Thermal Phase Curves

(an empirical perspective)

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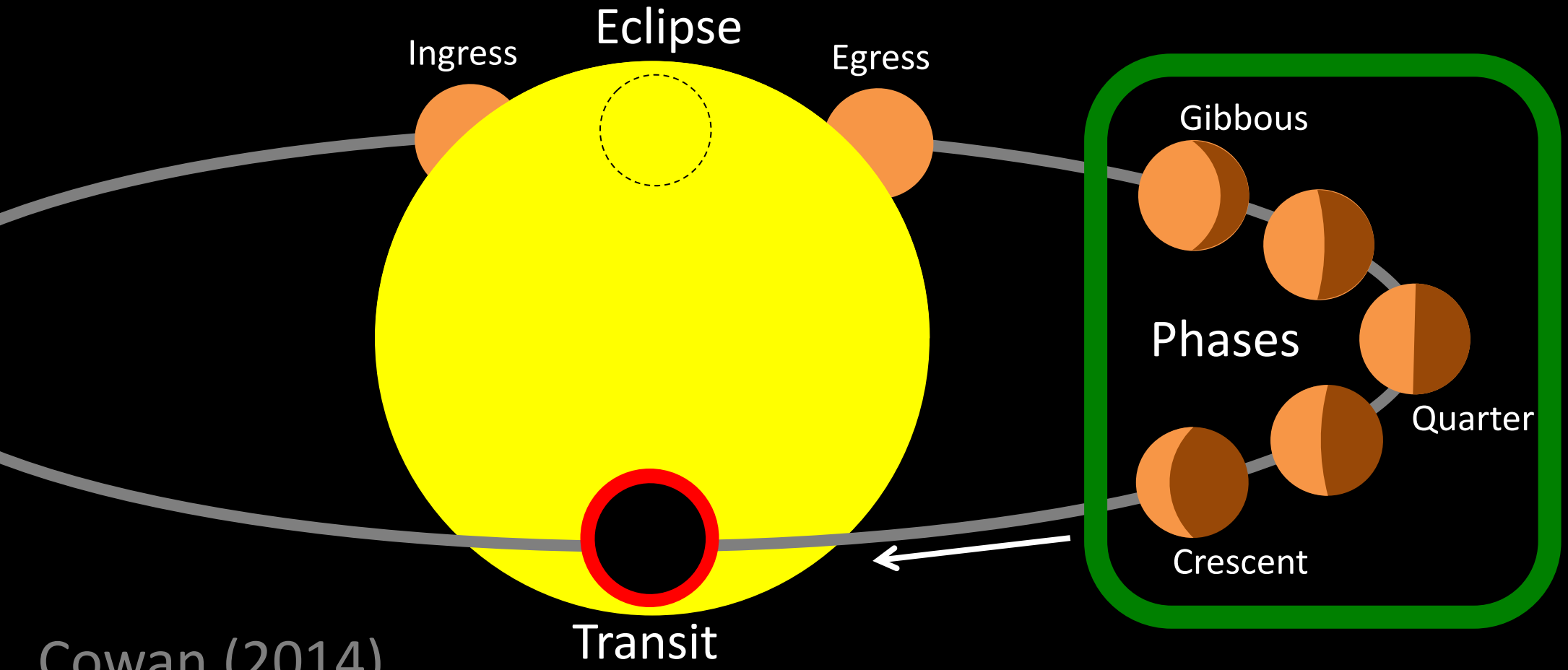
Outline

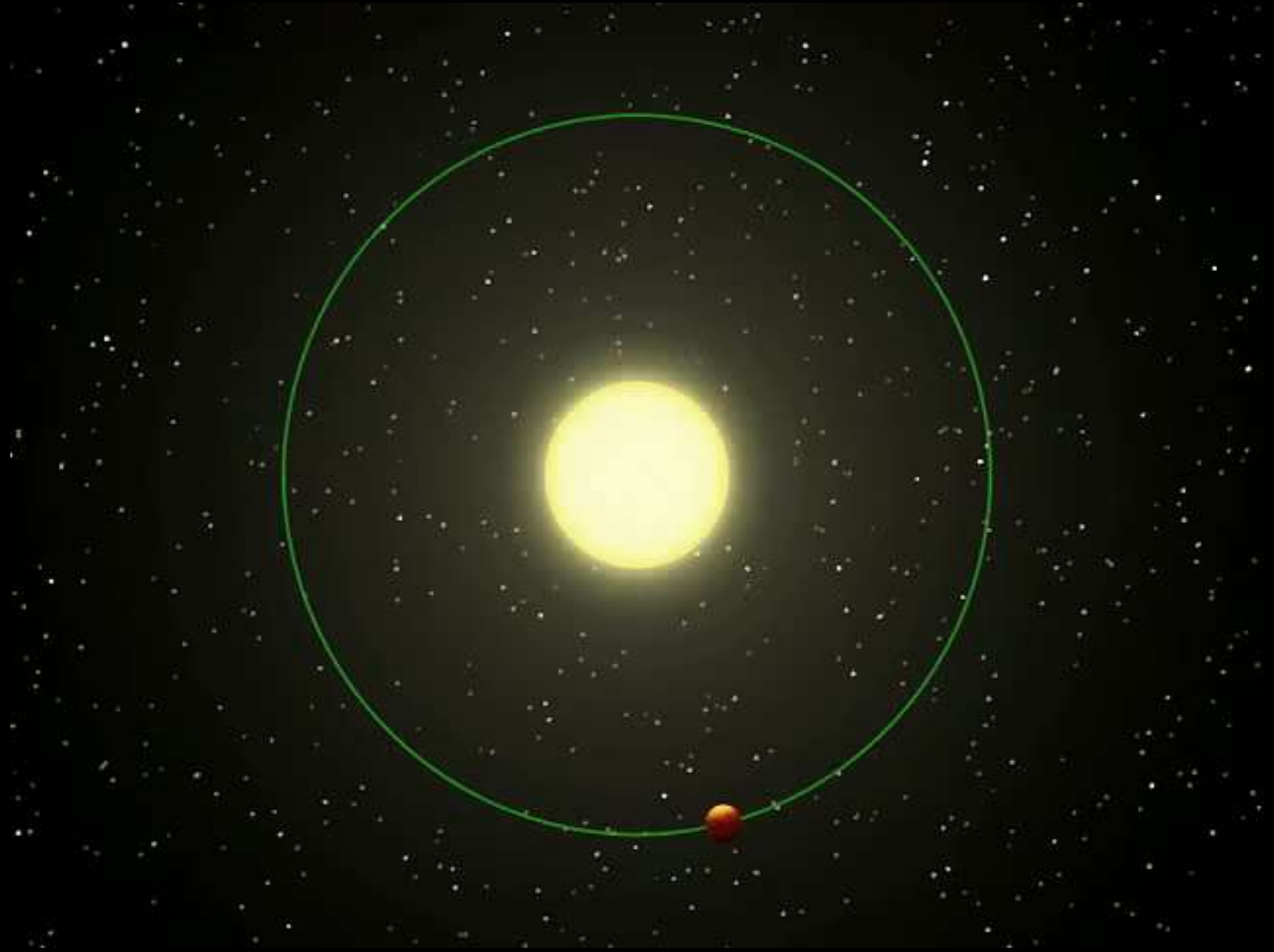
1. What are Thermal Phase Variations?
2. Interpreting Thermal Phase Curves
   - Phase Mapping
   - Spectroscopic Phase Curves
   - Flux to Effective Temperature
   - Global Energy Budget
   - Energy Balance Model

