Master in Space Sciences - Academic year 2021-2022

SPAT0063 Introduction to exoplanetology

Lecture 7: Direct exoplanet detection methods (2/2)
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In our last episode…

- Four pillars of high-contrast imaging
    - Adaptive optics —> put the light back inside the Airy pattern of the telescope, reduce brightness of speckles
    - Coronagraphy —> reduce the amount of starlight on the whole detector, or in a chosen zone
    - Observing strategy —> induce some kind of diversity between the planetary signal and the residual stellar speckles
    - Image processing —> subject of today's lecture

Outline

I. Direct detection: why and how?

II. High contrast imaging

  I. Coronagraphy

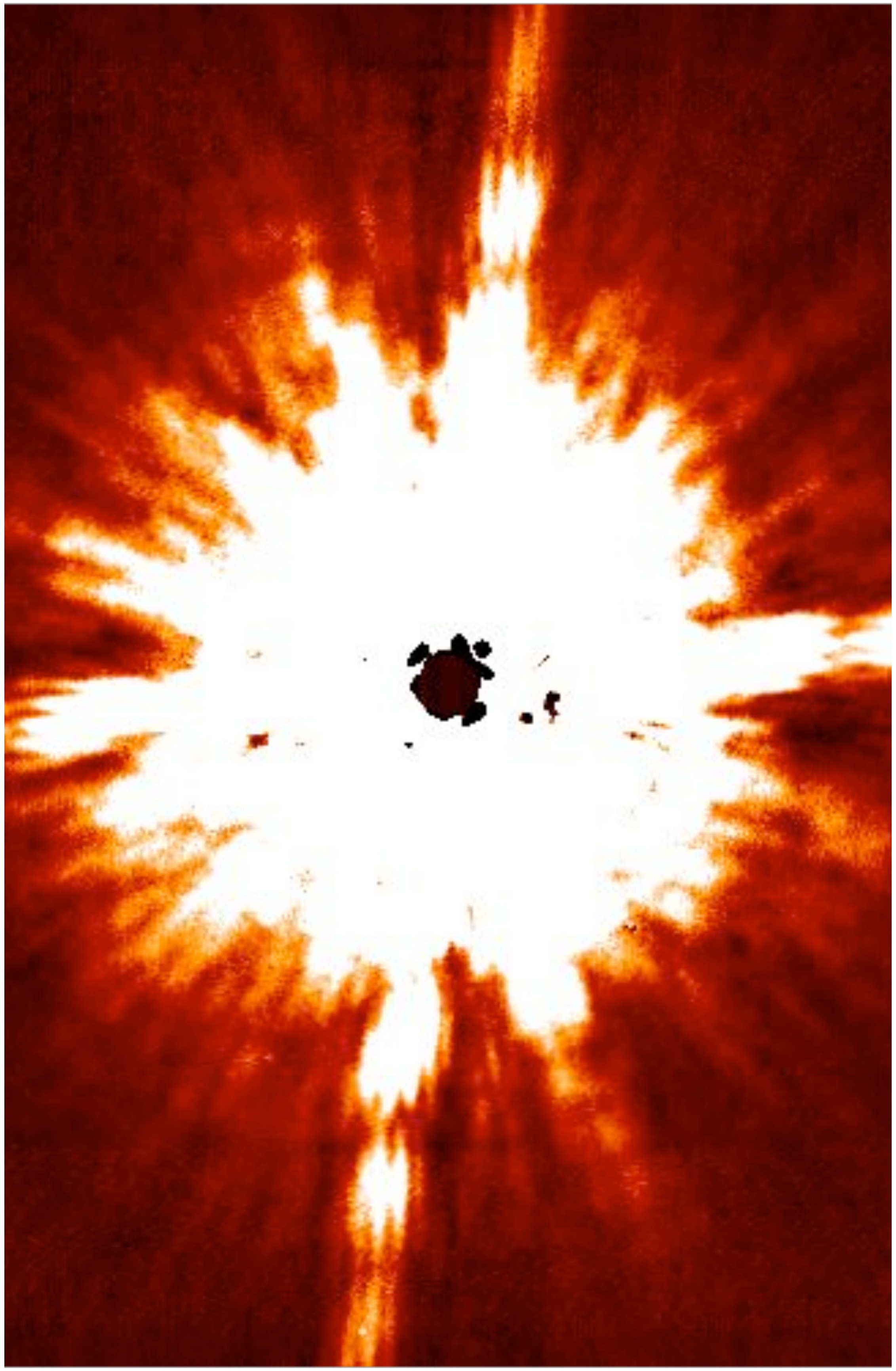
  II. Observing strategies

  III. Image processing

III. Main results from high-contrast imaging

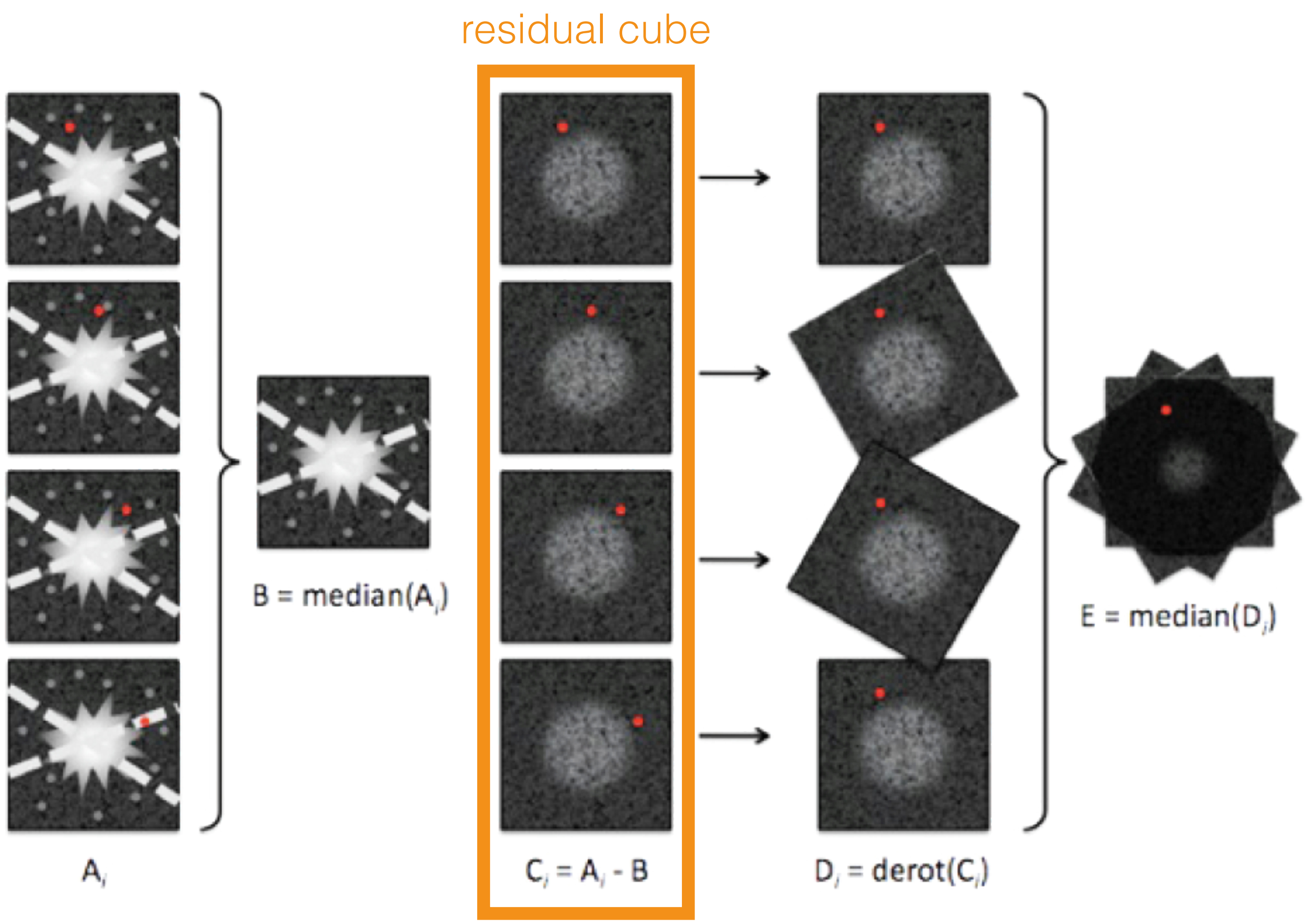
Getting rid of speckles

3. Image processing



Principle of post-processing

- Use [angular/spectral/other] diversity to build best possible reference PSF, and subtract it from the data
  - best reference PSF may vary from frame to frame
  - results in a « residual cube » of images (2D images vs angle or wavelength)



- Use residual cube to perform detection
  - standard method: derotate and combine residuals to produce final image, in which the signal-to-noise ratio is measured locally and used for detection
  - more advanced: use time evolution in residual cube + advanced statistical tools

The LOCI algorithm

- Locally Optimized Combination of Images
- Goal: make best use of a set of reference images
  - Express reference PSF as linear combination of all individual frames (e.g. in an ADI data cube)
- Least squares problem: solve a linear system to minimize residuals

coefficients to be determined

ref PSF

individual frames

$$O^R = \sum_{k \in K} c^k O^k,$$

to be minimized

target PSF

$$\sigma^2 = \sum_i m_i (O_i^T - O_i^R)^2 = \sum_i m_i \left(O_i^T - \sum_k c^k O_i^k \right)^2,$$

pixels

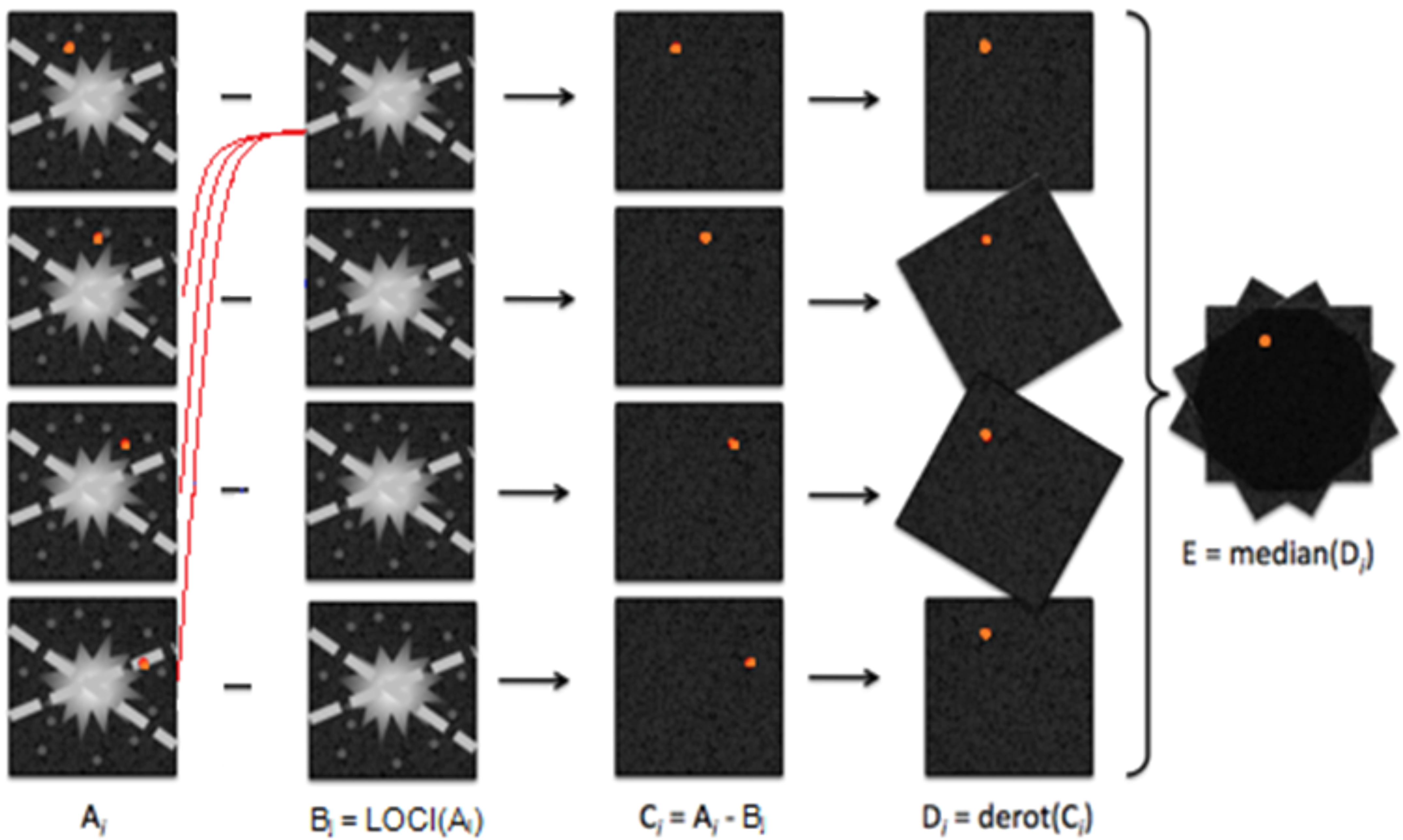
$$\frac{\partial \sigma^2}{\partial c^j} = \sum_i -2 m_i O_i^j \left(O_i^T - \sum_k c^k O_i^k \right) = 0, \quad \forall\, j \in K.$$

$$\sum_k c^k \left(\sum_i m_i O_i^j O_i^k \right) = \sum_i m_i O_i^j O_i^T, \quad \forall\, j \in K.$$

$$\boldsymbol{Ax} = \boldsymbol{b}$$

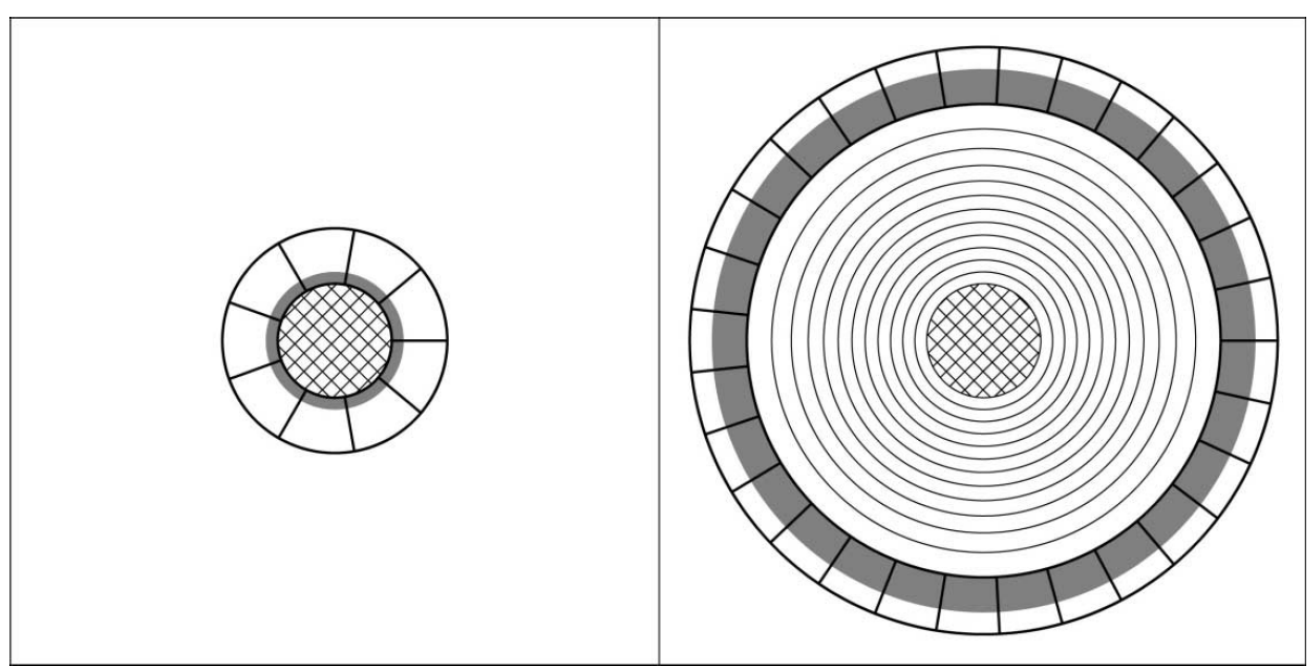
$$A_{jk} = \sum_i m_i O_i^j O_i^k, \quad x_k = c^k, \quad b_j = \sum_i m_i O_i^j O_i^T.$$

LOCI working with ADI



Practical use of LOCI

- To be applied locally because correlation between frames expected to depend on position
  - Optimize LOCI coefficient on « optimization » zone
  - Perform PSF subtraction on « subtraction » zone
  - Optim. zone > subtr. zone to avoid planet signal subtraction

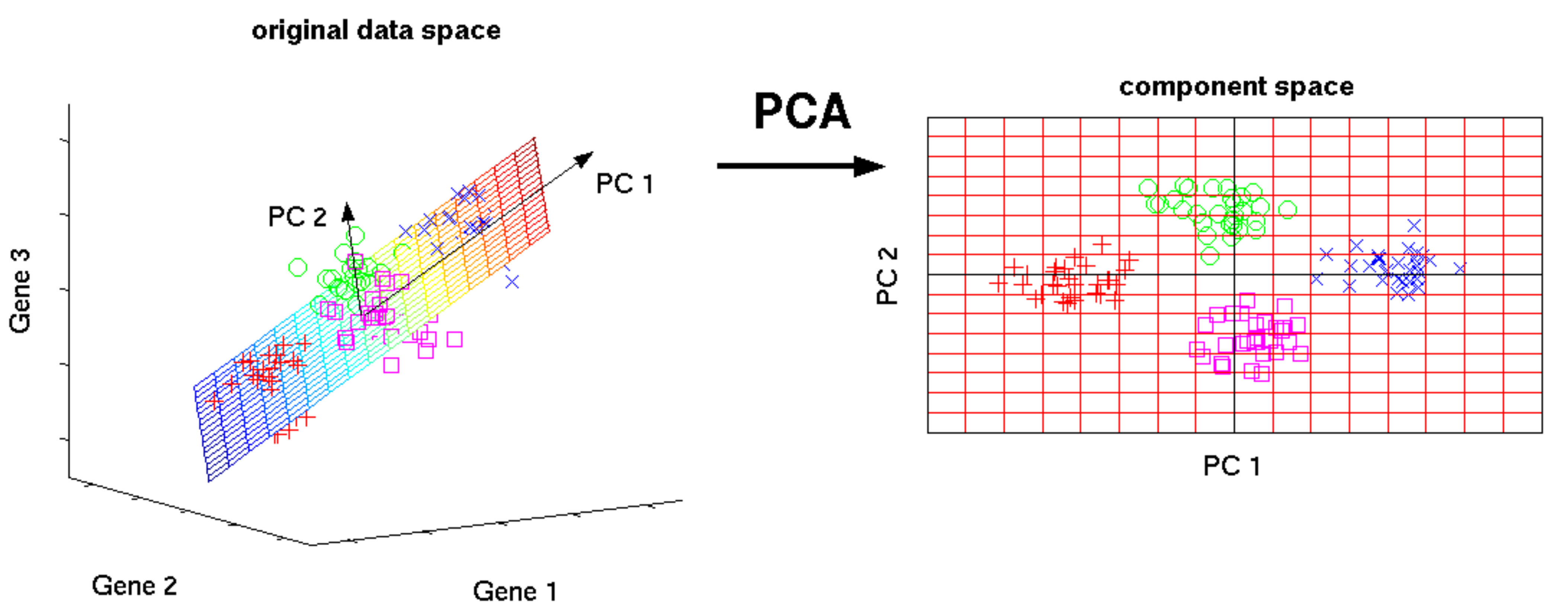


Pros and cons of LOCI

- Several free parameters
  - \+ Can be fine tuned to any particular data set
  - – Not very straightforward to use
- – Strong self-subtraction of planetary signal
  - LOCI tries to remove everything → bias on photometry
  - Can be evaluated with fake companions, or mitigated by introducing even more parameters (masking)
- – CPU intensive

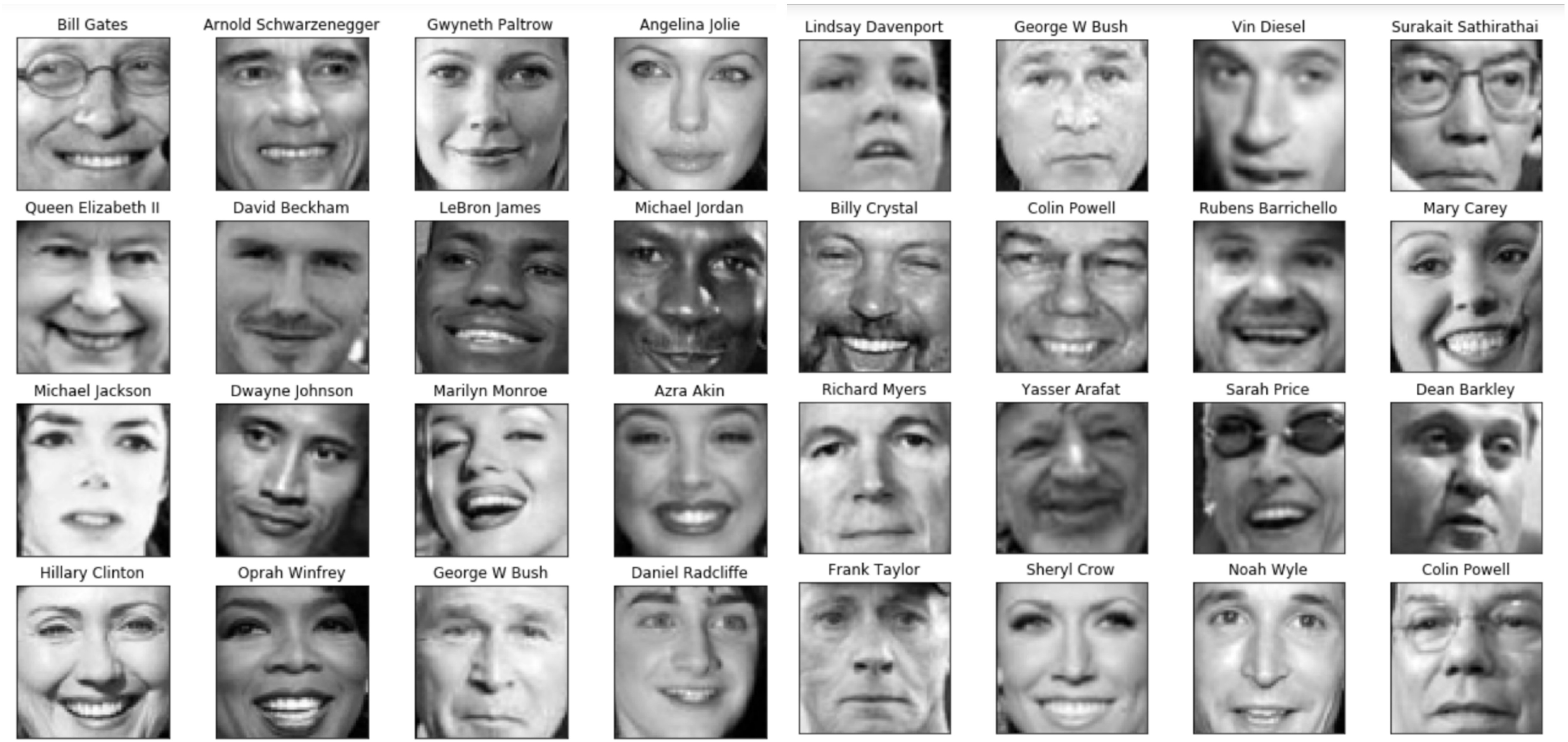
Principal Component Analysis (PCA)

- Method to reduce the dimensionality of a data set
  - try to explain data with a smaller number of **independent** variables
- Application to direct imaging
  - build an orthogonal basis of images to represent the science images
  - truncate the basis (= create low-rank subspace) to build reference PSF



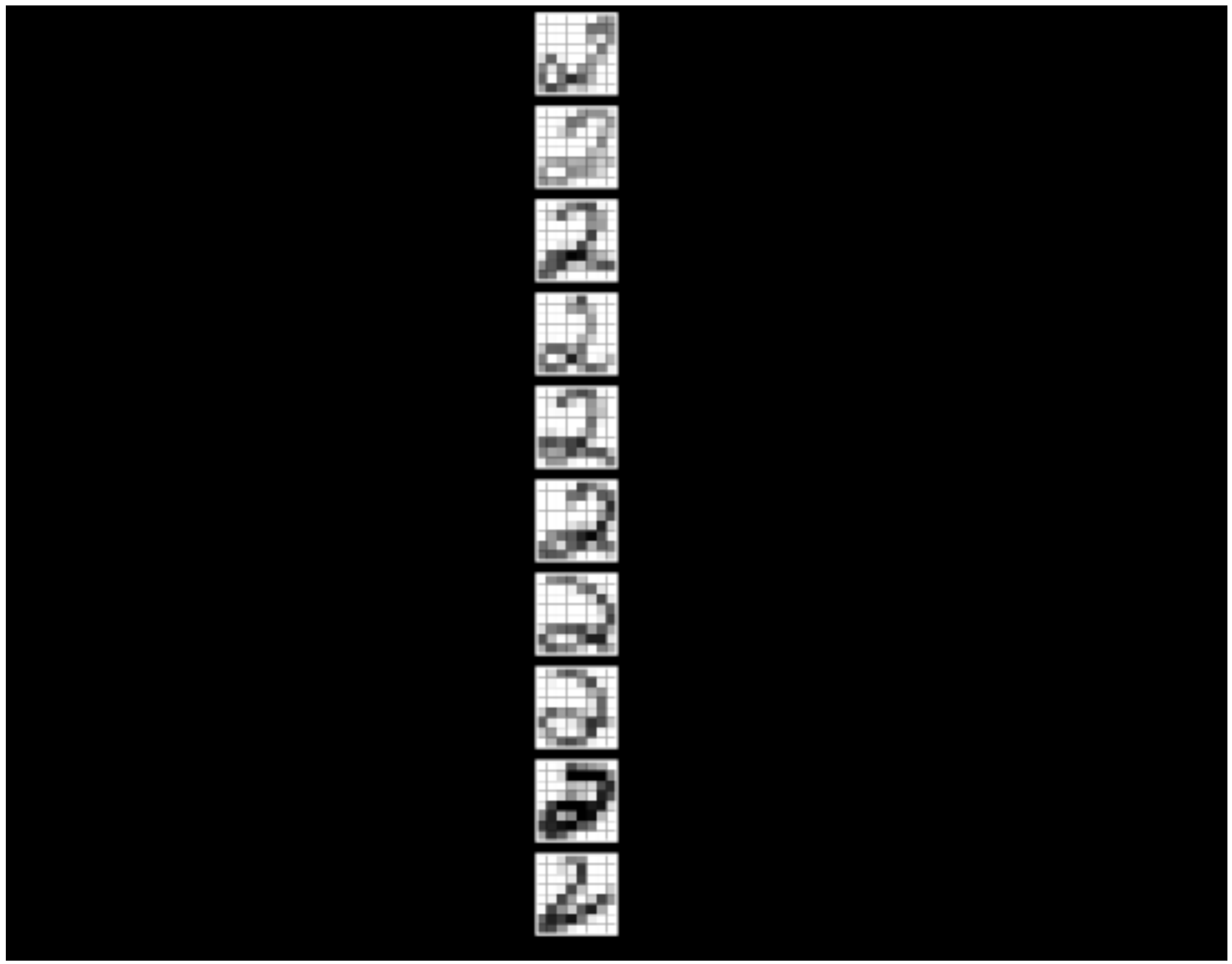
PCA with images

https://towardsdatascience.com/eigenfaces-recovering-humans-from-ghosts-17606c328184



1) start with 1000 faces, 64x64 pixels each

PCA with images



reshape images into vectors —> new matrix X $(N \times D^2)$

PCA with images

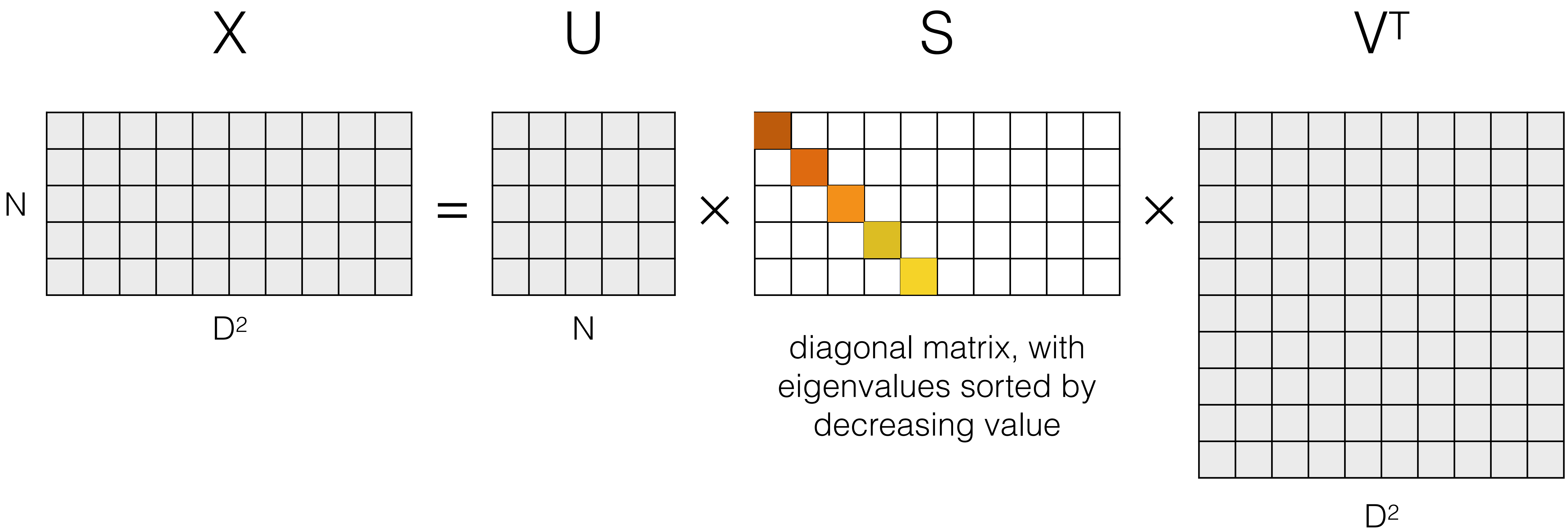
2) subtract mean
(shown here as 2D image… spooky!)

