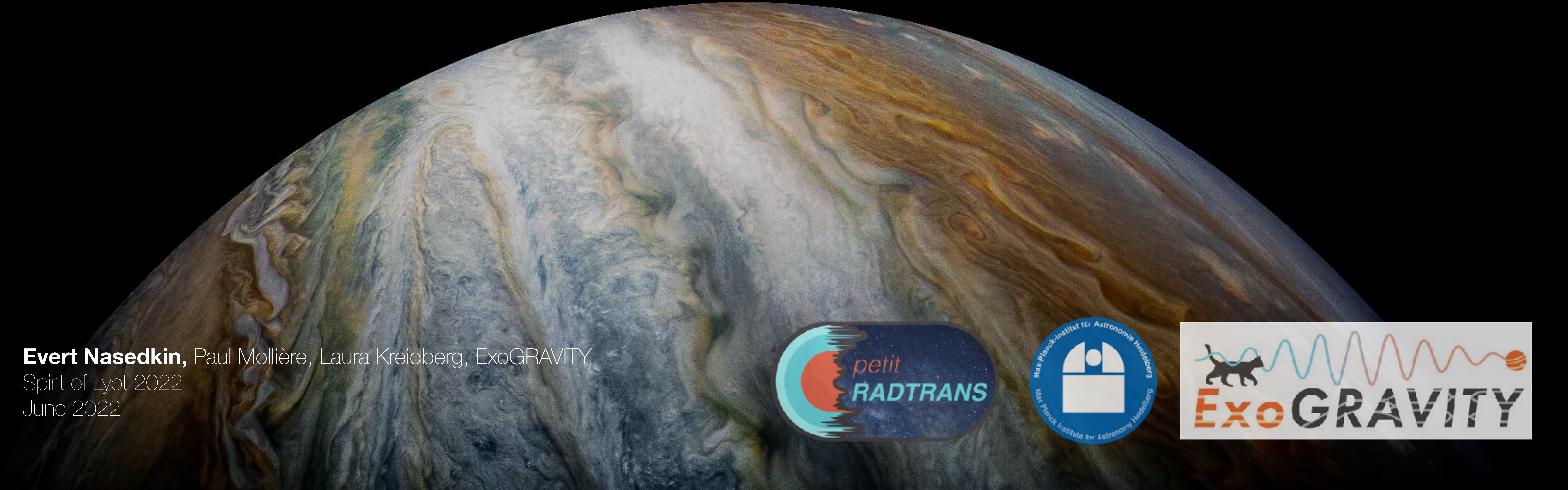
Four of a Kind: HR8799

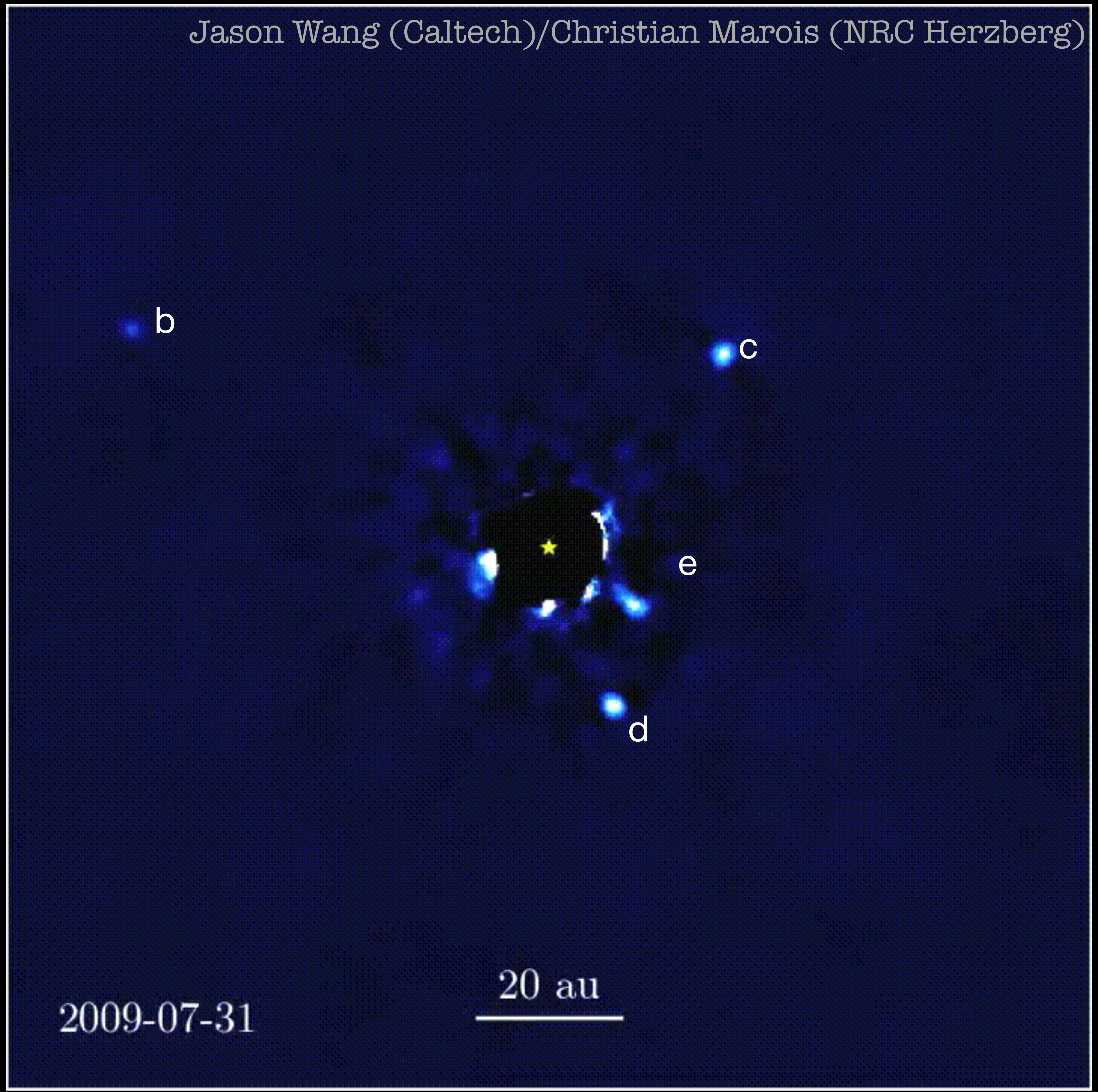
Exploring the atmospheres of the HR 8799 system with GRAVITY



Evert Nasedkin, Paul Mollière, Laura Kreidberg, ExoGRAVITY
Spirit of Lyot 2022
June 2022

NASA/JPL-Caltech/SwRI/MSSS; Processing & License: Kevin M. Gill

This is HR 8799

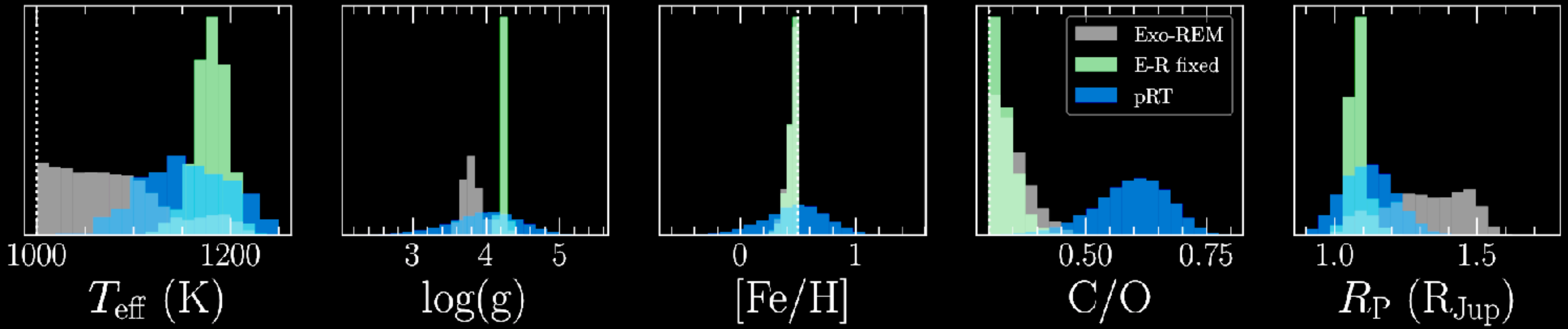


The goal of our project is to present a systematic retrieval study of the atmospheres of all four of the HR 8799 planets.

So you want to study
atmospheres?

Atmospheres

Mollière et al. 2020



Model

petitRADTRANS model based on Mollière 2020

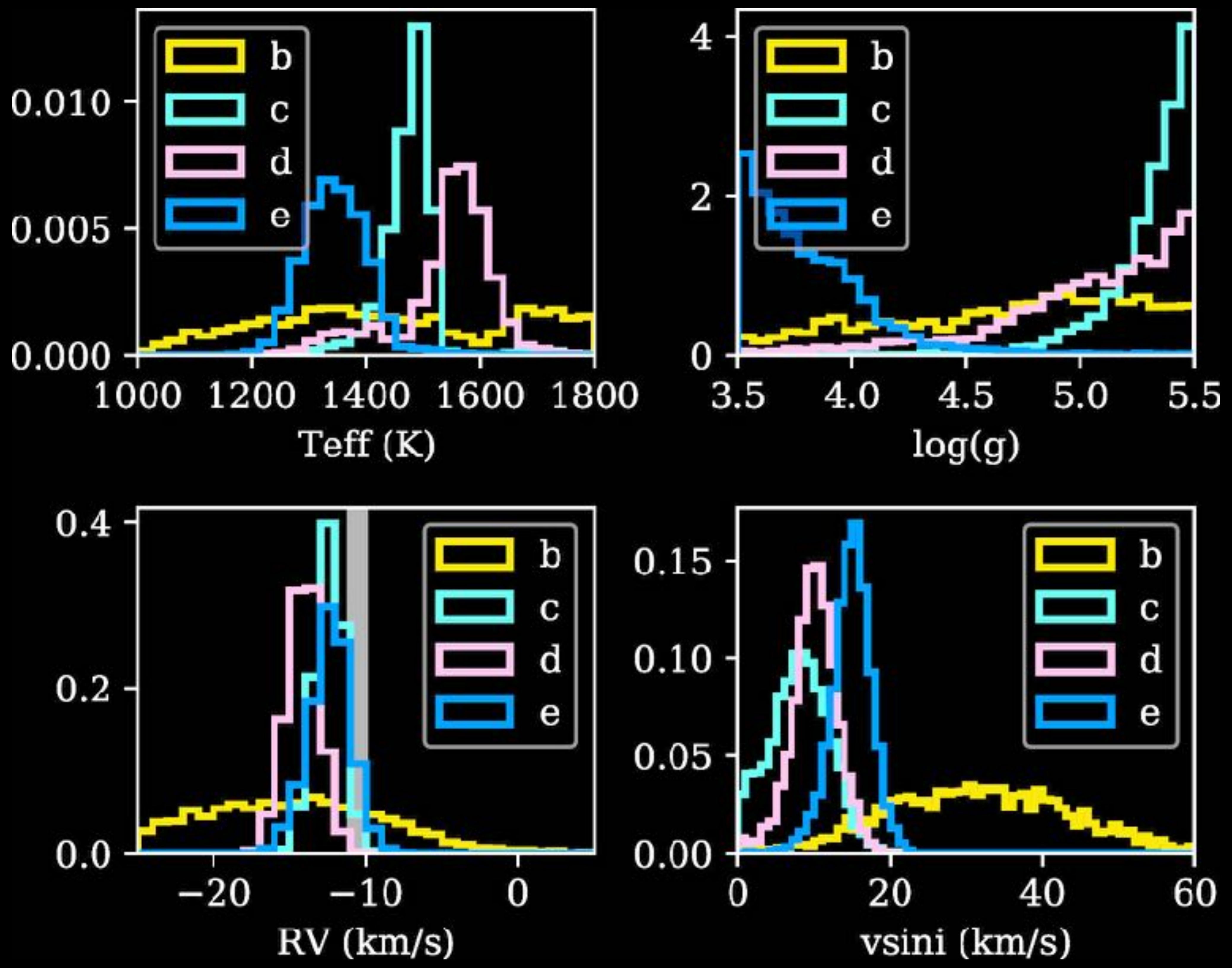
Data

Spectroscopic and photometric

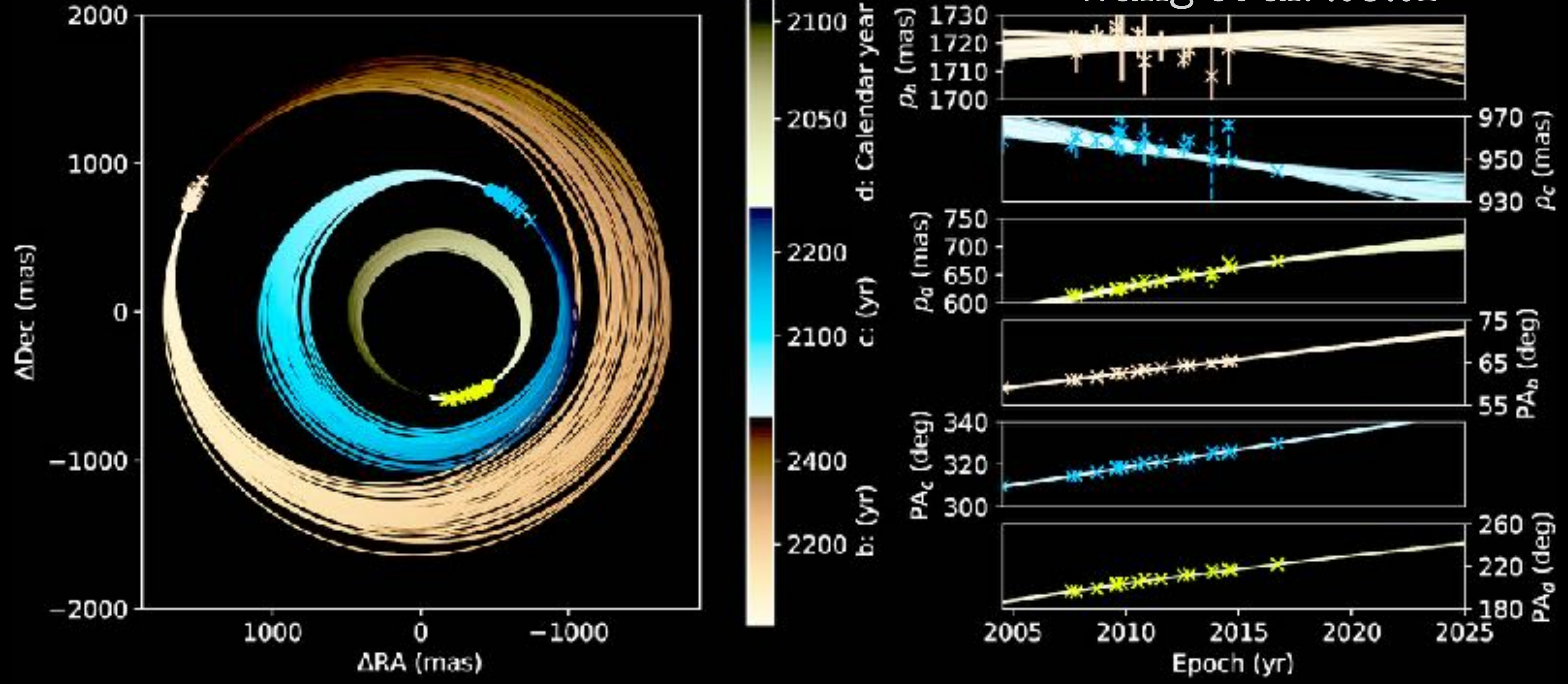
HR 8799

- The HR 8799 system is well studied:
  - Temperatures and masses, both from spectroscopic and astrometric measurements (Wang et al 2018, Brandt et al 2021)
  - Water and CO detections have been made for all four planets, but the C/O ratio is still not well constrained (Konopacky et al 2013, Ruffio et al. 2021).

