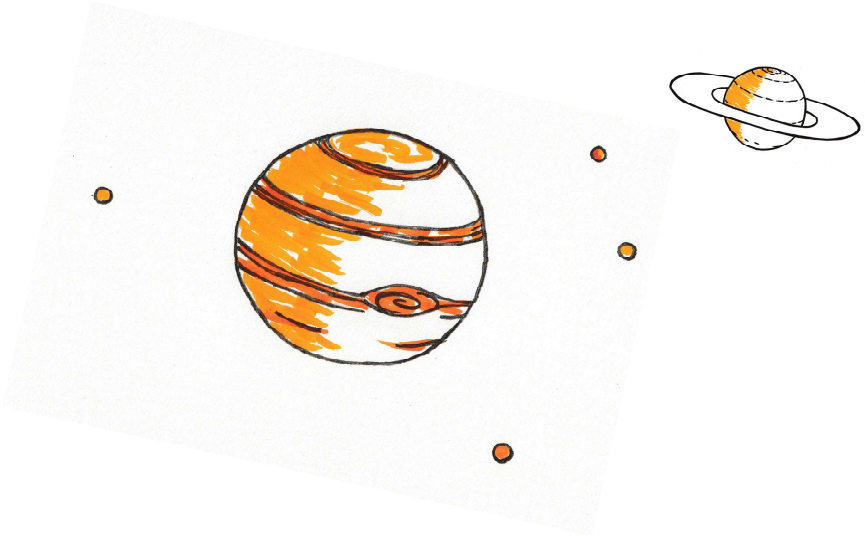
Finding Transiting Objects Near Snow Lines

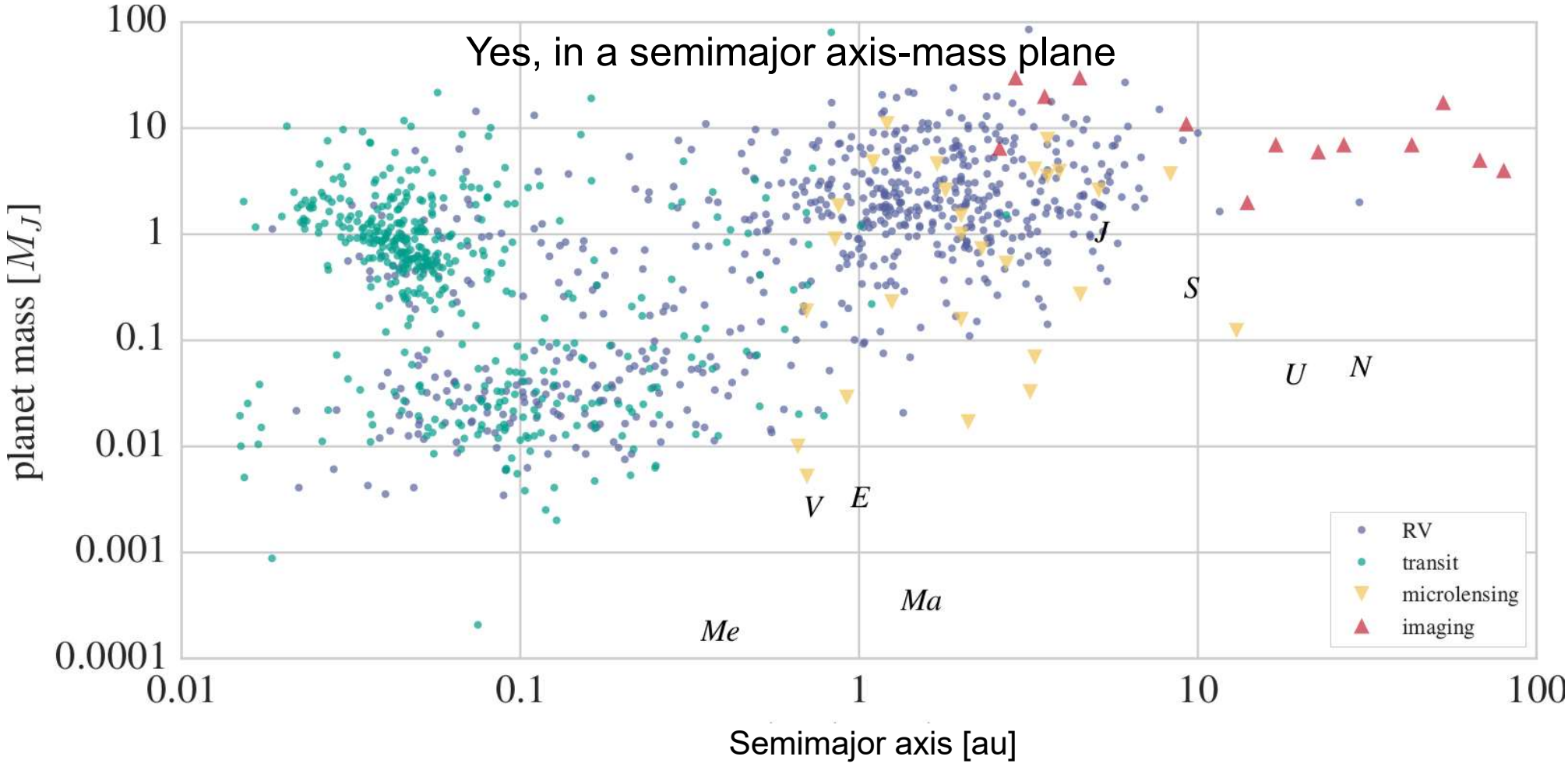


Hajime Kawahara (U. Tokyo)

Kento Masuda (Princeton), Sho Uehara (private company), Tomoyuki Tajiri, Masataka Aizawa (U. Tokyo)

Morgan MacLeod, David Latham, Allyson Bieryla (CfA), Othman Benomar (NYU)

Have we already detected solar planet analogs?



