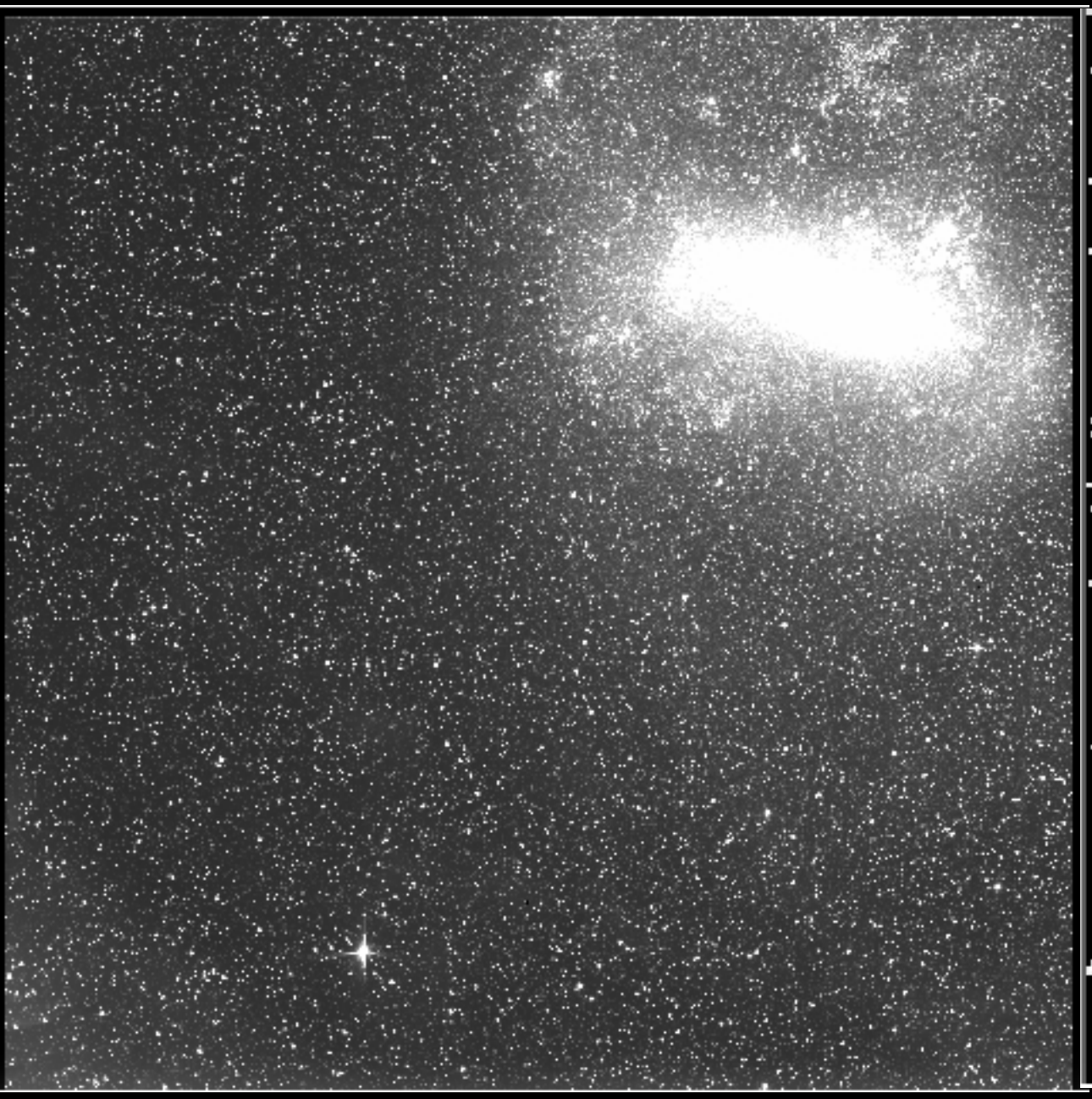
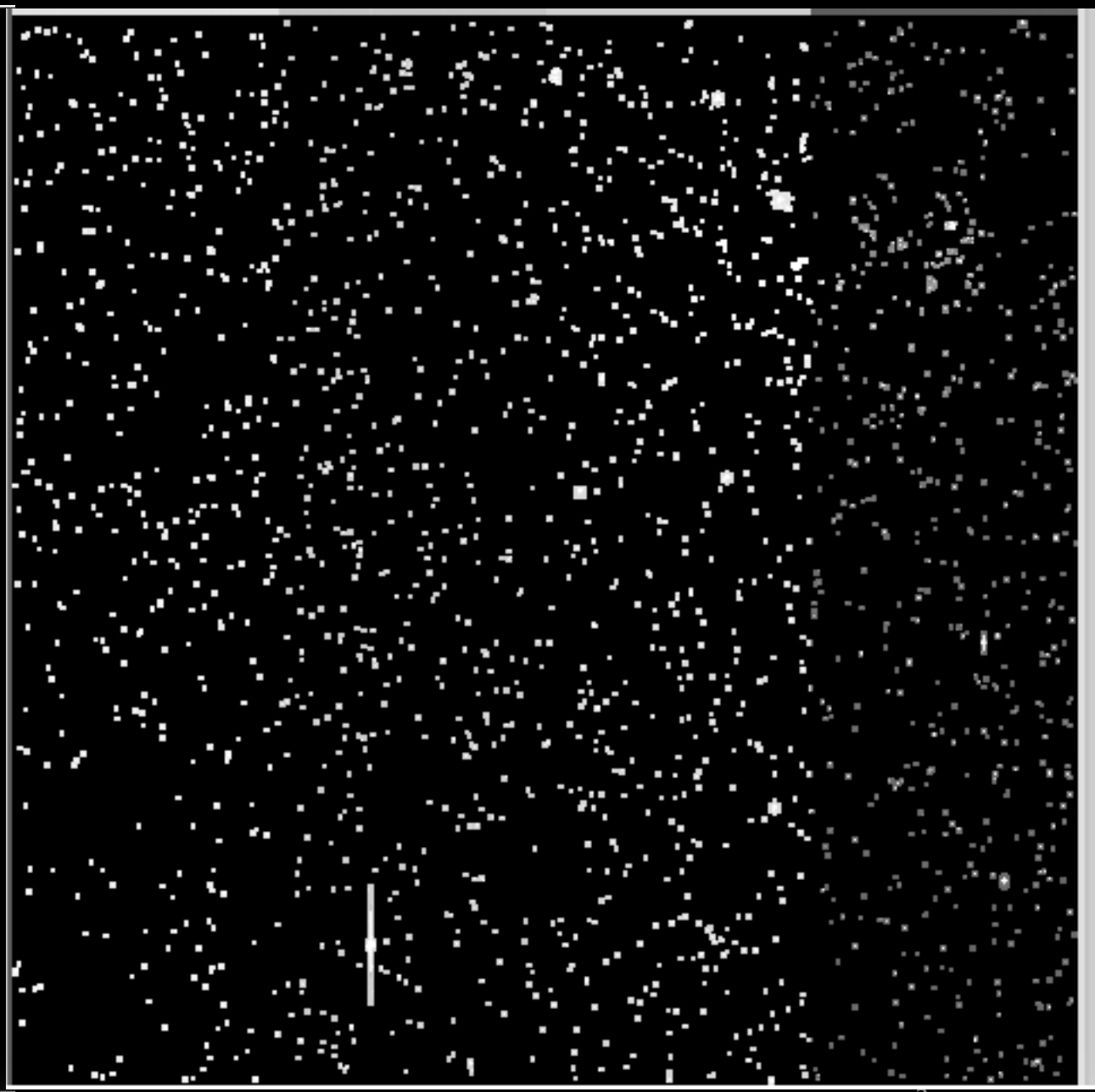
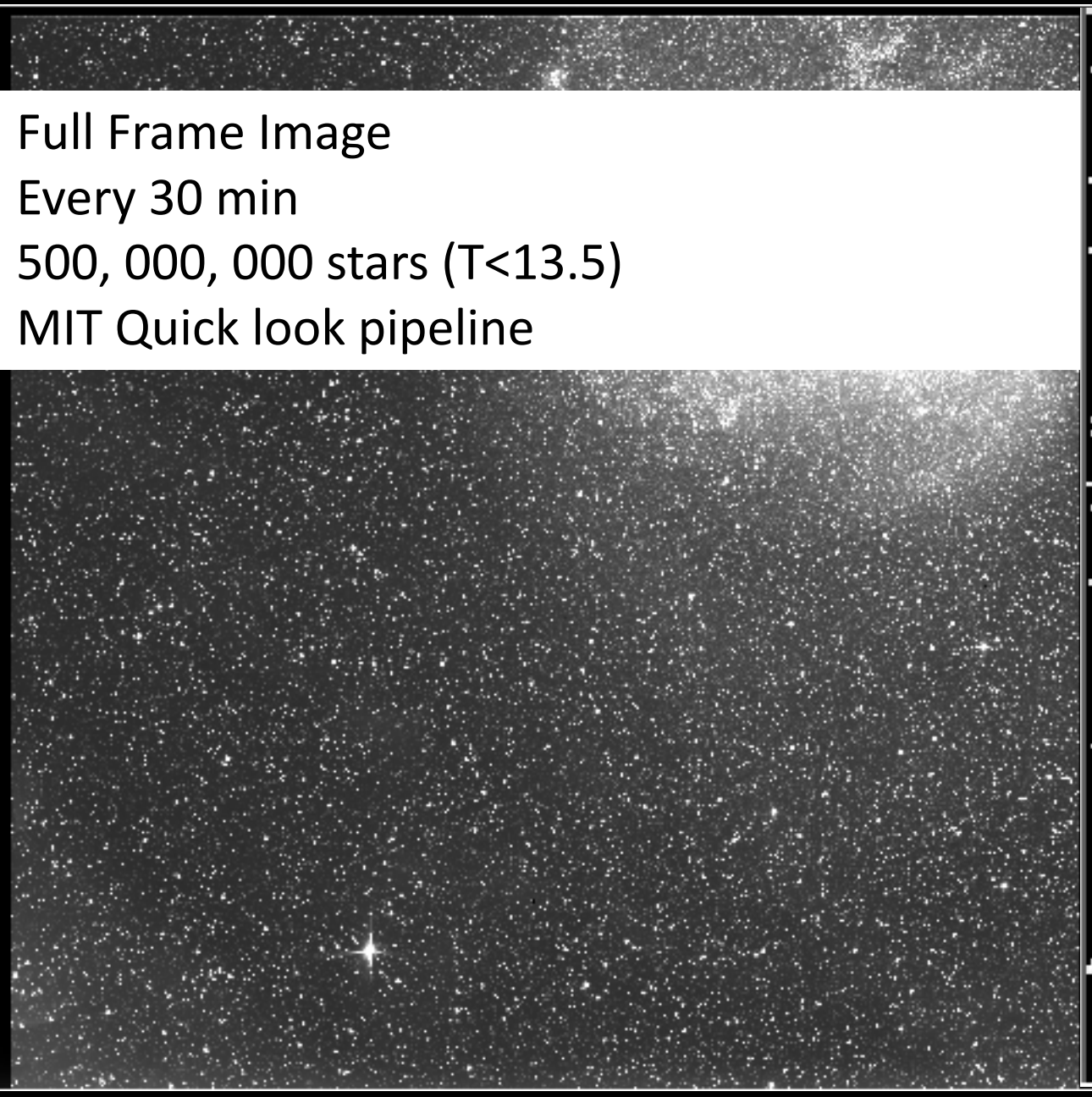
Planet Candidates from TESS Full Frame Images

Chelsea Huang (MIT, Juan Carlos Torres Fellow)

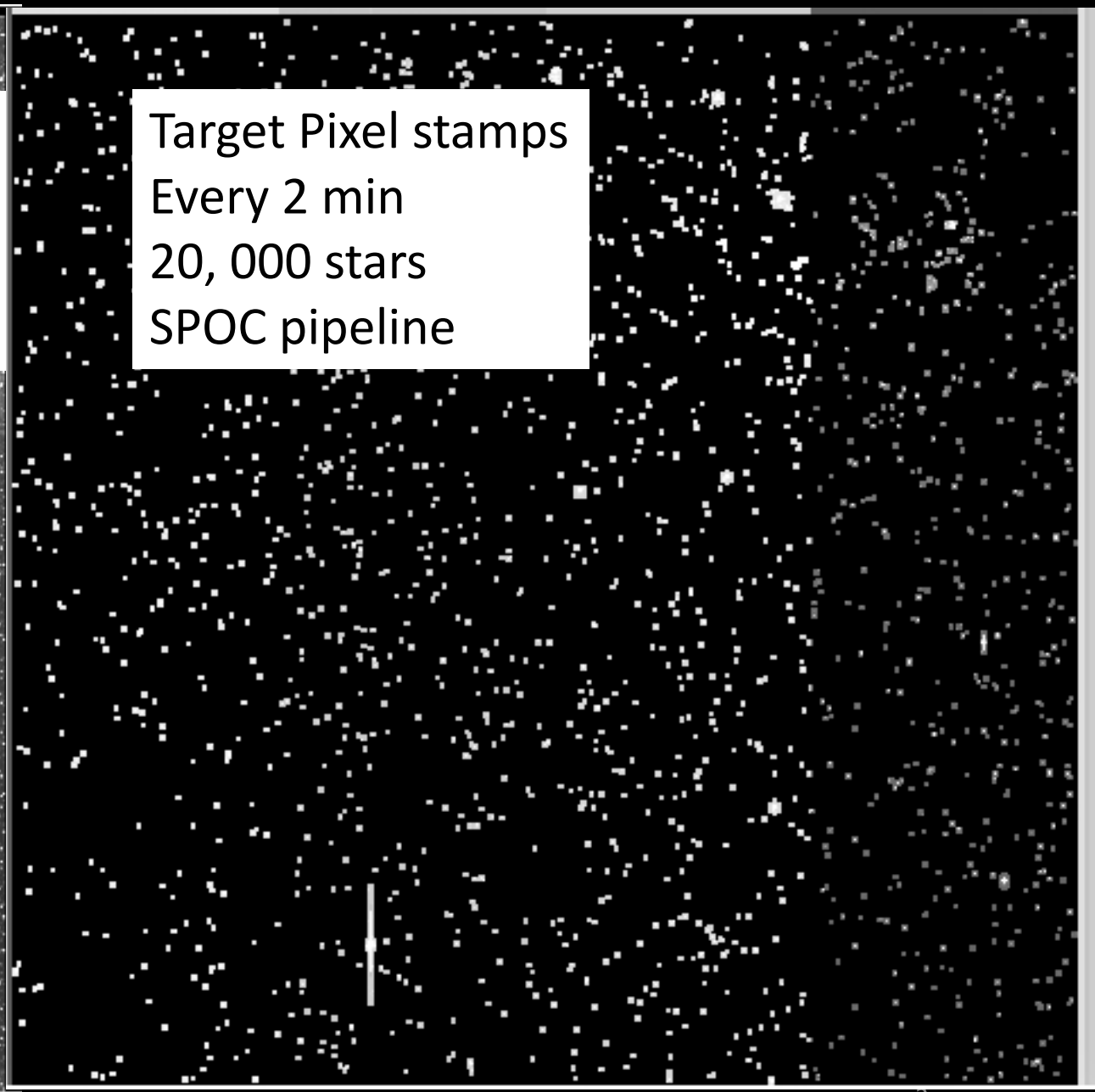
Michael Fausnaugh, William Fong, Andras Pal, Lizhou Sha, Avi shporer, Andrew Vanderburg, Matt Wall, Liang Yu, and all the vetters.



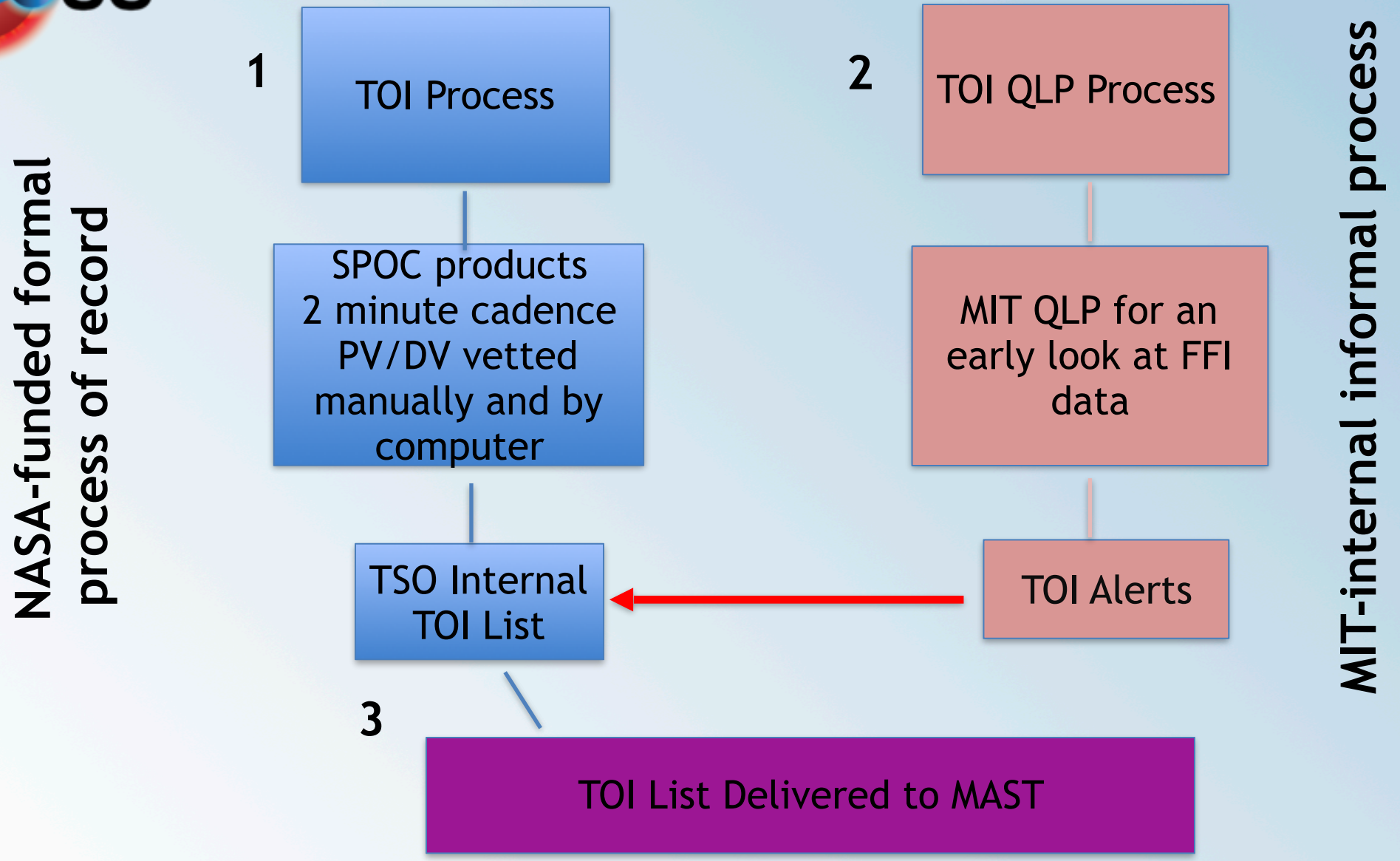




Full Frame Image
Every 30 min
500, 000, 000 stars (T<13.5)
MIT Quick look pipeline

