Strategies to achieve image

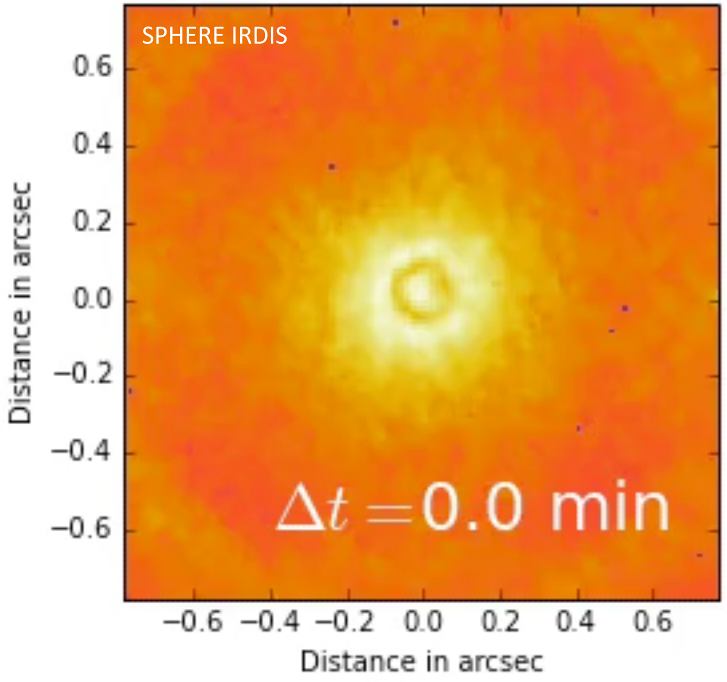
Julien Milli

How to decouple the stellar halo from the astrophysical object?

Most post-processing techniques rely on some source of image diversity between the exoplanet signal and the residual stellar light

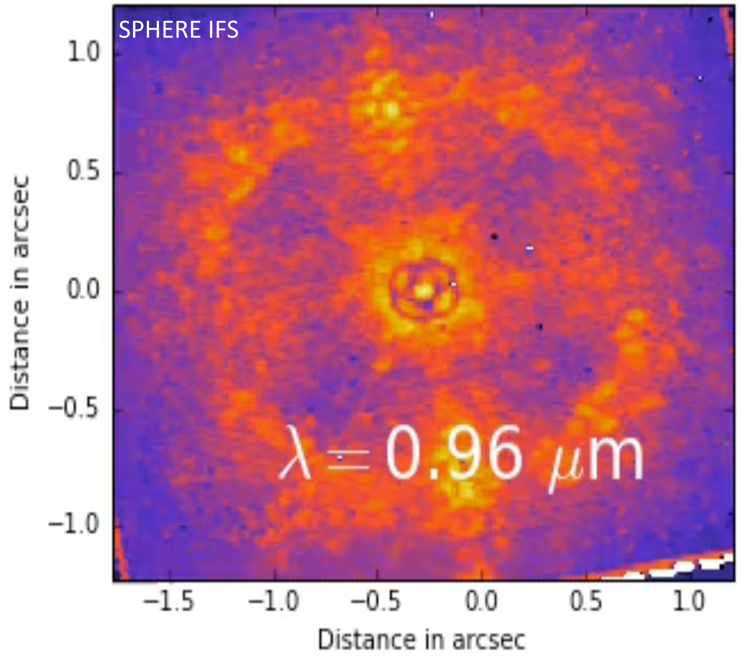
<u>Fixed stellar signal and variable astrophysical signal.</u>

E.g. pupil stabilized observations



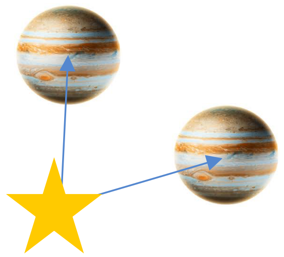
<u>Variable (but predictable) stellar signal and fixed astrophysical signal.</u>

E.g. Observations with Integral field units



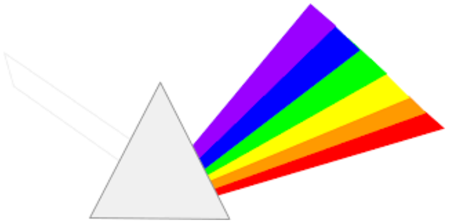
Different strategies to achieve diversity in imaging

- Angular diversity

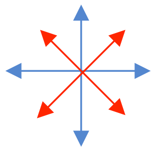


- Stellar diversity

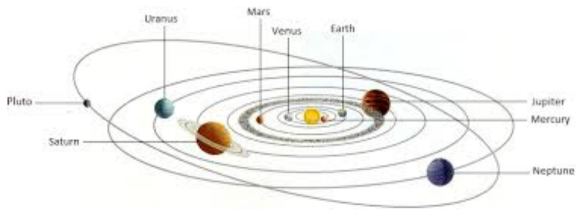
- Spectral diversity



- Polarimetric diversity

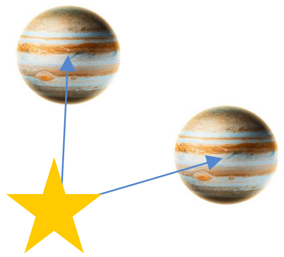


- Orbital diversity



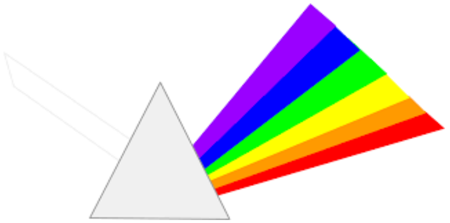
Different strategies to achieve diversity in imaging

- **Angular diversity**

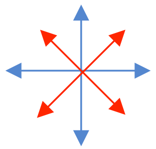


- Stellar diversity

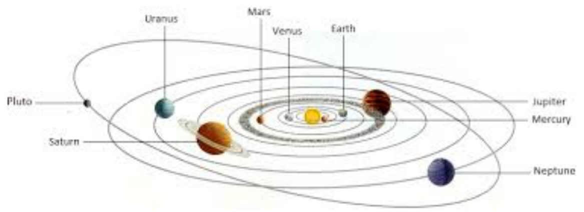
- Spectral diversity



- Polarimetric diversity

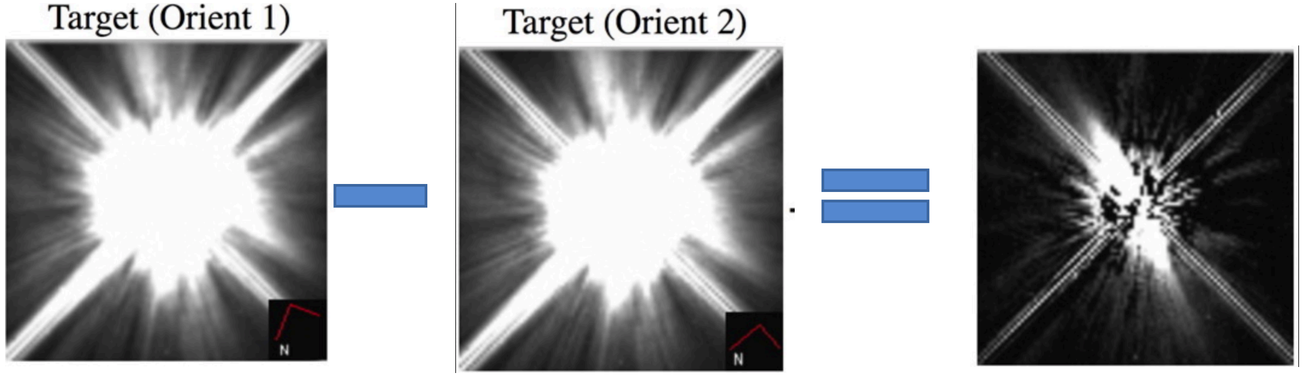


- Orbital diversity



Angularly decoupling the stellar and astrophysical signal

- Started originally from space with roll-angle subtraction: discrete orientations of the telescope provide the image diversity.



Critical points: accurate centering,
thermal breathing
Schneider et al. 1998

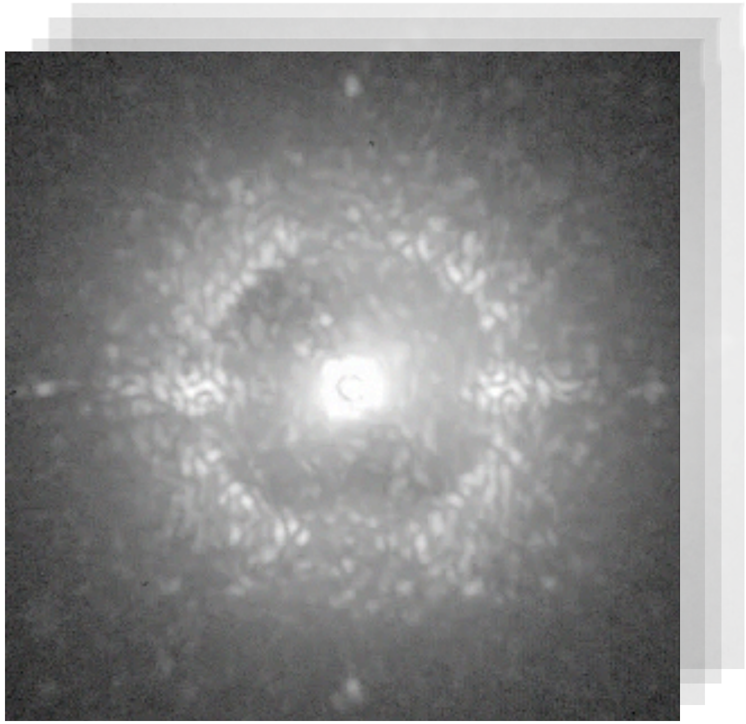
- Adapted to ground-based telescope with Angular Differential Imaging (Marois et al. 2006)

  First demonstration in 2008 for the detection of HR8799

Angular Differential Imaging (ADI)

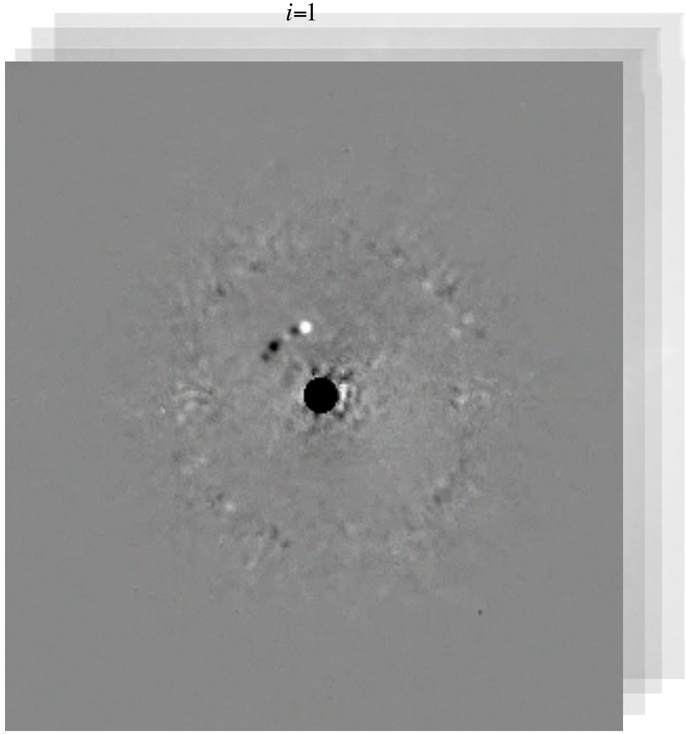
Coronagraphic sequence of pupil-stabilized images

I_k

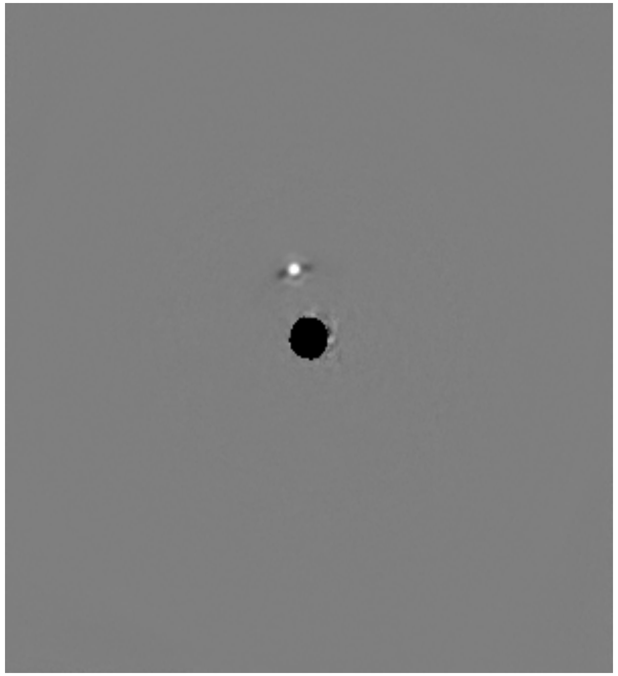


Residuals after subtraction (median for cADI or combination of images for LOCI, PCA and flavors)

