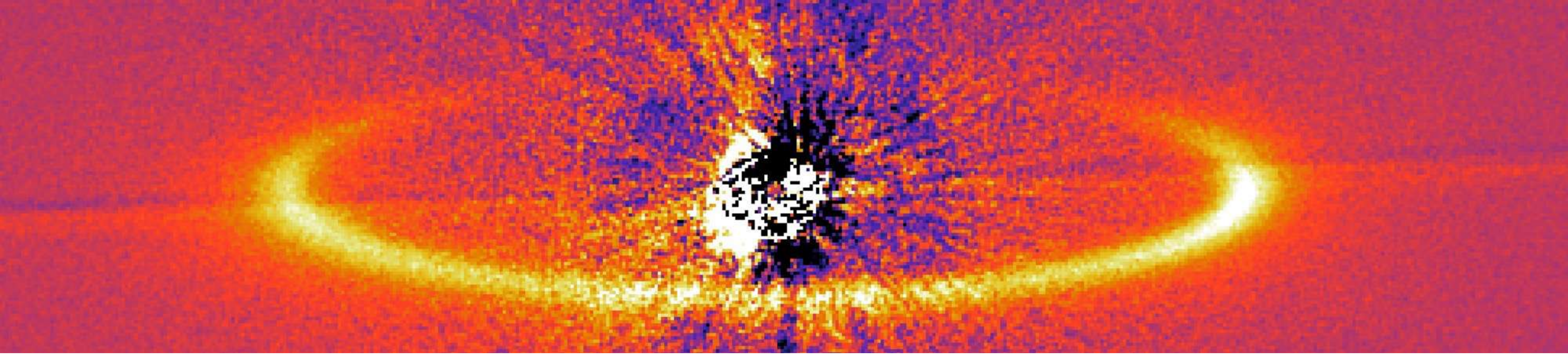


Imaging circumstellar disks

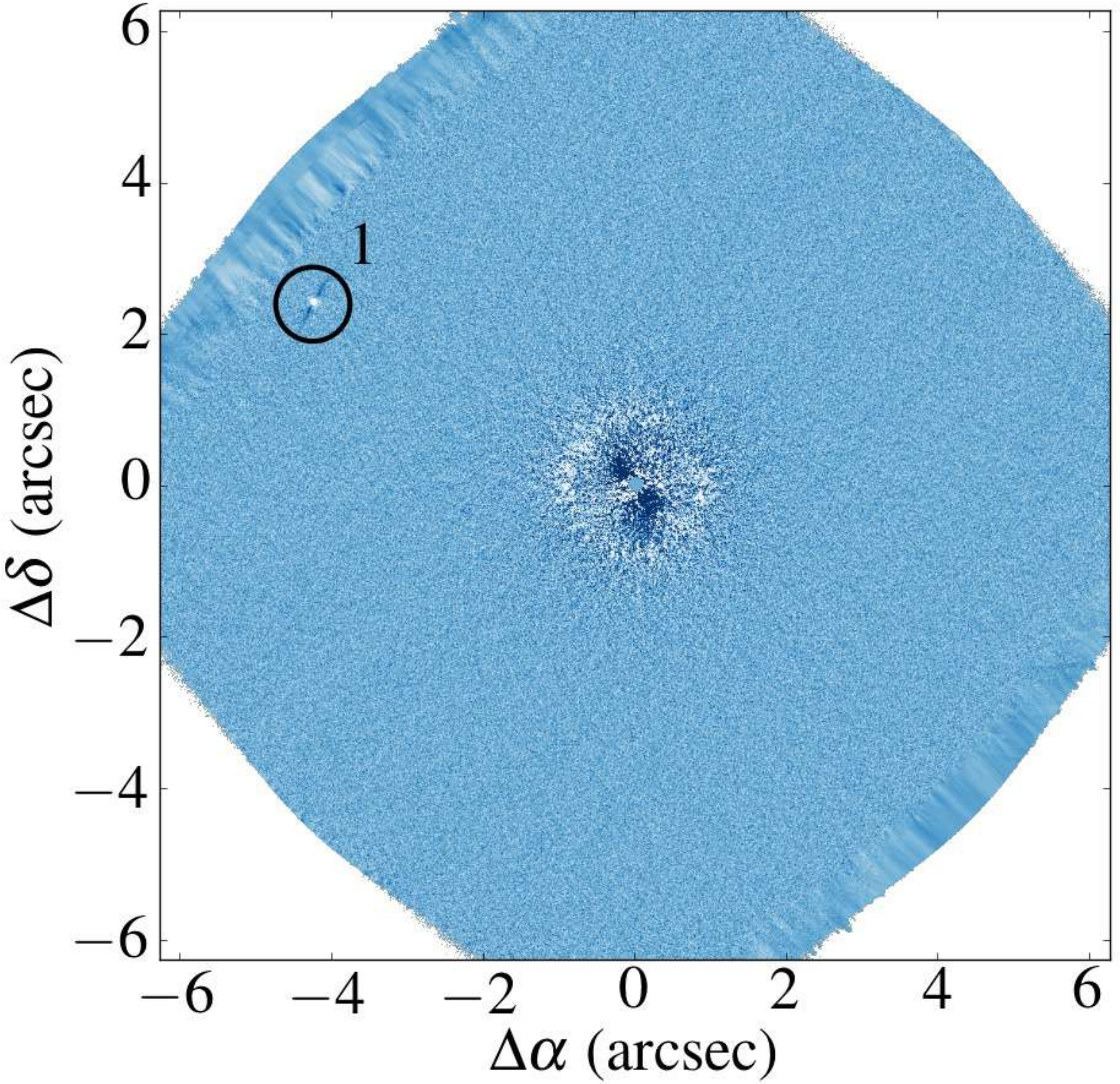
Julien Milli

IPAG

Point sources vs extended objects

One detection = 3 unknown variables

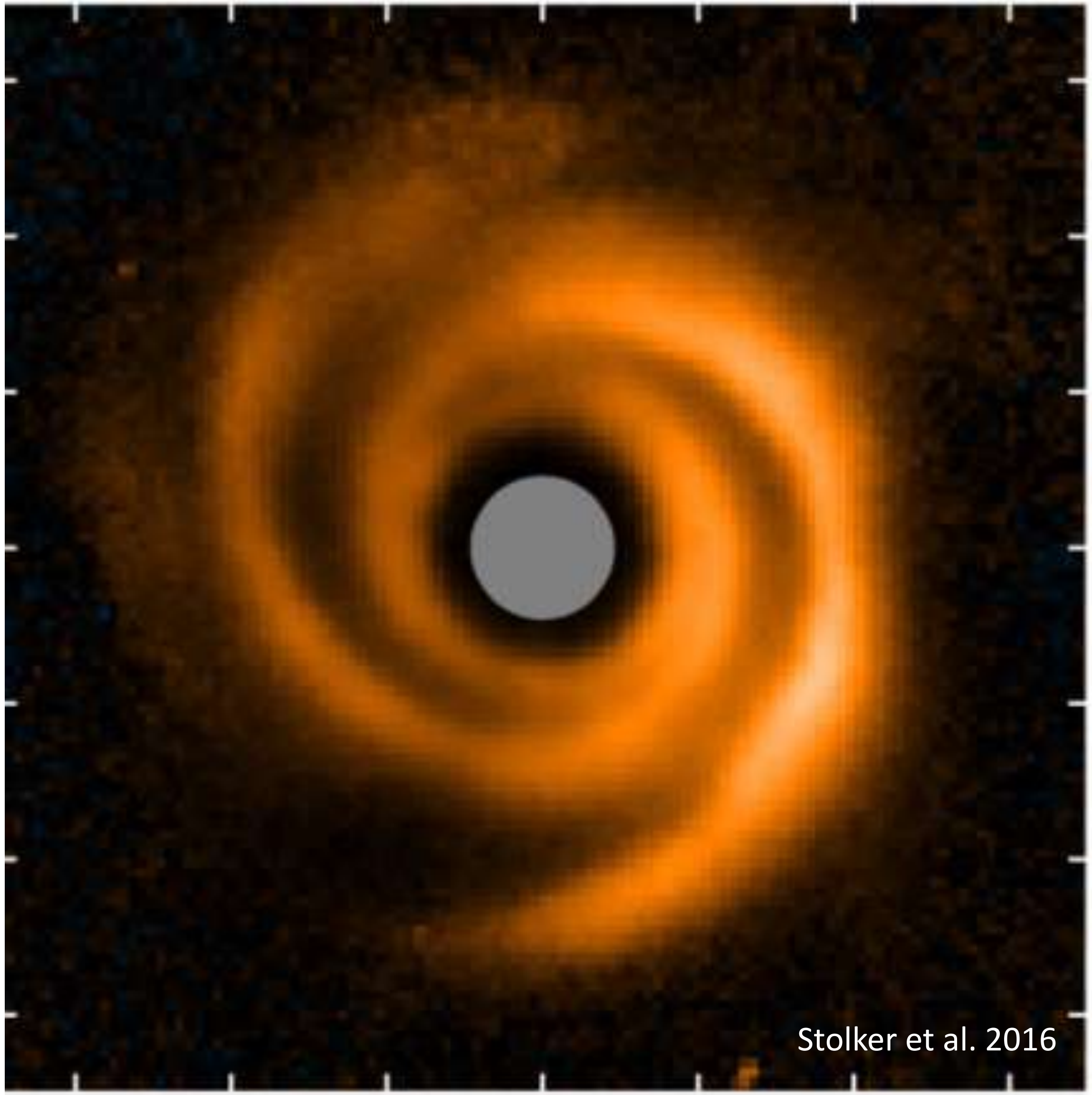
- Astrometry (x,y)
- Flux



Point sources vs extended objects

One detection = hundreds of unknown variables

- Surface Brightness Distribution of the object
- For 1”x1” at H, ~600 unknown (resolution elements)

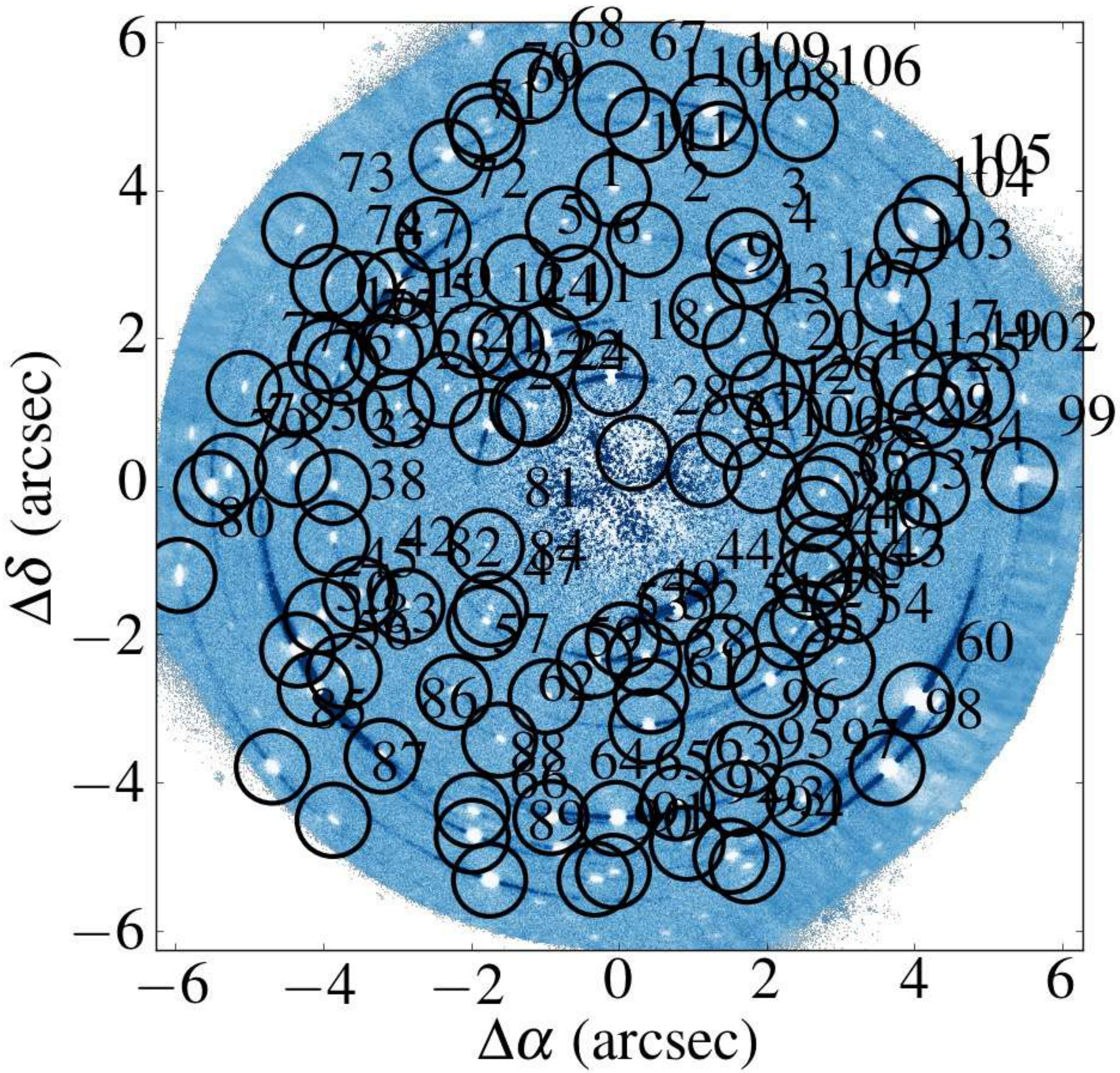


Point sources vs extended objects

One detection = hundreds of unknown variables

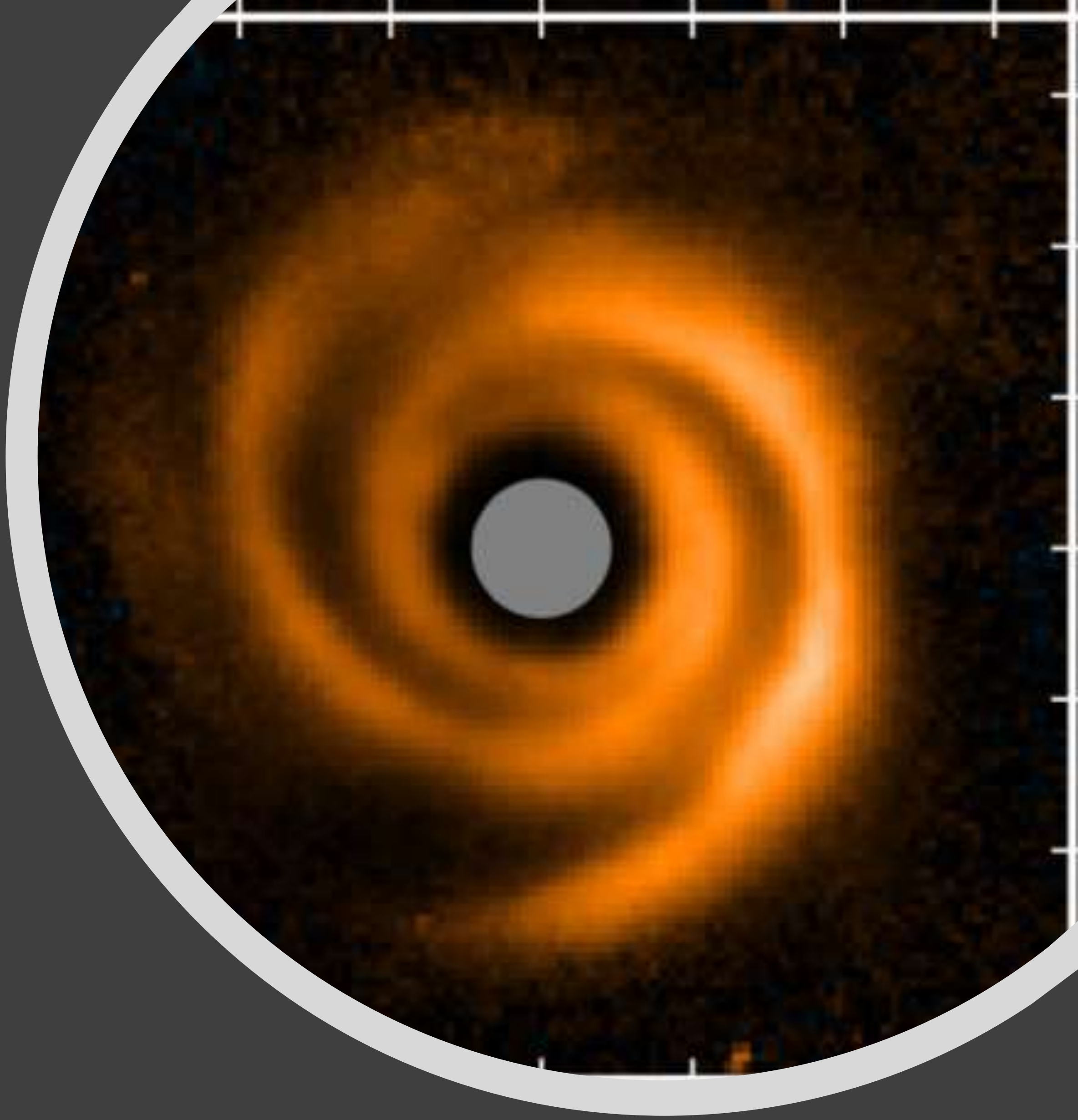
- Surface Brightness Distribution of the object
- For 1”x1” at H, ~600 unknown (resolution elements)

Main difference: the signature of a point-source is known → **Filtering**



Outline

1. **Science goals and questions**
2. Requirements for data processing algorithms
3. Current observation strategies and data processing techniques
4. Current limitations
5. Future prospects

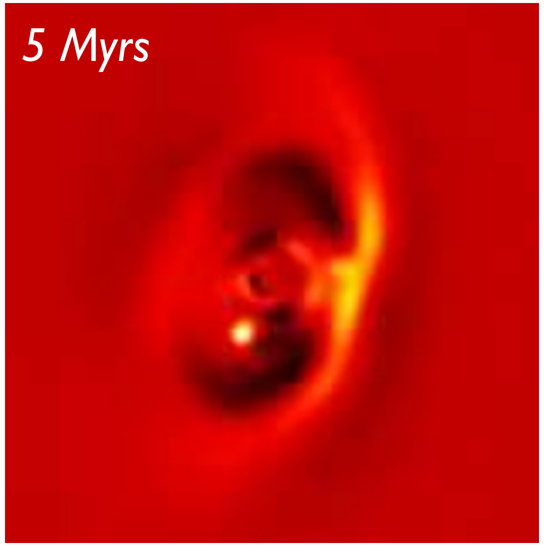


Protoplanetary disks

Context

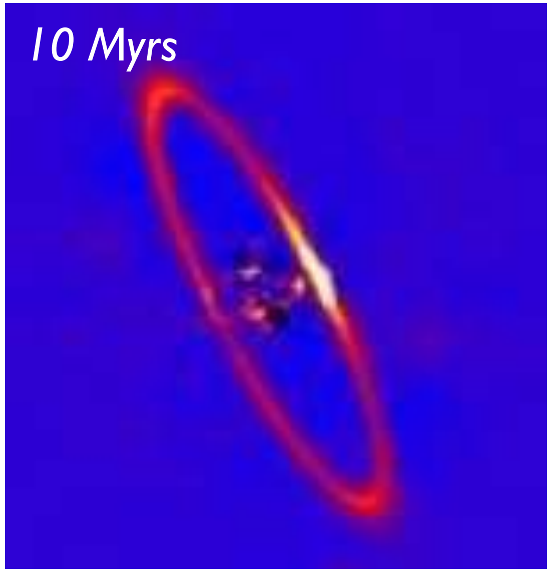
Dust = good tracer of the life cycle of planetary systems

Protoplanetary disk



PDS 70 (VLT/SPHERE)
Müller et al. 2018

Debris disk



HR 4796 (VLT/SPHERE)
Milli et al. 2017

Debris disks

Birth places of planets

- Understand where and how planets form
- Understand dust growth
- Probe the dust = building blocks of planets

Outcome of planetary formation

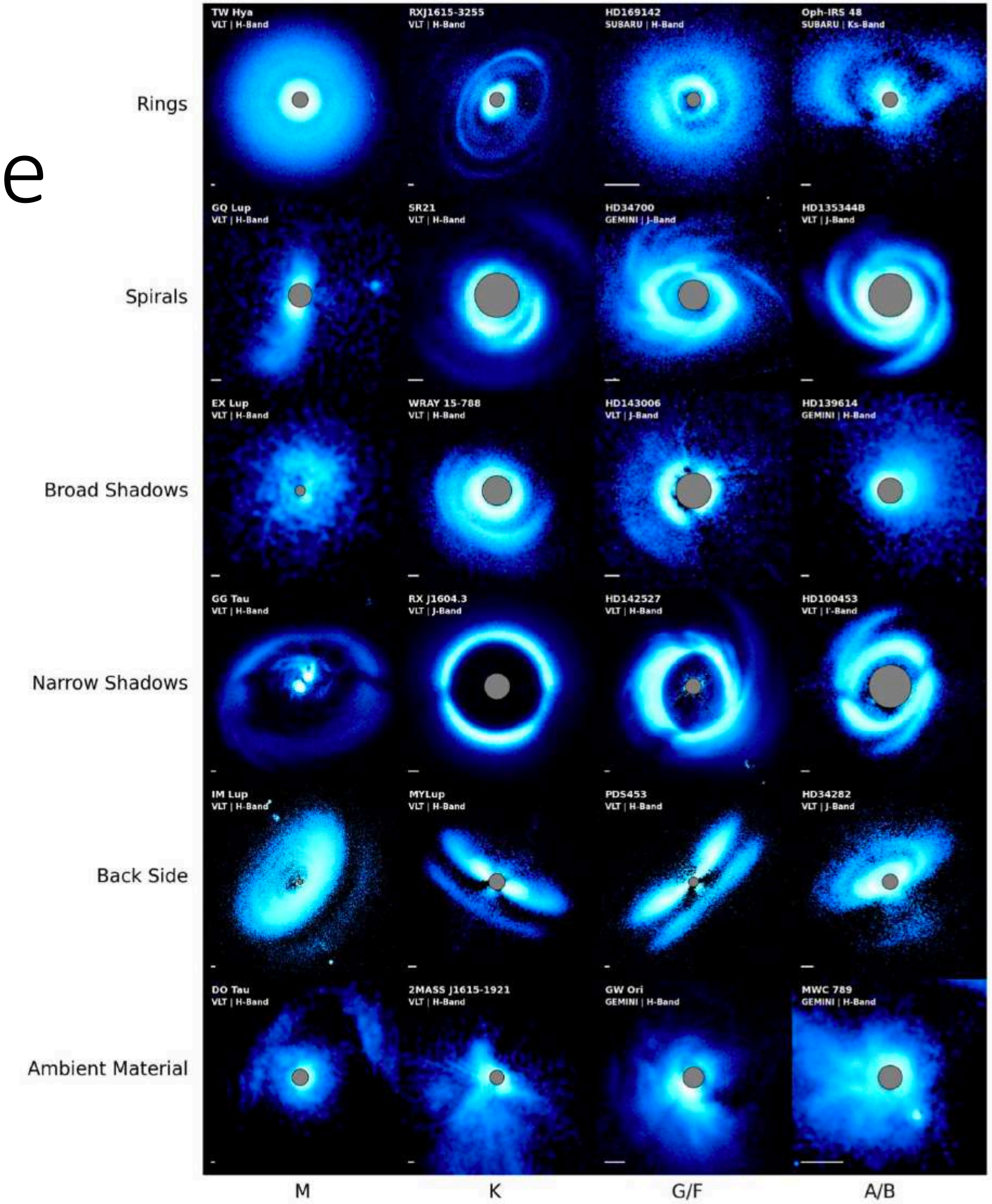
- Detect signposts of planets
- Probe the dust = breakup products of planetesimals
- Put our solar system asteroid/Kuiper belt in context

Protoplanetary disks

Goal 1: Detect and resolve

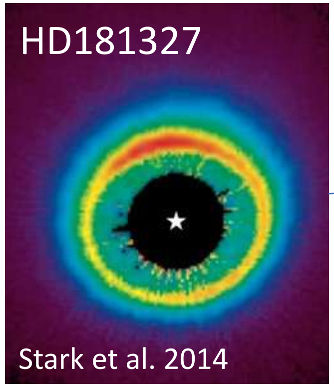
High detection rate of PPD with SPHERE ~90%

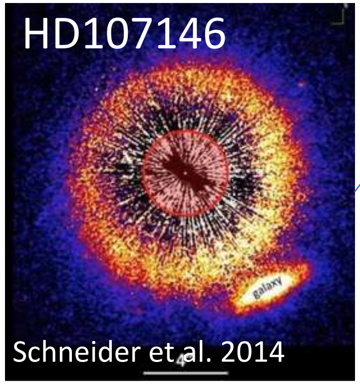
Demography of **protoplanetary disks** and morphological structures

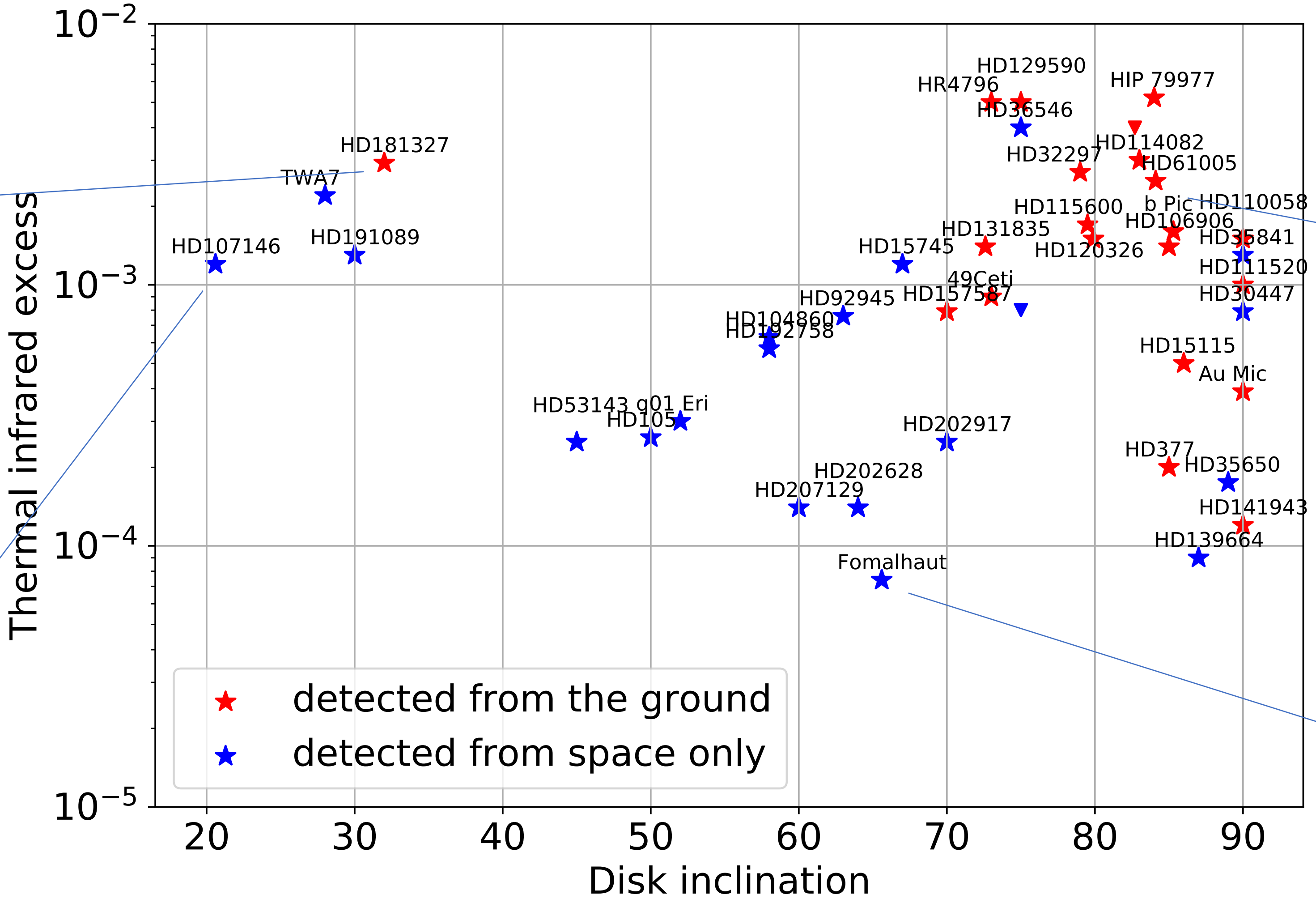


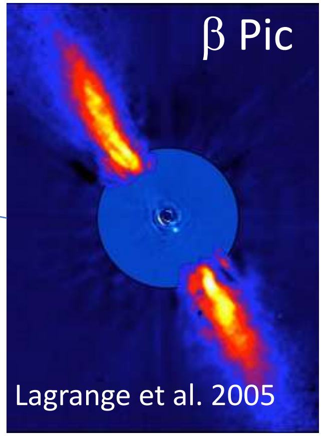
SPHERE, GPI and HiCIAO sample
Benisty et al. 2022