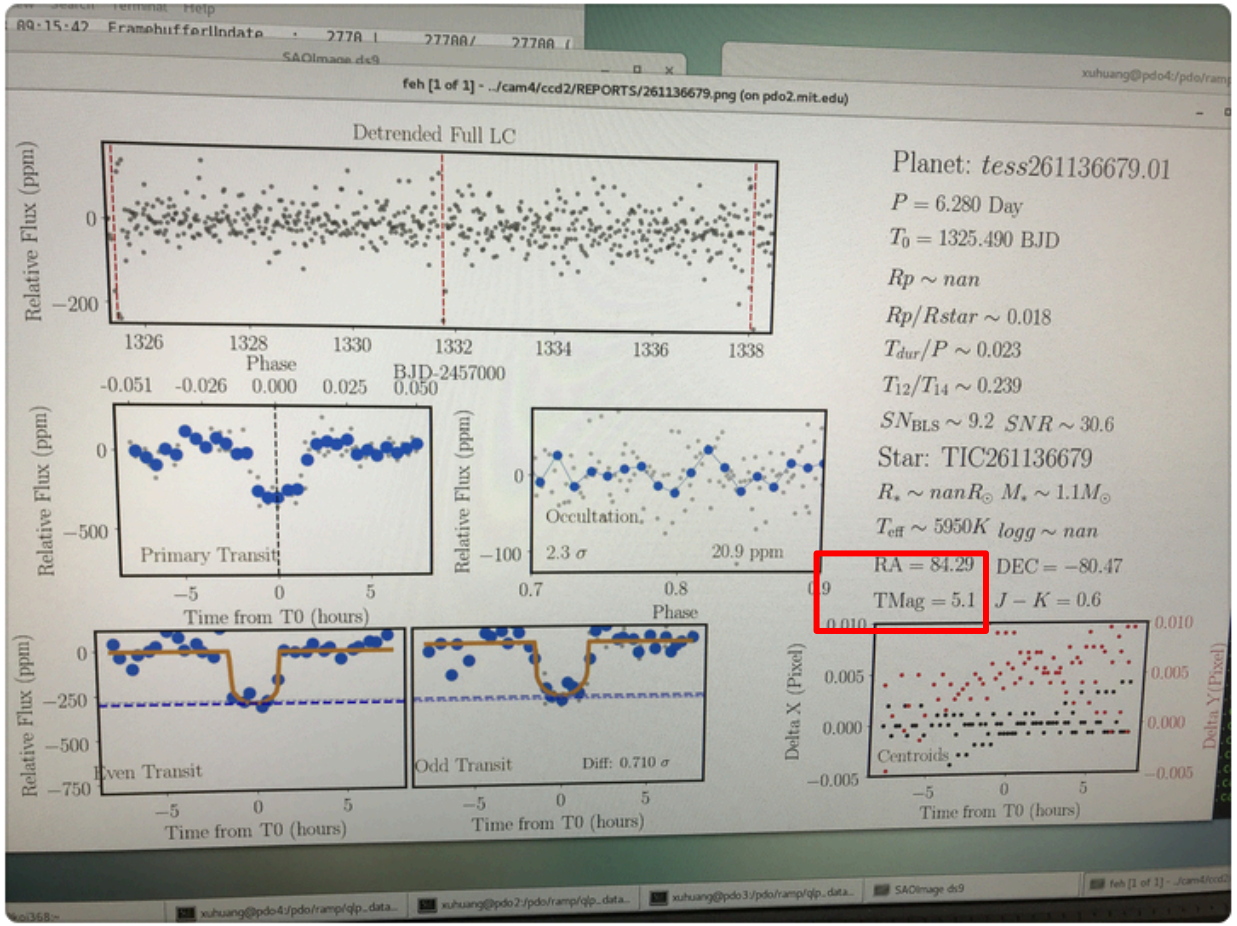


Target Pixel stamps
Every 2 min
20, 000 stars
SPOC pipeline


NASA-funded formal process of record
1
TOI Process
SPOC products 2 minute cadence PV/DV vetted manually and by computer
2
TOI QLP Process
MIT QLP for an early look at FFI data
MIT-internal informal process
TSO Internal TOI List
TOI Alerts
3
TOI List Delivered to MAST

Chelsea Huang 10:25 AM

Image from iOS



Then we see this super Earth 16 days after the start of Sector 1 …

Gaia says it is a high proper motion star; radius of planet based on Gaia are ~3RE

There is also a known RV planets with long period in the system

Sunday, August 12th

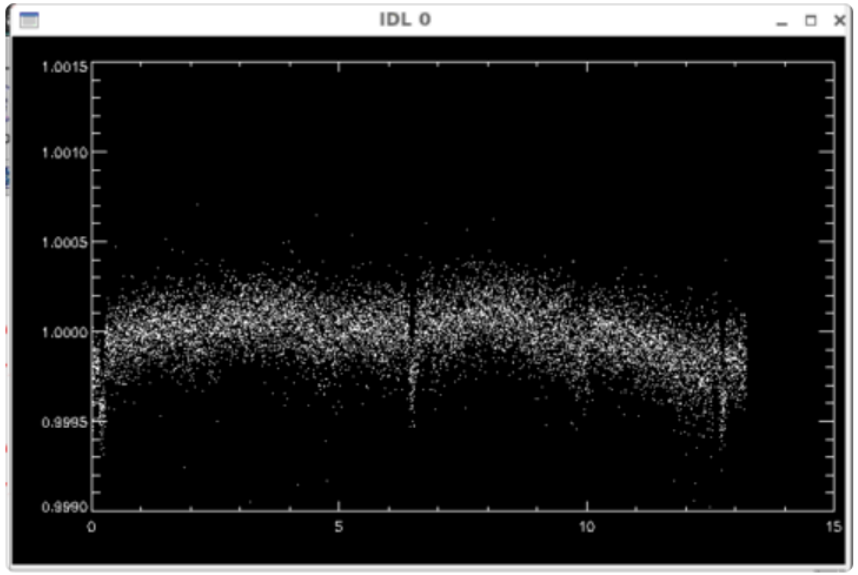
AndrewV 1:31 AM

!!

signal'

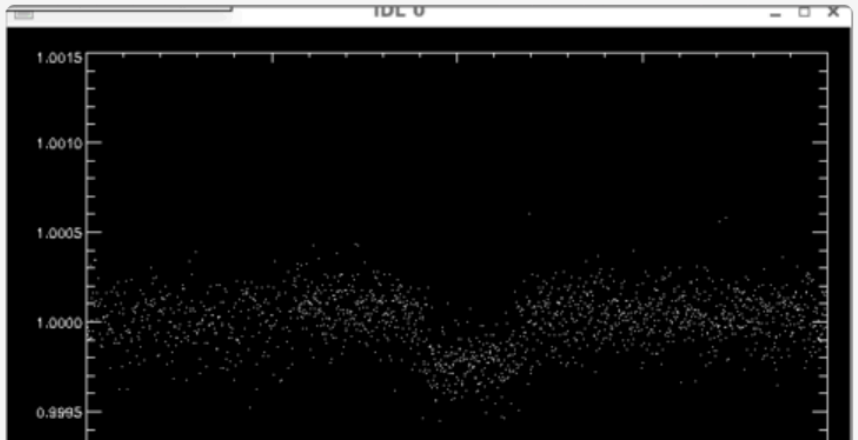
ss definitely there

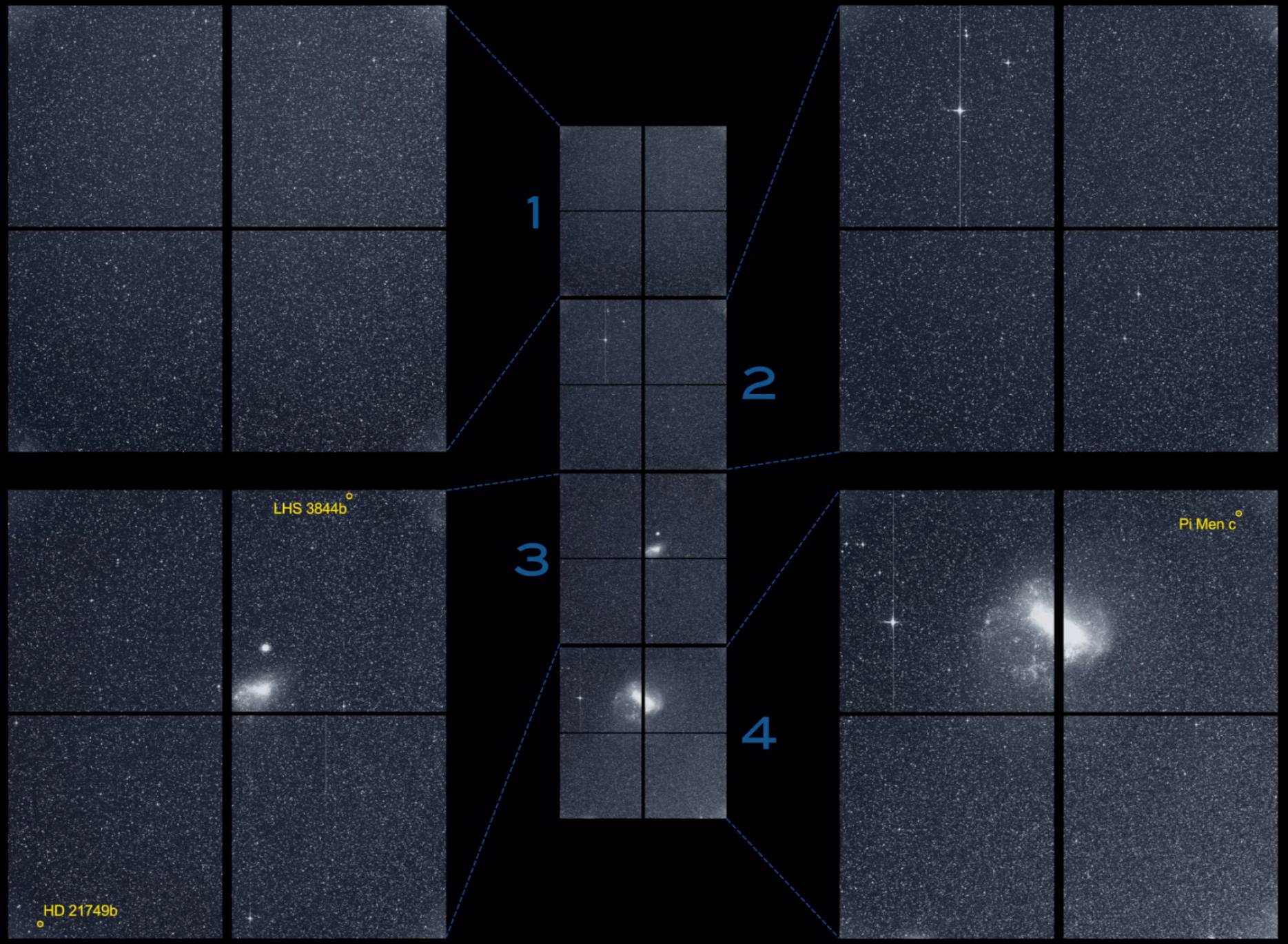
Pasted image at 2018-08-12, 12:31 AM



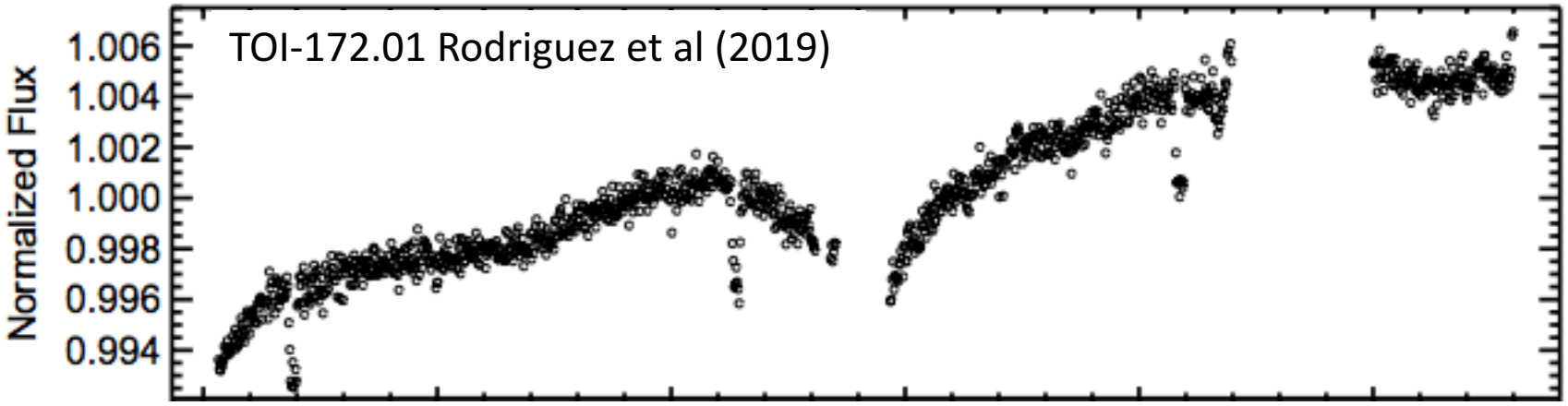
1:35 AM Here's my phase fold:

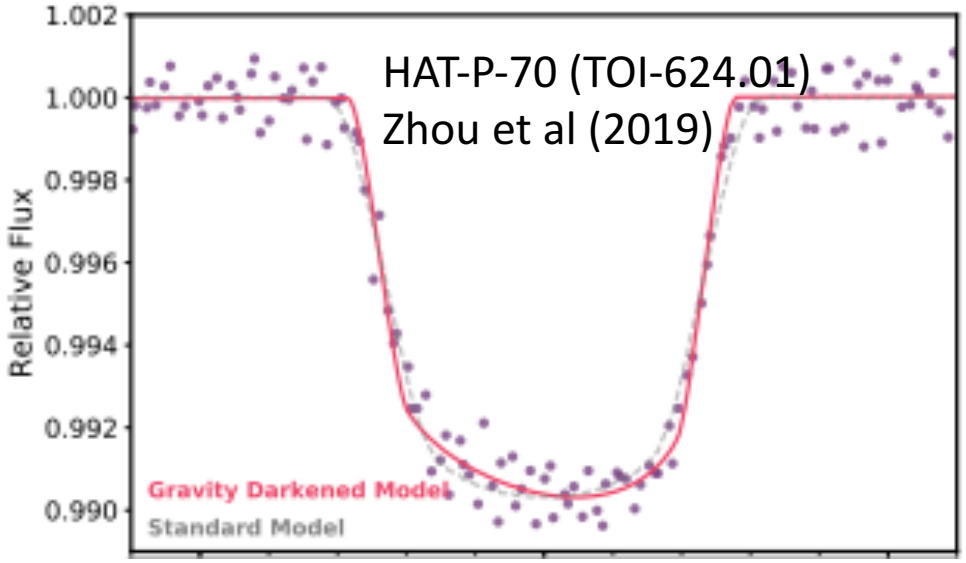
Pasted image at 2018-08-12, 12:35 AM

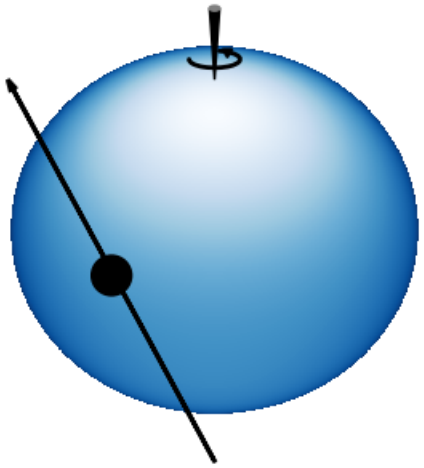



1
2
3
4
LHS 3844b
Pi Men c
HD 21749b

The Success Stories:

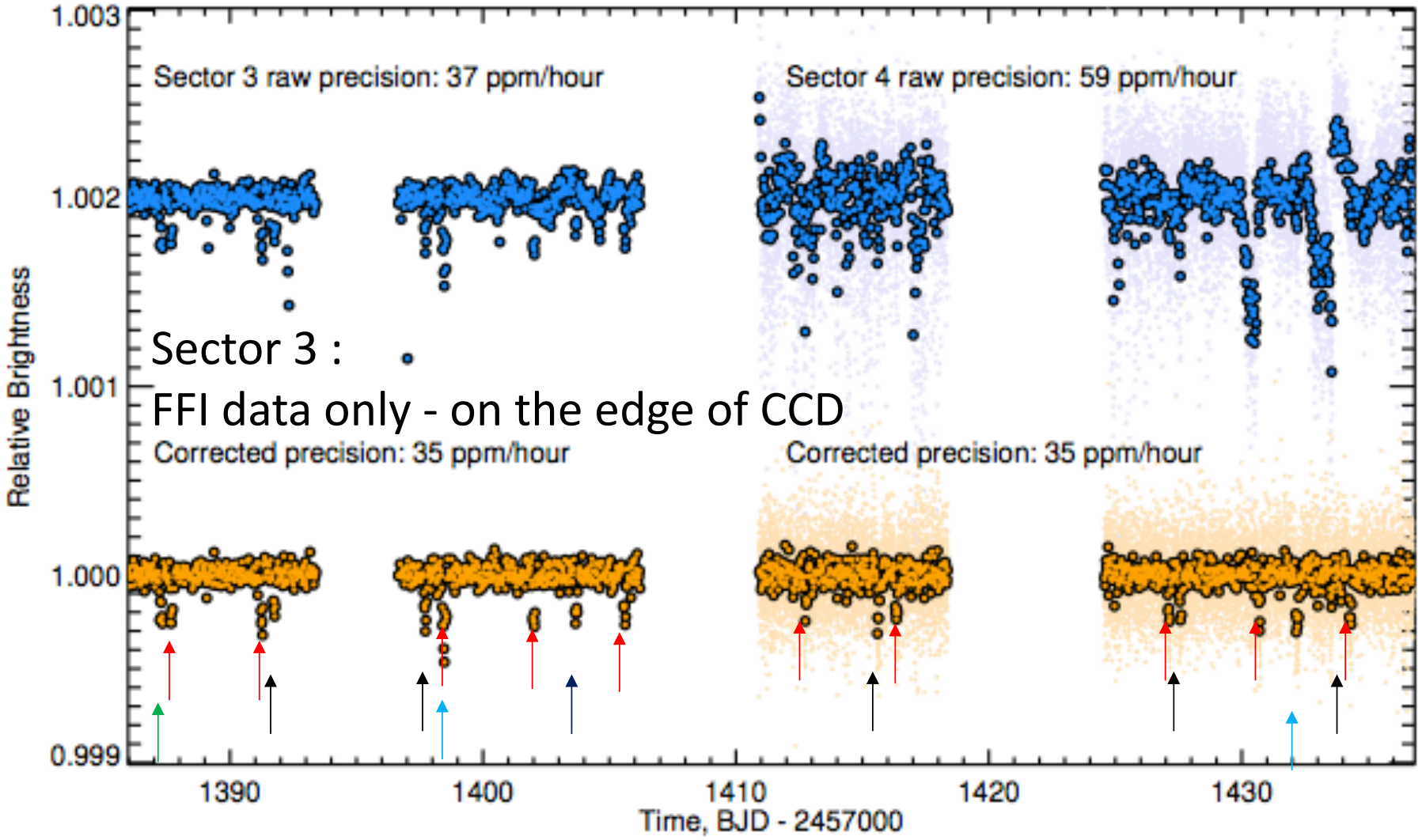






And many papers follow up
FFI candidates
I haven't mention here

The Success Stories: Brightest (V = 6.38) triple transiting system



Sector 3 :

FFI data only - on the edge of CCD

$R_1 = 2.1\ R_E$

$P_1 = 3.59$ d

$R_2 = 1.9 R_E$

$P_2 = 5.97$ d

$R_3 = 2.2\ R_E$

$P_3 = 11.23$ d

HR 858

(TOI-396.01, 02,03)

Vanderburg et al (2019)

How does QLP work?

