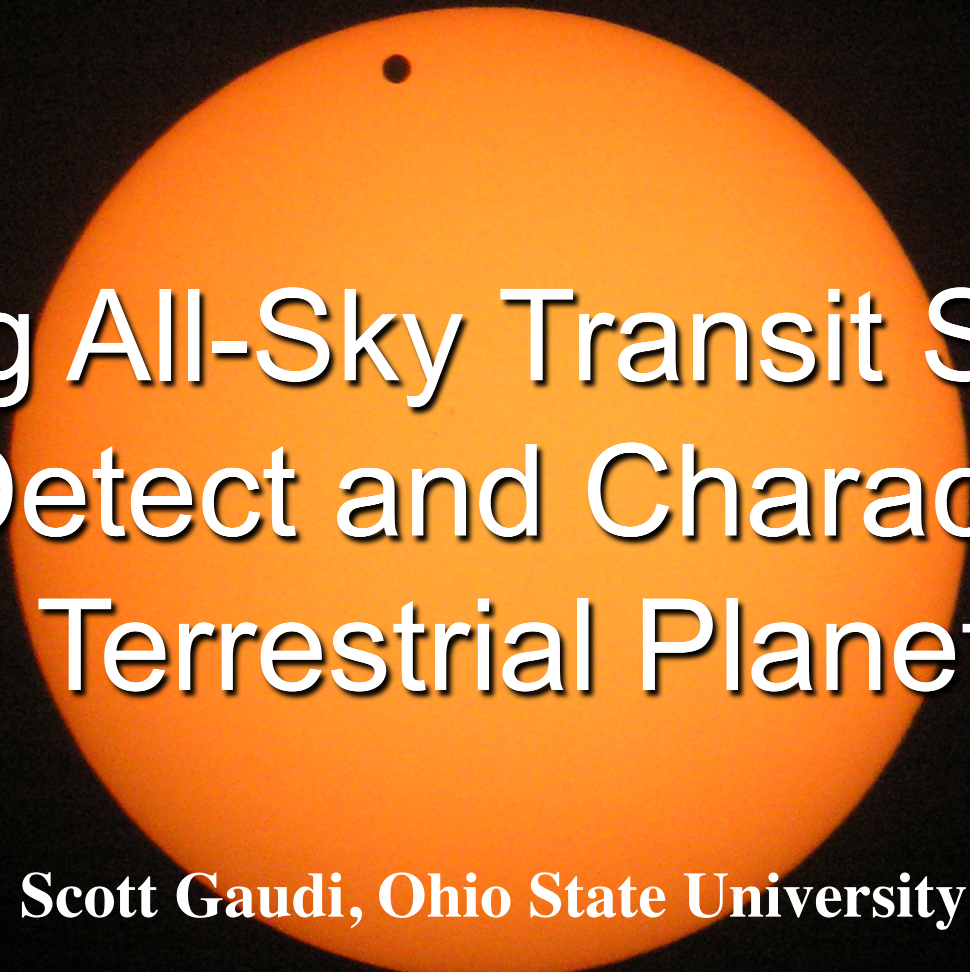
“Small Black Shadows”



Using All-Sky Transit Surveys to Detect and Characterize Terrestrial Planets

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Transiting planets are great!

- *Most information-rich systems!*
- Only way to measure mass + radius
- Best way to couple demographics with detailed individual characteristics of planets (i.e. temperatures, atmospheres, densities) over a broad range of planet/host properties.
- If we want to understand habitability, we probably want to understand both planet formation and the physics of planetary atmospheres (particularly for "Super-Earths").

Bright systems are great!

- *Most information-rich systems!*
- Host stars tend to be the most well-studied.
  - Array of auxiliary information.
- Allows one to harness (in principle) the power of the transiting systems.

Habitable Planets?