Phase Variations



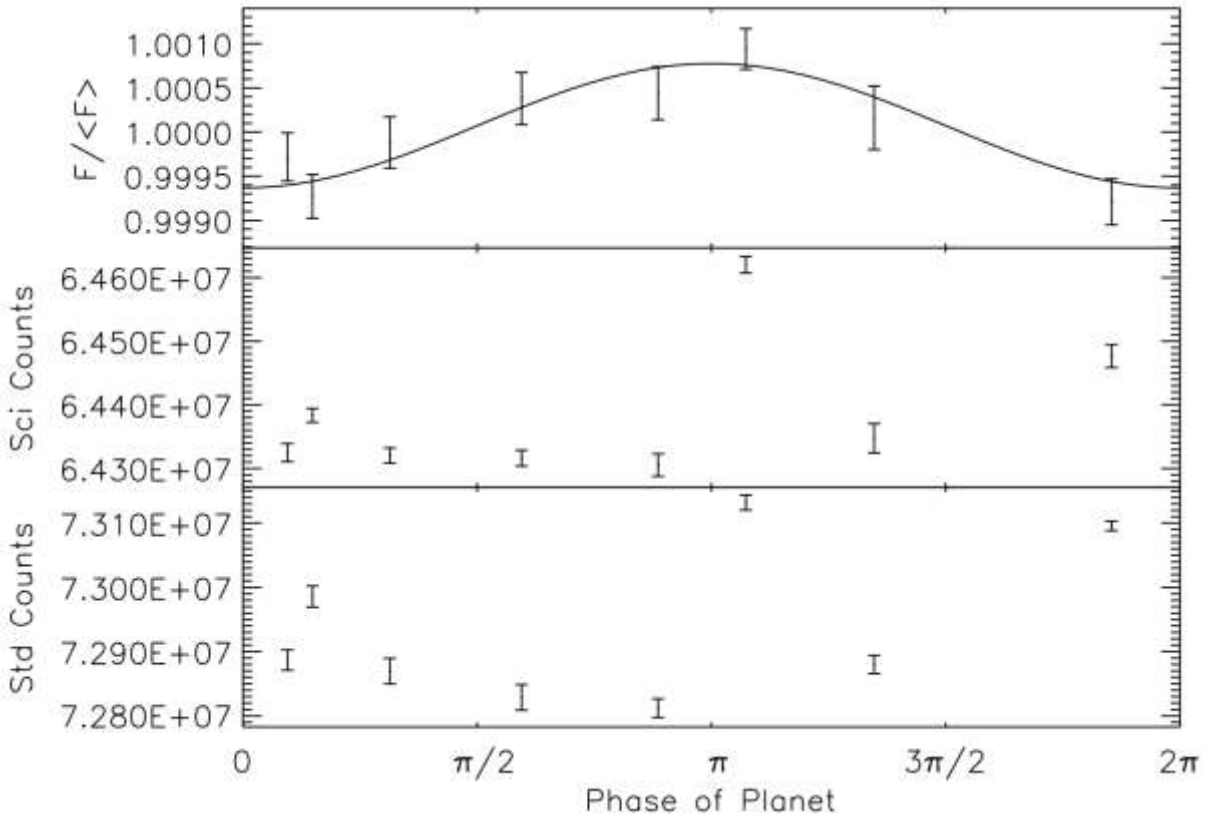
Cowan (2014)

Thermal Phase Variations

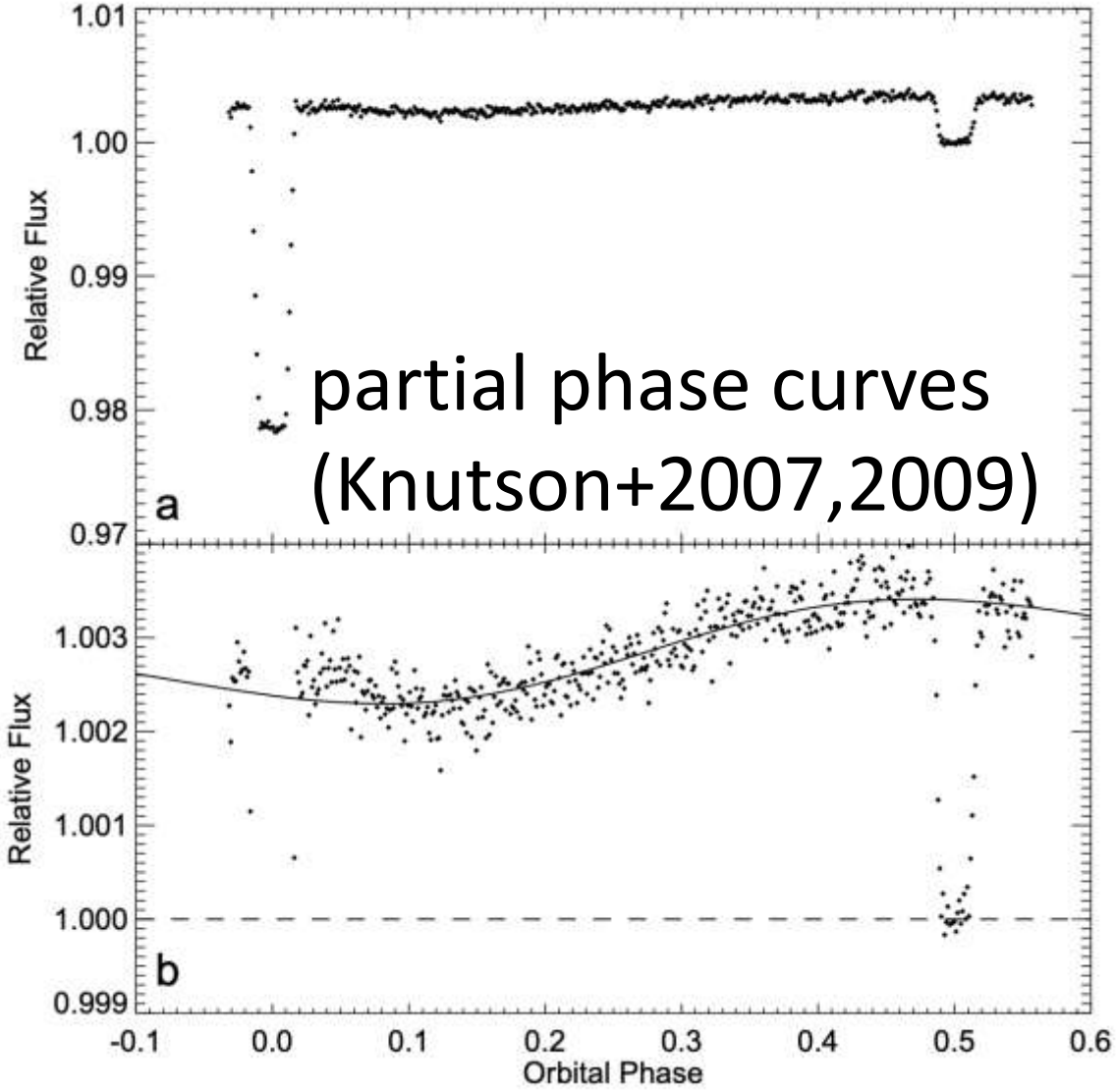


Harrington+(2006)

