Stellar and Exoplanetary Atmospheres Bayesian Analysis Simultaneous Spectroscopy

Giuseppe Morello

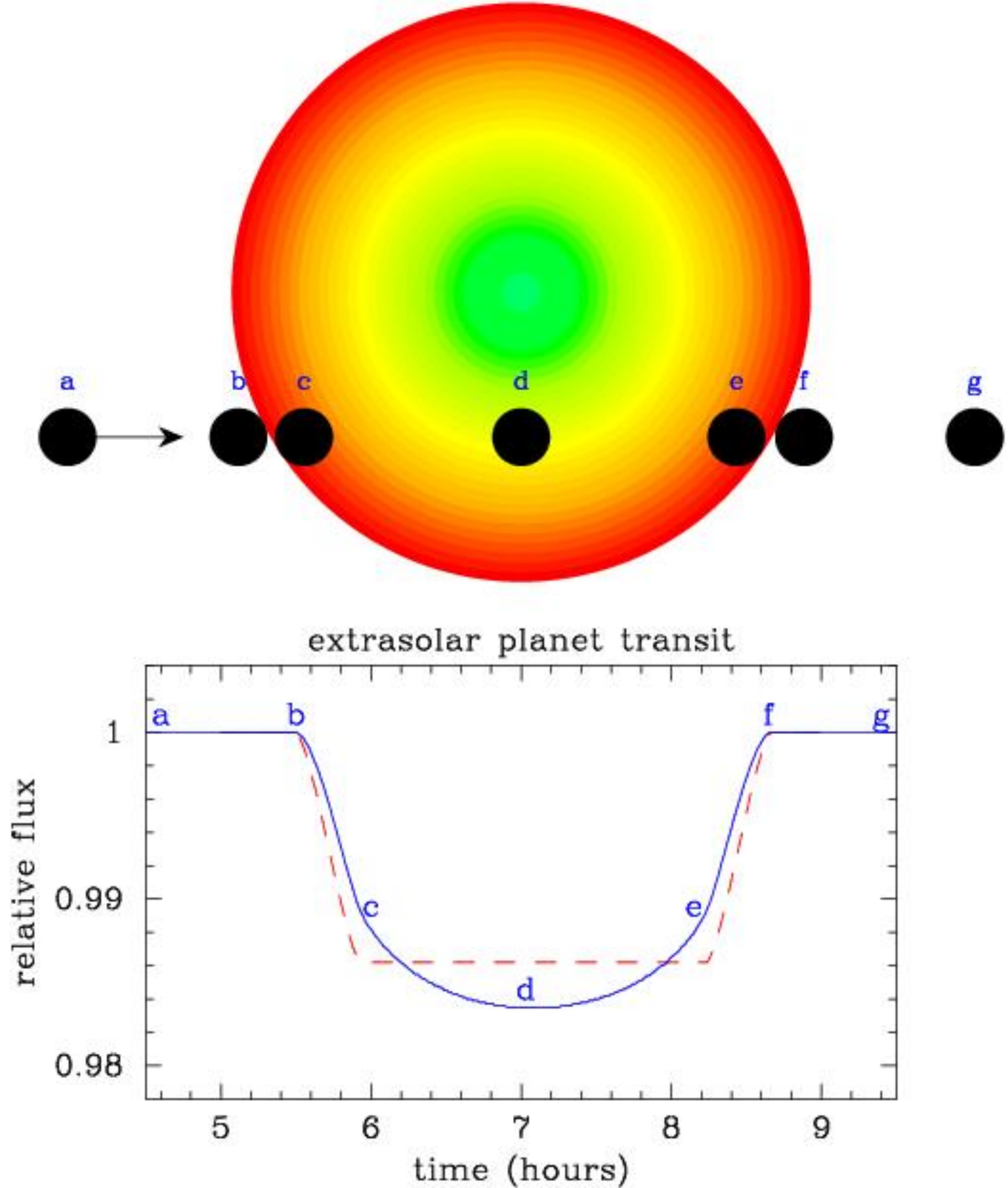
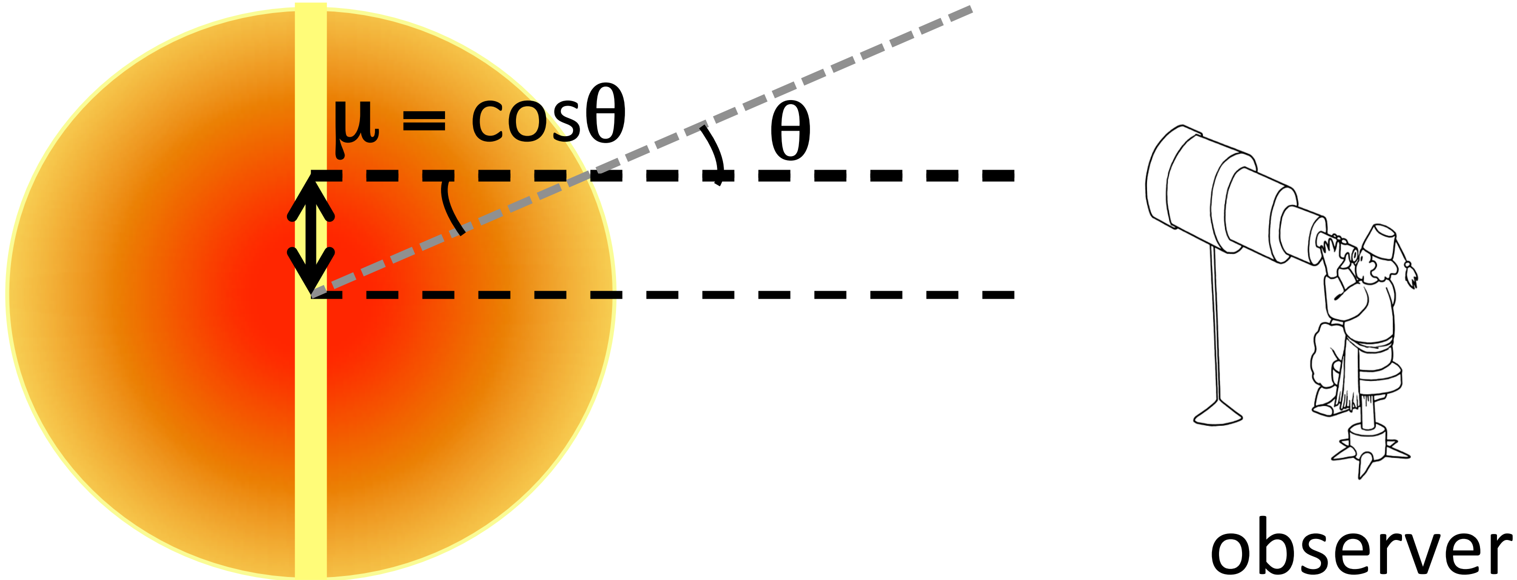


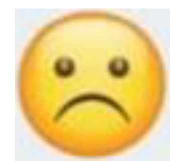
Image credit:
Coughlin, J. F.
(PhD thesis)



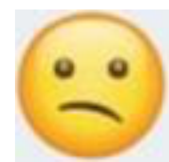
Limb-darkening laws

2-coefficients:

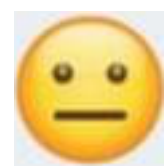
Quadratic $$\frac{I_\lambda(\mu)}{I_\lambda(1)} = 1 - u_1(1-\mu) - u_2(1-\mu)^2$$



Square-root $$\frac{I_\lambda(\mu)}{I_\lambda(1)} = 1 - v_1(1-\sqrt{\mu}) - v_2(1-\mu)$$



NEW Power-2 $$\frac{I_\lambda(\mu)}{I_\lambda(1)} = 1 - c\,(1-\mu^\alpha)$$



Claret-4 $$\frac{I_\lambda(\mu)}{I_\lambda(1)} = 1 - \sum_{n=1}^{4} a_n\,(1-\mu^{n/2})$$

Espinoza & Jordan 2016;
Morello et al. 2017;
Maxted 2018

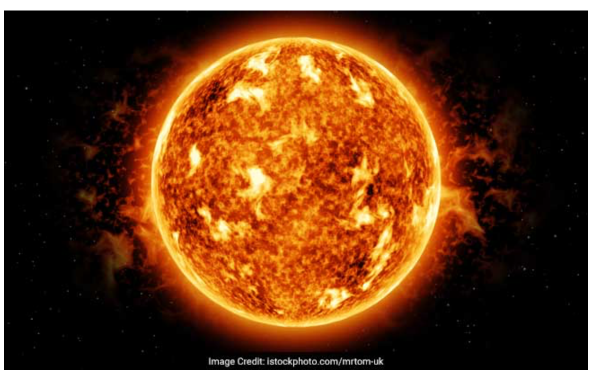
Why fitting for the stellar limb-darkening coefficients?

