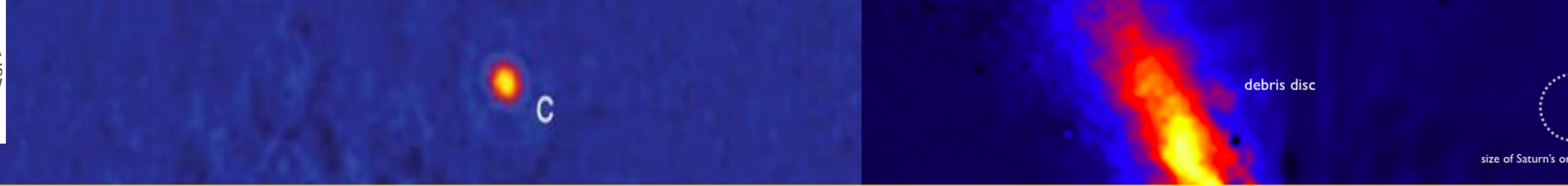
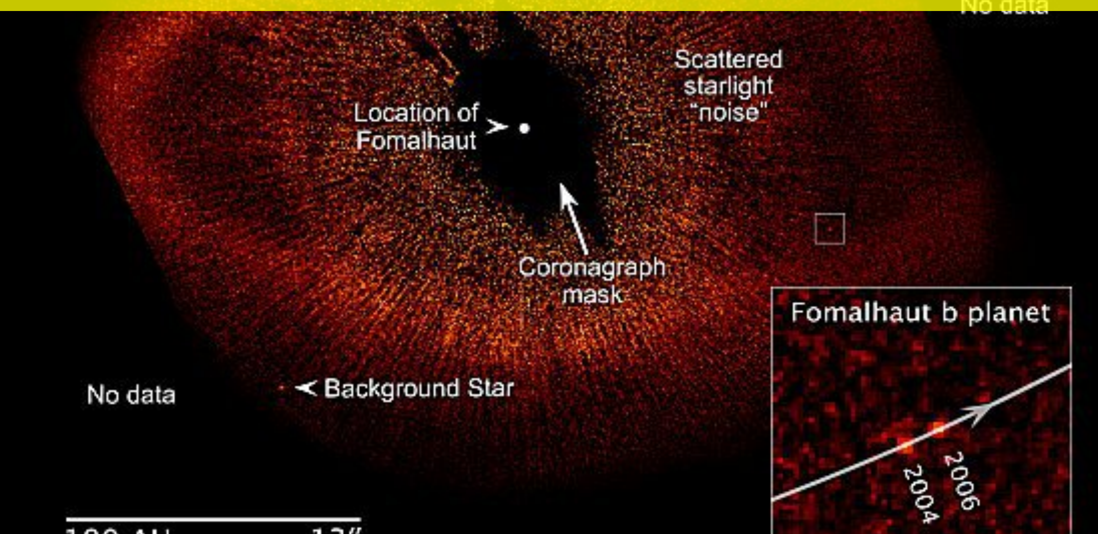


High-contrast imaging observations of exoplanets: where we are, where we go

Valentina D'Orazi
INAF – Osservatorio Astronomico di Padova



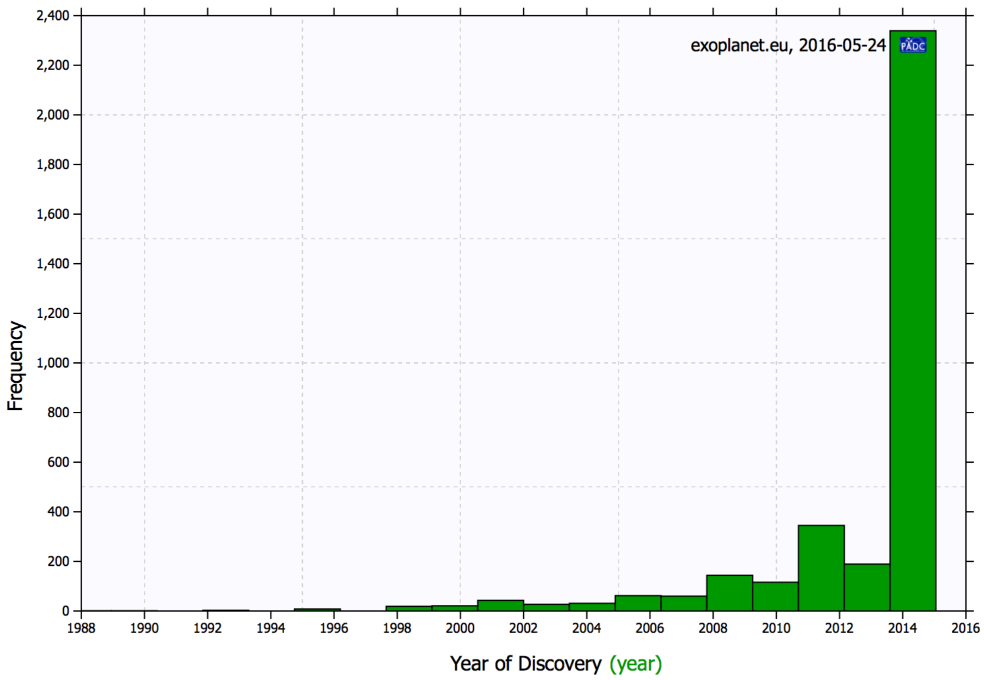
People: R. Claudi, S. Desidera, R.G. Gratton, D. Mesa, E. Sissa, the SPHERE consortium, the SHARK team, and many many more….

Bologna, Thursday seminars, May 26, 2016

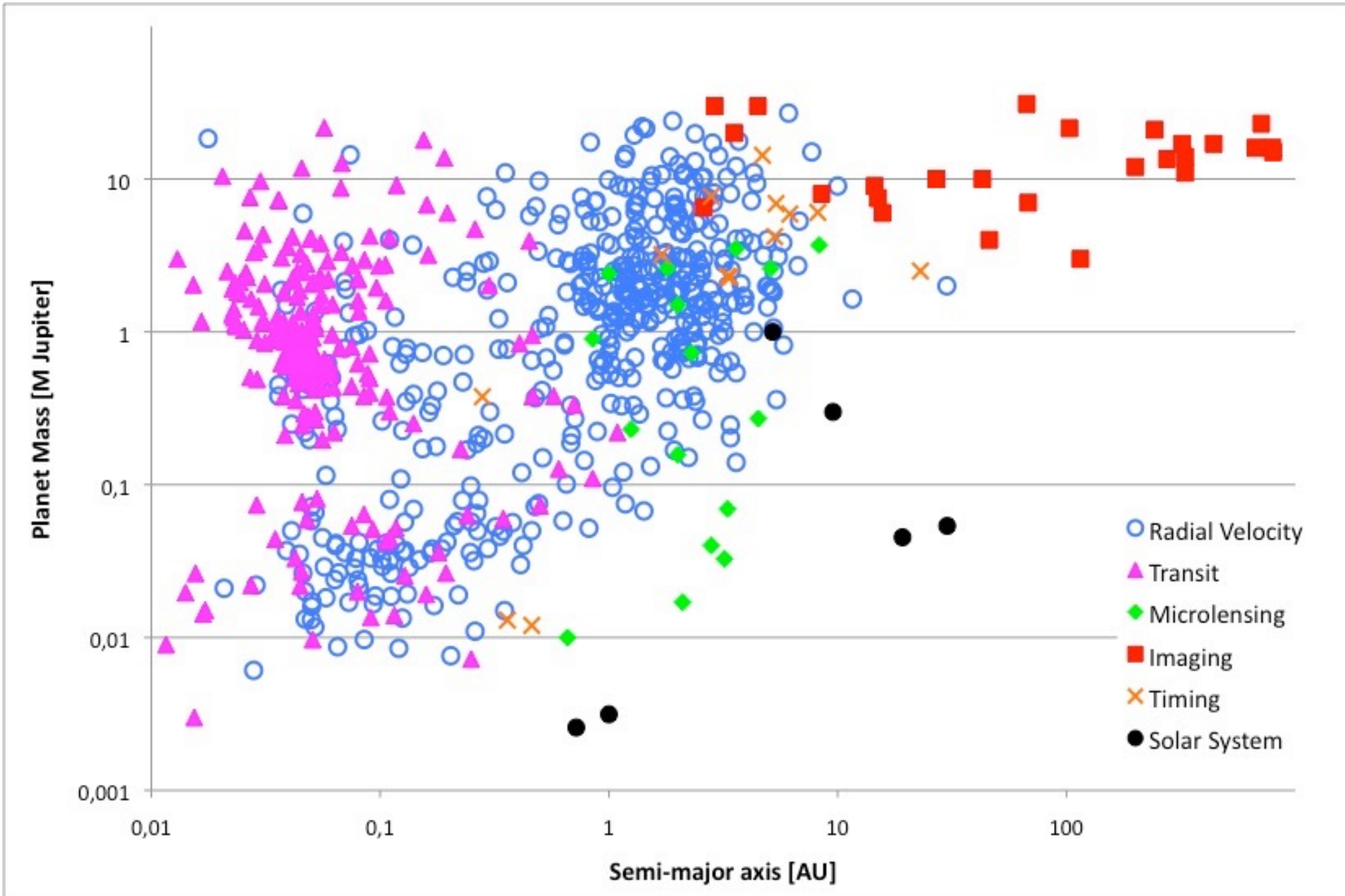
First discovery by Mayor & Queloz (1995) of a planet orbiting the solar analog 51 Peg, followed soon thereafter by the detection of planets around 47 UMa (Butler & Marcy 1996) and 70 Vir (Marcy & Butler 1996)

→ Outstanding efforts in detecting exoplanets: to date 1642 confirmed planets + 3786 unconfirmed Kepler candidates have been discovered (source http://exoplanet.org, May 2016).

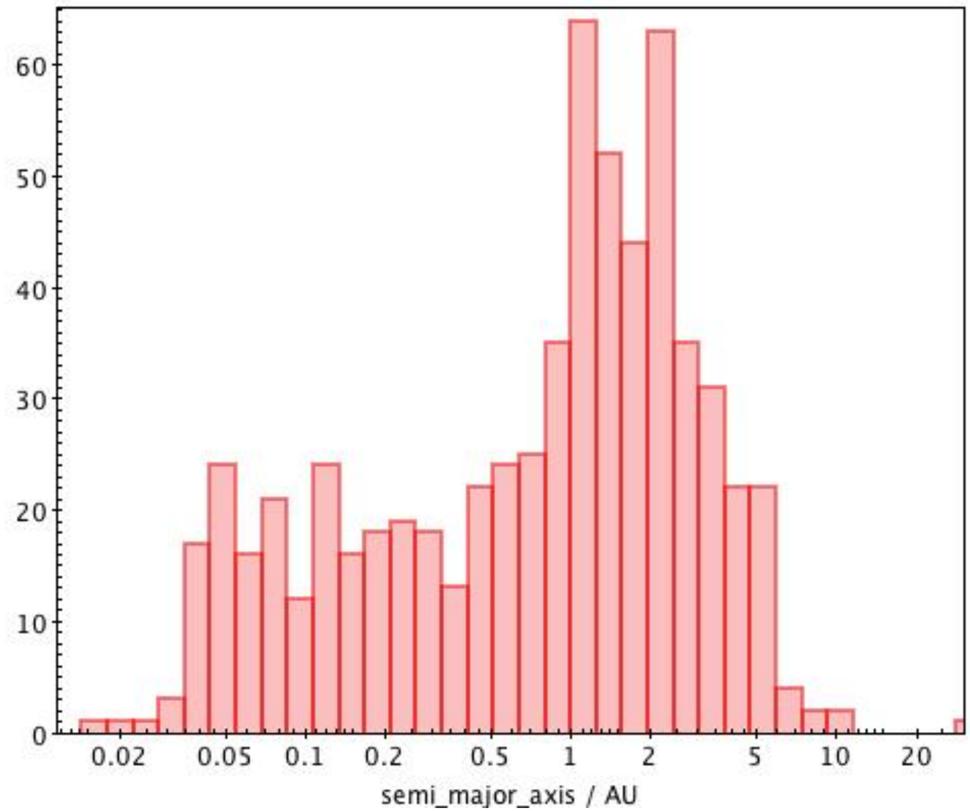
Different detection techniques (radial velocity, direct imaging, Microlensing, Transits) that sample different space parameter for planetary systems (i.e., mass, orbital distance) → <u>different formation mechanisms</u>



High-contrast Imaging Framework



Radial Velocity Biases

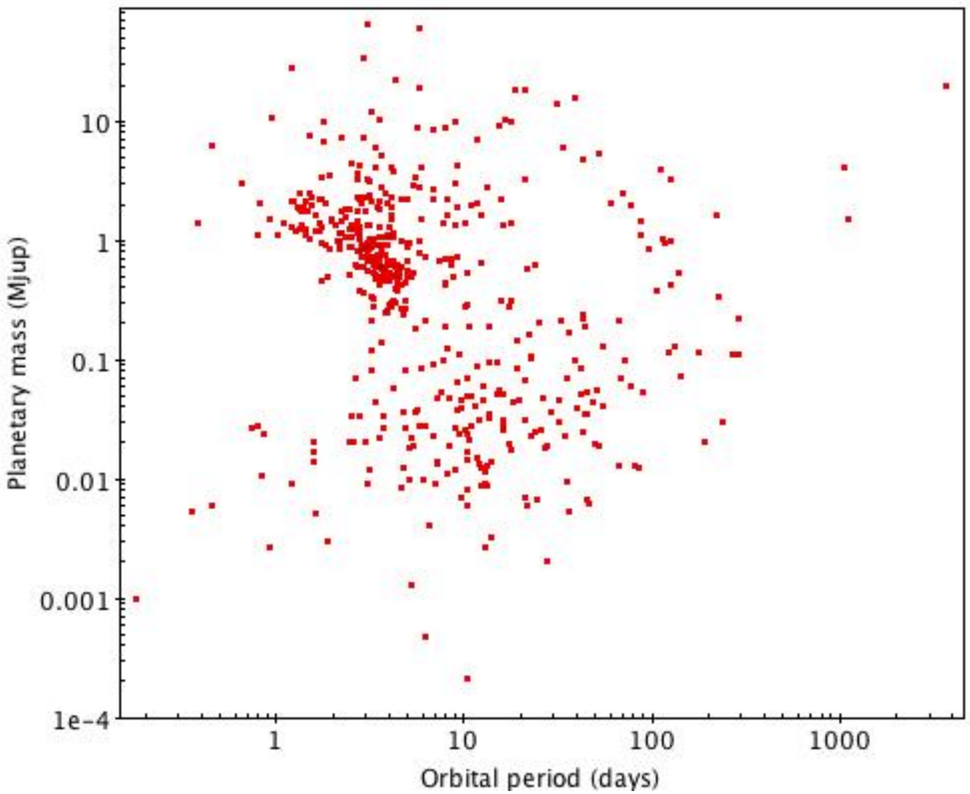


- QUIET STARS

$$K \propto \frac{M_p \sin i}{M_*^{1/2} a^{1/2}}$$

- Larger Planets
- Smaller Stars
- Closer Planets

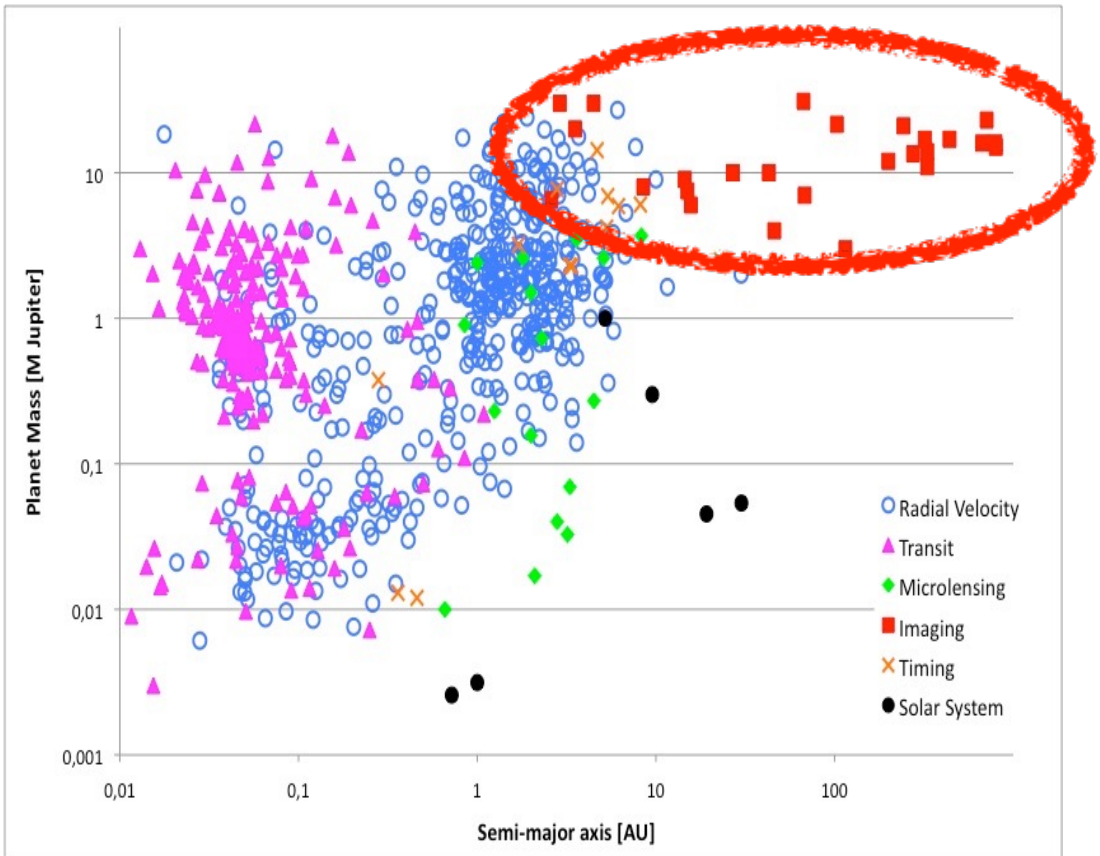
Transit Biases



$$\frac{dN_p}{da\,dM_p} \propto \frac{R_P^3}{R_*^{5/4}} \frac{L^{3/2}}{a^{7/4}}$$

- Larger Planets
- Smaller Stars
- Closer Planets
- QUIET STARS

Direct Imaging



Direct technique: Planet's photons
(Targets: young & nearby stars)

Orbital & Physical properties:

> L, a , e, i, ω
> Giant planets at wide orbits (>10 AU)
> Multiple: Architecture & Stability
> Planet – disk connection

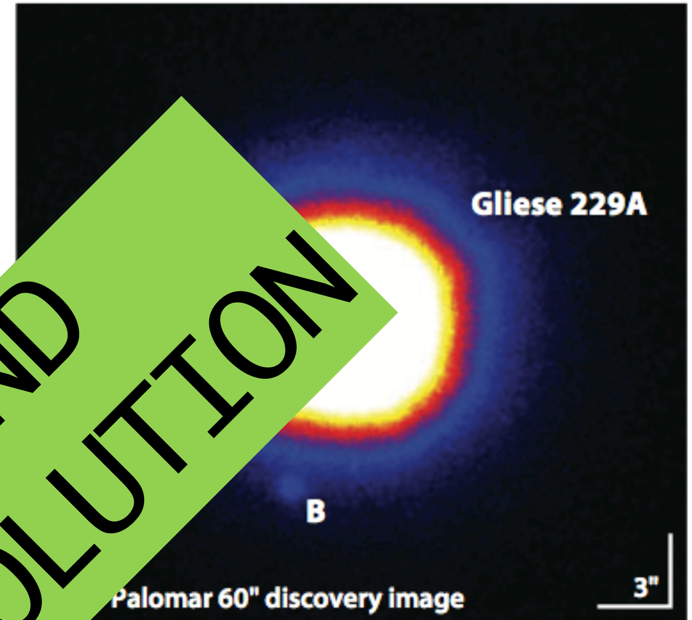
(Chauvin et al. 05, 10; Lafrenière et al. 07
Soummer et al. 11; Vigan et al. 12)

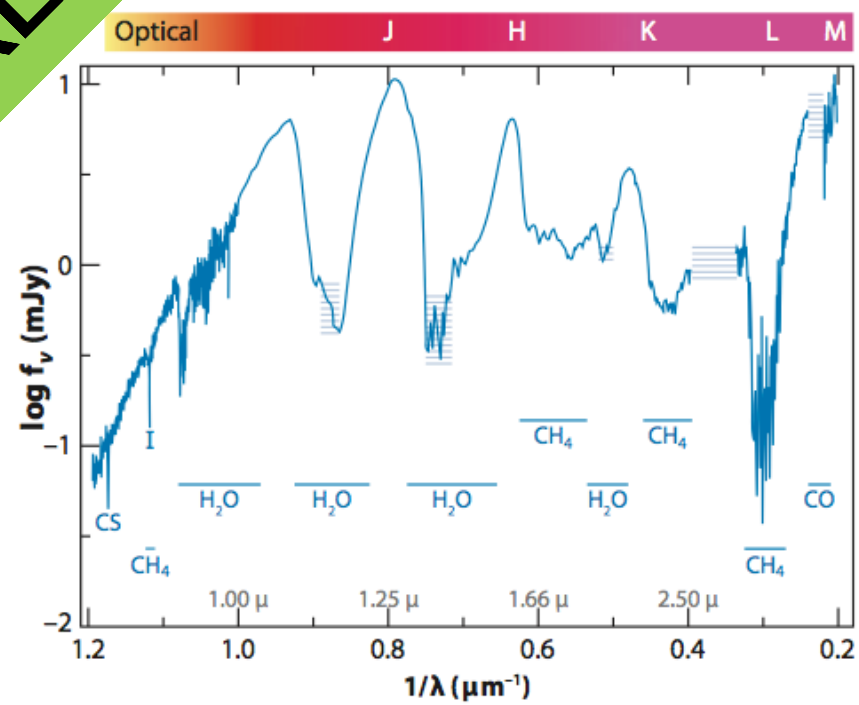
High-contrast spectroscopy

> Low-gravity, composition, non-LTE
chemistry, cloud coverage...

