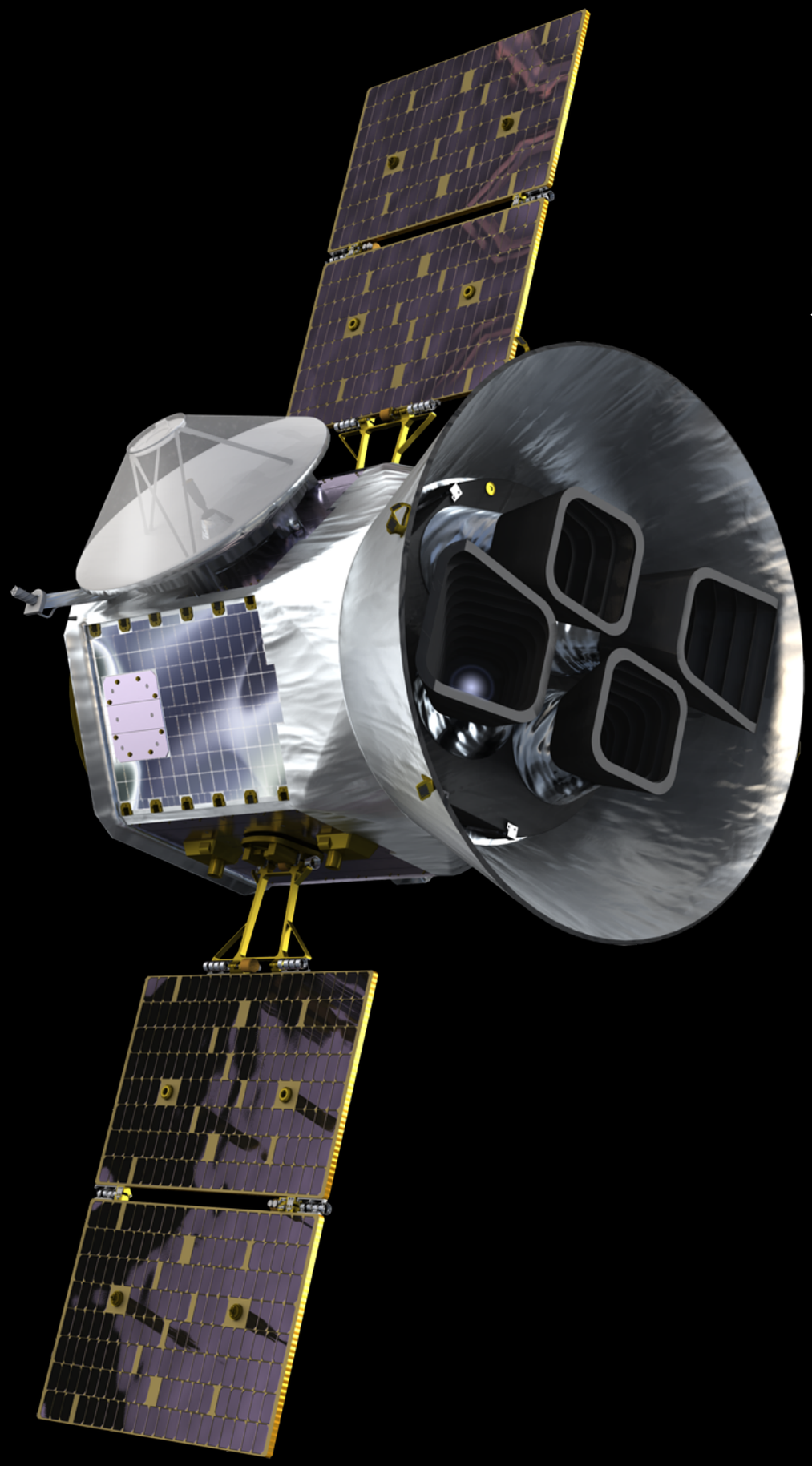

TESS

Science Mission Status

George Ricker (PI)
MIT

APAC Meeting

NASA HQ
23 October 2018

collaboration including:

MIT/MKI, MIT/LL, NASA Goddard, NASA Ames, NGIS, SpaceX, STScI, SAO, MPIA-Germany, Las Cumbres Observatory, Geneva Observatory, OHP-France, University of California, University of Florida, Aarhus University-Denmark, Harvard College Observatory, Princeton University, Vanderbilt University...

Graphics Credits: Zach Berta-Thompson (U. Colorado)

Topics

- Background: Why TESS?

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- ***Science Sector 1-3 completed; Sector 4 in Progress***

The TESS Science Mission in One Slide

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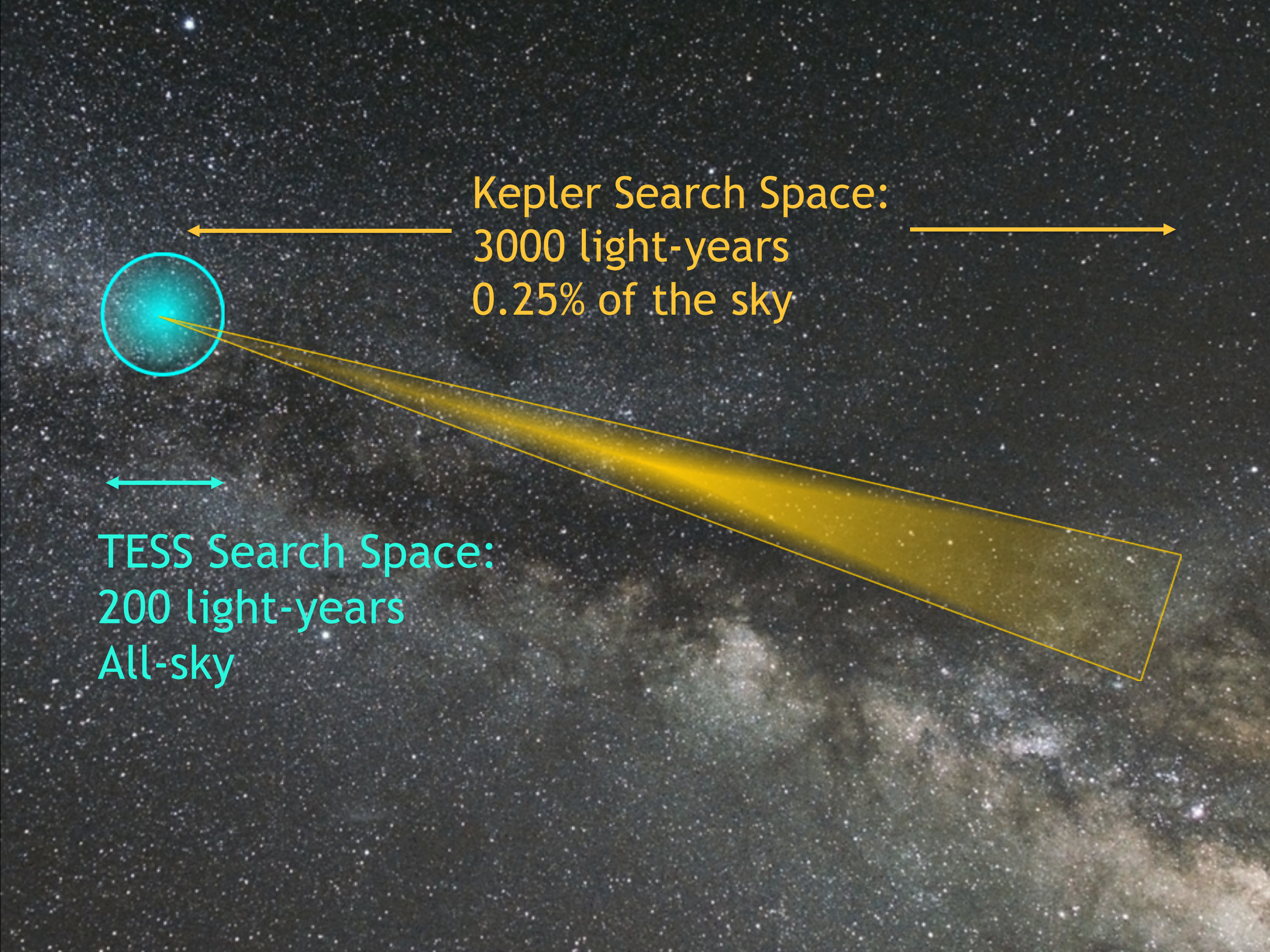
- Ground analyses of TESS data will reveal transiting planets by looking for regular dips in the brightness of each star
- Ground follow-up observations will:
  - *Confirm the presence of a transiting planet*
  - *Determine the mass of the planet*


Kepler Search Space:
3000 light-years
0.25% of the sky
TESS Search Space:
200 light-years
All-sky

Etendue Comparison of TESS and Kepler

- Definition of Etendue [$m^2 * deg^2$]:

$$\mathbf{E} = A_{optics} * \Omega_{net}$$

where $\Omega_{net} = \Omega_{gross} * \left(\frac{\textit{\# pixels telemetered}}{\textit{\# pixels in focal plane}} \right)$

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Kepler	0.71	105	0.06	4.2

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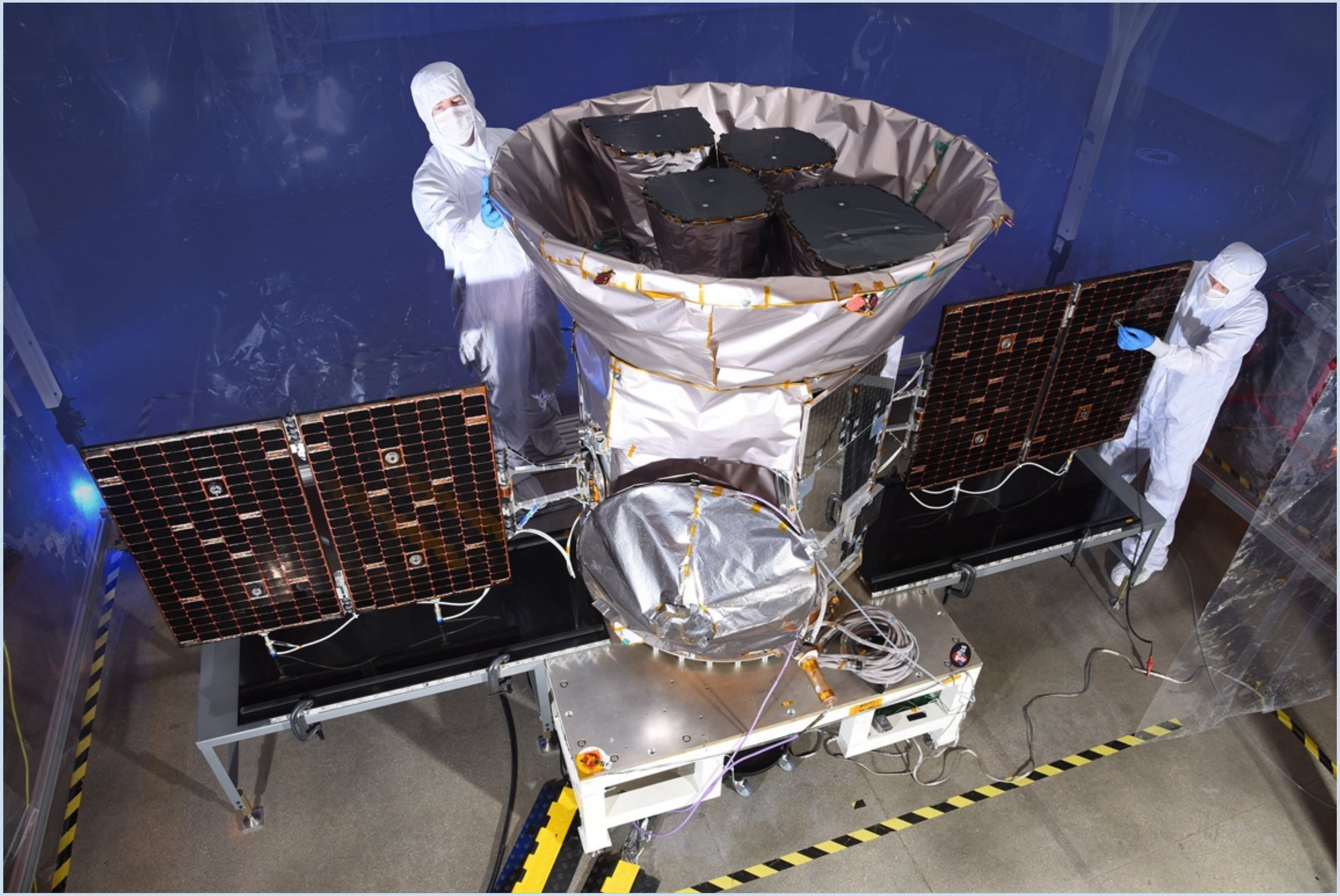
TESS is the highest etendue optical space mission yet flown: ~5 times greater than Kepler

Bryson et al. 2010
Ricker et al. 2016

TESS Observatory Undergoing Pre-Launch Testing



“Special” High Orbit Enables and Simplifies TESS

Advantages of TESS's 13.7 Day Lunar Resonant (P/2) Orbit

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Advantages of TESS's 13.7 Day Lunar Resonant (P/2) Orbit

- Extended & Unbroken Observations: *>300 hrs per orbit*
- Thermal Stability: *<40 mK/day (passive control only)*
- Earth/Moon Stray Light Level: *10^6 times less than LEO*
- Low Radiation Levels: *Outside of Earth's Radiation Belts*
- **Excellent Pointing Stability: No Drag, No Gravity Gradient**
- **Station keeping propellant:** *none required*
- **High Downlink Rates:** *100 Mbit/s (185 GB in ~5 hr at Apogee!)*

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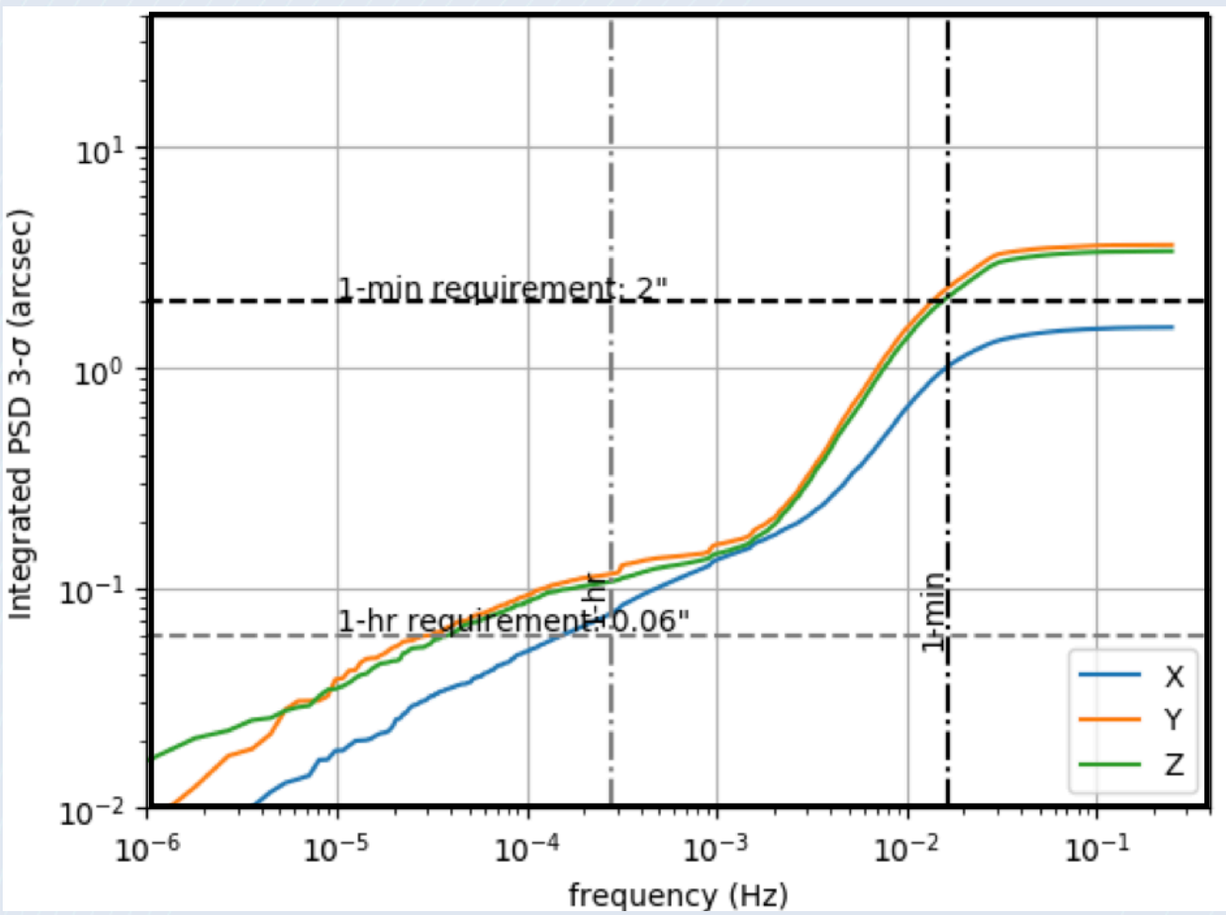
➡ $1/R^2$ advantage: ~ 23 dB improvement over an L2 orbit

Gangestad et al. 2013 (astro-ph 1306.5333)

Excellent Pointing Stability with Revised ACS Algorithm

A) **Original** Spacecraft ACS Algorithm (v 5.8)



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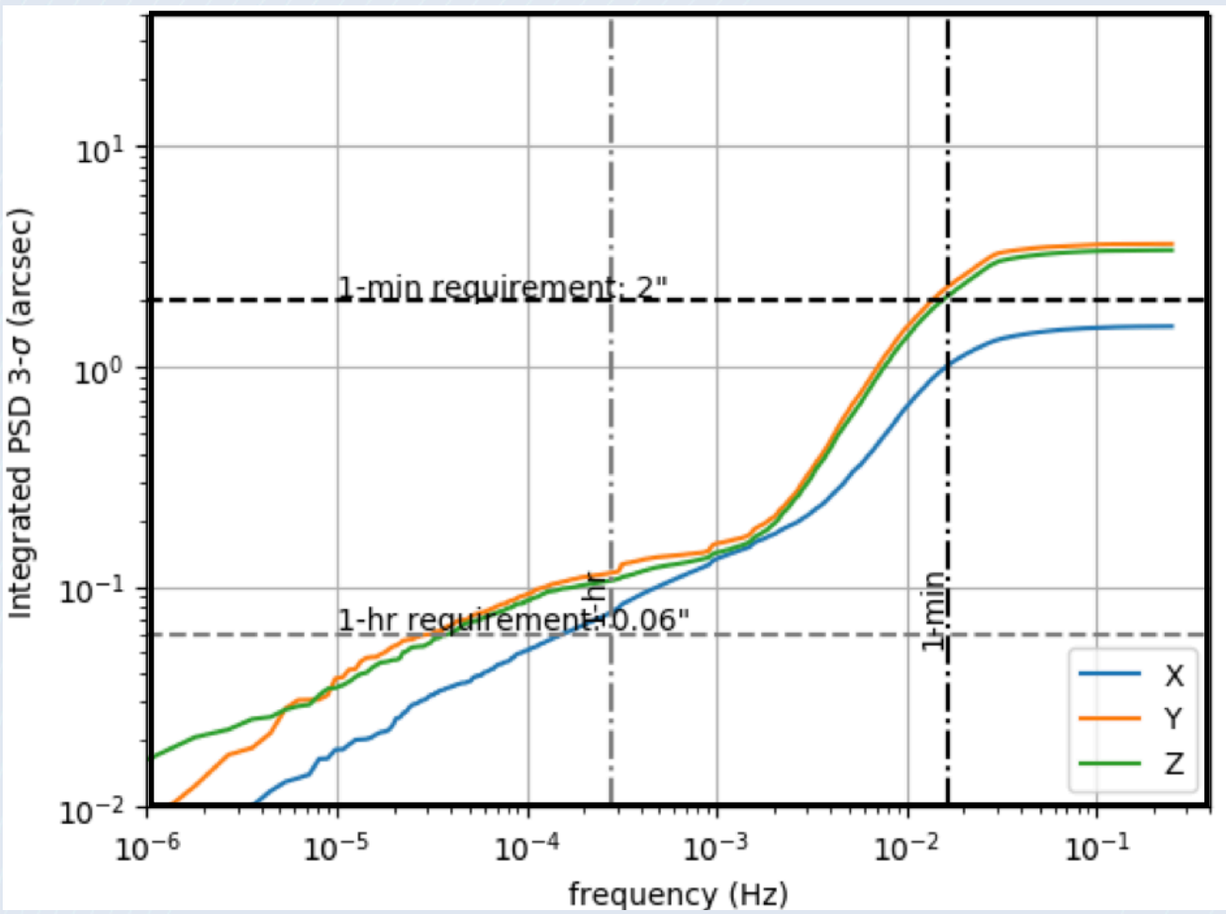

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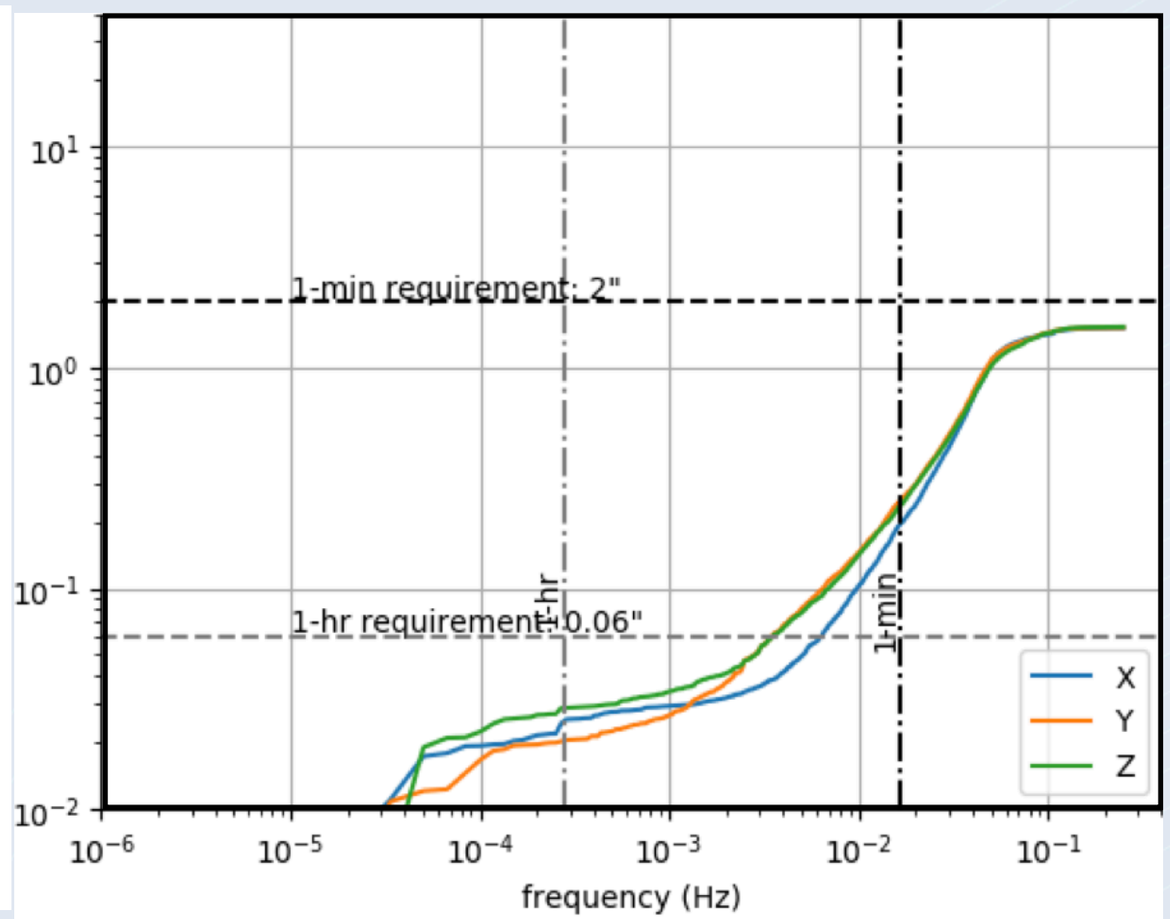
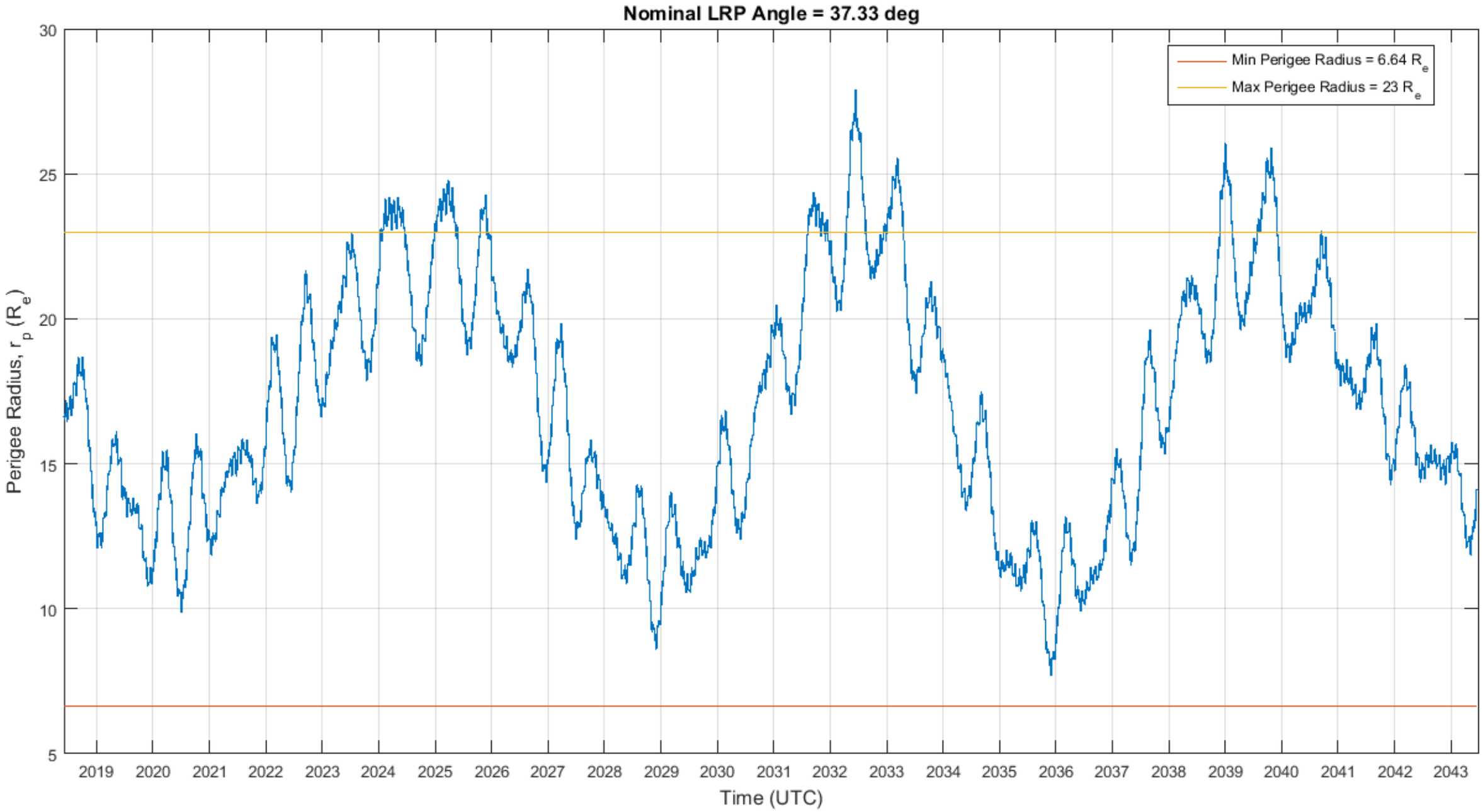


1 Hr Stability: 25 milliarcsec (3 sigma)
➪ ~ 10^{-3} pixel stability

TESS P/2 Resonant Orbit is Near Perfect!



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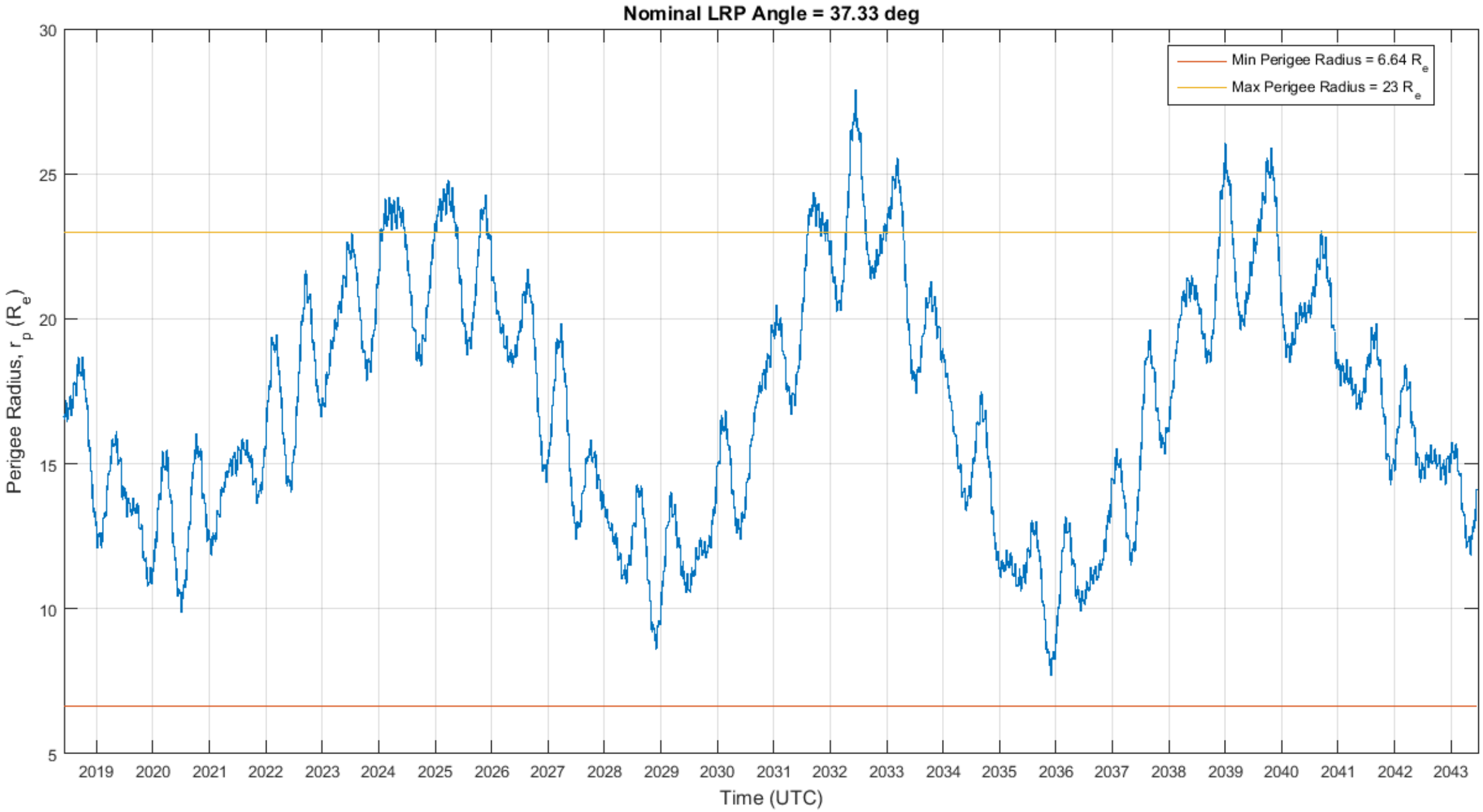

