Physical Models for Exoplanet Time-Series Observations

JWST Transiting Exoplanet ERS Bootcamp

June 24, 2021

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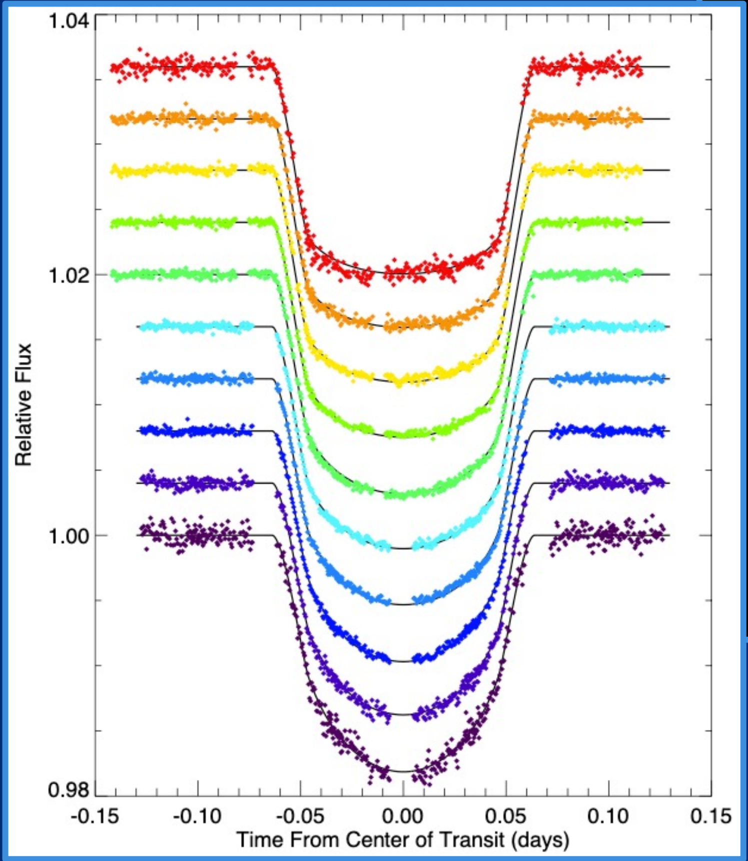
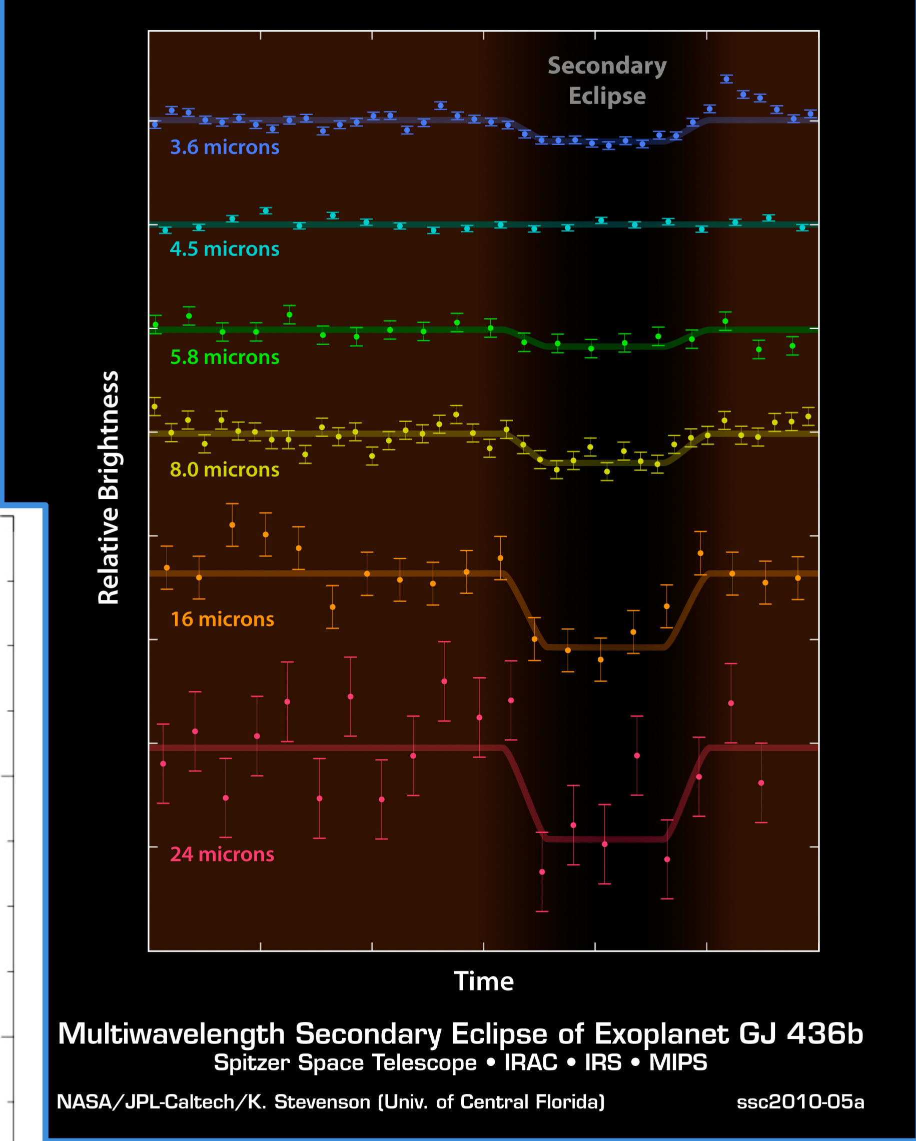
Common Types of Models

