Direct Imaging of Exoplanets with VLT/SPHERE

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Credits for the SPHERE project

12 European institutes

- PI: Jean-Luc Beuzit, Markus Feldt
- Instrument Scientist: David Mouillet
- GTO coordinator: Gaël Chauvin
- CoIs:
  - Anthony Boccaletti (LESIA)
  - François Ménard (IPAG)
  - Carsten Dominik (UvA)
  - Thomas Henning (MPIA)
  - Claire Moutou (LAM)
  - Hans-Martin Schmid (ETHZ)
  - Massimo Turrato (INAF)
  - Stéphane Udry (Geneva Obs.)
  - Farrhok Vakhili (Lagrange)
- Sub-system scientists:
  - IRDIS: Maud Langlois/Arthur Vigan
  - IFS: Raffaele Gratton
  - ZIMPOL: Hans-Martin Schmid
  - AO: Thierry Fusco
- +200 people in engineering, admin, astro, etc

- strong ESO team supporting the operations:
  - IS: Julien Girard
  - Deputy IS: Zahed Wahhaj & Arthur Vigan
  - Instrument fellow: Julien Milli

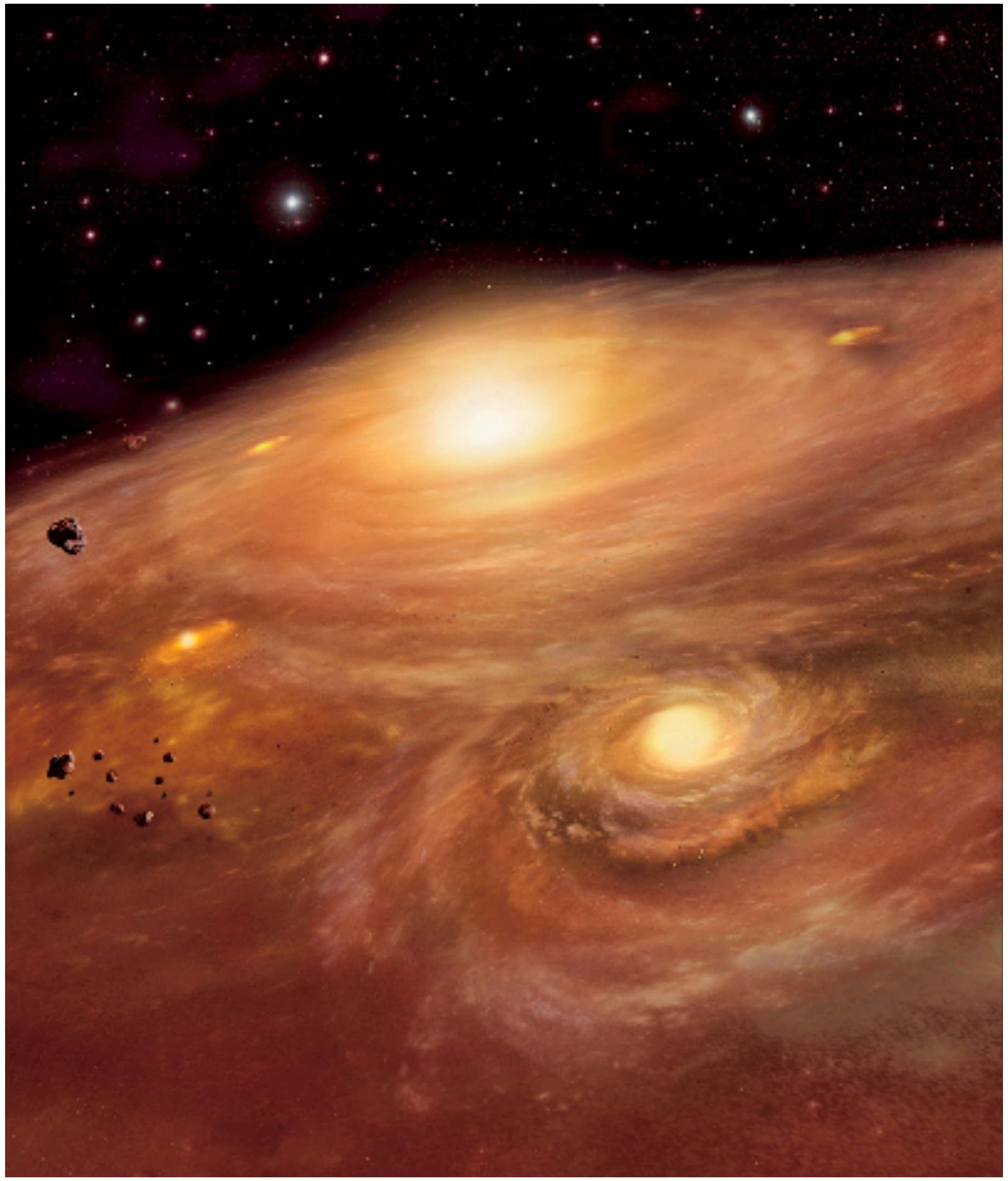
Outline

- Direct imaging in context
- Techniques for high-contrast imaging
- A new generation of instruments
- First results with SPHERE

Introduction

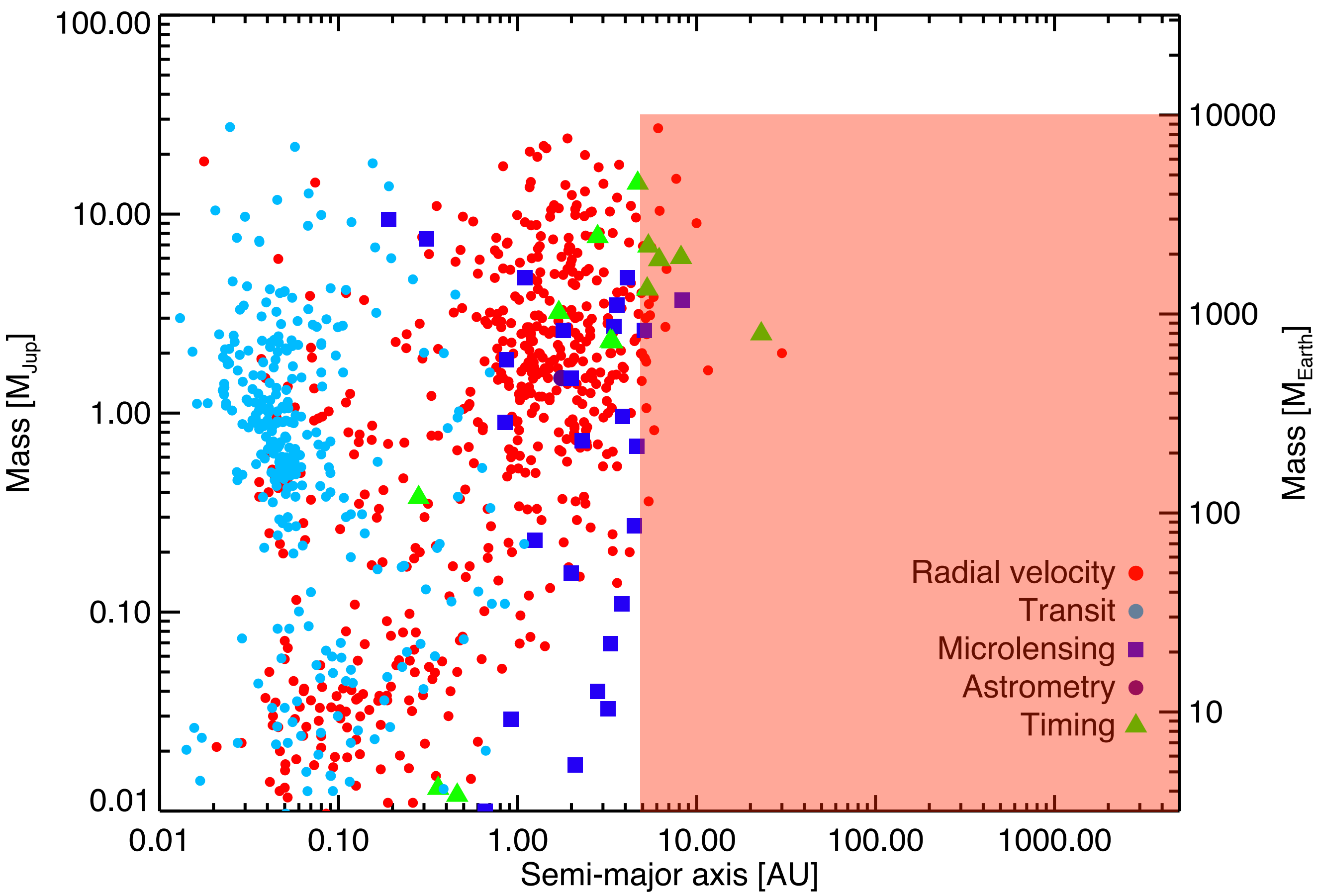
A multi-facet story

- stellar formation
- formation and physics of exoplanets
- architecture and evolution
- favorable conditions for life
- exo-biology and bio-signatures



Artist view of planet formation

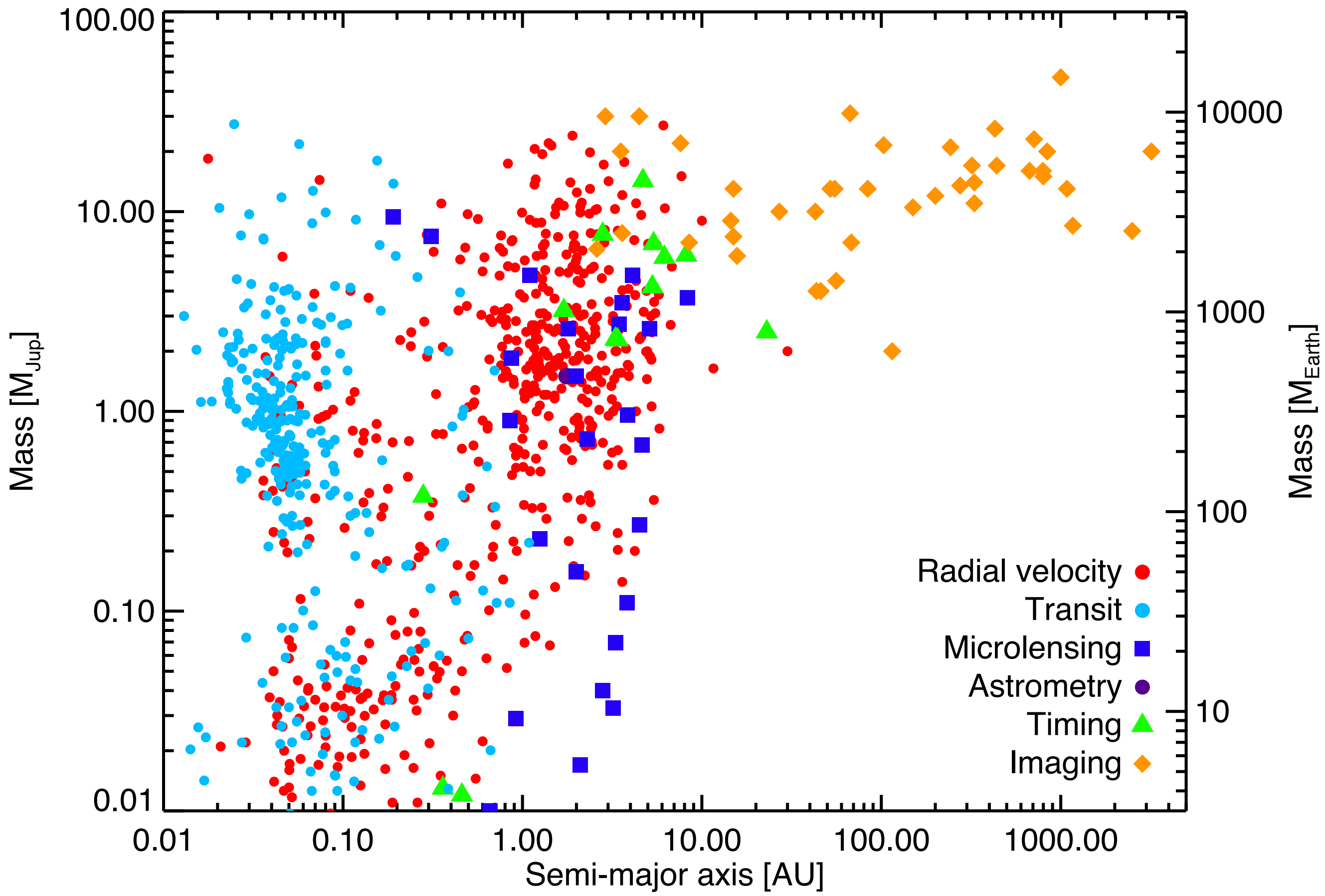
Direct imaging: context

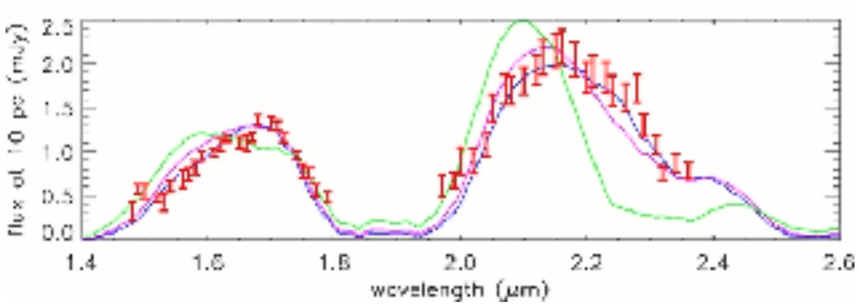


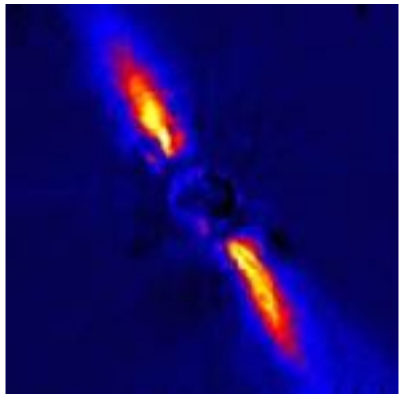
- Transmission & emission spectro
  - composition
  - vertical T-P structure
  - atmospheric circulation
  - evaporation

