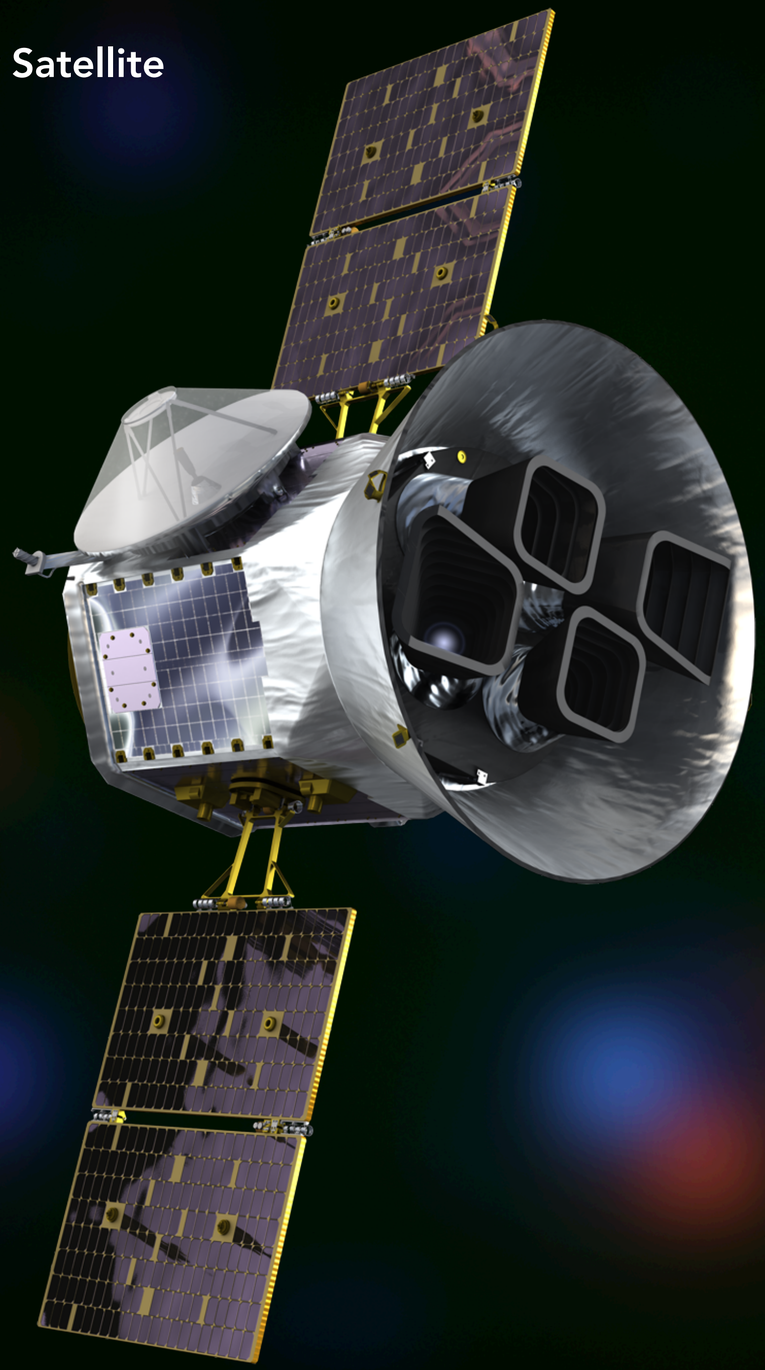
Transiting Exoplanet Survey Satellite



TESS Project Update

George Ricker
(MIT)

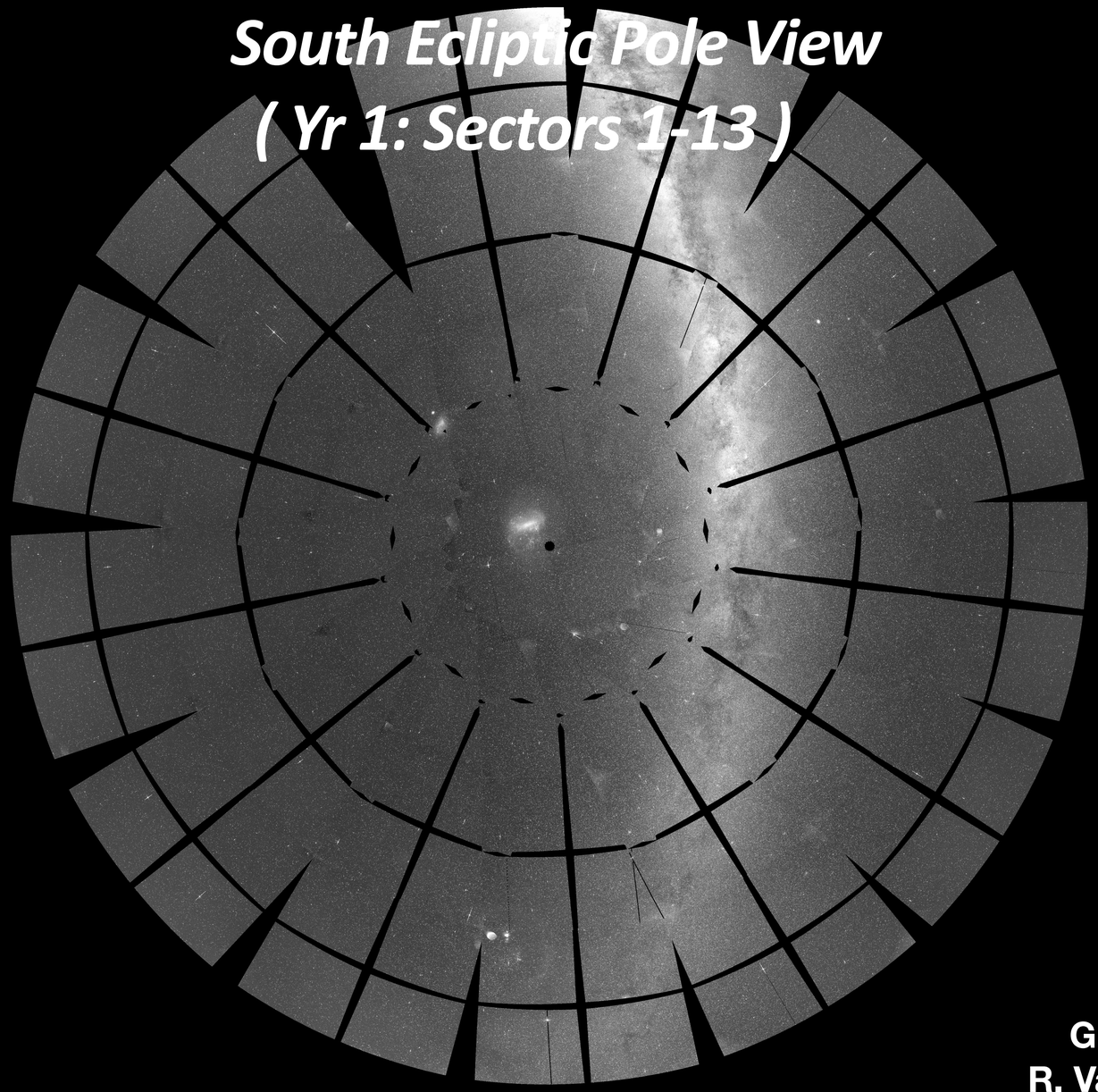
ExoPAG 23

5 January 2021

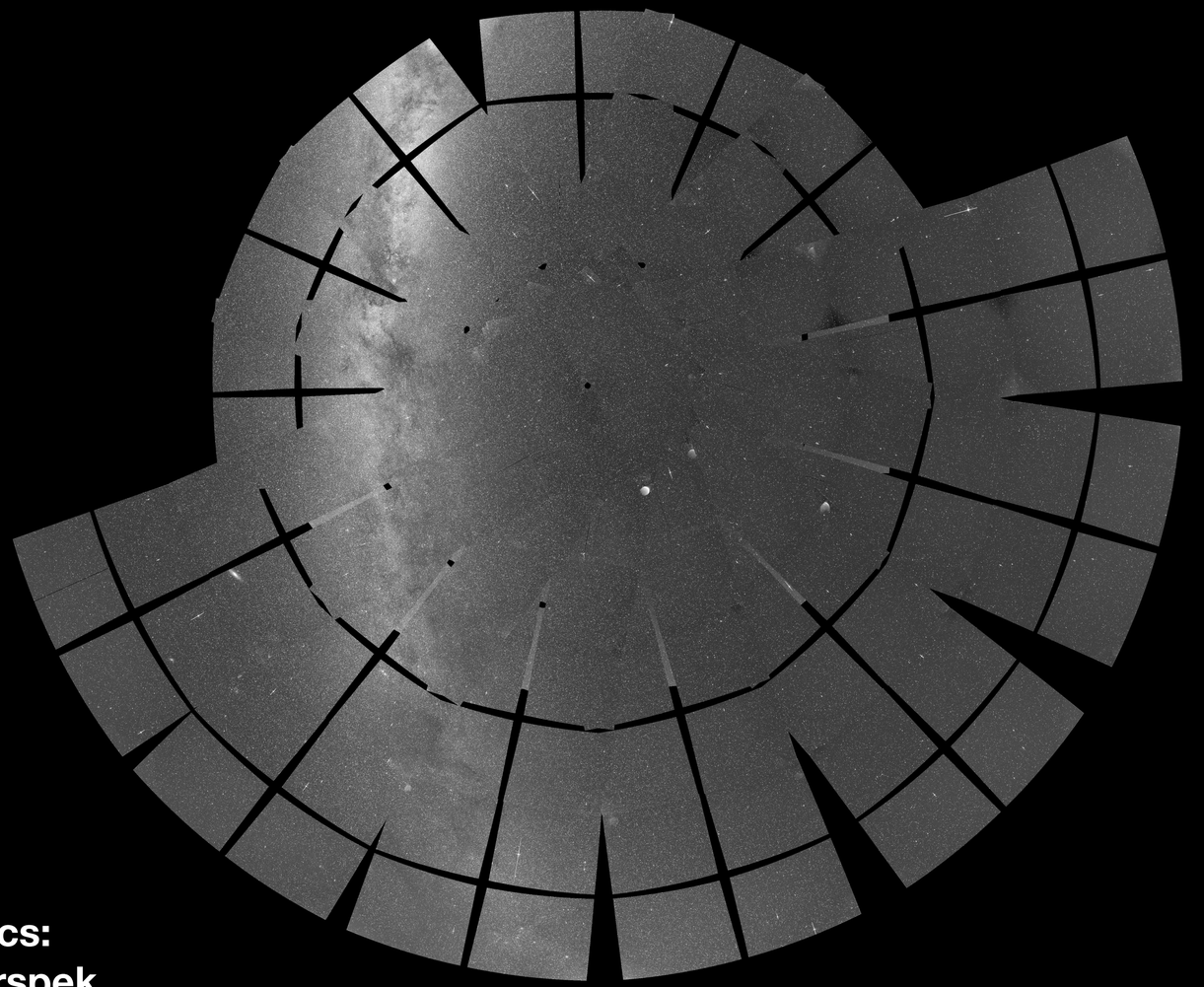
TESS is a collaboration including:
MIT/MKI, MIT/LL, NASA Goddard, NASA Ames, NGSS, SpaceX, STScI, SAO, MPIA-Germany, Las Cumbres Observatory, Geneva Observatory, OHP-France, University of California, Aarhus University-Denmark, Harvard College Observatory, Cornell University, Princeton University, Vanderbilt University...

