Exoplanet Demographics: Latest Results from The *Kepler* Group

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Chris Burke, and the Former *Kepler* Team

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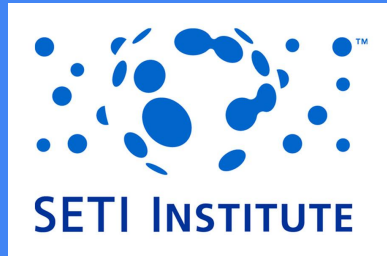
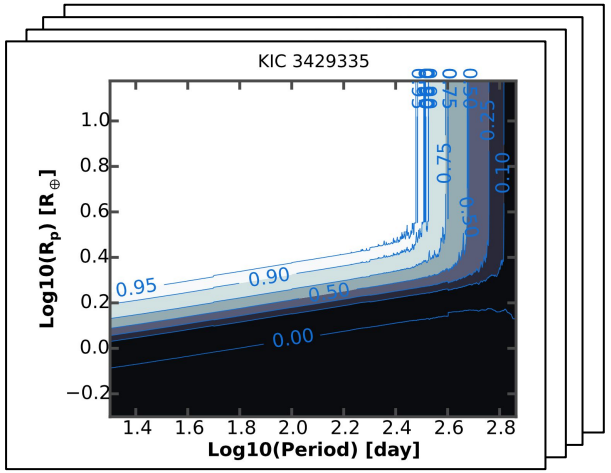


What's New This Time?

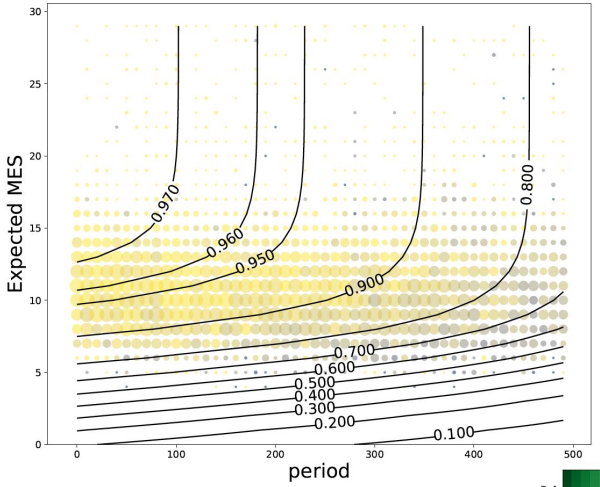
- Small, long-period planet occurrence around GK dwarfs
  - Near Earth orbital period, radius < 2.5 R_{Earth}
- Robust, high-resolution vetting completeness and false alarm reliability
  - Astrophysical FP reliability via Morton False Positive Probabilities
- A new Gaia-informed stellar properties catalog
  - Consistently treating the entire stellar sample through isochrone fitting
    - Berger et al. *in prep*.
  - Mostly single stars via fit quality cuts
- Chris Burke's Poisson-likelihood-based occurrence rates
  - Dual power law in period and radius
- Details in arXiv:1906.03575