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



Final image after derotation and collapse of the cube



SPHERE H2 images of PZ Tel B, credit: A. Vigan

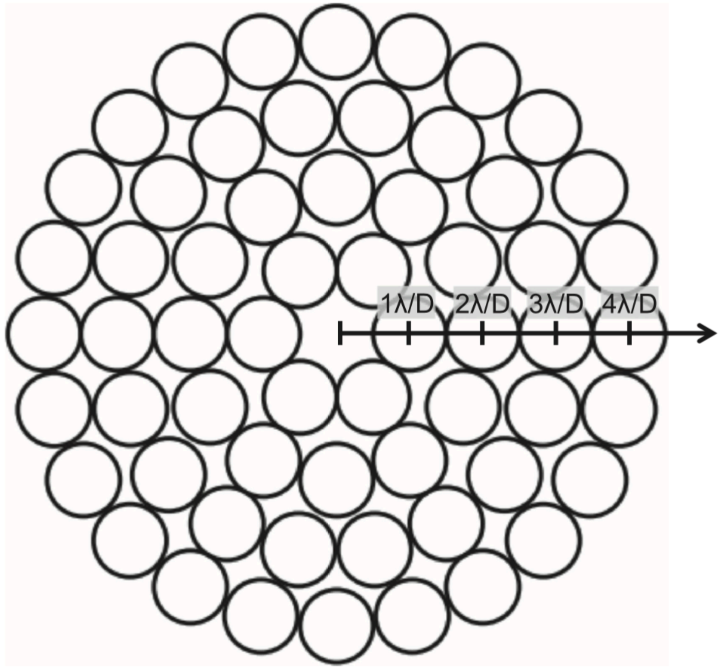
Shortcomings

- Self-subtraction and over-subtraction of the astrophysical signal
  - Can be calibrated in post-processing for point sources (Bonnefoy et al. 2011, Cantalloube et al. 2015, Pueyo et al. 2016, Ruffio et al. 2017)
  - More difficult to calibrate for circumstellar disks (Milli et al. 2012, Esposito 2014)

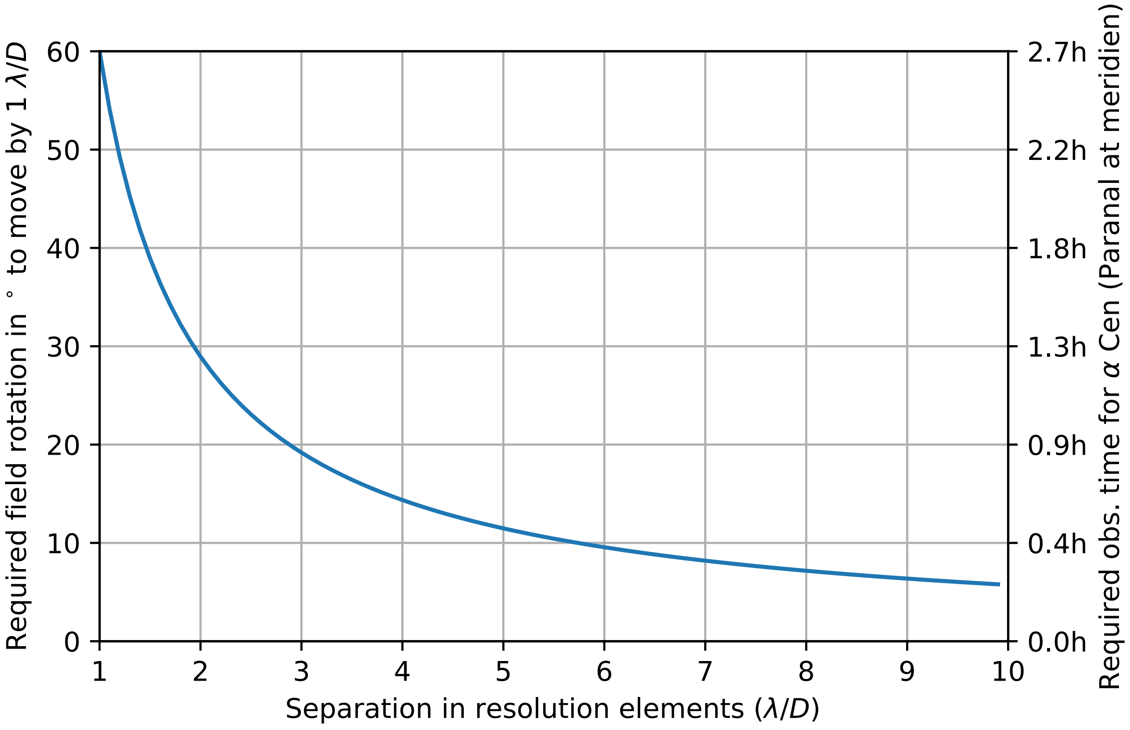
Talk L. Pueyo, F. Cantalloube

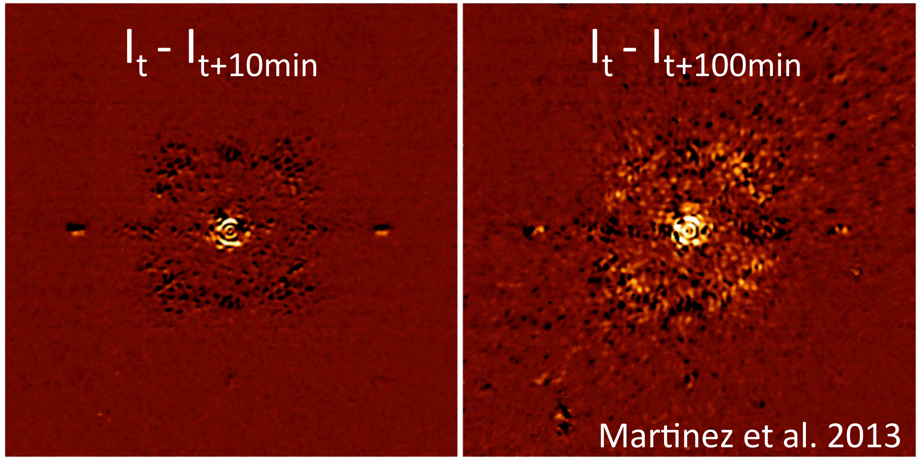
- Efficiency depends on field rotation and PSF stability (speckle decorrelation) → Trade-off !

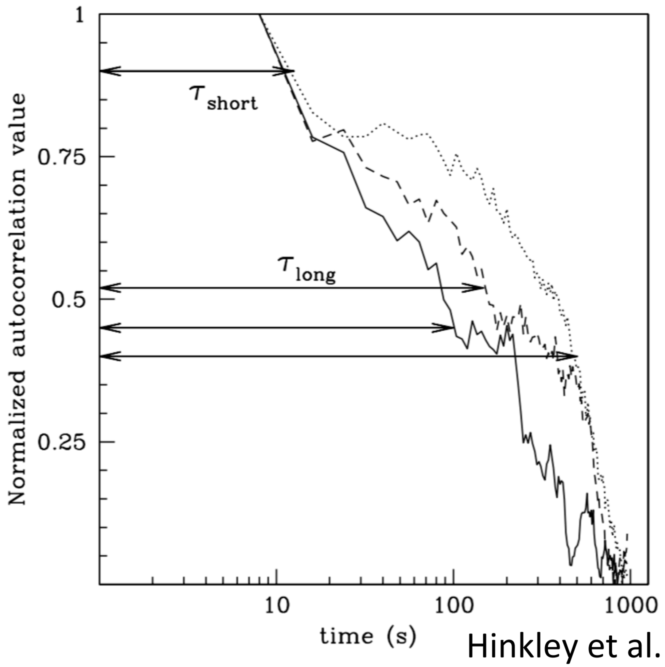
Low efficiency at short separations



Long speckle stability is required







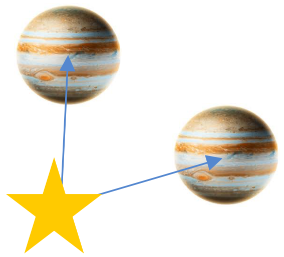
Hinkley et al. 2007

Roddier et al. 1982
Macintosh et al. 2005
Milli et al. 2016

Intrinsic limitation of ADI

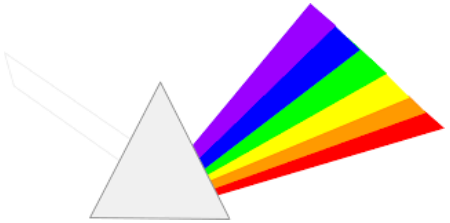
Different strategies to achieve diversity in imaging

- Angular diversity

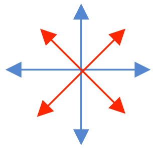


- **Stellar diversity**

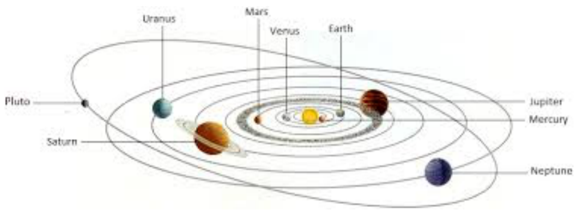
- Spectral diversity



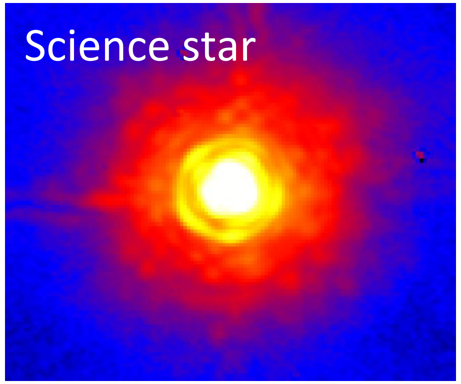
- Polarimetric diversity

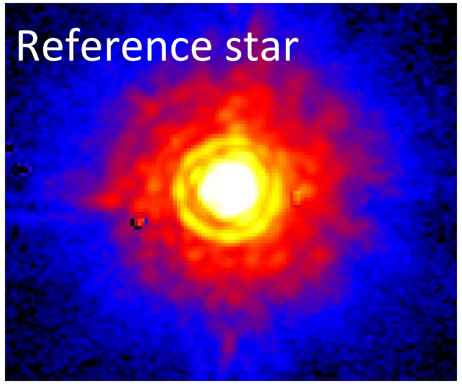


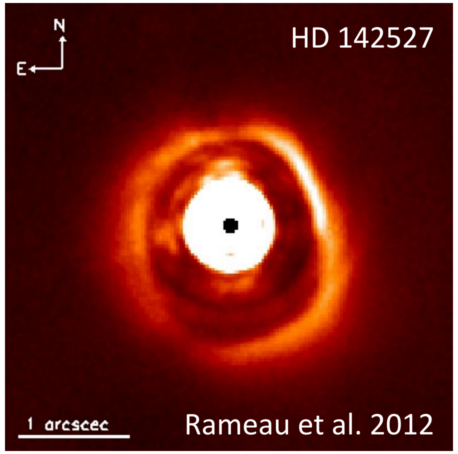
- Orbital diversity



Reference star differential imaging (RDI)



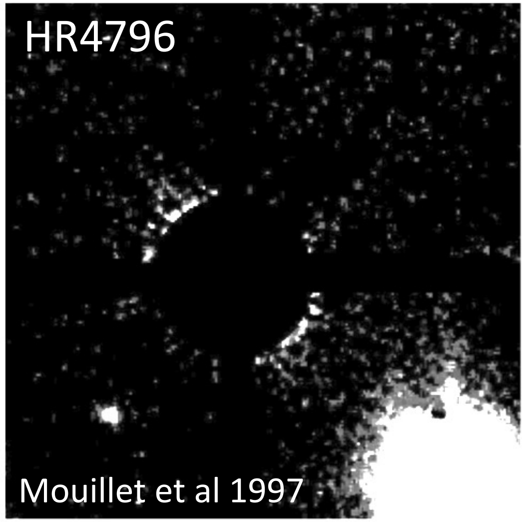




- Probably the first technique historically, both from space and with ground-based AO instruments (Beuzit et al. 1996)
- From space

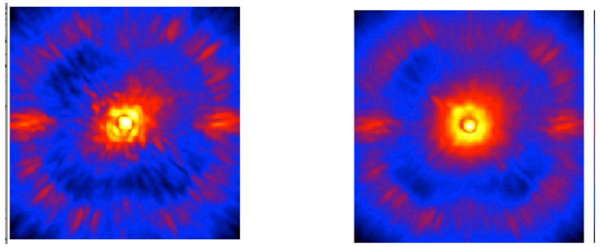
Talk E. Choquet

- From ground: disappointing with 1st AO systems. Renewed interest with higher Strehl AO system (1st gen at L or 2nd gen AO systems)

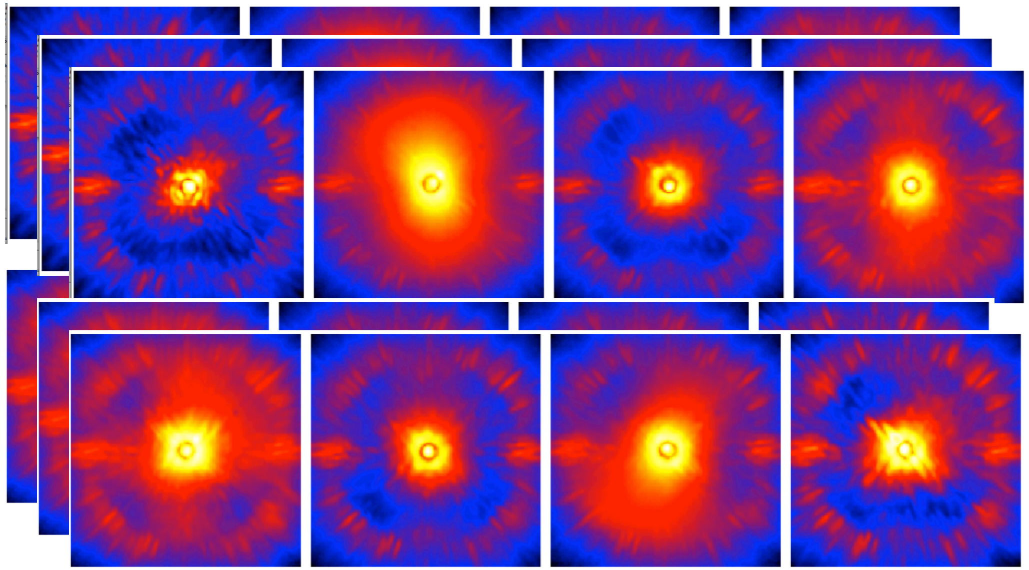


Sniper or machine gun approach?

