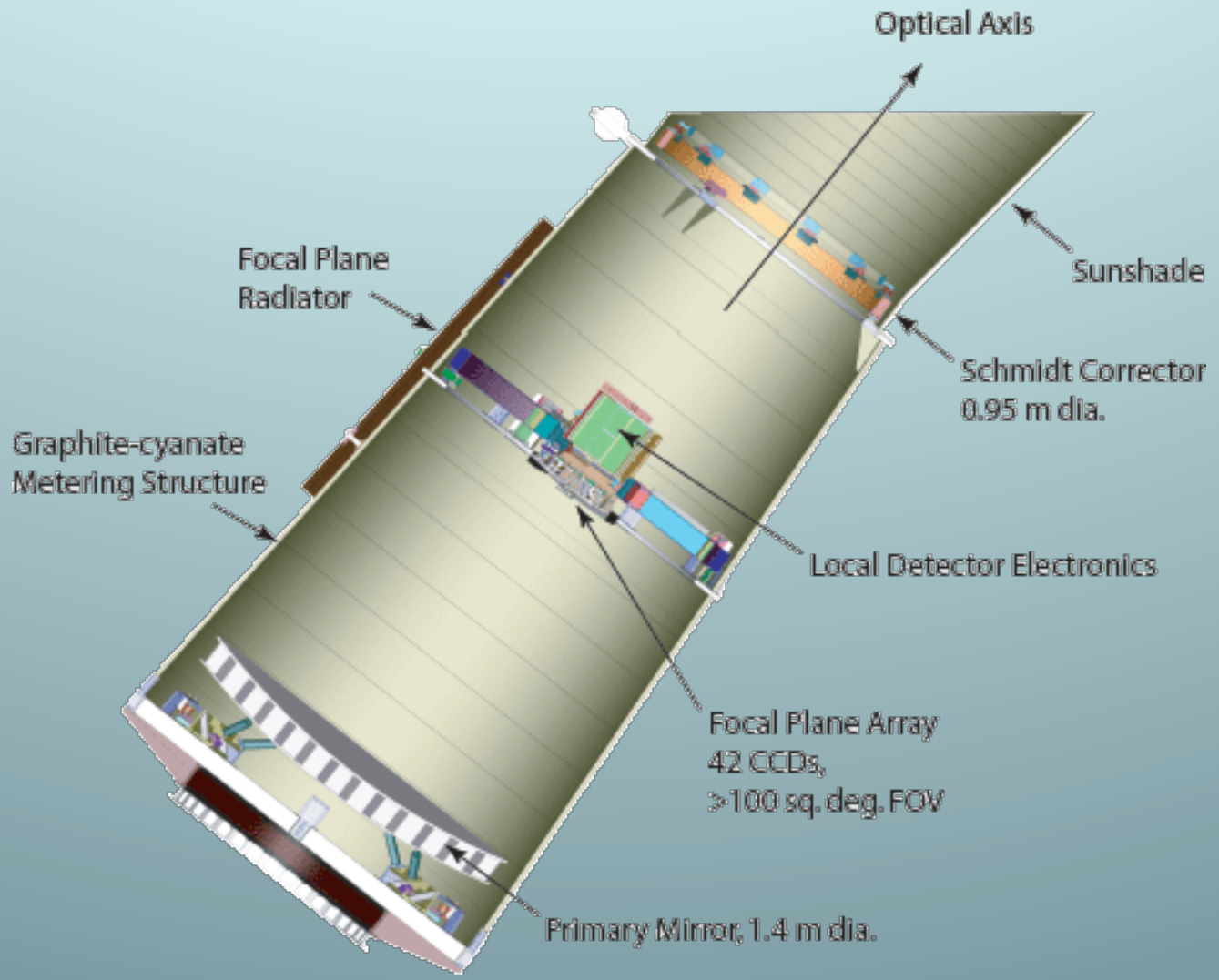
PREPARING FOR LAUNCH

Kepler
A Search for Earth-size Planets

- Spacecraft bus & Primary Mirror

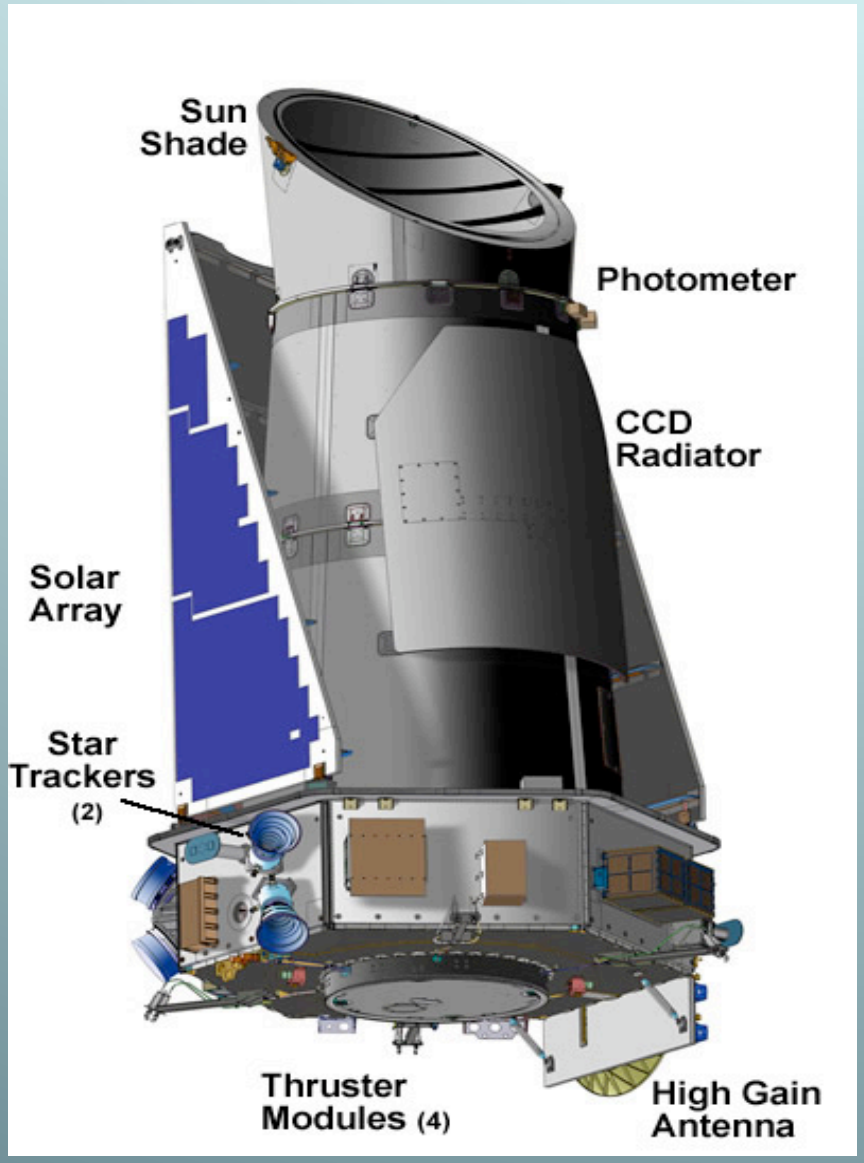
Telescope Schematic

Kepler
A Search for Earth-size Planets