Detection and Vetting Completeness

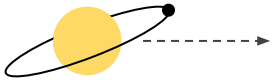
DR25 Per-Star Completeness Contours



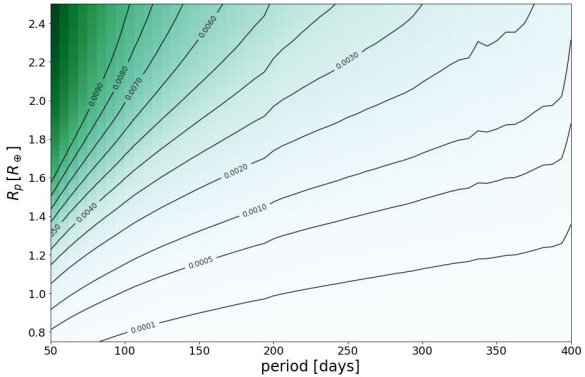
Fitted Vetting Completeness Model



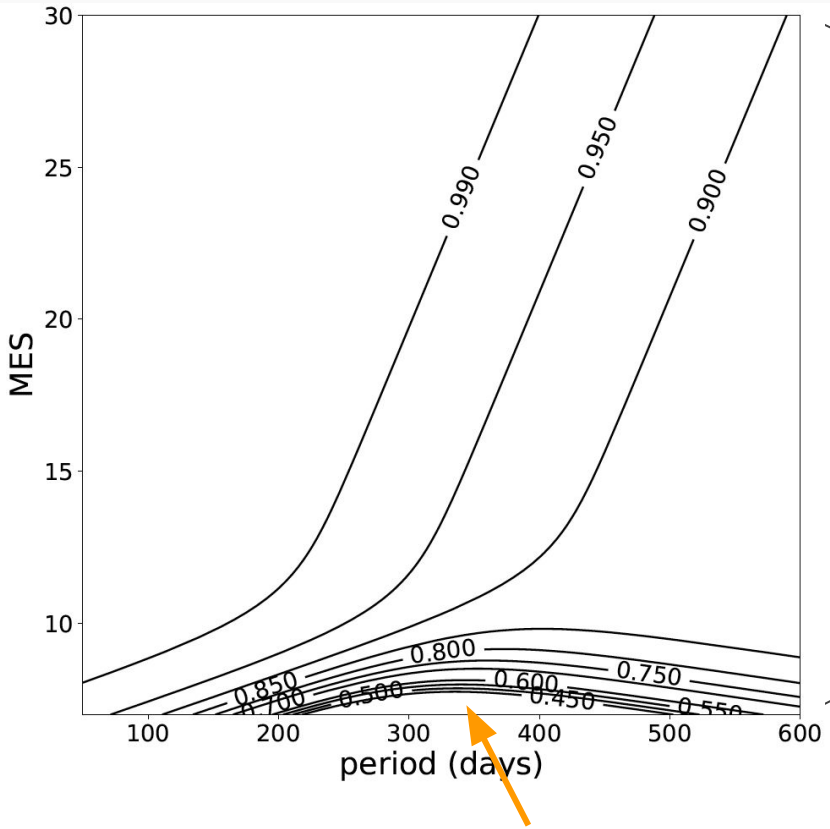
Geometric transit probability

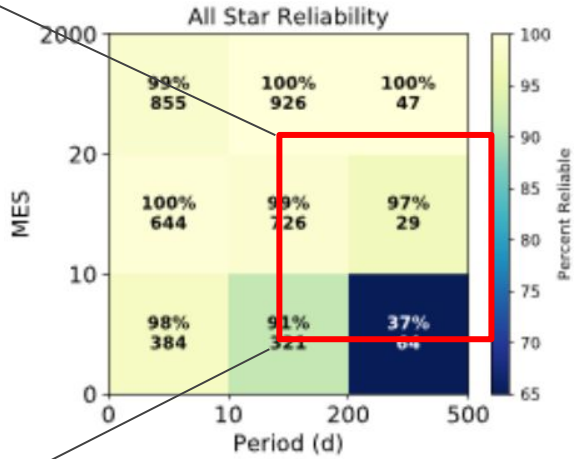


Summed over stars



Robust False Alarm Reliability Measurements

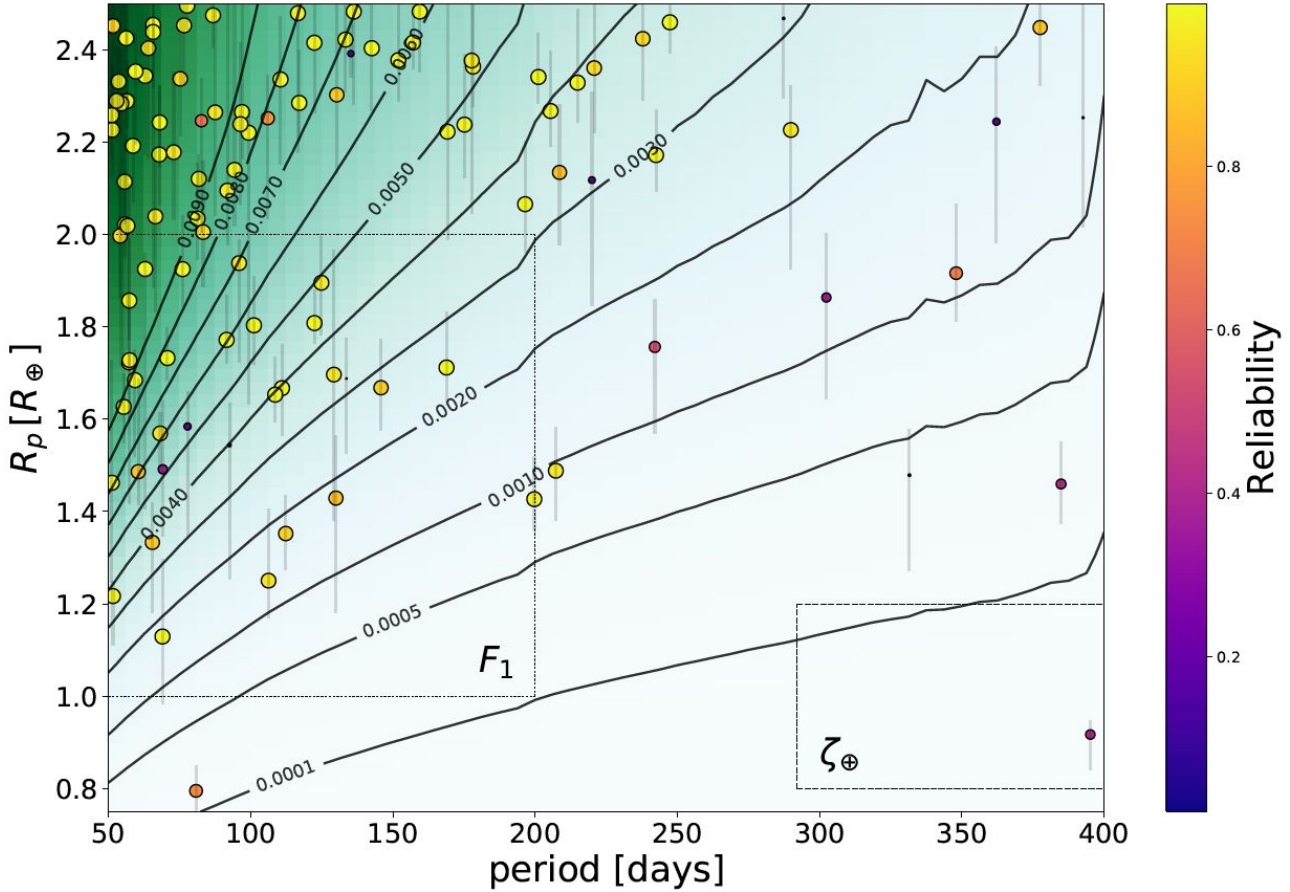




Effect of many instrumental artifacts near the *Kepler* orbit

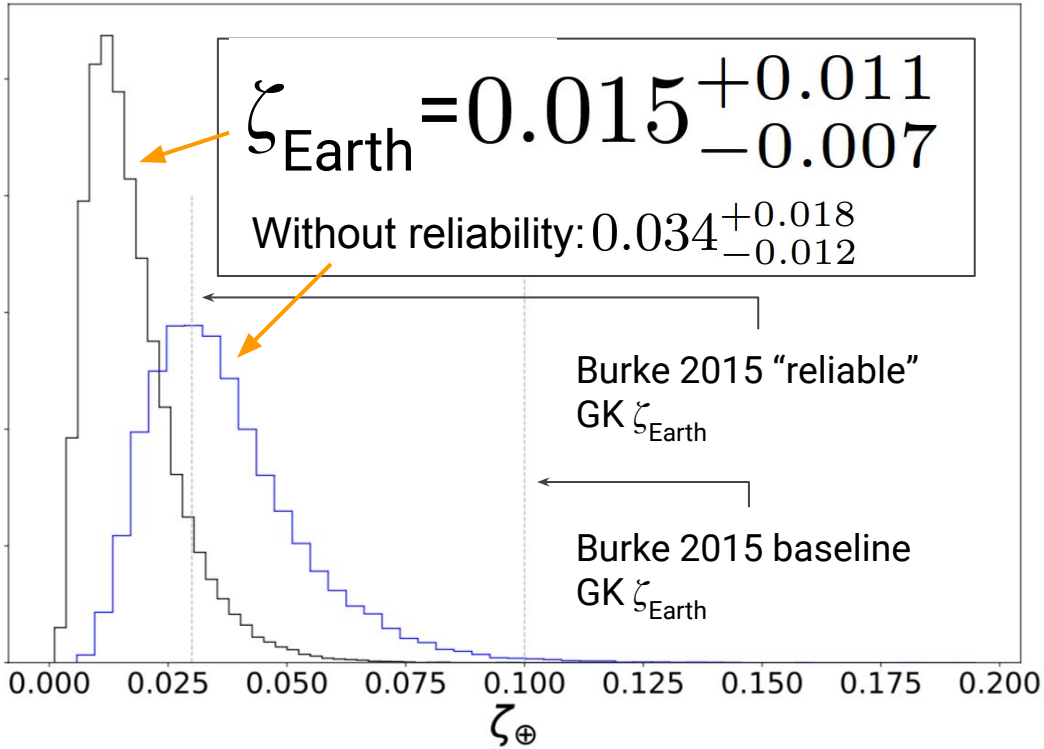
Our Baseline Planet Candidate Population

- Planets colored by reliability
- Few small, long-period planets
- Small, long-period planets have reliability < 0.5
- Contours are completeness averaged over all stars



ζ_{Earth} (within 20% of Earth's period and radius)

- We find that for long-period, small planets, reliability cuts the occurrence rate in half.
- Gaia vs. DR25 stellar radii cut ζ_{Earth} by 60%
- We expect that any occurrence rate method will see these kinds of impact



