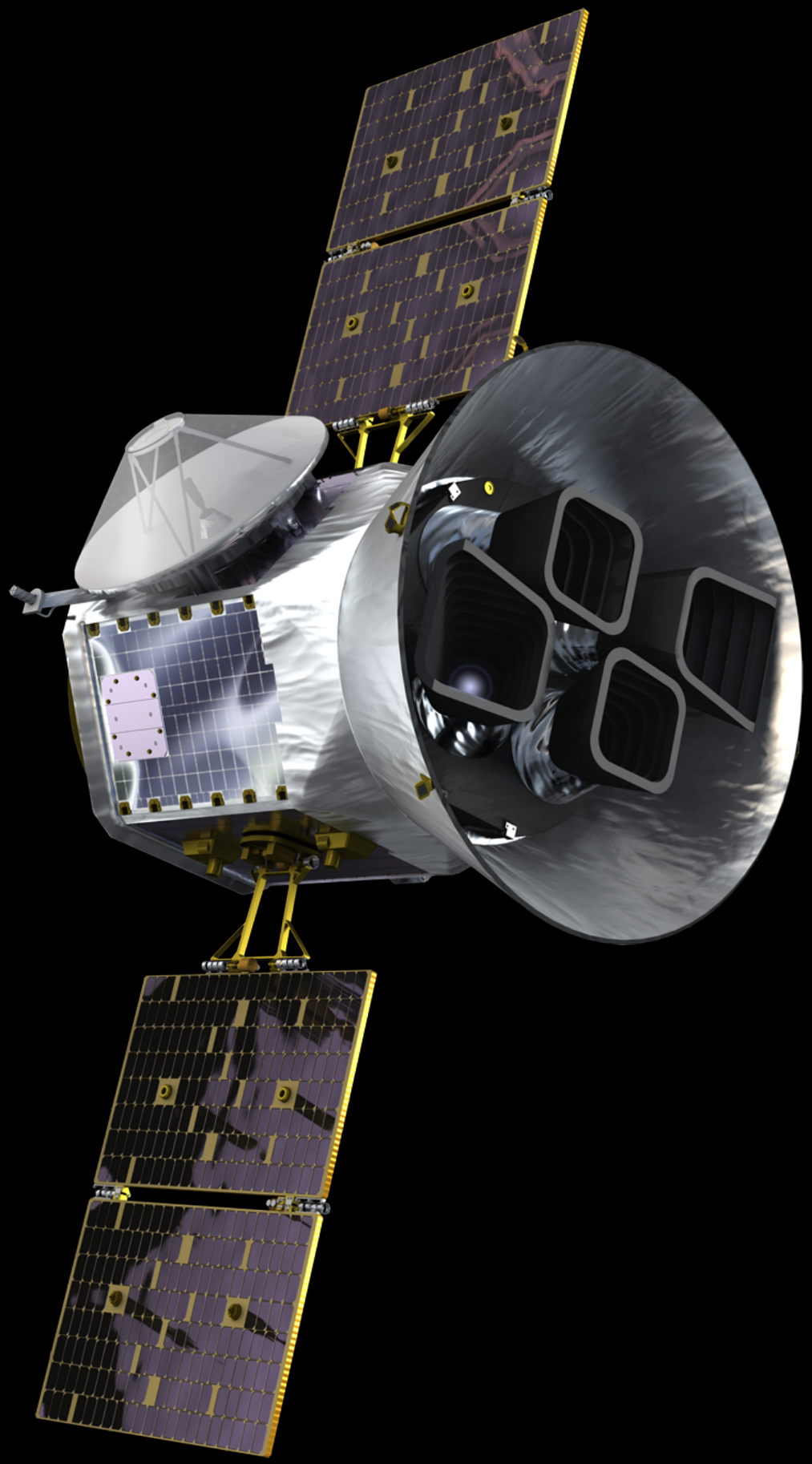

TESS:
Mission Update

George Ricker (MIT)

TESS PI

Astronomy and Astrophysics Advisory Committee

National Science Foundation

Alexandria VA

25 February 2019

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)

Mission Status Overview

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- TESS is on orbit and sky survey is underway!
  - *18 April 2018 SpaceX F9 launch and commissioning was fully successful*
  - *Special resonant orbit achieved is spot on*
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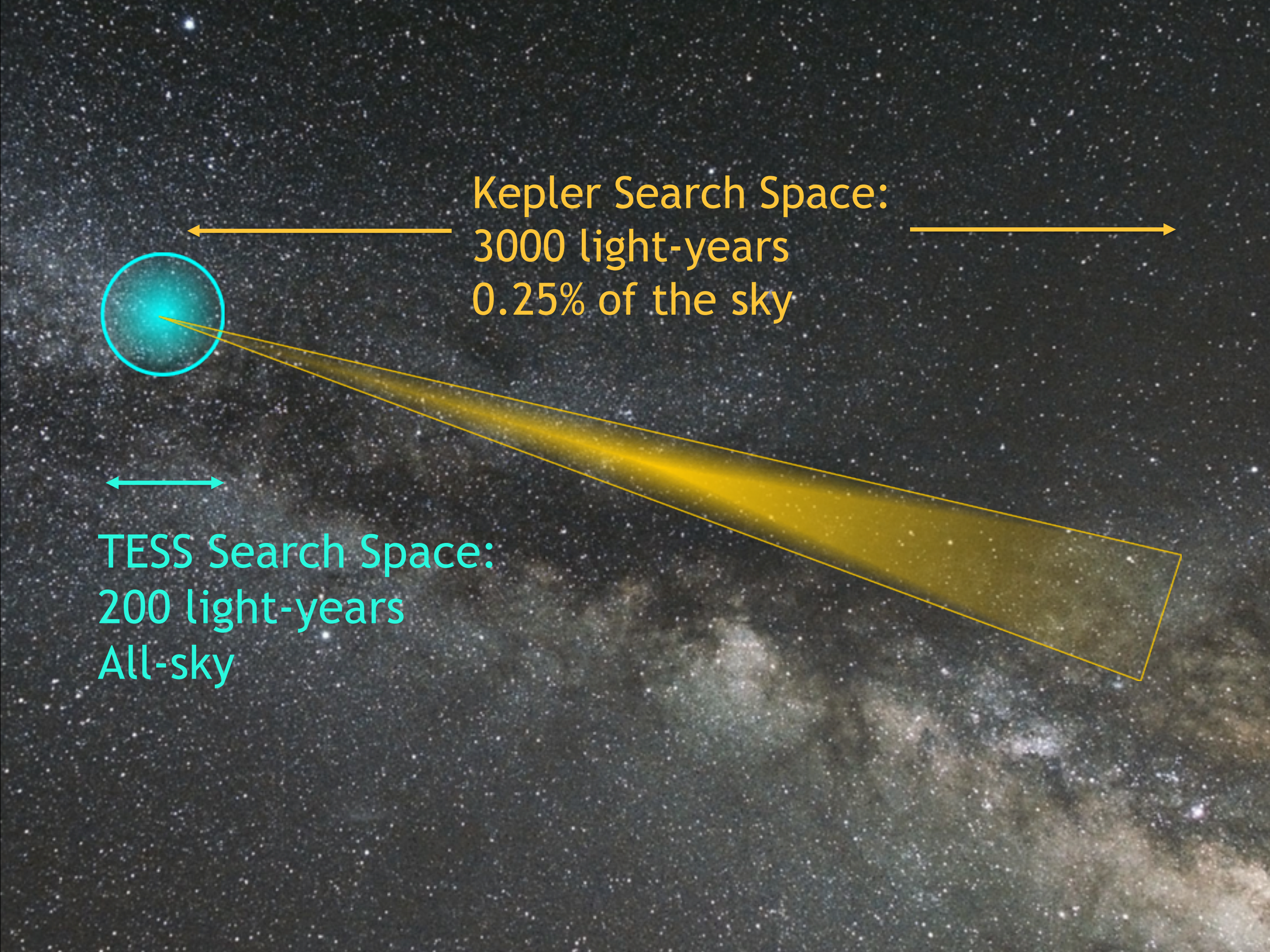
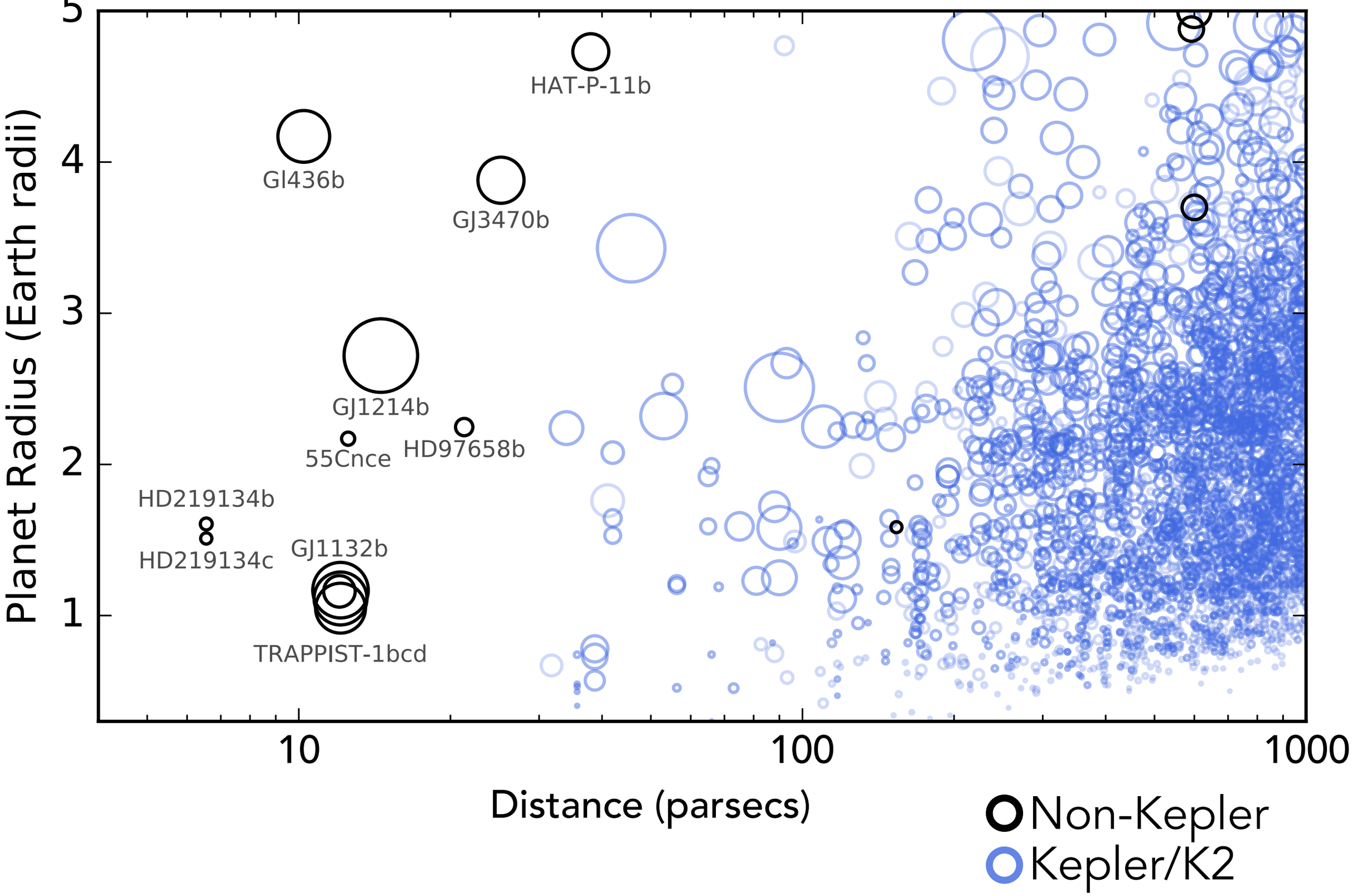
- ***Science Survey Sectors 1-7 completed; Sector 8 in Progress***


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

Exoplanet Population pre-TESS



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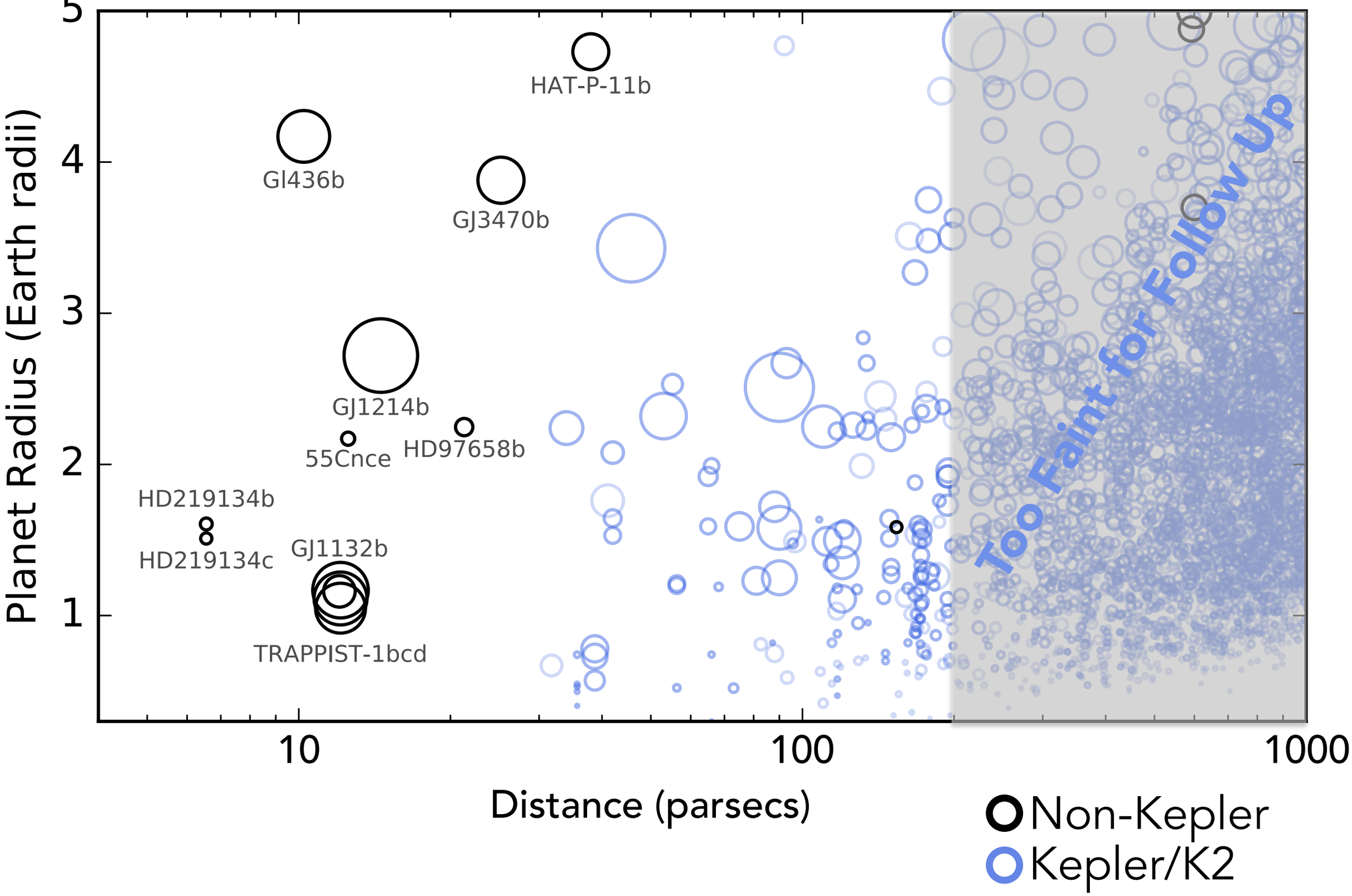
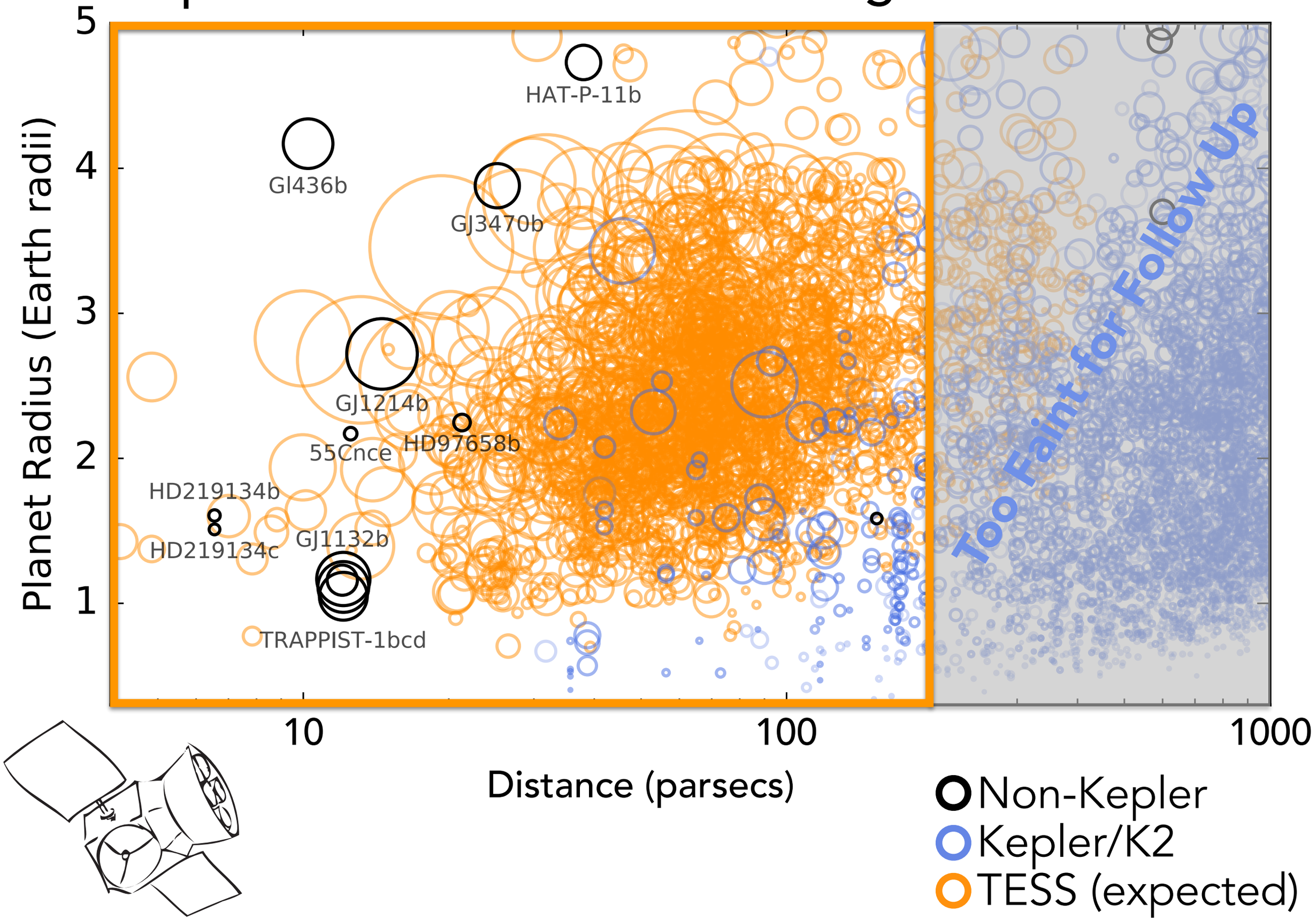
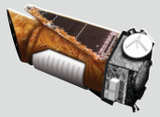
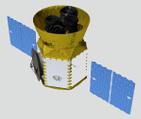


We predict TESS will fill in this region



TESS and Kepler

Mission Comparison	*Kepler* 	***TESS* Prime** 
Main goal	Measure frequency of Earths	Find planets around bright stars
Duration	8 years (4 *Kepler* + 4 *K2*)	2 years
Orbit	Heliocentric (373 d)	High-Earth (13.7 d)
Bandpass	0.4 – 0.8 μm	0.6 – 1.0 μm
Optical area	7100 cm^2	114 cm^2
Field of view	105 deg^2	2304 deg^2
% of pixels retained	0.003% (1 min) 6% (30 min)	8% (2 min) 100% (30 min)
Dwell time per star	*Kepler*: 4 years *K2*: 3 months	Typically 1–2 months
Magnitude of planet hosts	10-16	6-13

Etendue Comparison

	A_{optics} [m²]	Ω_{gross} [deg²]	Ω_{net} [deg²]	Etendue [m² deg²]
TESS	0.0114	2304	2304	26.3
Kepler	0.71	105	6.30	4.2

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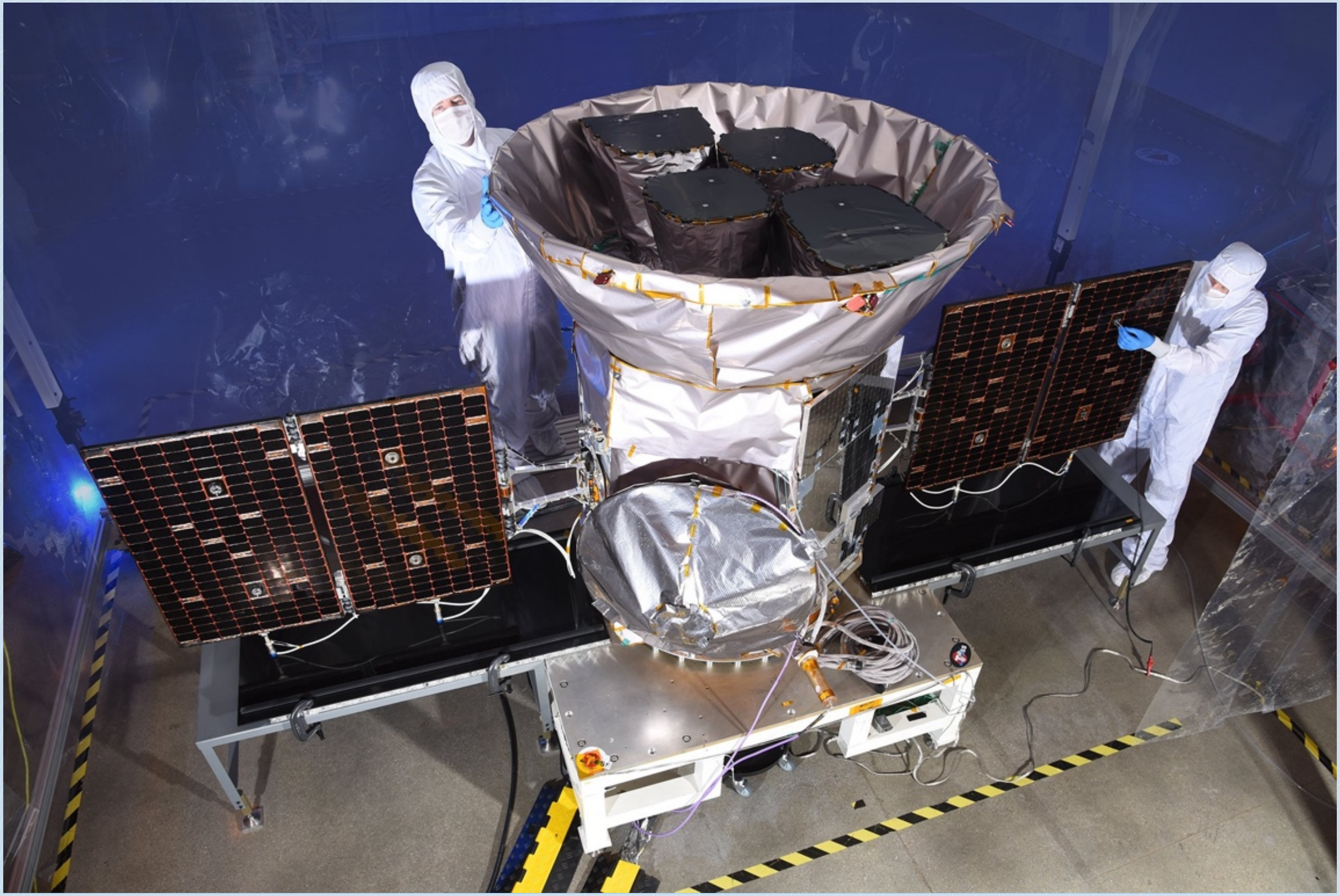
TESS is the highest etendue optical space mission yet flown:
~6 times greater than Kepler