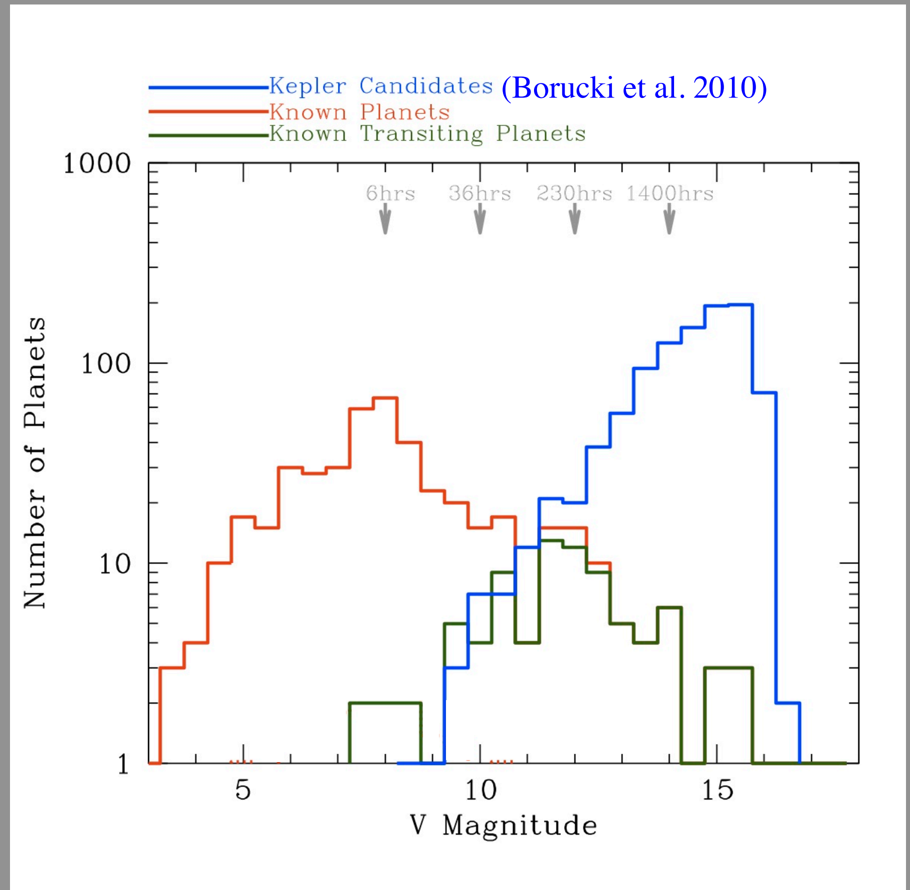
- Two complementary ways of confirming habitability of planets.
- Direct Imaging → favors more luminous stars.
- Transits → favors less luminous stars.

"Pale Blue Dot"

"Small Black Shadow"

Finding the brightest systems.

- Current transit surveys are not sensitive to:
  - Brightest systems.
  - Long-period systems.
  - Low-mass planets.
- Detailed coupled demographic + characteristic studies currently only possible for Hot Jupiters (with few exceptions)
- Planets detected by Kepler will only be *potentially* habitable.



All-Sky Surveys

- Earths at P< 30d, All-Sky
  - Transit probability ~1%
  - Must survey 10,000 stars
  - Distance ~30pc

$$N_{\min} \sim \frac{N_{\det}}{P_{tr} f} \sim \frac{100}{0.01 \times 1} \sim 10^4$$

$$d_{\min} \sim \left(\frac{3 N_{\min}}{4 \pi n_*} \right)^{1/3} \sim 30\text{pc}$$

- Survey requirements for T_{min}~3 years

$$\frac{\Omega}{4\pi} = \frac{3P}{T_{\min}} \sim \frac{90d}{1000d} \sim 1/10$$

(~4000 sq. deg)

- Jupiters?
  - 100 times further $\Rightarrow 10^6$ more stars!
  - Limited by number of targets, scale height, sky, not SNR

Plenty of Photons!