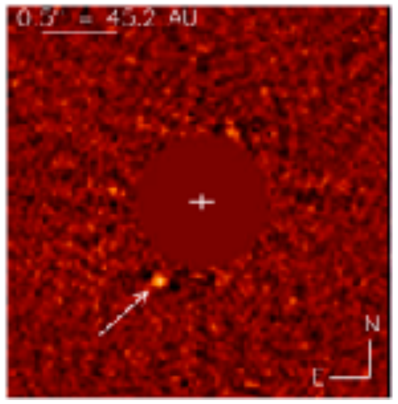
- Indirect methods
  - **Radial Velocity**
  - **Microlensing**
  - **Astrometry**
  - **Transit**: direct
- Orbital and physical properties:
  - most orbital parameters
  - system architecture & stability
  - planetary interiors
- Statistics
  - >1000 confirmed planets
    + 1000s *Kepler* **candidates**
  - frequency down to super-Earths
  - mass/orbit distributions
  - stellar host dependence (Fe/H; SpT; binarity; etc)

Direct imaging: context









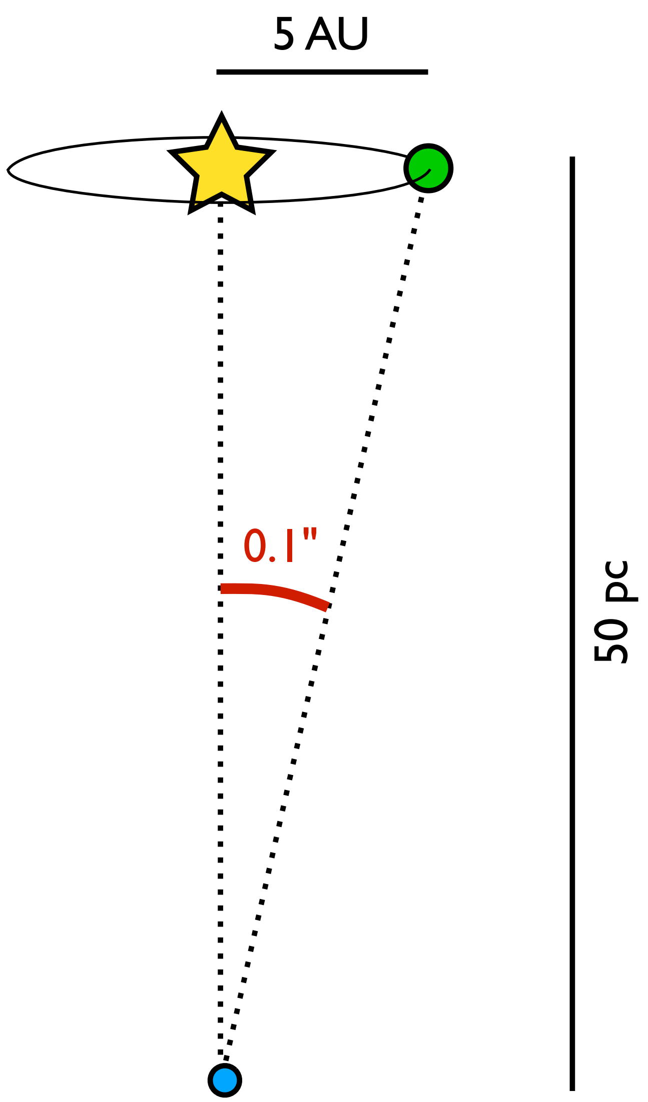
- Direct imaging measures **photons from the planet**
- Orbital and physical properties:
  - L, a, e, i, ω, t0
  - giant planets >1 M_{Jup} at wide-orbit >5 AU
  - system architecture & stability
  - planet-disk interactions
- Spectroscopy:
  - composition
  - cool, non-irradiated atmospheres
  - low gravity, non-LTE, clouds, ...

Chauvin et al. (2004); Lafrenière et al. (2007); Janson et al. (2010); Skemer et al. (2012); Mouillet et al. (1997); Lagrange et al. (2012); Kalas et al. (2004) ...

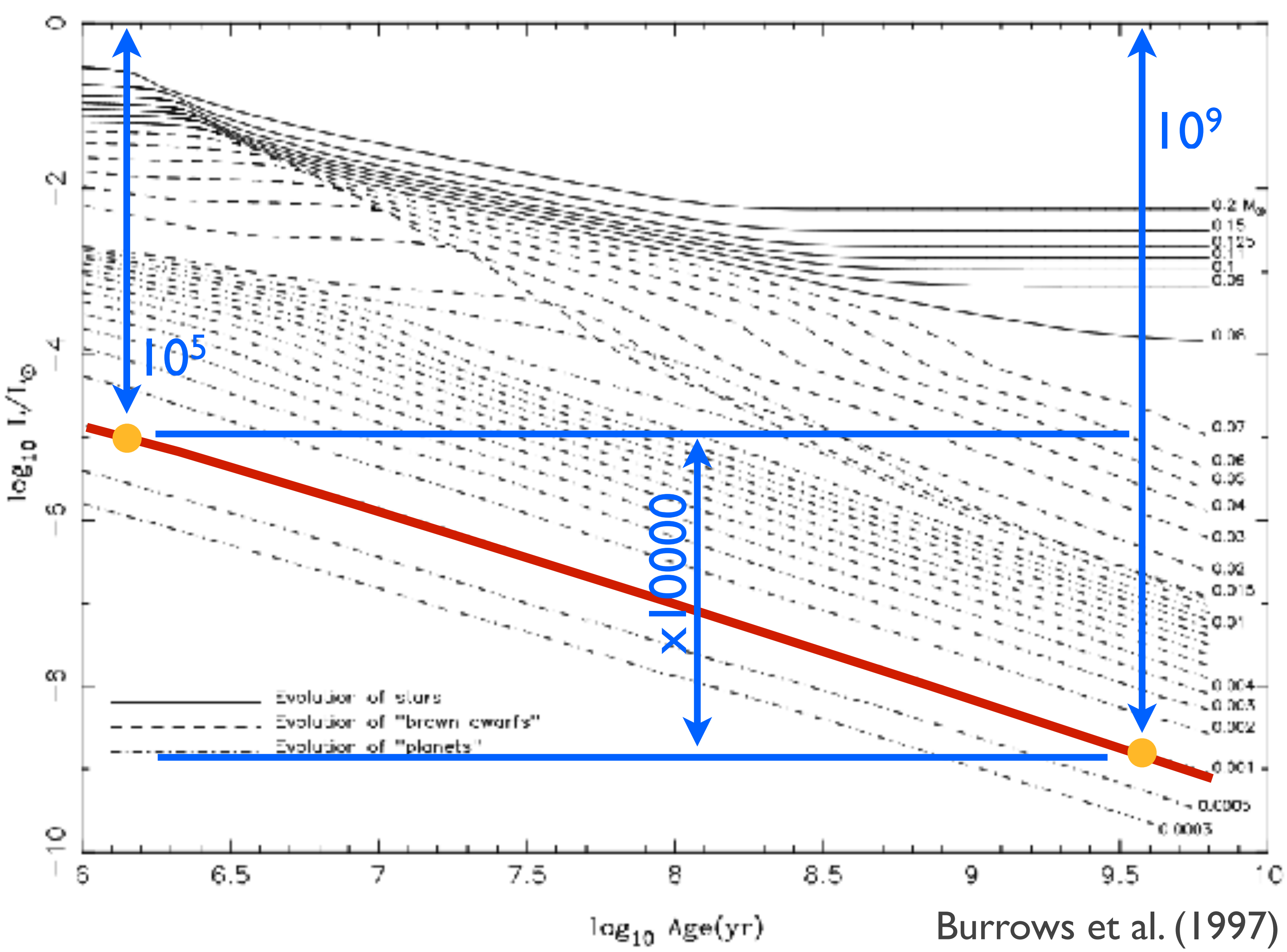
Observational challenge

Direct imaging has to overcome **2 difficulties**

High-angular resolution

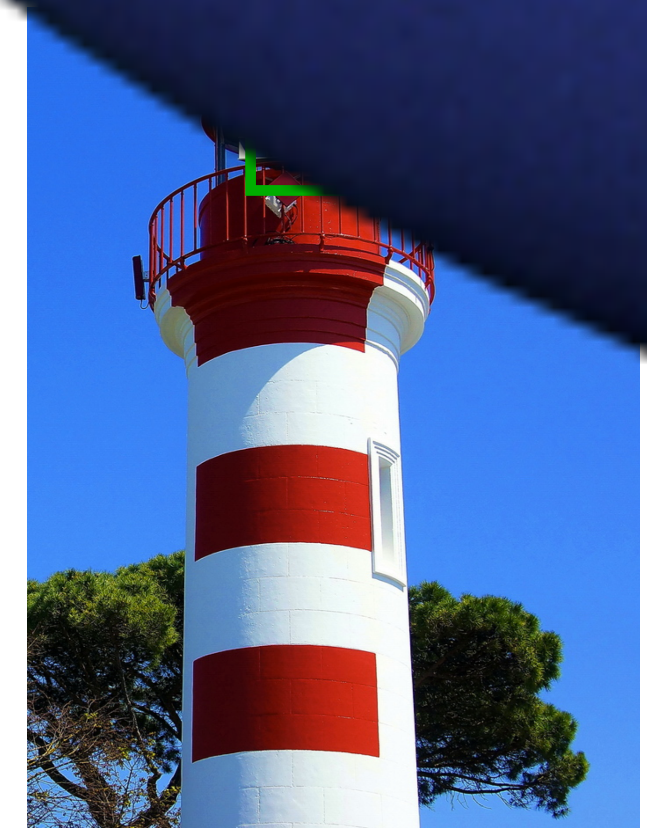


High-contrast



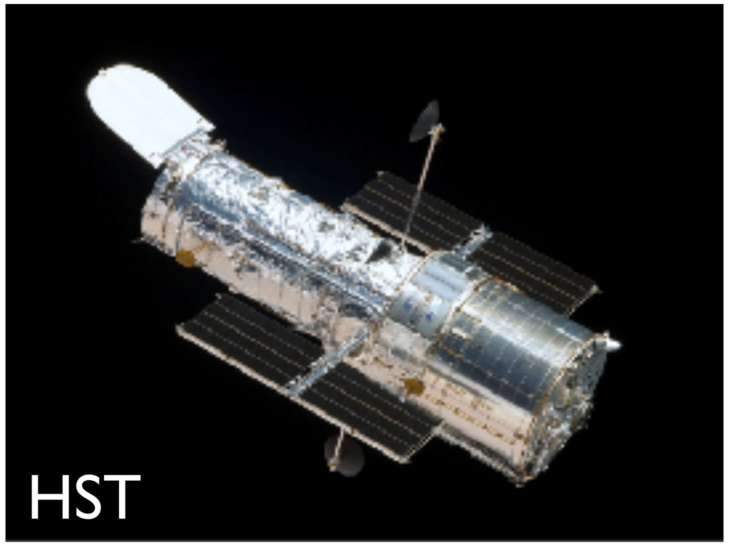
Burrows et al. (1997)

