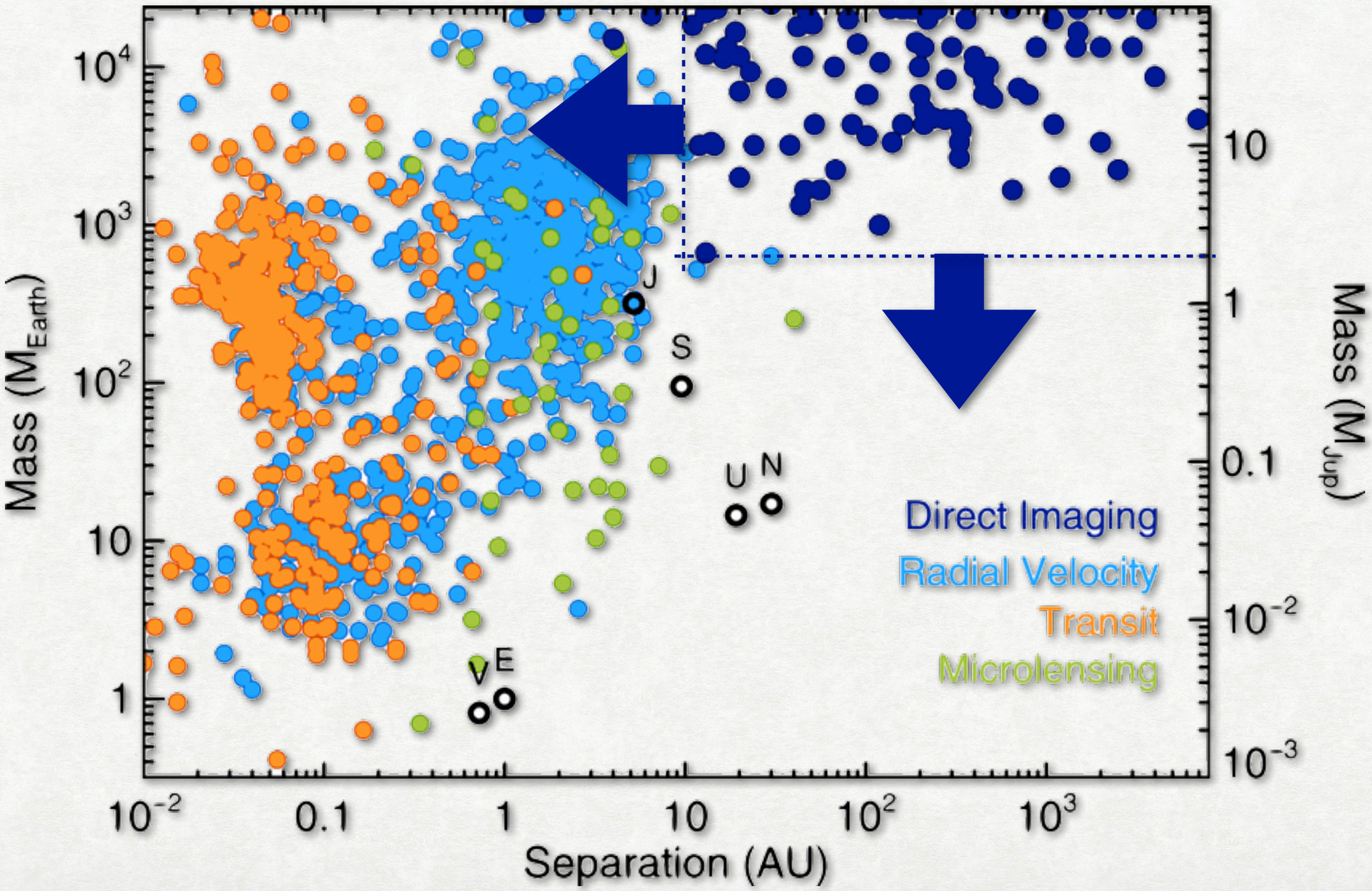
Ground-based thermal infrared astronomy – past, present and future
ESO on-line workshop, 12 - 16 October 2020

Background subtraction in High Contrast Imaging

Olivier Absil
University of Liège

EXOPLANET IMAGING TODAY

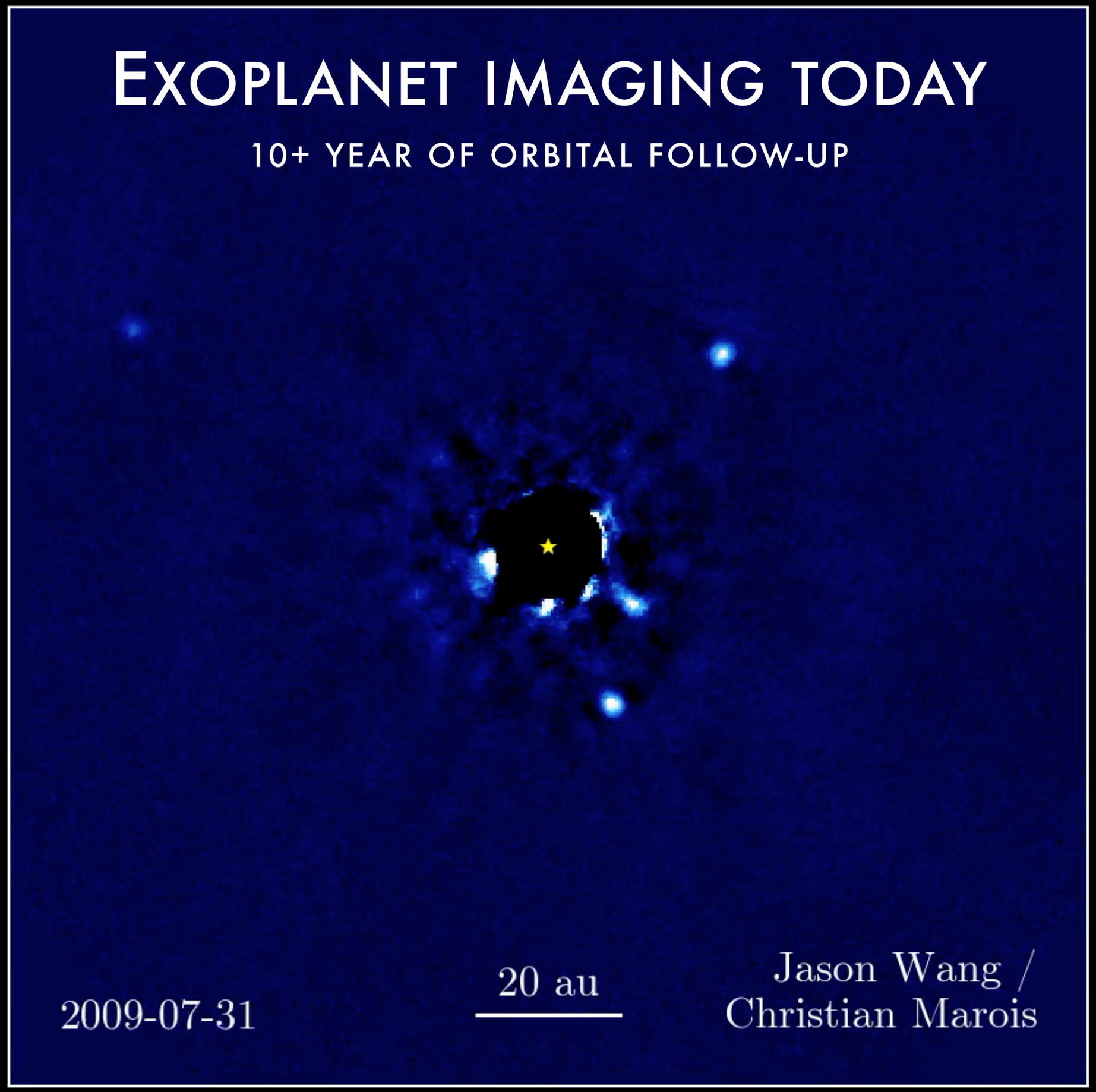
10+ YEAR OF DIRECT EXOPLANET DETECTION



Bowler et al. (2016)

