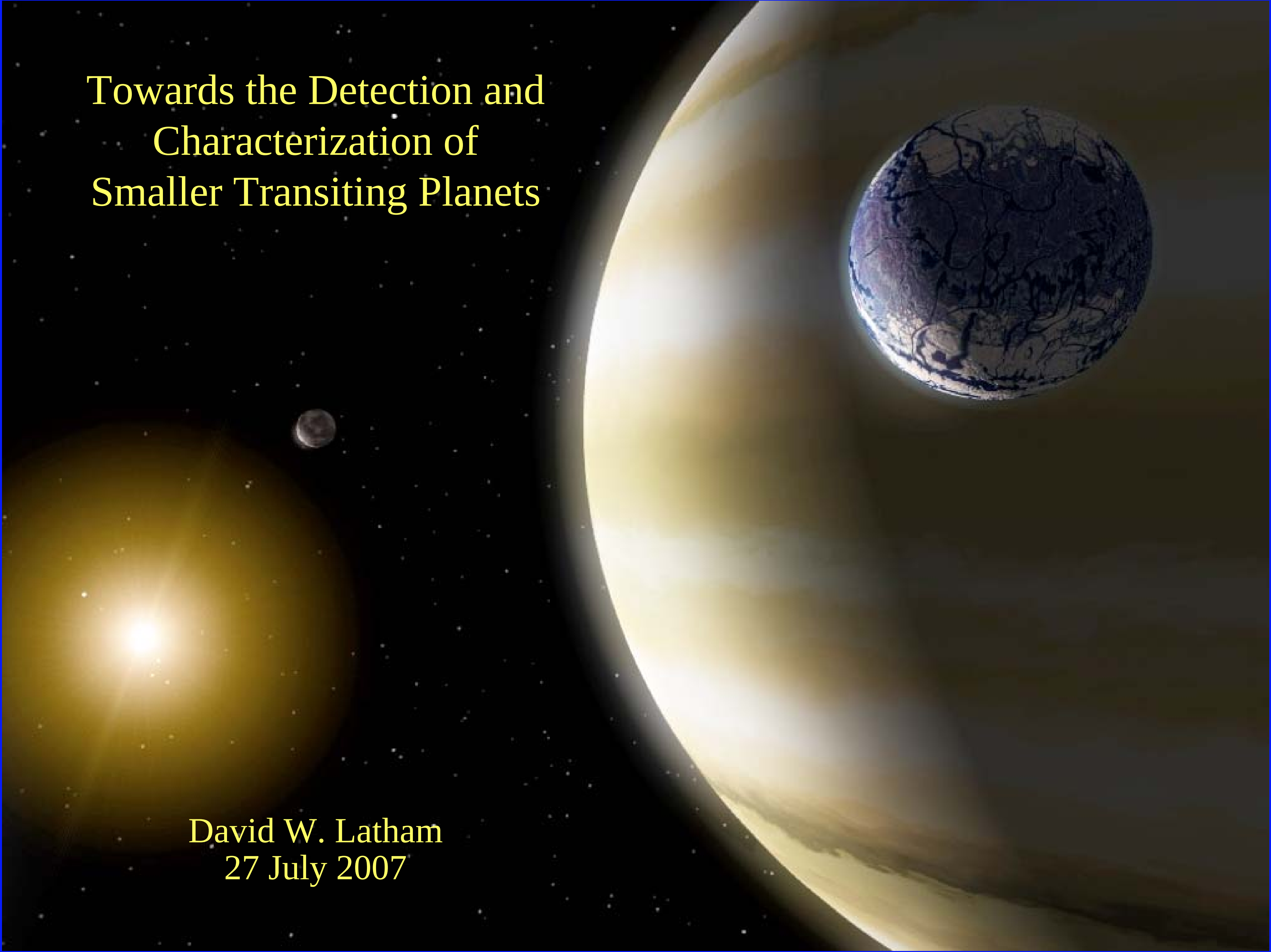
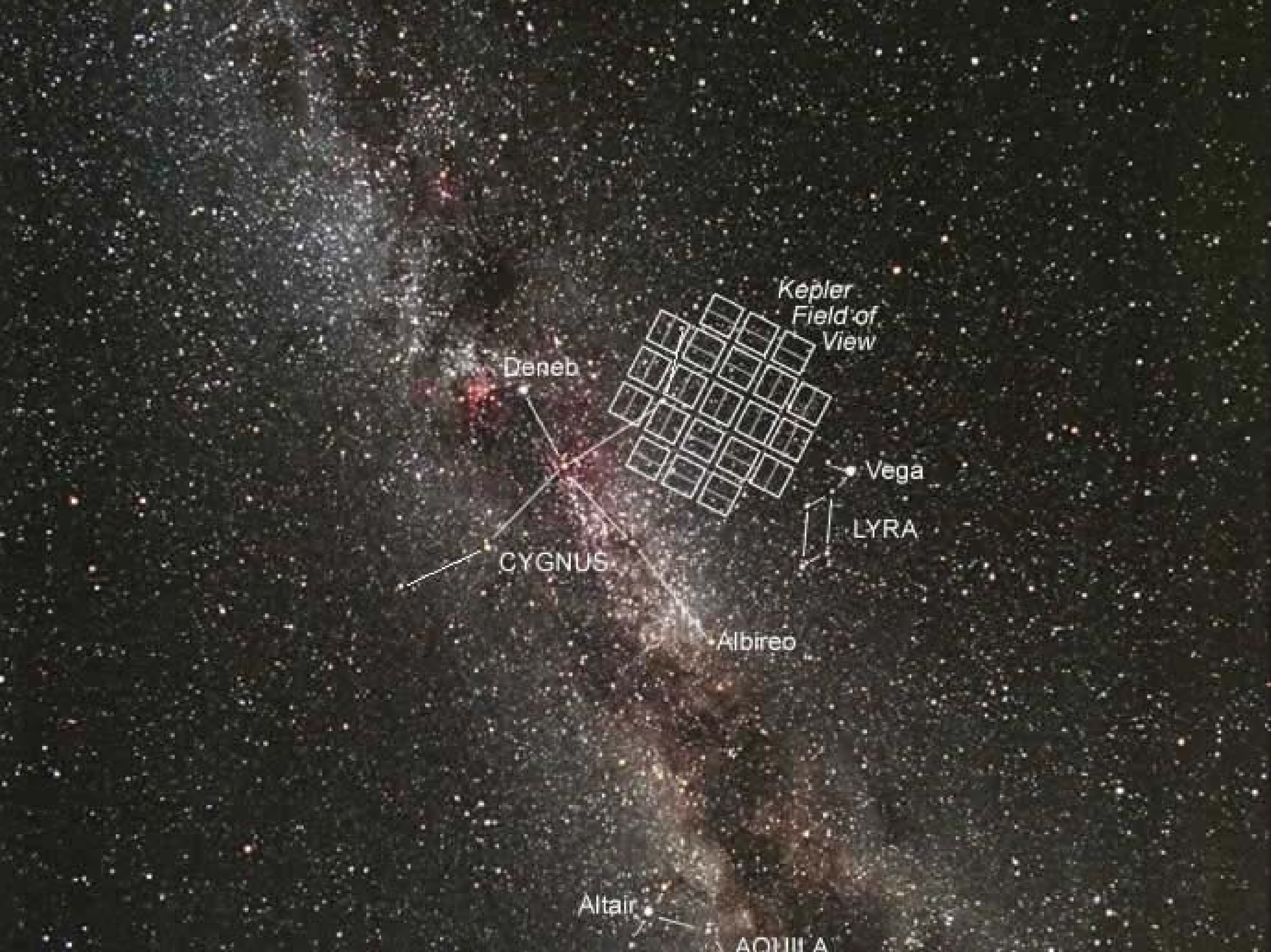
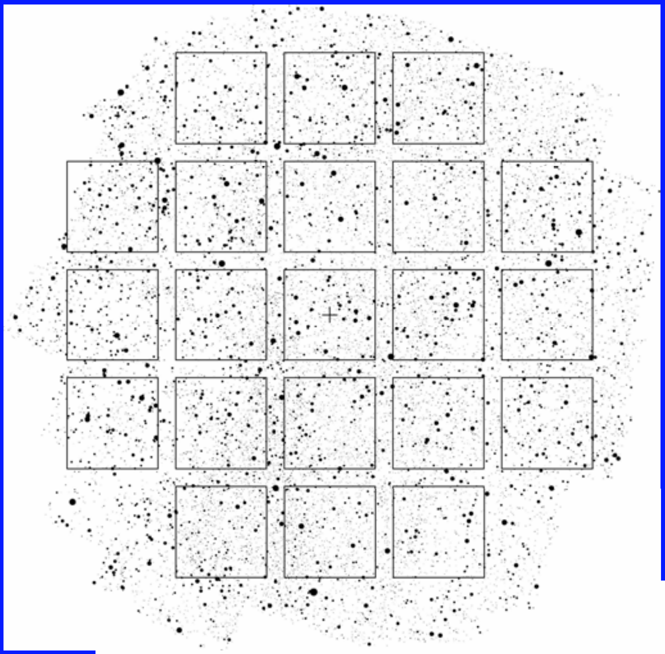