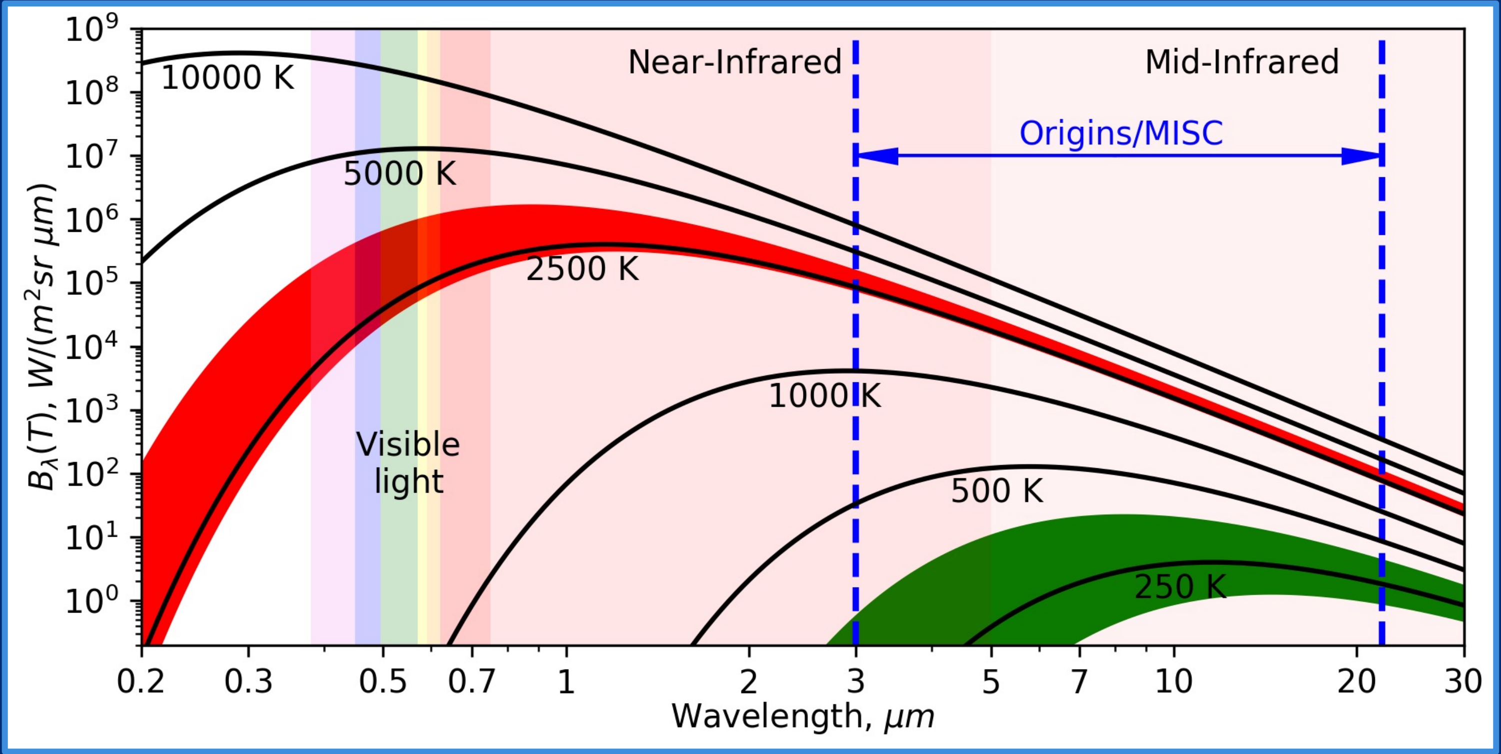
- Planet Emission
  - Dayside Eclipse
  - Phase-Resolved Emission
  - Eclipse Mapping
- Planet Transmission
  - Transit
  - Stellar Limb Darkening
- Other Astrophysical
  - Everything not including the planet's atmosphere



Knutson+ (2007)



Optimal Wavelengths



Transit spectroscopy is more favorable in optical and near-IR (near host star's peak emission)

Eclipse spectroscopy is more favorable in near-to-mid IR (near planet's peak emission)

Eclipse Models

- Definitions
  - Spectral intensity or "Flux" (F)
  - Planet radius (R_p)
  - Stellar radius (R_s)
  - Spectral radiance or "Brightness" (B)

Transit depth at photospheric base (or surface)

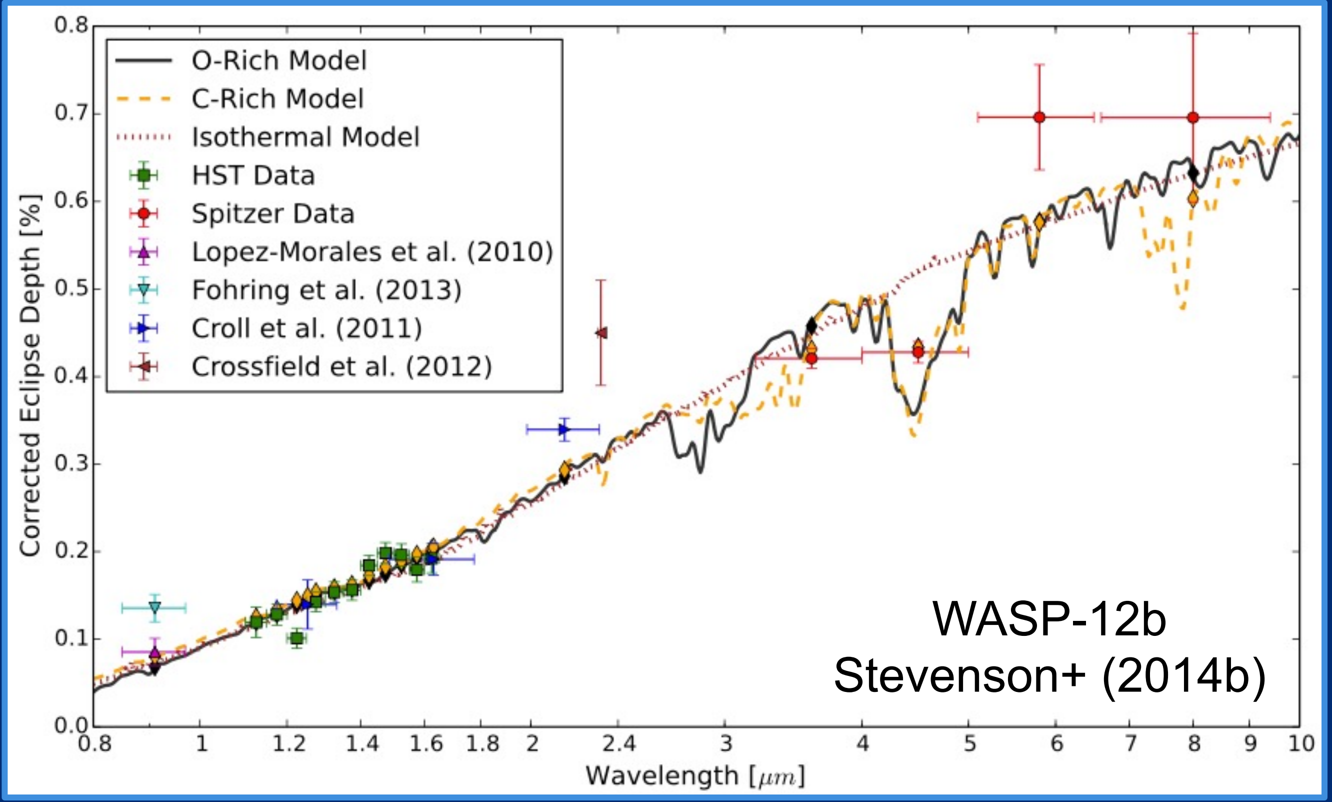
$$\boxed{D_{ecl}(\lambda) = \frac{F_{out} - F_{in}}{F_{out}} = \frac{R_p^2}{R_s^2} \times \frac{B_p(\lambda)}{B_s(\lambda)}}$$

Wavelength dependent brightness ratio

- Mandel & Agol (2002)
  - Mandatory reading for observers
  - Eclipse → No limb darkening
  - Uniform source case × brightness ratio

- BATMAN Python Package
  - Kreidberg (2015)
  - https://github.com/lkreidberg/batman
  - pip/conda install batman-package

- What about eclipse mapping?
  - De Wit et al. (2012)
  - Majeau et al. (2012)