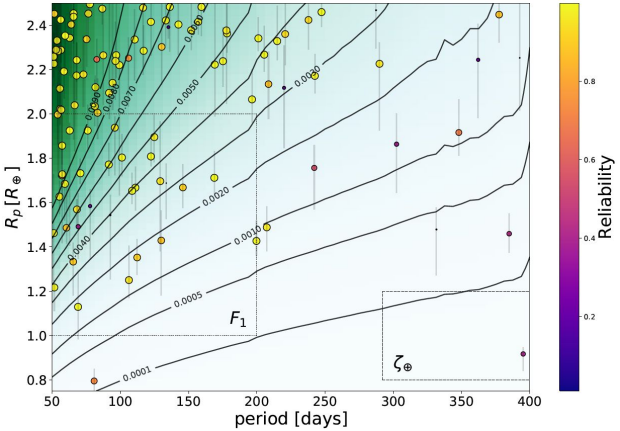
SAG 13 $\eta_{\oplus} = 0.126^{+0.095}_{-0.055}$ ($0.302^{+0.181}_{-0.113}$ without reliability)

Is This a Good Measurement?

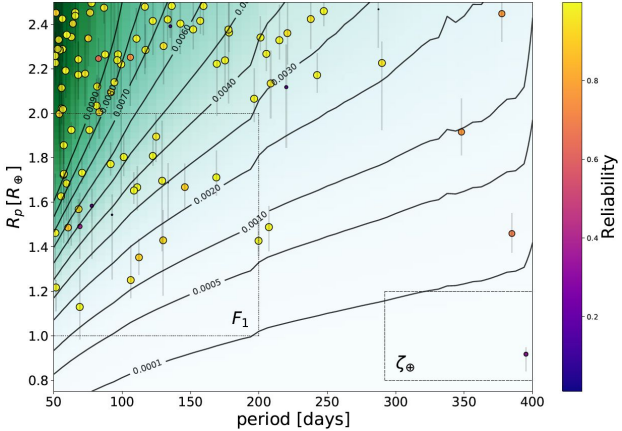
- These rates are low
  - Our SAG13 η_{Earth} value 0.126 is 4.6 times lower than the SAG13 nominal value 0.58
- Is the Robovetter being too harsh?
  - DR25 catalog has significantly fewer long-period, small candidates than previous catalogs
- For DR25, Robovetter thresholds were chosen to balance completeness and reliability
- Experiment: Try catalogs based on different Robovetter thresholds
  - High reliability, low completeness
  - Low reliability, high completeness
  - Pass DR25 false positives that the *Kepler* False Positive Working Group (FPWG) deemed as possible planets (ends up with low reliability, high completeness)
- Each choice of thresholds are as valid as the “standard” DR25 thresholds
  - So a “good” measurement should give the same value for these cases