Quick Look up Pipeline work flow

TESS Full Frame Image (FFI)

↓

Multi aperture photometry

↓

Light curve cotrending/detrending

↓

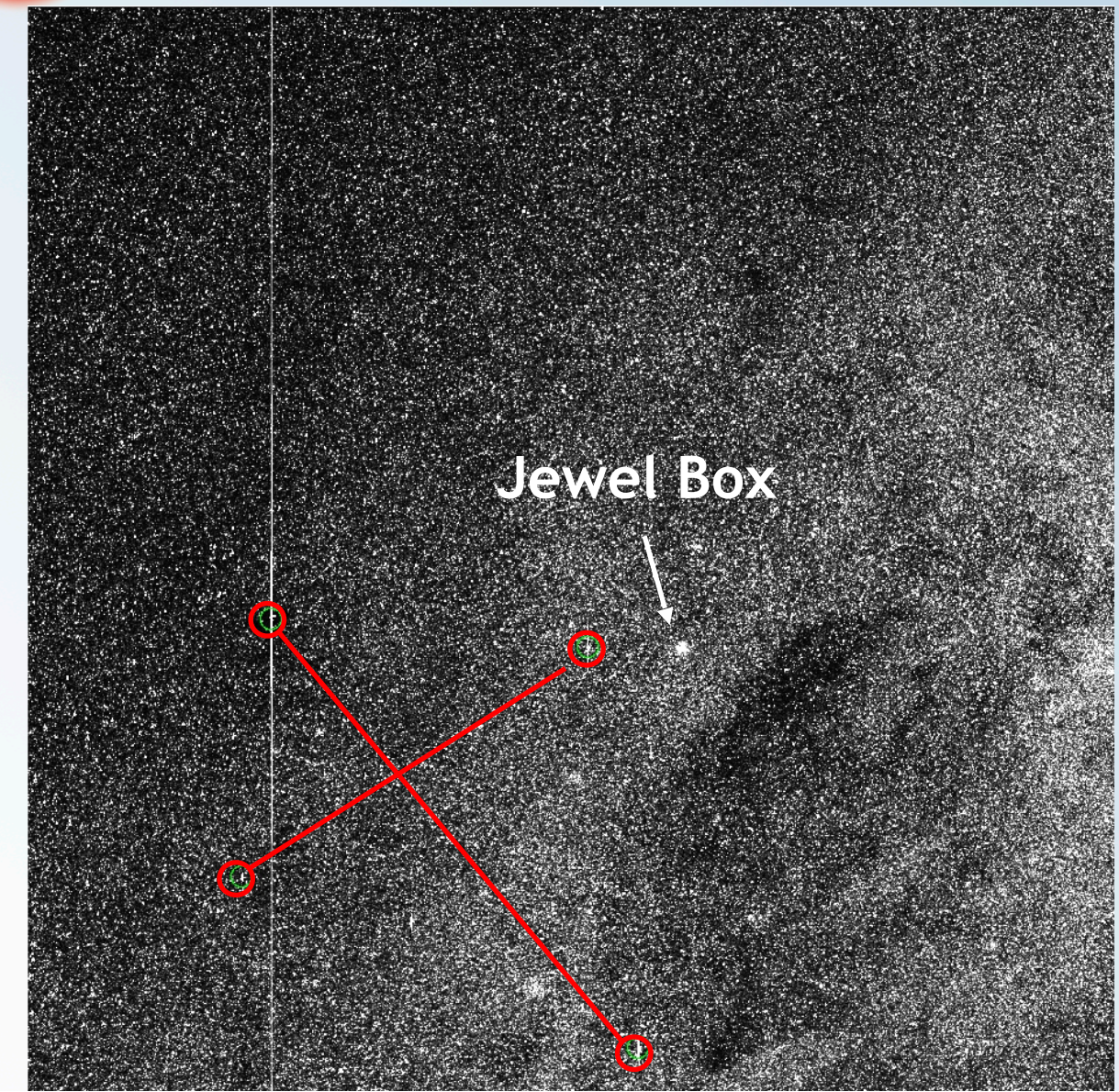
Merge into multi sector light curves

Box Least Square (BLS)

↓

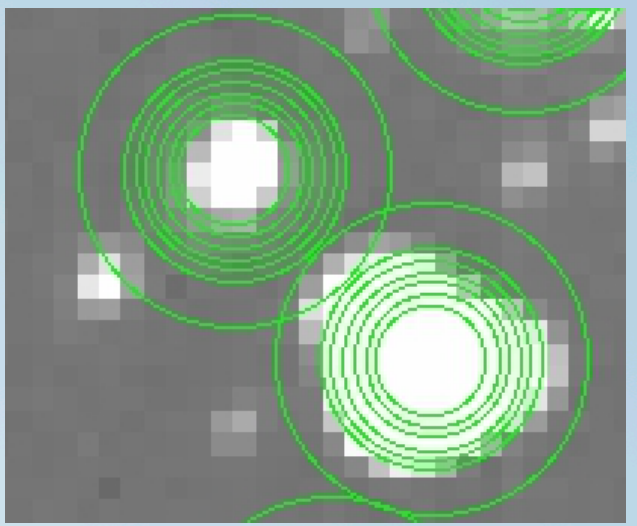
Signal to Pink noise > 9

Planetary candidate
data validation products



FFITools

- Reduce every star brighter than 13.5T_{mag}
- 5 circular apertures

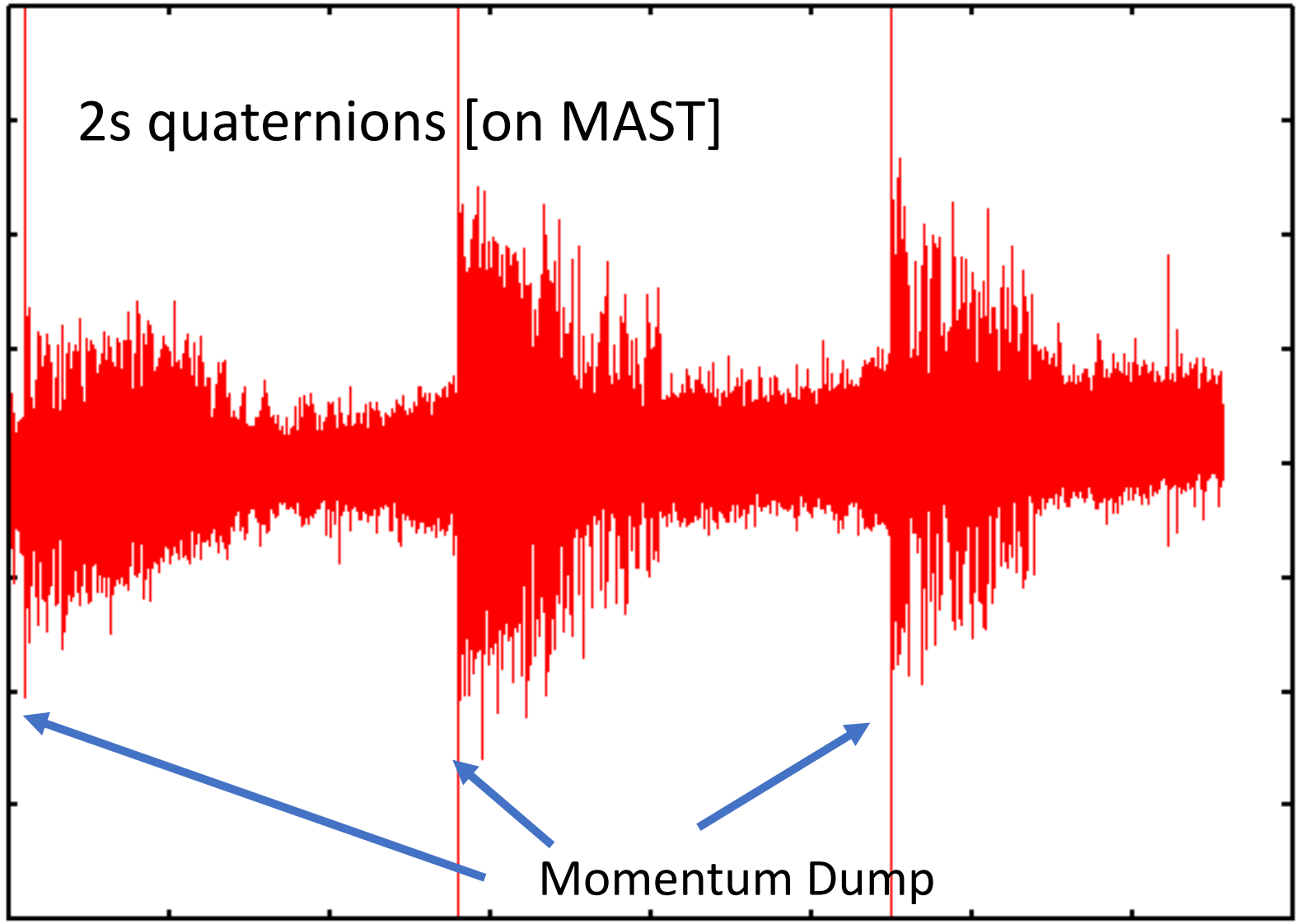


Catalog based multiple aperture photometry;
Source location is iteratively determined based on
Initial astrometric model developed by Al Levin (MIT)

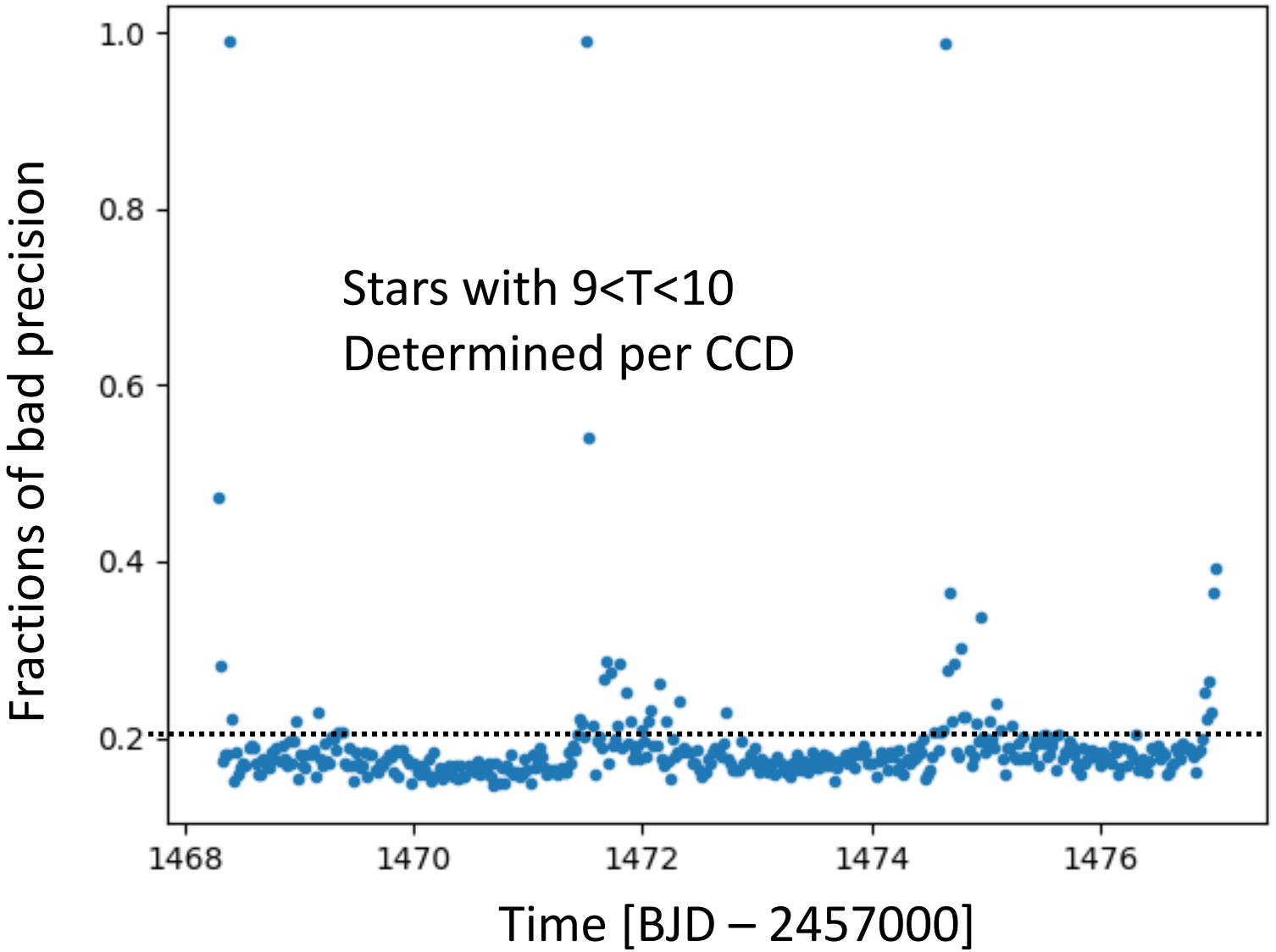
Detrending and Outlier flags

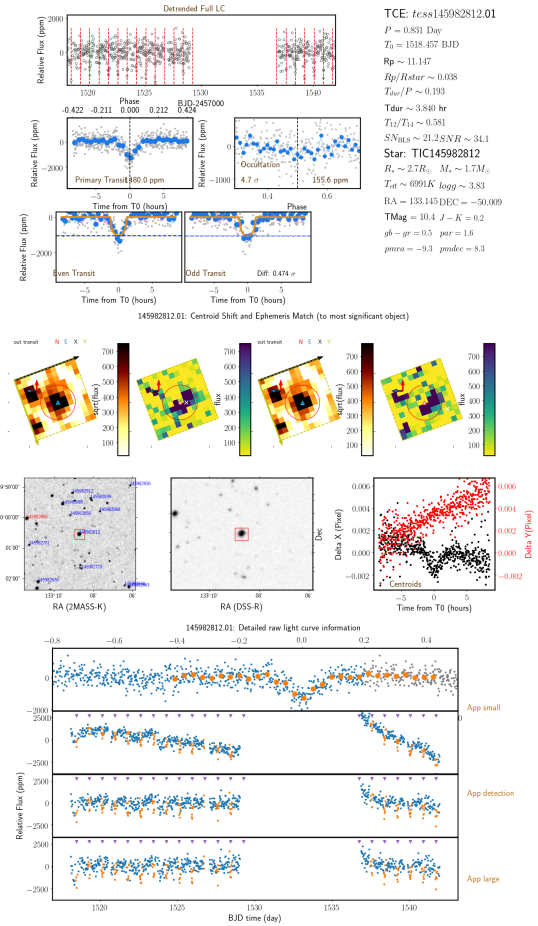
- Initial flag from quaternion time series analysis
- Use keplerspline (astronet, https://github.com/google-research/exoplanet-ml) for detrending
- Final flag from examine collection of light curves of bright stars

Detrending and Outlier flags



Detrending and Outlier flags



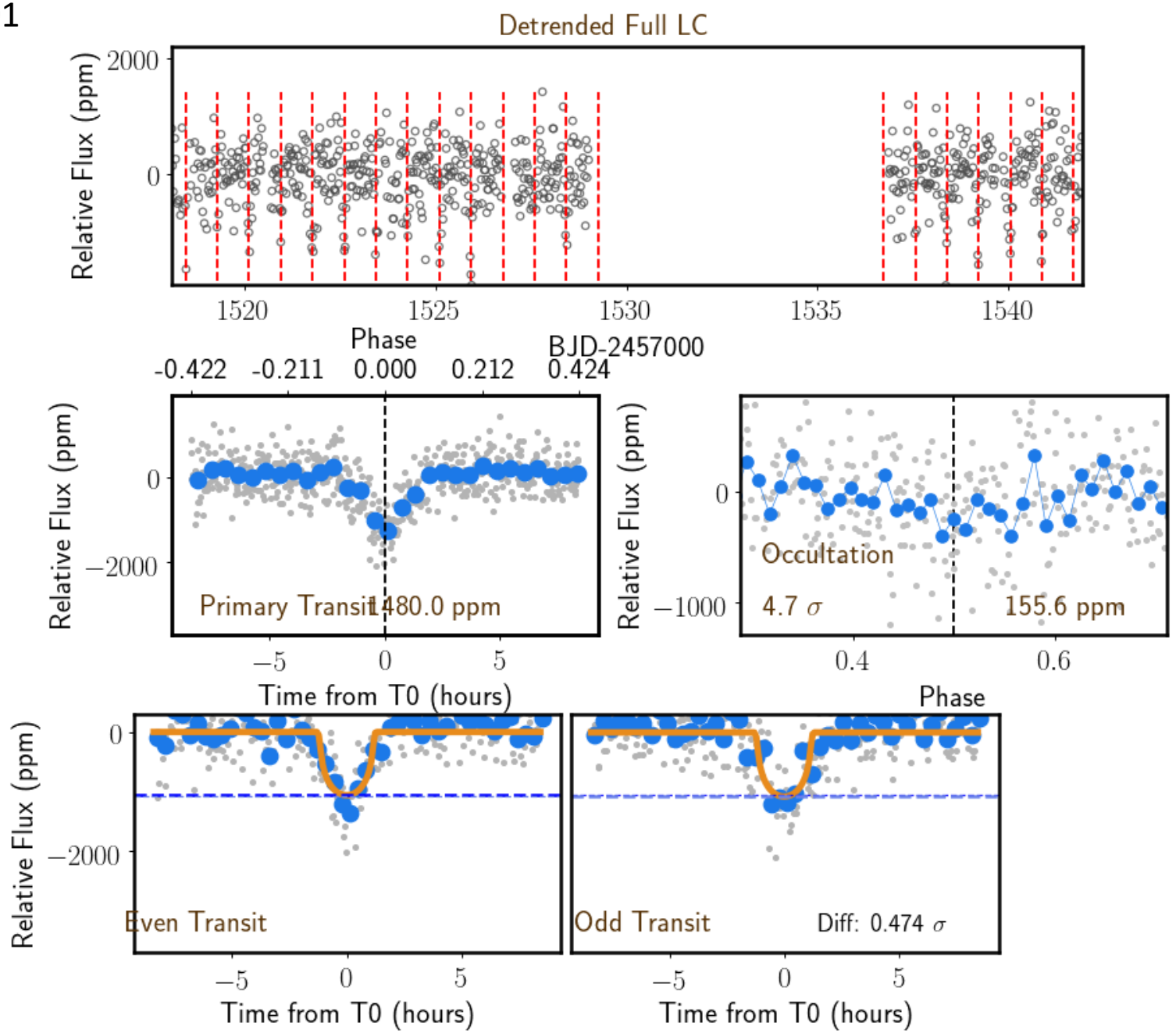


Quick Look Reports (QLR)

- Three Summary Pages
- Seven Section full reports

QLRs are released to the community at the same time with the alerts
Currently all candidates with Tmag <10 are released.