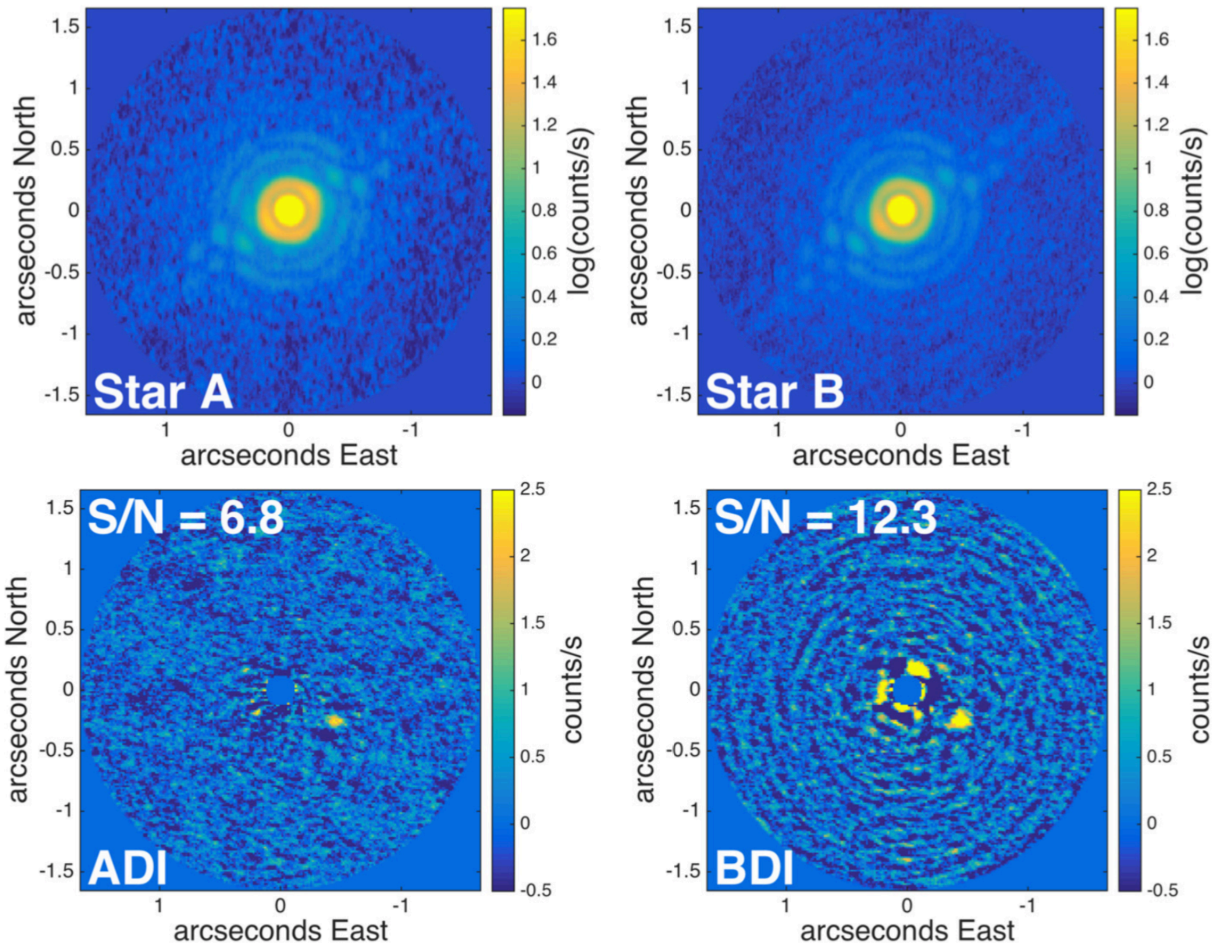
- A) (Carefully selected) **<u>Single reference</u>**
  - similar visual magnitude for AO performance
  - close on sky and in time
  - similar turbulence conditions



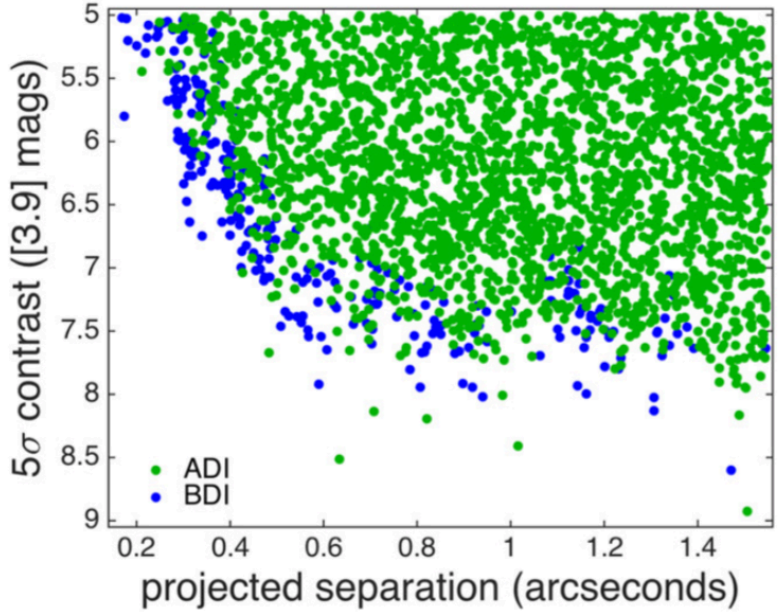
- B) **<u>Large library of references</u>**
  - Needs a large set of images available
  - No additional observing time required
  - Needs to identify the subset of adequate targets



A) Single reference: best possible case with binary differential imaging (BDI)

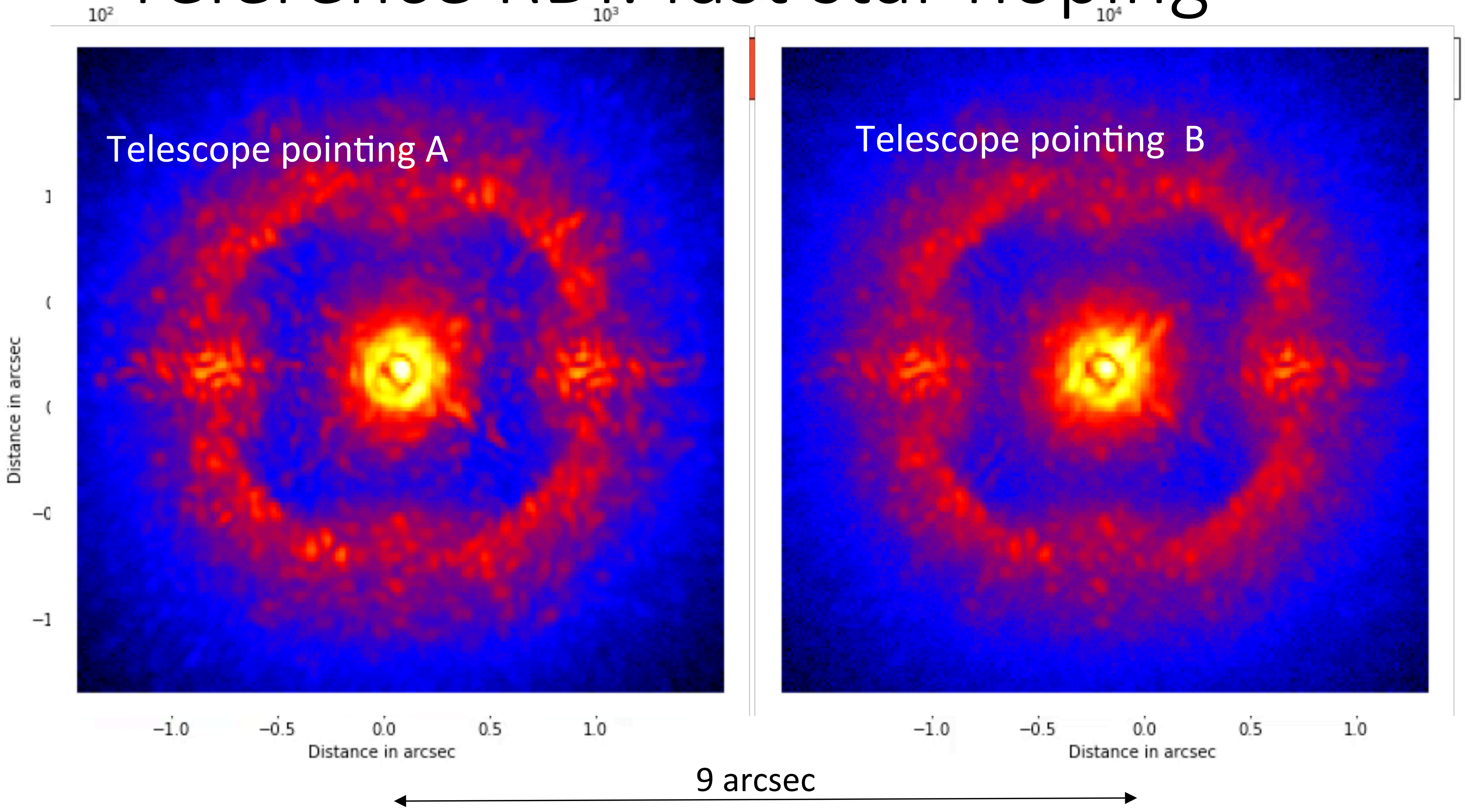


- Instantaneous PSF subtraction
- Requires sufficent field of view and post-AO anisoplanatic angle
- Could theoretically reach the photon-limit



Rodigas et al. 2015, HD37551 system with MagAO

Second best possible setup for single reference RDI: fast star hoping



Example with SPHERE IRDIS

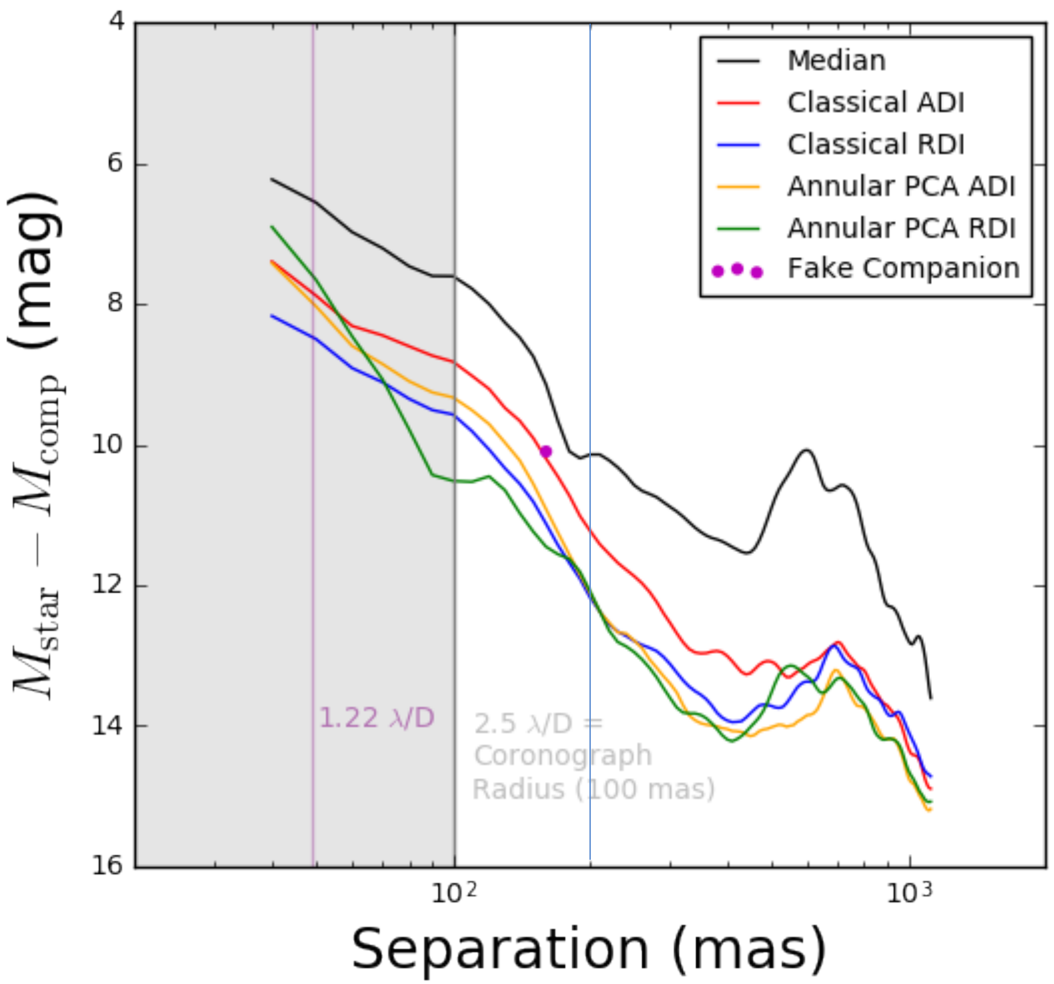
Binary system of 9” separation and similar R magnitude

