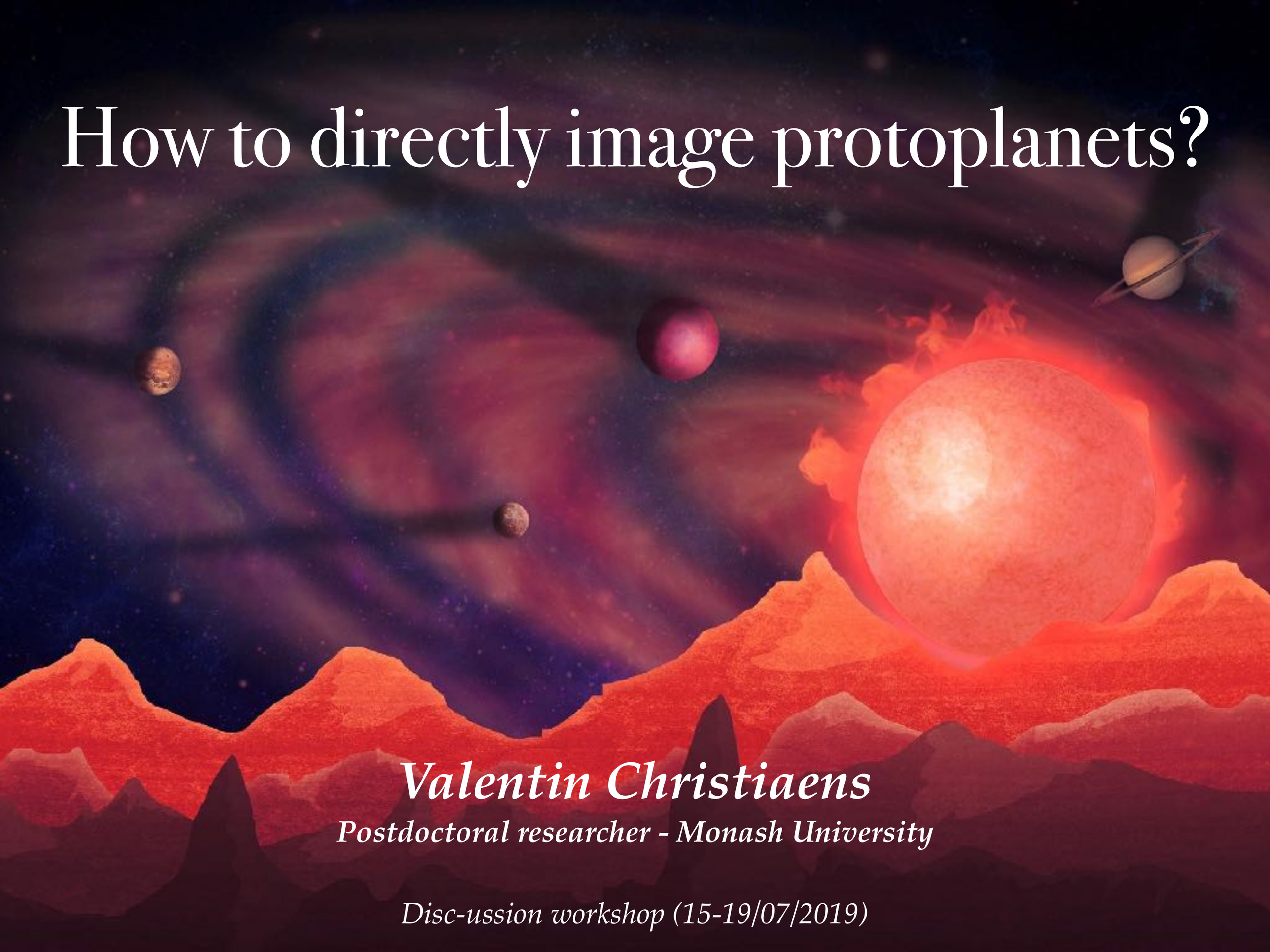
How to directly image protoplanets?



Valentin Christiaens

Postdoctoral researcher - Monash University

Disc-ussion workshop (15-19/07/2019)

Outline

- I. Introduction
  - Observing strategies
  - Image post-processing
- II. Direct imaging search
  - Results
  - Non-results
- III. New promising techniques
- IV. Future instruments

Why direct imaging?

- Invaluable information:

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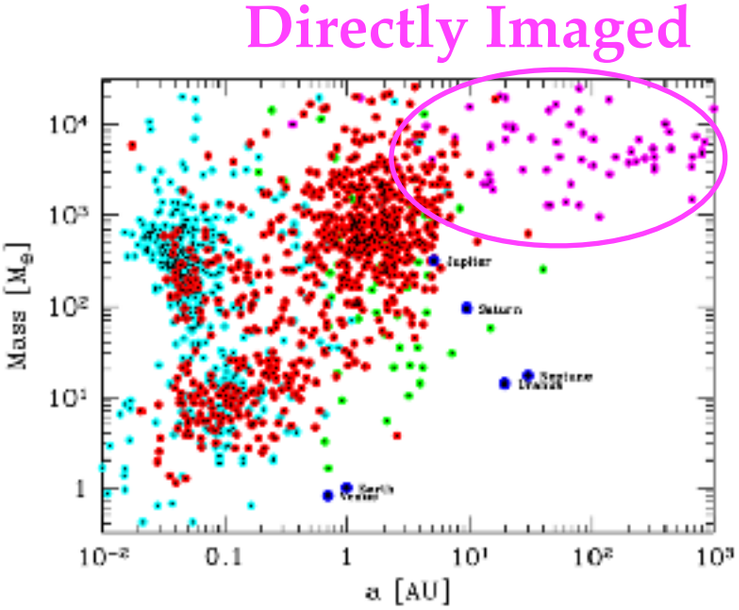

Mordasini+18

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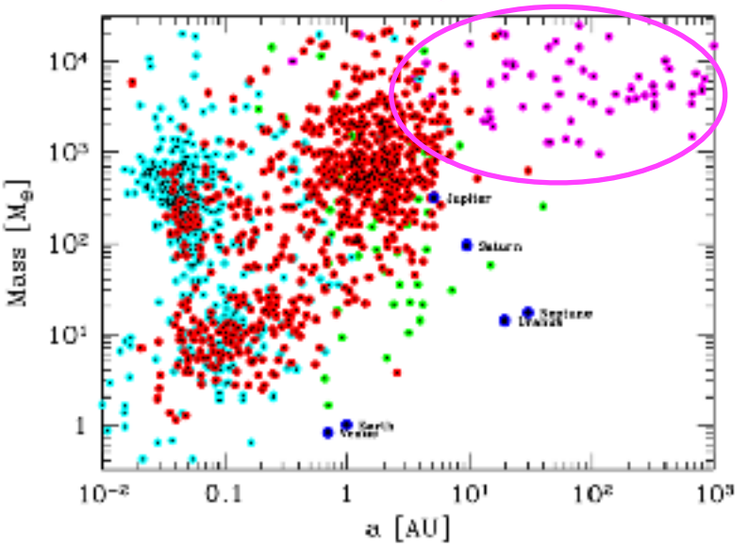
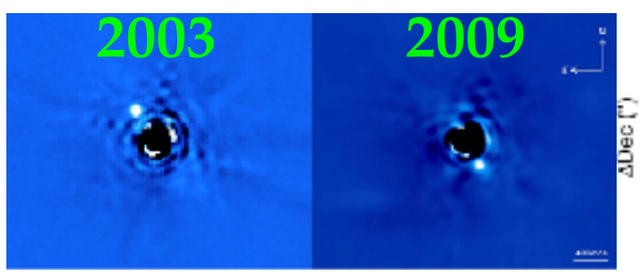
Directly Imaged

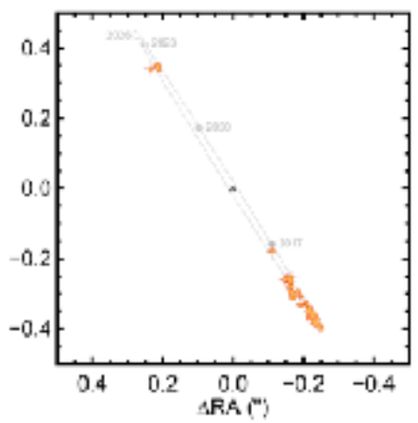


Mordasini+18

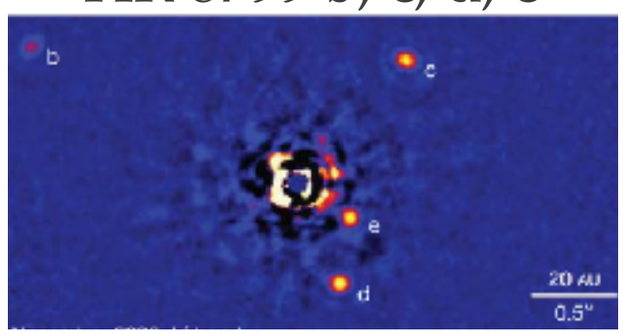
β Pic b



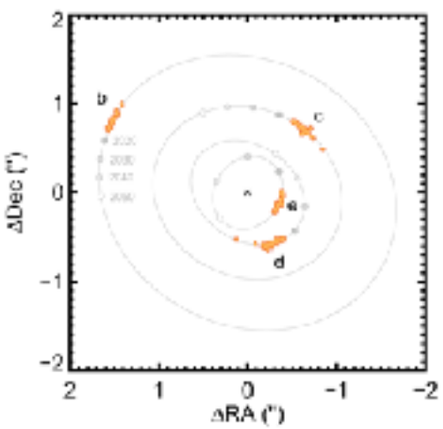
Lagrange+10



HR 8799 b, c, d, e



Marois+10



Bowler 2016

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(=> M_p, R_p)

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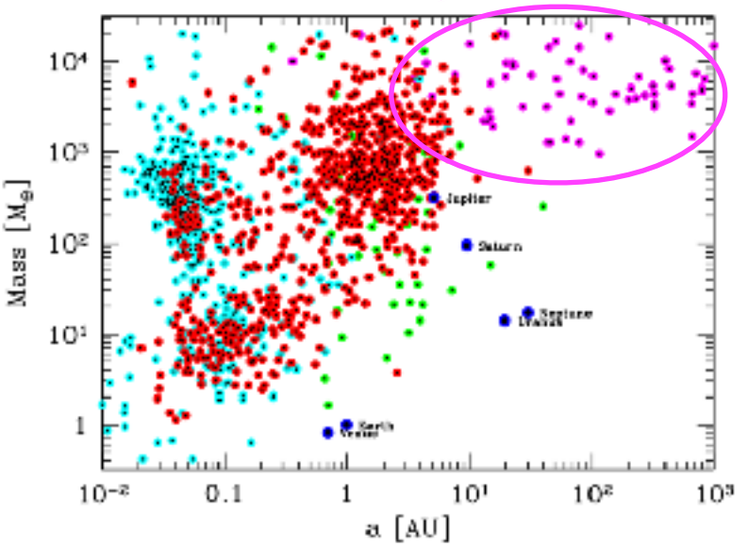

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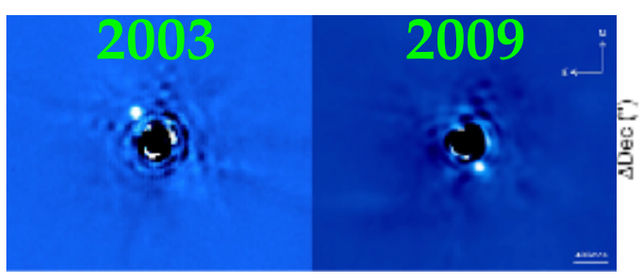
β Pic b



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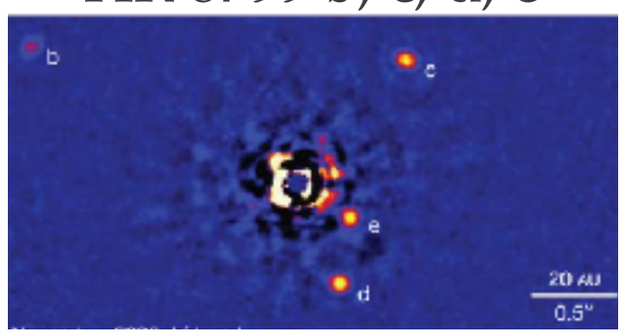

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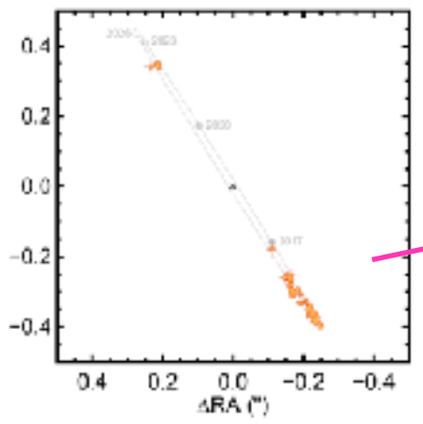

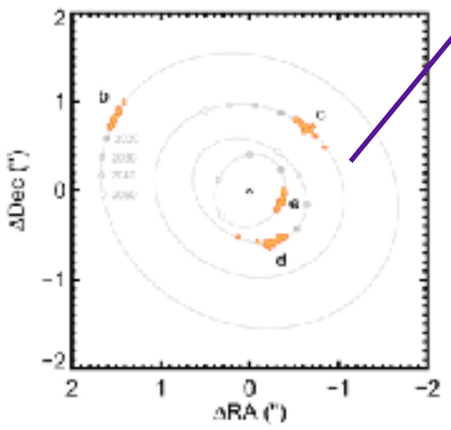

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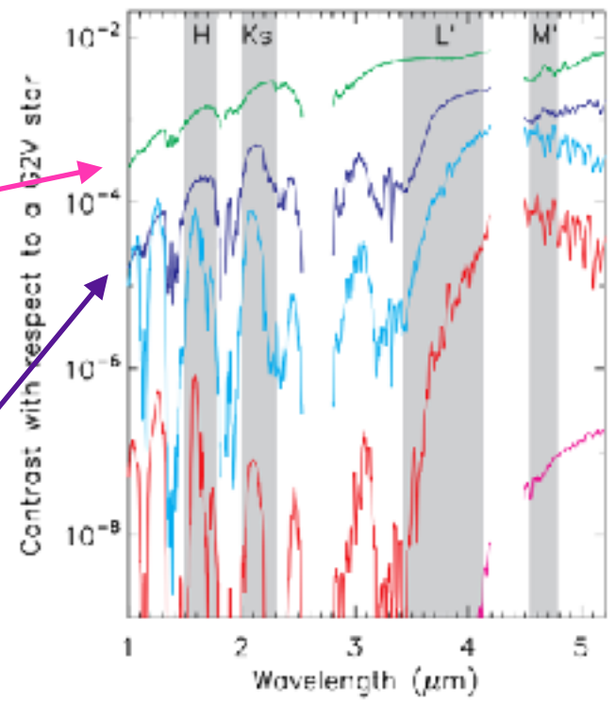

Skemer+15

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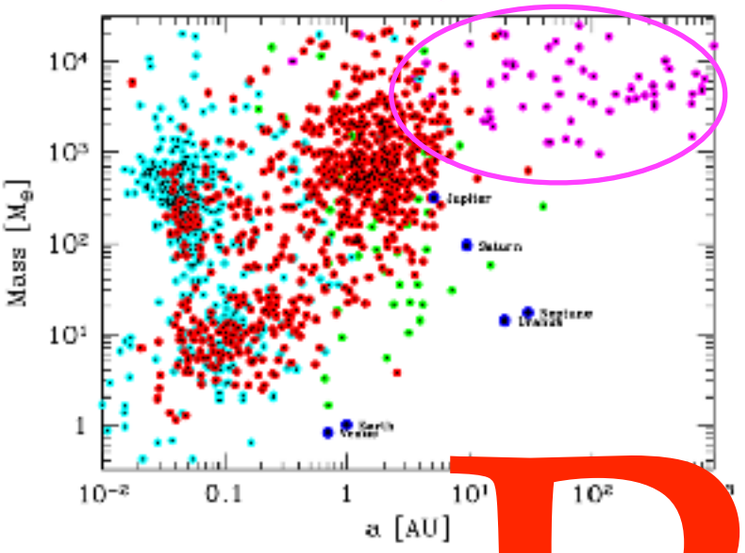

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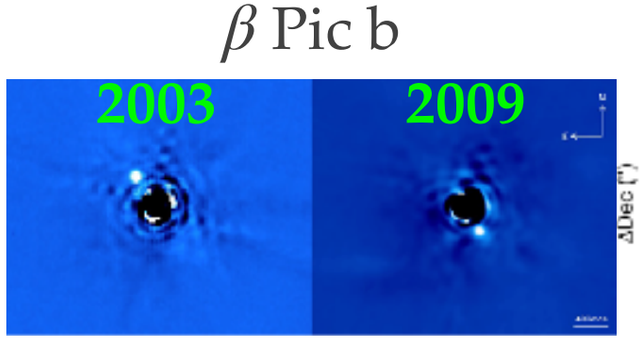
β Pic b



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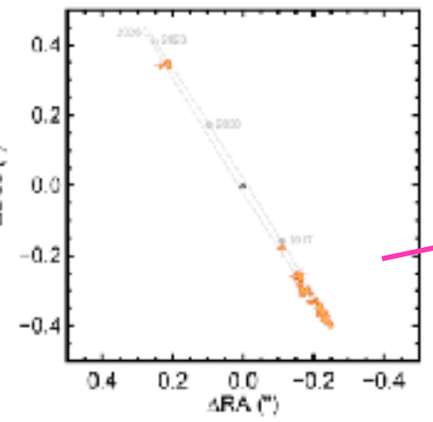
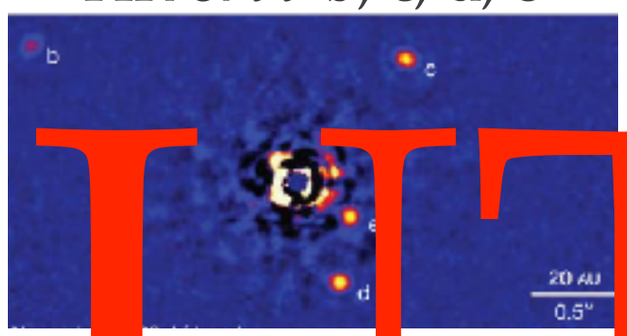
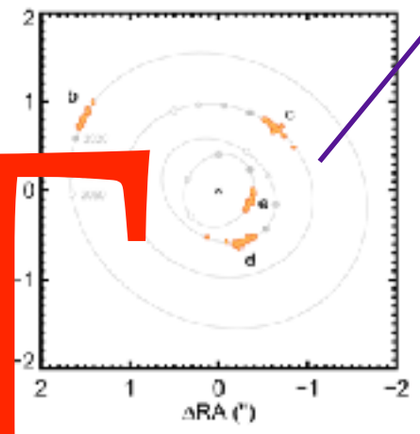


HR 8799 b, c, d, e



Mar +10



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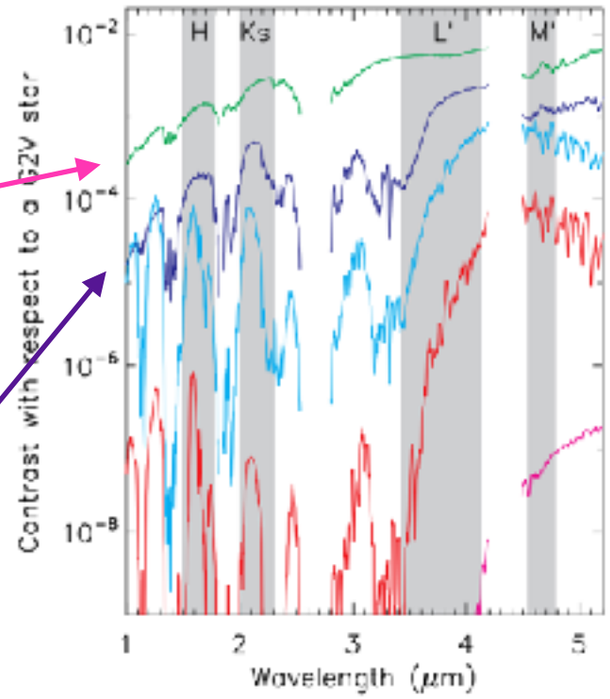

Skemer+15

BUT…

Challenge of high-contrast imaging

- 2 major hurdles: - **contrast:** $\frac{F_p}{F_*} \approx 10^{-6}$–$10^{-9}$
  - angular resolution: $\theta \sim \frac{\lambda}{D} \approx 0.1''$–$1''$

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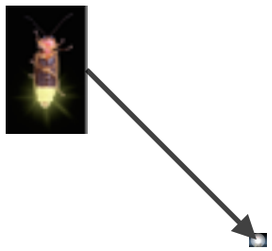

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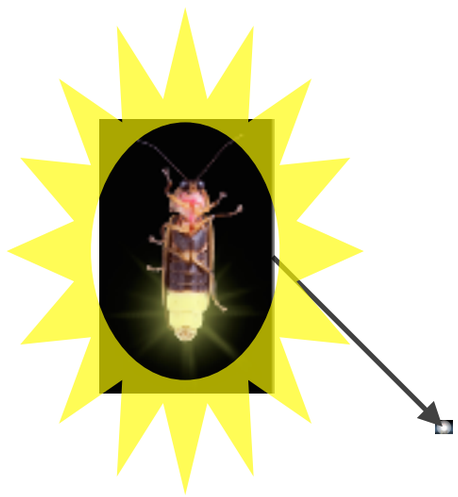

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Gravitational instability **Core accretion** + **Gravo turbulence (i.e. as binary stars)**

4 Pillars of high-contrast imaging

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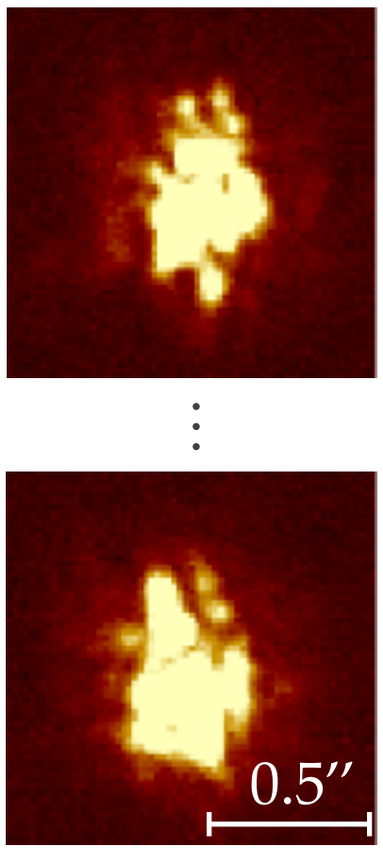
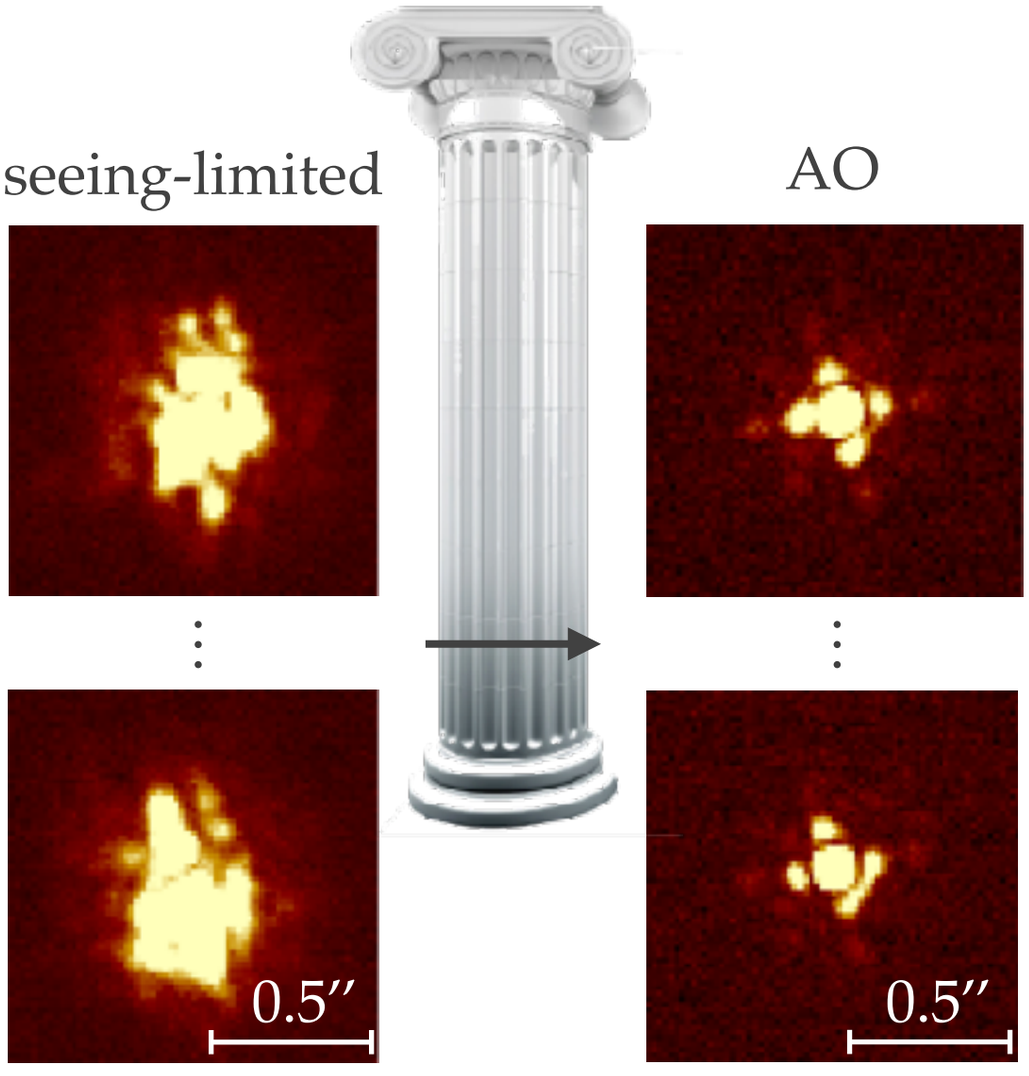
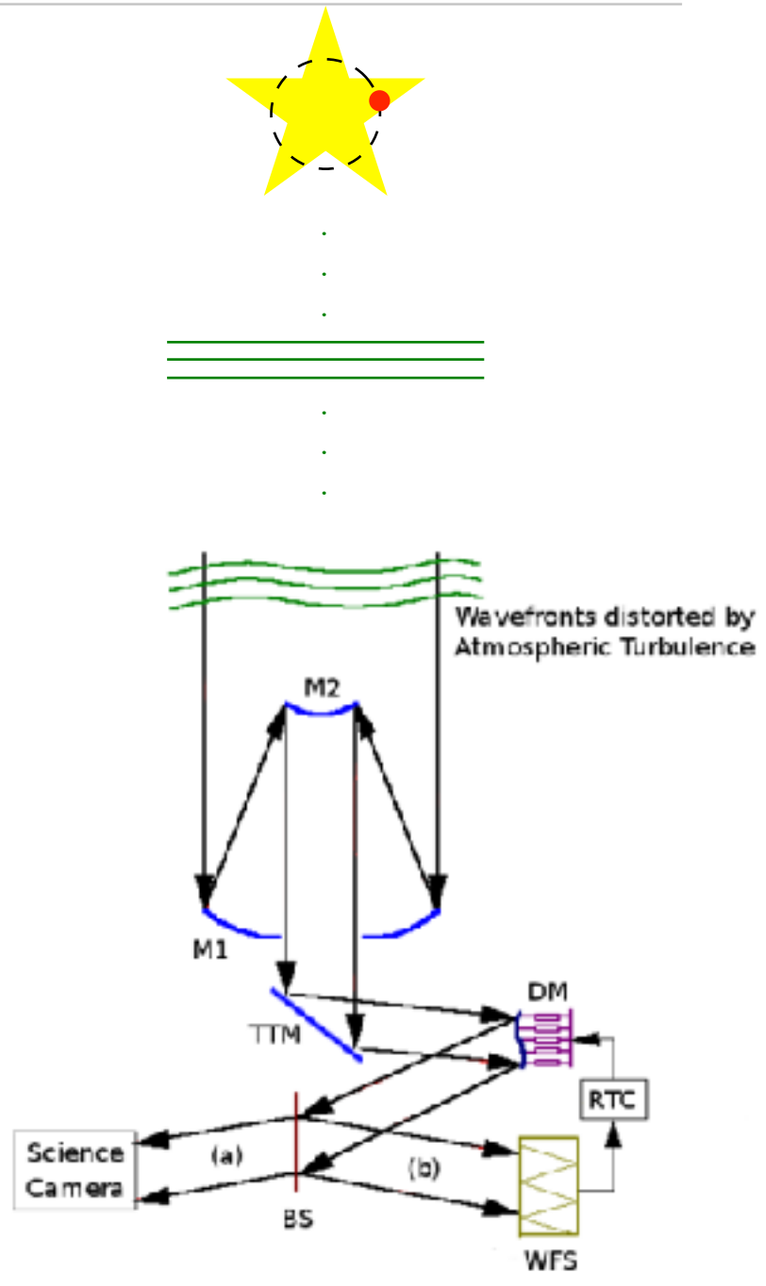
seeing-limited



4 Pillars of high-contrast imaging

Adaptive optics





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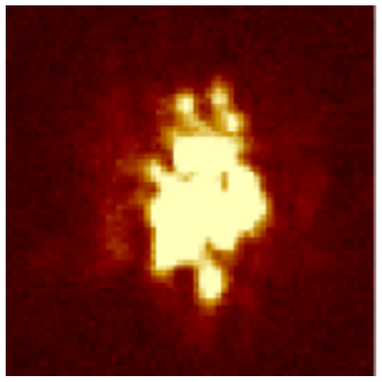
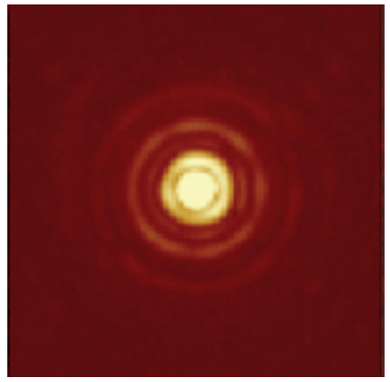
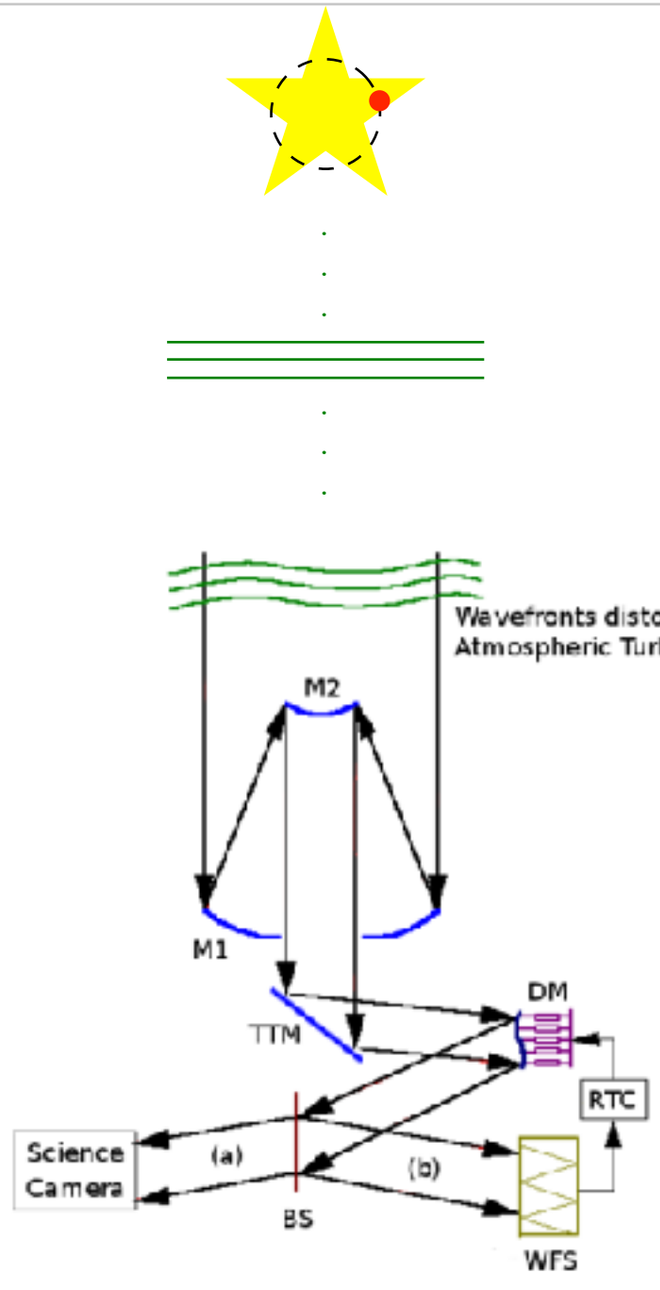


Extreme-AO





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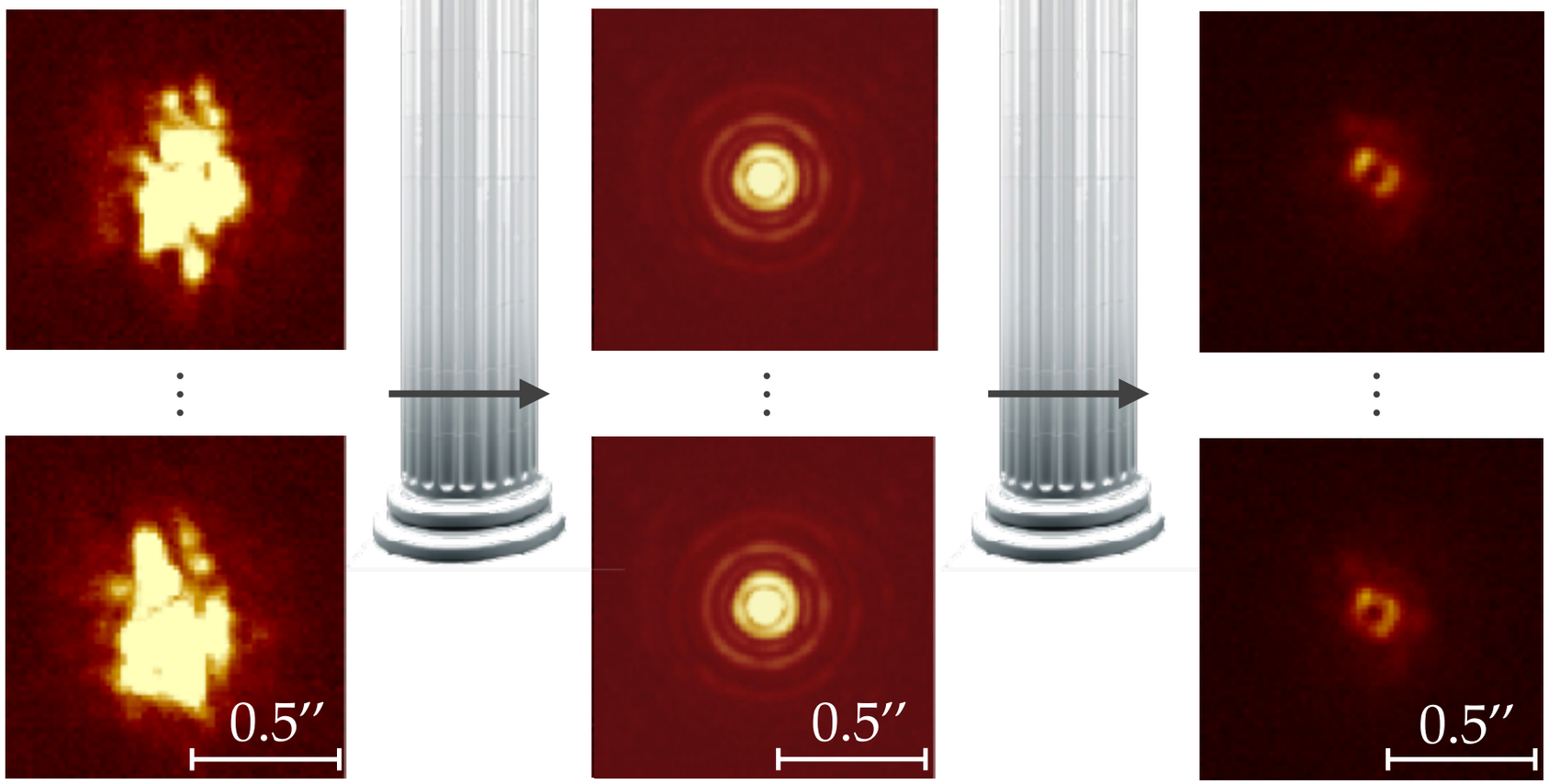
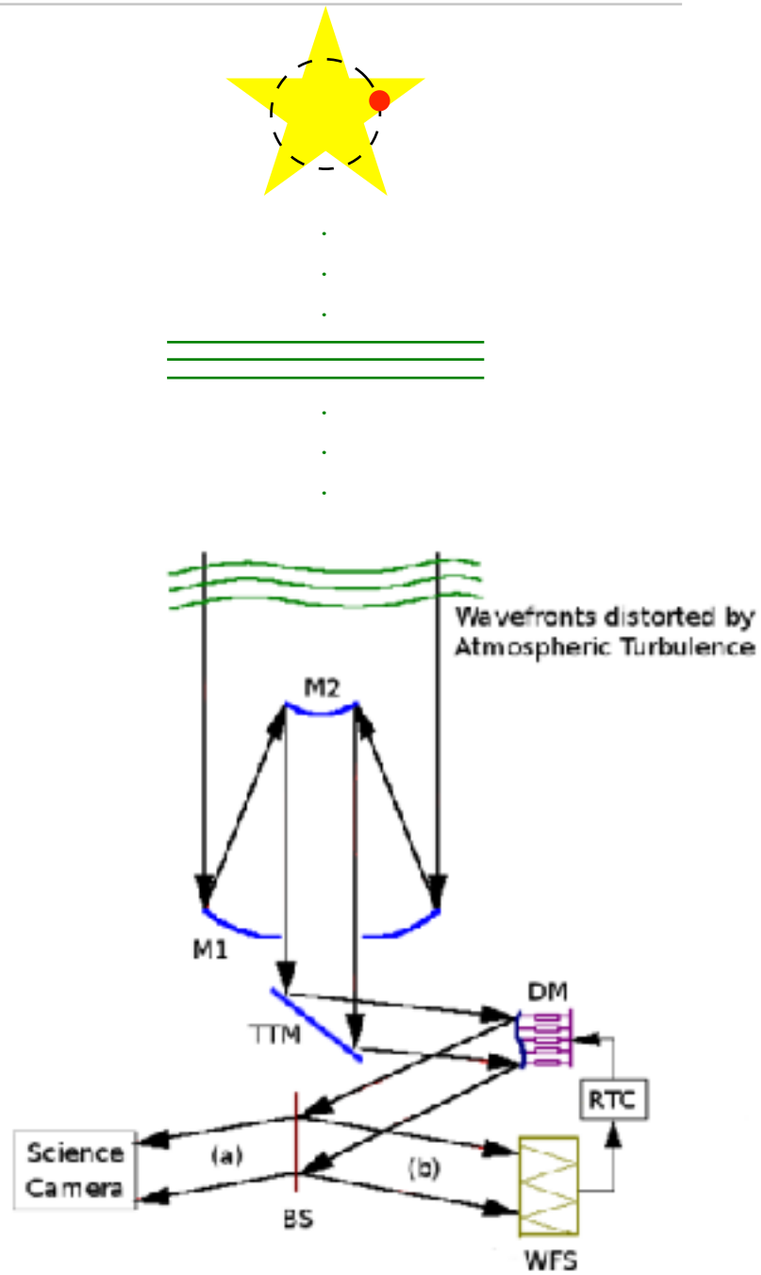
Adaptive optics **Coronagraphy**

seeing-limited Extreme-AO AO + coron.





