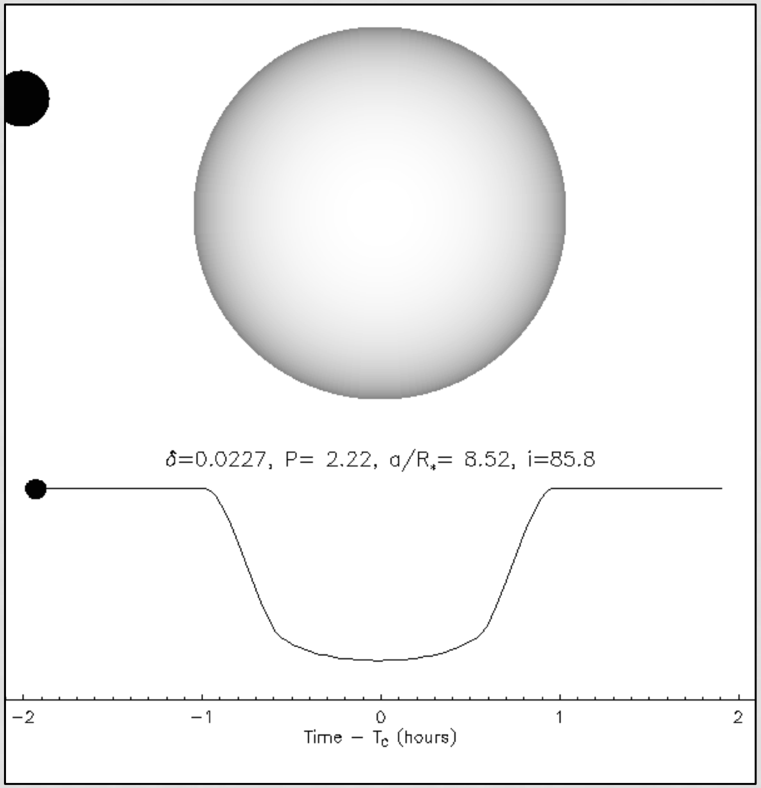
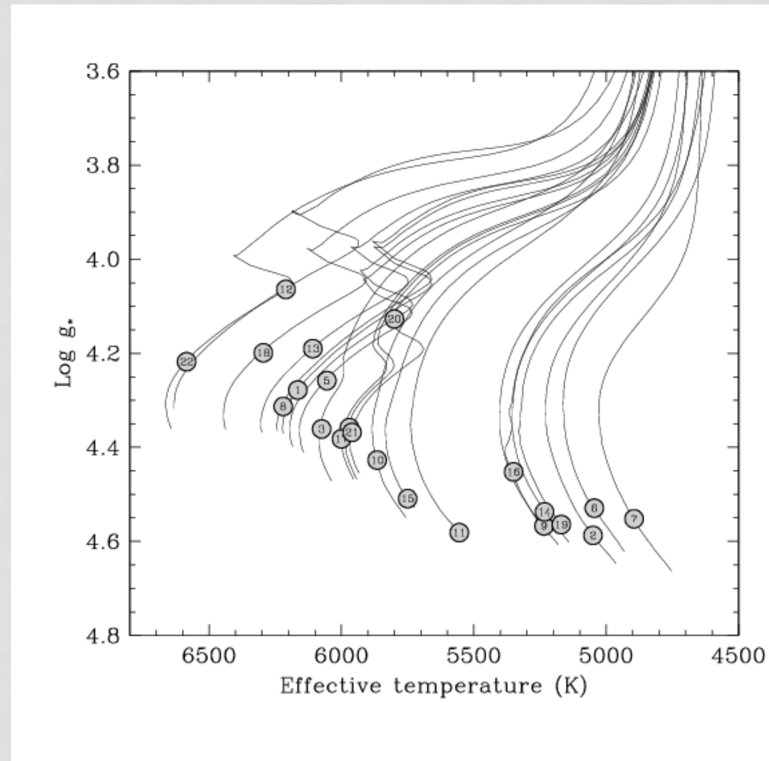
EXOFASTv2: A GENERALIZED, PUBLICATION QUALITY, GLOBAL EXOPLANET FITTING SUITE





