

Reconnaissance of terrestrial exoplanet atmospheres from the ground in advance of JWST

Hannah Diamond-Lowe

*In collaboration with: Zach Berta-Thompson, Yuri Beletsky,
Dave Charbonneau, Eliza Kempton, Matej Malik, Jason Dittmann*

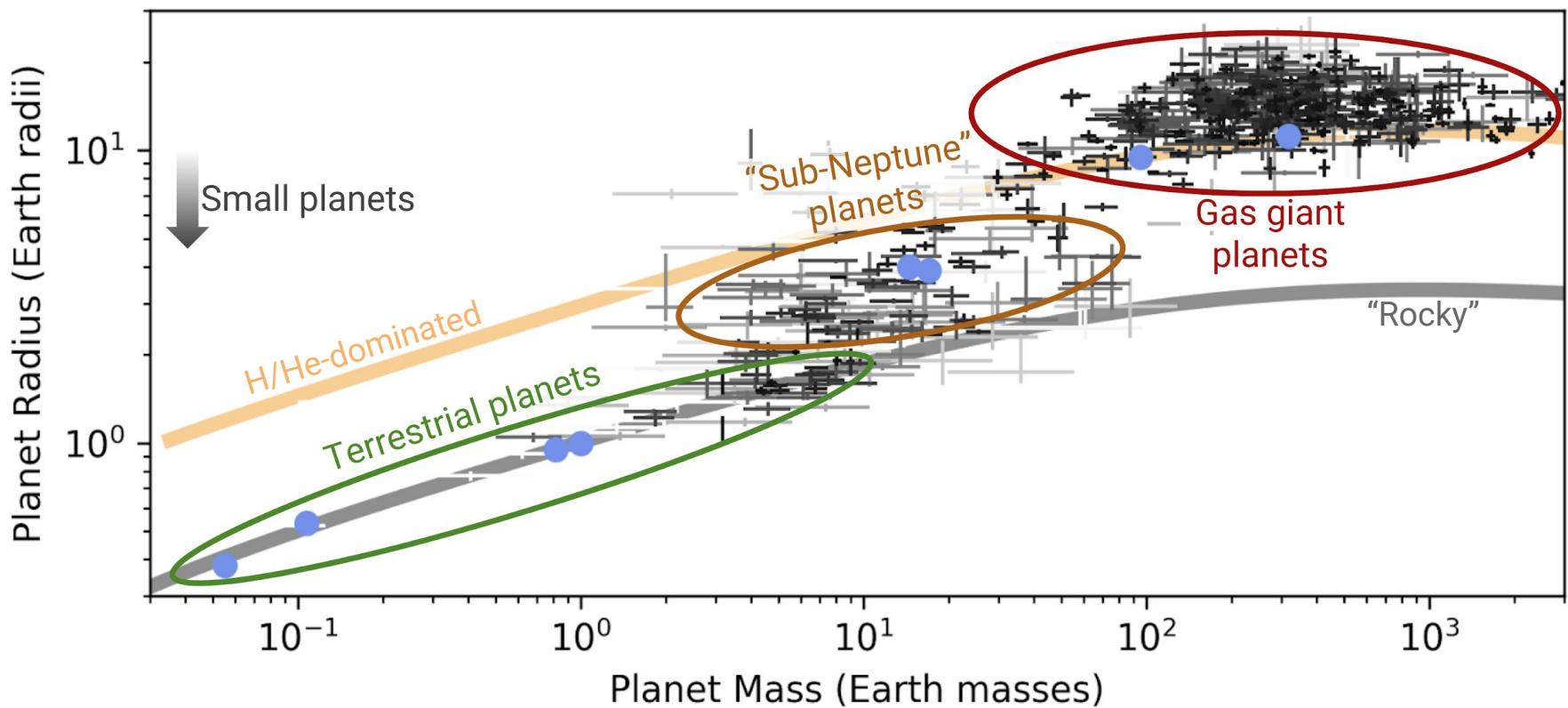


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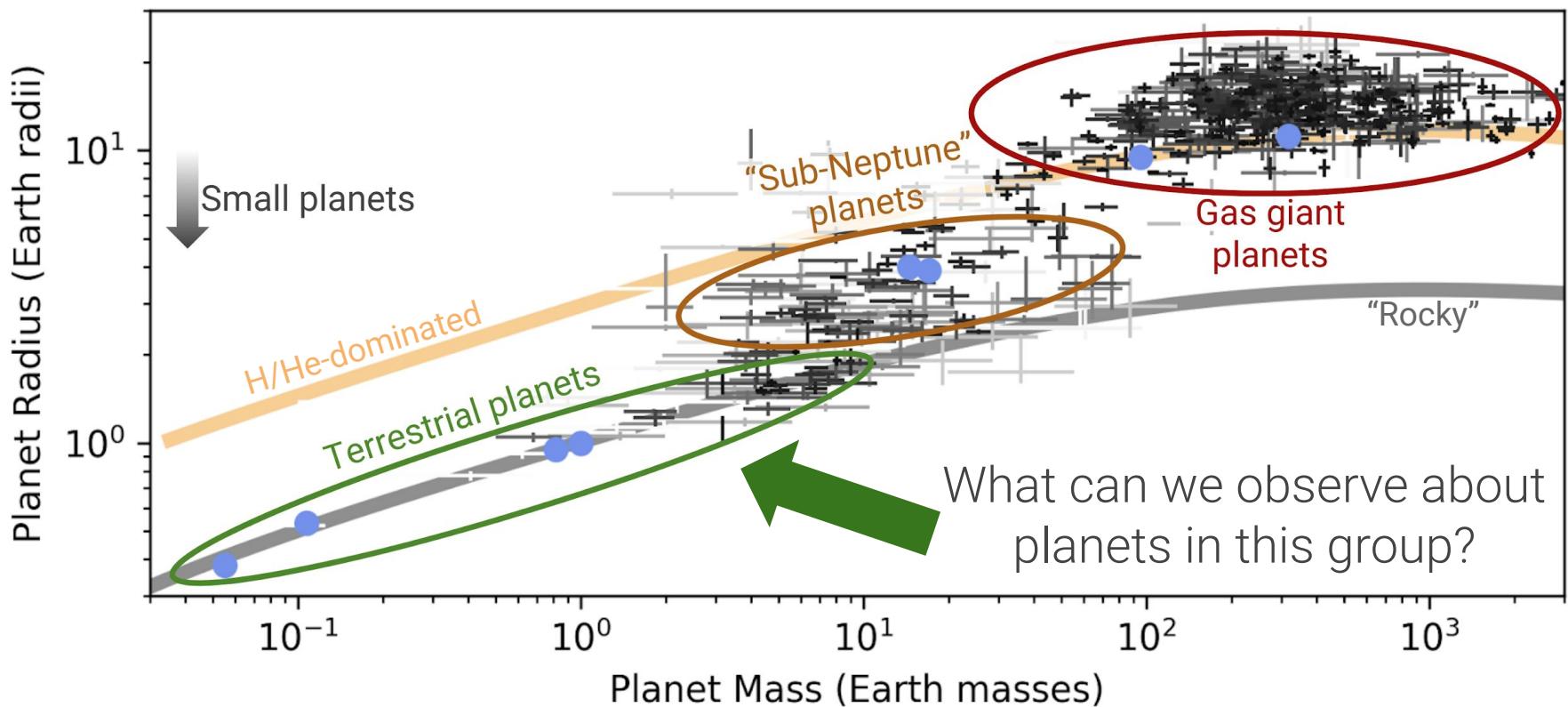
Exoplanet demographics