Ruffio et al. 2021



Wang et al. 2021



Context - Formation

- It is unclear how giant, widely separated planets form - gravitational instability or core accretion?
- The composition of these planets, particularly the carbon-to-oxygen number ratio (C/O) traces the location of formation, which can help us infer the mechanism

Öberg et al. (2011) APJ 743 1 L16

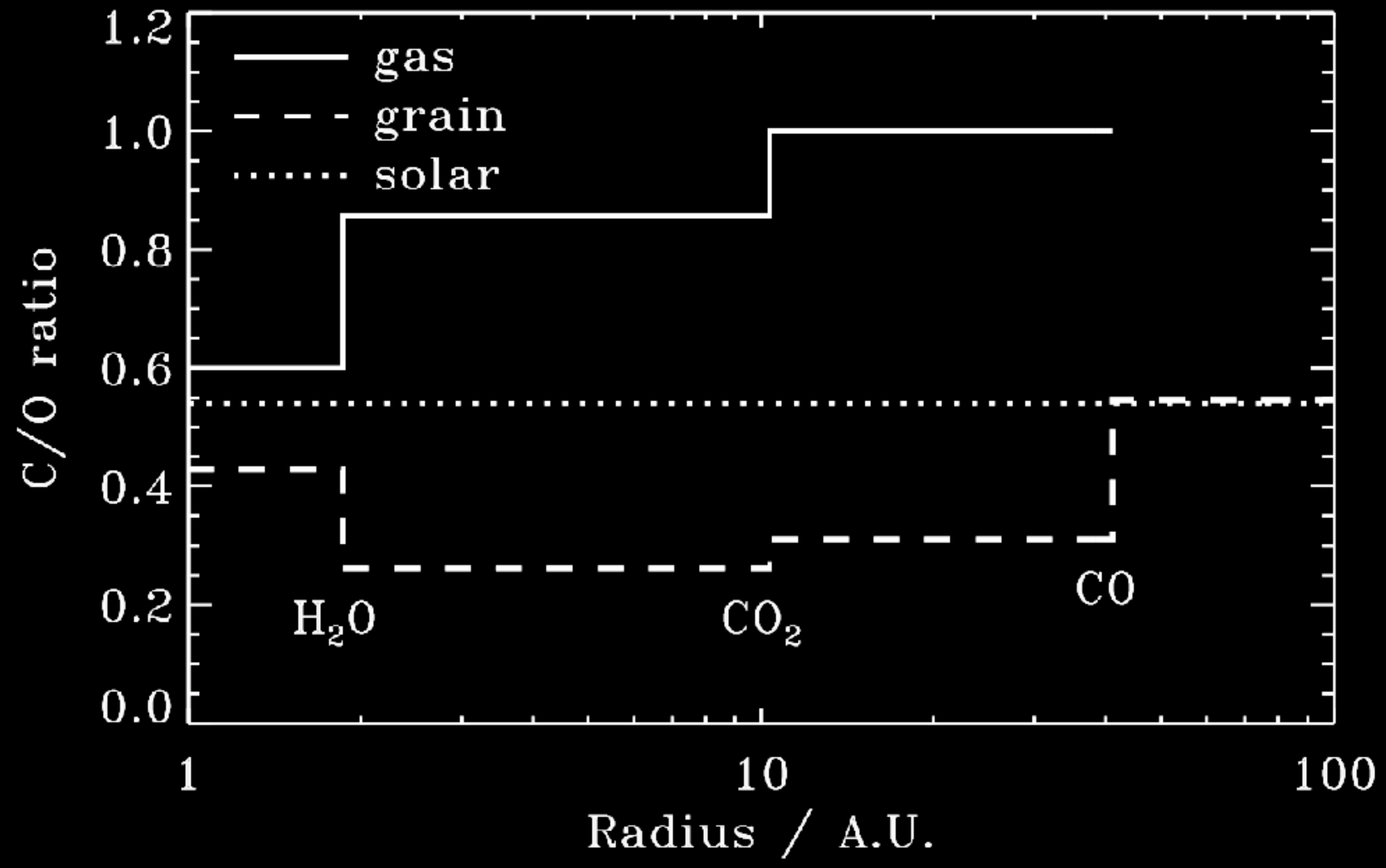
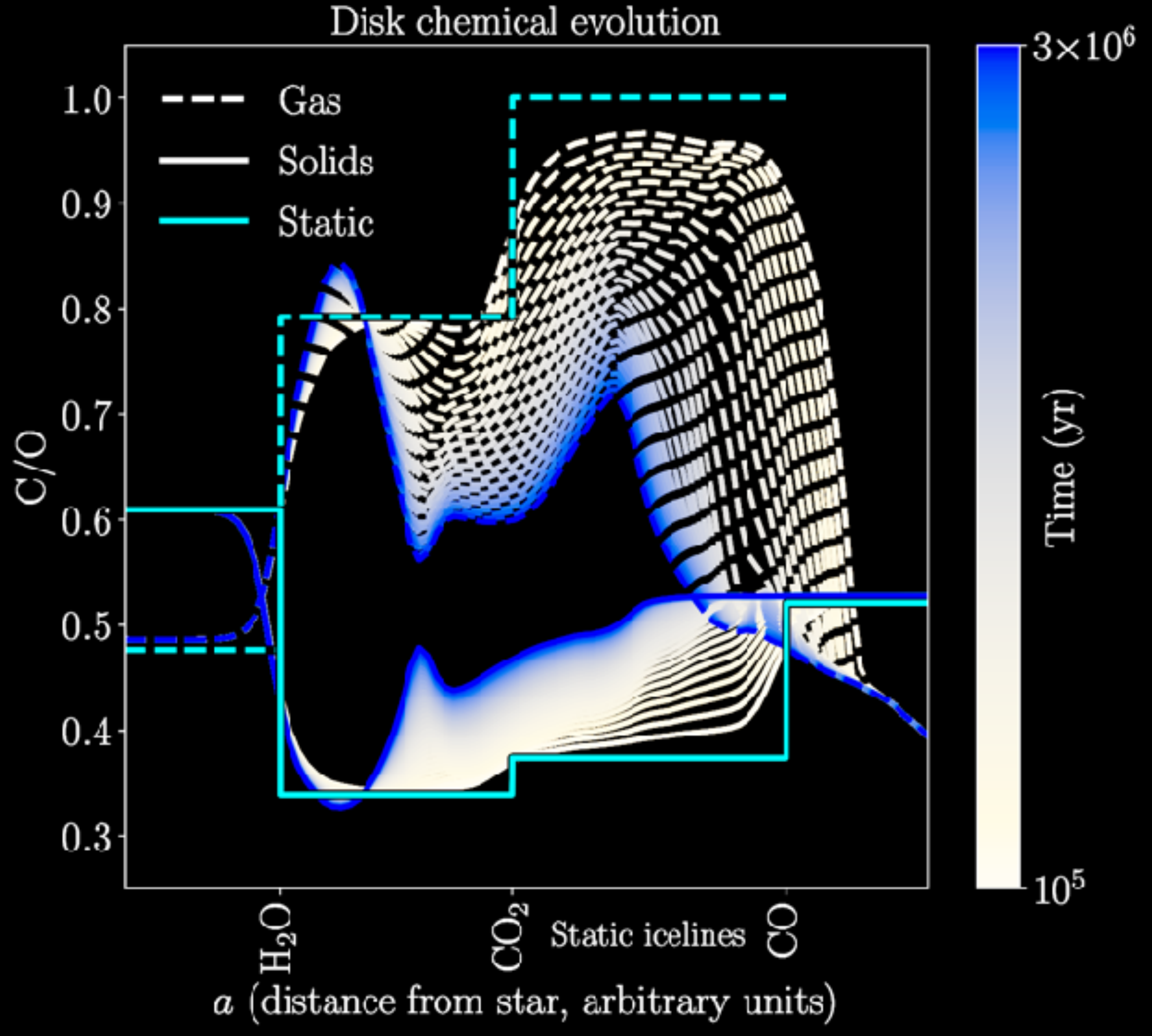
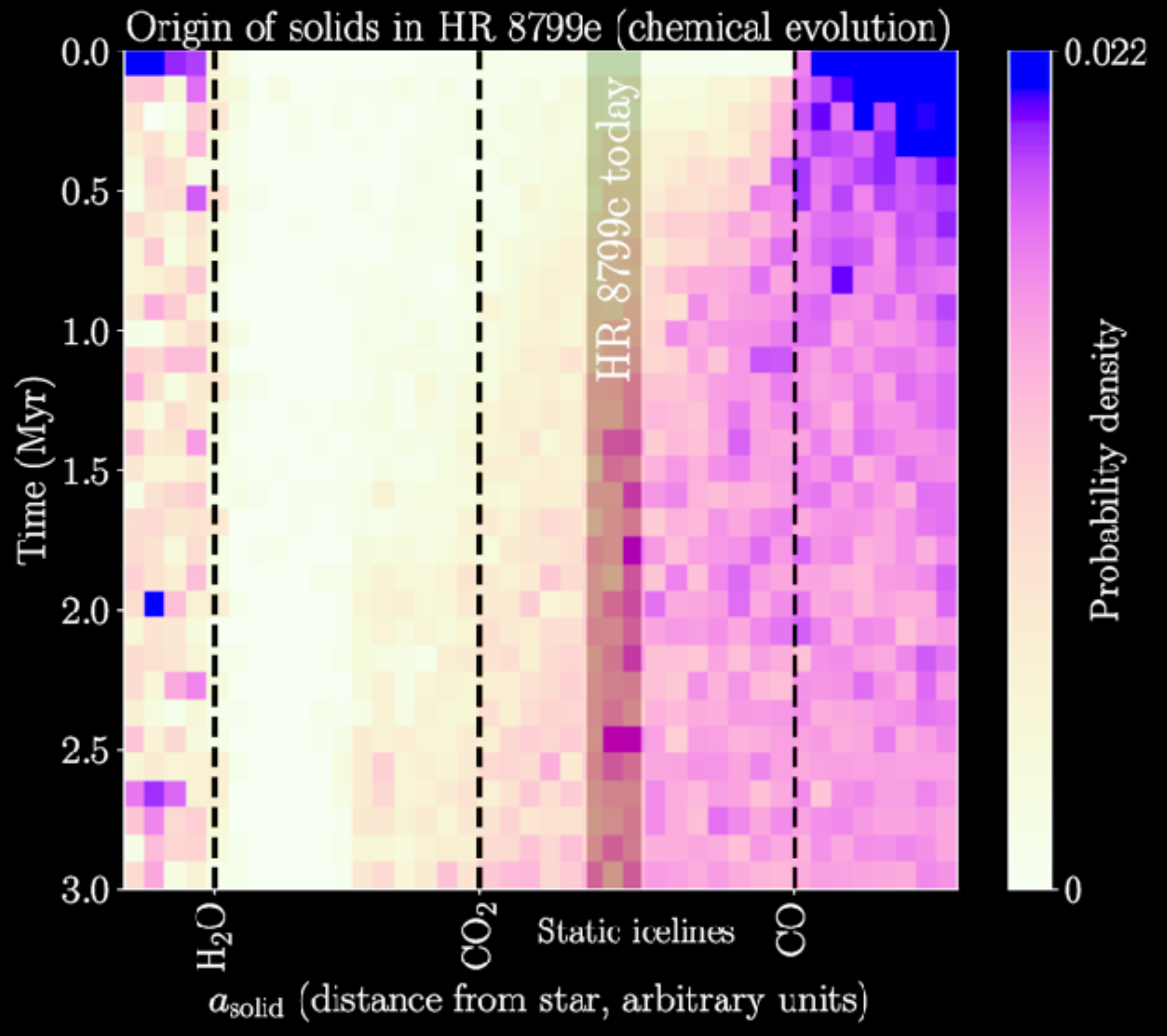


Fig. 1.— The C/O ratio in the gas and in grains, assuming the temperature structure of a 'typical' protoplanetary disk around a solar-type star (T_0 is 200 K, and $q = 0.62$). The H_2O, CO_2 and CO snow-lines are marked for reference.

Context - Formation *is complicated*





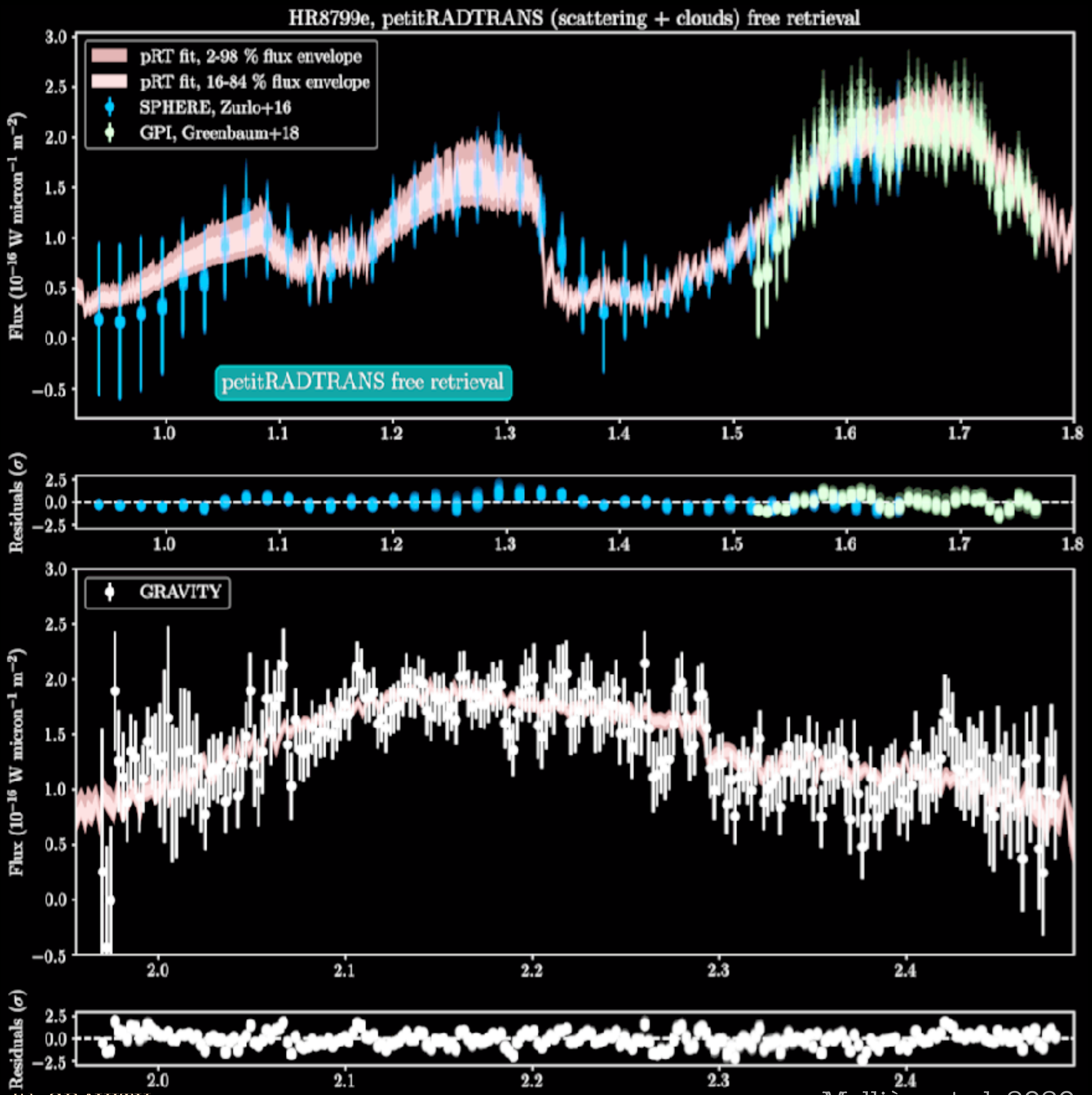
- Chemical evolution, pebble evaporation… what else?
- With well constrained C/O and Fe/H, we can start to make quantitative statements about the location of formation.
- Check out the paper: Mollière et al. 2022 or the poster [P079]