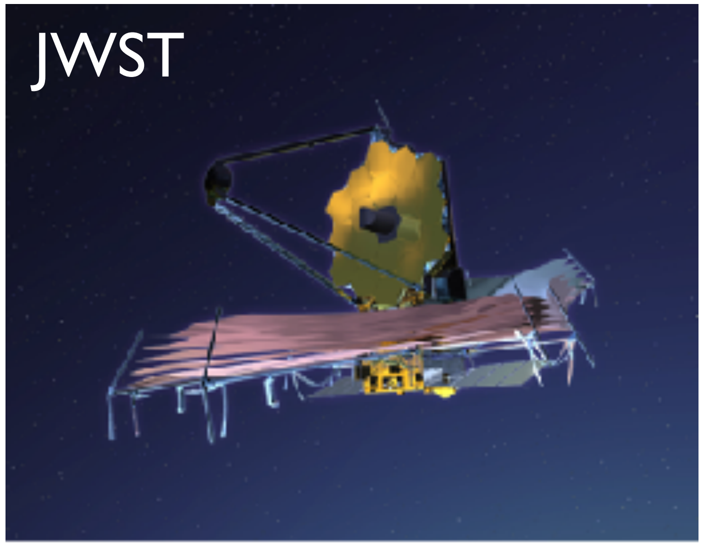
Observational challenge

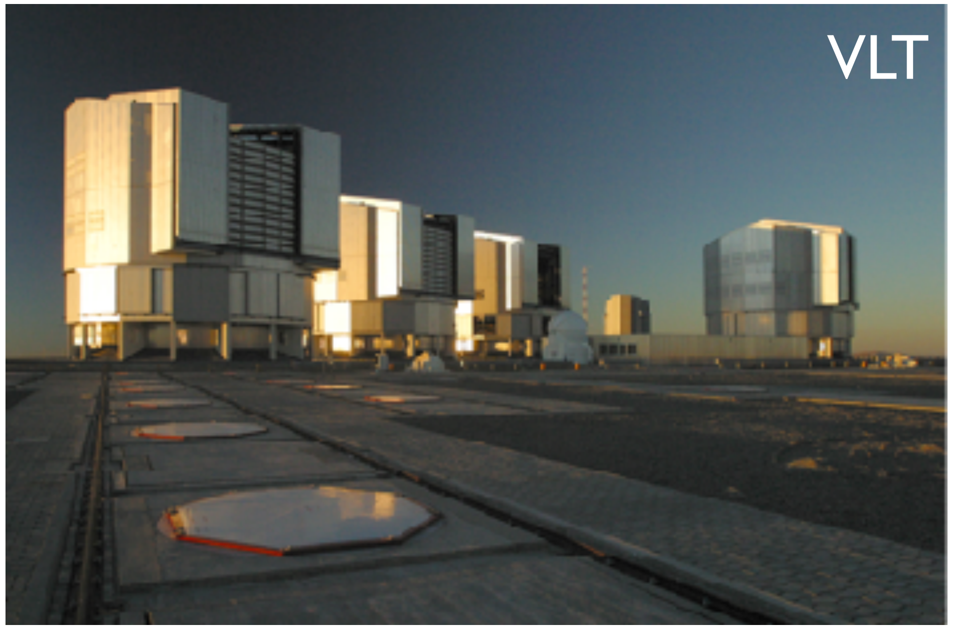


High-angular resolution

- Need for **large telescopes** at the **diffraction limit**
  - space
  - ground-based + AO



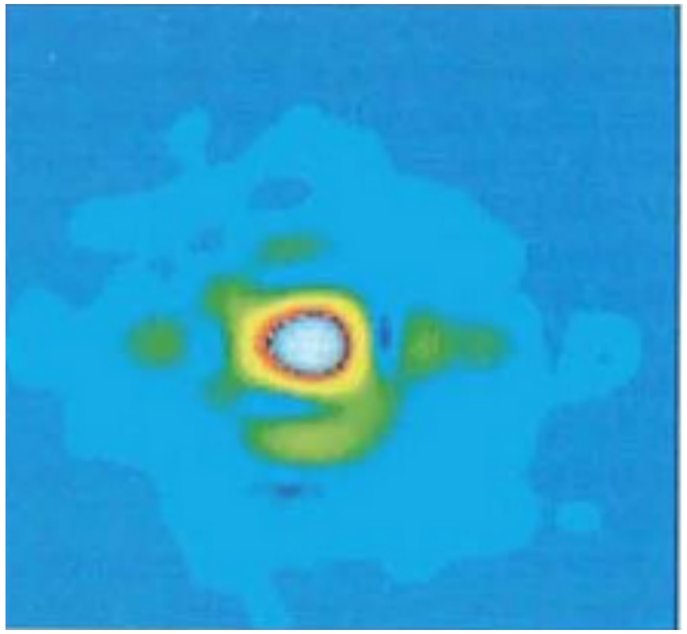




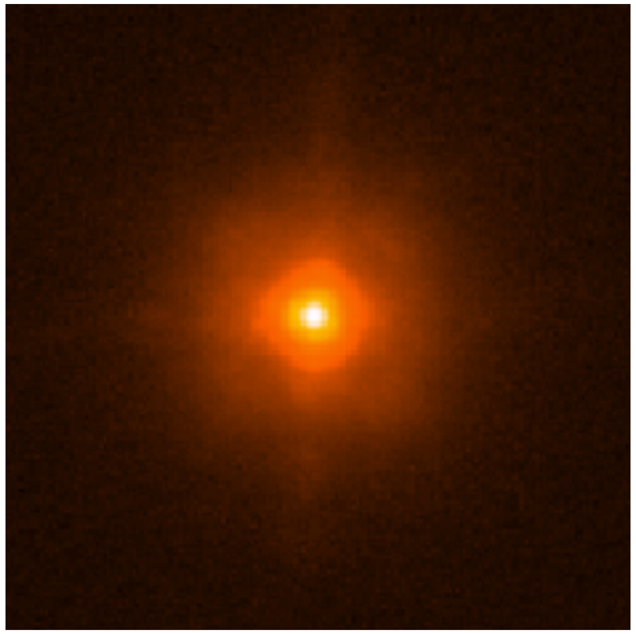
High-angular resolution: adaptive optics

- **Measure** the atmospheric turbulence using a wavefront sensor
- **Correct** it using a deformable mirror
- Correction limited by number of actuators and frequency of correction
- Different generations of systems:

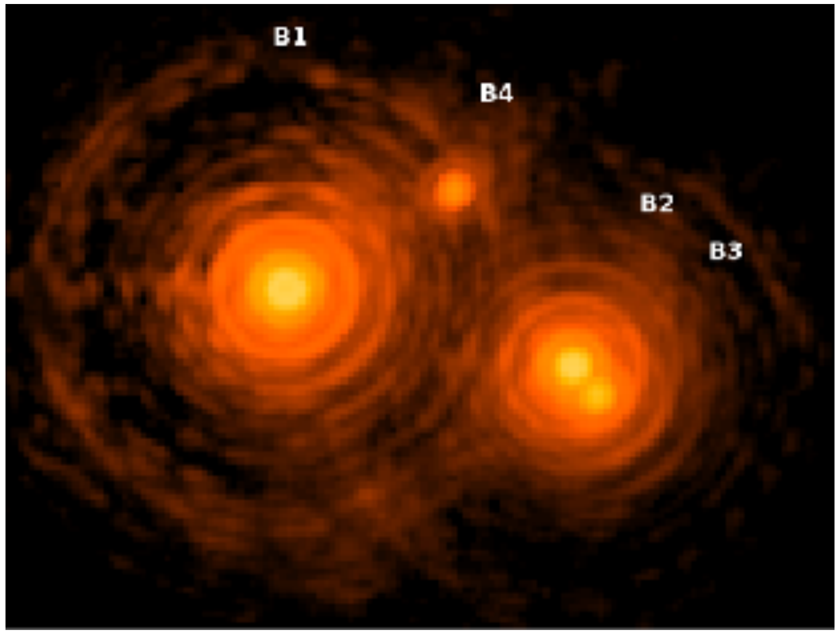
1990s
ESO3.6m/Come-On+
SH WFS; 52 actuators
Sr < 10%



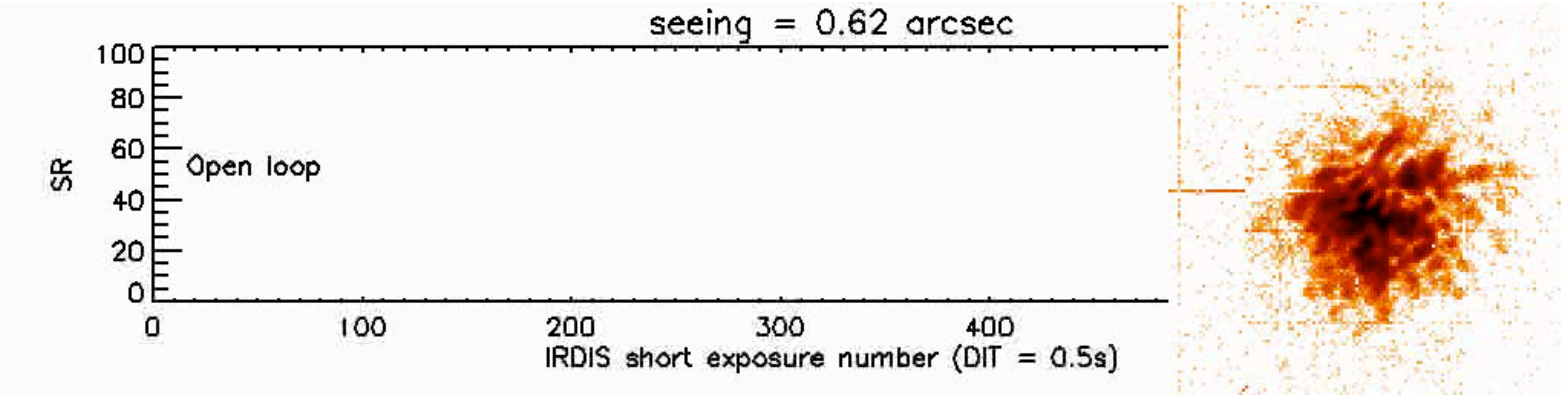
2000s
VLT/NaCo
SH WFS; 180 actuators
Sr = 40-50%

