Data Analysis in the era of
Strategies for efficient population studies

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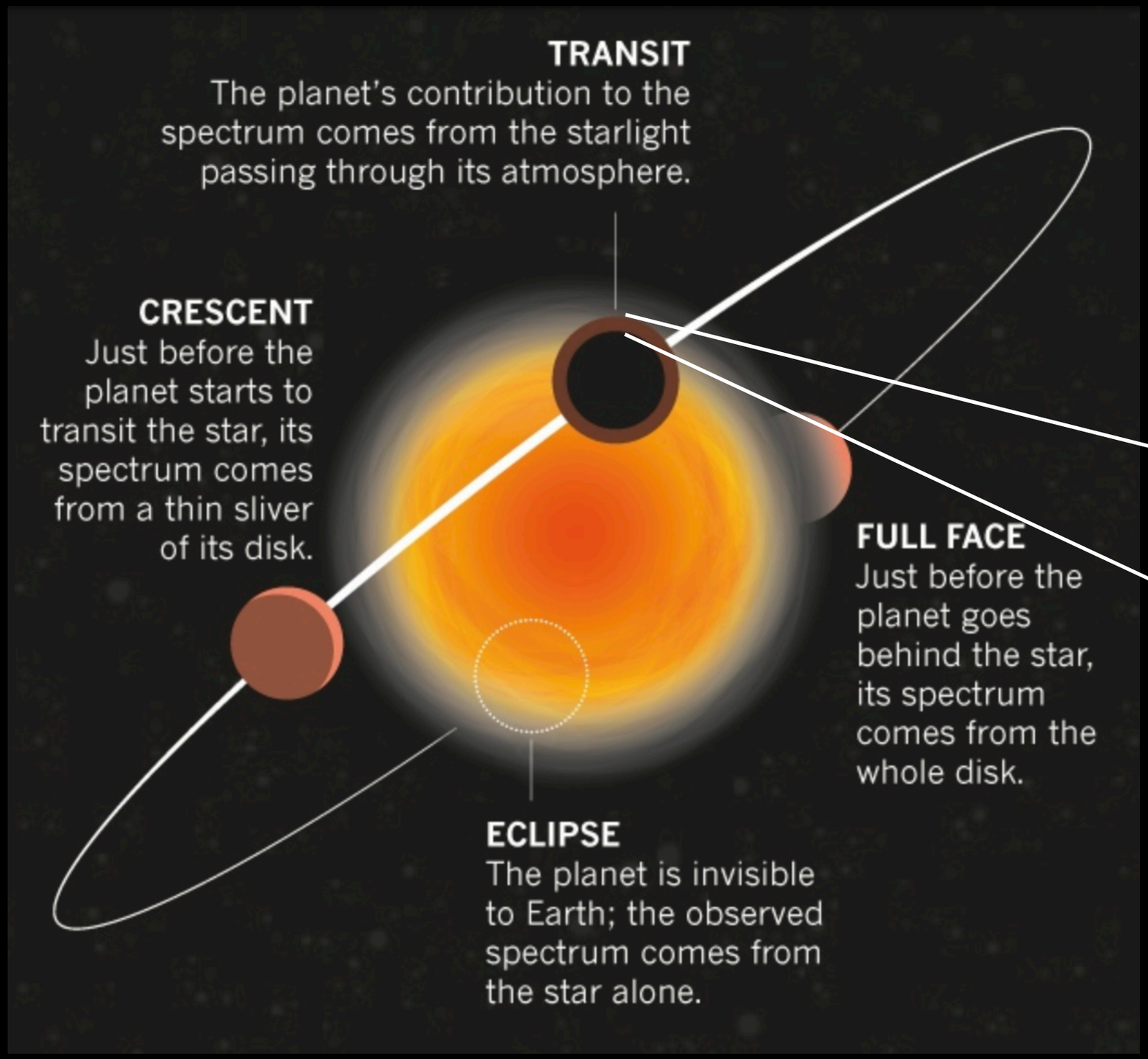
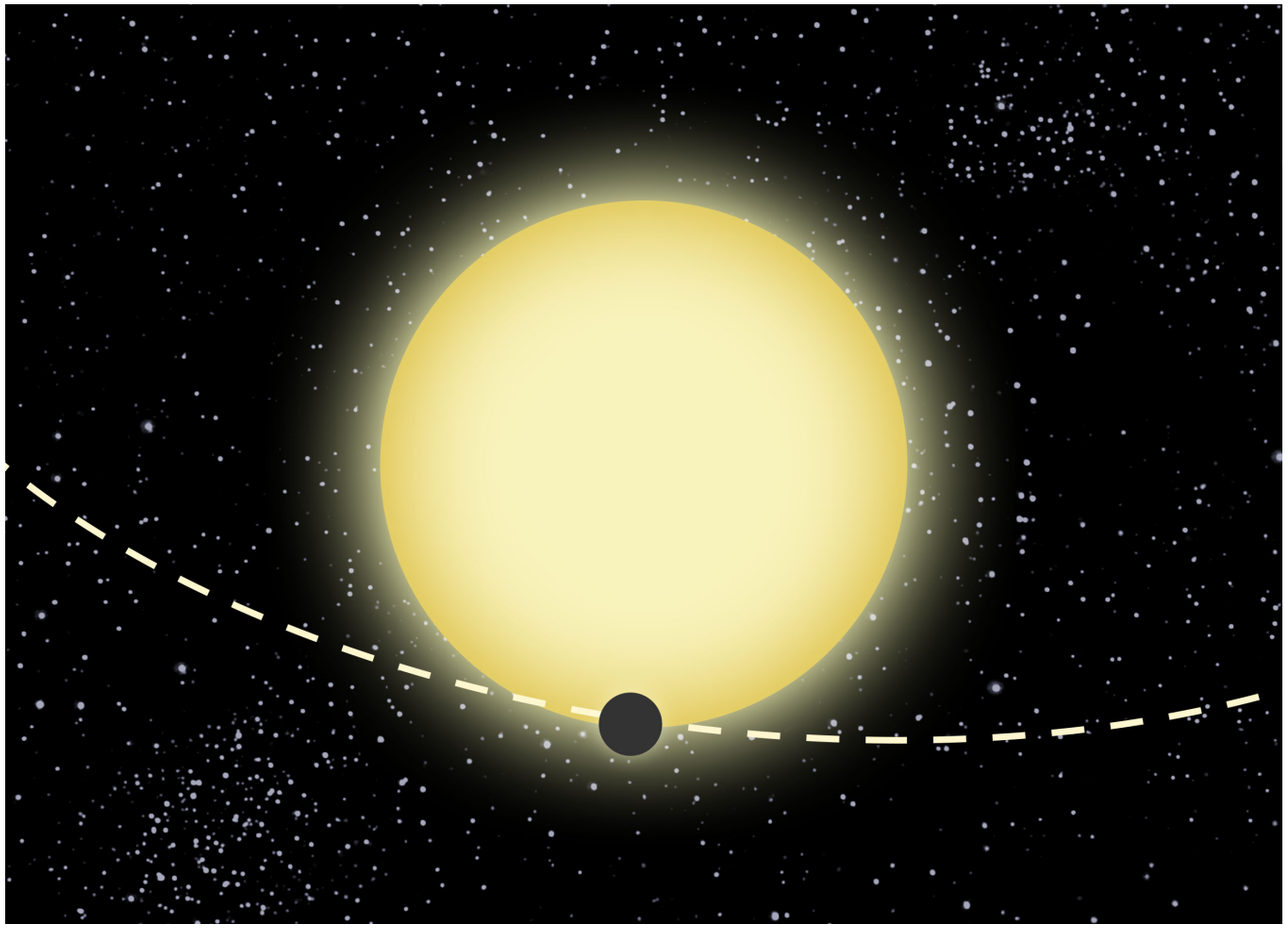
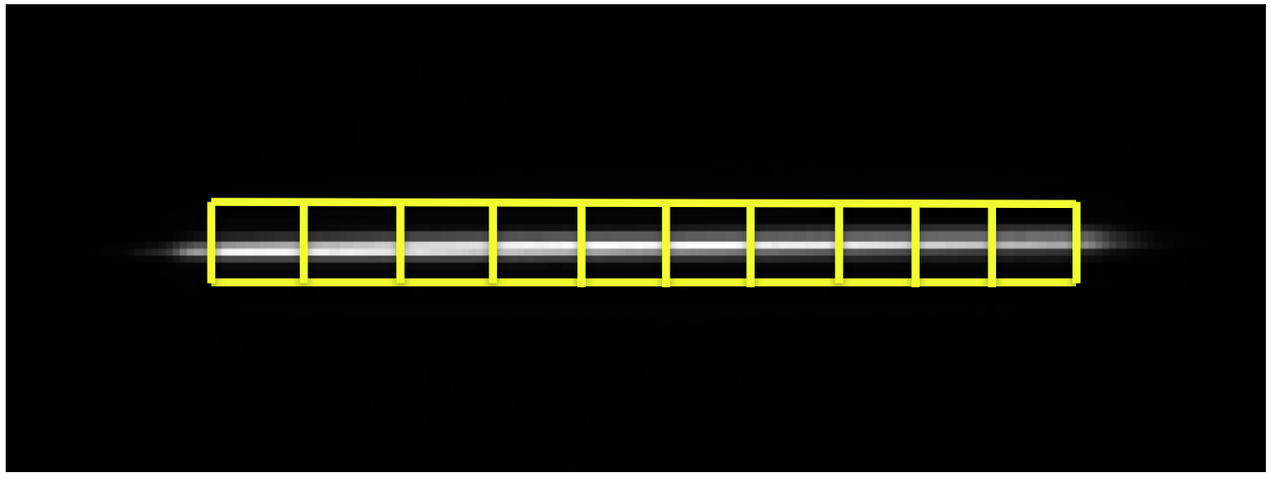
Transmission and emission spectroscopy