Different Robovetter Threshold PC Catalogs

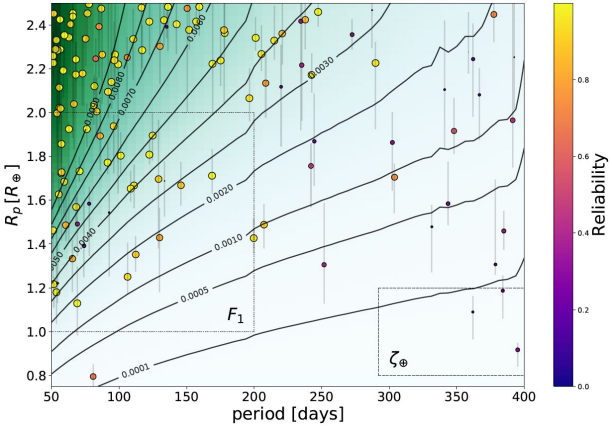
DR25



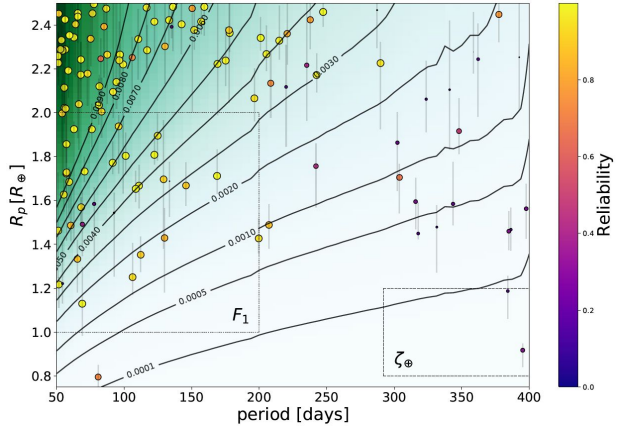
High Reliability



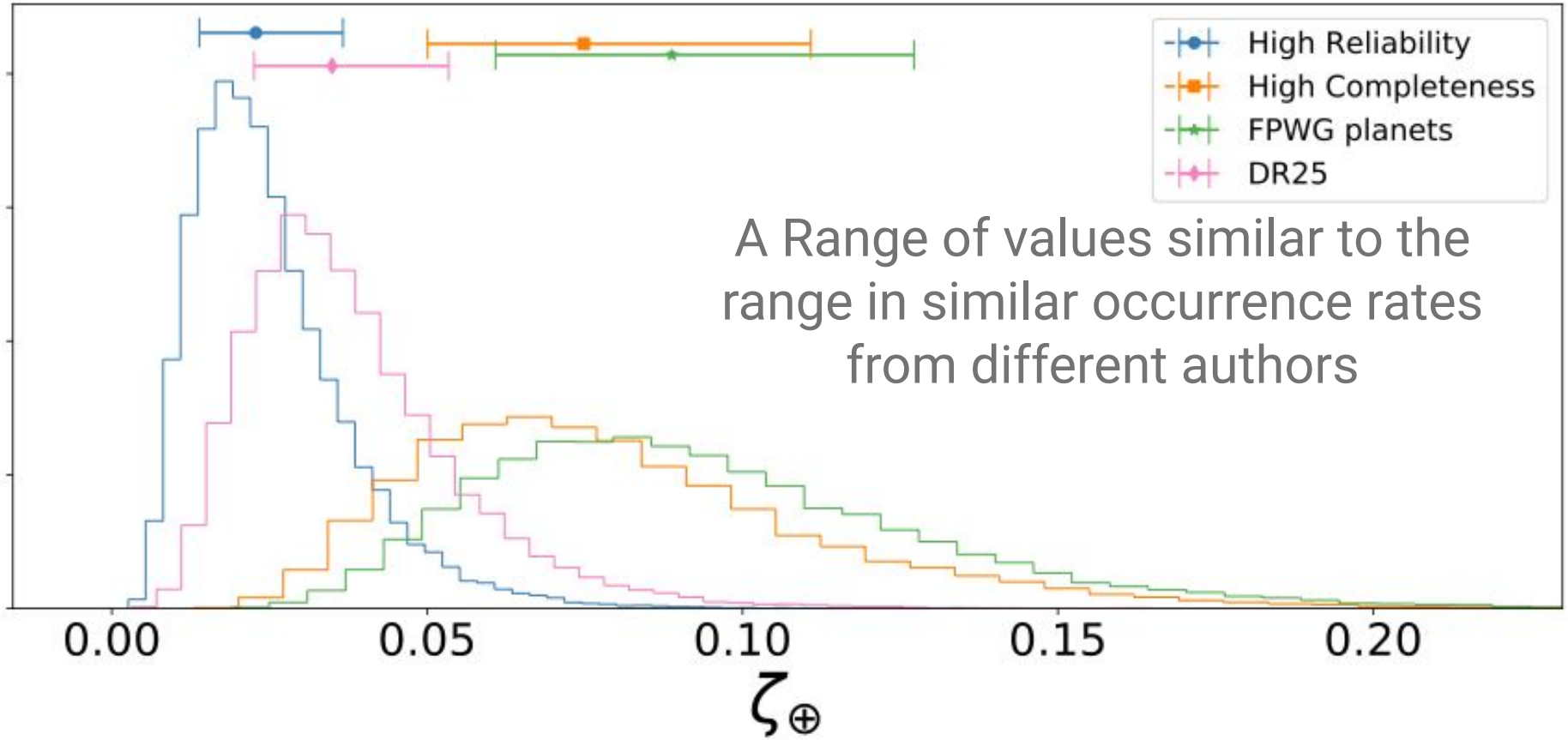