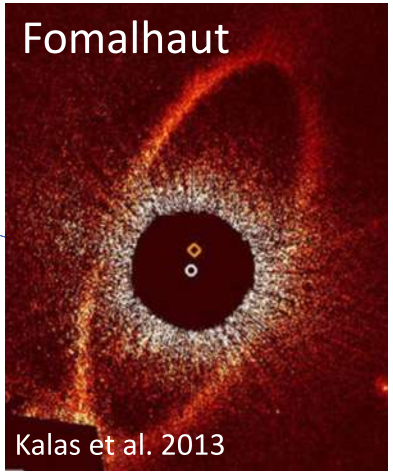
Goal 1: Detect and resolve







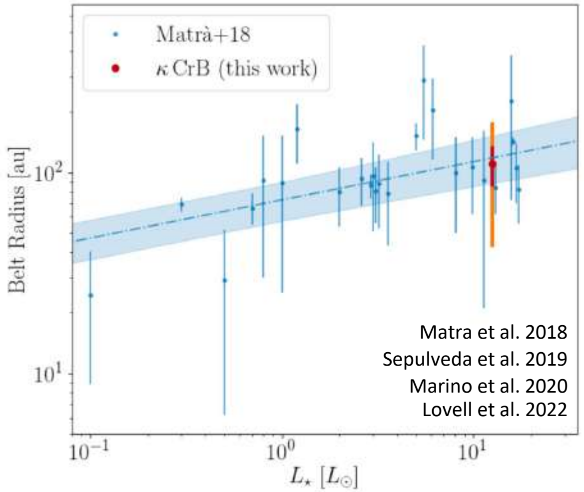




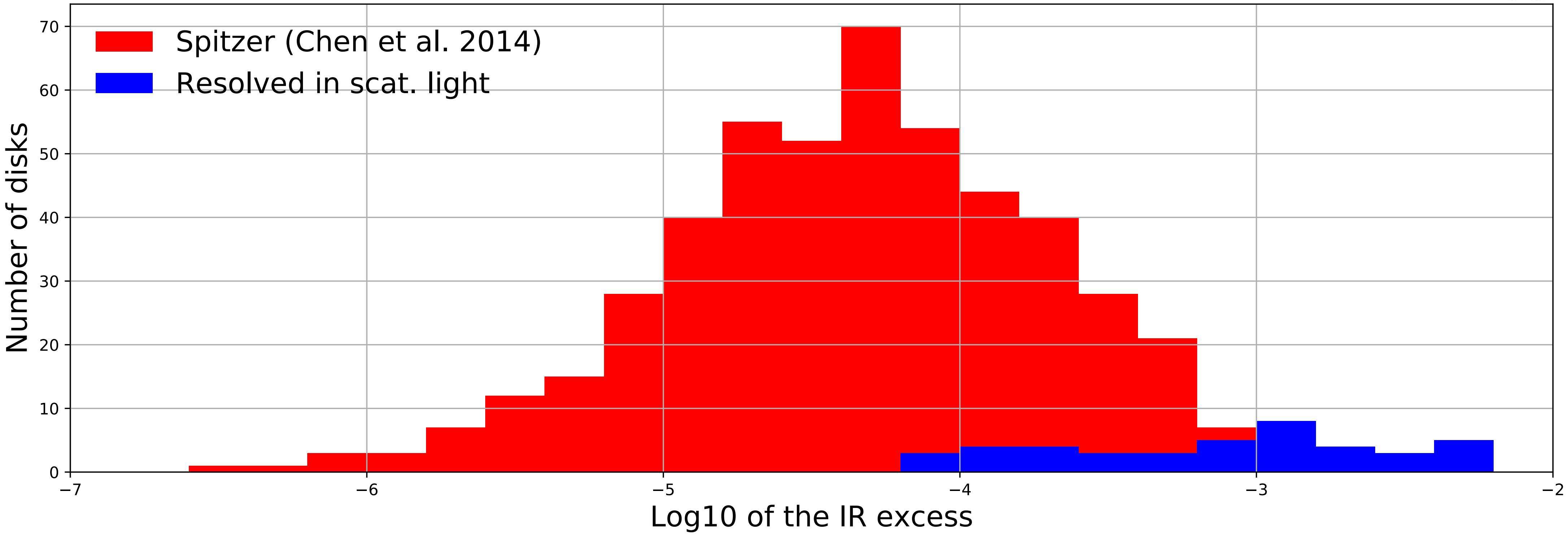
Bias towards highly inclined and massive **debris disks**

Debris disks

Goal 1: Detect and resolve

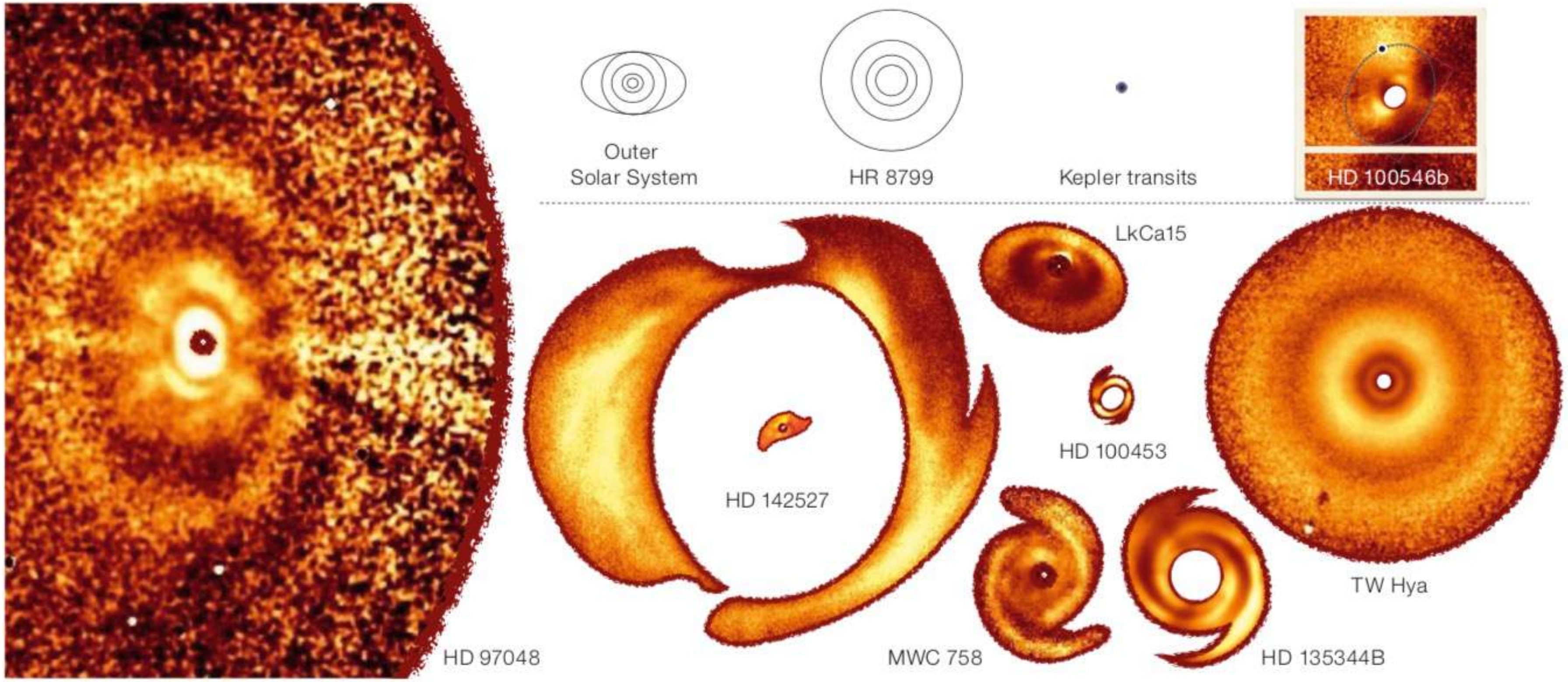


Matra et al. 2018
Sepulveda et al. 2019
Marino et al. 2020
Lovell et al. 2022



Only ~50 debris disks detected in scattered light → demographic studies still difficult

Goal 2: Detailed morphological studies



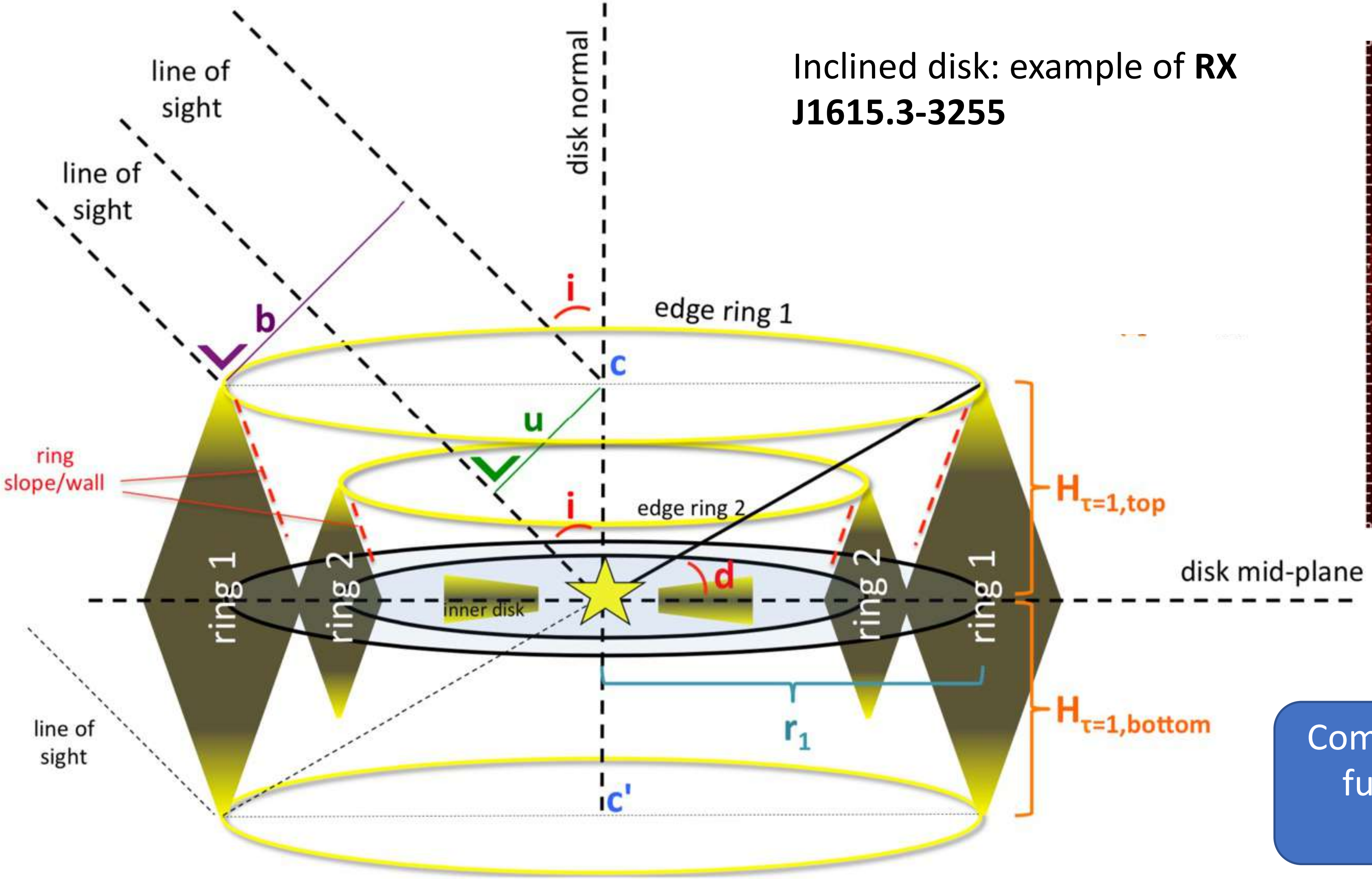
Gaps, cavities, spirals, dips

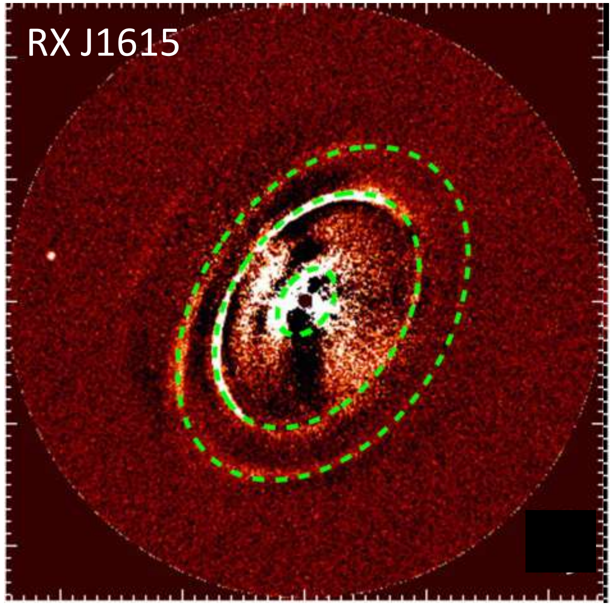
Planets Ice lines Gas	Planets Star	Planets Binarity	Shadows

Garufi et al. 2017

Goal 2: Detailed morphological studies

Inclined disk: example of **RX J1615.3-3255**

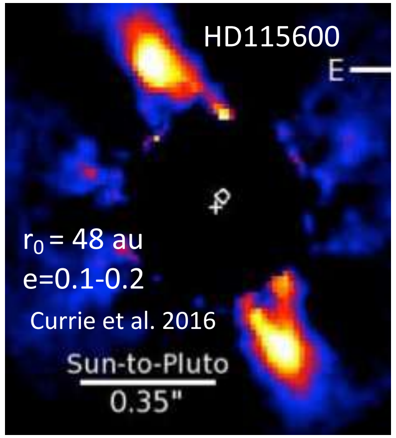


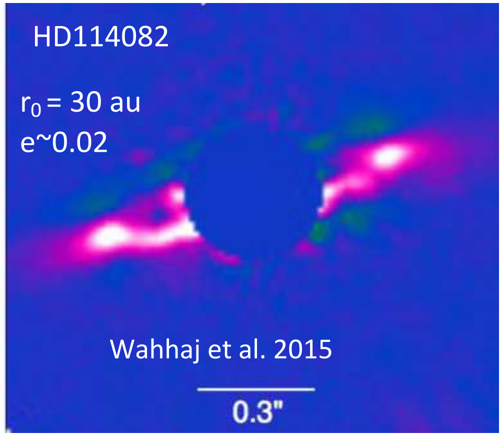


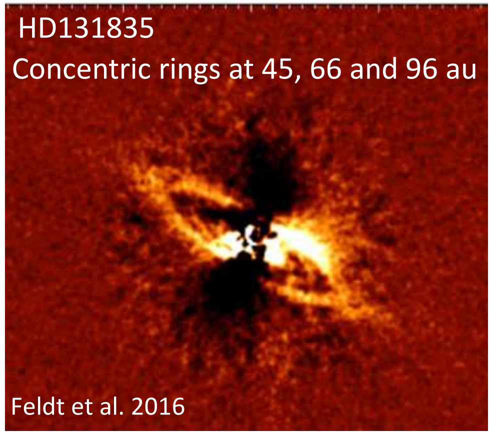
De Boer et al. 2016

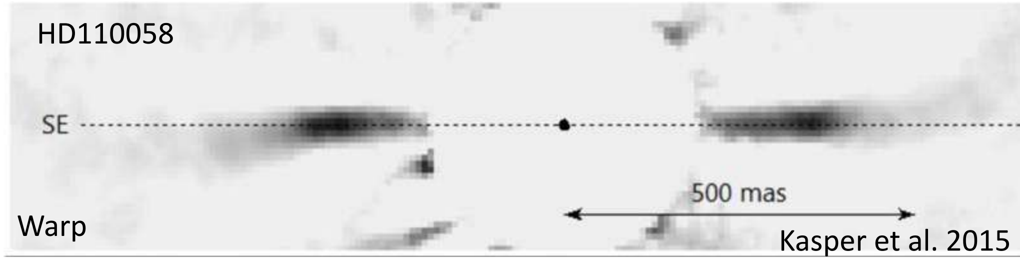
Combination of scattering phase function, disc geometry and illumination effects

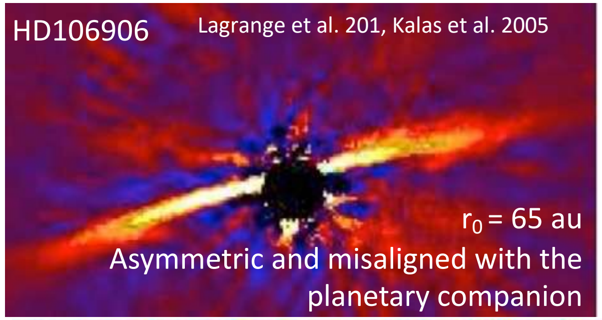
Goal 2: Detailed morphological studies

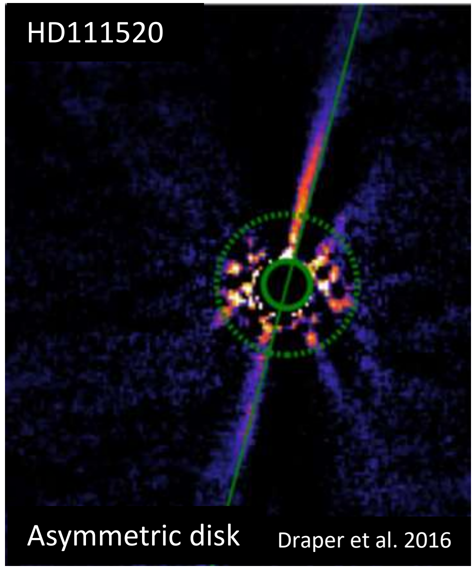










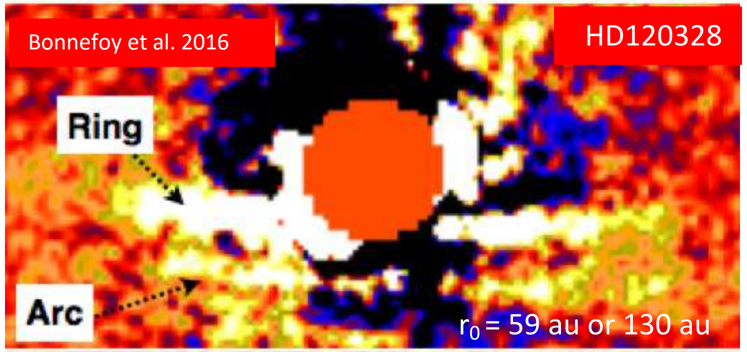


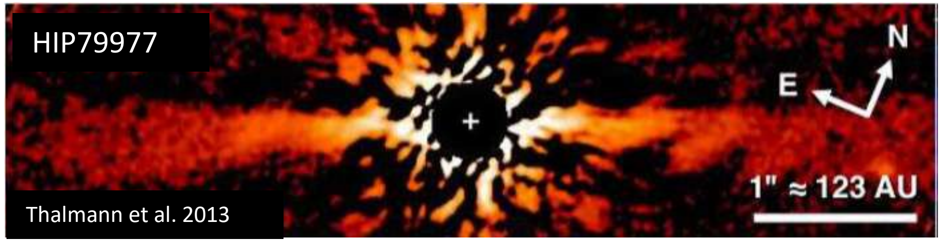
Elliptical rings in Sco Cen

Nearest OB association at ~ 140pc

10-15 Myrs

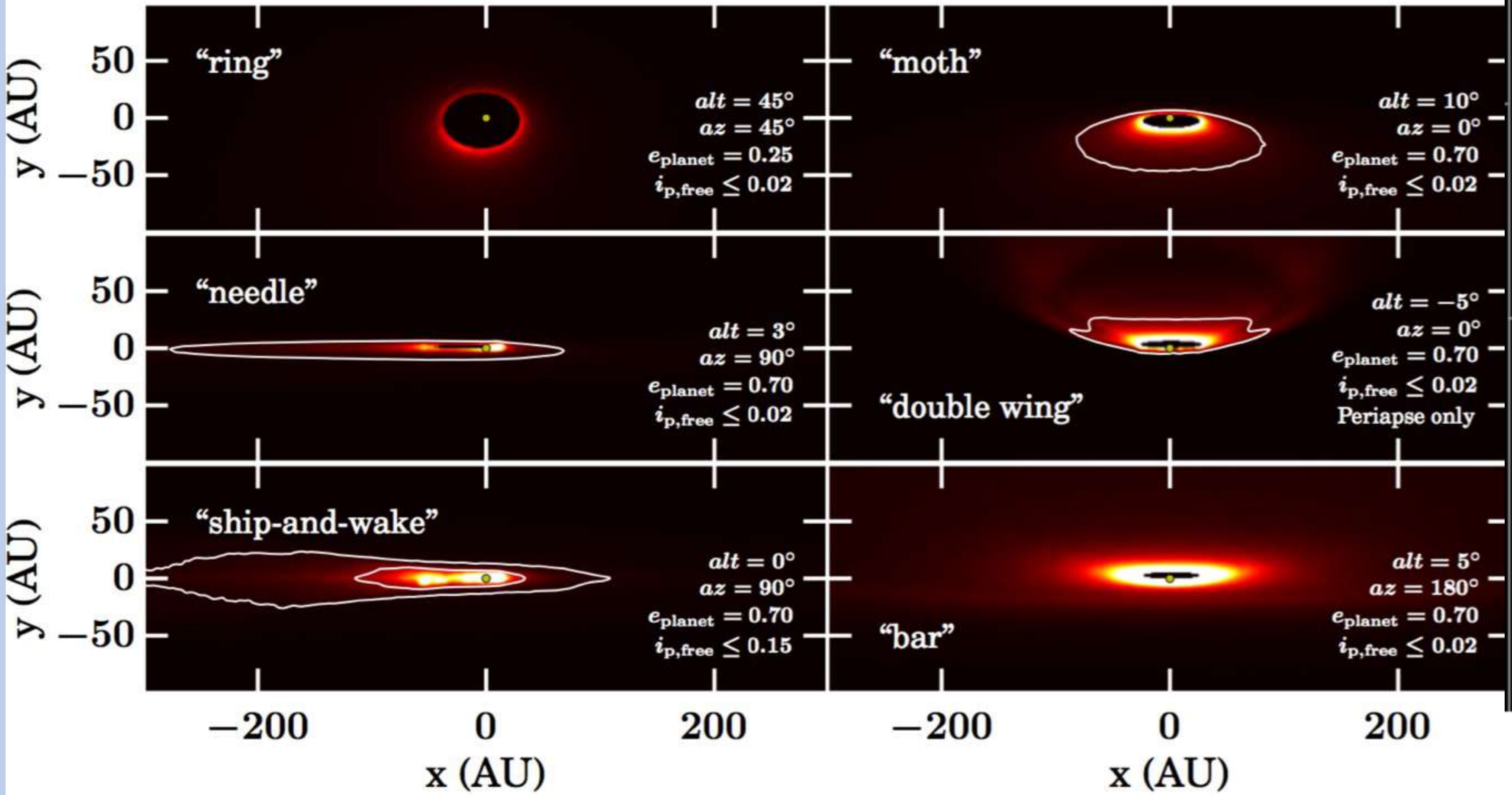
Host of 3 directly-imaged planets

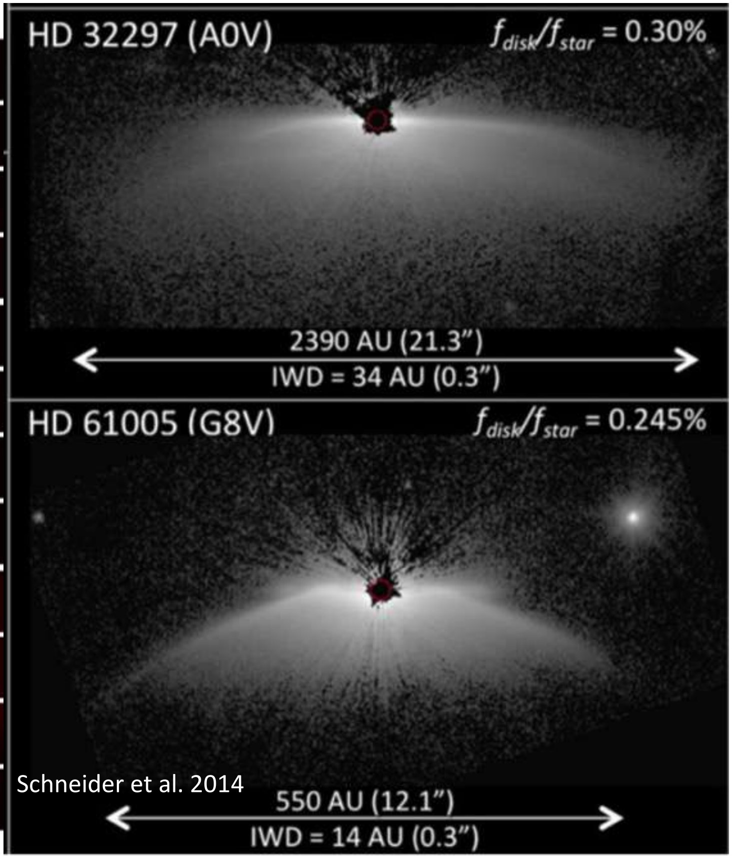




Goal 2: Detailed morphological studies

Classification proposed by Lee & Chiang 2016:



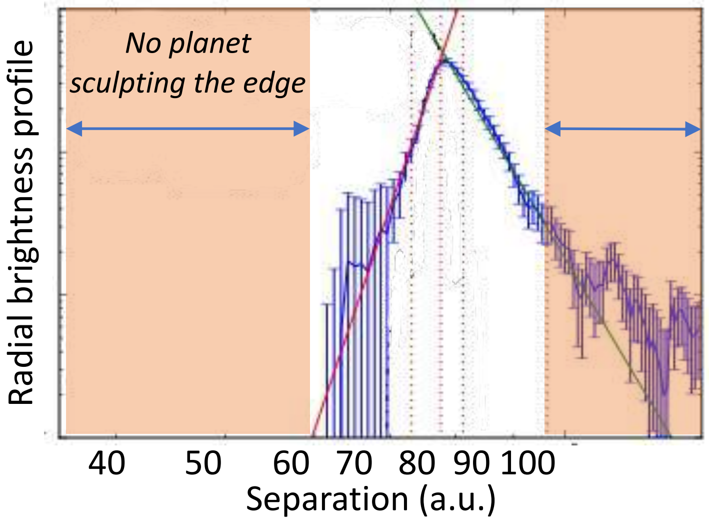


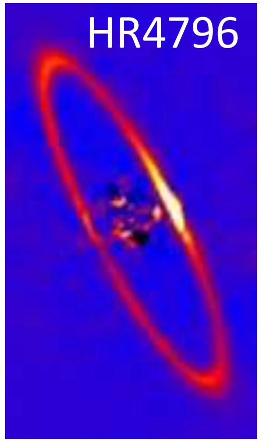
Schneider et al. 2014

A single eccentric planet secularly perturbing a ring of parent bodies releasing dust particles can explain most morphologies

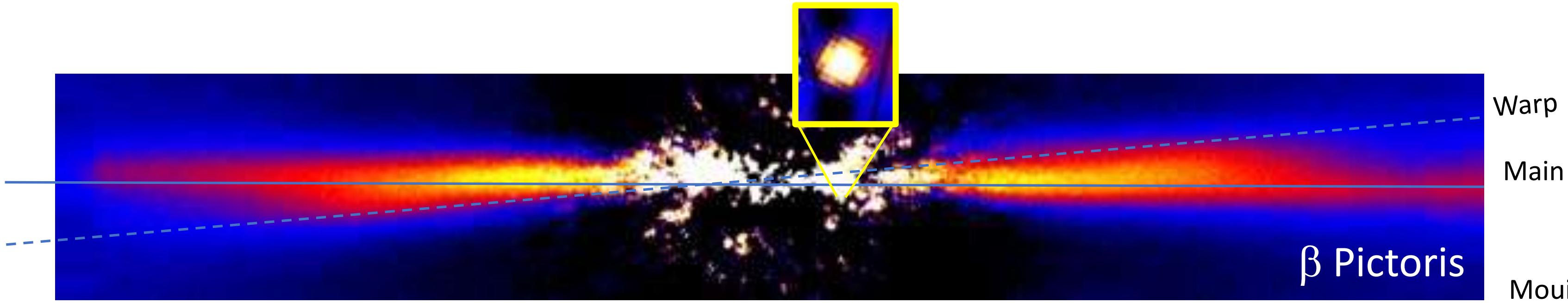
Goal 2: Detailed morphological studies

How to pinpoint the planet position ?



