The Kepler Exoplanet Survey:

Instrumentation, Performance and Results

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Basic Kepler Science Goal

- Determine frequency and orbital properties of terrestrial & larger planets in/near the habitable zones of a wide variety of stars.

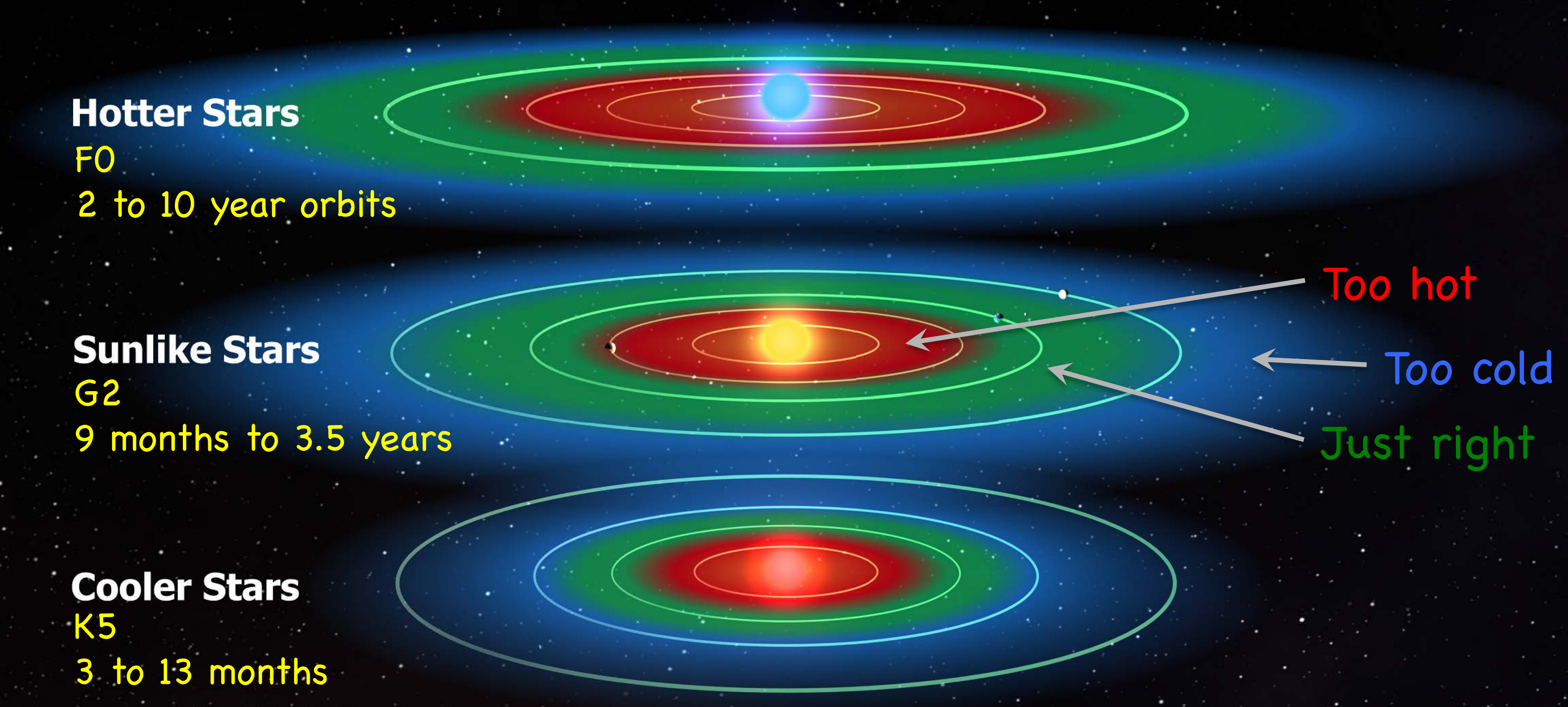
Kepler is designed to discover the frequency of potentially habitable worlds outside the Solar System: terrestrial planets in the habitable zones of their stars.

Concentrate on solar-like stars:
F, G, K and early M dwarfs

The Habitable Zone

The region around a star where liquid water might exist on a planet's surface

The Goldilocks Zone



Radial Velocity Detection Won't Do

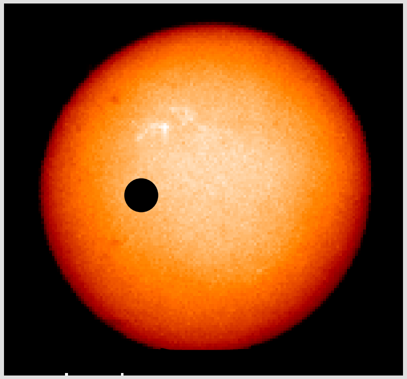
- Classic discovery method is spectroscopic detection of the reflex motion of the host star due to an orbiting planet is the.
  - RV detection gives the planet mass
- Long habitable zone orbits and low terrestrial planet masses make RV unsuitable for Kepler's goal
  - Best RV sensitivity of 0.5 m/s insufficient to see low mass planets in HZs
- Need to use the transit detection method.

Max reflex velocity for dwarf stars and 1 M_{earth} planet in HZ

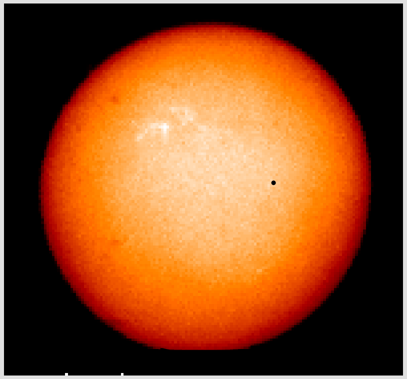
F5	0.06 m/s
G0	0.09
K0	0.13
M0	0.26

Discovering Planets with Transits

- When an extrasolar planet's orbit takes it directly between its star and the Earth the star will dim slightly
  - Relative change in brightness ($\Delta L/L$) is the ratio of areas (A_{planet}/A_{star})



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

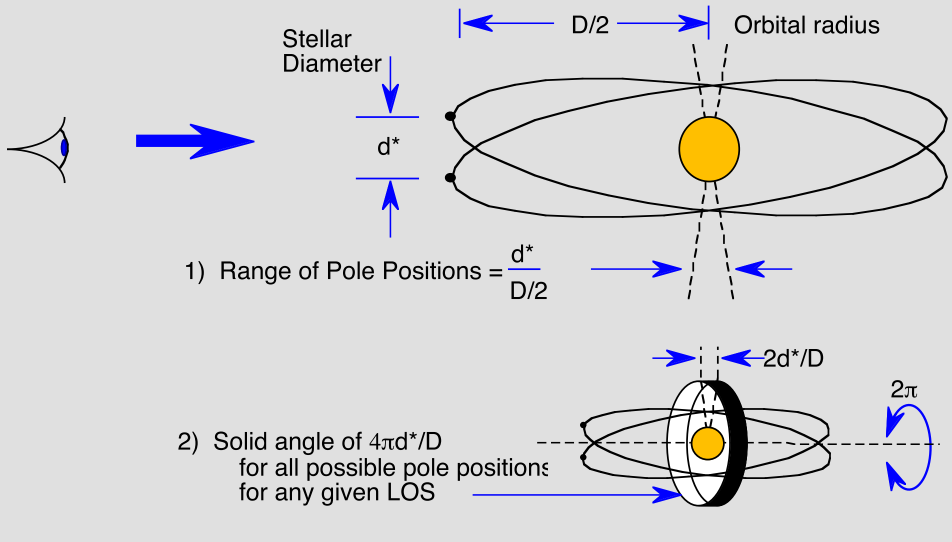


Earth or Venus
0.008% area of the Sun (1/12,000)

  - 0.008% is SMALL. Must get above the Earth's atmosphere to measure.
  - You must be patient. Transits last only a few hours out of the orbital period
  - Need at least 3 transits to be sure a planet is detected
    - May need more for sufficient reliability

Can’t See Every Planet

- Not all orbits are aligned to make a transit
- Geometry for transit probability



3) Geometric Transit Probability = d*/D

- Diameter of Sun: ~0.01 AU   Diameter of Earth’s orbit: 2 AU
- Probability of seeing a distant Earth-Sun analog transit: 0.5%
- Must look at a lot of stars to get statistical sample of planets.