Bryson et al. 2010
Ricker et al. 2016

TESS Observatory During Integration and Testing



TESS Orbit Greatly Simplifies Mission Operations

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

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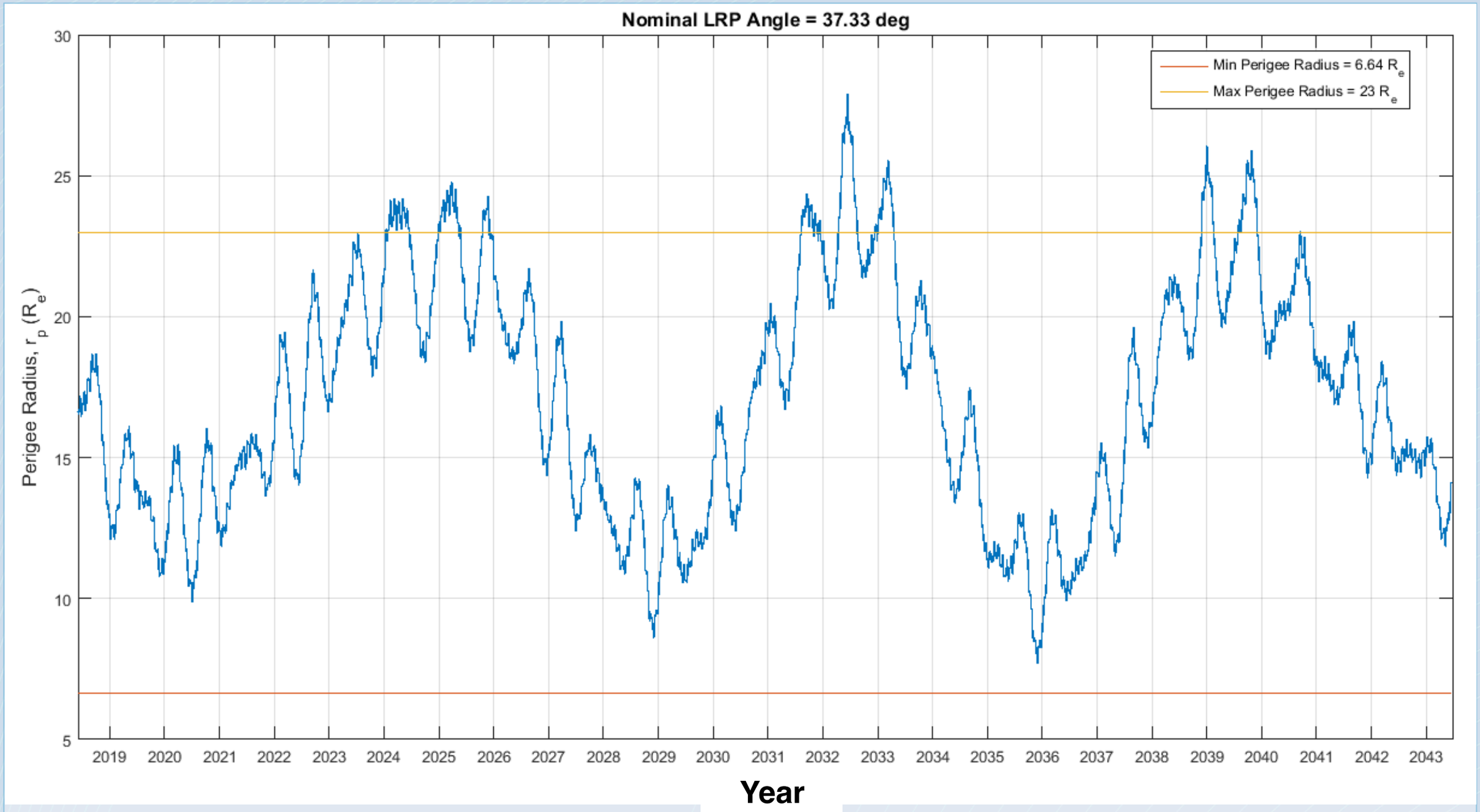
Advantages of TESS's 13.7 Day Lunar Resonant (P/2) Orbit

- Extended Observations: *~300 hrs per orbit*
- Thermal Stability: *<30 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 for **~100 years***
- **High Downlink Rates:** *100 Mbit/s (185 GB in ~5 hr at Apogee!)*

TESS P/2 Resonant Orbit is Near Perfect!



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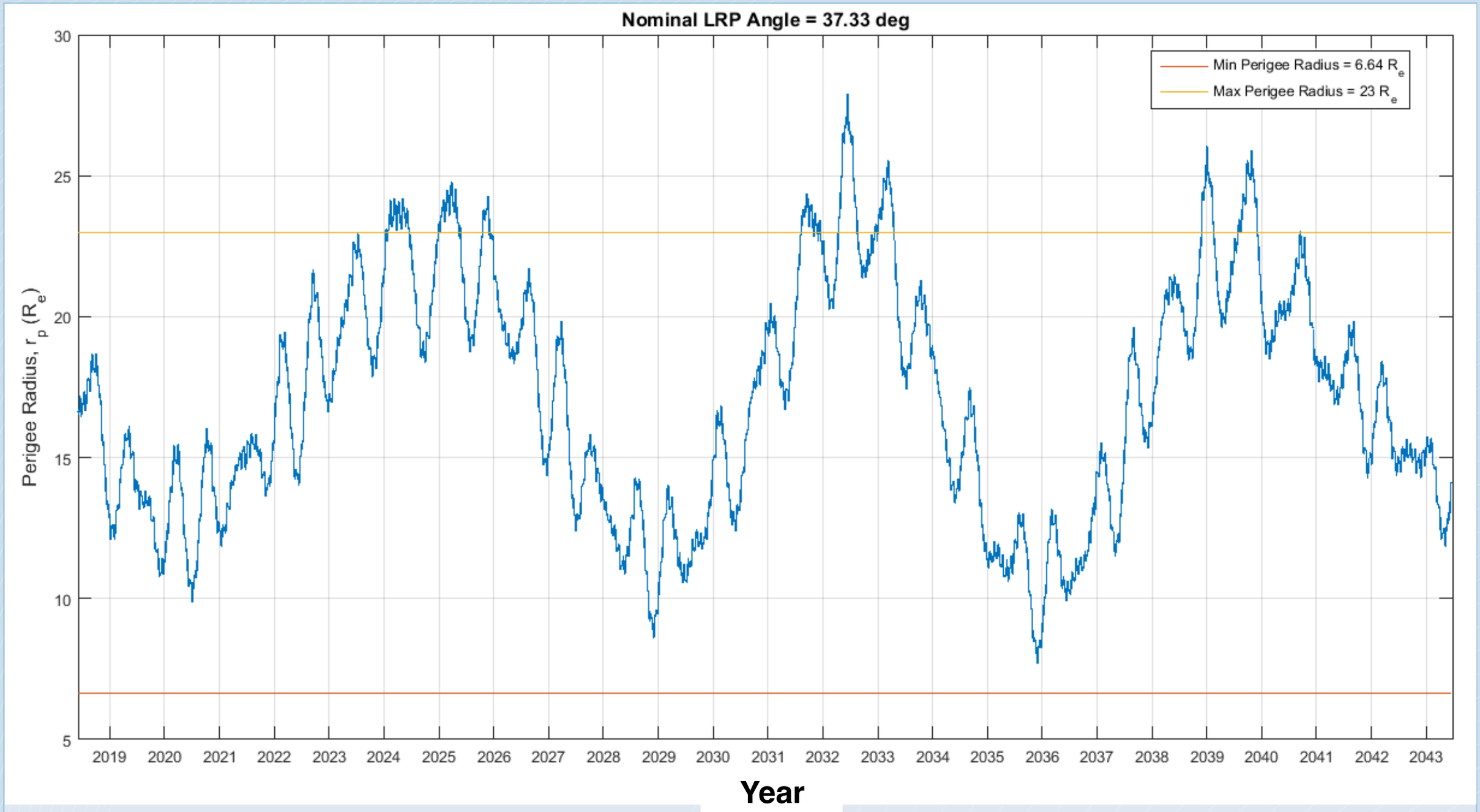

- Kozai oscillations will stabilize the orbit exactly as planned

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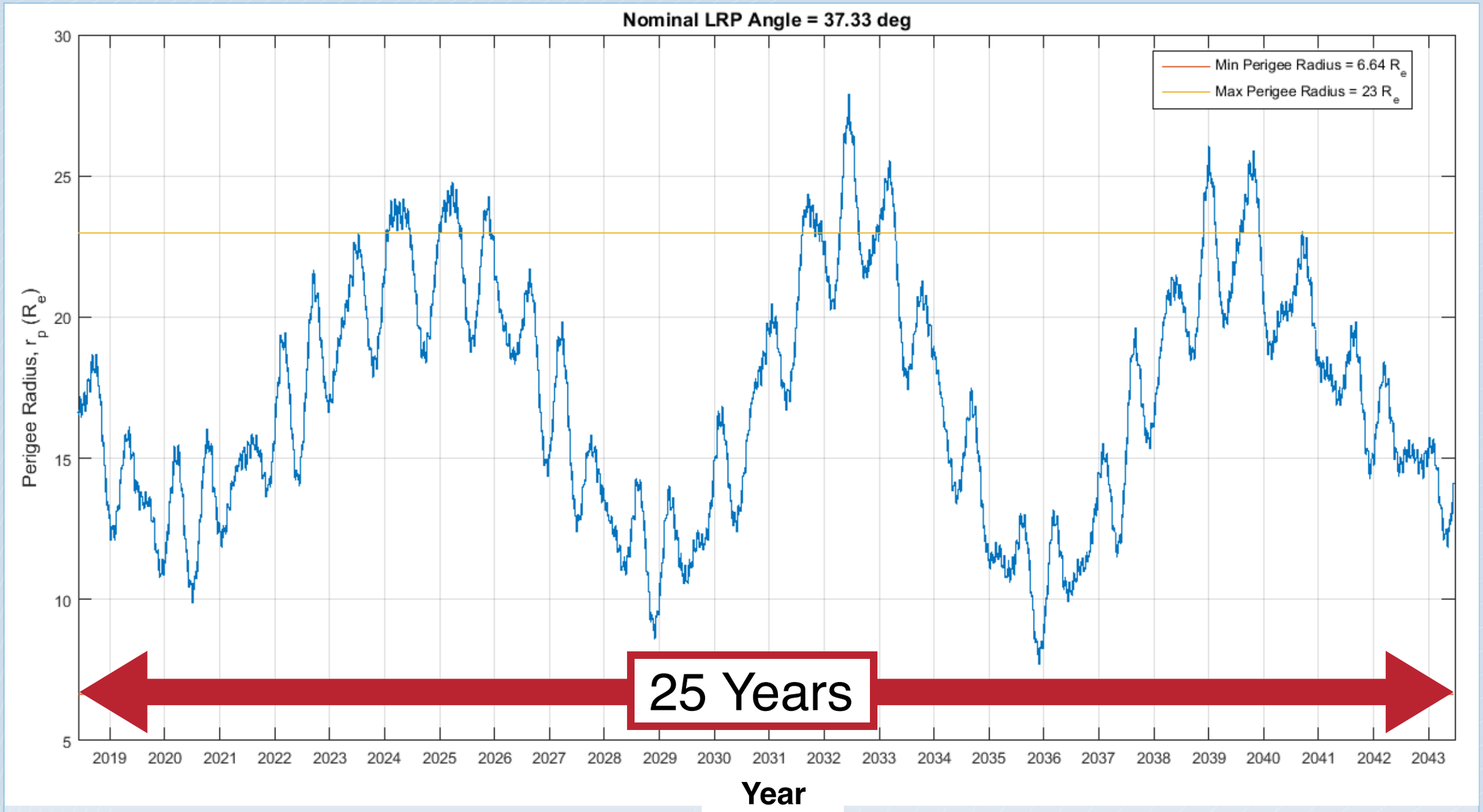
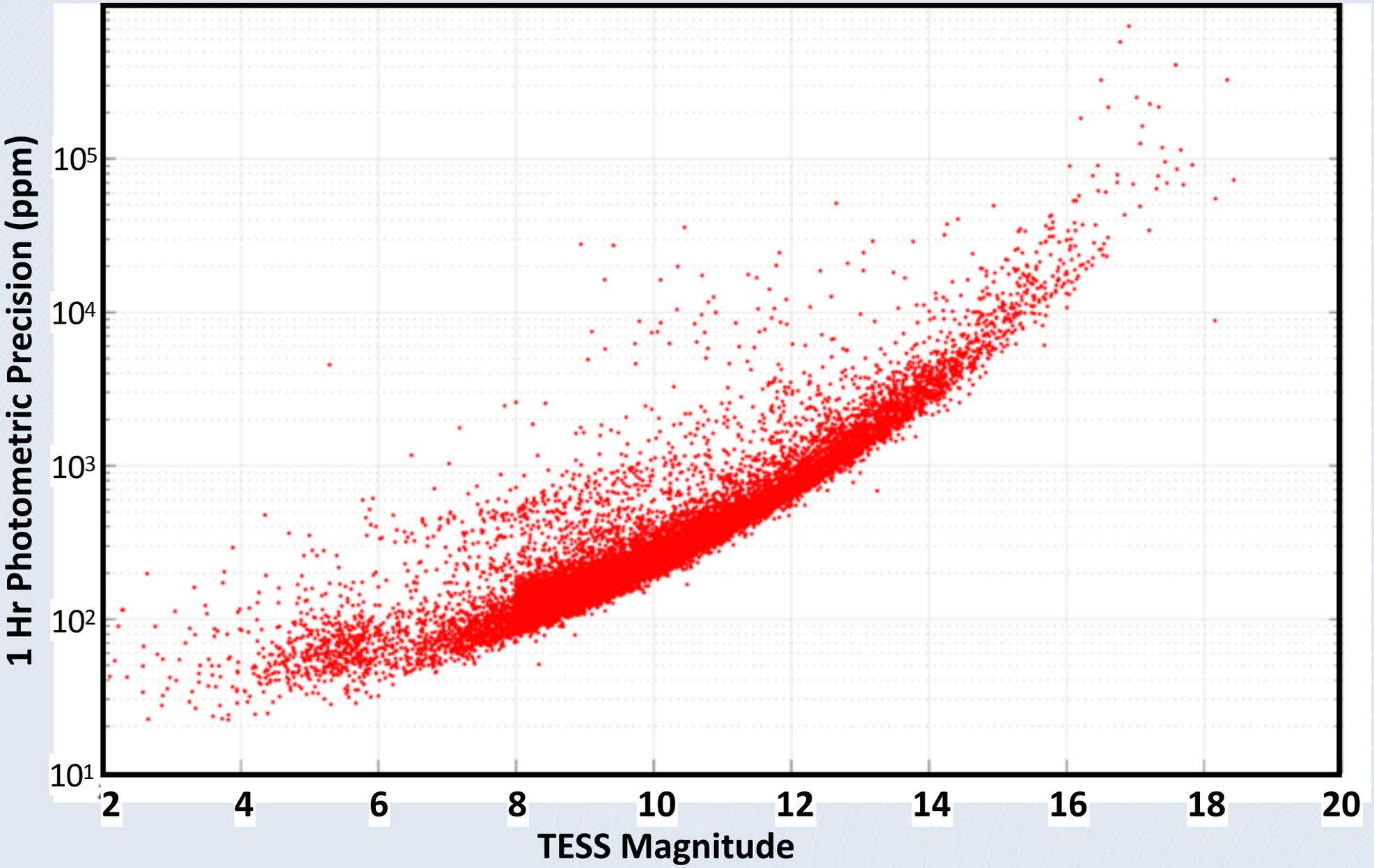


- Kozai oscillations will stabilize the orbit exactly as planned
- **Stable TESS orbit behavior is anticipated for >25 years**

TESS Photometric Precision

- Photometric precision of Sector 5 light curves is **~200 ppm** at T_{mag} = + 10
  - *Below L3 requirement of 230 ppm*
- Bright object limiting noise floor is **~20 ppm**
  - *Well below Level 1 requirement of 60 ppm*



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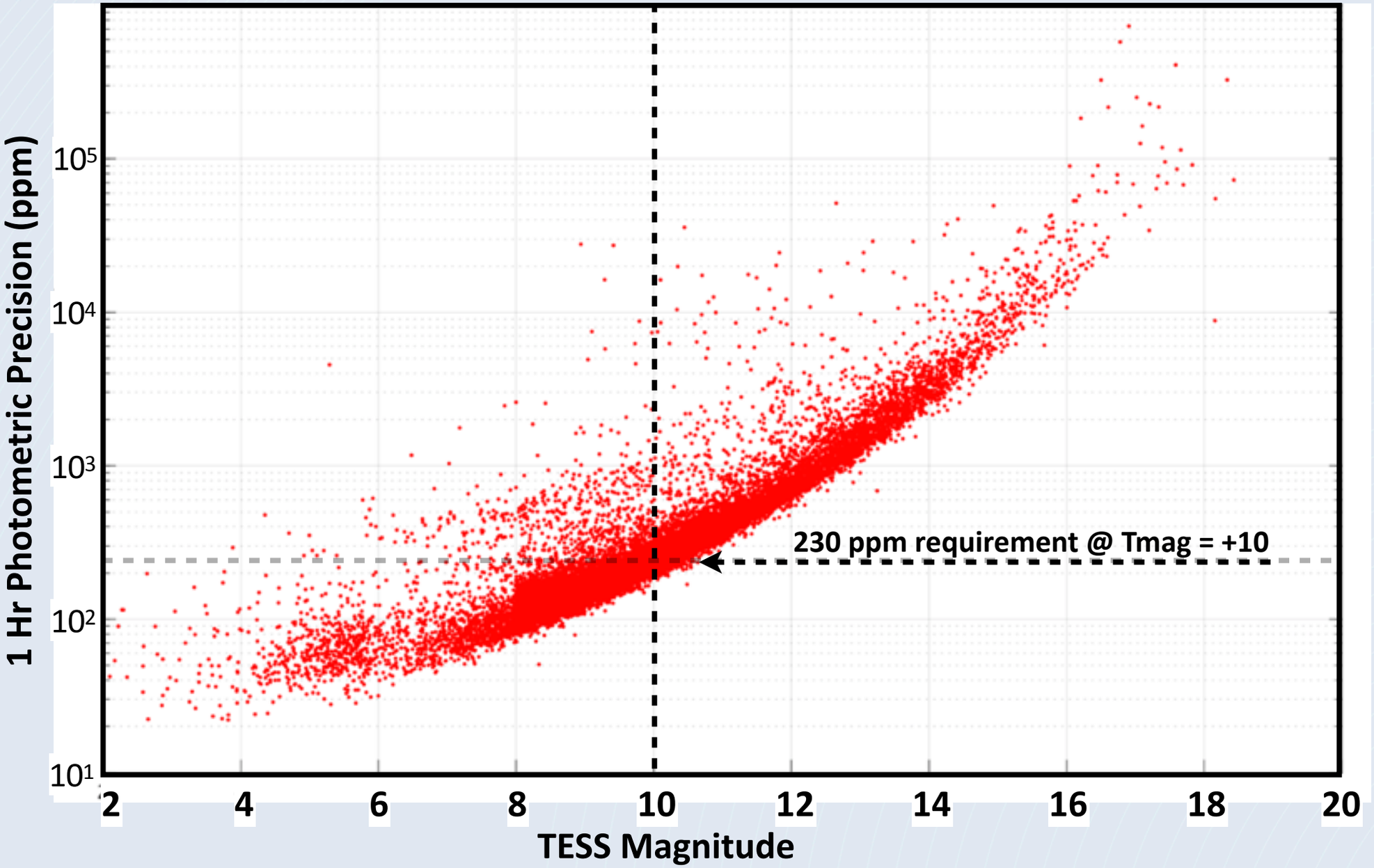

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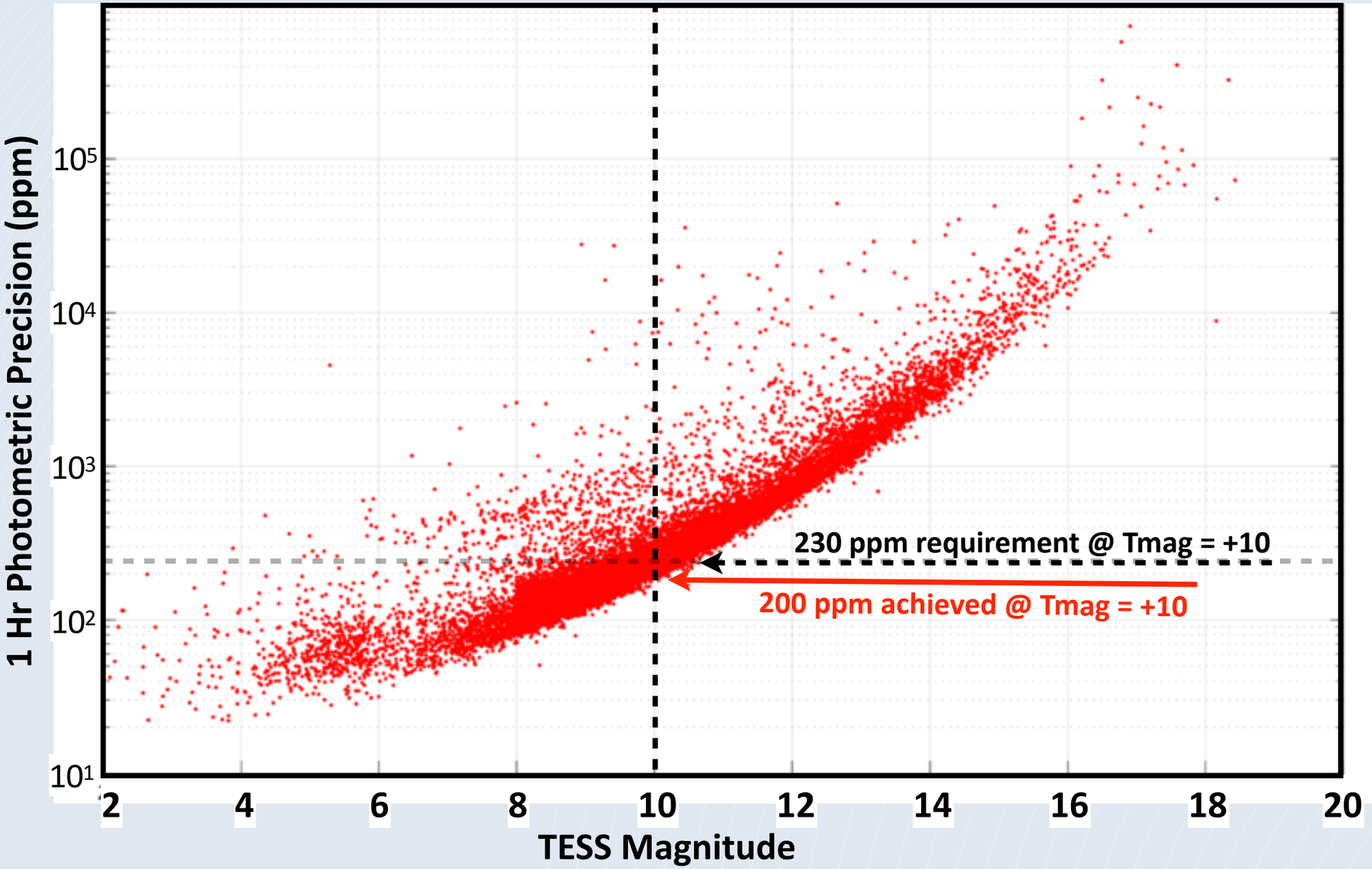

