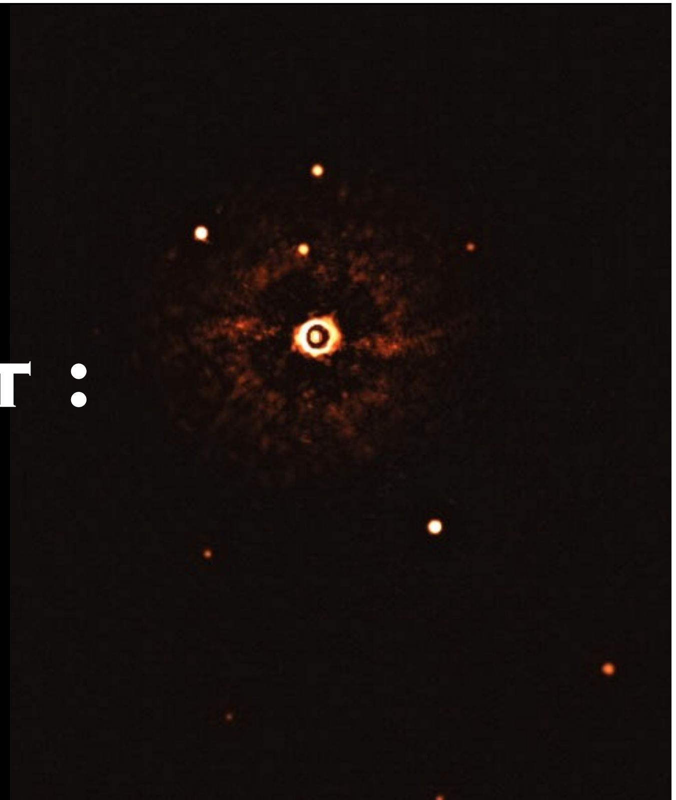
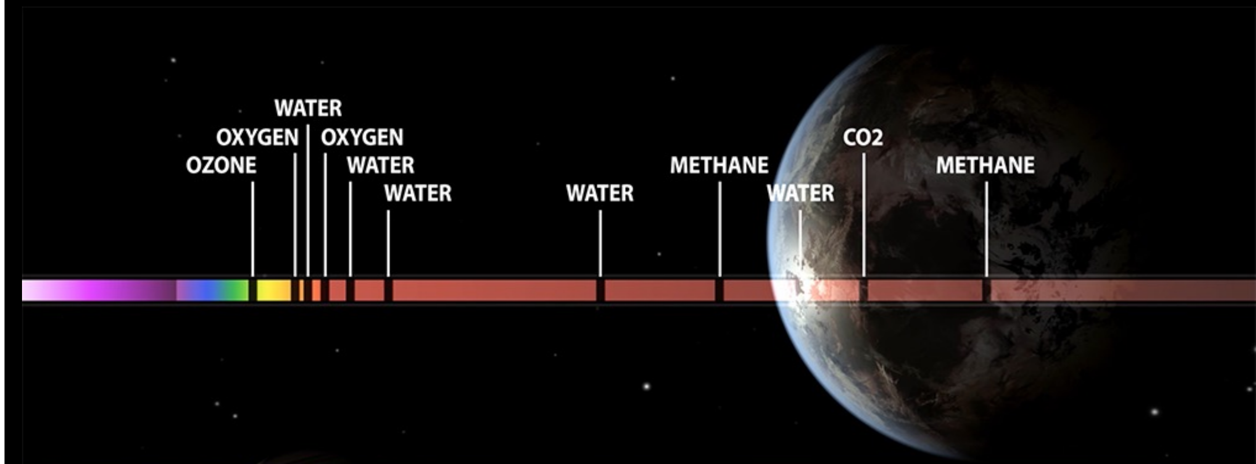
Planets in High-contrast : Detection and Characterisation

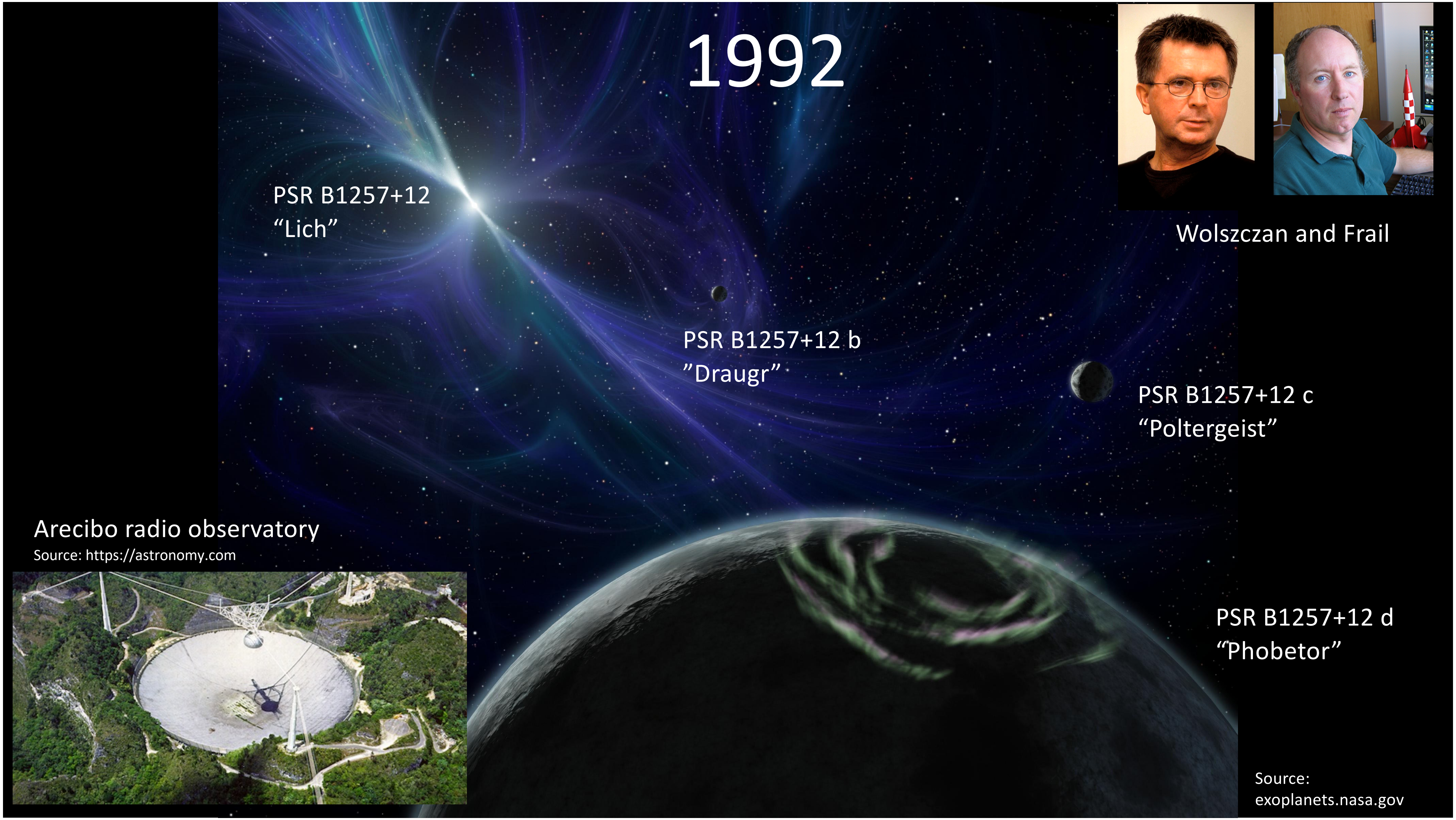




Gayathri Viswanath
PhD candidate
Department of Astronomy, Stockholm University


I'm from here!
KASARAGOD
KANNUR
WAYANAD
KOZHIKODE
MALAPPURAM
PALAKKAD
THRISSUR
ERNAKULAM
IDUKKI
KOTTAYAM
ALAPPUZHA
PATHANAMTHITTA
KOLLAM
THIRUVANANTHAPURAM
Kerala


A battle beyond time... beyond space.
BATTLE BEYOND THE STARS
40 STAR WARS
THE HITCHHIKER'S GUIDE TO THE GALAXY
DUNE
A Place Beyond Your Dreams. A Movie Beyond Your Imagination.
Journey with Wolff and Niki, an interstellar adventurer and a young rebel.
On a mission to rescue three stranded women from a planet no one has warned them about.
Because no one has ever returned.
SPACEHUNTER ADVENTURES IN THE FORBIDDEN ZONE IN 3-D
The first movie that puts you in outerspace.
A STEVEN SPIELBERG FILM
E.T. THE EXTRA-TERRESTRIAL IN HIS ADVENTURE ON EARTH
A STEVEN SPIELBERG FILM E.T. THE EXTRA-TERRESTRIAL
DEE WALLACE · PETER COYOTE · HENRY THOMAS AS ELLIOTT · MUSIC BY JOHN
WRITTEN BY MELISSA MATHISON · PRODUCED BY STEVEN SPIELBERG & KATHLEEN
DIRECTED BY STEVEN SPIELBERG · A UNIVERSAL PICTURE
STAR WARS
A NEW HOPE
At the end of the universe lies the beginning of vengeance.
STAR TREK II THE WRATH OF KHAN