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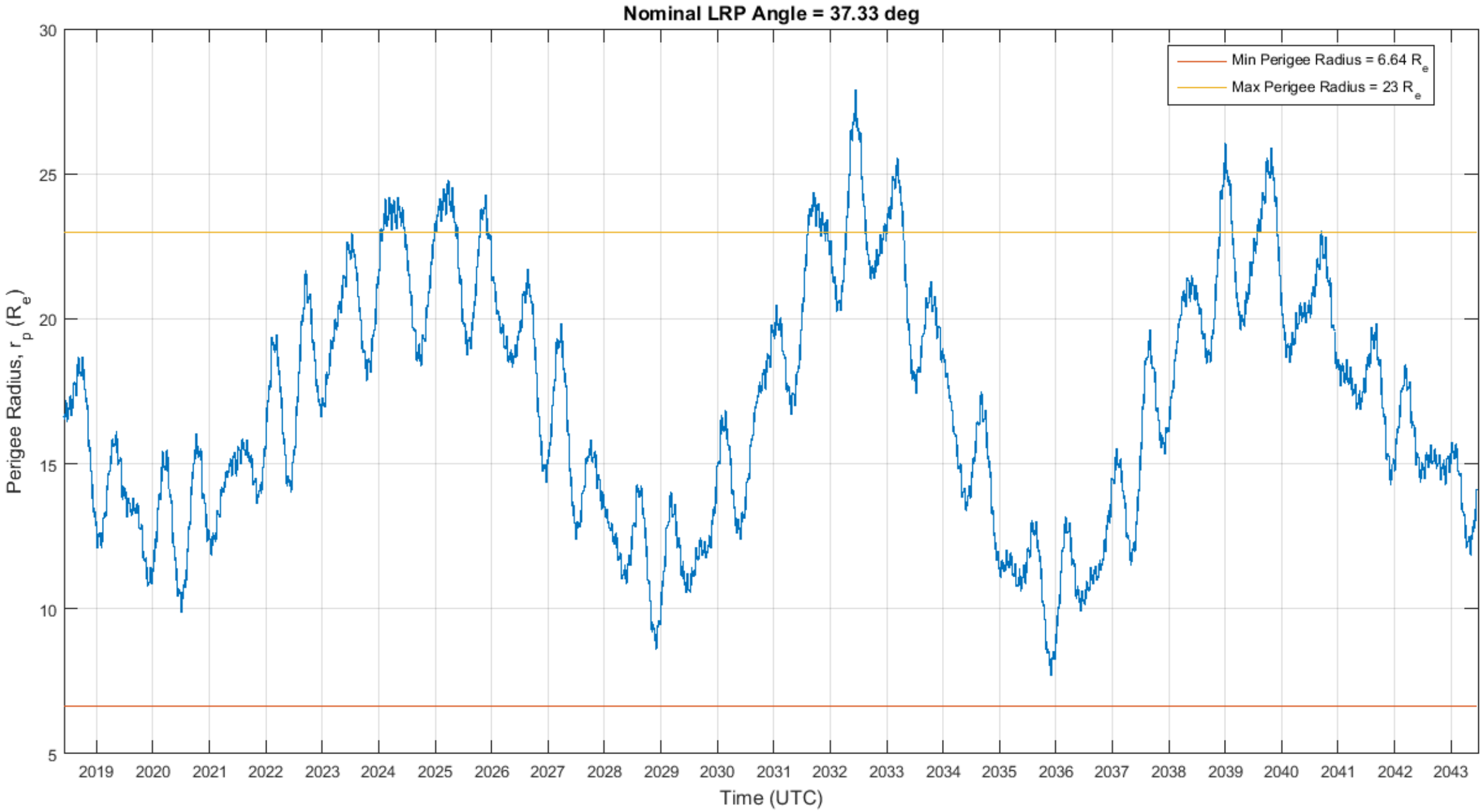
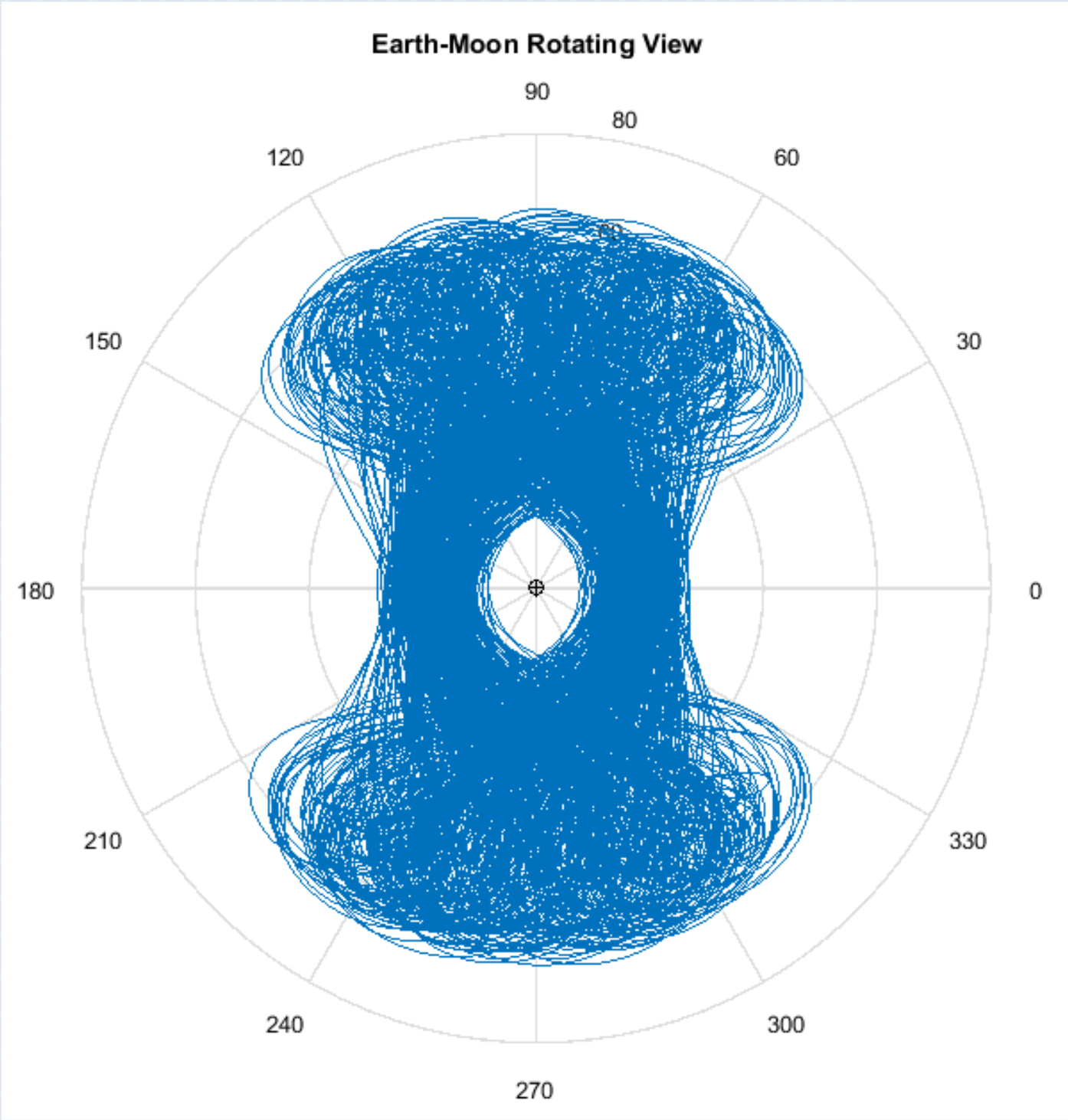


- Kozai oscillations will stabilize the orbit exactly as planned
- **Stable TESS orbit behavior is anticipated for >25 years**

Bottom Line: TESS Orbit is Excellent!



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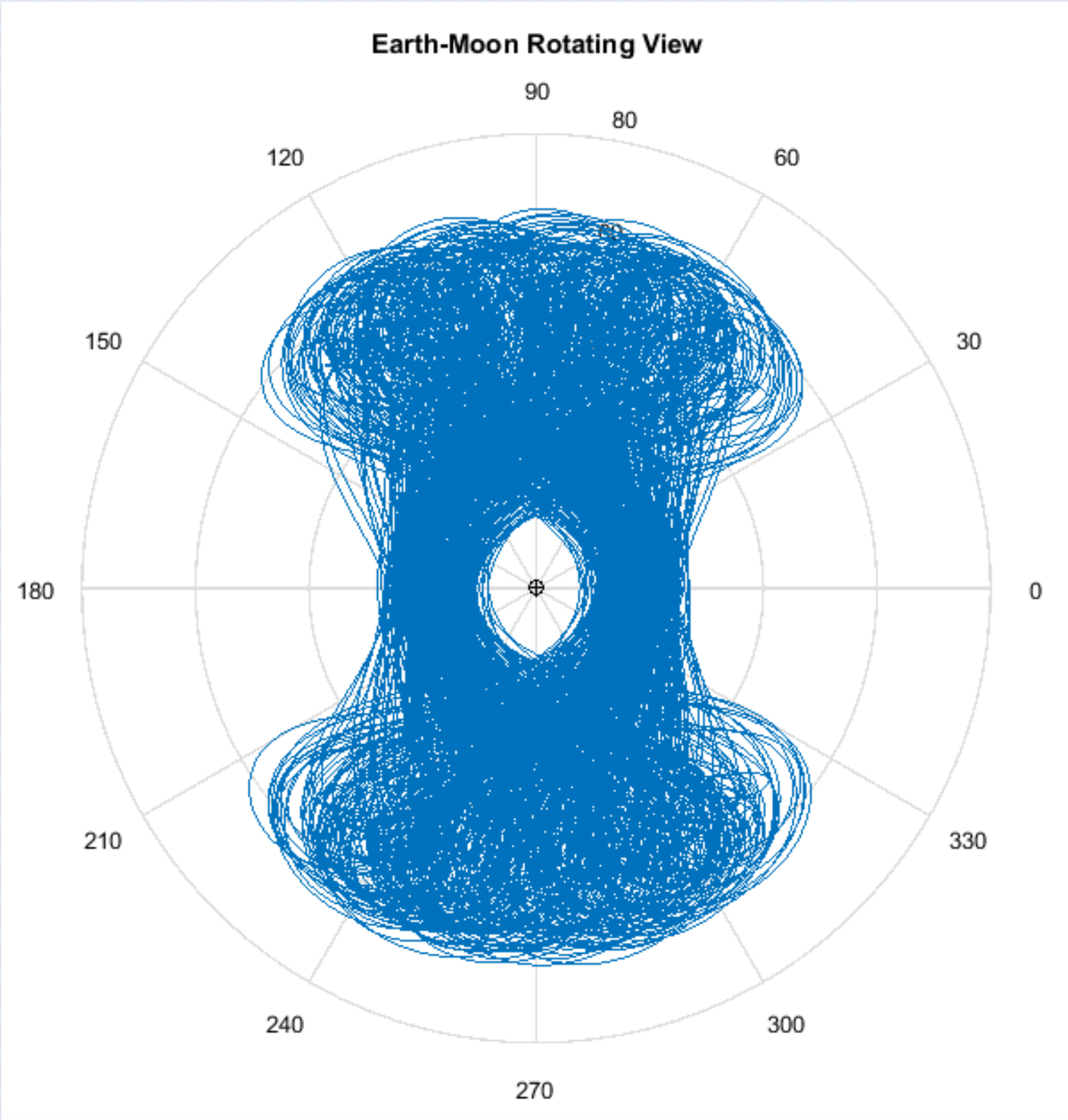

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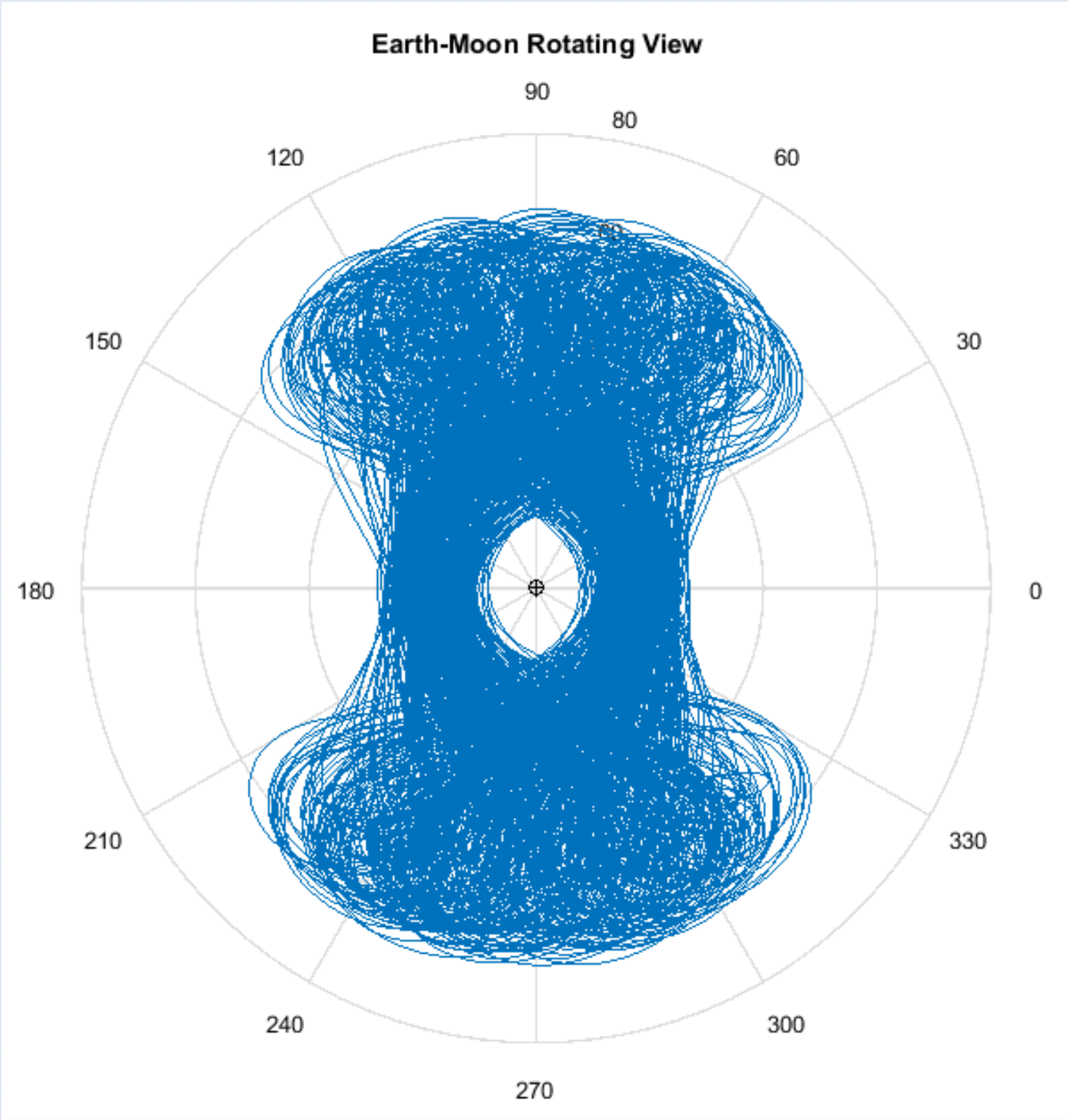

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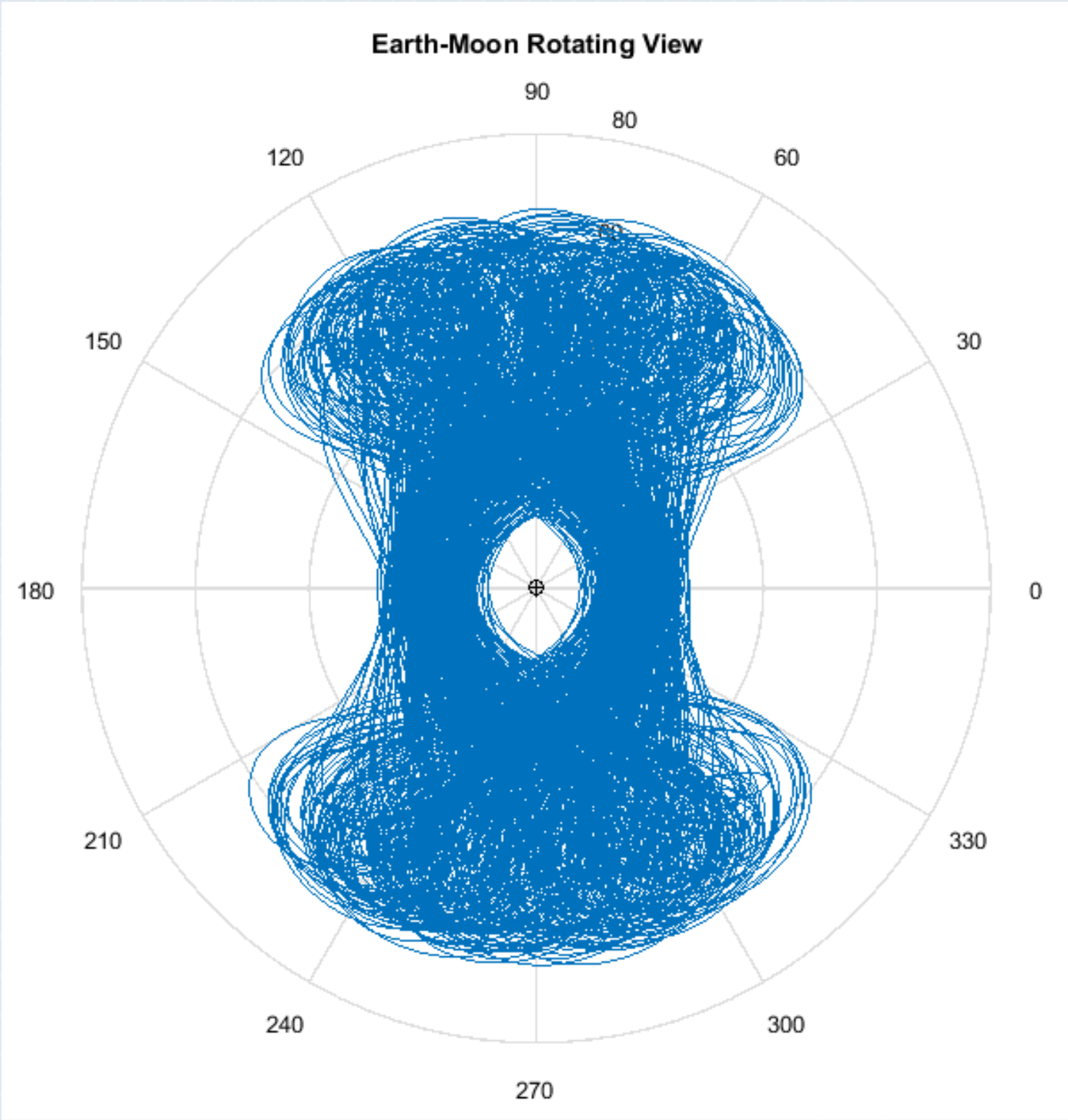

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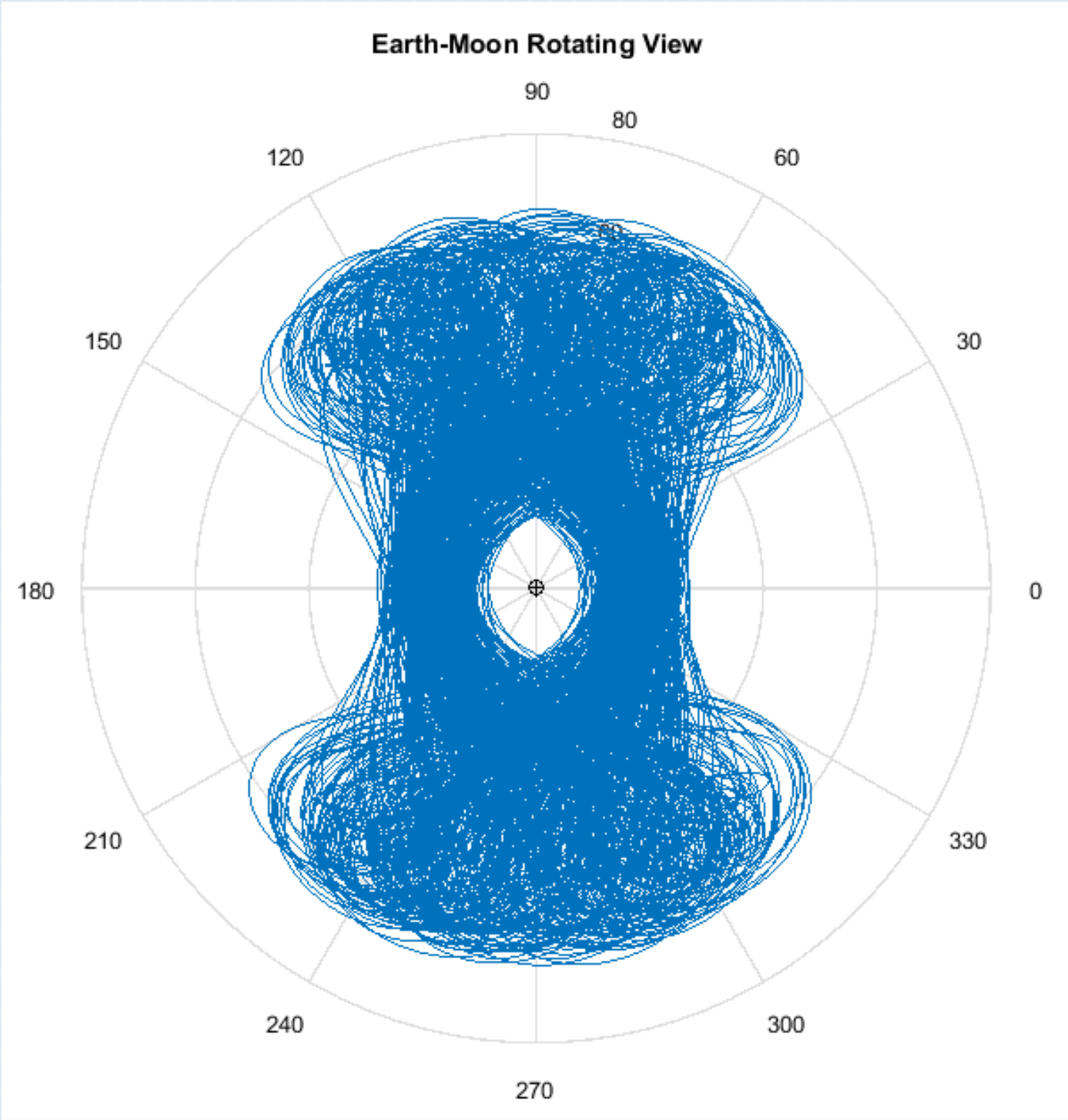

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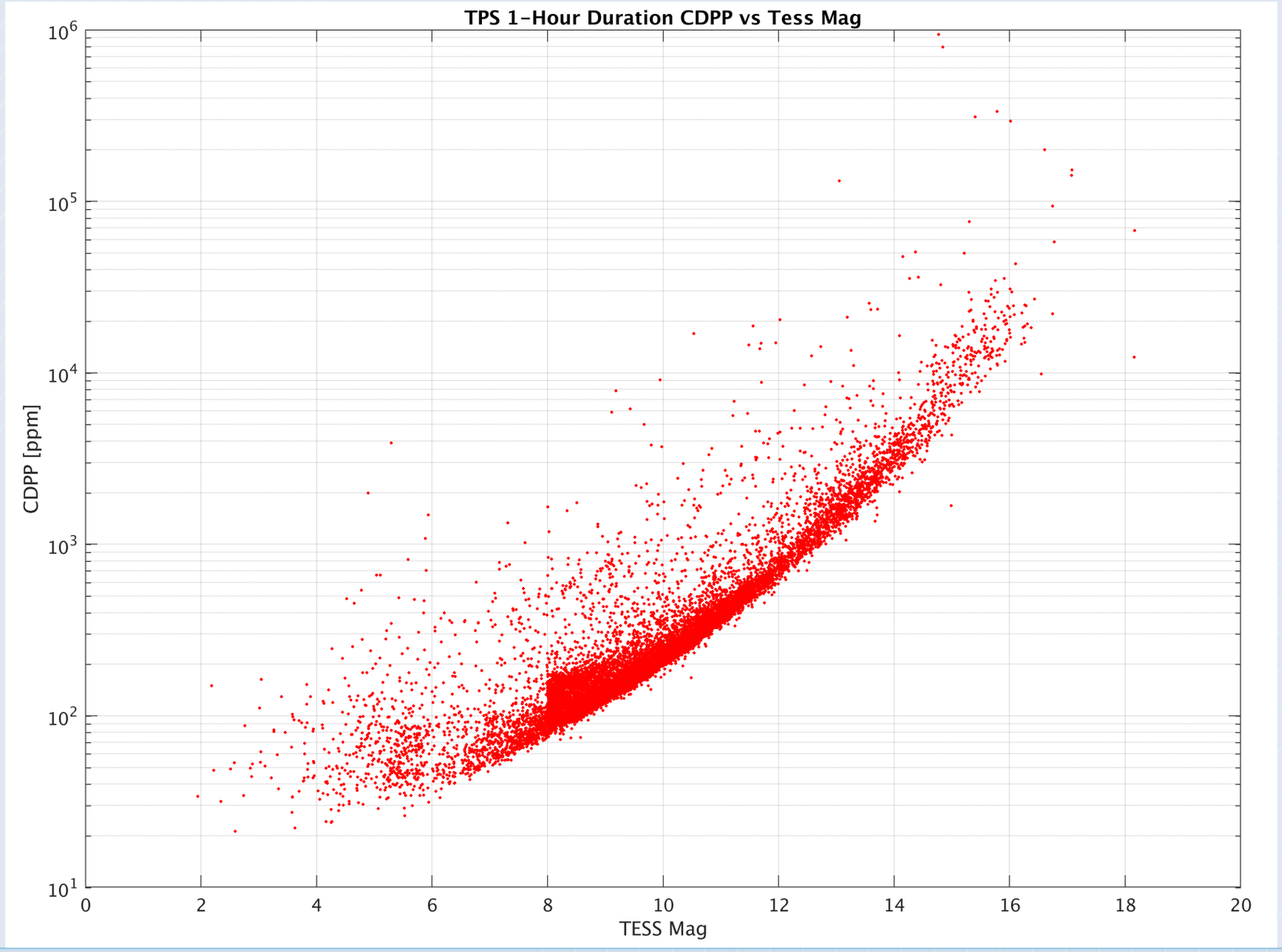
- Thus, stable operations anticipated until ~2038 !

TESS Photometric Precision

- Photometric precision of Sector 1 light curves is ~200 ppm at I=10
  - *Below L3 requirement of 230 ppm*
- Noise floor is ~30 ppm
  - *Well below Level 1 requirement of 60 ppm*



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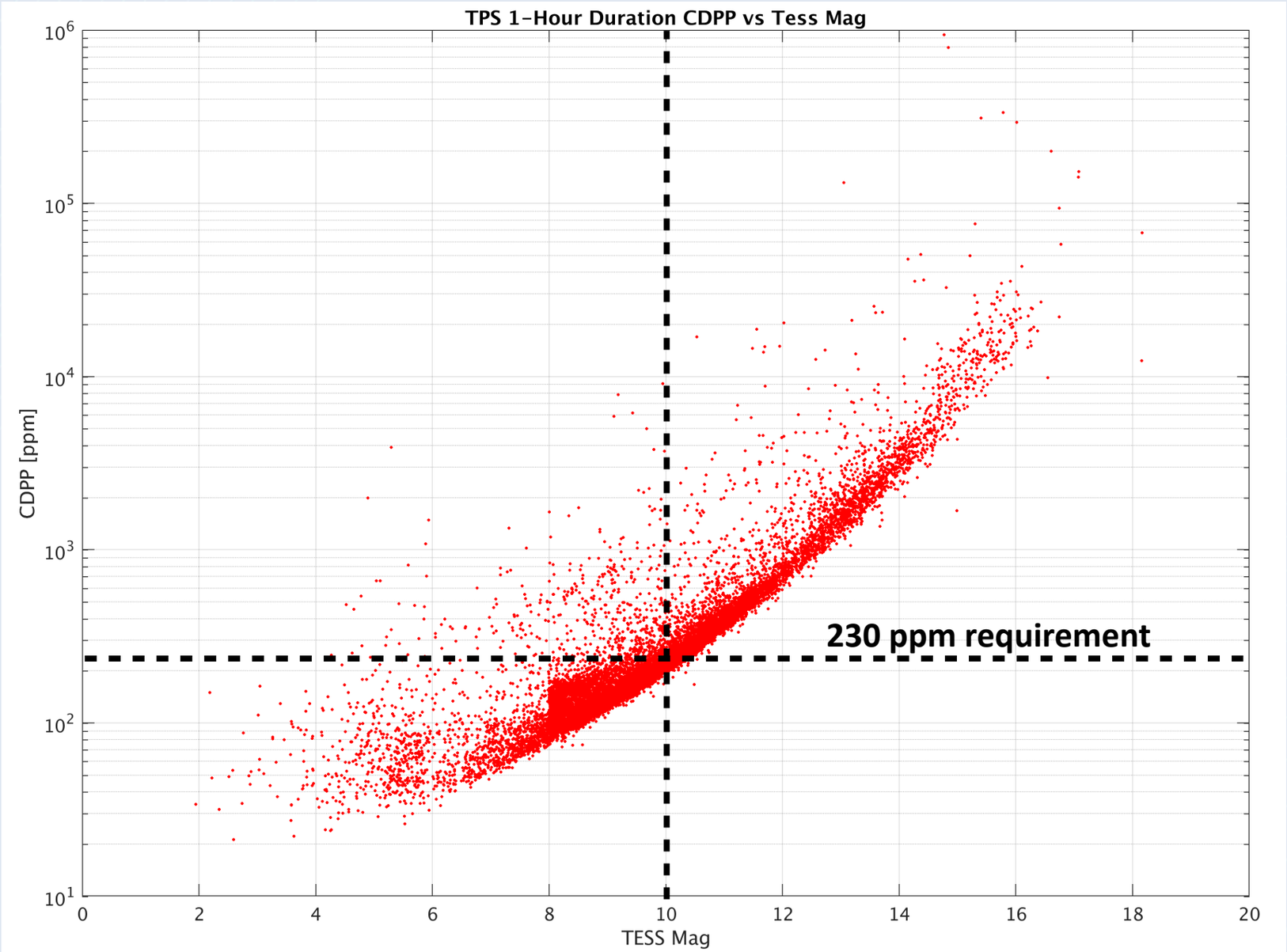

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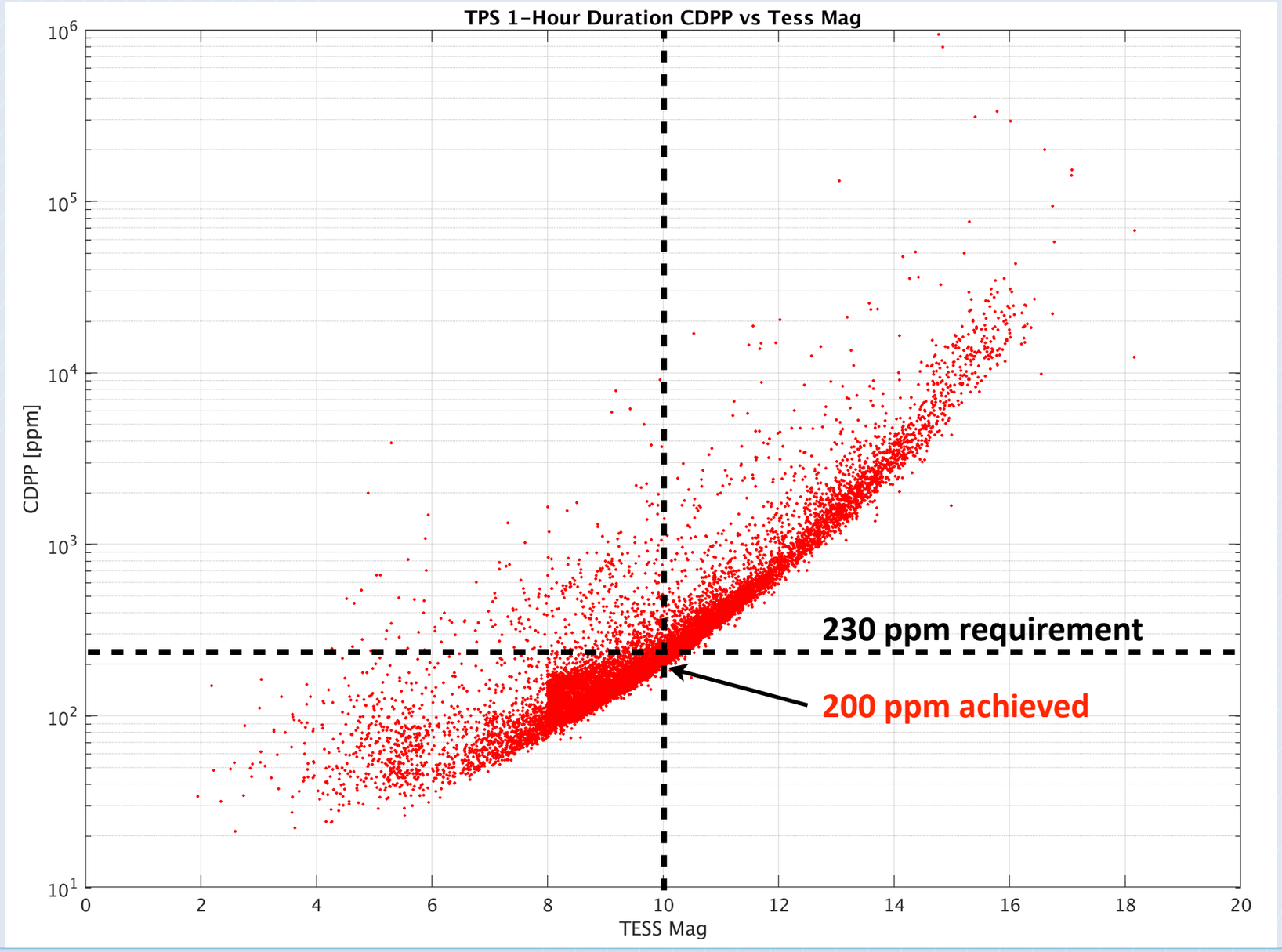