(Janson et al. 10; Bonnefoy et al. 09, 12)

CONTRAST AND ANGULAR RESOLUTION





The Solar System to 10 pc

Contrast:

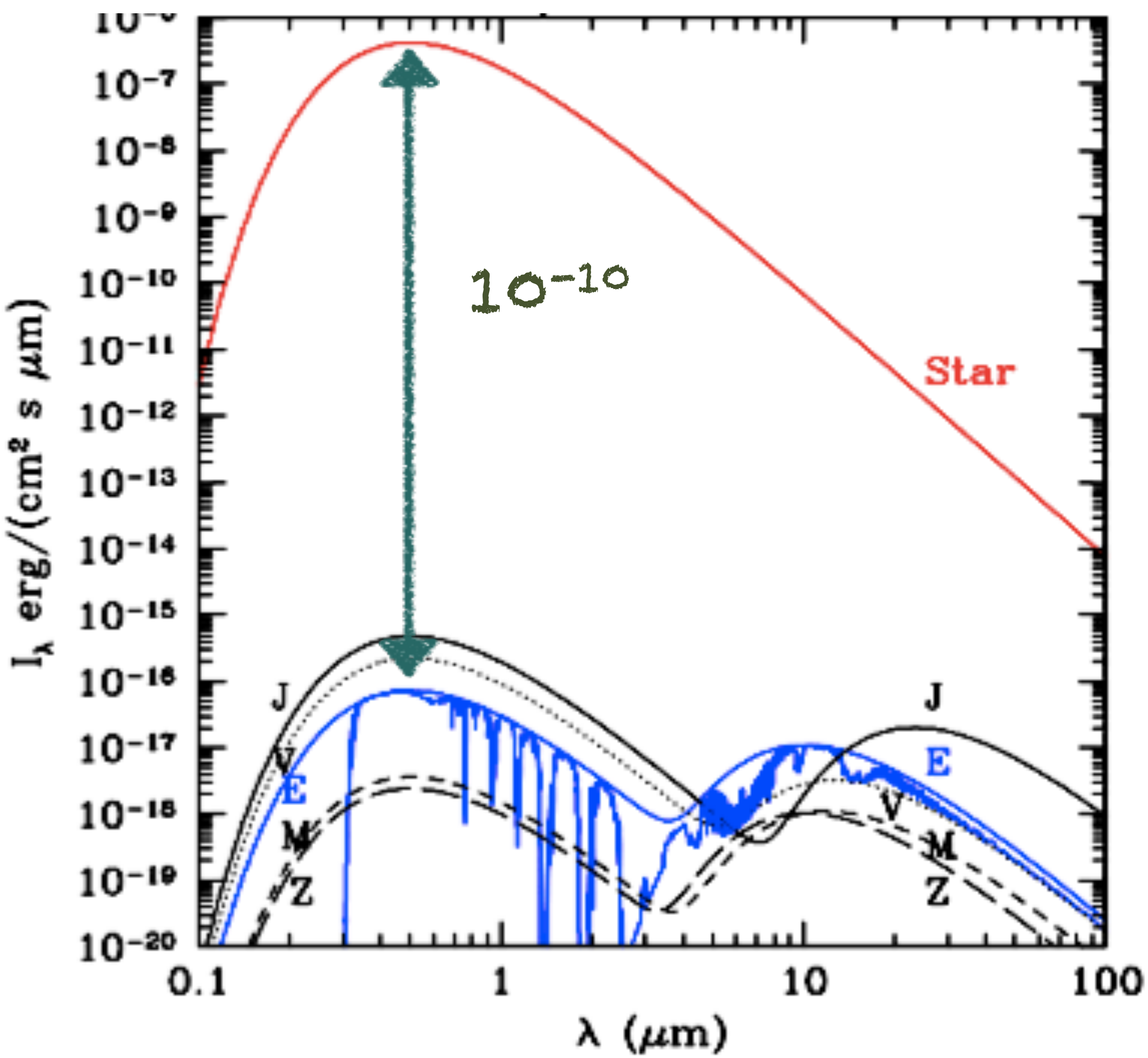
Jupiter/Sun = 10^{-8} = 20 mag

Earth/Sun = 10^{-10} = 25 mag

Angular Separation:

Jupiter = 0.5 arcsec @ 10 pc

Jupiter = 0.1 arcsec @ 50 pc



HIGH CONTRAST IMAGING

PROBLEMS and TECHNIQUES

Atmosphere + speckles

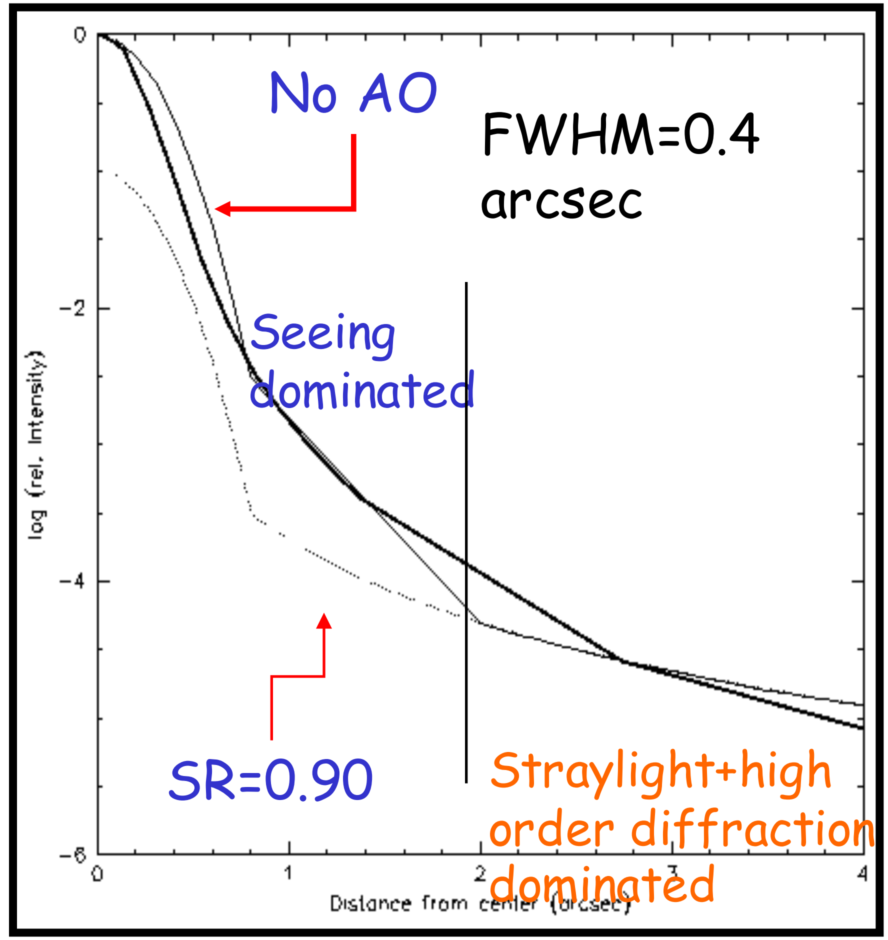
➔ Adaptive Optics

➔ Differential Imaging

Diffraction

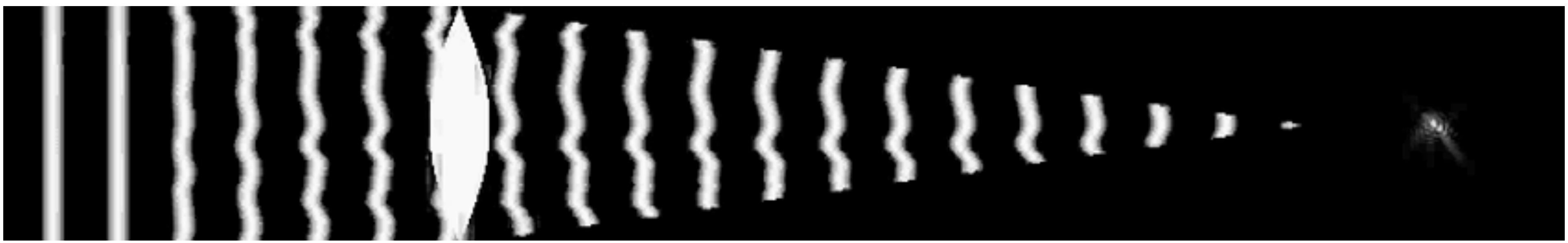
➔ Coronography

(Lyot, Apodizing Masks, Nulling, 4-quadrant..)



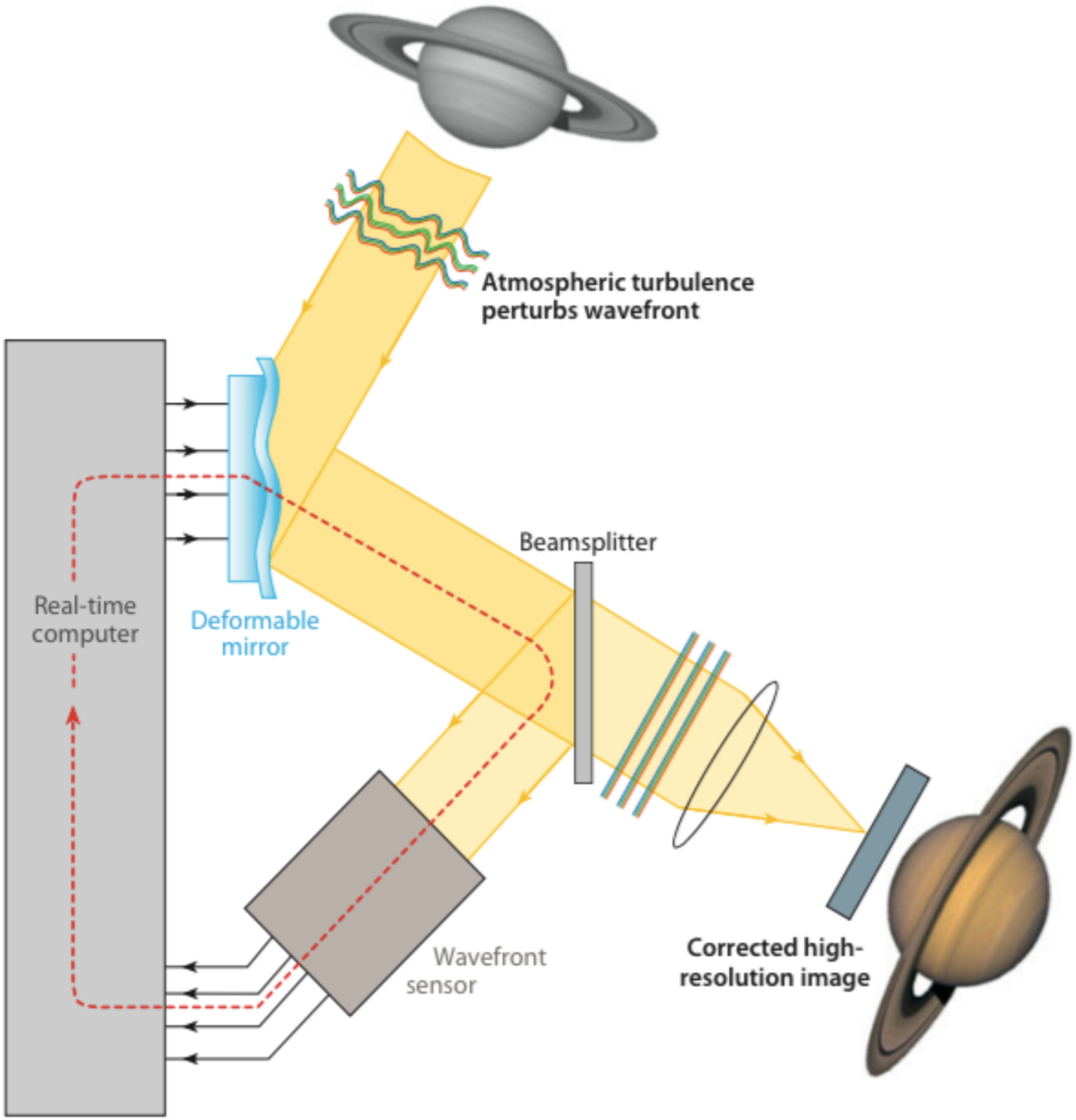
Speckles

Speckles are due to the interference between light rays passing through different atmospheric cells before to reach the telescope.
Because speckles are due to the interference of the wavefront they could be generate also by other causes



… turbulence evolution with time. Typical time:~ some milli seconds correction need systems more rapid than kHz

AO Working Principles

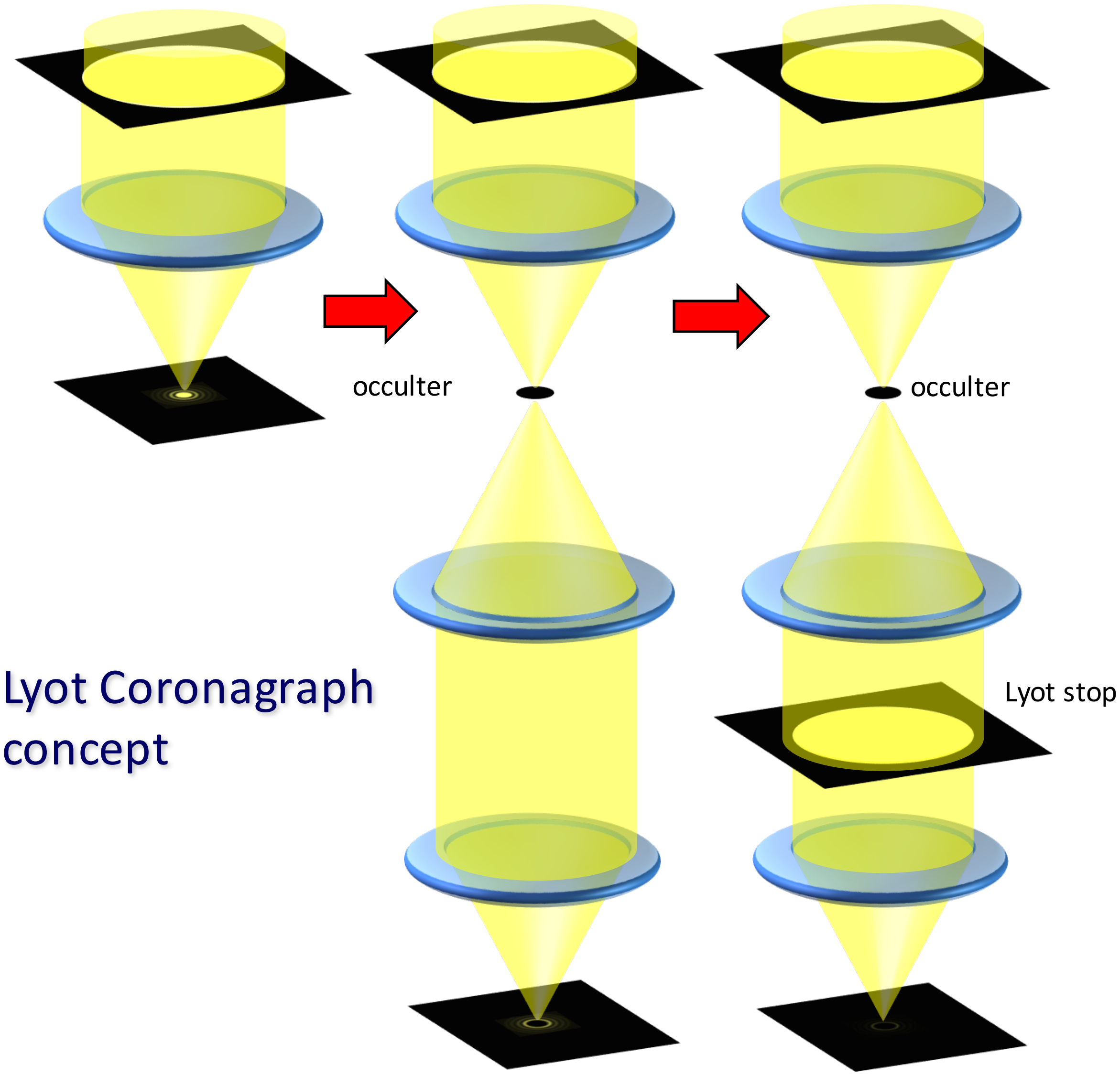


Davies & Kasper 2002

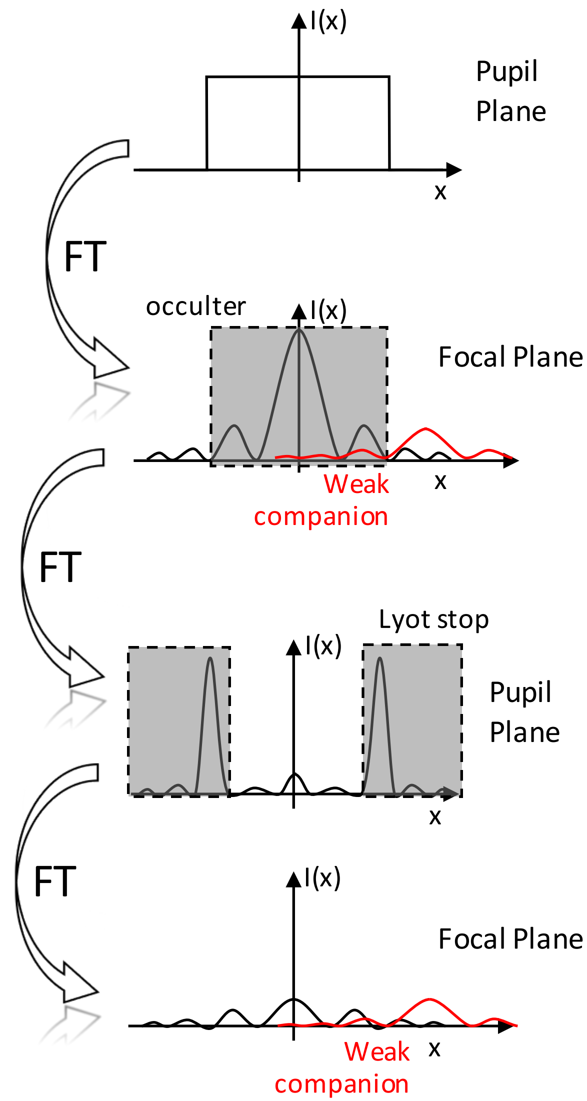
The AO system tries to regulate the optical path variations (wavefront) by measuring the deviations using a WFS, calculating an appropriate correction, and applying this correction to a deformable mirror

Restore the theoretical angular resolution. Concentrate the flux inside the diffraction peak

Coronagraphy: the principle



Lyot Coronagraph concept



Coronagraphic Zoo …

TABLE 1

Coronagraphs Able to Achieve 10^{10} PSF Contrast within $5\lambda/d$

Coronagraph	Abbreviation	Reference	Design(s) Adopted
"Interferometric" Coronagraphs			
Achromatic Interferometric Coronagraph	AIC	Baudoz et al. (2000)	
Common-Path Achromatic Interferometer-Coronagraph	CPAIC	Tavrov et al. (2005)	(=AIC)
Visible Nulling Coronagraph, X-Y shear (fourth-order null)[a]	VNC	Mennesson et al. (2003)	Shear distance =±0.3 pupil radius
Pupil Swapping Coronagraph	PSC	Guyon & Shao (2006)	Shear distance =0.4 pupil diameter
Pupil Apodization			
Conventional Pupil Apodization and Shaped-Pupil[b]	CPA	Kasdin et al. (2003)	Prolate[c] ($r = 4.2\lambda/d$, 8% throughput)
Achromatic Pupil Phase Apodization	PPA	Yang & Kostinski (2004)	$\phi = \phi_2(x) + \phi_2(y)$; $a = 2$; $\epsilon = 0.01$
Phase Induced Amplitude Apodization Coronagraph	PIAAC	Guyon (2003)	Prolate apodization
Phase Induced Zonal Zernike Apodization	PIZZA	Martinache (2004)	Not simulated
Improvement on the Lyot Concept with Amplitude Masks			
Apodized Pupil Lyot Coronagraph	APLC	Soummer et al. (2003a, 2003b)	$r = 1.8\lambda/d$
Apodized Pupil Lyot Coronagraph, N steps	APLCN	Aime & Soummer (2004)	$(N, r) = (2, 1.4); (3, 1.2); (4, 1.0)$
Band-limited, fourth-order[a]	BL4	Kuchner & Traub (2002)	$\sin^4$ intensity mask, $\epsilon = 0.21$
Band-limited, eighth-order	BL8	Kuchner et al. (2005)	$m = 1$, $l = 3$, $\epsilon = 0.6$
Improvement on the Lyot Concept with Phase Masks			
Phase Mask	PM	Roddier & Roddier (1997)	With mild prolate pupil apod.
4 Quadrant Phase Mask	4QPM	Rouan et al. (2000)	
Achromatic Phase Knife Coronagraph	APKC	Abe et al. (2001)	(=4QPM)
Optical Vortex Coronagraph, topological charge m	OVCm	Palacios (2005)	$m = 2, 4, 6, 8$
Angular Groove Phase Mask Coronagraph	AGPMC	Mawet et al. (2005)	(=OVC)
Optical Differentiation	ODC	Oti et al. (2005)	Mask: $x \times \exp^{-(x/10)^2 d}$

