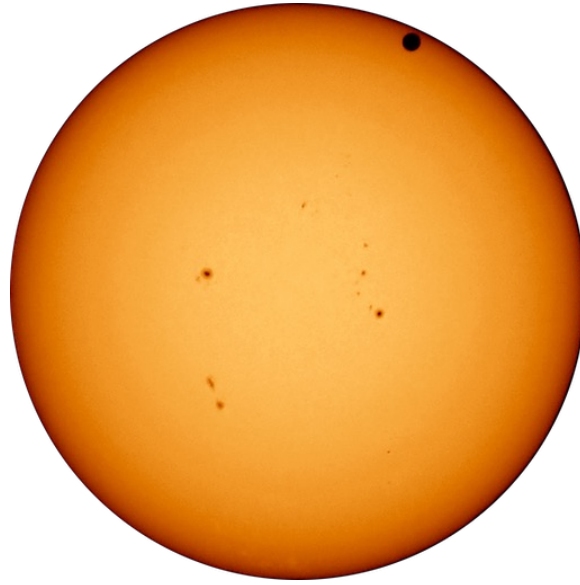


## Key Contributors:

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Nadiia Kostogryz (MPI, Solar System)  
Rosa Keers (MPI, Solar System)  
Sara Seager (MIT)

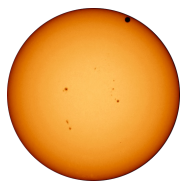
## Acknowledgements:

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limb-darkening (Néstor Espinoza)  
batman (Laura Kreidberg)

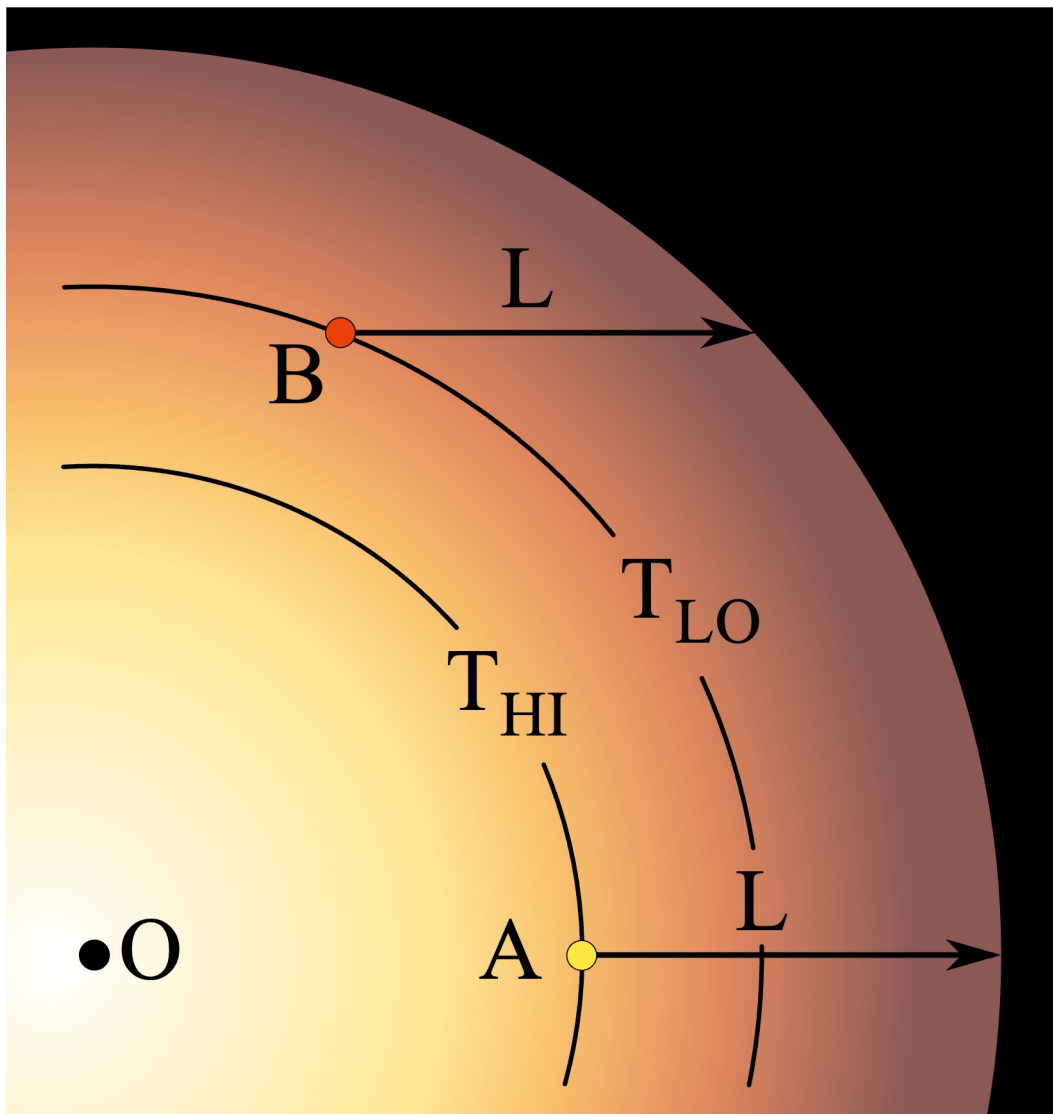


# Limb Darkening for JWST Spectroscopic Light Curves Theory vs. Data

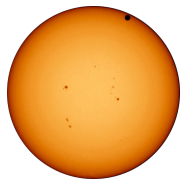
Dr. Jeff A. Valenti  
Space Telescope Science Institute