Jason Eastman

Sagan Summer Workshop

2018-07-23

THANKS TO THE EXPERT HELPERS

Joey Rodridguez
CfA
Power user, debugger

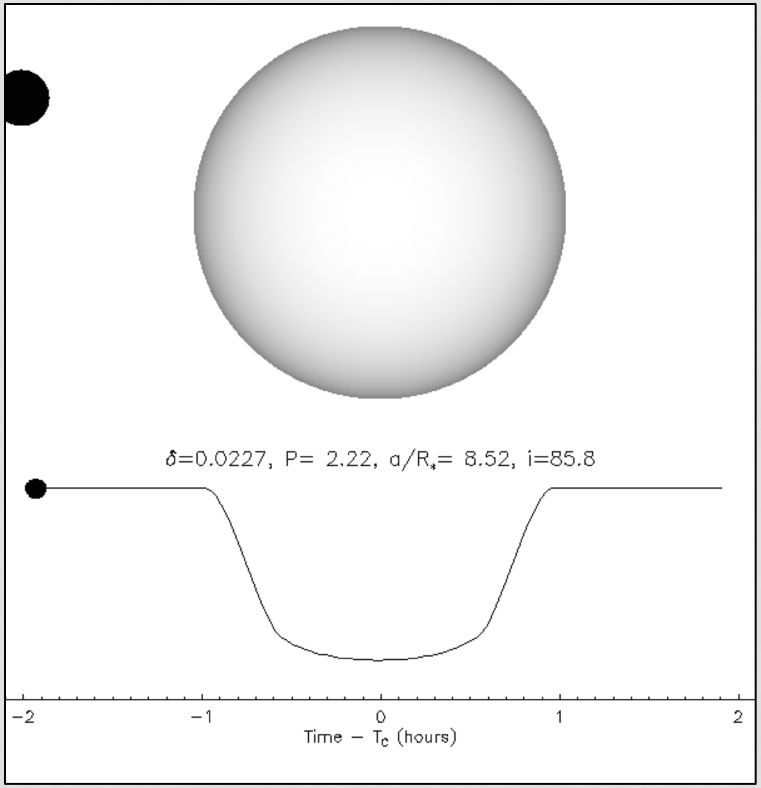
Tobias Cornelius Hinse
KASI

Julian van Eyken
NexSci

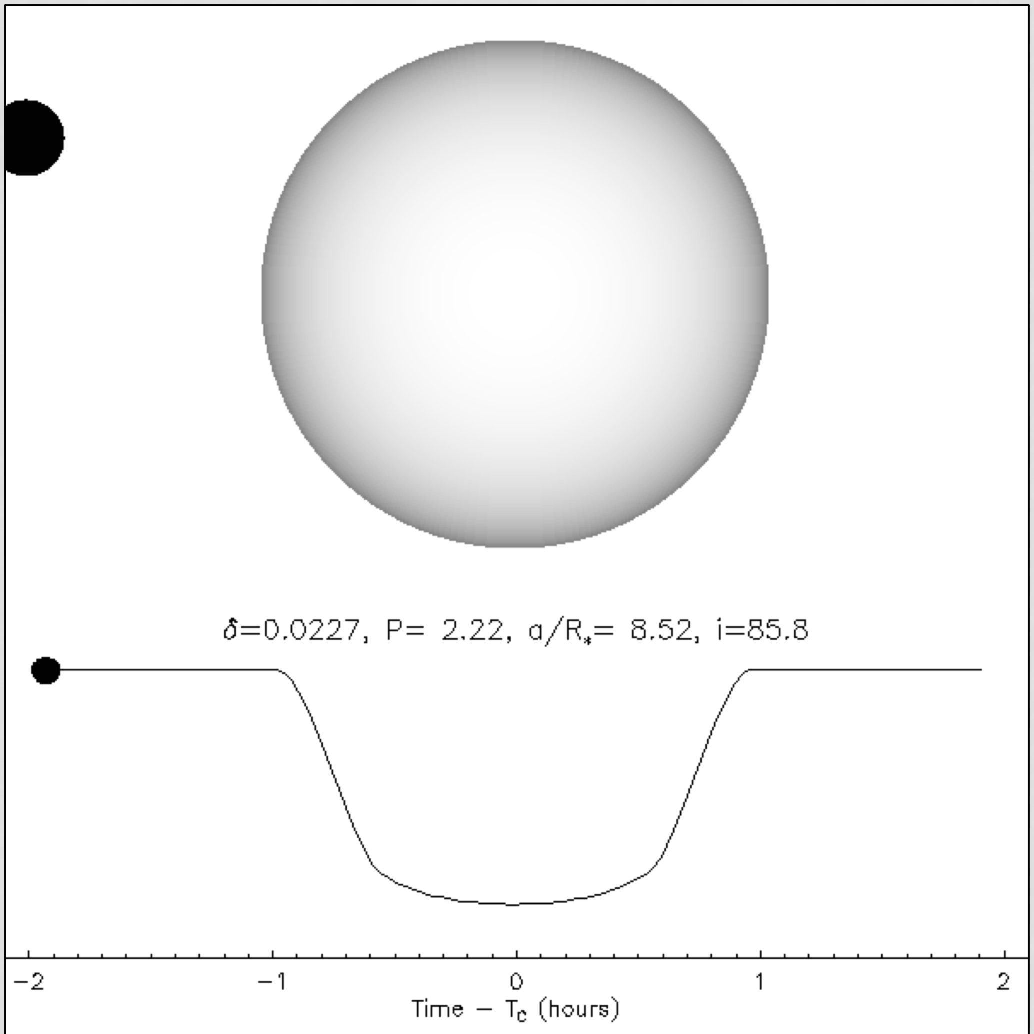
Jonathan Jackson
PSU

EXOFAST
EASTMAN ET AL., 2013

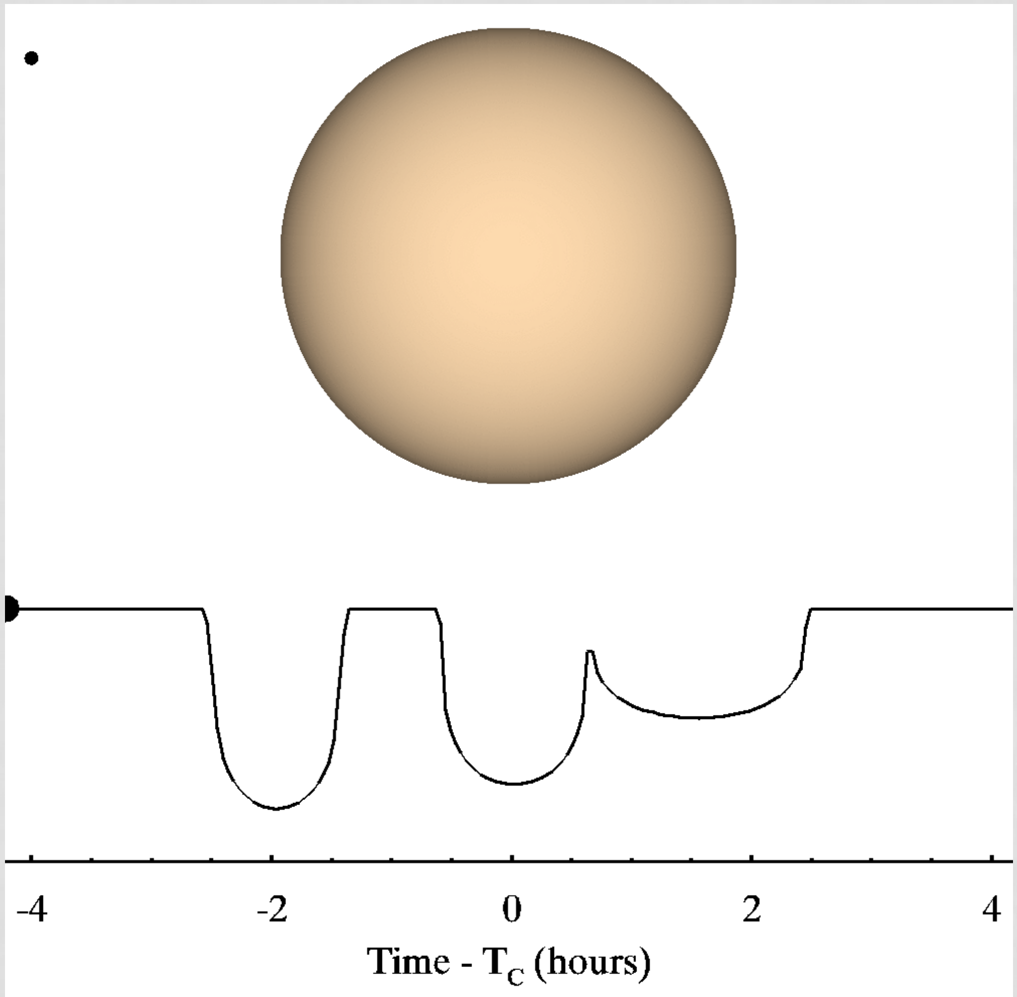
- Differential Evolution Markov Chain Monte Carlo exoplanet modeling code
- Simultaneously models the star and planet with both RV and transits
- But only models a very specific scenario
  - Fixed ephemeris
  - Single wavelength
  - Single planet
  - Single RV instrument
  - Solar type star
  - … few realistic data sets



EXOFAST
EASTMAN ET AL., 2013



EXOFASTv2
EASTMAN ET AL., 2017



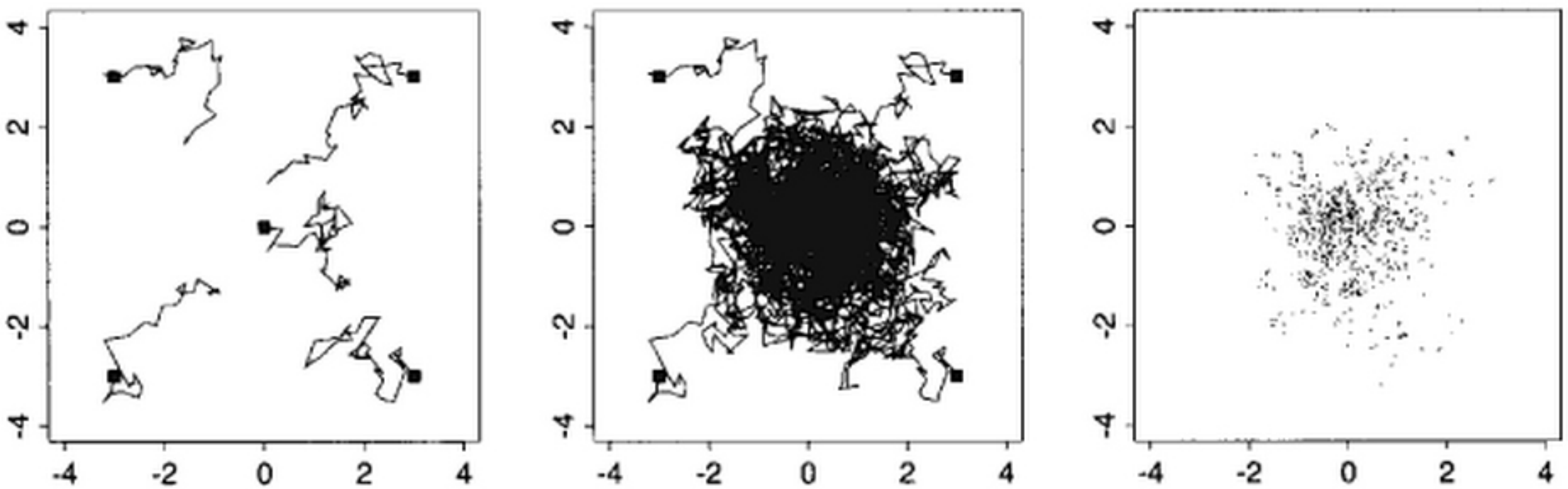
EXOFASTv2

EASTMAN ET AL., 2017

- **Arbitrary number of planets**
  - Arbitrary mix of circular, eccentric, RM, DT, RV, and/or transit data
  - Dynamical constraints on eccentricity
  - Single transit planets
- **Simultaneous Stellar properties**
  - SED modeling
    - Gaia, Schlegel priors
  - **MIST stellar tracks**
  - YY stellar evolutionary model
  - Torres relations
  - Direct M_*, R_* priors
  - **Transit ρ_* constraint**
    - **Discrepancy => false positive**
- Arbitrary number of wavelengths
  - Secondary eclipse depth
  - Quadratic Limb darkening parameters
- **Priors on any fitted or derived quantities**
- Arbitrary number of RV data sources
  - Jitter
  - Zero point
- **Chen & Kipping exoplanet mass-radius relation**
- Arbitrary number of transits
  - Arbitrary number of detrending parameters
  - Normalization
  - TTV
  - TDV
  - TδV
  - Red noise
- **No IDL License required!**