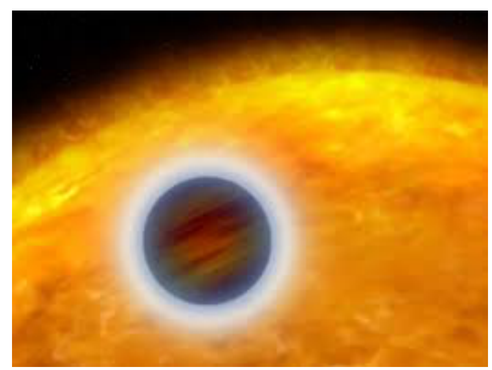
Stellar science

- Testing the stellar-atmosphere models
- The effect of stellar activity is not well known
- No other techniques are available (in almost all cases)

Exoplanetary science

- Avoiding potential biases in the exoplanet radius and orbital parameters
- Wrong radius → mean density → structure model
- Avoiding potential biases in the transmission spectrum of the exoplanetary atmosphere





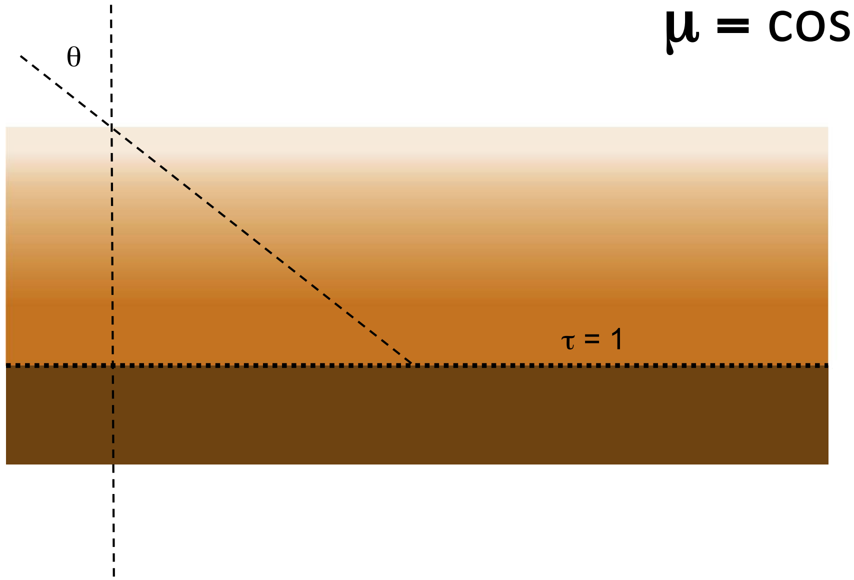
But