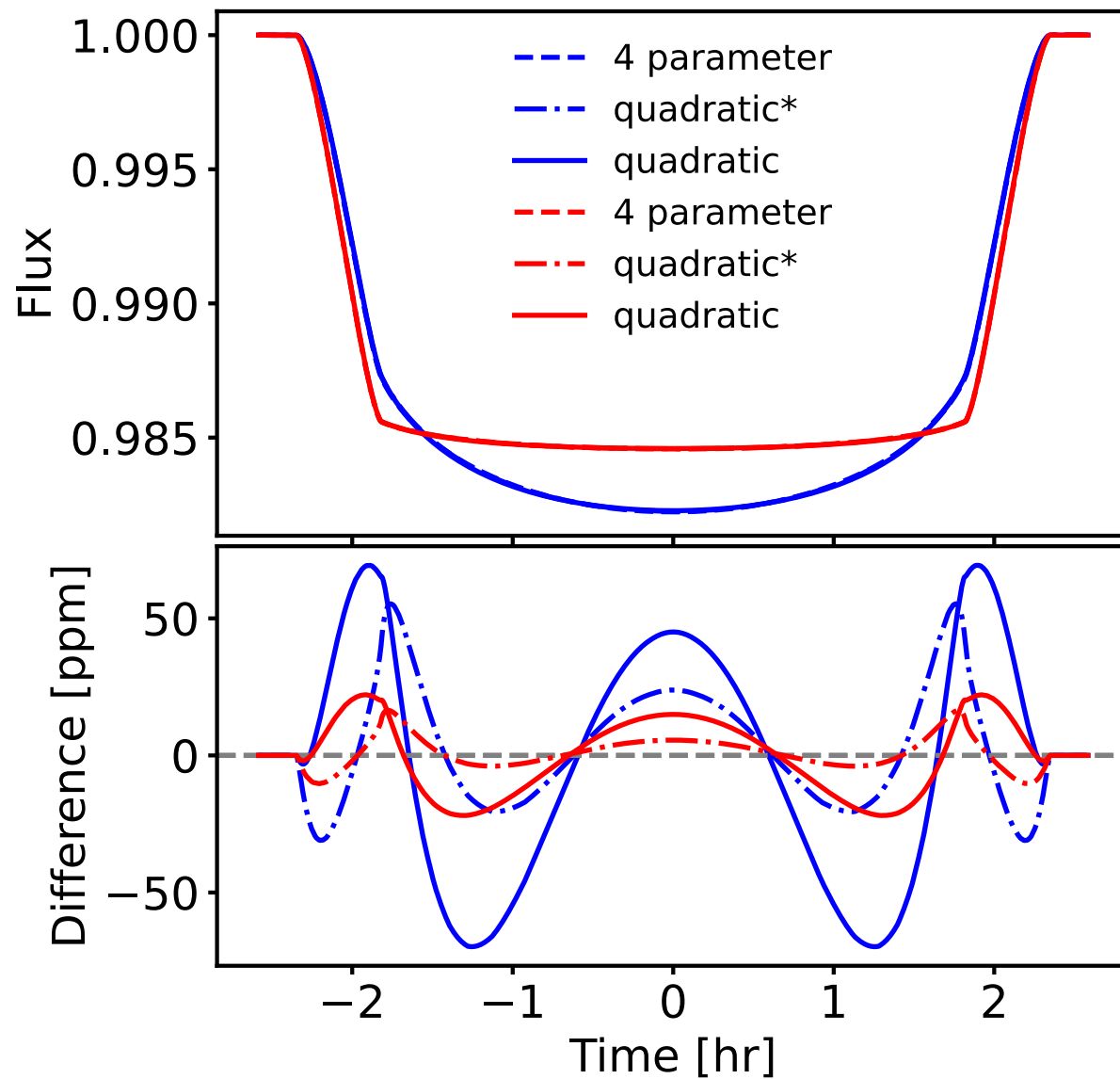
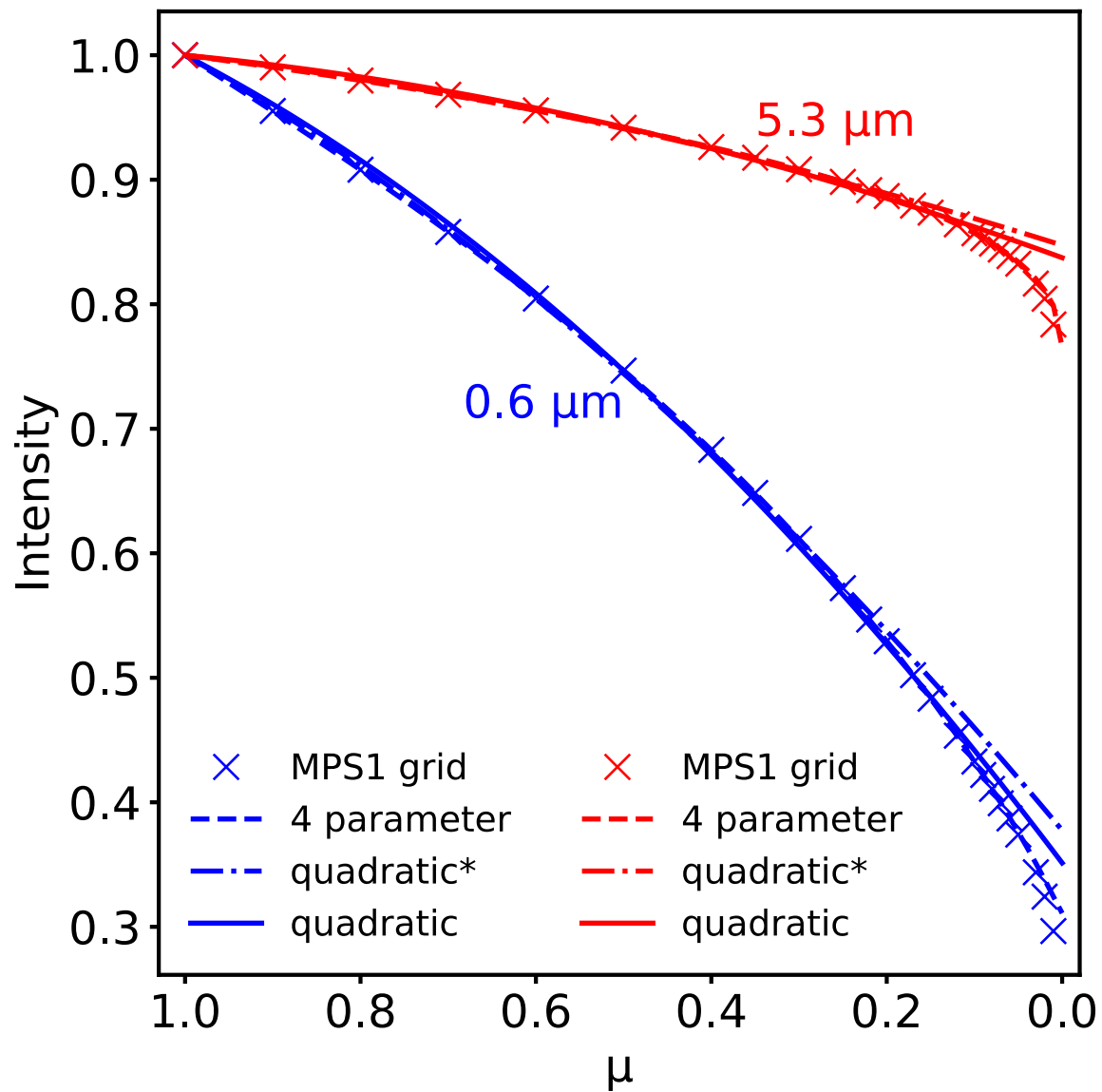
## What is limb darkening?

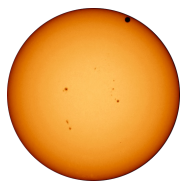


- At disk center, we see deeper (A)
- Near the limb, we see higher up (B)
- Deeper layers are hotter ( $T_{HI}$ ), brighter
- Higher layers are cooler ( $T_{LO}$ ), fainter



# Limb darkening functional forms, e.g., quadratic, 4 parameter





## The Dilemma – Theoretical or Empirical?

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- Limb darkening is required to model transit light curves.
- Theoretical values don't always reproduce observed light curves.
- Observers sometimes solve for limb darkening empirically.
- Observers can only afford to solve for 2 limb darkening parameters
- Models say that 4 parameters are required to describe limb darkening.
  
