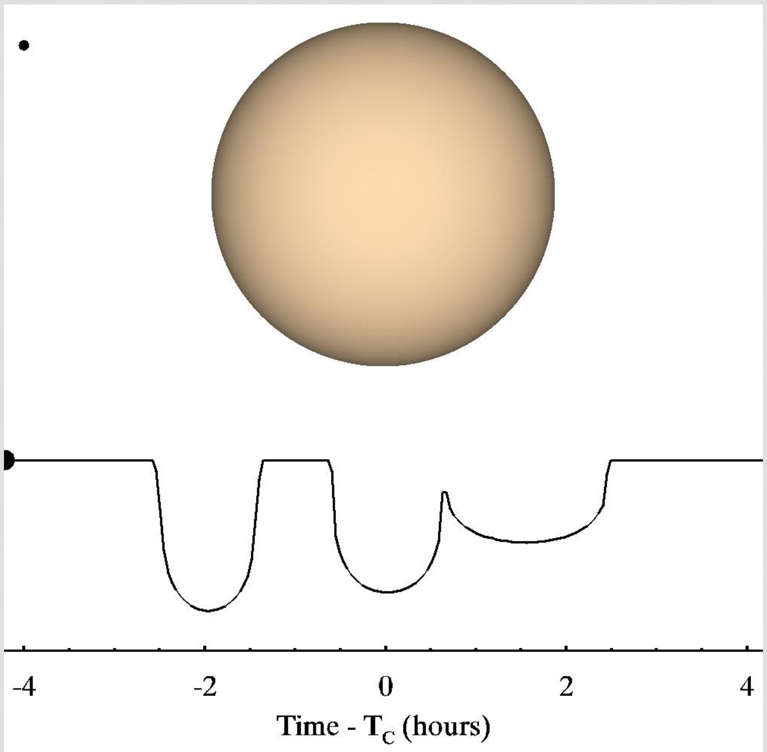
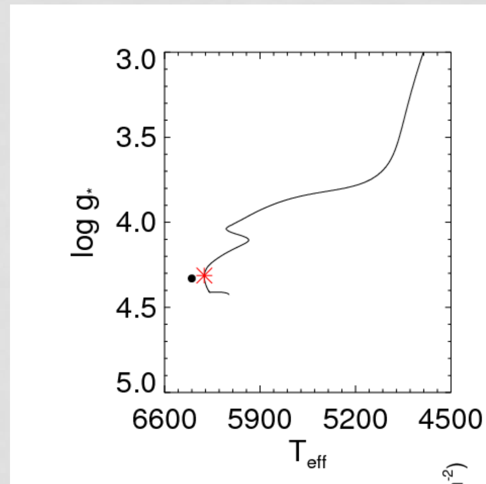
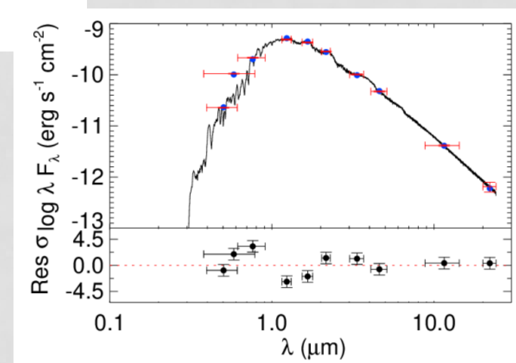
TRANSIT PIPELINES







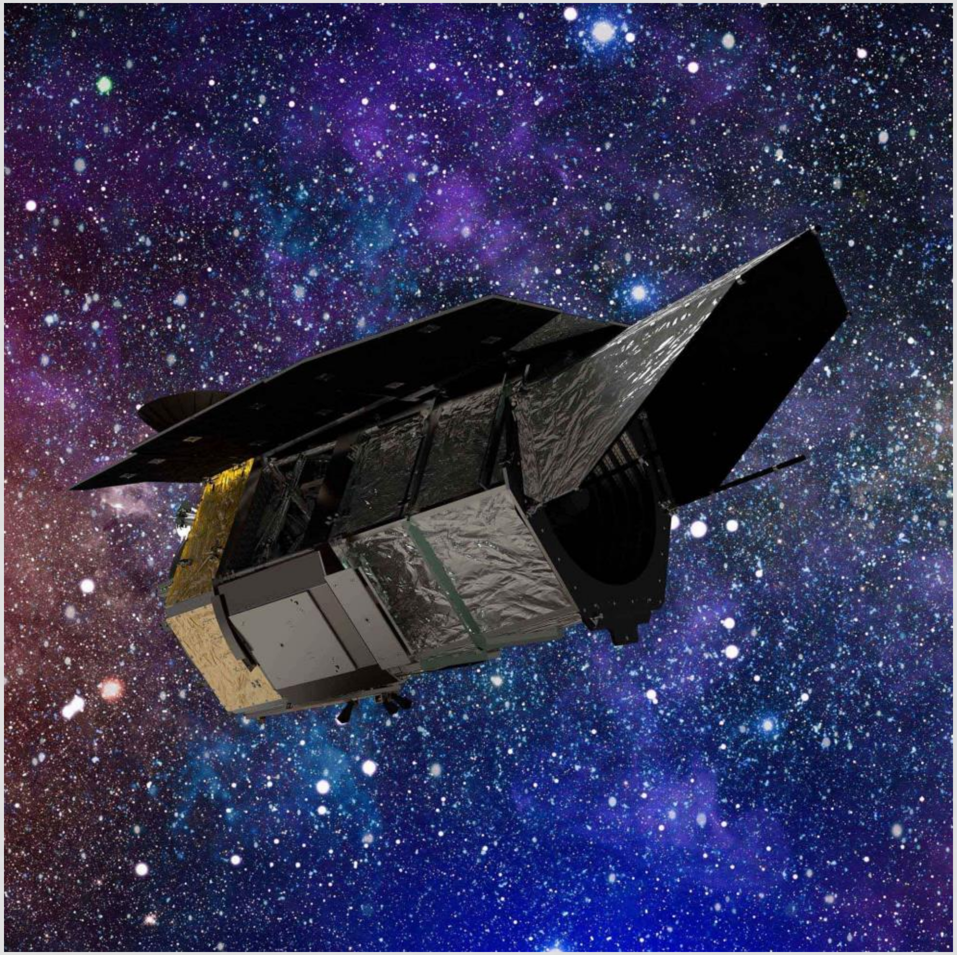
Jason Eastman
Center for Astrophysics | Harvard & Smithsonian

CENTER FOR ASTROPHYSICS HARVARD & SMITHSONIAN

Summer Sagan Workshop
2026.07.23

ROMAN SPACE TELESCOPE

- 60,000-200,000 transiting planets
  - Wilson et al., 2023
- All faint
  - ~no RVs
    - No mass, eccentricity
- High spatial resolution
  - But crowded fields
- Multi-color
  - sorta

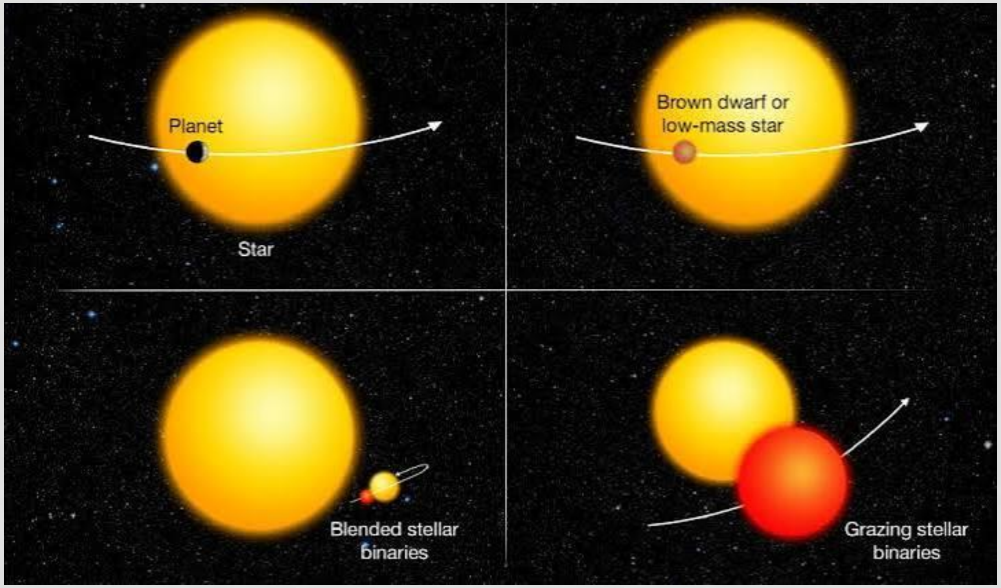


TRANSIT PIPELINE

- Pixels to lightcurves
  - Jay Anderson’s talk
- Lightcurves to transiting planet candidate
  - Community driven
  - e.g., TRExS (Transits in the Roman Galactic EXoplanet Survey)
- Planet candidate vetting
- Planet candidate characterization