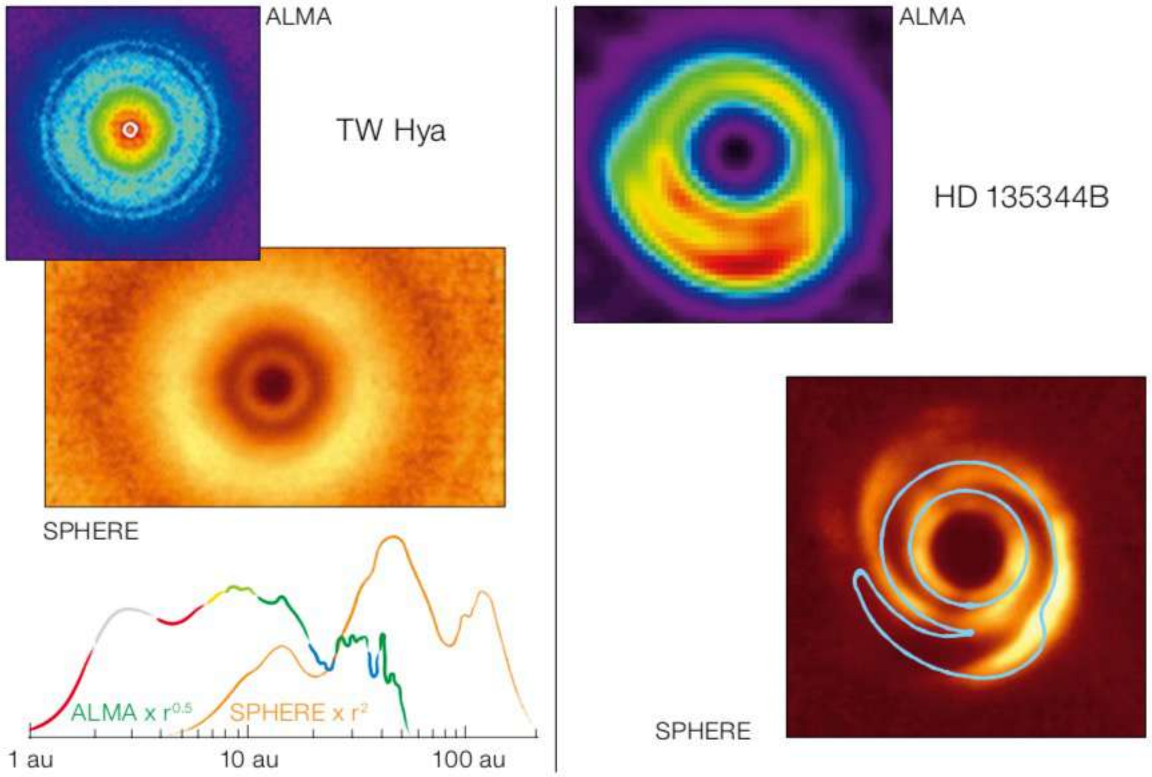


Milli et al. 2017
Lazzoni et al. 2017

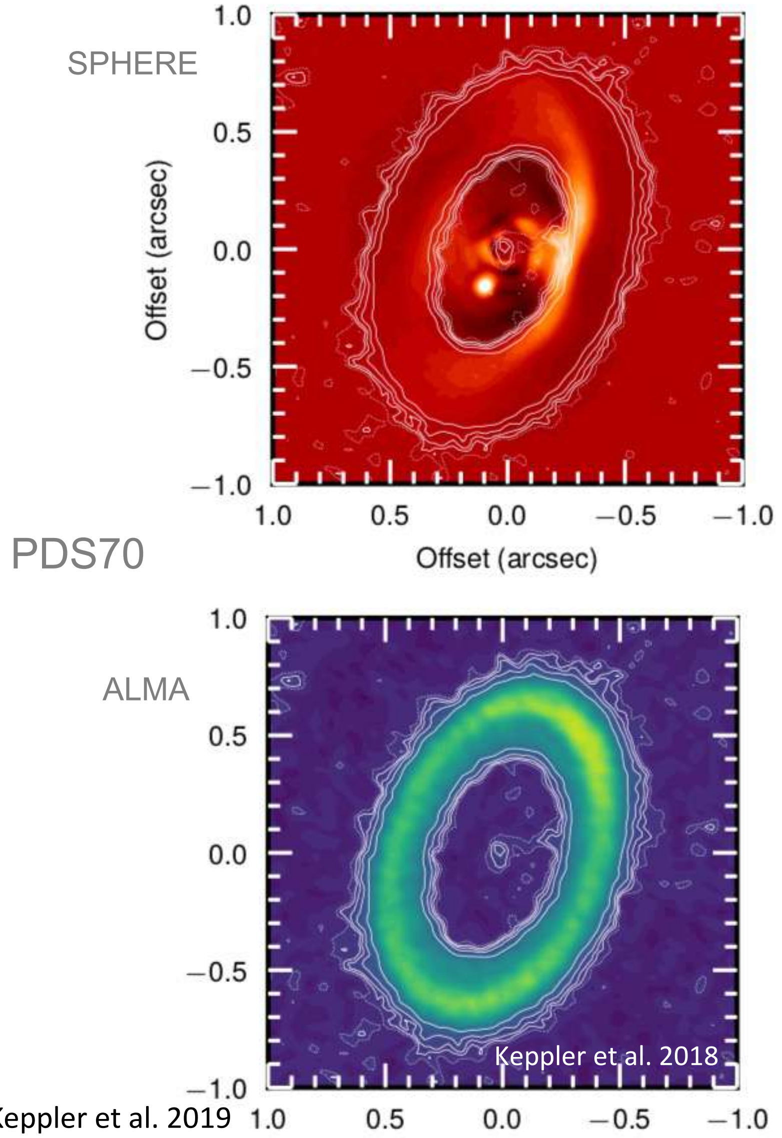


Mouillet et al. 1997

Goal 3: Comparisons with thermal emission



Garufi et al. 2018

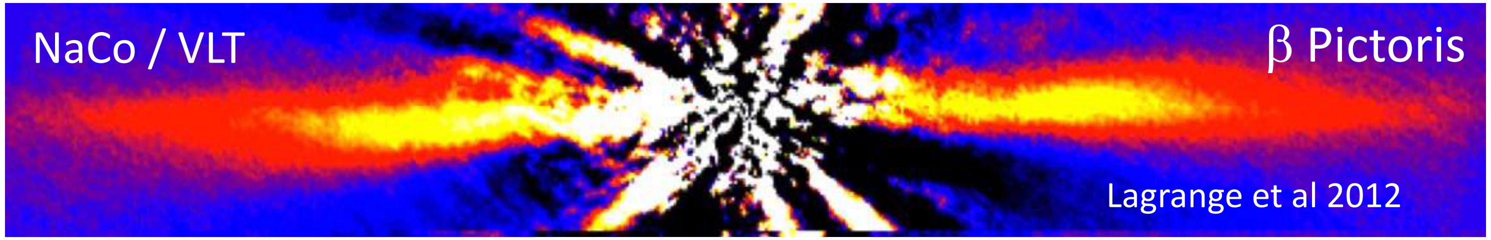


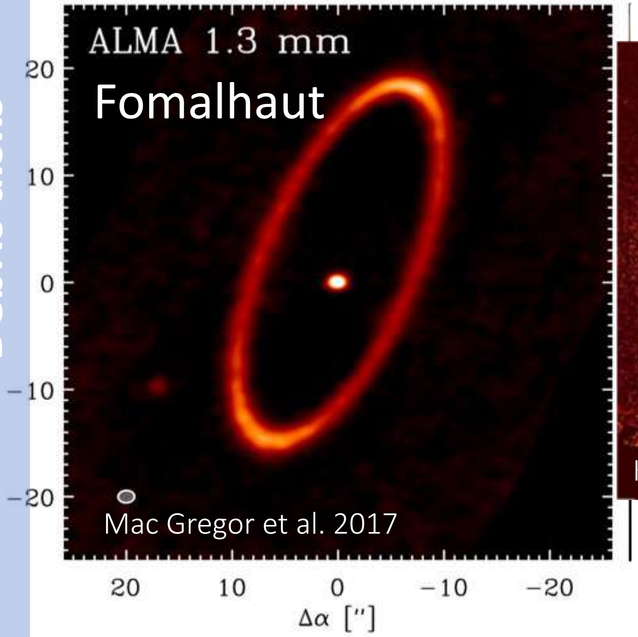
Keppler et al. 2019

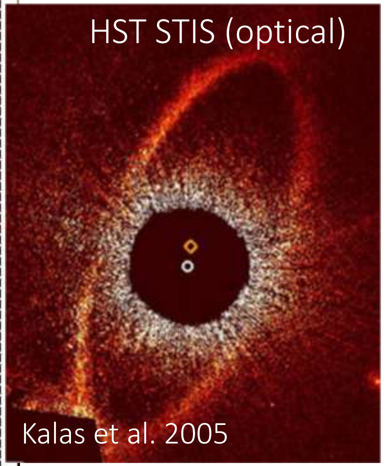
Different dust populations are probed, at different heights in the disk

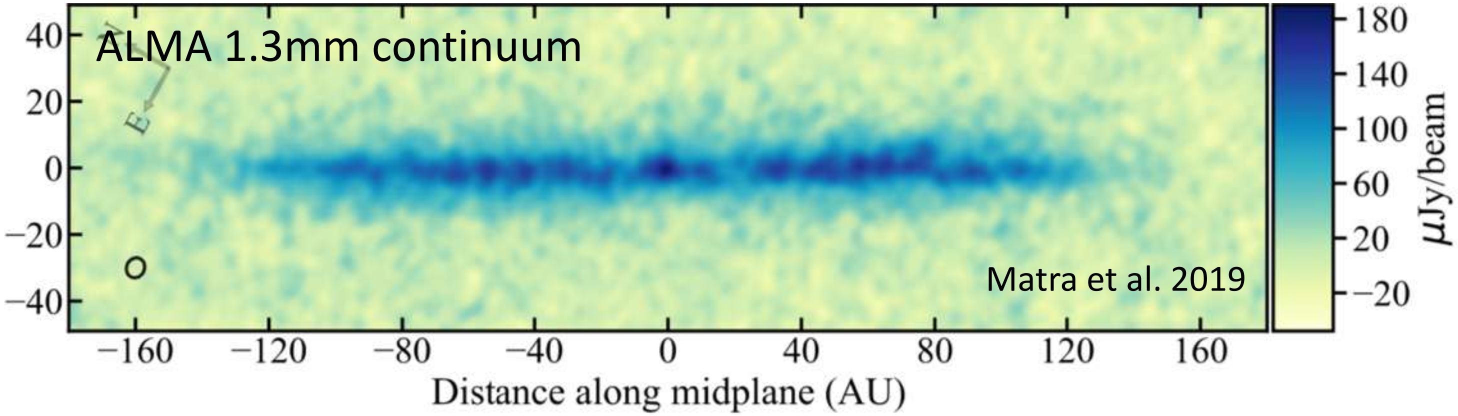
Goal 3: Comparisons with thermal emission

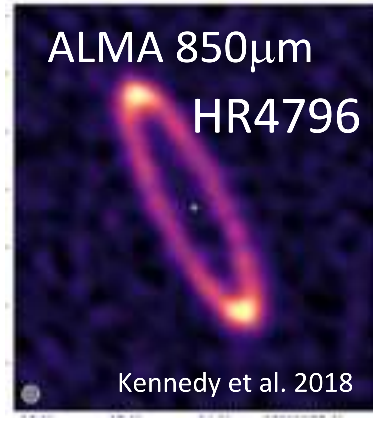
Debris disks

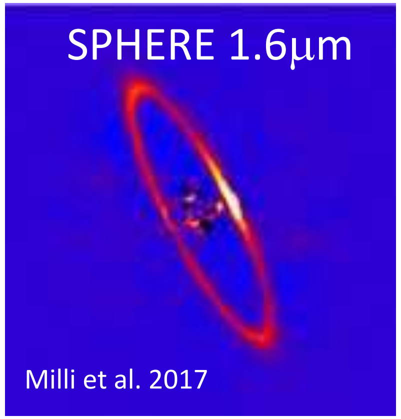


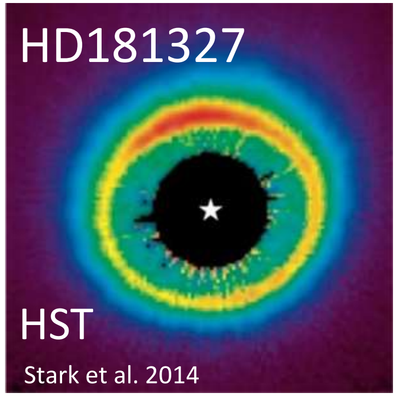


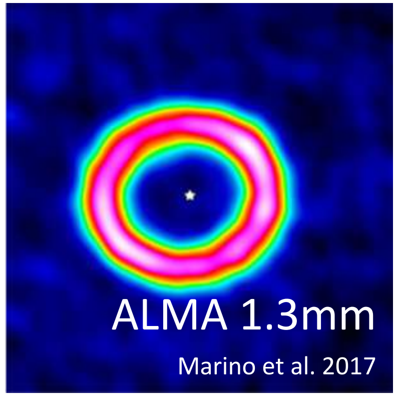








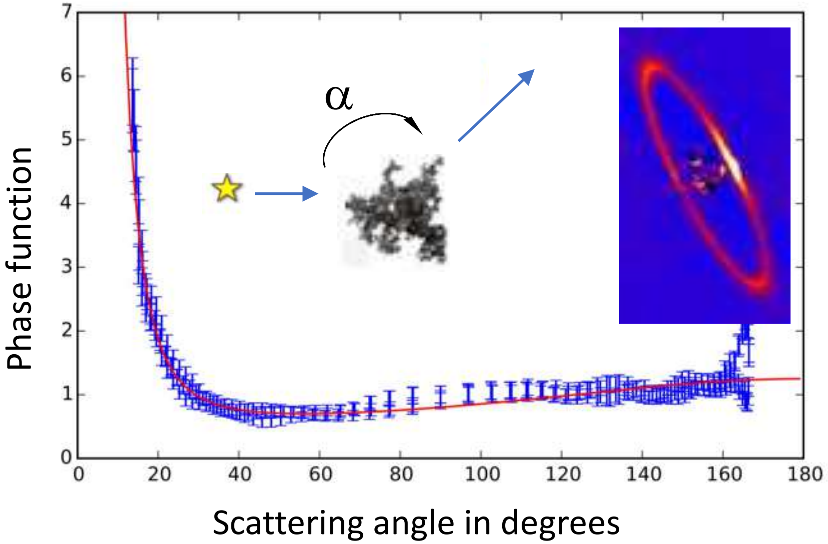




Debris disks

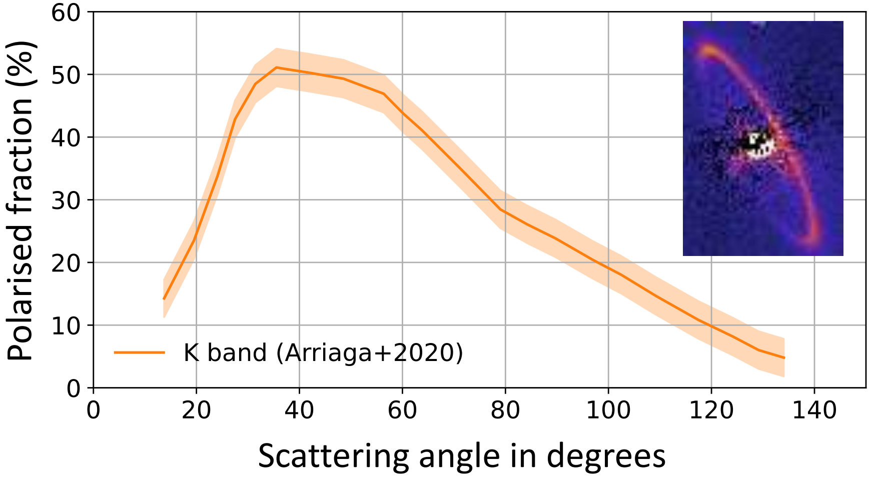
Goal 4: Scattering properties

1. Phase function

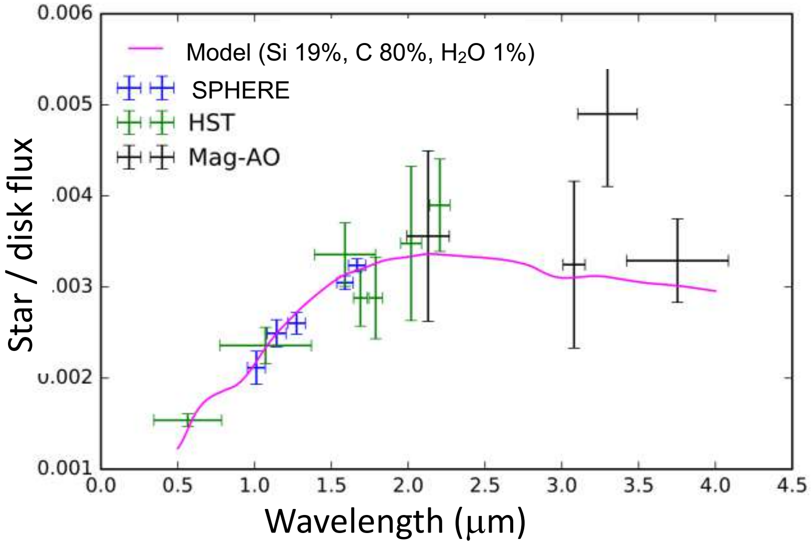


Conclusions : **aggregates ~20μm**

2. Polarization

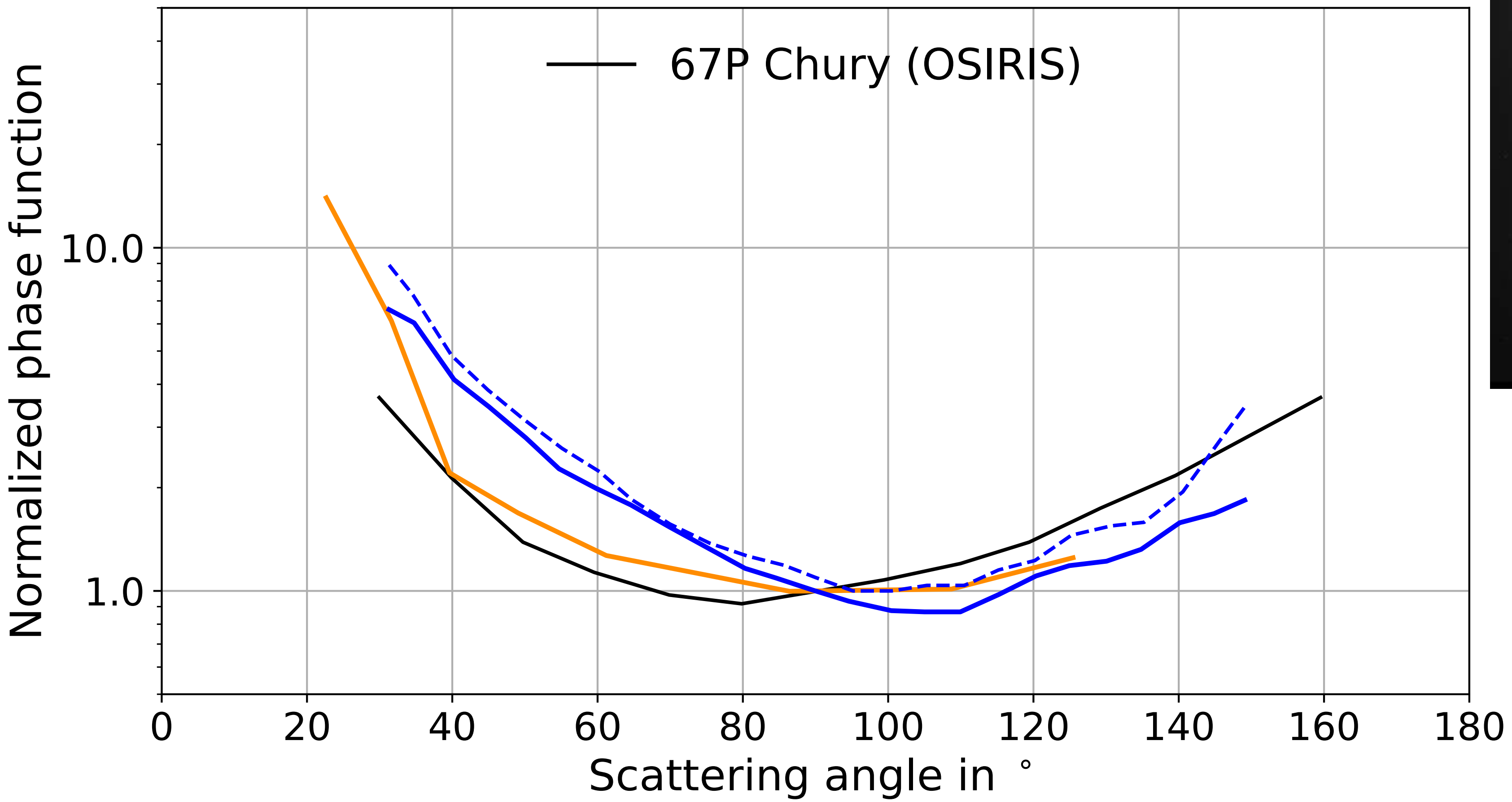


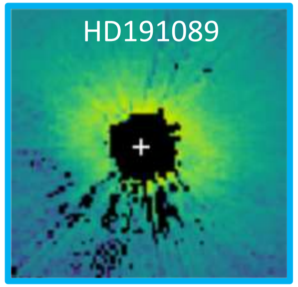
3. Spectral reflectance



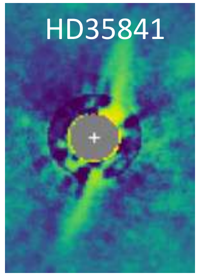
3 diagnostic tools: phase function, polarimetry, reflectance
→ composition, shape, size and porosity

Goal 4: Scattering properties





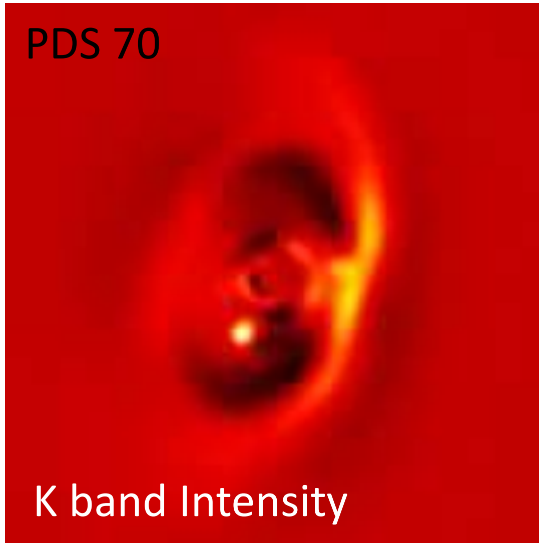
Ren+2019



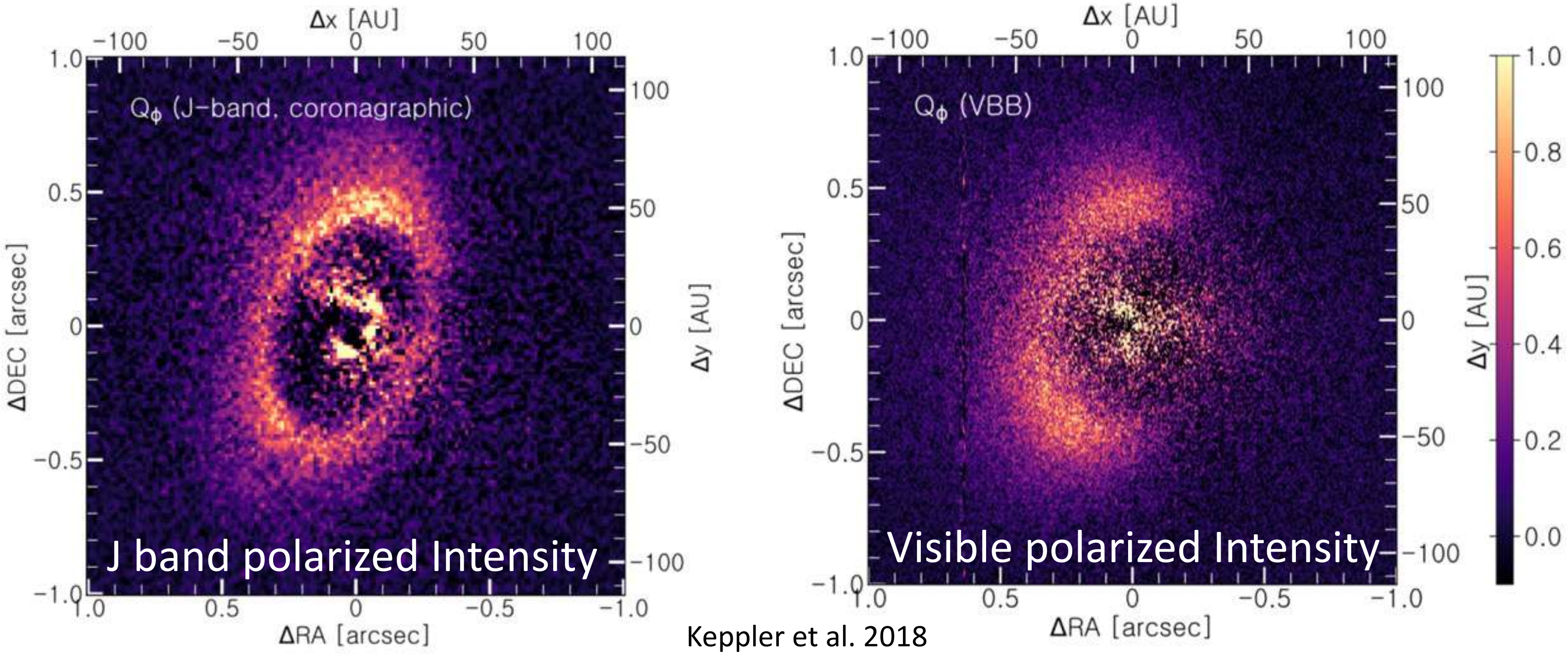
Esposito+2018

Comparison to comets in our solar systems

Goal 4: Scattering properties



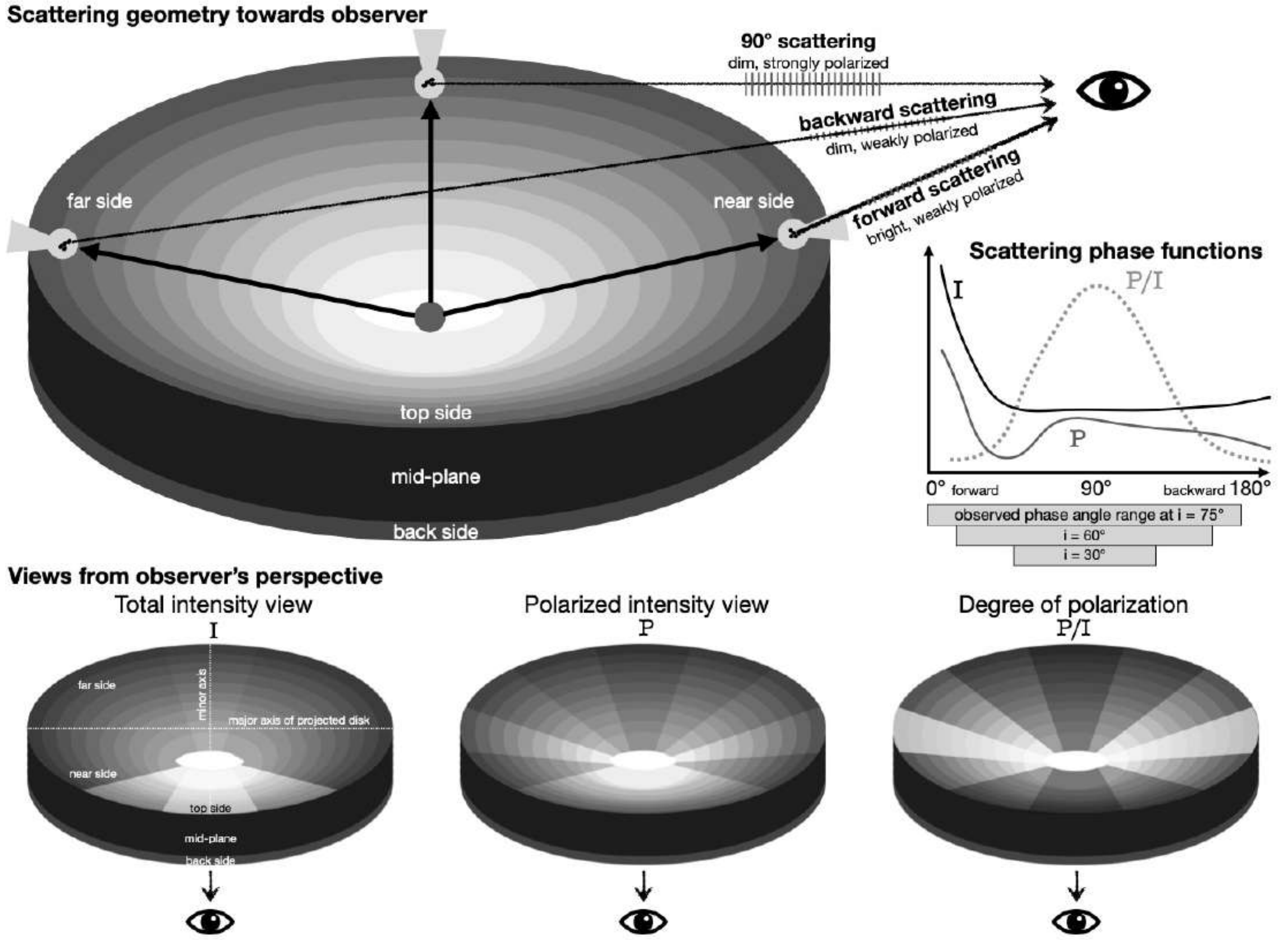
Müller et al. 2018

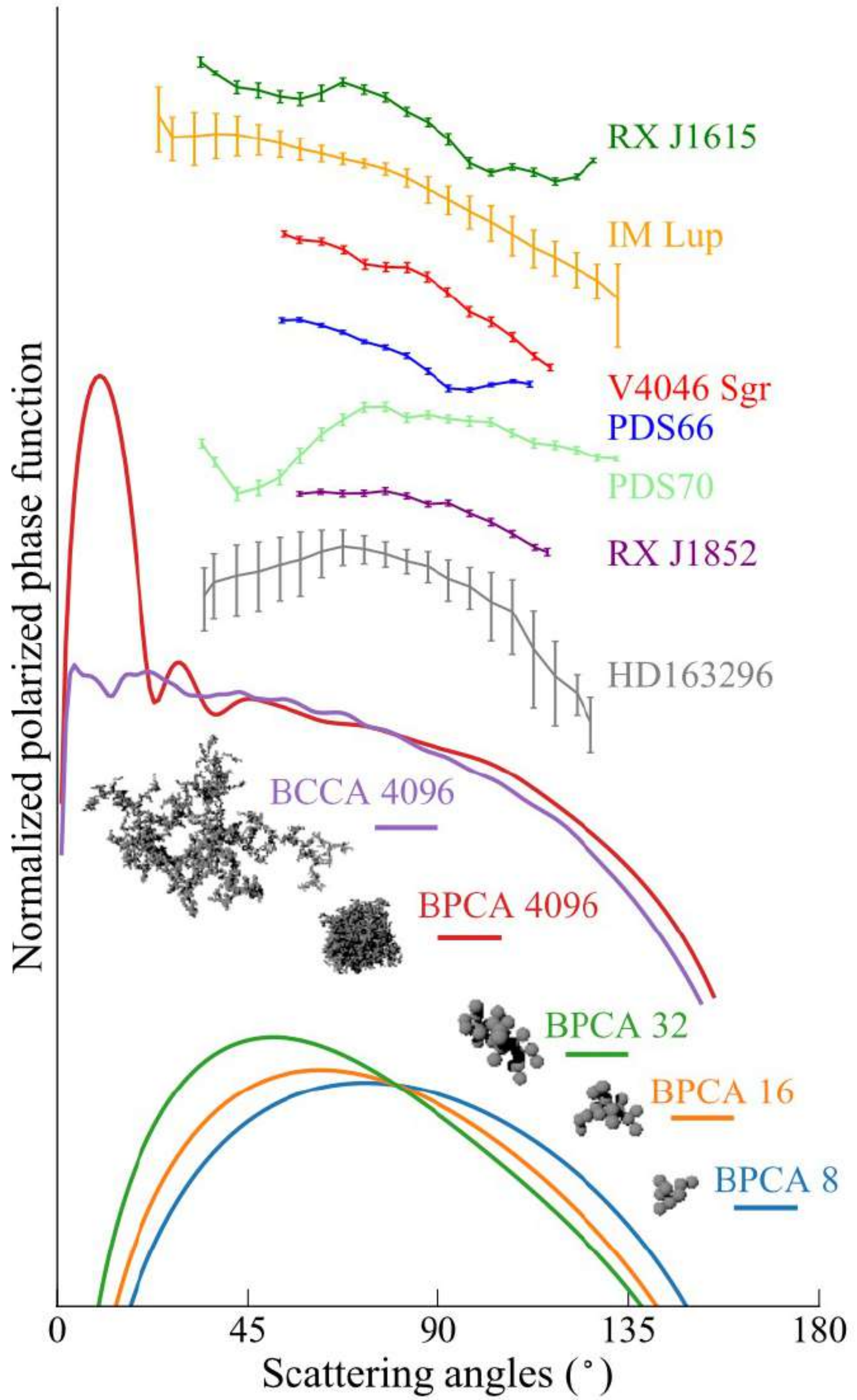


Keppler et al. 2018

Multiple scattering makes the interpretation more complex than in optically thin debris disks → direct retrieval of optical properties not possible

