Planetary Aeronomy: A Case Study of WASP-69b

W. Garrett Levine (Yale University)

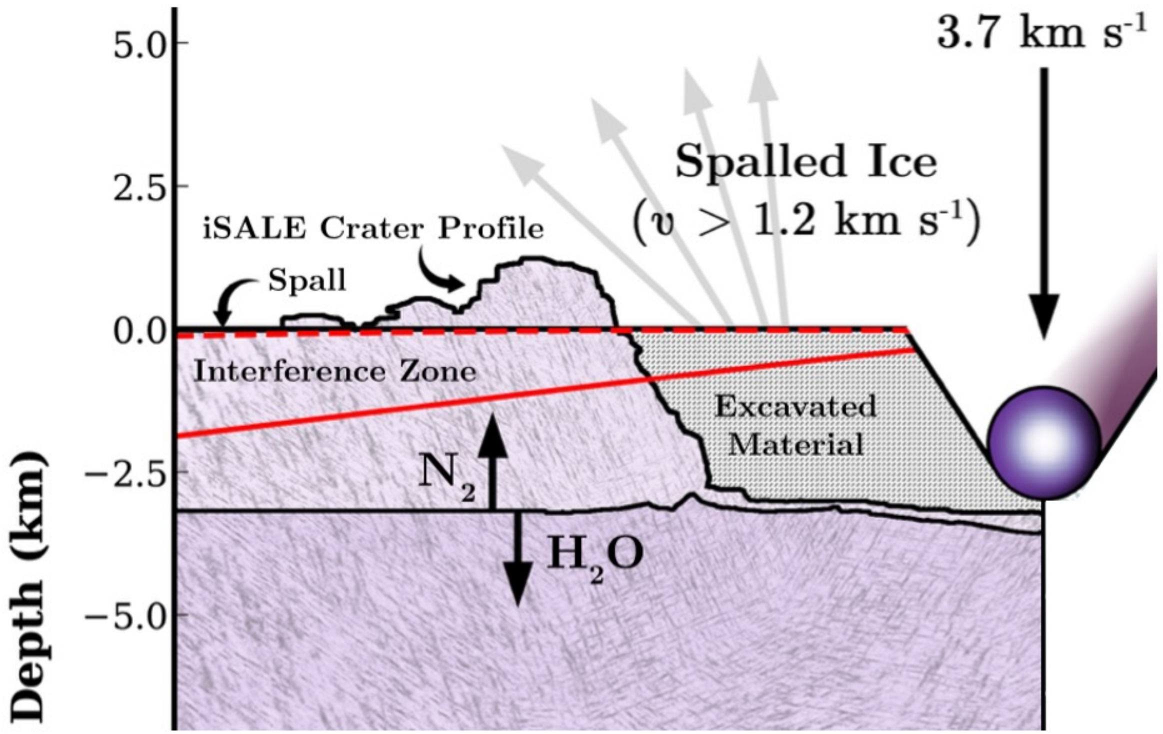
Exoplanet Explorers Webinar

February 16, 2024

Contextualizing Interstellar Minor Planets

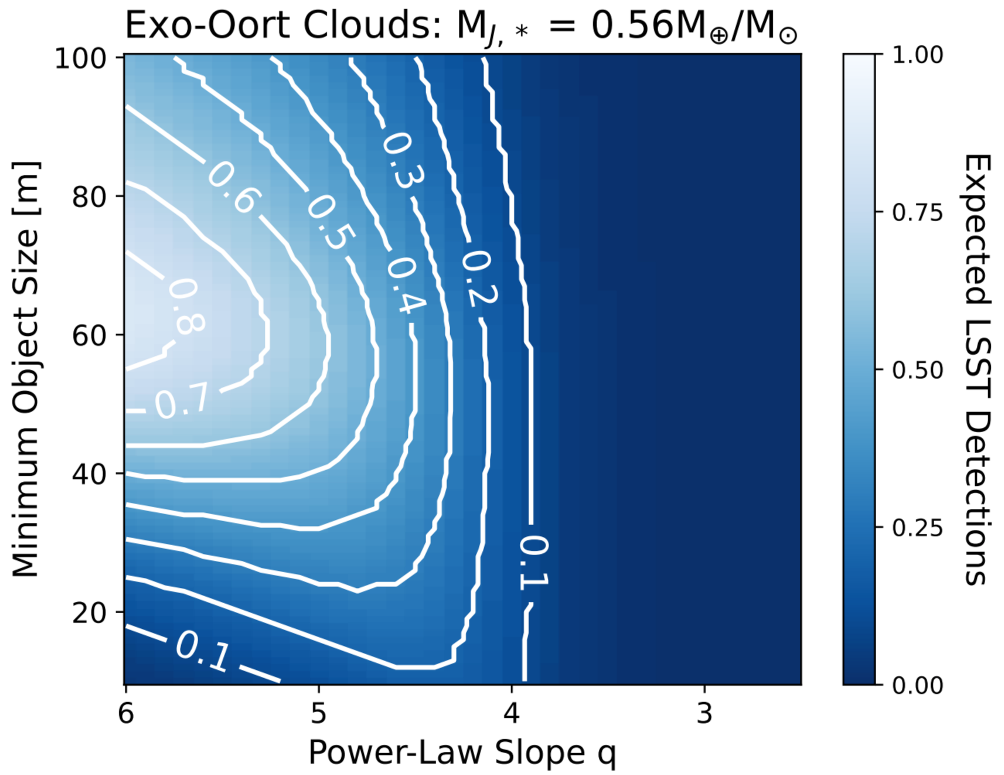
Case Studies: Assessing formation hypotheses for `Oumuamua and Borisov from first principles.

Levine et al. (2021a); Levine et al. (2021b)



Population-Level: Predicting planet-formation constraints from exo-comet counts in LSST.

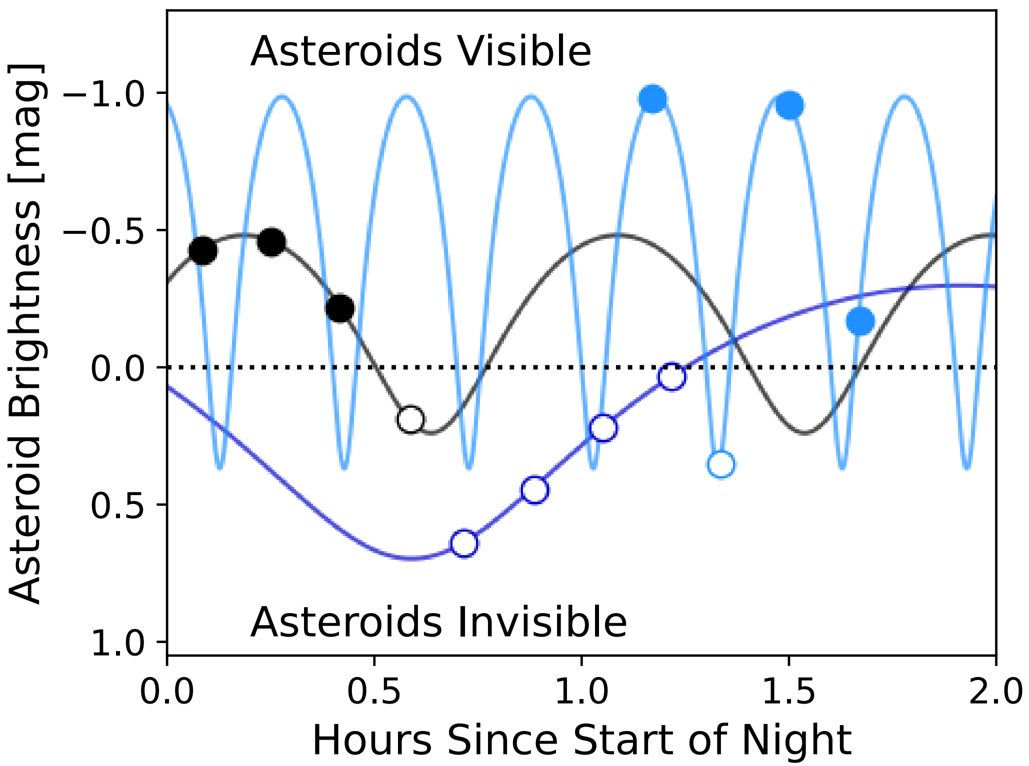
Levine et al. (2023a), Pearce et al. (*in prep*)



Contextualizing Near-Earth Minor Planets

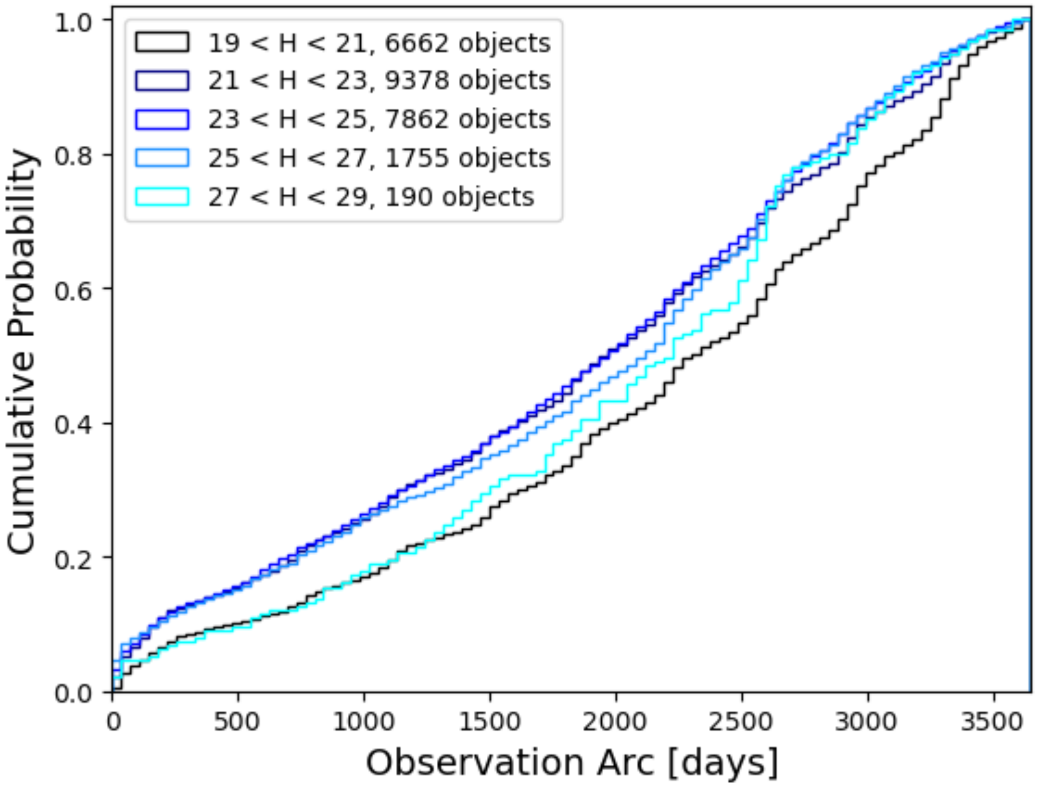
Debiasing Surveys: Showing that an overlooked selection effect related to asteroid shapes could resolve discrepant population estimates.

Levine et al. (2023b)

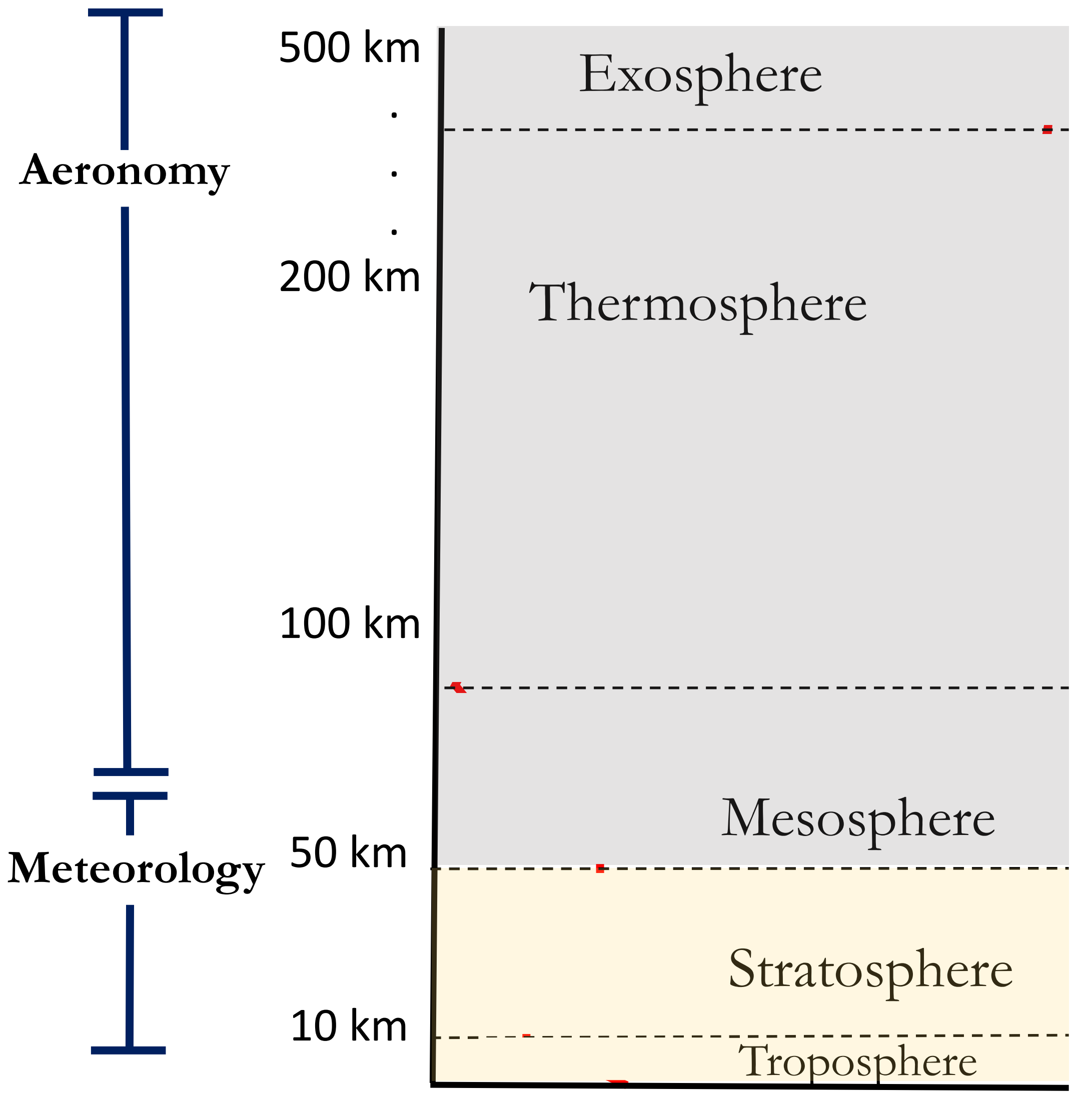


Activity Detection: Identifying outgassing volatiles on near-Earth objects from astrometry in wide-field surveys like LSST.

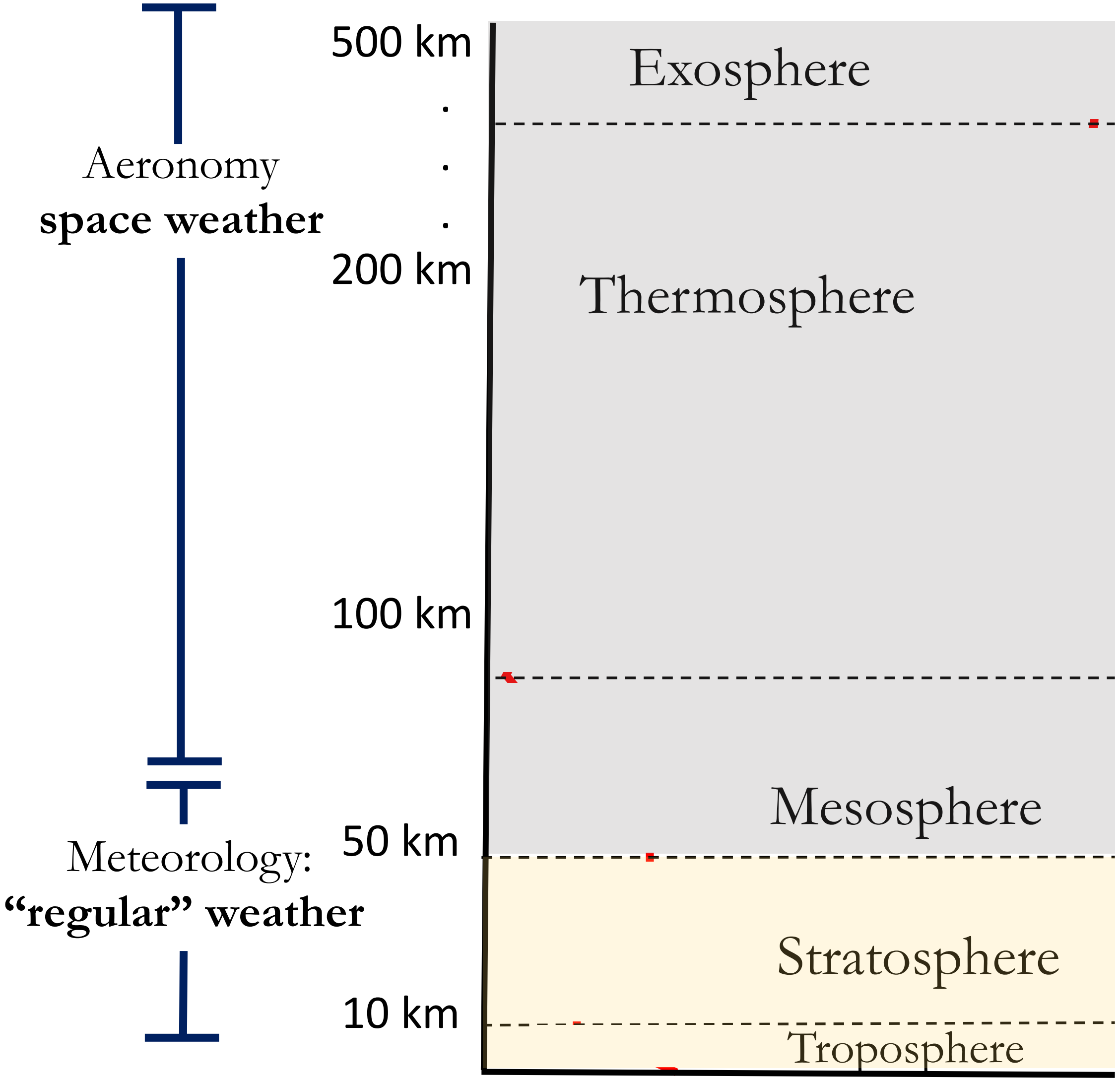
Levine et al. (*in prep*)



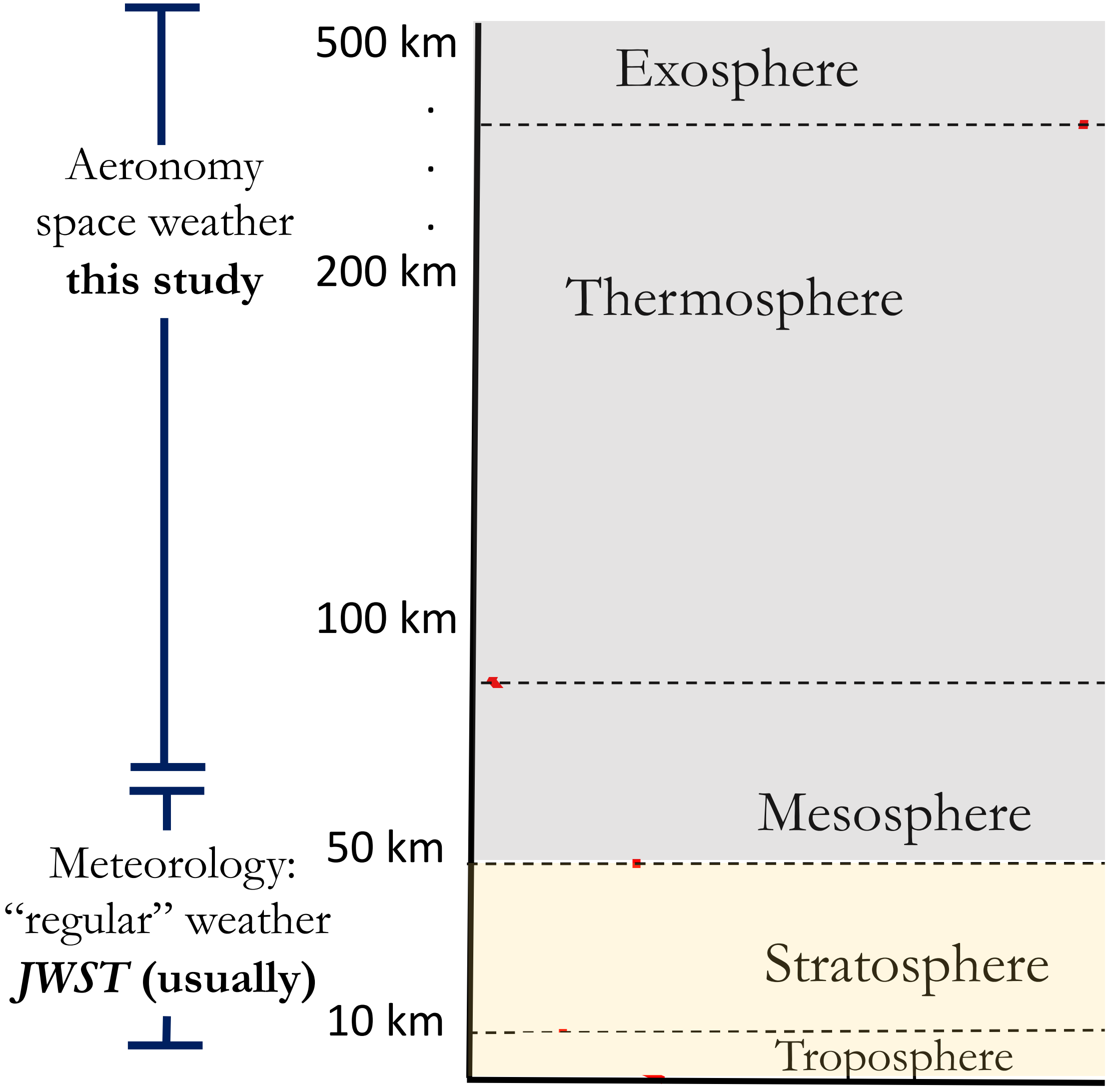
Today's Topic: Planetary Aeronomy (Upper Atmospheres)



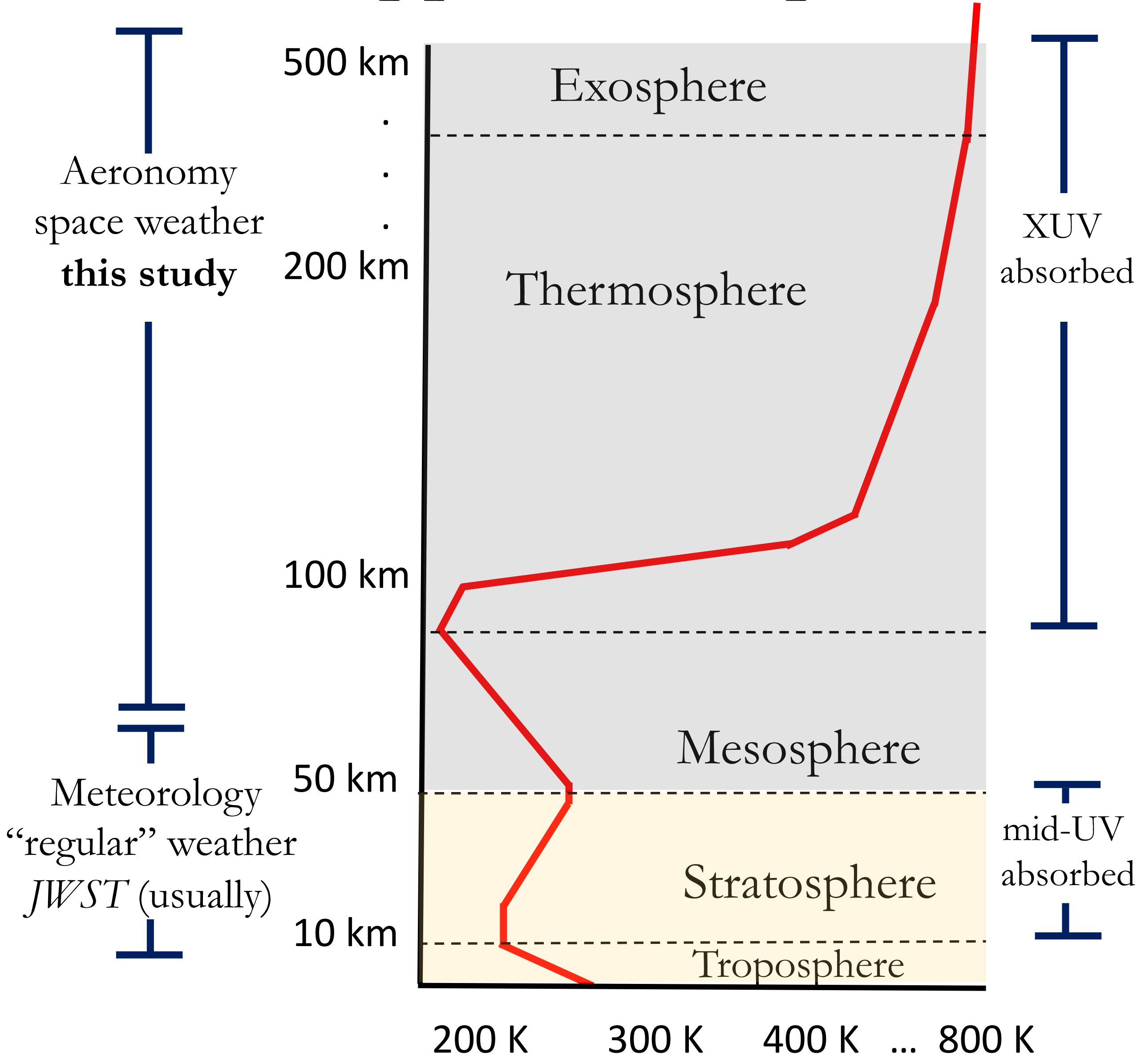
Today's Topic: Planetary Aeronomy (Upper Atmospheres)



Today's Topic: Planetary Aeronomy (Upper Atmospheres)



Today's Topic: Planetary Aeronomy (Upper Atmospheres)



Today's Topic: Planetary Aeronomy (Upper Atmospheres)

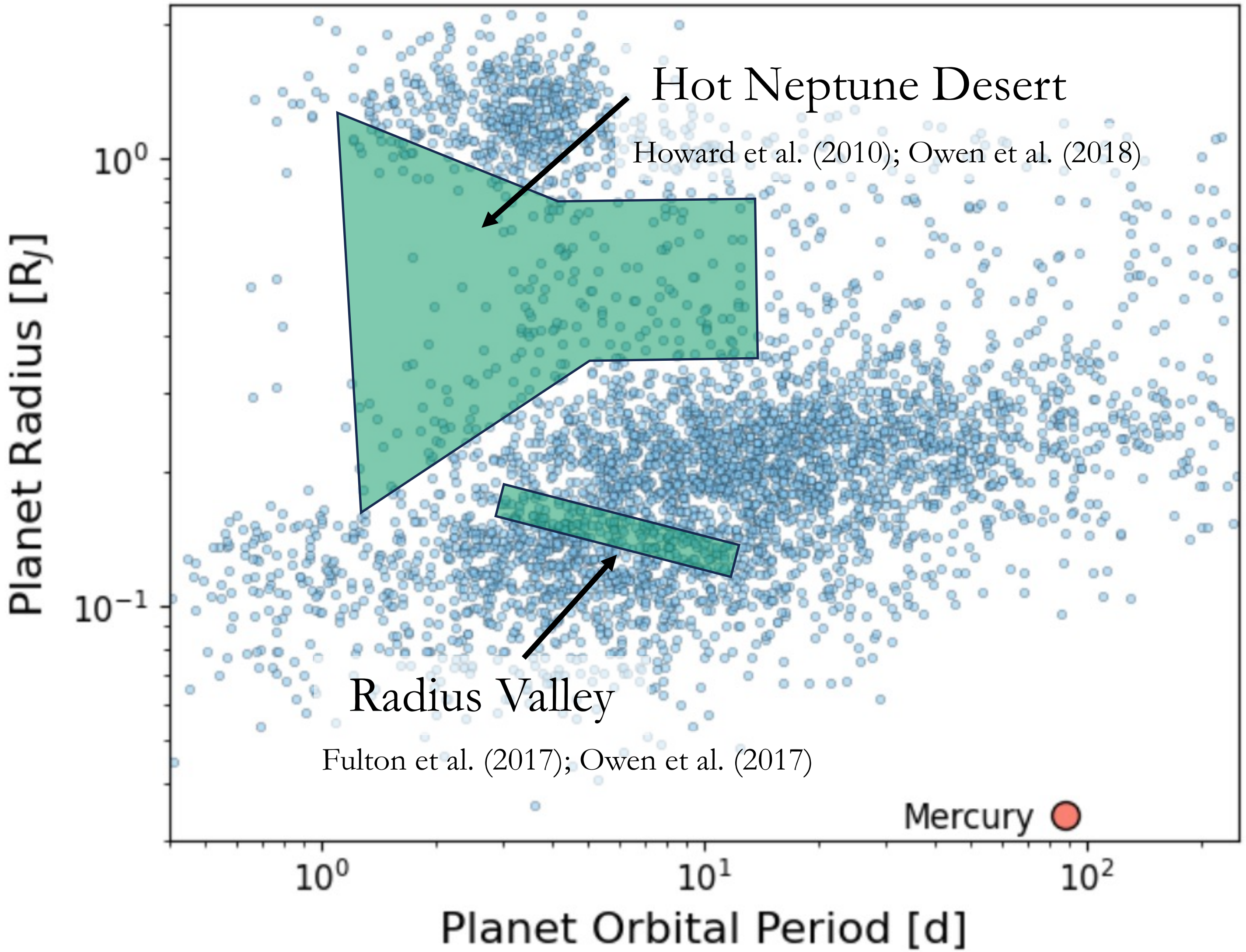
Goal of Study: Understand the response of planetary atmospheres to changes in their space weather environments. Levine et al. (*in prep*) ← submitting next week!

Today's Topic: Planetary Aeronomy (Upper Atmospheres)

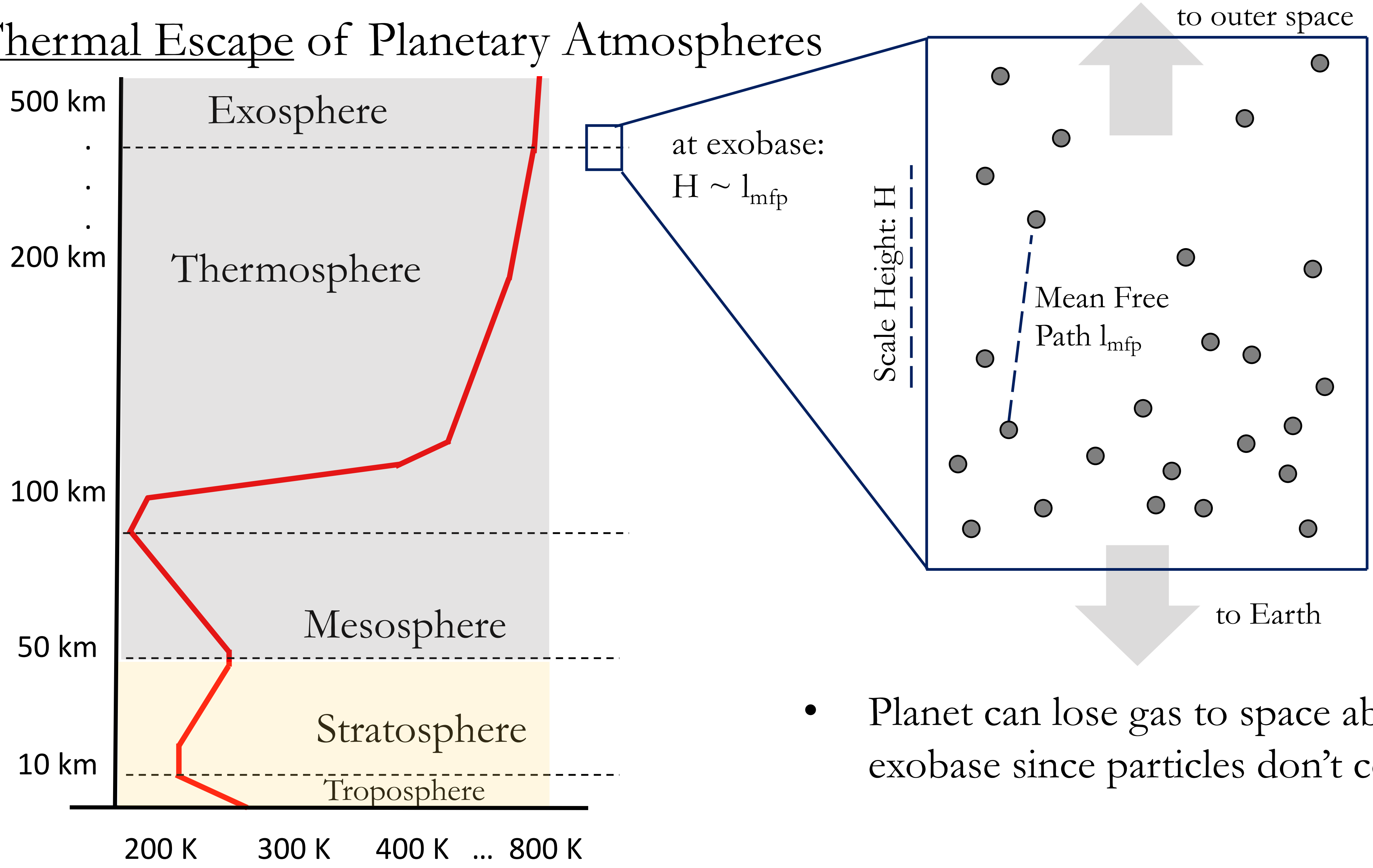
- Earth's thermosphere responds to the Sun's changing XUV output across the eleven-year magnetic activity cycle.