Towards the Detection and Characterization of Smaller Transiting Planets

David W. Latham
27 July 2007

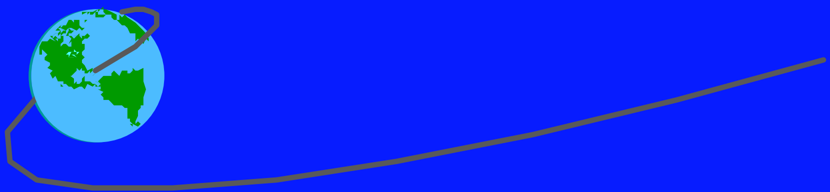

Kepler
Field of
View
Deneb
Vega
LYRA
CYGNUS
Albireo
Altair
AQUILA

Kepler Mission Concept



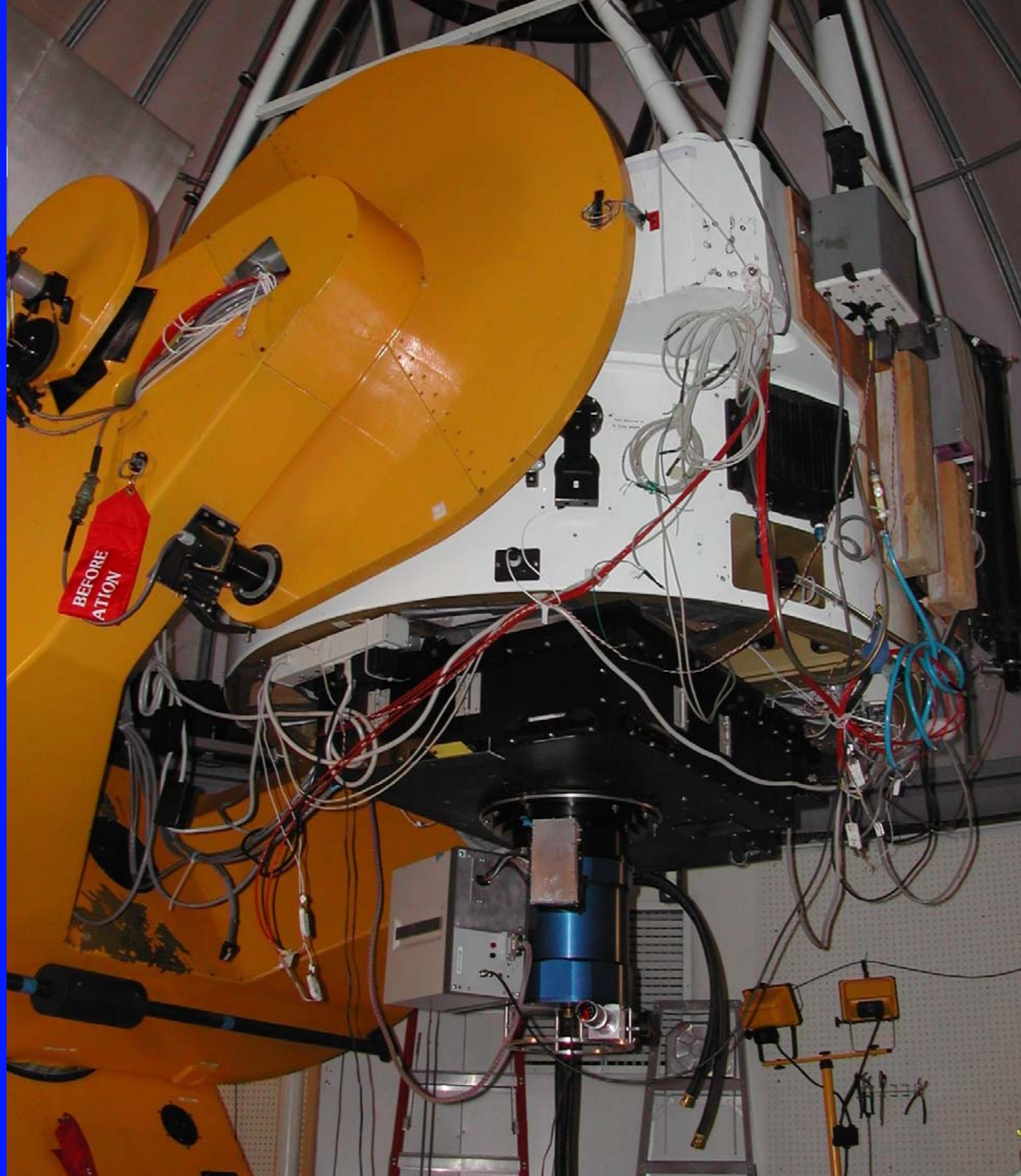
- *Kepler Mission* is optimized for finding habitable planets (10 to 0.5 $M_\oplus$) in the HZ (out to 1 AU) of solar-like stars
- Monitor 100,000 main-sequence stars
- Use a one-meter Schmidt telescope: FOV >100 deg^2 with an array of 42 CCD
- Photometric precision: < 20 ppm in 6.5 hours for V = 12 solar-like star

  => 4σ detection for Earth-size transit
- Mission: Earth-trailing orbit for continuous viewing, $\geq$ 4 year duration



Kepler Input Catalog

- Used to select optimum targets
- Includes all known stars in Kepler FOV
  ~ 10 million stars (USNO-B)
- Photometry
  - 2MASS JHK + SDSS griz + D51
  ~ 2 million stars down to K~14.5 mag
- Astrophysical characteristics
  - Teff, log(g), [Fe/H], reddening; Mass, Radius
  - Radial and rotational velocities


BEFORE
ATION

Transit Photometry

- Transit observations are hard to schedule
  - Solution: combine time with Kepler photometry
- KeplerCam light curves published:
  - TrES-1, HD 149026, HD 189733, XO-1,
  - TrES-2, HAT-P-1, WASP-1, WASP-2
- Submitted:
  - TrES-3, HAT-P-2, HAT-P-3
- Coming:
  - TrES-4, HAT-P-4