3) compute eigenfaces V, using e.g. SVD

$$X = USV^T$$

V = orthogonal basis of images

Singular Value Decomposition



Columns of V (= lines of V^T) are principal directions / axes. Here, they correspond to images ('eigenfaces').

PCA with images

4) Project individual faces on eigenfaces and sum

(—> weighted combination of eigenfaces)

here using **50 eigenfaces**: reconstruct the main traits without the details

PCA with images

4) Project individual faces on eigenfaces and sum

(—> weighted combination of eigenfaces)

100 eigenfaces: more details

PCA with images

4) Project individual faces on eigenfaces and sum

(—> weighted combination of eigenfaces)

250 eigenfaces: most details now included

PCA with images

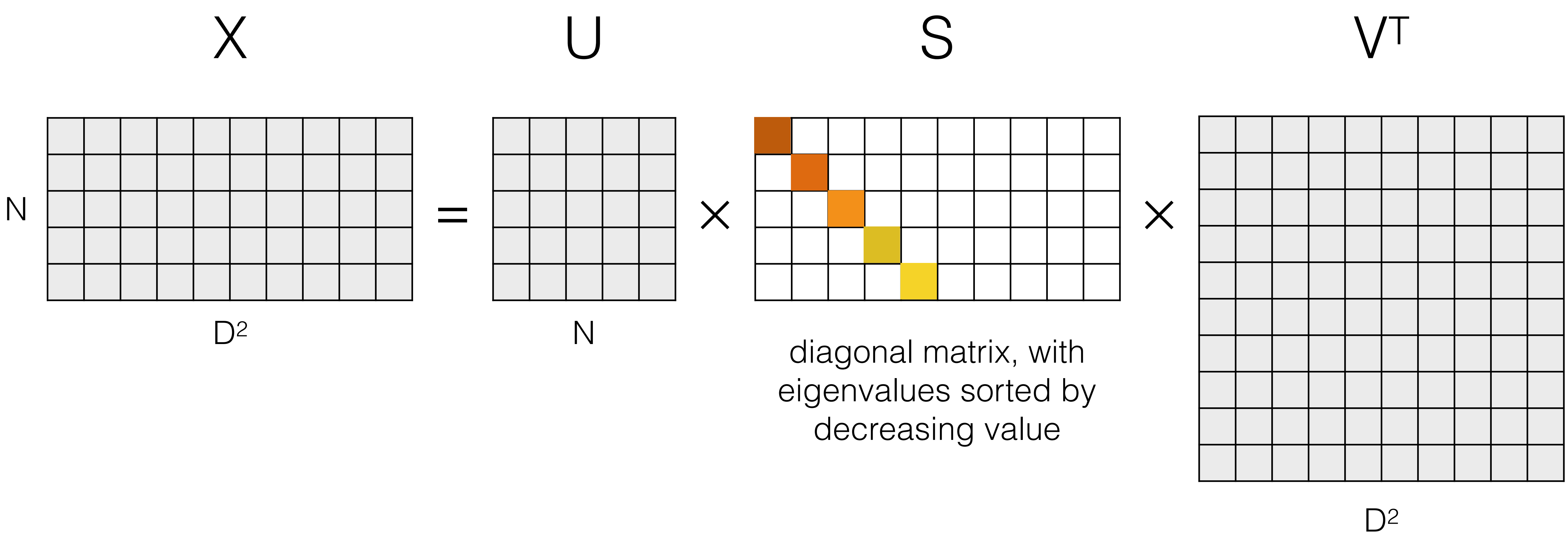
4) Project individual faces on eigenfaces and sum

(—> weighted combination of eigenfaces)

… and **1000 eigenfaces**: back to original pictures!

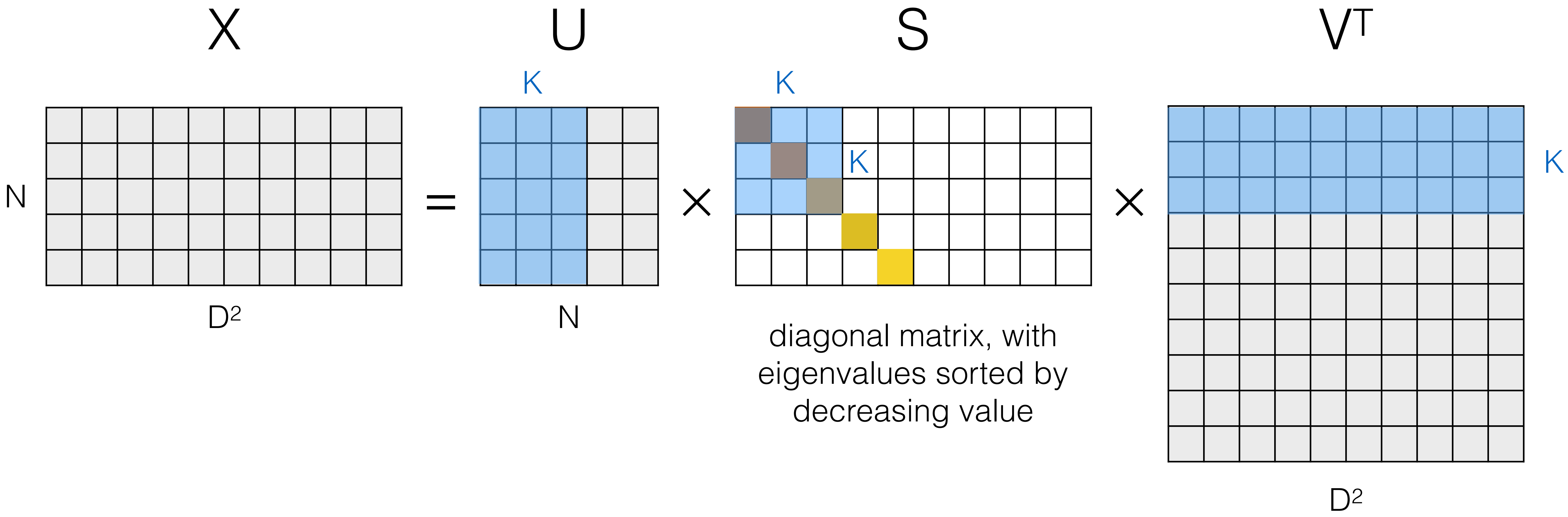
The maths of PCA

- Subtract mean (M) from data set (D): $X = D - M$
- Compute principal directions (aka eigenvectors) using SVD
    - $X = USV^T$, with V the principal directions / axes
    - V can also be computed as eigenvectors of covariance XX^T matrix



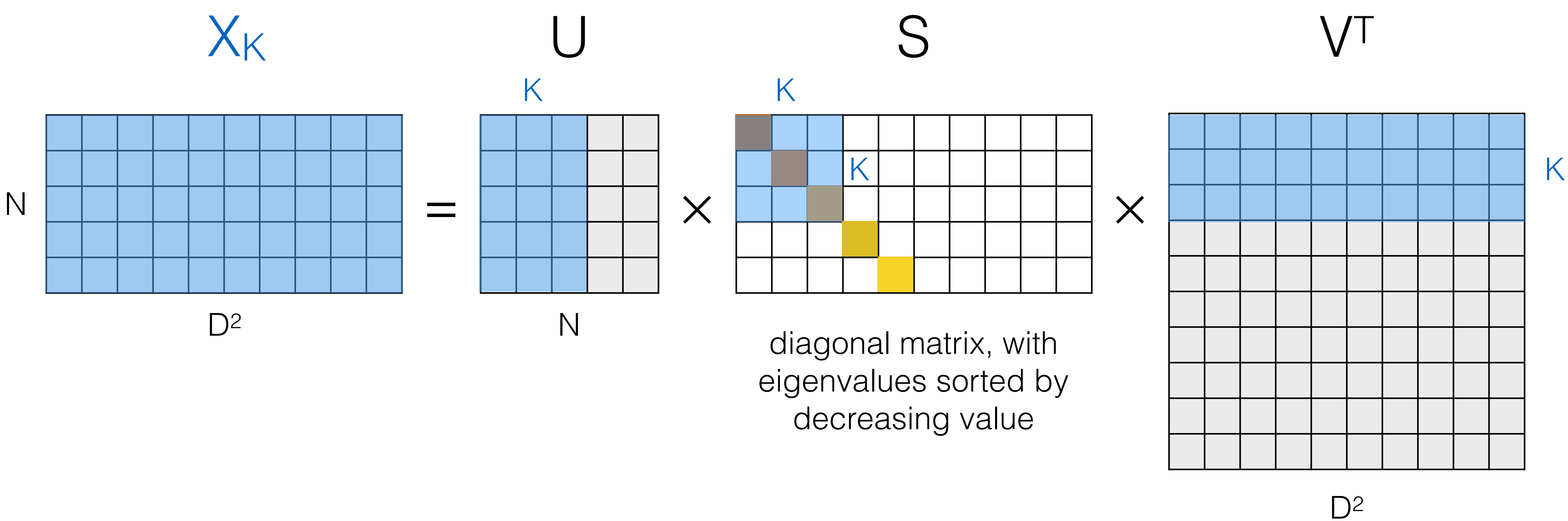
The maths of PCA

- Choose first K eigenvectors in V → V_K
  - truncated basis will capture only the features that are most common in the images
  - if planet diversity (movement) is large enough, and K is low enough, it will not be captured

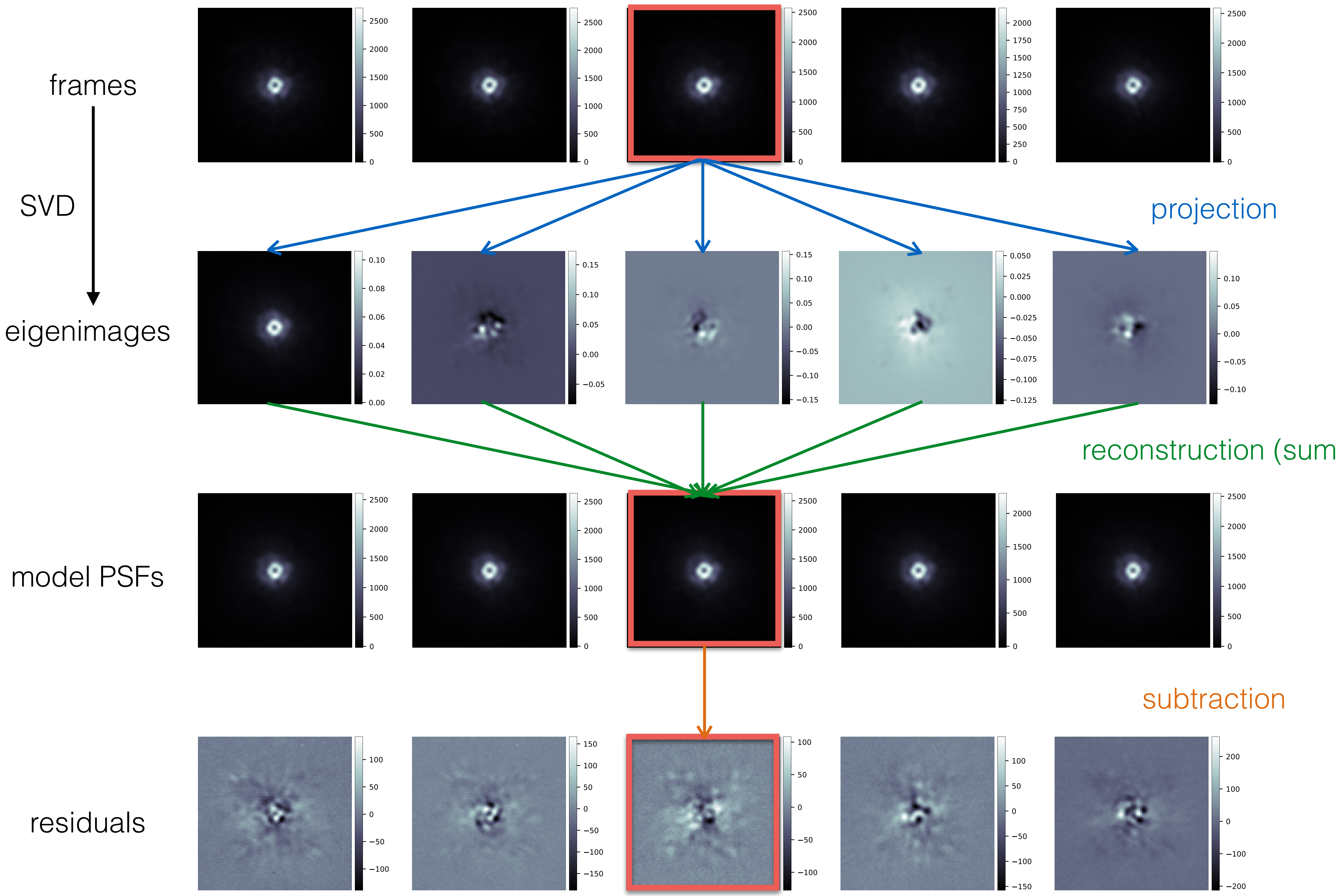


The maths of PCA

- Project data onto these principal directions
  - The projections $P_K = X\ V_K$ (= $U_K\ S_K$) are the first K principal components, telling how much of each eigenvector is needed to reproduce a given image in X
- The reconstruction $X_K = U_K\ S_K\ V_K^T$ is our PCA-truncated estimation of the PSF, to be subtracted from each individual frame to remove (quasi)static features



(note: here the data is not mean-subtracted —> first eigenimage contains mostly the mean)

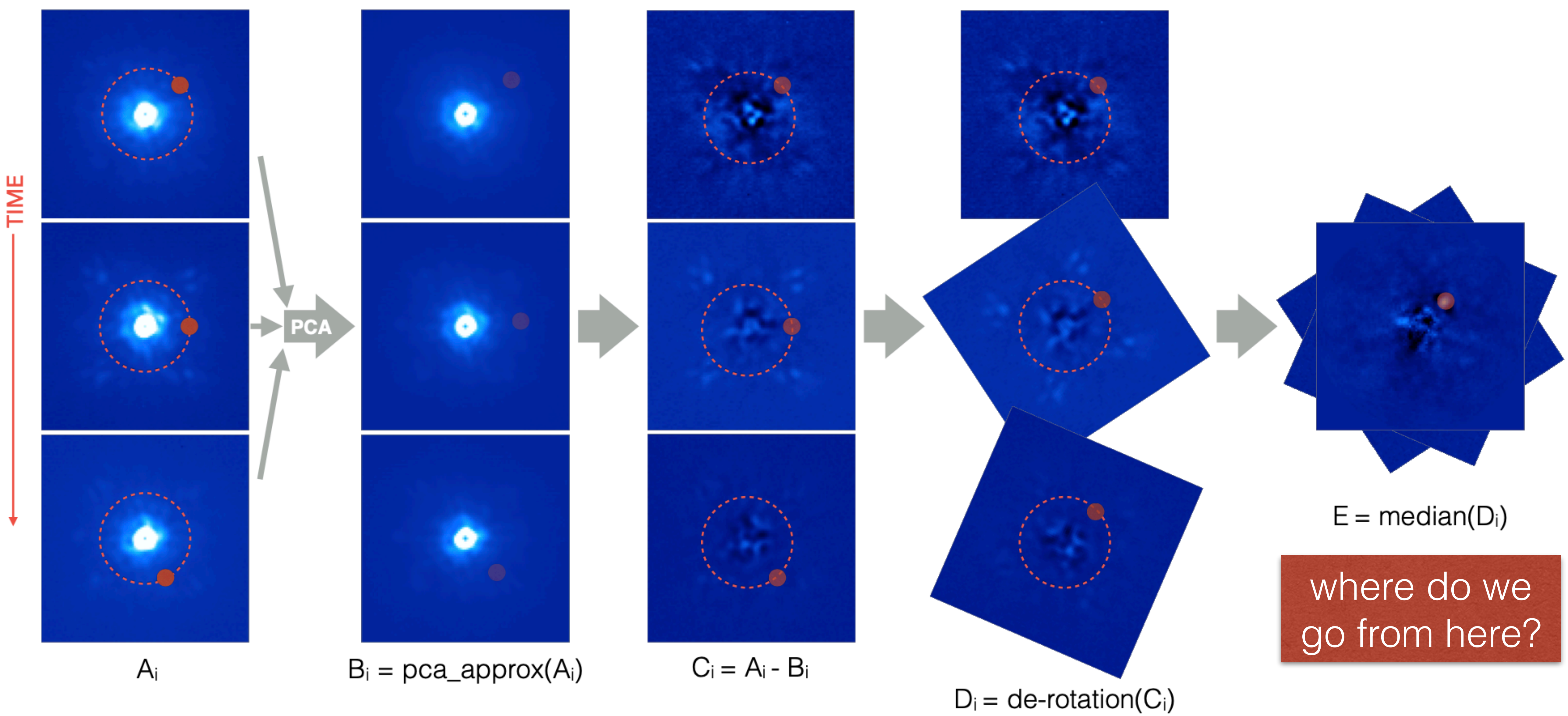


Reconstruct PSF of (mean-subtracted) image as projection onto low-rank subspace (= first K principal components), hoping that moving planet will not be captured.

Pros and cons of PCA

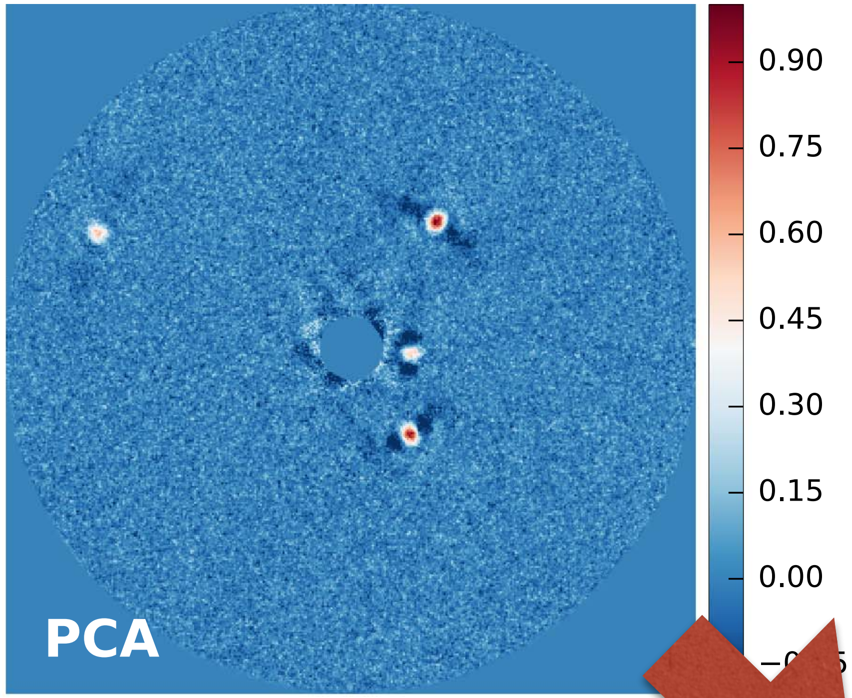
- + Can be applied to whole image at once
  - + CPU time can be drastically reduced!
  - – In practice, annulus-wise version is generally better because of radial structure of noise
- – Self-subtraction reduced, but still present
  - + Reduced bias wrt LOCI, generally more linear
  - – Fake companion injection still needed to recover flux (can also be handled by forward modeling)