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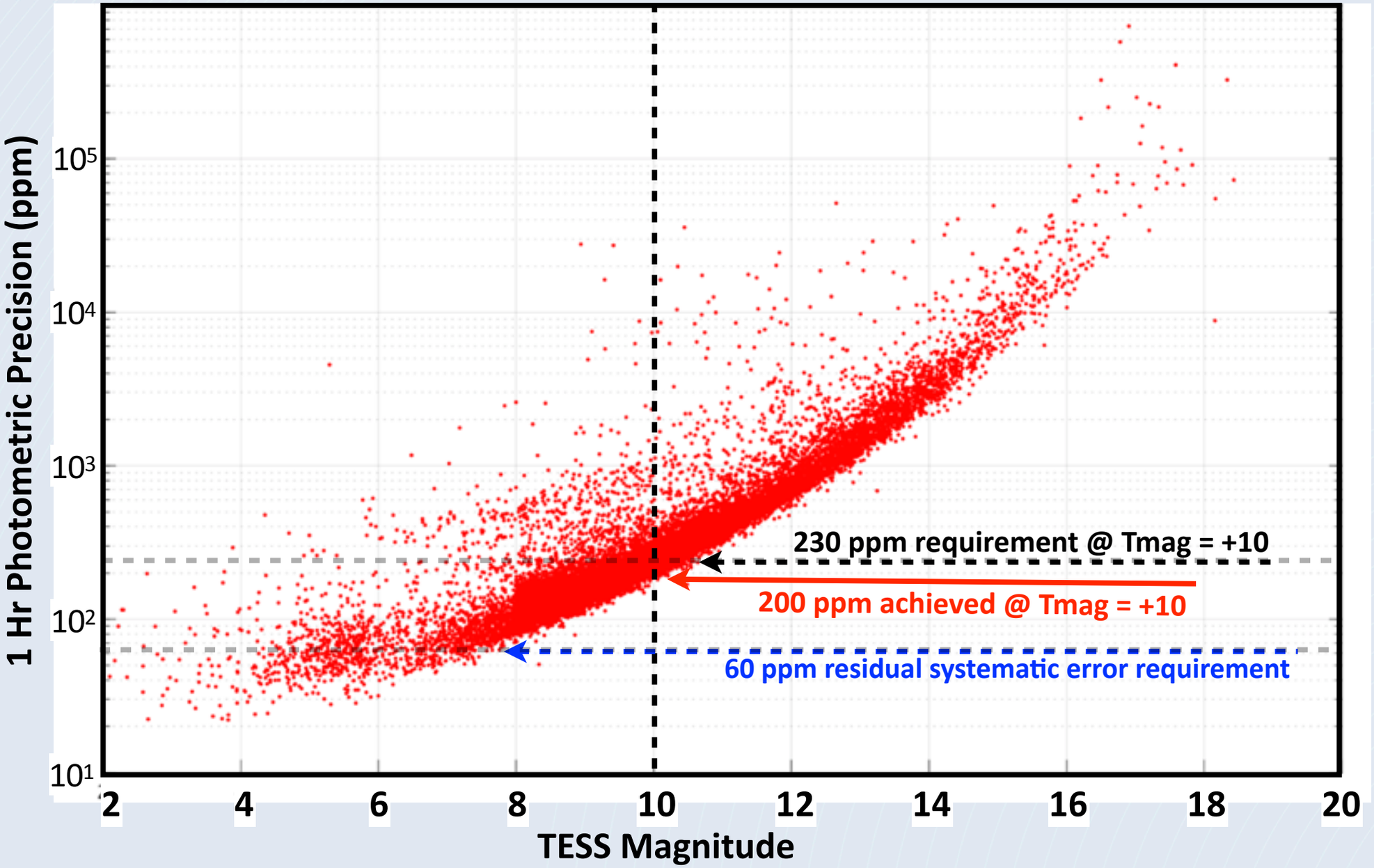

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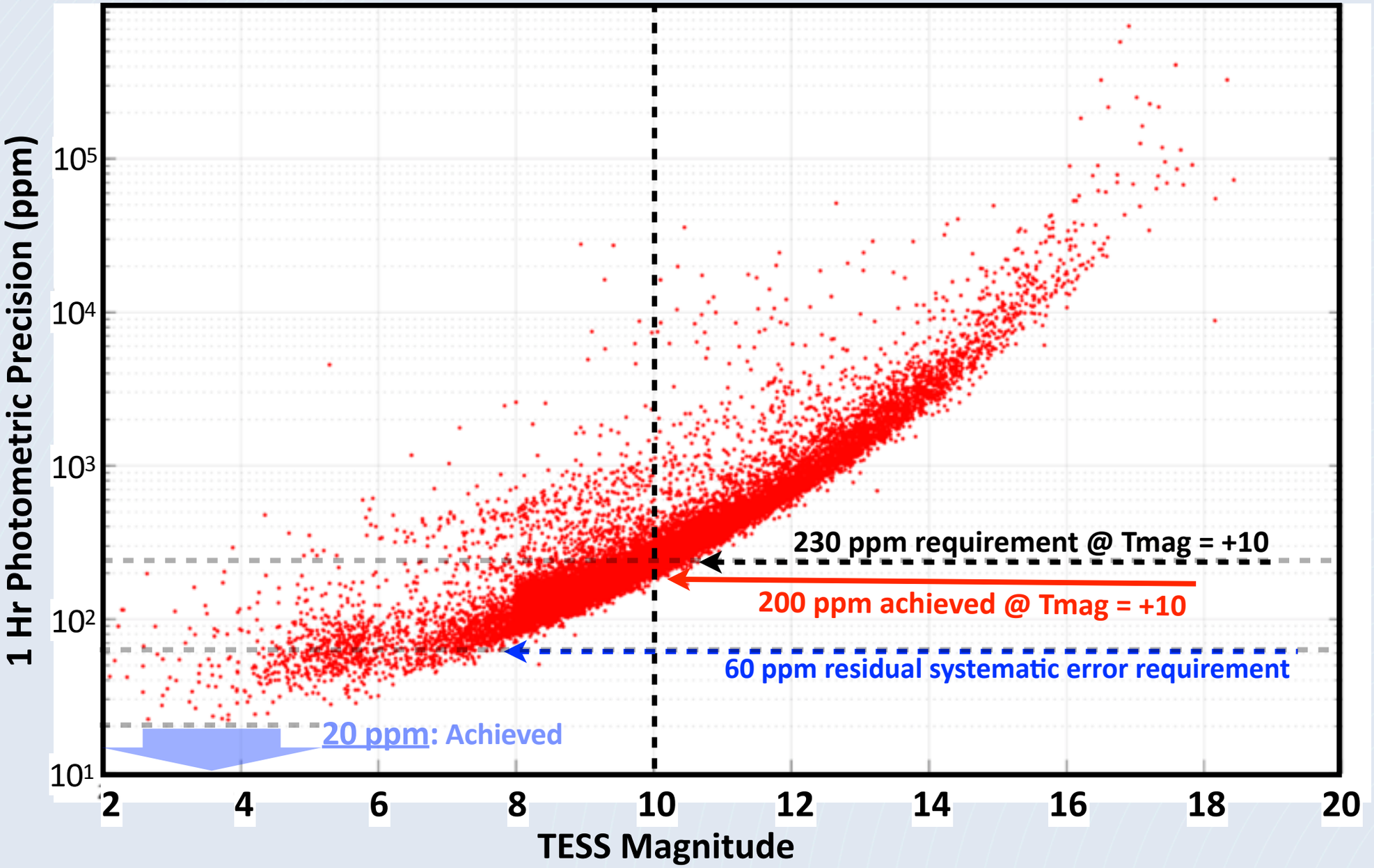
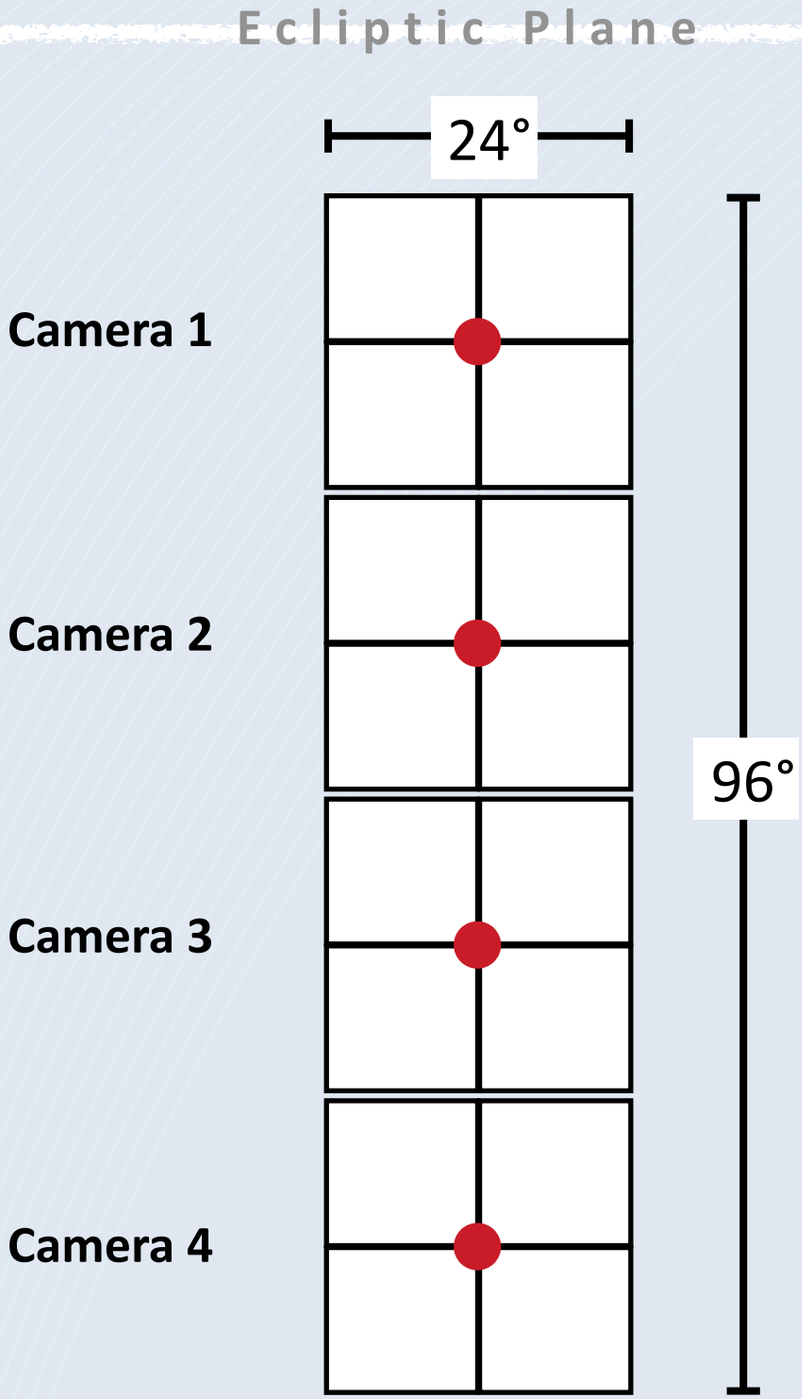
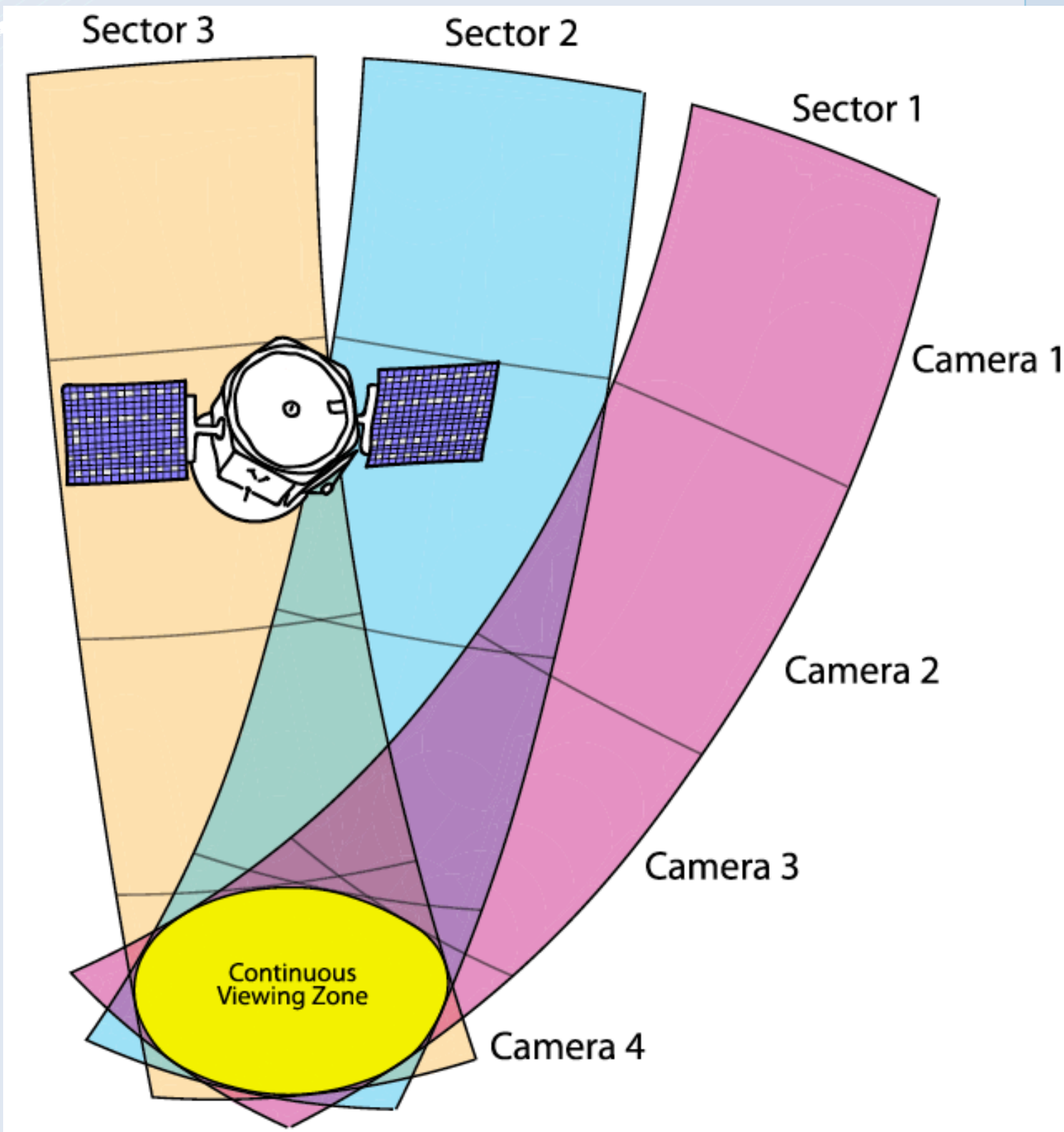


Commissioning Completed:
24 July 2018

TESS Science Survey Began:
25 July 2018

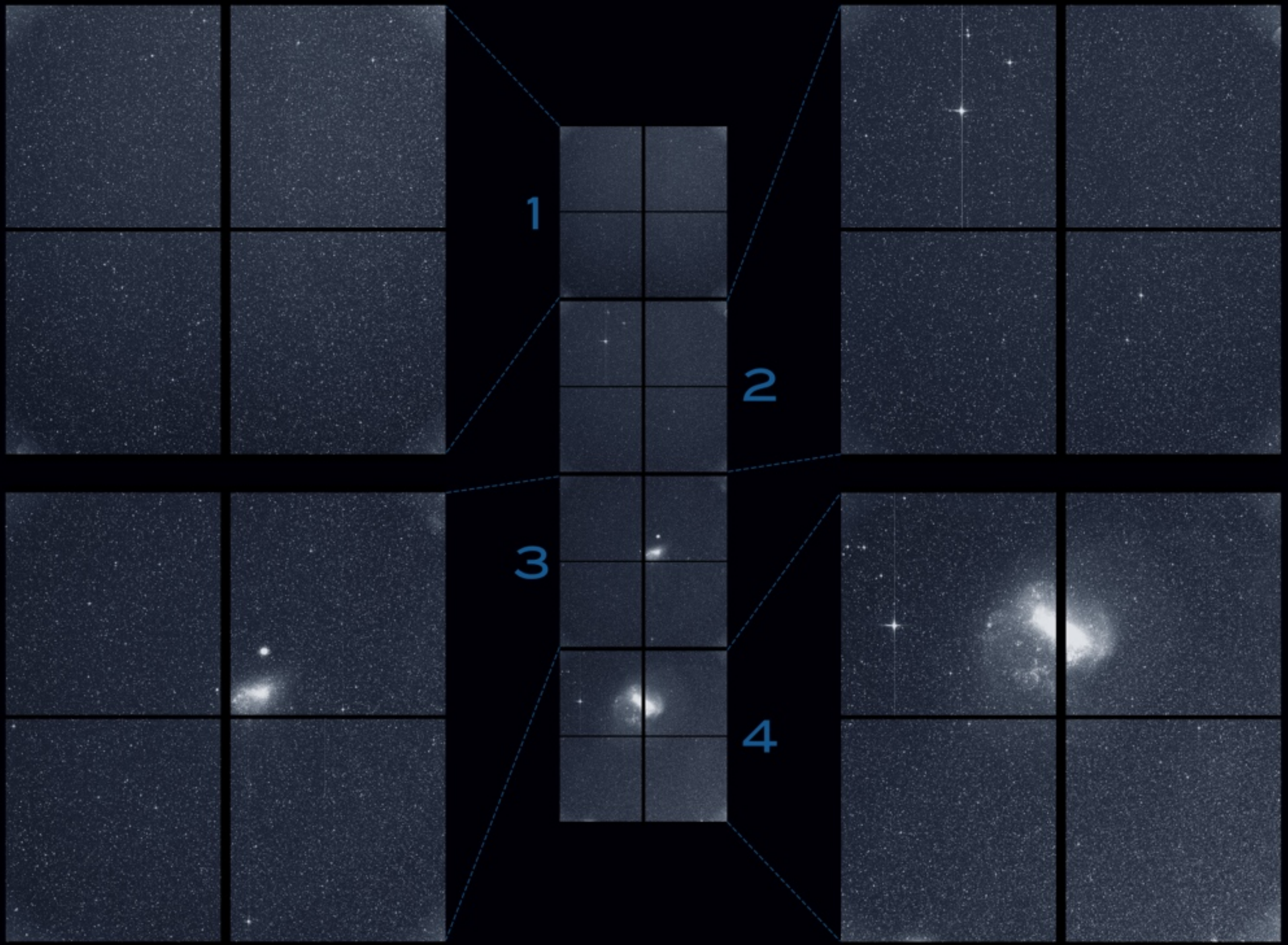
TESS Year 1: Initial Southern Hemisphere Pointings





Official “First Light” Image from TESS Sector 1

(1 of ~1200 FFIs from Sector 1)