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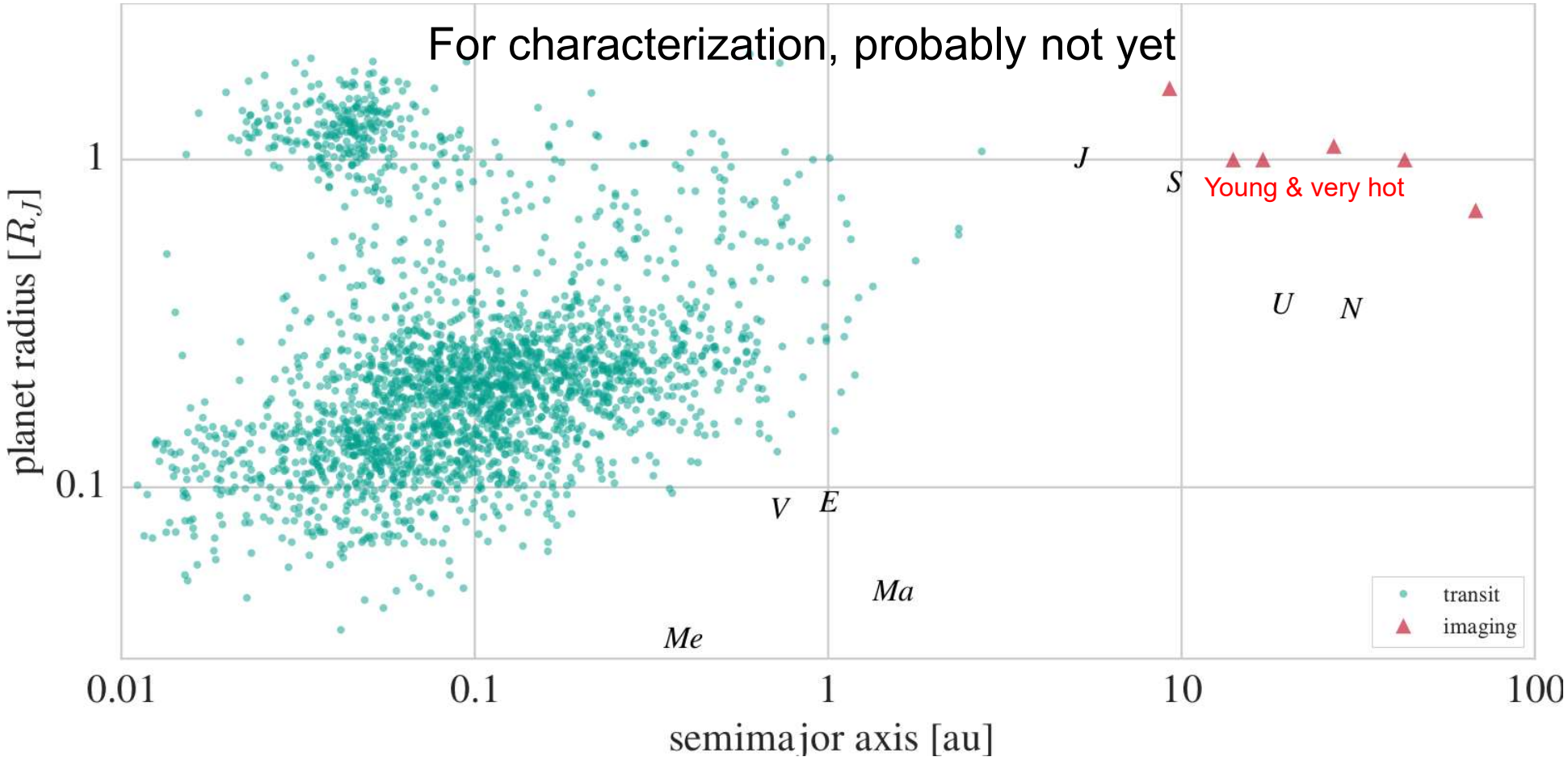
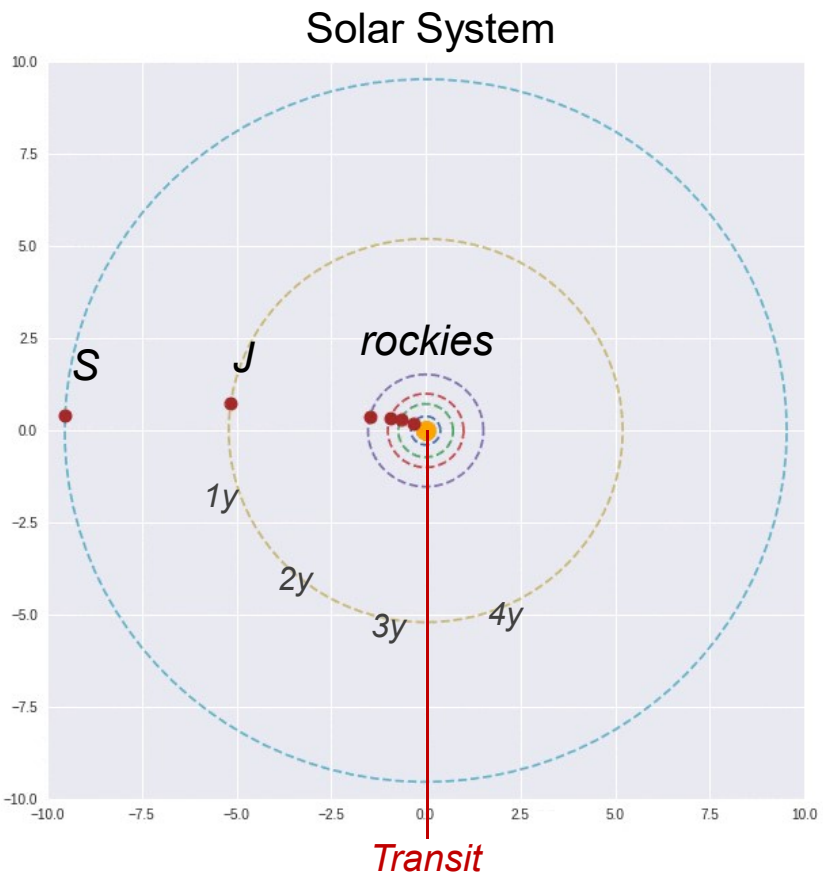
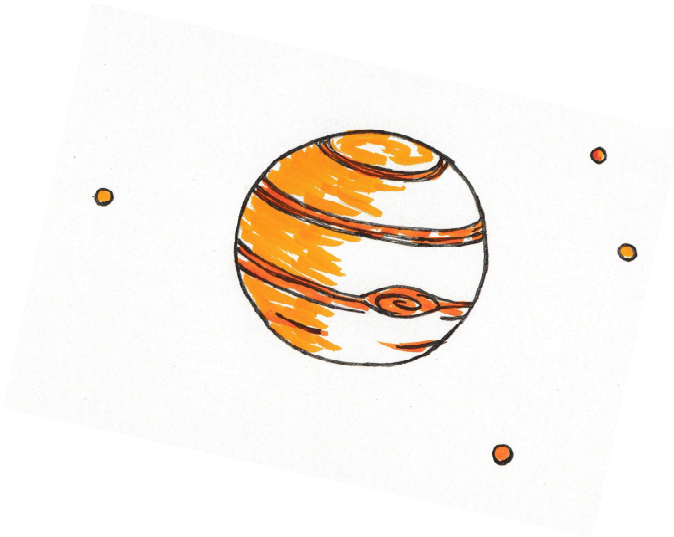


Hunting for single transiting events in *Kepler* archival data



Standard pipelines normally require >~3 transiting events for efficient detection

Jupiter will exhibit a single or no transit during the lifetime of *Kepler spacecraft* (4yr)



How to find long-period transiting object

- Visual Inspection by many citizen scientists (Planet Hunters; Wang+15)
- Visual Inspection by a student (Uehara, *H.K.,* Masuda+16)
- Machine Learning (Foreman-Mackey+16)

