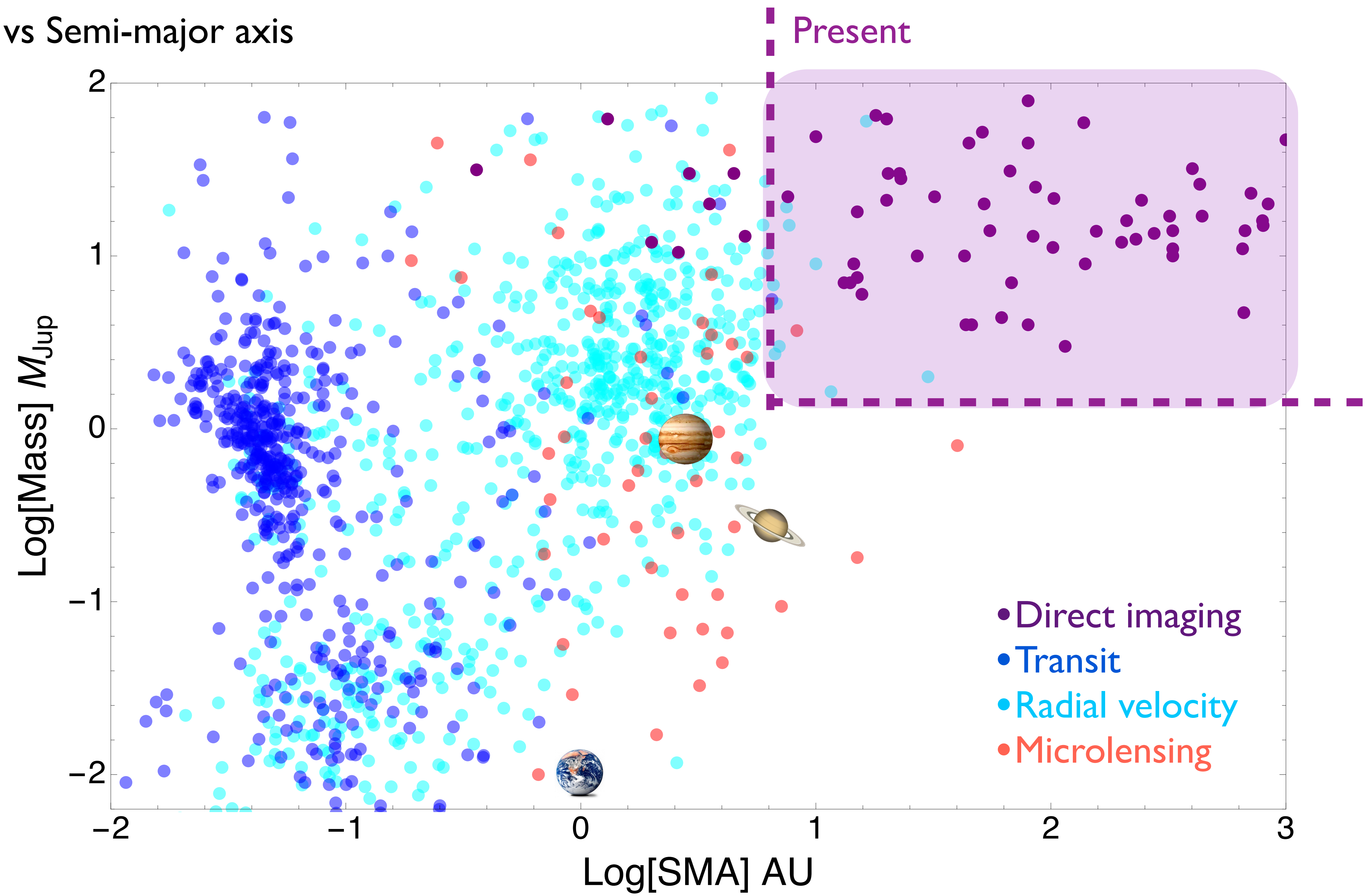
Characterizing imaged exoplanets with high-dispersion spectroscopy

Mamadou N'Diaye (OCA/Lagrange)