1
2
3
4

Messier 30
Globular cluster

Beta Piscis Austrini

1

2

Beta Gruis

Alpha Tucanae

NGC 104
Globular cluster

Small Magellanic Cloud
Galaxy

Gamma Hydri

3

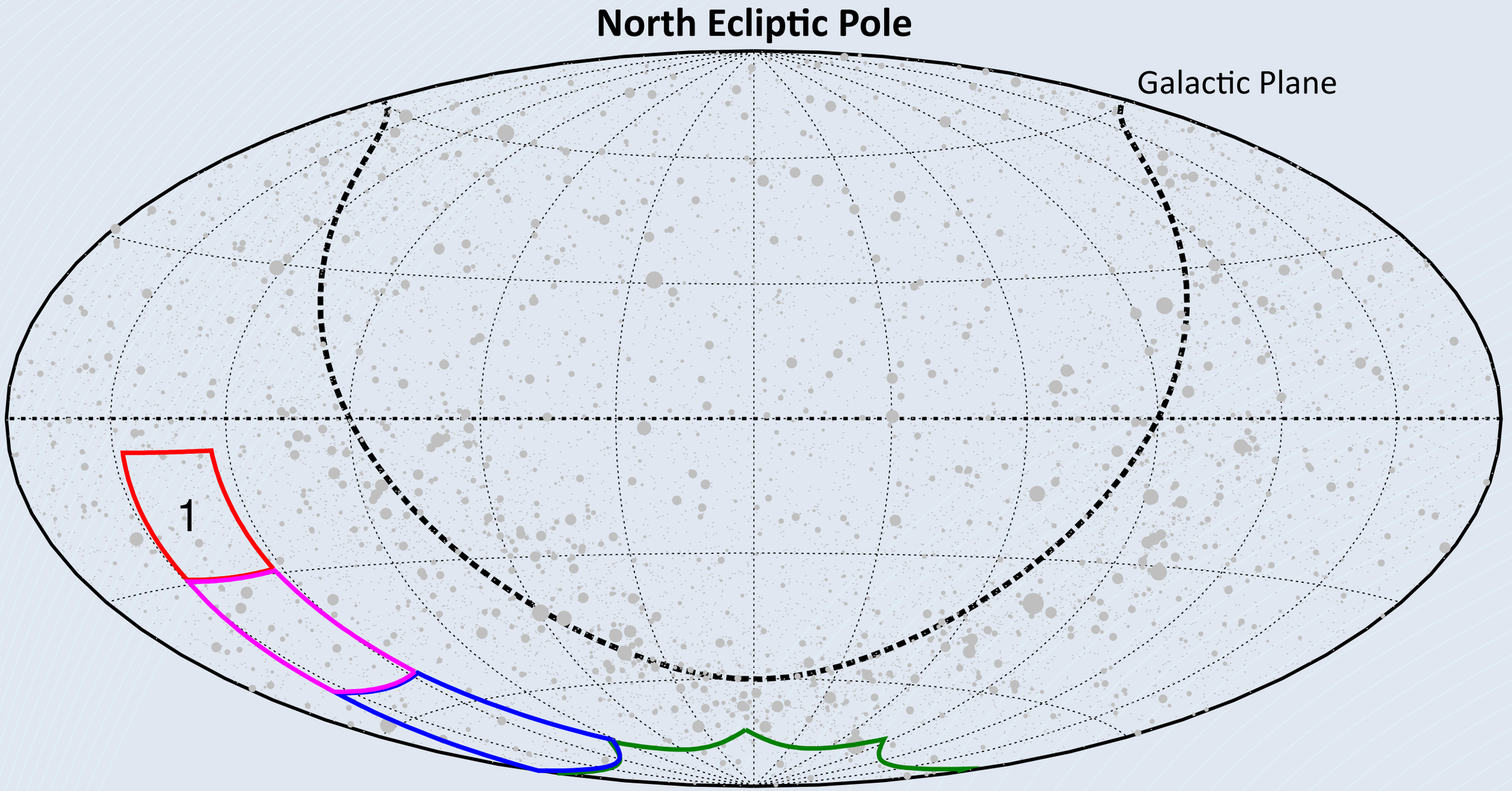
4

R Doradus
Variable star

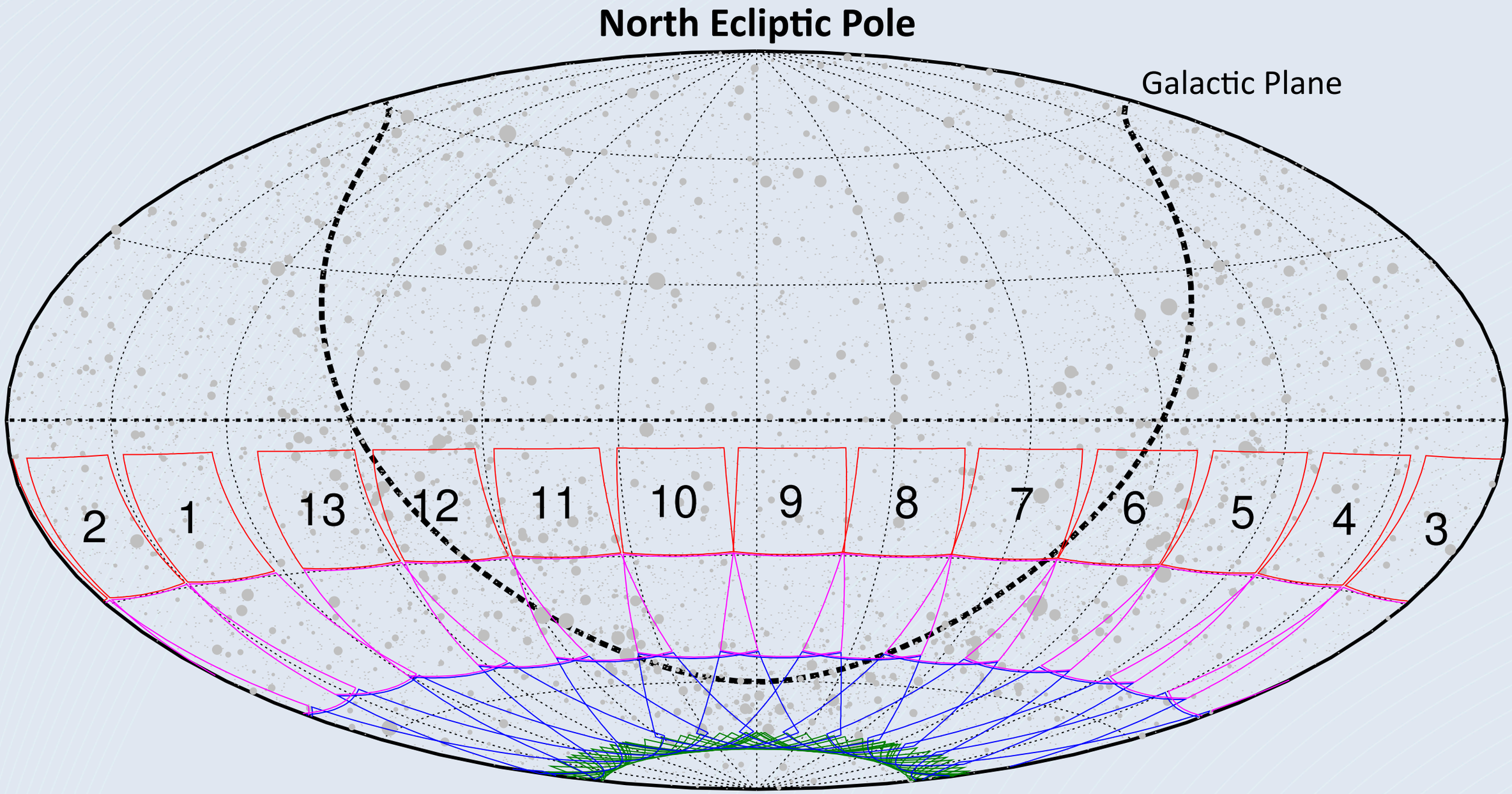
Large Magellanic Cloud
Galaxy

Alpha Pictoris

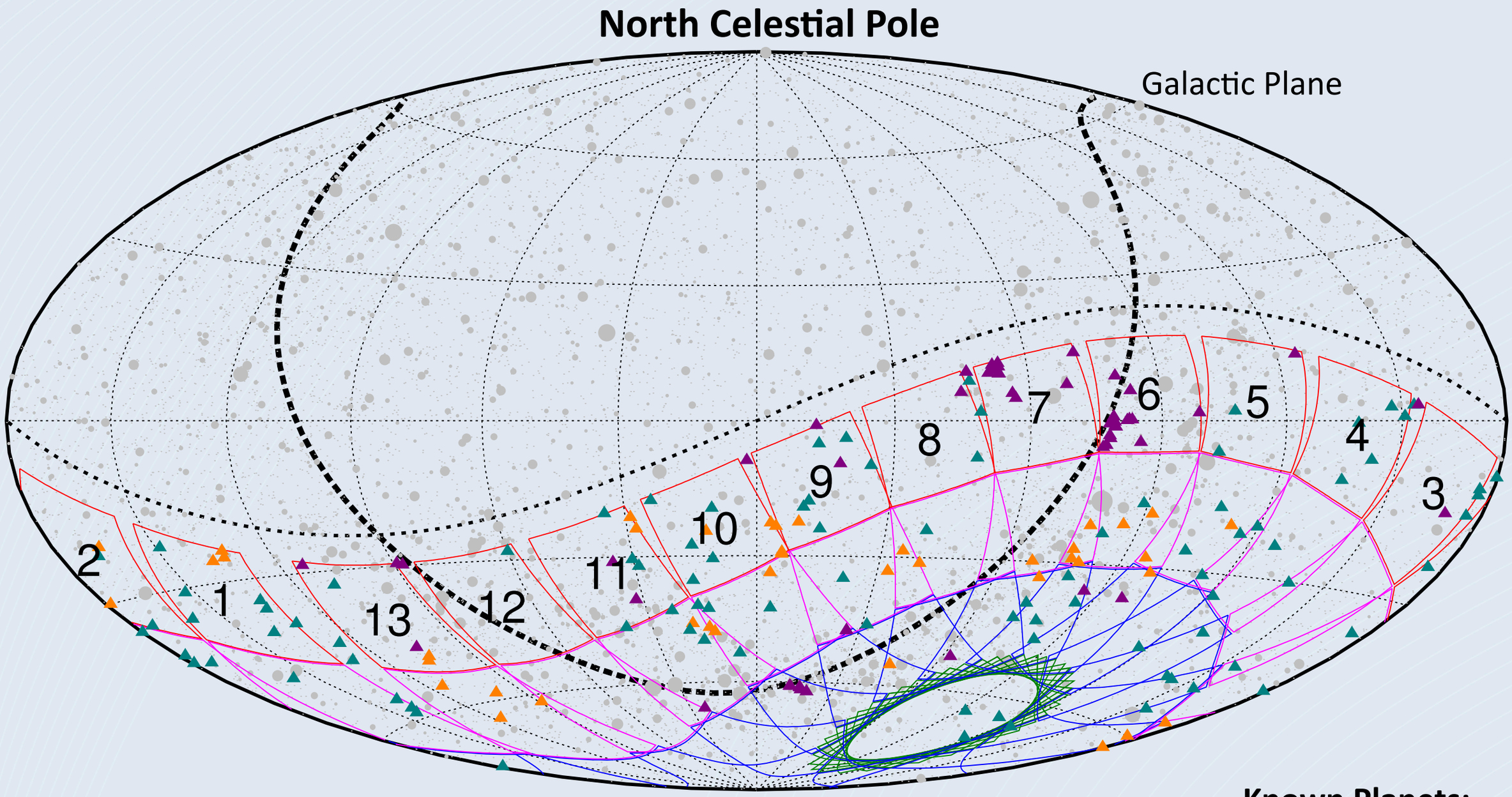
Science Sector #1: Ecliptic Coordinates



All Year 1 Science Sectors: Ecliptic Coordinates



All Year 1 Science Sectors: Celestial Coordinates



Figures: Andras Pal

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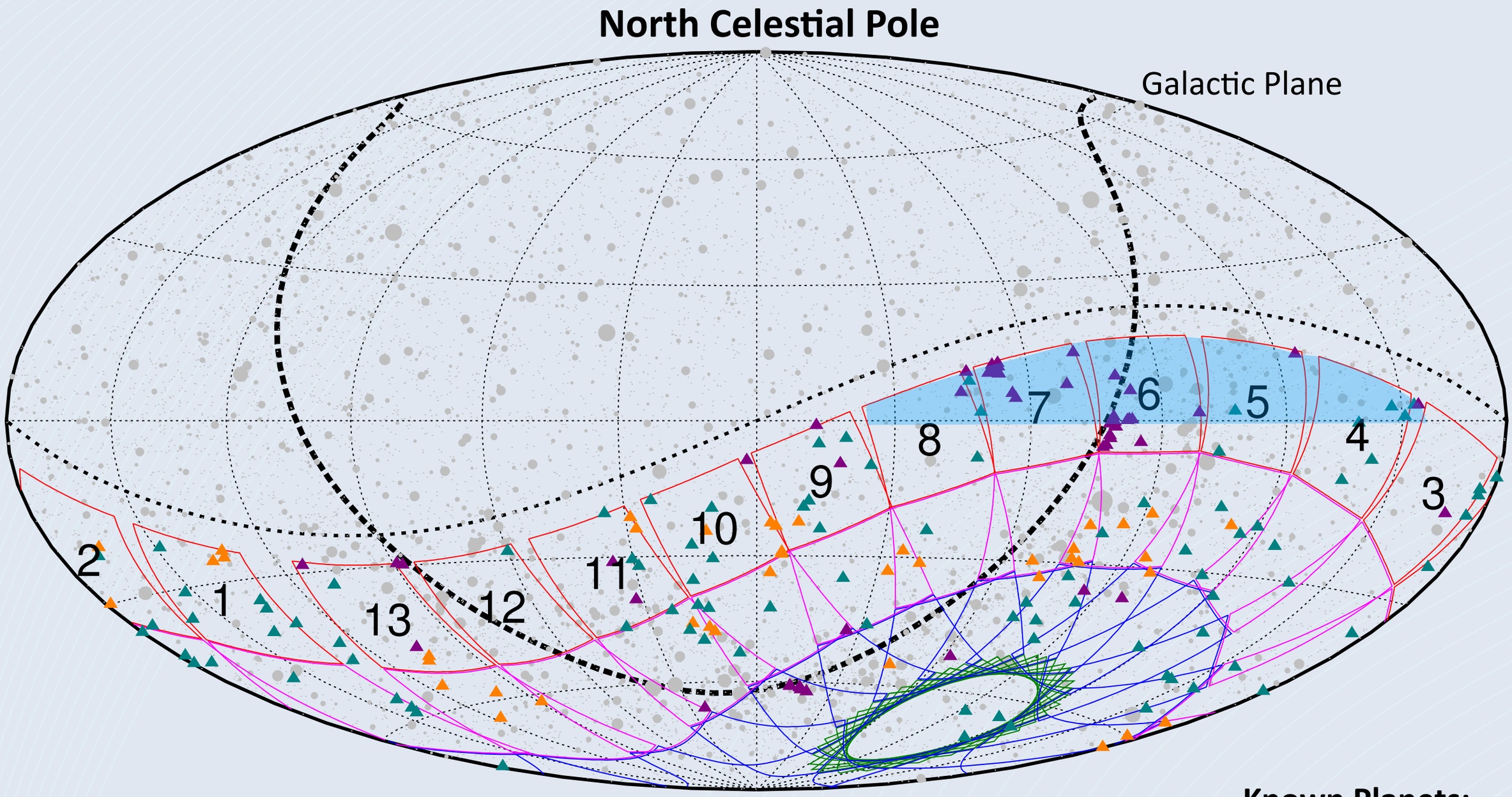

Figures: Andras Pal

Sectors 1 and 2: First TESS Data Dissemination

- Initial Full Data Release on December 6th
  - *6 weeks earlier than originally planned*
  - *Accompanying documentation included*
  - *Posted here at MAST for public download*
- Initial 8% of Sky Survey
  - *Sectors 1 and 2 (of 26 scheduled over next two years)*
  - *~30,000 light curves at 2 min cadence*
  - *~2000 Full frame images at 30 min cadence*
- Full sensitivity for the two sectors surveyed
  - *~ 3500 square degrees*
  - *~20,000,000 stars and galaxies brighter than I_{mag} = +18 (S/N > 10)*
  - *Continuous viewing of the Large Magellanic Cloud for 2 months*
    - *Anticipated in full 12 month survey: microlensing events, variable stars, ...*

TESS Objects of Interest (TOI) Evaluation Effort

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Team Goal:

Issue prompt Alerts for Ground Observers to establish masses for TESS-discovered small planets ASAP, thus satisfying TESS's Level 1 Mission Requirements

385 TOIs (so far!)

Yield from 5 sectors:

104 TOIs with TESS $R_p < 4R_E$

54 false positives

189 alerted with QLP parameters

196 alerted with SPOC parameters

TESS small planets (< 4 R_E) thus far:

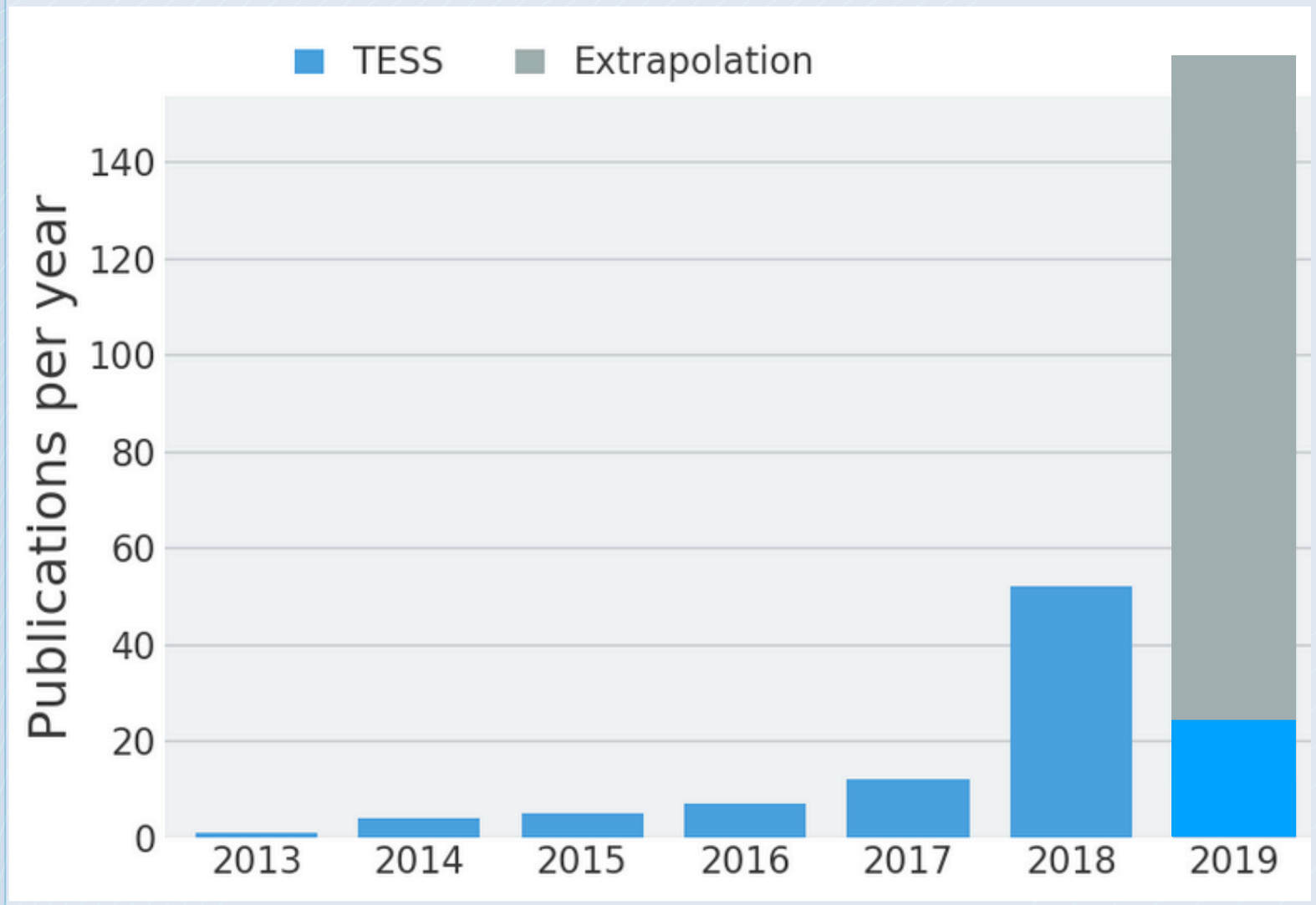
Mass measurements underway: 30

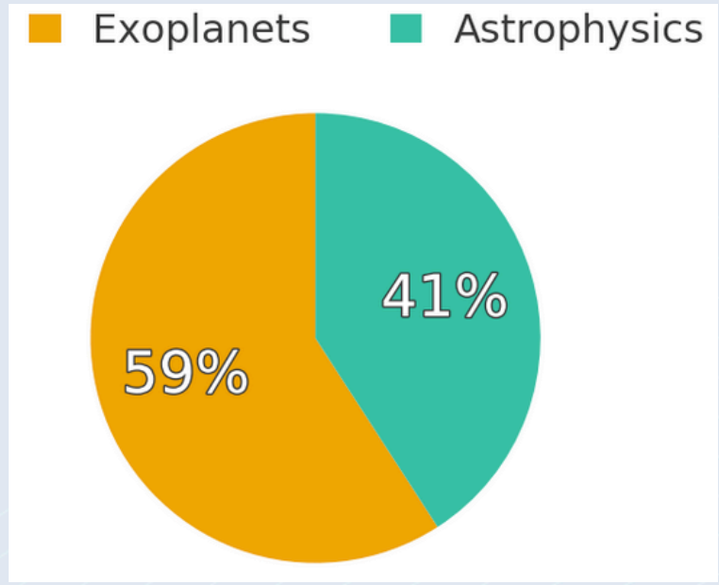
Mass measurements complete: 6

QLP = MIT Quick Look Pipeline

SPOC = NASA Ames Kepler-derived Pipeline

TESS Publications Trending





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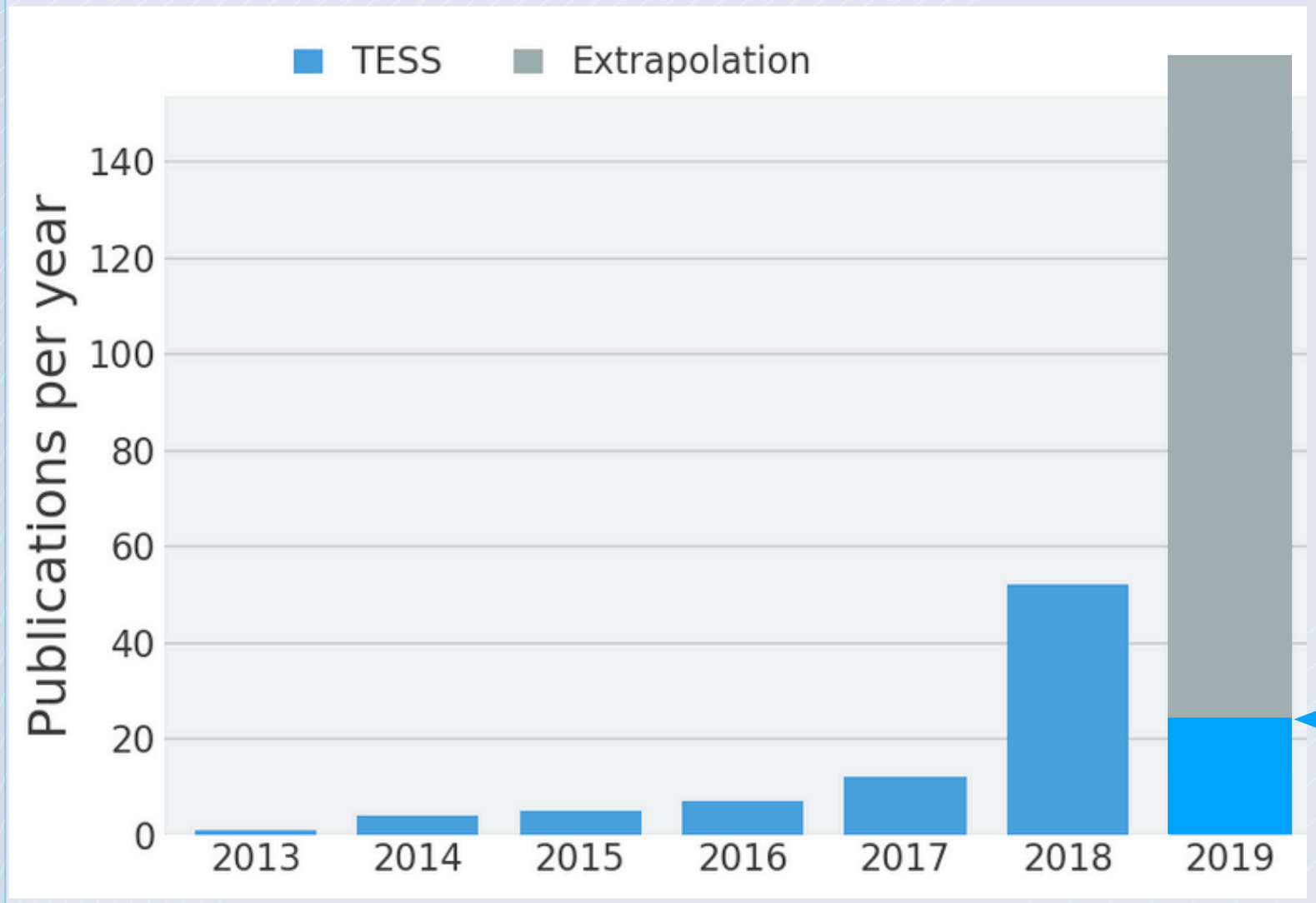
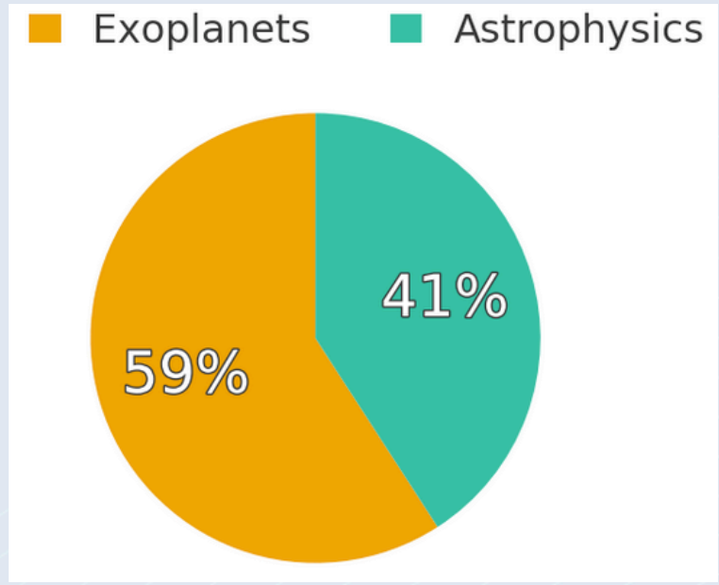
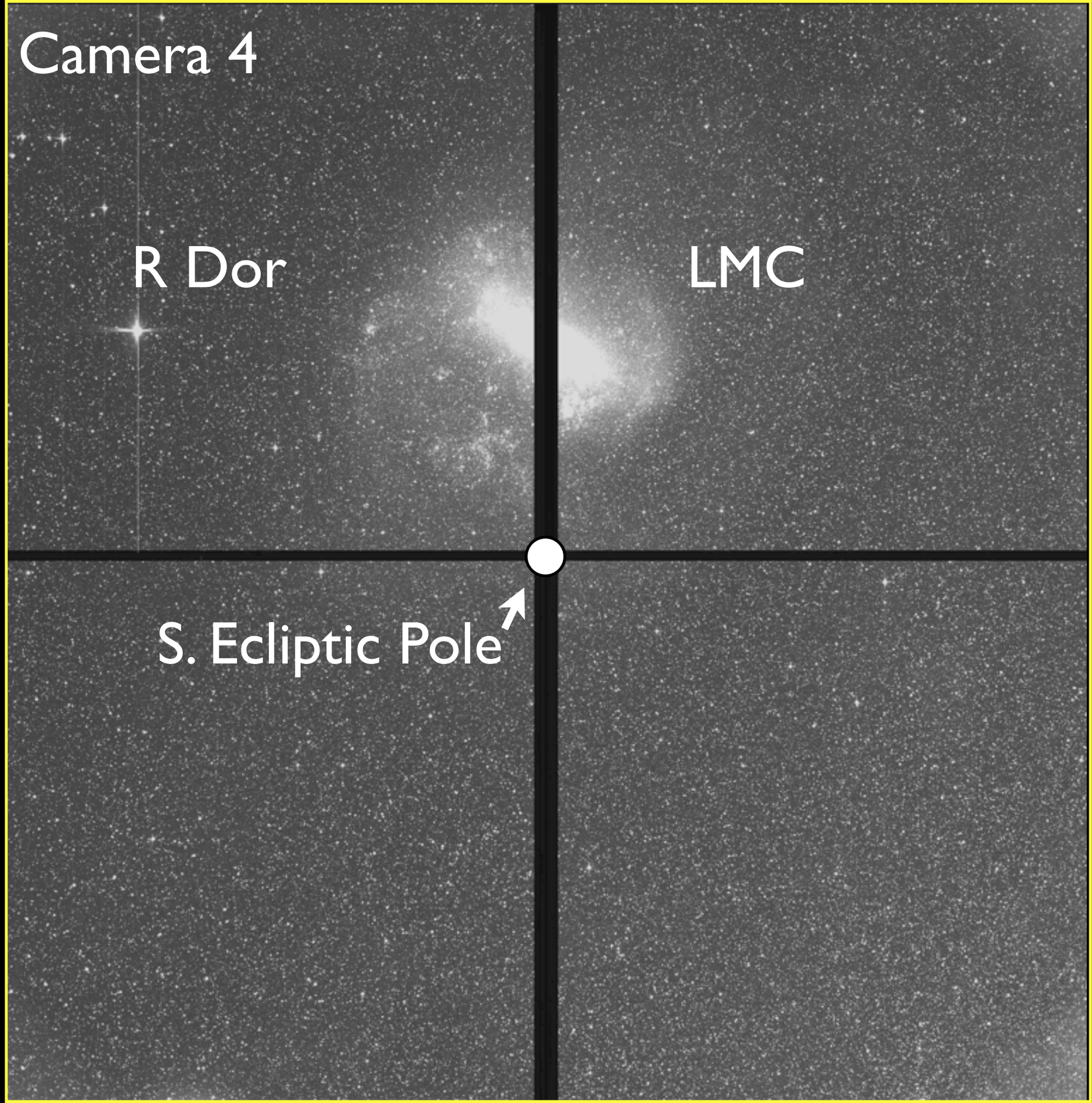