Guyon et al., 2006, ApJ Suppl, 167, 81

Quasi static speckles

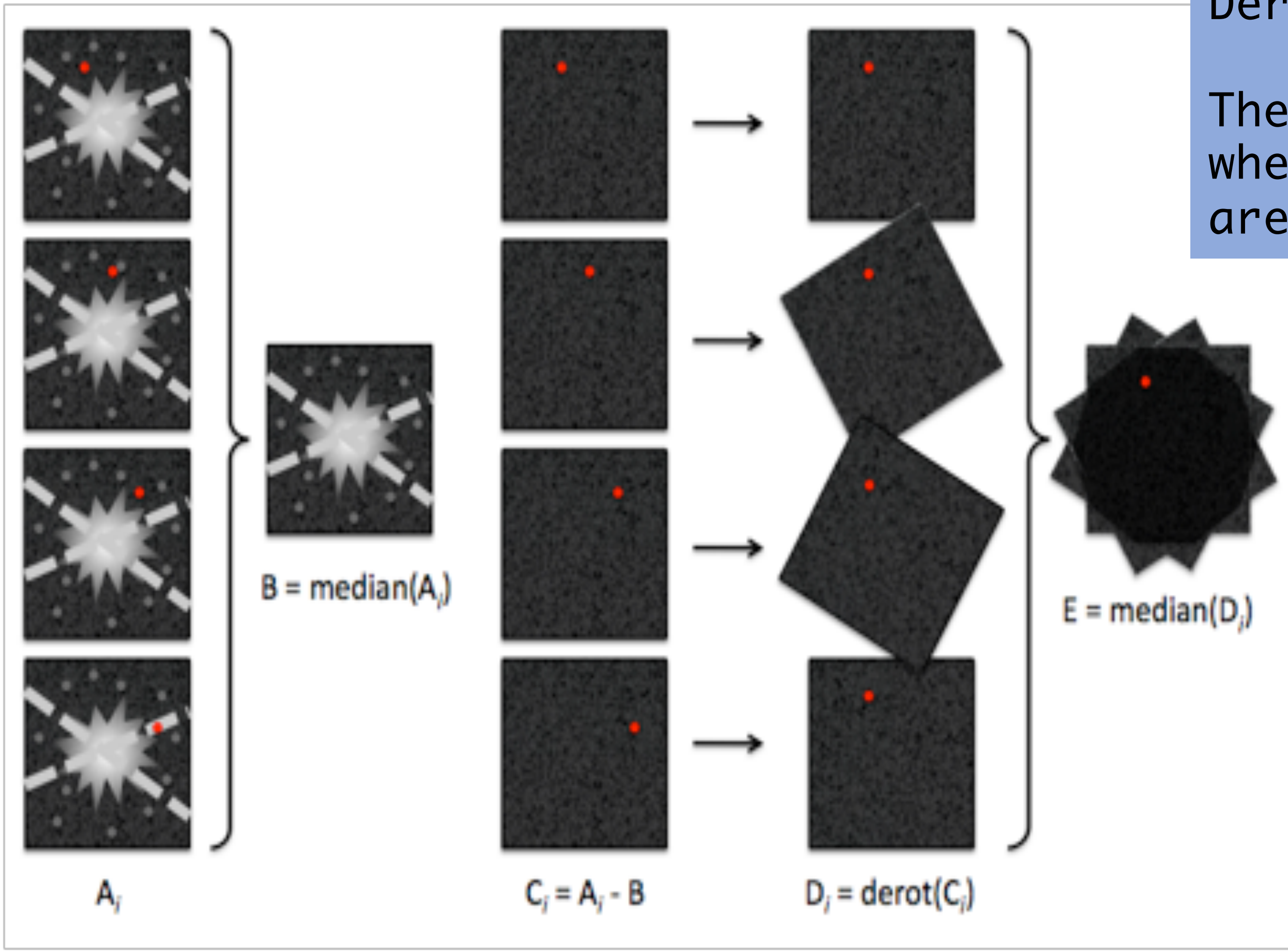
The major noise-source limitation in high-contrast imaging is another class of instrumental speckles: **the quasi-static speckles** (Beuzit et al. 1997; Oppenheimer et al. 2001; Marois et al. 2003; Boccaletti et al. 2003, 2004; Hinkley et al. 2007)

Quasi-static speckles correspond to slowly varying instrumental wavefront aberrations (amplitude and phase errors) present in the system, which finally dominate the companion signal. These speckles have various causes, among others mechanical or thermal deformations, or Fresnel effect, and evolve on a shorter timescale than long-lived aberrations (5 – 10 minutes)

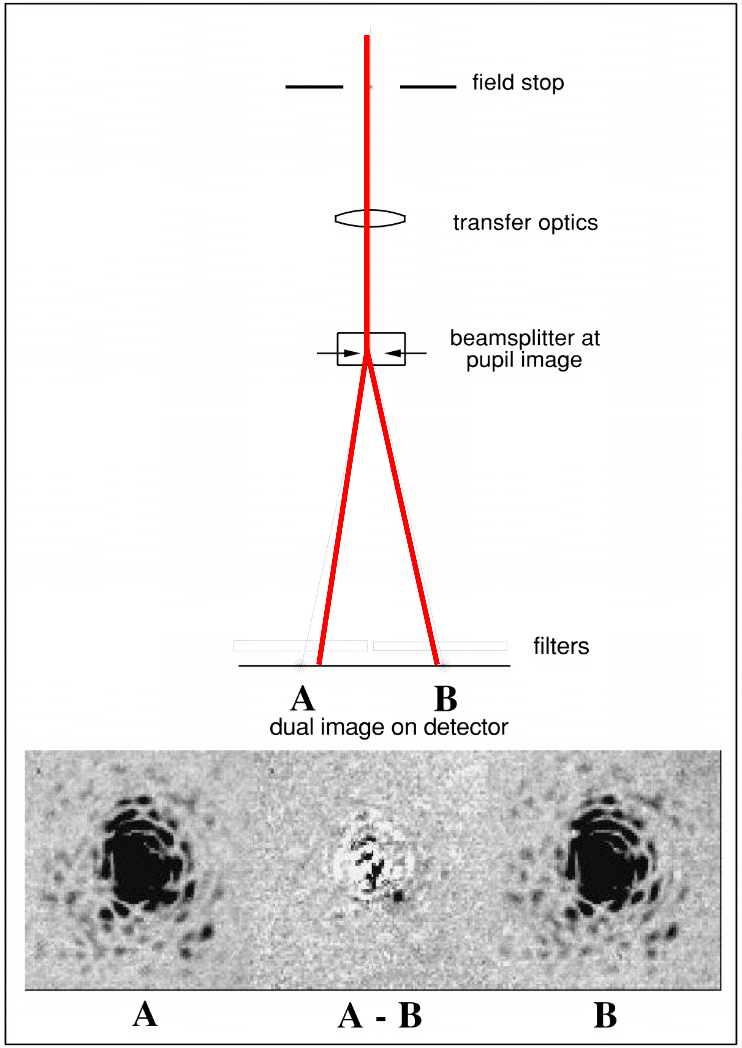
Angular differential Imaging (ADI)

Derotator: OFF

The planet moves whereas the speckels are fixed.

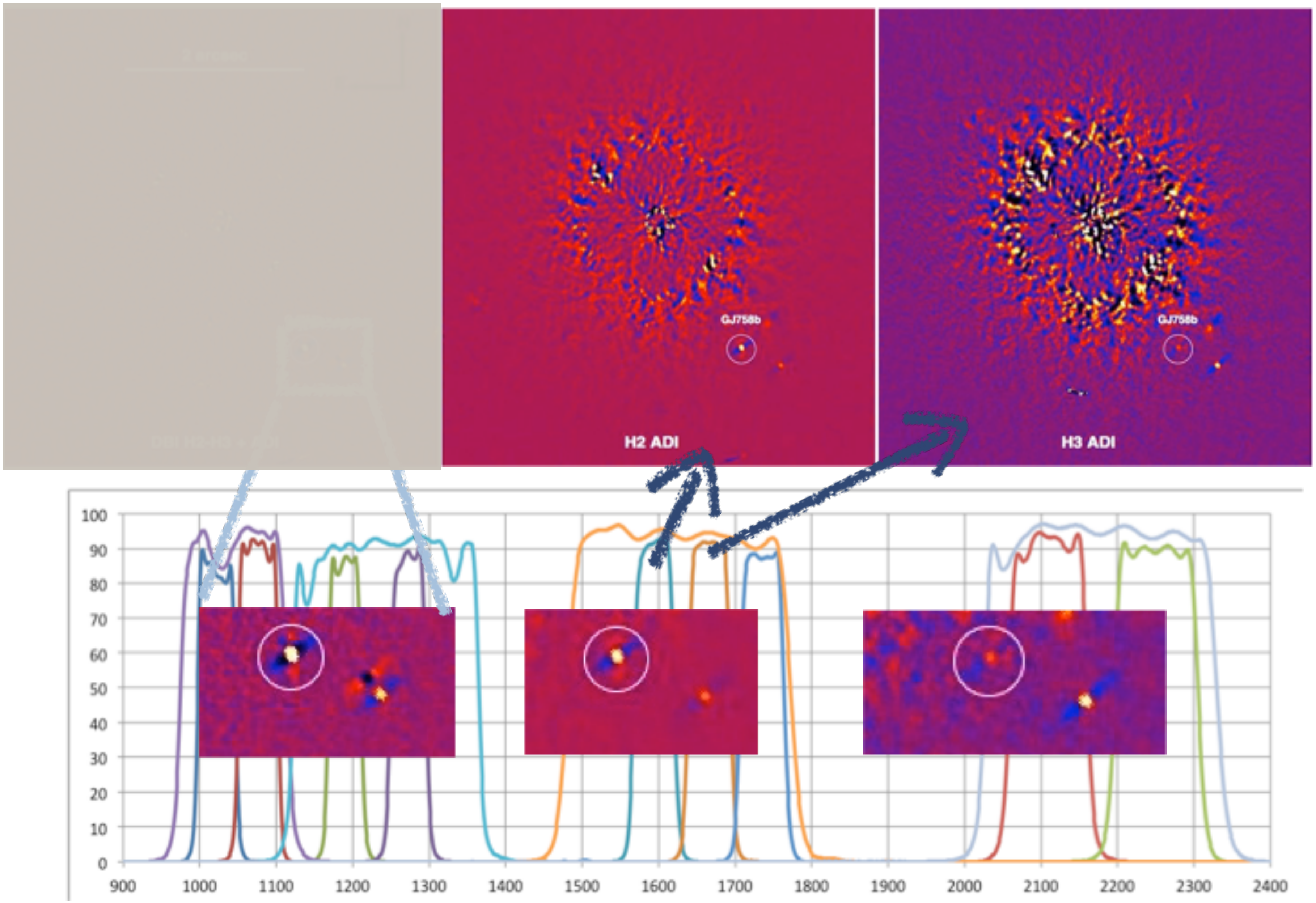


Simultaneous Differential Imaging (SDI)



Planets and the host star have different spectral features. This information can be used to suppress speckle noise.
(Racine+ 1999, Marois+ 2005)

For this, one needs simultaneous images at two similar wavelengths at which the brightness of the planet varies, e.g. in and out of a molecular band (e.g., CH_4)



GJ758b
H2 ADI
GJ758b
H3 ADI
100
90
80
70
60
50
40
30
20
10
0
900
1000
1100
1200
1300
1400
1500
1600
1700
1800
1900
2000
2100
2200
2300
2400

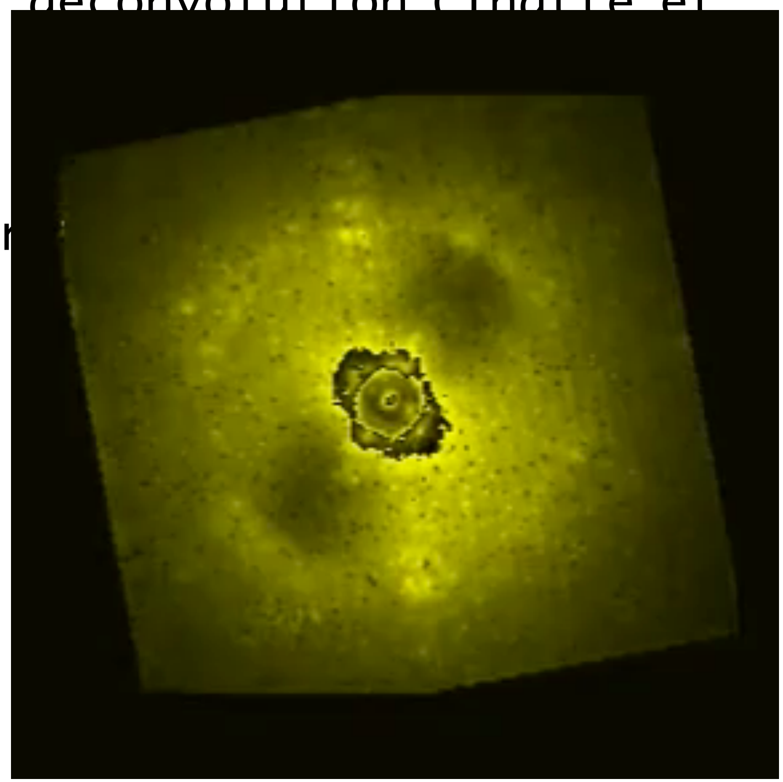
Spectral deconvolution

Simultaneous observation of several monochromatic images can be used to reduce the impact of speckles (Sparks and Ford, 2002).

For a given observation, the location of a companion around a star is constant while the location of speckles from the star increases with wavelength and their intensity decreases.

For a wide enough wavelength range this allows subtraction of the speckles. This process is known as spectral deconvolution (Thatte et al. 2007).

…......(we will see this approach is used i



PCA, T-Loci etc.

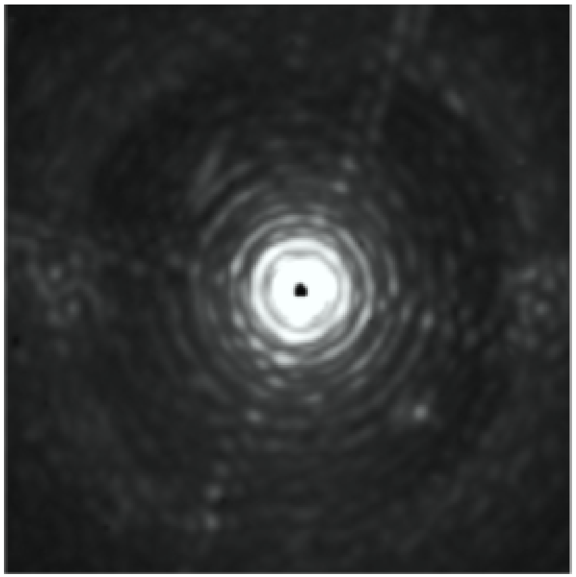
Some differential image techniques can be coupled to improve contrast:

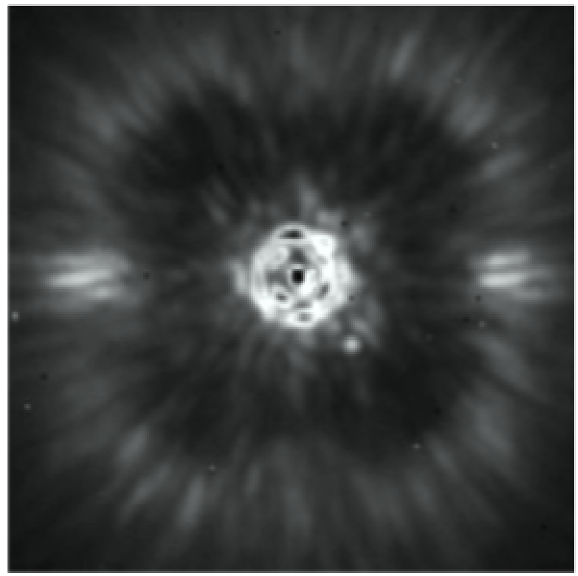
– e.g. ADI with speckle deconvolution or spectral differential imaging or polarimetric differential Imaging

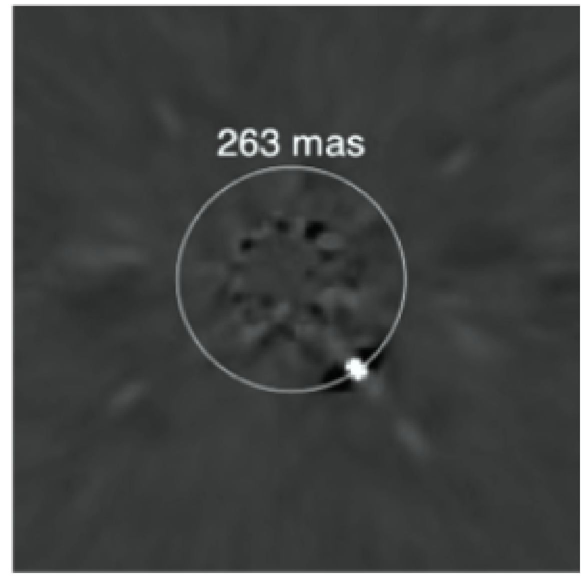
→ This can be obtained in a single step using **Principal Component Analysis (PCA)**

Alternatively, other algorithms can be used Such es e.g., LOCI (Locally Optimised Combination of Images) and T-Loci (Template Loci)

The three pillars of high-contrast imaging



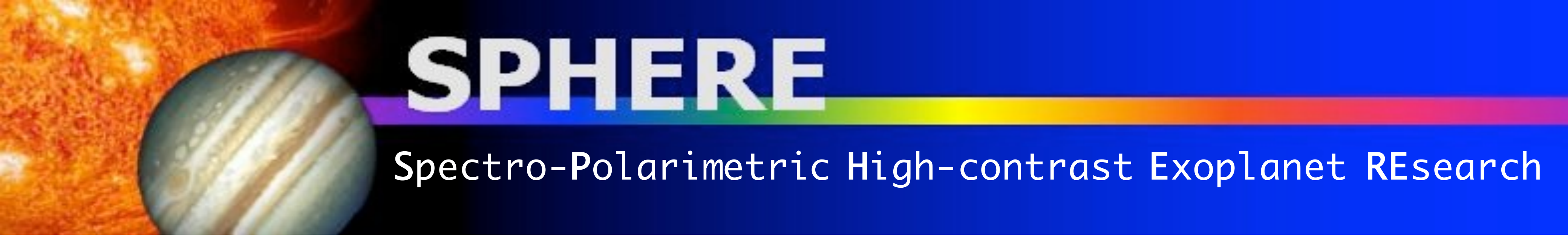




High-order AO: Contrast ~10^3

Coronagraphy: Contrast ~10^4

Differential imaging: Contrast ~10^6



What is SPHERE?