Lagrange seminar - Nov 27, 2018

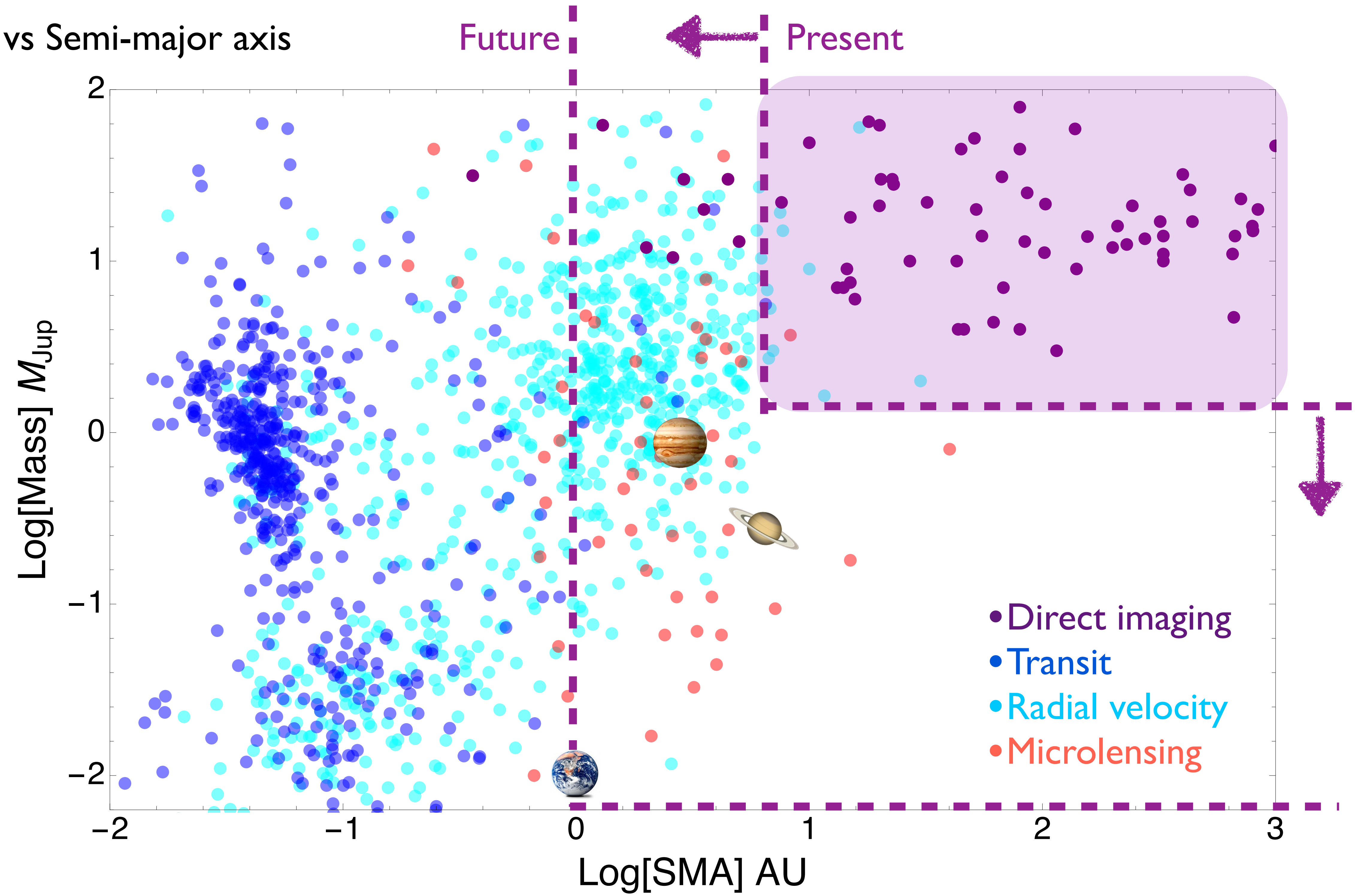
Detection of extrasolar planets

Mass vs Semi-major axis

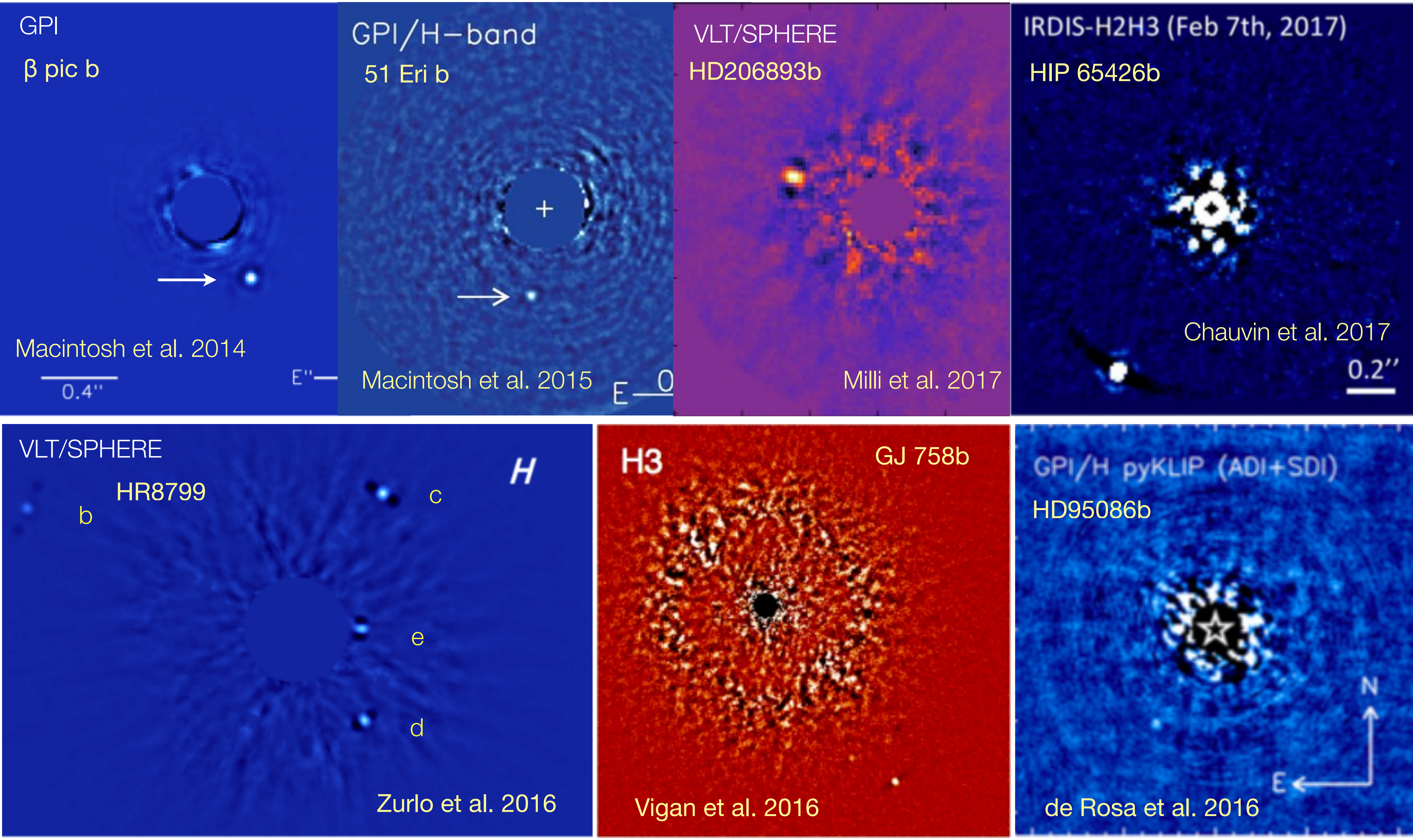


Detection of extrasolar planets

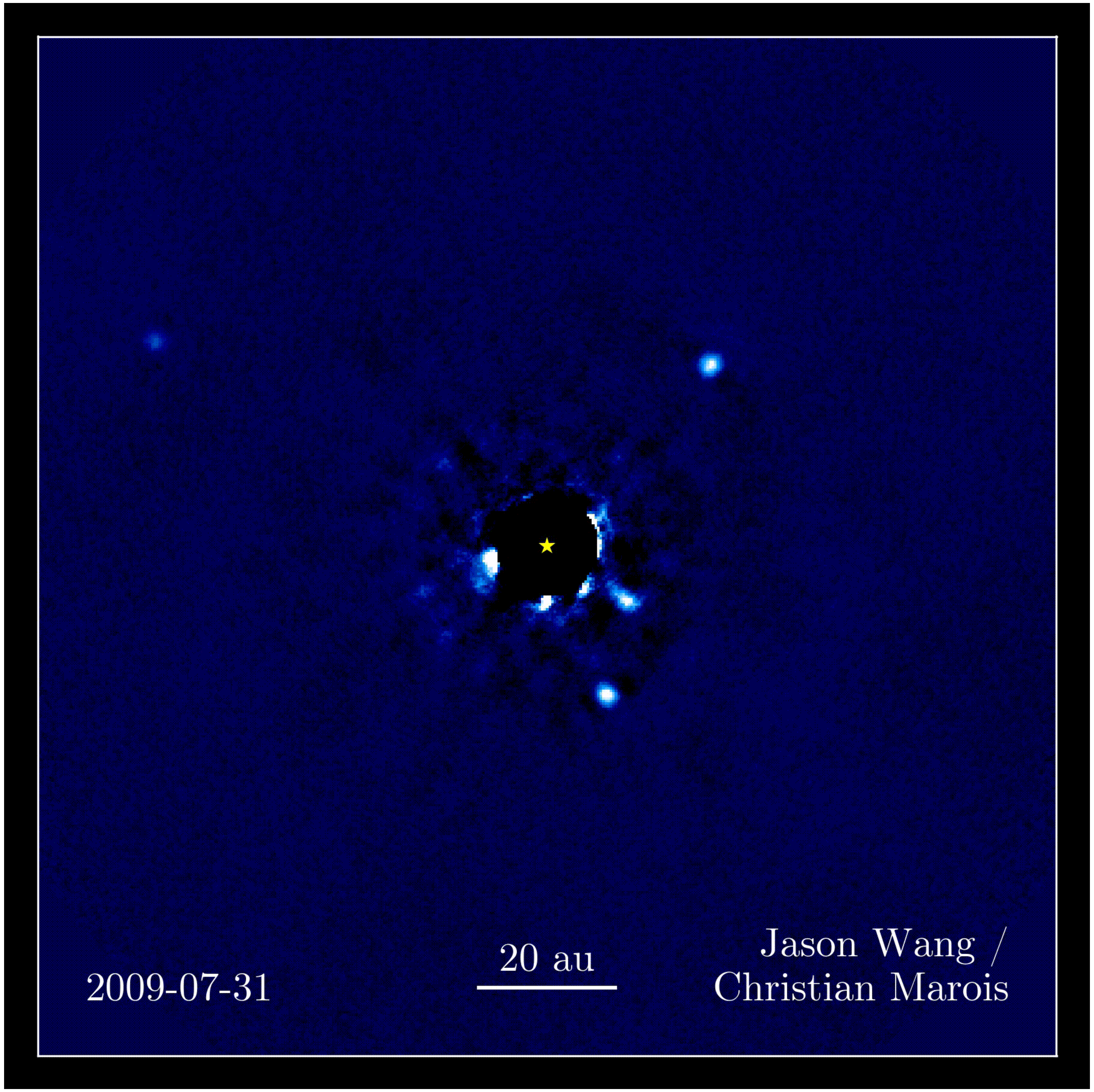
Mass vs Semi-major axis



Imaging exoplanets in thermal emission



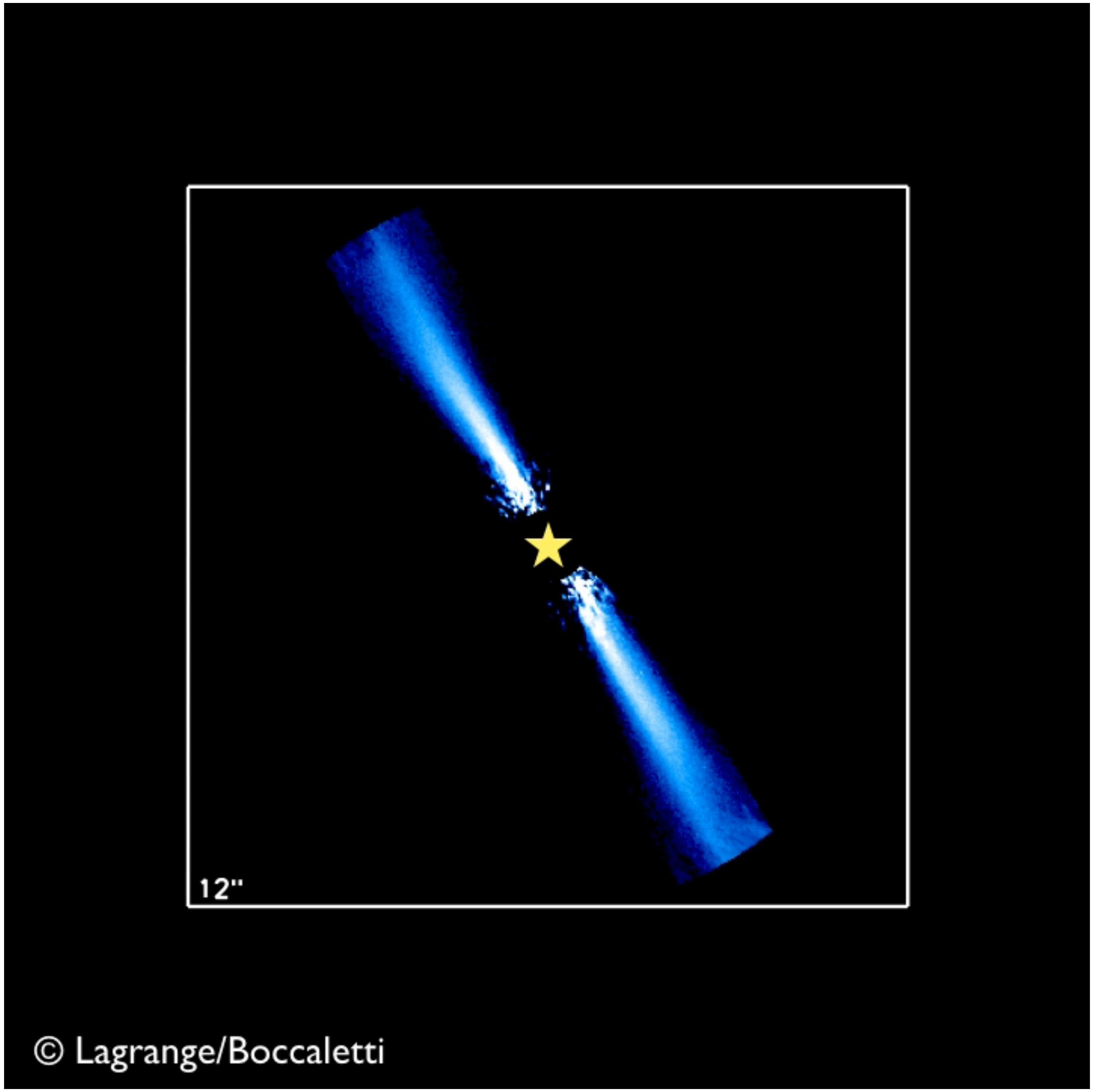
HR8799



20AU
~2x Saturne-Sun
distance

Jason Wang/Christian Marois

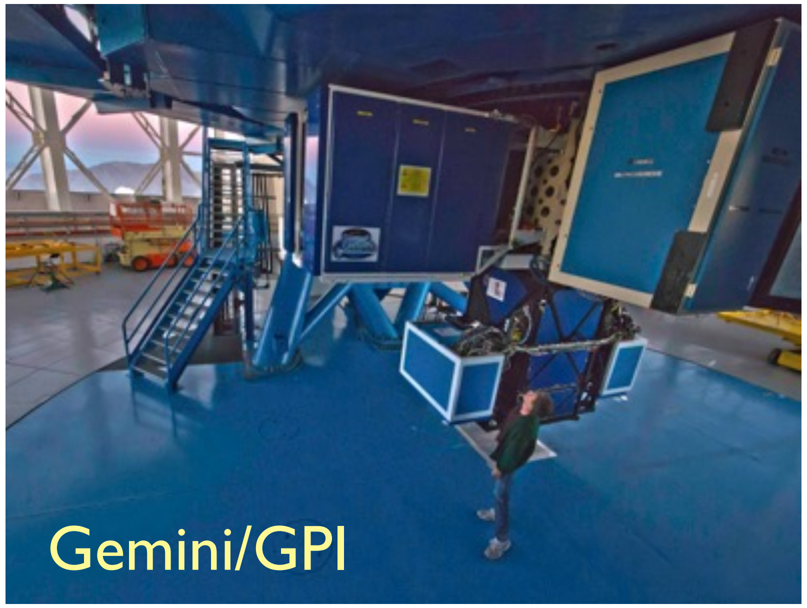
Beta pictoris b

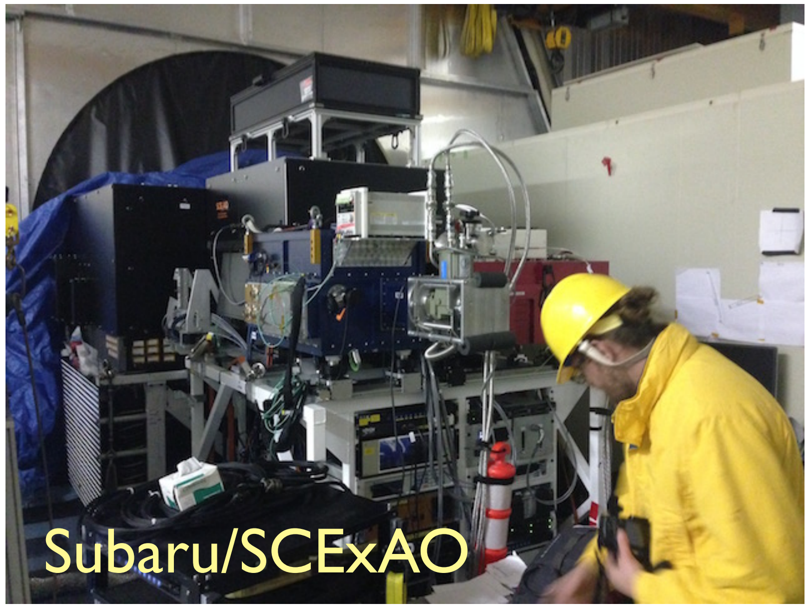


Lagrange et al. 2018

Exoplanet imagers for warm or massive gaseous planets

- Extreme adaptive optics
- Coronagraphy
- Image post-processing
  - 10^6-10^7 raw contrast at 0.2" in H-band

