Follow-up photometry in another band benefits reducing Kepler's false positive rates

Mu-Tian Wang, Hui-gen Liu, Jiapeng Zhu, Ji-Lin Zhou

[1]School of Astronomy and Space Science, Nanjing University, Nanjing 210023, China.

[2] Key Laboratory of Modern Astronomy and Astrophysics, Ministry of Education, Nanjing, 210023, People's Republic of China

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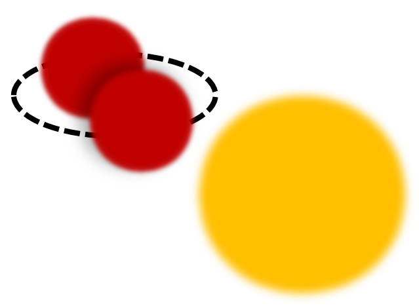
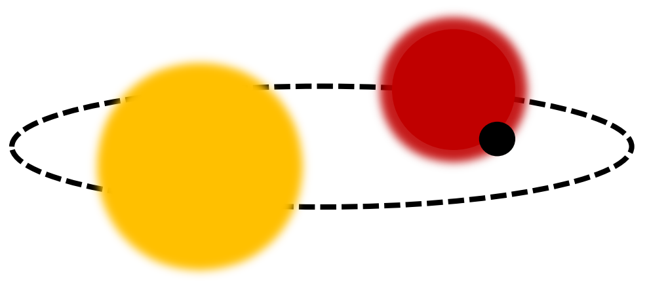
Contact: mutianw@smail.nju.edu.cn

Introduction

Two common false positives in Kepler



Background Eclipsing Binaries (BEBs): a bright target star blended with eclipsing binary in the background.



Companion Transiting Planets (**CTPs**): A planet transiting the unresolved stellar companion of the target star

Color-dependent depth of stellar blends

Blends featuring multiple stars with different colors will project color-dependent depth signature on different observing band-passes. While the apparent depths of the non-emitting planet transits will remain constant regardless of the observing photometry. Therefore, the color-dependent feature could be utilized as a discriminator to separate false positives from planet transits.

False positive probability (FPP)

Extra photometry other than Kepler adds up to total information about the candidate, improving the false positive probability compared to the FPP derived from single-band photometry.

Objective

1. Compare the **false positive rule-out fraction** when using different reference photometry (**SDSS z, 2MASS Ks and TESS**) at different precisions (**1/3/10 times of Kepler**) to follow-up Kepler candidates.

2. Explore how the **false positive probability (FPP)** of Kepler candidates will increase/reduce if it is observed in an additional photometry.

BEB and CTP Monte Carlo simulation

We carry out physics-based simulation of representative Kepler false positives that:

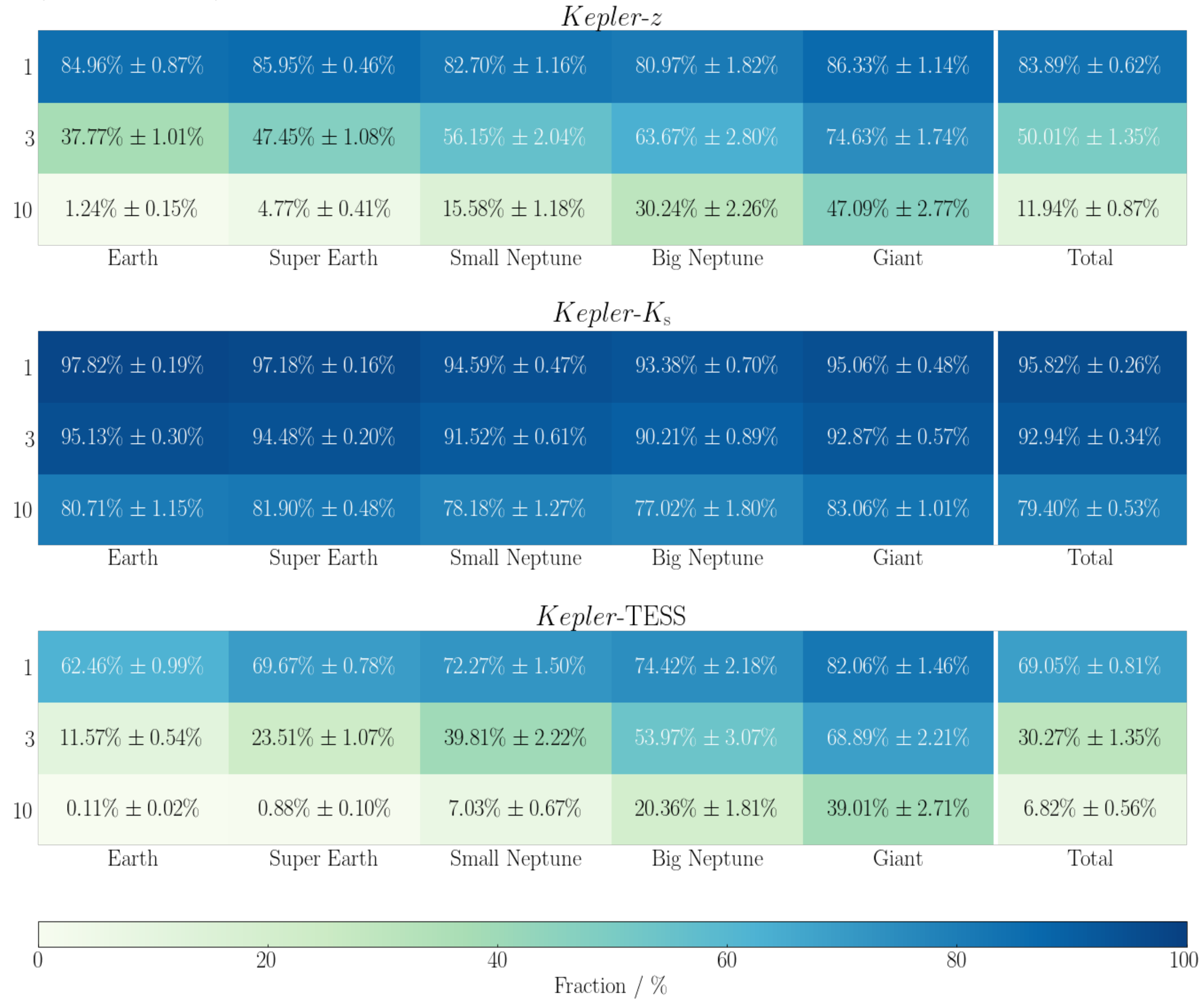
- match the KIC stellar properties, binary statistics and galactic stars population.
- have synthesized multi-band photometry predicted by MIST isochrone.
- have estimated multi-band signal-to-noise ratio (SNR) of transit signal (modified from Kepler CDPP).

If the difference between depths in Kepler and reference band exceeds 5σ, we consider the false positive is identified, this quantity can be expressed as:

$$SNR_{\mathrm{RF-KP}} = \frac{|\delta_{\mathrm{RF}} - \delta_{\mathrm{KP}}|}{\sqrt{\sigma_{\mathrm{RF}}^2 + \sigma_{\mathrm{KP}}^2}} > 5$$

Rule-out fraction of BEBs

Accounting for the background star's gradient across entire Kepler field, we derive the mean fraction of BEBs that will show detectable depth variations in following table, classified by BEBs' apparent depth (characterized by the apparent planet radii they mimic), the choice of reference band and the assumed photometric precision therein.