Goal 4: Scattering properties



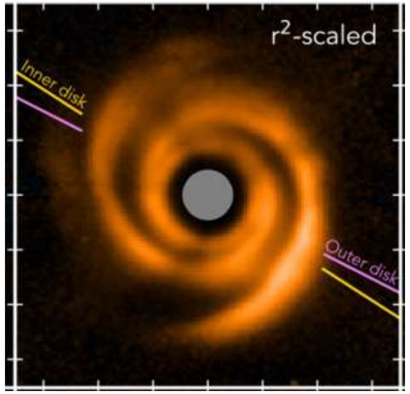


Benisty et al. 2022

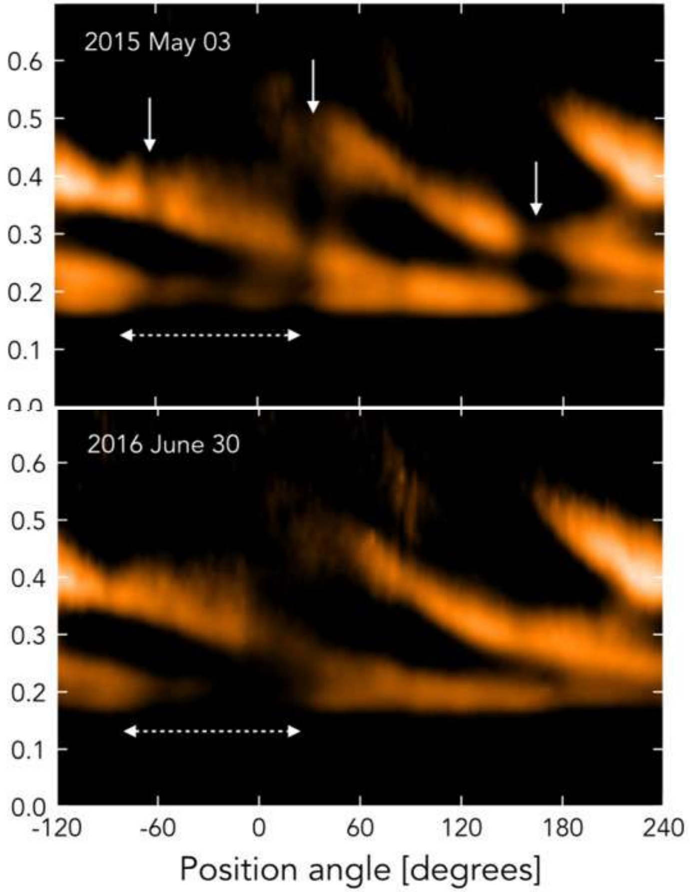
Goal 4: Variability studies

Protoplanetary disks

SAO 206462



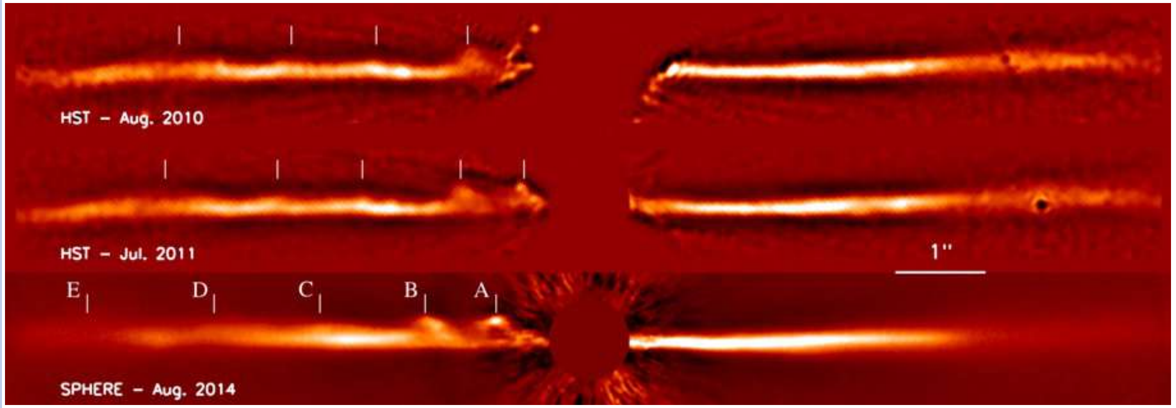
Stolker et al. 2017



Shadows from an inner disk

Debris disks

AU Mic



Sezestre et al. 2017
Boccaletti et al. 2016

Flares, resonances, recent impacts

Content

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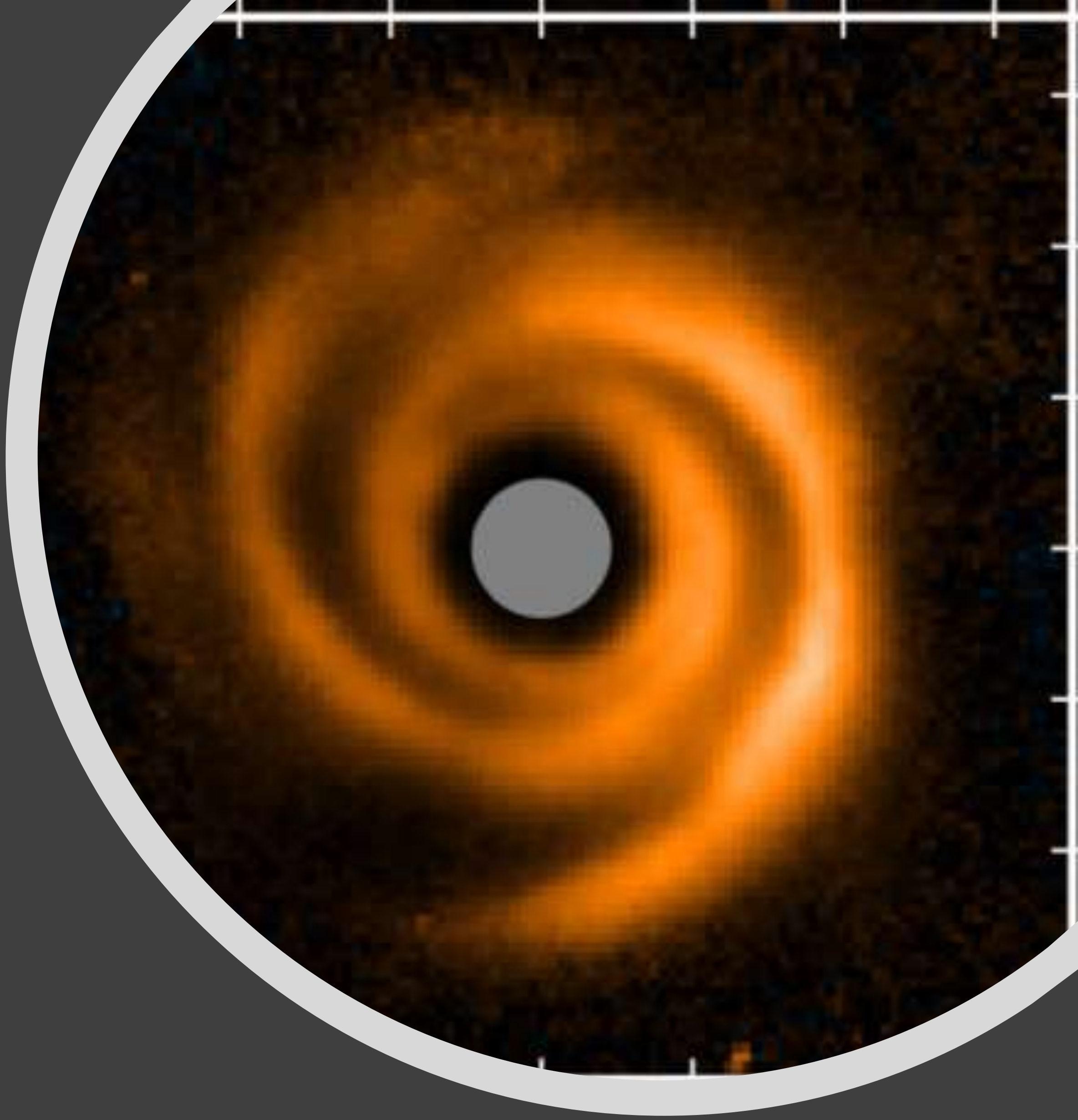
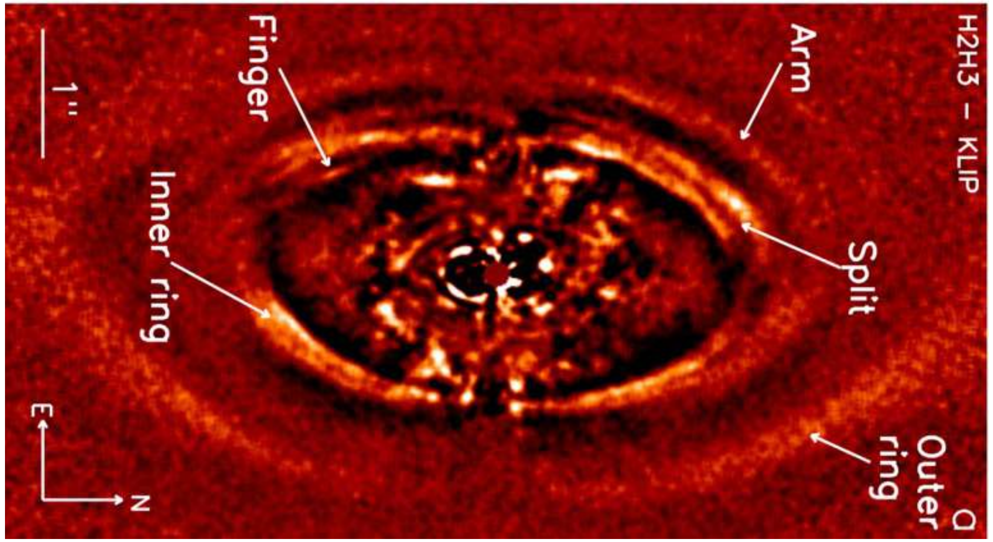


Fidelity

HD141569 in ADI

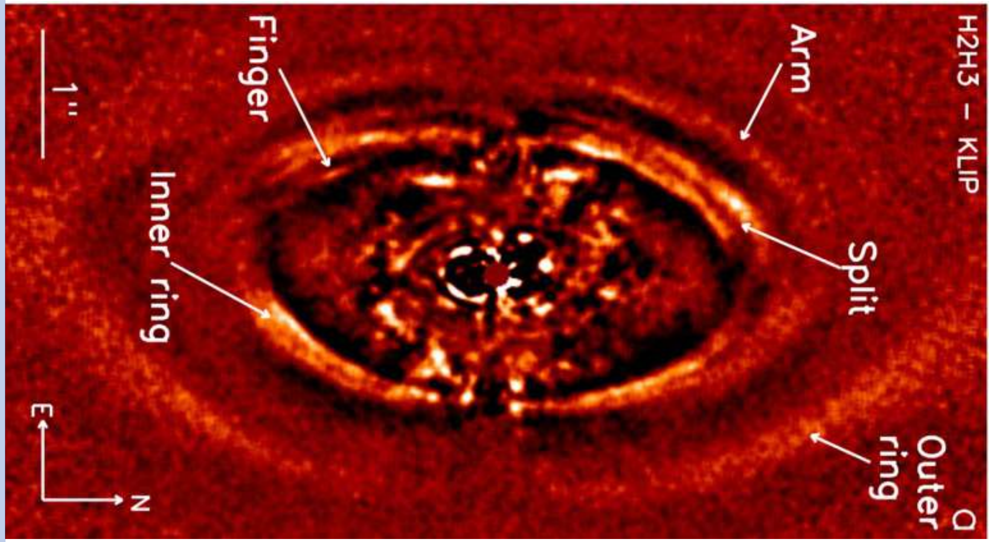


The quality of the interpretation comes from the capability to measure reliably fine details in the image

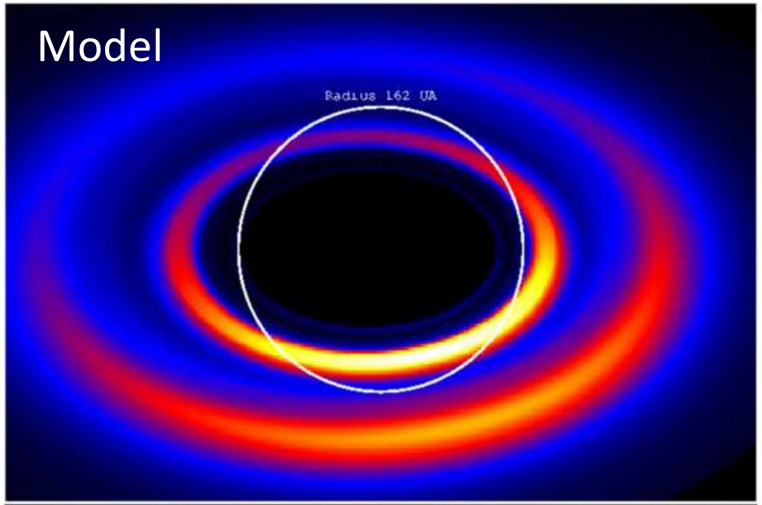
- Deviation from symmetry
- Width and sharpness of a ring
- Spirals
- Streamers

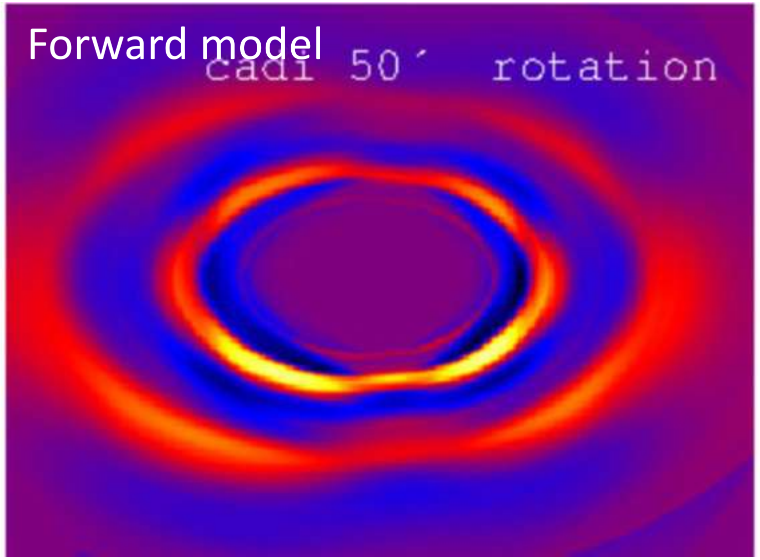
Fidelity or forward modelling capabilities + low computation time

HD141569 in ADI



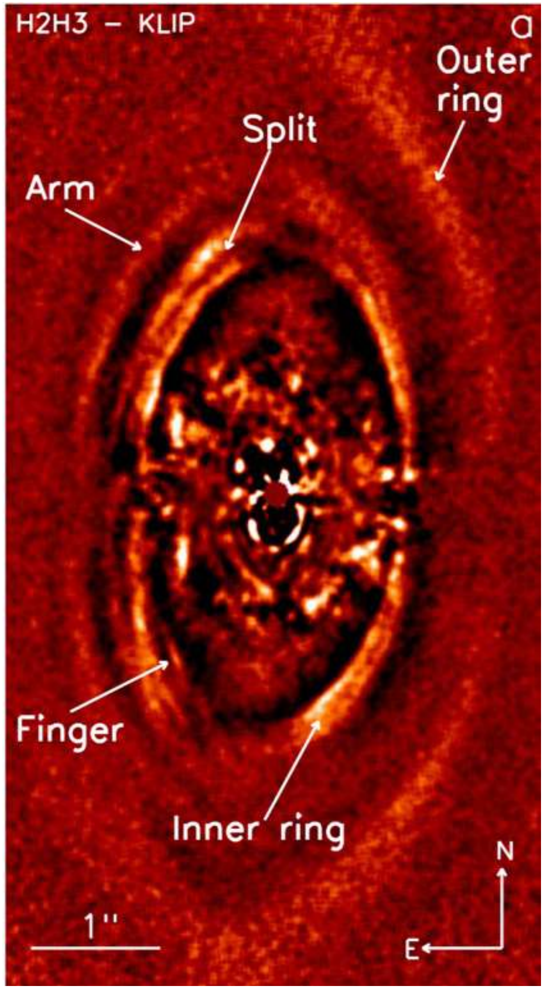
Perrot et al. 2016



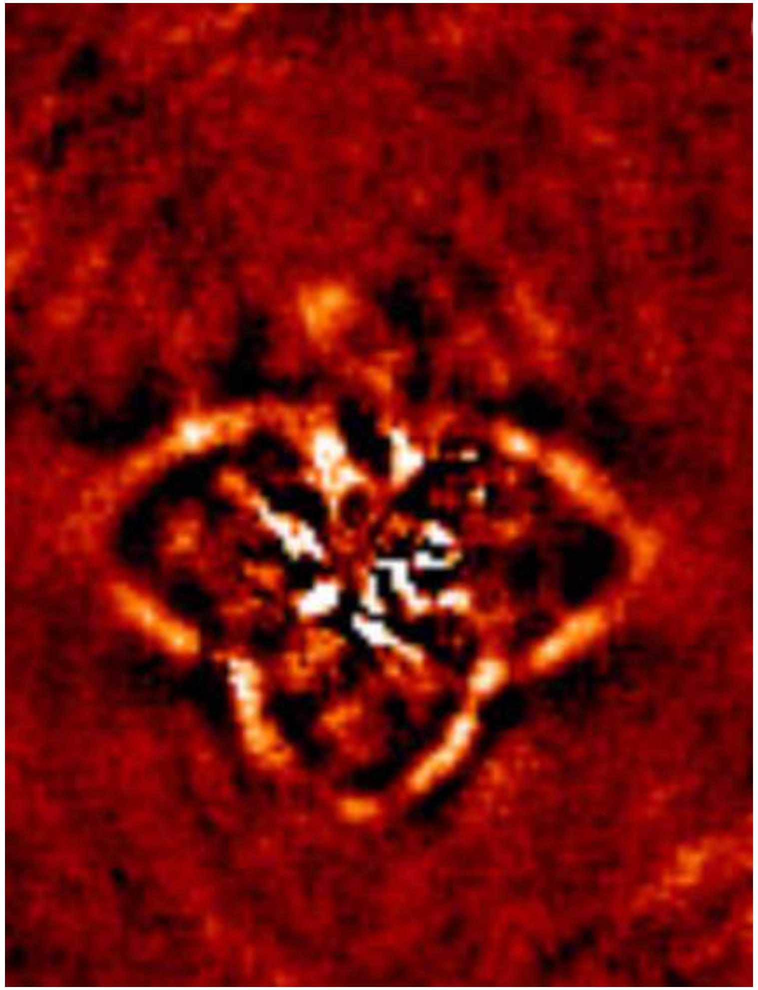


Fidelity or forward modelling capabilities + low computation time

HD141569 in ADI



Perrot et al. 2016

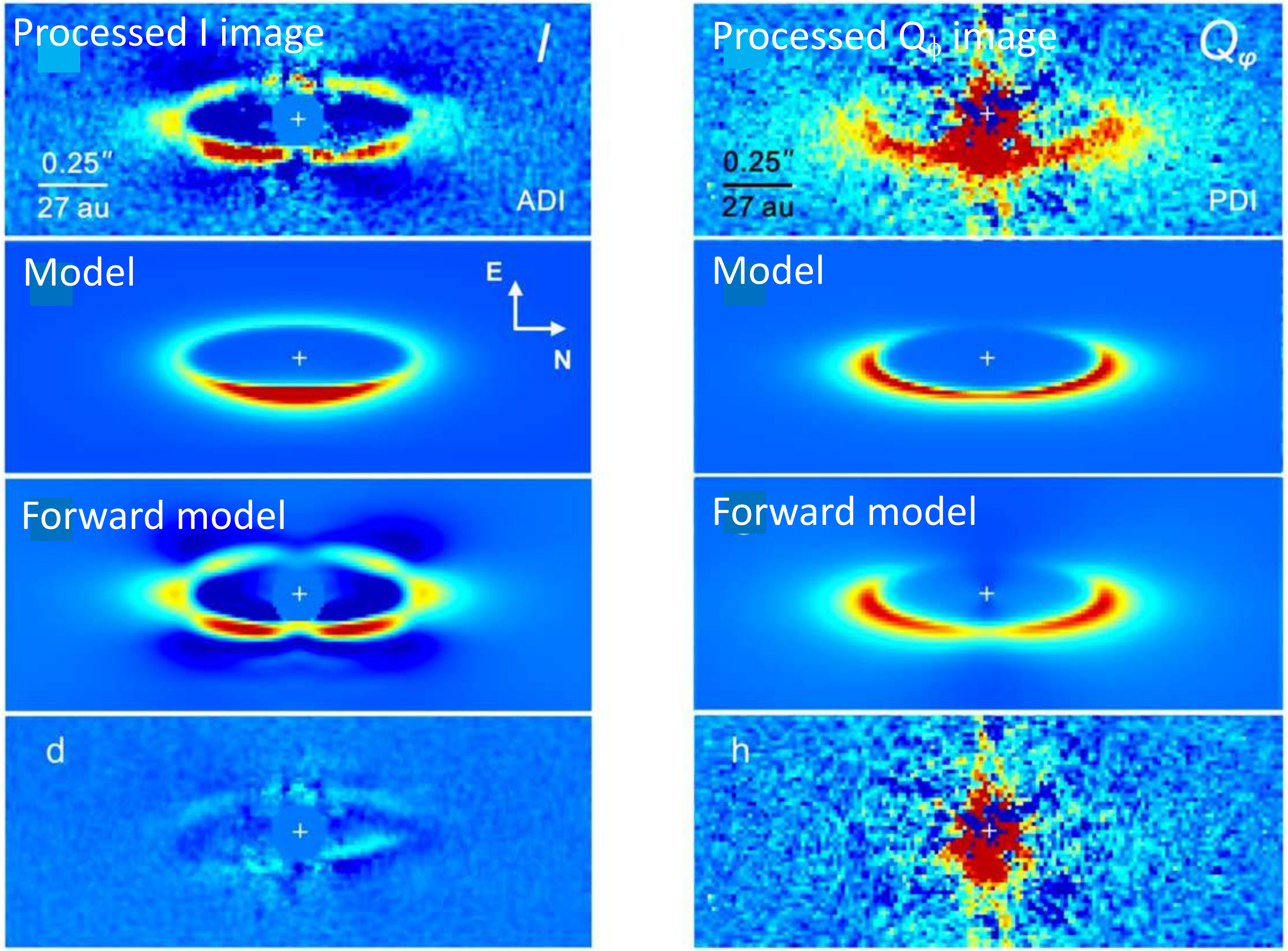


Fake disk injected at 90^{o} to inspect the biases

Fidelity or forward modelling capabilities + low computation time

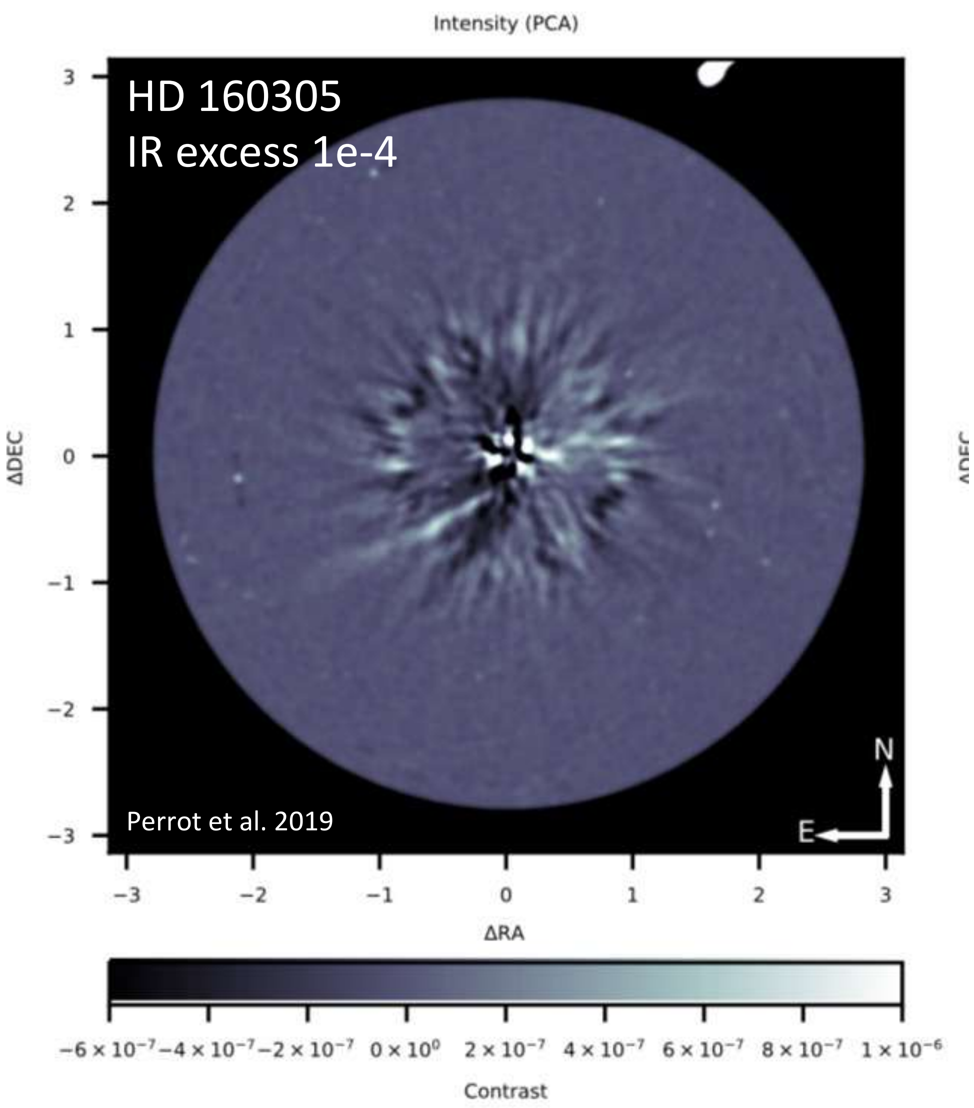
If the geometry is simple, a full forward modelling approach including minimisation can be done

Example on HD117214 with SPHERE
(Engler et al. 2020)

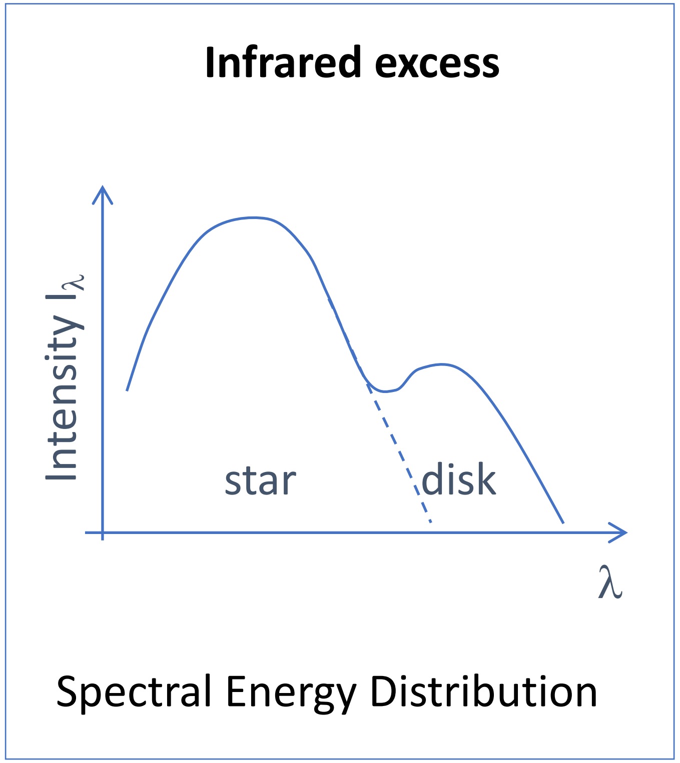


Engler+2020

Sensitivity to faint disks



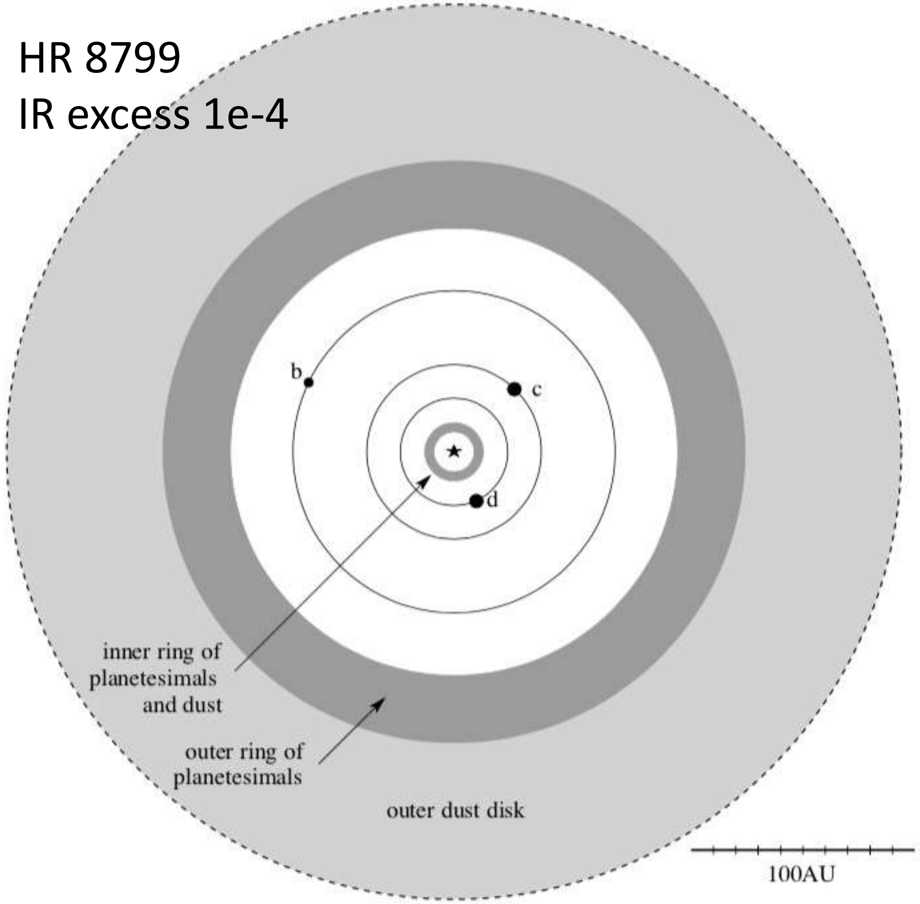
Case 1 : no information beyond the SED
Blind search