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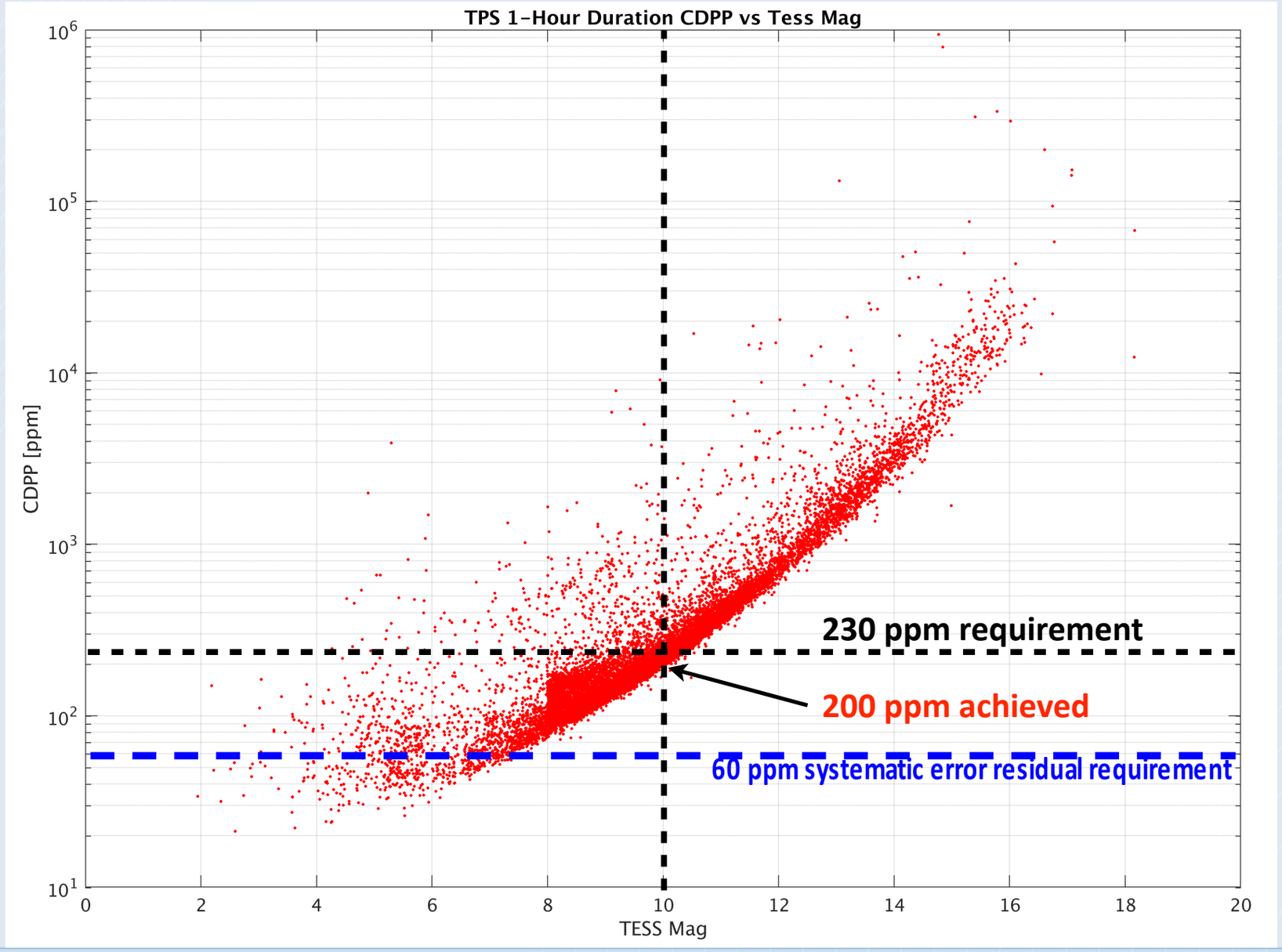

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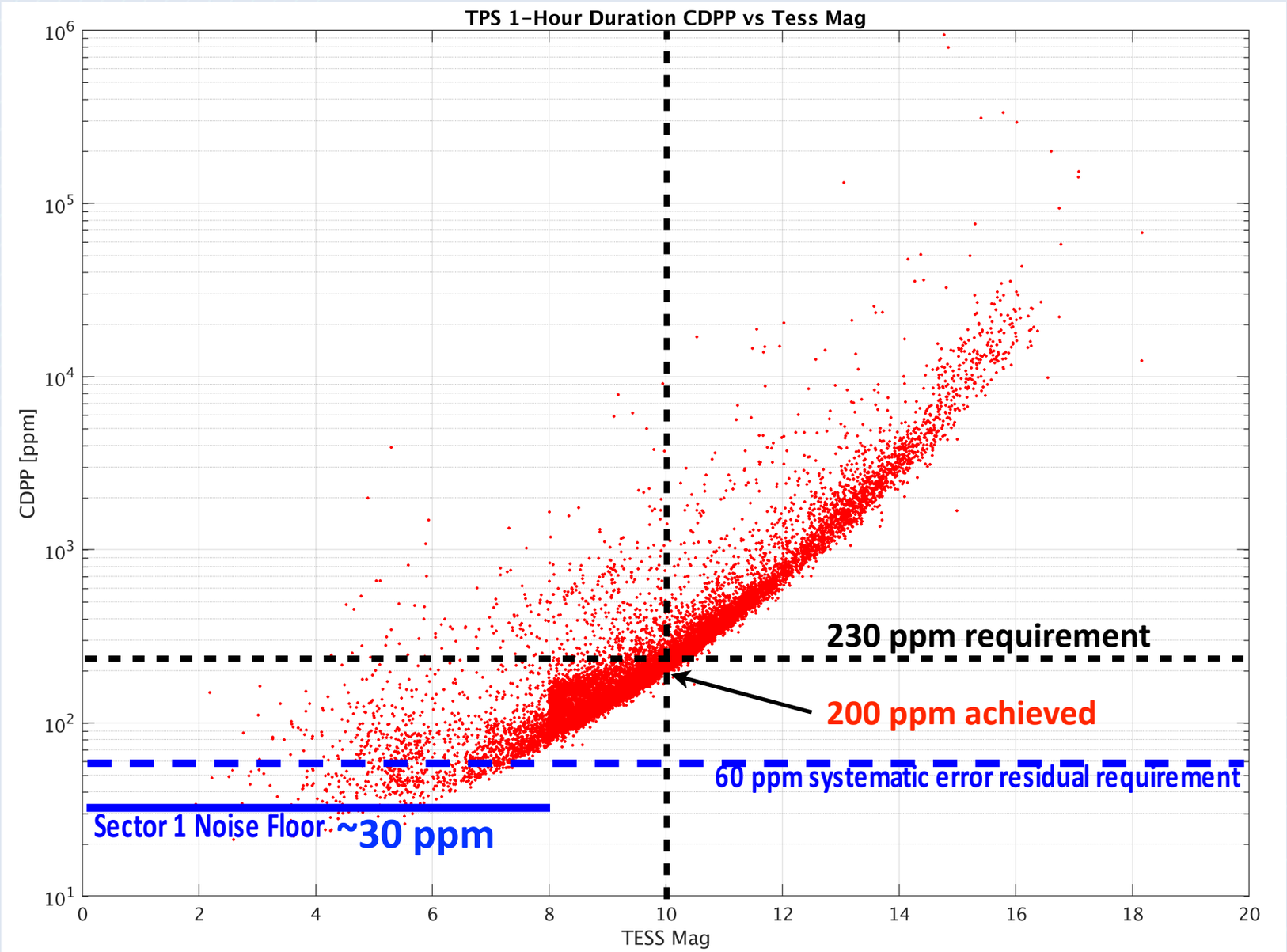
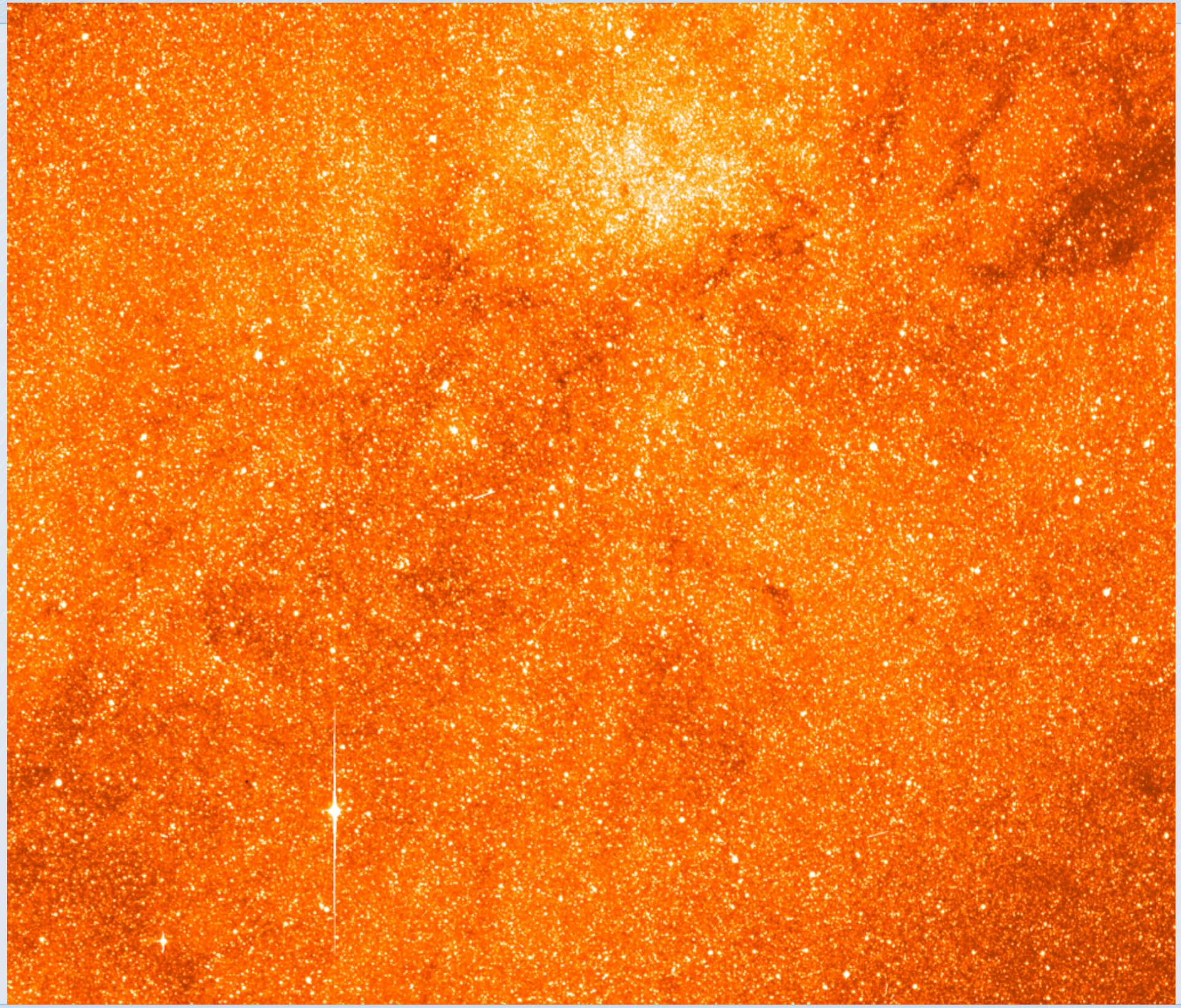


TESS "Test Image" Released on 18 May 2018



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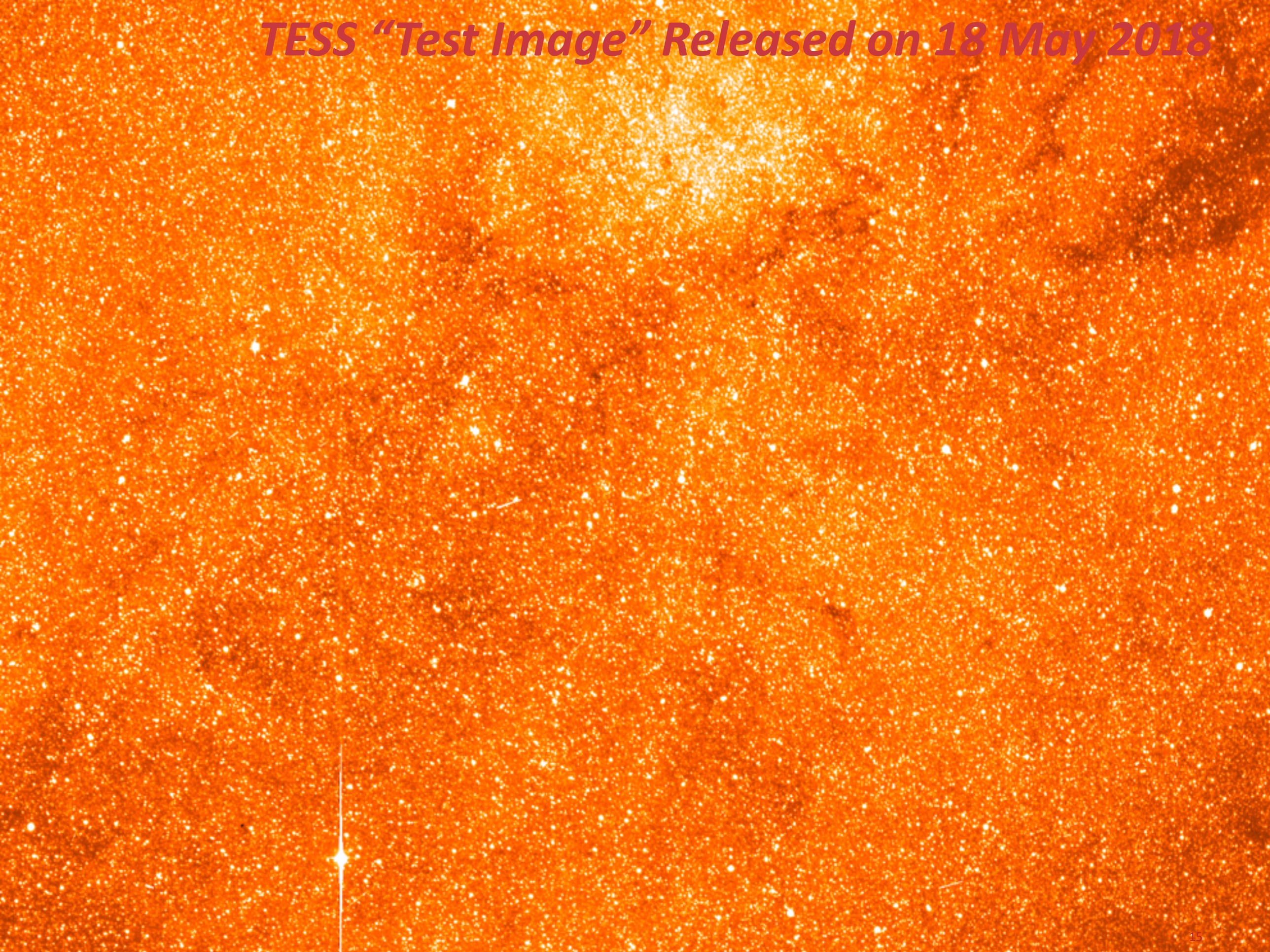
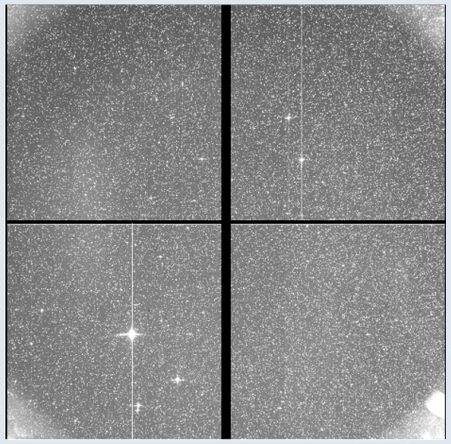


Image PSF Varies Over FOV as Modeled



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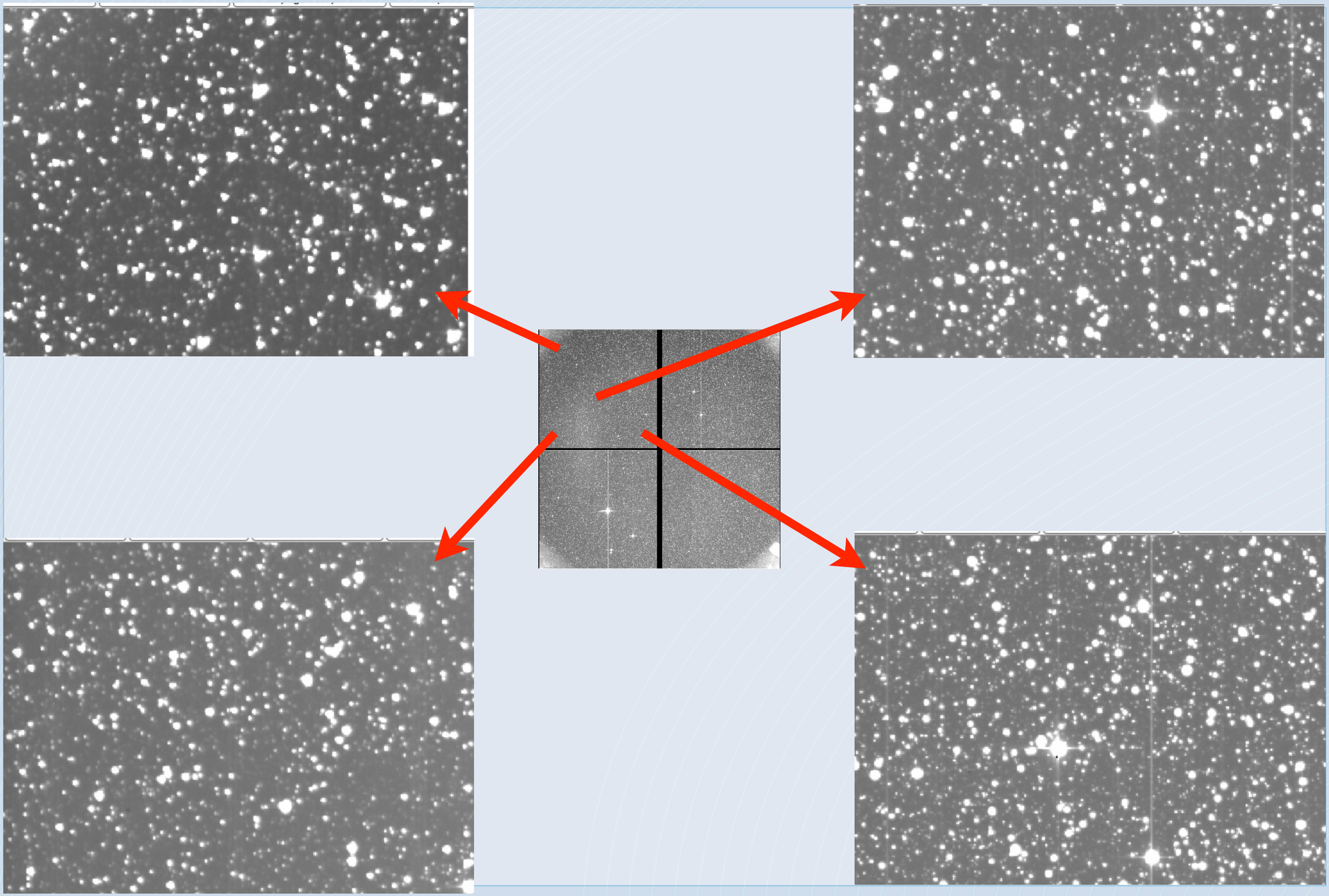

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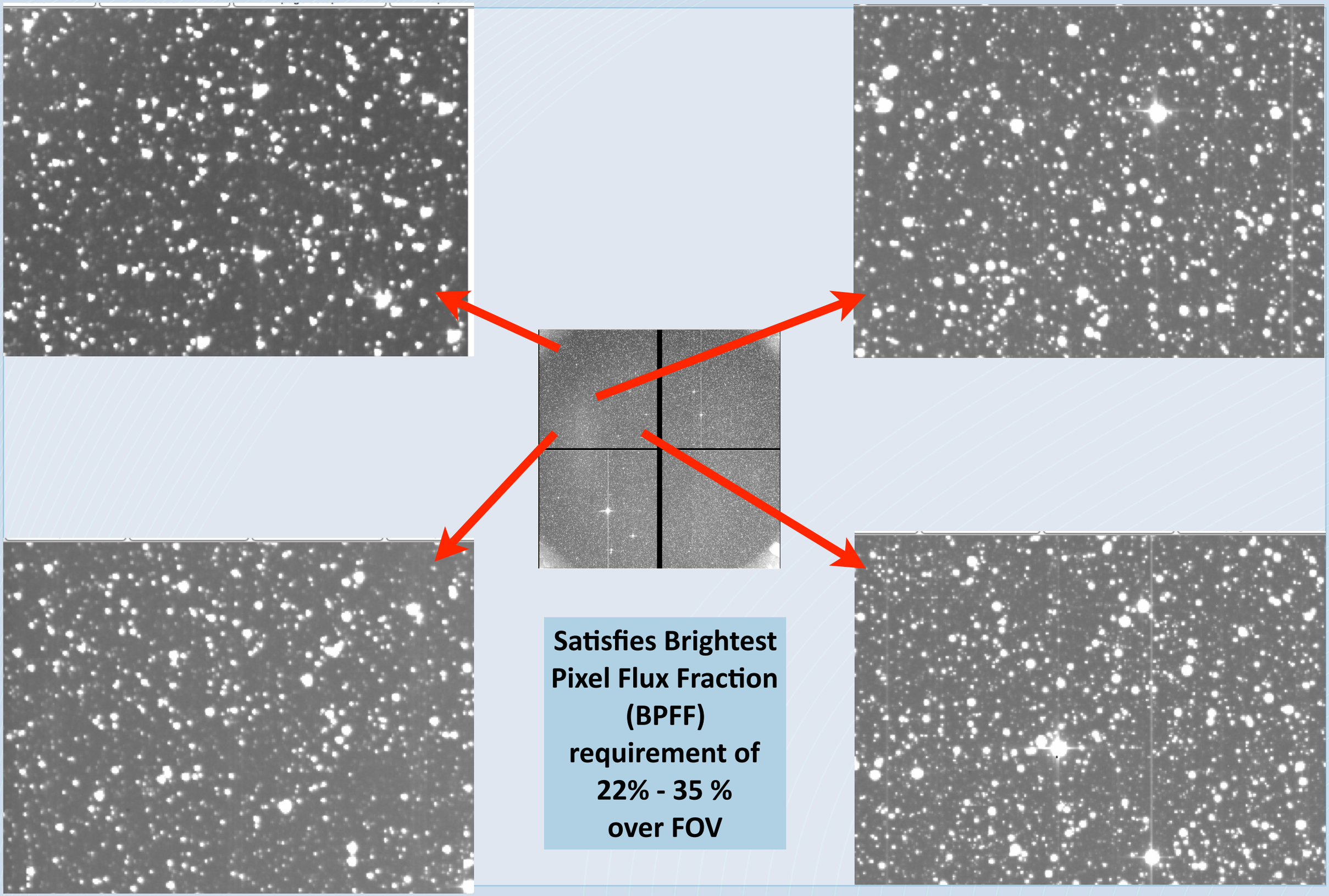
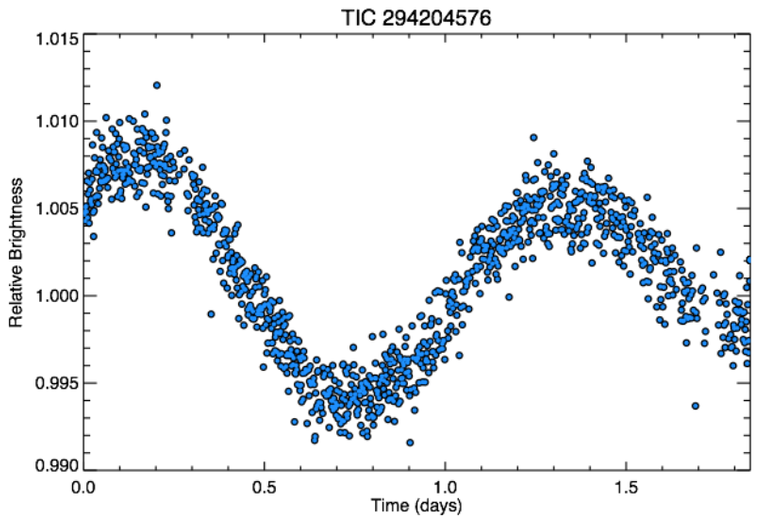


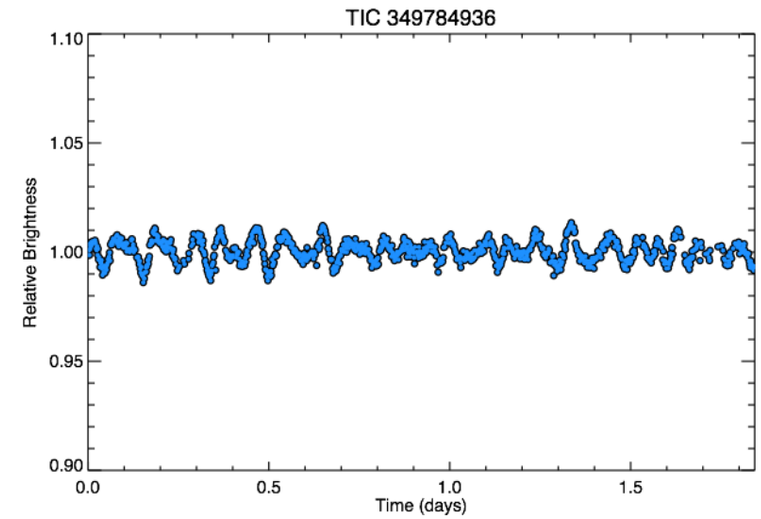
Satisfies Brightest Pixel Flux Fraction (BPFF) requirement of 22% - 35 % over FOV

Commissioning: Sub-mmag Variability Evident in >10^4 Stars

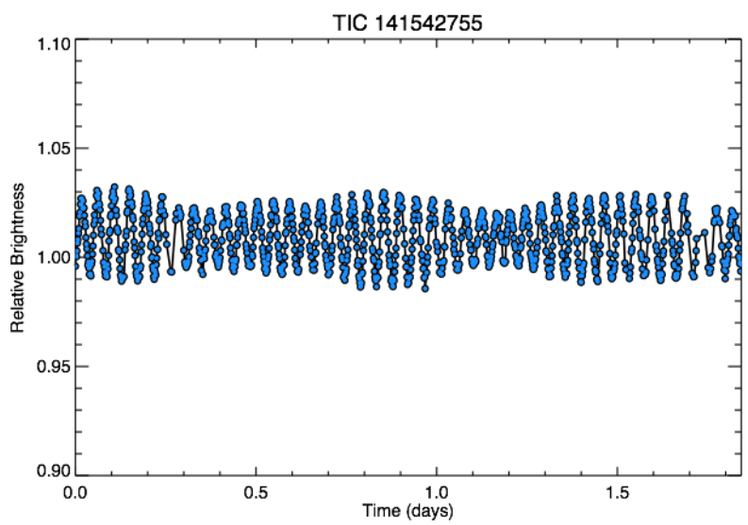


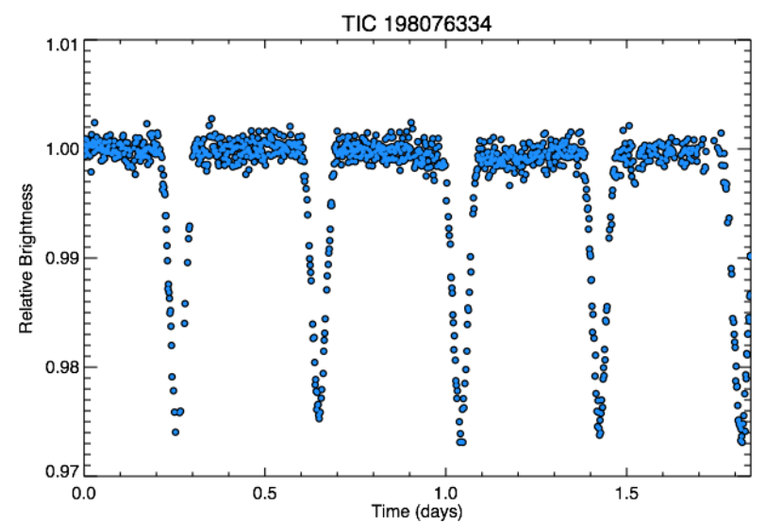
⇐ **Spotted Star?**

Pulsator: ⇐
γ Dor?



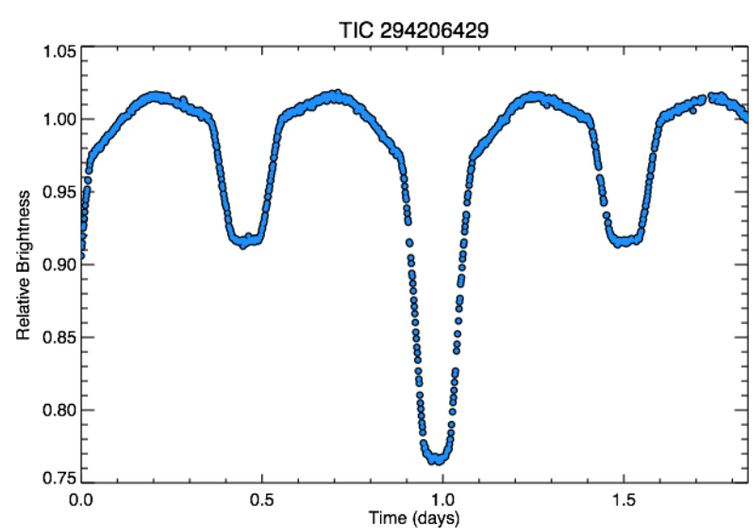
Pulsator: ⇐
γ Dor?
∂ Scuti?





⇐ **Eclipsing Binary**
+
Background Star
Blend?

Eclipsing Binary ⇐
+
Background Star
Blend?