Transit Models

F_{out}

F_{in}

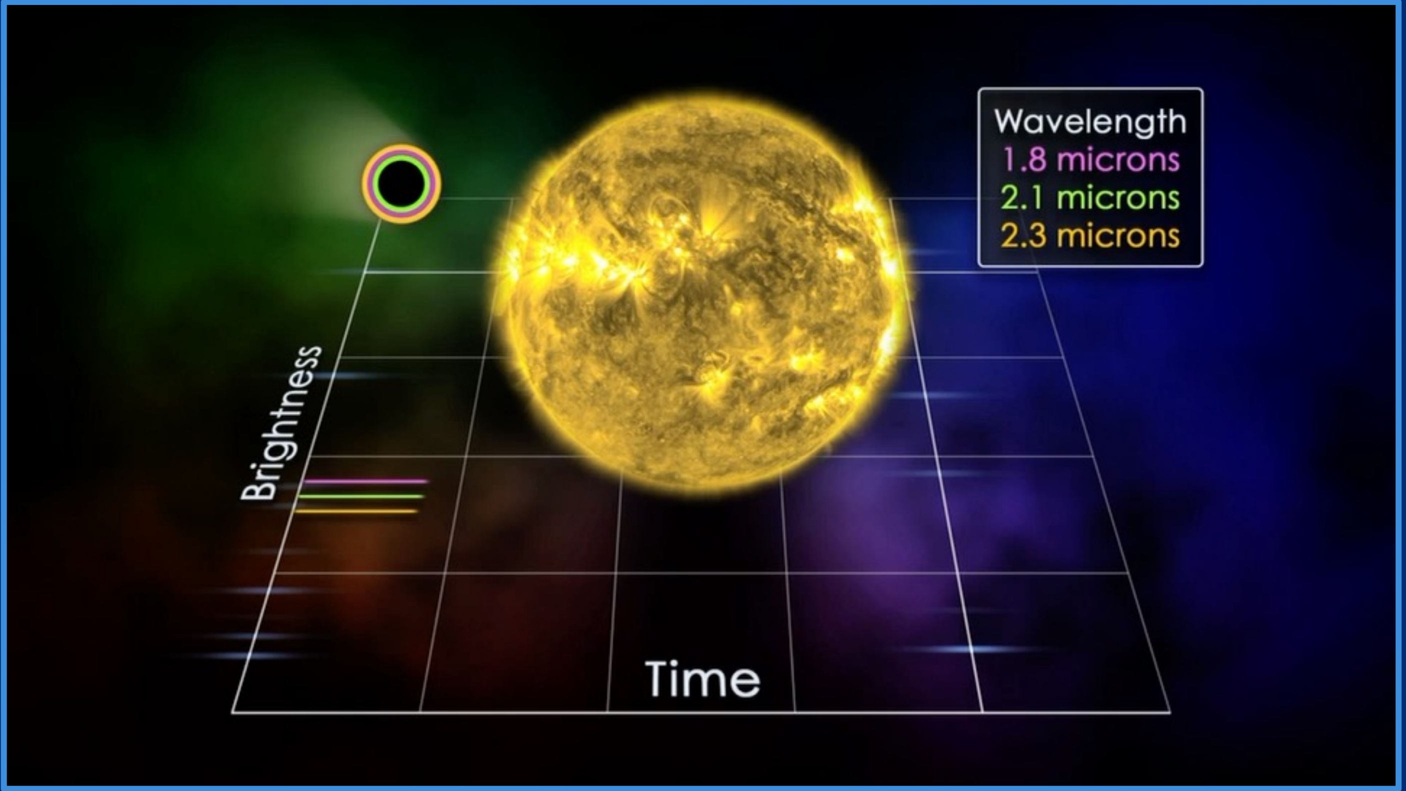
Transit depth at photospheric base (or surface)

Ignore this term since $H \ll R_p$

$$D_{tr}(\lambda) = \frac{F_{out}-F_{in}}{F_{out}} = \frac{R_p^2}{R_s^2} + \frac{2A_\lambda H R_p}{R_s^2} + \cancel{\frac{(A_\lambda H)^2}{R_s^2}}$$

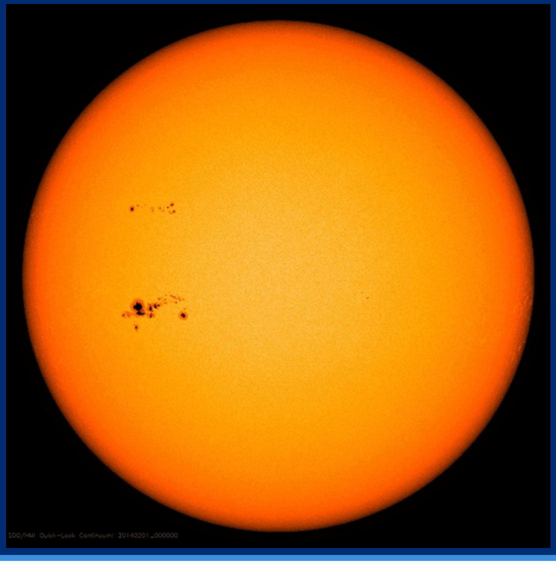
Wavelength dependent change in opacity (or apparent planet size)

- Definitions
  - Planet radius (R_p)
  - Stellar radius (R_s)
  - Scale height ($H = k_B T_{eq}/\mu_m g_p$)
  - # of scale heights (A_λ)
- Mandel & Agol (2002)
  - Non-linear & quadratic limb darkening
  - Small planet approximation
    - Erratum: Eq 8 is missing a π
- ExoTiC-ISM Python Package
  - Laginja & Wakeford (2020)
  - https://github.com/hrwakeford/ExoTiC-ISM
- Important considerations
  - Limb darkening
  - Nightside planet flux