exoatlas (Z. Berta-Thompson)
Seager+ (2007)

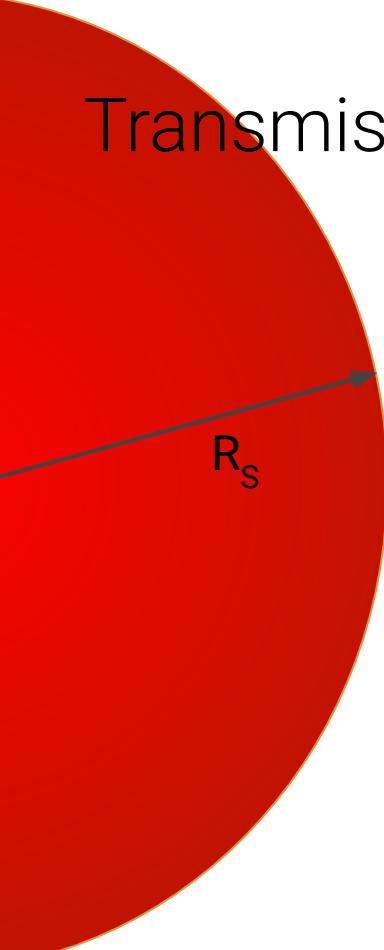


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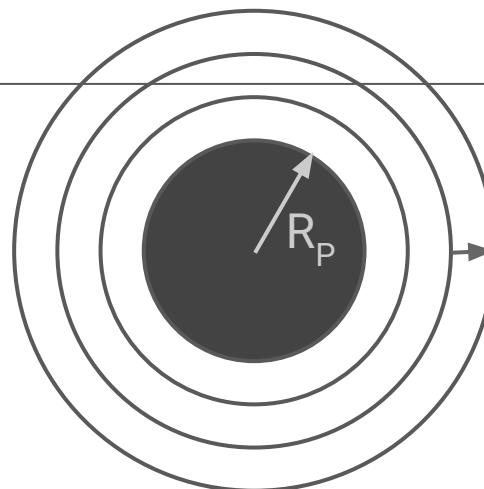


Transmission spectroscopy



Transit depth

$$\delta = \frac{R_p^2}{R_s^2}$$



Atmospheric scale height

$$H = \frac{k_B T_{eq}}{\mu g}$$

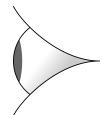
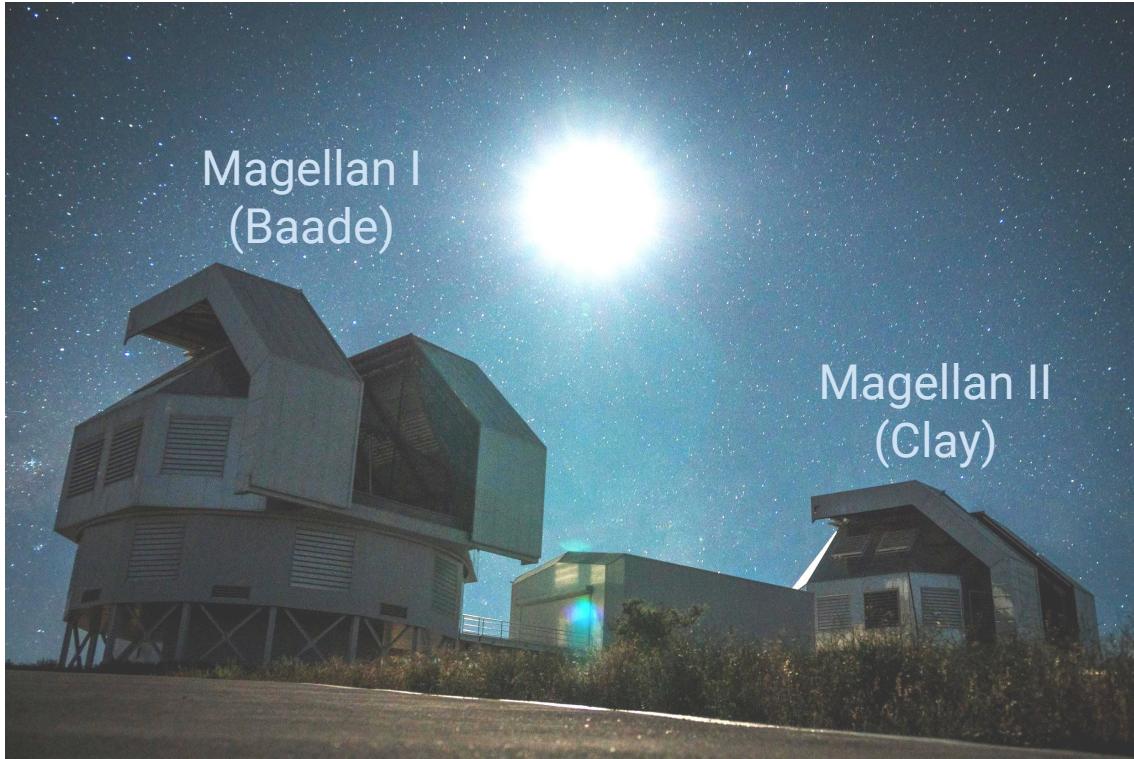