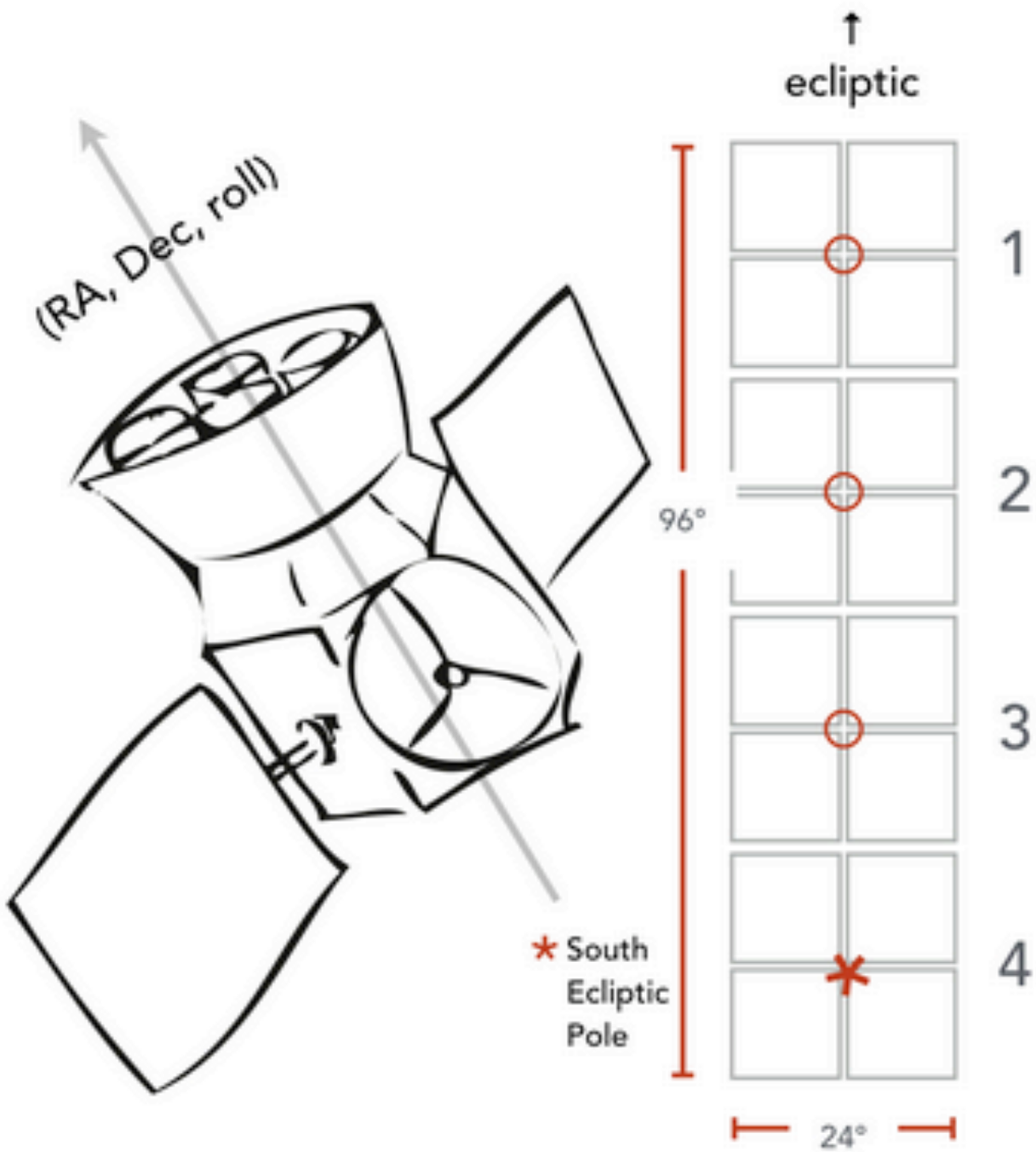
All examples shown were observed at same pointing and same epoch

MIT Quick Look Pipeline:
Xu Huang & Andrew Vanderburg

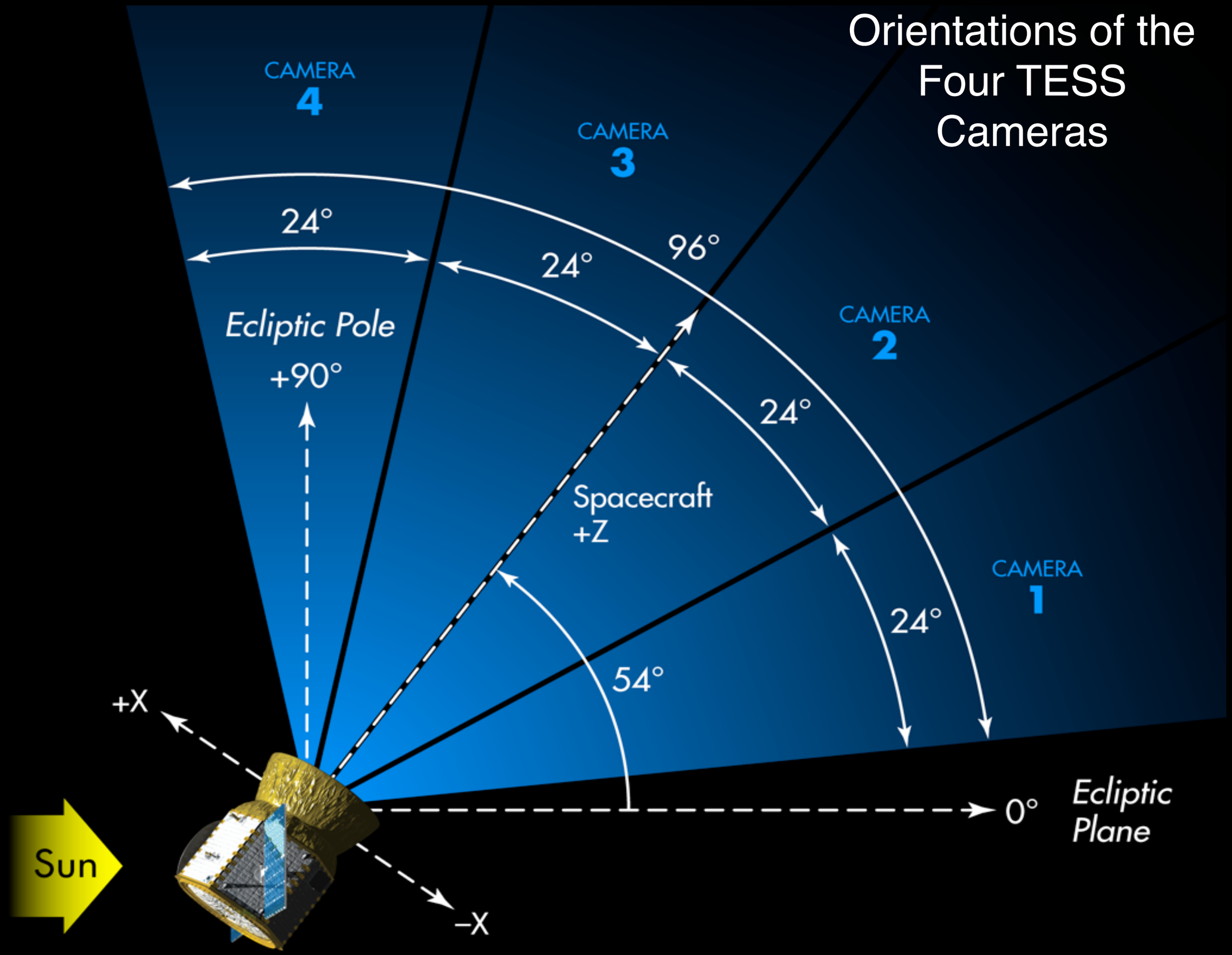
Commissioning Completed:
24 July 2018

TESS Science Survey Began:
25 July 2018

TESS Year 1: Southern Hemisphere



Orientations of the Four TESS Cameras



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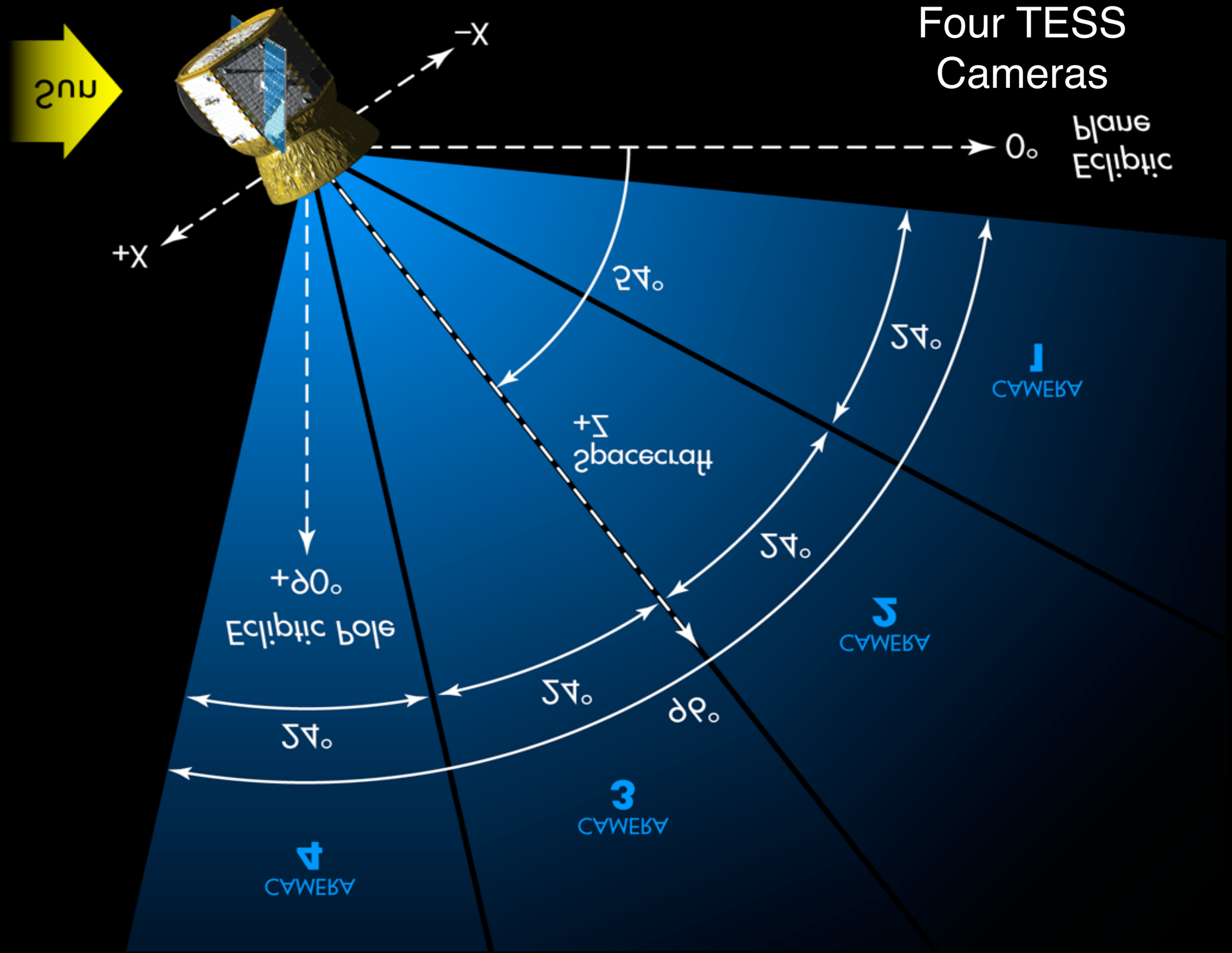
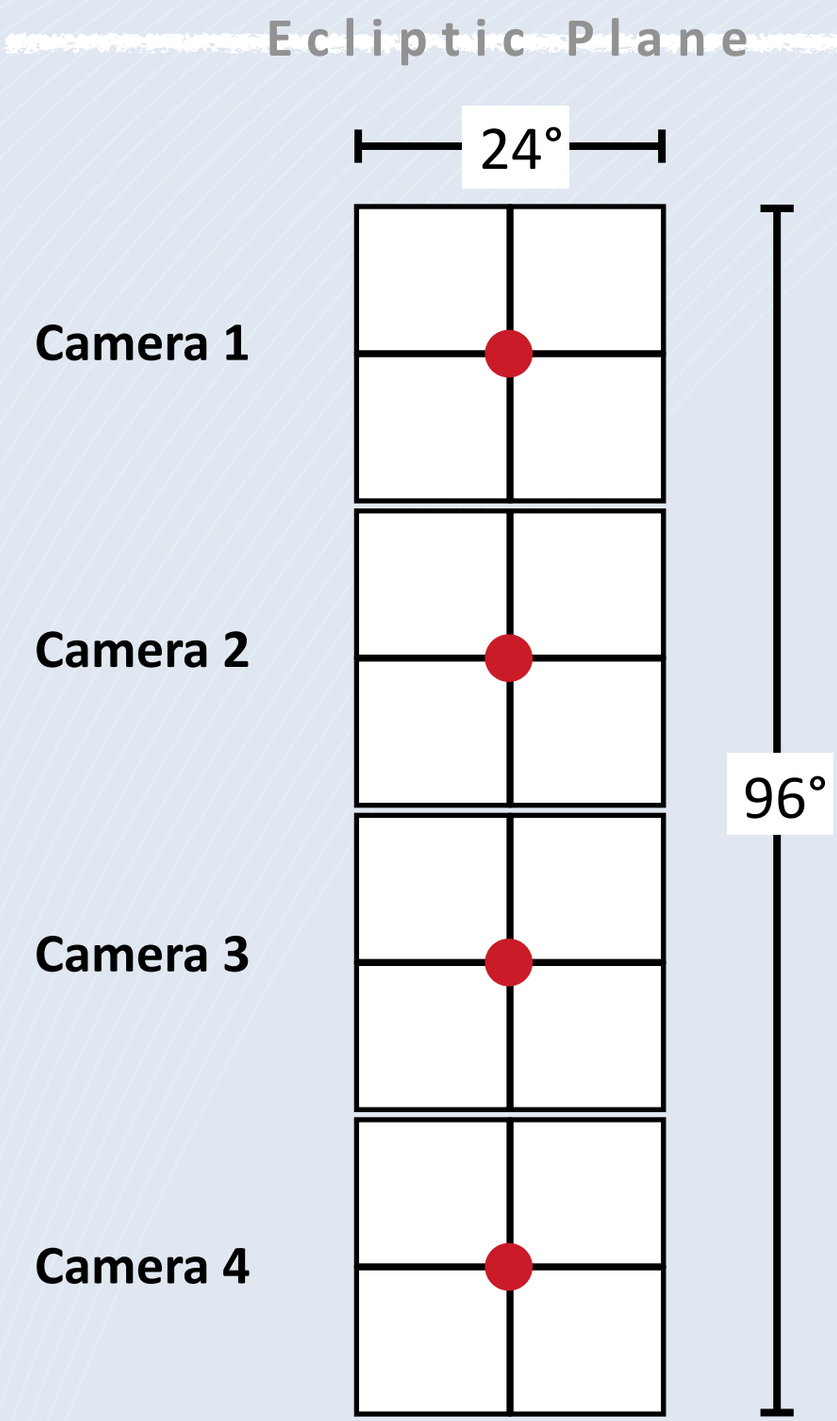


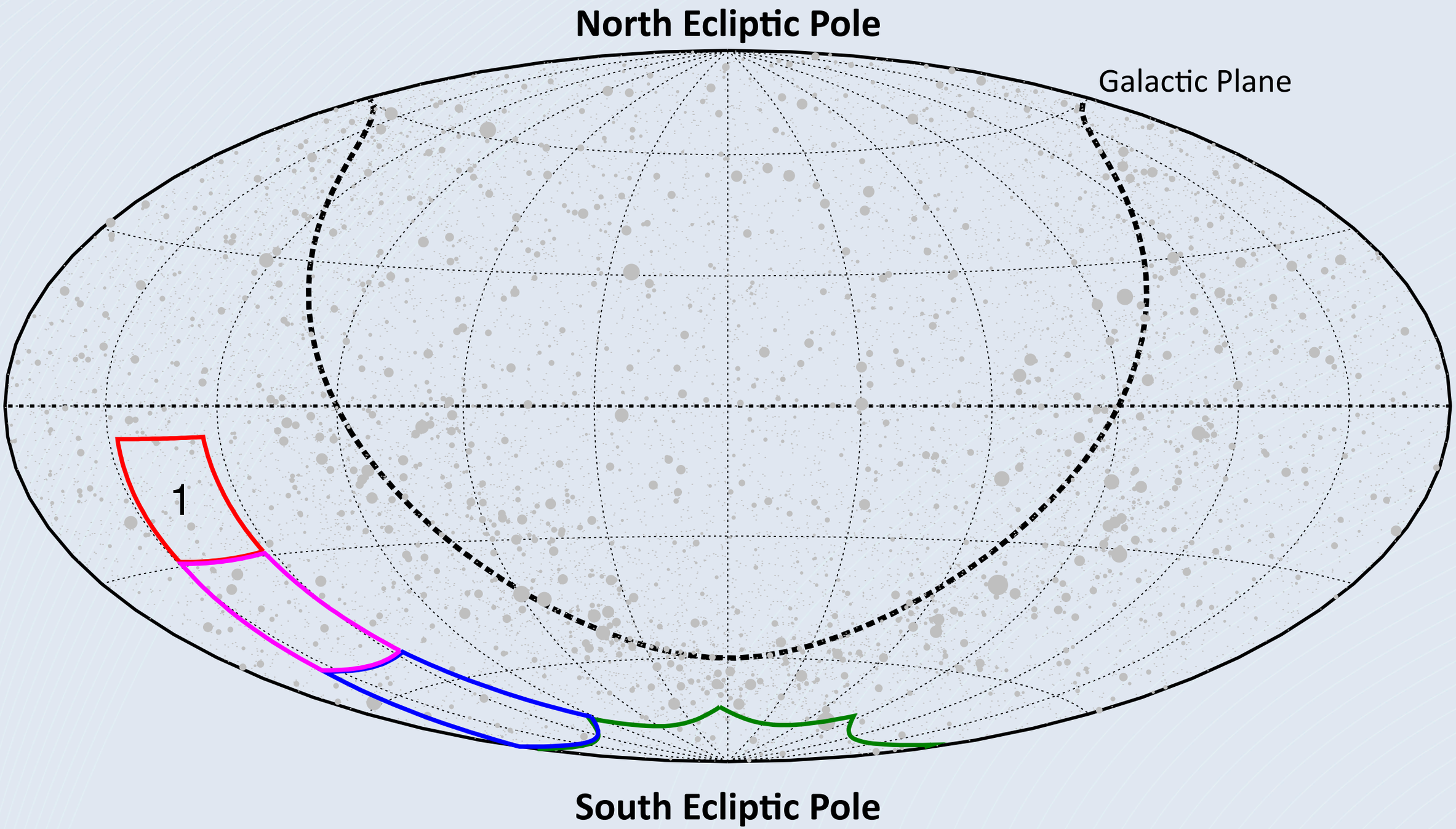
TESS Camera Configuration for Science Sector #1



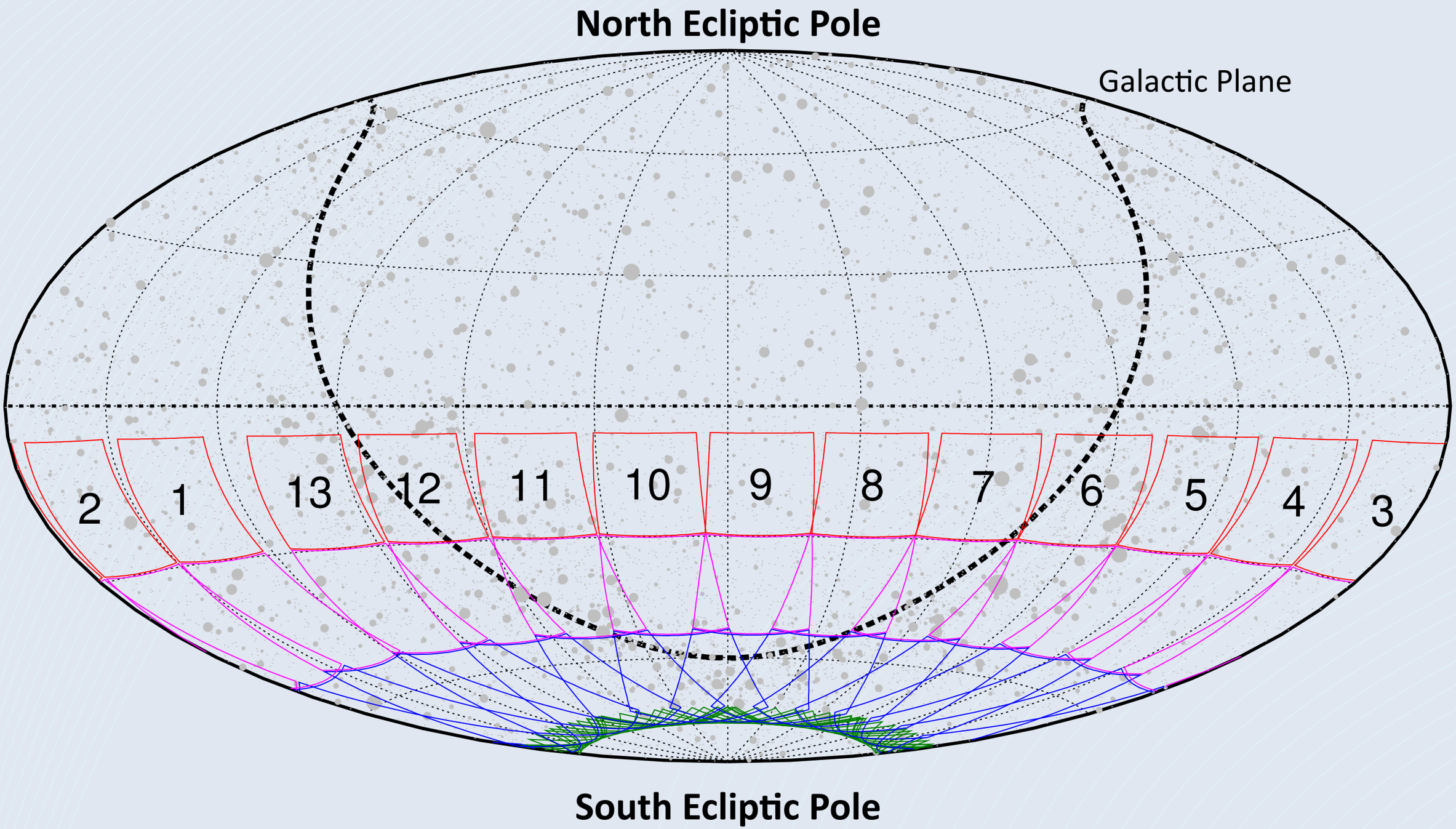
- Sector 1 commenced:
  - *25 July 2018 at 23h UTC*
- Sector 1 completed:
  - *23 August 2018 at 14h UTC*

TESS Camera Number	Camera FOV Center (Ecliptic Coordinates)	
	Lambda	Beta
1	315.8	-18.0
2	315.8	-42.0
3	315.8	-66.0
4	315.8	-90.0

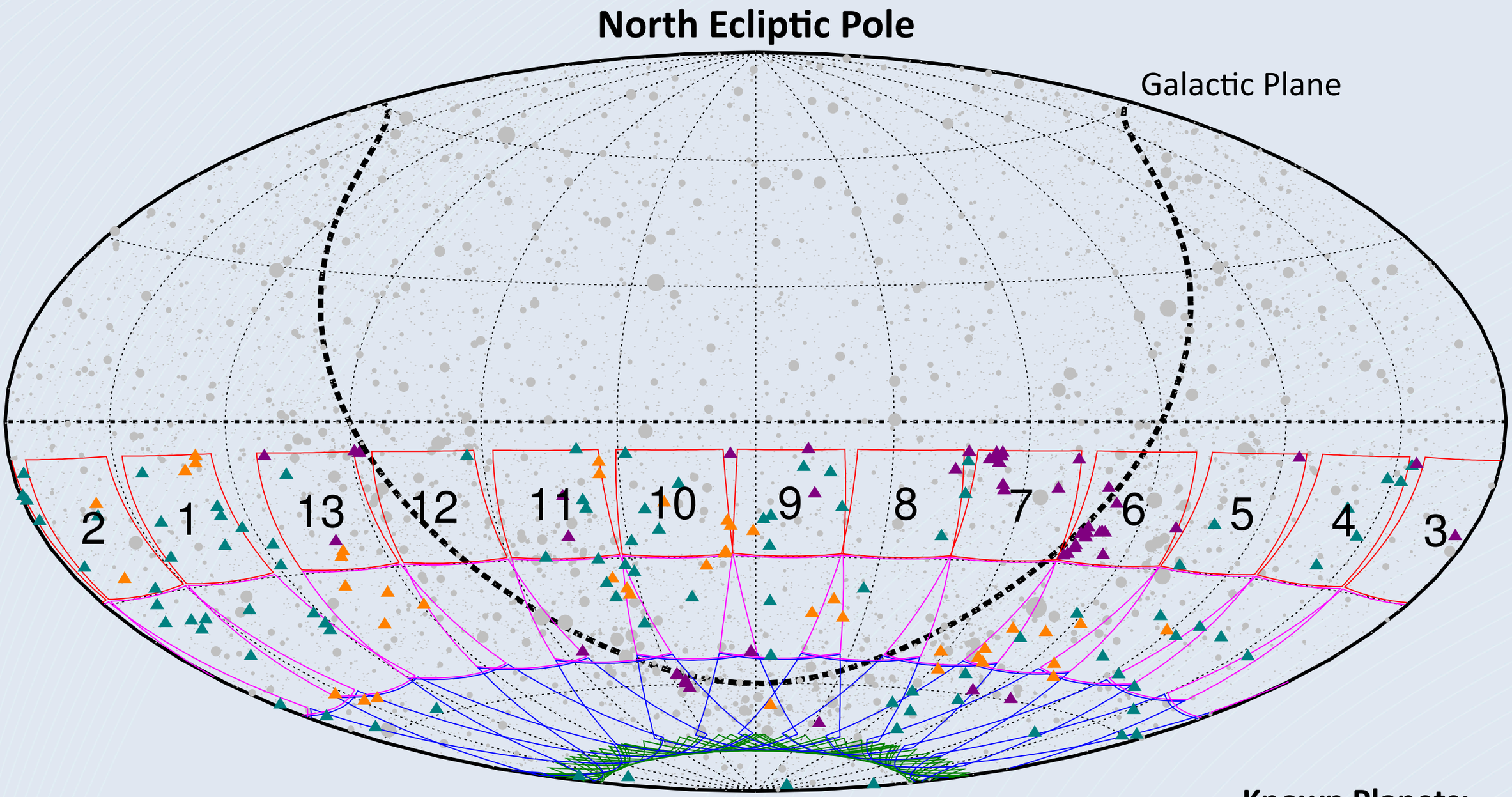
Science Sector #1: Ecliptic Coordinates



All Year 1 Science Sectors: Ecliptic Coordinates



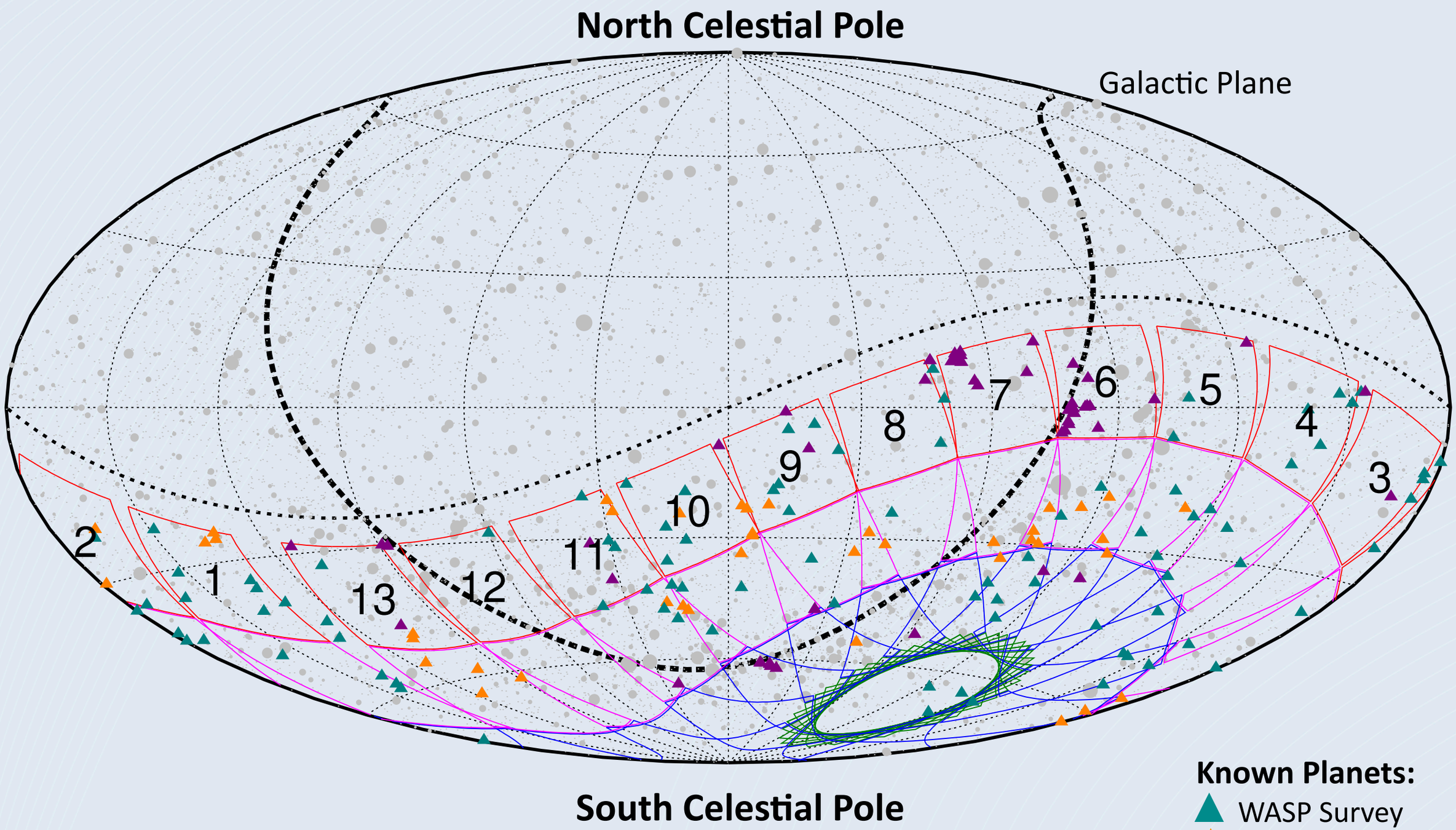
All Year 1 Science Sectors: Ecliptic Coordinates



Known Planets:

- WASP Survey
- HATS Survey
- Other Surveys

All Year 1 Science Sectors: Celestial Coordinates



Figures: Andras Pal

TESS Sectors Completed to Date

Schedule of Observations

The table below contains details of sector observations. *Note that all future sector pointings are preliminary and may change.*

Sector	Start	End	Orbit IDs	Camera 1 (RA, Dec)	Camera 2 (RA, Dec)	Camera 3 (RA, Dec)	Camera 4 (RA, Dec)
✔ 1	Jul 18 2018	Aug 22 2018	9, 10	324.6, -33.2	338.6, -55.1	19.5, -72.0	90.0, -66.6
✔ 2	Aug 23 2018	Sep 20 2018	11, 12	352.1, -23.1	5.7, -44.3	33.4, -62.2	90.0, -66.6
✔ 3	Sep 21 2018	Oct 17 2018	13, 14	17.2, -12.2	28.5, -33.9	47.4, -53.9	90.0, -66.6
4	Oct 19 2018	Nov 15 2018	15, 16	41.8, -2.8	49.9, -25.5	61.9, -47.5	90.0, -66.6

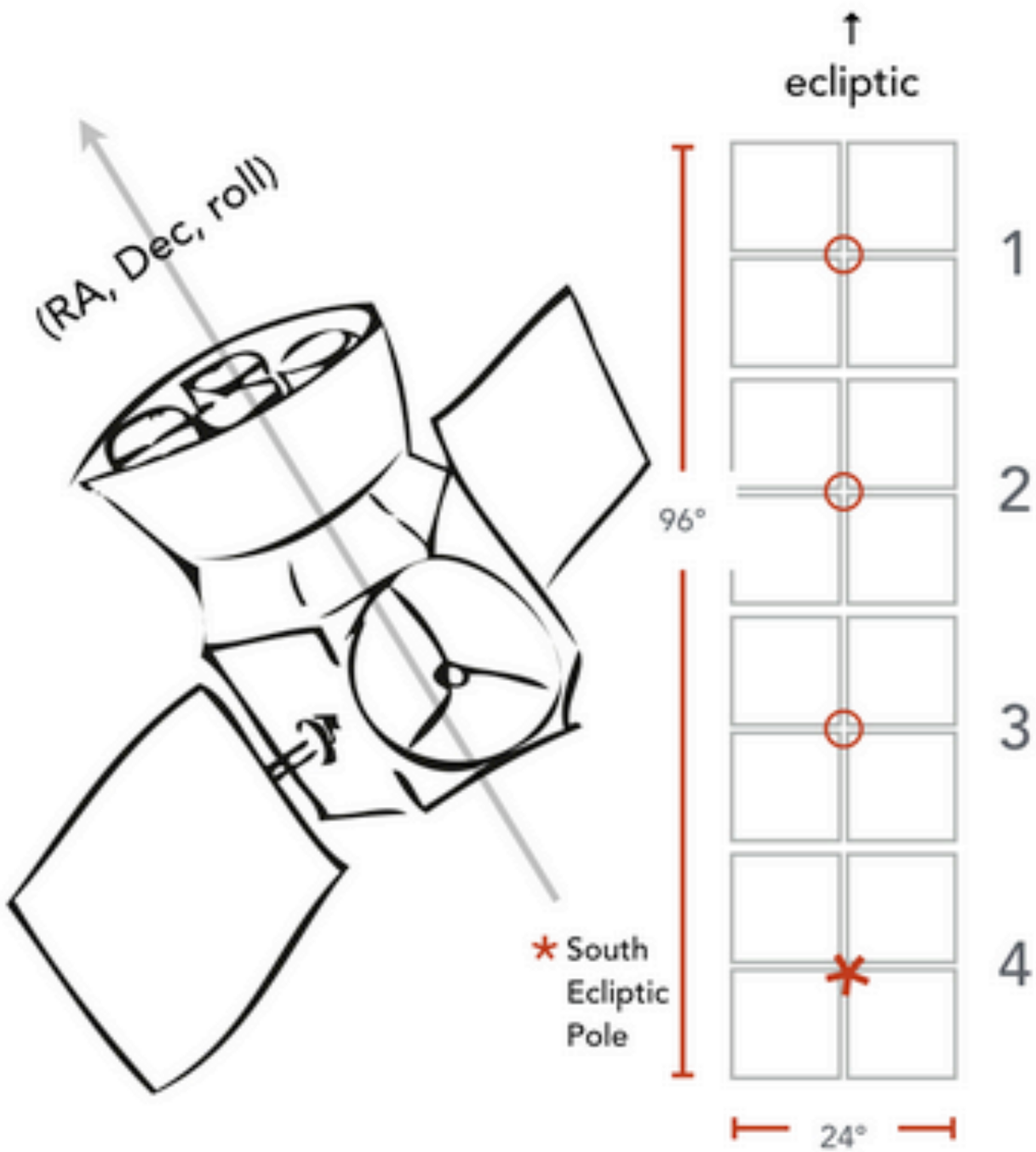
Underway Now

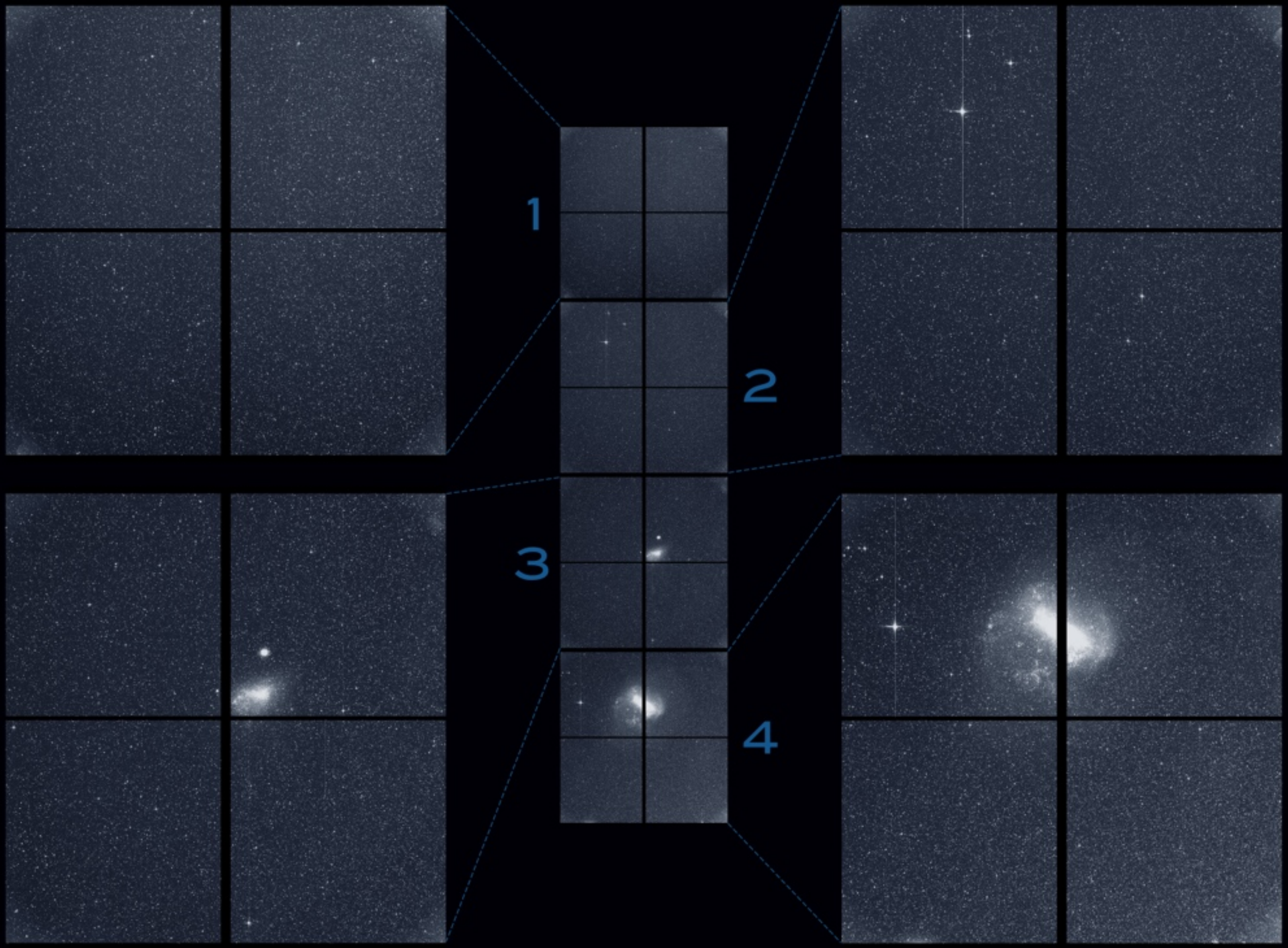
Four Camera “First Light”