TESS Montage of Sectors 1-26 from Prime Mission

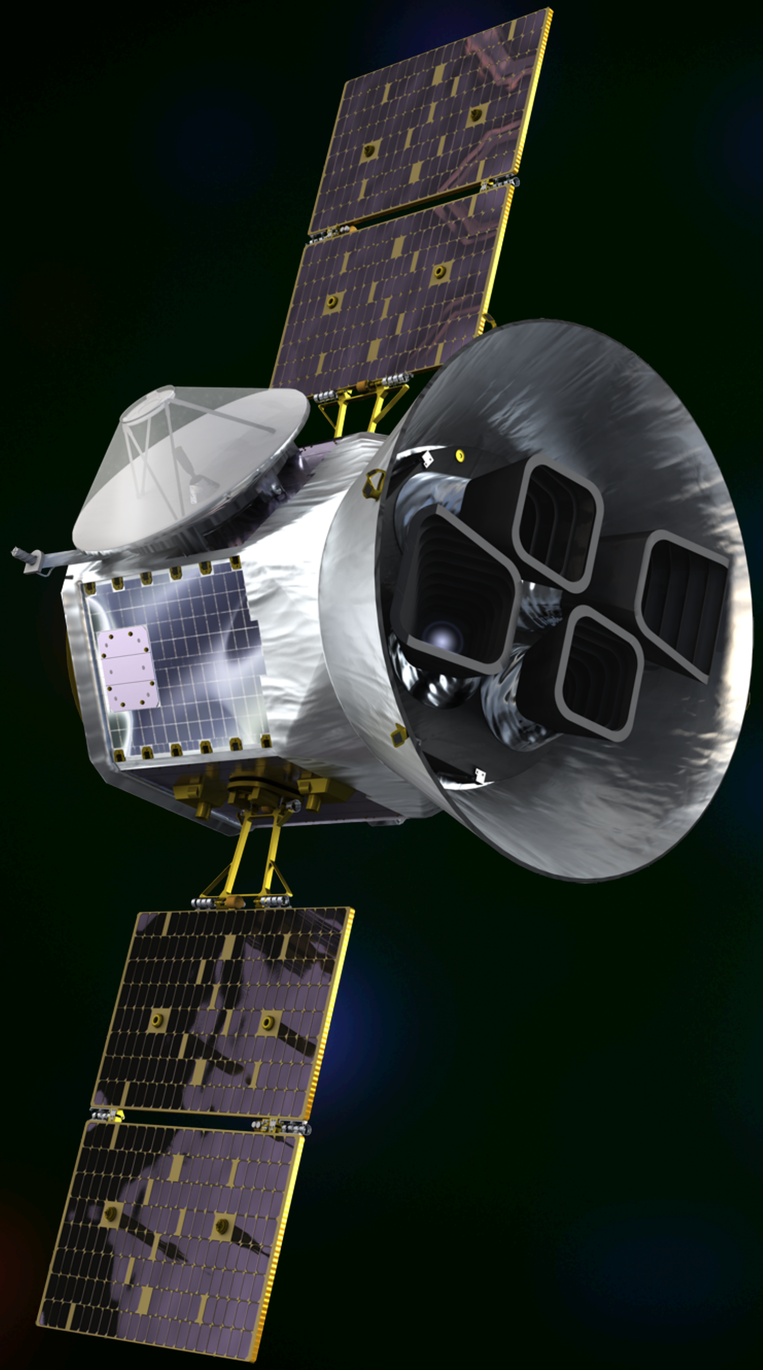
South Ecliptic Pole View
(Yr 1: Sectors 1-13)



North Ecliptic Pole View
(Yr 2: Sectors 14-26)



Graphics:
R. Vanderspek

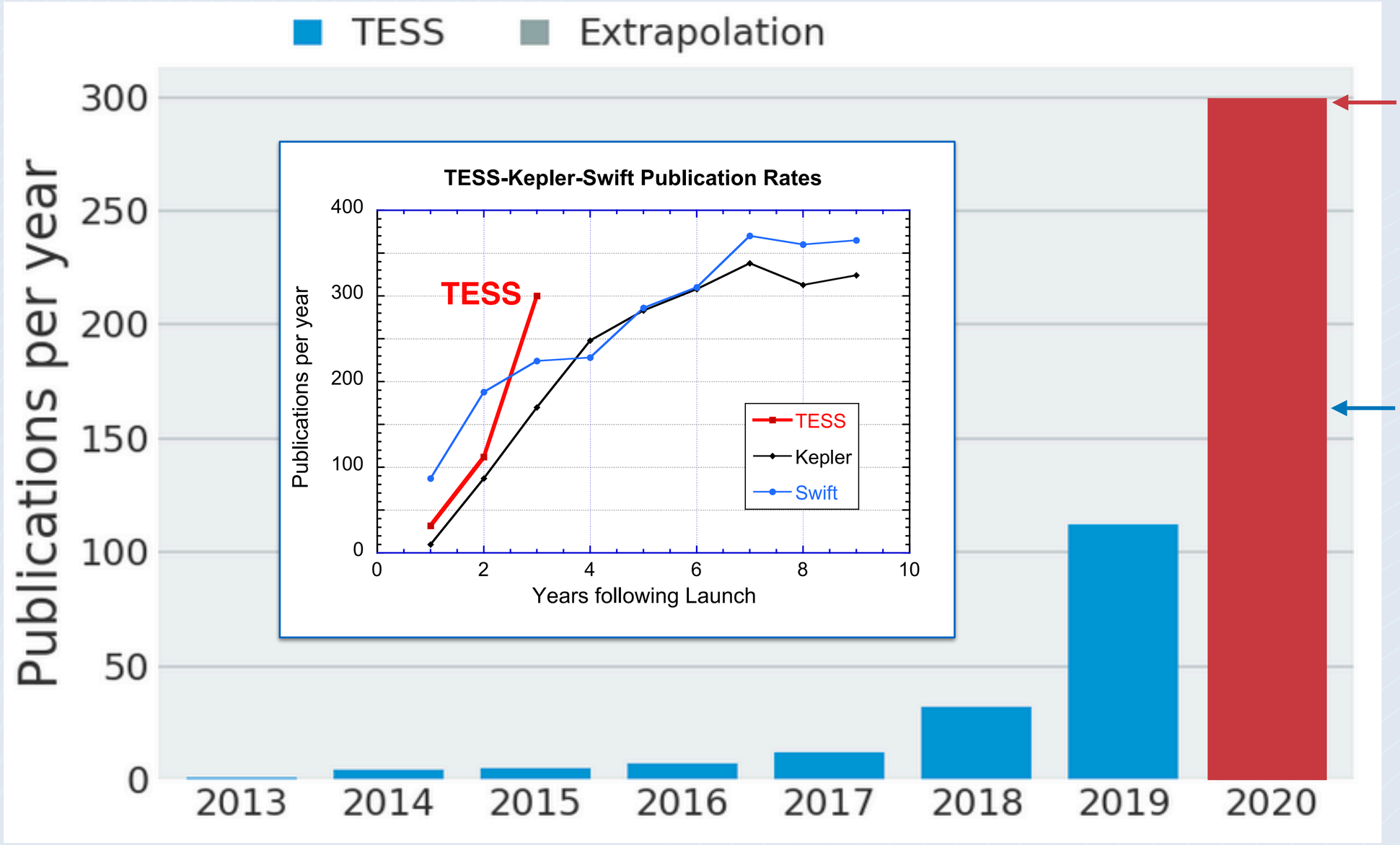


TESS Project Update:

Exoplanet Observations

Many TESS
transiting exoplanet discovery
papers are in press
or
in preprint

TESS Publications on arXiv by Year



TESS Exoplanets Detected as of 12/31/20:

— 2440 Planet Candidates (“TOIs”)

➡ ~1/3 of PCs have $R_{PC} < 4\ R_{\oplus}$

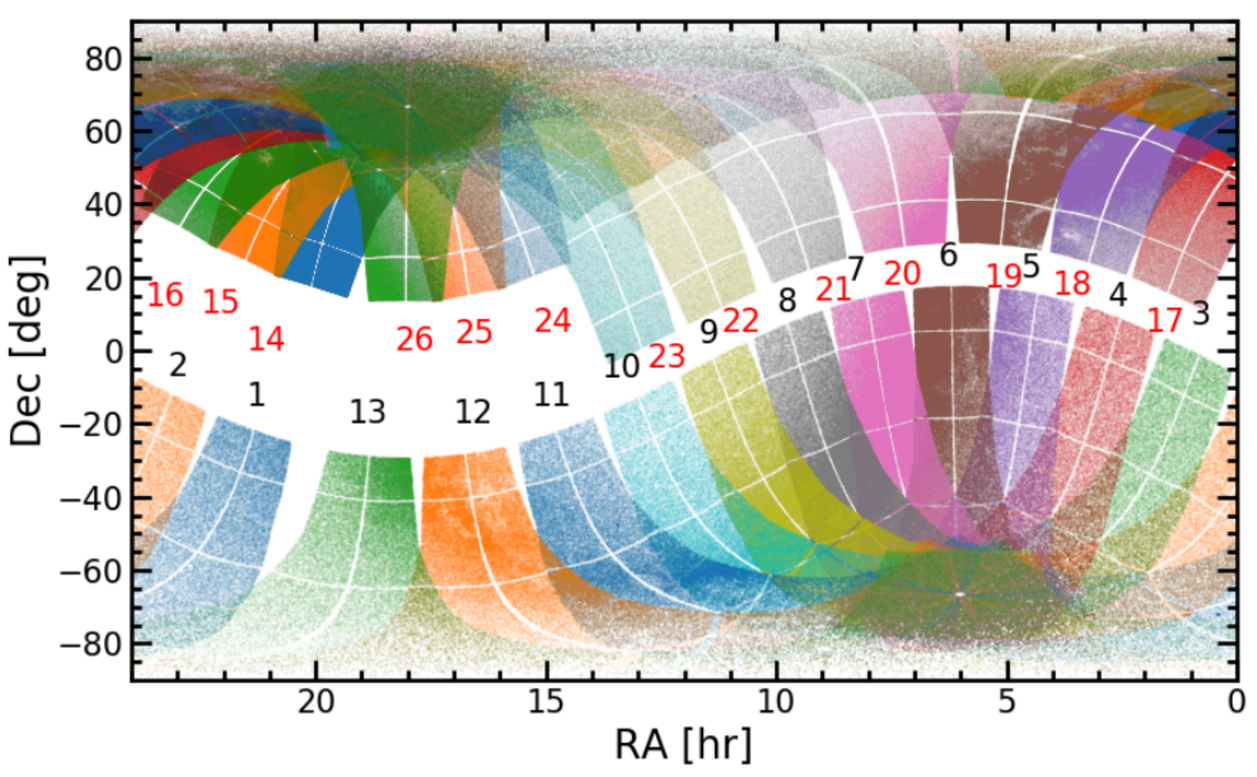
— See https://exoplanetarchive.ipac.caltech.edu/

Photometry of 10 Million Stars from the First Two Years of TESS Full Frame Images

Chelsea X. Huang,[1,*] Andrew Vanderburg,[2] Andras Pál,[1] Lizhou Sha,[1,2] Liang Yu,[1] Willie Fong,[1] Michael Fausnaugh,[1] Avi Shporer,[1] Natalia Guerrero,[1] Roland Vanderspek,[1] and George Ricker[1]

[1] *Kavli Institute for Astrophysics and Space Research, Massachusetts Institute of Technology, Cambridge, MA, USA 02139*