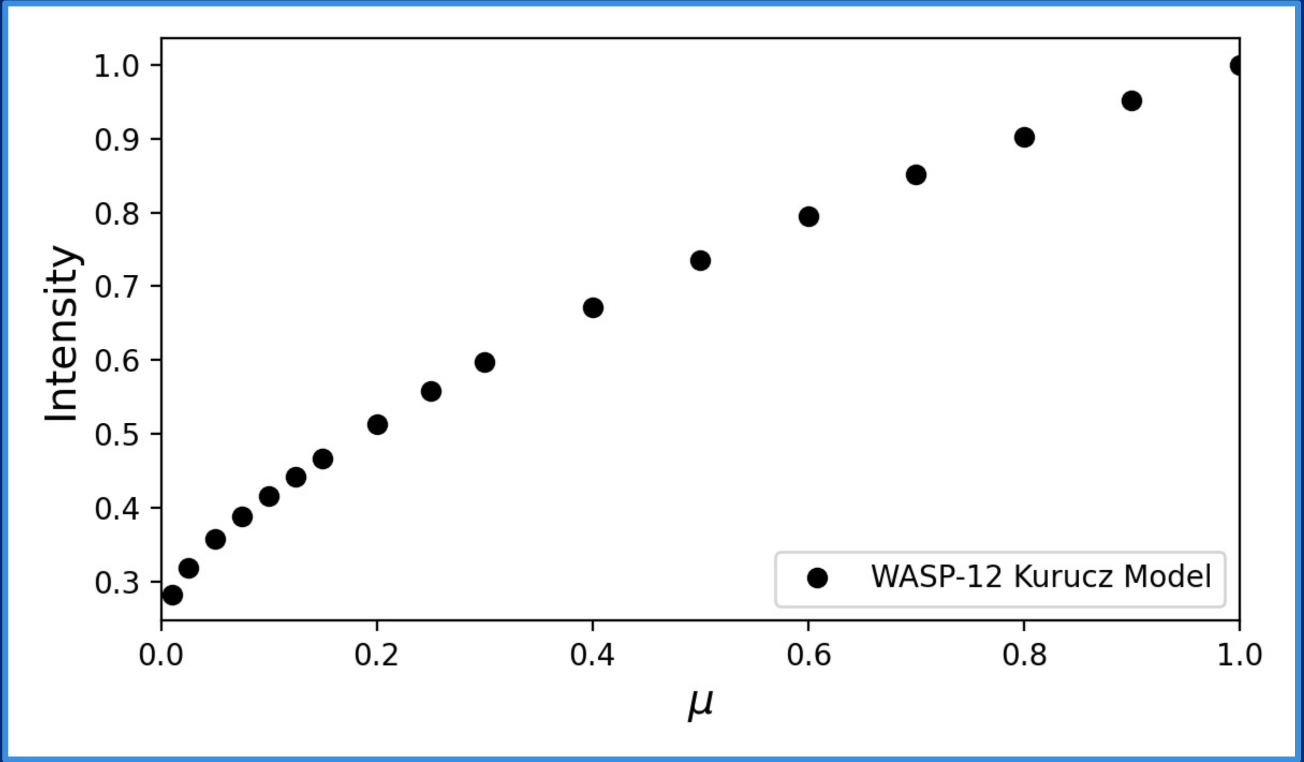
Limb Darkening (LD) Models

- Kurucz and Phoenix LD models
  - 1D or 3D
  - T_{eff}, log(g), Fe/H → model(I,μ)



Star limb

Star center



Limb Darkening (LD) Models

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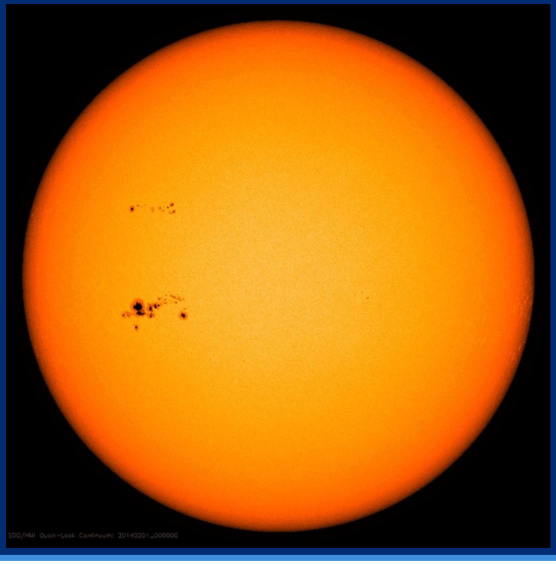
- Most popular models
  - Linear; $I = 1 - c_1[1 - \mu]$
  - Quadratic; $I = 1 - c_1[1 - \mu]$ - $c_2[1 - \mu]^2$
  - 4-parameter non-linear; $I = 1 - \sum_{k=1}^{4} c_k\left[1 - \mu^{k/2}\right]$
    - Claret (2000)
  - c_1, c_2, c_3, c_4 = LDC = limb darkening coefficients

- Alternatives to using quadratic models
  - Logarithmic, square-root, 3-parameter
  - Often provides better fit
  - Depends on host star type & LC precision
  - Espinoza & Jordán (2016)



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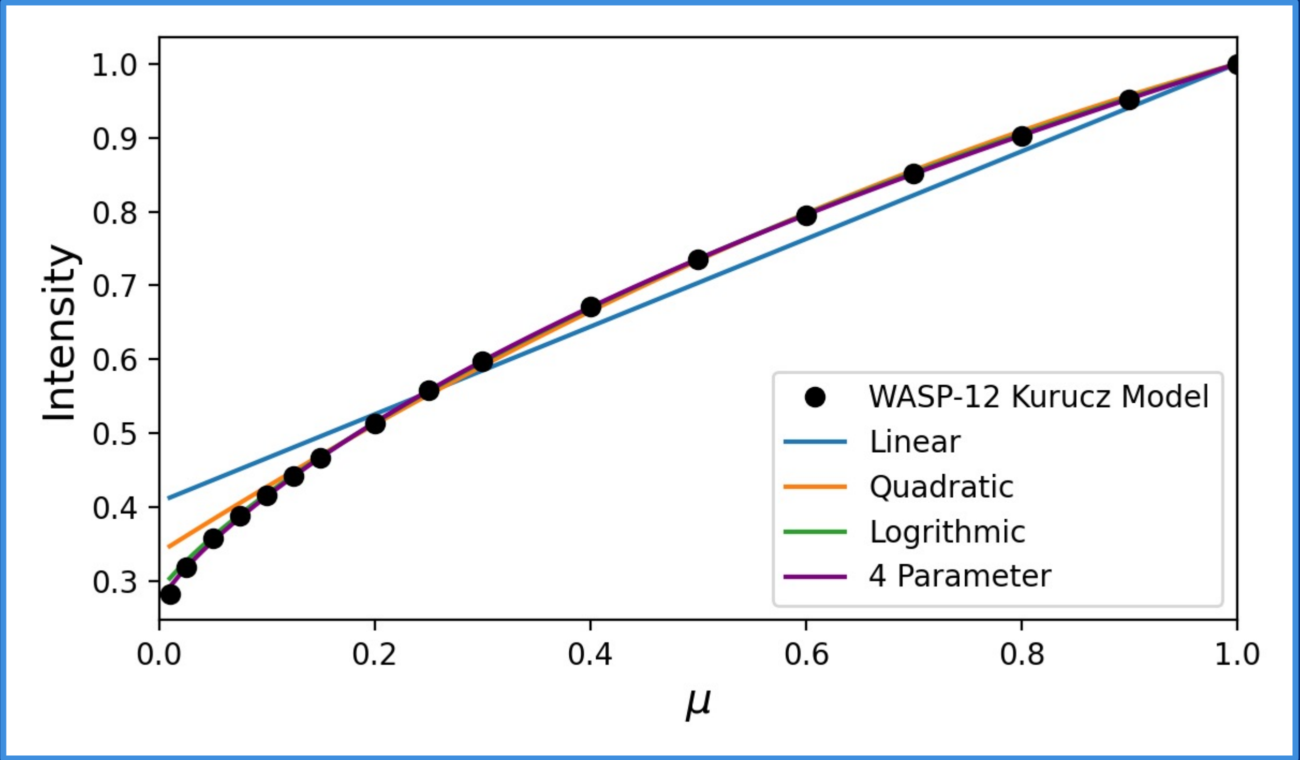

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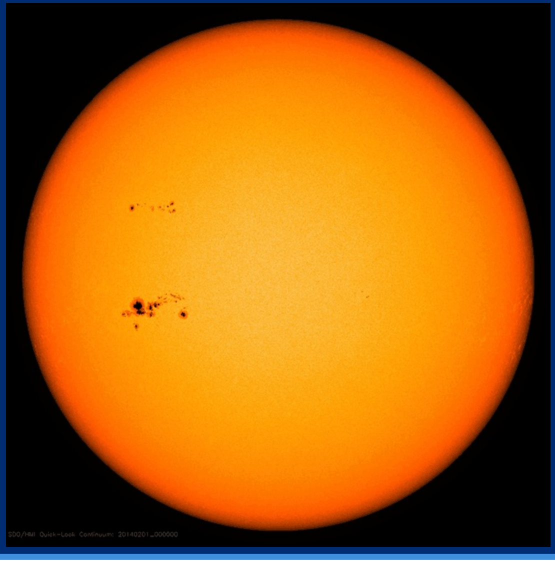