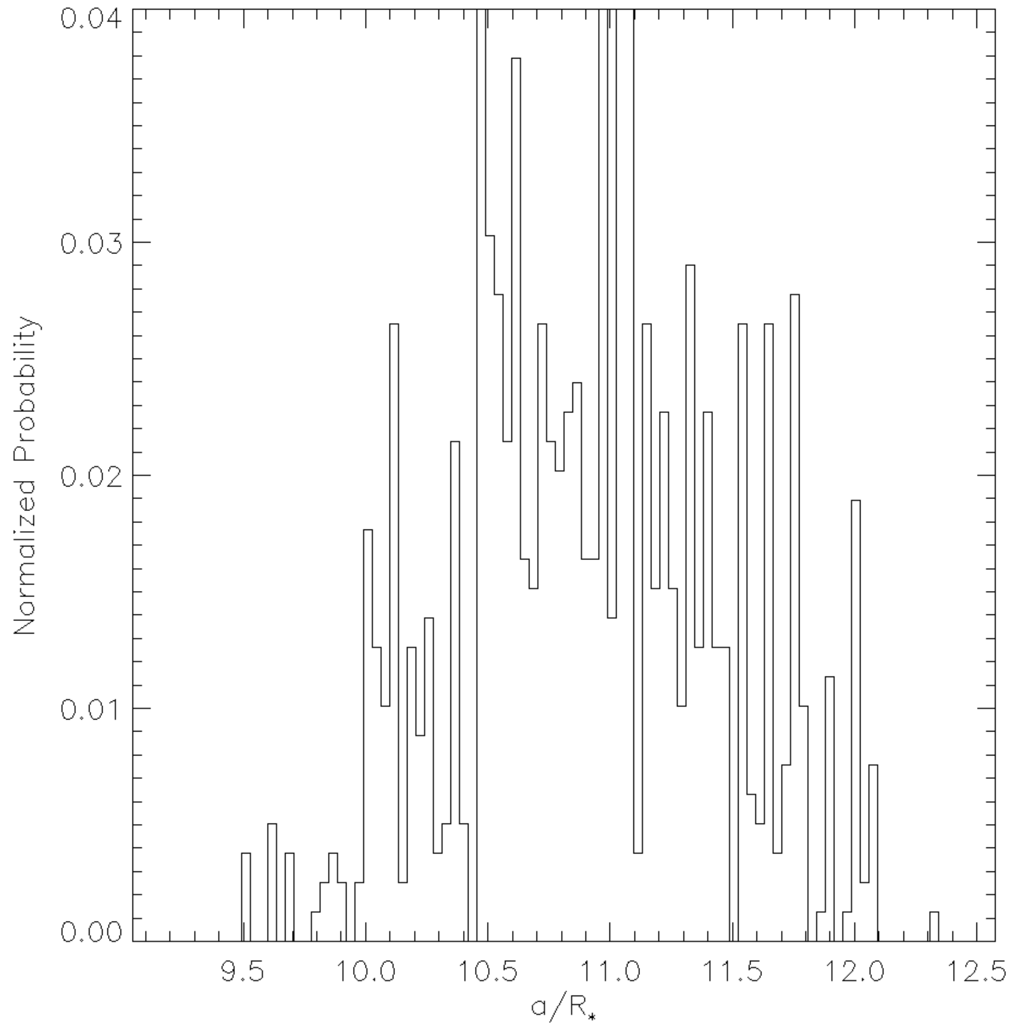
https://github.com/jdeast/EXOFASTv2

WHAT IS MCMC?