[2] *Department of Astronomy, University of Wisconsin-Madison*



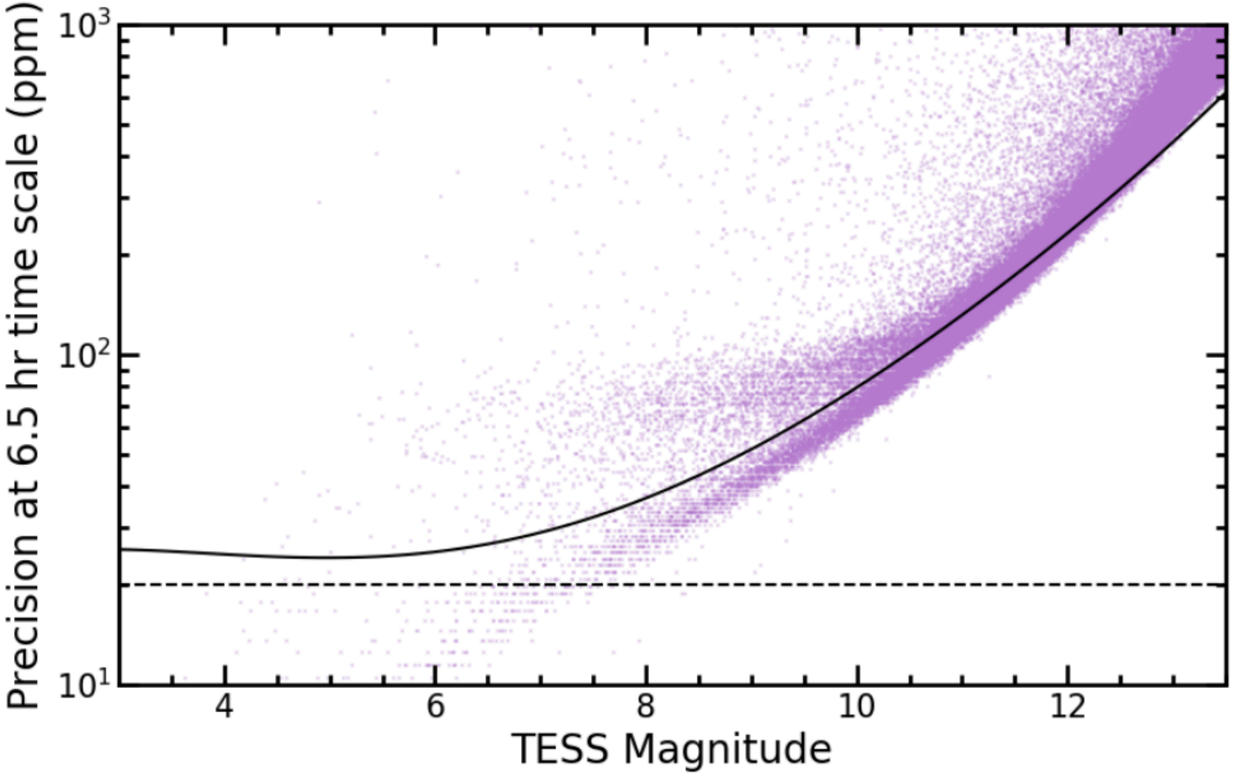
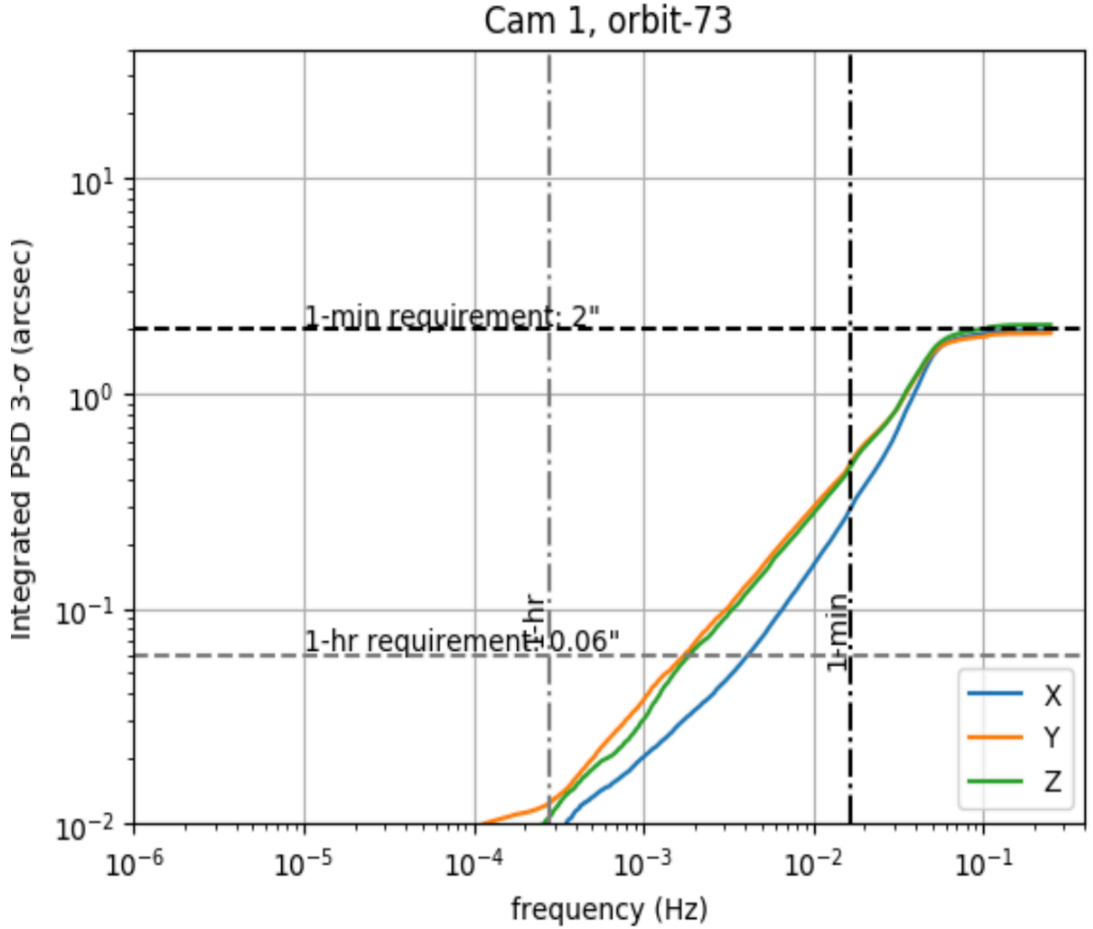
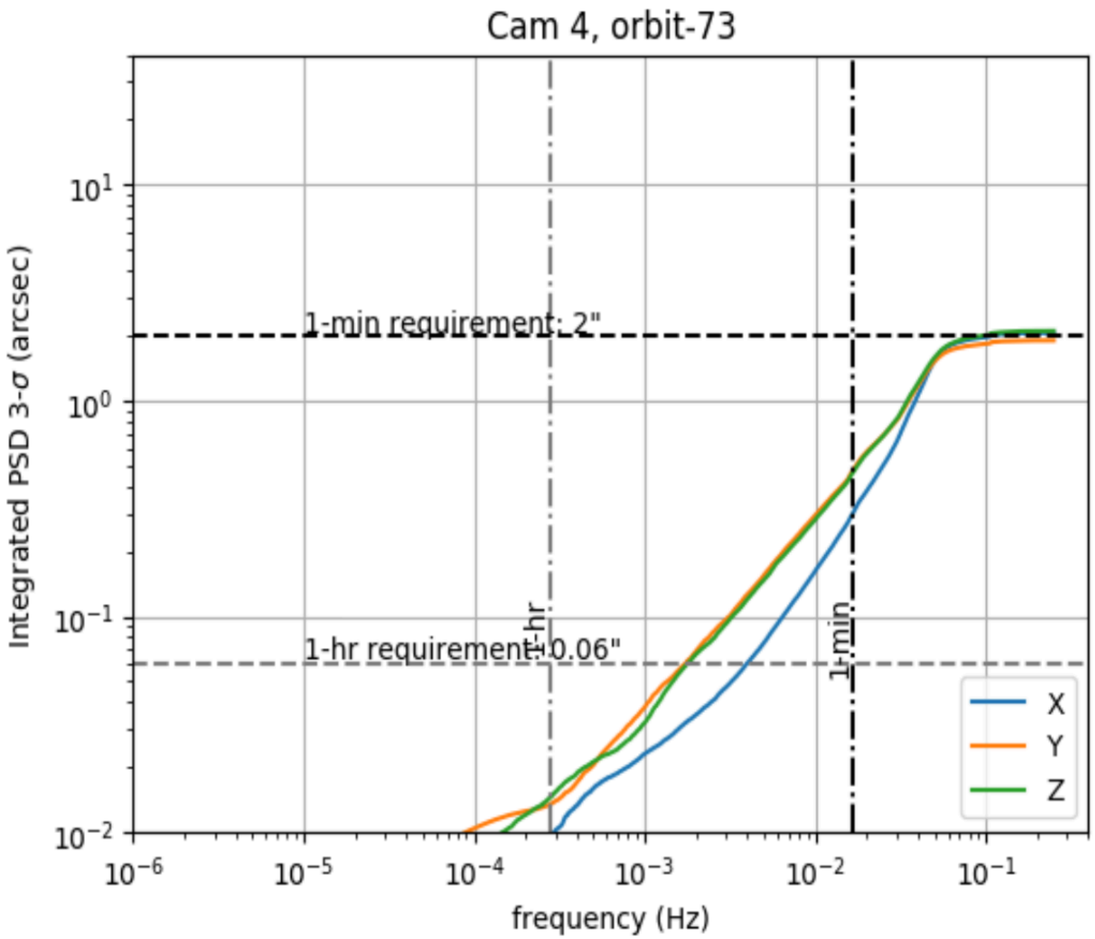


Figure 1. Left: An illustration of all the stars for which we extracted photometry from the TESS Primary Mission FFIs in terms of their equatorial coordinates. Right: The photometric precision of the time series, compared to expected theoretical precision estimated in Sullivan et al. (2015) (solid line). The dashed horizontal line is a reference indicating 20 ppm precision.

TESS's Exceptional Pointing Stability is a Key to its Photometric Precision





1 min: 0.5 arcsec (3σ) = 24 millipix

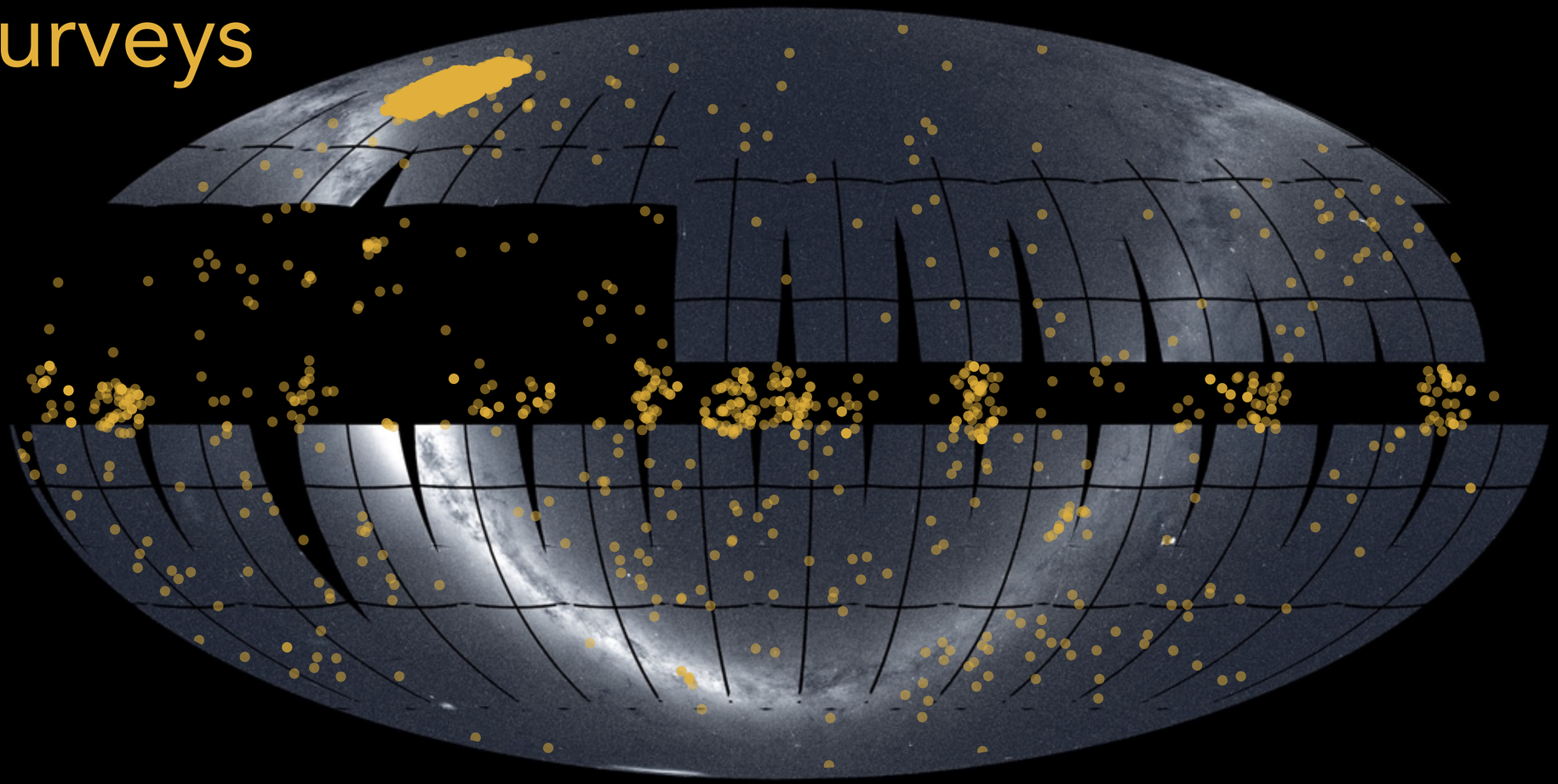
1 hr: 13 milliarcsec (3σ) = 0.6 millipix ~ 20 Si atomic spacings!

Values are 4x better than the original mission requirement

2,440 TESS planet candidates

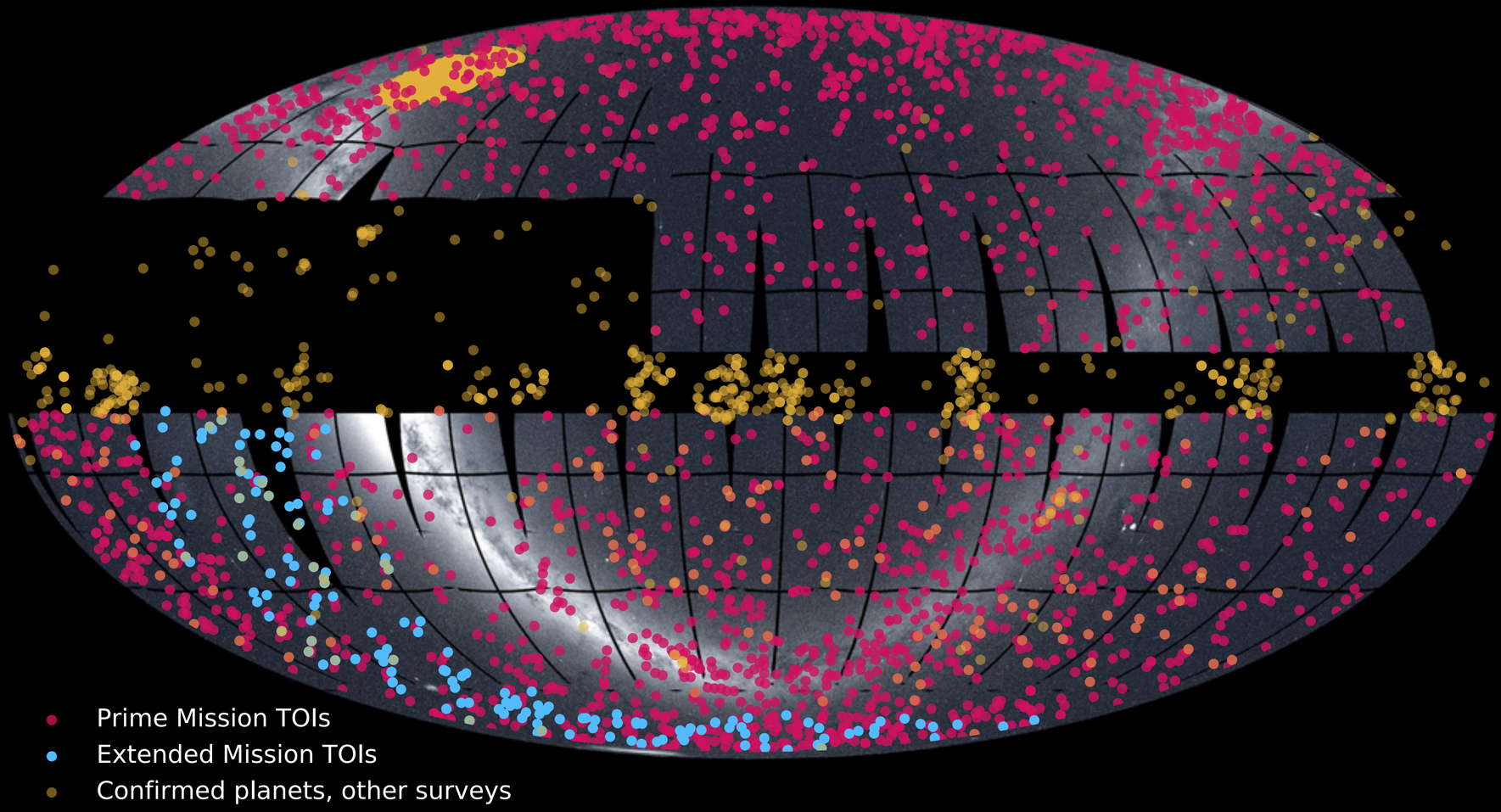
TESS image data courtesy of NASA/MIT/TESS: Natalia Guerrero & Team: Ethan Kruse (USRA), Greggy Bazile