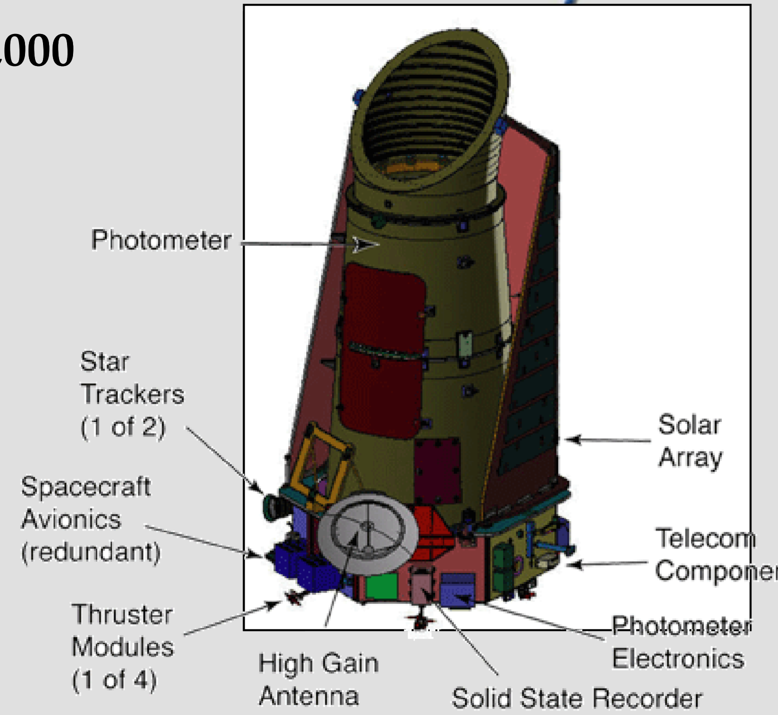
Kepler Mission Requirements

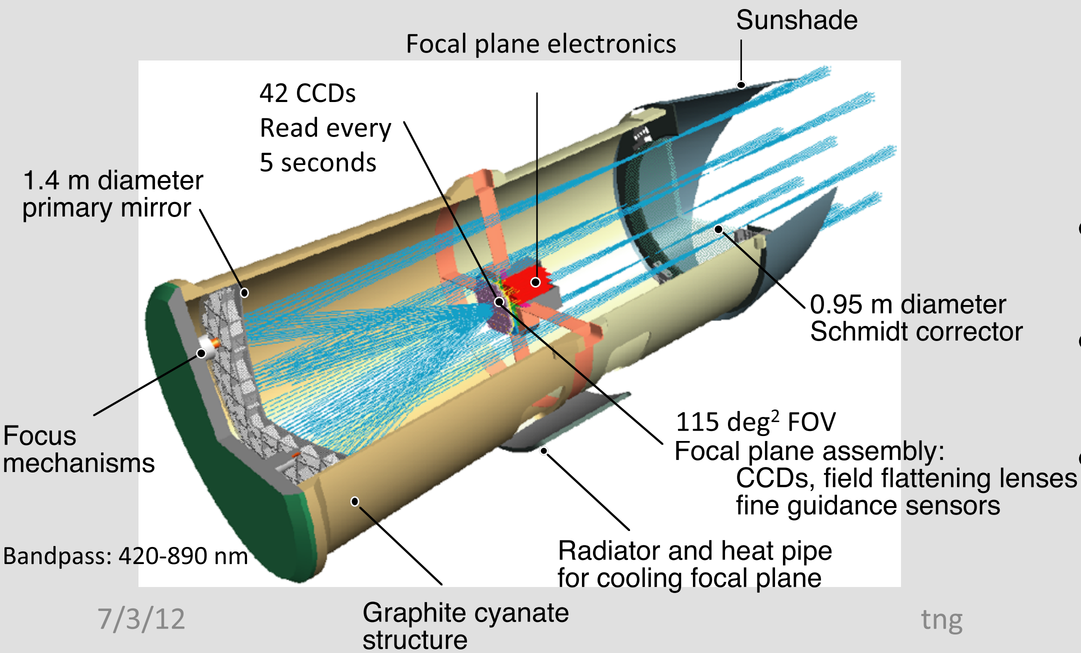
- Monitor >100,000 solar-like stars for 4 years
- Don't blink! Continuous observation is needed.
  - Must catch transits only 6 – 16 hours long
- Sufficient sensitivity to see an earth-size planet transiting a solar-size star
  - Need 7σ detection of planet with 1 year orbit period
    - Controls false detections due to random noise
  - Requires ~4σ detection of single 80 ppm transit: 20 ppm 1σ
  - Noise budget for our fiducial 12th magnitude star
    - 14 ppm photon noise in 6.5 hr transit with 1 meter aperture
    - 10 ppm stellar variability (noise level of the Sun)
    - 10 ppm instrument noise (read noise, dark current, pointing stability, etc.)

Kepler Mission Design

- **Continuously and simultaneously monitor >150,000 stars cool dwarf stars (F-M)**
- **95 centimeter Schmidt telescope**
  - **>115 deg^2 field-of-view**
  - **42 CCDs, 96M pixels, 4 arcsec/pixel**
  - **Sample every 30 minutes**
    - **1000 targets with 1 sec samples.**
- **Photometric precision of < 20 ppm in 6.5 hours on V_{mag}= 12 solar-like star**

→ 4σ detection of 1 Earth-sized transit

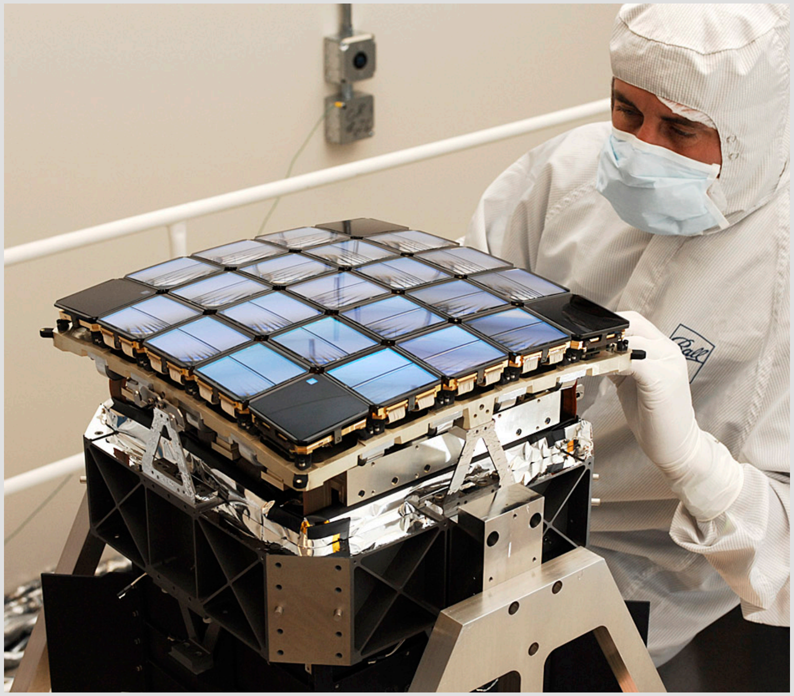




Bandpass: 420-890 nm

- **Heliocentric orbit for continuous visibility of target field**
- **3.5 year lifetime with capability of >10 years (budget requirement)**
- **Break data collection monthly for down-link and quarterly to roll 90° for Sun attitude**

Focal Plane Array



FPA under assembly at Ball Aerospace

21 science CCD modules

- Two 1044 x 2200 back illuminated CCDs from e2v
- 27μm pixels
- Sapphire field flattener lens.

>115 deg^2 field of view

- 4 arcsec pixels

430 – 890 nm passband

Shutterless operation

Single CCD module

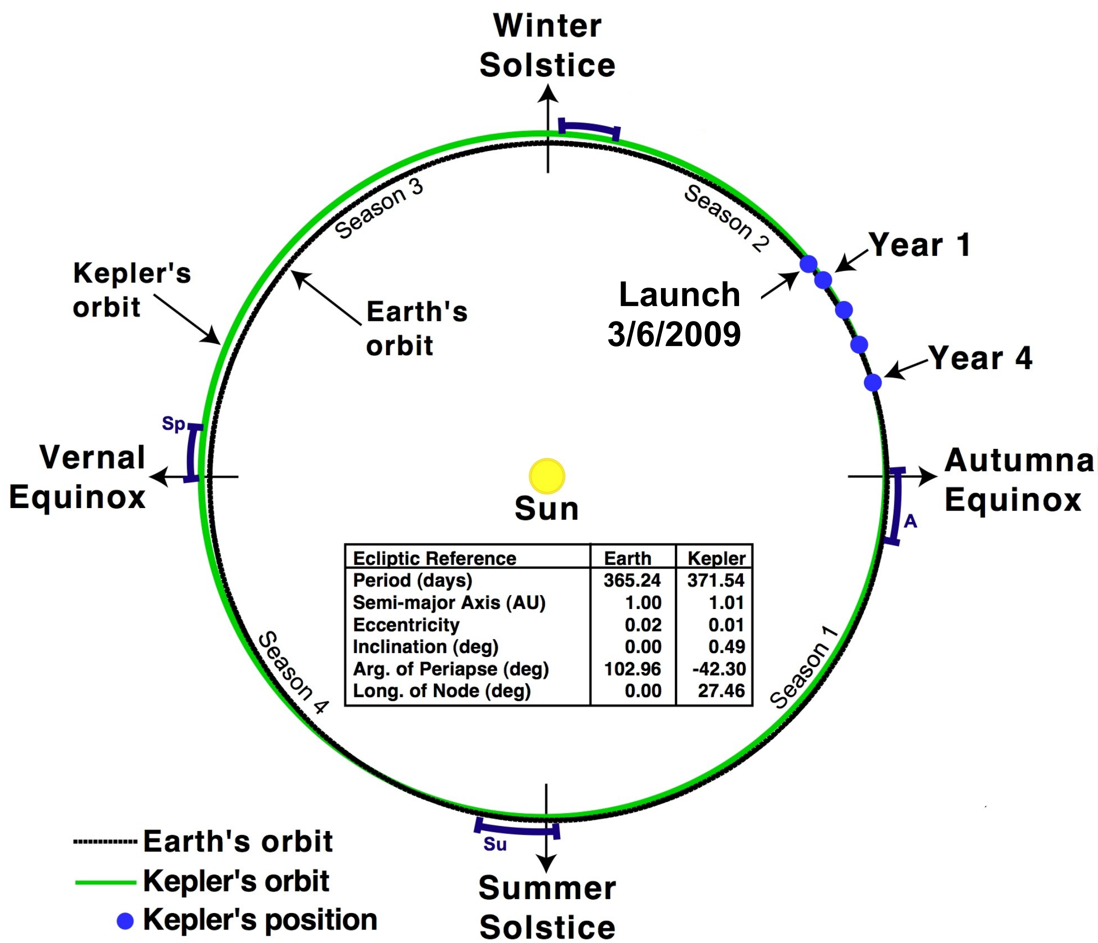
Kepler Implementers

- Proposed by Bill Broucki at NASA Ames Research Center
  - Selected as the 10th Discovery mission.
- Overall management by Jet Propulsion Laboratory, CalTech
- Ball Aerospace Corporation built and integrated the hardware
- Mission Operations at LASP (University of Colorado) and Ball Aerospace
- Science operations and flight phase management at NASA Ames Research Center