Know Your **Model**

petitRADTRANS

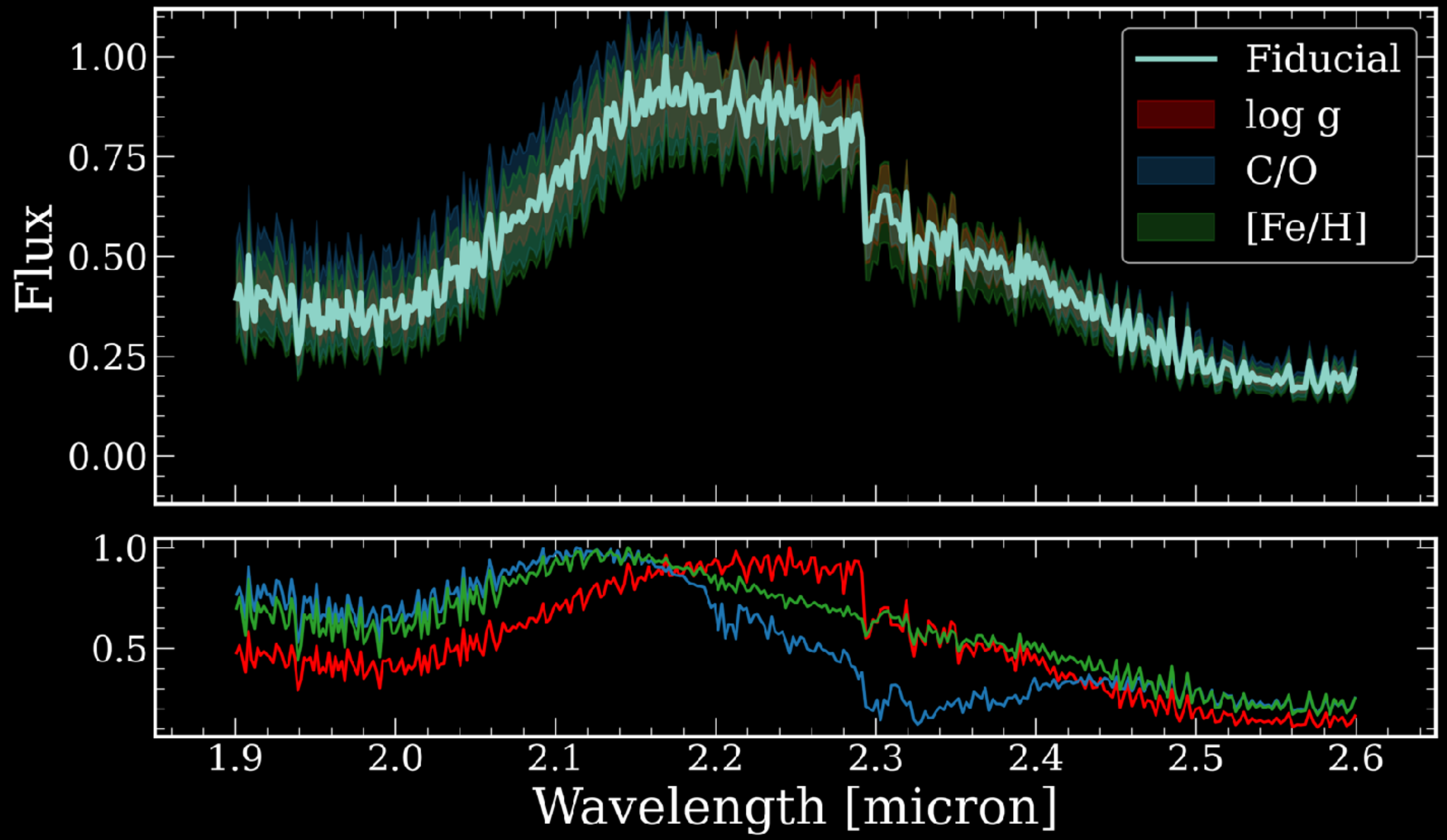
- Our model is based on Mollière et al. (2020), using petitRADTRANS:
  - Flexible, 6 parameter T-P profile
  - Combination of EXOMOL and HITEMP opacity sources, using the correlated-k method for the radiative transfer.
  - Equilibrium chemistry with disequilibrium carbon quenching, or free chemistry.
  - $MgSiO_3$ and Fe clouds, parameterised as in Ackerman & Marley (2001), with scattering

pip install petitradtrans



Mollière et al. 2020

What can we learn?



Mollière et al. 2020

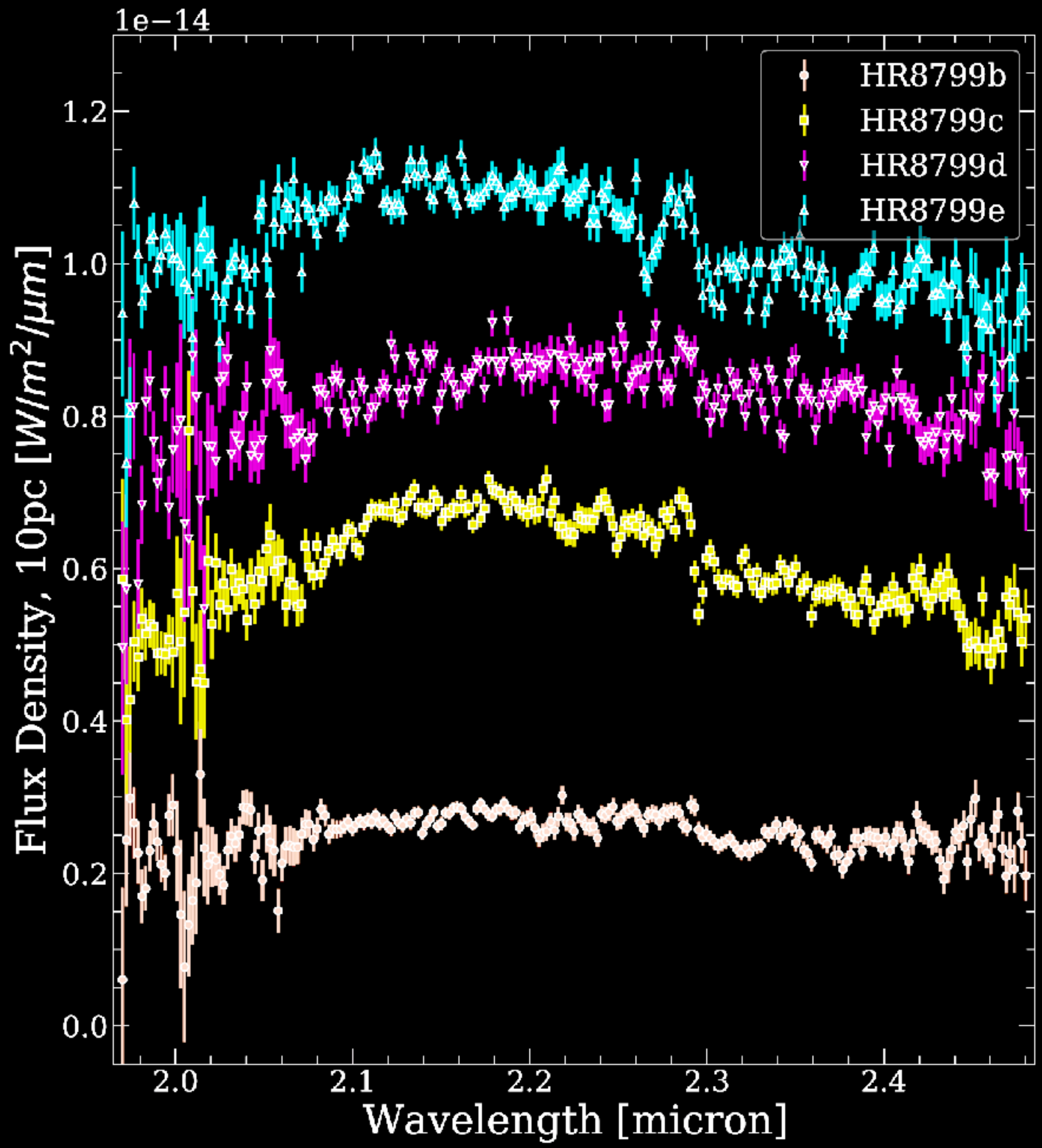
Know Your **Data**

ExoGRAVITY

- To date, VLTI/GRAVITY has been used to explore several directly imaged systems through the ExoGRAVITY program:
- **Beta Pic b,c:** Nowak et al. 2019
- **HR8799e:** Mollière et al. 2020
- **PDS 70 b,c**: Wang et al. 2021
- **HD 206893:** Kammerer: et al. 2021
- **More to come!**

Spectra!

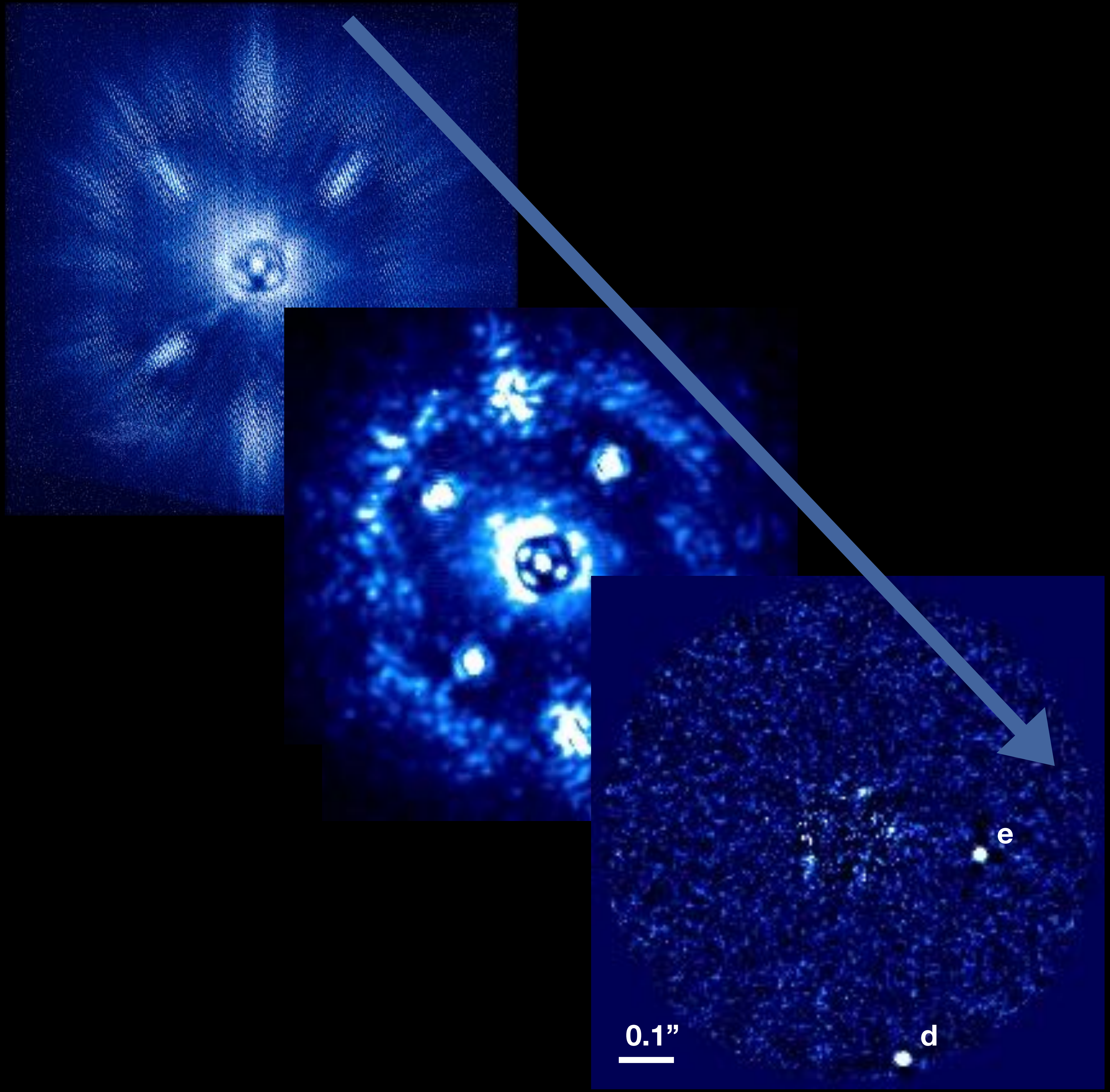
- The first GRAVITY data for HR 8799 e was taken in 2018 (Gravity Collaboration et al. 2019)
- Total of 14.3 hours of integration over all four planets.
- Thanks Mathias Nowak and Sylvestre Lacour for the data reduction!
- c,d and e share similar overall flux levels and features, while the b is dimmer, as expected for a smaller and cooler planet.



High Contrast Imaging

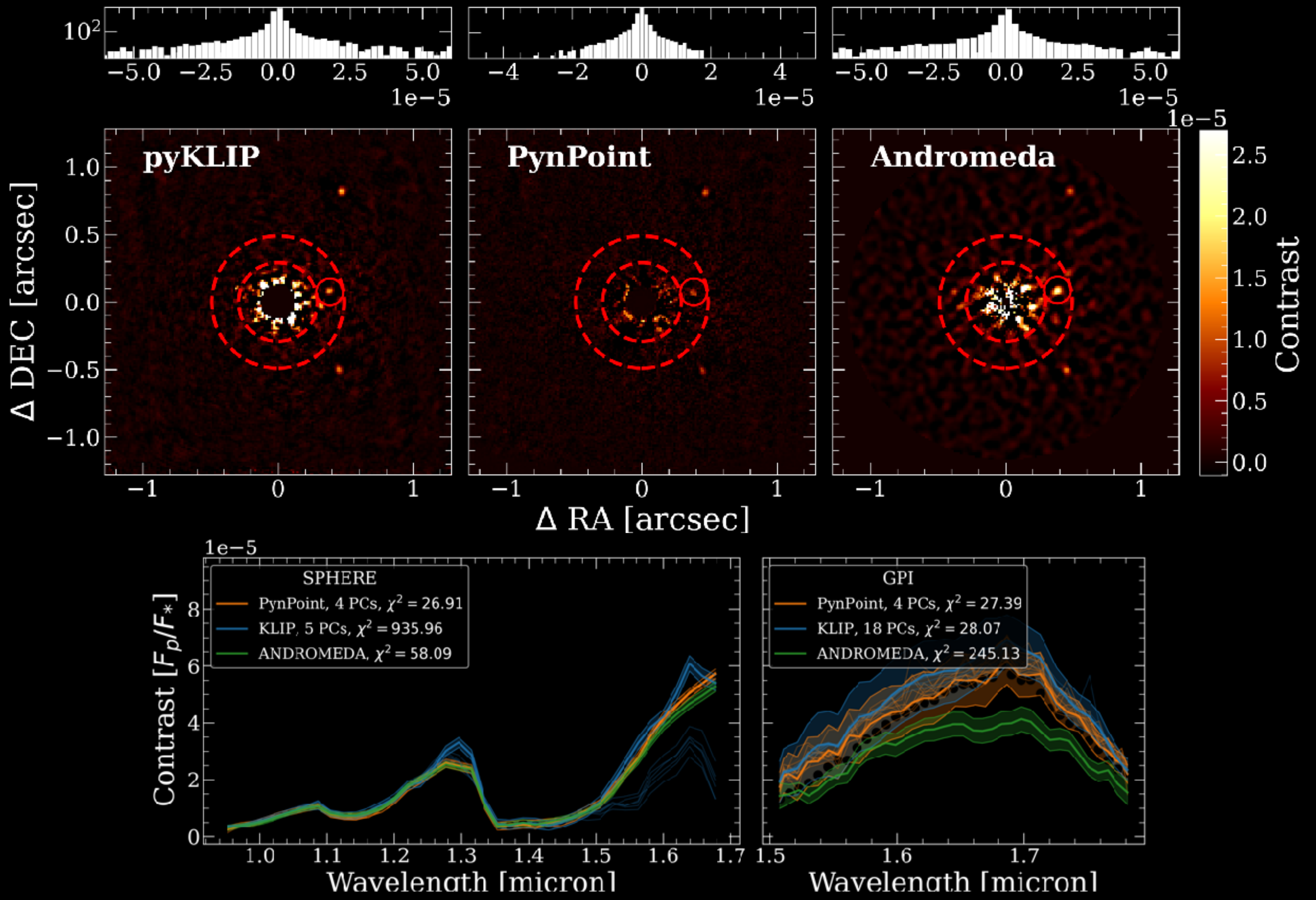
- We reprocessed archival SPHERE and GPI data in order to resolve known incompatibilities between the datasets.