- Community uses both approaches.
- Choice depends on data quality, spectral type, science goals, ...
- Ultimately, we need better models.

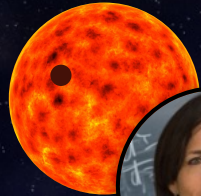


# REVEALING SIGNATURES OF HABITABLE WORLDS HIDDEN BY STELLAR ACTIVITY



**Prof. Dr. Andrew  
Collier Cameron**

**Discovering Earth "twins"**  
with extreme precision  
RV ground-based  
spectroscopy and new  
methodology for its  
analysis.



**Prof. Dr.  
Sara Seager**

**Characterizing Earth  
"cousins" atmospheres**  
with JWST via transmission  
spectroscopy and new  
atmospheric retrieval  
methodology.



**Dr. Alexander  
(Sasha) Shapiro**

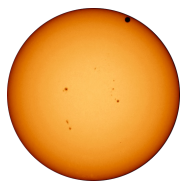
**Modelling stellar signals**  
in RV and transmission  
spectroscopy with  
frontier computer  
simulations.



**Dr. Jeff Valenti**

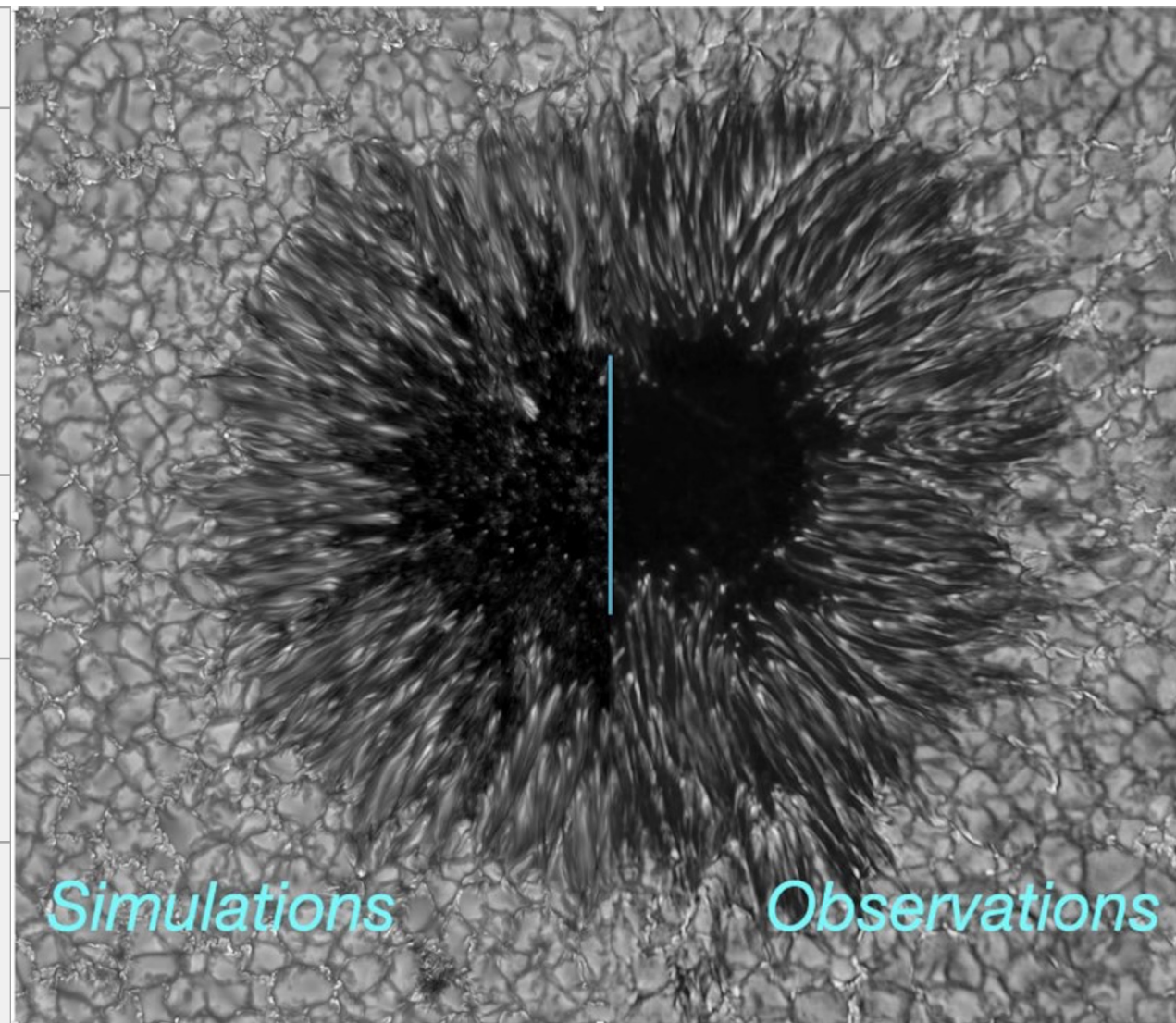
**Observational tests**  
Compare model  
predictions with  
accurate stellar  
observations.