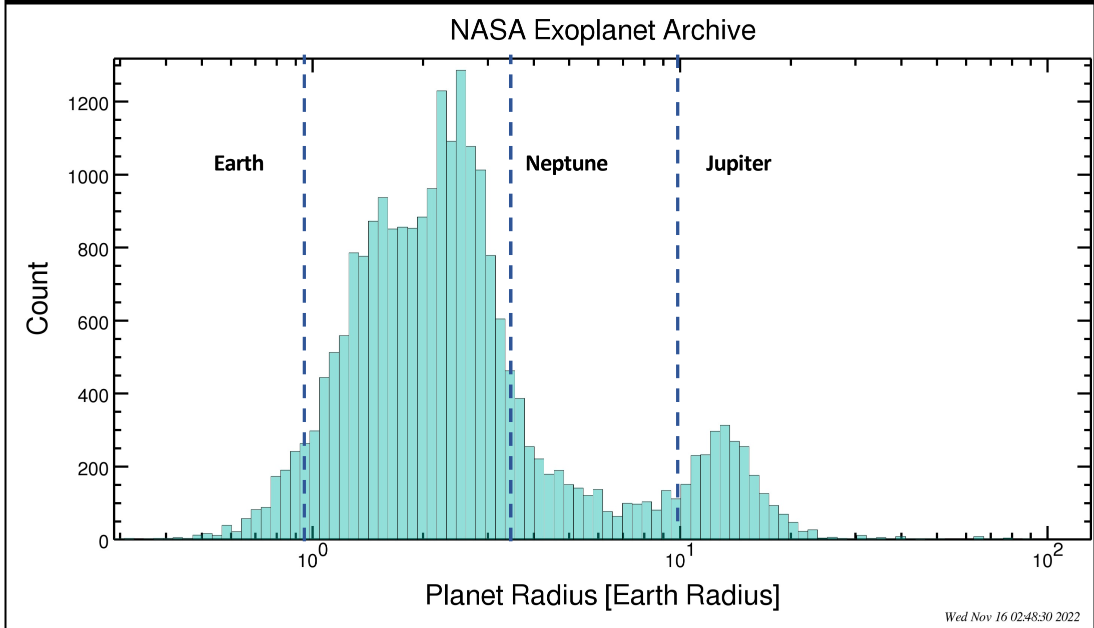

1992
PSR B1257+12
“Lich”
Wolszczan and Frail
PSR B1257+12 b
”Draugr”
PSR B1257+12 c
“Poltergeist”
Arecibo radio observatory
Source: https://astronomy.com
PSR B1257+12 d
“Phobetor”
Source:
exoplanets.nasa.gov

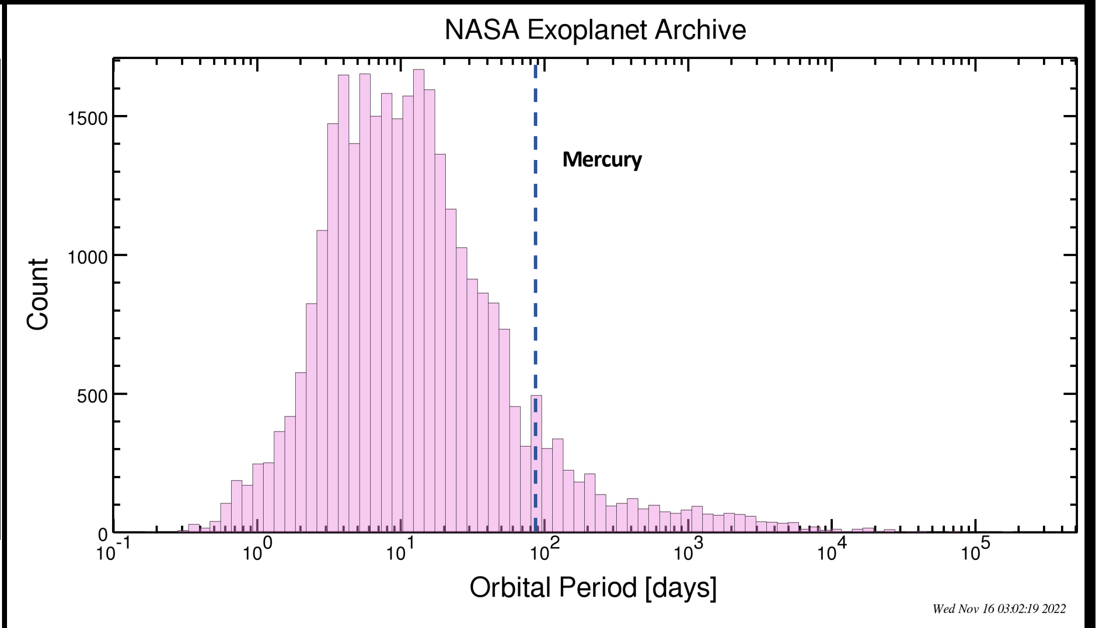
5,206 confirmed exoplanets

3,894 host stars

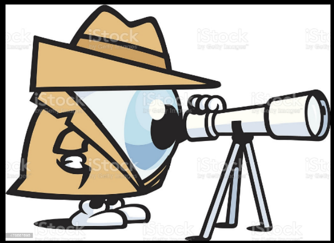
869 multi-planet systems

Planets in multi-star systems (upto 4 stars!)





Source: Generated via the Confirmed Planets Plotting Tool in NASA Exoplanet Archive



How do we look for exoplanets?