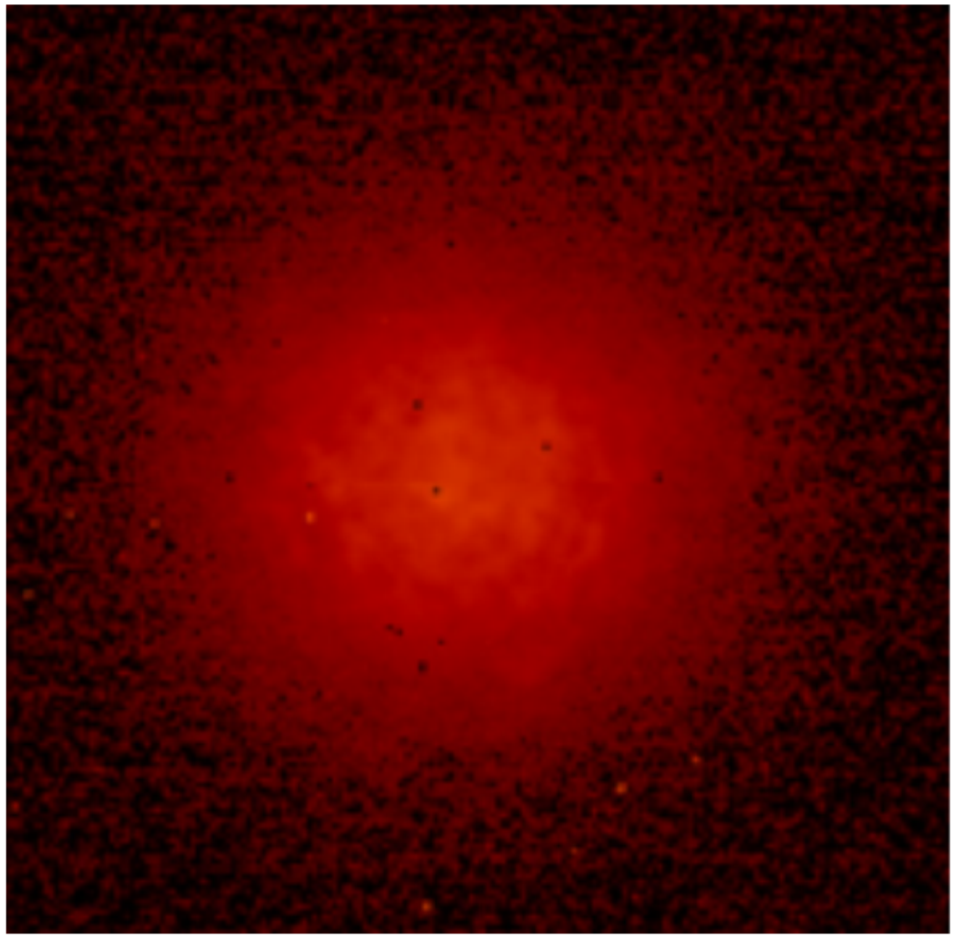




Current performance: 10^5-10^6 contrast

High-contrast imaging recipe

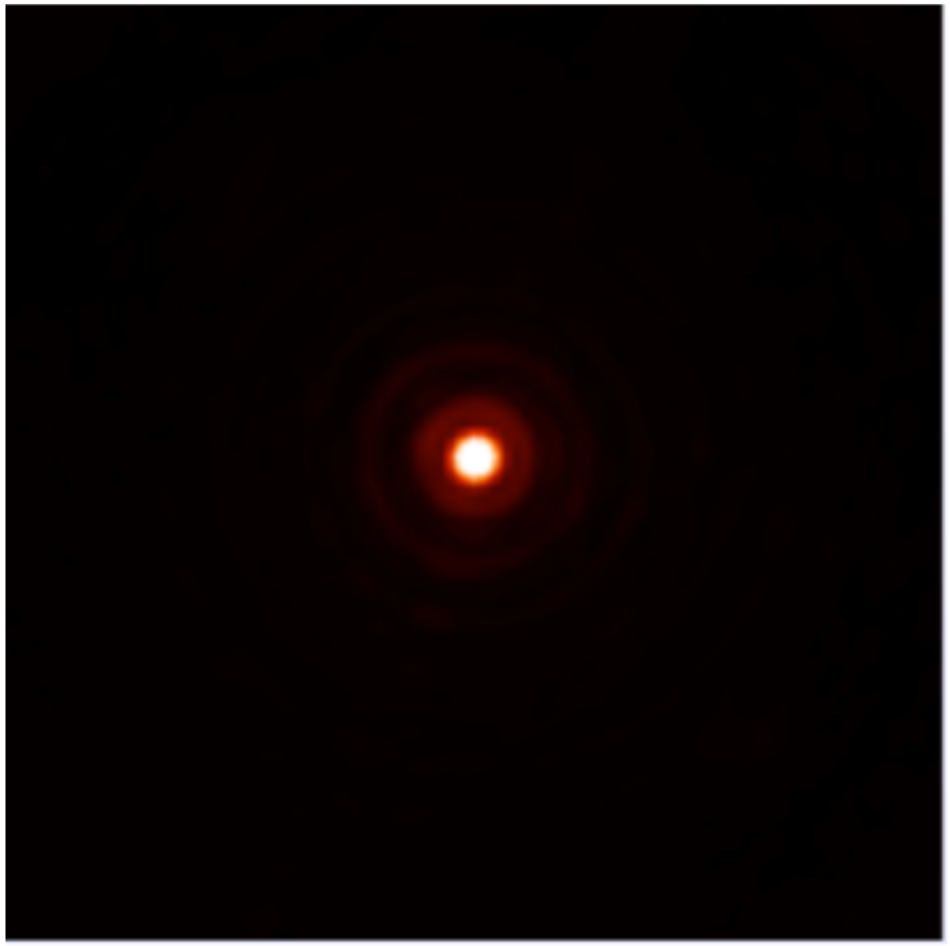
Star image



Petit et al. 2016

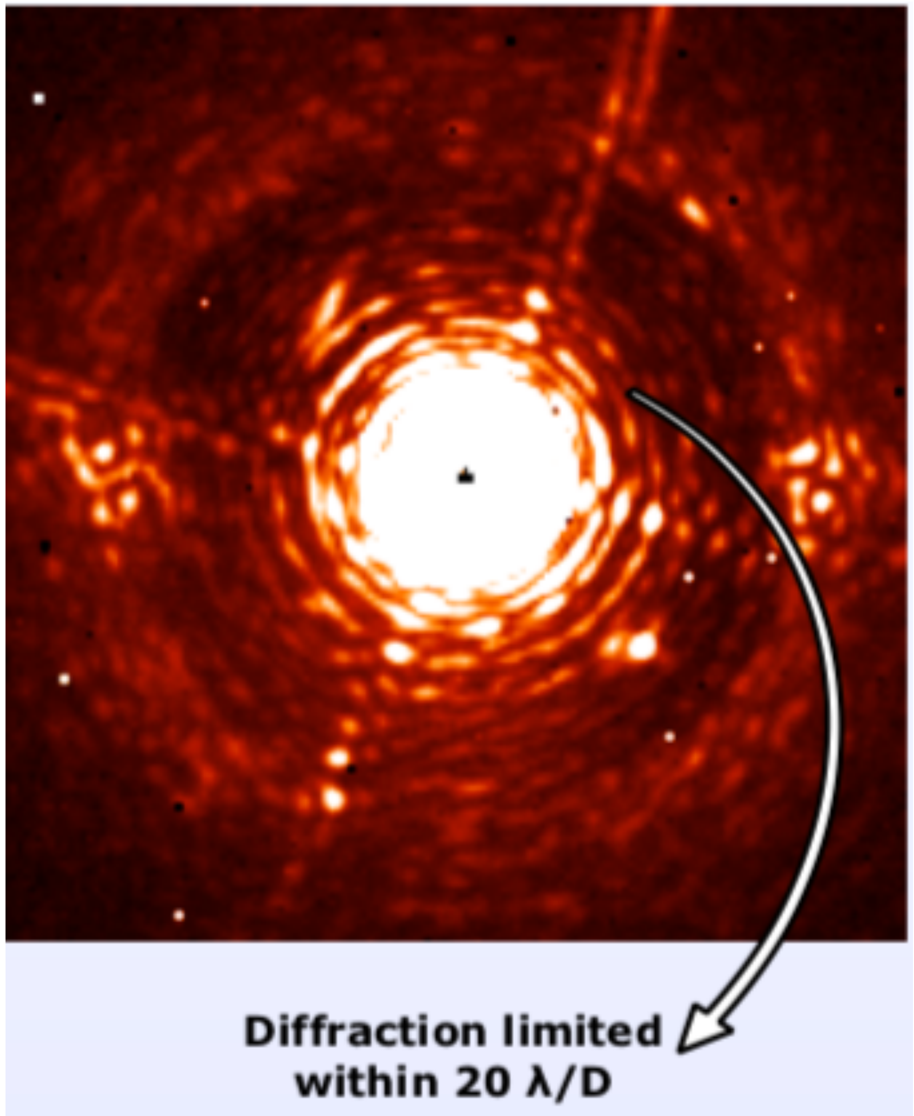
High-contrast imaging recipe

Star image after extreme adaptive optics



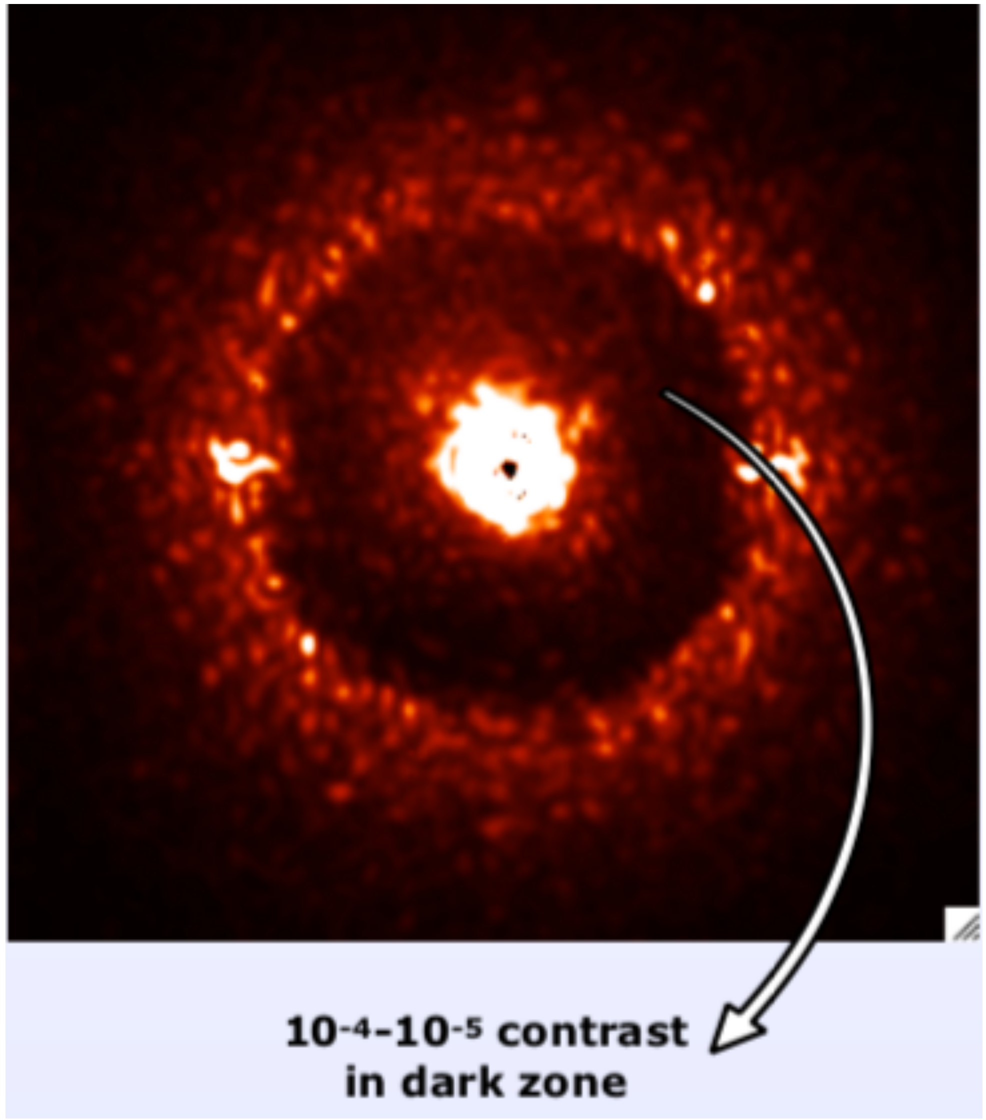
High-contrast imaging recipe

Star image after saturation



High-contrast imaging recipe

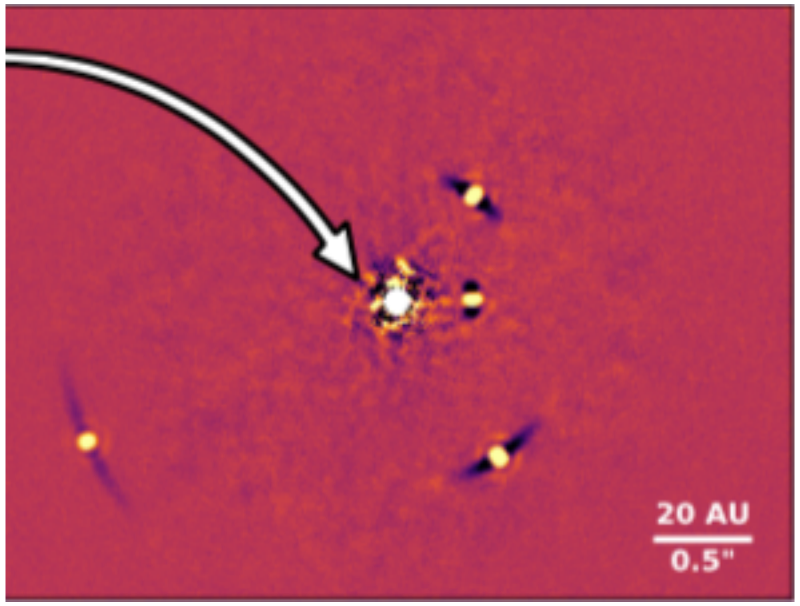
Star image after coronagraphy



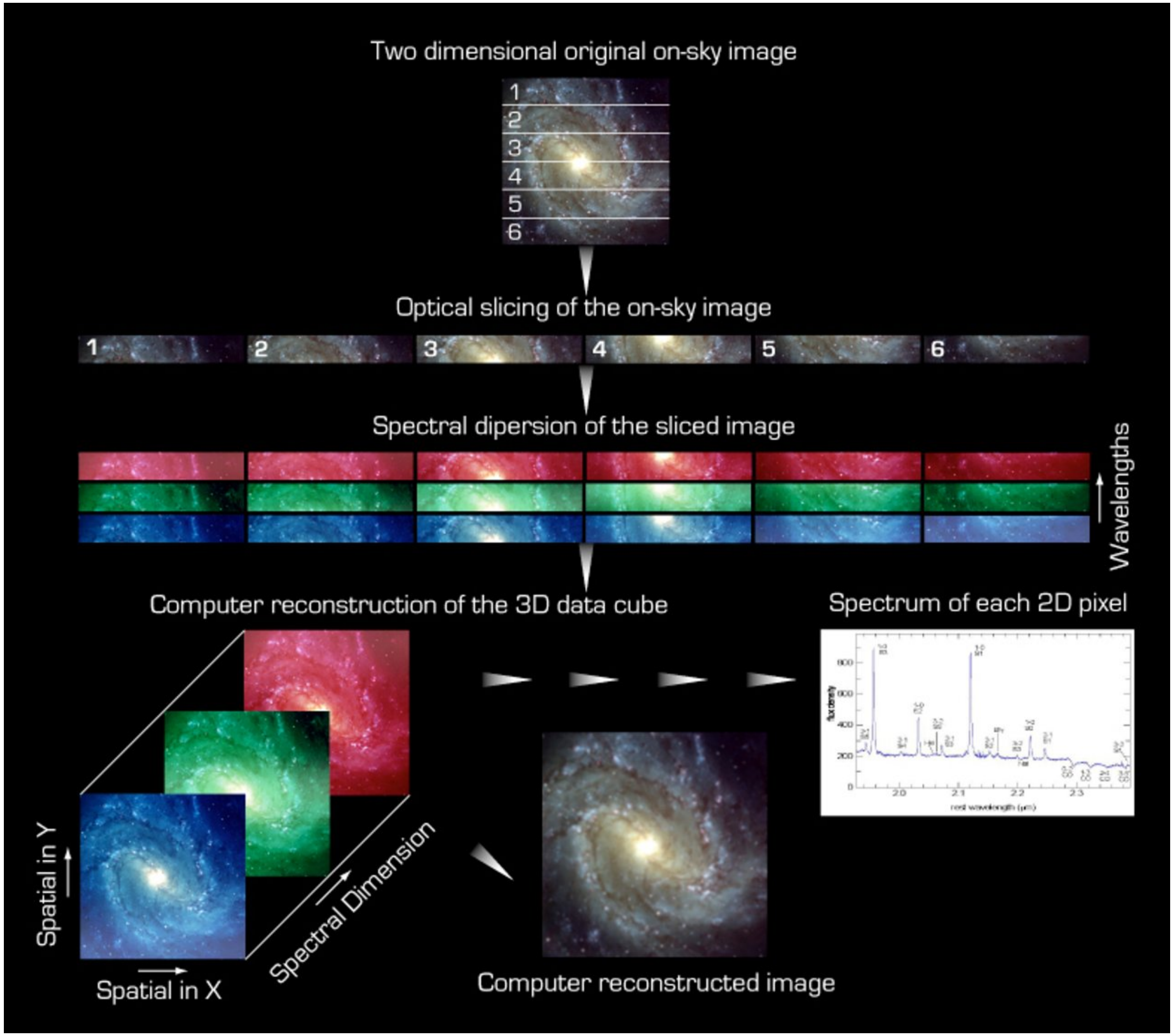
High-contrast imaging recipe

Star image after post processing

10^{-5}-10^{-6} contrast
down to 0.2”