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Kepler ~200,000 targets

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Kepler ~200,000 targets

KOI ~8,000 targets
w/ inner planets/FPs

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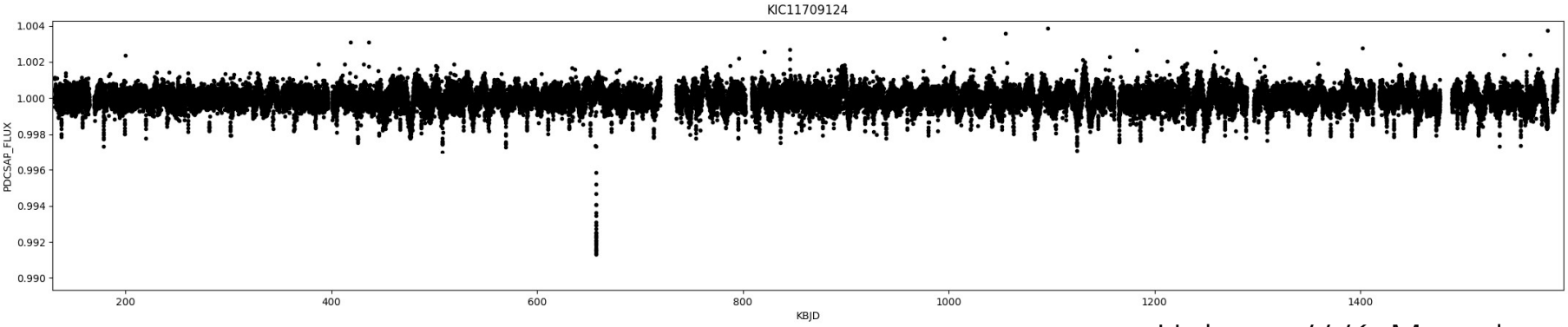
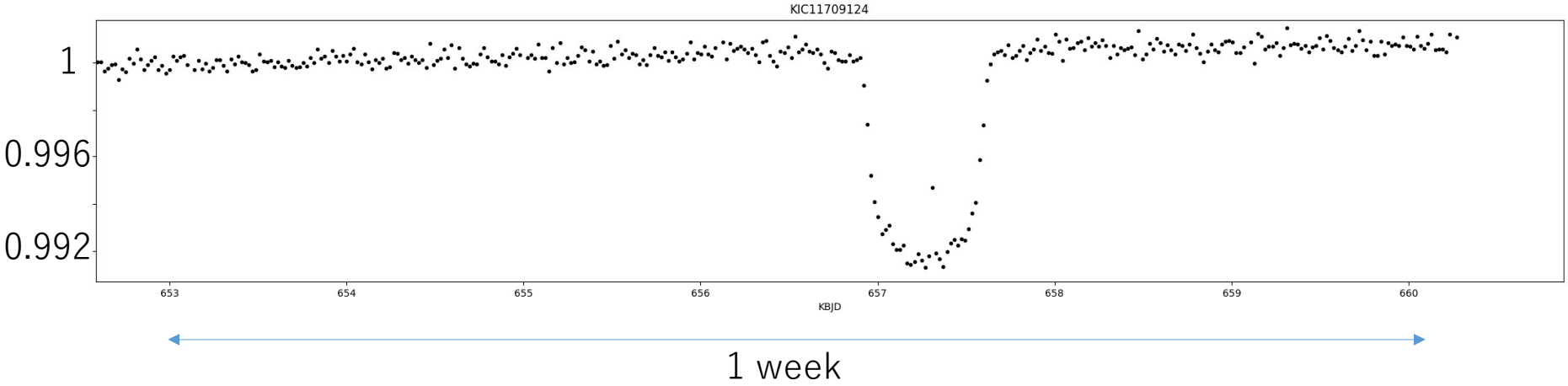
Visual Inspection by Sho Uehara

Long Period Transiting Jupiters in Kepler



Uehara, *H.K.*, Masuda et al. (2016)