Radial Velocity

Astrometry

Transit detection

Gravitational microlensing

Pulsar timing variation

Direct imaging

Orbital brightness modulations

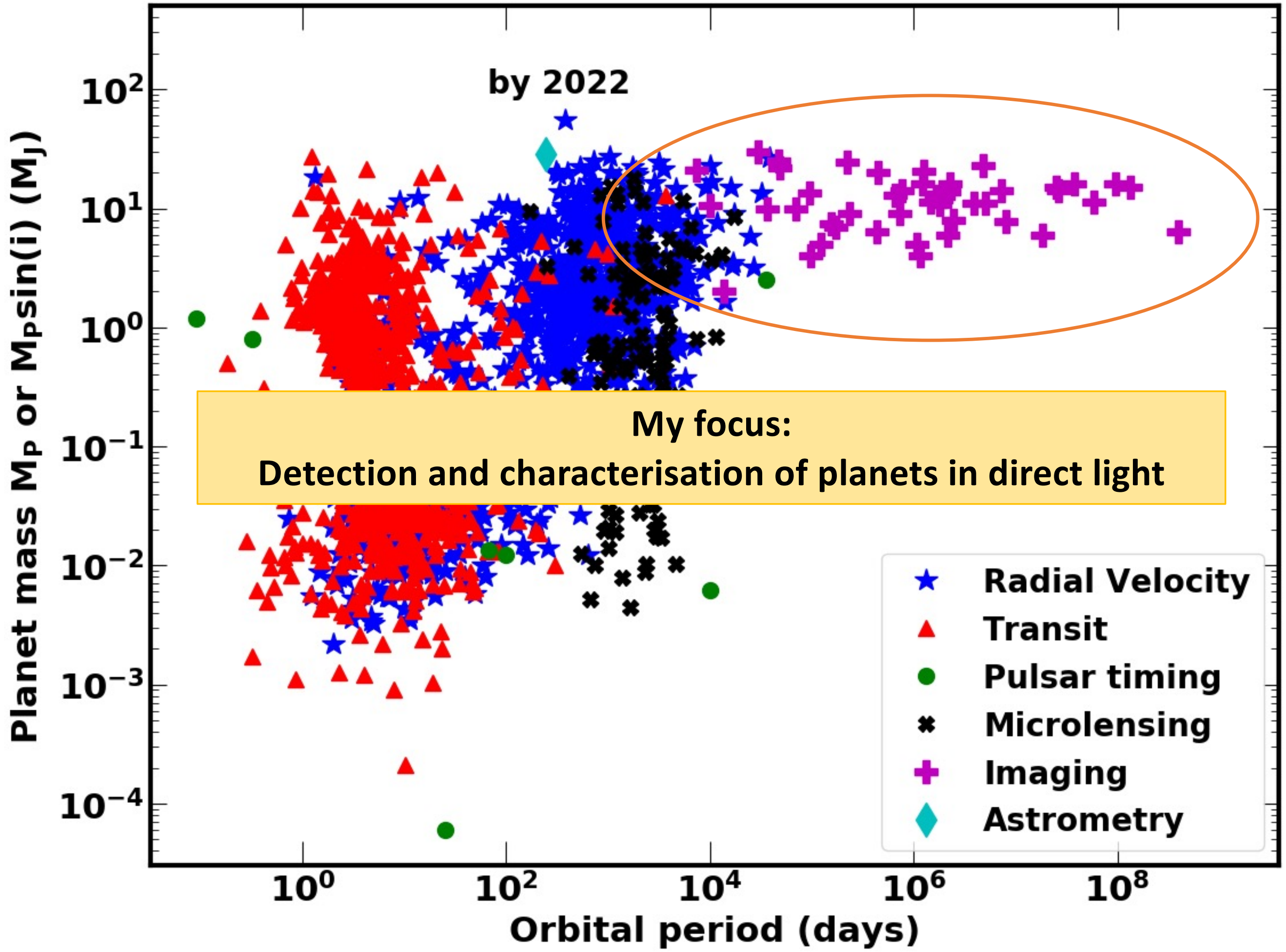
Eclipse timing variations

Disk Kinematics

Direct vs. Indirect techniques

- Limited information from Indirect detection methods like RV, Transits etc.
- Direct imaging: photons from the planet
- Provides abundance of information – orbit, brightness, mass, atmospheric properties
- Provides concrete, independent evidence
- Targets a unique population

Ideal Targets: giant planets in wide orbits



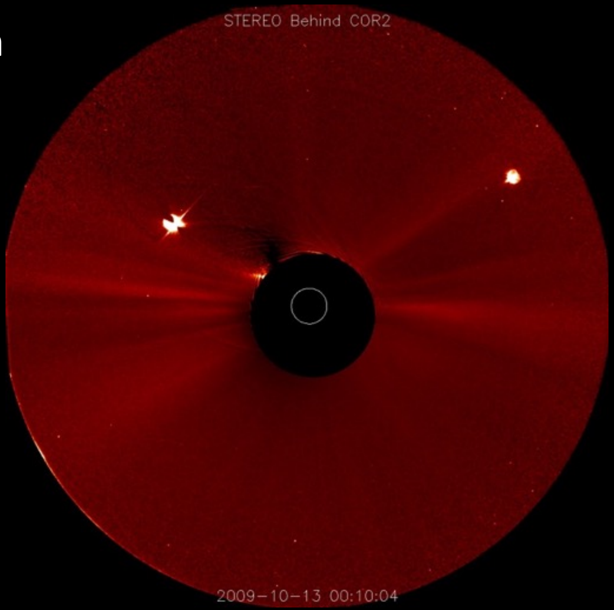
Based on data from NASA Exoplanet Archive, as on 29 March, 2022

High Contrast Imaging (HCI)

- Concept: snapshot of the planet in its orbit
- Main challenge : Planet is too faint compared to star
- What do we want? Improve Contrast! (F_P/F_s)
- How?

Say Cheese!

Block out the problem



Coronagraphy
Source: NASA/STEREO

High Contrast Imaging (HCI)

Correct for atmospheric seeing: Adaptive Optics

Source: Keck observatory/ Sean Goebel

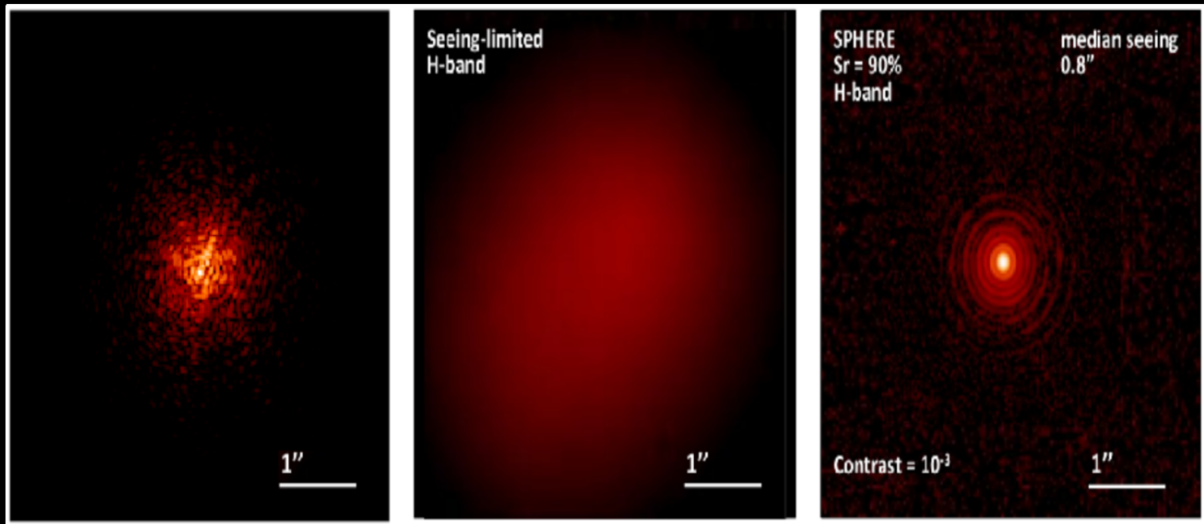


Image of a point source taken with VLT H band. Left: Short exposure without AO. Middle: long exposure without AO. Right: Long exposure with SPHERE's SAXO extreme AO correction.
Source: Cantalloube (2016)

High Contrast Imaging (HCI)

Code better!