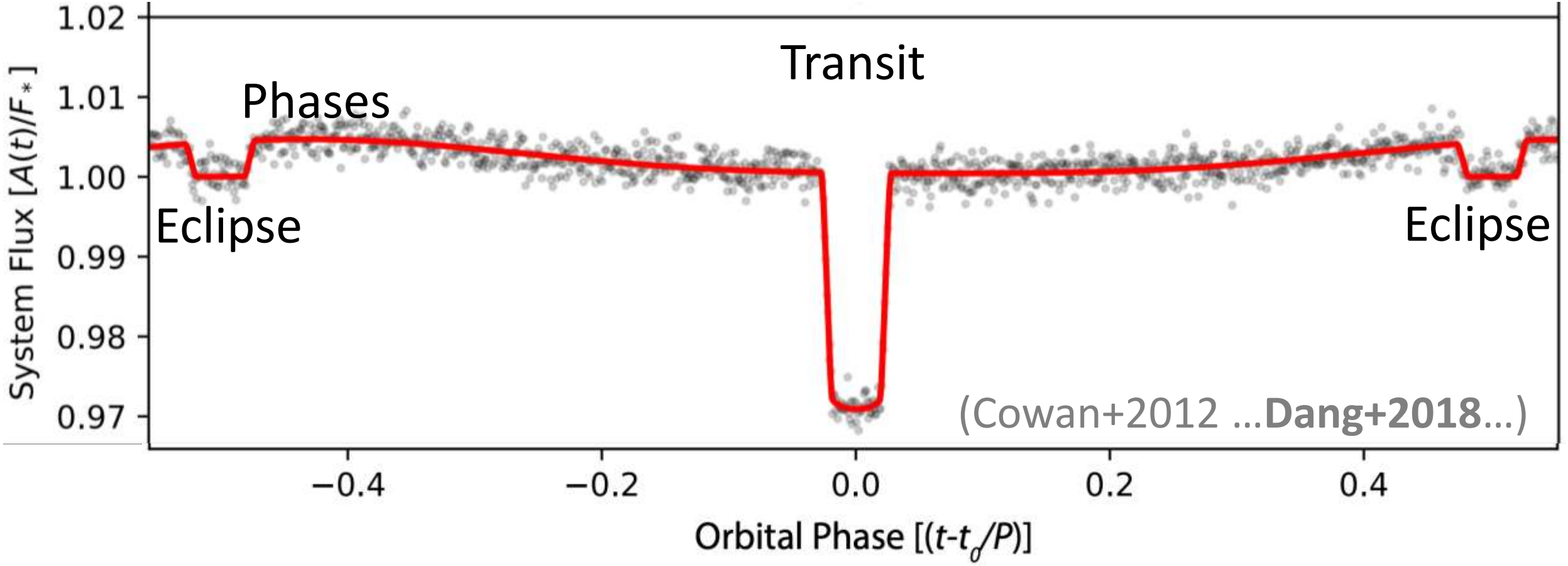
A Brief History of Exoplanet Phase Curves



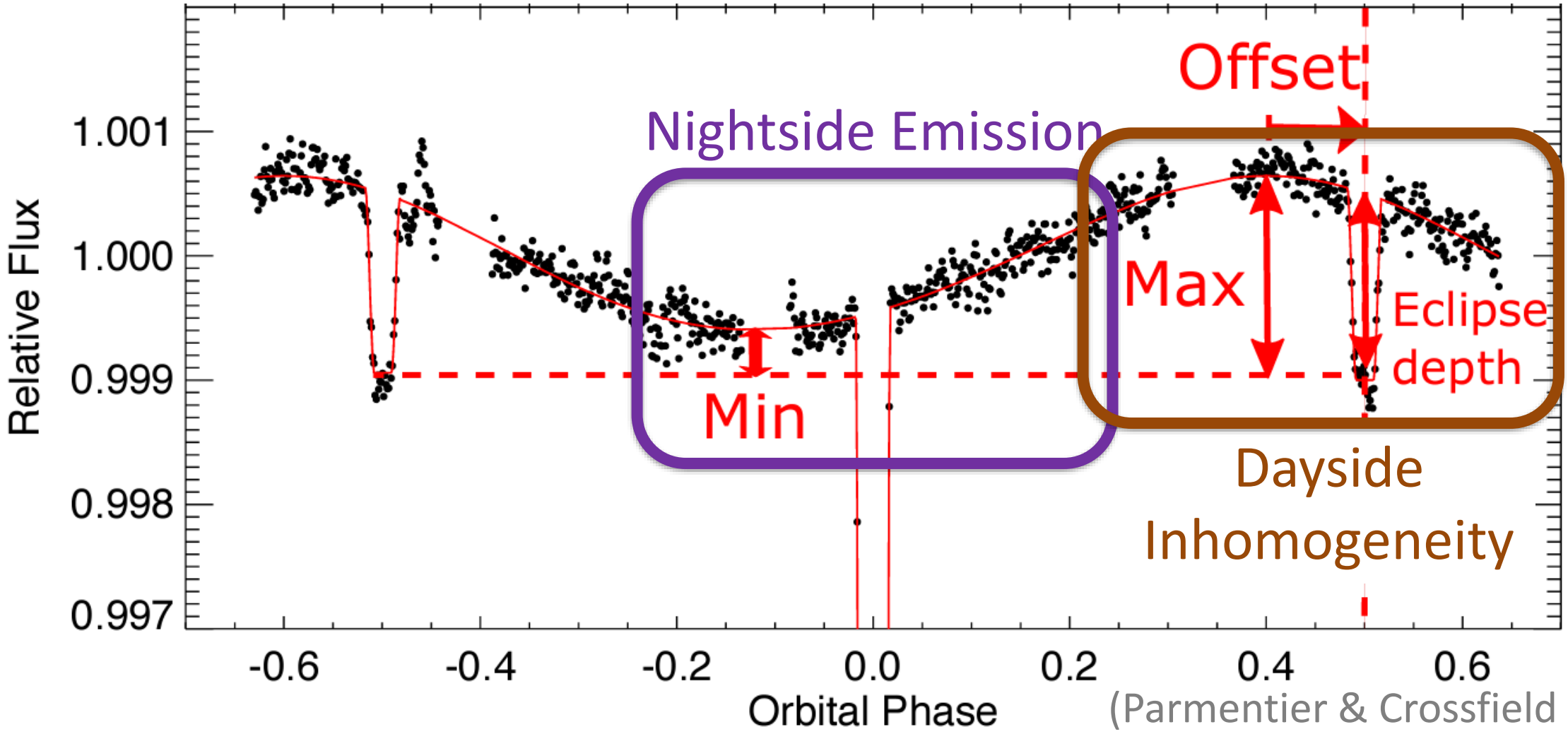
multi-epoch phase curves
(Harrington+2006; Cowan+2007)



Continuous, Full-Orbit Phase Curve



What do Phase Curves tell us?