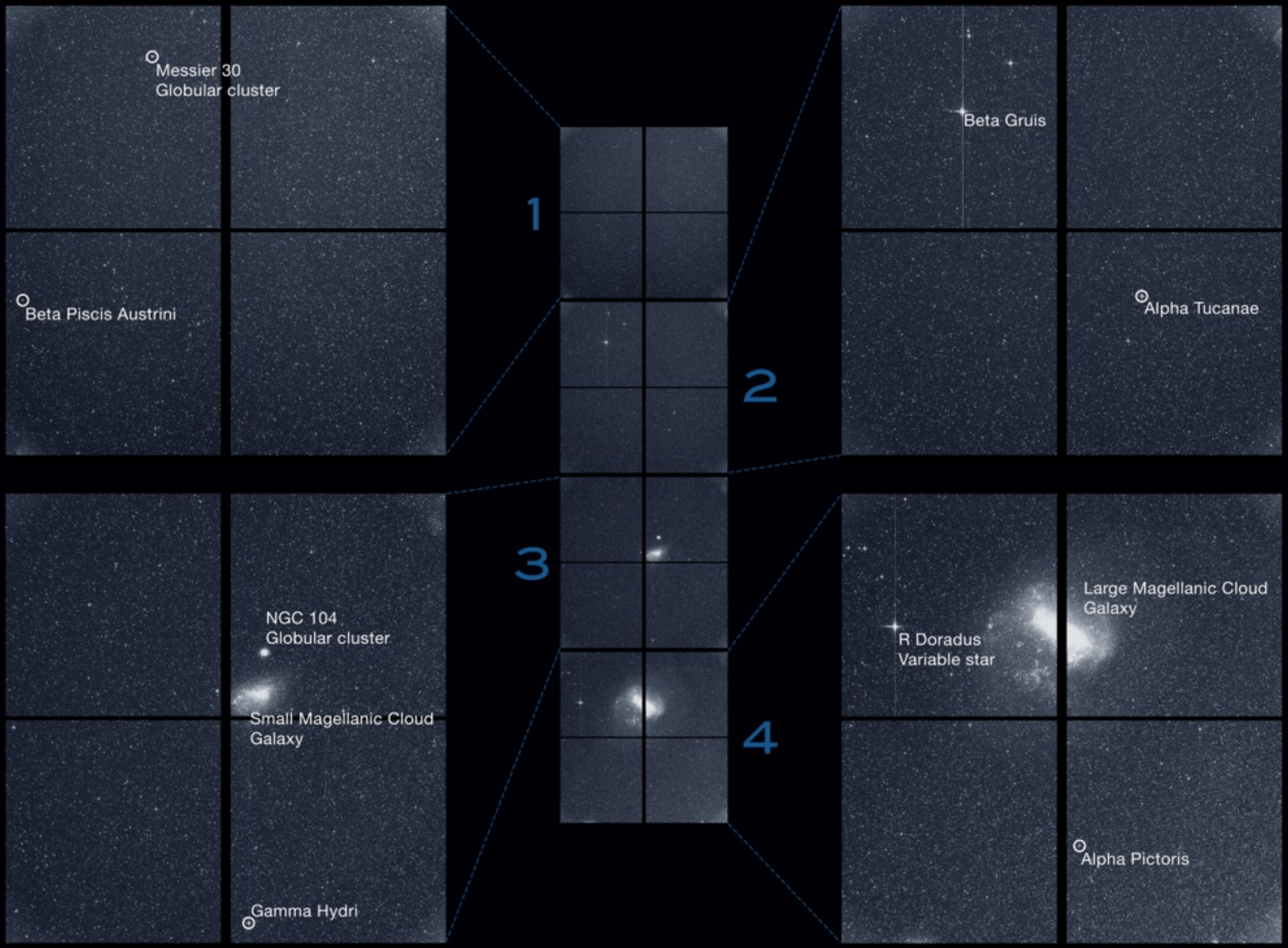
30 min FFI in Sector 1

(1 of ~1200 Images)

TESS Year 1: Southern Hemisphere




1
2
3
4


Messier 30
Globular cluster
Beta Piscis Austrini
1
Beta Gruis
Alpha Tucanae
2
NGC 104
Globular cluster
Small Magellanic Cloud
Galaxy
Gamma Hydri
3
R Doradus
Variable star
Large Magellanic Cloud
Galaxy
4
Alpha Pictoris

Scattered Light in TESS Images

- Scattered light from the bright Earth and Moon was always anticipated for certain viewing conditions
  - *Original proposal predicted Camera 1 and sometimes Camera 2 would be affected for periods of days during certain observation sectors*

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  - *Design goal was to reduce scattered light from Earth by 10^7 at angles >35°-37° from camera boresights*
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  - *Measurements of actual lens hood performance conducted on orbit*
    - *Approx 5%-10% of sky solid angle in Sectors 1 and 2 exhibit variable scattered light levels 2-6x higher than expected for sum of zodiacal light + CCD readout noise*

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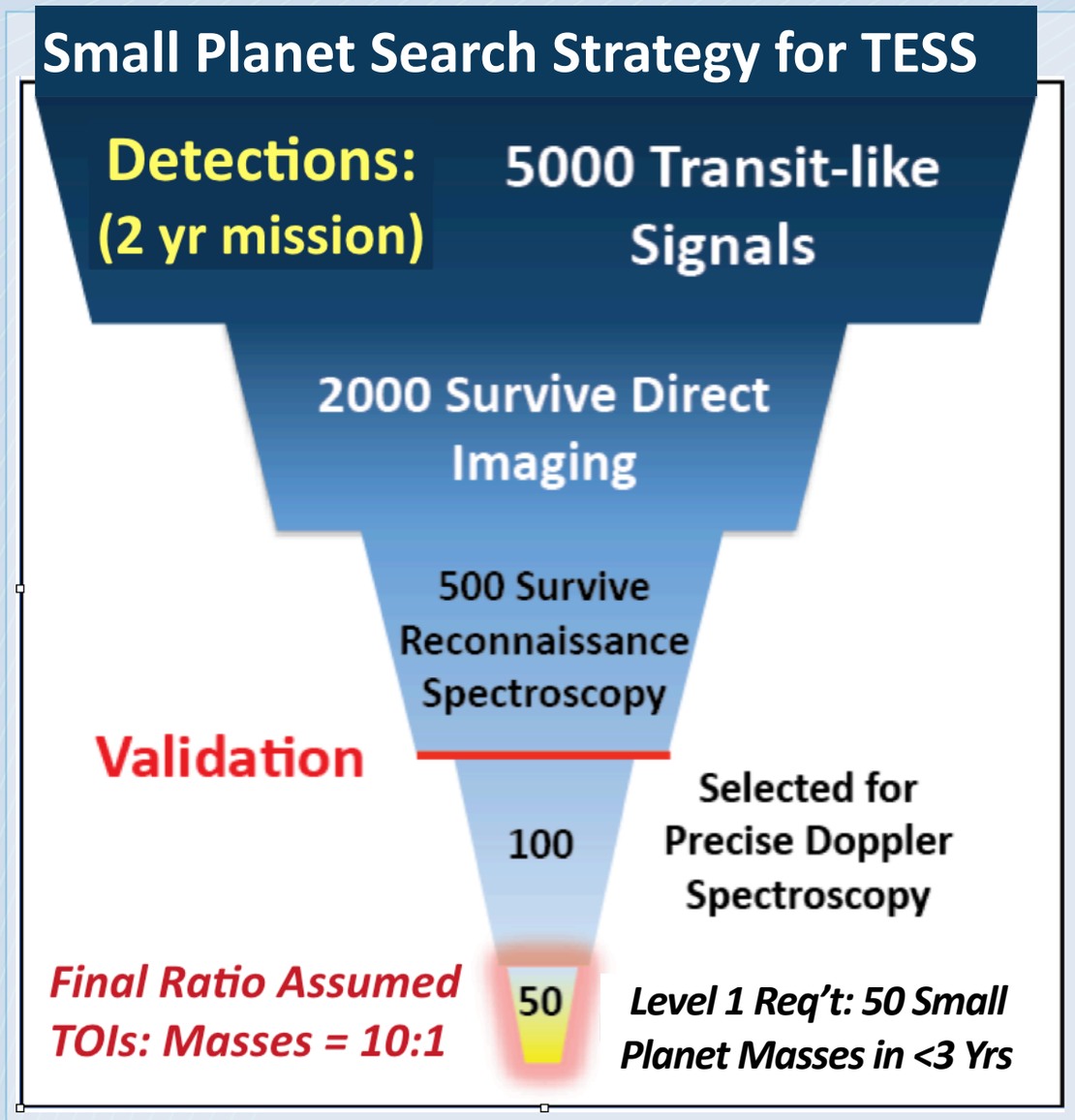
- Lab measurements of flight spare lens hood in progress at MIT
  - *Will provide additional quantitative guidance as to when/where in camera FOVs observers can expect scattered light to be present in TESS images*

TESS Alerts Enable Rapid Followup for Planet Candidates



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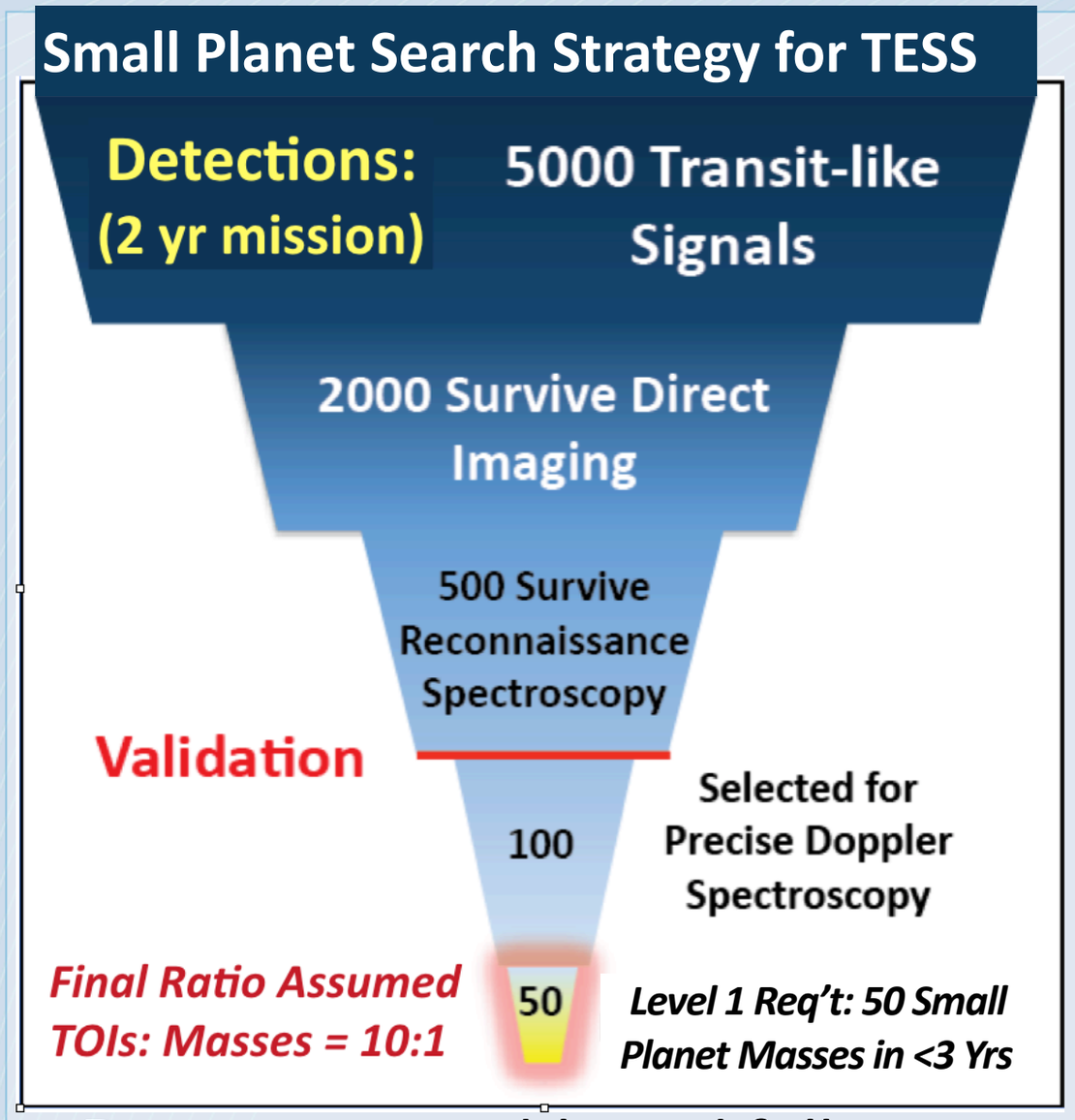

- **Prompt** ground-based follow-up program req'd to establish TESS objects as small (<4 R_E) exoplanets
  - ➡ *Imaging (Direct & AO)*
  - ➡ *Recon Spectroscopy*
  - ➡ *PRV Spectroscopy*

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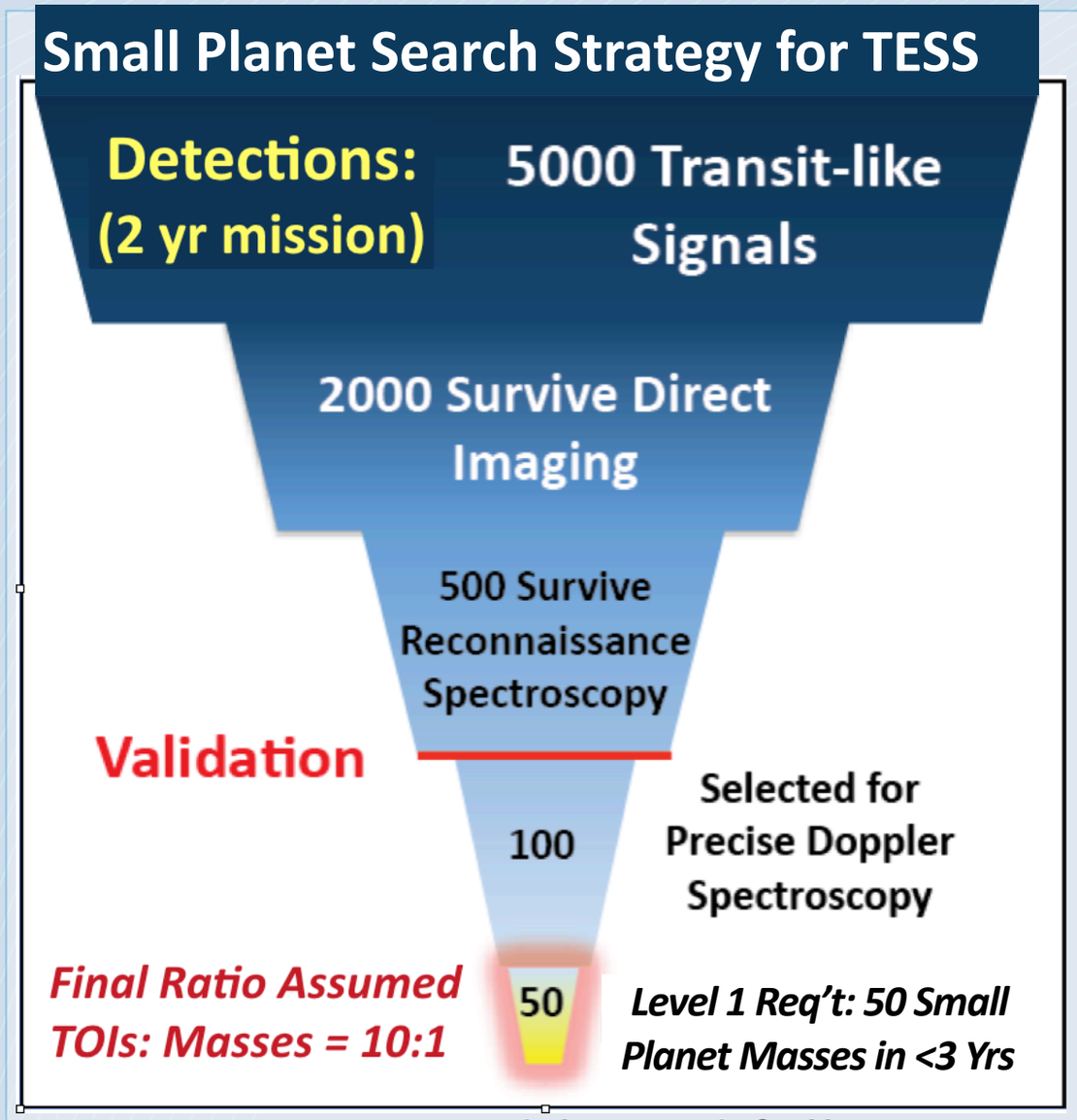

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  - ***73 Alerts*** *posted on* ***5 September*** *at* ***tess.mit.edu/alerts***
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  - **Four publications** *on astro-ph already*
  - *Will include time-sensitive astrophysical events*

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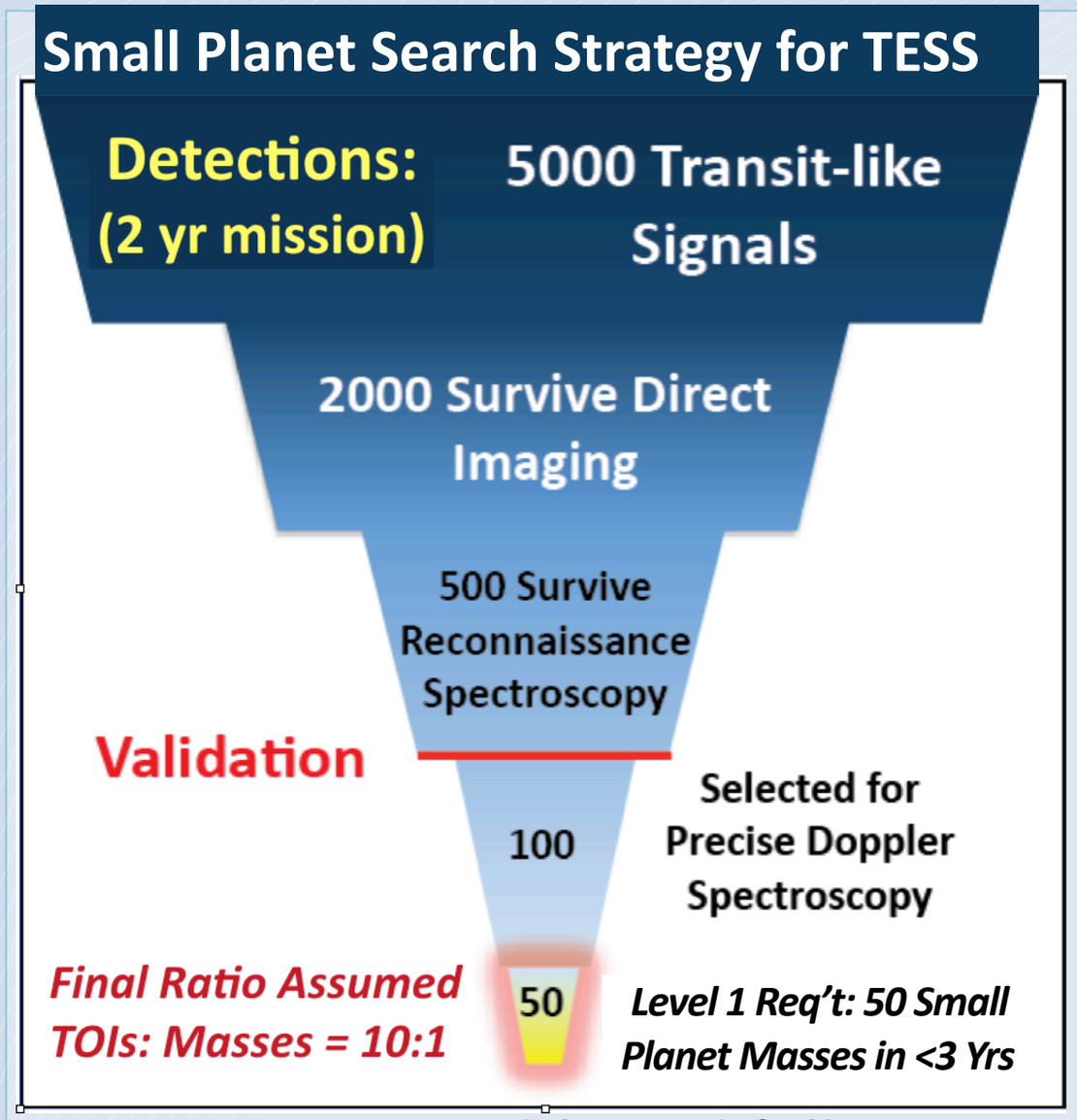

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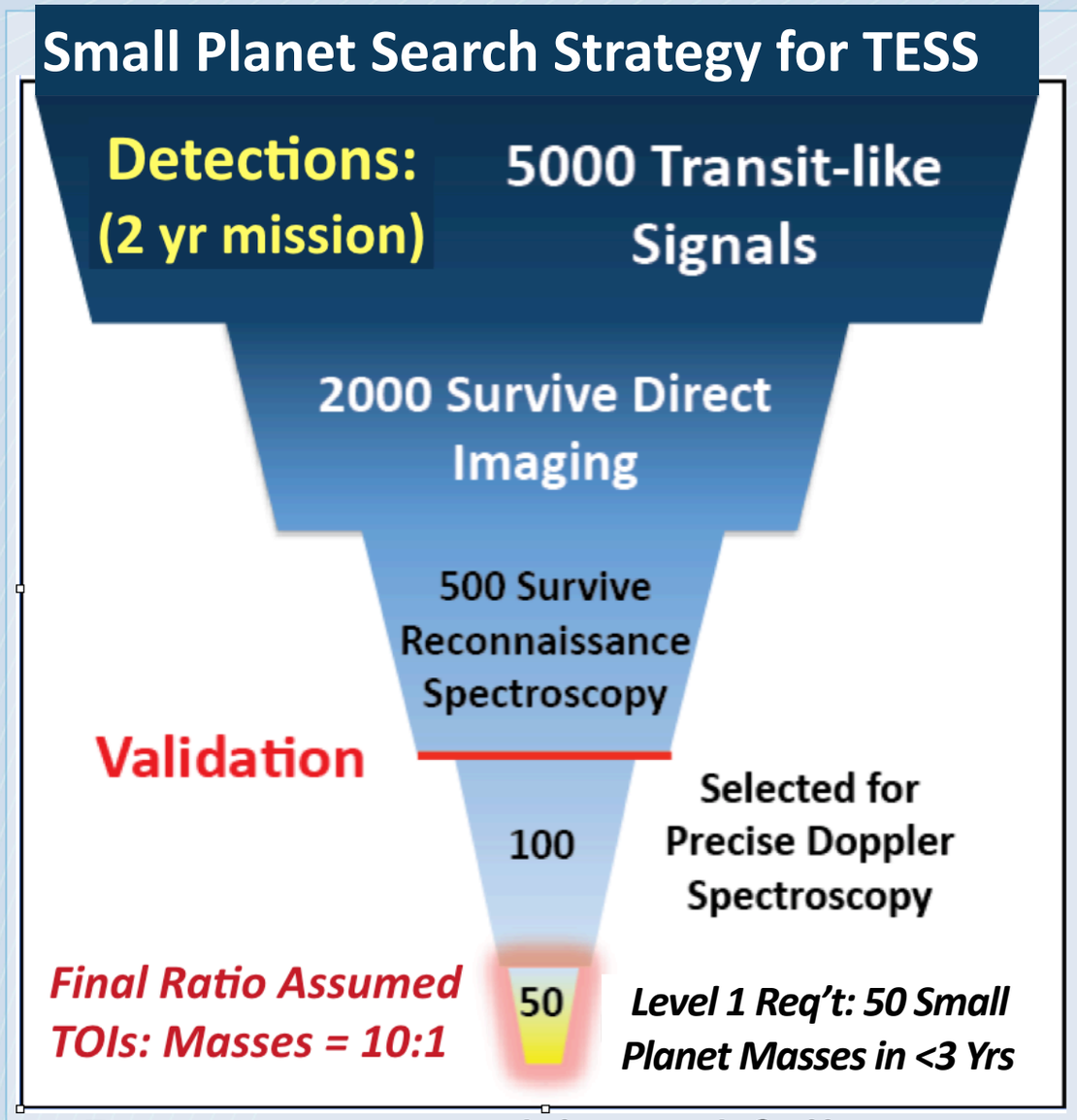

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  - *Public release of TESS Alerts thereafter*

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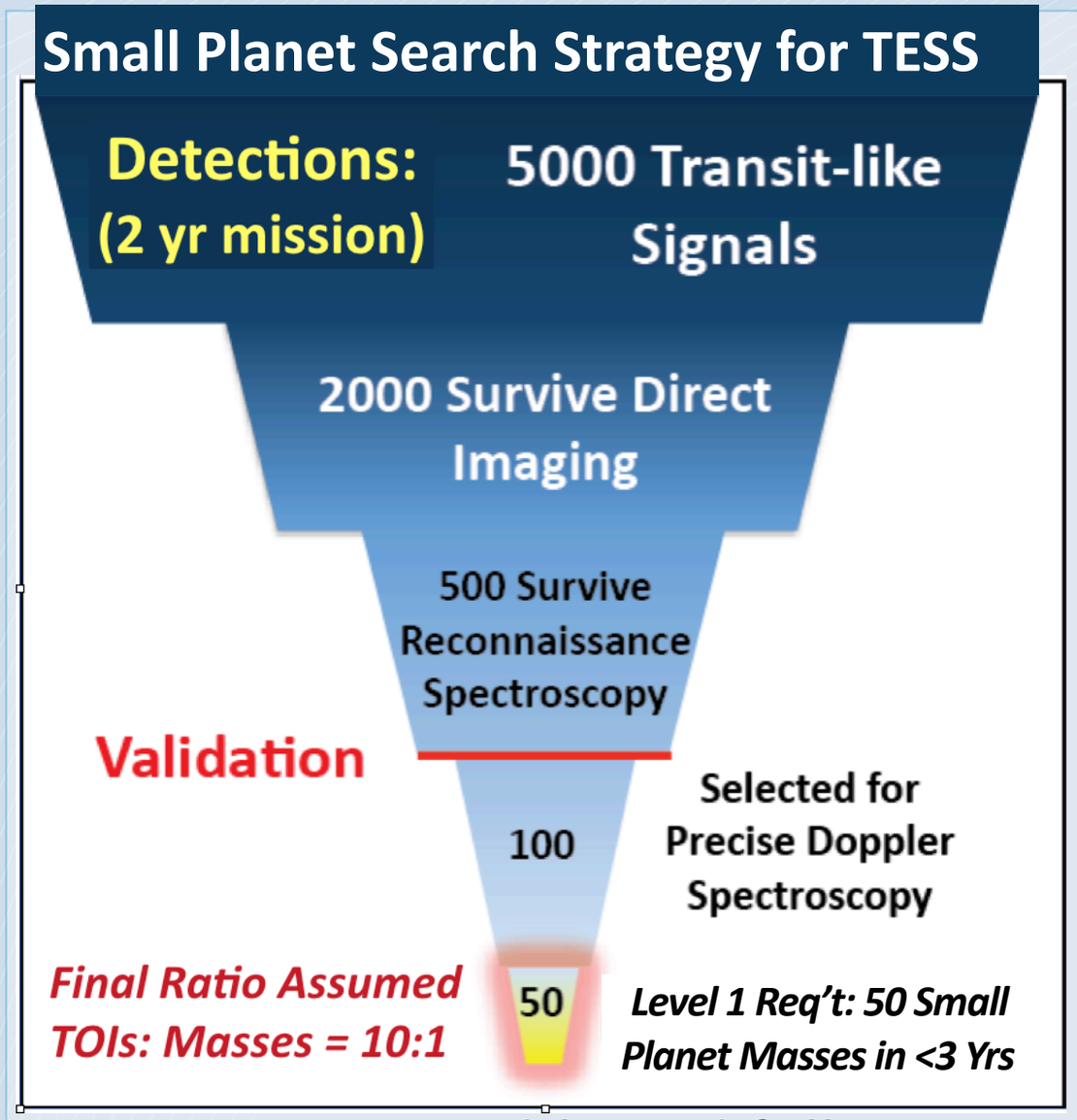

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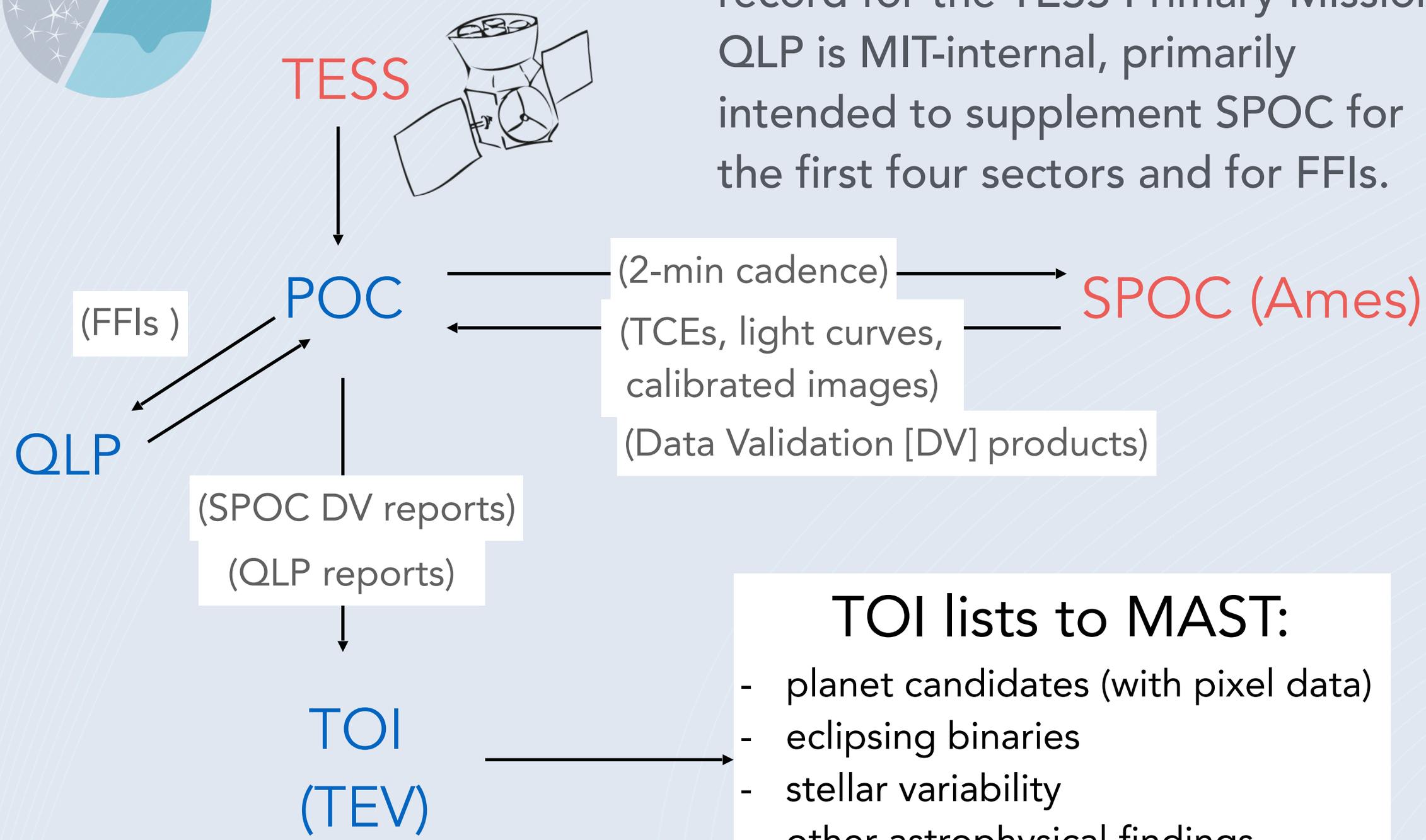
- TESS Deliveries to MAST:
  - *Now: SPOC postage stamps for Alerts as they occur*
  - *Soon: Preliminary FFIs by Late November*

Initial Processing of TESS Transit-like Signals

SPOC (Ames) is the pipeline of record for the TESS Primary Mission. QLP is MIT-internal, primarily intended to supplement SPOC for the first four sectors and for FFIs.