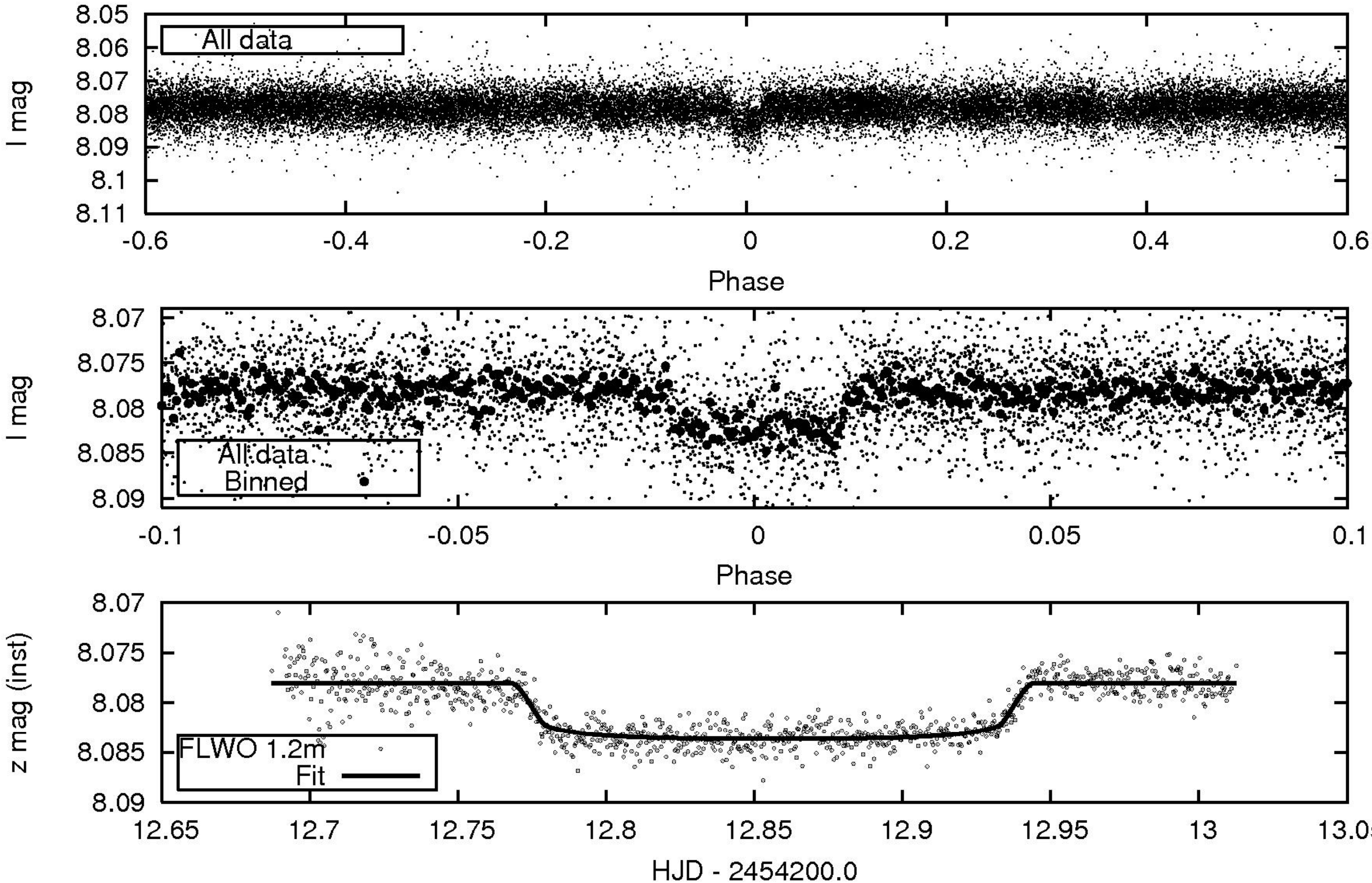
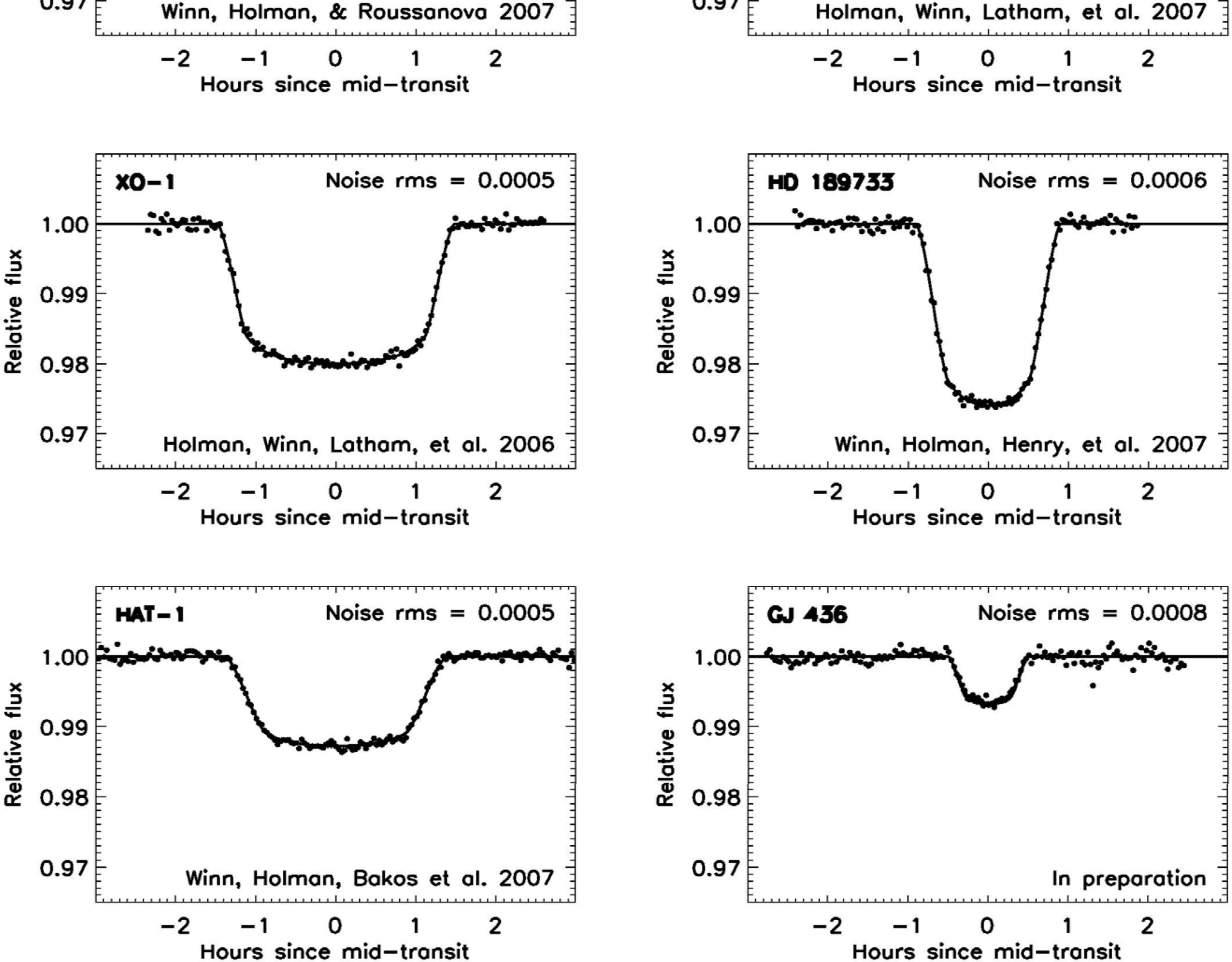
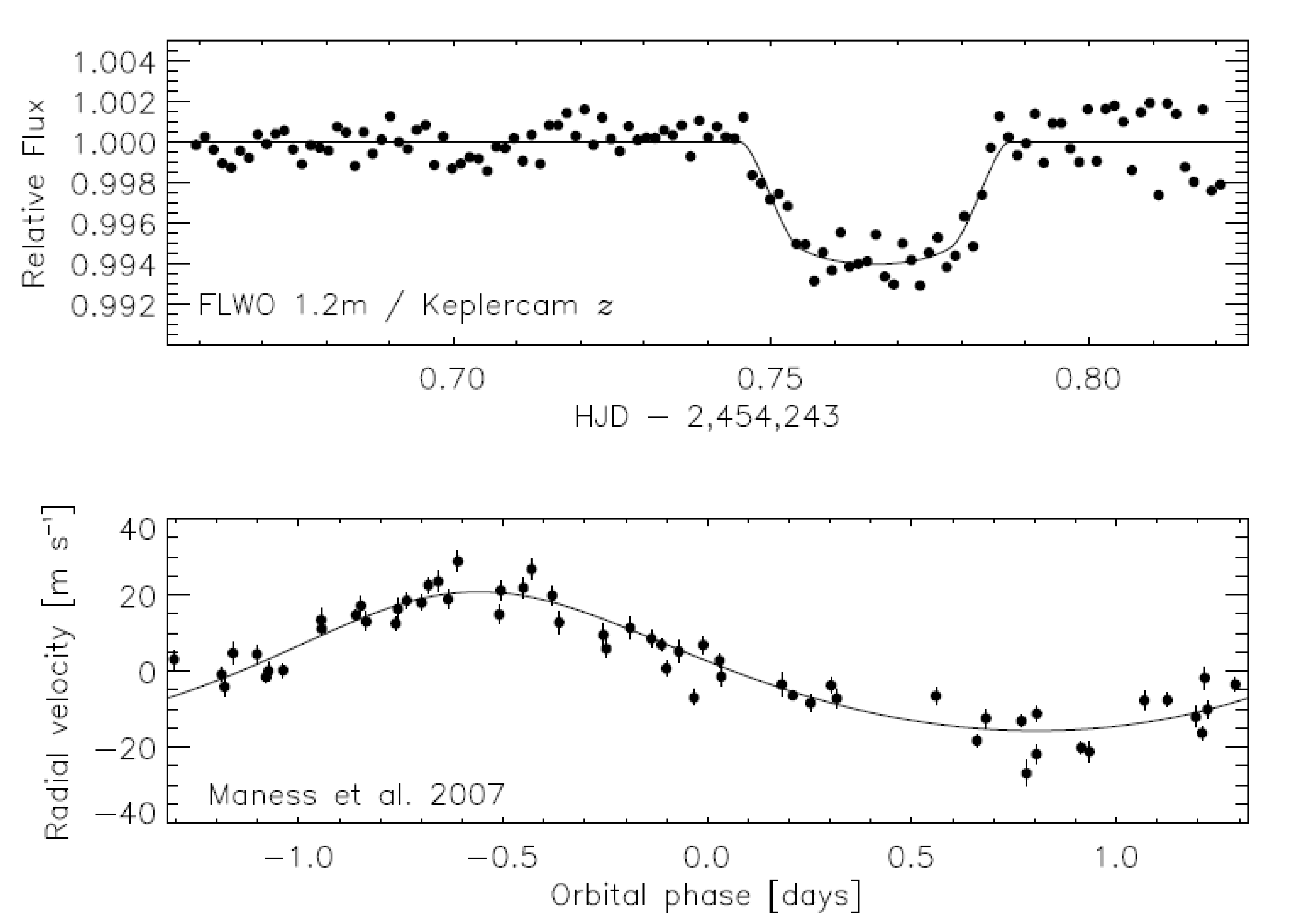