(Parmentier & Crossfield 2018 from Knutson et al. 2012)

The Case for Phase Measurements

- **Short Period Exoplanets are not Spherical Cows**
  - Day-Night contrasts of 100's to 1000's of K
    (hence the phase variations)
  - Even Dayside is Inhomogeneous
    (hence the phase offset)

➢ Need nightside to properly understand global climate

(Cowan & Agol 2011b; Schwartz & Cowan 2015)

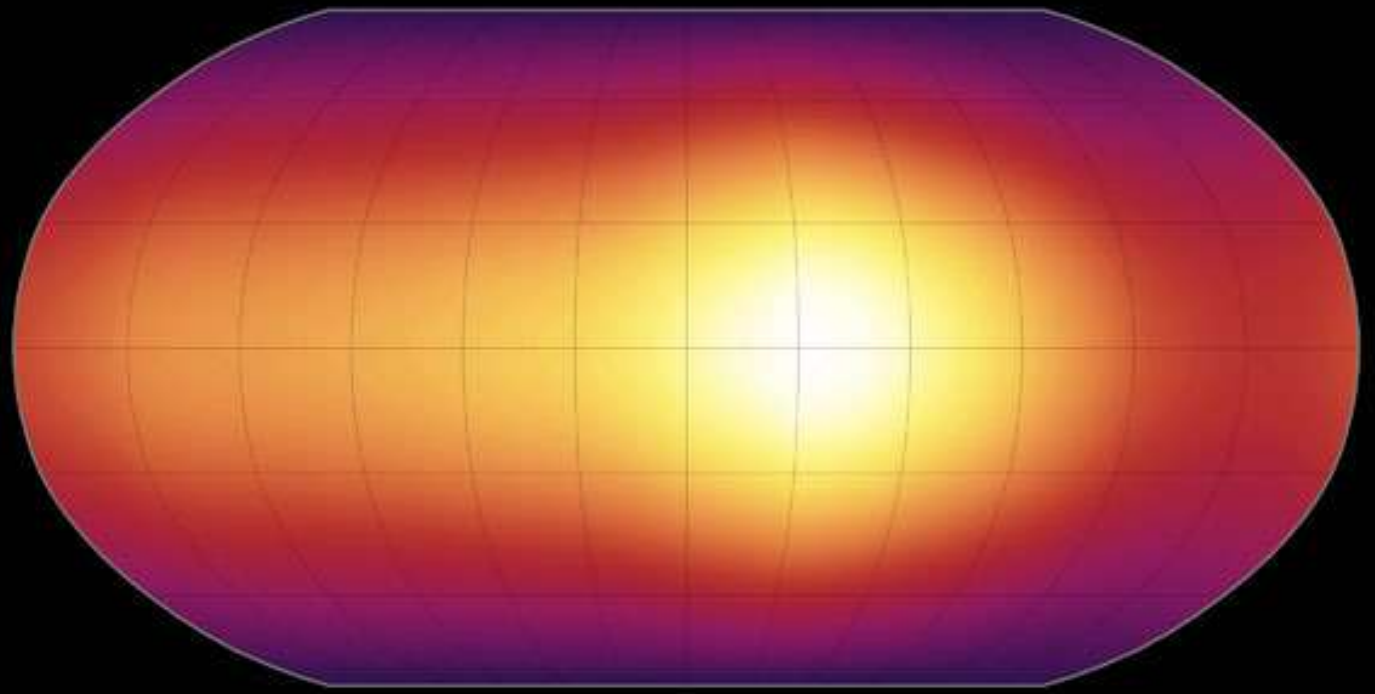
- Also true for non-transiting planets
- *Also applies to high-resolution spectroscopy*

Phase Mapping

(Cowan & Agol 2008; Cowan et al. 2013; **Cowan & Fujii 2018**)

Thermal Phase Mapping

HD 189733b



N-S Part of map is made up

Knutson + (2007)
Cowan & Agol (2008)
Cowan, Fuentes & Haggard (2013)

Exo-Cartography:
a classic inverse problem

Viewing Geometry

Lightcurve Kernel Map

$$F(t) = \oint K(\mathbb{G}, \theta, \phi, t) M(\theta, \phi) d\Omega$$

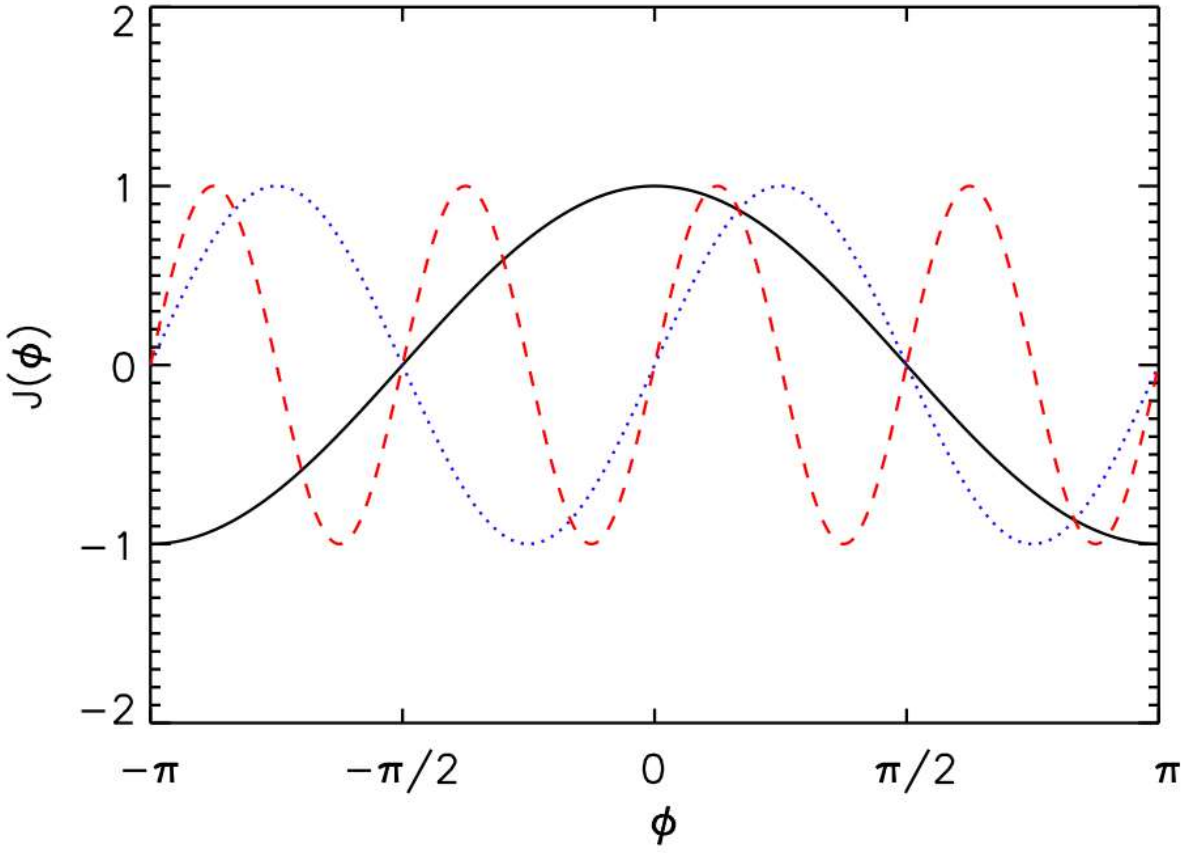
Fredholm Integral Equation of the First Kind