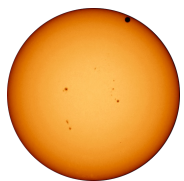


## REVEAL models in this presentation

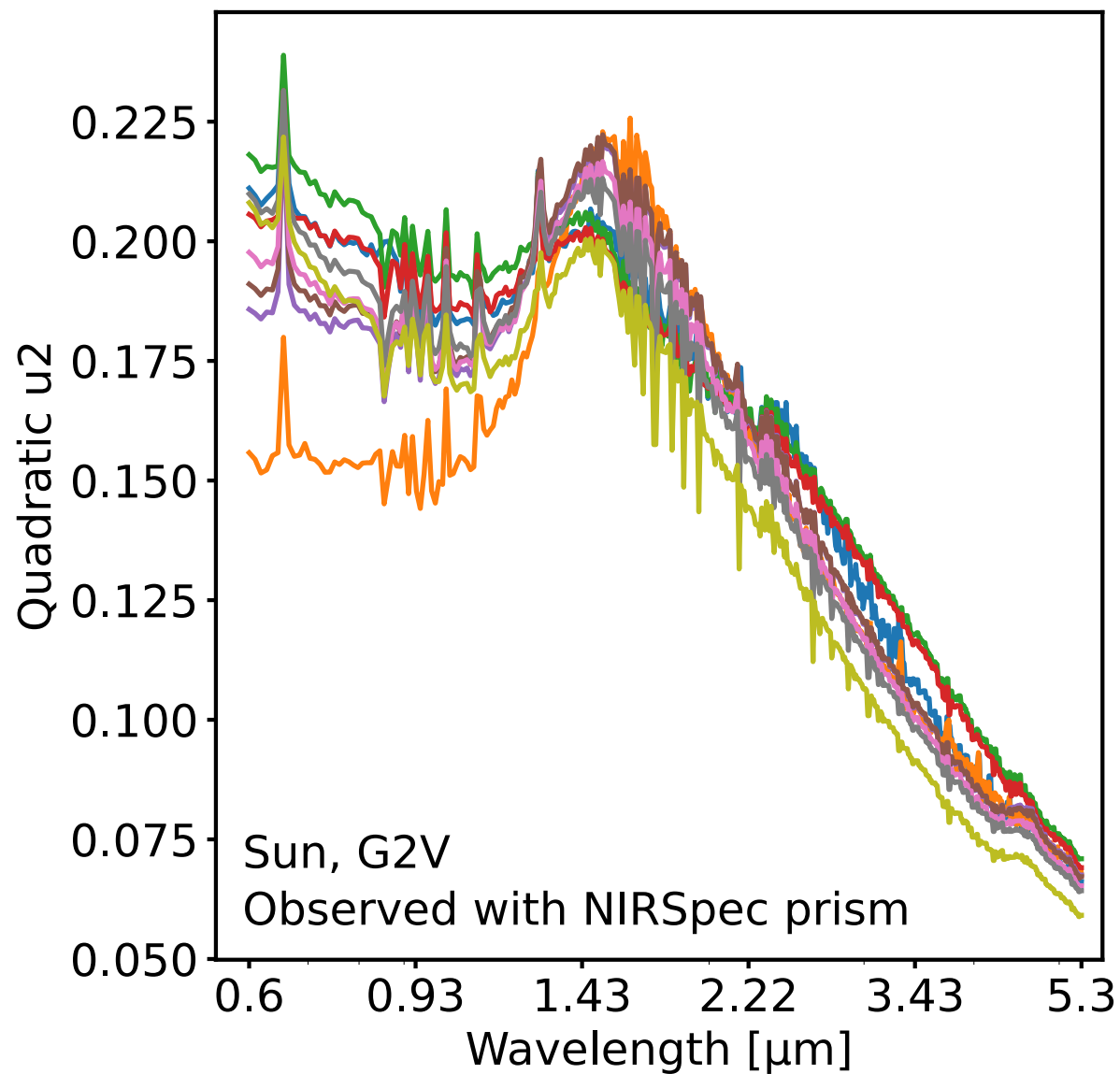
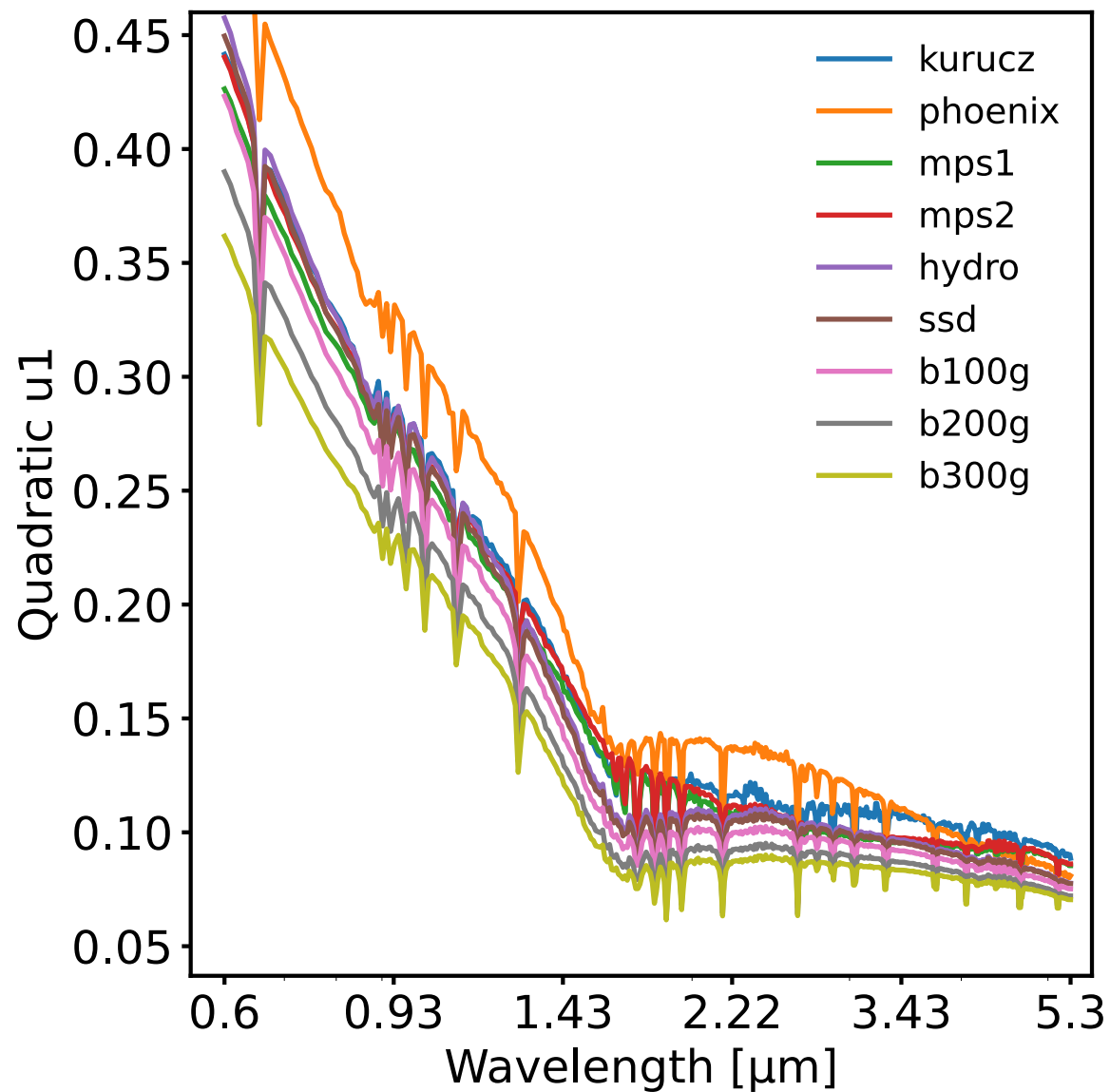
Model	Description
Hydro	Non-magnetic MURaM simulations
SSD	Hydro + small-scale dynamo near the surface
B100G	SSD + global dynamo yielding 100 G mean magnetic field
B200G	SSD + global dynamo yielding 200 G mean magnetic field
B300G	SSD + global dynamo yielding 300 G mean magnetic field