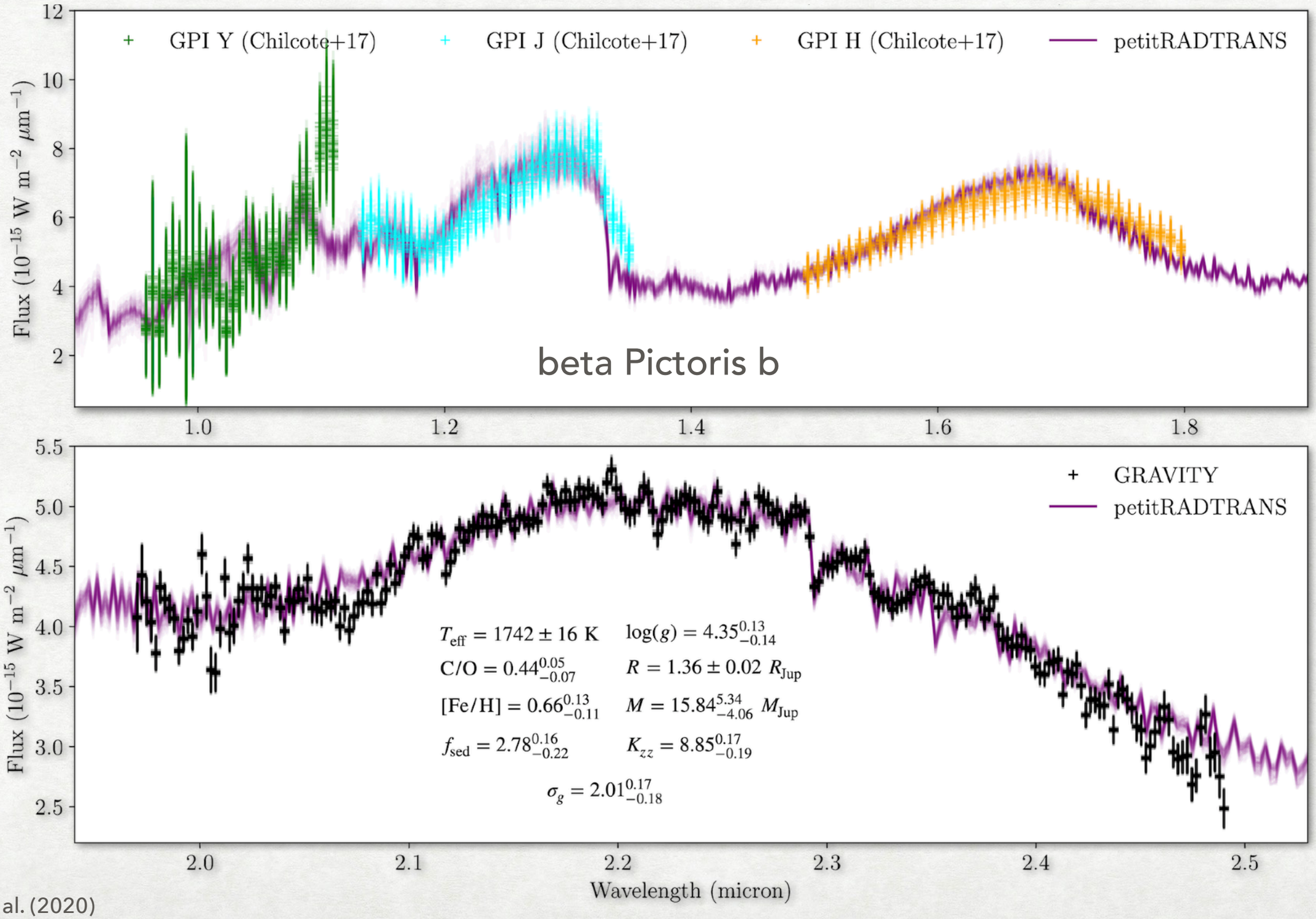
EXOPLANET IMAGING TODAY

10+ YEAR OF ORBITAL FOLLOW-UP



EXOPLANET IMAGING TODAY

EXQUISITE EMISSION SPECTRA → PHYSICS & FORMATION

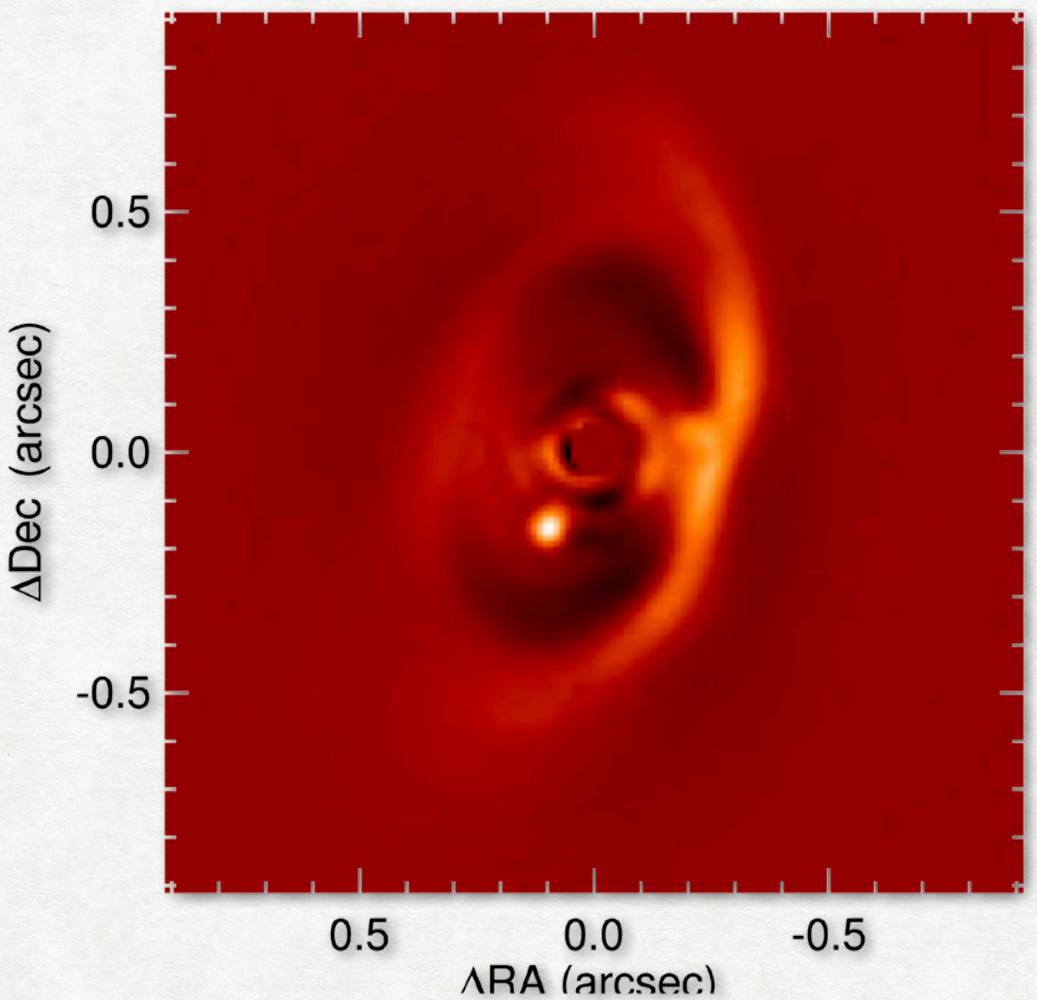


Nowak et al. (2020)