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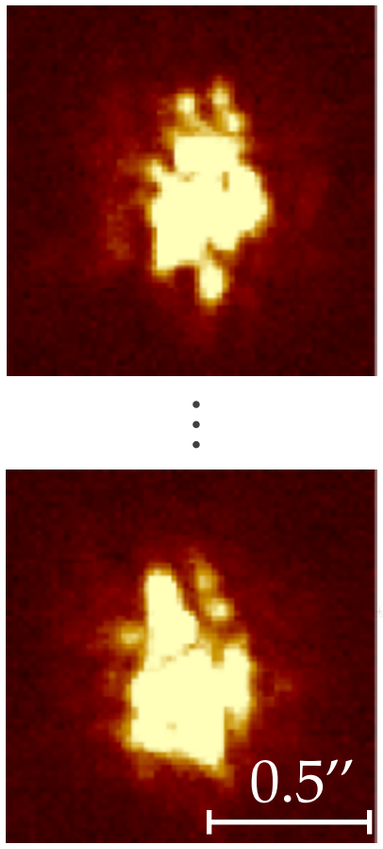

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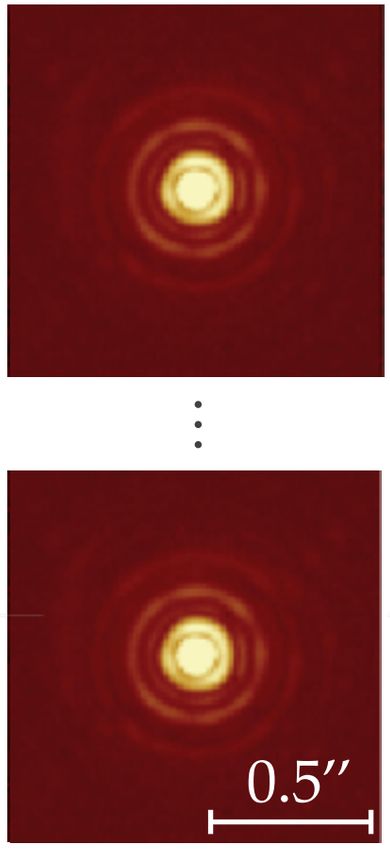
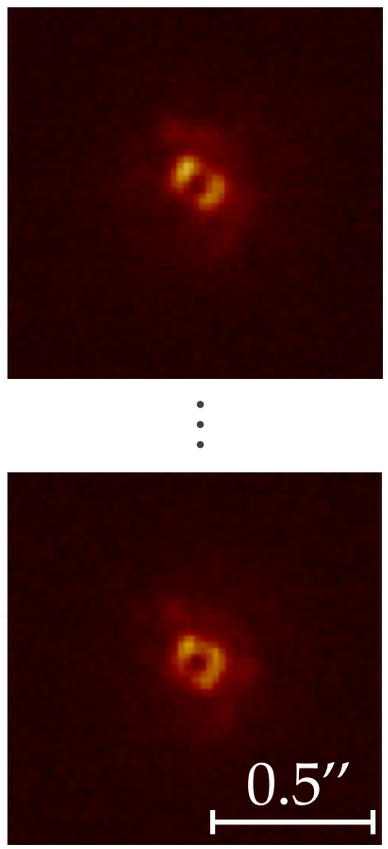
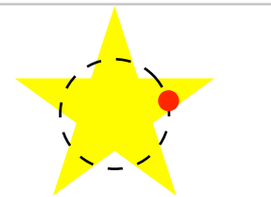
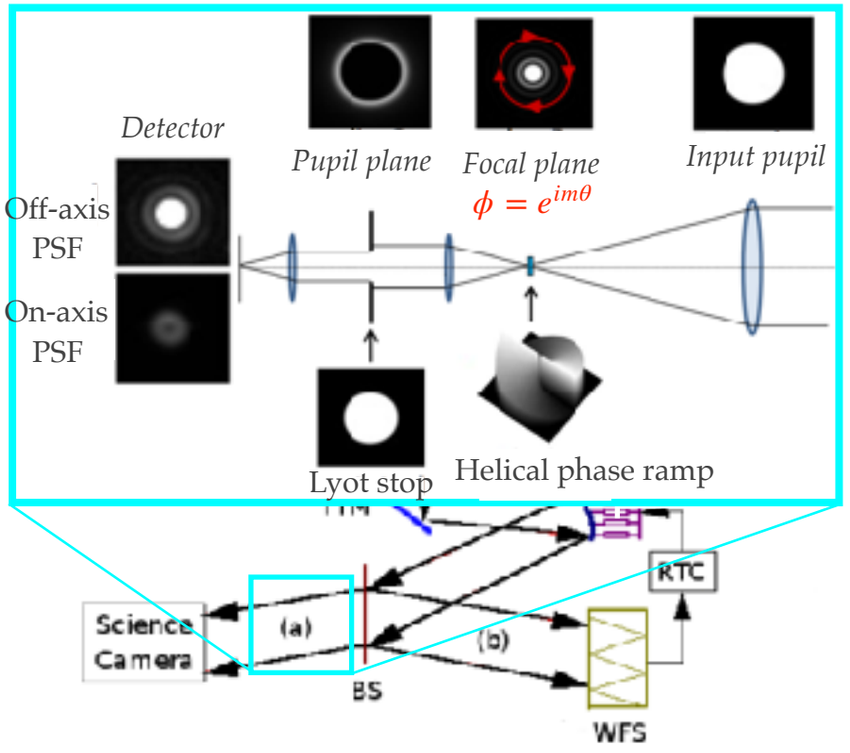


AO + coron.







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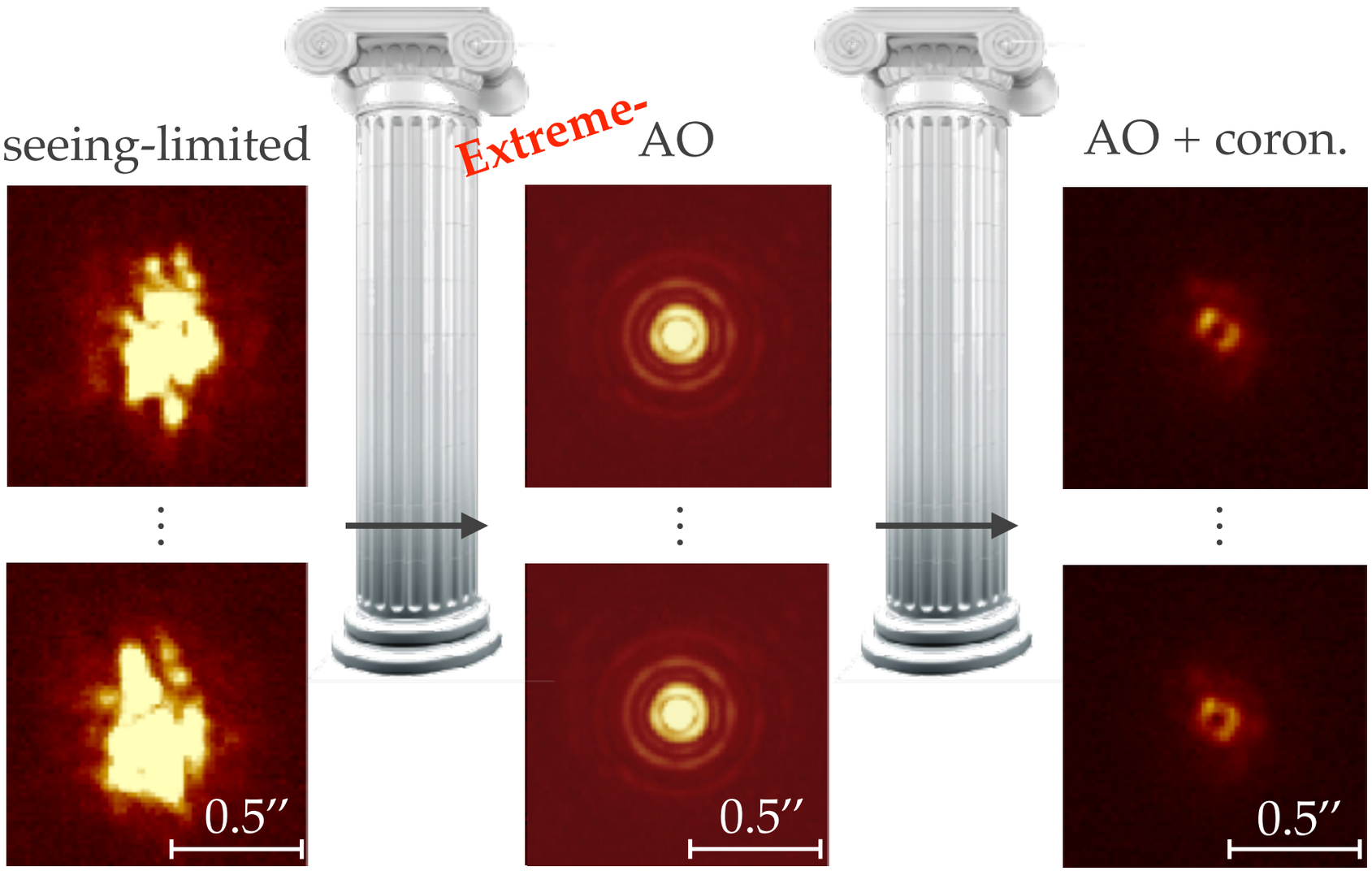

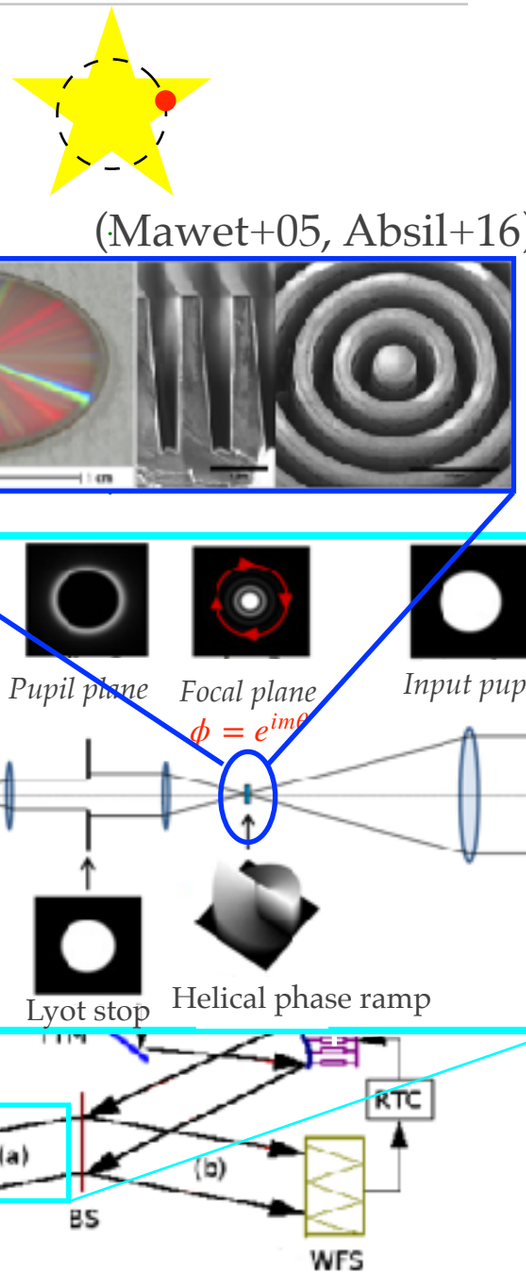

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Adaptive optics

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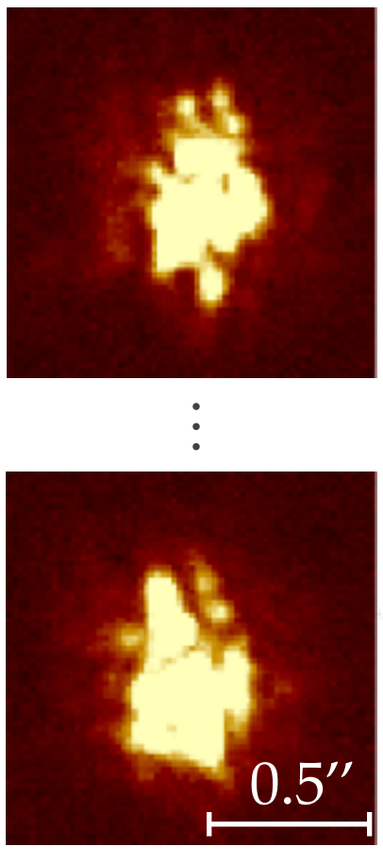

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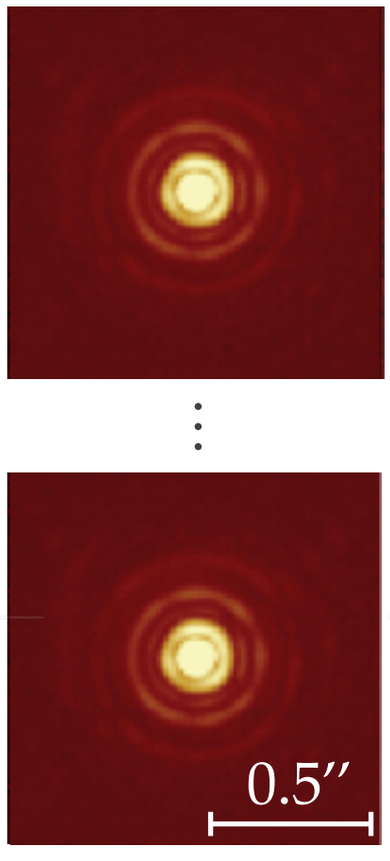


Coronagraphy

AO + coron.

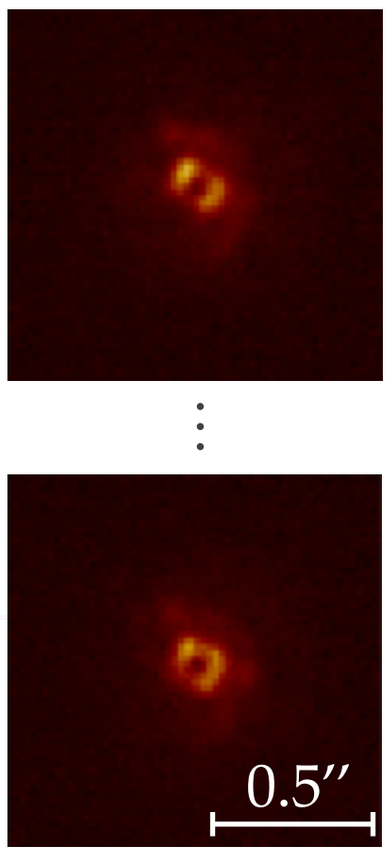
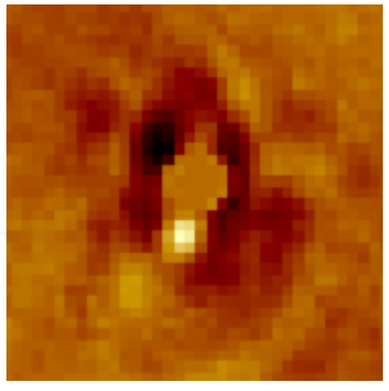


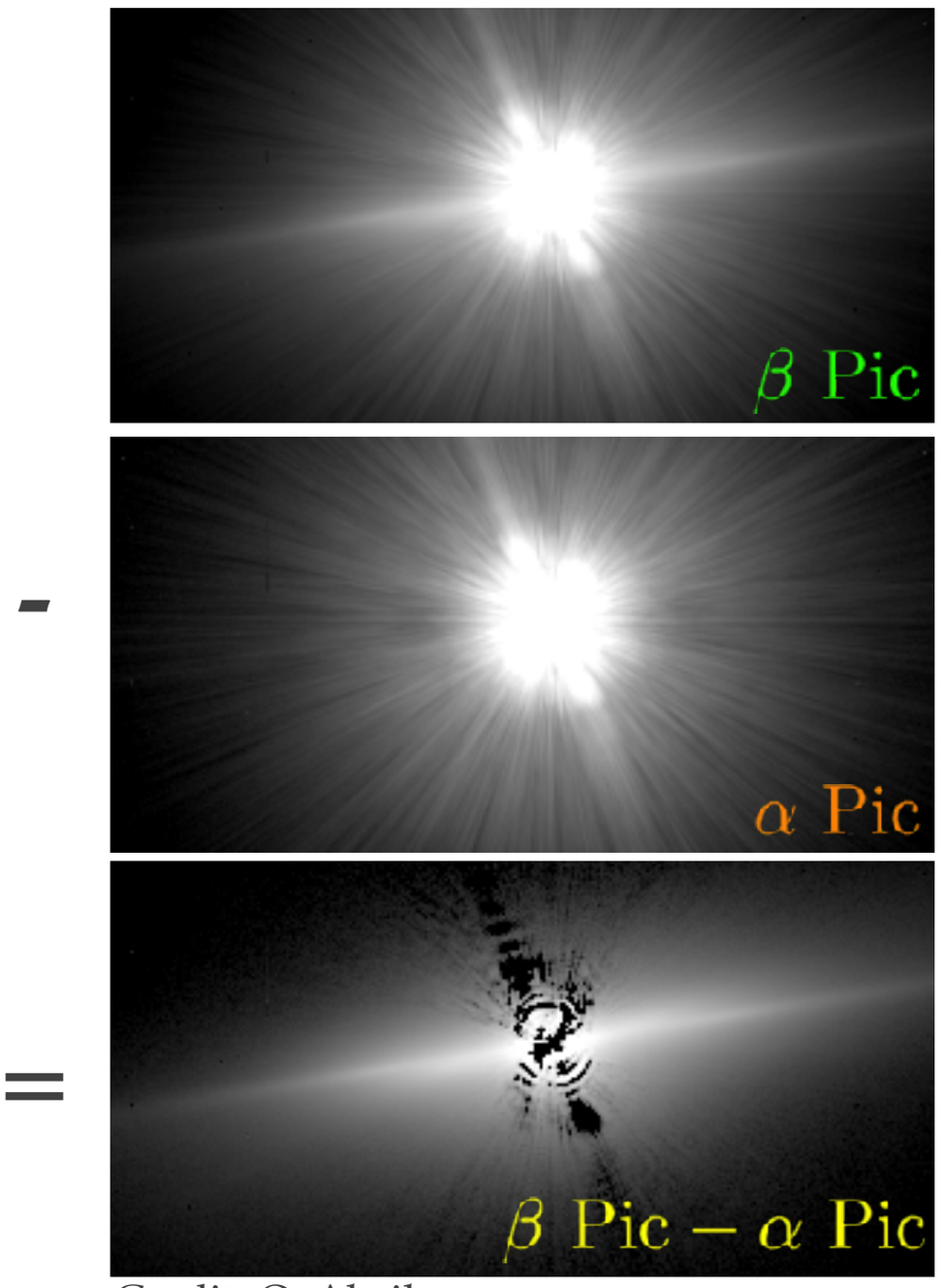
Image post-processing
Observing technique

AO + coron.
PSF subtracted
Frames combined



Differential imaging (1)

Reference star Differential Imaging (RDI)



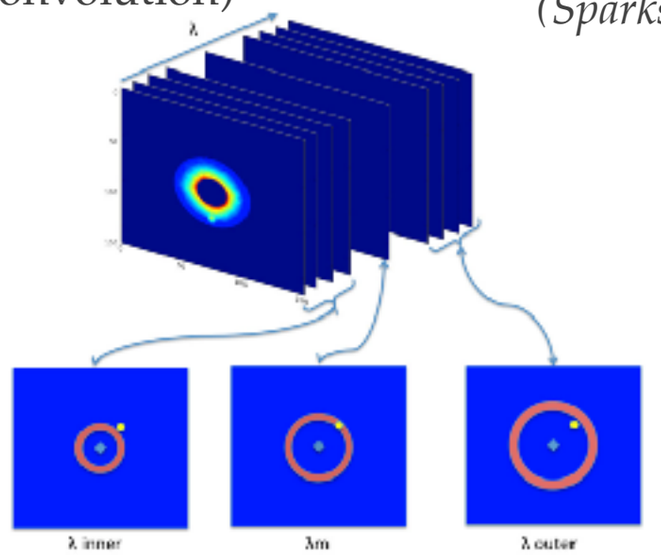
Credit: O. Absil

Differential imaging (2)

Spectral Differential Imaging (SDI)

(or spectral deconvolution)

(Sparks & Ford 2002)



The companion stays fixed,
while the PSF expands with WL

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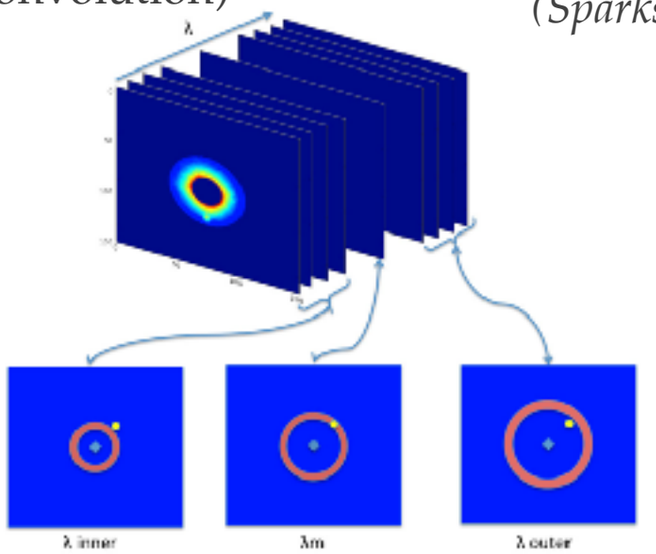

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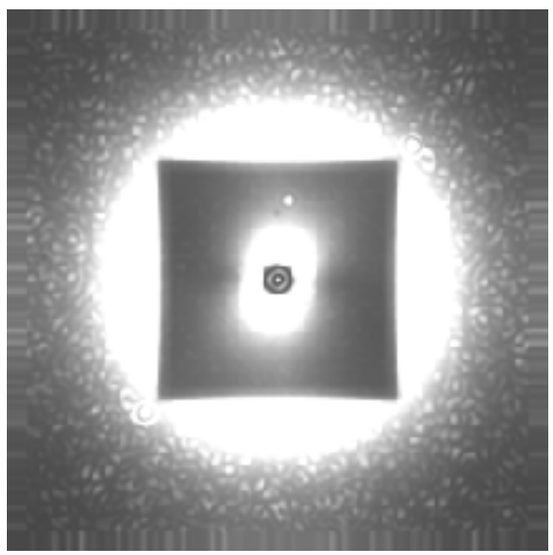

Credit: B. MacIntosh

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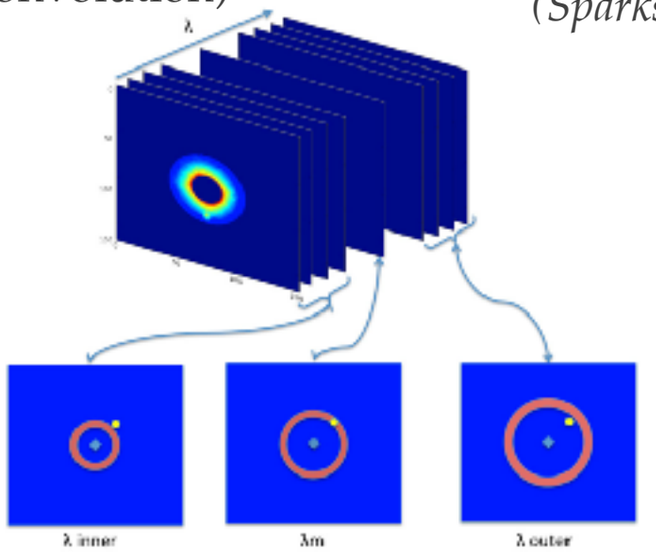

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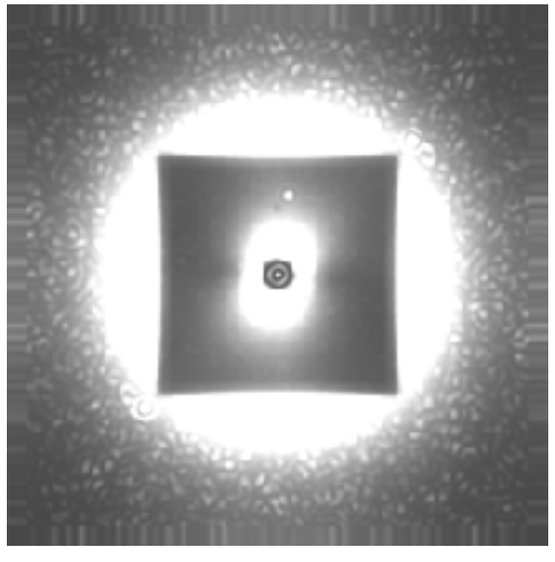

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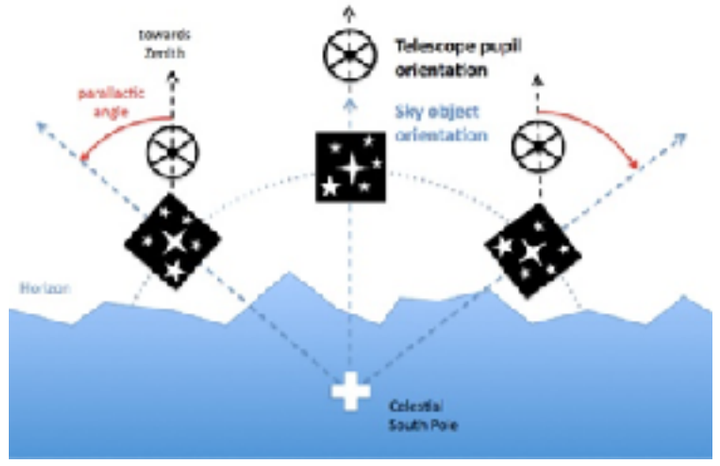
Angular Differential Imaging (ADI)

(Marois+2006)



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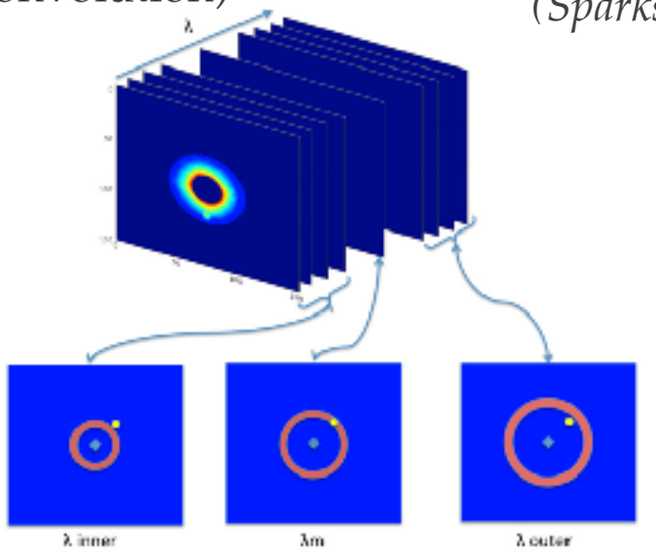
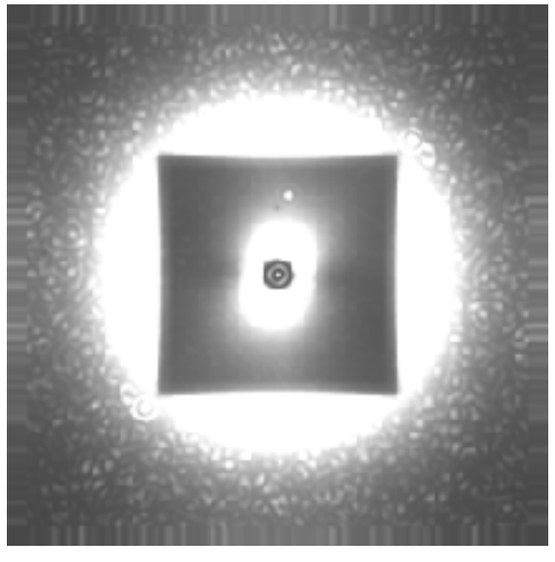


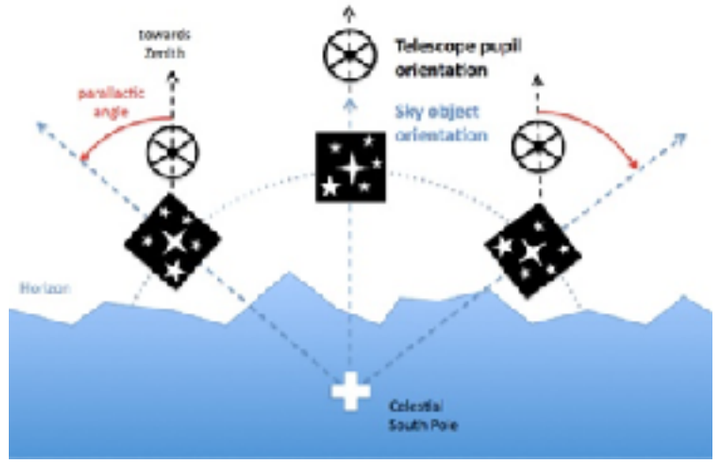
The companion stays fixed,
while the PSF expands with WL



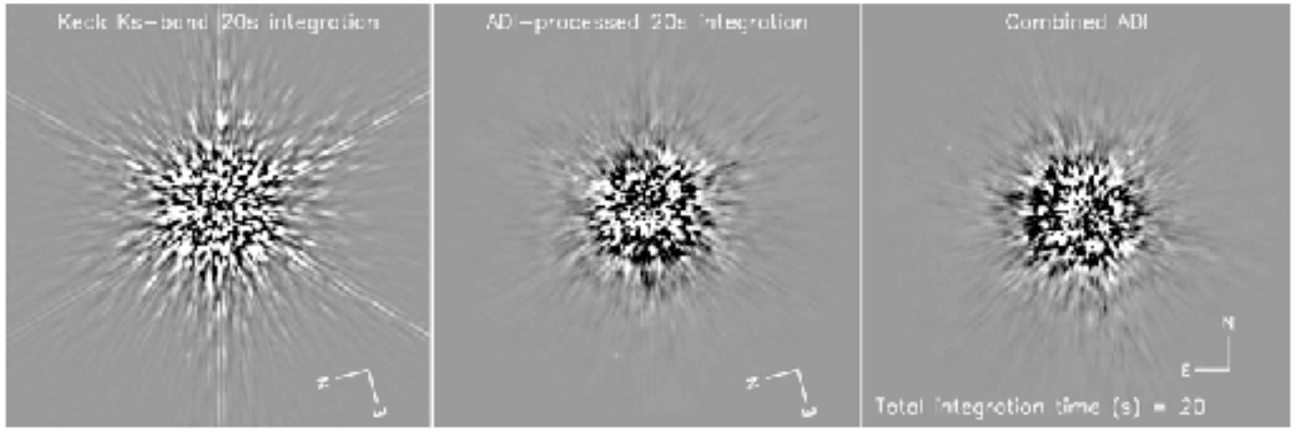
Credit: B. MacIntosh

Angular Differential Imaging (ADI)

(Marois+2006)



The companion rotates with the field,
while the PSF stays fixed

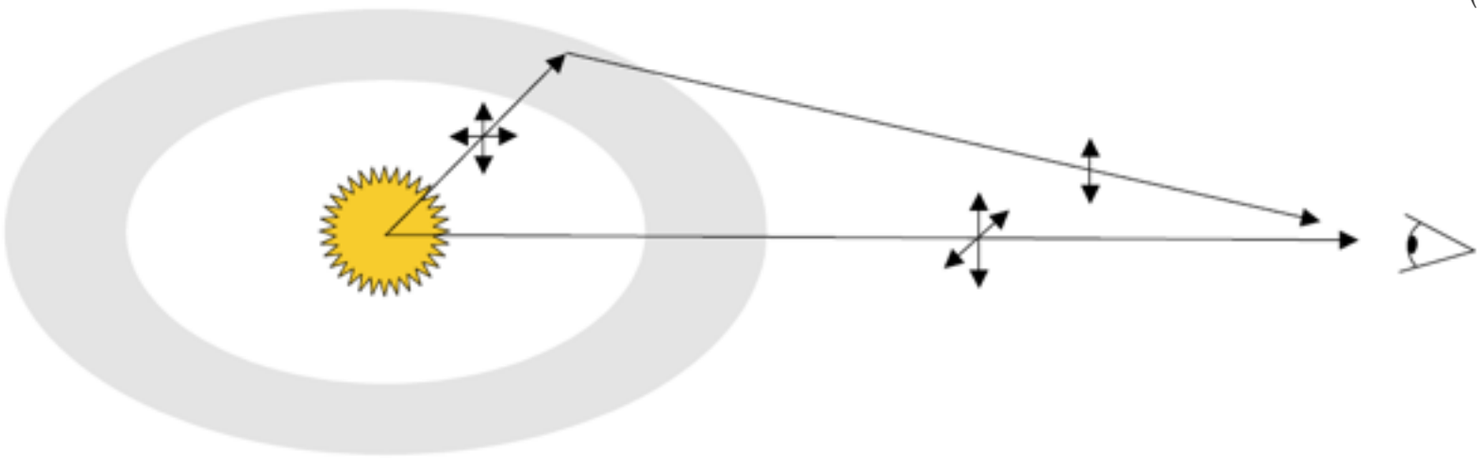


Credit: C. Marois

Differential imaging (3)

Polarimetric Differential Imaging (PDI)

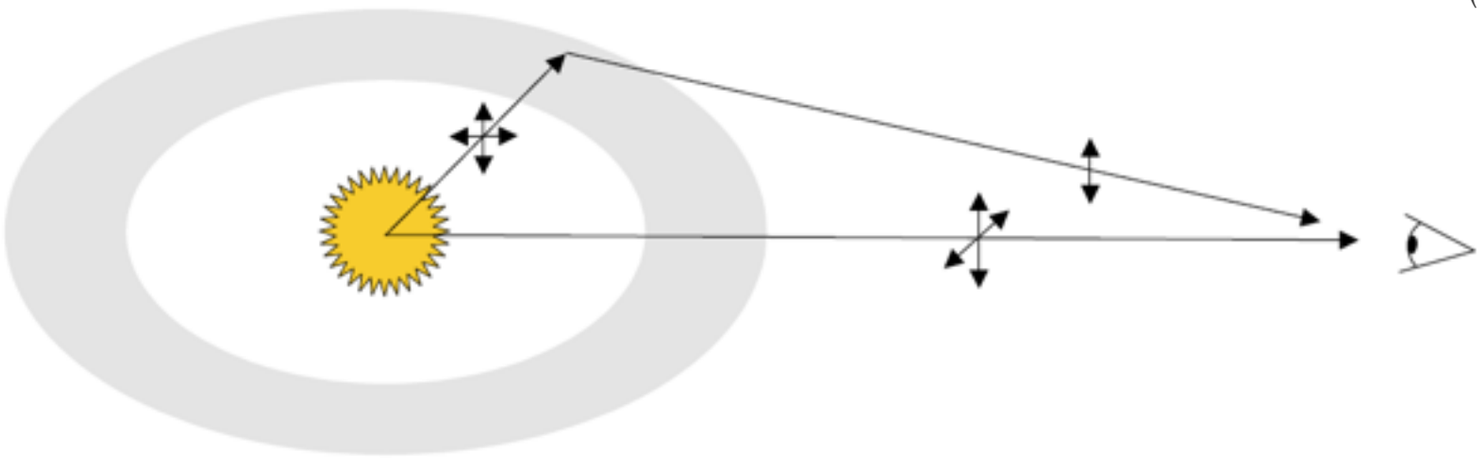
(Kuhn+2001; Quanz+2011)

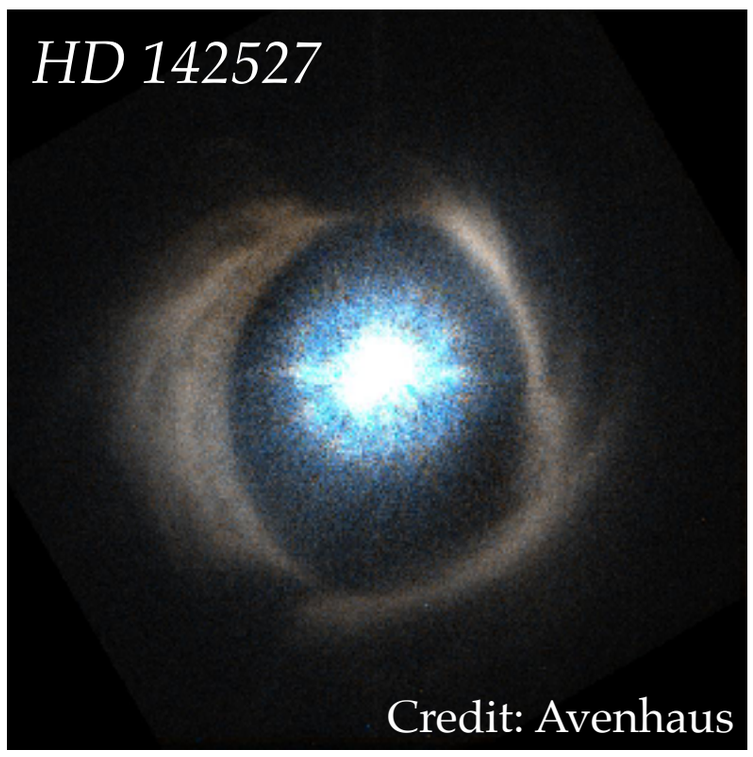


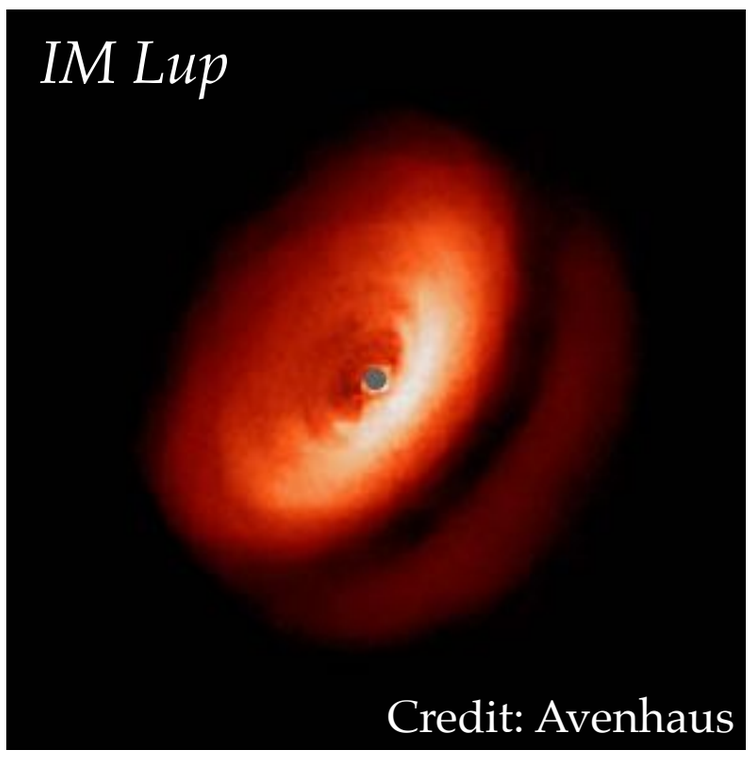
Differential imaging (3)