- It is not entirely clear how this processing affects the planet signal.



Data Processing

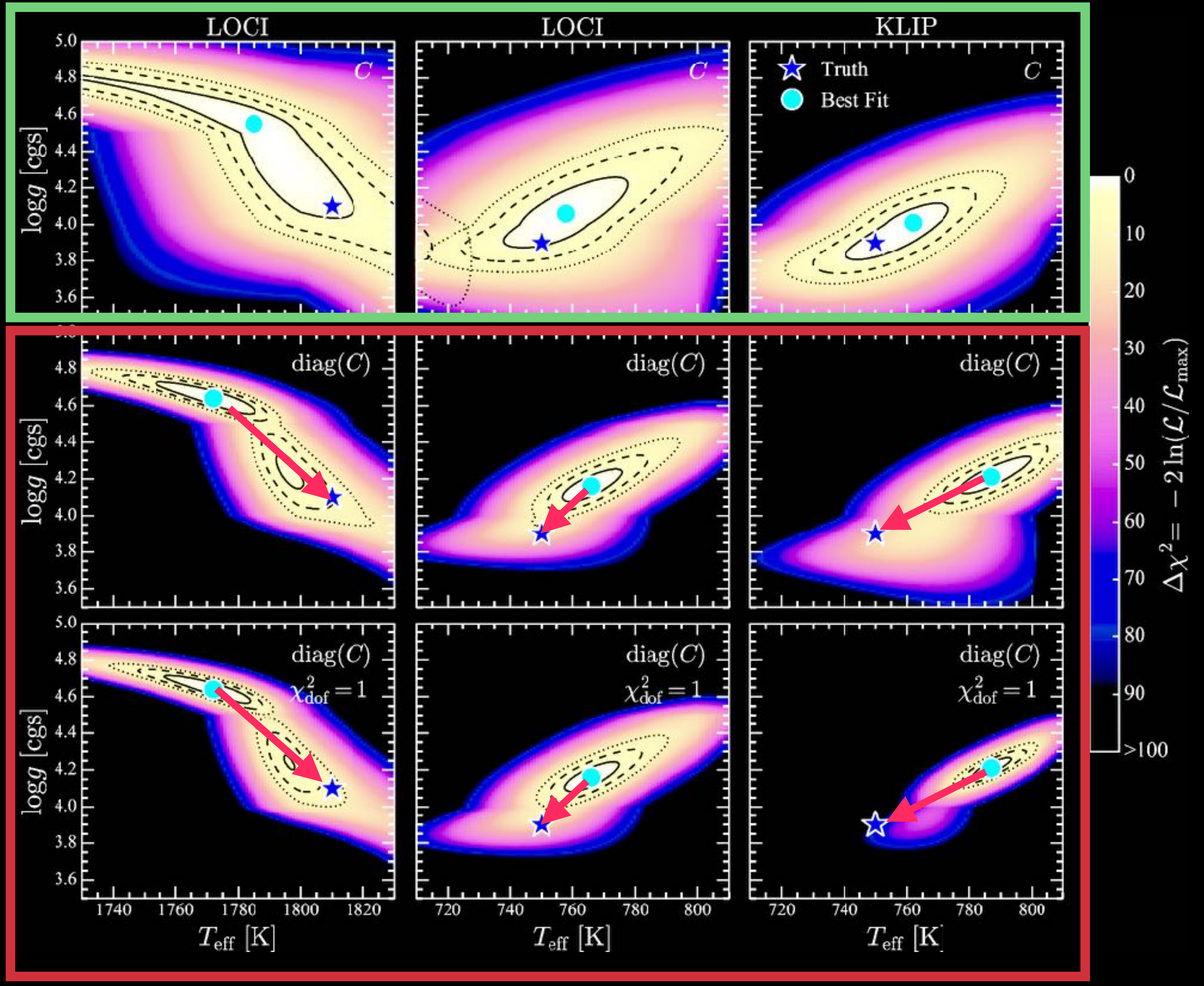
- Both spectral shape and uncertainties strongly depend on algorithmic choice.
- So how do you choose your algorithm?
- PCA Based:
  pyKLIP (Wang+ 2015)
  PynPoint
  (Quanz & Amara 2012)
- Likelihood Minimisation:
  ANDROMEDA
  (Cantalloube+ 2015)



Correlated Noise

- Both IFU and Interferometric data are correlated in wavelength, though the total correlation also depends on the choice of processing algorithm.

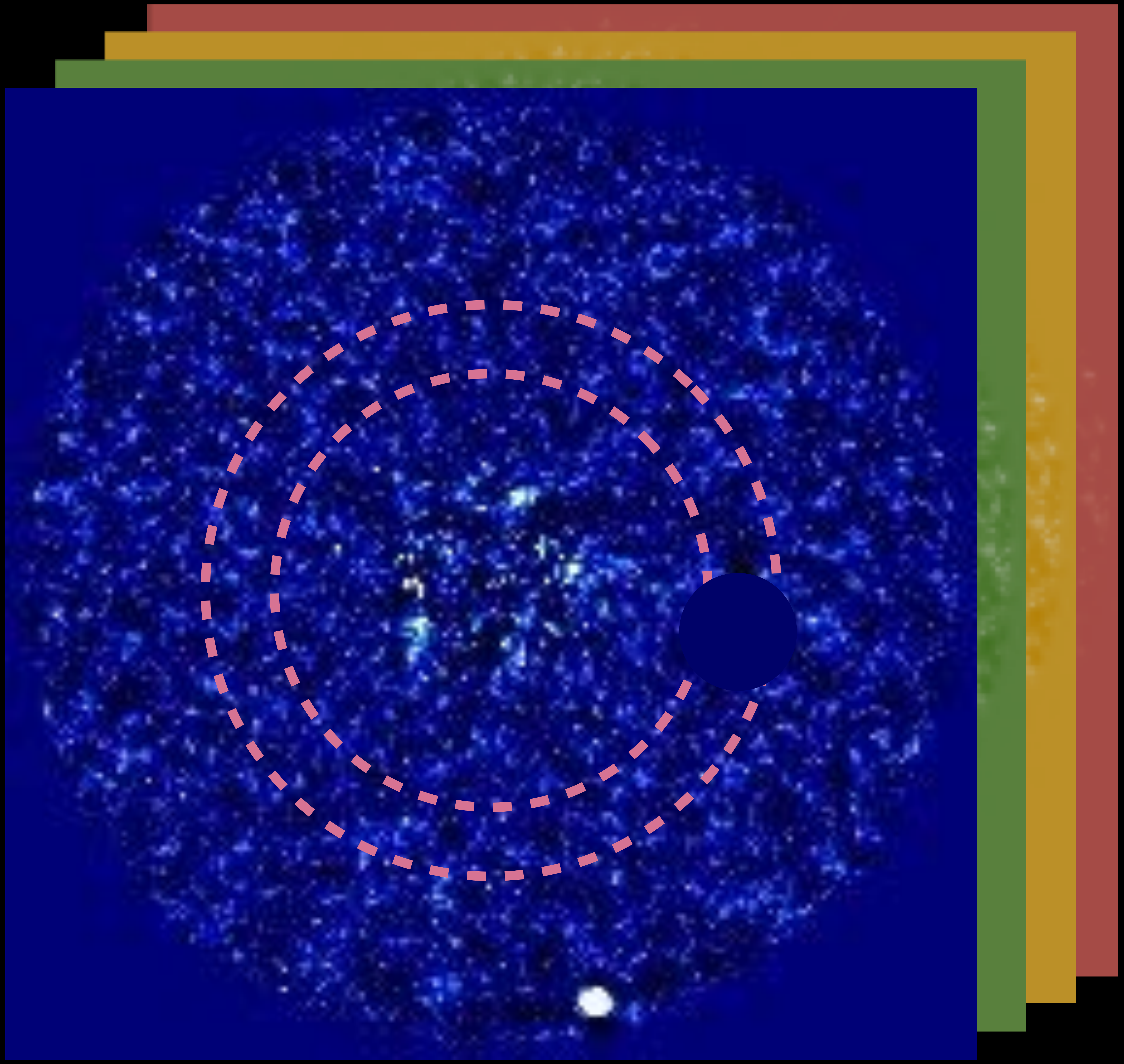
- Failure to account for for correlations will lead to biased parameter estimates and underestimated posterior uncertainties (Greco & Brandt 2016)



Correlated Noise

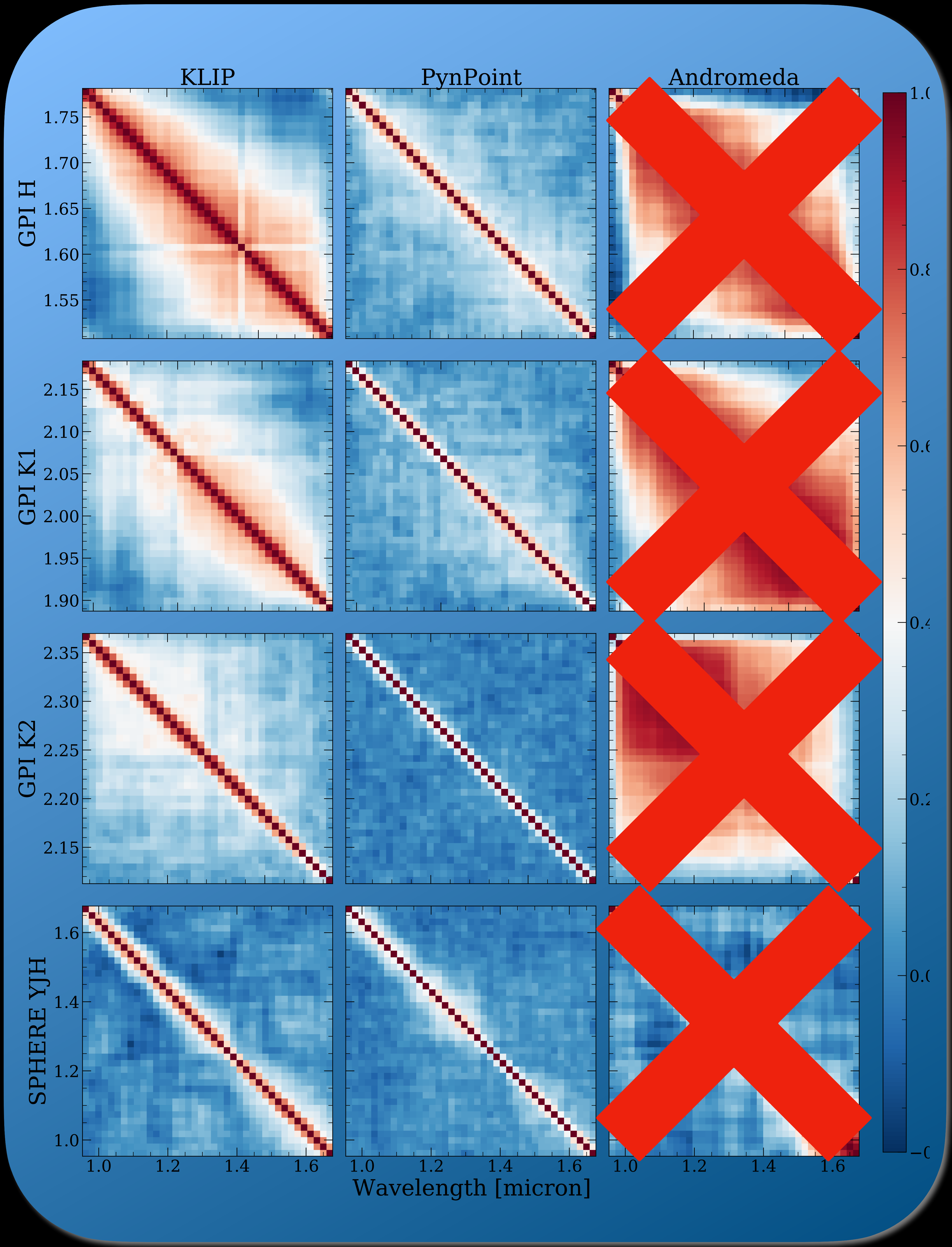
- Based on Greco & Brandt (2016)
- We calculate the mean covariance in an annulus at the separation of the companion
- The companion itself is masked out

$$\psi_{ij} = \frac{\langle I_i I_j \rangle}{\sqrt{\langle I_i^2 \rangle \langle I_{j^2} \rangle}} = \frac{C_{ij}}{\sqrt{C_{ii} C_{jj}}},$$