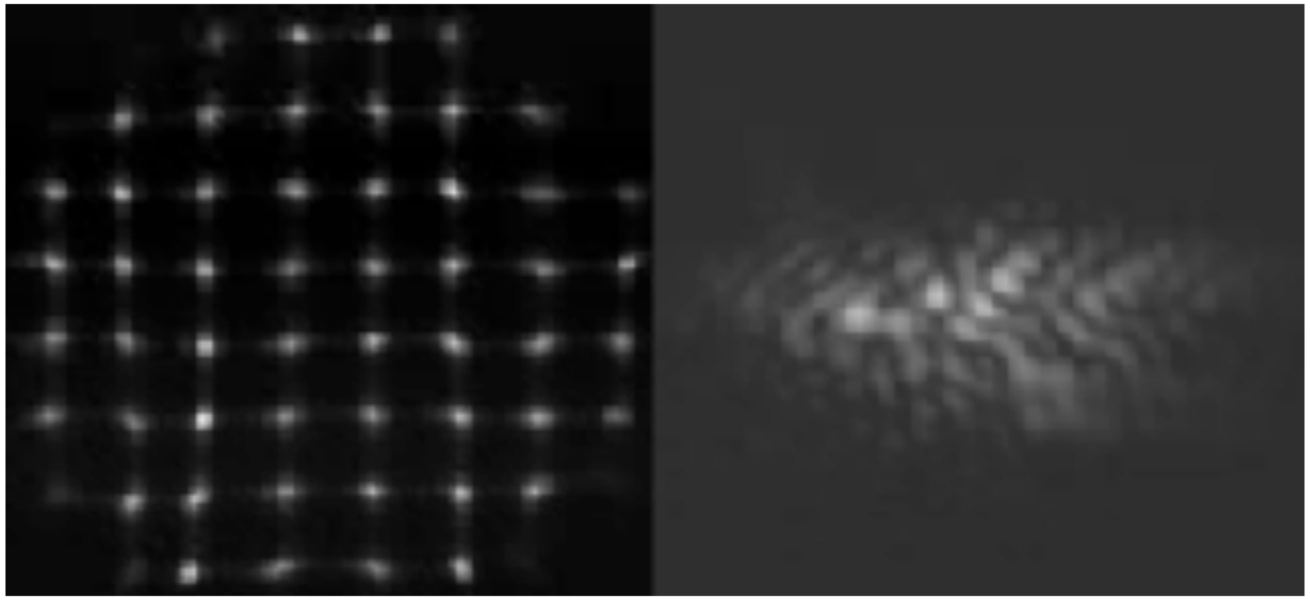


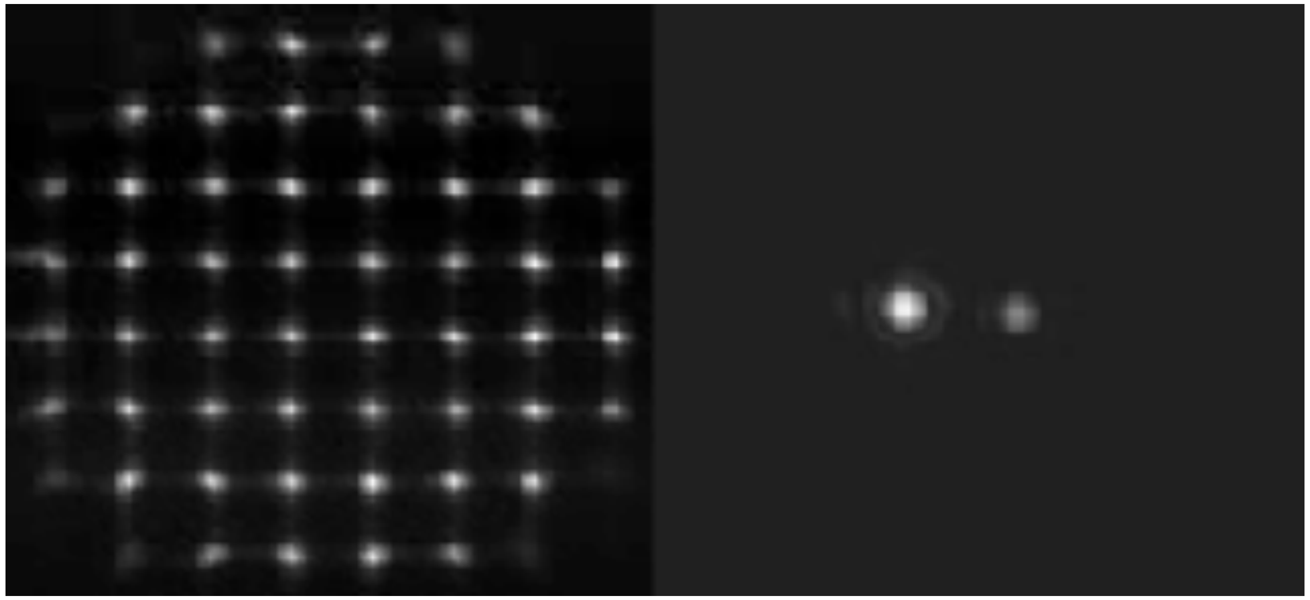
2010s
LBT/SPHERE/GPI
SH/Pyr WFS; >1000 actuators
Sr > 80%



Adaptive optics in action



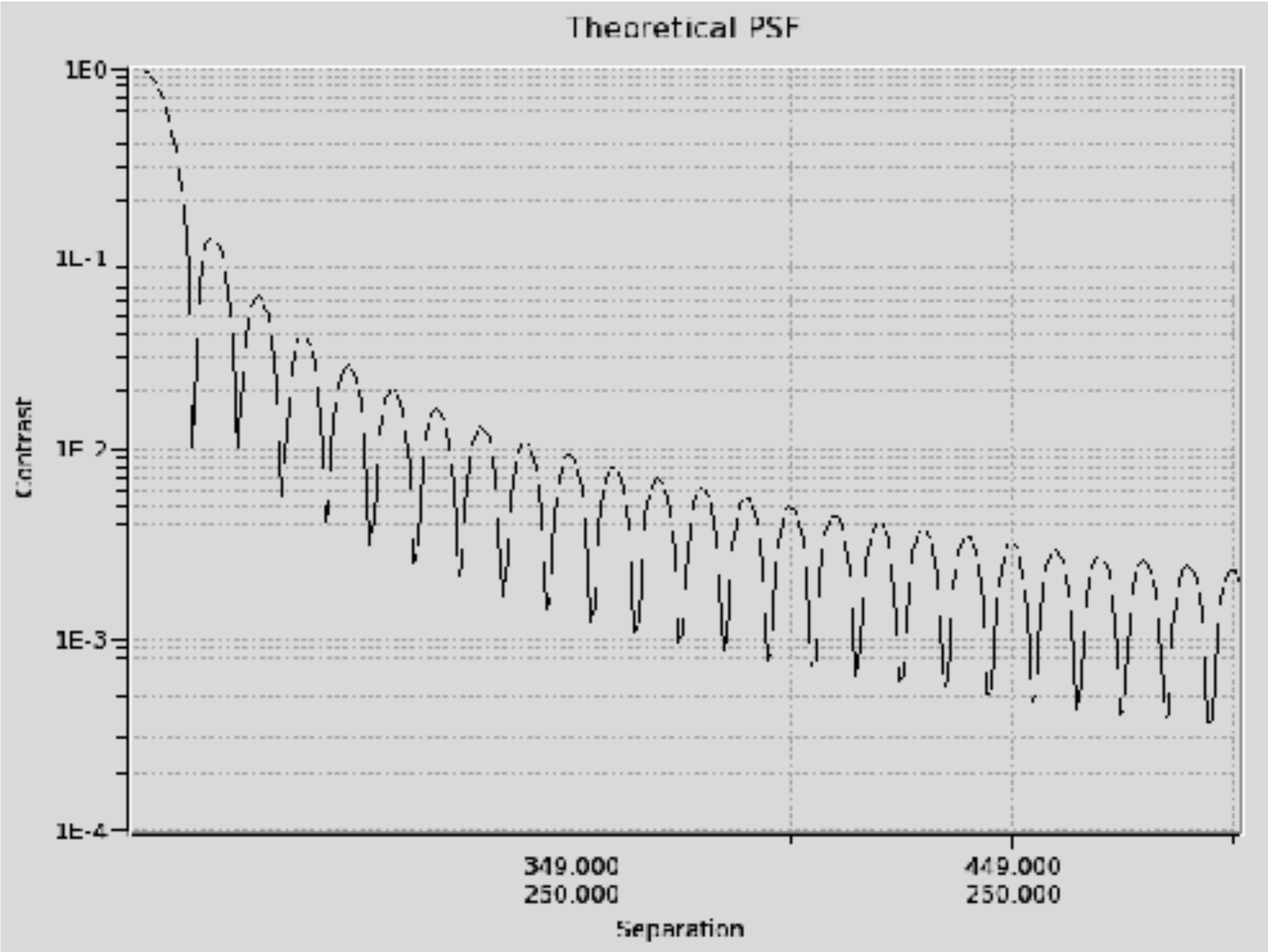




High-contrast

Sensitivity limited by the star/planet luminosity difference

- **long integration times**

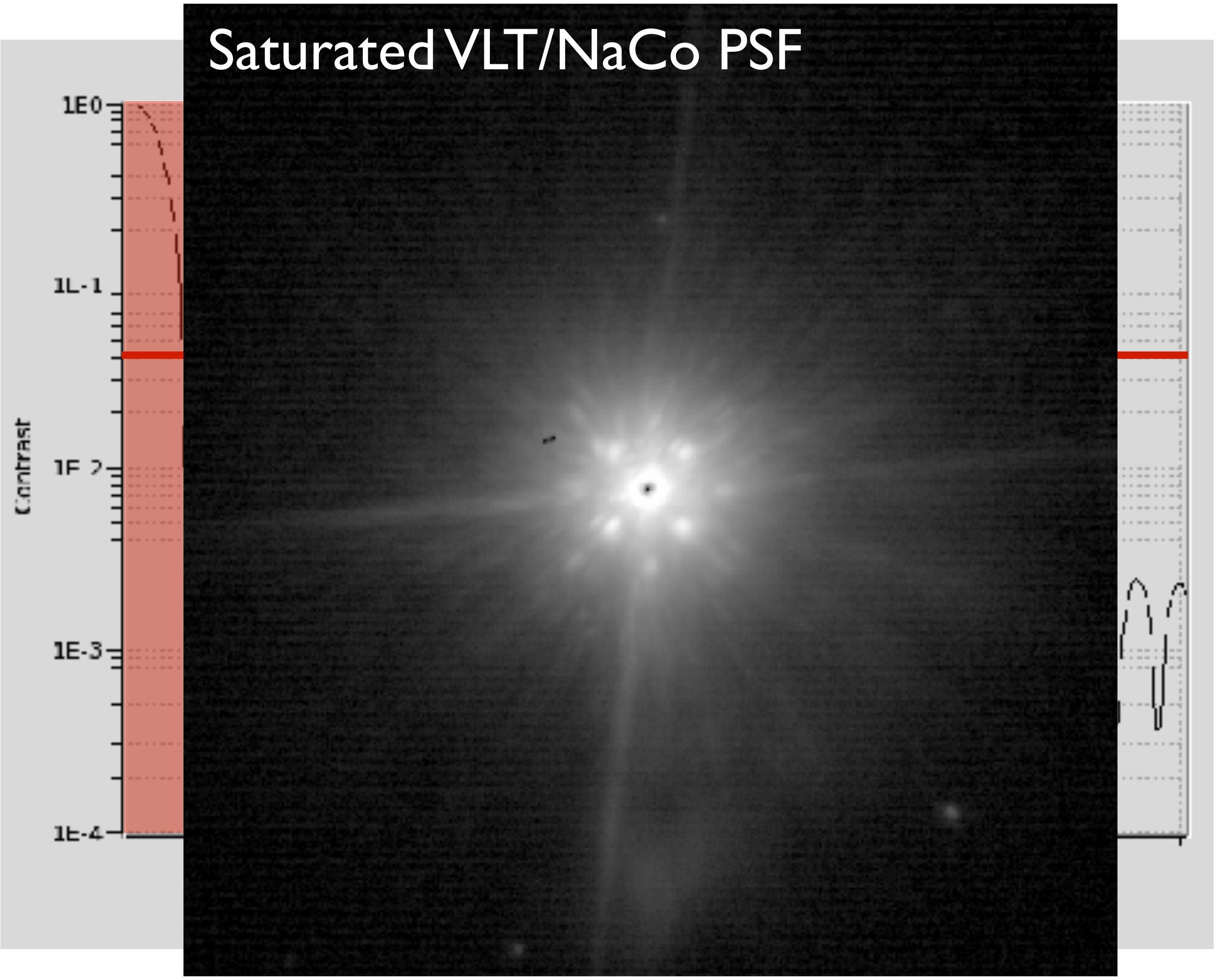


- Advantages:
  - ?
- Drawbacks:
  - extremely long integration times
  - limited by detector overheads
  - ultimately limited by diffraction

High-contrast

Sensitivity limited by the star/planet luminosity difference

- long integration times
- **saturated imaging**

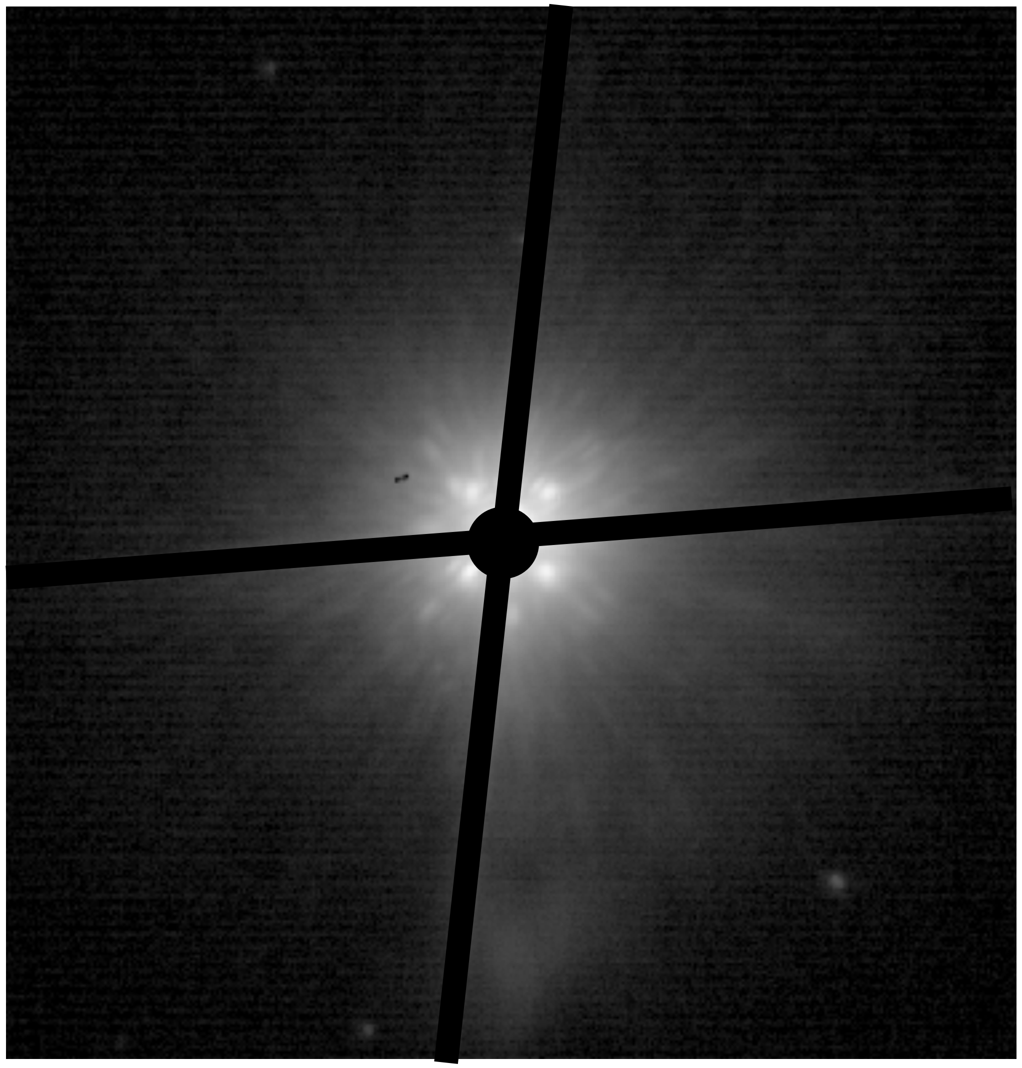


- Advantages:
  - increased sensitivity in PSF wings
  - improved SNR
- Drawbacks:
  - loss of angular resolution
  - remanence effects on detectors
  - ultimately limited by diffraction