- Signal-to-noise ratio (all transits)

$$SNR \sim 10\left(\frac{M_*}{M_\odot}\right)^{\beta}\left(\frac{R_p}{R_\oplus}\right)^{2}\left(\frac{P}{30\mathrm{d}}\right)^{-1/3}\left(\frac{d}{30\mathrm{pc}}\right)^{-1}\left(\frac{D}{10\mathrm{cm}}\right)$$

- Maximum distance for rocky planets ~ 30 pc for P~30d, SNR~10.
- Weak function of mass for fixed period (Pepper & Gaudi 2005):
- β~1/3 for *V*, 1/2 for *I*, and -1/6 for J

Habitable Zone

- Transit Depth

$$\delta \approx 10^{-4}\left(\frac{R_p}{R_\oplus}\right)^2\left(\frac{M_*}{M_\odot}\right)^{-2}$$

- Transit Probability

$$P_{tr} \approx 0.5\%\left(\frac{M_*}{M_\odot}\right)^{-1}$$

- Duty Cycle

$$\text{Duty Cycle} \approx 0.15\%\left(\frac{M_*}{M_\odot}\right)^{-1}$$

$$a_{HZ} \propto L_{bol}^{1/2}$$

$$L_{bol} \propto M_*^4$$

$$P_{HZ} \propto M_*^{5/2}$$

$$R_* \propto M_*$$

Yields of a Transit Survey

- Signal-to-Noise Limited Survey

$$\frac{dN_{\text{det}}}{dM_*} \approx P_{tr} \frac{\Omega}{3} d_{\max}^3 \frac{dn}{dM_*}$$

$$P_{tr} \approx 0.5\% \left(\frac{M_*}{M_\odot} \right)^{-1}$$

$$SNR_{All} \propto \left[M_*^{\frac{3\alpha - 15}{6}} \right] d_*^{-1}$$

$$\frac{dn}{dM_*} \propto M_*^{-1}$$

Dependence on Mass and Filter

- Signal-to-Noise Ratio

$$SNR_{All} \propto M_*^{-1/2} d_*^{-1}$$

(*V* band)

$$SNR_{All} \propto M_*^{-1} d_*^{-1}$$

(*J* band)

- Detected HZ Planets: low-mass stars strongly favored (Gould et al. 2003)

$$\frac{dN_{\mathrm{det}}}{dM_*} \propto M_*^{-7/2}$$

(*V* band)

$$\frac{dN_{\mathrm{det}}}{dM_*} \propto M_*^{-5}$$

(*J* band)

- In *J*, ~400 times more detections for mid-M versus solar type stars.
- *J* versus *V*: factor of ~6 at $0.3M_{Sun}$, factor of ~25 at $0.1M_{Sun}$