Planetary Aeronomy May Explain Trends in Radii

- Planetary outflows driven by stellar XUV may shrink radii on astronomical timescales.
- Changing stellar XUV output across activity cycle naturally varies a model input.
- Long-term mass-loss models should correctly predict atmospheres' responses on yearslong timescales.

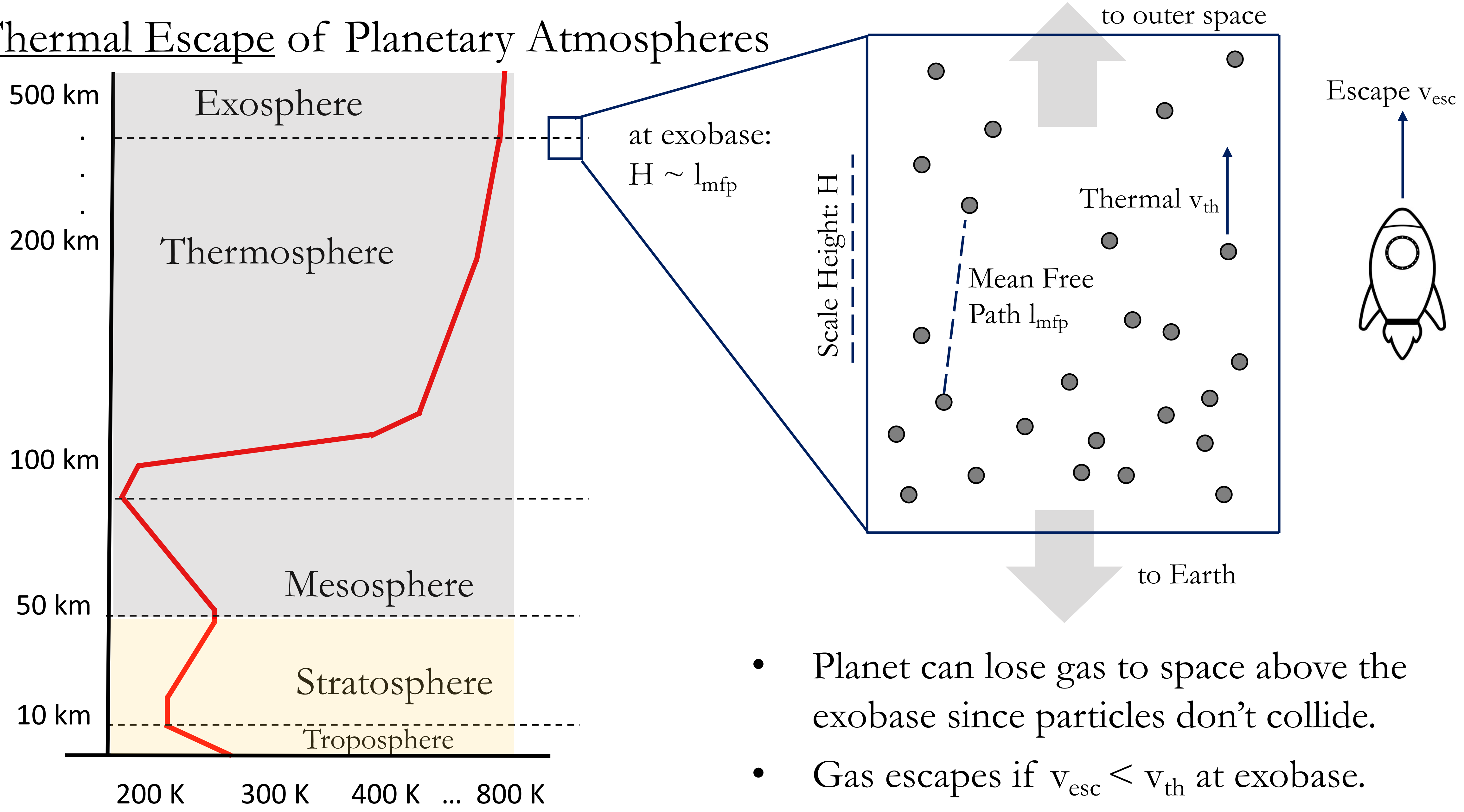


Thermal Escape of Planetary Atmospheres



- Planet can lose gas to space above the exobase since particles don't collide.

Thermal Escape of Planetary Atmospheres



- Planet can lose gas to space above the exobase since particles don't collide.
- Gas escapes if $v_{esc} < v_{th}$ at exobase.

Thermal Escape of Planetary Atmospheres

- Gas escapes if $v_{esc} < v_{th}$ at exobase.

at **Earth**'s exobase: $v_{esc} > v_{th}$

$$\frac{v_{\mathrm{esc}}}{v_{\mathrm{th}}} = \sqrt{\frac{2GM_p m}{kTR_{ex}}}$$

Atmospheric escape is easier when:

- exobase is hot.
- planet is light.
- planet is large.

at **WASP-69b**'s exobase: $v_{esc} \sim v_{th}$

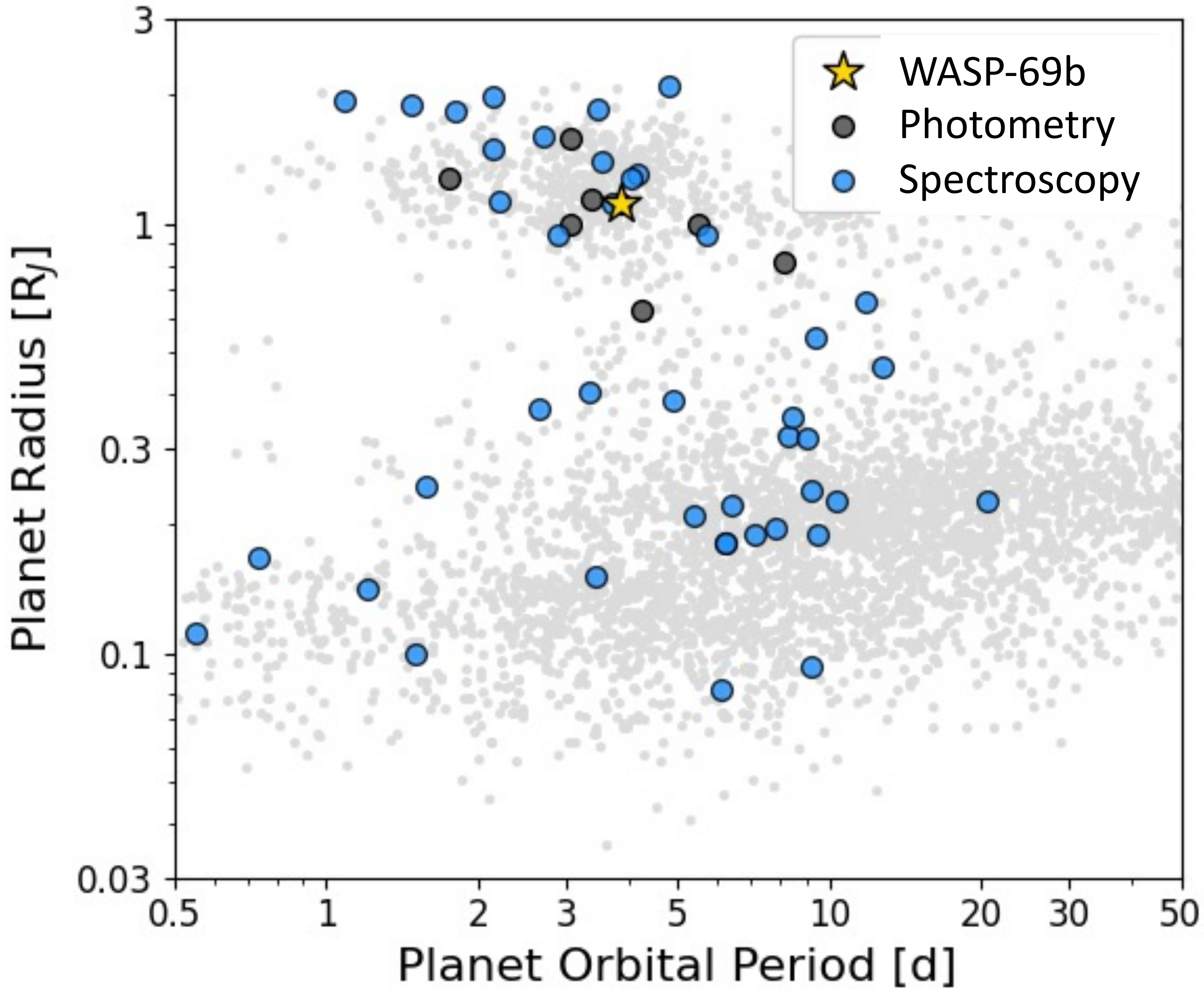
Observing Planetary Thermospheres

Recent thermosphere tracer:

- Metastable He 10830Å
  - -optically thick at high altitude (i.e. indicator of aeronomy)
  - -no interstellar absorption
  - -visible from ground

- This Study: observe one exoplanet over time.

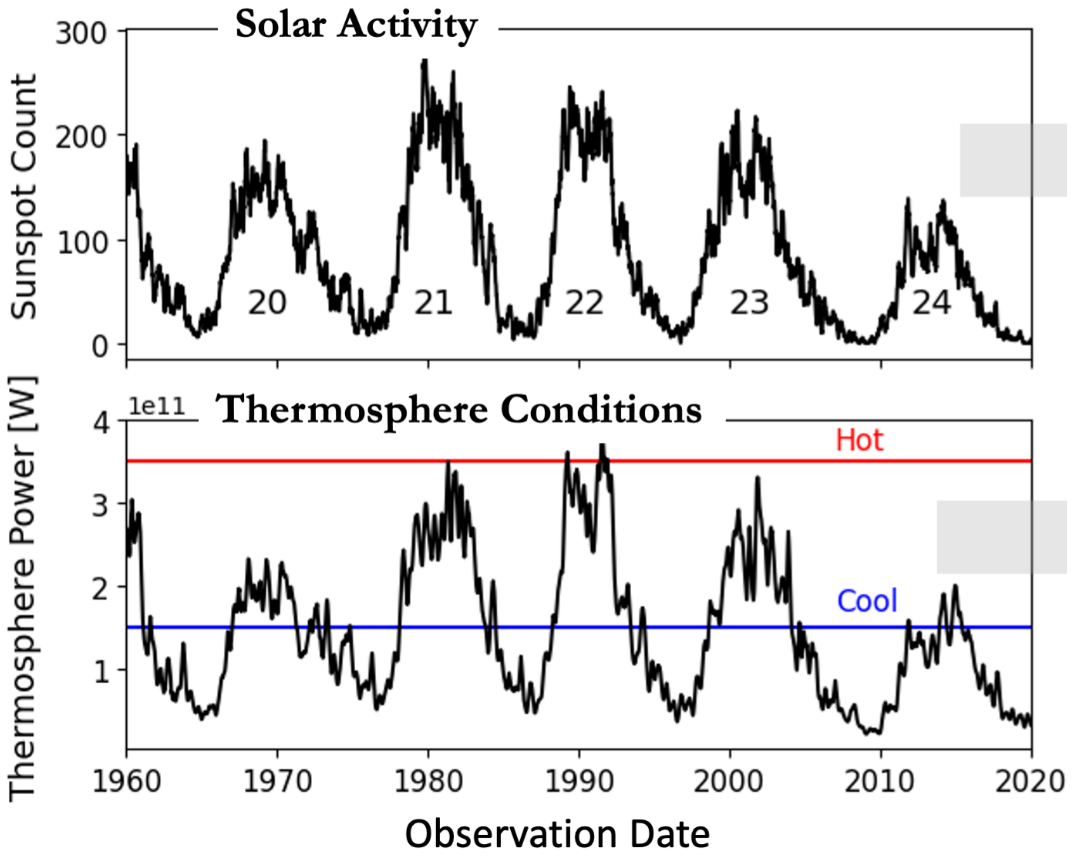
Single-Epoch (Attempted) Metastable He Measurements



Planetary Thermospheres Change with Stellar XUV

Understand the response of exoplanet atmospheres to changes in their space weather environments.

Earth-Sun System

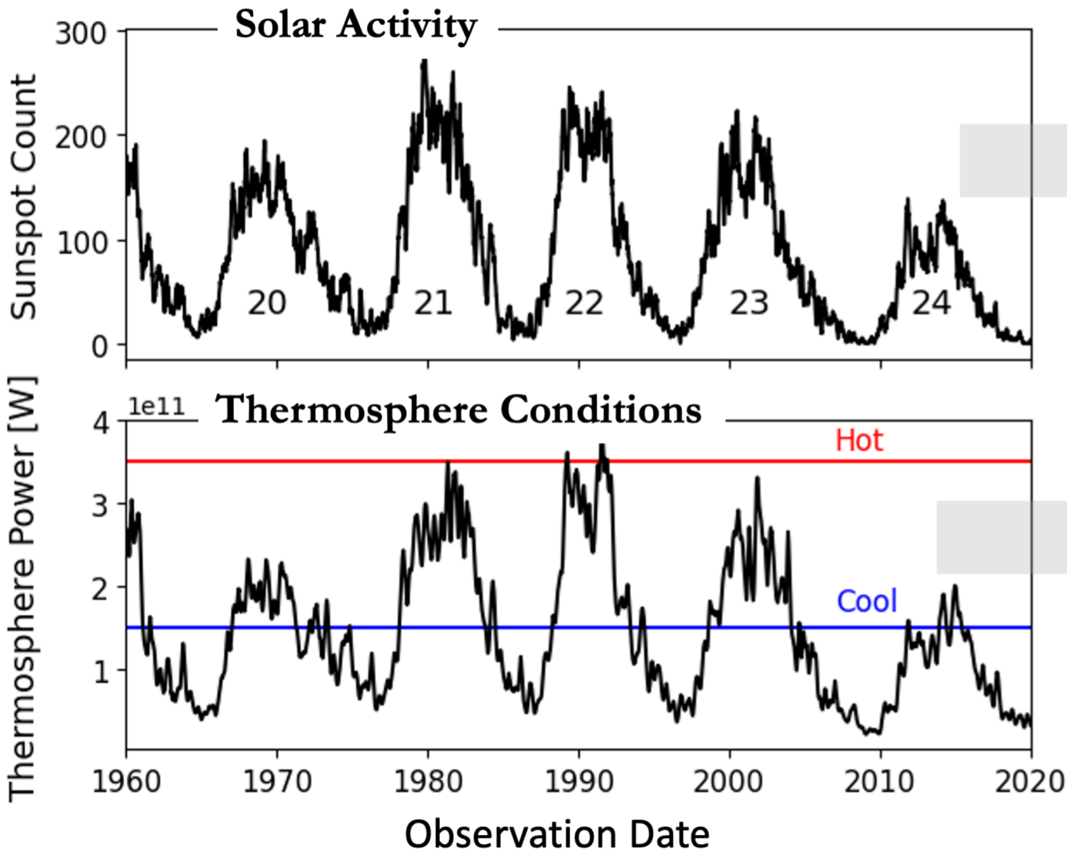


Levine et al. (*in prep*)

Planetary Thermospheres Change with Stellar XUV

Understand the response of **exoplanet atmospheres** to changes in their space weather environments.

Earth-Sun System



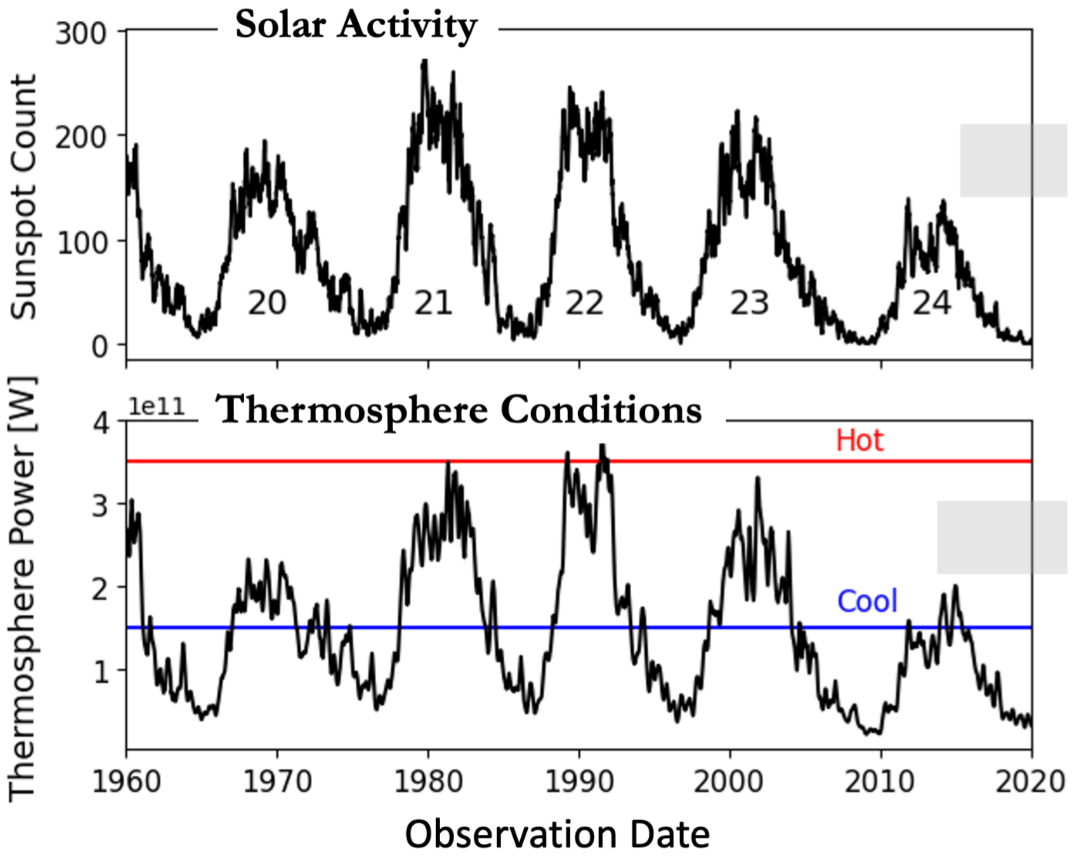
1. **Atmospheric data.**

Levine et al. (*in prep*)

Planetary Thermospheres Change with Stellar XUV

Understand the response of exoplanet atmospheres to changes in their **space weather environments**.

Earth-Sun System



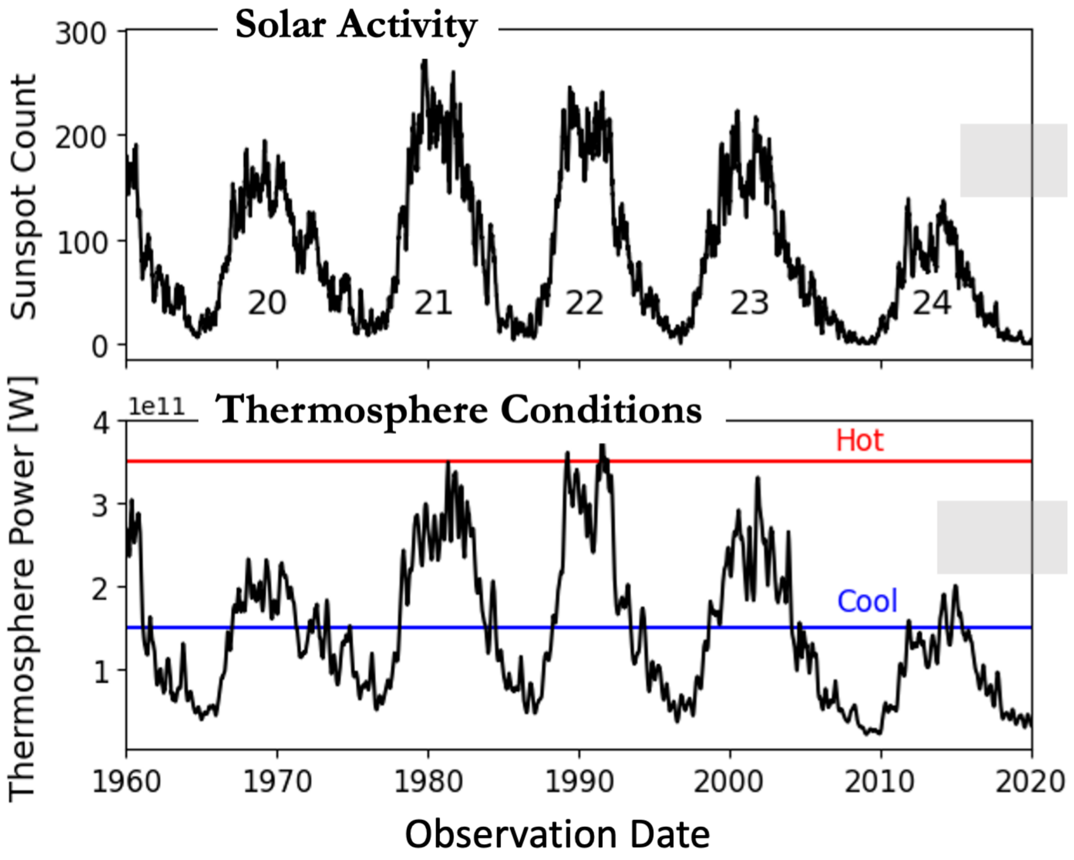
1. Atmospheric data.
2. **Stellar XUV output.**

Levine et al. (*in prep*)

Planetary Thermospheres Change with Stellar XUV

Understand the response of exoplanet atmospheres to **changes** in their space weather environments.

Earth-Sun System



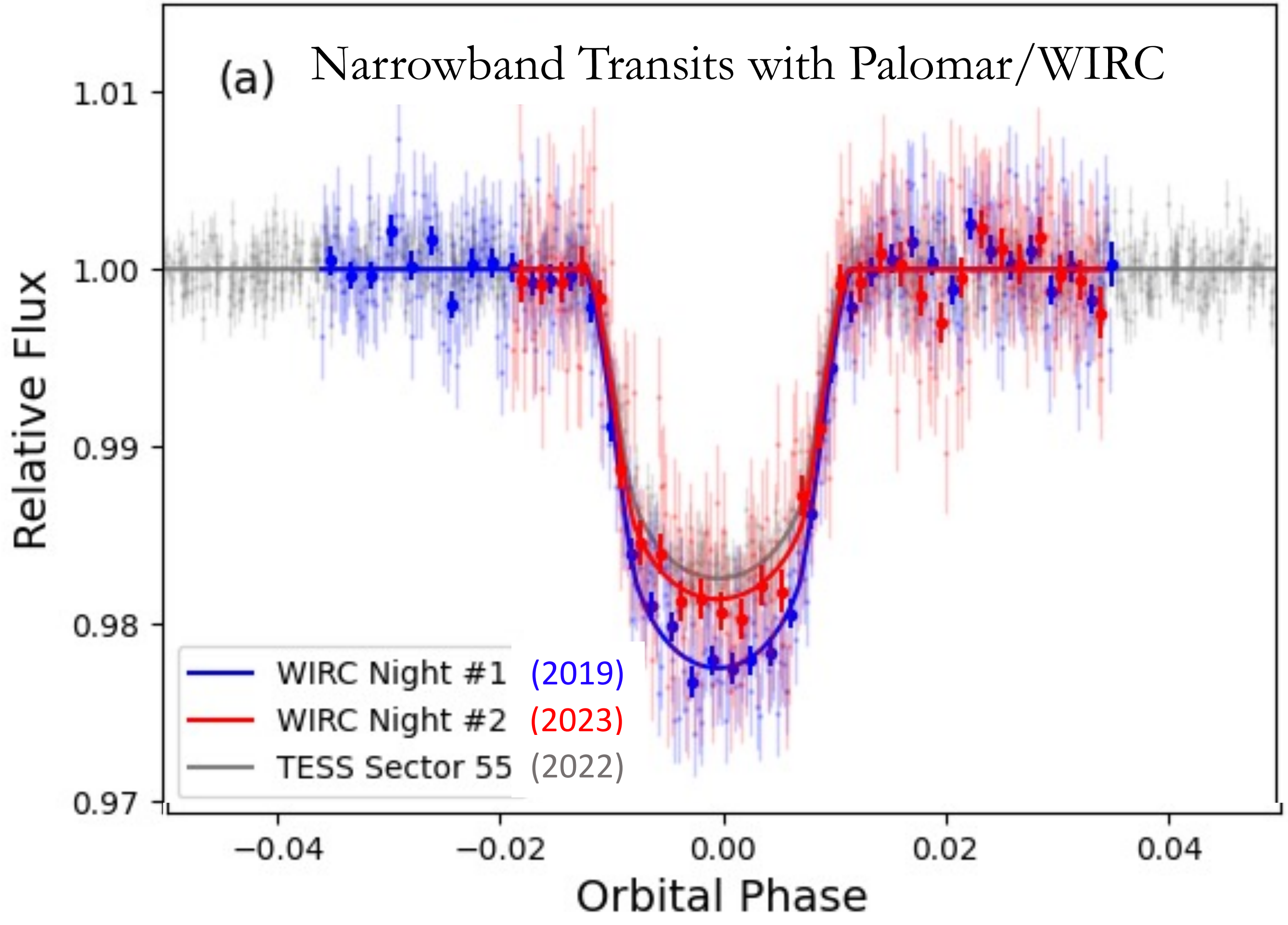
1. Atmospheric data.
2. Stellar XUV output.
3. **Long-term monitoring**.

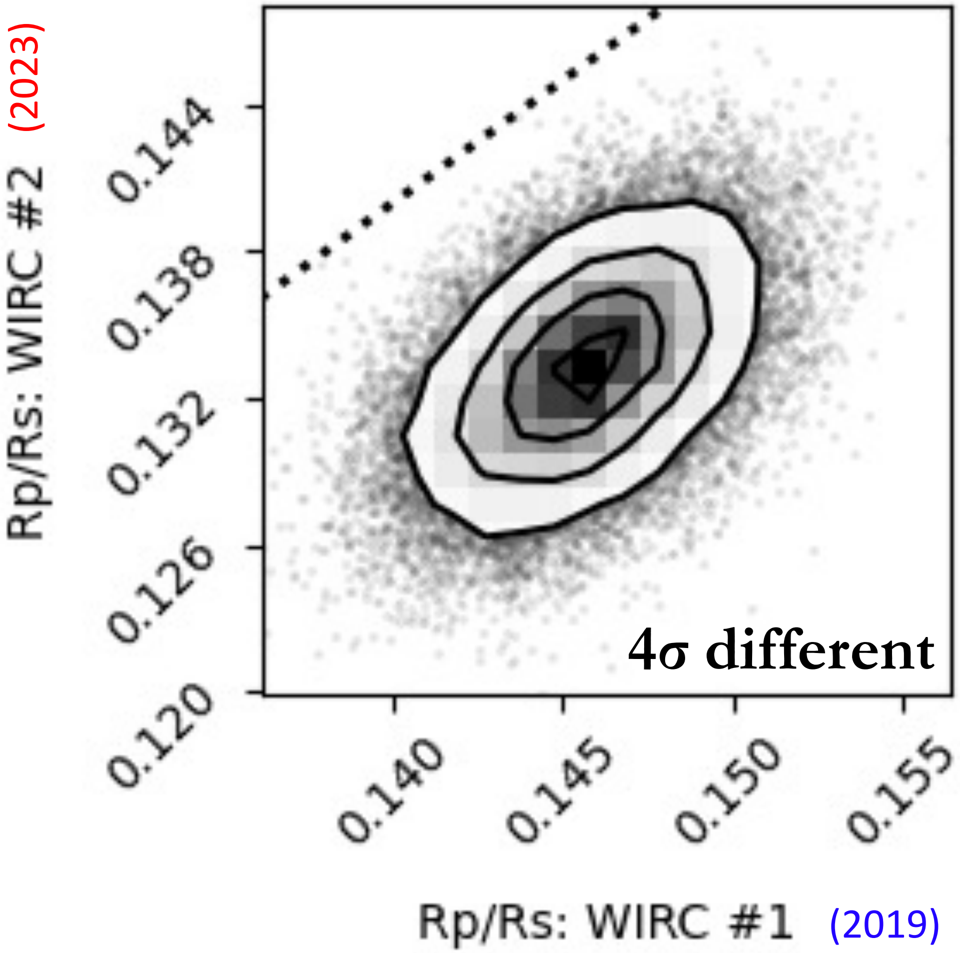
We need data over multiple wavelengths and epochs.

Levine et al. (*in prep*)

Planetary Thermospheres Change with Stellar XUV

1. Atmospheric data. 2. Stellar XUV output. 3. Long-term monitoring.



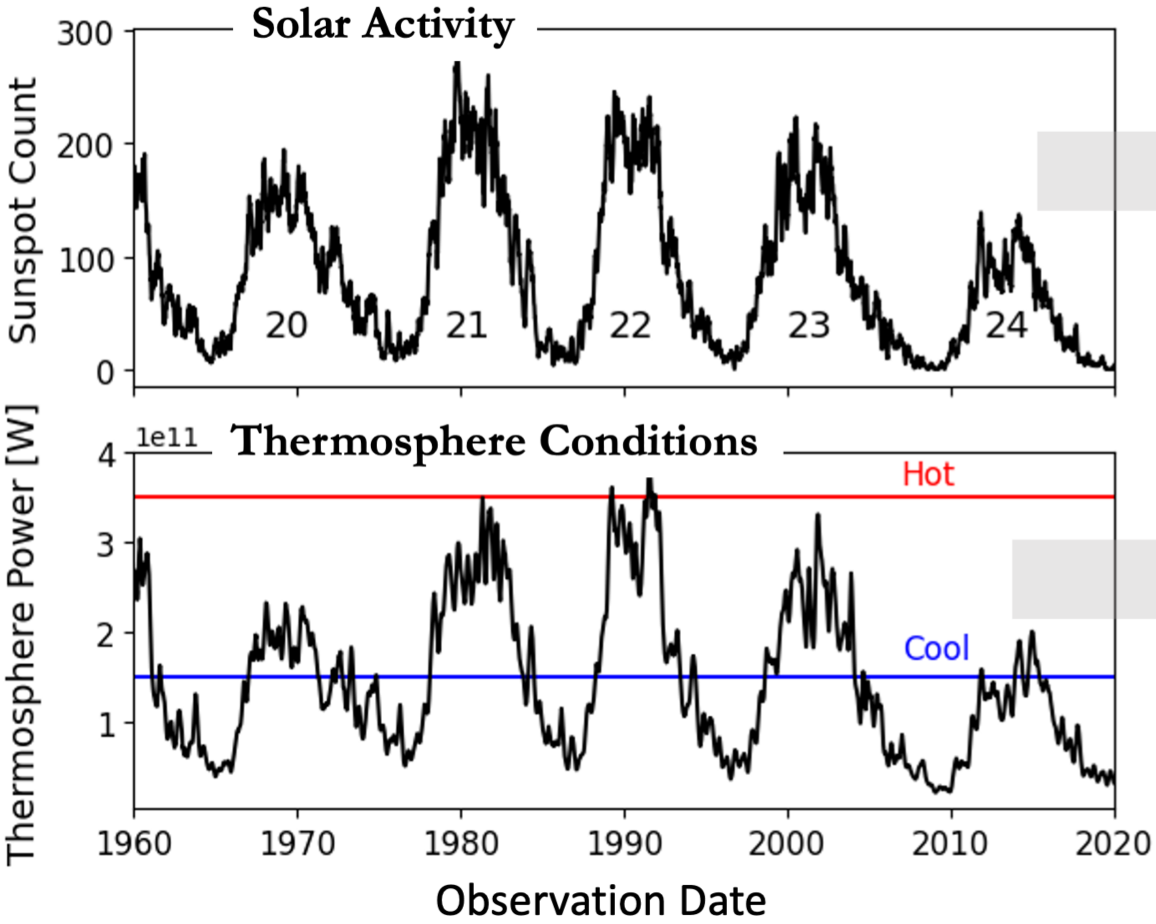


Levine et al. (*in prep*)

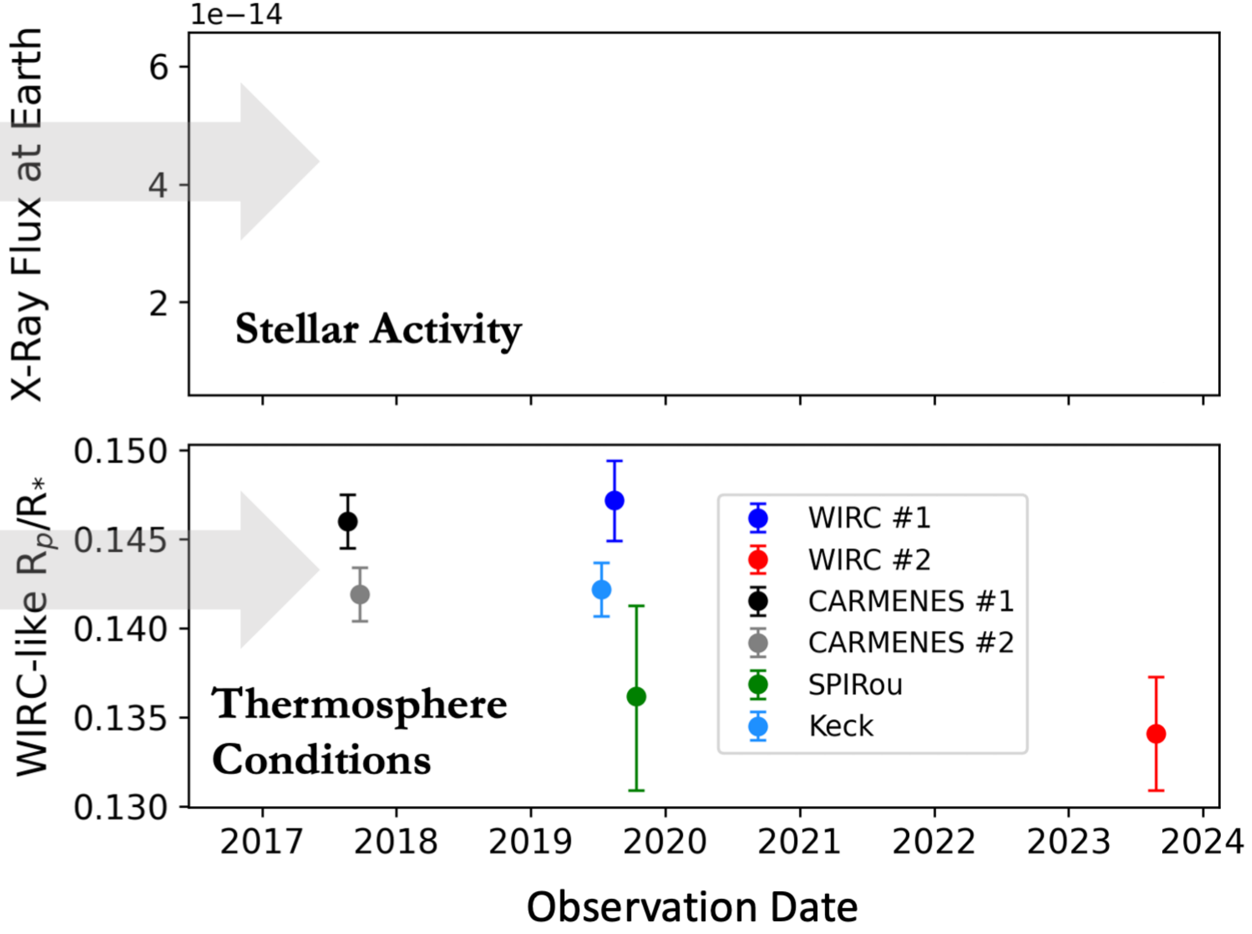
Planetary Thermospheres Change with Stellar XUV