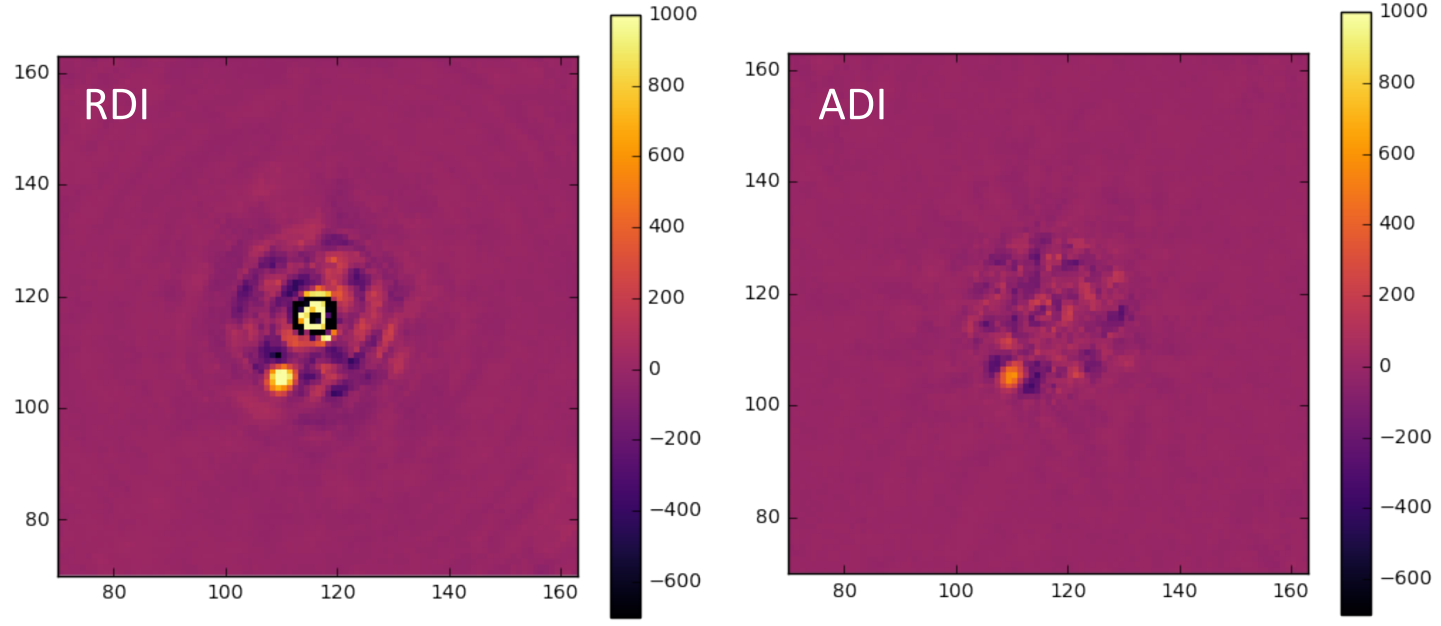
No light contamination (IRDIS FoV=11”)

Combined offset done at the telescope → fast transition between A and B less than 20s.

Duty cycle of 2min20

Comparison between ADI and single ref RDI





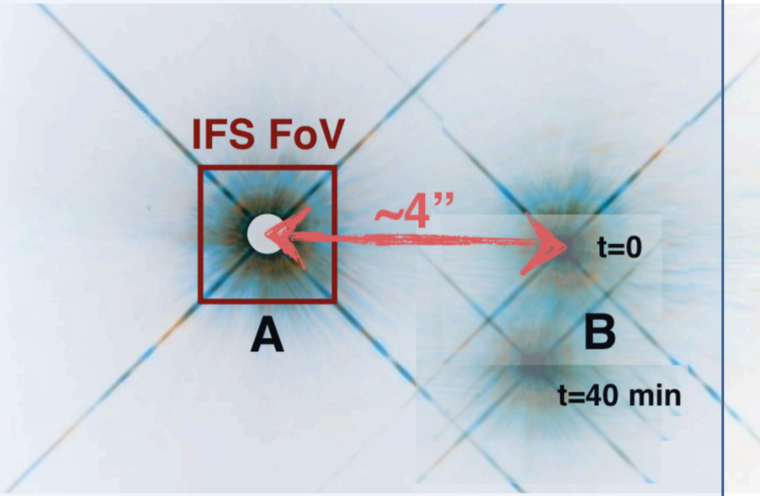
Fake companion injected with a contrast of 10^{-4} at 150mas (image not throughput-corrected)

Turnover point at ~200mas below which RDI beats ADI

Pantojas, Girard, Milli et al. in prep

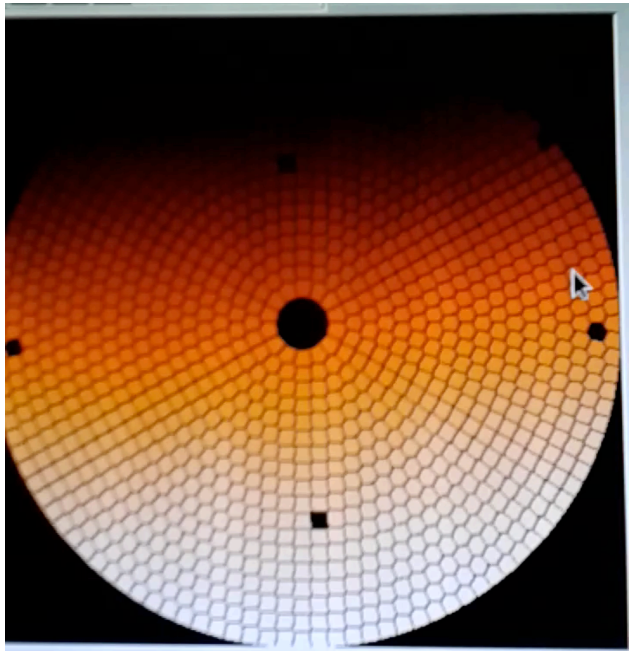
α Cen AB with single ref RDI

- Same setup with SPHERE IFS
- Similar performance between ADI and RDI so far
  (Girard et al. in prep)



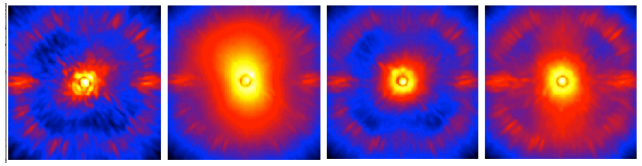
IRDIS FoV

- Next: Mid-infrared AO-corrected imaging with VISIR in fast choping : NEAR experiment



On-sky demonstration of 10Hz choping (8ms transition) in closed loop AO with UT4 DSM (M. Kasper)

B) RDI based on a library of frames



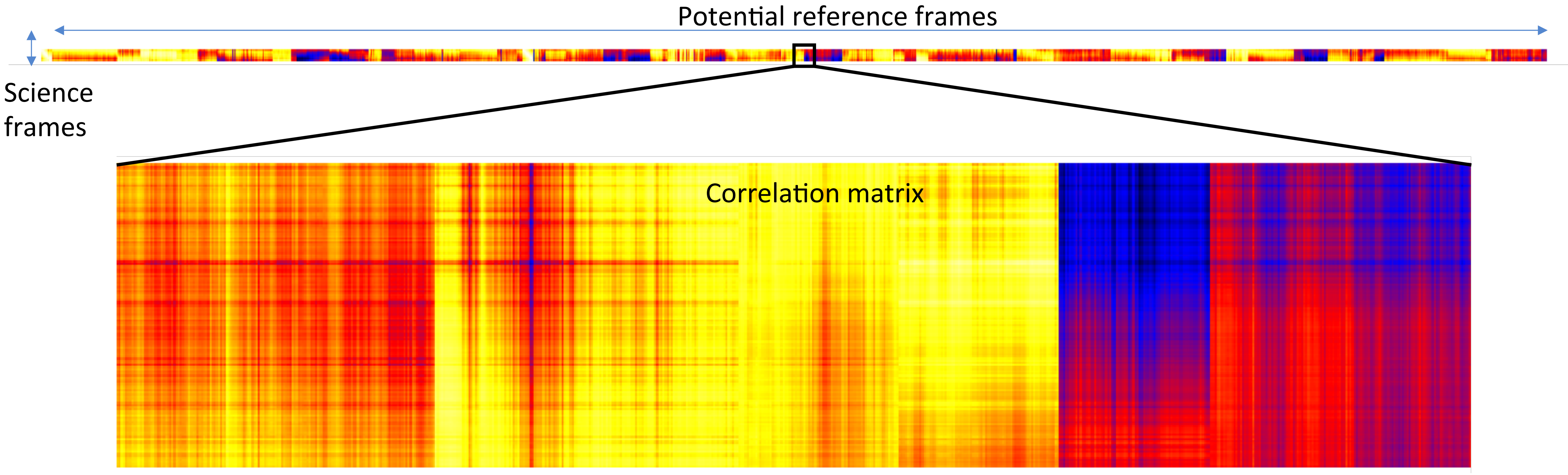
- Requirements: large number of targets, high level of AO correction (1st gen AO at L or 2nd gen AO)

  Mawet et al. 2014, Gerard et al. 2015, Wahhaj et al. 2015, Draper et al. 2016, Serabyn et al. 2017, Ruane et al. 2017

- Many open questions
  - How shall we select the relevant frames for a given science target?
  - How many frames shall we use?
  - Where can we hope to gain in sensitivity over ADI?

- Example on a SPHERE program called SHARDDS, ~60 targets in broad band H (~20 000 frames), 40min on source for each target

Selecting the frames: correlation



If one works in patches or annuli, as many correlation matrices as patches

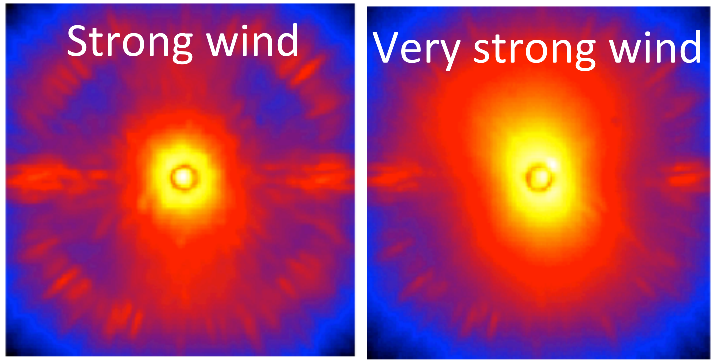
→ Very computer intensive, maybe not tractable for large libraries of $>10^6$ frames (matrix of $10^6 \times 10^6$)

→ Should the library be adapted per frame or per target?

Selecting the frames based on scalar parameters

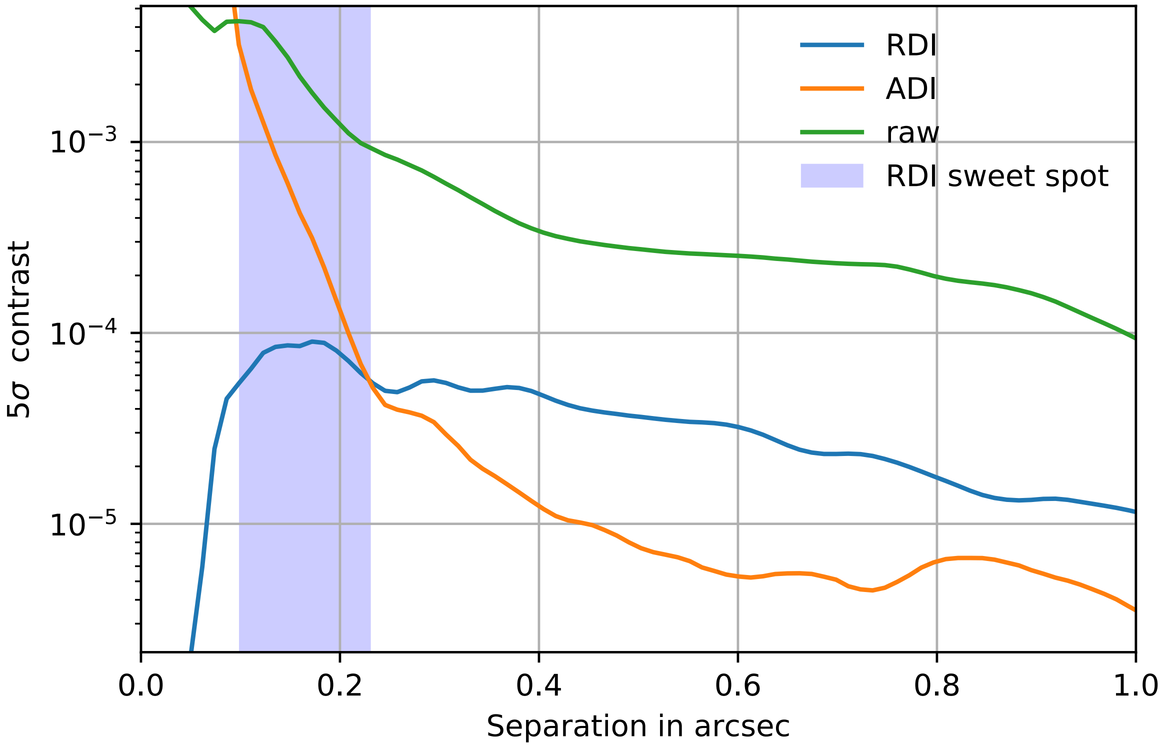
Talk V. Bailey

- Instrument, telescope and environmental data contain a lot of useful information for a preselection promising references
  - AO telemetry: Strehl or wavefront error, RTC-estimated atmospheric parameters
  - Atmospheric and turbulence conditions from site monitors (ASM) or forecasts institutes (ECMWF). Example with wind:



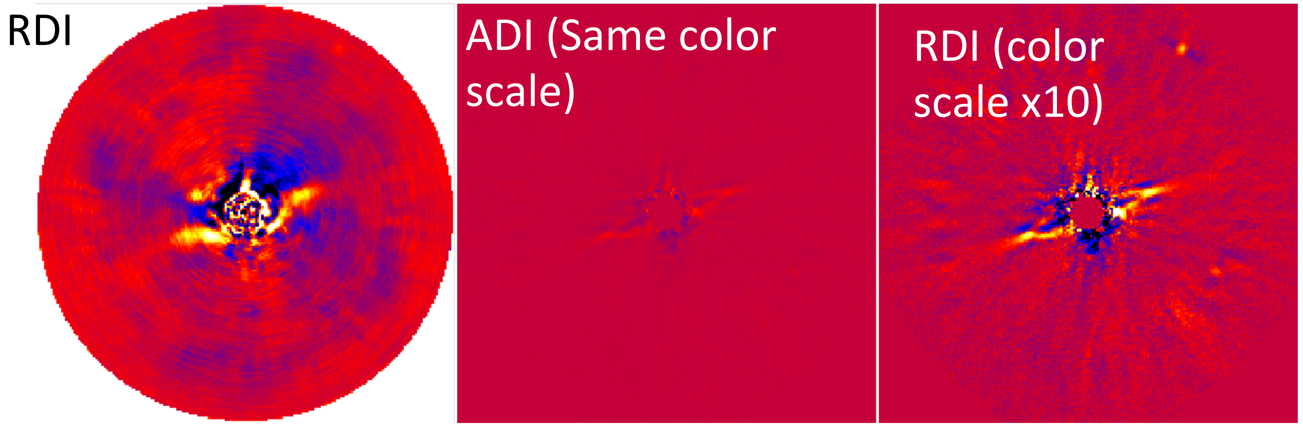
- Available tools : exploratory factor analysis (Bailey et al. 2016) or neural networks

