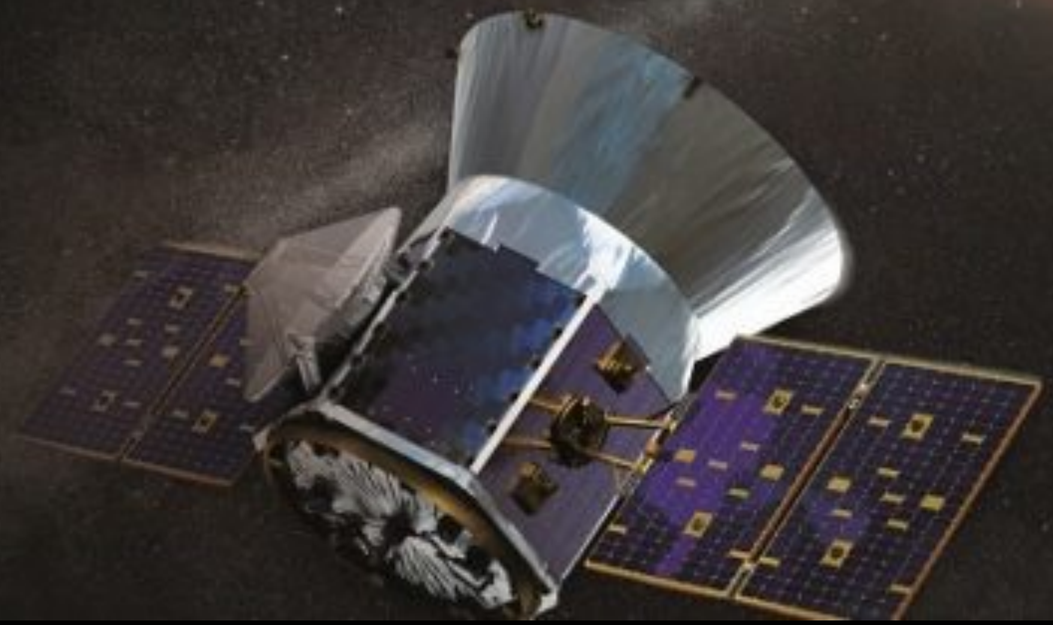
The Trivial Case of Finding Tiny Planets 600 Trillion Miles Away from Earth

Lilith: A Versatile Instrument and All-Sky Simulator for use with Space-Based Astrophysics Observatories



Jeffrey C. Smith

SETI Institute

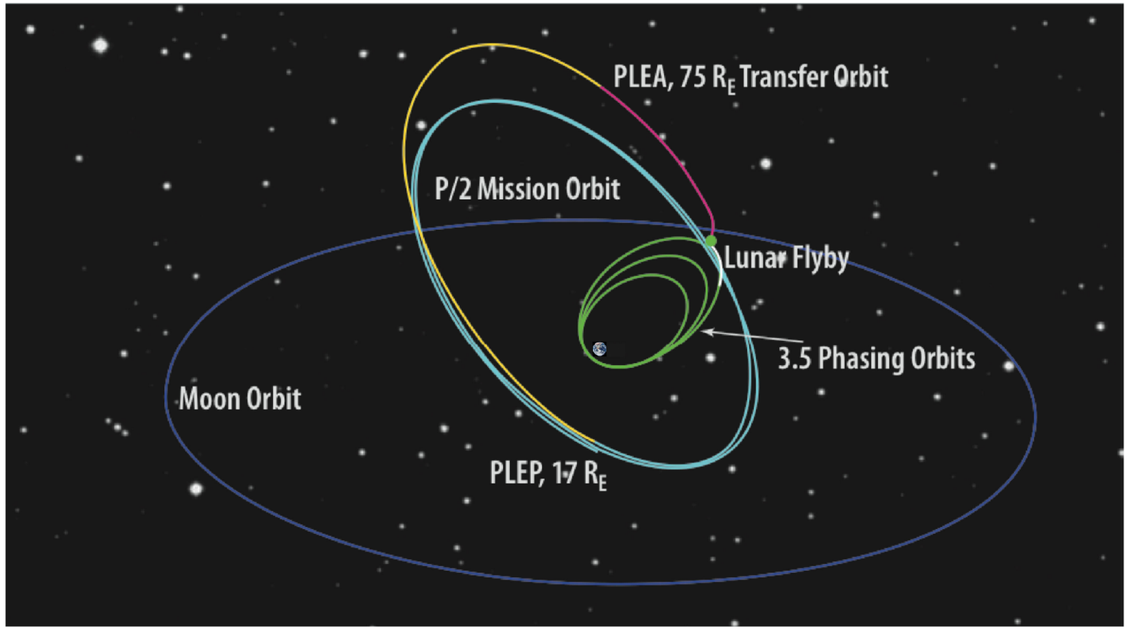
with Peter Tenenbaum, Joe Twicken and Jon Jenkins

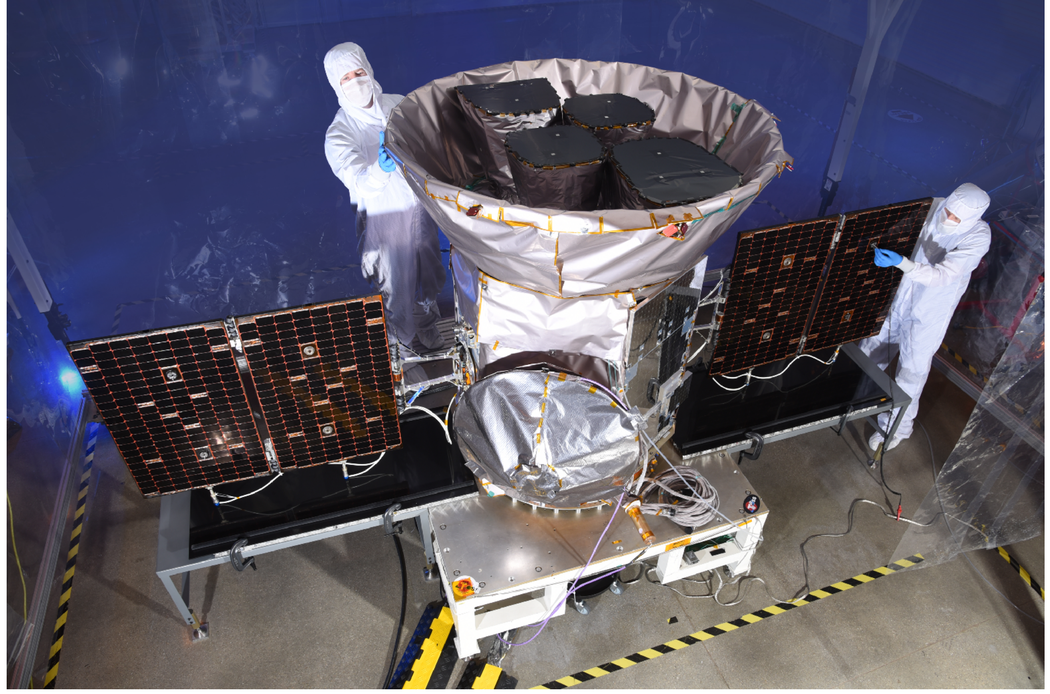
ADASS 2018

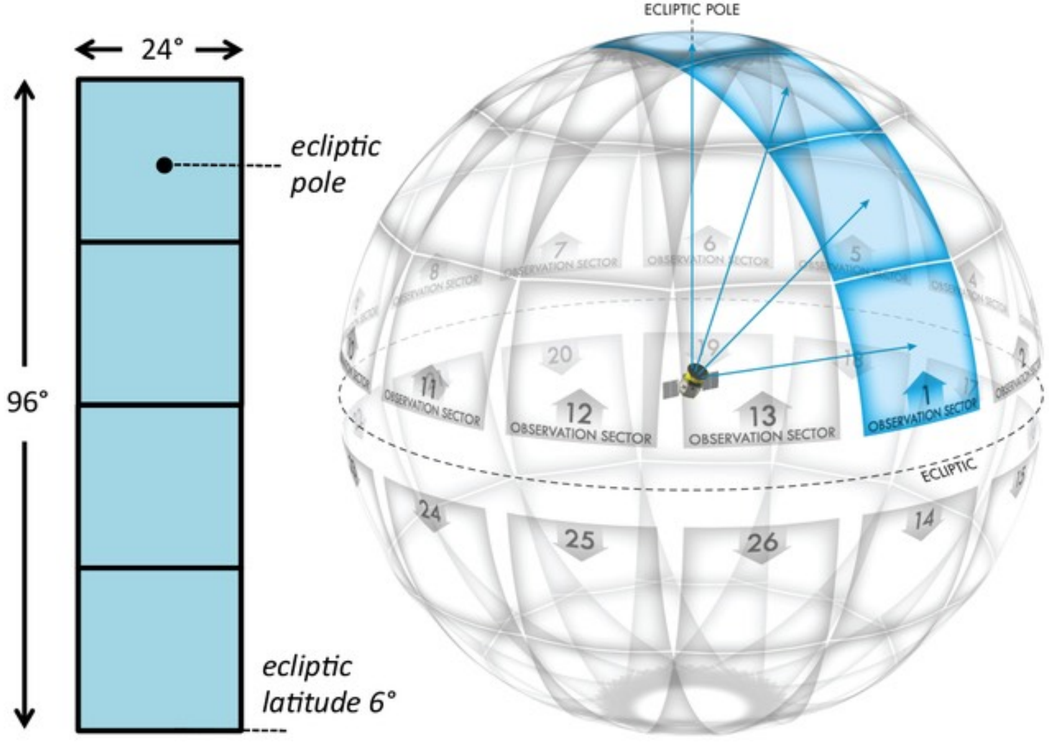
Nov. 15th, 2018

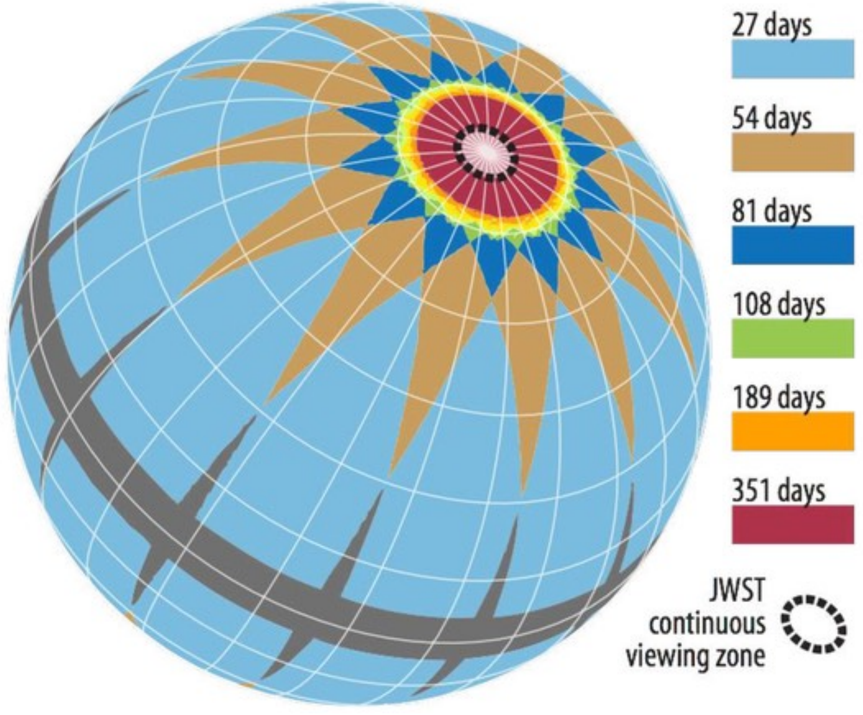
The TESS Mission

The TESS Mission
Not the topic of this talk!