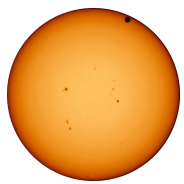






# Spread in limb darkening predicted by stellar atmosphere models



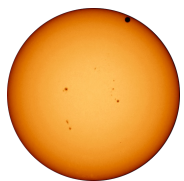


## Disclaimer

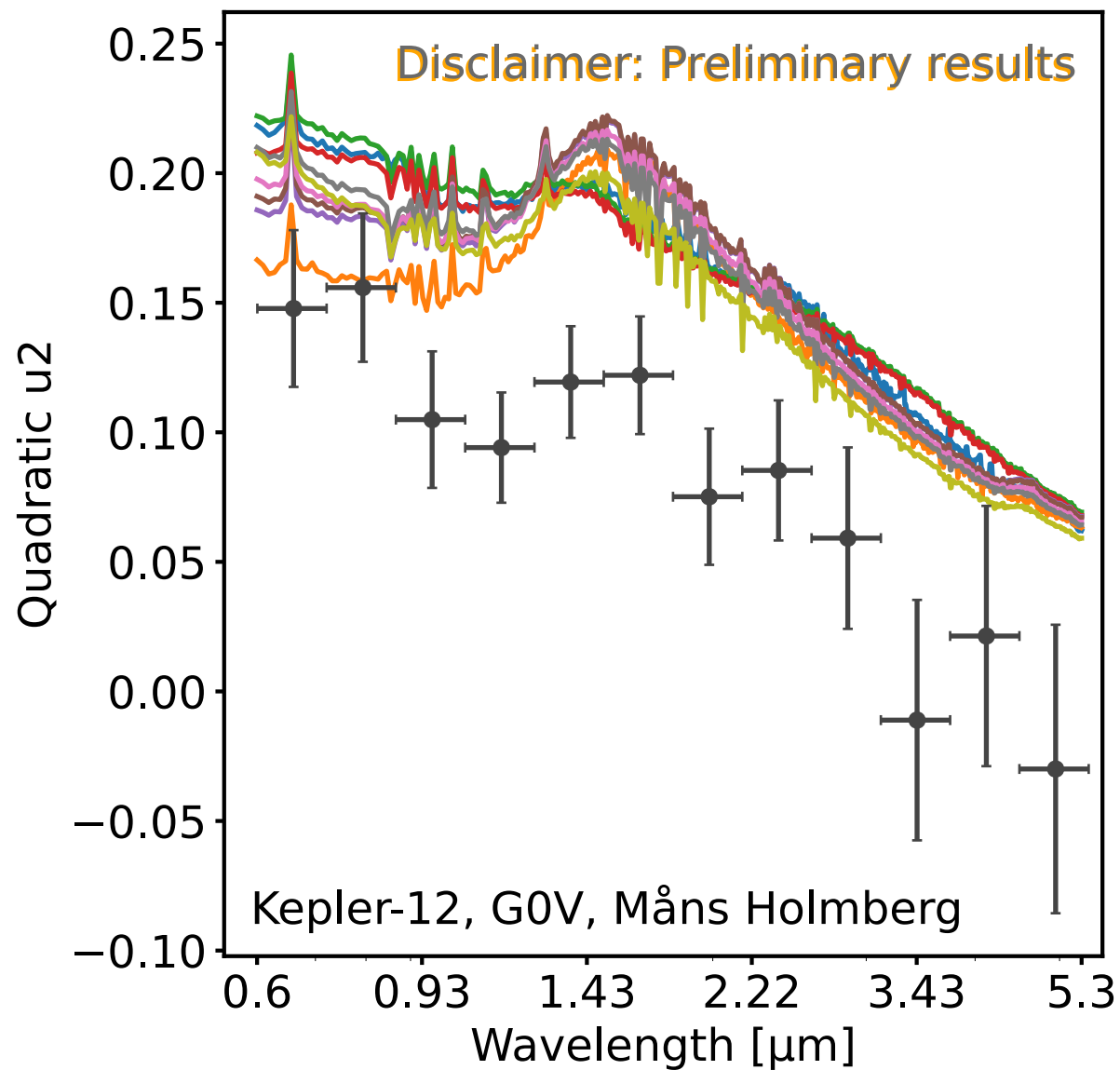
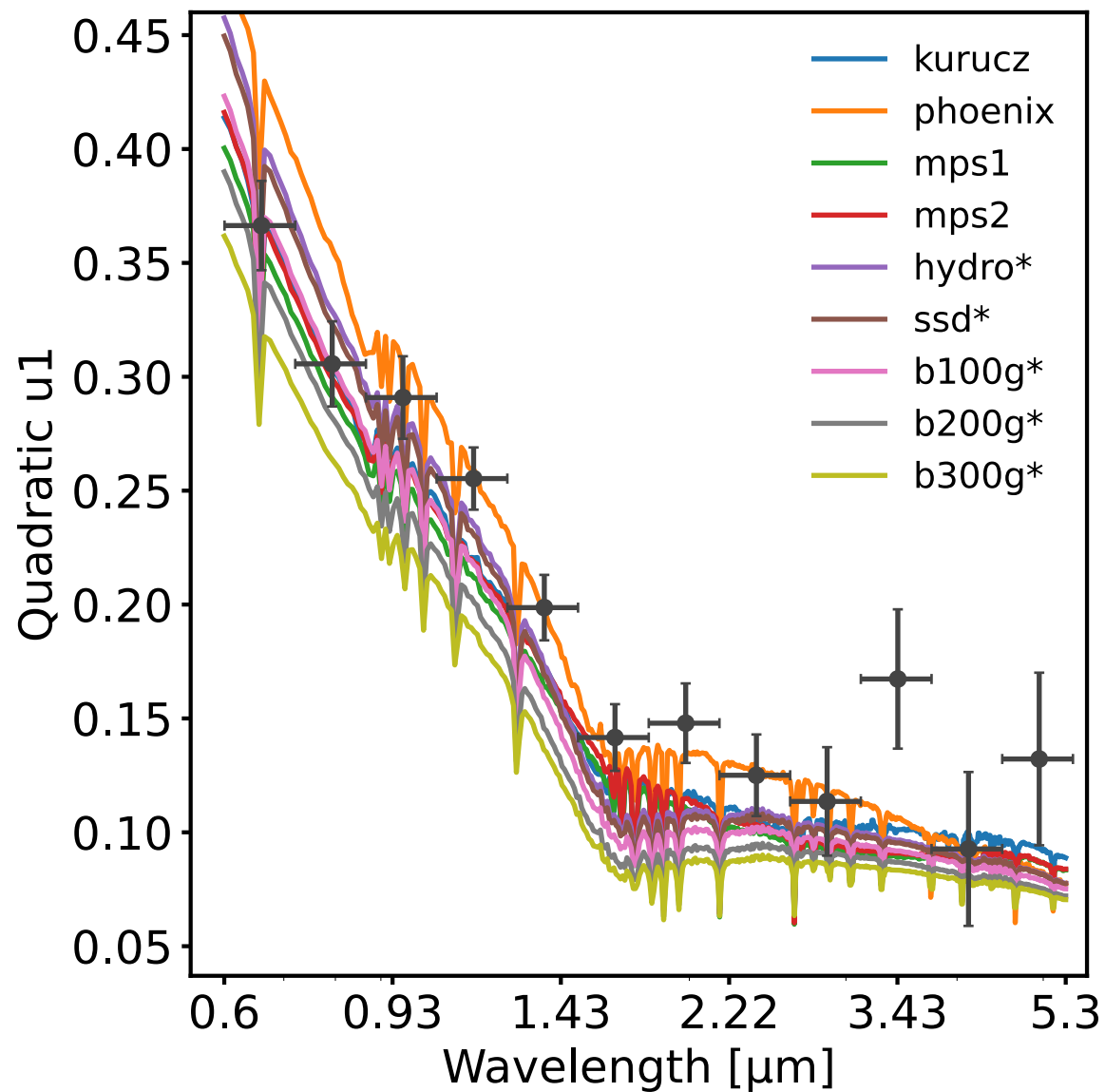
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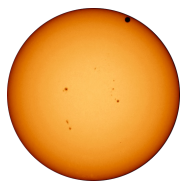
- Results on the remaining slides are preliminary
  - Measurements and models are still being finalized
  - My analysis needs to be checked and improved
- But showing the figures here will stimulate discussion...