Figure adapted from Parke Loyd

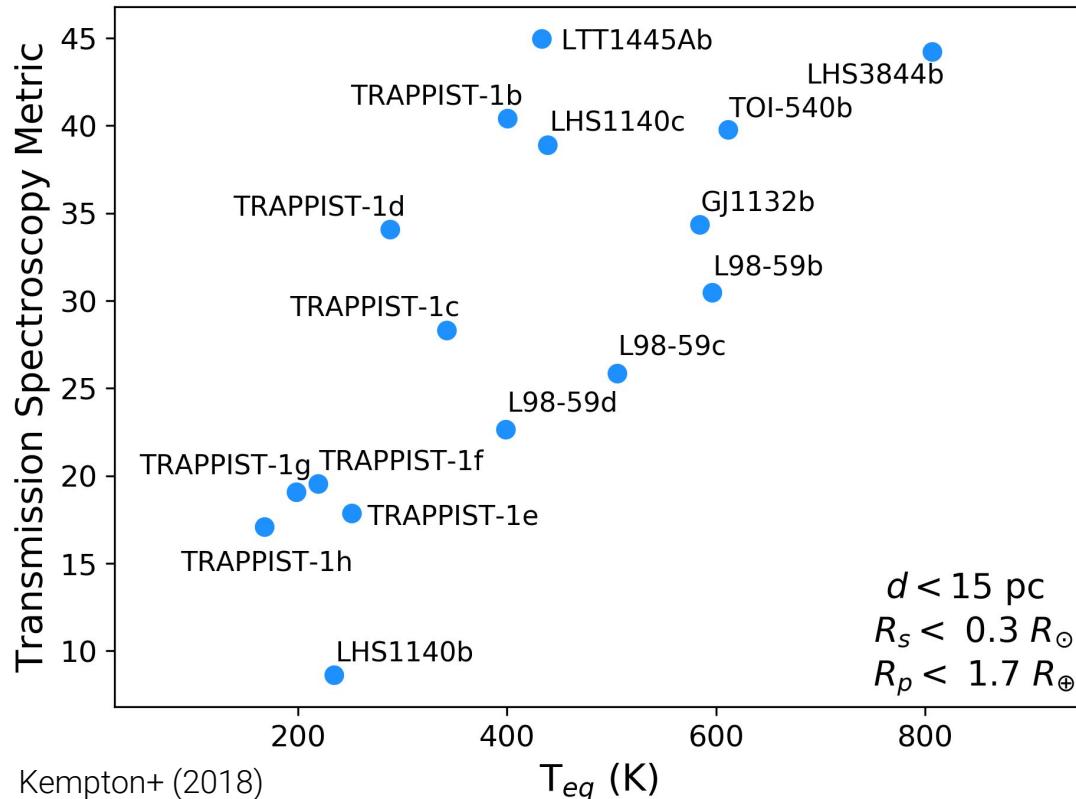
Ground-based telescopes and instruments

IMACS
Multi-object
spectrograph
 $0.61\text{-}0.93\mu\text{m}$
12' FoV



LDSS3C
Multi-object
spectrograph
 $0.61\text{-}1.01\mu\text{m}$
4' FoV

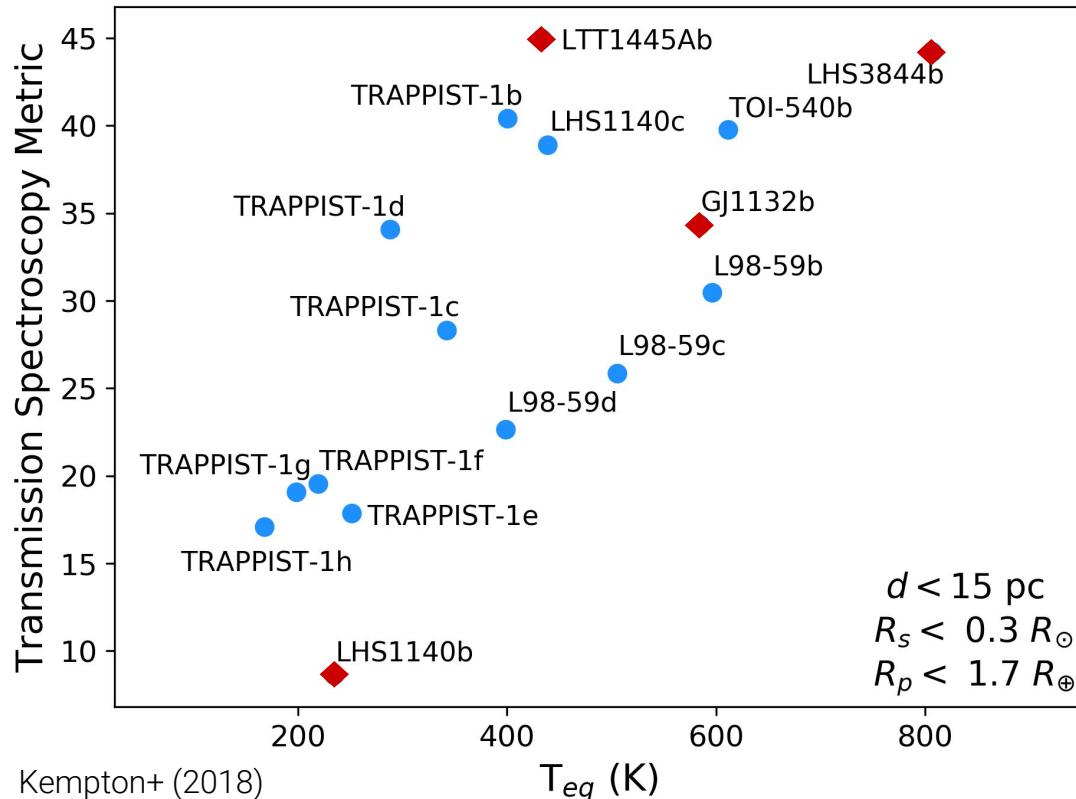
Terrestrial exoplanet targets for atmospheric study



Terrestrial planet discoveries

- Berta-Thompson+ (2015)
- Gillon+ (2016, 2017)
- Dittmann+ (2017)
- Ment+ (2019)
- Vanderspek+ (2019)
- Kostov+ (2019)
- Winters+ (2019)
- Ment+ (*in prep.*)

Terrestrial exoplanet targets for atmospheric study

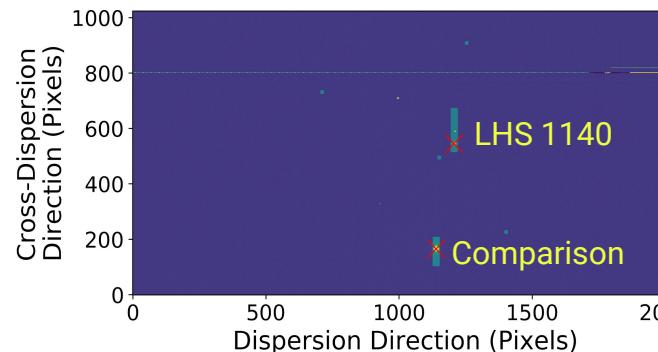


Multi-year transmission spectroscopy program with Magellan Baade/IMACS and Magellan Clay/LDSS3C

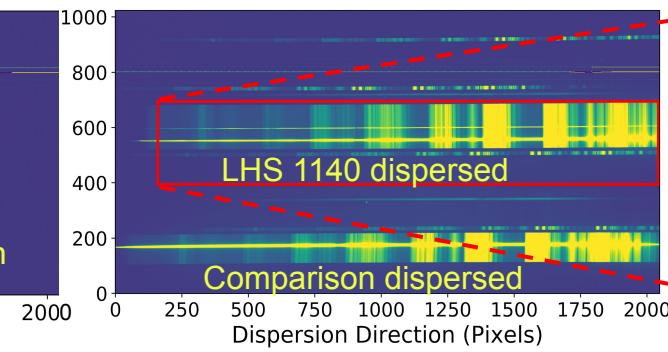
Detour into data extraction, reduction, and analysis

- Overview of raw data → transit depth measurement
- Highlight steps most relevant to JWST