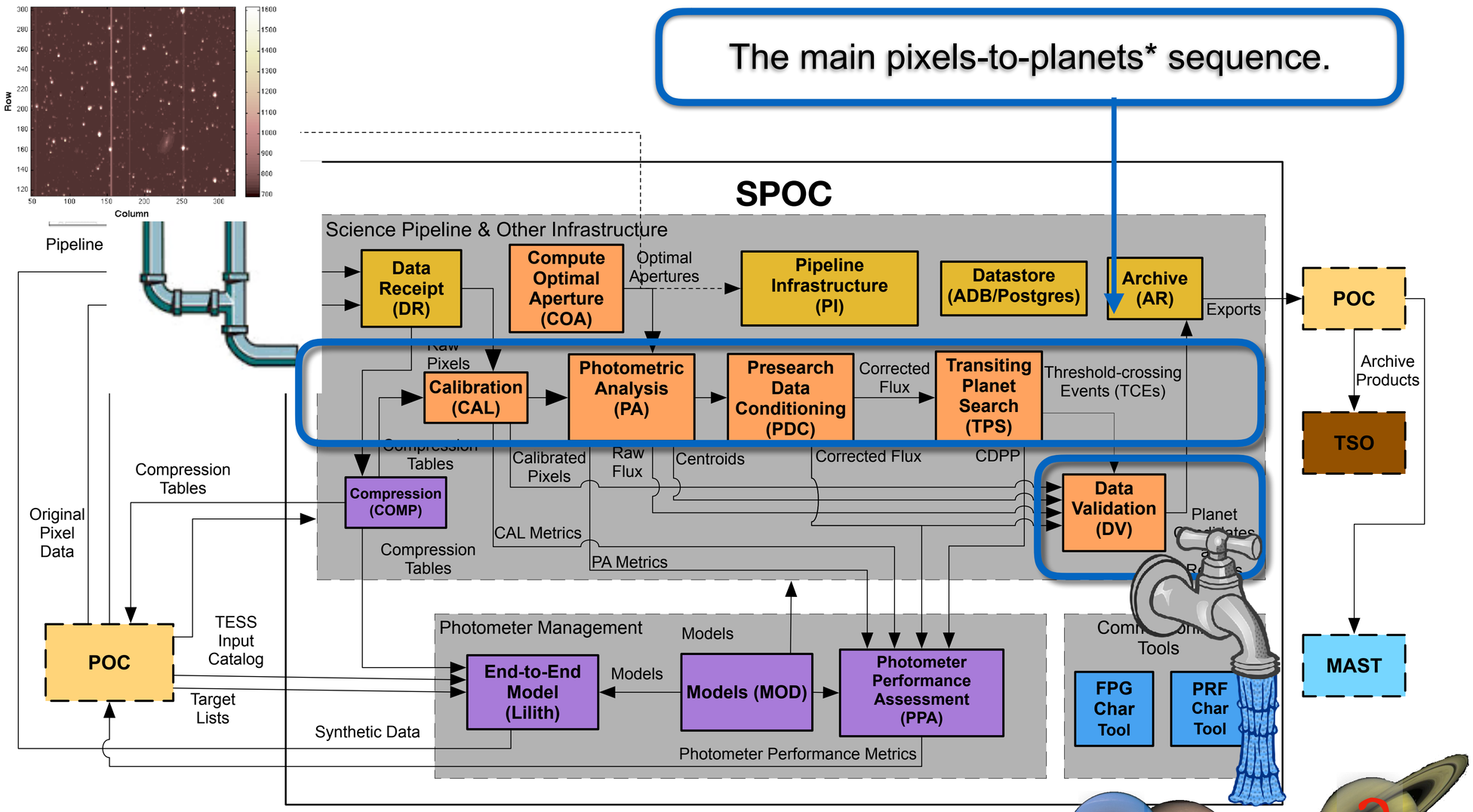

PLEA, 75 R_E Transfer Orbit
P/2 Mission Orbit
Lunar Flyby
3.5 Phasing Orbits
Moon Orbit
PLEP, 17 R_E




24°
96°
ecliptic pole
ecliptic latitude 6°
ECLIPTIC POLE
ECLIPTIC
OBSERVATION SECTOR

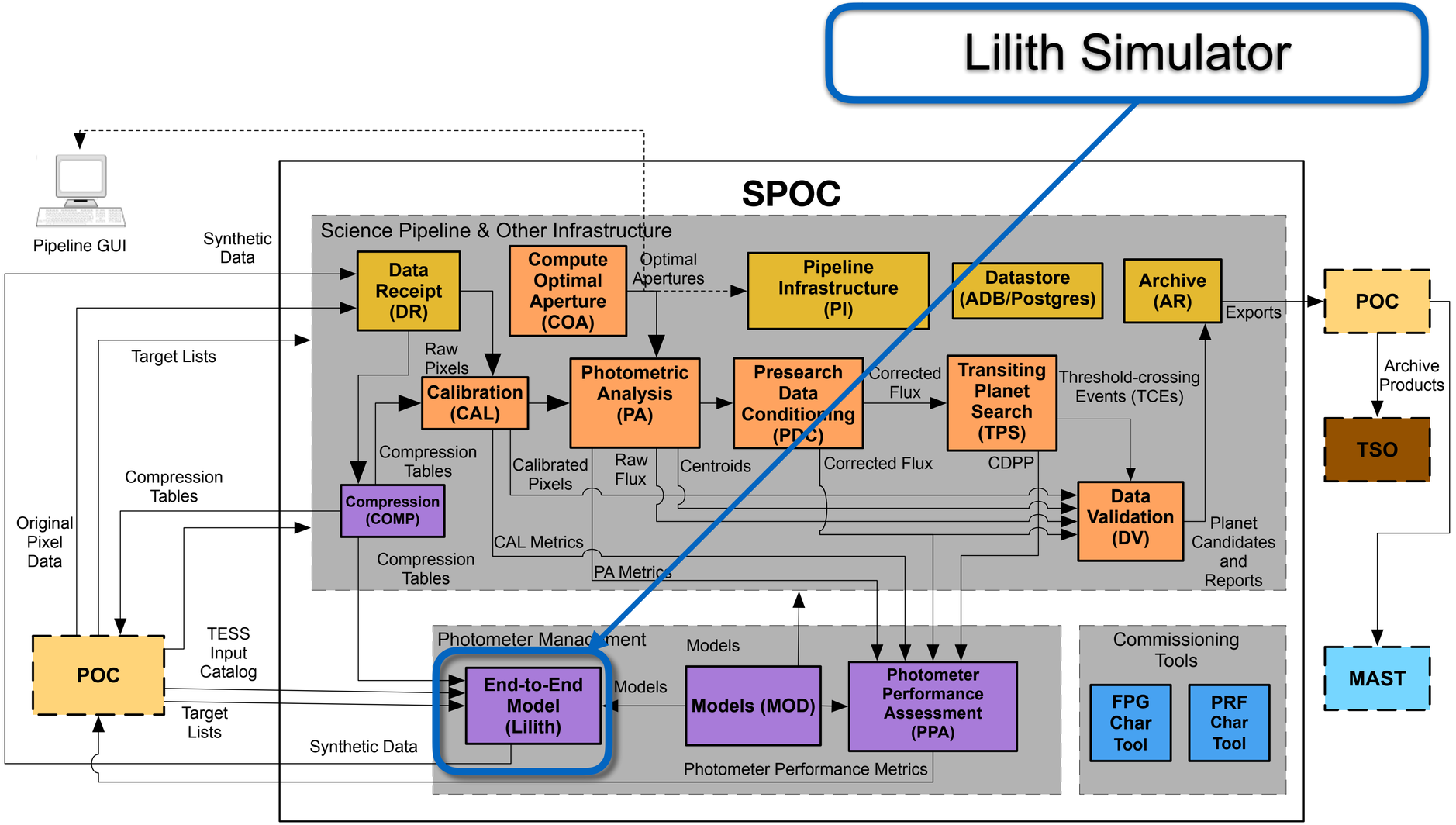

27 days
54 days
81 days
108 days
189 days
351 days
JWST continuous viewing zone

Science Pipeline Flowchart



* Potential planets, Lots of follow-up analysis to confirm the planets!

What We Will Be Talking About



What's in the simulations? (…and Why?)

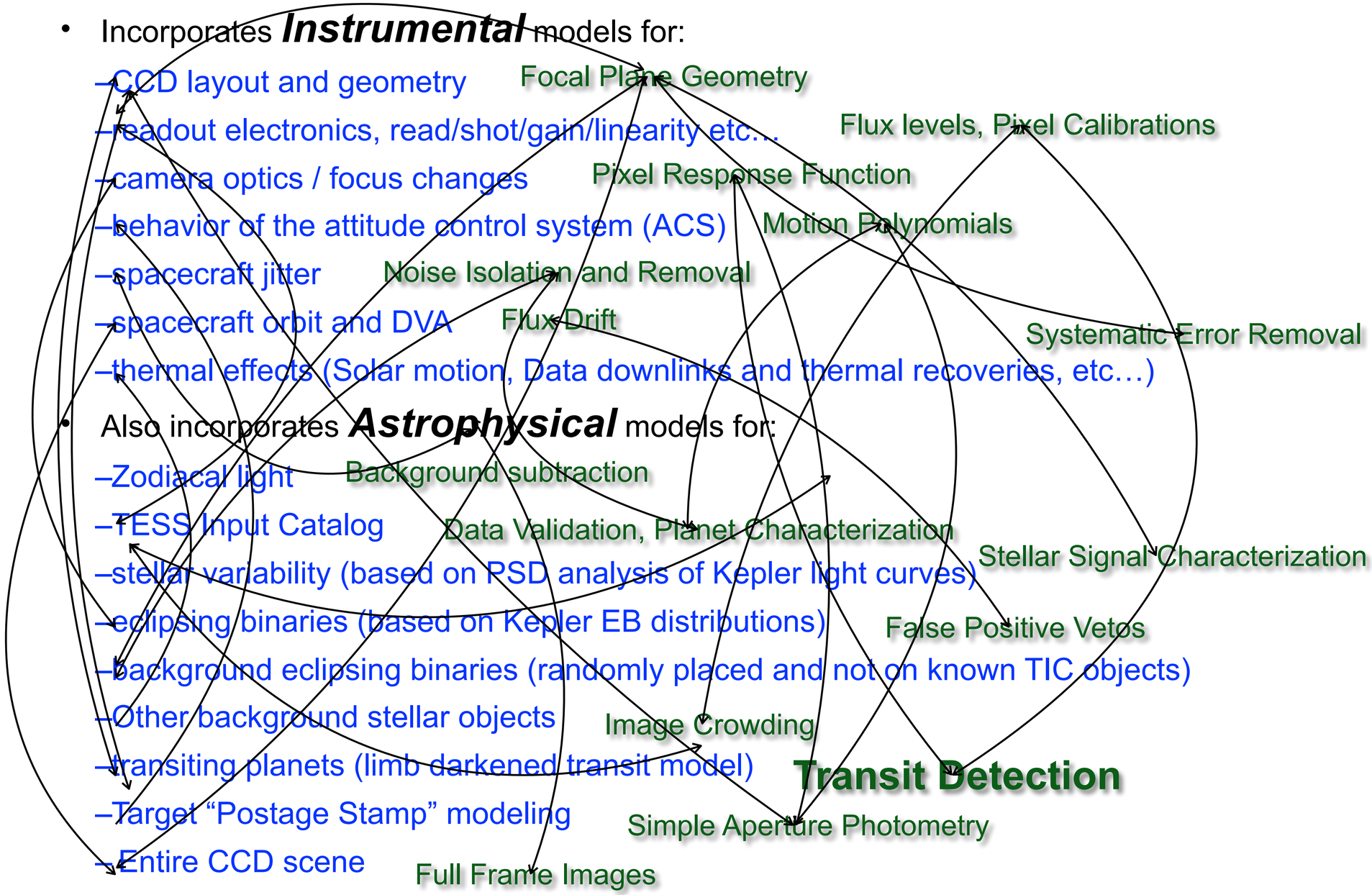
- Incorporates ***Instrumental*** models for:
  - –CCD layout and geometry
  - –readout electronics, read/shot/gain/linearity etc…
  - –camera optics / focus changes
  - –behavior of the attitude control system (ACS)
  - –spacecraft jitter
  - –spacecraft orbit and DVA
  - –thermal effects (Solar motion, Data downlinks and thermal recoveries, etc…)
- Also incorporates ***Astrophysical*** models for:
  - –Zodiacal light
  - –TESS Input Catalog
  - –stellar variability (based on PSD analysis of Kepler light curves)
  - –eclipsing binaries (based on Kepler EB distributions)
  - –background eclipsing binaries (randomly placed and not on known TIC objects)
  - –Other background stellar objects
  - –transiting planets (limb darkened transit model)
  - –Target "Postage Stamp" modeling
  - – Entire CCD scene

What's in the simulations? (…and Why?)

