The Kepler Follow-up Observation Program

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and
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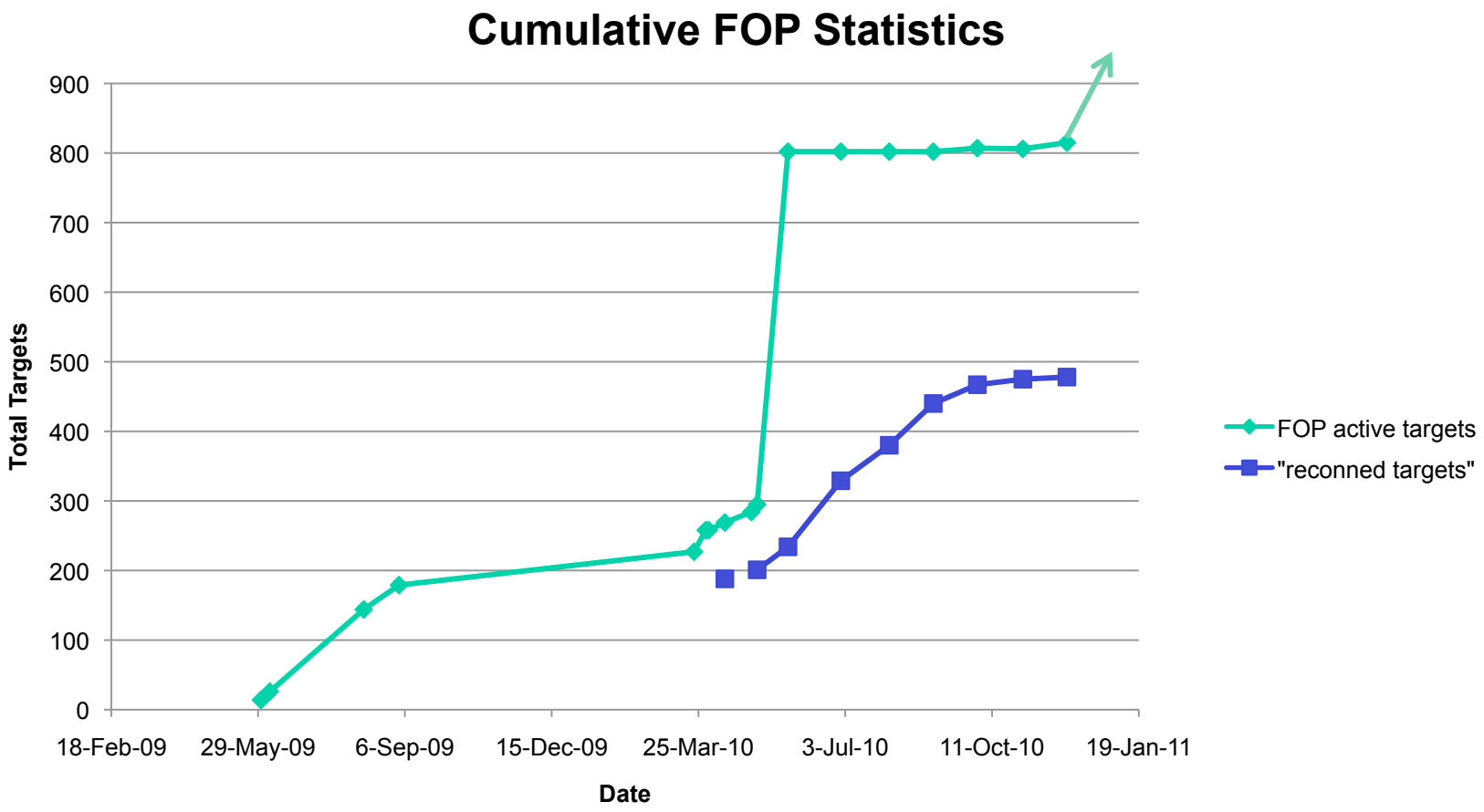
SAO

STScI

Kepler Progress to date

- Just finished 7th quarter of observations (Q0-Q7)
  - 2 May 2009 through 22 Dec 2010
  - Planet search through Q6
- ~160,000 star observed (varies by quarter)
- >700 Kepler Objects of Interest (KOIs) identified
  - A KOI is a series of transit-like signals with a definite period
    - Exclude eclipsing binaries as best we can from shape of light curve
  - Periods from <1 day to several hundred days
    - Planet search approaching complete for P<45 days
    - Only recently began automatic search for P>45 days
      - *Picking up smaller and longer period planet candidates*
- >700 planet candidates
  - Most <4 Earth-radii in size. Many multiple-planet systems.
  - This is terra incognita in astrophysics and planetary science, with no equivalent mission definitely on the horizon.

FOP KOI status



KOI follow-up Protocol

- Need to find false positives (KOIs due to eclipsing binaries, etc.)
- Need to refine host star characteristics, show RV variation consistent with a planet and measure planet mass where possible
- Protocol
  - Centroid motion analysis with Kepler data to ensure that the Kepler target is the source of the transit signal
    - Finds background eclipsing binaries
  - High resolution, moderate SNR spectroscopy
    - Refine host star characteristics
    - Look for large RV variations => stellar mass object produces transit signal
  - High resolution imaging (AO or speckle) to find nearby background stars for input to centroid motion analysis
  - High resolution, high SNR spectroscopy for precision RV measurements
    - RV variation consistent with planetary mass object
    - Measure planet mass or constrain masses to systems with transit timing variations
    - Rossiter-McLaughlin measurements
  - Co-analysis of photometry and RV to identify EBs in hierarchical systems (BLENDER)