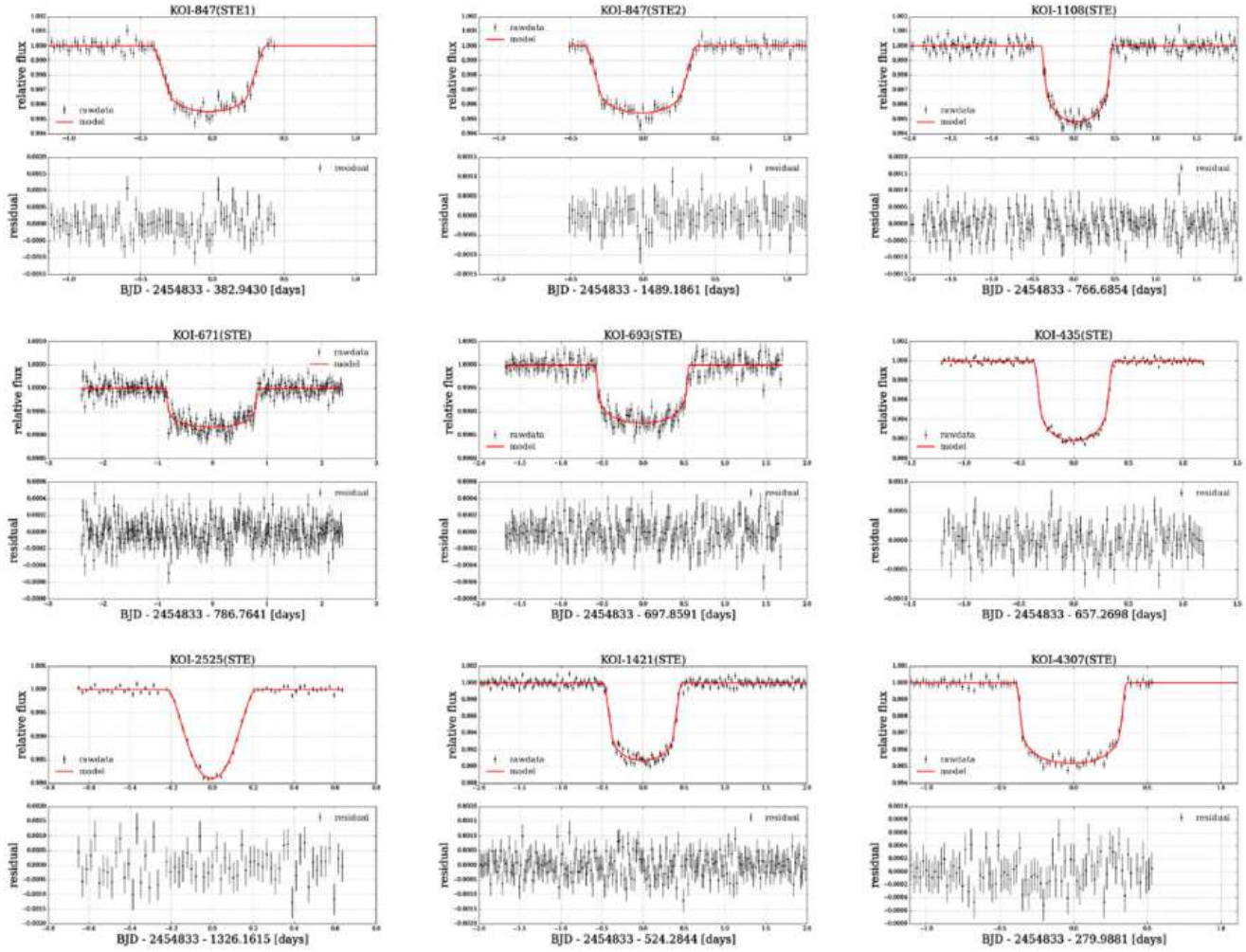


We searched for such events in ~8,000 KOI targets

14 new systems,

7 are consistent with exoplanets

others:
EB or high-e planets



Inner transit events give us …

Duration $T_{\rm tot} = \dfrac{2\sqrt{1-b^2}R_\star}{V},$

Kepler-3rd law $V = \left(\dfrac{2\pi G M_\star}{P}\right)^{\frac{1}{3}}$

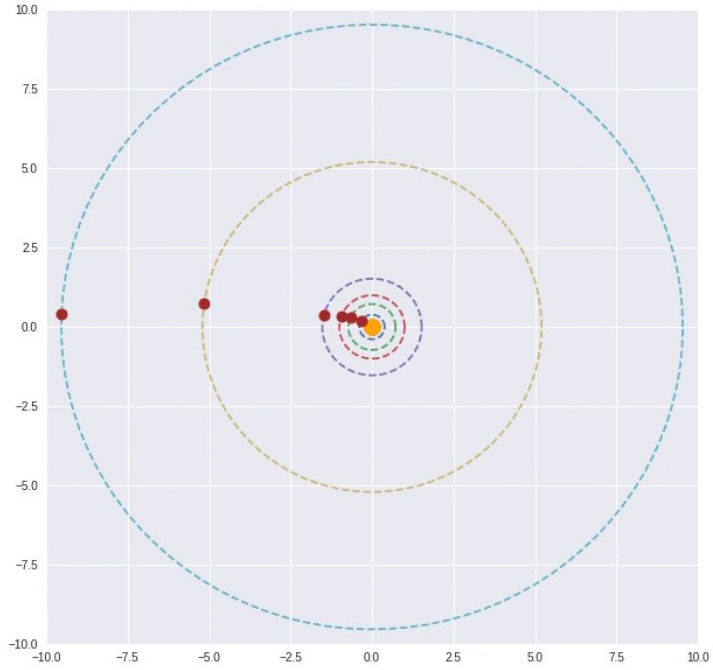
$$\therefore\ T_{\rm tot}^3 = \frac{3(1-b^2)^{3/2}}{\pi^2}\frac{P}{\rho_\star}$$

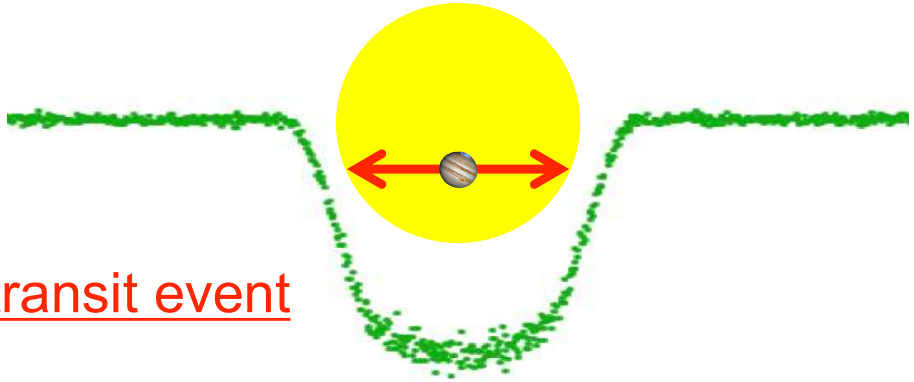
- *period* + duration ⇨ stellar density

Known inner planets, known its period

→we know the *stellar density*

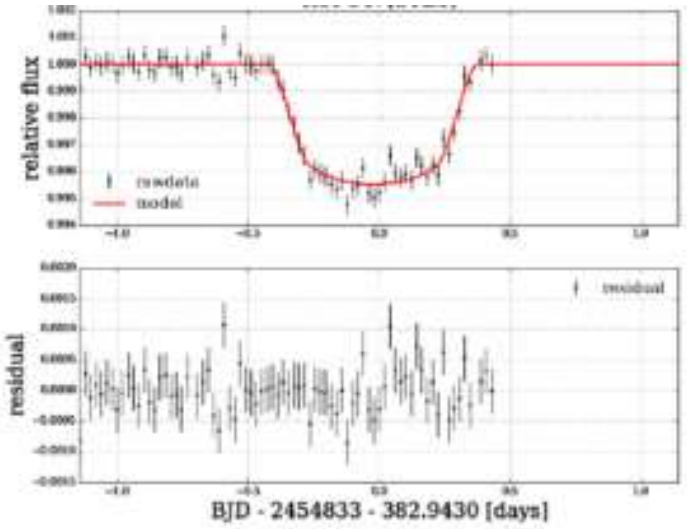
→we can estimate the period even for a single transit event