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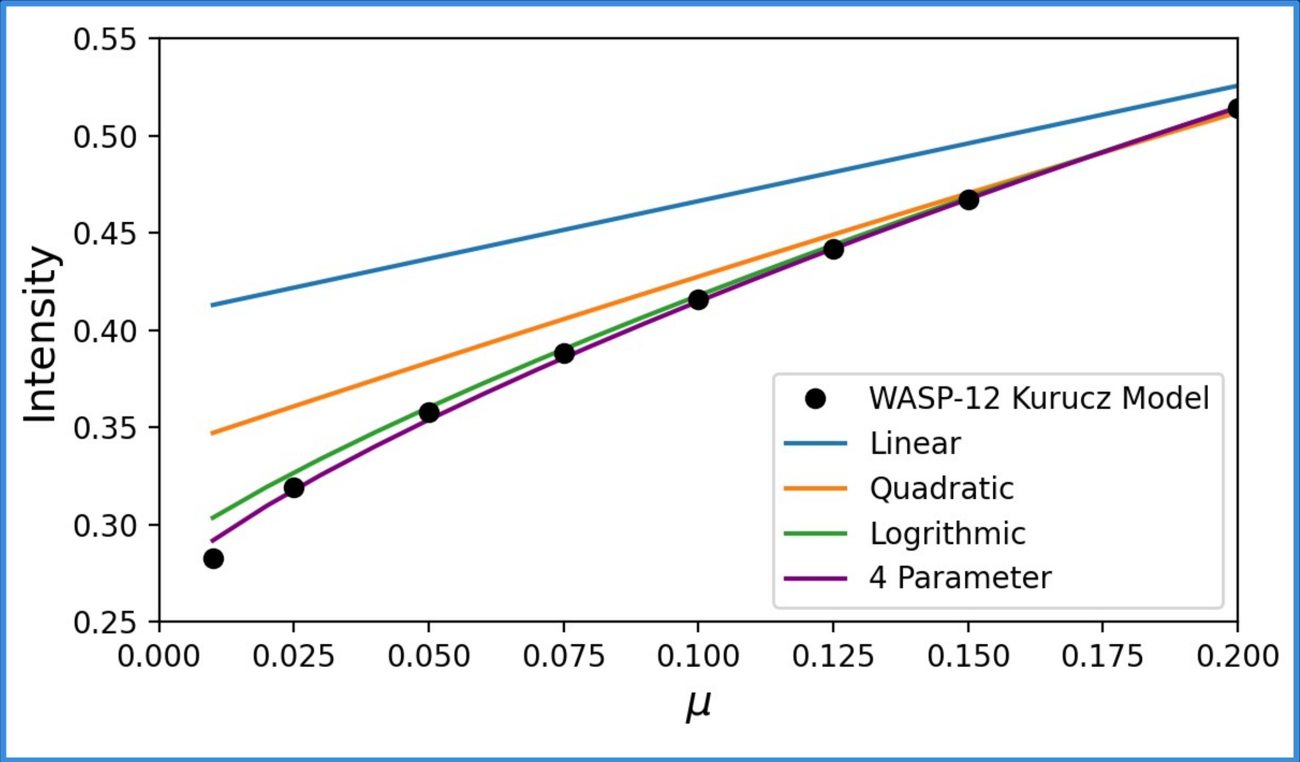


Fixed vs. Fitted LD Coefficients

Fixed LDCs

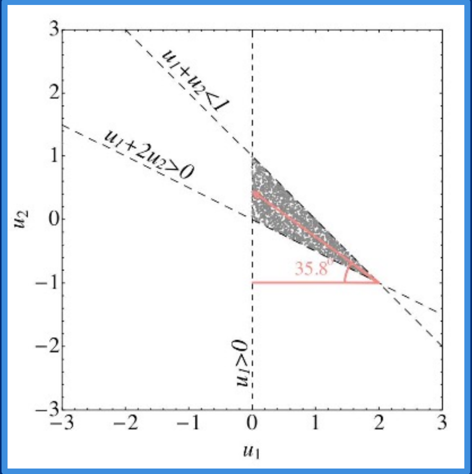
- ExoCTK Limb Darkening Calculator
  - https://exoctk.stsci.edu/limb_darkening
  - Inputs: target name, model grid, pre-defined bandpass, # of spectroscopic channels
- Nestor Espinoza's "`limb-darkening`"
  - https://github.com/nespinoza/limb-darkening
  - Inputs: stellar parameters, model grid, response function
- Hannah Wakeford's "`ExoTiC-ISM`"
  - Uses 1D and 3D stellar models