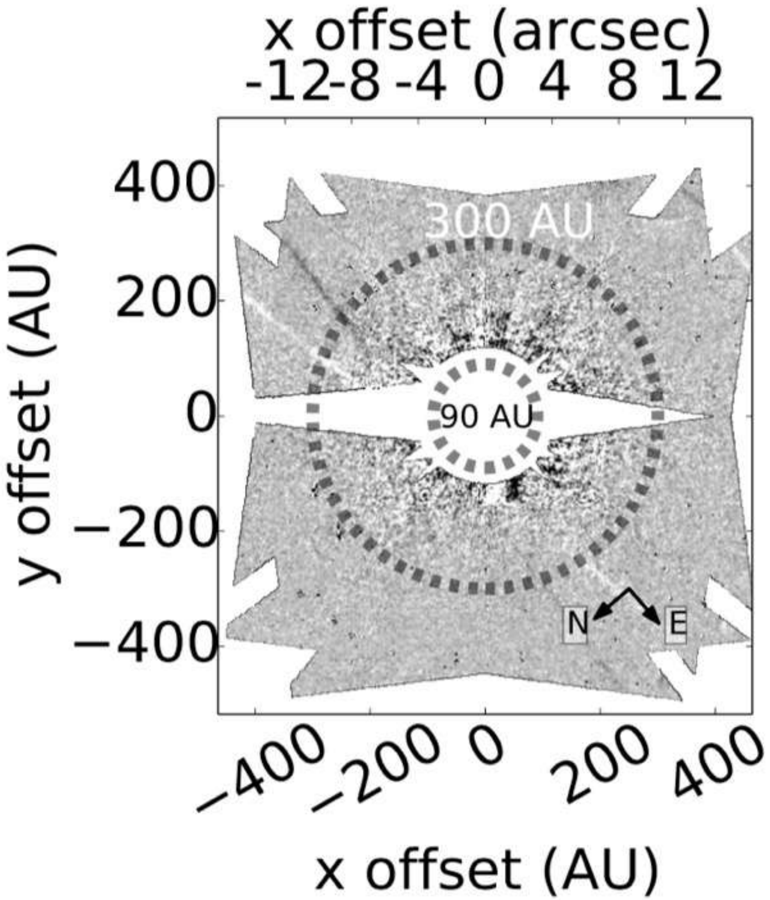
Rule of thumb: IR excess > 1e-4 from the ground

Sensitivity to faint disks

HR 8799
IR excess 1e-4



Case 2 : Inclination is known

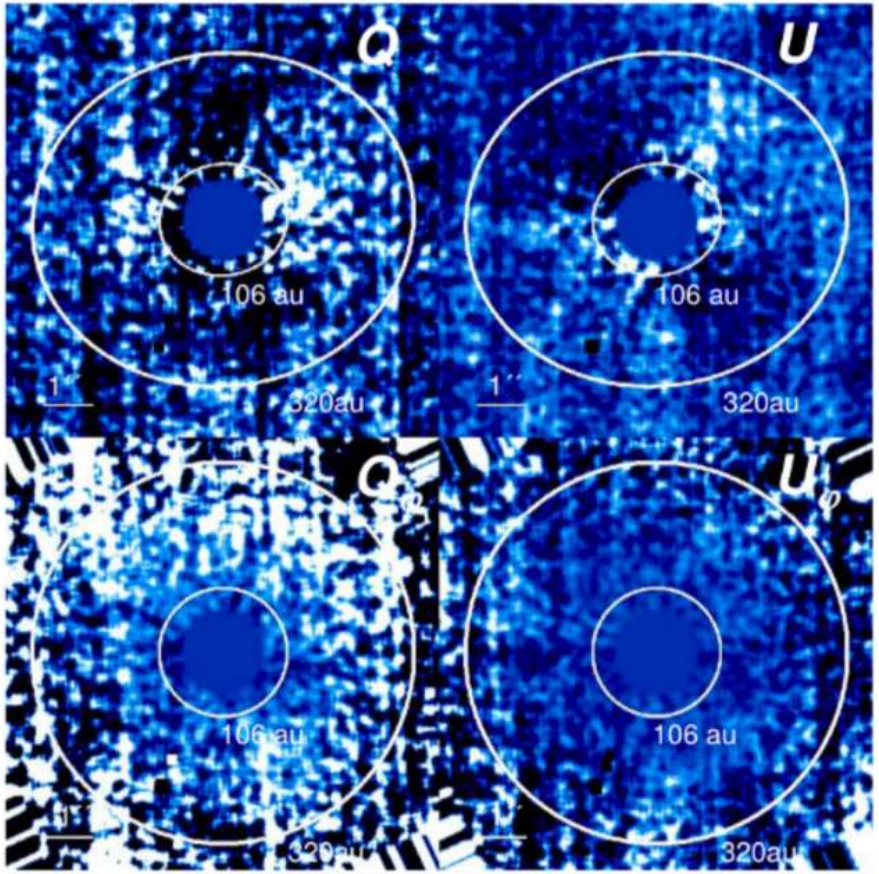


Azimuthal averaging can be used

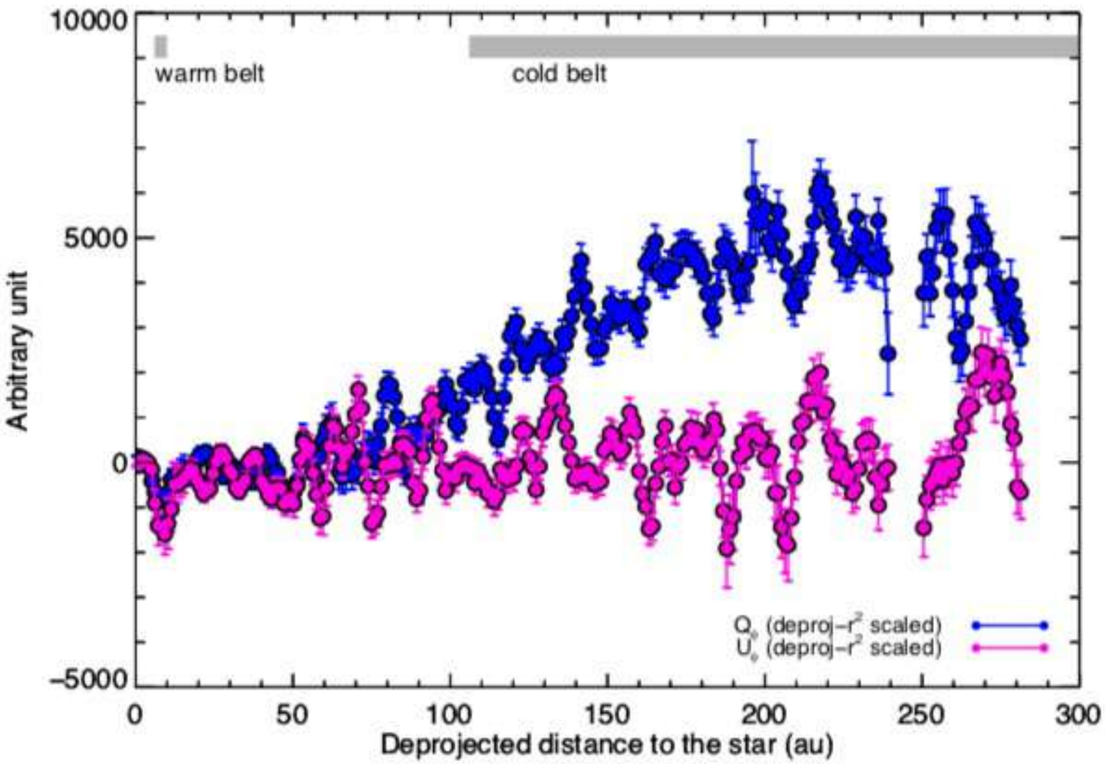
Gerard et al. 2016

Sensitivity to faint disks

HD 95086



Case 2 : Inclination is known



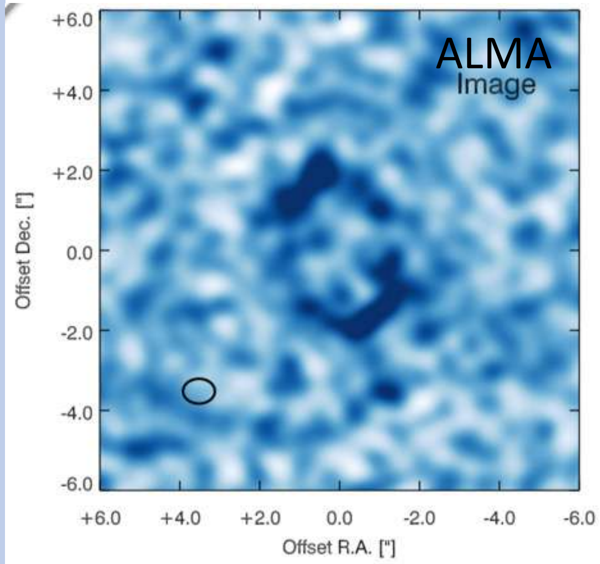
Chauvin et al. 2018

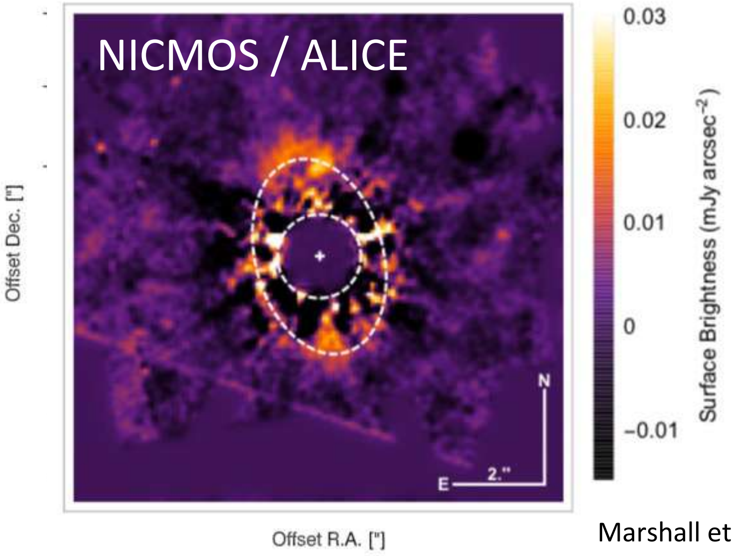
Sensitivity to faint disks

Case 3 : Morphology is known (e.g. from ALMA)

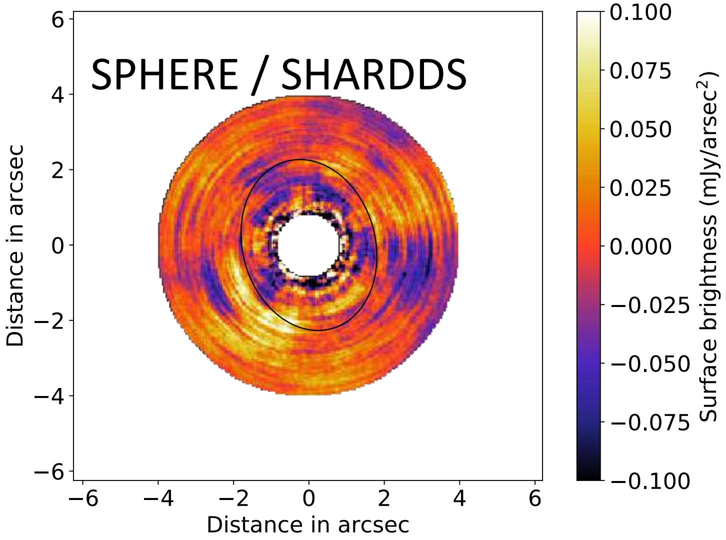
Spatial averaging techniques (spatial binning) can be used

HD105
IR excess 2e-4



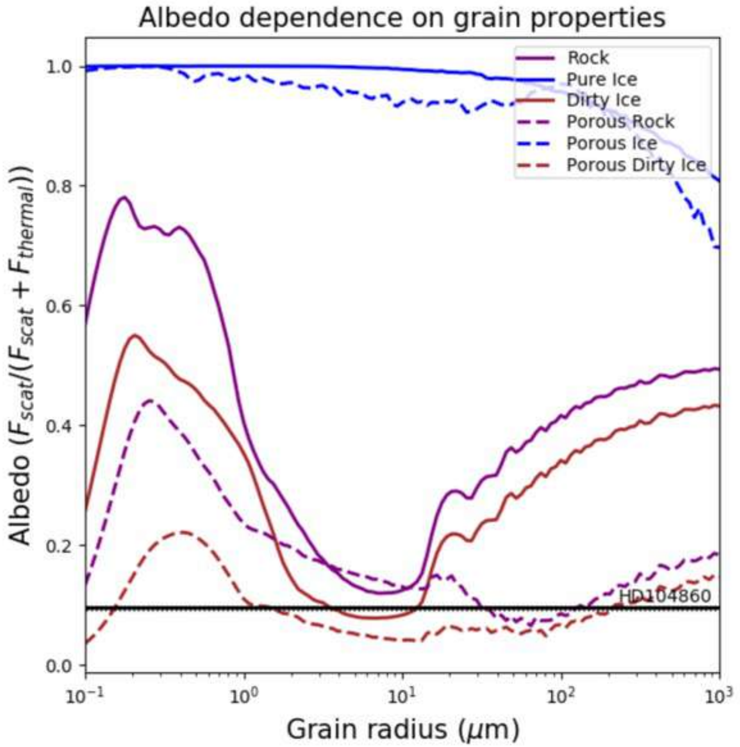


Marshall et al. 2019



Detection limits

Typically expressed in contrast/arcsec^2, mJy/arcsec^2 or mag/arcsec^2
→ can be converted in albedo (with assumptions), and constrain the dust properties



Choquet et al. 2018

In intensity imaging, the algorithm throughput depends on the extension of the disk

No standards for disks detection limits yet

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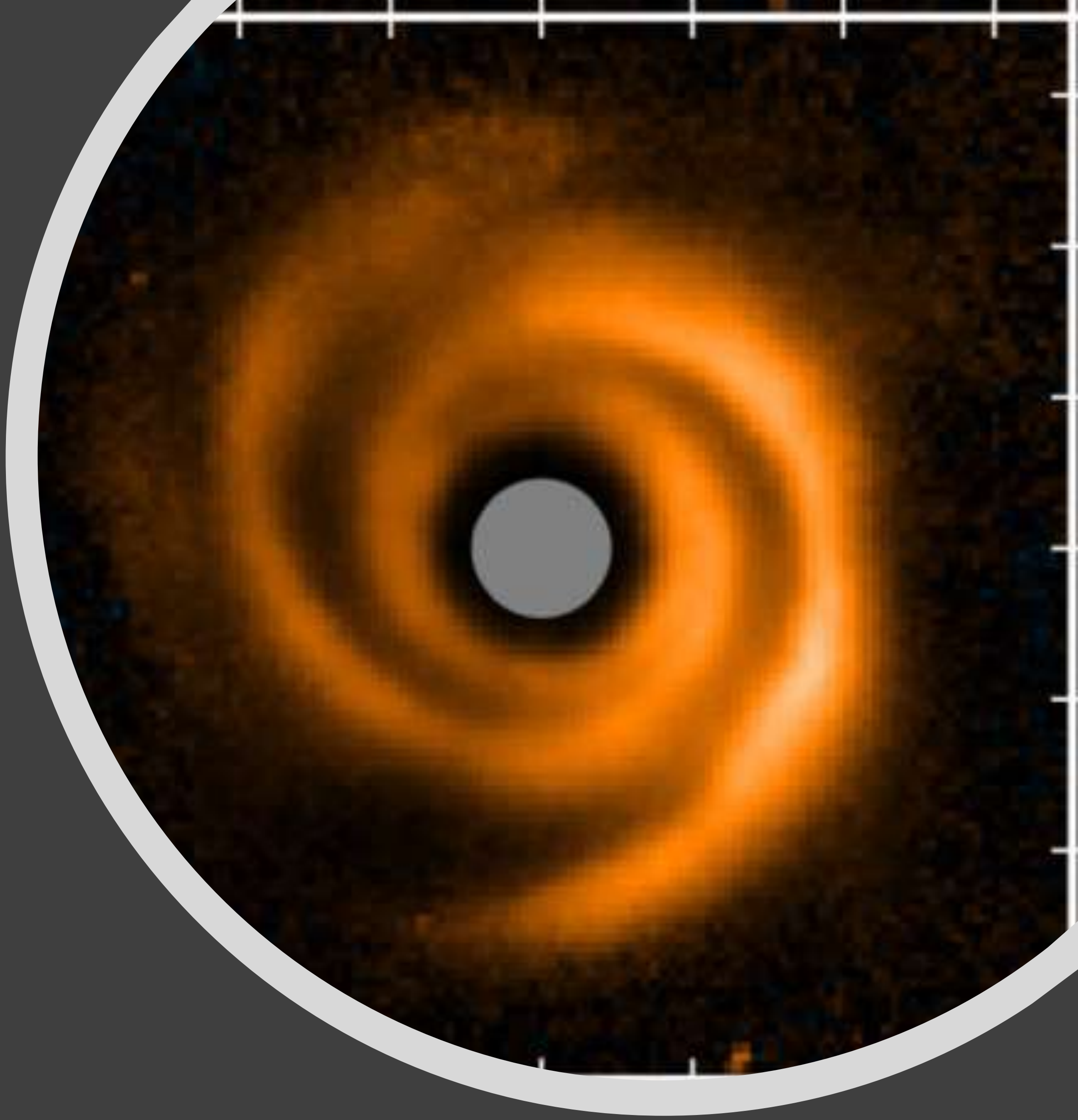
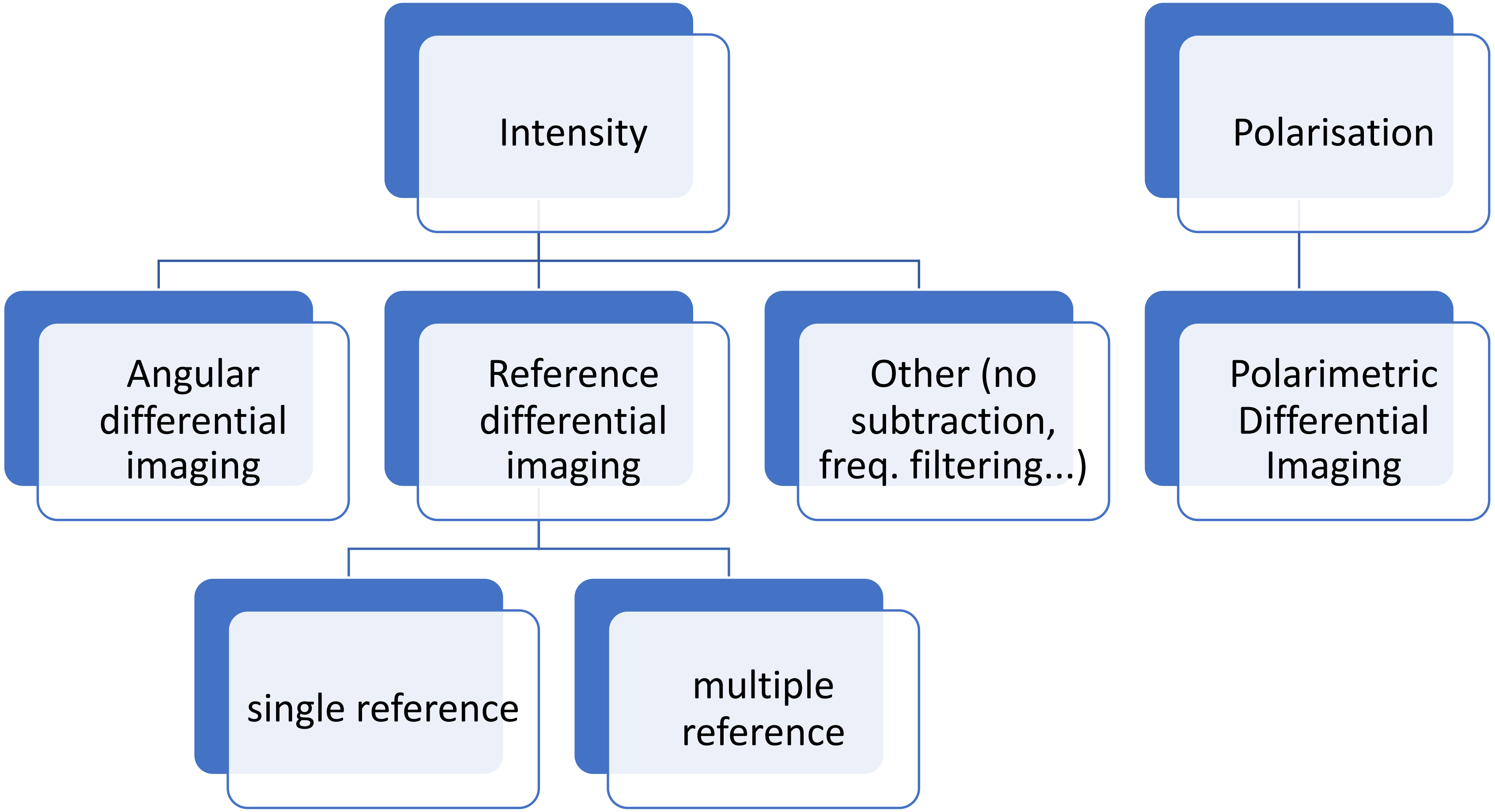
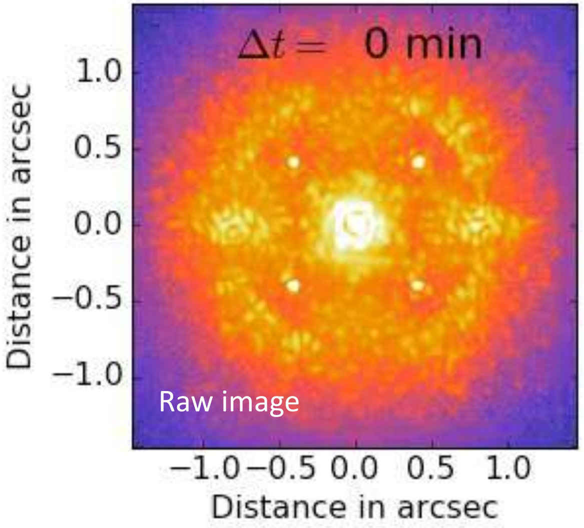


The family tree of disk-friendly techniques



Various techniques, one goal: remove the stellar light by using some diversity parameters

Angular differential imaging of disks



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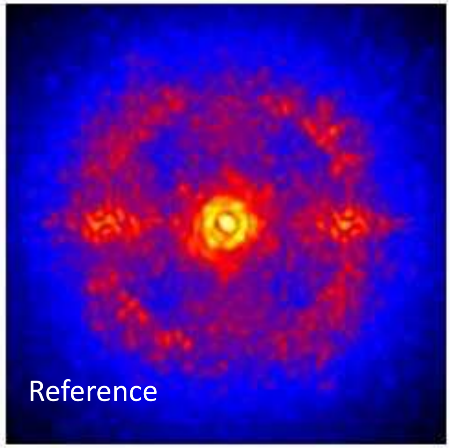

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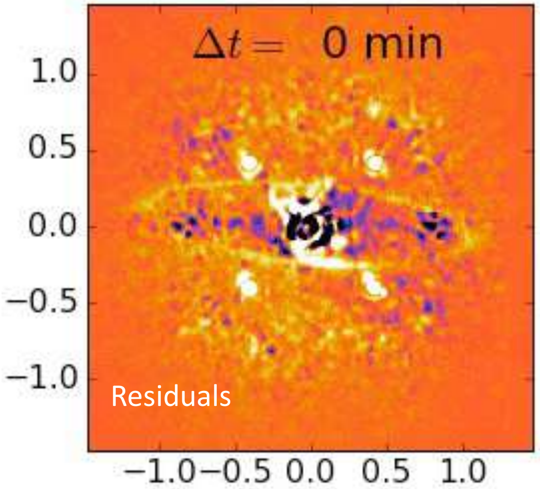
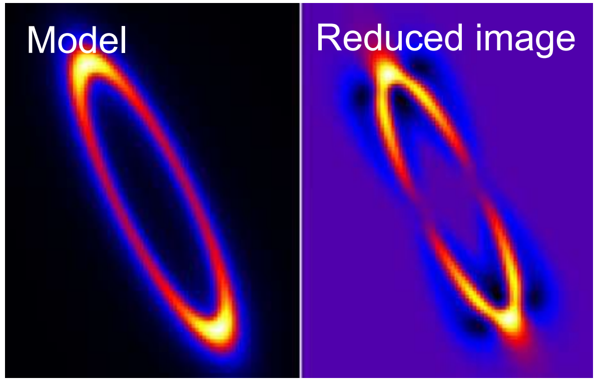


Reconstruction Algorithm (median, LOCI, PCA…)

$$\sum_{i=1}^{n} \alpha_i I_i$$



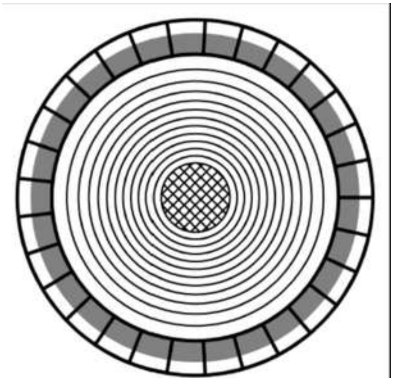
Self-subtraction dependent on the azimuthal extension of the object

Milli et al. 2012
Esposito et al. 2014

Some workarounds

Conservative parameters

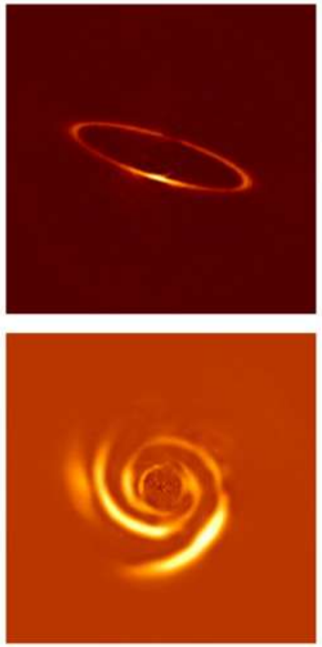
- Large optimization regions or full frame



- Few modes subtracted
- Positive coefficients, sparcity (dLOCI, NMF)

Pueyo et al. (2012) Soummer at al. (2011), Ren et al. 2018

Iterating



Pairet et al. 2018

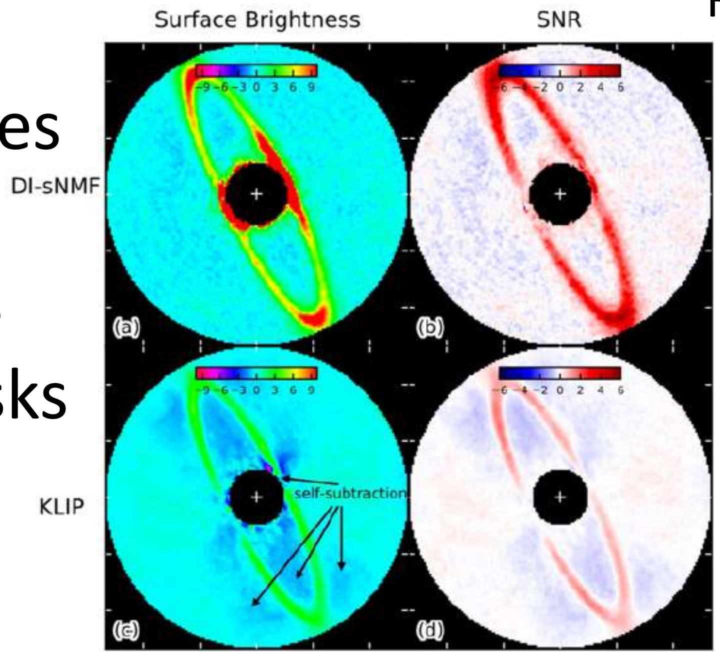
Masking

- Binary mask on the disk signal
- Preserves the disk but reduces the S/N
- Not applicable for pole-on disks

Pueyo et al. 2012, Milli et al. 2012

Data imputation

NMF with masked data



Ren et al. 2020

Inverse approach

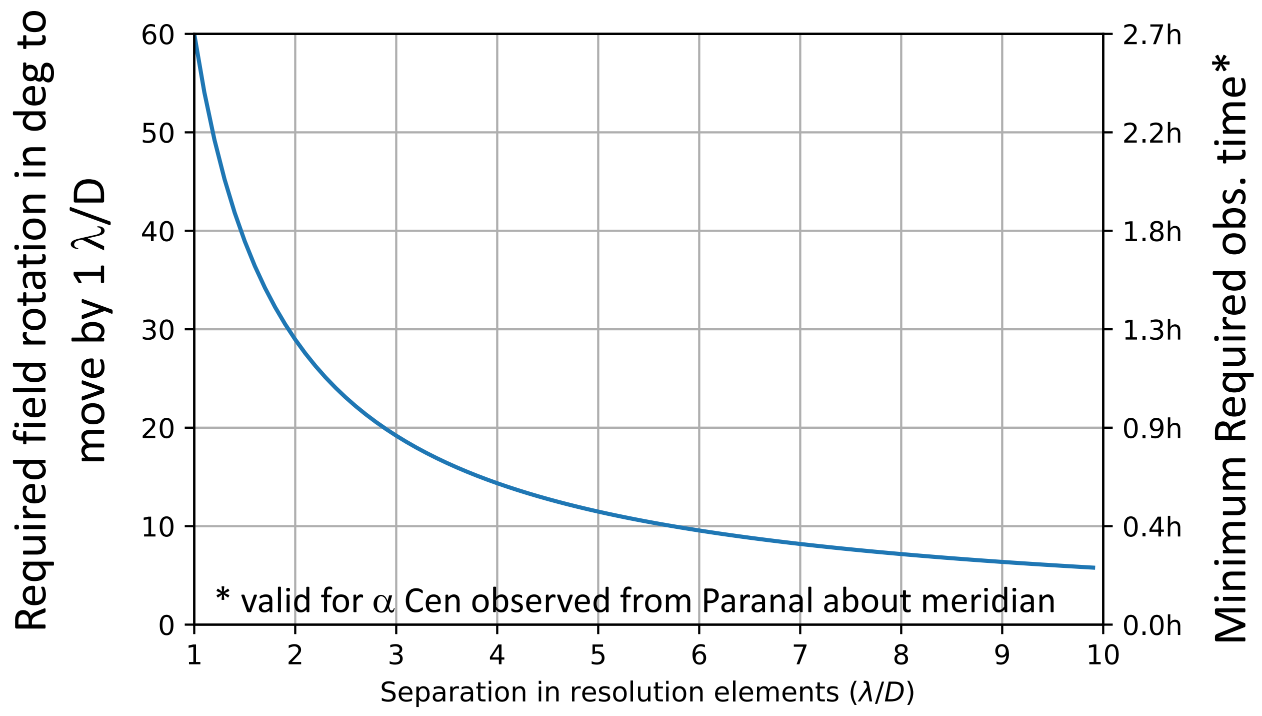
MAYONNAISE

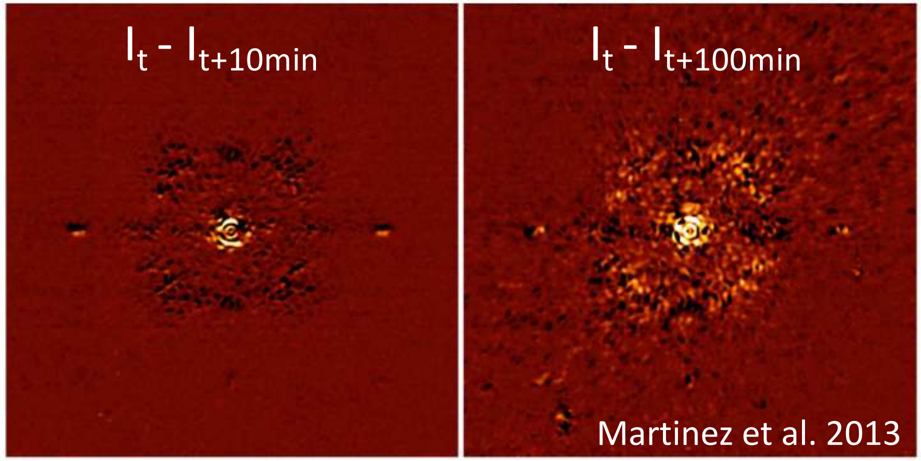
REXPACO

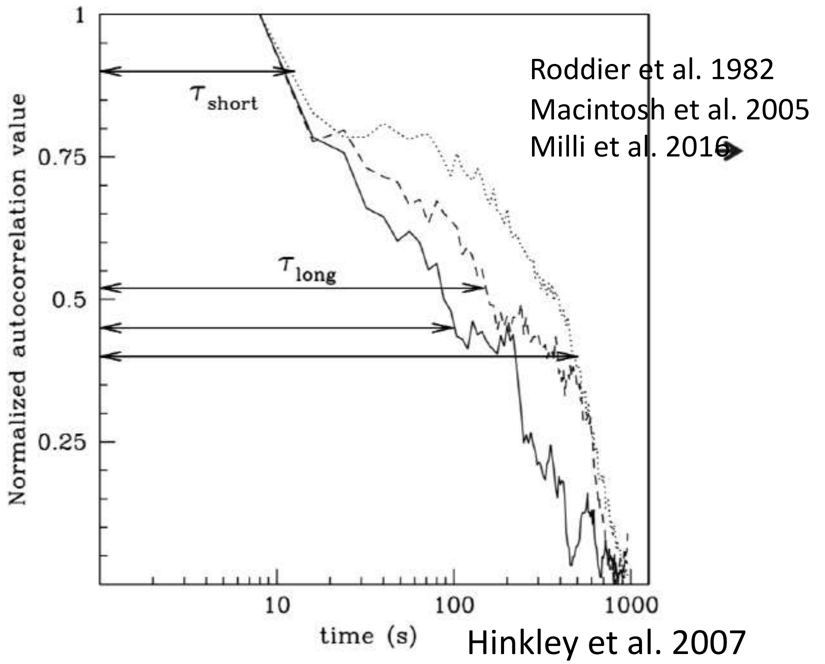
Next talk by Olivier F.