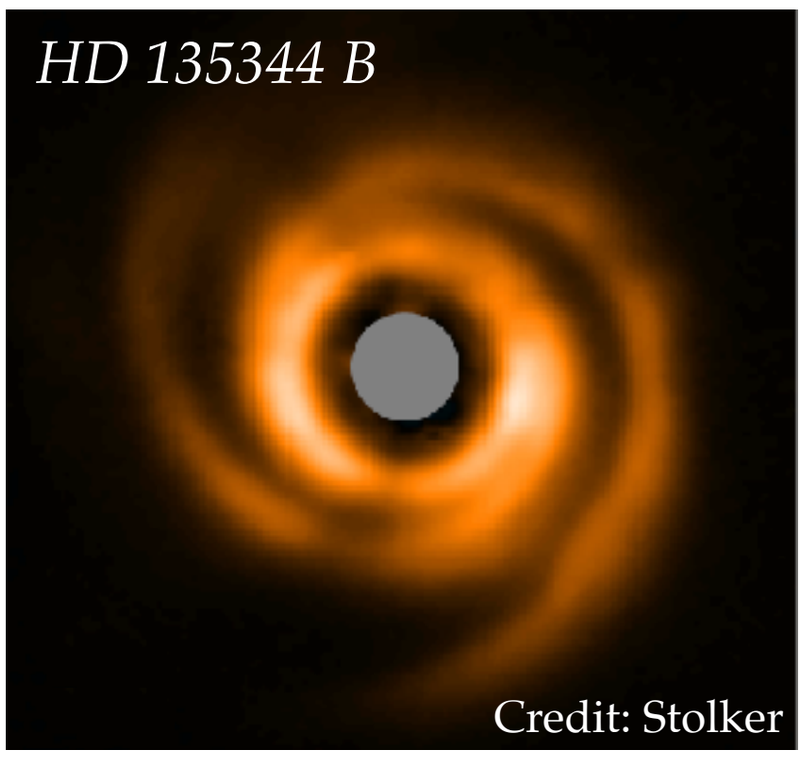
Polarimetric Differential Imaging (PDI)

(Kuhn+2001; Quanz+2011)



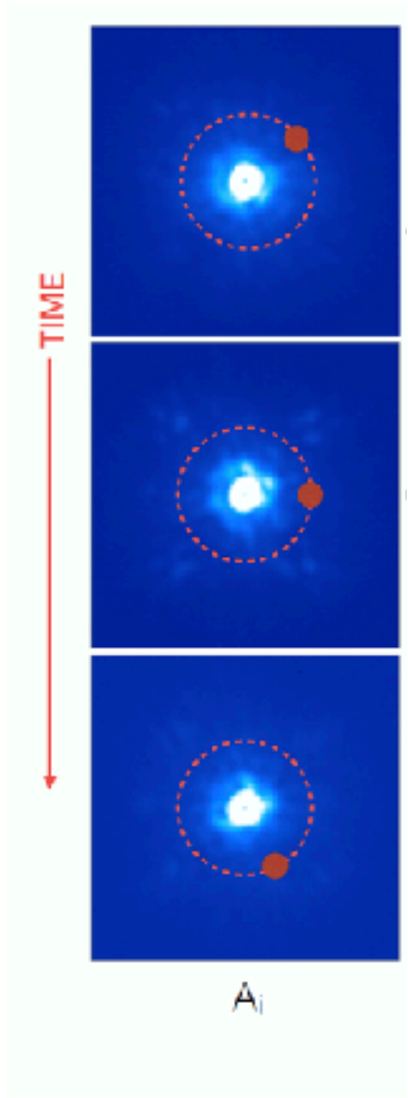






median-ADI

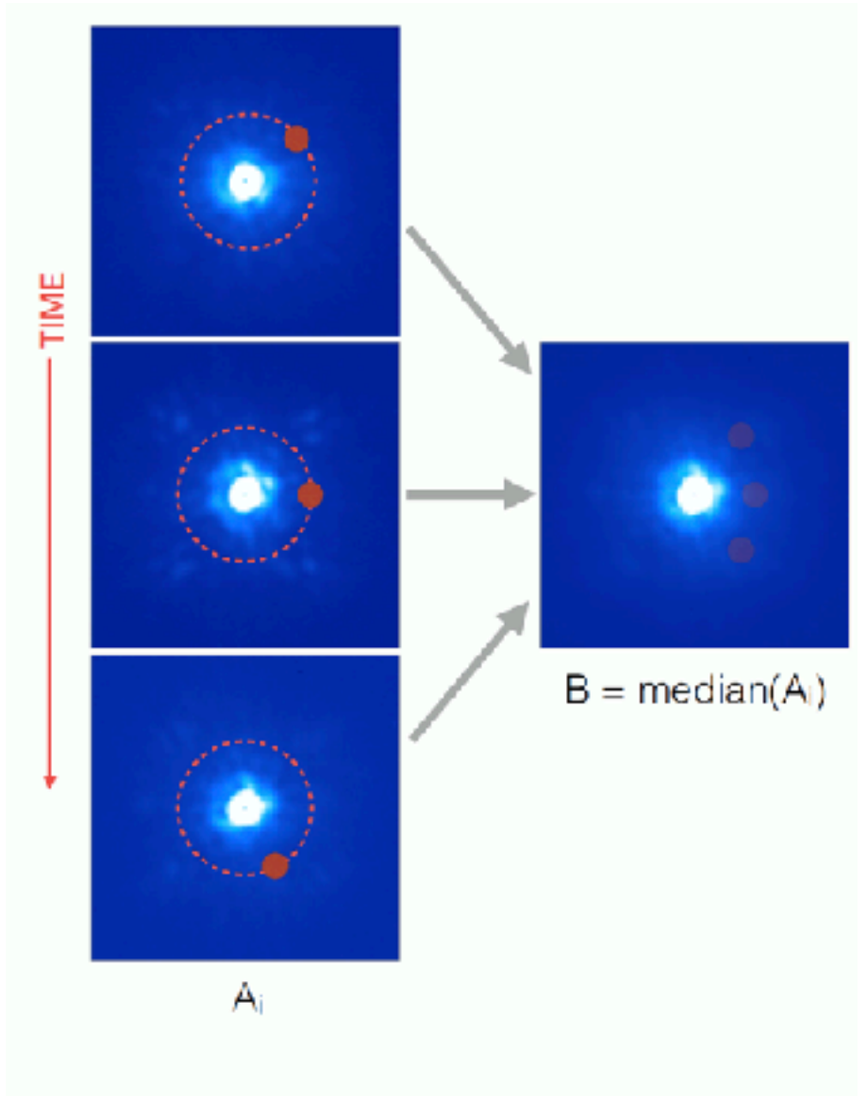
(Marois+2006)



Credit: C. Gomez

median-ADI

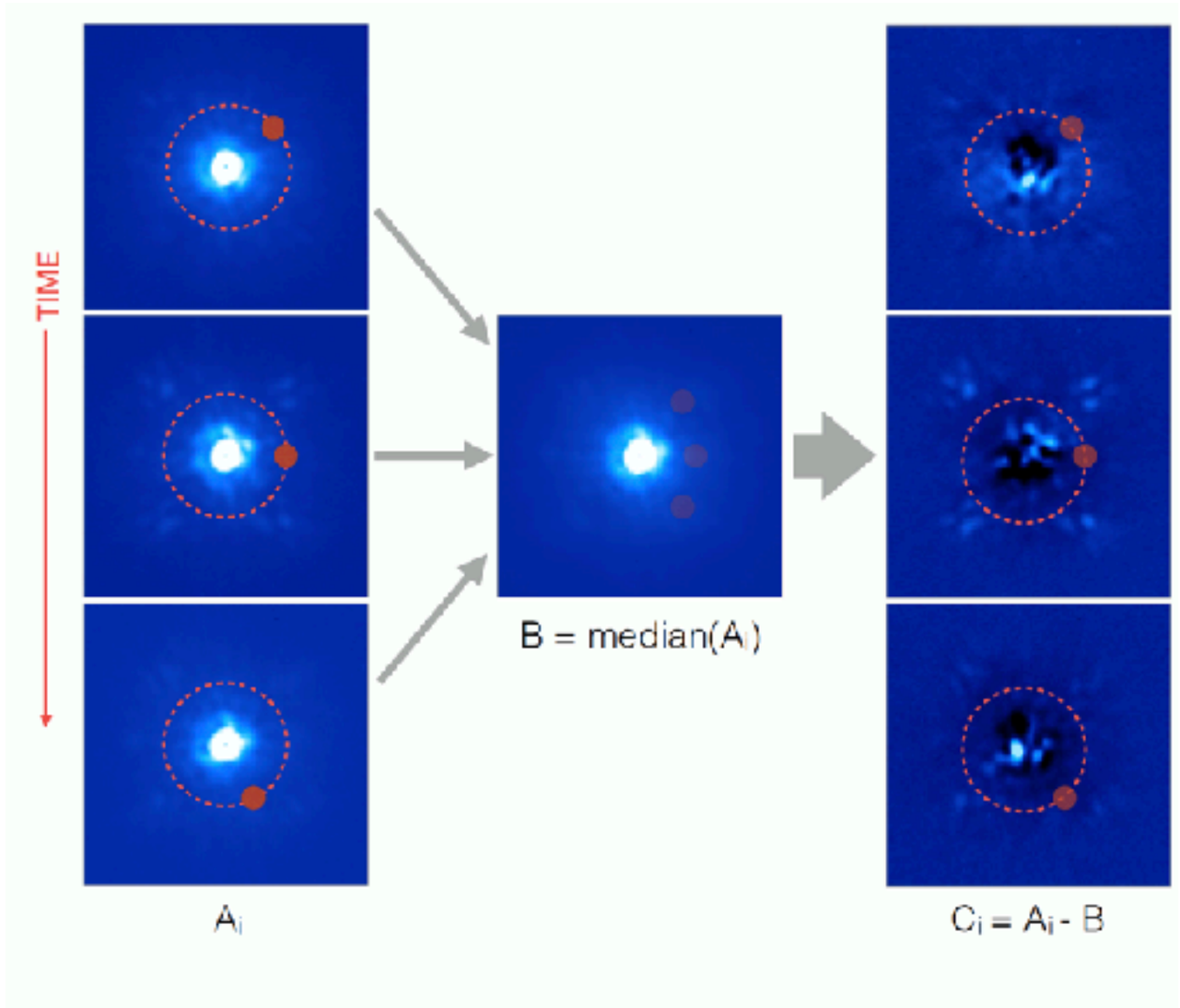
(Marois+2006)



Credit: C. Gomez

median-ADI

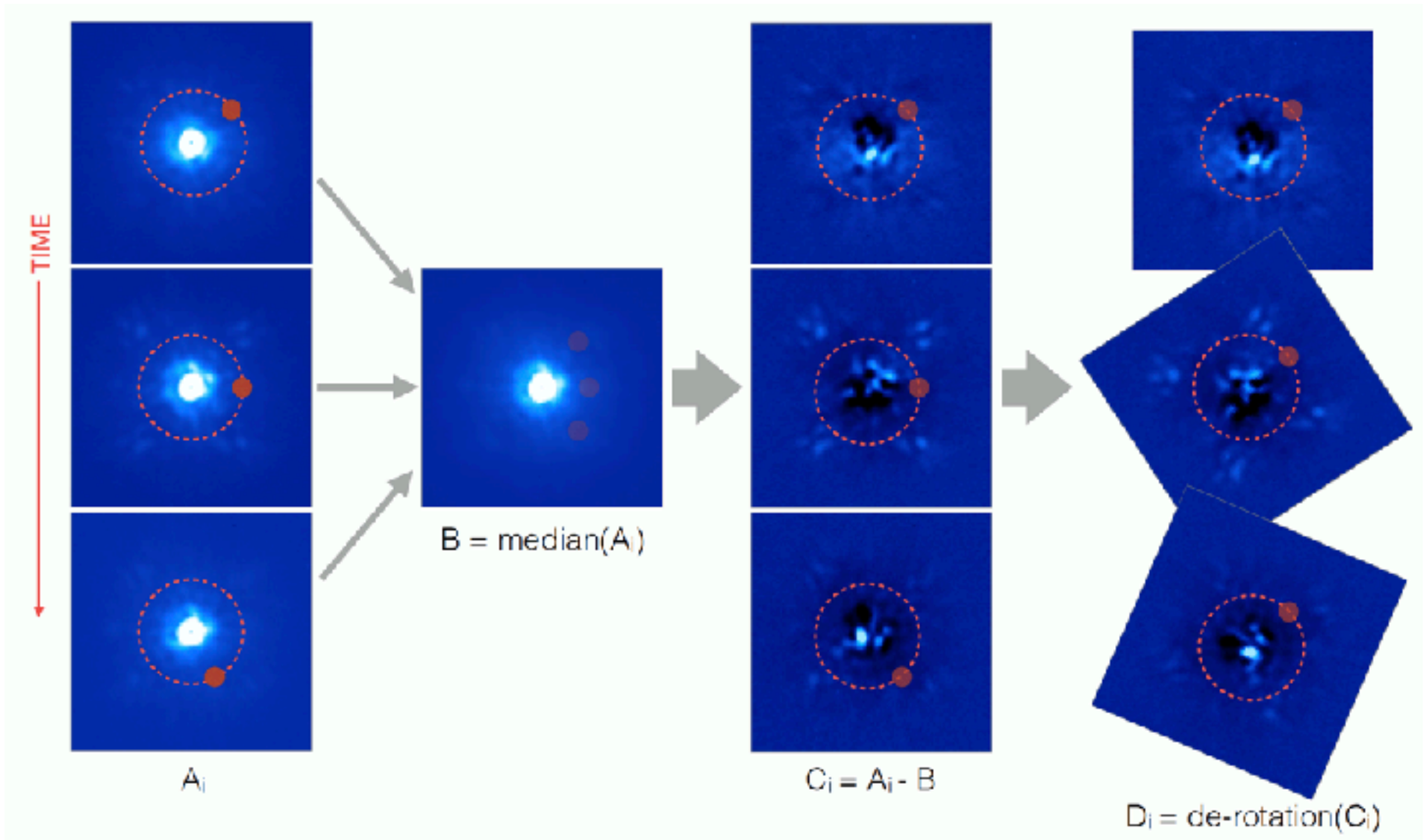
(Marois+2006)



Credit: C. Gomez

median-ADI

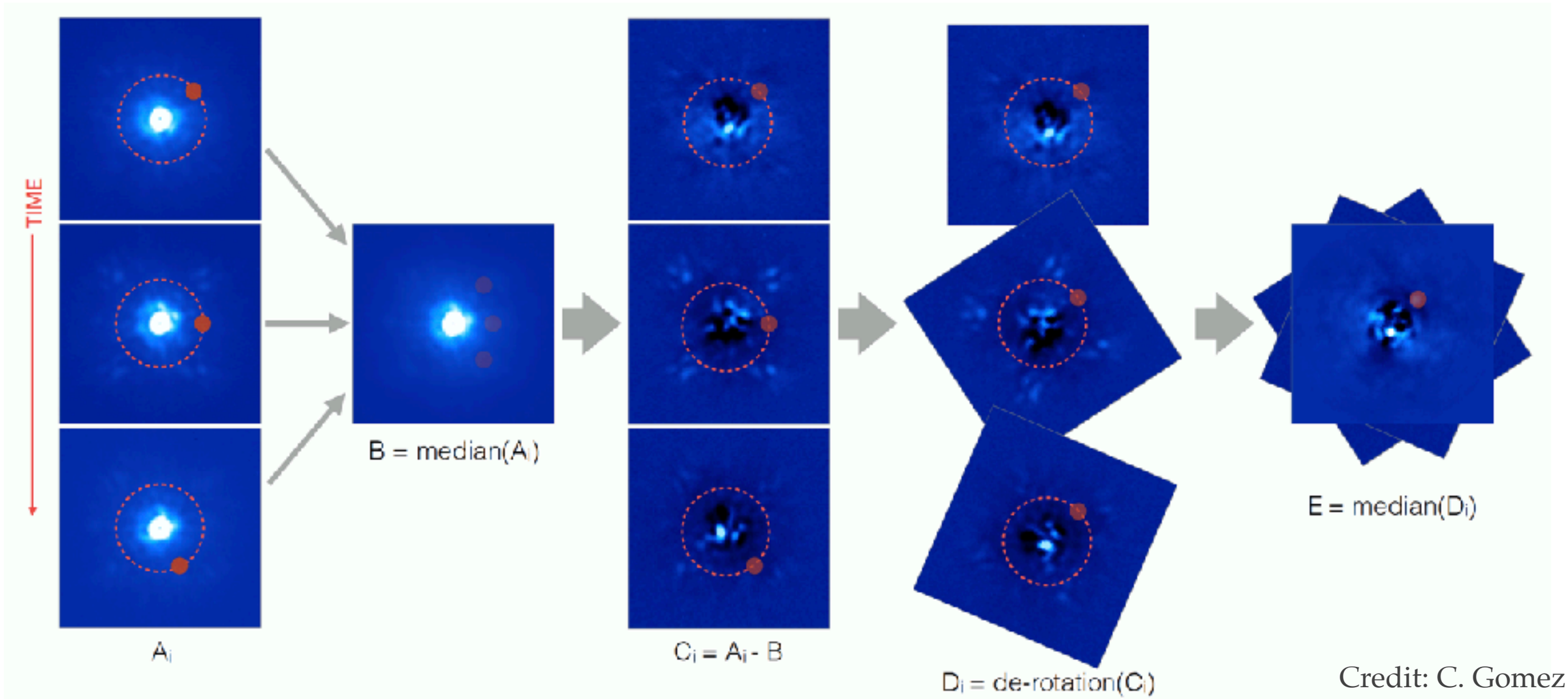
(Marois+2006)



Credit: C. Gomez

median-ADI

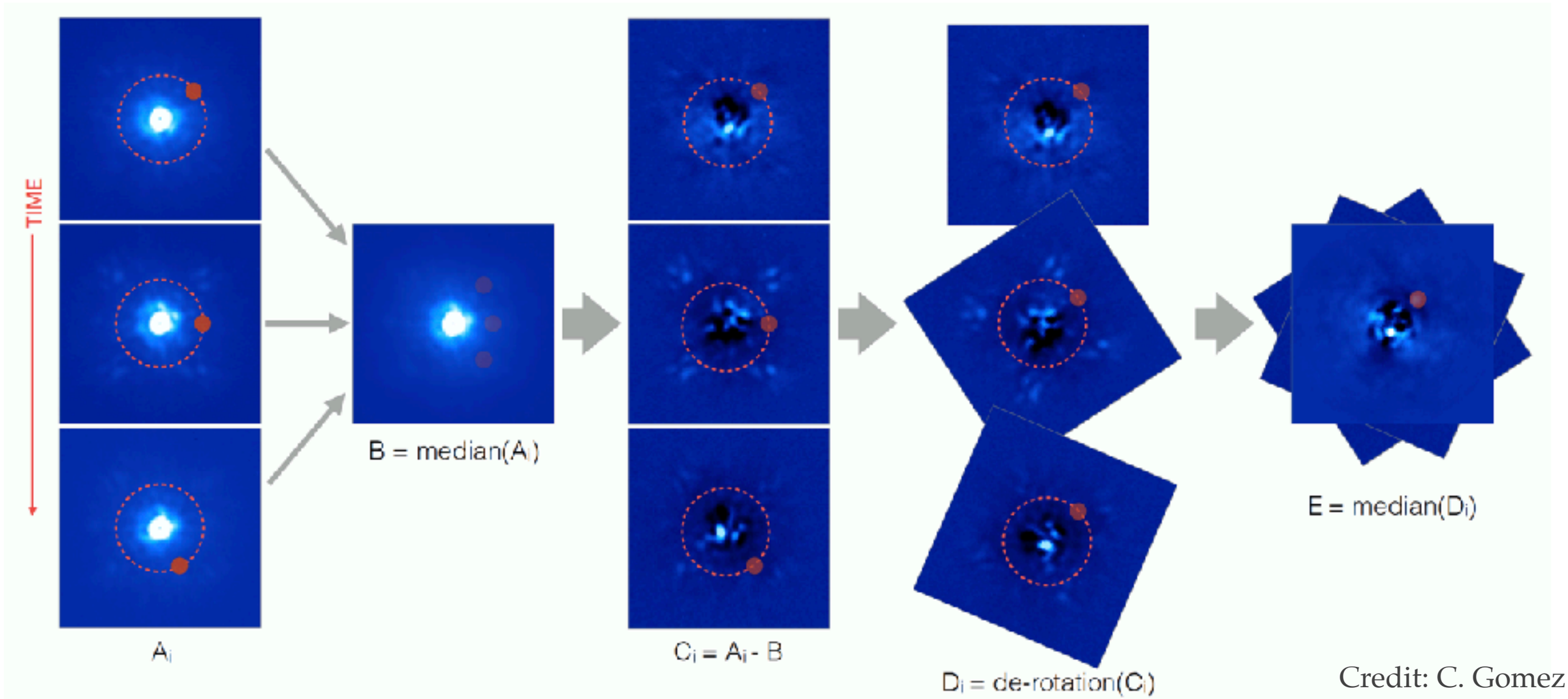
(Marois+2006)



Credit: C. Gomez

median-ADI

(Marois+2006)

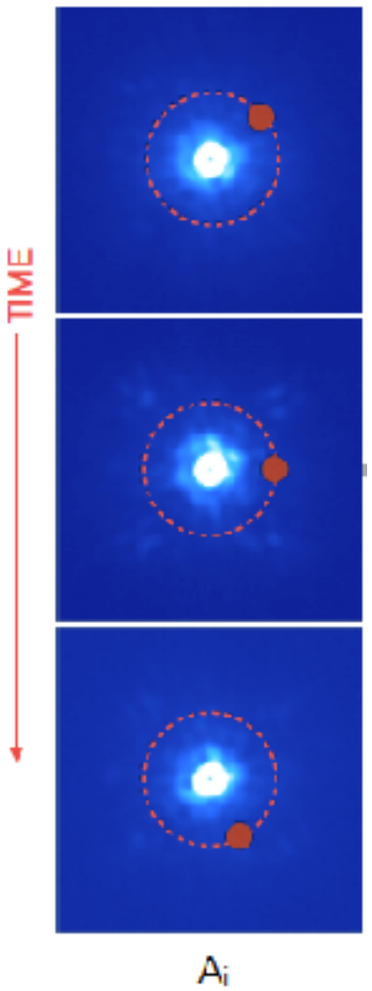


Credit: C. Gomez

- Limitation: quasi-static speckles

Principal component analysis (PCA) + ADI

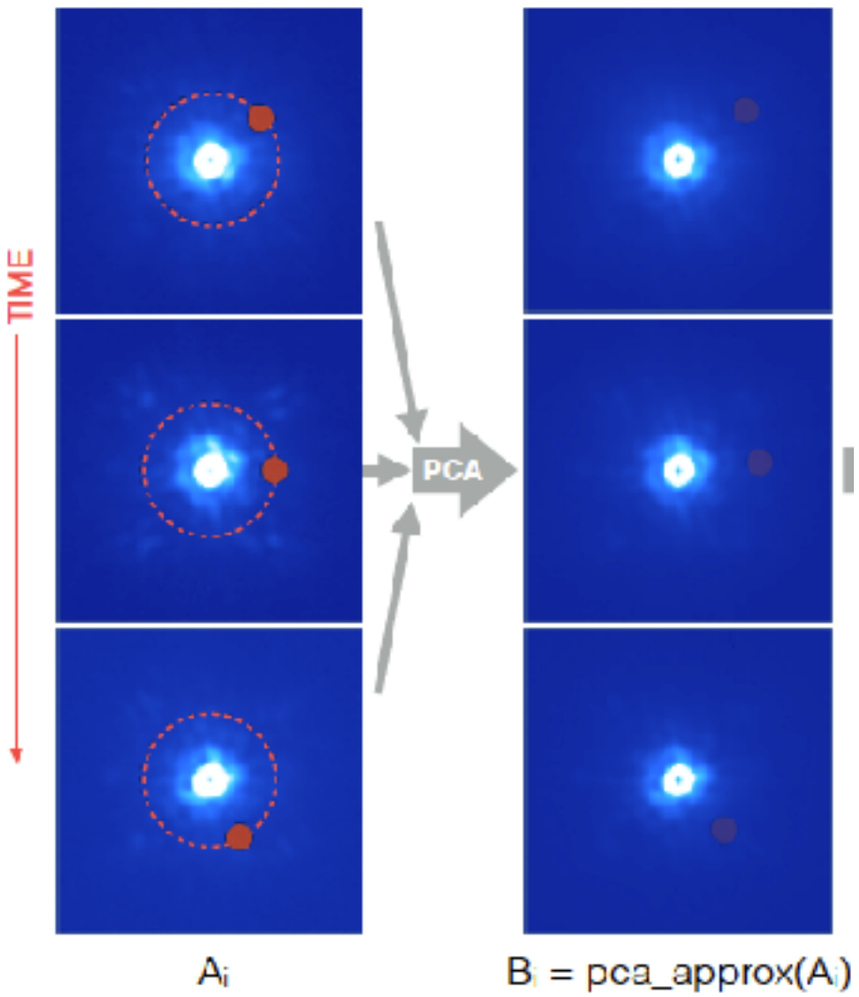
(Amara & Quanz 2012; Soummer+2012)



Credit: C. Gomez

Principal component analysis (PCA) + ADI

(Amara & Quanz 2012; Soummer+2012)



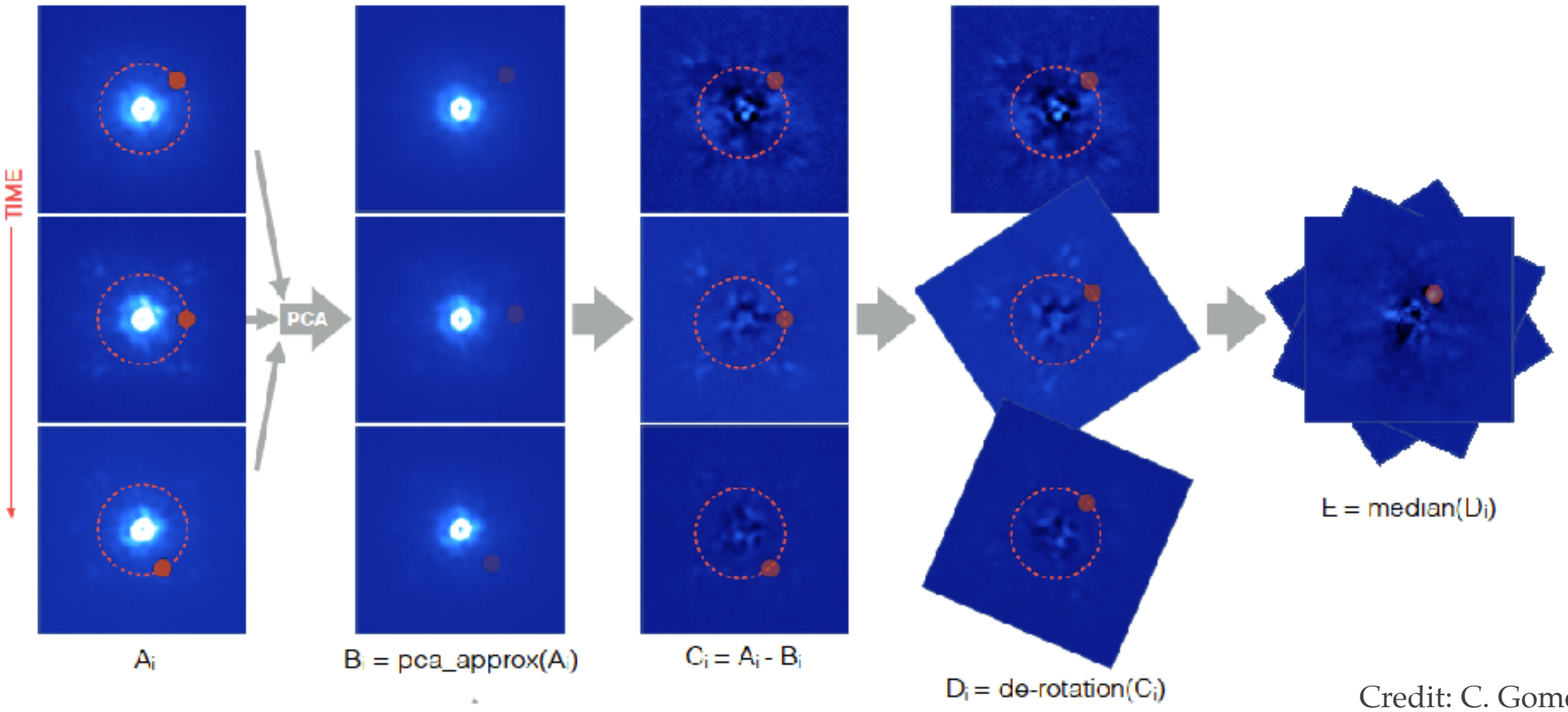
Credit: C. Gomez

$$B_i = \sum_{j=1}^{n_{\rm pc}} < A_i, \phi_j > \phi_j,$$

where ϕ_j are a set of orthonormal eigenvectors of $\mathbf{A}^{\mathrm{T}}\mathbf{A}$.

Principal component analysis (PCA) + ADI

(Amara & Quanz 2012; Soummer+2012)



Credit: C. Gomez

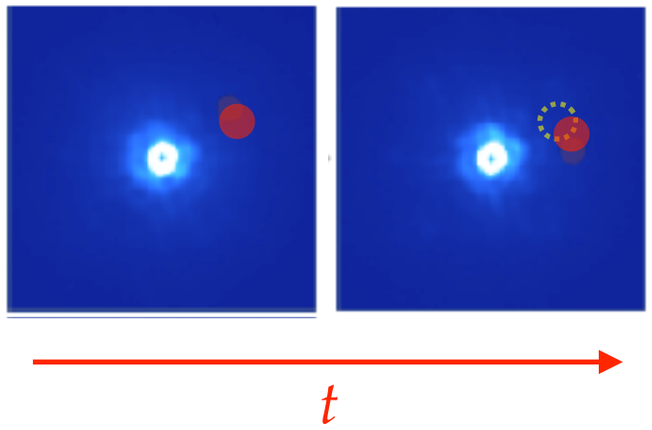
$$B_i = \sum_{j=1}^{n_{\rm pc}} < A_i, \phi_j > \phi_j,$$

where ϕ_j are a set of orthonormal eigenvectors of $\mathbf{A}^{\mathrm{T}}\mathbf{A}$.

ANDROMEDA

(Mugnier+2009; Cantalloube+2015)

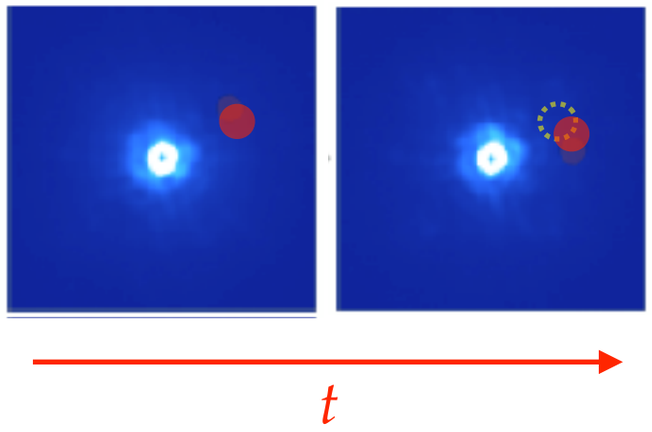
Pairwise subtraction
of frames with
~0.5 FWHM rotation



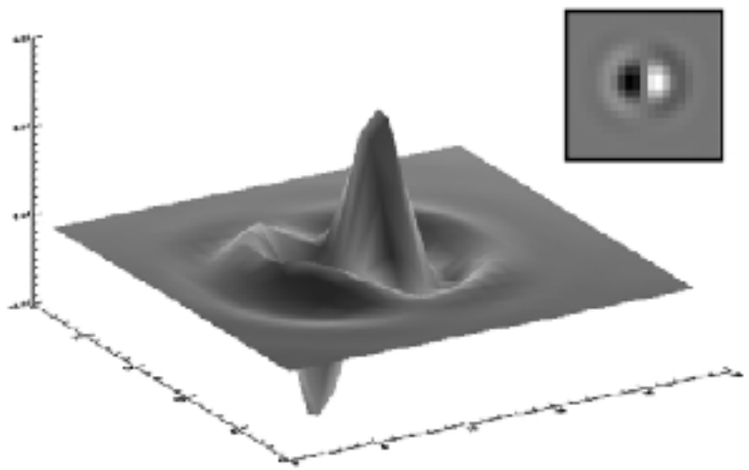
ANDROMEDA

(Mugnier+2009; Cantalloube+2015)

Pairwise subtraction of frames with ~0.5 FWHM rotation



Maximum match-filter in the residual images

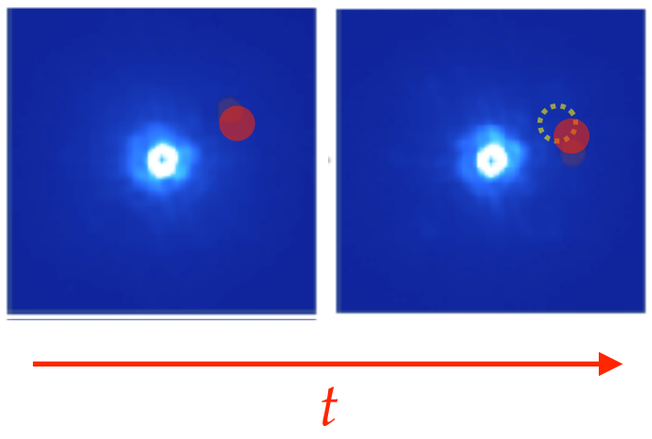


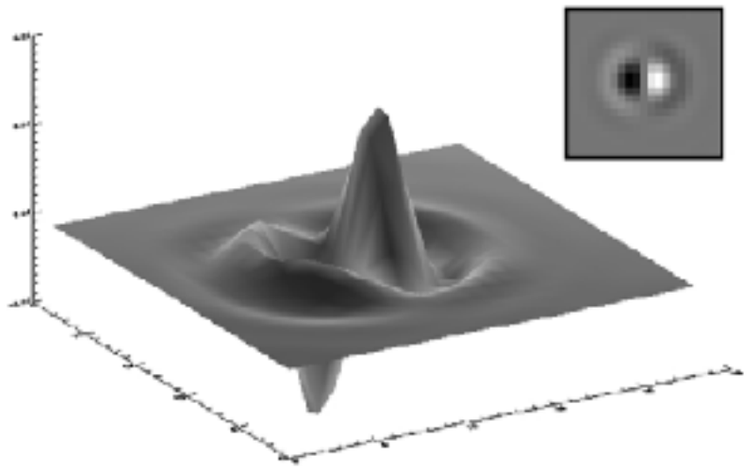
$$L(\mathbf{r}_0, a) \propto \exp\{-\frac{1}{2}\sum_k \sum_{\mathbf{r}} \frac{|\Delta(\mathbf{r},k) - a\, p(\mathbf{r},k;\mathbf{r}_0)|^2}{\sigma_\Delta^2(\mathbf{r})}\}$$

ANDROMEDA

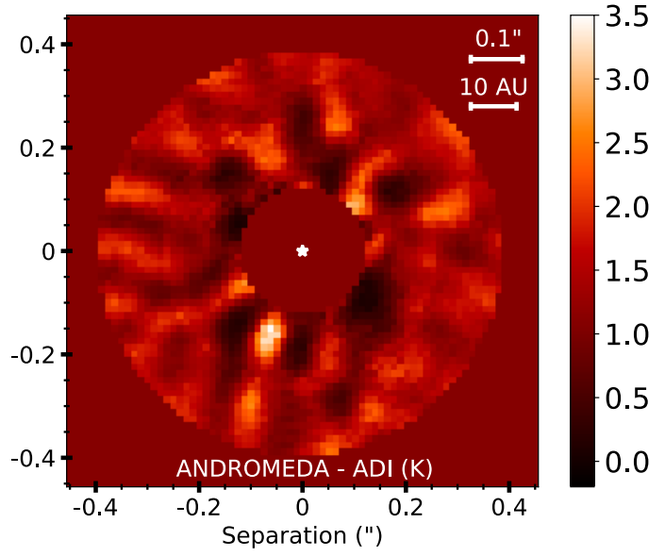
(Mugnier+2009; Cantalloube+2015)

Pairwise subtraction of frames with ~0.5 FWHM rotation → Maximum match-filter in the residual images → (Combination of all residual images) → { Astrometry / Photometry ; Detection SNR map





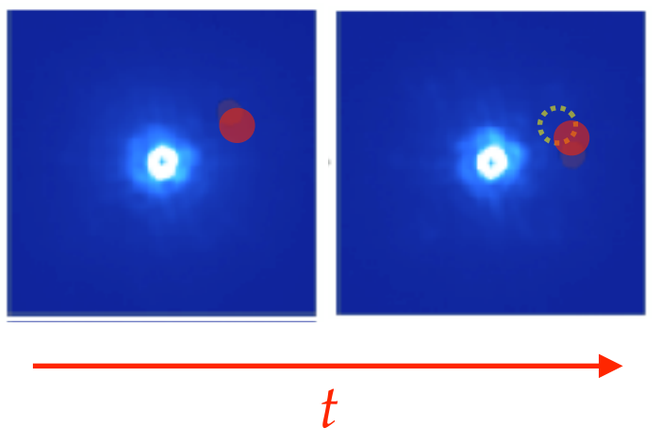
$$L(\mathbf{r}_0, a) \propto \exp\{-\frac{1}{2}\sum_k \sum_{\mathbf{r}} \frac{|\Delta(\mathbf{r},k) - a\, p(\mathbf{r},k;\mathbf{r}_0)|^2}{\sigma_\Delta^2(\mathbf{r})}\}$$