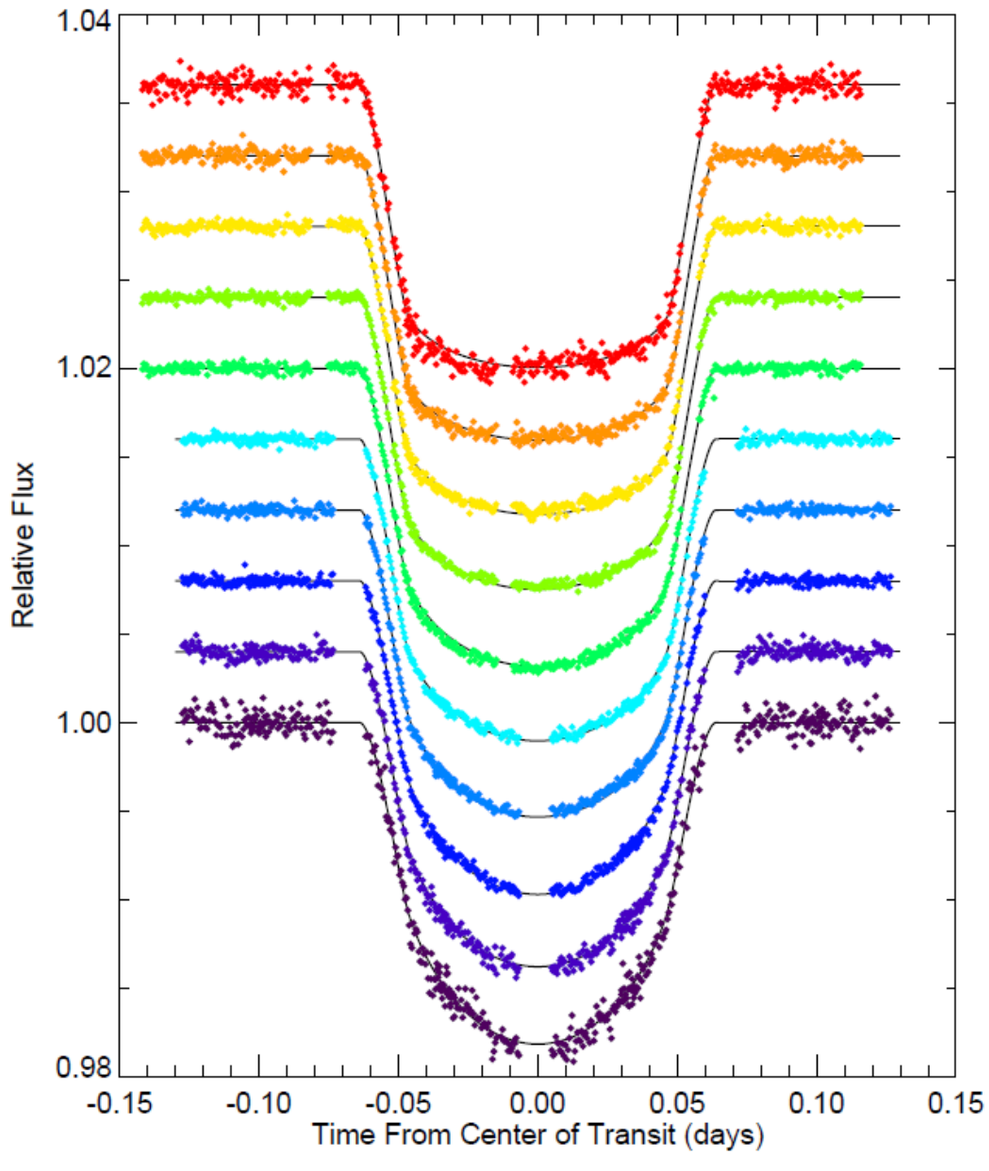


Hecht 2006

Transmission spectroscopy







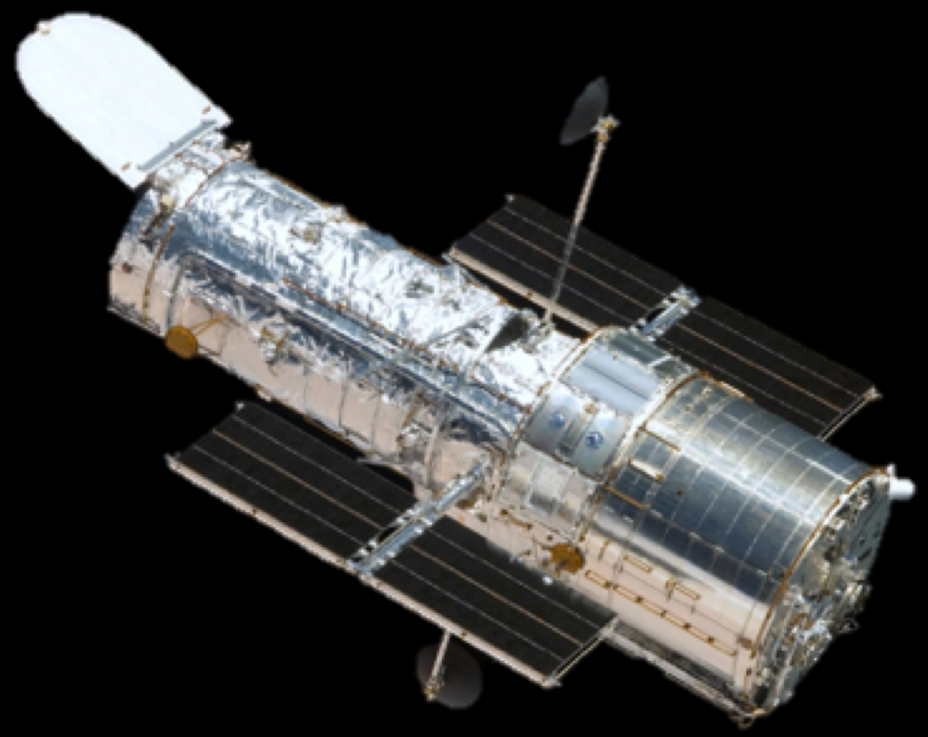
Knutson et al. 2007

The legacy of HST/WFC3:
Towards population studies of exoplanet atmospheres

WIDE-FIELD CAMERA 3 - WFC3
installed in 2009 during HST Service Mission 4

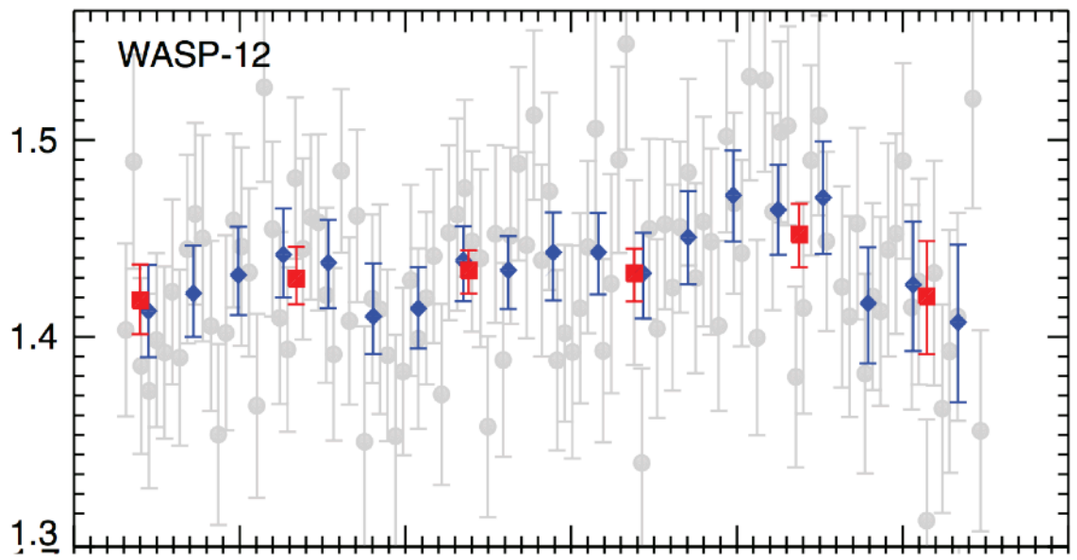
Step 1 - High S/N observations

Wavelength

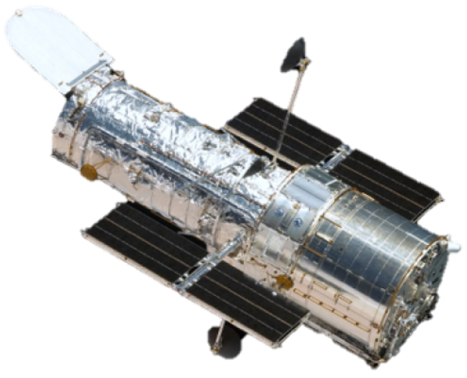


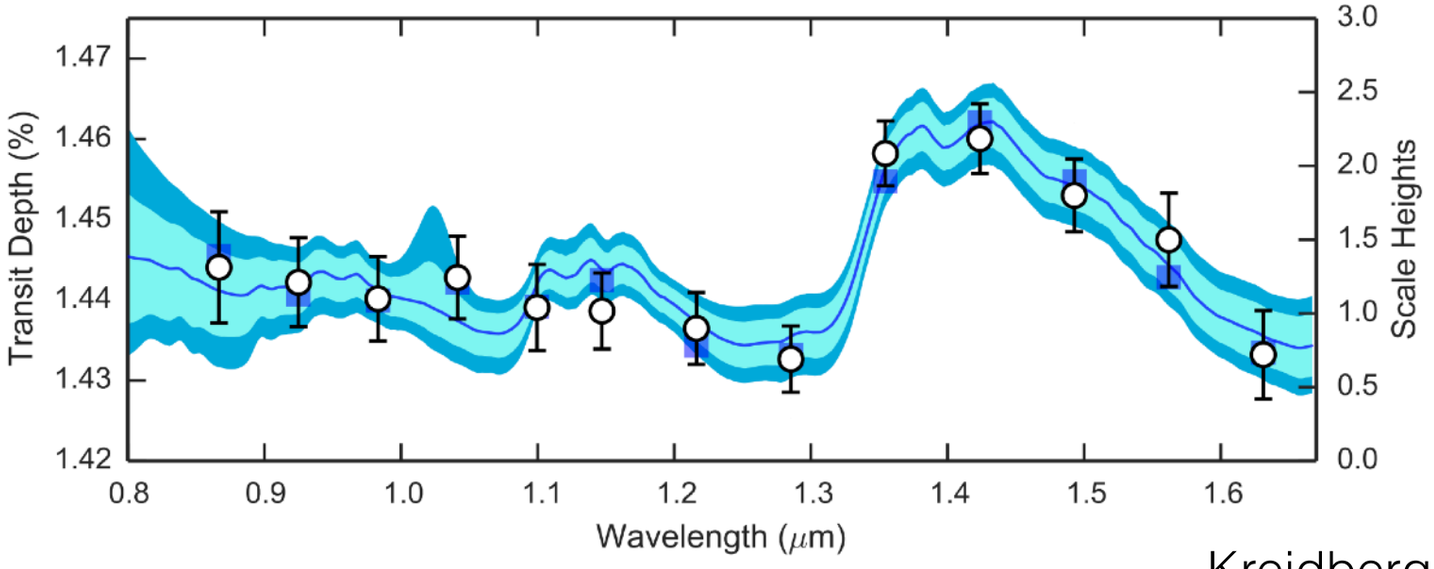
Step 1 - High S/N observations

WASP-12 b



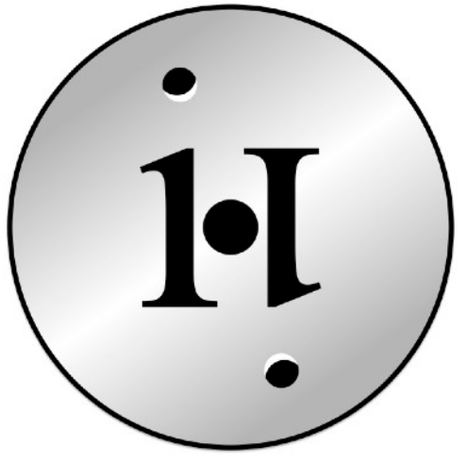