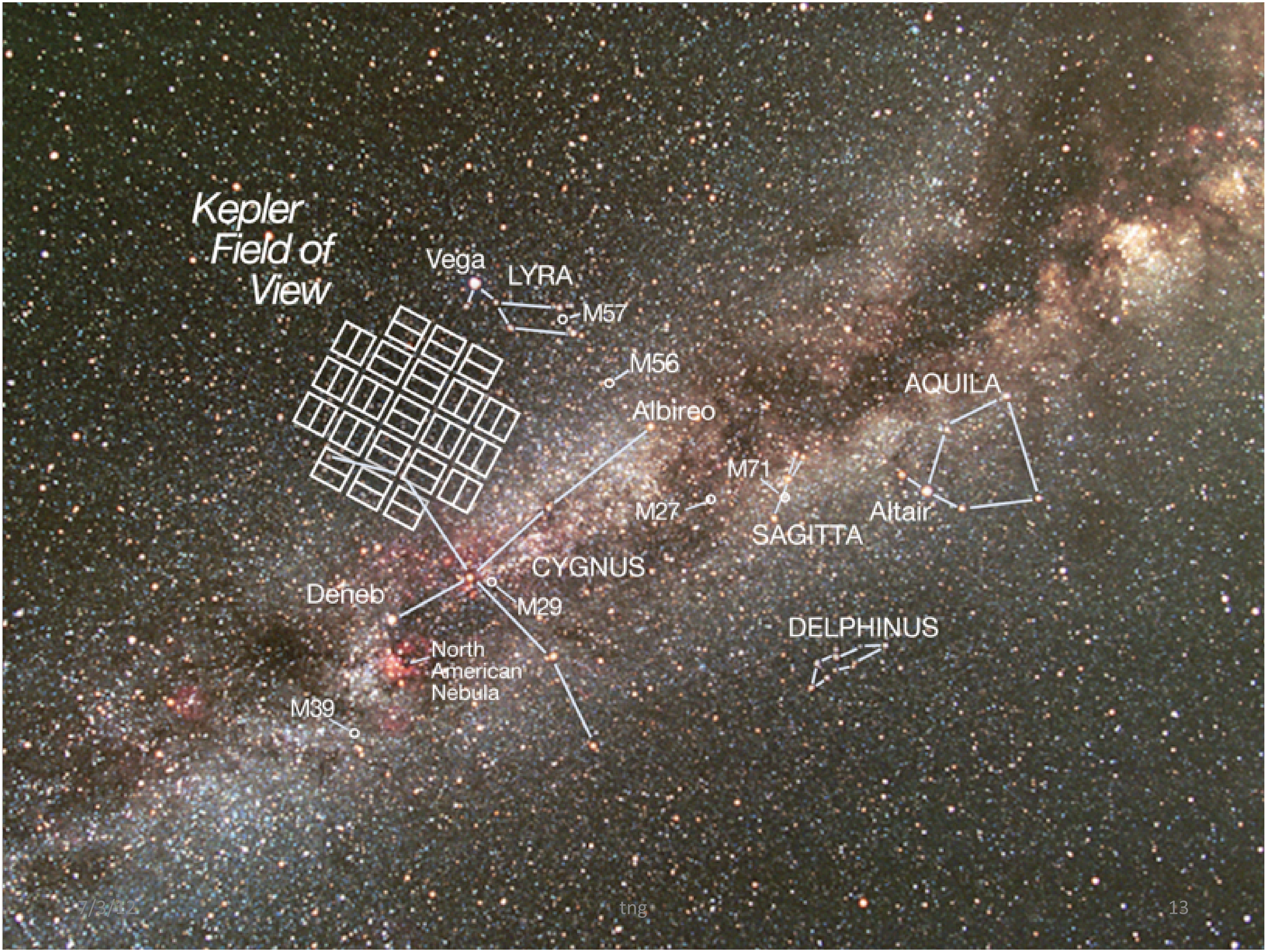
Kepler Launched March 6, 2009

EARTH-TRAILING HELIOCENTRIC ORBIT

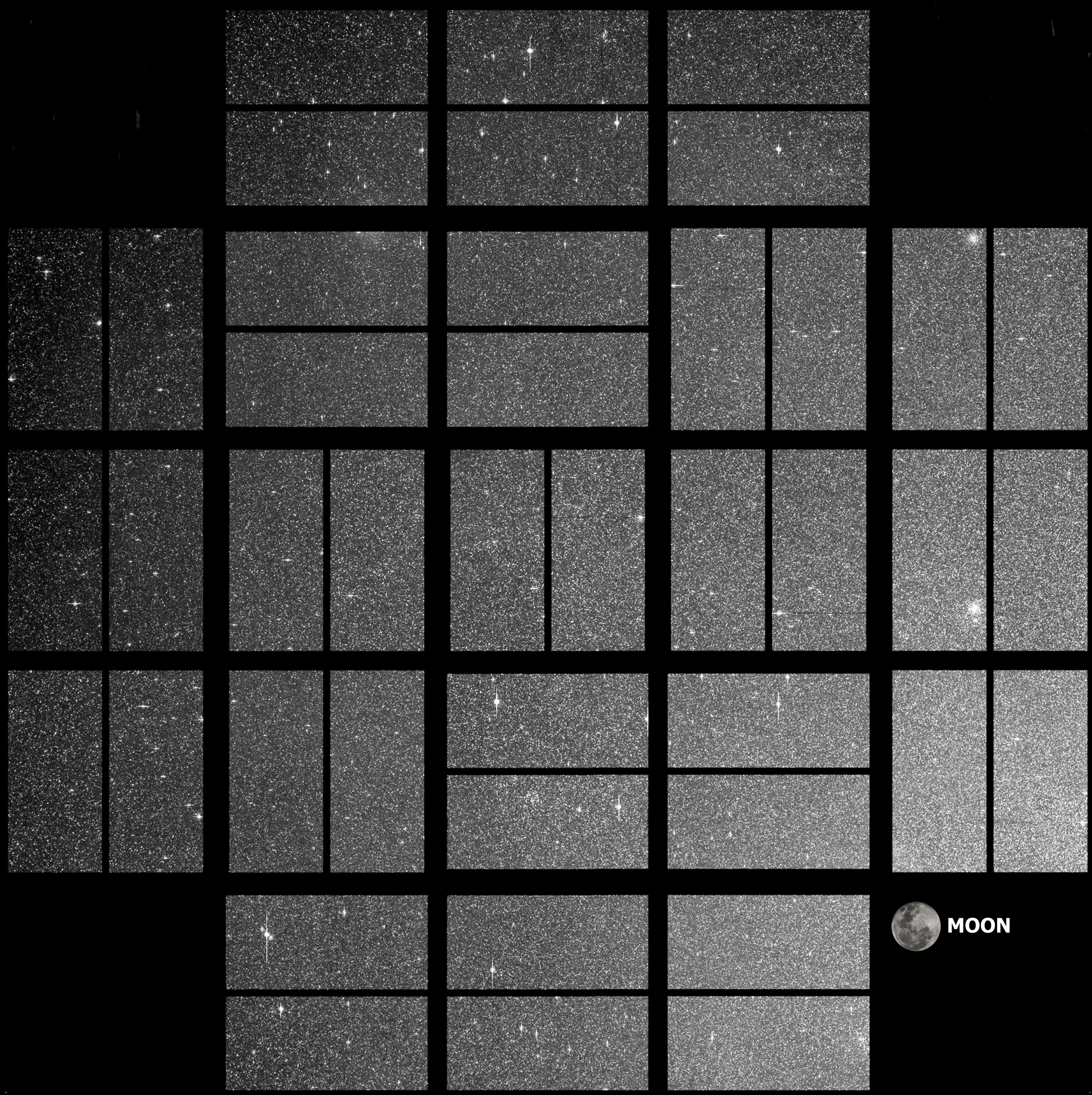
Delta II 2925-10L



Ecliptic Reference	Earth	Kepler
Period (days)	365.24	371.54
Semi-major Axis (AU)	1.00	1.01
Eccentricity	0.02	0.01
Inclination (deg)	0.00	0.49
Arg. of Periapse (deg)	102.96	-42.30
Long. of Node (deg)	0.00	27.46

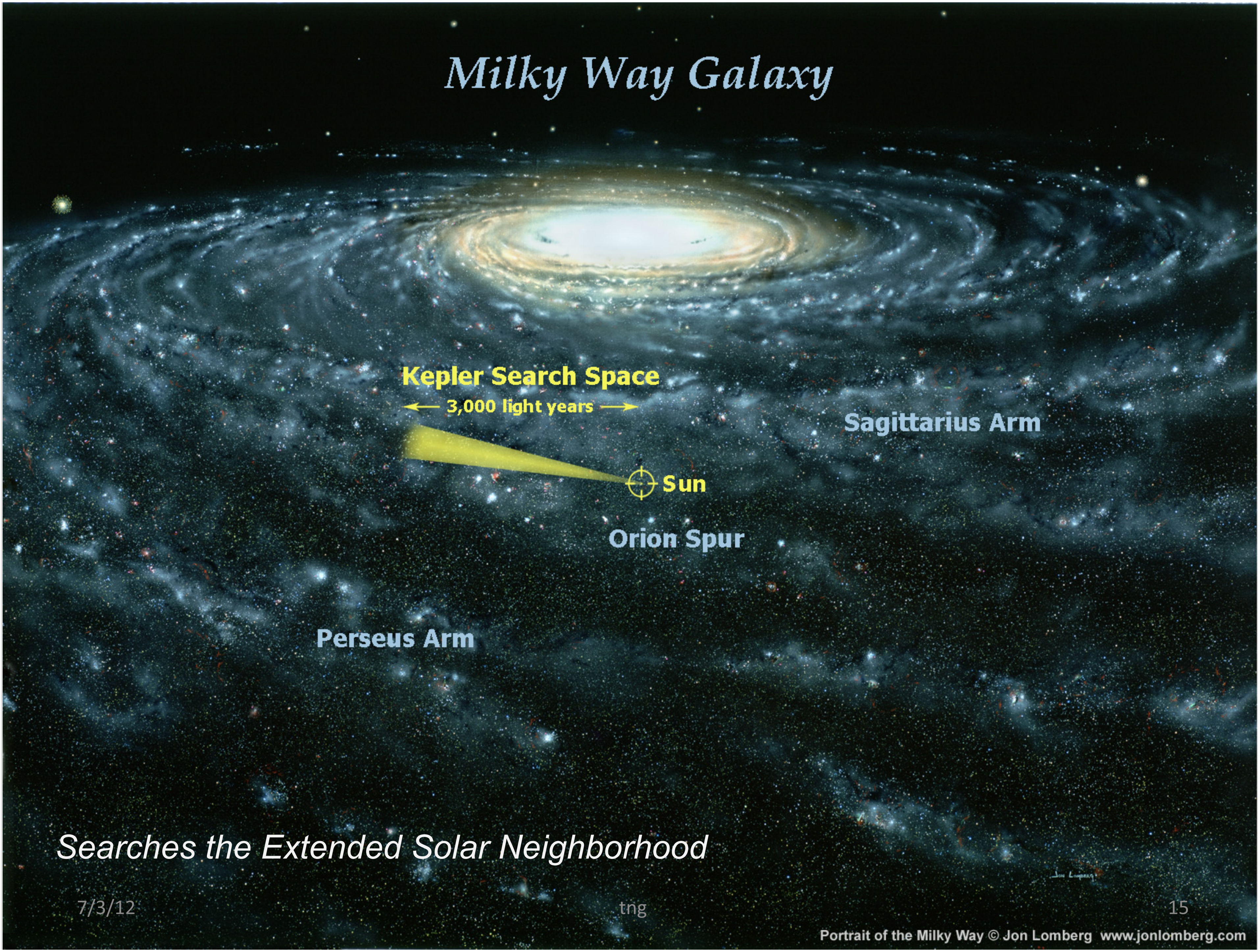

Kepler Field of View
Vega
LYRA
M57
M56
Albireo
AQUILA
M71
M27
SAGITTA
Altair
CYGNUS
Deneb
M29
DELPHINUS
North American Nebula
M39