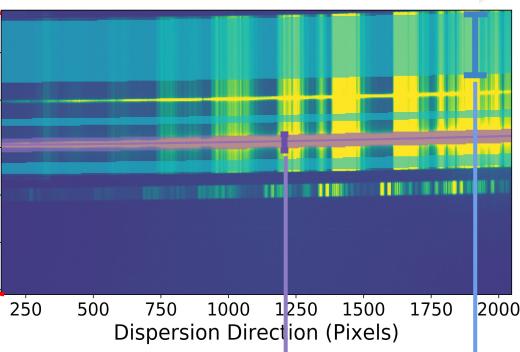
1. Identify stars



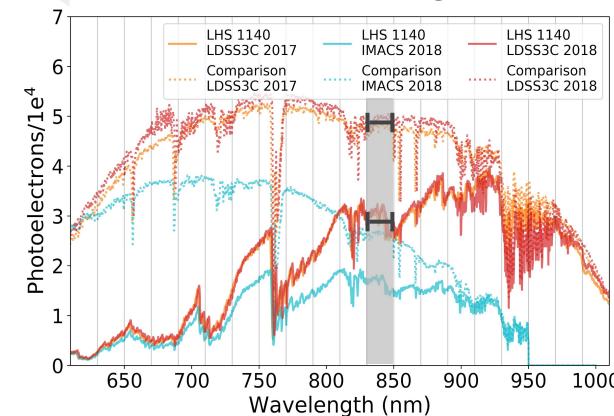
2. Extraction box



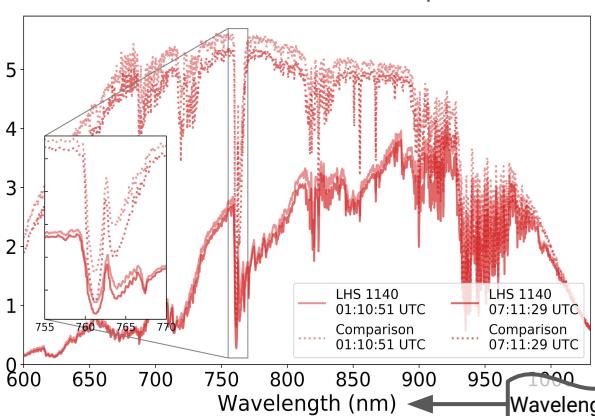
3. Stellar spectrum & sky



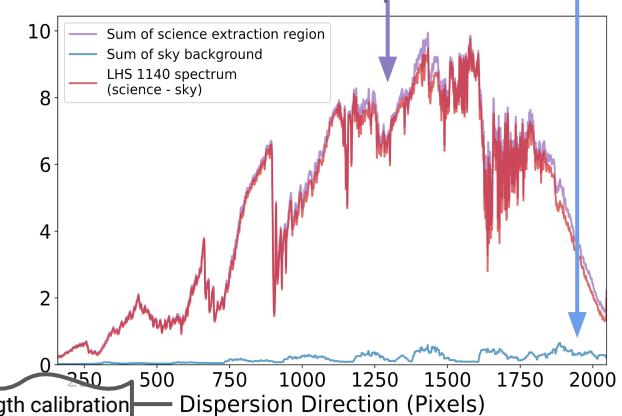
6. 20 nm wavelength bins



5. Final extracted spectra

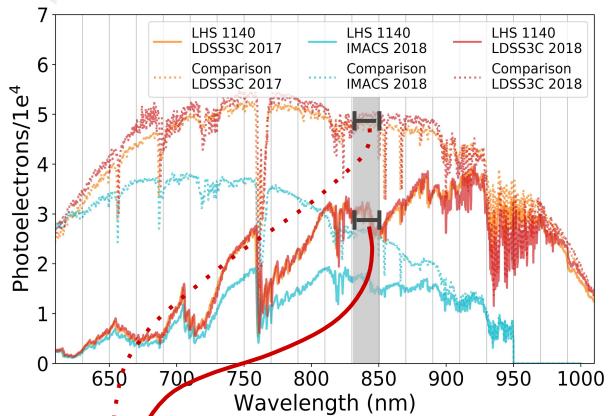


4. Extracted spectrum

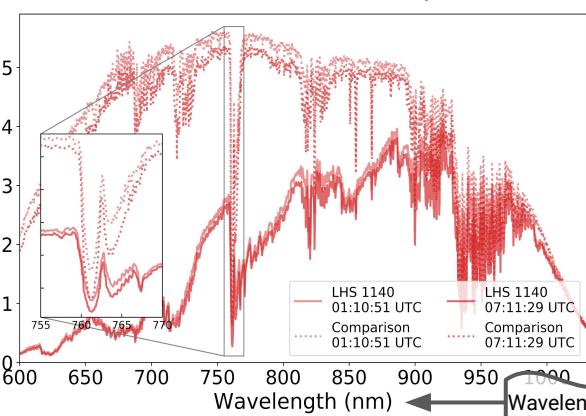