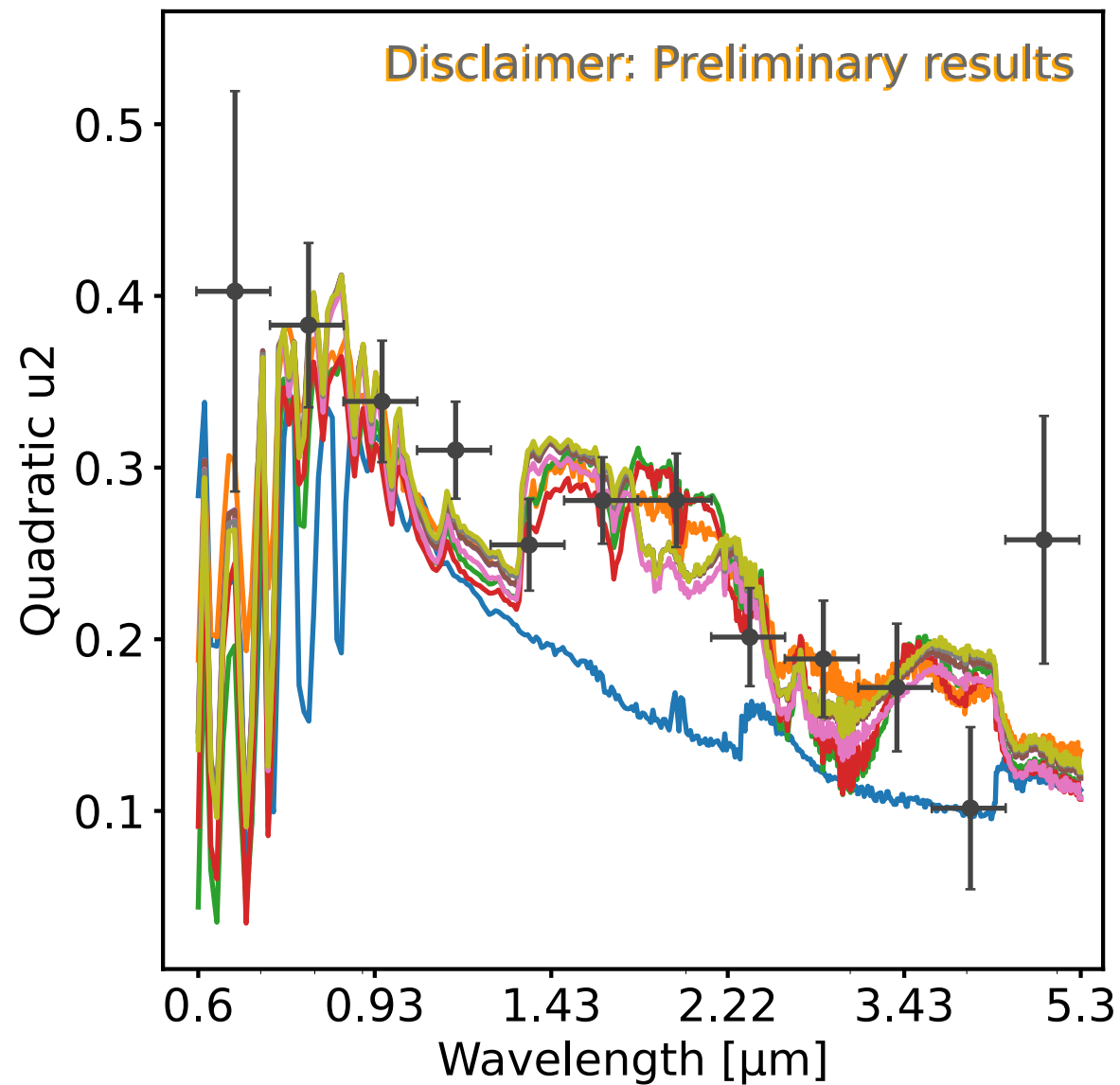
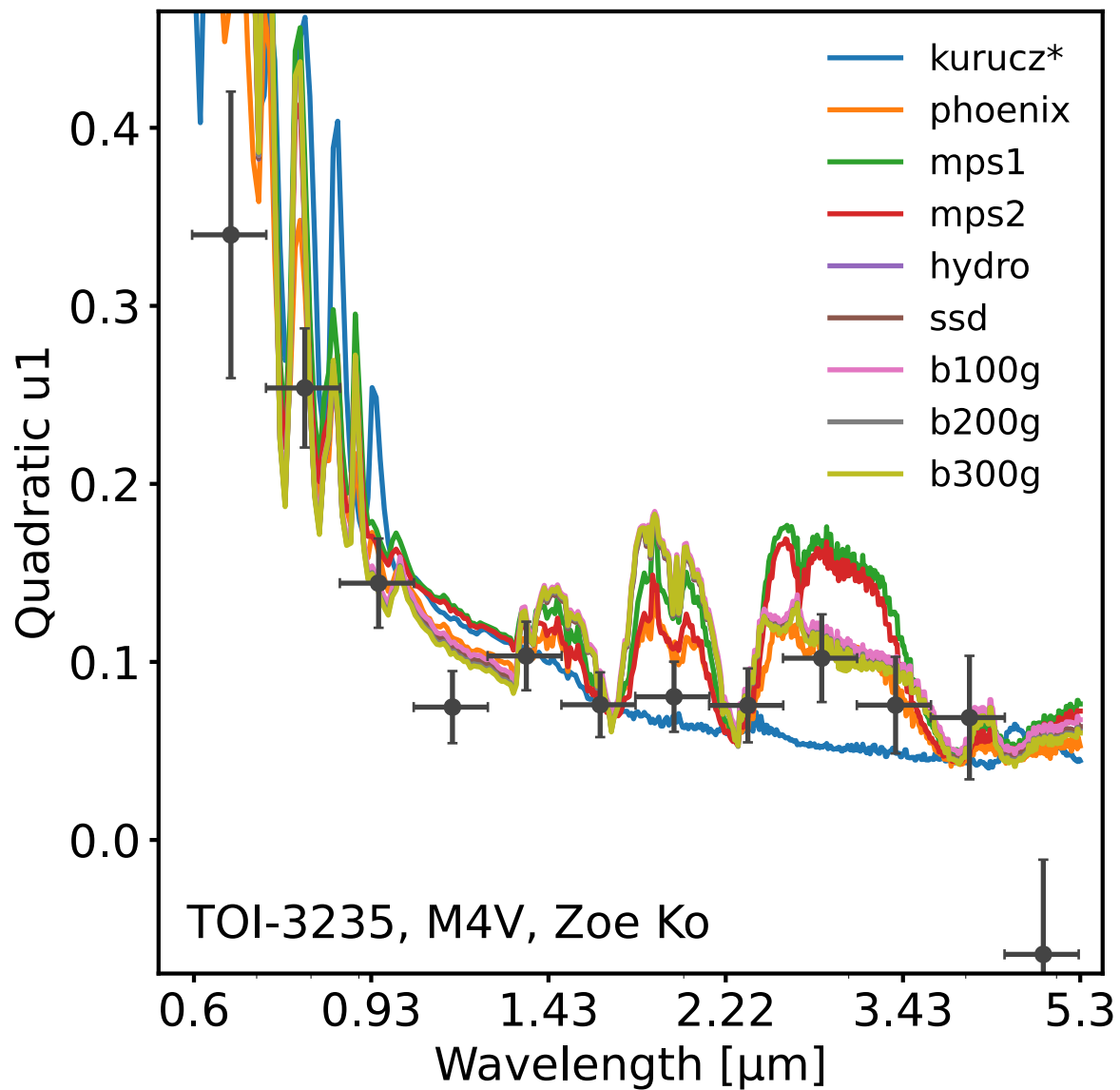