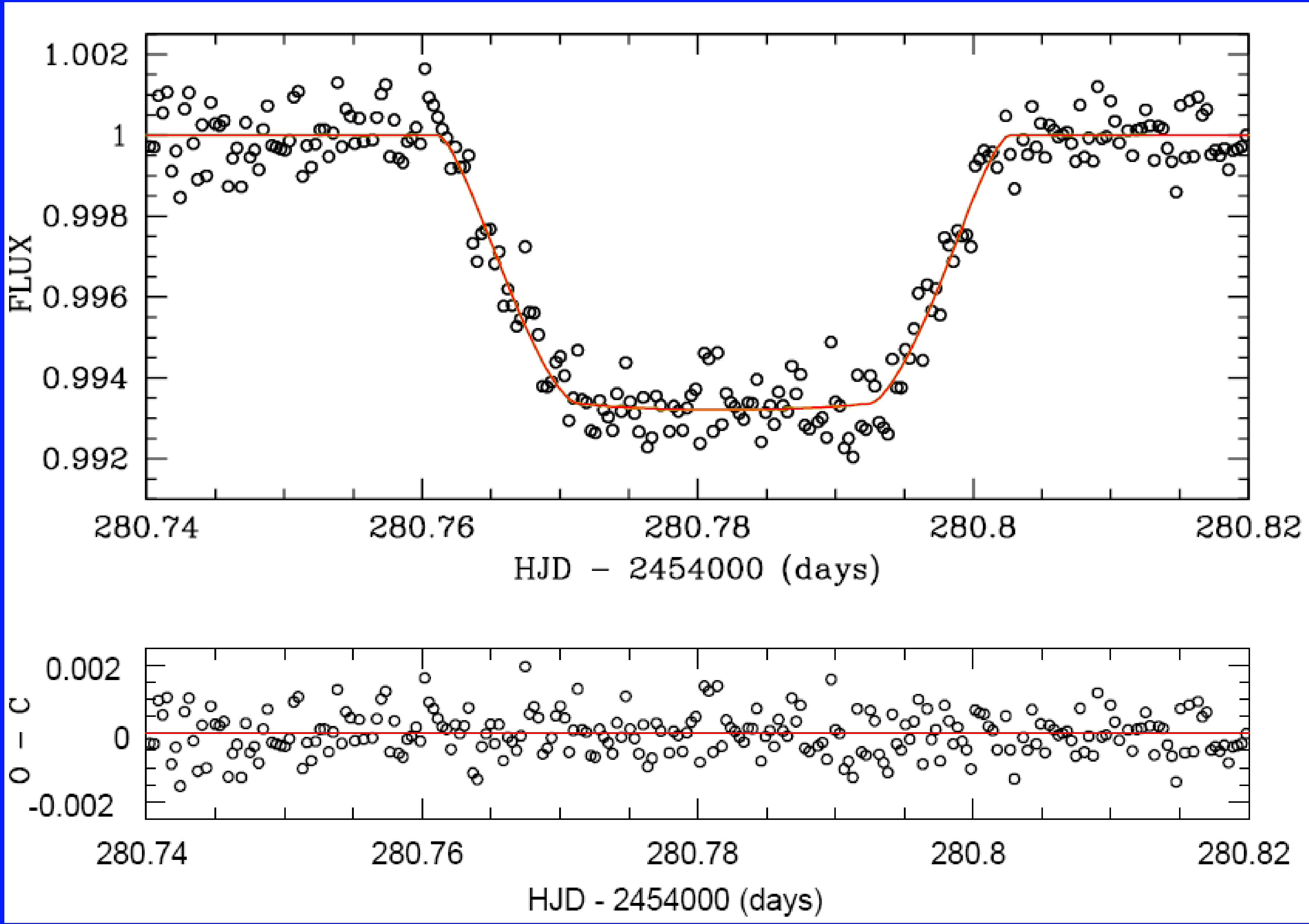
FIG. 1.— The upper panel shows the unbinned HATNet and WHAT joint light curve with 26400 data-points, phased with the $P = 5.63341$d period. The 5mmag deep transit is detected with a signal-to-noise of 26. The middle panel shows the same HATNet and WHAT data with the transit zoomed-in and binned with $\phi = 0.0005$ bin-size. The lower panel exhibits the Sloan z-band photometry follow-up taken by the FLWO 1.2 m telescope. Overplotted is our best (Mandel & Agol 2002) fit.