FPWG PCs



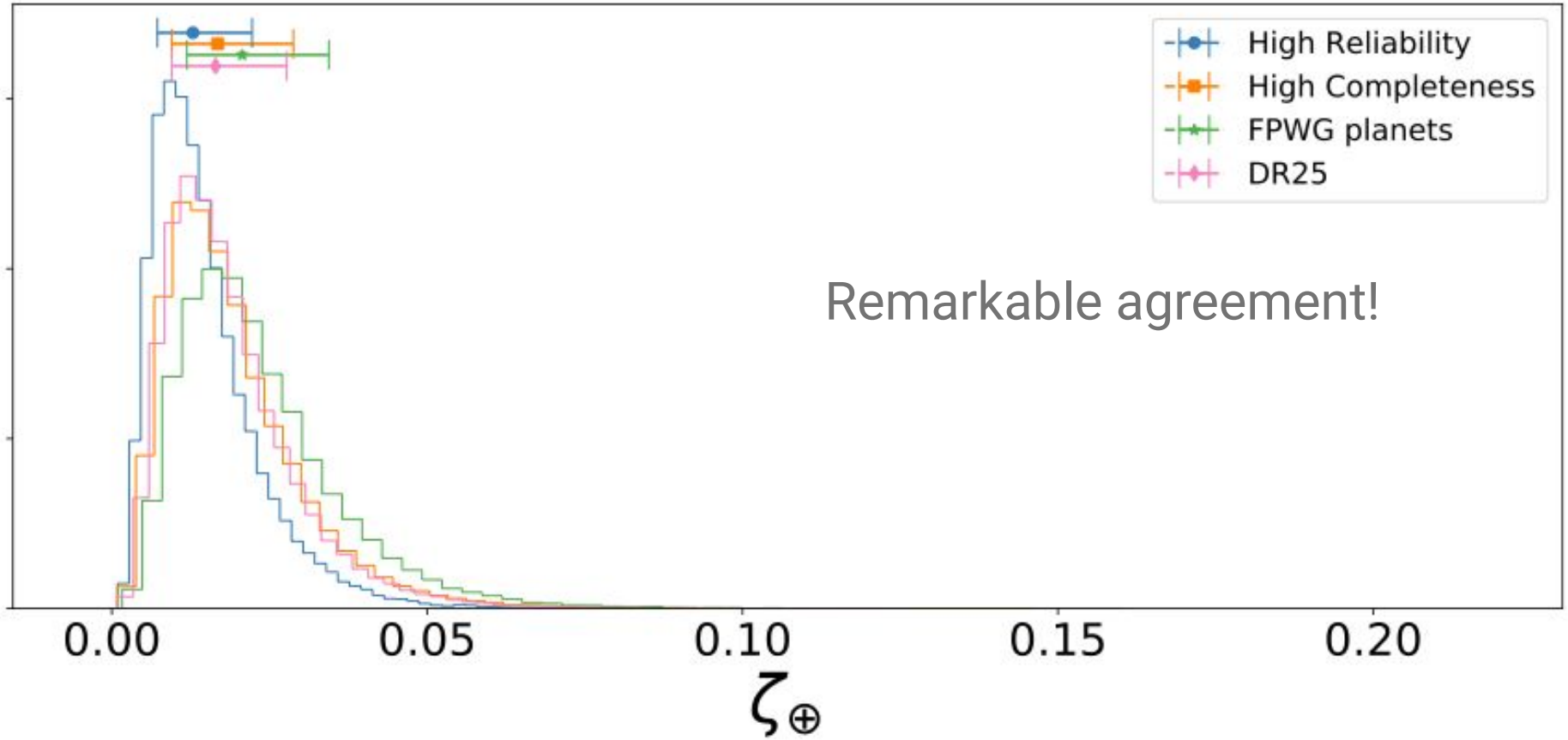
High Completeness



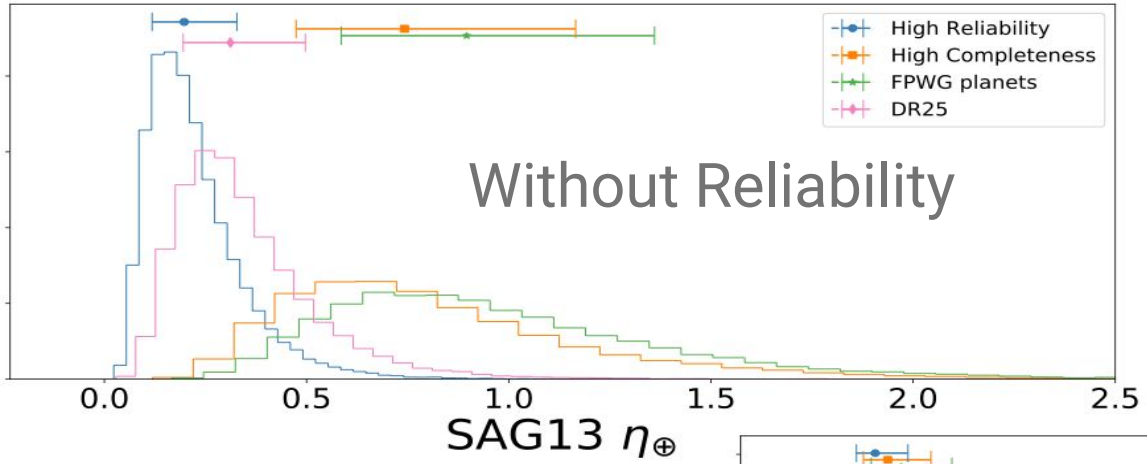
ζ_{Earth} With Completeness, Without Reliability