CANDIDATE VETTING

- Centroid shifts
- Multi-color, infrared
  - Secondary eclipses
  - Phase curves
- Shape analysis
  - Eccentricity
  - Stellar density



~no prior photometry, astrometry

~no RVs

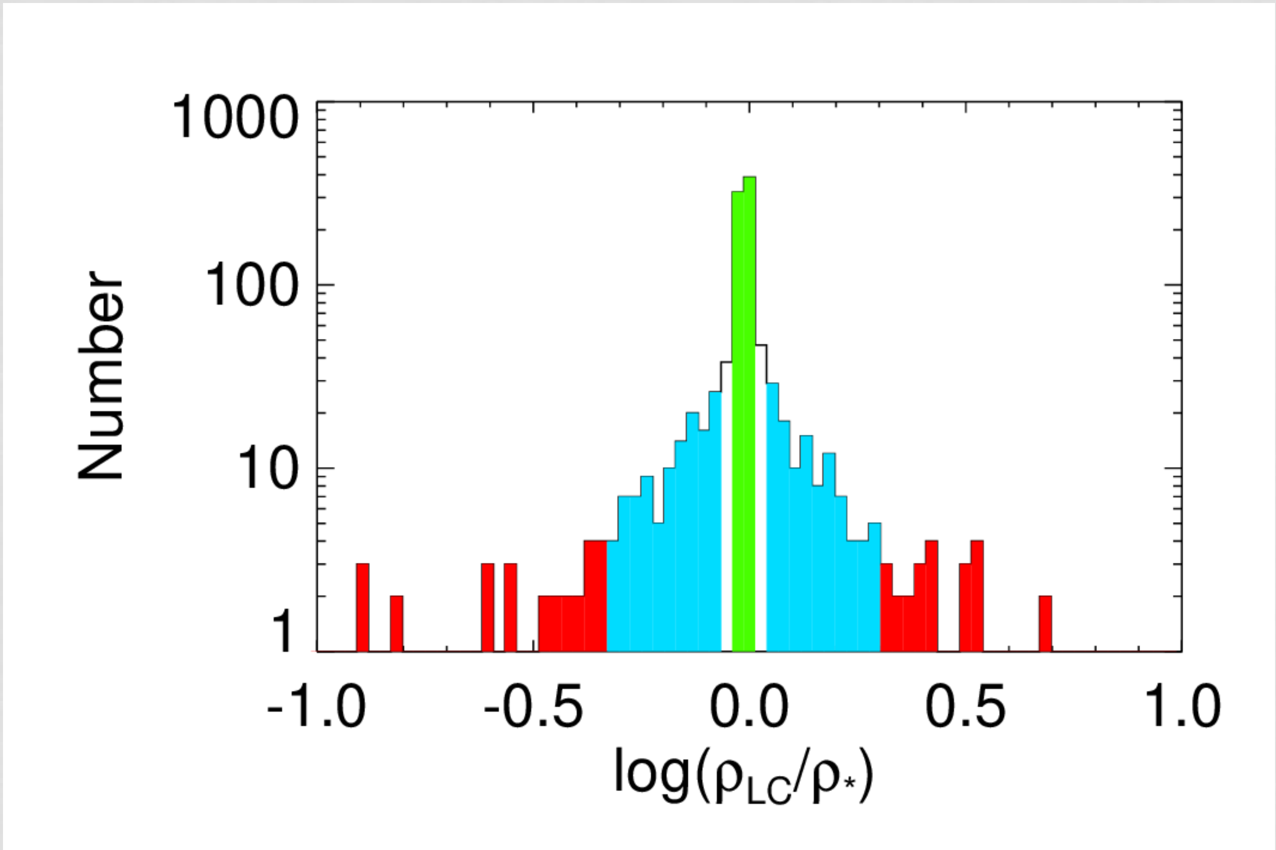
MODELING ASSUMPTIONS

Assumptions likely to be violated and have a significant impact:

- Companion has negligible mass
- All light is from planet host star

Both imply a stellar companion – i.e., false positive

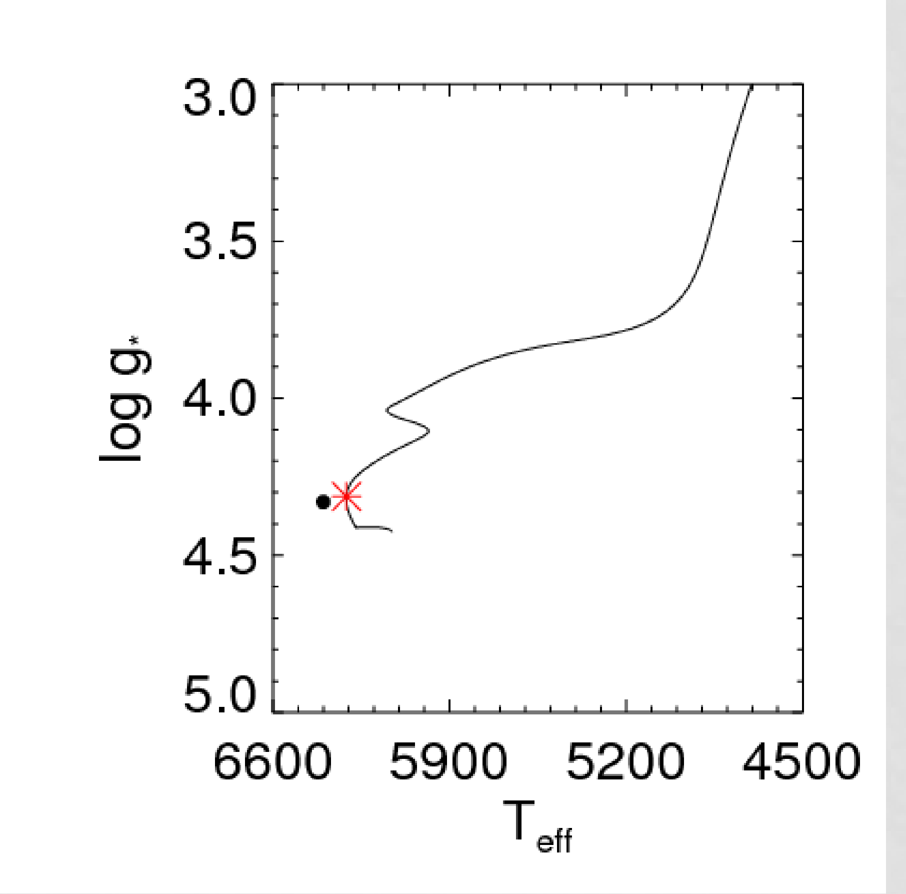
STELLAR DENSITY CONSTRAINT



$$\rho_* = \frac{3M_*}{4\pi R_*^3} \qquad \rho_{*,Tran} = \left(\frac{a}{R_*}\right)^3 \frac{3\pi}{GP^2}$$