- Incorporates ***Instrumental*** models for:
  - –CCD layout and geometry — Focal Plane Geometry
  - –readout electronics, read/shot/gain/linearity etc… — Flux levels, Pixel Calibrations
  - –camera optics / focus changes — Pixel Response Function
  - –behavior of the attitude control system (ACS) — Motion Polynomials
  - –spacecraft jitter — Noise Isolation and Removal
  - –spacecraft orbit and DVA — Flux Drift
  - –thermal effects (Solar motion, Data downlinks and thermal recoveries, etc…) — Systematic Error Removal
- Also incorporates ***Astrophysical*** models for:
  - –Zodiacal light — Background subtraction
  - –TESS Input Catalog — Data Validation, Planet Characterization
  - –stellar variability (based on PSD analysis of Kepler light curves) — Stellar Signal Characterization
  - –eclipsing binaries (based on Kepler EB distributions) — False Positive Vetos
  - –background eclipsing binaries (randomly placed and not on known TIC objects)
  - –Other background stellar objects — Image Crowding
  - –transiting planets (limb darkened transit model) — **Transit Detection**
  - –Target "Postage Stamp" modeling — Simple Aperture Photometry
  - – Entire CCD scene — Full Frame Images

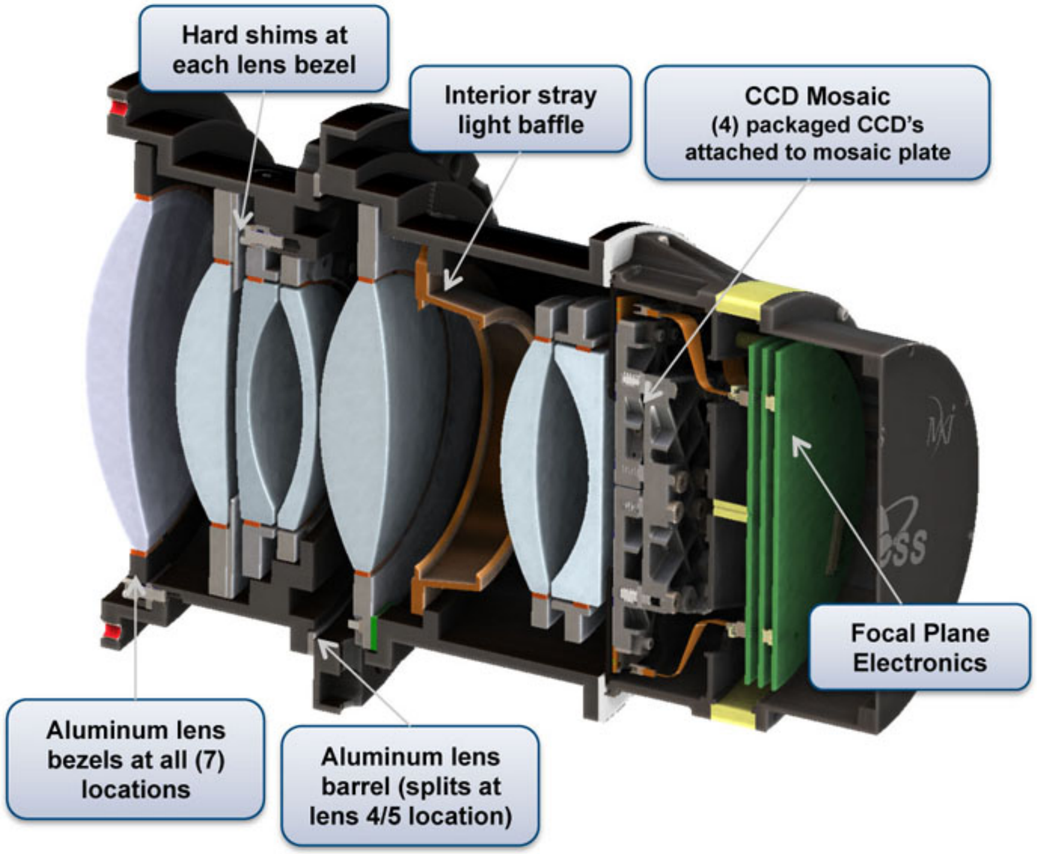
What's in the simulations? (…and Why?)

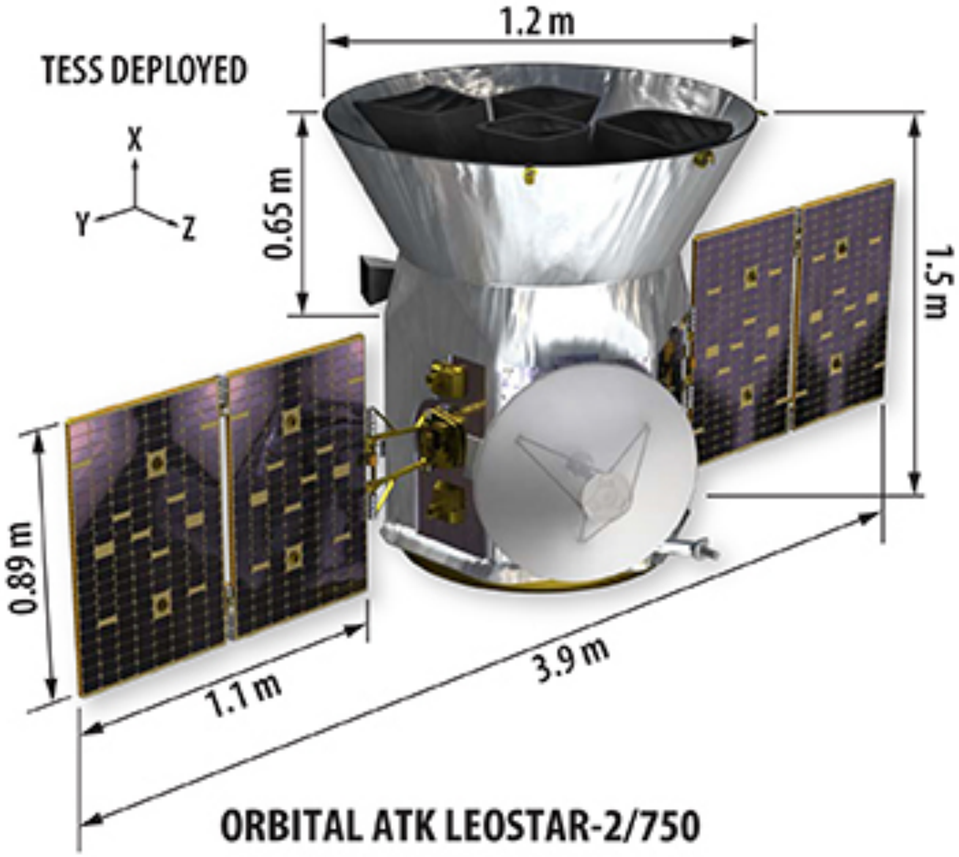
- Incorporates ***Instrumental*** models for:
  - CCD layout and geometry
  - readout electronics, read/shot/gain/linearity etc…
  - camera optics / focus changes
  - behavior of the attitude control system (ACS)
  - spacecraft jitter
  - spacecraft orbit and DVA
  - thermal effects (Solar motion, Data downlinks and thermal recoveries, etc…)
- Also incorporates ***Astrophysical*** models for:
  - Zodiacal light
  - TESS Input Catalog
  - stellar variability (based on PSD analysis of Kepler light curves)
  - eclipsing binaries (based on Kepler EB distributions)
  - background eclipsing binaries (randomly placed and not on known TIC objects)
  - Other background stellar objects
  - transiting planets (limb-darkened transit model)
  - Target "Postage Stamp" modeling
  - Entire CCD scene



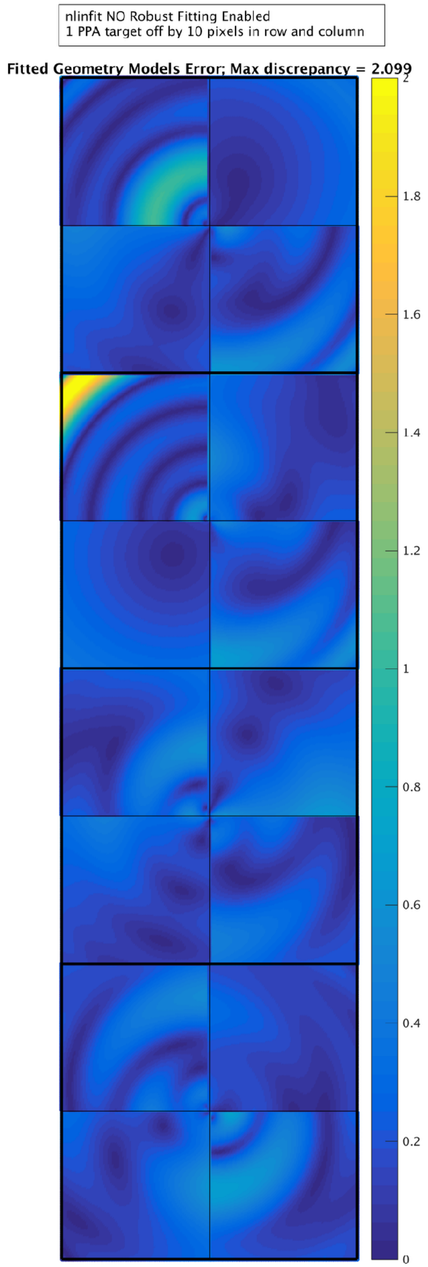
The importance of *Realistic* Simulated Data

- Focal Plane Geometry (FPG) Model characterizes the mapping of stellar coordinates to pixel location
  - –RA/Decl. => Pixels
  - –Has to account for all optical perturbations of the image.
  - –Critical for target selection and aperture photometry.



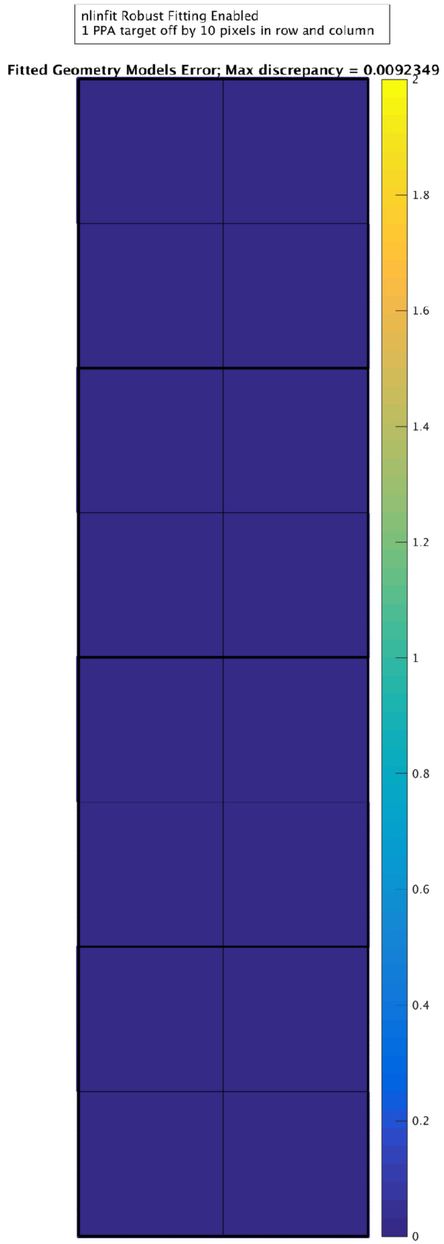


Validation & Verification of FPG



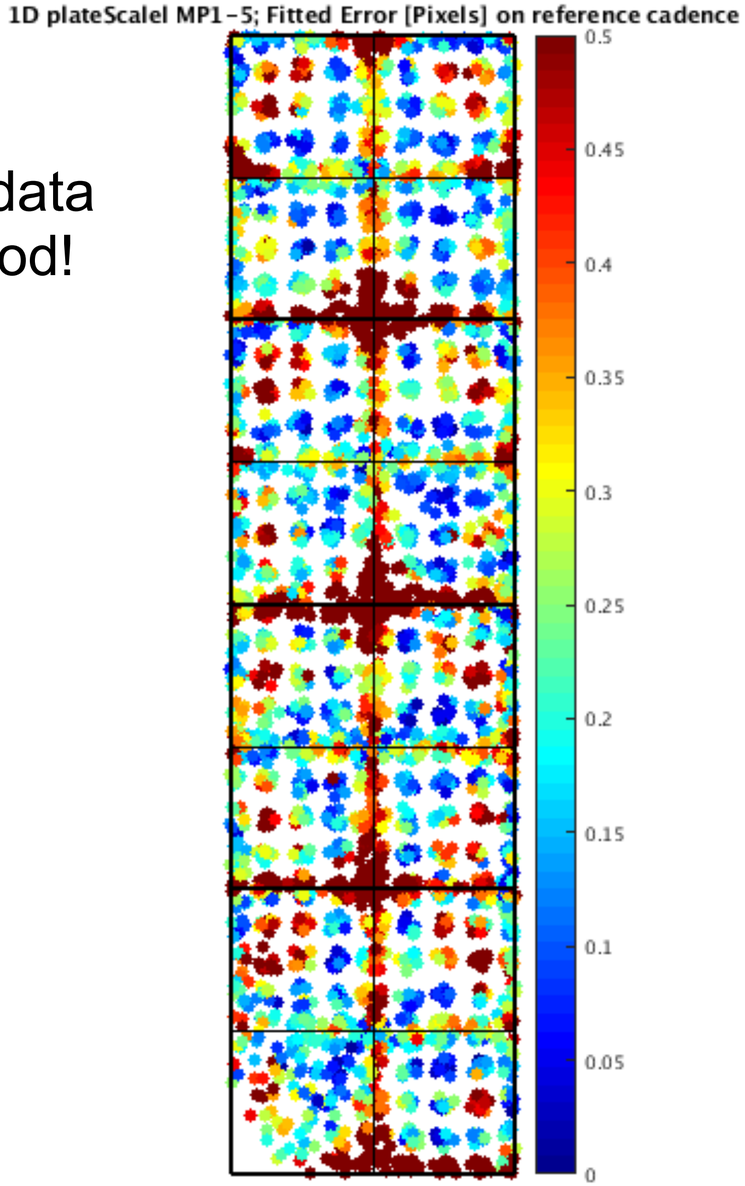
Worked Beautifully!

FPG fits out simulated perturbations in model



Real Commissioning Data

Fit to real data
Not so good!



Real Commissioning Data

Fit to real data
Not so good!

????