Drawing and Reality

Kepler
A Search for Earth-size Planets



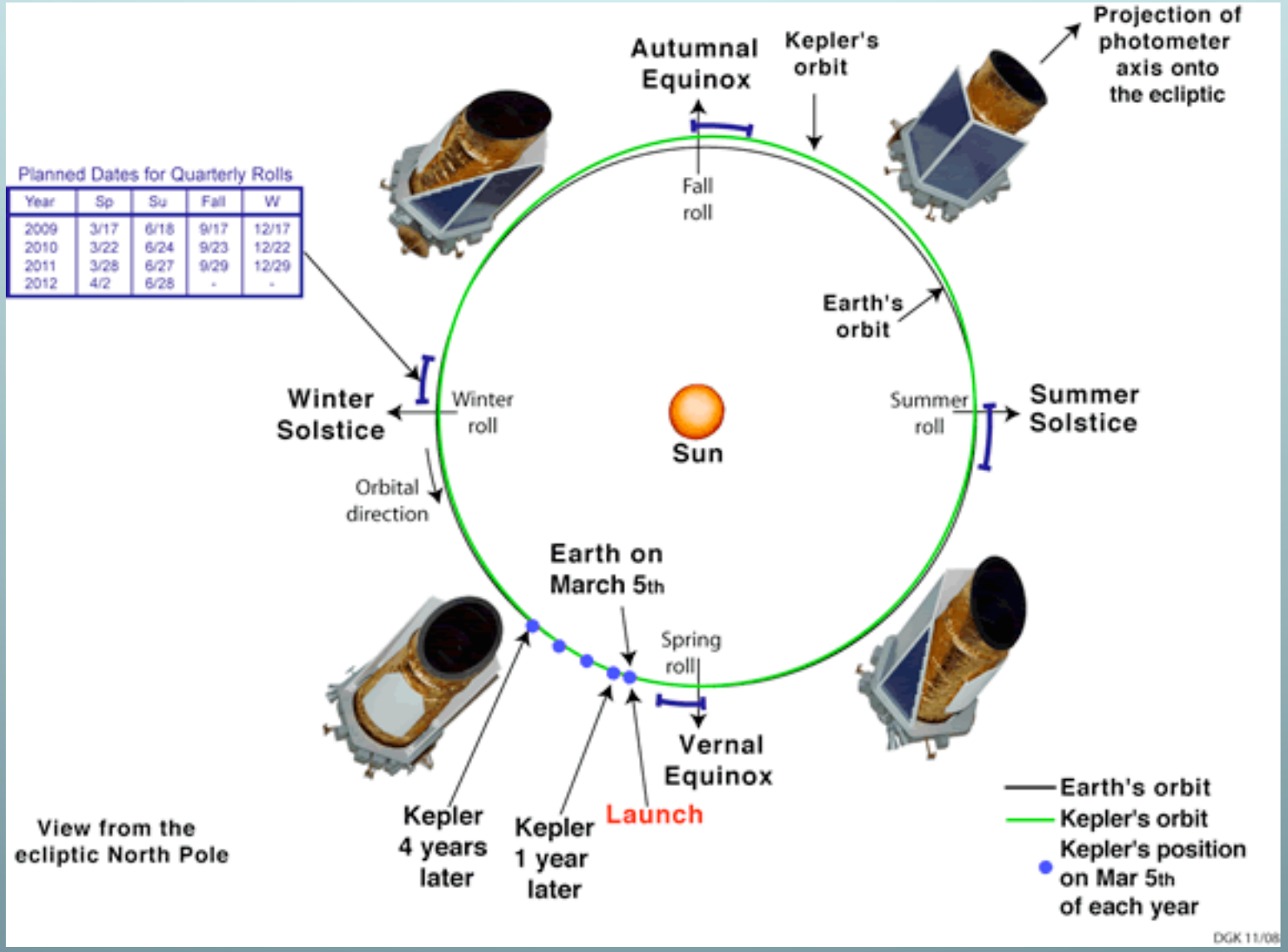
LAUNCH ON MARCH 6, 2009

Kepler

A Search for Earth-size Planets

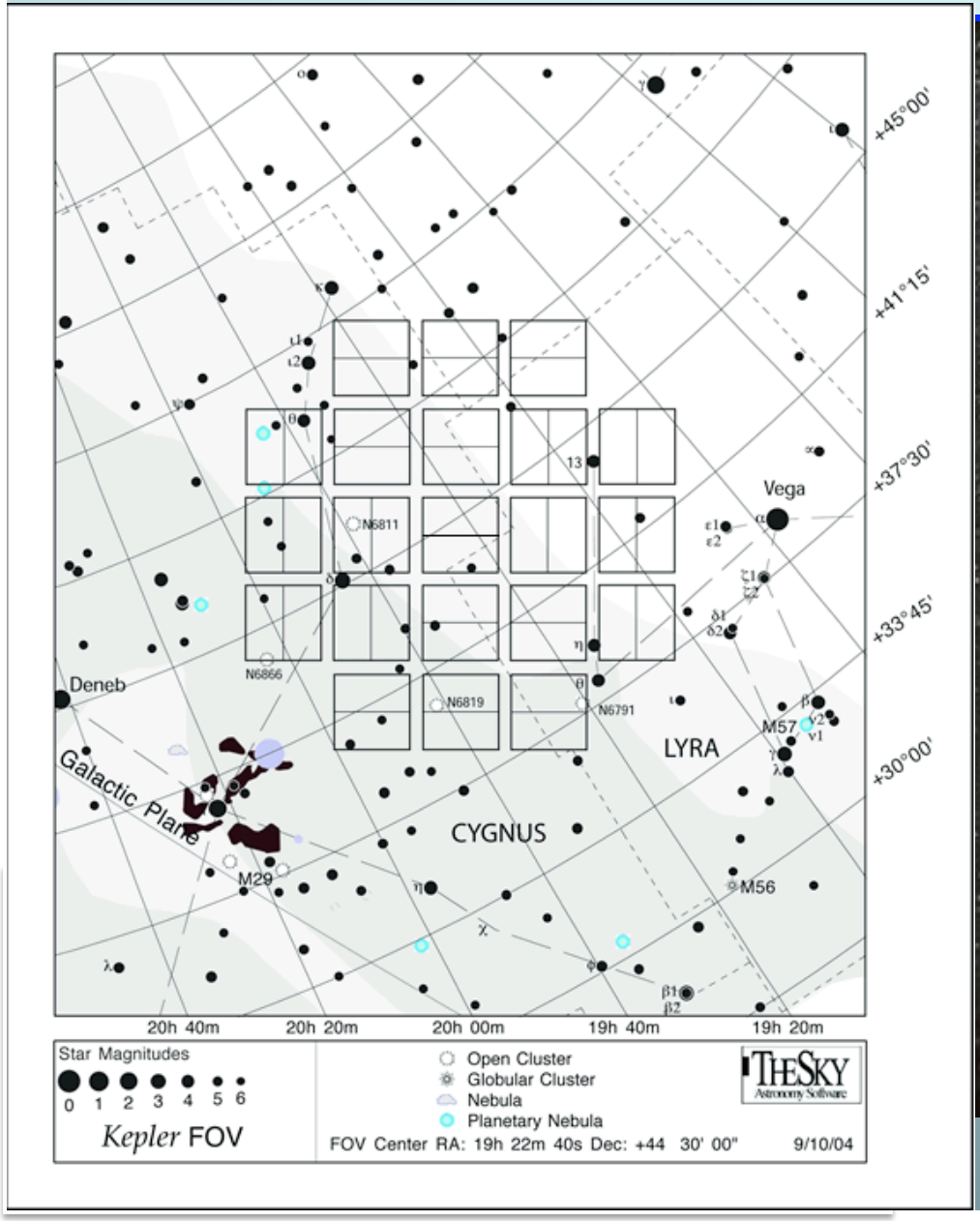
KEPLER SPACECRAFT ORBIT