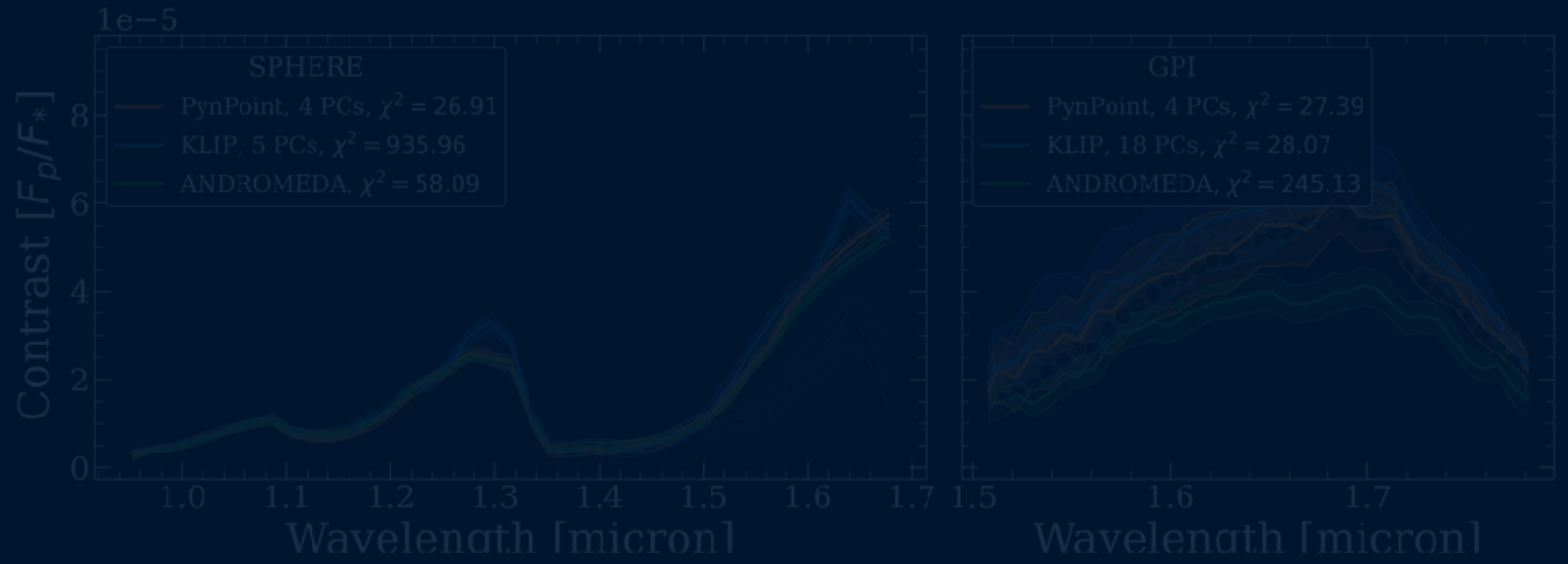
Correlated Noise

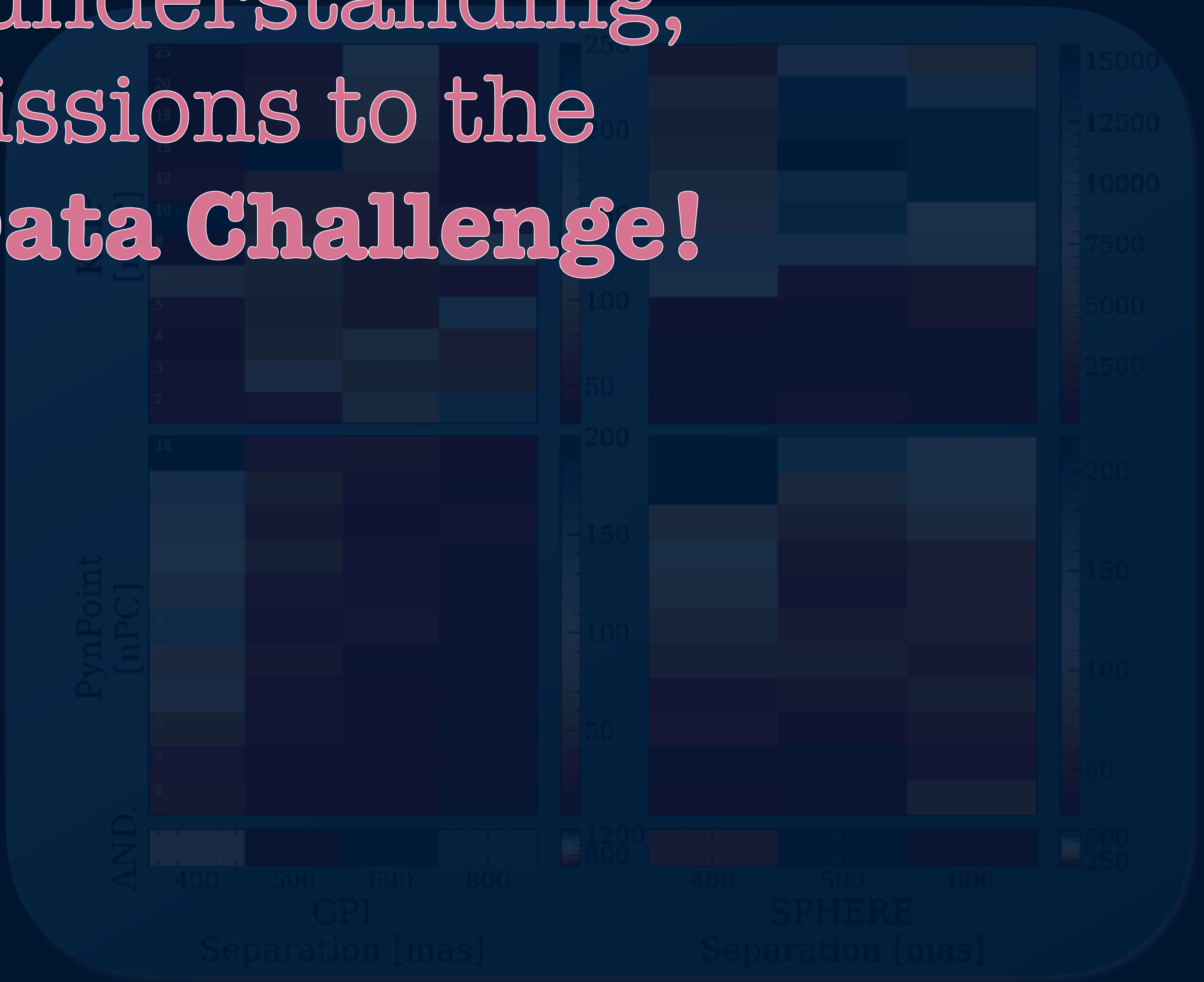
- We computed the correlation matrix for each of our datasets
- However, this is only valid for the PSF subtraction algorithms, and can't be applied to ANDROMEDA
- For ANDROMEDA we use the error estimate computed from the algorithm.



High Contrast Imaging

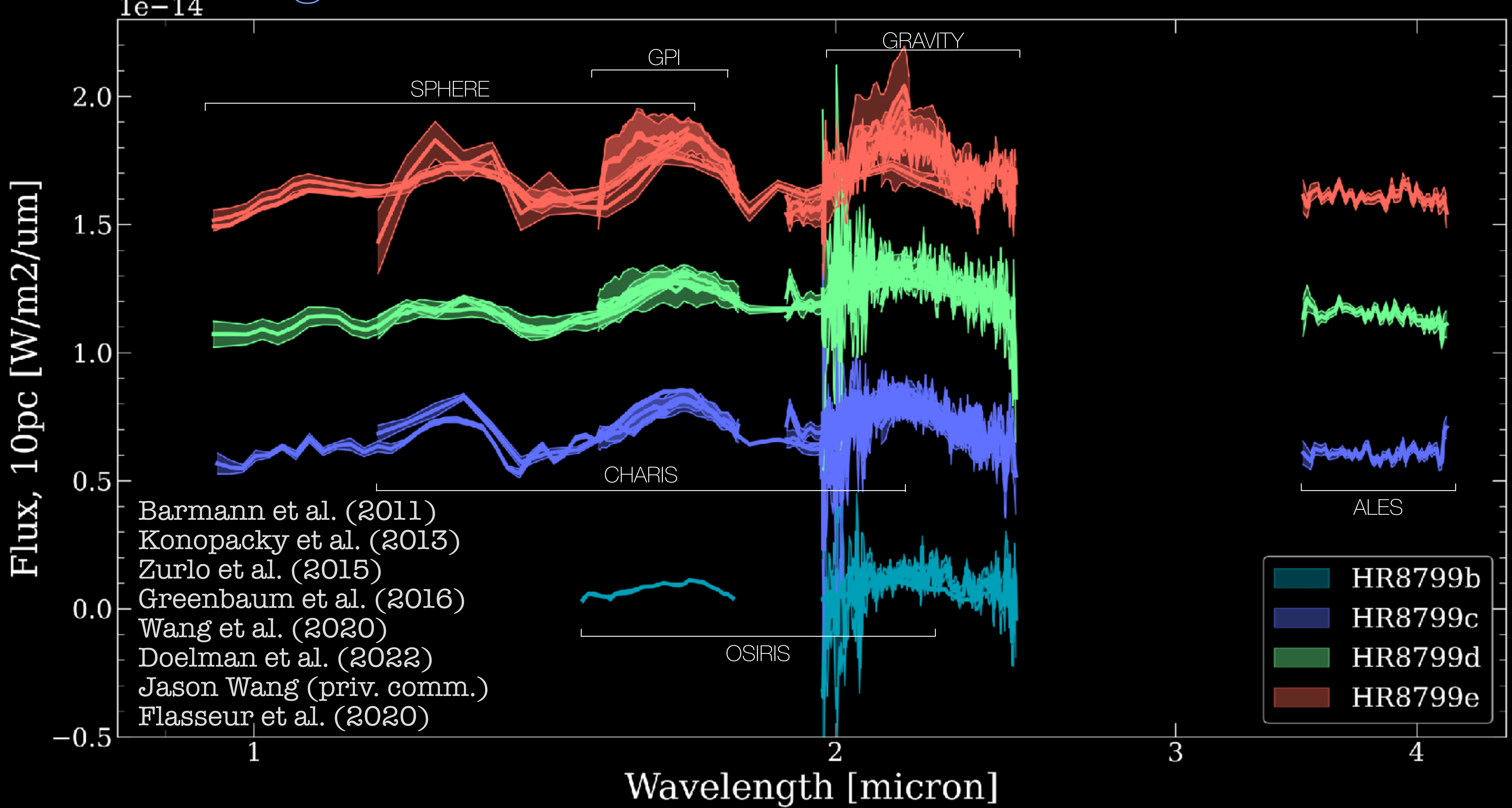
- We used injection tests to optimise the algorithmic parameters to ensure we correctly extracted the real planet spectra
- The accuracy of the extraction depended strongly on the SNR of the injected planet.
- From these tests, we chose to use KLIP to extract the real companions, using a low number of principle components





For a more complete understanding, we need your submissions to the
Exoplanet Imaging Data Challenge!

Combining the datasets

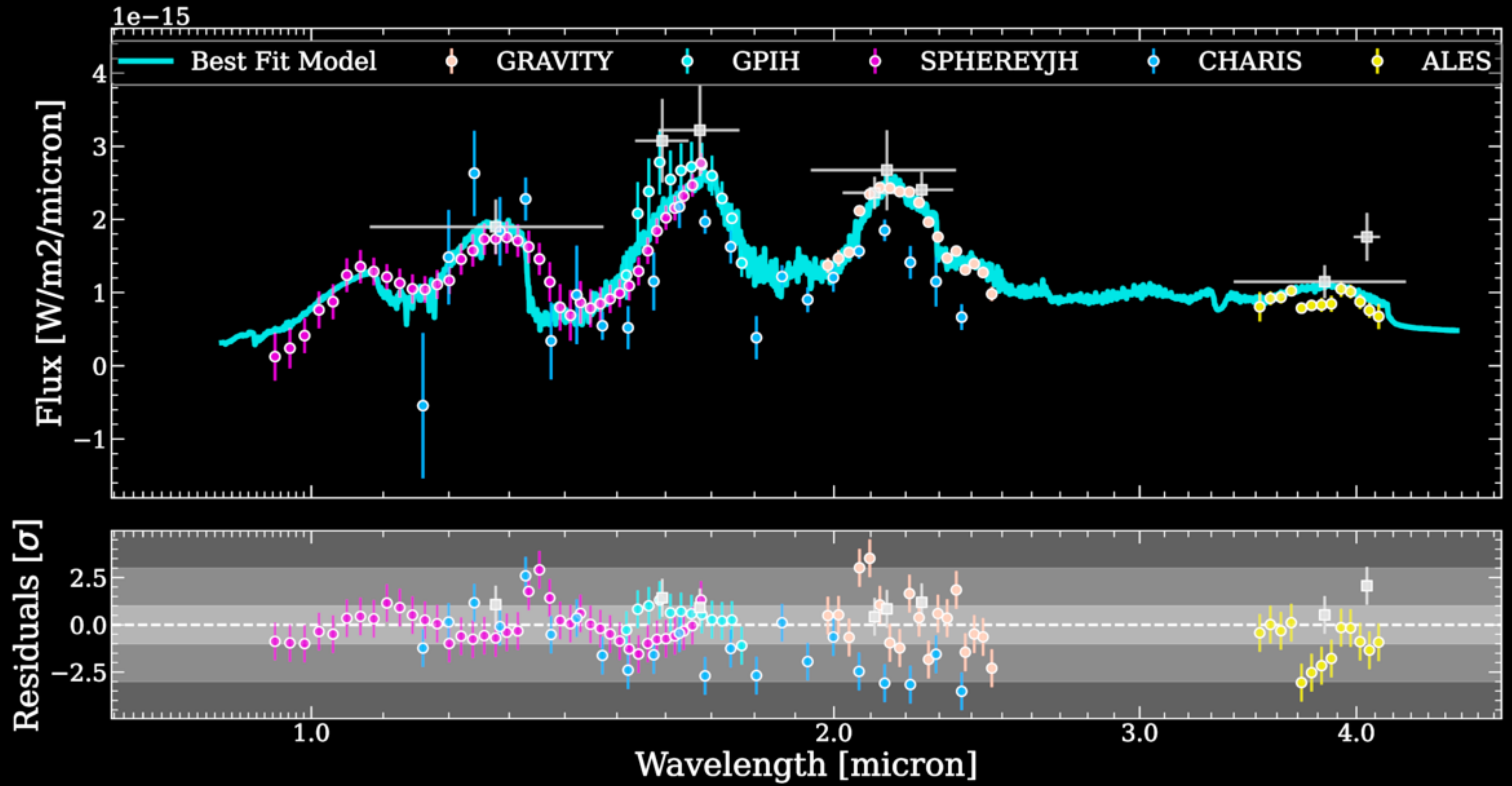


Know Your **Planets**

Fitting the Data!

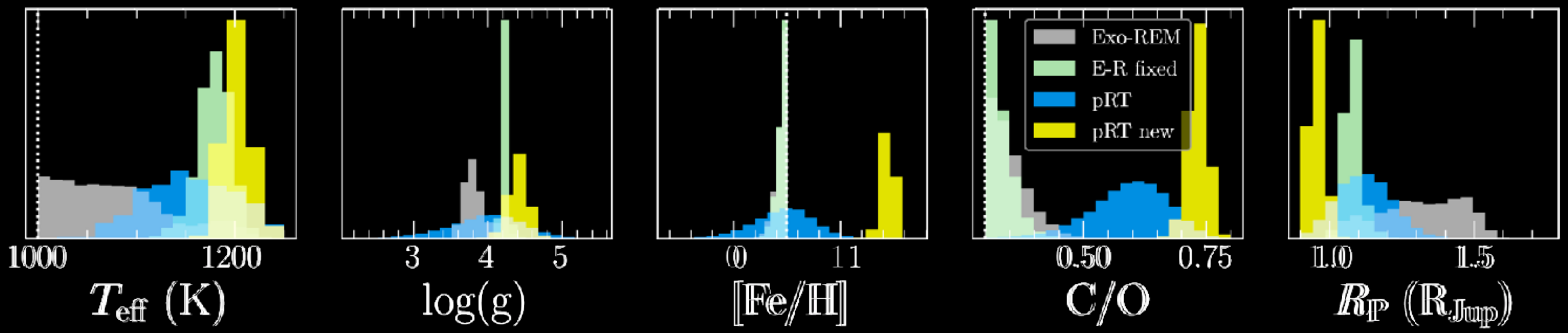
- Using variations on our petitRADTRANS model, we’ve run ~40 retrievals across all four planets

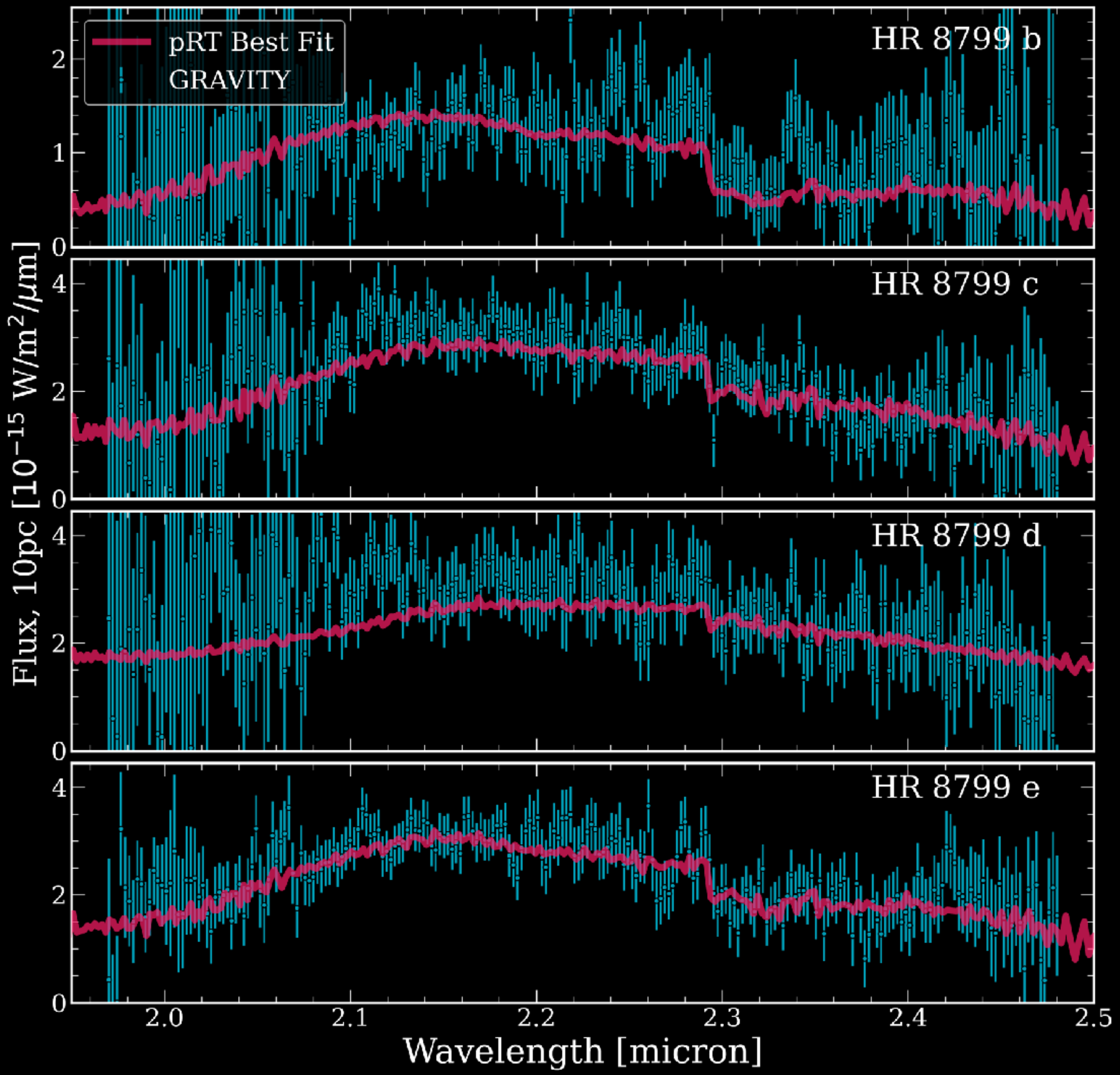
- Consistent with literature, all of the planets are cloudy and around 1000K-1200K