1. Atmospheric data. 2. Stellar XUV output. **3. Long-term monitoring.**

Earth-Sun System



WASP-69 System

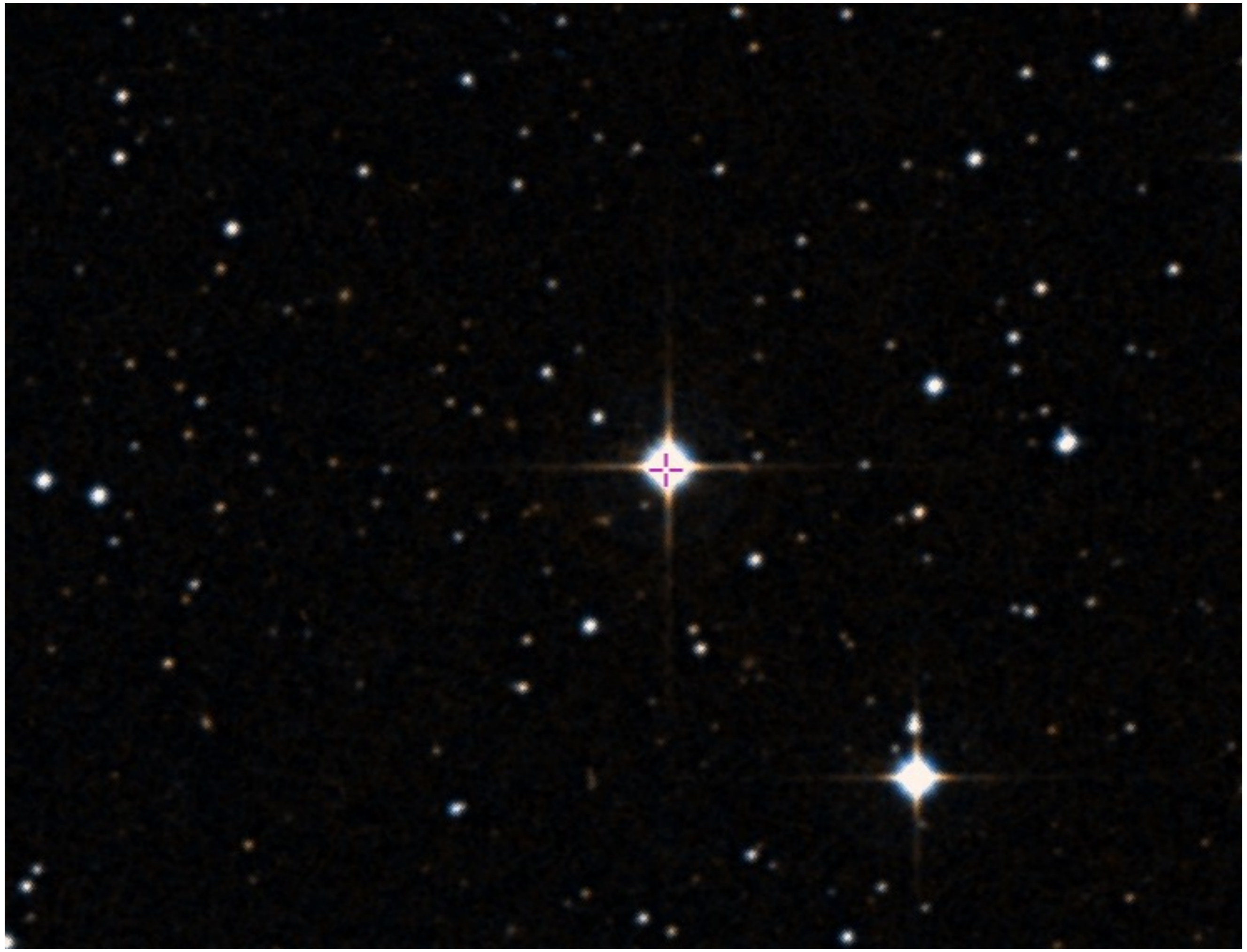


Levine et al. (*in prep*)

Planetary Thermospheres Change with Stellar XUV

1. Atmospheric data. **2. Stellar XUV output.** 3. Long-term monitoring.

- *Swift Observatory* measured X-ray flux of WASP-69 in Sep. 2023.
- Time awarded via DDT to follow-up observed metastable He variability from planetary thermosphere.
- Total of 11.9ks (3.4hr) of exposure time across five visits.

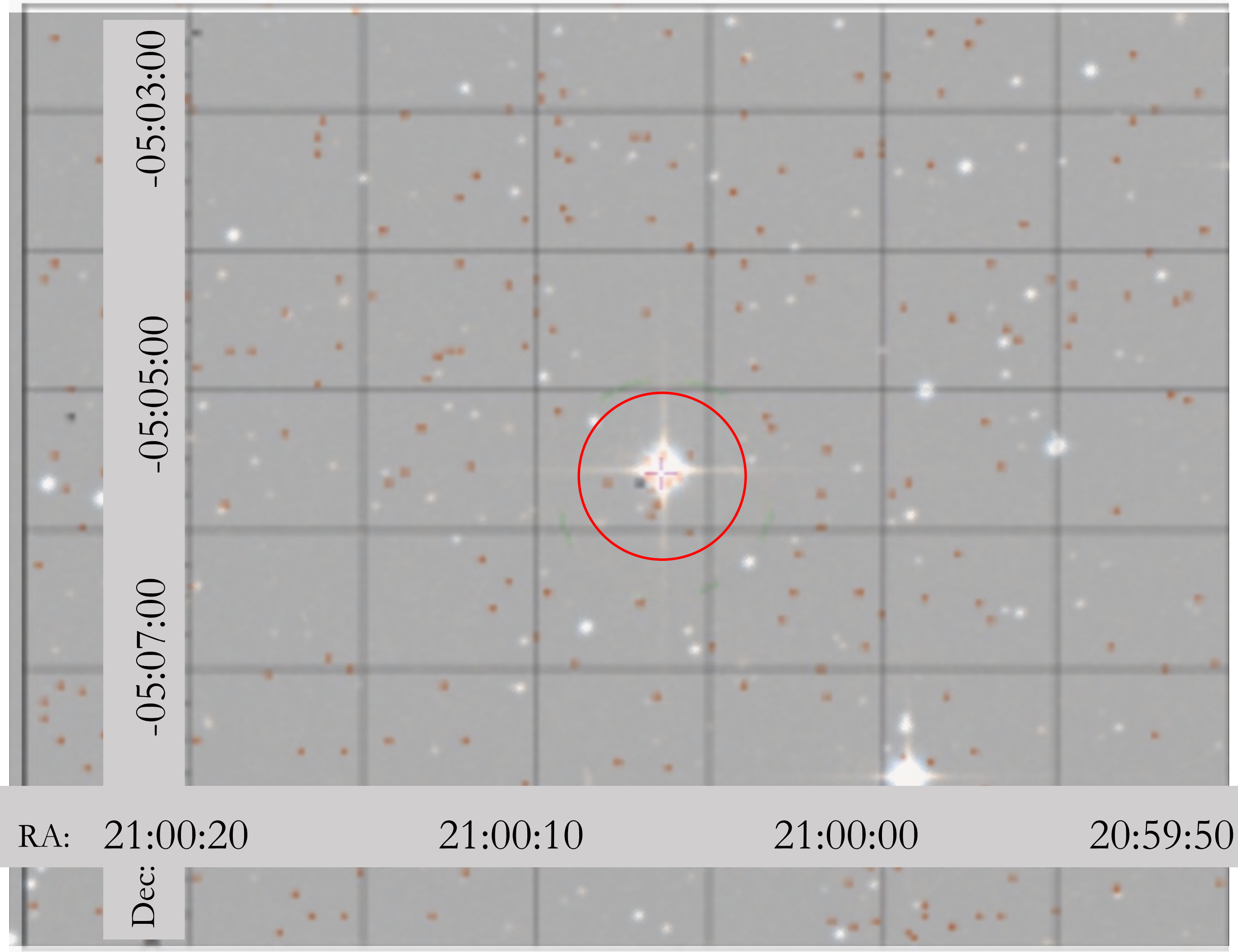


Levine et al. (*in prep*)

Planetary Thermospheres Change with Stellar XUV

1. Atmospheric data. **2. Stellar XUV output.** 3. Long-term monitoring.

- *Swift Observatory* measured X-ray flux of WASP-69 in Sep. 2023.
- Time awarded via DDT to follow-up observed metastable He variability from planetary thermosphere.
- Total of 11.9ks (3.4hr) of exposure time across five visits.
- Marginal (2σ, not 3σ) detection.

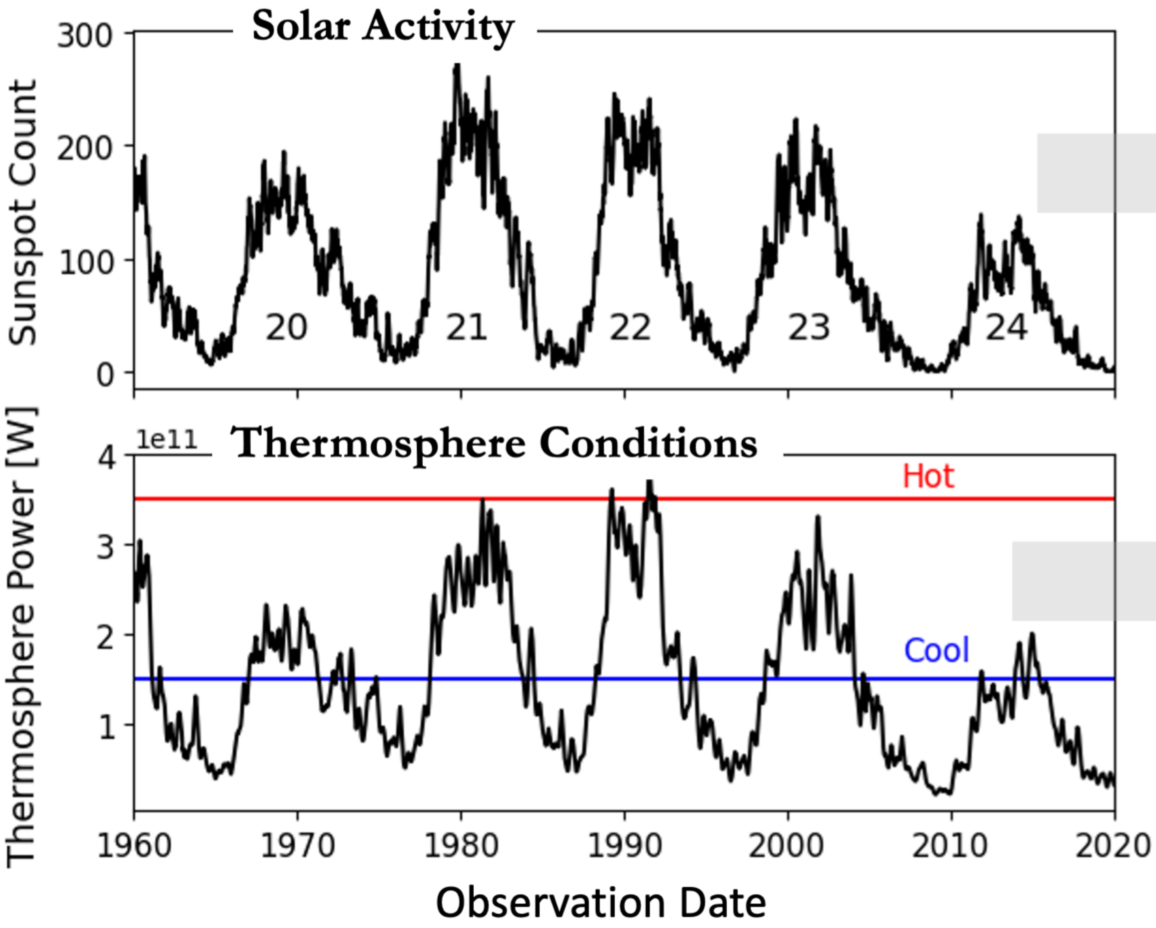


Levine et al. (*in prep*)

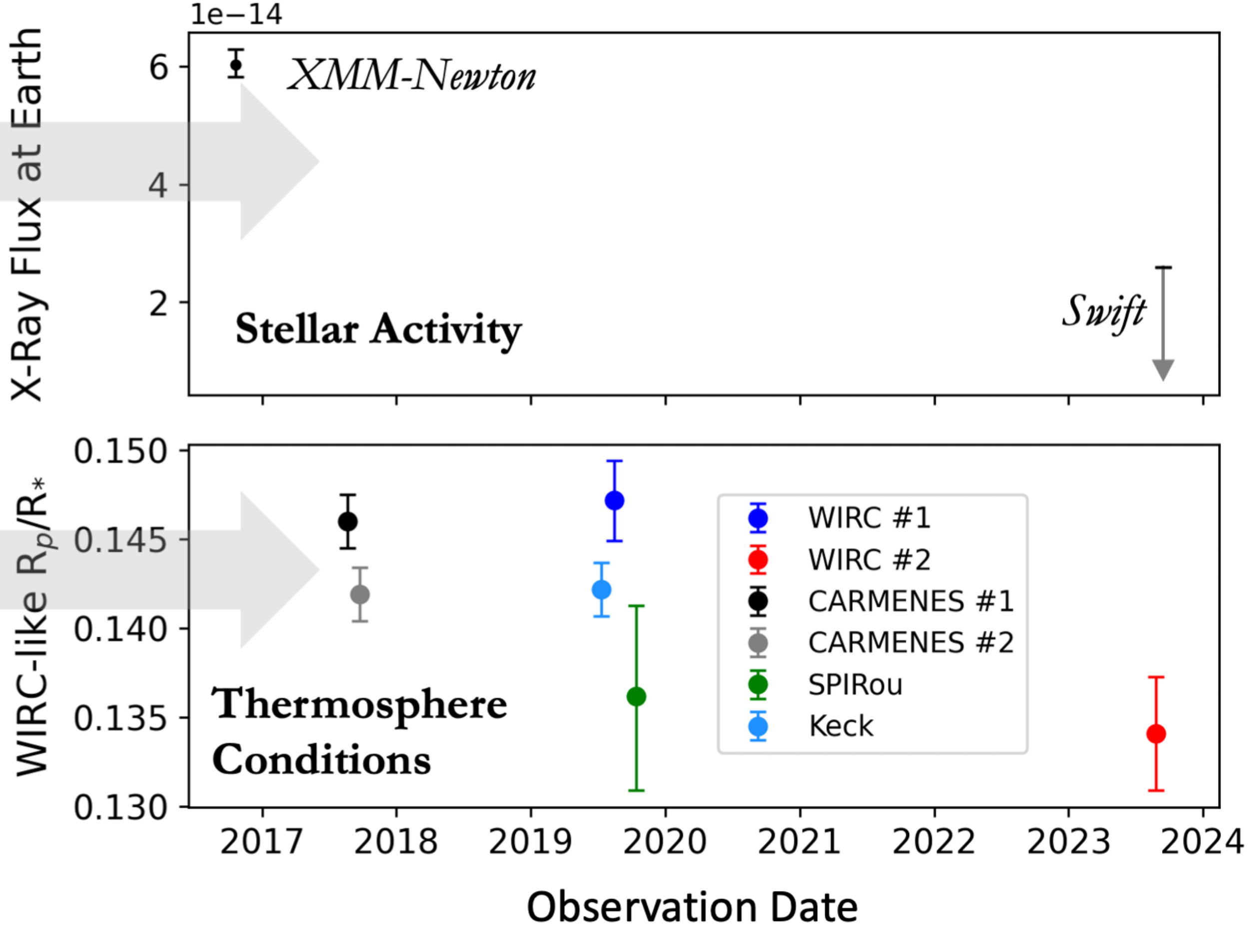
Planetary Thermospheres Change with Stellar XUV

1. Atmospheric data. **2. Stellar XUV output.** **3. Long-term monitoring.**

Earth-Sun System



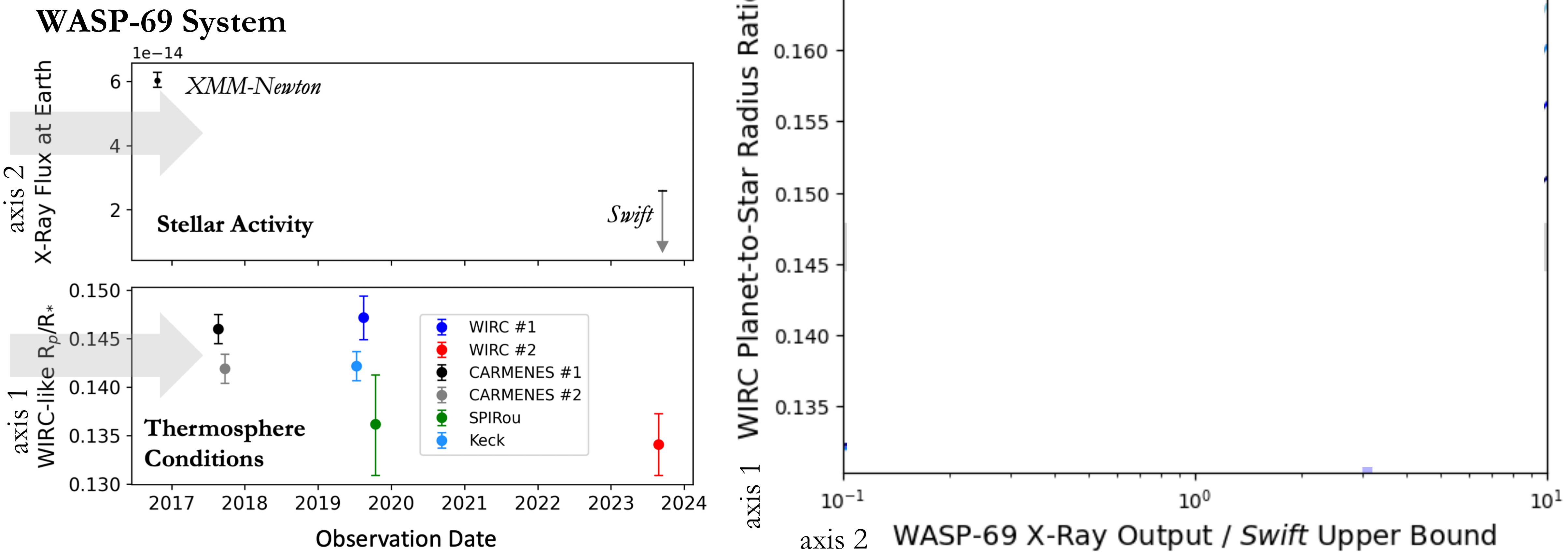
WASP-69 System



Levine et al. (*in prep*)

Modeling Multi-Wavelength & Contemporaneous Data

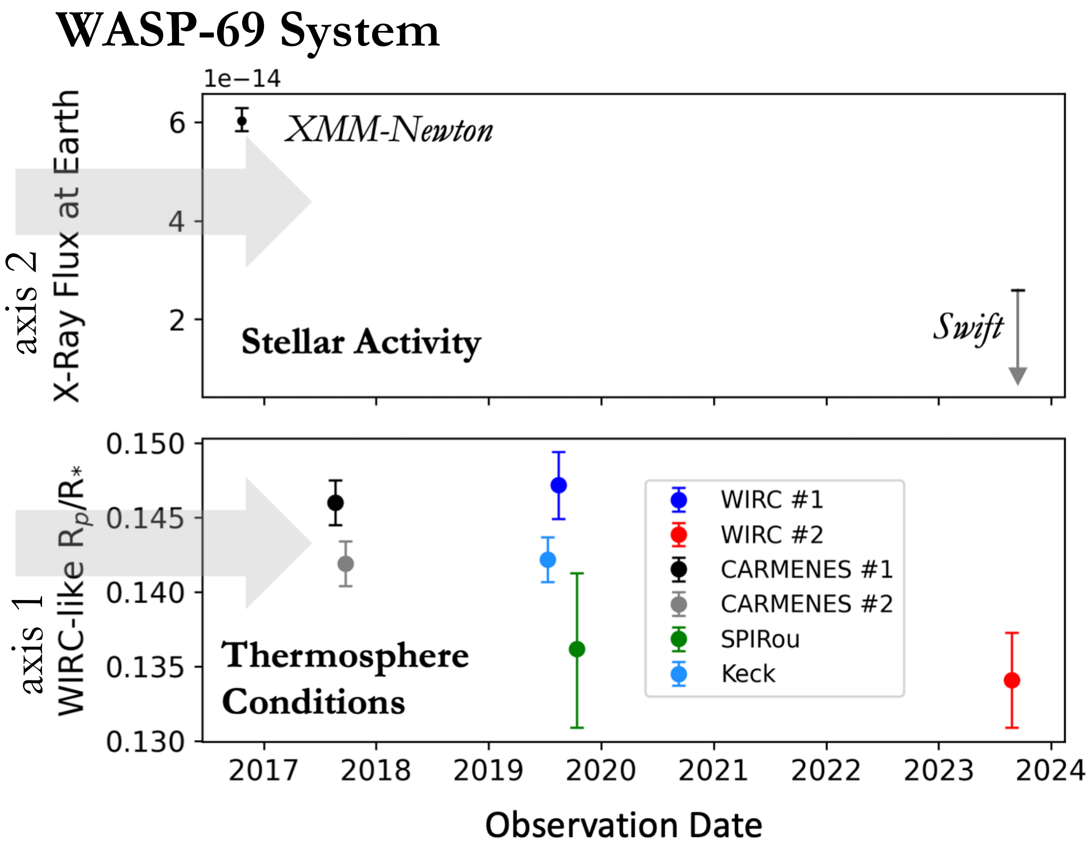
- Determine changes in stellar XUV that are consistent with archival atmospheric data.

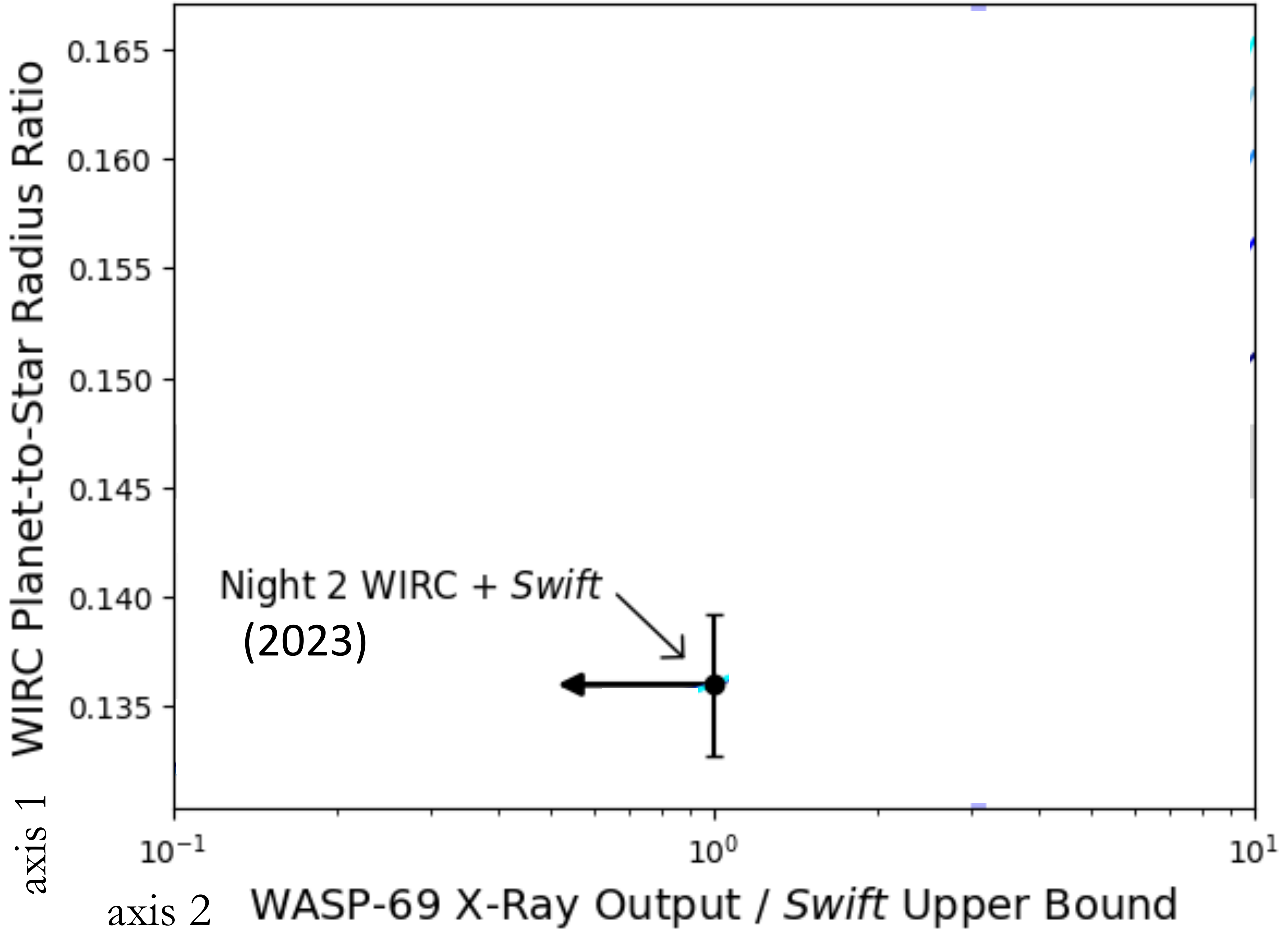


Levine et al. (*in prep*)

Modeling Multi-Wavelength & Contemporaneous Data

- Determine changes in stellar XUV that are consistent with archival atmospheric data.

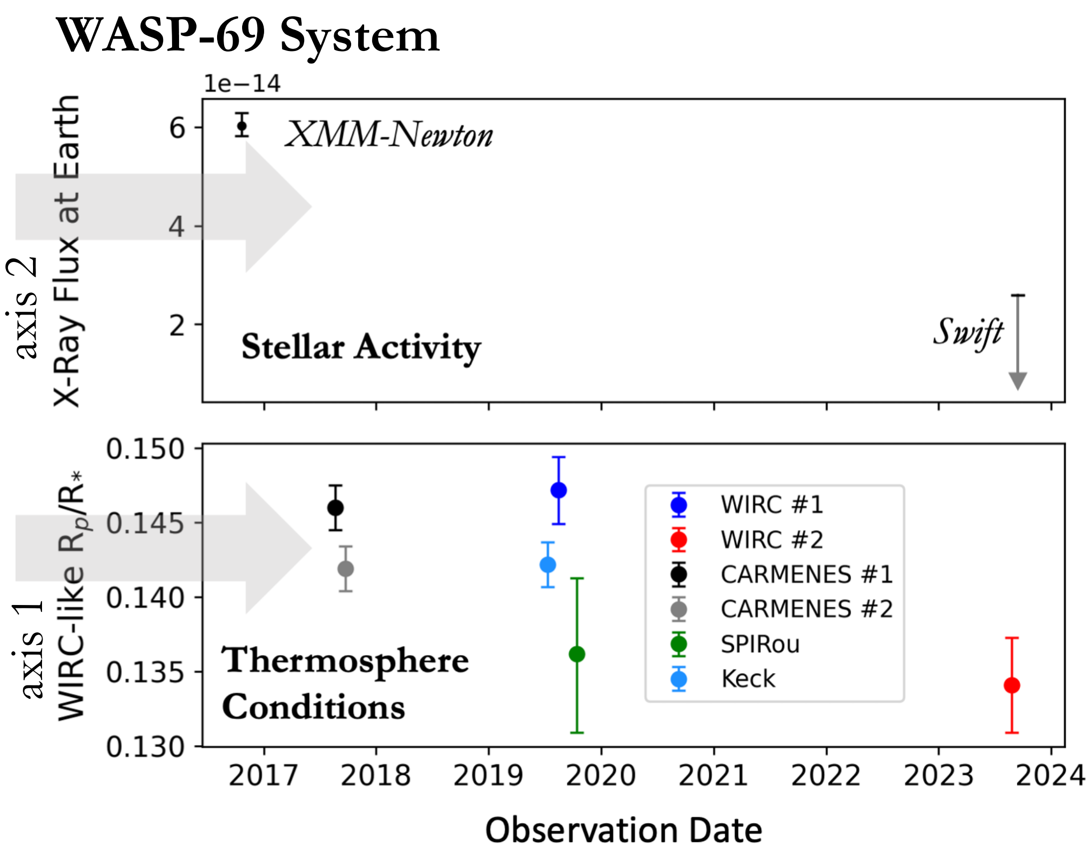


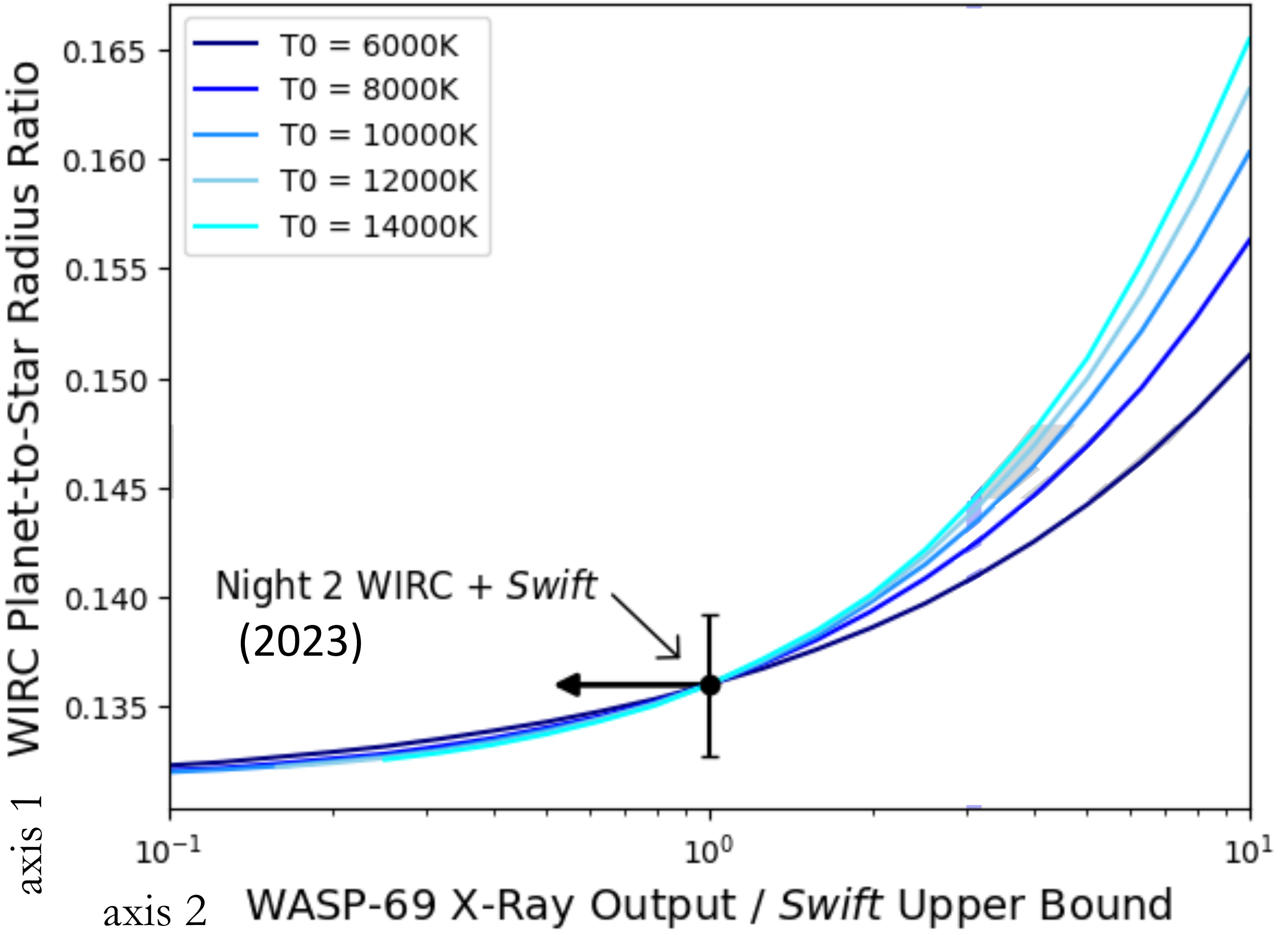


Levine et al. (*in prep*)

Modeling Multi-Wavelength & Contemporaneous Data

- Determine changes in stellar XUV that are consistent with archival atmospheric data.