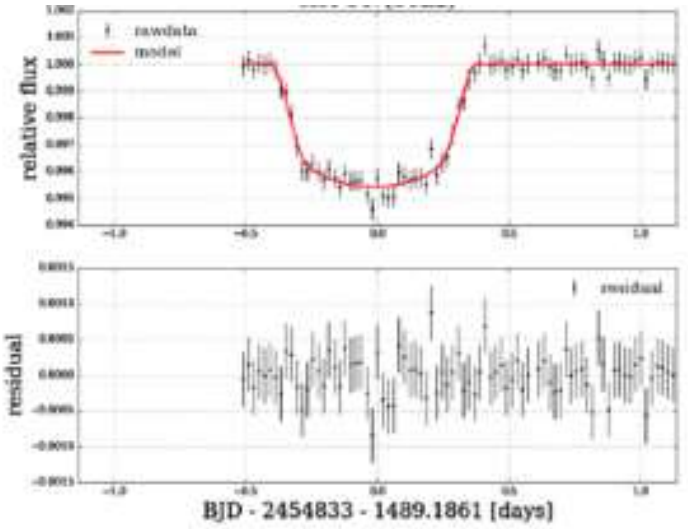


1 in ***7*** systems is a double transiting events:
Test for the period estimate

Transit 1
⇨ P = 550 – 1360 day

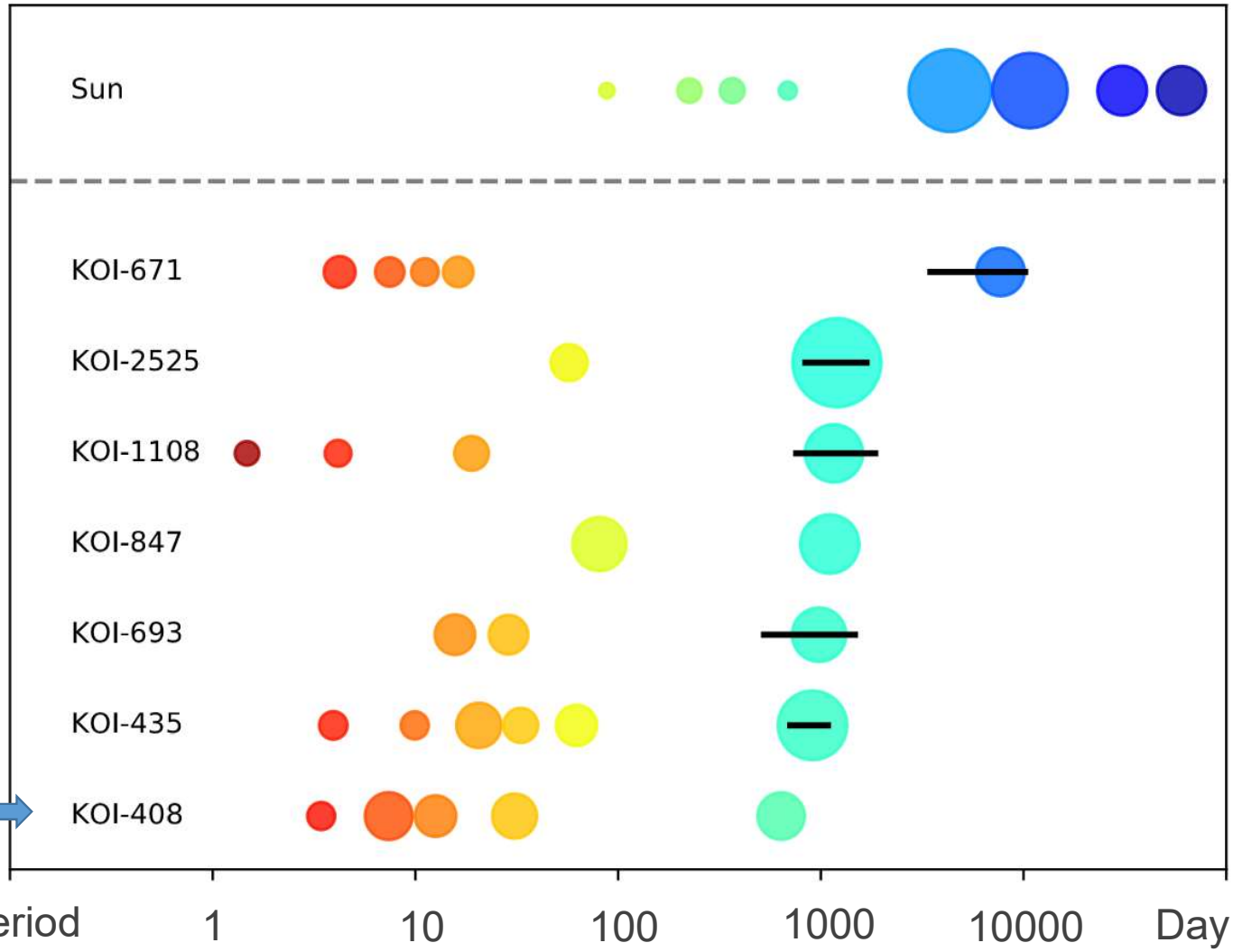


Transit 2
⇨ P = 540 – 1220 day



Interval = 1106 day

At least, ***1 in 5*** compact multis has a gas giant/neptune around the snow line



Schmitt+ 2017 AJ,152,42

Uehara, H.K., Masuda et al. 2016 ApJ

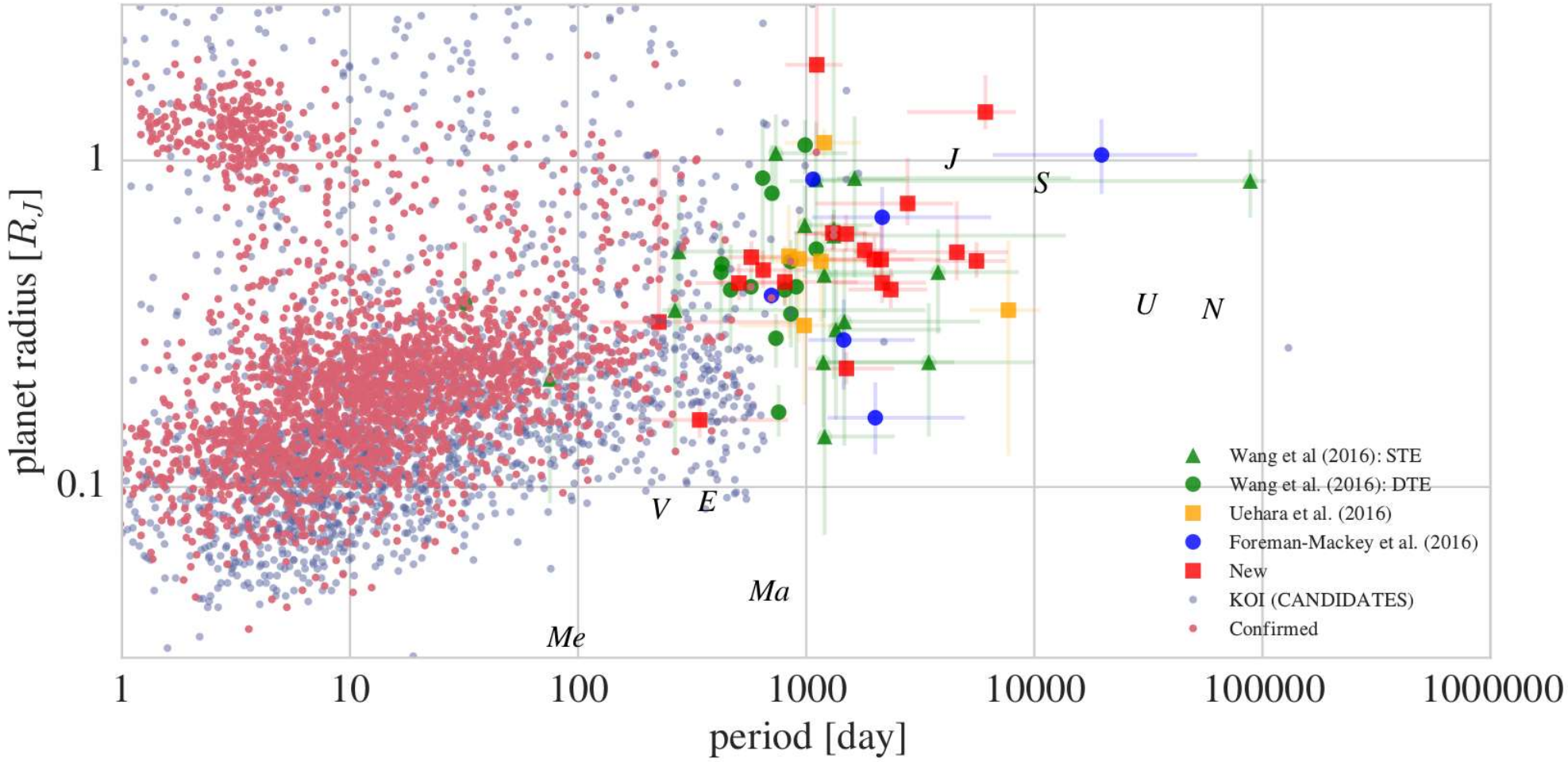
Compiling everything

- Visual Inspection by many citizen scientists (Planet Hunters; Wang+15)
- Visual Inspection by a student (Uehara, *H.K.,* Masuda+16)
- Machine Learning (Foreman-Mackey+16)