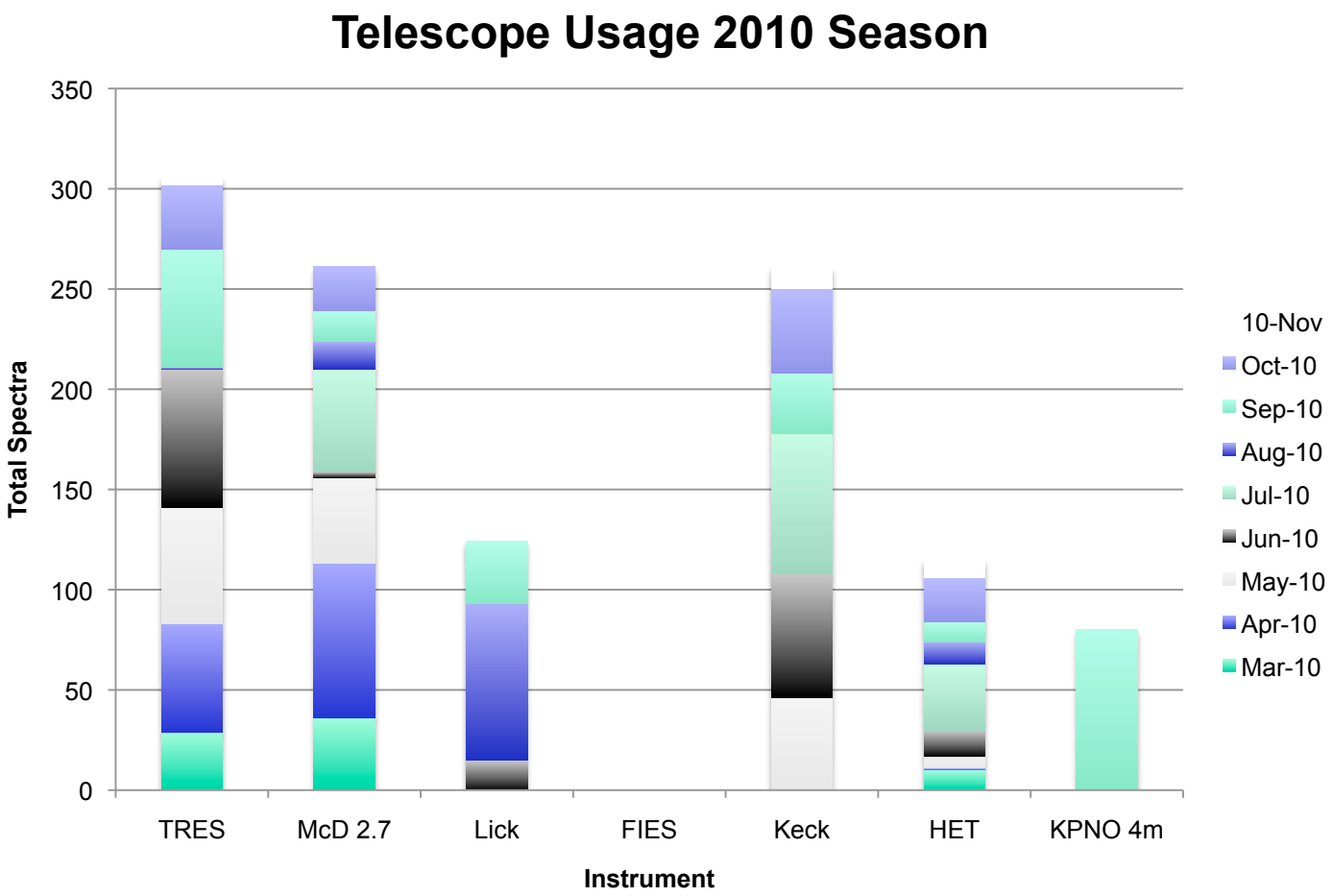
Kepler RV Follow-up

- Kepler RV follow-up observations have 2 key purposes
- Verify planet's existence
  - Moderate precision (100 m/s) reconnaissance spectroscopy looks for RV variation consistent with stellar mass objects
  - High precision (1-10 m/s) spectroscopy
    - Mass consistent with planetary mass
    - RM measurement verifies planet and measures orbit inclination
- Determine planet's mass
  - Gives density to distinguish rocky from liquid or gaseous planets
  - Current Precision of 1-3 m/s typically gets only more massive planets in short period orbits
  - Need 0.5-1 m/s or better for Earth mass planets (Earth itself shows 10 cm/s reflex velocity)

Kepler RV Requirements

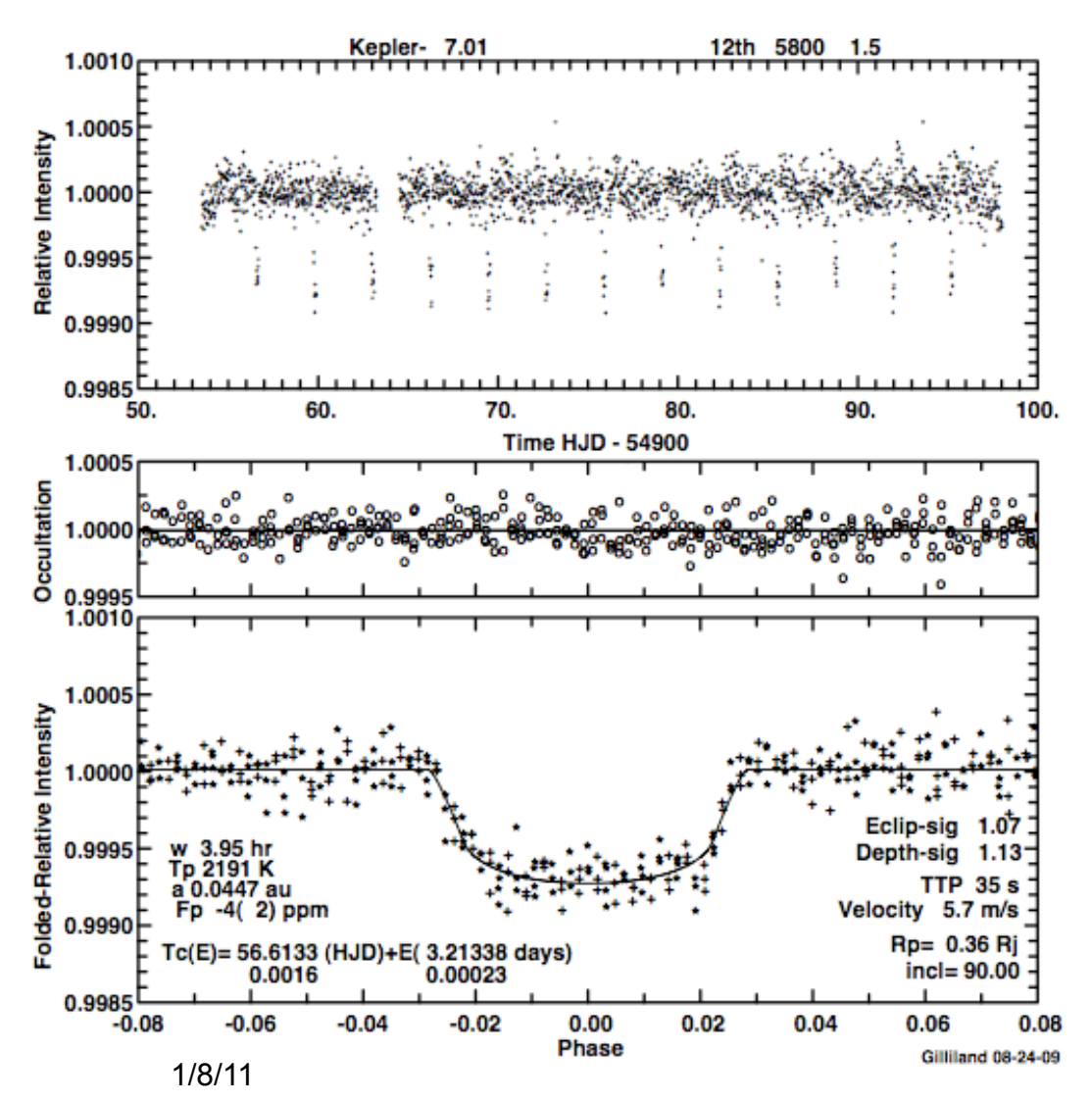
- Four precision RVs obtained at quadrature are the bare minimum for planet confirmation and mass measurement (more needed if orbit is eccentric)
  - Kepler-10b and CoRoT-7b show that ~40 precision RVs are needed to ensure detection and mass accurate to 10% (CoRoT-7b remains uncertain after 100 RVs.)
- Kepler stars typically have V=13-16
- Lick and HET are stretched to reach V=12 in 1 hour
- At V=14 most stars require 8m class telescopes
  - Subaru, Gemini, Keck
  - Though using 3.6 m telescope HARPS is competitive with the current Keck HIRES
  - The HARPS-N Collaboration will have 80 nights/yr guaranteed time (half for Kepler work) on a 3.6 m telescope