Last step: detection

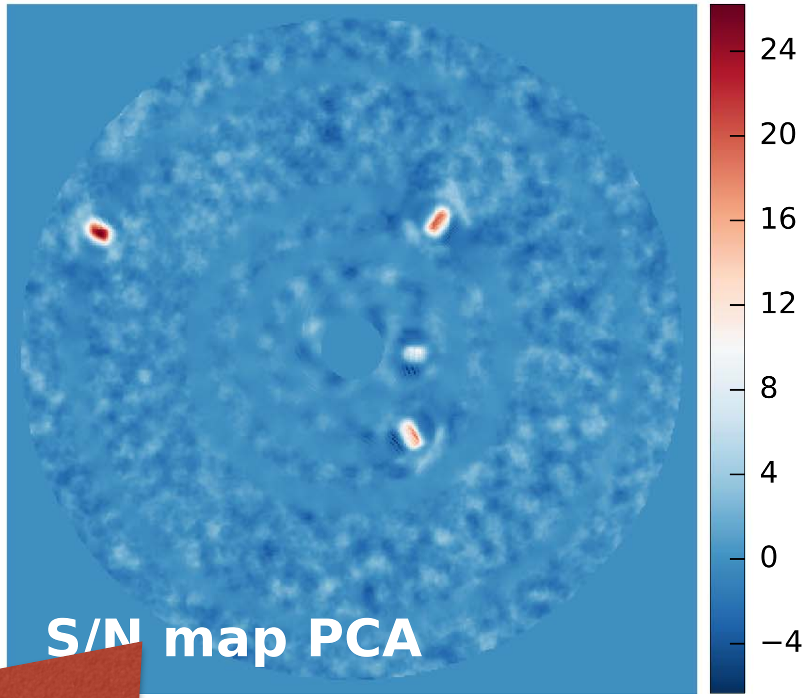


SNR map

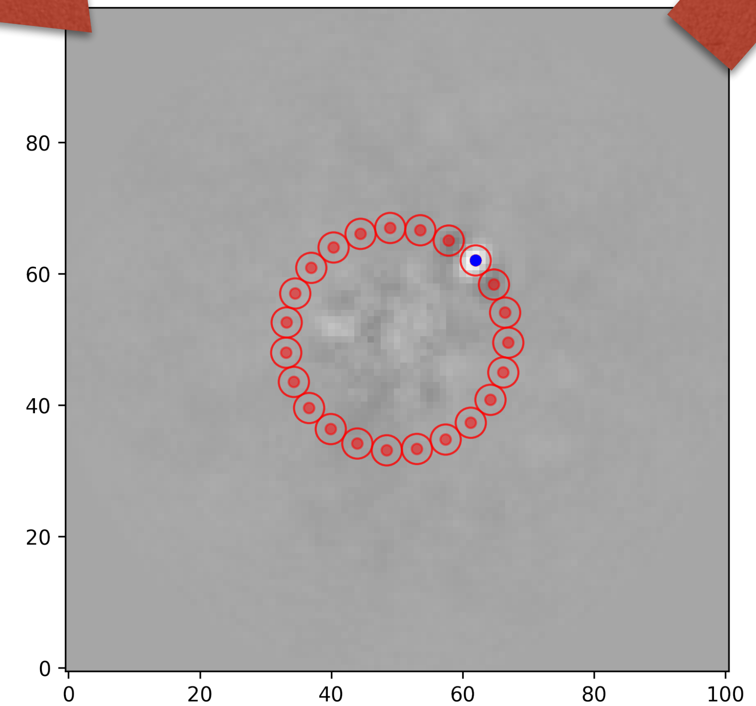
Final frame



SNR map



Annular noise estimation

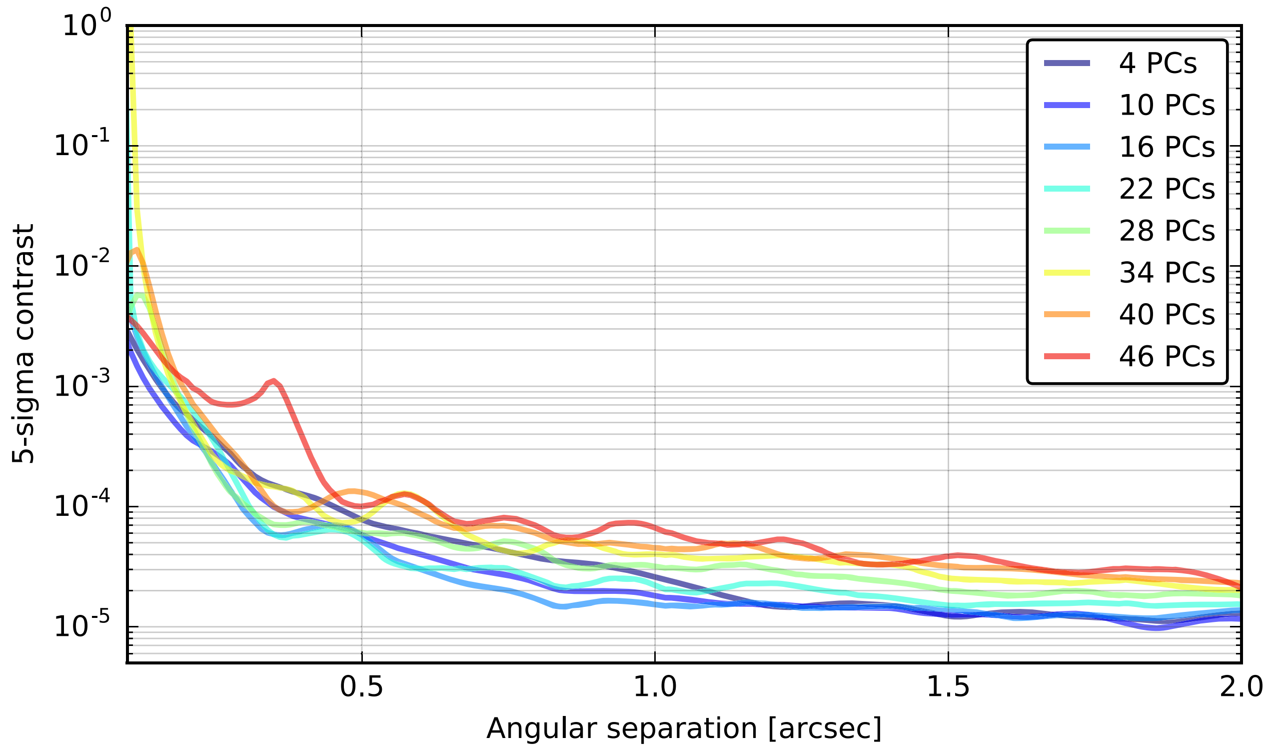


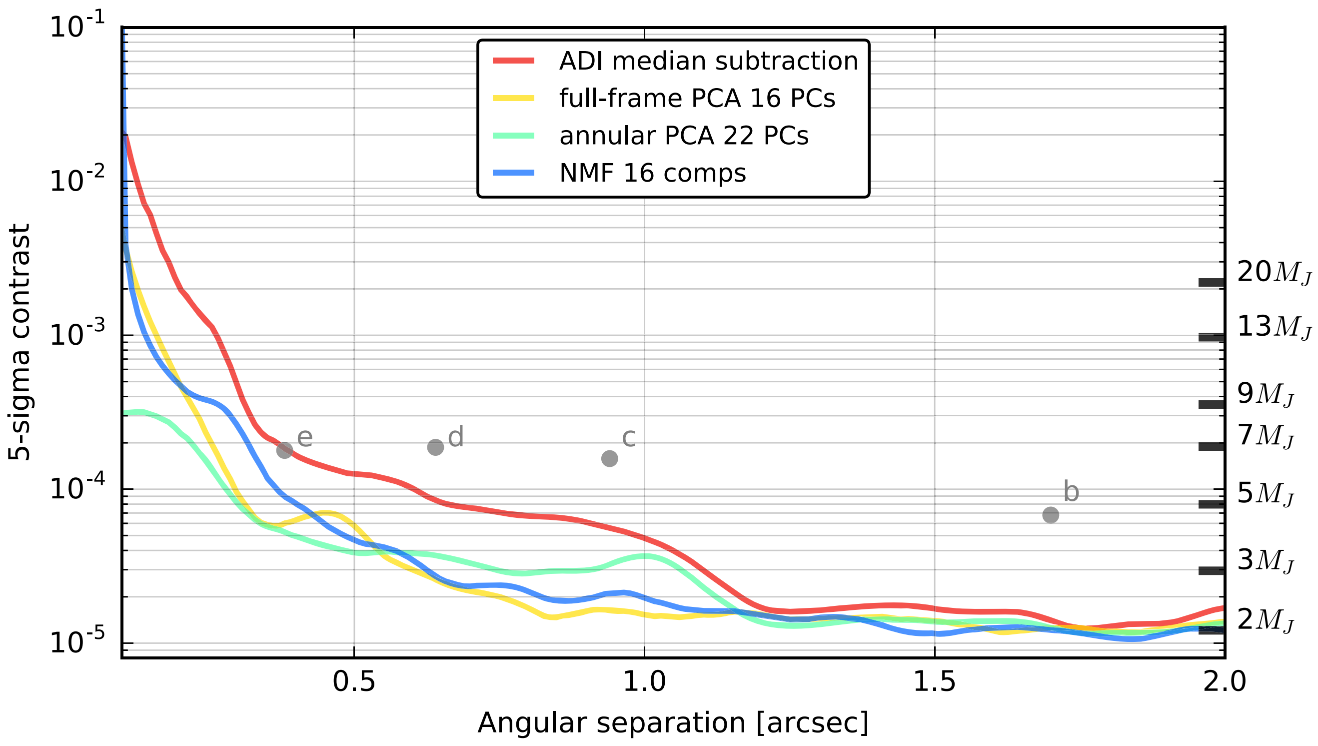
Detection is made by comparing signal with noise

SNR map can then be thresholded, typically at SNR=5

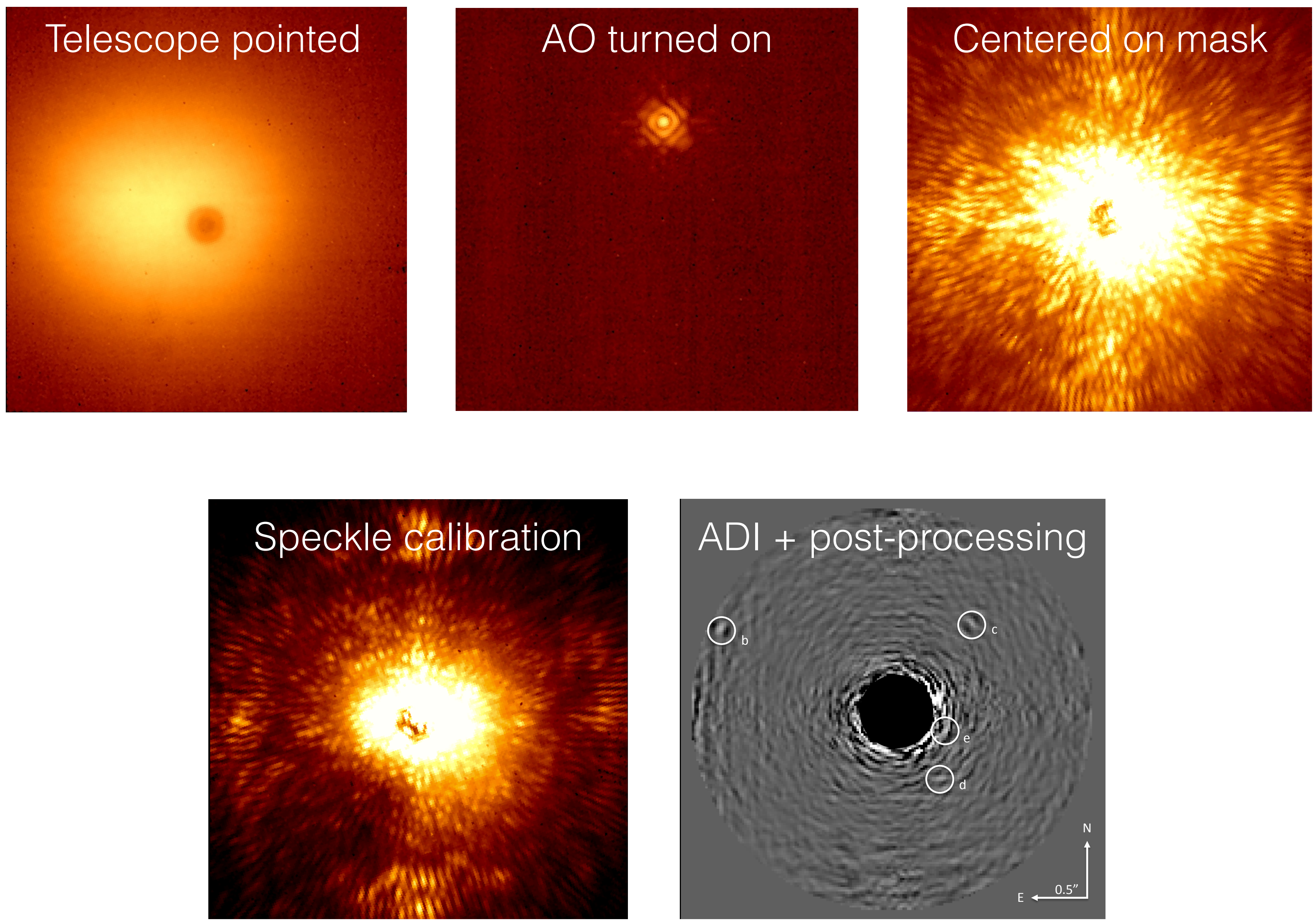
Detection limits

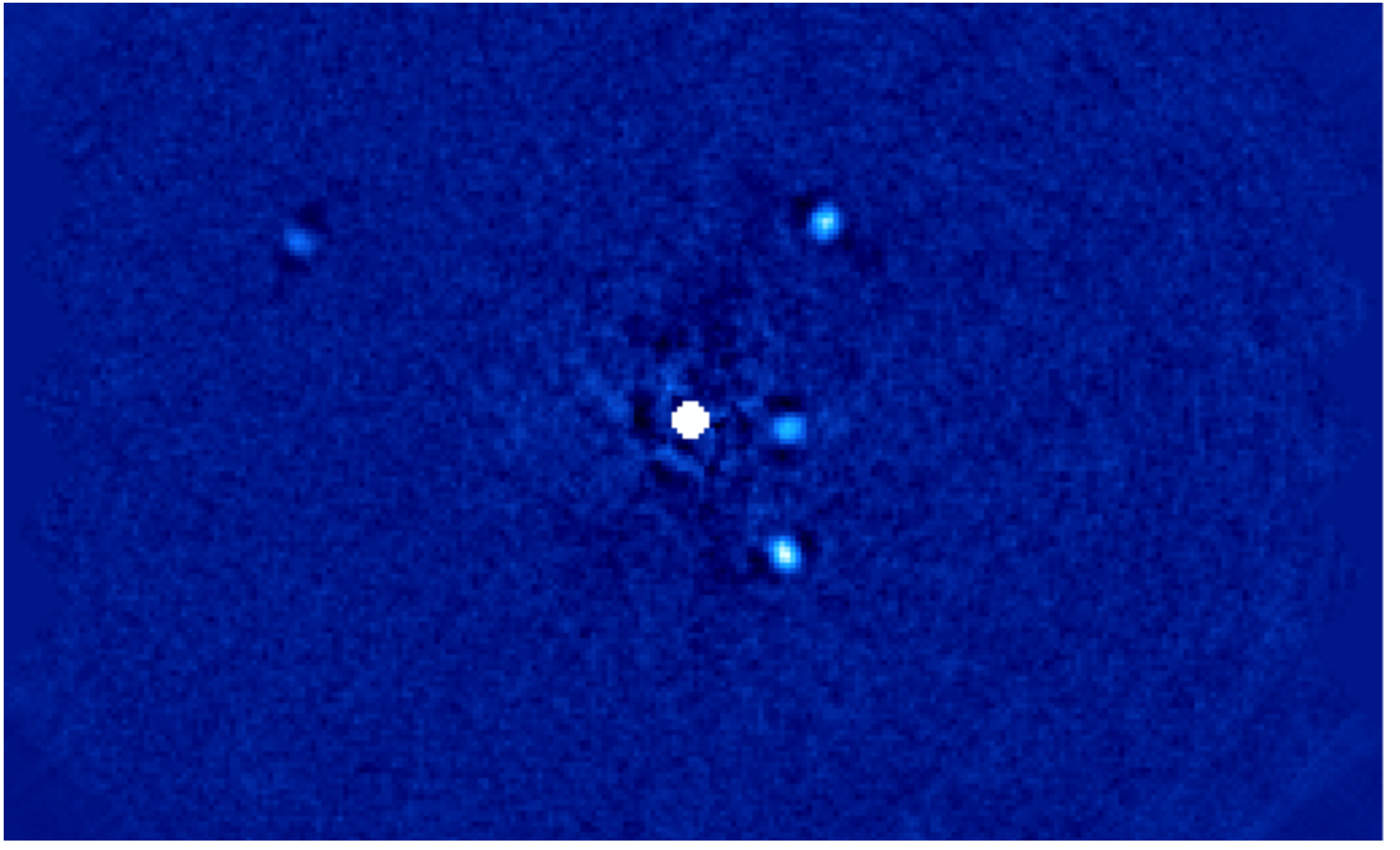
- Determine the faintest companion that could have been detected based on the data
- Contrast curves: displays this sensitivity limit as a function of angular separation





All steps in one picture



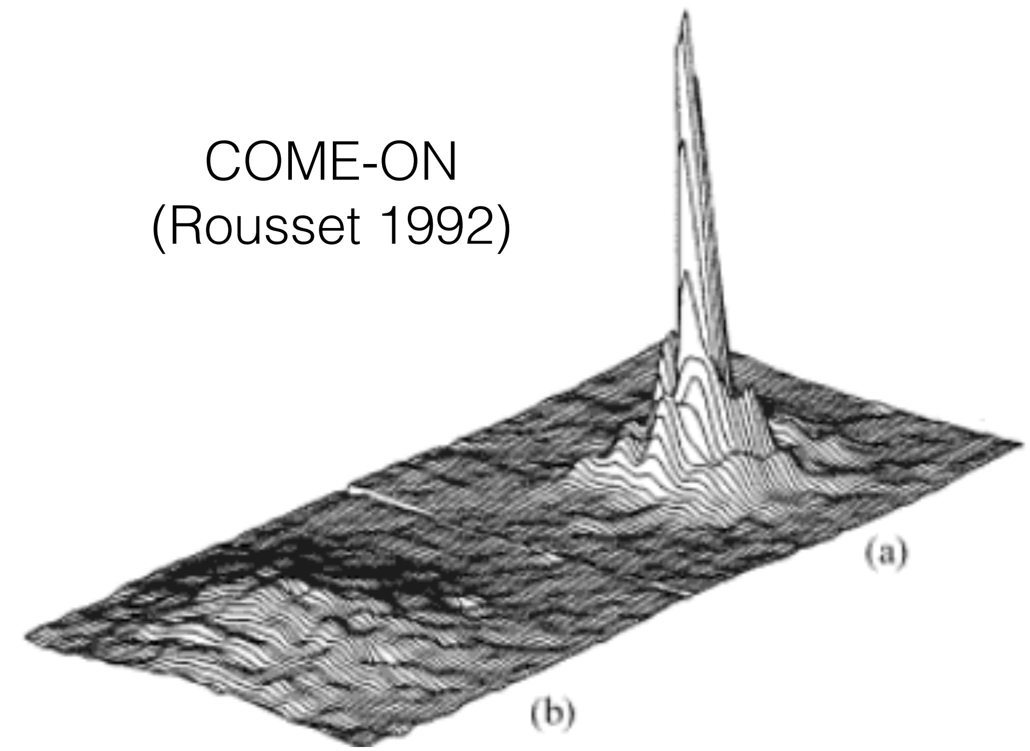


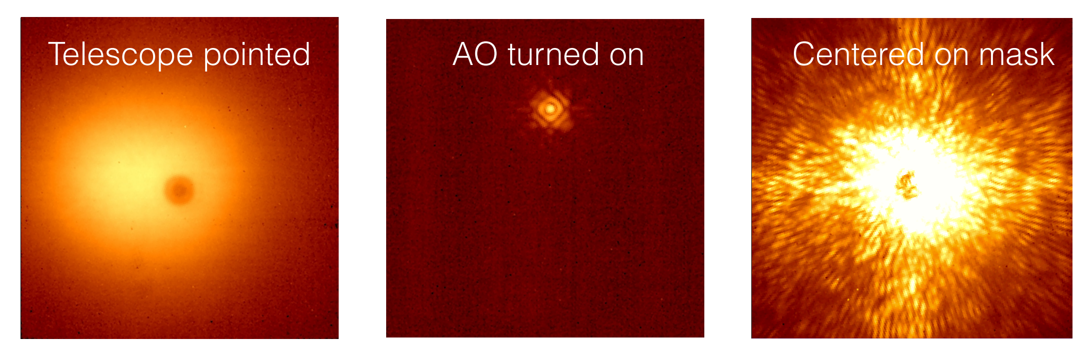
III. Main results from high-contrast imaging

Precursor instruments

- OHP 1.52m / COME-ON (1989-1992)
  - 19 actuators (demonstrator, moved to Chile)
- ESO 3.6m / COME-ON+ (1993-1996)
  - 52 actuators @ 200Hz —> first scientific results (Strehl ratio ~ 20%)
- ESO 3.6m / ADONIS (1996-2001)
  - First AO system widely offered to the community
  - Includes Lyot coronagraph
- Some early experiments also in the US (Lick observatory)
- Still far from detecting exoplanets!

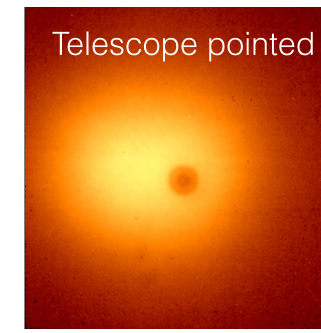
COME-ON
(Rousset 1992)

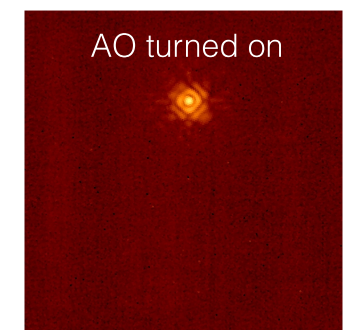


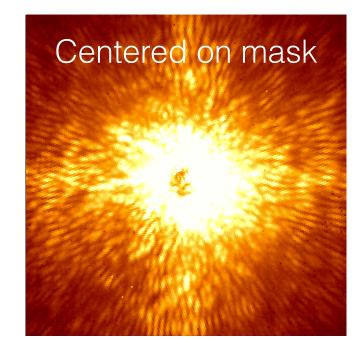


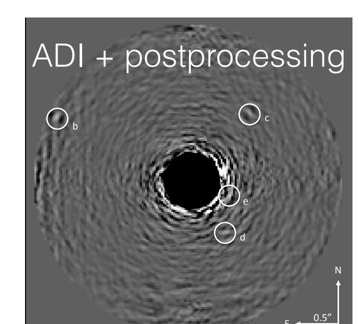
10m-class telescopes: a 1st generation of AO instruments

- AO-assisted IR cameras on large telescopes
  - VLT/NACO (= NAOS adaptive optics + CONICA camera)
  - Keck/NIRC2 behind Keck-AO
  - Gemini/NIRI & NICI
  - Subaru/CIAO & HiCIAO
- AO operation started at Keck and VLT in 2001
- First use of custom observing strategies and data processing (ADI, SDI)





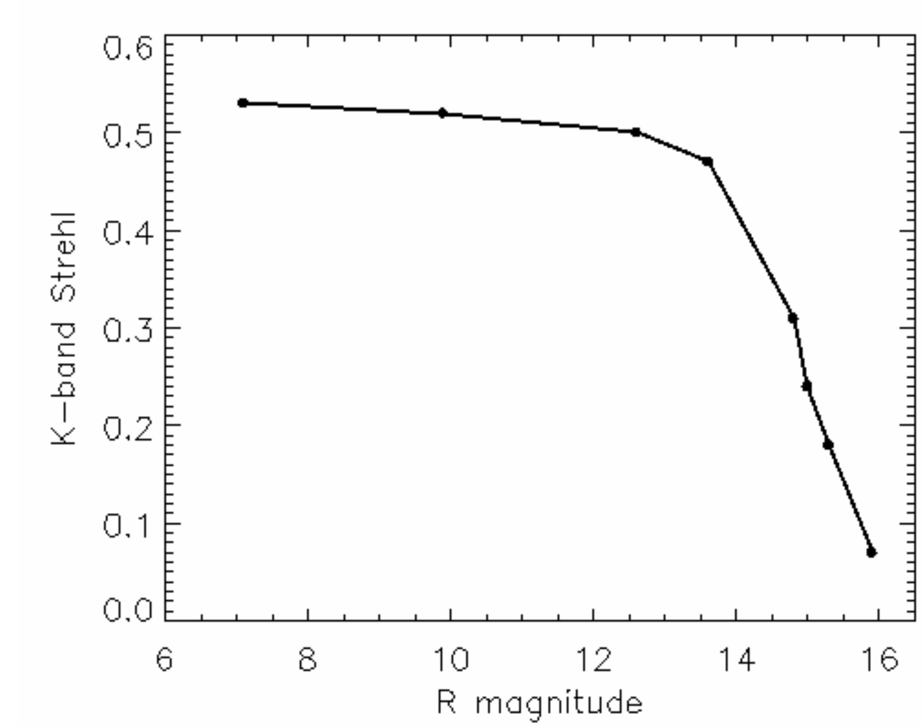




10m-class telescopes: first generation

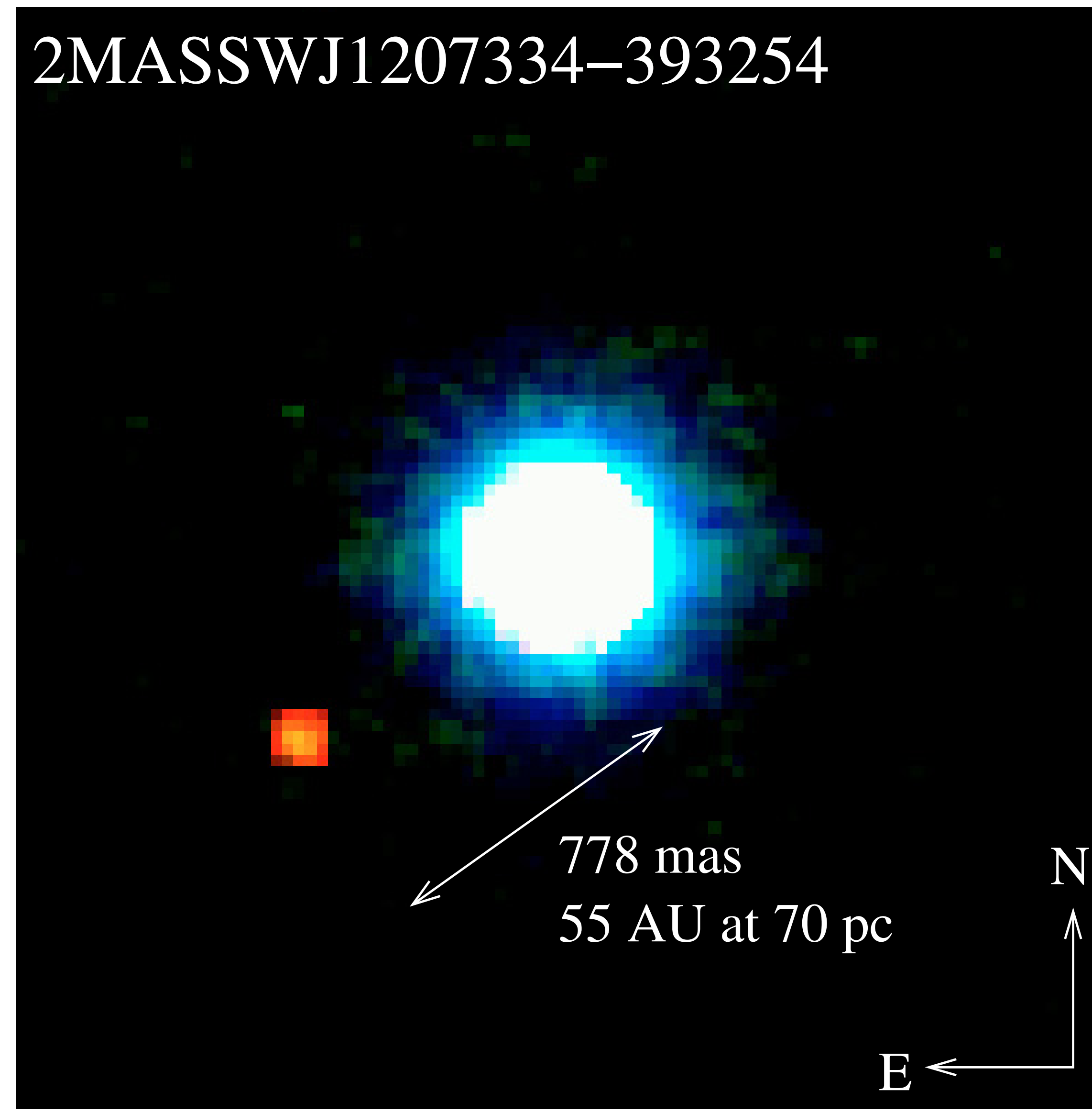
- Working in the 1-5 μm regime (JHKLM bands)
- Typically 200 to 300 actuators using a Shack-Hartman sensor
- Strehl ratio up to 60% at K band
- Still mostly Lyot coronagraphs
  - being upgraded with vortex phase masks, APP, etc.