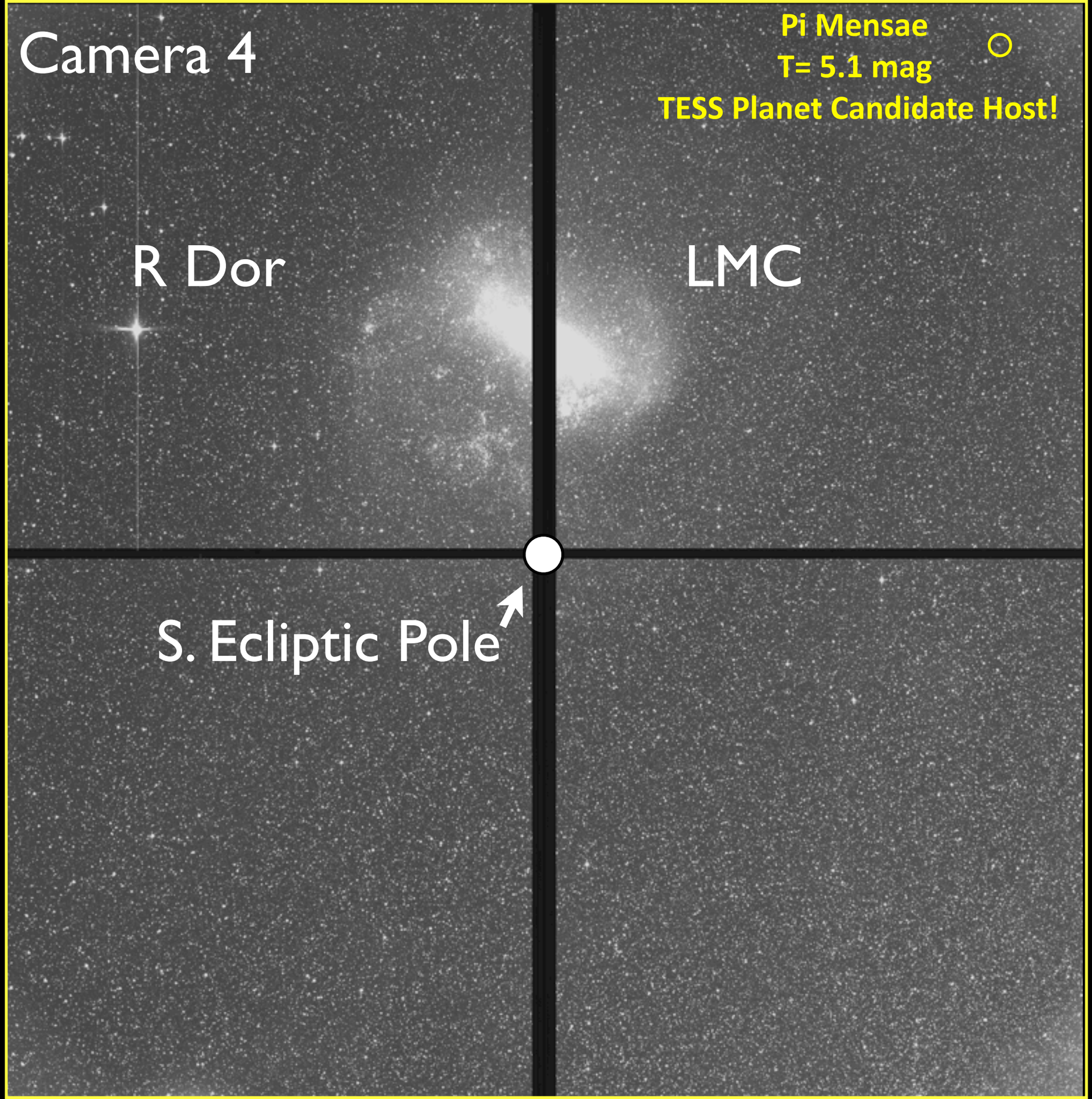


Rate since Jan 1:

26 publications in 53 days

=> 1 per ~2 days


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

Transiting Super-Earth in π Mensae

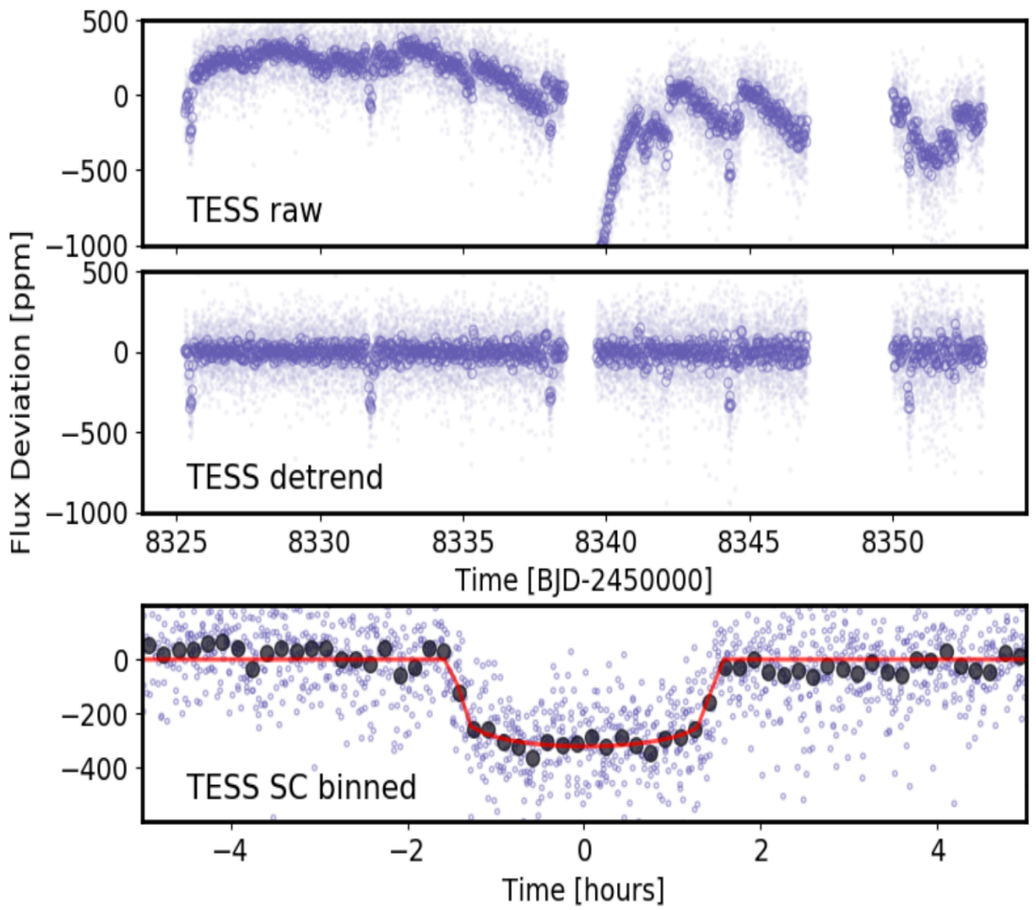


FIG. 2.— Raw (*top*) and corrected (*middle*) *TESS* light curves. The lighter points are 2 min cadence. The darker points reprent tim average of the light curve to 30 min exposure time. The interruptions are from the data downlink and the pointing anomaly. The botton panel shows the phase-folded light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

π Mensae c

Huang+ 2018 arXiv:1809.05967

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

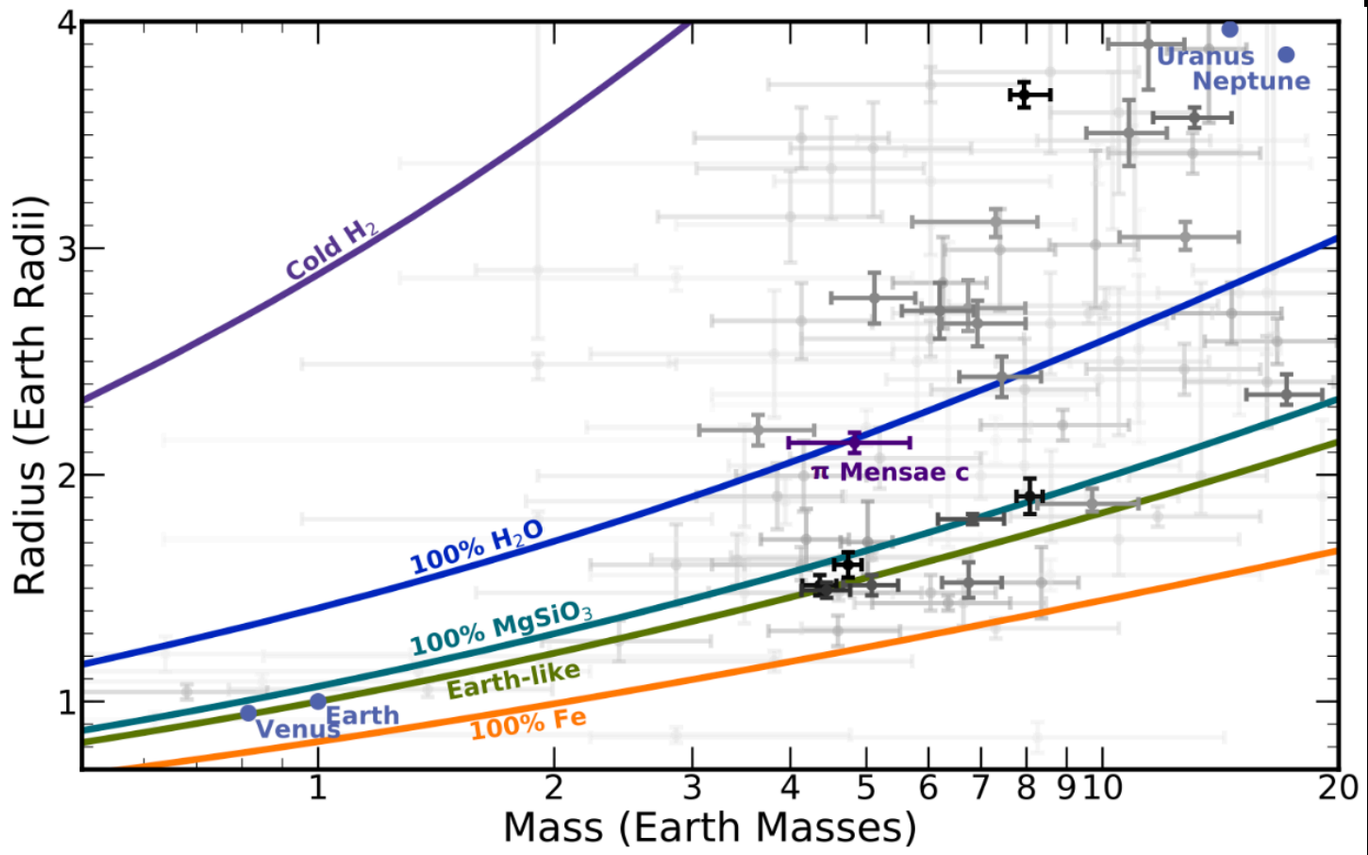
CHELSEA X. HUANG[1,2], JENNIFER BURT[1,2], ANDREW VANDERBURG[3,4], MAXIMILIAN N. GÜNTHER[1,2], AVI SHPORER[1], JASON A. DITTMANN[5,6], JOSHUA N. WINN[7], ROB WITTENMYER[8], LIZHOU SHA[1], STEPHEN R. KANE[9], GEORGE R. RICKER[1], ROLAND VANDERSPEK[1], DAVID W. LATHAM[10], SARA SEAGER[1,6], JON JENKINS[11], DOUGLAS A. CALDWELL[12] KAREN A. COLLINS[11], NATALIA GUERRERO[1], JEFFREY C. SMITH[12], SAM QUINN[11], STÉPHANE UDRY[12], FRANCESCO PEPE[12], FRANÇOIS BOUCHY[12], DAMIEN SÉ GRANSAN[12], CHRISTOPHE LOVIS[12], DAVID EHRENREICH[12], MAXIME MARMIER[12], MICHEL MAYOR[12], BILL WOHLER[13], KARI HAWORTH[1], EDWARD MORGAN[1], MICHAEL FAUSNAUGH [1], DAVID CHARBONNEAU[10], NORIO NARITA[14, 15], AND THE *TESS* TEAM

Draft version September 18, 2018

ABSTRACT

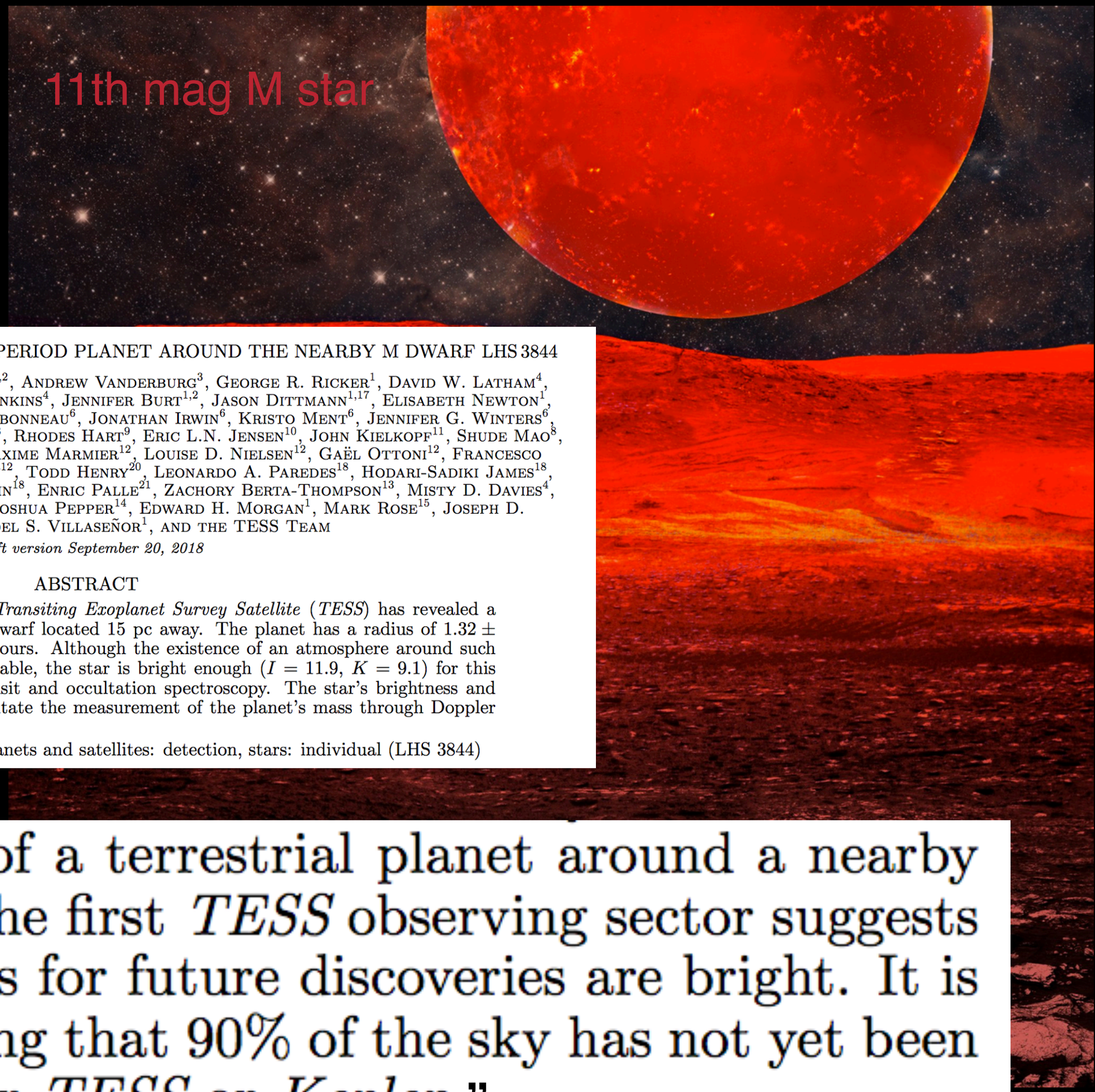
We report the detection of a transiting planet around π Men (HD 39091), using data from the *Transiting Exoplanet Survey Satellite* (*TESS*). The solar-type host star is unusually bright ($V = 5.7$) and was already known to host a Jovian planet on a highly eccentric, 5.7-year orbit. The newly discovered planet has a size of 2.14 ± 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 ± 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

ABSTRACT

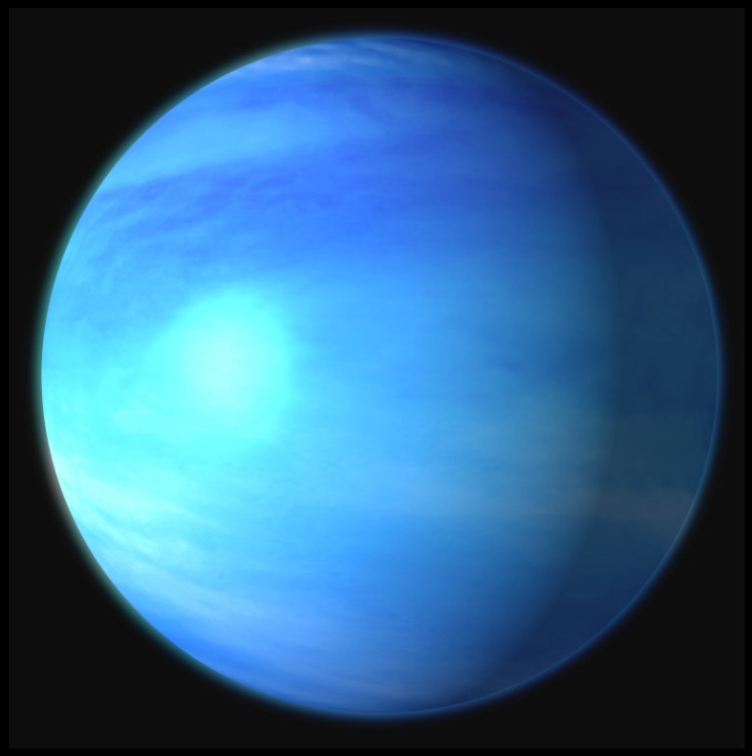
Data from the newly-commissioned *Transiting Exoplanet Survey Satellite* (*TESS*) has revealed a "hot Earth" around LHS 3844, an M dwarf located 15 pc away. The planet has a radius of $1.32 \pm 0.02\ R_\oplus$ and orbits the star every 11 hours. Although the existence of an atmosphere around such a strongly 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*."