Advanced post processing techniques

Angular Differential Imaging (ADI

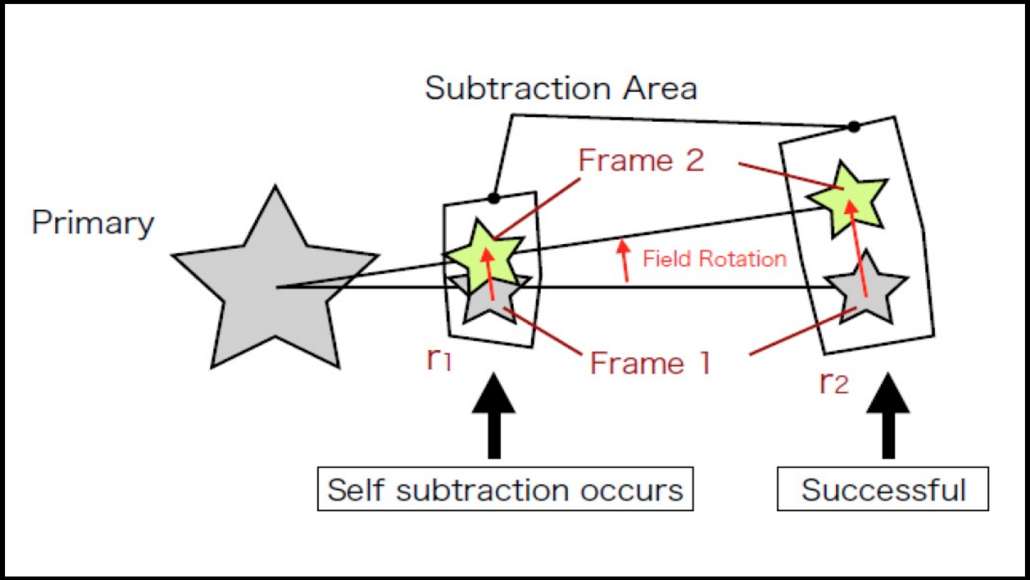
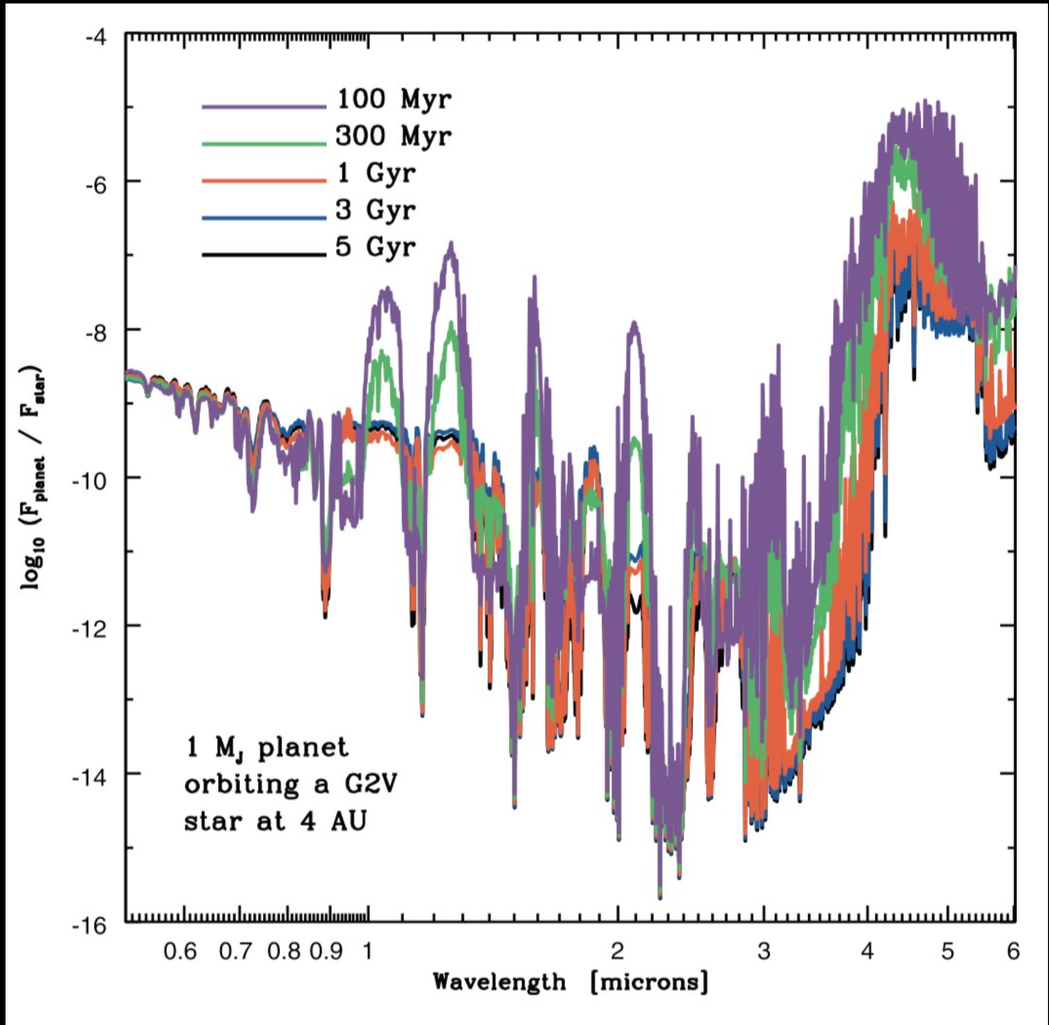
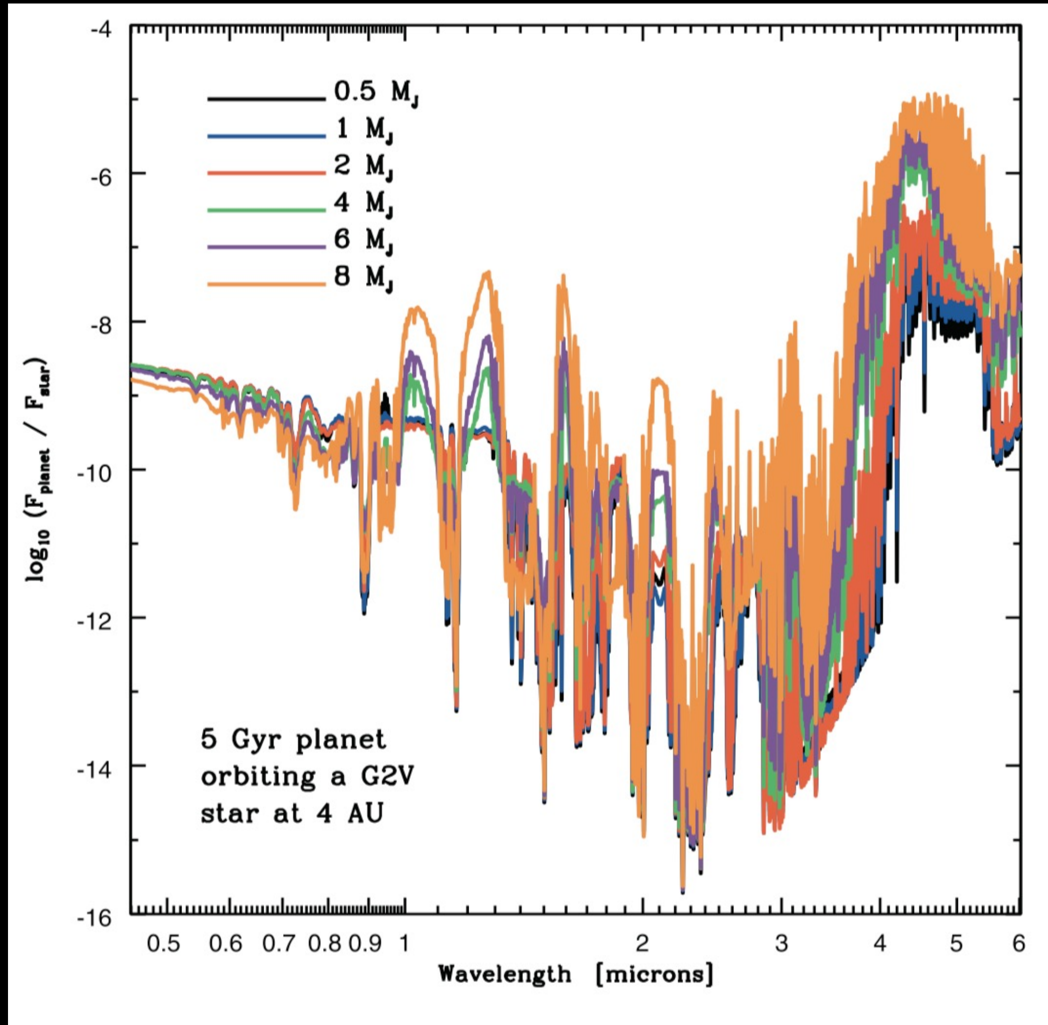


Illustration of using field rotation of companion to average out its signal.

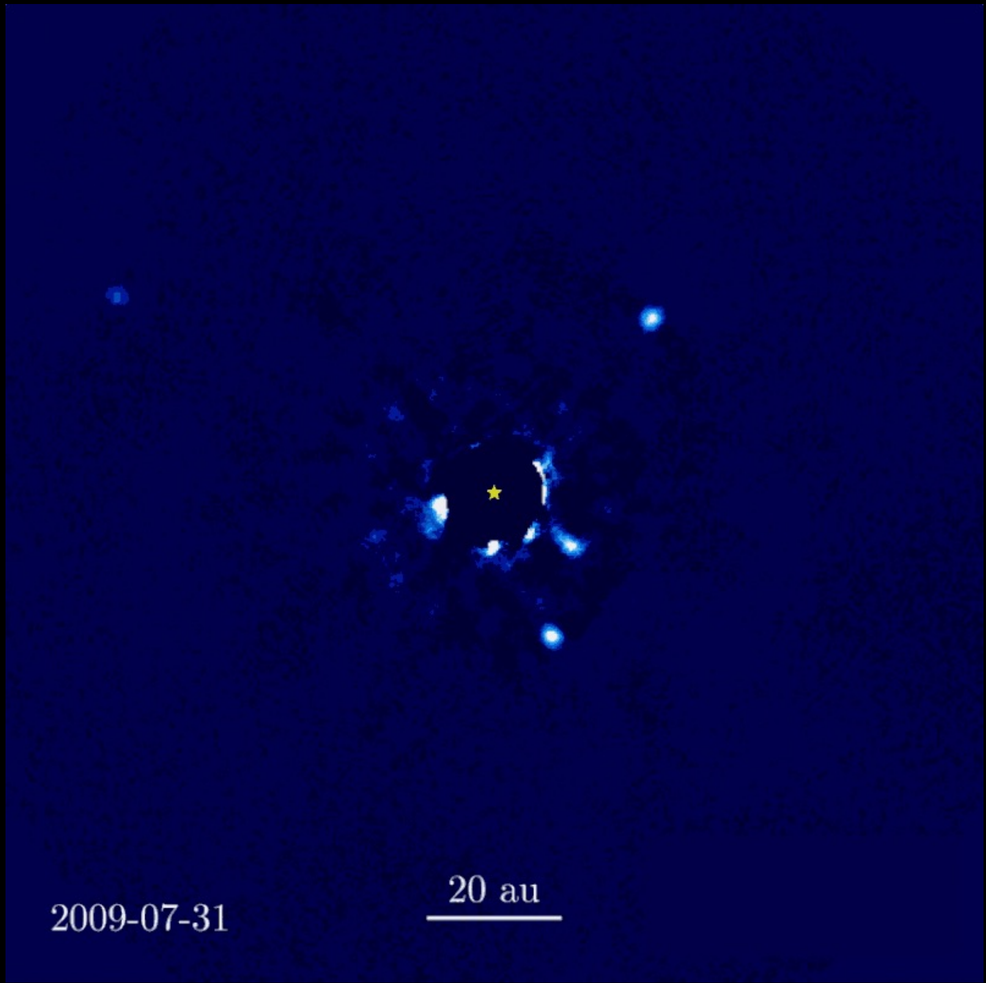
Credit: Samland (2019)