Comparison ADI-RDI from the SHARDDS library



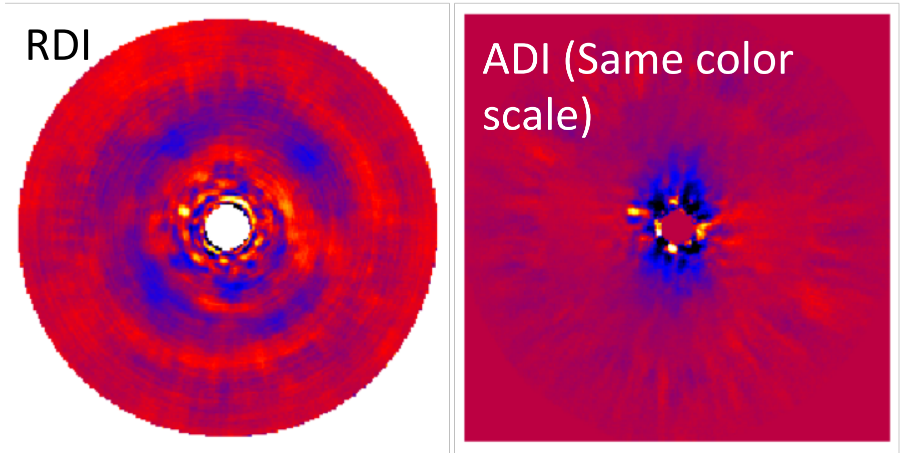
Turnover point at ~200mas

Disk of HD 114082



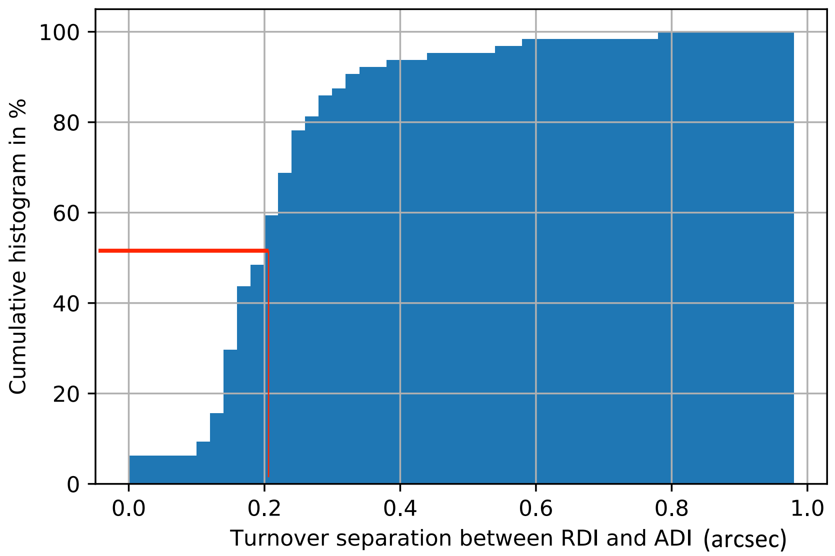
Wahhaj et al. 2016

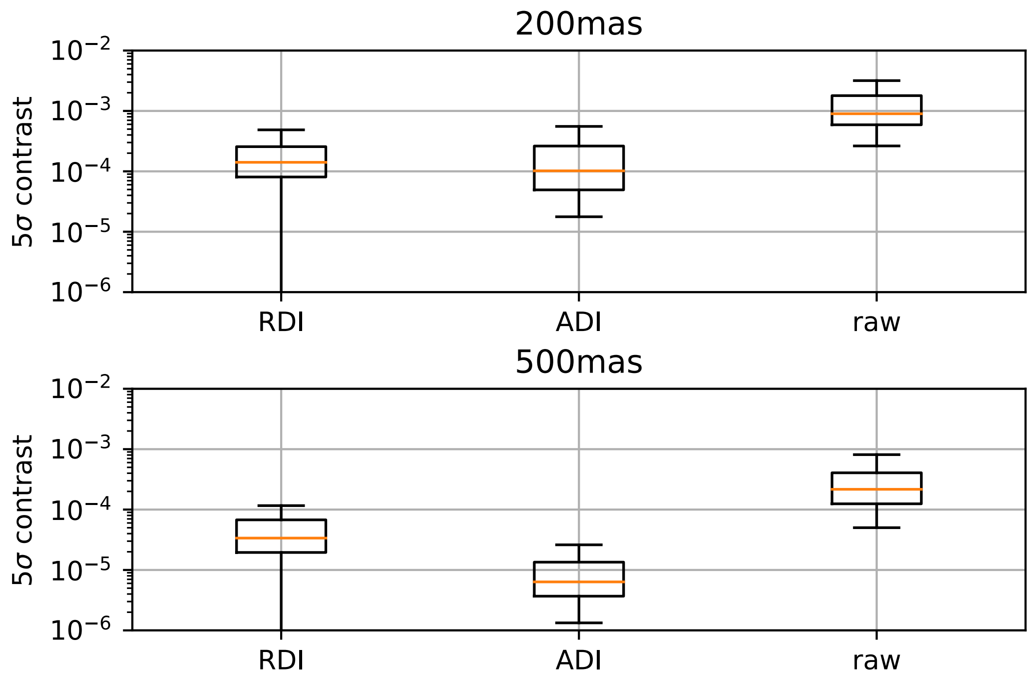
Brown dwarf HD 206893B



Milli et al. 2017

Turnover point between ADI and RDI

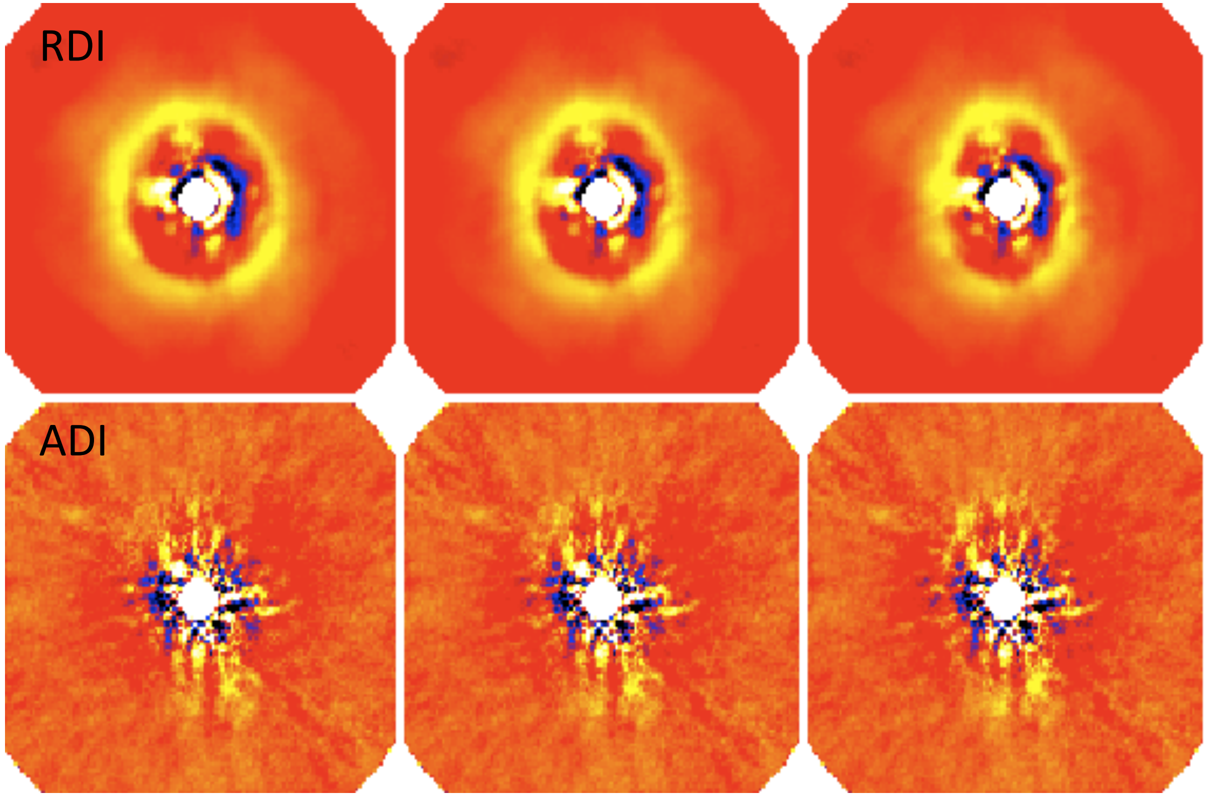




Similar performance at 200mas for point sources between ADI and RDI

But unrivalled contrast for extended disks

Synthetic disks of semi-major axis 0.5”

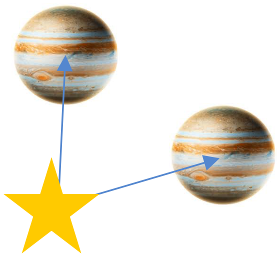


Contrast : 1 x 10^{-4}
Inclination: 20°

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

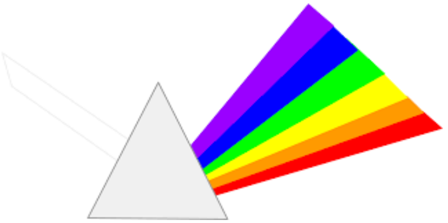
Contrast : 1 x 10^{-4}
Inclination 40°

Different strategies to achieve diversity in imaging

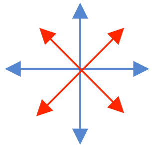


- Angular diversity

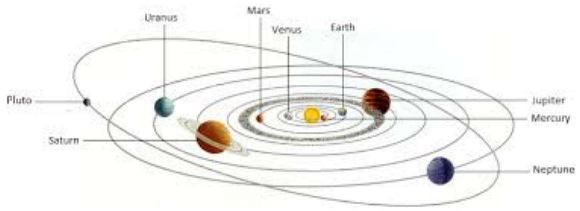
- Stellar diversity



- **Spectral diversity**

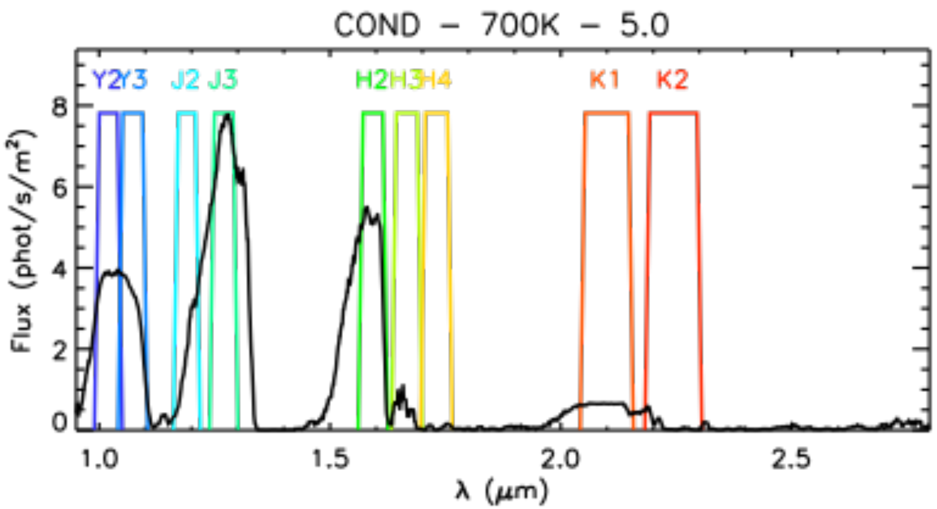


- Polarimetric diversity
- Orbital diversity



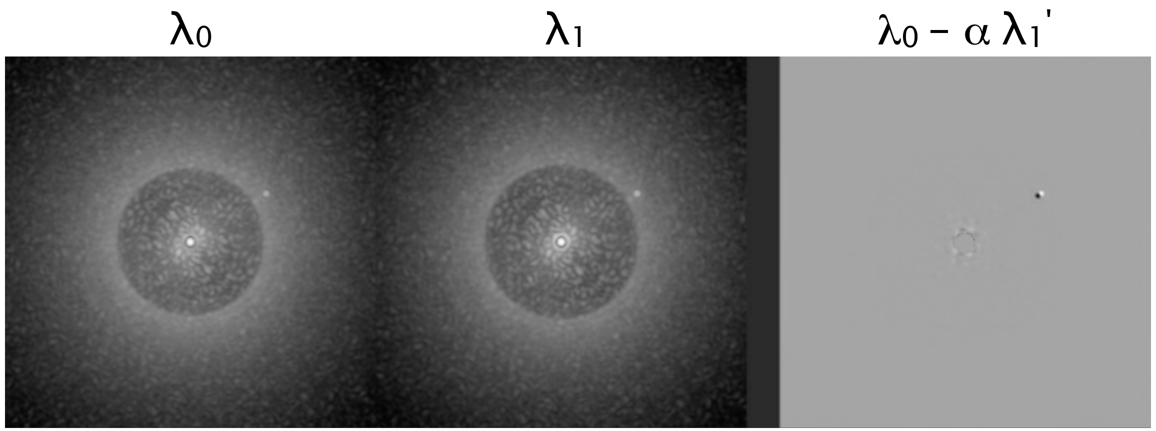
Spectral Differential Imaging (SDI)

- Based on spectral features of a planet vs star: CH_4/H_2O absorption expected for cool low-mass companions



Example of SPHERE dual-band filters

stretched λ_1



Ideally: large planet flux ratio between λ_1 and λ_2.