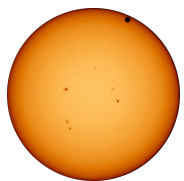
# G0V, Kepler-12



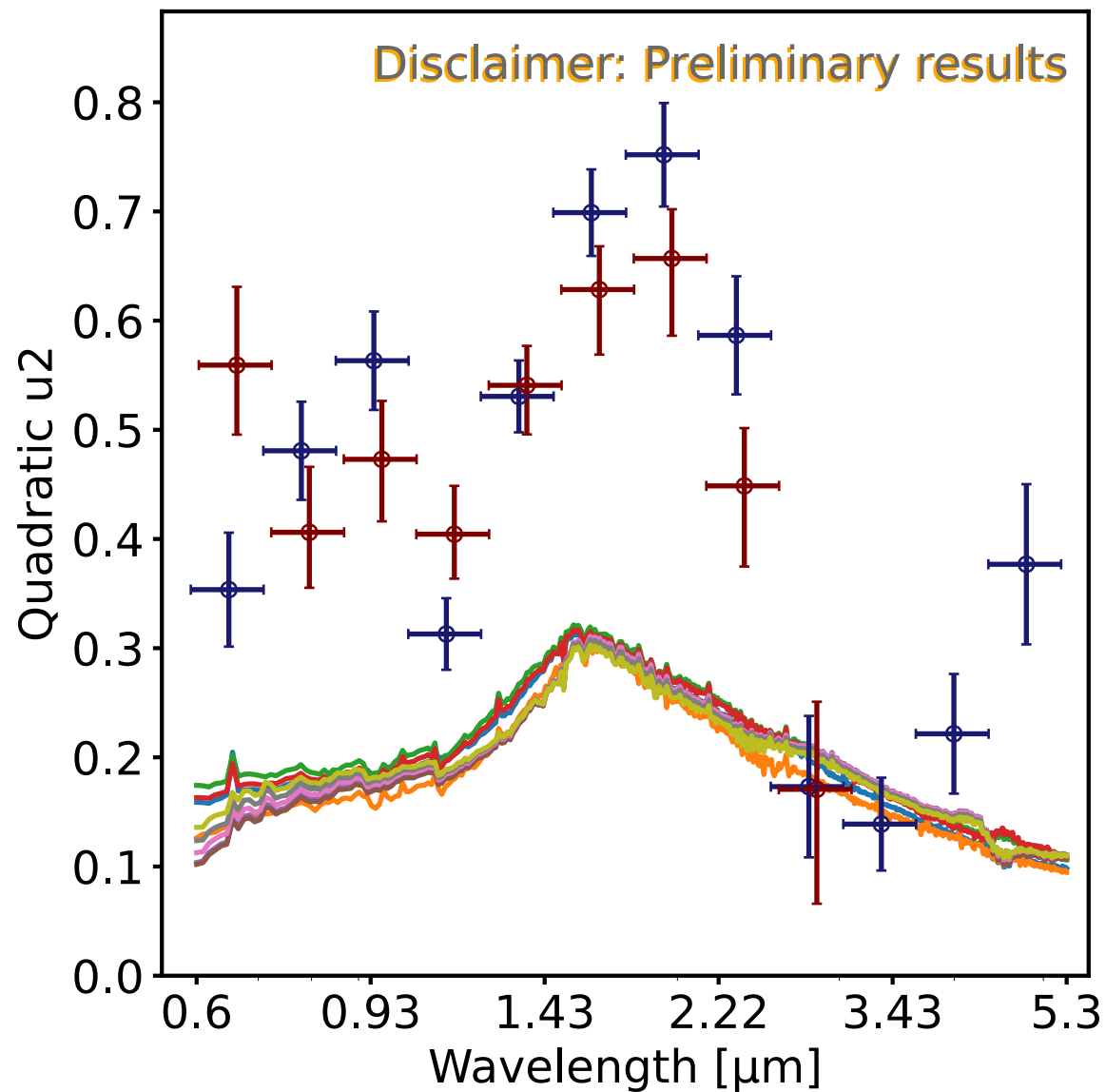
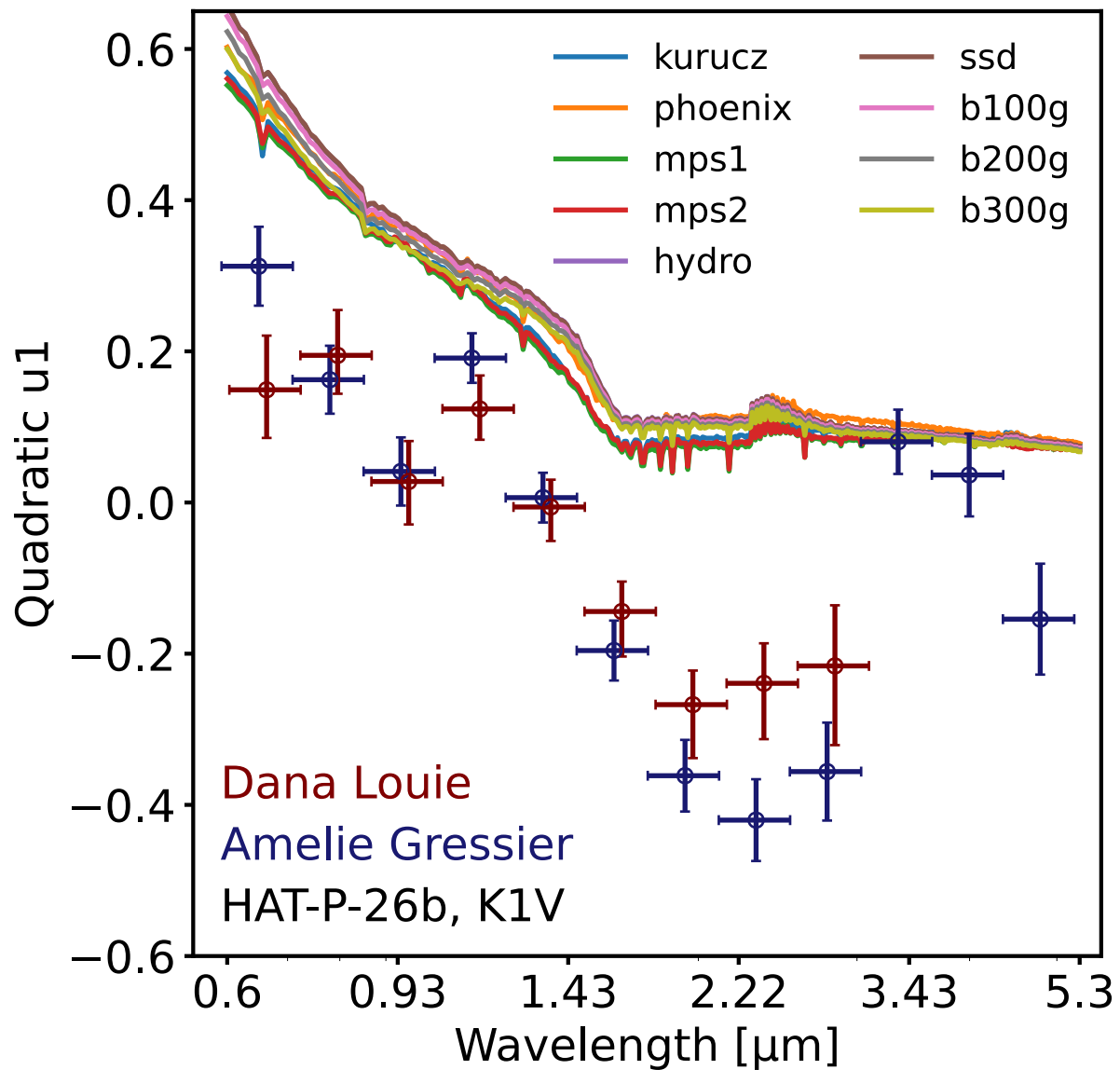