TOI-599.01



TCE: $tess145982812.01$

$P = 0.831$ Day

$T_0 = 1518.457$ BJD

Rp ~ 11.147

$Rp/Rstar \sim 0.038$

$T_{dur}/P \sim 0.193$

Tdur ~ 3.840 hr

$T_{12}/T_{14} \sim 0.581$

$SN_{\rm BLS} \sim 21.2 SNR \sim 34.1$

Star: TIC145982812

$R_* \sim 2.7 R_\odot \quad M_* \sim 1.7 M_\odot$

$T_{\rm eff} \sim 6991K \quad logg \sim 3.83$

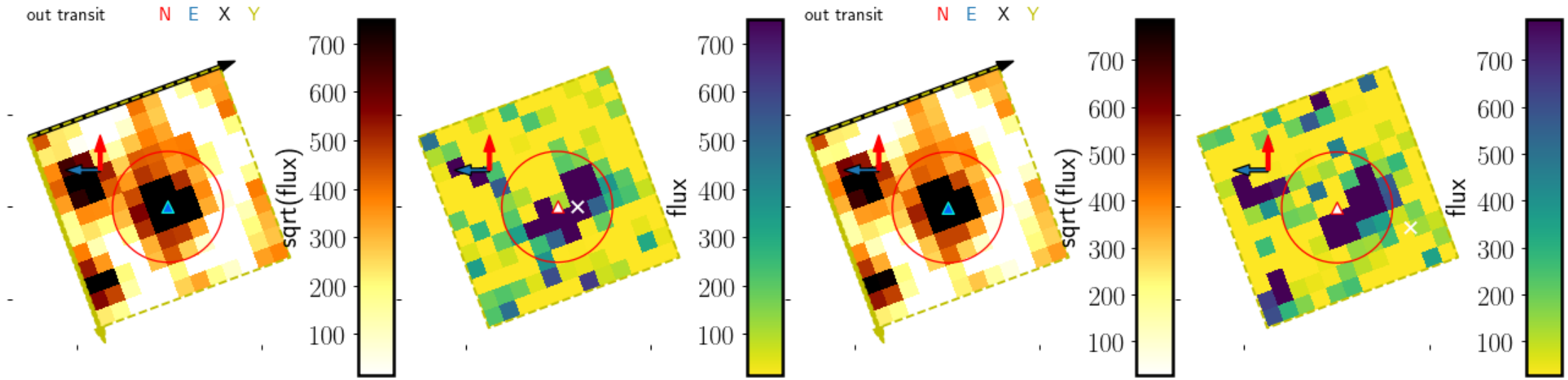
RA $= 133.145$ DEC $= -50.009$

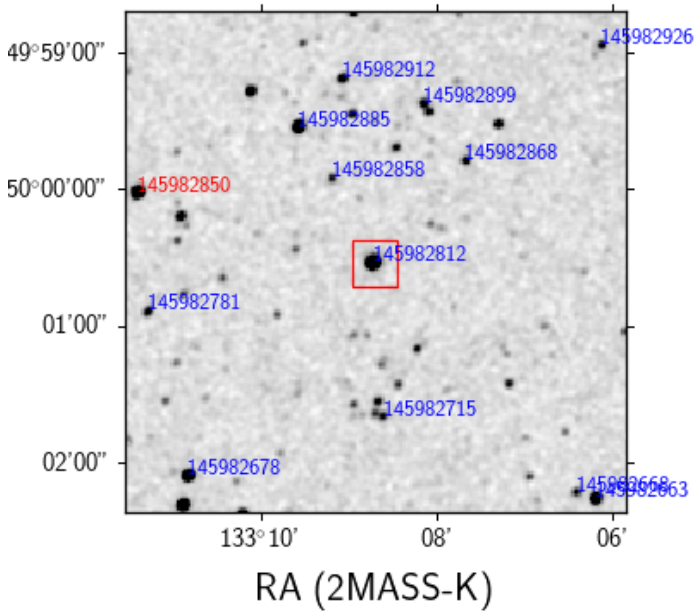
TMag $= 10.4 \quad J - K = 0.2$

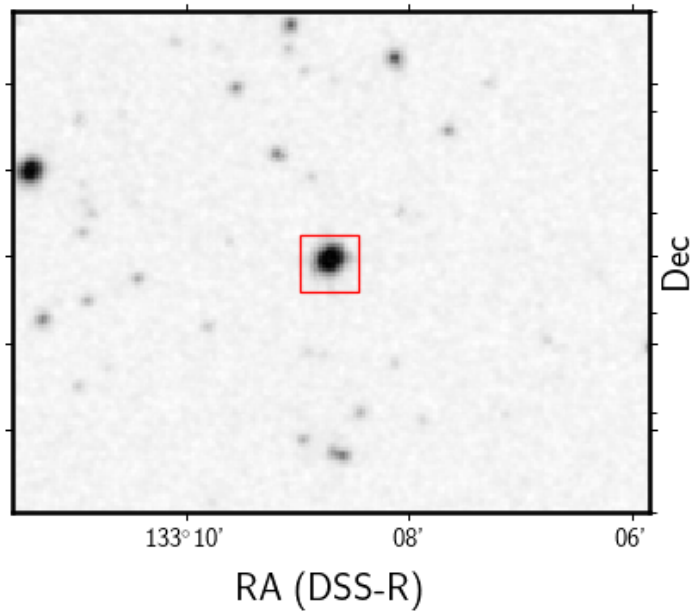
$gb - gr = 0.5 \quad par = 1.6$

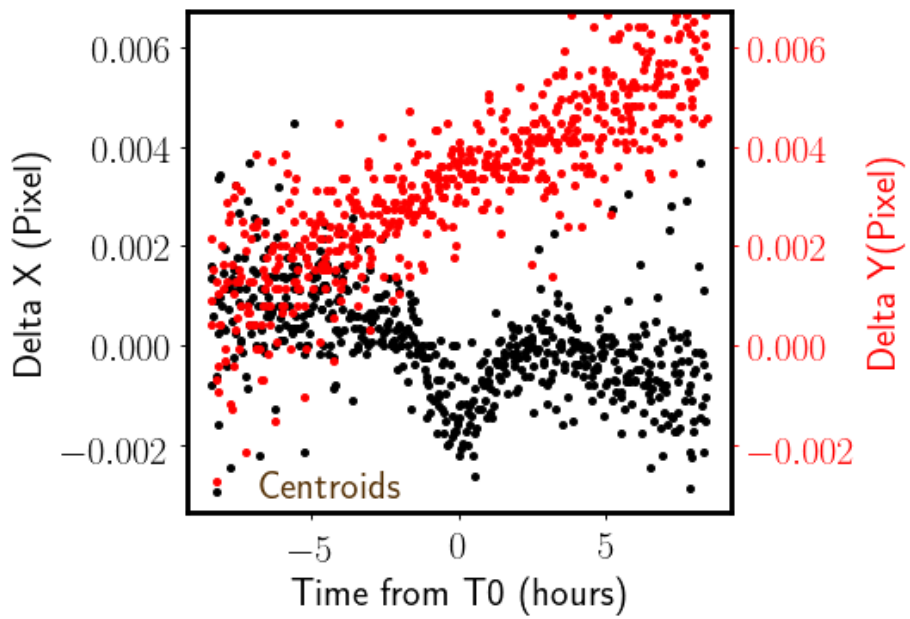
$pmra = -9.3 \quad pmdec = 8.3$

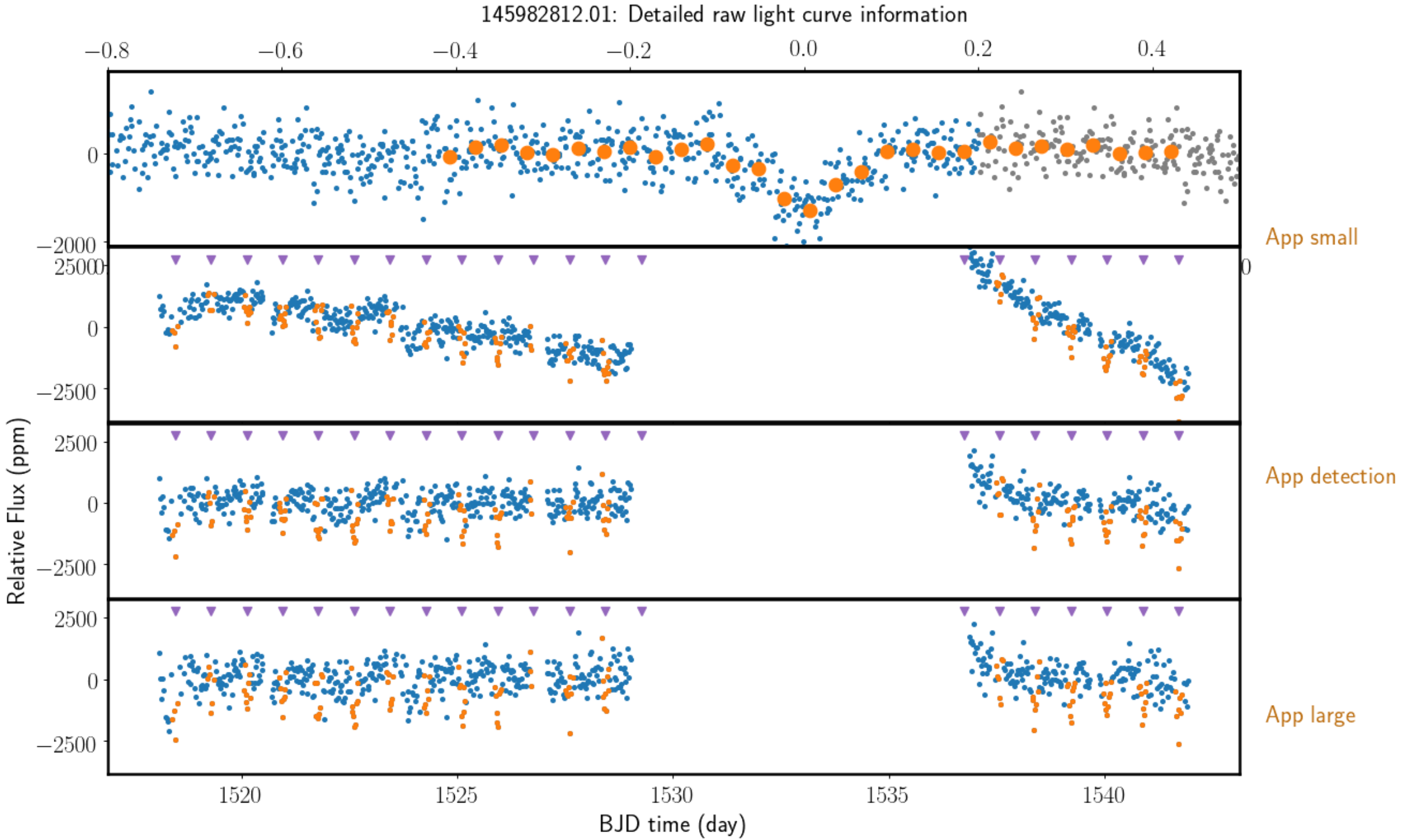
145982812.01: Centroid Shift and Ephemeris Match (to most significant object)



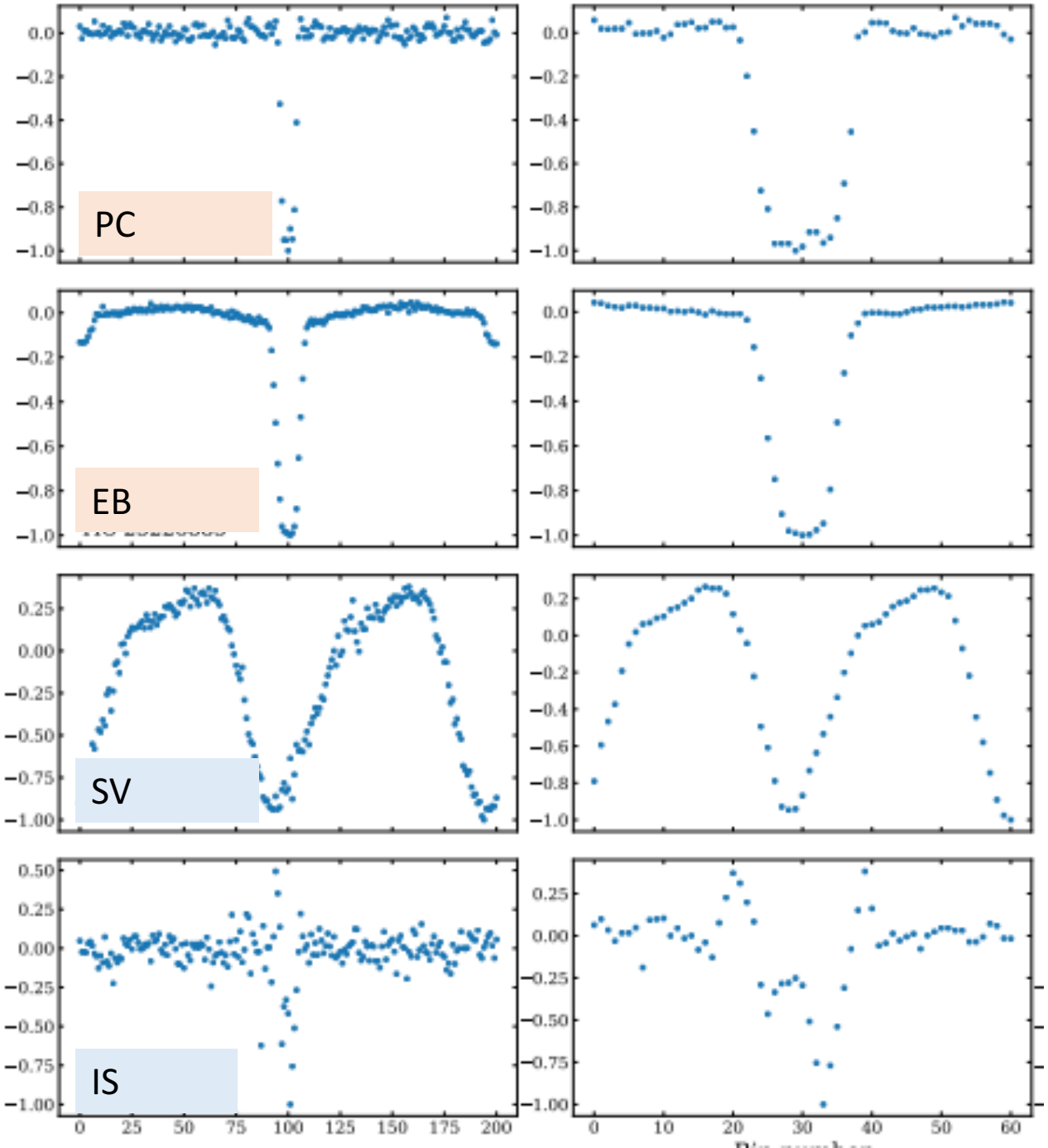







145982812.01: Detailed raw light curve information
−0.8
−0.6
−0.4
−0.2
0.0
0.2
0.4
0
−2000
App small
2500
0
−2500
2500
0
−2500
App detection
2500
0
−2500
App large
Relative Flux (ppm)
1520
1525
1530
1535
1540
BJD time (day)