(Aster, Borchers & Thurber 2013)

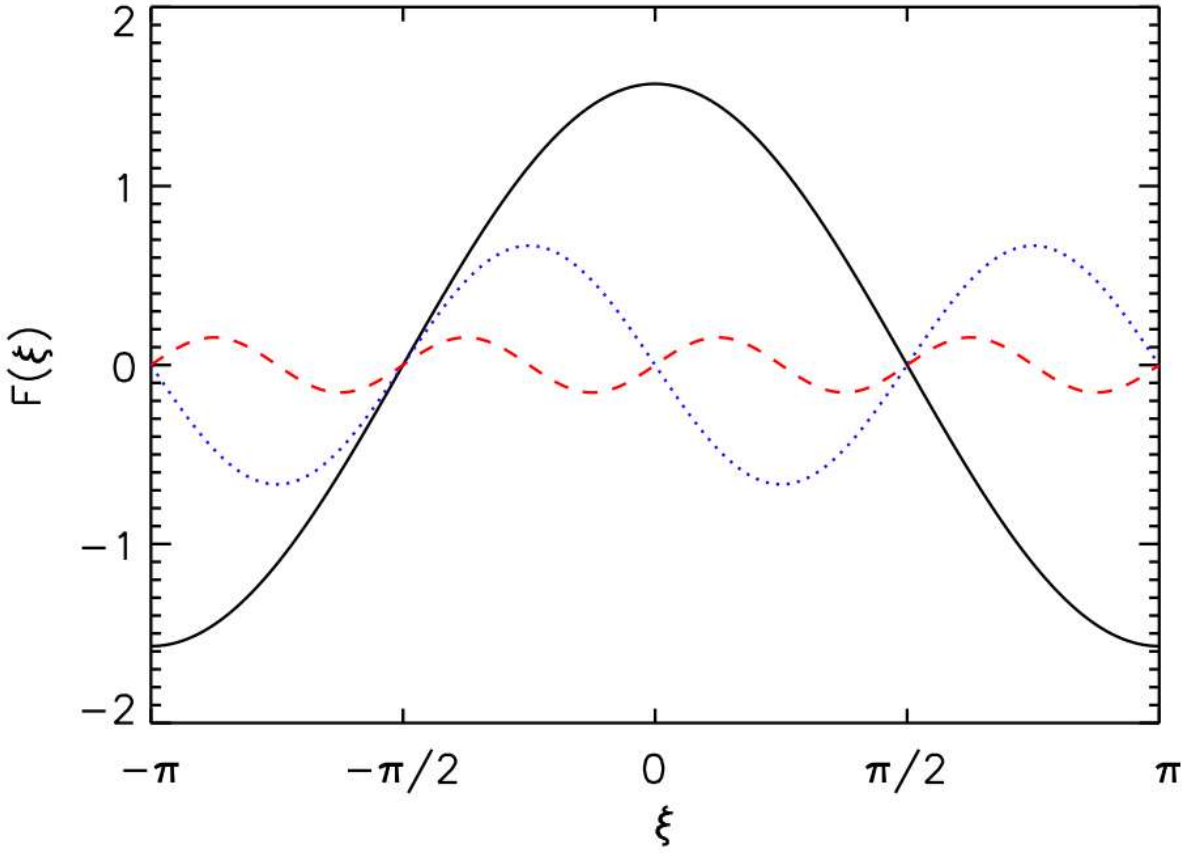
- Different Maps Can Produce Identical Lightcurves
- Some Maps Produce Flat Lightcurve (*Nullspace*)