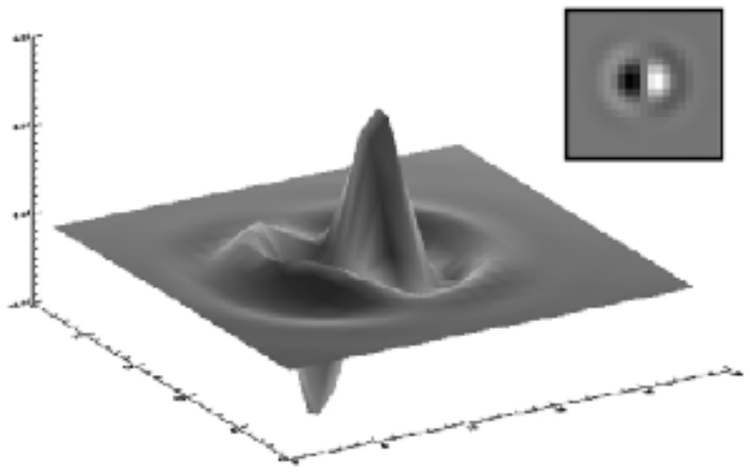


ANDROMEDA

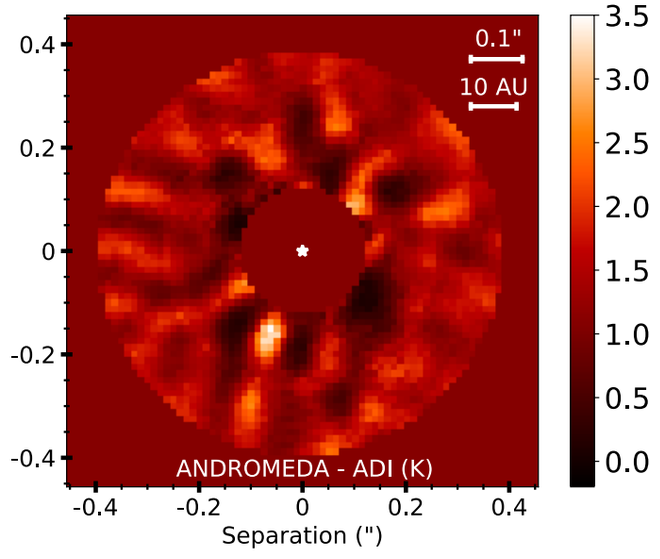
(Mugnier+2009; Cantalloube+2015)

Pairwise subtraction of frames with ~0.5 FWHM rotation → Maximum match-filter in the residual images → (Combination of all residual images) → { Astrometry / Photometry, Detection SNR map





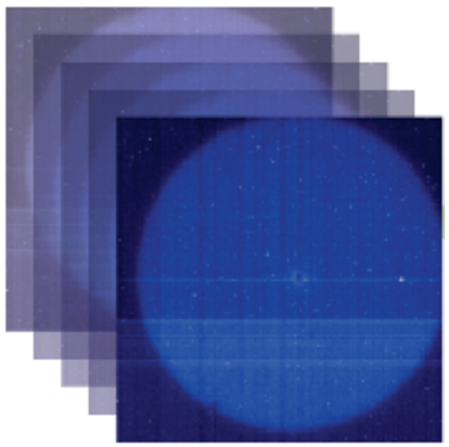
$$L(\mathbf{r}_0, a) \propto \exp\{-\frac{1}{2}\sum_k \sum_{\mathbf{r}} \frac{|\Delta(\mathbf{r},k) - a\, p(\mathbf{r},k;\mathbf{r}_0)|^2}{\sigma_\Delta^2(\mathbf{r})}\}$$



Pro: In theory only sensitive to point sources

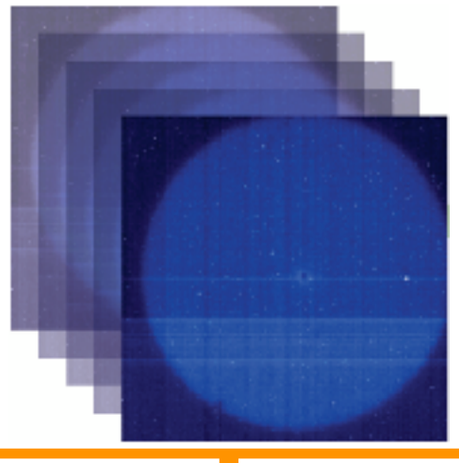
Pipeline

Raw images



Pipeline

Raw images

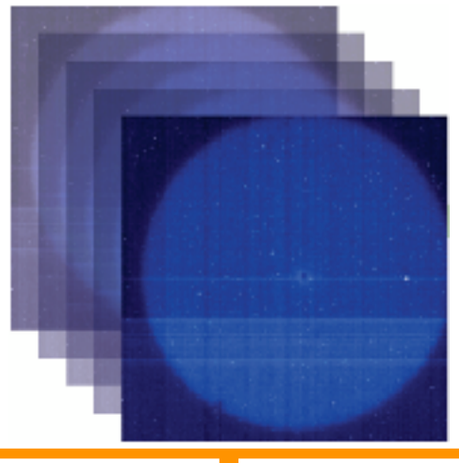


Basic calibration

- Dark subtraction
- Flat fielding
- Bad pixel correction
- Sky/Bkg subtraction

Pipeline

Raw images



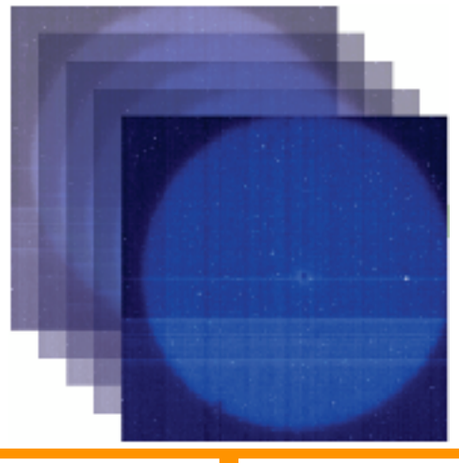
Basic calibration

- Dark subtraction
- Flat fielding
- Bad pixel correction
- Sky/Bkg subtraction

Bad frames removal

Pipeline

Raw images



Basic calibration

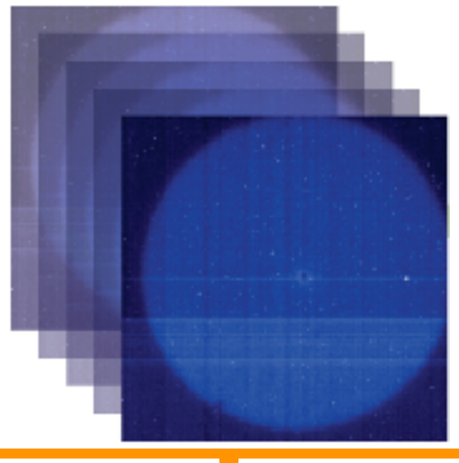
- Dark subtraction
- Flat fielding
- Bad pixel correction
- Sky/Bkg subtraction

Bad frames removal

Image recentering

Pipeline

Raw images



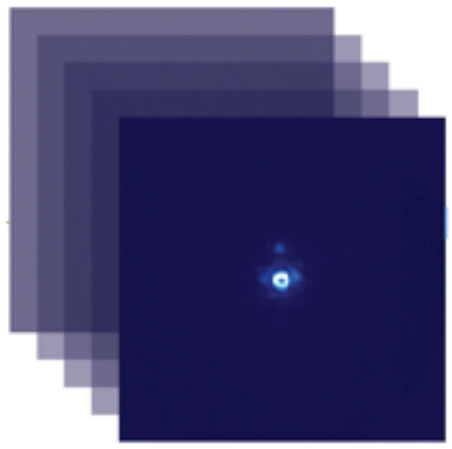
Basic calibration

- Dark subtraction
- Flat fielding
- Bad pixel correction
- Sky/Bkg subtraction

Bad frames removal

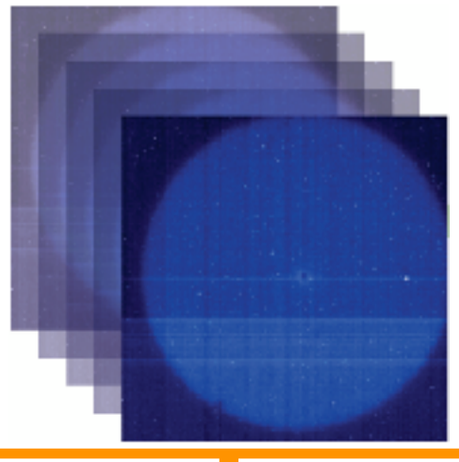
Image recentering

Calibrated images



Pipeline

Raw images



Basic calibration

- Dark subtraction
- Flat fielding
- Bad pixel correction
- Sky/Bkg subtraction

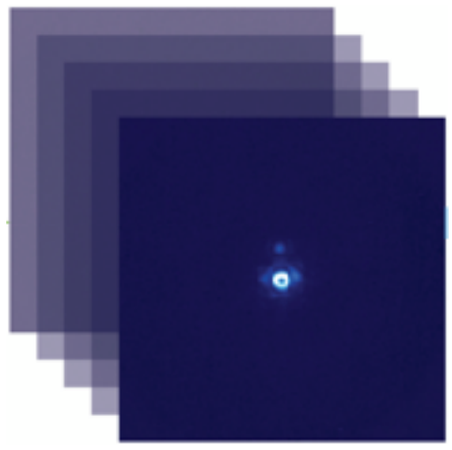
Bad frames removal

Image recentering

PSF modeling

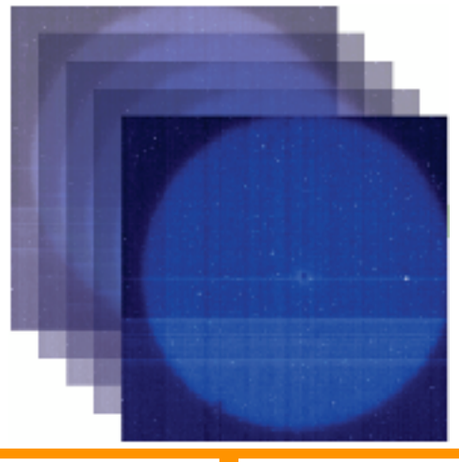
ADI	+	Median
SDI		PCA
RDI		ANDROMEDA
ASDI		LOCI
⋮		⋮

Calibrated images



Pipeline

Raw images



Basic calibration
- Dark subtraction
- Flat fielding
- Bad pixel correction
- Sky/Bkg subtraction

Bad frames removal

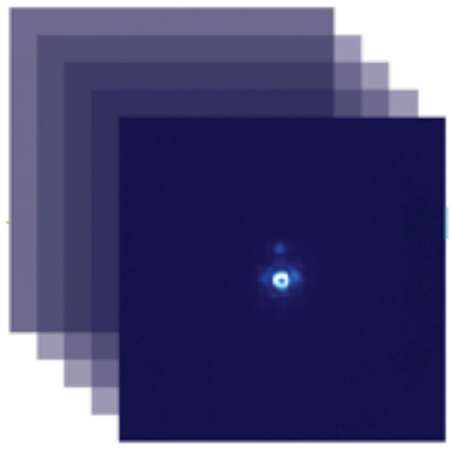
Image recentering

PSF modeling

ADI		Median
SDI	+	PCA
RDI		ANDROMEDA
ASDI		LOCI
⋮		⋮

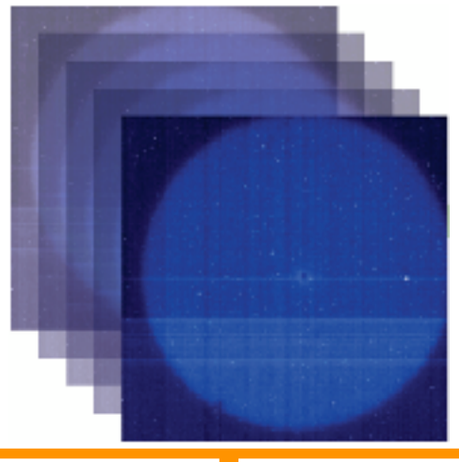
PSF subtraction

Calibrated images



Pipeline

Raw images



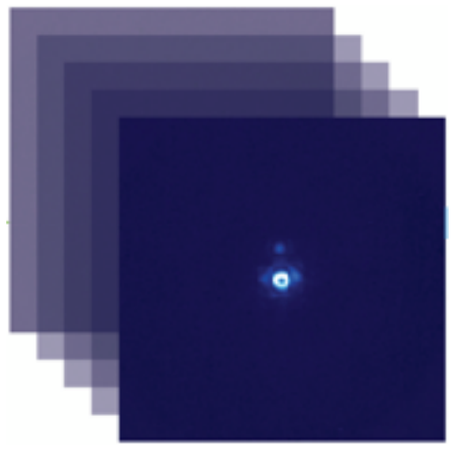
Basic calibration

- Dark subtraction
- Flat fielding
- Bad pixel correction
- Sky/Bkg subtraction

Bad frames removal

Image recentering

Calibrated images



PSF modeling

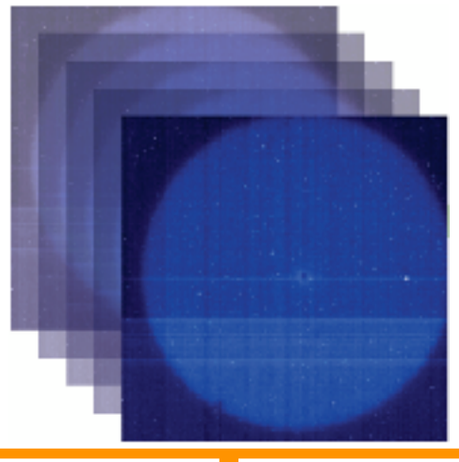
ADI		Median
SDI	+	PCA
RDI		ANDROMEDA
ASDI		LOCI
⋮		⋮

PSF subtraction

Image combination

Pipeline

Raw images

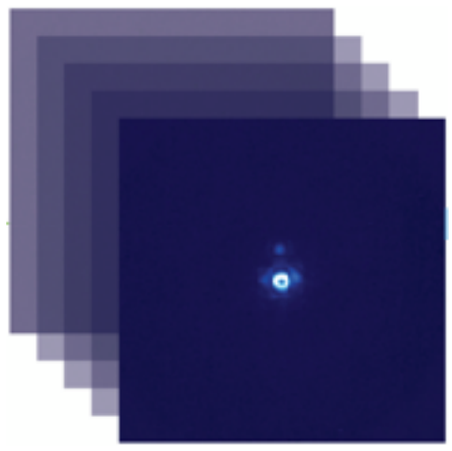


Basic calibration
- Dark subtraction
- Flat fielding
- Bad pixel correction
- Sky/Bkg subtraction

Bad frames removal

Image recentering

Calibrated images



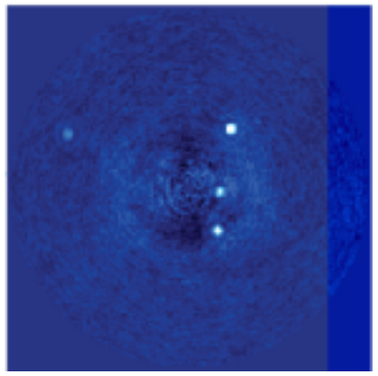
PSF modeling

ADI		Median
SDI	+	PCA
RDI		ANDROMEDA
ASDI		LOCI
⋮		⋮

PSF subtraction

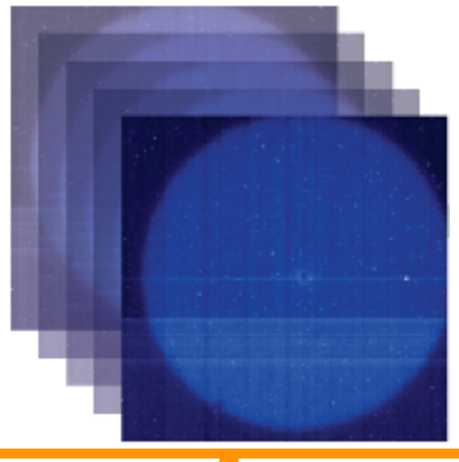
Image combination

Final image



Pipeline

Raw images



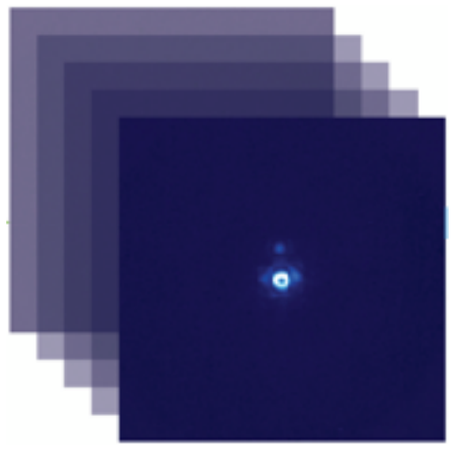
Basic calibration

- Dark subtraction
- Flat fielding
- Bad pixel correction
- Sky/Bkg subtraction

Bad frames removal

Image recentering

Calibrated images



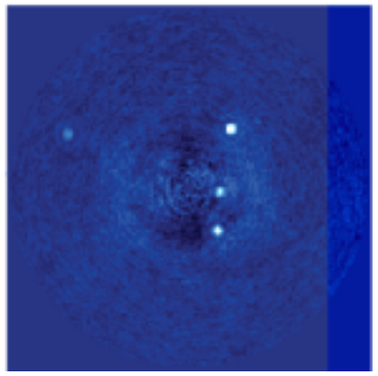
PSF modeling

ADI		Median
SDI	+	PCA
RDI		ANDROMEDA
ASDI		LOCI
⋮		⋮

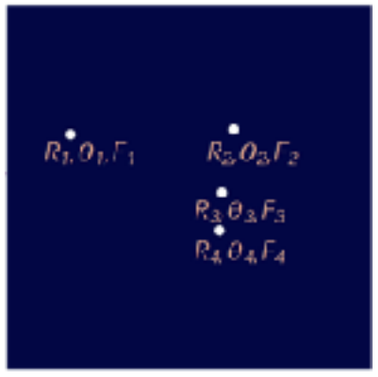
PSF subtraction

Image combination

Final image

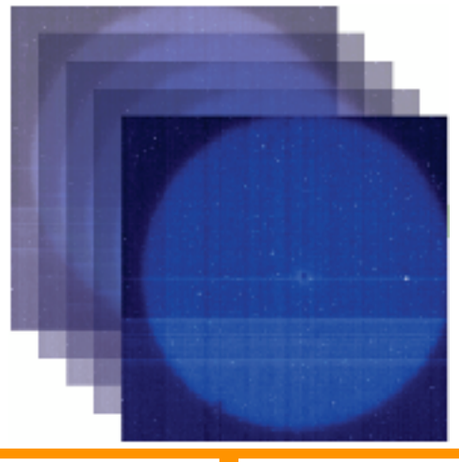


Characterization of detected companions



Pipeline

Raw images



Basic calibration

- Dark subtraction
- Flat fielding
- Bad pixel correction
- Sky/Bkg subtraction

Bad frames removal

Image recentering

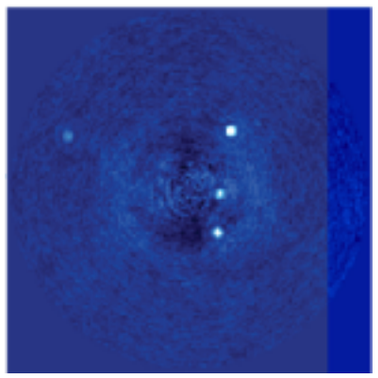
PSF modeling

ADI		Median
SDI	+	PCA
RDI		ANDROMEDA
ASDI		LOCI
⋮		⋮

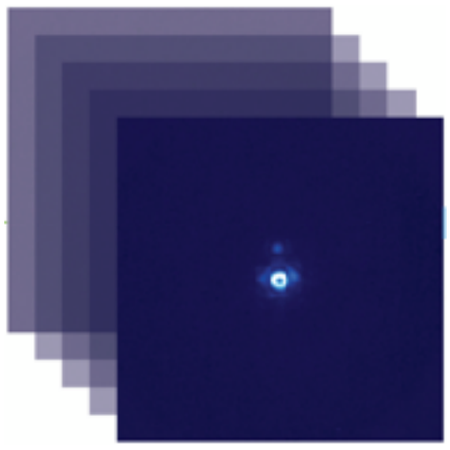
PSF subtraction

Image combination

Final image



Calibrated images



Forward modelling

Characterization of detected companions

Need to reduce a new high-contrast imaging dataset?

Don’t want to ask the SPHERE consortium to reduce your data?

Need to reduce a new high-contrast imaging dataset?

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- Well-documented: https://vip.readthedocs.io/en/latest/
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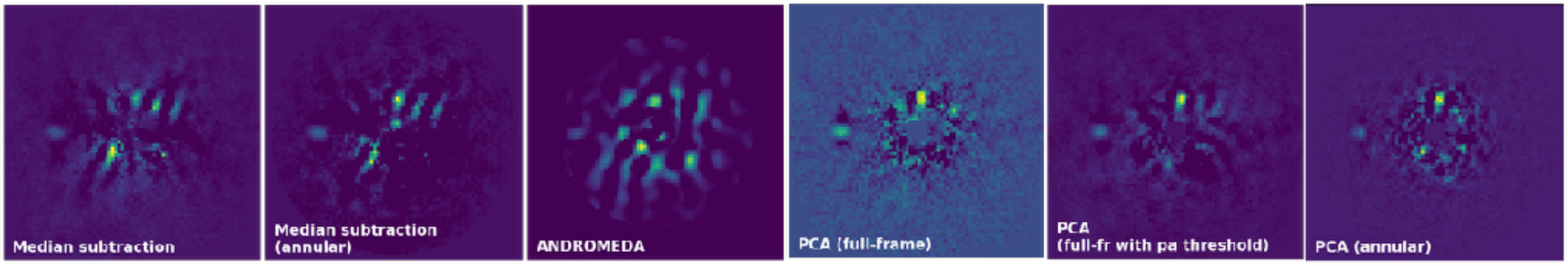
Find your own planet now!



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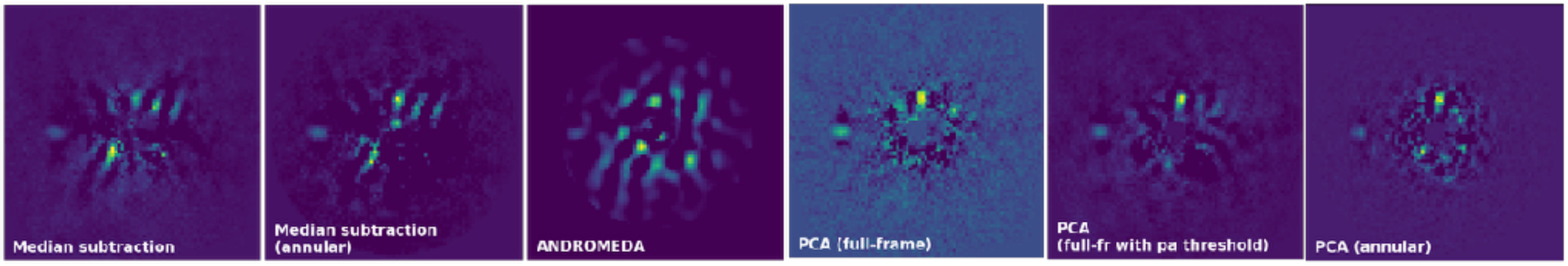

Available here (FOR FREE! *): https://github.com/vortex-exoplanet/VIP

* As long as proper citation to the Gomez Gonzalez et al. 2017 paper is made

Exoplanet direct images

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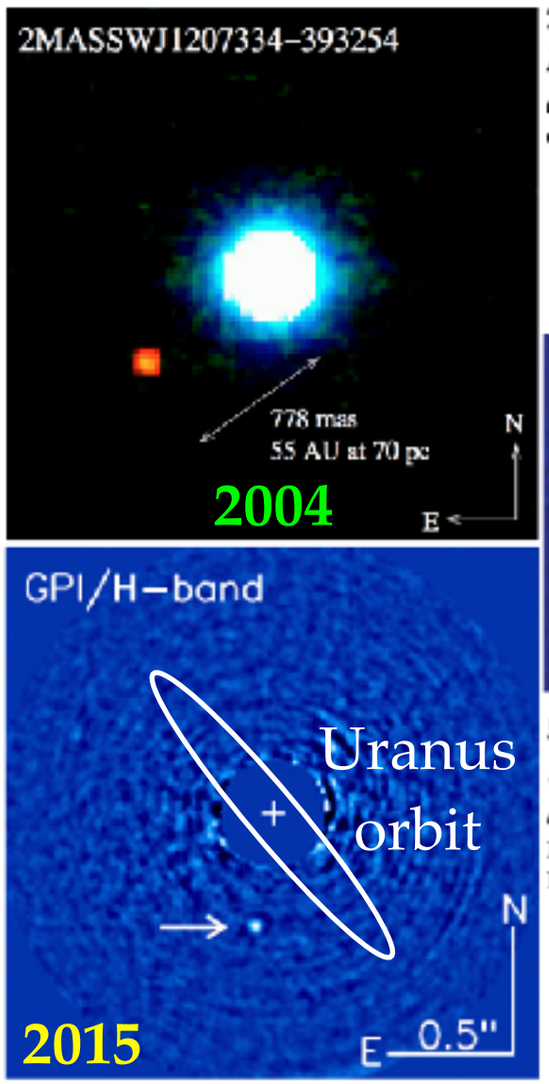
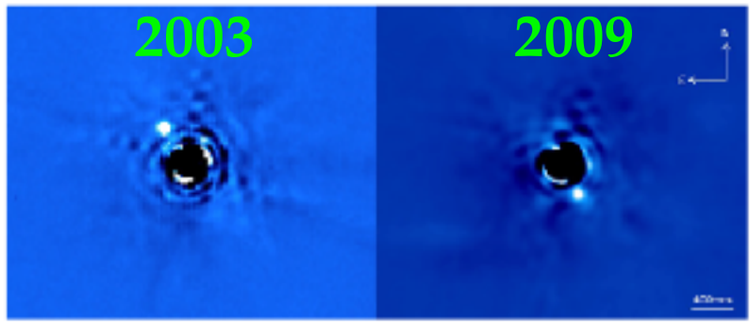
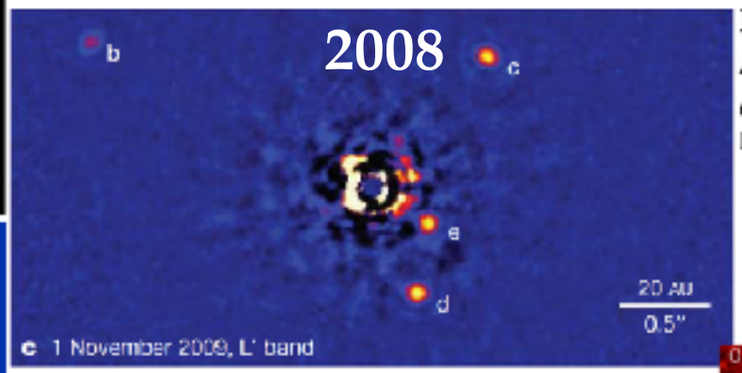


2M1207 b
$M \sim 4\ M_J$
$a \sim 55$ au
Chauvin et al. 2004, 2005

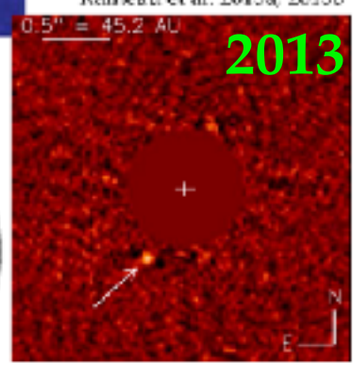
Beta Pic b
$M \sim 7\ M_J$
$a \sim 10$ au
Lagrange et al. 2009, 2010





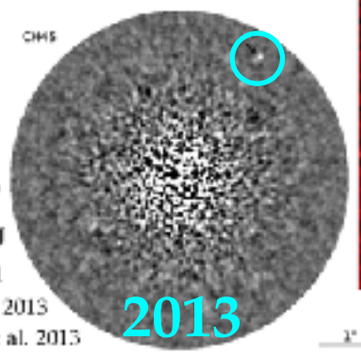
HR 8799 b, c, d, e
$M \sim 7, 10, 10, 9\ M_J$
$a \sim 68, 38, 24, 13$ au
Marois et al. 2008, 2010

HD 95086 b
$M \sim 5\ M_J$
$a \sim 56$ au
Rameau et al. 2013a, 2013b



51 Eri b
$M \sim 2$–$12\ M_J$
$a \sim 13$ au
Macintosh et al. 2015
De Rosa et al. 2015

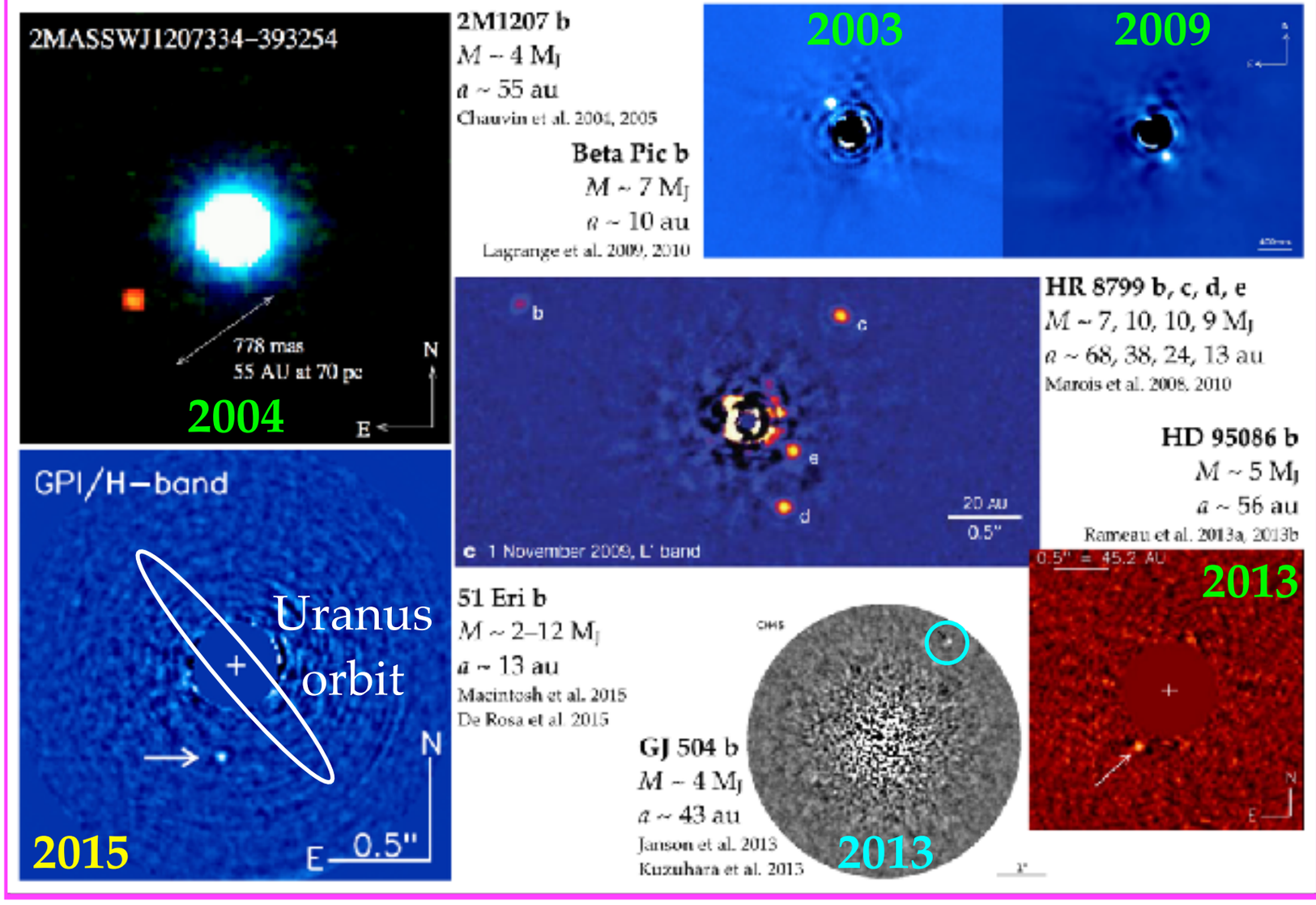
GJ 504 b
$M \sim 4\ M_J$
$a \sim 43$ au
Janson et al. 2013
Kuzuhara et al. 2013

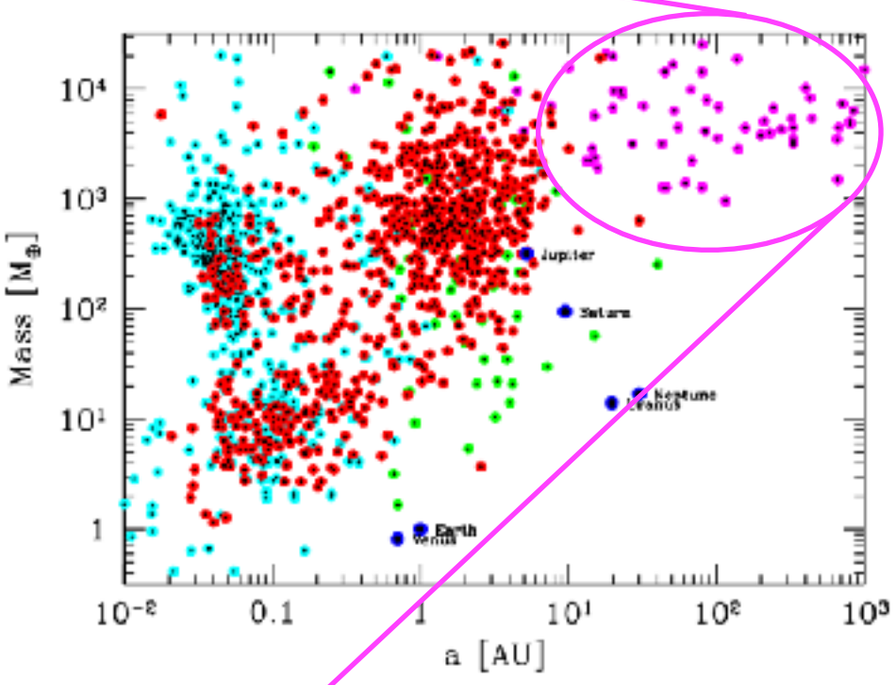


10m-class telescopes

Exoplanet direct images

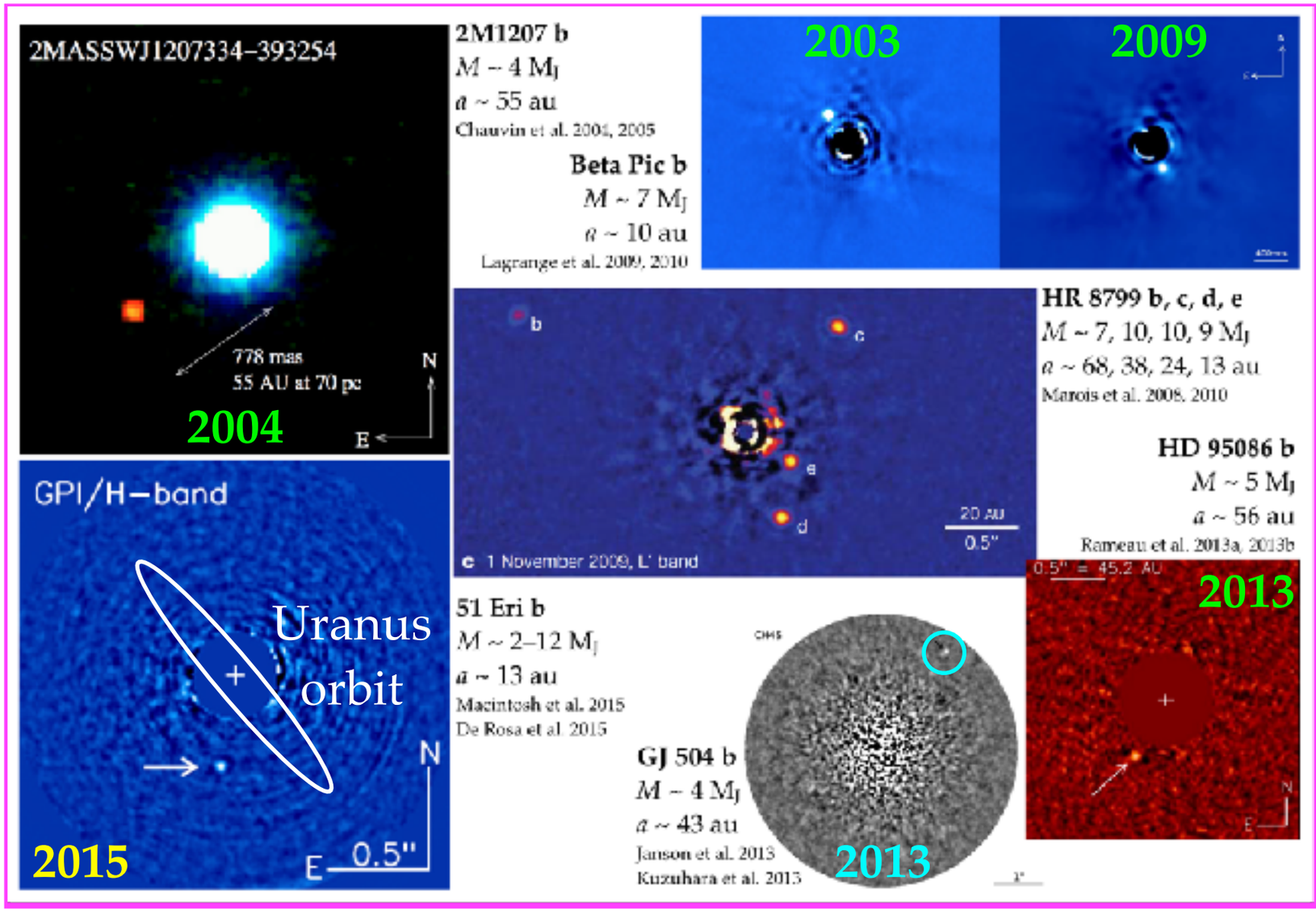
Directly Imaged

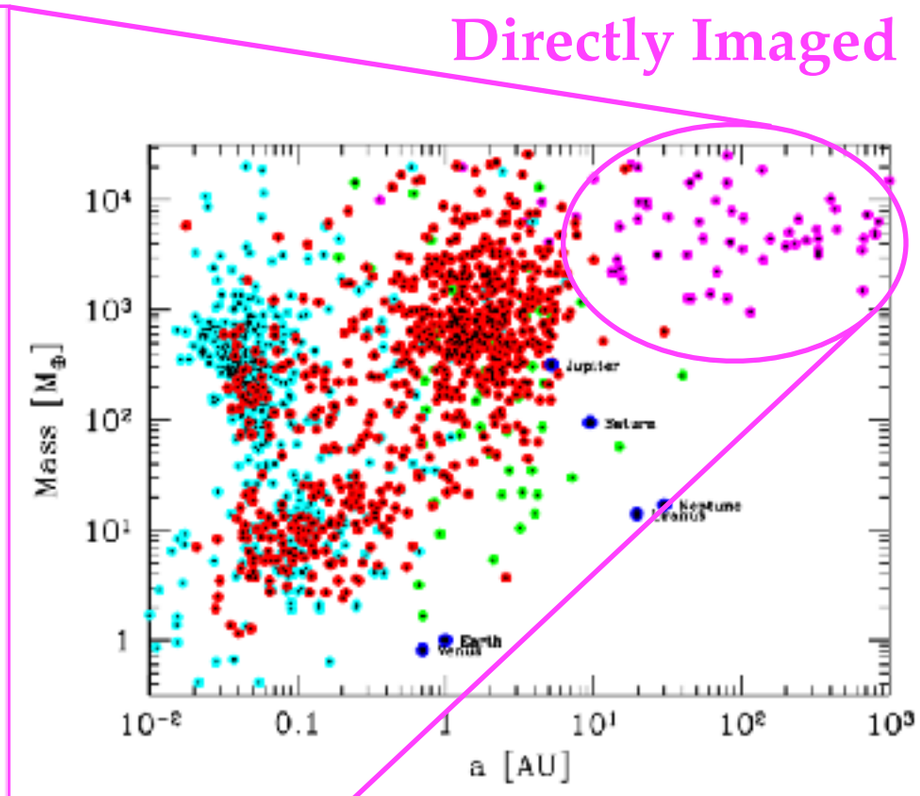




Mordasini+18

Exoplanet direct images





- Occurrence: ~ 1% of all stars have 5-13M_J between 30-300 AU (Bowler+16)
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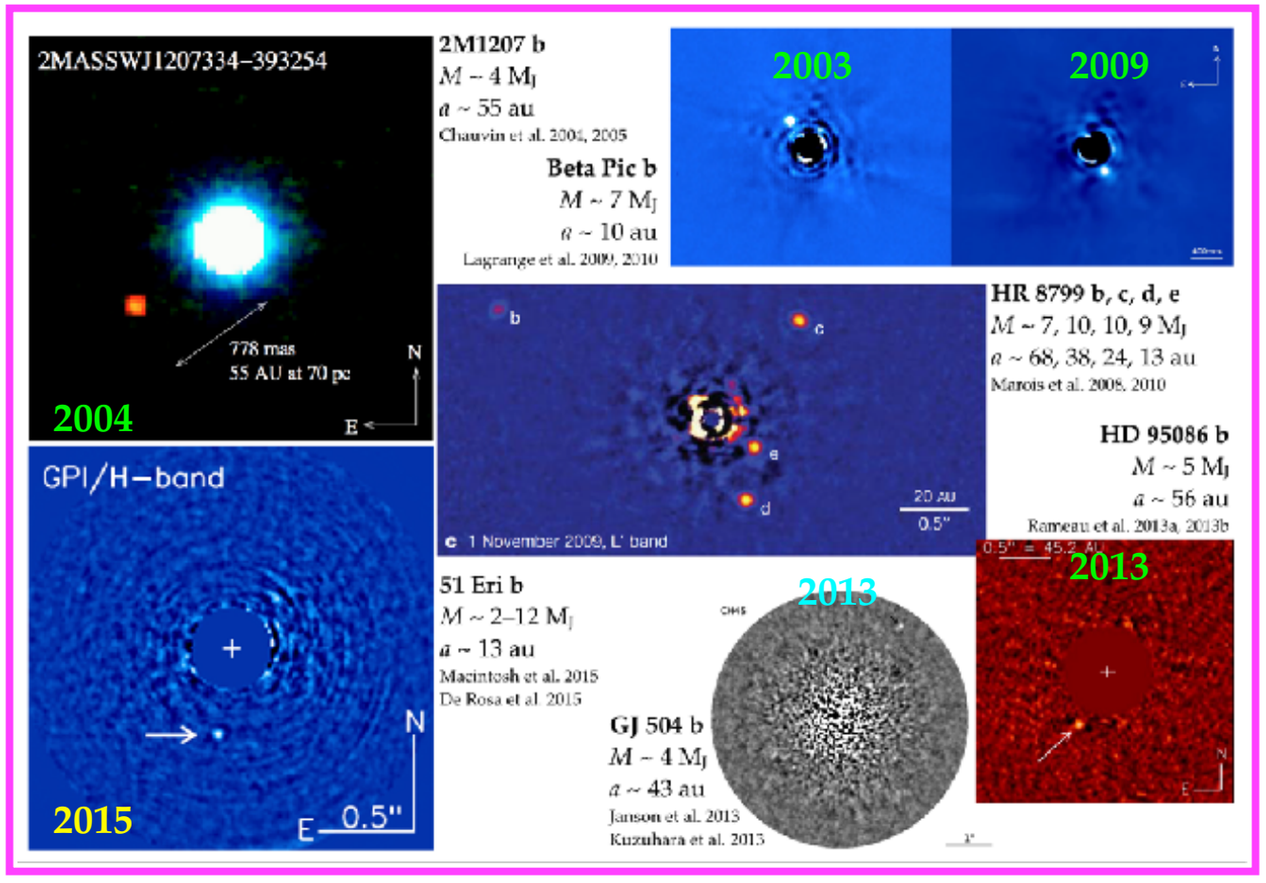