3,189 transiting planets from other surveys



TESS image data courtesy of NASA/MIT/TESS: Natalia Guerrero & Team: Ethan Kruse (USRA), Greggy Bazile

There are thousands of worlds across the night sky



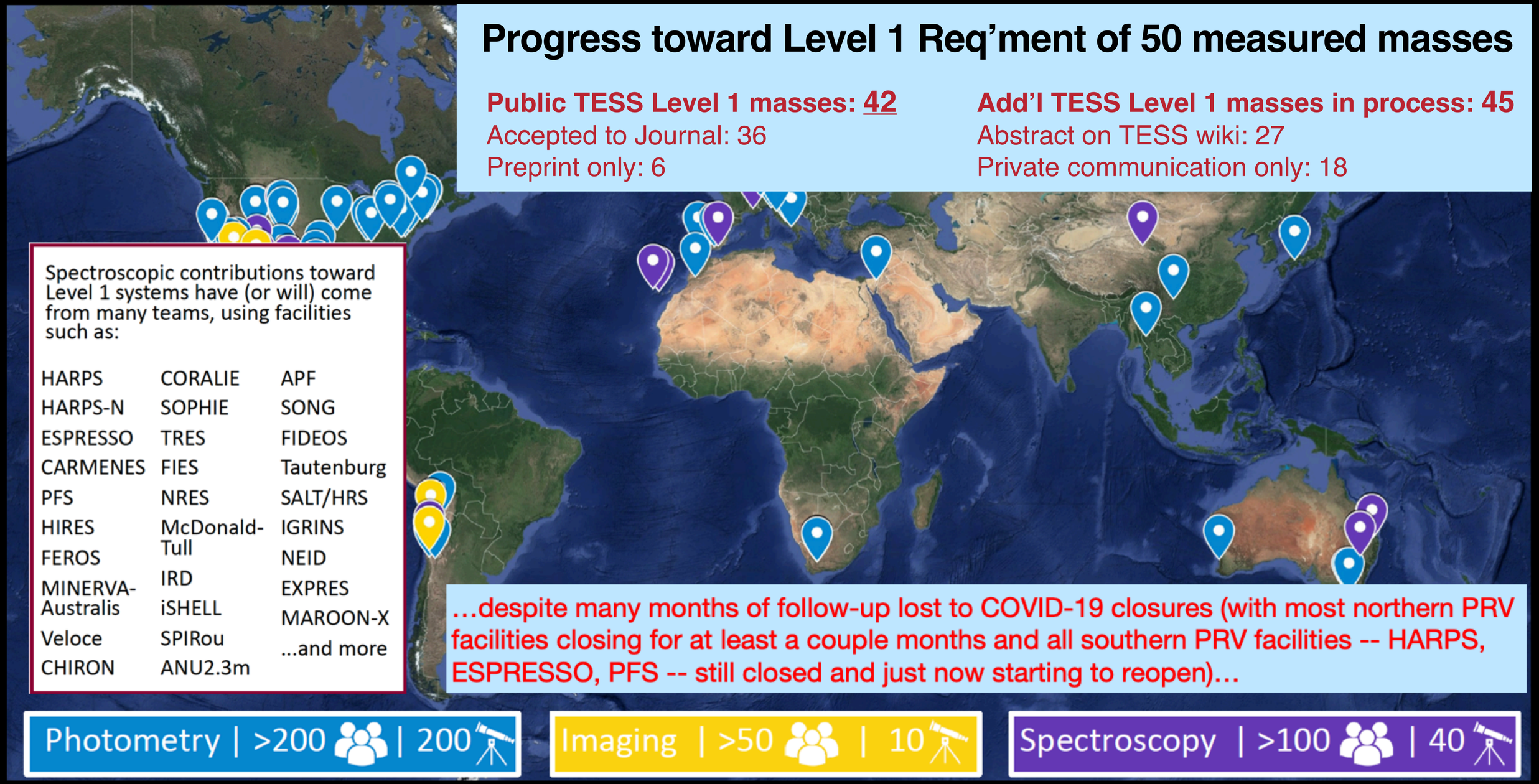
TESS image data courtesy of NASA/MIT/TESS: Natalia Guerrero & Team: Ethan Kruse (USRA), Greggy Bazile

TESS Follow-Up Program (TFOP)— (S. Quinn, private comm)

Progress toward Level 1 Req'ment of 50 measured masses

Public TESS Level 1 masses: 42
Accepted to Journal: 36
Preprint only: 6

Add'l TESS Level 1 masses in process: 45
Abstract on TESS wiki: 27
Private communication only: 18



Spectroscopic contributions toward Level 1 systems have (or will) come from many teams, using facilities such as:

HARPS	CORALIE	APF
HARPS-N	SOPHIE	SONG
ESPRESSO	TRES	FIDEOS
CARMENES	FIES	Tautenburg
PFS	NRES	SALT/HRS
HIRES	McDonald-Tull	IGRINS
FEROS	IRD	NEID
MINERVA-Australis	iSHELL	EXPRES
Veloce	SPIRou	MAROON-X
CHIRON	ANU2.3m	...and more

…despite many months of follow-up lost to COVID-19 closures (with most northern PRV facilities closing for at least a couple months and all southern PRV facilities -- HARPS, ESPRESSO, PFS -- still closed and just now starting to reopen)…

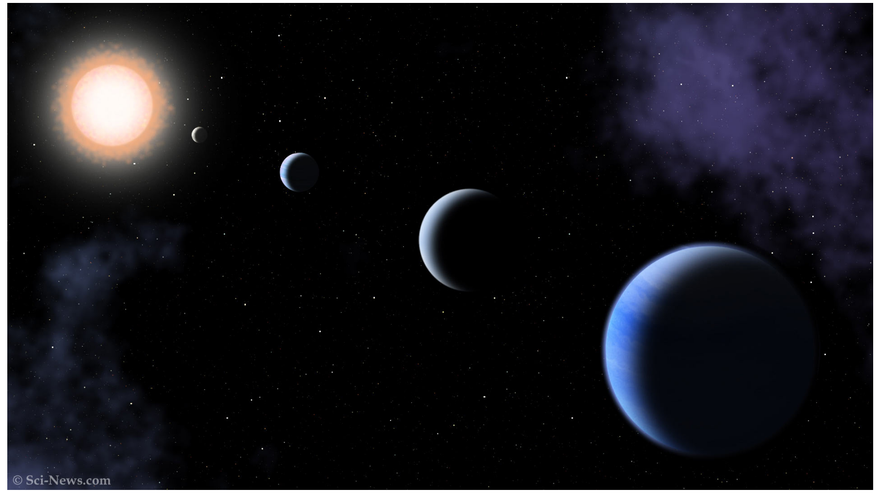
Photometry | >200 | 200

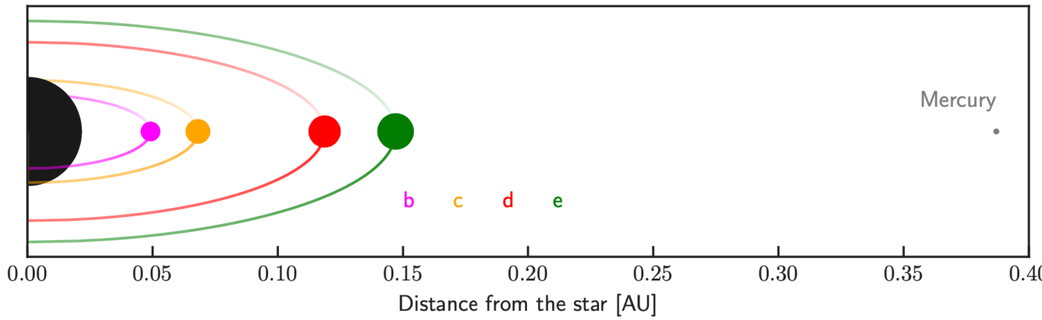
Imaging | >50 | 10

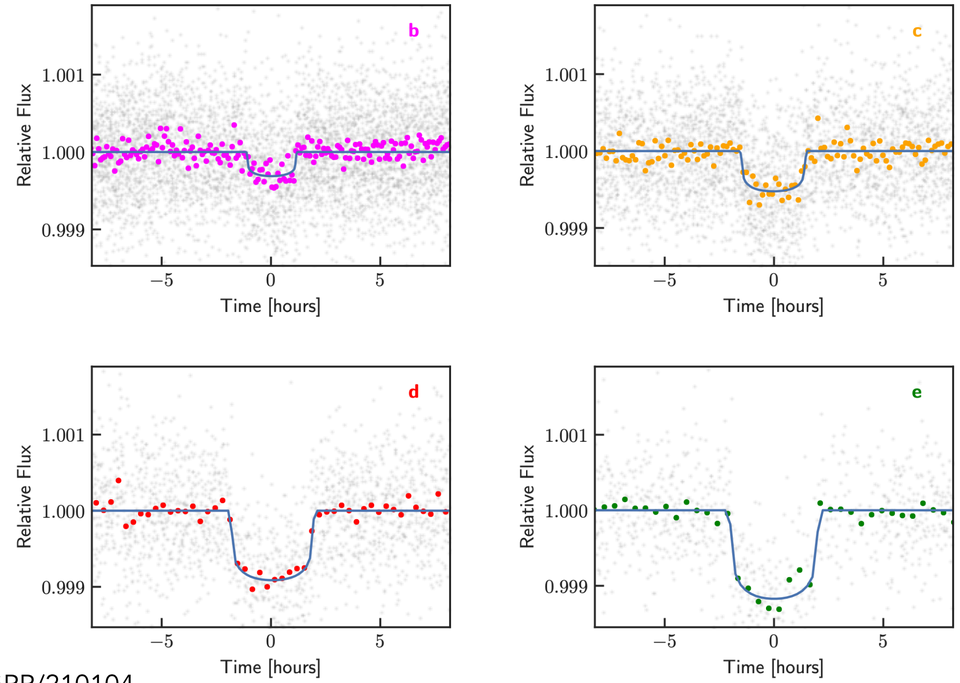
Spectroscopy | >100 | 40

TOI 1233: a "Super-Earth" and three sub-Neptunes orbiting the bright Sun-like star **HD 108236**

Tansu Daylan:
arXiv:2004.11314







Multiple small planets hosted by a bright star provide cosmic laboratories to test models of planet formation and evolution.

HD 108236: **the brightest Sun-like star** to host **at least** four transiting planets.