Keck-AO

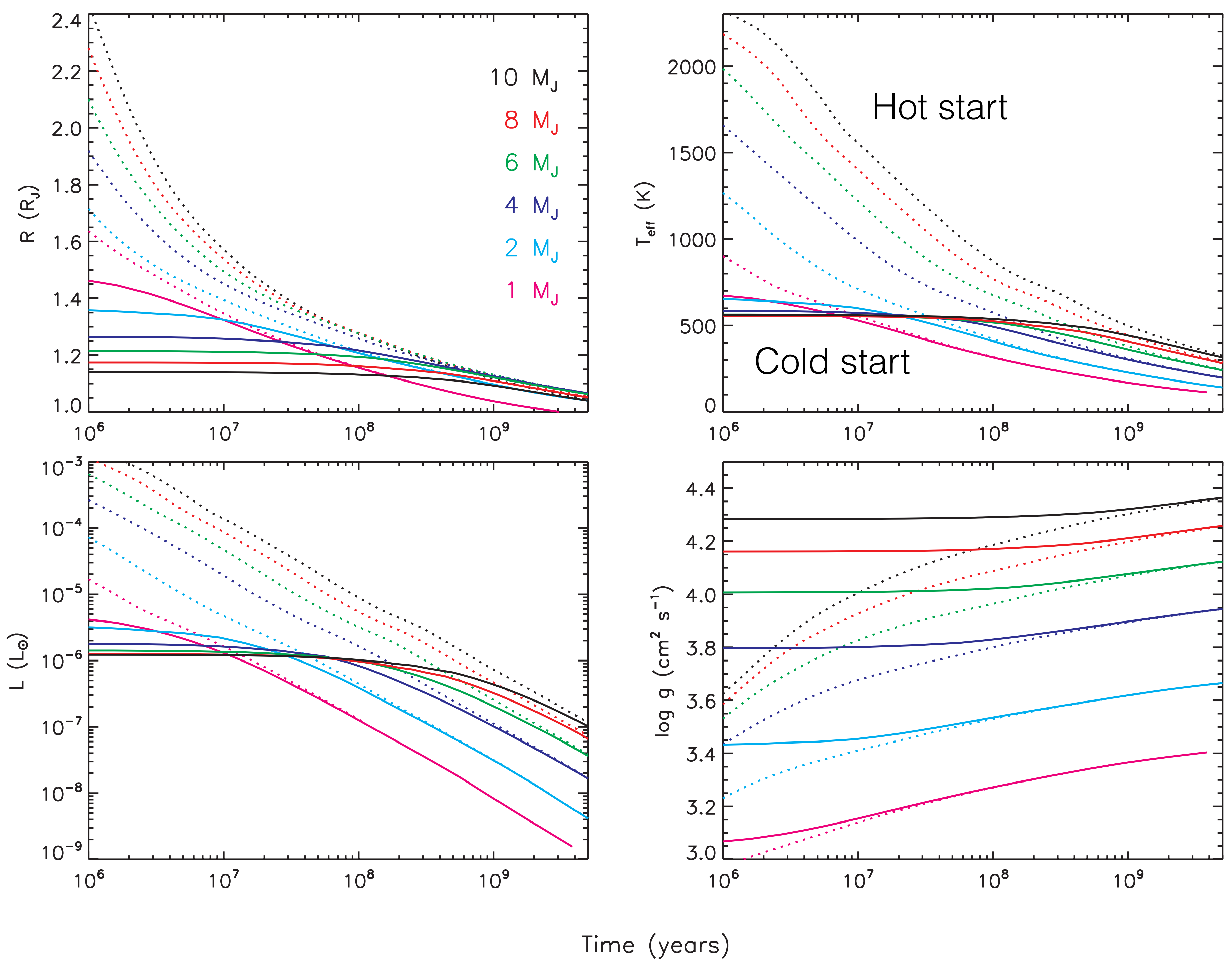


2004: first detection of a planetary-mass object

- A giant planet close to a young brown dwarf
  - Low contrast (4.5 to 6.5 mag)
  - Moderate angular separation (0.78" = 55 AU)
- Detected with NACO
  - Confirmed to be co-moving in 2005
- Mass: 2 - 5 M_{Jup}
  - Did it form like a planet? — more likely a low-mass binary system

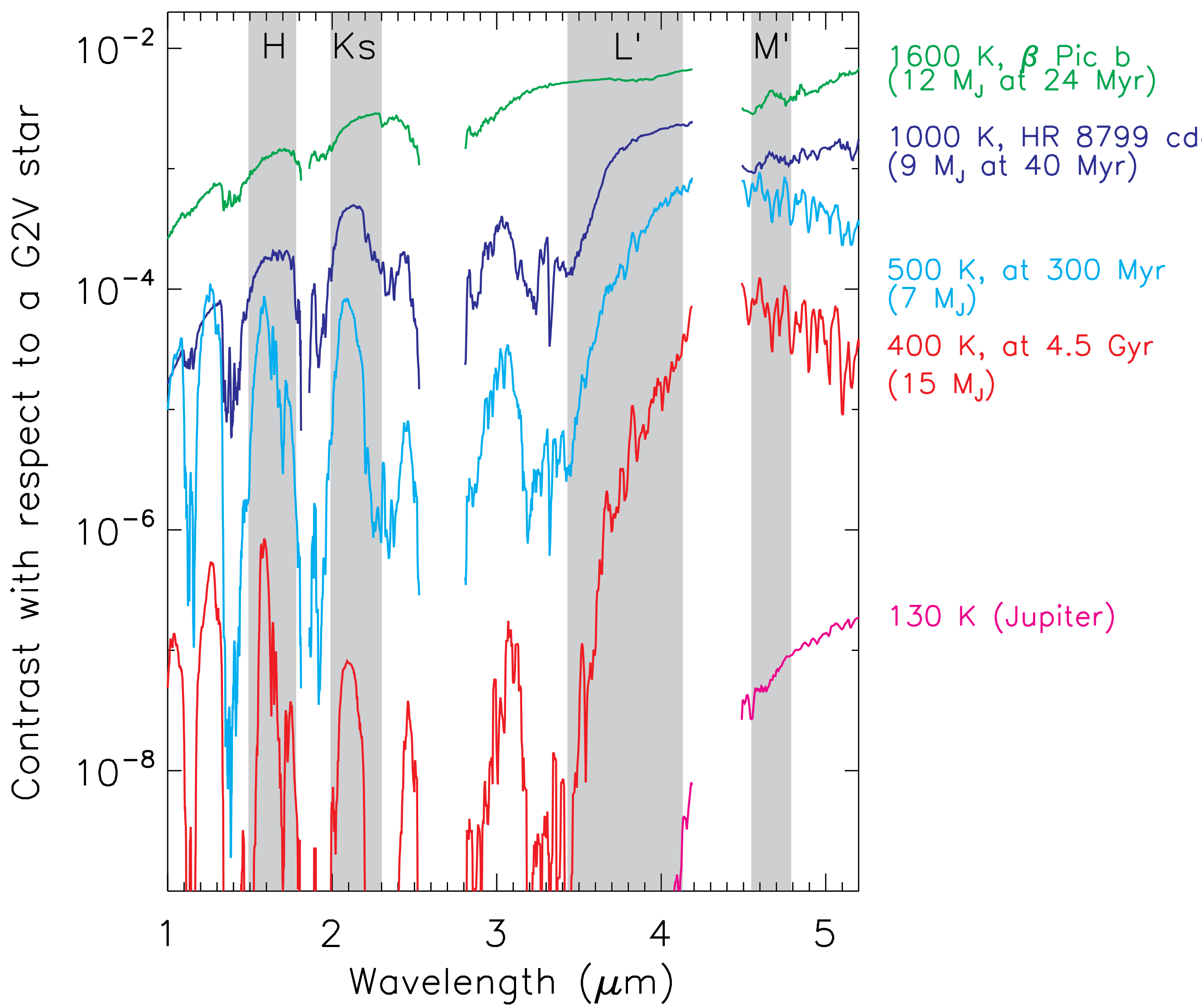


Why look for young planets?



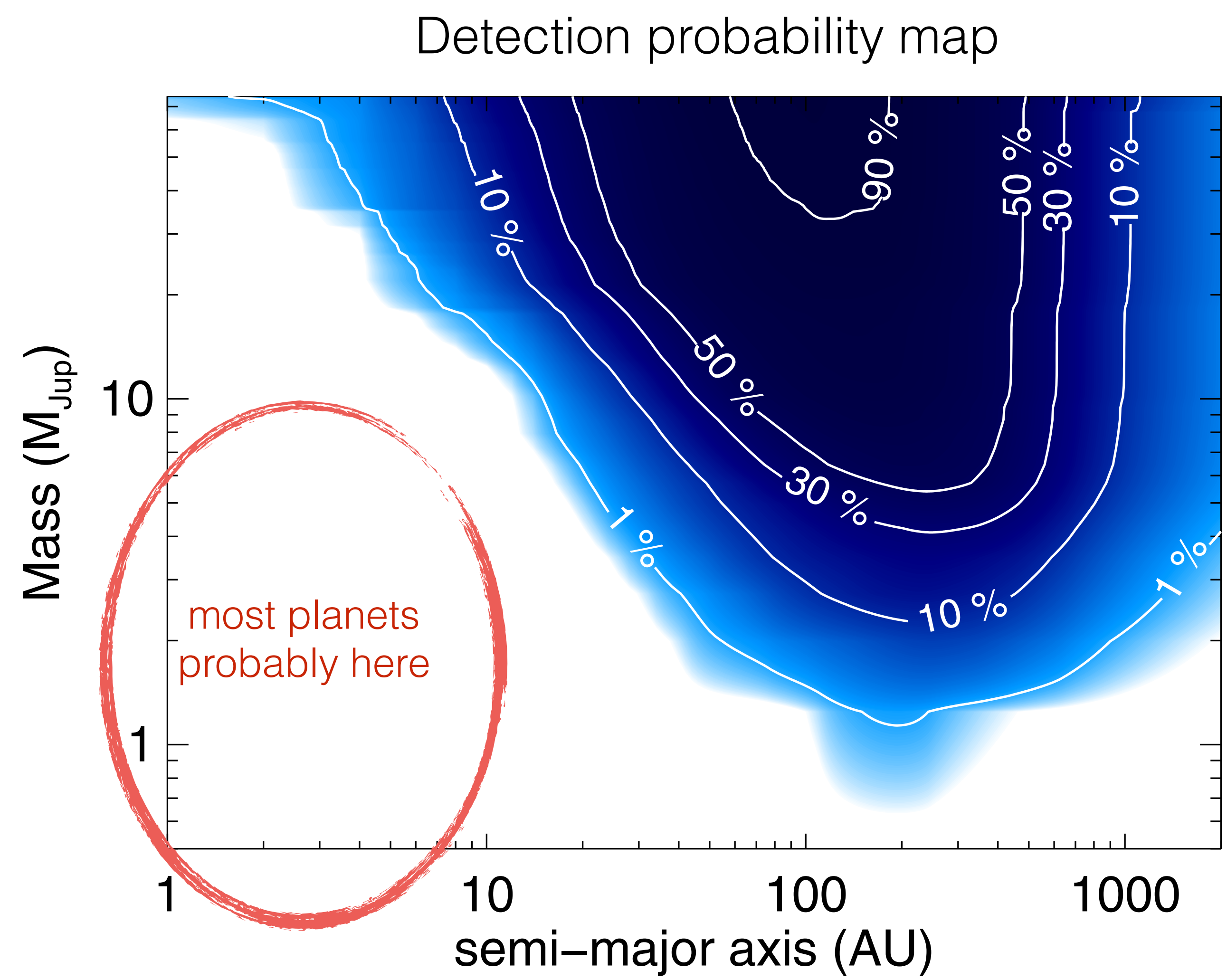
Which wavelength is best?

- Visible
  - Image quality not very good (now changing with XAO)
  - Polarimetry possible
- Near-infrared (1 - 2 μm)
  - Good image quality
  - Contrast not favorable
- Thermal infrared (3 - 5 μm)
  - High background emission
  - Excellent image quality
  - Contrast more favorable



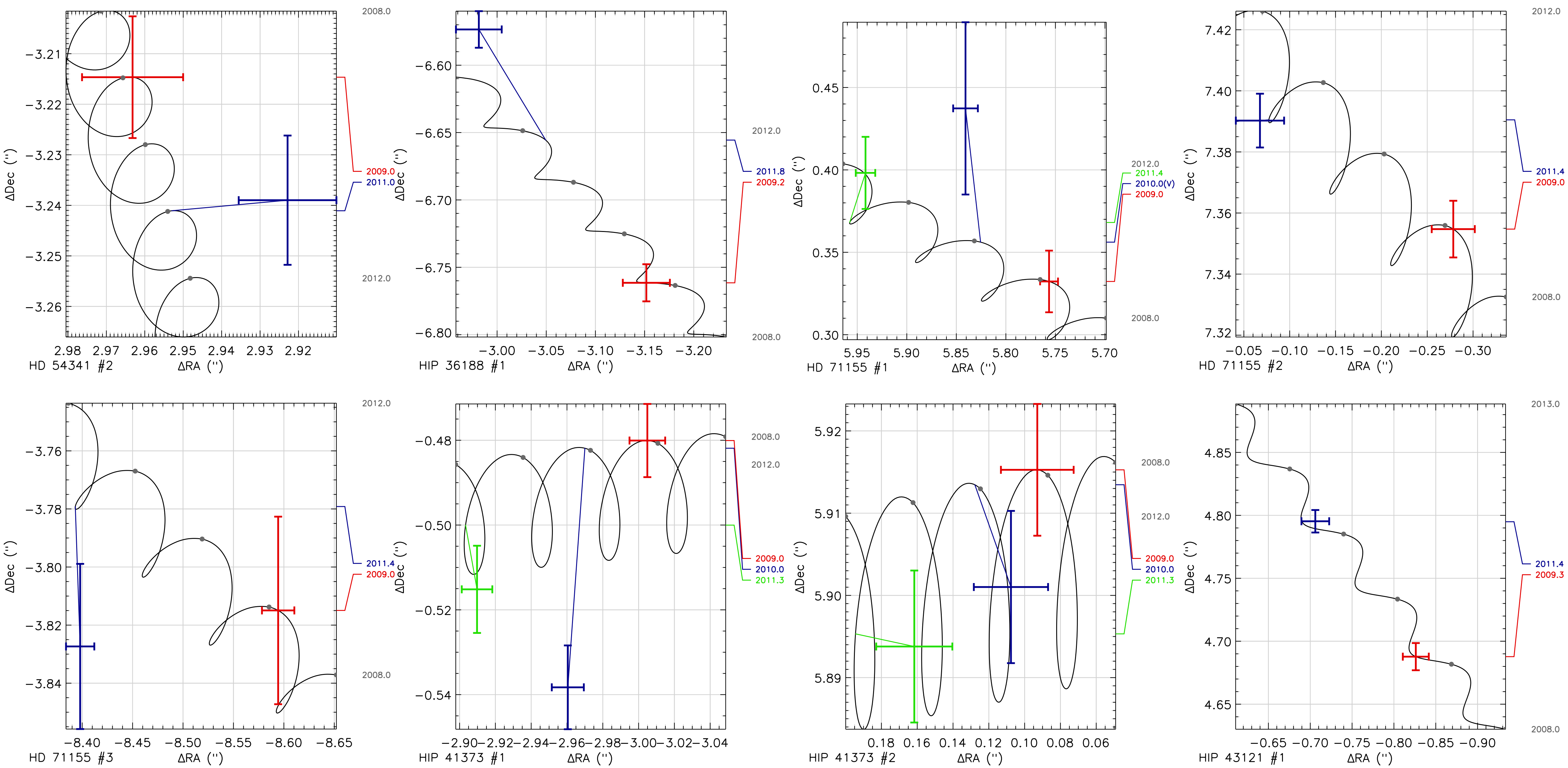
Early planet surveys

- Many surveys since 2005
  - Mostly carried out in the near-IR (between 1.5 and 4 μm)
  - Using mostly ADI or three-wavelength SDI (more recently also IFS-based SDI)
- Hundreds of stars observed
- Mostly non detections
  - Only scraping the top of the iceberg…?



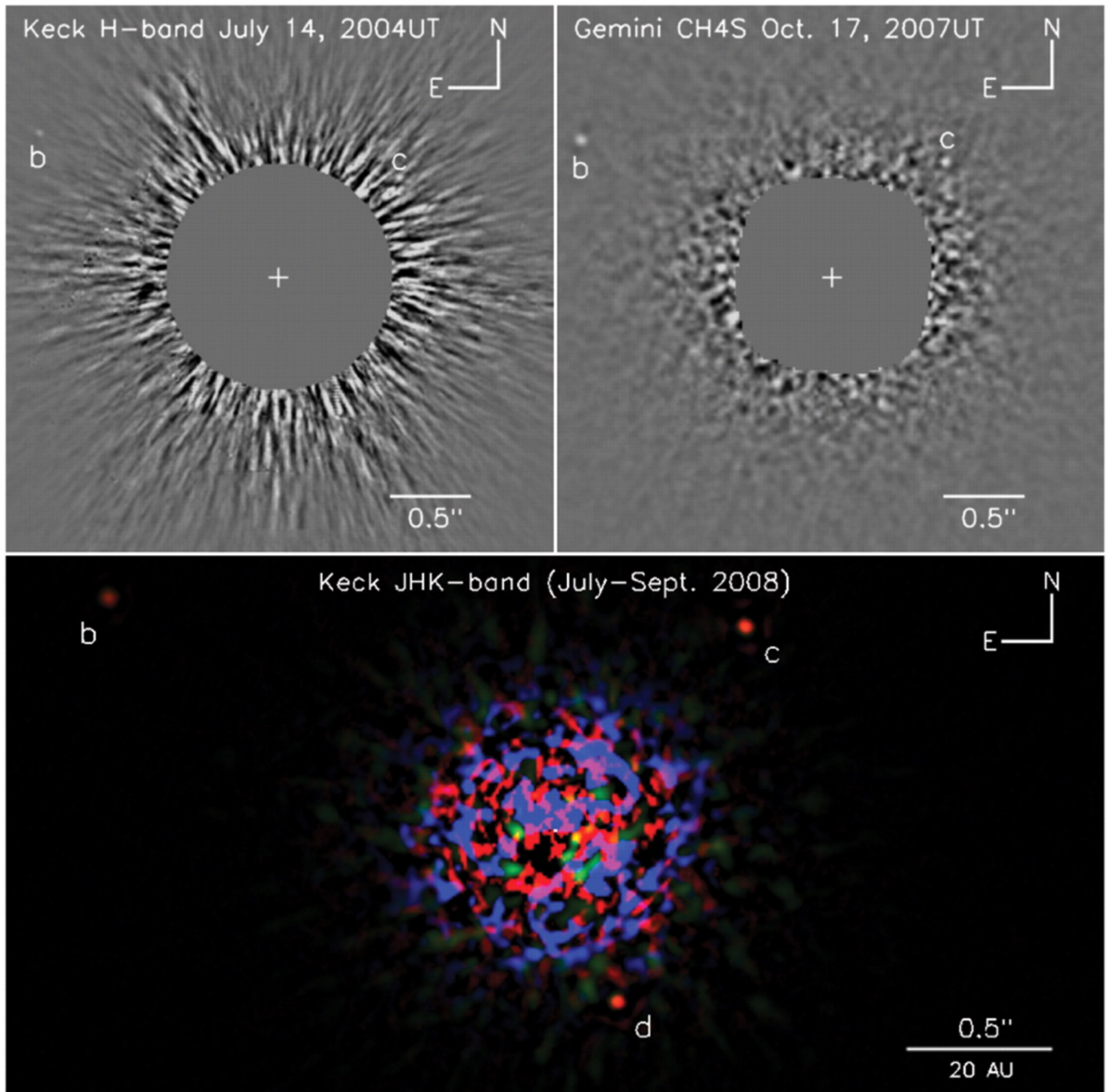
Chauvin et al. 2015 - NACO H-band ADI survey (86 stars)

Wasting time on candidate follow-up…



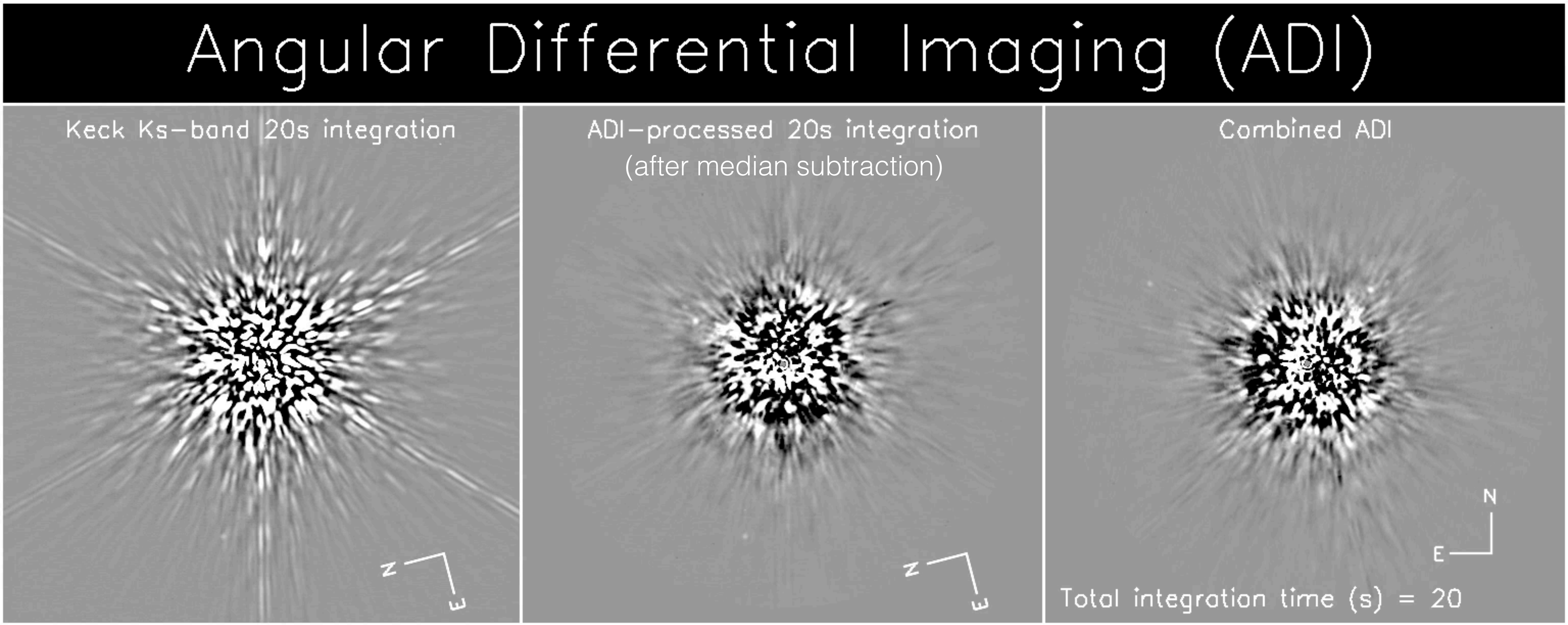
need to check if companion is co-moving with host star, or if it's a background source

2008: first detection around a main sequence star (ADI)



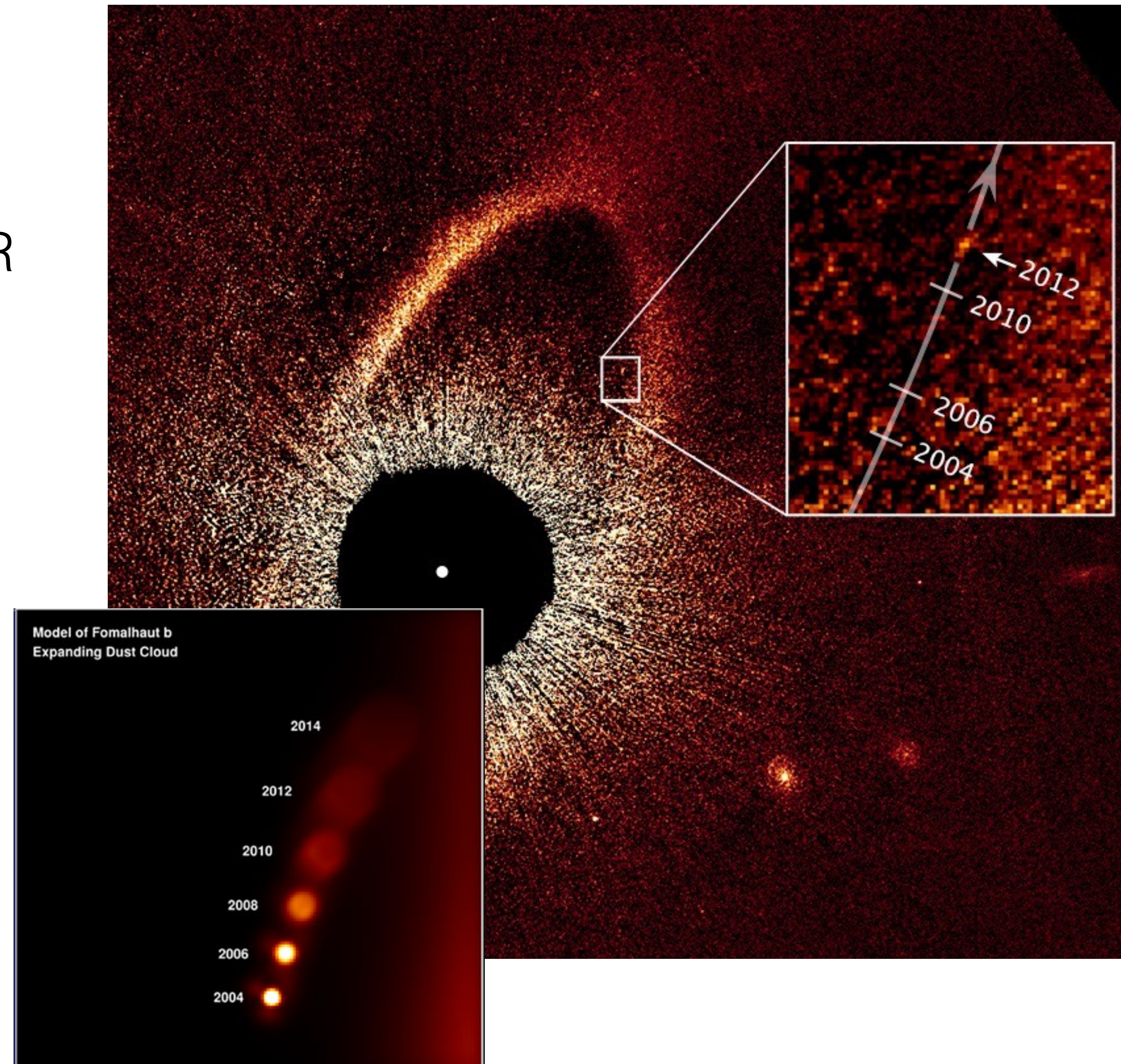
Contrast ~ 14 mag ($\sim 10^{-6}$)