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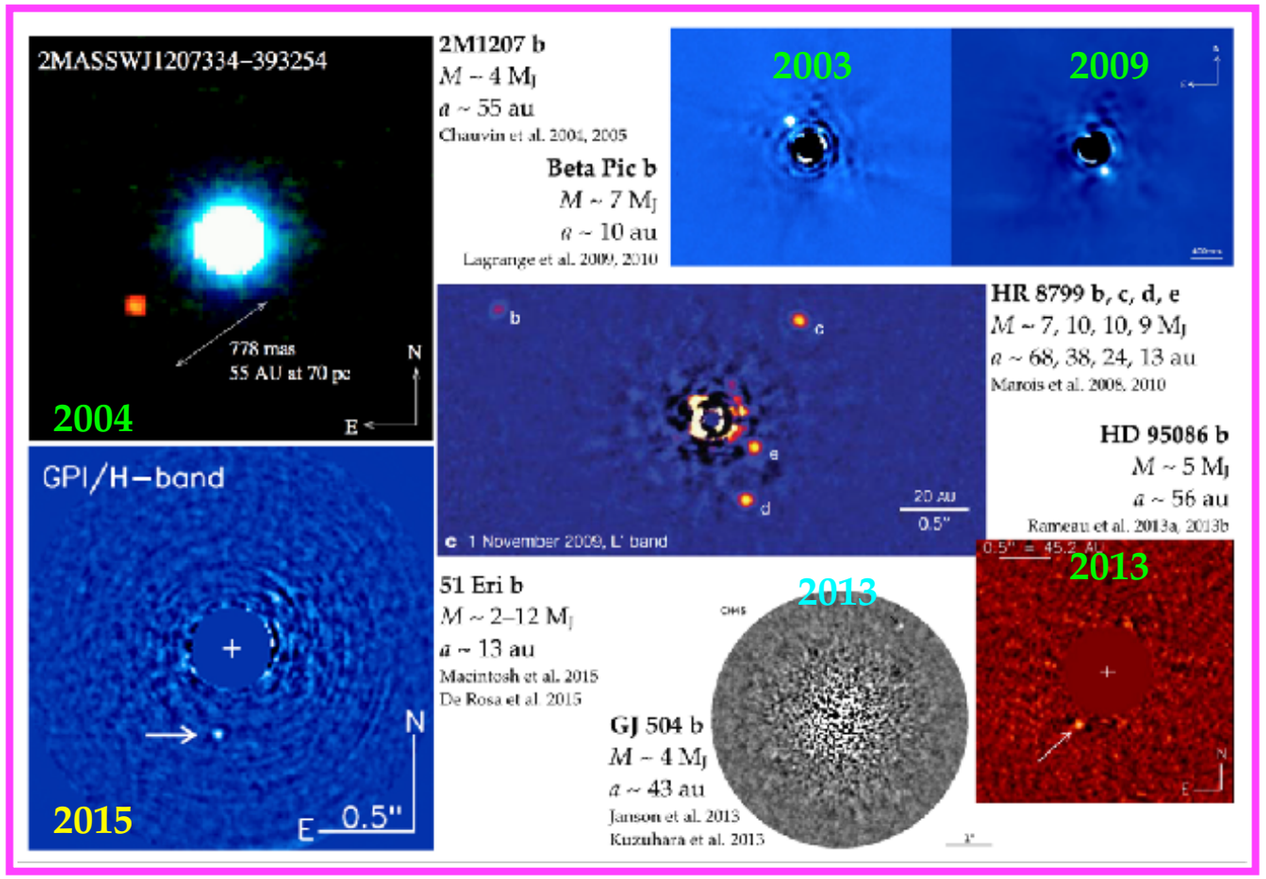
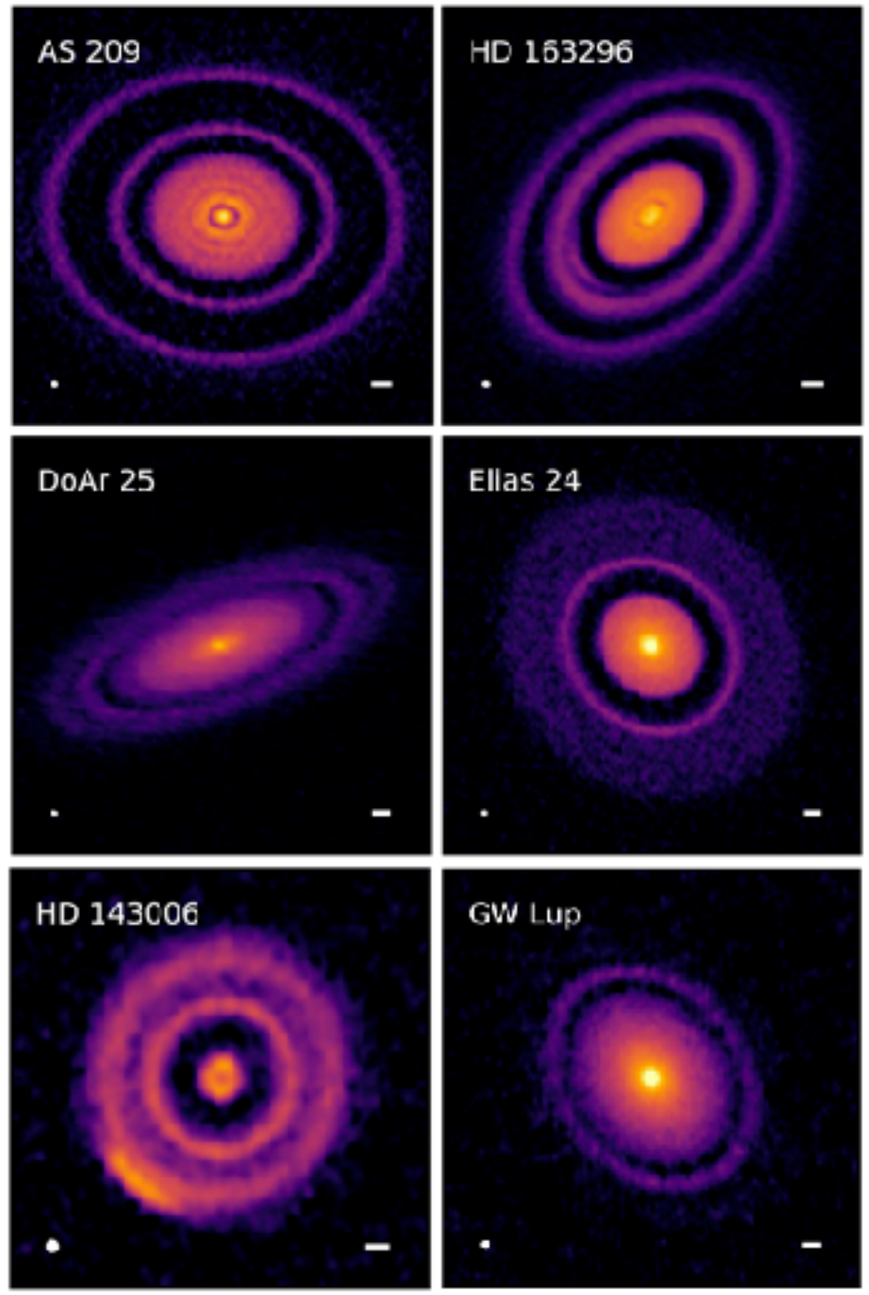


= evolved



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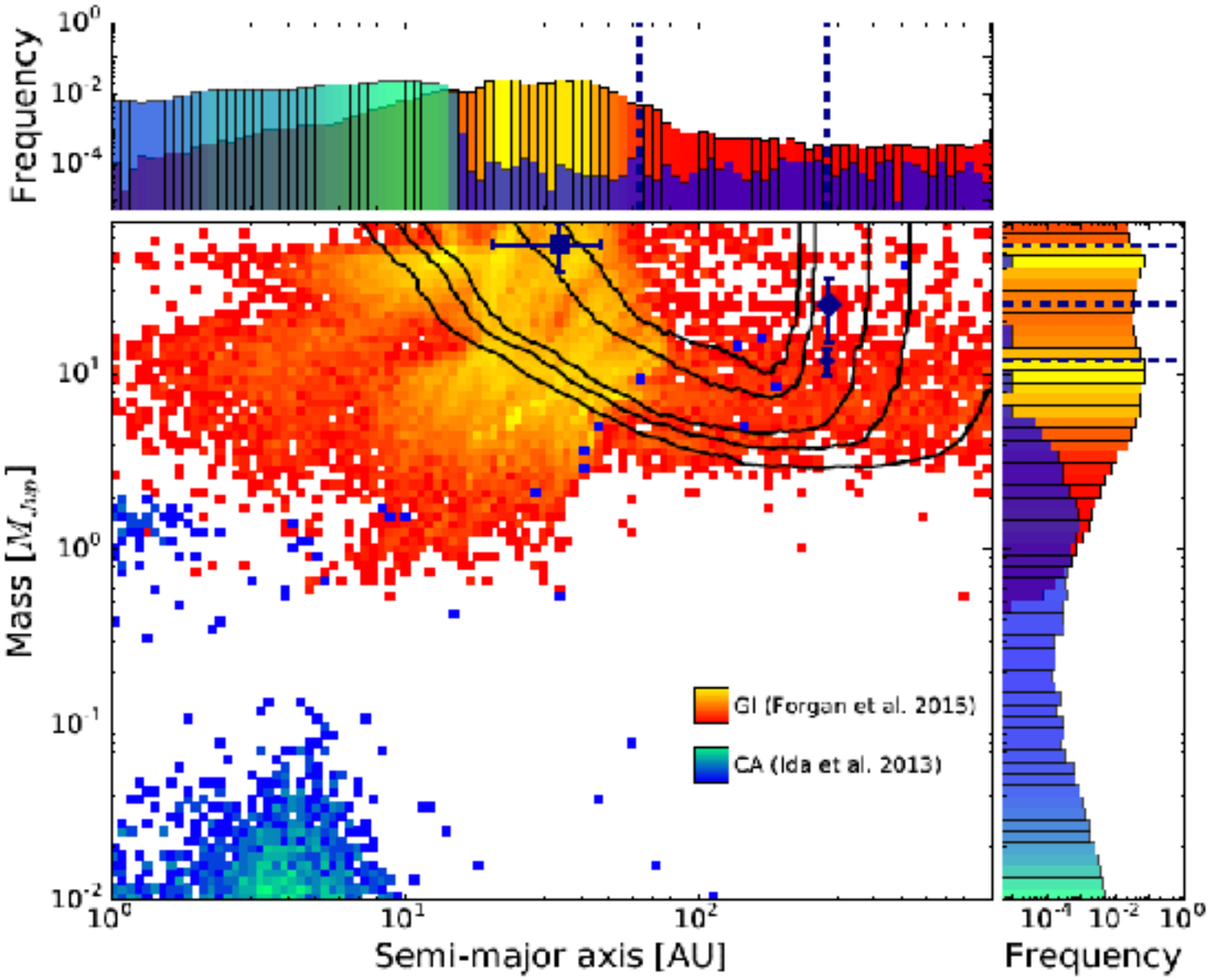
DSHARP, Andrews+2018

What about Solar-type stars?

Vigan+2017



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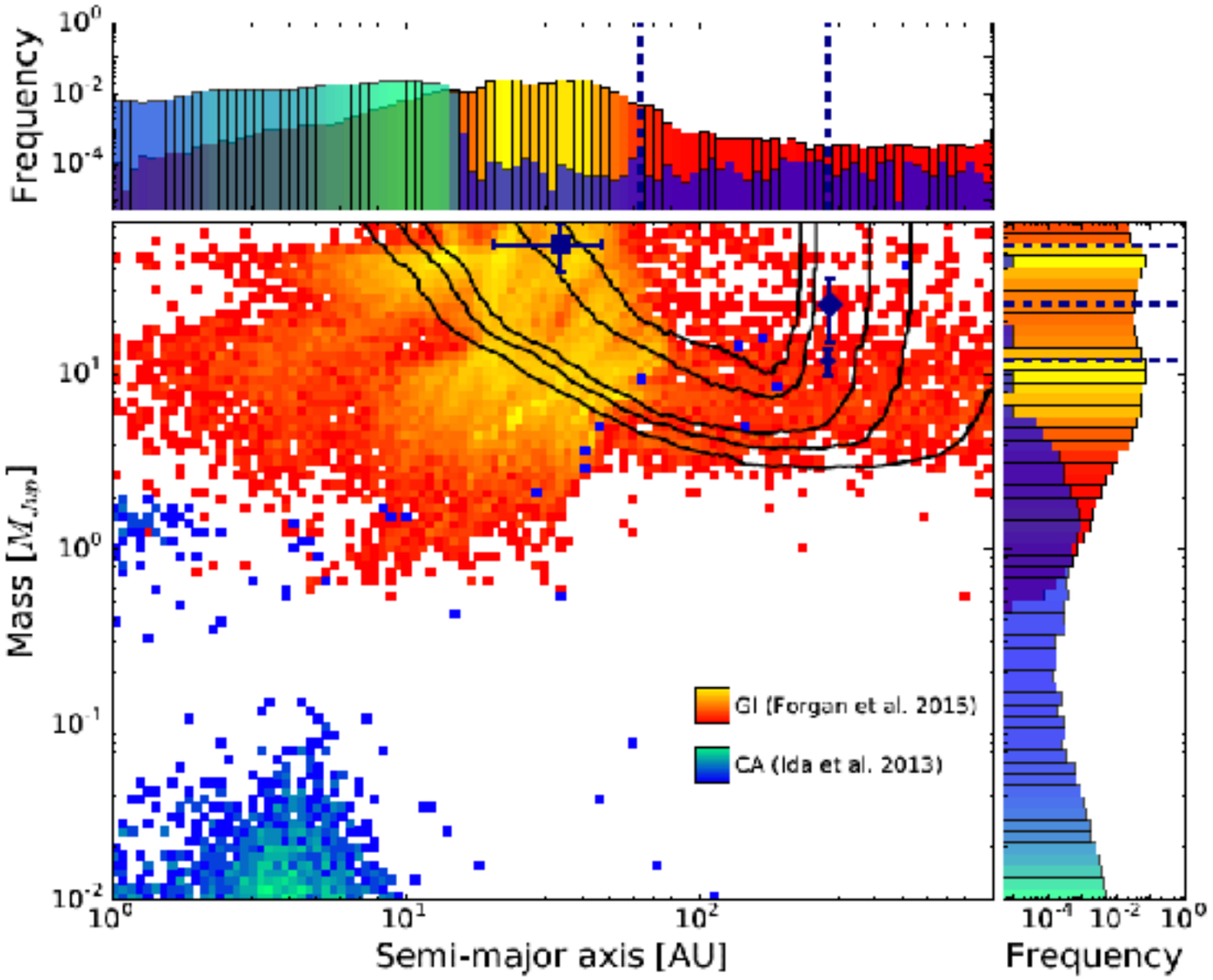

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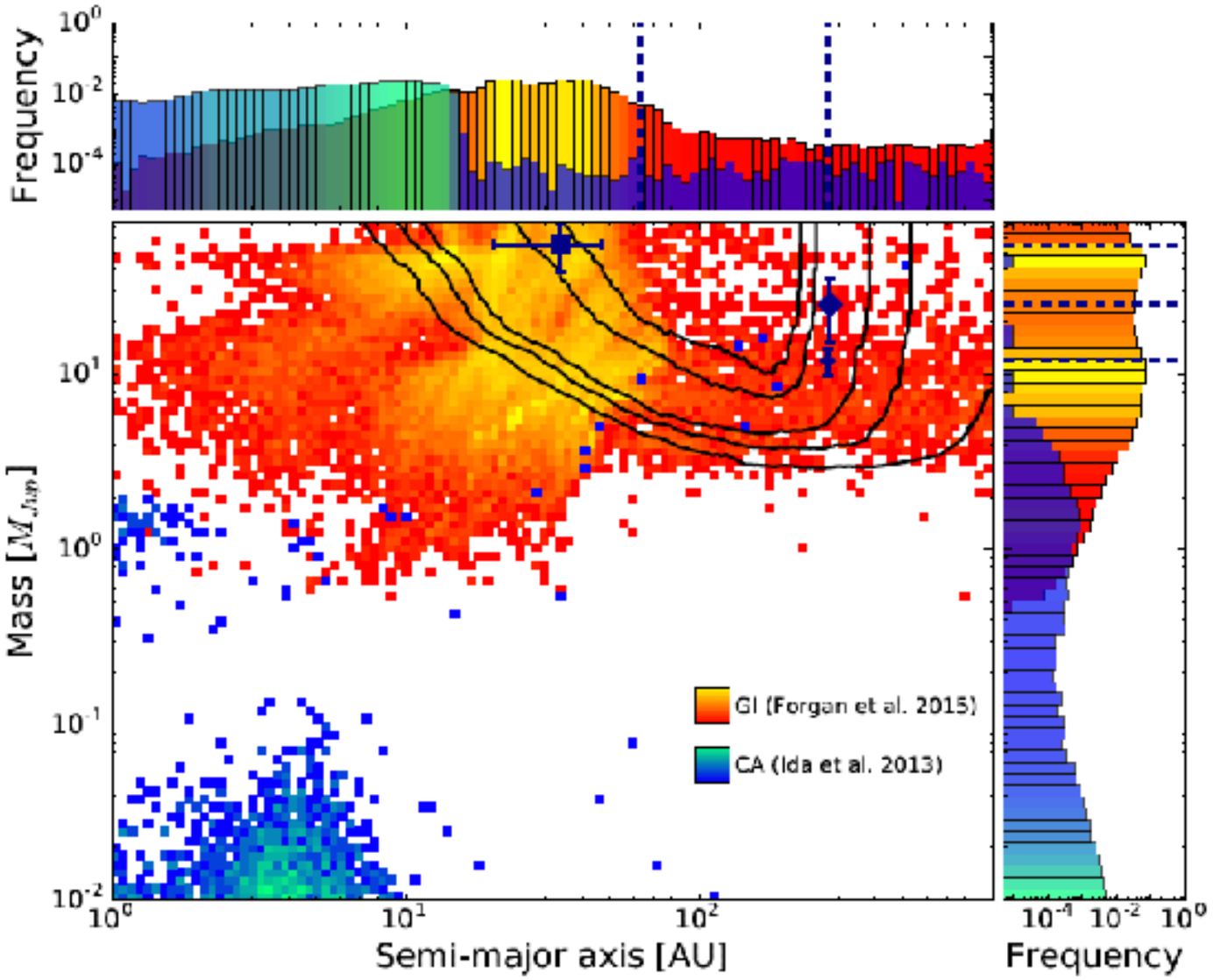

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=> Need of constraints at younger ages!

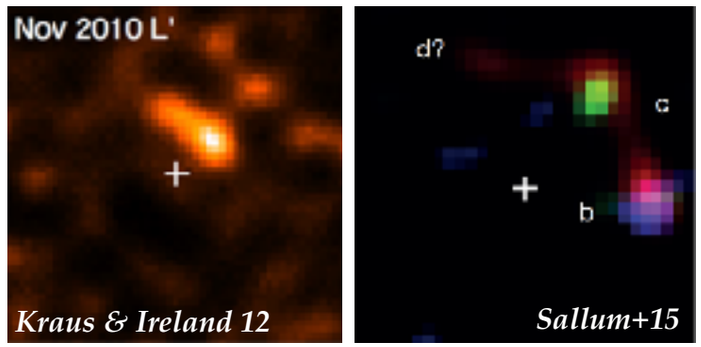
Any detection in protoplanetary disks?

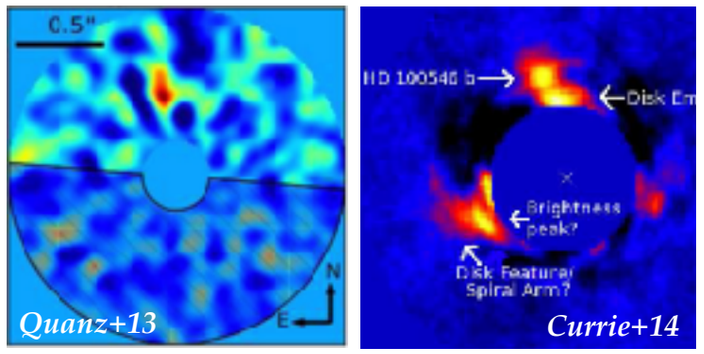
LkCa 15 b, c, d

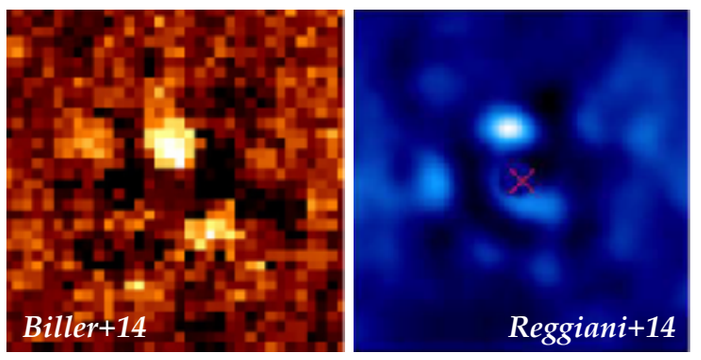
HD 100546 b, c

HD 169142 b, c

Protoplanet claims







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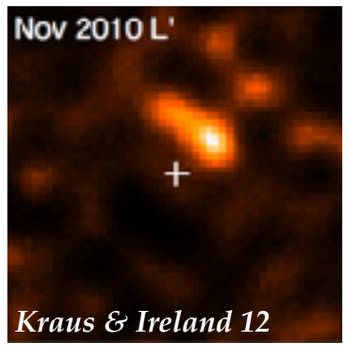

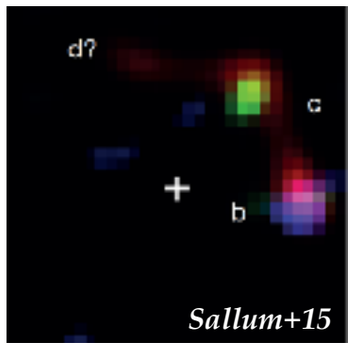

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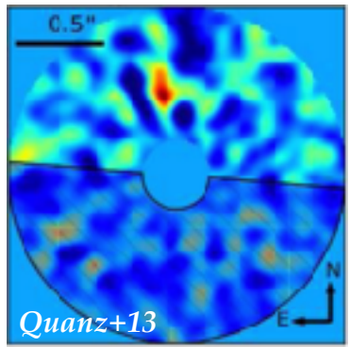
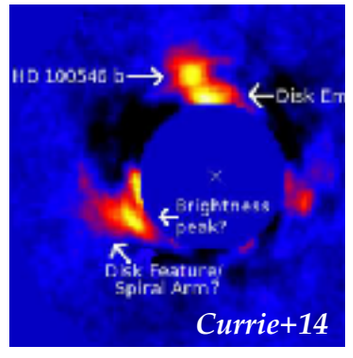
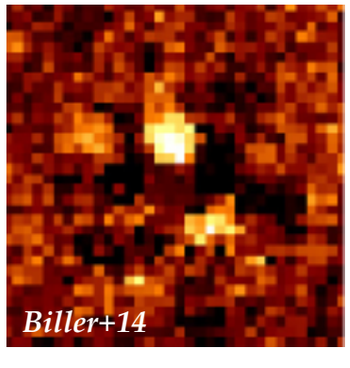
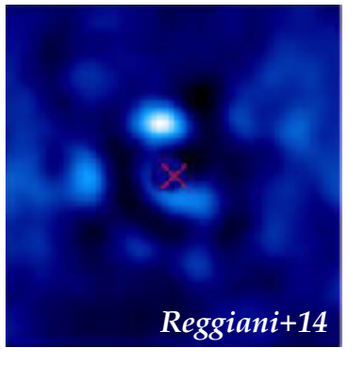


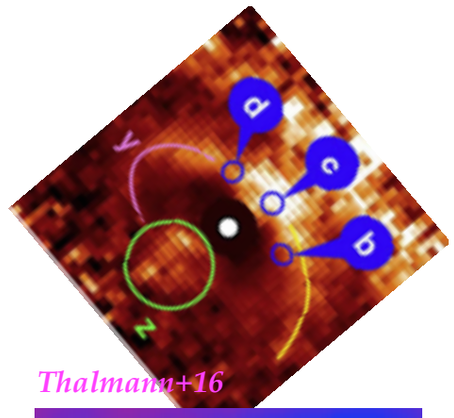


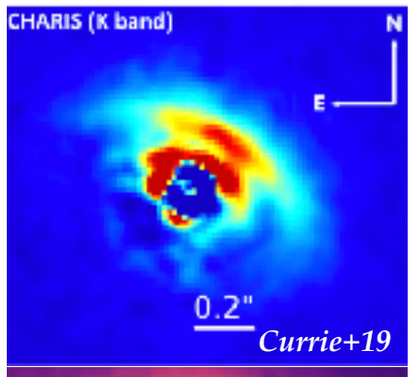
HD 169142 b, c

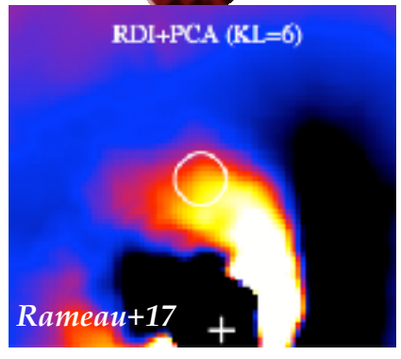


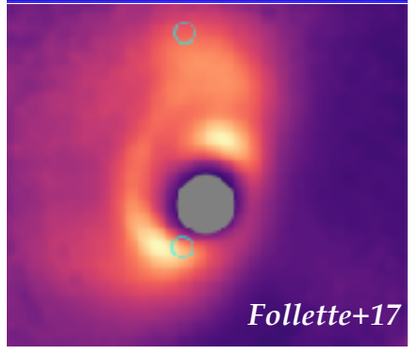


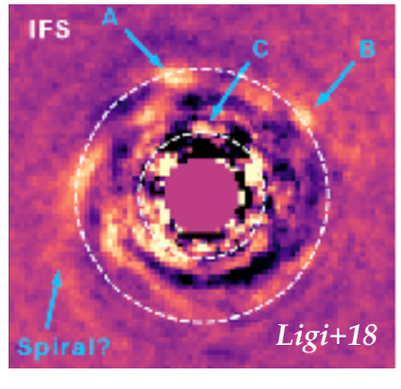
Counter-evidence

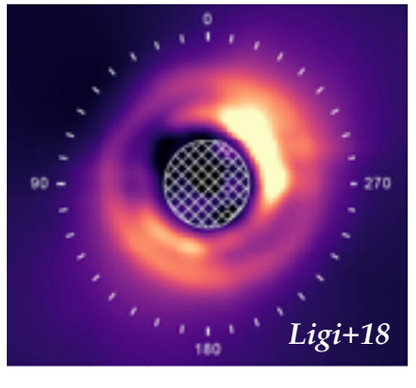












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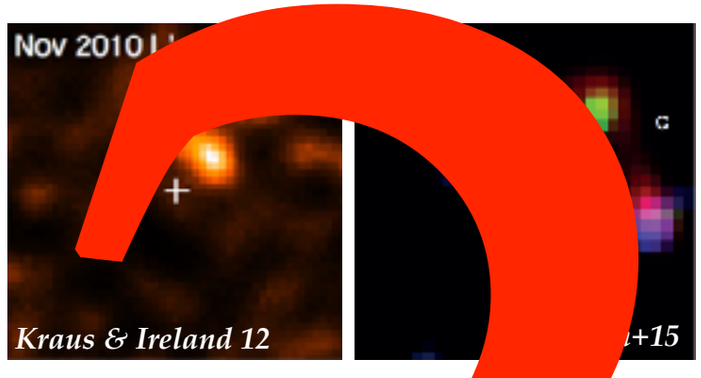

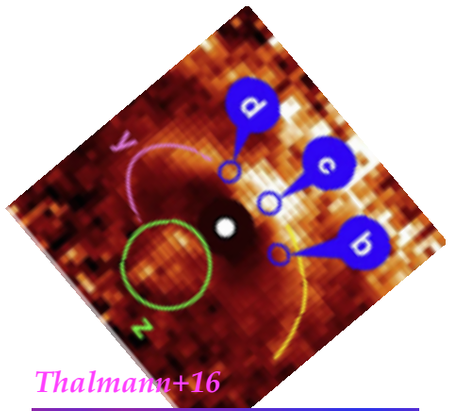

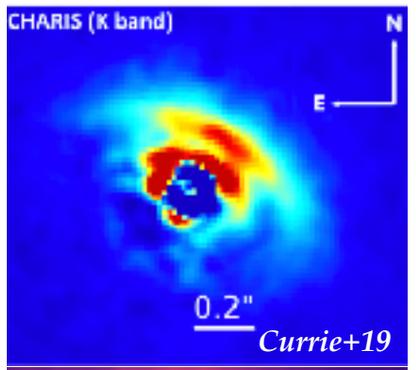

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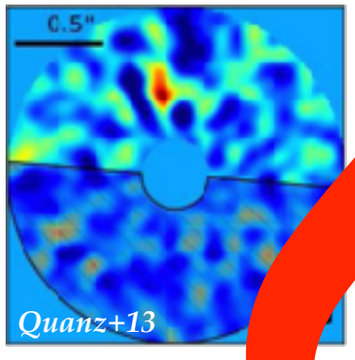
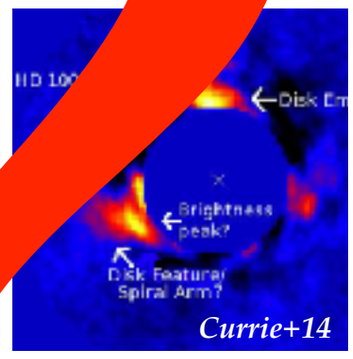
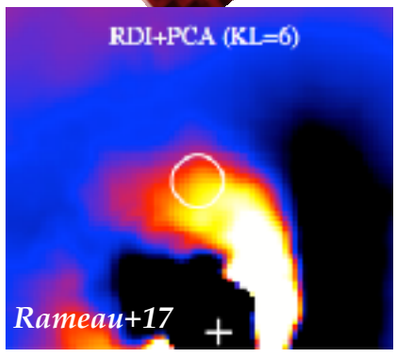
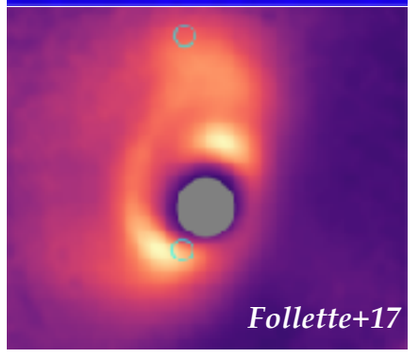
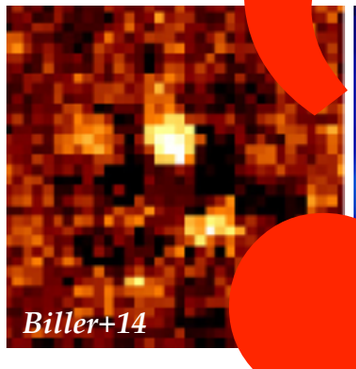


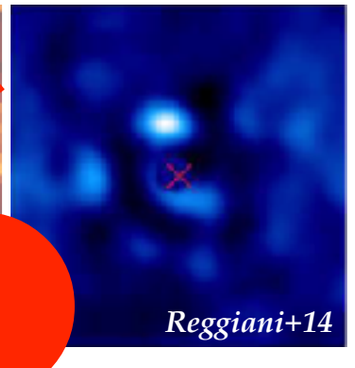


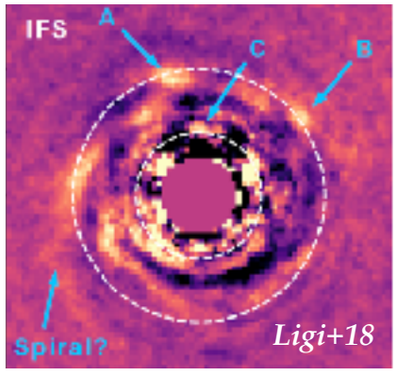


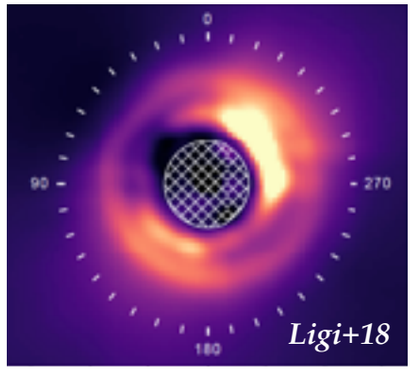


HD 169142 b, c









What can we do then?

Detections at multiple epochs / instruments / techniques

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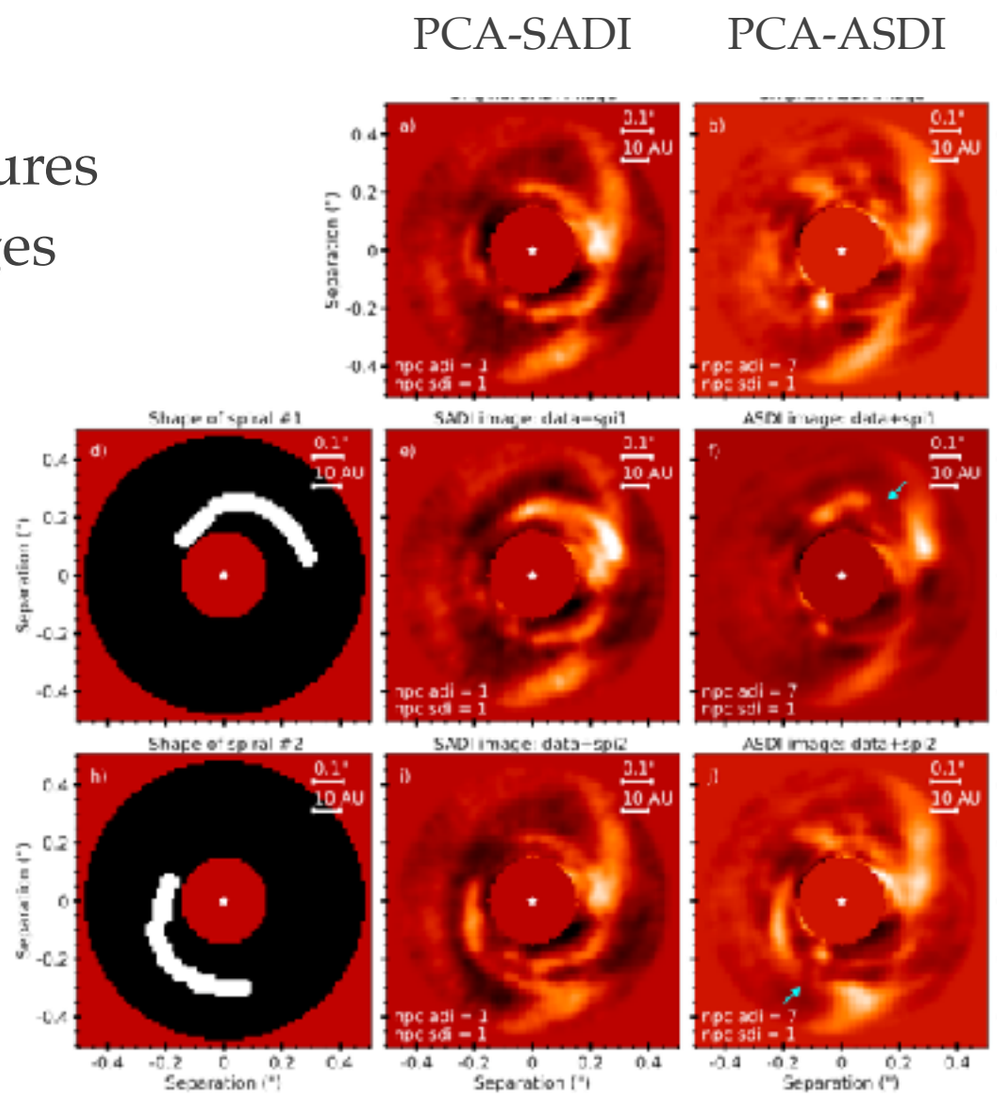
Detections at multiple epochs / instruments / techniques

Forward modelling (1)

- Inject extended features and re-process images



Christiaens+2019a

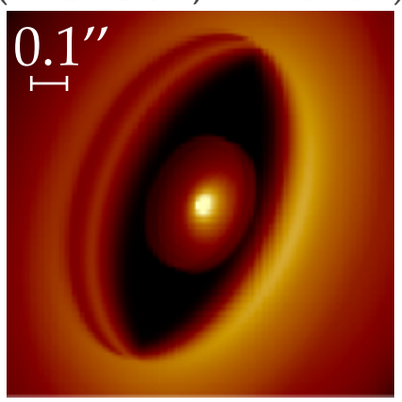
What can we do then?