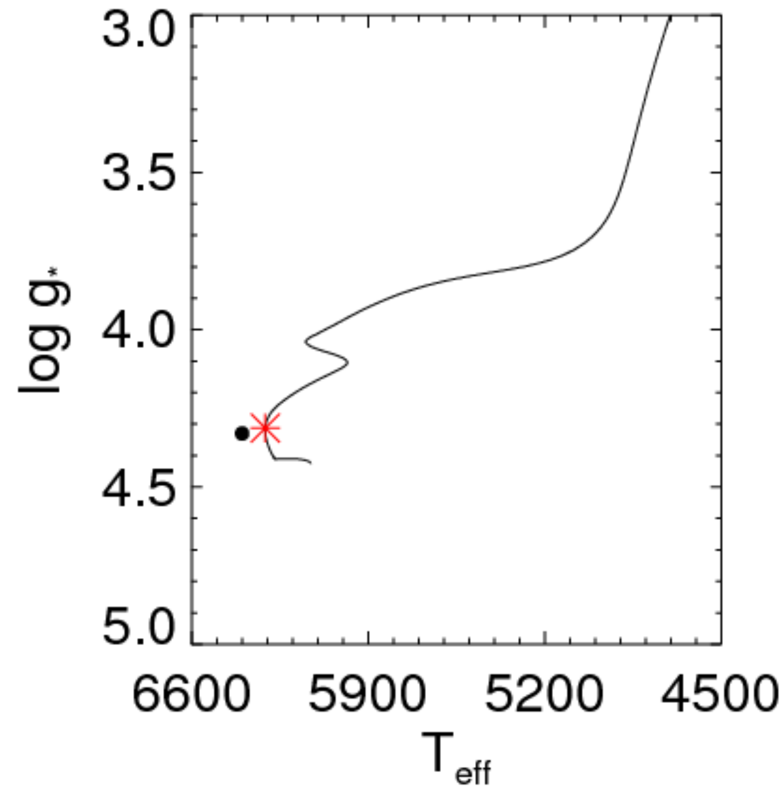
Gelman, et. al., 2003

UNCERTAINTIES: MCMC



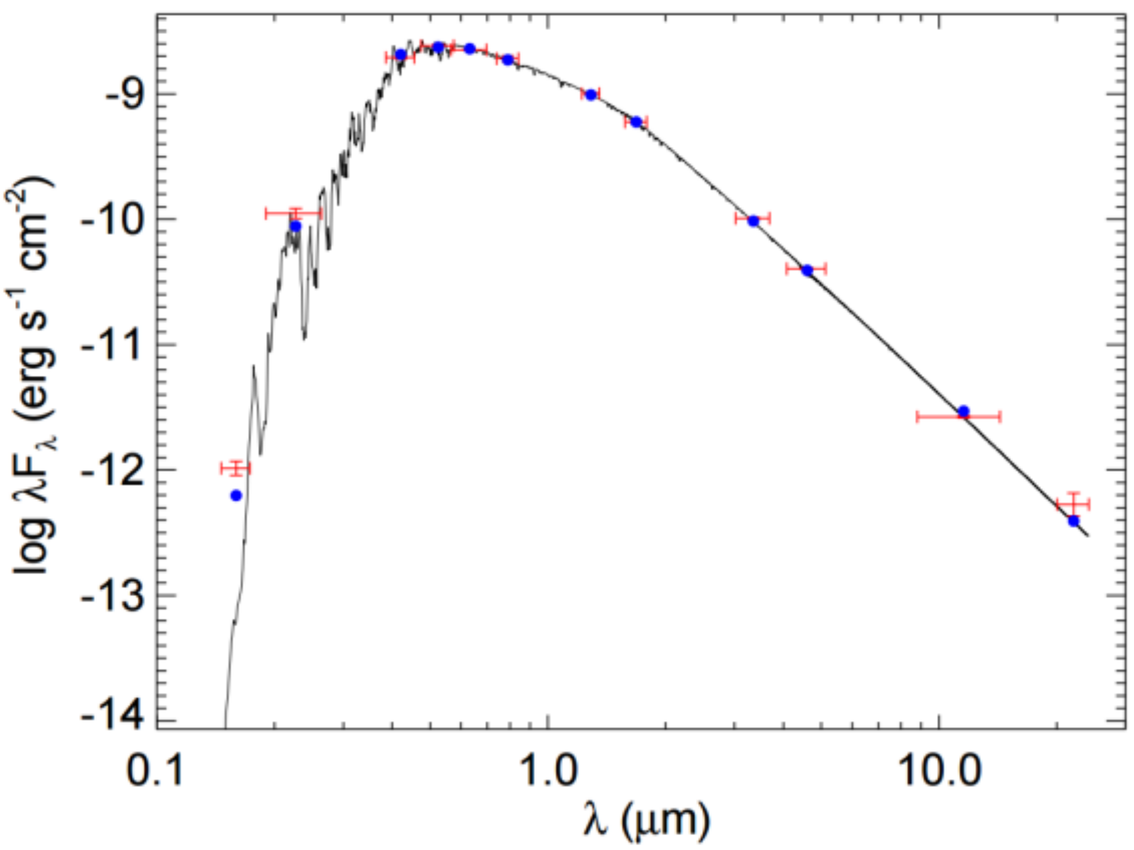
MIST STELLAR TRACKS

- 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



Code contributed by Keivan Stassun

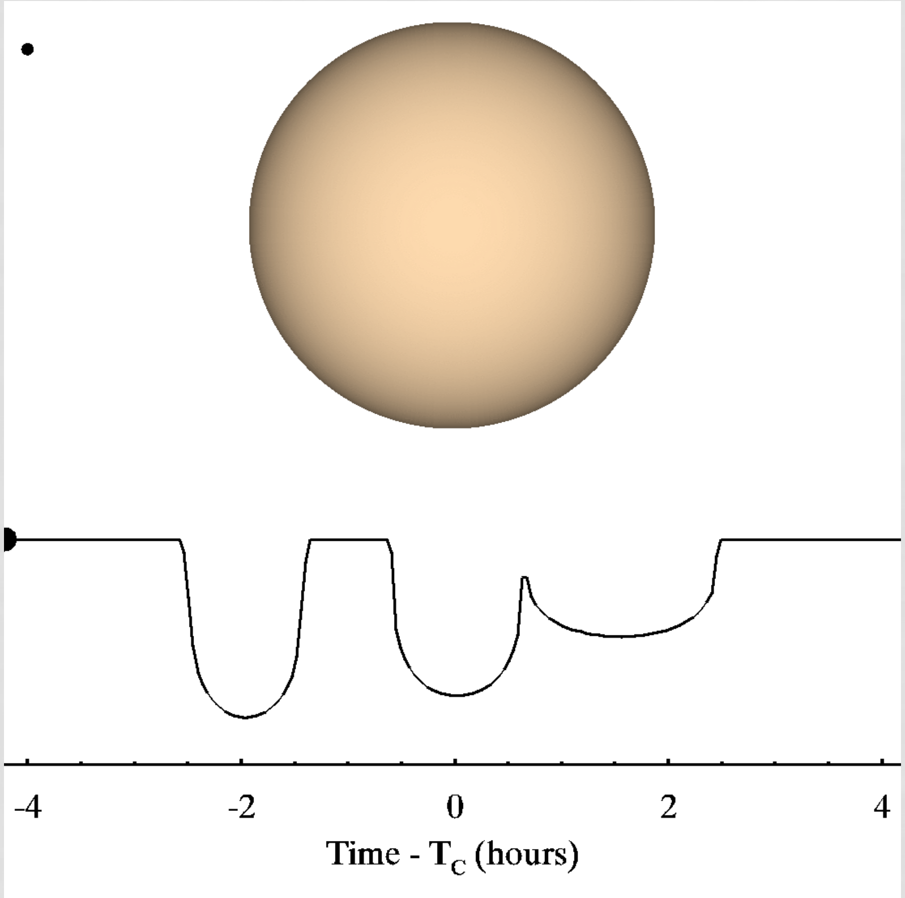
- Broadband photometry + SED Model constrains
- T_{Eff}
- R_*
- Distance
- Extinction
- Very powerful with Gaia DR2