HD 21749b

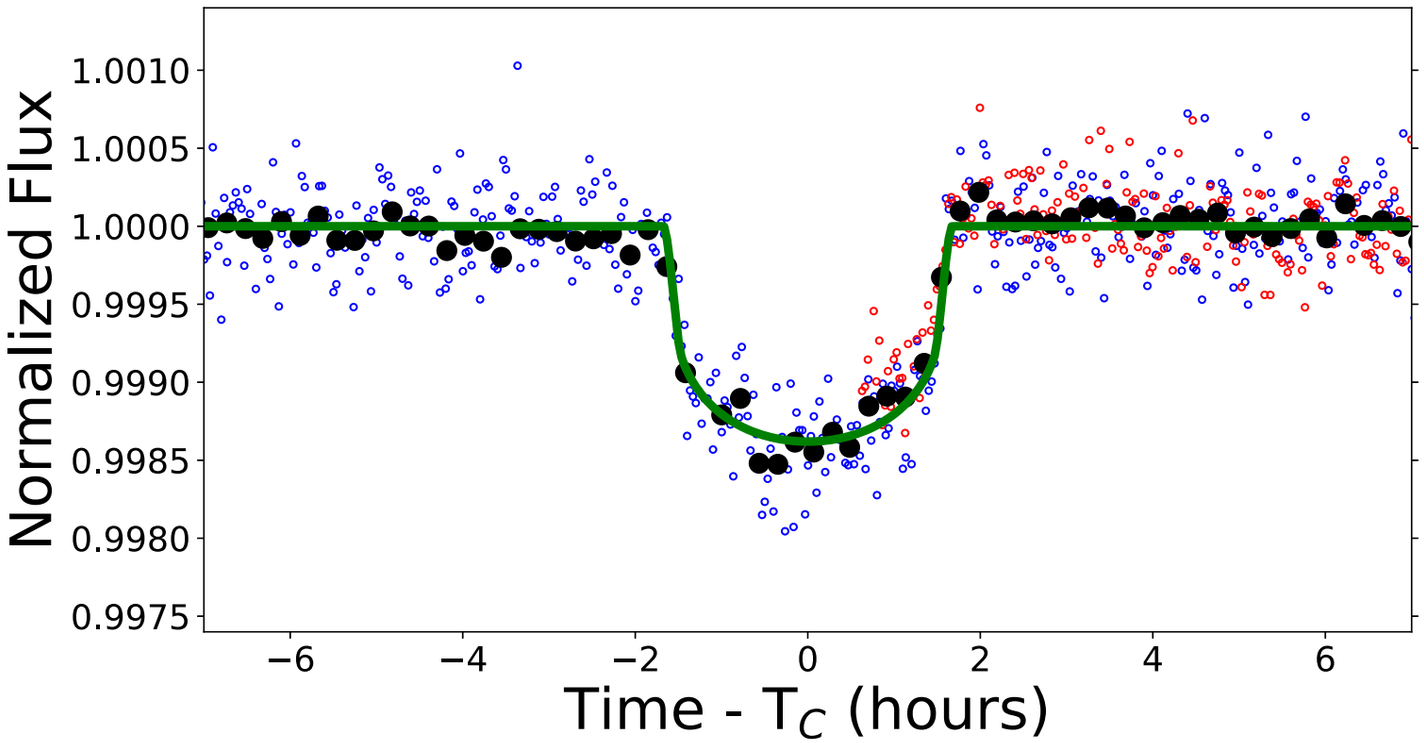
8th Mag K star

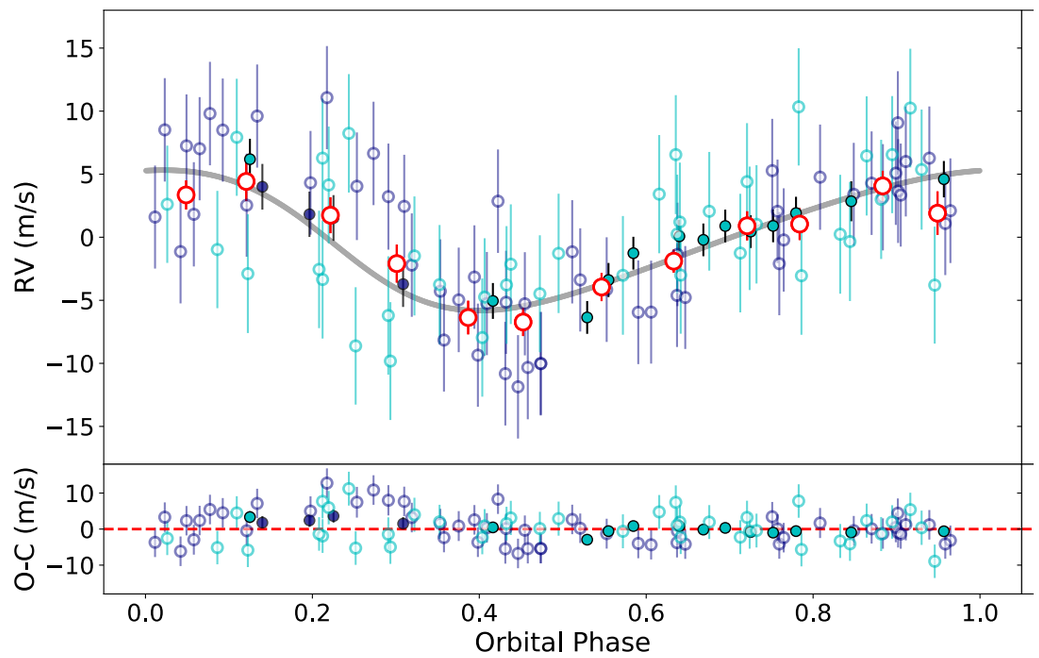


Dragomir et al. (2019)
arXiv:1901.00051

THE LONGEST PERIOD *TESS* PLANET YET: A SUB-NEPTUNE TRANSITING A BRIGHT, NEARBY K DWARF STAR

Diana Dragomir[1,2], Johanna Teske[2,3,4], Maximilian N. Günther[1,5], Damien Ségransan[6], Jennifer A. Burt[1,5], Chelsea X. Huang[1,5], Andrew Vanderburg[7,8], Elisabeth Matthews[1], Xavier Dumusque[6], Keivan G. Stassun[9], Joshua Pepper[10], George R. Ricker[1], Roland Vanderspek[1], David W. Latham[11], Sara Seager[1,12,13], Joshua N. Winn[14], Jon M. Jenkins[15], Thomas Beatty[16,17], François Bouchy[6], R. Paul Butler[3], Jeffrey D. Crane[4], Jason D. Eastman[11], Jim Francis[1], B. Scott Gaudi[18], Robert F. Goeke[1], David James[11], Todd C. Klaus[19], Rudolf B. Kuhn[20,21], Christophe Lovis[6], Michael B. Lund[9], Scott McDermott[22], Martin Paegert [11], Francesco Pepe [6], Joseph E. Rodriguez[11], Lizhou Sha[1], Stephen A. Shectman[4], Robert J. Siverd[9], Aylin Garcia Soto [1], Daniel J. Stevens[16,17], Ian B. Thompson[4], Joseph D. Twicken[23], Stéphane Udry[6], Steven Villanueva Jr.[1], Sharon X. Wang[3], Bill Wohler[23], Xinyu Yao[10], Zhuchang Zhan[1,12], and the *TESS* Team



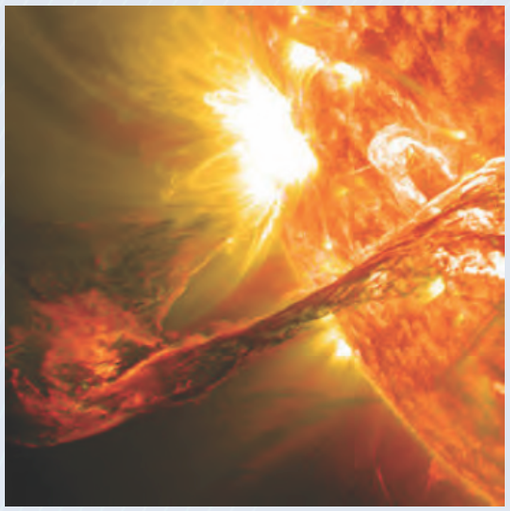


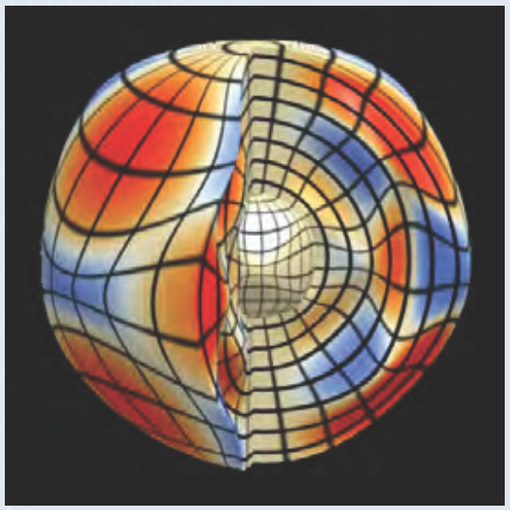
HARPS radial velocities

PFS radial velocities

Just in case you thought TESS was only about exoplanets…

Time Domain Astrophysics with TESS Full Images





✓ Preliminary TESS Results in Early Sectors

Solar System Objects:

Thousands in 2 years…

- Occultation Events
- ✓ Comets
- ✓ Asteroids

Explosive & Variable Extragalactic Sources:

Thousands (?) in 2 years…

- ✓ Supernovae
- AGNs
- Blazars
- Quasars
- Tidal Disruption Events
- Gamma-ray Bursts
- Kilonovae (Gravitational Wave Counterparts)
- Hypernovae

Variable Stars:

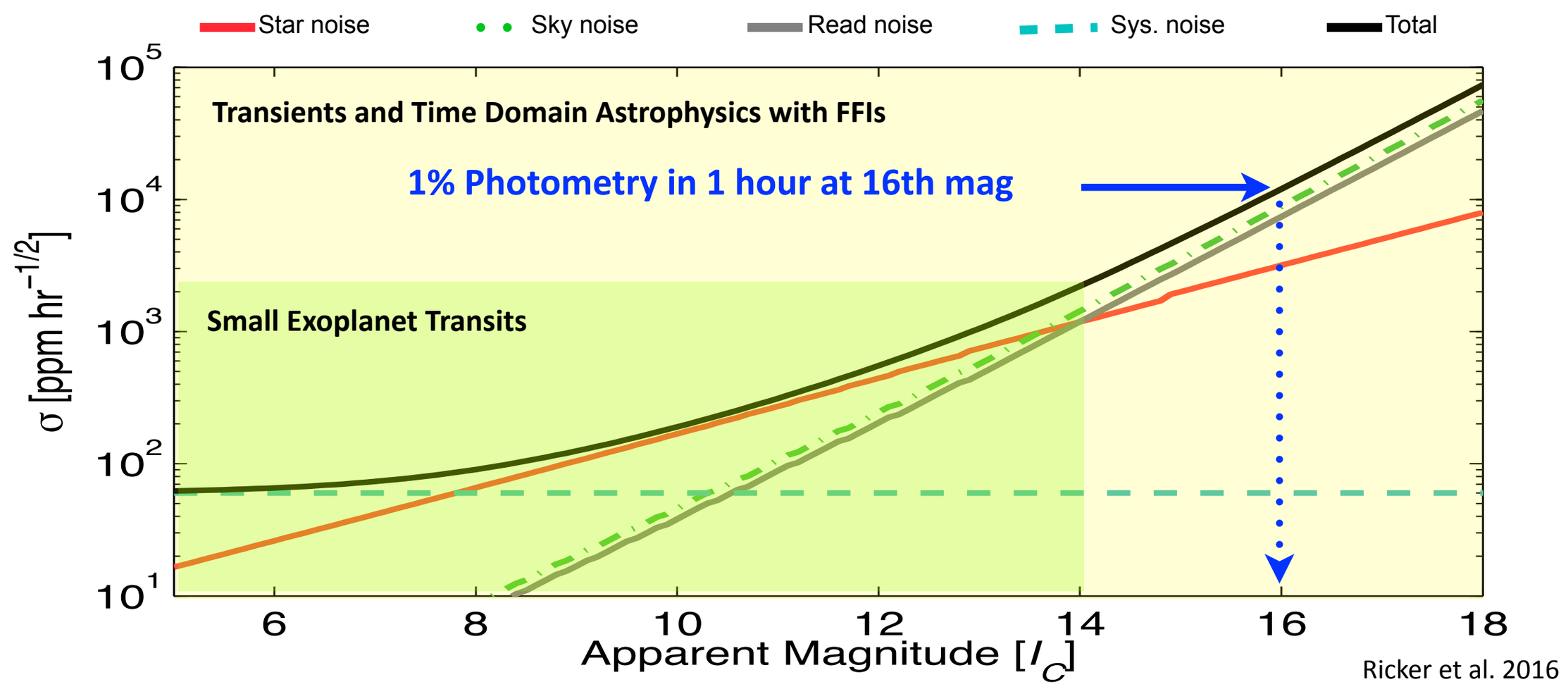
Millions in 2 years…

- ✓ Asterioseismology
- Brown Dwarfs
- ✓ Eclipsing Binaries
- ✓ Flare Stars
- ✓ Cepheids
- T Tauri Stars
- Cluster Gyrochronology
- ✓ White Dwarfs
- ✓ Neutron Stars
- Emission line stars (Be stars)
- RR Lyrae Stars
- WD Oscillations
- Novae
- Young Stellar Objects

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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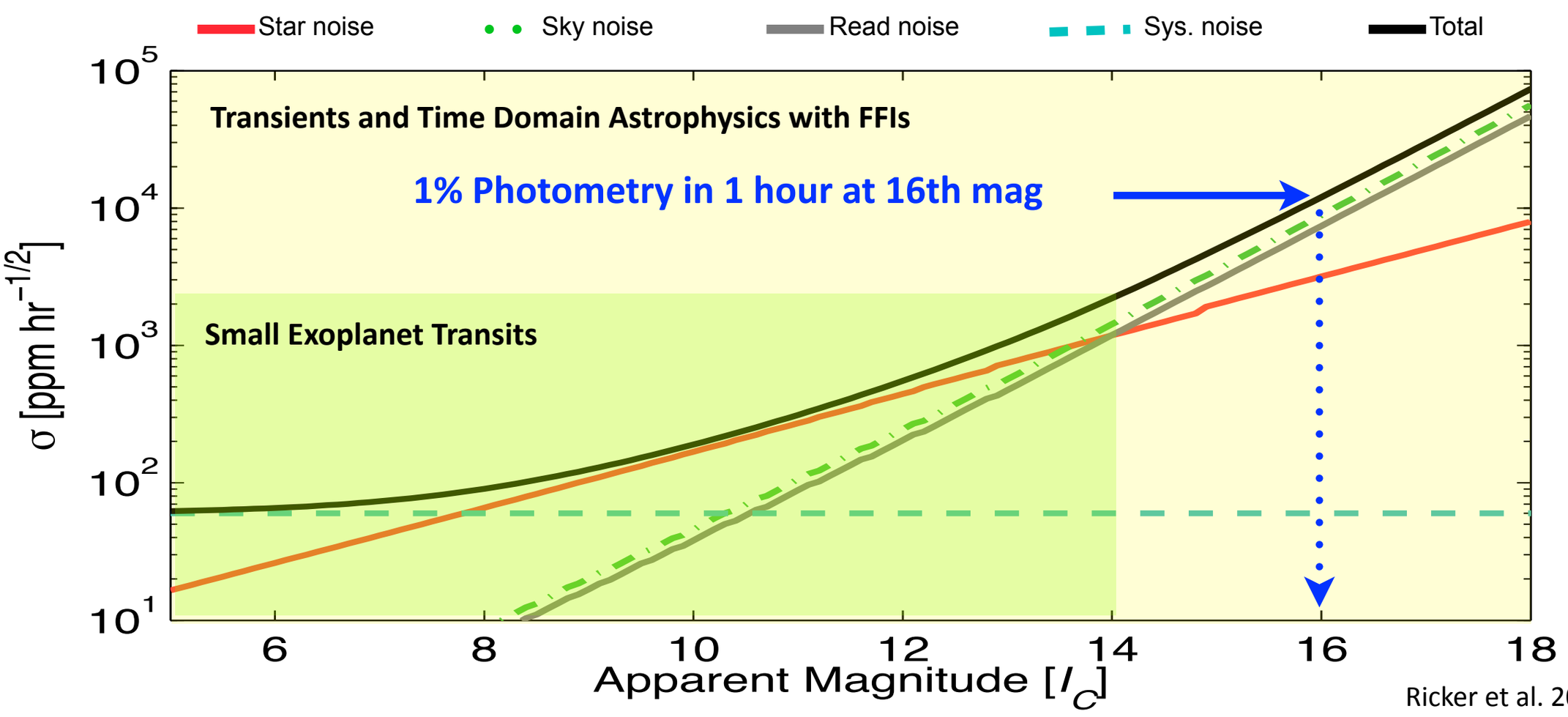
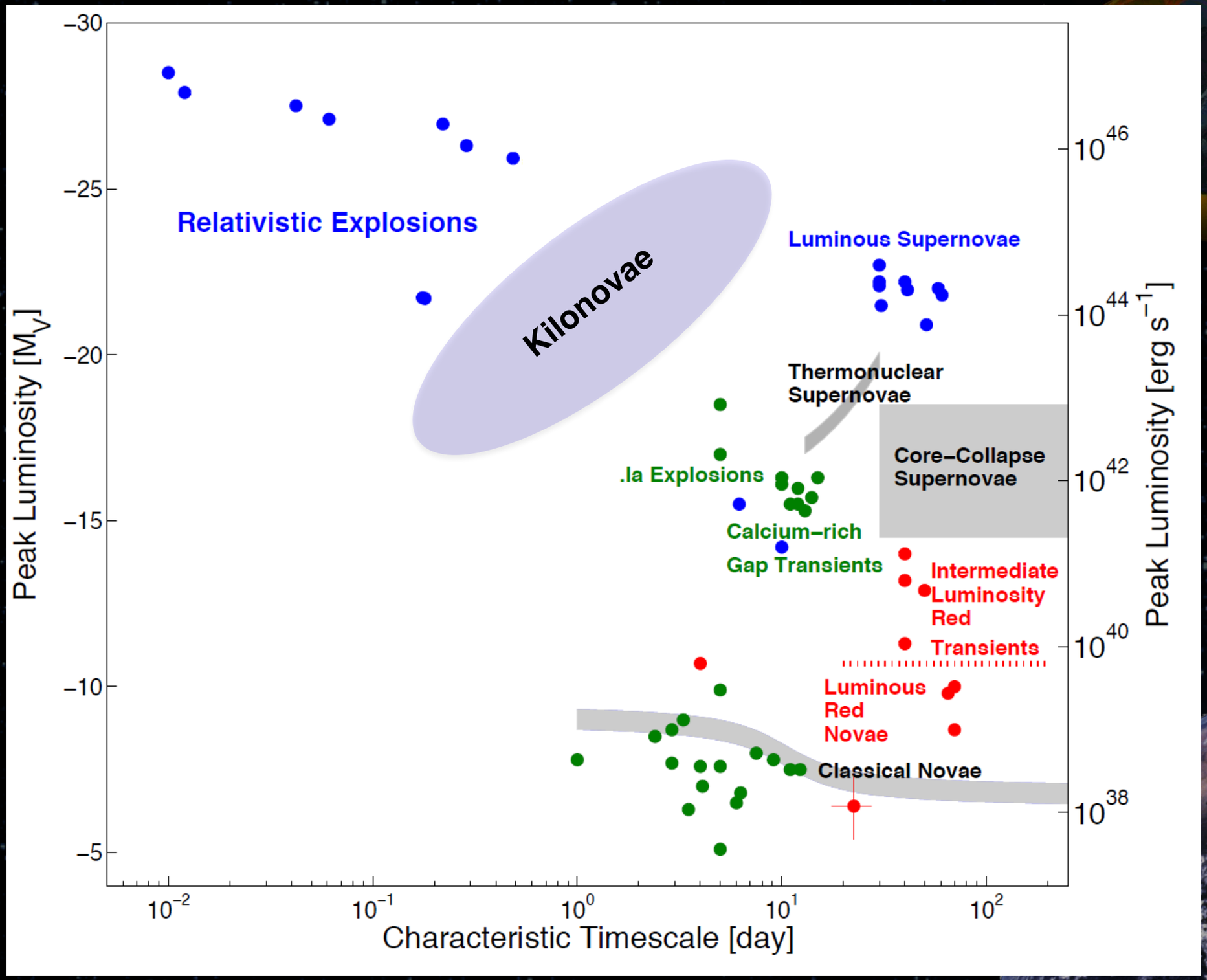