Mandel et al. 2013





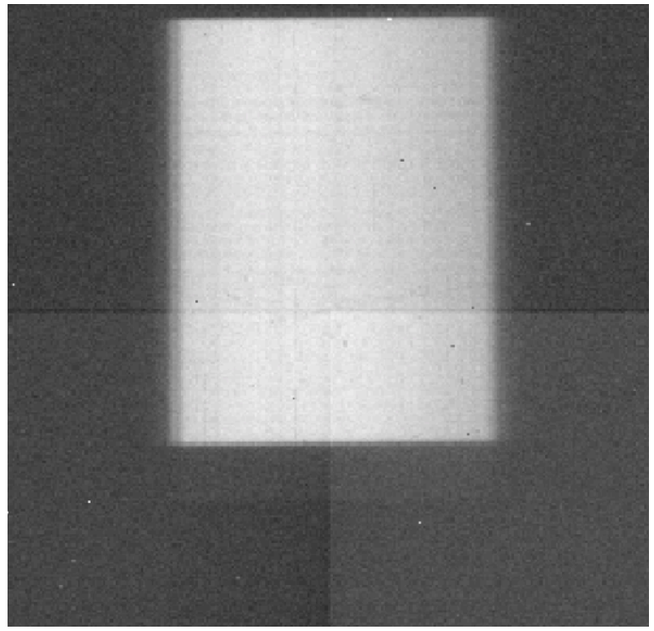
Kreidberg et al. 2015

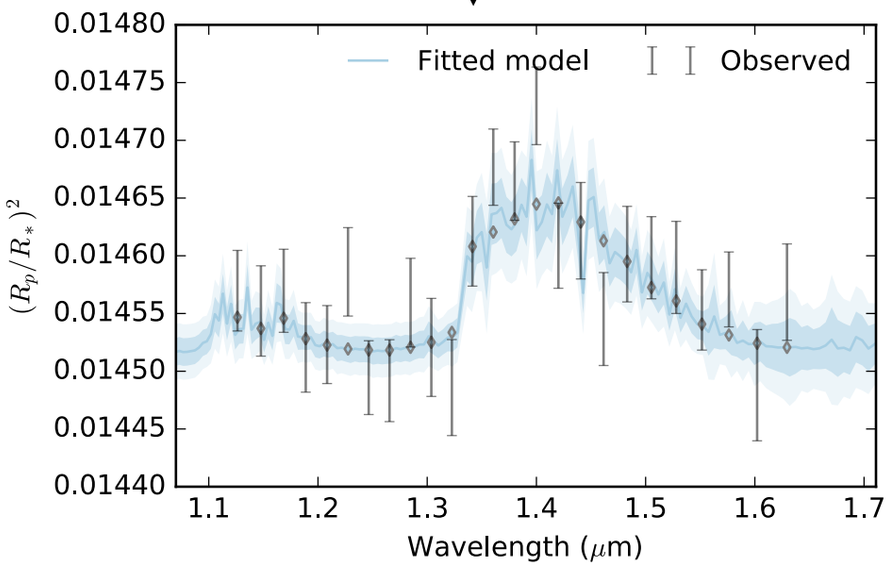
Step 2 - *A pipeline*



IRACLIS

- ☑ Specialised for WFC3 scanning
- ☑ Specialised for exoplanets
- ☑ Reliable and fast
- ☑ Automated end-to-end analysis
- ☑ Open source



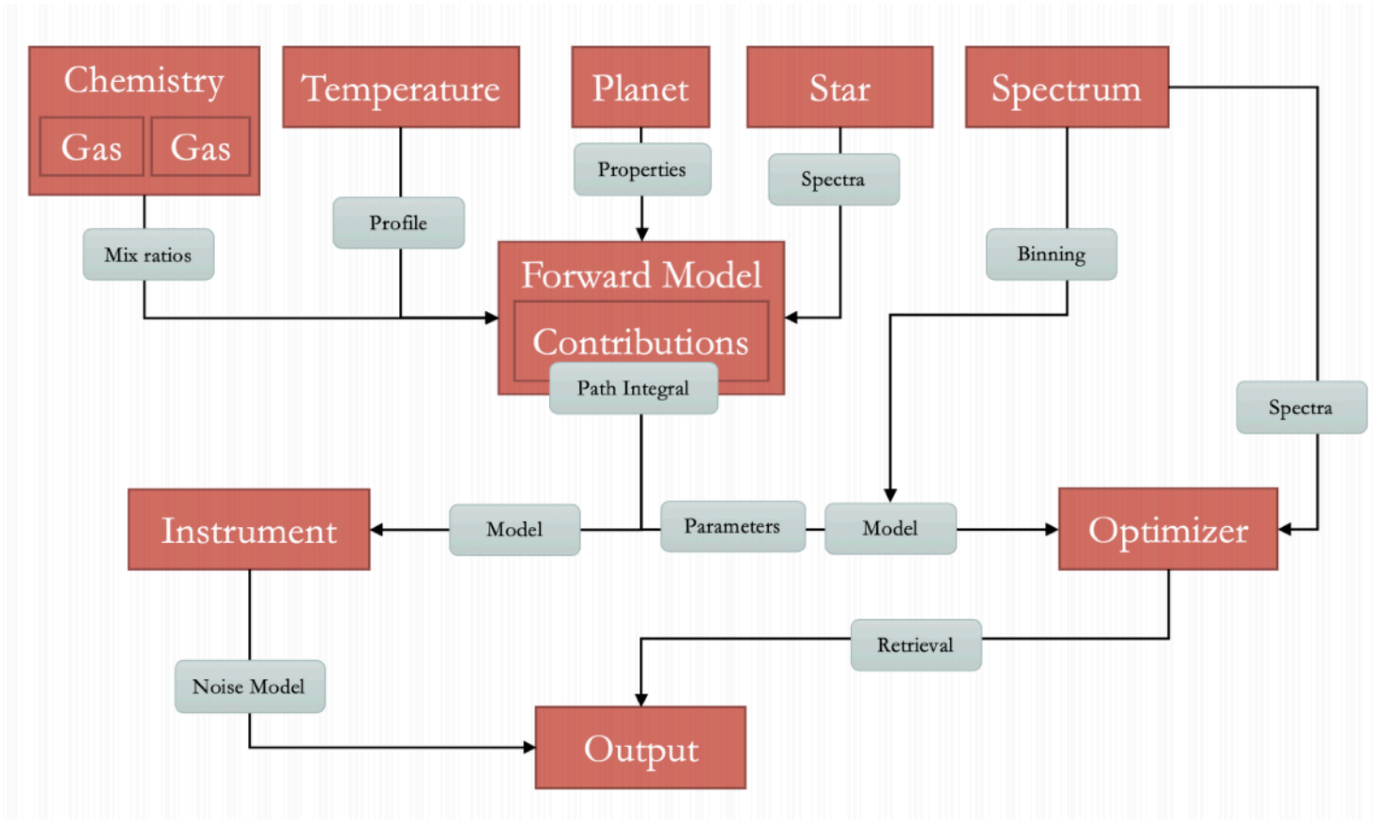


Tsiaras 2017 - PhD thesis

Step 3 - A retrieval

Tau-Rex 3

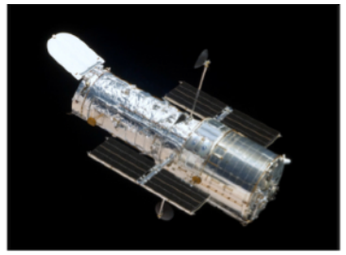
- ☑ Fully Bayesian
- ☑ Flexible modeling
- ☑ Reliable and fast
- ☑ Automated end-to-end analysis
- ☑ Open source