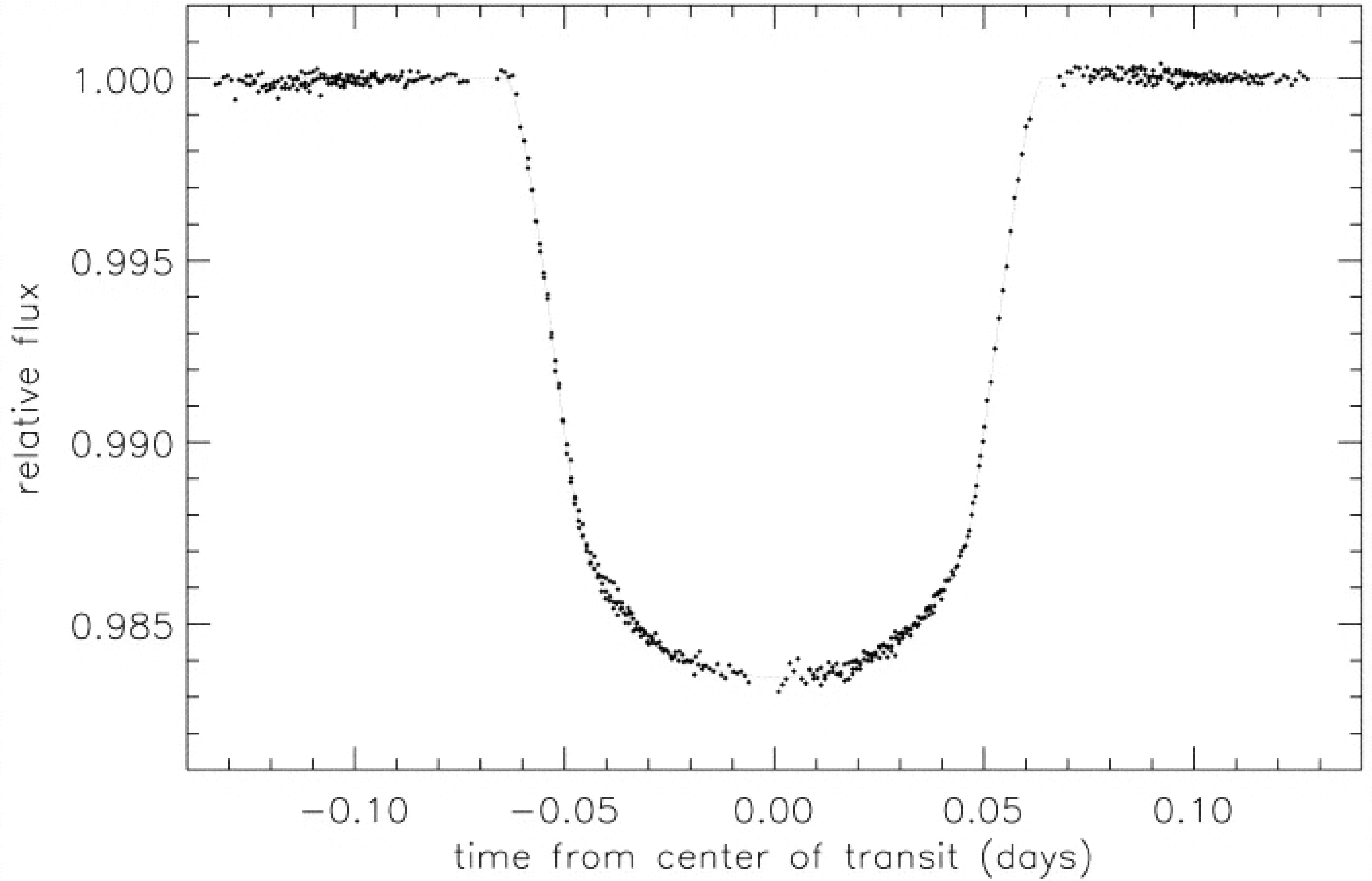
0.97
Winn, Holman, & Roussanova 2007
−2 −1 0 1 2
Hours since mid−transit
0.97
Holman, Winn, Latham, et al. 2007
−2 −1 0 1 2
Hours since mid−transit
XO−1
Noise rms = 0.0005
Relative flux
1.00
0.99
0.98
0.97
Holman, Winn, Latham, et al. 2006
−2 −1 0 1 2
Hours since mid−transit
HD 189733
Noise rms = 0.0006
Relative flux
1.00
0.99
0.98
0.97
Winn, Holman, Henry, et al. 2007
−2 −1 0 1 2
Hours since mid−transit
HAT−1
Noise rms = 0.0005
Relative flux
1.00
0.99
0.98
0.97
Winn, Holman, Bakos et al. 2007
−2 −1 0 1 2
Hours since mid−transit
GJ 436
Noise rms = 0.0008
Relative flux
1.00
0.99
0.98
0.97
In preparation
−2 −1 0 1 2
Hours since mid−transit

Gliese 436: R=3.8 R_{Earth}, M=23 M_{Earth}





FLUX
1.002
1
0.998
0.996
0.994
0.992
280.74
280.76
280.78
280.8
280.82
HJD - 2454000 (days)
O - C
0.002
0
-0.002
280.74
280.76
280.78
280.8
280.82
HJD - 2454000 (days)