EXOPLANET IMAGING TODAY

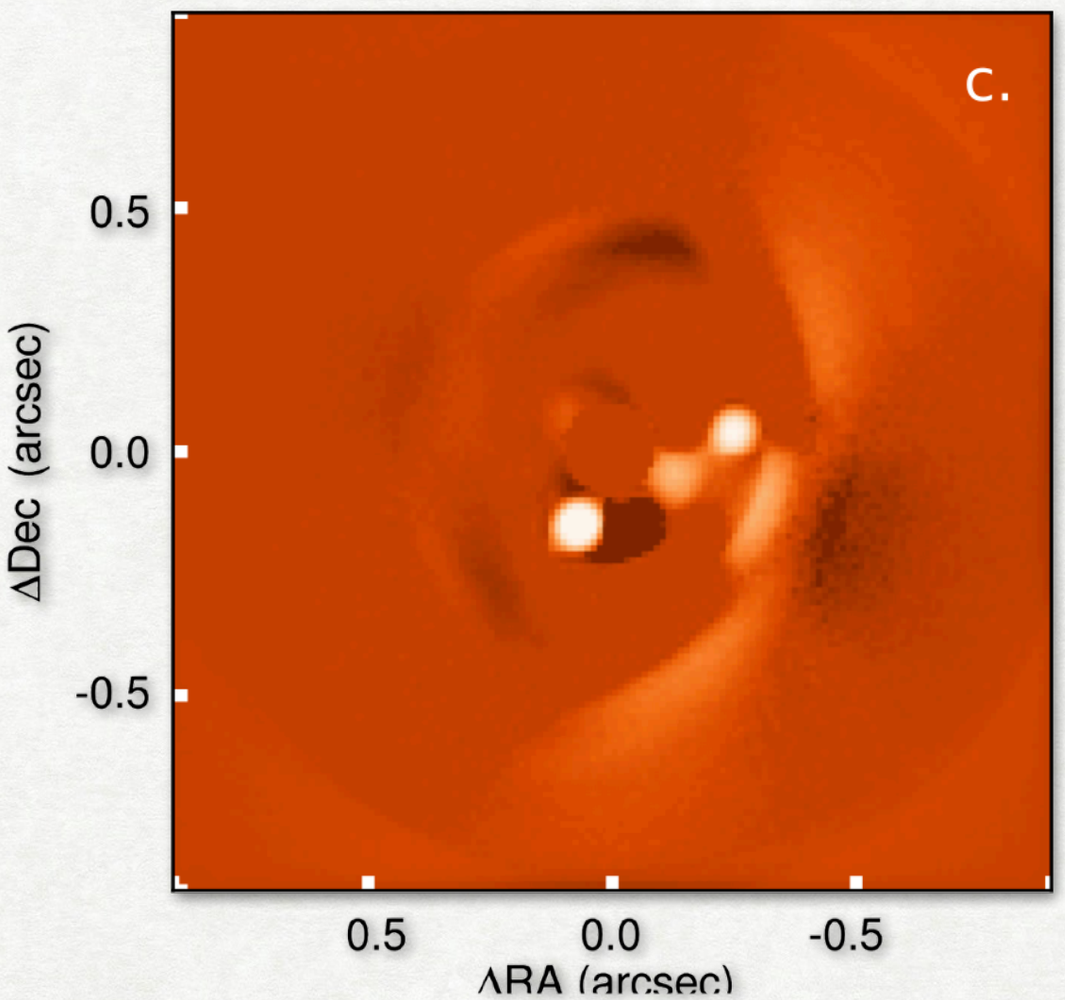
DIRECTLY PROBING PLANET FORMATION

observations



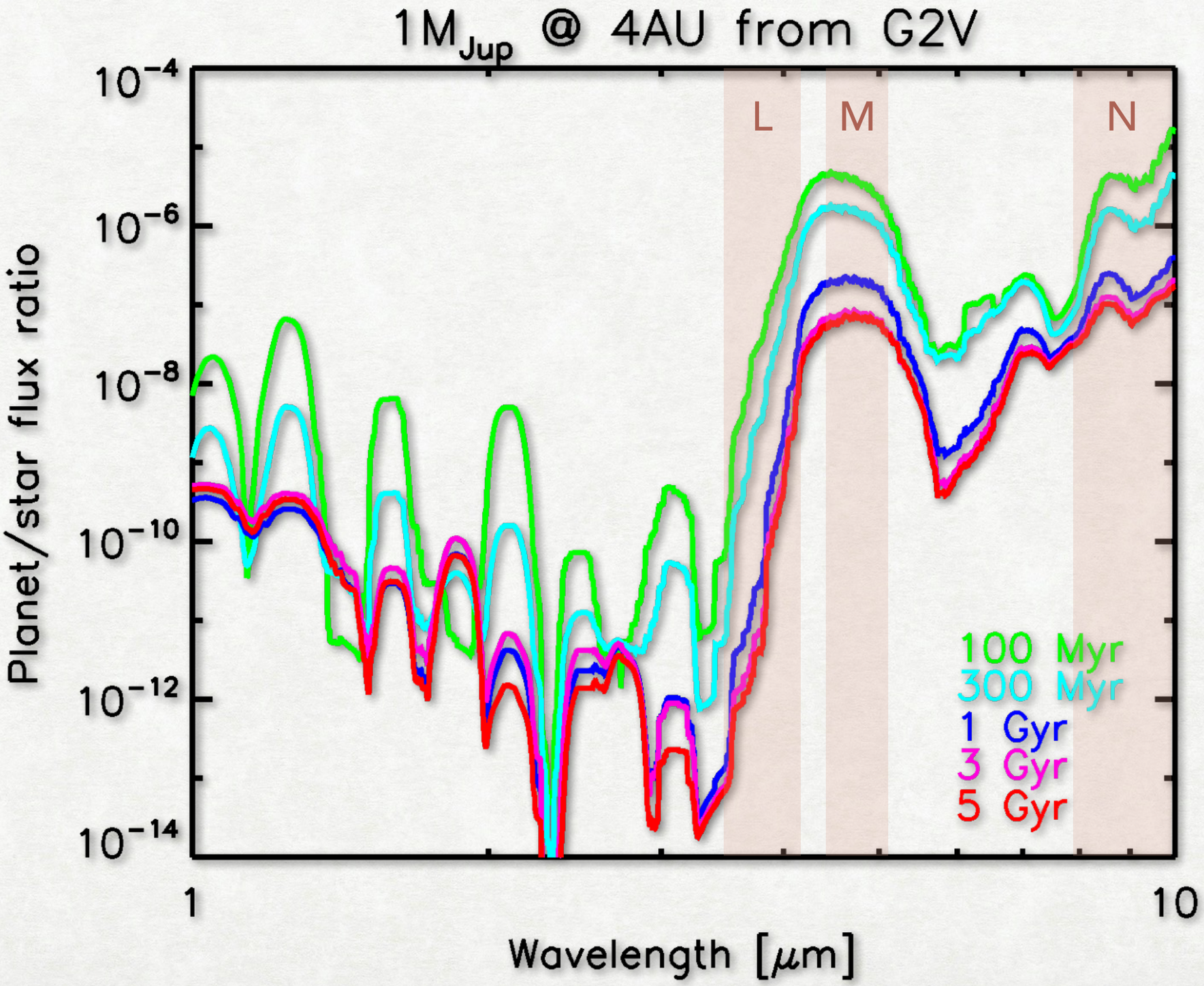
Müller et al. (2018)

hydro simulations



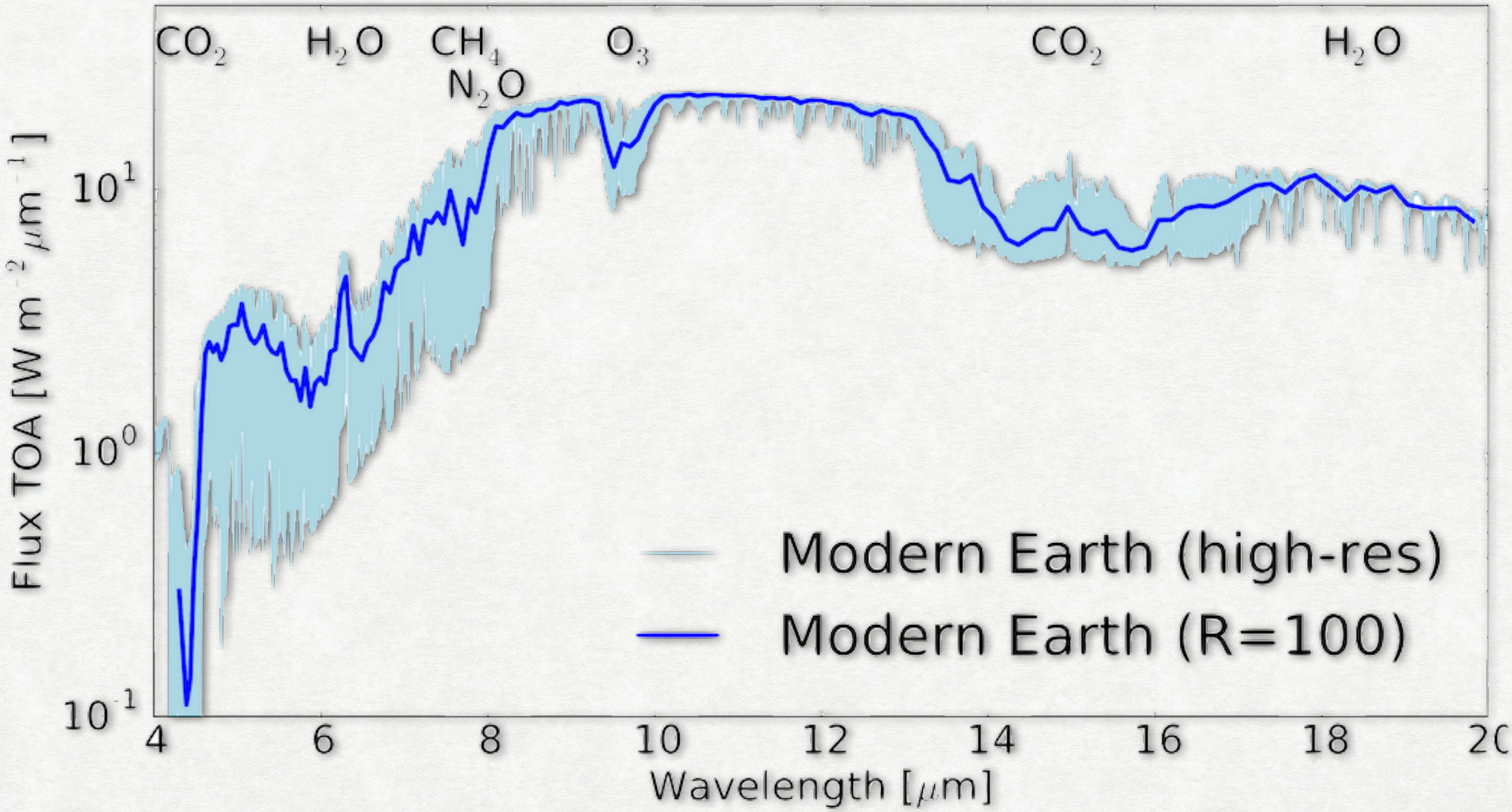
Toci et al. (2020)

WHY THERMAL IR MATTERS



Burrows et al. (1997)

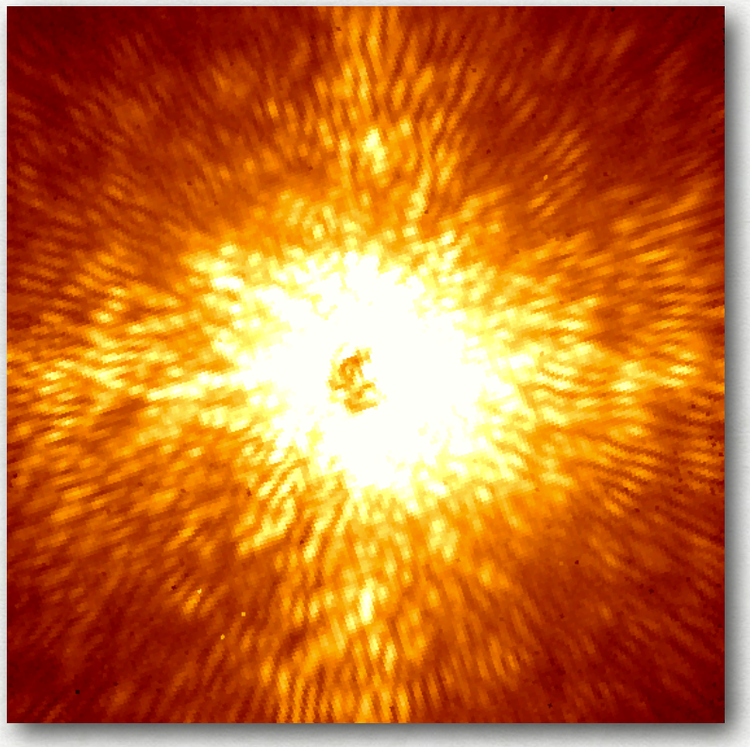
Why thermal IR matters



Rugheimer & Kaltenegger (2018)