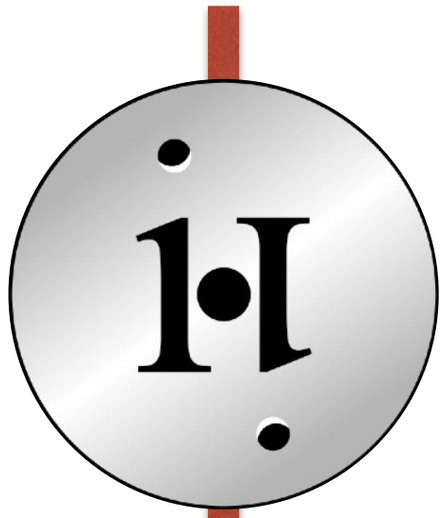


Al Refaie et al. 2019

Step 4 - OPEN SCIENCE

The new standard in data analysis



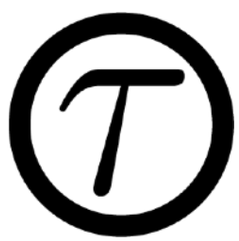


spectrum

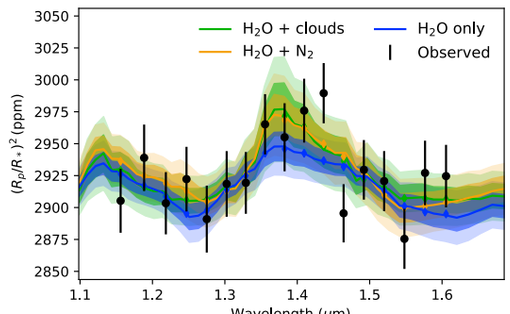
archive.stsci.edu

github.com/ucl-exoplanets

exomol.com



ExoMol



First catalogue of exoplanet atmospheres

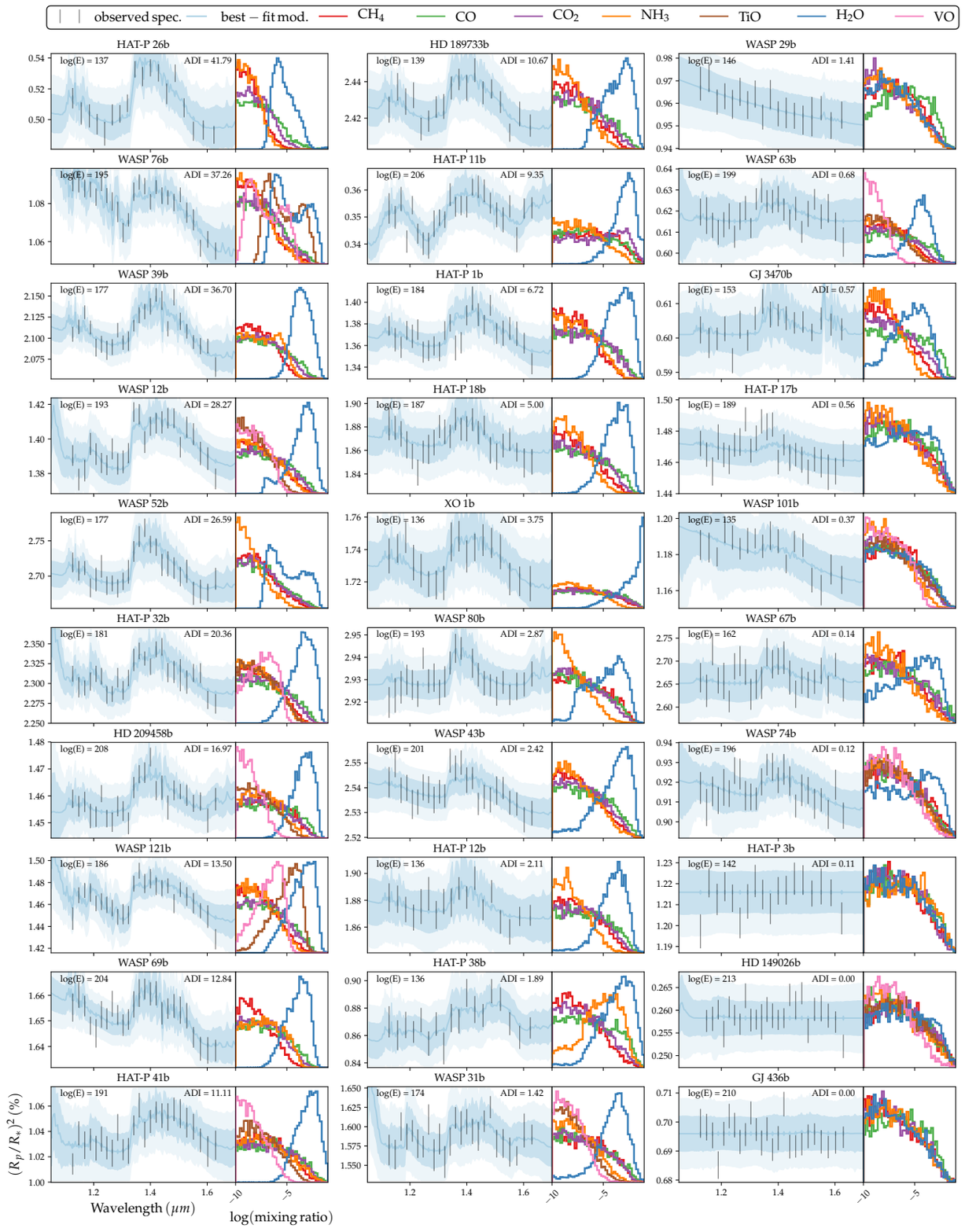
- **50** Datasets analysed
  largest data volume ever

- **30** exoplanet atmospheres
  largest sample ever

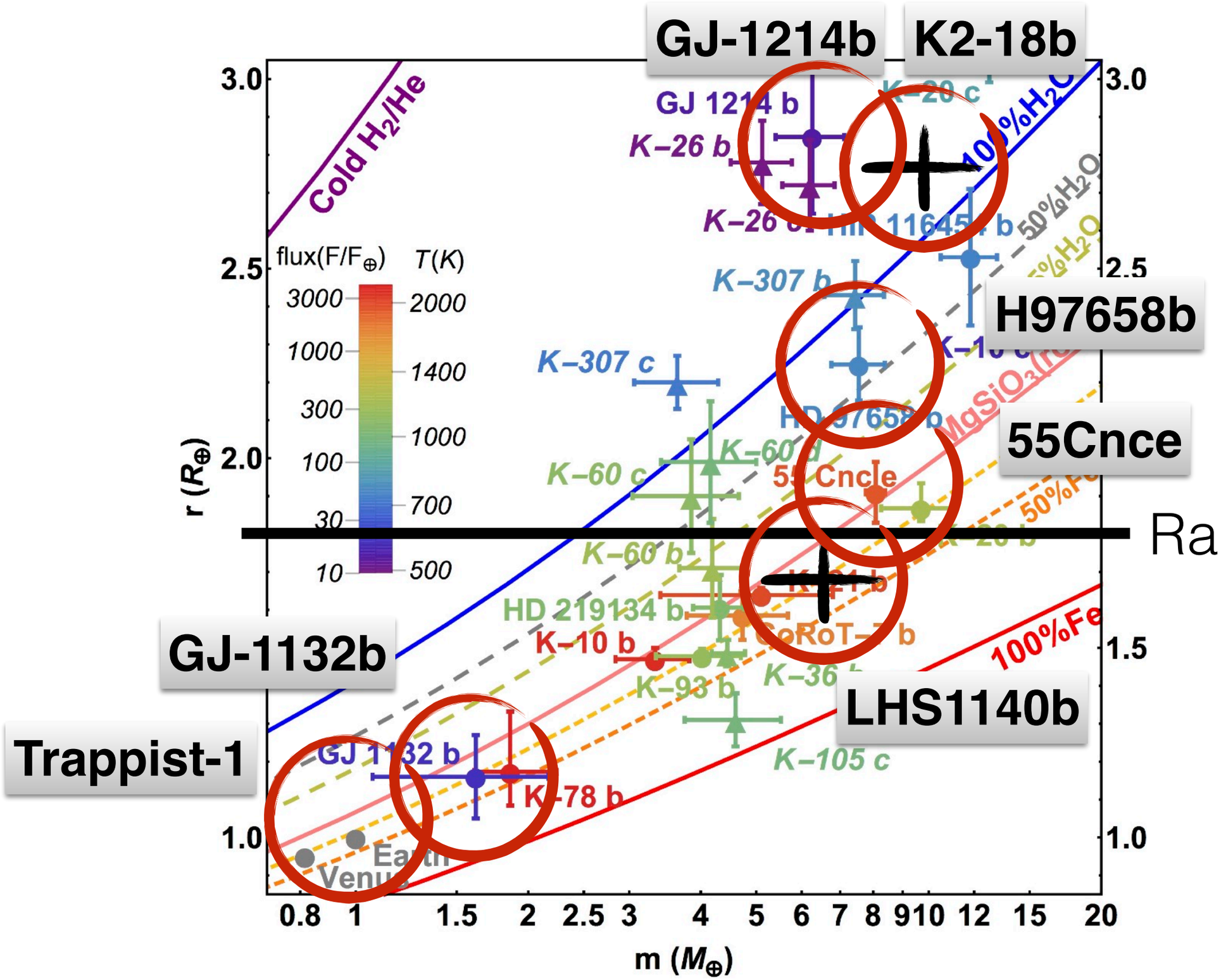
- **16** clear detections with **H2O**

Tsiaras et al. 2018

- **And many more in the years that followed**



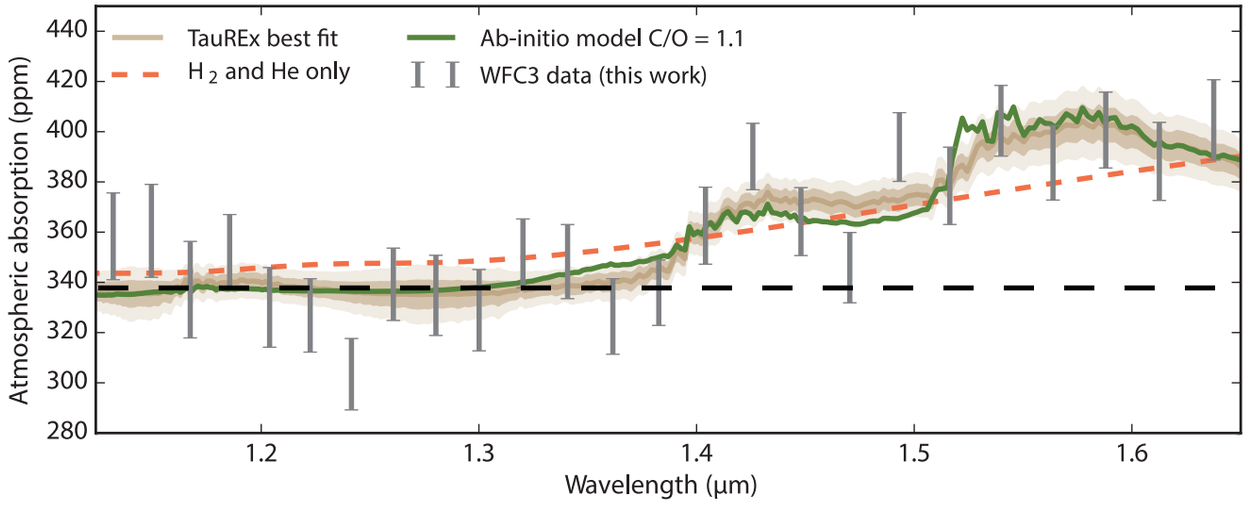
First observations of Super-Earths



First detections of super-Earth atmospheres

55 Cancri e

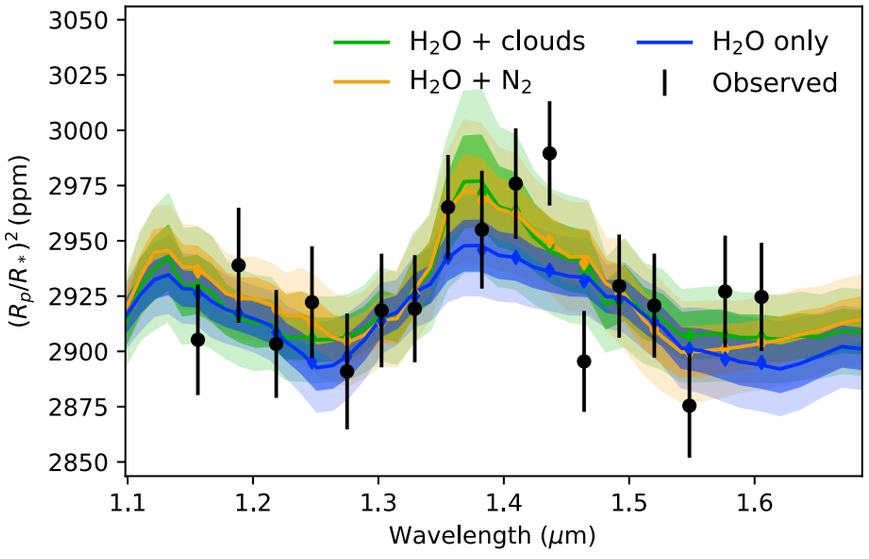
- +2000 K Temperature
- A light atmosphere (high C/O?)