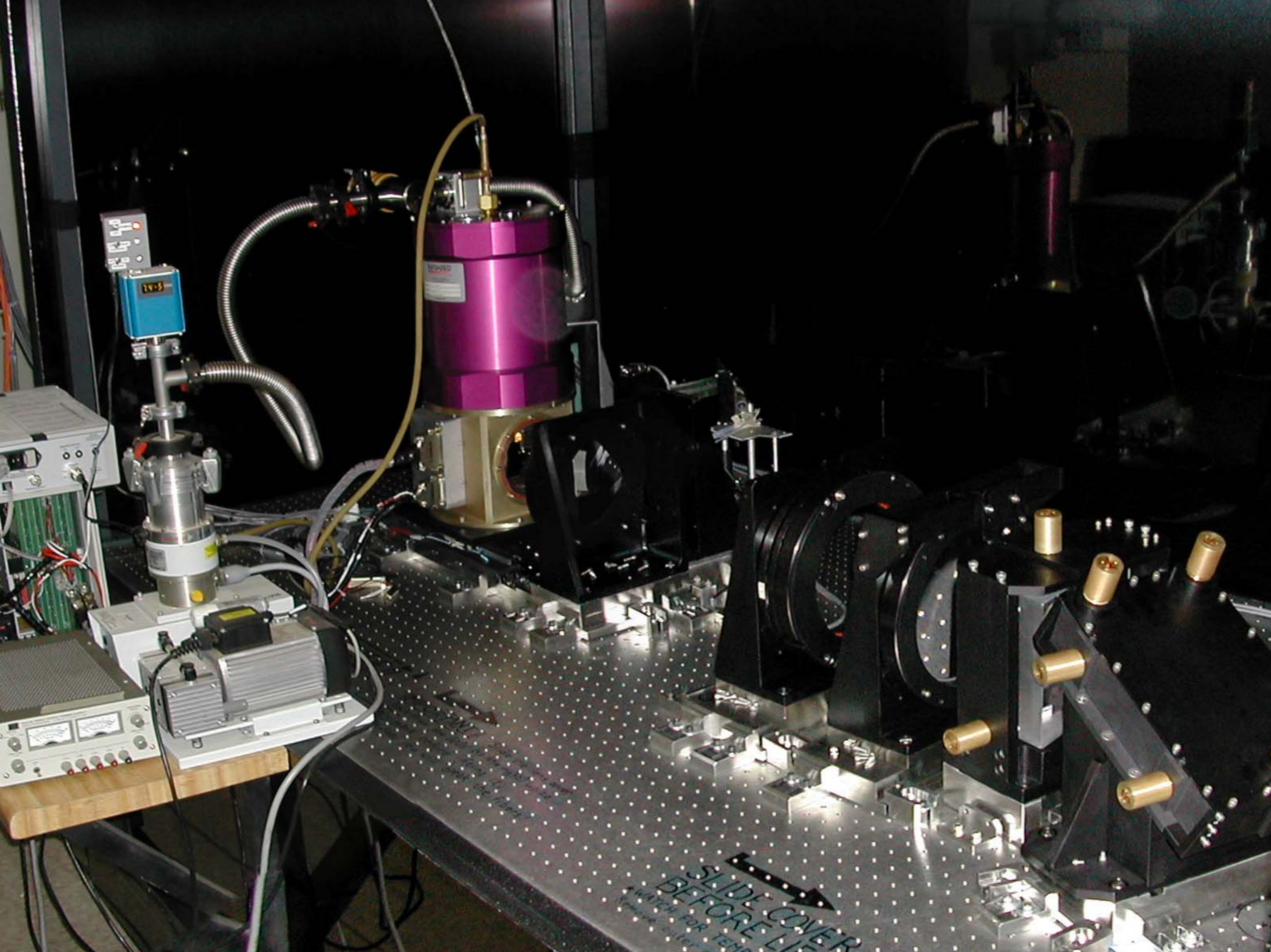

1.000
0.995
0.990
0.985
relative flux
−0.10
−0.05
0.00
0.05
0.10
time from center of transit (days)

Follow-Up Spectroscopy

- Initial reconnaissance spectroscopy
  - Identify stellar imposters
  - Characterize host star
    - CfA Digital Speedometers
    - New fiber-fed TRES instrument at FLWO
- Precise radial velocities for orbits/masses
  - HIRES, HET, HARPS-North

Reconnaissance Spectroscopy

- SAO Instruments
  - CfA Digital Speedometers (1978-2007)
  - TRES fiber-fed echelle (2007-
- Success rate
  - 540 candidates: Vulcan, TrES, HAT, KELT
  - 4031 spectra so far
  - 8 confirmed transiting planets
  - A few more coming


SLIDE COVER
BEFORE

Pushing to Lower Masses

- Keck 10-m with HIRES: 1 to 2 m/s
  - 1 m/s projected to require 2.5 hours at V=12
- ESO 3.6-m with HARPS: 20 to 50 cm/s
  - 1 m/s requires 1 hour at V=12
  - Located in Chile

Achieving better than 1 m/s: Stability & Simultaneous ThAr reference

ΔRV =1 m/s

⇕

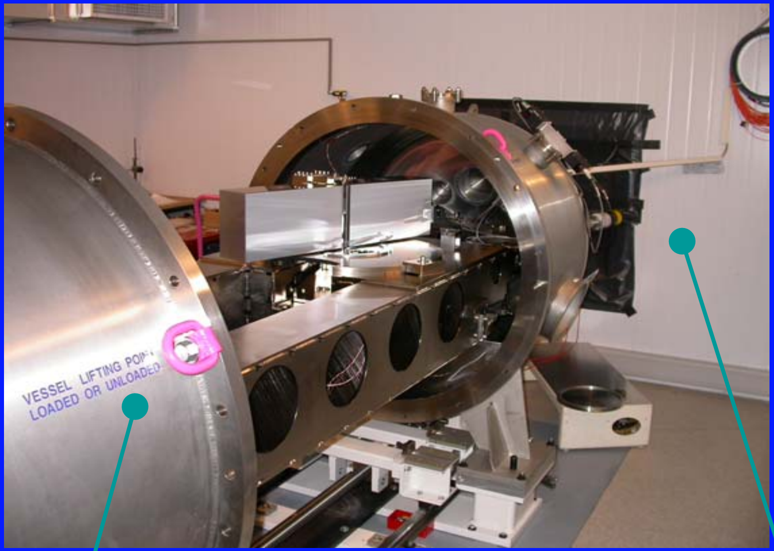
$\Delta\lambda$=0.00001 A

⇕

15 nm

⇕

1/1000 pixel



ΔRV =1 m/s

⇕

ΔT =0.01 K

⇕

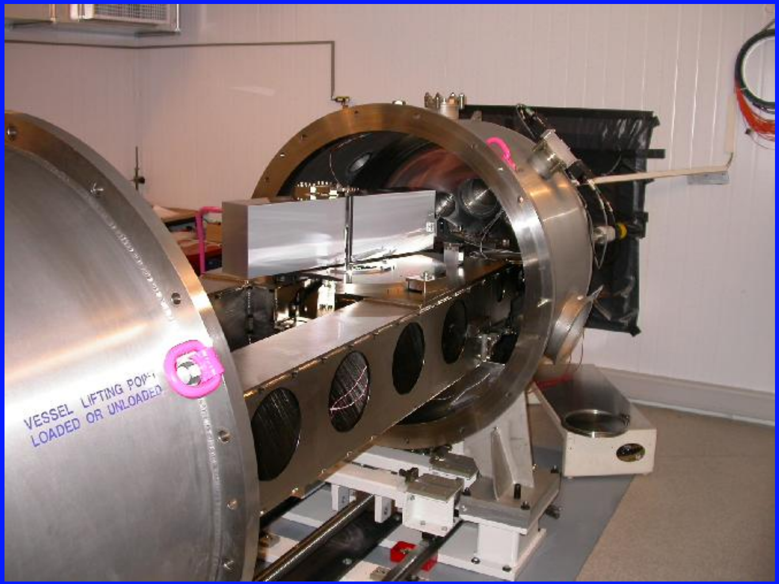
Δp=0.01 mBar

Vacuum operation

Temperature control

New Earths – HARPS North

- Collaboration with Geneva
- Ready for Kepler follow-up in 2009
- ~100 nights/year goal; MOU for WHT



Origins of Life in the Universe
Initiative at Harvard

• Formally approved with funding profile, May 2006

• Synergy between 5 areas at Harvard, 3 new facilities

• Pre-biotic Chemistry
• Extraterrestrial Samples
• New Earths

• Led by Dimitar Sasselov

Other Initiatives

- All-sky survey from space
  - Smaller planets than ground-based surveys
  - Complements Kepler
  - Finds brighter targets, allows better follow-up
- Giant Telescope, Super HARPS
  - Push Doppler precision to the limit

The Legacy of Kepler

- Frequency/characteristics of rocky planets
  - Mass, radius, density, orbital distributions
  - Host star characteristics
  - Information for the design of future missions

Legacy of All-Sky Survey

- The brightest and nearest transiting planets
  - Best targets for follow-up studies for years to come