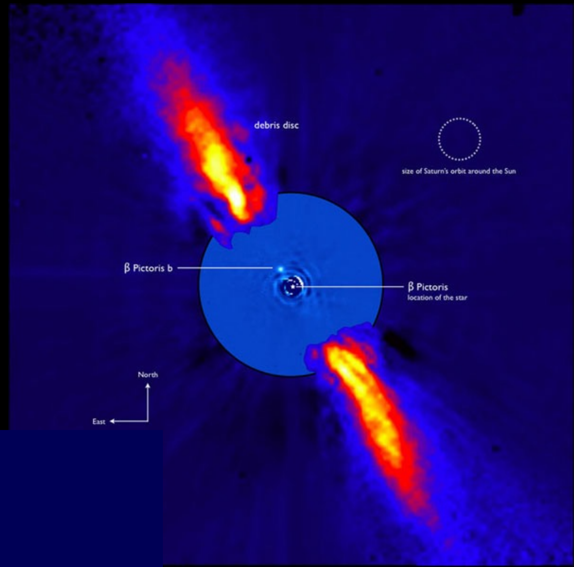
Source: Burrows et al. (2004)

HR 8799 system

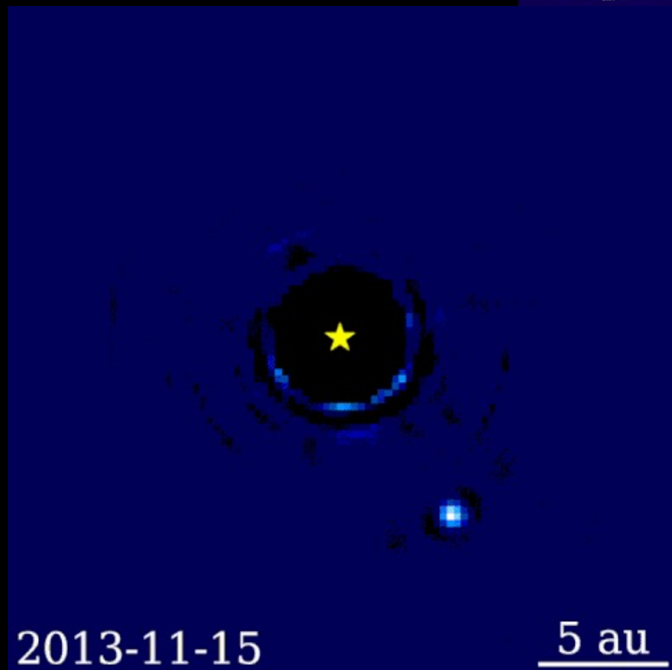


Video: Jason Wang (Caltech) / Christian Marois (NRC Herzberg)

Beta Pictoris b



Source: ESO/ A-M. Lagrange et al./ Sky & Telescope.

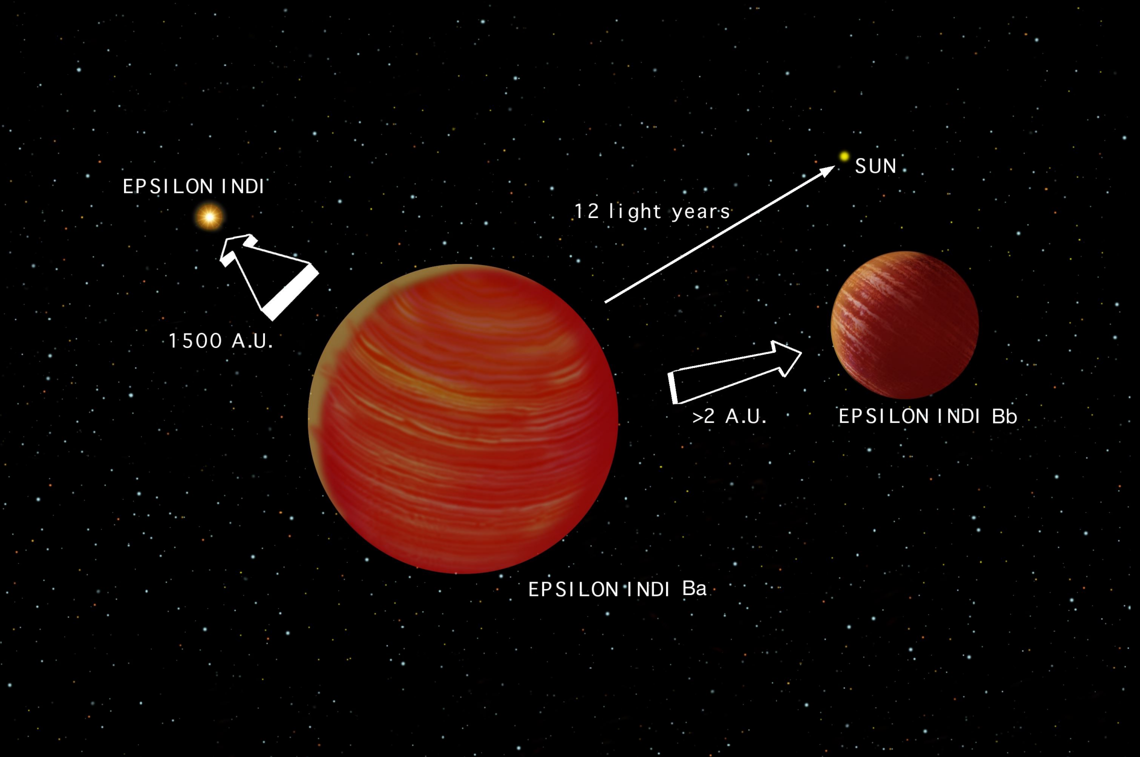


Source: https://jasonwang.space/orbits.html

High-contrast investigation of ϵ Indi

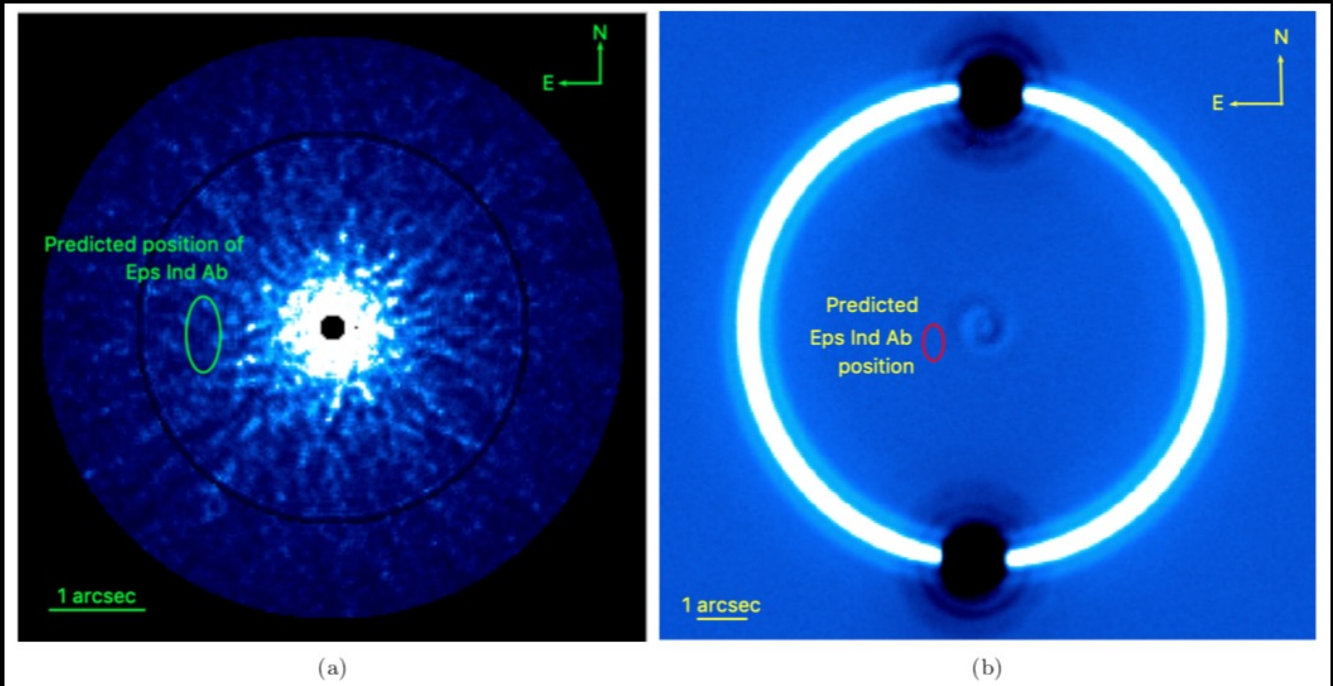
- K5 type star ε Ind A (0.76 $M_\odot$) 3.6 pc away
- Visible to naked eye (V = 4.7)
- Binary companions ε Ind Ba, Bb – both T-type dwarfs ~50 M_J each discovered in 2005
- Long term RV signals from ε Ind A point to a planetary mass companion
- Detected by RV and astrometry (Feng et al. 2019)

$$M_P = 3.25^{+0.39}_{-0.65}\, M_J \;;\; a = 11.55^{+0.98}_{-0.86}\; au$$



Artist's conception of the ϵ Indi system showing ϵ Indi A and its brown-dwarf binary companions.
Credit: Wikipedia