Forward modelling (2)

- Create a RT model and post-process it

MODEL

RT model
(MCFOST; Pinte+09)



(log scale)

OBS

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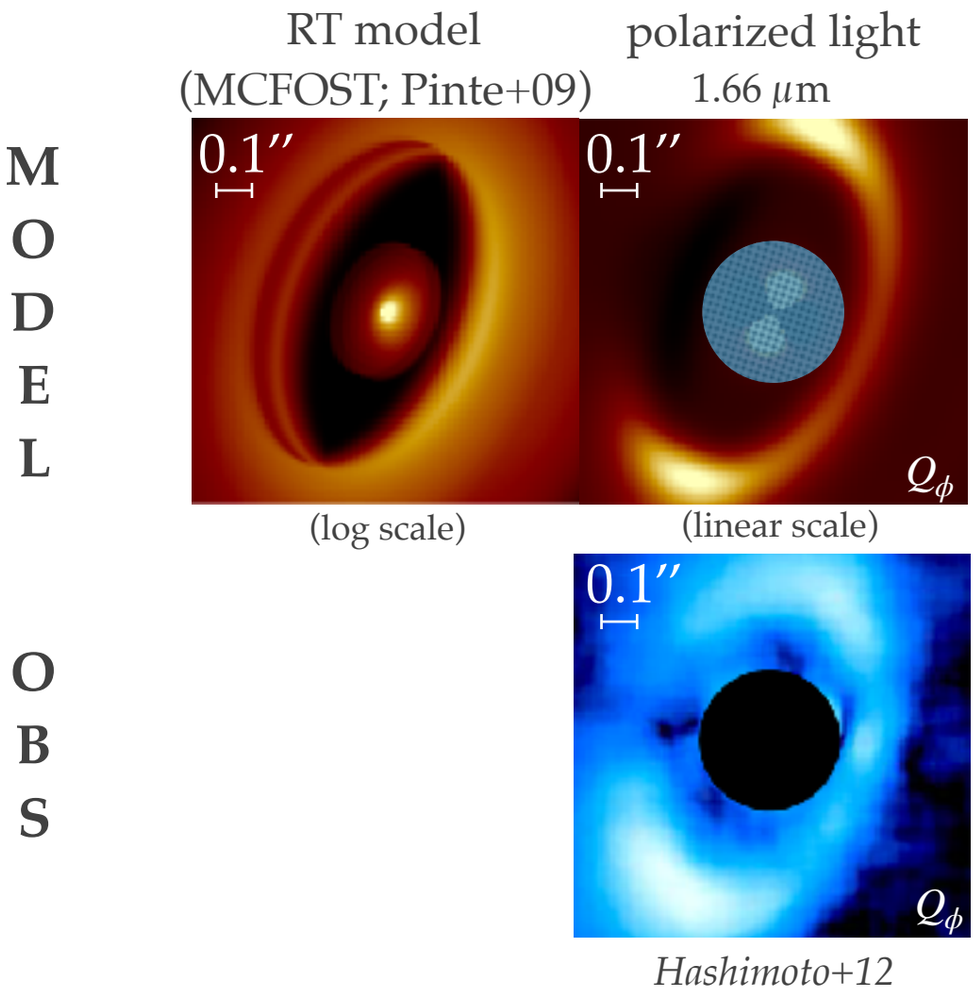

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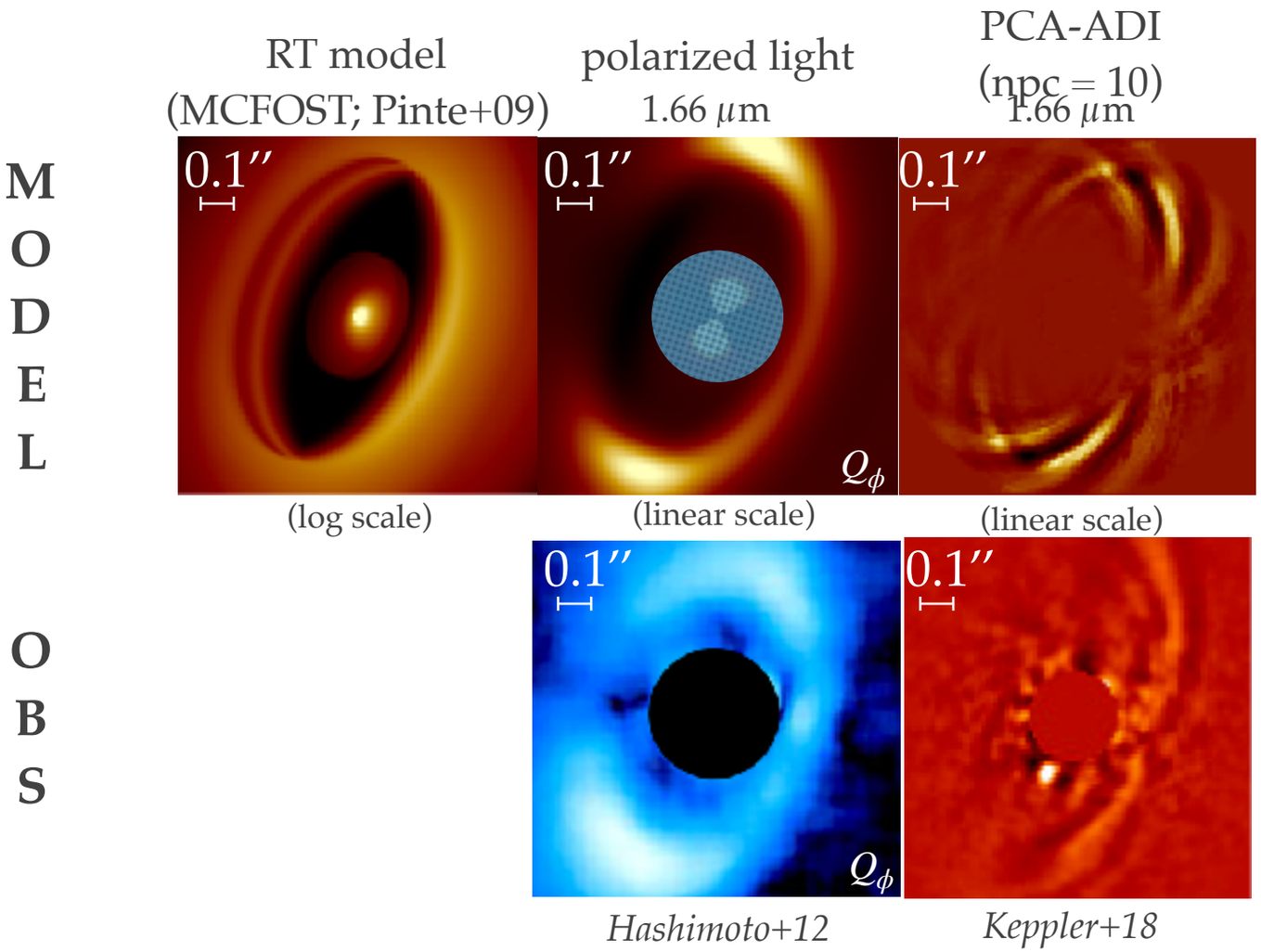

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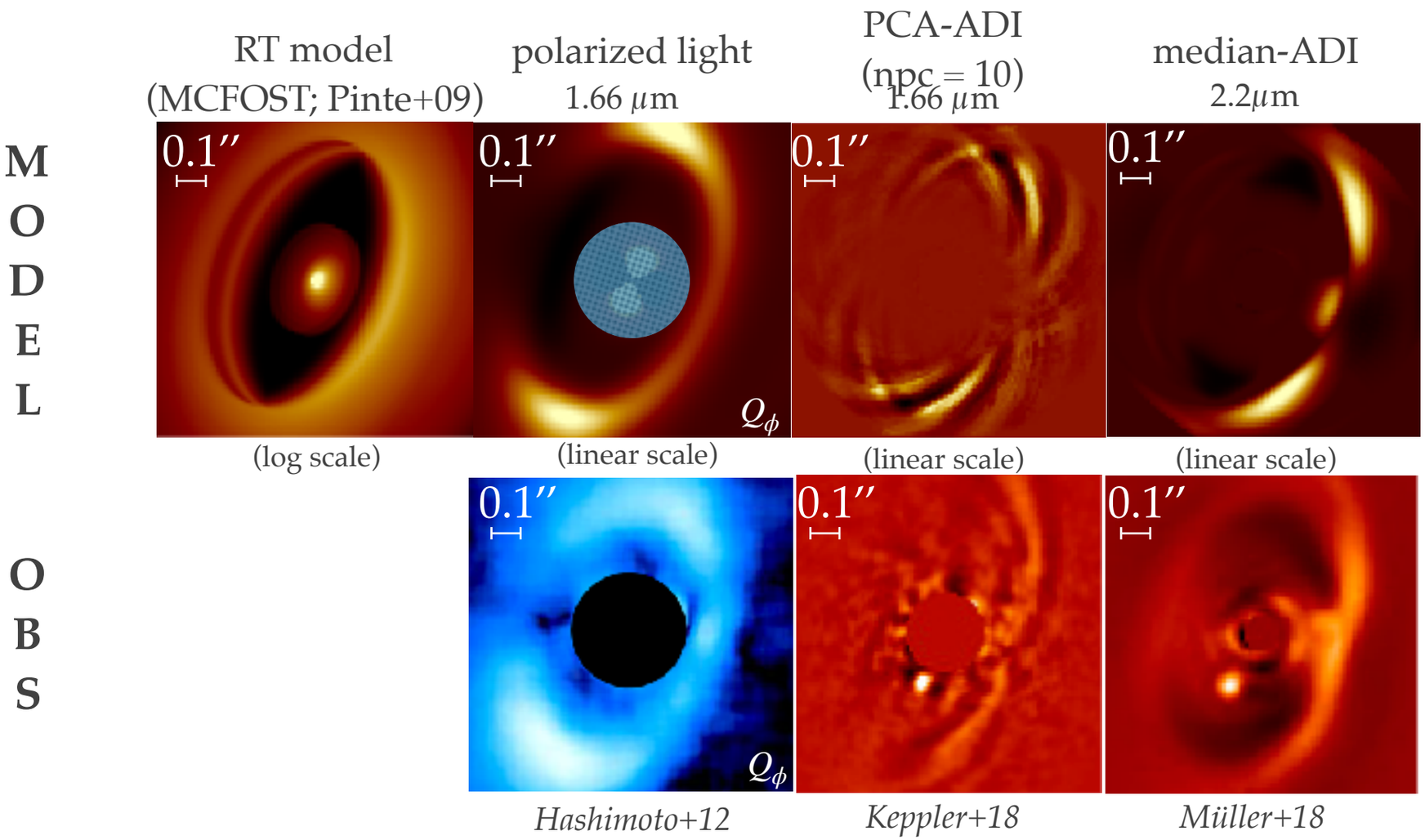

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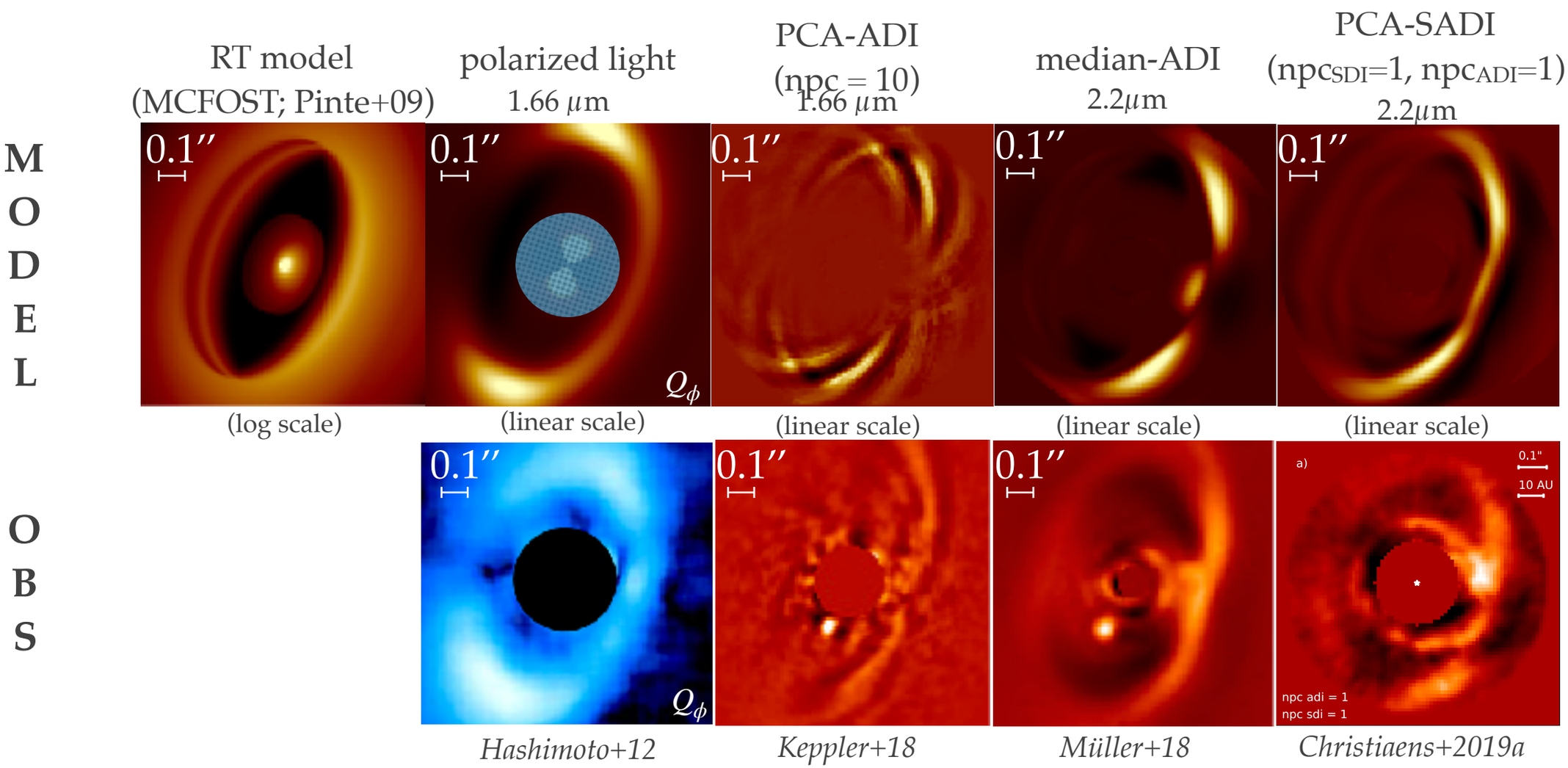

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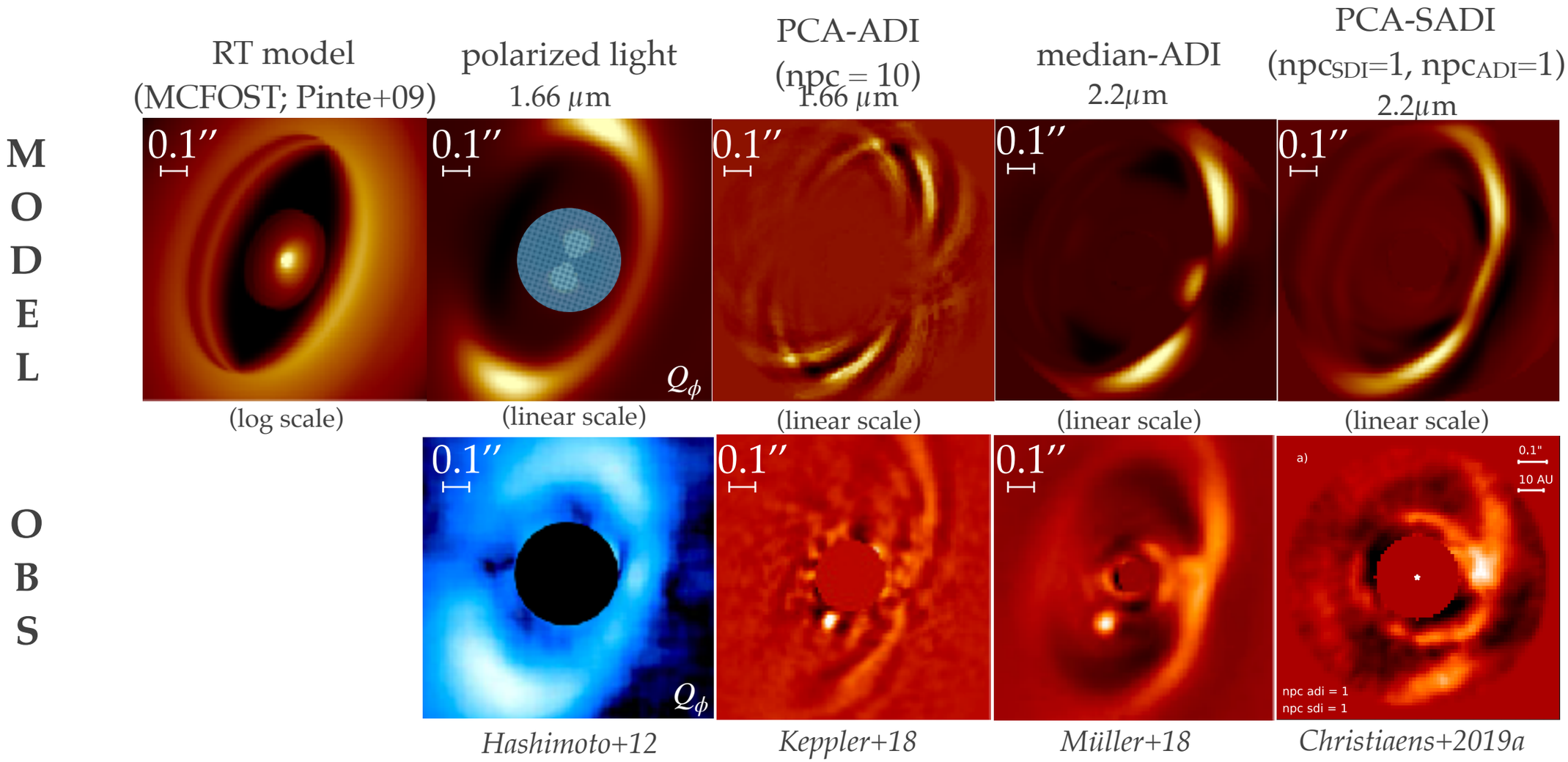


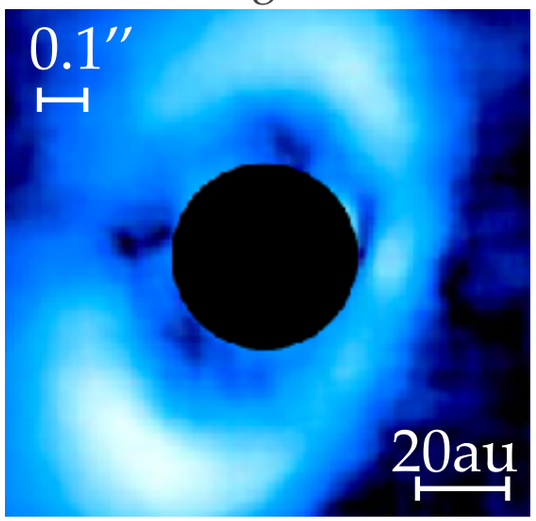
- Create total intensity disc model based on simultaneous polarized observations

Christiaens/Ginski+ in prep.

PDS 70: the only robust case?

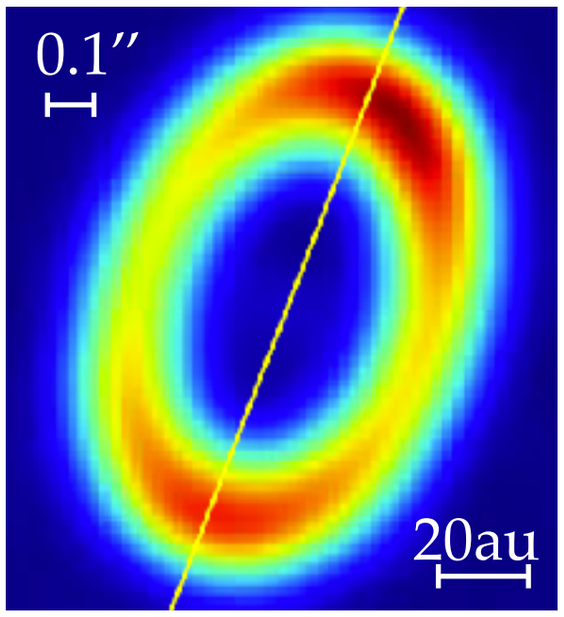
Disk

Polarized light - 1.66 μm



Hashimoto+2012

Continuum - 0.88 mm



Long+2018

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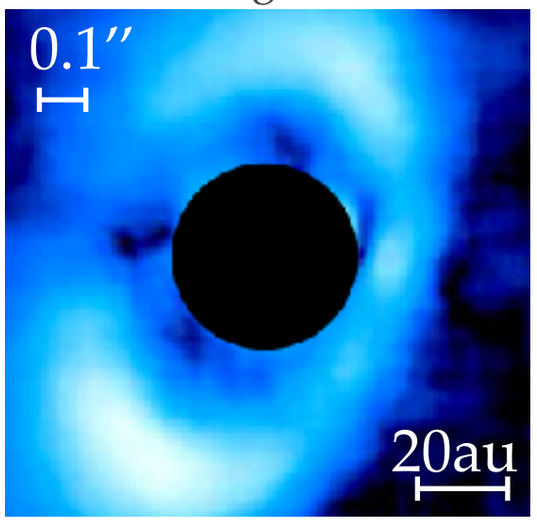

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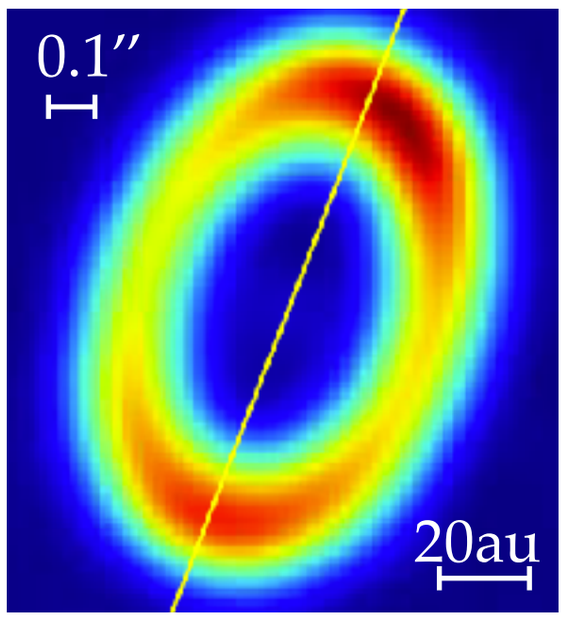
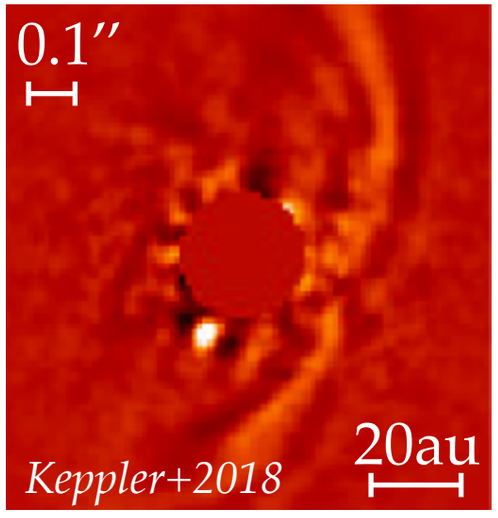


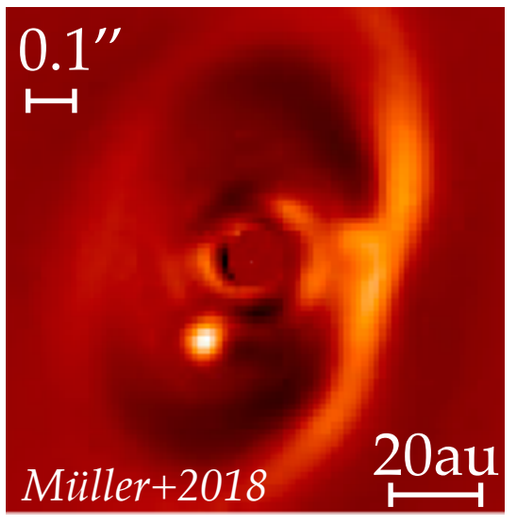
Long+2018

Protoplanet(s)

PCA-ADI - 2.2 μm



m-ADI - 2.2 μm



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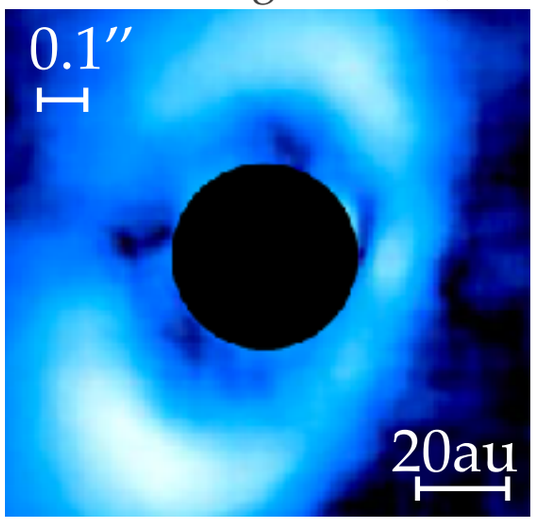

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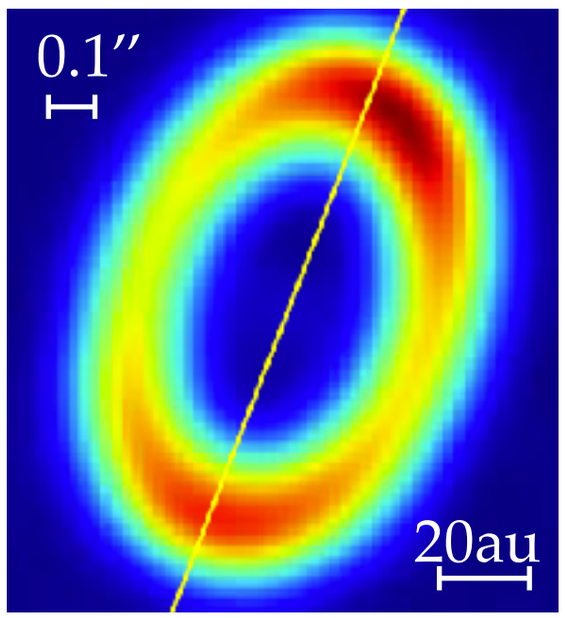

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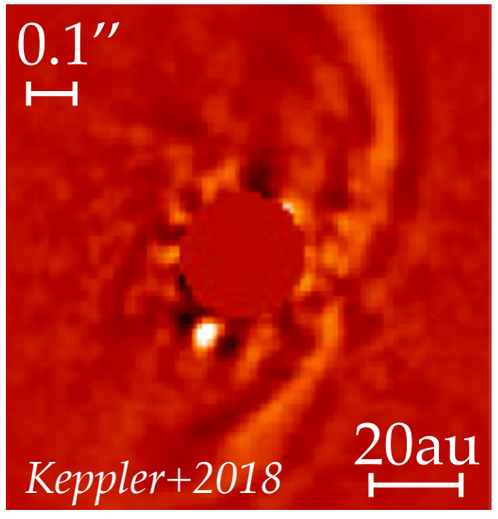

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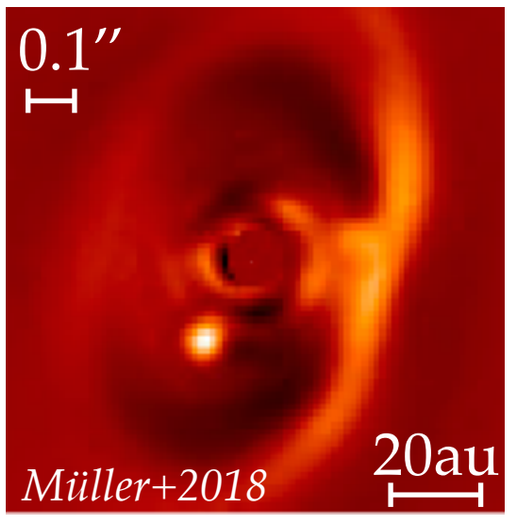
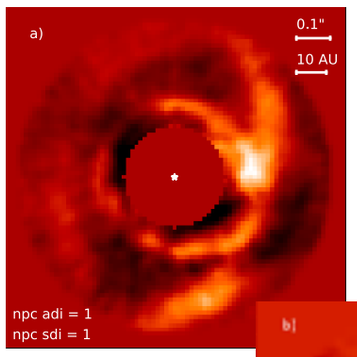
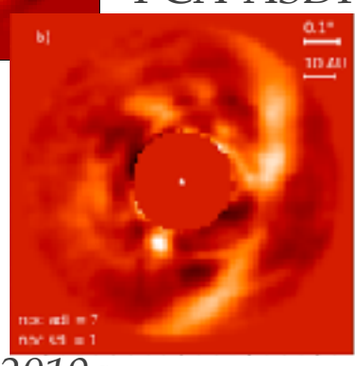


PCA-SADI



PCA-ASDI



Christiaens+2019a

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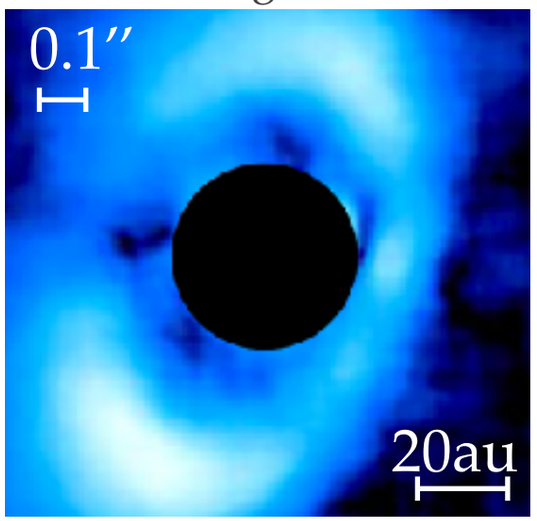

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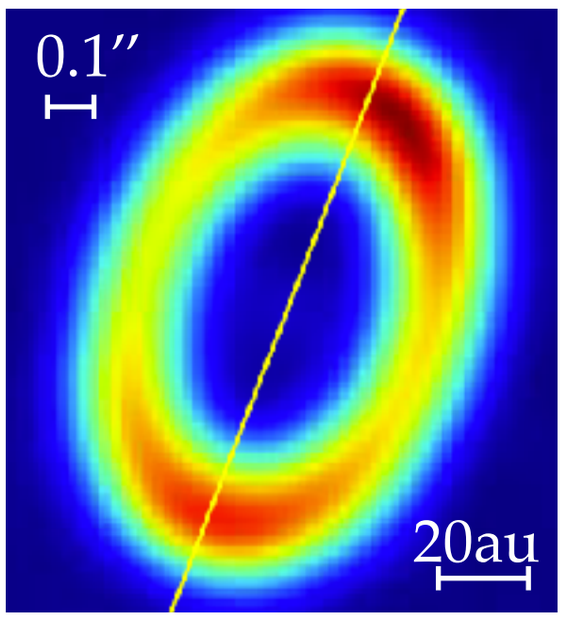

Long+2018

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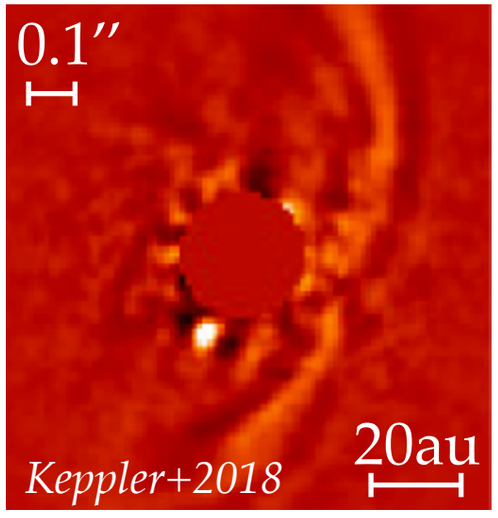
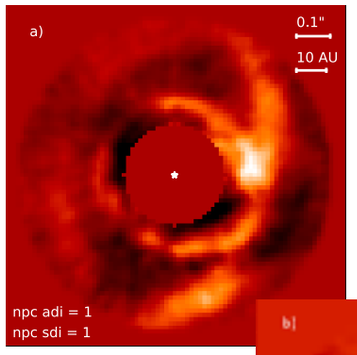
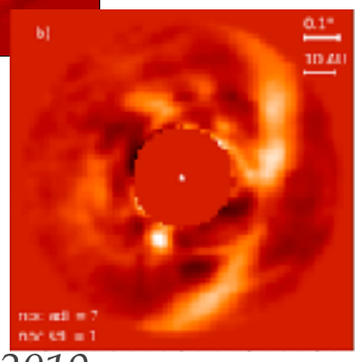


PCA-SADI



PCA-ASDI



Christiaens+2019a

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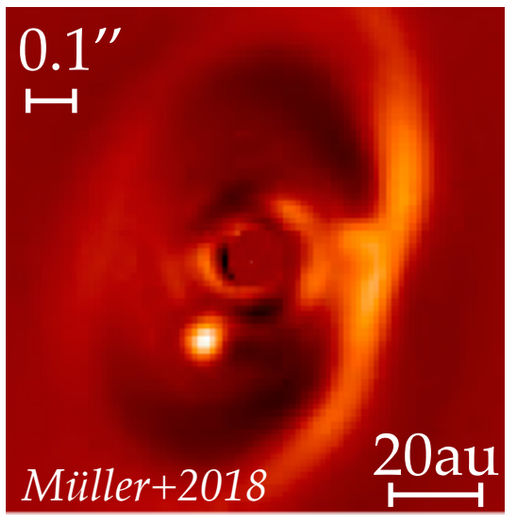

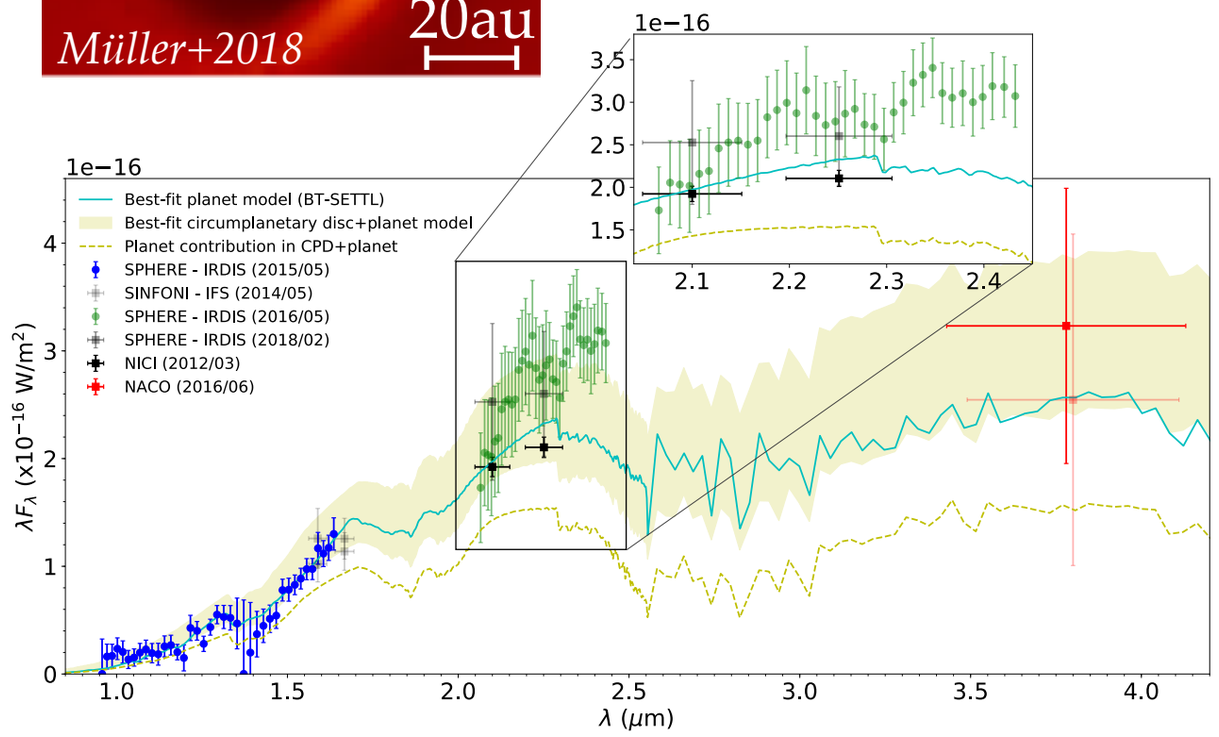

=> ~10 M_{Jup} with CPD?

Christiaens+2019b

PDS 70: the only robust case?