High-contrast

Sensitivity limited by the star/planet luminosity difference

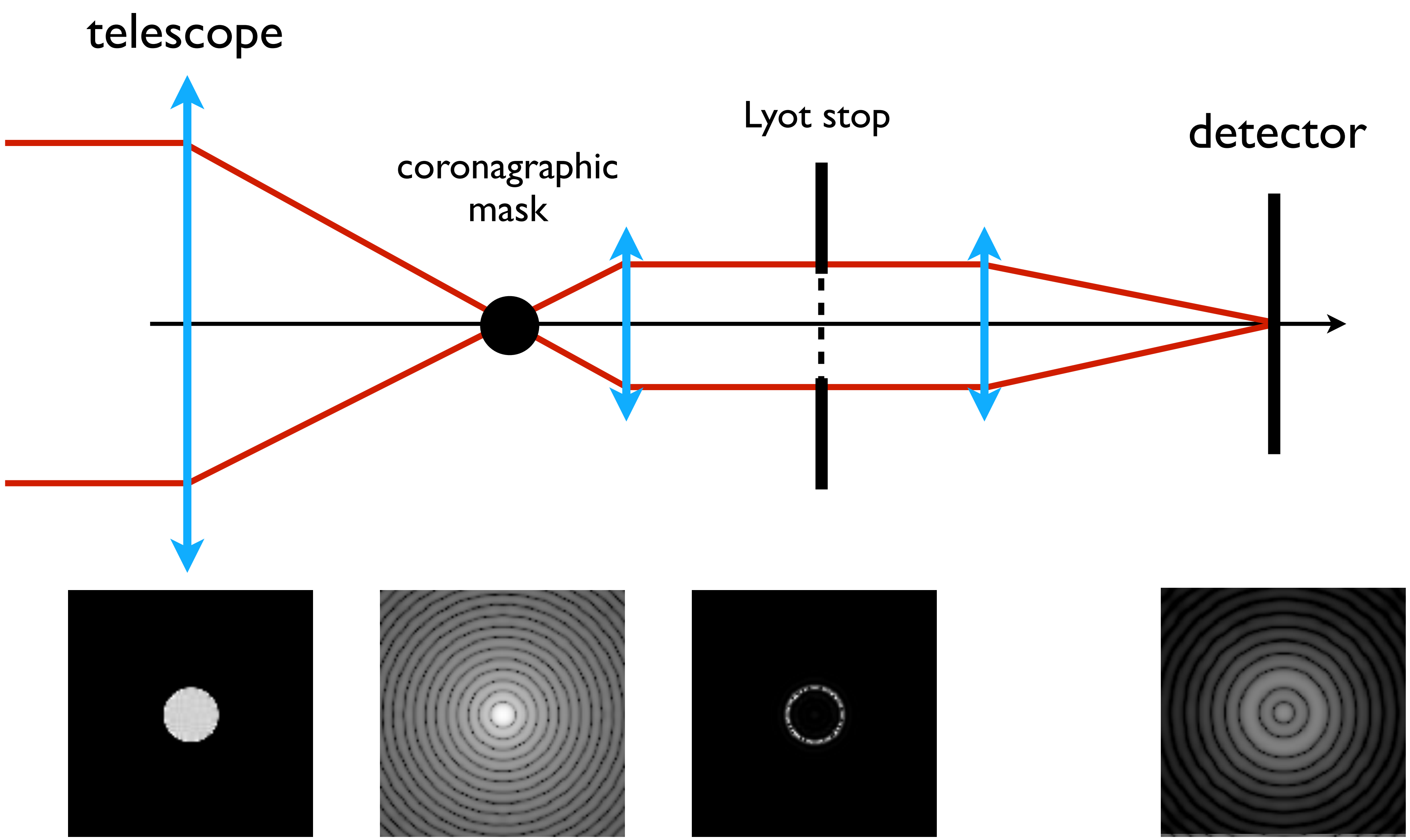
- long integration times
- saturated imaging
- **coronagraphy**

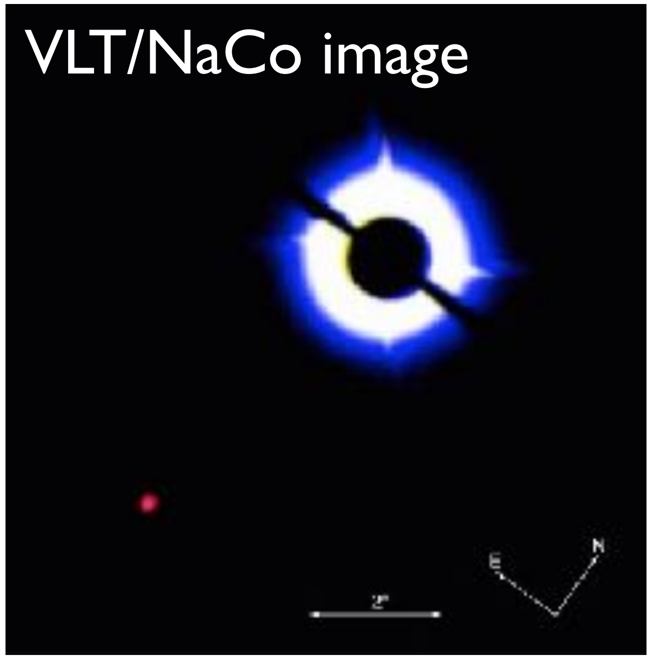


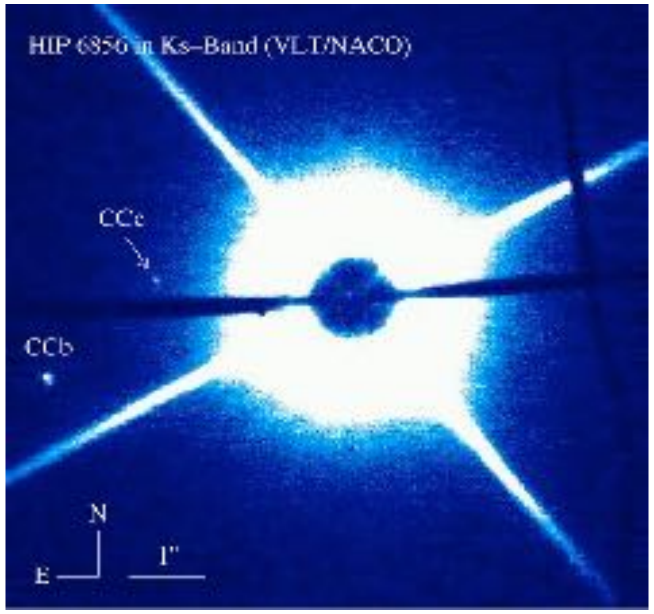
- Advantages:
  - suppress diffraction
  - improved SNR
- Drawbacks:
  - possible loss of angular resolution
  - increased system complexity
  - high Strehl ratio required

High-contrast: coronagraphy

- Proposed in 1930 by Bernard Lyot to observe the solar corona
- Generalized to point like sources
- Very active field of research