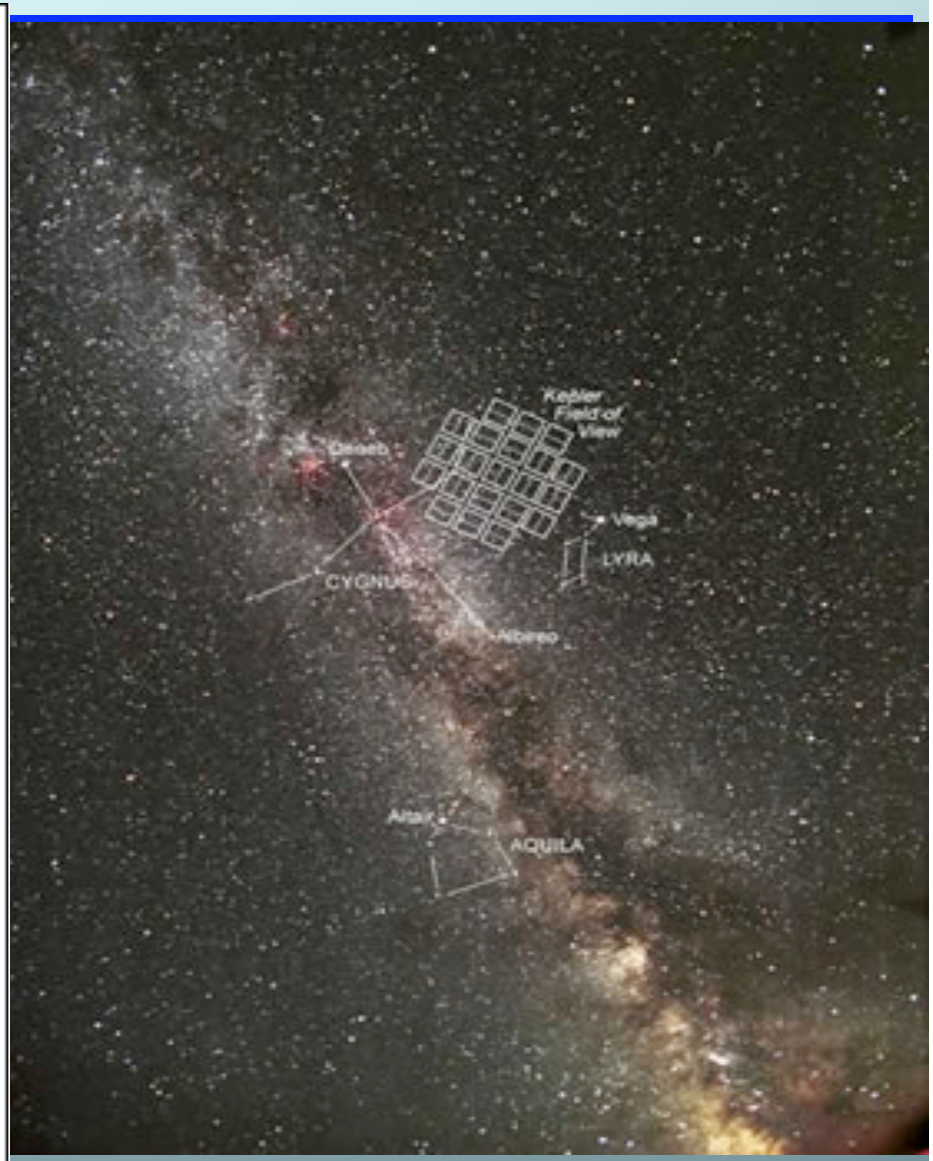
A Search for Earth-size Planets



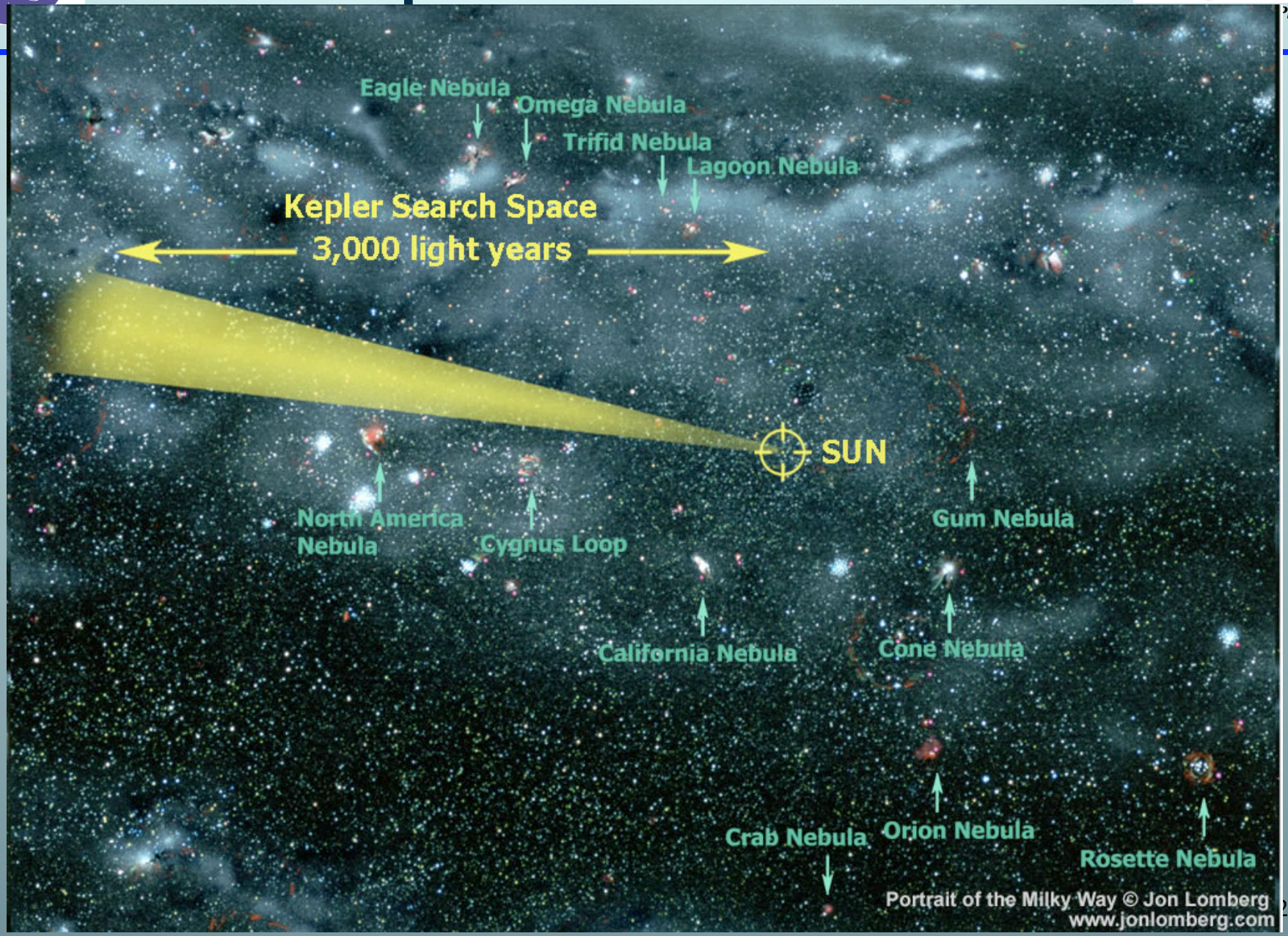
Kepler Field of View

Kepler
A Search for Earth-size Planets

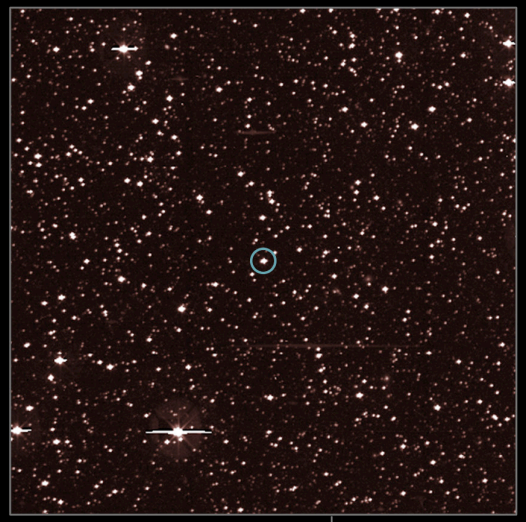