Strong parameter degeneracies may hamper convergence of the light-curve fits

Impact of geometric approximations

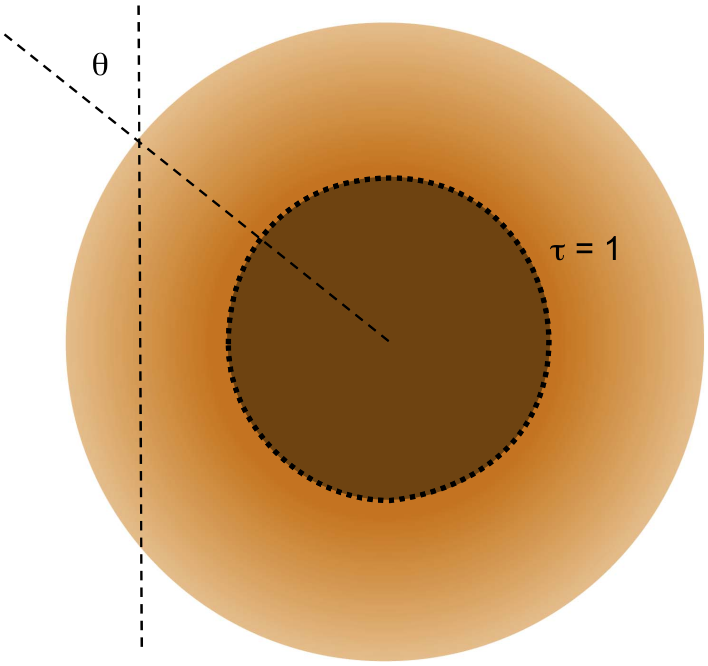
Geometry of stellar-atmosphere models

Plane-parallel



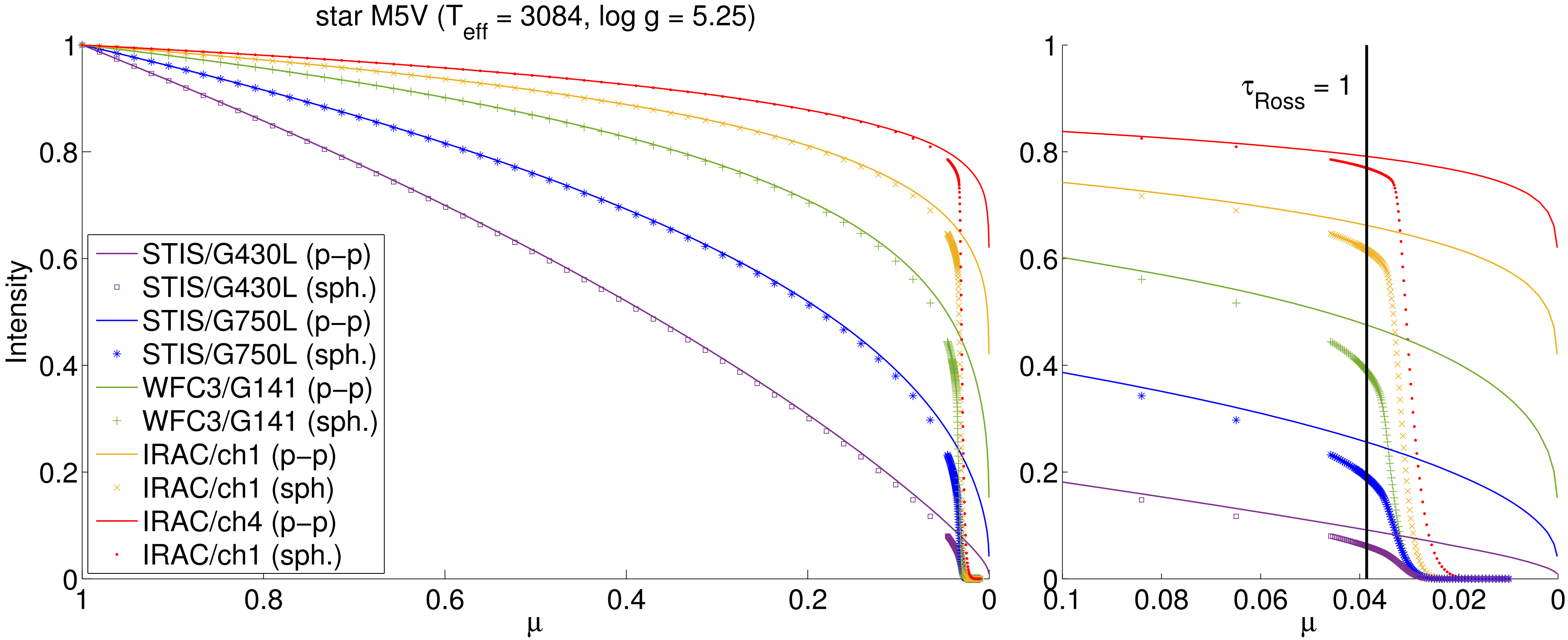
$$\mu = \cos\theta$$

Spherical



Stellar intensity profiles

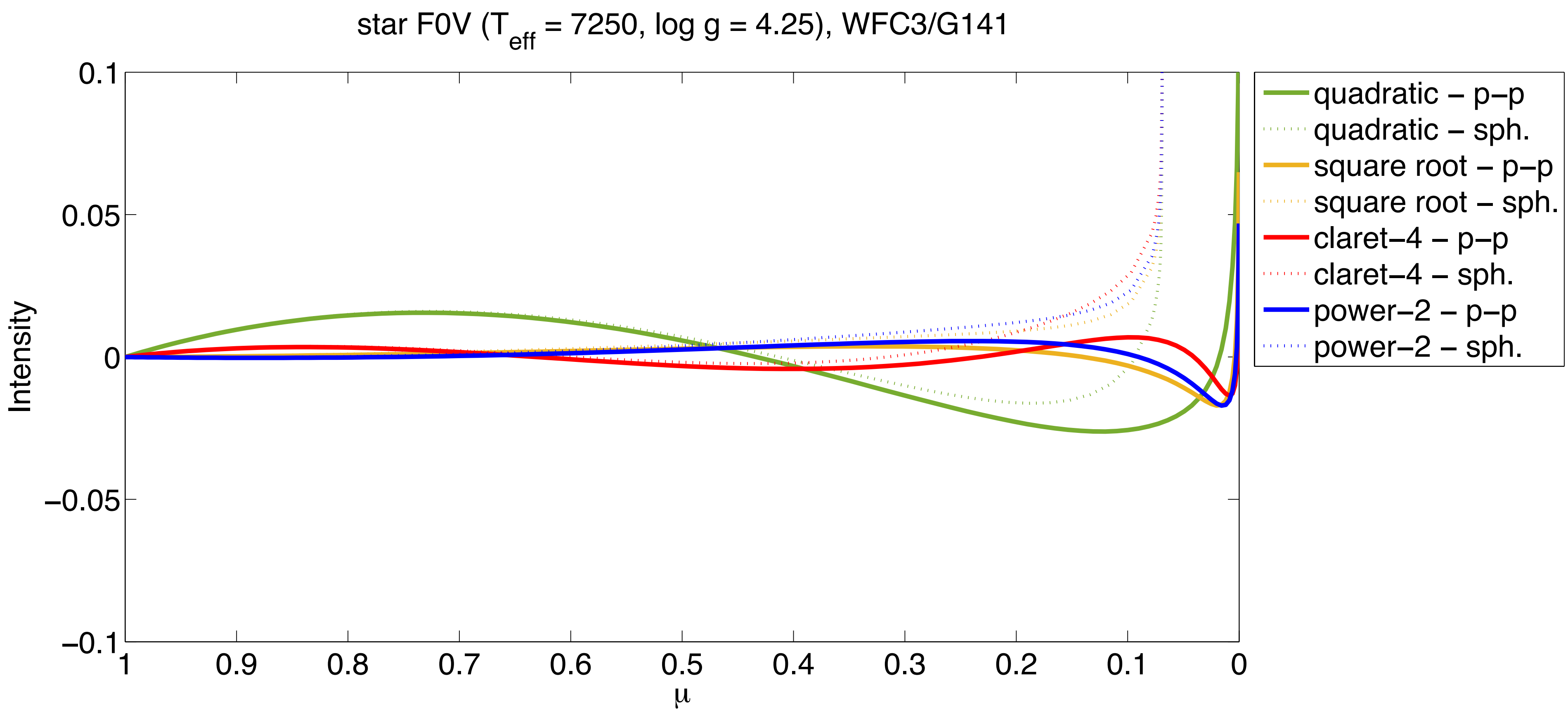
$\mu = \cos\theta$



Morello et al. 2017

Parametric intensity profiles (1)

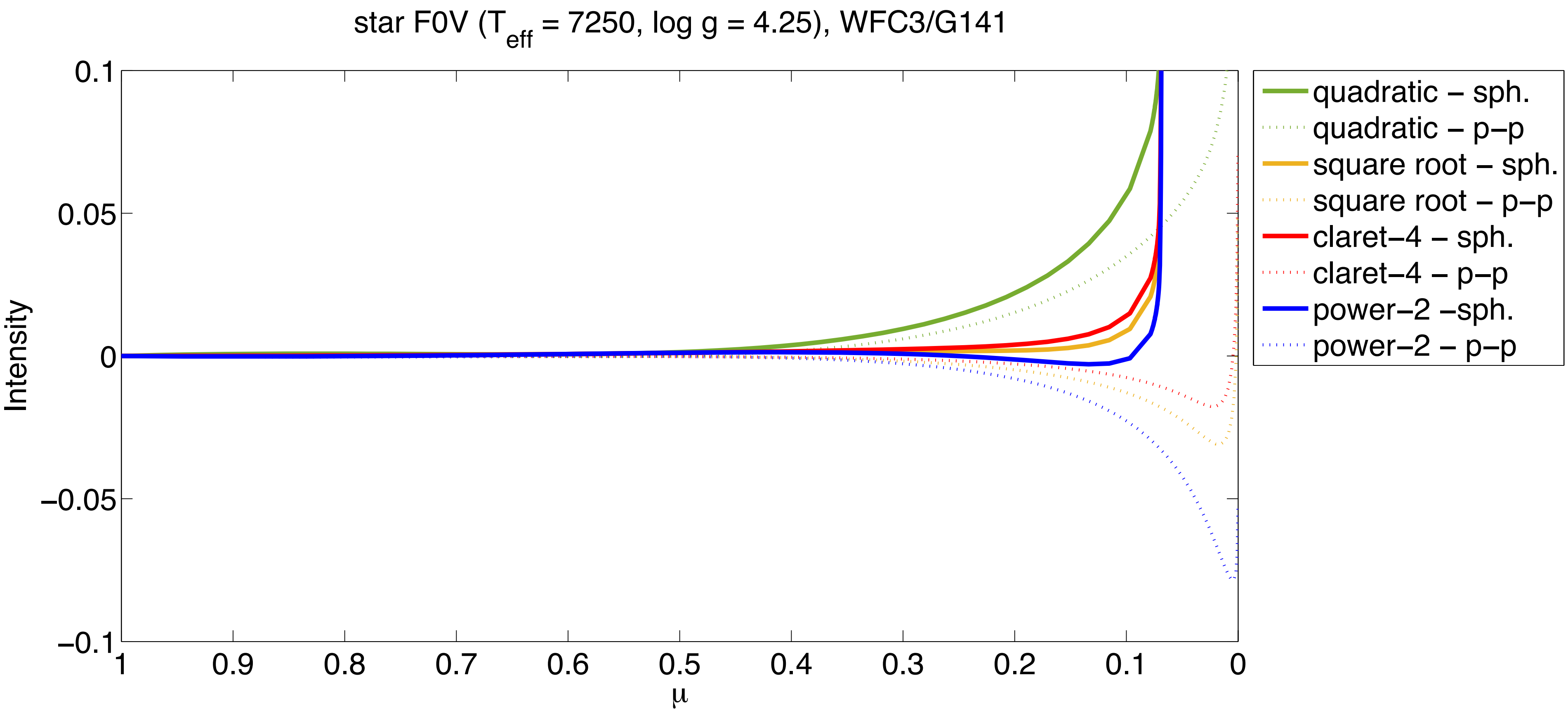
With *theoretical* limb-darkening coefficients (best-fit I(μ))