Tsiaras et al. 2016

K2-18 b

- ~300 K Temperature
- H2O detection

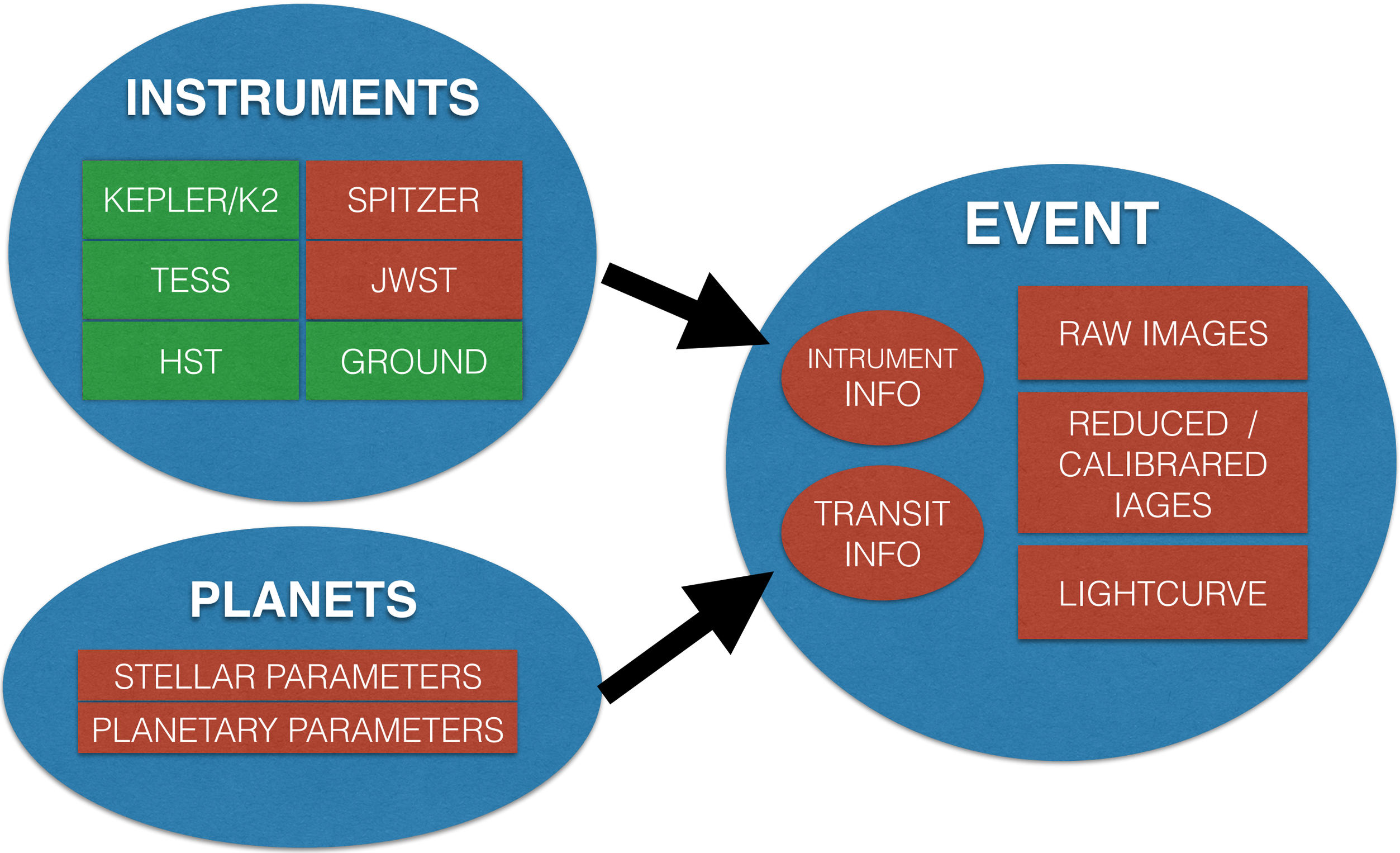


Tsiaras et al. 2019 - Nature Astronomy

The challenges…

1. Database
   - **Easy access to past observations**
   - **Multi-level products**
2. Follow-up
   - **Robust parameters to select targets and to schedule observations**
3. Pipeline
   - **Multiple instruments**
   - **Multiple approaches to de-trending**
   - **HPC capabilities**

Database


INSTRUMENTS
KEPLER/K2
SPITZER
TESS
JWST
HST
GROUND
EVENT
INTRUMENT INFO
TRANSIT INFO
RAW IMAGES
REDUCED / CALIBRARED IAGES
LIGHTCURVE
PLANETS
STELLAR PARAMETERS
PLANETARY PARAMETERS