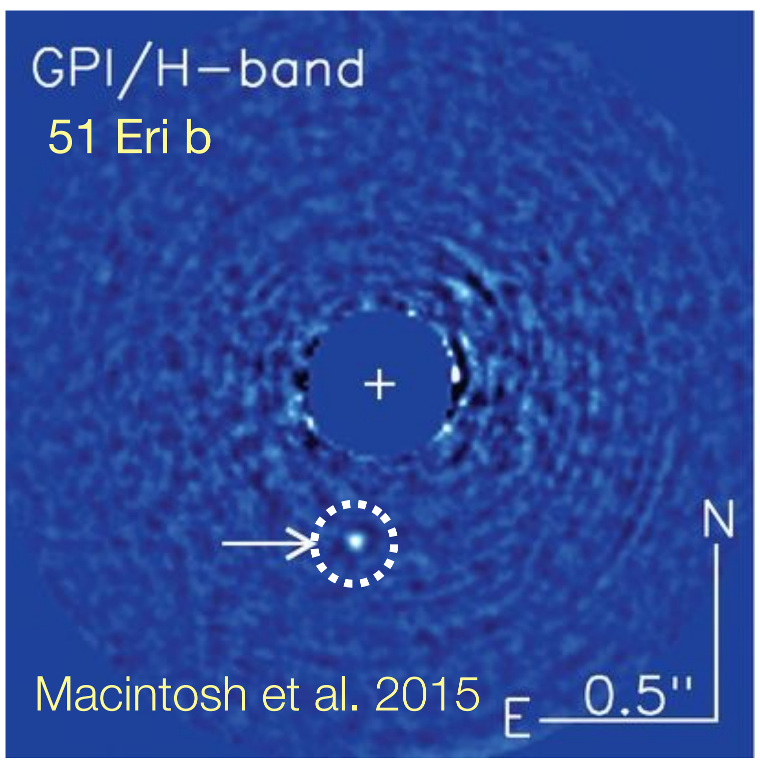


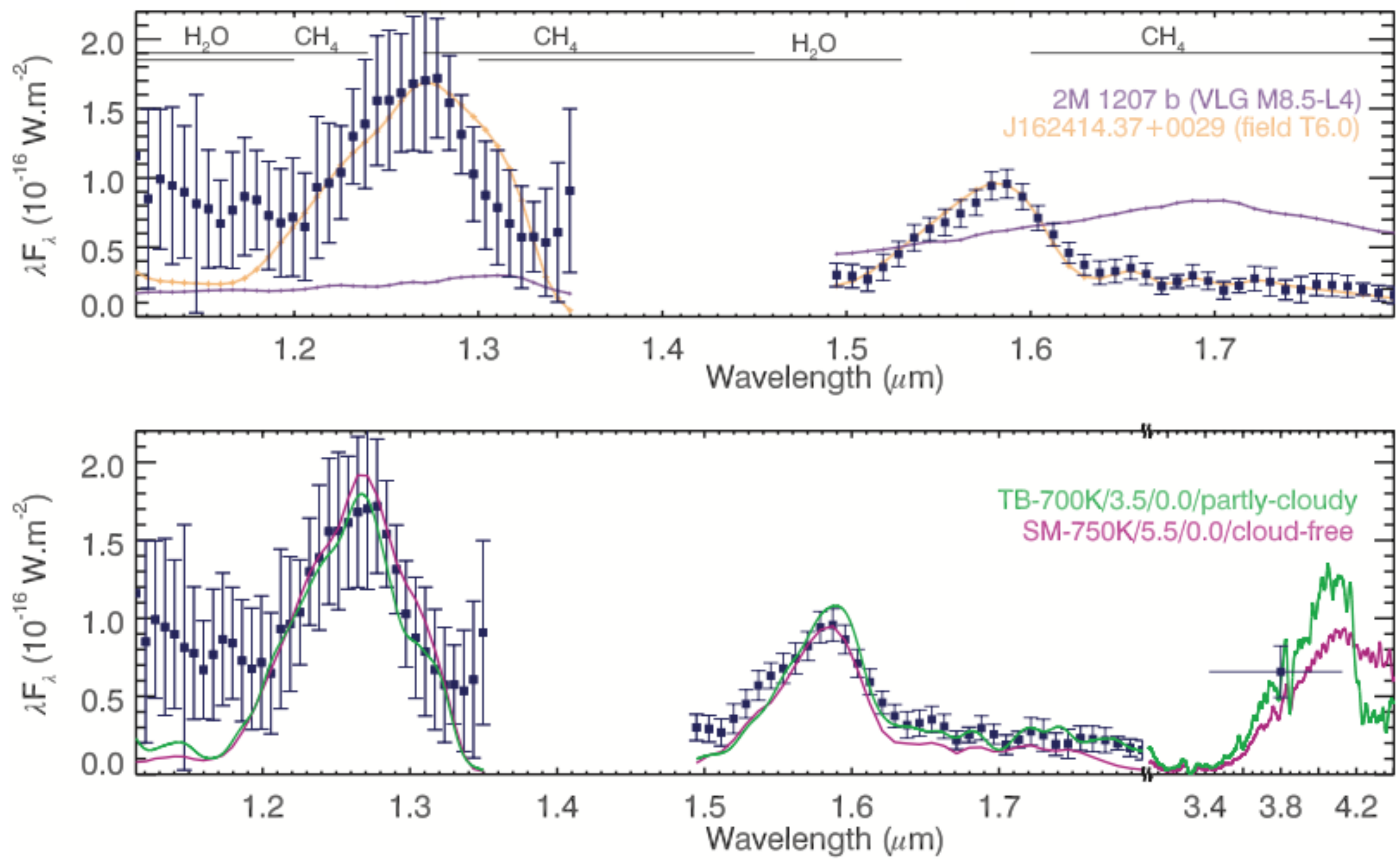
Integral field spectrograph (IFS)