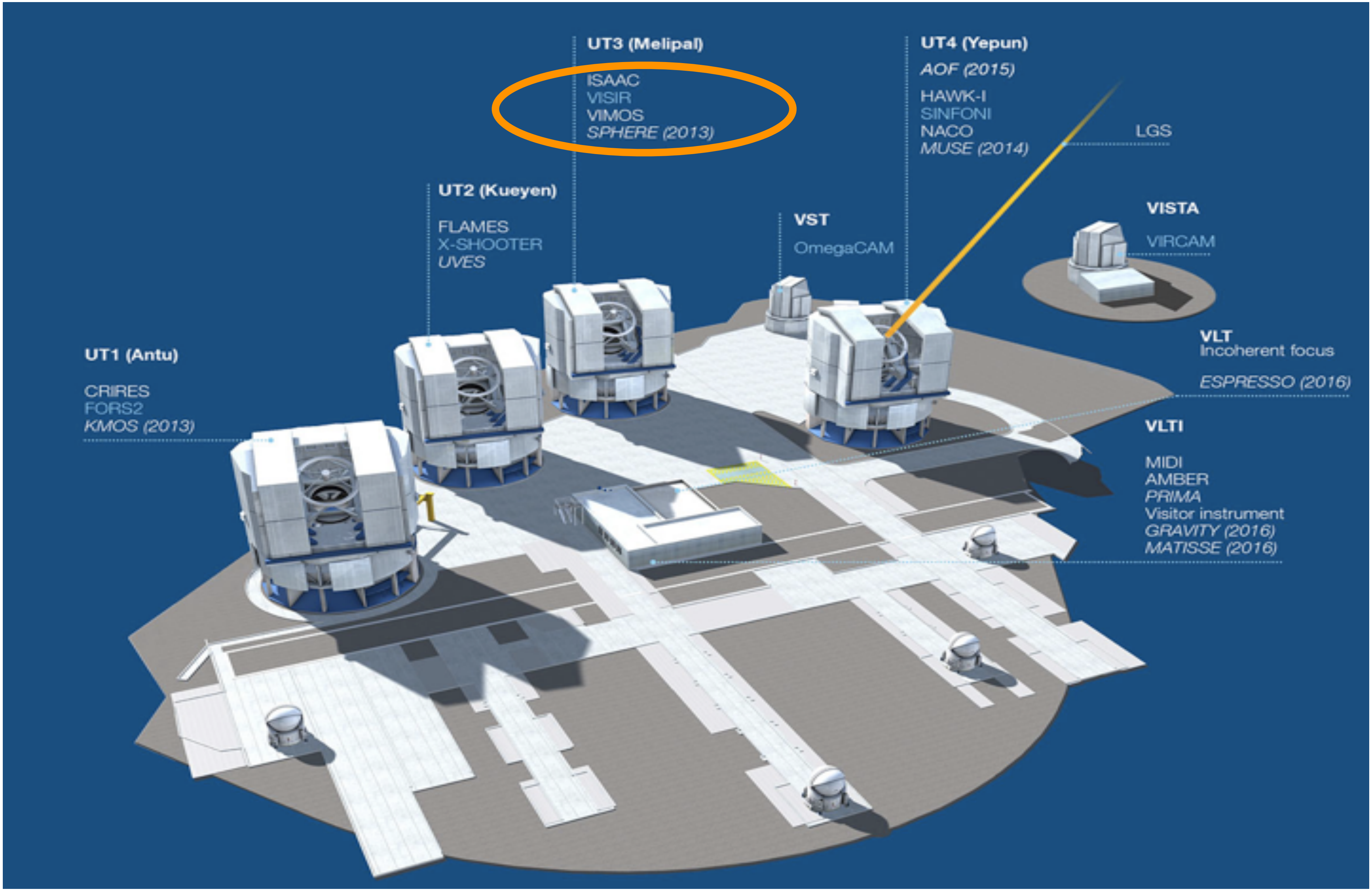
SPHERE is the new high-contrast imager for the VLT

It has passed the commissioning and was offered in spring 2015

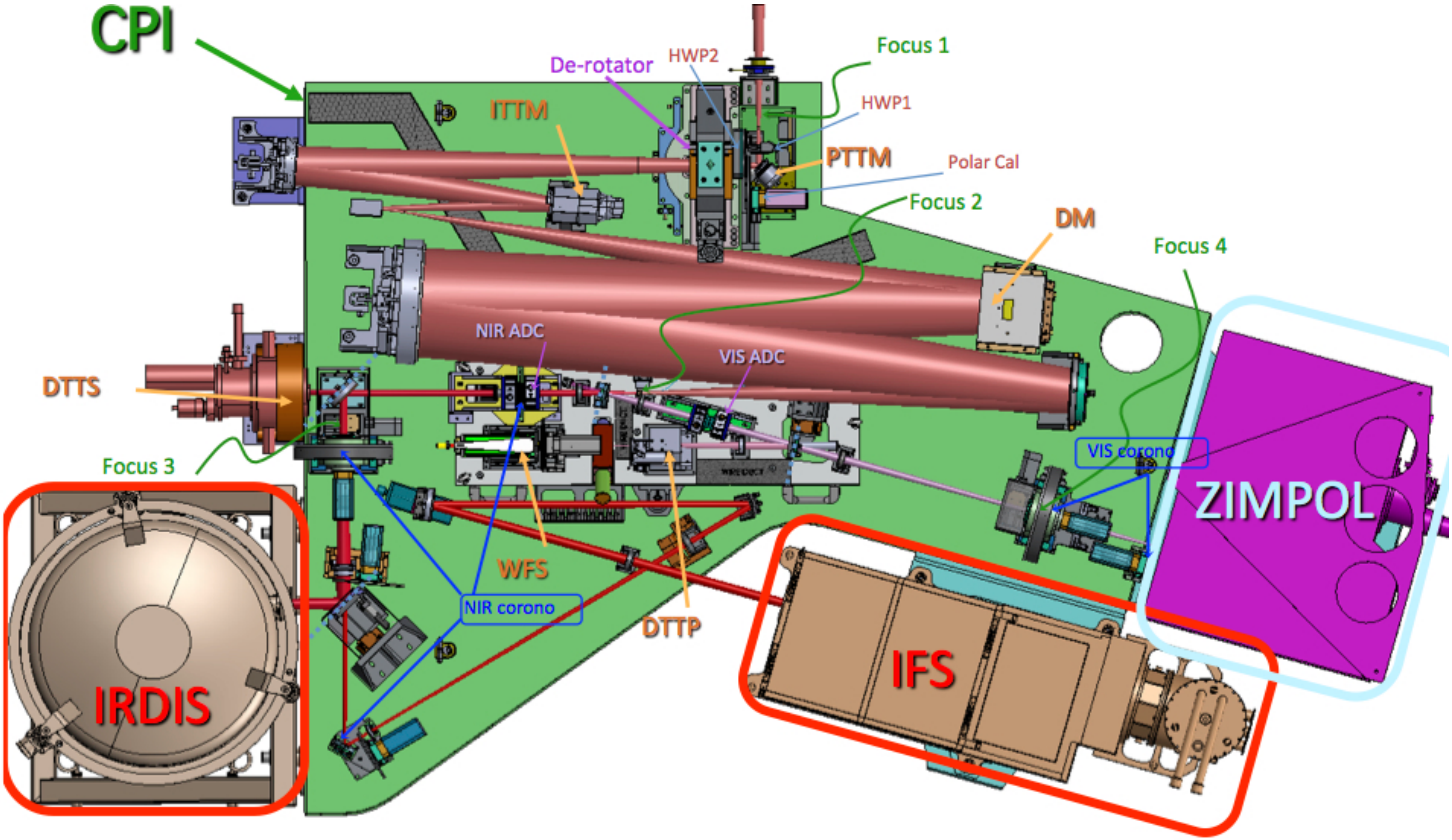
SPHERE also provides narrow-field (few arcsec), very high quality diffraction-limited imaging over the wavelength range 0.6-2.5 micron

It requires a bright NGS (I<14-16)

The SPHERE Consortium

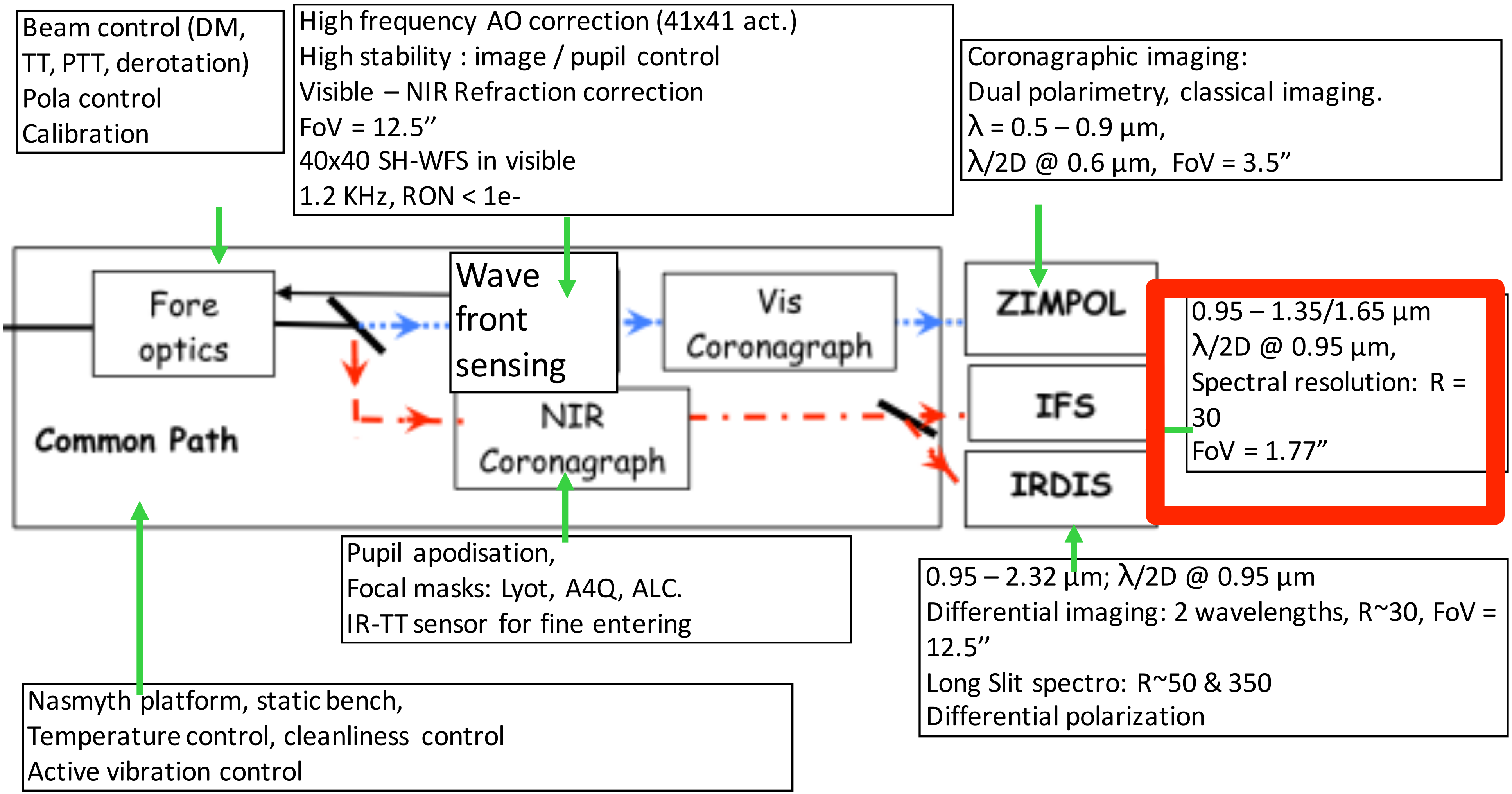


The Mechanical design



Beuzit et al., 2008, SPIE, 7014

Concept overview

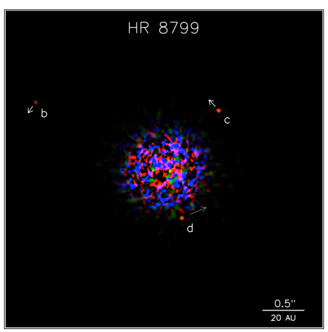


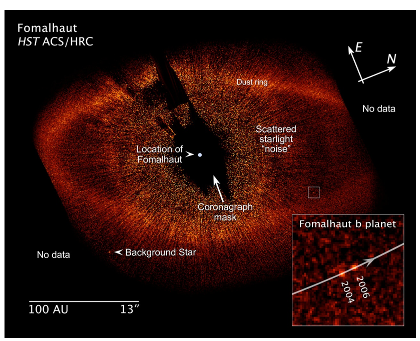
Science objectives

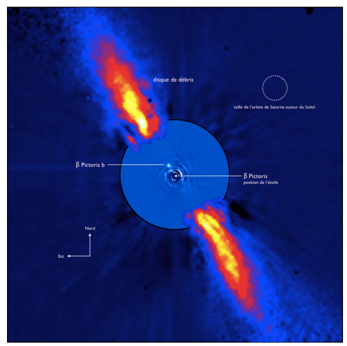
- High contrast imaging down to planetary masses

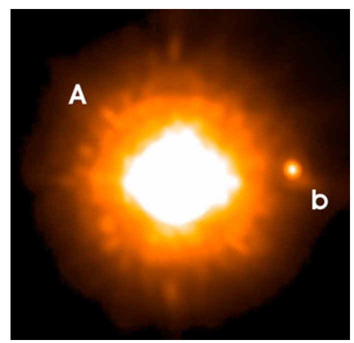
- Investigate large target sample: statistics, variety of stellar classes, evolutionary trends

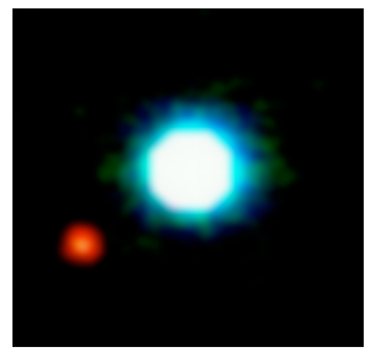
- First order characterization of the atmosphere (clouds, dust content, Methane, water absorption, effective temperature, radius, dust polarization











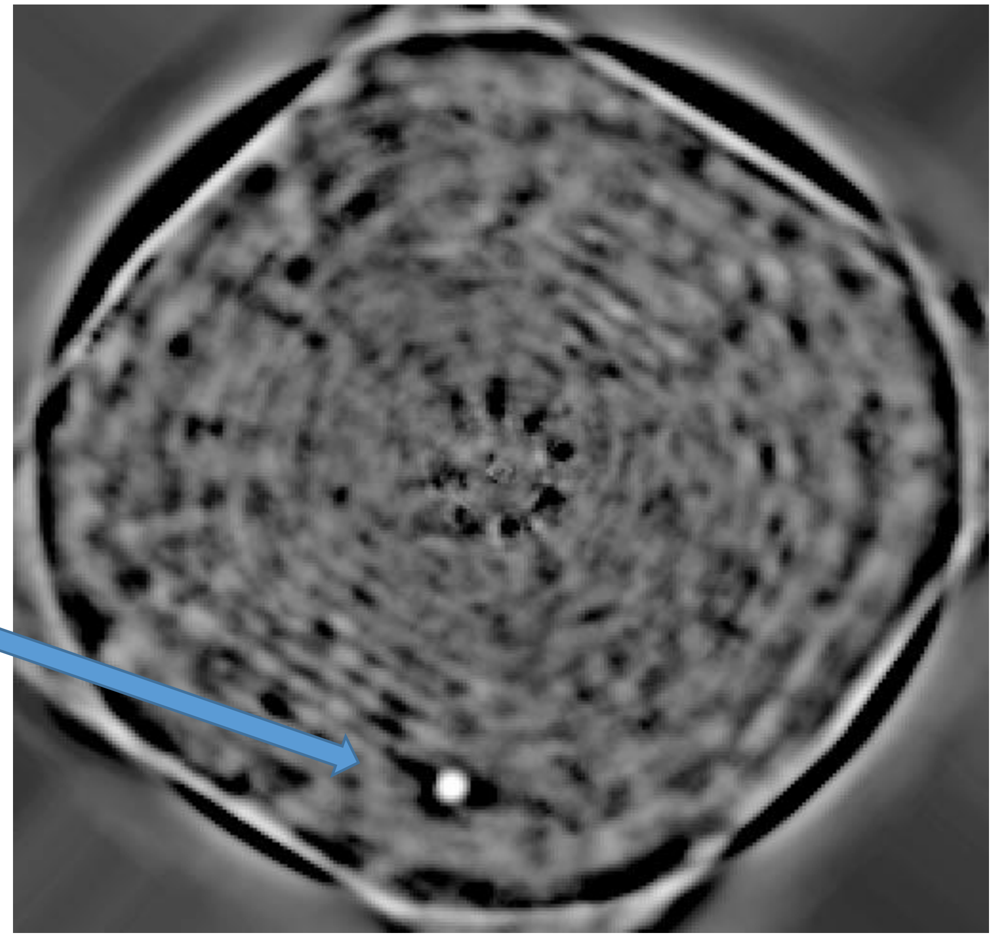
12^{th} May 2014: IFS First Light

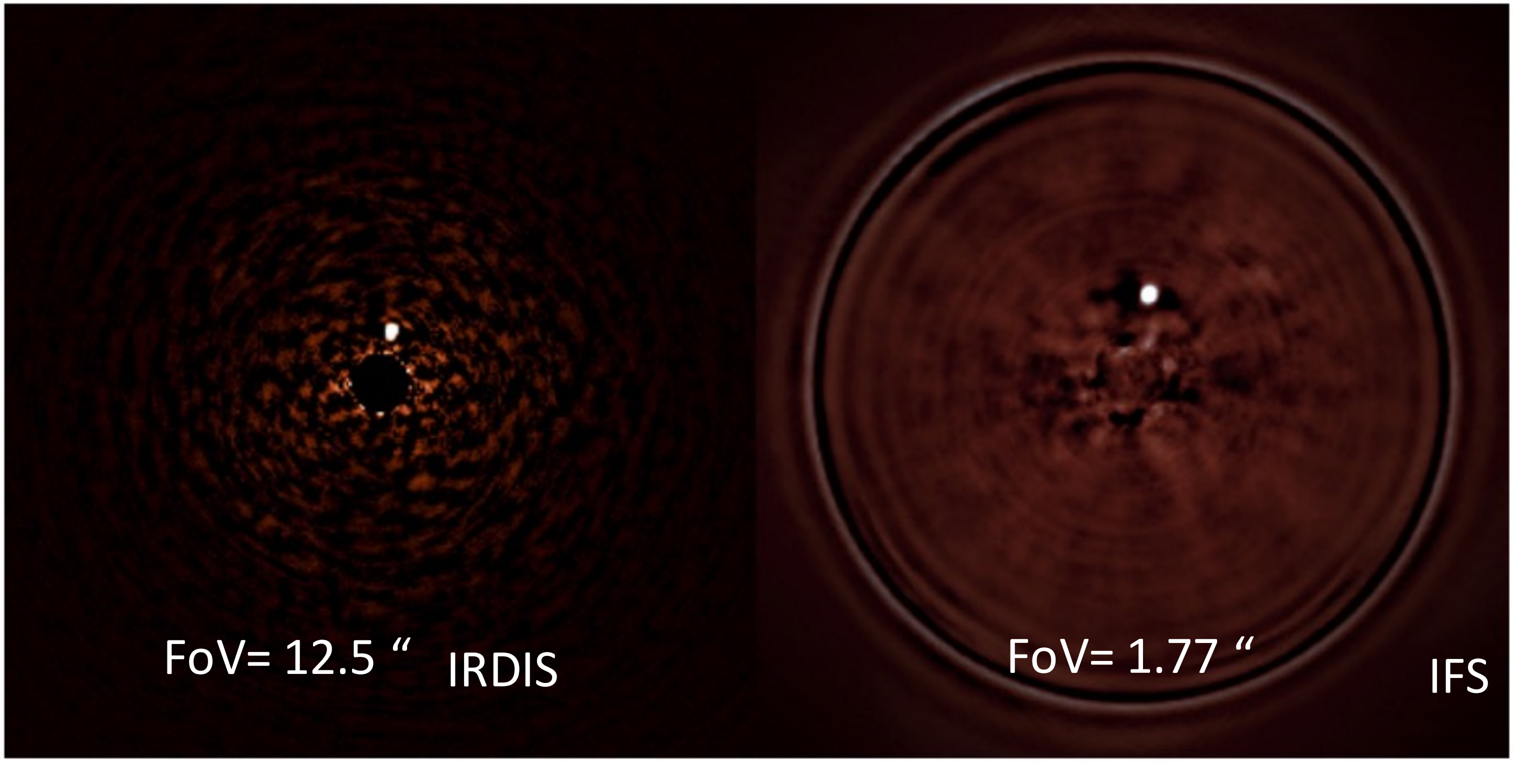
HD114714: Early-type star V=8.5

SDI+ADI

WD detected at a S/N~30
sep=0.6 arcsec

contrast is ~12.5 mag
($\sim 10^{-5}$)





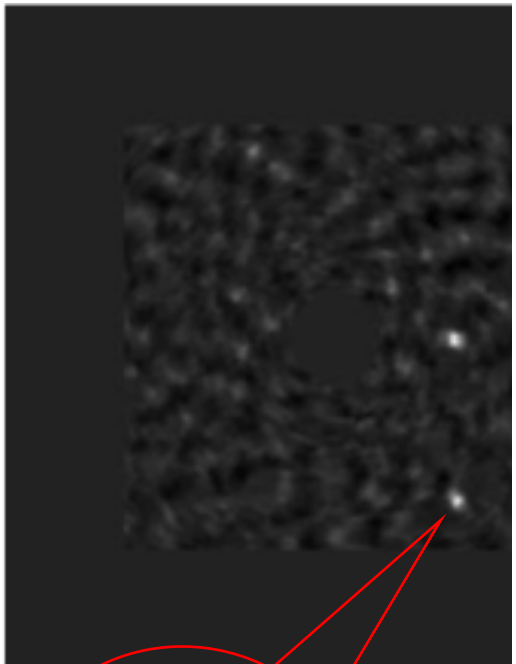
13.9 AU

Figure 17: Detection in parallel by IRDIS (left) and IFS (right) of a faint companion at 0.24" around the bright star HR7581 (see ESO Press Release 1417, http://www.eso.org/public/news/eso1417/).