FOP Telescope Usage - 1



500 high precision RV spectra in 2010 to confirm 10 planets in 4 systems

Kepler-4

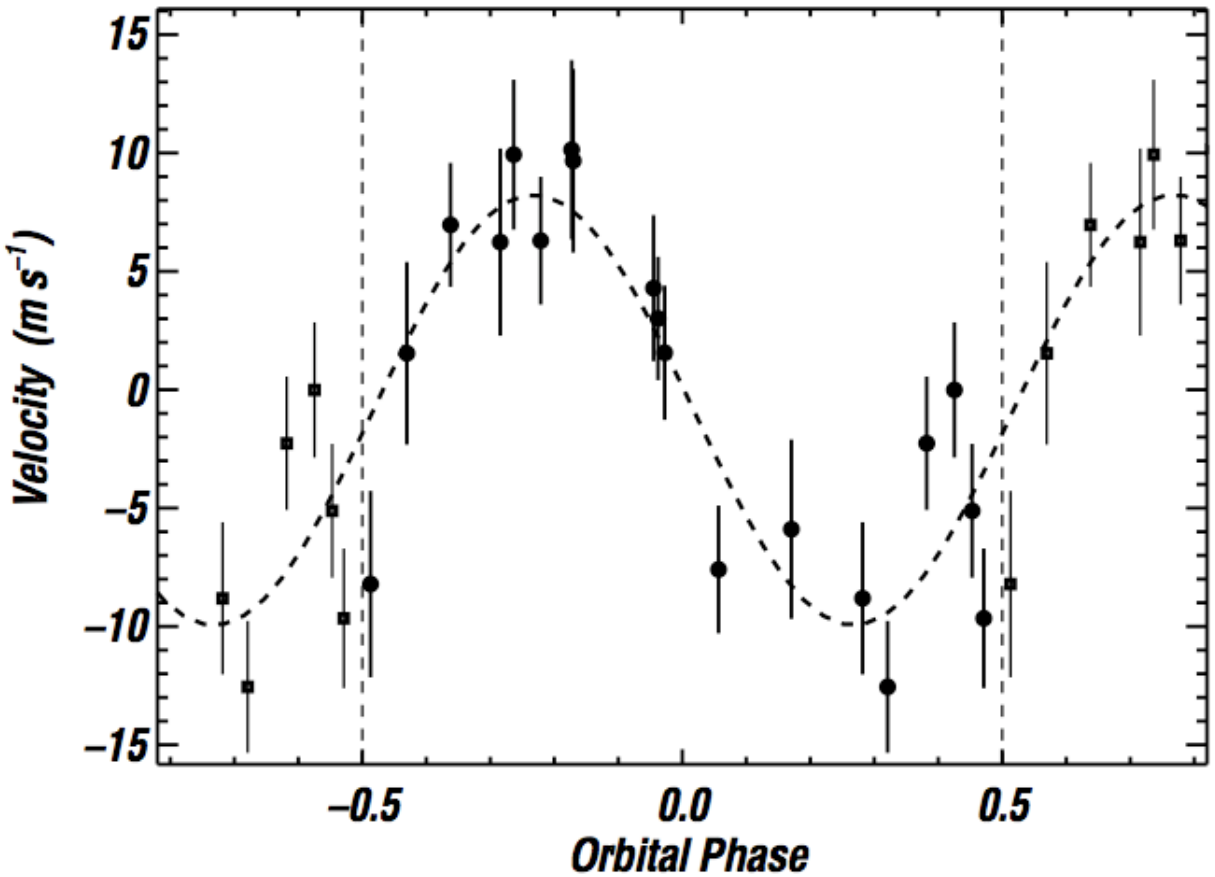


P = 3.21338d

R = 0.36 R_{JUP}

Kepler-4: RV from HIRES

Circular Orbit: adequate fit



RMS = 3.3 m/s

Planet Radius vs Mass

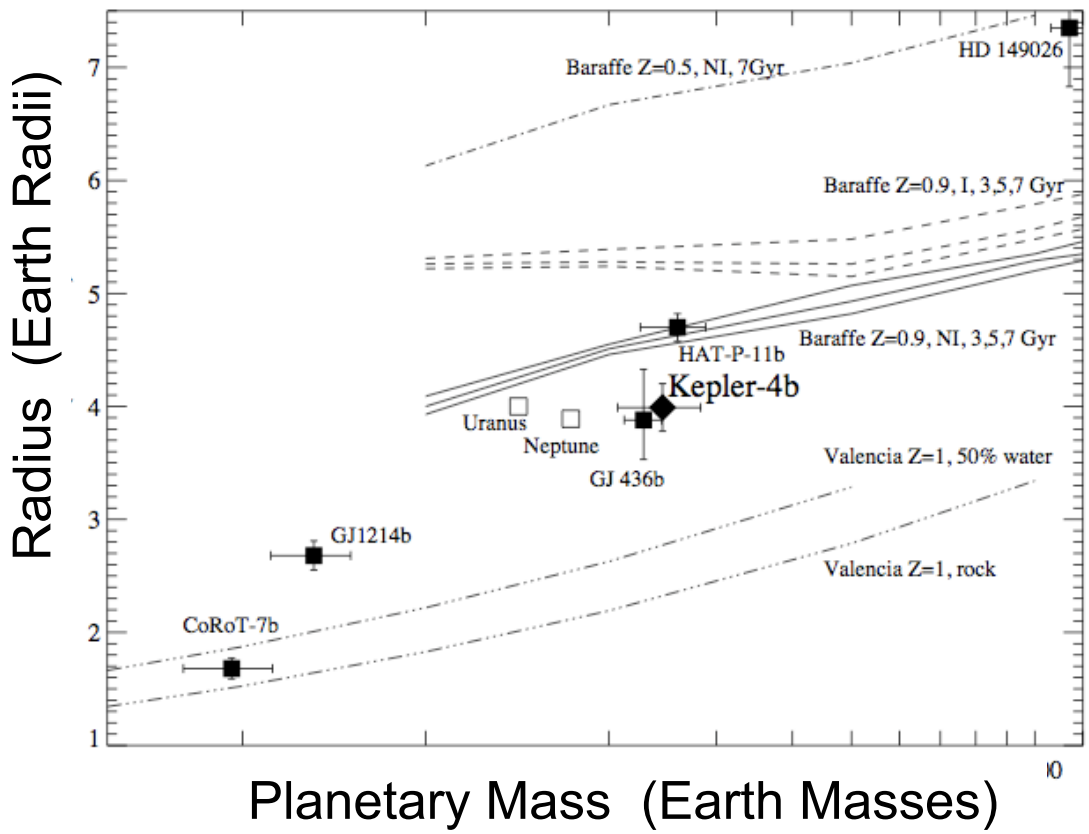
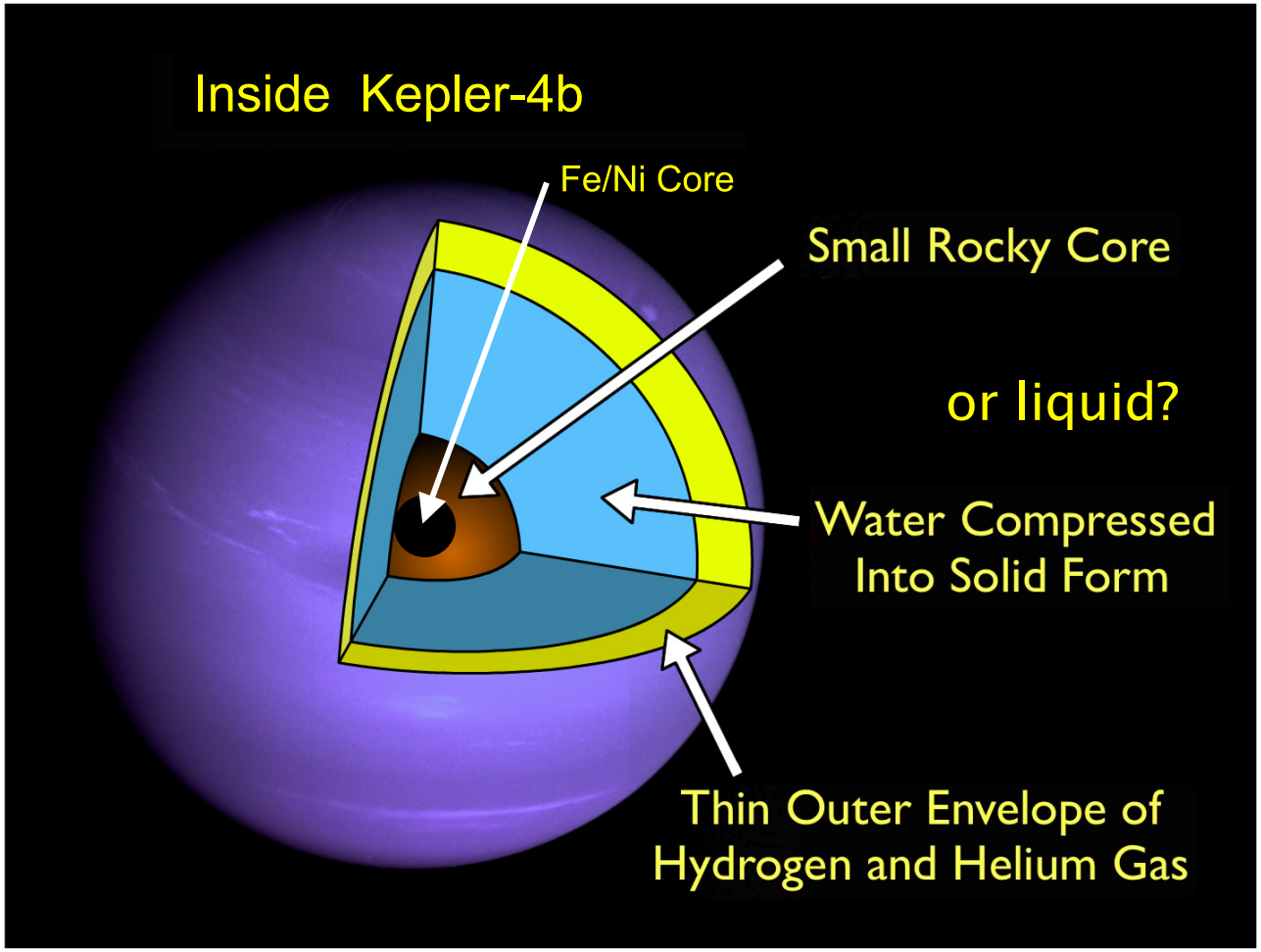


Fig. 4.— Kepler-4b is shown in a mass-radius plot, along with other hot Neptunes, the hot super-Earths CoRoT-7b (Léger et al. 2009; Queloz et al. 2009) and GJ1214b (Charbonneau et al. 2009), and model curves by Baraffe, Charbrier, & Barman (2008) and by Valencia, Sasselov, & O'Connell (2007), showing increasing heavy-element fractions toward the bottom of the Figure. Multiple dashed and solid curves show model results for differing ages; "I" indicates irradiated and "NI" non-irradiated models. Kepler-4b appears to be denser than HAT-P-11b but similar to GJ 436b, denser than the non-irradiated $Z = 0.9$ model by Baraffe, Charbrier, & Barman (2008), but much less dense than is expected for a water or rocky planet.

Inside Kepler-4b



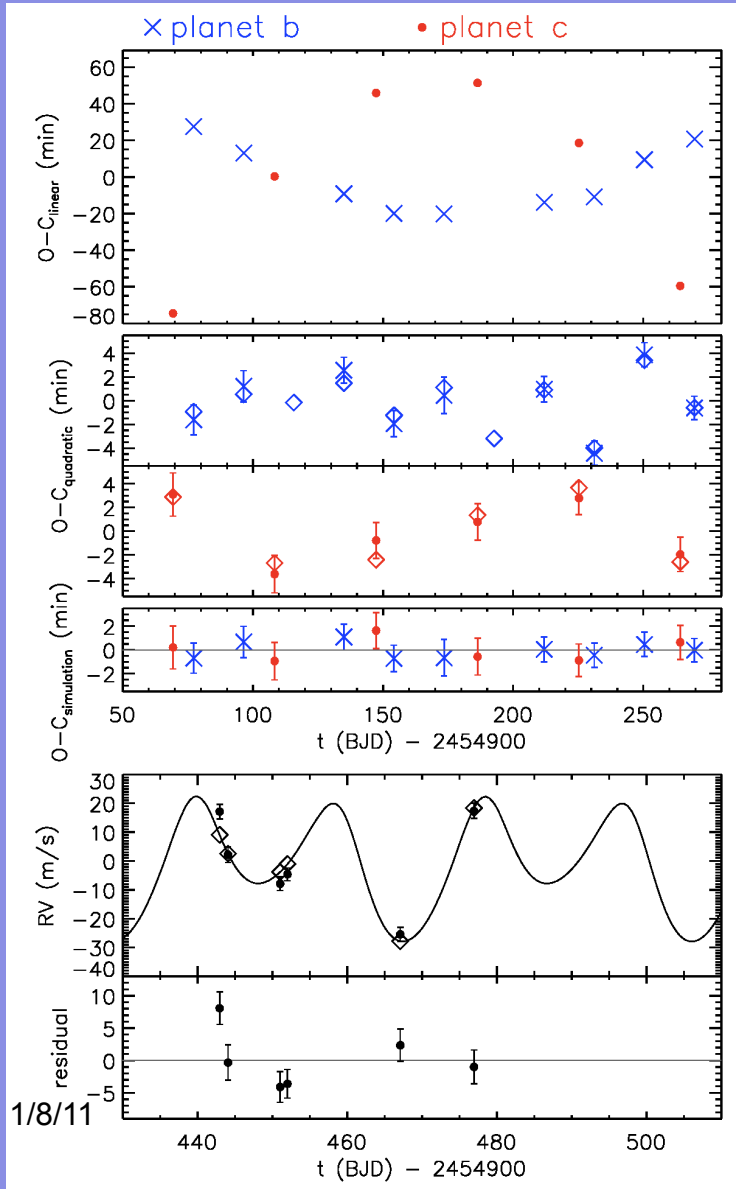
ρ = 1.9 gm/cc

Interior Structure:

Degeneracy:
Fe, Rock, Ice, Gas

Dave Stevenson,
Deming et al. 2007,
Chiang &
Murray-Clay 2007
Seager et al. 2008
Valencia et al. 2007
Figueira et al. 2009

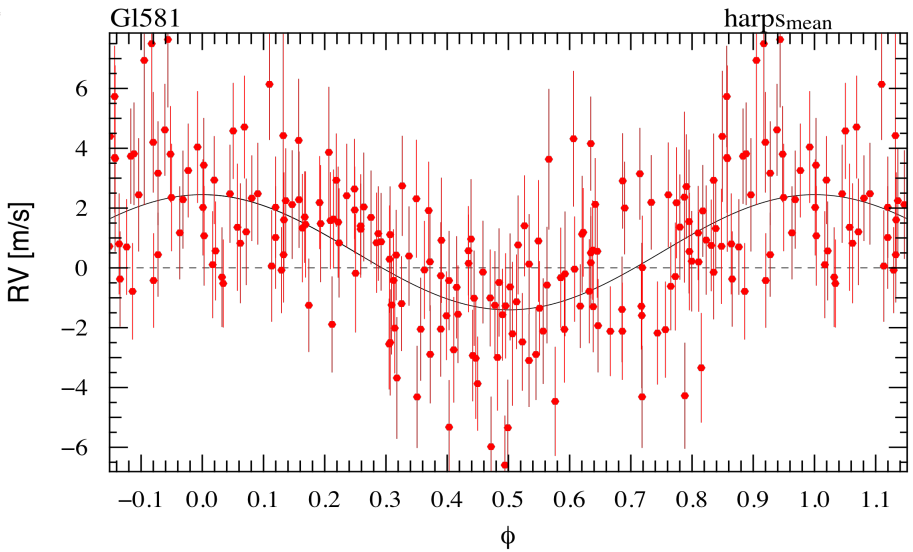
Model from Fortney, Marley, & Jones 2007



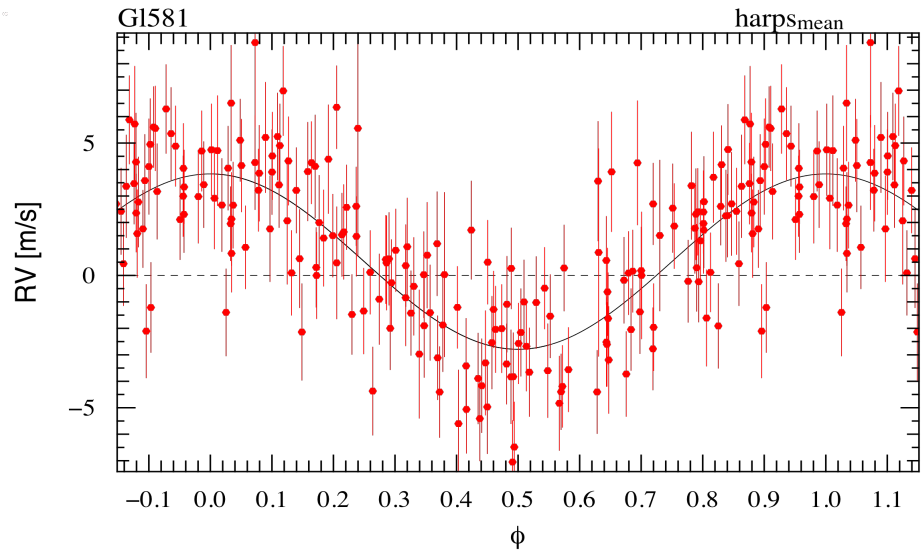
Kepler-9:

Two Saturn-size
Planets exhibiting TTVs,
verifying their existence..

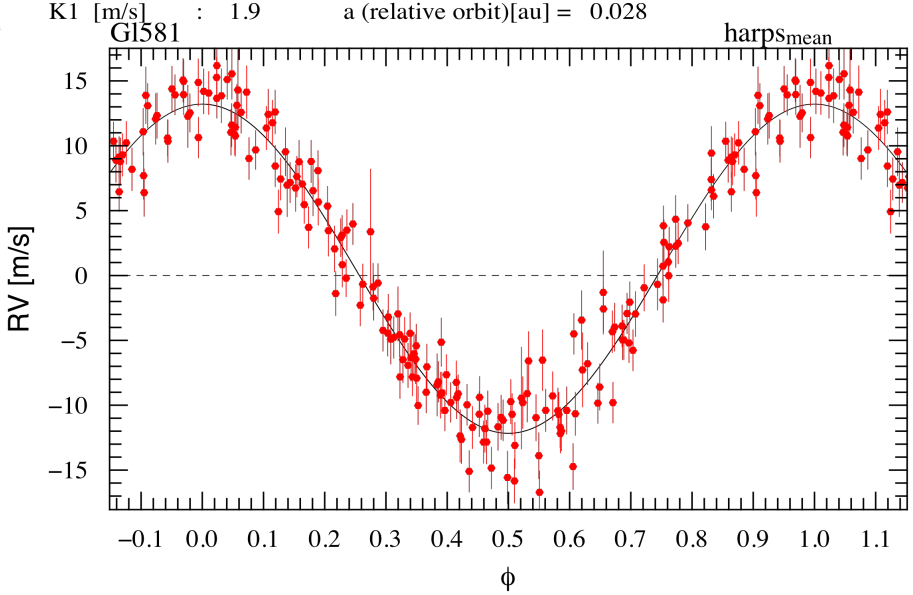
RVs from Keck constrain the planet masses 10x more precisely than from TTVs.



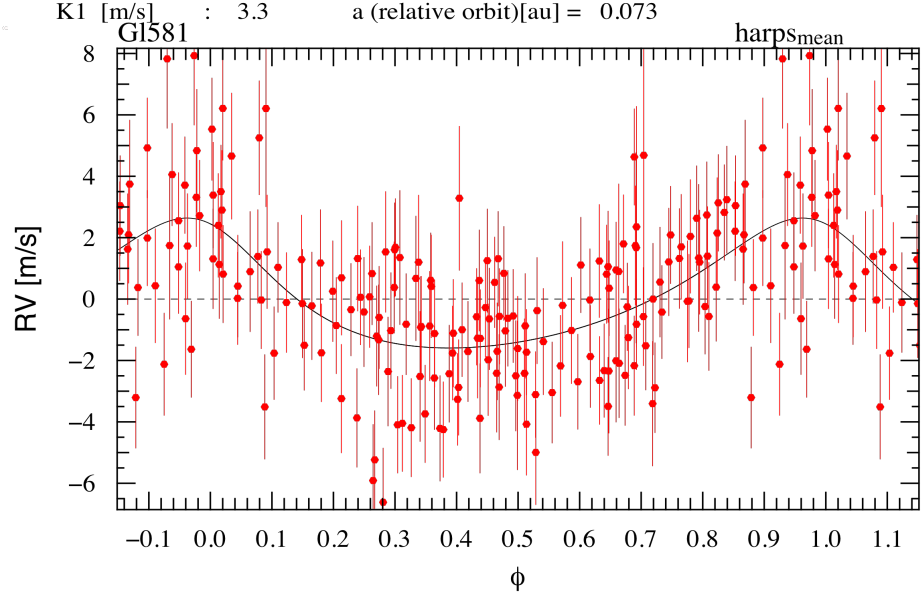
P [days] : 3.150 a_1.sin(i) [1E−3 au] = 0.00056
e : −0.000 f(m) [1E−9 Msol] = 0.00000
ω [deg.] : 0.0 m_1 [Msol]=0.31
phi$_0$: 54525.79 m_2.sin(i) = 0.00636[M_{jup}], 0.118[M_{nept}], 2.02[M_{earth}]
K1 [m/s] : 1.9 a (relative orbit)[au] = 0.028