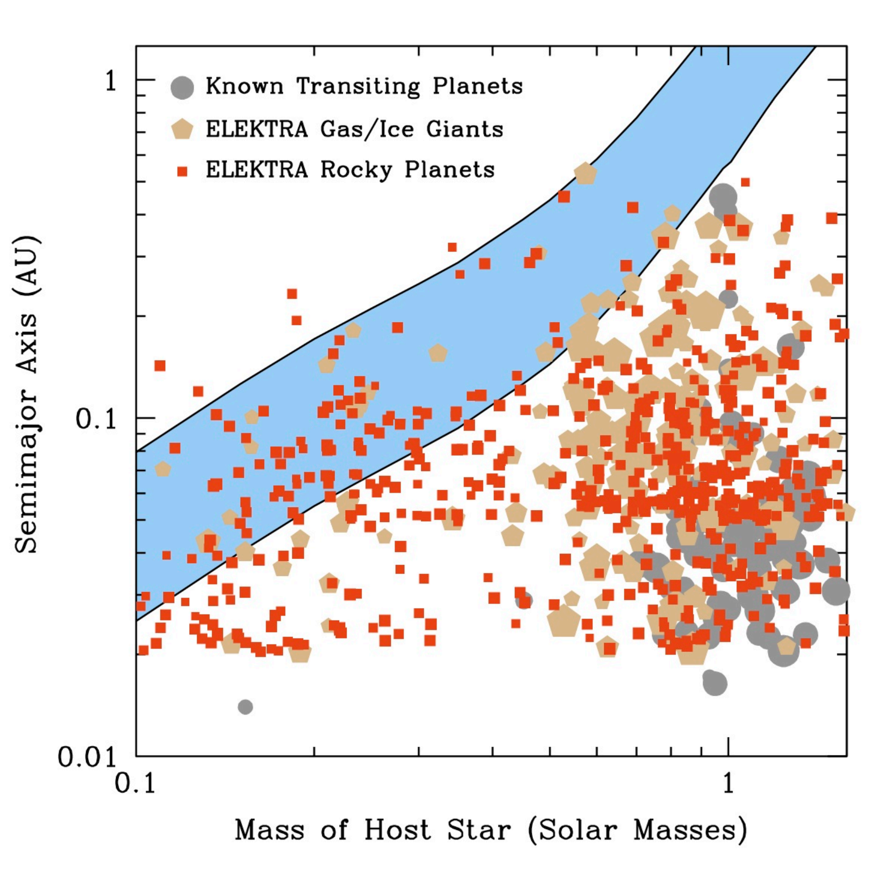
Future Wide-Field Transit Surveys

- **TESS** (PI G. Ricker, Deming et al. 2009)
  - Red-visible (600-1000nm)
  - All-Sky
  - 6 telescopes, each with ~18° x 18° FOV (total ~5% of the sky)
  - Target magnitudes (V<13)
  - Number of stars: ~2.5 million
- **ELEKTRA** (PI C. Beichman)
  - Near-IR (660-1700nm)
  - 80% of the sky.
  - 6 telescopes, each with ~17° x 17° FOV (total ~4% of the sky)
  - Target magnitudes: *V* or *J*<10
  - Number of stars: ~ 2 million
- **PLATO**
  - Optical
  - ~50% of the sky
  - Total ~1000 sq. deg. (~2% of the sky)
  - Target magnitudes: *V<13*
  - Number of stars: ~300,000
  - Astroseismology + transits

Yields

ELEKTRA/TESS:

- Hundreds of Rocky ($1\text{-}10M_E$) Planets
- Thousands of Ice/Gas Giant Planets
- ELEKTRA: ~70 Rocky ($1\text{-}10\ M_E$) Habitable Planets



Confirmation and Characterization

- RV amplitude:

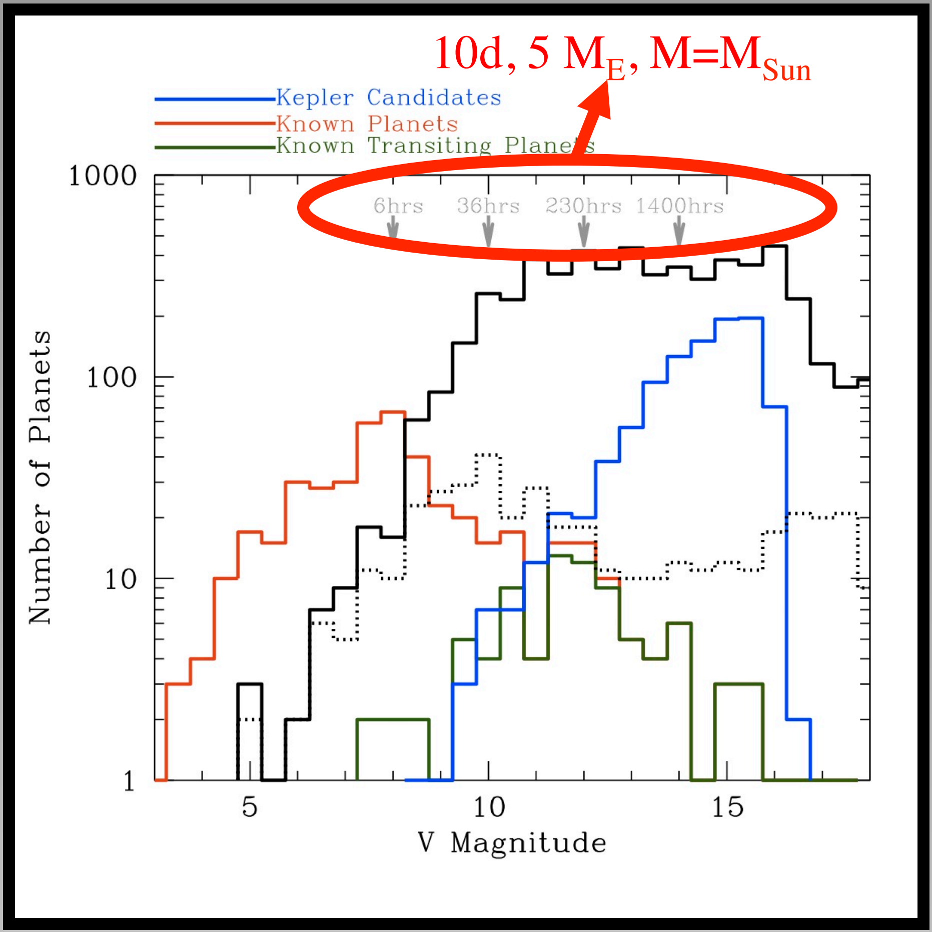
$$K \approx 3 \text{ m s}^{-1}\left(\frac{M_p}{5M_\oplus}\right)\left(\frac{M_*}{0.3M_\odot}\right)^{-3/2}$$