The power of ADI



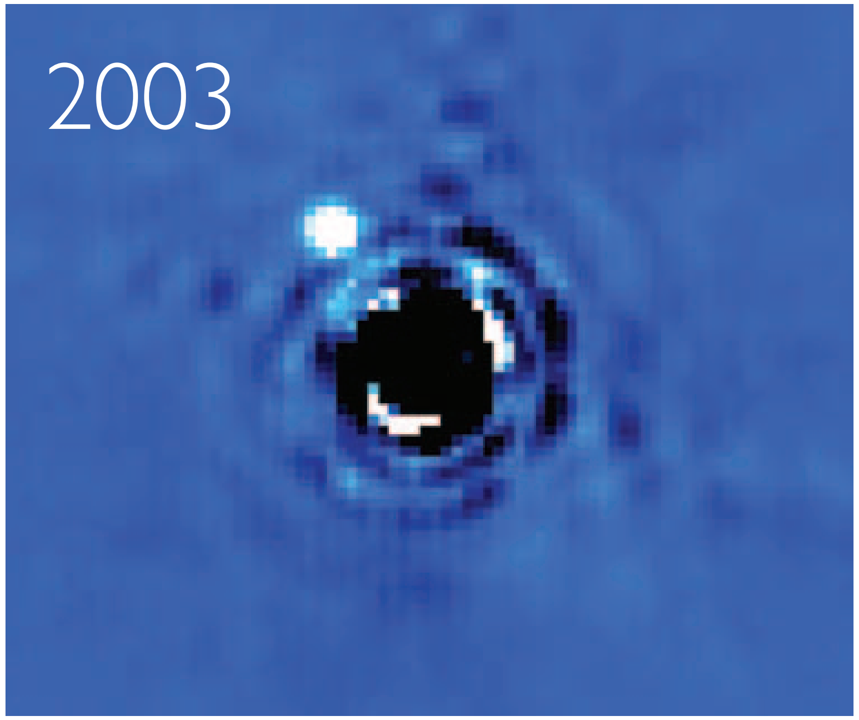
Fomalhaut b: a most mysterious planet

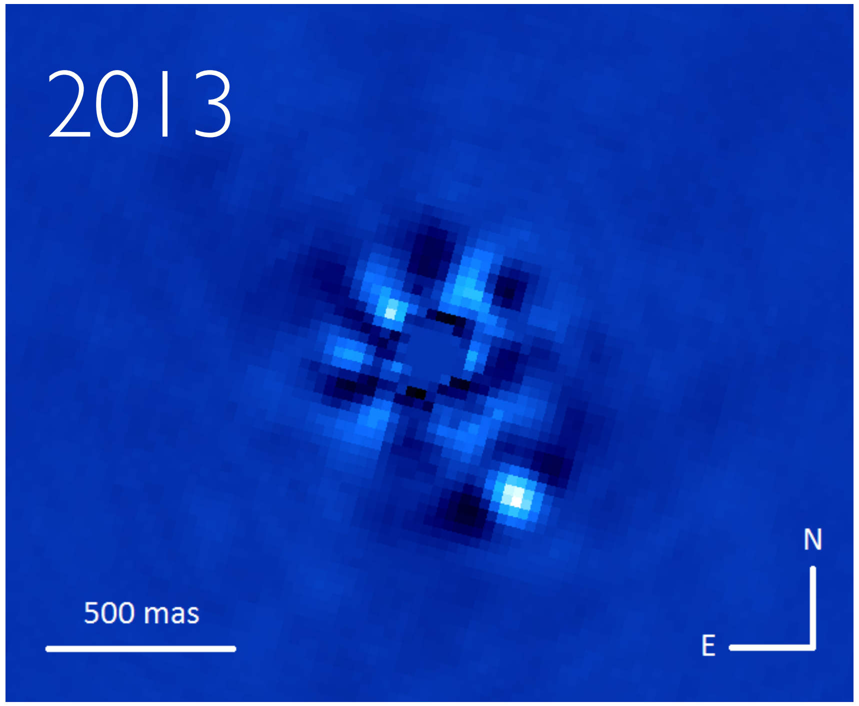
- At first, suspected to shepherd the dust
- Never confirmed in the IR —> could it be dust around small core?
- 2012: orbit shown to be disk-crossing
    - Recent ejection due to another planet?
- 2020 update: massive planetesimal collision?



The long awaited beta Pic b

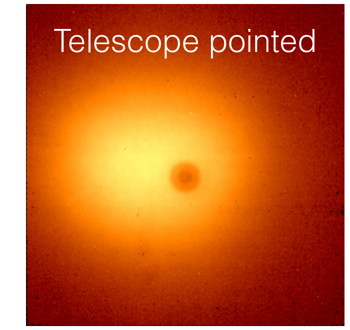
- Detected in archival NACO data using improved processing
- 13 M_{Jup} planet on a 11 AU orbit
- Predicted in 1997 based on disk shape
    - Detection consistent with prediction

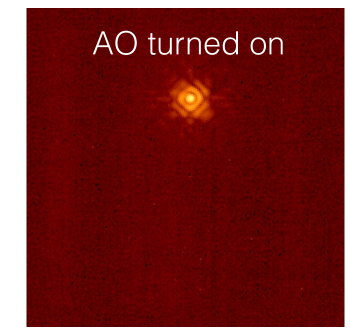


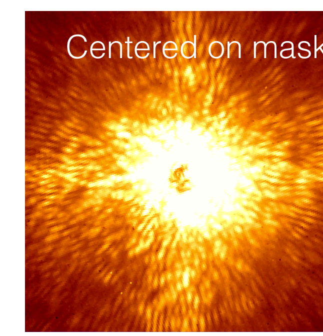


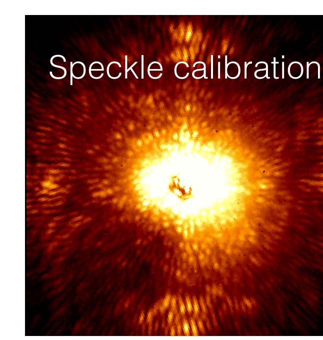
10m-class telescopes: 2nd generation (xAO)

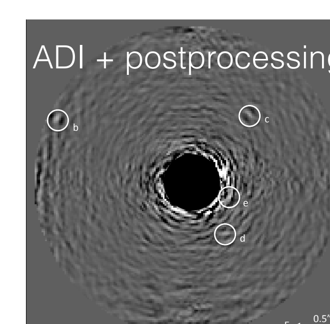
- Extreme AO instruments coming online since 2013
  - VLT/SPHERE (includes IRDIS, IFS and ZIMPOL)
  - Gemini/GPI
  - Subaru/SCExAO + HiCIAO camera
  - LBT/AO + various cameras
  - Also at Magellan (6.5m) and Palomar (5m)
- Operating wavelengths: from visible to near-infrared
- Optimized for exoplanet imaging, with specific speckle-calibration techniques / observing strategies







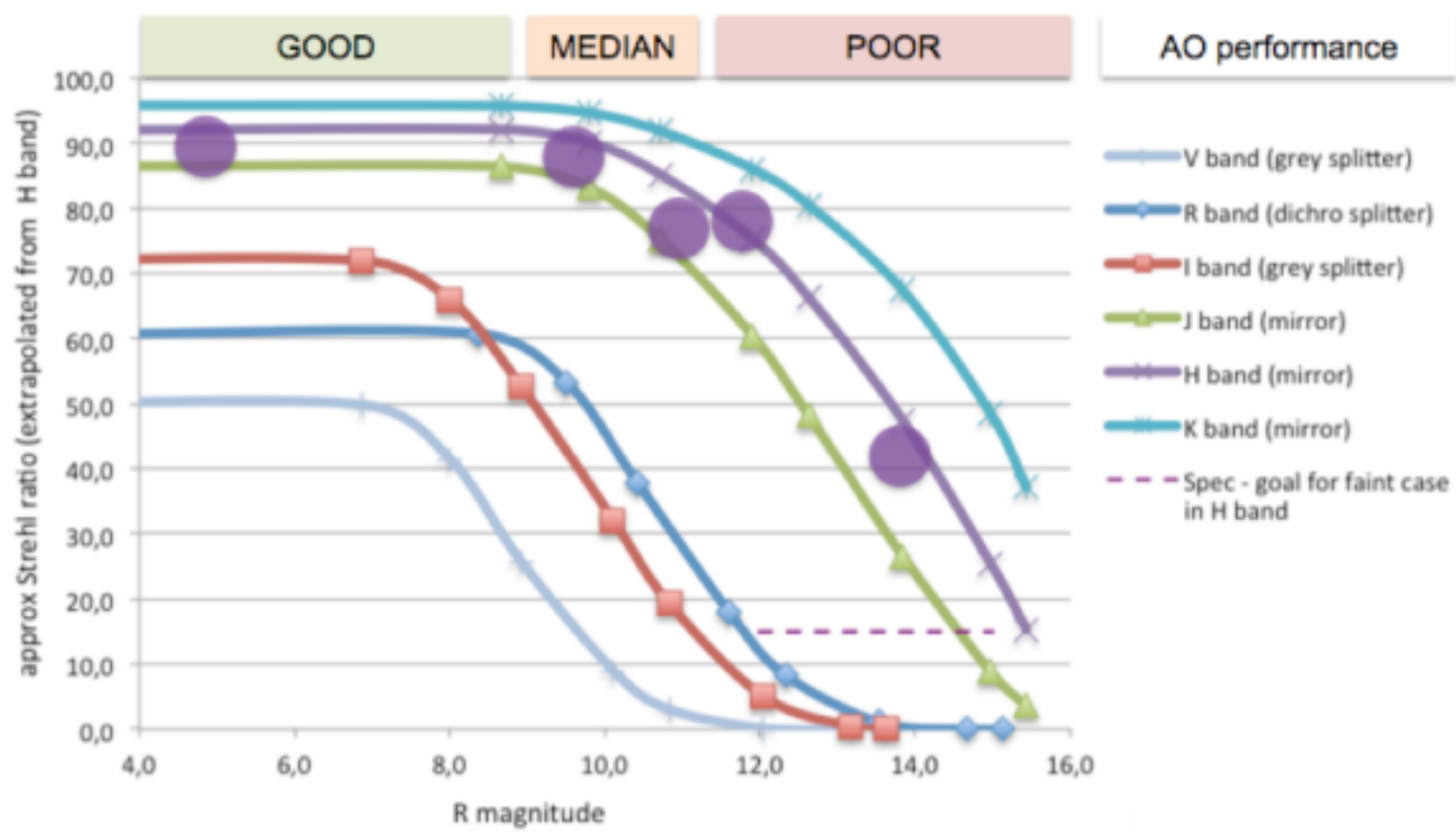




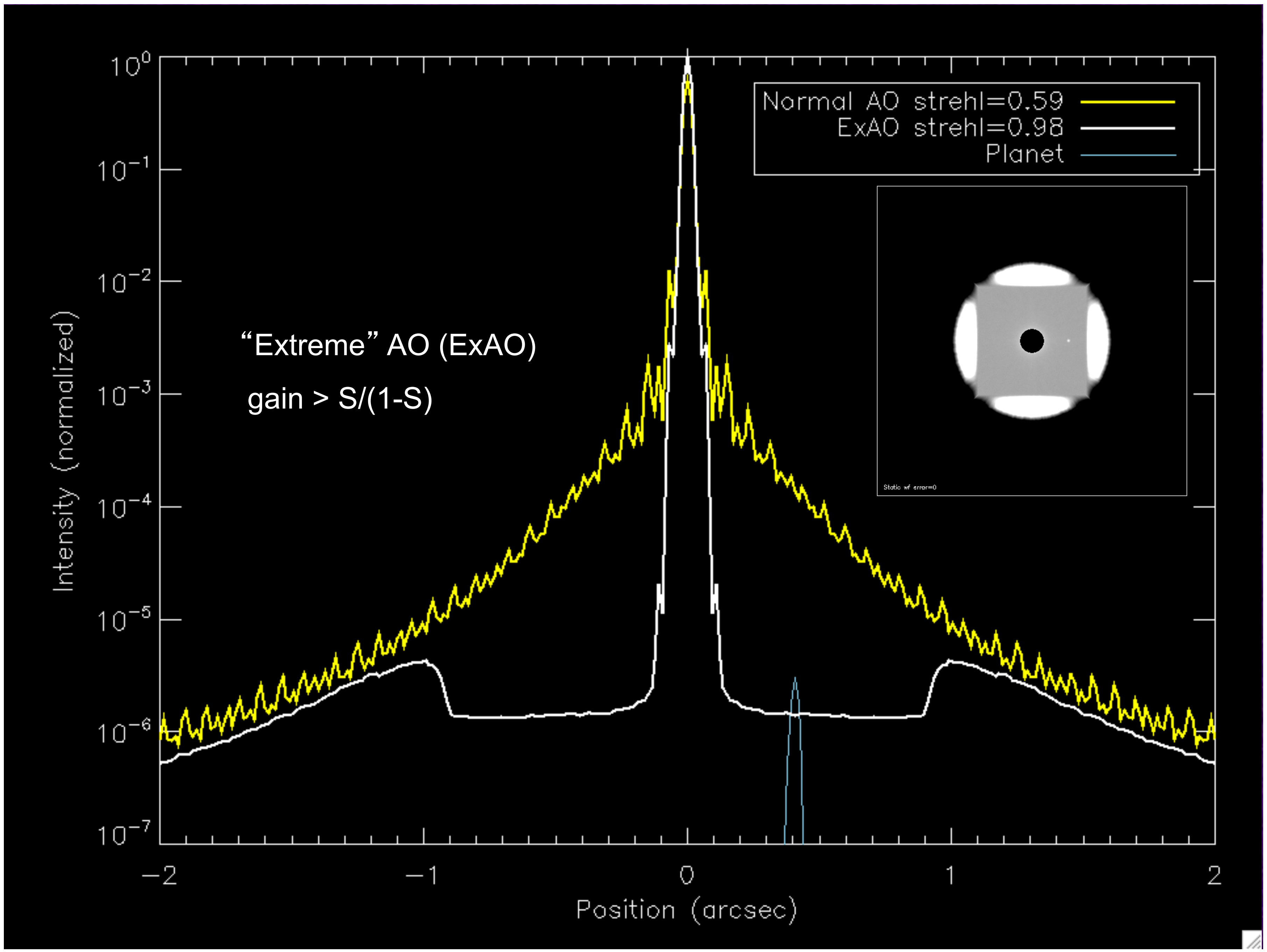
10m-class telescopes: 2nd generation (xAO)

- Extreme adaptive optics (1000+ actuators)
  - Strehl ratios up to 95% at K band (or 99.5% at N!)
  - First adaptive secondary mirrors

- Advanced coronagraphs
  - Apodized Lyot
  - Vortex
  - PIAA
- Integral field spectrographs

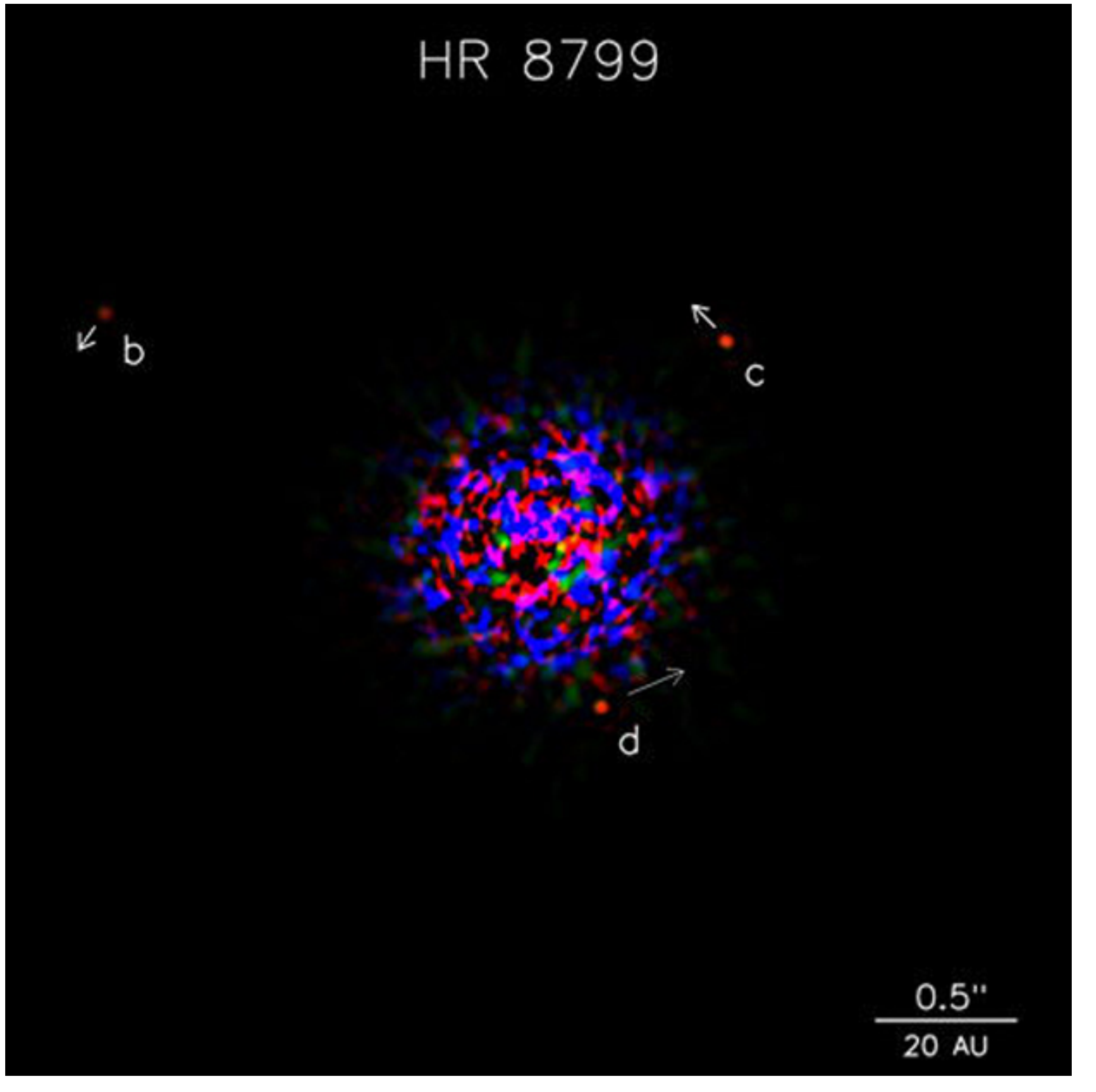


The XAO improvement

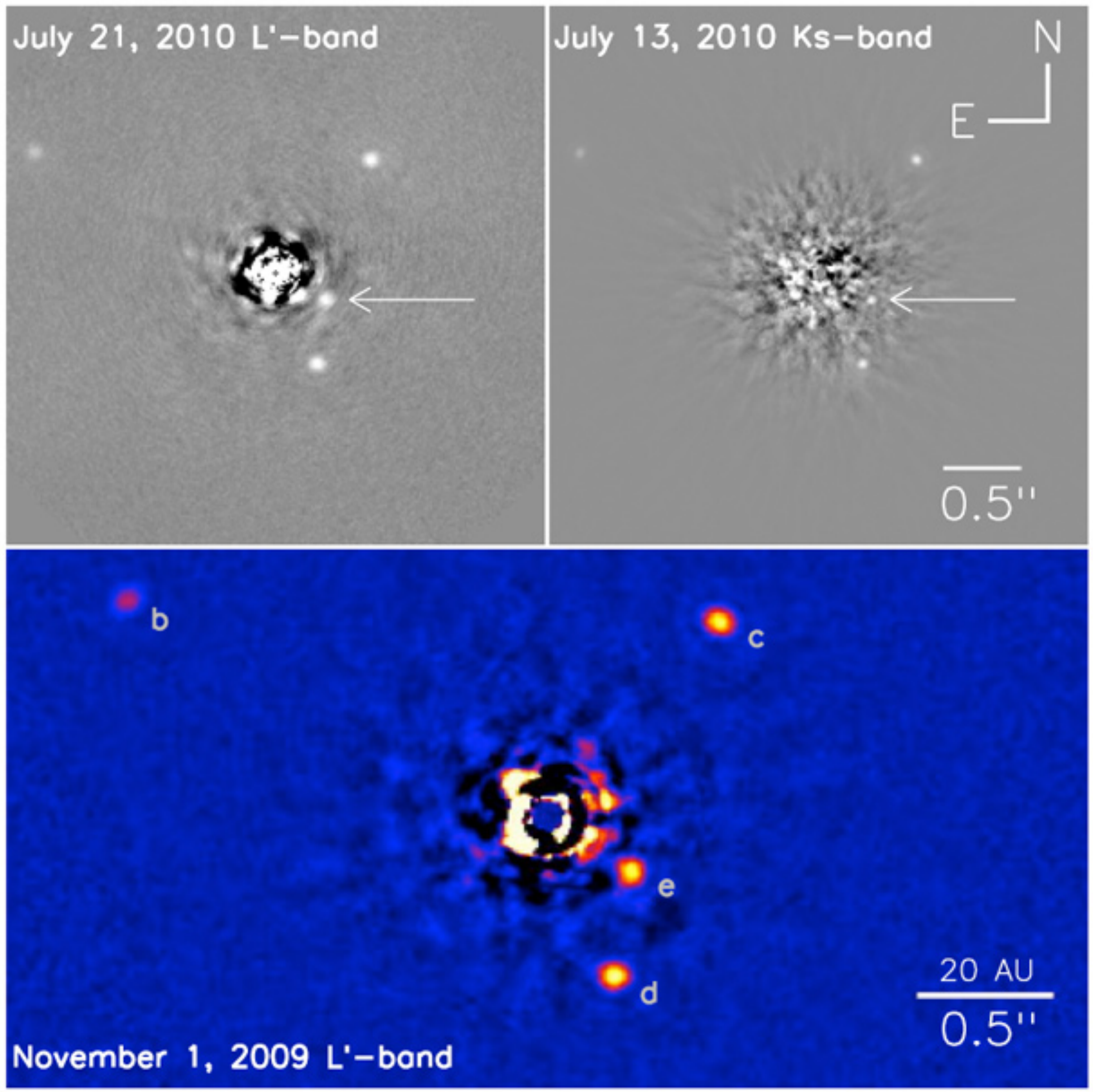


From first detection to thorough characterization

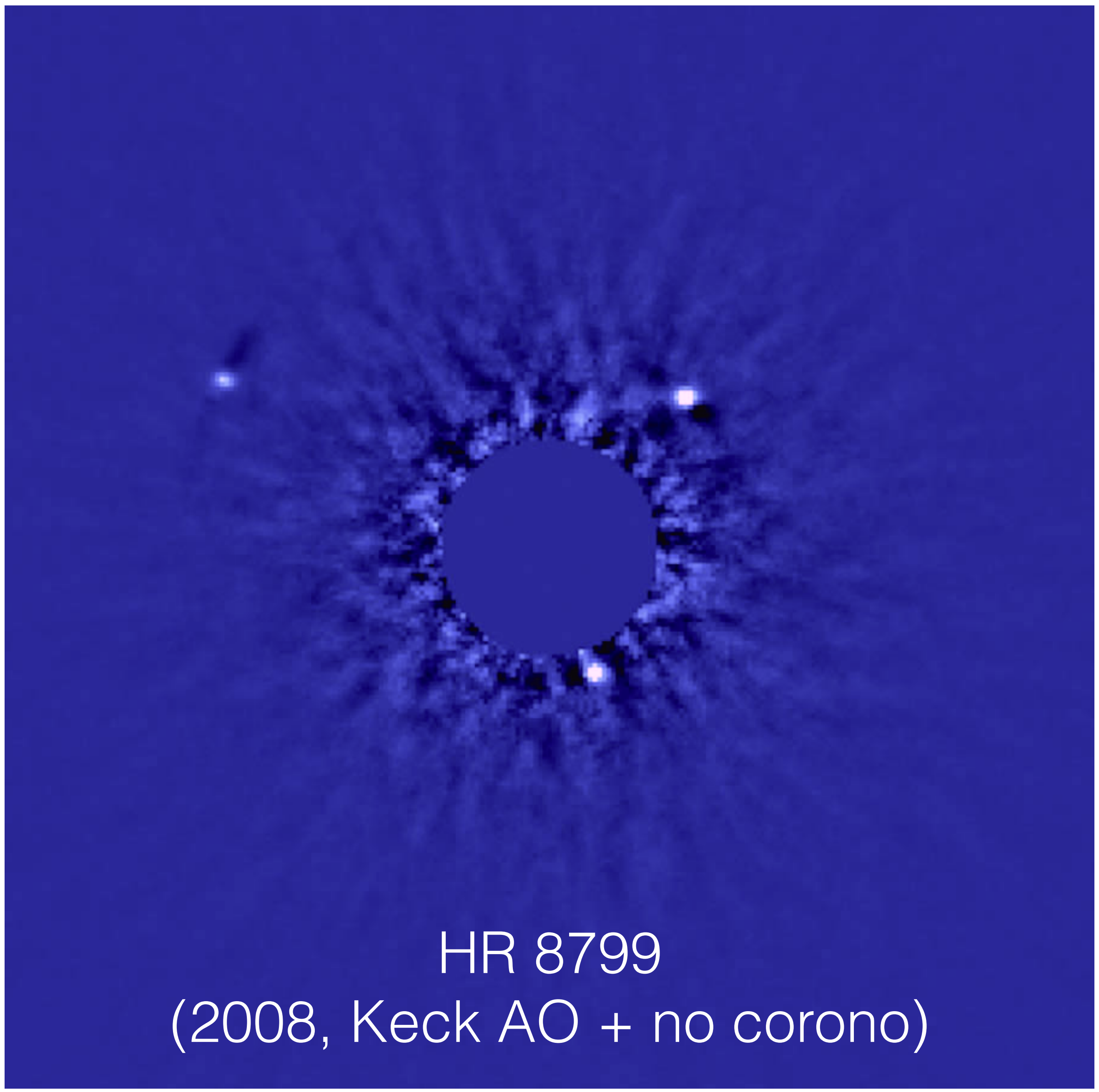
Illustration on HR 8799: evolution since 2008