But: many know cold objects don't show CH_4 absorption (cf Beth Biller's talk)

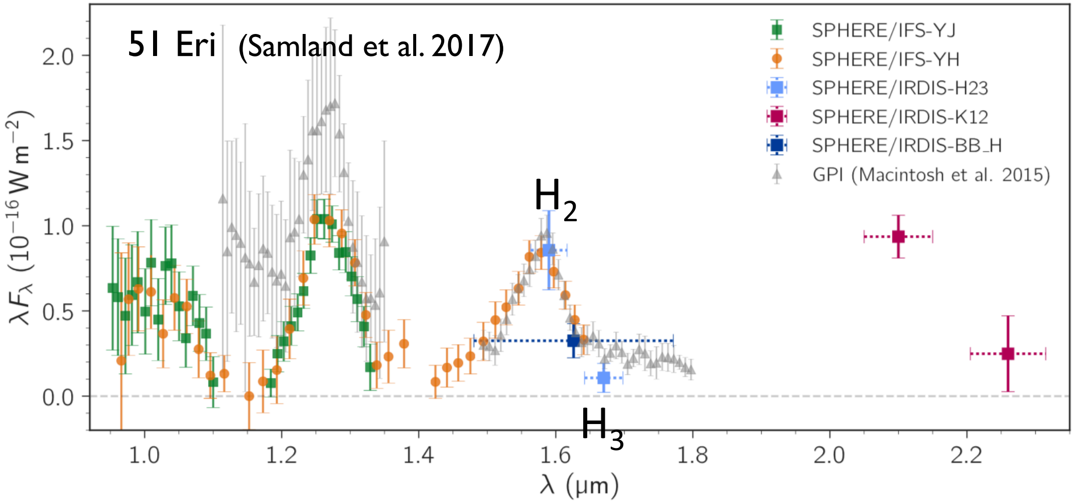
→ Flux attenuation

Sparks & Fords 2002, Lenzen et al. 2004

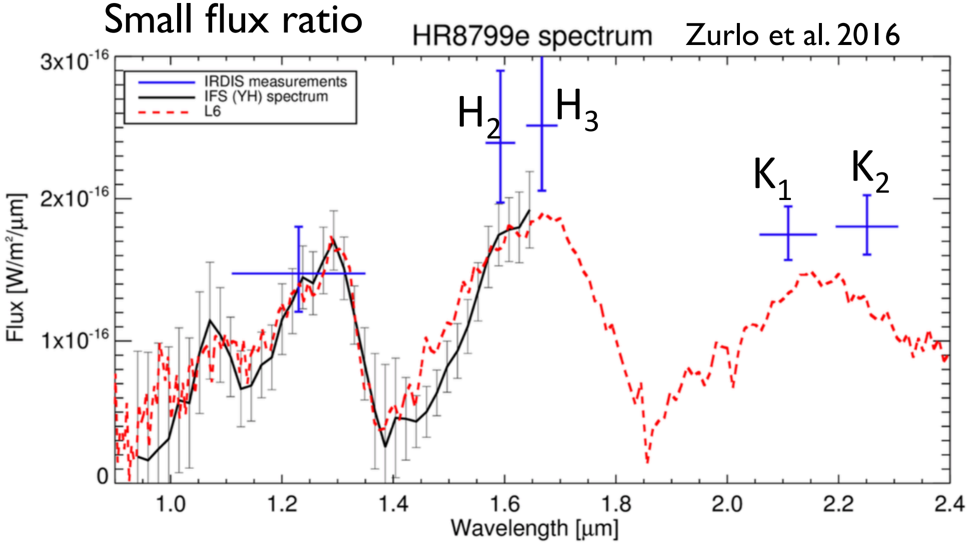
Maire et al. 2014, Rameau et al. 2015

SDI flux attenuation

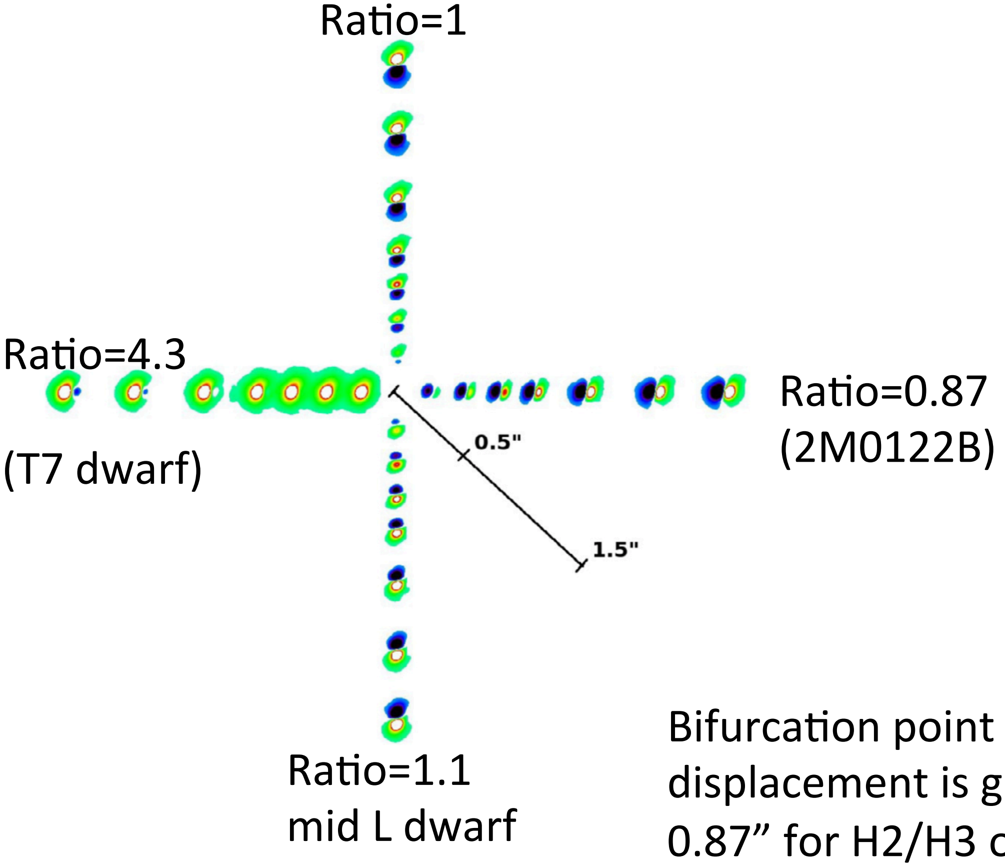
Large flux ratio between dual band filters



Small flux ratio



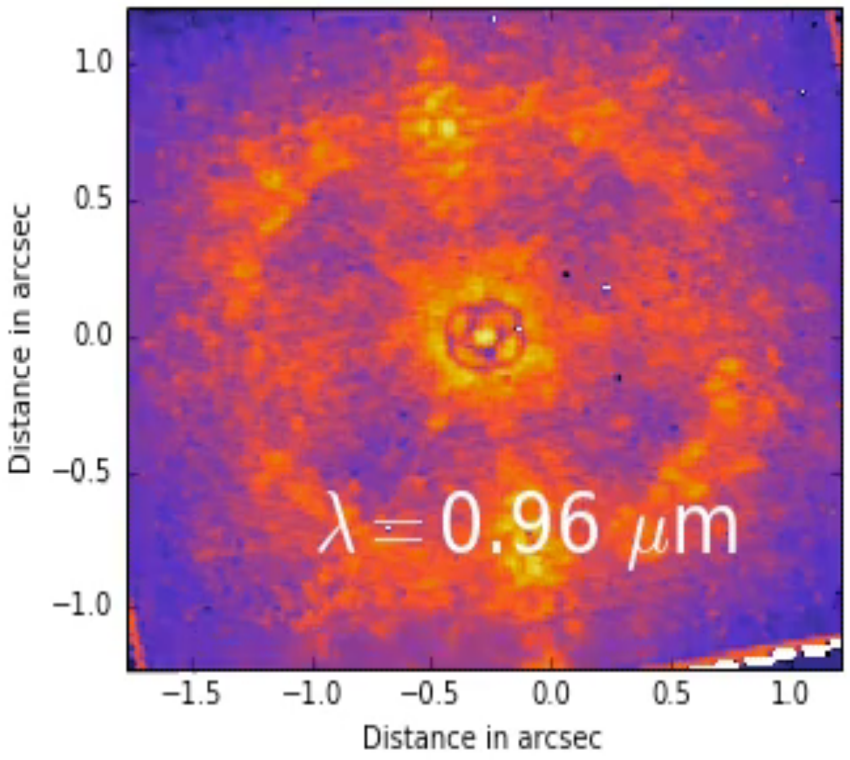
- Typical SDI signature



Bifurcation point when the radial displacement is greater than 1λ/D: 0.87” for H2/H3 on SPHERE

Rameau et al. 2015

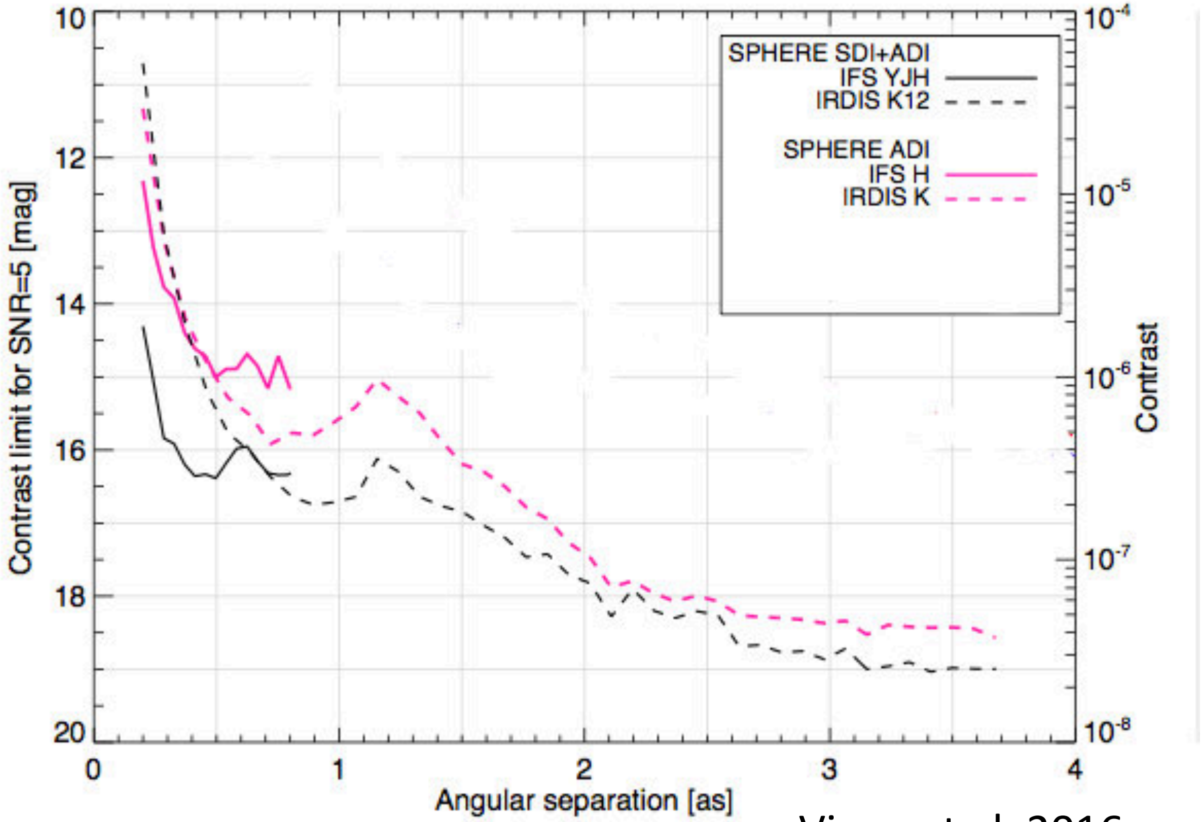
Spectral Differential Imaging with an IFS