Kepler Full Field Image

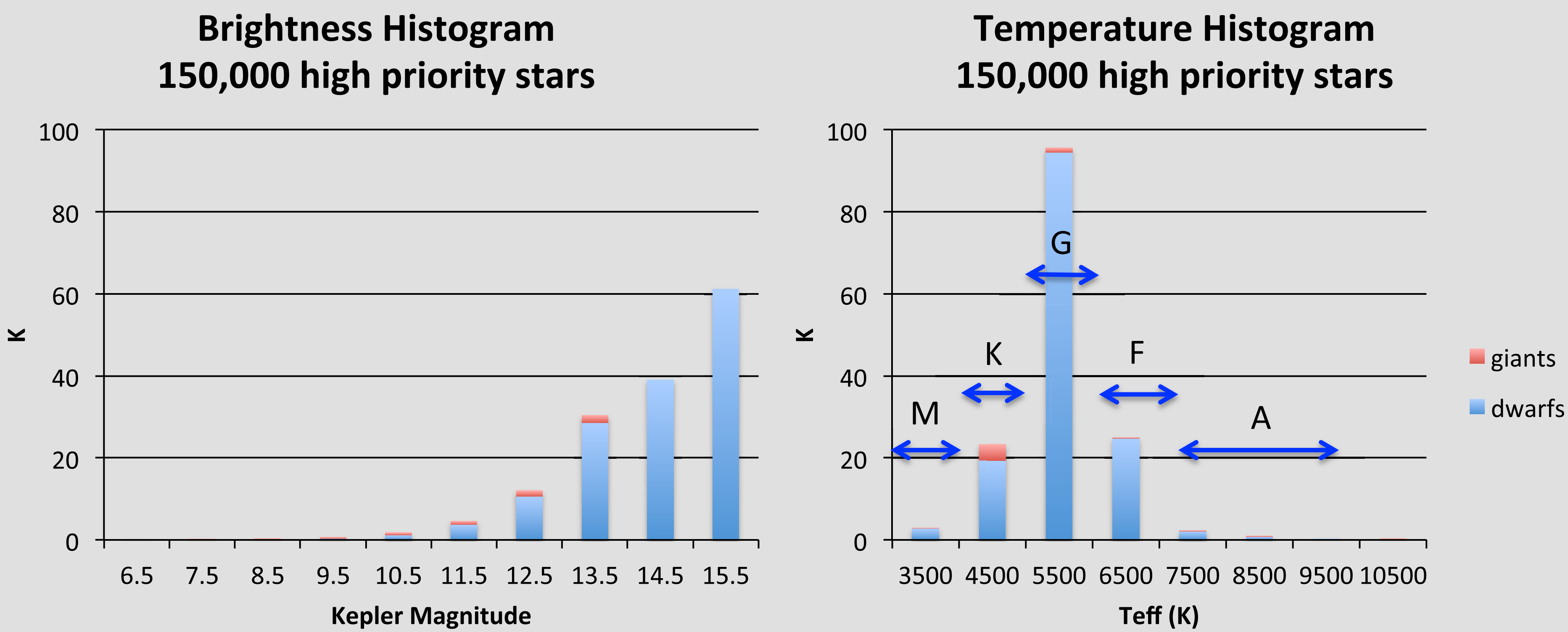


Kepler records and sends back about 5% of this image

Small "postage stamps" around each of ~150,000 target stars


Milky Way Galaxy
Kepler Search Space
3,000 light years
Sagittarius Arm
Sun
Orion Spur
Perseus Arm
Searches the Extended Solar Neighborhood
Portrait of the Milky Way © Jon Lomberg www.jonlomberg.com

Kepler Target Star Distribution



Representative target distribution

Targets vary somewhat by season as stars fall on and off the detectors.

Mission status and performance

- On orbit 40 months, collecting survey data for 38 months
- H/W functioning well
  - But lost one detector module early in mission due to electrical short
    - 4.8% of focal plane
    - Effects data completeness in 19% of FOV due to rolls
- Just started 14^{th} quarter of data collection

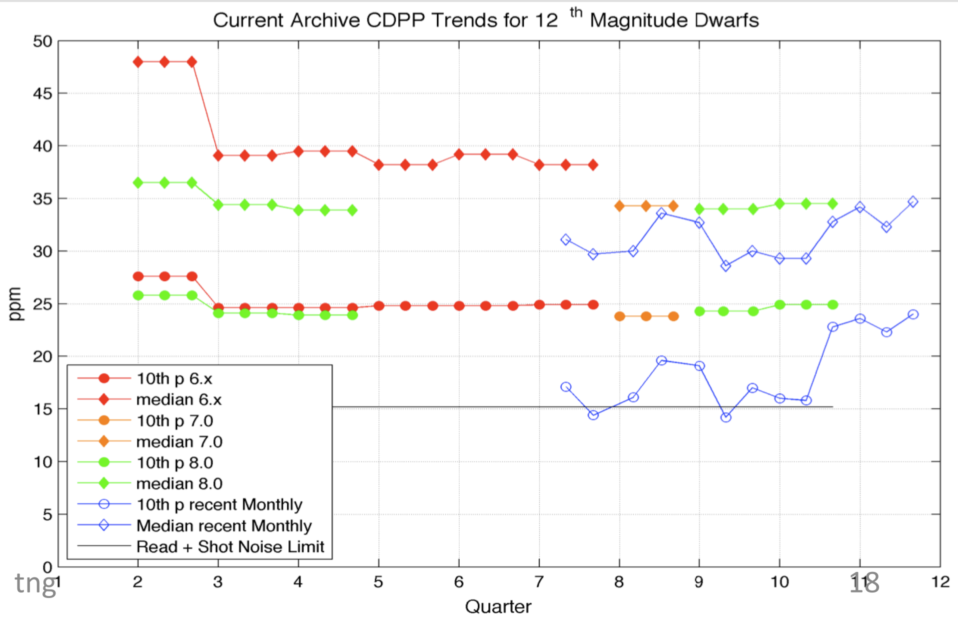
Instrument Health

No significant changes since launch

Dark Current: increasing by 0.33e^{-}/s/year => additional 0.2 ppm noise in 6.5 hours at Kp=12

Charge Transfer Inefficiency: linear increase from Q4 to Q12 from about 60 to 140 PPM, ~40 PPM per year. Might amount to 400 PPM increase after 8 years. Will need to reassess our photometric aperture selection towards the end of an extended mission.

Throughput: flux from bright stars dropping 1%/year => 8*0.5% increase in shot noise after 8 years (optical ghost signals increasing ~0.2%/year)



Noise performance nearly constant from Q3-Q11 once pipeline improvements have been taken into account.

Doug Caldwell, SETI Institute

Kepler Saw Some Excess Noise

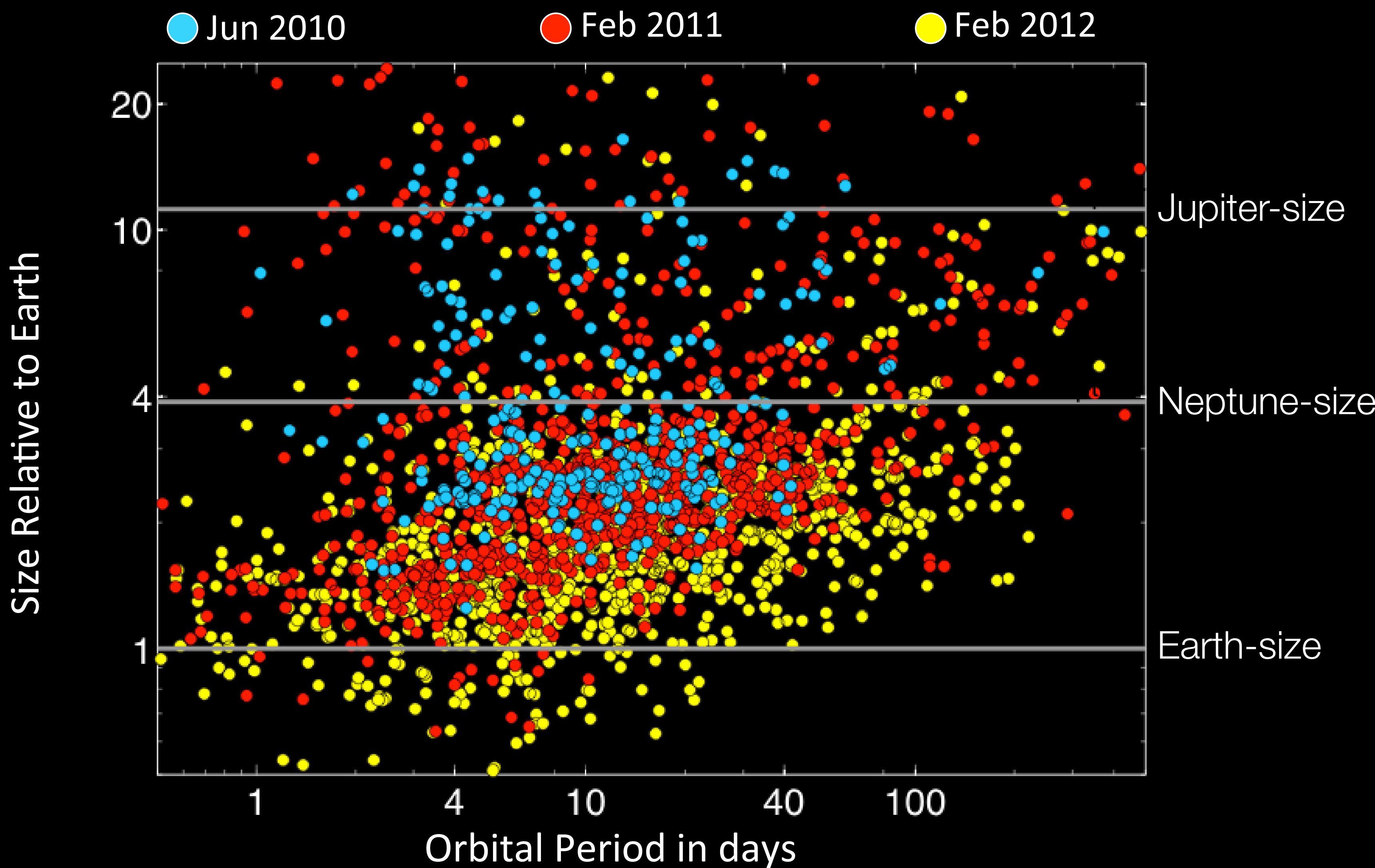
- Noise levels seen on-orbit for 12th magnitude dwarfs show a median of ~30 ppm instead of the design requirement of 20 ppm for 6.5 hr transits
- Investigation shows most "sunlike" stars are noisier than the sun on transit time scales
- Instrument performance is close to design value