High-contrast investigation of of ϵ Indi

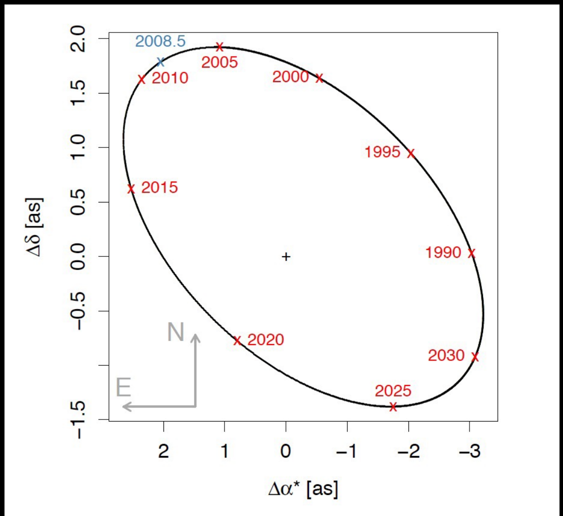


(a) Final detection probability map from NaCo reduced data, and
(b) Final reduced image from NEAR
Source: Viswanath et al. (2021)

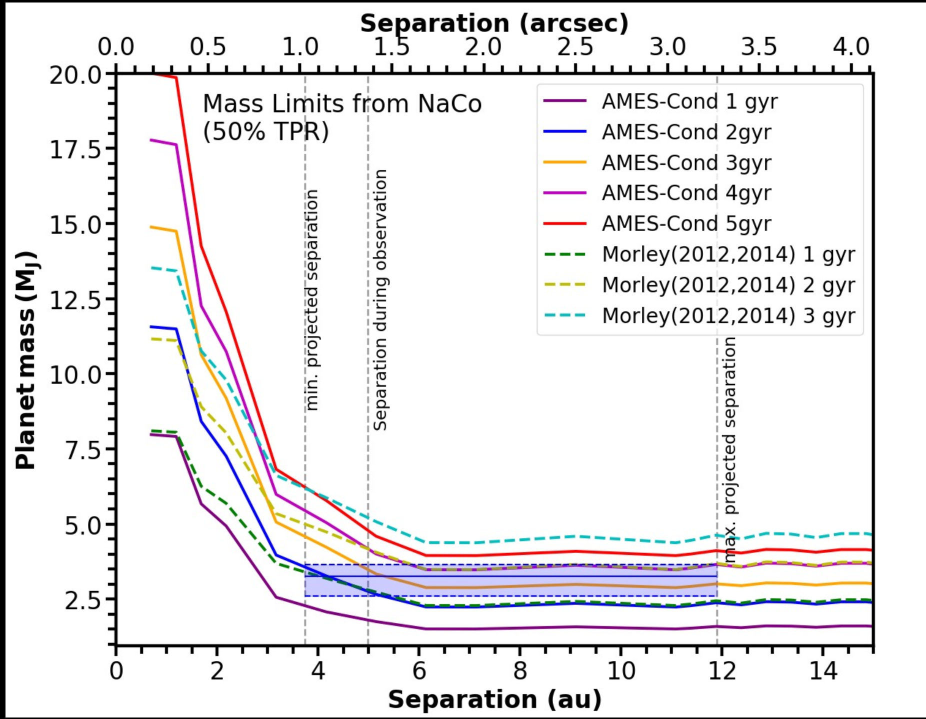
- Deep AO imaging observations with 3.8 μm L′ band of NaCo (Oct-Nov 2018) and 10-12.5 μm NEAR band (Sep 2019) at VLT
- Combined data covers near- to mid- infrared, where older/colder planets peak in thermal emission.
- No companions were detected in both the images.

High-contrast investigation of of ϵ Indi

- Arrived at uprecendented sensitivities close to the bright star (200-300 K)
- From the non-detection at 1.37”, between the two models, we place a lower age limit of 2 Gyr on the system – consistent with the literature
- Projected separation looks more favourable in coming years – possible detection with ERIS, MIRI or METIS



Source: Feng et al. (2019)



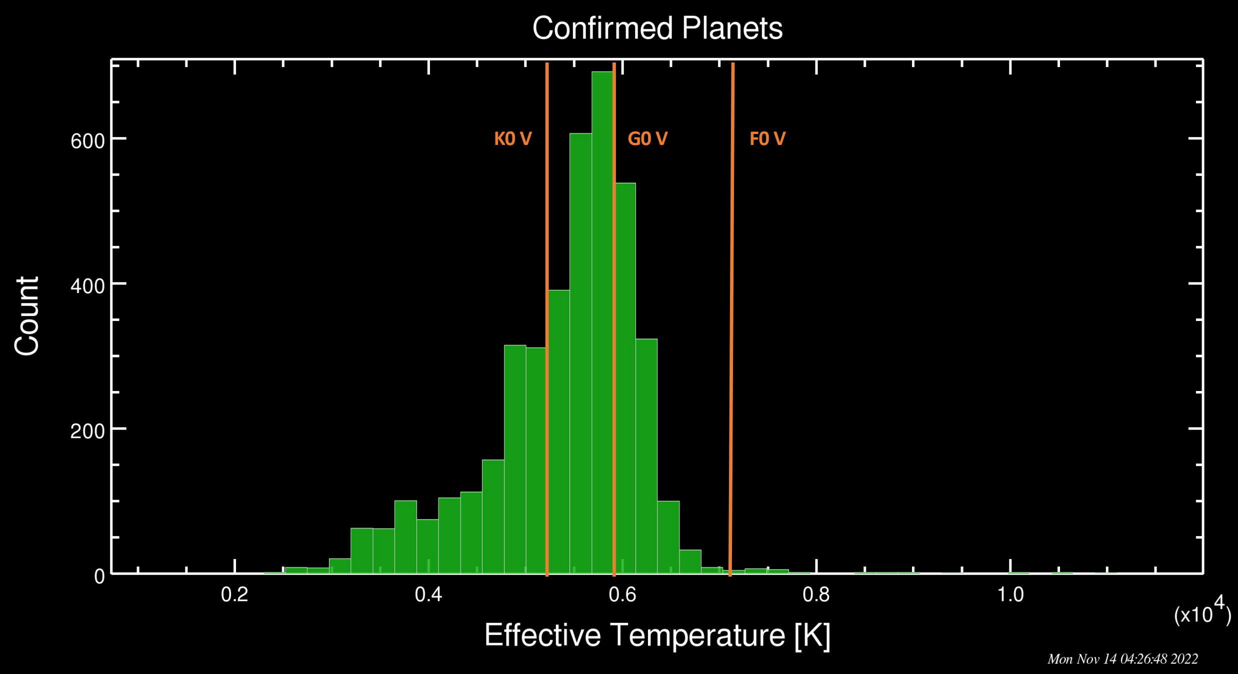
Mass detection limits derived from the contrast curves from NaCo data, using AMES-Cond and Morley (2012, 2014) atmospheric models.
Source: Viswanath et al. (2021)

BEAST detection of companions around HIP 81208

- Substellar companion demographics as a function of stellar mass significant
- Most host stars are of F-G-K type
- The B-star Exoplanet Abundance Study (BEAST) Janson et al. (2019) is a dedicated HCI survey around 85 B-type stars with SPHERE at VLT; Extreme AO and coronagraphy
- Ongoing since 2019;

Janson et al. (2021b)

Squicciarini et al. (2022)



Source: Generated via the Confirmed Planets Plotting Tool in NASA Exoplanet Archive

BEAST detection of companions around HIP 81208

Target HIP 81208

Region	UCL of Sco-Cen
Distance	~ 148 pc
Stellar type	B9V (8383 K)
Mass	2.8 $M_{\odot}$
Age	17 Myr

No known binary companion ;
Likely no disk from the SED

BEAST detection of companions around HIP 81208

- Observed twice with BEAST, in Aug 2019 and April 2022
- Low resolution YJH spectroscopy with IFS
- Imaging data in K_1, K_2 (2.1, 2.25 microns) band with IRDIS
- Total integration time 0.85 hr
- Data reduced with BEAST's Data Centre software (Delorme et al. 2017); ADI based reduction for IRDIS and PCA-based for IFS
- An inner brown dwarf companion (~70 M_J) at 0.32″ in both IFS and IRDIS images.
- An outer stellar mass companion (~0.14 $M_\odot$) at ~1.5″ revealed in the IRDIS images.