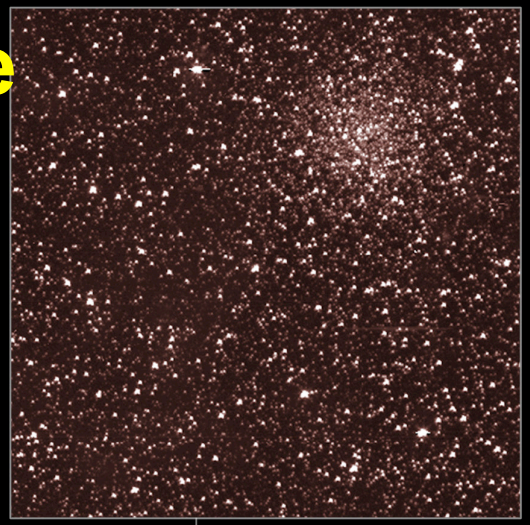
Kepler Field of View



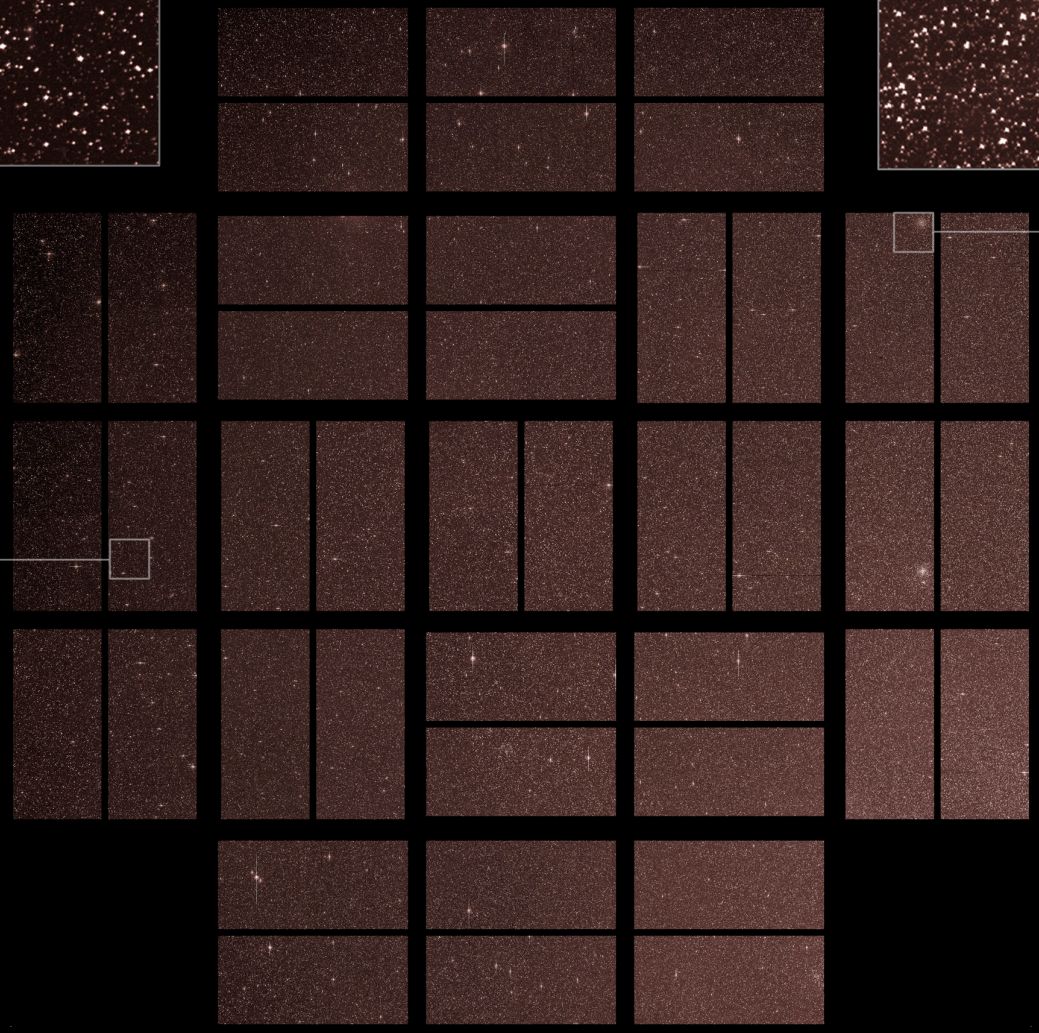
First Light Image



TrES-2

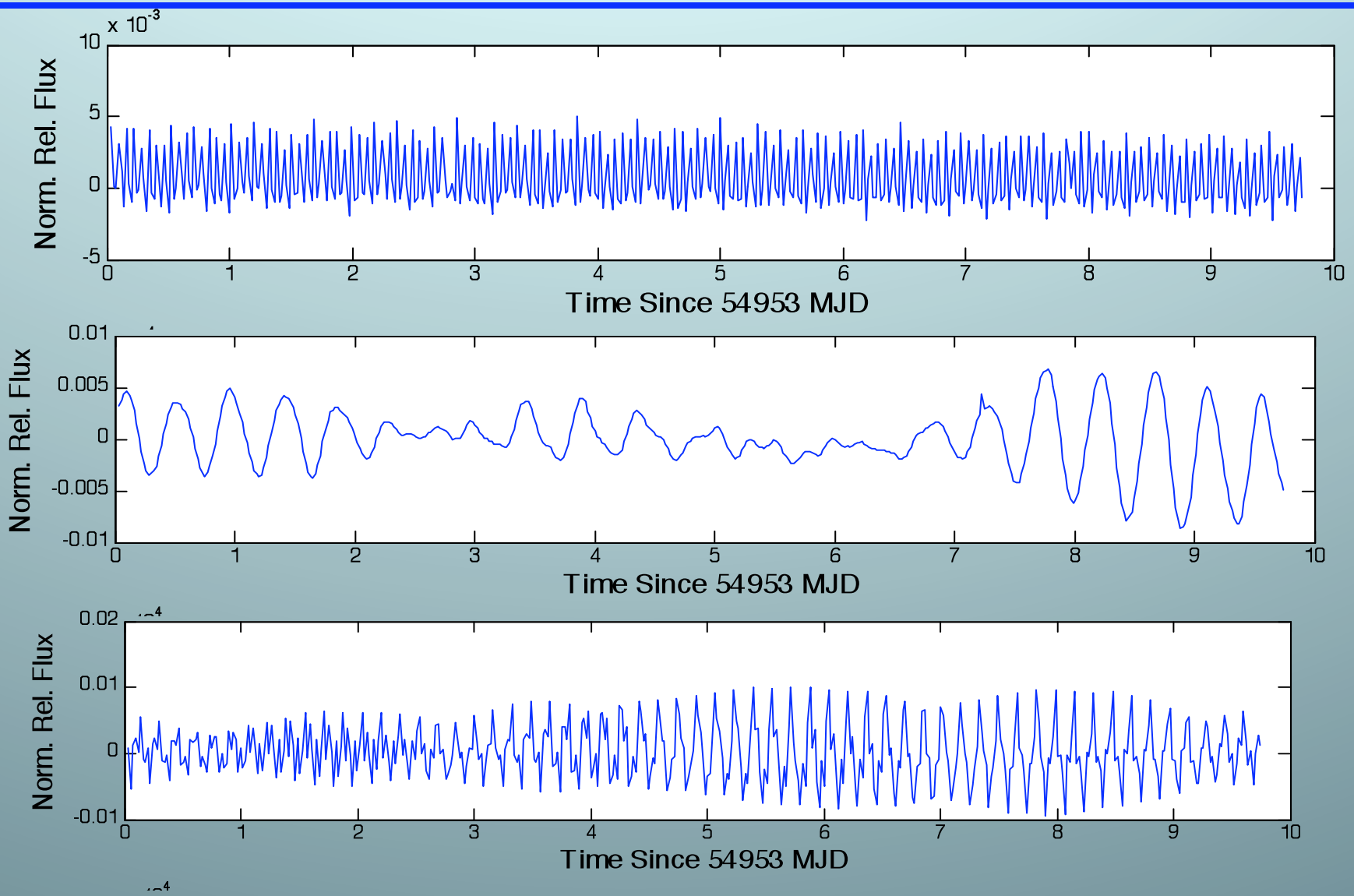


NGC 6791



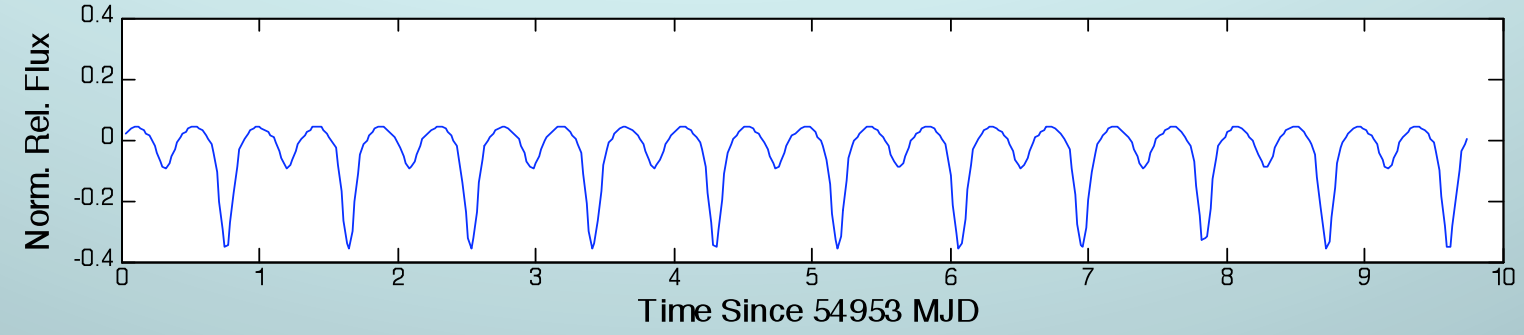
SAMPLE LIGHT CURVES