THE HCI POST-PROCESSING CHALLENGE

Raw HCI data

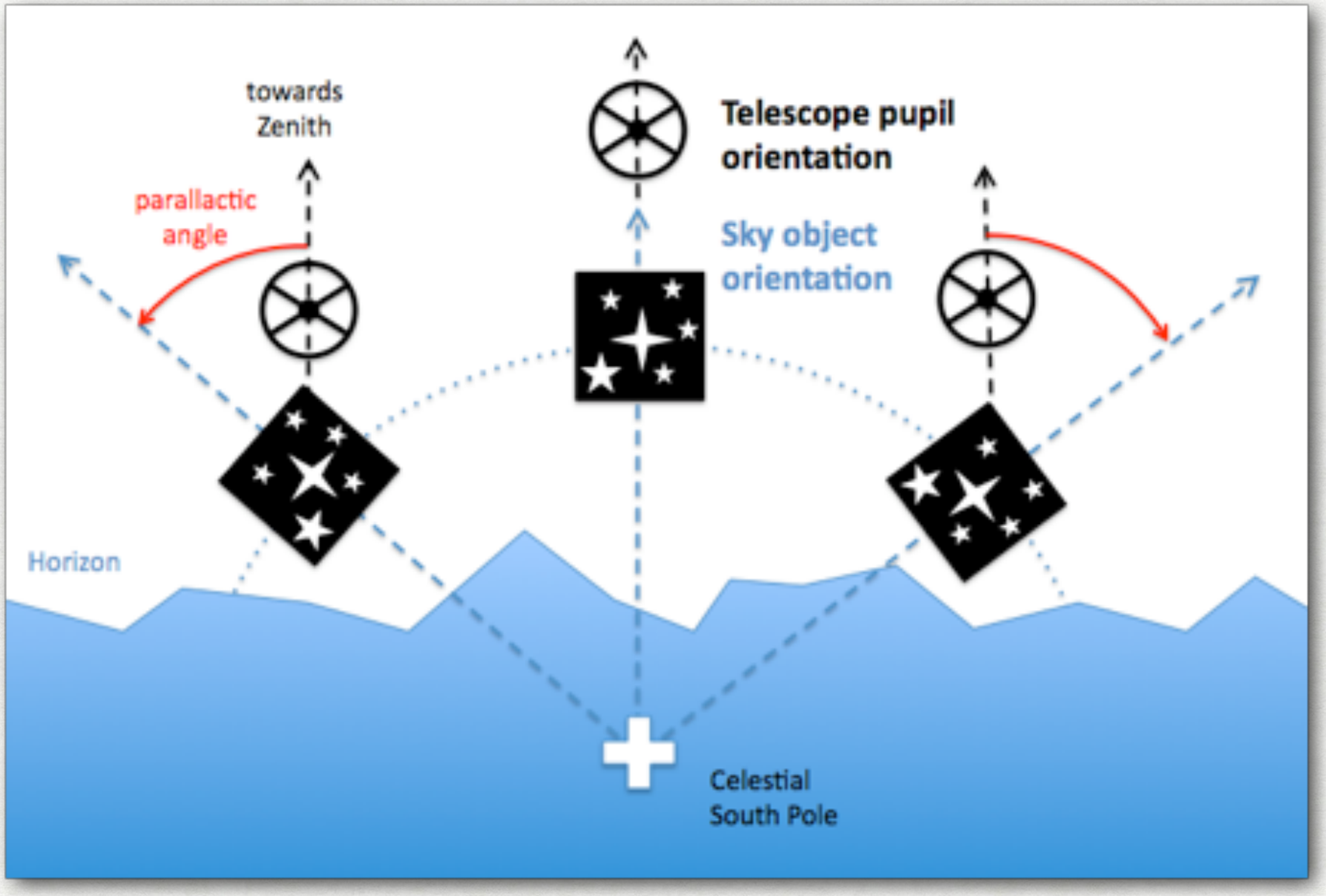


Close-up view on individual speckles

This is our background, varying at all timescales.
Rapid variations average out, quasi-static structures not.

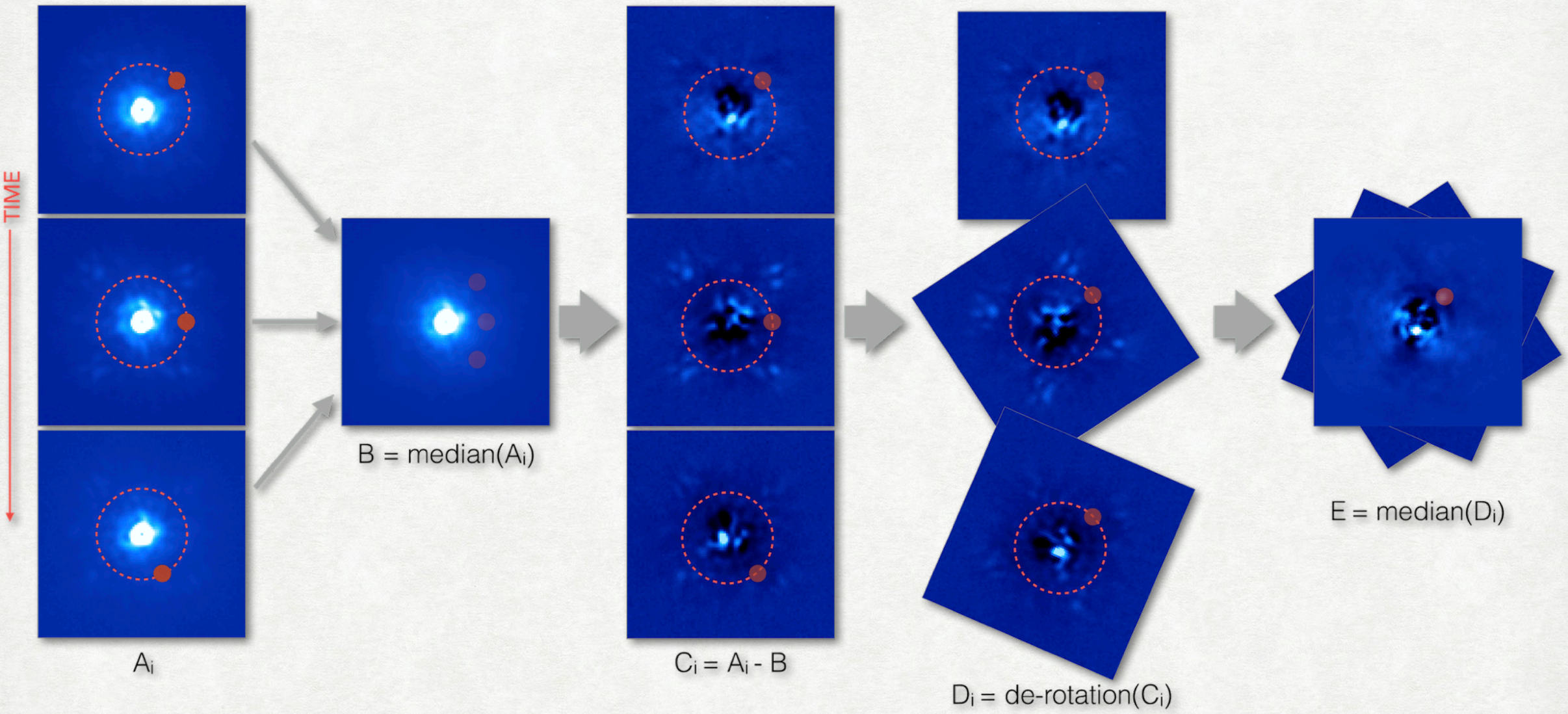
ANGULAR DIFFERENTIAL IMAGING

PUPIL TRACKING REVOLUTIONIZED THE FIELD OF DIRECT IMAGING

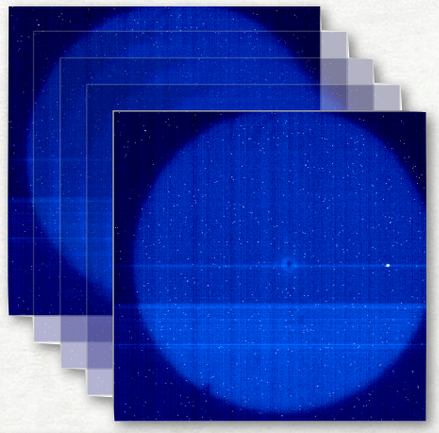


Prevents quasi-statics from moving, while the field rotates → **diversity**

PSF SUBTRACTION AT WORK



HCI POST-PROCESSING PIPELINE



Raw astronomical images

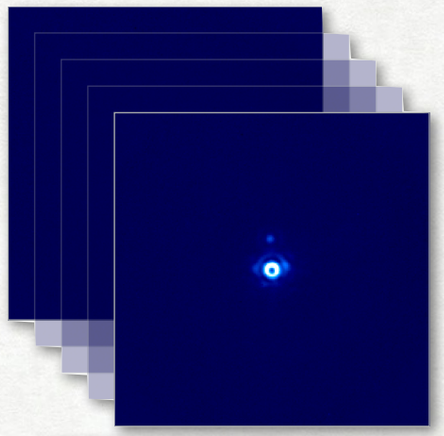


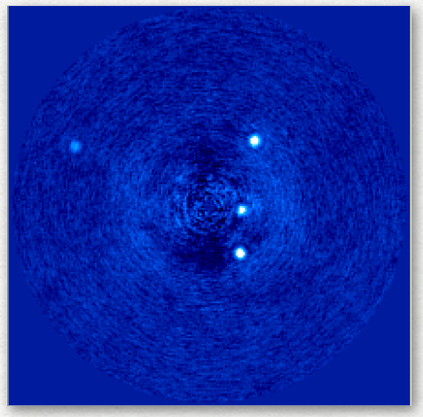
Image recentering

- Center of mass
- 2d Gaussian fit
- DFT cross-correlation

Reference PSF creation

- Pairwise
- Median
- PCA, NMF
- LOCI
- LLSG

Characterization of *detected* companions



Final residual image

Image combination

- Mean, median, trimmed mean

De-rotation (for ADI) or rescaling (for mSDI)

PSF reference subtraction

Bad frames removal

- Image correlation
- Pixel statistics (specific image regions)