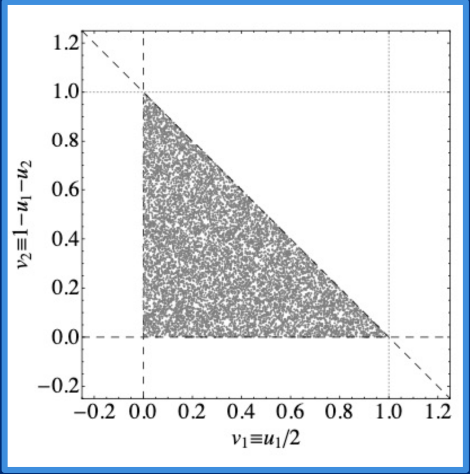
Exoplanet Characterization Toolkit

ExoCTK

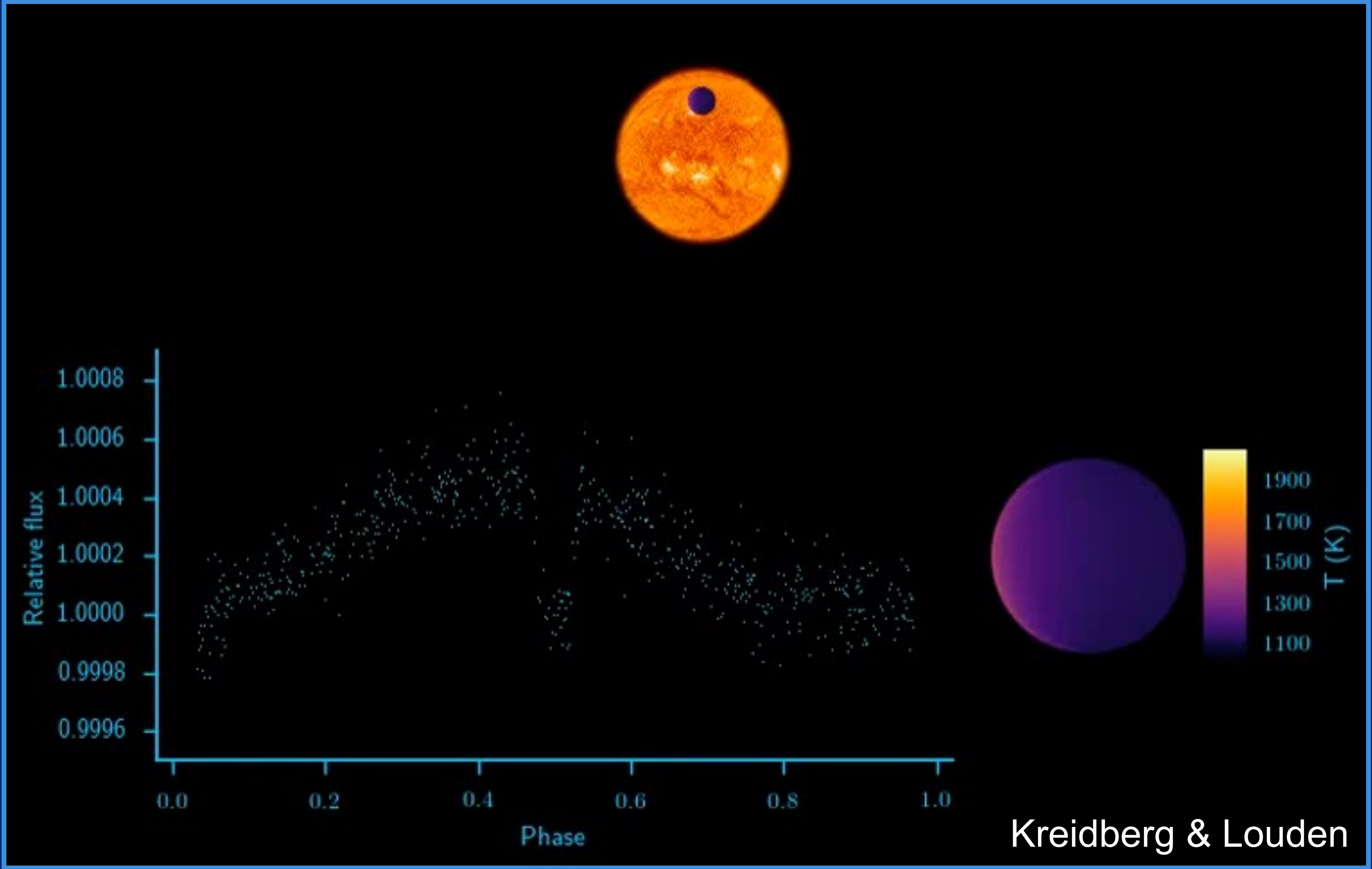
Fitted LDCs

- Use "triangular sampling" for efficient, uninformative sampling of 2-parameter laws (Kipping, 2013)
  - Re-parameterizing models to only explore physically plausible regions of parameter space



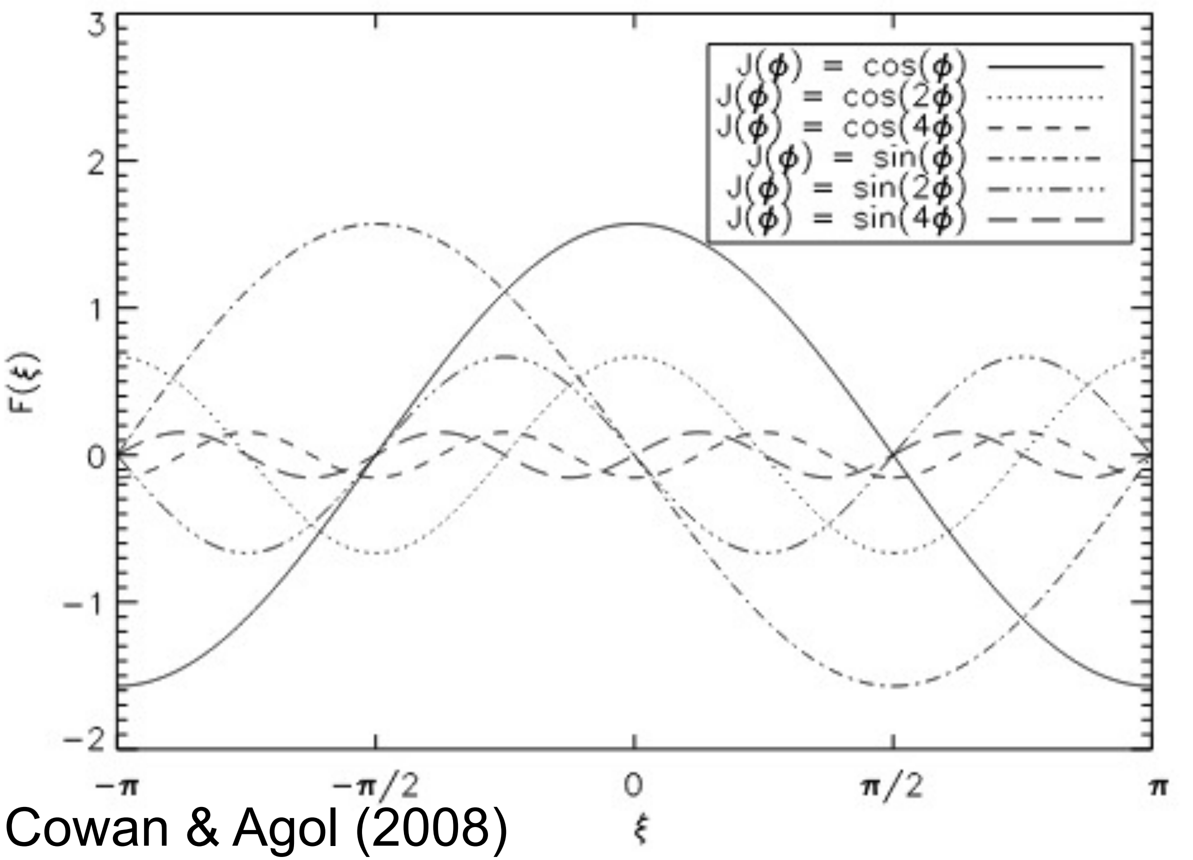


Phase Curve Models



Phase Curve Models

- Sinusoidal (superposition of sin/cos)
  - Popular, easy to use
  - Symmetric and asymmetric components
  - Can yield unphysical results



Cowan & Agol (2008)