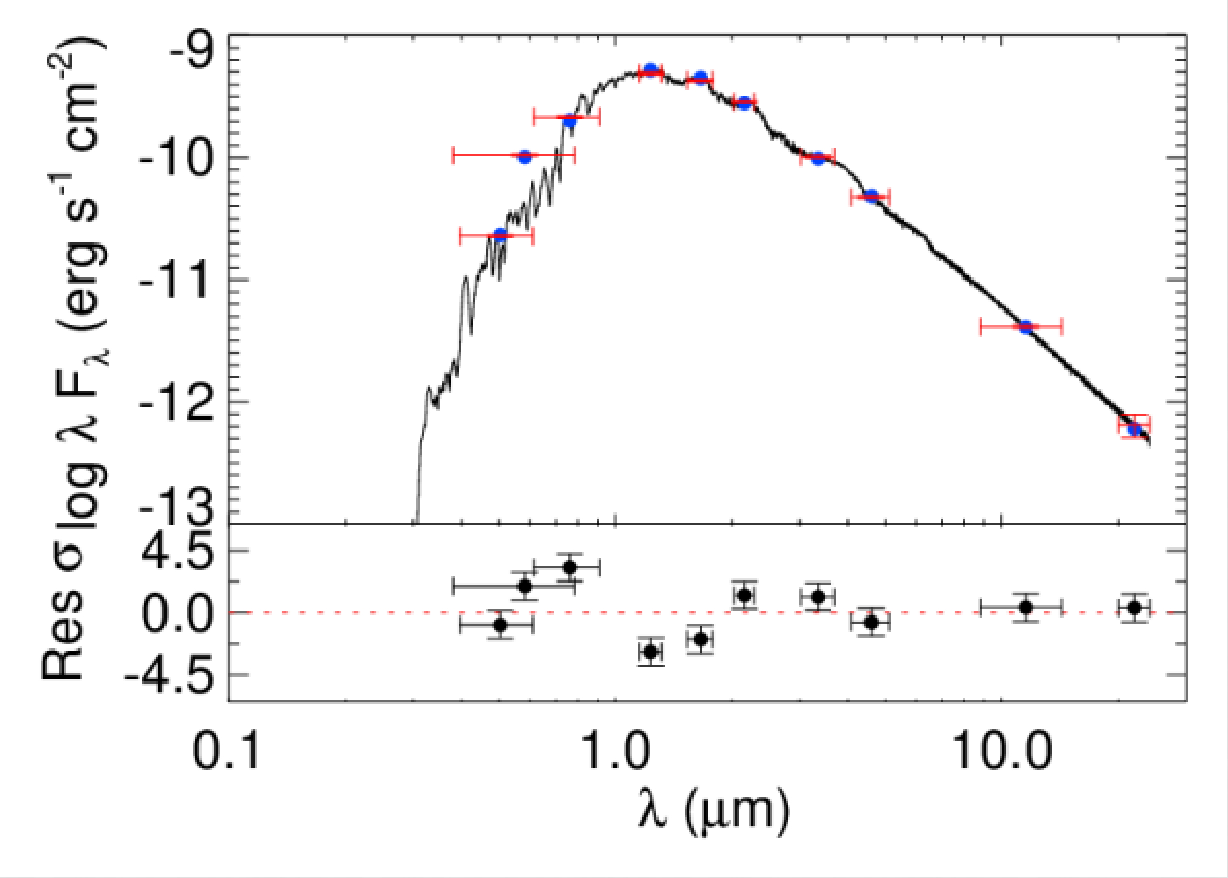
STELLAR TRACKS

- Applicable to most stars
  - $0.1 < M_* < 300$
- Links transit and star in a global, self-consistent model
- Encodes well-understood physics of stellar evolution
- Global model is penalized for straying from MIST-predicted stellar values



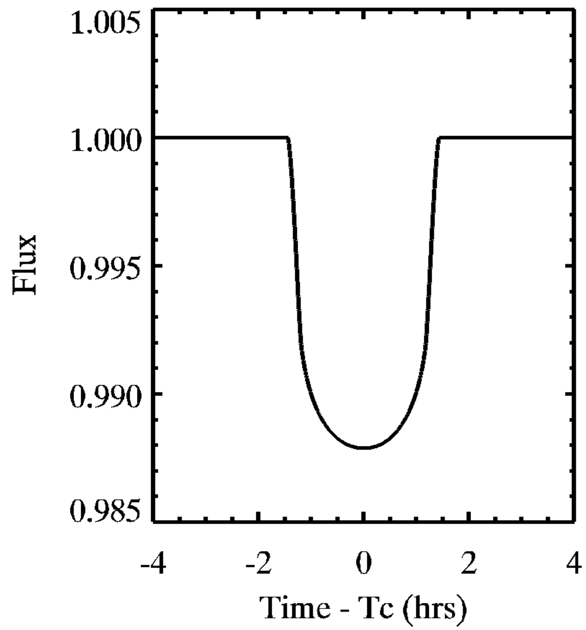
Choi et al., 2016; Dotter et al., 2016

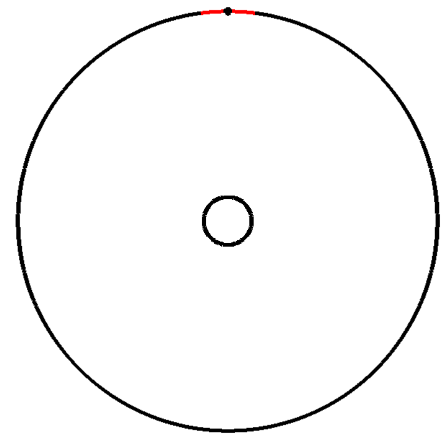
SED MODELING



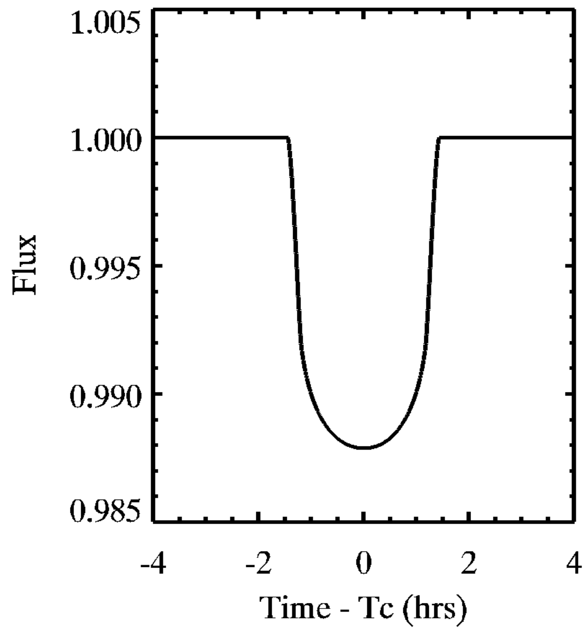
- Broadband photometry + SED Model constrains
- T_{Eff}
- R_*
- Distance
- Extinction

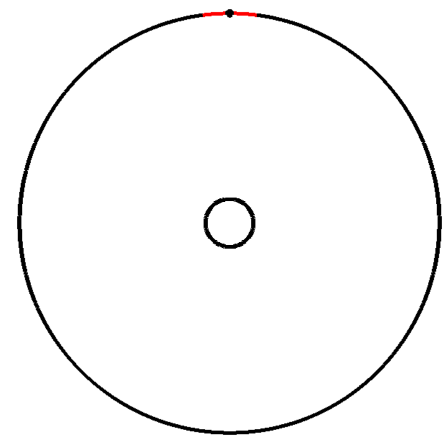
ECCENTRICITY





Transit	RV	Stellar
T_C=0.00	T_C=0.00	R_*=1.00
Period=3.00	Period=3.00	M_*=1.00
a/R_*=8.76	K=100.00	$\log g_*$=4.41
R_p/R_*=0.10	e=0.00	T_{eff}=5800.00
i=90.00	ω_*=-180.00	[Fe/H]=0.00
e=0.00	γ_*=0.00	vsini=2000.00
ω_*=-180.00		λ_*=0.00
u_1=0.39		
u_2=0.27		
F_0=1.00		