Late Breaking: **5th TOI-1233 Planet** from CHEOPS was announced **today** (Bonfanti et al. 2021)

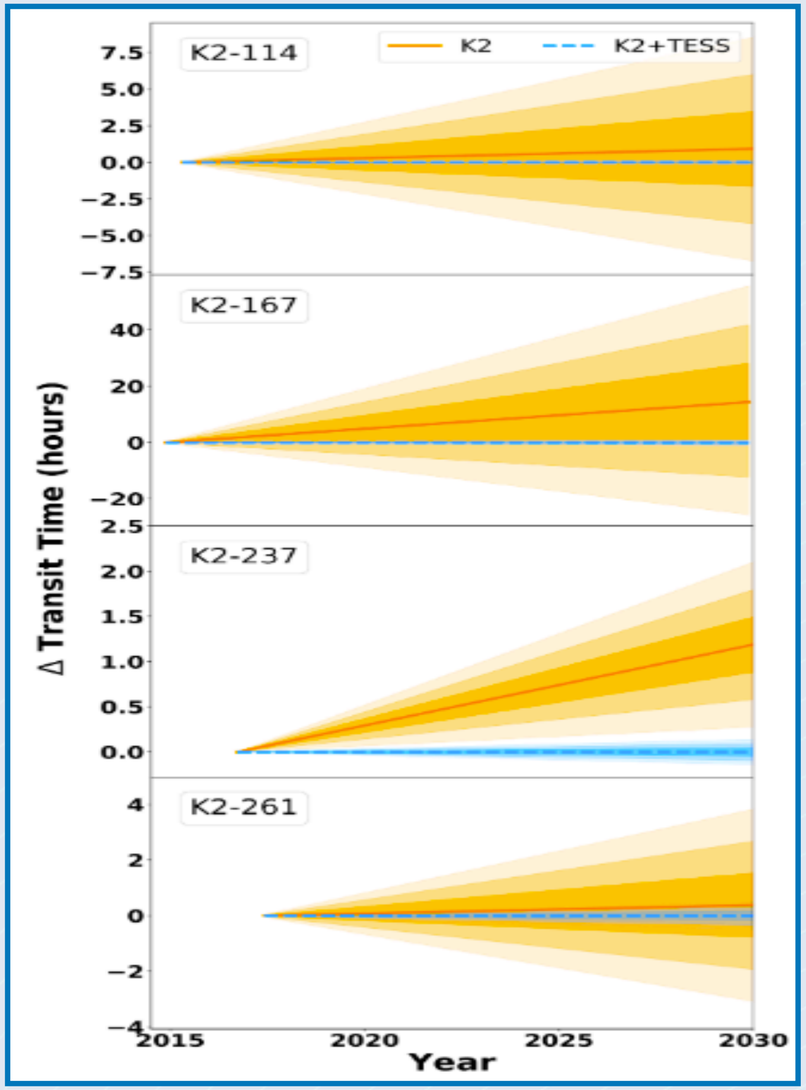
The K2 & TESS Synergy I: Updated Ephemerides and Parameters for K2-114, K2-167, K2-237, & K2-261

- Established updated ephemerides and system parameters for three Jovian sized planets and a sub-Neptune with orbital periods less than 12 days
- The updated ephemerides significantly reduce the uncertainty in prediction of future times of transit, which is essential for planning observations with the James Webb Space Telescope and other future facilities
- The TESS extended mission is expected to observe more than half of the K2 fields, enabling this type of analysis on a larger number of systems

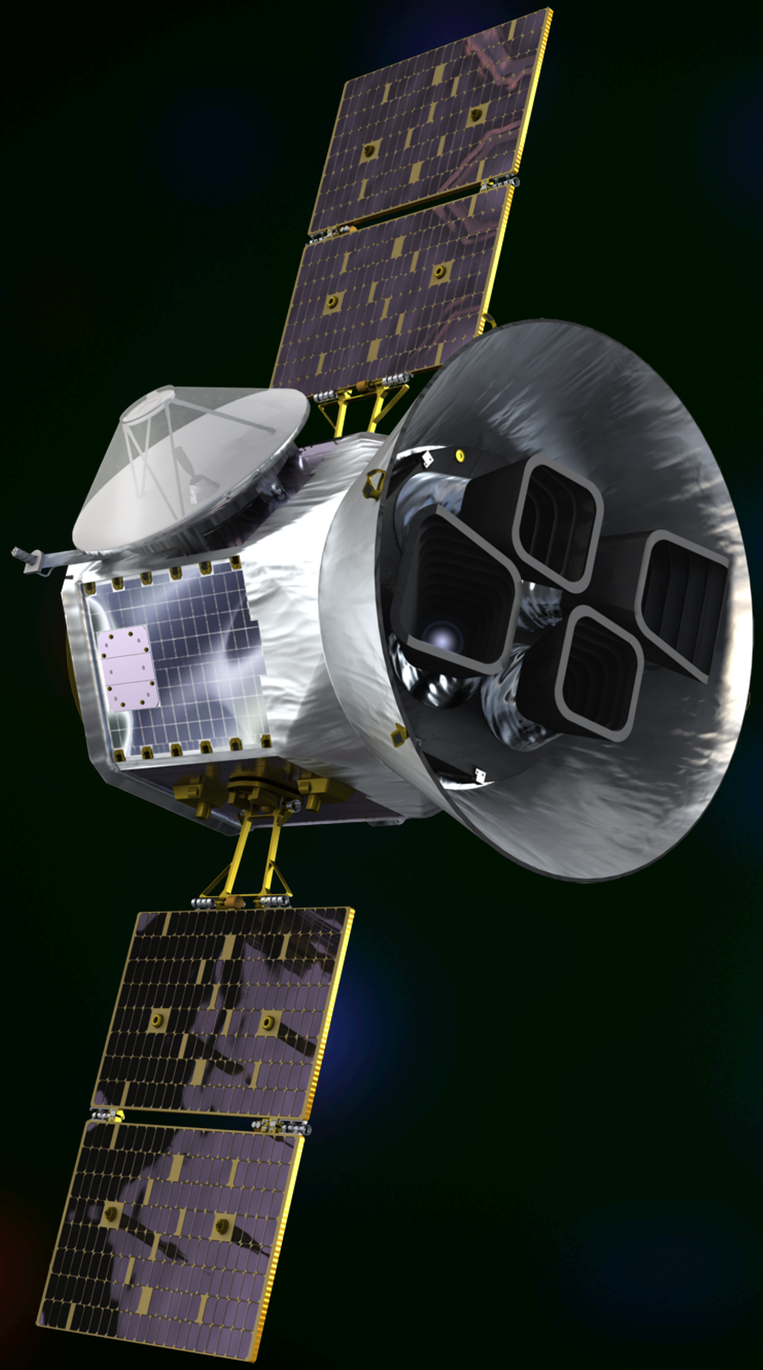
Map of K2 targets that were observed in TESS years 1 (red) and 2 (blue)

Mma Ikwut-Ukwa + 2020

arXiv:2007.00678



The difference in time of transit predicted by the K2 discovery papers as compared to the updated predictions from TESS, projected to the year 2030. The shaded regions indicate 1, 2, and 3-sigma confidence intervals.

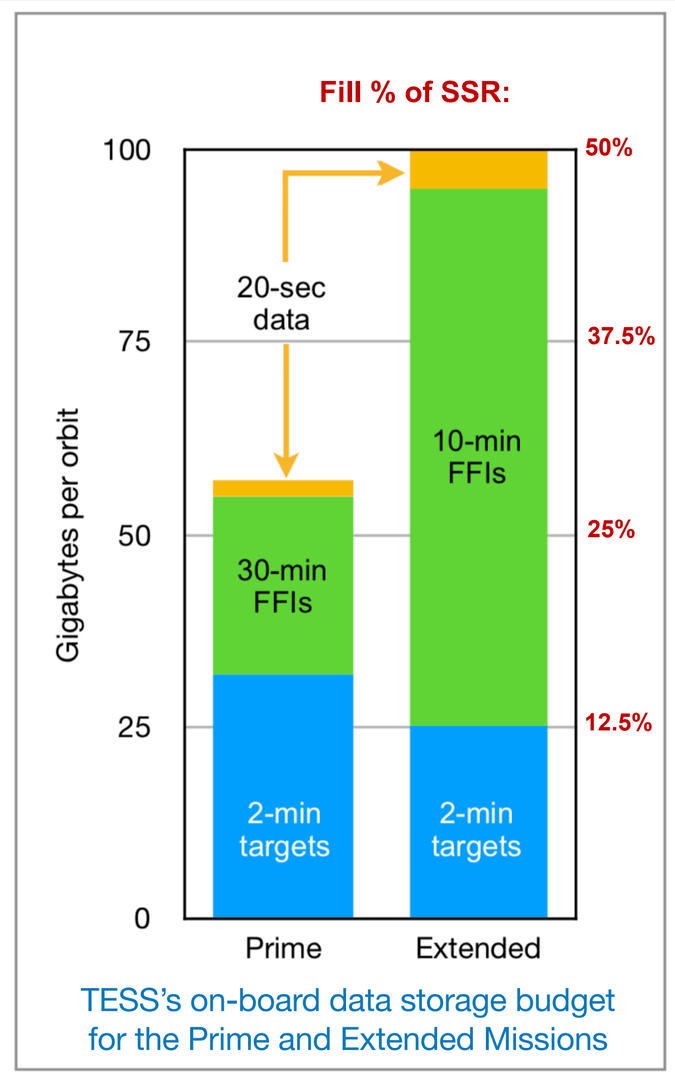


TESS Project Update:

Extended Mission

TESS Data Cadences in Extended Mission

- **FFI cadence reduced to 10 min**
  - Replaces prime mission's 30 minute cadence
- **"Postage Stamps" are augmented**
  - 120s cadence is unchanged
  - 20s cadence has been added
- **Solid State Recorder (SSR) volume usage has increased from ~30% to ~50% in Extended Mission**
  - Margin is needed in case a DSN downlink does not occur for a given TESS orbit, and a make-up DSN pass is needed during the following orbit



TESS's on-board data storage budget for the Prime and Extended Missions

Faint Star Search with TESS FFIs

Goal: To search for new planet candidates around faint stars using TESS FFIs (Sector 1 - present)

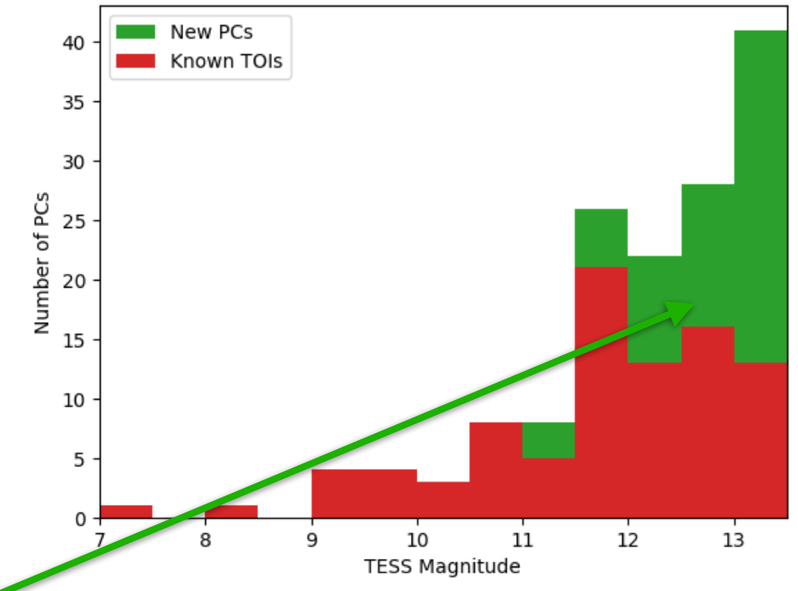
Initial search: 10.5 < TESS mag < 13.5 (20 x 10^6 stars)
Deeper search: 13.5 < TESS mag < 15 (50 x 10^6 stars)

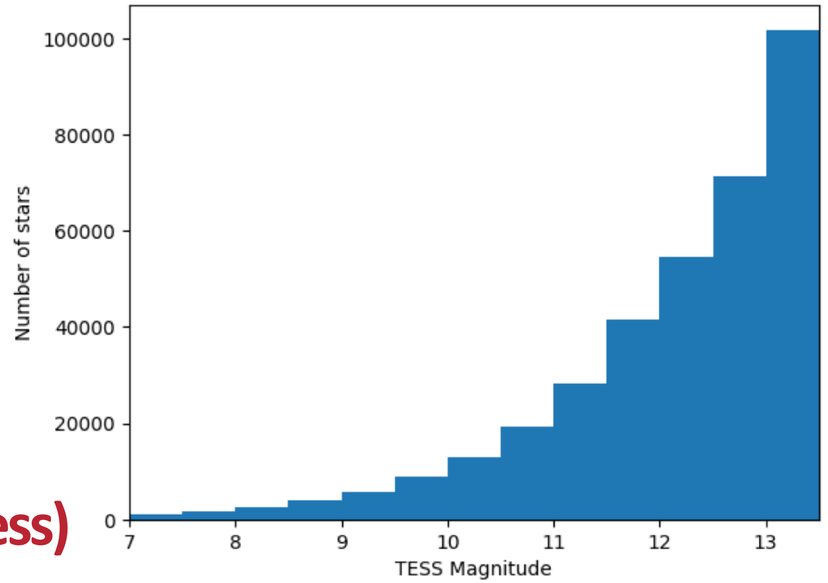
Results so far: 58 new candidates from search of 400k stars with TESS mag < 13.5 in Sector 1

Projected Results: 3000+ new candidates from initial search; potentially an additional 7000+ from deeper search