Component	Variance (ppm^2)	Noise (ppm)	Baseline Noise (ppm)
Intrinsic stellar	380.5	19.5	10.0
Poisson + readout	283.0	16.8	14.1
Intrinsic detector	116.2	10.8	10.0
Quarter dependent	60.1	7.8	—
Total	839.8	29.0	20.0

Global roll-up of Kepler noise sources for 12th magnitude star. "Baseline Noise" are the noise levels assumed for photometer design.
From Gilliland, R. (2011) ApJS *197* 6

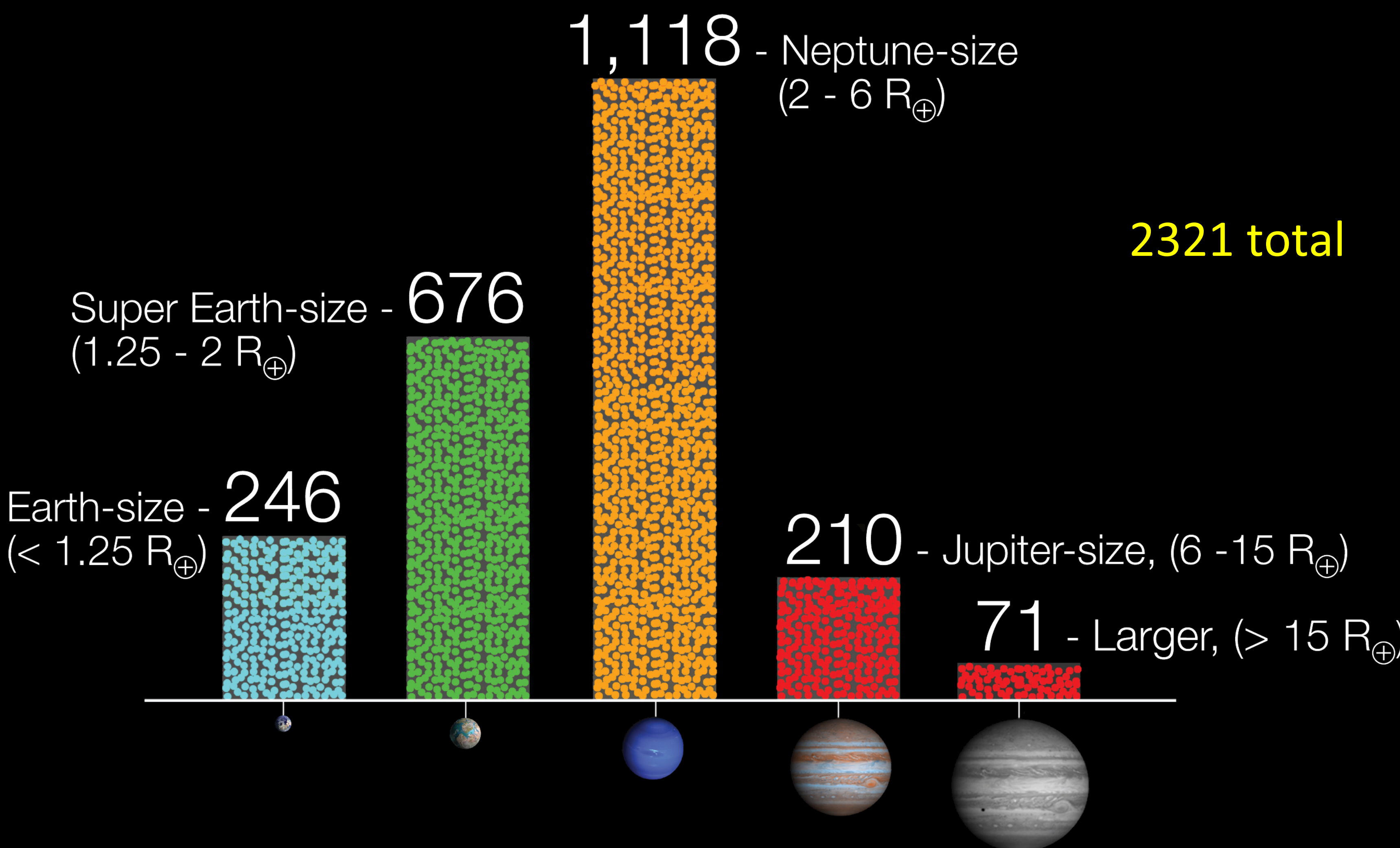