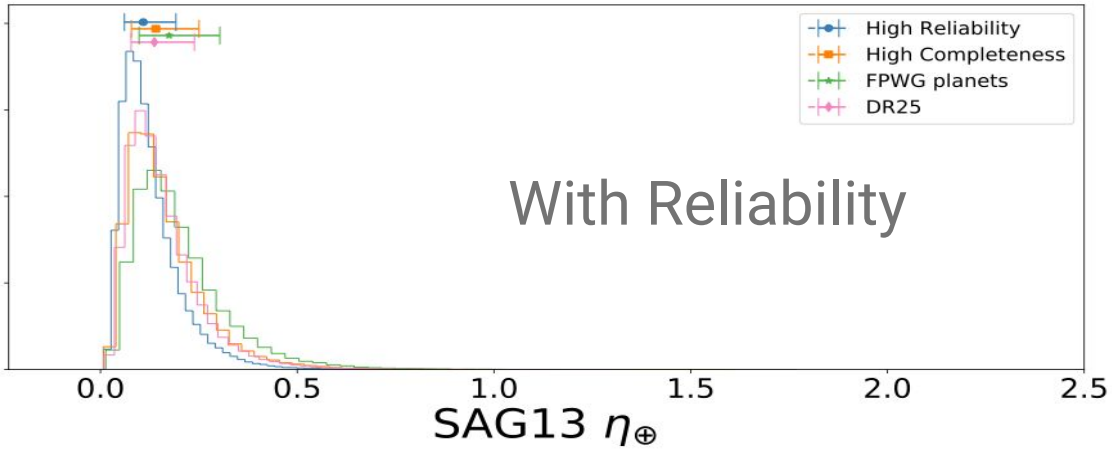


ζ_{Earth} With Completeness and Reliability



SAG13 η_{Earth} Is Similar



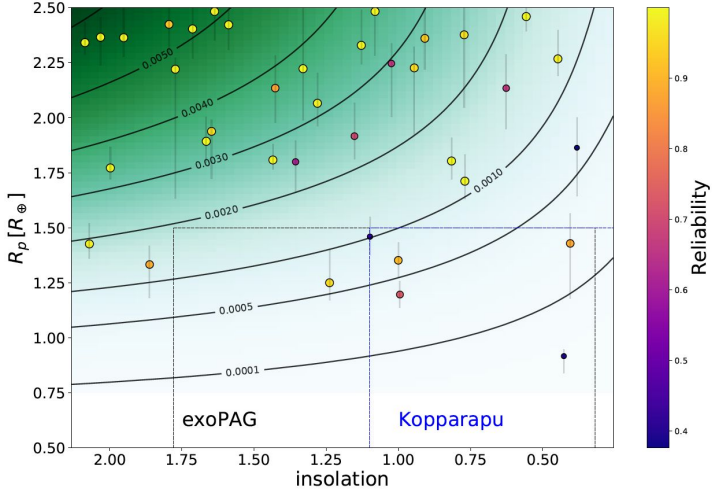


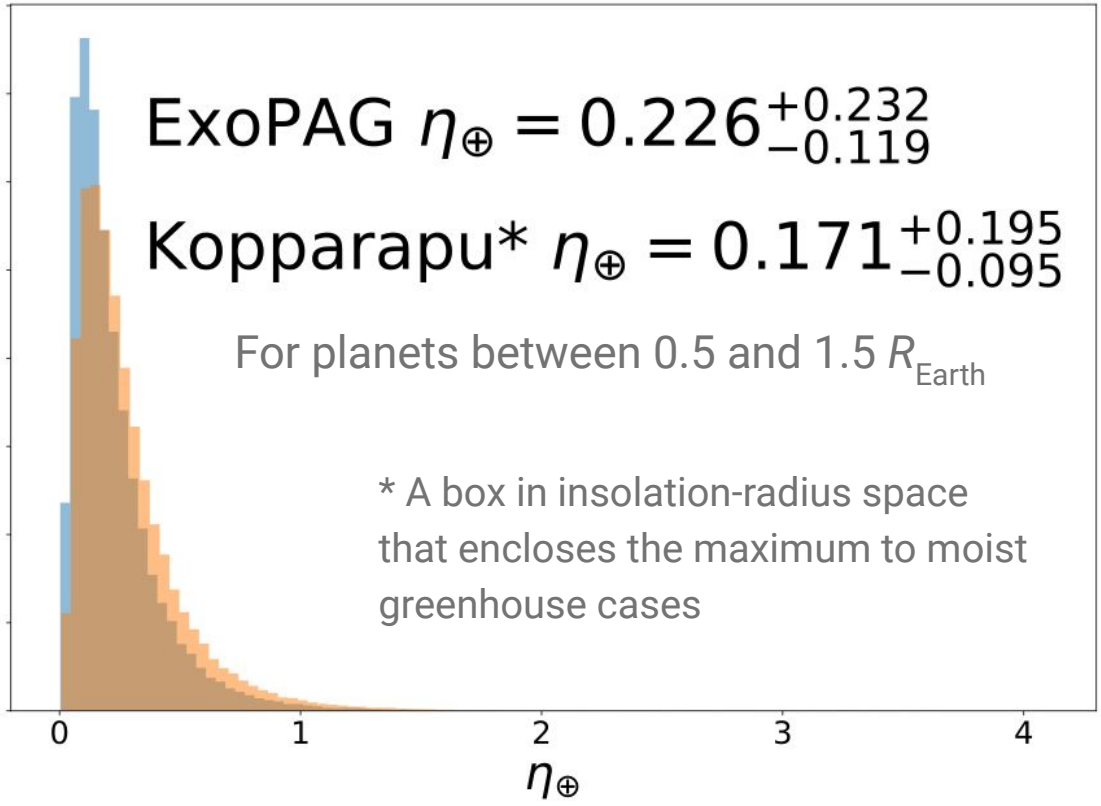
Lesson

- Occurrence rates are sensitive to completeness and reliability
- Vetting completeness and reliability are individually sensitive to vetting choices
  - Makes occurrence rates that account for, *e.g.*, only completeness sensitive to vetting choices
- But occurrence rates accounting for completeness and reliability together are relatively insensitive to vetting choices
  - At least for our method
- Apply your favorite occurrence rate method to these four catalogs to test for agreement
  - Available via Github, including synthetic data to measure reliability and completeness
  - https://github.com/stevepur/DR25-occurrence-public/
- **We propose that insensitivity to these vetting choices is necessary (though not sufficient) for a good occurrence rate measurement**

η_{Earth} in Insolation-Radius (Preliminary!!)