P [days] : 12.917 a_1.sin(i) [1E−3 au] = 0.00393
e : −0.000 f(m) [1E−9 Msol] = 0.00005
ω [deg.] : 0.0 m_1 [Msol]=0.31
phi$_0$: 54529.76 m_2.sin(i) = 0.01752[M_{jup}], 0.324[M_{nept}], 5.57[M_{earth}]
K1 [m/s] : 3.3 a (relative orbit)[au] = 0.073



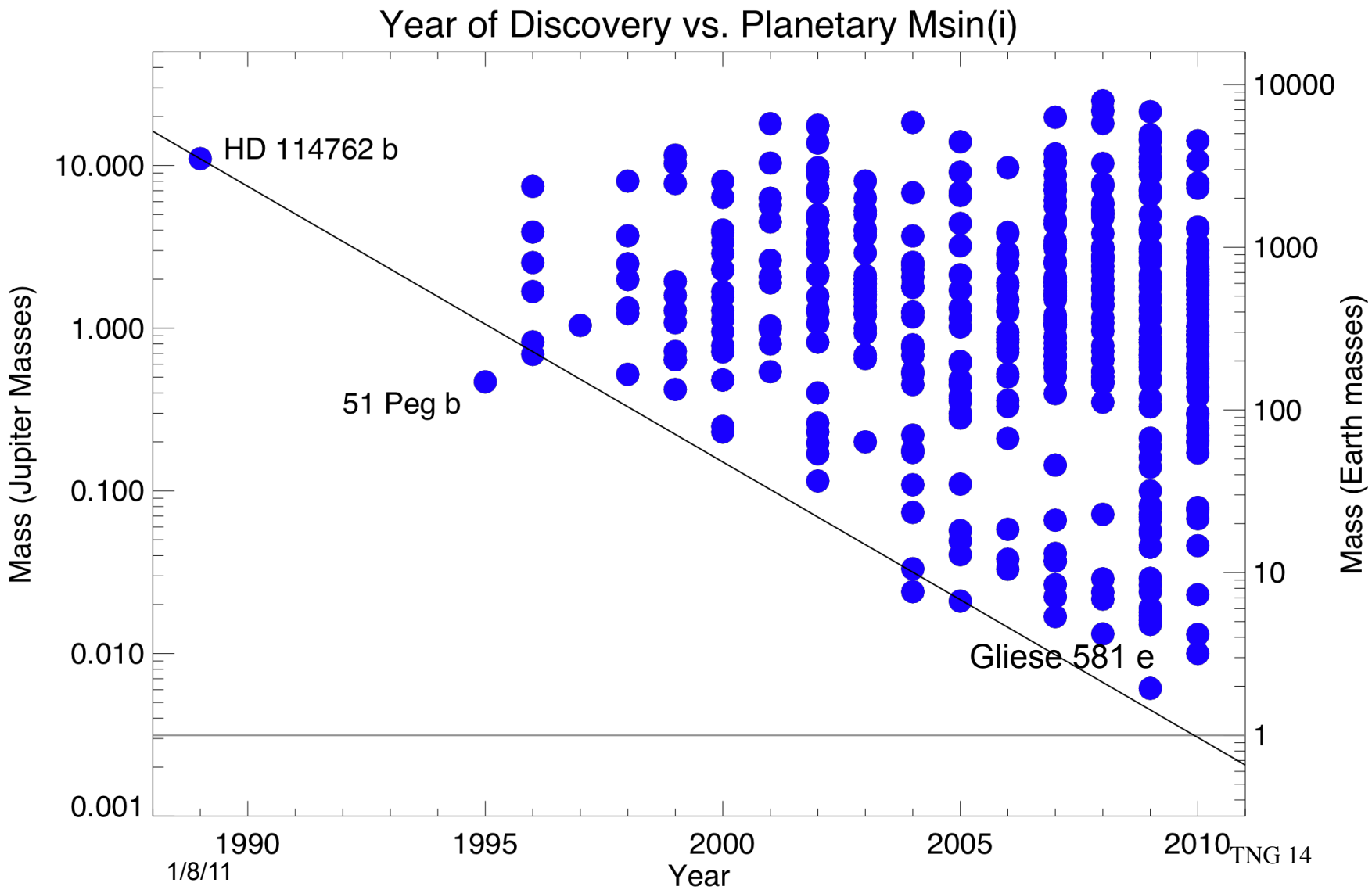
P [days] : 5.369 a_1.sin(i) [1E−3 au] = 0.00626
e : −0.000 f(m) [1E−9 Msol] = 0.00114
ω [deg.] : 0.0 m_1 [Msol]=0.31
phi$_0$: 54524.91 m_2.sin(i) = 0.05007[M_{jup}], 0.925[M_{nept}], 15.91[M_{earth}]
K1 [m/s] : 12.7 a (relative orbit)[au] = 0.041



P [days] : 66.641 a_1.sin(i) [1E−3 au] = 0.01248
e : 0.271 f(m) [1E−9 Msol] = 0.00006
ω [deg.] : 24.5 m_1 [Msol]=0.31
phi$_0$: 54538.75 m_2.sin(i) = 0.01861[M_{jup}], 0.344[M_{nept}], 5.92[M_{earth}]
K1 [m/s] : 2.1 a (relative orbit)[au] = 0.218