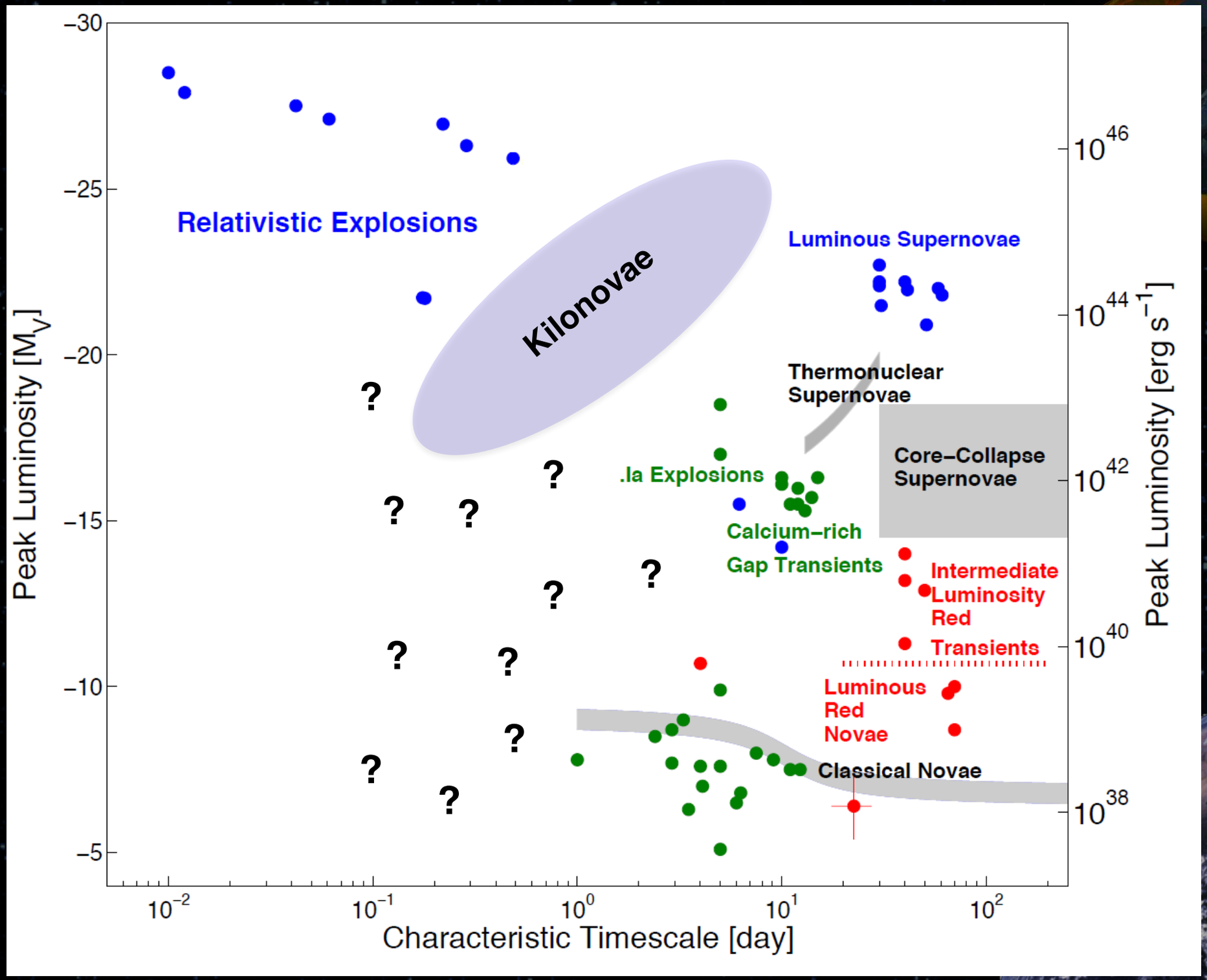
Ricker et al. 2016

TESS and Depth



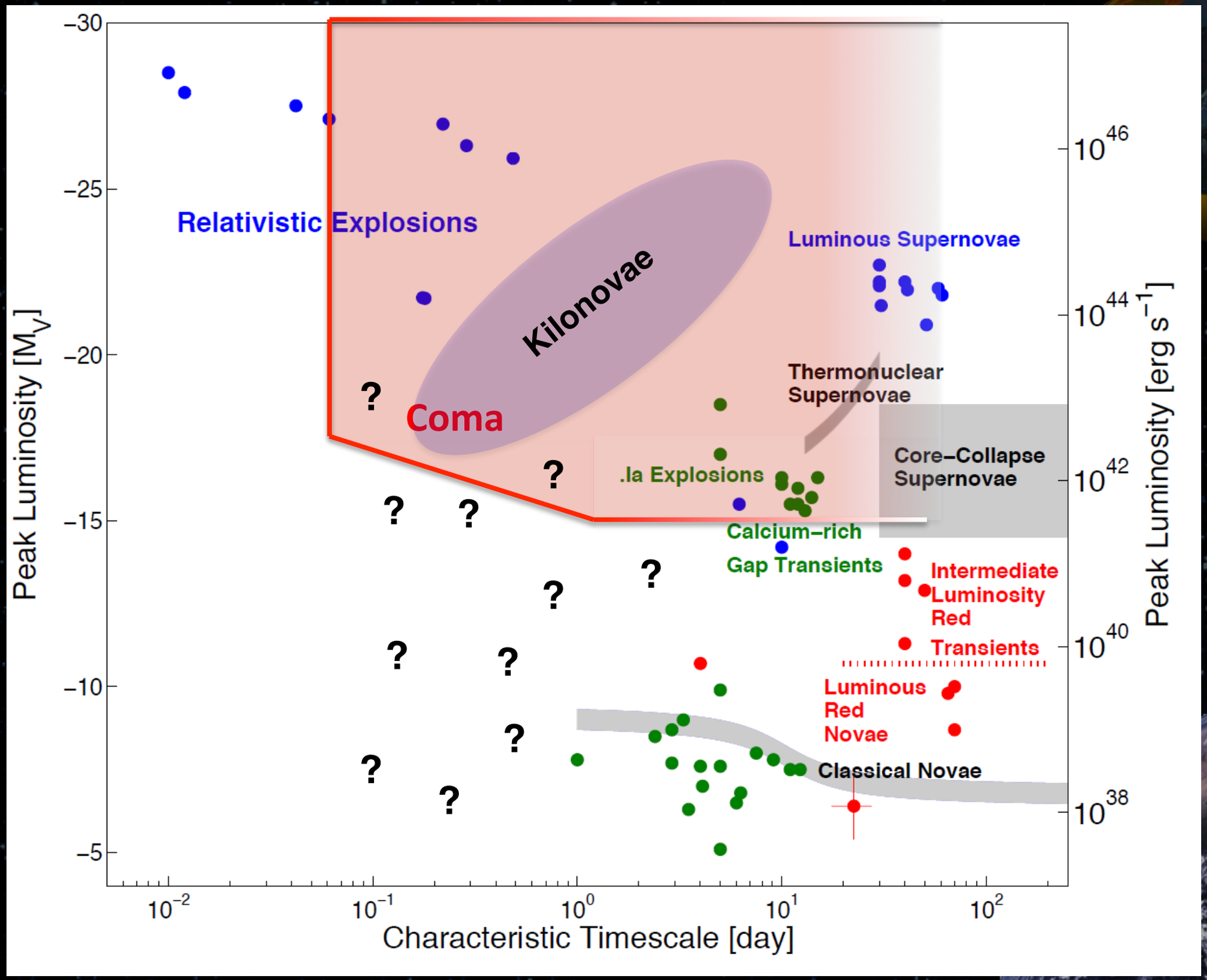
Plot Credit: Mansi Kasliwal

TESS and Depth



Plot Credit: Mansi Kasliwal

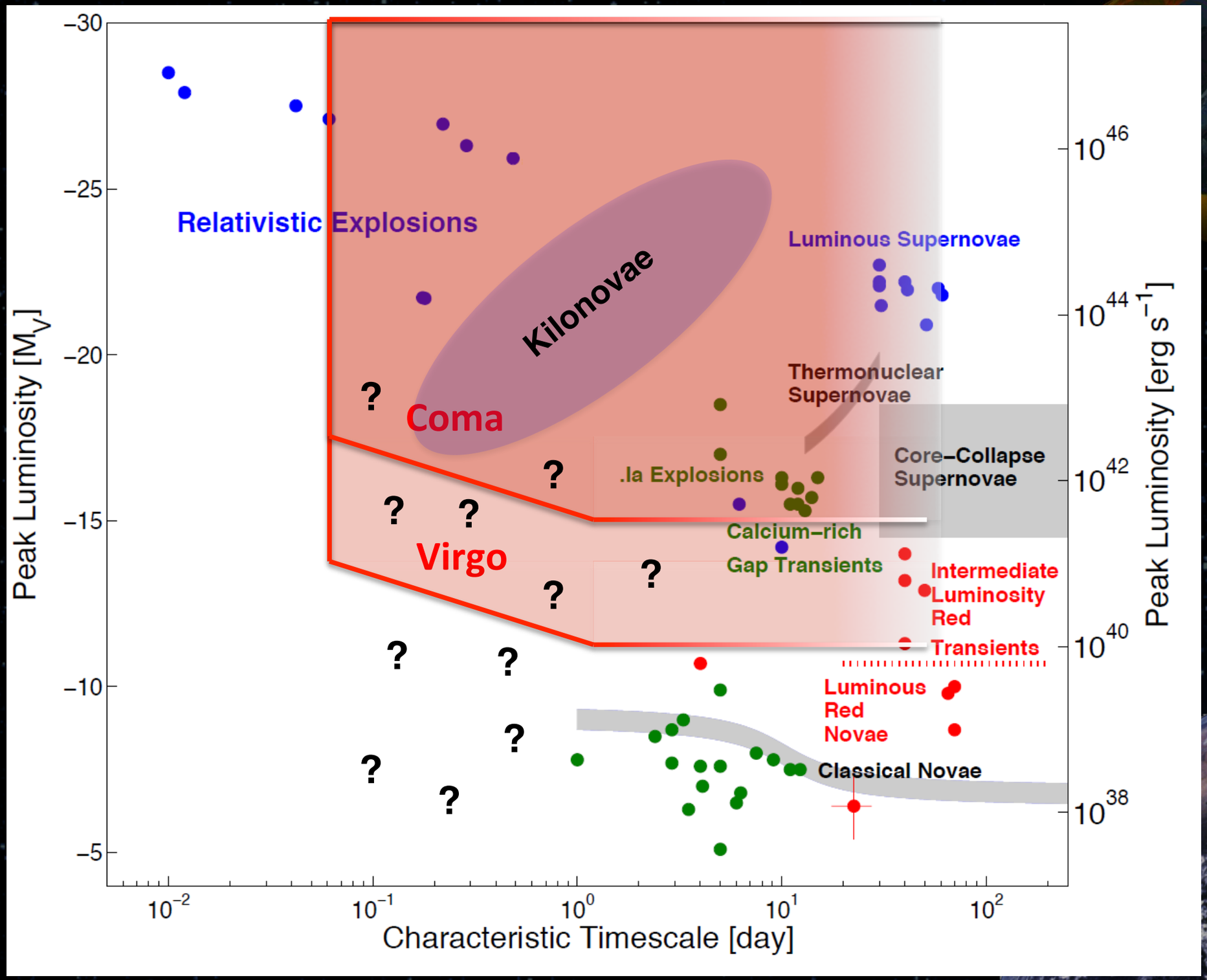
TESS and Depth



B. Shappee 2015

Plot Credit: Mansi Kasliwal

TESS and Depth



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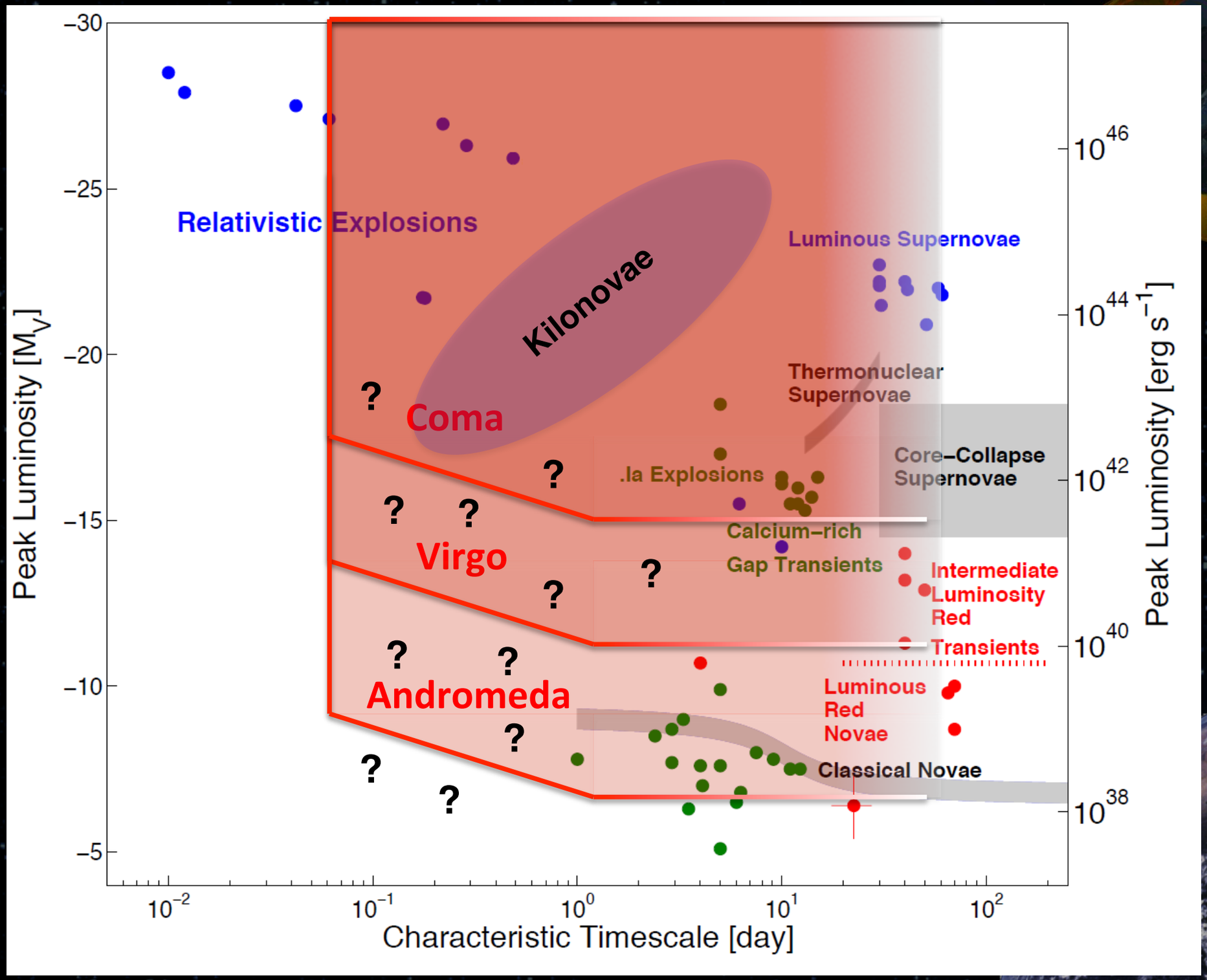
Plot Credit: Mansi Kasliwal

TESS and Depth



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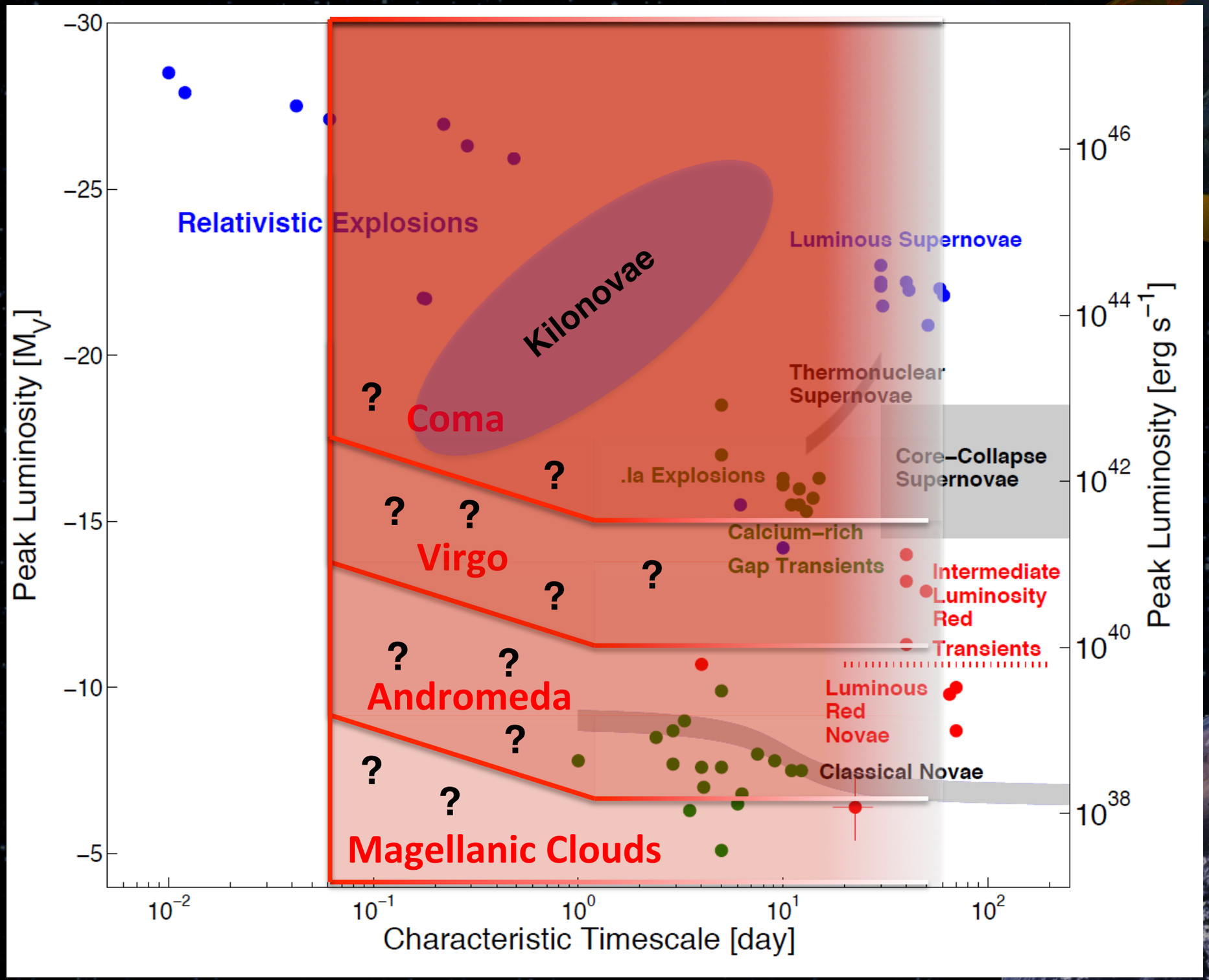
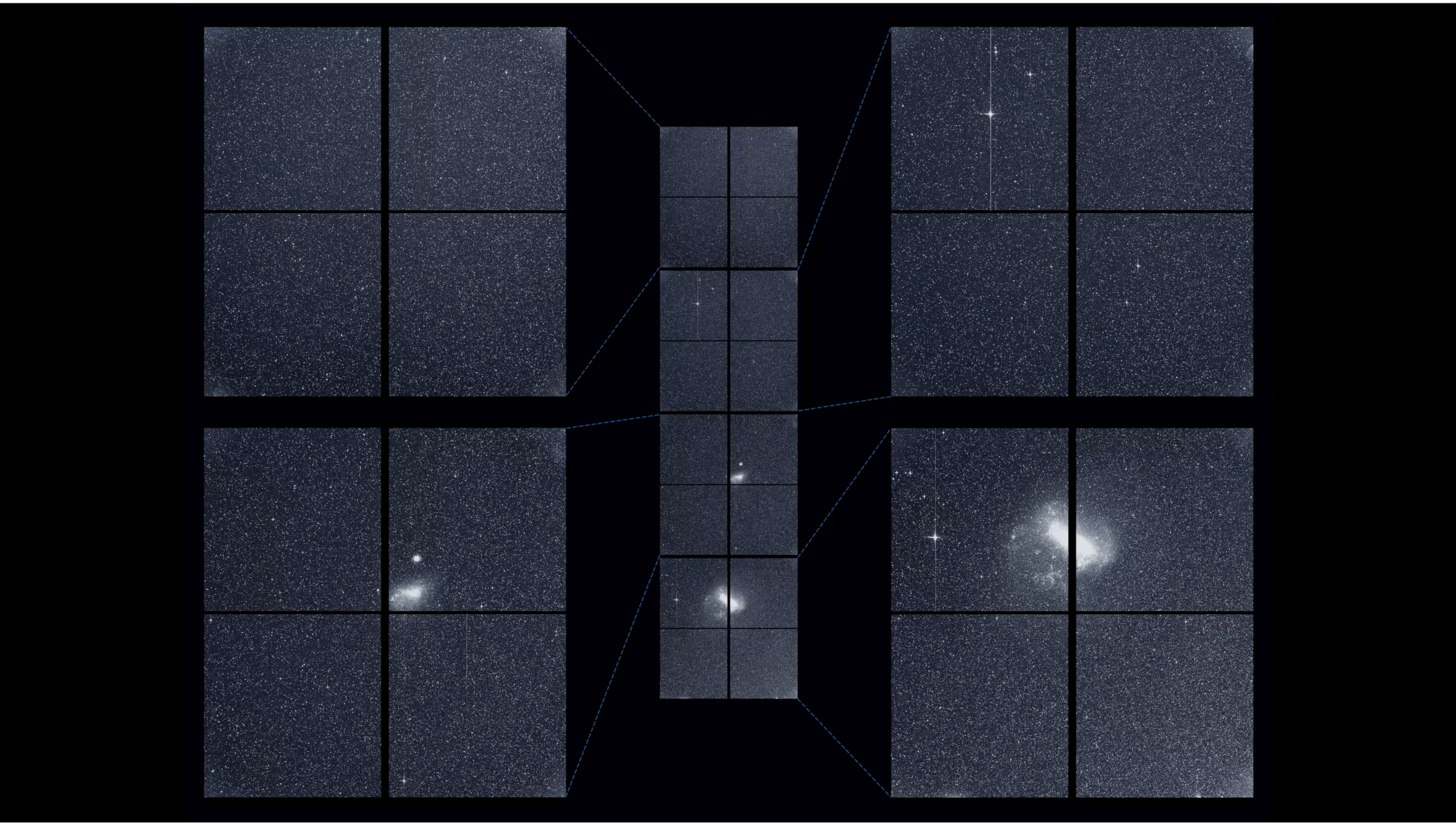
TESS and Depth