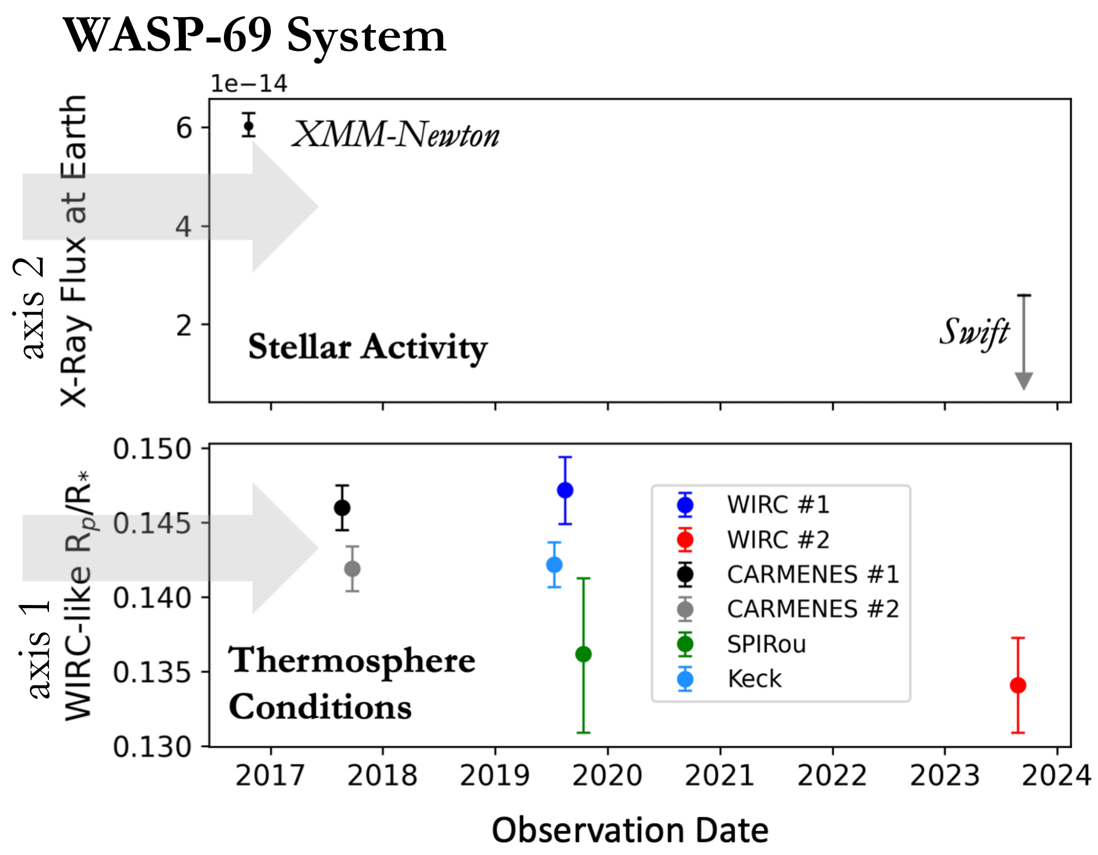


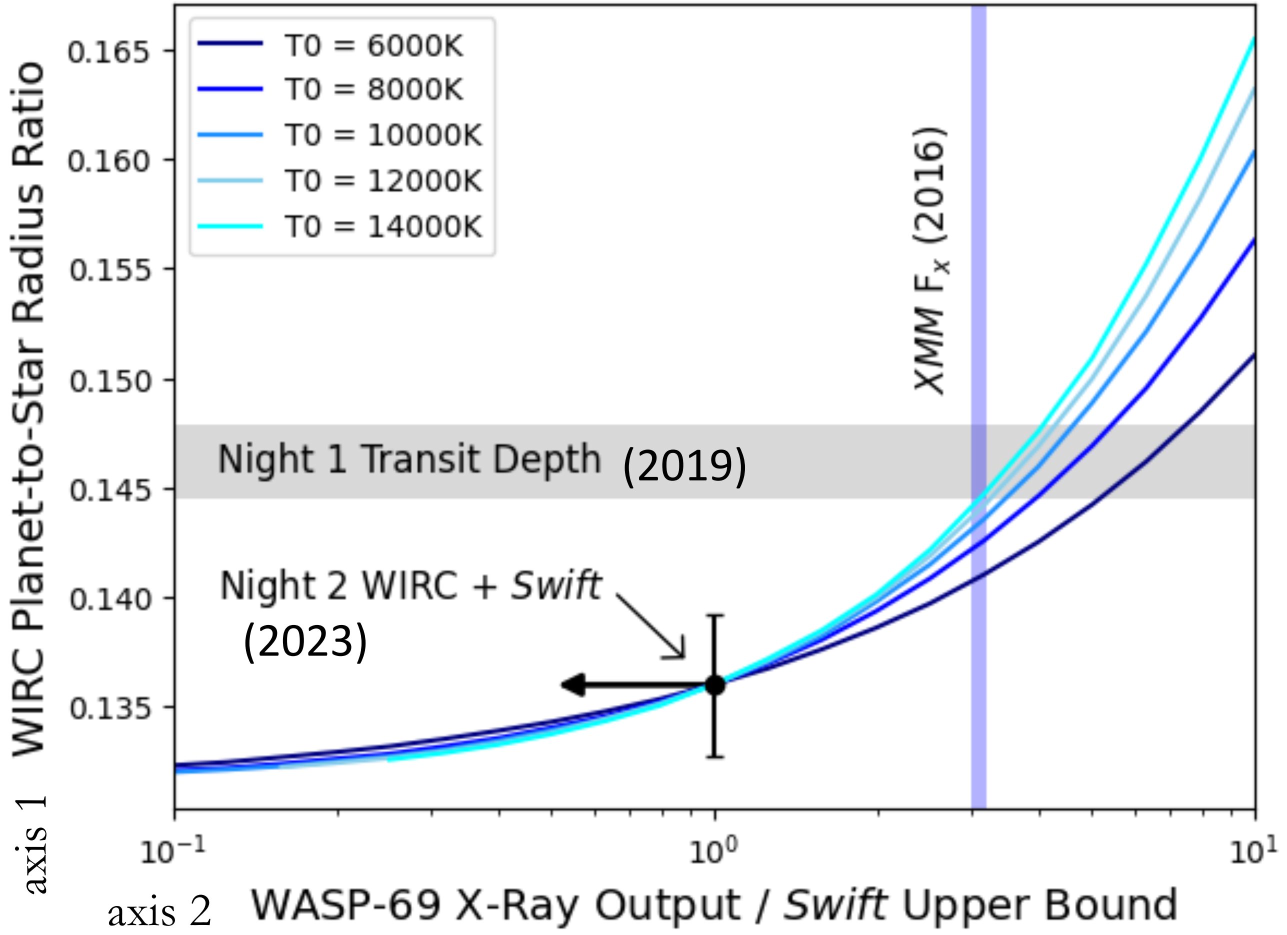


Levine et al. (*in prep*)

Modeling Multi-Wavelength & Contemporaneous Data

- Determine changes in stellar XUV that are consistent with archival atmospheric data.

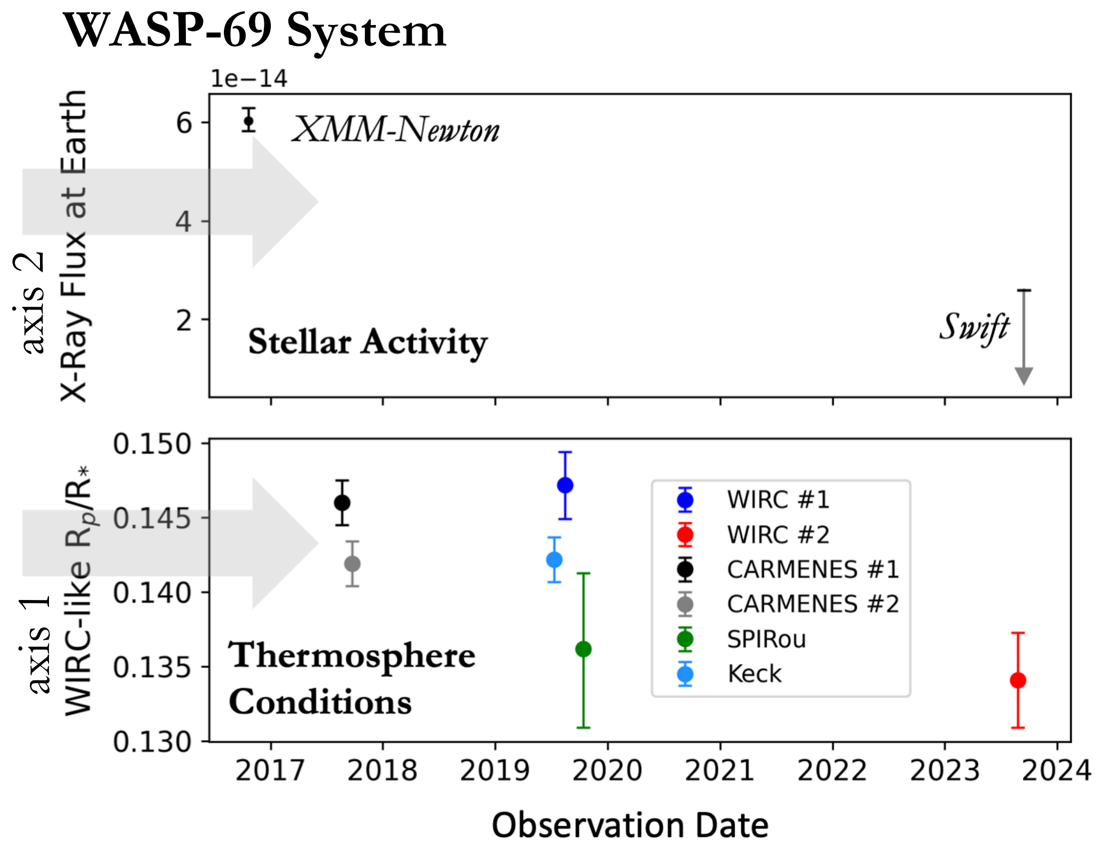


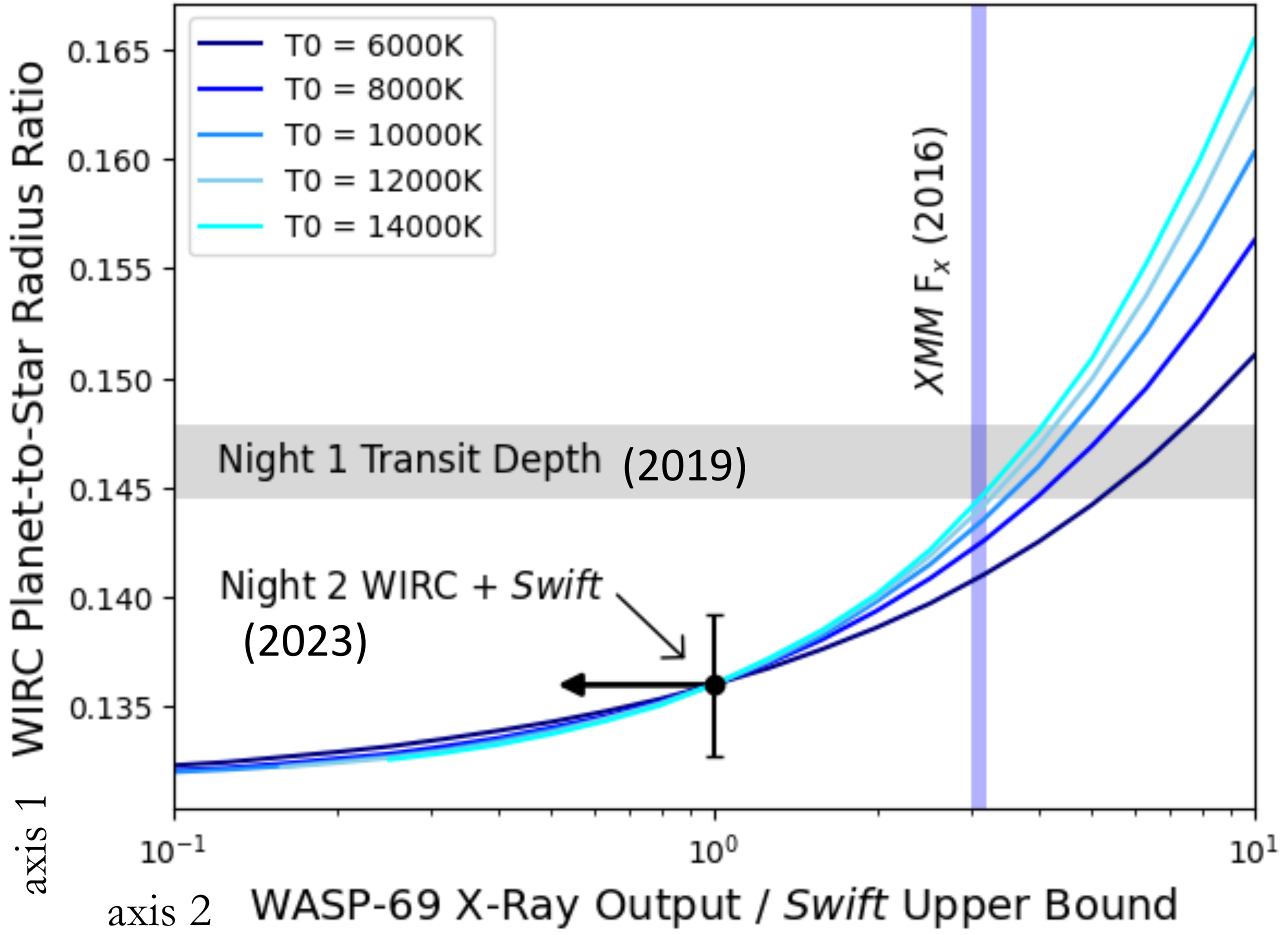


Levine et al. (*in prep*)

Looking Ahead: Sustaining the WASP-69 Campaign

- *TESS* will re-observe WASP-69 -- chance to also take atmospheric and XUV data.
- Many other systems already with archival metastable He data.



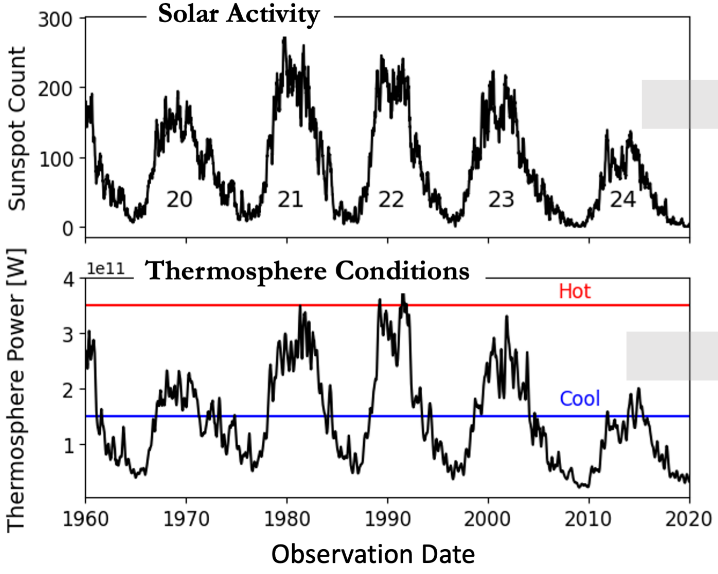


Levine et al. (*in prep*)

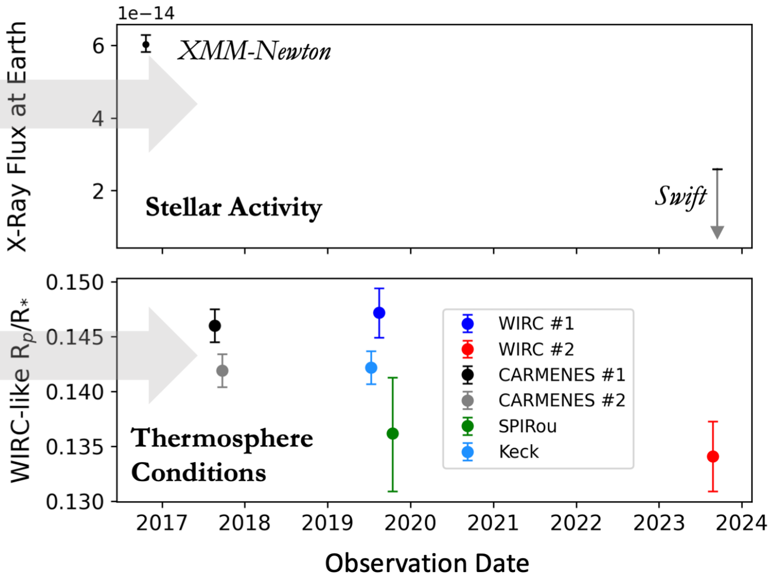
Conclusions: A Pilot Study on Planetary Aeronomy

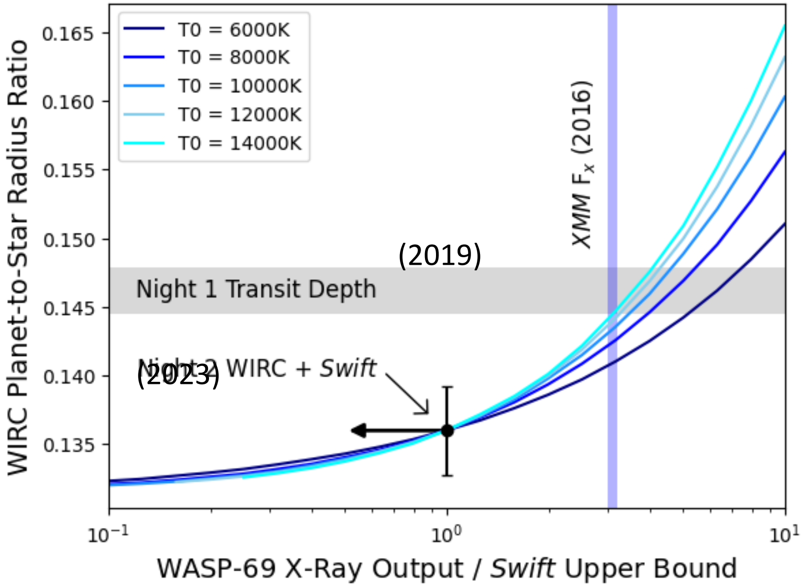
Thank you, collaborators: Shreyas Vissapragada (Harvard/CfA), Adina Feinstein (Univ. Colorado), George King (Univ. Michigan), Lia Corrales (Univ. Michigan), Aleck Hernandez (Wayne State Univ.), Heather Knutson (Caltech), Mike Greklek-McKeon (Caltech)

Earth-Sun System



WASP-69 System





Levine et al. (*in prep*)

BACKUP SLIDES

Planetary Aeronomy: A Case Study of WASP-69b

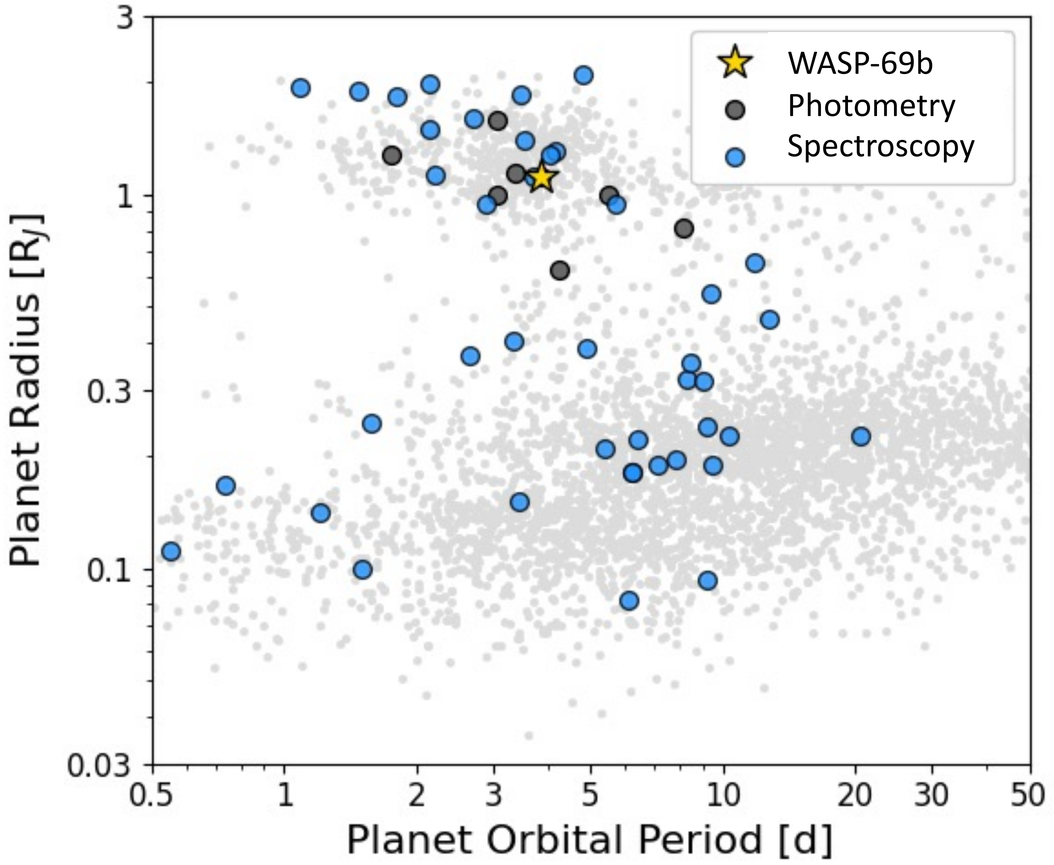
W. Garrett Levine (Yale University)

Exoplanet Explorers Webinar

February 16, 2024

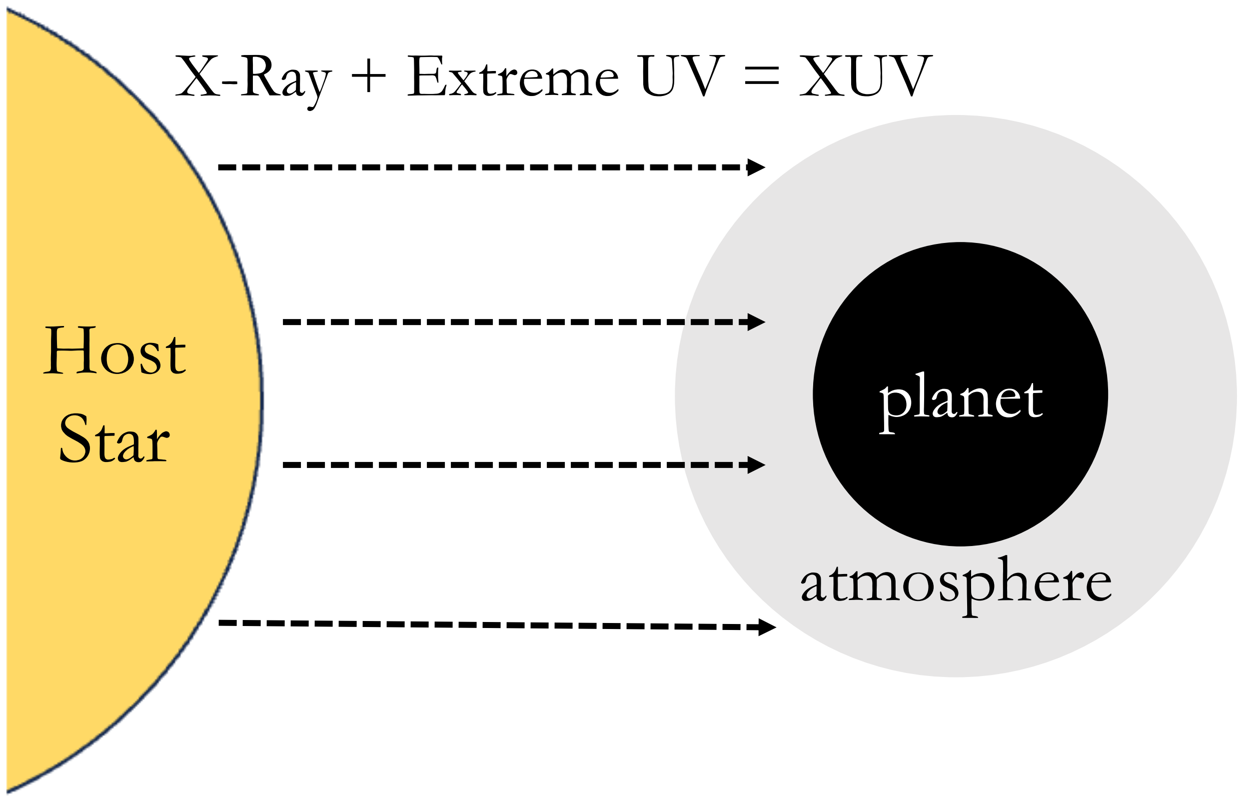
Looking Ahead: More Systems + *JWST*

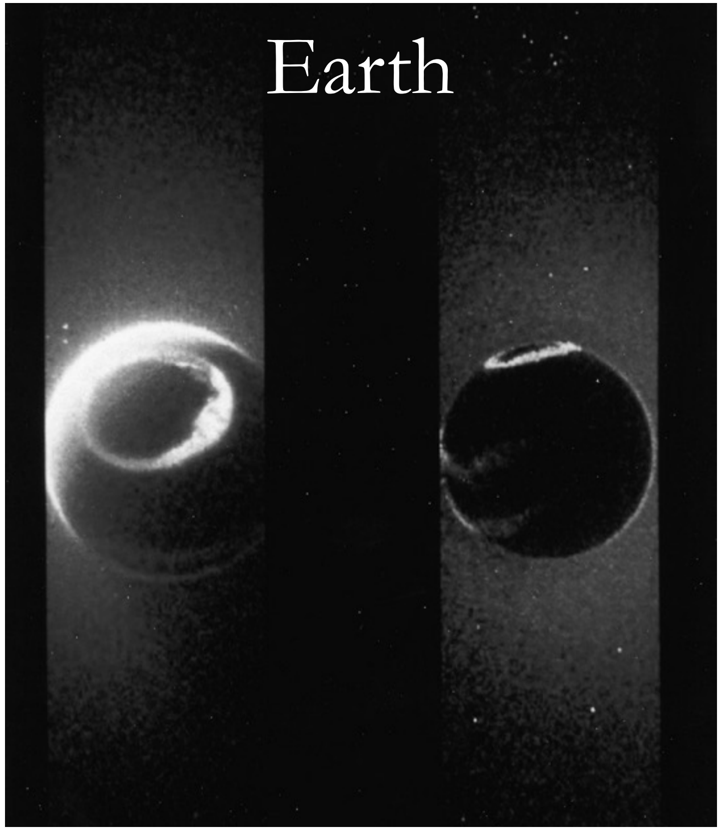
- Many confirmed systems already have archival metastable He data.



Planetary Atmospheres Evolve on Many Timescales

Understanding the response of exoplanet atmospheres to changes in their space weather environments. Levine et al. (*submitted*)

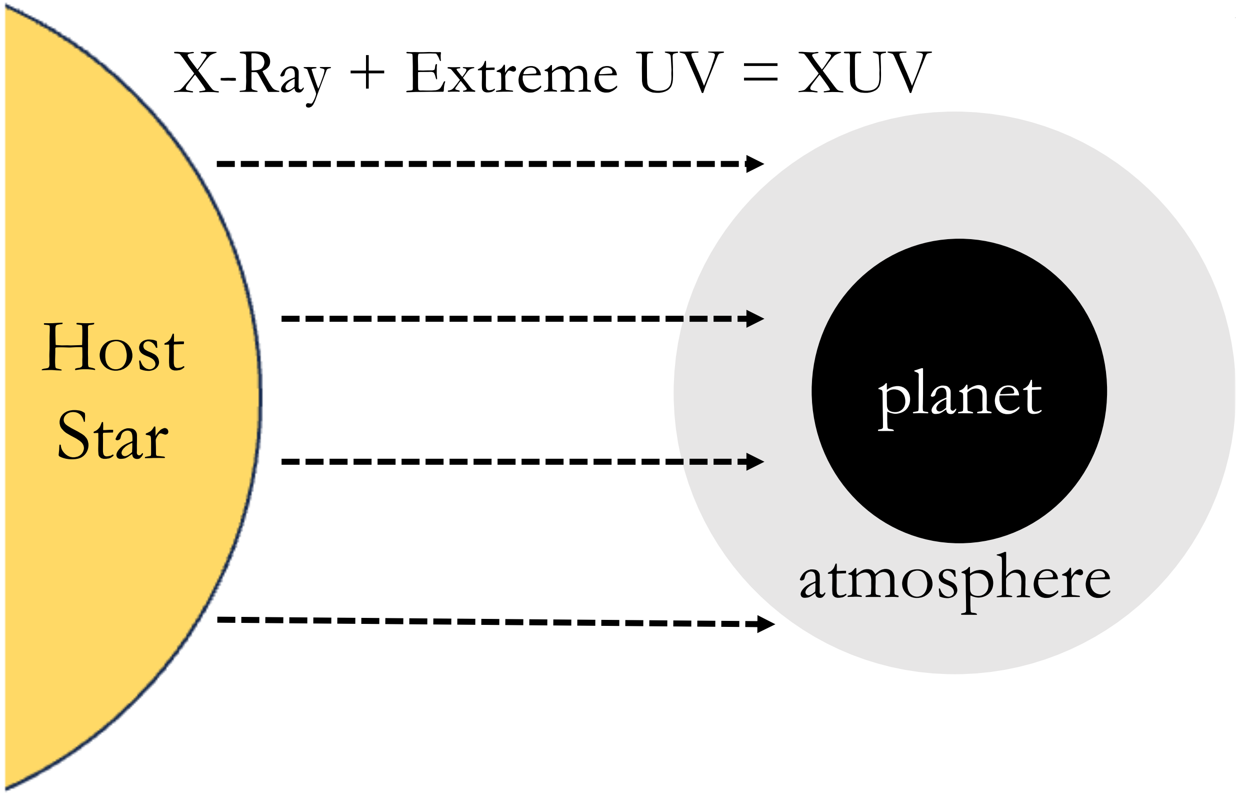




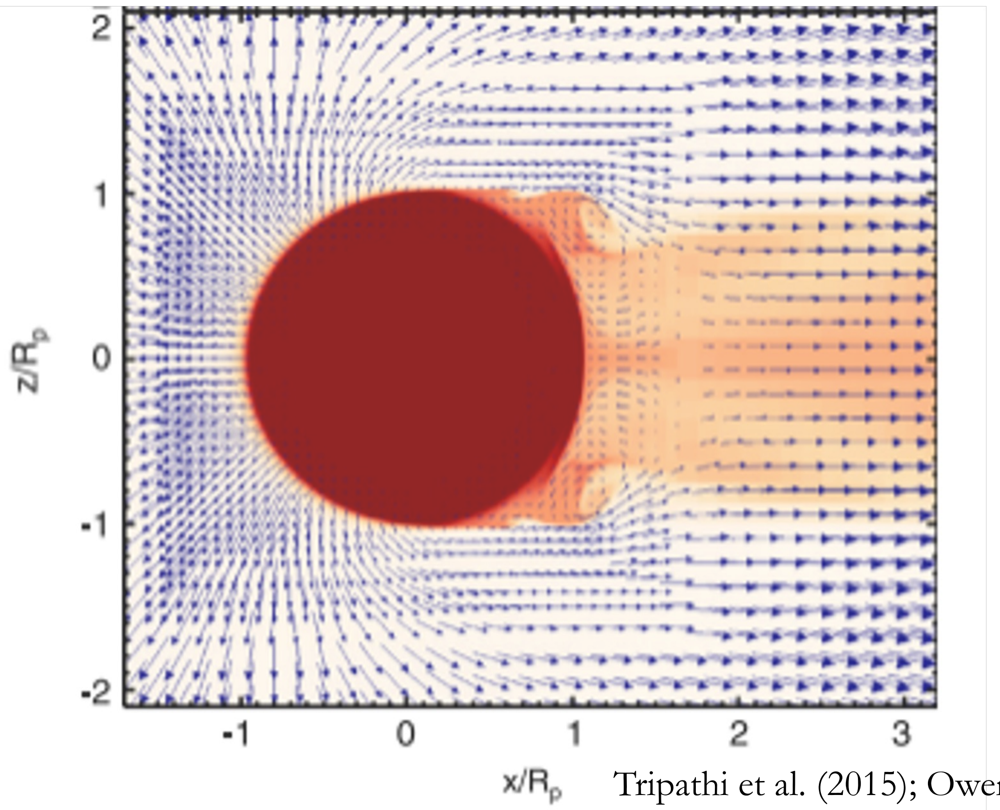
Credit: NASA (Dynamics Explorer I)

Planetary Atmospheres Evolve on Many Timescales

Understanding the response of exoplanet atmospheres to changes in their space weather environments. Levine et al. (*submitted*)



Exoplanets



Tripathi et al. (2015); Owen (2019)