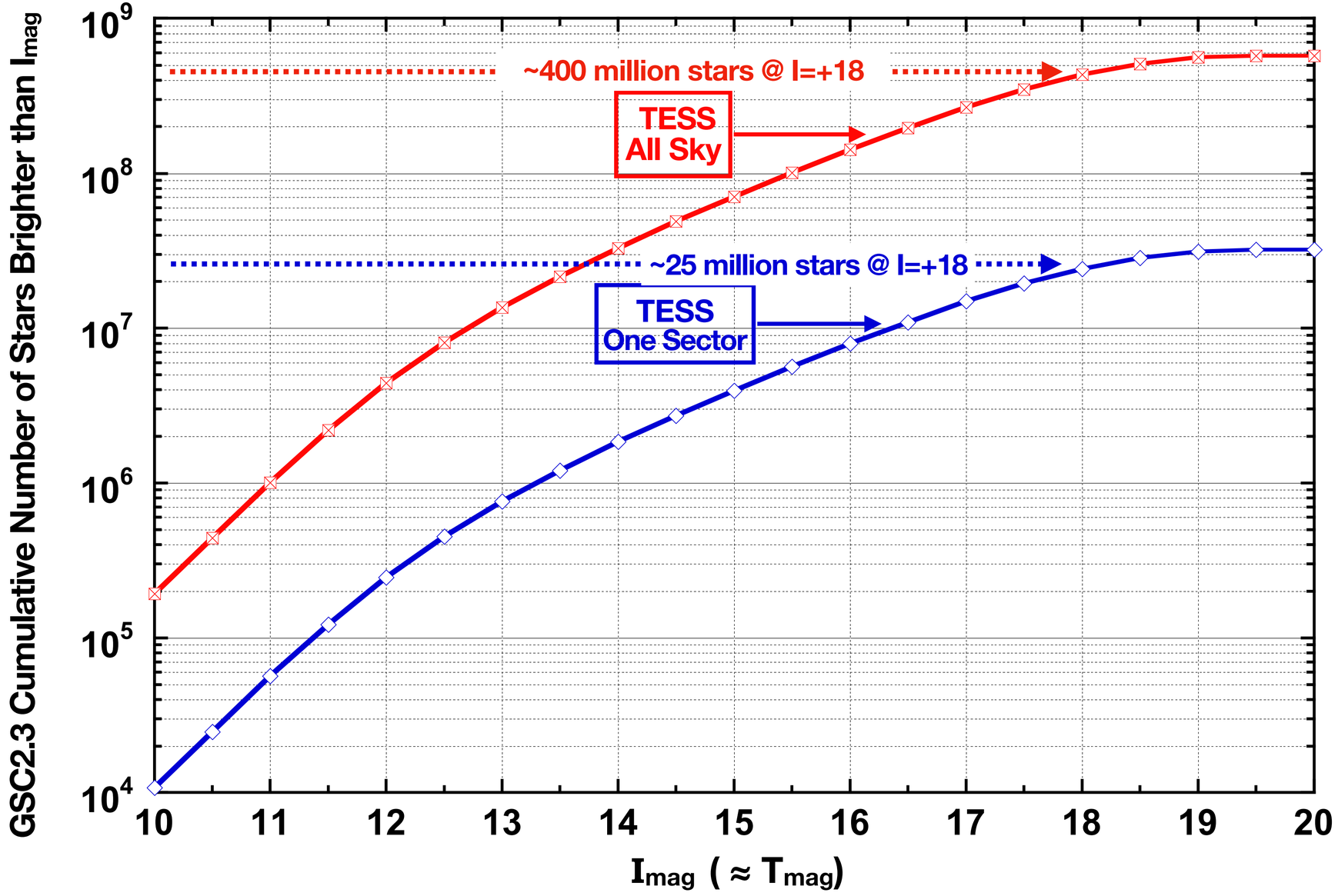
Basis: Modifications of QLP by M. Kunimoto and T. Daylan (in progress)

Sector 1 Results





TESS can photometer an enormous number of stars!



Star Count Data in I band (HST Guide Star Catalog v2.3, B. Lasker et al. 2008)

Growing Number of TESS High Level Science Products (HLSPs) at MAST

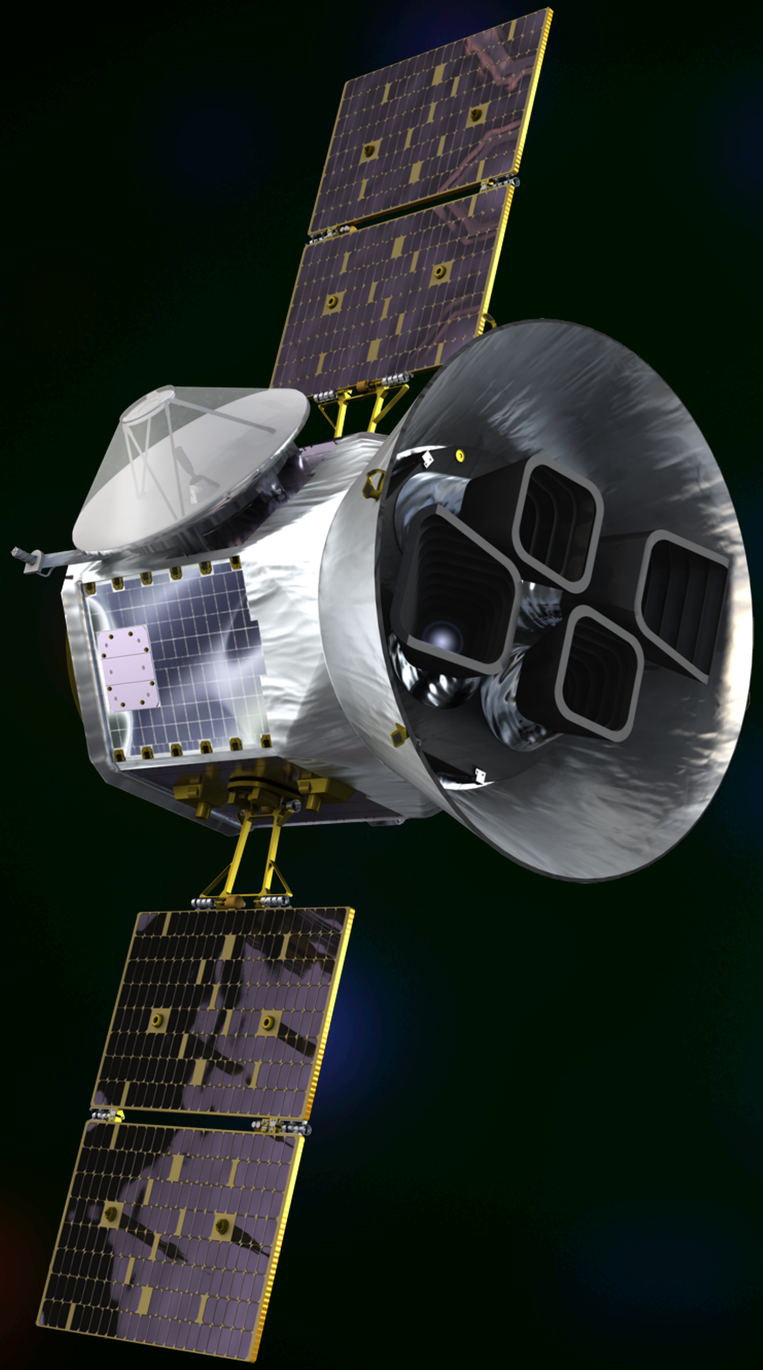
TESS Data HLSP	Initial Year	Authors	TESS Data Source	Initial Number of Sectors	Number of Objects	Remarks/Future Work	Applications
TASOC LCs	2019	R. Handberg et al.	FFIs	2 (S1-S2)	**~ 1.7 million** in 2 sectors	Add'n of co-trending	Asteroseismology
Eleanor LCs	2019	A. Feinstein et al.	FFIs	13 (S1-S13)	**~ 13 million** in 13 sectors	T=16 mag limit	Time domain astrophysics
PATHOS LCs	2019	D. Nardillo	FFIs	13 (S1-S13)	**> 200,000** in 13 sectors		Open and globular clusters, young stellar associations
CDIPS LCs	2019	L. Bouma et al.	FFIs	13 (S1-S13)	**> 670,000** in 13 sectors		Young cluster and moving group candidate stars
SPOC LCs	2020	D. Caldwell et al.	FFIs	13 (S14-S26)	**~ 4 million** in 13 sectors	T=13.5 mag limit	Exoplanets
QLP LCs	2020	X. Huang et al.	FFIs	26 (S1-S26)	**~ 10 million** in 26 sectors	S27 onwards; Extension to T=15 mag (Kunimoto et al. in prep)	Exoplanets, Variable Stars
DIAMANTE LCs	2020	M. Montalto et al.	FFIs	13 (S1-S13)	**~ 1 million** in 13 sectors		Exoplanets
TICA FFIs	2020	M. Fausnaugh et al.	FFIs	4 (S27-S31)	**~ 15 million per sector** (T < +17 limit; estimate based on GSC 2.3)	Front end product from MIT QLP with BCS added; Prompt releases for Yr 3+	Asteroids, NEOs, transients, binary stars and WDs, new classes of time variability studies

https://archive.stsci.edu/hlsp/qlp

Comparison: "Special Planets" anticipated from TESS Primary and Extended Missions

	Prime Mission	Extended Mission	Prime + Extended Missions
Timeframe	Jul 2018 – Jun 2020	Jul 2020 – Sep 2022	**Jul 2018 - Sep 2022**
Total new small planets ($R < 4R_E$)	908	**1331**	**2239**
Planets in or near habitable zone ($0.5 < S/S_E < 2$)	58	**91**	**149**
Planets with periods longer than 20 days	199	**509**	**708**

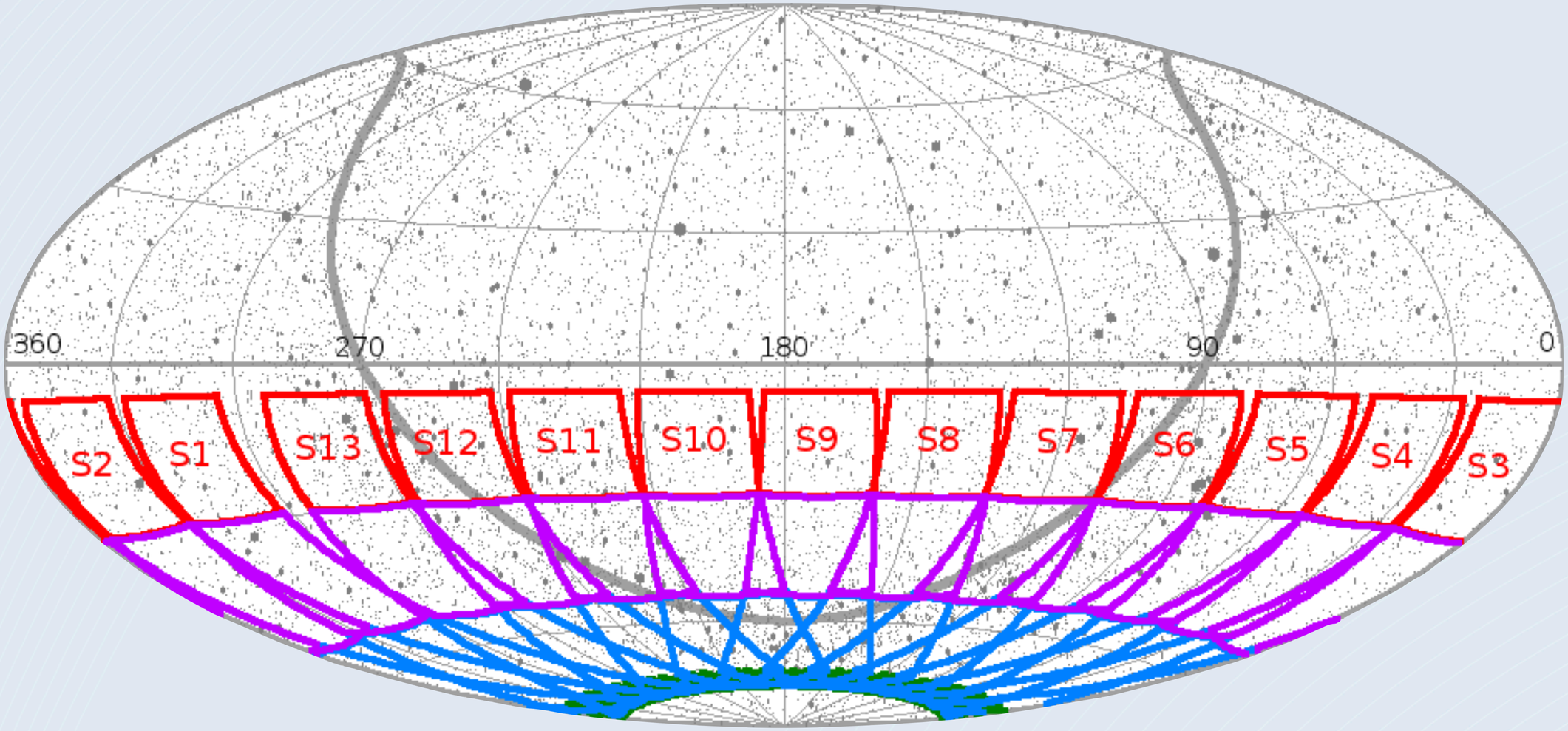
Simulations from TESS Extended Mission Proposal
(Sullivan+ 2015; Bouma+ 2017; Barclay+ 2018)



TESS Project Update:

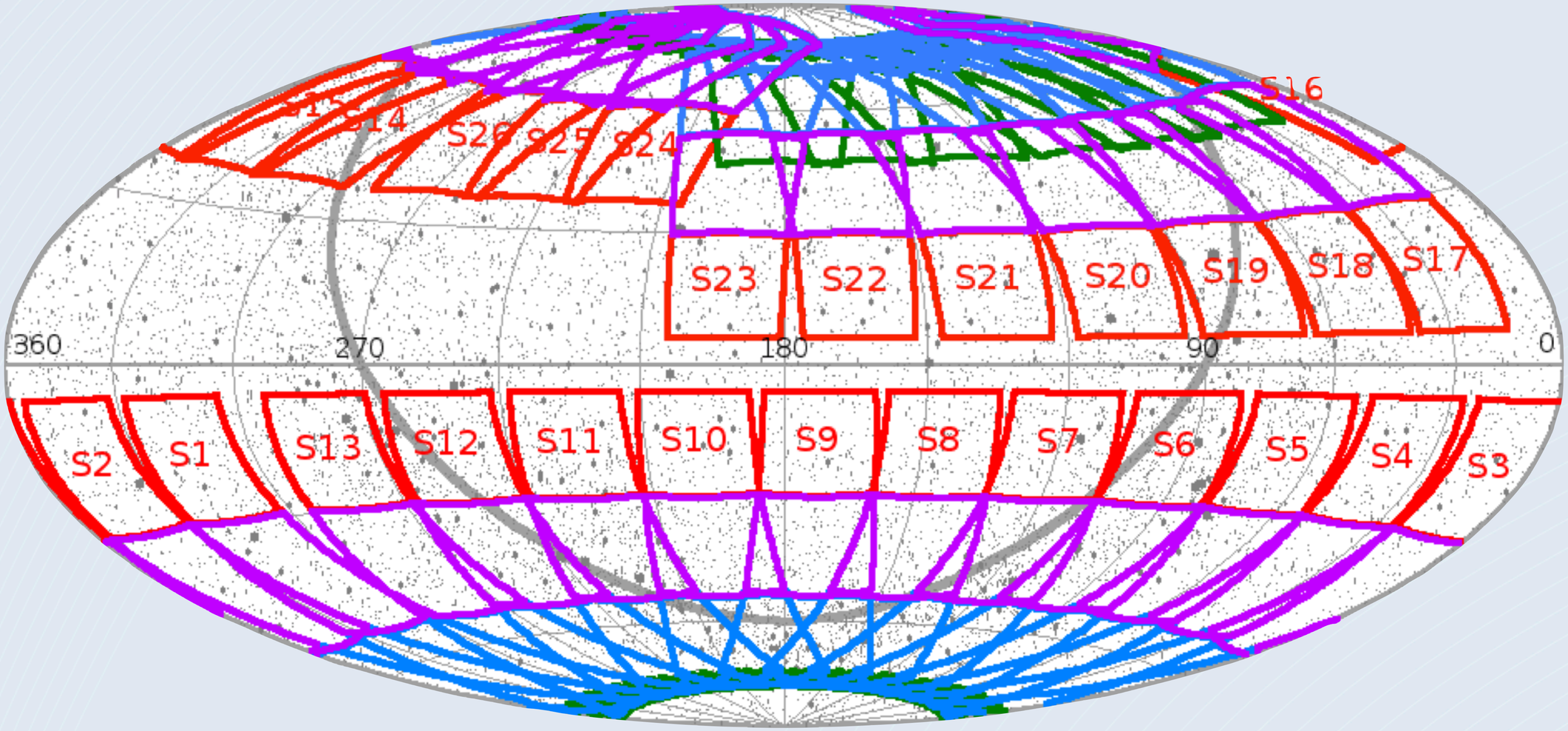
Extended Mission Sky Survey Plans

TESS Sky Coverage Maps



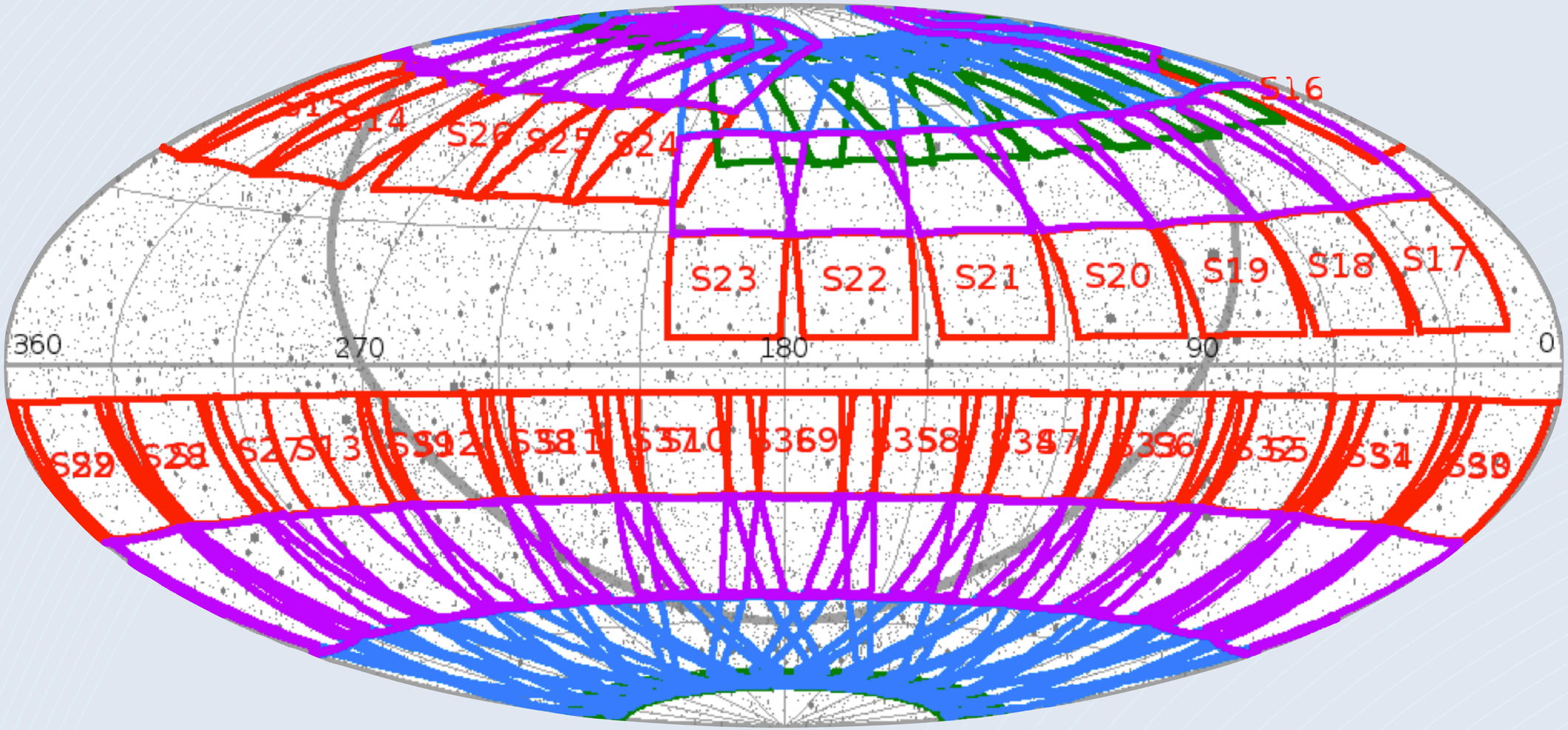
Year 1 of the Mission (Jul 2018-Jun 2019)

TESS Sky Coverage Maps



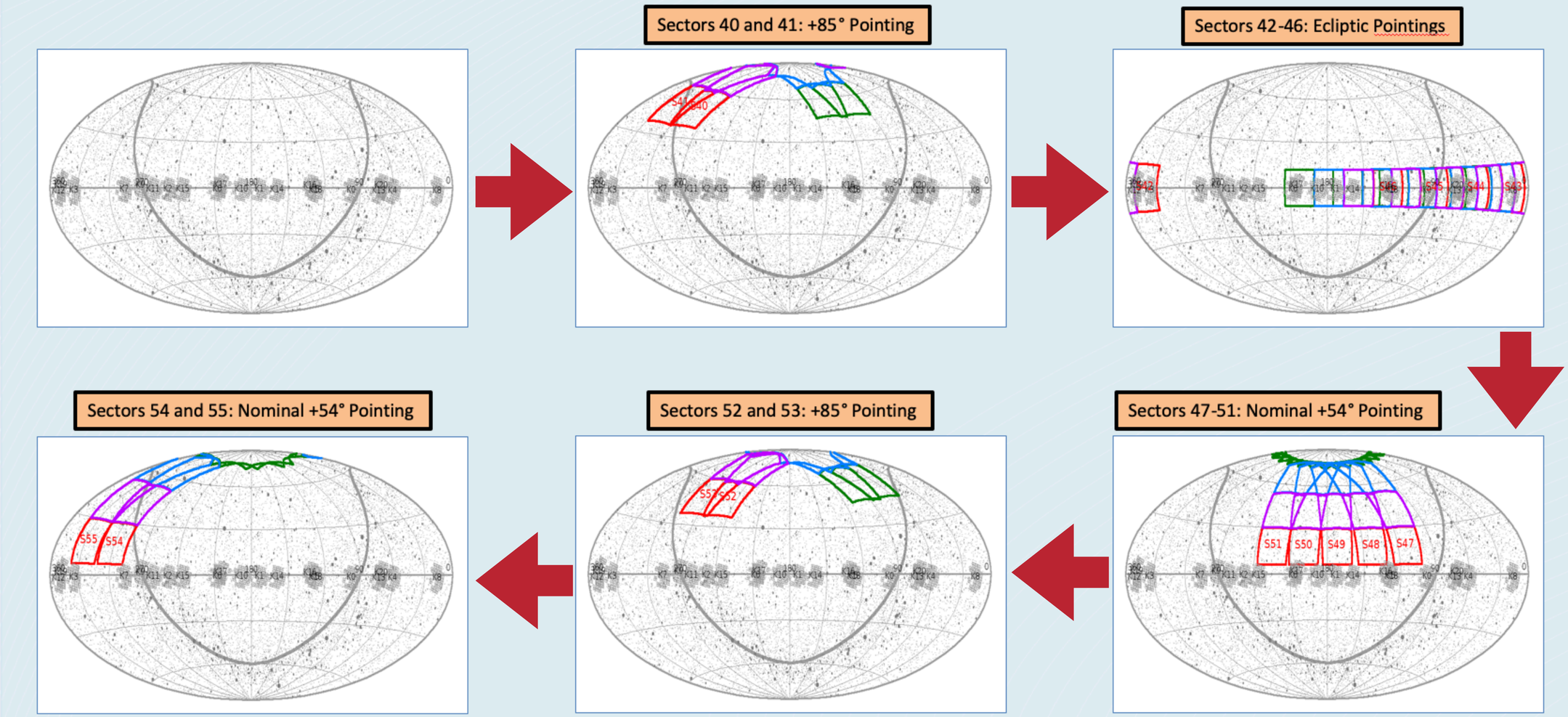
Adding Year 2 of the Mission (Jul 2019-Jun 2020)

TESS Sky Coverage Maps



Then Year 3 of the Mission (Jul 2020-Jun 2021)

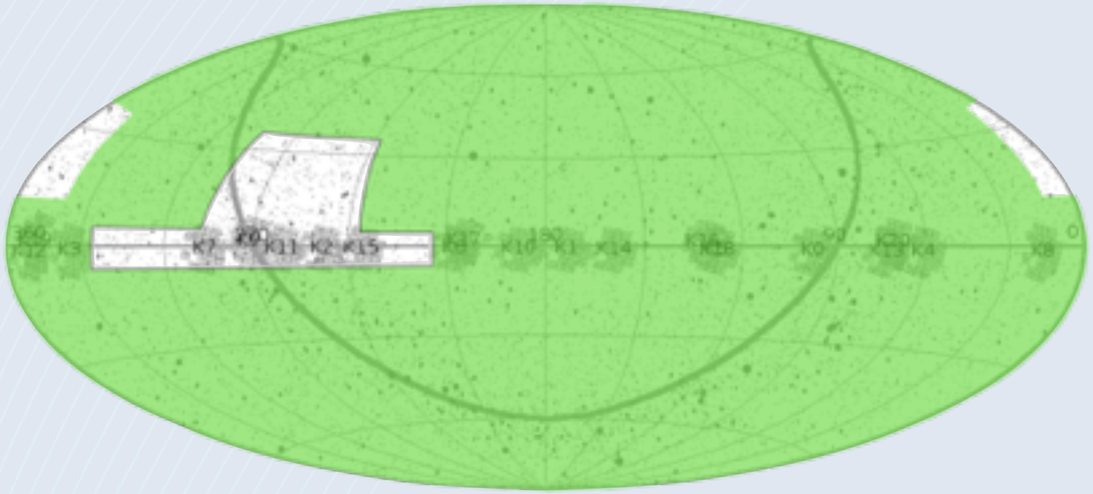
Sector Pointings for "Year 4" (16 sectors: 7/2021-9/2022)



Notes:

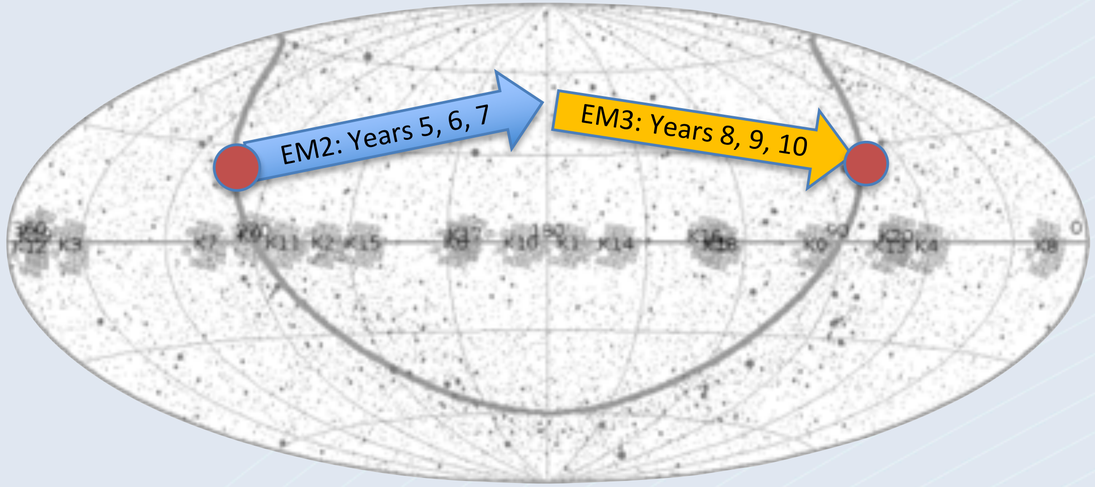
- Each TESS Ecliptic Pointing covers a 96° long swath in Ecliptic Longitude => ~27% of the Ecliptic per pointing
- Interior sectors of the Ecliptic swath could have 4 sectors of overlap => ~110 days of observation for those stars
- More than 60% of the Ecliptic could be covered during 5 sectors => ~ 60% of the K2 Planets would be re-observed
- Plan is somewhat complex so as to avoid undue impacts of Earth-Moon scattered light