STELLAR DENSITY CONSTRAINT

- Start with Kepler's Law
  - $P^2 = \frac{4\pi^2 a^3}{GM_*}$
- Multiply by 1
  - $P^2 = \frac{4\pi^2 a^3}{GM_*} \frac{R_*^3}{R_*^3}$
- Regroup
  - $P^2 = \frac{4\pi^2 R_*^3}{GM_*} \left(\frac{a}{R_*}\right)^3$
  - $\frac{a}{R_*}$ is observable (duration of the transit)
  - Period is observable
  - Measure $\rho_* = \frac{3M_*}{4\pi R_*^3} = \left(\frac{a}{R_*}\right)^3 \frac{\pi}{3GP^2}$

MULTI-PLANET SYSTEMS

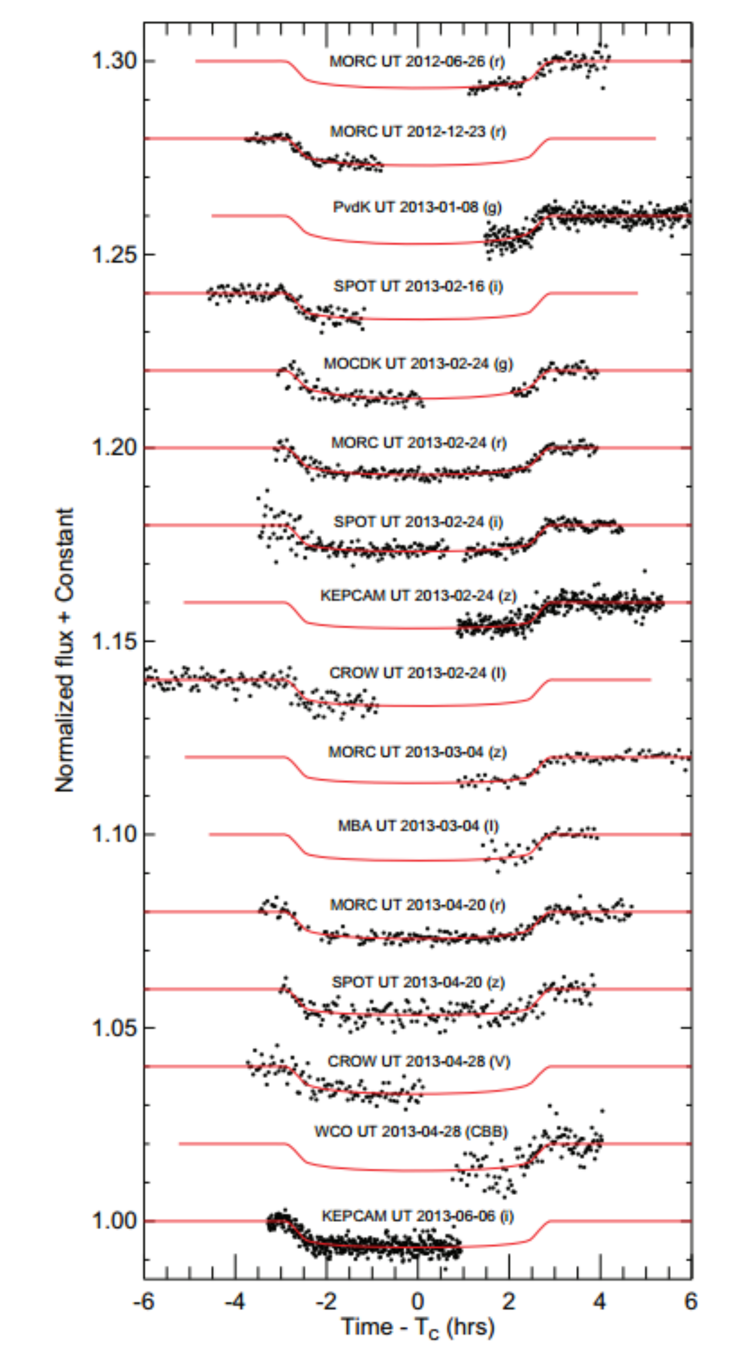
- Self consistent stellar density across multi-planet systems
  - R_*, M_*, P, and Kepler's law means a/R_* is derived, not fit
- Dynamical constraints on eccentricity
  - No orbit crossing
- Simultaneous transits
- TTVs, TDVs, TδVs