Low-resolution spectroscopy on imaged exoplanets

Spectrum for 51 Eri b



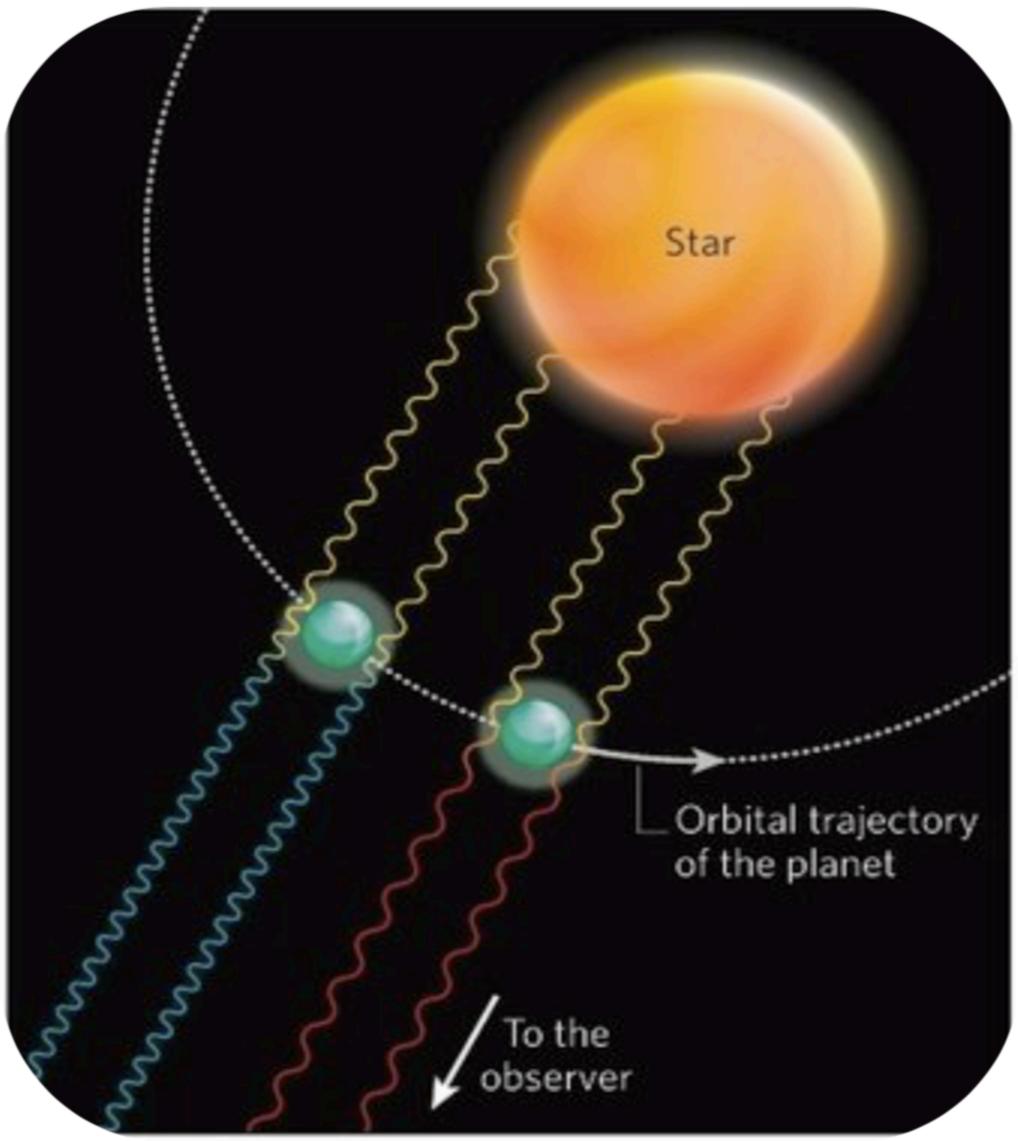


Limited resolution R=50-400 on current exoplanet imagers

Macintosh et al. 2015

Spectroscopic observations of exoplanets

Resolution from 4k to 100k and more

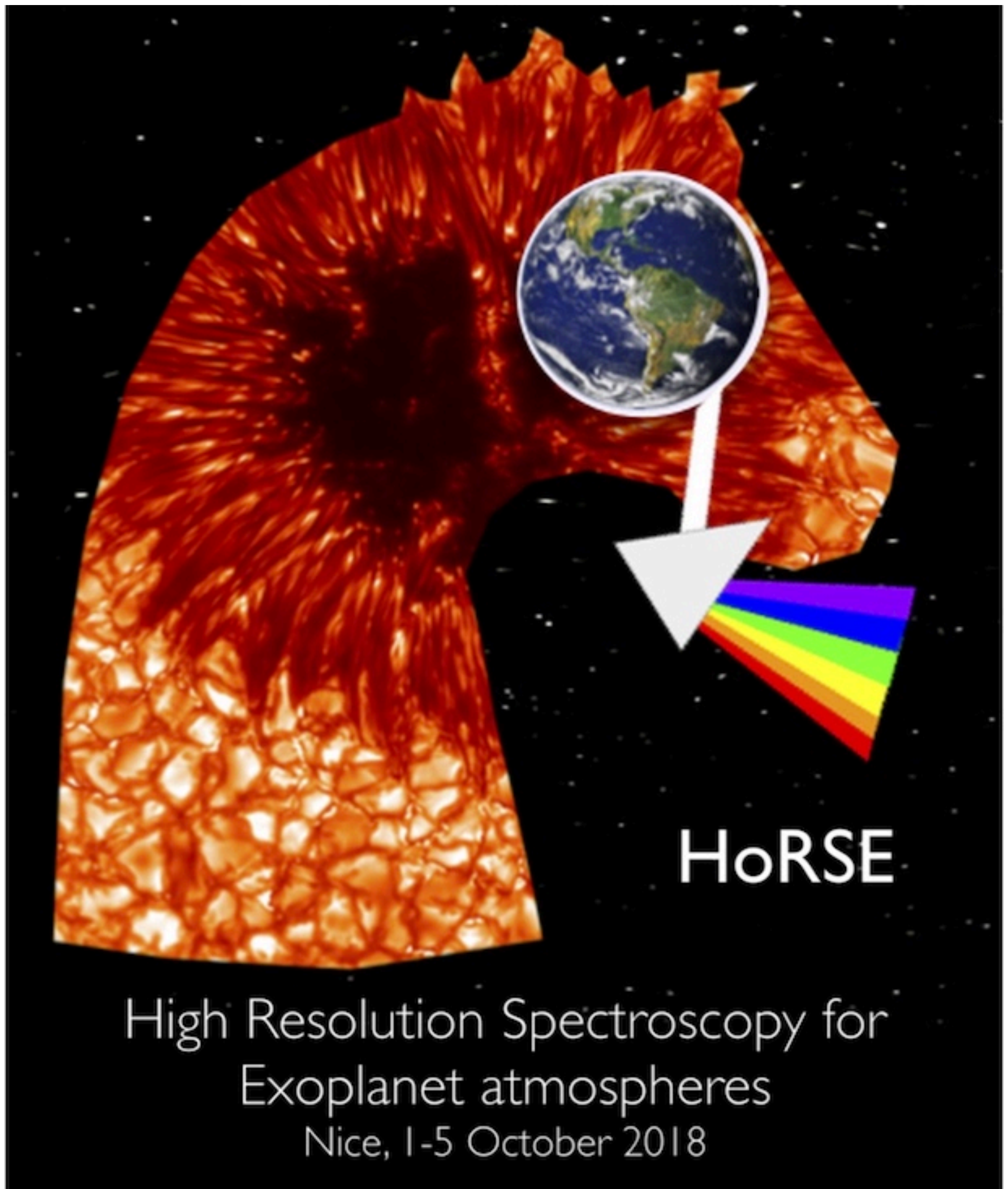


- Width of the spectral line
  - Spin of the planet
- Shift of the spectral lines
  - Orbital motion of the planet
- High resolution spectrum
  - Chemical composition of the planet atmosphere (CO, H2O, CH4, NH3, O3, etc)

Handful information on the planet nature

I. Snellen

High dispersion spectroscopy of exoplanets



Resolution from 4k to 100k and more

What could be probe?

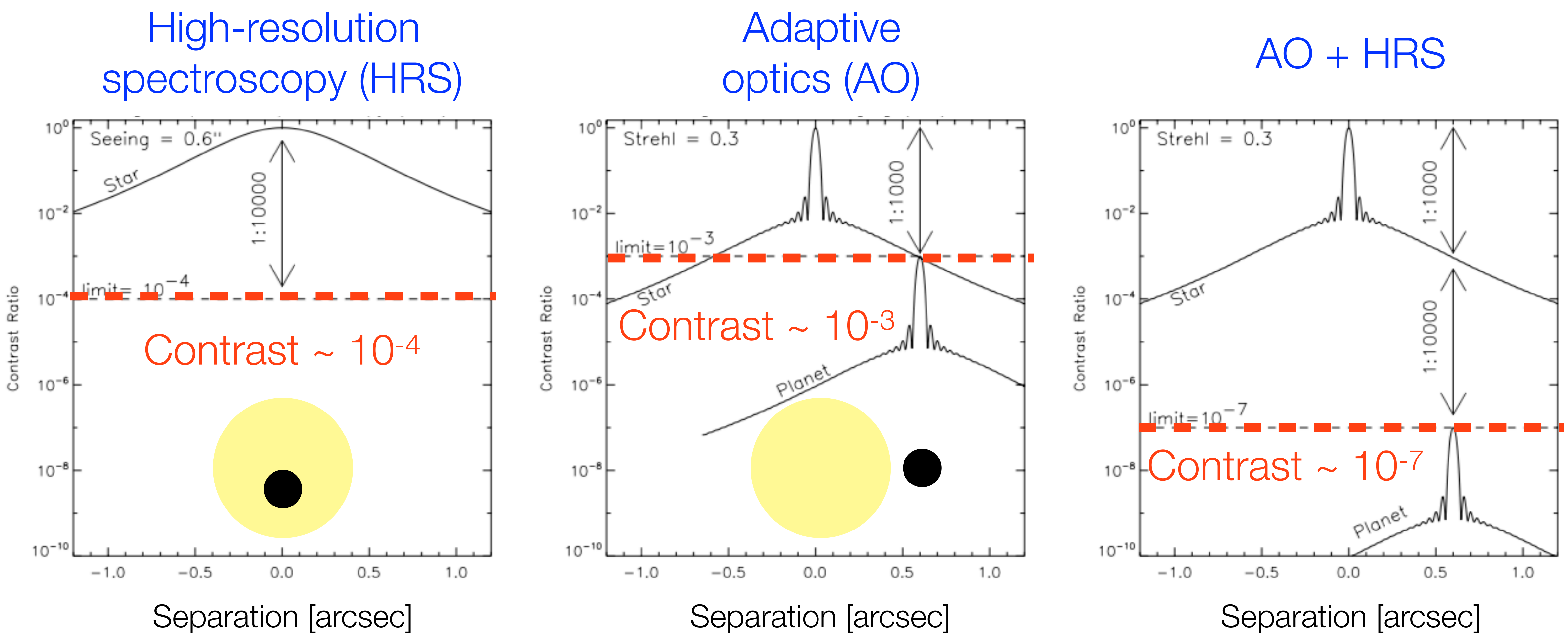
- Molecular & atomic abundances
- Atmospheric temperature structure
- Winds, circulation & rotation
- Exospheres
- Surface sputtering and disintegrating planets
- Clouds, hazes and scattering processes
- Isotopes and isotopologues

Chairs A. Chiavassa, M. Brogi

High dispersion spectroscopy for warm or massive gaseous planets?

- Issue: low res spectrograph (**R=50-400**) on current exoplanet imagers
  - limited information on planet atmospheric composition
- Solution: high res spectrograph (**R=4k-100k**) in combination with
  - adaptive optics (classical or extreme)
  - post processing methods
  - possibly coronagraphy

Adaptive optics (AO) +
High resolution spectroscopy (HRS)

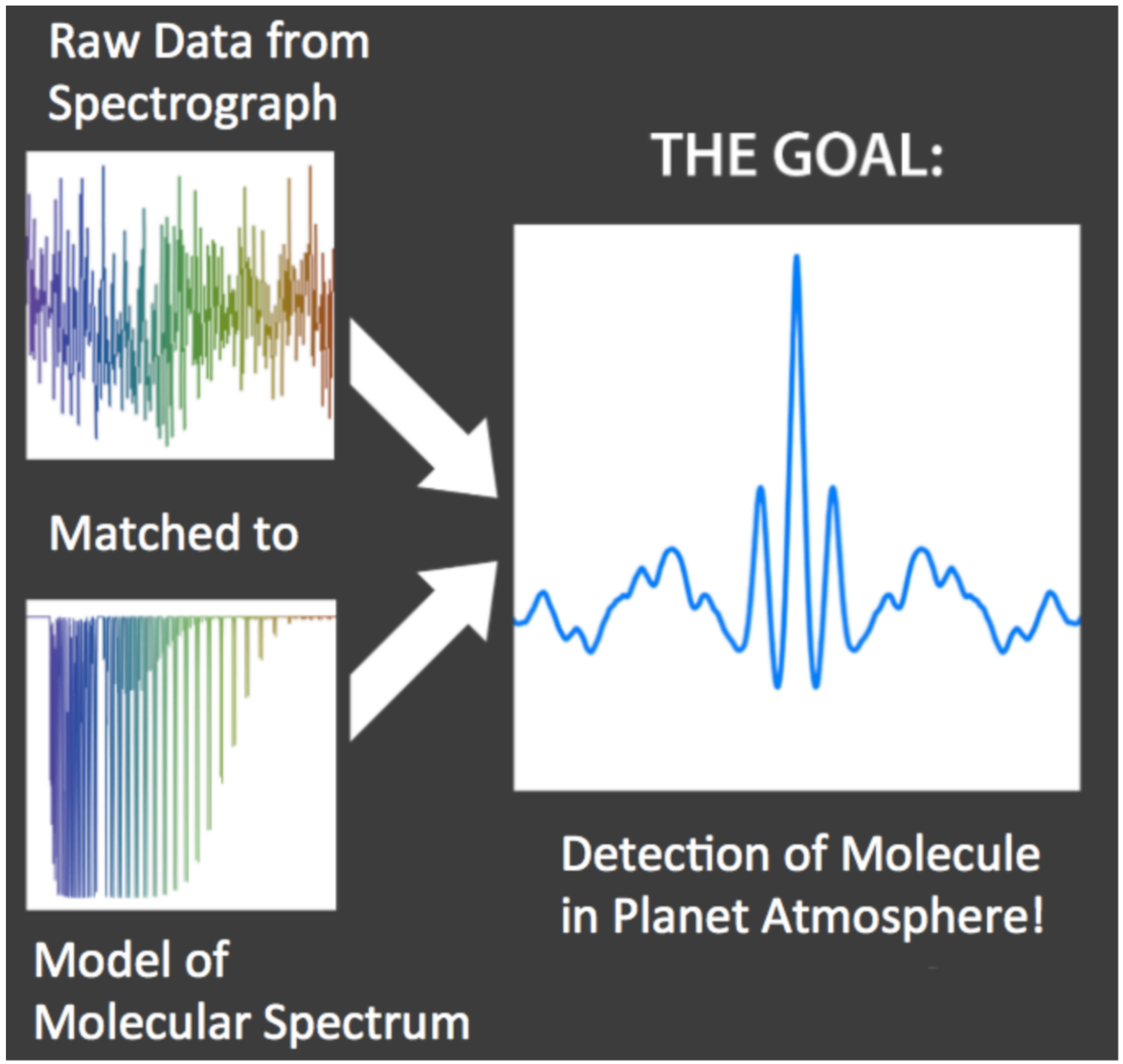


$$S/N = \frac{S_{\text{planet}}}{\sqrt{S_{\text{star}}/K + \sigma^2_{\text{bg}} + \sigma^2_{\text{RN}} + \sigma_{\text{Dark}}}} \sqrt{N_{\text{lines}}}$$

K ~Contrast

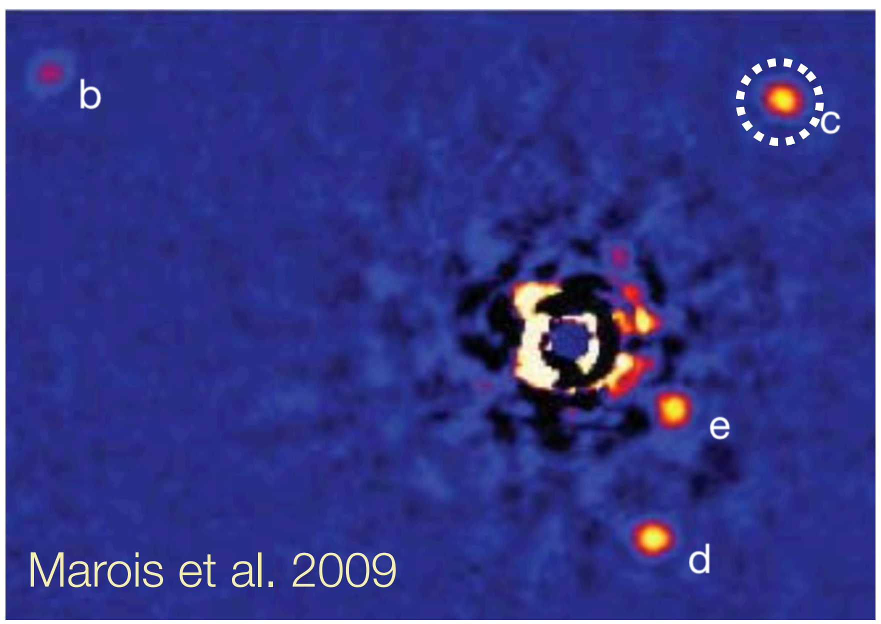
Sparks & Ford 2002, Riaud & Schneider 2007, Snellen et al. 2015, Lovis et al. 2017