Transiting Exoplanet Survey Satellite

MIT: Instrument, operations CfA: Optics, Science Center Ames: Spacecraft, launch

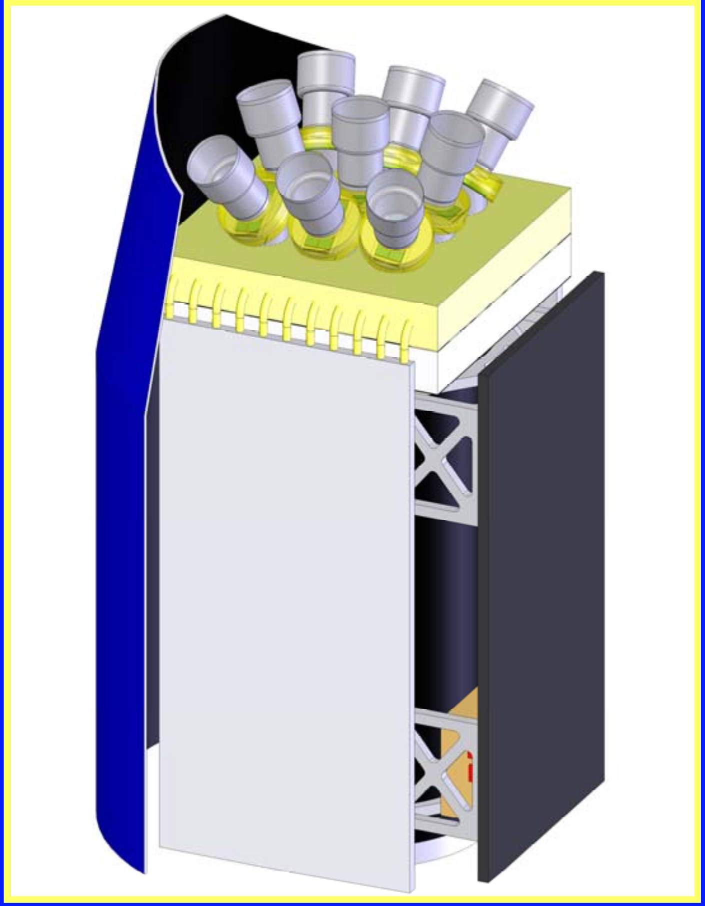
All-sky survey in 2 years

Neptunes, even Earths

Periods up to 2 months

10^6 targets, $\sim 10^3$ planets

University-style experiment



TESS Scientific Goals

- Survey 100% of the sky
  - Discover >1000 bright nearby transiting exoplanets
  - Period coverge up to 60 days
  - Planet size coverage down to super earths
    - Emphasize cool dwarf host stars
- Finish the survey by 2013
  - Follow up most interesting planets with HARPS (N&S)
  - Provide targets for JWST (launch in 2013)

Targets for TESS Searches

- Solar-type (G+K) Stars:

  ~10^6 brighter than I = +12

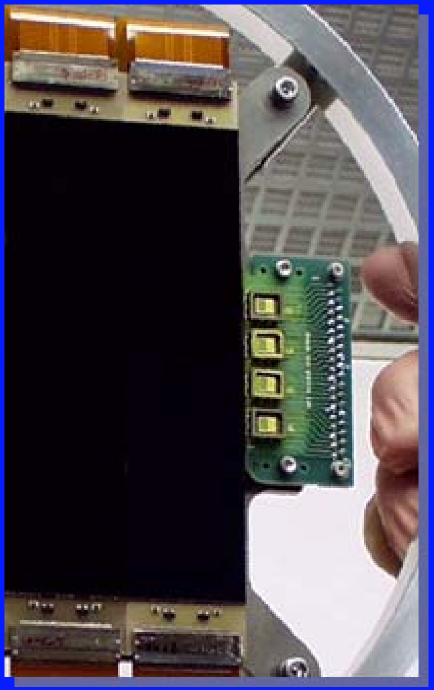
- M Dwarfs:

  ~10,000 within 30 pc

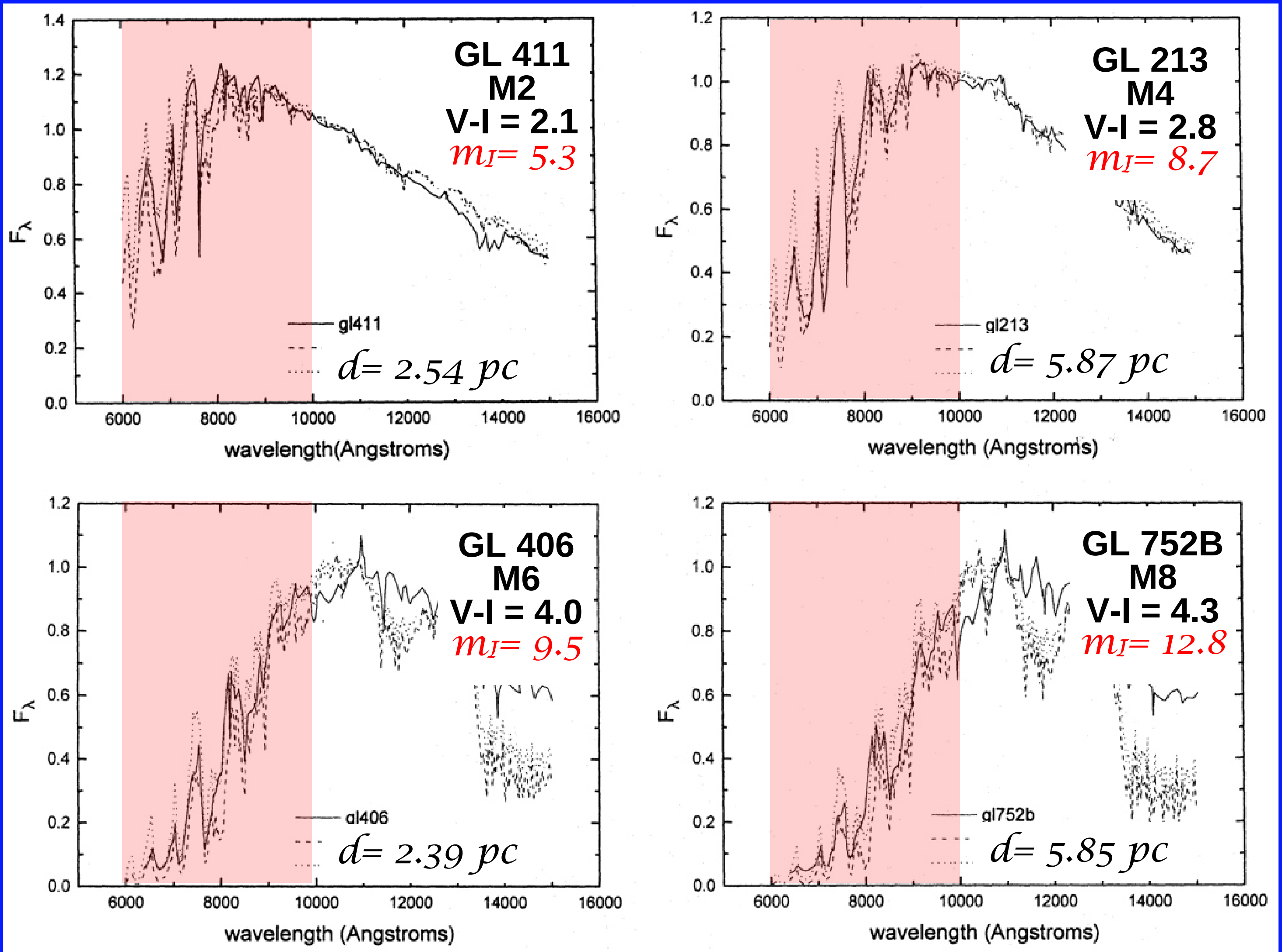
Mockup of TESS Camera Array

CCDs Selected for TESS

MIT Lincoln Lab 4Kx4K, 15 µ pixels, 144 Mpixels total
Frame transfer in 5 ms, Flight proven on HETE 2
Low-power hybrid electronics