GJ 9827
Rodriguez et al., 2017

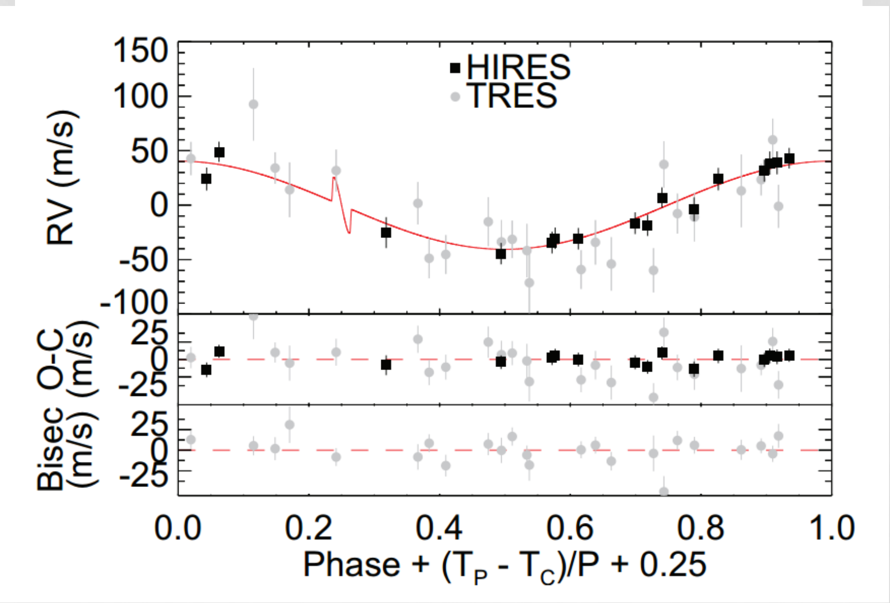
ARBITRARY TRANSITS

- Models heterogeneous observed wavelengths
- Abitrary number of additive and multiplicative detrending variables
  - Airmass trends
  - Drifts
  - Merdian flips
- Secondary eclipses, thermal, and reflected light, dilution optionally included



MULTIPLE RV DATA SOURCES

- Each RV instrument modeled
- Automatically fits new zero point, "jitter" term for each
- Can separate same instrument to fit new zero point for changes to the instrument
- Optionally fits common linear, quadratic trends



KELT-6b, Collins et al

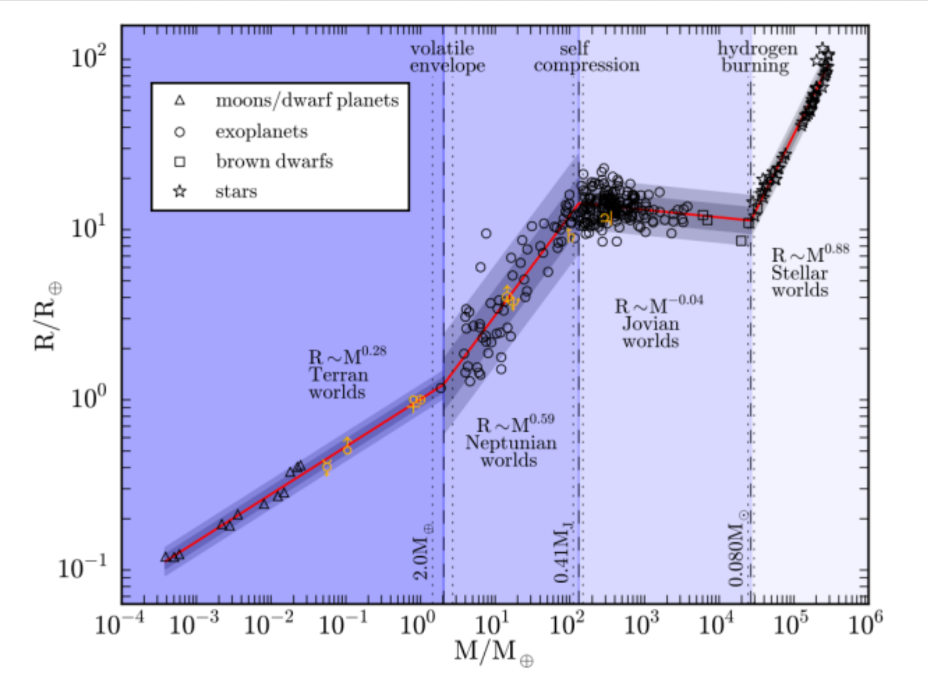
PARAMETER TABLE

TABLE 1
MEDIAN VALUES AND 68% CONFIDENCE INTERVAL FOR HAT-3B.TORRES., CREATED USING EXOFASTV2 COMMIT NUMBER 4714ED6

Parameter	Units	Values
Stellar Parameters:		
M_*	Mass ($M_\odot$)	$0.904^{+0.040}_{-0.042}$
R_*	Radius ($R_\odot$)	0.849 ± 0.015
L_*	Luminosity ($L_\odot$)	$0.456^{+0.017}_{-0.016}$
ρ_*	Density (cgs)	2.08 ± 0.14
$\log g$	Surface gravity (cgs)	$4.536^{+0.023}_{-0.025}$
$T_{\rm eff}$	Effective Temperature (K)	5145^{+43}_{-41}
[Fe/H]	Metallicity	$0.285^{+0.077}_{-0.076}$
$[{\rm Fe/H}]_0$	Initial Metallicity	0.262 ± 0.072
Age	Age (Gyr)	$4.7^{+4.8}_{-3.2}$
EEP	Equal Evolutionary Point	338^{+24}_{-34}
A_v	V-band extinction	$0.0127^{+0.0078}_{-0.0085}$
σ_{SED}	SED photometry error scaling	$1.87^{+0.53}_{-0.36}$
d	Distance (pc)	$134.9^{+1.8}_{-1.7}$
π	Parallax (mas)	7.416 ± 0.097
Planetary Parameters:		b
P	Period (days)	$2.899705^{+0.000053}_{-0.000054}$
R_P	Radius ($R_{\rm J}$)	0.934 ± 0.024
T_C	Time of conjunction ($\rm BJD_{TDB}$)	$2454218.76014^{+0.00035}_{-0.00034}$
T_0	Optimal conjunction Time ($\rm BJD_{TDB}$)	$2454218.76014^{+0.00035}_{-0.00034}$
a	Semi-major axis (AU)	$0.03849^{+0.00056}_{-0.00060}$
i	Inclination (Degrees)	$86.38^{+0.24}_{-0.23}$
T_{eq}	Equilibrium temperature (K)	1165^{+13}_{-12}