Updated from 2020
Mollière et al. 2020

HR8799e Atmospheric Parameters





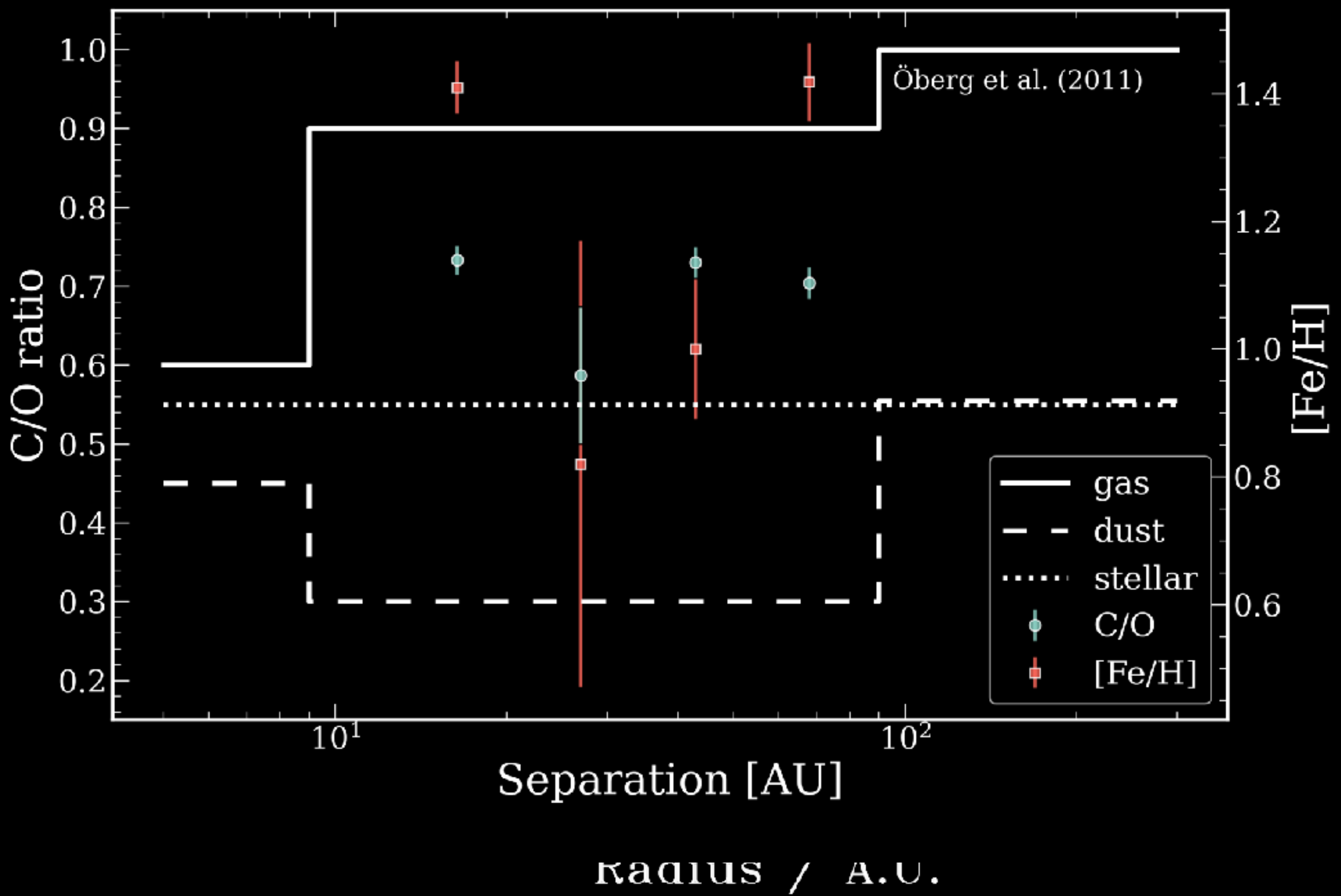
pRT Best Fit
GRAVITY
HR 8799 b
HR 8799 c
HR 8799 d
HR 8799 e
Flux, 10pc [10^{-15} W/m^2/μm]
Wavelength [micron]
0
1
2
4
2.0
2.1
2.2
2.3
2.4
2.5

Preliminary results: C/O

- The C/O ratios of all of the planets are generally super-stellar.

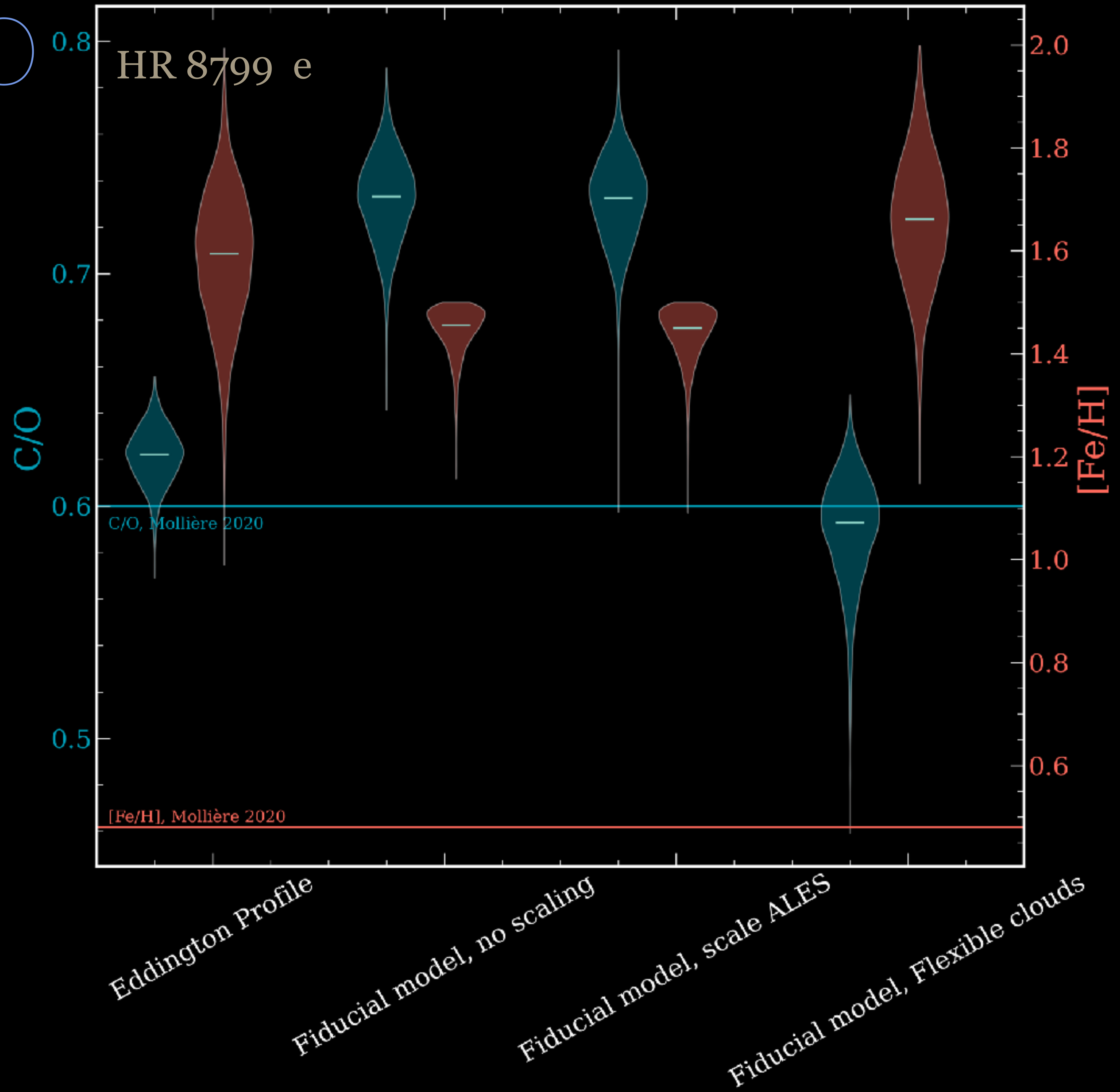
- The C/O ratio strongly depends on the choice of data and model used in the retrieval - here we present the results of our baseline model.

- The metallicities of all of the planets are strongly enriched. Together with the C/O ratio, this suggests pebble drift and evaporation.



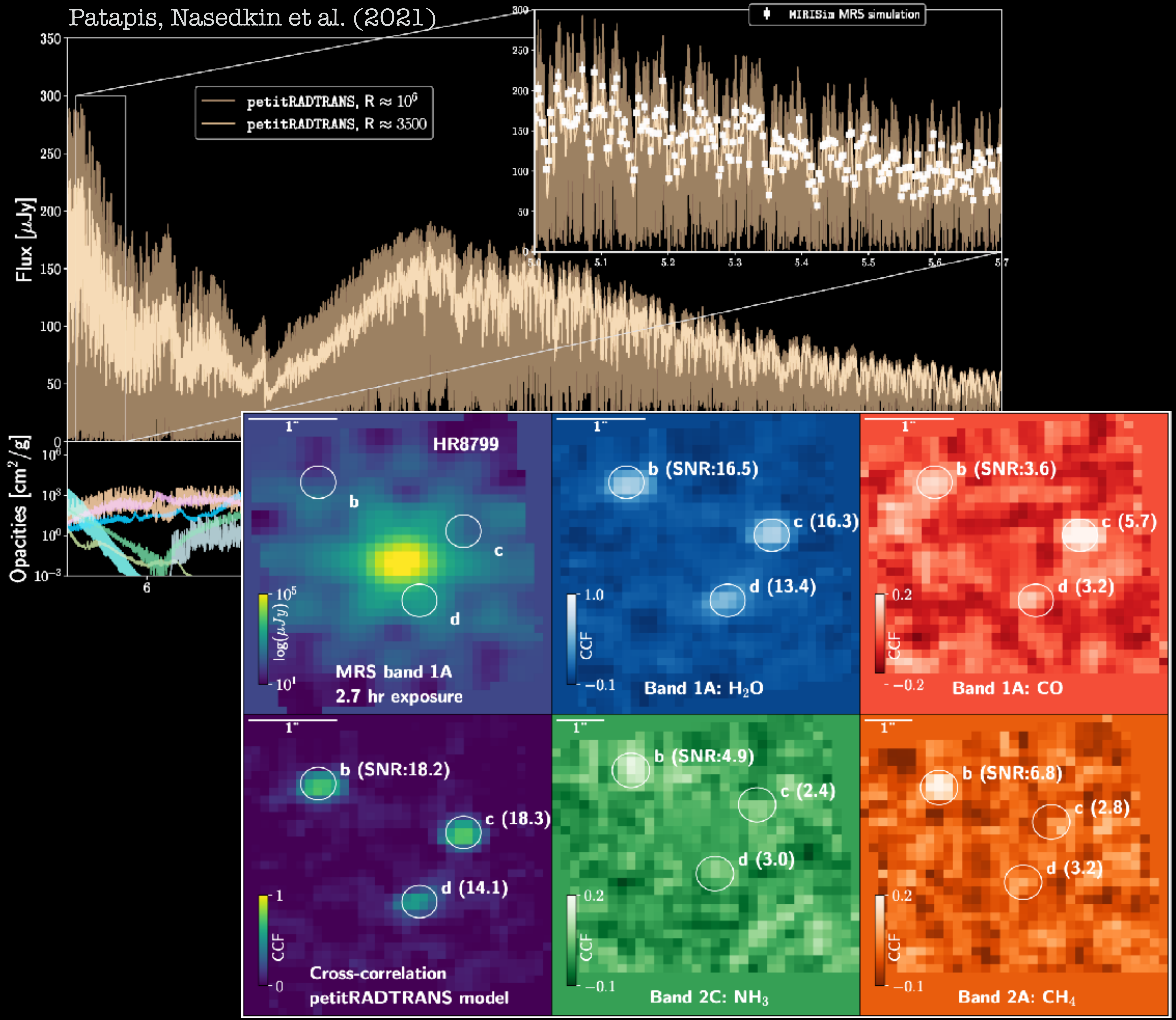
Preliminary results: C/O

- The C/O ratio of the planets depends on both the data and model selection.
- Free chemistry C/O ratios do not agree with disequilibrium chemistry models (but are not well constrained)
- [Fe/H] is even more incompatible with Mollière+ 2020
- Your model should only be as free as justified by your data!



Future Work

- Mid infrared observations with the Medium Resolution Spectrometer of JWST/MIRI are essential to understanding clouds and composition
  - Broad wavelength coverage
  - Silicate cloud features
  - Individual molecular lines/ molecular mapping



Summary

1) Know your data
   Dealing with systematics is difficult, errors and correlations in your data will impact the physical understanding from retrievals

2) Know your model
   All models are wrong, some are useful!
   Any one fit doesn't tell the full story.

This is the most in depth retrieval study of the HR8799 planets to date

We have placed the most precise constraints on important planet parameters thanks to the excellent GRAVITY data.

- Temperatures of 1000K-1200K
- Abundant H_2O and CO - can we do better with next generation instruments?
- Cloudy atmospheres - Though some degeneracies with isothermal atmospheres.
- Superstellar C/O and [Fe/H] - Solid enrichment? Pebble evaporation?