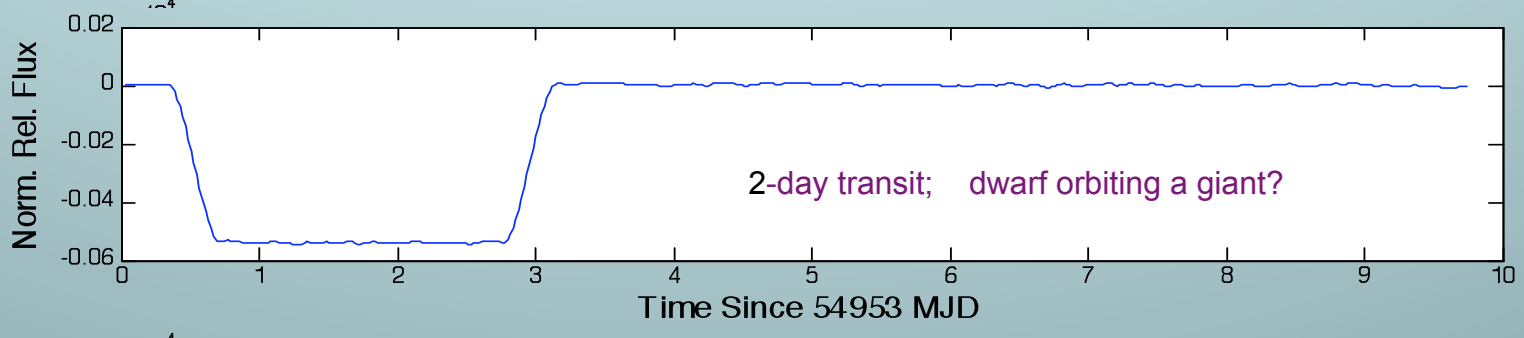
Kepler
A Search for Earth-size Planets



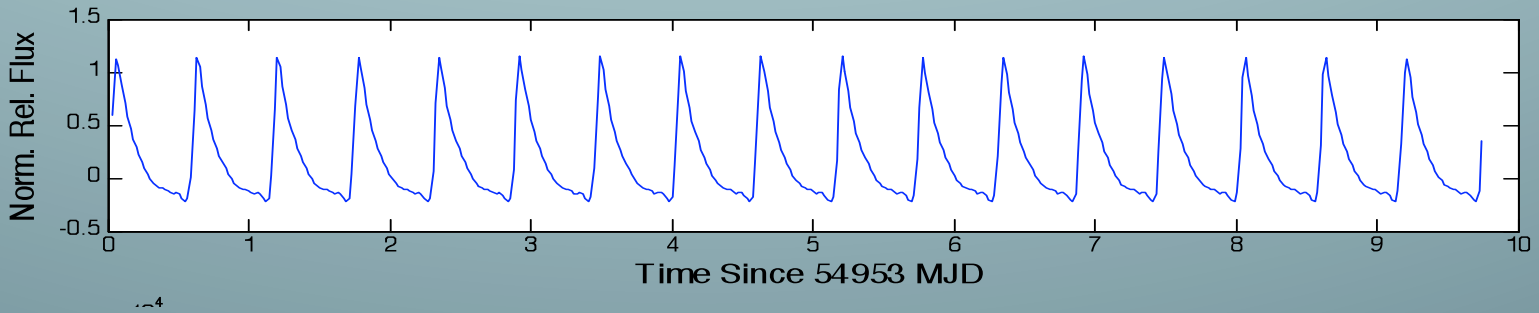
SAMPLE LIGHT CURVES

Kepler
A Search for Earth-size Planets





2-day transit; dwarf orbiting a giant?