- Habitable zone η_{Earth}
- Same method but period replaced with insolation
- Some issues to work out



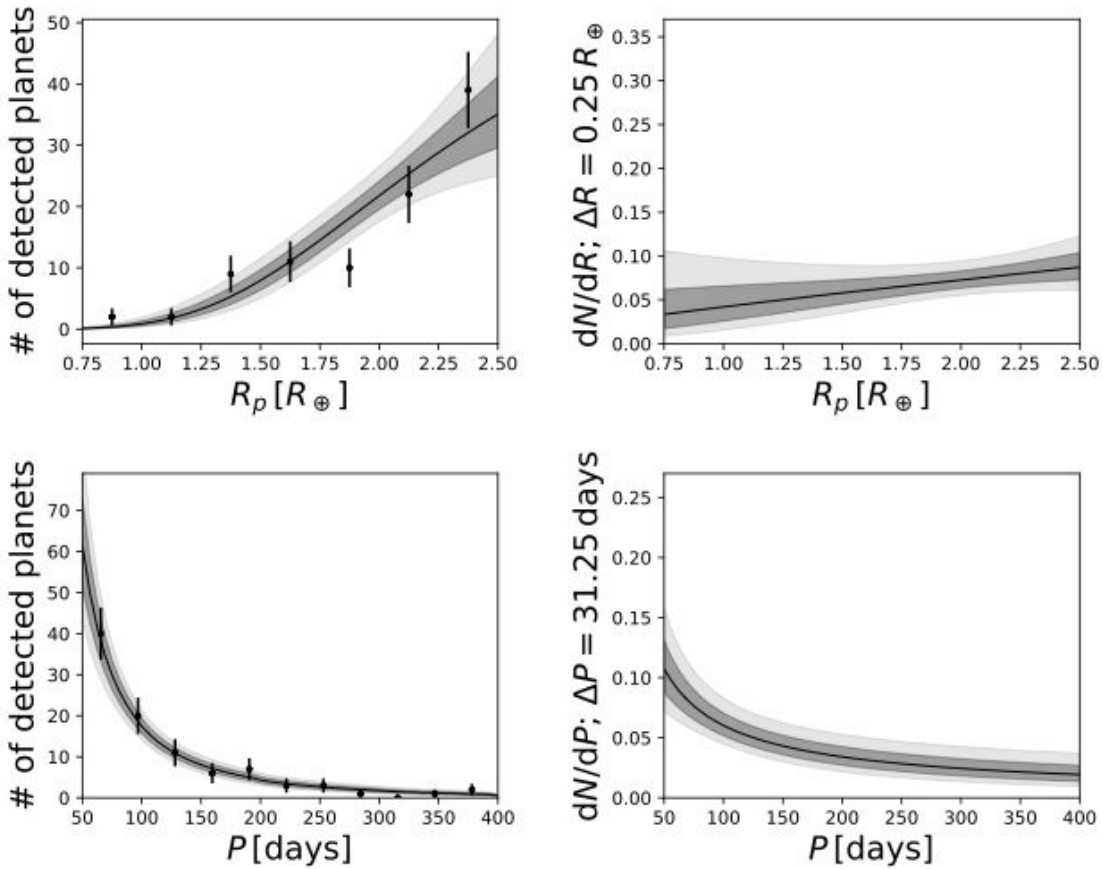


What's Next?

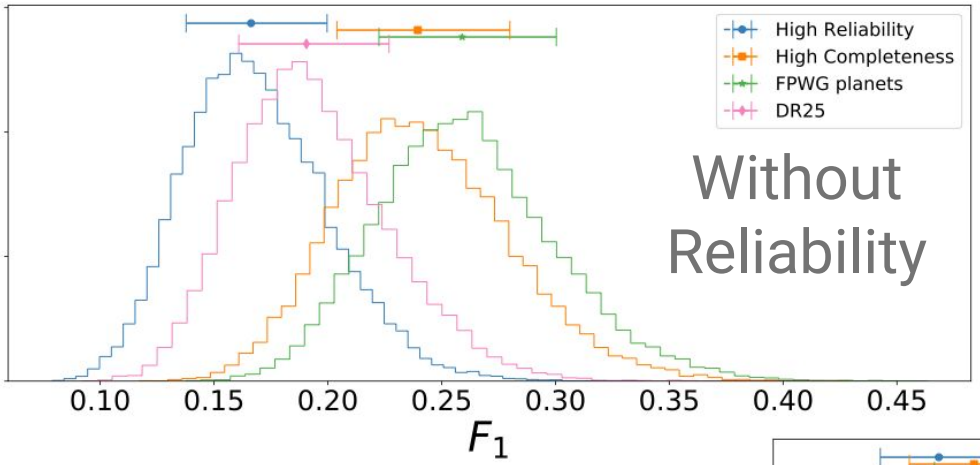
- Improved Robovetter vetting for higher completeness *and* reliability
  - Make better use of pixel-level data
  - More probabilistic analysis replacing hard thresholds
- Improved population models
  - Informed by theory
- Better understanding of uncertainties
  - Particularly in completeness analysis
- Account for correlations in multi-planet systems
- Generalize
  - To K2/TESS/CHEOPS/PLATO… data
    - Different systematics
  - Other detection methods
  - Integration of data from multiple detection methods