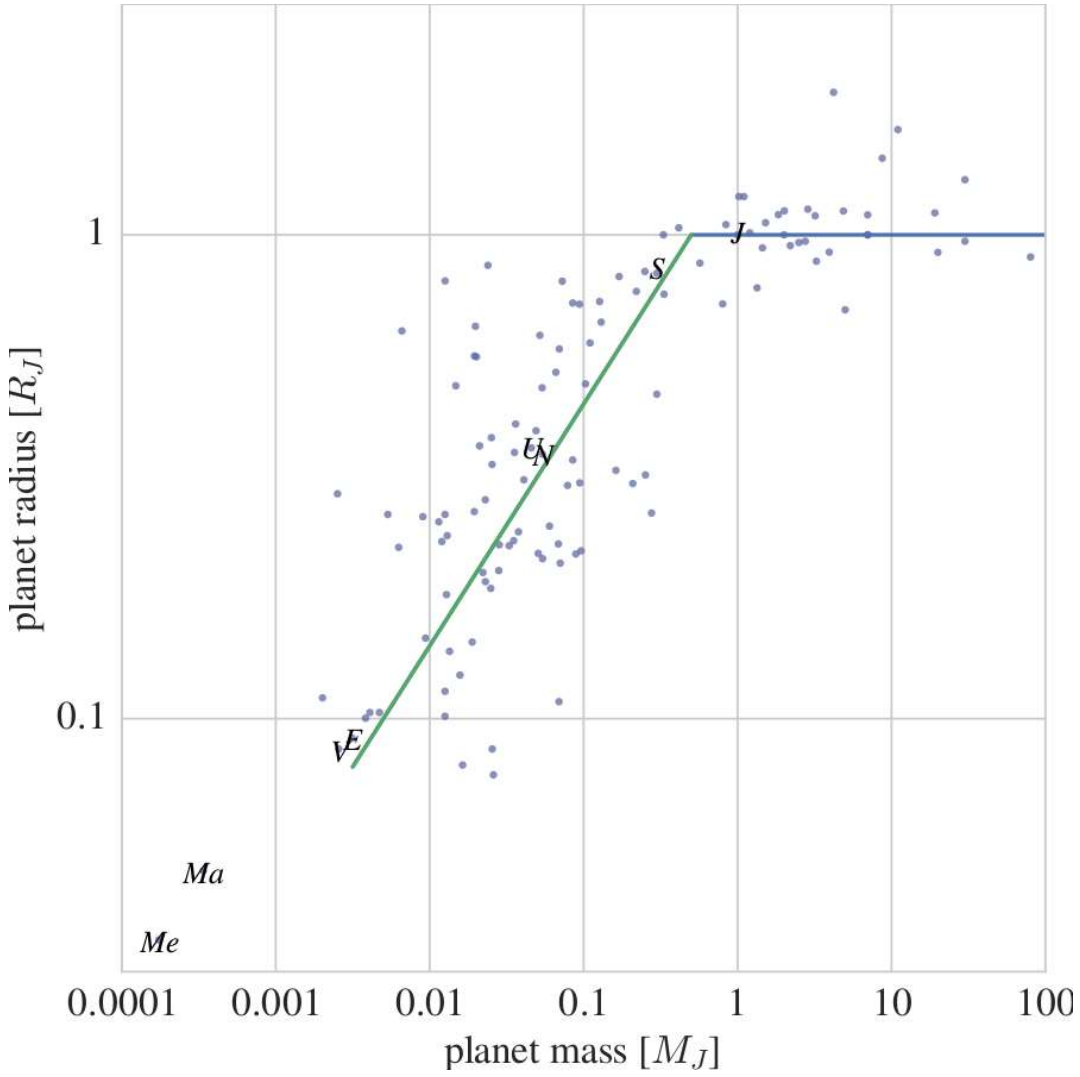
+ new STEs in KIC 200,000 targets (but less confident, not complete yet)

=> Compiling those findings, we have a tentative list of transiting planets around the snowline

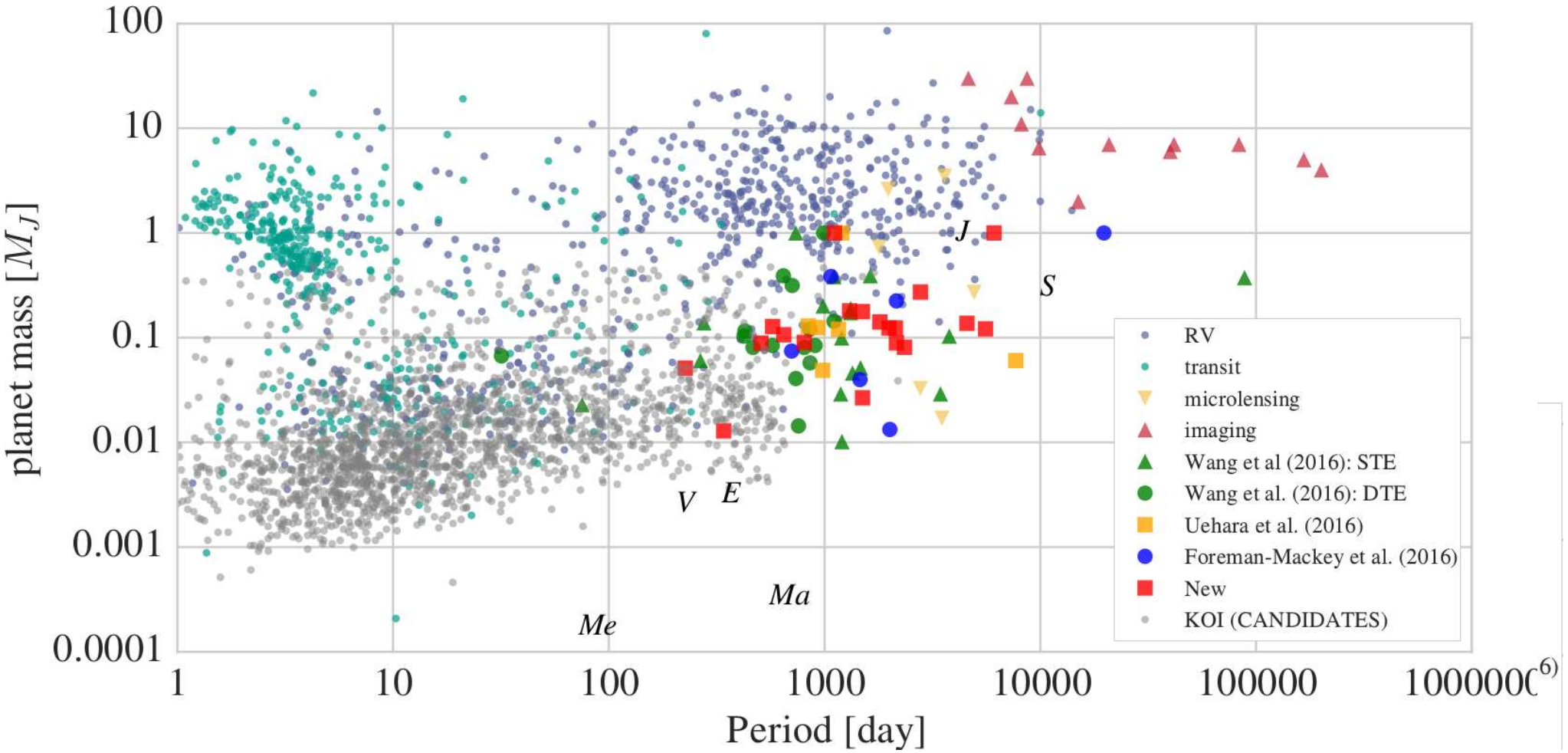
Preliminary results for all the *Kepler* stars



A simple mass-radius relation



Many Neptunes around snowline?