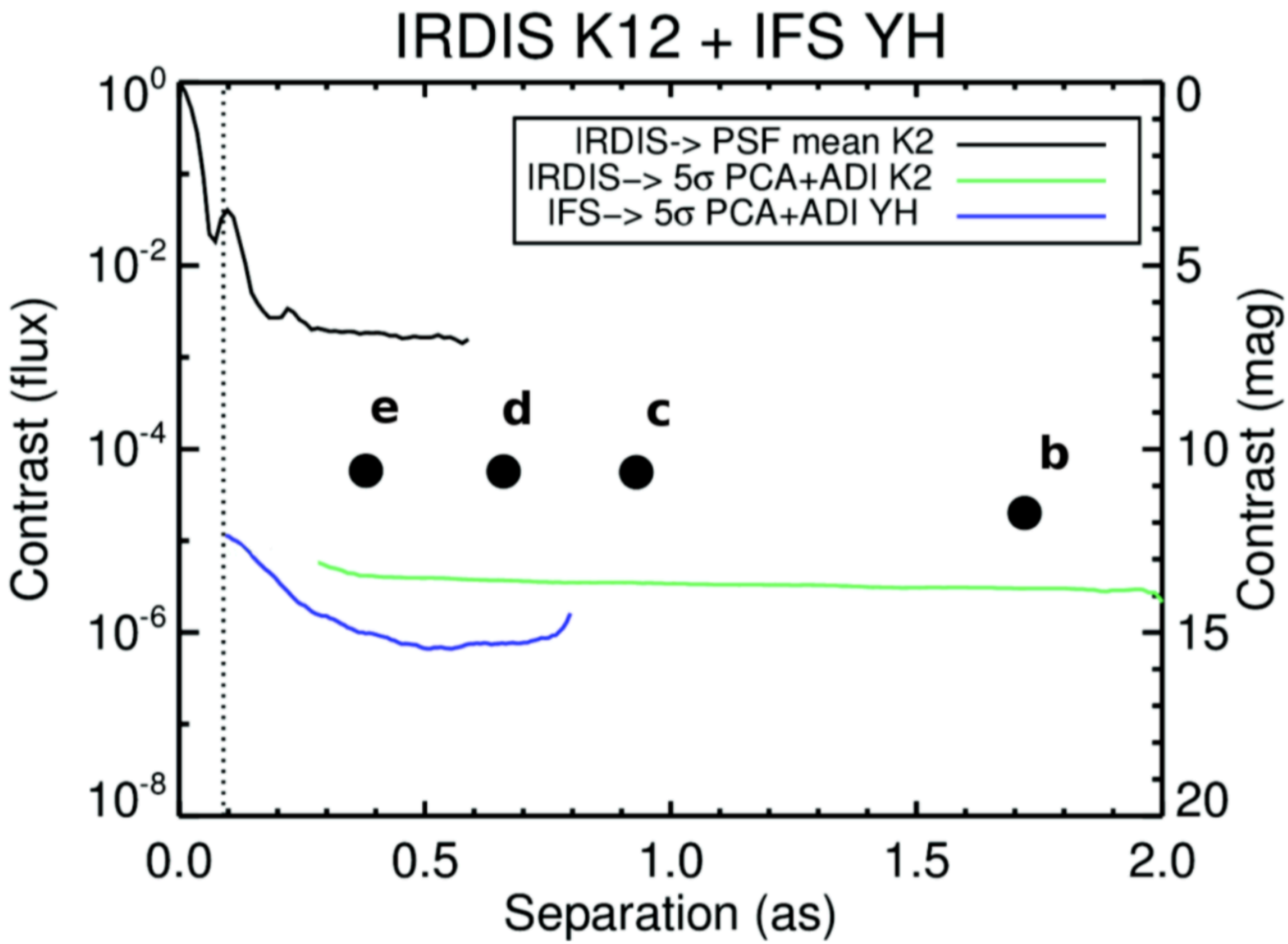
Star: iota Sgr = HR7581, J=2.29, distance=55.7±0.6 pc.
The star is a K-giant (M_J=-1.44; V-J=2.48) and was known as an astrometric binary (see e.g. Makarov and Kaplan, 2005), but the companion was never detected before.

HR8799: a system with four planets

IFS: Y-H



The two inner planets (d and e) are detected with IFS



SHINE
SPHERE High-contrast ImagiNg survey for Exoplanets

SHINE Team: G. Chauvin, S. Desidera, M. Bonnefoy, A. Cheetham, M. Feldt, R. Gratton, A.-M. Lagrange, M. Langlois, M. Meyer, A. Vigan, F. Allard, J.-L. Baudino, H. Beust, B. Biller, A. Boccaletti, M. Bonavita, W. Brandner, E. Buenzli, J. Carson, R. Claudi, M. Cudel, S. Daemgen, P. Delorme, V. D'Orazi, R. Galicher, C. Ginski, J. Girard, C. Gry, J. Hagelberg, M. Janson,; M. Kaspser, M. Keppler, T. Kopytova, E. Lagadec, J. Lannier, H. Le Coroller, R. Ligi, A.-L. Maire, C. Mordasini, C. Moutou, A. Mueller, S. Perretti, C. Perrot, S. Quanz, D. Rouan, G. Salter, M. Samland, J. Schlieder, E. Sissa, C. Thalmann, Z. Wahhaj, F. Wildi, A. Zurlo,

IPAG, MPIA, LAM, ONERA, LESIA, INAF, Geneva Observatory, Lagrange, ASTRON, ETH-Z, UvA, ESO

SPHERE Consortium: Jean-Luc Beuzit (PI), David Mouillet (PS), Gael Chauvin (GTO coordination), Markus Feldt (Co-PI) and Co-Is: F. Ménard (IPAG, Grenoble), T. Henning (MPIA, Heidelberg), H. Le Coroller (LAM, Marseille), A. Boccaletti (LESIA, Paris), S. Udry (Observatoire de Genève), M. Turatto (INAF, Padova), H.M. Schmid (ETH, Zurich), F. Vakili (Lagrange, Nice), C. Dominik (UvA, Amsterdam)

SPHERE GTO

- **GTO: 260 nights over 5 years**
  - Organised as a project in its own, with 4 science programs:
    - ✓ SHINE (200 nights): Survey for Exoplanets of 400-600 stars in NIR
    - ✓ DISK (20 nights): Suvey for Proto-planetary & Debris Disks Study
    - ✓ REFPLANETS (18 nights): Planets in Visible/Reflected Light
    - ✓ Other SCIENCE (12 nights): Solar system, Evolved stars, Clusters, X-Gal…

SHINE GTO

200 nights between Feb 2015 and early-2020

Team organization: 1- Sample, 2-Observation/Reduction, 3-Characterization and 4- Statistics

Observing runs in visitor mode

- **Current status (May 2016):**
  - ✓ Executed SHINE nights: 70.5 nights (*35% of total SHINE-GTO)*
  - ✓ Weather loss (bad seeing and low-wind effect) ~ 25%
  - ✓ SPHERE (+ VLT) technical loss < 5%
- **Obtained data**
  - ✓ known and new targets: **180+ targets** in (very) good conditions
  - ✓ **Impressive detection performances (IFS and IRDIS)**
  - ✓ **Candidates: 500+**; Follow-up phase started since end-2015;
  - ✓ Characterization led to 8 SHINE publications in 2015 and early 2016 (GJ758, PZTel, HD1160, HR8799, HD106906, HD100546,HR4796, HD141569 and more to come…)

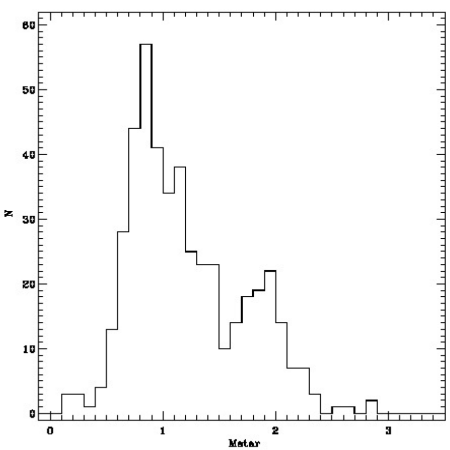
SHINE Sample

- **Criteria of selection**
  - Selected according to criteria of:

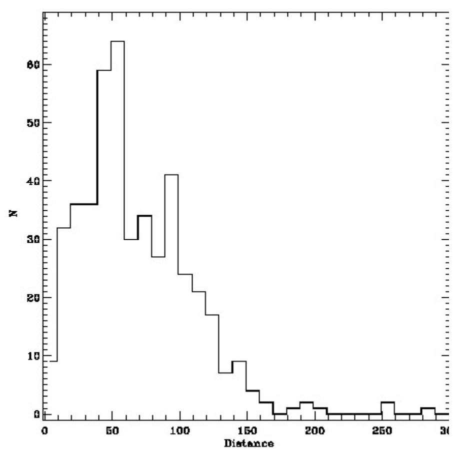
    ✓ Age, distance, Mass, Brightness (AO performances), declination, binarity (no SB and close VB)

    ✓ Science priorities according to Figure of Merit for planet detection

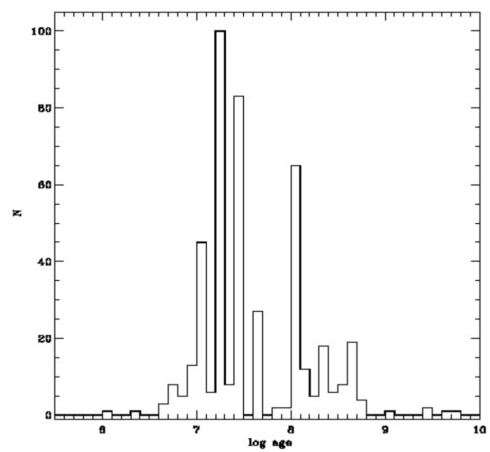
  - Special targets: additional targets of special interest outside the boundaries of statistical sample (stars with disks, stars with known substellar companions, etc.)



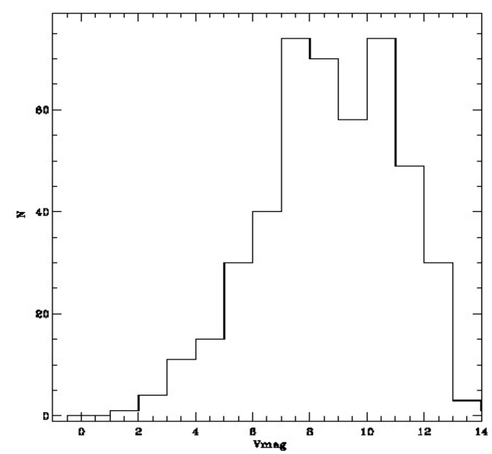
Stellar mass



Distance



Age



Magnitudes

Observing/analysis strategy

- **Observing mode**

  IRDIS in H2 and H3
  and IFS in Y-J simultaneously
  Coronography: Apodised Lyot Coronograph (APLC)
  Angular and spectral differential imaging

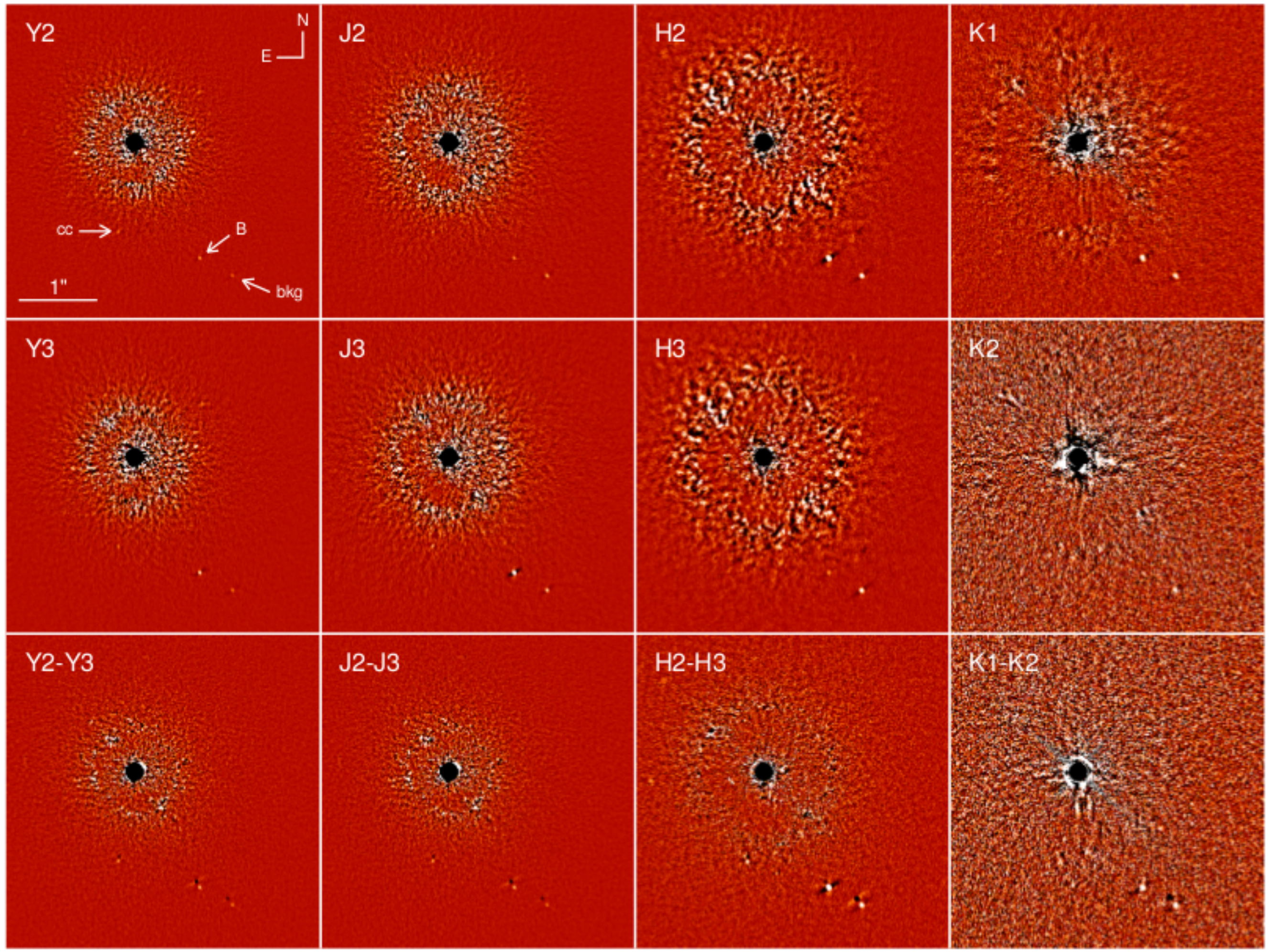
- **Data reduction & analysis**
  - Data reduction team for real-time quick look analysis:
    - ✓ SPHERE Data-center (Delorme et al.)
    - ✓ Final products, reduced images, detection limits, candidate detection & astro, spectro-photometric characterisation
  - Archival reduction and candidate ranking team
    - ✓ Candidate colors and extracted spectra
    - ✓ Ranking priorities for characterization & follow-up

Early-results: Brown dwarfs

A super-solar metallicity atmosphere for GJ758 B?

GJ758, G9V,
d=15.8pc
metal-rich MS-star +
BD companion
@46AU
(Thalman et al. 2009)

IRDIS DBI
(Y23, H23, K12)
Aug 13-14th, 2014 (Comm-3)



Early-results: Brown dwarfs

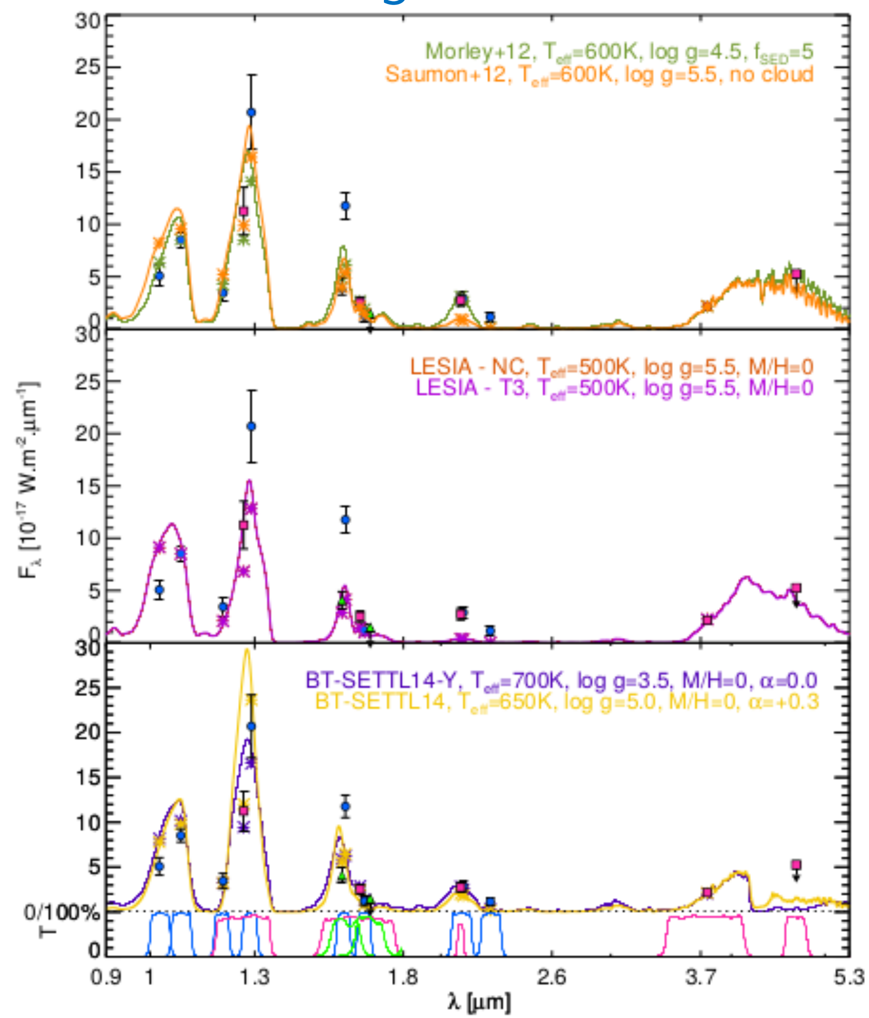
A super-solar metallicity atmosphere for GJ758 B?

SED Analysis (1-5 micron)

→ Spectral type T8

Atmosphere fit: Teff = 600+-100K, and probably metal-rich (TBC)

Vigan et al. 2016

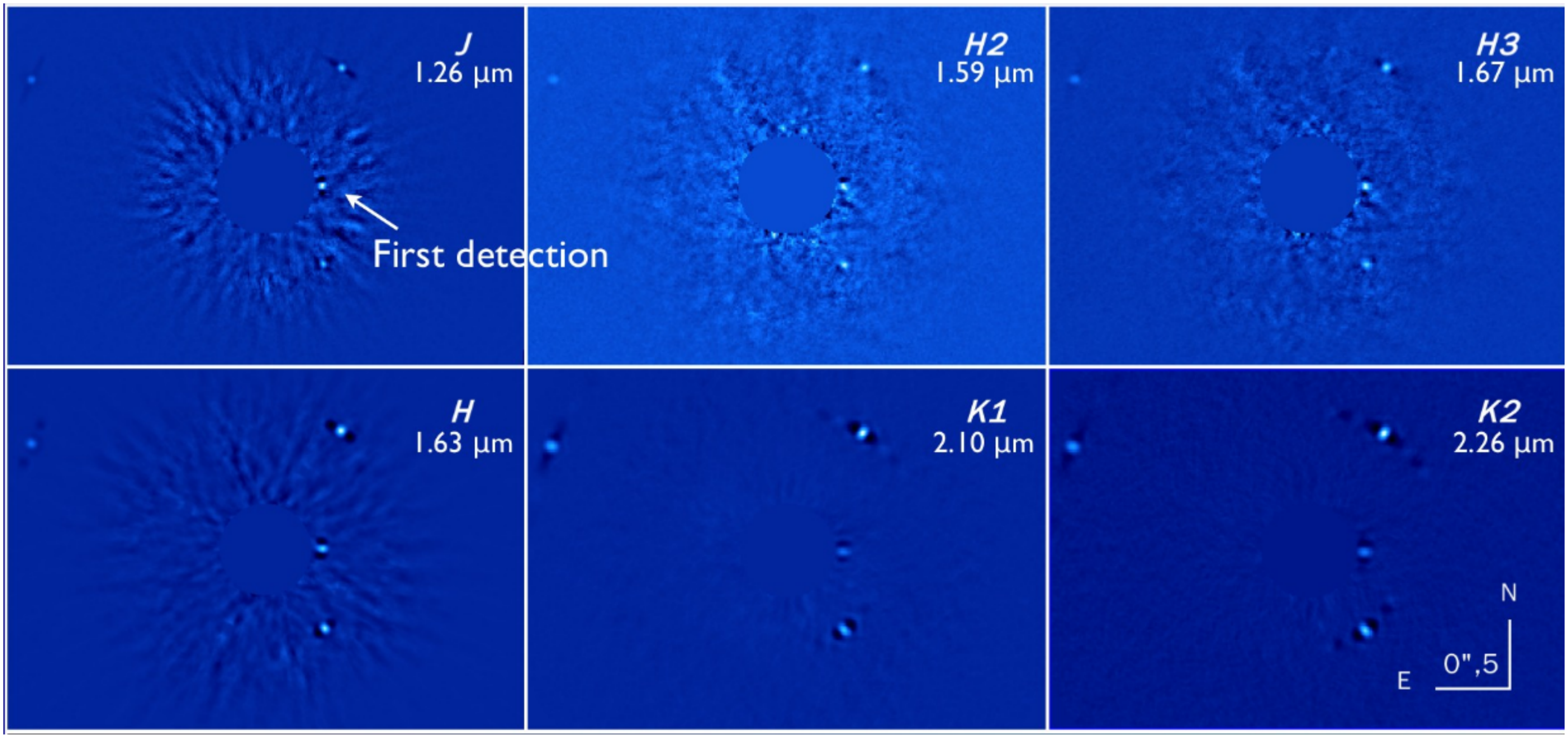


Early results: exoplanetary systems

Revisiting HR8799bcde

A5V Columba member (30-40 Myr), d = 39.4pc
Planets bcde imaged (Marois et al. 2008, 2010)

IRDIS (+IFS) observations Comm-2 and -3, SVT (Jul – Dec, 2014)



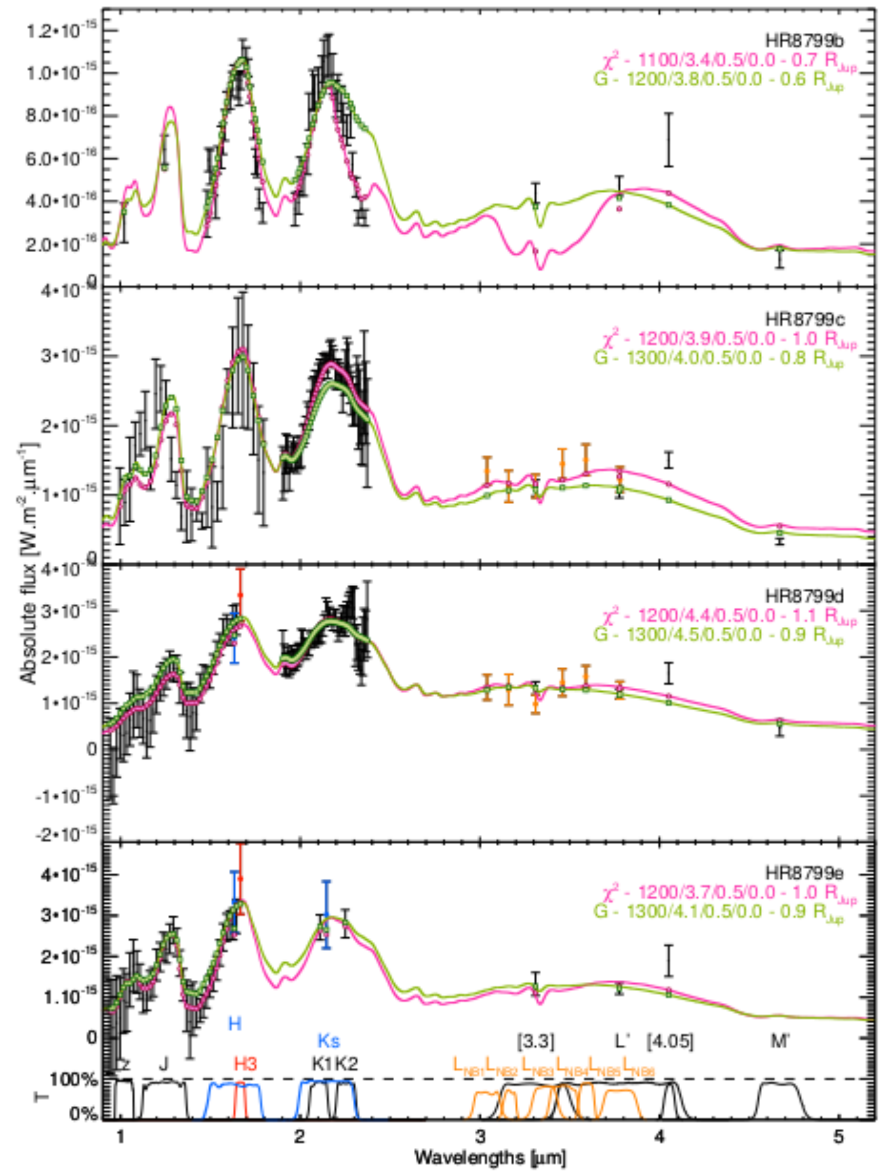
Combining SPHERE/IFS and IRDIS with GPI/LBT etc..