BEAST detection of companions around HIP 81208

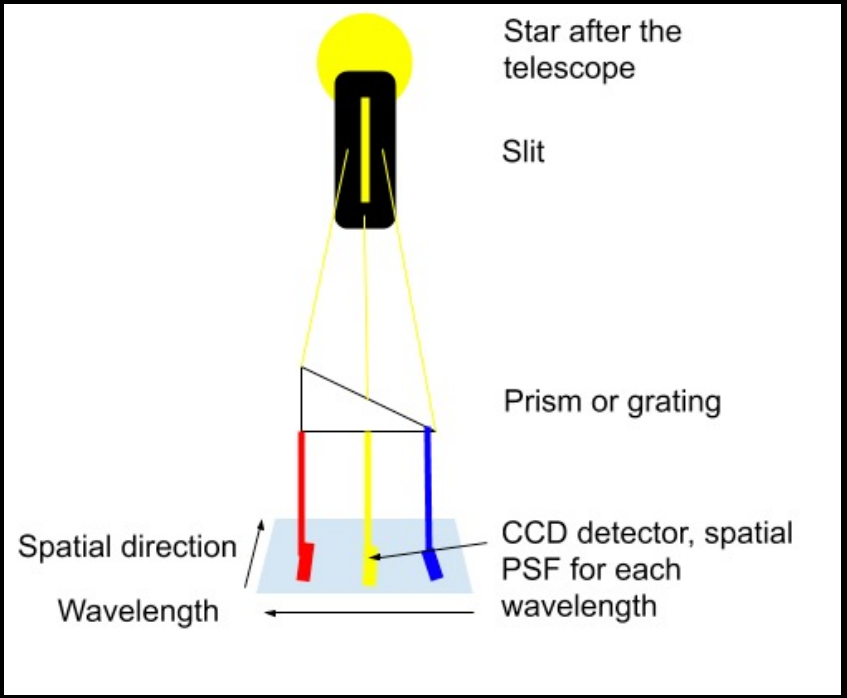
- IFS Spectrum analysis
- Candidate mass characterisation
- Orbital characterisation between the two epochs
- Viswanath et al. (2022) in prep….

*** Image removed since the paper is under preparation ***

SPHERE IRDIS K band image of HIP 81208 from 2019 epoch. Source: Viswanath et al. (2022, in prep)

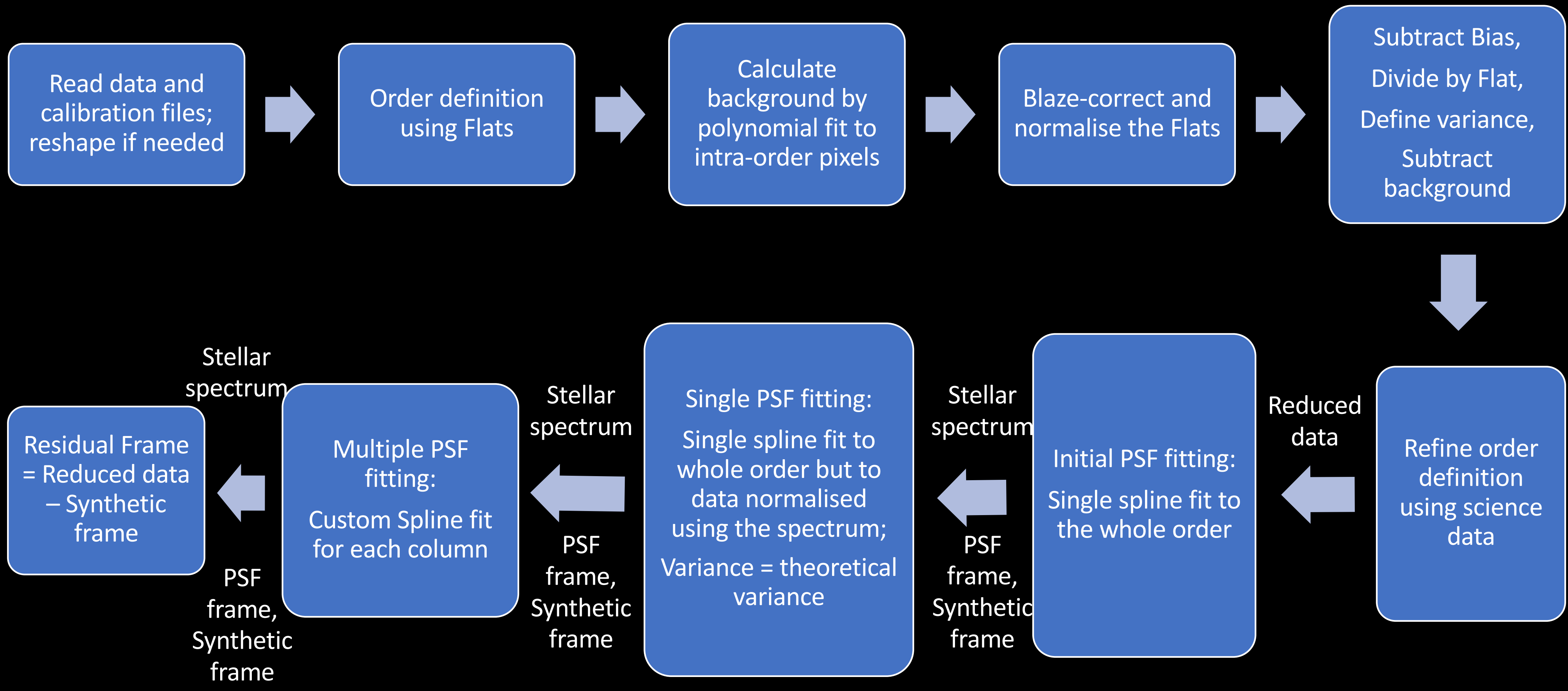
High Dispersion Spectroscopy (HDS) with HCI

- Techniques to study exoplanet atmospheres ; direct imaging and transit spectroscopy (indirect)
- Need high resolution (>100,000) to separate planet lines from stellar - HDS
- Challenge same as before – planet is much fainter than star
- Solution: Combine HDS with HCI! Outcome is a 2D spectrum
- Need for efficient spectral extraction algorithms
- In 2019, Alexis Brandeker developed an optimal spectral extraction code for such high-contrast spectroscopy for Ultra Violet Echelle Spectrograph (UVES)



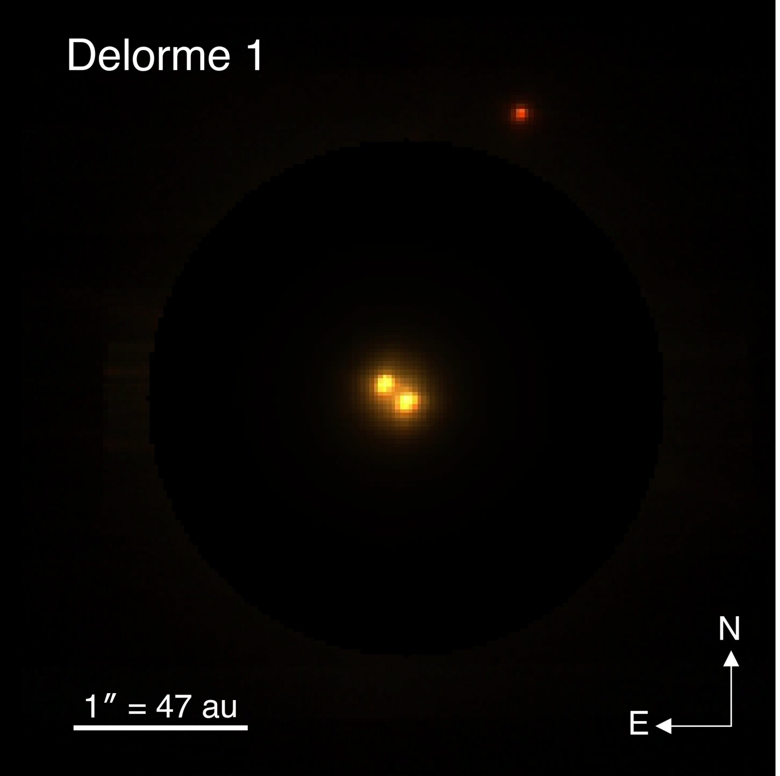
Schematic structure of a high-dispersion spectrograph. Source: E. Taillanter (2019)

Optimal Spectral Extraction: A Rough Pipeline Outline!