Limitations of Angular Differential Imaging (ADI)

Efficiency depends on field rotation and PSF stability





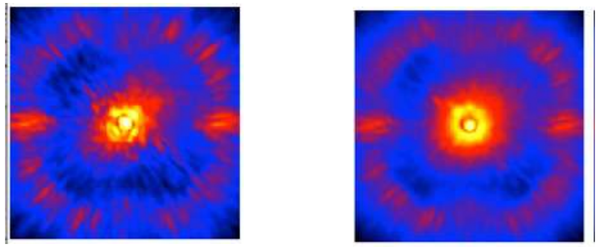


Inefficient at short separations

Reference differential imaging

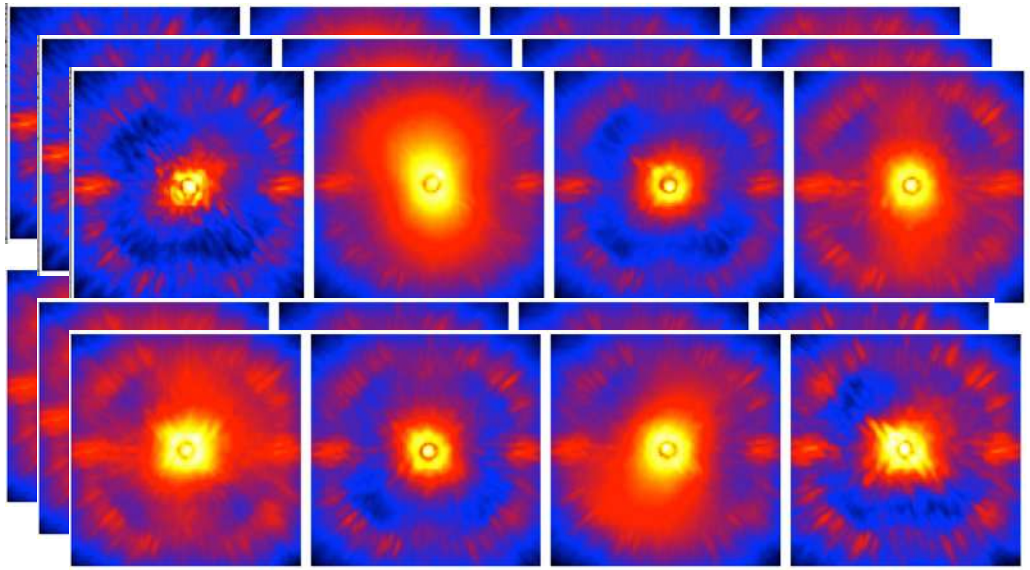
A) (Carefully selected) **<u>Single reference</u>**

- similar visual magnitude for AO performance
- close on sky and in time
- similar turbulence conditions

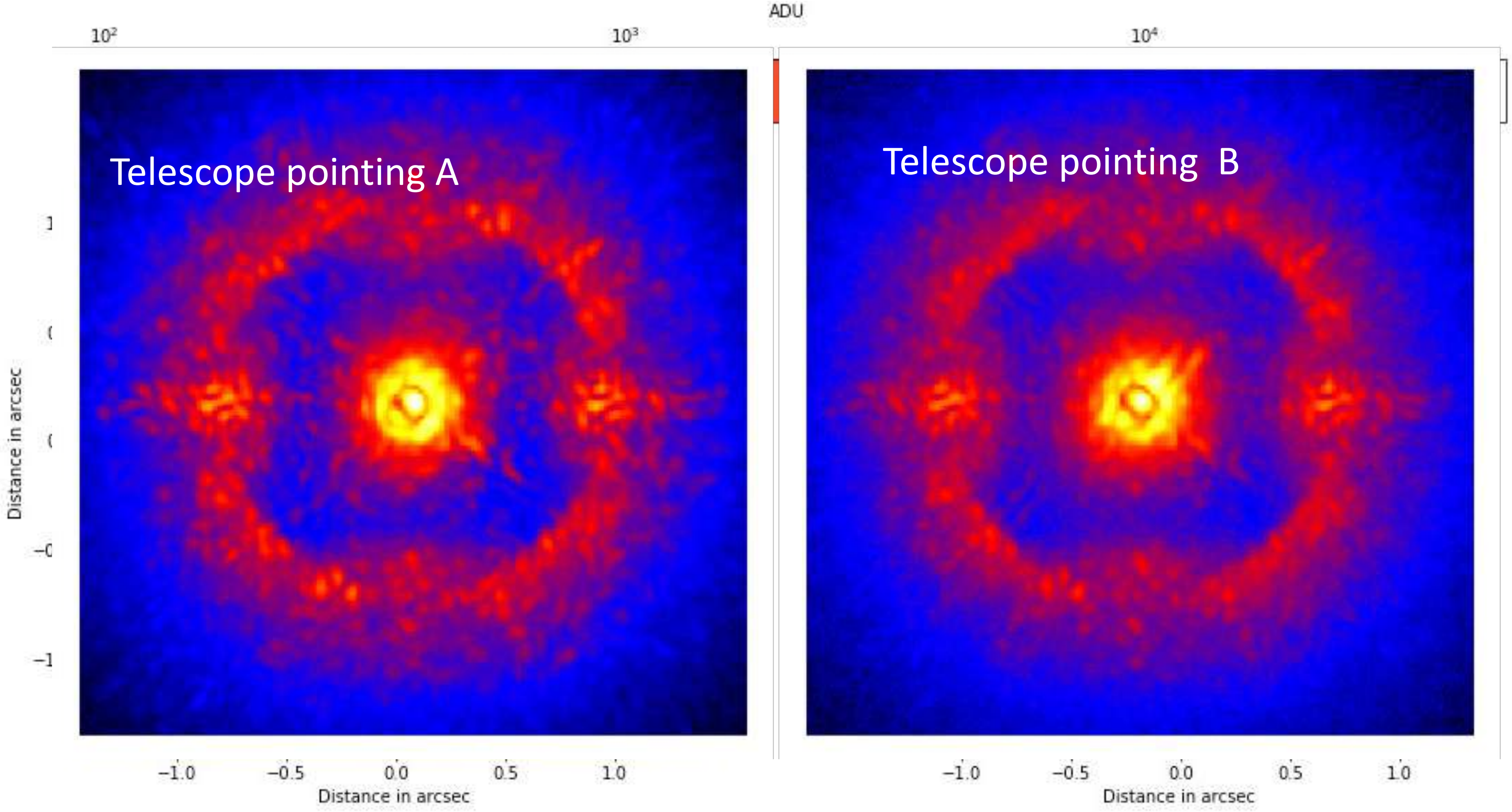


B) **<u>Large library of references</u>**

- Needs a large set of images available
- No additional observing time required
- Needs to identify the subset of adequate targets



Single reference differential imaging

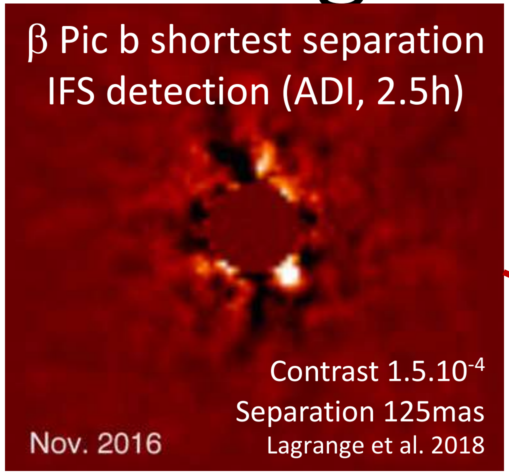


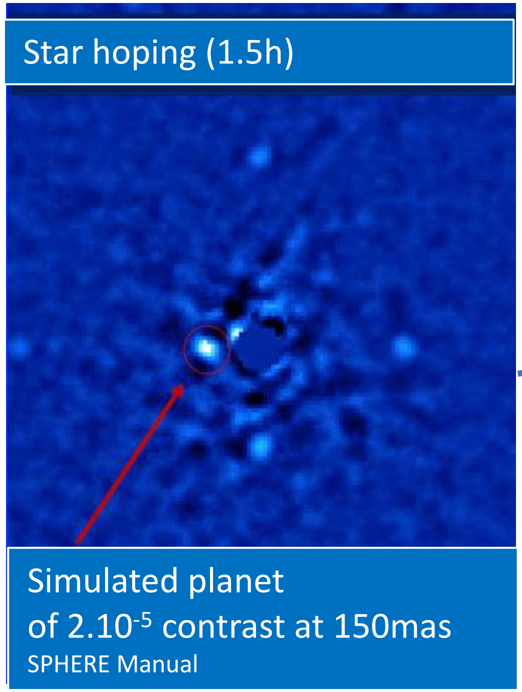
Example with SPHERE IRDIS on a binary system with 9” separation and similar R magnitude

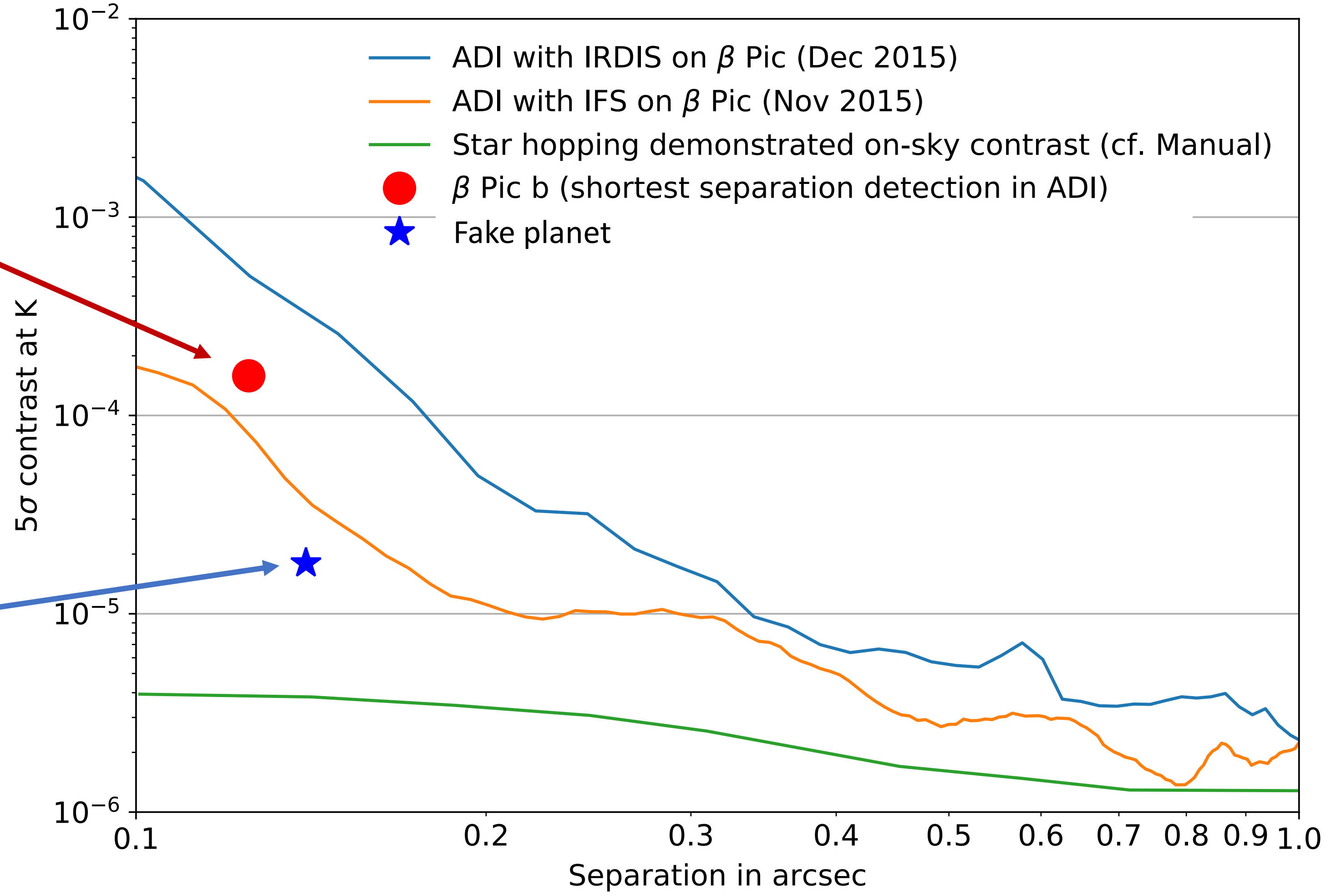
Combined offset done at the telescope → fast transition between A and B less than 20s (best case)

Duty cycle of 2min20

Single reference differential imaging: results

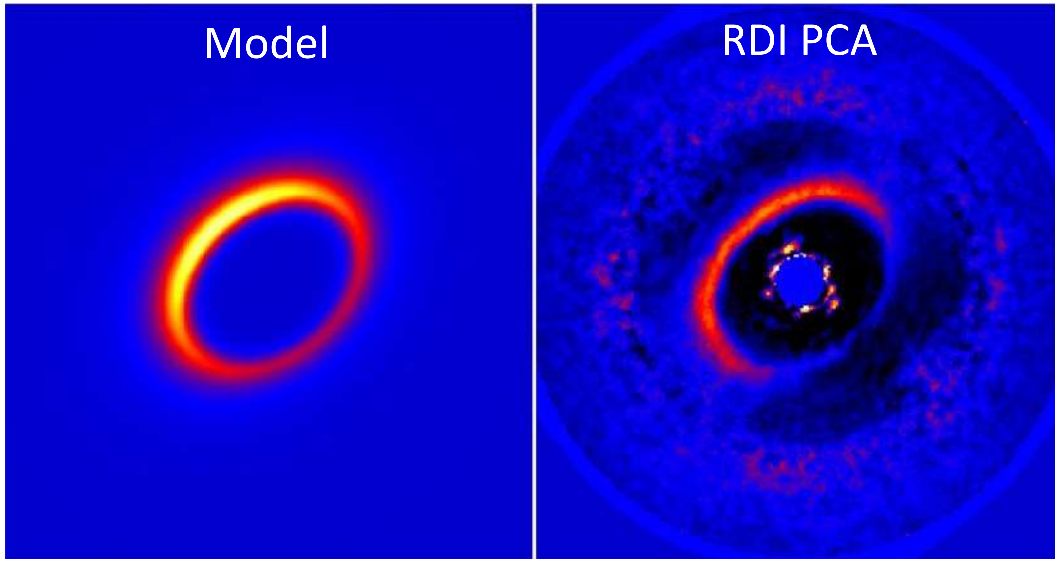


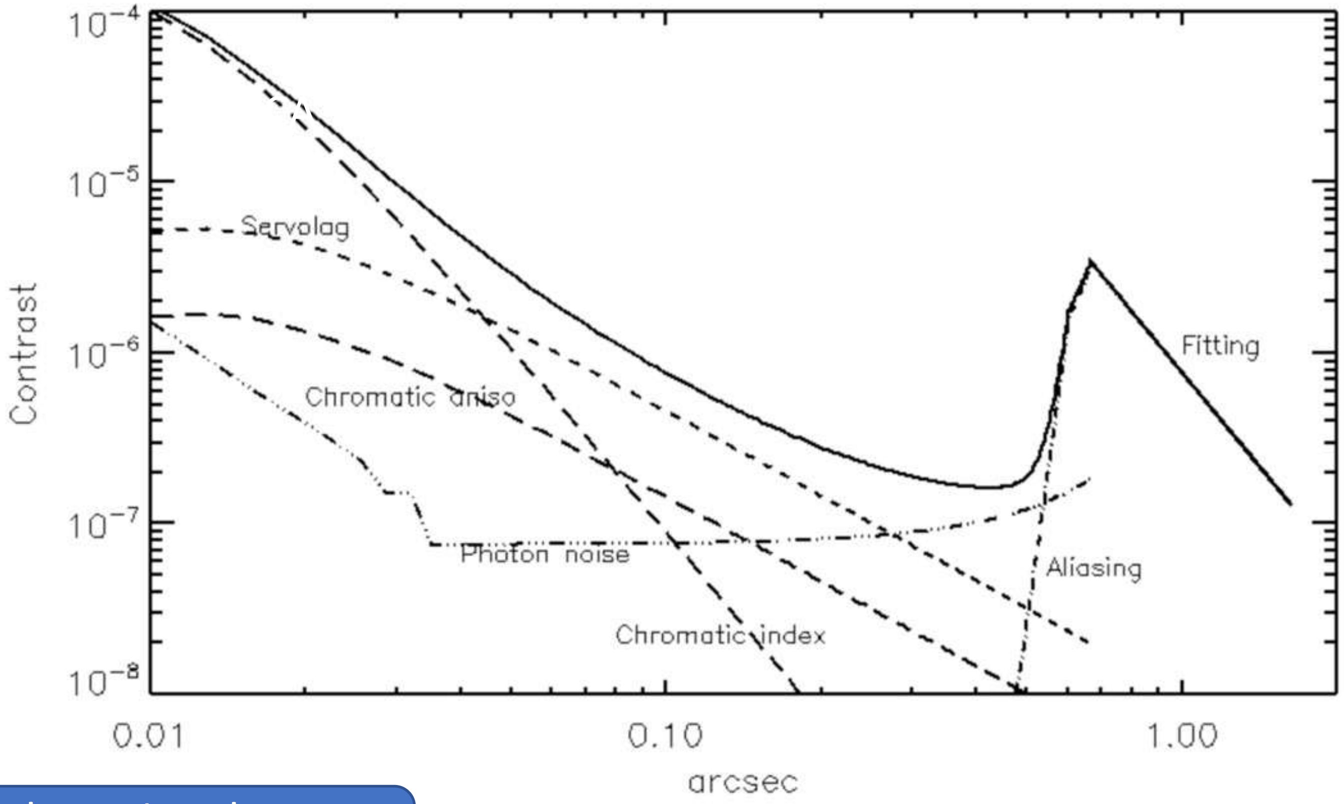




SPHERE manual, Wahhaj et al. 2021

Single reference differential imaging: results

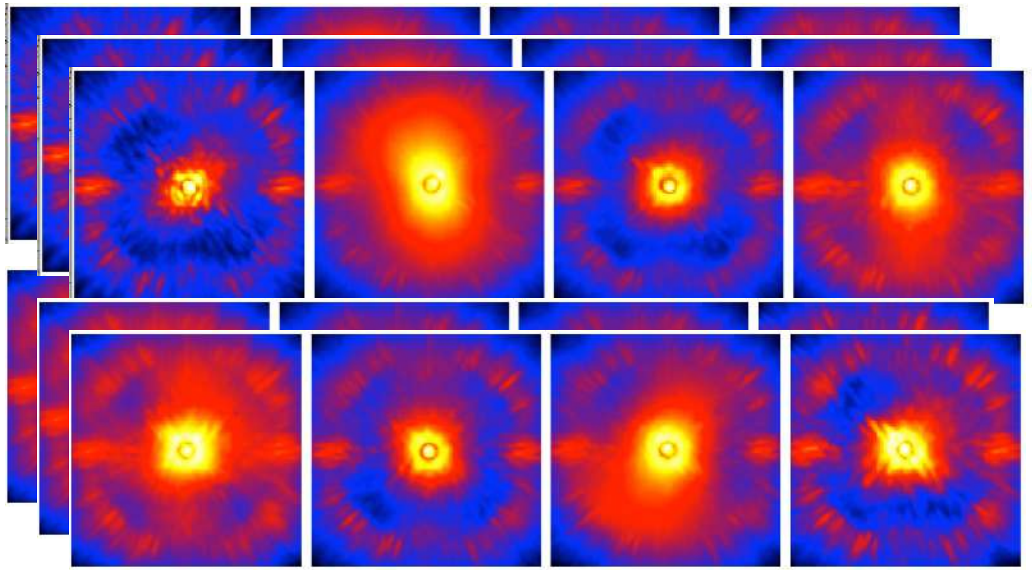




No self-subtraction, some over-subtraction due to different profiles and gradients

Multiple reference differential imaging

Master set of possible reference frames

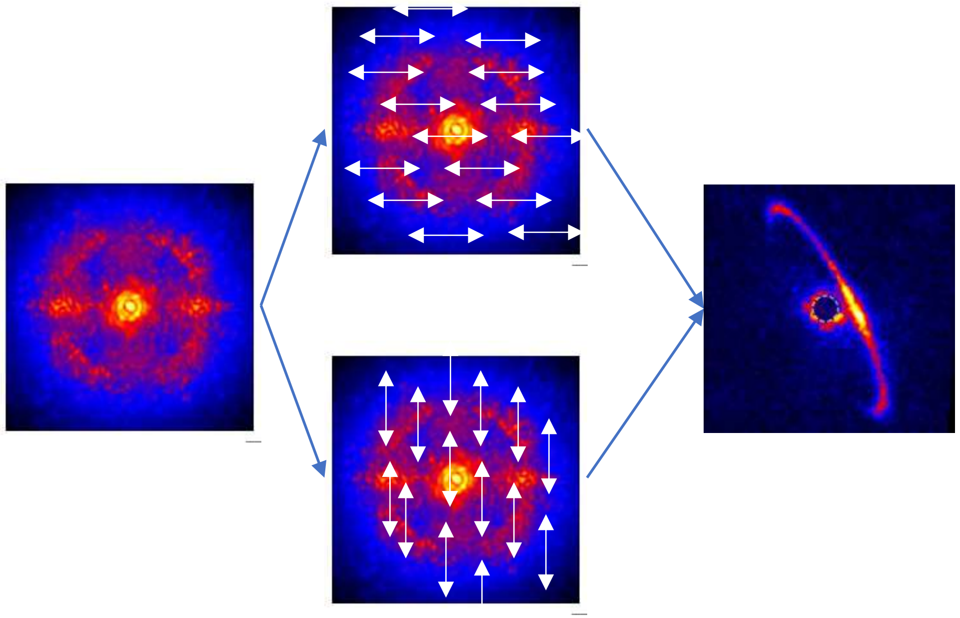


Benefits:

- Large number of images available as references in the archive
- No additional observing time required to observe a reference star
- No sidereal timing constraints compared to ADI

See talks specific to RDI this afternoon

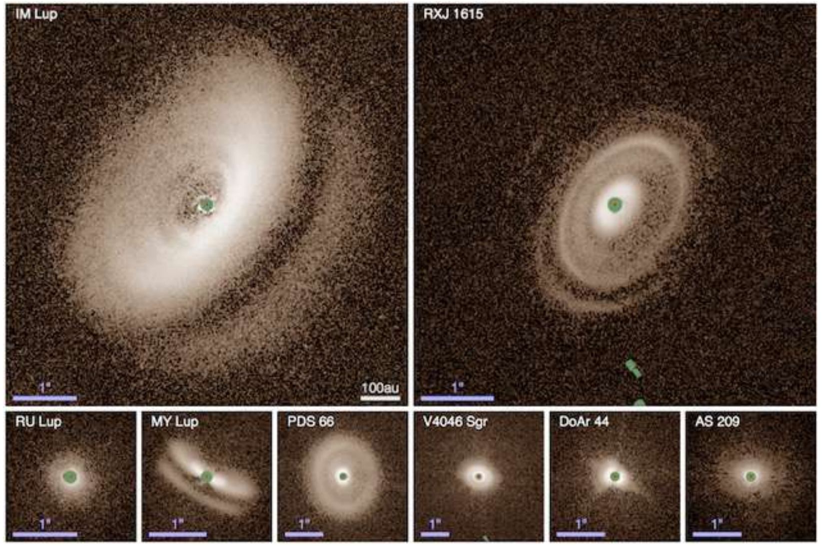
Polarimetry



Instantaneous differential imaging
Insensitive to the disk extension

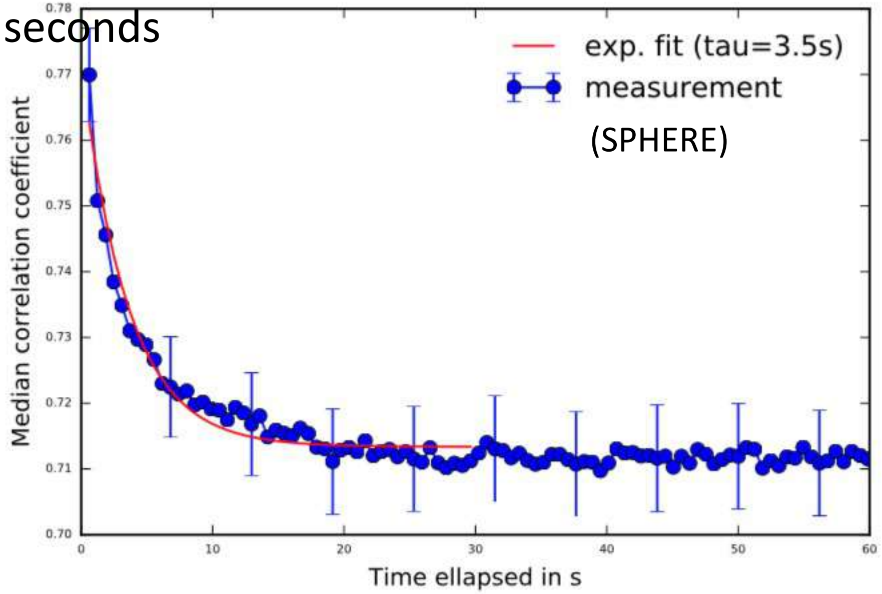
Possibility to deconvolve (Denneulin et al. 2021)

Efficient technique for bright protoplanetary disks



Avenhaus et al. 2018

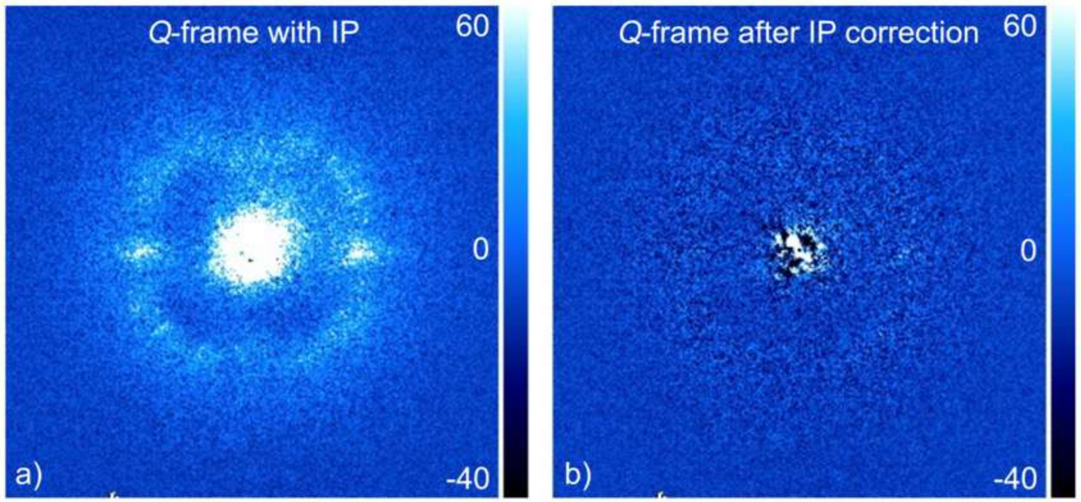
Fast decorrelation of the speckles over a few seconds