Planets b and c: reproduced by SED of peculiar **or young, L9-T2 brown-dwarfs** dereddened with Corundum grains.

Planets d and e: share similar properties with **population of young, dusty L6-L8** dwarfs.

Atmospheric fits:
(BT-SETTL14, Exo-REM4, Cloud AE-60):
Teff = 1100 – 1300 K; Log(g) = 3.5-4.5

Bad fit for Planet b > clouds?



Bonnefoy et al. 2016

Early results: exoplanetary systems

HD 106906 AB

Lower Centaurus Crux Group Member
Age = 13±2 Myr; d= 98.2pc
Resolved as a tight binary (2.5 Msun) with
11±2 M_{jup} planetary Mass Companion located at 650 AU (7.2 arcsec).

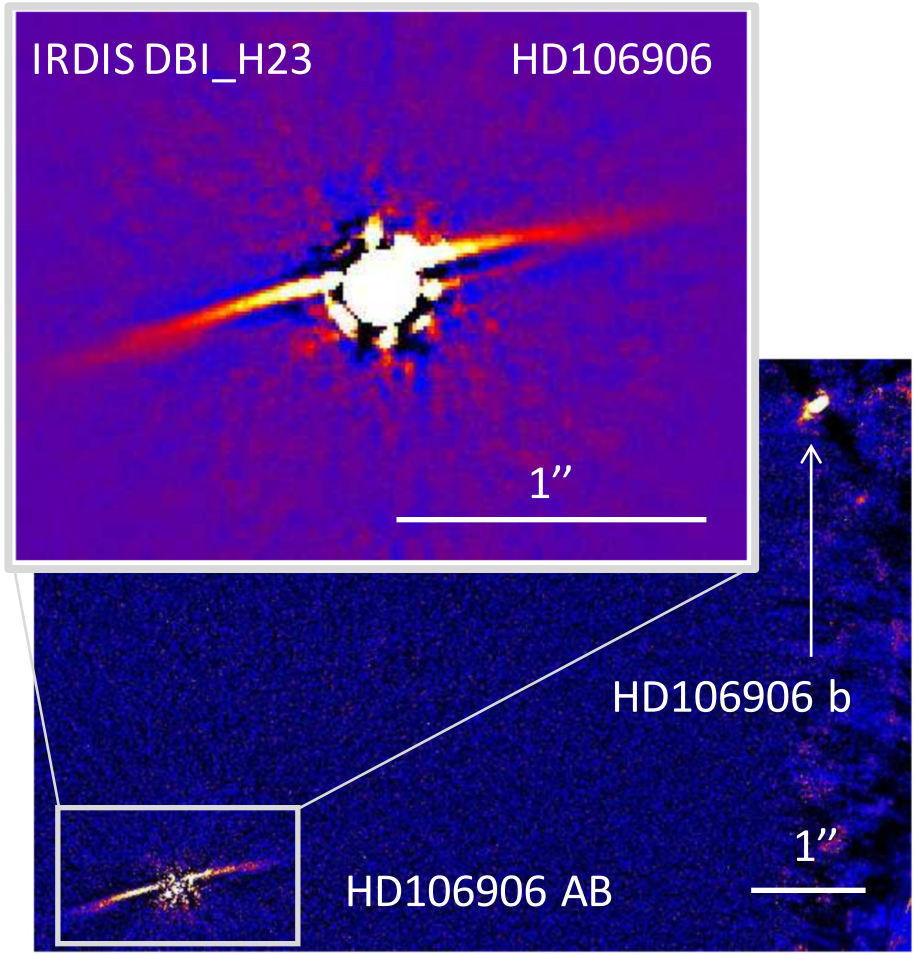
The planet discovered by Bailey et al. (2014) during the commissioning run of the Magellan adaptive optics system (MagAO)

IRDIS DBI_H23 (SHINE, March 30th, 2015)

Discovered a highly inclined (i=85°), ring-like disk at a distance of 65 AU from the star + strong brightness asymmetry with respect to its semi-major axis

Discovering new features!

Lagrange et al. (2015)



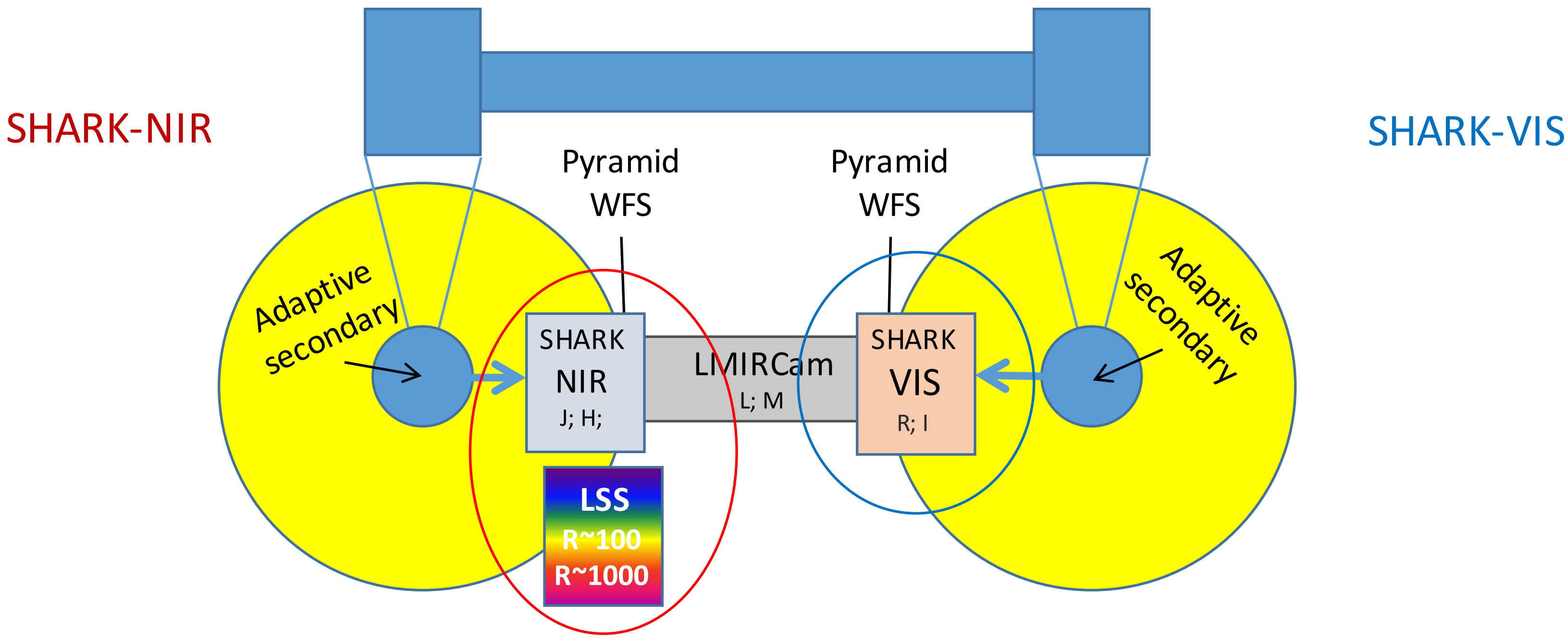
SHARKs@LBT

a high contrast imager with coronagraphic and spectroscopic capabilities for the
large binocular telescope

The SHARK Instrument Team: J.Farinato, F.Pedichini, E.Pinna, C.Baffa, A.Baruffolo, M.Bergomi, L.Carbonaro, E.Carolo, A.Carlotti, M.Centrone, L.Close, J.Codona, M.De Pascale, M.Dima, S.Esposito, D.Fantinel, G.Farisato, W.Gaessler, D.Greggio, J.C.Guerra, O.Guyon, P.Hinz, F.Lisi, D.Magrin, L.Marafatto, A.Puglisi, R.Ragazzoni, B.Salasnich, M.Stangalini, D.Vassallo, C.Verinaud, V.Viotto

The SHARK science Team: VD, S.Antoniucci, V. Testa, F.Bacciotti,S.Benatti, M.Bonavita, A.Bongiorno, M. Bonnefoy, L. Borsato, E. Brocato, E. Cappellaro, G. Chauvin, R. Claudi, I. Crossfield, P. Delorme,S. Desidera, F. Fiore, A. Fontana, E. Giallongo, T. Giannini, V. Granata, R. Gratton, T. Henning, M. Kasper, F. Leone, AL Maire, L. Malavolta, J. Males, F. Massi, D. Mesa, G. Micela, V. Nascimbeni, B. Nisini, I. Pagano, G. Piotto, L. Podio, M. Rieke, E. Sani, G. Scandariato, E. Sissa, A. Sozzetti, M. Turatto, S. Zibetti, A. Zurlo.

What is SHARK?



SHARK basic features are:

- ✓NIR Coro-Camera (J,H)
- ✓NIR Low Resolution Spectroscopy (2 spectral resolutions, R~100 and R~1000)
- ✓VIS Coro-Camera (R,I)

Coronagraphic Techniques

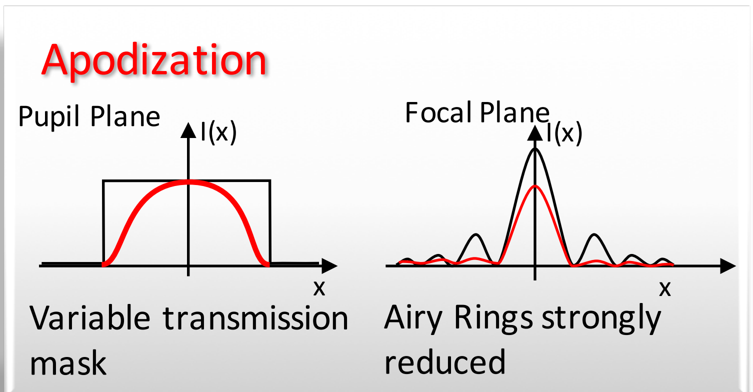
Coronagraph	IWA	Contrast	Throughput	Sensitivity	Bandwidth	# of planes
Classical Lyot	4-5 λ/D	10^{-4}	> 80%	High	?	2
Gaussian Lyot	4-5 λ/D	10^{-4}	?	Medium	?	2
Shaped pupils	3-5 λ/D	10^{-5} - 10^{-7}	30-50%	Low	20 %	2-3
APP	2-4 λ/D *	10^{-5} - 10^{-7}	30-60%	Low	5-10%	2-3
APLC	3-5 λ/D	10^{-5} - 10^{-7}	15-50%	Medium	10-20%	3
Vortex	1-2 λ/D	10^{-4}	> 80%	Medium-High	5-10%	2
Apodized vortex	2-3 λ/D	10^{-8}	< 20%	Medium-High	5-10%	3
PIAA-CMC	1-2 λ/D	10^{-8}	> 80%	Medium-High	5-10%	6

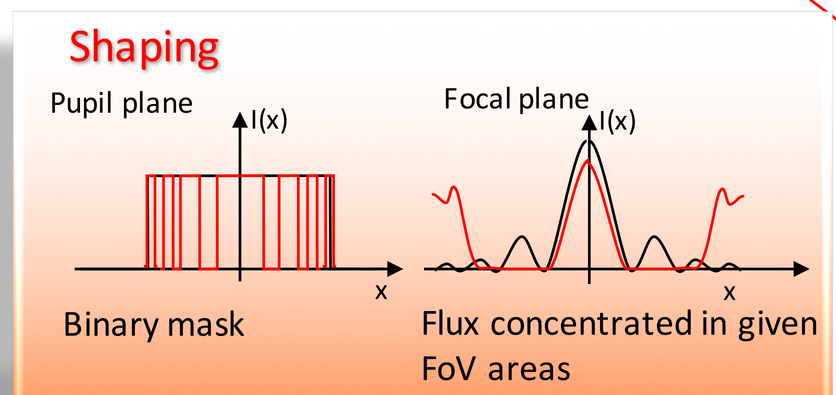
High contrast only on one side

Poor contrast due to obscuration and spiders

Low throughput

Too many surfaces



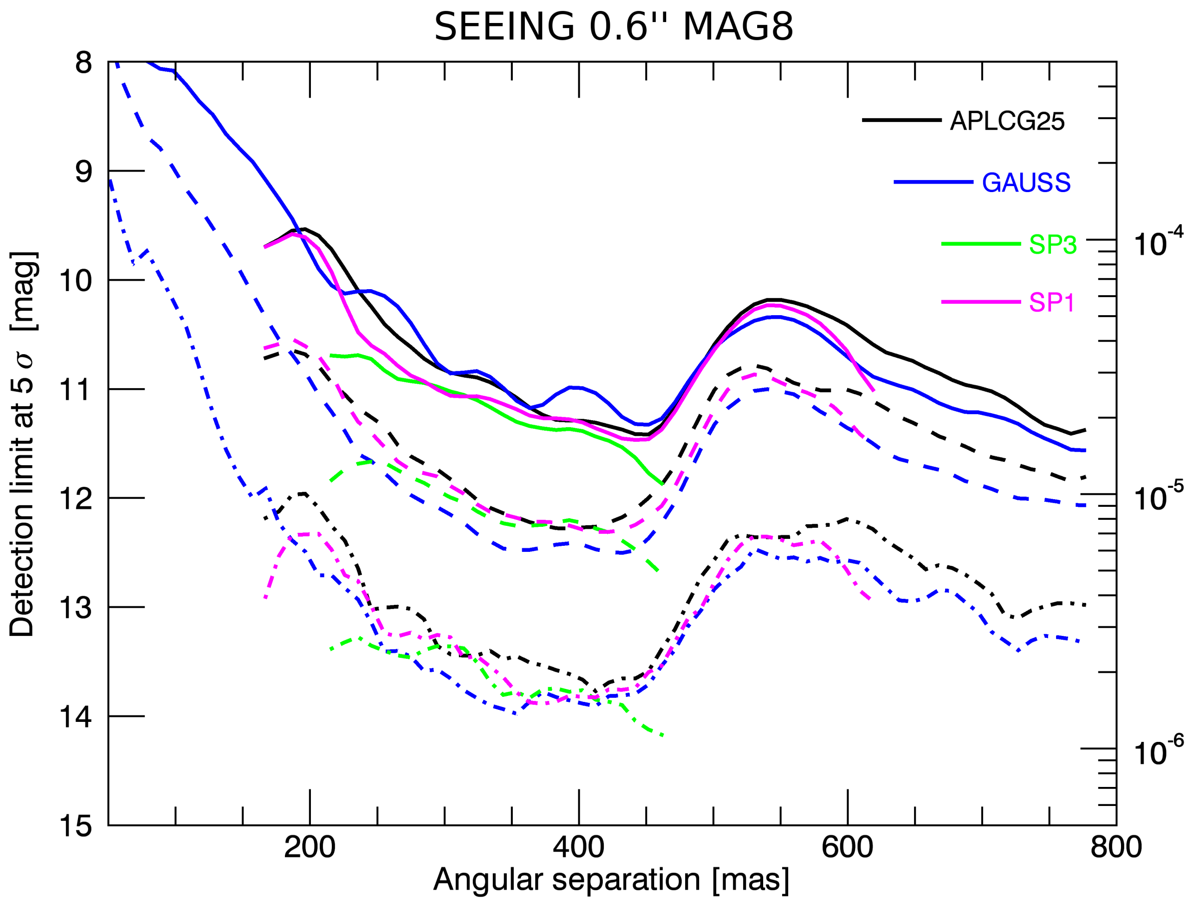


SHARK-NIR Schedule Milestones

SHARK-NIR is a fast track facility:

- ✓~~T_0 in May 2015 (MoU for the CDP signed)~~
- ✓~~Conceptual Design Review in December 2015~~
- ✓Final Design Review: December 2016
- ✓Installation at the telescope: July-August 2018
- ✓Commissioning from September 2018
- ✓**SHARK NIR on SKY in fall 2018** (~3 years from T_0)

Simulations: seeing 0.6", Mv=8

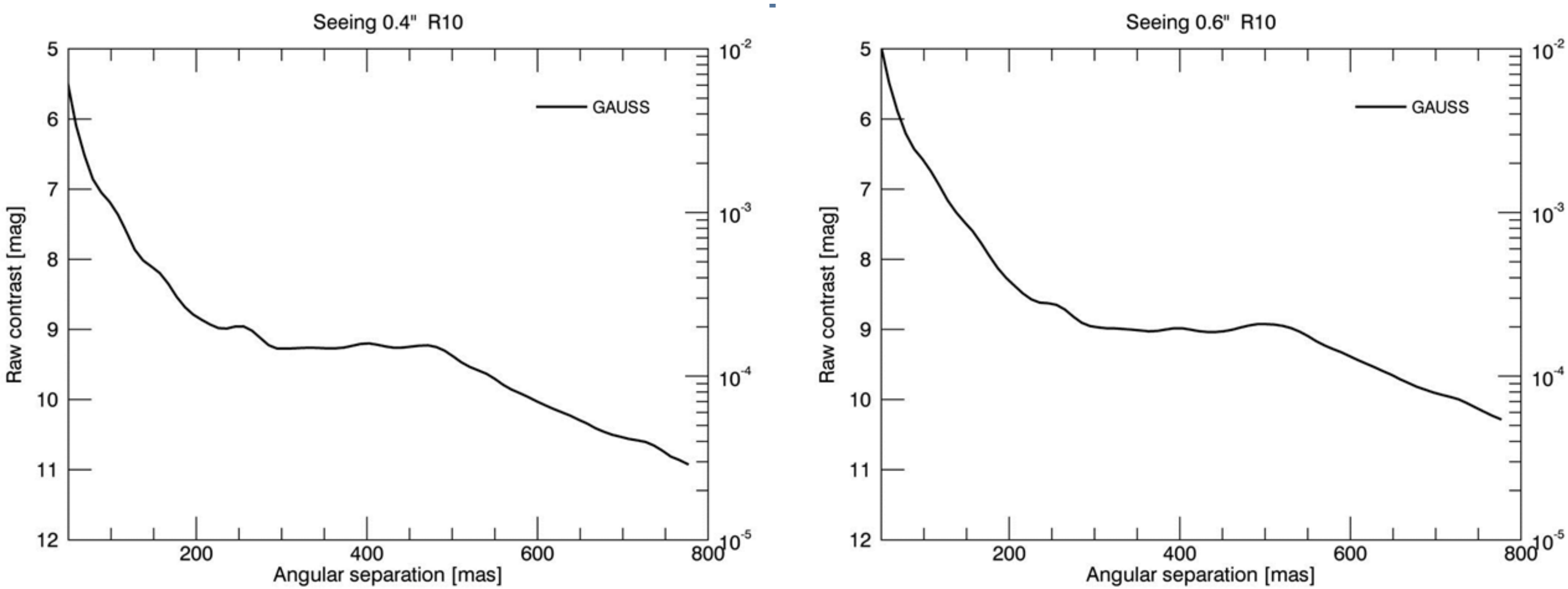


Coro IWA: 4λ/D (160 mas in H Band), goal 2-3λ/D **EXO-PLANETS**

Contrast: 10^{-6} (goal 10^{-7}) in the range 300-500mas, 10^{-5} (goal 10^{-6}) for IWA<300 mas;