Database: 600 known planets

HST
~600 transits
and growing…

Kepler/K2
~6000 transits

TESS
~6000 transits
and growing…

Ground
~4000 transits
and growing…

Follow-up: the ExoClock project

www.exoclock.space

Space
- Kepler/K2
- TESS
- HST
- Spitzer
- CHEOPS

Ground
- ExoClock Network
- ETD
- Exoplanet Watch
- TelescopeLive
- LCO

Literature

Reliable catalogue of transit parameters

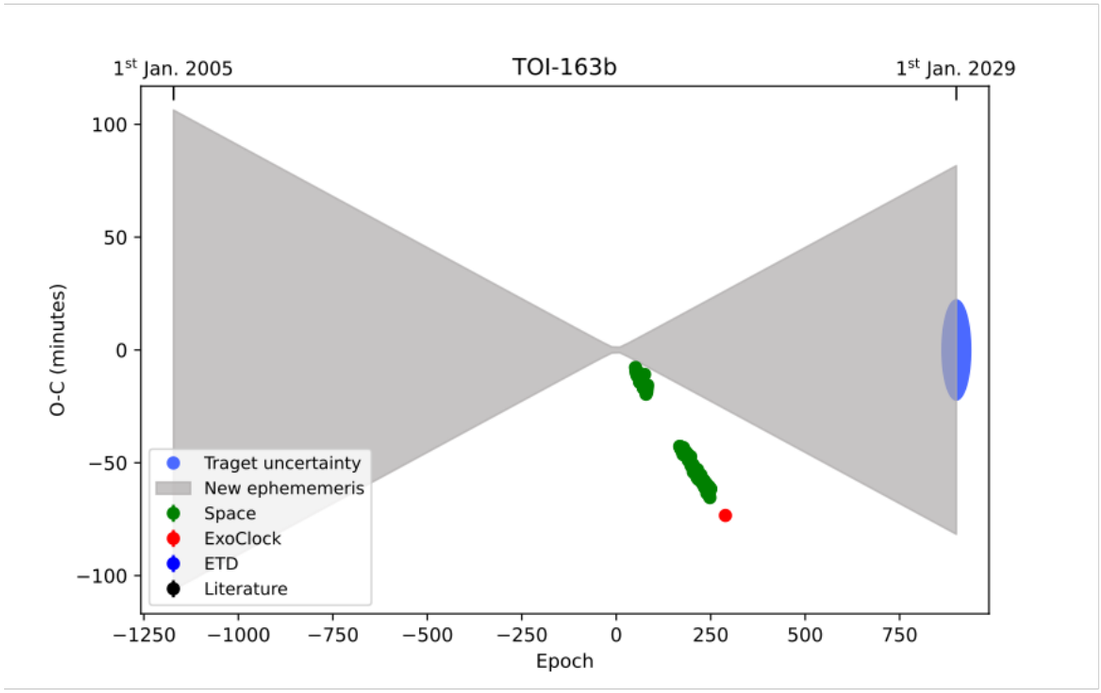
- Ephemeris
- Depth
- Duration

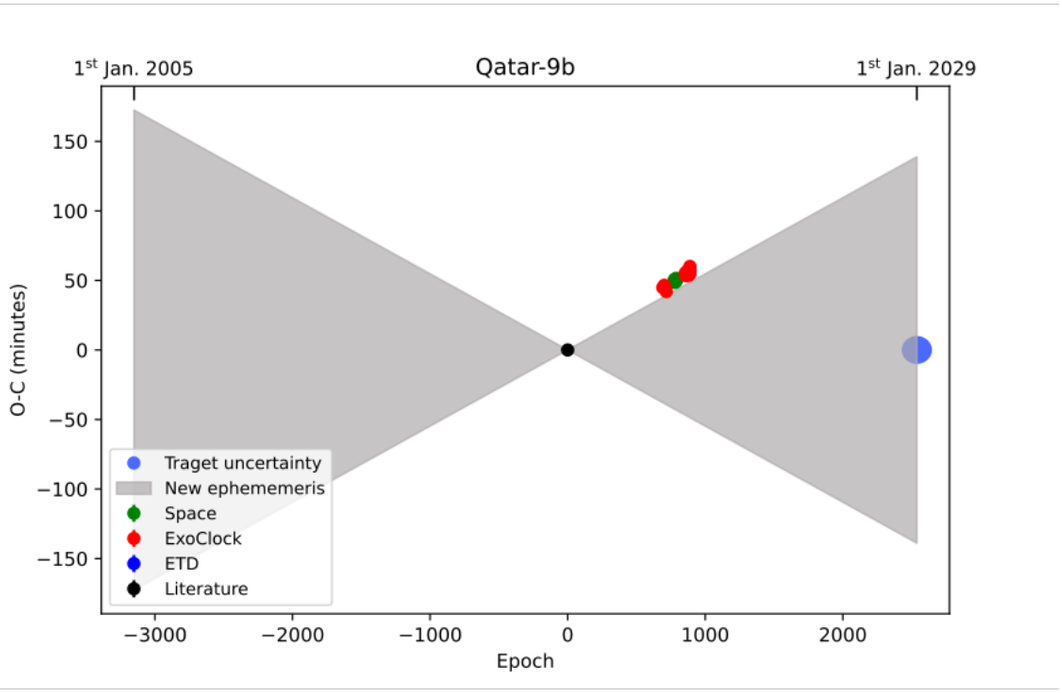
Kokori et al. 2021, 2022

Follow-up: fixing parameters…

Initial parameters
25% of the planets need to be fixed

Ephemerides
45% of the planets need to be fixed





Follow-up: the ExoClock project

500 participants from 35 countries

4000 observations for 350 planet

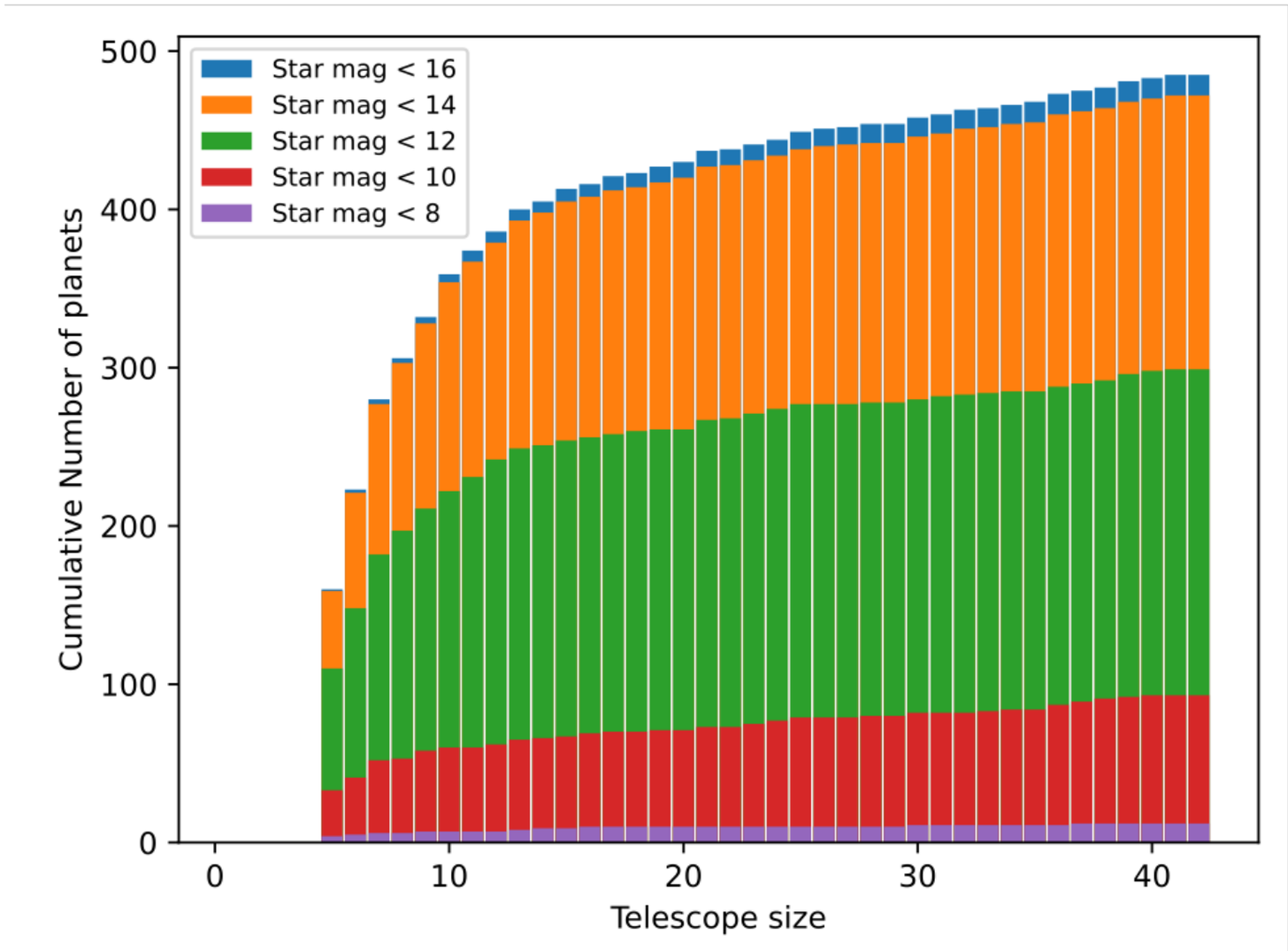
2 Data Releases

- Create a global community
- Involve and train citizens scientist
- Reach out many communities

Kokori et al. 2021, 2022

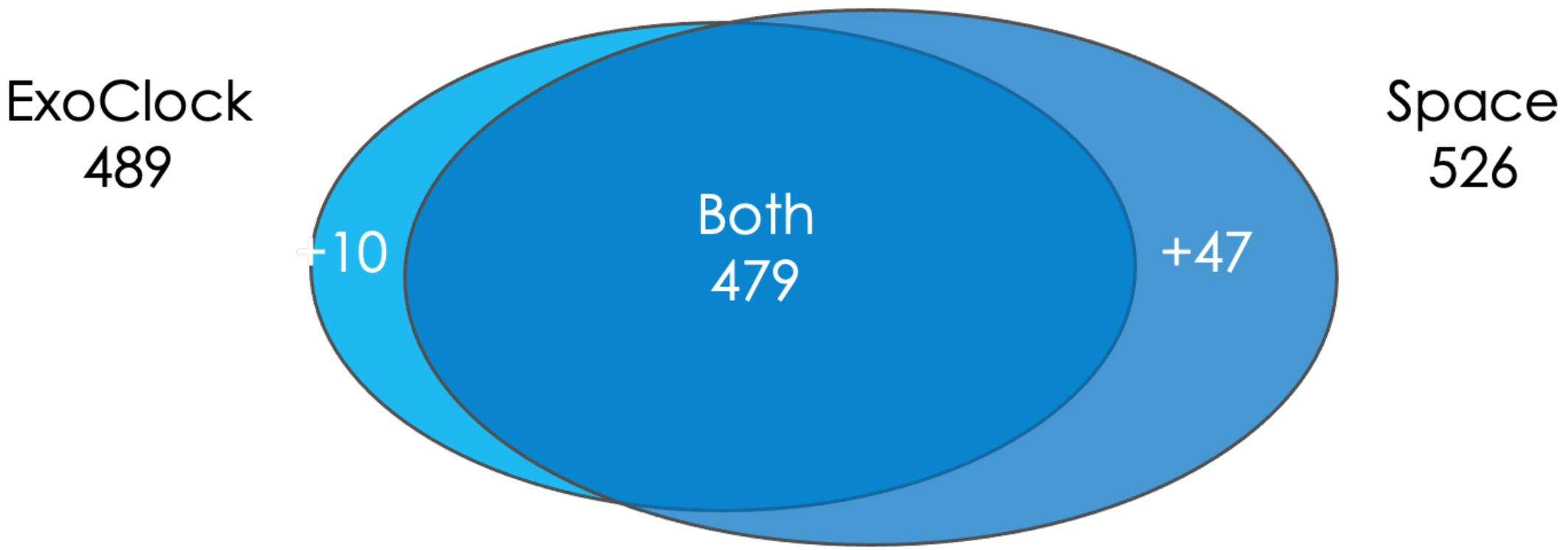
The power of small telescopes

70% of the targets can be observed by telescopes < 20 inches



Space and Ground

Target coverage - achievable – 94%
(ignoring TESS gaps or long-period planets)