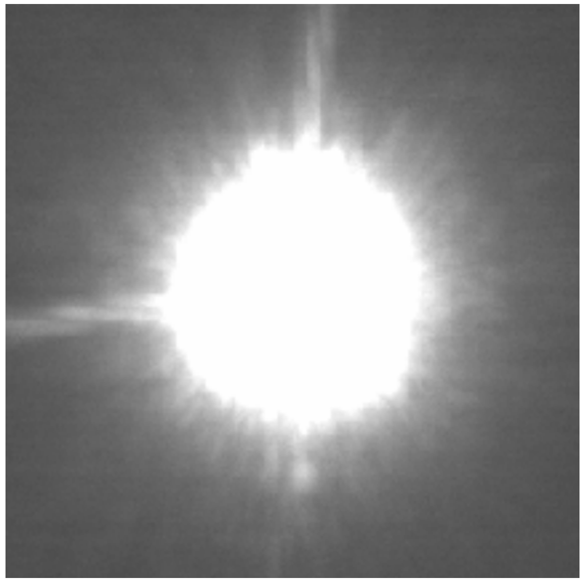


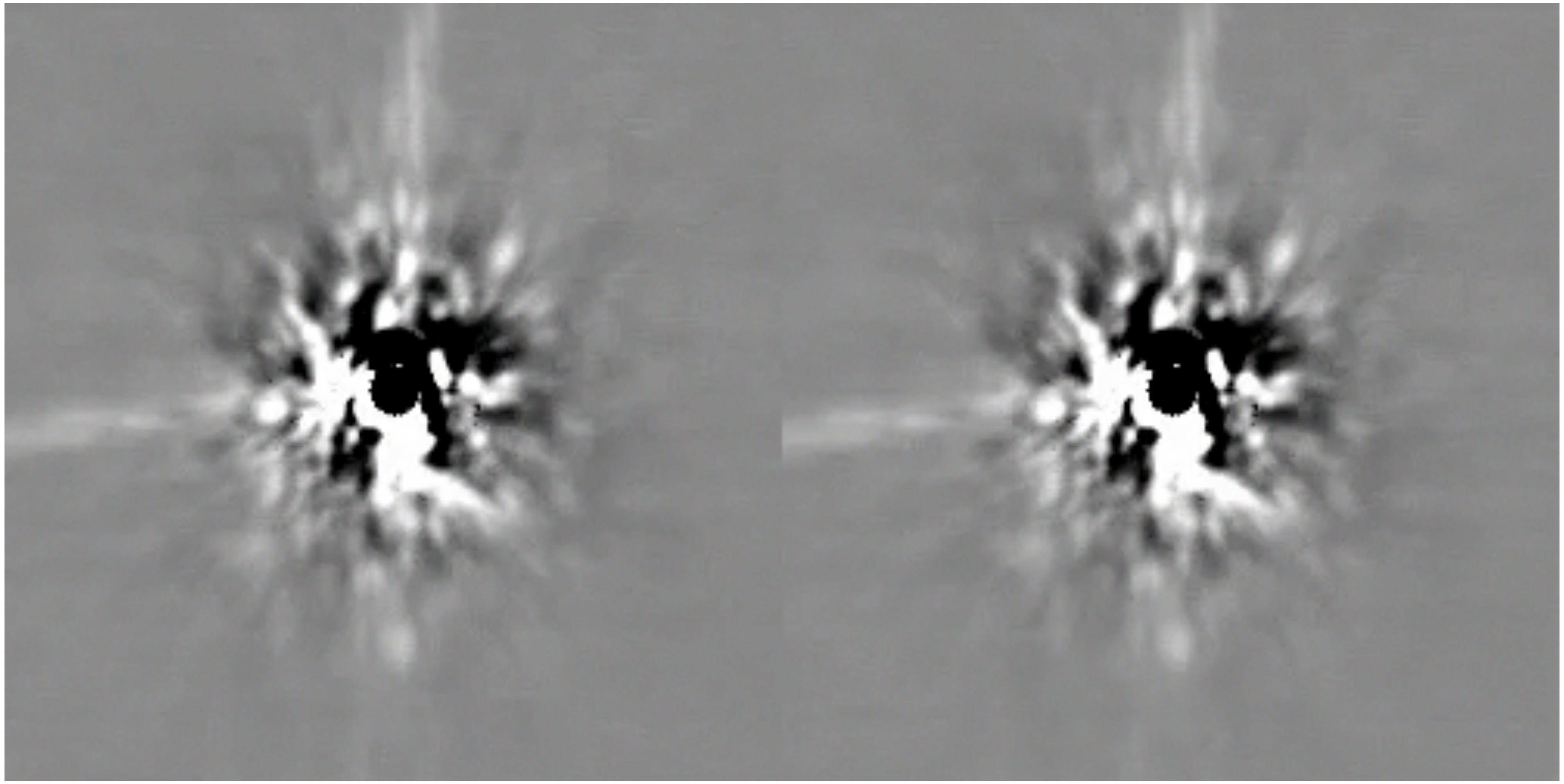


Quasi-static speckles

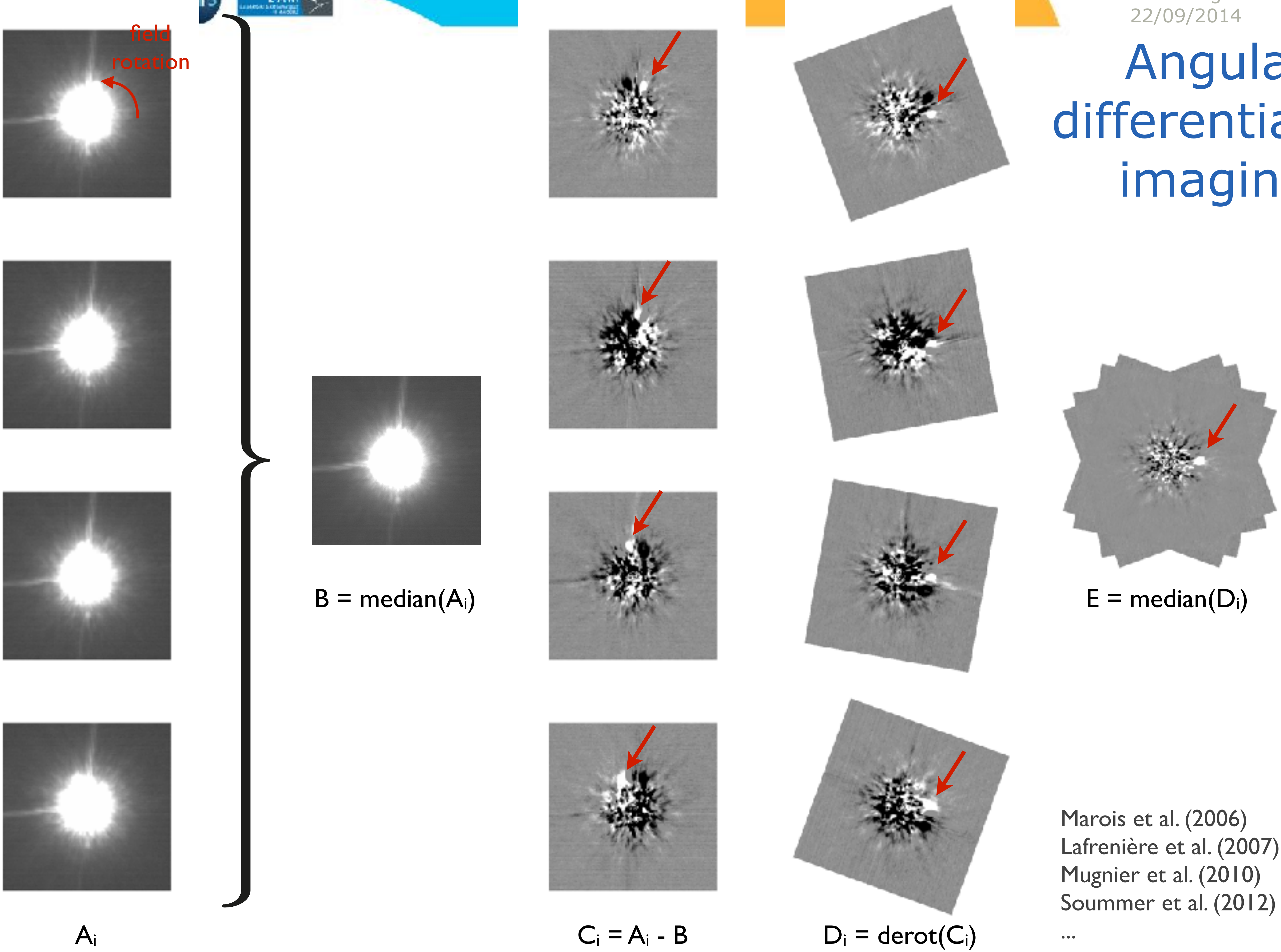
- high-angular resolution + high-contrast → **not enough!**
  - limitations: atmospheric and instrumental **speckles**
  - speckles are **not static**, but definitely **not random**
- optimized **observing strategy**, **data analysis** and **target selection**

Racine et al. (1999)
Macintosh et al. (2005)
Soummer et al. (2007)
Hinkley et al. (2007)
...





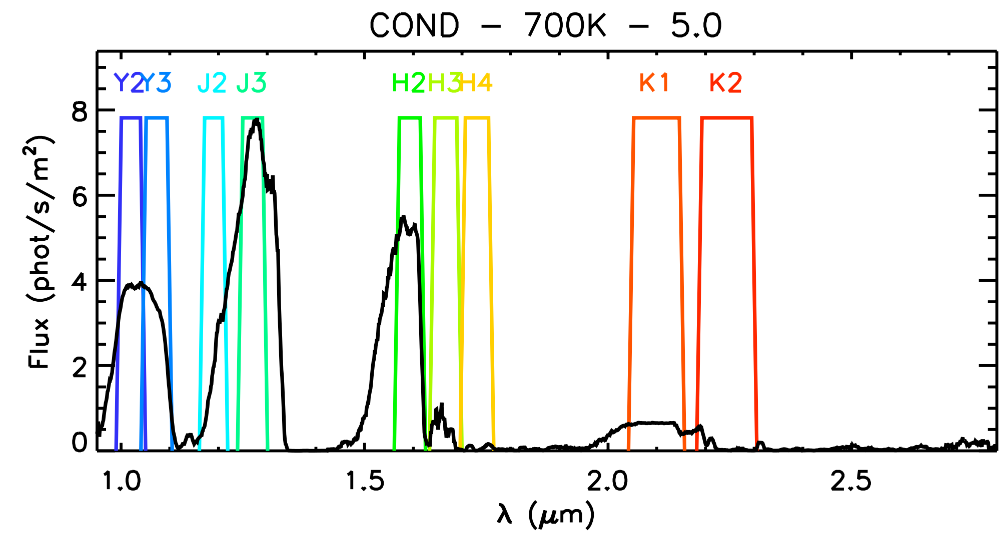
Angular differential imaging



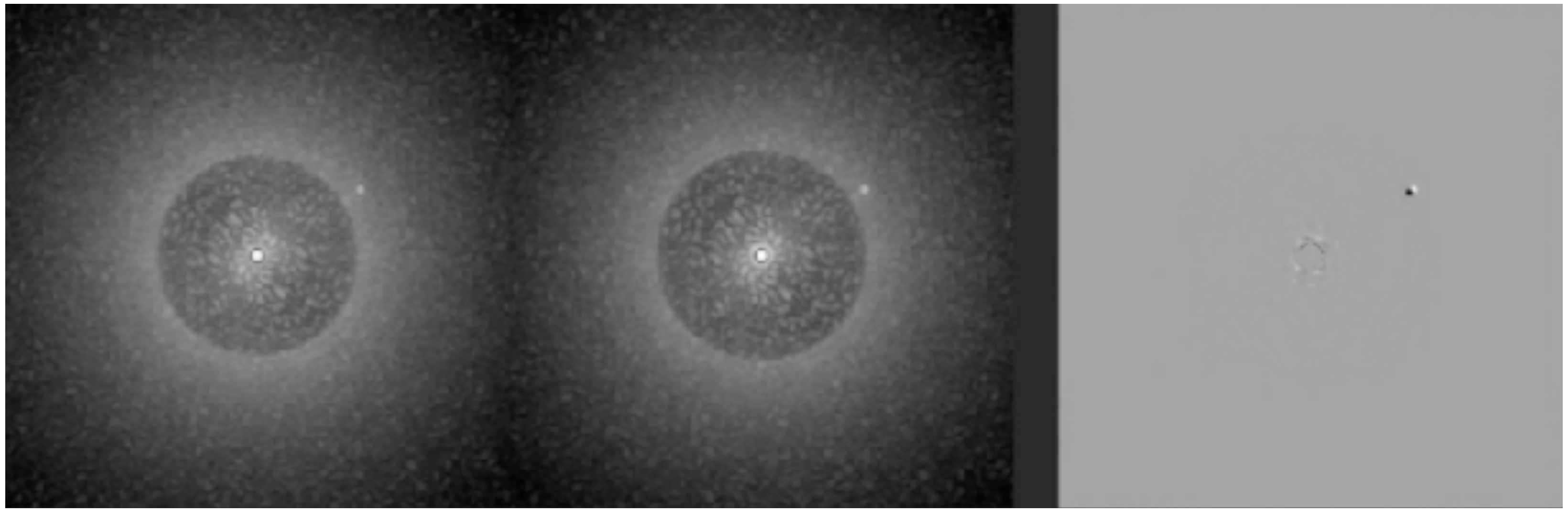
Marois et al. (2006)
Lafrenière et al. (2007)
Mugnier et al. (2010)
Soummer et al. (2012)
...

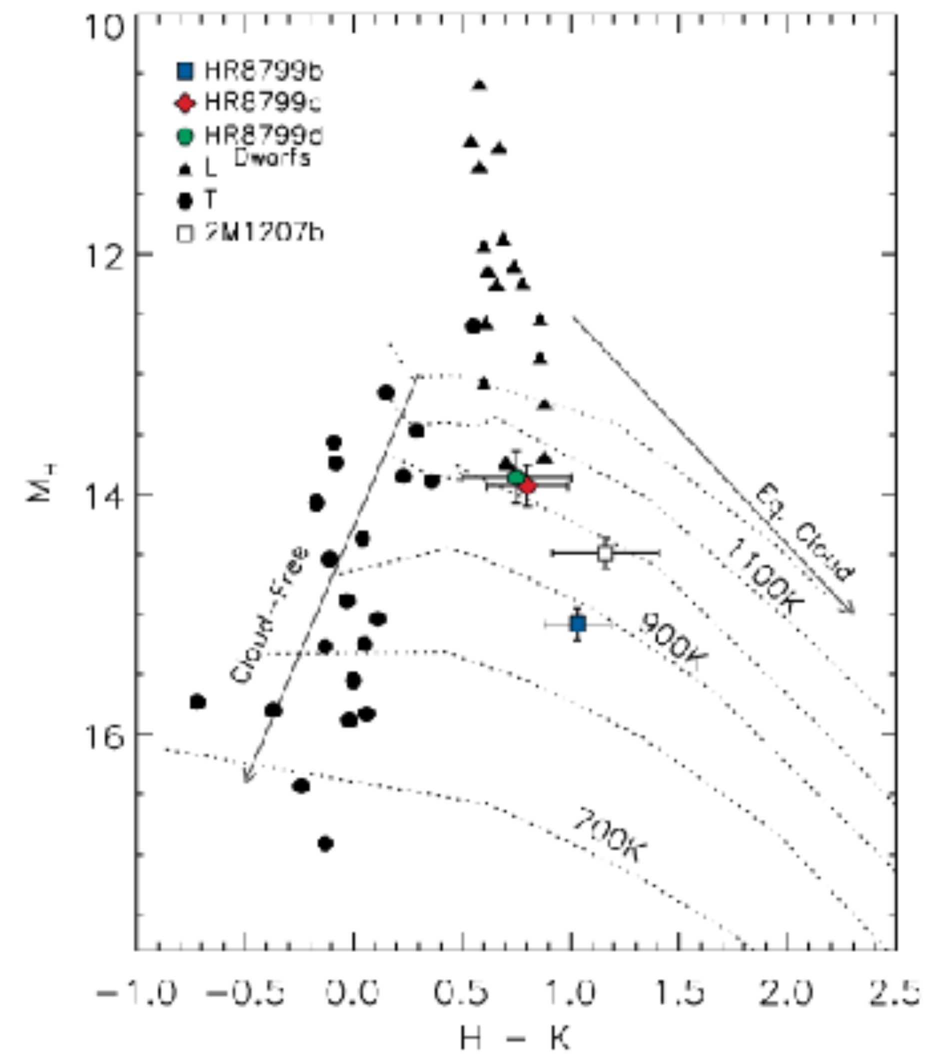
Spectral differential imaging

- Based on **expected spectral features** of the planets vs. flat stellar spectrum
- CH_4 / H_2O absorptions expected for cold, low-mass planets