1/8/11

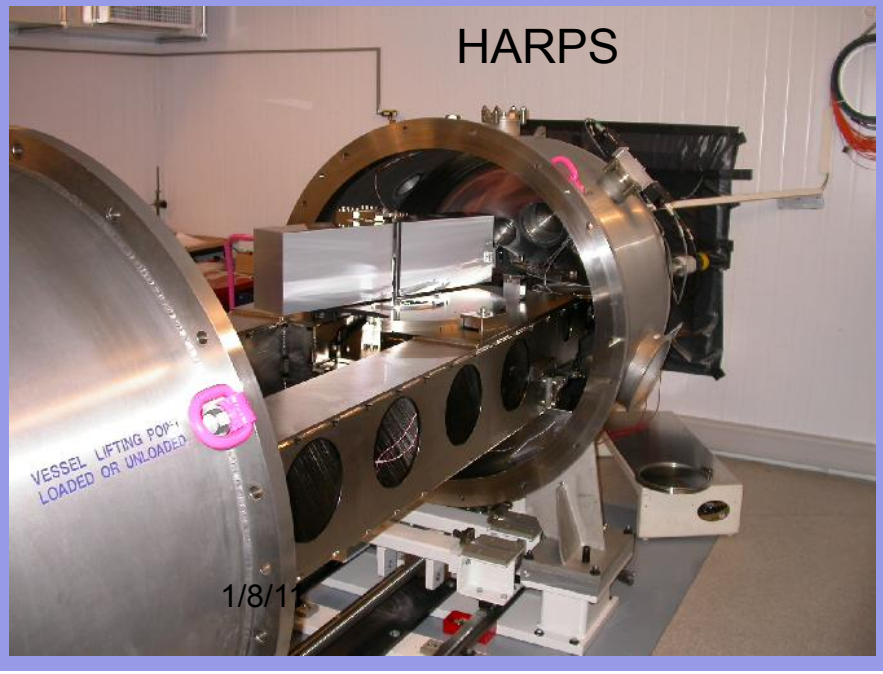
TNG 13

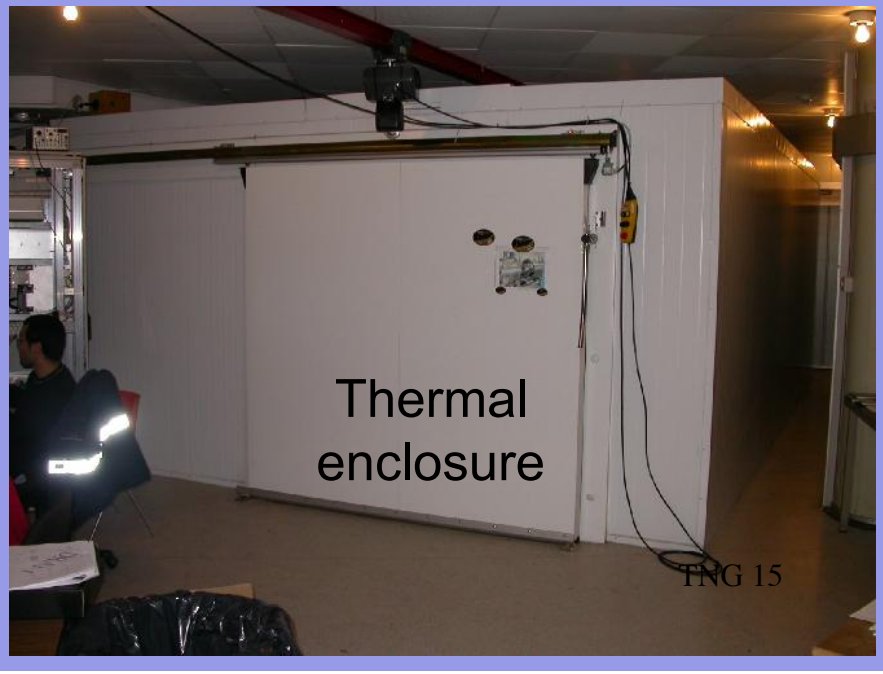

Year of Discovery vs. Planetary Msin(i)
HD 114762 b
51 Peg b
Gliese 581 e
Mass (Jupiter Masses)
10.000
1.000
0.100
0.010
0.001
Mass (Earth masses)
10000
1000
100
10
1
1990
1995
2000
2005
2010
Year

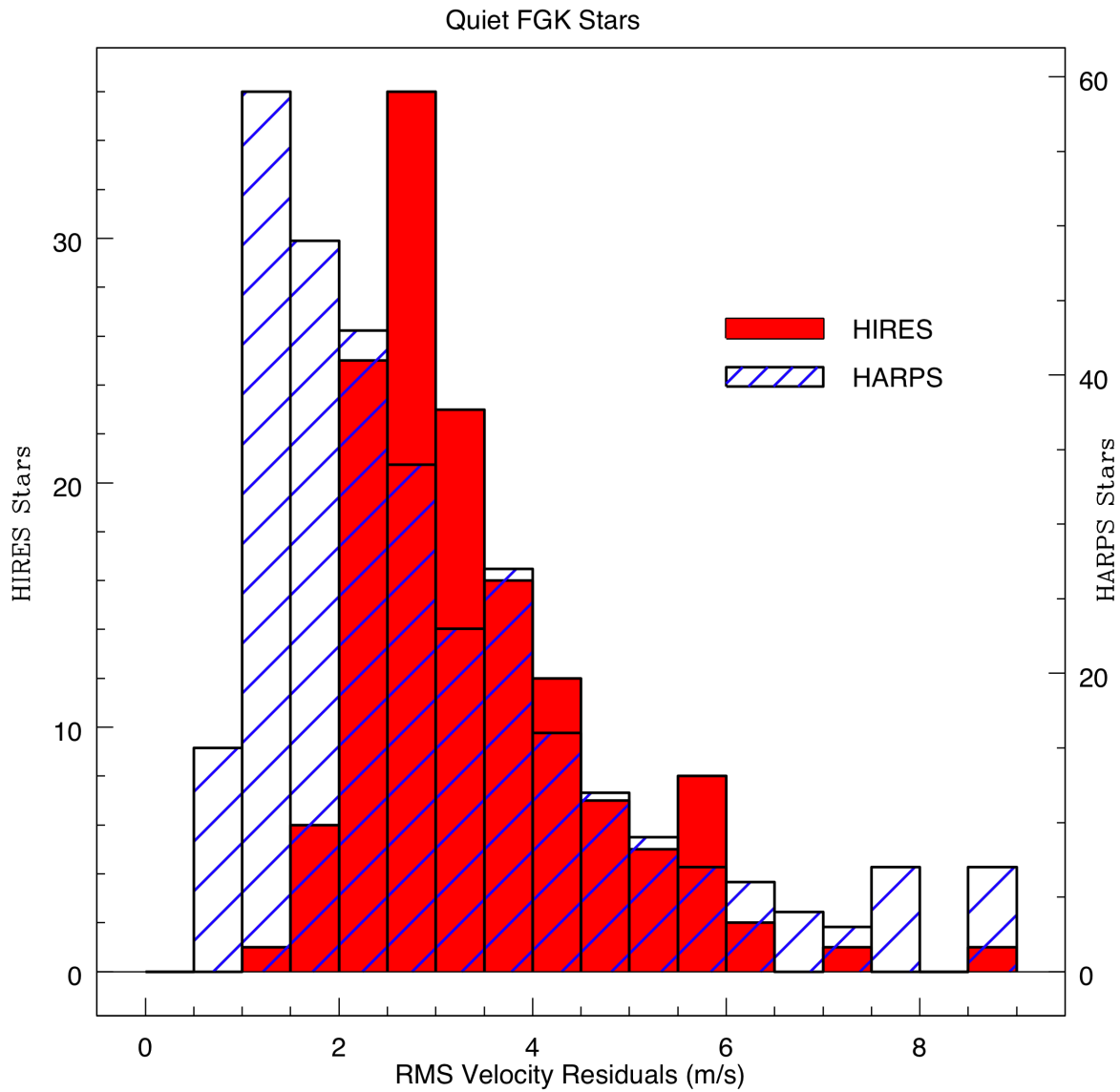
High Accuracy Radial velocity Planet Searcher