Pipeline - multiple instruments

REDUCTION

- Non-linearity
- Bias
- Dark
- Flat
- Persistance
- Gain

BACKGROUND

- Sky
- Cosmic Rays

CALIBRATION

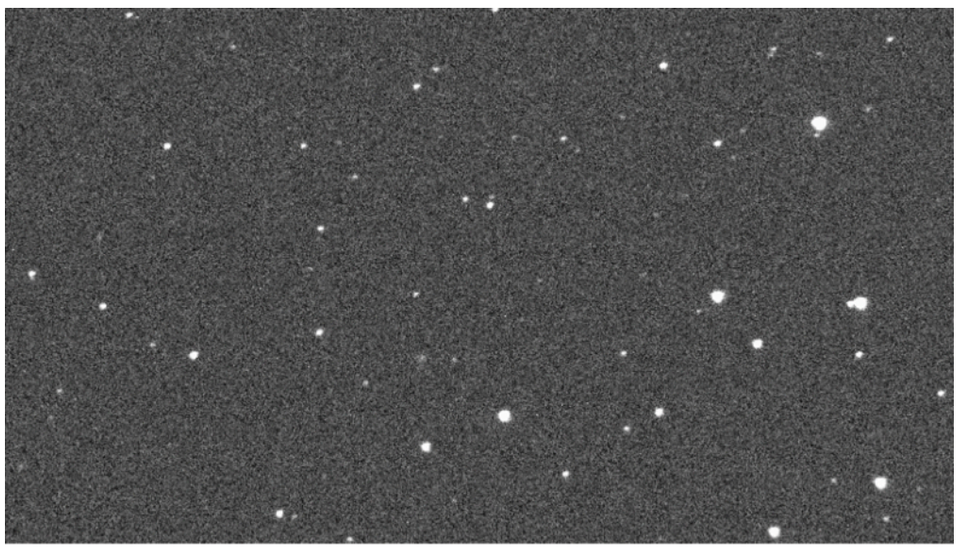
- Drifts
- Rotation

Extraction

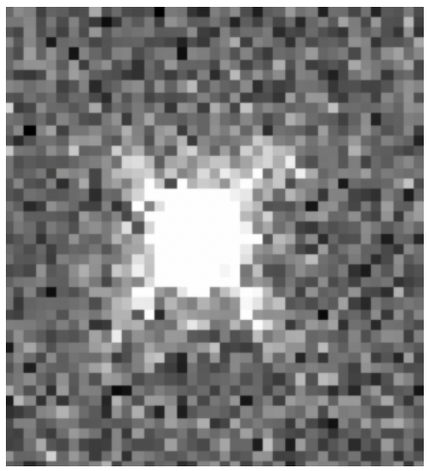
- Optimal Aperture
- Fractional pixels

Pipeline - multiple instruments

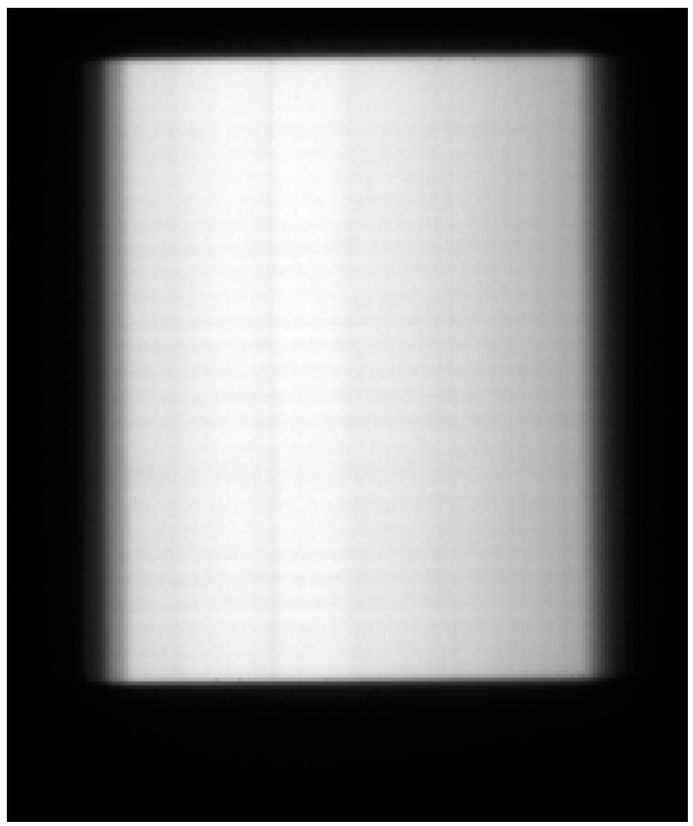
Ground telescope
Photometry



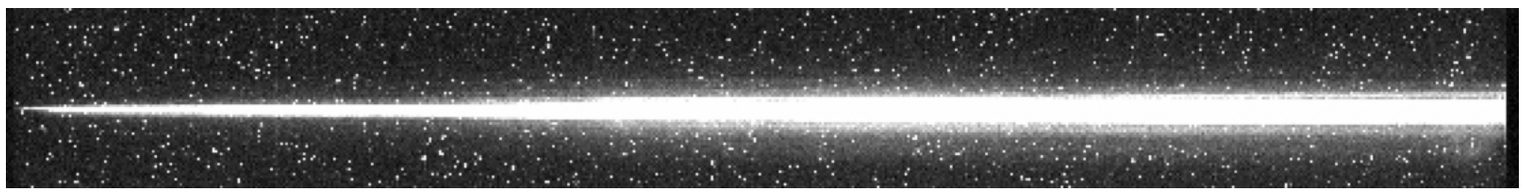
HST/WFC3
Photometry



HST/WFC3
Spectroscopy



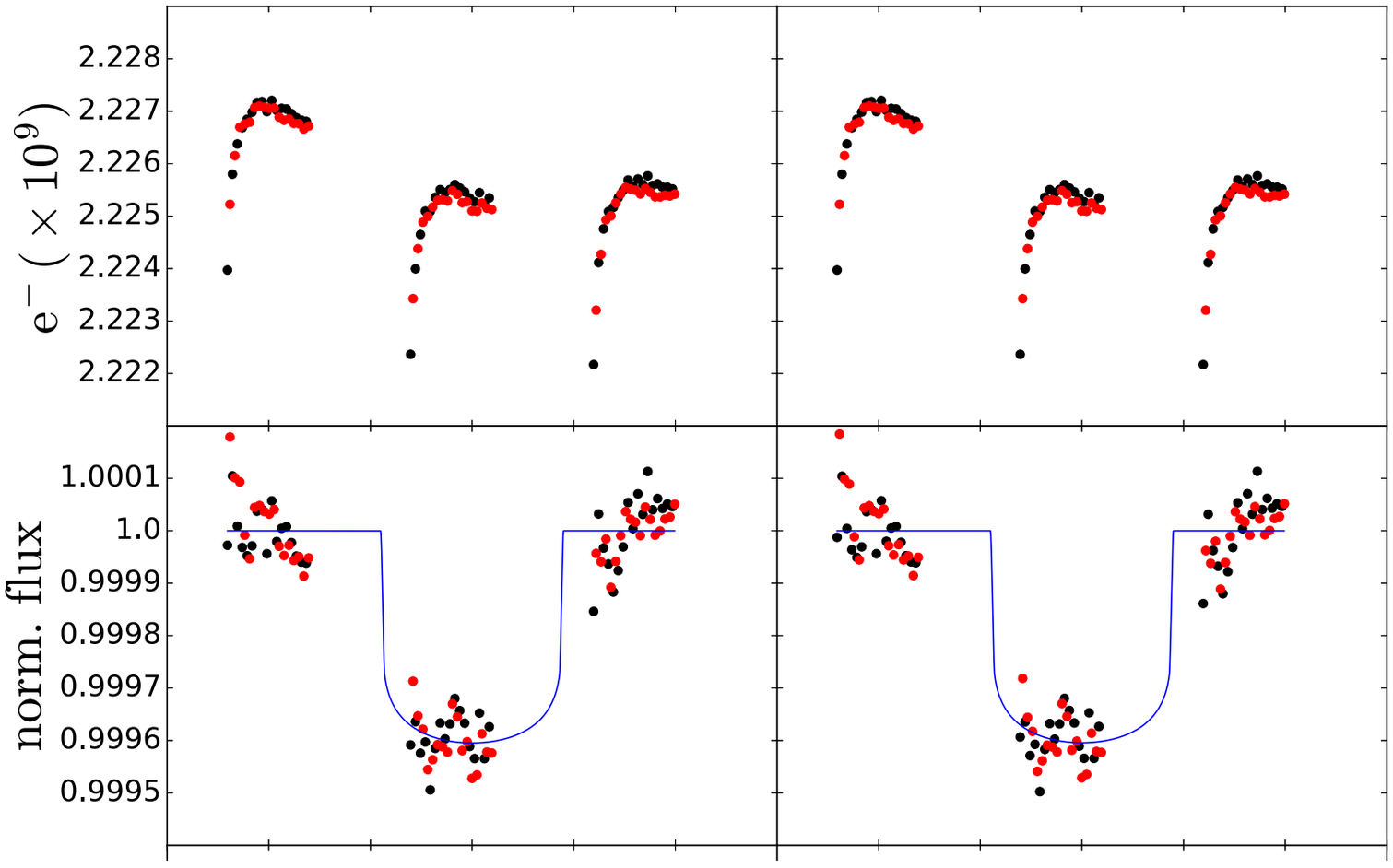
HST/STIS - Spectroscopy



ARIEL- Spectroscopy

Pipeline - multiple approaches to de-trending

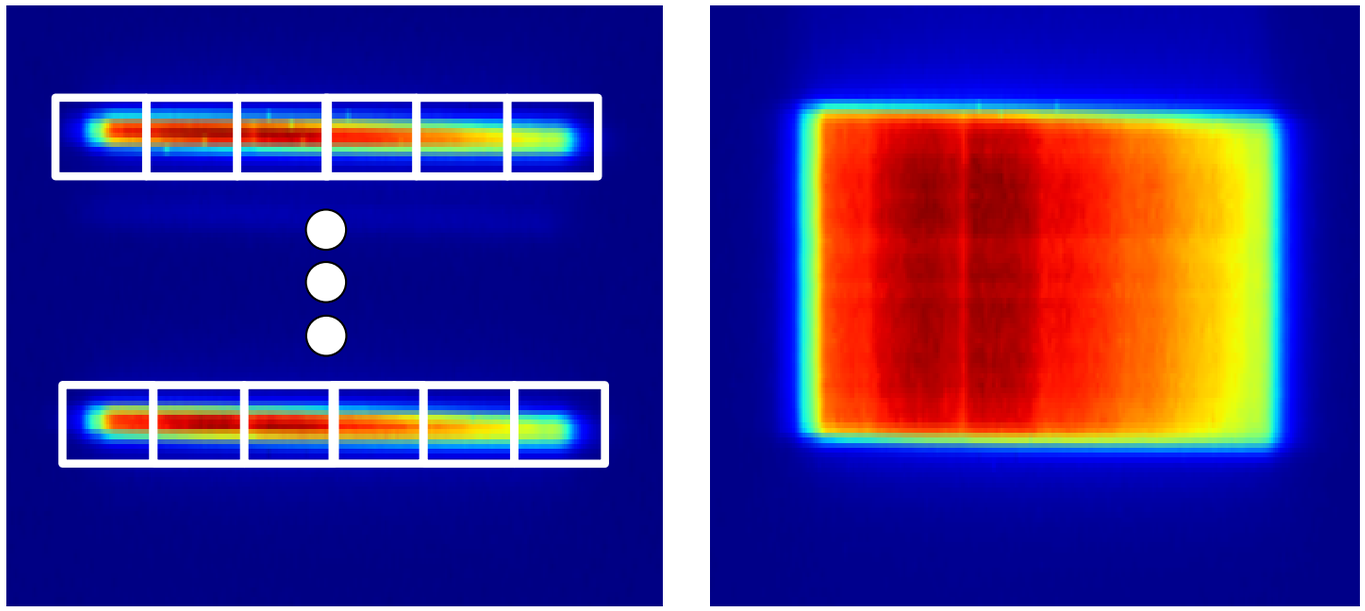
Classic parametrised de-trending on HST

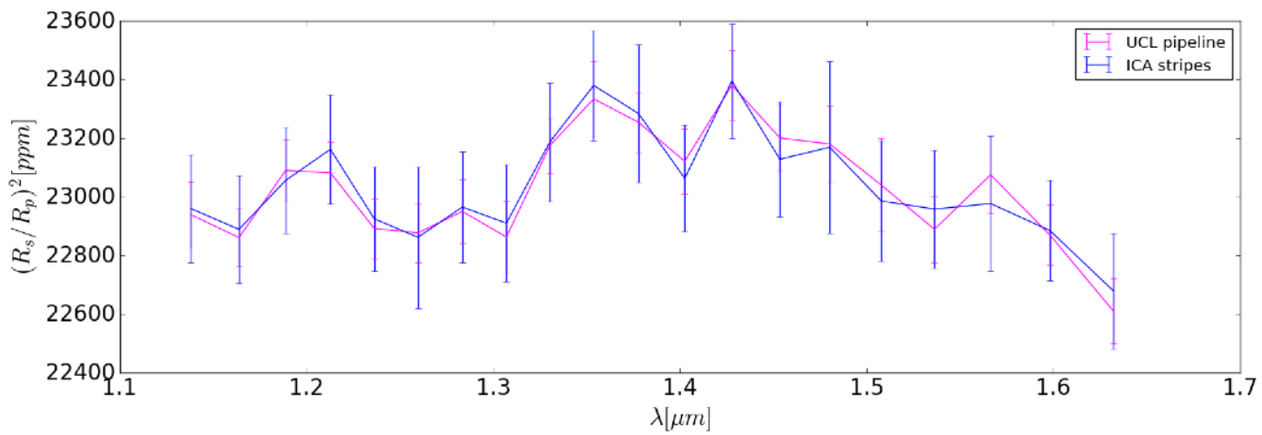


Tsiaras et al. 2016

Pipeline - multiple approaches to de-trending

ICA applied on HST

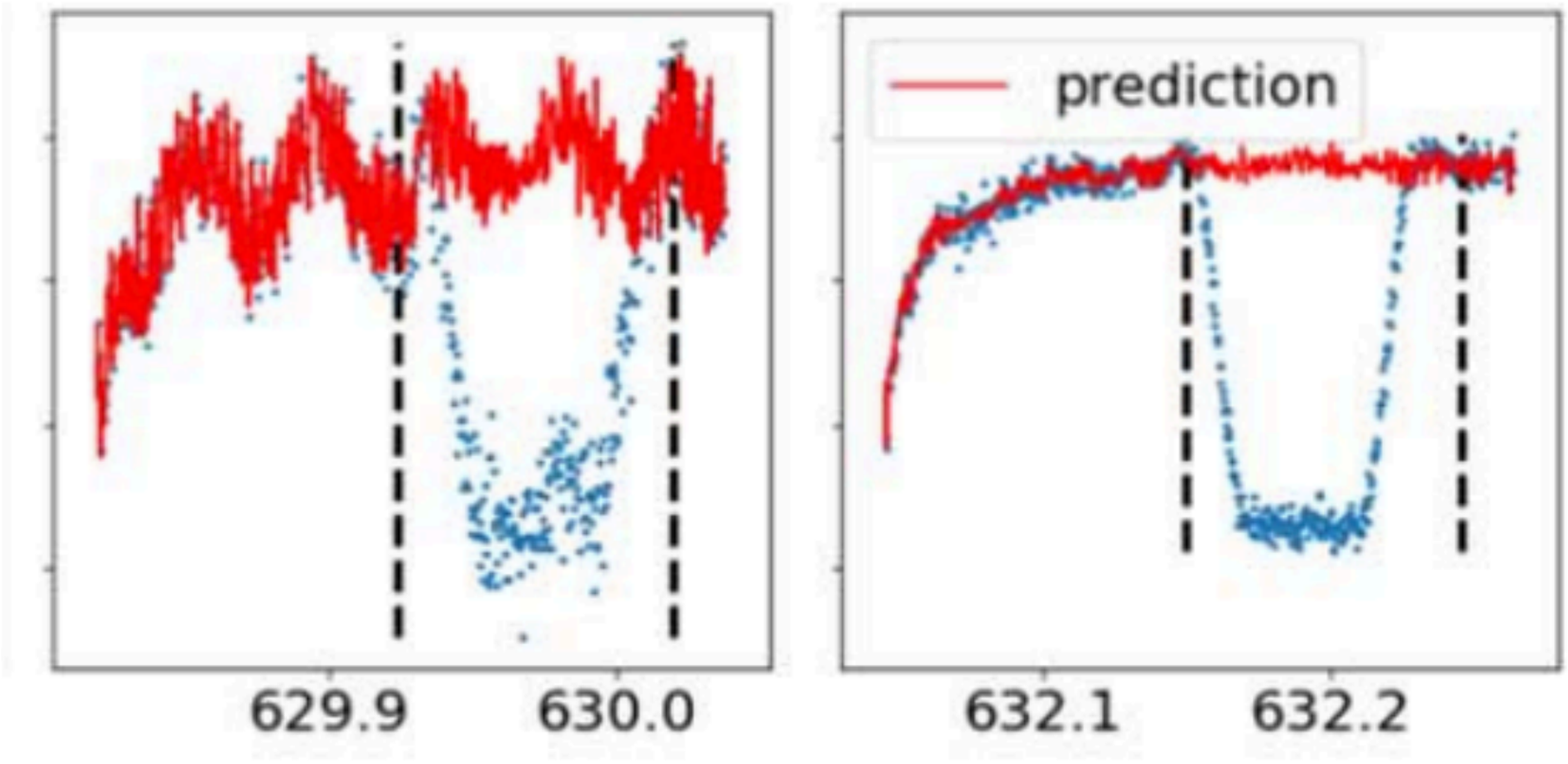