EXOPLANET MASS-RADIUS RELATION

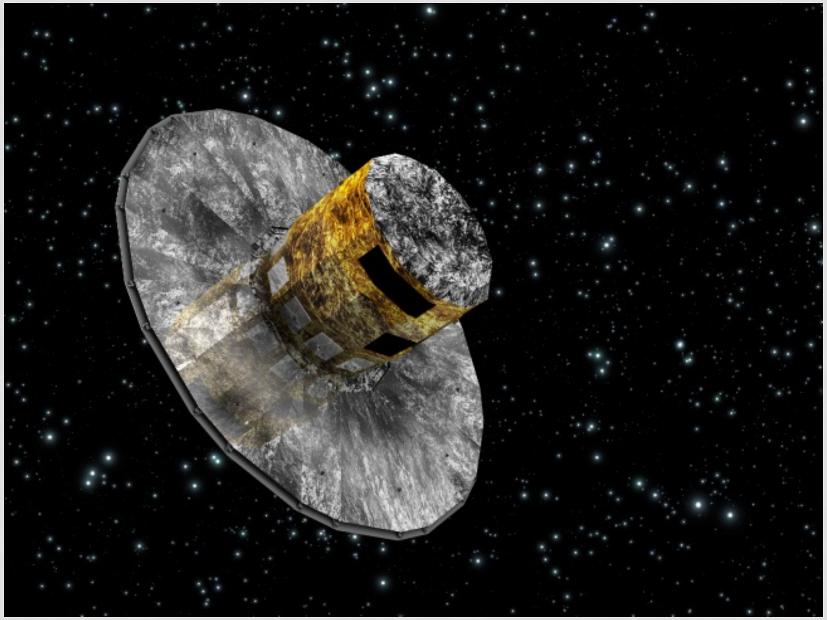
- Estimates planet mass without RV
  - Or radius without transits
- Allows planet-mass-based constraints on other parameters
  - E.g., Hill Sphere
- Realistic estimates for feasibility of follow-up efforts
  - Is RV signal detectable?



Chen & Kipping, 2017

PRIORS

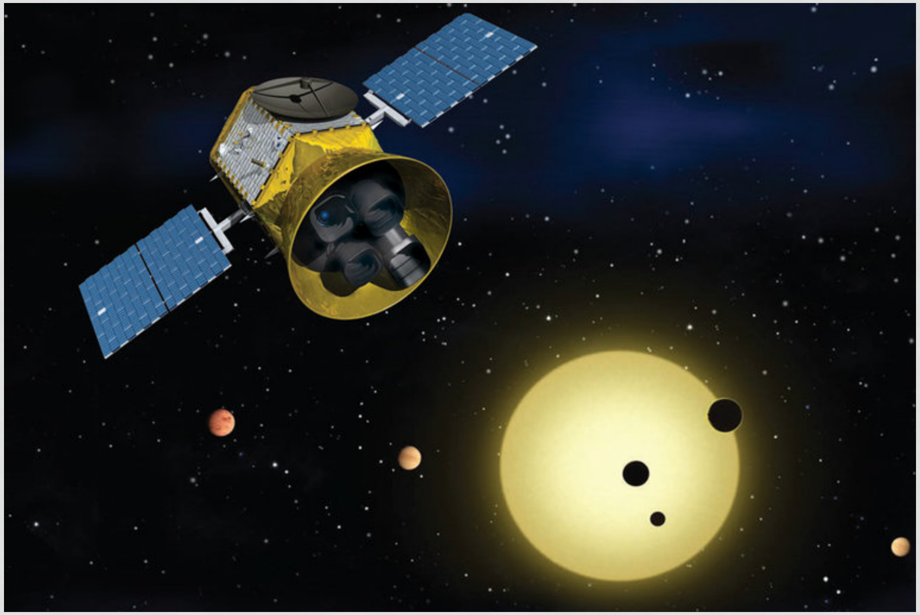
- Easily impose priors on any fitted **or derived** parameter
- Gaia parallax
  - Available for virtually *all TESS targets*
  - Powerful constraint on L_*
    - And therefore R_* and R_P
- M_*, R_*
  - From alternative stellar models
- Literature values



Gaia Spacecraft
Source: http://www.esa.int

EXOFASTv2 + TESS

- Homogeneous characterization
  - RV feasibility
  - Single Transit characterization
- Detailed characterization
  - Model with follow up data
- Enables sophisticated, uniform, global analysis by the community



PUBLICATIONS WITH EXOFASTV2

- **Kepler-503b: An Object at the Hydrogen Burning Mass Limit Orbiting a Subgiant Star, Cañas, et al., 2018**
- A Compact Multi-Planet System With A Significantly Misaligned Ultra Short Period Planet, Rodriguez et al., 2018
- Two warm, low-density sub-Jovian planets orbiting bright stars in k2 campaigns 13 and 14, Yu et al., 2018
- A System of Three Super Earths Transiting the Late K-Dwarf GJ9827 at 30 pc, Rodriguez et al., 2018
- **Qatar Exoplanet Survey: Qatar-6b – A Grazing Hot Jupiter, Alsubai et al., 2018**
- A Multi-Planet System Transiting the V=9 Rapidly Rotating F-Star HD106315, Rodriguez et al., 2017
- Several others in prep

HANDS-ON EXERCISES

1. RVs from Multiple Telescopes
2. Transits in Multiple Photometric Bands
3. The Effect of Maximum Steps on the MCMC Fit
4. Long-cadence Transit Data
5. The Effect of the Starting Values on the Fit
6. Stellar Fits Using Different Stellar Models

BONUS EXERCISES

- Fit an Spectral Energy Distribution with Gaia DR2
- Impact of using different data sets
- Fit multi-planet systems

https://tinyurl.com/y7mhpm6g

EXOFASTv2

EASTMAN ET AL., 2017

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