Magnitude Range: 5-10 in R Band

Simulations: s=0.4"- 0.6", Mv=10,NO ADI



Coro IWA: 3λ/D (120 mas in H Band), goal 2λ/D **Disks-Jets**
Contrast: for the Jets case, 10^{-4} (goal 10^{-5}); for the Disks case 10^{-3} (goal 10^{-4})
Magnitude Range: 5-12 in R Band FoV: 10"-15"

Coro IWA: 4λ/D (160mas in H Band), goal 2-3λ/D **AGN-QSO**
Contrast: 10^{-3} (goal 10^{-4}) for IWA<300 mas; 10^{-5} (goal 10^{-6}) for IWA>300mas
Magnitude Range: 9-14 in R Band FoV: 5" for DLAs, 10" for AGNs

Exoplanets: detection and characterisation

Discs around young stars and their jets

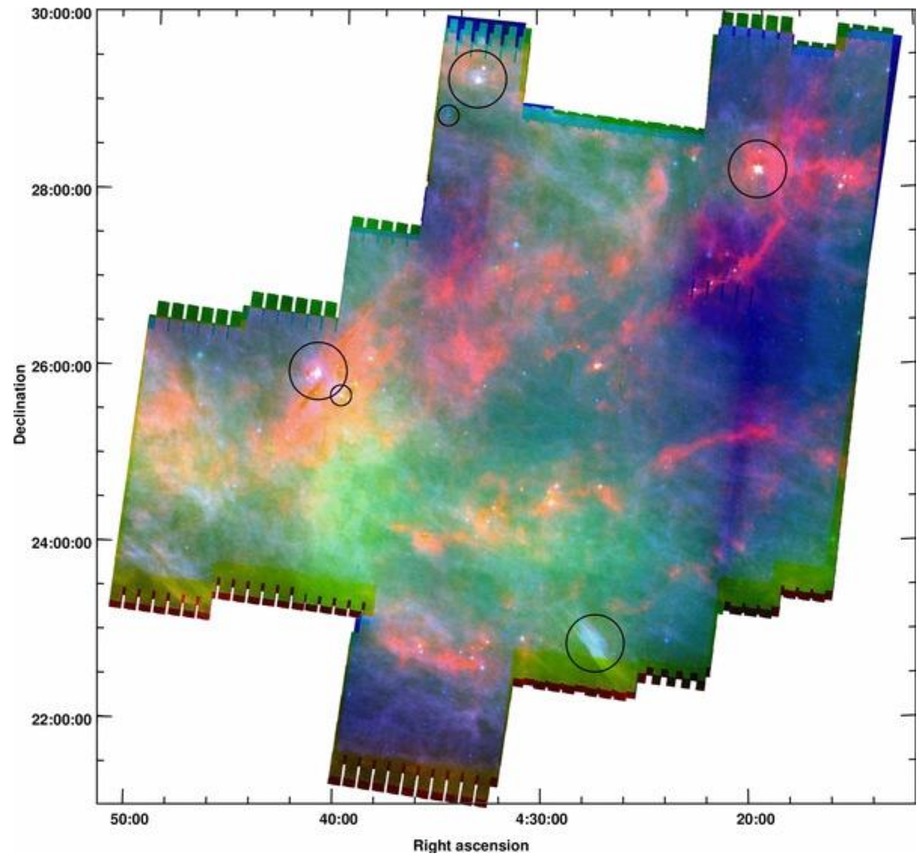
Extragalactic science: AGN and QSO

Planets in wide orbits of low-mass stars

A special niche for SHARK is offered by the LBT AO at faint mag, especially with AO upgrade: wide planets orbiting low-mass stars (e.g., K/M dwarfs in young associations and SFRs like Taurus)

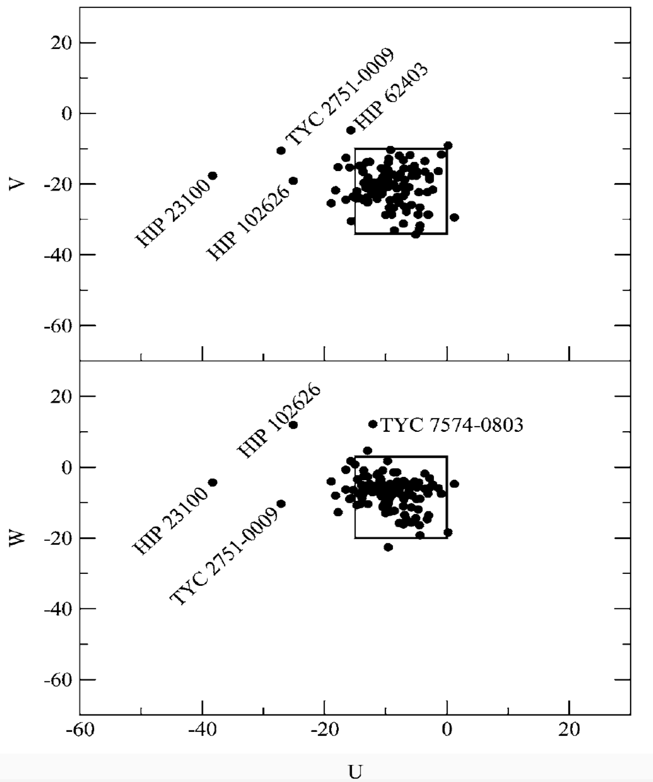
Giant planets in Star Forming Regions

Taurus-Auriga: ages of about 1-2 Myr, at a distance of about 140 pc. About 350 members were identified, 130 of which brighter than R=15.

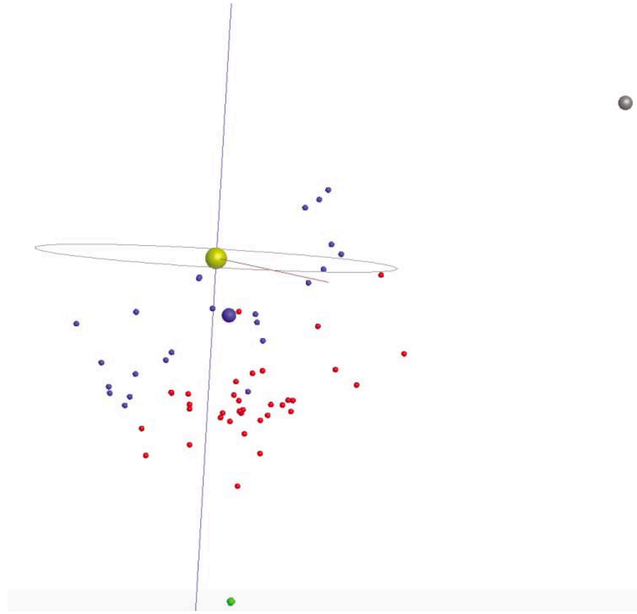


Planets around K/M type stars in young (loose) associations

Several members of young moving groups (age~10-100 Myr) were recently identified, with special effort for low-mass stars.
→ stream of stars with common age and motion through the Milky Way and with no overdensity of stars discernable in any region (e.g., the Ursa Maior, AB Dor, Beta Pic)



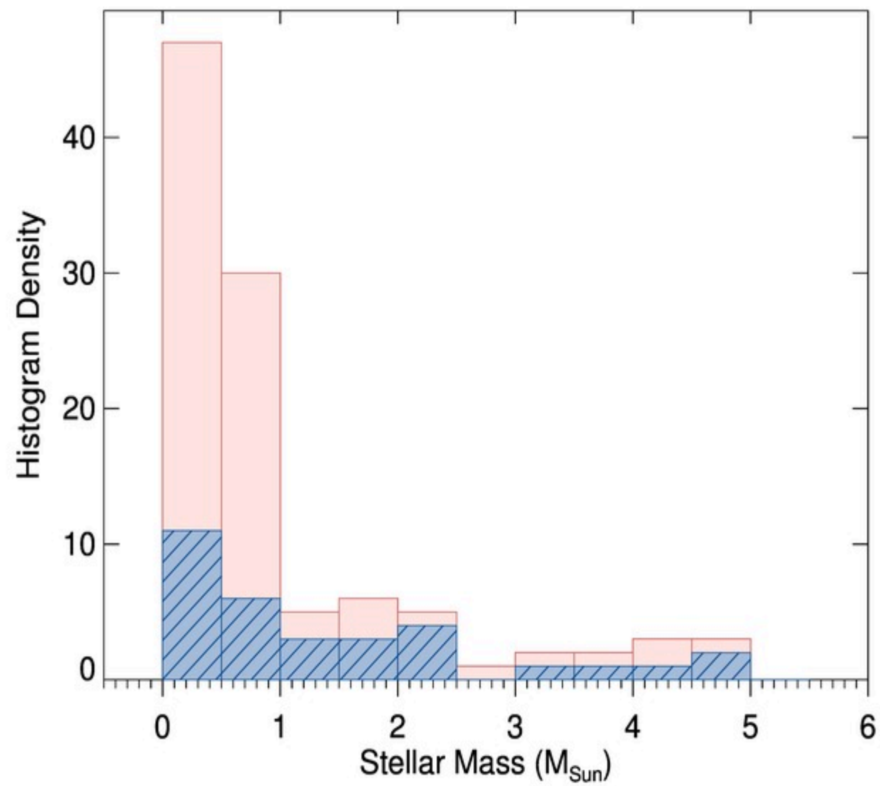
Zuckerman & Song (2004)



Observational investigations of planetary system and theoretical studies indicate that giant planets form in < 10 Myrs and Earth-like terrestrial planets in ~30 Myrs.
→ **Thus, local, post T Tauri stars promise to reveal the story of the formation and early evolution of planetary systems.**

There are several tens of potential targets, depending on exact magnitude limit of the instrument, accessible for a deep search for planets in wide orbits

With the current limit at R<10.5 our sample comprises 33 targets, whereas adopting R=12.5 we would gain more than a factor of three in sample size (that is 108 objects)



SPHERE and GPI will be mostly limited to solar-type and early-type stars (in the Southern hemisphere)

What does this kind of science require?

Coro IWA required: minimum 4 λ/D, goal 2-3 λ/D

Contrast : 10^{-6} (goal 10^{-7}) in the range IWA=300-500 mas,
10^{-5} (goal 10^{-6}) for IWA<300 mas

→ A contrast of 10^{-6} (ΔM=15), assuming a distance for the system of 140 pc and ages of 10 Myr and 100 Myr, would correspond to mass limits of M=4.24 M_{jup} and M=5.29 M_{jup}, respectively (employing models by Allard and collaborators).

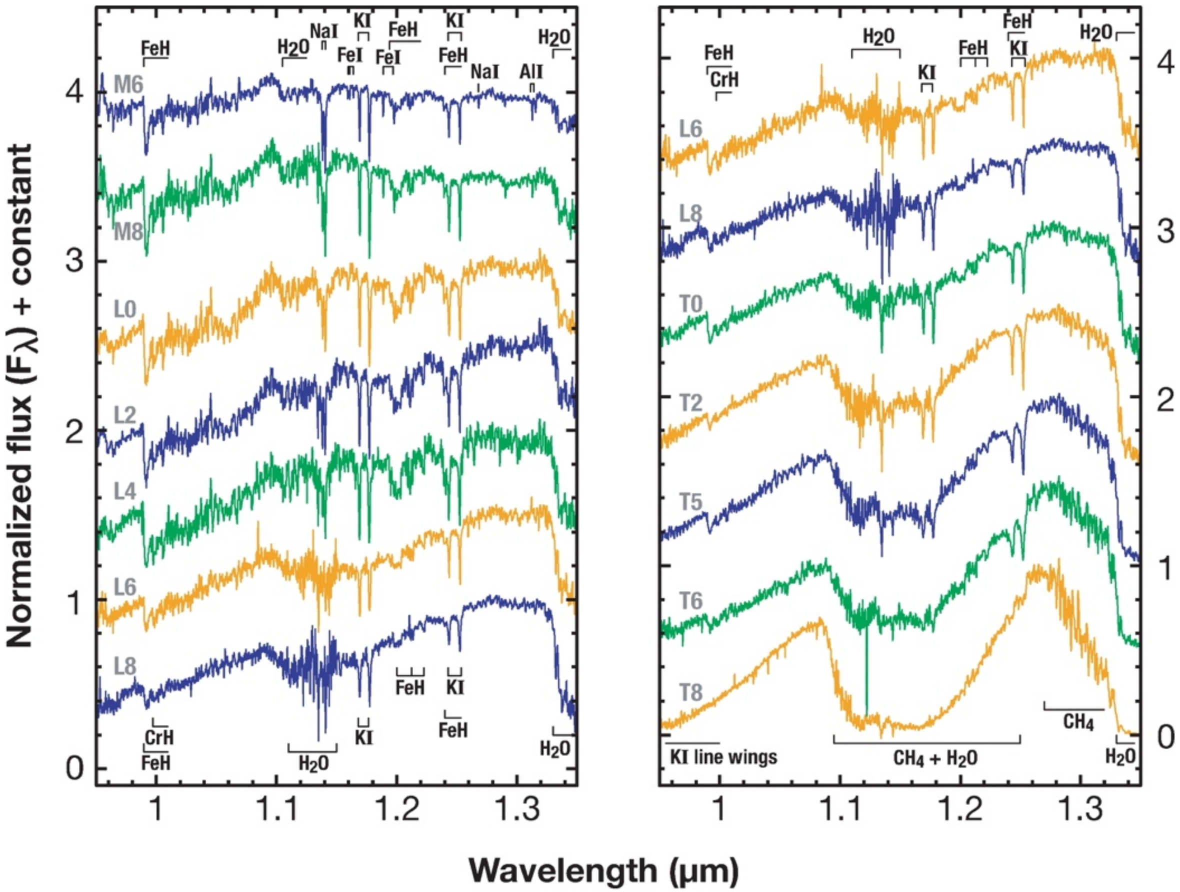
synergy with LMIRCAM : extension to thermal infrared for SED determination and broad spectral coverage to remove degeneracies affecting NIR photometry

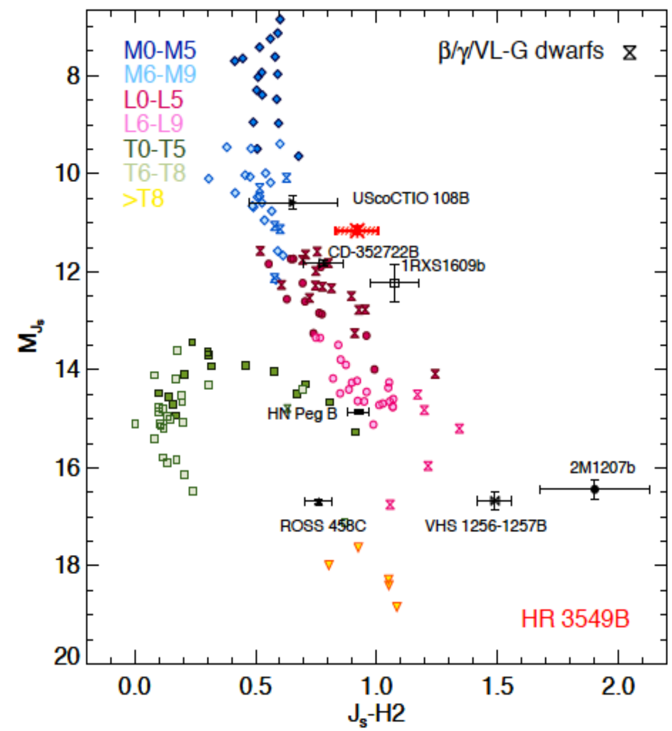
synergy with VIS Channel : feature Hα and accretion mechanisms

Photometric and spectroscopic characterisation of known planets/BDs

The L-T transition

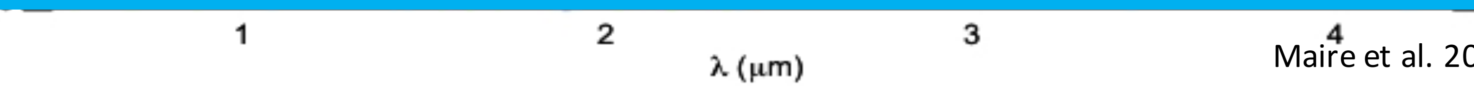
Mesa+ 2016, submitted





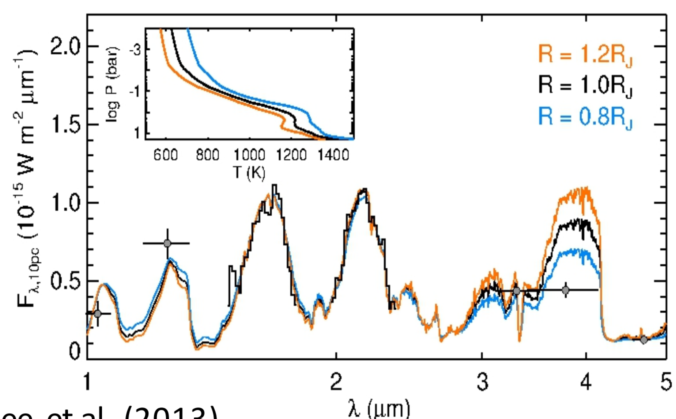
The implementation of a long slit spectroscopic mode will furnish spectral classification (L vs T) if R=30 and molecular band identification if R > 100.

We plan to have two LSS modes: a low-resolution (R~100) and a high-resolution (R~1000), depending on target magnitudes and properties, as needed.

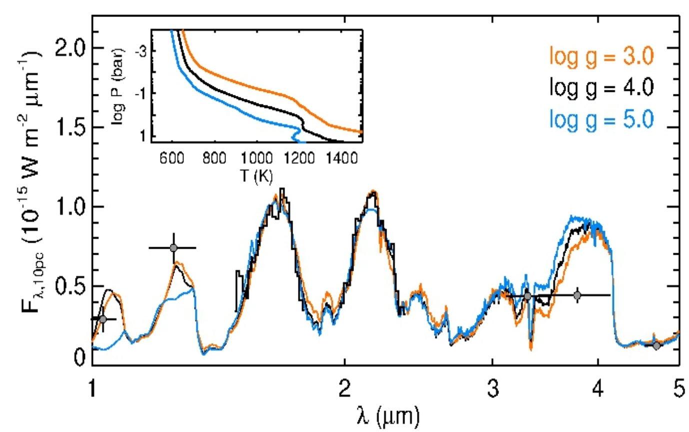


Maire et al. 2016

Synergy with LMIRCAM will provide us with large and critical spectral coverage that is CRUCIAL as to breaking degeneracies affecting NIR-only spectroscopic observations



Lee et al. (2013)

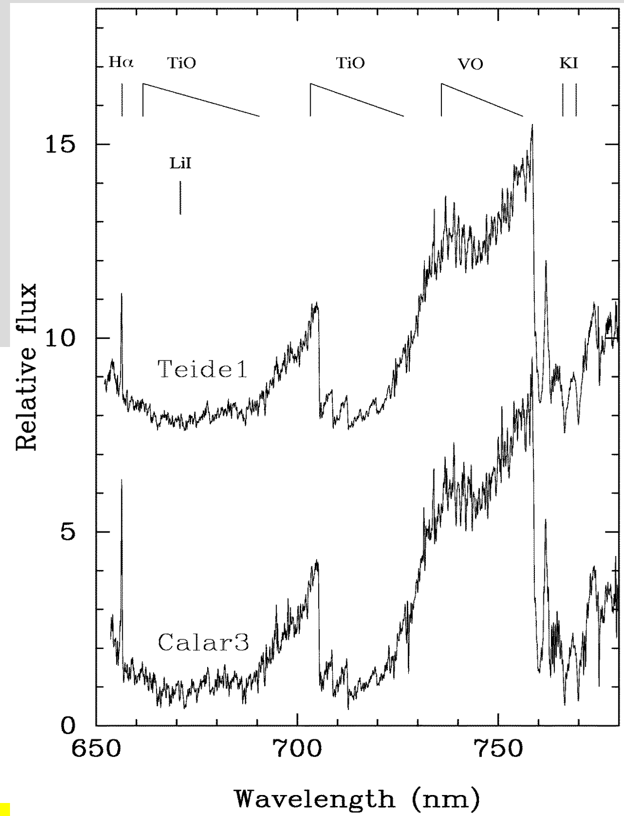


Brown dwarfs in open clusters

Brown dwarfs (BDs) -intermediate objects between stars and planets- are still poorly understood, especially in terms of formation mechanisms (star-like, or planetary-like formation??)

Formation of gas-giant planets: core accretion (Jupiter/Saturn mass, up to ~10 AU) and disc instability (up 10 Mjup, 10-100 AU).

→ Two populations of giants planets segregated by orbital distance: the closer planets formed by core accretion and the outer ones by disk instability, showing that stellar and planetary mechanisms overlap in the substellar regime.