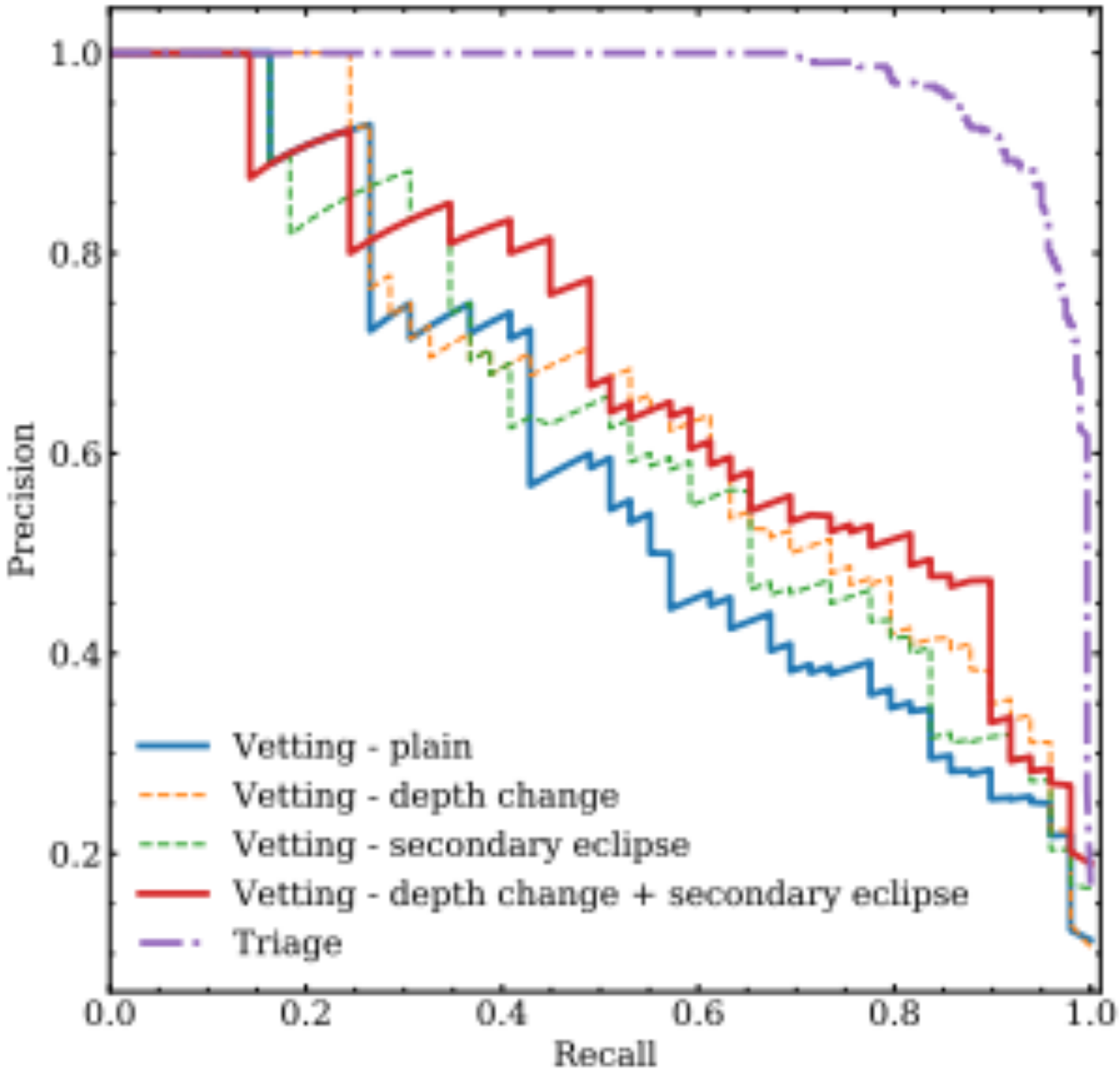
Global view



Local view

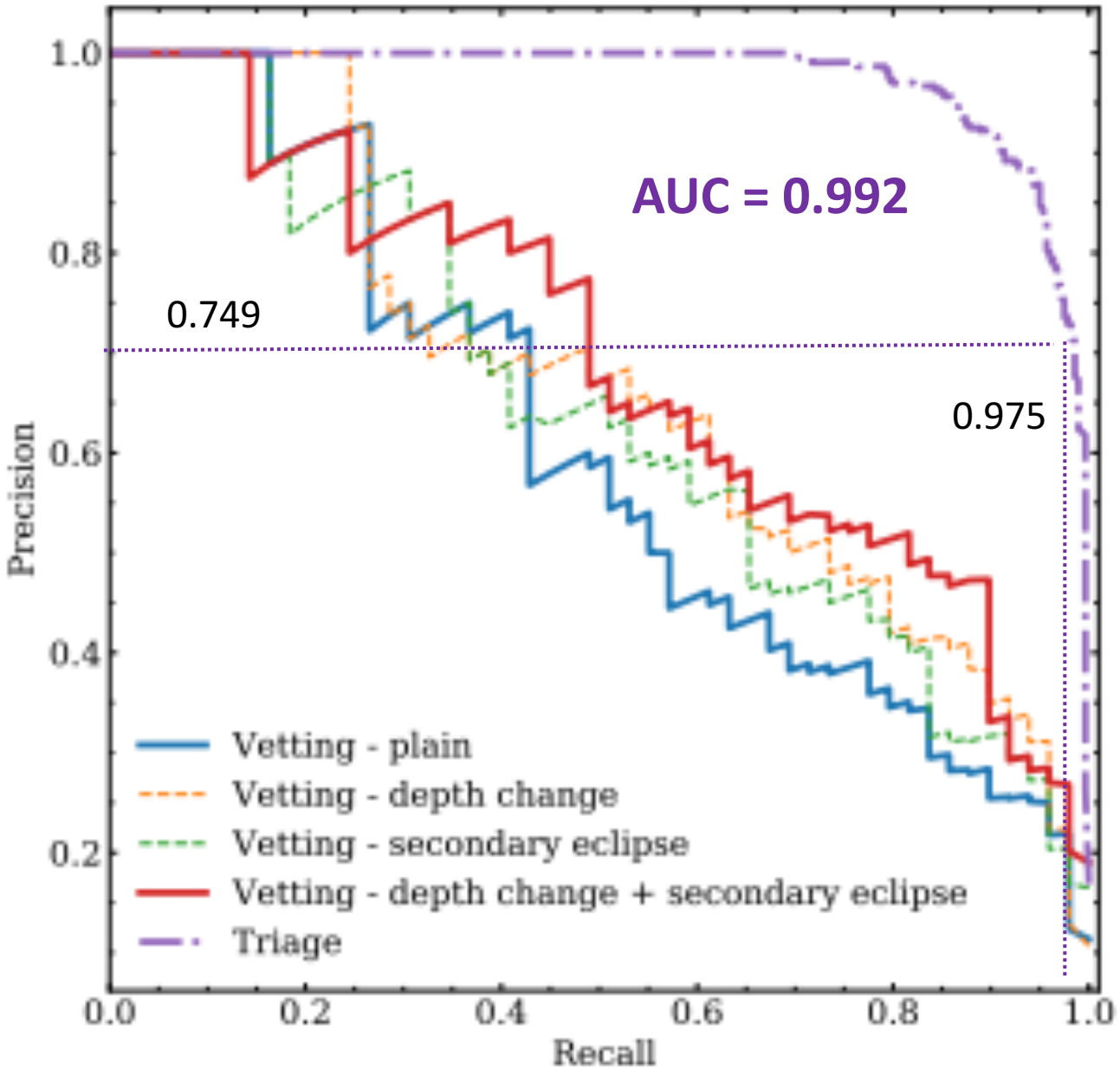
Use Machine Learning to remove the most obvious False positives

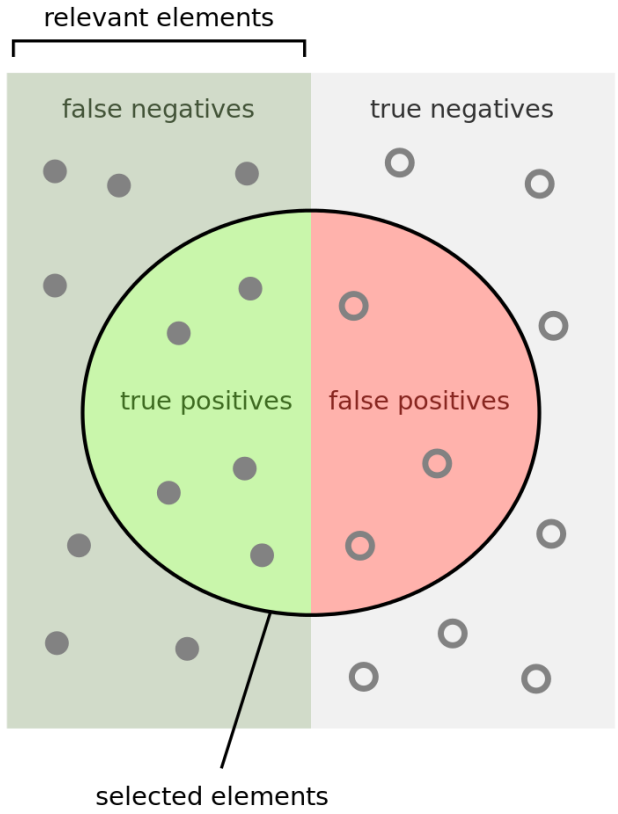
Yu et al (2019)



Trained on human labeled datasets From S1-5;
The triage process is implemented in the pipeline From Sector 6 onwards.

Yu et al (2019)





How many selected items are relevant?

Precision =

How many relevant items are selected?

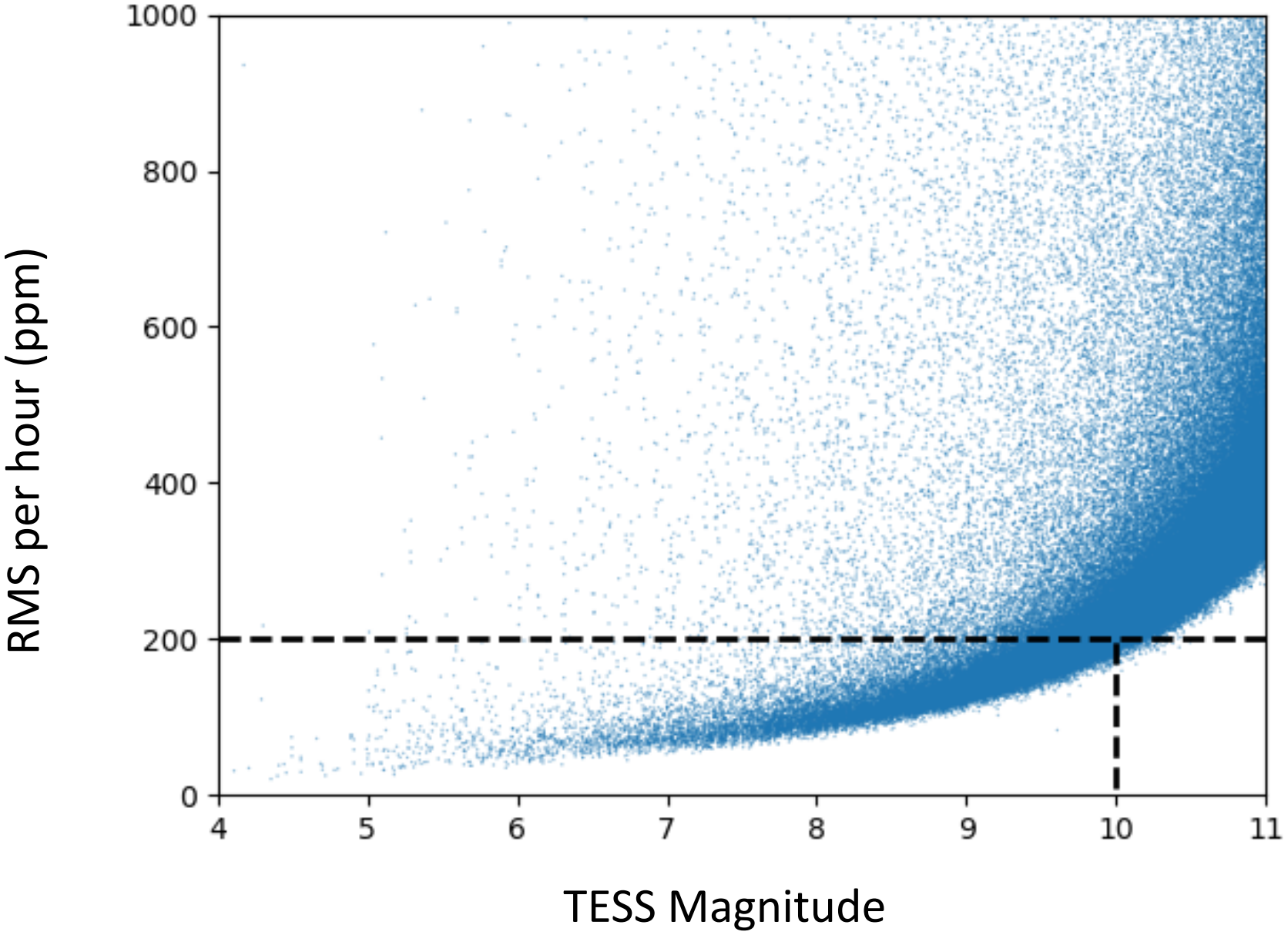
Recall =

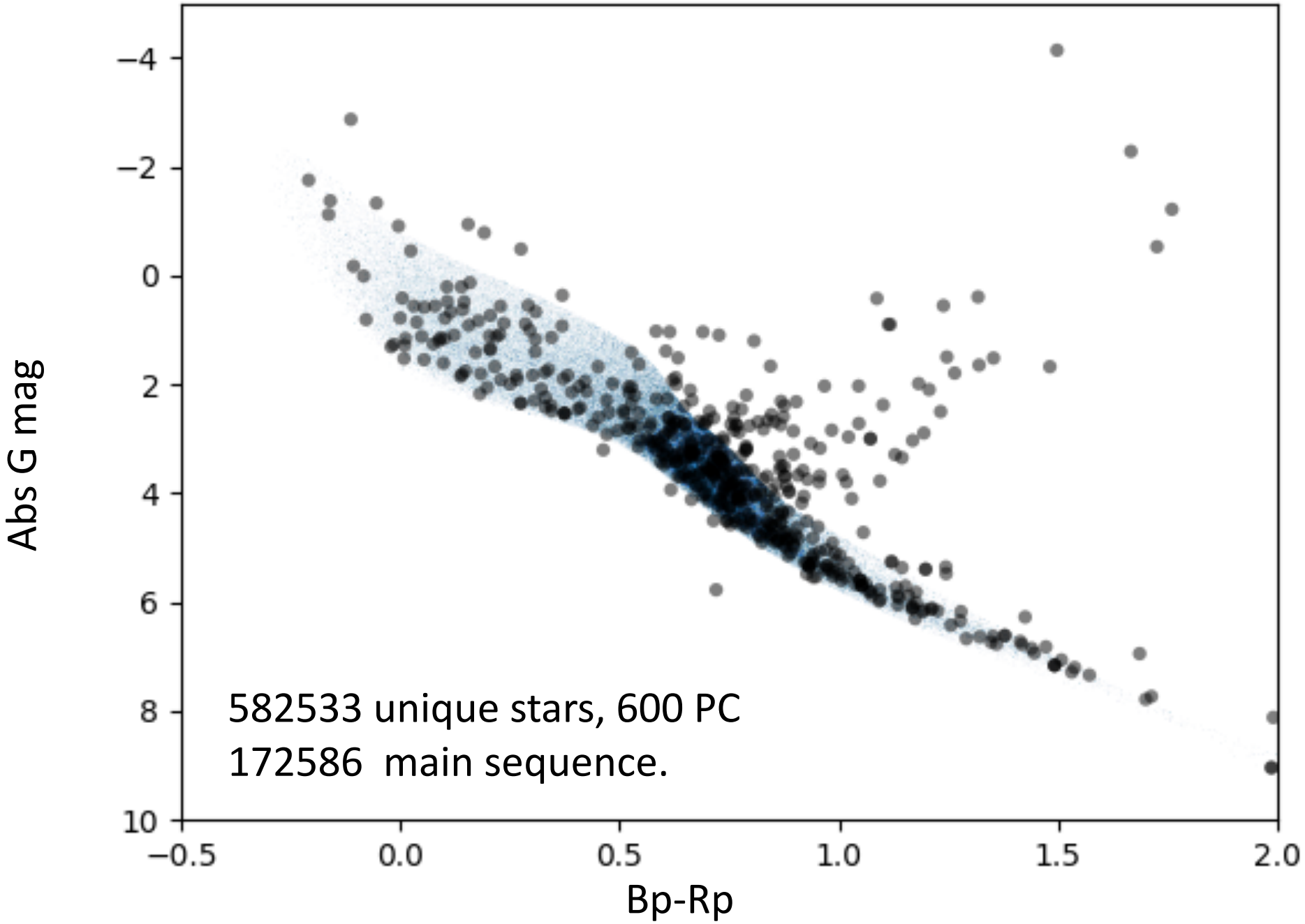
Yu et al (2019)

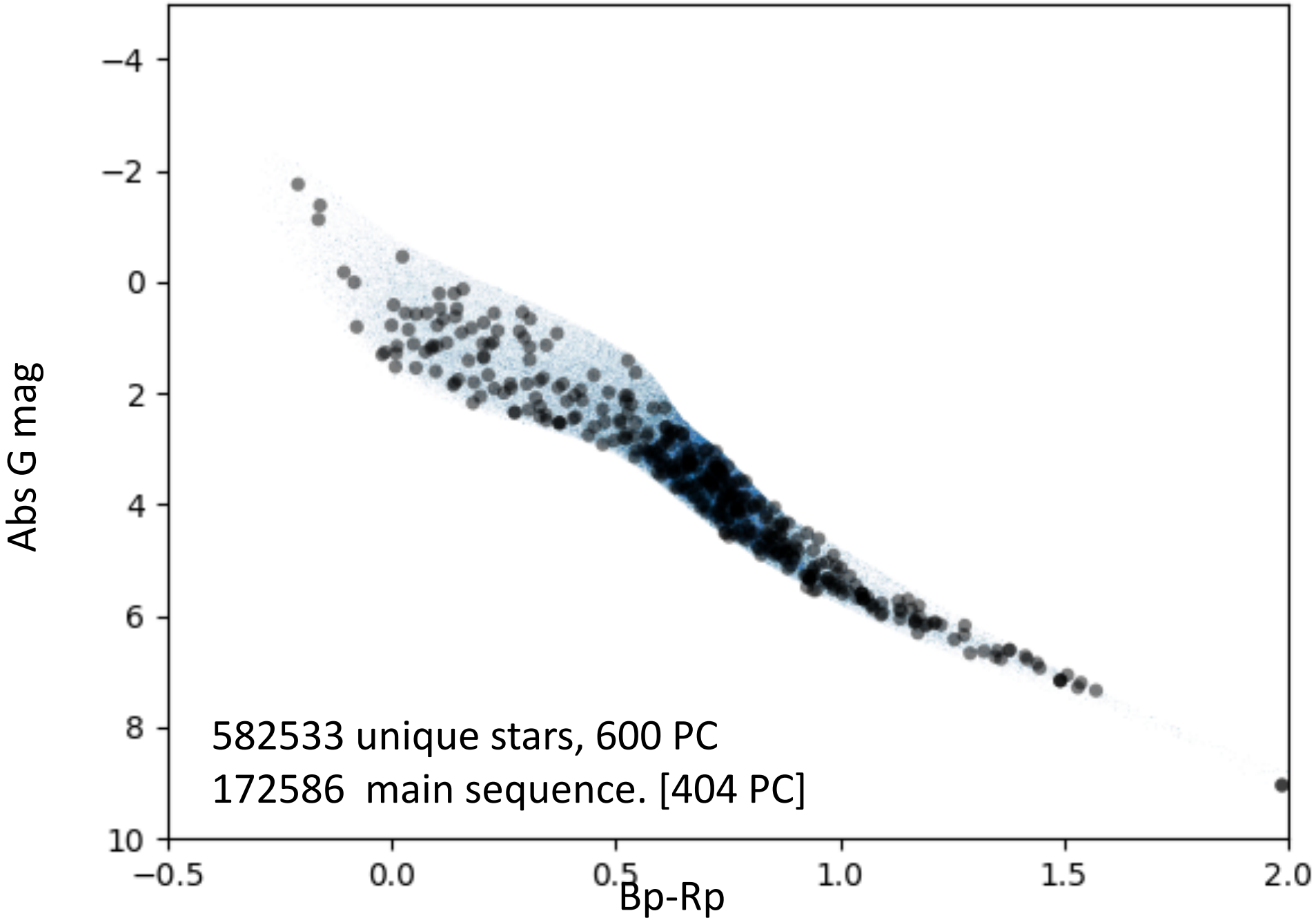
A magnitude limited catalog from Sector 1 - 9 Main Sequence stars

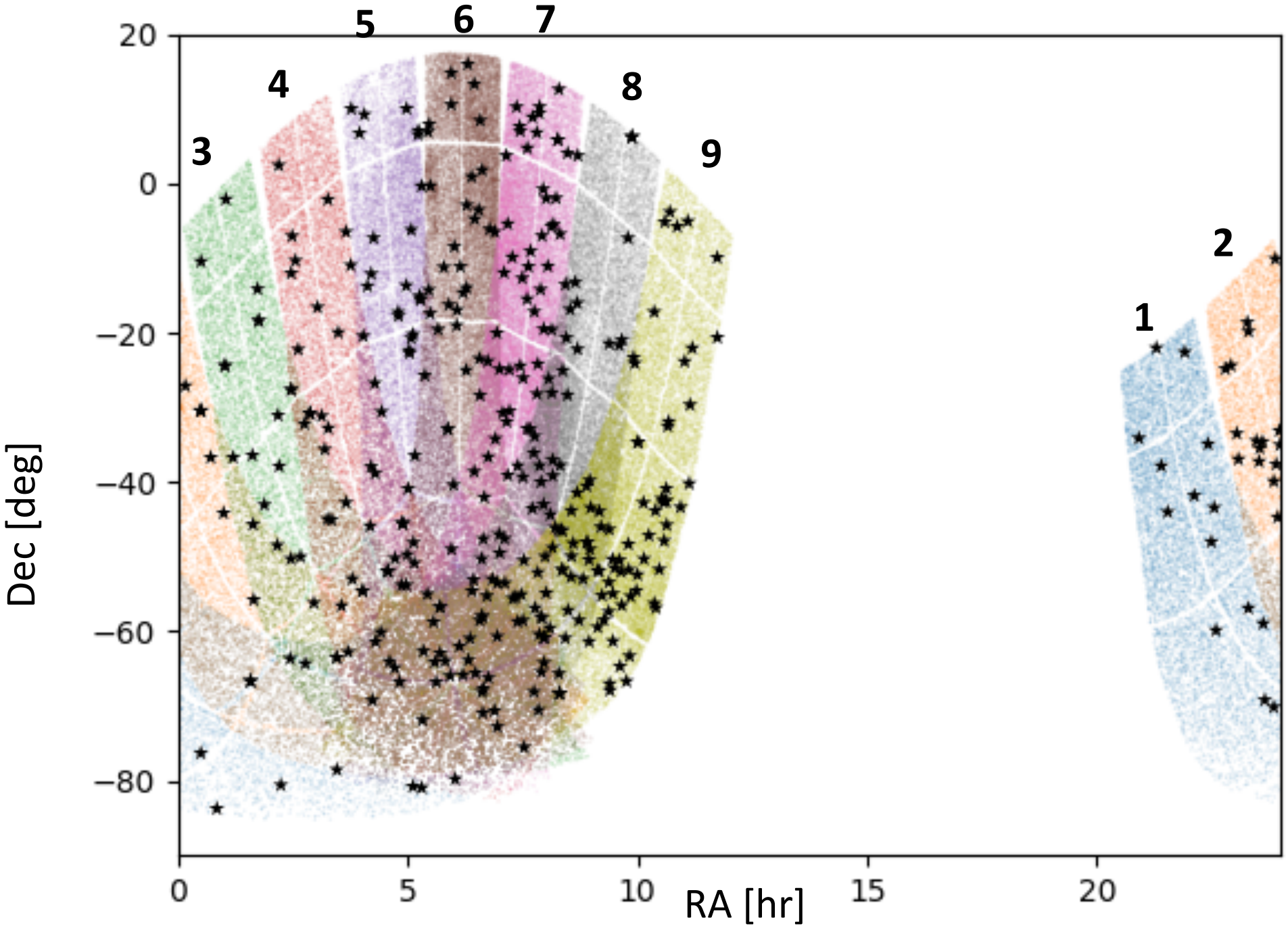
What is the difference compare to the TOI list?