Morello et al. 2017

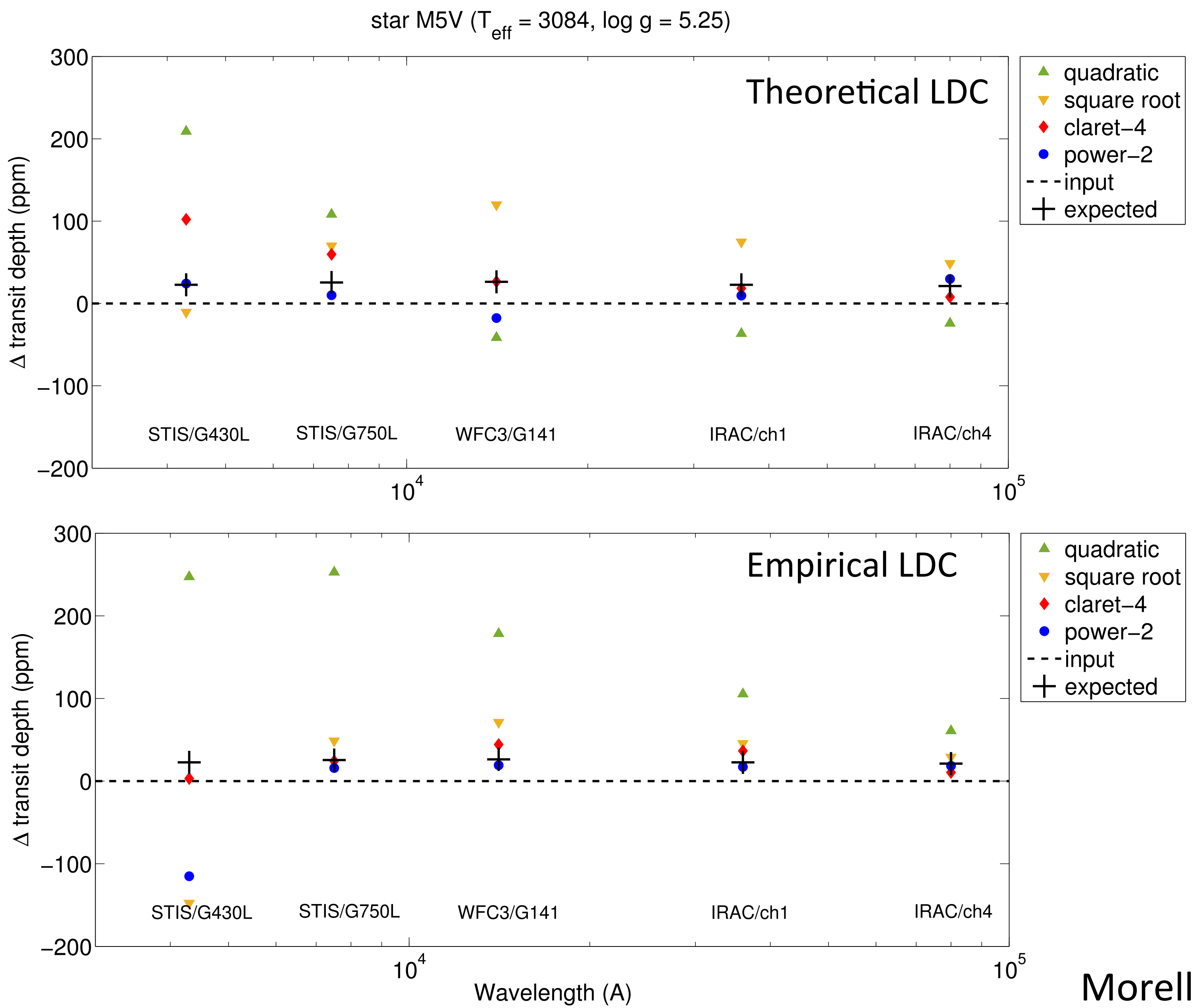
Parametric intensity profiles (2)

With *empirical* limb-darkening coefficients (best-fit light-curve)