Analytic Interlude:
Sinusoidal Mapping Nullspace

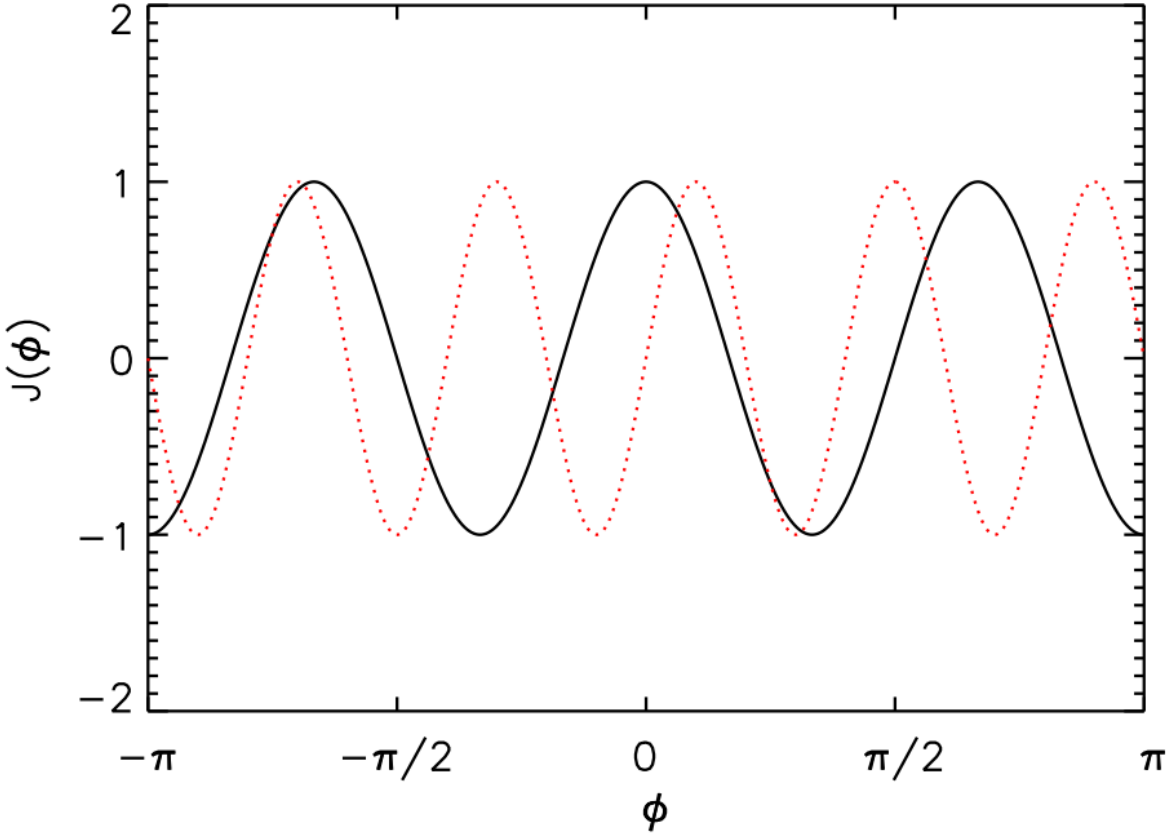
Sinusoidal Maps



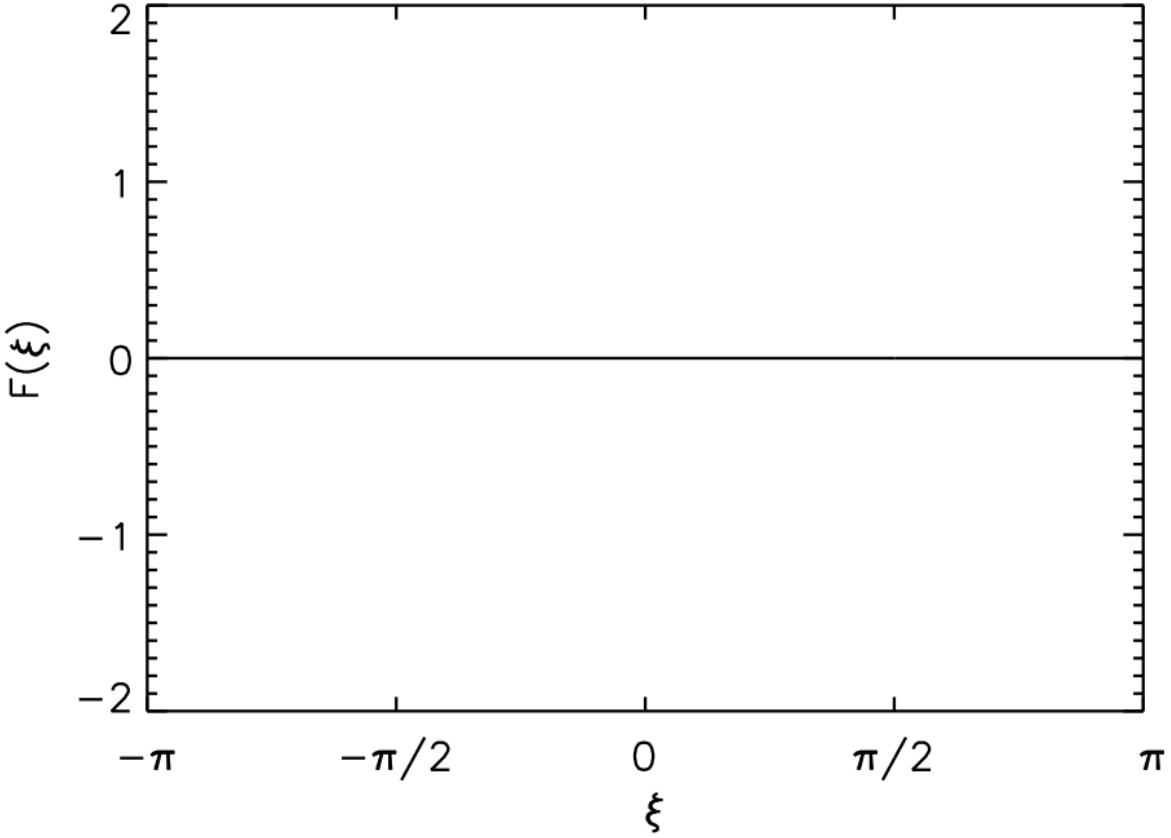
Resulting Phase Curves



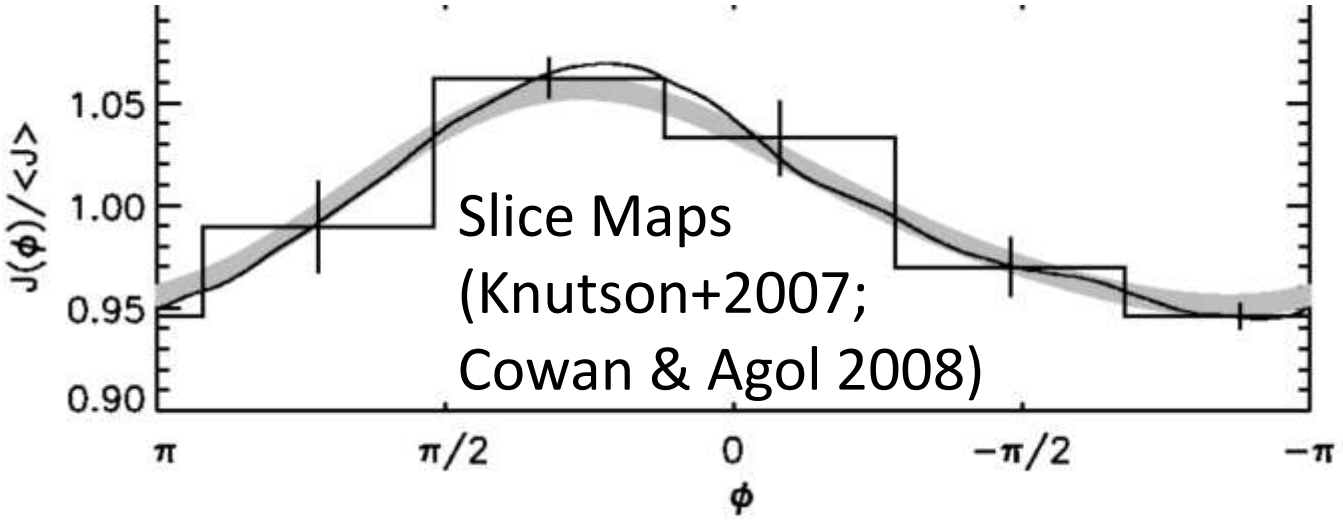
Sinusoidal Maps



Resulting Phase Curves