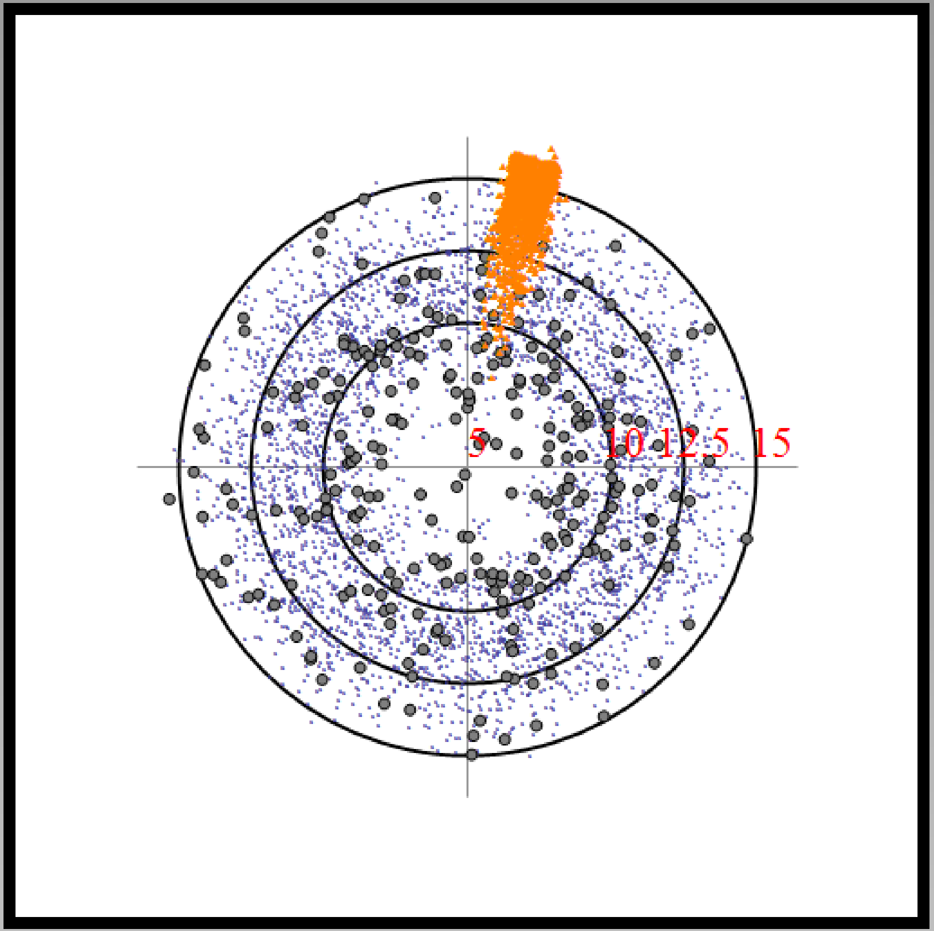
(habitable planets)

- Bright systems facilitate follow-up.

$$T \sim 8 \text{ hrs}\left(\frac{SNR}{10}\right)^2\left(\frac{K}{3\text{m/s}}\right)^{-2} 10^{0.4(V-10)}$$