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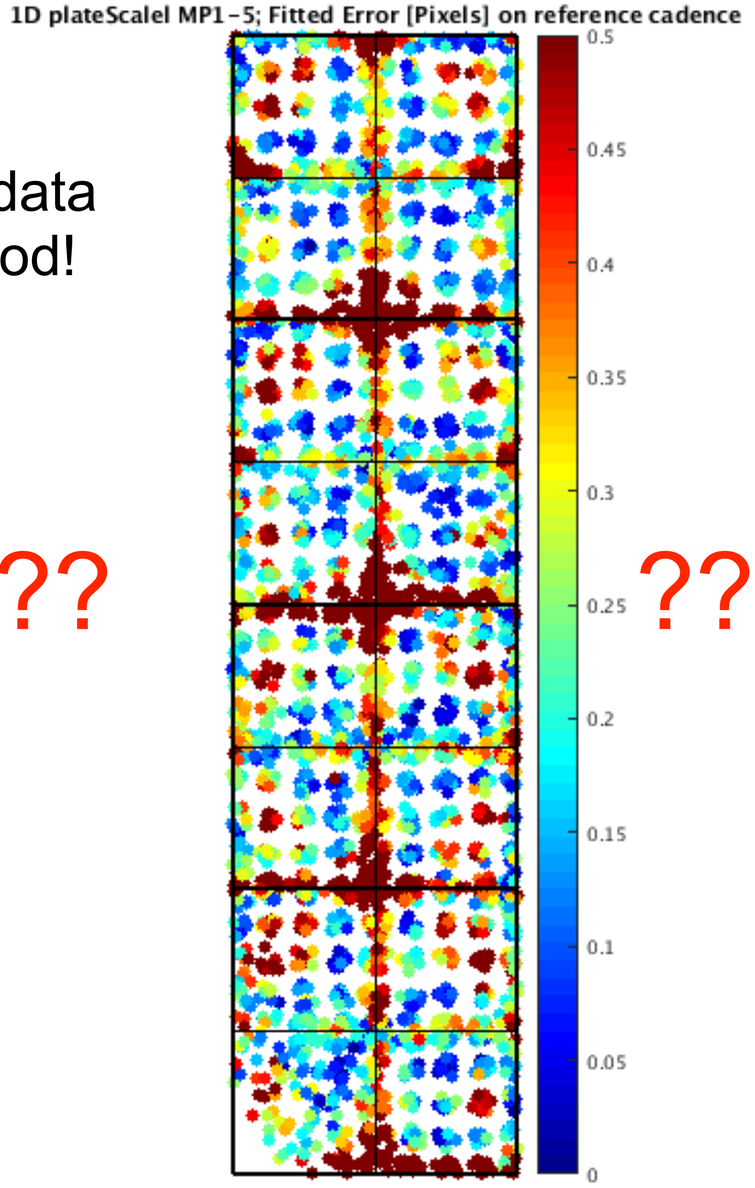
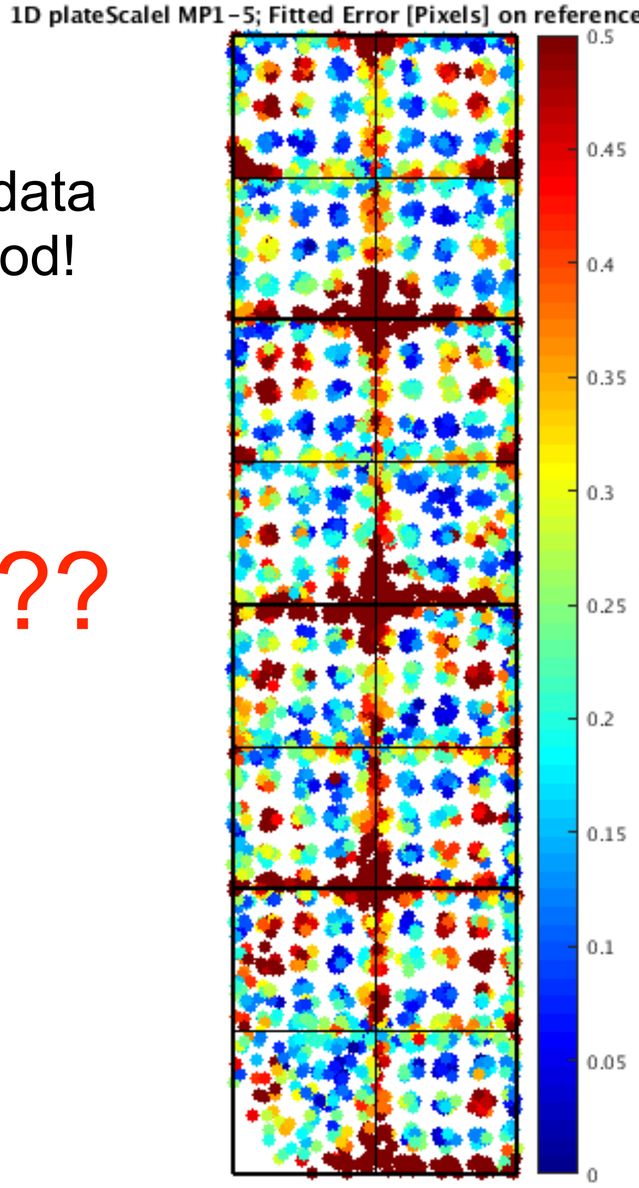


Real Commissioning Data

Fit to real data
Not so good!

????



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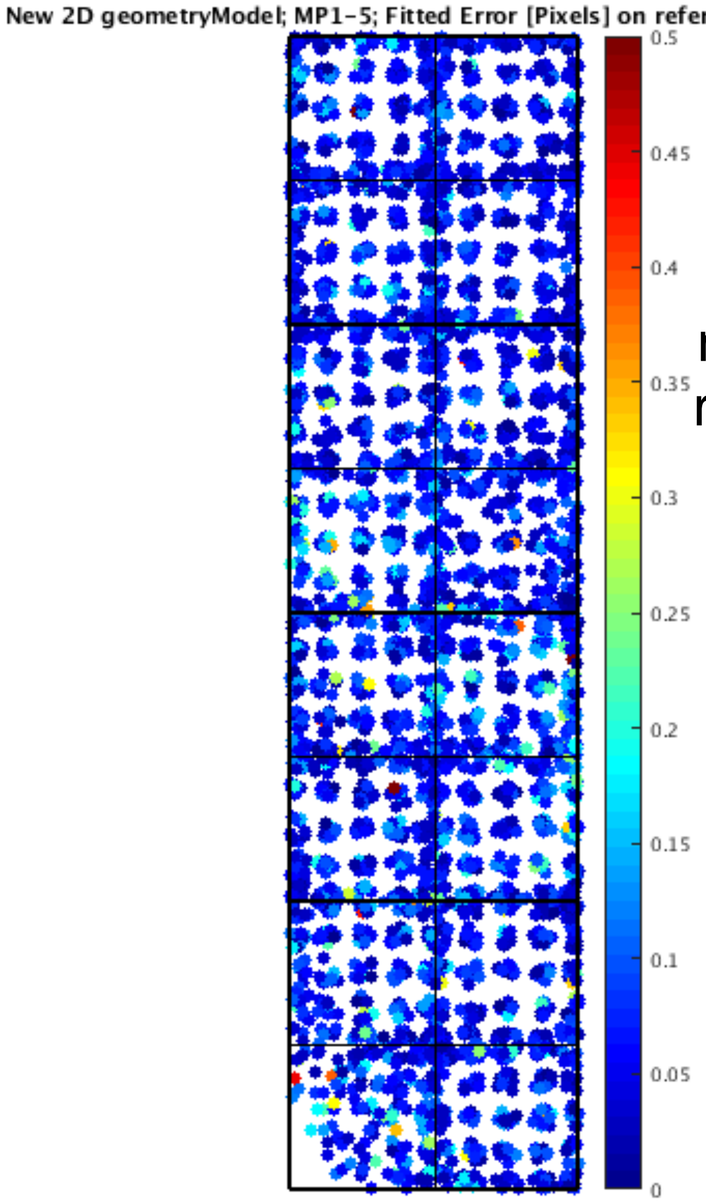
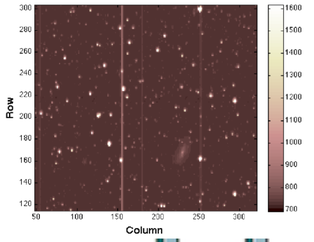


Needed more generalized FPG model to account for all real-world perturbations

Can the Pipeline Find the Planets?



The main pixels-to-planets sequence.

Pipeline GUI

Science Pipeline & Other Infrastructure

Synthetic Data

Data Receipt (DR)

Compute Optimal Aperture (COA)

Optimal Apertures

Pipeline Infrastructure (PI)

Datastore (ADB/Postgres)

Archive (AR)

Exports

POC

Archive Products

TSO

MAST

Target Lists

Raw Pixels

Calibration (CAL)

Photometric Analysis (PA)

Presearch Data Conditioning (PDC)

Corrected Flux

Transiting Planet Search (TPS)

Threshold-crossing Events (TCEs)

Compression Tables

Calibrated Pixels

Raw Flux

Centroids

Corrected Flux

CDPP

Compression Tables

Compression (COMP)

Data Validation (DV)

Planet Candidates

CAL Metrics

PA Metrics

Original Pixel Data

POC

TESS Input Catalog

Target Lists

Compression Tables

Photometer Management

End-to-End Model (Lilith)

Models

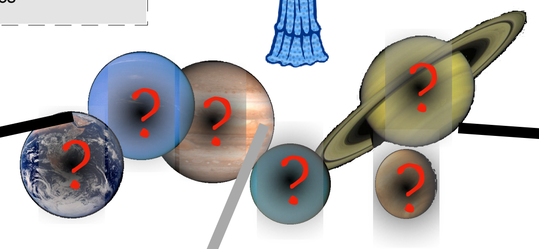
Models (MOD)

Models

Photometer Performance Assessment (PPA)

Synthetic Data

Photometer Performance Metrics



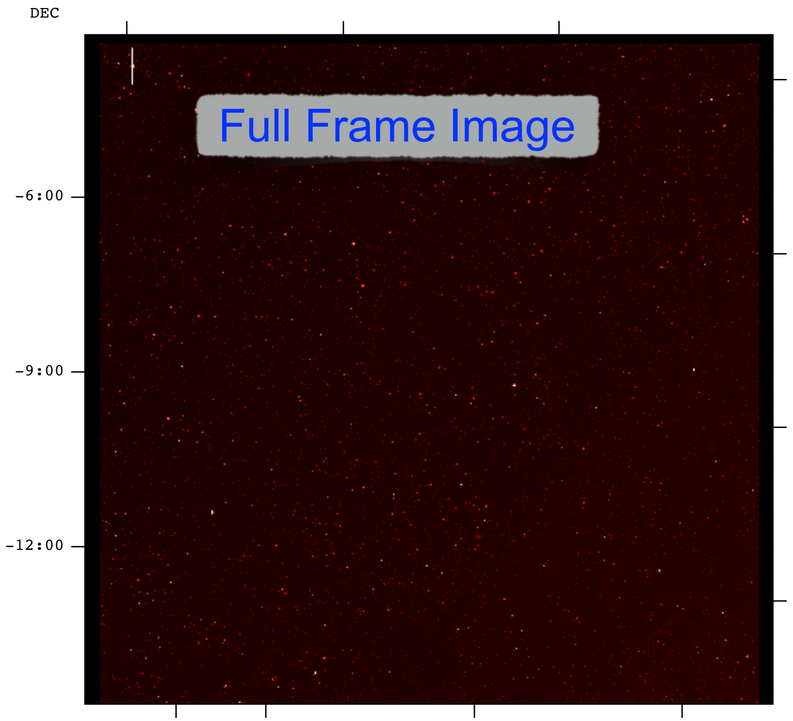
Planet!

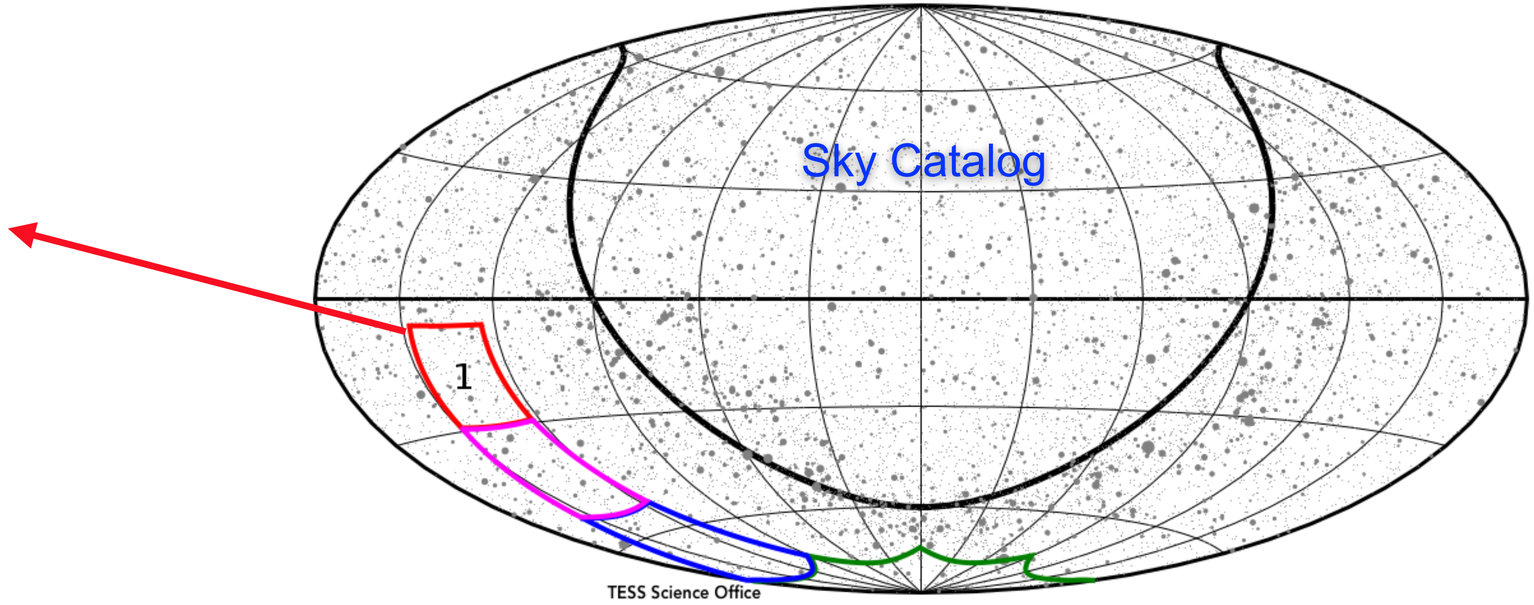
Not Planet!

other classification?