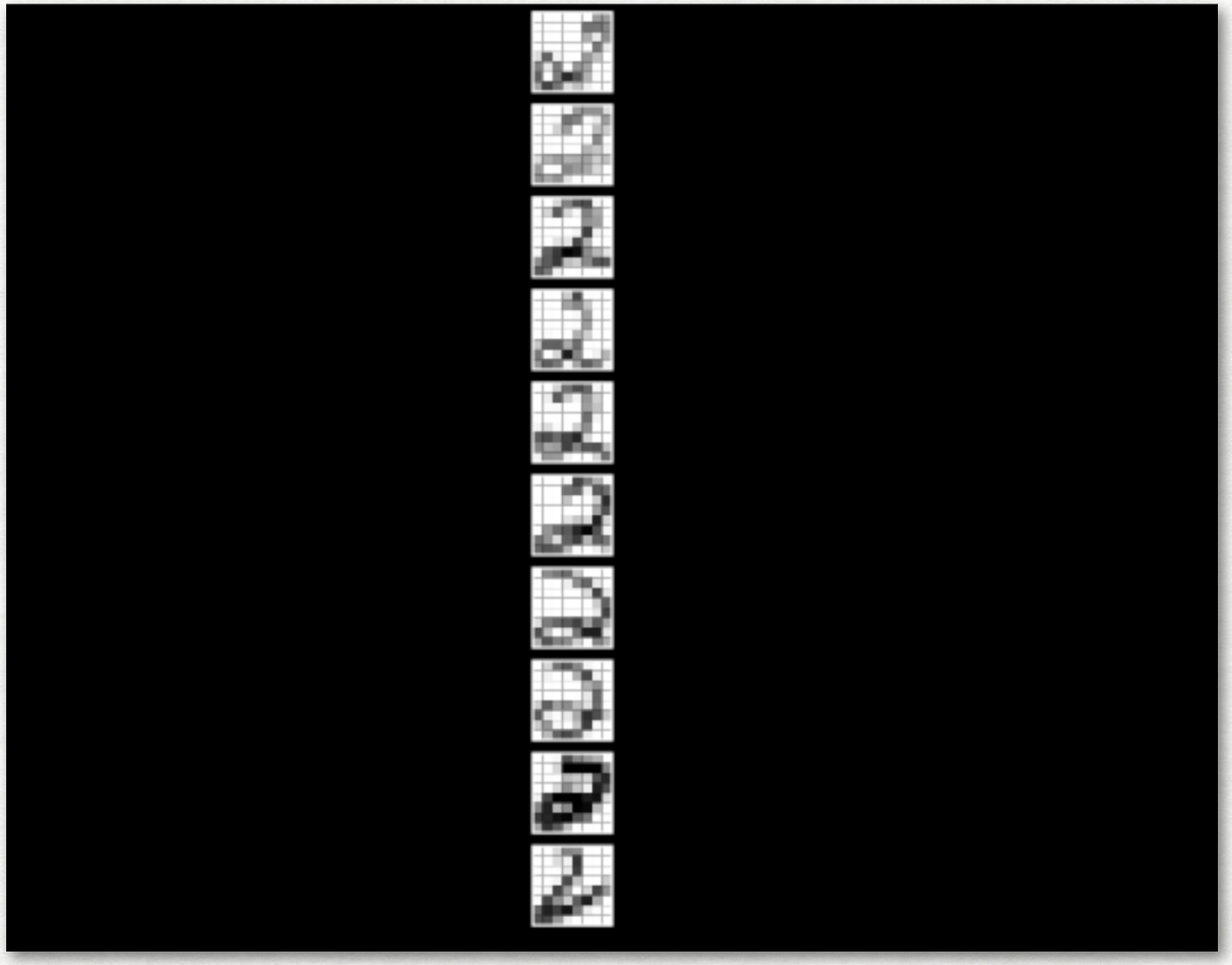
Basic calibration and "cosmetics"

- Dark/bias subtraction
- Flat fielding
- Sky (thermal background) subtraction
- Bad pixel correction

today's talk

Beyond median subtraction: PCA

First turn you 3D data cube into a 2D matrix

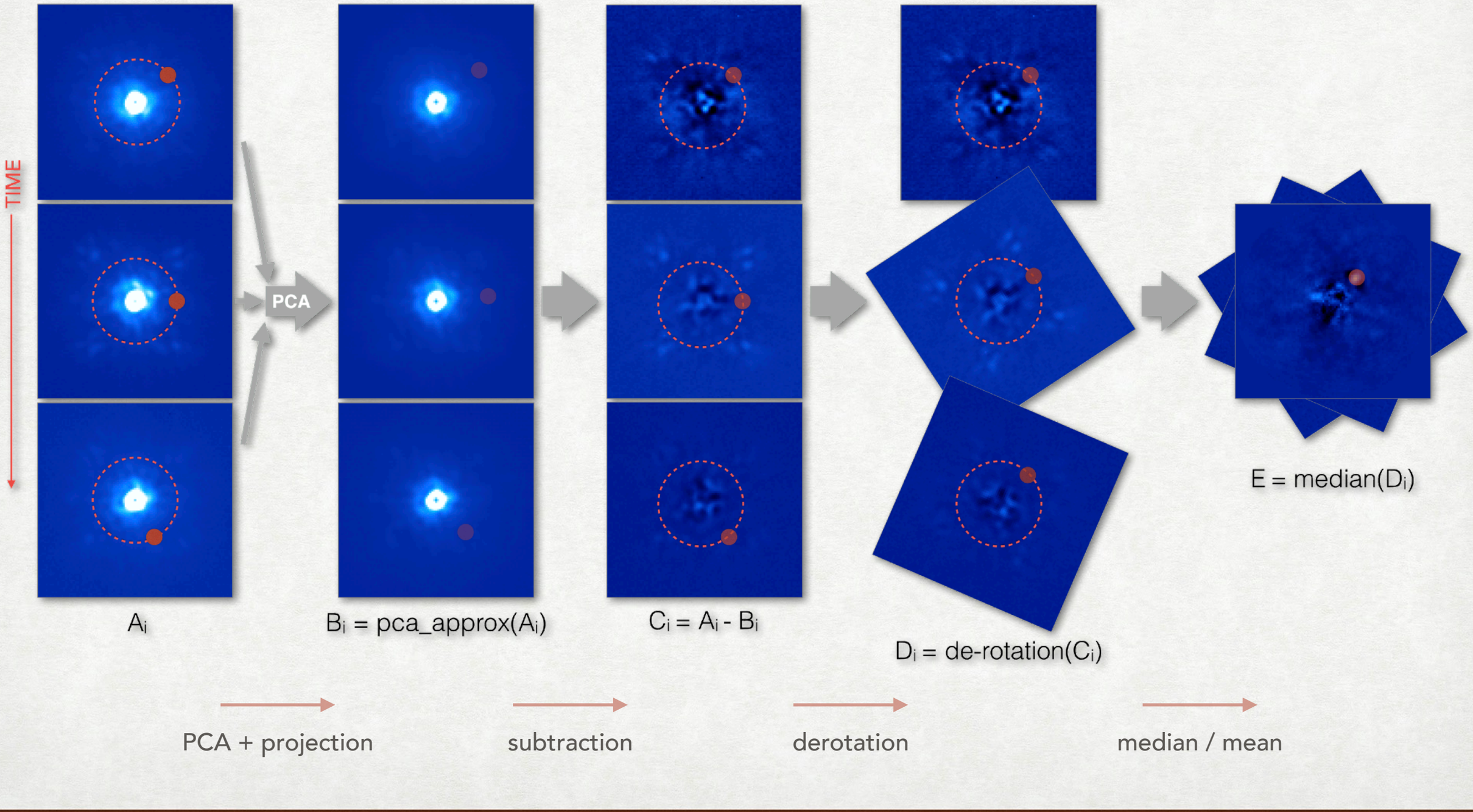


Then apply standard tools such as Singular Value Decomposition

Beyond median subtraction: PCA

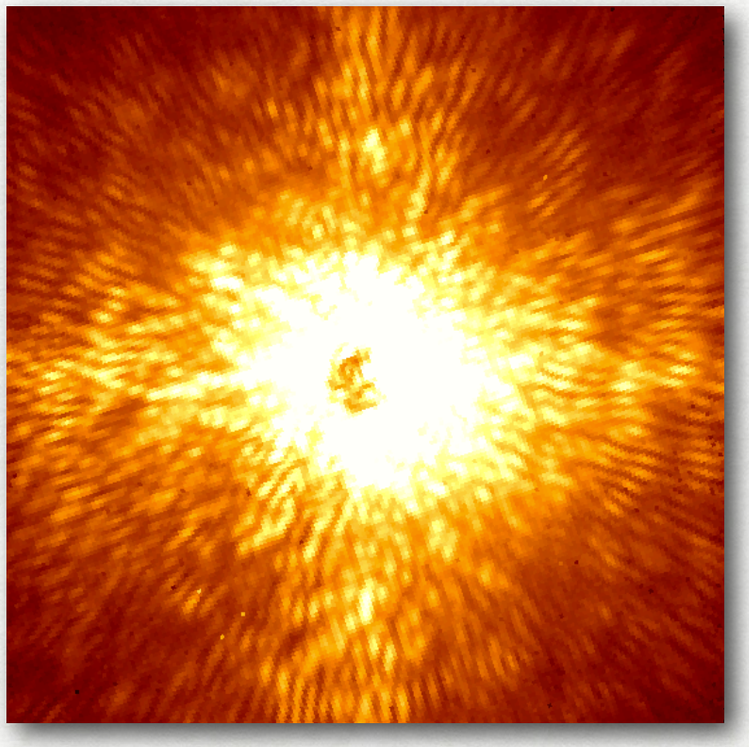
SVD → eigenvectors, aka principal components