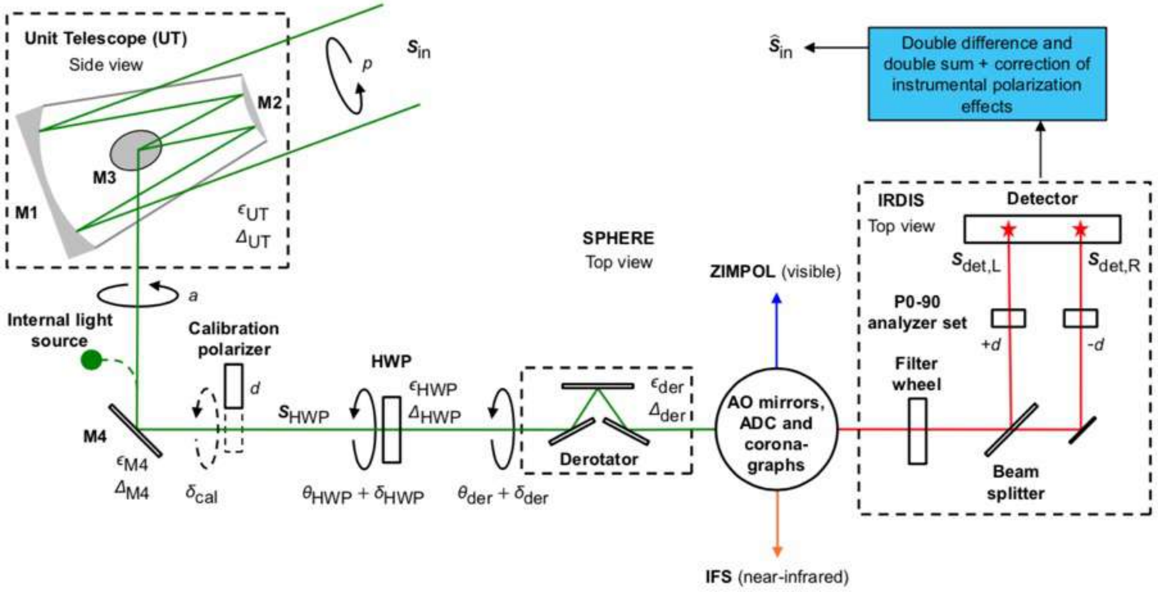


Milli et al. 2016, see also Hinkley et al. 2007

Polarimetry: challenges

- Accuracy of instrumental polarization + cross-talk correction: ~0.1% with current xAO systems, based on a Mueller matrix formalism





De Boer et al. 2019, van Holstein et al. 2019, Millar-Blanchaer et al. 2017

- Unresolved polarimetric signal from central source → U_ϕ signal

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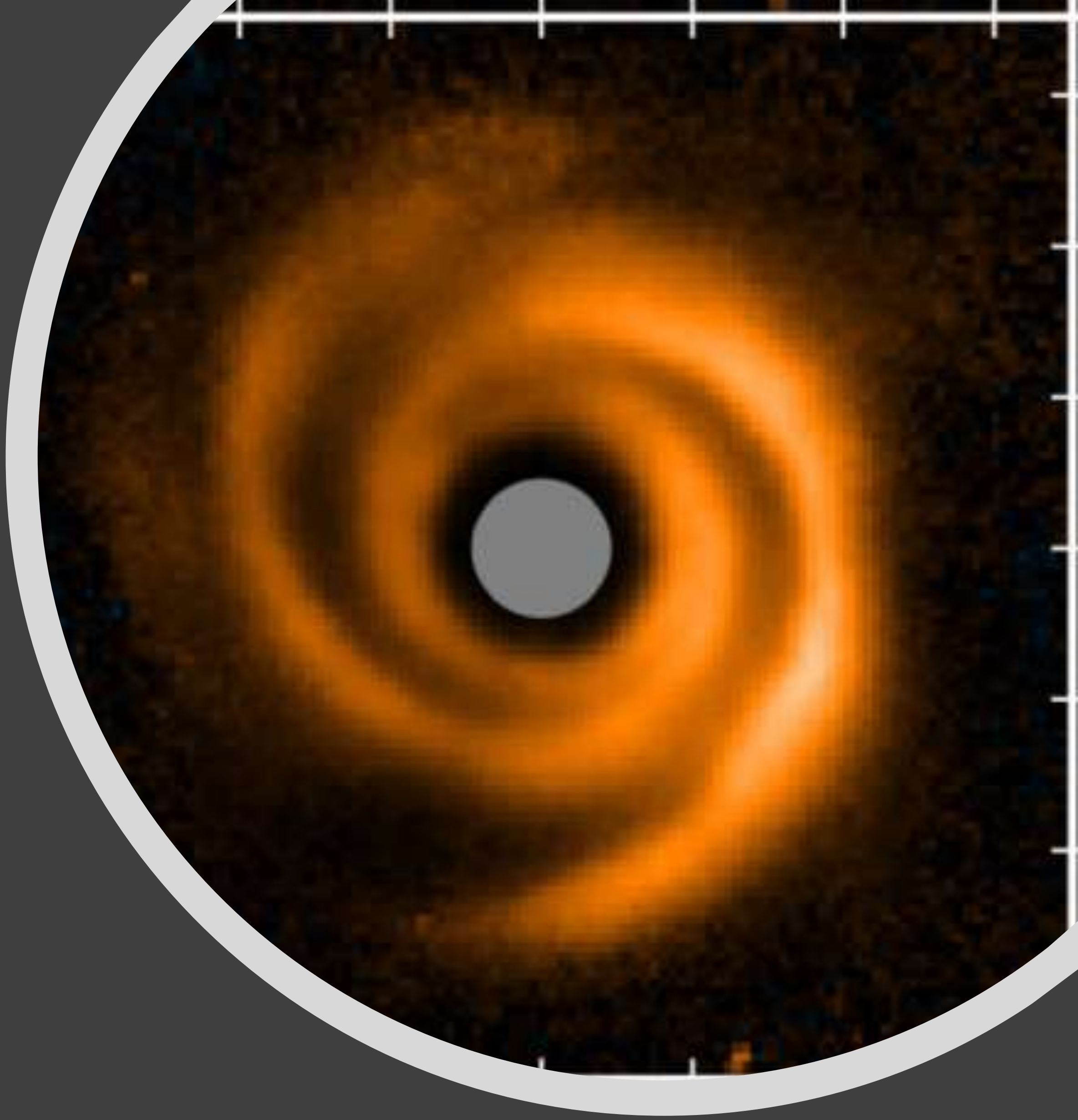
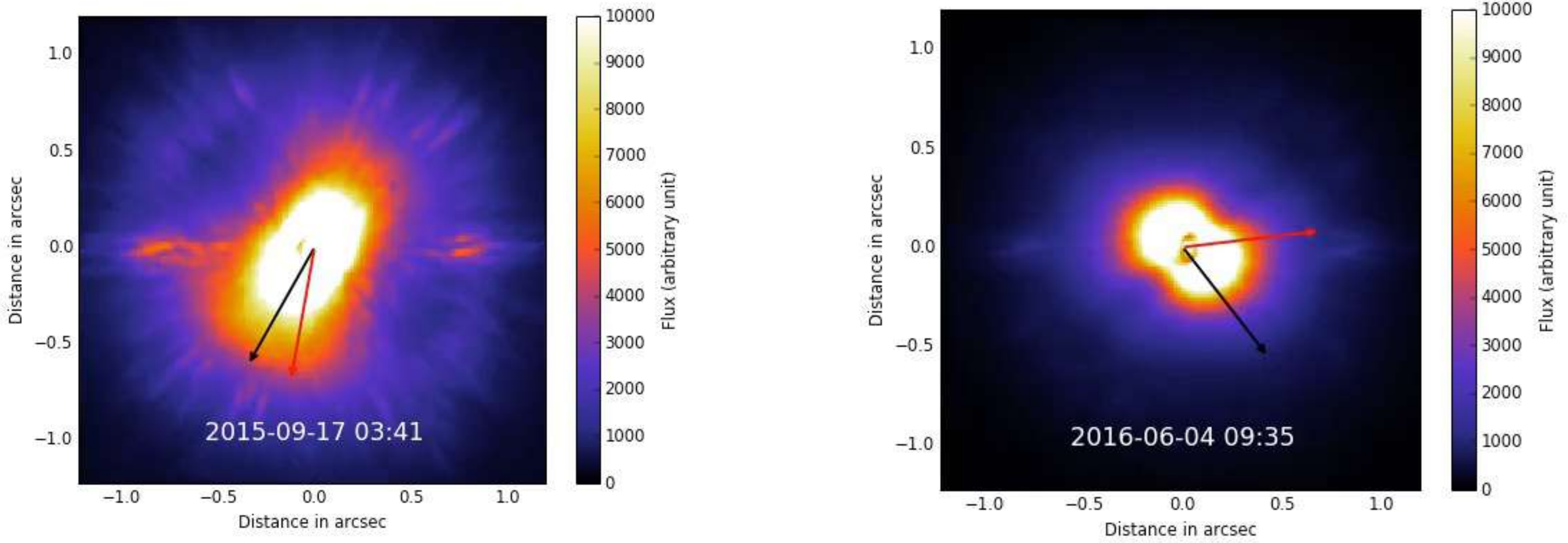


Servolag error aka wind-driven halo

SPHERE H band images



→ 200mbar (~12km) wind direction (forecast)

→ wind direction on the platform (measurement)

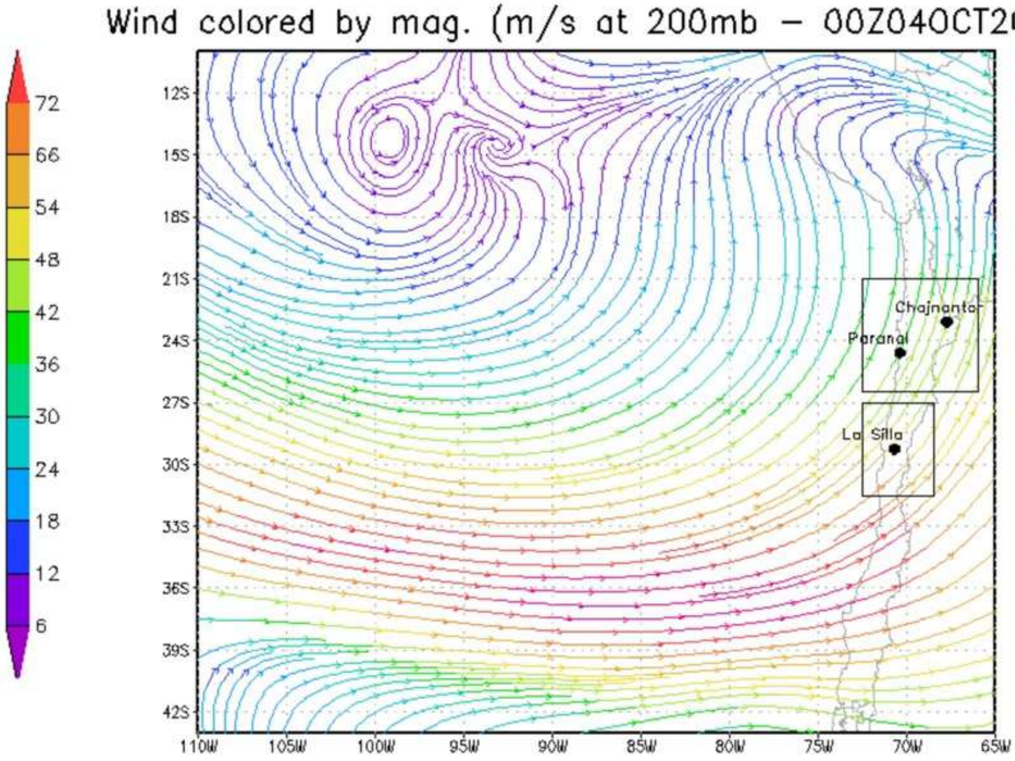
Fixed on sky → angular diversity does not work anymore

Cantalloube et al. 2018, 2019, 2020,Madurowicz et al. 2019

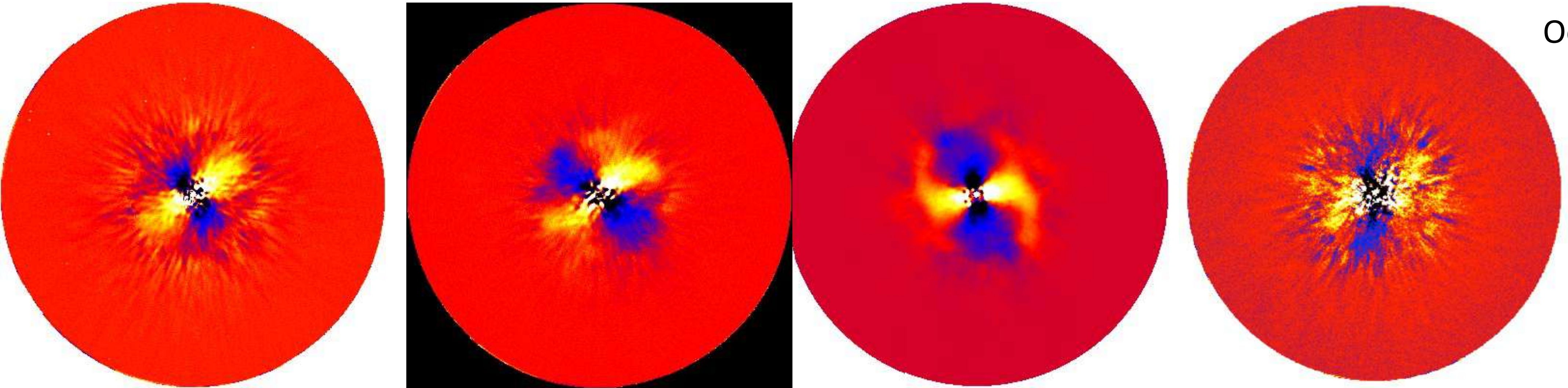
Servolag error aka wind-driven halo

Strong altitude winds create a PSF elongation (rotating with the sky in pupil-stabilized mode)

Ways to disentangle: 2nd epoch, PSF reconstruction techniques, weather cross validation



Typical post-processed images in ADI

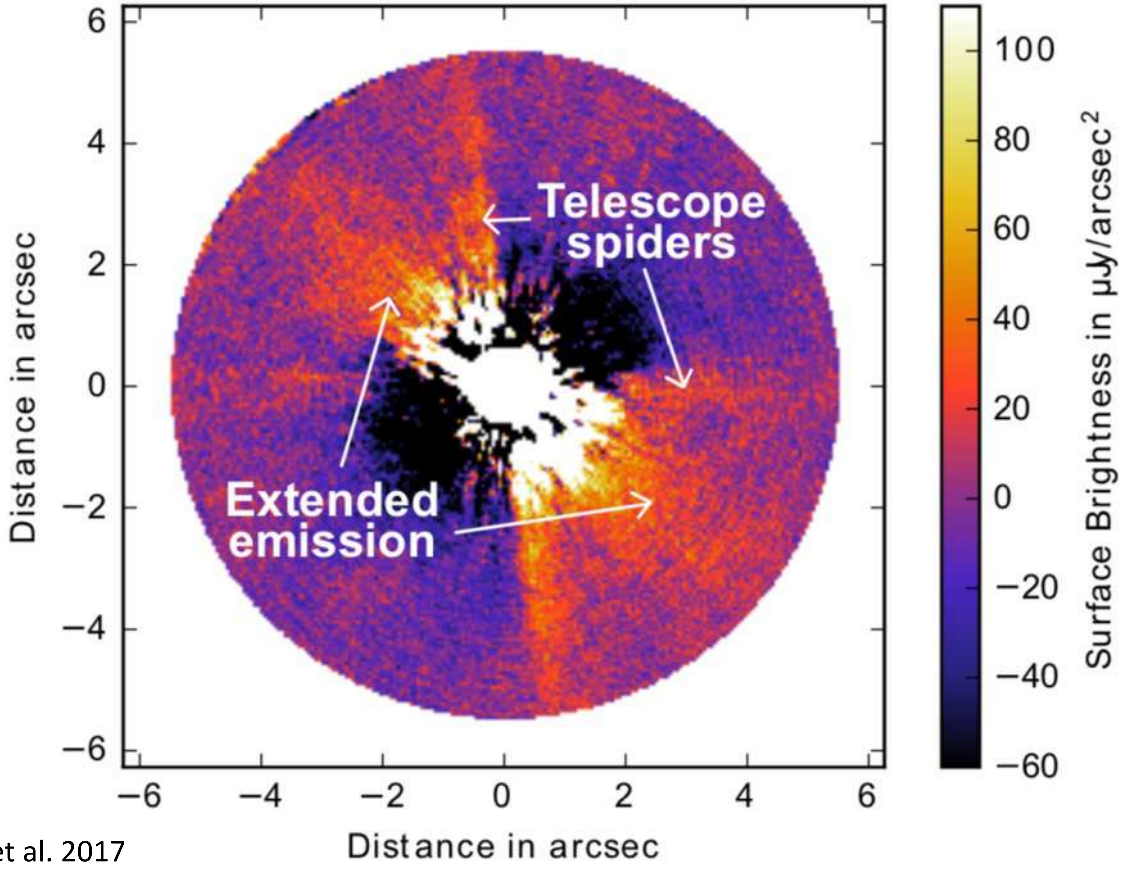


Occurs for τ_0<2-3ms

Cantalloube et al. 2020

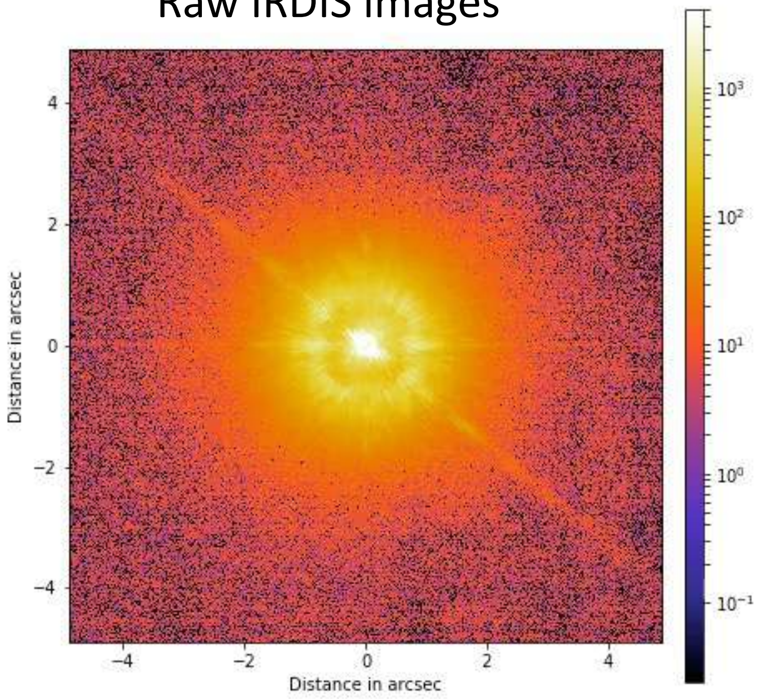
Extended signal identification

HD206893

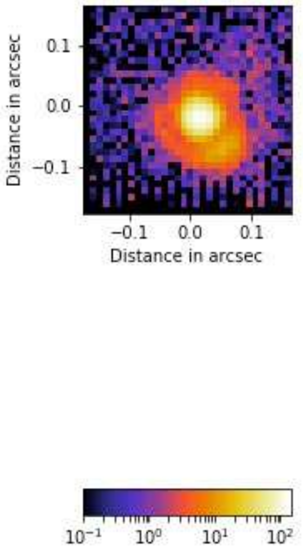


Milli et al. 2017

Raw IRDIS images



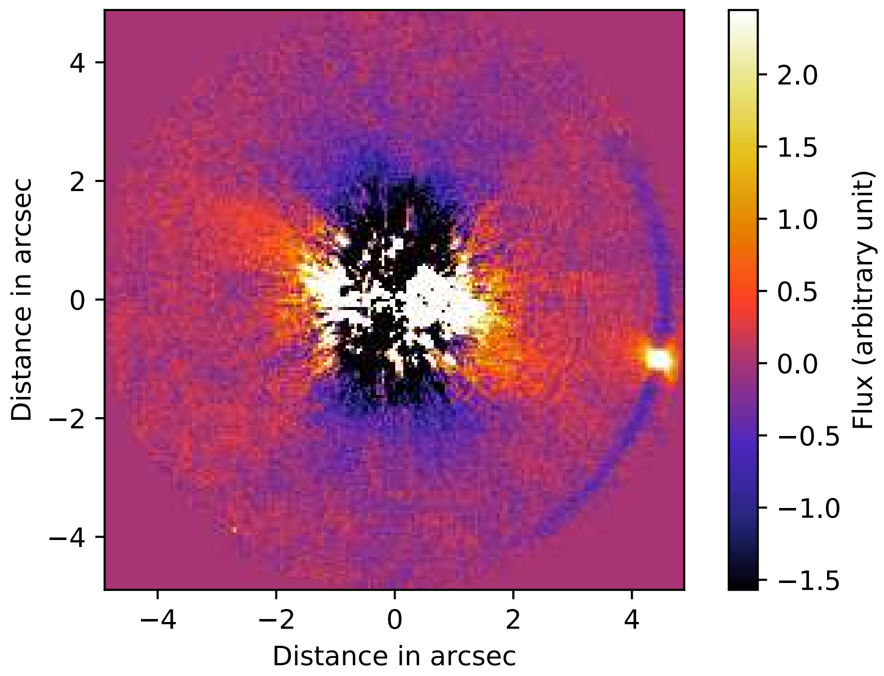
DTTS



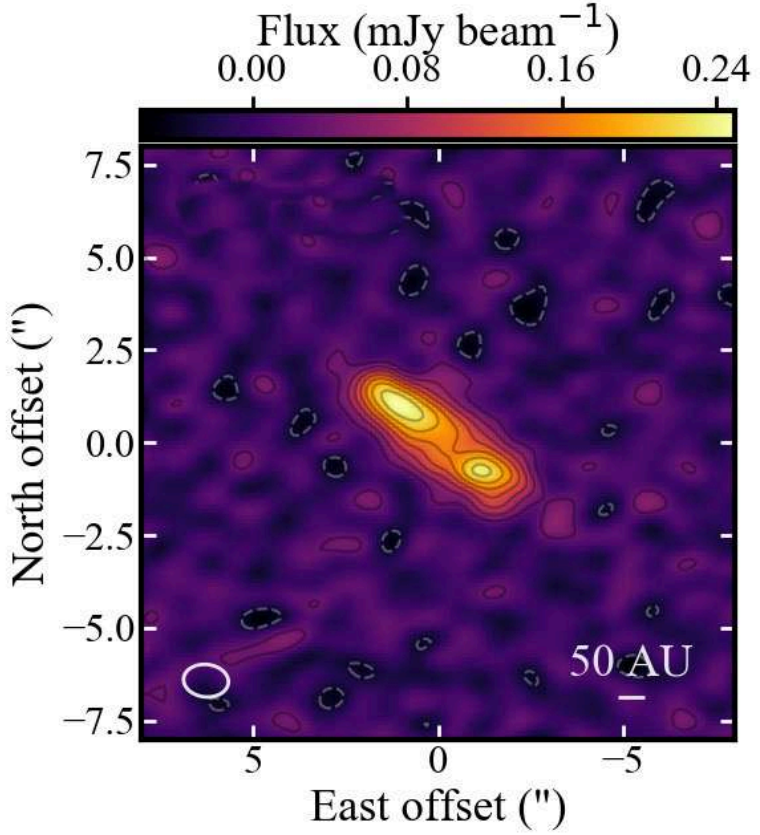
Culprit: Low Wind Effect

Similar cases with mm-bright disk and scattered light faint disk

SPHERE (SHARDDS survey)

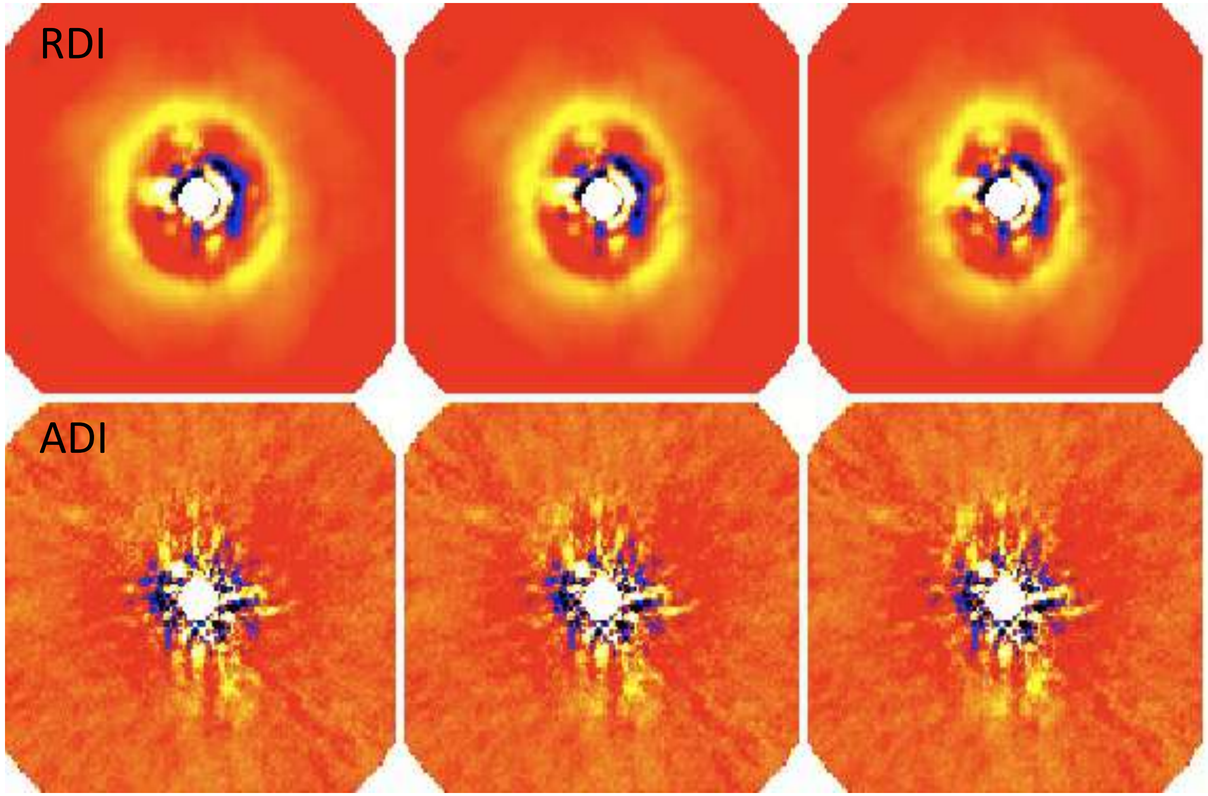


ALMA (REASONS survey)



Matra et al in prep.