Kepler-*z*

	Earth	Super Earth	Small Neptune	Big Neptune	Giant	Total
1	84.96% ± 0.87%	85.95% ± 0.46%	82.70% ± 1.16%	80.97% ± 1.82%	86.33% ± 1.14%	83.89% ± 0.62%
3	37.77% ± 1.01%	47.45% ± 1.08%	56.15% ± 2.04%	63.67% ± 2.80%	74.63% ± 1.74%	50.01% ± 1.35%
10	1.24% ± 0.15%	4.77% ± 0.41%	15.58% ± 1.18%	30.24% ± 2.26%	47.09% ± 2.77%	11.94% ± 0.87%

Kepler-K_s

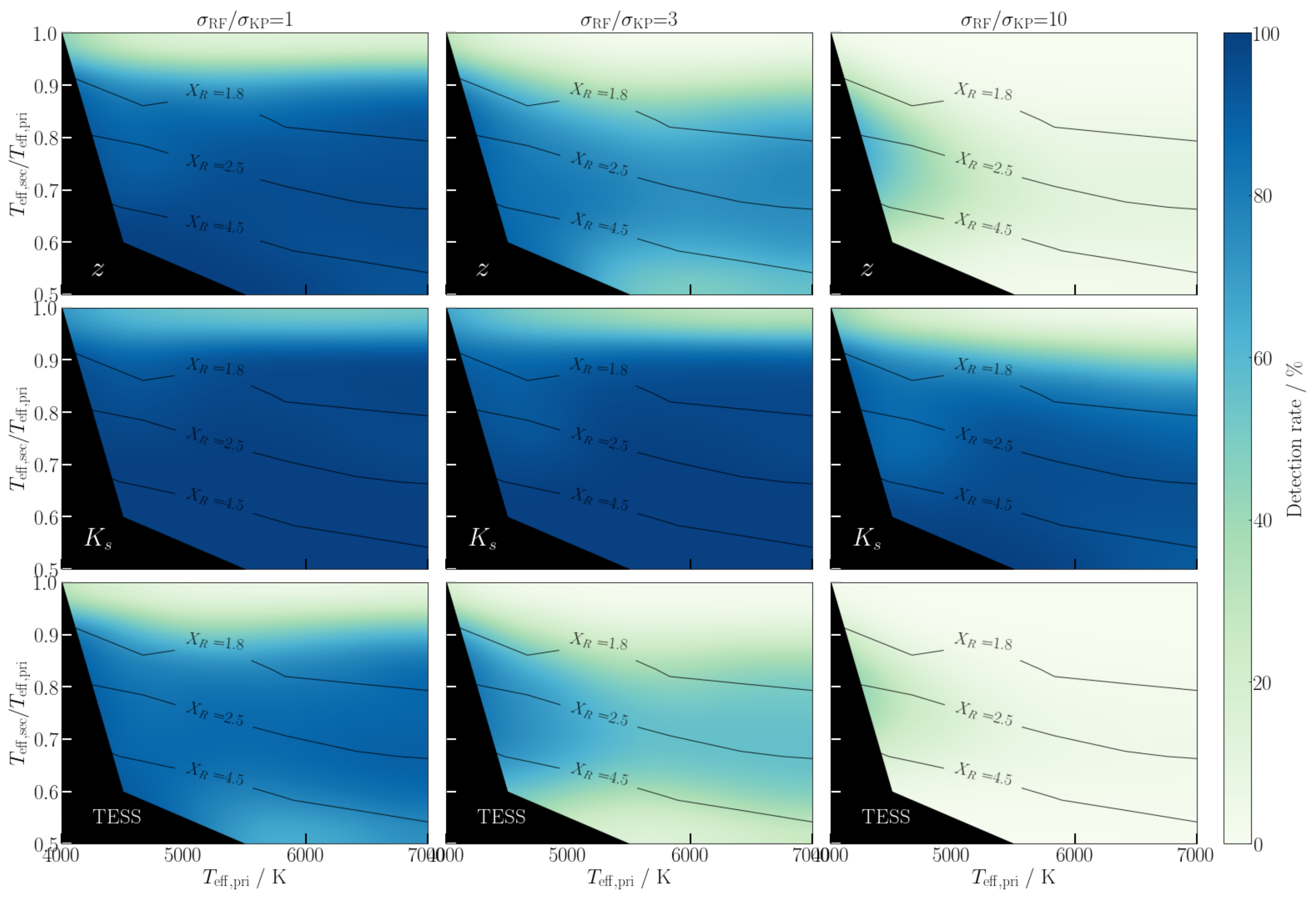
	Earth	Super Earth	Small Neptune	Big Neptune	Giant	Total
1	97.82% ± 0.19%	97.18% ± 0.16%	94.59% ± 0.47%	93.38% ± 0.70%	95.06% ± 0.48%	95.82% ± 0.26%
3	95.13% ± 0.30%	94.48% ± 0.20%	91.52% ± 0.61%	90.21% ± 0.89%	92.87% ± 0.57%	92.94% ± 0.34%
10	80.71% ± 1.15%	81.90% ± 0.48%	78.18% ± 1.27%	77.02% ± 1.80%	83.06% ± 1.01%	79.40% ± 0.53%