Earth's Atmosphere

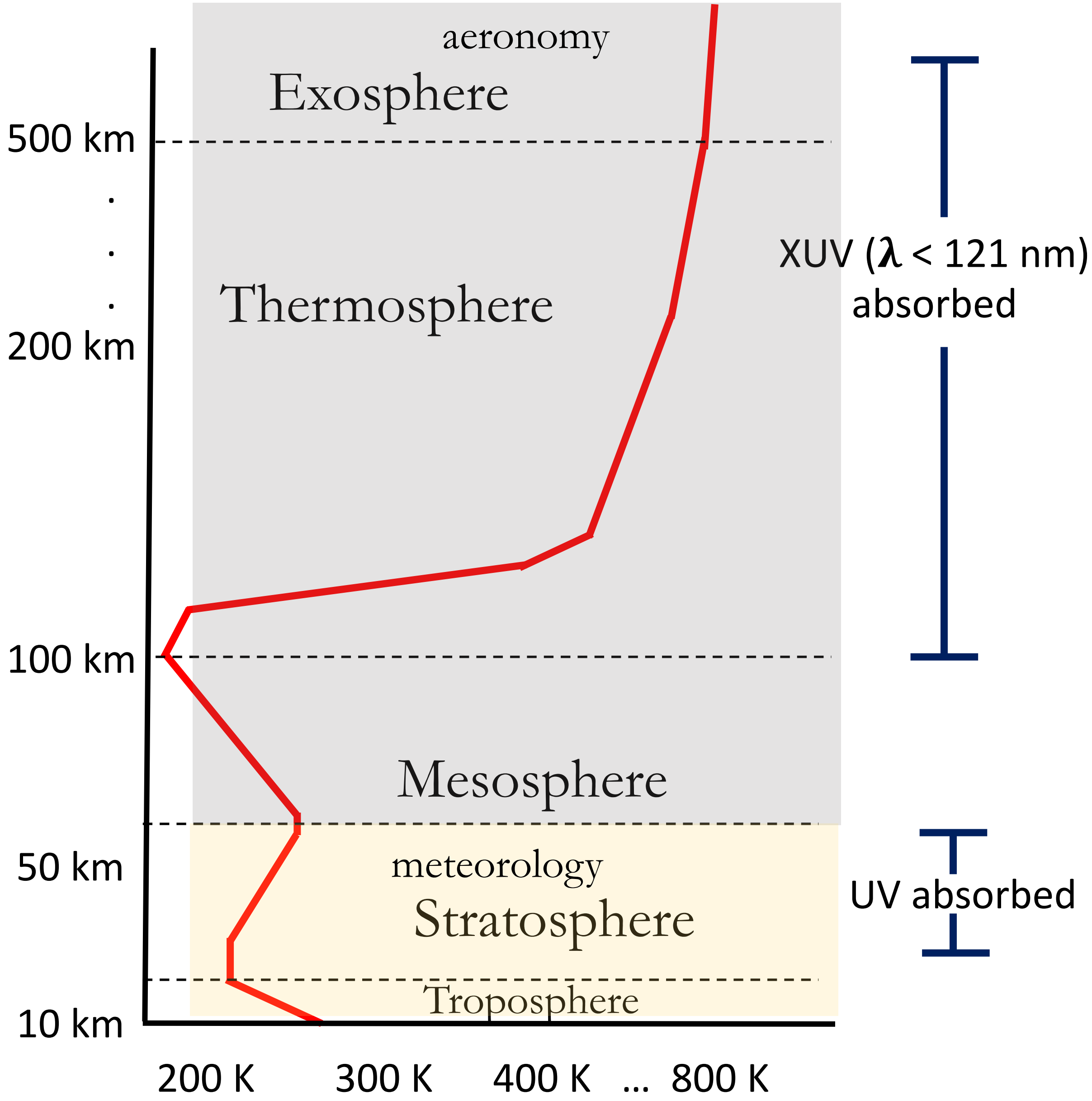

Credit: NASA/Johnson

Upper Boundary

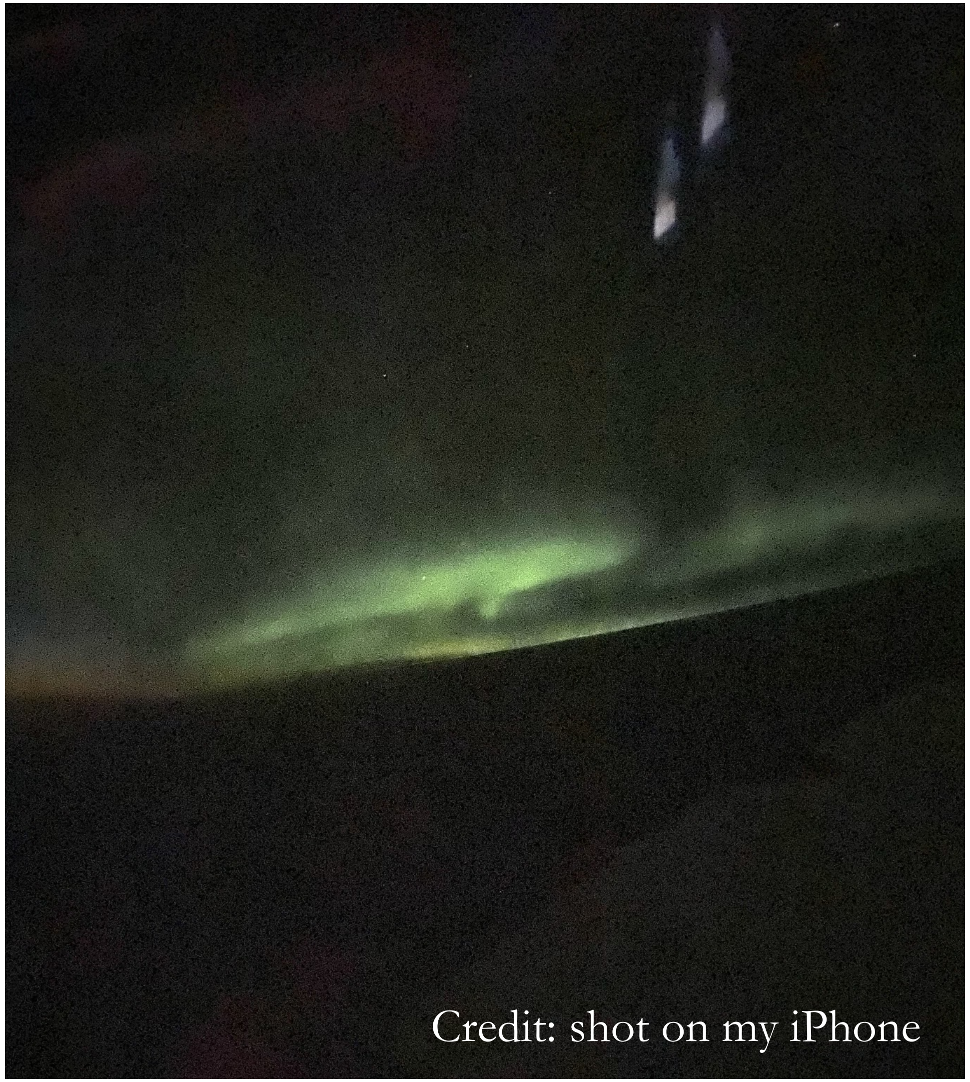
P ~ 0

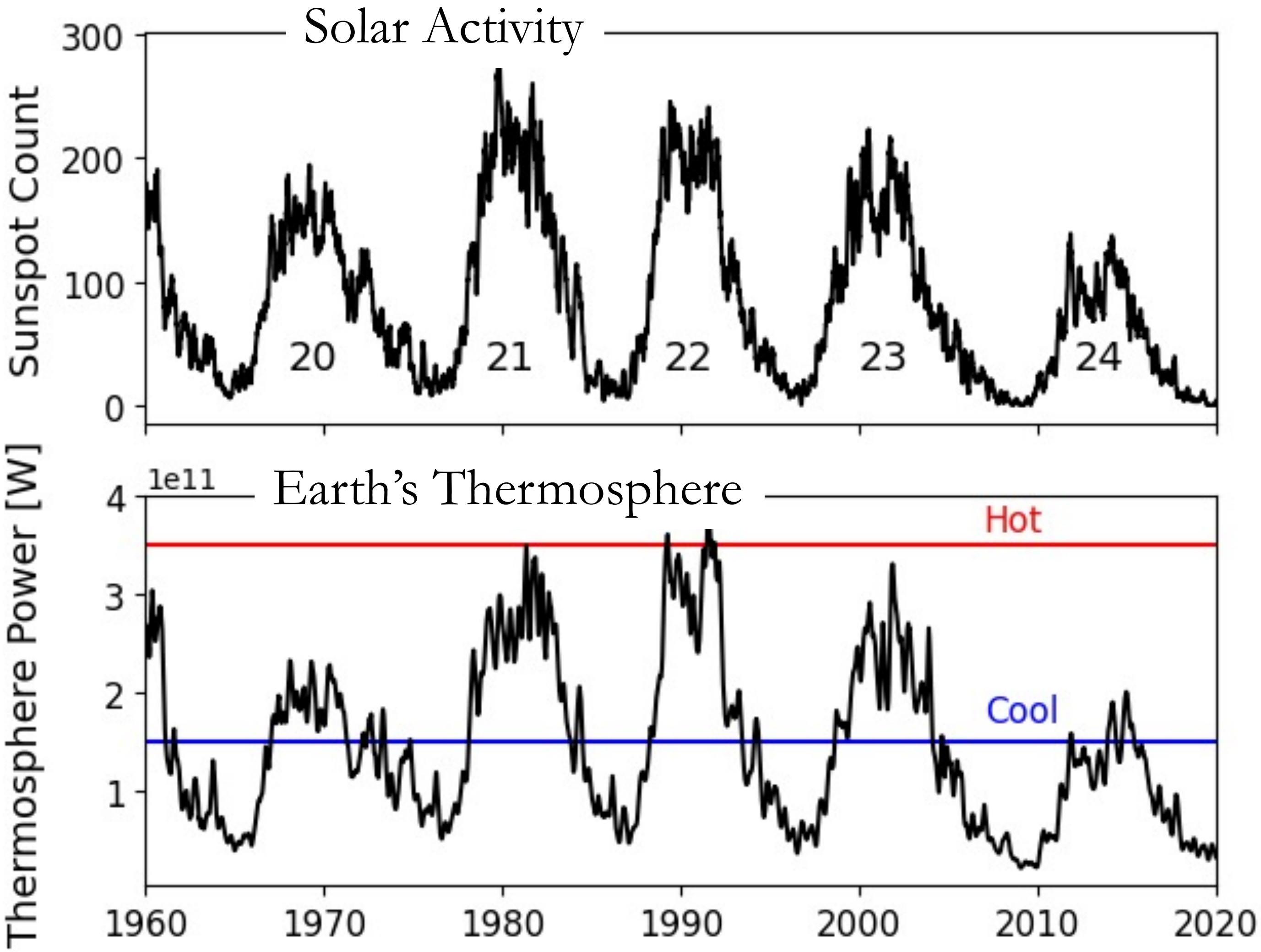
P ~ 1atm

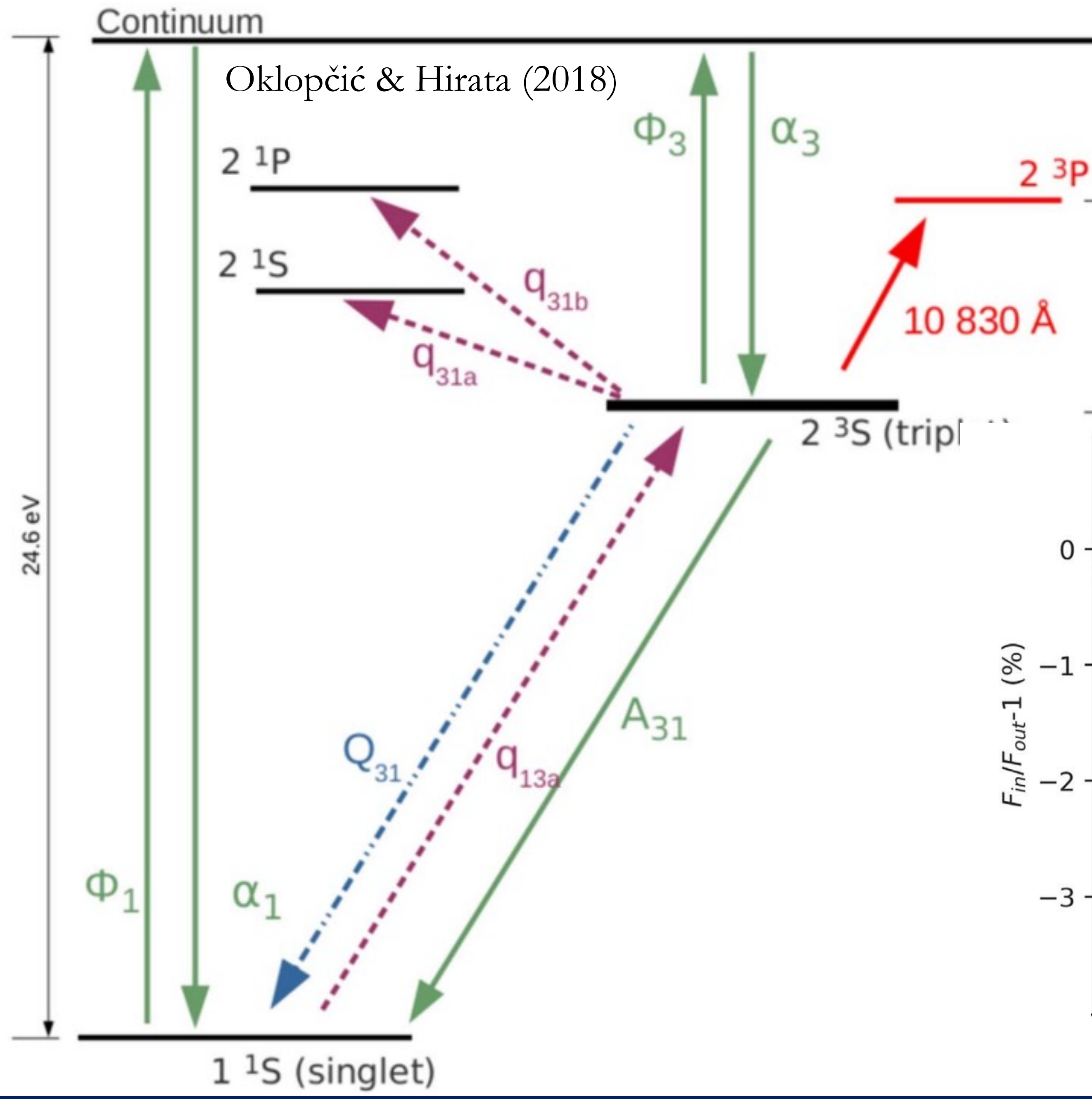
Lower Boundary

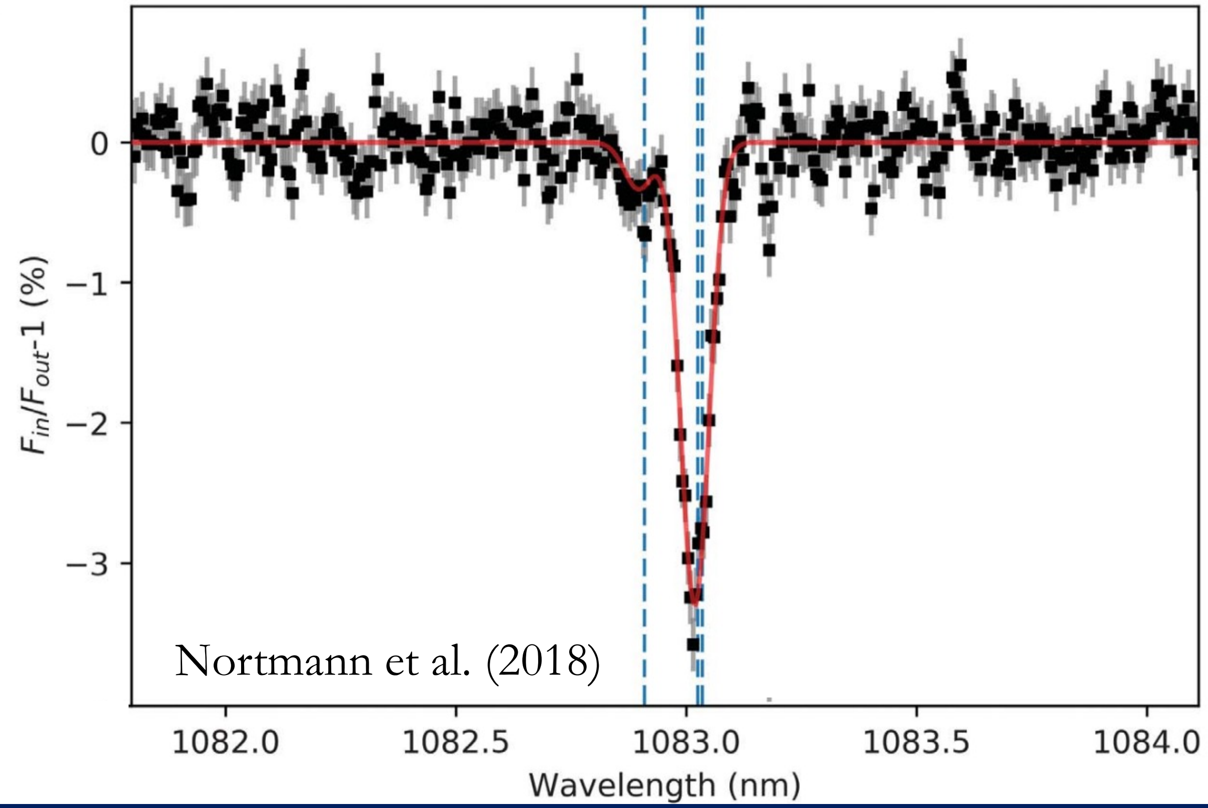


Planetary Thermospheres Change with Stellar XUV






Continuum
Oklopčić & Hirata (2018)
2 ¹P
2 ¹S
Φ_3
α_3
2 ³P
q_{31b}
q_{31a}
10 830 Å
1.1 eV
4.8 eV
24.6 eV
2 ³S (tripl
Q_{31}
q_{13a}
A_{31}
Φ_1
α_1
1 ¹S (singlet)
radiative transitions
collisions with electrons
collisions with H I atoms
Energy separations not to scale.


F_{in}/F_{out}-1 (%)
0
−1
−2
−3
1082.0
1082.5
1083.0
1083.5
1084.0
Wavelength (nm)
Nortmann et al. (2018)

Observing Atmospheric Escape

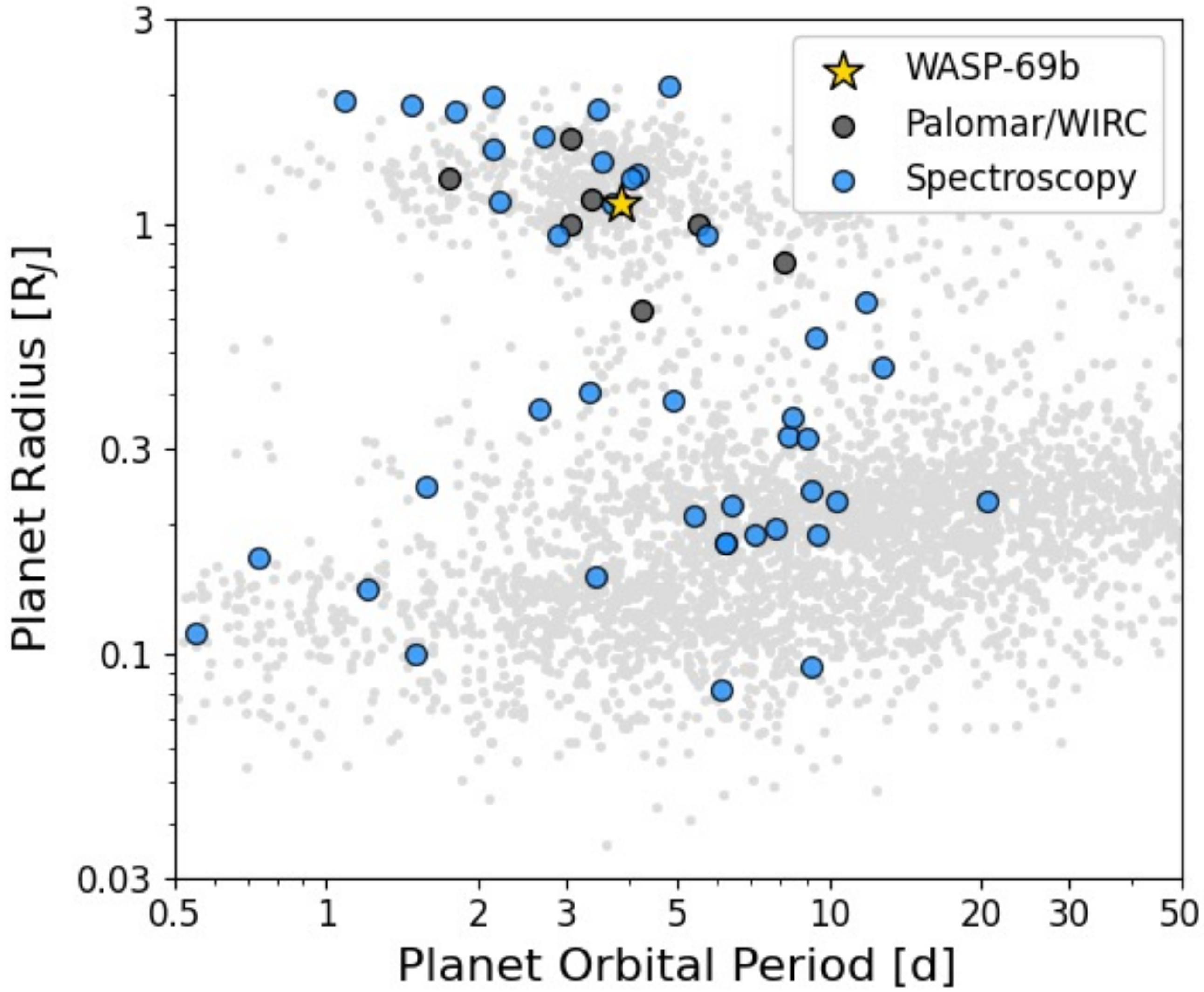
First atmospheric escape tracers:

- Lyman α
  - -absorbed in ISM
  - -mostly requires *Hubble*
- UV metal lines
  - -low signal-to-noise
- Balmer series (Hα, etc.)
  - -low signal-to-noise
  - -only the hottest hot Jupiters

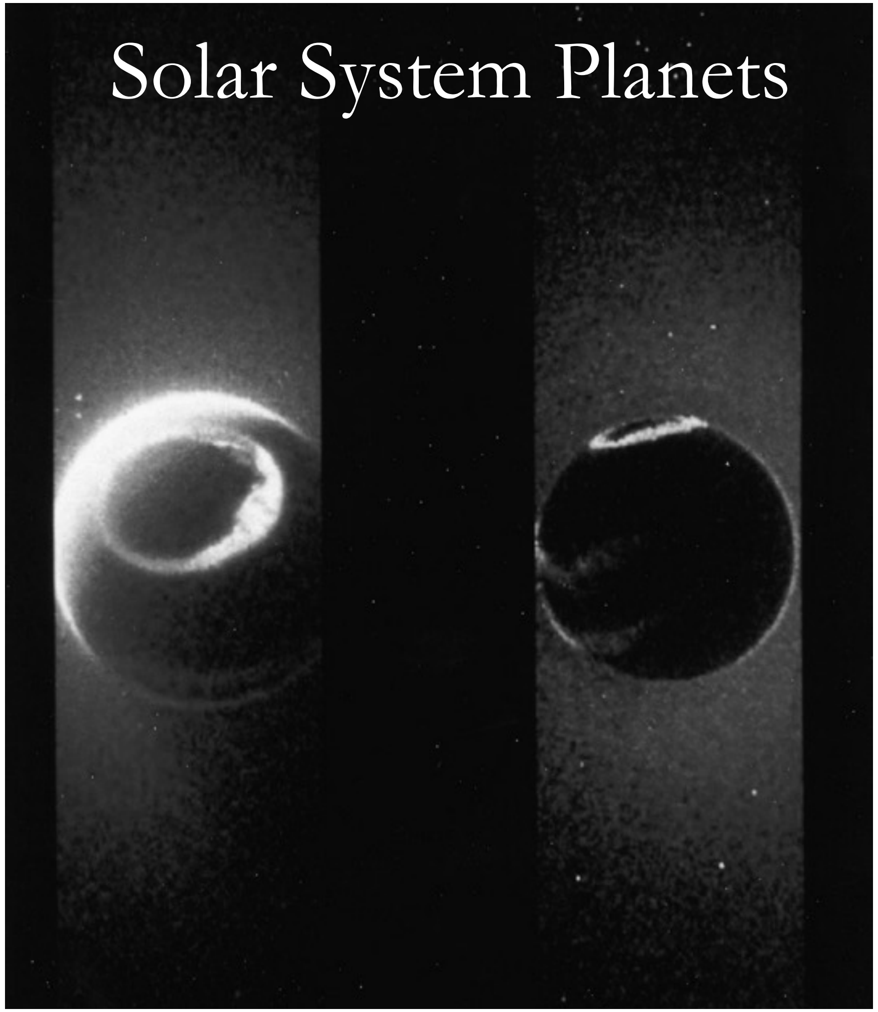
Recent prolific tracer:

- metastable He 10830 Å
  - -no ISM absorption
  - -visible from ground

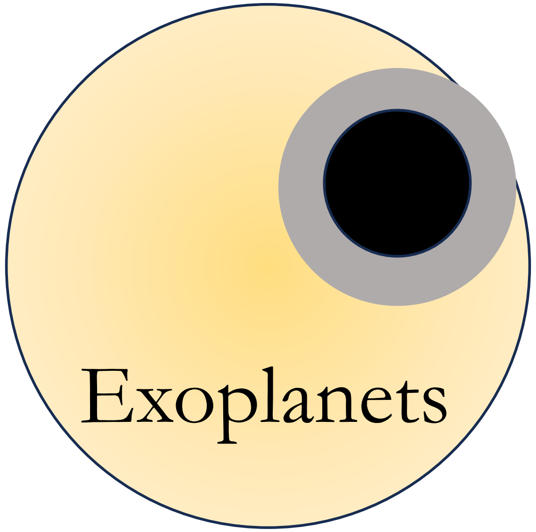
Planets with (Attempted) Metastable He Measurements

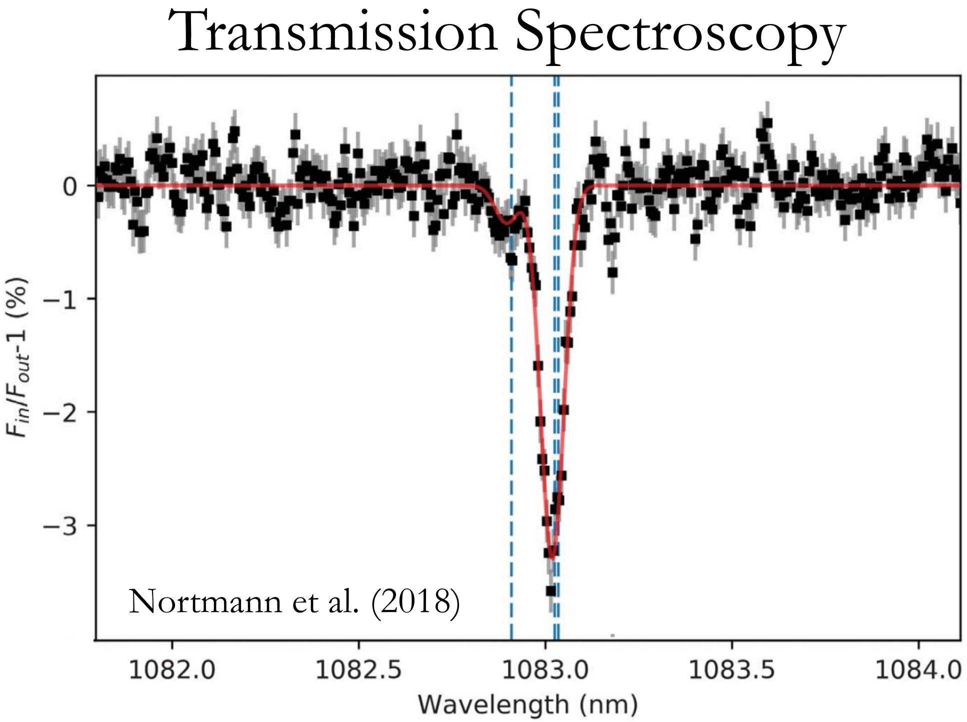


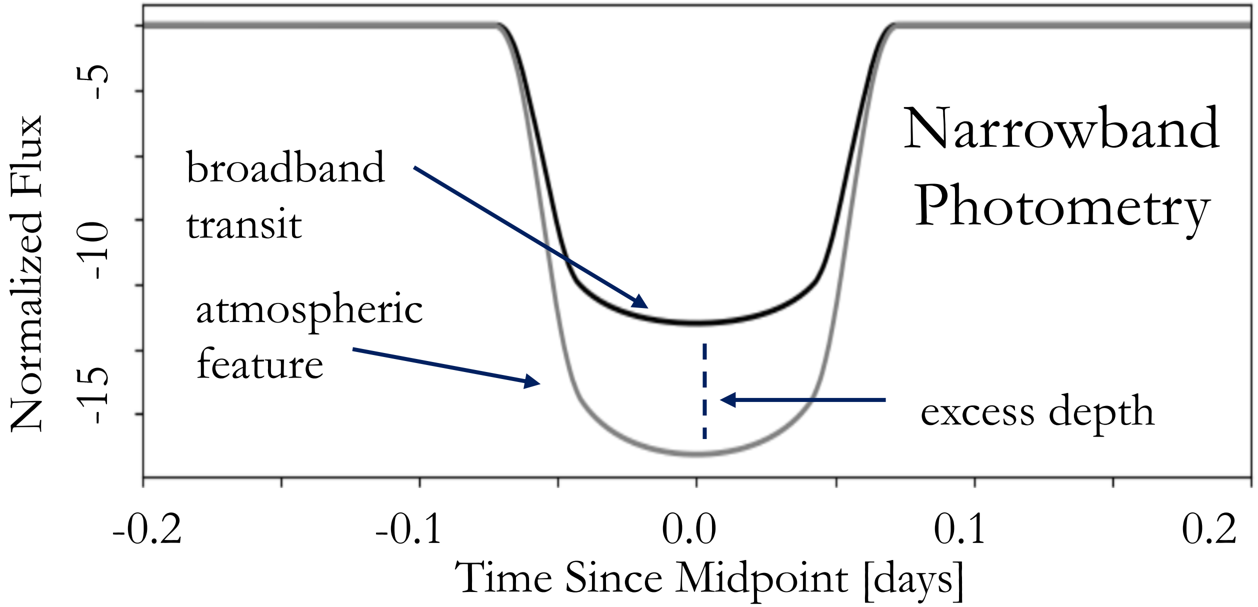
Observing Planetary Thermospheres



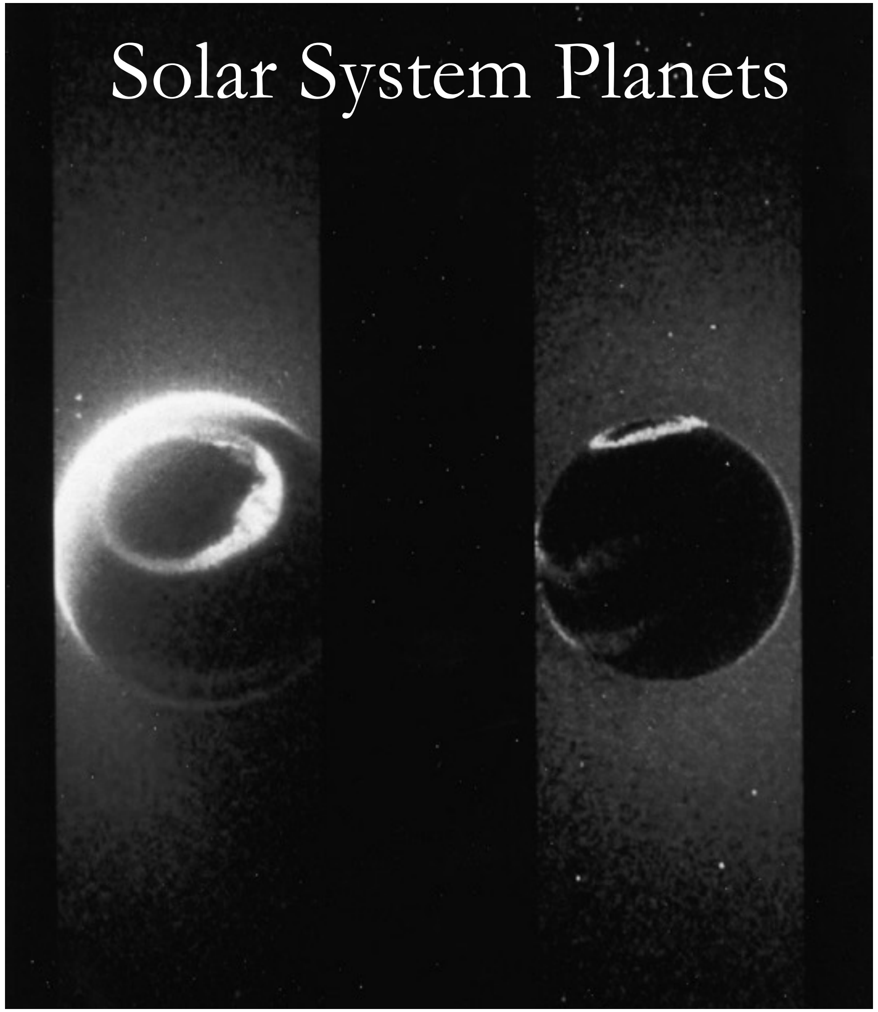
Credit: NASA (Dynamic Explorer I; 1982)