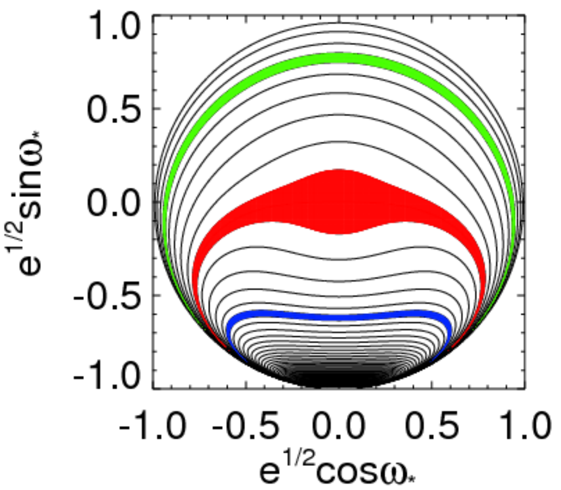


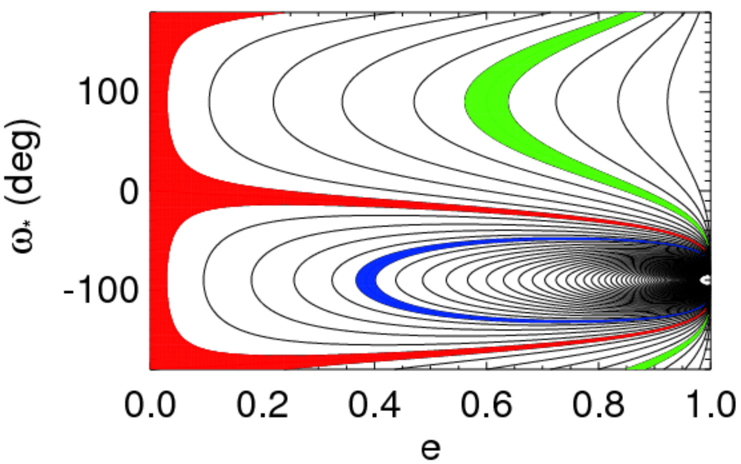


$$\frac{\sqrt{1-e^2}}{1+e\sin\omega_*}$$

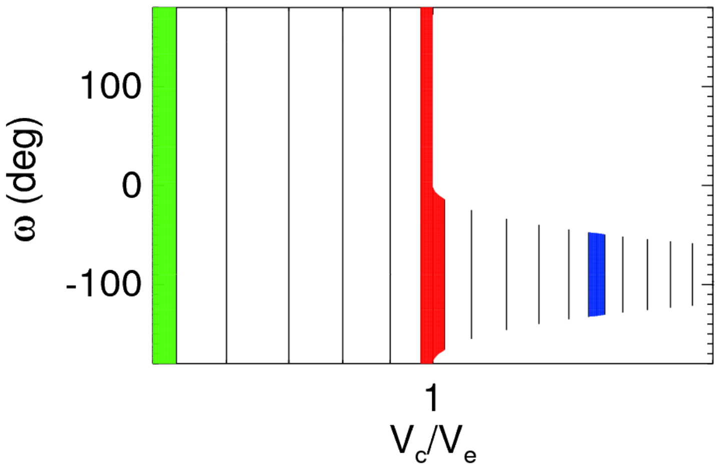
Transit	RV	Stellar
T_C=0.00	T_C=0.00	R_*=1.00
Period=3.00	Period=3.00	M_*=1.00
a/R_*=8.76	K=100.00	$\log g_*$=4.41
R_p/R_*=0.10	e=0.00	T_{eff}=5800.00
i=90.00	ω_*=-180.00	[Fe/H]=0.00
e=0.00	γ_*=0.00	vsini=2000.00
ω_*=-180.00		λ_*=0.00
u_1=0.39		
u_2=0.27		
F_0=1.00		
V_e/V_c=1.00		

e, ω_* TRANSIT DEGENERACY





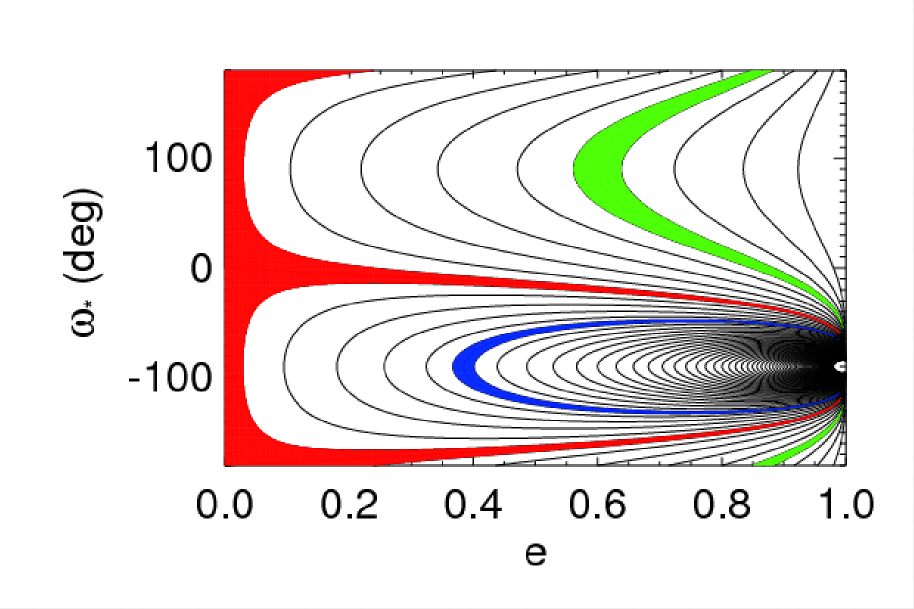
$$\frac{V_c}{V_e} = \frac{\sqrt{1-e^2}}{1+esin\omega_*}$$



Eastman, 2023

ECCENTRICITY: LOWER LIMIT

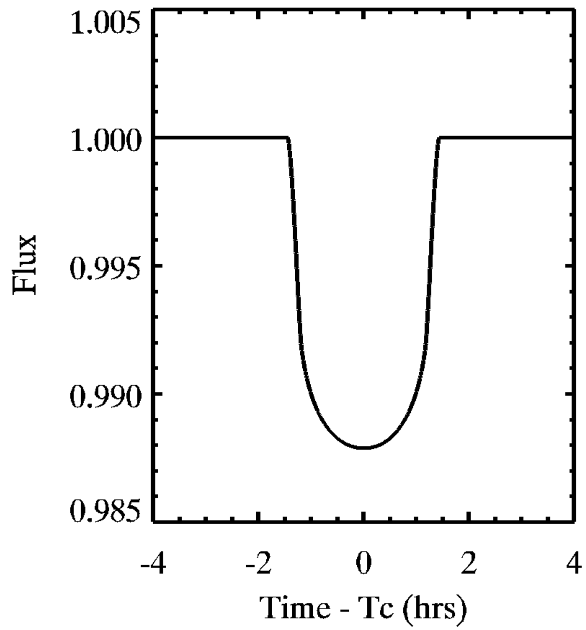
- Any departure from circular duration implies non-zero eccentricity
  - Dawson et al., 2012
  - Kipping et al., 2014
  - Price et al., 2015
- Complex joint constraint with ω_*
- Bonus: prior volume is dramatically diminished at high eccentricities

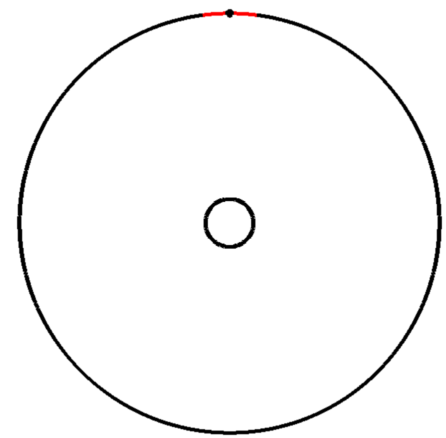


ECCENTRICITY: UPPER LIMIT

- Planet cannot collide with star
  - $e < 1 - \frac{R_*}{a} - \frac{R_P}{a}$
  - e < 0.78 (Hot Jupiter)
- Transit Asymmetry
  - High eccentricities can change velocity during transit
  - Ingress and egress differ
  - In practice, this hasn't been observed
  - However, the lack of asymmetry can provide the strictest data-driven upper limit

Must model planet with eccentricity





$$\frac{\sqrt{1-e^2}}{1+e\sin\omega_*}$$

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Period=3.00	Period=3.00	M_*=1.00
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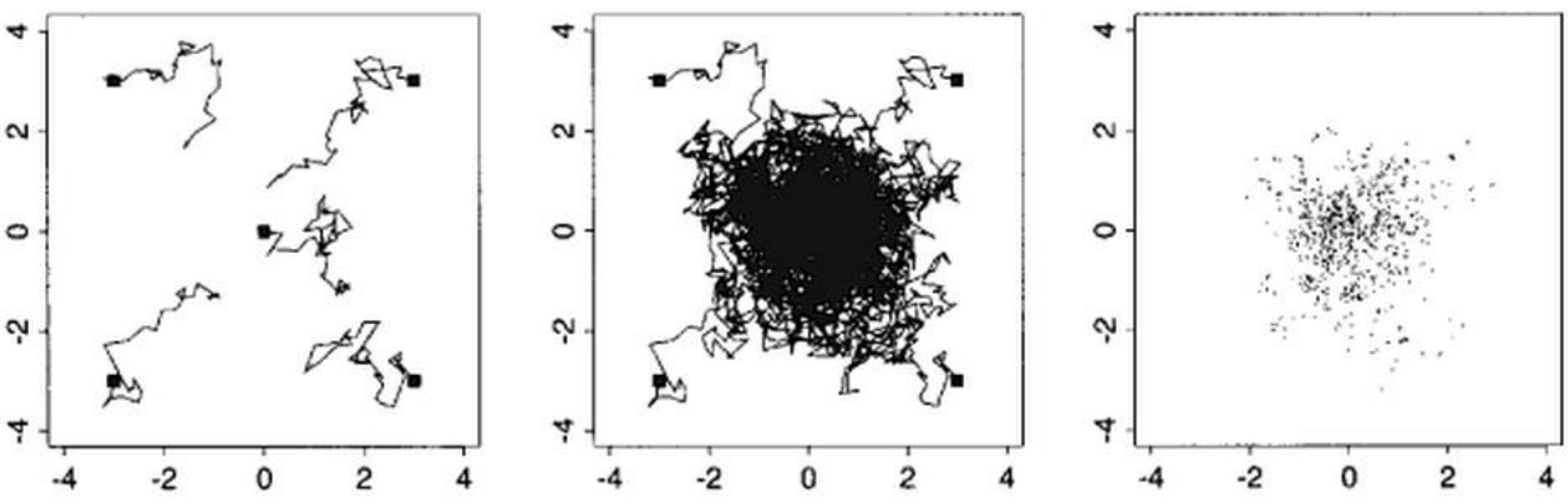
R_p/R_*=0.10	e=0.00	T_{eff}=5800.00
i=90.00	ω_*=-180.00	[Fe/H]=0.00
e=0.00	γ_*=0.00	vsini=2000.00
ω_*=-180.00		λ_*=0.00
u_1=0.39		
u_2=0.27		
F_0=1.00		
V_e/V_c=1.00		