Near-UV emission from Delorme 1 (AB)b

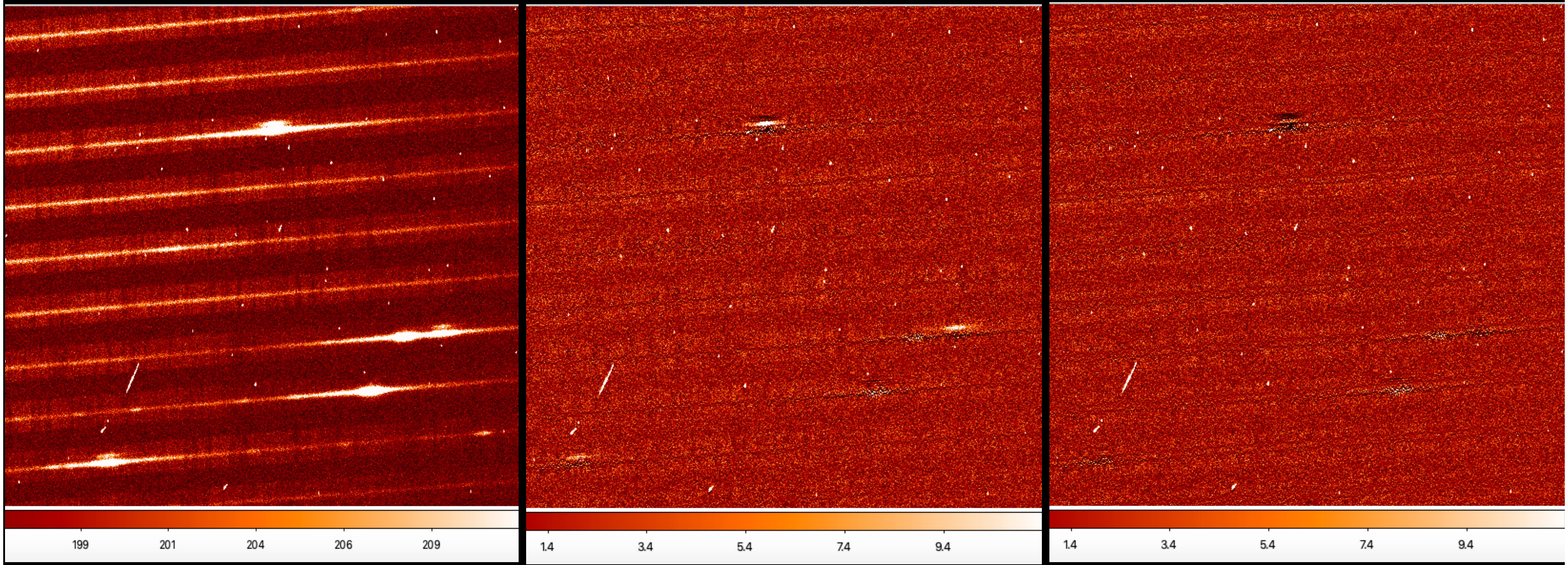
- M5.5 type low-mass binary (~0.2 $M_{\odot}$), separated by ~12 au
- 12-14 M_J circumbinary companion discovered at a separation of ~84 au (Delorme et al. 2013)
- Observed with Naco L′, Astrolux Z′, WISE and MUSE NFM
- Indication of ongoing accretion - H_{α}, H_{β} and He I emission (Eriksson et al. 2020) and H I (Paβ, Paγ, Brγ) emission (Betti et al. 2022)
- Estimated age ~40 Myr; similar to `Peter Pan disc' systems (see e.g., Boucher et al. 2020)



MUSE NFM observation of Delorme 1 system. Source: Eriksson et al. (2020)

Near-UV emission from Delorme 1 (AB)b

- Follow up observation with UVES at VLT /UT2 in Oct, 2021
- Blue arm (330-452 nm) ; Integration time of ~0.4 hr; R_{λ} ~ 50,000; slit width 0.8”
- Pipeline for reduction – Optimal spectral extraction algorithm, with some added modifications like proper sky backrgoudn estimation, masking planet location while PSF extraction etc.
- Extraction of the 1D planet spectrum based on current PSF extraction routine; gives a second residual frame with the planet signal also removed.

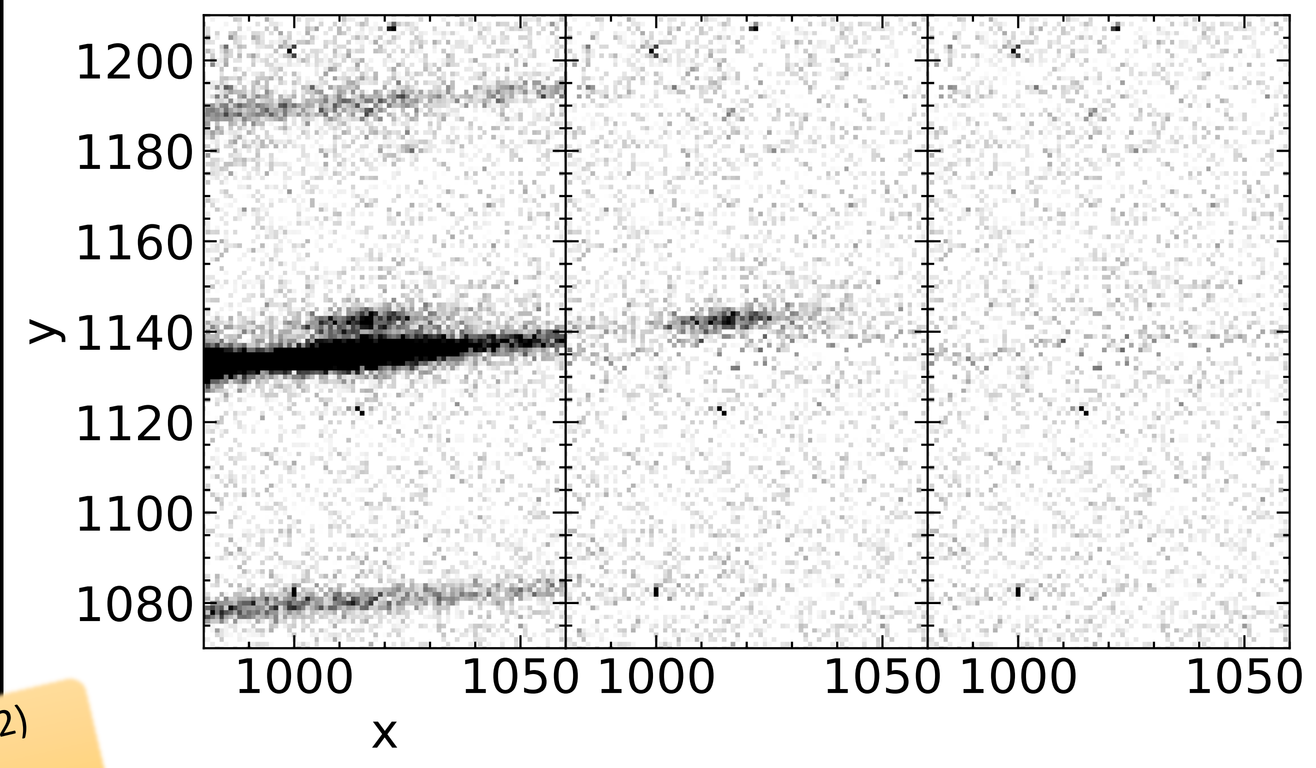


Cut out of the data frame: (Left) After basic reduction, with both stellar and companion lines present; (Middle) The residual frame after PSF subtraction, with the stellar lines removed; (Right) The final residual frame after the companion lines are removed.

Near-UV emission from Delorme 1 (AB)b

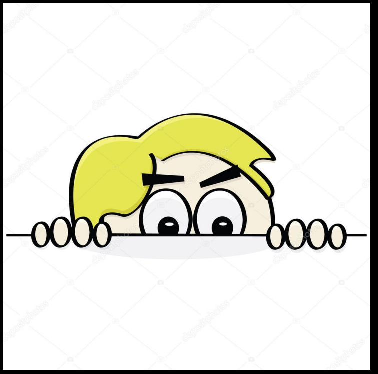
- First detection of HI emission in Near-UV (from Hγ to Hη)
- Tentative detection of H11 and H12, HeI, CaII H&K and possibly FeI, CrI and TiI.
- Estimated $\dot{M}_{acc}$ using L_{acc} derived from L_{line} using both stellar scaling relations and planetary accretion models

Eriksson, Viswanath, Janson et al. (2022) submitted to A&A



Hϵ line in the order 24 of the Delorme 1 (AB)b UVES spectrum (Blue Arm).
Source: Eriksson et al. (2022, submitted to A&A)

Sneak Peek!



Optimal Spectral Extraction : CRIRES+

Optimizing the code for CRIRES+

Test application to archival CRIRES data for β Pic b

Up Next…..

Reduction and Analysis of the Red arm (476 – 684 nm) of

UVES data for Delorme 1 (AB)b