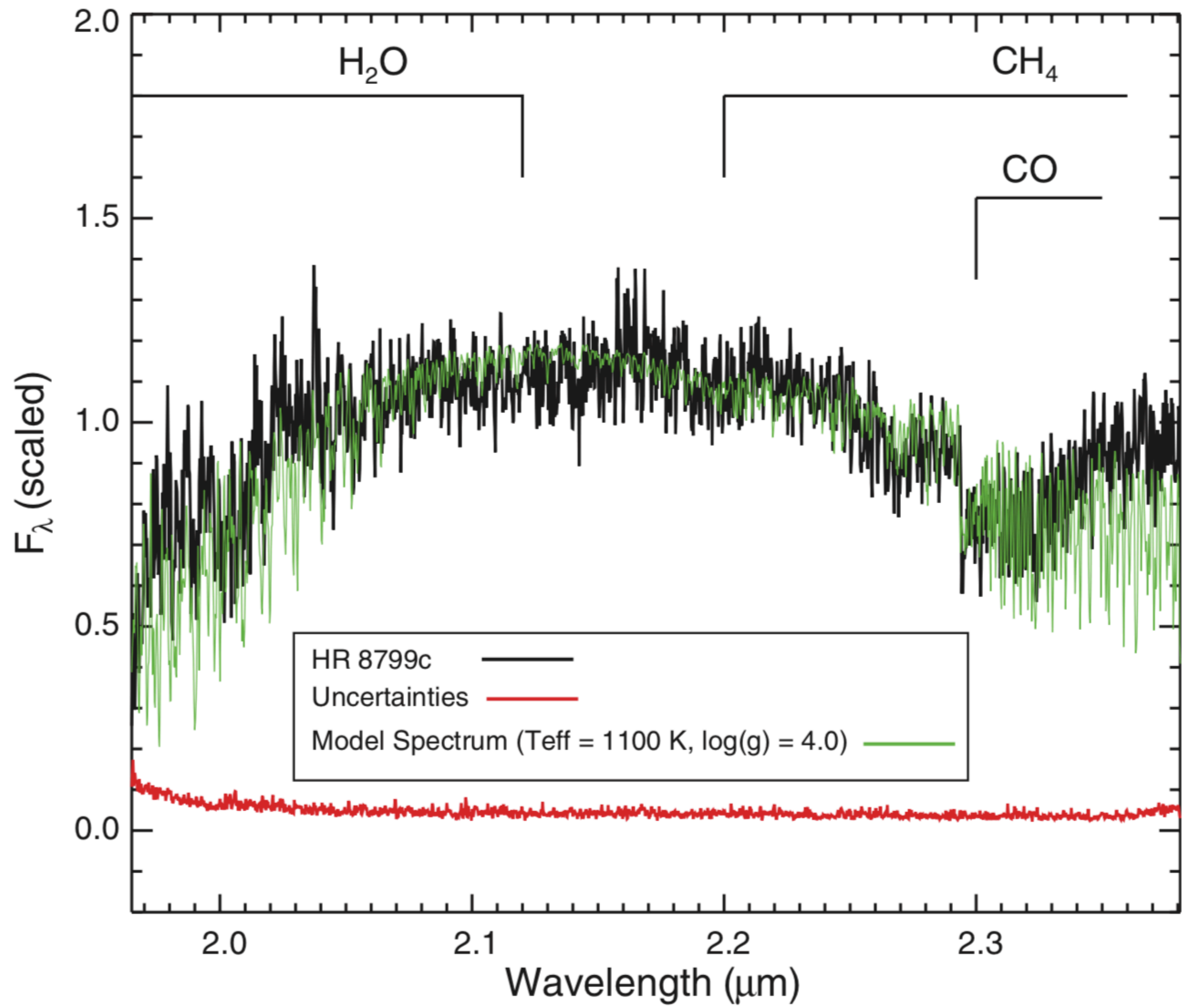
Cross-correlation technique



Spectral analysis on HR8799c

KECK/OSIRIS, R~4000, K-band



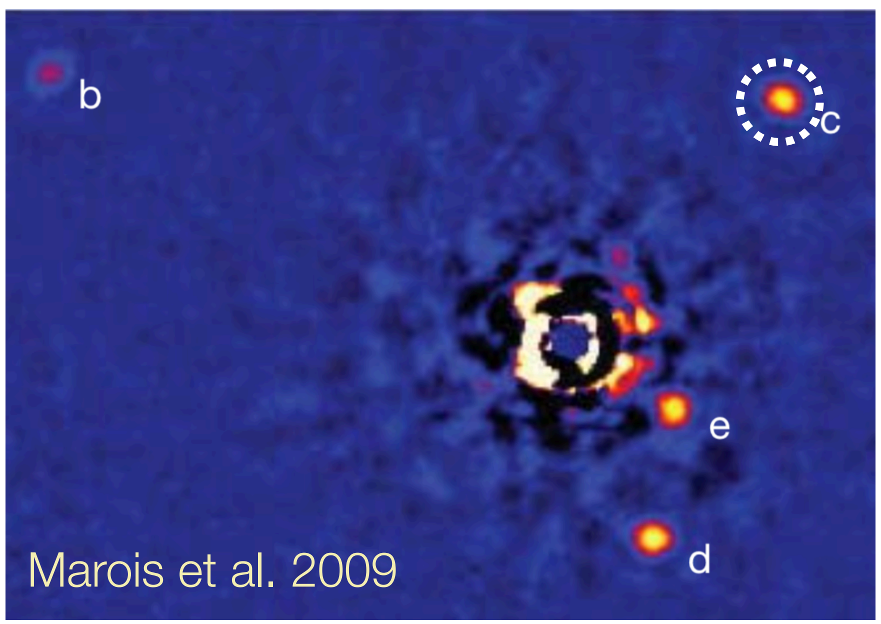


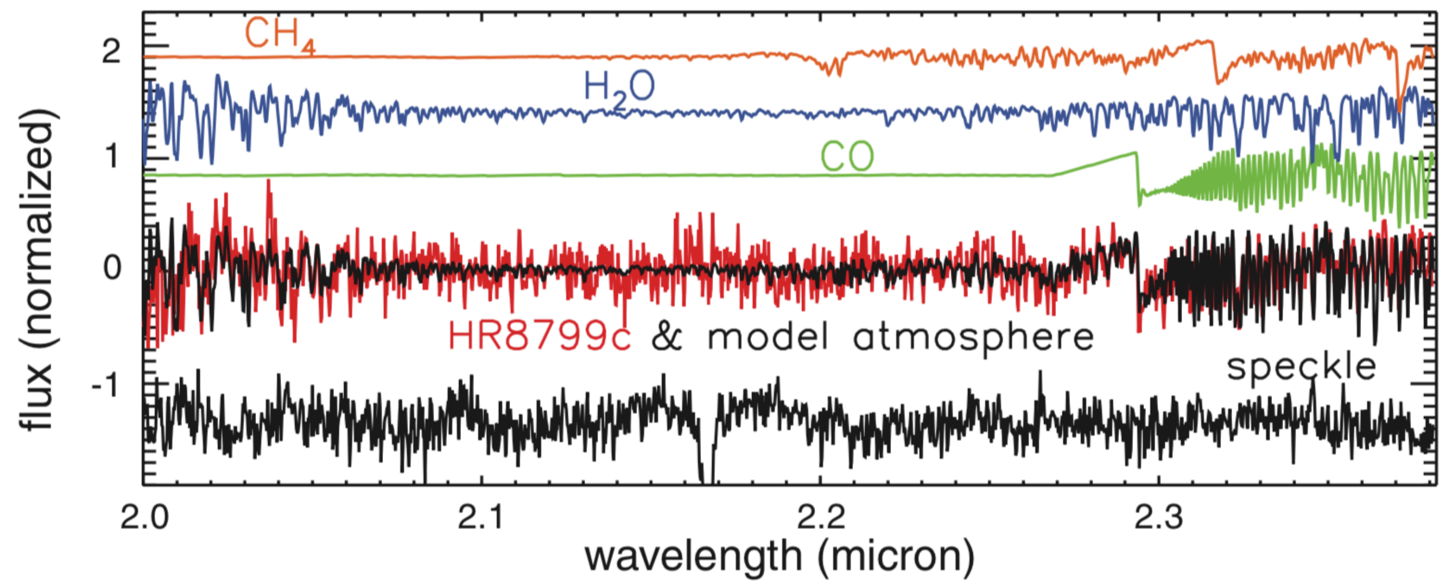
Clear drop at 2.19μm (CO line)