Candidates as of Feb 2012

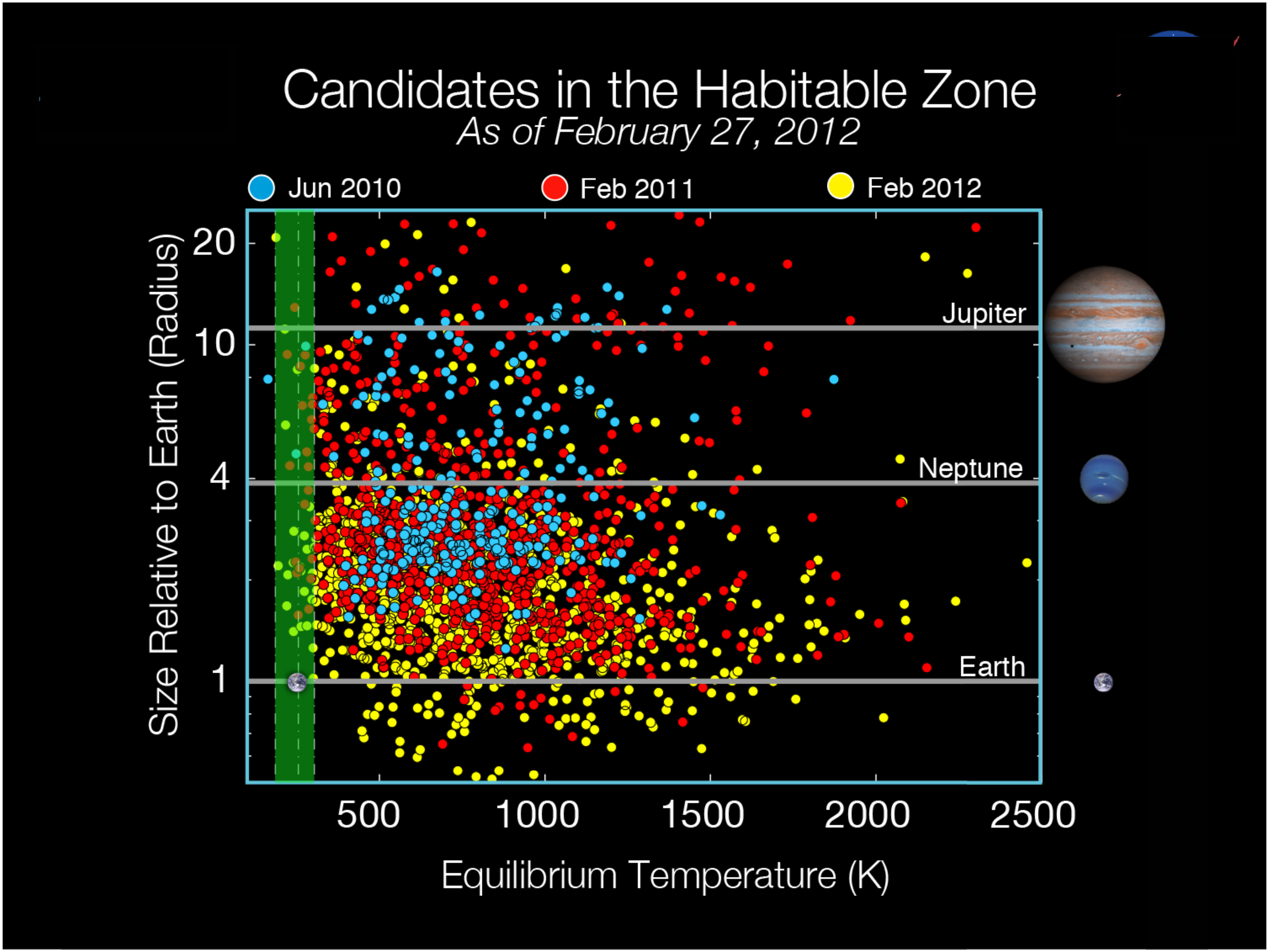
2321 total



Numbers of Planet Candidates

As of February 27, 2012

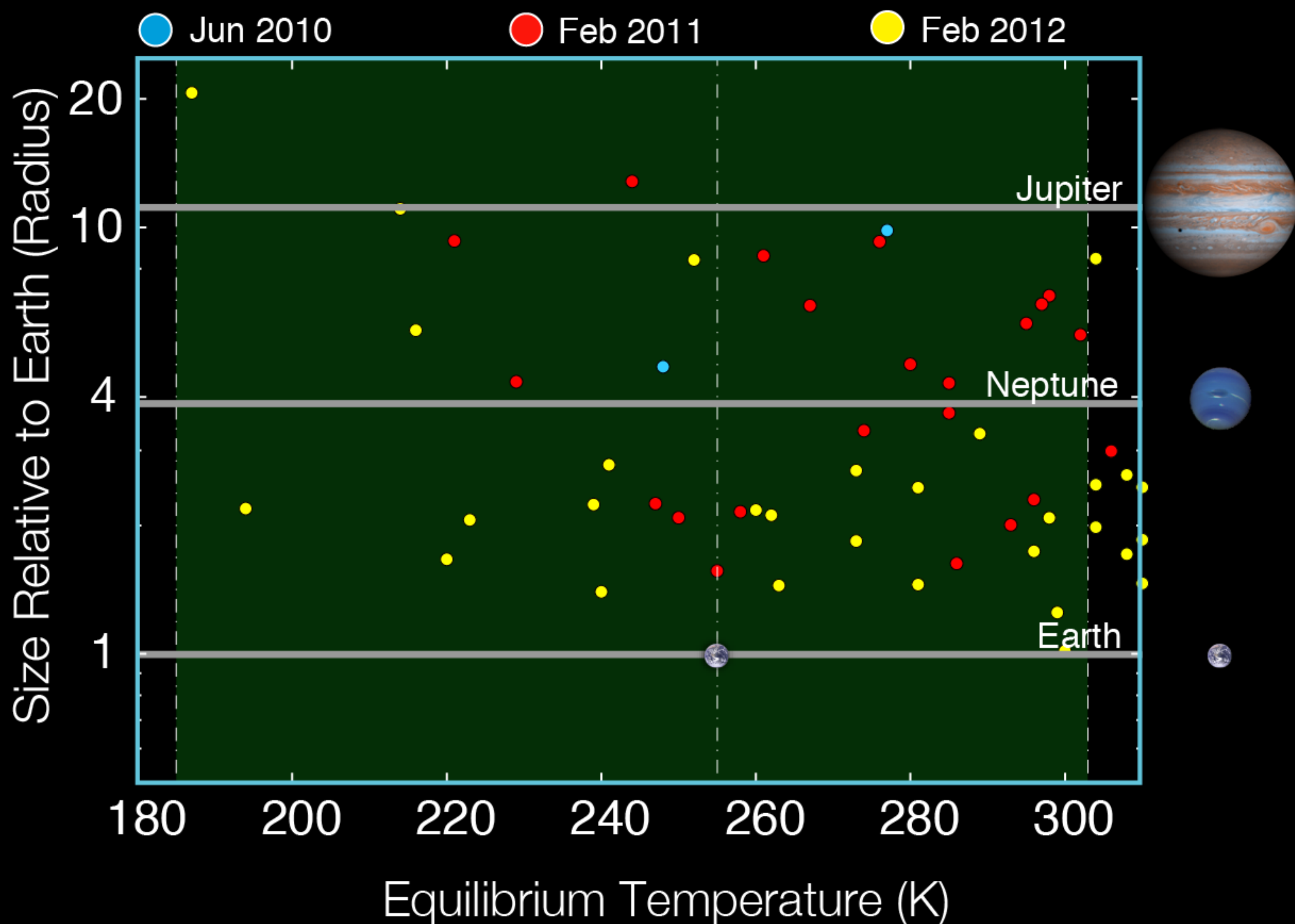


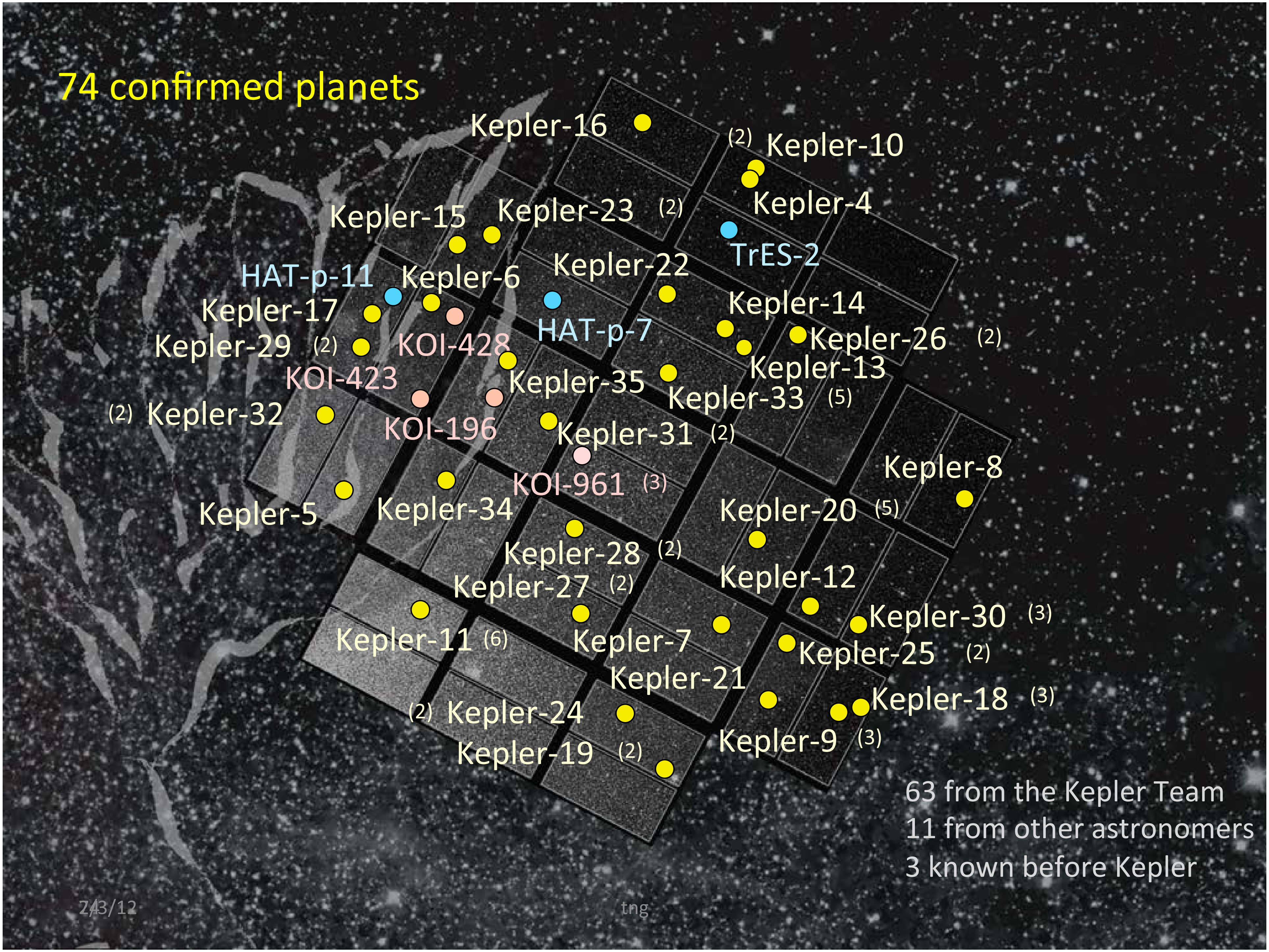


Candidates in the Habitable Zone
As of February 27, 2012
Jun 2010
Feb 2011
Feb 2012
Size Relative to Earth (Radius)
20
10
4
1
Jupiter
Neptune
Earth
500
1000
1500
2000
2500
Equilibrium Temperature (K)