basis truncation → low rank subspace, capturing quasi-stationary features

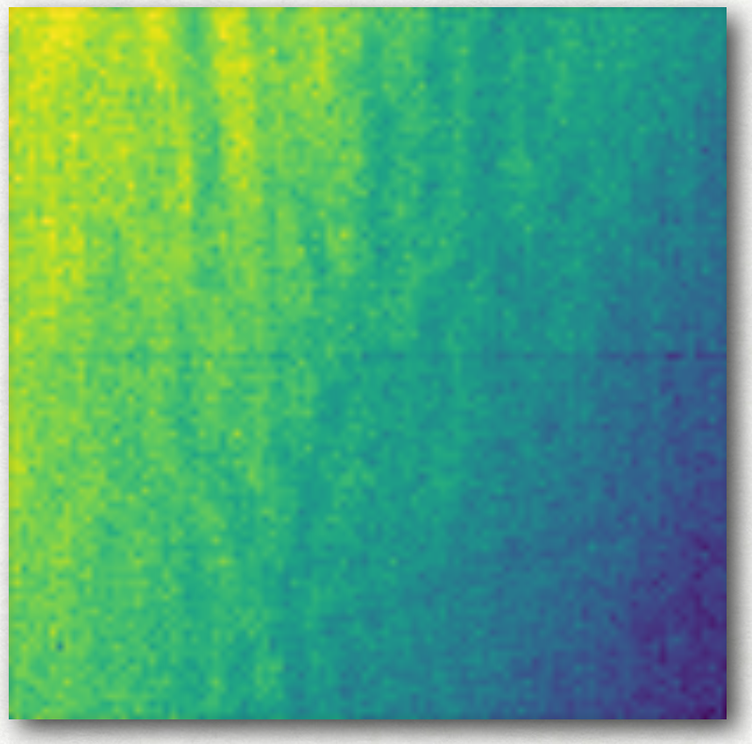


Where do we go from here?

« my » background



« your » background



Lesson #1: Pupil tracking helps

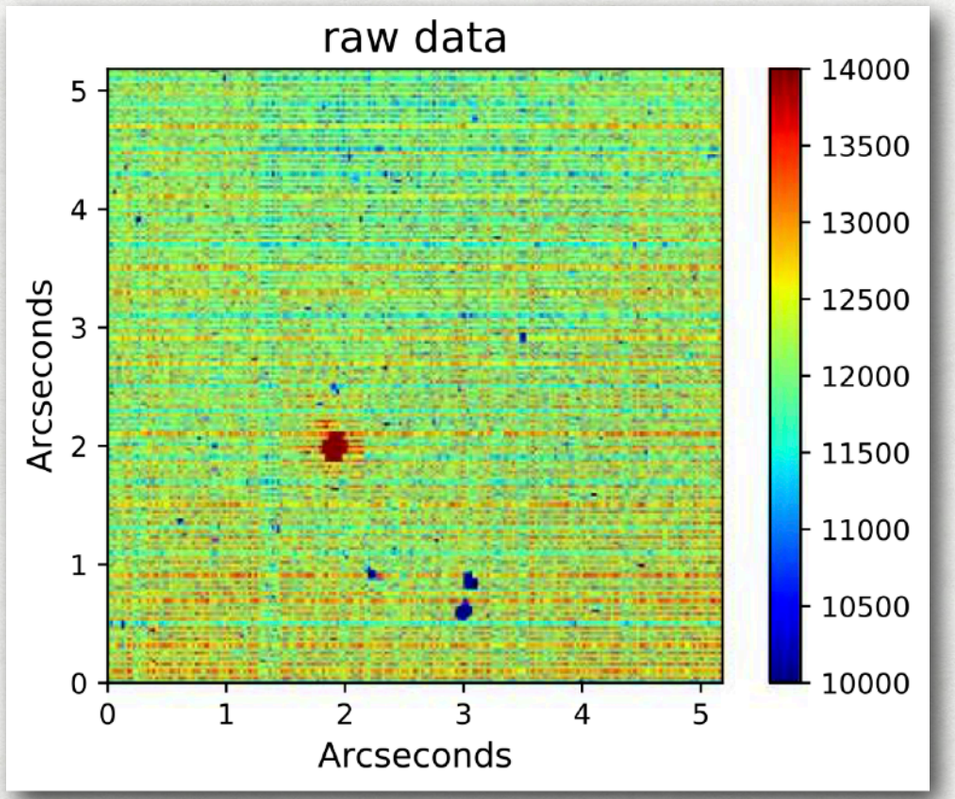
- Most quasi-static background structures are attached to the telescope pupil
  - pupil tracking keeps them from moving during observations
    → can be more readily identified and subtracted
- Pupil tracking provides easy way to mask spiders at cold
- Mid-IR uses short exposures → field rotation usually not a problem
- Conclusion: generalize the use of pupil tracking!!!
  - usually not a major effort if derotator can be accessed

Lesson #2: Low-rank approximations

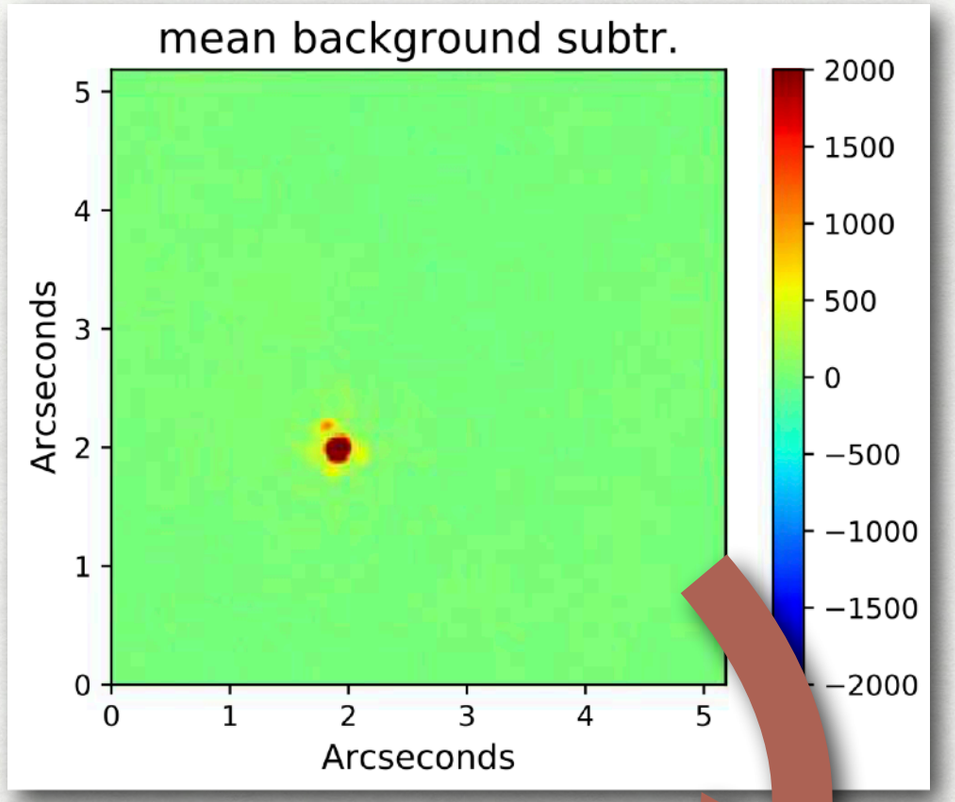
- Efficient way to disentangle rotating field from quasi-static background features (in pupil tracking)
- Most appropriate for point sources — known to affect images of extended sources
  - self-subtraction: source partly captured in low-rank subspace
  - over-subtraction: source projection onto low-rank subspace ≠ 0
- Possible solutions for mid-IR background subtraction
  - compute the coefficients of the low-rank approximation far from source
  - more straightforward when dedicated background measurements are available (chopping / dithering)

Full example: NACO at M band

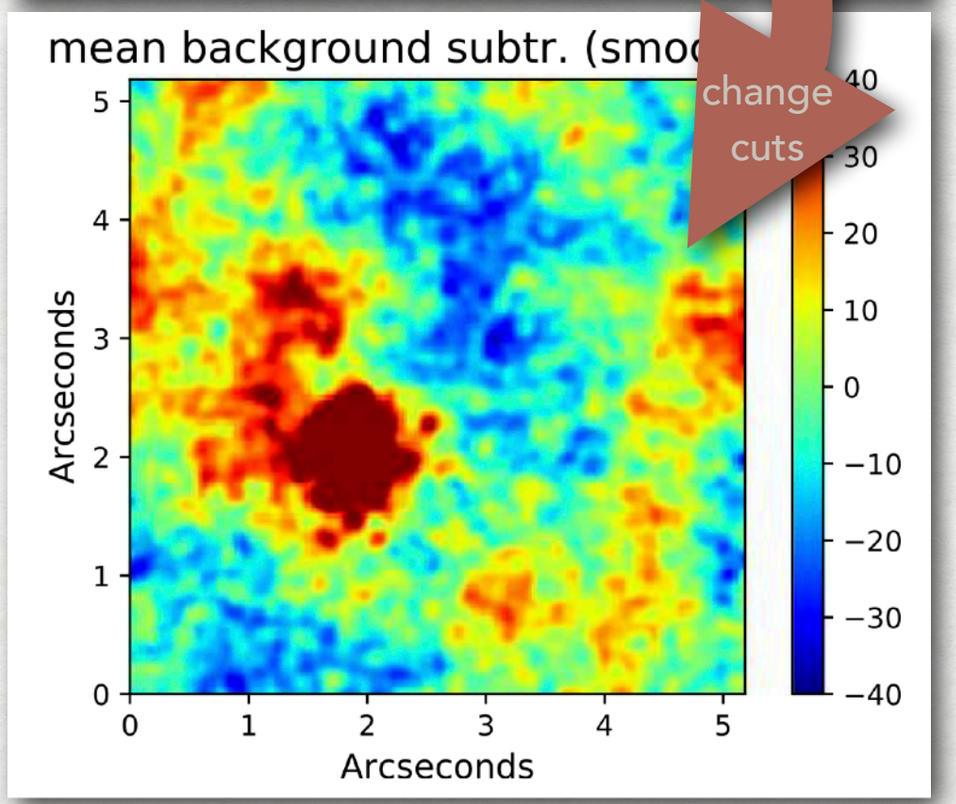
Illustrations from Hunziker et al. (2018)