TOI lists to MAST:

- planet candidates (with pixel data)
- eclipsing binaries
- stellar variability
- other astrophysical findings

TESS Alerts Web Page for Science Sector #1

George | Alerts | All Types | All Deliveries | CSV | +

Show 25 entries Search:

tic_id	toi_id	dsp	RA	Dec	Tmag	Rp	Period	Duration	Transit Depth	src
261136679	00144.01	PC	84.29120	-80.46914	5.10	1.86	6.27	3.09	249	spoc
394137592	00120.01	PC	4.44641	-66.35898	7.14	12.2	11.5	8.56	2.39e+3	spoc
403224672	00141.01	PC	338.98461	-59.86449	7.36	1.97	1.01	1.53	220	spoc
263003176	00130.01	PC	12.54118	-83.74396	7.43	2.36	14.3	4.65	411	spoc
391949880	00128.01	PC	79.52248	-80.96466	7.90	2.77	4.94	2.20	399	spoc
290131778	00123.01	PC	319.69940	-26.61608	8.80	7.72	3.31	5.63	3.18e+3	spoc
129637892	00155.01	PC	321.11497	-37.85014	9.00	18.4	5.44	5.97	8.23e+3	qlp
266980320	00118.01	PC	349.55684	-56.90388	9.15	4.93	6.04	2.12	1.70e+3	spoc
234994474	00134.01	PC	350.03130	-60.06520	9.17	1.58	1.40	1.26	566	spoc
267263253	00135.01	PC	7.32894	-76.30408	9.21	15.9	4.13	4.49	1.01e+4	spoc
278683844	00119.01	PC	99.23798	-58.01524	9.23	2.10	5.54	2.79	631	spoc
62483237	00139.01	PC	336.40231	-34.90962	9.30	2.69	11.1	2.14	1.37e+3	spoc
144065872	00105.01	PC	337.45720	-48.00309	9.48	12.5	2.18	2.87	1.18e+4	spoc
277683130	00138.01	PC	328.92619	-61.67329	9.53	8.29	6.20	2.18	3.72e+3	spoc
92352620	00107.01	PC	313.78311	-34.13557	9.64	18.8	3.95	4.56	1.30e+4	spoc
149603524	00102.01	PC	87.13996	-63.98843	9.72	15.4	4.41	3.77	1.41e+4	spoc
235037761	00131.01	PC	353.82677	-64.56177	9.74	12.7	6.24	1.57	9.11e+3	spoc
25375553	00143.01	PC	328.76765	-22.61257	9.77	17.6	2.31	3.42	6.94e+3	spoc
350743714	00165.01	PC	88.88593	-57.29059	9.79	18.8	7.76	3.22	8.29e+3	qlp
140068425	00140.01	PC	330.30157	-49.06003	9.81	5.07	2.28	0.860	1.08e+3	spoc
201248411	00129.01	PC	0.18710	-54.83051	9.82	9.54	0.981	0.761	7.05e+3	spoc
231670397	00104.01	PC	319.94961	-58.14888	9.85	12.7	4.09	5.59	3.59e+3	spoc
219338557	00133.01	PC	354.39574	-58.95464	9.88	2.16	8.20	2.31	946	spoc
207081058	00121.01	PC	331.86723	-41.81546	9.93	14.8	14.8	5.45	1.41e+4	spoc
389525208	00154.01	PC	313.26148	-38.59487	10.0	41.3	6.75	2.34	1.95e+4	qlp

Showing 1 to 25 of 73 entries Previous 1 2 3 Next

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TESS Alerts Web Page for Science Sector #1

George | Alerts | All Types | All Deliveries | CSV | +

Show 25 entries Search:

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149603524	00102.01	PC	87.13996	-63.98843	9.72	15.4	4.41	3.77	1.41e+4	spoc
235037761	00131.01	PC	353.82677	-64.56177	9.74	12.7	6.24	1.57	9.11e+3	spoc
25375553	00143.01	PC	328.76765	-22.61257	9.77	17.6	2.31	3.42	6.94e+3	spoc
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201248411	00129.01	PC	0.18710	-54.83051	9.82	9.54	0.981	0.761	7.05e+3	spoc
231670397	00104.01	PC	319.94961	-58.14888	9.85	12.7	4.09	5.59	3.59e+3	spoc
219338557	00133.01	PC	354.39574	-58.95464	9.88	2.16	8.20	2.31	946	spoc
207081058	00121.01	PC	331.86723	-41.81546	9.93	14.8	14.8	5.45	1.41e+4	spoc
389525208	00154.01	PC	313.26148	-38.59487	10.0	41.3	6.75	2.34	1.95e+4	qlp

Showing 1 to 25 of 73 entries Previous 1 2 3 Next

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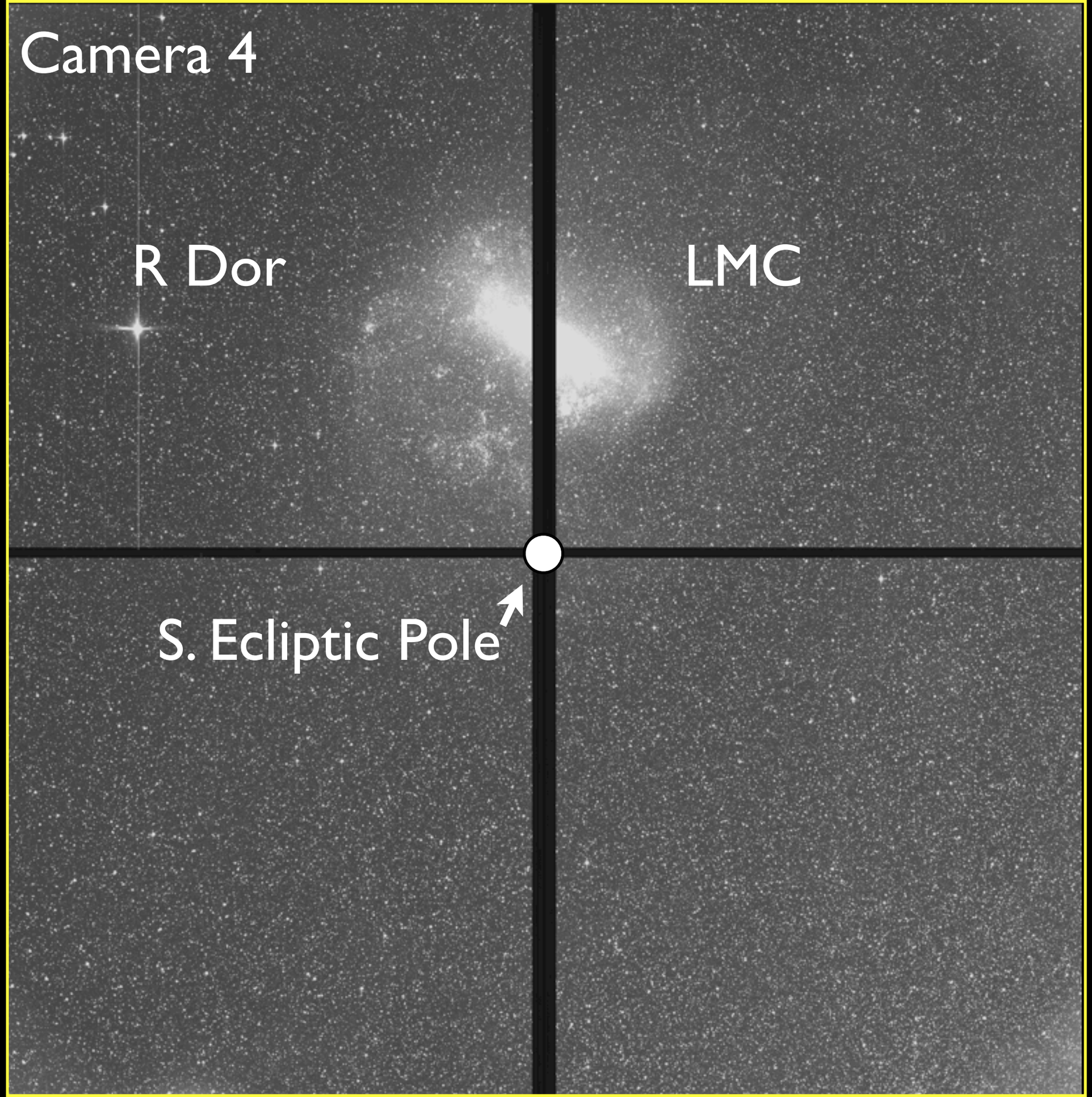
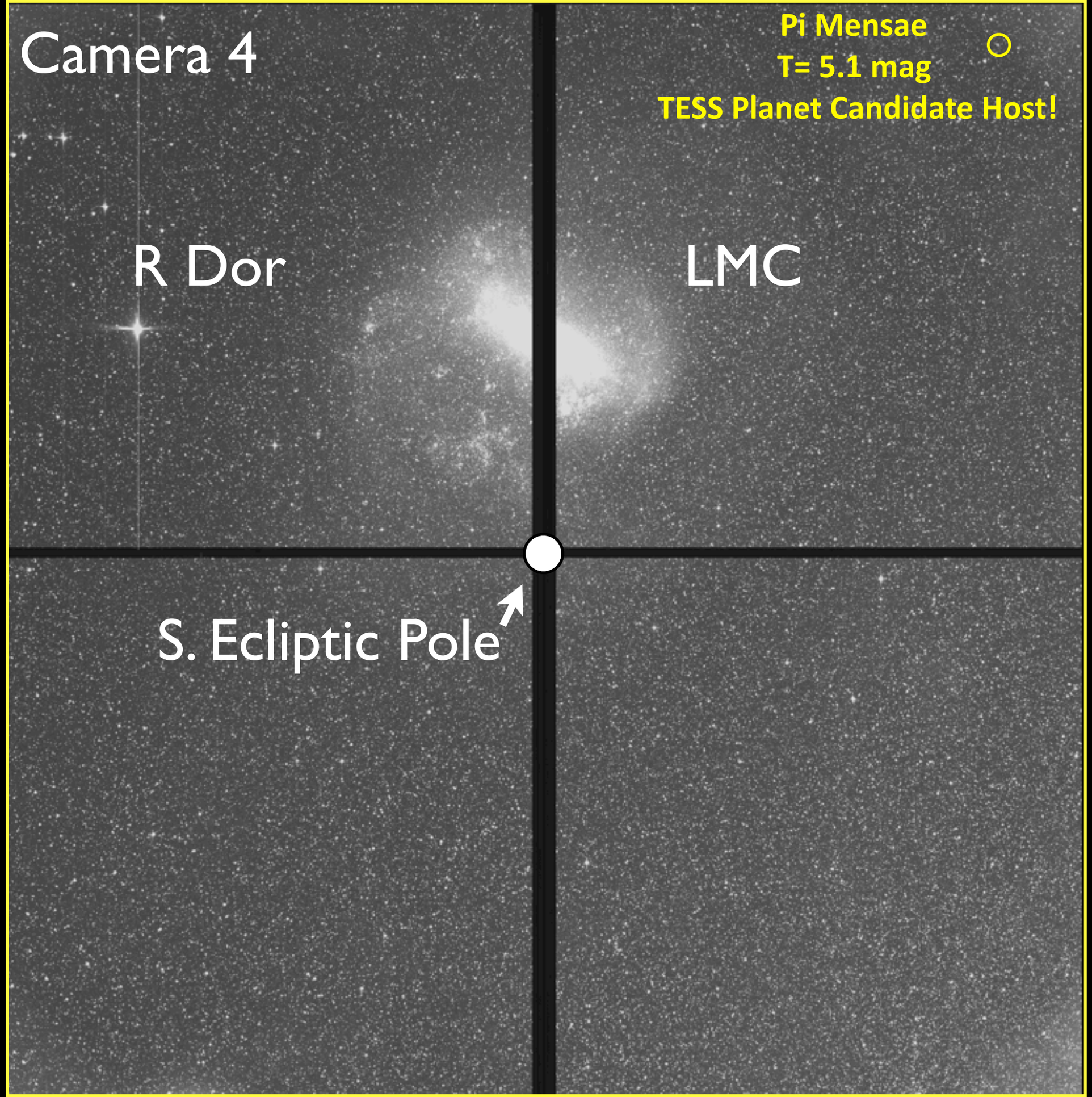
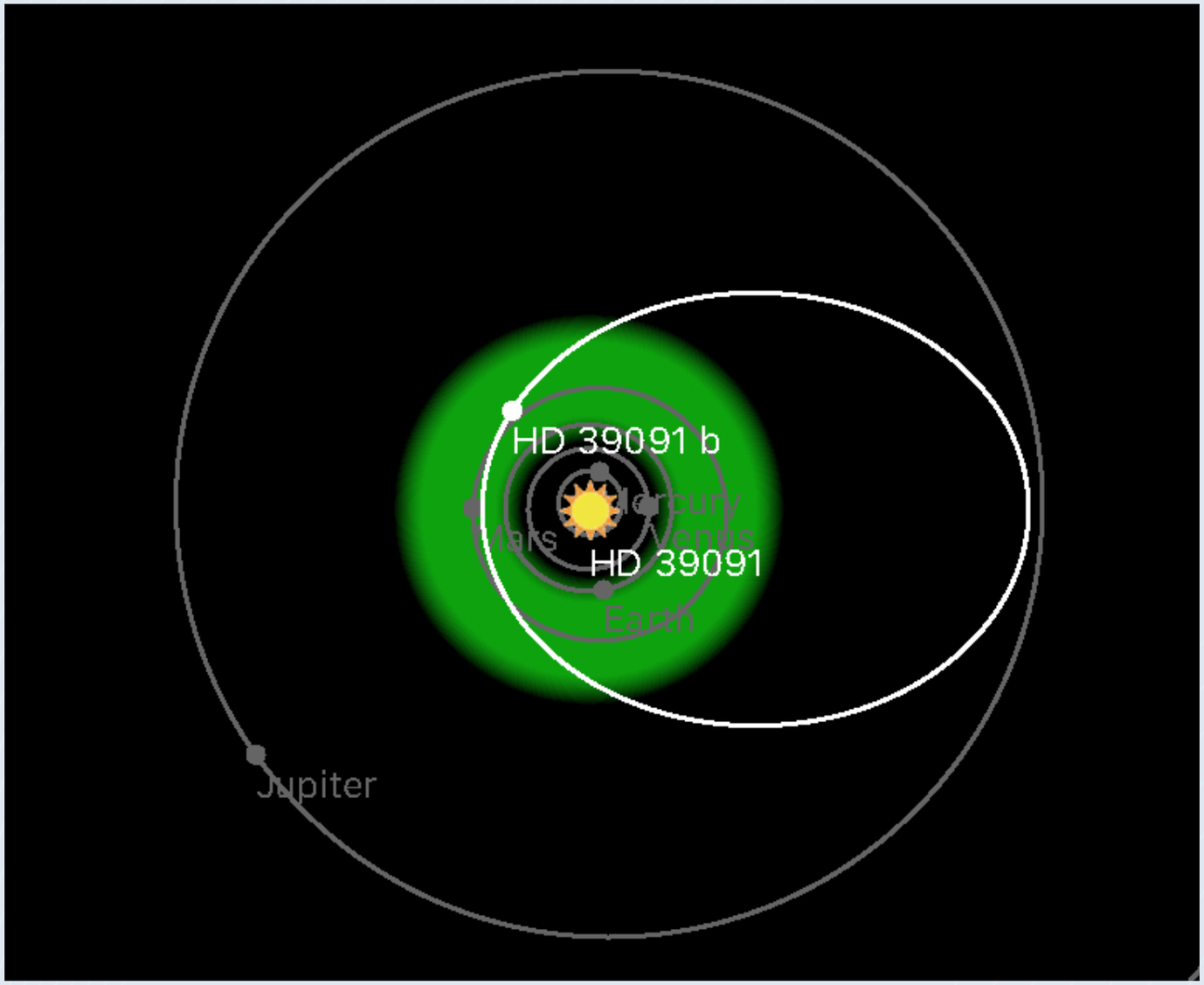

Camera 4
R Dor
LMC
S. Ecliptic Pole


Camera 4
Pi Mensae
T= 5.1 mag
TESS Planet Candidate Host!
R Dor
LMC
S. Ecliptic Pole

Giant Planet Orbiting Pi Mensae (aka HD 39091)



<u>Pi Mensae b</u>

Initial Discovery:
2001(RV)

P= 5.6 yrs

Ecc= 0.6

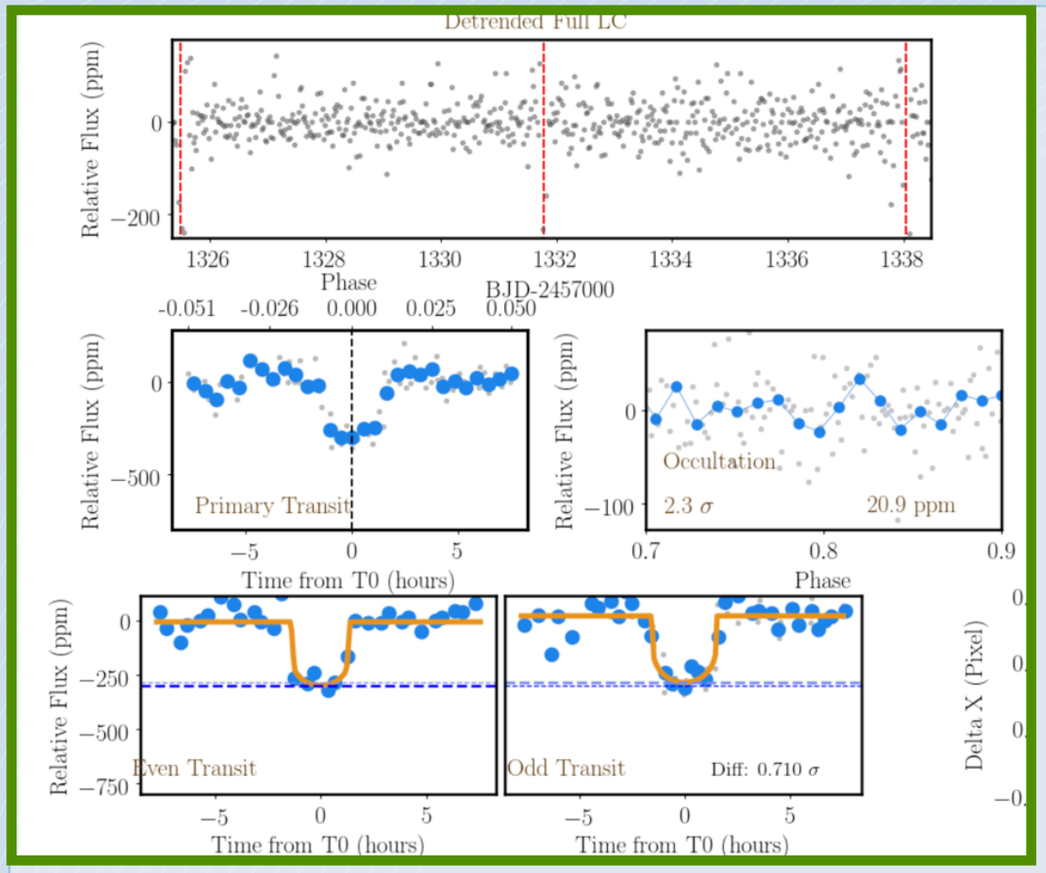
M_P= 10.3 M_{Jup}

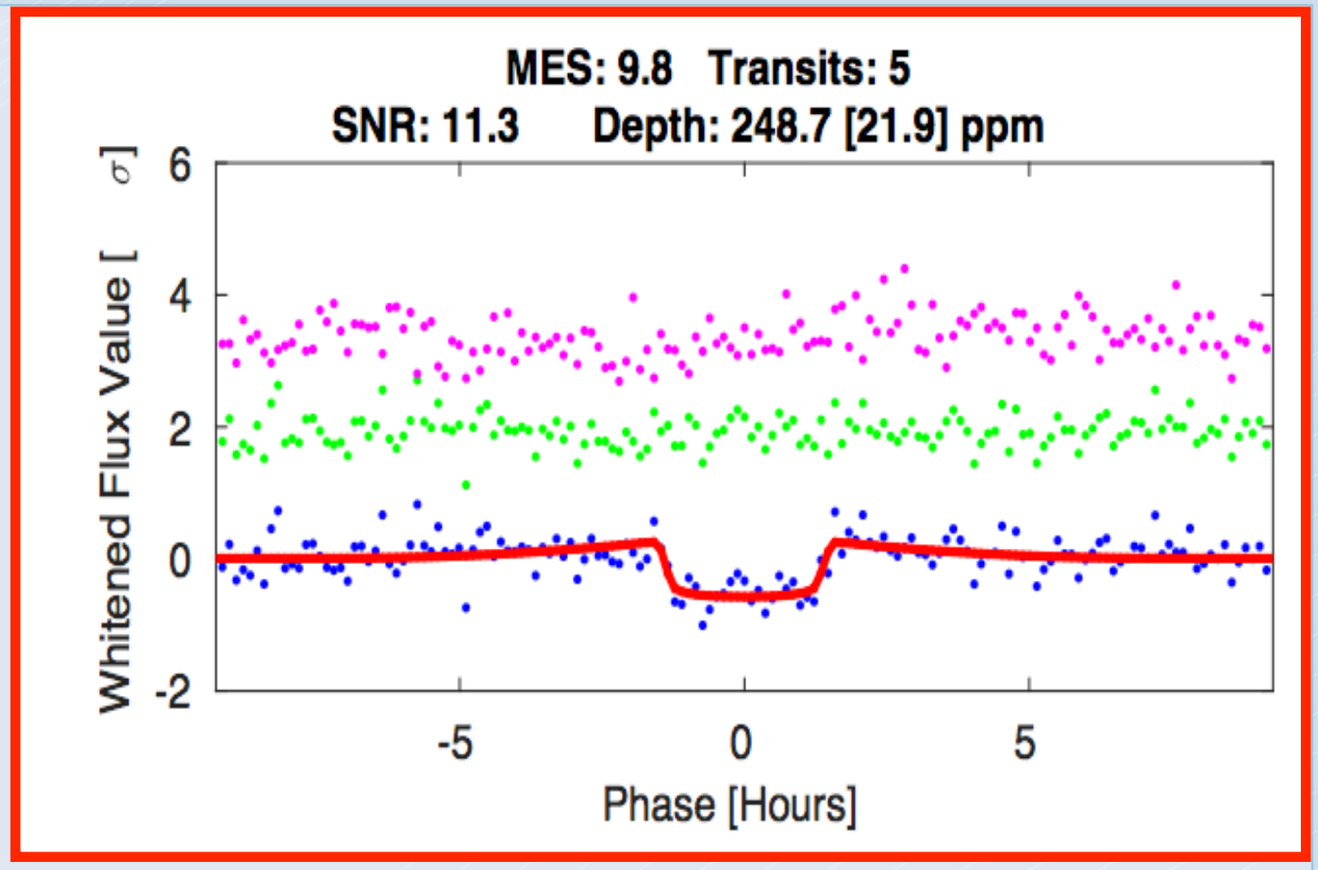
= 3300 M_{Earth}

R_{Star} = 1.15 R_{Sun}

TESS Finds a Small Planet Candidate in the Pi Mensae System

TESS Alerts Webpage, TOI 144.1 DV Report, posted 5 September 2018





QLP Discovery Light Curve

SPOC Light Curve

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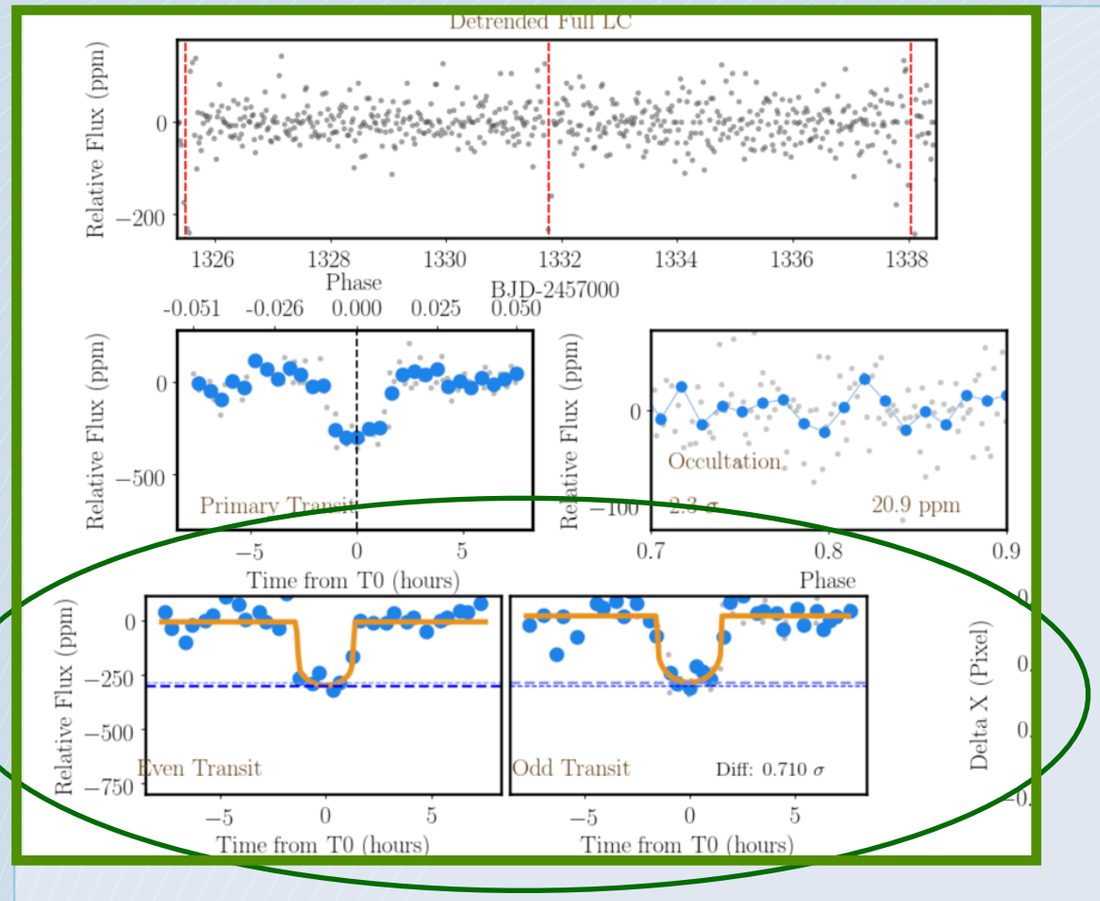
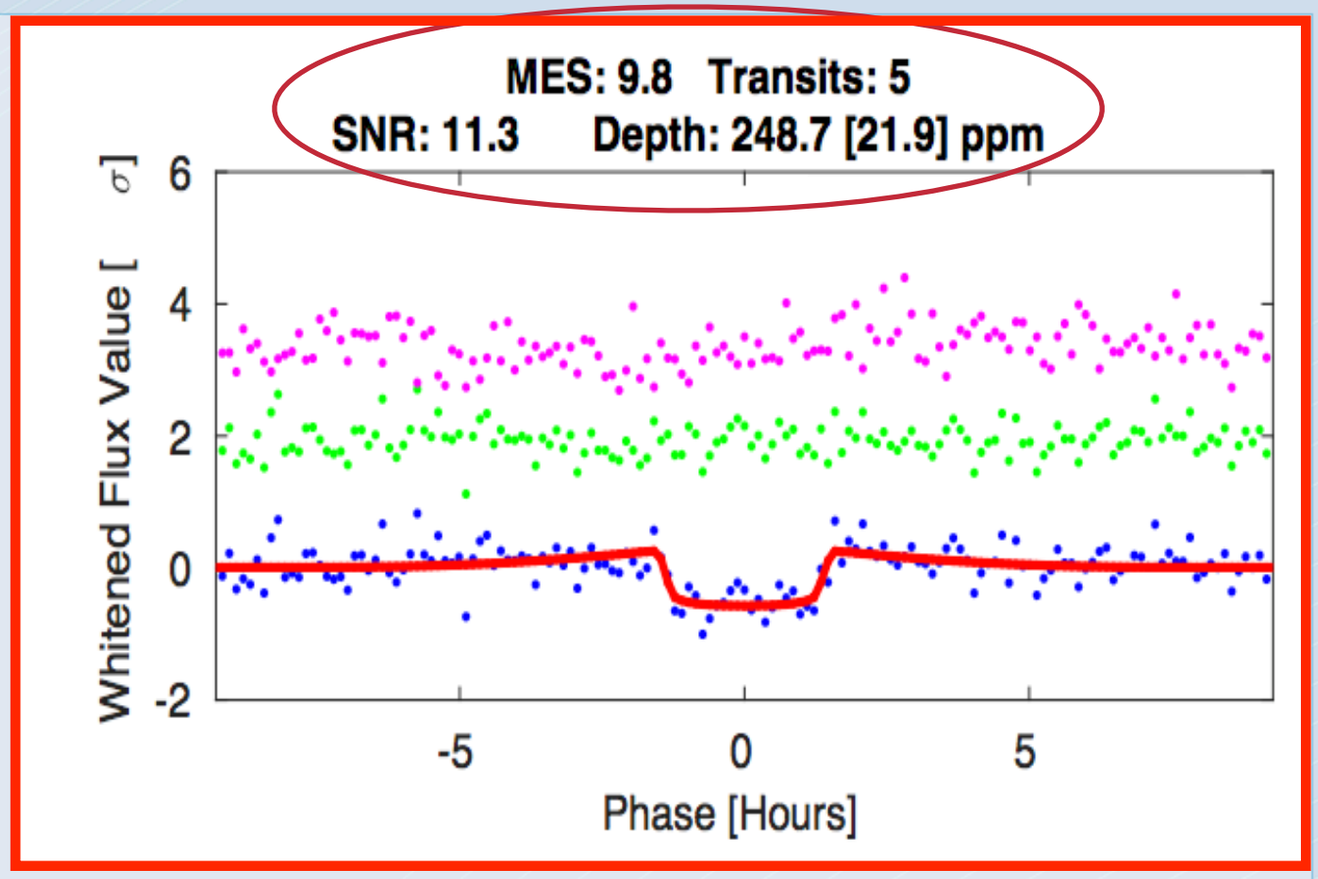




QLP Discovery Light Curve

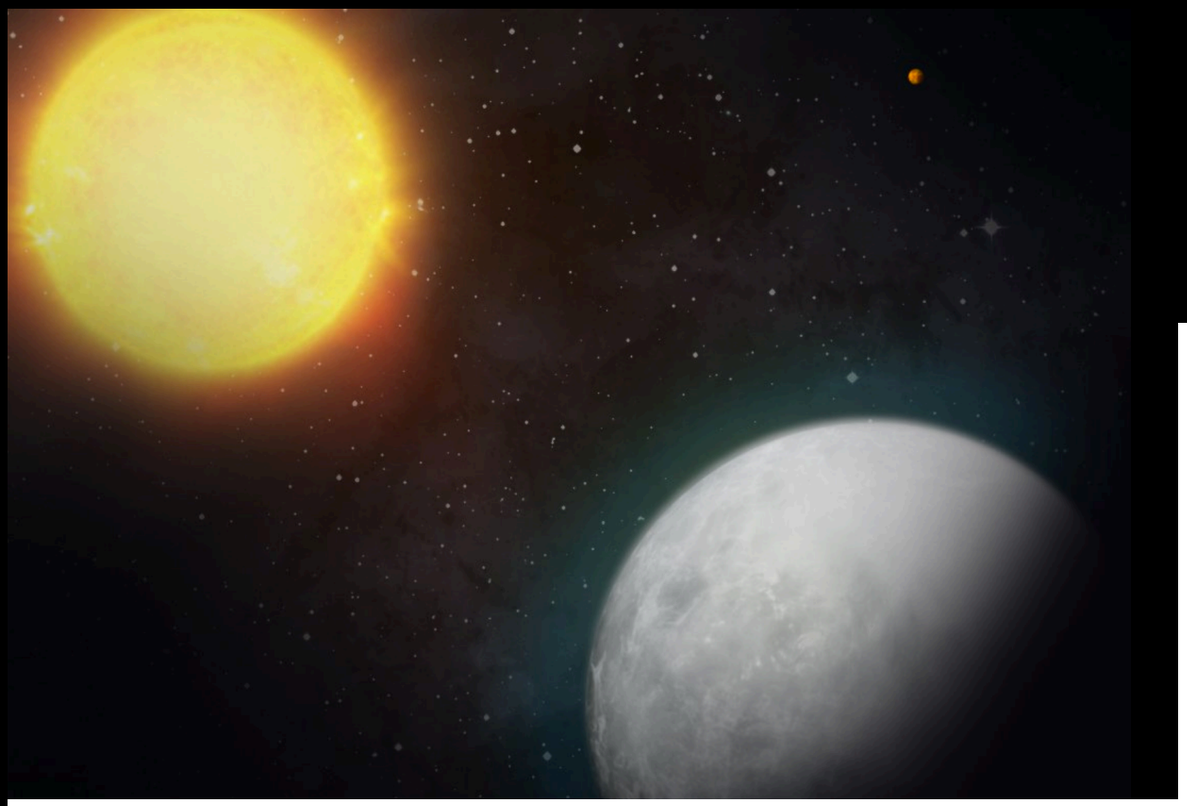
SPOC Light Curve

QLP and SPOC found same initial transit depth (250ppm), same SNR for Pi Mensae Planet Candidate

=> 2.1 R_{Earth} for the 2nd Planet Candidate

π Mensae c

Huang+ 2018 arXiv:1809.05967



Transiting Super-Earth in π Mensae

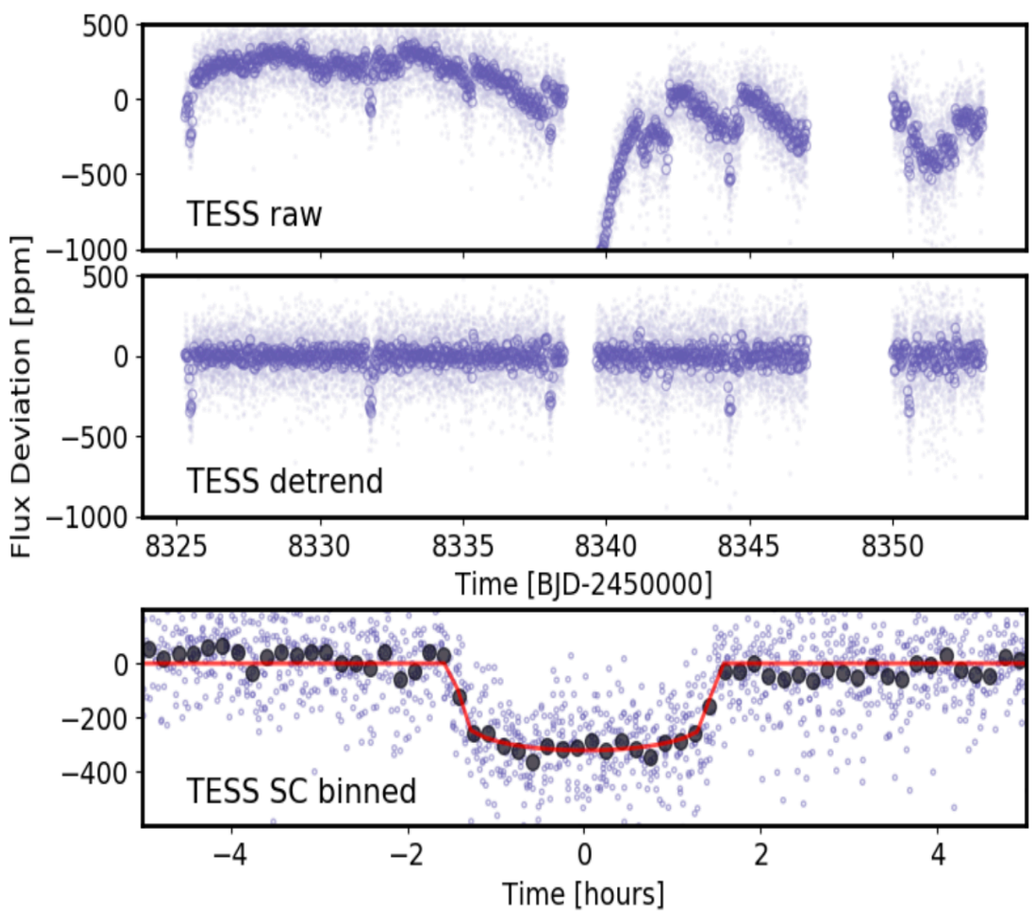


FIG. 2.— Raw (*top*) and corrected (*middle*) *TESS* light curves. The lighter points are 2 min cadence. The darker points reprent tim average of the light curve to 30 min exposure time. The interruptions are from the data downlink and the pointing anomaly. The botton panel shows the phase-folded light curve, along with the best-fitting model. The black dots represent 5-minute averages.