λ_0 λ_1 $\lambda_0-\lambda_1$

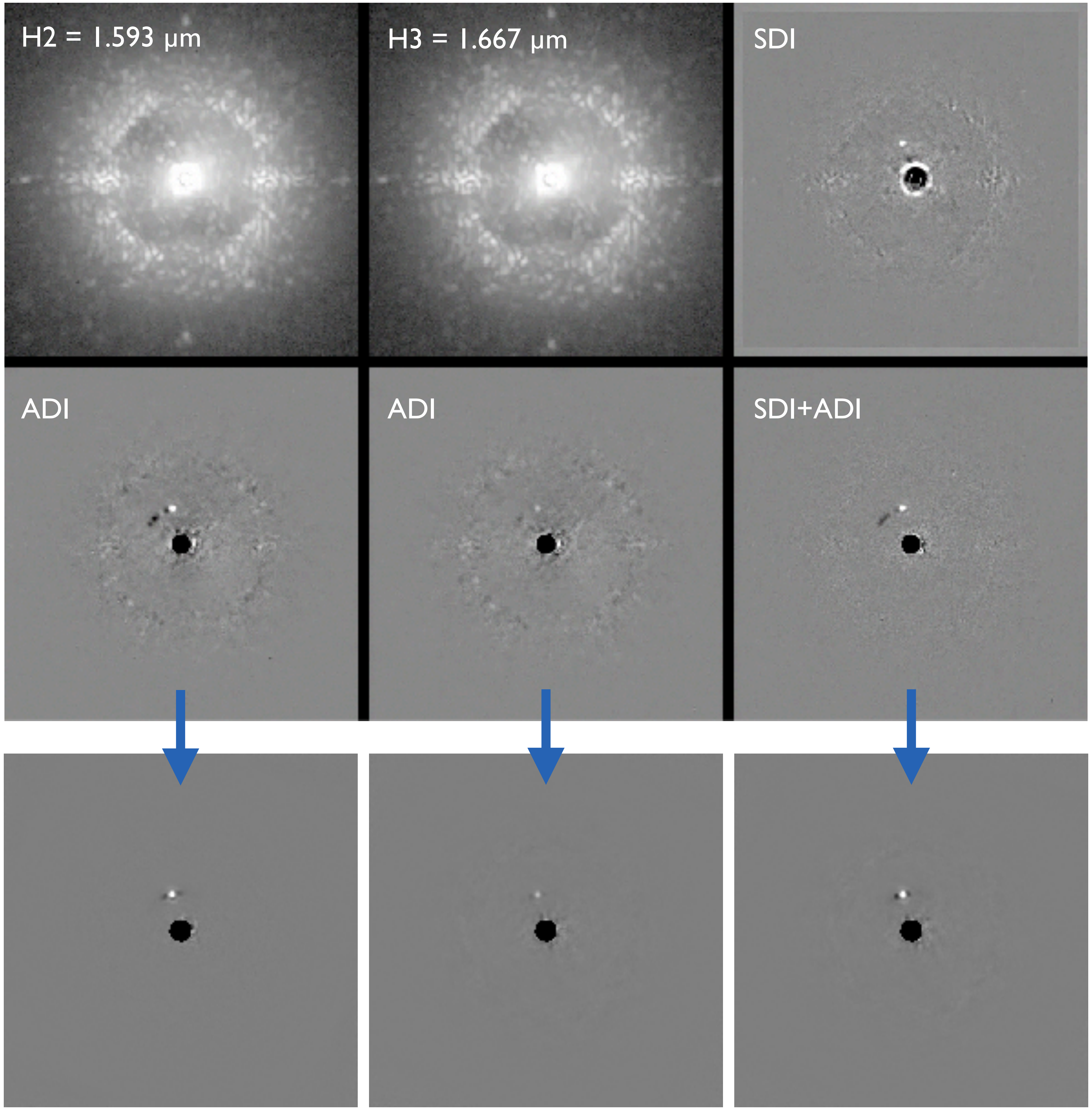




- Caveat: known cold objects don't show CH_4 abs.
  - HR8799b and 2M 1207b
  - unexpected role of CO/CH_4 non-equ. chemistry
  - except 51 Eridani b (see later)

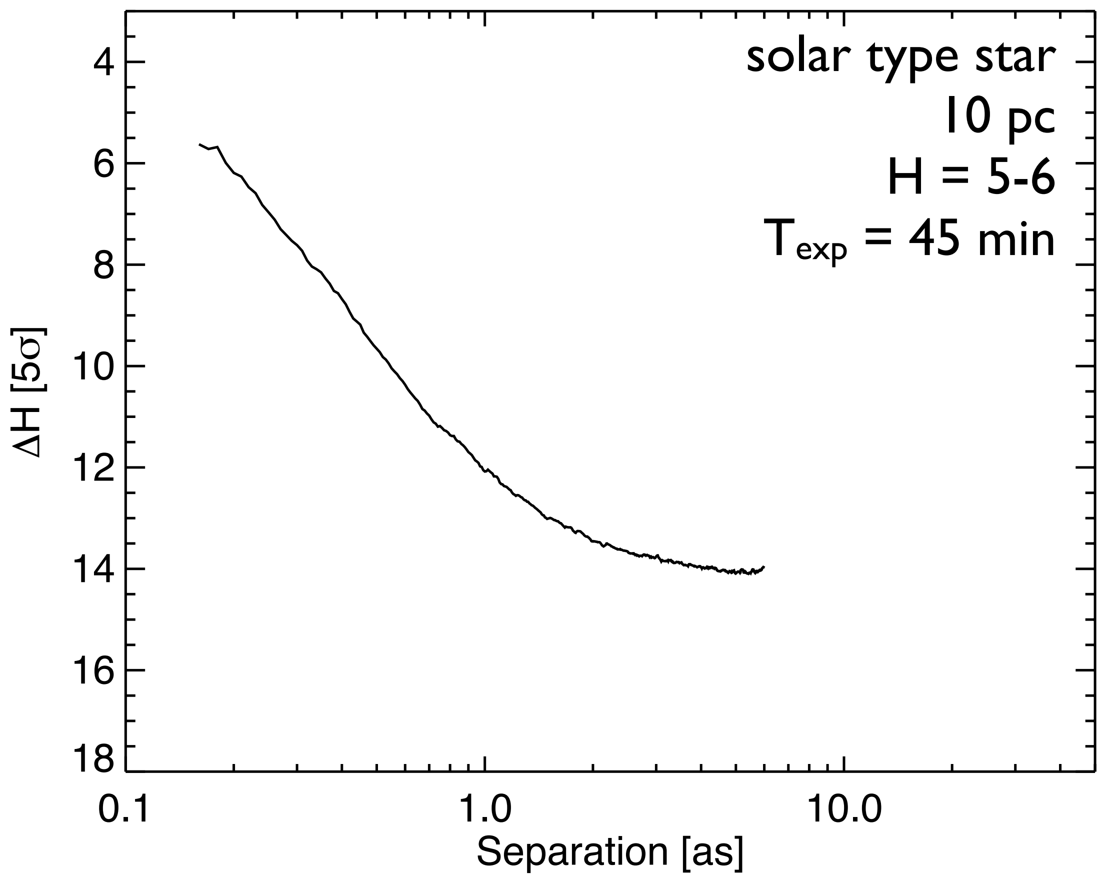
Barman et al. (2011); Konopacky et al. (2012); ...

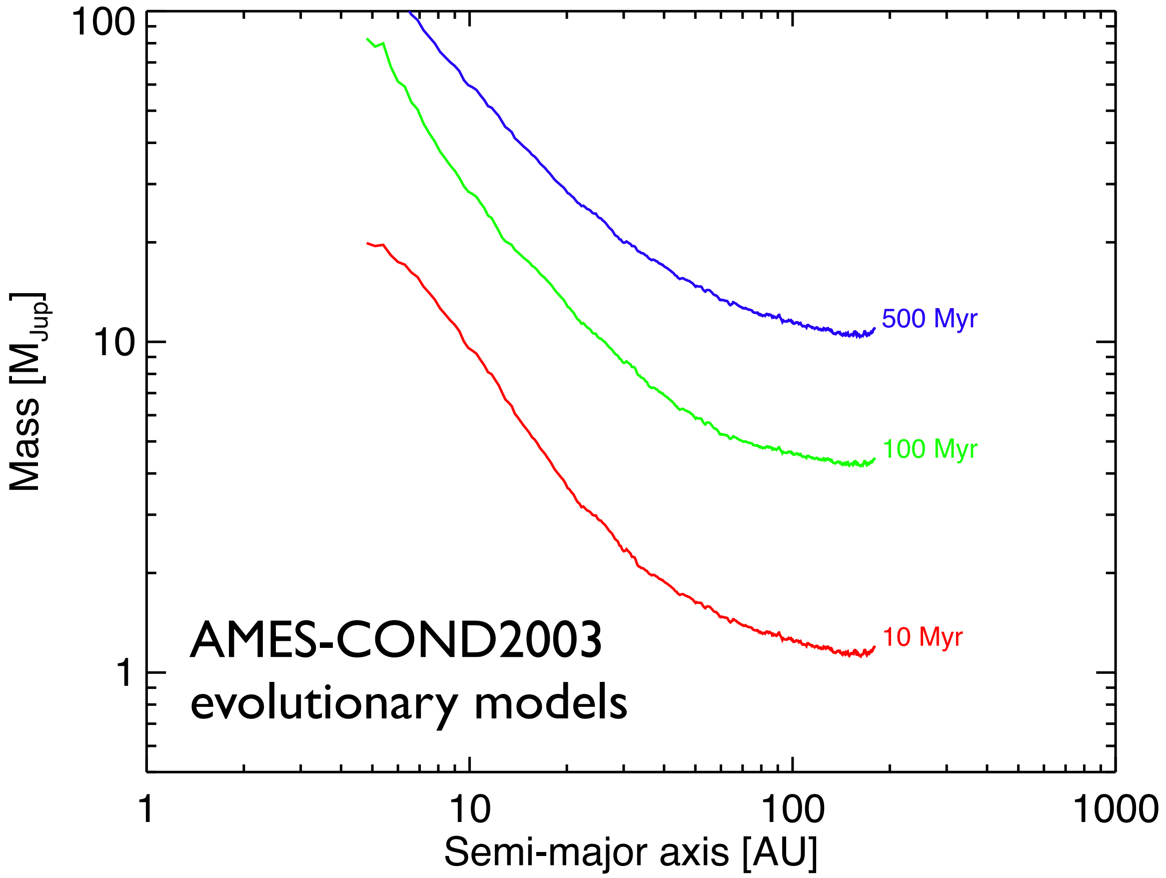
Spectral + angular differiential imaging



Target selection

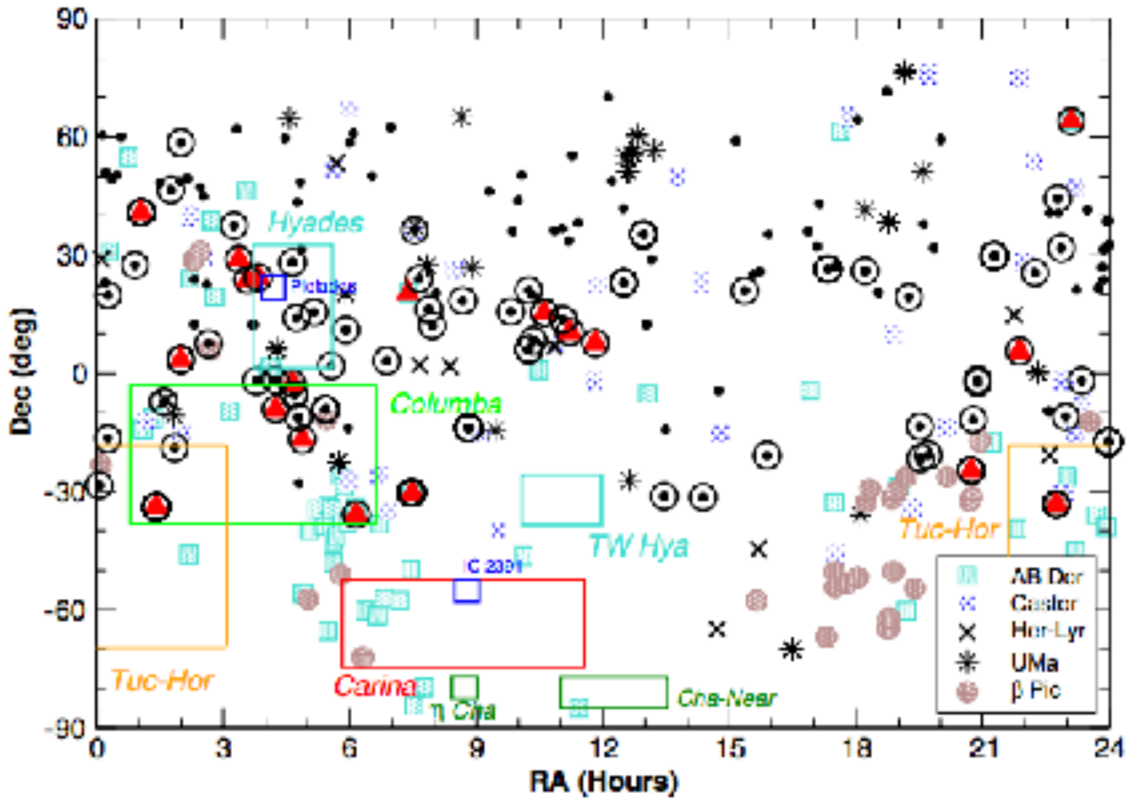
- high-angular resolution + high-contrast + obs. strategy + data analysis
  ➙ increased sensitivity at small separation (0.1"-0.2")
- what about physical units: semi-major axis [AU] and mass [MJup]?
  ➙ significant role of **target selection**