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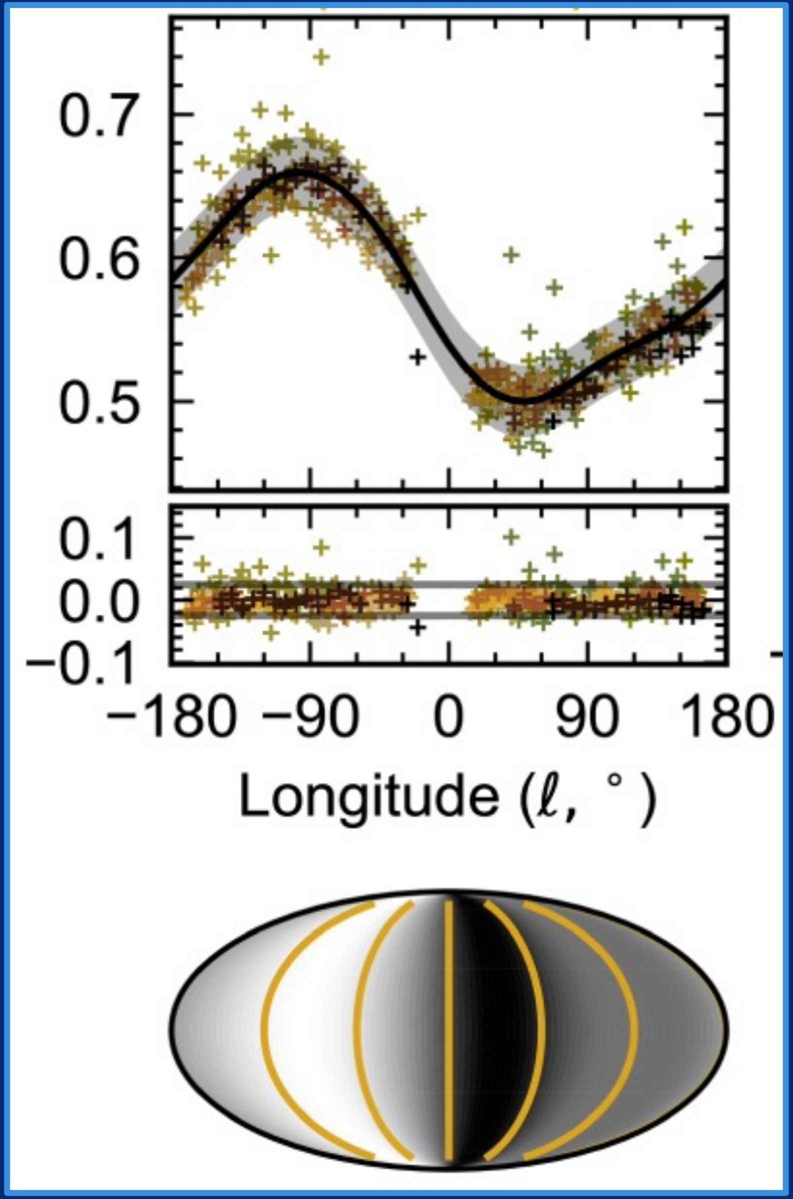
  - Model in unphysical

Mayorga et al. (2020)



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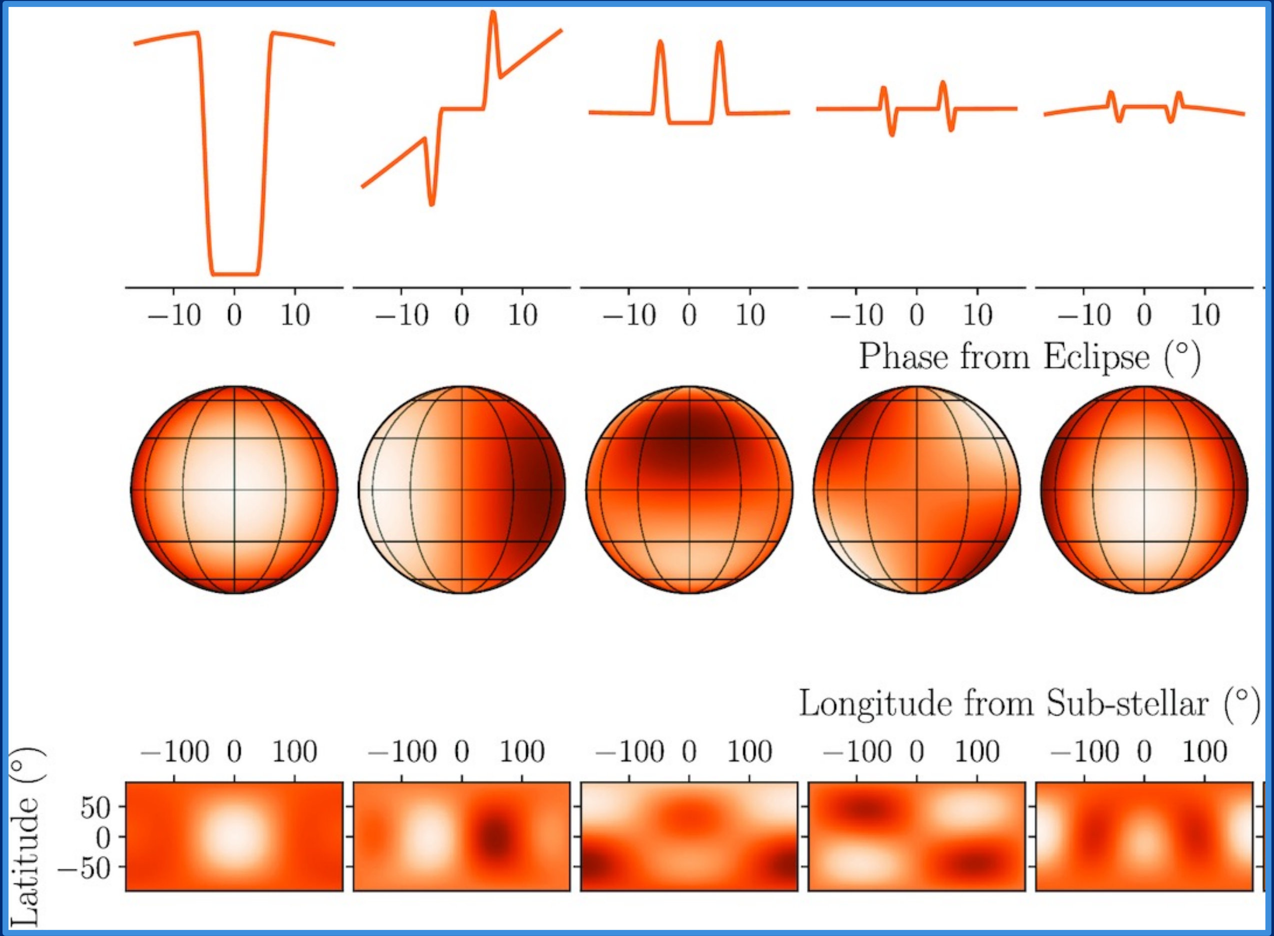
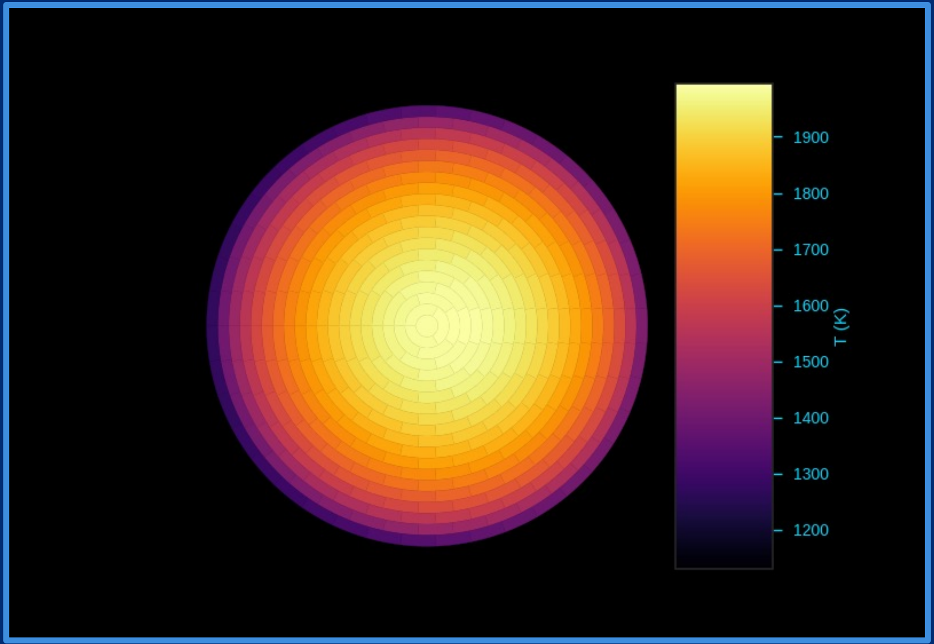
- Spherical harmonics (Rauscher, 2018)
  - Eigencurves have fewer parameter degeneracies
  - Number of eigencurves can be tuned to match complexity/quality of the data
  - Useful for eclipse mapping