- Geneva Observatory
- Physikalisches Institut, Bern
- Haute-Provence Observatory
- Service d'Aeronomie, Paris
- ESO

Better than 1 m/s



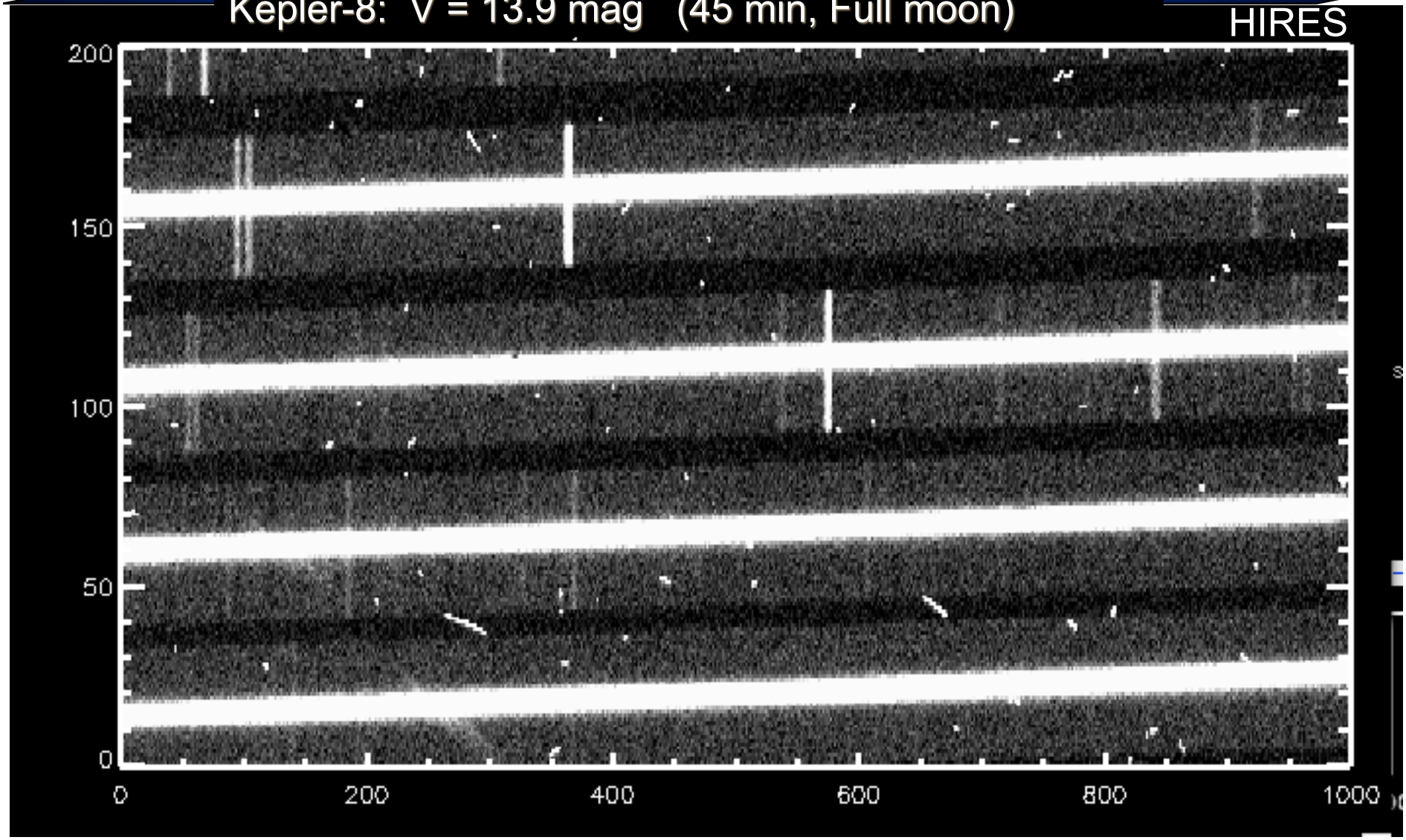



Quiet FGK Stars
HIRES
HARPS
HIRES Stars
HARPS Stars
RMS Velocity Residuals (m/s)
0
10
20
30
0
20
40
60
0
2
4
6
8

HARPS-N Collaboration:
Geneva, CfA, UK, INAF-TNG
HARPS-N Status
Formal agreements now signed
INAF guarantees 80 n/yr for 5 yr on 3.6m TNG
HARPS-N Collaboration: half for Kepler work
On schedule for 1 April 2012 first light
Fully funded
Francesco Pepe PI, Dave Latham Co-PI
tessi 2007

Precise Doppler at V > 13.5

Kepler-8: V = 13.9 mag (45 min, Full moon)



Current Situation

- With Kepler's current telescope and instrument resources we can only follow-up ~25 Earth-size candidates
  - Even with HARPS-N these will be confined to short period planets around lower mass stars
- To reap the benefits of the Kepler survey NASA needs to
  - Allocate more time on existing large telescopes with high precision RV instrumentation
  - Invest in modern spectrometer upgrades

Kepler Recommendations

- Kepler recommends allocation of additional time on Keck HIRES for planetary RV work
  - Kepler was given 20 nights last year. Progress will be proportional to time allocation.
- Kepler endorses the recommendations of the NRC 2010 Decadal Report and the Precise Radial Velocity community on instrumentation development.
  - Fund improvements to HIRES
    - Higher sensitivity, HARPS+ precision, sky subtraction
  - Fund research and development of 10 cm/s class RV instrumentation
    - Push down to 10 cm/s precision

Decadal Survey on "New Worlds: Seeking Nearby, Habitable Planets."

- The report describes a "New Worlds Technology Development Program" in which "NASA and NSF should support an aggressive program of ground-based high-precision radial velocity surveys of nearby stars to identify potential candidates.
  - *"…The first task on the ground is to improve the precision radial velocity method by which the majority of the close to 500 known exoplanets have been discovered… Using existing large ground--based or new dedicated mid--size ground-based telescopes equipped with a new generation of high--resolution spectrometers in the optical and near--infrared, a velocity goal of 10 to 20 centimeters per second is realistic...The role of target--finding for future direct--detection missions … can be done at least partially by pushing ground--based radial--velocity capabilities to a challenging but achievable precision below 10 centimeters per second." (p. 7--8)*
  - *"…Improve radial velocity measurements on existing ground-based telescopes to discover planets within a few times the mass of Earth as potential targets for future space-based direct-detection missions." (p. 7--10)*

The Precise Radial Velocity (PRV) Community Response to the NRC 2010 Decadal Report

Excerpts

- "Augment the existing program of PRV observations of Kepler candidates by obtaining observing time at existing facilities, both domestic and international, having the requisite instrumentation."
- "Support upgrades of existing spectrographs and building new PRV spectrographs on NASA-- and NSF--funded telescopes, with some of these upgrades or even new instruments proceeding on a rapid enough timescale to be valuable for Kepler follow--up."
- "Initiate an open, competitive program to develop advanced PRV spectrographs for existing U.S. observatories both in the optical and near--Infrared, especially those situated in the northern hemisphere."
- "Accelerate the development of PRV spectrographs by explicitly encouraging applications for technology fellowships in this area."

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