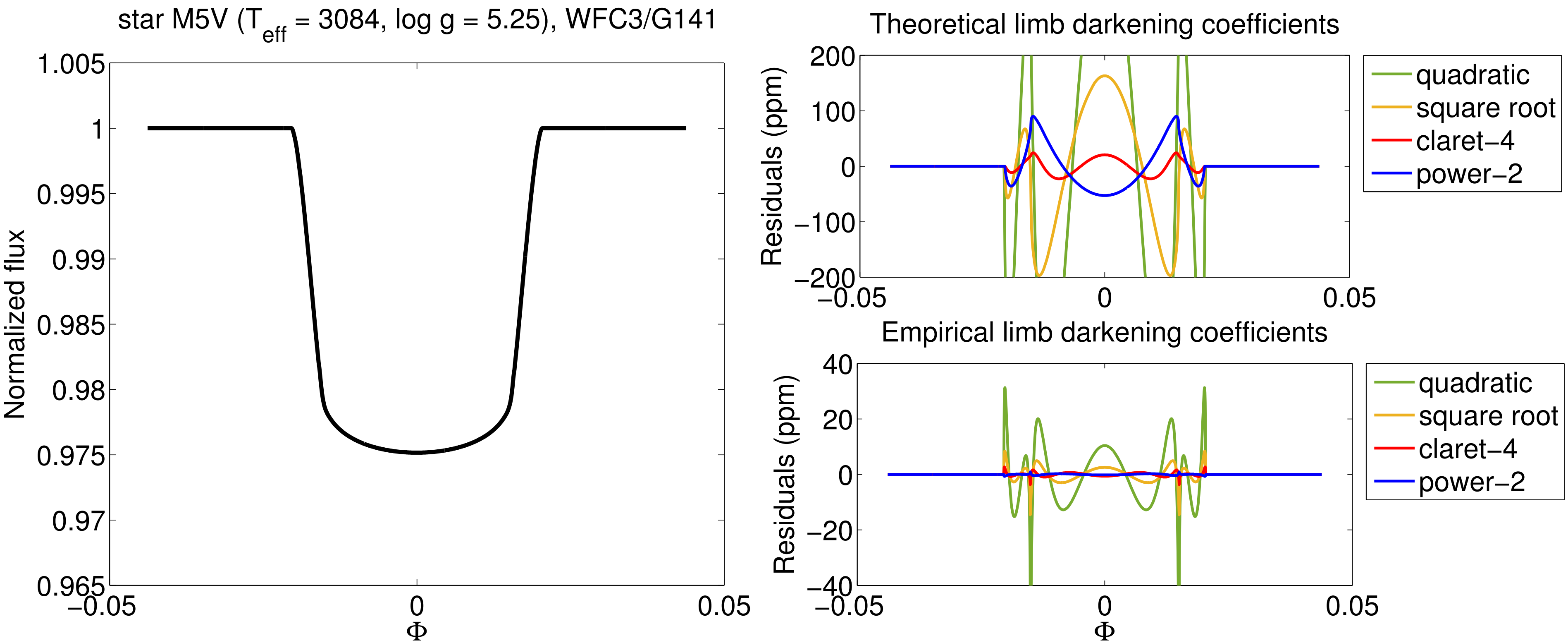
Morello et al. 2017

Transit depth bias



Morello et al. 2017

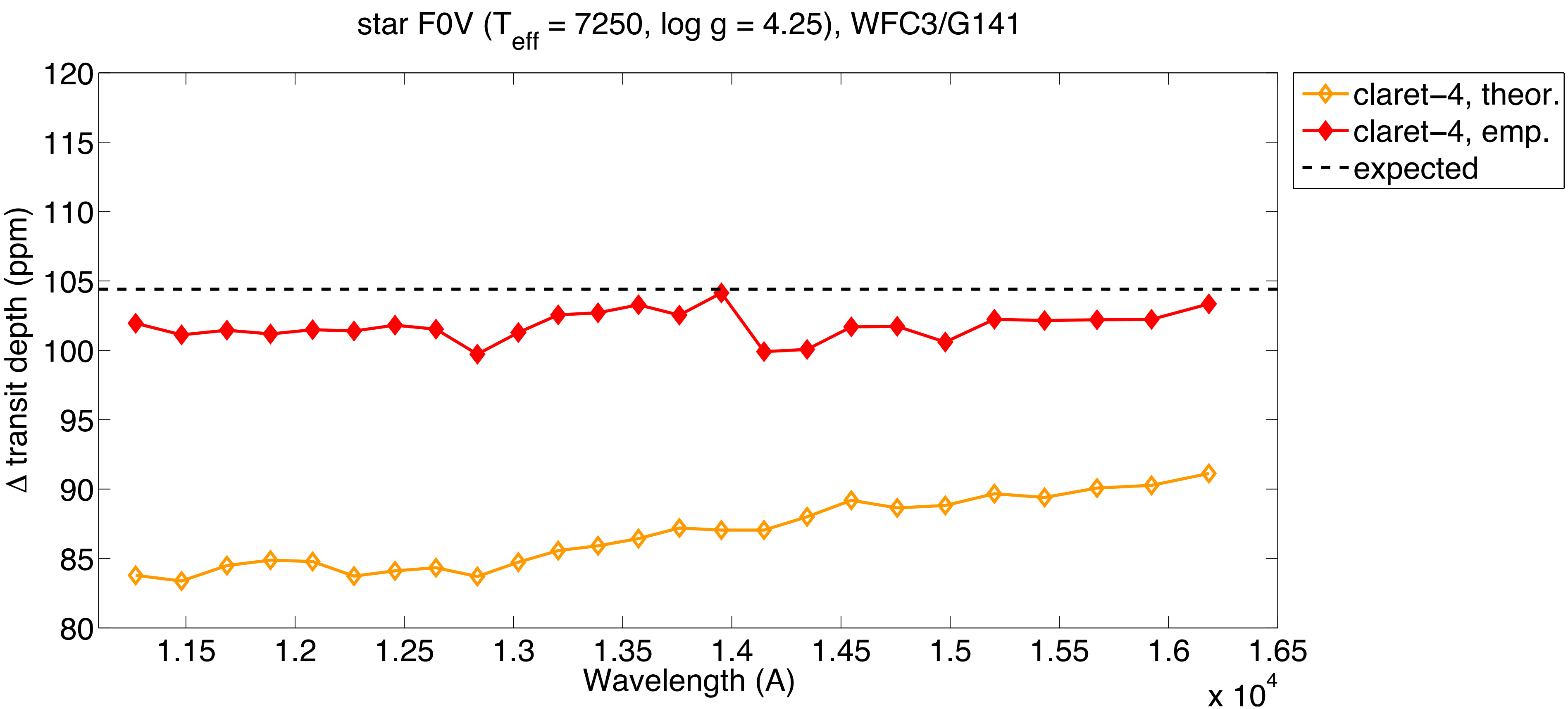
Transit light-curve models



NOTE: Because of parameter degeneracies the transit depth and orbital parameters can be significantly biased even if the fitting residuals are very small!

Morello et al. 2017

WFC3-like exoplanet spectroscopy

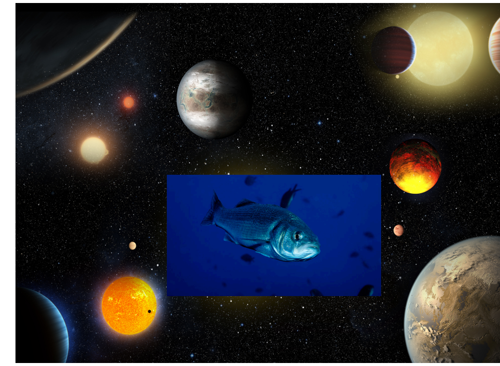


Morello et al. 2017

Methods and results

SEA BASS

Stellar and **E**xoplanetary **A**tmospheres
Bayesian **A**nalysis **S**imultaneous **S**pectroscopy

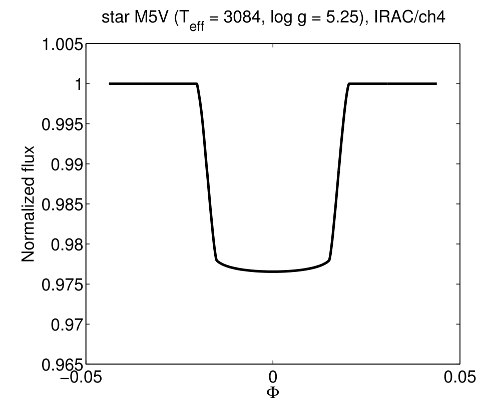


1

INFRARED TRANSITS

- ✓ Two-coefficient limb-darkening laws,
  or
- ✓ Fixed limb-darkening coefficients

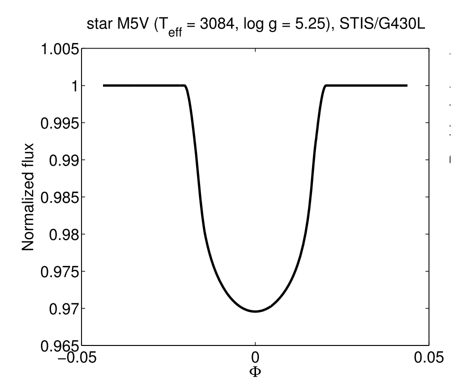
=> geometric parameters (orbital, transit duration)



2

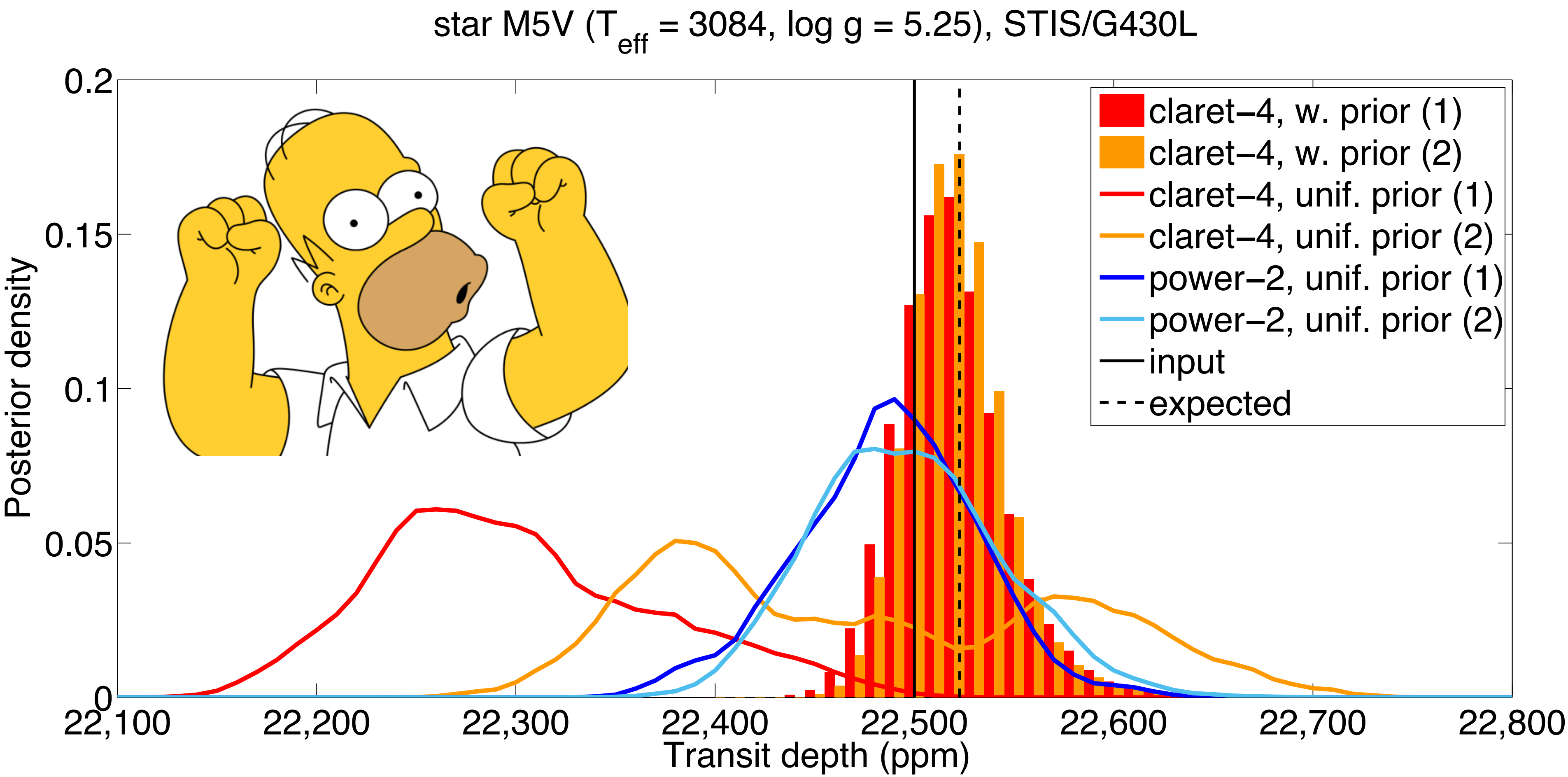
VISIBLE/UV TRANSITS

- ✓ Informative Bayesian priors on the geometric parameters
- ✓ Fully empirical four-coefficient limb-darkening