B. Shappee 2015

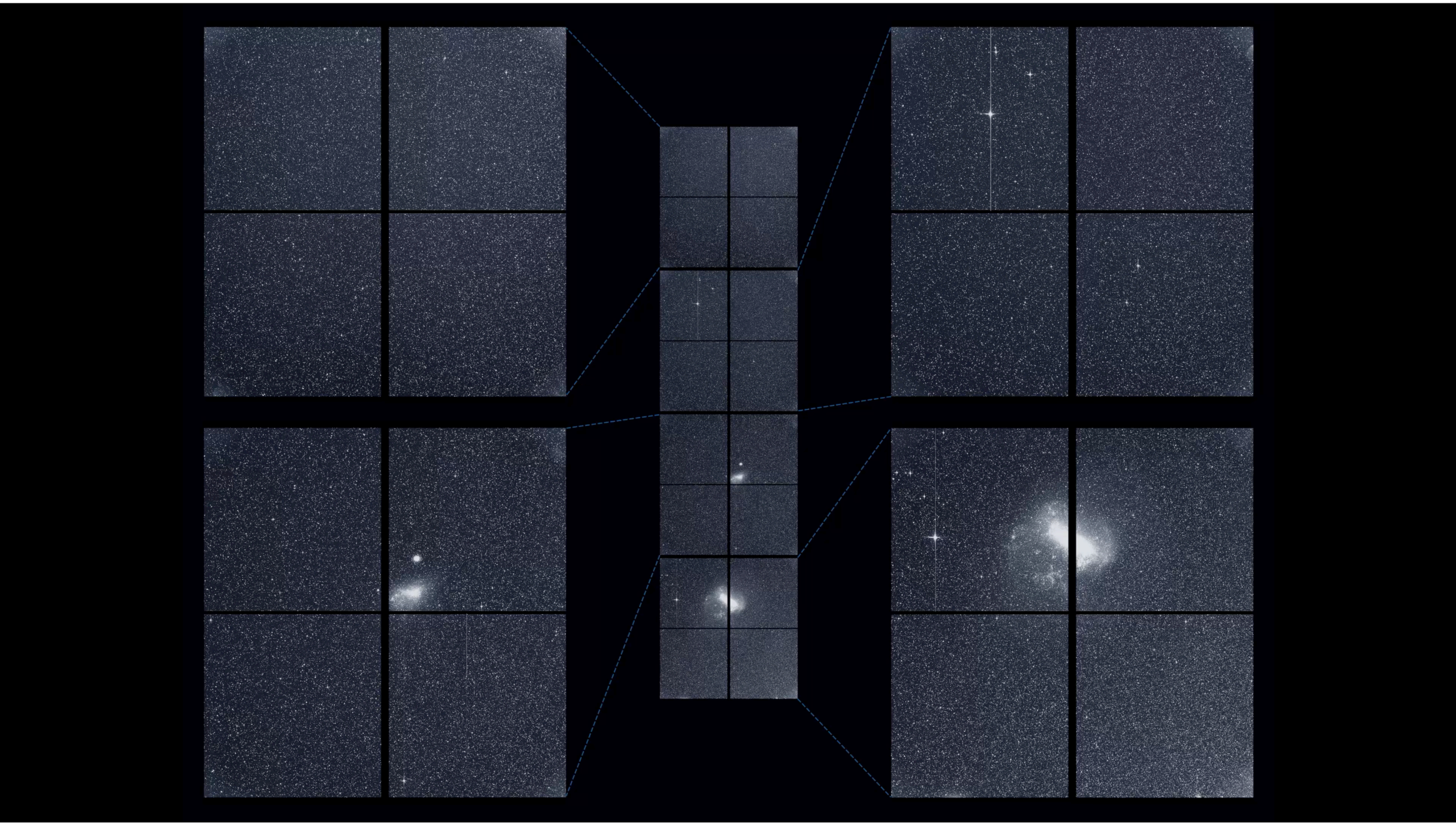
Plot Credit: Mansi Kasliwal

Supernovae Detected by TESS in Early Observations



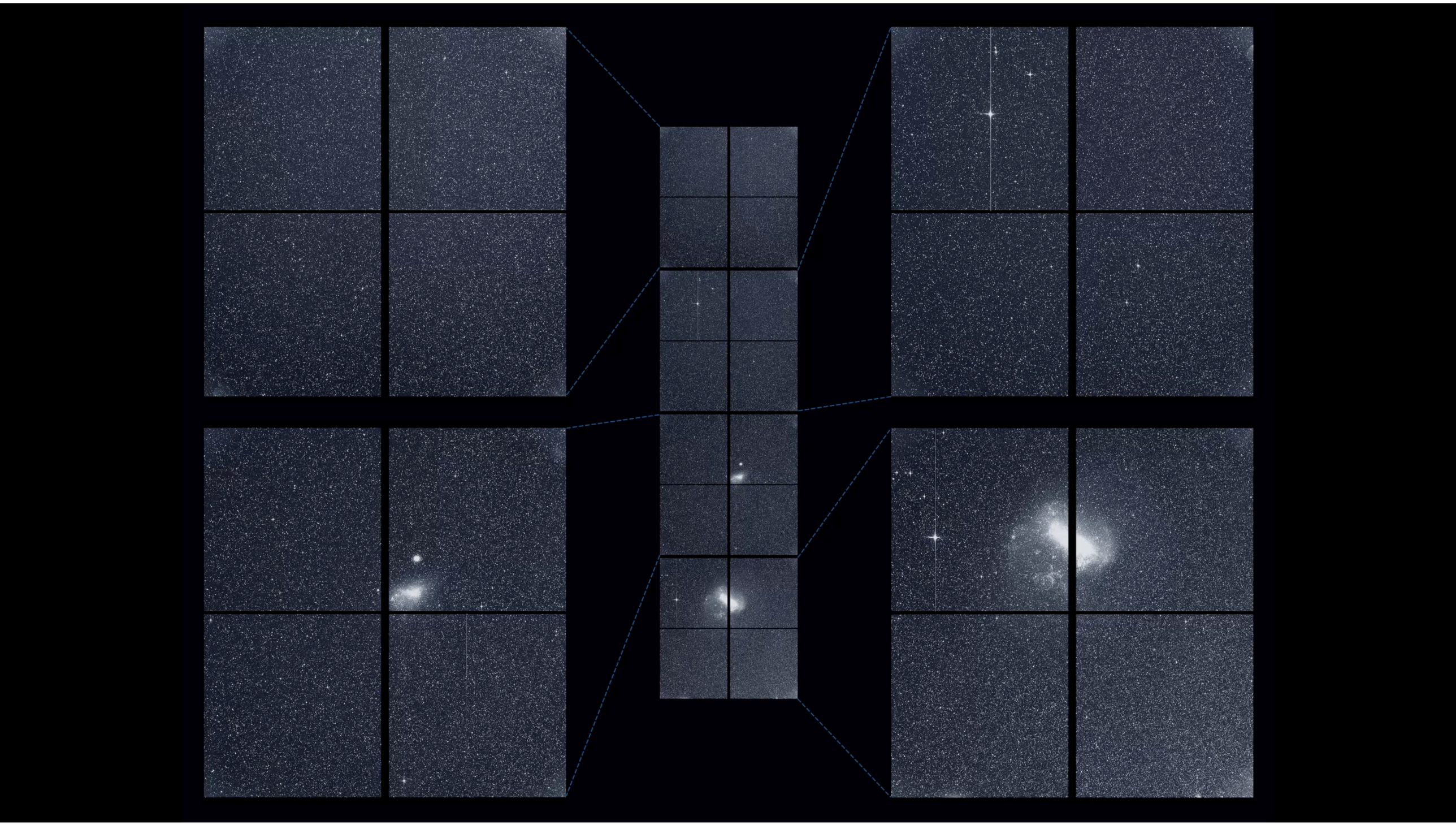
M. Fausnaugh+ 2019

Supernovae Detected by TESS in Early Observations



M. Fausnaugh+ 2019

Supernovae Detected by TESS in Early Observations



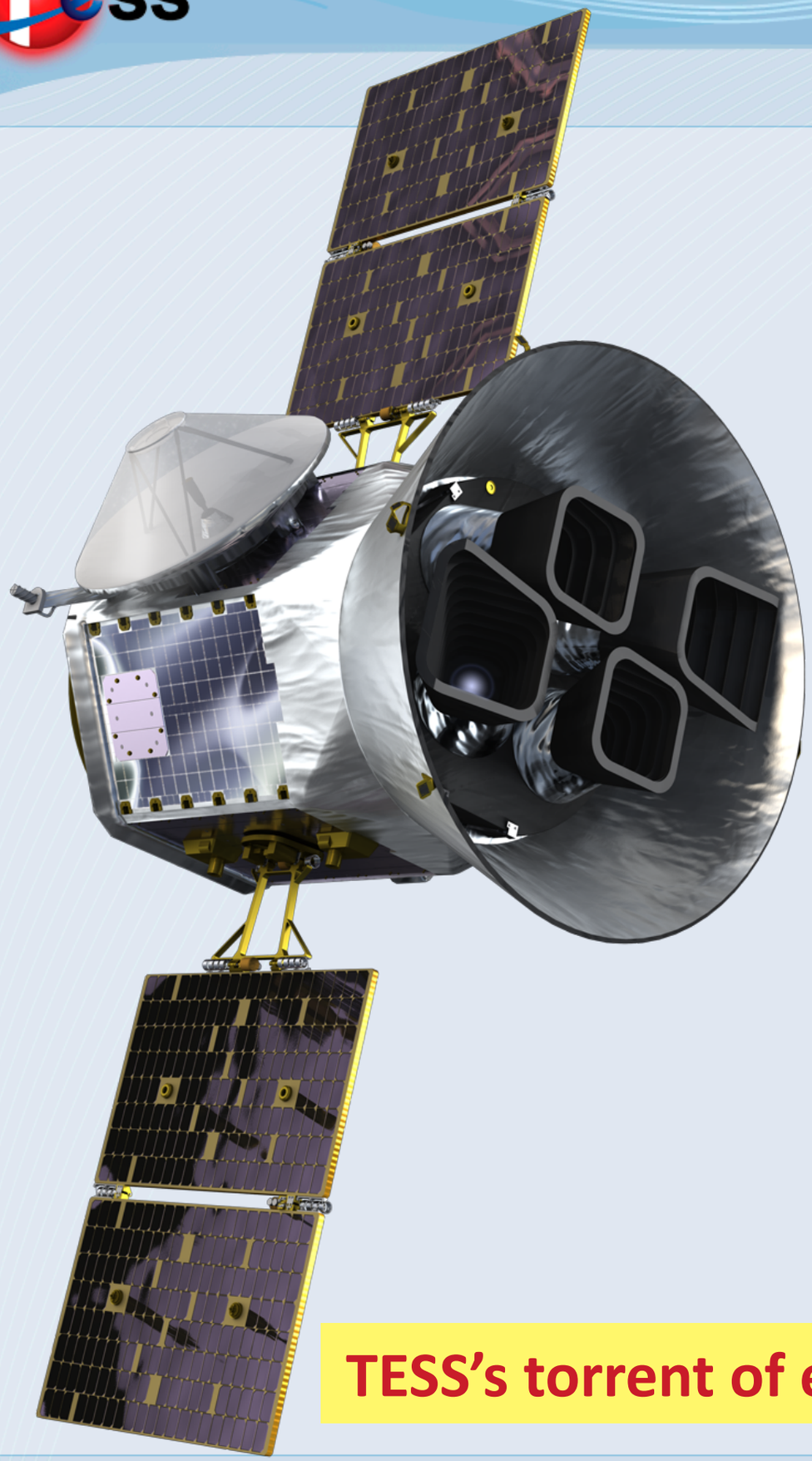
… 35 More SN in process

M. Fausnaugh+ 2019

TESS Enables Time-Domain Astronomy in the Coming Decade

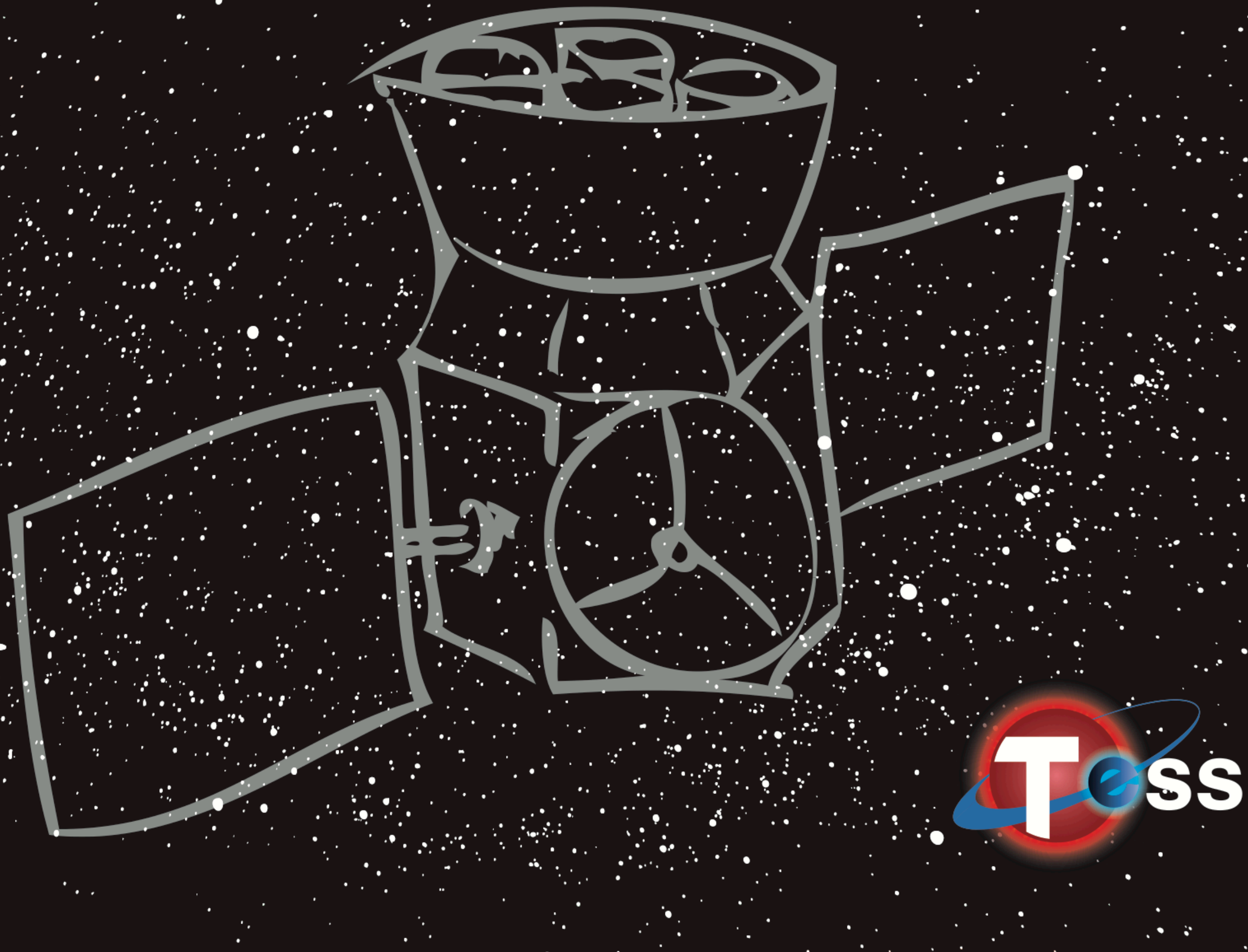
	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028
TESS		Prime Mission: S. Hemi / N. Hemi		Extended Mission #1		Extended Mission #2 ??			Extended Mission #3 ??		
CHEOPS			CHEOPS Baseline Mission								
JWST					JWST Design Mission……						
LIGO		O3		O4	……						
LSST					Ten Year LSST Survey ……						
NGLT's						EELT, GMT, TMT ……					
PLATO									PLATO ……		

TESS Early Mission Takeaways

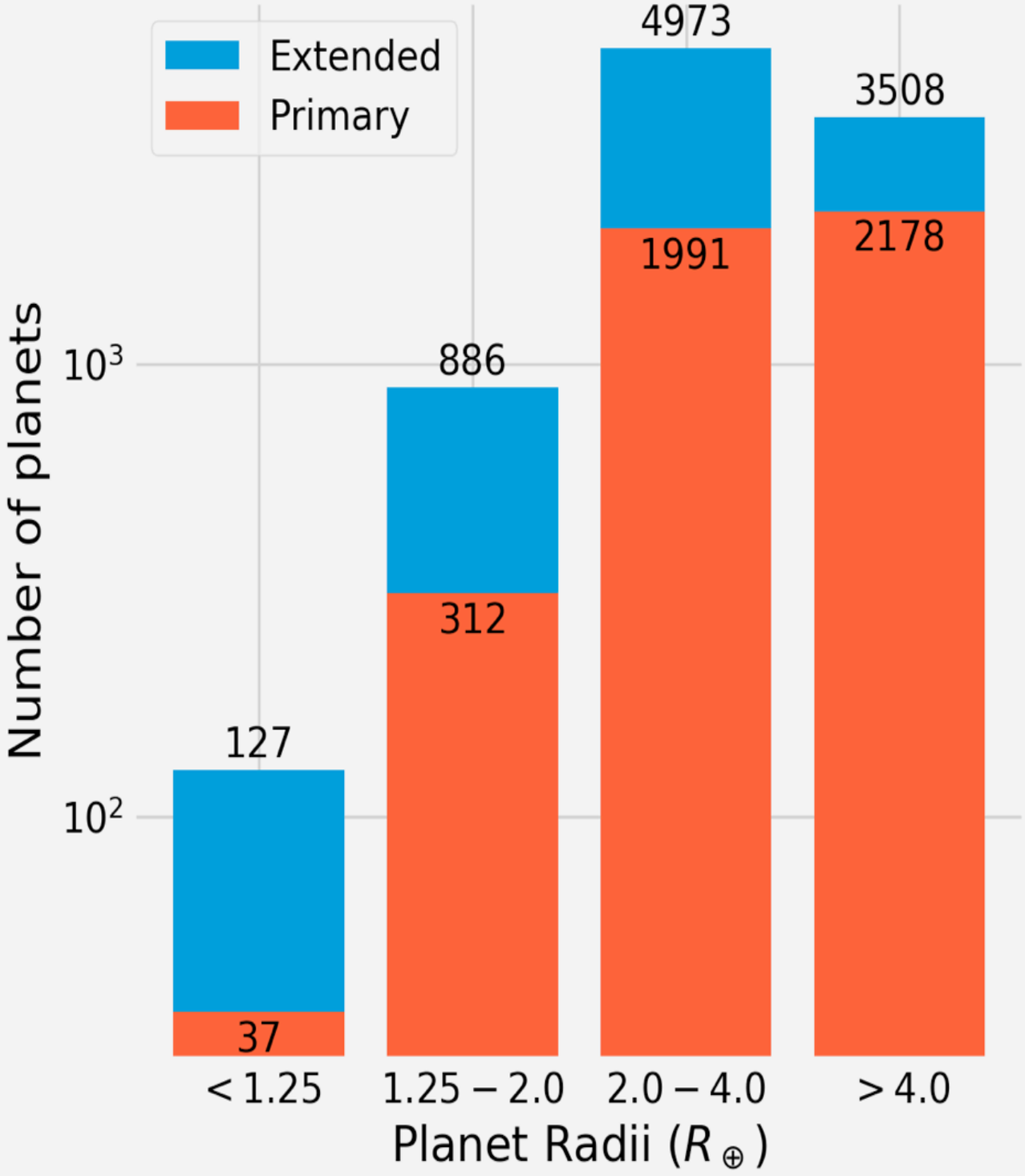


- TESS's unique lunar resonant orbit is greatly simplifying the mission
  - *Stable operations in principle could last until 2038 or later*
- TESS's spacecraft stability is exquisite
  - *20 milli-arcseconds on 1 hour time scales*
- TESS's camera performance is superb
- TESS's sky survey sector-by-sector is well underway
  - *Sectors #1-7 are complete; #8 in progress*
- TESS's full frame images are enabling a wide range of astrophysics discoveries
  - *Also* ***Stellar Astrophysics, Planetary Astronomy, Extragalactic "Multi-Messenger Astronomy"***

TESS's torrent of exciting new discoveries has commenced...


TESS

TESS Extended Mission: Best is Yet to Come...

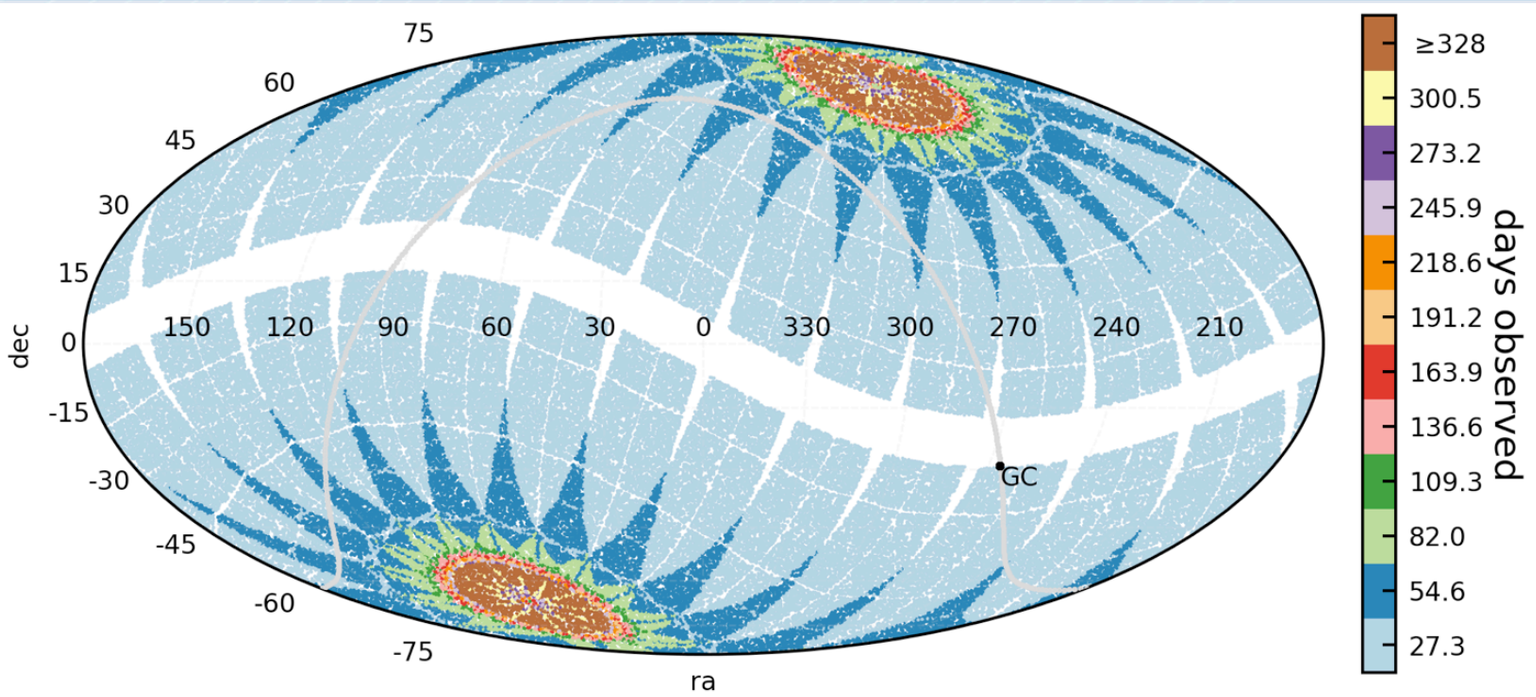


- **NB: Log Scale on Y-axis**
- **TESS Extended Mission (2020-2022)**
  - *Should <u>double</u> number of planets*
    - *4,518 in Primary*
    - *9494 in Extended*
  - *3x as many Earth-sized planets*
  - *Many more planets in HZ*

T. Barclay

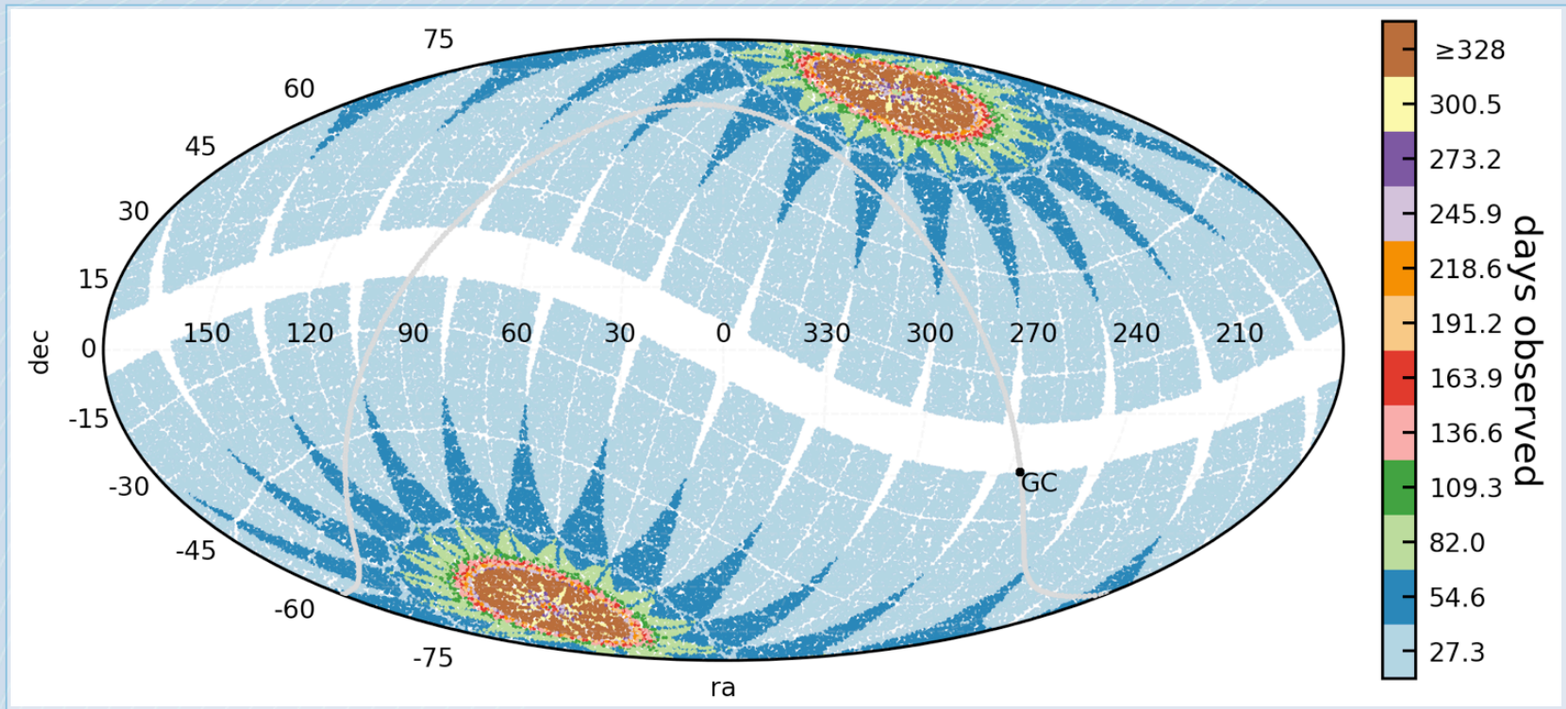
Sky Coverage for Primary & Extended Missions

Sky Coverage for Primary & Extended Missions



Primary Mission

Sky Coverage for Primary & Extended Missions



Primary Mission

Extended Mission