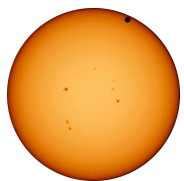
# M4V, TOI-3235



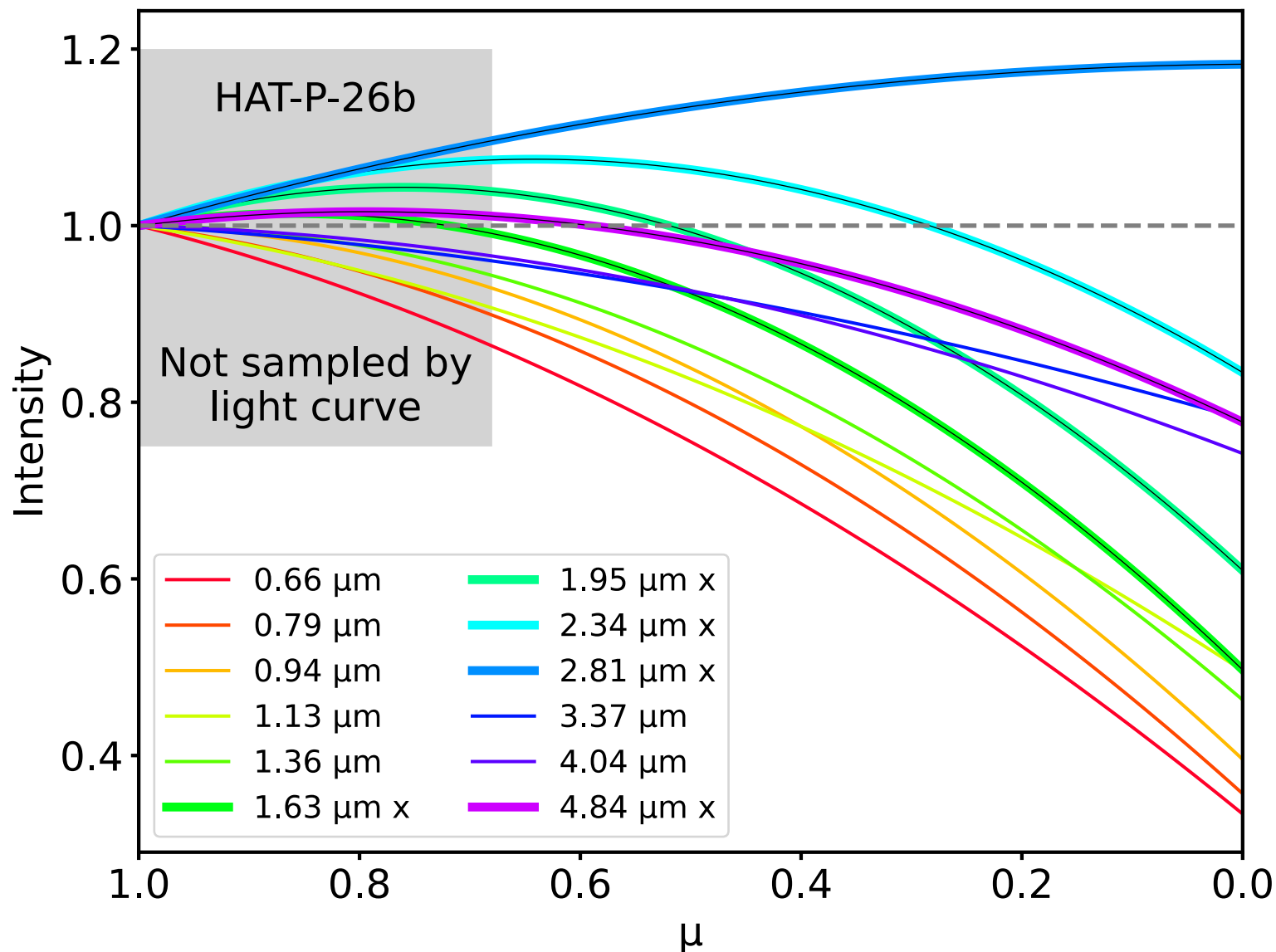


# K1V, HAT-P-26





## Some derived values of $u_1$ , $u_2$ are unphysical (brighter towards limb)



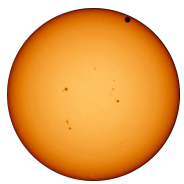
Kipping (2013)

$q_1$ ,  $q_2$  transformation

- Positive intensity
- Monotonic decrease
- Simplifies sampling

Coulombe+ (2024)

$q_1$ ,  $q_2$  can lead to bias  
 $u_1$ ,  $u_2$  is best option



## Take home messages

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- Limb darkening needs attention.
- One JWST transit yields precision comparable to the spread in models.
- Significant discrepancies between observations and models in some cases.
  
- We need more and better observational tests of limb darkening.
- Ultimately, we need models that accurately predict limb darkening.