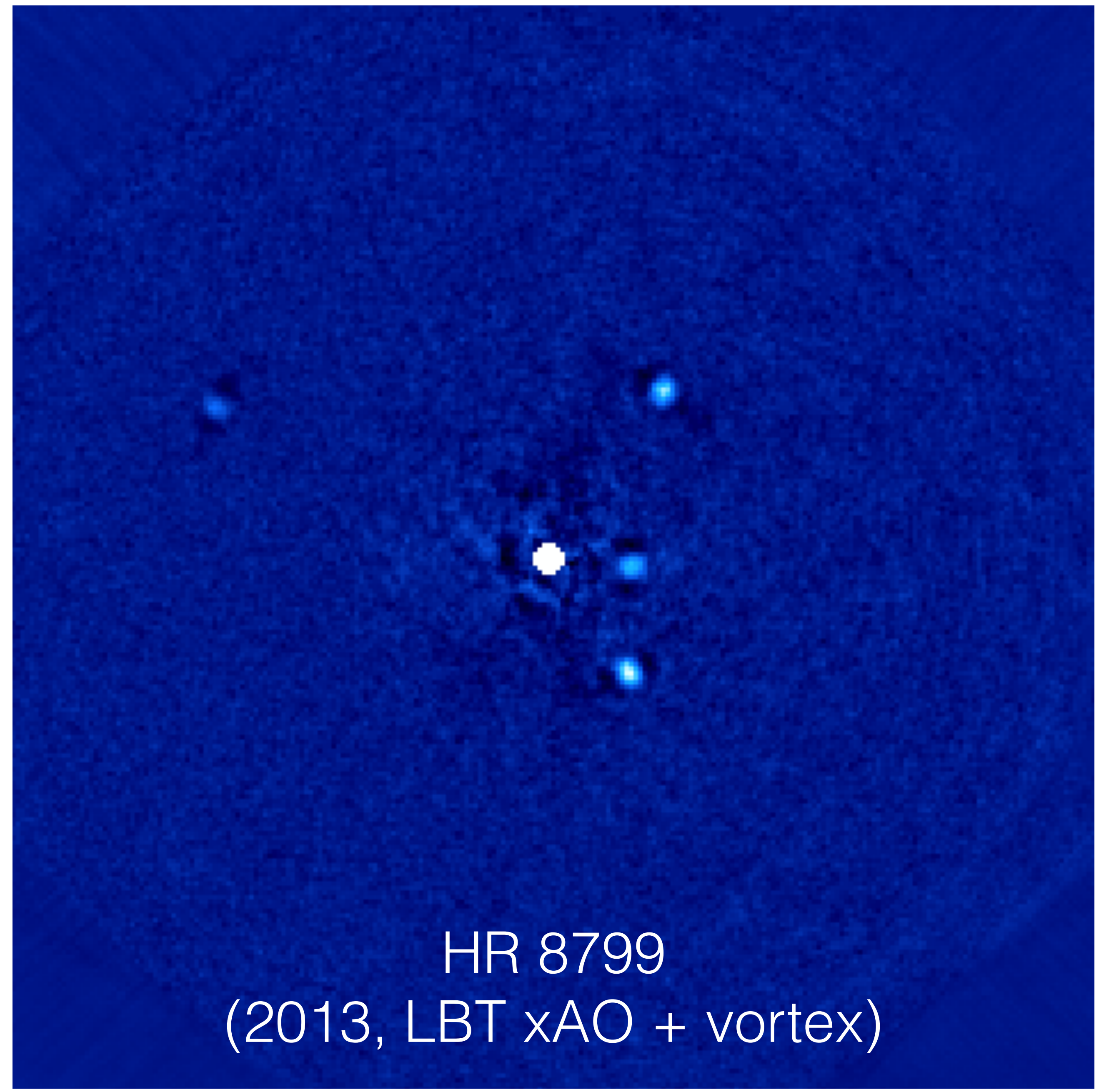


4^{th} planet with ADI+LOCI



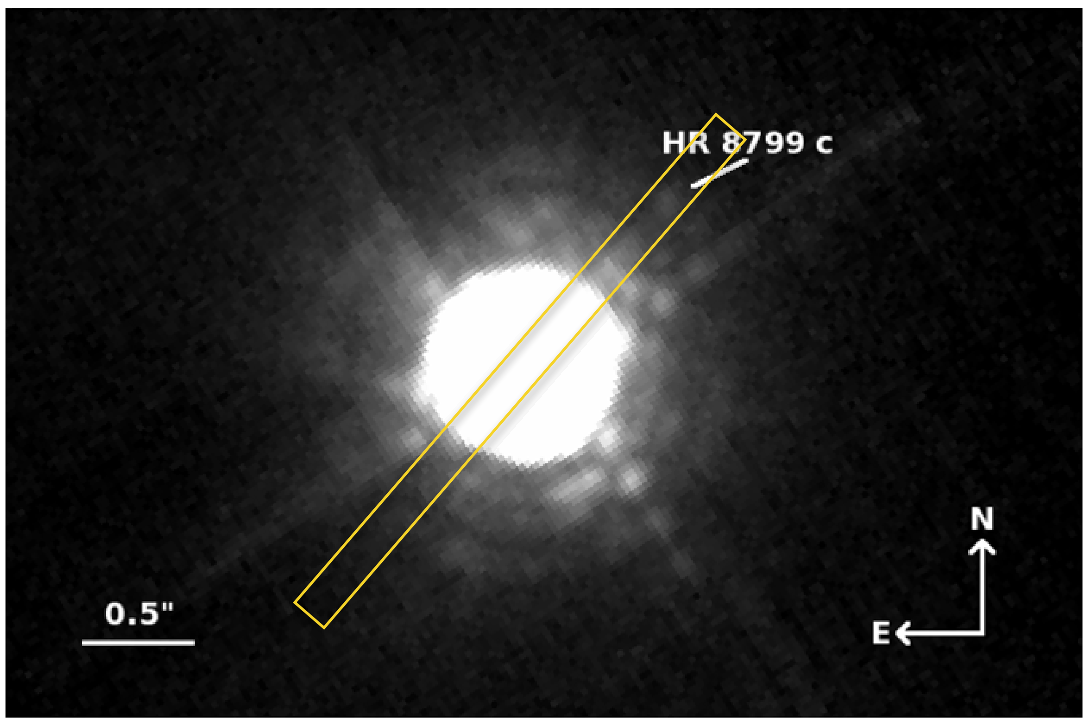
Upgraded instruments

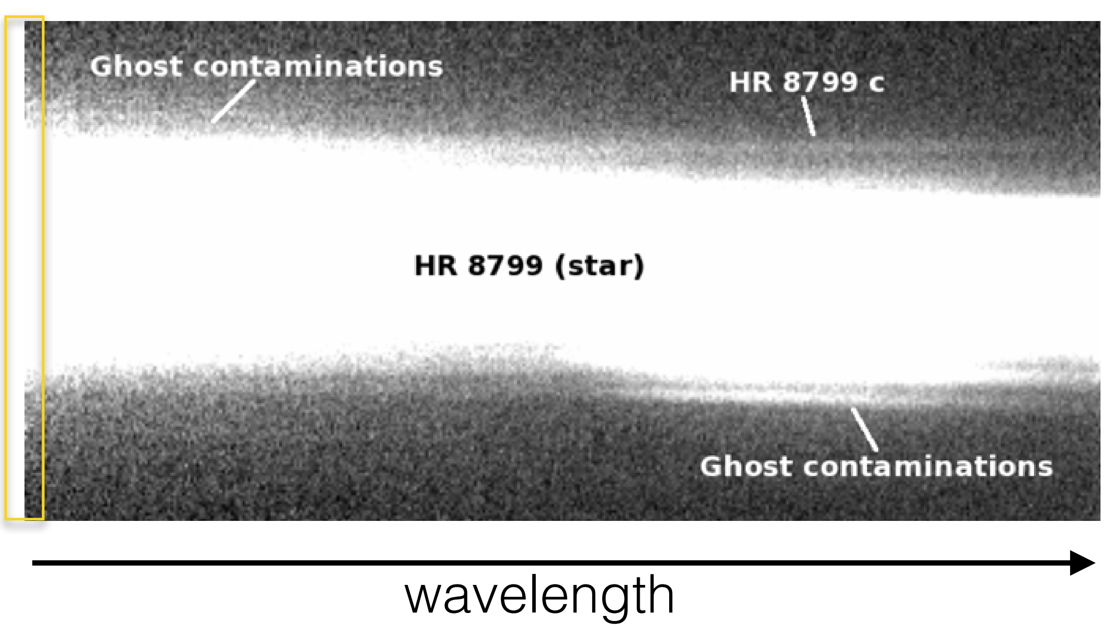


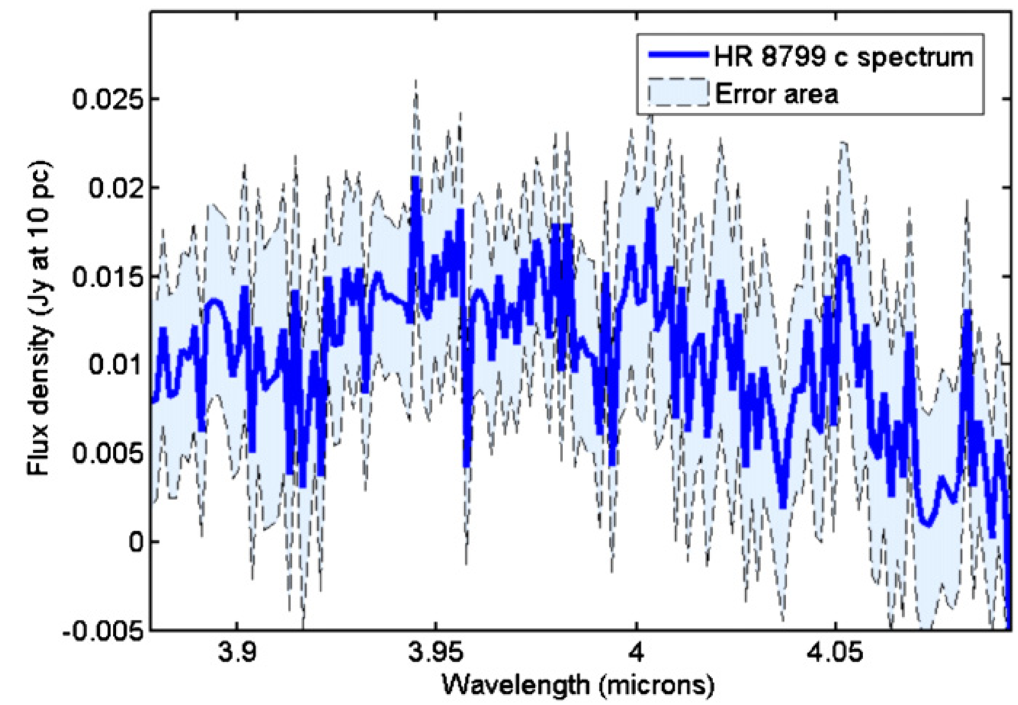


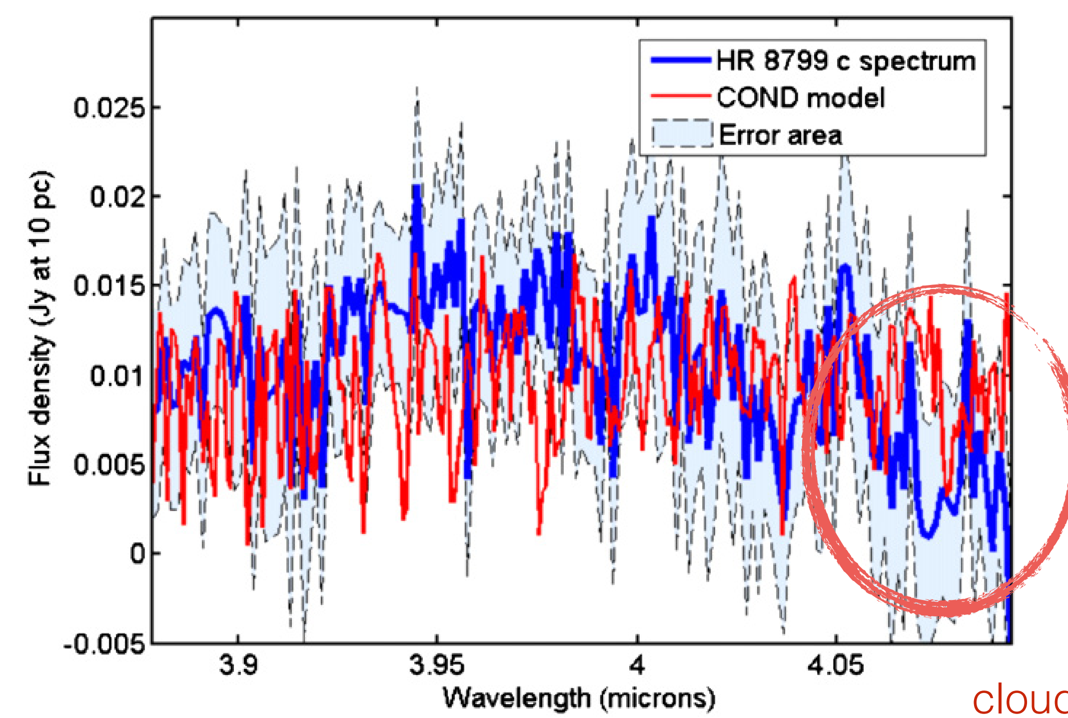
2010: long slit spectroscopy

VLT/NACO slit spectroscopy





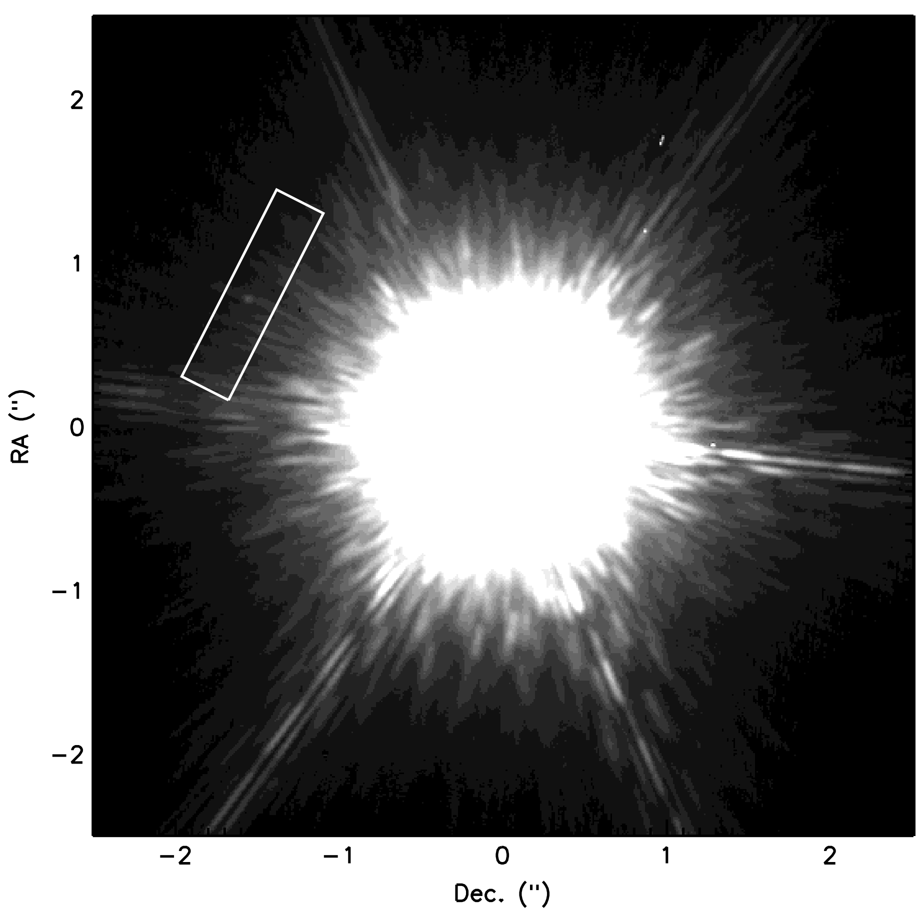


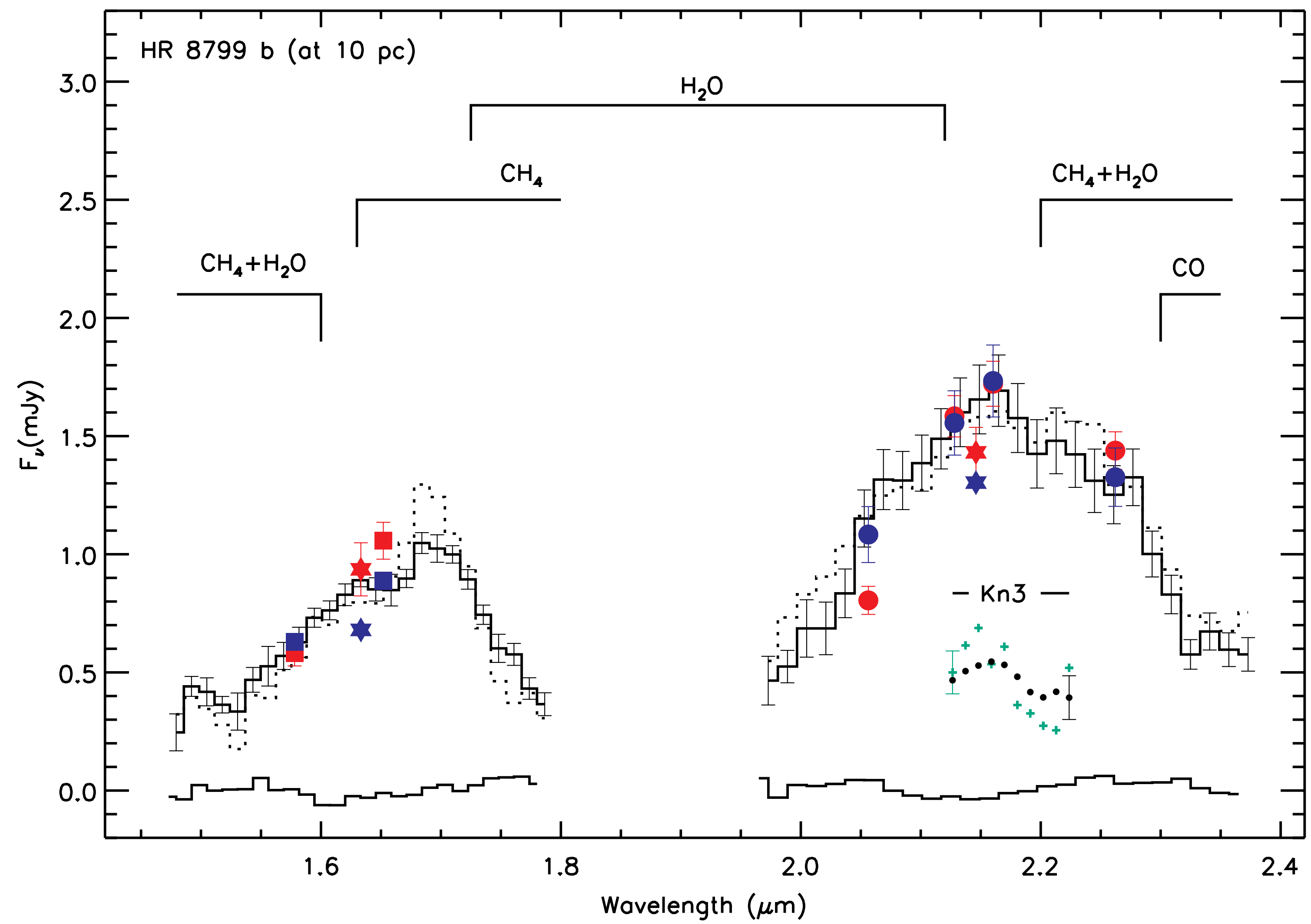


clouds?
non-equilibrium?

2011: HK band IFS

Keck/OSIRIS integral
field spectroscopy



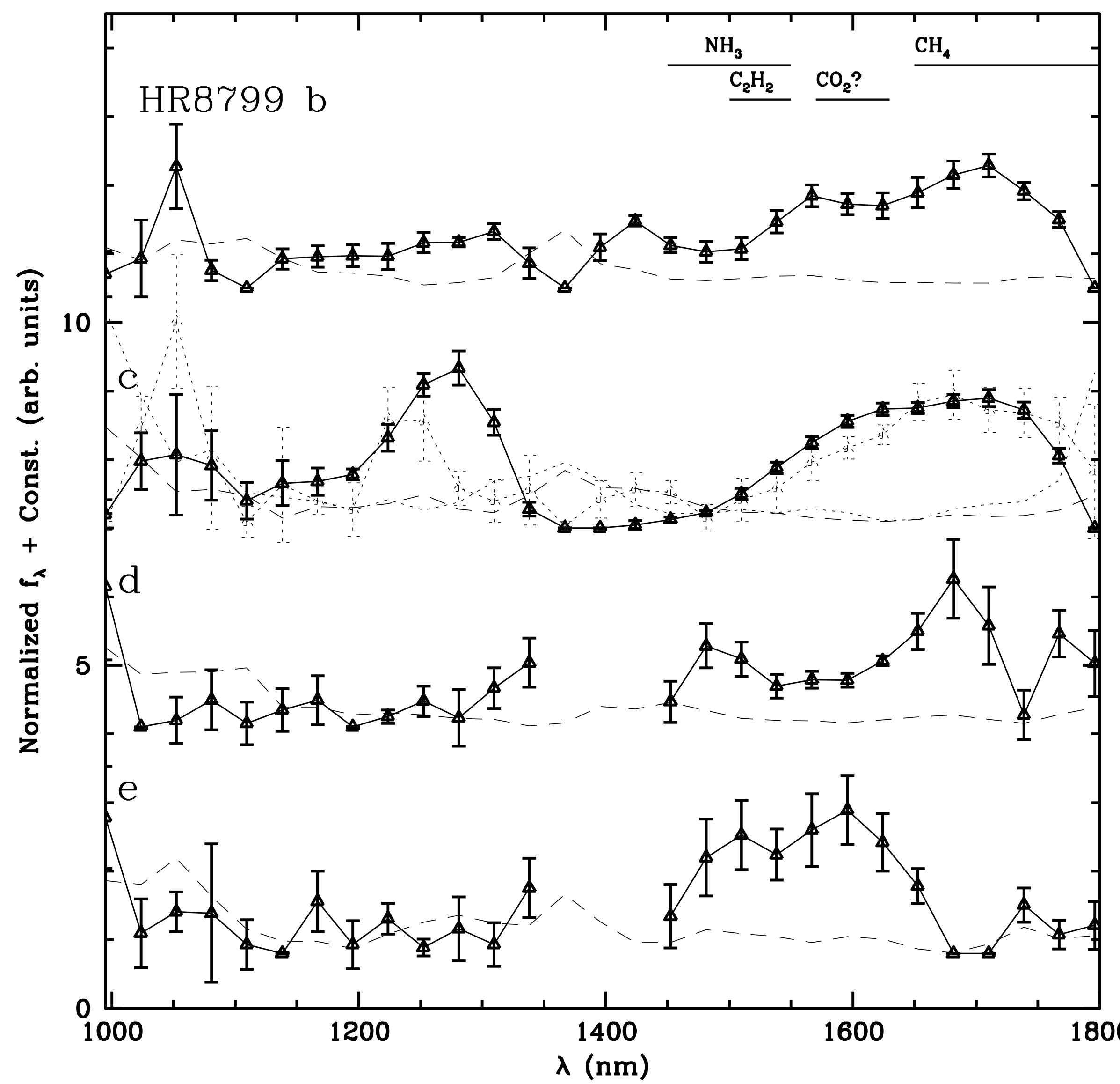


Model fitting requires thick dust clouds and low gravity (creates triangular shape).
Water vapor clearly identified, tentative methane absorption (later disproved).