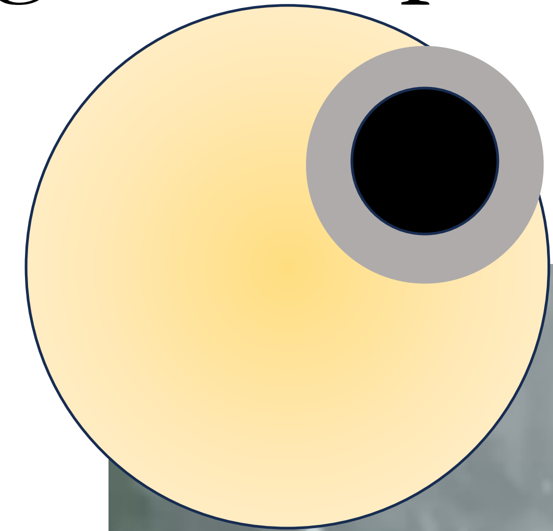




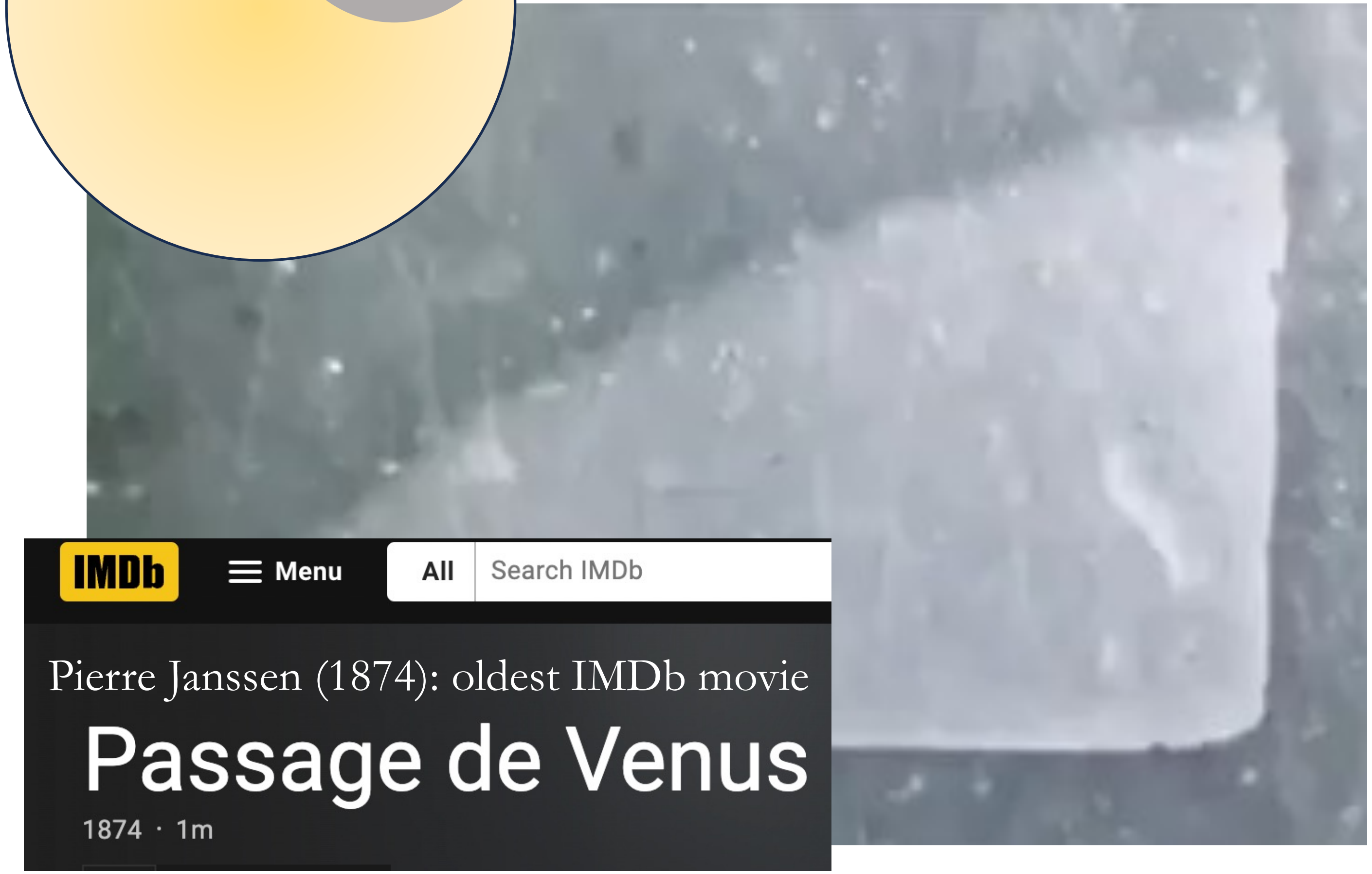
Observing Atmospheric Escape



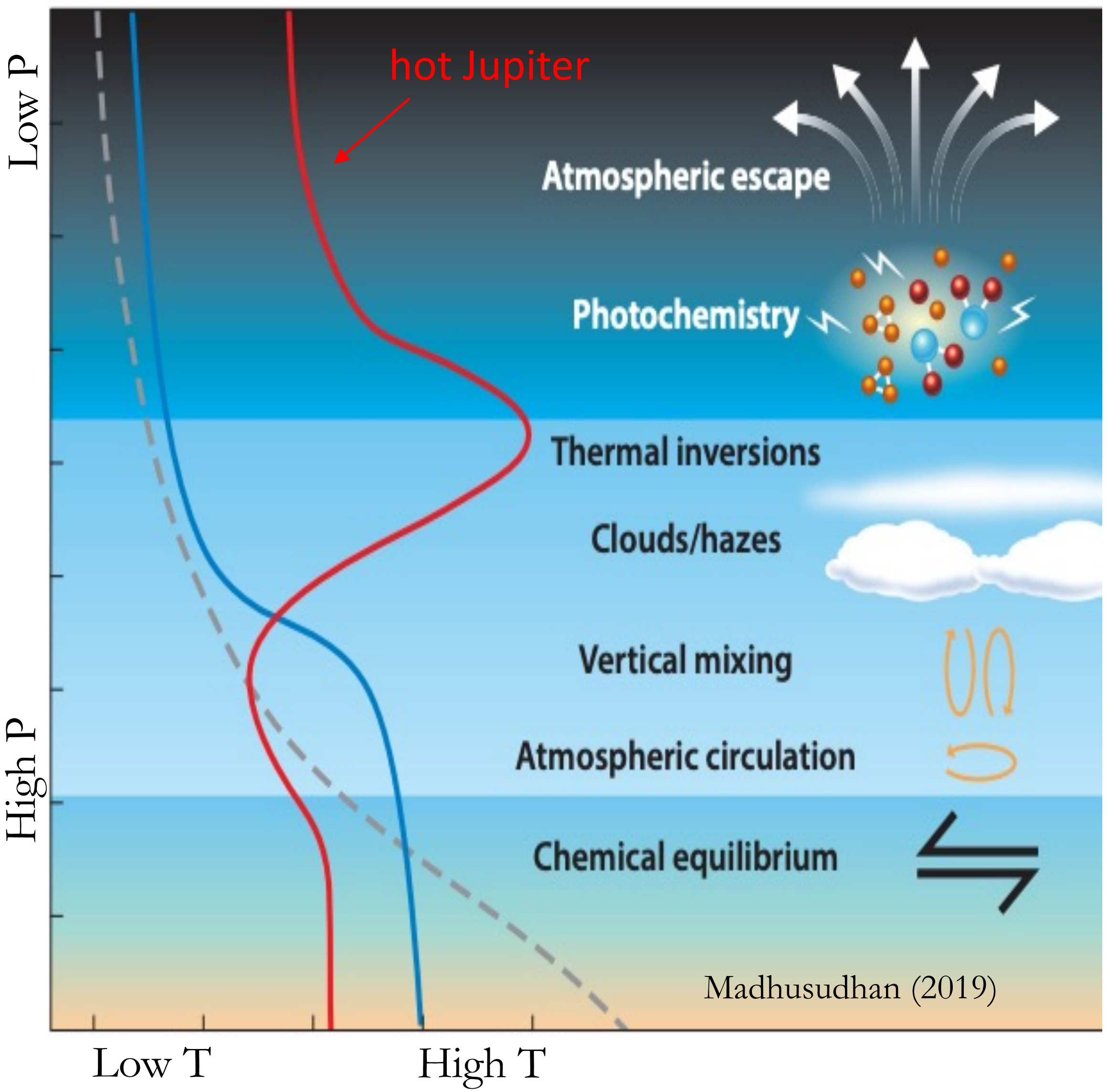
Credit: NASA (Dynamics Explorer I)

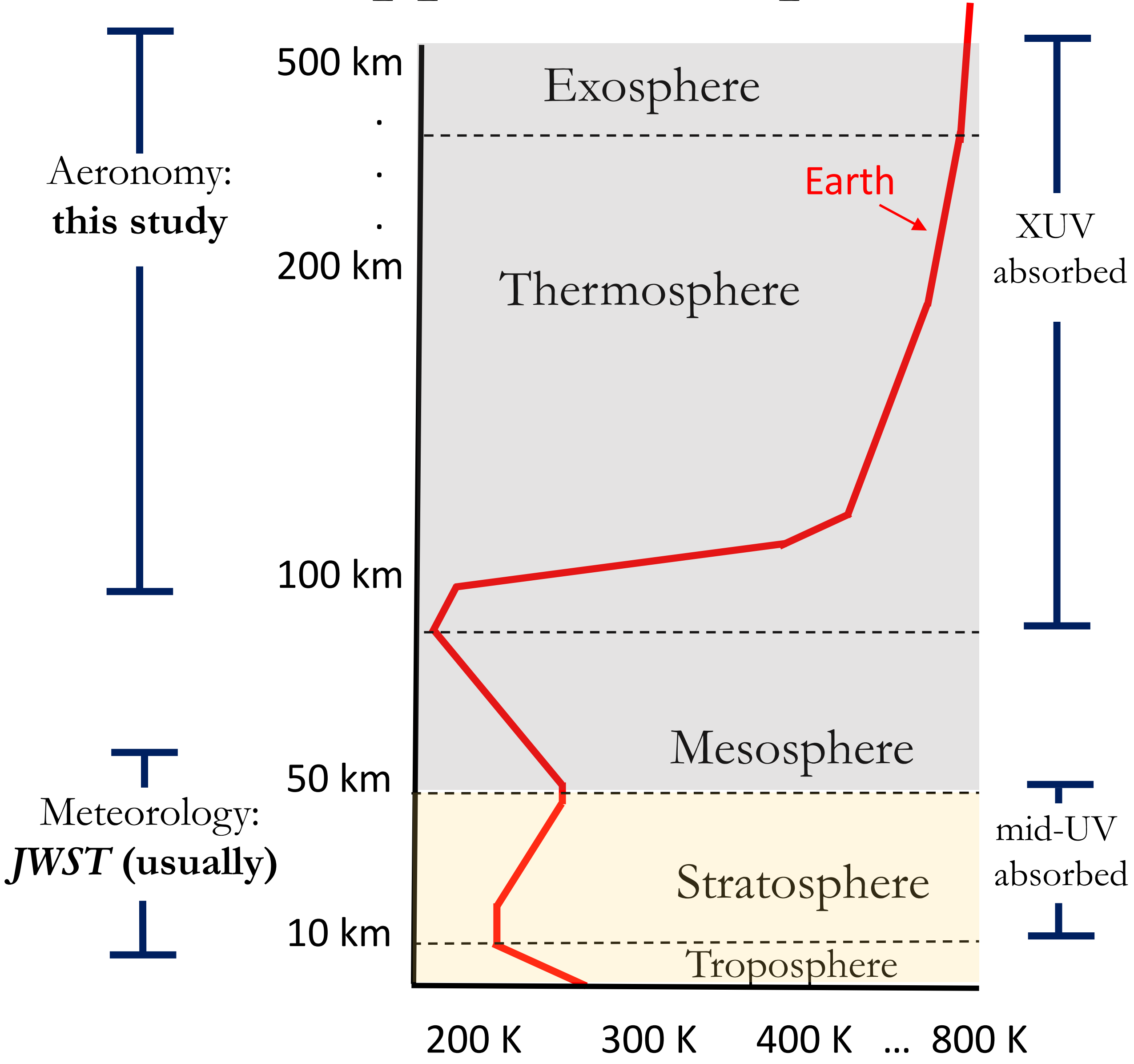


Exoplanets

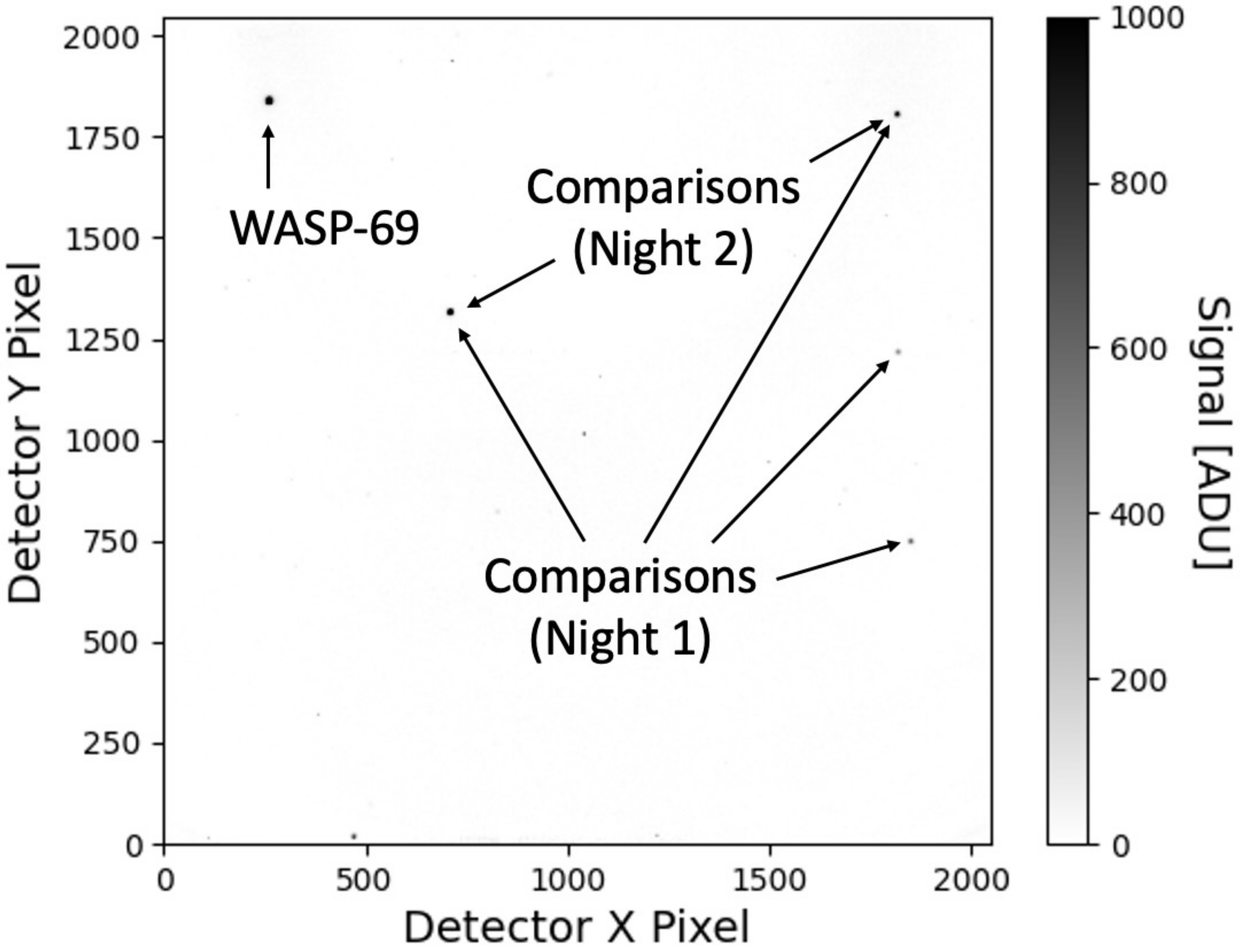


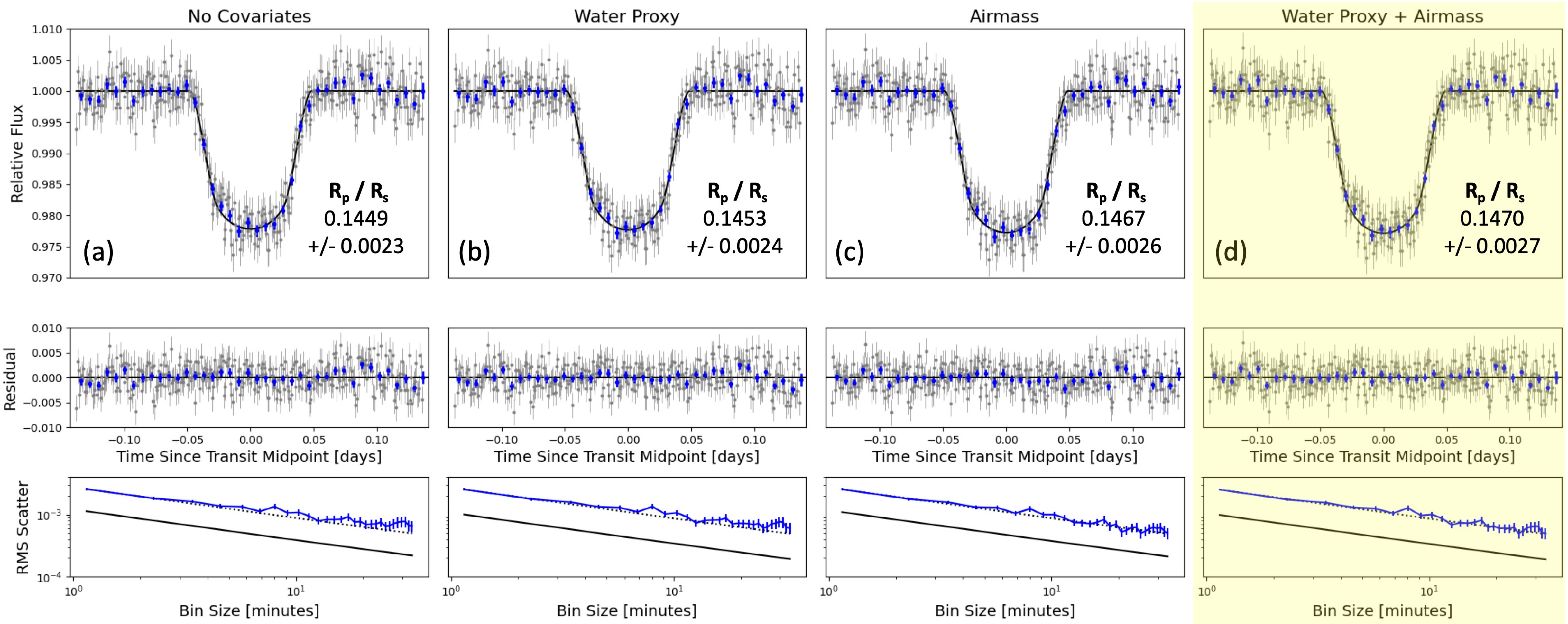
Today's Topic: Planetary Aeronomy (Upper Atmospheres)

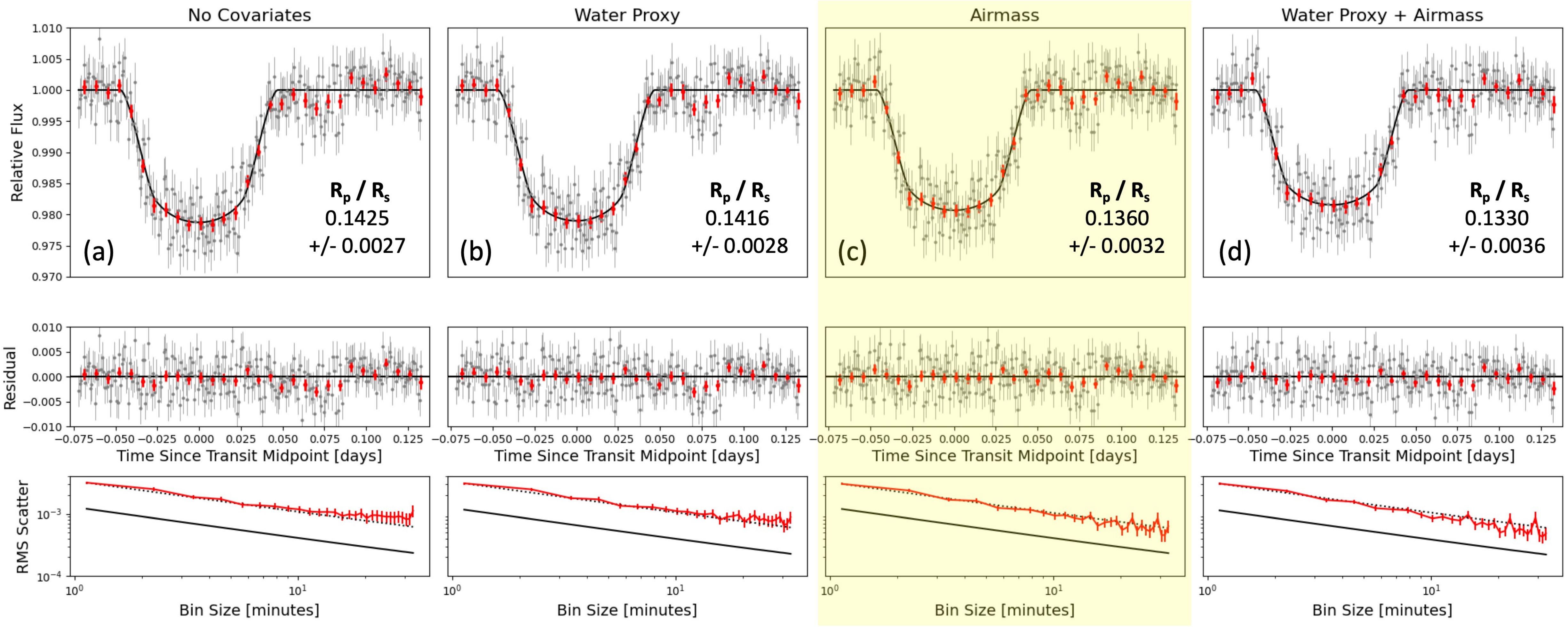




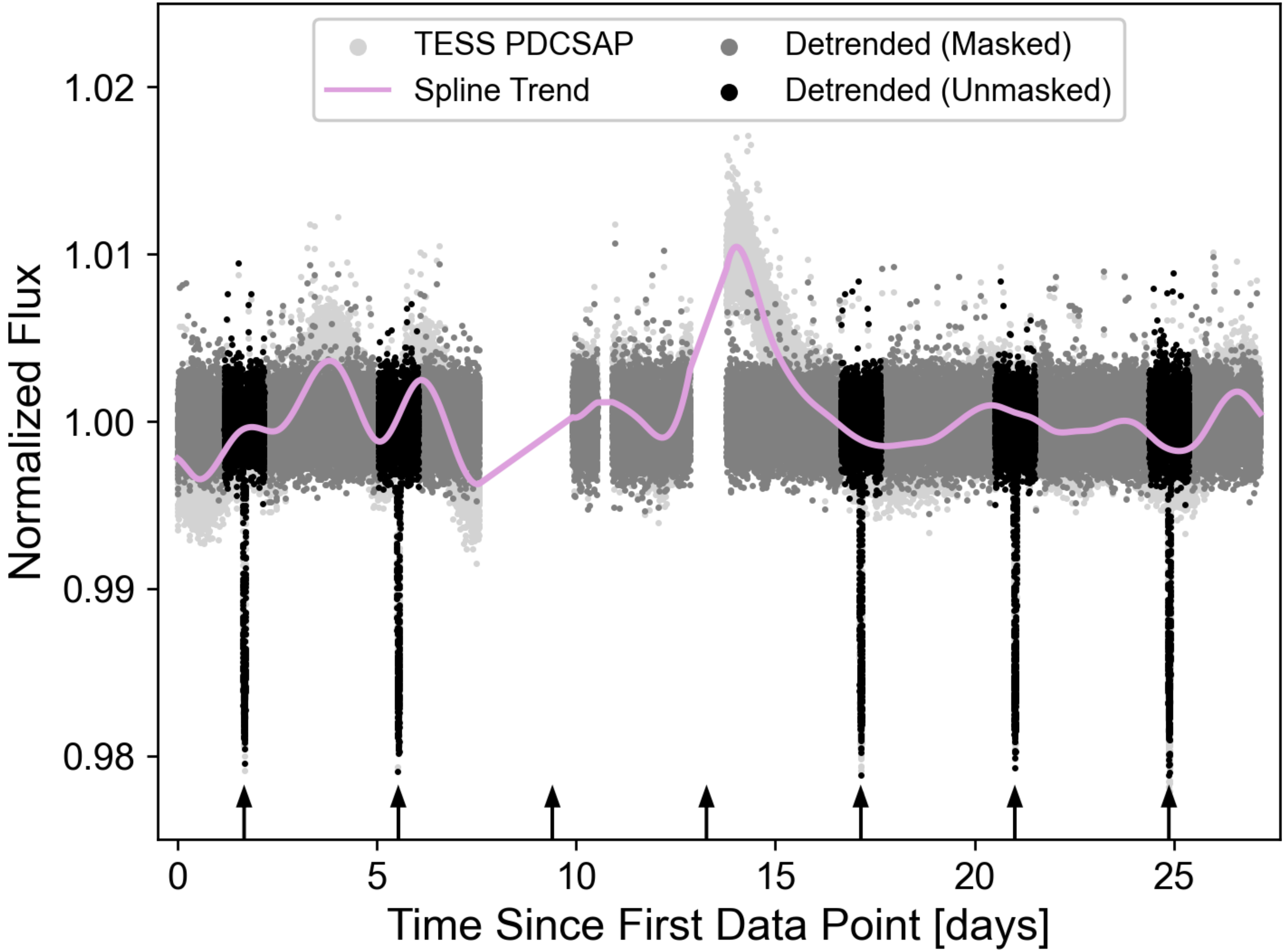

Credit: NASA/GSFC

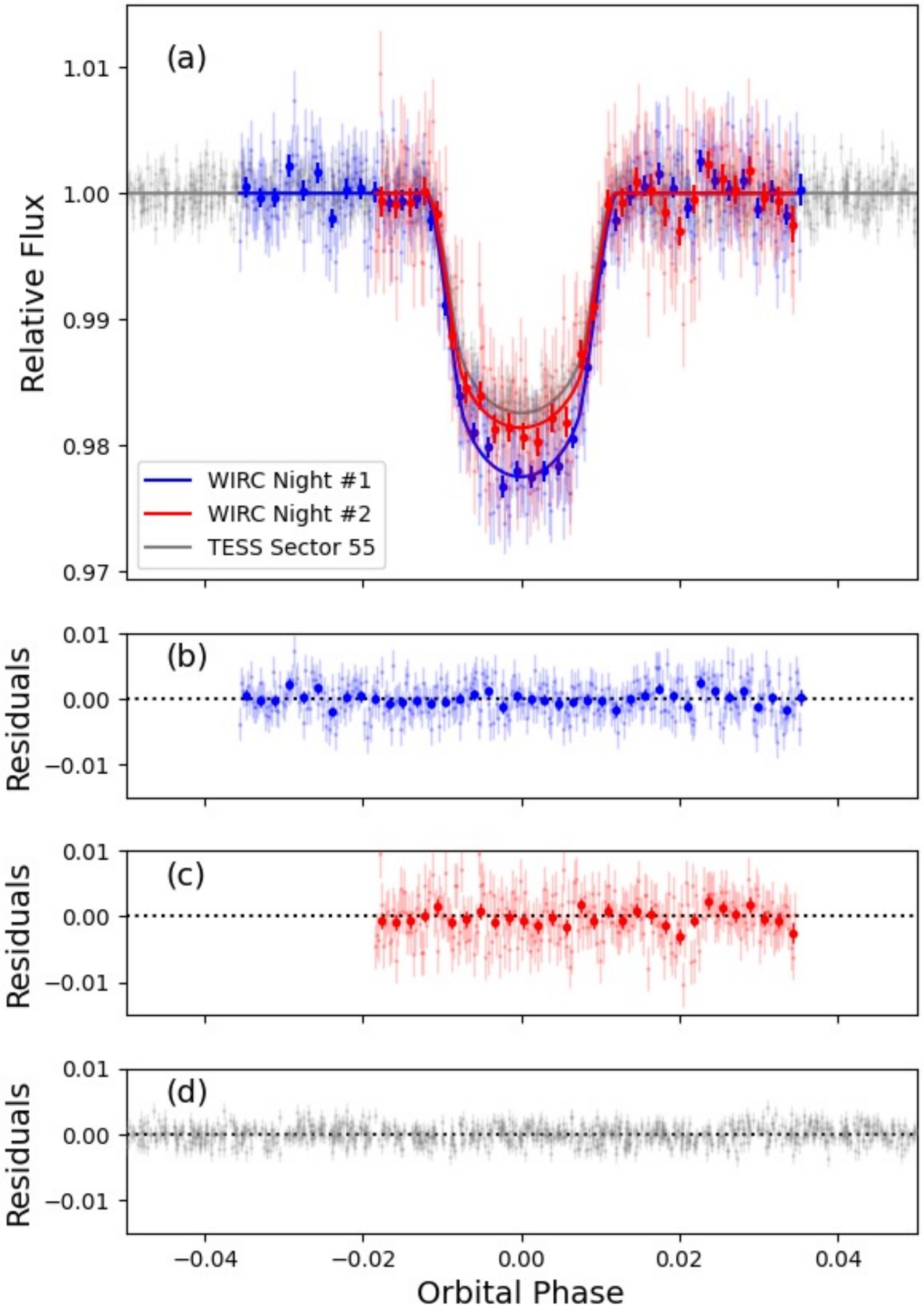

WASP-69
Comparisons
(Night 2)
Comparisons
(Night 1)
Detector Y Pixel
Detector X Pixel
Signal [ADU]
2000
1750
1500
1250
1000
750
500
250
0
0
500
1000
1500
2000
1000
800
600
400
200
0


No Covariates
Water Proxy
Airmass
Water Proxy + Airmass
Relative Flux
Residual
RMS Scatter
R_p / R_s
0.1449
+/- 0.0023
R_p / R_s
0.1453
+/- 0.0024
R_p / R_s
0.1467
+/- 0.0026
R_p / R_s
0.1470
+/- 0.0027
(a)
(b)
(c)
(d)
Time Since Transit Midpoint [days]
Bin Size [minutes]

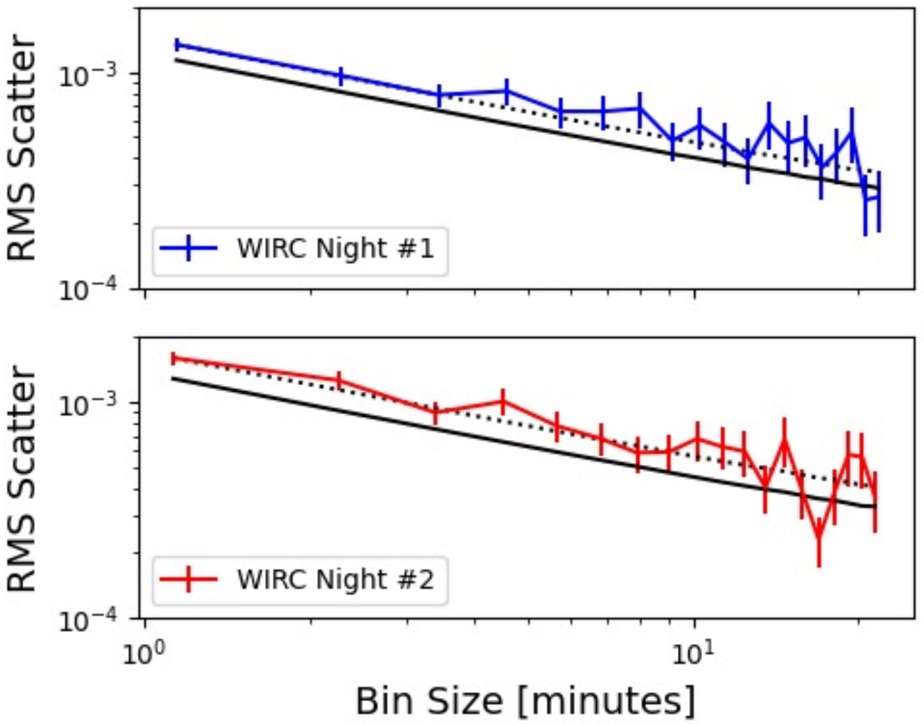


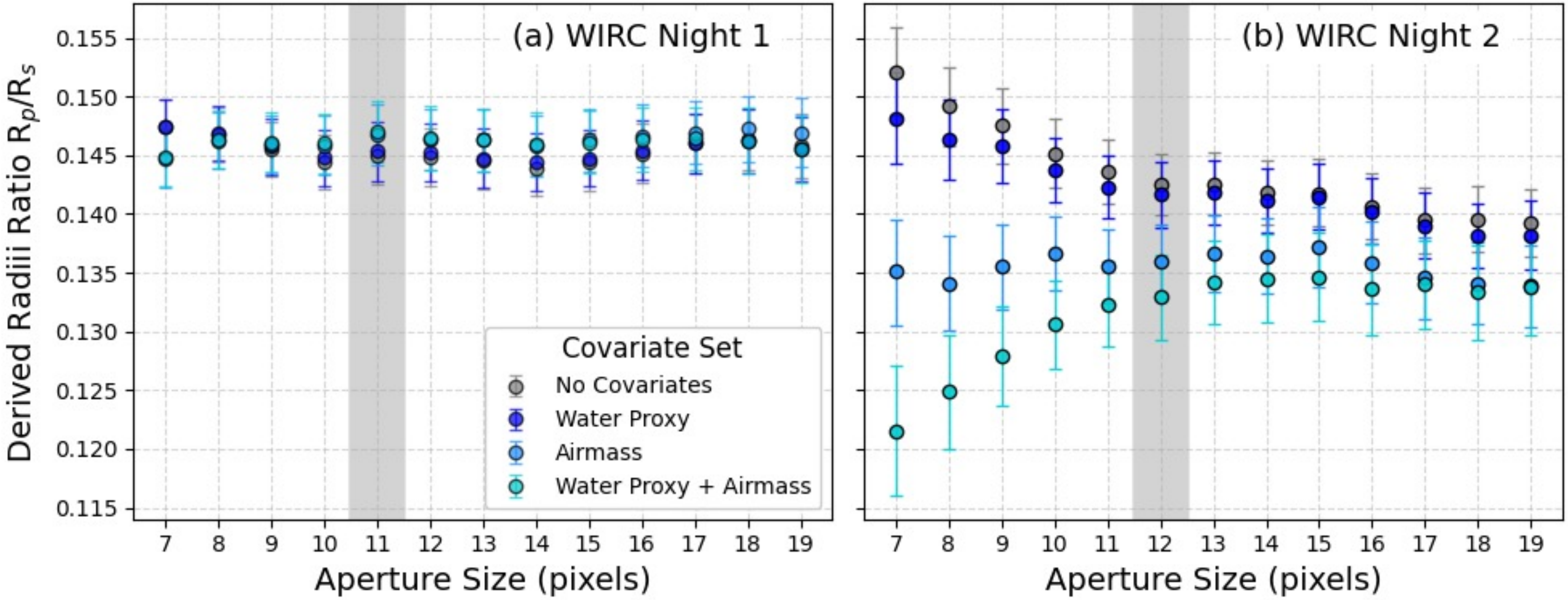
No Covariates
Water Proxy
Airmass
Water Proxy + Airmass
Relative Flux
Residual
RMS Scatter
Time Since Transit Midpoint [days]
Bin Size [minutes]
(a)
R_p / R_s
0.1425
+/- 0.0027
(b)
R_p / R_s
0.1416
+/- 0.0028
(c)
R_p / R_s
0.1360
+/- 0.0032
(d)
R_p / R_s
0.1330
+/- 0.0036