- Host stars very well characterized.
  - Median GAIA parallaxes of ~0.3%.
  - Densities + radii ⇒ independent, precise masses and radii
  - Space velocities, detailed abundances, ages





•Measure masses to 10% for ~100 terrestrial planets with ~1500 hours of telescope time (scaling from Keck). See also Brown & Latham 2008

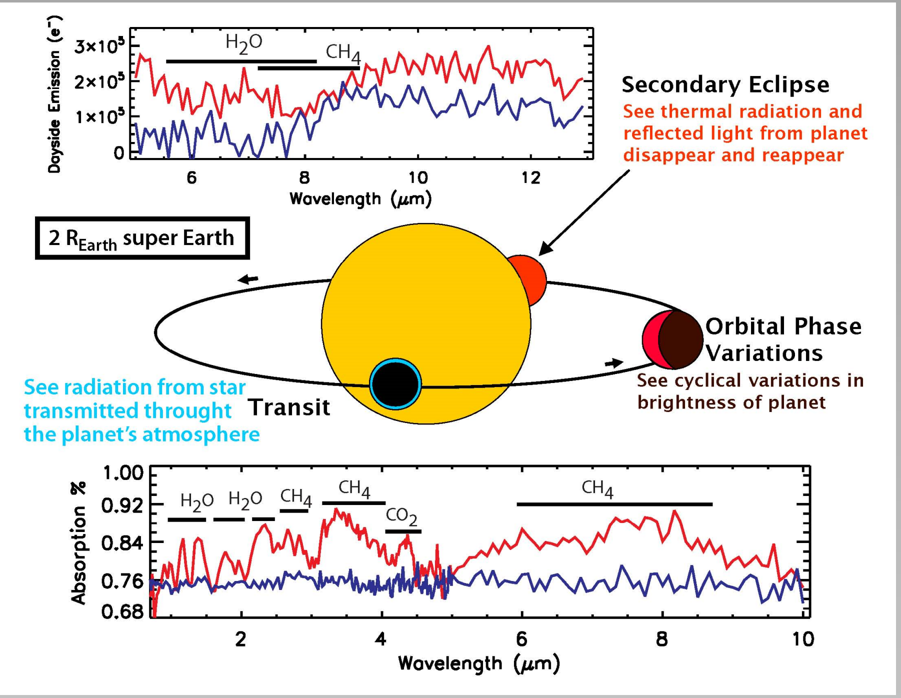
•Mass function to 30-50% per bin with a resolution of 0.1 dex.

Science Returns

- Brightest,closest transiting planets in the sky!
- Demographics of Short/Intermediate Period Planets:
  - Planet parameters
    - Radius, Period, Semimajor Axis, Equilibrium Temp.
    - Mass, Density, Composition, Spin-Orbit Alignment
  - Stellar parameters
    - Mass, Age, Abundances, Stellar populations
- "Strange New Worlds": Rare Systems
  - TESS/ELEKTRA: 2-3 million stars
    - ~10 times more than Kepler
    - Multiple systems, moons, rings, resonant systems, young stars, halo stars, long-period planets, multiple stars, stellar clusters/associations, metal-poor stars…
  - Single-transit events of long-period systems
  - Habitable planets around solar-type stars?
- Frequency of Habitable Planets for Low-Mass Stars
  - Complementary to *Kepler* and *WFIRST*.
  - ELEKTRA will measure η_E to a precision of ~10% $\eta_E^{-1/2}$ for $M<0.5M_{Sun}$

Targets for JWST

- JWST presents both a curse and an opportunity.
- Can characterize the atmospheres of habitable super Earths
- Must find the bright transiting systems first.
- All-sky transit survey is likely the easiest way to accomplish this.



See Deming et al. 2009, Kaltenegger & Traub 2009.

Long Period Planets

- Single transit events (e.g., Yee & Gaudi 2008)

$$P_{1,TR} \approx 10^{-6}\left(\frac{P}{30\text{ years}}\right)^{-5/3} \quad \text{(T=120 days)}$$

- Habitable Planets around Solar-Type Stars
  - Some targets will be sufficiently bright that single-transit events can be detected for terrestrial planets.
  - Estimate of period, frequency, targets for follow-up.