Simulated Scene and CCD Readout

tess2019157223826-1-4-0016-s_ffic.fits.gz_1





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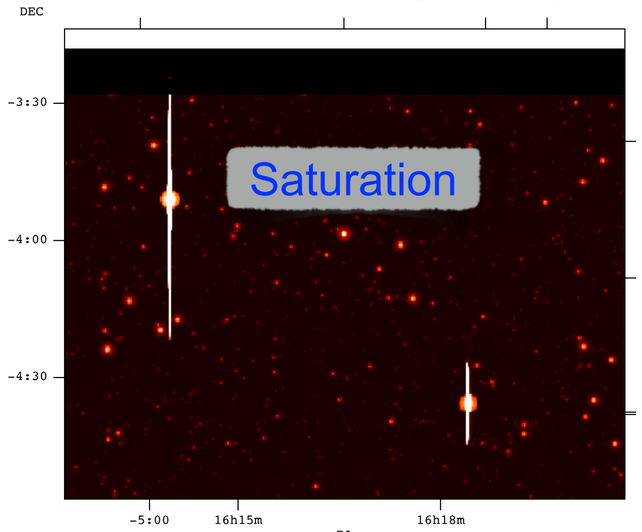

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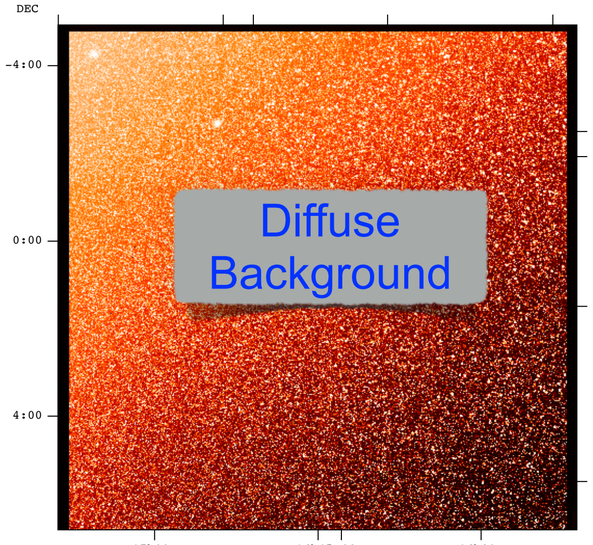
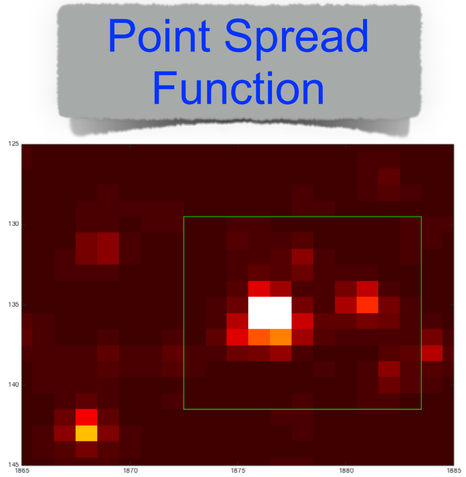
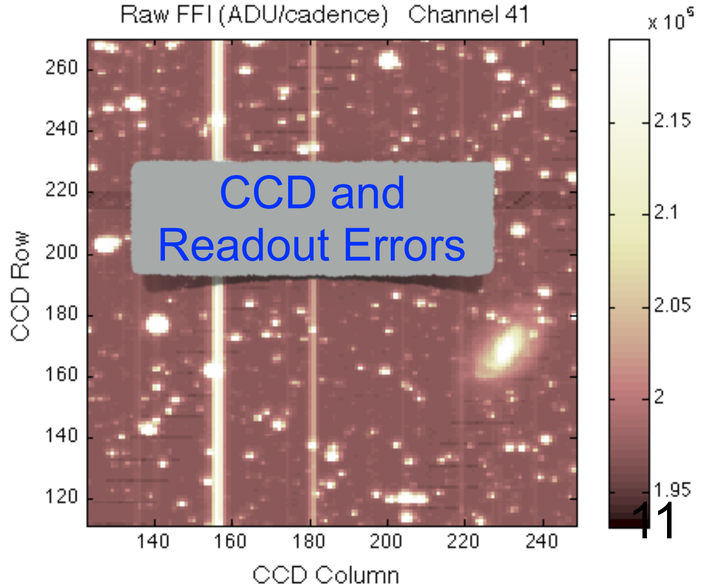
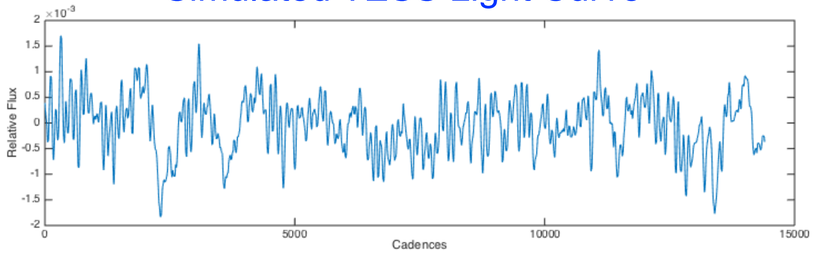