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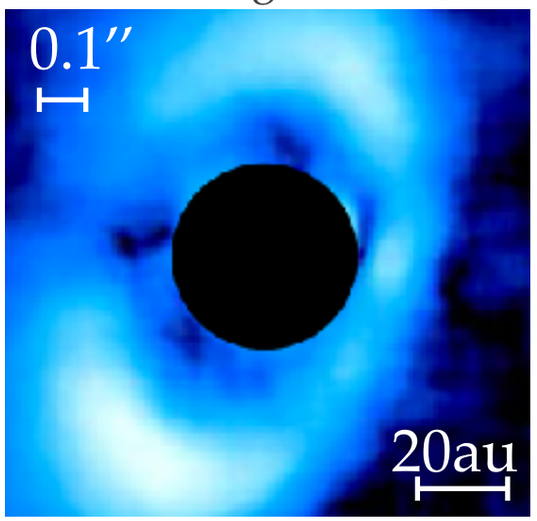

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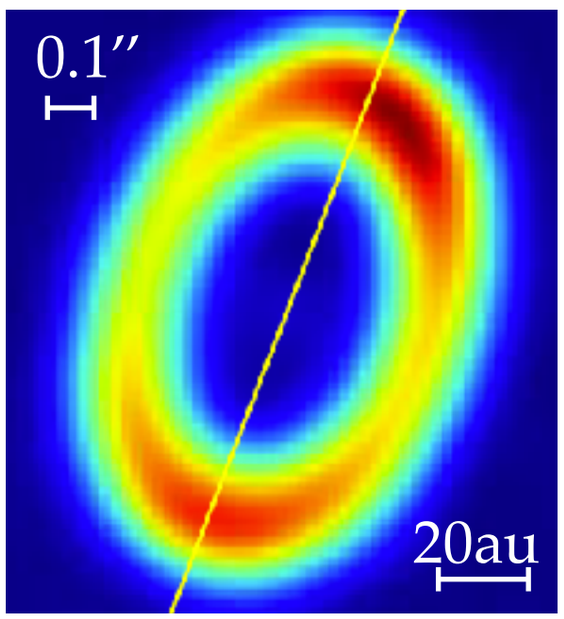

Long+2018

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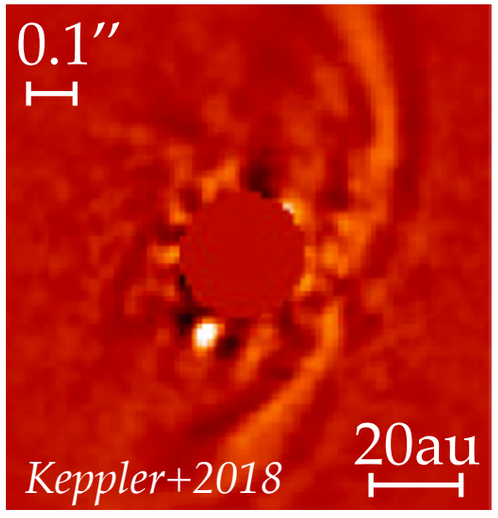
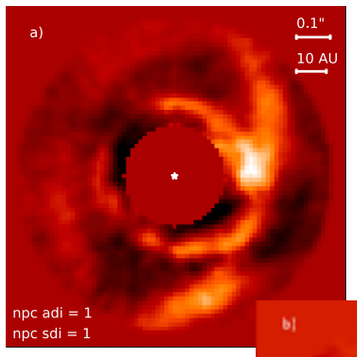
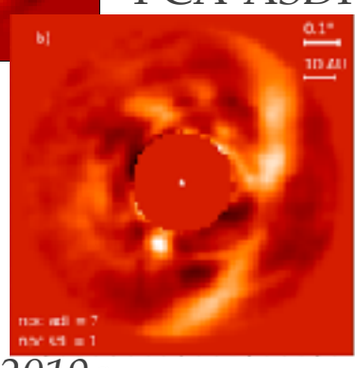


PCA-SADI



PCA-ASDI



Christiaens+2019a

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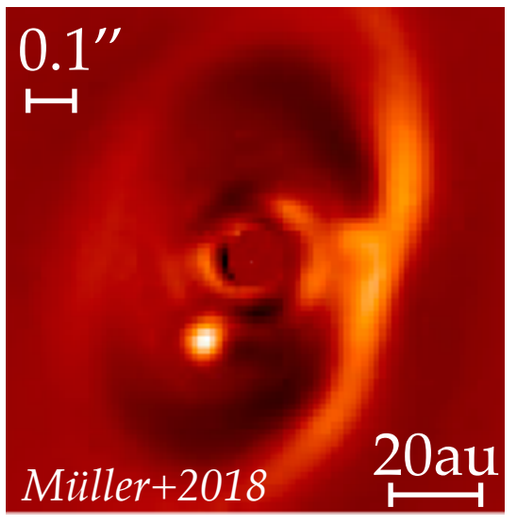
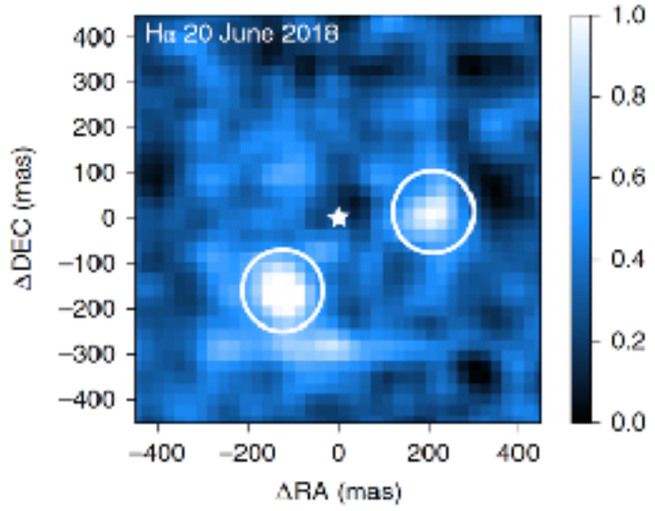
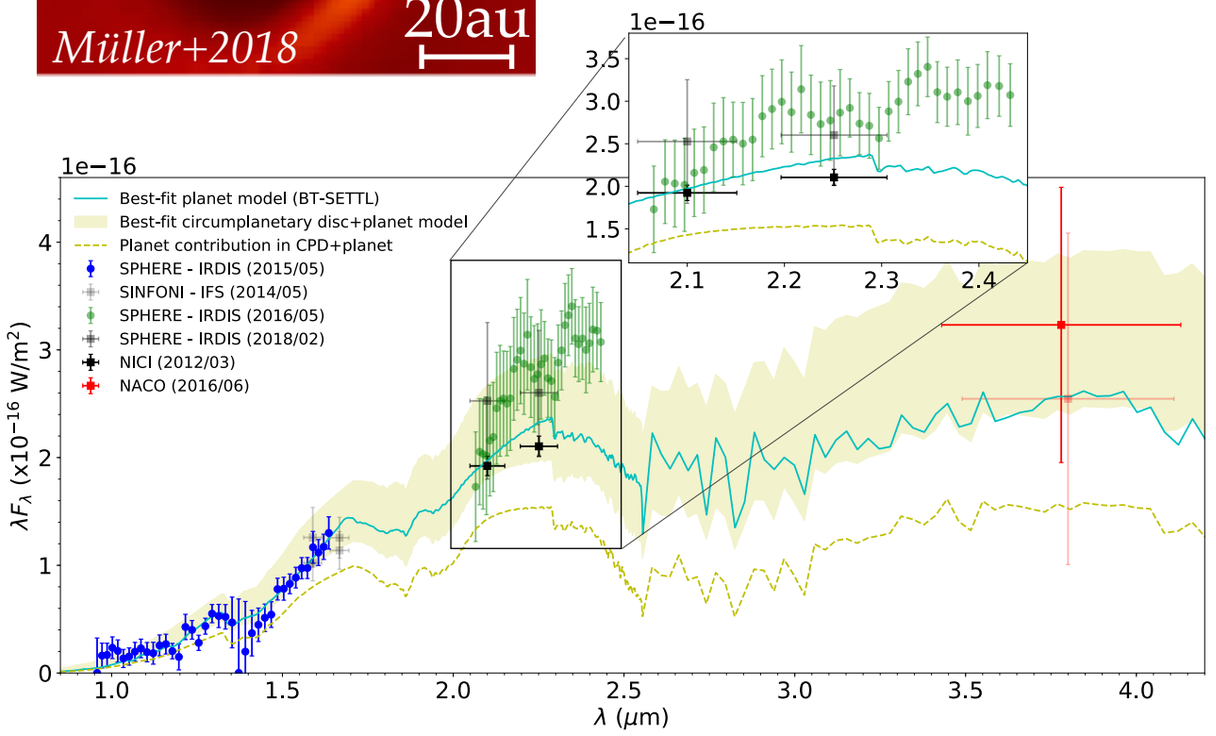


Haffert+2019





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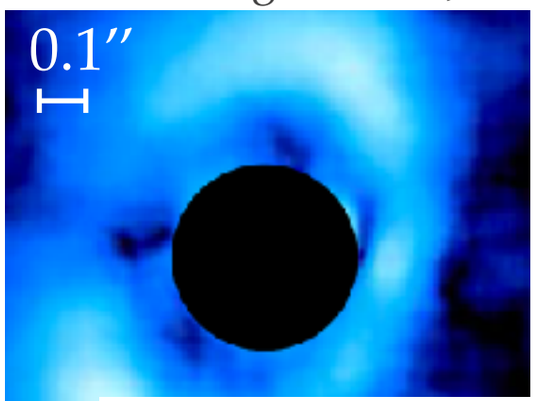

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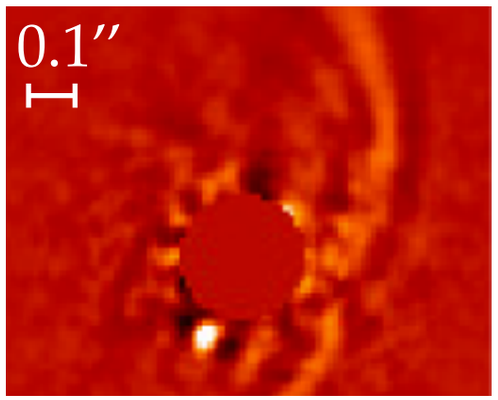

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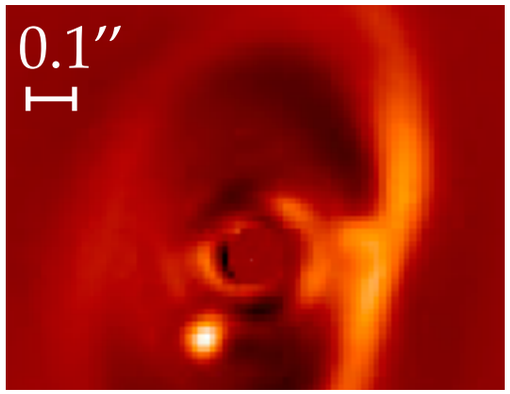
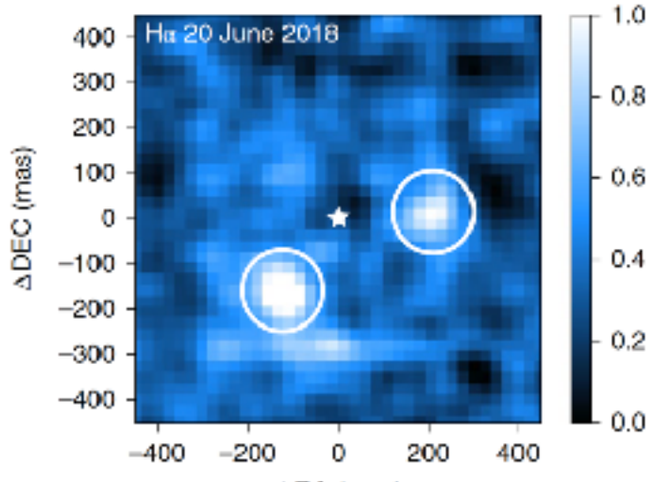
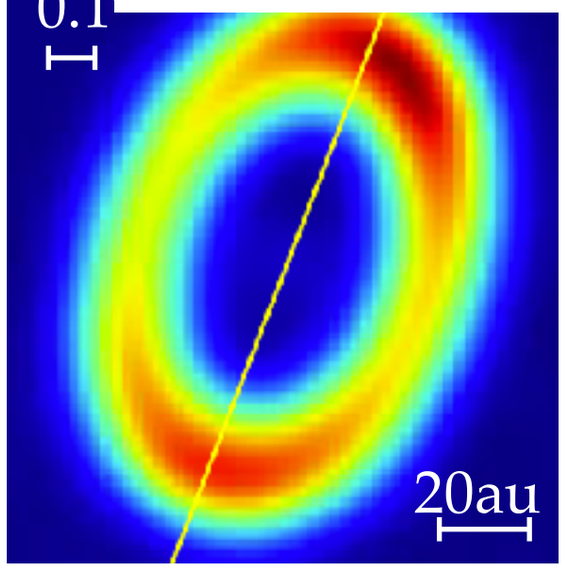


Haffert+2019



Co

TO BE CONTINUED…



Long+2018

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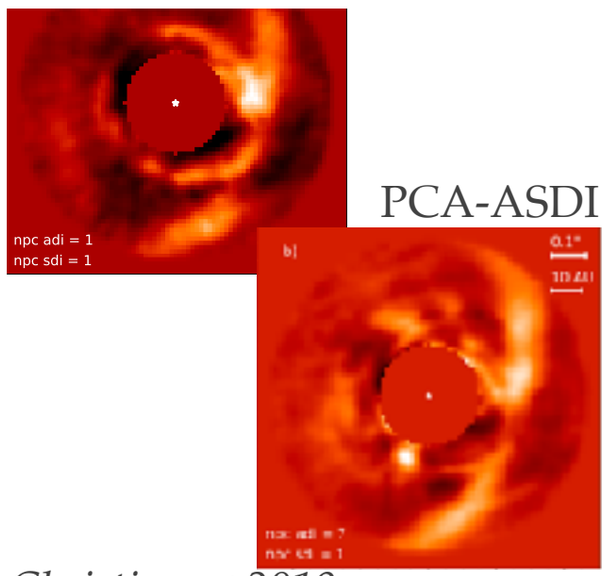
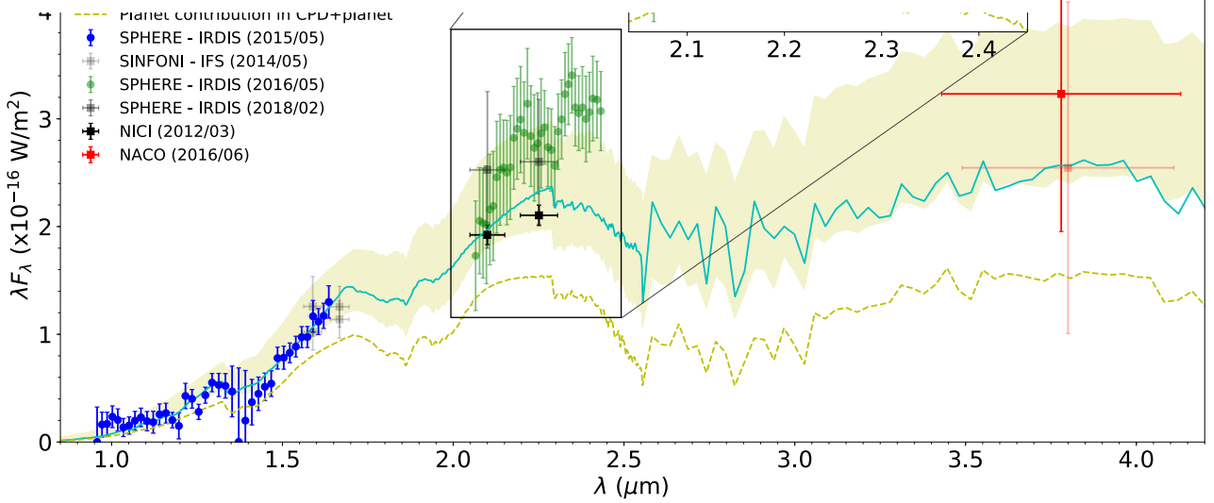


Christiaens+2019a



=> ~10 M_{Jup} with CPD?

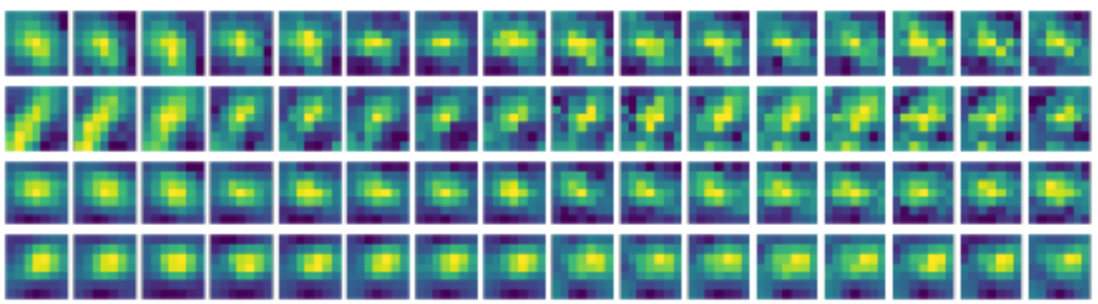
Christiaens+2019b

Machine learning

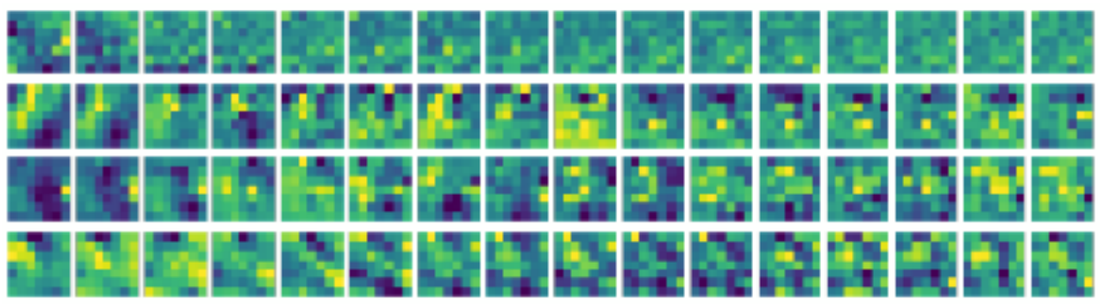
(Gomez Gonzalez+18, Hou Yip+19)

- Machine trained with post-processed patches of images:

Positive samples (companions)



Negative samples (speckle+bkg)



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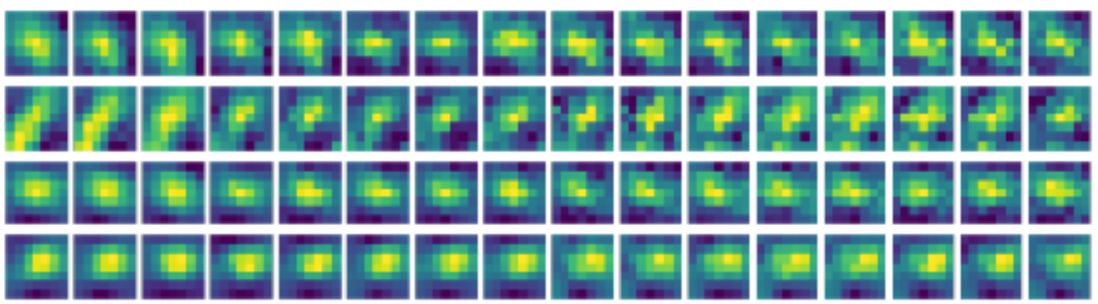

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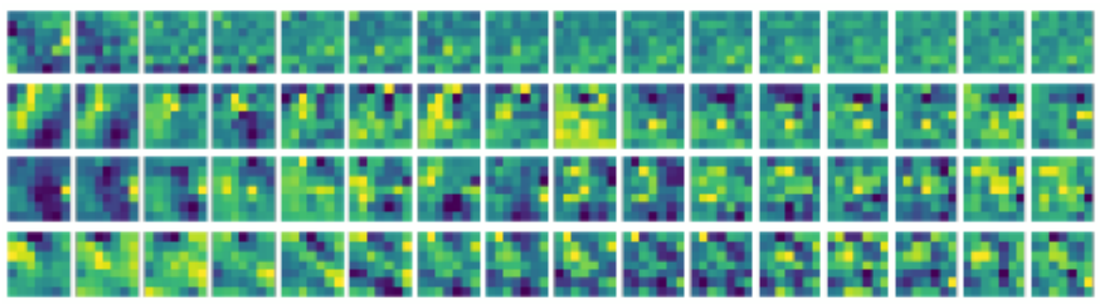
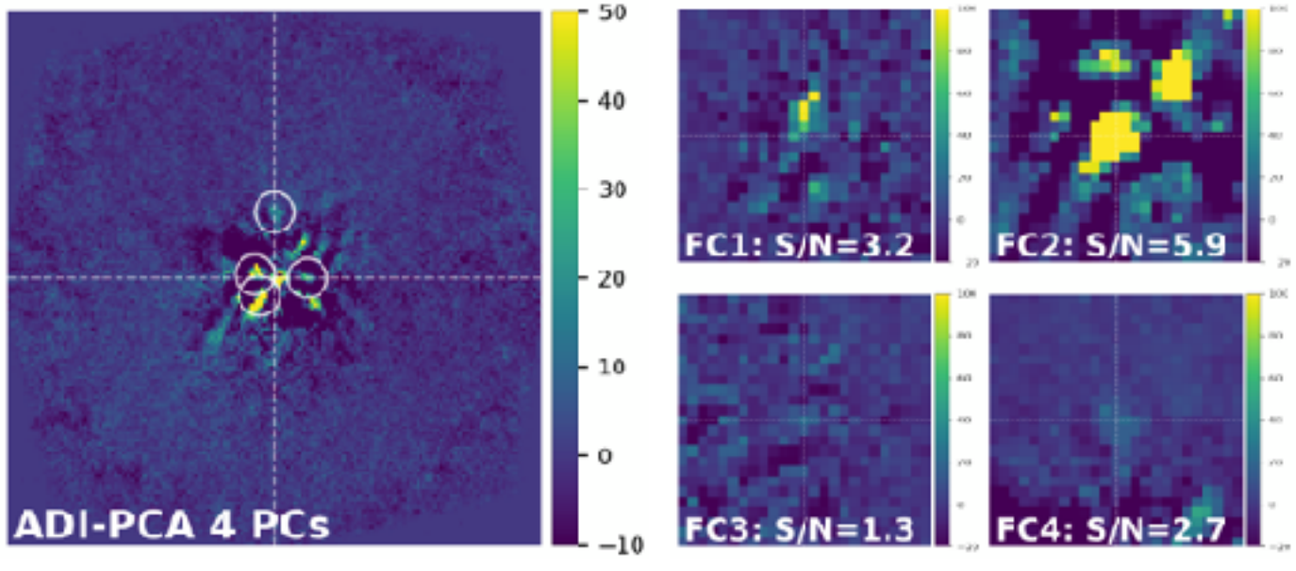
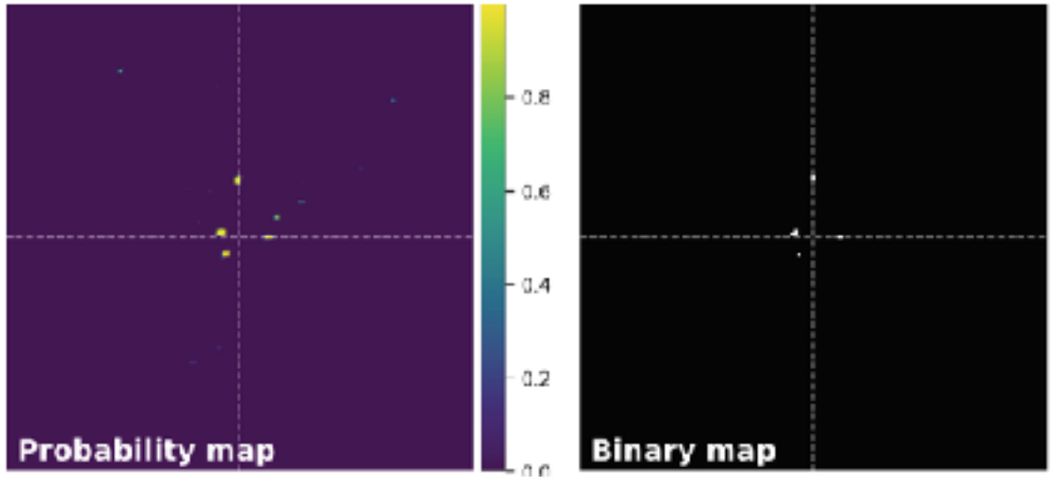


- Comparison to classical post-processing:

PCA-ADI



Machine learning

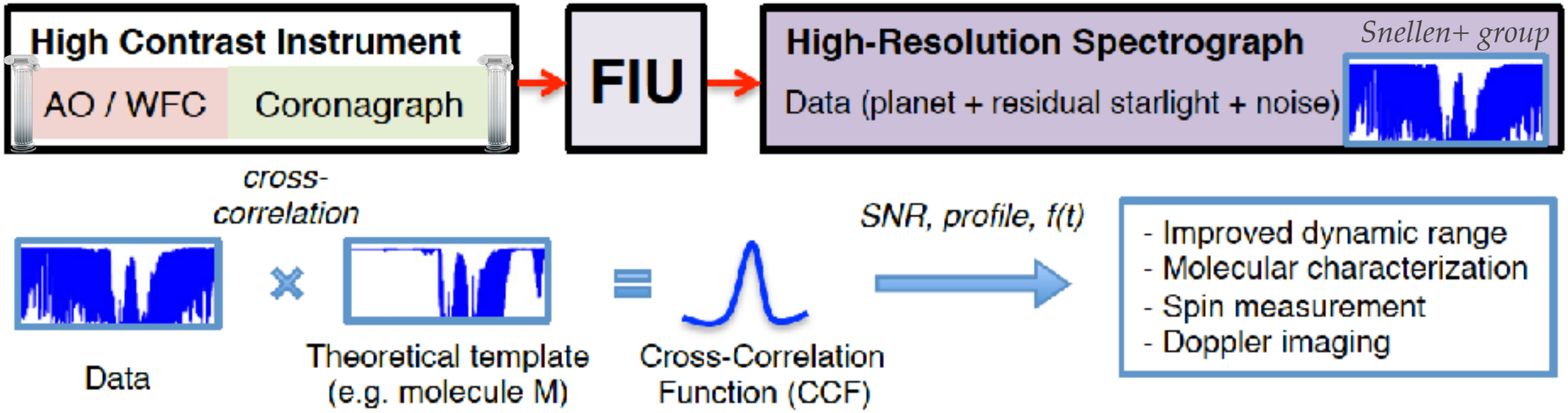


=> 1.0-2.5 mag contrast improvement!

High-dispersion coronagraphy (HDC)

(Mawet+17, Wang+17)

- Principle



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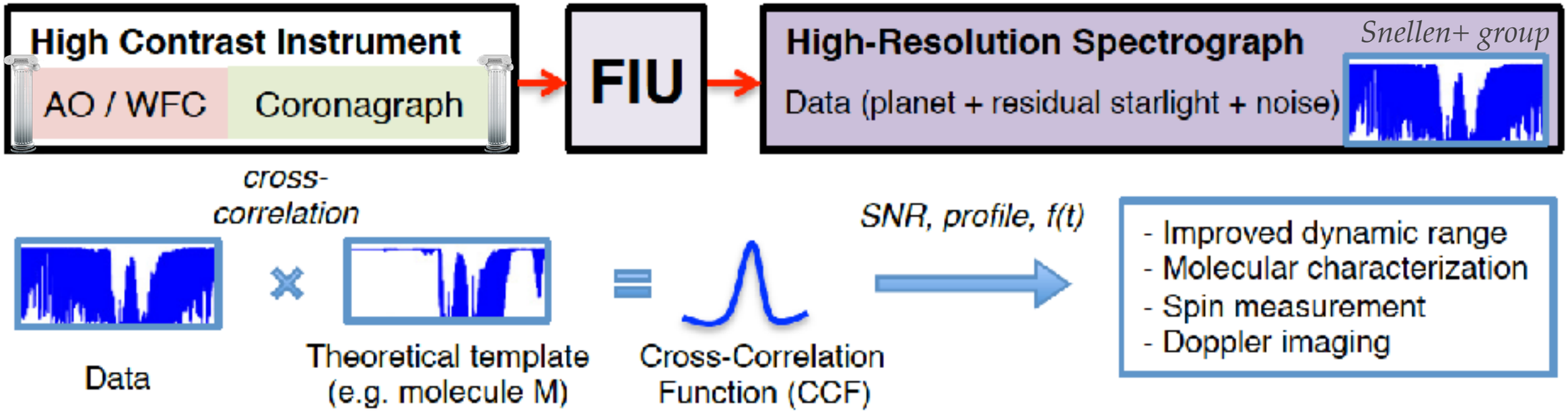
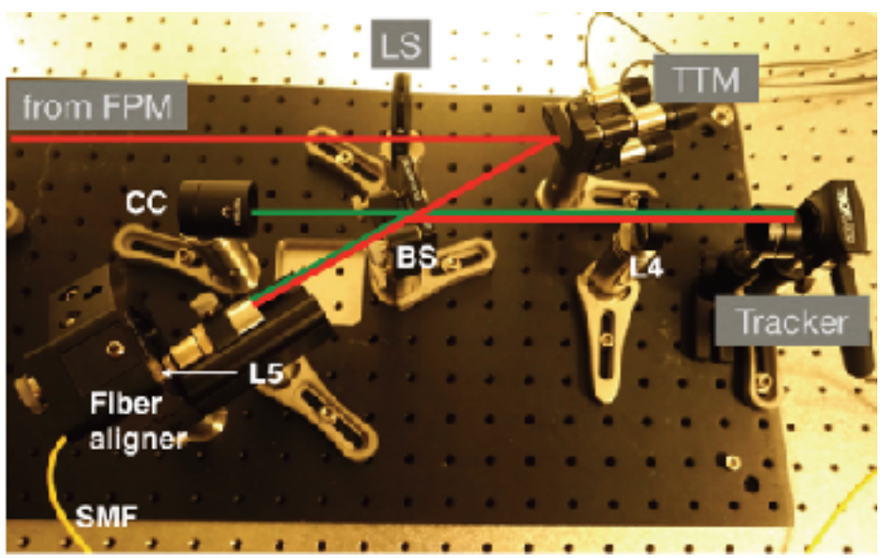


- Lab demo



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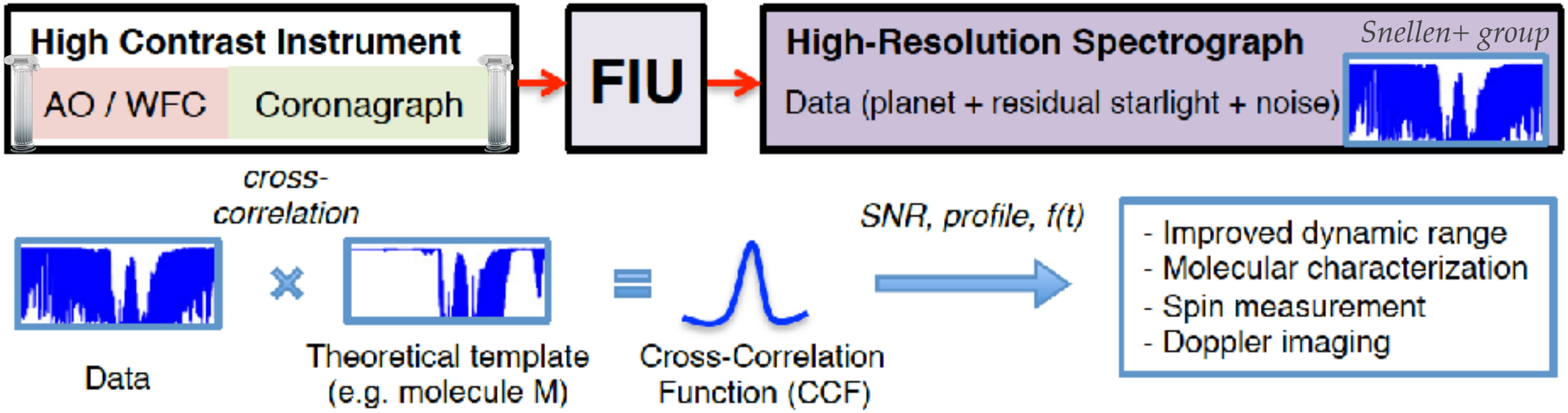

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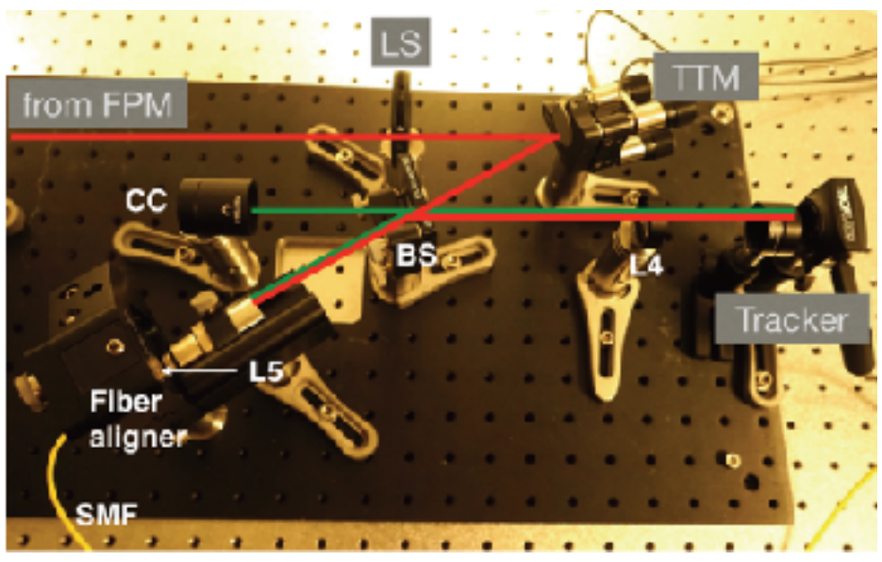
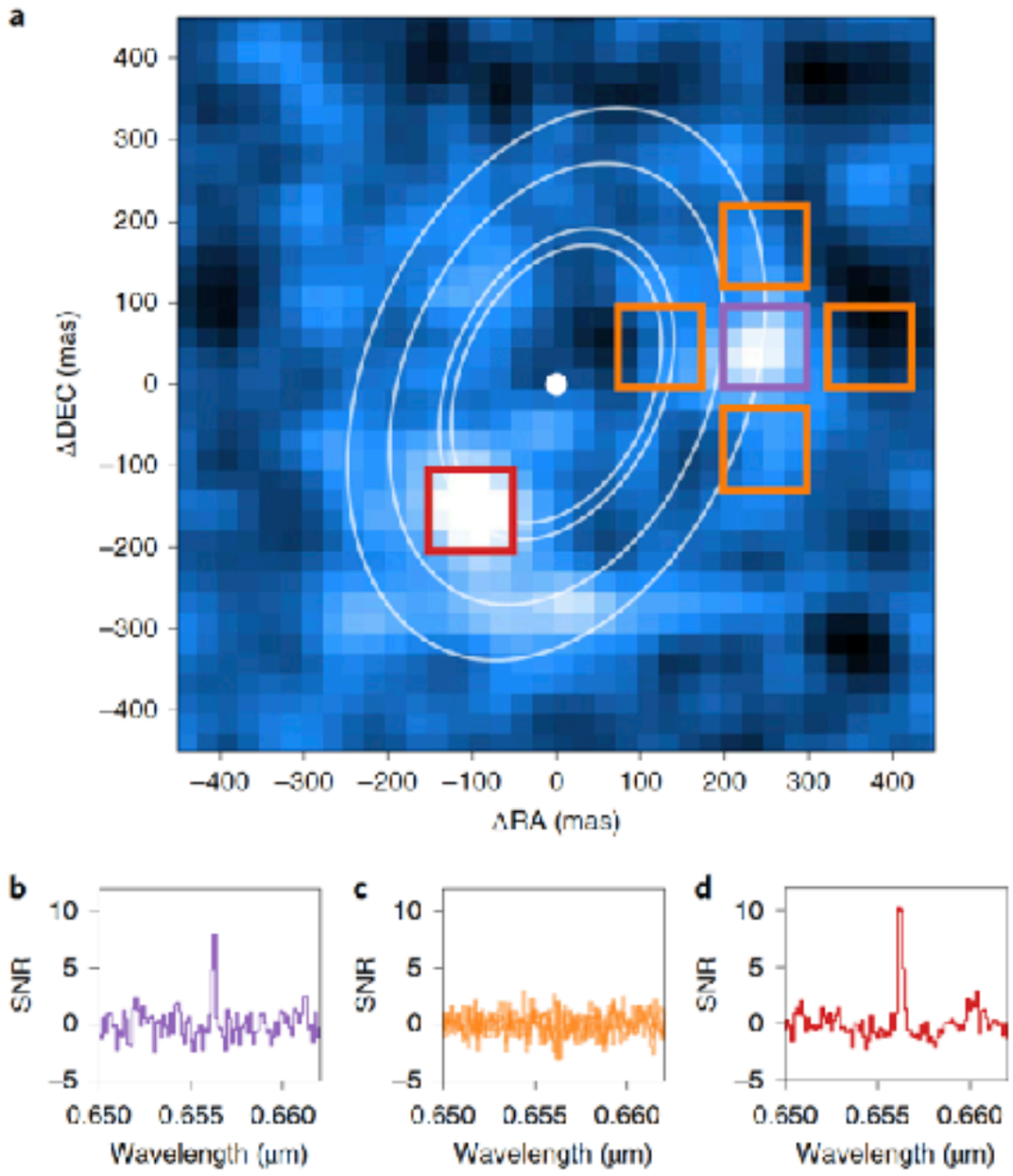


- Instruments in prep.:
  - Keck/KPIC (Mawet+)
  - VLT/HiRise = SPHERE+CRIRES (Vigan+)
  - ELT?