CHARACTERIZING EXOPLANETS

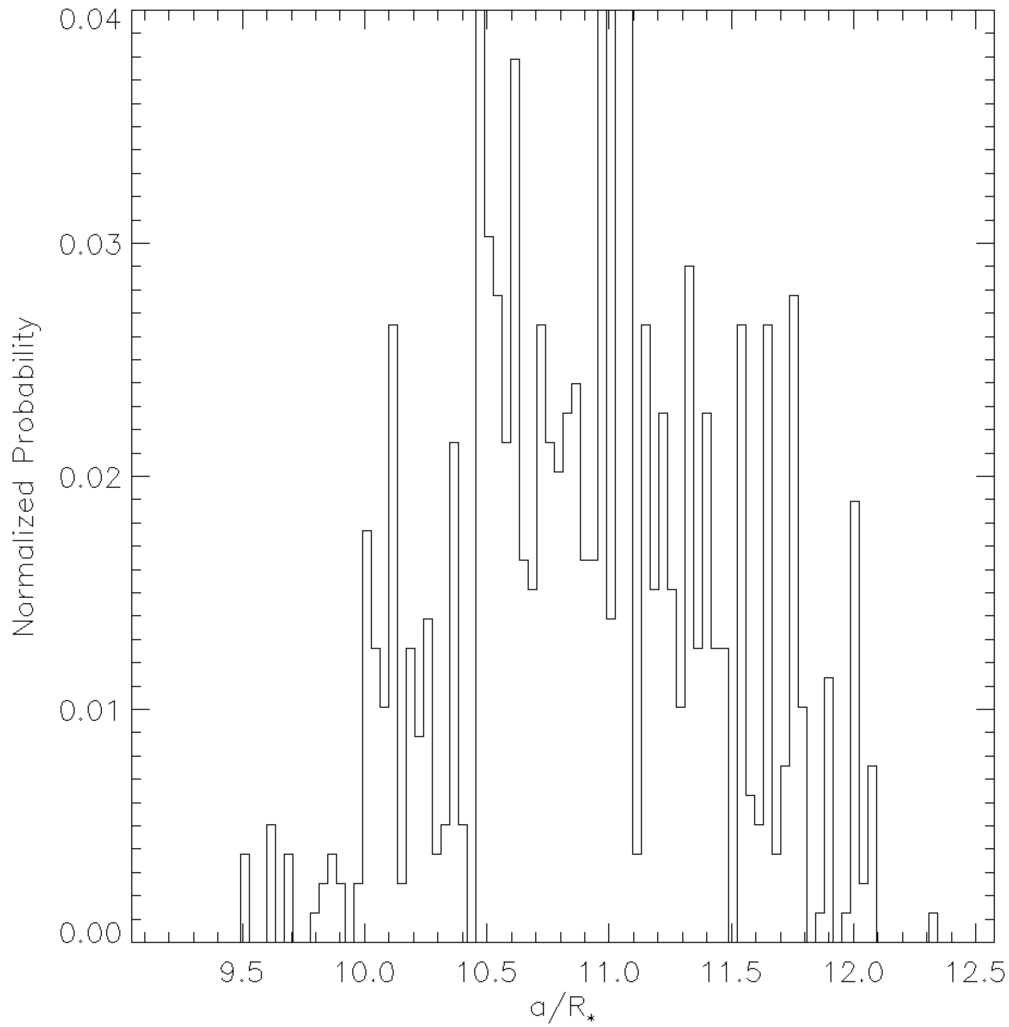
- Juliet, Allesfitter
  - built on top of powerful python libraries
    - emcee, BATMAN, etc
  - GPs
- Exoplanet
  - Very fast (PyMC3, 5?)
  - GPs
  - Collection of low-level codes
- EXOFASTv2
  - IDL (!)
  - Includes star
  - Physical model
  - Many effects
- EXOZIPPy
  - EXOFASTv2 in Python
  - Only edit config files
  - Much faster
    - Built on PyMC6
  - Work in progress…

BASIC MODELING IDEA - MCMC



Gelman, et. al., 2003

UNCERTAINTIES: MCMC



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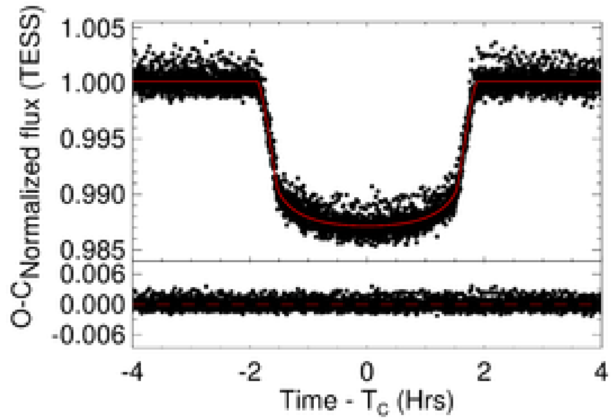

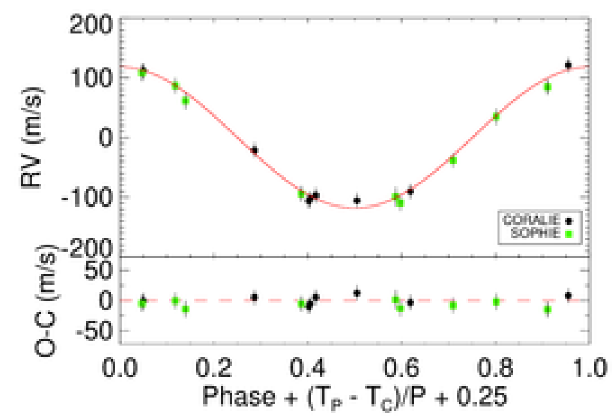

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logg_0 4.1301478
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age_0 1.5919796
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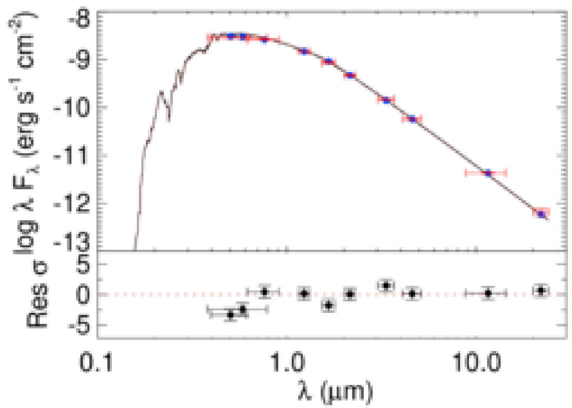