Diamond-Lowe+ (2020)

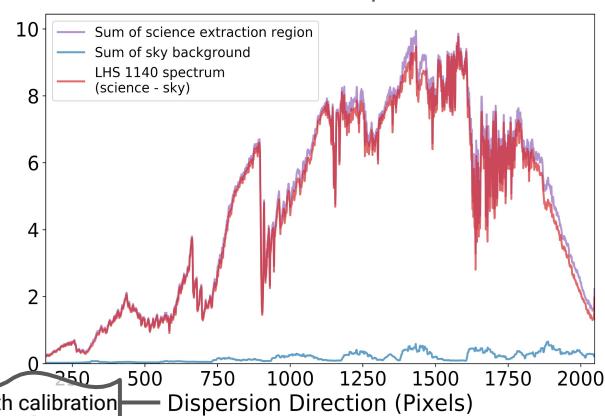
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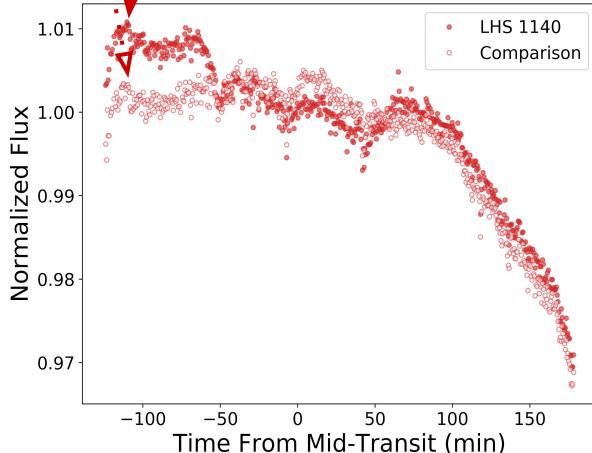
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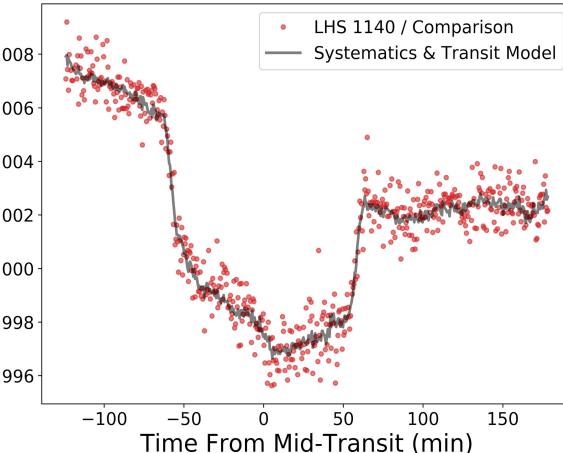
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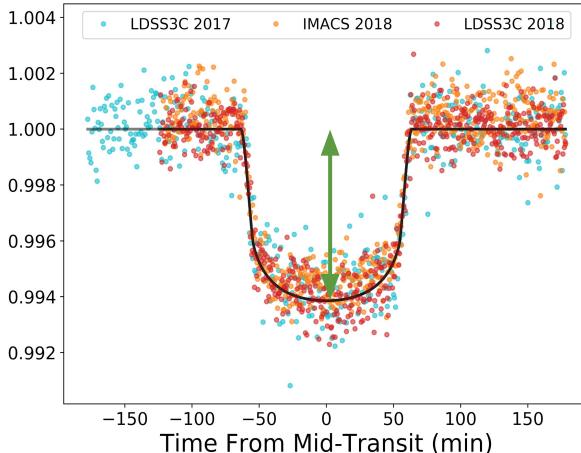
7. Raw light curves