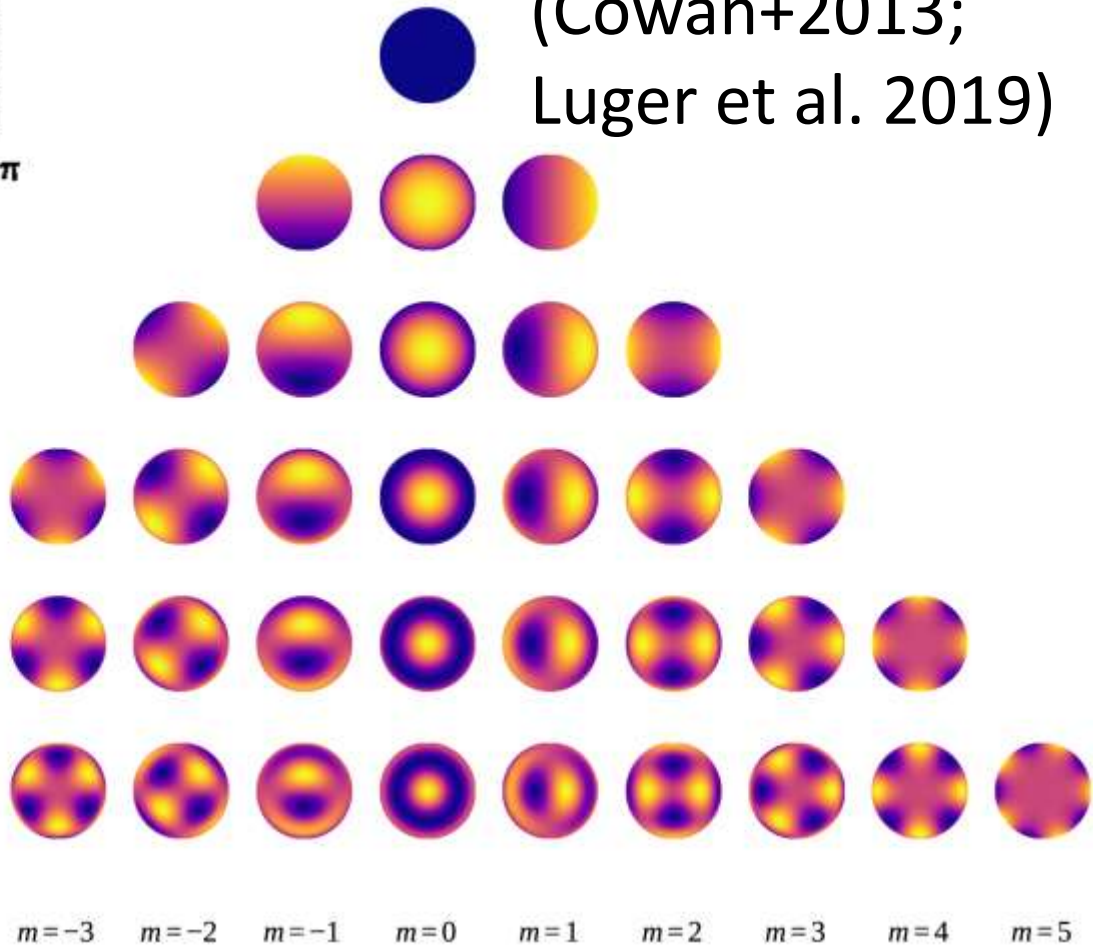


Alternative Basis Maps

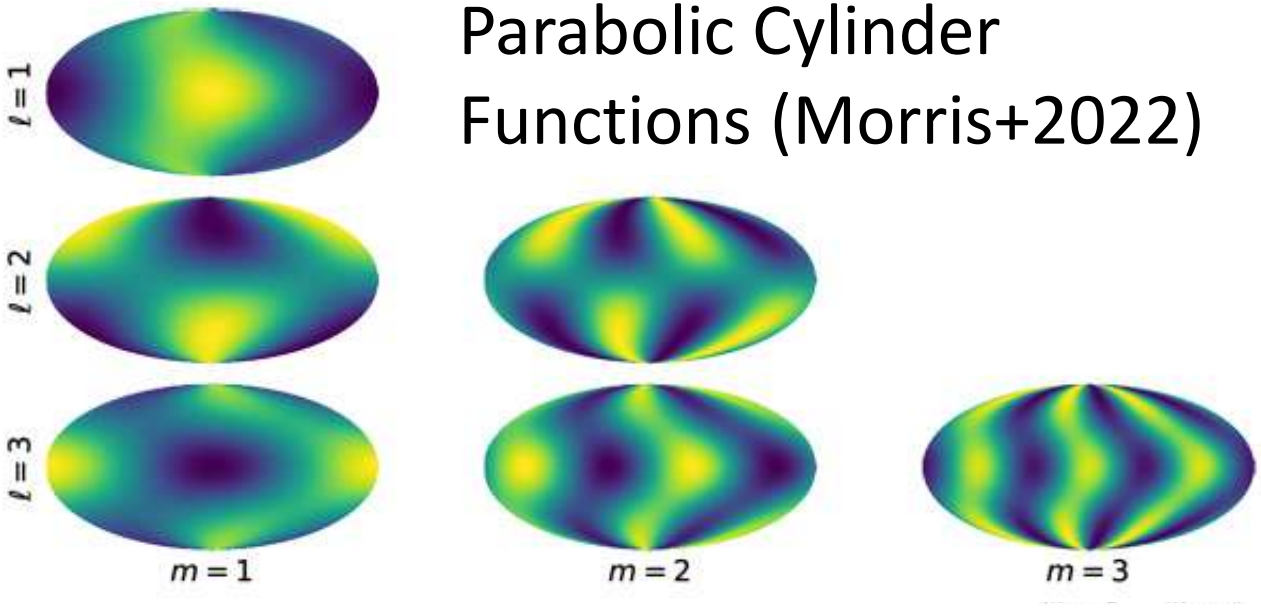


Slice Maps
(Knutson+2007;
Cowan & Agol 2008)

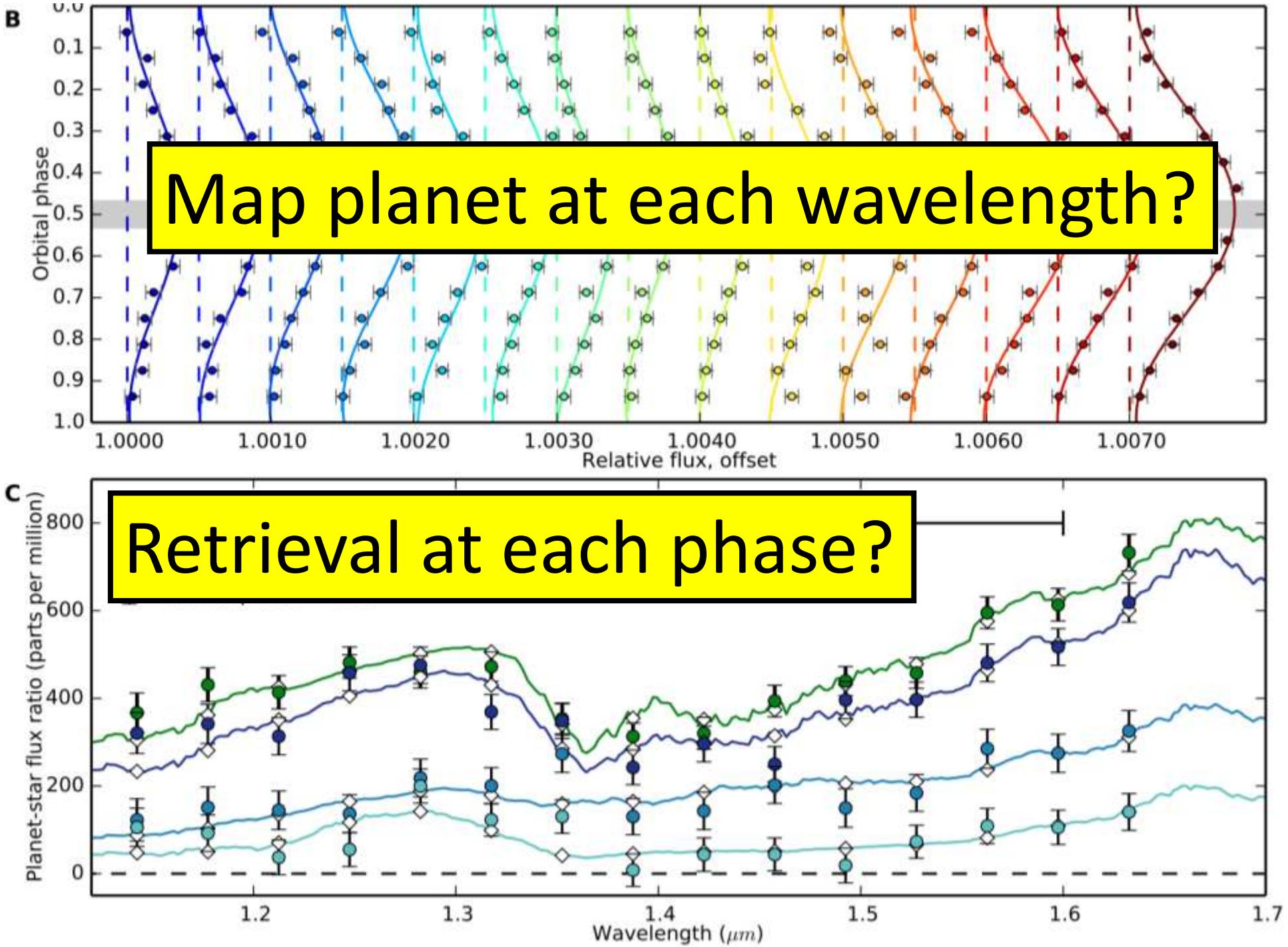
Spherical Harmonics
(Cowan+2013;
Luger et al. 2019)