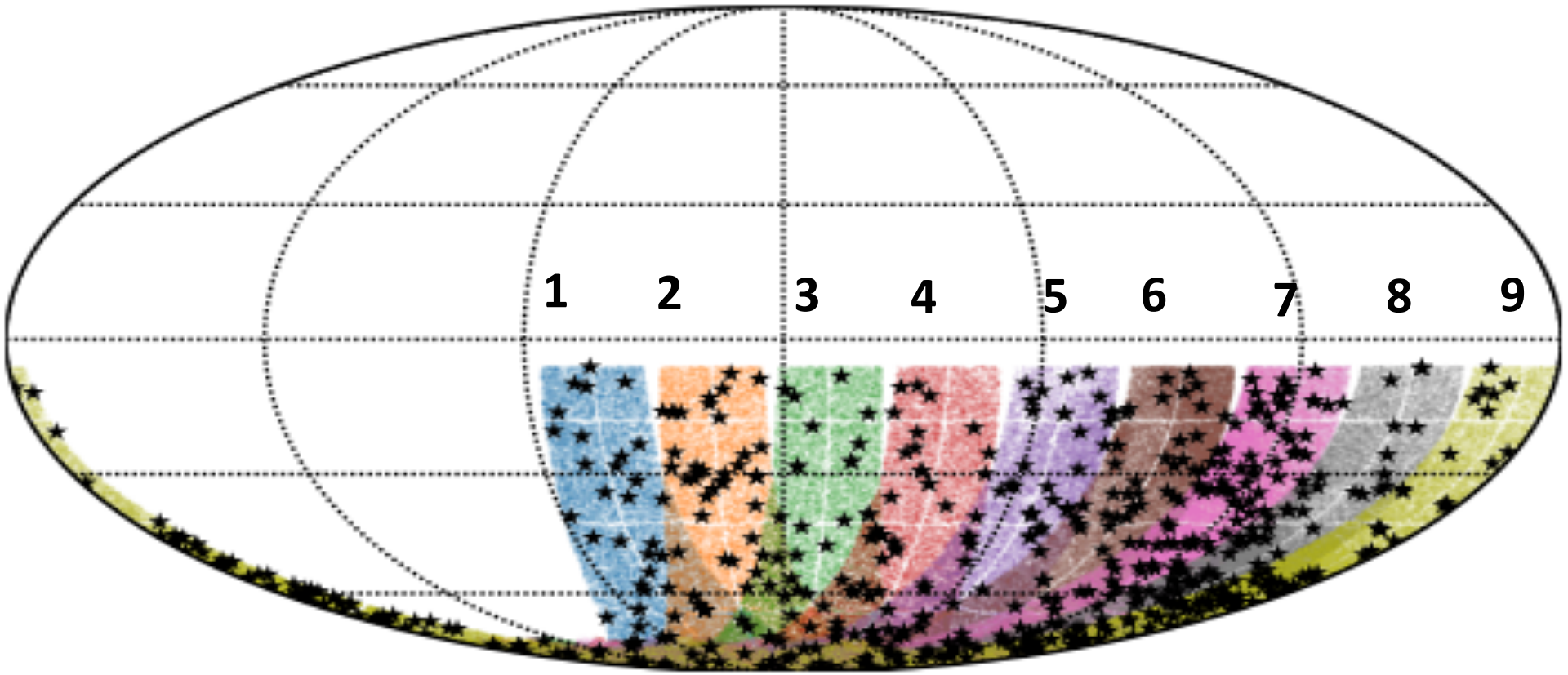
- Uniformly produced from the FFI;
- Removed candidates with defect;
- Vetted complete till Tmag 11;

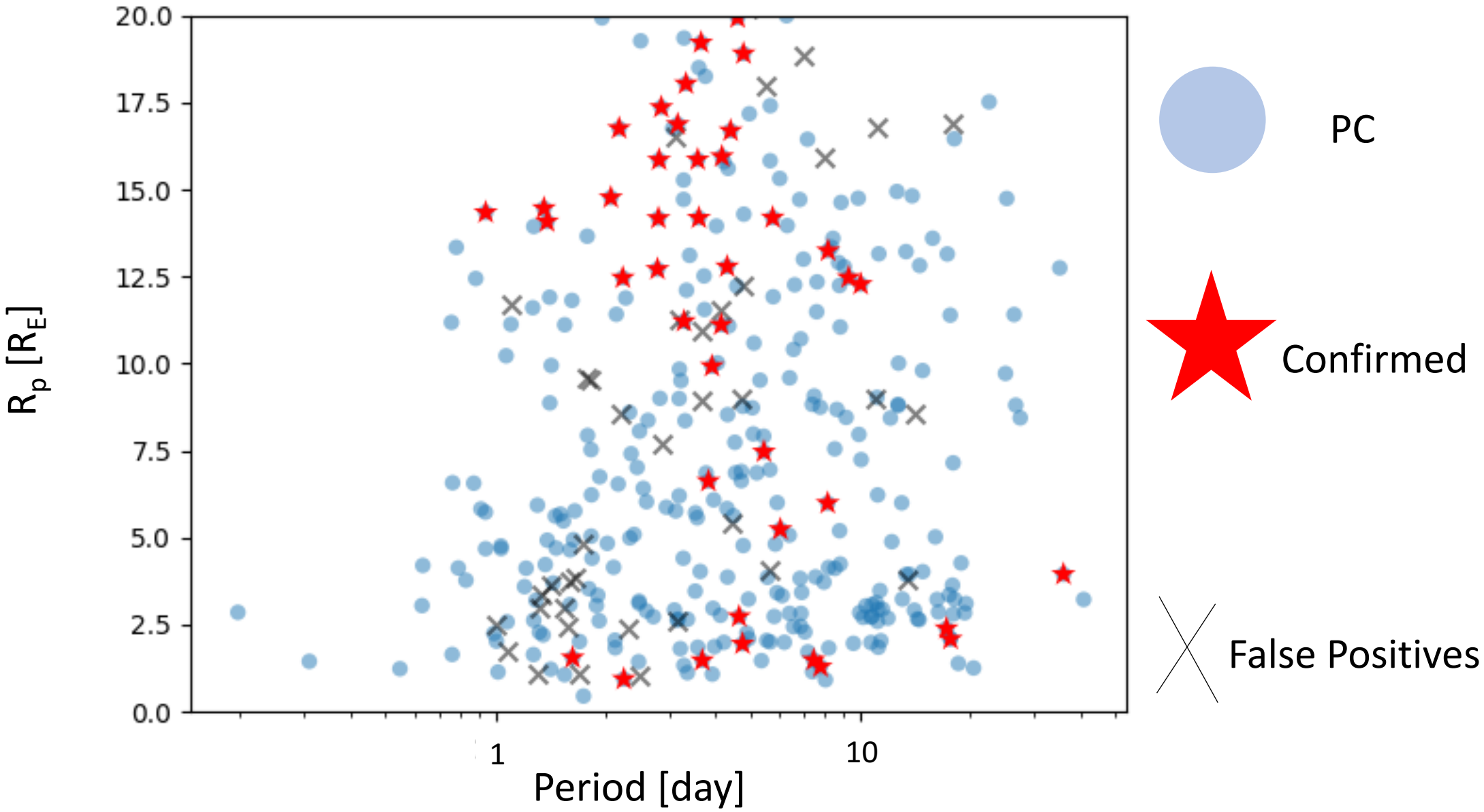

RMS per hour (ppm)
1000
800
600
400
200
0
4
5
6
7
8
9
10
11
TESS Magnitude

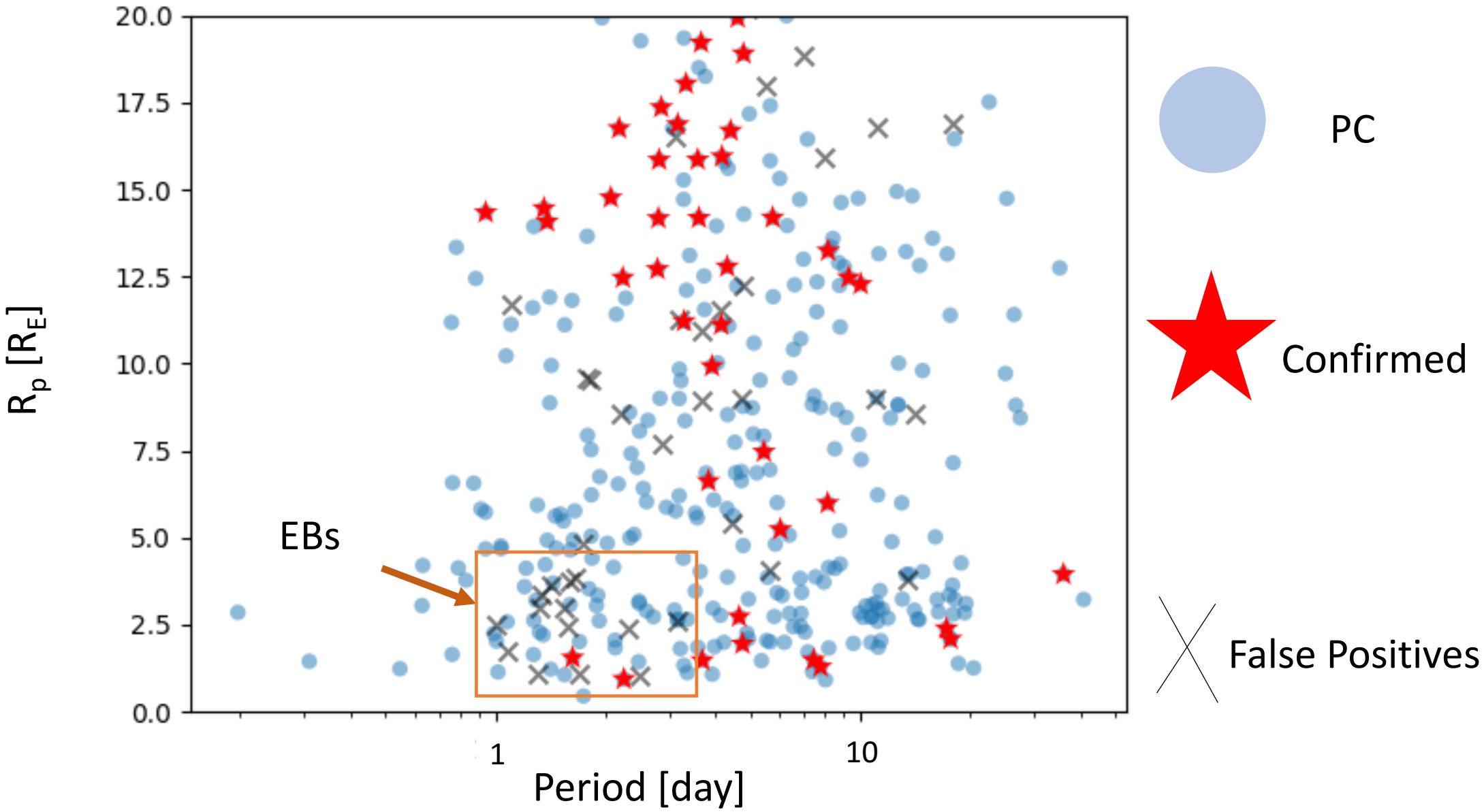

Abs G mag
−4
−2
0
2
4
6
8
10
−0.5
0.0
0.5
1.0
1.5
2.0
Bp-Rp
582533 unique stars, 600 PC
172586 main sequence.

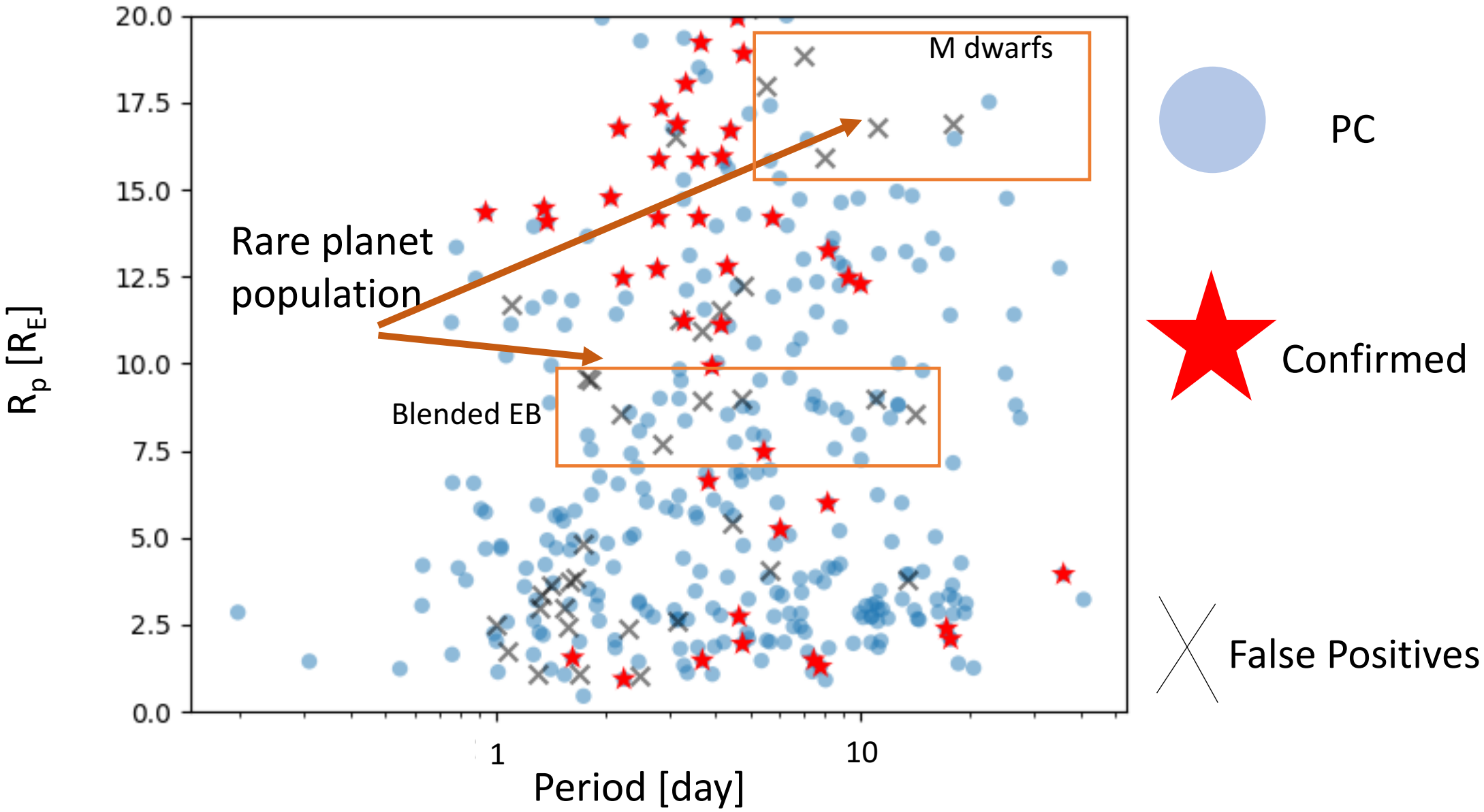

Abs G mag
−4
−2
0
2
4
6
8
10
−0.5
0.0
0.5
1.0
1.5
2.0
Bp-Rp
582533 unique stars, 600 PC
172586 main sequence. [404 PC]


5
6
7
4
8
3
9
1
2
20
0
−20
−40
−60
−80
Dec [deg]
0
5
10
15
20
RA [hr]


1
2
3
4
5
6
7
8
9


20.0
17.5
15.0
12.5
10.0
7.5
5.0
2.5
0.0
R_p [R_E]
1
10
Period [day]
PC
Confirmed
False Positives


20.0
17.5
15.0
12.5
10.0
7.5
5.0
2.5
0.0
R_p [R_E]
EBs
1
10
Period [day]
PC
Confirmed
False Positives


20.0
17.5
15.0
12.5
10.0
7.5
5.0
2.5
0.0
R_p [R_E]
1
10
Period [day]
M dwarfs
Rare planet population
Blended EB
PC
Confirmed
False Positives

Completeness of the pipeline - BLS

Single Sector (sector 3, Camera 1, effective baseline 17.6 day [out of 27 day])

Worst case scenario

SN>9 BLS completeness [%]	**2 R_E**	**4 R_E**	**10 R_E**
3 day	69 [13]	75 [2]	86[1]
6 day	71[13]	79 [3]	89[1]
12 day	73 [15]	80[4]	92[1]

Completeness of the pipeline - Triage

Single Sector (sector 3, Camera 1, effective baseline 17.6 day [out of 27 day])