HRSDI

High-resolution Spectral Differential Imaging *(Haffert+19)*

- Concept:
  1) subtract a scaled, continuum-normalised spectrum of the star at each spaxel
  2) look for residual sharp spectral features



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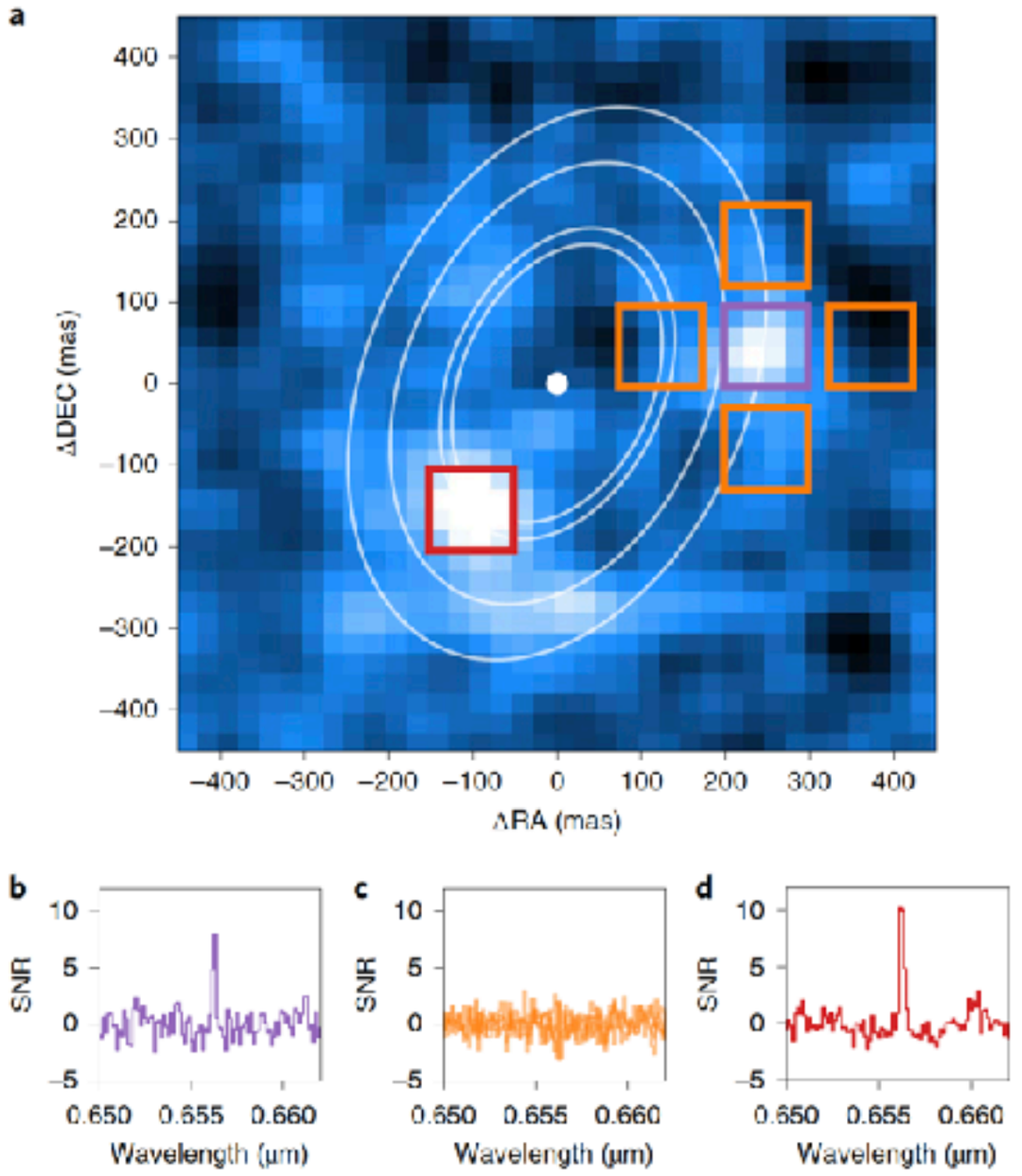
- E.g. Hα line
  - Velocity offset
  - Line width
  - Line shape

} Rules out other origins than true companions

=> Estimate of mass accretion rate



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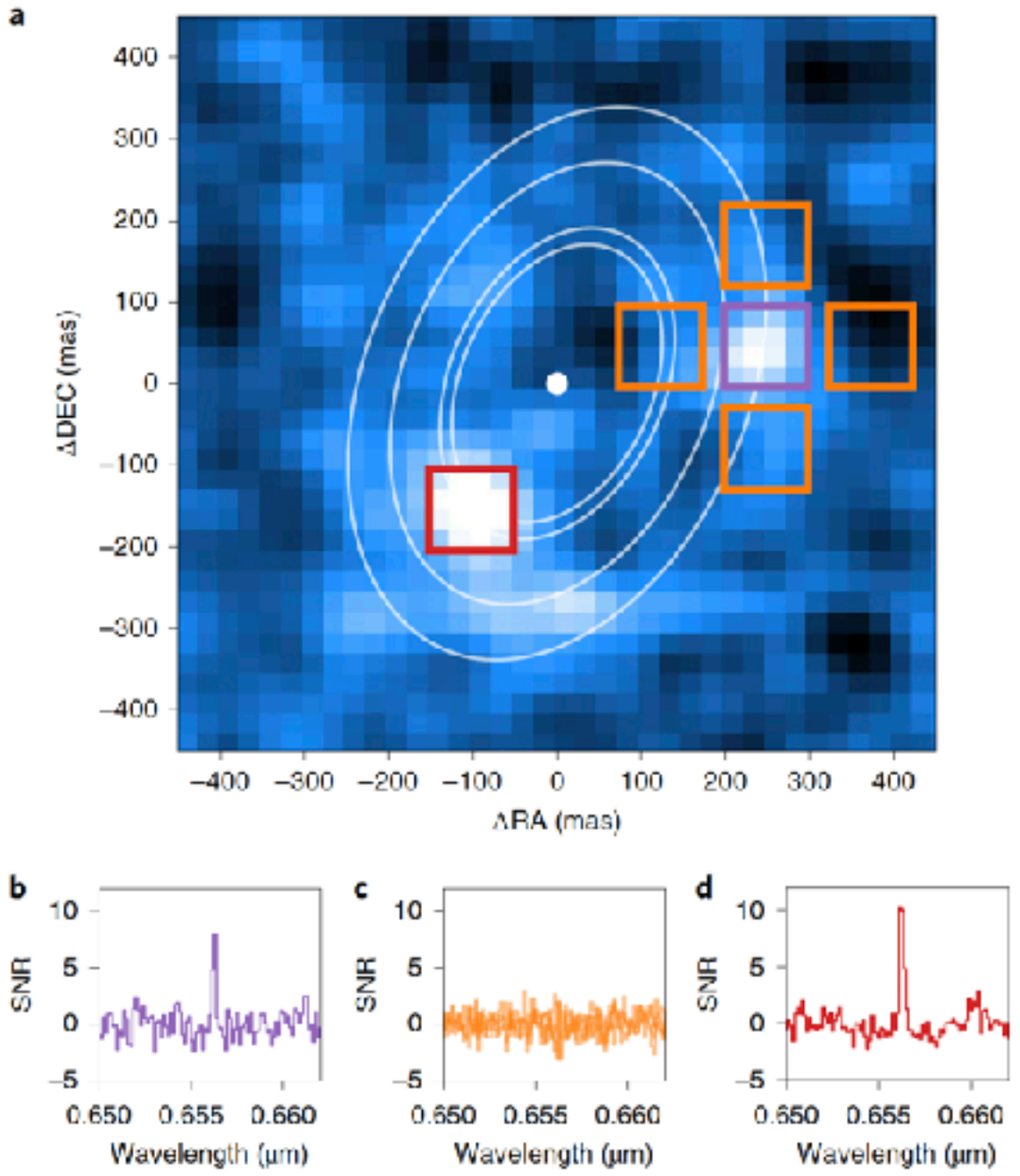
  } Rules out other origins than true companions

  => Estimate of mass accretion rate

- Pros
  - No bias from the disk
  - Time-efficient (5min in Hα)



At the VLT

- NEAR (= VISIR 2.0)

- Upgrade: AO+coronagraph+new chopping
- Mid-IR instrument at the VLT (up to λ~10μm).
- Inner working angle: ~0.3" at 10μm
  => Potential for embedded protoplanets in large discs
- Science Verification starts in Sept 2019

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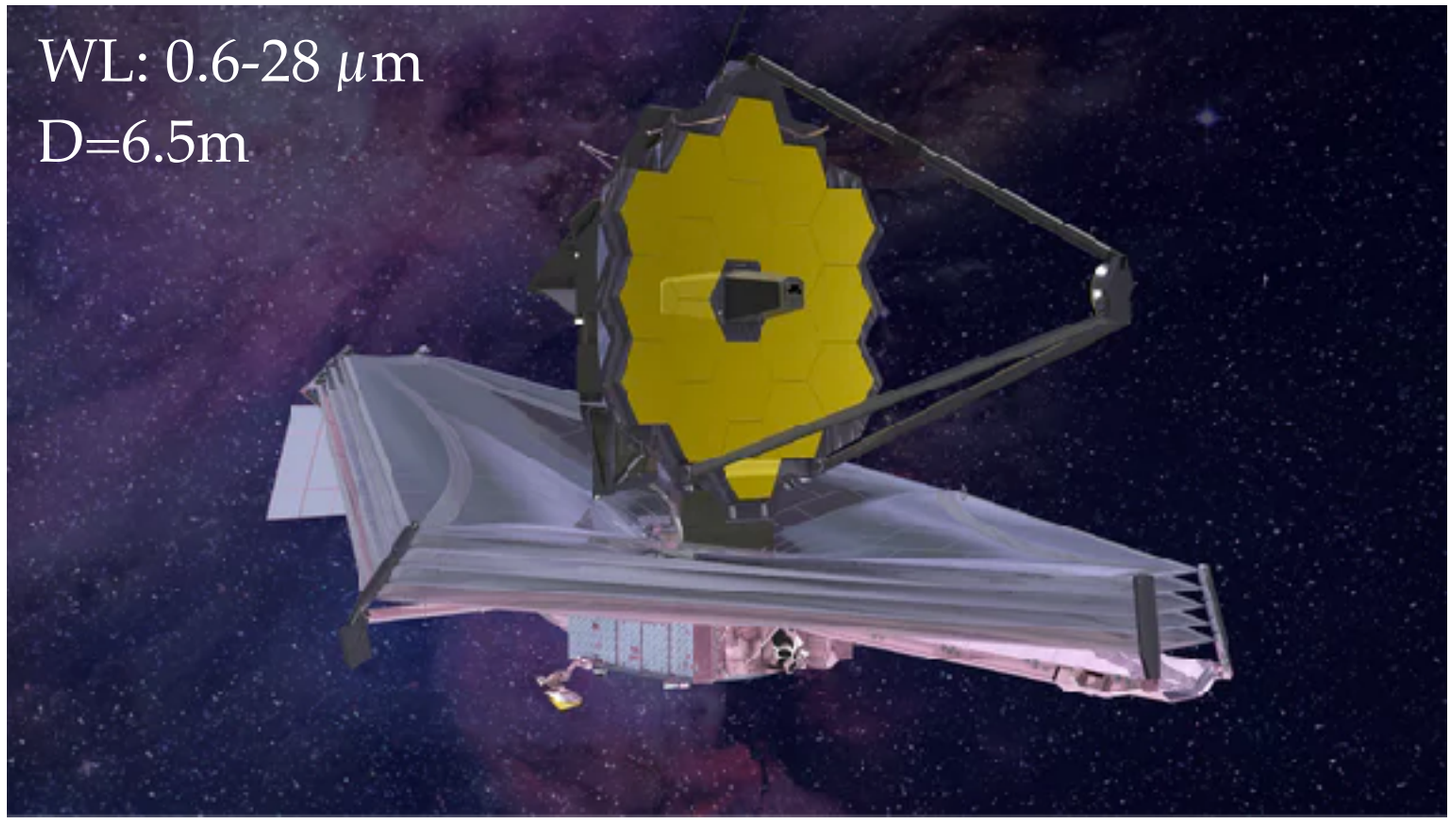
ERIS (= NACO 2.0)

- Upgrade: new detector, improved AO
- NIR to thermal IR (λ~1-5μm)
- vortex coronagraph
- Inner working angle: ~0.1″ at 3.8μm
- Online in 2020

JWST

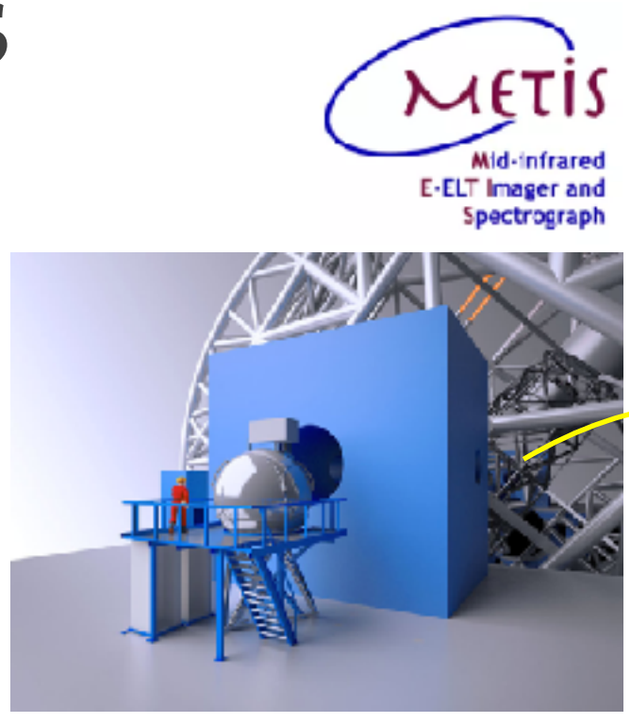


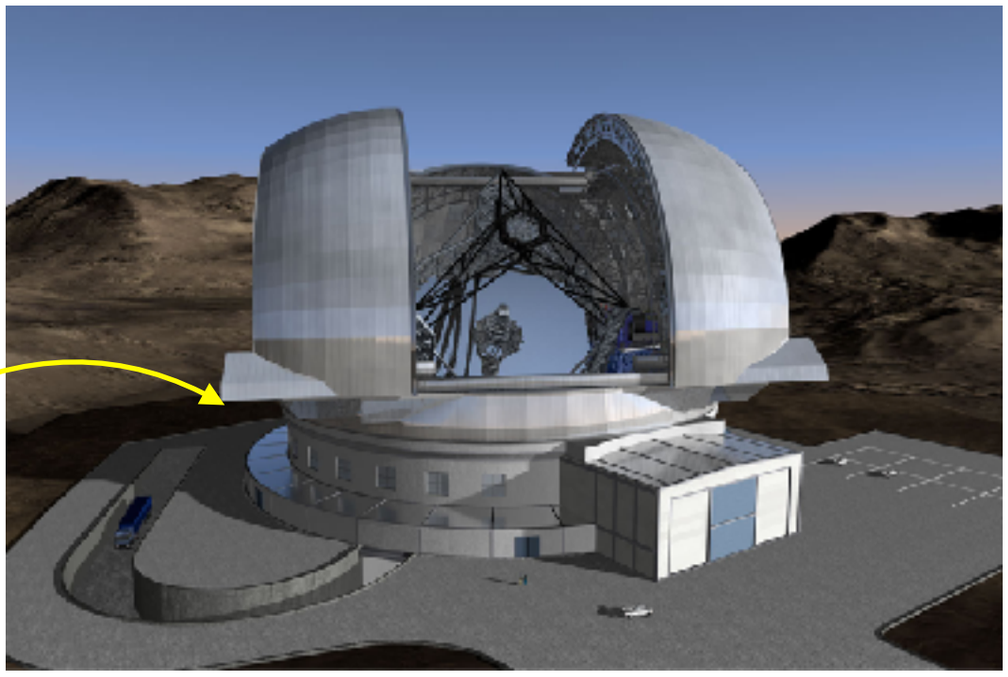
- NIRSPEC: 0.6–5 μm
- MIRI: 5–28 μm
- Characterization of protoplanets and young Neptunes far from their star (Schlieder+17)

At the ELT

At the ELT

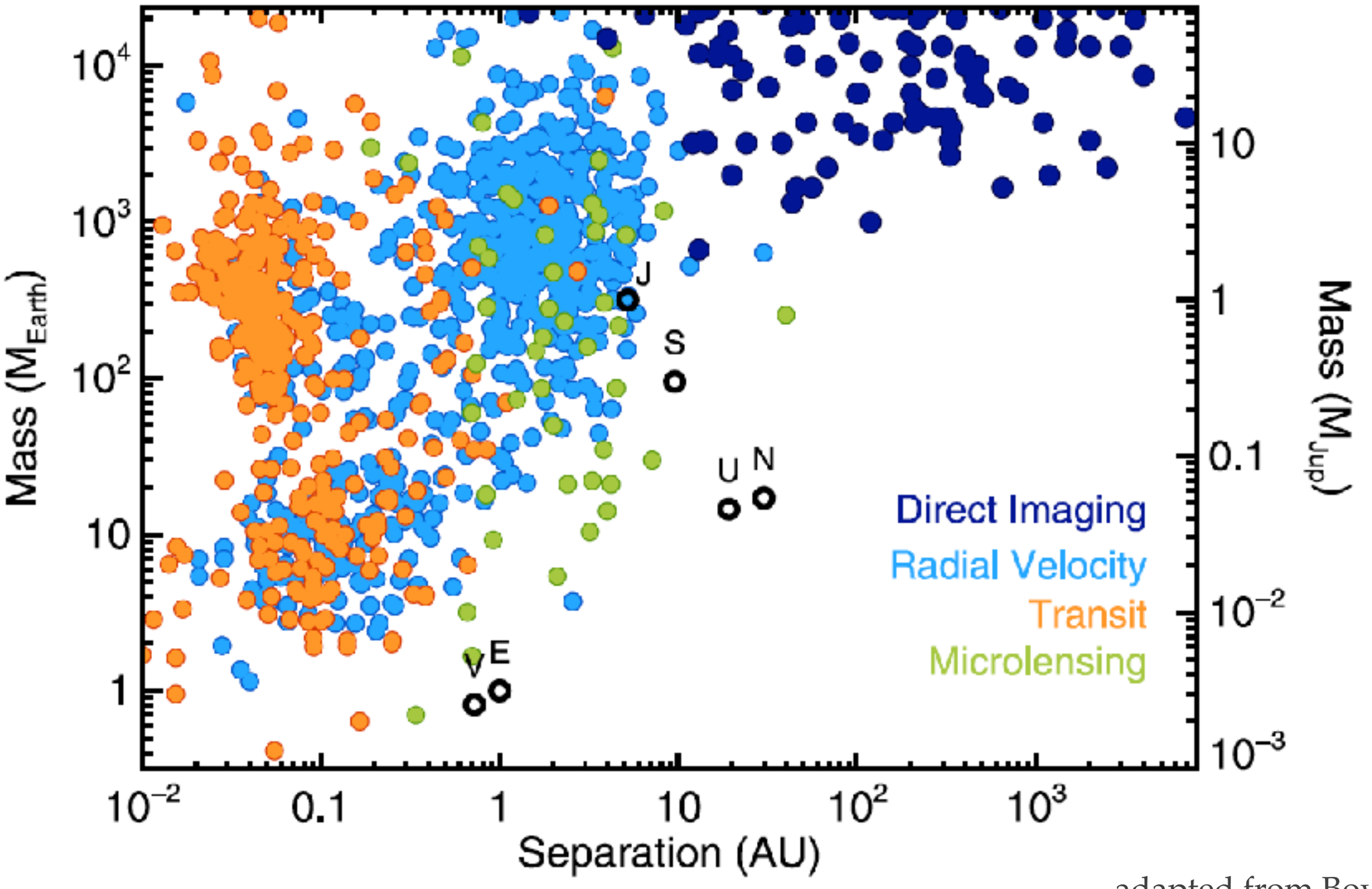
- METIS





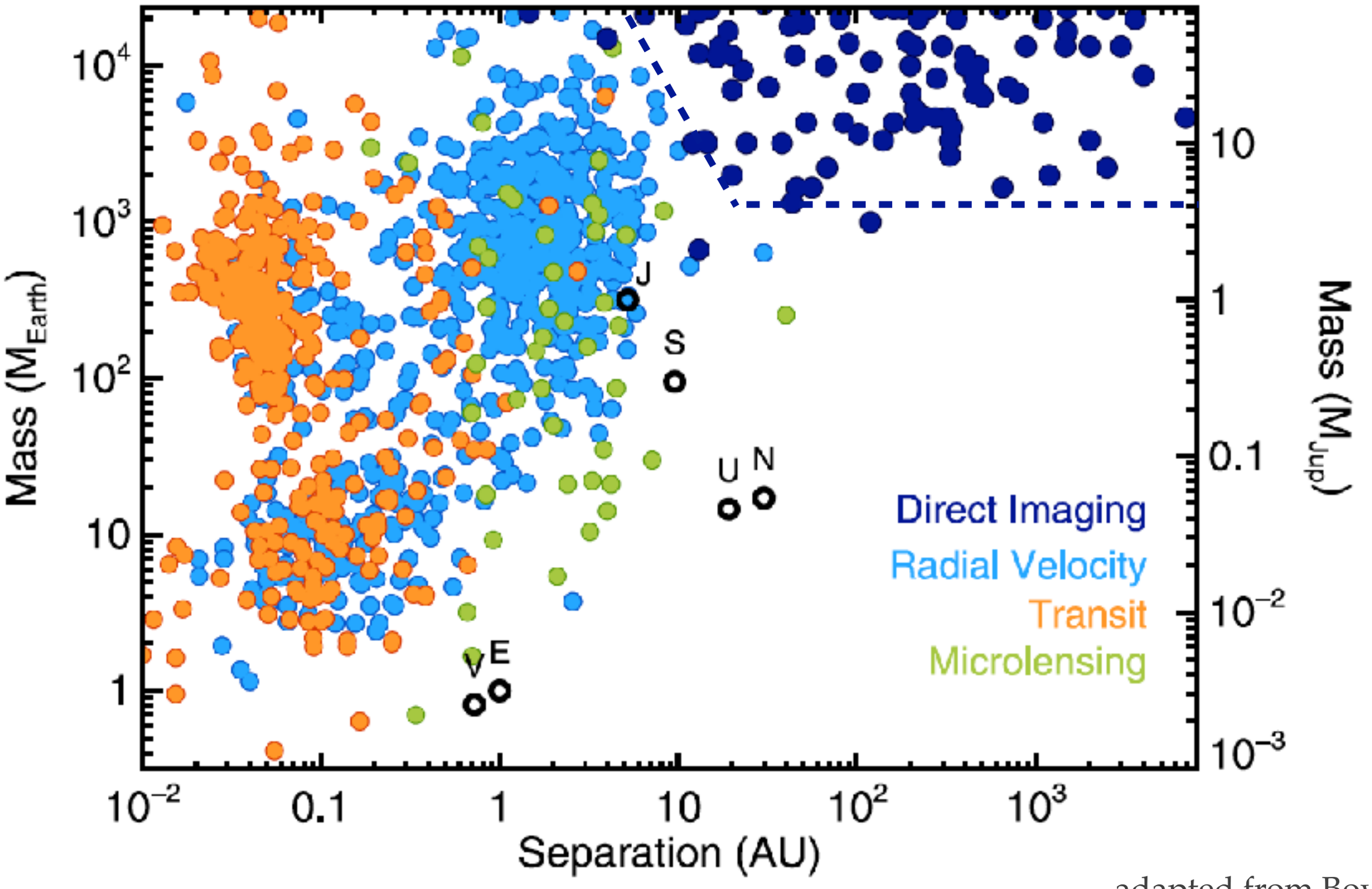
- Spectrograph and imager at λ~3–20μm with **D = 39m**
- Imaging and characterization of:
  - protoplanets (140 pc)
  - nearby (<10pc) exo-Earths (Brandl+14; Quanz+15ab)
- HDC+ELT => Biosignatures on nearby exo-Earths (Snellen+15)

Mass vs radial separation diagram



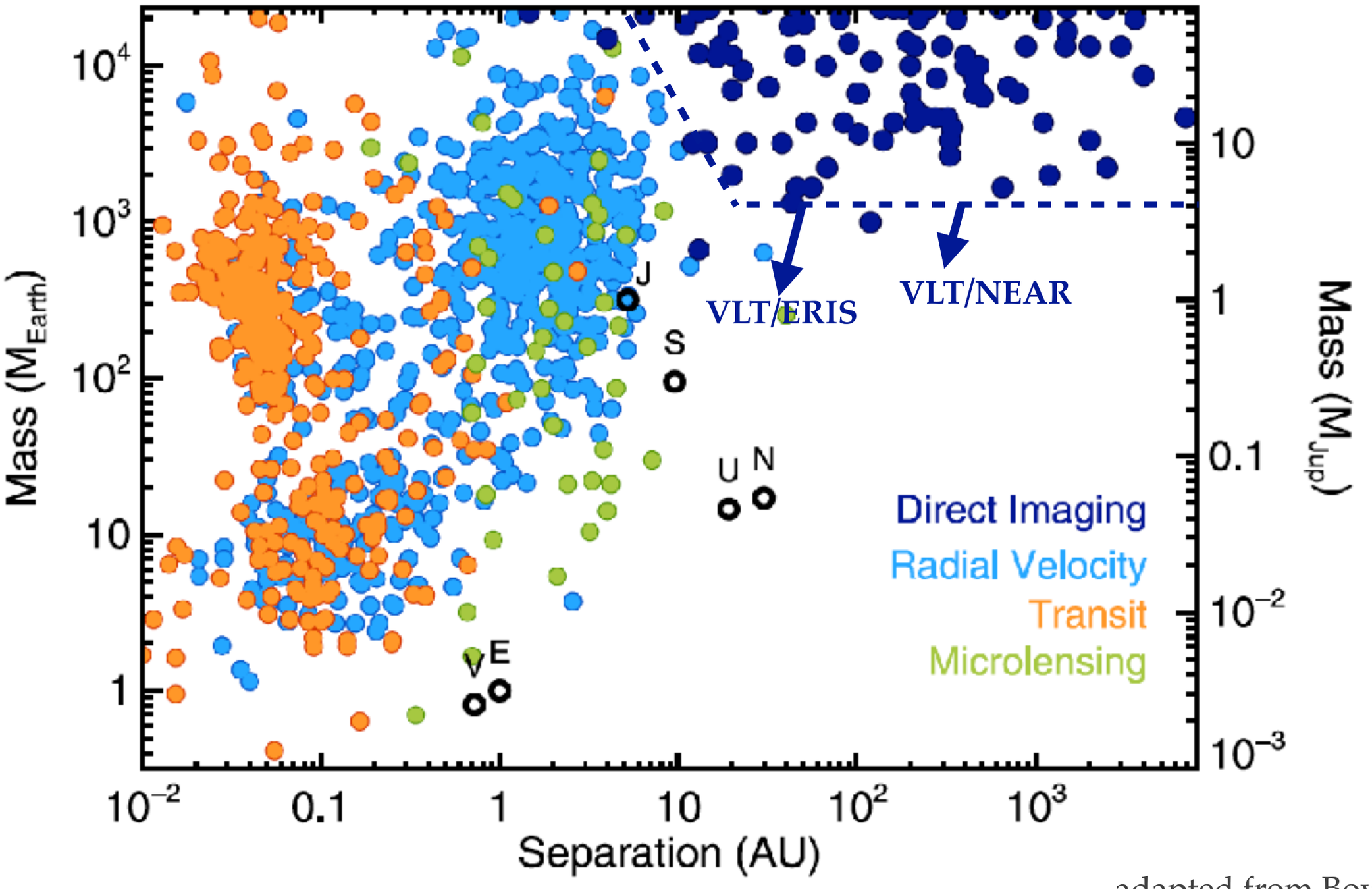
adapted from Bowler 2016

Mass vs radial separation diagram



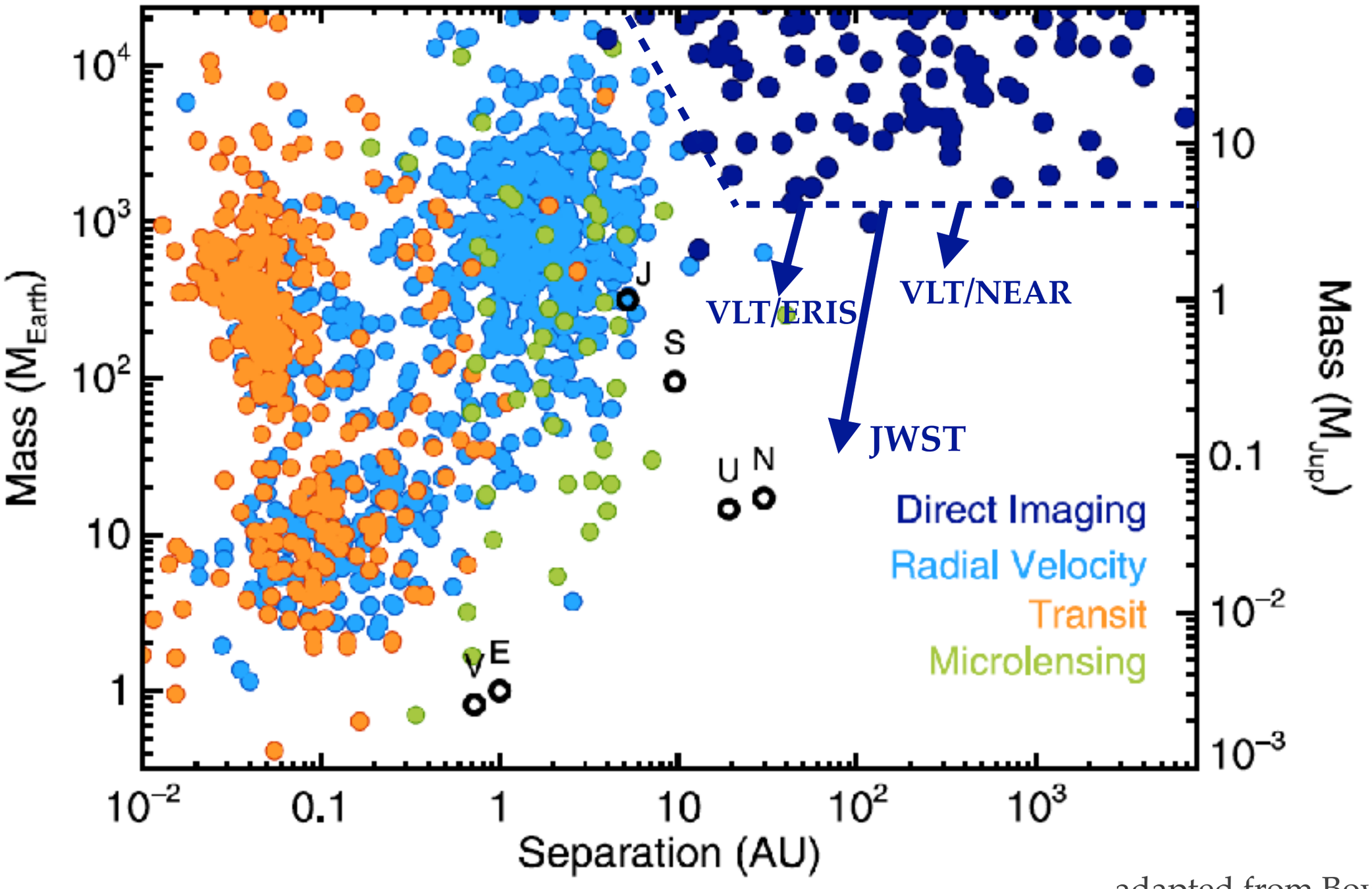
adapted from Bowler 2016

Mass vs radial separation diagram



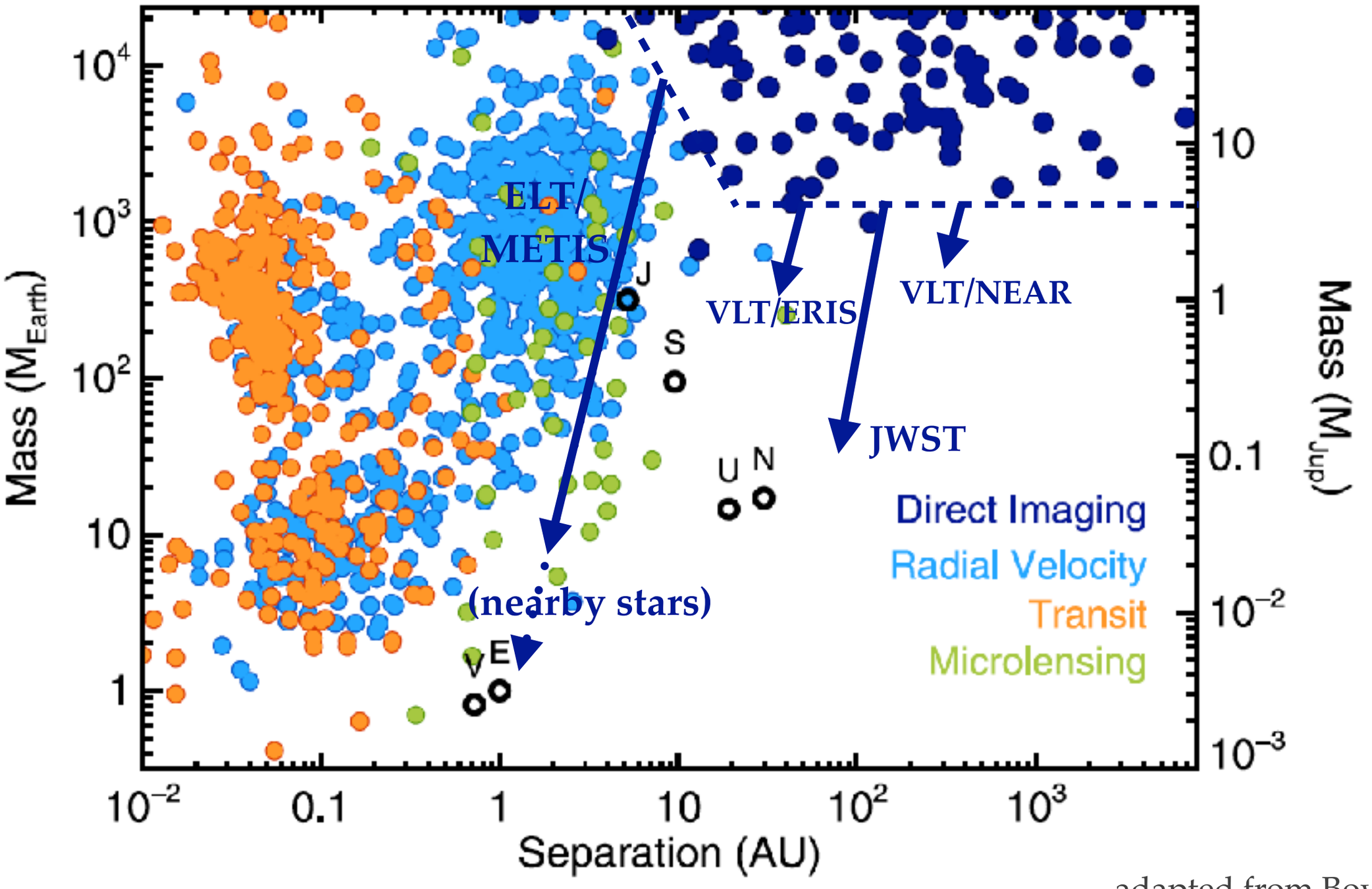
adapted from Bowler 2016

Mass vs radial separation diagram



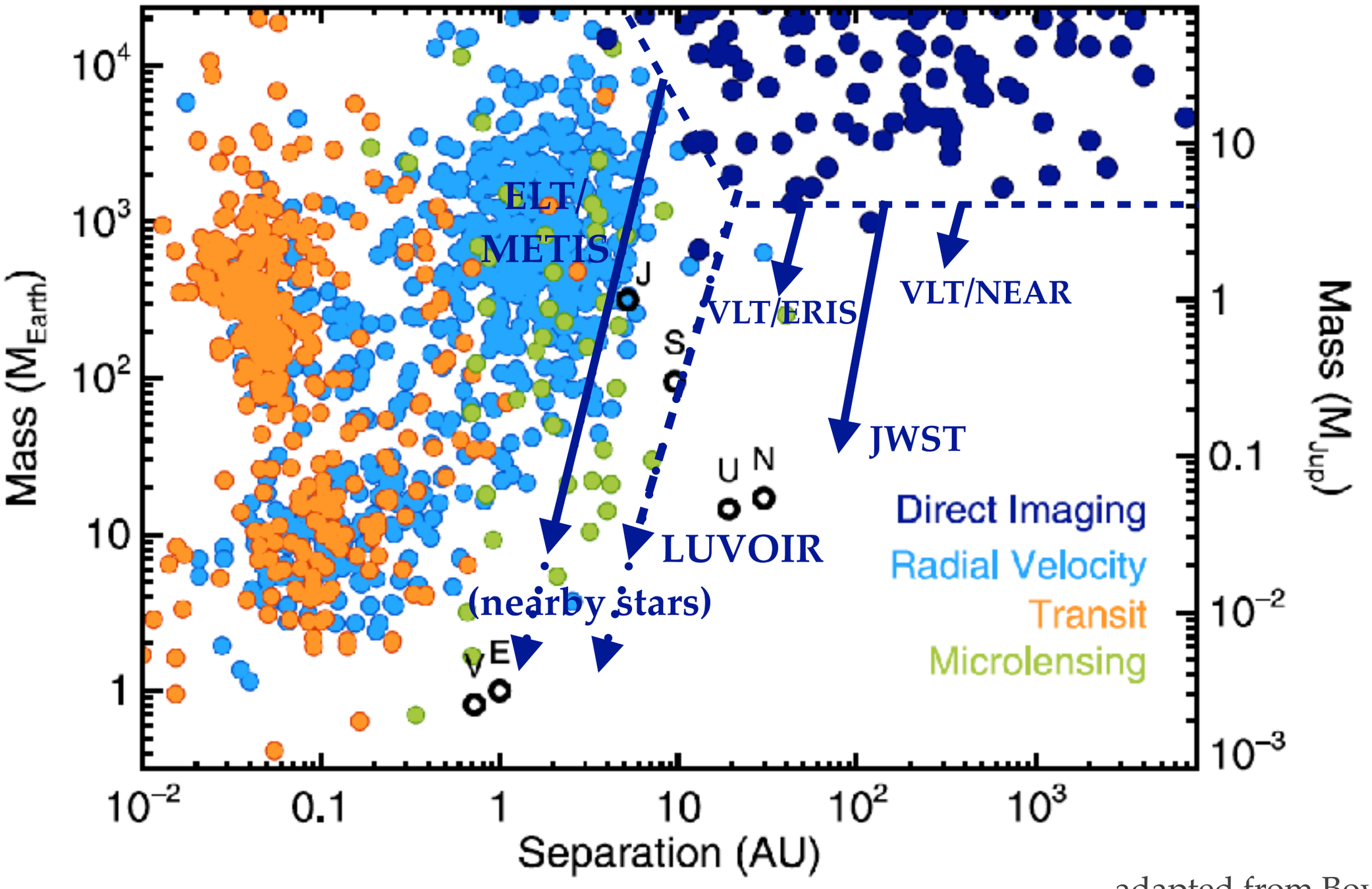
adapted from Bowler 2016

Mass vs radial separation diagram



adapted from Bowler 2016

Mass vs radial separation diagram



adapted from Bowler 2016

Take-away messages

- Direct imaging surveys at >10Myr:
  - Very few 5-13 MJ GPs on large (30–300 au) orbits (~1% occurrence)
  - CA unlikely to explain the few detections => gravo-turbulence?
  - GI very inefficient OR very quick inward migration

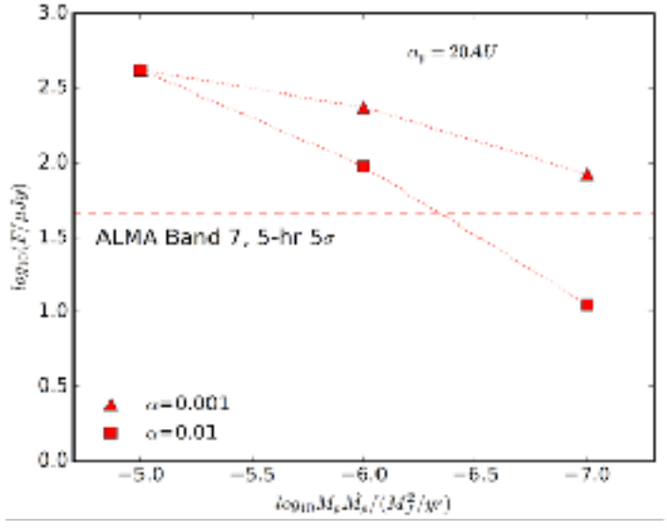
- At <10Myr?
  - A lot of false positives due to disc signals filtered into point sources
  - Most robust detection: PDS 70 b (and c)
  - Forward modelling required!

- HRSDI: new promising technique to detect accreting planets

- Upcoming IR instruments: high potential for planet formation

Food for disc-ussion

- Limitations of IR HCI to study protoplanets: strong emission from the disc
  => Are we bound to image planets that already carved large gaps?
- Need for longer IR wavelengths
  - Is the disc expected to be fainter (less bias)?
- Directly imaged adolescent planets = those creating the large DSHARP gaps?
  - Occurrence of large gaps at large separations?
- Synergy with ALMA
  - Potential for independent planet flux and mass estimates
  - BUT… direct detection easier in larger gaps <-> Kinematic detection requires gas
  - Constraints on CPD (e.g. α)?



(Zhu+18)