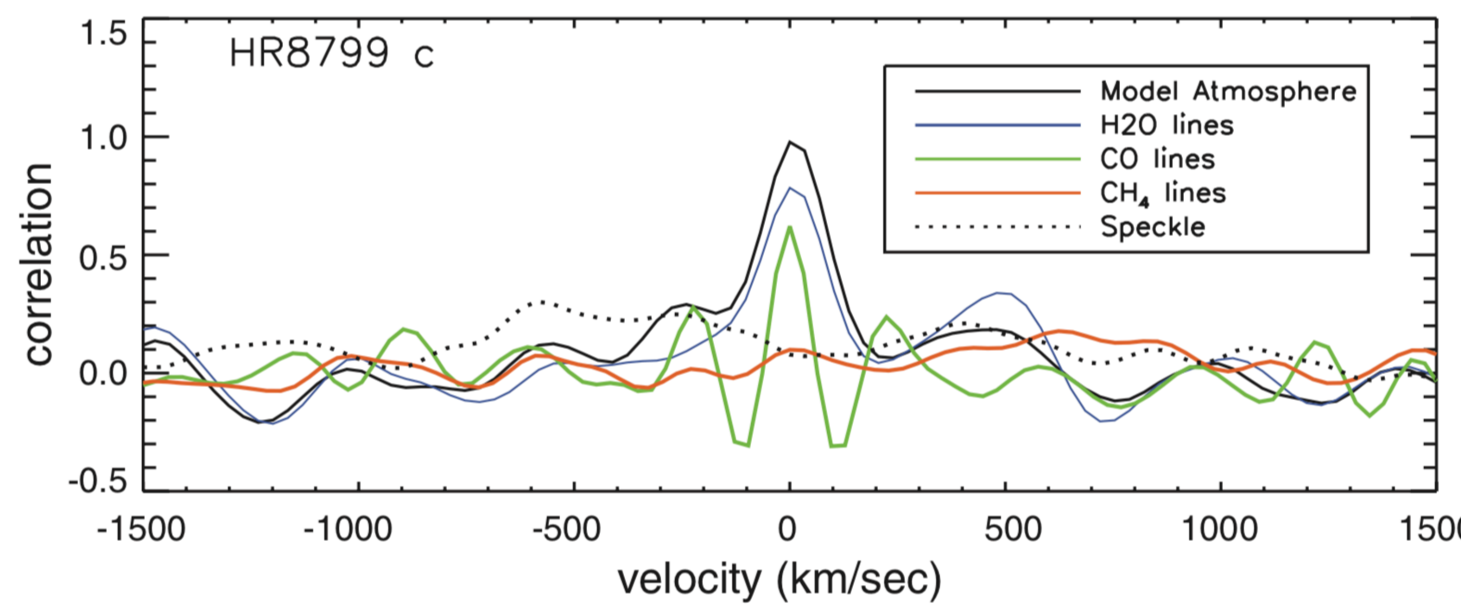
Konopacky et al. 2013

Spectral analysis on HR8799c

Cross-correlation analysis





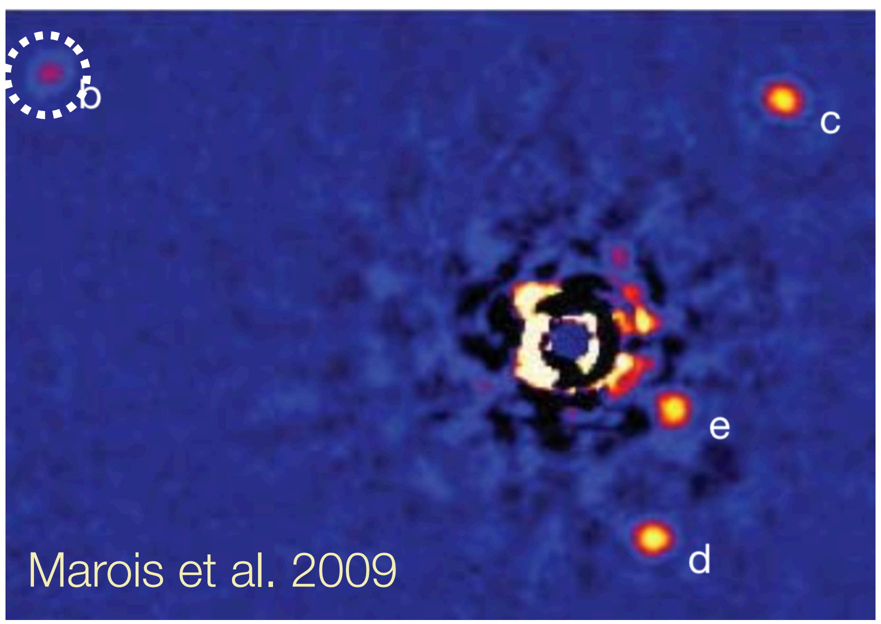


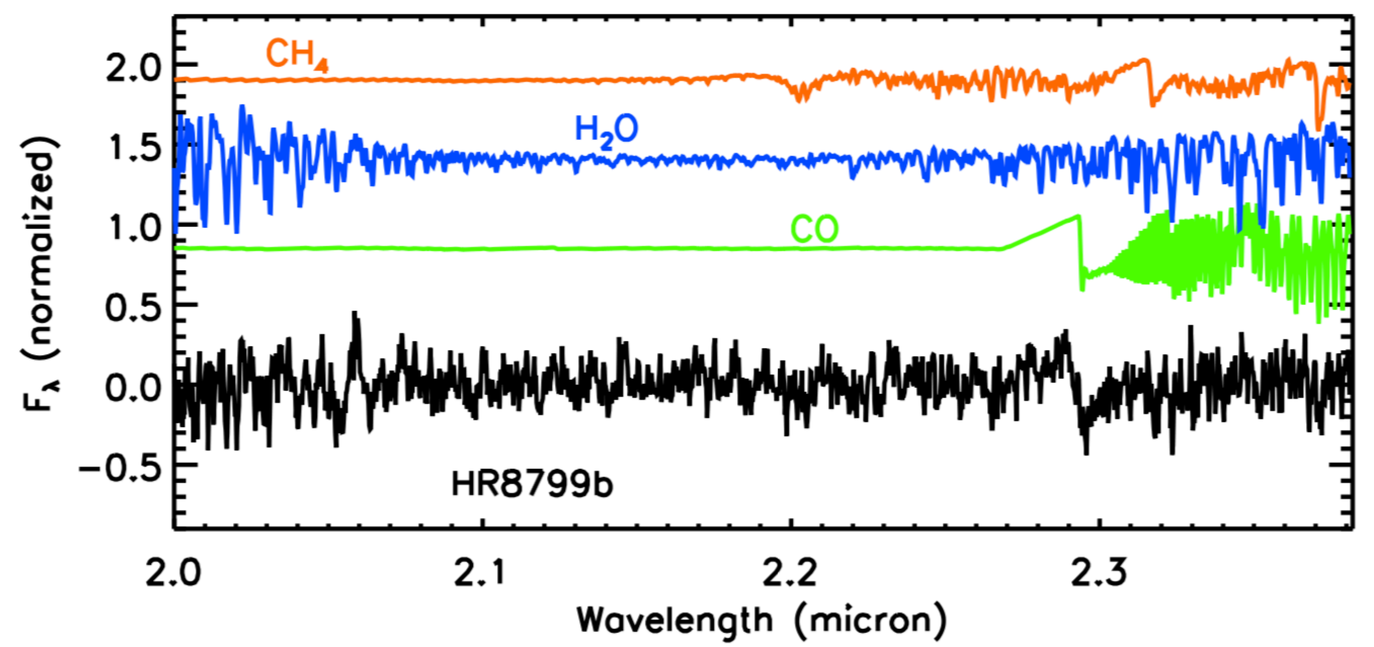
Detection of CO and H2O

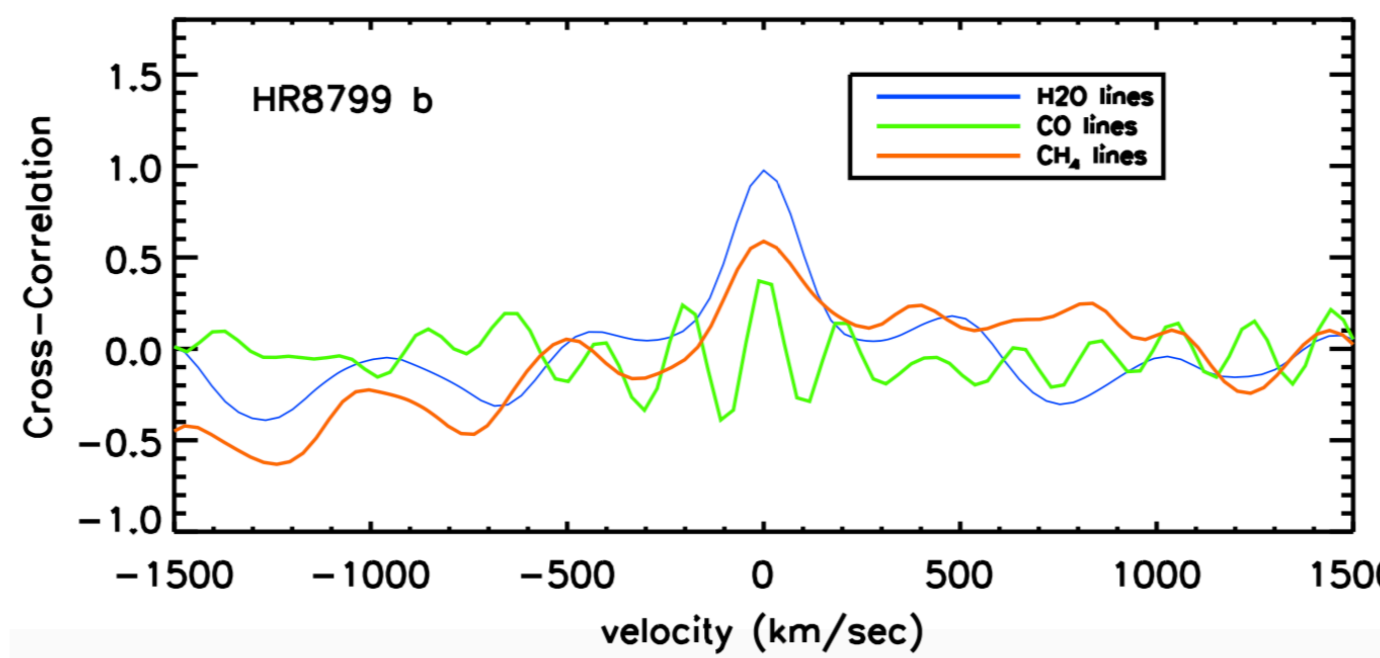
Konopacky et al. 2013

Spectral analysis on HR8799b

Cross-correlation analysis



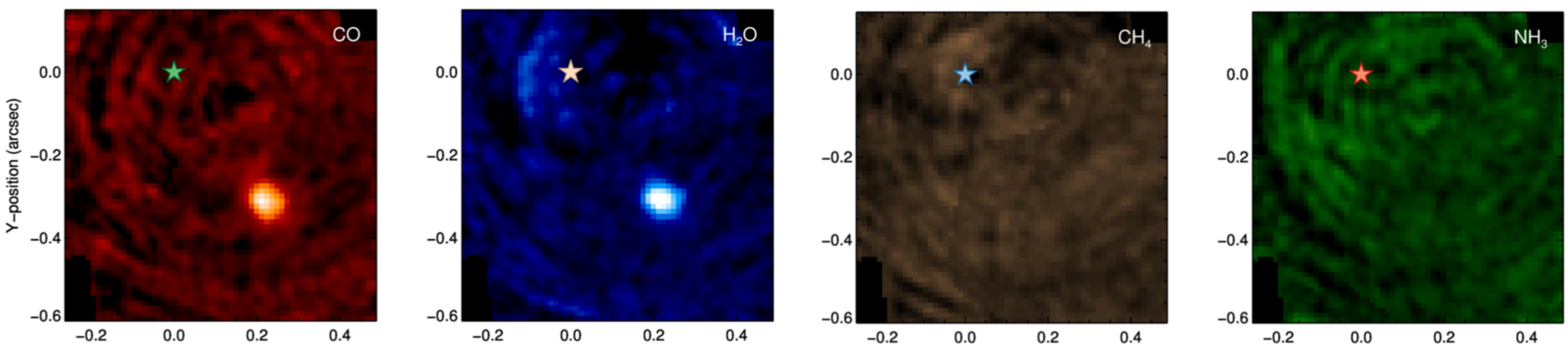




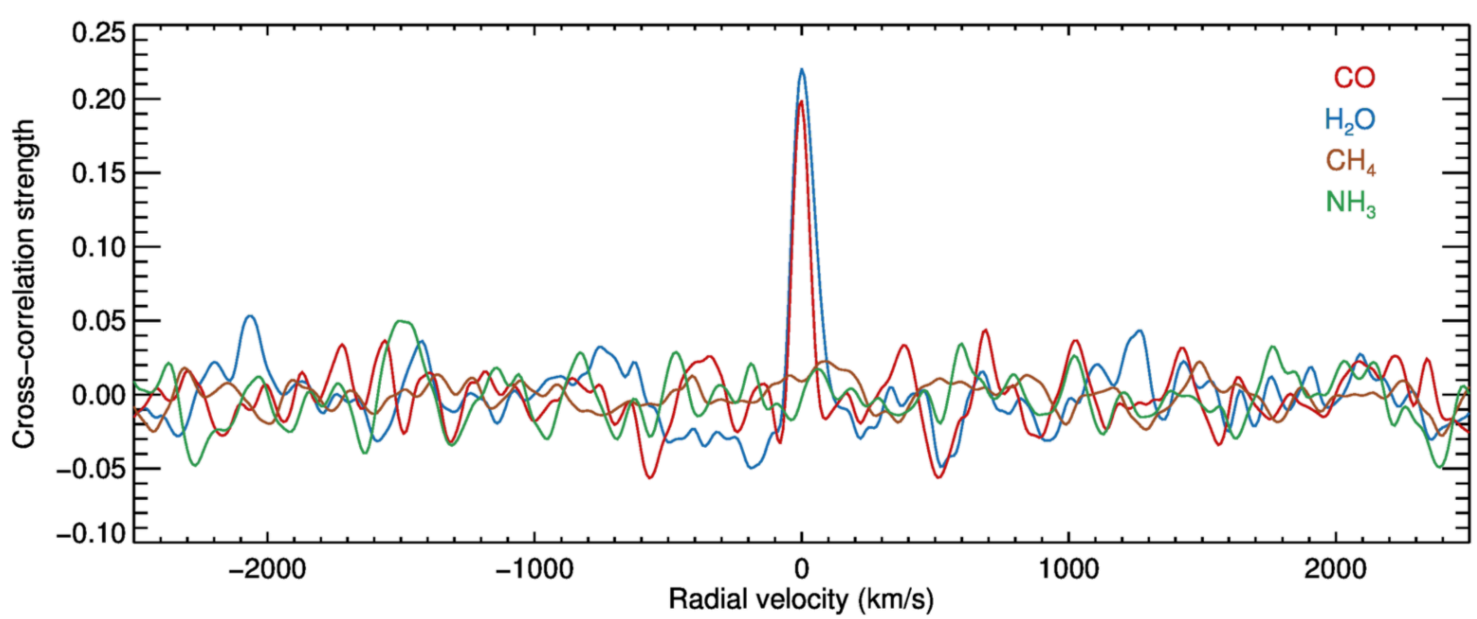
Barman et al. 2015

Spectral analysis on beta pic b

VLT/SINFONI, R~5000, K-band, Strehl ~19-27%



1D cross-correlation function



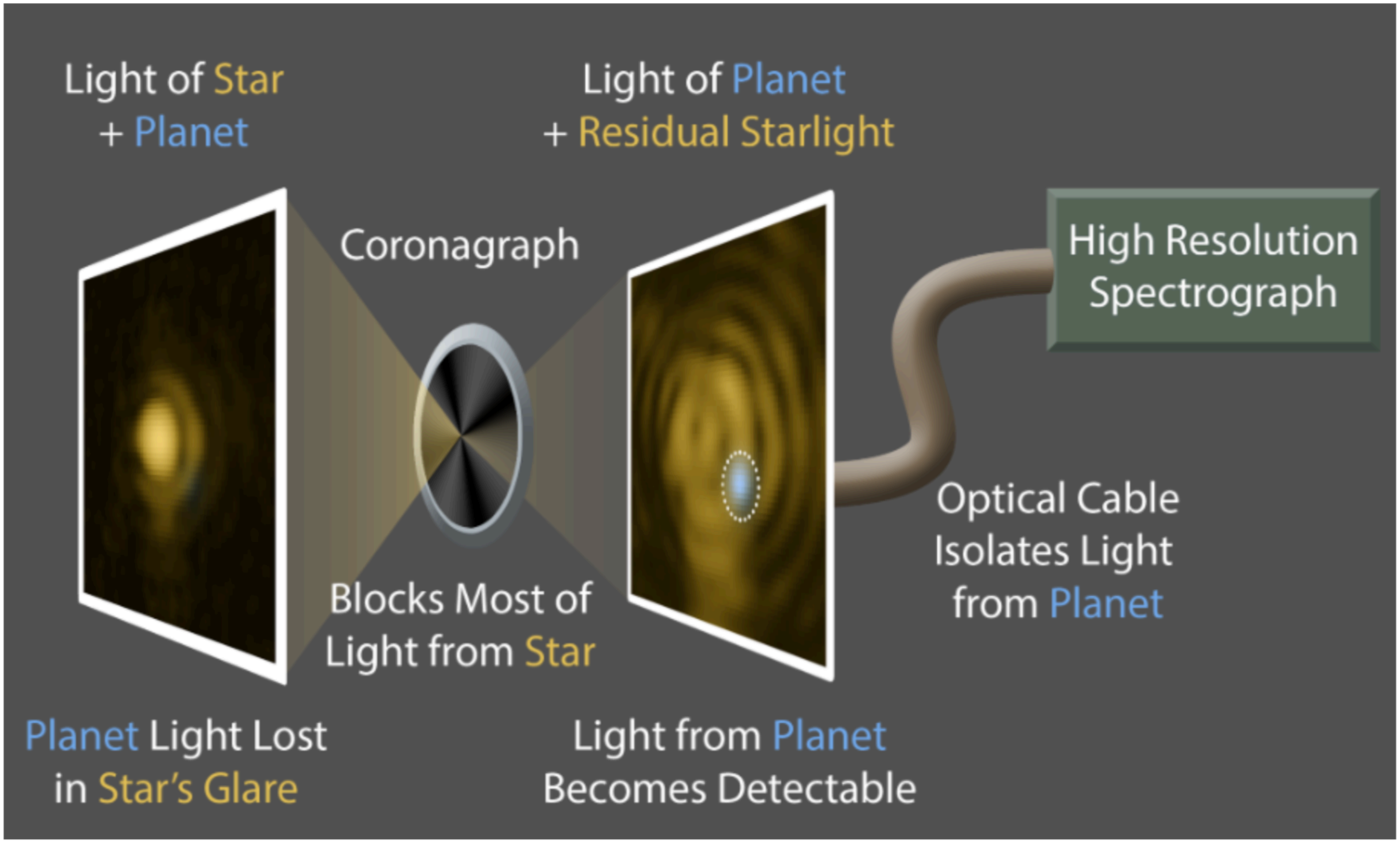
S/N
CO ~14.5
H2O ~17.0

Hoeijmakers et al. 2018

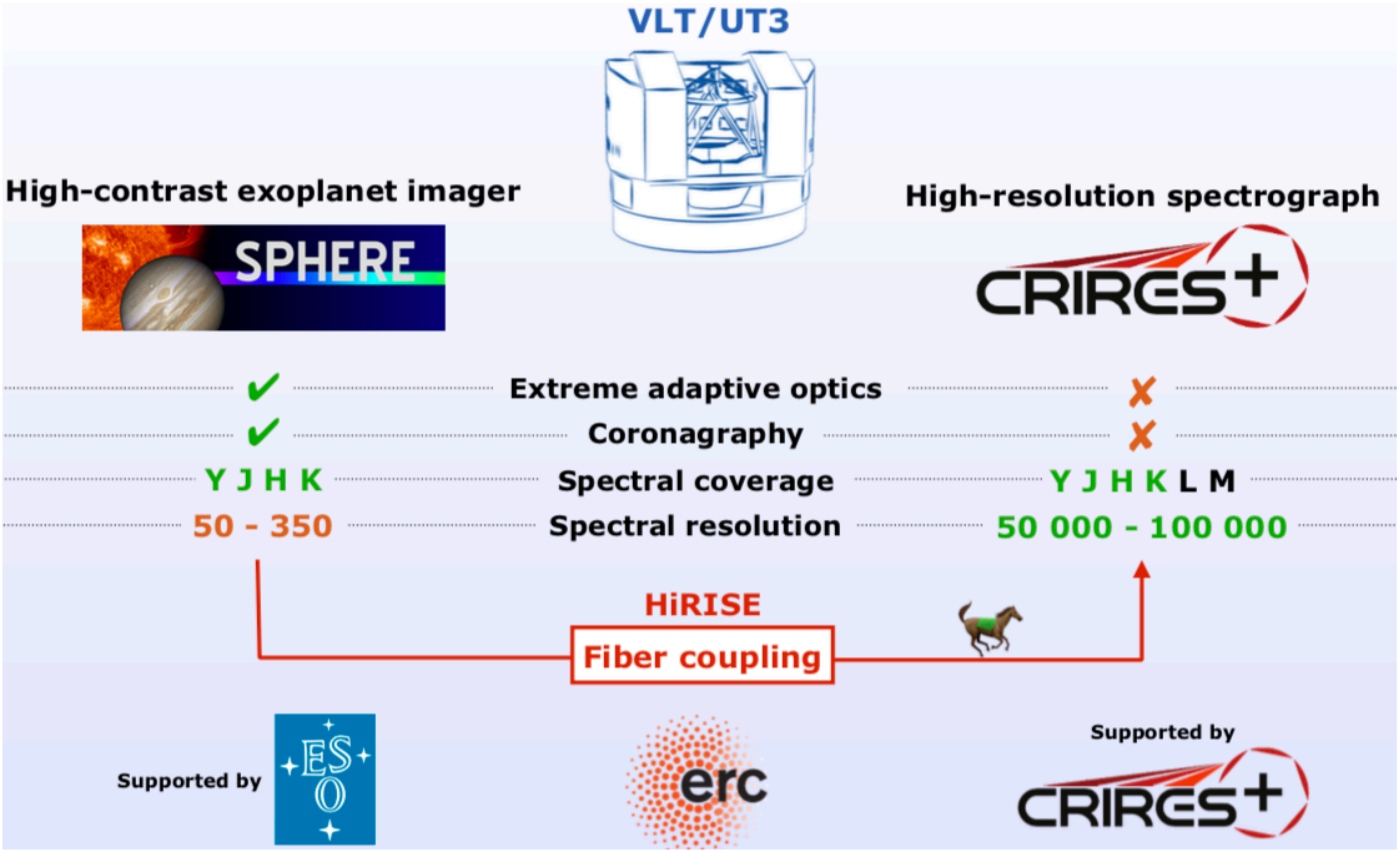
High dispersion coronagraphy for imaged exoplanets

$$S/N = \frac{S_{\text{planet}}}{\sqrt{S_{\text{star}}/K + \sigma_{\text{bg}}^2 + \sigma_{\text{RN}}^2 + \sigma_{\text{Dark}}}} \sqrt{N_{\text{lines}}}$$

K ~Contrast

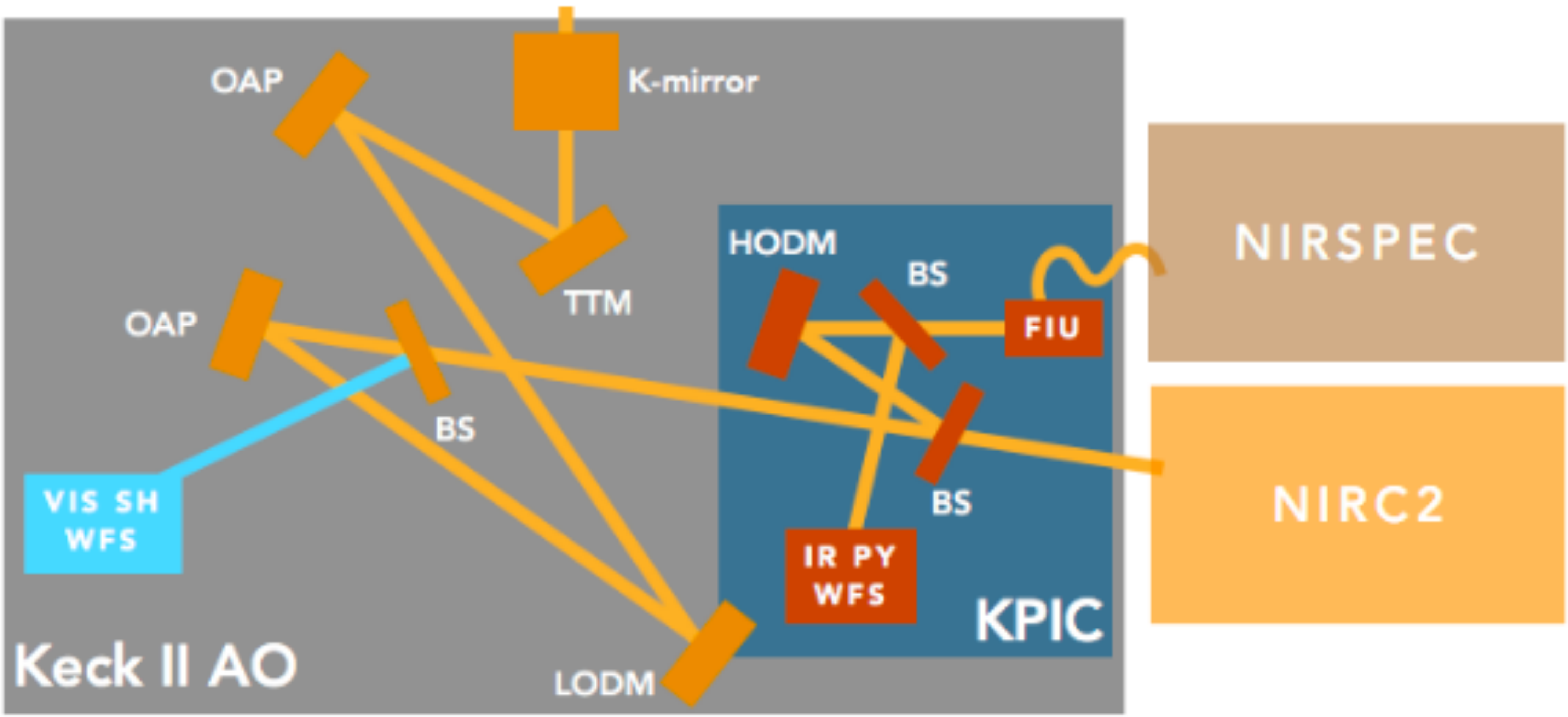


Future prospects
VLT/SPHERE & CRIRES+