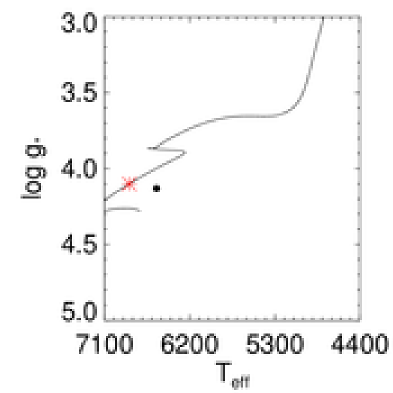

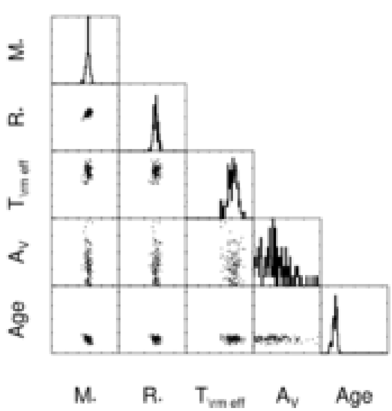

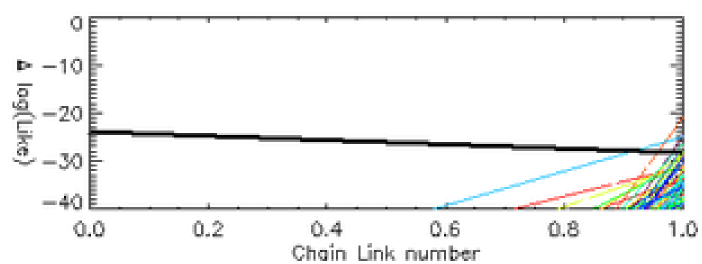

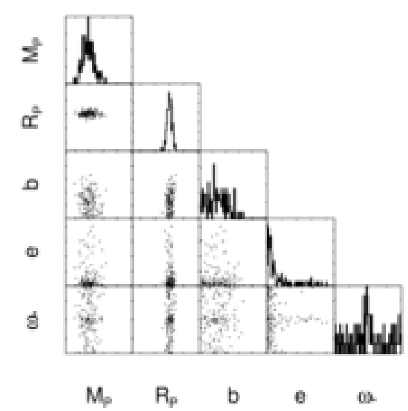

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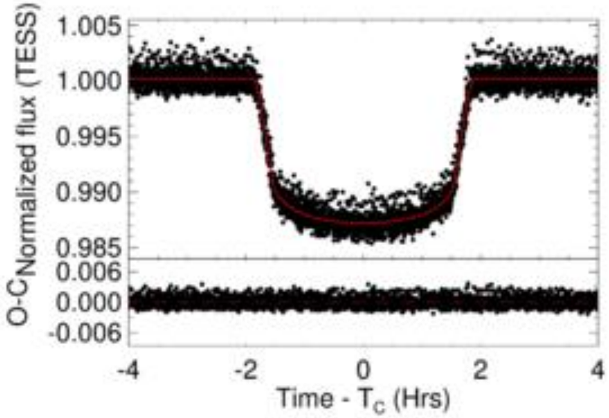

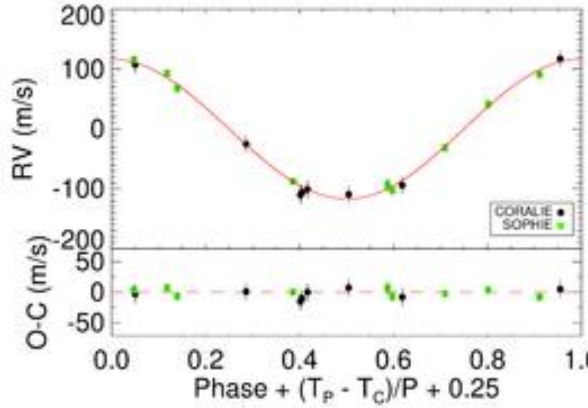

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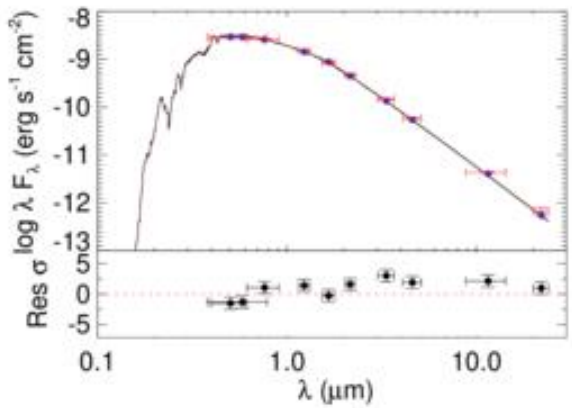

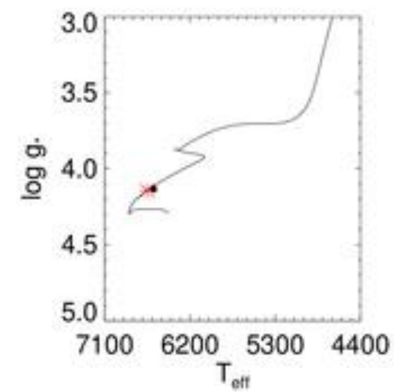

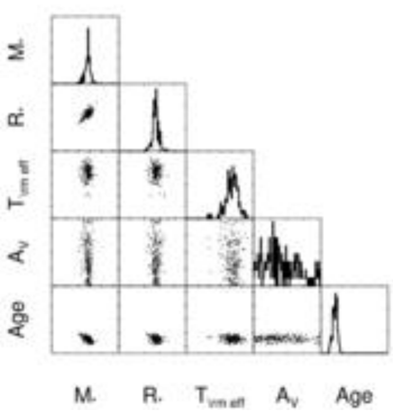

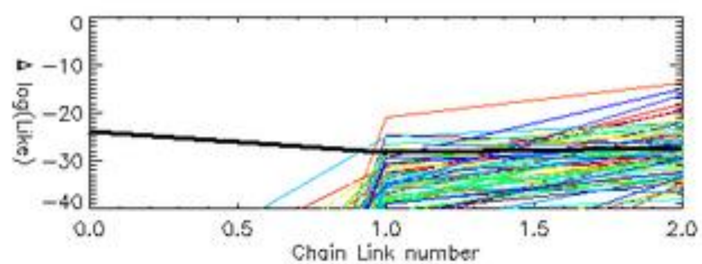

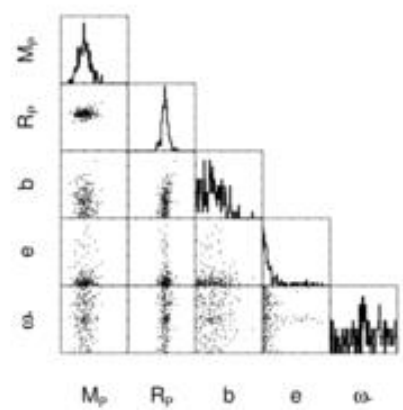

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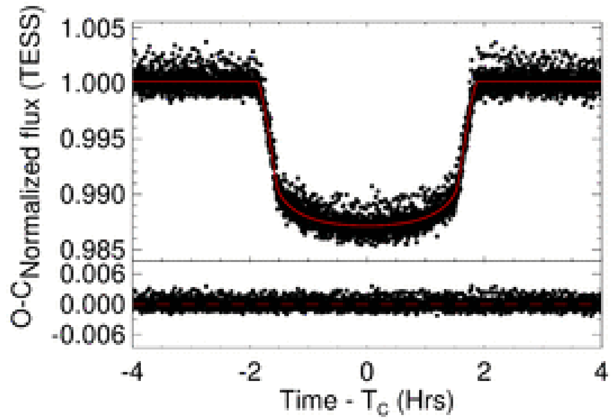

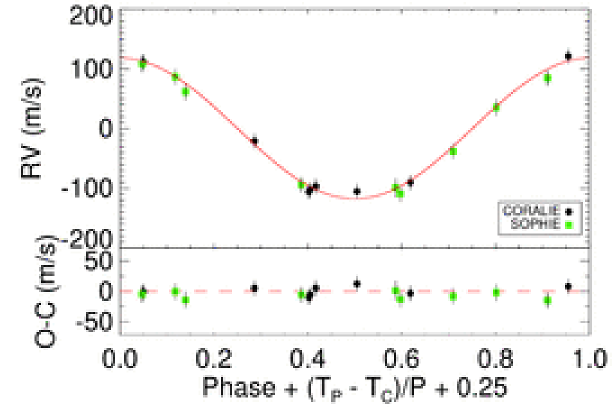

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teff_0 6549.3018
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logg_0 4.1301478
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Av_0 0.0097498726
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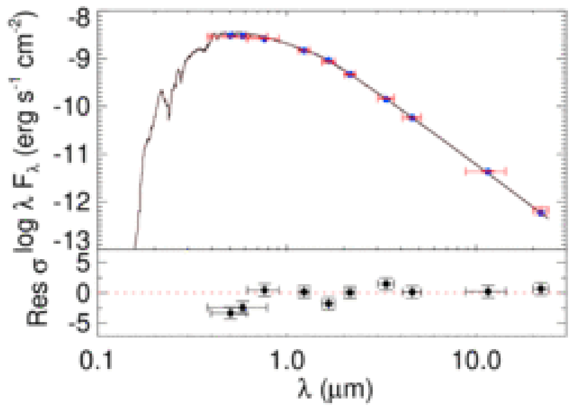