DRAFT VERSION SEPTEMBER 18, 2018
Preprint typeset using LaTeX style emulateapj v. 01/23/15

TESS DISCOVERY OF A TRANSITING SUPER-EARTH IN THE Π MENSAE SYSTEM

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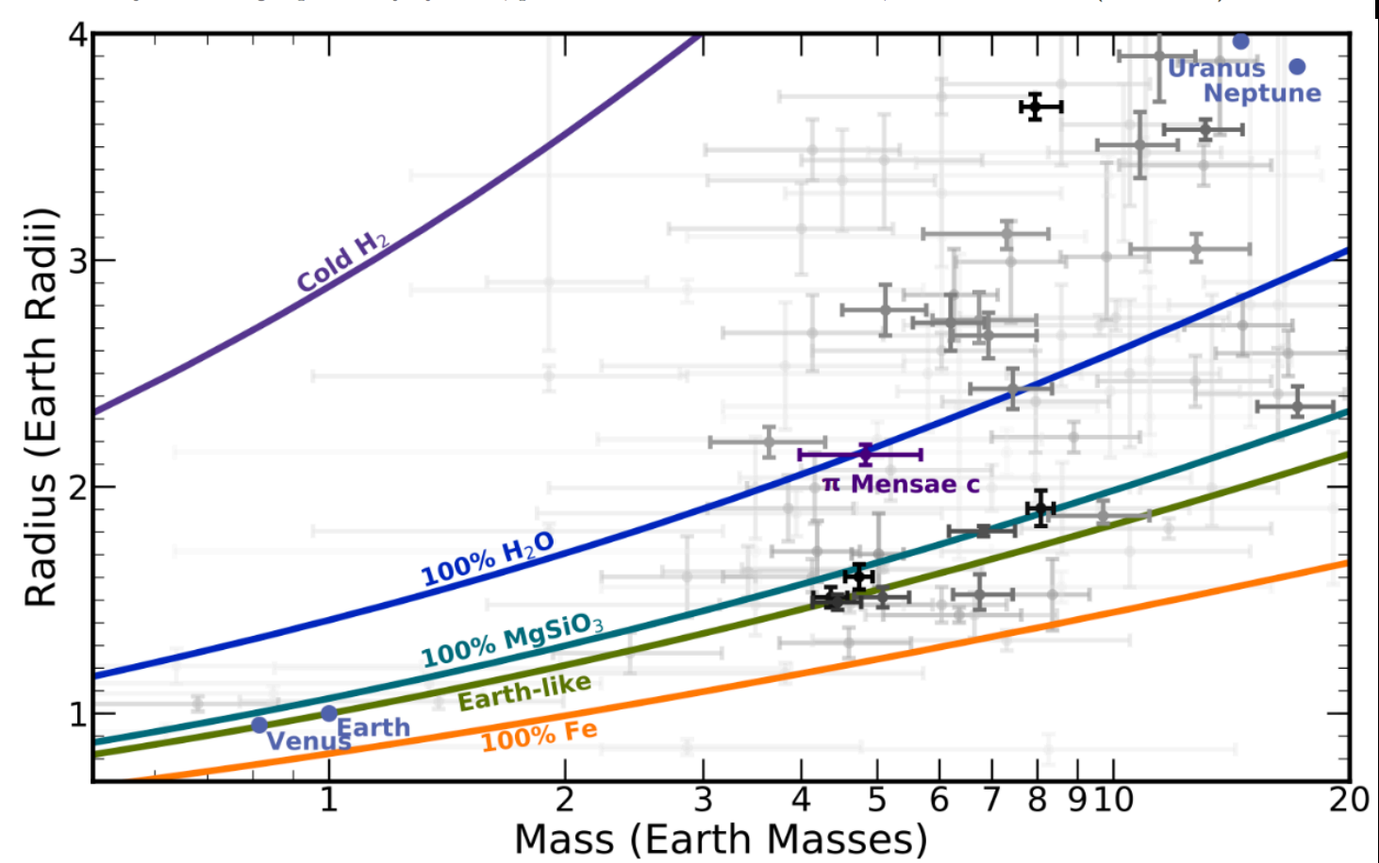
Draft version September 18, 2018

ABSTRACT

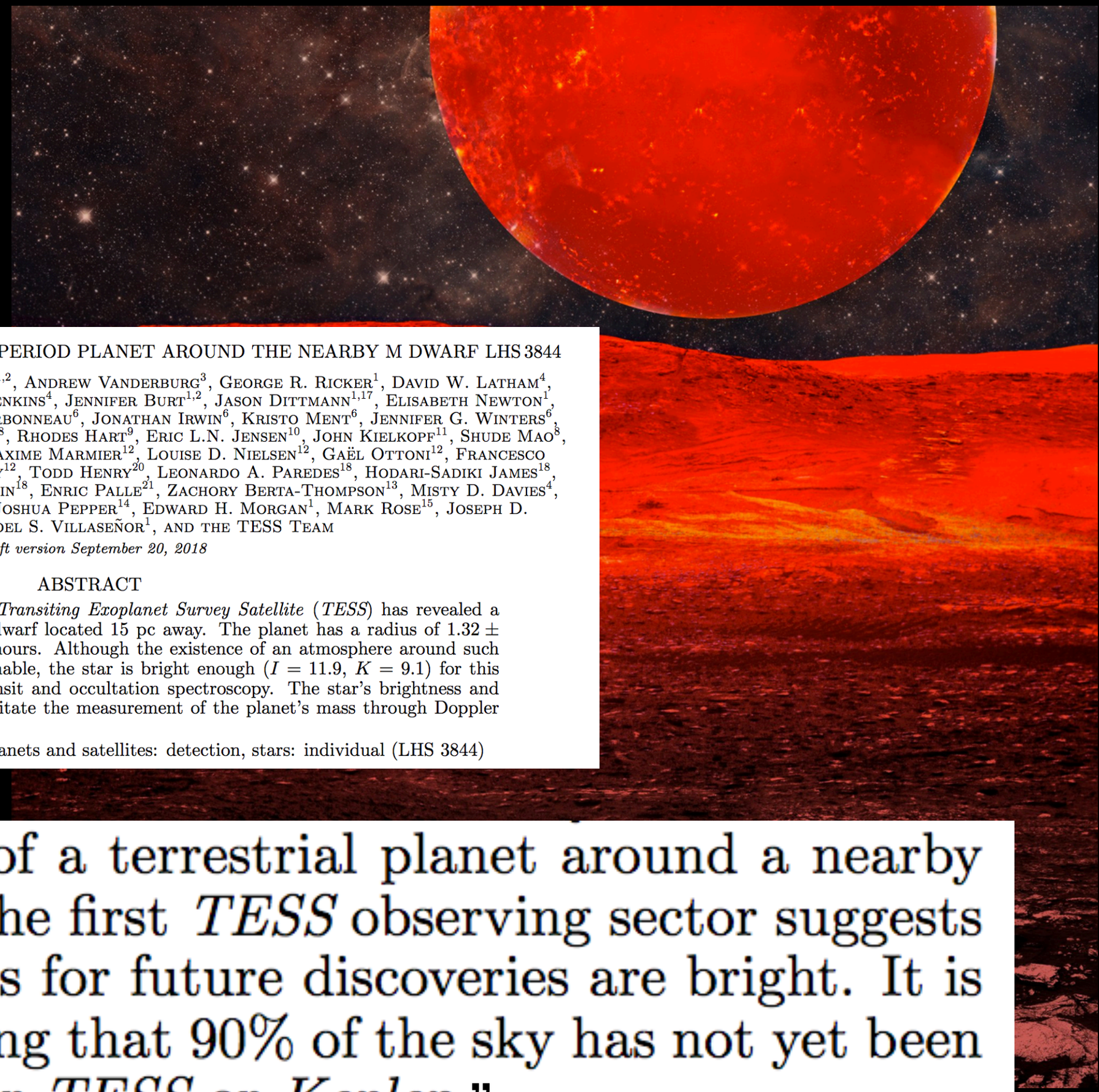
We report the detection of a transiting planet around π Men (HD 39091), using data from the *Transiting Exoplanet Survey Satellite* (*TESS*). The solar-type host star is unusually bright ($V = 5.7$) and was already known to host a Jovian planet on a highly eccentric, 5.7-year orbit. The newly discovered planet has a size of $2.14 \pm 0.04\ R_\oplus$ and an orbital period of 6.27 days. Radial-velocity data from the HARPS and AAT/UCLES archives also displays a 6.27-day periodicity, confirming the existence of the planet and leading to a mass determination of $4.82 \pm 0.85\ M_\oplus$. The star's proximity and brightness will facilitate further investigations, such as atmospheric spectroscopy, asteroseismology, the Rossiter-McLaughlin effect, astrometry, and direct imaging.

Subject headings: planetary systems, planets and satellites: detection, stars: individual (HD 39091)



LHS 3844b

Vanderspek+ 2018
arXiv:1809.07242



TESS DISCOVERY OF AN ULTRA-SHORT-PERIOD PLANET AROUND THE NEARBY M DWARF LHS 3844

Roland K. Vanderspek[1], Chelsea X. Huang[1,2], Andrew Vanderburg[3], George R. Ricker[1], David W. Latham[4], Sara Seager[1,17], Joshua N. Winn[5], Jon M. Jenkins[4], Jennifer Burt[1,2], Jason Dittmann[1,17], Elisabeth Newton[1], Samuel N. Quinn[6], Avi Shporer[1], David Charbonneau[6], Jonathan Irwin[6], Kristo Ment[6], Jennifer G. Winters[6], Karen A. Collins[6], Phil Evans[7], Tianjun Gan[8], Rhodes Hart[9], Eric L.N. Jensen[10], John Kielkopf[11], Shude Mao[8], William Waalkes[13], François Bouchy[12], Maxime Marmier[12], Louise D. Nielsen[12], Gaël Ottoni[12], Francesco Pepe[12], Damien Ségransan [12], Stéphane Udry[12], Todd Henry[20], Leonardo A. Paredes[18], Hodari-Sadiki James[18], Rodrigo H. Hinojosa[19], Michele L. Silverstein[18], Enric Palle[21], Zachory Berta-Thompson[13], Misty D. Davies[4], Michael Fausnaugh[1], Ana W. Glidden[1], Joshua Pepper[14], Edward H. Morgan[1], Mark Rose[15], Joseph D. Twicken[16], Jesus Noel S. Villaseñor[1], and the TESS Team

Draft version September 20, 2018

EP] 19 Sep 2018

ABSTRACT

Data from the newly-commissioned *Transiting Exoplanet Survey Satellite* (*TESS*) has revealed a "hot Earth" around LHS 3844, an M dwarf located 15 pc away. The planet has a radius of $1.32 \pm 0.02\ R_{\oplus}$ and orbits the star every 11 hours. Although the existence of an atmosphere around such a strongly irradiated planet is questionable, the star is bright enough ($I = 11.9$, $K = 9.1$) for this possibility to be investigated with transit and occultation spectroscopy. The star's brightness and the planet's short period will also facilitate the measurement of the planet's mass through Doppler spectroscopy.

Subject headings: planetary systems, planets and satellites: detection, stars: individual (LHS 3844)

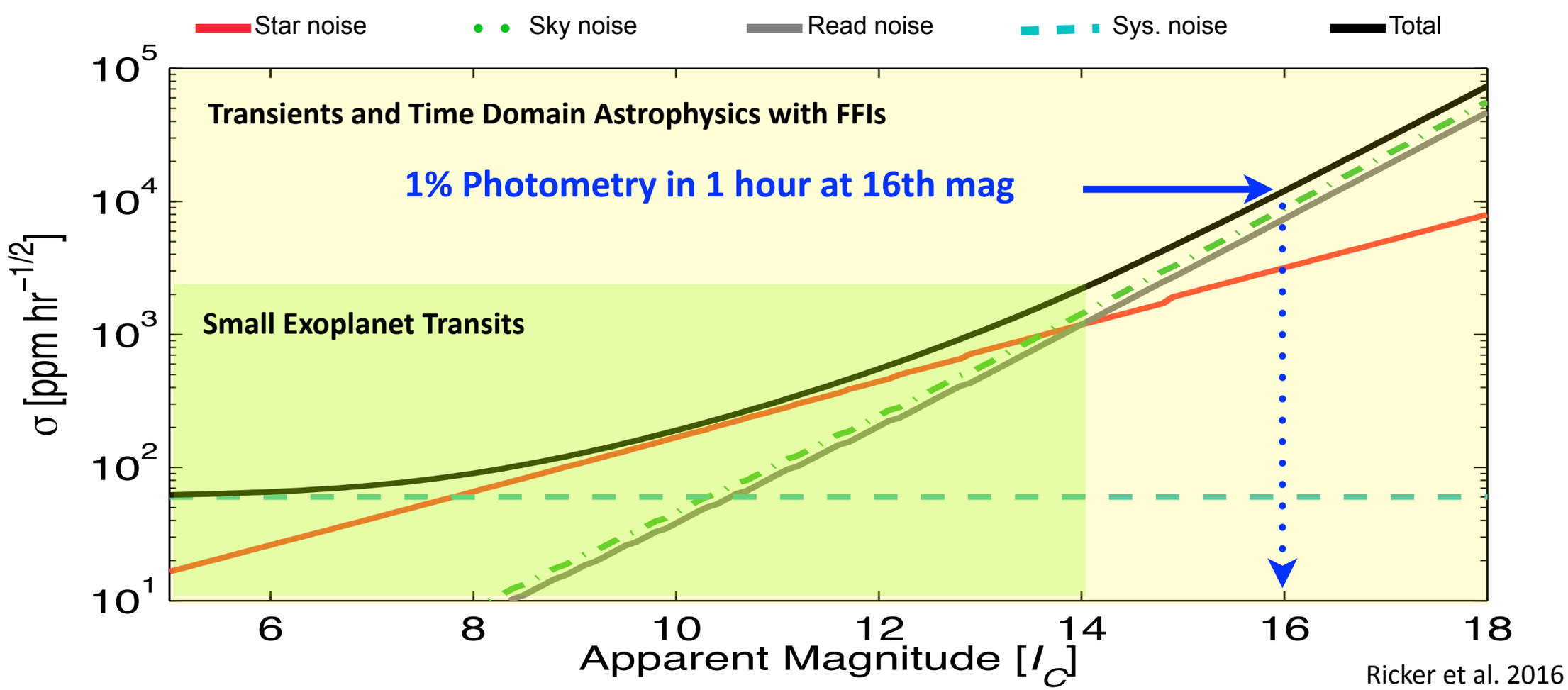
"The discovery of a terrestrial planet around a nearby M dwarf during the first *TESS* observing sector suggests that the prospects for future discoveries are bright. It is worth remembering that 90% of the sky has not yet been surveyed by either *TESS* or *Kepler*."

Just in case you thought TESS was only about exoplanets…

TESS also goes deep…

- In one hour:
  - 1% photometry at 16th mag
  - <10% photometry at 18th mag
- In 12 hours:
  - Approximately 10% photometry at 19.5 mag

~300 Million
Stars + Galaxies



Ricker et al. 2016

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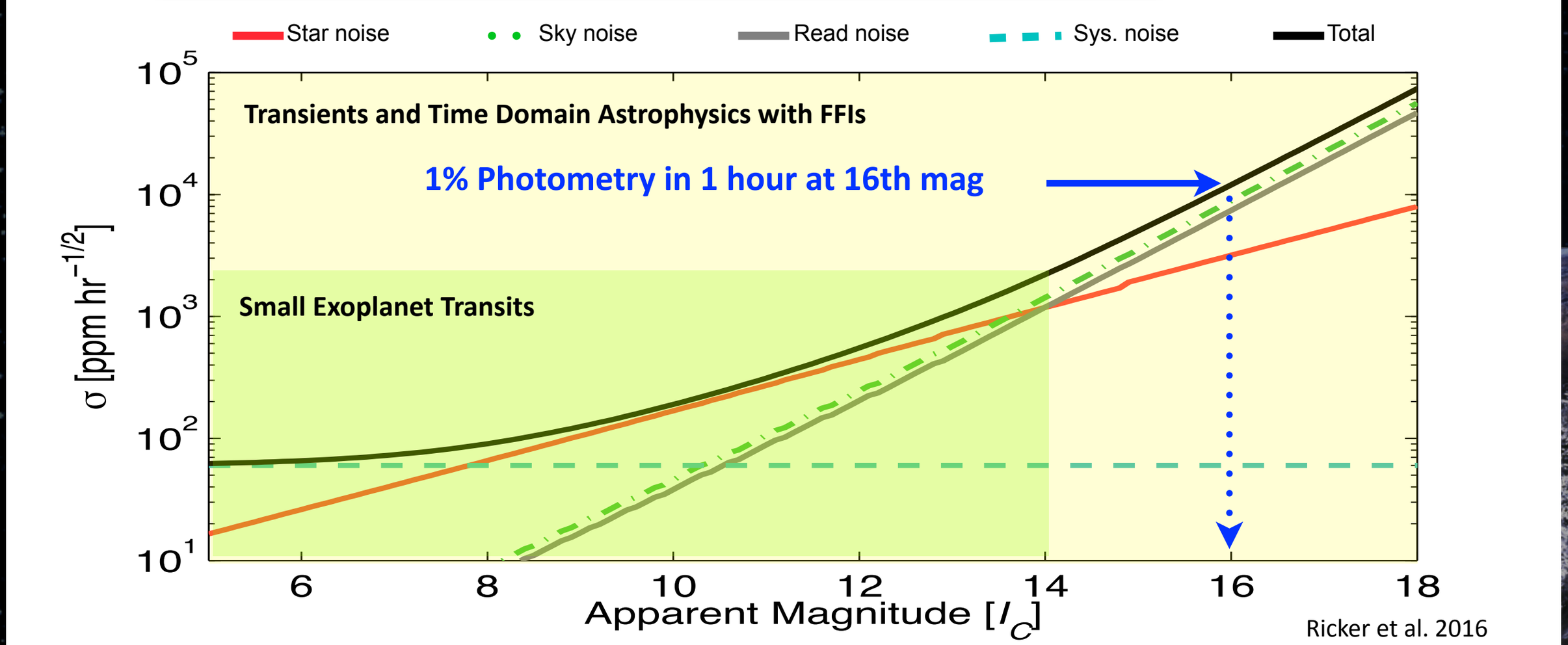
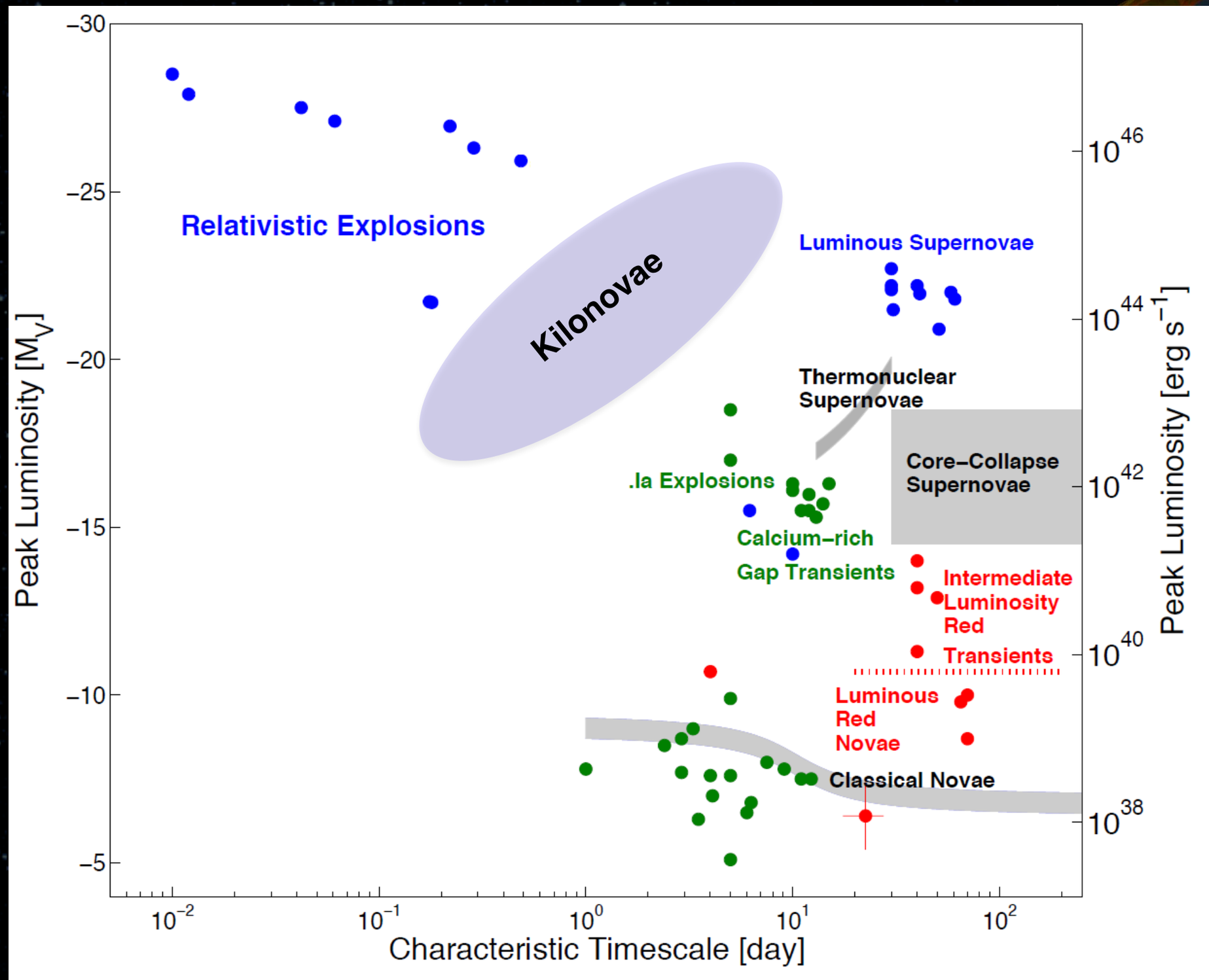