References

ExoGRAVITY
GRAVITY Collaboration, Nowak et al. 2019
GRAVITY Collaboration, Lacour et al. 2019
Mollière et al. 2020
GRAVITY Collaboration, Lacour et al. 2021
Wang et al. 2021
Kammerer et al. 2021

Data
Zurlo et al. 2015
Greenbaum et al. 2016
Wang et al. 2020
Biller et al. 2021
Doelman et al. (i2021)

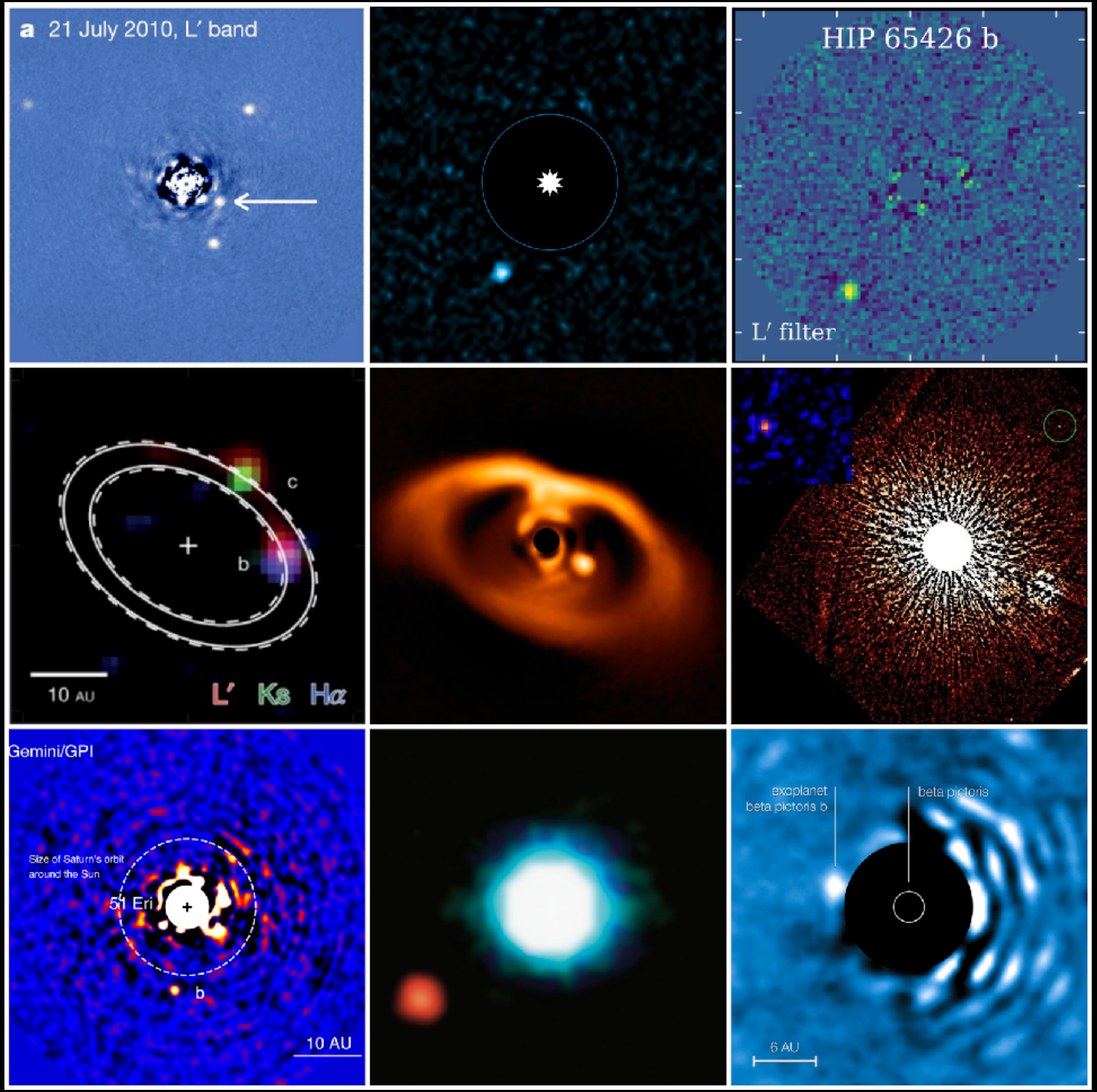
References
Ackermann & Marley 2001
Öberg et al. 2011
Greco & Brandt 2016
Marois et al. 2008
Marois et al 2010
Barman et al. 2011
Marley et al. 2012
Konopacky et al. 2013
Lavie et al. 2016
Wang et al. 2020
Wang et al. 2021
Brandt et al 2021
Amara & Quanz 2012
Stolker et al. 2019
Cantalloube et al. 2015
Wang et al. 2015
Ruffio et al. 2021
Mollière et al. 2022

APEx 2021

Context

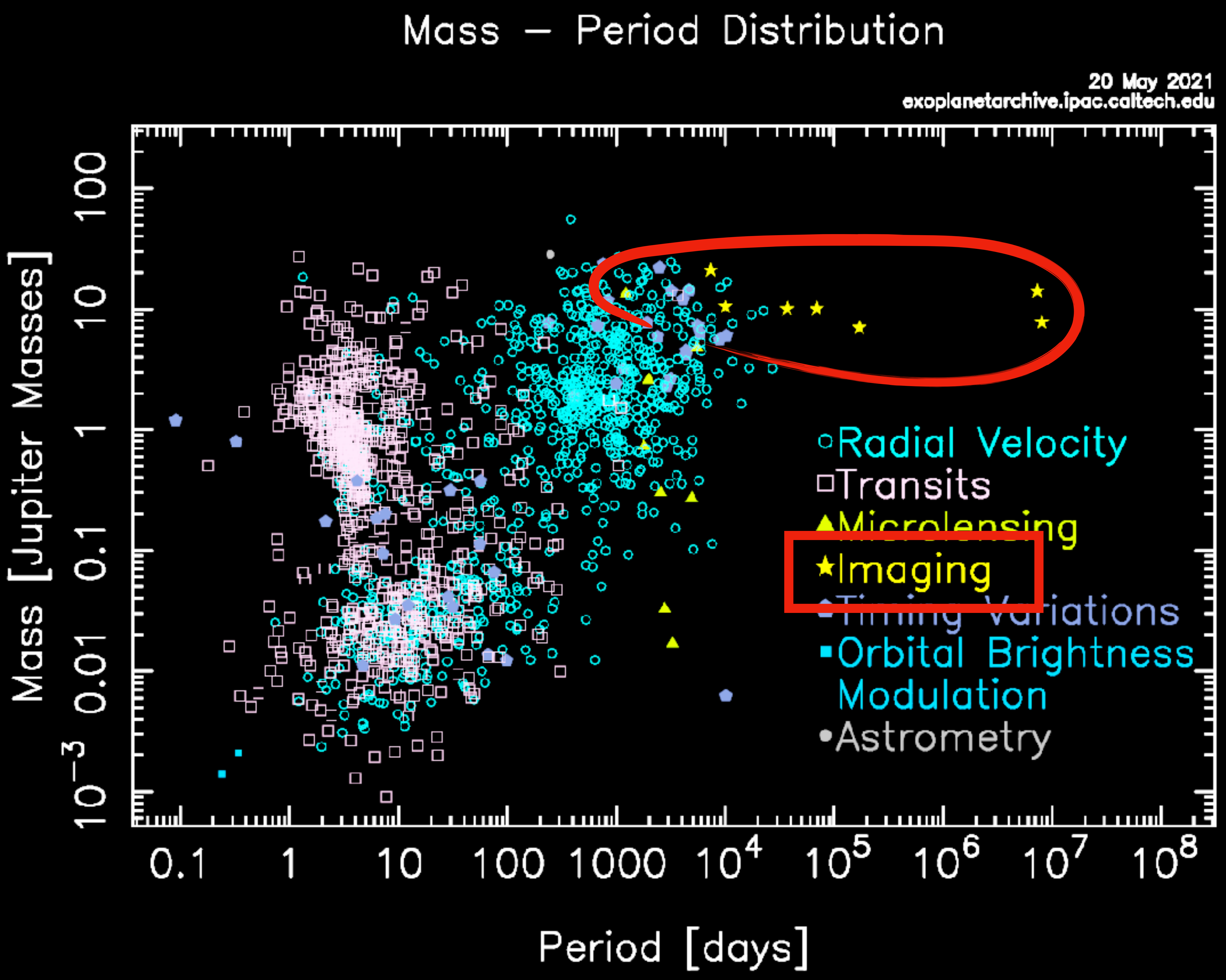
- We only know a small handful (~20) of directly imaged exoplanets, but each provides a rich laboratory to study their chemistry, dynamics and formation history.

- HR 8799 (top left) is unique in having 4 planets observed in the system, allowing a comparative study of planets with a shared formation history.



Context

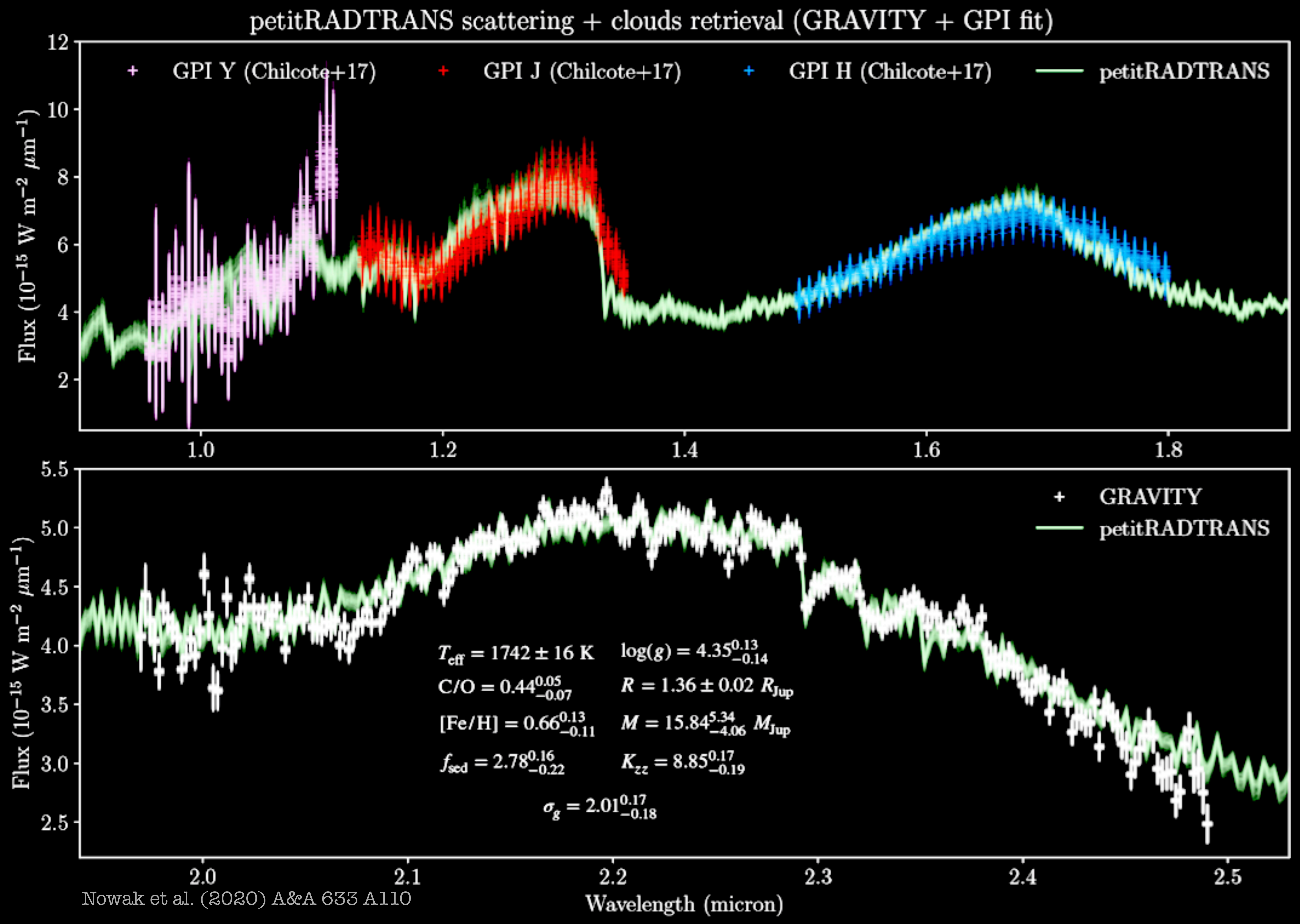
- Directly imaged planets are **young, hot** and **massive**
- Their mass and temperature range is more similar to brown dwarfs than most exoplanets.
- The young age of these systems makes them useful laboratories for studying their formation and evolution.



petitRADTRANS

- petitRADTRANS is an open source, 1D radiative transfer code designed to compute the emission and transmission spectra of exoplanets.
- Implements a range of atmospheric structures, cloud models and opacity sources.
- 117 publications listed on NASA/ADS

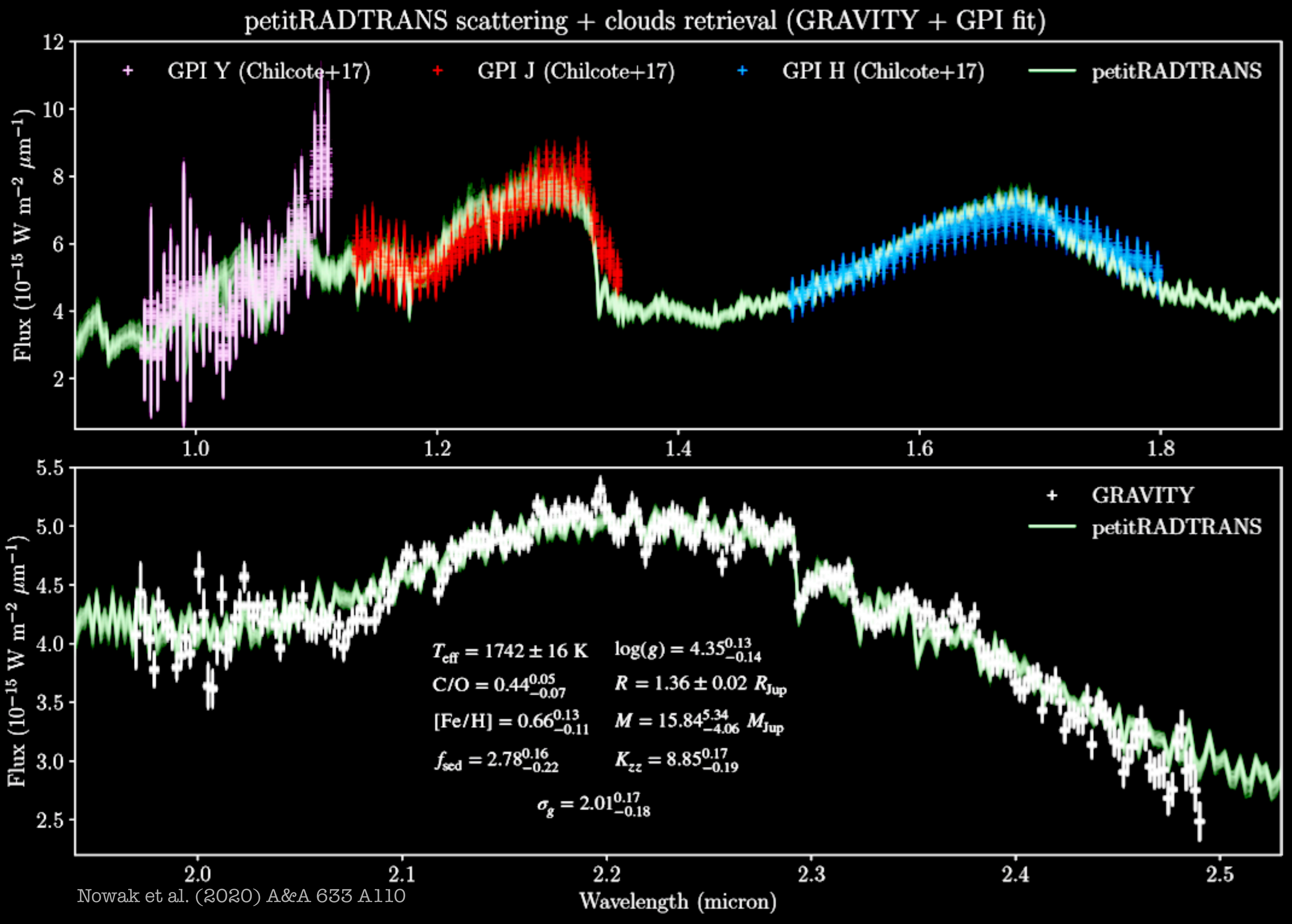
pip install petitradtrans



Nowak et al. (2020) A&A 633 A110

petitRADTRANS

- Numerous updates to pRT since Mollière 2020:
  - Updated opacity tables and improved c-k handling
  - Improved CIA handling
  - New cloud particle size distributions
  - New retrieval package
  - High resolution retrievals
  - (Dis)equilibrium chemistry integration
  - General improvements to speed and usability