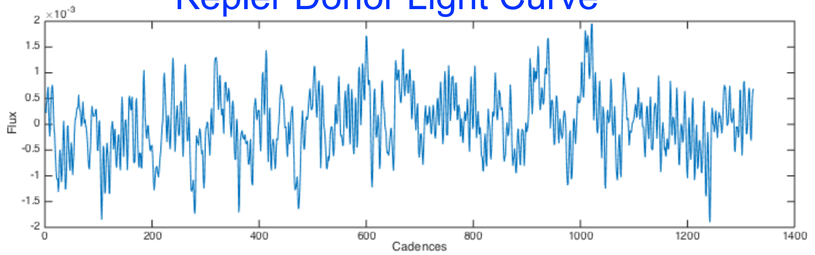


Simulated Star and Planet Distributions

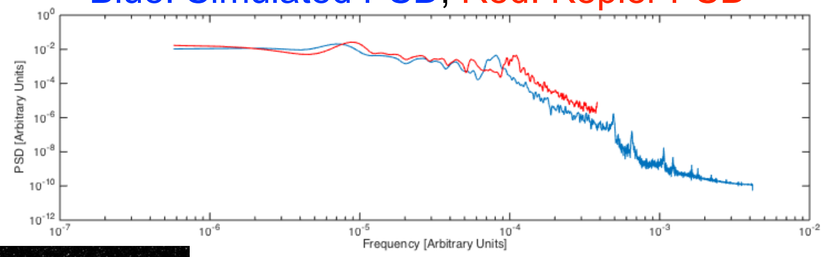
Simulated TESS Light Curve

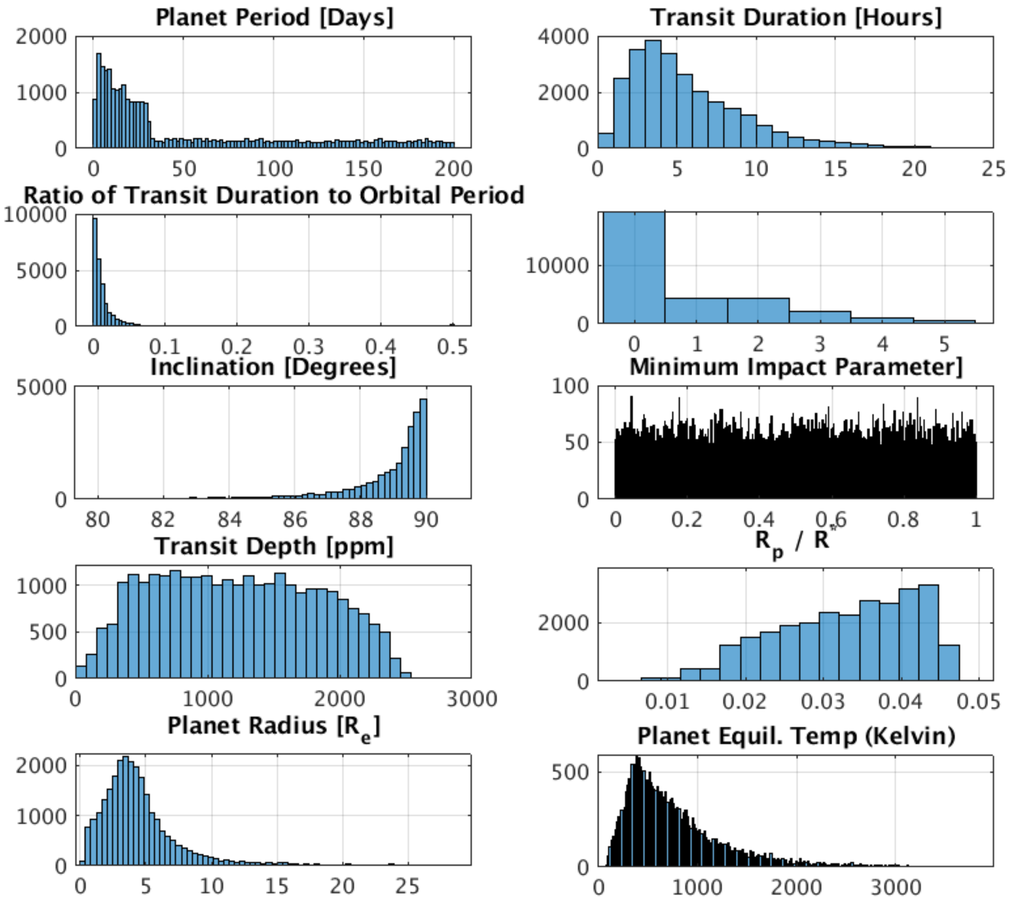


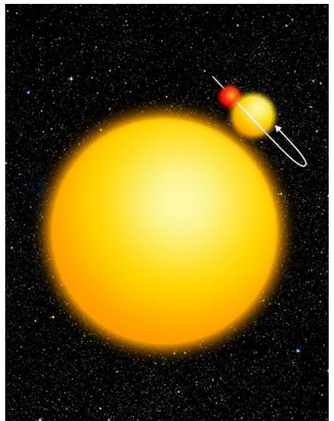
Kepler Donor Light Curve

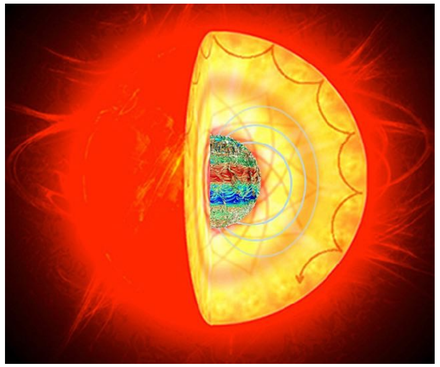


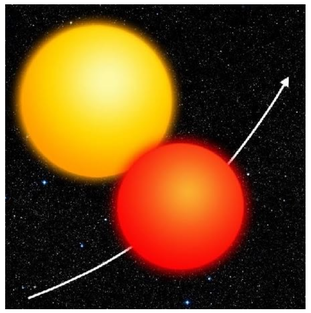
Blue: Simulated PSD, Red: Kepler PSD

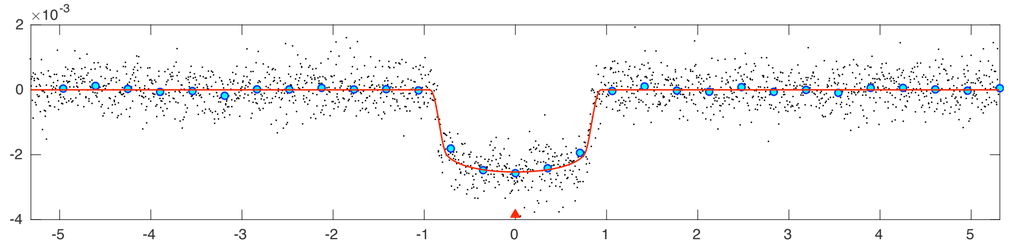




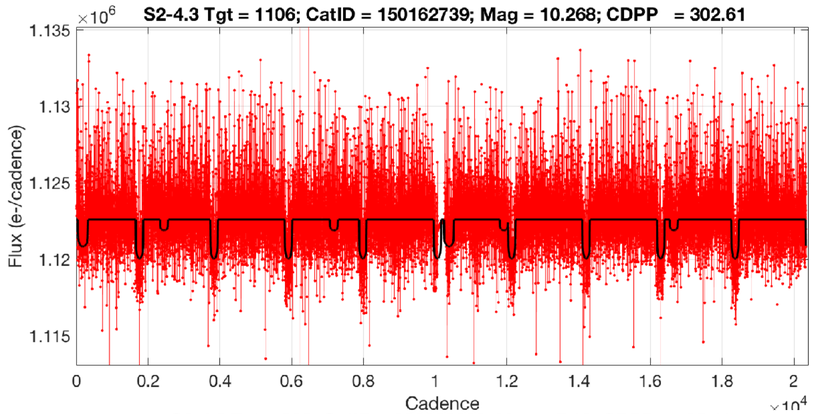


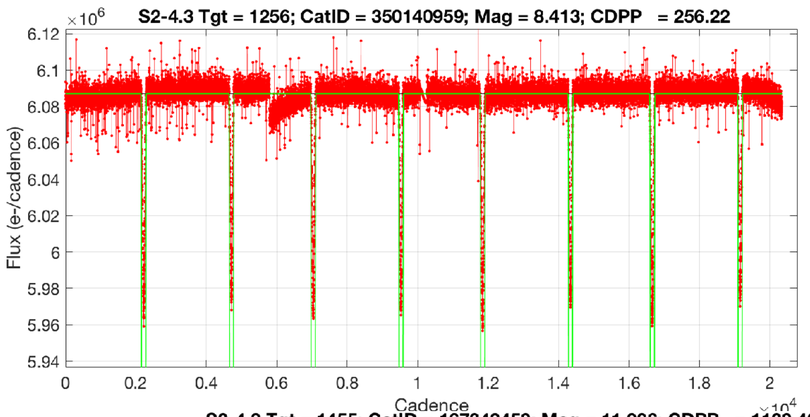


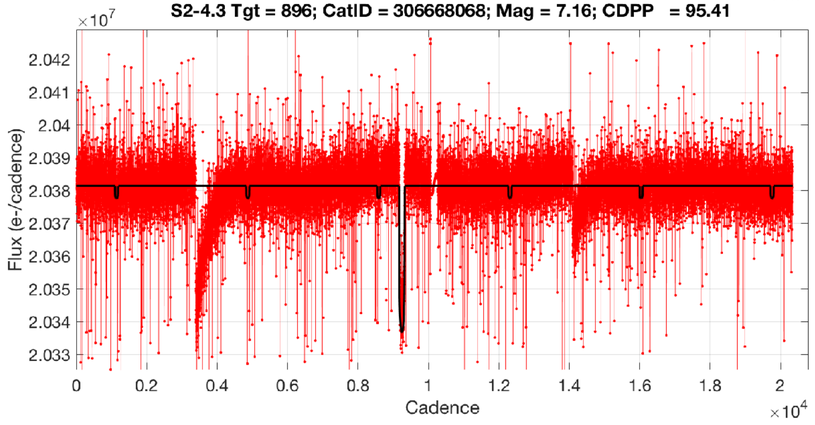


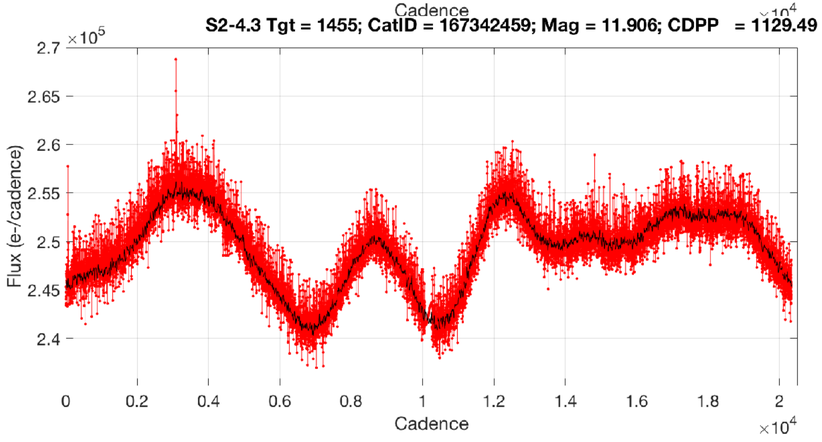


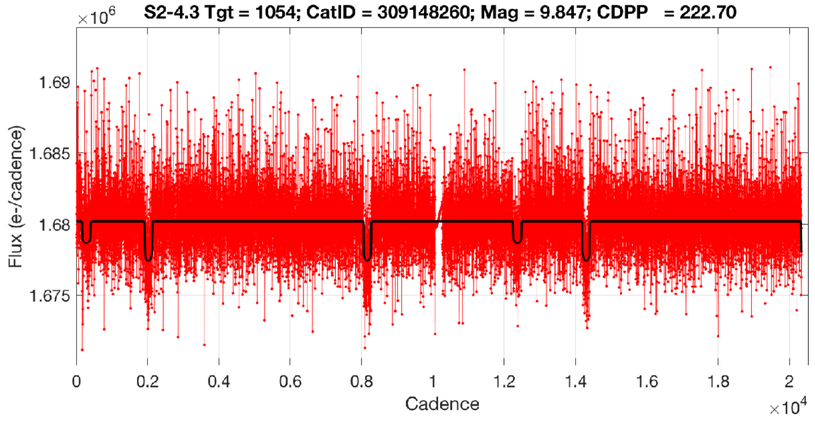
Sample Simulated Light Curves

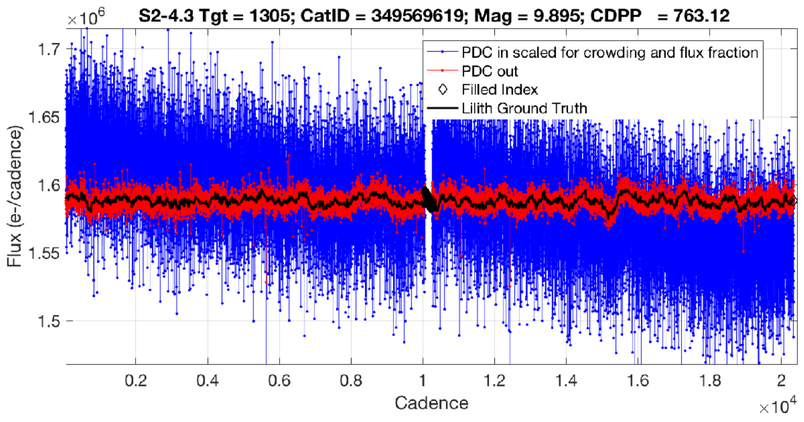








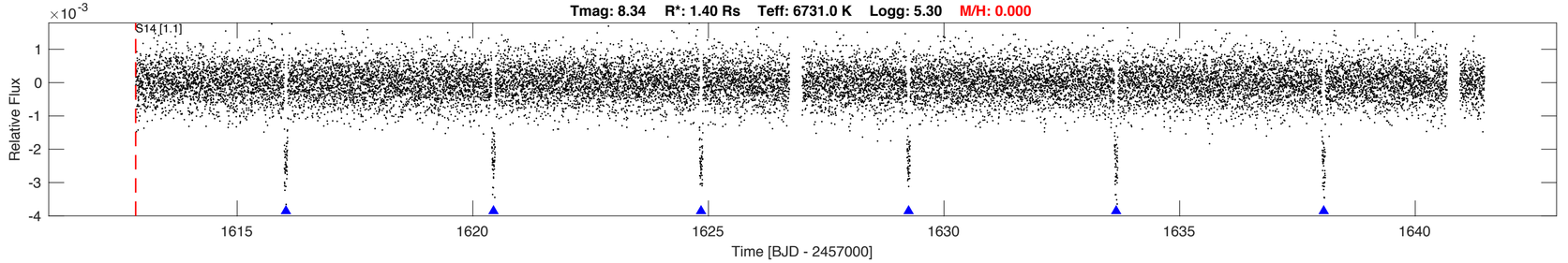


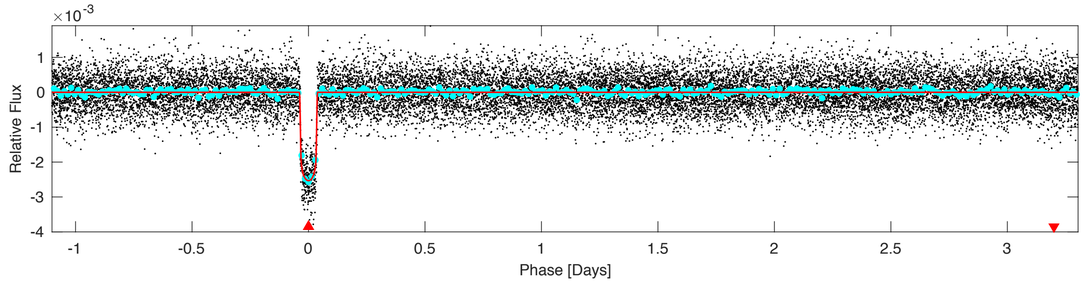


A Trivial Detection

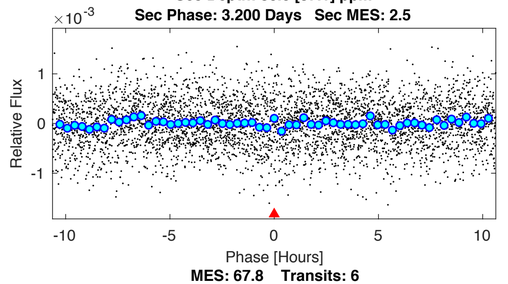
TIC: 296932181 Candidate: 1 of 1 Period: 4.405 d

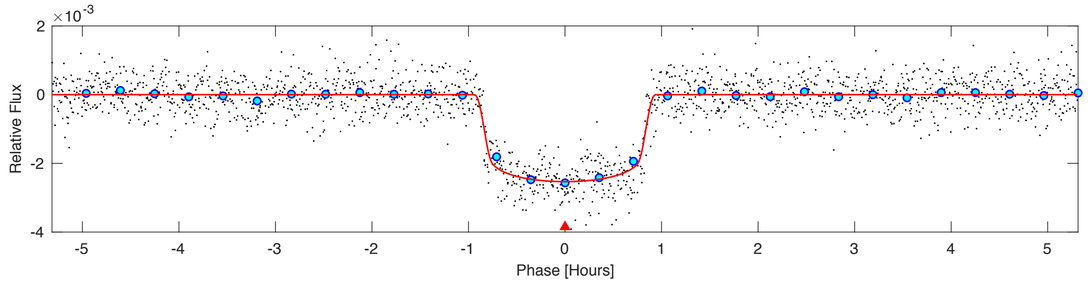
Tmag: 8.34 R*: 1.40 Rs Teff: 6731.0 K Logg: 5.30 M/H: 0.000



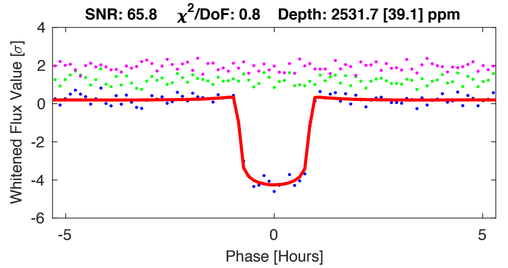


Sec Depth: 80.0 [37.1] ppm
Sec Phase: 3.200 Days Sec MES: 2.5

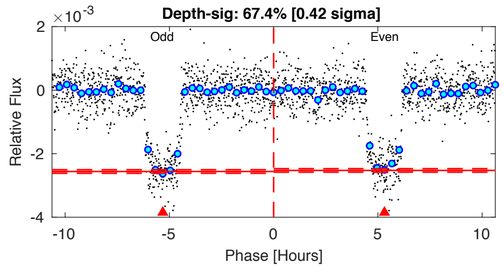




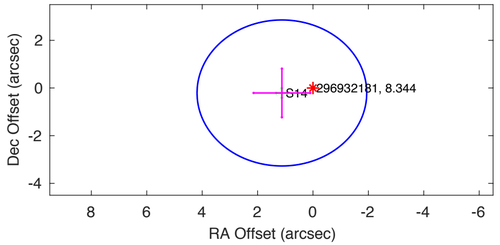
MES: 67.8 Transits: 6
SNR: 65.8 χ^2/DoF: 0.8 Depth: 2531.7 [39.1] ppm



Depth-sig: 67.4% [0.42 sigma]



Difference Image
Out of Transit Centroid Offsets



DV Fit Results:

Period = 4.40472 [0.00014] d
Epoch = 1616.0340 [0.0004] BTJD
Rp/R* = 0.0472 [0.0029]
a/R* = 19.90 [8.34]
b = 0.01 [44.37]

Seff = 219.77 [117.13]
Teq = 982 [131] K
Rp = 7.21 [0.98] Re
a = 0.1279 [0.0345] AU