8. Modeling systematics

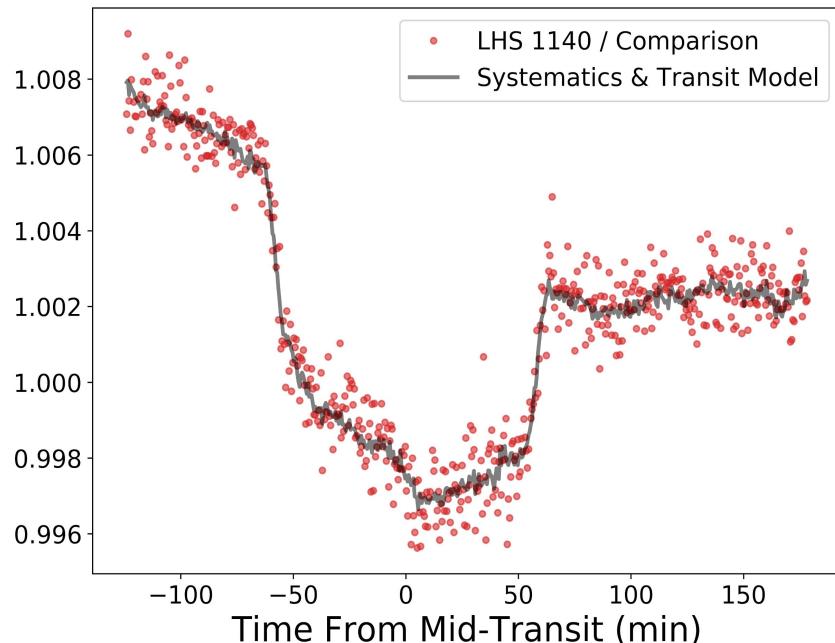


9. Joint fit transit depth



Modeling the light curve

- Always model the light curve and the transit model simultaneously
- Choose the method that makes sense for the data



Modeling the light curve

Linear decorrelation

$$S(t) = 1 + \sum_{n=1}^{N_{\text{poly}}} c_n P_{n-1}(t) + \sum_{m=1}^{M_{\text{phys}}} c_m R_m(t, * \lambda)$$

E.g., Diamond-Lowe+ (2018)

Gaussian process

$$k(r^2) = A^2 \left(1 + \sqrt{3 \frac{r^2}{L^2}} \right) e^{-\sqrt{3 \frac{r^2}{L^2}}}$$

See: Gibson+ 2012, 2014; Evans+ 2017;
Kirk+ 2017
george (Foreman-Mackey 2015)

Pros	Cons
<ul style="list-style-type: none">- Easy to implement- Simple to compute (fast)	<ul style="list-style-type: none">- Assumes uncorrelated noise
<ul style="list-style-type: none">- Allows for uncorrelated <i>and</i> correlated noise- More conservative error bars	<ul style="list-style-type: none">- Slower to compute (not suitable for large data sets with >10k points)

Modeling the light curve

Linear decorrelation

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Gaussian process

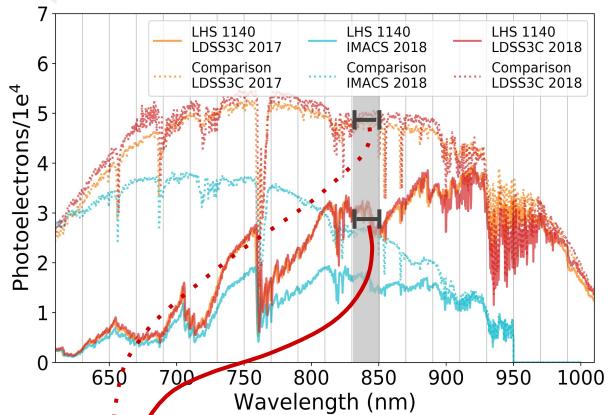
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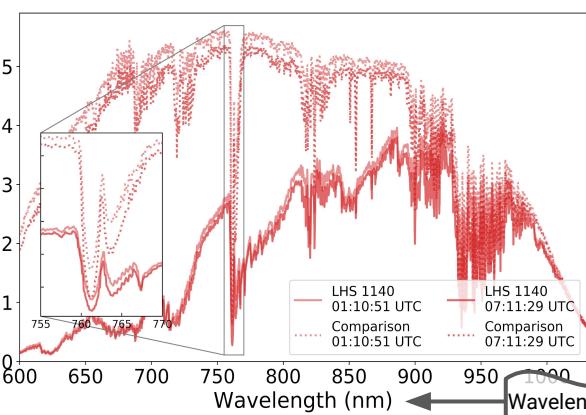
Sample the parameter space:

- MCMC
`emcee` (Foreman-Mackey+ 2013)
- Dynamic nested sampling
`dynesty` (Speagle 2019)

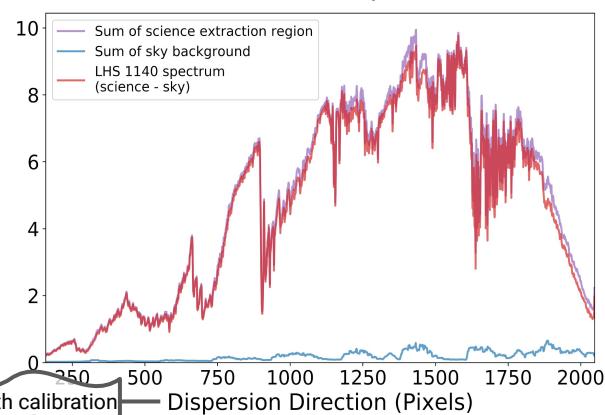
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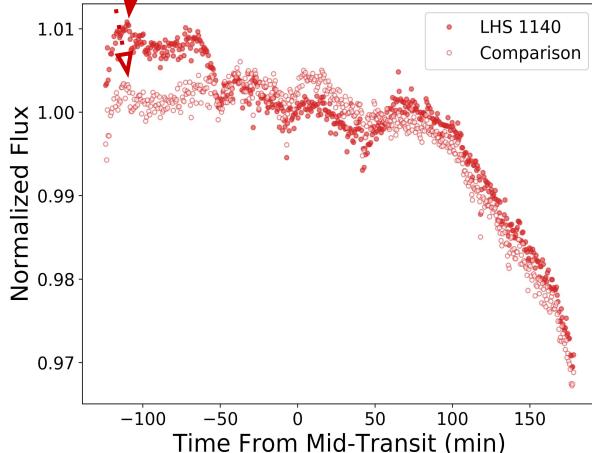
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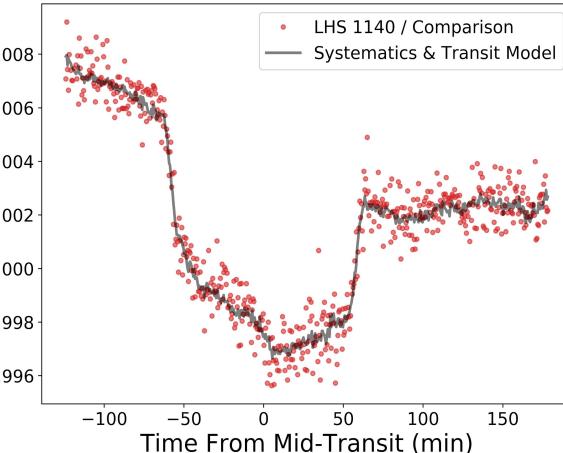
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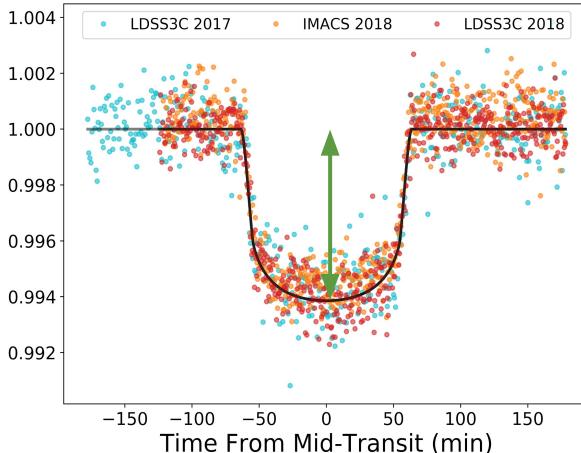
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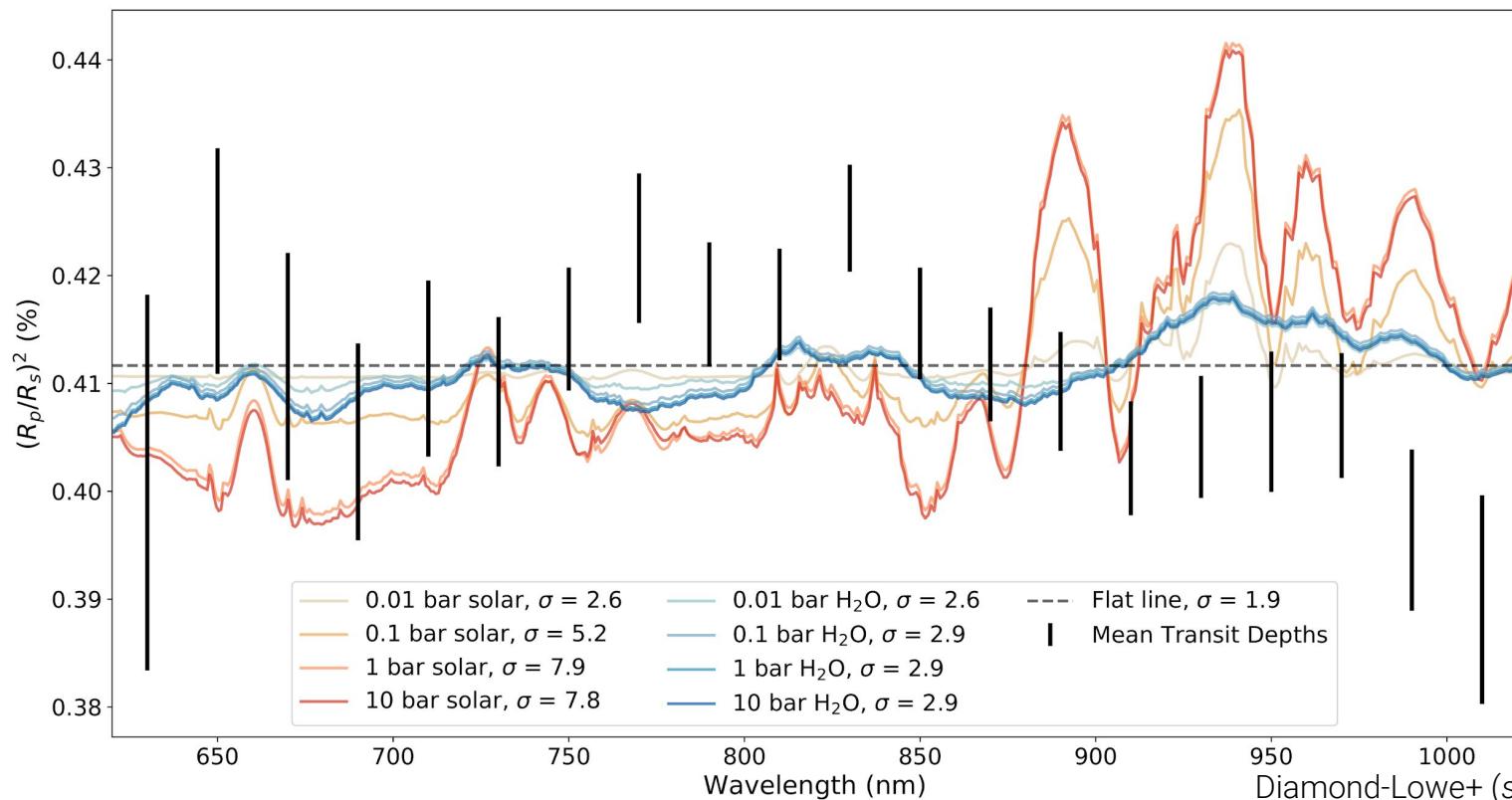