Long-period transiting objects more

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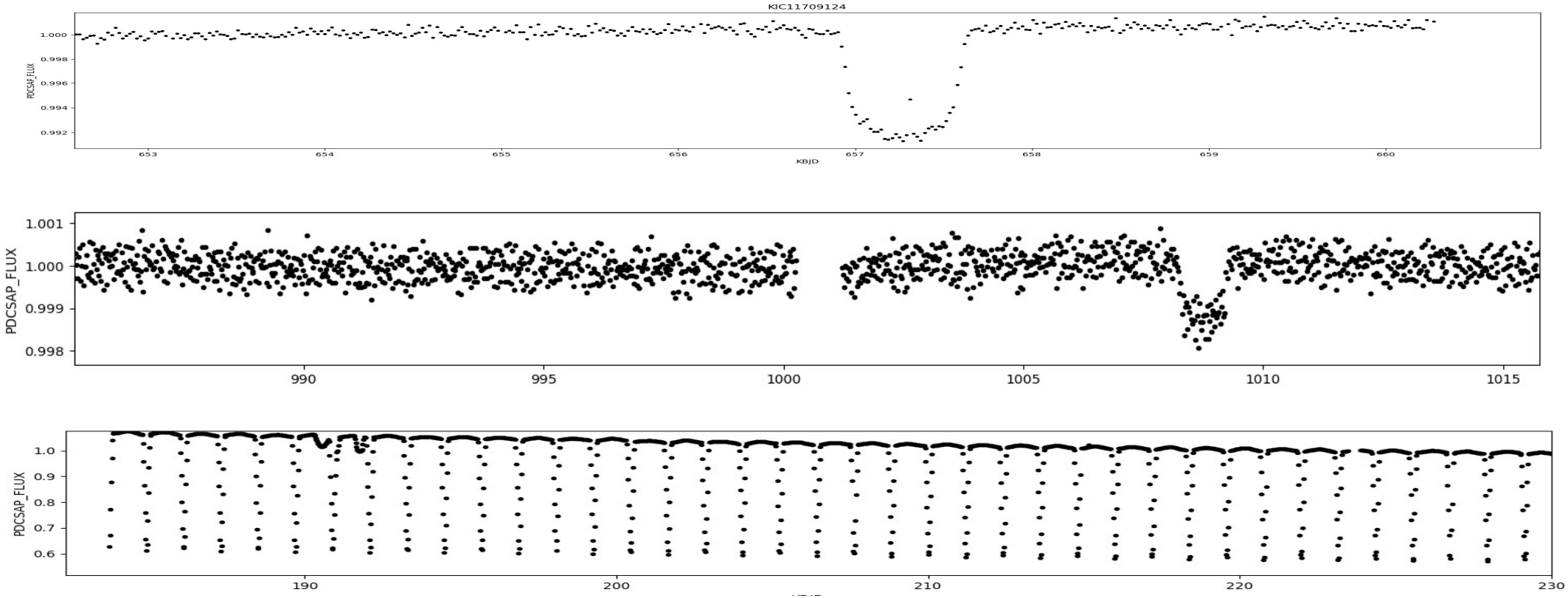
➡ Anomaly Detection (Tajiri, *H.K.*, Masuda in prep)

- Pair-wise Signal Search (*H.K.* Masuda, MacLeod to be submitted)


KIC11709124
PDCSAP_FLUX
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0.996
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654
655
656
657
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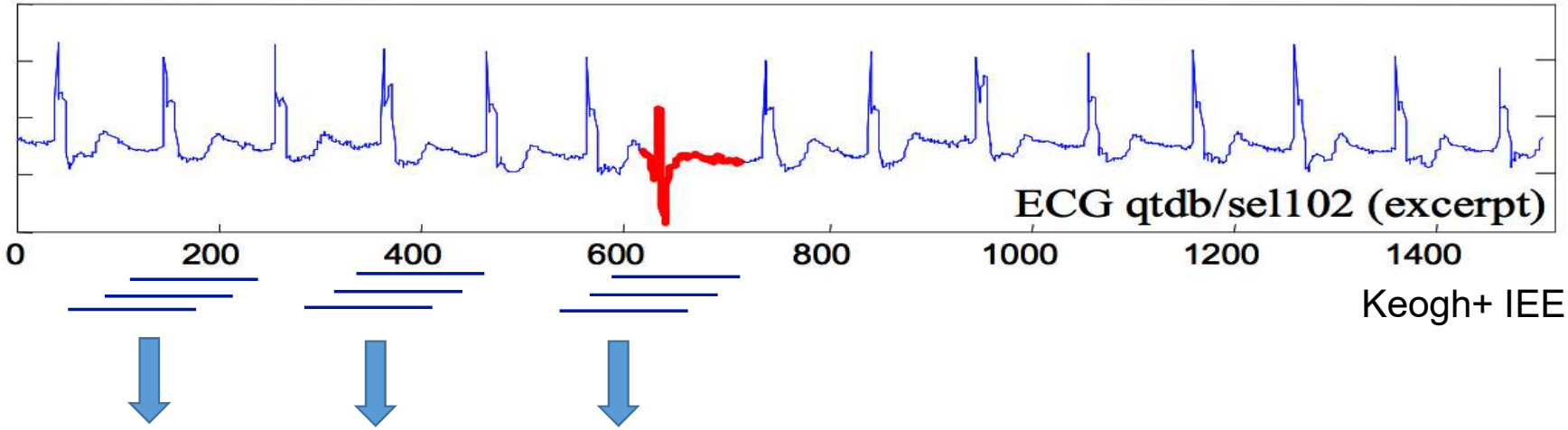
659
660
KBJD
PDCSAP_FLUX
1.001
1.000
0.999
0.998
990
995
1000
1005
1010
1015
PDCSAP_FLUX
1.0
0.9
0.8
0.7
0.6
190
200
210
220
230

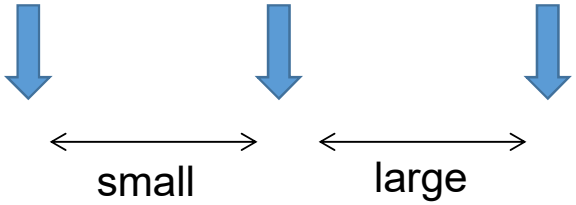
Anomaly detection: You don't really know what you want to find

Example: Changing Point Detection of Discord of Heartbeat



Keogh+ IEEE (2005)

Extracting "feature" matrices by singular value decomposition



Measuring "distance" between the feature matrices (anomaly score)

Irregular heartbeat in a heartbeat star

Preliminary results in a survey in ~2,000 Kepler EB stars

(Tajiri, *H.K.*, Masuda in prep)

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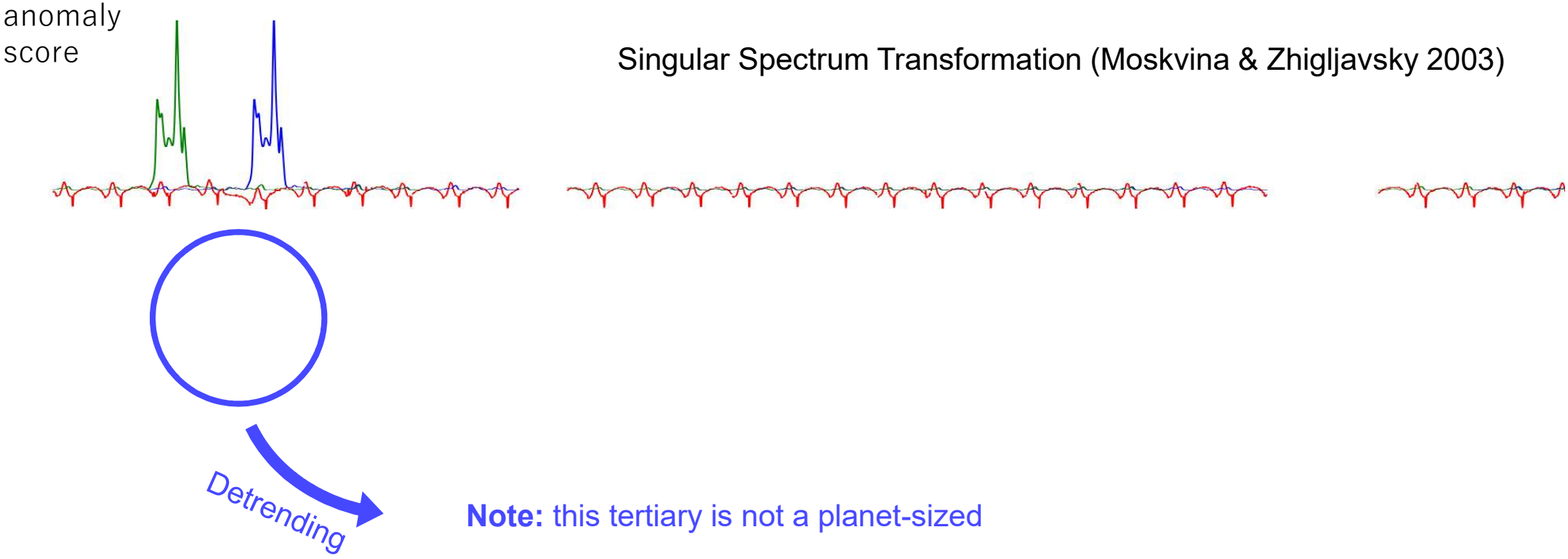