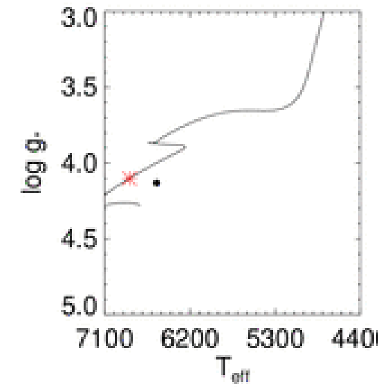

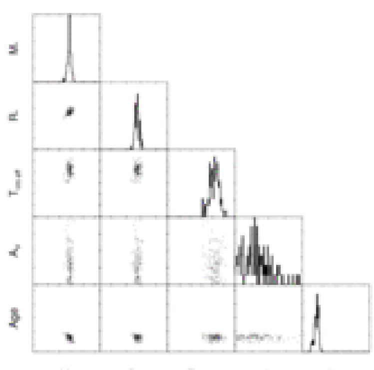

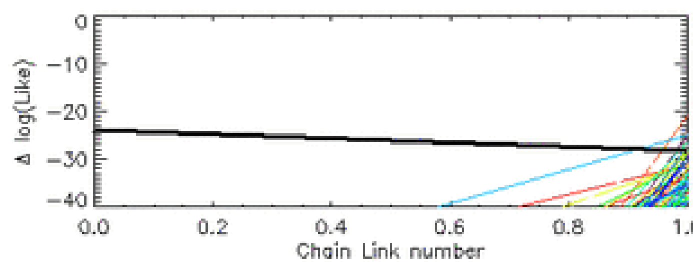

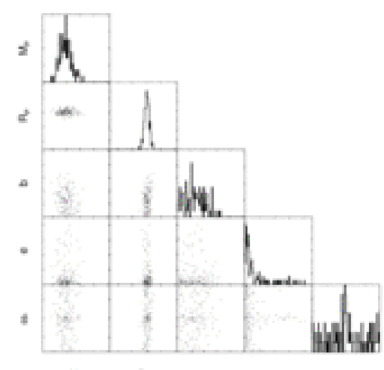

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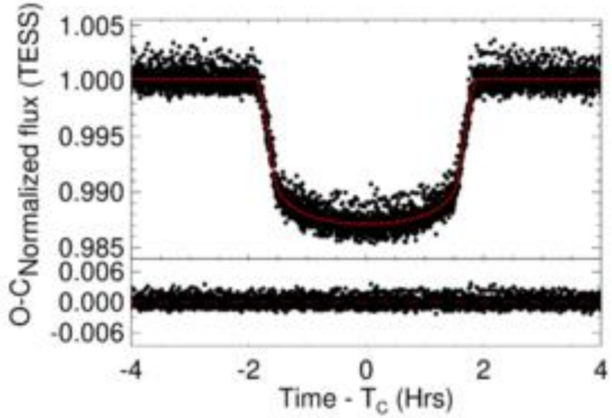

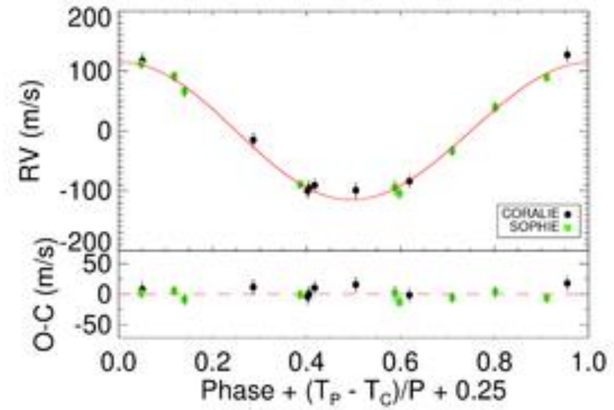

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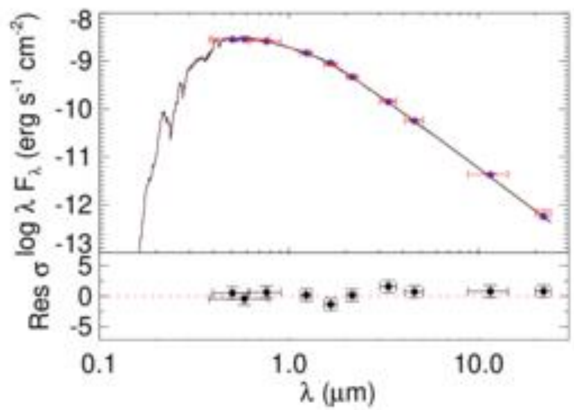
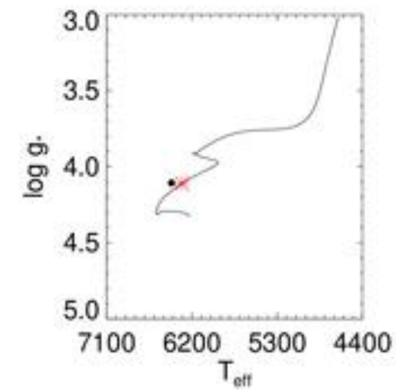
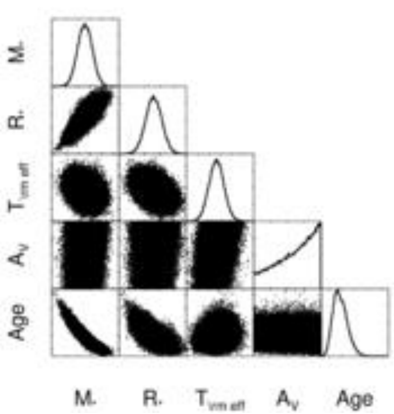
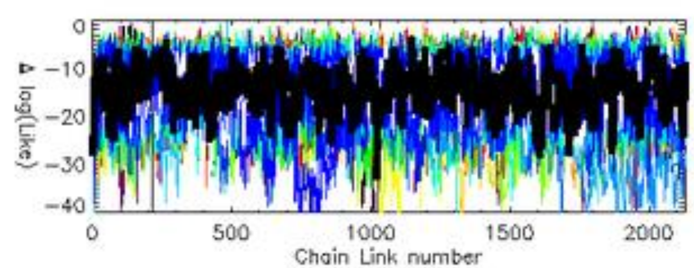
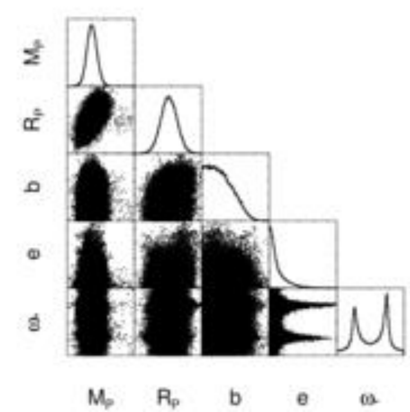