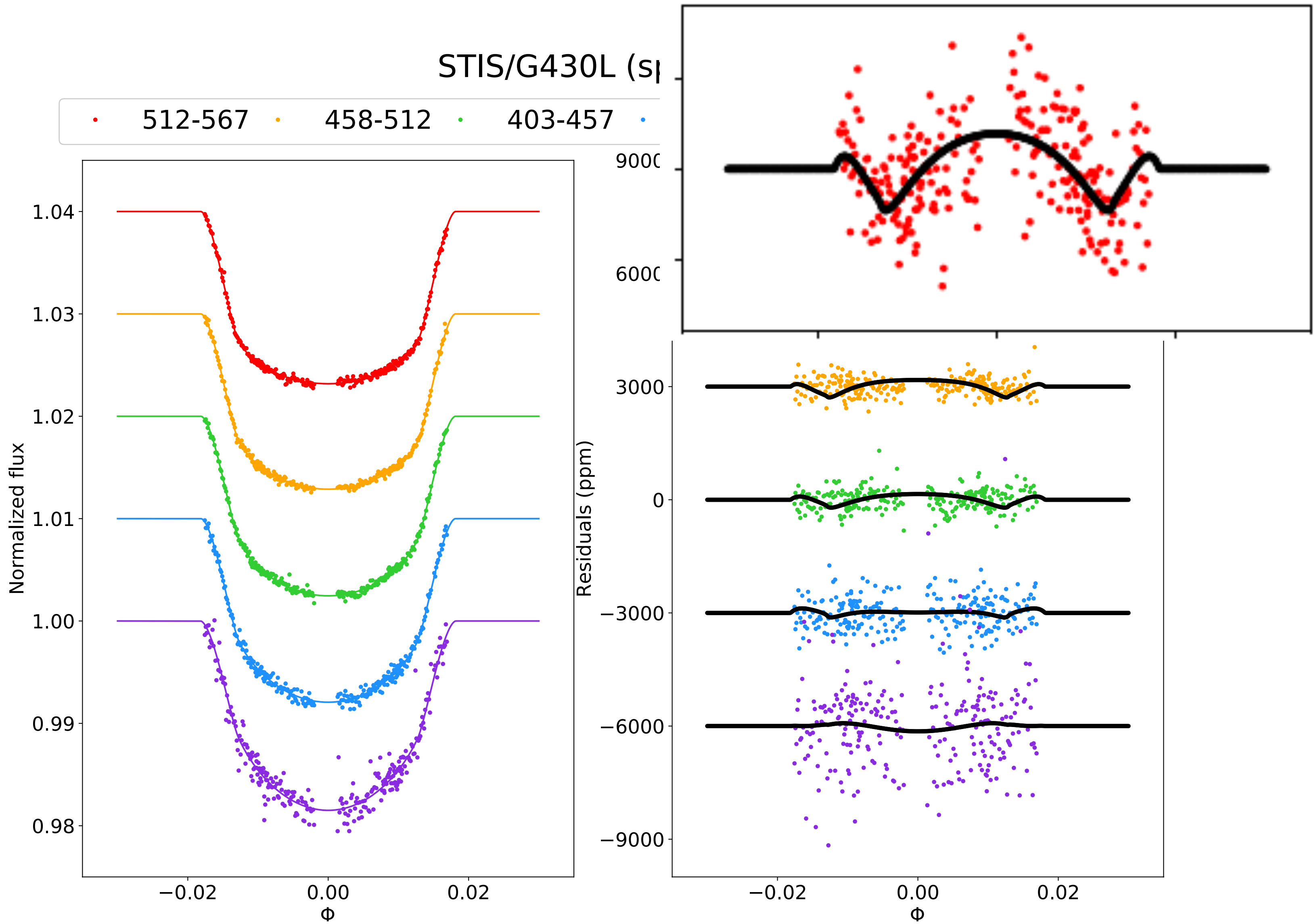
Morello et al. 2017; Morello 2018

Simulation results



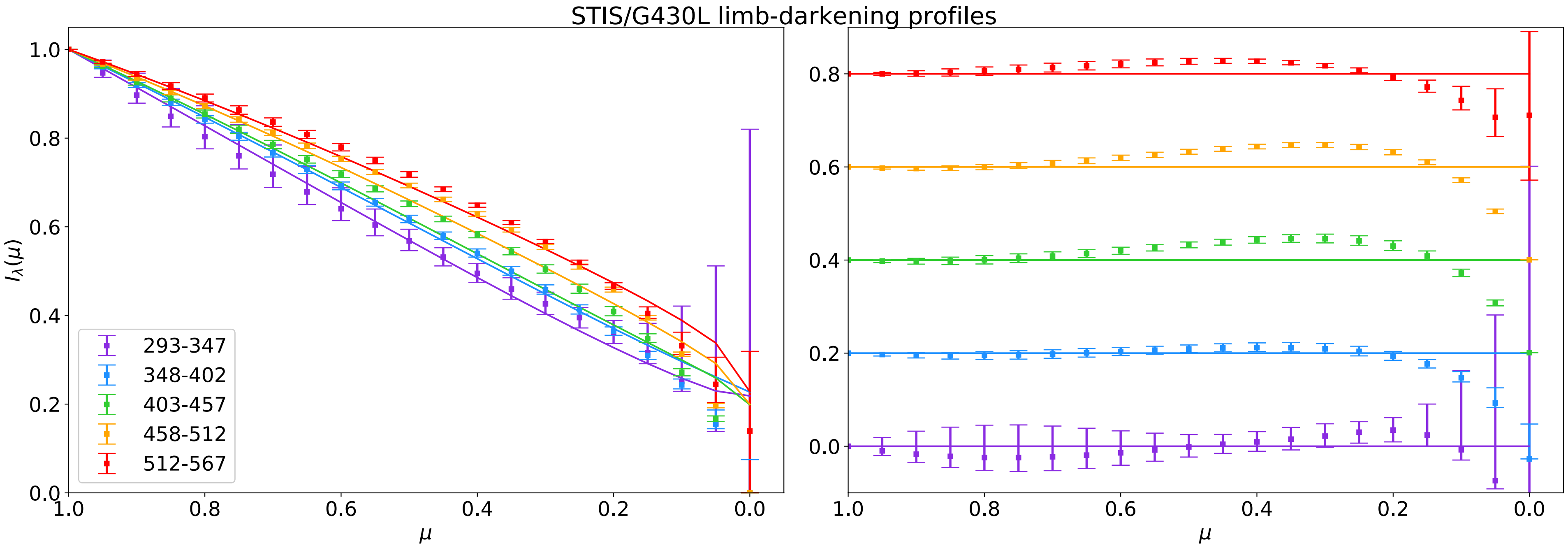
Morello et al. 2017

Spitzer/IRAC + *HST*/STIS observations (1)