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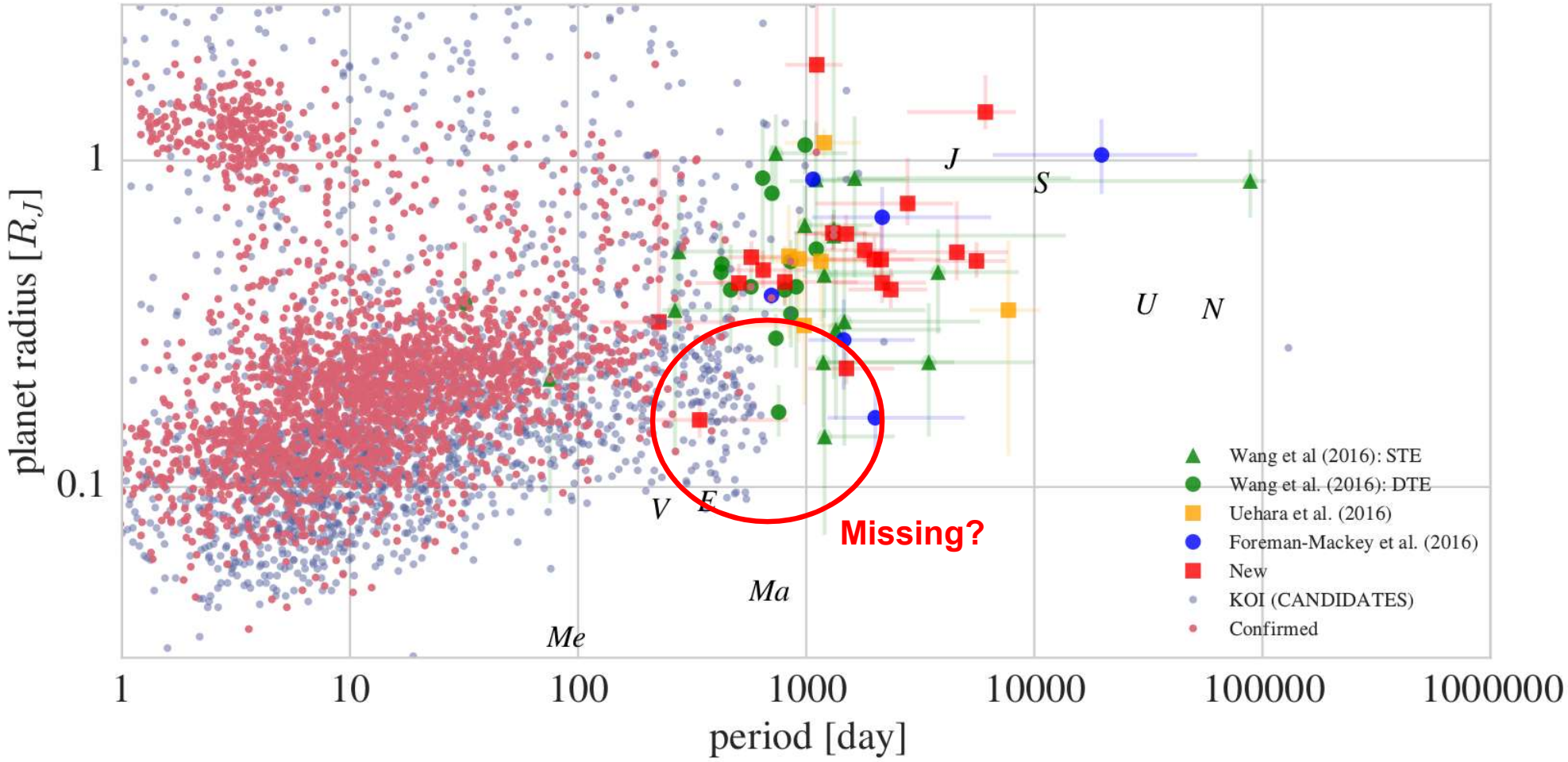


Problems

- Probably, many FPs in the tentative compiled list!

-> follow-up observation using Subaru or other facilities

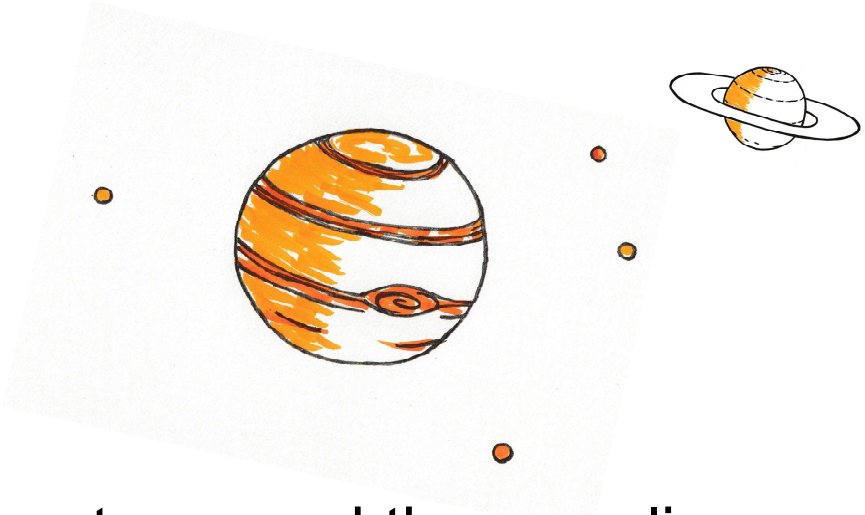
- Difficult to explore those planets beyond a period – radius plane

-> “Saturn mass at 2-3 au is detectable” Lauren’s talk!

- We need a long-life continuous monitoring of nearby stars

  TESS, PLATO, or a new dedicated (micro)satellite

Summary



1. Single and double events reveal exoplanets around the snowline

Many Neptunes/sub-Saturns around the snowline?

2. Those events are also a useful probe of circumbinary stars/planets and compact object binaries via self-gravitational lensing

Need long-life continuous monitoring of nearby stars!