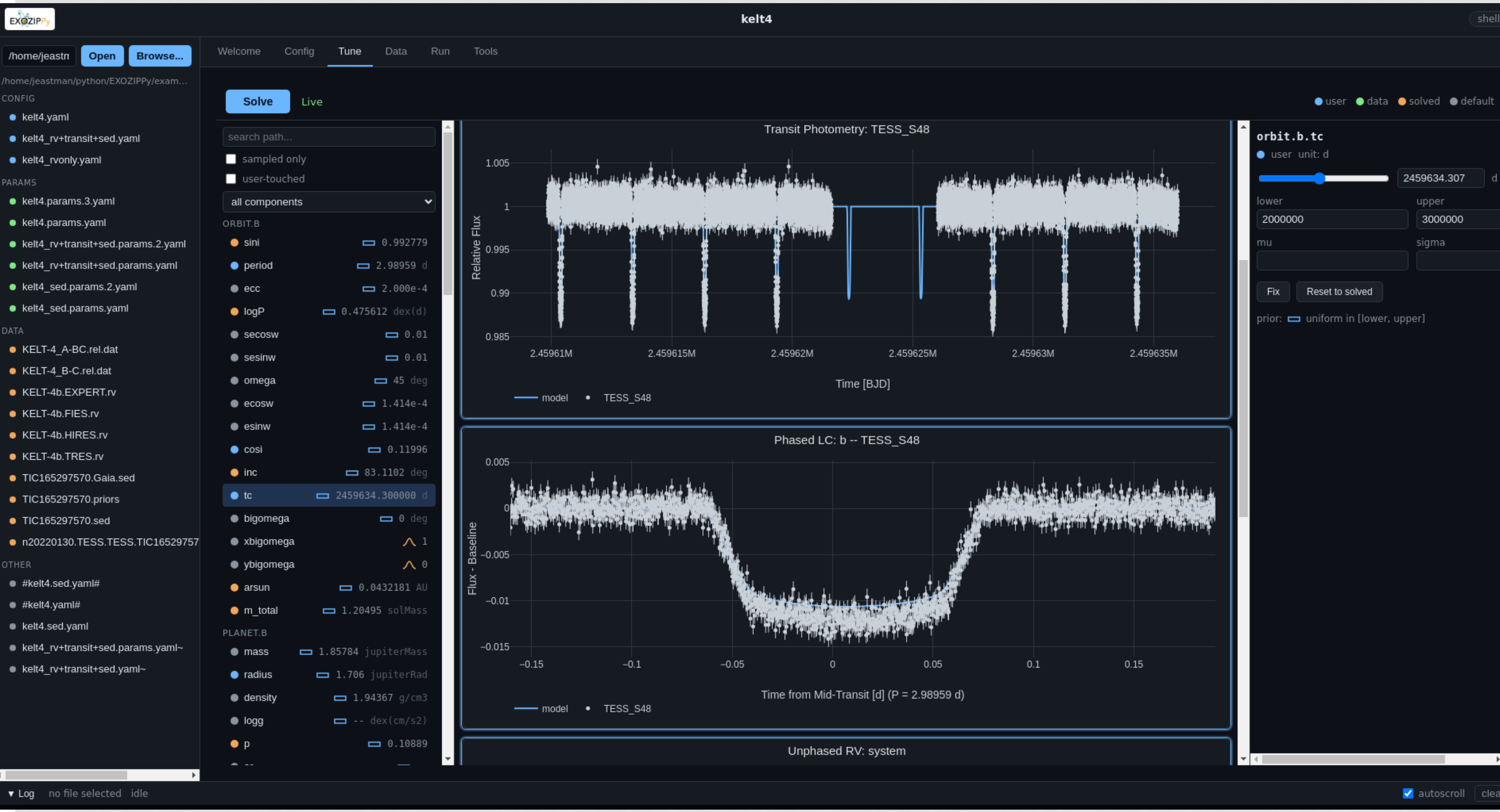
EXOFASTv2

- Battle tested global modeling suite
  - Used in about half of TESS discovery papers
- Is its own light curve to publication-quality model pipeline
- Can model the star
  - SED, evolutionary model, empirical relations
- Along with the planet
  - Transits, RVs, astrometry
- https://github.com/jdeast/EXOFASTv2

EXOZIPPy

- `EXOFASTv2` meets `exoplanet` meets `MulensModel`
- A ground-up reimagining of global modeling in Python, PyMC6
- User friendly wrapper around PyMC
  - Need not be used for exoplanets at all!
- Ships with core exoplanet "components"
  - Transit, RV, SED, star, planet, empirical relations, evolutionary model (WIP), mulensing
- Still in active development, but kinda sorta functional; alpha testers welcome, but expect rough edges, bugs, and rapid, breaking changes
  - https://github.com/jdeast/exozippy/
  - https://www.reddit.com/r/exozippy/
- Official release in ~November

With PSU grad student, Phoebe Sandhaus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/home/jeastm
Open
Browse...
/home/jeastman/python/EXOZIPPy/exam...
CONFIG
kelt4.yaml
kelt4_rv+transit+sed.yaml
kelt4_rvonly.yaml
PARAMS
kelt4.params.3.yaml
kelt4.params.yaml
kelt4_rv+transit+sed.params.2.yaml
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KELT-4b.FIES.rv
KELT-4b.HIRES.rv
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TIC165297570.sed
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OTHER
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#kelt4.yaml#
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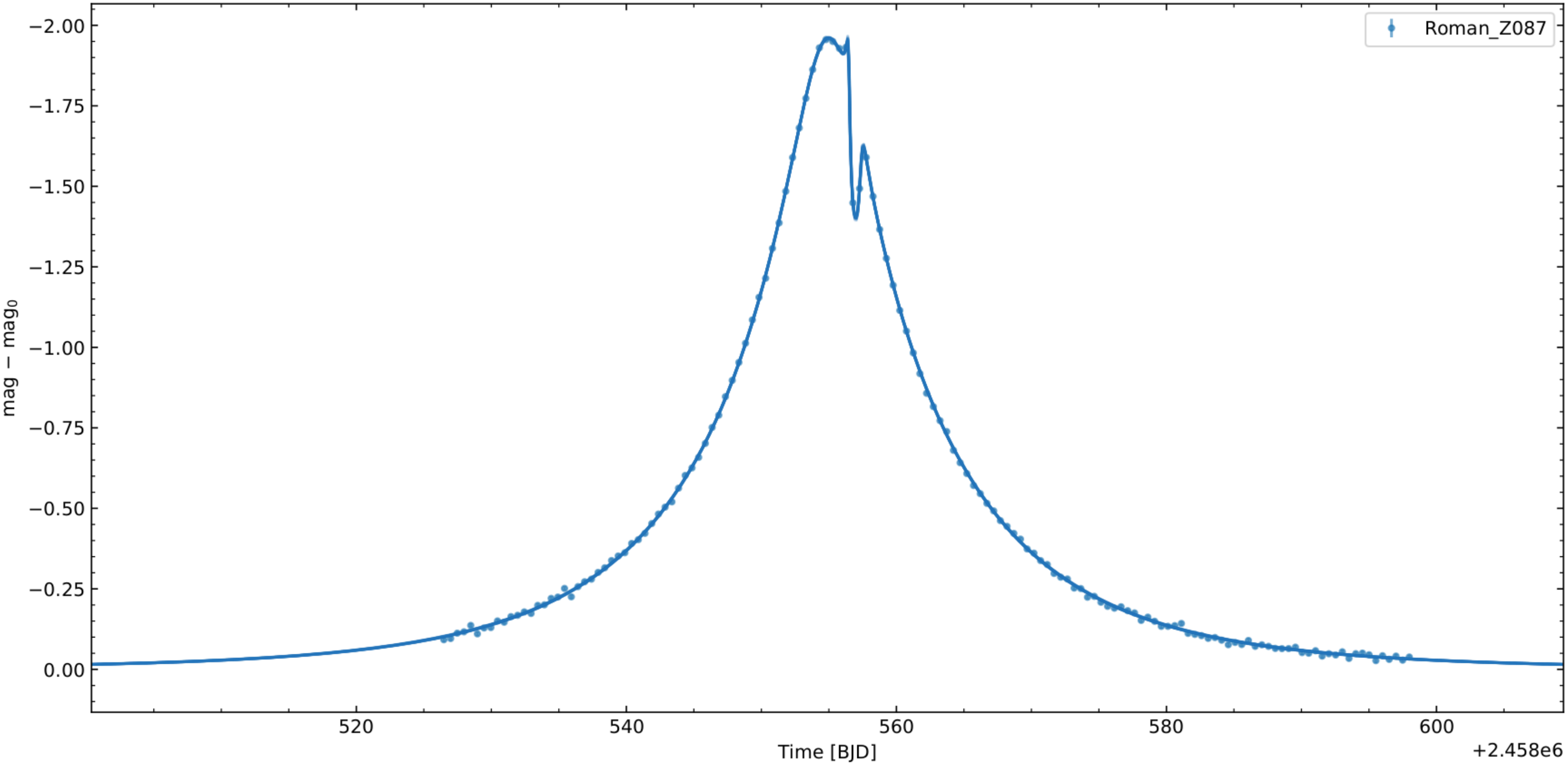
kelt4_rv+transit+sed.yaml~
Welcome
Config
Tune
Data
Run
Tools
Solve
Live
user
data
solved
default
search path...
sampled only
user-touched
all components
ORBIT.B
sini 0.992779
period 2.98959 d
ecc 2.000e-4
logP 0.475612 dex(d)
secosw 0.01
sesinw 0.01
omega 45 deg
ecosw 1.414e-4
esinw 1.414e-4
cosi 0.11996
inc 83.1102 deg
tc 2459634.300000 d
bigomega 0 deg
xbigomega 1
ybigomega 0
arsun 0.0432181 AU
m_total 1.20495 solMass
PLANET.B
mass 1.85784 jupiterMass
radius 1.706 jupiterRad
density 1.94367 g/cm3
logg -- dex(cm/s2)
p 0.10889
Transit Photometry: TESS_S48
Relative Flux
Time [BJD]
model
TESS_S48
Phased LC: b -- TESS_S48
Flux - Baseline
Time from Mid-Transit [d] (P = 2.98959 d)
model
TESS_S48
Unphased RV: system
orbit.b.tc
user unit: d
2459634.307
d
lower
upper
2000000
3000000
mu
sigma
Fix
Reset to solved
prior: uniform in [lower, upper]
Log
no file selected
idle
autoscroll
clear


Roman_Z087
mag − mag$_0$
−2.00
−1.75
−1.50
−1.25
−1.00
−0.75
−0.50
−0.25
0.00
520
540
560
580
600
Time [BJD]
+2.458e6

SUMMARY

- We have a lot of characterization work to do
  - ~100k new planets
- Transits alone – be careful about eccentricity
- Tools like Allesfitter, Juliet, exoplanet, EXOFASTv2 are great

But EXOZIPPy is literally built for Roman