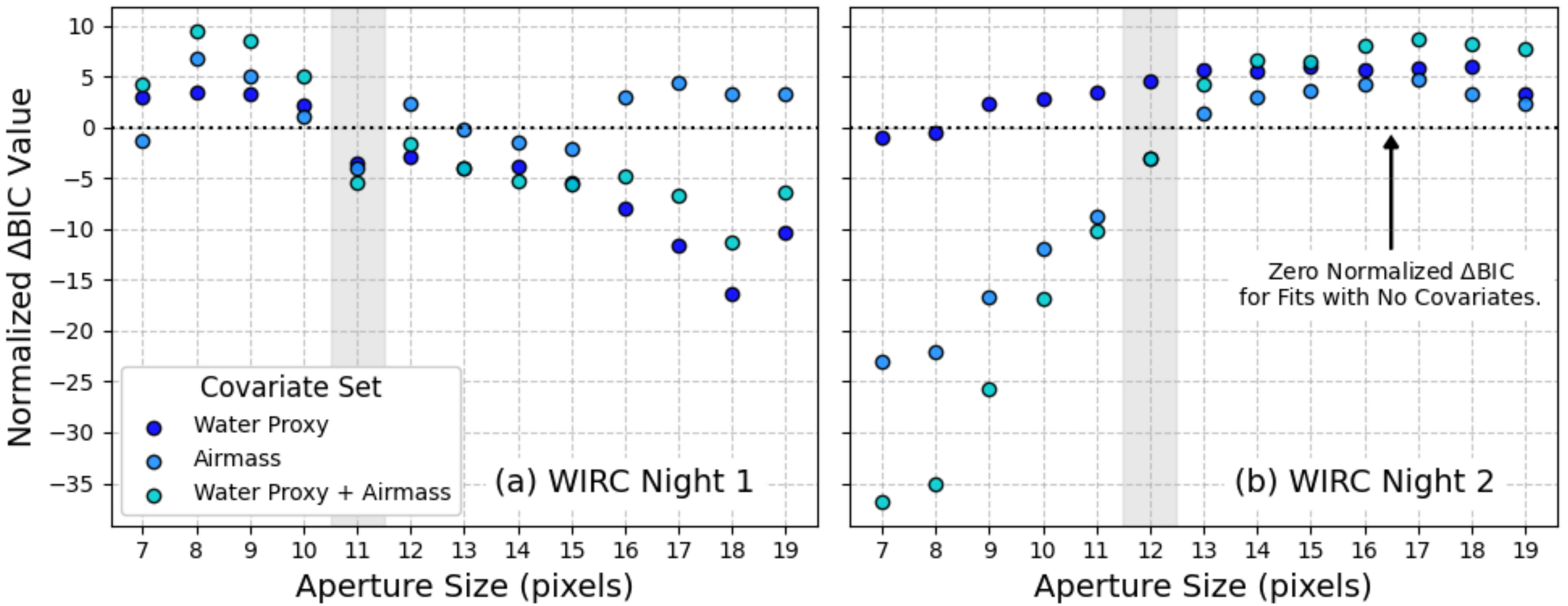

TESS PDCSAP
Spline Trend
Detrended (Masked)
Detrended (Unmasked)
1.02
1.01
1.00
0.99
0.98
Normalized Flux
0
5
10
15
20
25
Time Since First Data Point [days]

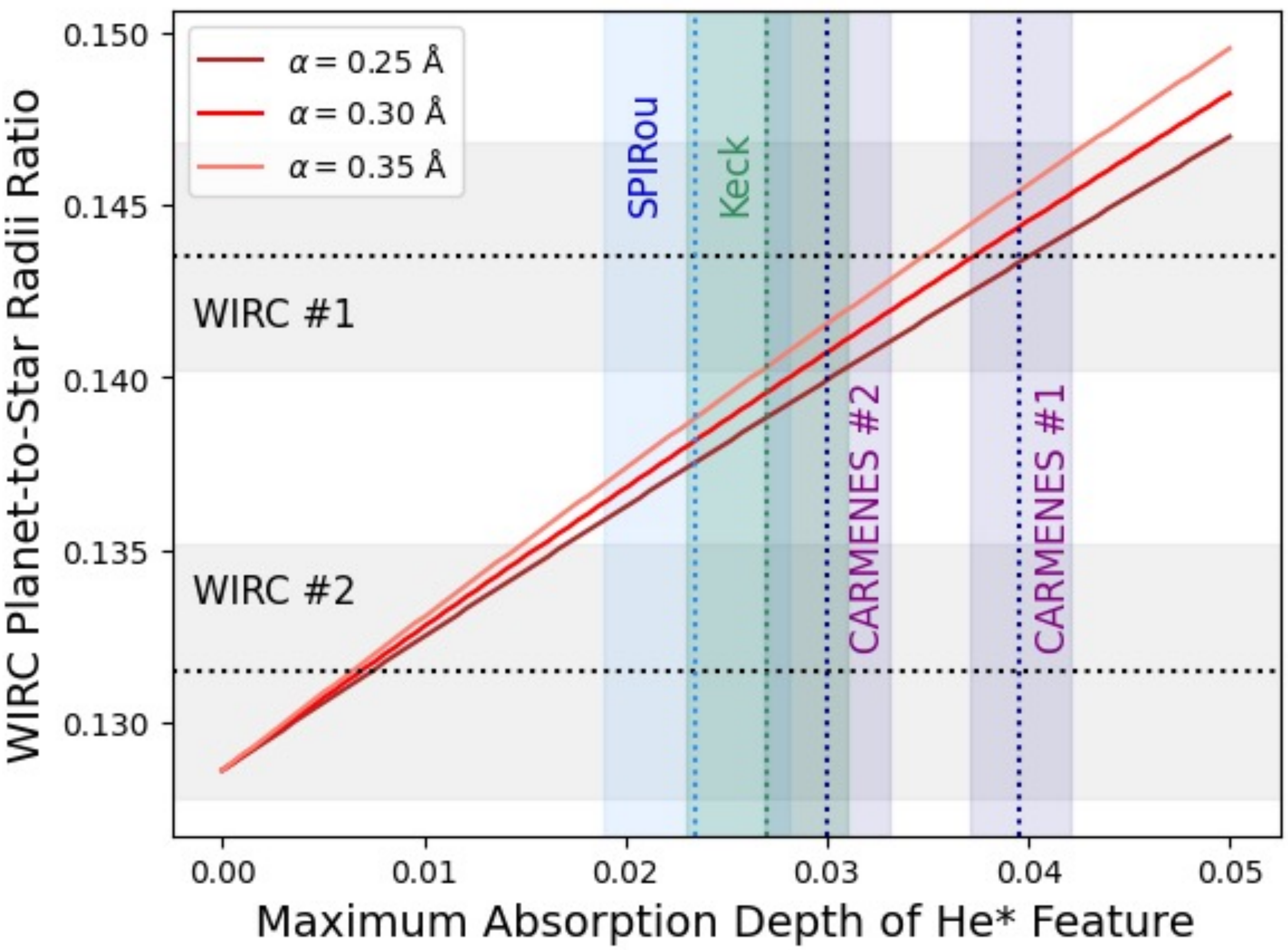


Parameter	Prior	Posterior
P	$\mathcal{N}(3.8681390, 1.0)$	$3.8681363^{+0.0000017}_{-0.0000017}$
$t_0 - 2457000$	$176.17789 + \mathcal{U}(0, 1)$	$176.1794^{+0.0012}_{-0.0011}$
a/R_s	$\mathcal{U}(5.00, 20.00)$	$12.73^{+0.45}_{-0.45}$
b	$\mathcal{U}(0, 1)$	$0.616^{+0.045}_{-0.047}$
R_s	$\mathcal{N}(0.813, 0.05)$	$0.81^{+0.05}_{-0.05}$
$(R_p/R_s)_{\mathrm{T}}$	$\mathcal{U}(0.00, 0.25)$	$0.1245^{+0.0026}_{-0.0020}$
$(R_p/R_s)_{\mathrm{W,1}}$	$\mathcal{U}(0.00, 0.25)$	$0.1435^{+0.0033}_{-0.0031}$
$(R_p/R_s)_{\mathrm{W,2}}$	$\mathcal{U}(0.00, 0.25)$	$0.1315^{+0.0037}_{-0.0037}$

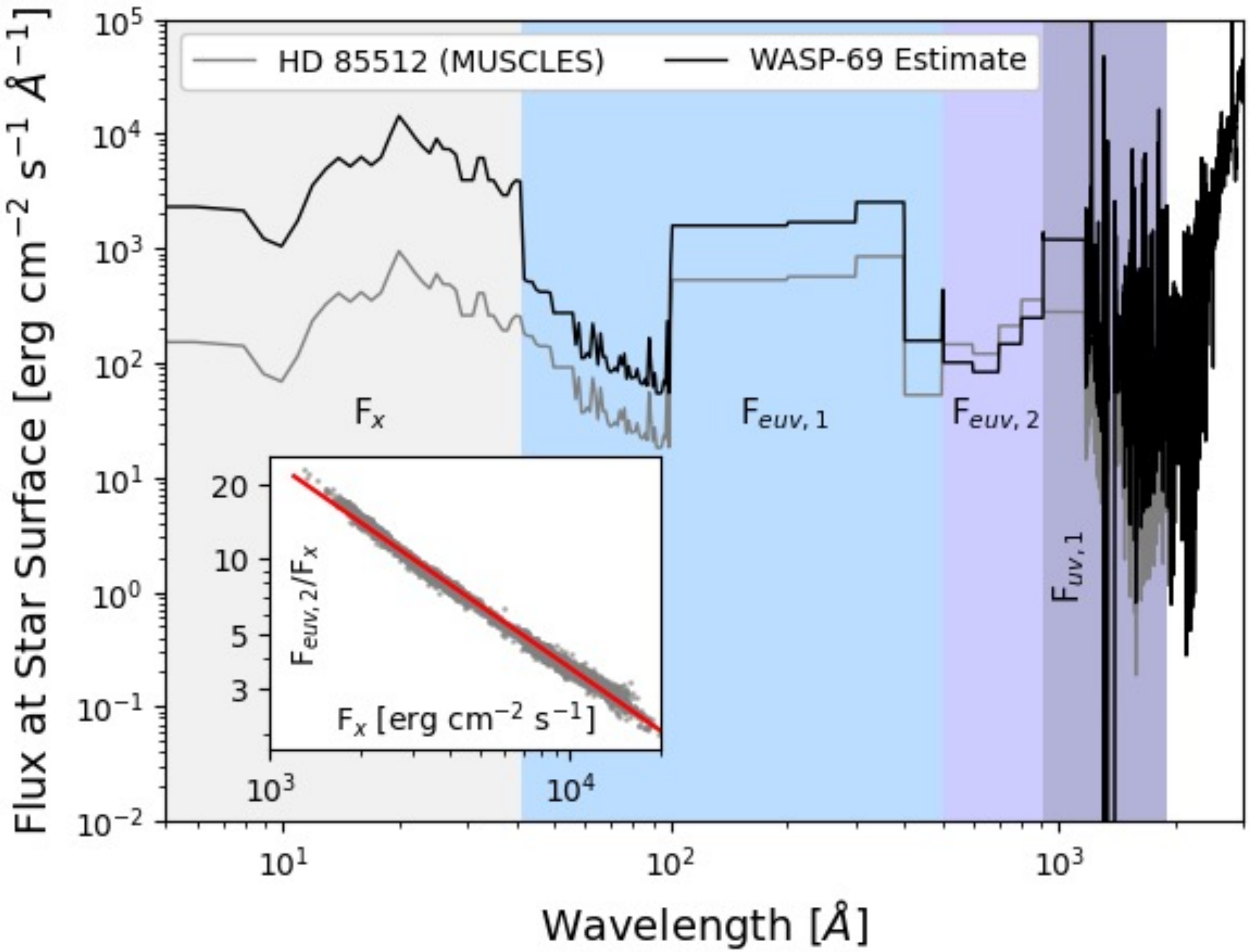



(a) WIRC Night 1
(b) WIRC Night 2
Derived Radiii Ratio R_p/R_s
0.155
0.150
0.145
0.140
0.135
0.130
0.125
0.120
0.115
7 8 9 10 11 12 13 14 15 16 17 18 19
Aperture Size (pixels)
Covariate Set
No Covariates
Water Proxy
Airmass
Water Proxy + Airmass


Normalized ΔBIC Value
Covariate Set
Water Proxy
Airmass
Water Proxy + Airmass
(a) WIRC Night 1
(b) WIRC Night 2
Zero Normalized ΔBIC
for Fits with No Covariates.
Aperture Size (pixels)
Aperture Size (pixels)



$\alpha = 0.25$ Å
$\alpha = 0.30$ Å
$\alpha = 0.35$ Å
SPIRou
Keck
CARMENES #2
CARMENES #1
WIRC #1
WIRC #2
WIRC Planet-to-Star Radii Ratio
0.150
0.145
0.140
0.135
0.130
0.00
0.01
0.02
0.03
0.04
0.05
Maximum Absorption Depth of He* Feature


HD 85512 (MUSCLES)
WASP-69 Estimate
Flux at Star Surface [erg cm^{-2} s^{-1} Å^{-1}]
Wavelength [Å]
F_x
$F_{euv,1}$
$F_{euv,2}$
$F_{uv,1}$
$F_{euv,2}/F_x$
F_x [erg cm^{-2} s^{-1}]

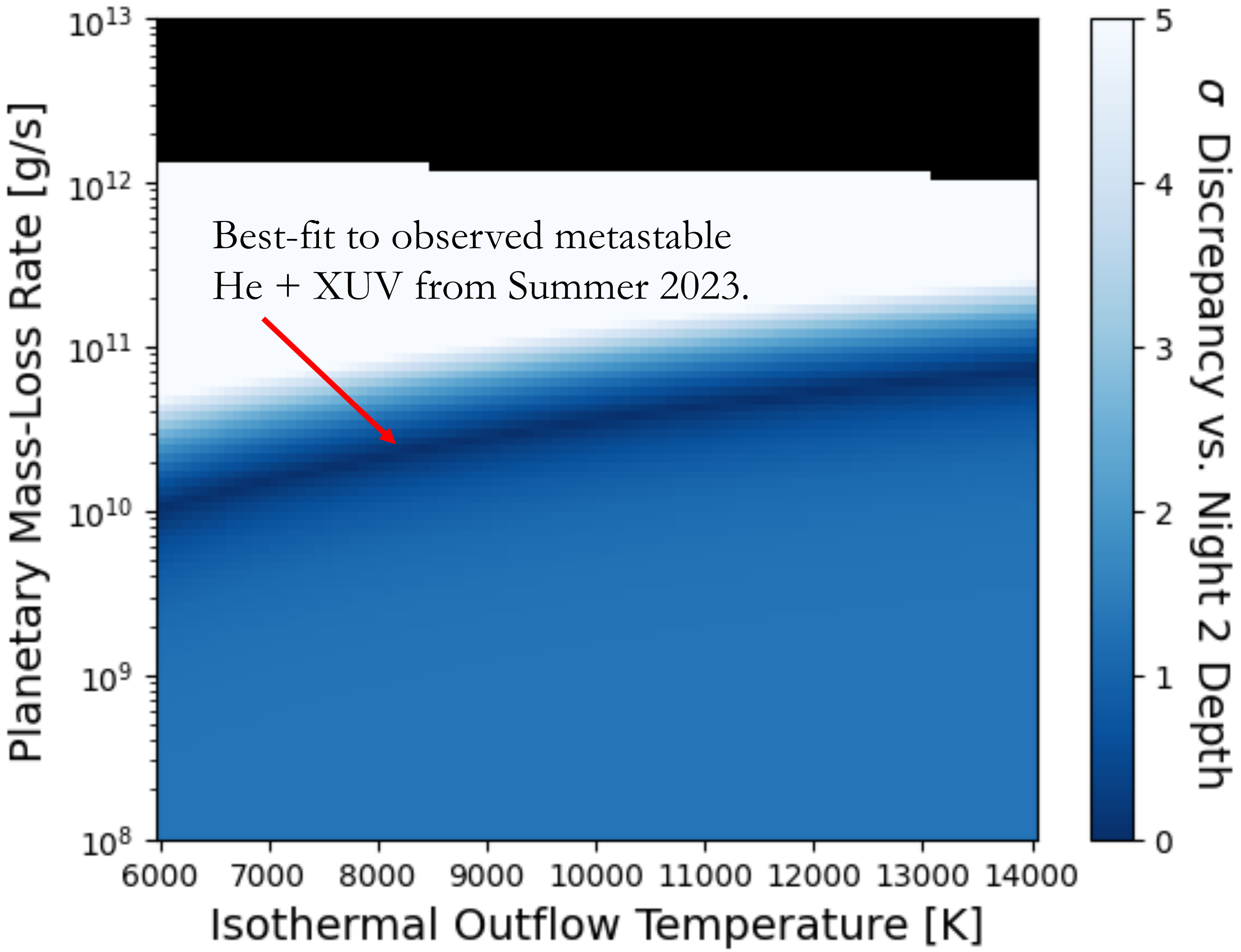
Modeling Multi-Wavelength & Contemporaneous Data

`p-winds` package

- Model of upper atmosphere structure and H/He level populations as isothermal hydrodynamic escape.

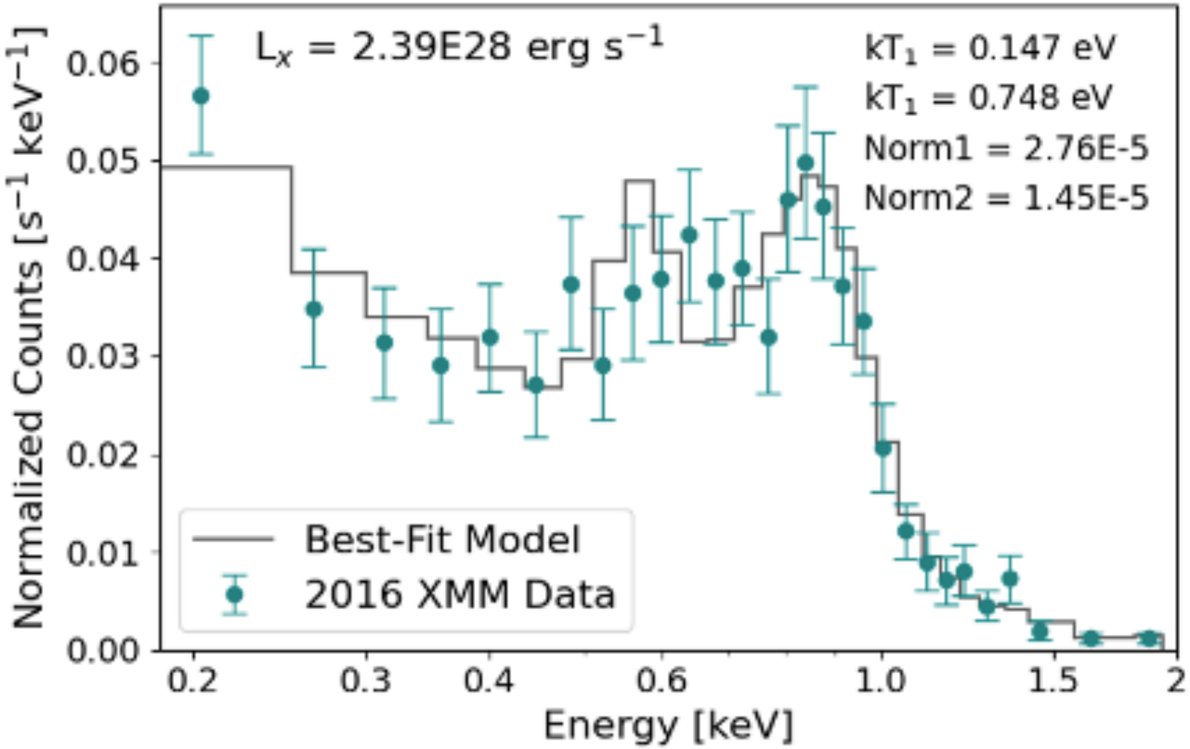
Parker (1958); Oklopčić & Hirata (2018); Lampón et al. (2020)

- Requires an input mass-loss rate, thermosphere temperature, and stellar irradiation spectrum.



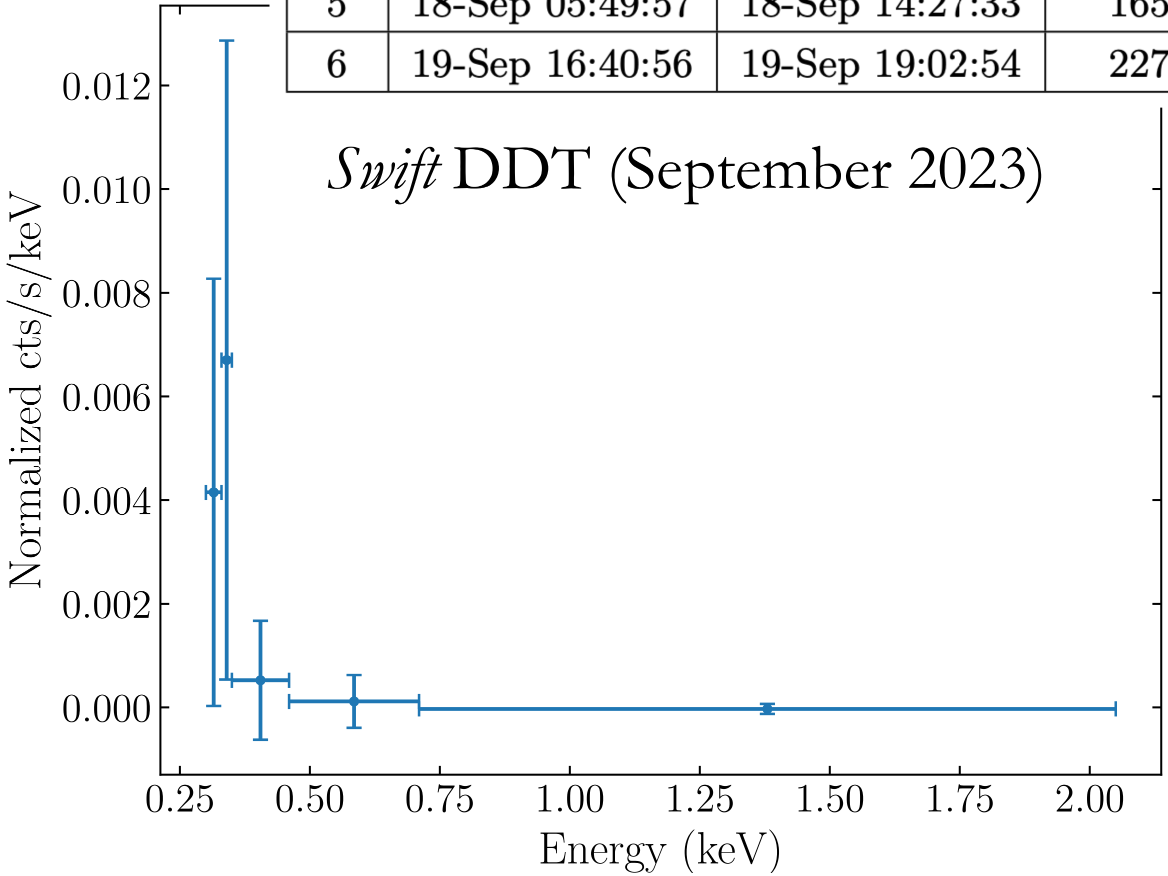
Levine et al. (*submitted*)

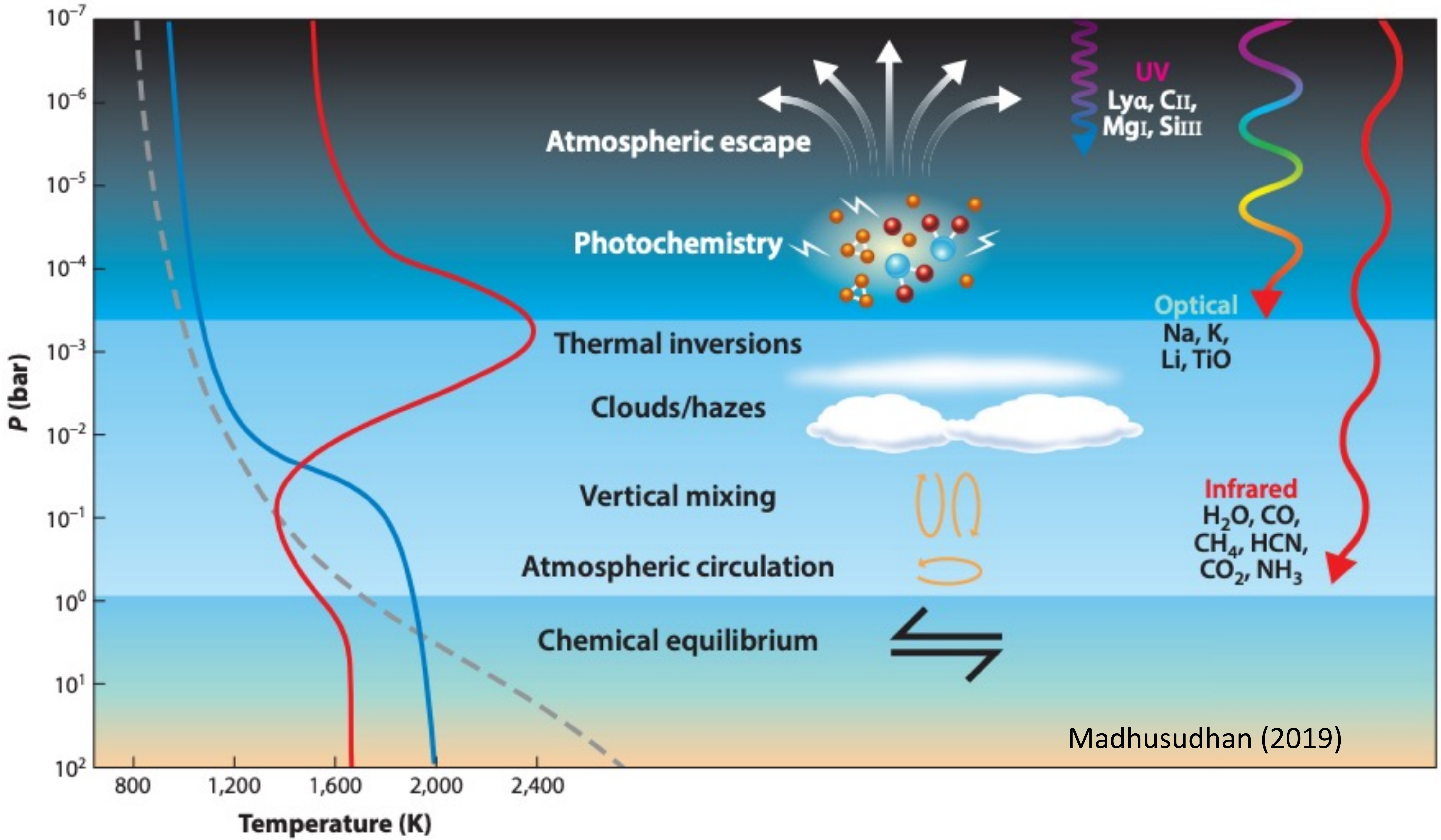
XMM ObsID 0783560201, PI: Salz



ID	UT Start	UT End	Exp. [s]
2	13-Sep 03:59:57	13-Sep 17:14:02	2319
3	14-Sep 09:59:57	14-Sep 20:14:26	1650
4	15-Sep 09:53:57	16-Sep 16:31:29	5928
5	18-Sep 05:49:57	18-Sep 14:27:33	1651
6	19-Sep 16:40:56	19-Sep 19:02:54	2277

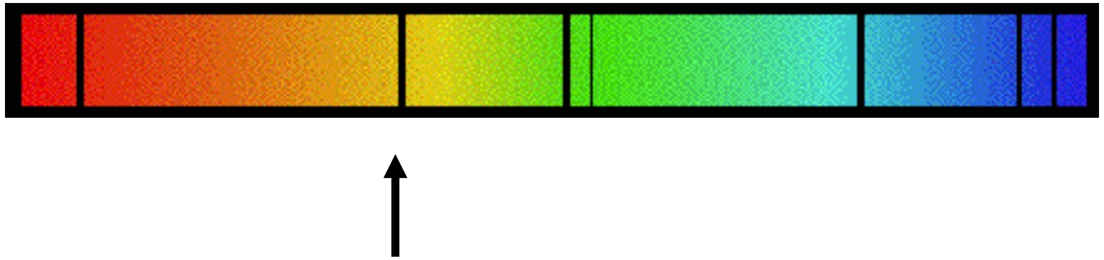
Swift DDT (September 2023)



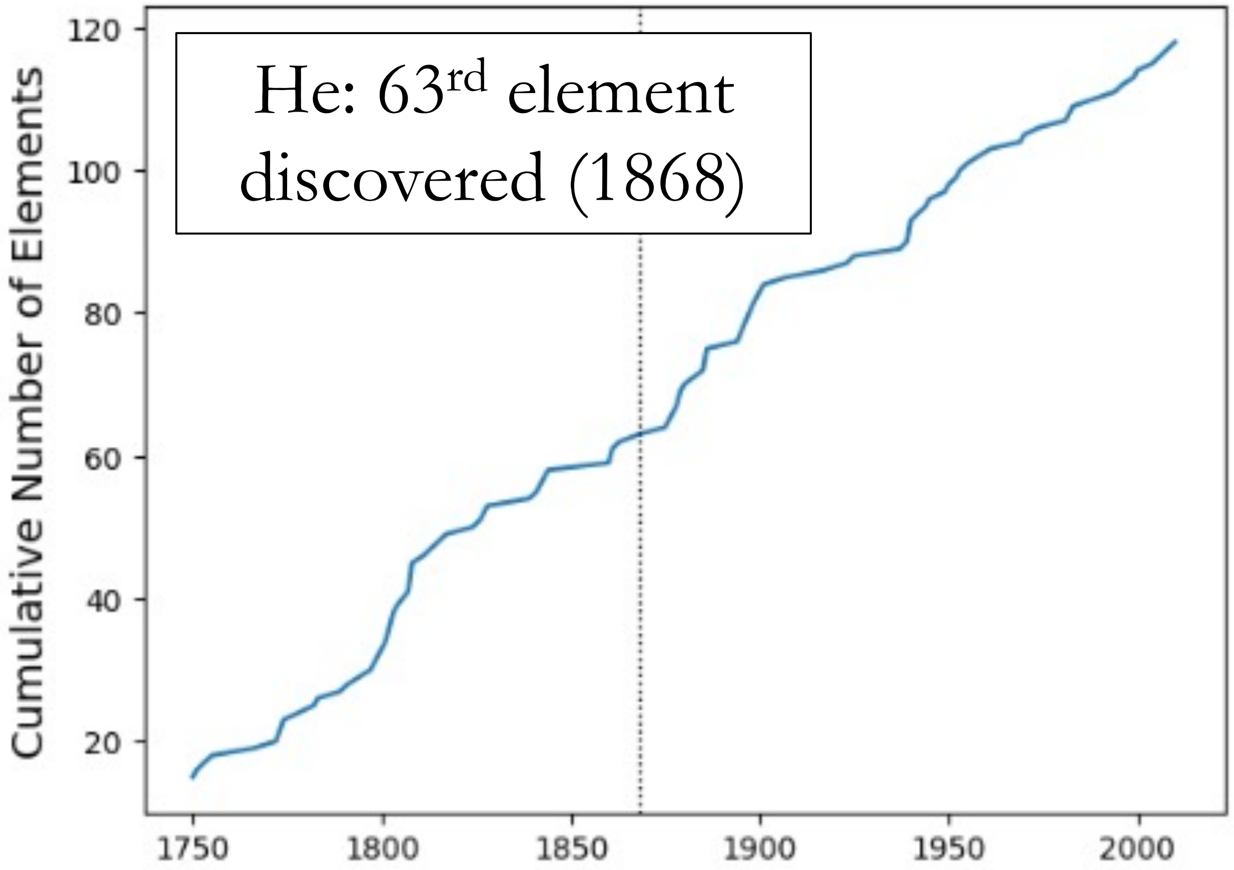


Madhusudhan (2019)

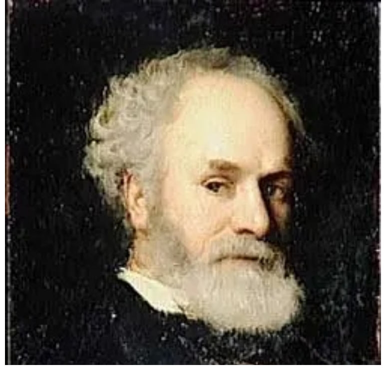
Helium: the only element discovered by astronomers.



This line was unknown and correctly attributed to a new element.



- Pierre Janssen: co-discoverer of He and creator of oldest film on IMDB.