MEASURED LIGHT CURVE NOISE, SO FAR

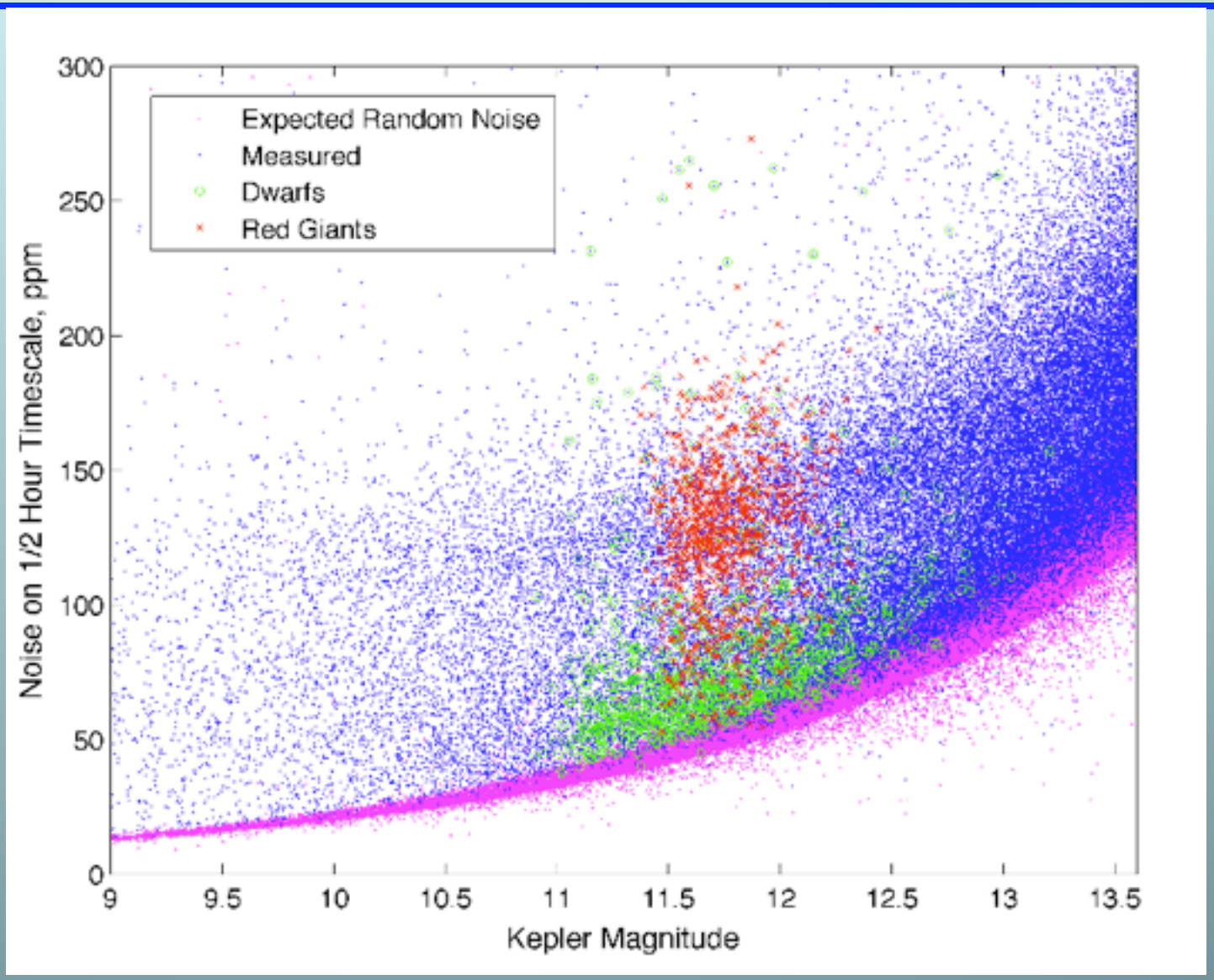
Kepler
A Search for Earth-size Planets

Magenta = expected noise (non-variable)

Blue = measured

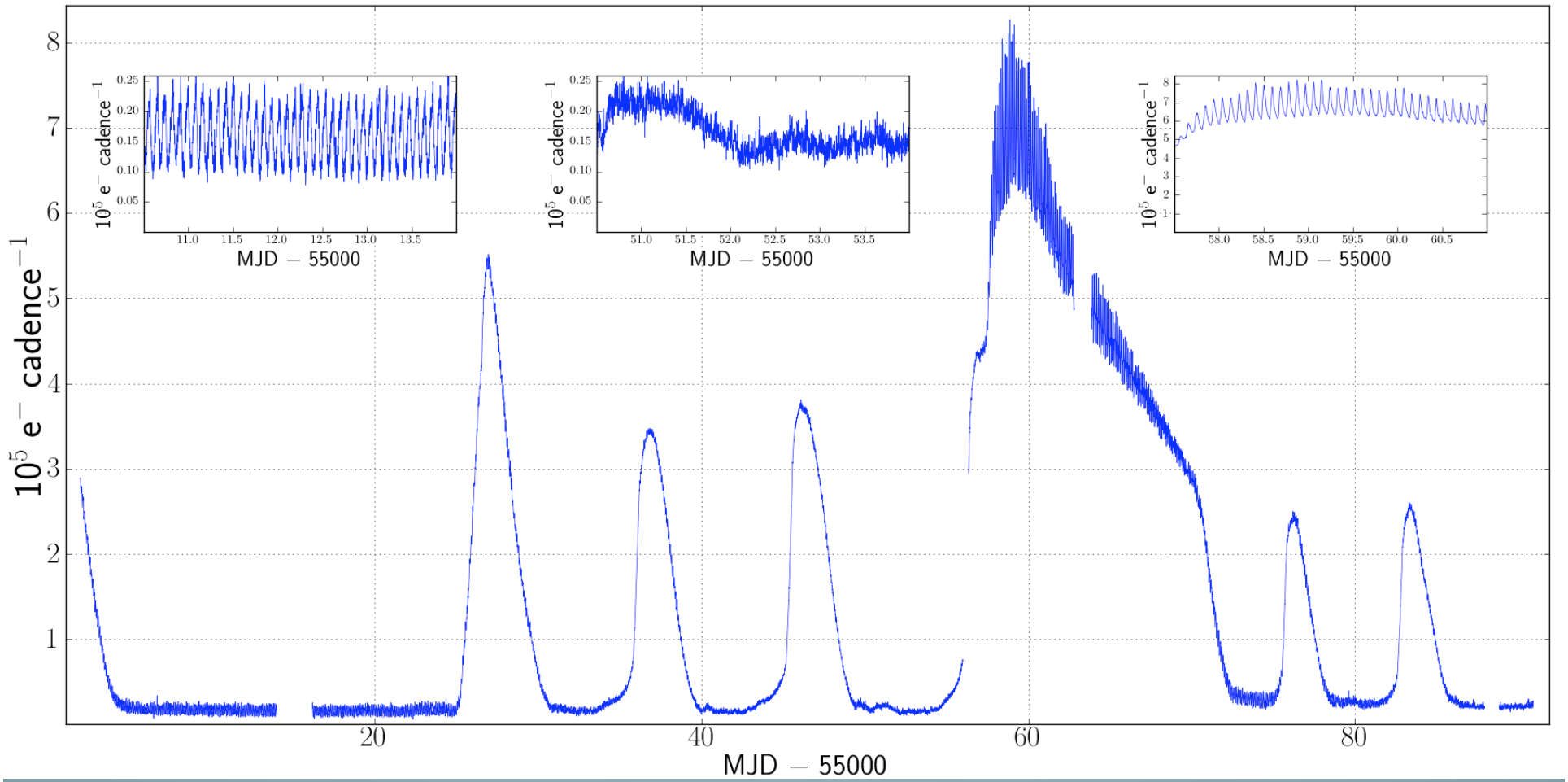
Green = 1000 dwarfs

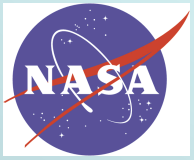
Red = 1000 giants



Dwarf Nova – V344 Lyr

Kepler
A Search for Earth-size Planets



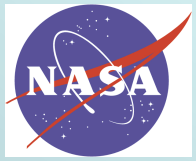


Kepler Planets – Real or Not?