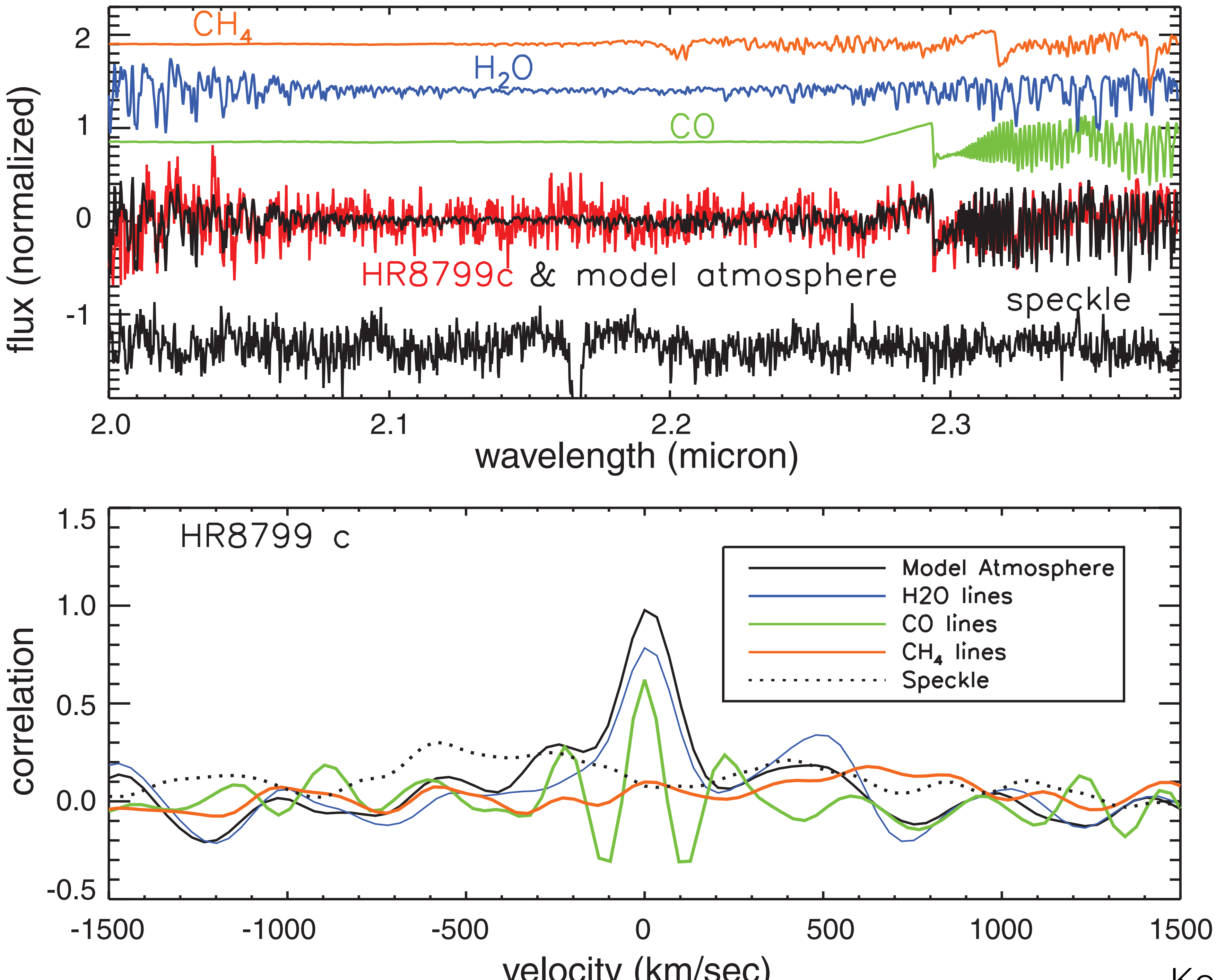
2013: first full IFS study using SDI

- Huge diversity between the measured spectra!
- Similarities with brown dwarf spectra
- Tentative evidence for methane and other species
- Cloudy models required

Palomar / Project 1640 IFS spectra



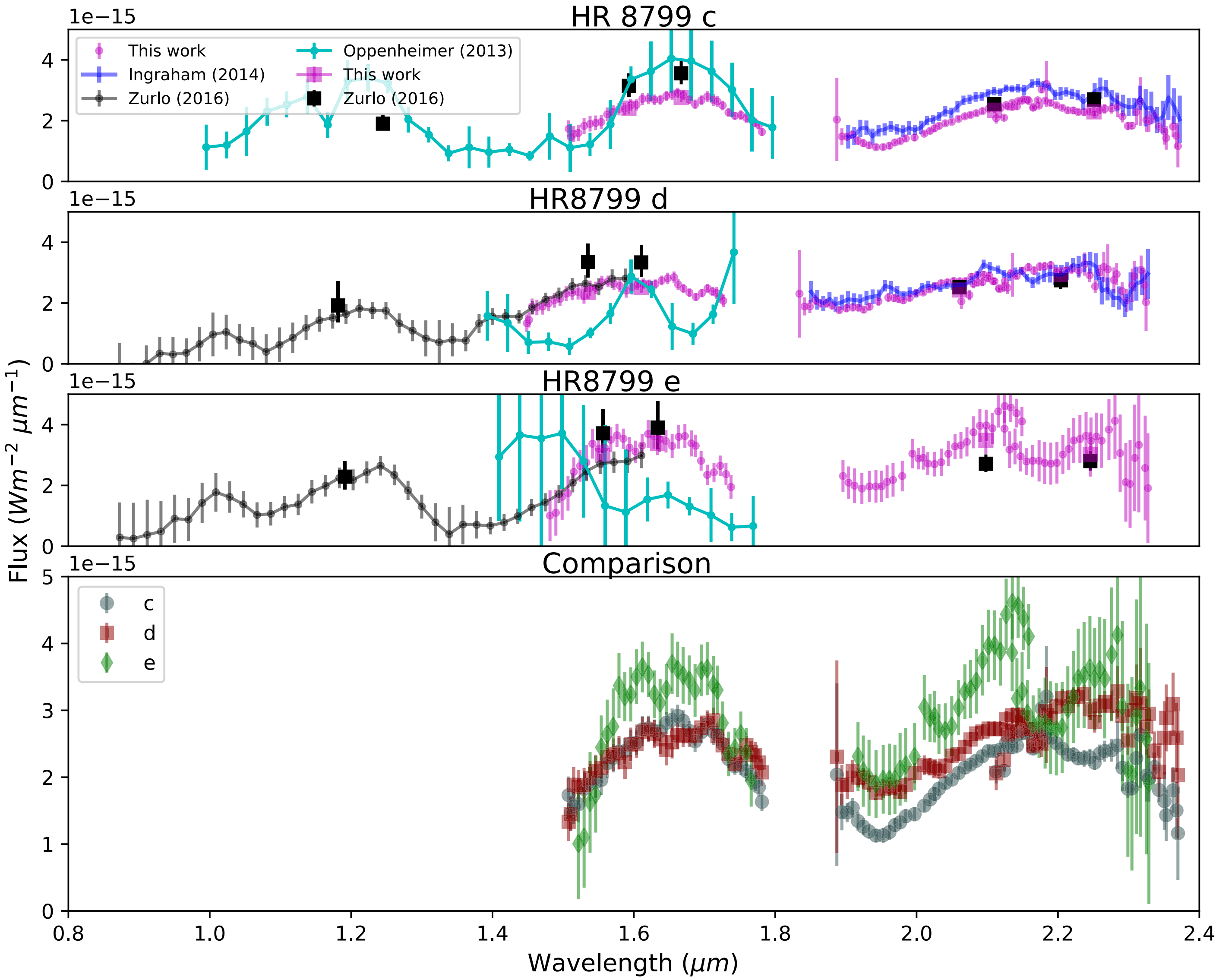
Higher spectral resolution: use cross-correlation

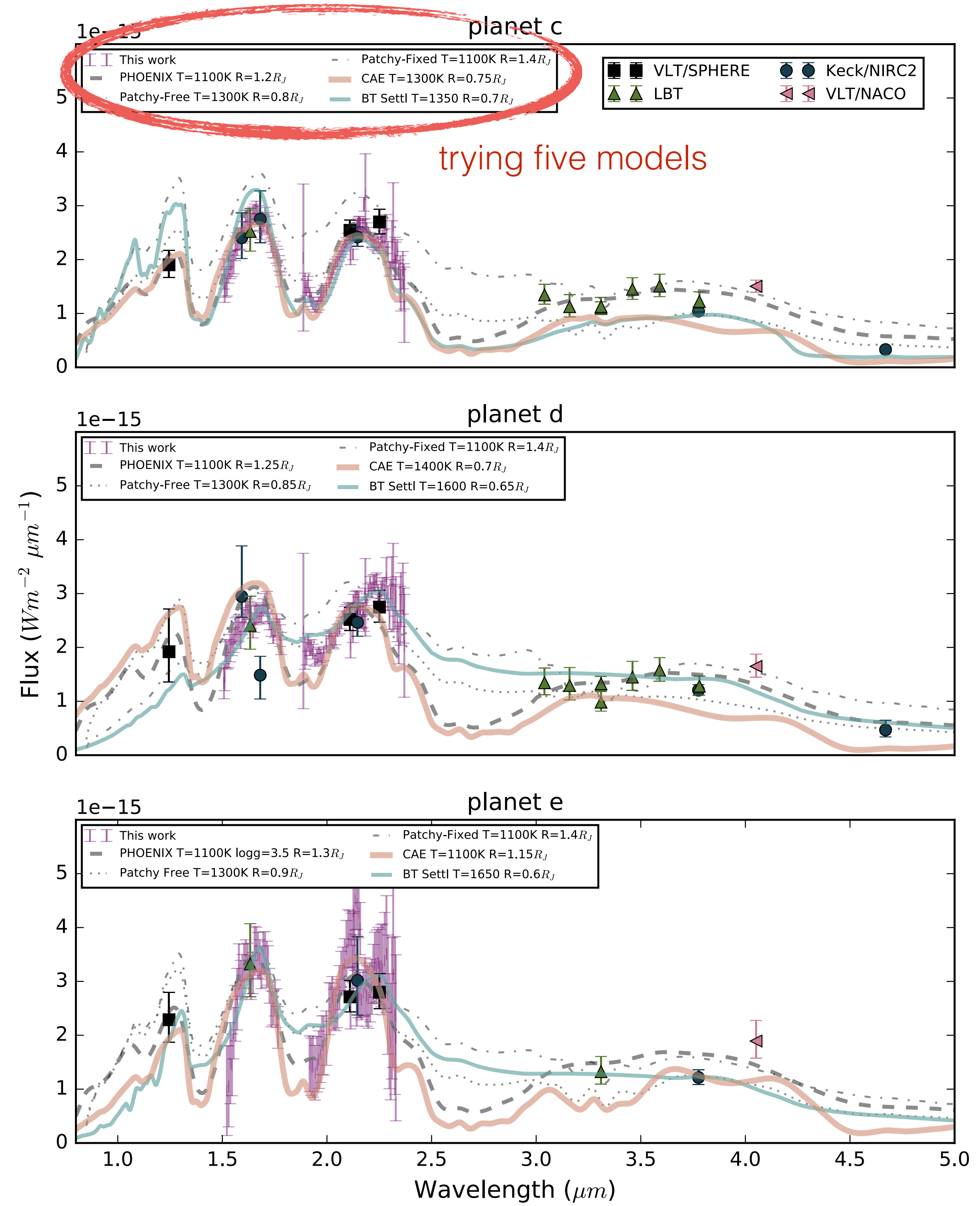


Konopacky et al. 2013

2018: state of the art with xAO-fed IFS

Gemini / GPI IFS spectra

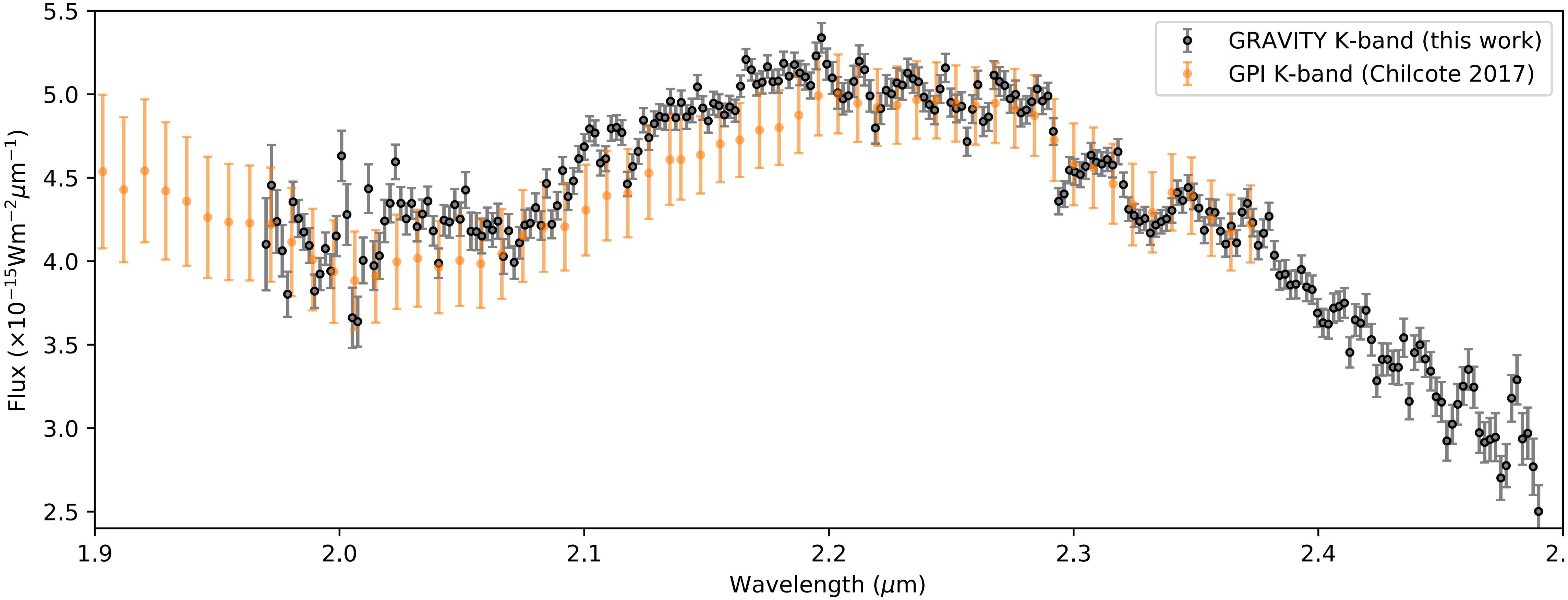




Models can now be constrained, although ideally would require to know mass and age

Now exquisite spectra with infrared interferometry!

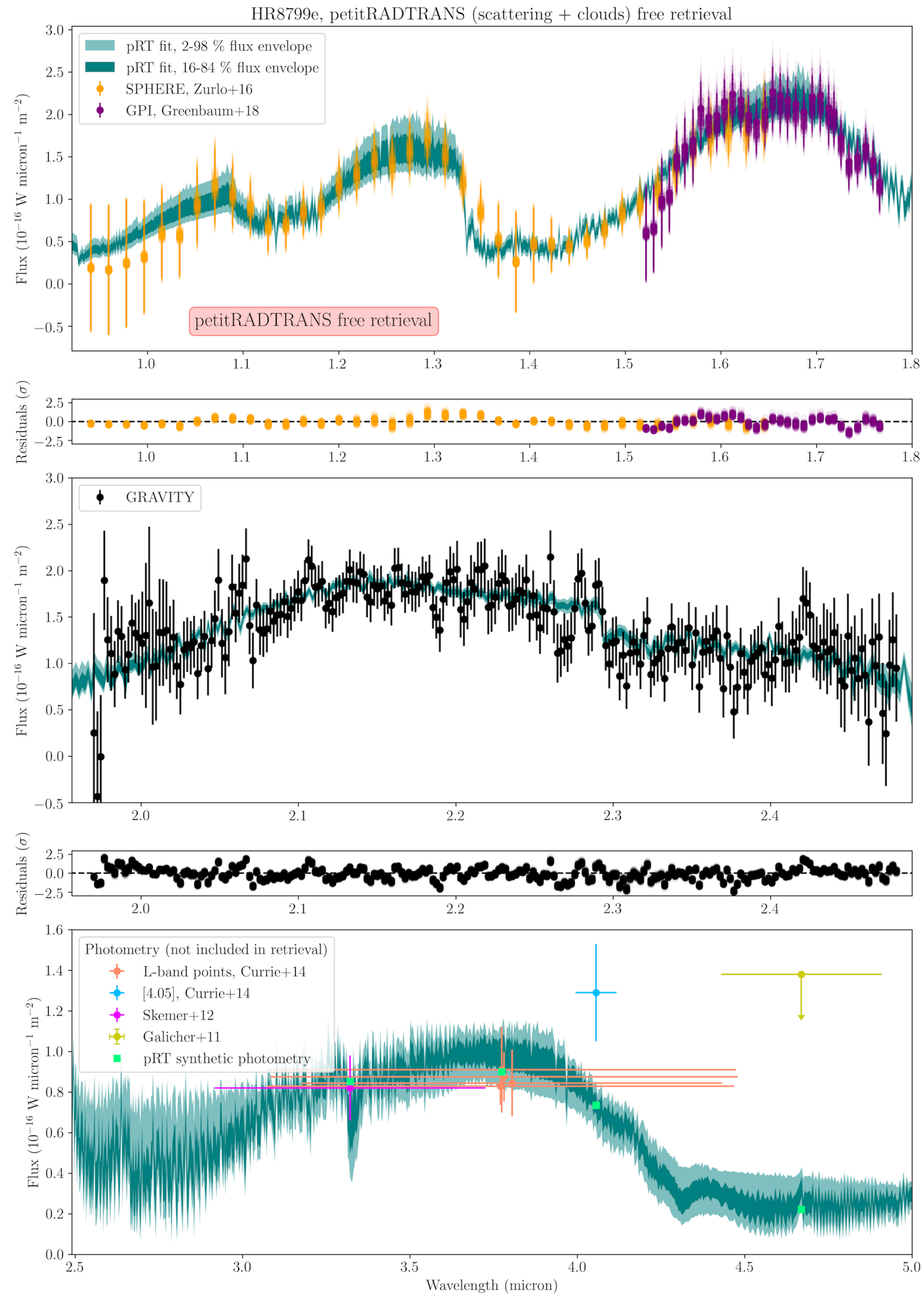
here, beta Pic b with VLTI/GRAVITY — HR 8799 planets also observed



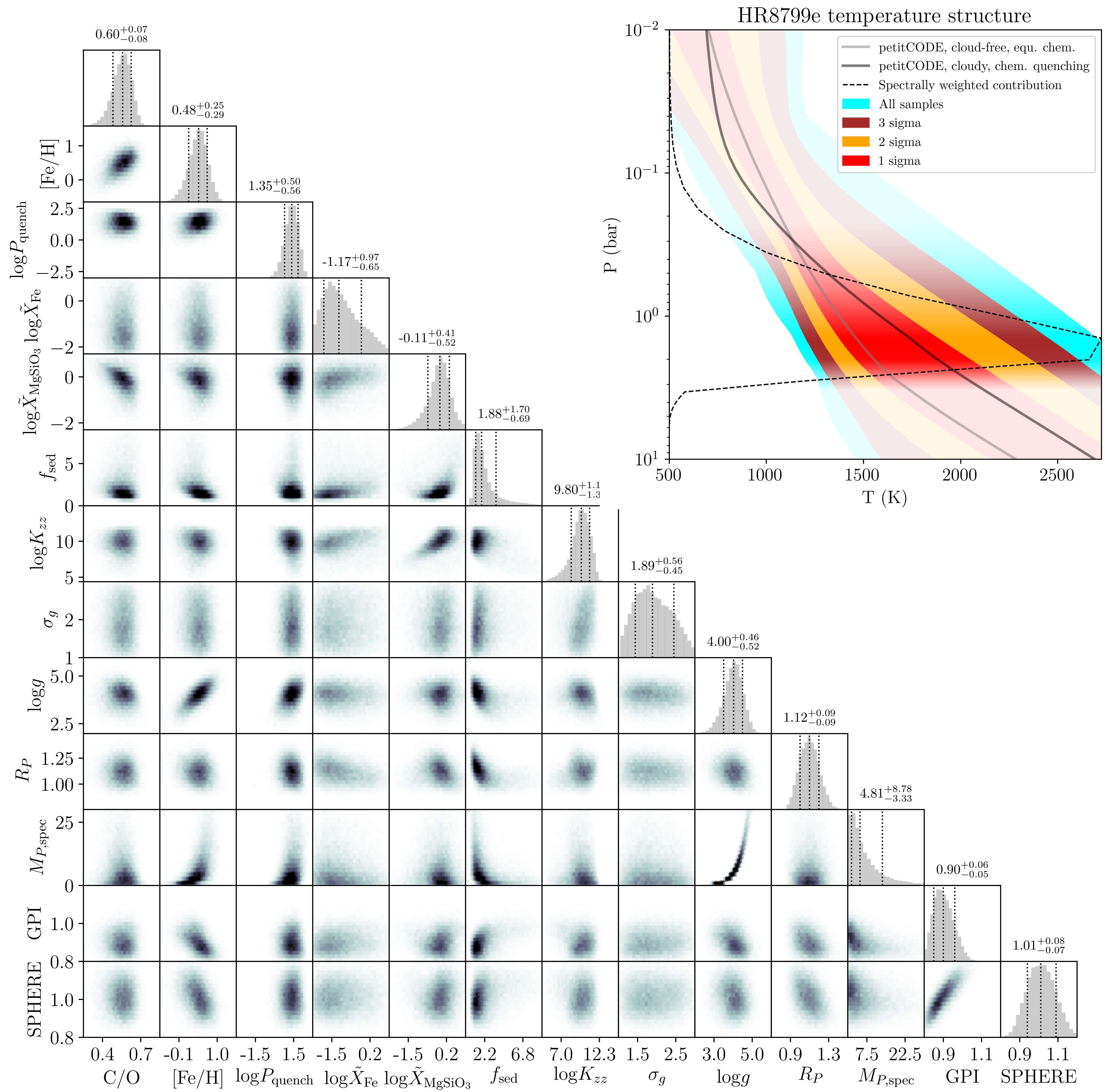
Entering the era of atmospheric retrieval

- Atmospheric model produces spectrum for a set of parameters + PT profile

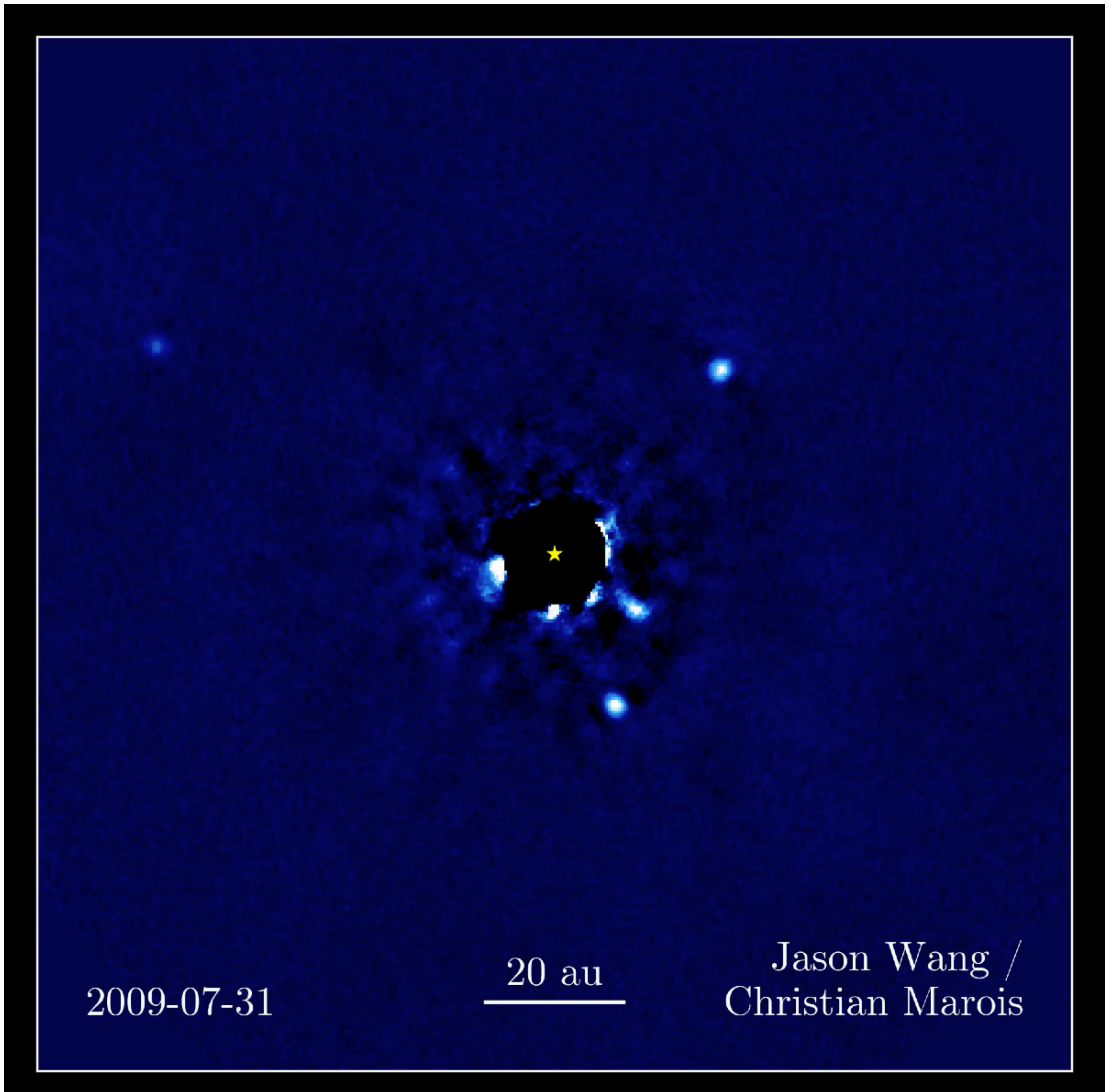
- Goal: invert model to retrieve parameters from spectrum
    - generally based on MCMC methods
    - can handle many parameters at a time



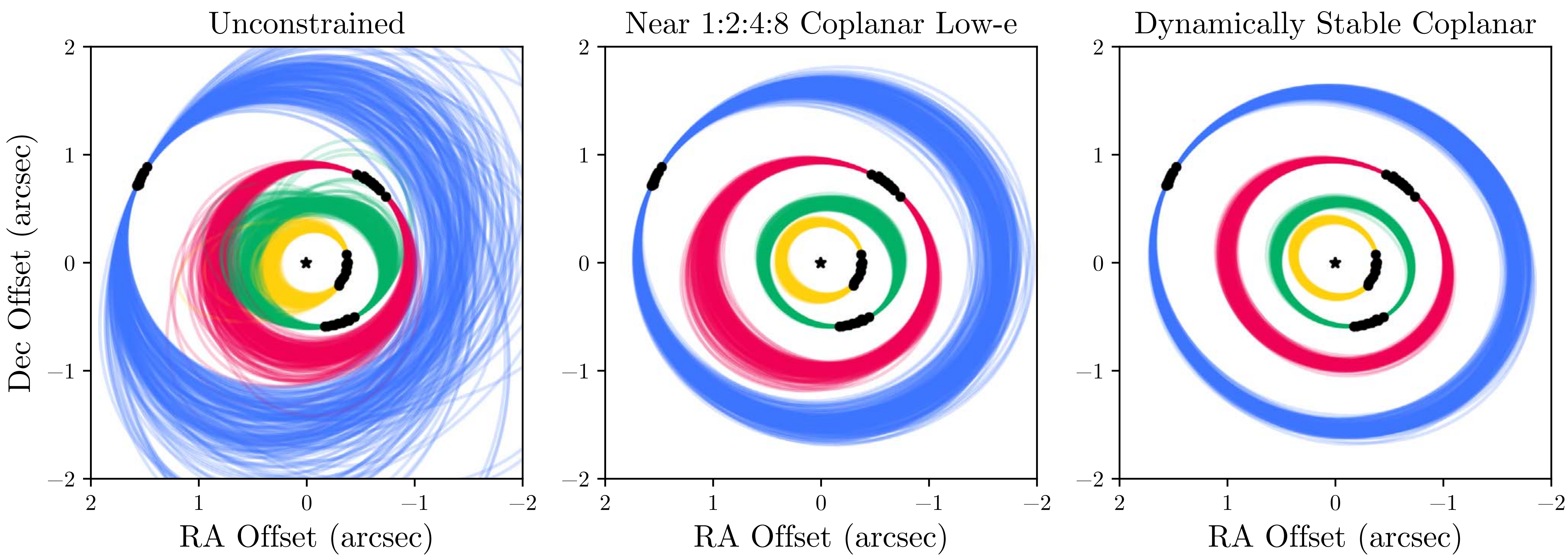
Atmospheric retrieval is used to constrain the value of many model parameters at the same time, as well as the P-T profile. Here, posterior distributions are shown for HR8799e.