Ag = 13.86 [9.81] [1.31 sigma]
Teffp = 2930 [361] K [5.07 sigma]

DV Diagnostic Results:

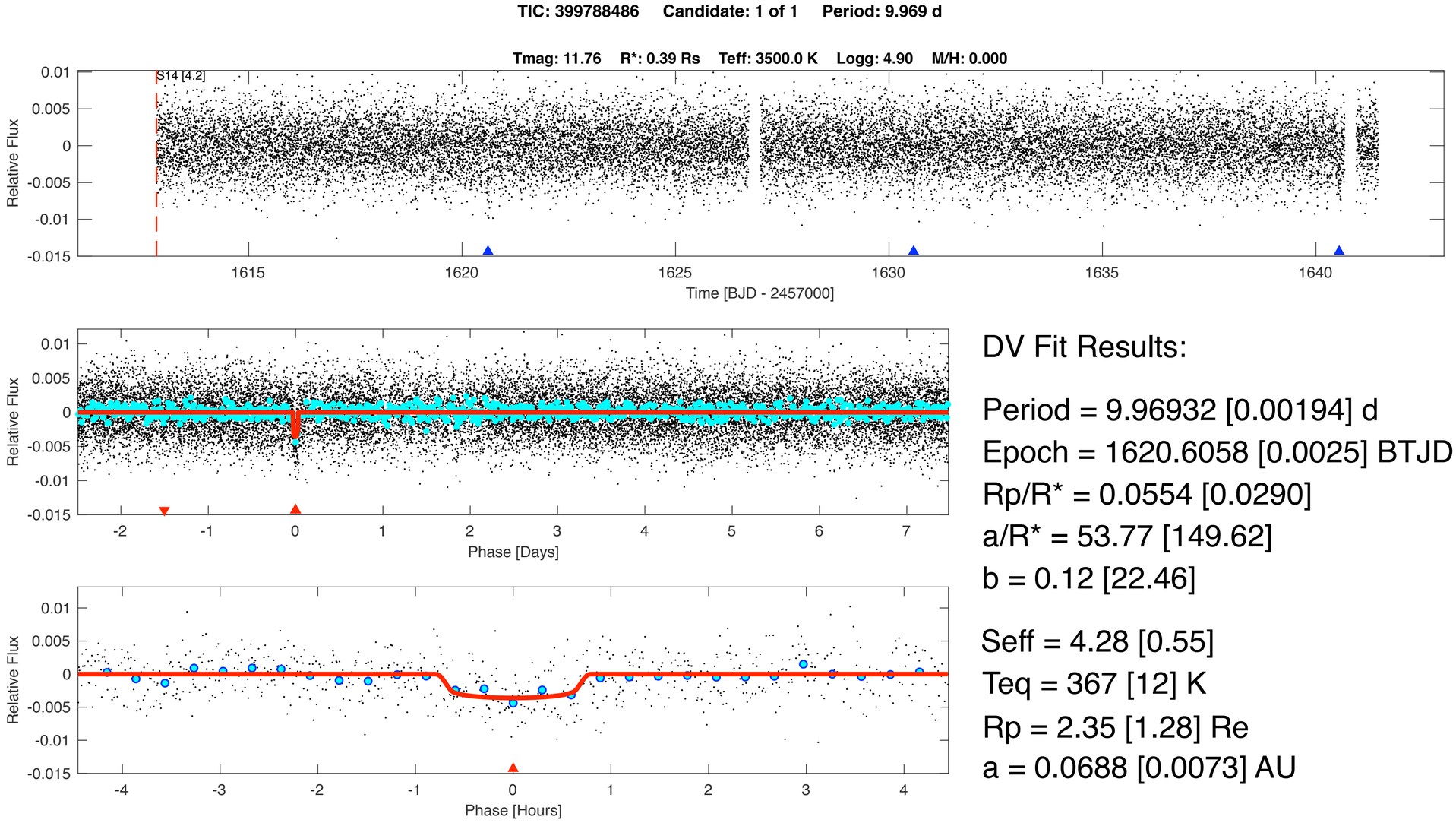
ShortPeriod-sig: N/A
LongPeriod-sig: N/A
ModelChiSquare2-sig: 90.8%
ModelChiSquareGof-sig: 100.0%
Bootstrap-pfa: 0.00e+00
GhostDiagnostic-chr: 8.879

OotOffset-rm: 1.141 arcsec [1.12 sigma]
TicOffset-rm: 1.315 arcsec [1.29 sigma]
OotOffset-tot: 1
TicOffset-tot: 1
DiffImageQuality-fgm: 1.00 [1/1]
DiffImageOverlap-fno: 1.00 [1/1]

Software Revision: spoc-3.1.16-20171109 -- Date Generated: 16-Nov-2017 06:12:35 Z

This Data Validation Report Summary was produced in the TESS Science Processing Operations Center Pipeline at NASA Ames Research Center

A More Difficult Decision…



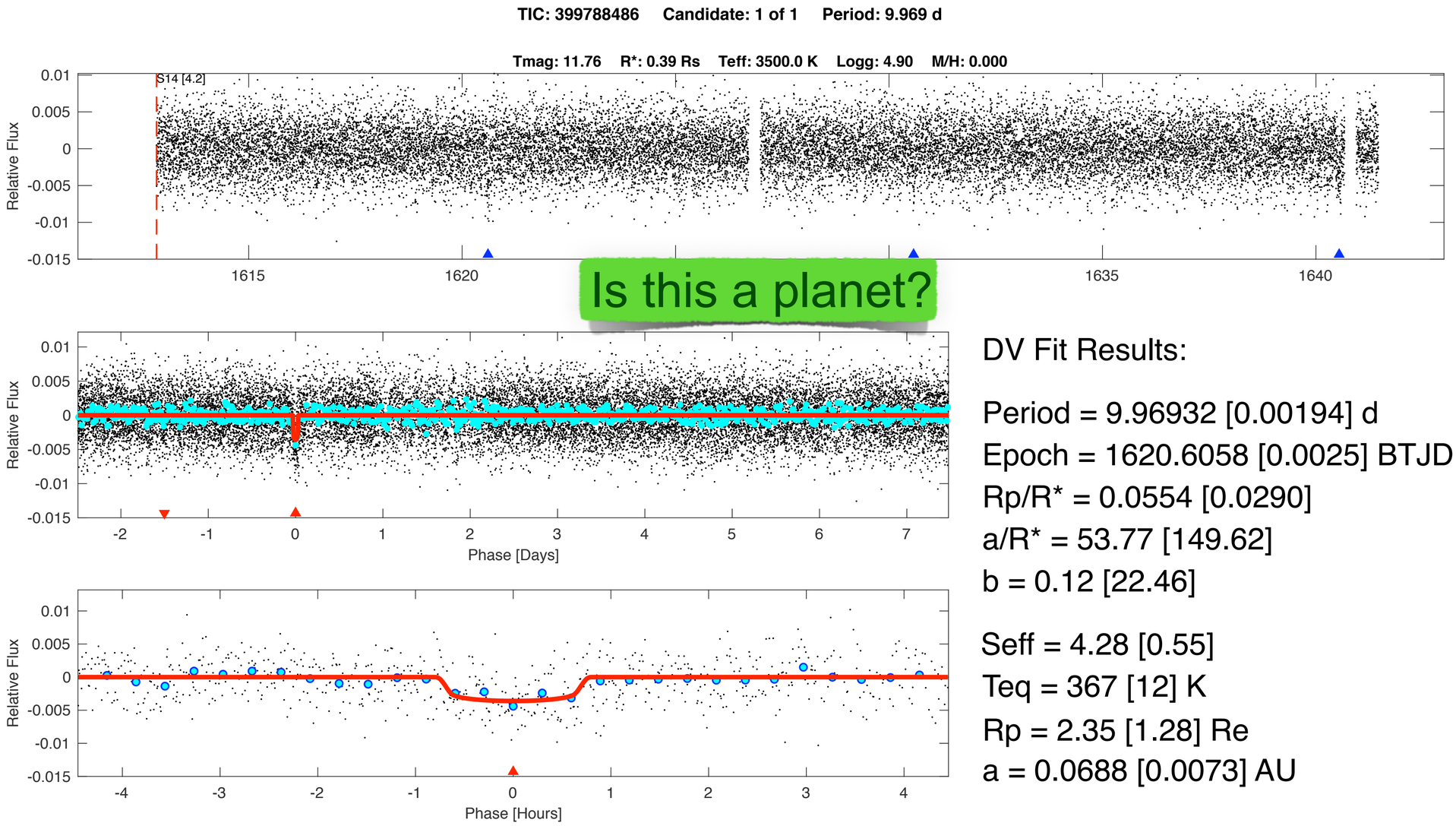
DV Fit Results:

Period = 9.96932 [0.00194] d
Epoch = 1620.6058 [0.0025] BTJD
Rp/R* = 0.0554 [0.0290]
a/R* = 53.77 [149.62]
b = 0.12 [22.46]

Seff = 4.28 [0.55]
Teq = 367 [12] K
Rp = 2.35 [1.28] Re
a = 0.0688 [0.0073] AU

Software Revision: spoc-3.1.16-20171109 -- Date Generated: 16-Nov-2017 06:52:48 Z
This Data Validation Report Summary was produced in the TESS Science Processing Operations Center Pipeline at NASA Ames Researc

A More Difficult Decision…



DV Fit Results:

Period = 9.96932 [0.00194] d
Epoch = 1620.6058 [0.0025] BTJD
Rp/R* = 0.0554 [0.0290]
a/R* = 53.77 [149.62]
b = 0.12 [22.46]

Seff = 4.28 [0.55]
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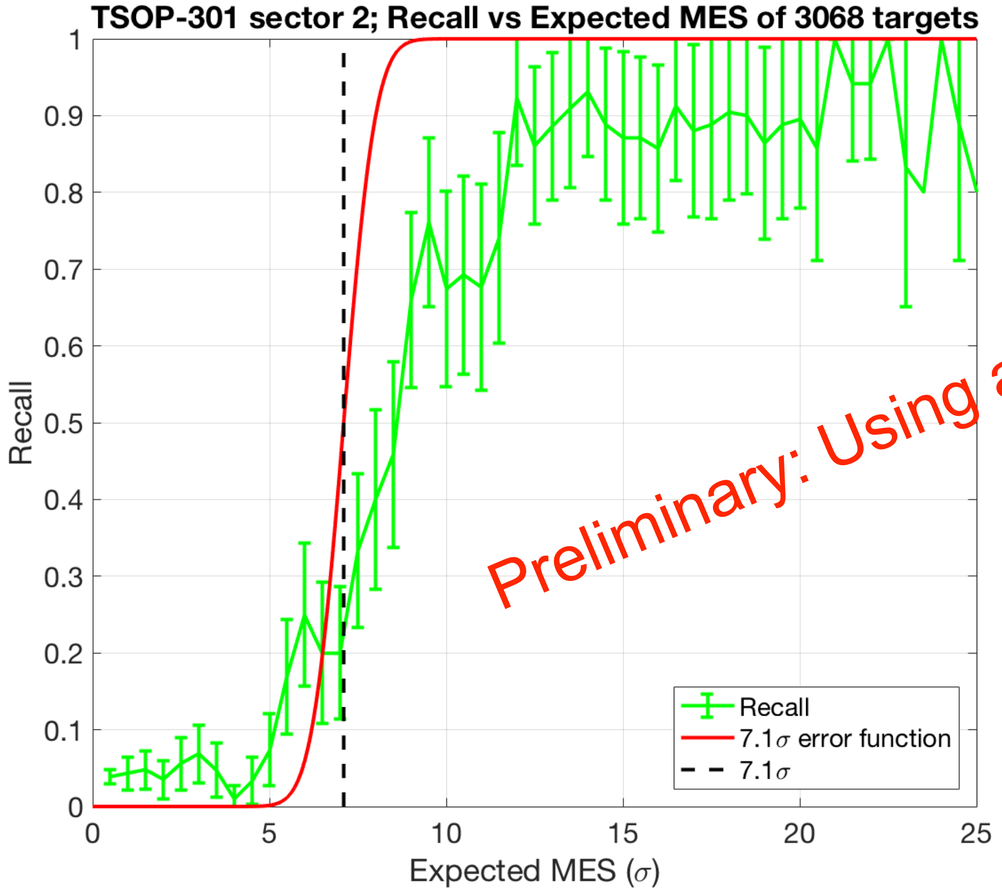
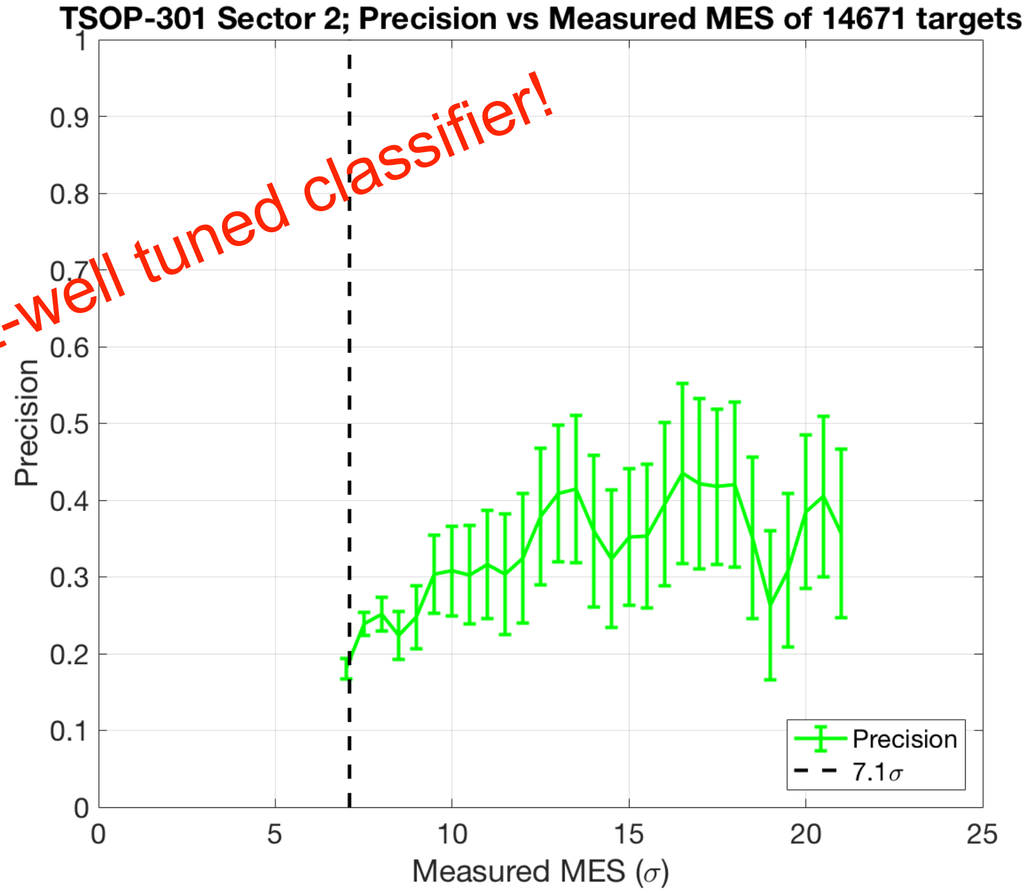
Software Revision: spoc-3.1.16-20171109 -- Date Generated: 16-Nov-2017 06:52:48 Z
This Data Validation Report Summary was produced in the TESS Science Processing Operations Center Pipeline at NASA Ames Researc