Detection limits



Contrast : 1 x 10^{-4}
Inclination: 20°

Contrast : 1 x 10^{-4}
Inclination 30°

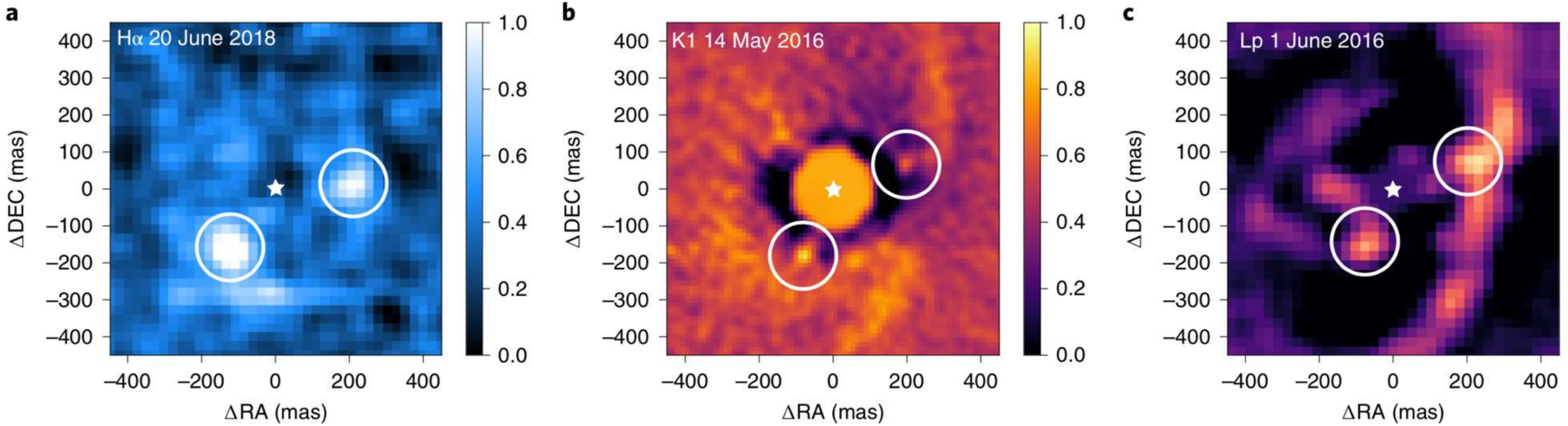
Contrast : 1 x 10^{-4}
Inclination 40°

Dependence on the disk geometry

- Inclination
- Width and radius
- Azimuthal extension

Separate disk features from point sources

PDS 70 system

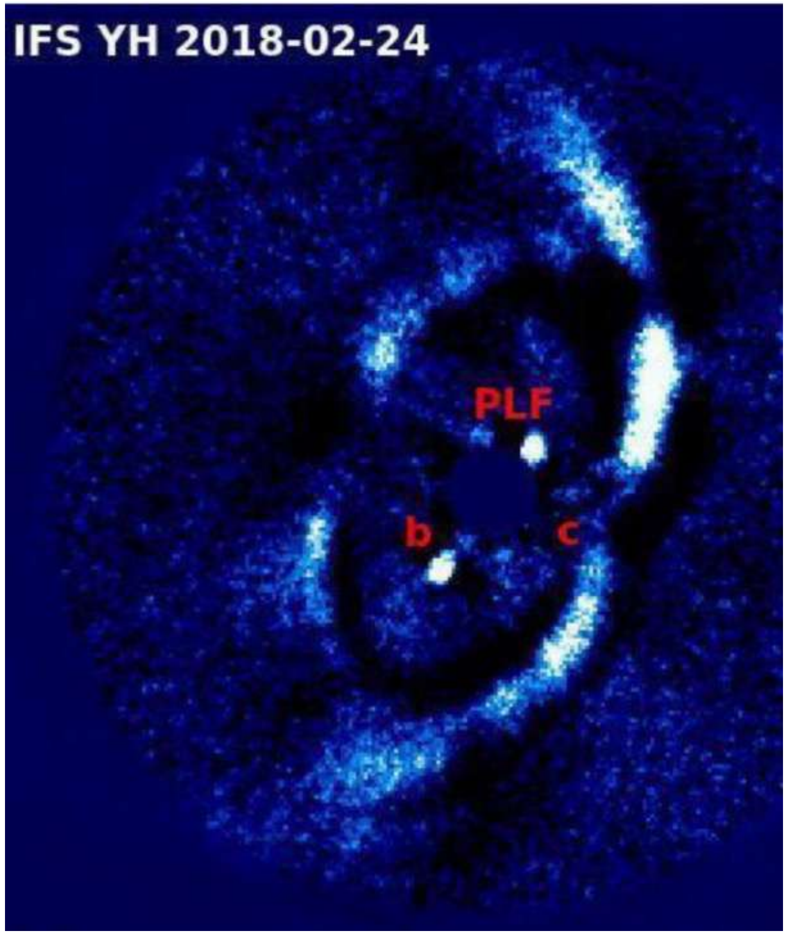


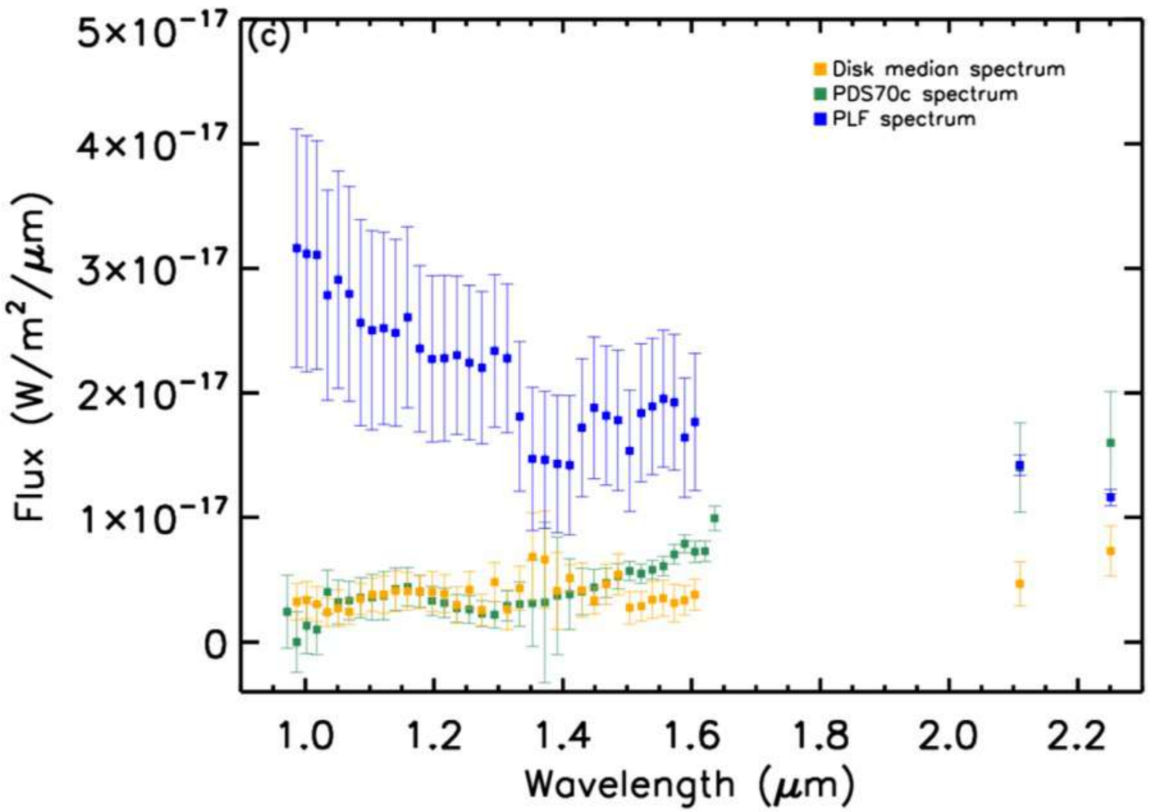
Narrow spectral lines can provide an answer

Haffert et al. 2019

Separate disk features from point sources

PDS 70





Colors can also be used

Mesa et al. 2019

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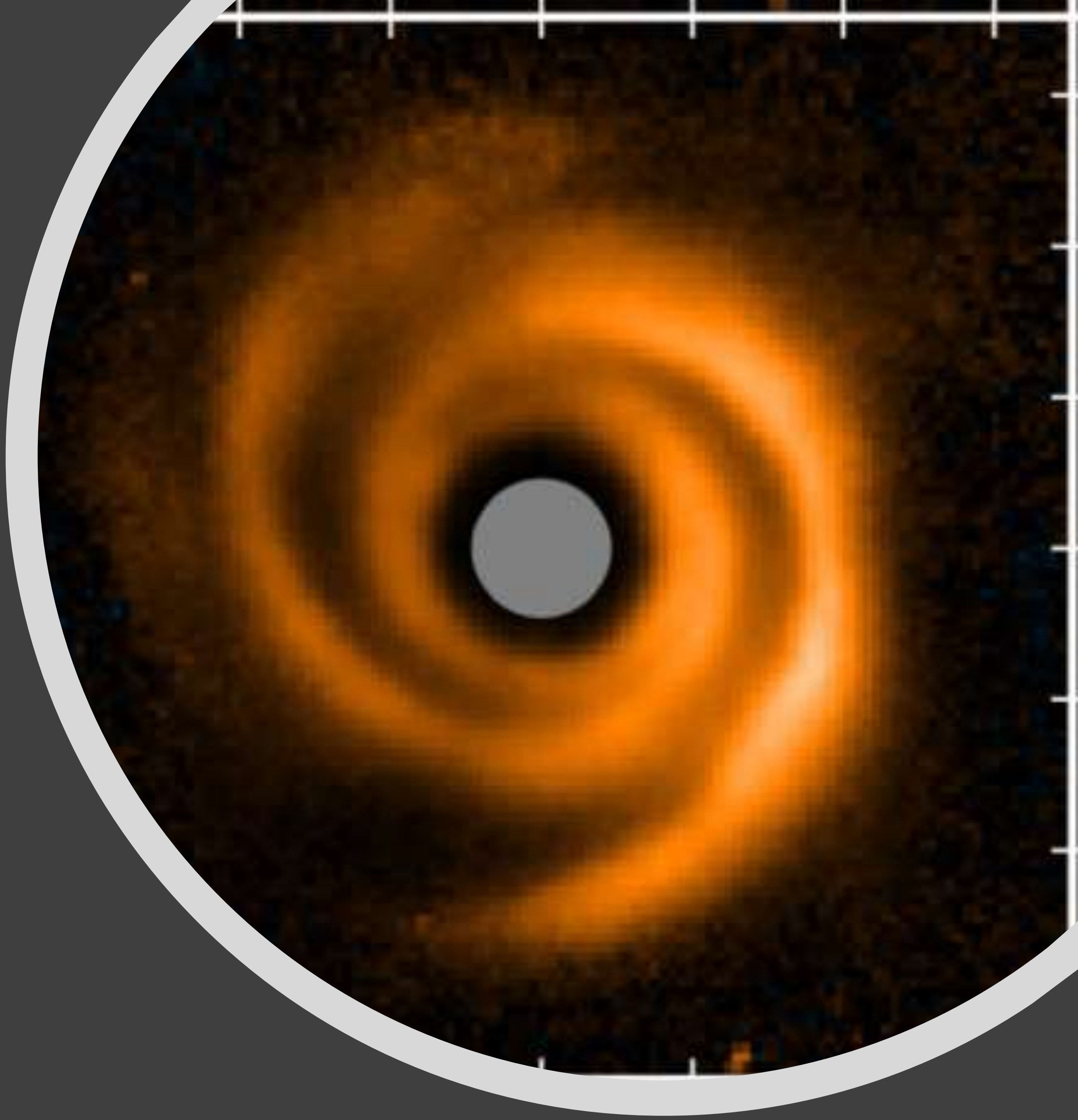
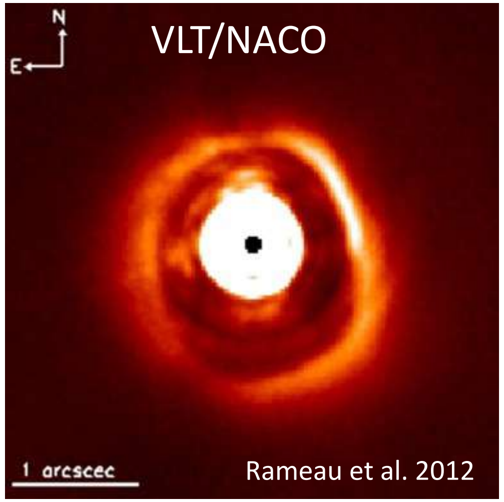
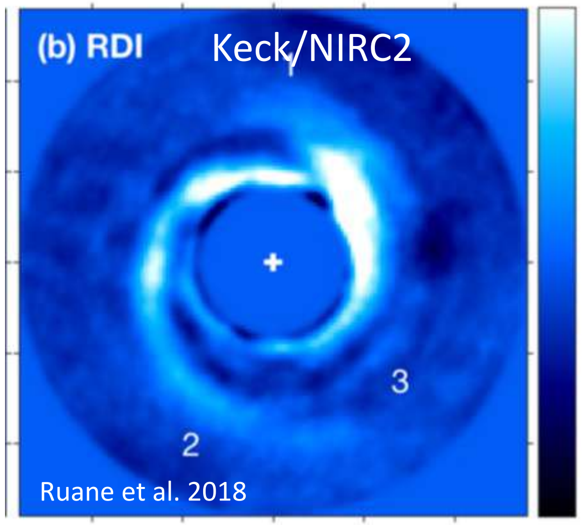
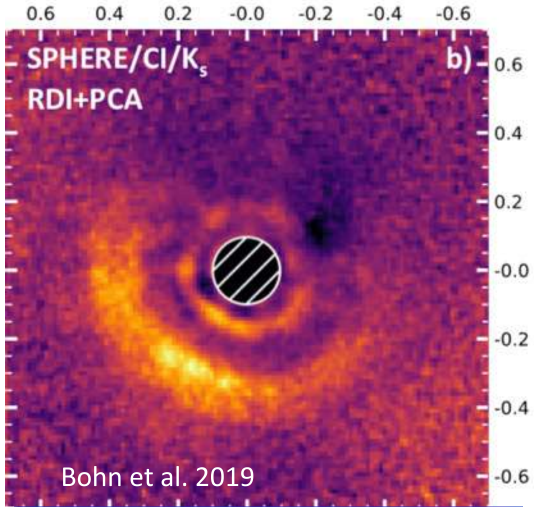
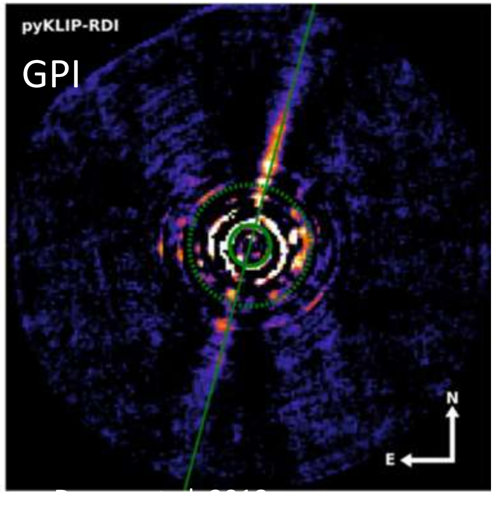


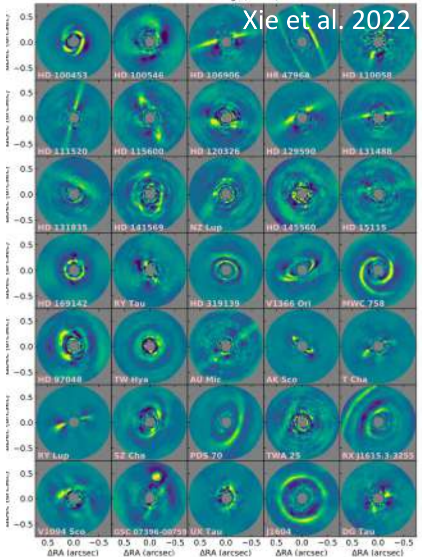
Optimal exploitation of RDI for disk imaging











RDI = only way to get the unpolarized flux of pole-on disks, or inner regions of inclined disks

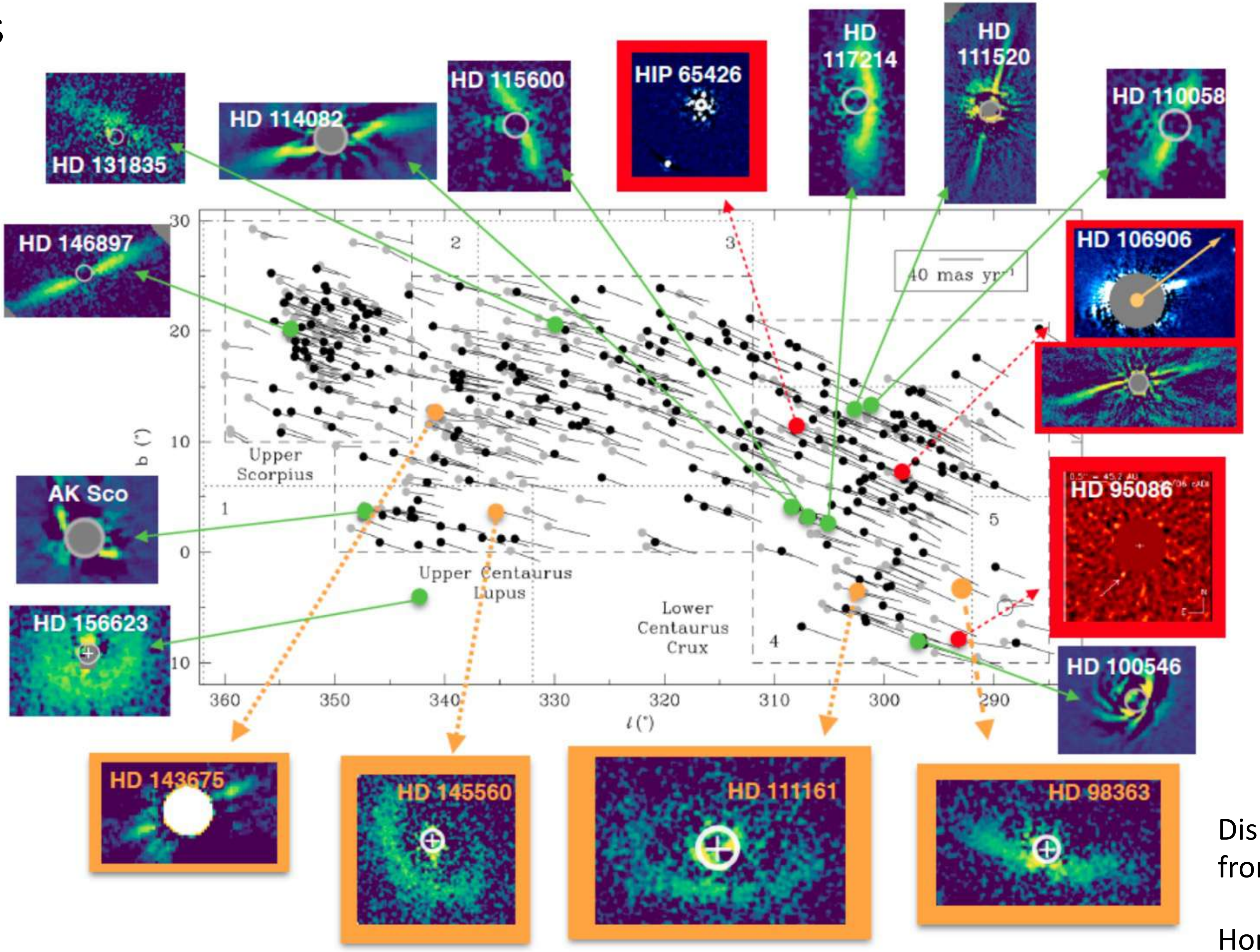
Successful application for almost all ground- or space-based high-contrast imagers

Systematic study of the RDI parameter space for xAO instruments (e.g. Xuan et al. 2018, Ruane et al. 2019 for NIRC2, Xie et al. 2022) : frame selection, optimization regions, telemetry…

Lessons learnt from the ALICE program (Choquet et al. 2014, Hagan et al. 2018): assembling the library is a huge effort that is worth it

Demographics

Lack of quantitative surface brightness measurements or upper limits to allow demographic studies

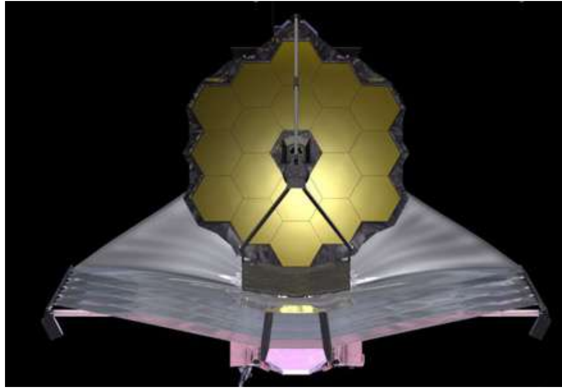


Combination unpolarized (RDI) + PDI observations will be very useful

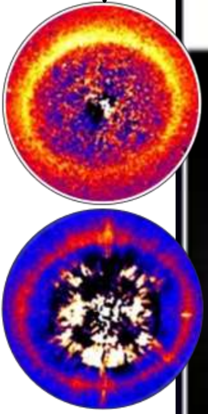
Disks in ScoCen from GPI

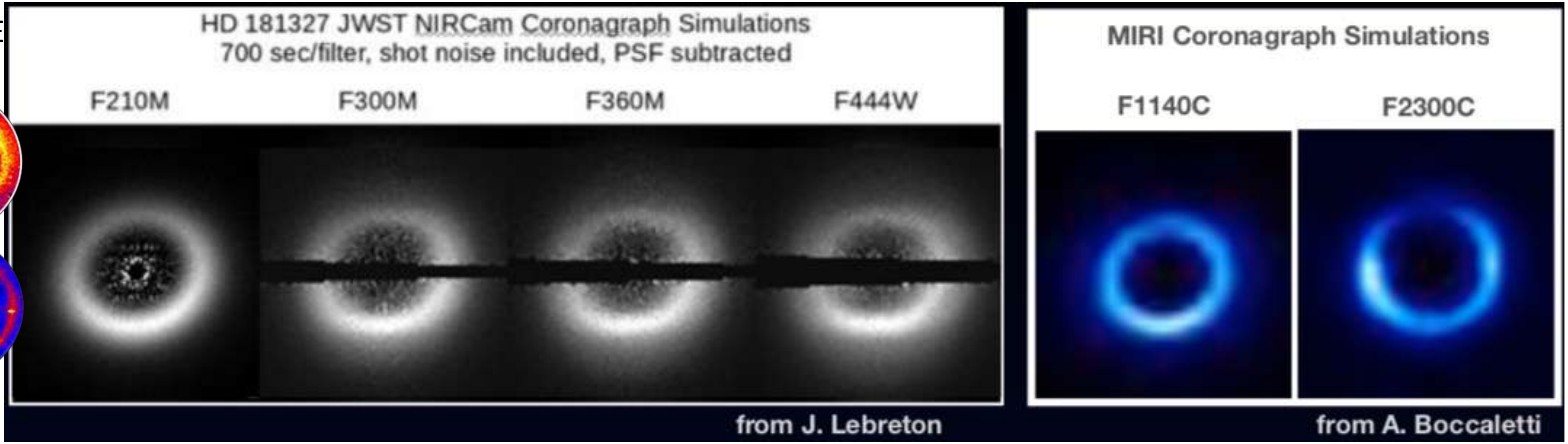
Hom et al. 2019

Spectral characterization with JWST



SPHERE
1.6µm





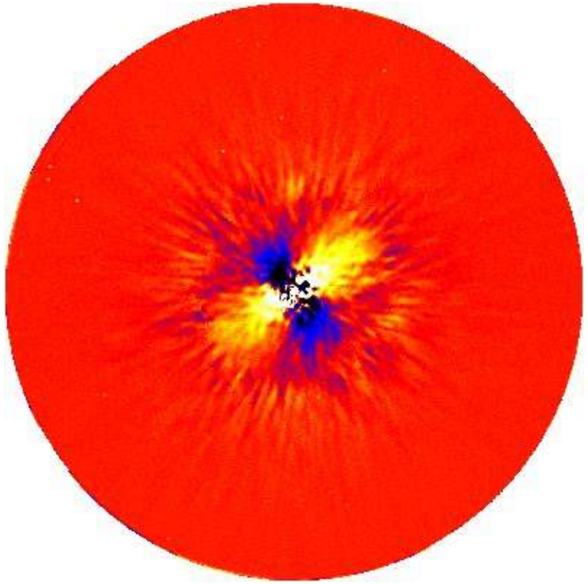
0.6µm 2µm 5µm 30µm λ

Characterization of known disks at large separation in spectral windows unavailable from the ground

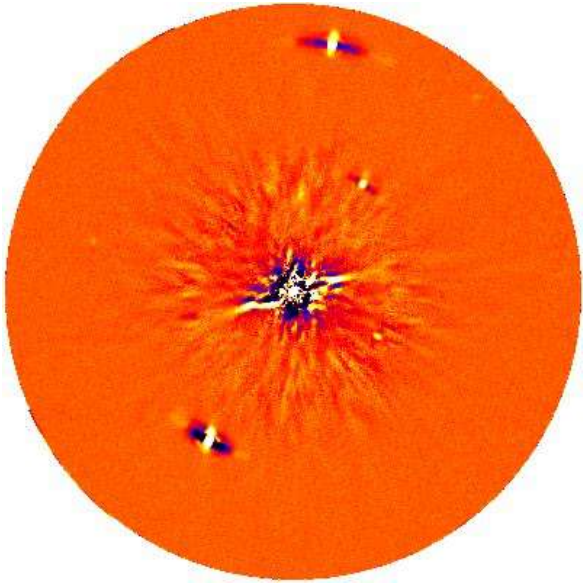
Only ±5° roll angle → no roll subtraction for extended objects, RDI is the baseline
Benefit from NICMOS and STIS experience → rapid results with current RDI algorithms

More detection with upgraded ground-based instruments

Upgrade of exisiting xAO instruments: SPHERE+, GPI, MagAO-X
Example with SPHERE+:



AO 1.3kHz



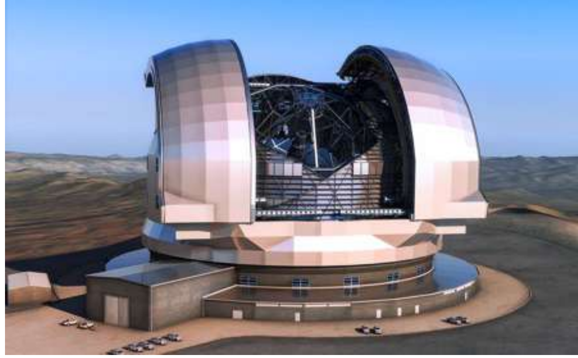
AO 3kHz with predictive control

No more servolag error and wind-driven halo

Systematic ADI+PDI simultaneous observations with a polarized beam splitter.

- Will enable more quantitative analysis
- Might trigger developments of new algorithms solving simultaneously for unpolarized and polarized flux (e.g. Lawson et al. 2022)

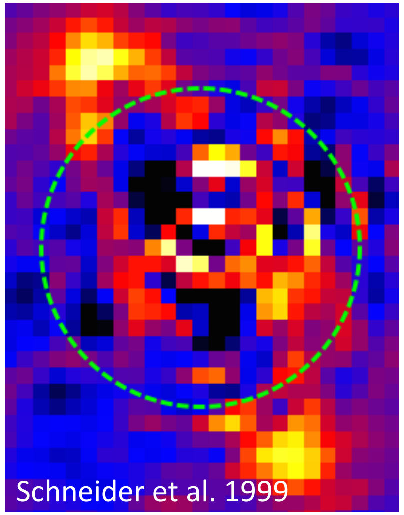
Closer in with the ELTs



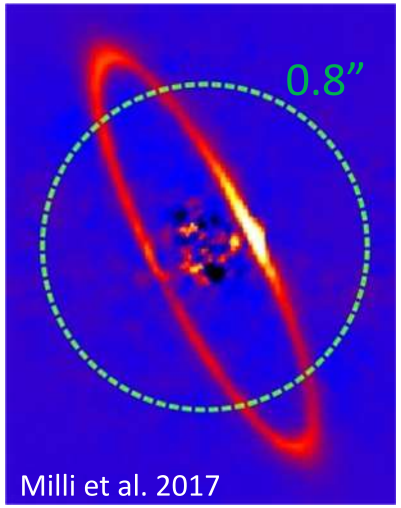
Inside 0.4” is where the most interesting signals are hiding:

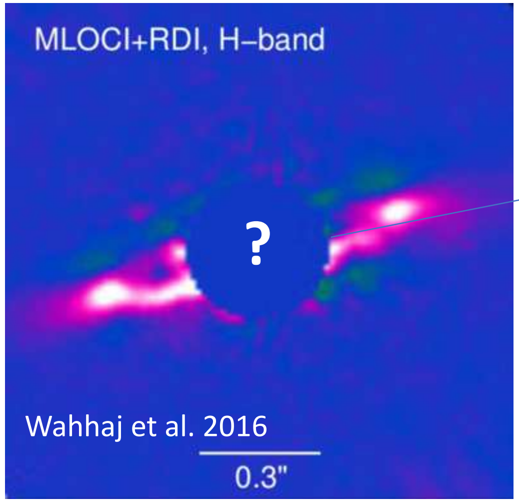
- Planets in formation or sculpting the inner edge of Kuiper belts analogs
- Peaks of forward-scattering for inclined systems → dust characterization
- Warmer dust populations (1-5au) and catastrophic events

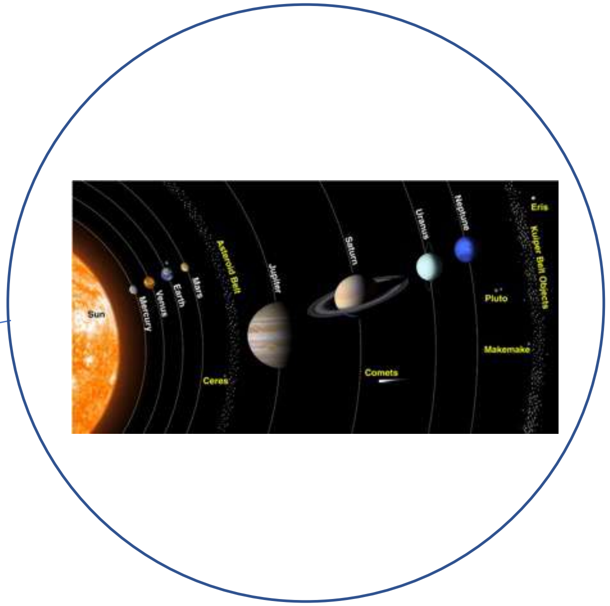
HST/NICMOS

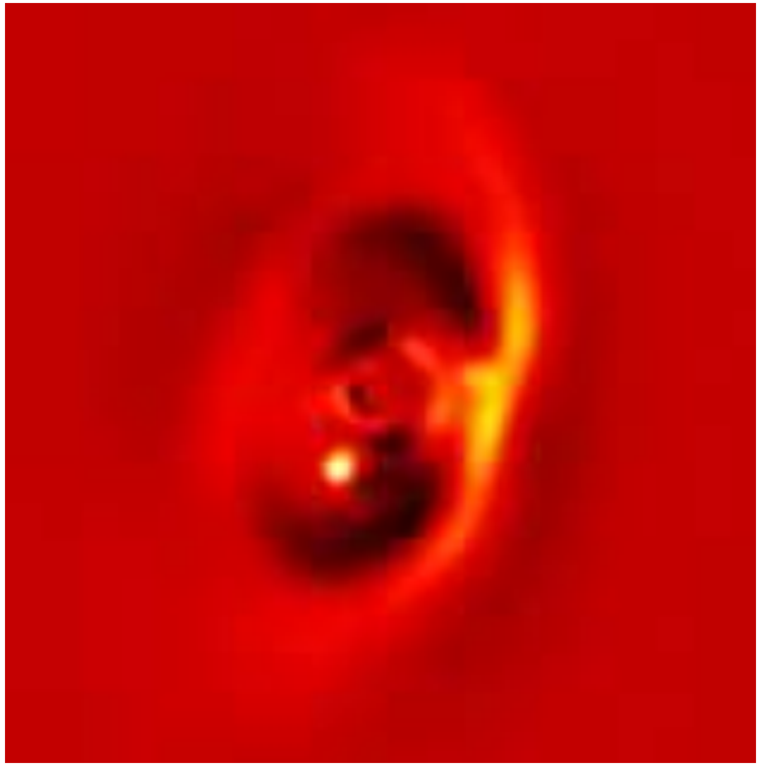


VLT/SPHERE









Conclusions

Circumstellar disks are one of the success of extreme AO instruments currently on-sky

Two future areas of investigation for disk post-processing techniques:

- Fidelity in extraction of detailed morphological features and surface brightness to enable insightful interpretations (signposts of planets, dust properties…)
- Sensitivity for faint disks or pole-on disks to enable demographic studies