Damiano et al. 2017

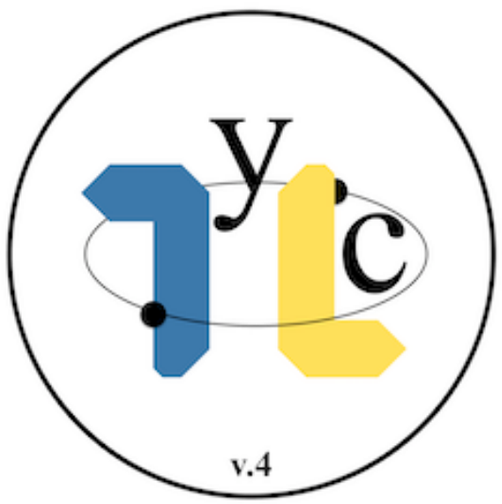
Pipeline - multiple approaches to de-trending

LSTM networks applied on Spitzer

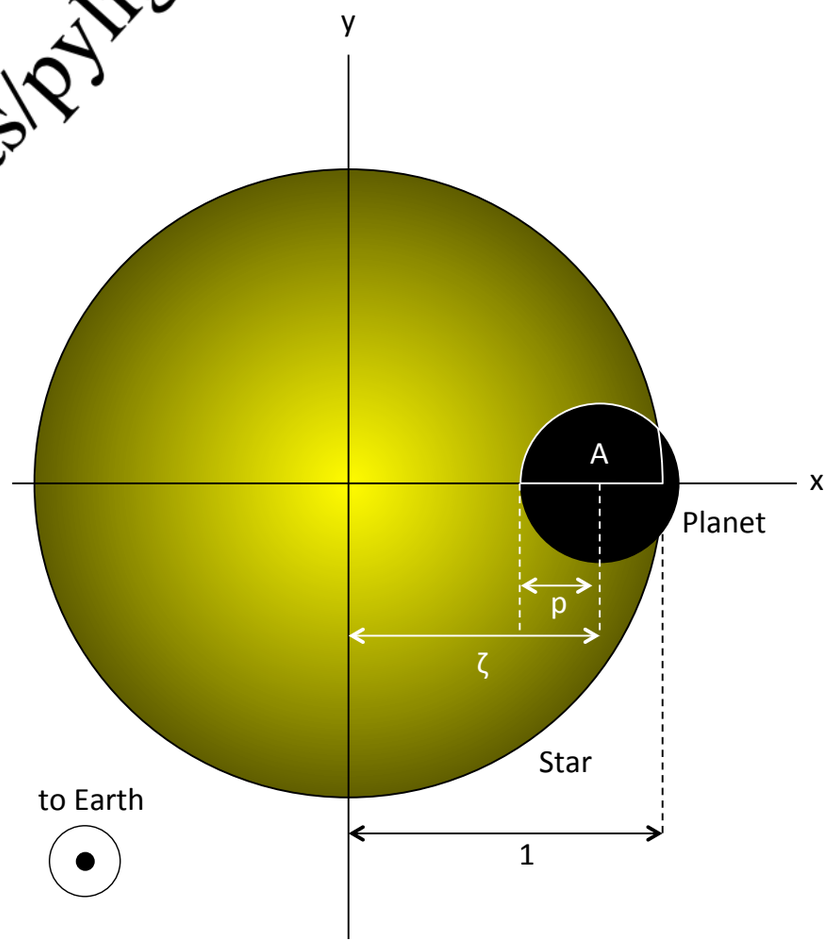


Morvan et al. 2020

Pipeline - HPC capabilities



check on GitHub
github.com/ucl-exoplanets/pylightcurve



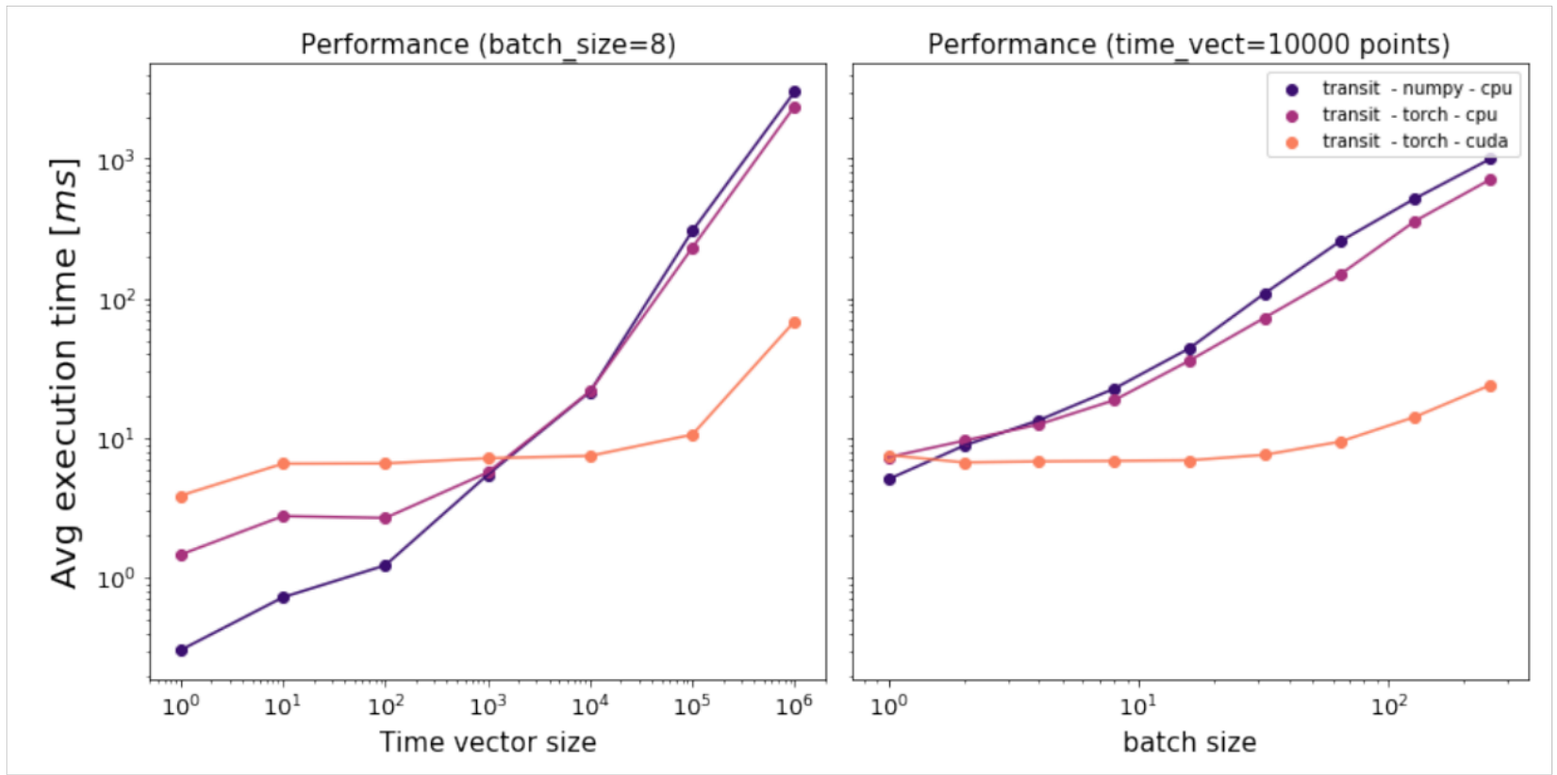
Comparison with Batman

Array-size	Speed increase
2500	x35
5000	x25
10000	x15
20000	x5

Pipeline - HPC capabilities

check on GitHub
github.com/ucl-exoplanets/pylightcurve-torch

- GPU compatibility
- Real large-scale applications
- Deep learning applications



PyLIghtcurve-torch package: Morvan+ 2020

Population studies:
a **simple** concept, a **challenging** plan

1. Prepare an **open, multi-level database**.

2. **Follow up** the targets and **fix the parameters**.

3. Prepare an **open, stand-alone data analysis framework**.