Well-constrained orbits

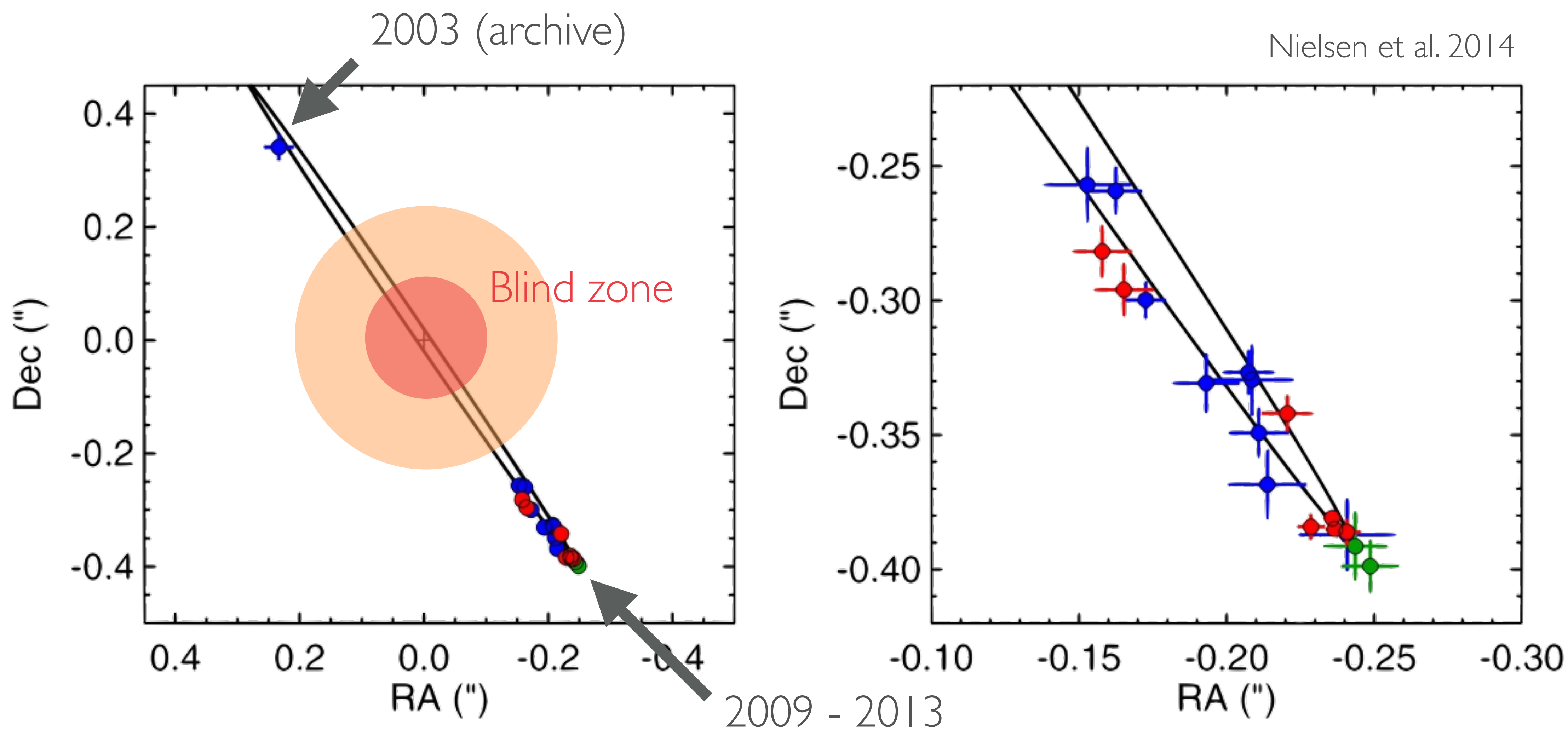


Dynamical studies



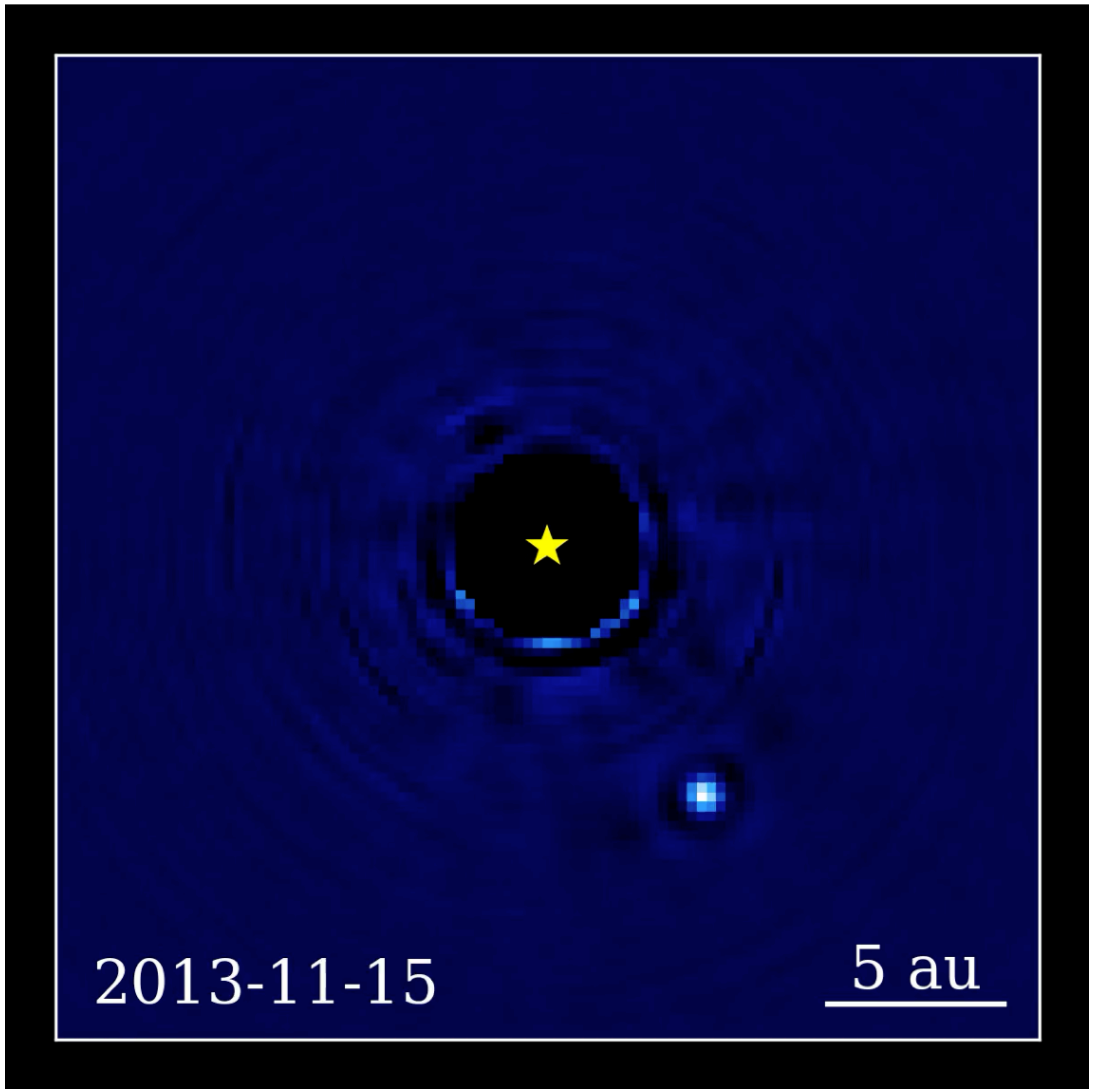
- Orbital architecture (mean motion resonance) informs on planetary mass, considering stability over 40 Myr (estimated age of system)

Full 3D orbits



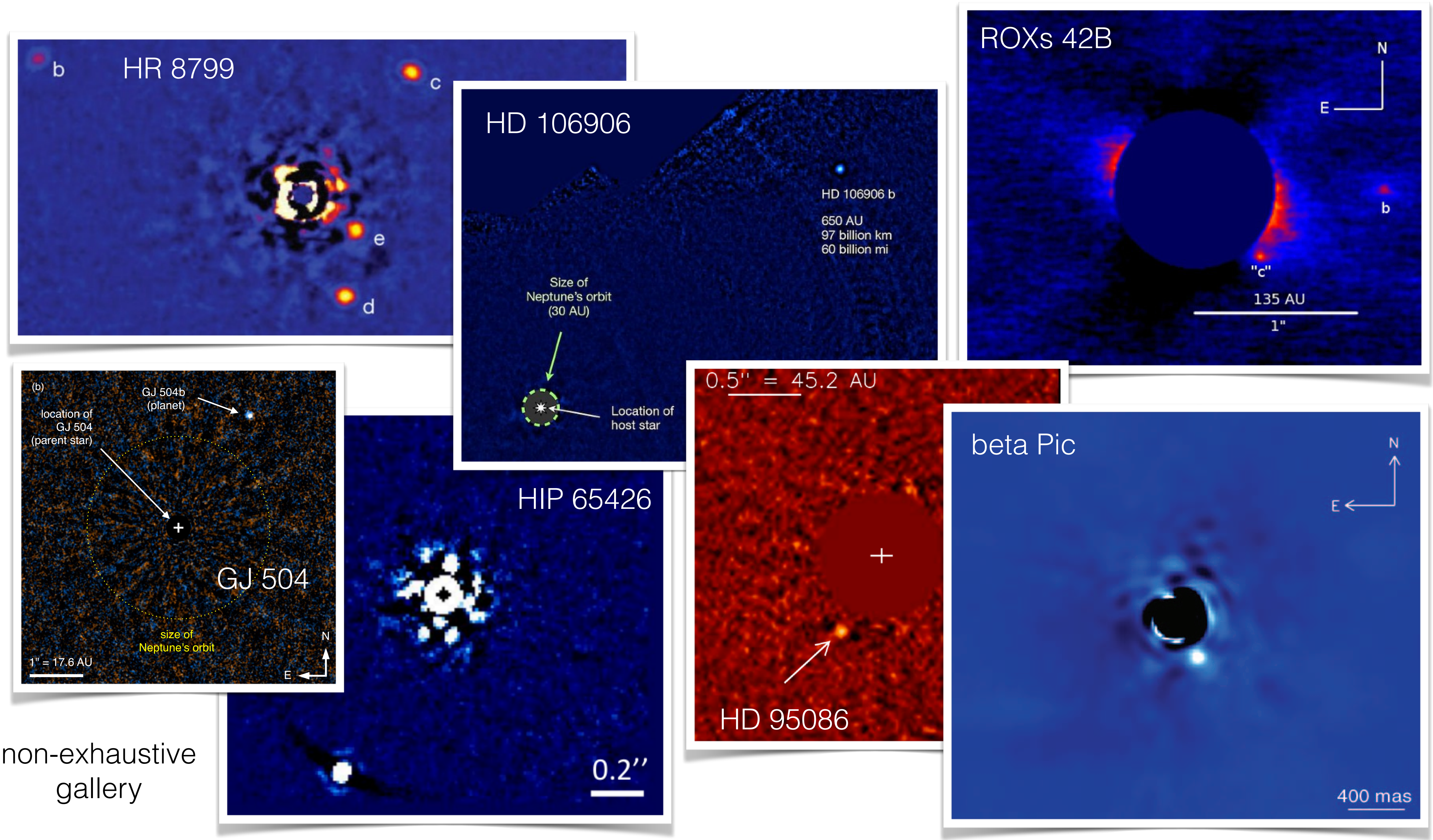
- Possible transit around mid-2017, but nothing found!
- Imaging now combined with RV and astrometry to derive true mass (so far only possible for beta Pic planets, close enough to their star)

beta Pictoris b emerging from the blind zone



Only ~20 planets imaged

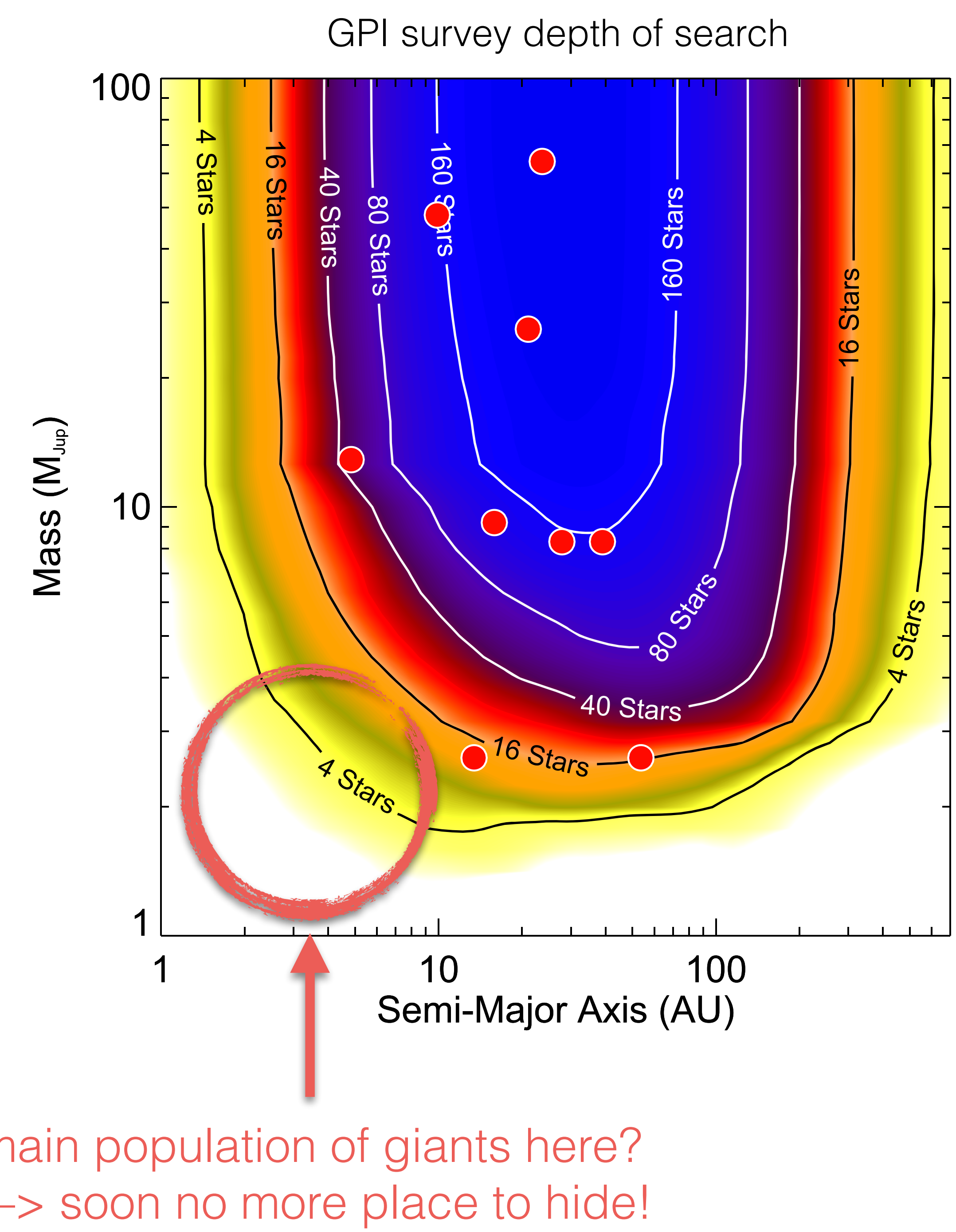
(young planets detected in thermal emission)



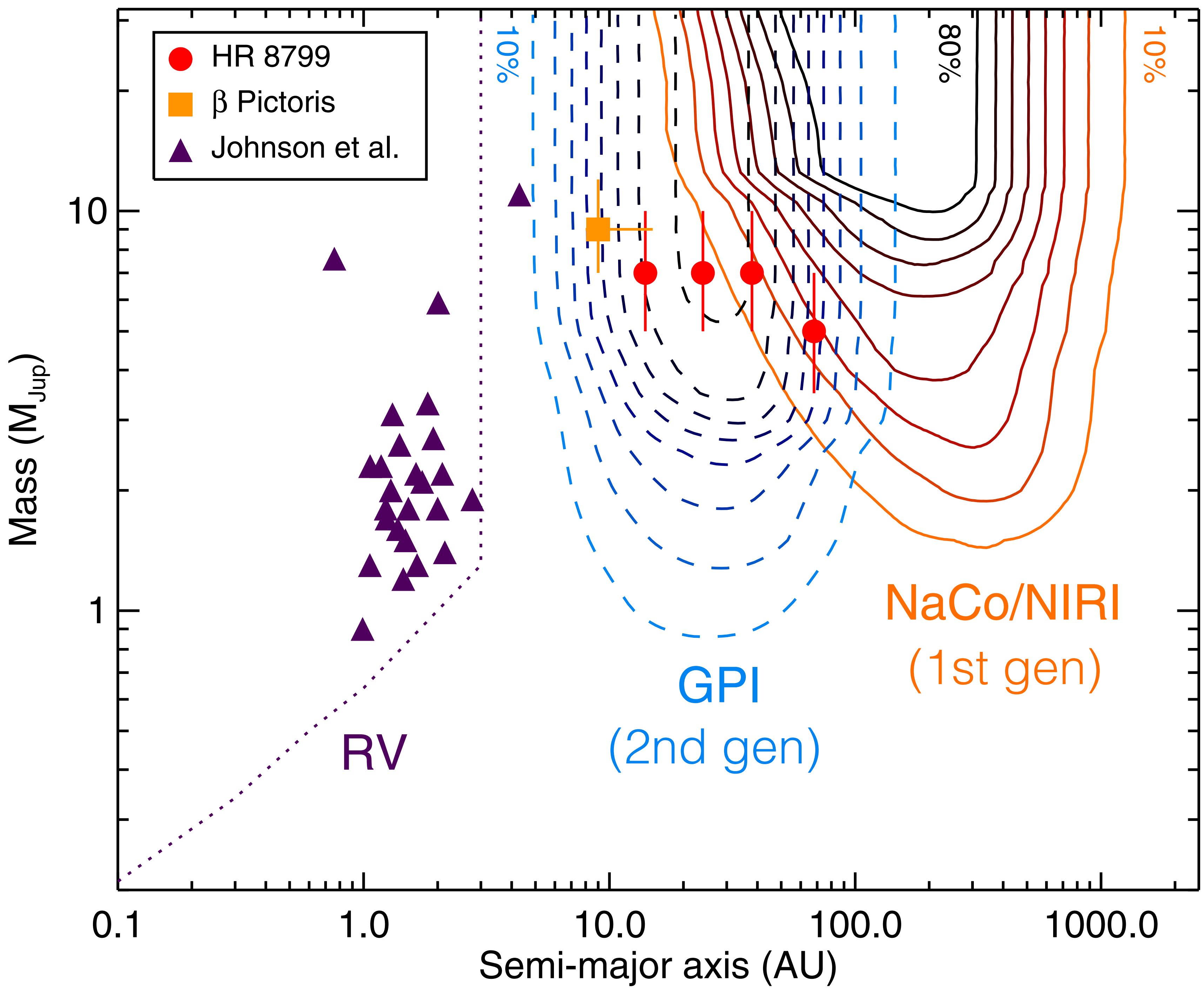
non-exhaustive gallery

Many more out there?

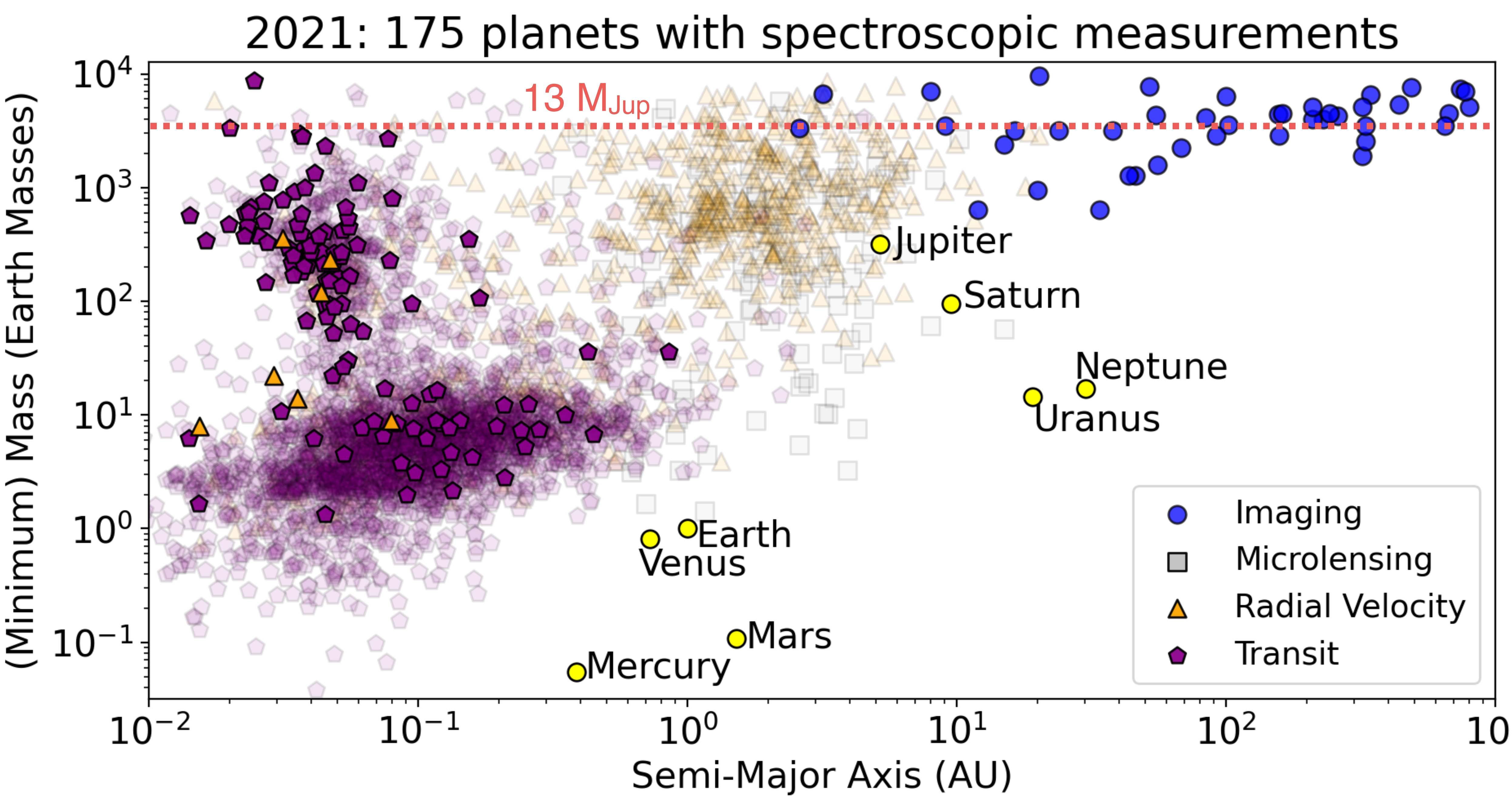
- Beta Pic b, HR 8799 bcde detected because of proximity and youth
    - Not representative of « median » target
- New XAO instruments still fall short of main planet population around ice lines (2-5 au)
    - ELTs will be game-changing
    - Following up Gaia astrometric trends could be very productive in the coming years
- HR 8799 system still pretty unique!



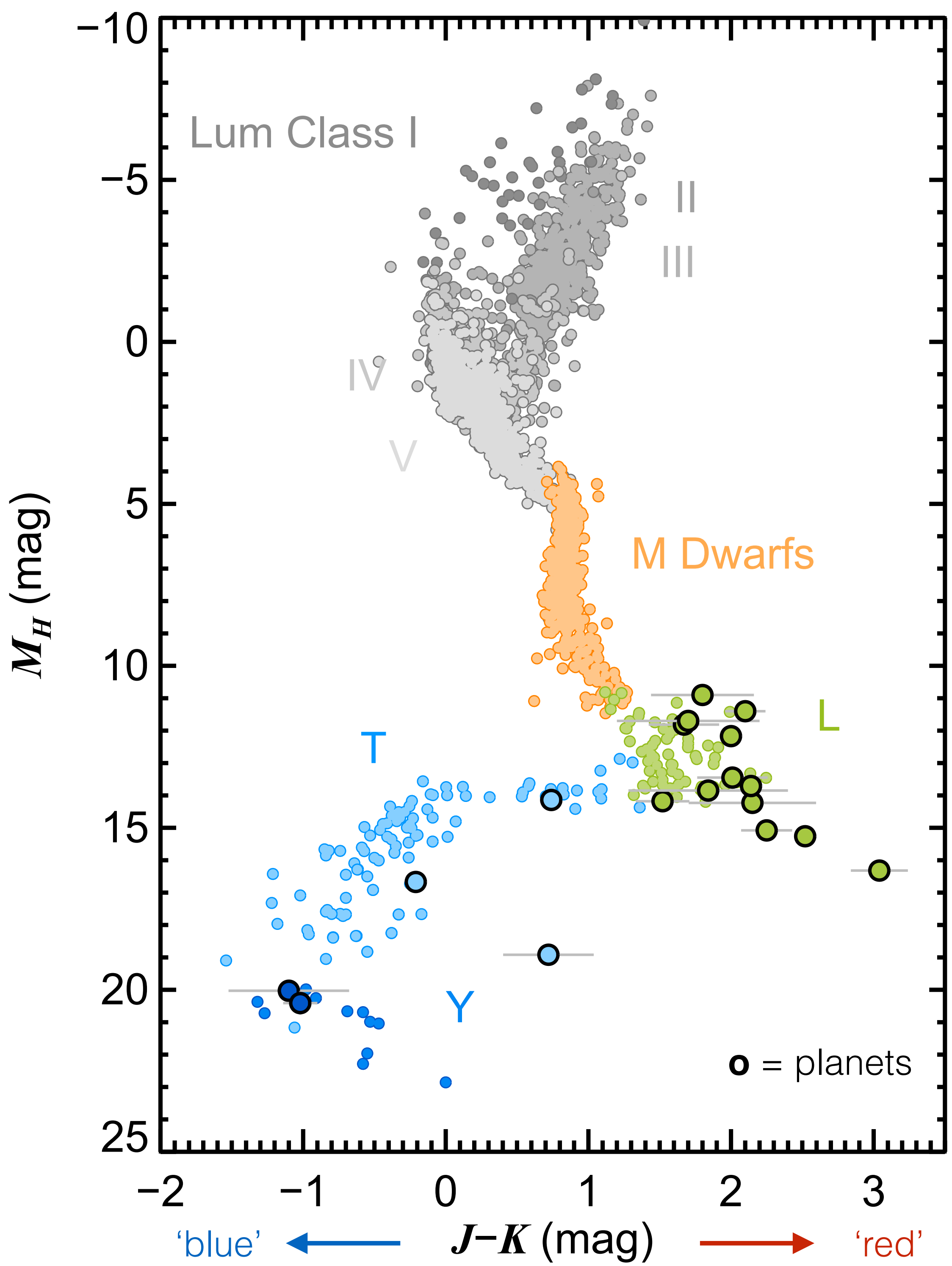
Gap with RV slowly filled



Twice more detections when also counting low-mass brown dwarfs



Brown dwarf or planet?



- Exoplanet and (young) brown dwarfs look very similar
- Color-magnitude diagram shows that exoplanets extend the L-dwarf sequence to redder and fainter magnitudes
- Understood to be due to delayed transition from cloudy (L-type) to cloud-free (T-type) atmospheres under low gravity

L-T transition: clouds disappearing with cooldown

- Disappearance of clouds change the colors of low-mass objects
- L-T transition still poorly understood due to the small number of detected planets