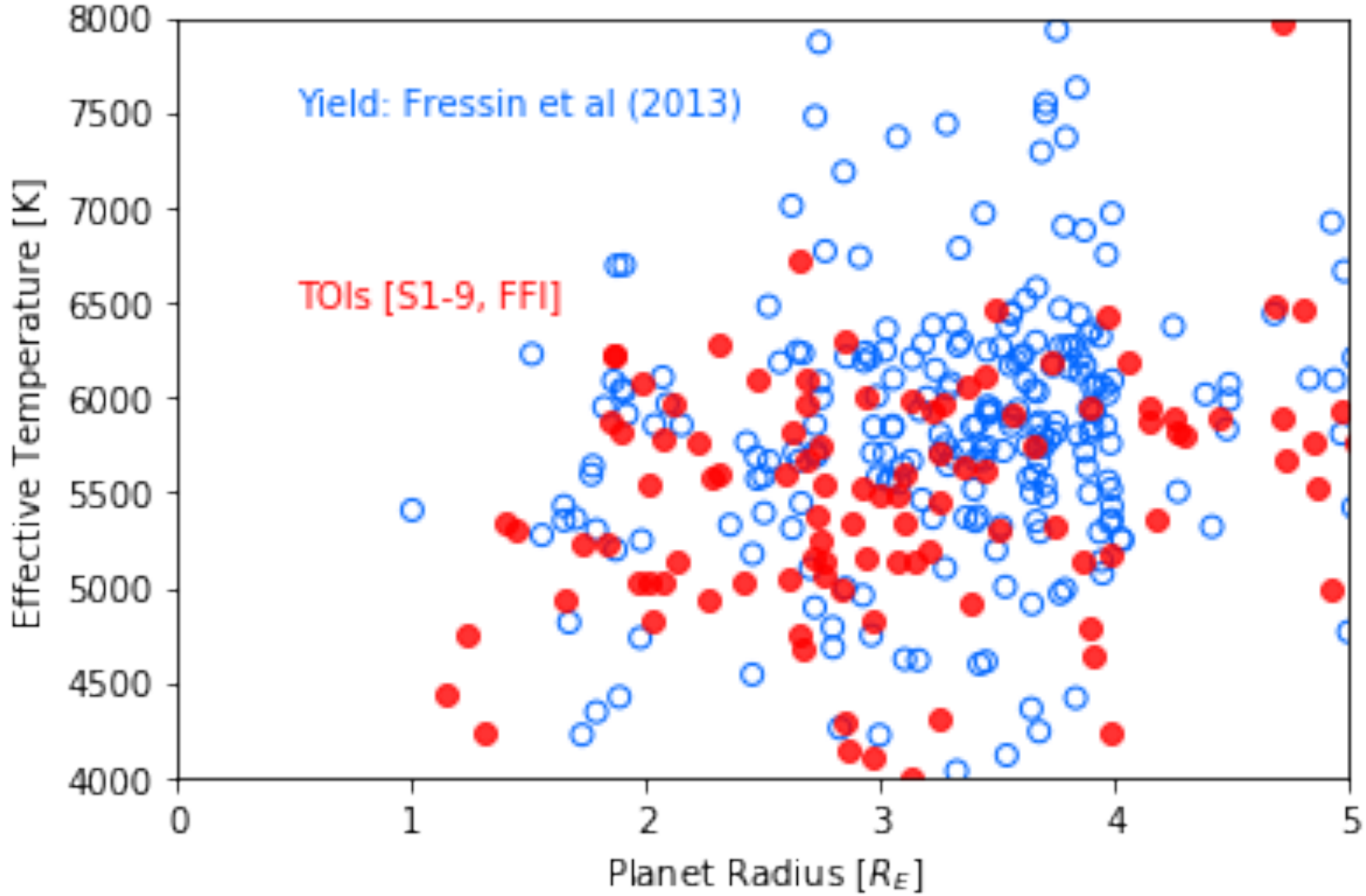
Worst case scenario

Triage completeness [%]	**2 R_E**	**4 R_E**	**10 R_E**
3 day	88 [18]	98 [4]	99[3]
6 day	80 [20]	85 [4]	98[3]
12 day	73 [22]	85[5]	94[3]

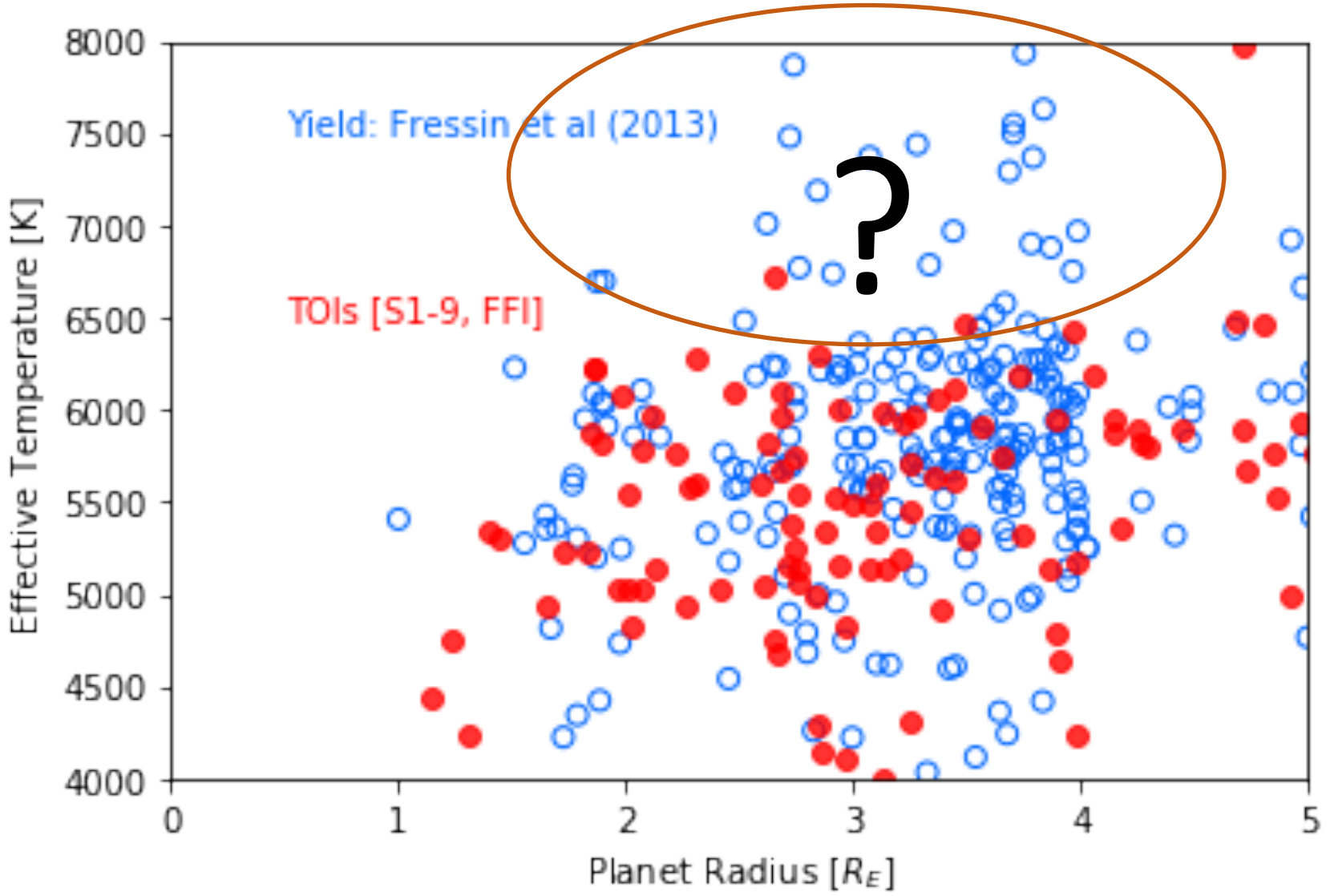
Completeness of the pipeline - Human Vetter

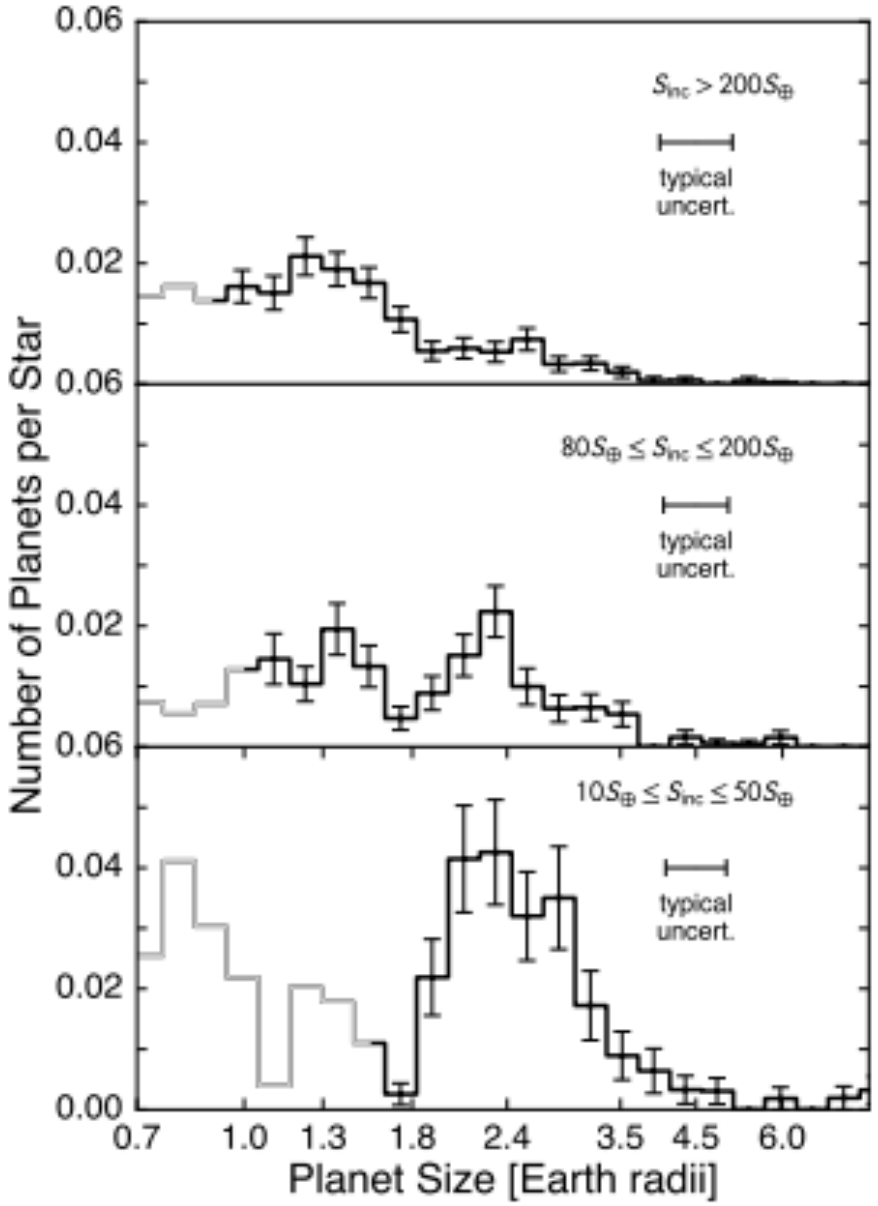
?

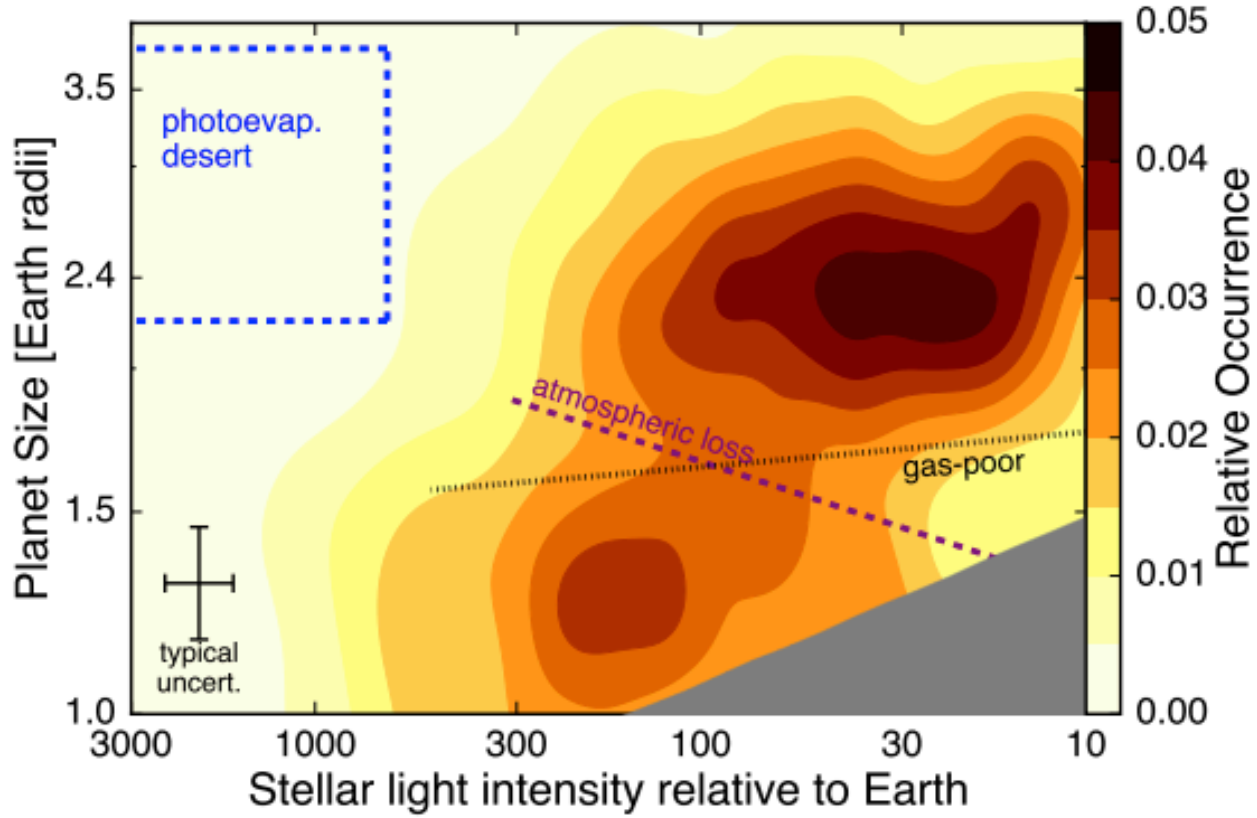
Human Vetter -> Machine Learning
with secondary eclipse/ centroid information

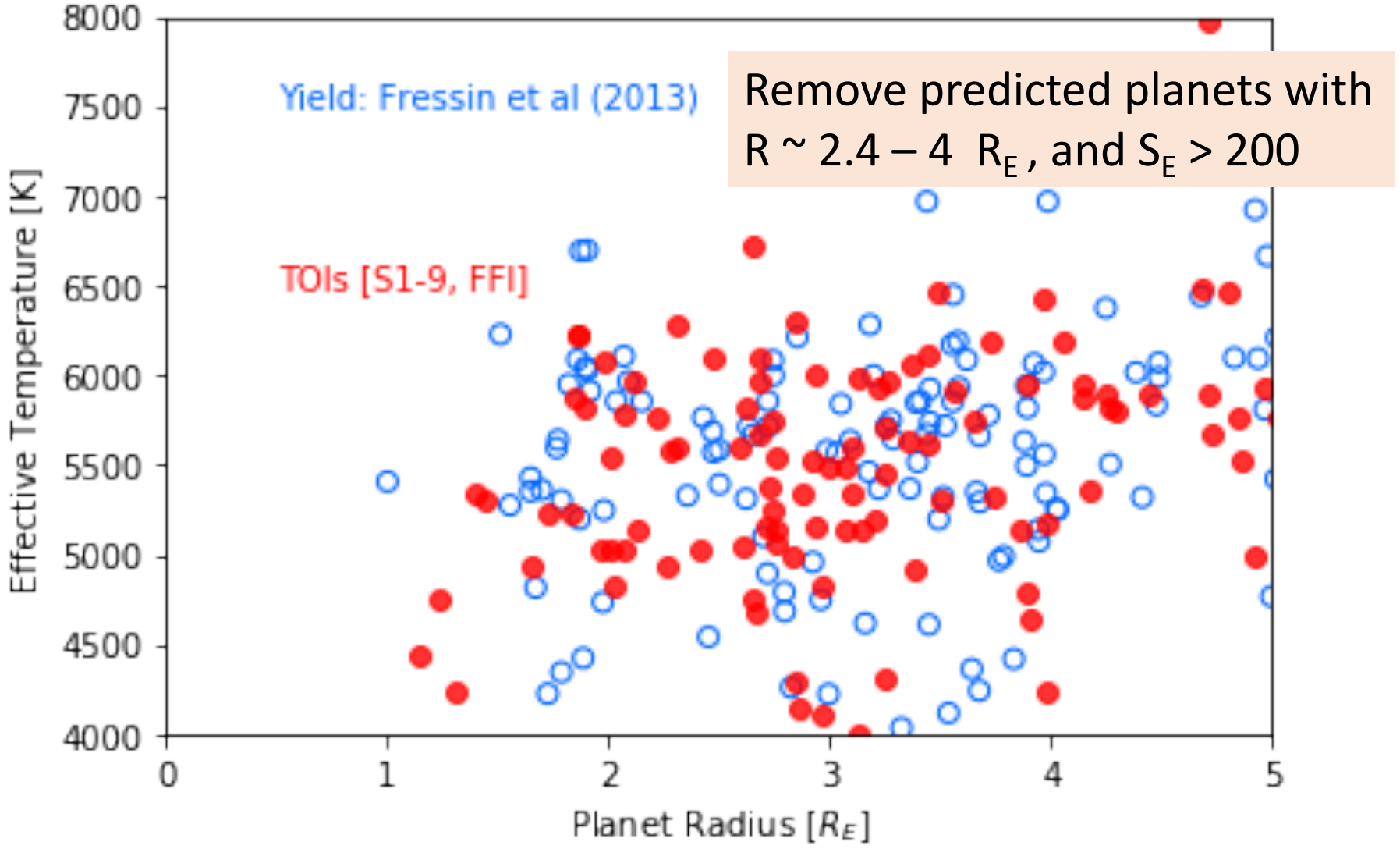


Planet yield result adopted from Barclay et al (2018) table, adjust for S 1-9


Yield: Fressin et al (2013)
TOIs [S1-9, FFI]
?
Effective Temperature [K]
8000
7500
7000
6500
6000
5500
5000
4500
4000
0
1
2
3
4
5
Planet Radius [R_E]