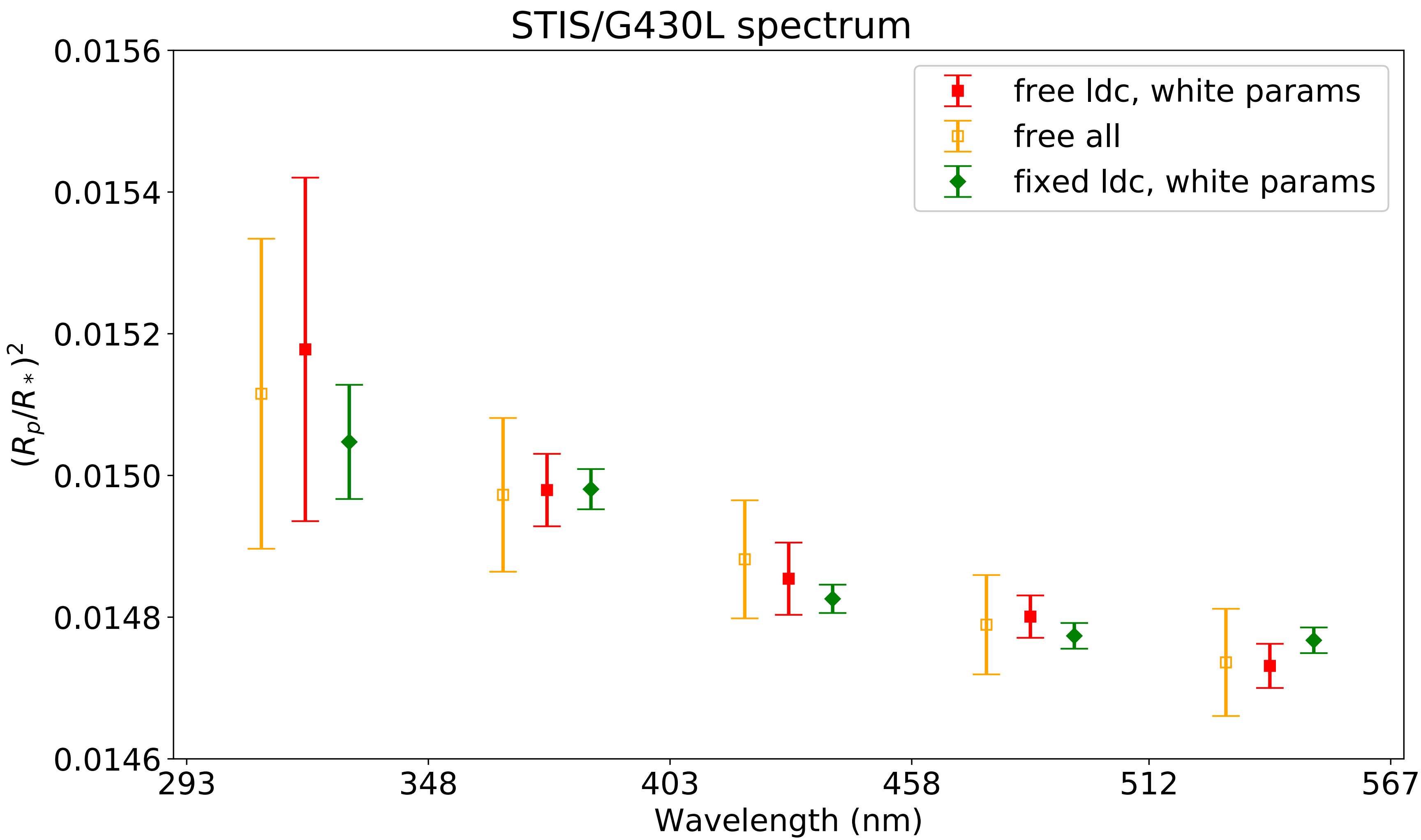
Morello 2018

Spitzer/IRAC + *HST*/STIS observations (2)



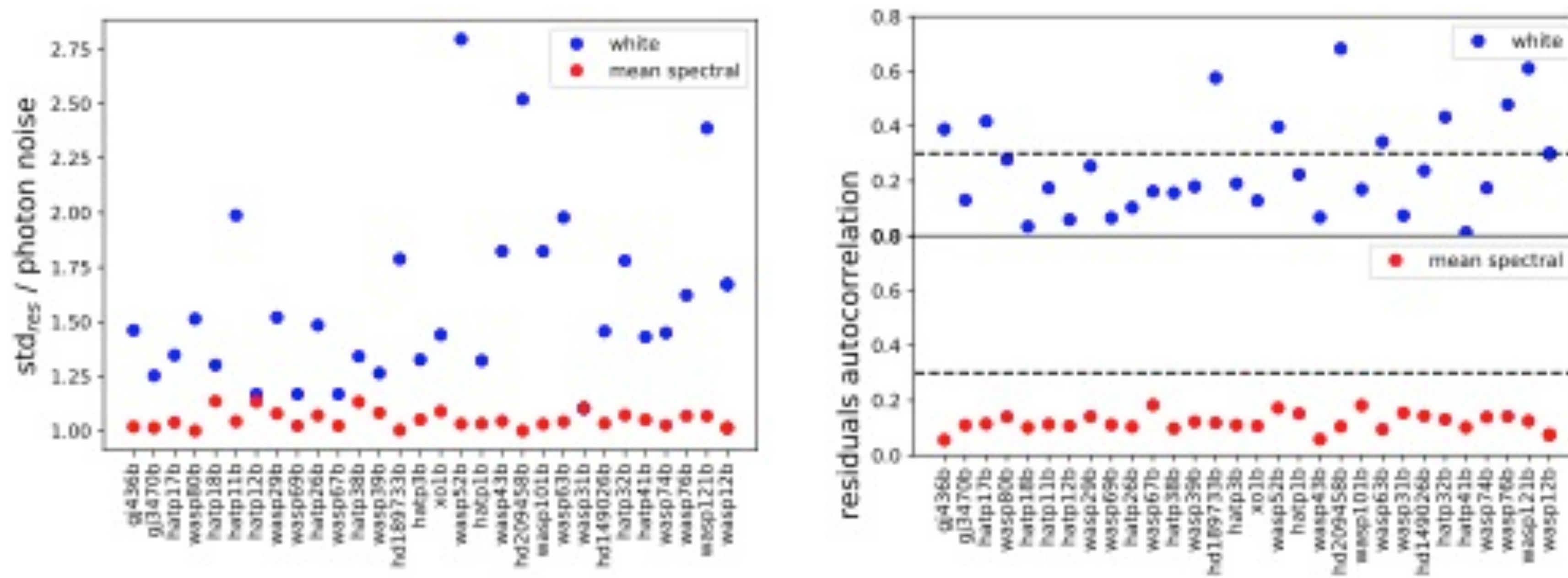
Morello 2018

Spitzer/IRAC + *HST*/STIS observations (3)