Vigan et al. 2018

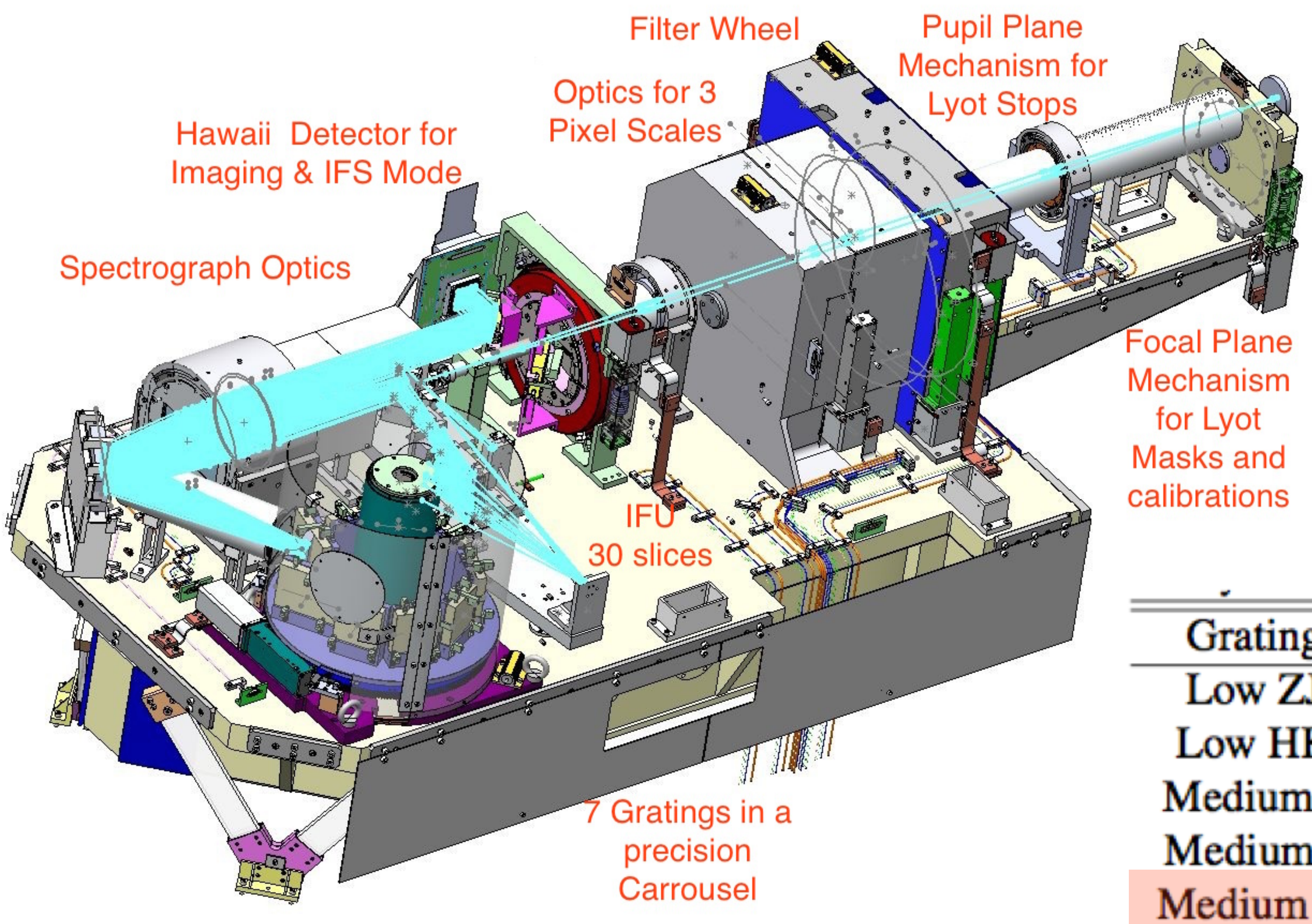
Future prospects
Keck Planet Imager and Characterizer



Mawet et al. 2018

Future prospects
FRIDA on Gran Telescopio Canarias

Near infrared imager and integral field spectrograph



- ~11m aperture diameter
- GTCAO, SR~60% in K-band
- Coronagraph masks

Grating	l/mm	order	Range (μm)	Resolution Power R
Low ZJ	30	2nd	0.9-1.35	1371
Low HK	30	1st	1.45-2.5	1032
Medium z	1st	200	0.9-1.15	3597
Medium J	1st	300	1.16-1.34	6701
Medium H	1st	150	1.45-1.82	4326
Medium K	1st	100	1.95-2.5	3916
High H	1st	720	1.617-1.653	26546
High K	1st	600	2.110-2.175	32172

Watson et al. 2016, N'Diaye et al. 2018

Conclusion

- High dispersion spectroscopy for imaged exoplanets
  - promising for **both detection & characterization**
  - viable to study rocky planets with ground-based instruments

- More to come with forthcoming instruments
  - on the current 8-10m class telescopes
    (VLT, KECK, Subaru, Magellan, GTC)
  - on the ELTs
    (ELT/HARMONI, TMT/IRIS)

Extra slides