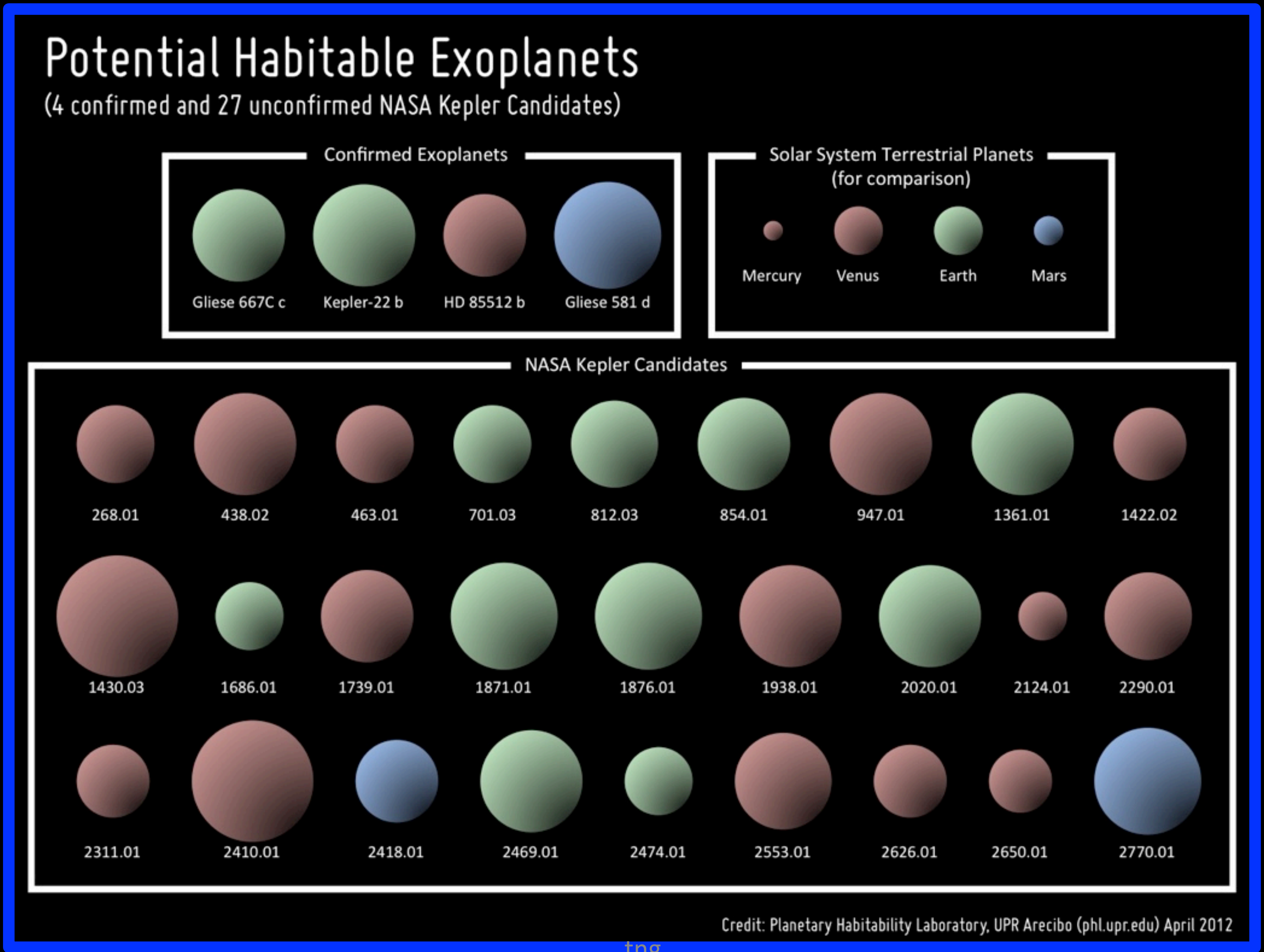
HZ Candidates

48 with T_{eq} between 185 and 303 K



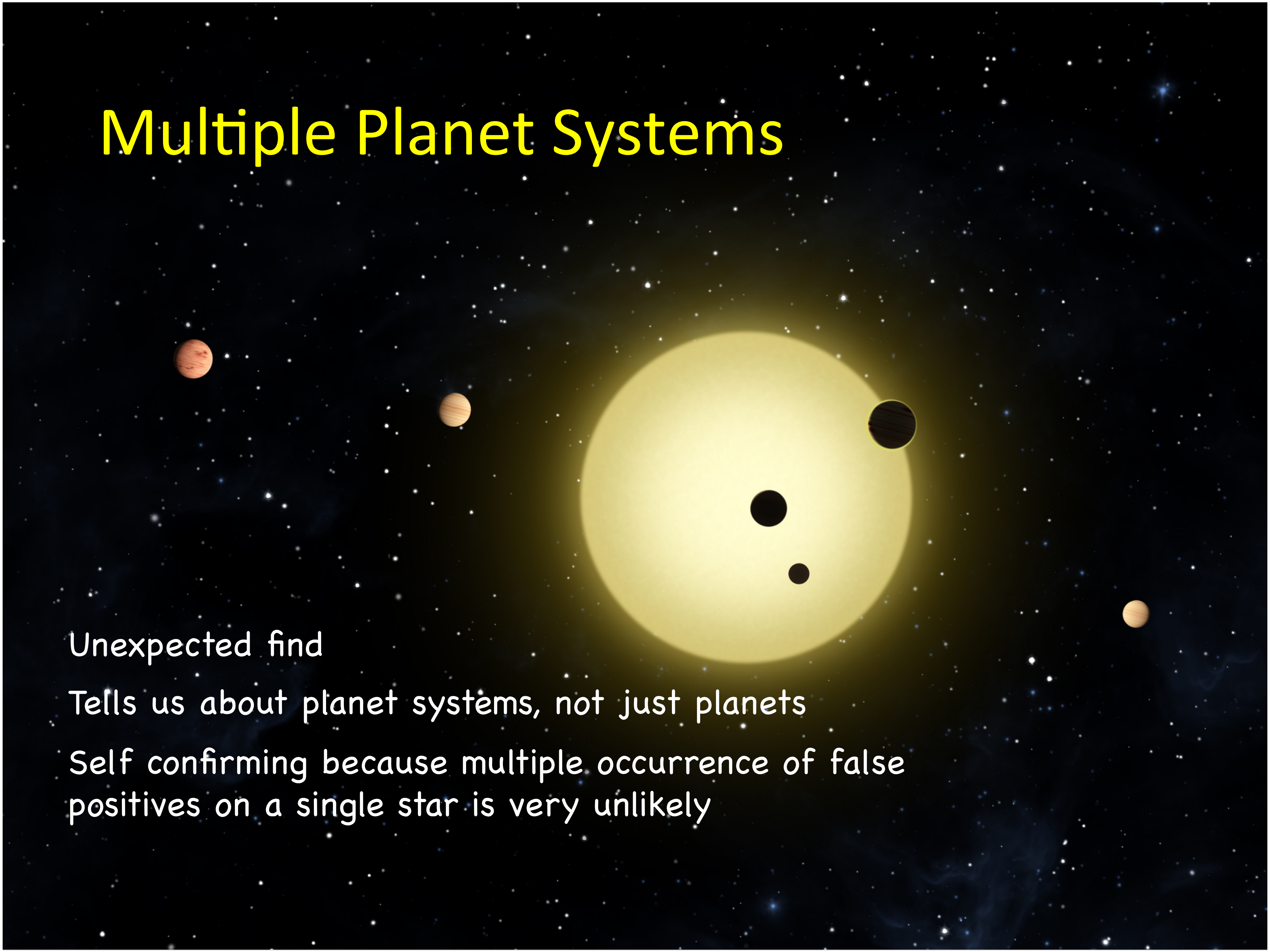

74 confirmed planets
Kepler-16
(2) Kepler-10
Kepler-4
Kepler-15
Kepler-23 (2)
TrES-2
HAT-p-11
Kepler-6
Kepler-22
Kepler-17
HAT-p-7
Kepler-14
Kepler-26 (2)
Kepler-29 (2)
KOI-428
Kepler-13
KOI-423
Kepler-35
Kepler-33 (5)
(2) Kepler-32
KOI-196
Kepler-31 (2)
Kepler-8
KOI-961 (3)
Kepler-5
Kepler-34
Kepler-20 (5)
Kepler-28 (2)
Kepler-27 (2)
Kepler-12
Kepler-30 (3)
Kepler-11 (6)
Kepler-7
Kepler-25 (2)
Kepler-21
Kepler-18 (3)
(2) Kepler-24
Kepler-19 (2)
Kepler-9 (3)
63 from the Kepler Team
11 from other astronomers
3 known before Kepler
2/13/12
tng

Many habitable zone planets.
Lots of Earth-size planets.
No confirmed Earth-size HZ planet yet. But soon!



Batalha et al. 2012, arXiv: 1202.5852

Multiple Planet Systems



Unexpected find

Tells us about planet systems, not just planets

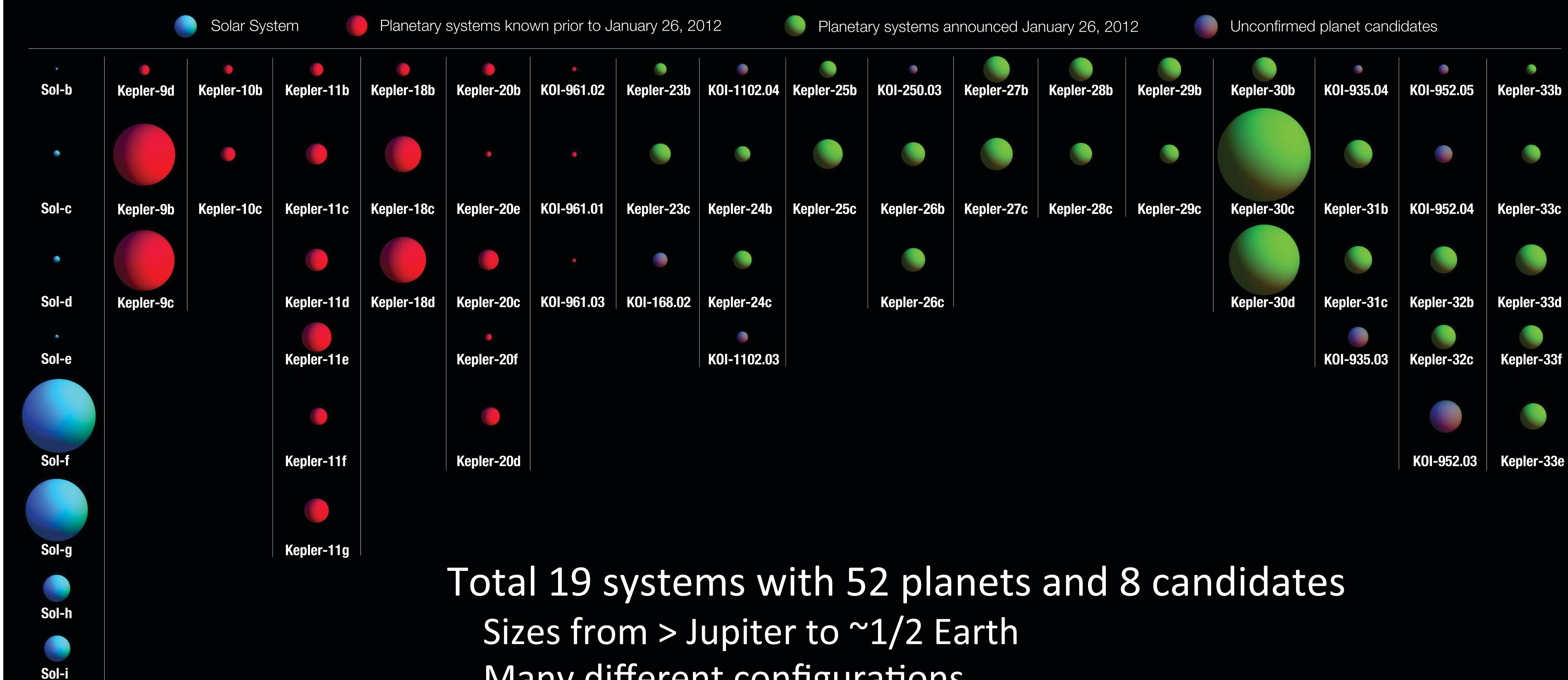
Self confirming because multiple occurrence of false positives on a single star is very unlikely

Multi-planet systems

- Feb 2012 candidate catalog
  - 2321 candidates around 1791 unique stars
  - 365/1791 stars host multiple candidates
  - 898/2321 candidates are part of multiple systems
  - Fraction of stars with multiple systems: 20%

- Expect to soon publish paper confirming ~800 of these candidates based on their presence in multiple planet systems.
  - This method explained in Lissauer, J. (2011) ApJ *750* 112