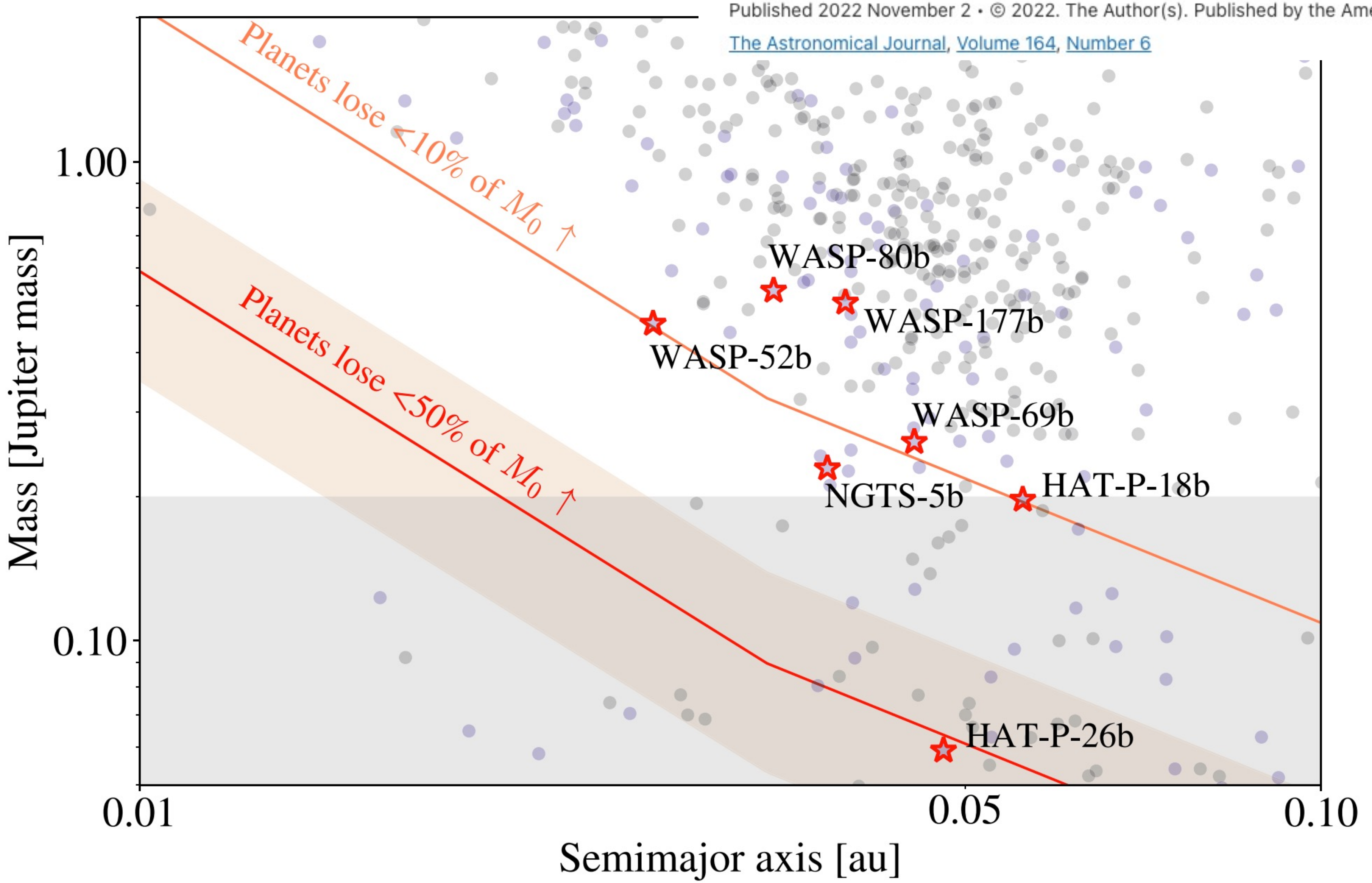


OPEN ACCESS

The Upper Edge of the Neptune Desert Is Stable Against Photoevaporation

Shreyas Vissapragada[1], Heather A. Knutson[1], Michael Greklek-McKeon[1], Antonija Oklopčić[2], Fei Dai[1], Leonardo A. dos Santos[3], Nemanja Jovanovic[4], Dimitri Mawet[4,5], Maxwell A. Millar-Blanchaer[6], Kimberly Paragas[1] + Show full author list

Published 2022 November 2 • © 2022. The Author(s). Published by the American Astronomical Society.
The Astronomical Journal, Volume 164, Number 6



Motivation: Palomar 200” Telescope

THE POSSIBILITIES OF LARGE TELESCOPES

BY GEORGE ELLERY HALE

Honorary Director of the Mount Wilson Observatory

1928

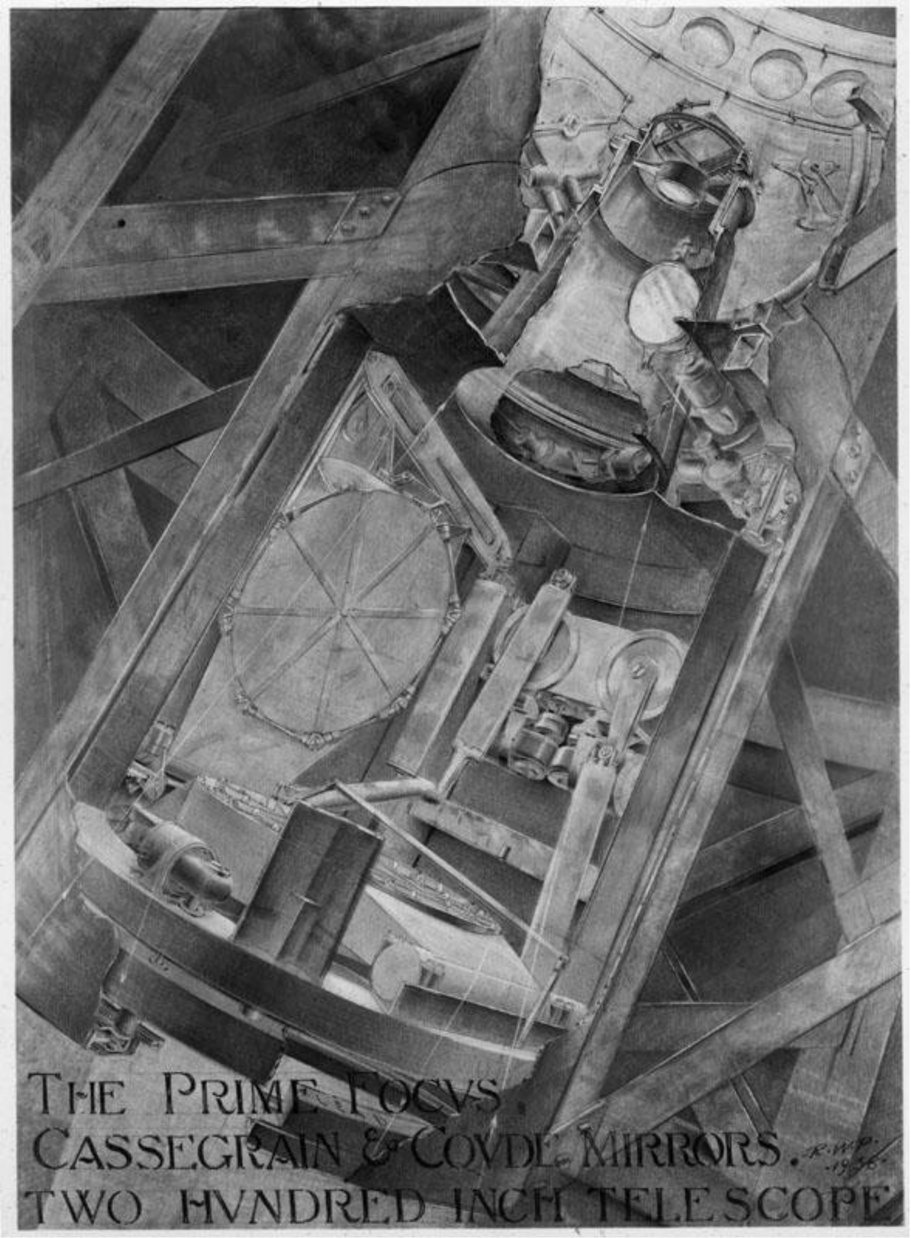
1. Structure of the Universe
2. Evolution of Stars
3. Constitution of Matter

Goal: reach the main sequence of Milky Way globular clusters.

- $6mn ($100mn today) gift from the Rockefellers essentially started Caltech's astronomy program.

- Hale Telescope is still the 20th largest telescope in the world.

- When Palomar was designed, Nazi Germany was just inventing "night vision."

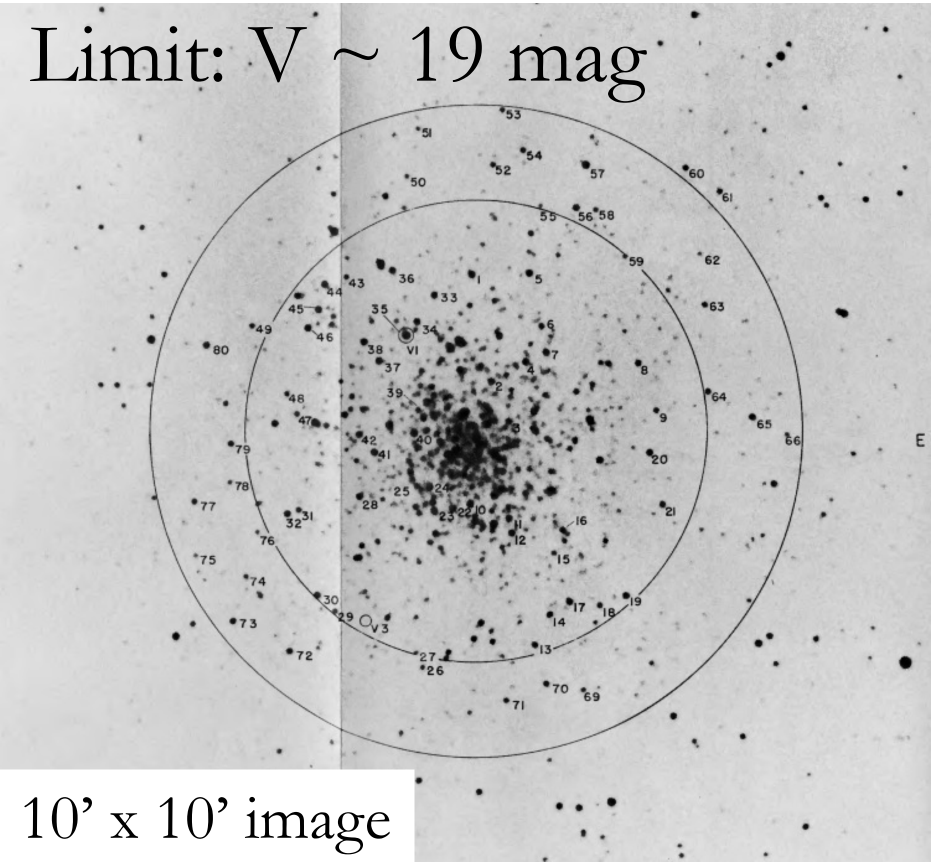


Main Sequence of Globular Clusters

- Sun-like main sequence star from 4kpc: V ~ 17.5 mag.

NGC 6356: Sandage et al. (1960)

Limit: V ~ 19 mag

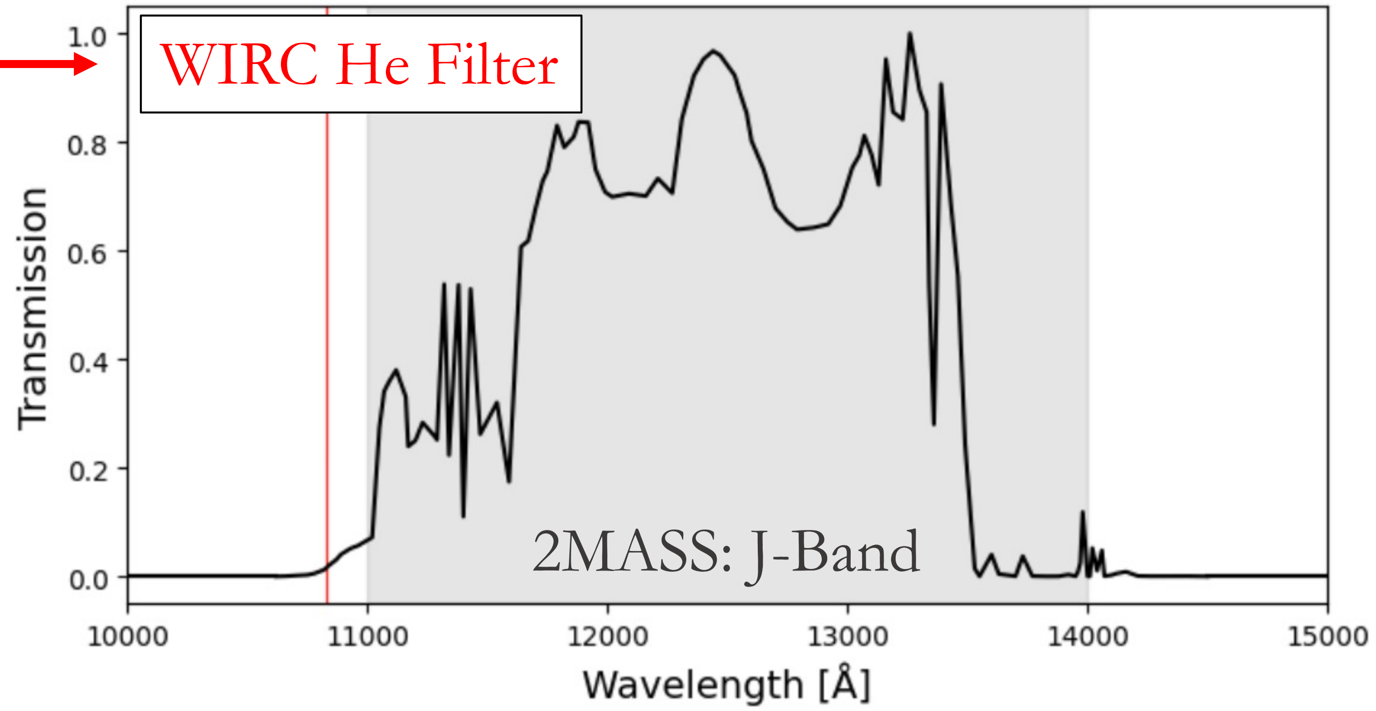


10' x 10' image

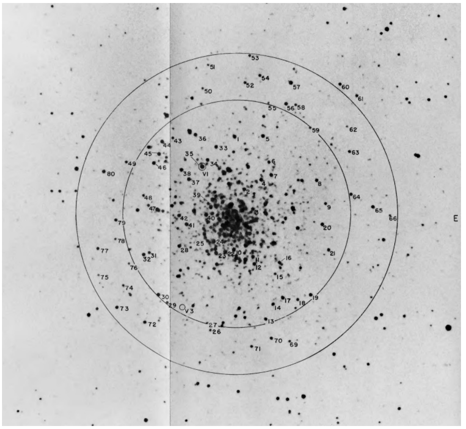
Constraint #1: Star Brightness

- On Palomar/WIRC, my requisite SNR needs J < 11 mag stars.

0.2% width of 2MASS J-Band.

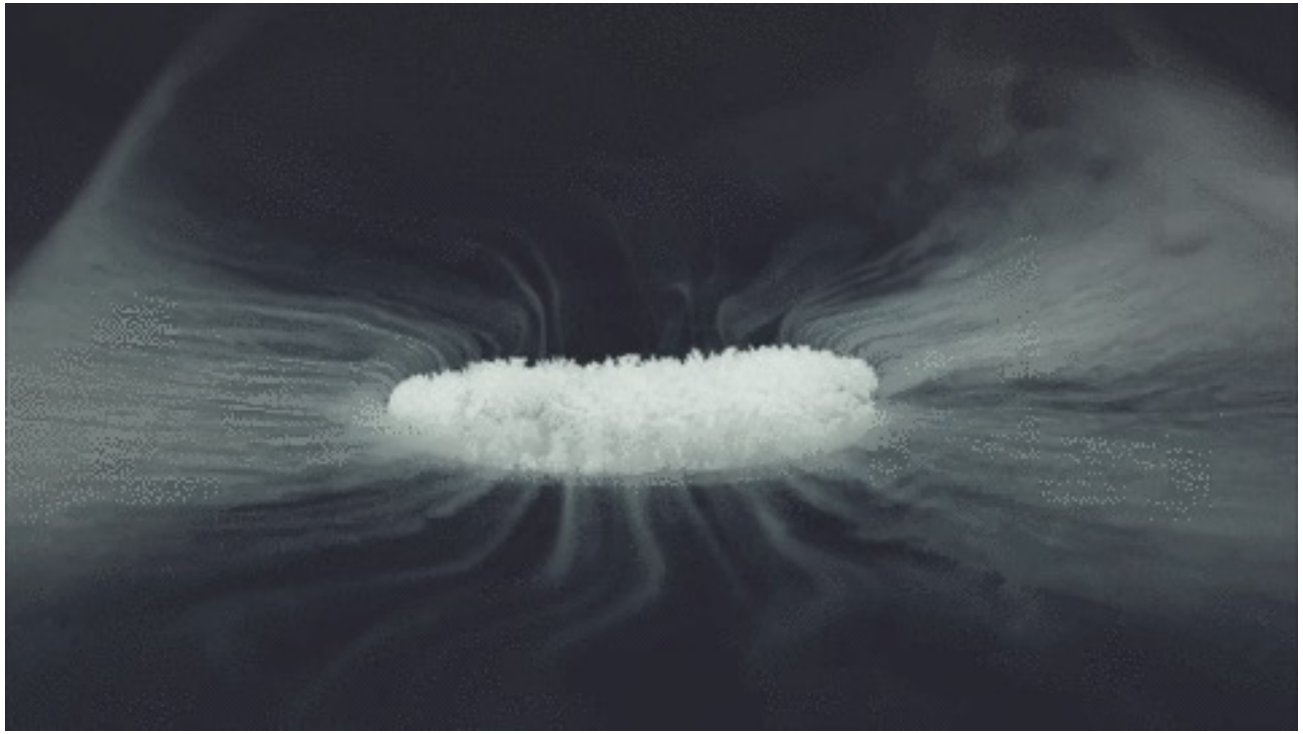


Limit: V ~ 19 mag



- He filter (6Å FWHM) makes these targets appear as 17-18 mag.
- Modern instrumentation allows 90s exposures and time-domain astronomy.

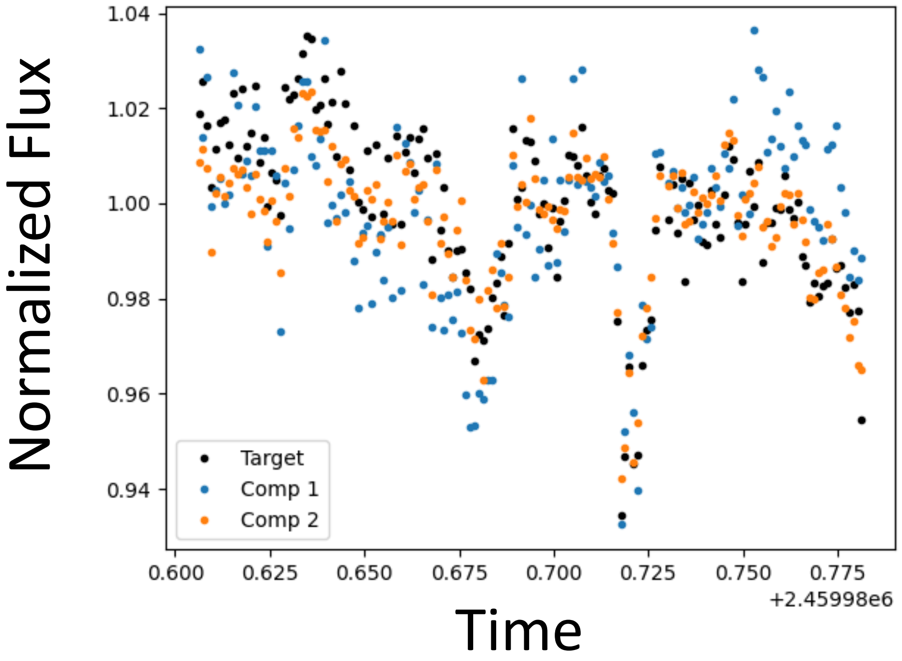
Constraint #1.5: Uninterrupted Observing

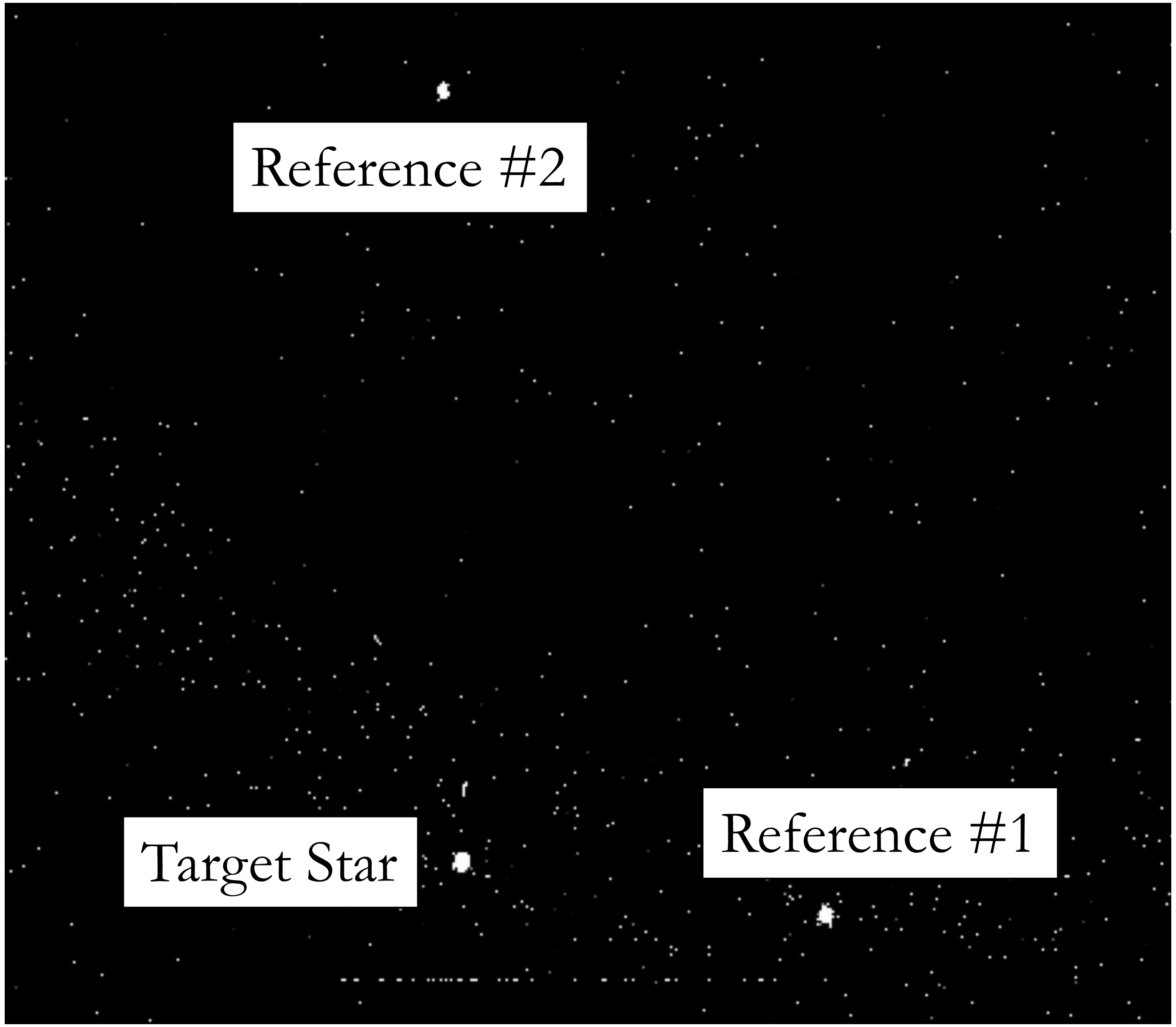


Constraint #2: Reference Star Availability

Differential Photometry:

- Need a few stars in WIRC field-of-view that are within 1-2 mag of target star.

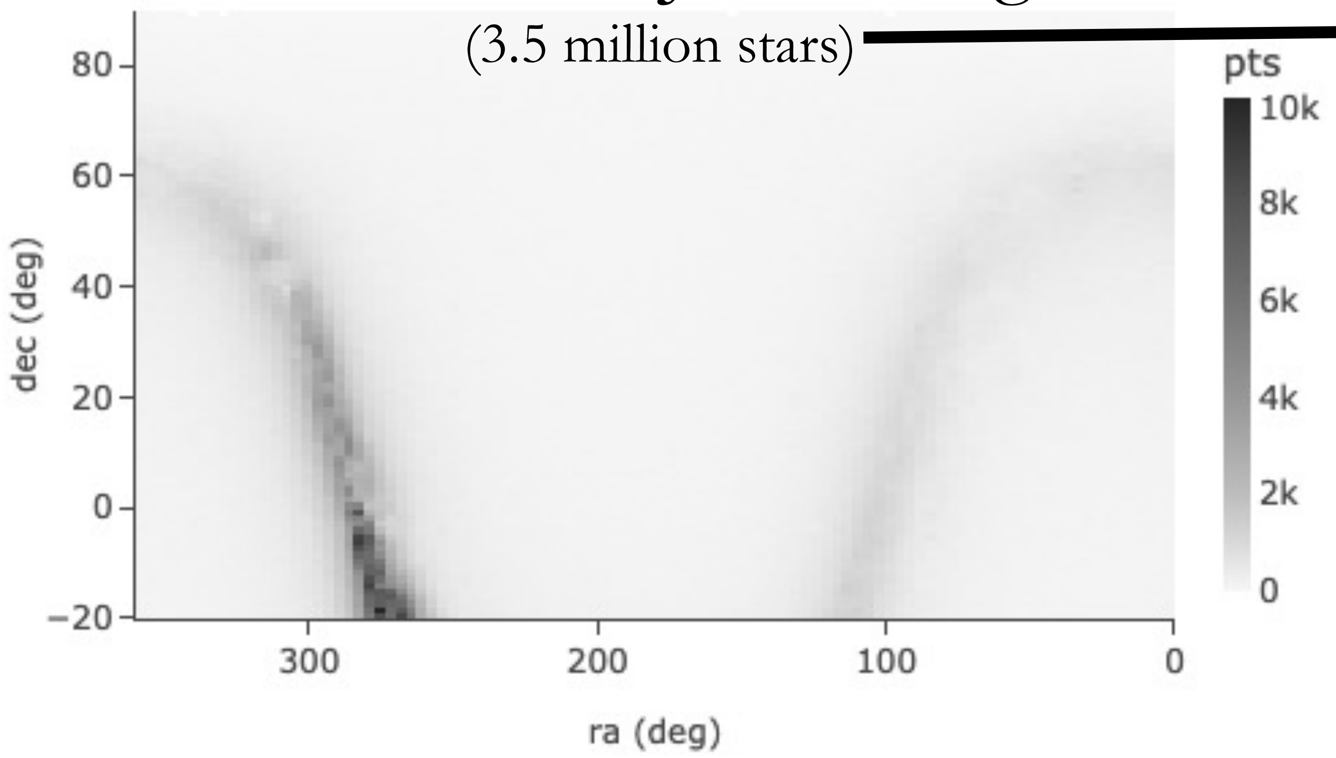




Constraint #2: Reference Star Availability

2MASS: J ~ 11 mag

(3.5 million stars) → 3×10^{-6} sr/star



- WIRC: 6×10^{-6} sr FOV
- Expectation:

$$\frac{6 \times 10^{-6}\ \text{sr}}{3 \times 10^{-6}\ \text{sr/star}} = 2\ \text{stars in WIRC FOV}$$

for J ~ 11.

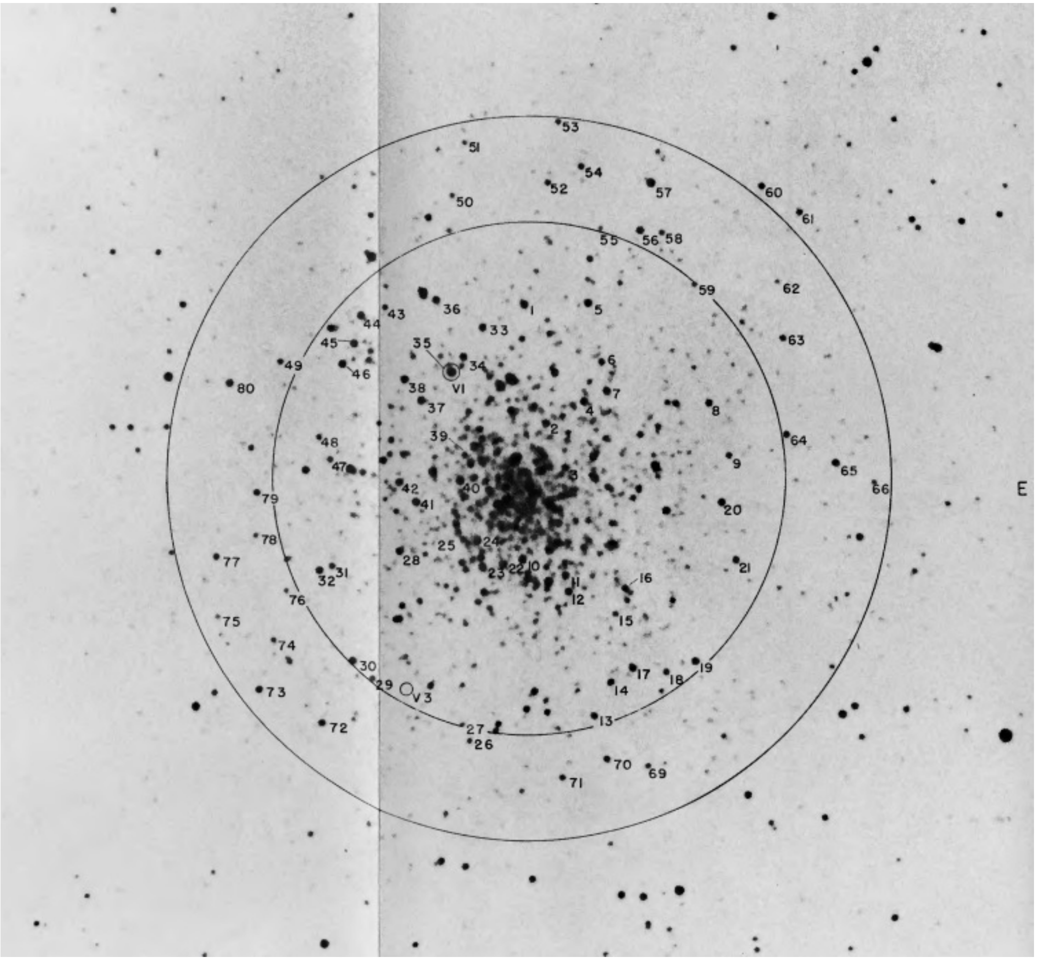
- Galactic Plane: field star density enhanced by a factor of a few.
- J ~ 11 is the brightest star for which we can expect several references.

Why Palomar Works for Helium Transits

- 1928: reaching the main sequence of globular clusters was a priority.
  - required stars around 18th magnitude.

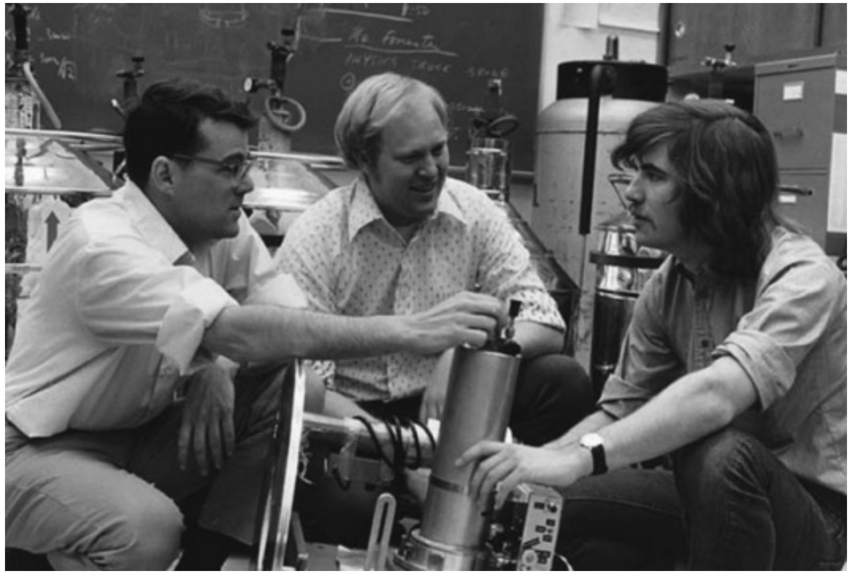
- Today: my SNR requires target stars brighter than J ~11 mag.
  - FWHM 6Å filter makes these host stars look like 17-18 mag.

- Coincidentally: star count statistics imply that I need stars J ~ 11 mag or dimmer to expect several reference stars.



Sandage et al. (1960)

"Although contour maps are presented, a careful comparison of the contours with the single-pixel scans on which they are based indicates that Neugebauer and Becklin had not received sufficient time on the 200-inch telescope to map the region thoroughly (Guido Munch had let them have a little time out of his allocation)."
-Low, Rieke, Gehrz (2007), ARAA



INFRARED OBSERVATIONS OF THE GALACTIC CENTER*

E. E. Becklin and G. Neugebauer
California Institute of Technology, Pasadena
Received June 13, 1967

ABSTRACT

Infrared radiation from the nucleus of the Galaxy has been detected at effective wavelengths of 1.65, 2.2, and 3.4 μ with angular resolutions from 0′.08 to 1′.8. The structure consists of: (1) a dominant source 5′ in diameter; (2) a pointlike source centered on the dominant source; (3) an extended background; and (4) additional discrete extended sources. Contour maps of the 2.2-μ brightness distribution of the galactic center region are given for resolutions of 1′.8, 0′.8, and 0′.25.

A comparison of the infrared and radio observations shows that the dominant infrared source and the radio source Sagittarius A have the same coordinates and similar sizes.

An analysis of the observed infrared radiation predicts about 25 mag of visual absorption between the Sun and the galactic center if the source of infrared radiation is stellar. A comparison is also made between the infrared radiation from the galactic center and that from the nucleus of M31 which shows agreement in both the apparent structure and infrared luminosity of the two nuclei.

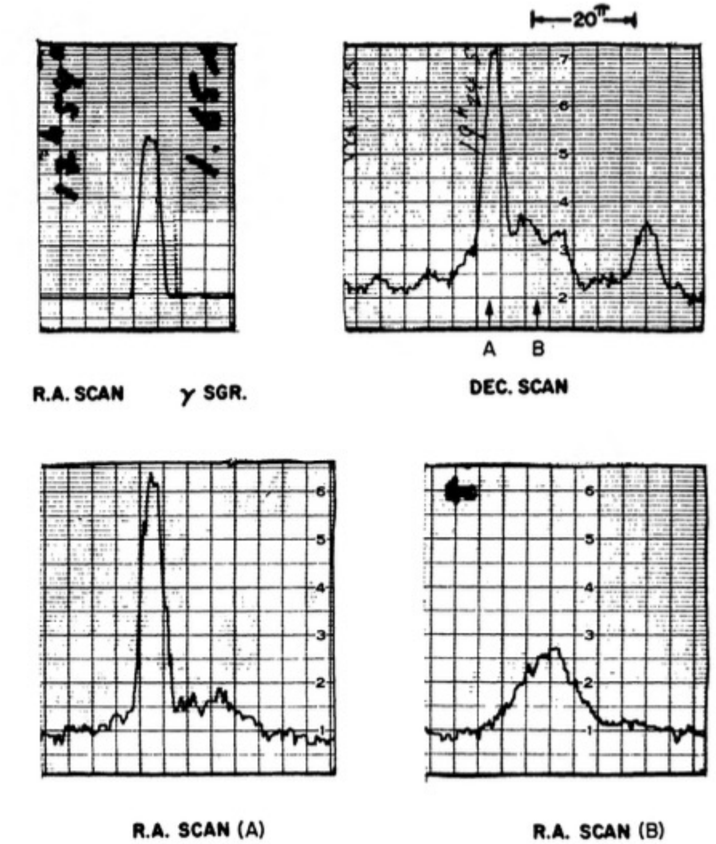


Fig 3 —Strip-chart recordings of right-ascension and declination scans of the galactic center region and of γ Sagittarius at 2.2 μ obtained with the 200-inch telescope using an aperture of 0′08 are shown. The right-ascension and declination scan rates in the sky are the same. The right-ascension scans were made at the declinations labeled "A" and "B". The amplifier gain was the same for all scans of the galactic center region and was reduced by a factor of 320 for γ Sagittarius.