How well can we find Simulated Planets?





Preliminary: Using a not-well tuned classifier!

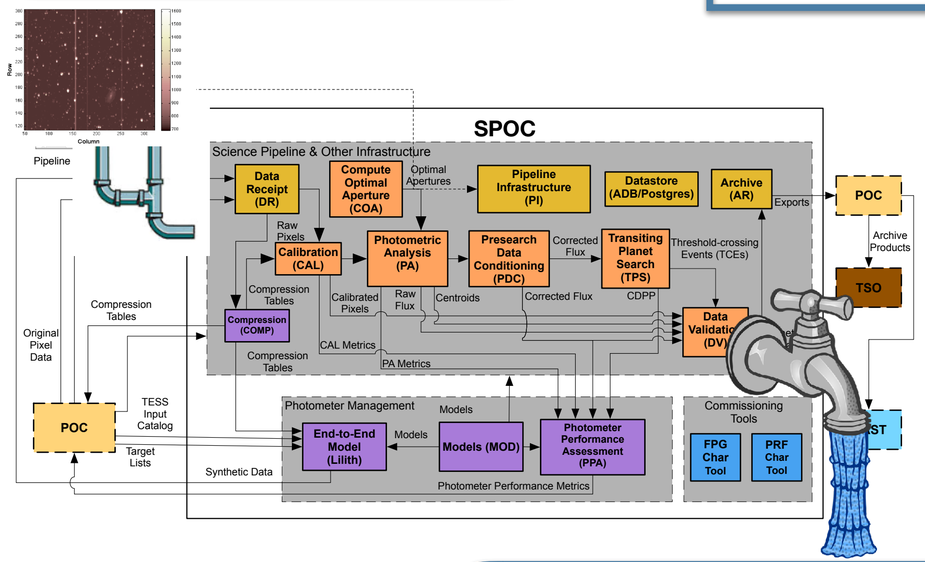
- See Megan Ansdell talk from two days ago for an application of this data.

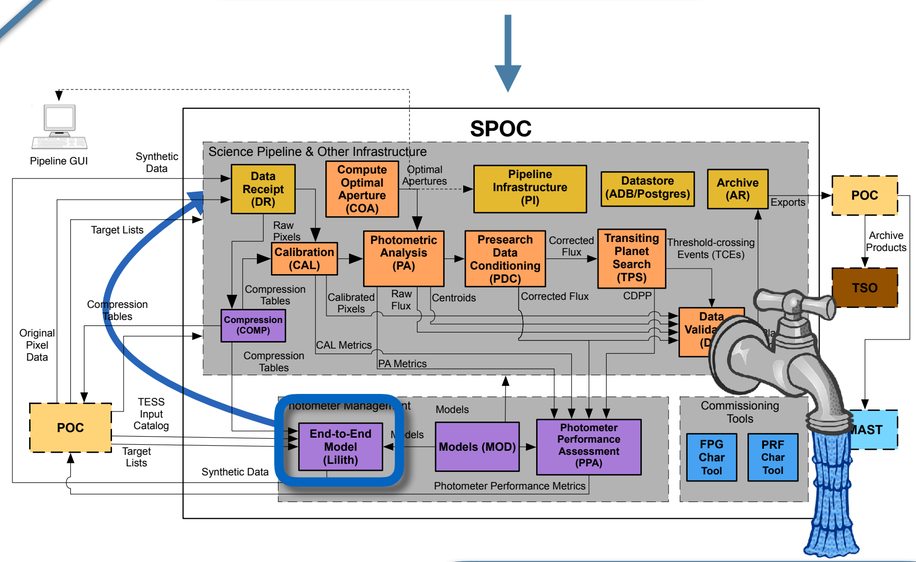
Proposal: Parallel Data Products for the Users

Real Flight Data

Use real data to tune simulation

Simulated Data



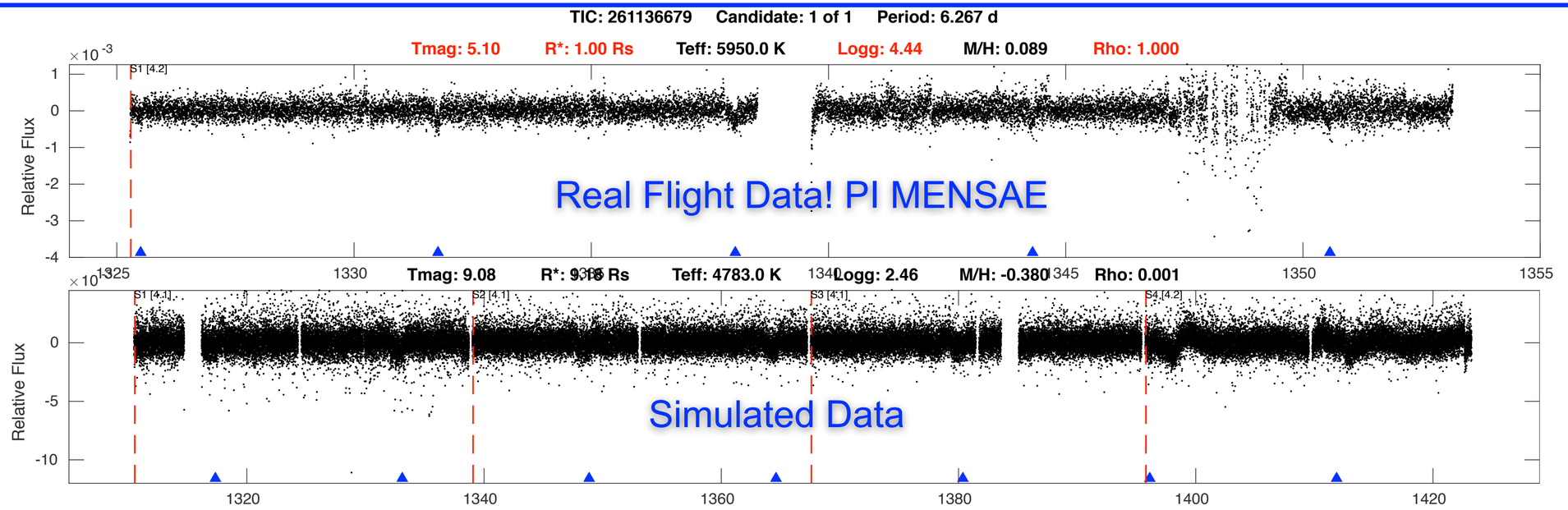


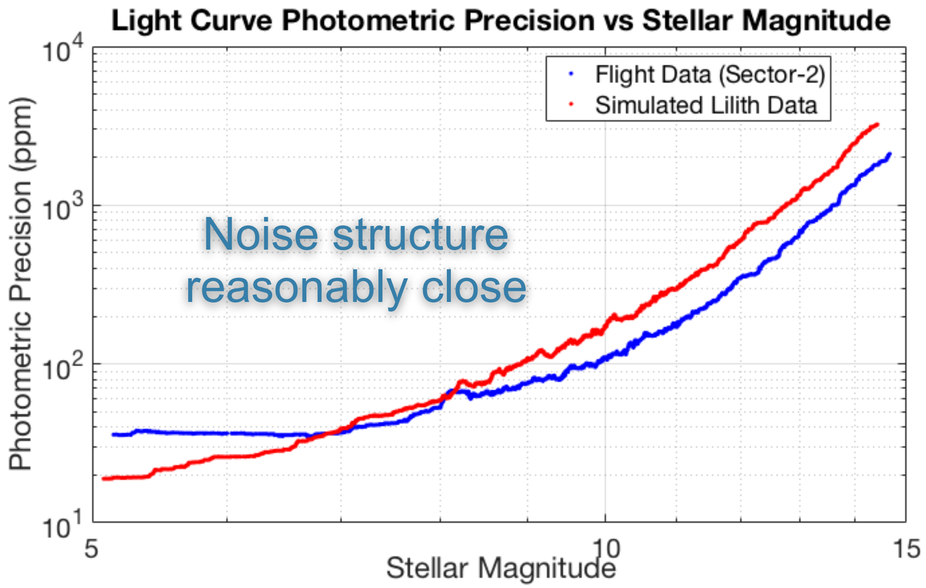
Real Data Outputs

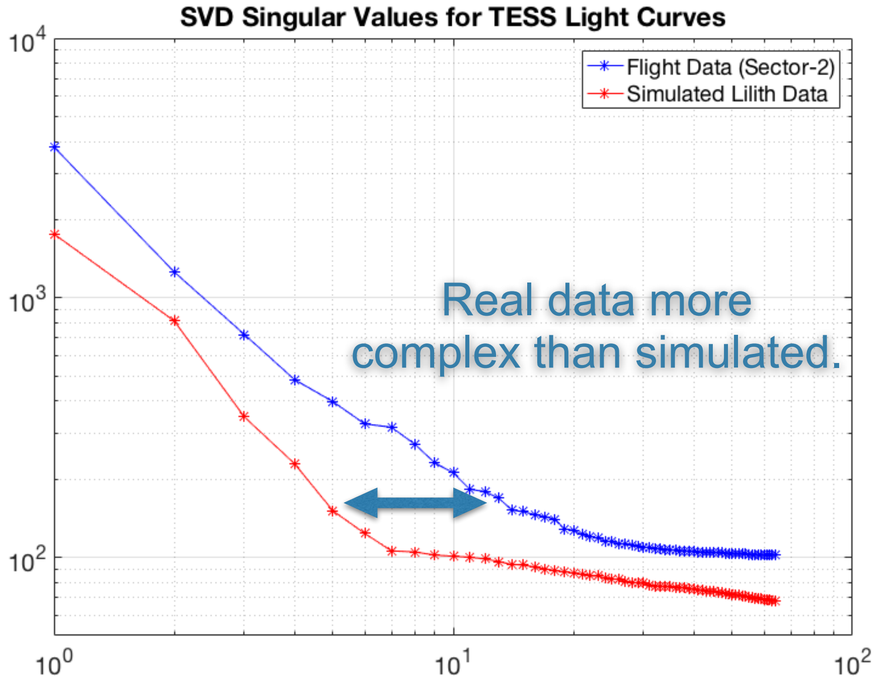
Simulated Data Outputs

- **Raw pixel data passed through the SPOC pipeline just like any real flight data**
  - Continue to provide simulated data set with updated astrophysics and instrumental models.
    - *Provide fully simulated data with ground-truth that parallels real flight data to assist researchers in adapting their tools to the TESS data set.*
    - *How well do **your** signals behave in our data processing pipeline?*

Signal Complexity, Simulated vs Real







Thank you!

https://tess.gsfc.nasa.gov

MAST TESS data archive:
https://archive.stsci.edu/tess/index.html

Why Called “Lilith?”

- Named by someone who *hates* acronyms!
- Name comes from the song “Lilith/Eve” by industrial rock band *Machines of Loving Grace*, due to the first lines of that song: “I’m talking darkest night / A shoddy simulation of paradise...”.
- This wasn’t me! I’ve never even heard of this band!