mean subtraction



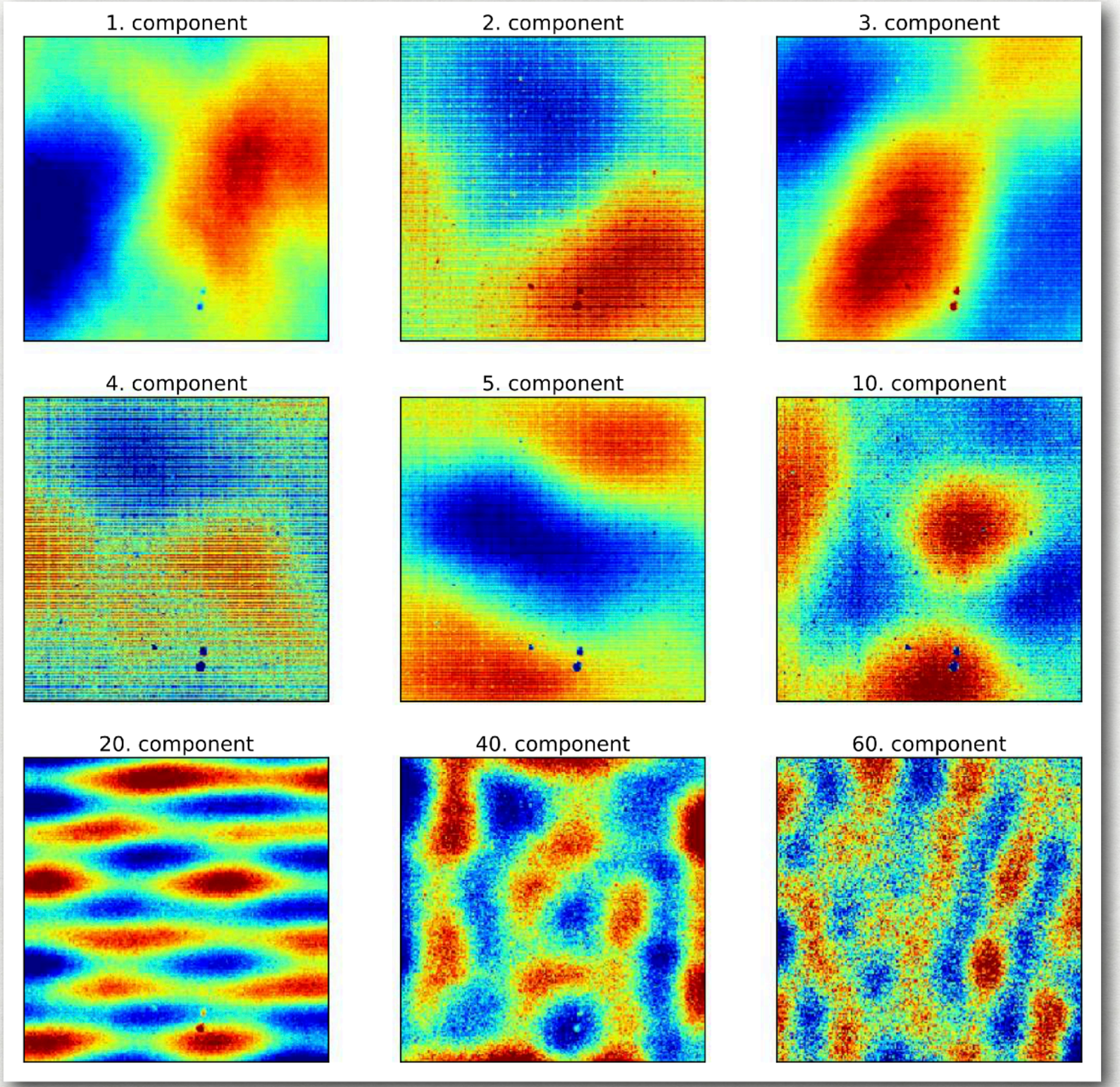
change cuts



Hunziker et al. (2018)

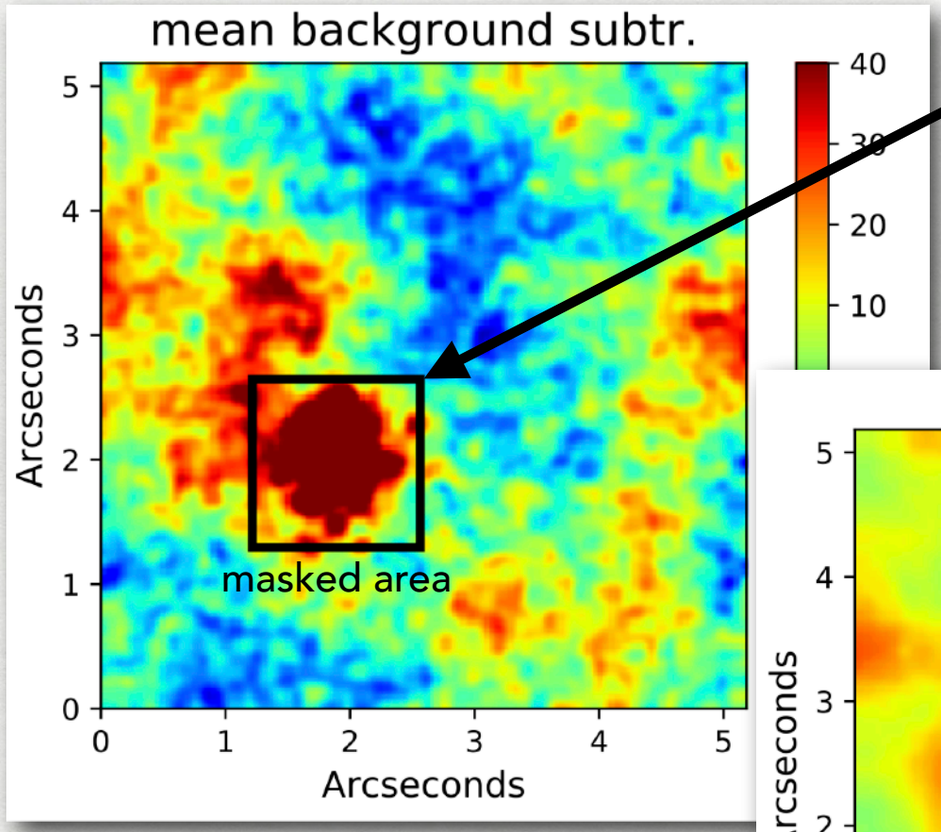
PCA ON DEDICATED BACKGROUND FRAMES

PCs ordered by increasing contribution to the representation of the background



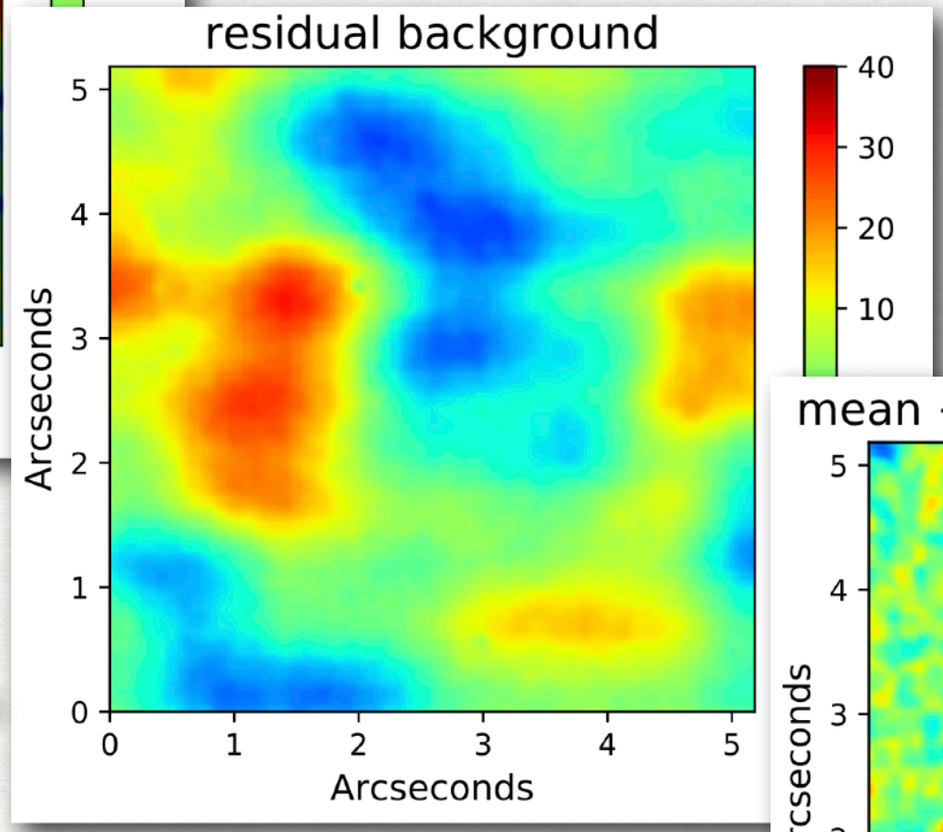
Hunziker et al. (2018)