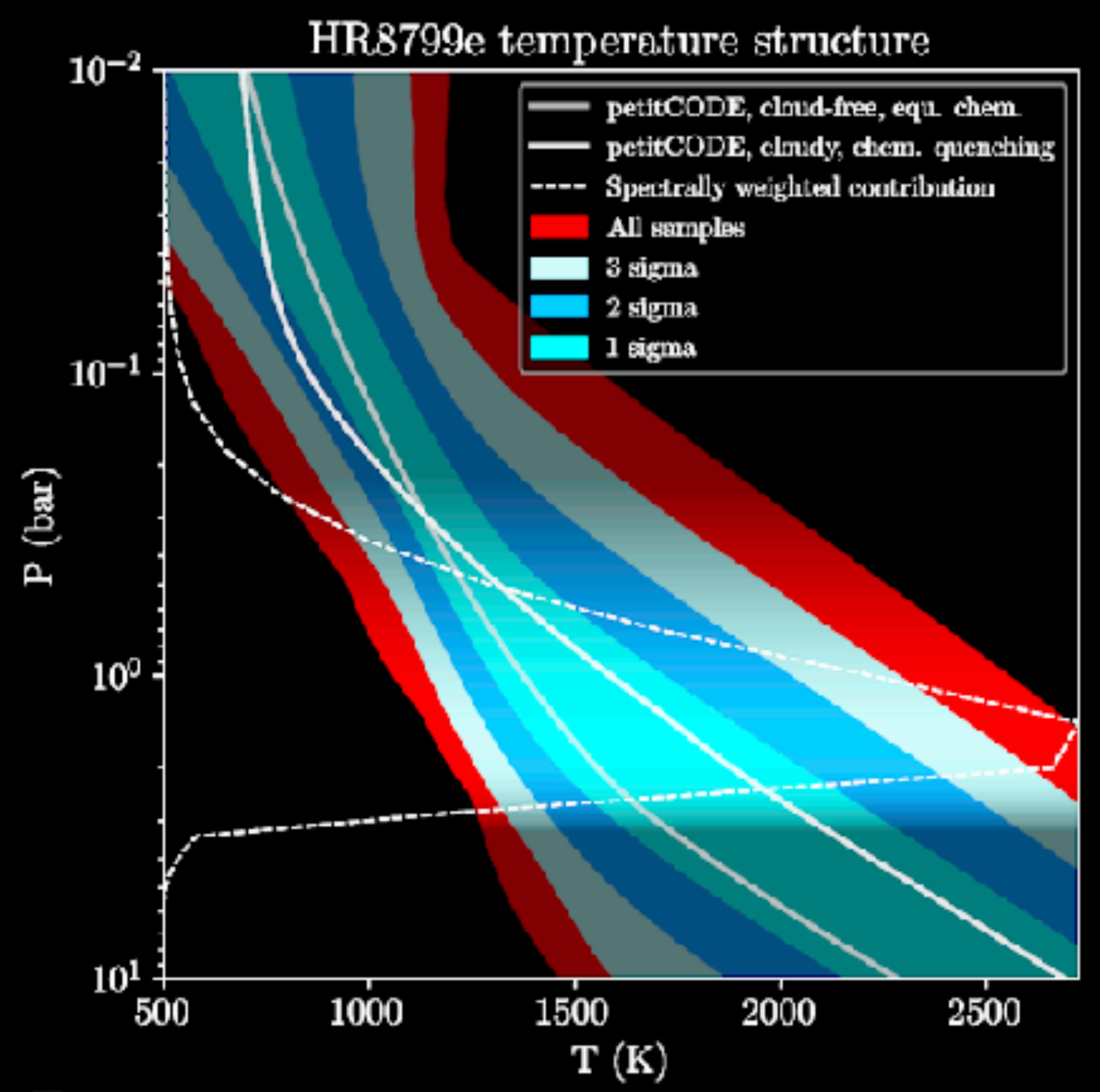


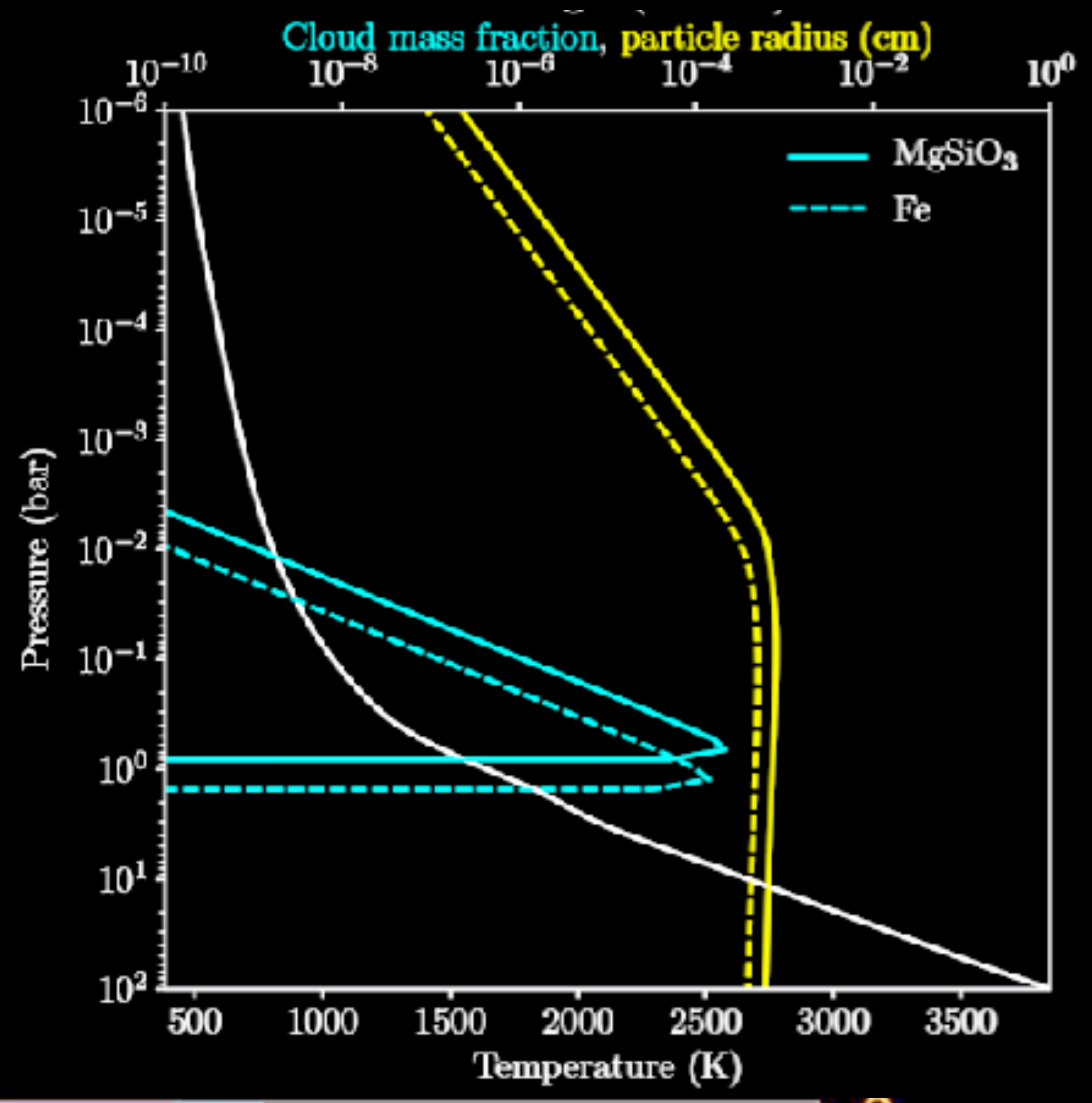
Nowak et al. (2020) A&A 633 A110

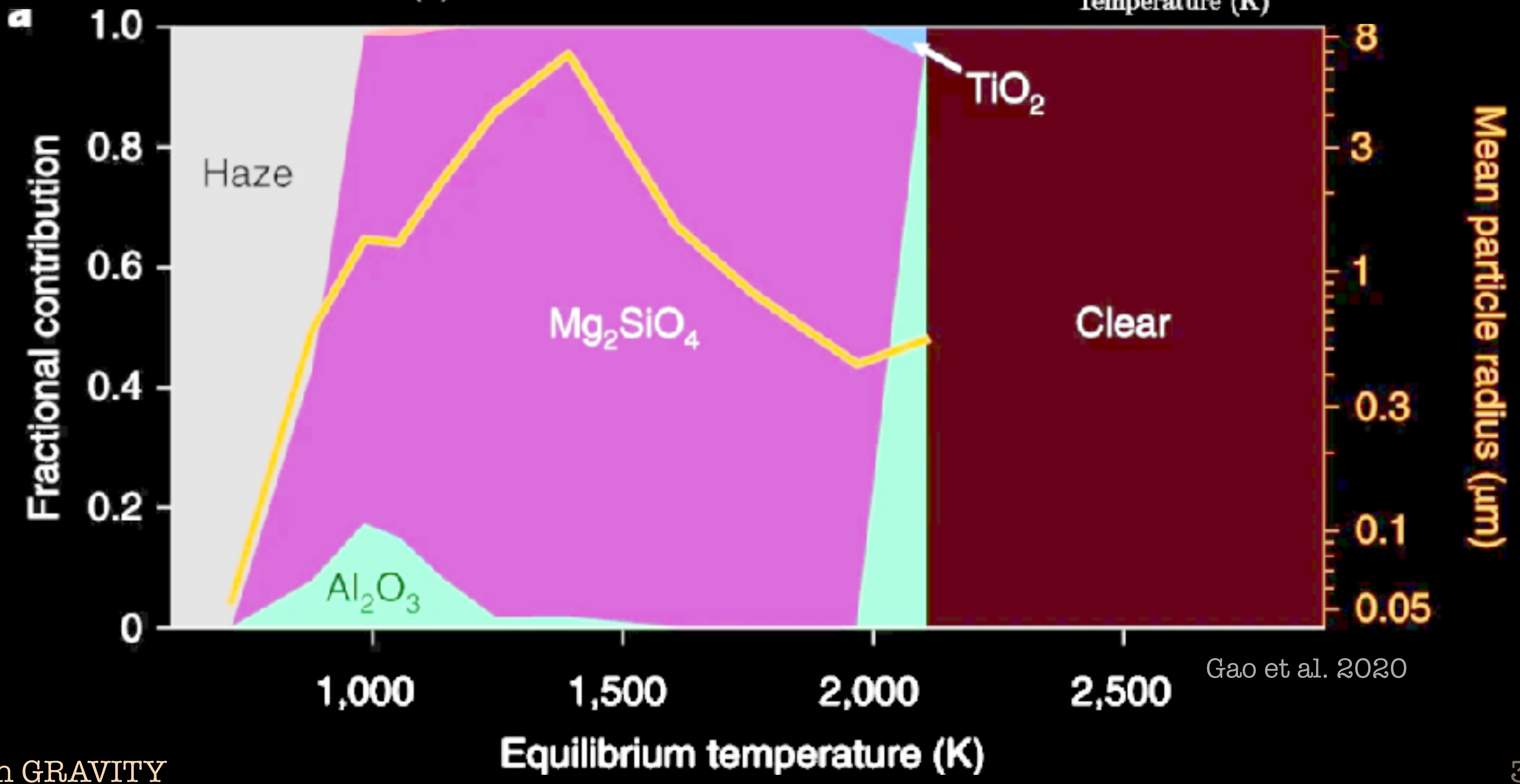
Modelling the HR8799 Planets

- We base our temperature profile on Mollière et al. 2020:
  - adiabatic deep in the atmosphere
  - Spline interpolation in the upper atmosphere to avoid isothermal degeneracy with clouds
- Our cloud choice is determined by condensation temperatures, and the nucleation energy arguments of Gao et al. 2020.

Mollière et al. 2020







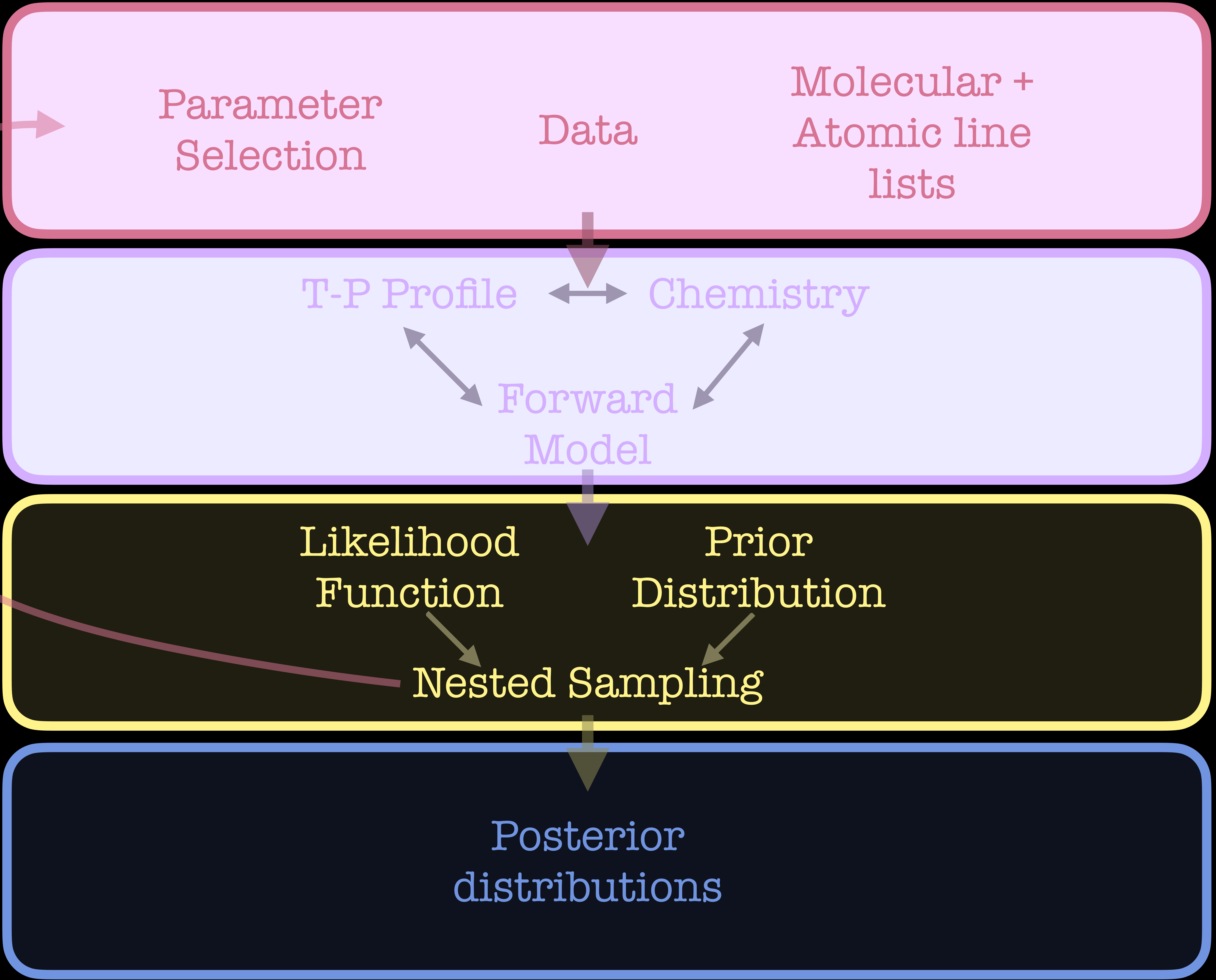
Gao et al. 2020

Atmospheric Retrieval

- Measuring the emission spectra of an exoplanet is extremely challenging compared to brown dwarf or solar system observations.

- So let’s use our simple model and try to understand some of the broad strokes physics

- We can fit this to the spectral and photometric data



Preliminary results: Chemistry

- Our fiducial model for each planet uses disequilibrium chemistry, interpolating a grid in C/O [Fe/H] space.
- For HR 8799 b, we can compare this to a free chemistry retrieval.