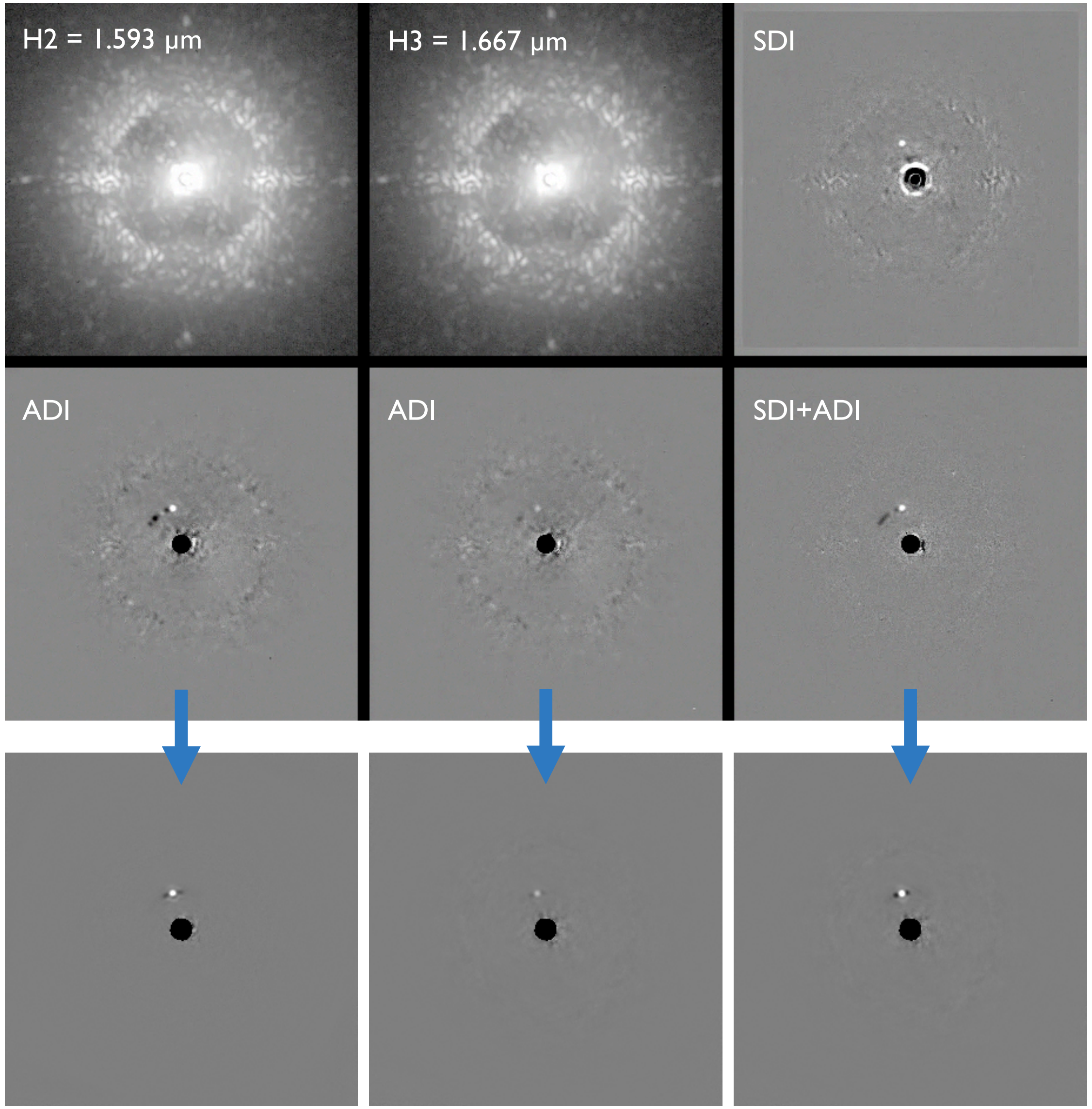
- Speckle separation to the star should scale with wavelength (1st order)
- Bifurcation point is much smaller than in dual-band imaging: 45mas for SPHERE IFS in YJH mode → one can retrieve the full spectrum

Combining spectral and angular differential imaging

Deepest SPHERE / IFS observations, on Sirius



Vigan et al. 2016

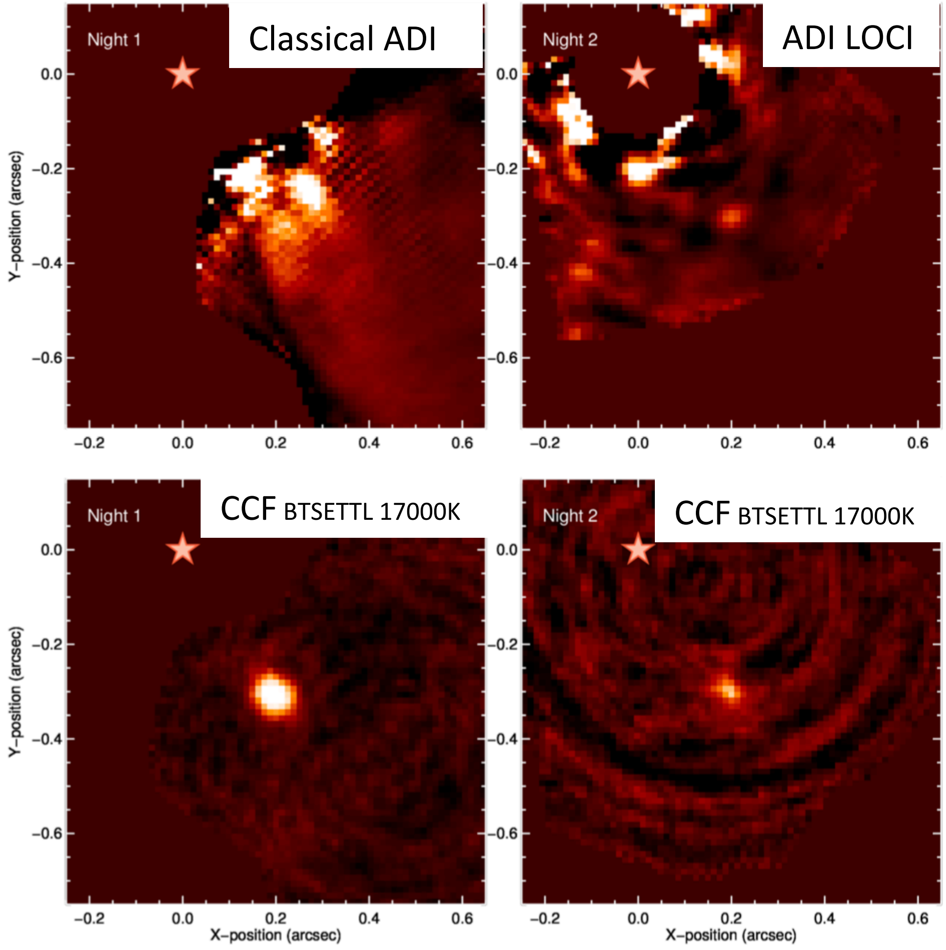


ASDI observations with an IFS yield very low contrasts at short separations

More diversity with higher spectral resolution

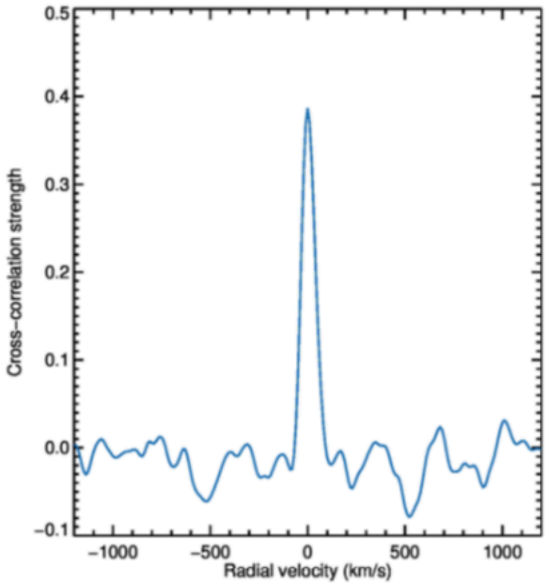
Talks J. Wang, D. Mawet

β Pic b detected with medium resolution IFS



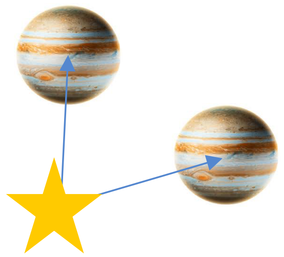
(Hoeijmakers 2018)

- Higher spectral resolution introduces more spectral diversity and allows the use of molecular templates (cross-correlation using CO, CH4 or evolutionary model templates)
- Medium resolution IFS observations (R~5000 with SINFONI) already provides enhanced detection capabilities wrt ADI.



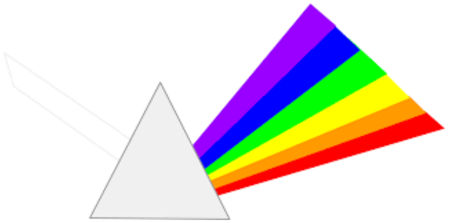
Different strategies to achieve diversity in imaging

- Angular diversity

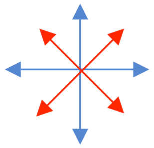


- Stellar diversity

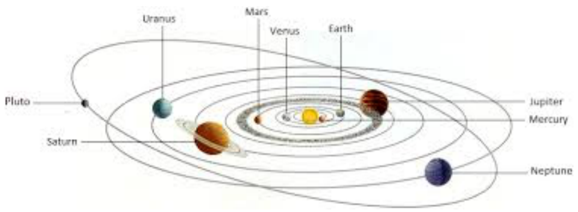
- Spectral diversity



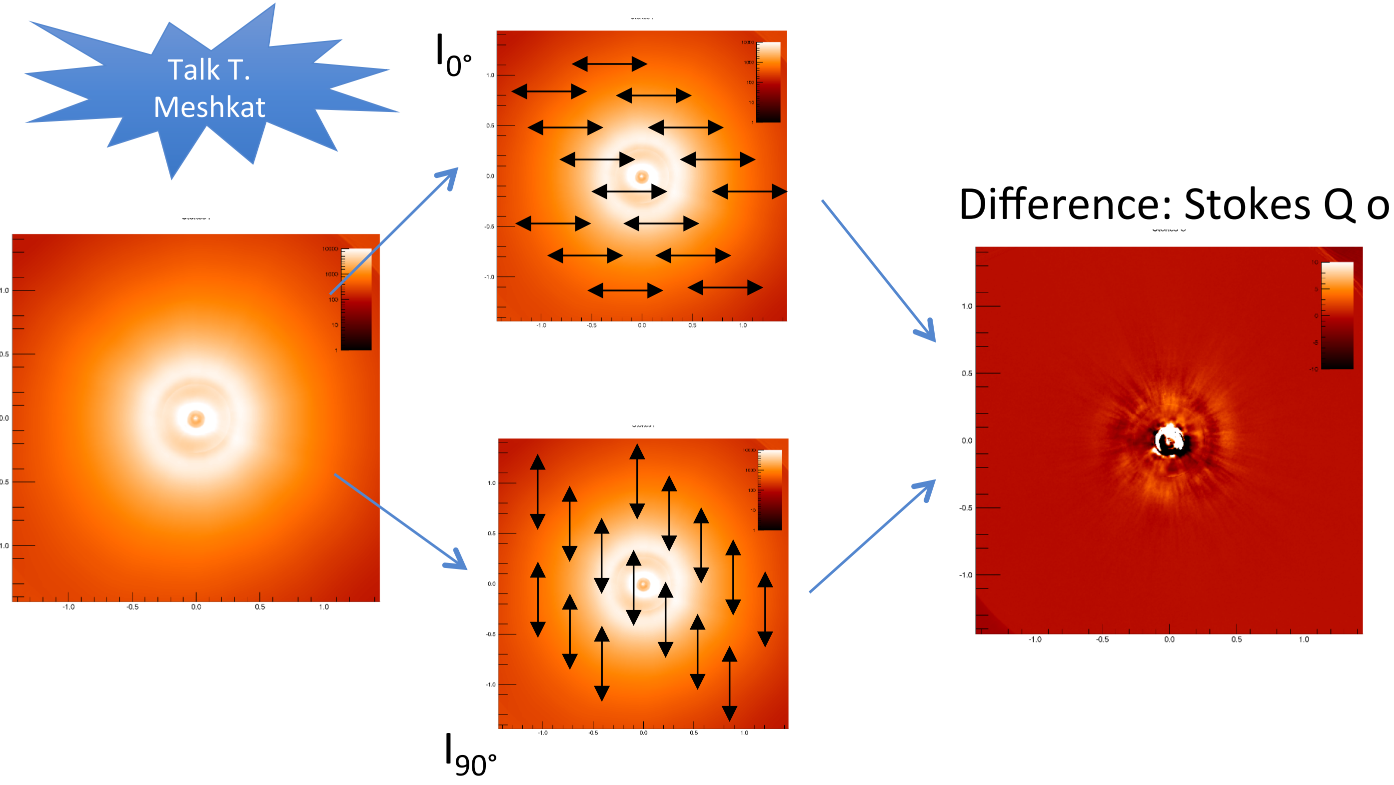
- **Polarimetric diversity**

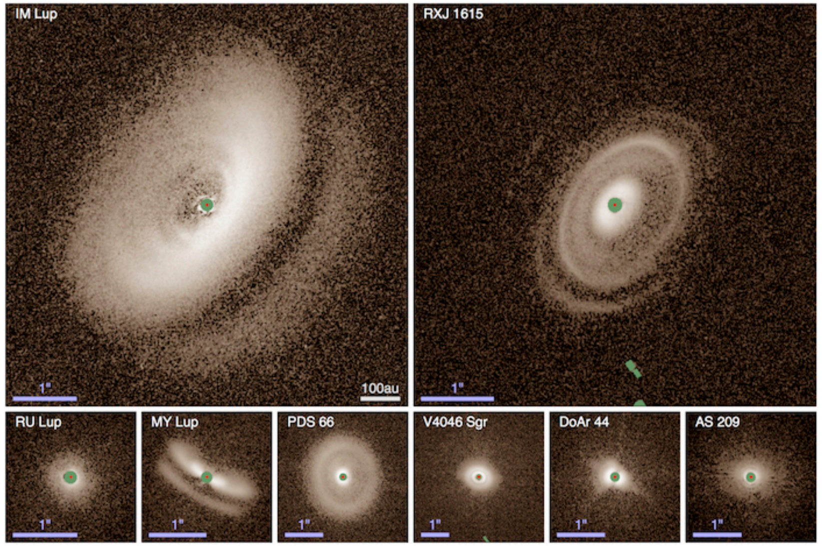


- Orbital diversity



Polarimetric Differential Imaging (PDI)





Avenhaus et al. 2018

- Very efficient tool to achieve high contrast
- Instantaneous subtraction: speckles are assumed to be independent of polarization
- Accurate calibration of the instrumental calibration is required