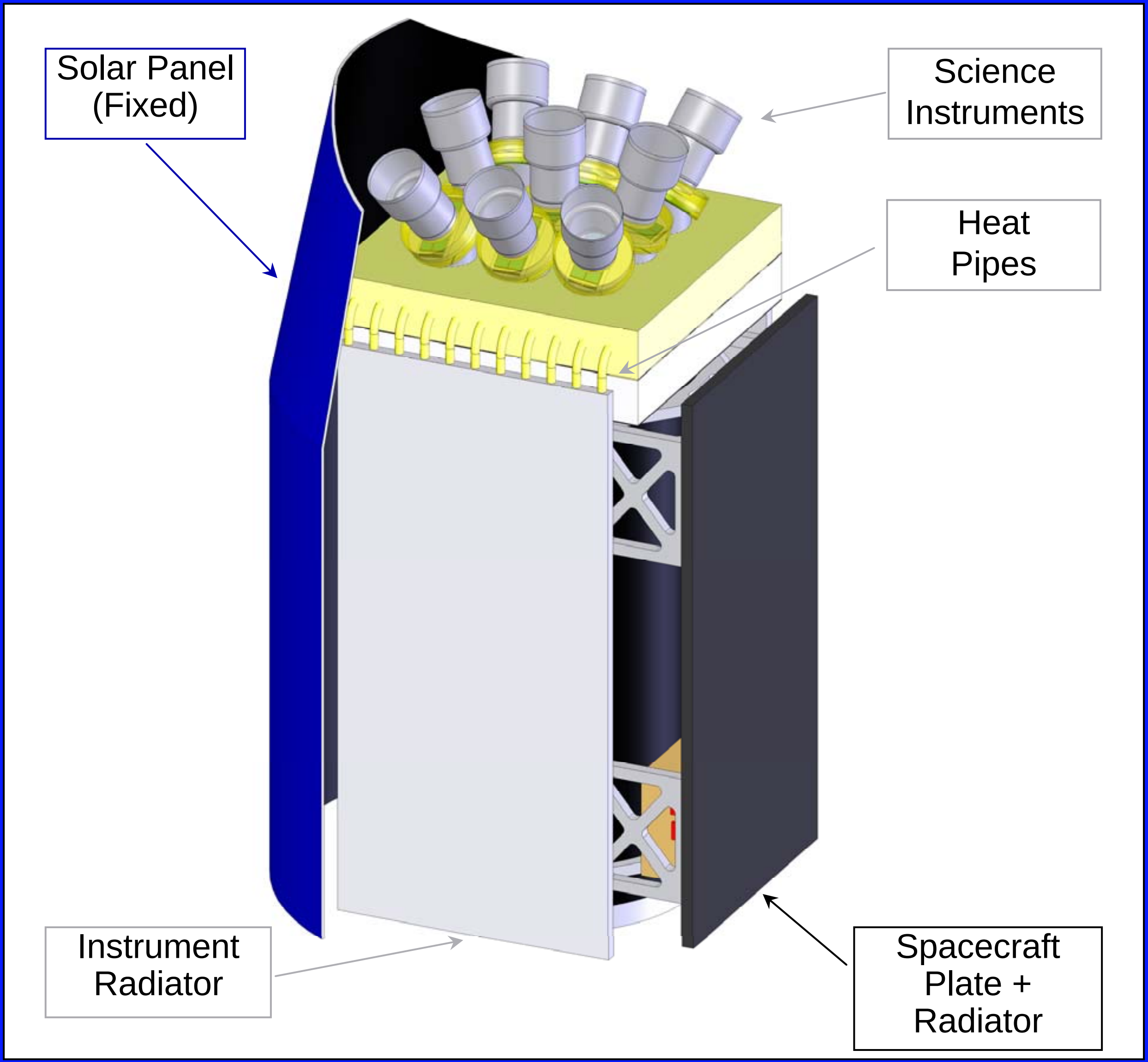


M Dwarf Spectra & TESS Passband



Spectra: Brett '95 Magnitudes: Bessell '91

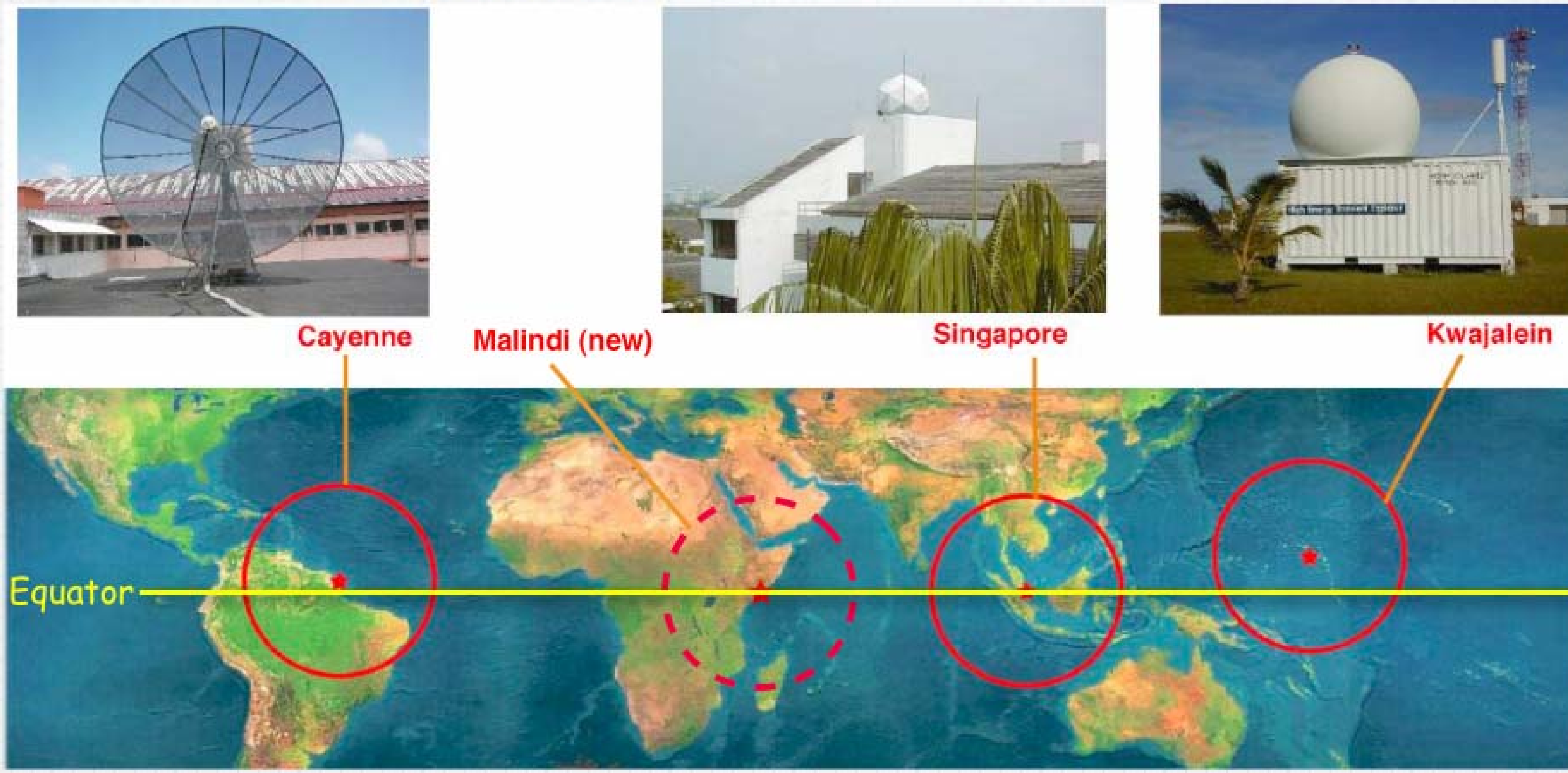
TESS Spacecraft (NASA Ames)



HETE-2 Satellite:
"Alpha Version for TESS"

- Developed, integrated, tested on-campus at MIT
- Reliable, low cost system (\$7M spacecraft + \$18M launch)
- Launched October 2000; in operation 6+ years for GRB searches
- Low earth orbit (600 km); low inclination (i = 2 degrees)

Dedicated TESS Network (extant from HETE-2)



- i < 2° orbit: radiation damage >1000 times lower than for i=28° orbit
- Three S-band stations along equator (+ one additional)
- Can achieve 15 GB/day (since 4 x 15 = 60 passes per day)

- Cayenne: Sup'Aero (France)
- Singapore: RIKEN-Japan
- Kwajalein: MIT Kavli Institute
- Malindi (New station; Italy)

TESS Status

- Seeking private funds (MIT and CfA)
- Seed money allocated
  - Hardware preliminary design underway
  - Lab test of prototype camera underway