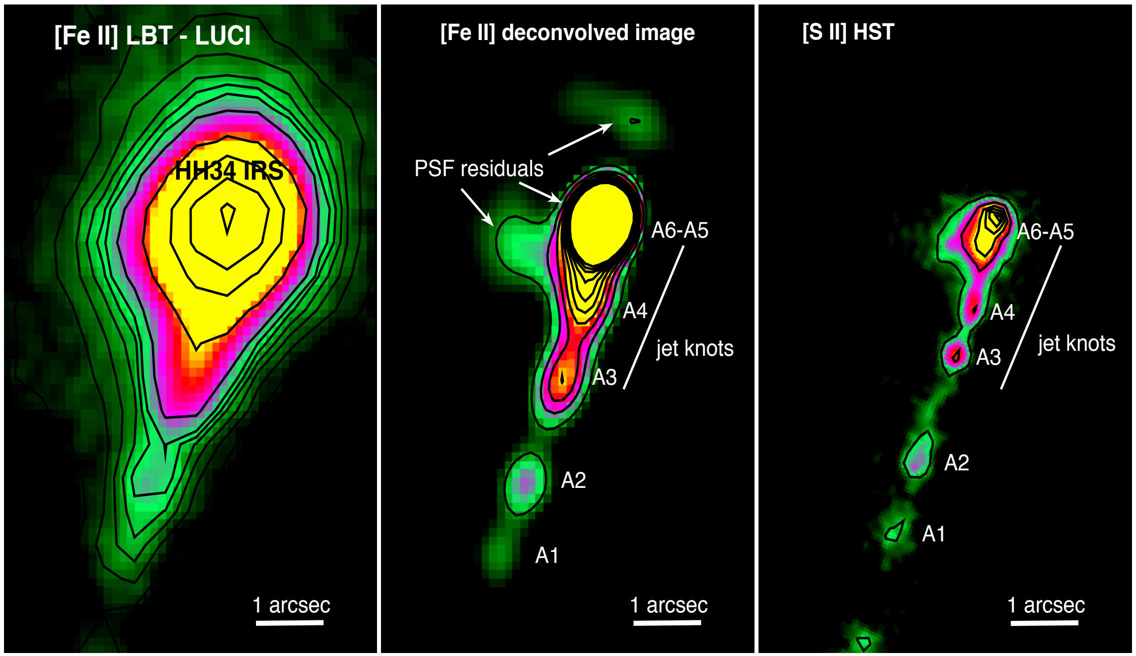
→ statistical properties -occurrence, the mass, and the main orbital parameters- should help to identify the dominant mechanism to forming substellar companions.

Objects belonging to moving groups/local associations are preferred objects: they are nearby (20-100pc) and young (several to several hundred Myr), so their substellar objects (planets and BDs) are relatively bright → PLEIADES (known age, distance, metallicity)

Discs around Young Stars and their Jets

- High-contrast imaging of circumstellar discs with NIR coronagraphy.
- Coronagraphic or classical imaging of stellar jets
- 2D kinematical maps of Jets

Narrow-band images of jets reveal the generation mechanism and its feedback on the star/disc



Antoniucci+ (2014)

Goals:

understand dynamic role of jets in shaping the disc structure

Probe the innermost regions of discs and jets in T Tauri stars (Binocular observations VIS+NIR)

H_2 as key tracer: SYNERGY with LMIRCAM

Requirements: **Classical Imaging** + CORO IWA<3λ/D (~100 mas); Contrasts 10^{-4} for discs and 10^{-3} for jets

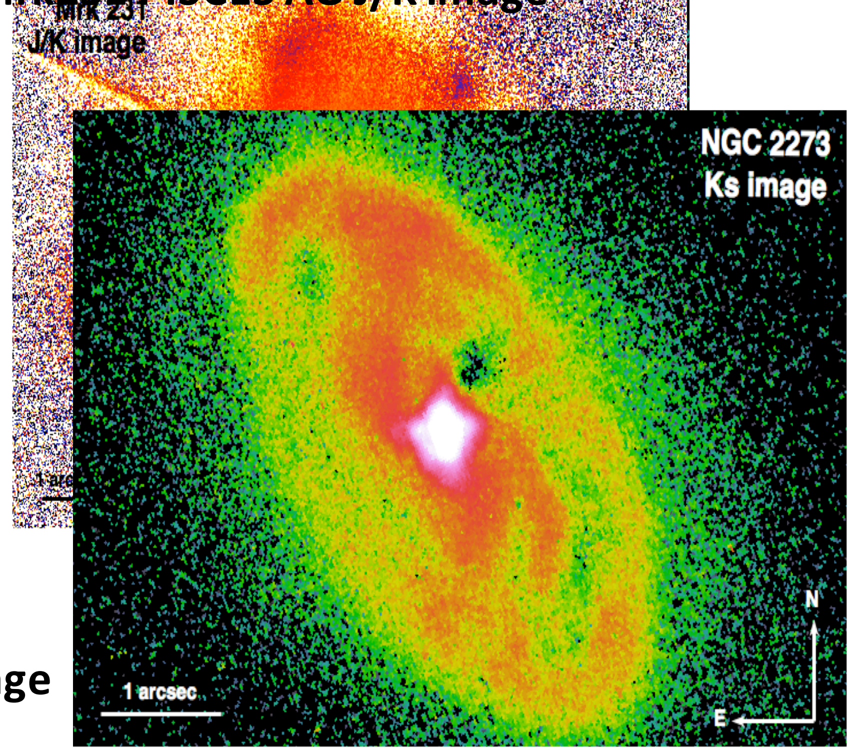
AGNs and QSOs

(1) Discover and fully characterise the AGN close pairs;
(2) Constrain the Black Hole feeding mechanism (e.g., SN driven winds *vs* gravitational asymmetries) in local Seyfert galaxies
(3) Trace, in bright quasars, molecular outflows powerful enough to clean the inner kpc and quench the star formation

- Dust lane maps on scales down to hundreds pc to investigate whether outflows are dusty or rather the AGN driven feedback has already swept the ISM;

- Color maps of SF regions in the galaxy nucleus and disk to constrain the SF rate, the age, and the metallicity.

Mrk231 PISCES AO J/K image



NGC 2273 PISCES AO K image

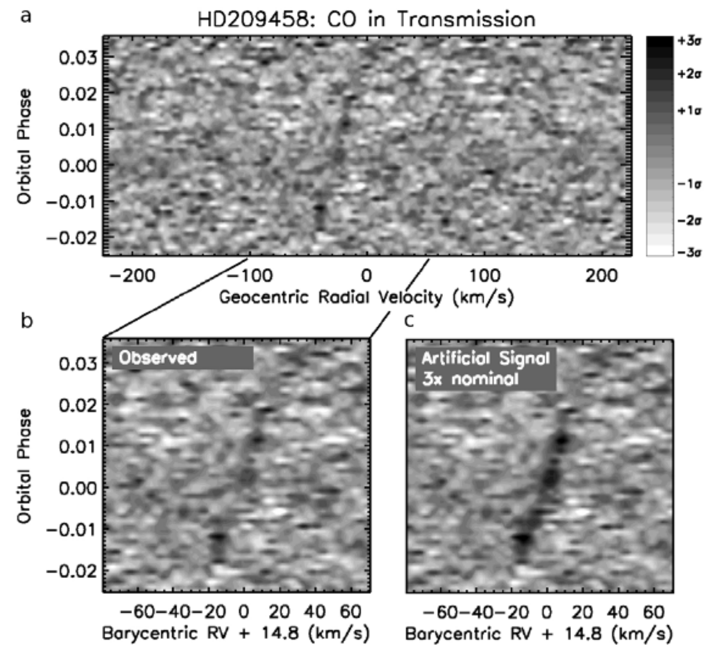
Requirements:
Binocular VIS and NIR both imaging and coro modes. + Synergy with LMIRCAM for H2
Coronagraphs with 2<λ/D<8; FoV of 5”x5” and ~20”x20” for DLAs and AGN inner morphology.

New frontiers in exoplanet detection and characterisation

Combining high-dispersion spectroscopy with high-contrast imaging

High-dispersion spectroscopy as a very powerful tool to characterise exoplanet atmospheres (and NOT only!) →

- Molecular Bands are resolved in tens of individual lines
- Strong Doppler effects due to orbital motion of the planet (up to >150 km/sec) so that moving planet lines can be distinguished from stationary telluric & stellar lines

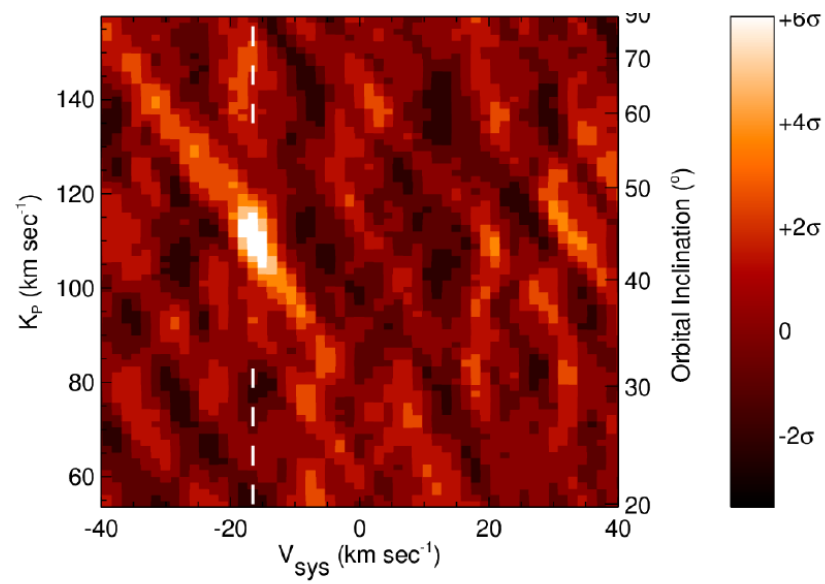


CRIRES @VLT (NIR domain, R~100,000)

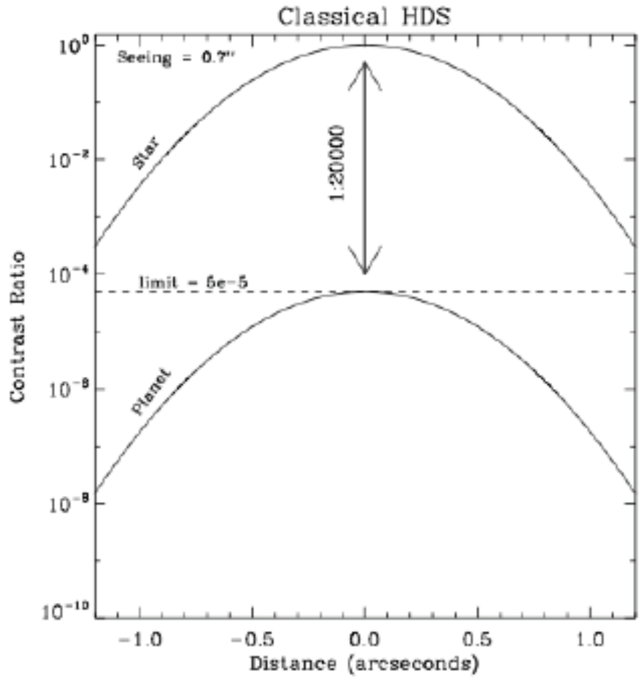
Snellen et al. (2010) carbon monoxide at 2.3 micron in the transmission spectrum of HD209458b

Brogi et al. (2012) CO at 2.3 micron in the thermal spectrum of the non-transiting planet tau Bootis (mass and orbital inclination determined)

Birkby et al. (2013) Water absorption in the thermal spectrum of HD189733b



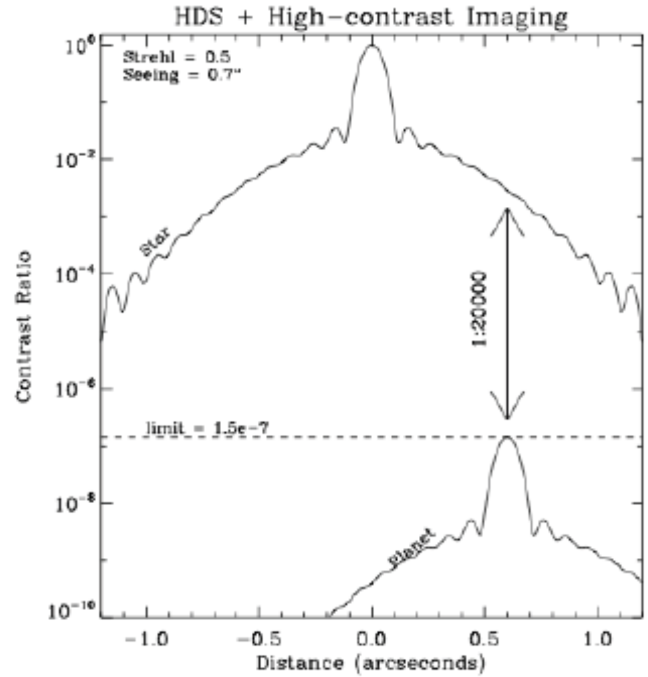
Classical HDS



$$\mathrm{SNR} = \frac{S_{\mathrm{planet}}}{\sqrt{S_{\mathrm{star}} + \sigma_{\mathrm{bg}}^2 + \sigma_{\mathrm{RN}}^2}}$$

Limits: 10^{-5} with VLT

HDS + HCI



$$\mathrm{SNR} = \frac{S_{\mathrm{planet}}}{\sqrt{S_{\mathrm{star}}/K + \sigma_{\mathrm{bg}}^2 + \sigma_{\mathrm{RN}}^2}}$$

$\times \sqrt{N_{\mathrm{lines}}}$

Limits: $10^{-5}/\sqrt{K}$ with VLT

Snellen et al. (2015)

$\times \sqrt{N_{\mathrm{lines}}}$

How far can we push this with the ELTs?

High-resolution IFU (R=100,000) in the optical domain (0.6 – 0.9 micron) implementation for V-SHARK and then possibly for PCS?

Probing the **habitable** zone of nearby M-dwarfs
→ we can target stars like e.g., Proxima Centauri

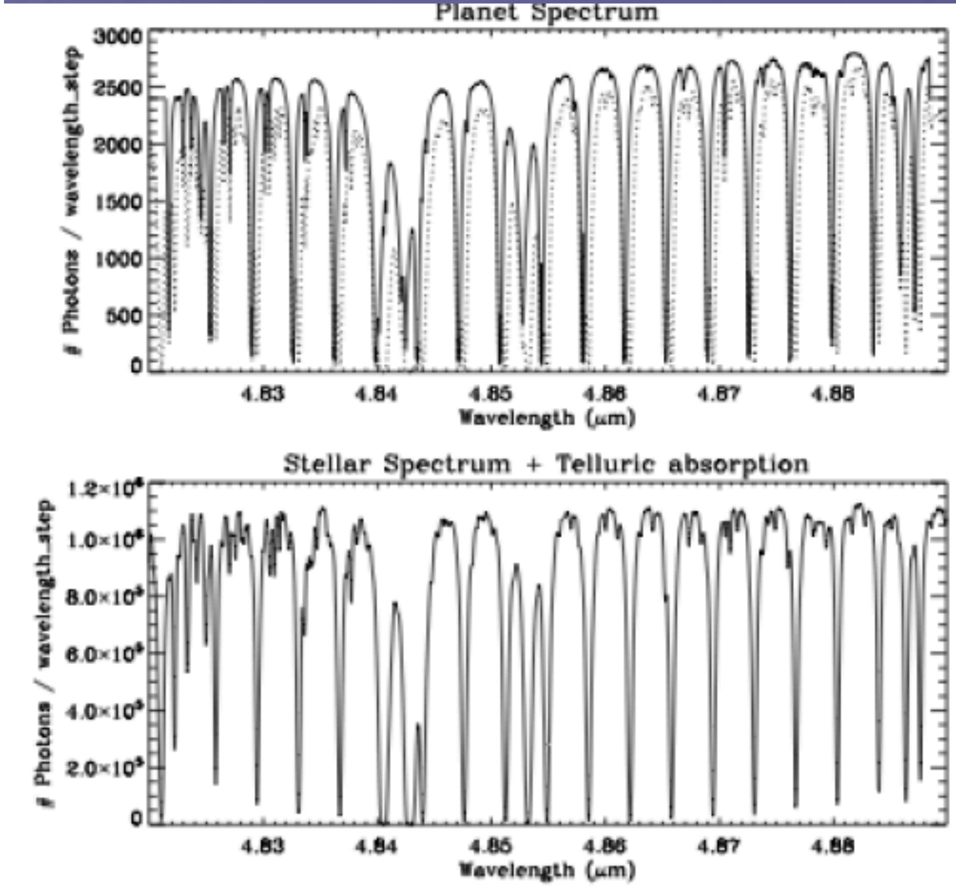
V=11.05 mag
Stellar radius 0.141 R_sun
Distance 1.30 pc
Planet radius 1.5 Earth
Orbital radius 0.032 AU
Angular distance from star 25 mas

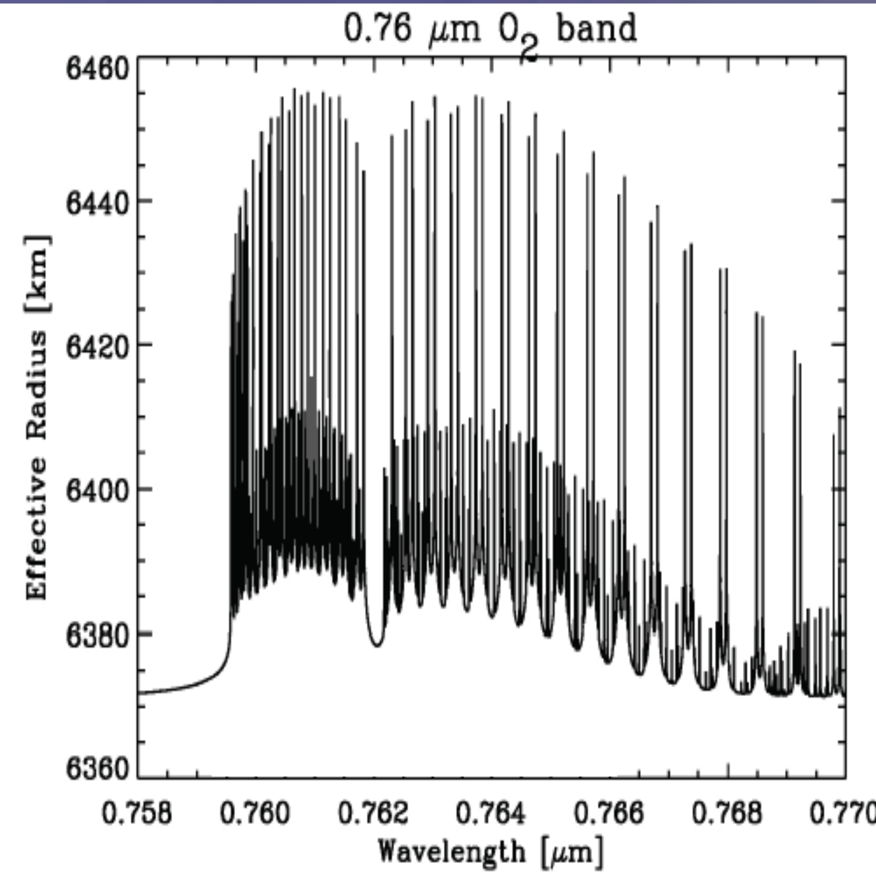
Back-of-the envelope calculations demonstrate that the planet can be detected with a contrast of almost 10^{-8} at 25 mas separation with a SNR ~8/10 (in agreement with preliminary simulations by Snellen et al.)

Although being more challenging (lower Strehl ratios than NIR/MIR), the optical regime has the obvious advantage that sky background is significantly smaller + we can cover the O_2 band (biomarker!) at 770 nm

The World's Biggest Eye on the Sky

ESO
European
Southern
Observatory

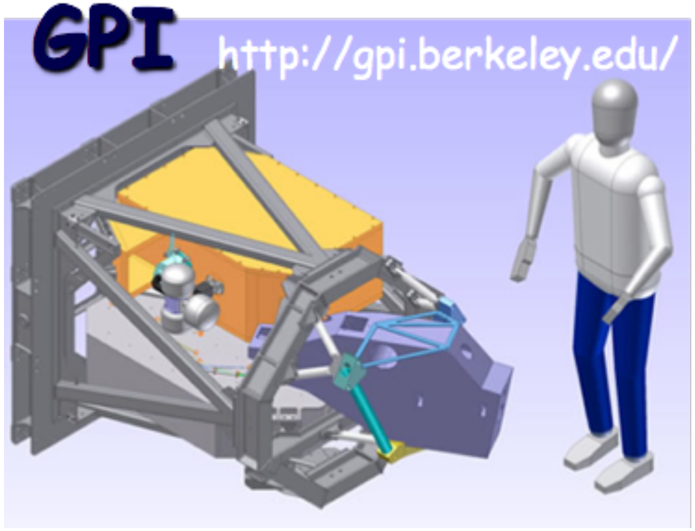




Towards the characterisation of Earth-like planets

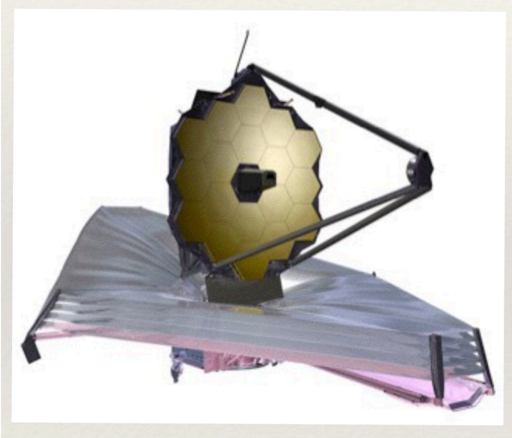
E-ELT (European Extremely Large Telescope)

Planet imagers for the next future



Ground based 8 m telescopes (2013 -)

Hi-Ciao (Subaru)
SPHERE (VLT)
GPI (Gemini)
SHARKs (LBT)



JWST (2018 -)

- < 5 micron NIRCAM/TFI
- > 5 micron: MIRI

ELT Instruments (> 2020 -)

-NIR: PCS (E-ELT), PFI (TMT), HRCAM (GMT)
-MIR: METIS (E-ELT), MIRES (TMT), MIISE (GMT)


THANK YOU!