Kepler
A Search for Earth-size Planets

False Transits can be caused by:

1. M dwarfs transiting giants and supergiants
2. White dwarfs transiting solar-type stars
3. Grazing eclipses of one star by another
4. Full eclipses in a faint background binary whose light is blended with a foreground bright star
5. Triple systems – difficult in short term
6. Other even more insidious effects

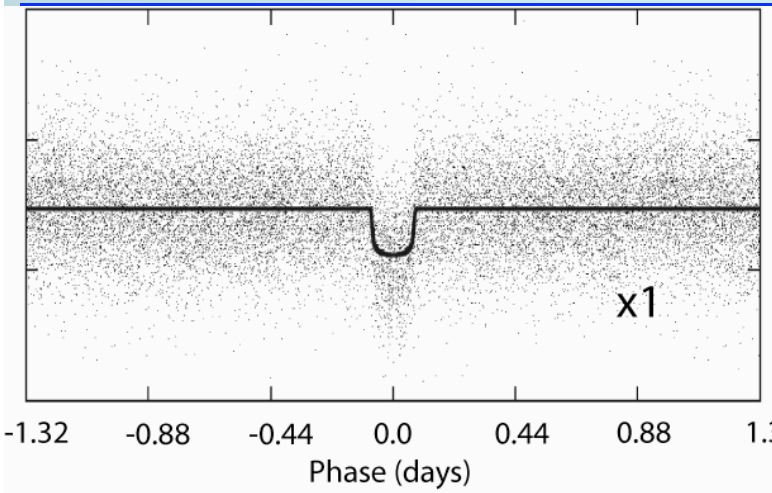


VALIDATION of PLANETS

Kepler
A Search for Earth-size Planets

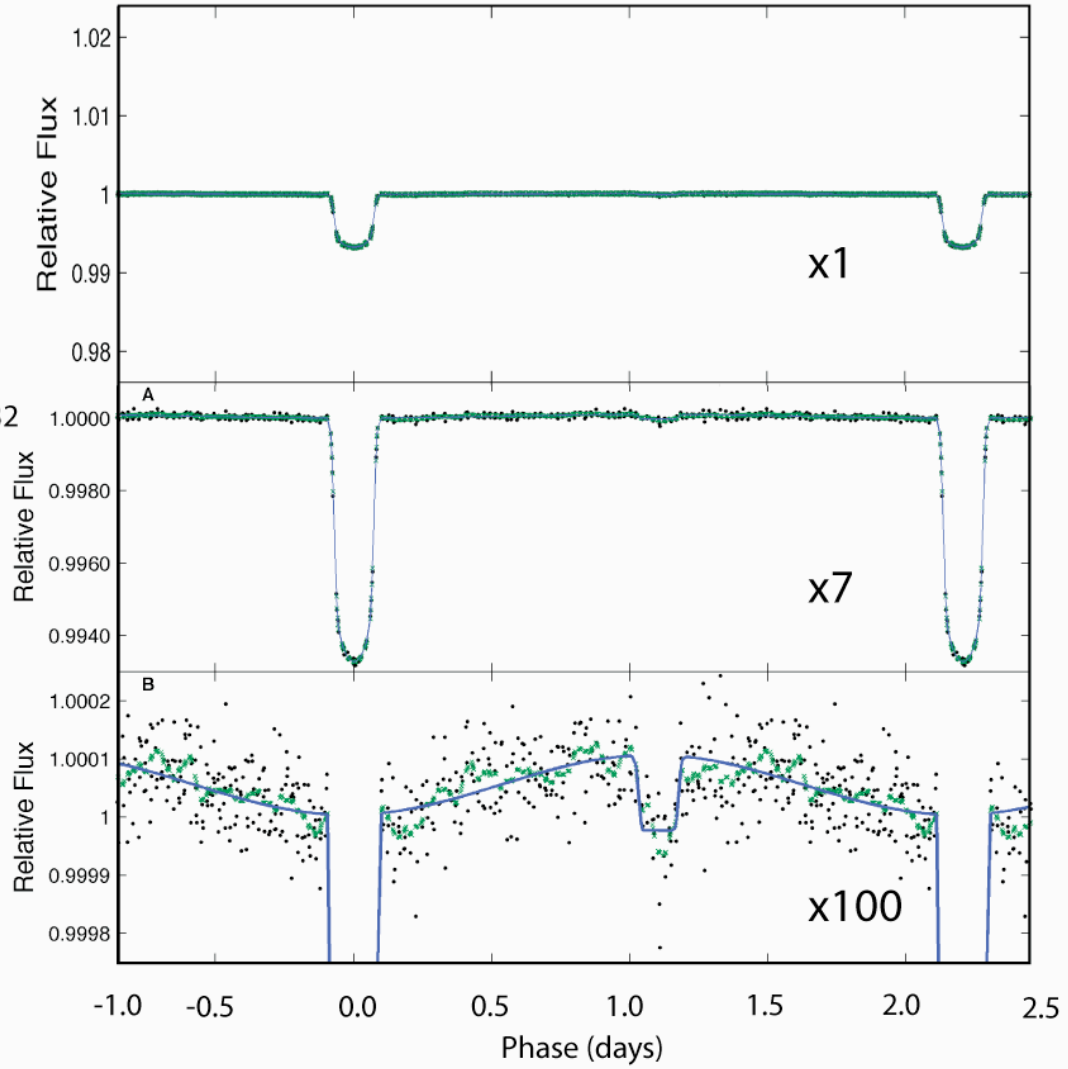
- SNR > 7, to rule out statistical fluctuations
- Three or more transits to confirm orbital periodicity
- Light curve depth, shape, and duration consistent
- Image subtraction to identify signals from background stars
- Radial velocity
  - Medium precision to rule out stellar companions
  - High precision to measure mass of super-Earths and giant planets
  - Rossiter-McLaughlin effect to confirm orbiting planet
- High spatial resolution images to identify extremely close background stars; Observe eclipse of background stars.
- Check for color change during transit
- More tests as the mission progresses and planets get smaller

Exo-Planet HAT P-7b Kepler Light Curve



16,620 HATNet data points (57.7 days of data)

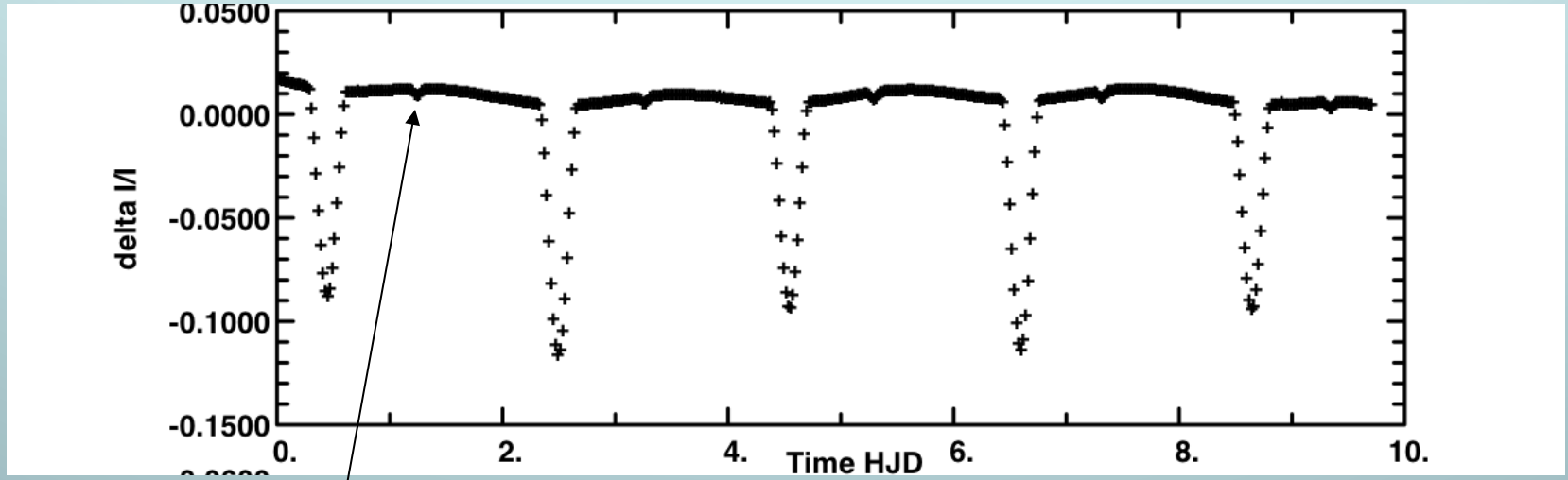
HAT-P-7b data from the ground
A. Pal et al., 2008