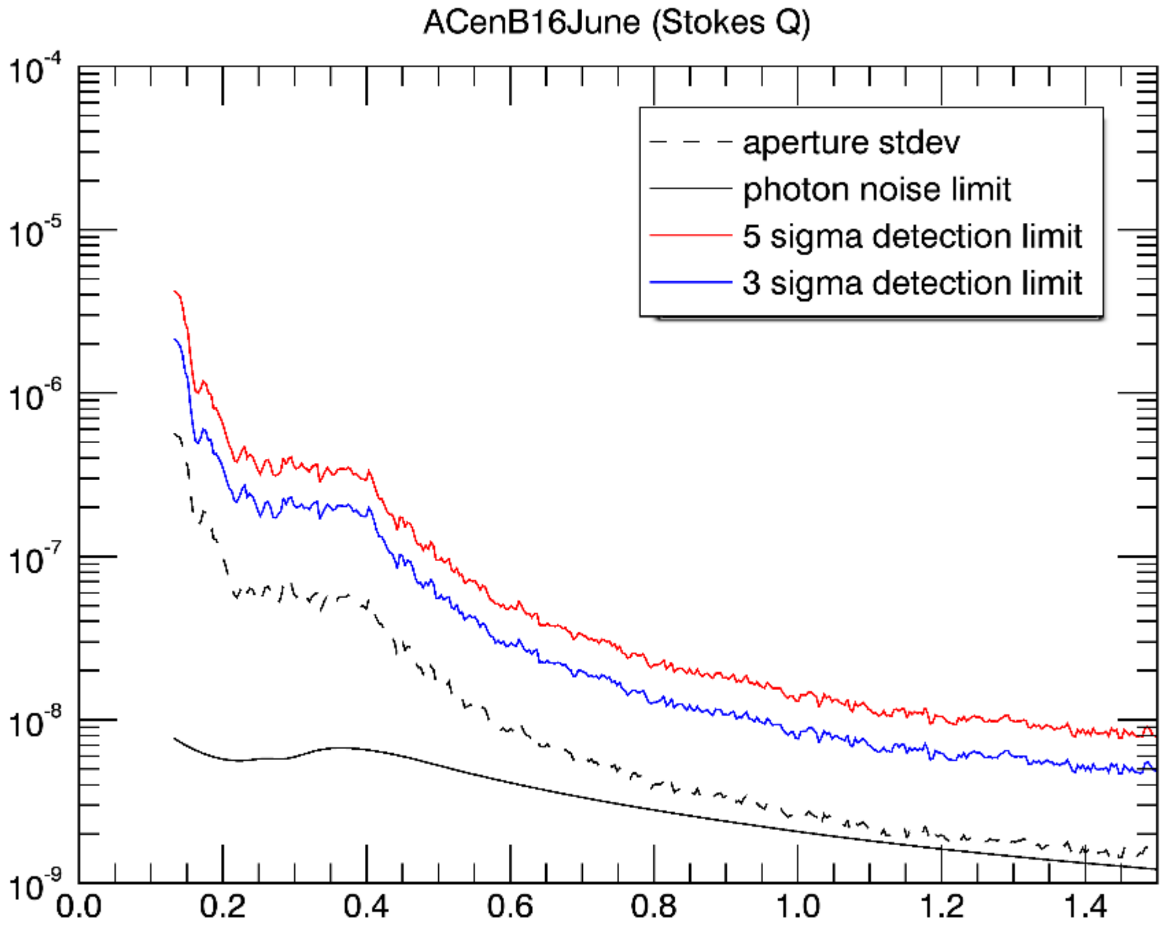
- Very efficient to detect polarized scattered light of disks
- For planets, one can hope to detect:
  - Reflected light
  - Thermal light if they have asymmetric cloud coverage or oblateness

Schmid et al. 2006, Perrin et al. 2014, Millar Blanchaer et al. 2016

Best contrast reached on α Cen B with SPHERE Zimpol

- Final contrast for Stokes Q with 2h in broad band filter and very good conditions
  0.2''-0.4'': ~3 10^{-7}
  0.6''-0.8'': ~3 10^{-8}
  > 1.0'': ~1 10^{-8}

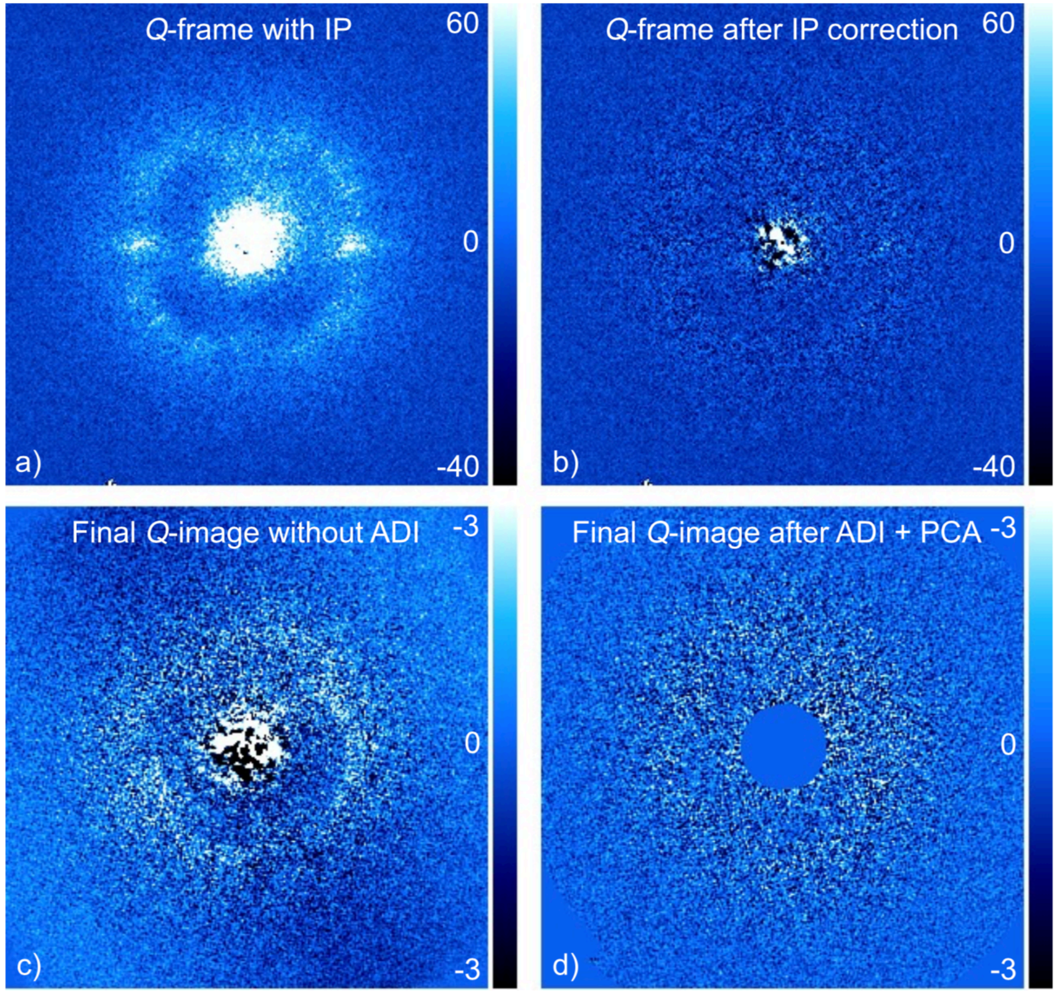
- Factor 10 above a 10 Earth planet

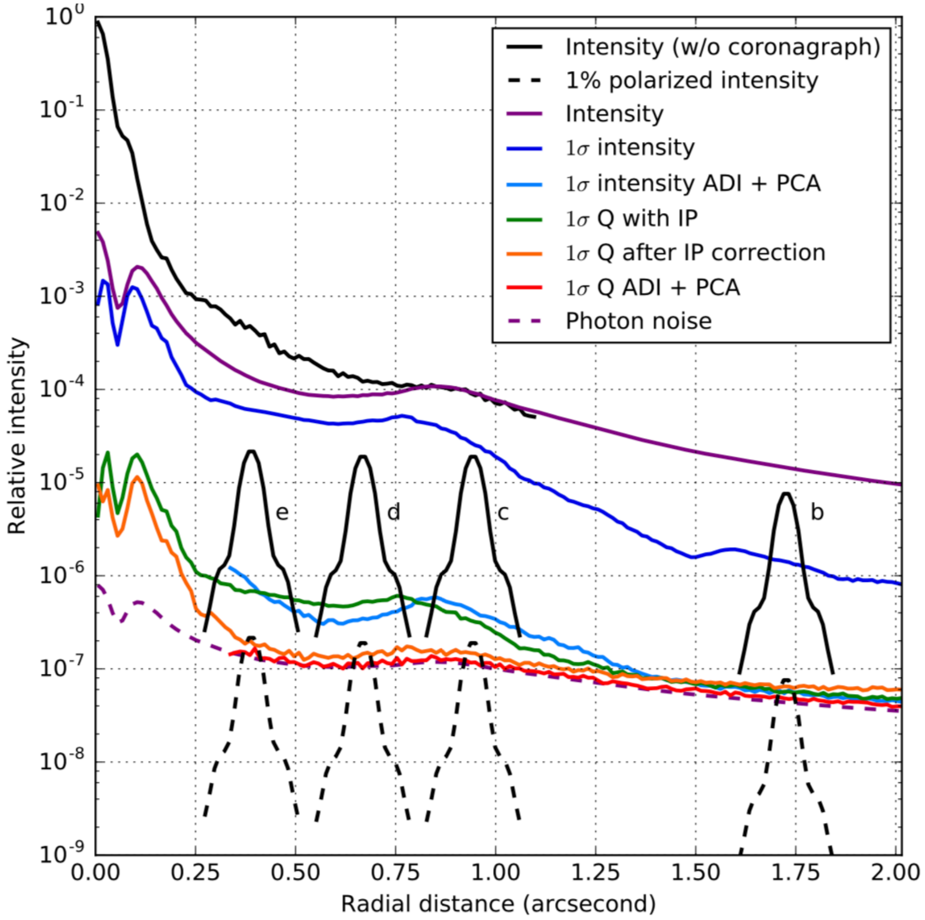


Separation in arcsec

Hunziker et al. in prep
Schmid et al. in prep

Combining PDI with ADI

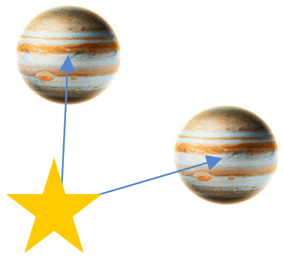




Example with SPHERE IRDIS at H: constraints on
<1% polarisation for HR8799 bcde.
<0.1% polarisation for PZ Tel B
Photon noise limit reached at 0.3”

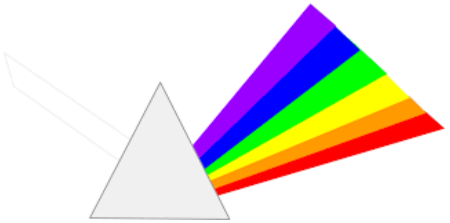
Van Holstein et al. 2017

Different strategies to achieve diversity in imaging

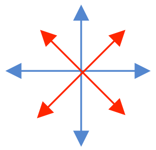


- Angular diversity

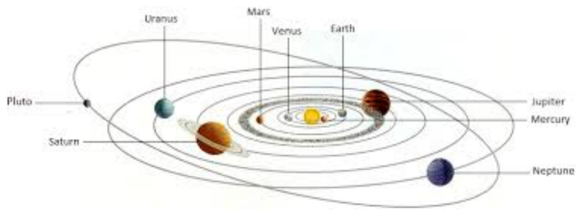
- Stellar diversity



- Spectral diversity



- Polarimetric diversity
- **Orbital diversity**



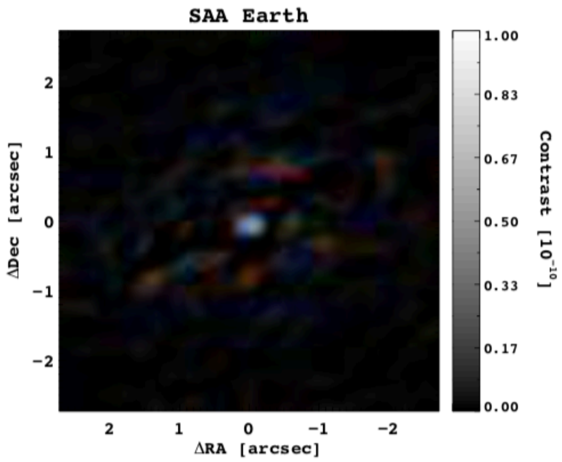
Orbital Differential Imaging (ODI)

Provides an additional gain and addresses the issue of orbital movements for shorter-period planets.

From space

- RDI
- Temporal filtering
- Orbital co-adding

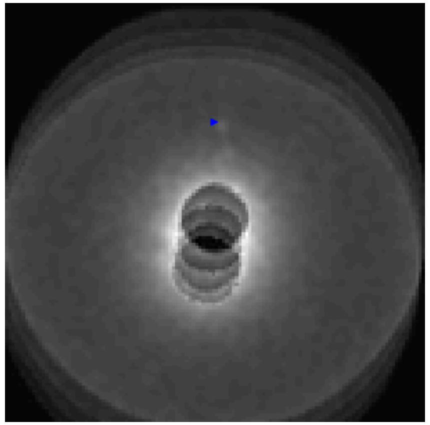
Males et al. 2013, 2015



From the ground

- Individual ADI
- Orbital co-adding
- Grid search of orbital parameters

Le Coroller et al. 2015, Nowak et al. 2018



Gain in sqrt(number of visits)

Conclusions

- Diversity is the key to decouple planetary from stellar signal
- Many strategies developed or in development. Not mentionned here: IRS (Image Rotation and Subtraction, Ren+2012, Dou+2016)
- Currently planet cancellation often limits the accuracy of those diversity techniques or the regions where it is applicable
- Image diversity is one part of the game to reach very high contrasts and lessons learnt from past instruments show that it must be considered at the design stage