Projecting and subtracting

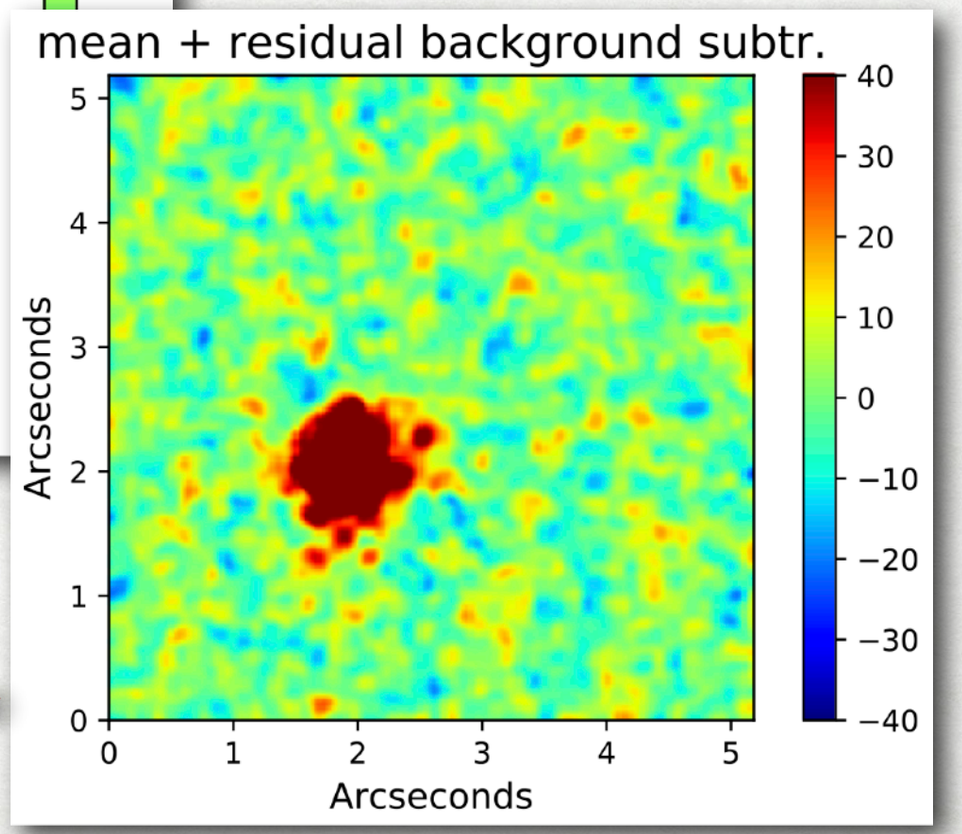


Small masked area does not significantly affect background reconstruction accuracy

projection onto low-rank subspace (K=60)



subtraction



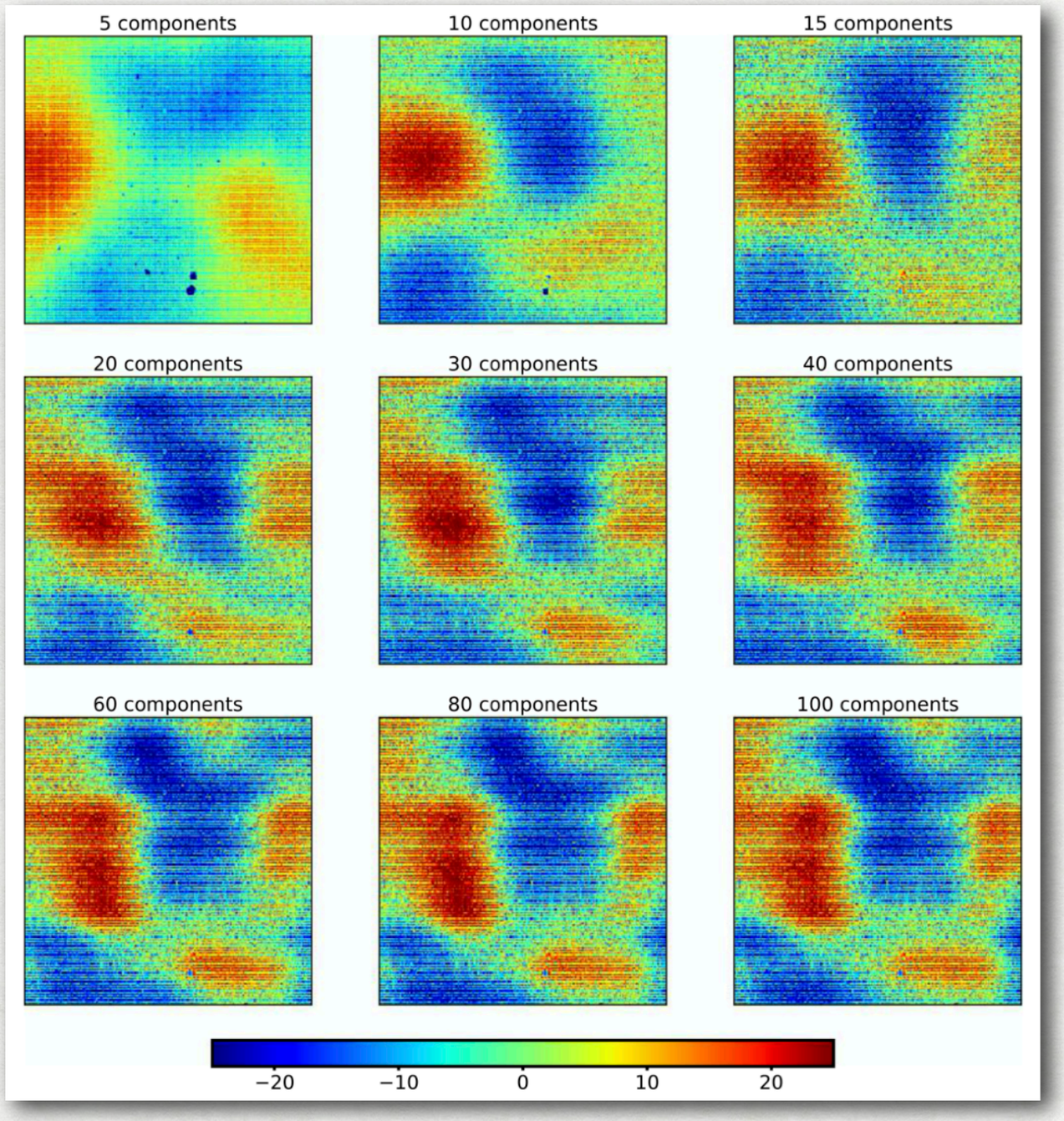
Available in your favorite HCI package:

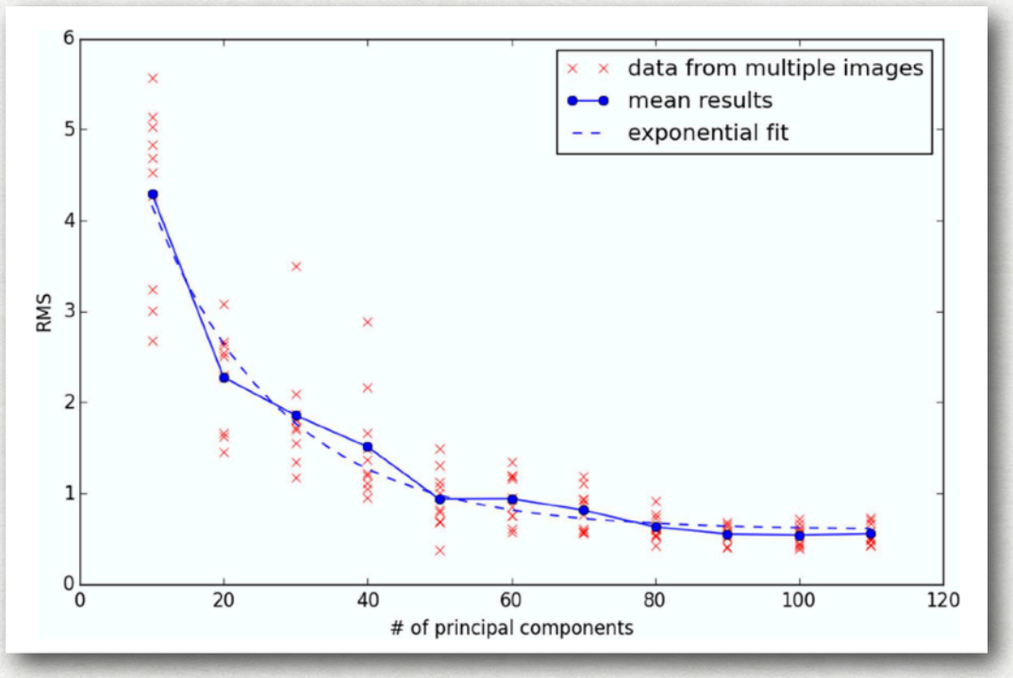
VIP PynPoint

Hunziker et al. (2018)

Background estimate vs #PC

Background representation after projection onto low-rank subspace





Caution: data-specific behavior!
(here NACO M band)

Hunziker et al. (2018)

Beyond PCA

- Several HCI post-processing algorithms proposed in last ~5 years
- Maximum likelihood / matched filter (Cantalloube+2015, Pueyo2016, Ruffio+2017, Flasseur+2018)
  - tailored to searching for specific features (e.g., point sources)
- Morphological component analysis (Pairet+2020)
  - also target-specific: use appropriate basis for signal to become sparse
- (Supervised) deep learning (Gomez Gonzalez+2018, Yip+2019)
  - currently focusing on detecting specific features (point sources)
  - could be used to learn the background structure if sufficiently large training data set can be provided
  - pre-trained convolutional neural networks are now available off-the-shelf (ResNet, UNet, Inception, etc)

An interdisciplinary problem?

- Background subtraction also studied in computer vision
- Usually used for identification of moving objects in video streams
  - not meant to handle the addition of foreground and background light
- Rich literature on how to model the background
  - Gaussian mixture models, robust PCA, fuzzy models, neural nets, …
    (see Bouwmans 2014, for a review)
- Generally not designed to reach the accuracy needed in mid-IR observations
  - challenges are more related to data stream, robustness to illumination changes, repetitive motion, etc

Conclusions

Pupil tracking is your friend! :-)

Low-rank approximations look promising to model & subtract background residuals