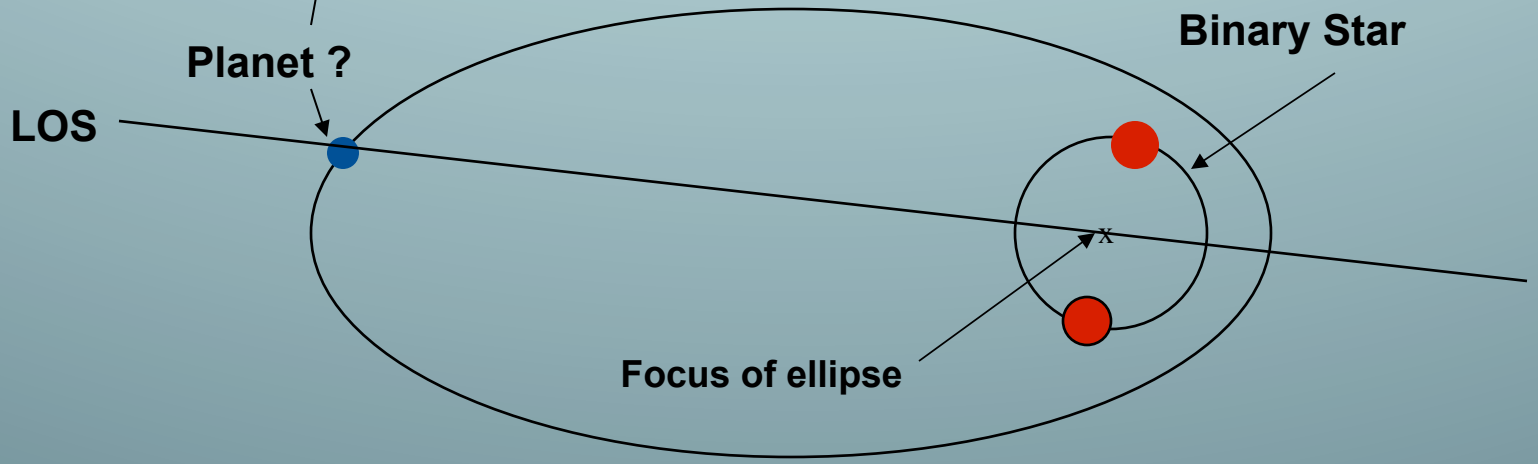


Kepler Commissioning data (10 days)
W. Borucki et al., 2009

BINARY WITH CIRCUMBINARY PLANET?

Kepler
A Search for Earth-size Planets



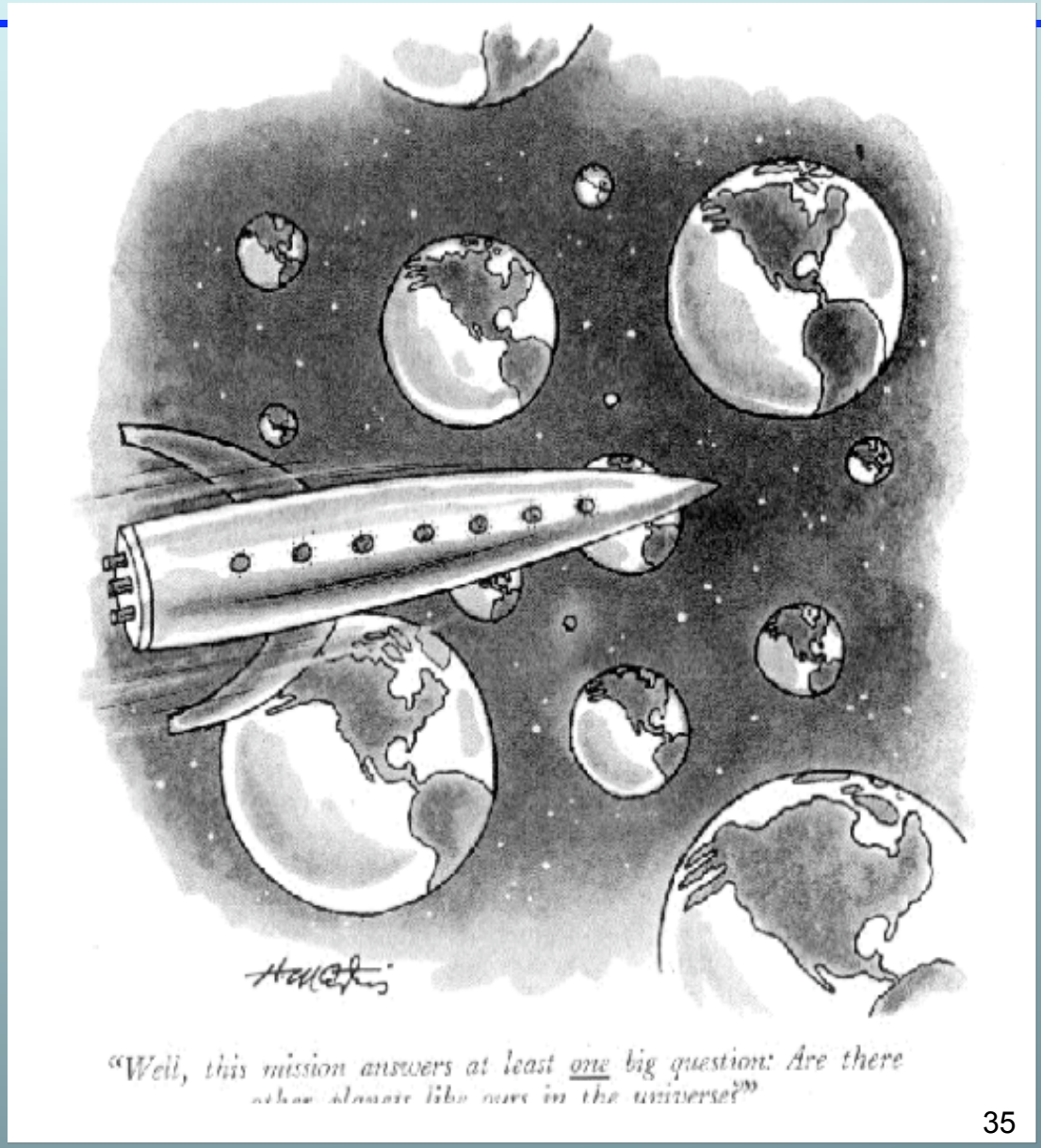


NASA HQ View ;-)

Kepler
A Search for Earth-size Planets

"Kepler will answer at least one big question:

Are there other planets like ours in the universe?"



Drawing by H. Martin; © 1991
The New Yorker Magazine, Inc.