TESS Total Sky Coverage and Orbit Precession



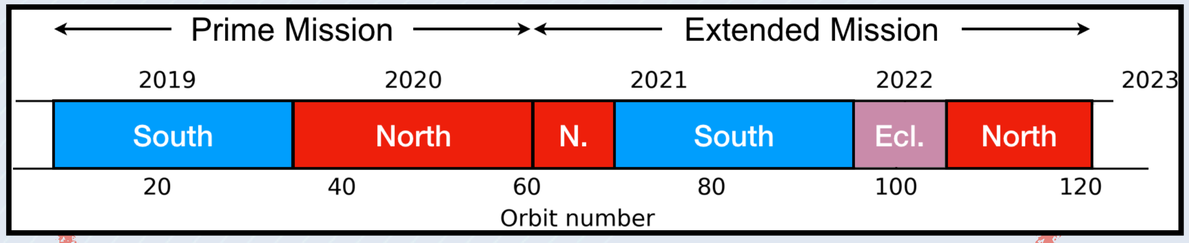
Sky Coverage in Prime plus Extended Mission:
88% in 51 months

(Includes 15 of the 20 K2 Fields)



Apparent migration on the sky of excess scattered light region as the TESS orbit precesses

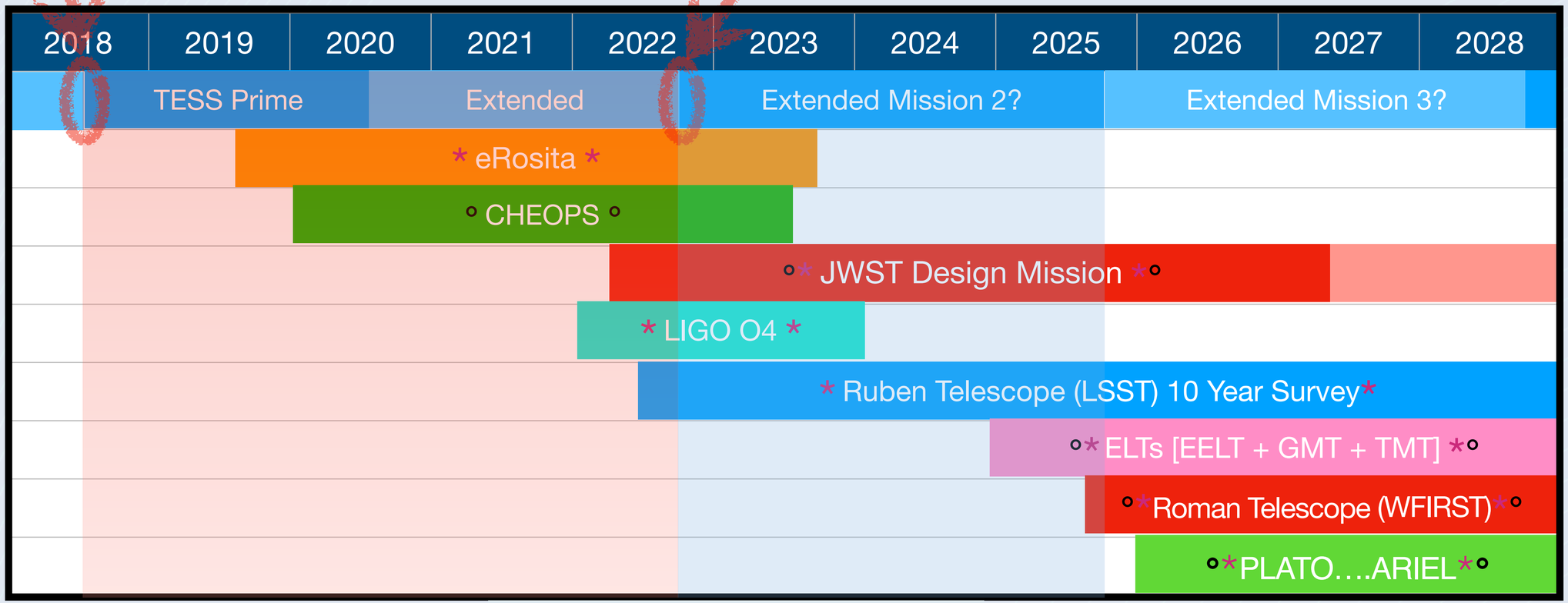
Timelines for the Coming Decade: TESS and Related Missions



Legend:

°Exoplanet Mission

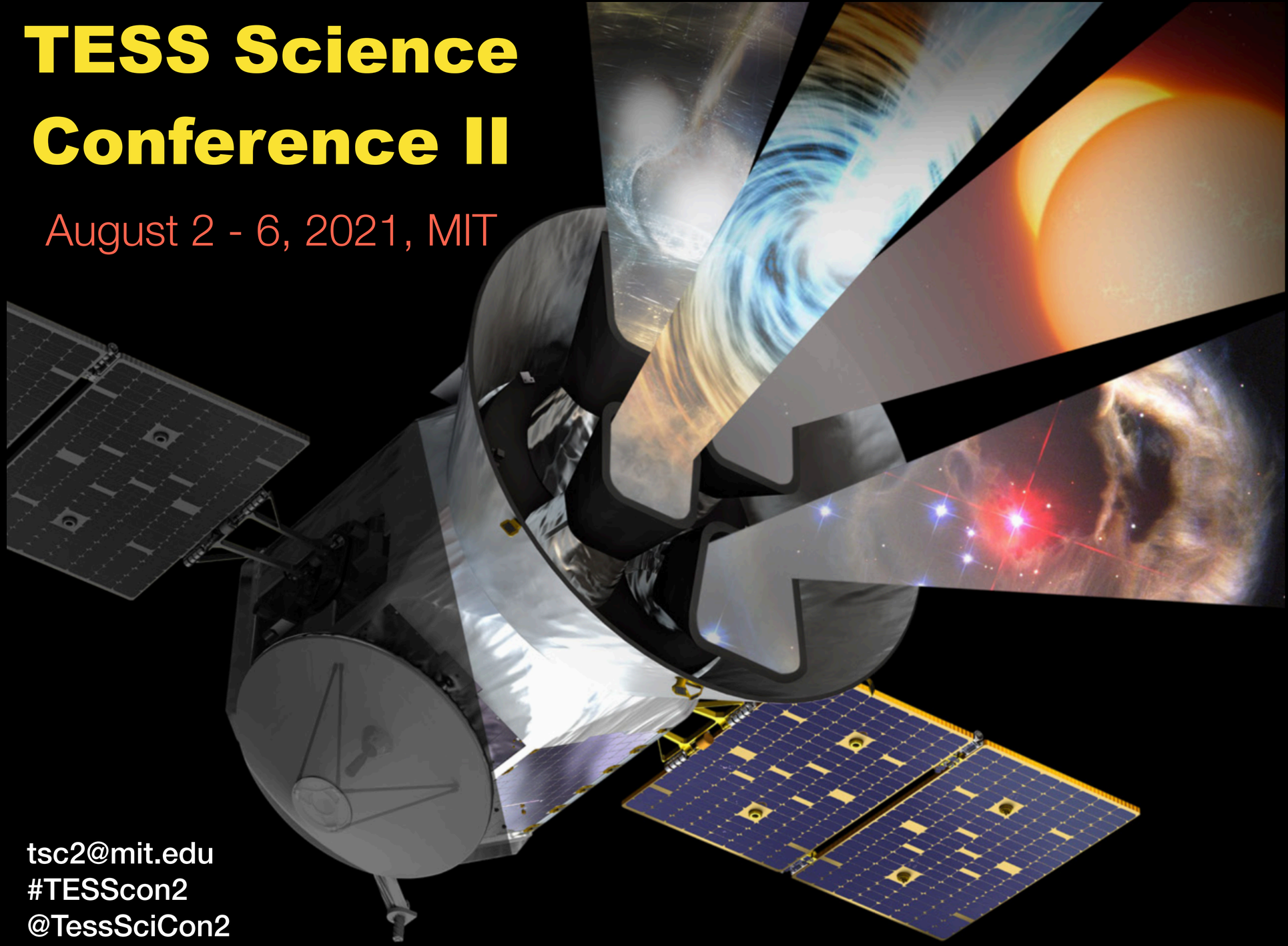
*Transient Observatory



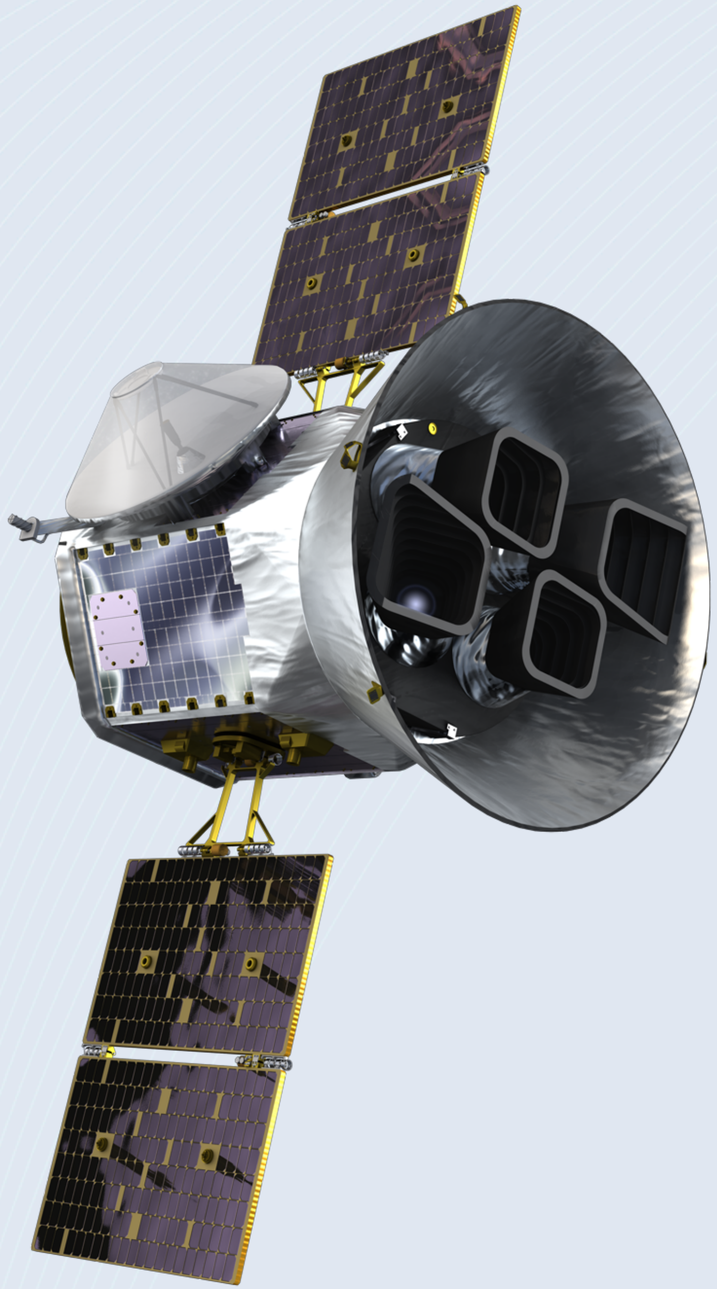
HST/Chandra/Swift

TESS Science Conference II

August 2 - 6, 2021, MIT



tsc2@mit.edu
#TESScon2
@TessSciCon2



Takeaways: TESS's Current Mission Status

- TESS's unique lunar resonant orbit is greatly simplifying the mission
  - *Stable operations in principle could last until 2038 or later*
- TESS's spacecraft stability is exquisite
  - *< 20 milli-arcseconds (**1/1000th pixel**) on 1 hour time scales*
- TESS's camera performance is superb
  - *Focus is stable to ~1μm on 1 hour time scales*
  - *Photometric precision is <20 ppm (**3x better than planned**) for bright stars*
  - *Achieving stacked FFI limiting magnitudes below I_{mag}= +21*
- TESS's initial sky survey sector-by-sector was completed successfully
- TESS's extended mission commenced on July 5, 2020
- TESS's full frame images are enabling a wide range of astrophysics discoveries
  - ***Rich trove of high-value exoplanet targets for future missions***
  - ***Transient Science: Stellar Astrophysics, Extragalactic "Multi-Messenger Astronomy", …***
  - ***"Precovery" transient observations are routine***
- **TESS's high science ranking by NASA in mid-2019**
  - ***#1 for Scientific Merit in NASA's 2019 Senior Review of Explorer Missions***
  - ***Invited to the 2022 Astrophysics Senior Review (hopefully, extension to 2025…)***