Backup Slides

DR25 Occurrence Fit



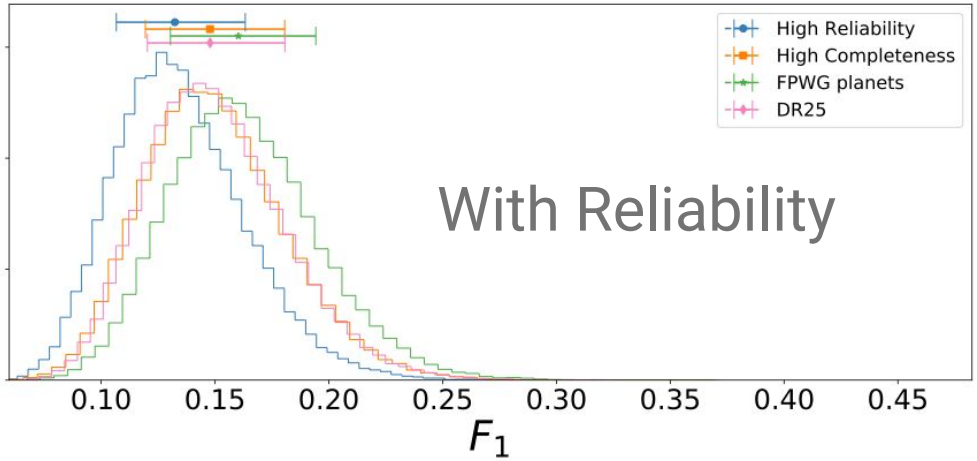
Short Orbits, Larger Planets Is Similar



Without Reliability

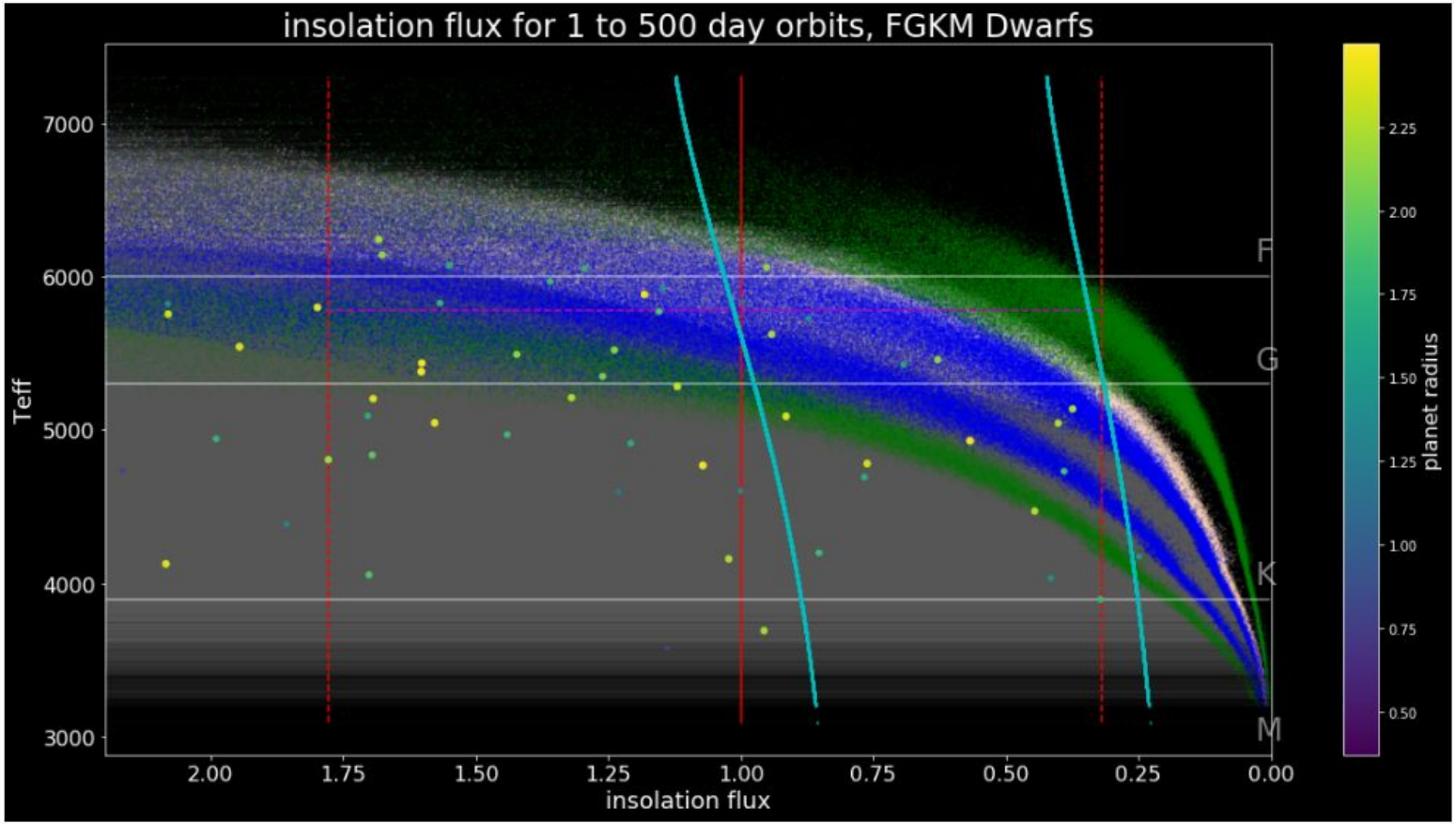
50-200 days, 1-2 R_{Earth}

(Burke F_1)



With Reliability

Insolation for the Stellar Population



DR25 Insolation-Radius Occurrence Fit