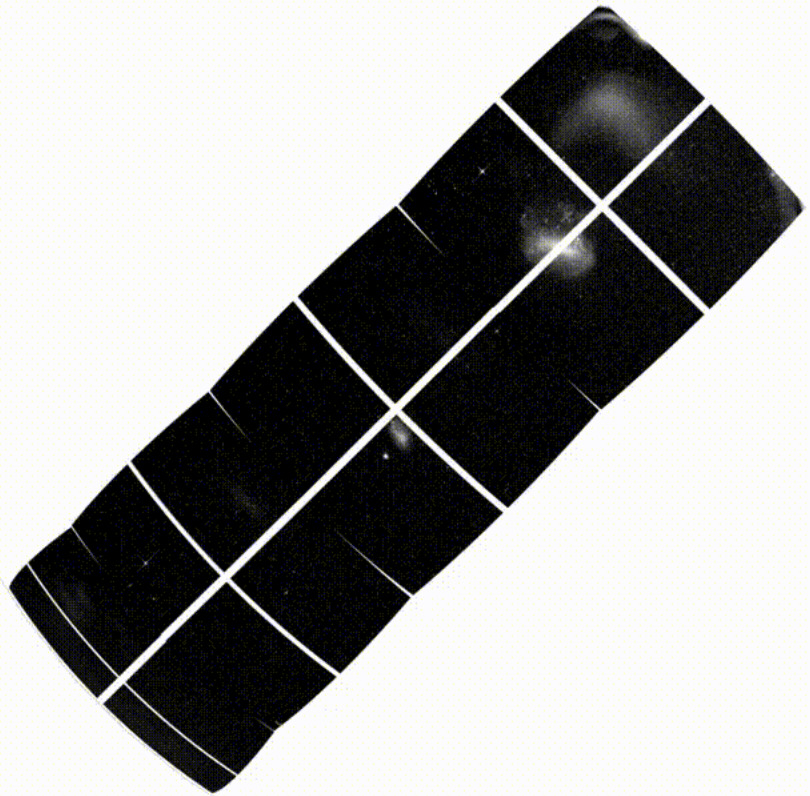

Number of Planets per Star
0.06
0.04
0.02
0.06
0.04
0.02
0.06
0.04
0.02
0.00
$S_{inc} > 200S_{\oplus}$
typical uncert.
$80S_{\oplus} \leq S_{inc} \leq 200S_{\oplus}$
typical uncert.
$10S_{\oplus} \leq S_{inc} \leq 50S_{\oplus}$
typical uncert.
0.7
1.0
1.3
1.8
2.4
3.5
4.5
6.0
Planet Size [Earth radii]


Planet Size [Earth radii]
3.5
2.4
1.5
1.0
photoevap. desert
atmospheric loss
gas-poor
typical uncert.
3000
1000
300
100
30
10
Stellar light intensity relative to Earth
0.05
0.04
0.03
0.02
0.01
0.00
Relative Occurrence



Remove predicted planets with
$R \sim 2.4 - 4\ R_E$, and $S_E > 200$

NASA TESS's View of the Southern Hemisphere



By Ethan Kruse
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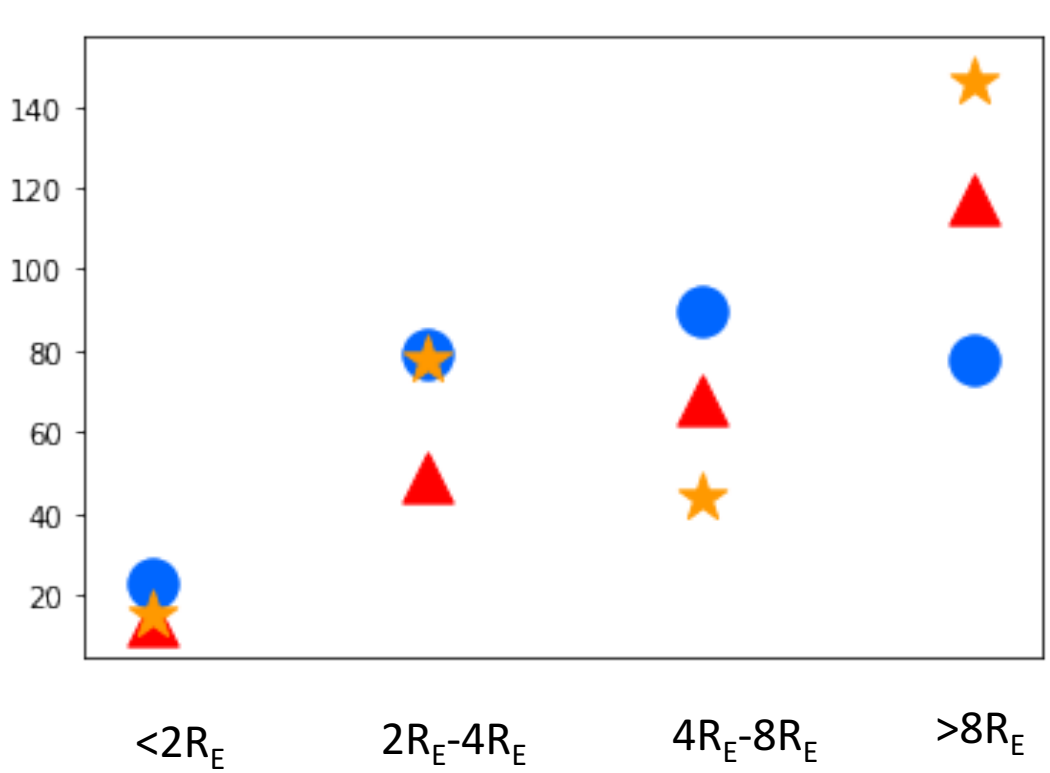
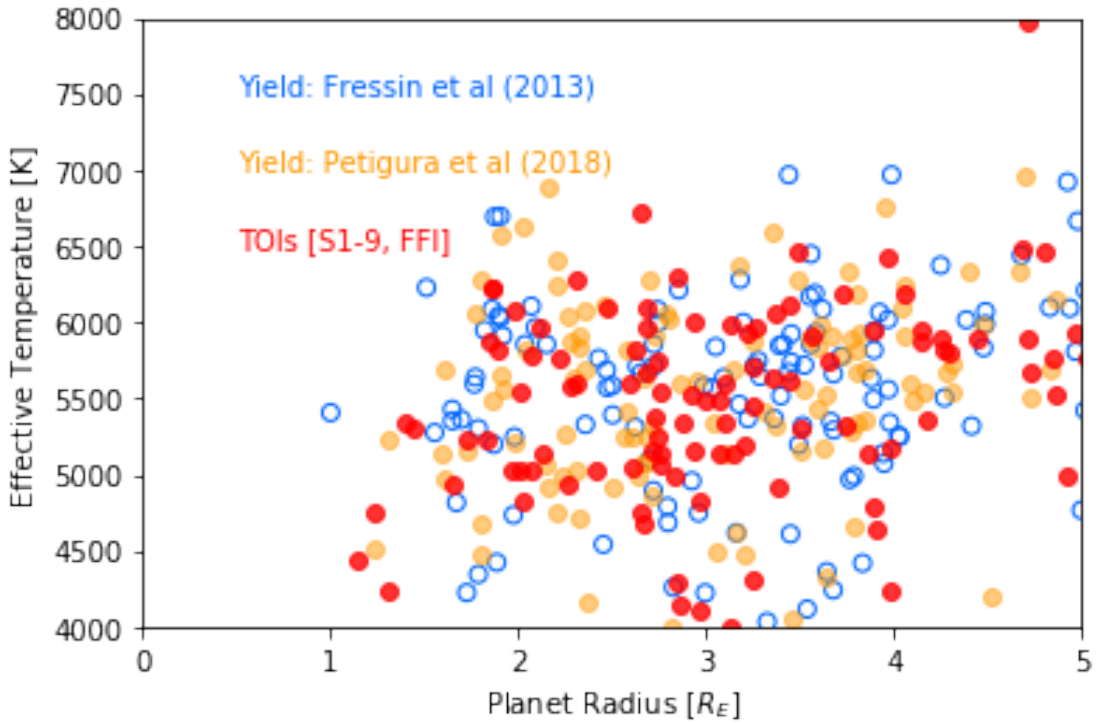
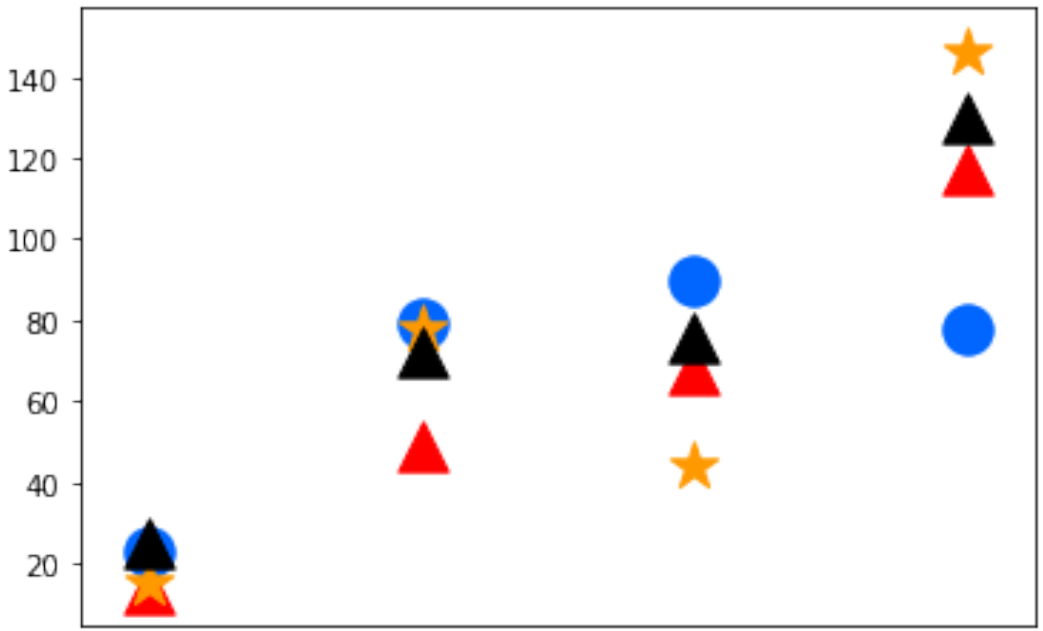
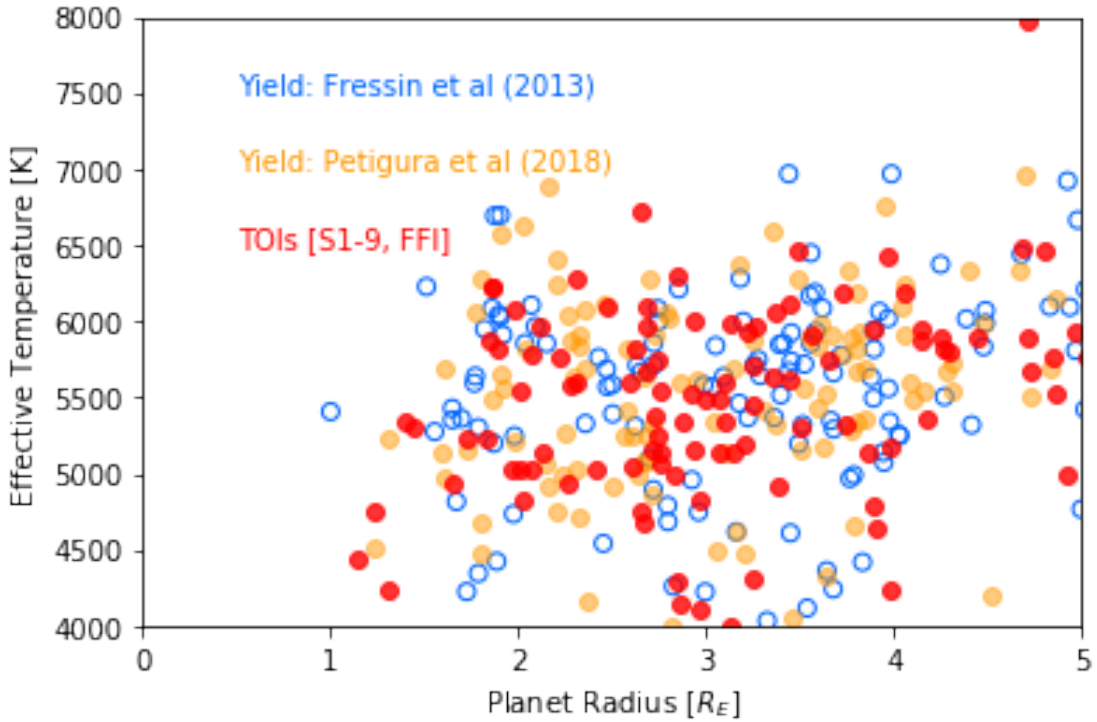
Sector 1
Jul 2018-Aug 2018

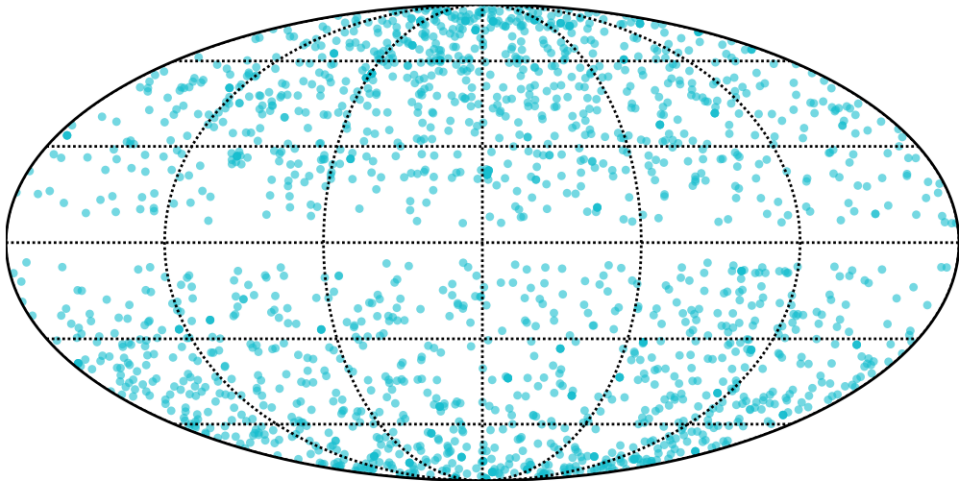

140
120
100
80
60
40
20
<2R_E
2R_E-4R_E
4R_E-8R_E
>8R_E

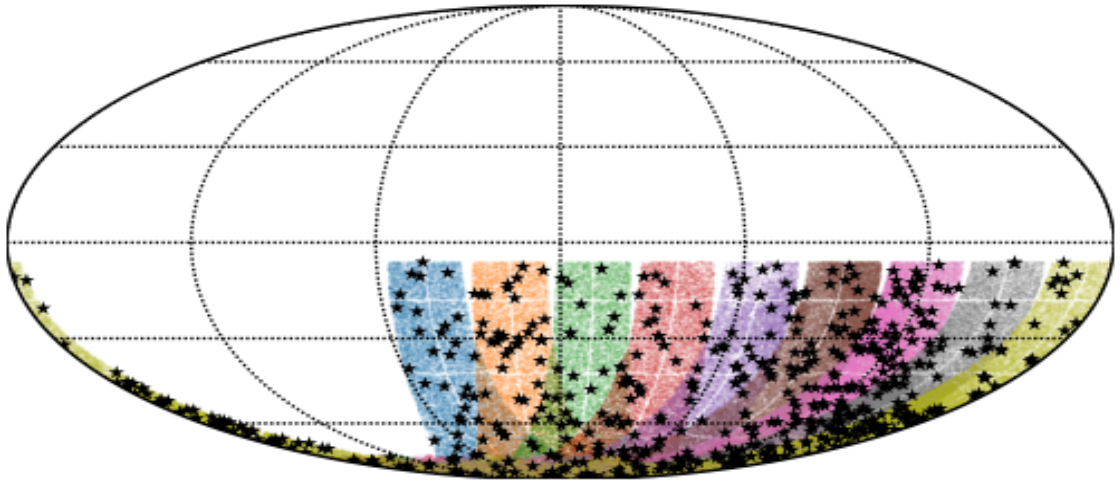

Yield: Fressin et al (2013)
Yield: Petigura et al (2018)
TOIs [S1-9, FFI]
Effective Temperature [K]
Planet Radius [R_E]
8000
7500
7000
6500
6000
5500
5000
4500
4000
0
1
2
3
4
5

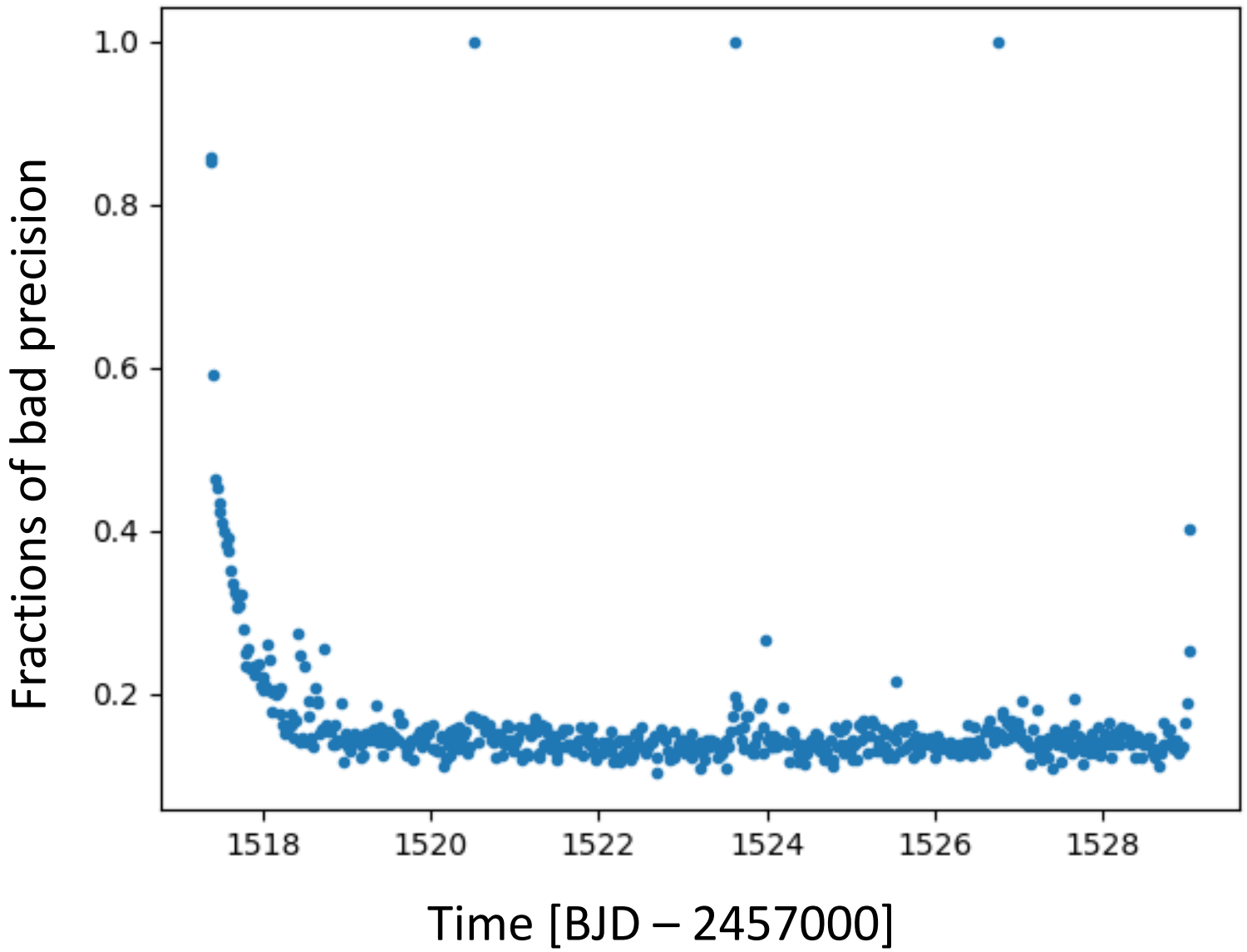


<$2R_E$ $2R_E$-$4R_E$ $4R_E$-$8R_E$ >$8R_E$








Fractions of bad precision
1.0
0.8
0.6
0.4
0.2
1518
1520
1522
1524
1526
1528
Time [BJD – 2457000]