Parabolic Cylinder
Functions (Morris+2022)



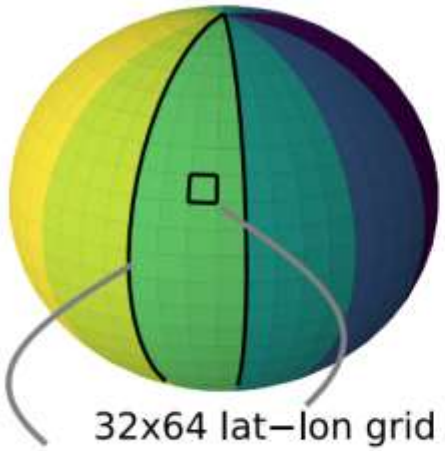
Spectroscopic Phase Curves (Stevenson+2014; Cubillos+2021)

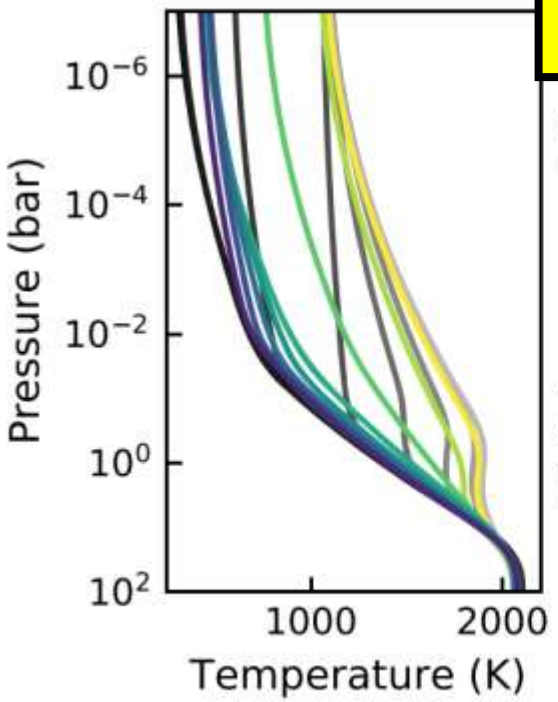


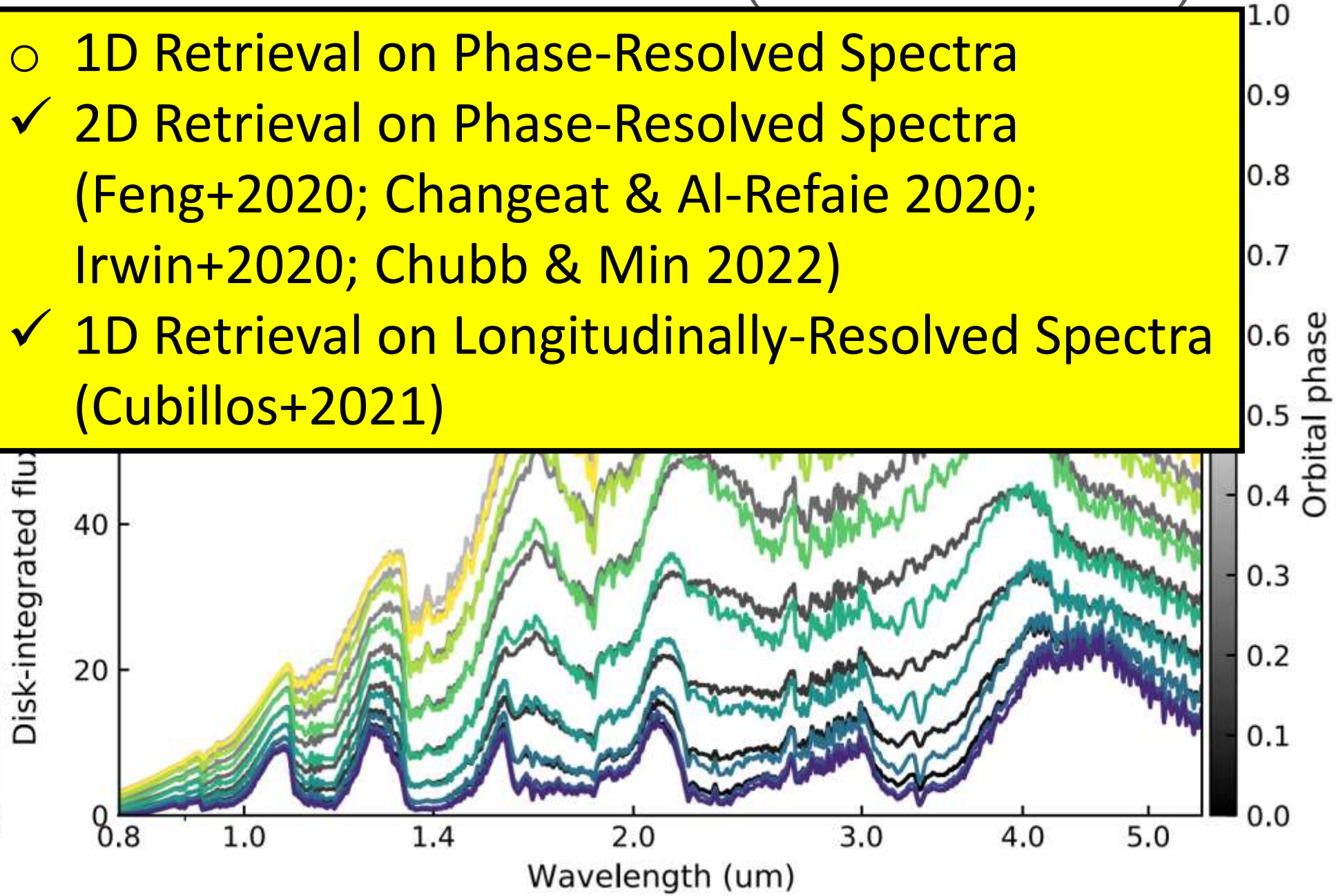
(Stevenson et al. 2014)

(Cubillos et al. 2021)

- ○ 1D Retrieval on Phase-Resolved Spectra
- ✓ 2D Retrieval on Phase-Resolved Spectra (Feng+2020; Changeat & Al-Refaie 2020; Irwin+2020; Chubb & Min 2022)
- ✓ 1D Retrieval on Longitudinally-Resolved Spectra (Cubillos+2021)







Energy Budgets

(Cowan & Agol 2011b; Schwartz & Cowan 2015; Pass et al. 2019)

Brightness Temperature

Flux Ratio (e.g., eclipse depth)

$$B_{\lambda,\,\mathrm{planet}} = \frac{F_p/F_*}{(R_p/R_*)^2} \cdot B_{\lambda,\,\mathrm{star}}$$

Transit Depth

$$T_{\mathrm{bright}} = \frac{hc}{k\lambda} \cdot \left[\ln\left(\frac{2hc^2}{\lambda^5 B_{\lambda,\mathrm{planet}}} + 1 \right) \right]^{-1}$$

Inverse Planck Function