Kepler's Confirmed Multiple Planet Systems



Total 19 systems with 52 planets and 8 candidates

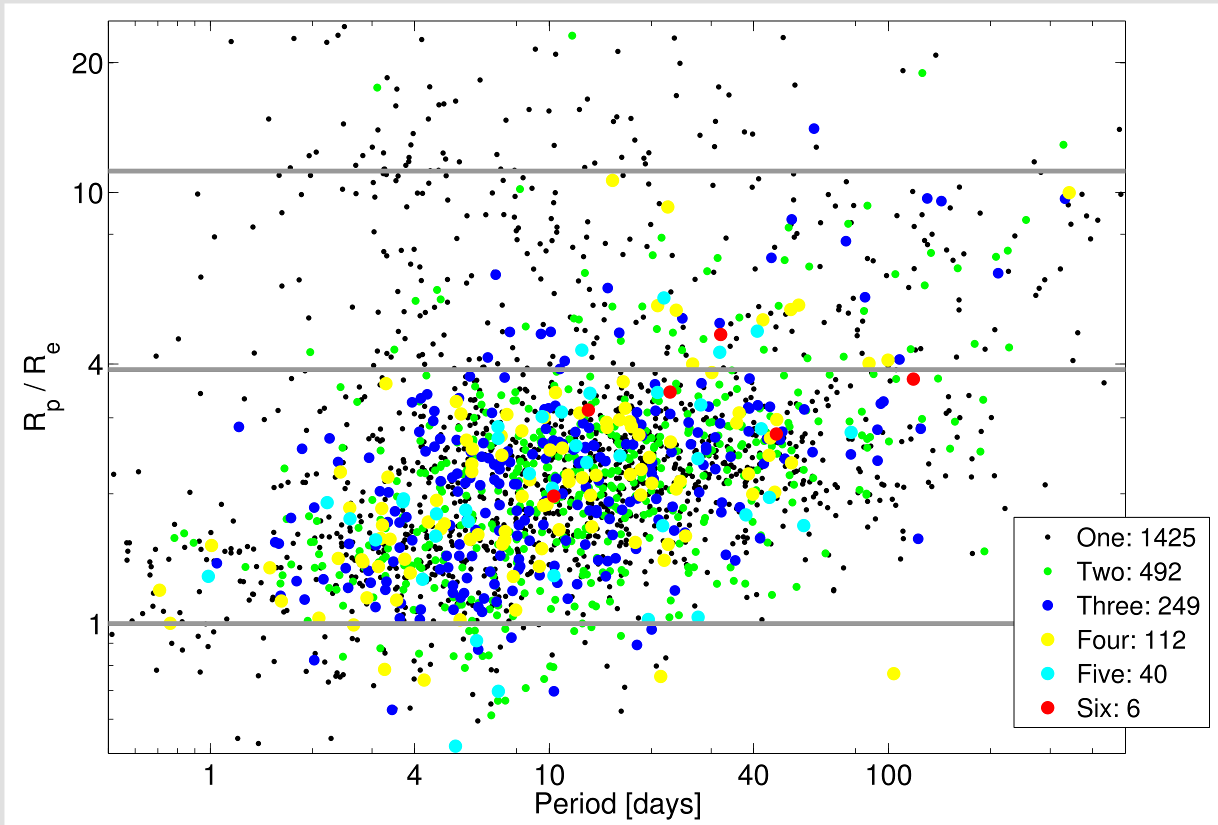
- Sizes from > Jupiter to ~1/2 Earth
- Many different configurations

(2 systems post date this chart)

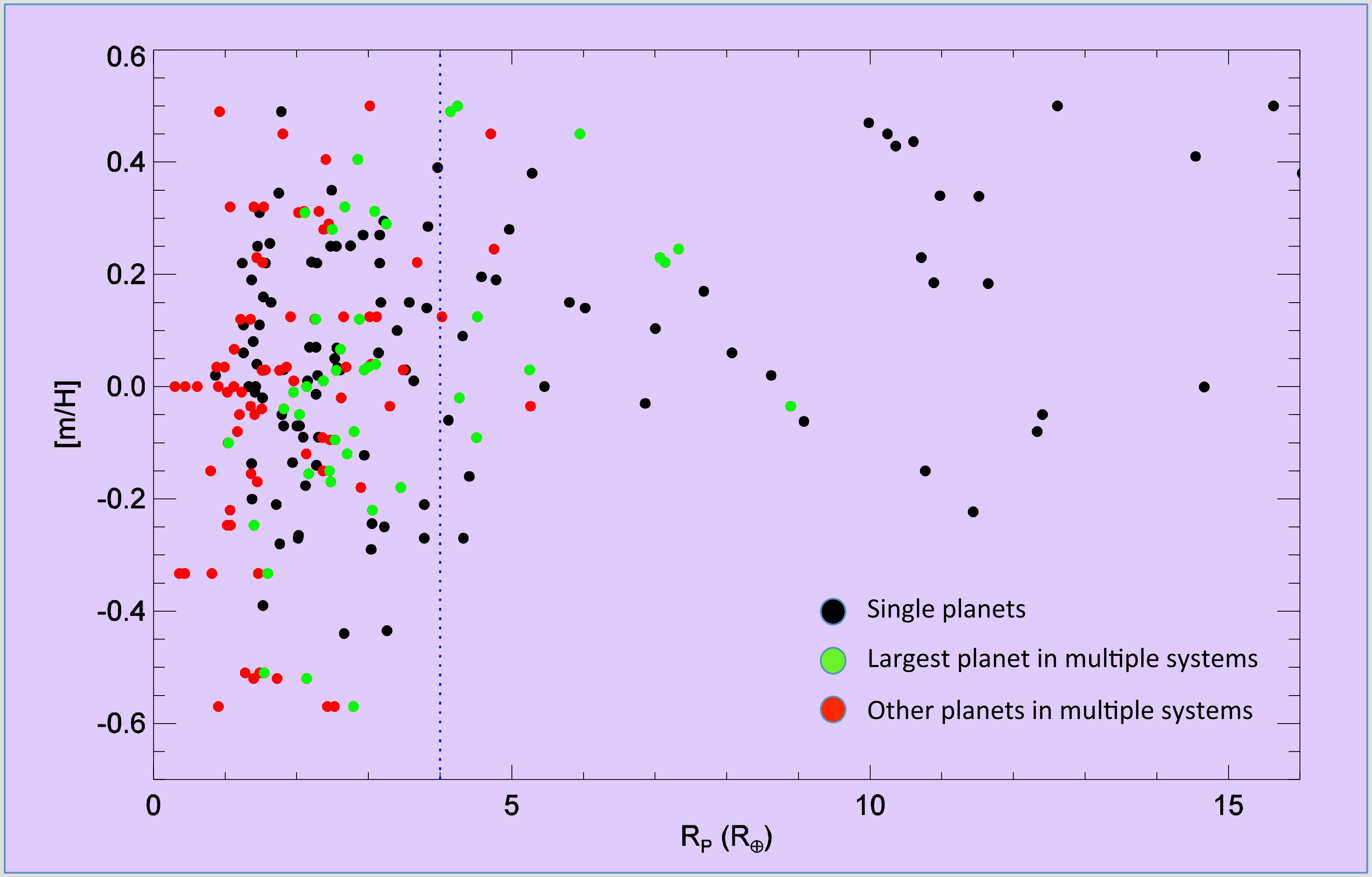
Hot Jupiters are Lonely

Dearth of short period (hot) giant planets in multi-planet systems persists

(Latham, et al. 2011, ApJ, **732**, L24)



Giant Planets Need Metals



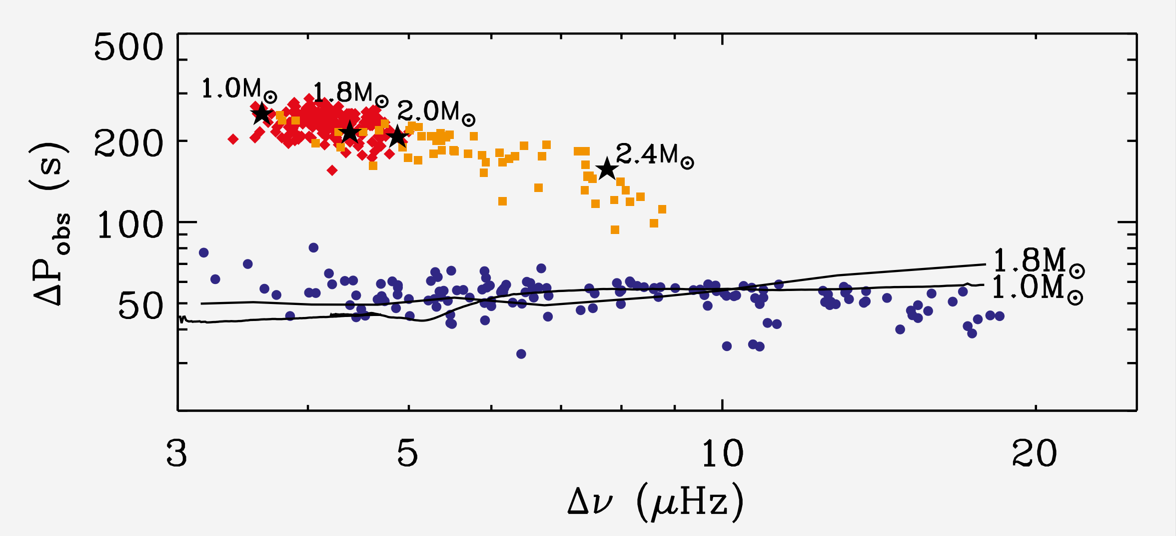
Buchhave, L. (2012) Nature, Vol. 486, pg. 375

Results - Astrophysics

- Kepler's 20 ppm precision provides unprecedented sensitivity for studying stellar variability
  - Kepler is a watershed for many aspects of stellar physics
- Lots of interesting new objects, hierarchical multiple systems, eccentricity driven ringing, many more …
- Big deal is asteroseismology
  - Acoustic oscillations in stars can be seen as small brightness variations on time scales of minutes to hours
    - Analysis gives stellar parameters: mass, T_{eff}, age
    - Probes internal structure of stars
  - Thousands of stars being observed at 30 minute cadence
  - More thousands are rotated monthly into the 1000 targets that Kepler can sample at 1 sec cadence

Core Helium vs. Hydrogen Shell Burning Stars

Red giant stars burning helium in their cores are nearly indistinguishable photometrically from those burning only hydrogen in a shell during part of their evolution.



Plotting pressure mode spacings (X axis) from the envelope vs gravity mode spacings (Y axis) from the core clearly separate H shell burning stars (blue points) from He core burning stars (red and orange points).

From Bedding, T. (2011) Nature *471* 608

What's Next

- Now have well over 3000 planet candidates
  - Search of 10 quarters of observations
  - Publication of a new candidate list to occur this fall
    - Small radii, longer orbits
- Radial velocity work to measure masses of some smaller planets
  - Get densities to find the transition from gassy and icy planets to rocky planets in the 2.5 – 1 R_{earth} region.
- Extended mission
  - 3.5 year prime mission will end in November with Q15
  - Extended mission will then start to provide a total of 7.5 years of data which should make up for higher than predicted stellar noise level
  - Fill in the area of the plot to see HZ earths around G type dwarfs
- Continue with marvelous astrophysics

Kepler Extended Mission Target:

Habitable Zone Earths