Mansfield et al. (2020)

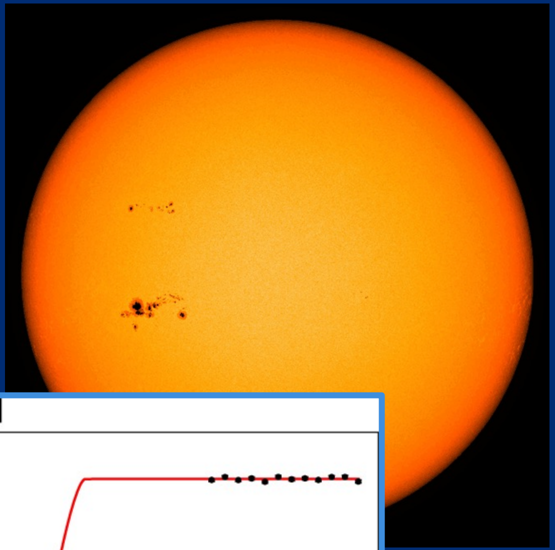


Phase Curve Models

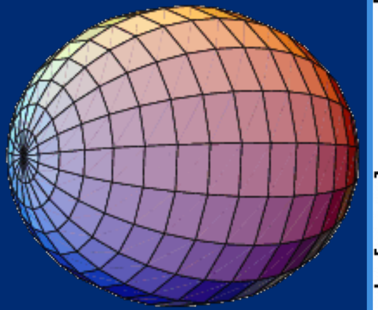
- First principles (Zhang & Showman, 2017)
  - Physically motivated using day-night temperature difference and horizontal wind speed
- Planets on eccentric orbits are even more complex
  - Lewis et al. (2010, 2013); Cowan & Agol (2011)
- Python Packages
  - SPIDERMAN
    - https://github.com/tomlouden/SPIDERMAN
  - STARRY
    - https://github.com/rodluger/starry

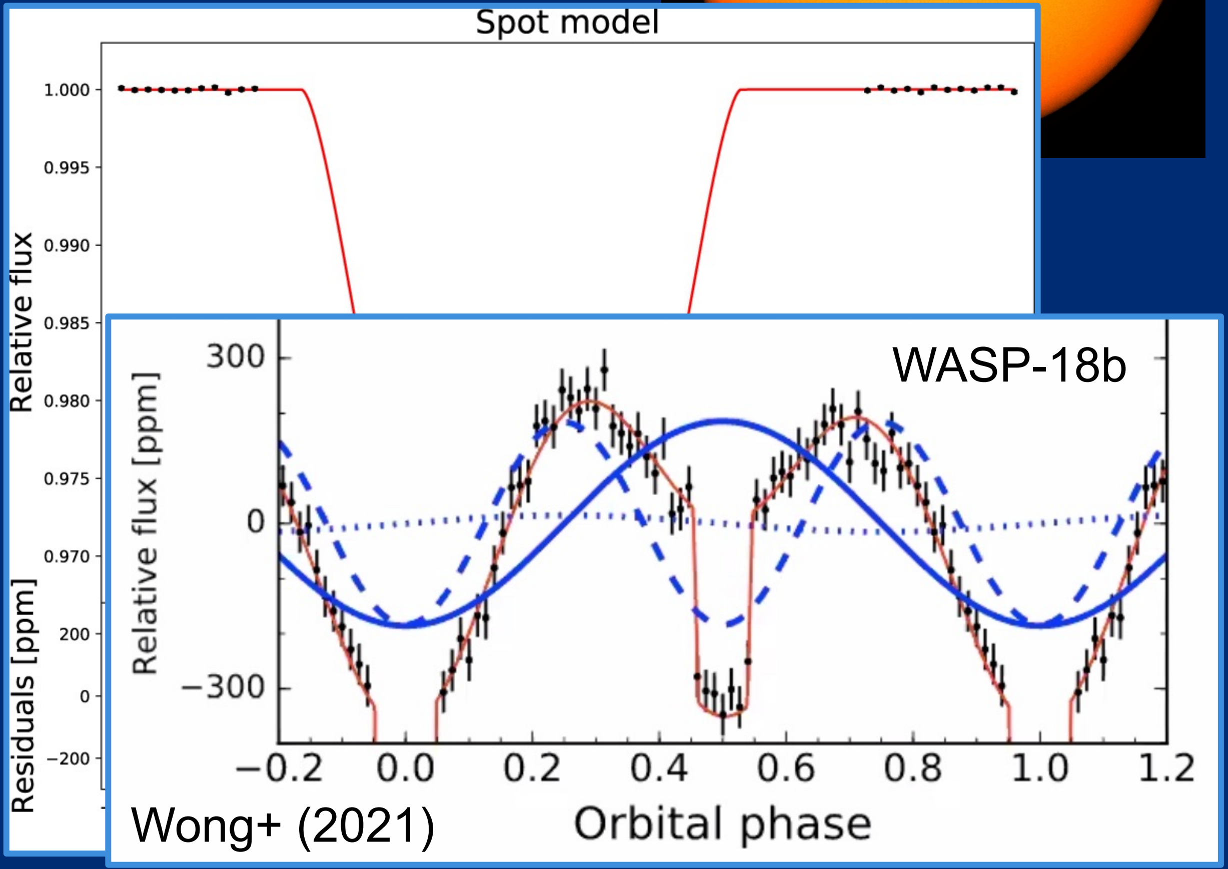


Other Astrophysical Models



- Stellar flux isn't always constant in time or across its surface
- Stellar rotation
  - Slowly varying
  - Linear or quadratic function in time
- Stellar Spots/Faculae Crossing
  - Can cause bump/dip in light curve during transit
  - Need to use spot models
- Ellipsoidal Distortion
  - Dashed blue curve
  - Star/planet is prolate spheroid
- Doppler Boosting
  - Dotted blue curve
  - Small, relativistic effect





Helpful Advice

- **Binning is sinning** (e.g., May & Stevenson, 2020)
  - Don't bin your data along the time axis to speed up your uncertainty estimation
  - **Recommend fitting the unbinned data plotting the binned data**
- **Timing is everything** (e.g., Eastman+, 2010)
  - JWST FITS files provide 6 time columns within hdulist['INT_TIMES',1].data()
  - MJD_UTC start, mid, end of integration
  - BJD_TDB start, mid, end of integration
  - **Recommend using 'int_mid_BJD_TDB' keyword**
- **Exoplanets have a nightlife** (e.g., Kipping & Tinetti, 2010)
  - Nightside planet flux could pollute the measured transit depth
  - Contamination is larger for hotter planets and at longer wavelengths
  - Without proper correction, nightside flux could produce slope in measured transmission spectrum
  - **Recommend always estimating transit depth contamination due to nightside emission**
- For more high-level information, read review articles (e.g., Kreidberg, 2018; Sing, 2018; Deming+, 2019)

References

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