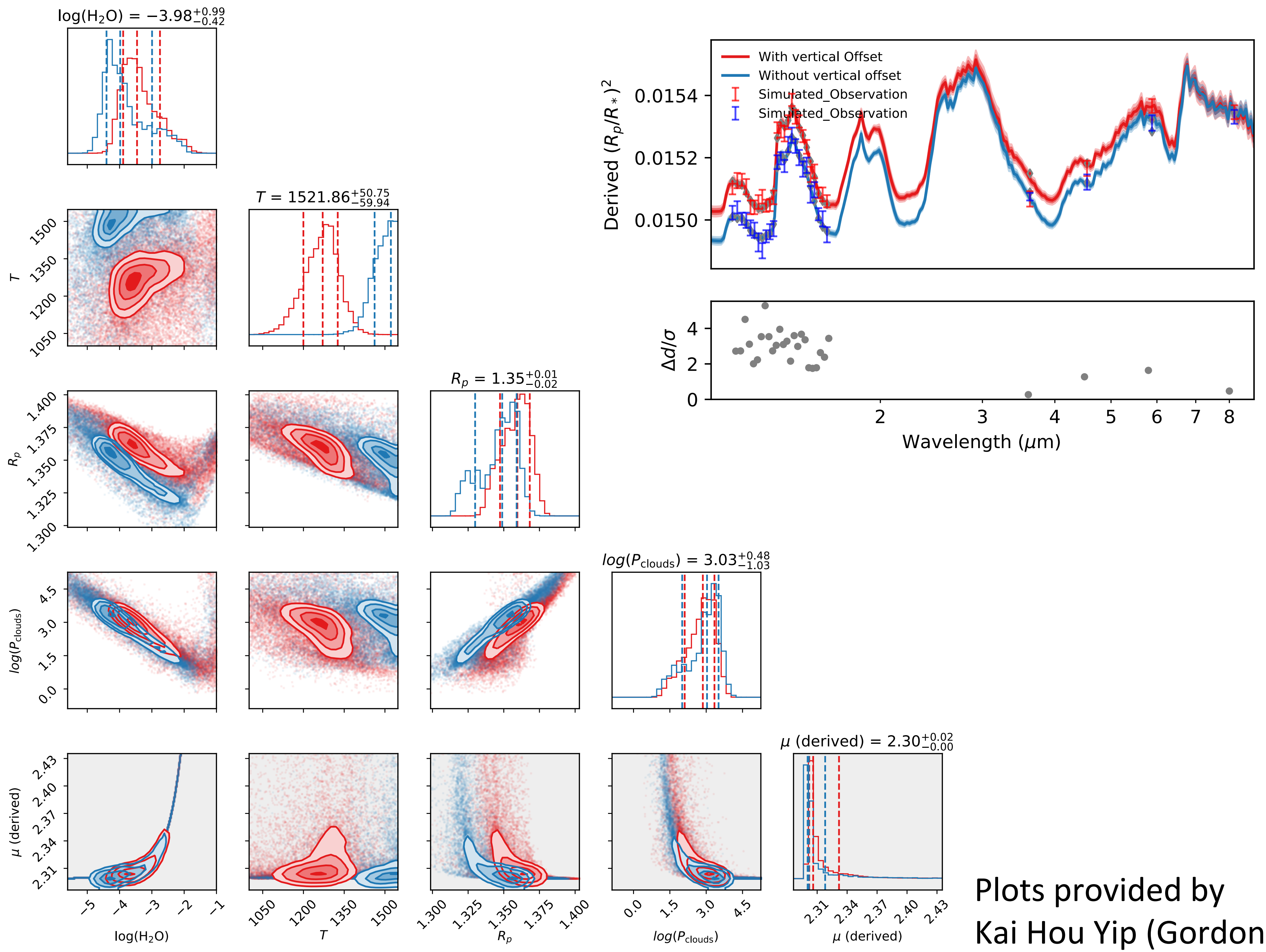


Morello 2018

~50% of *HST*/WFC3 transits have systematic residuals when limb-darkening is not fitted



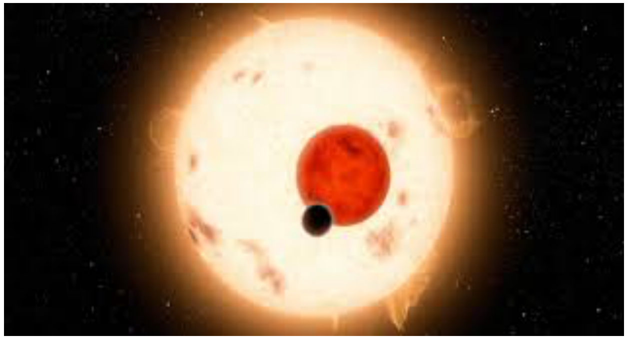
Tsiaras et al. 2018

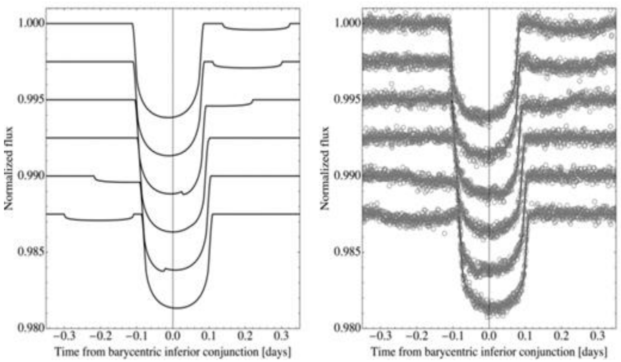


Plots provided by
Kai Hou Yip (Gordon)

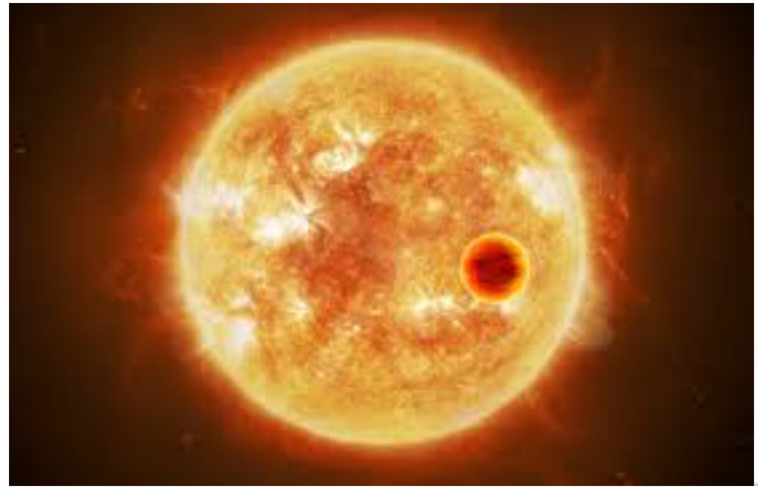
Other disturbing effects

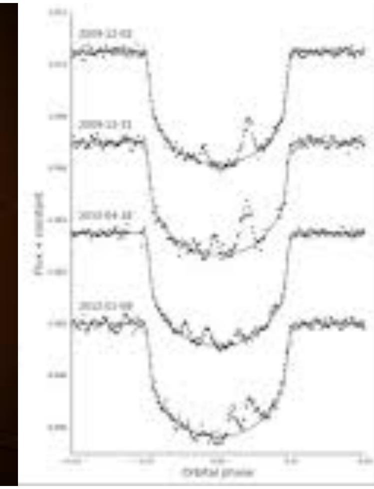
Exomoons



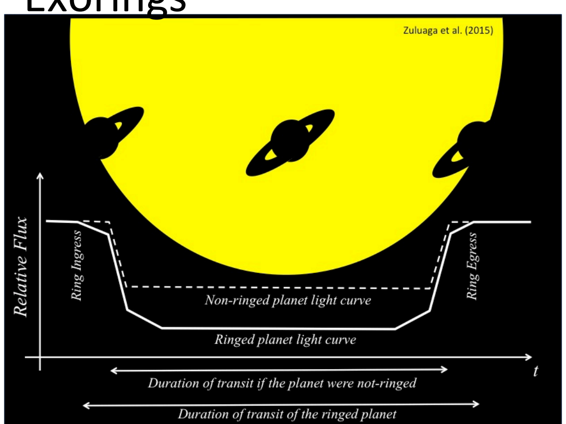


Stellar activity

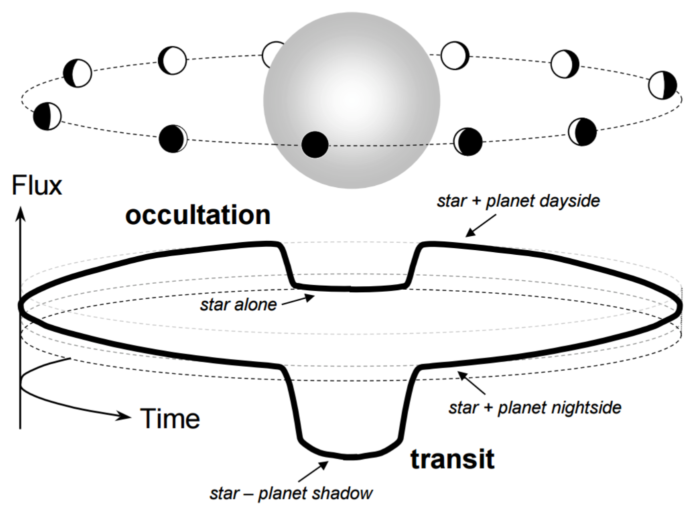




Exorings



Exoplanet phase-curve



Kipping 2009a, b, 2011; Zuluaga et al. 2015; Sarkar et al. 2018; Showman & Guillot 2002; Morello et al. (in prep.)

Conclusions

- Fitting for (four) stellar limb-darkening coefficients in transit light-curve fits to avoid biases in the exoplanet parameters;
- Also important for exoplanet spectroscopy;
- Highly significant for *HST*/WFC3 and next-generation instruments onboard JWST and ARIEL;
- Multiwavelength Bayesian approach (SEA BASS) to minimize the biases and break parameter degeneracies;
- Successfully applied to HST/STIS observations of HD209458b;

Next steps:

- Priors from stellar physics (testing stellar models on Kepler/K2, TESS data);
- Disentangling other astrophysical signals.

Thank you