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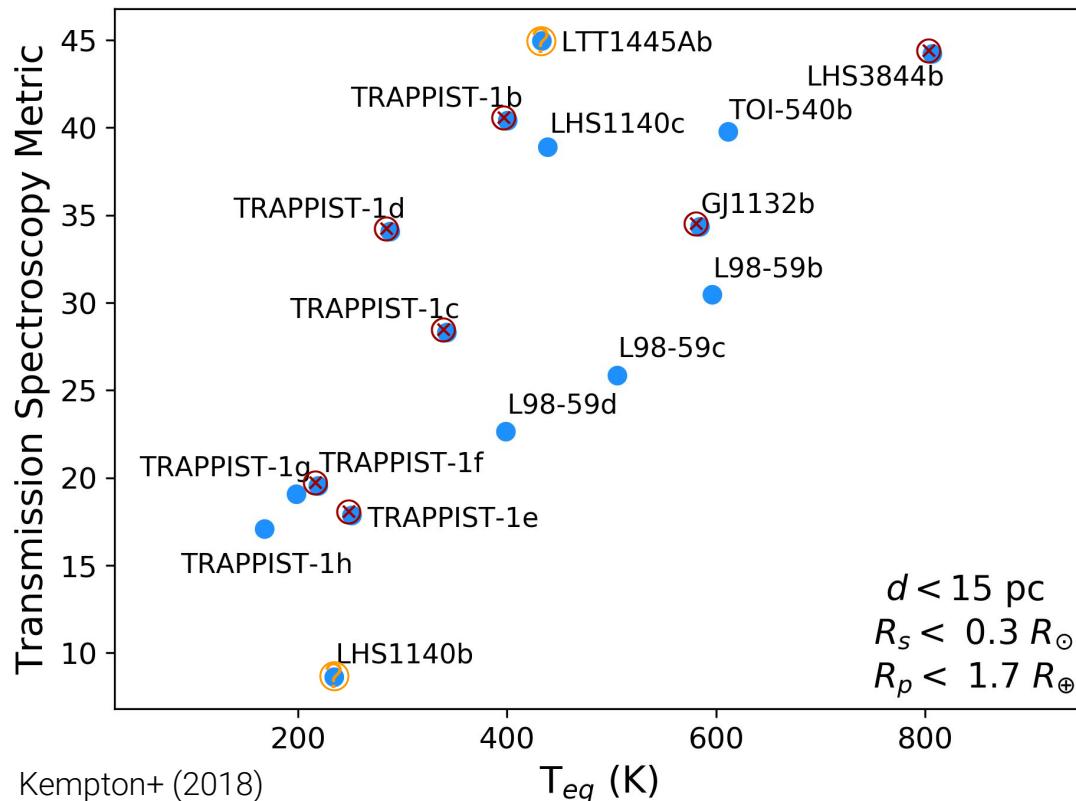


Transmission spectrum: LHS 3844b

HELIOS (Malik+ 2017, 2019)
Exo-Transmit (Kempton+ 2017)



Terrestrial exoplanet targets for atmospheric study



Clear, low mean molecular weight atmosphere?

de Wit+ (2016, 2018)
Kreidberg+ (2019)
Diamond-Lowe+ (2018, 2020 submitted)

Conclusions from ground-based transit observations

- ▶ GJ 1132b (19 S_⊕) & LHS 3844b (70 S_⊕) do not possess low mean molecular weight ($\mu \sim 2$) atmospheres
- ▶ Along with results from the TRAPPIST-1 planets, it looks like clear low mean molecular weight atmospheres do not occur on terrestrial exoplanets
- ▶ Choosing the appropriate modeling method and error bar estimator is key to building the transmission spectrum