Kepler-TESS

	Earth	Super Earth	Small Neptune	Big Neptune	Giant	Total
1	62.46% ± 0.99%	69.67% ± 0.78%	72.27% ± 1.50%	74.42% ± 2.18%	82.06% ± 1.46%	69.05% ± 0.81%
3	11.57% ± 0.54%	23.51% ± 1.07%	39.81% ± 2.22%	53.97% ± 3.07%	68.89% ± 2.21%	30.27% ± 1.35%
10	0.11% ± 0.02%	0.88% ± 0.10%	7.03% ± 0.67%	20.36% ± 1.81%	39.01% ± 2.71%	6.82% ± 0.56%

Rule-out fraction of CTPs

Separating CTPs into several groups with similar spectral type compositions, we calculate the mean fraction of CTPs (that host a Jupiter-size planet) that will show detectable depth variations in the figures below, according to different choices of reference band and the assumed photometric precision σ_{RF} therein. X_R denotes the ratio of planet's true radius ($1R_{\mathrm{jup}}$) to apparent radius.



False positive probability

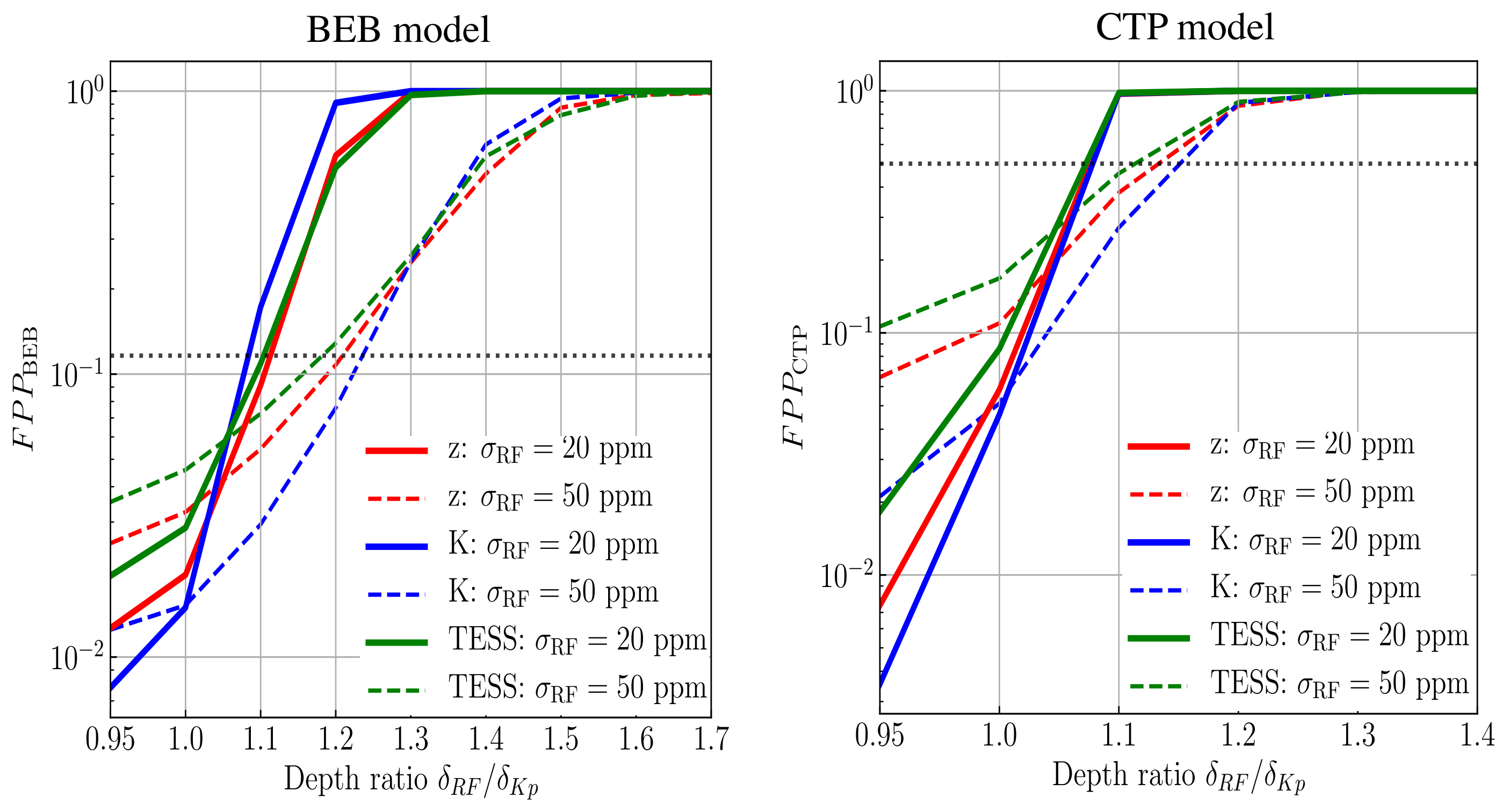
We adopt a Bayesian framework to calculate the double-band FPP for small planet candidates.

$$FPP = \frac{p_{\mathrm{FP}}\mathcal{L}_{\mathrm{FP}}}{p_{\mathrm{TP}}\mathcal{L}_{\mathrm{TP}} + p_{\mathrm{FP}}\mathcal{L}_{\mathrm{FP}}}$$

p is the prior probability for the hypothesized false positive or true planet to exist, $\mathcal{L}$ is the likelihood that the double-band apparent depth can be produced by the corresponding model.

Double-band false positive probability

We apply the FPP calculation framework to small planet candidates (100-200 ppm) from typical Kepler target stars (Kepler mag~14). In BEB model, using the double-band depth ratio could more easily identify the blend nature of these candidates. In CTP model, the depth ratio also give hints toward the planet host star in a binary system.



Conclusions

1. **Ks band** can **most effectively** identify false positives' depth variation.

2. Using **z / TESS** as the reference band is **much sensitive to photometry precision.**

3. On the relation between **rule-out rate** and **photometric precision:**
   z / TESS (σ_{RF}/σ_{KP}=1) ~ K_s (σ_{K_s}/σ_{KP}=10)

4. Double-band photometry can improve the **false positive probability** of small planet candidates **by factors up to 1-2 orders.**

Reference

1. J. M. Désert et al., "Low false positive rate of kepler candidates estimated from a combination of spitzer and follow-up observations," Astrophys. J., vol. 804, no. 1, 2015.
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3. D. Raghavan et al., "A survey of stellar families: Multiplicity of solar-type stars," Astrophys. Journal, Suppl. Ser., vol. 190, no. 1, pp. 1–42, 2010.