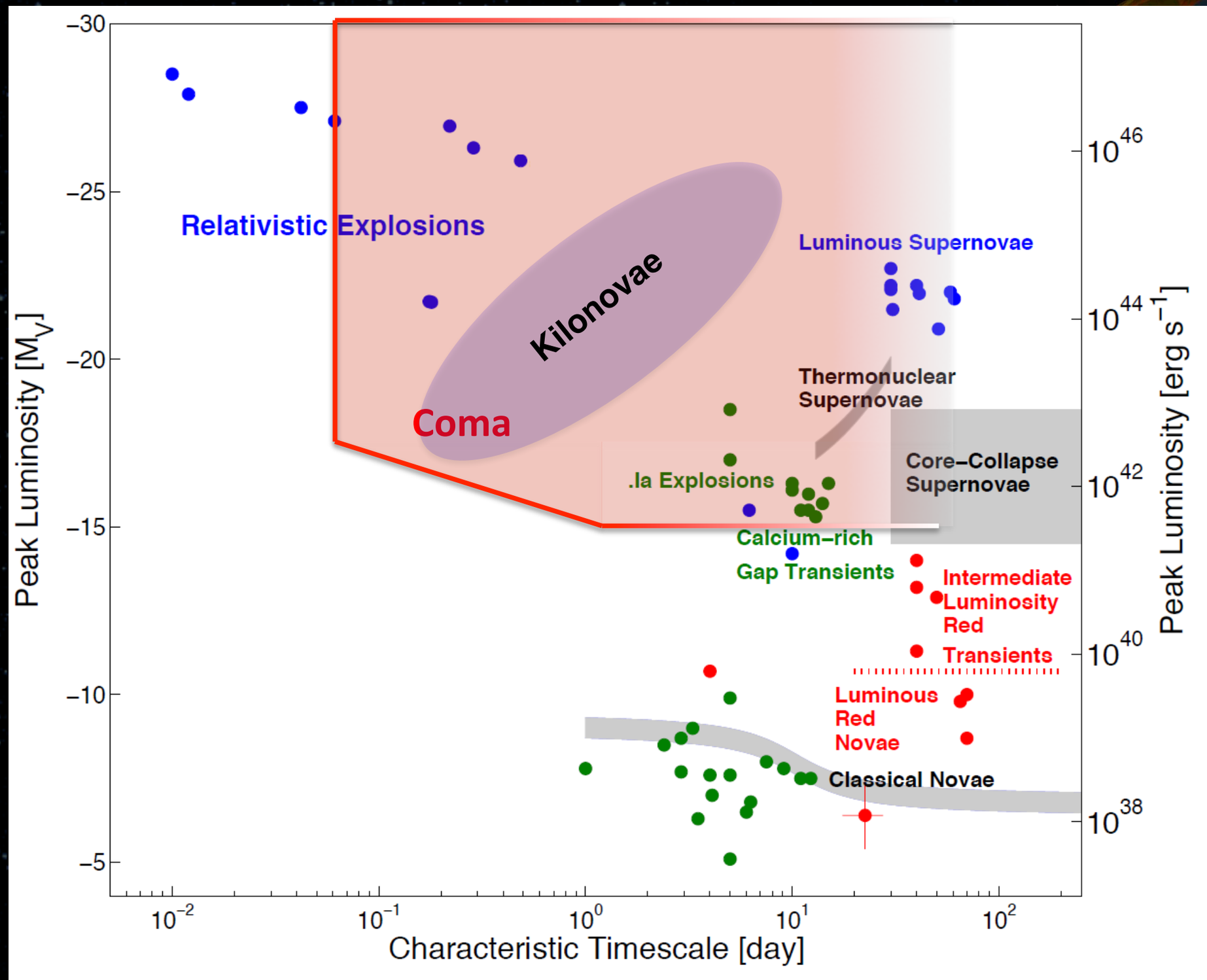
Ricker et al. 2016

TESS and Depth



Plot Credit: Mansi Kasliwal

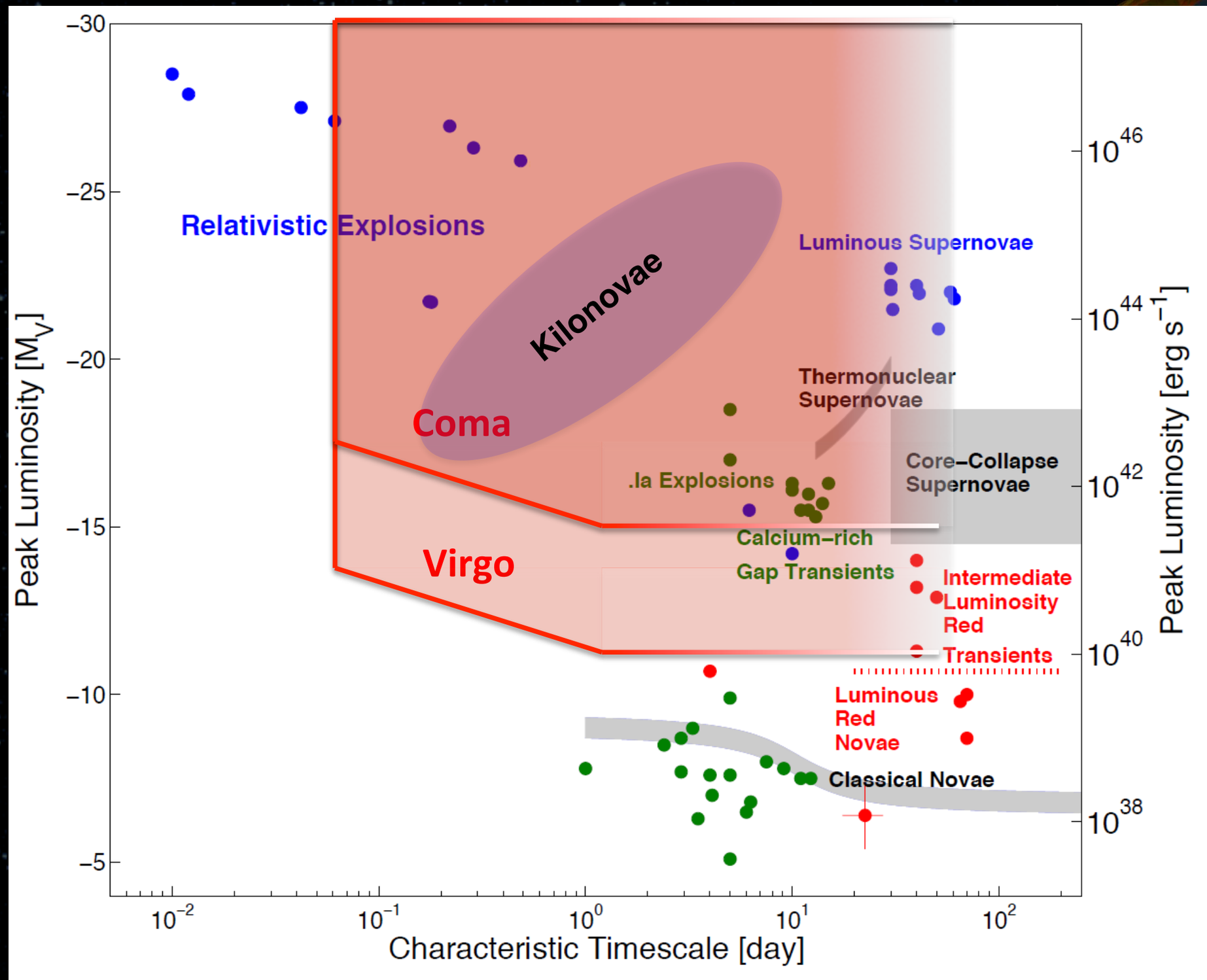
TESS and Depth



B. Shappee 2015

Plot Credit: Mansi Kasliwal

TESS and Depth



B. Shappee 2015

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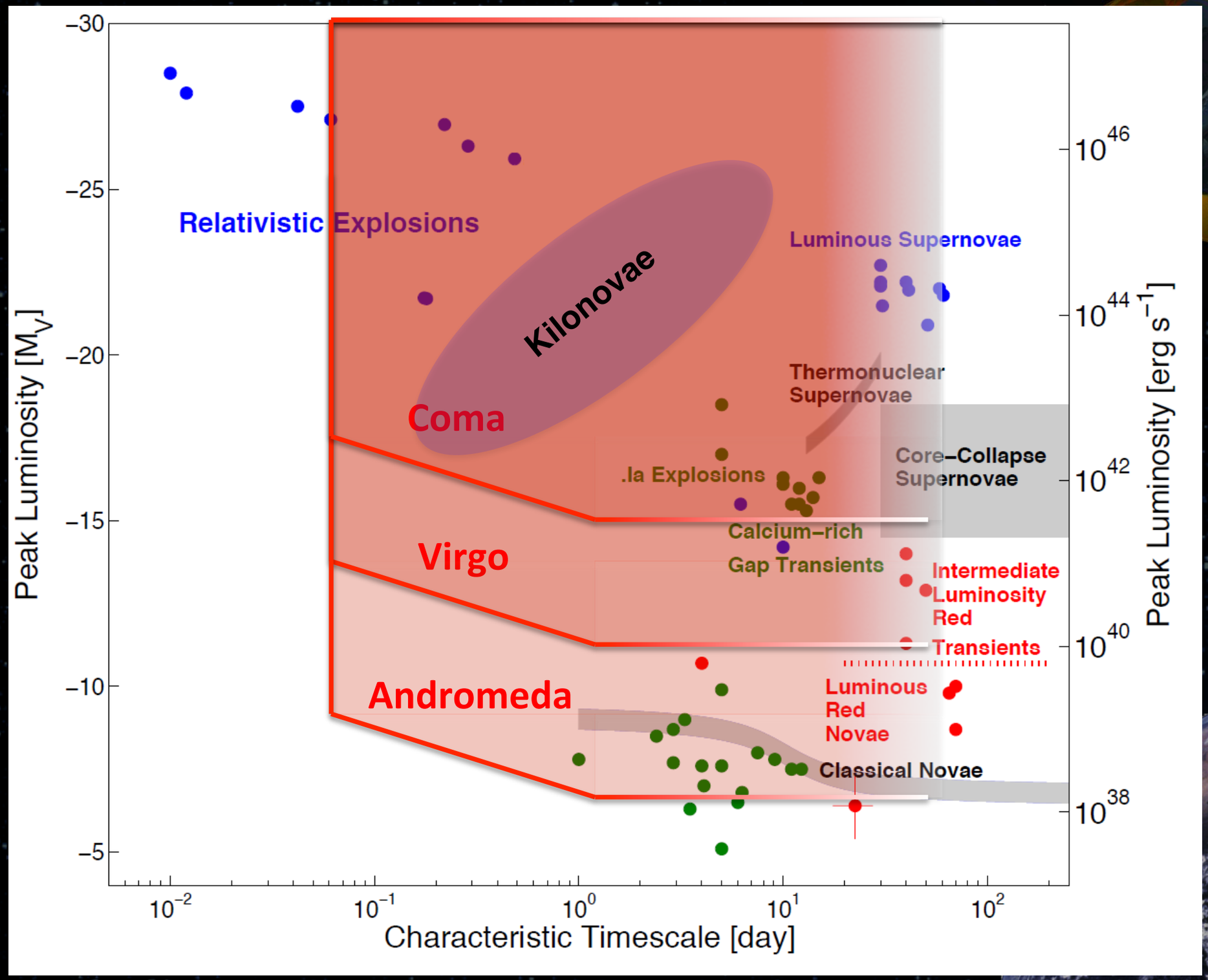
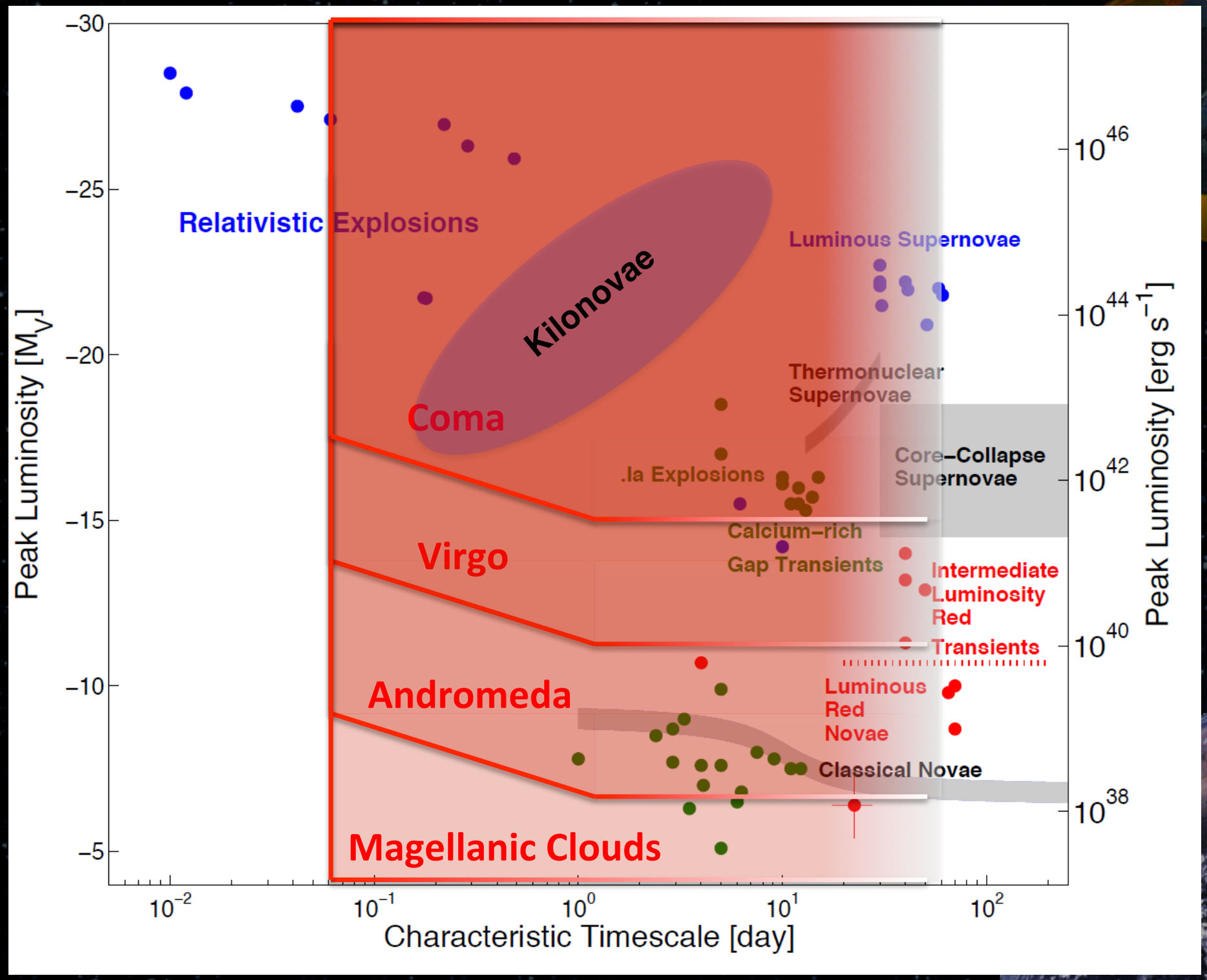
TESS and Depth



B. Shappee 2015

Plot Credit: Mansi Kasliwal

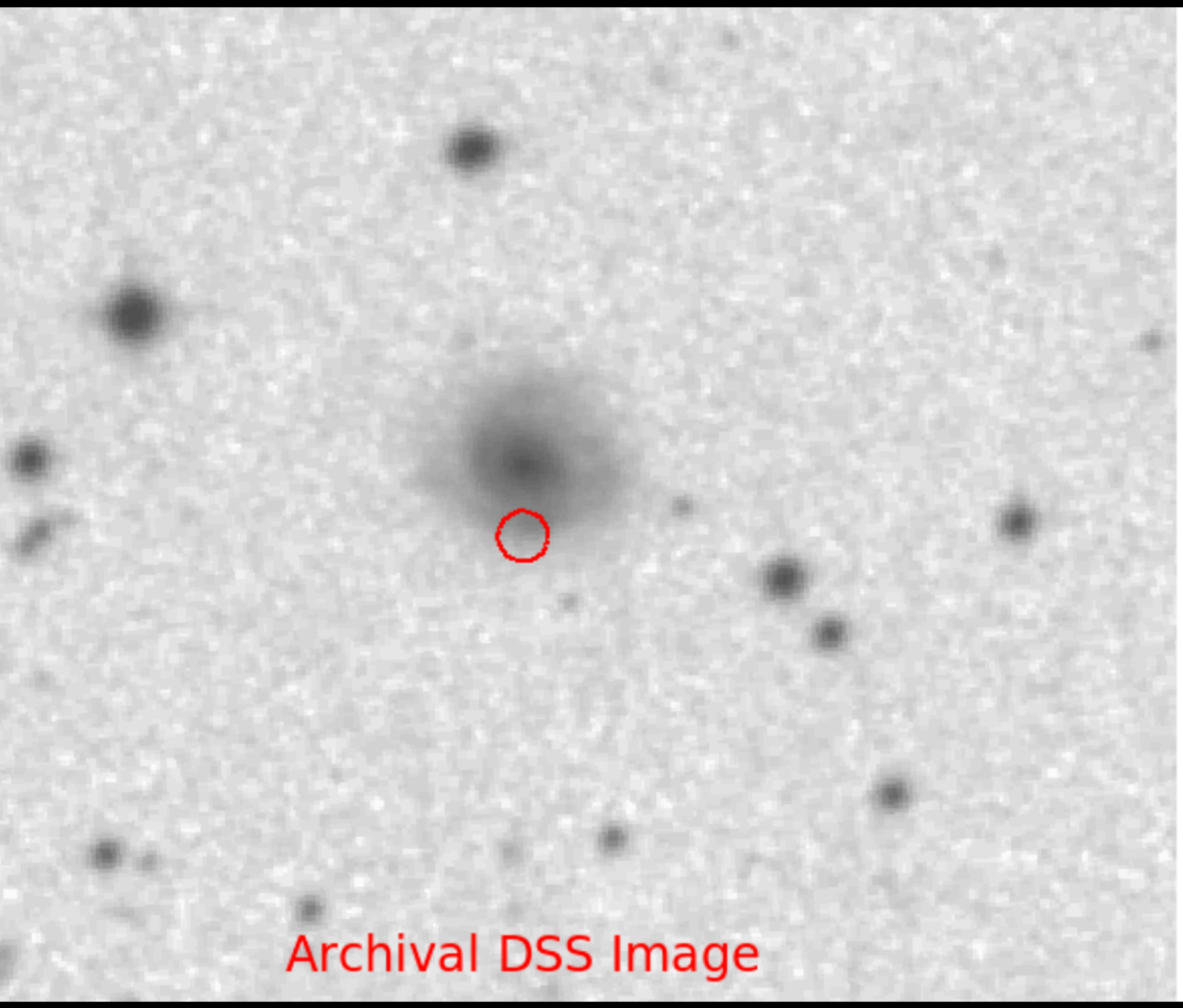
TESS and Depth

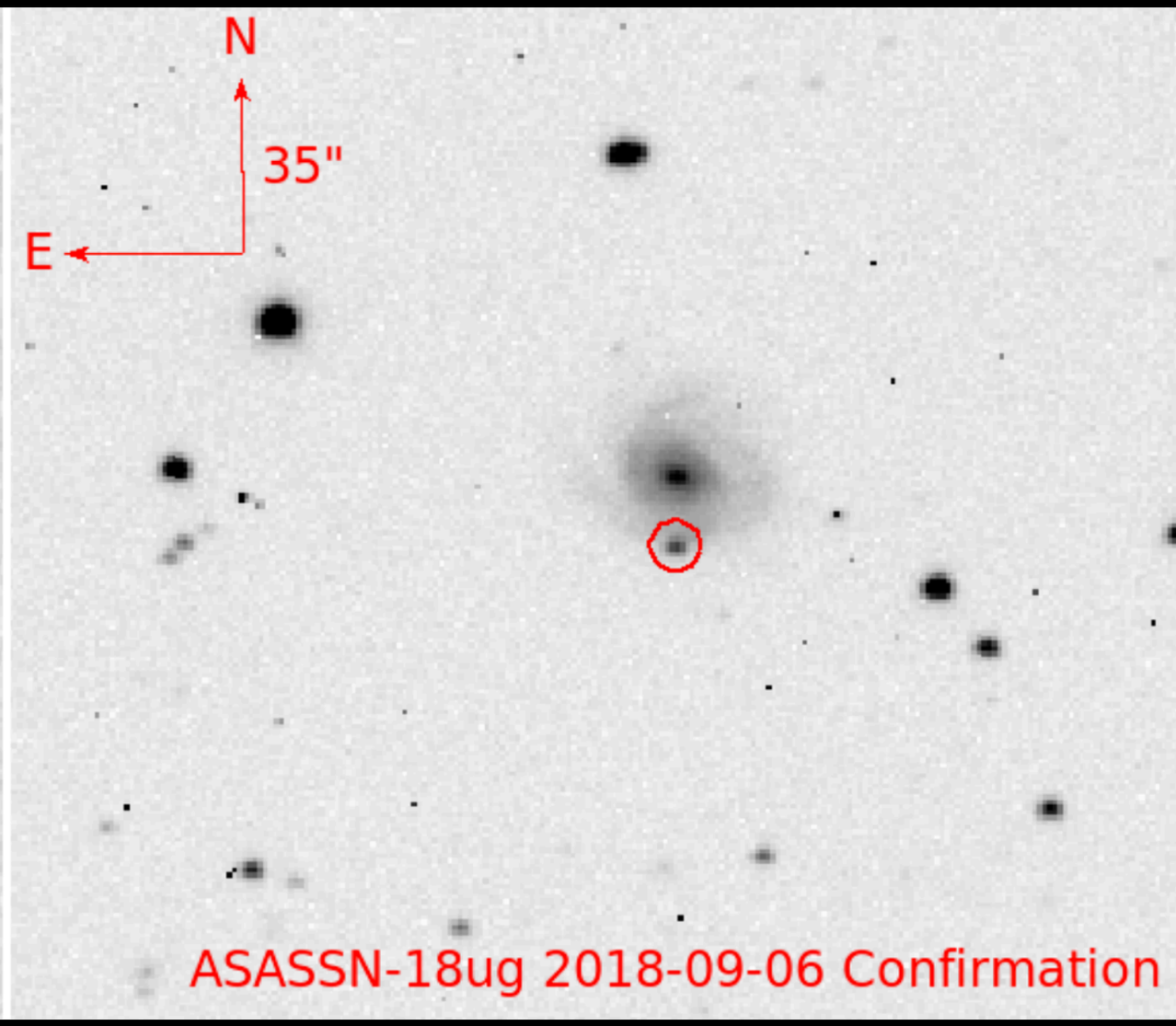


B. Shappee 2015

Plot Credit: Mansi Kasliwal

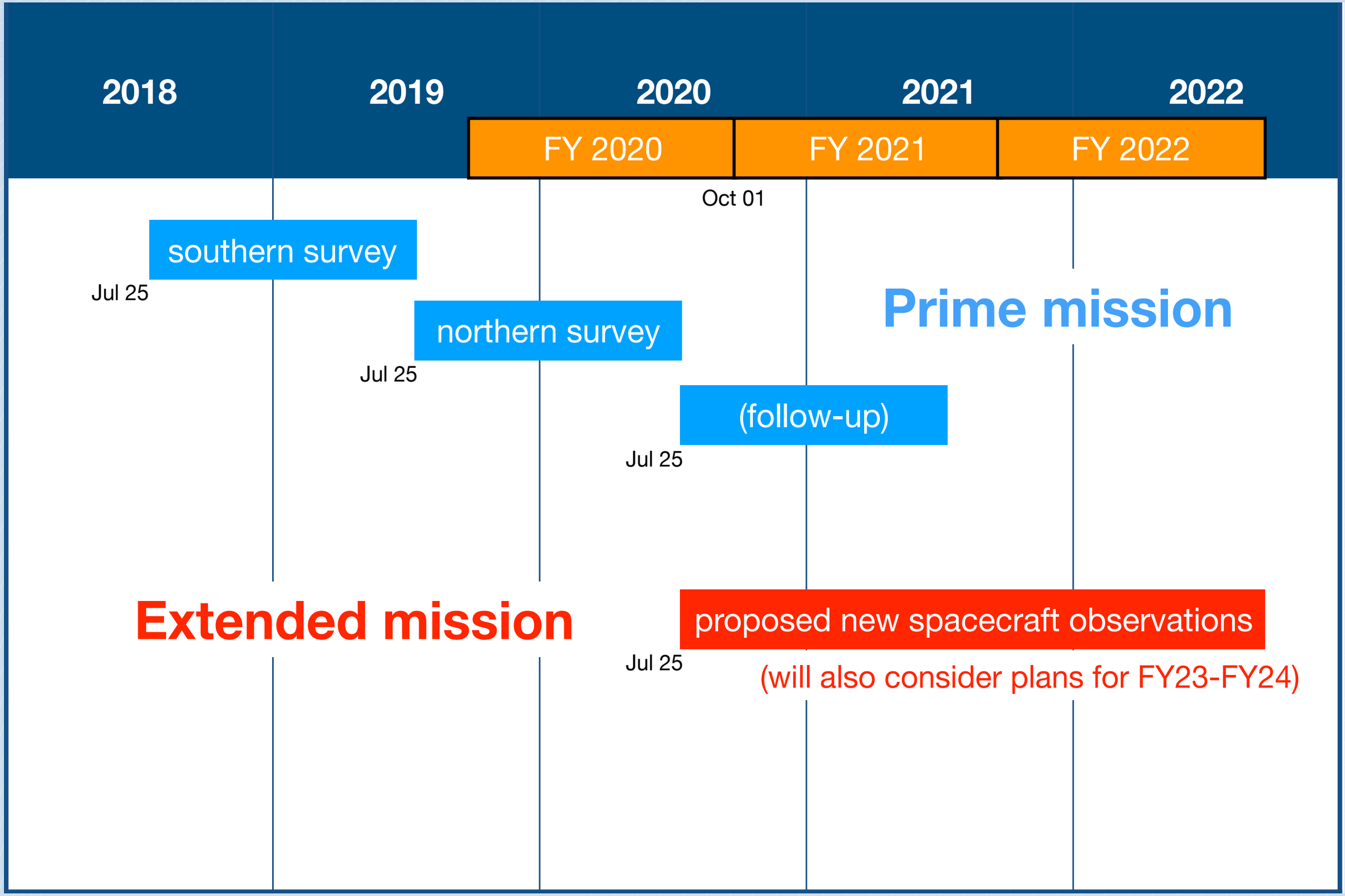
All Sky Automated Survey for SuperNovae (ASAS-SN, Shappee et al. 2014) ATels



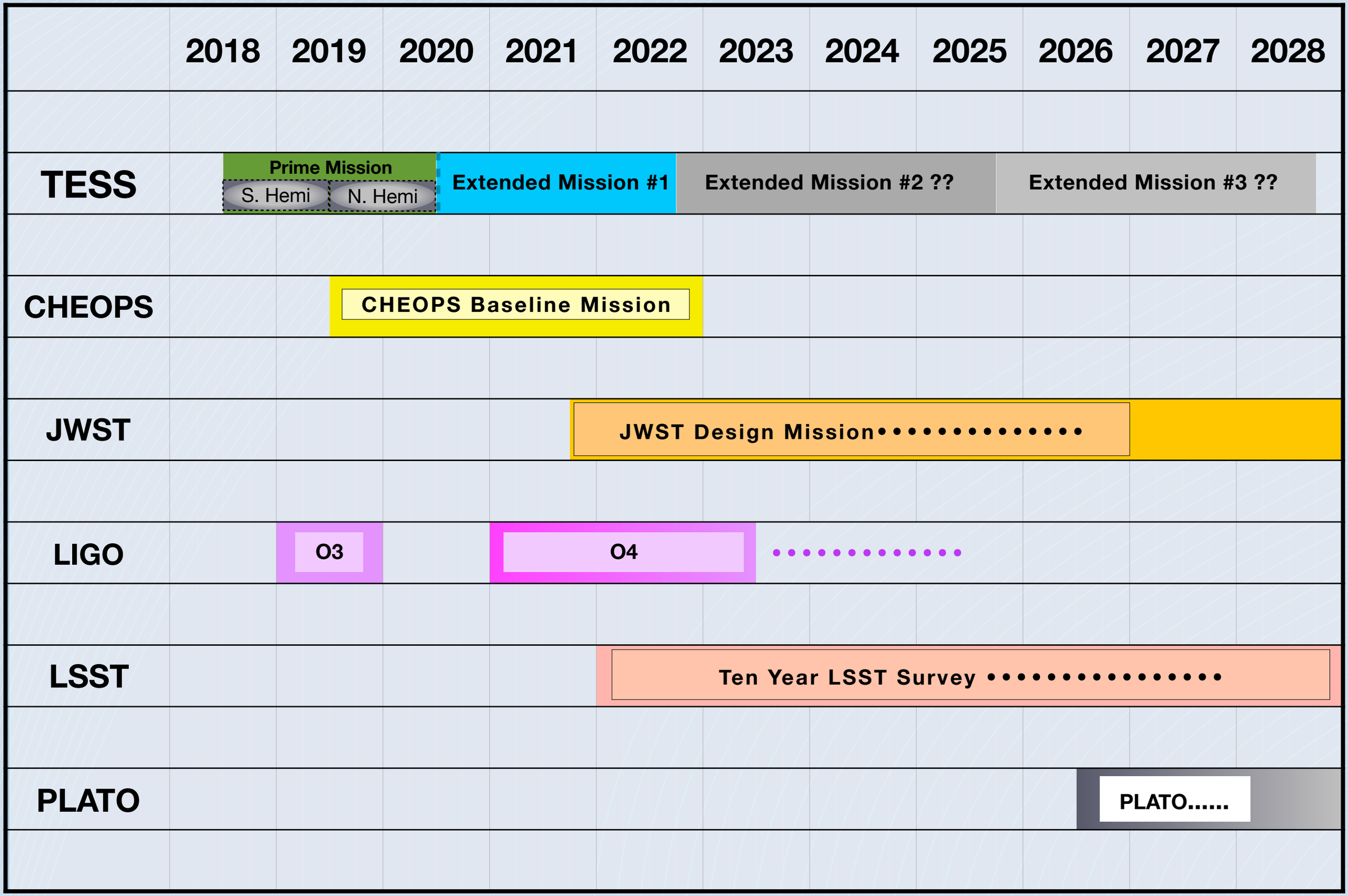


- Six ATels issued in/during sky regions overlapping first 3 TESS Sectors
- 18qk, 18rn, 18sk, 18tb, 18ug, 18xf
- All six were much brighter at discovery than TESS's Limiting Magnitude...

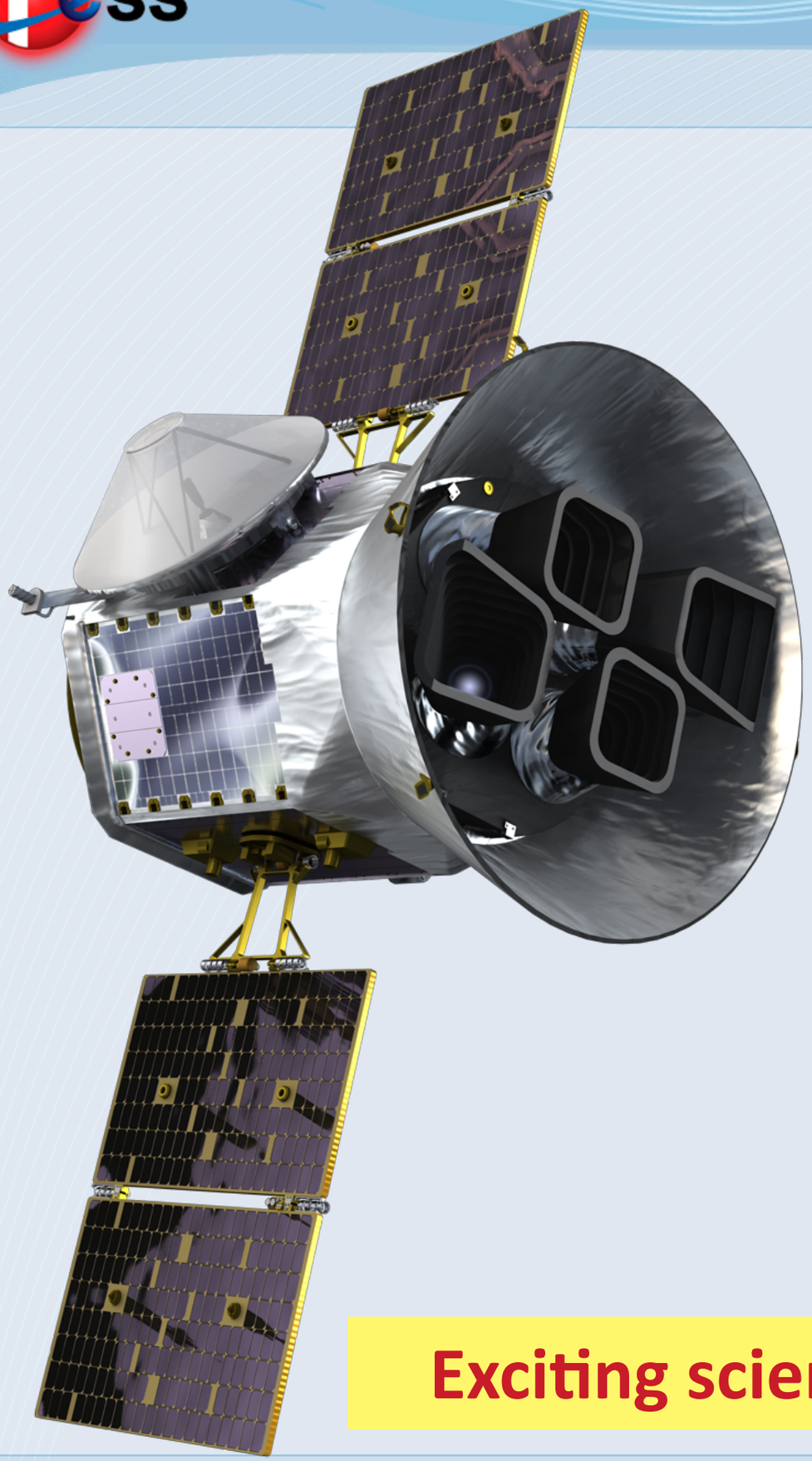
TESS Schedule for an Extended Mission



TESS Enables Time-Domain Astronomy in the Coming Decade

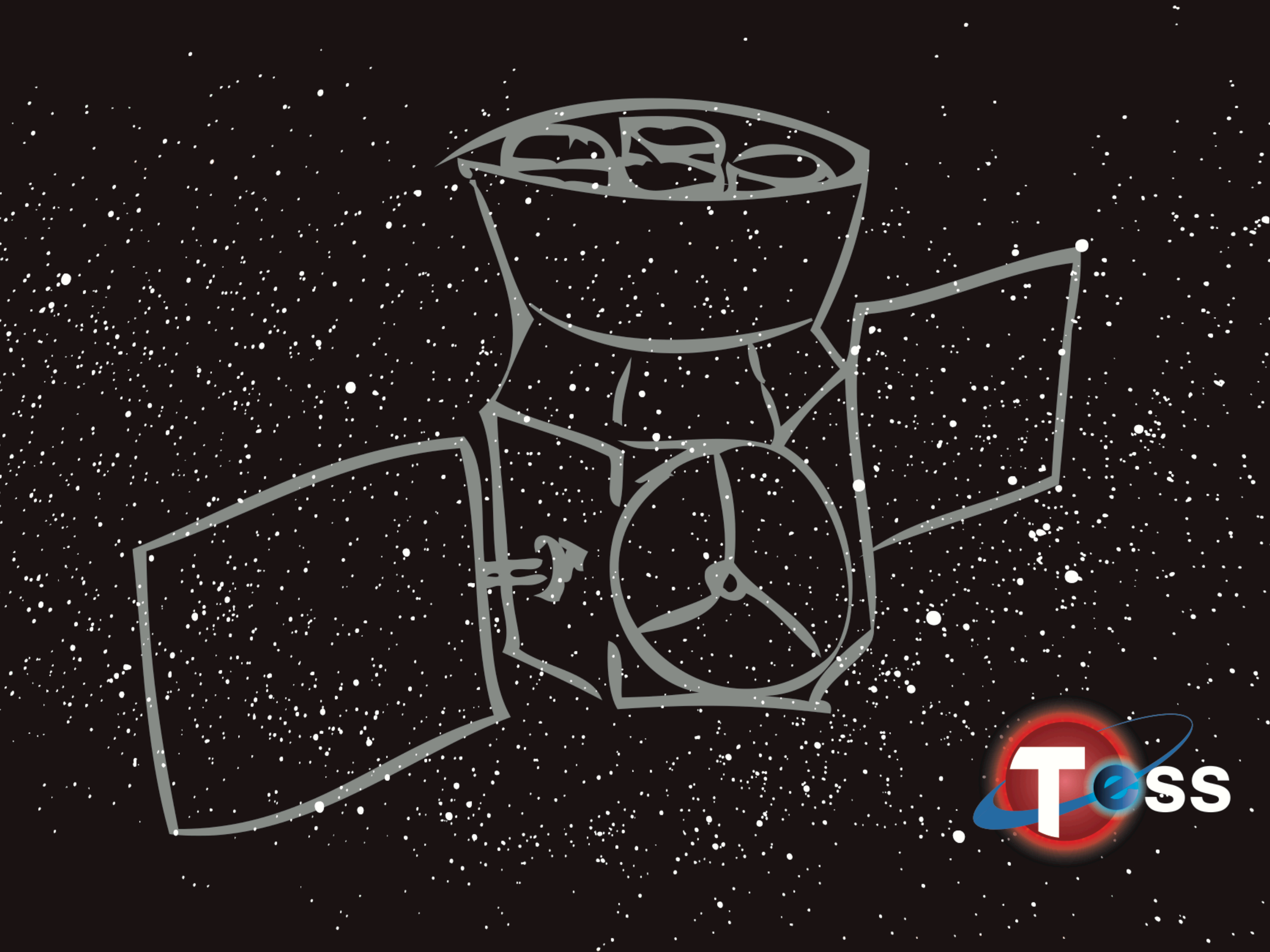


TESS Early Mission Takeaways



- TESS's unique resonant orbit is greatly simplifying the mission
  - *Stable operations in principle could last until ~2038*
- TESS's camera performance is excellent
- TESS's onboard data compression is ~2-3 times better than expected
  - *<10 min FFI's in Extended Mission*
- TESS's Science Survey by Sky Sector is underway
  - *Sectors #1-3 are complete; #4 in progress*
- TESS's discovery space encompasses more than exoplanets
  - *Also **Stellar Astrophysics, Planetary Astronomy, "Multi-Messenger Astronomy"***

Exciting science from TESS has now begun...


Tess

Schedule for Initial MAST Data Release

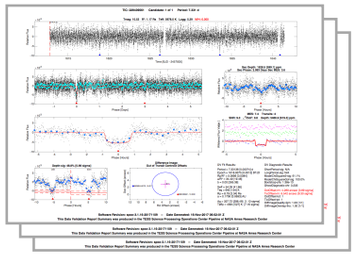
- Target date for MAST release of TESS Sectors 1&2 is late November
  - *Two months **earlier** than date in TESS Science Data Management Plan*
  - *MAST needs until 13 November, given their staff and commitments*
- Preparatory steps complete by early November
  - *Staging & testing of S1 and S2 data at MAST*
  - *Completion of engineering data format definitions*
  - *Incorporation of preliminary lab testing data of spare lens hood*
  - *Completion of Instrument Handbook (1st Revision)*
  - *SciDAT of Sectors 1 and 2 (ScatLight, WCS, Hot Columns, Sensitivity, CR effects...)*
- Data product and website test and review (~2 weeks)
  - *Products at MAST*
  - *Instrument Handbook*

Planet candidate

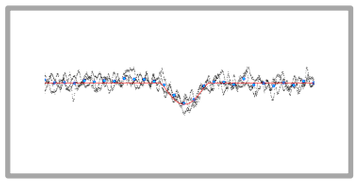
Alert with information useful for follow-up

Table of parameters

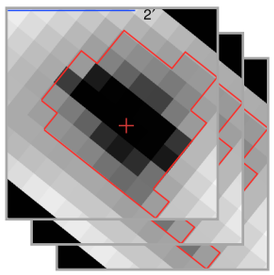
- TIC ID
- TOI ID
- Planet name
- # planet
- RA
- Dec
- Tmag
- Epoch
- Period
- Transit duration
- Transit depth
- Sector #
- Group vetting comments
- Impact parameter
- log g
- Stellar radius
- Planet radius
- T_{eq}
- T_{eff}
- $Insol_p$
- SNR_p



target DV summary (PDF)



detrended target light curve (FITS)



target pixel file (TPF)