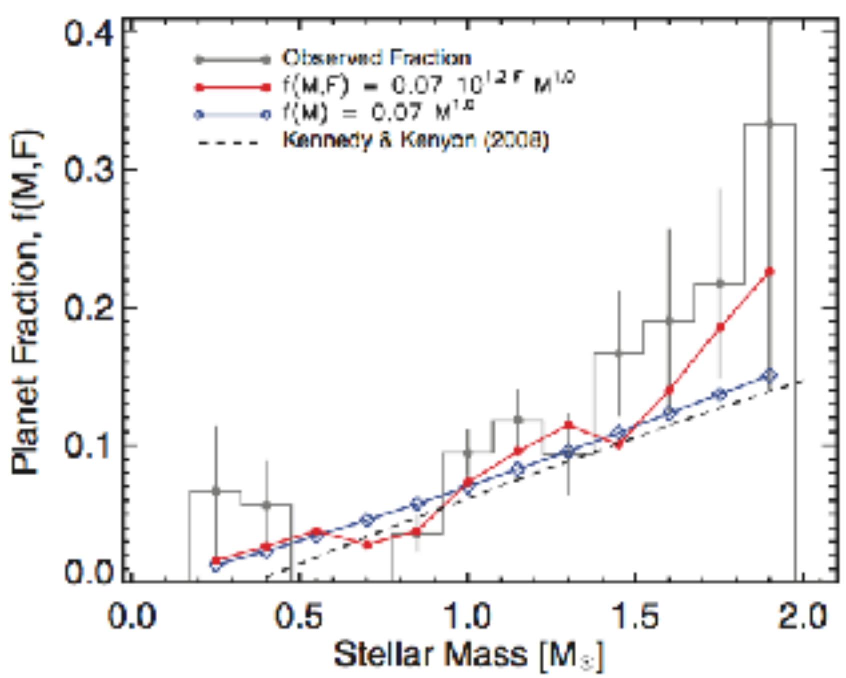


Target selection

- several criteria for target selection
  - **distance** ➙ closer is better
    - 0.1" = 10 AU @ 100 pc
  - **age** ➙ younger is better
    - nearby young associations and moving groups identified since the 1990s
    - ~300 known young (<300 Myr) nearby (<100 pc) stars
  - **stellar mass** ➙ more massive is better??
    - indications of stellar mass / planet mass correlation (e.g. Johnson et al. 2010)
  - **IR excess** ➙ presence of disk



Shkolnik et al. (2012)



Johnson et al. (2010)

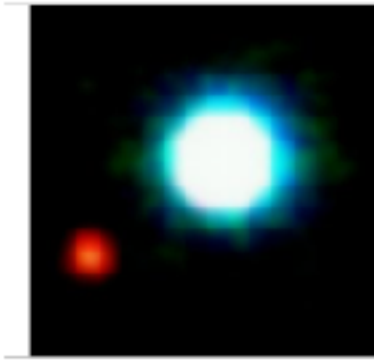
Direct imaging surveys

Census of all published direct imaging surveys:

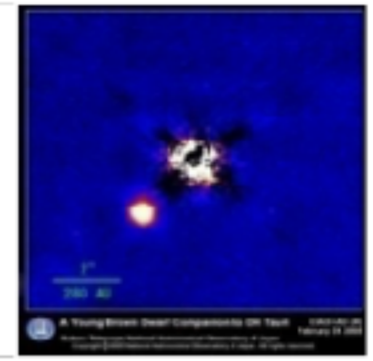
Reference	Telescope	Instr.	Mode	Filter	FoV ($''\times''$)	#	SpT	Age (Myr)
Chauvin et al. 2003	ESO3.6m	ADONIS	Cor-I	H, K	13×13	29	GKM	$\lesssim 50$
Neuhäuser et al. 2003	NTT	Sharp	Sat-I	K	11×11	23	AFGKM	$\lesssim 50$
	NTT	Sofi	Sat-I	H	13×13	10	AFGKM	$\lesssim 50$
Lowrance et al. 2005	HST	NICMOS	Cor-I	H	19×19	45	AFGKM	$10 - 600$
Masciadri et al. 2005	VLT	NaCo	Sat-I	H, K	14×14	28	KM	$\lesssim 200$
Biller et al. 2007	VLT	NaCo	SDI	H	5×5	45	GKM	$\lesssim 300$
	MMT		SDI	H	5×5	-	-	-
Kasper et al. 2007	VLT	NaCo	Sat-I	L'	28×28	22	GKM	$\lesssim 50$
Lafrenière et al. 2007	Gemini-N	NIRI	ADI	H	22×22	85		10-5000
Apai et al. 2008[a]	VLT	NaCo	SDI	H	3×3	8	FG	12-500
Chauvin et al. 2010	VLT	NaCo	Cor-I	H, K	28×28	88	BAFGKM	$\lesssim 100$
Heinze et al. 2010ab	MMT	Clio	ADI	L', M	15.5×12.4	54	FGK	100-5000
Janson et al. 2011	Gemini-N	NIRI	ADI	H, K	22×22	15	BA	20-700
Vigan et al. 2012	Gemini-N	NIRI	ADI	H, K	22×22	42	AF	10-400
	VLT	NaCo	ADI	H, K	14×14	-	-	-
Delorme et al. 2012	VLT	NaCo	ADI	L'	28×28	16	M	$\lesssim 200$
Rameau et al. 2013c	VLT	NaCo	ADI	L'	28×28	59	AF	$\lesssim 200$
Yamamoto et al. 2013	Subaru	HiCIAO	ADI	H, K	20×20	20	FG	125 ± 8
Biller et al. 2013	Gemini-S	NICI	Cor-ASDI	H	18×18	80	BAFGKM	$\lesssim 200$
Brandt et al. 2013[b]	Subaru	HiCIAO	ADI	H	20×20	63	AFGKM	$\lesssim 500$
Nielsen et al. 2013	Gemini-S	NICI	Cor-ASDI	H	18×18	70	BA	50-500
Wahhaj et al. 2013[a]	Gemini-S	NICI	Cor-ASDI	H	18×18	57	AFGKM	~ 100
Janson et al. 2013[a]	Subaru	HiCIAO	ADI	H	20×20	50	AFGKM	$\lesssim 1000$
Chauvin et al. 2014	VLT	NaCo	ADI	H	14 x 14	80	FGK	< 300

Family portrait of directly imaged companions

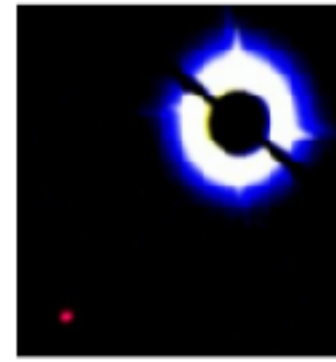
2M1207



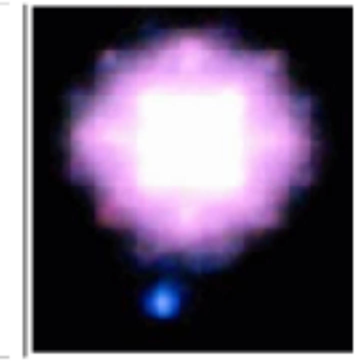
DH Tau



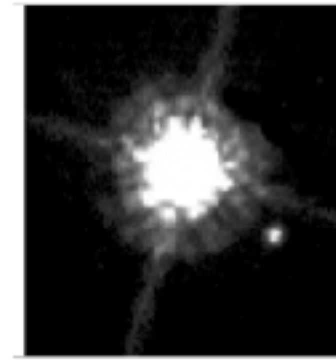
AB Pic



SCR1845



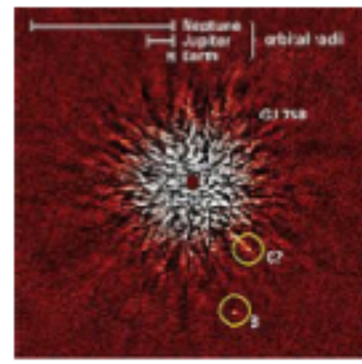
CHXR 73



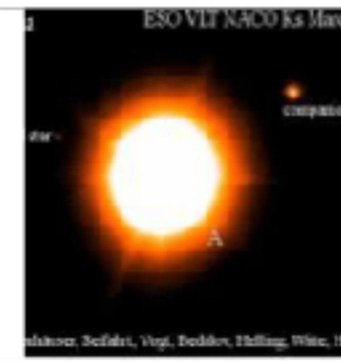
Wide orbit

- low mass KM stars
- q = 2-20% or a > 200 AU

GJ 758



CT Cha



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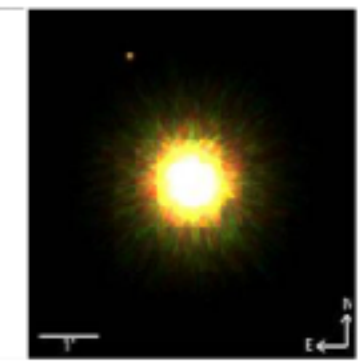
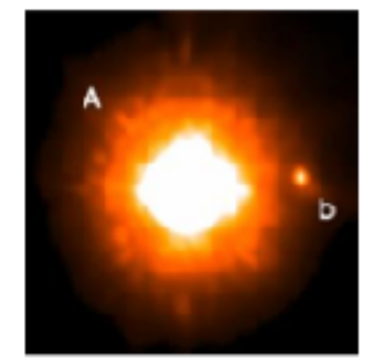


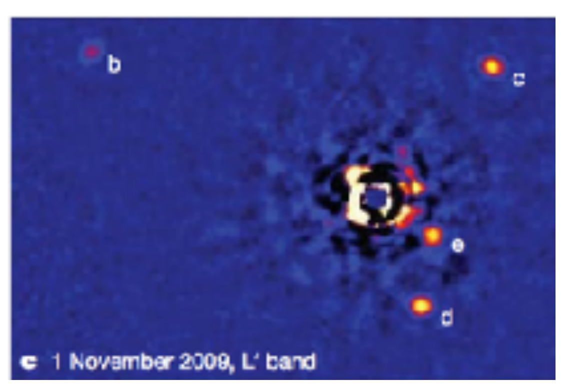
GQ Lup



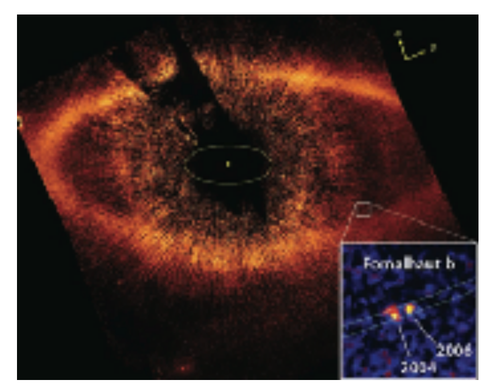
Close(r) orbit

- A4V-A5V massive primaries
- q = 0.5%; a < 120 AU
- disk signatures

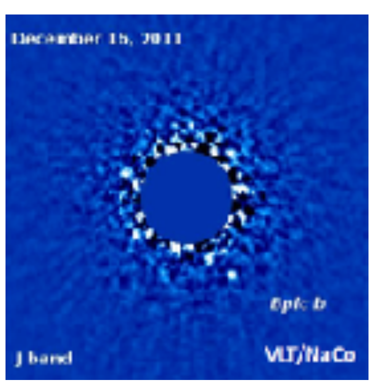
HR8799



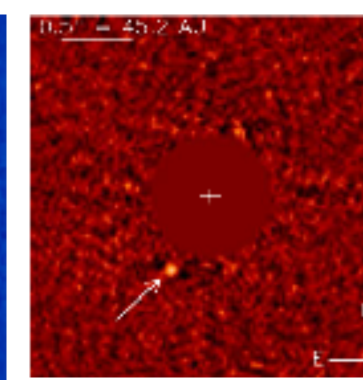
Fomalhaut



Beta Pic



HD95086



Last 10 years: major progress in 3 areas

1/ Physics of Giant Planets

Photometry & Spectroscopy

Atmosphere & physical properties

2/ Architecture & Stability

Astrometry & Disk/Planet relative position

Orbits, dynamical interactions, resonances & long-term evolution

3/ Occurrence & Formation

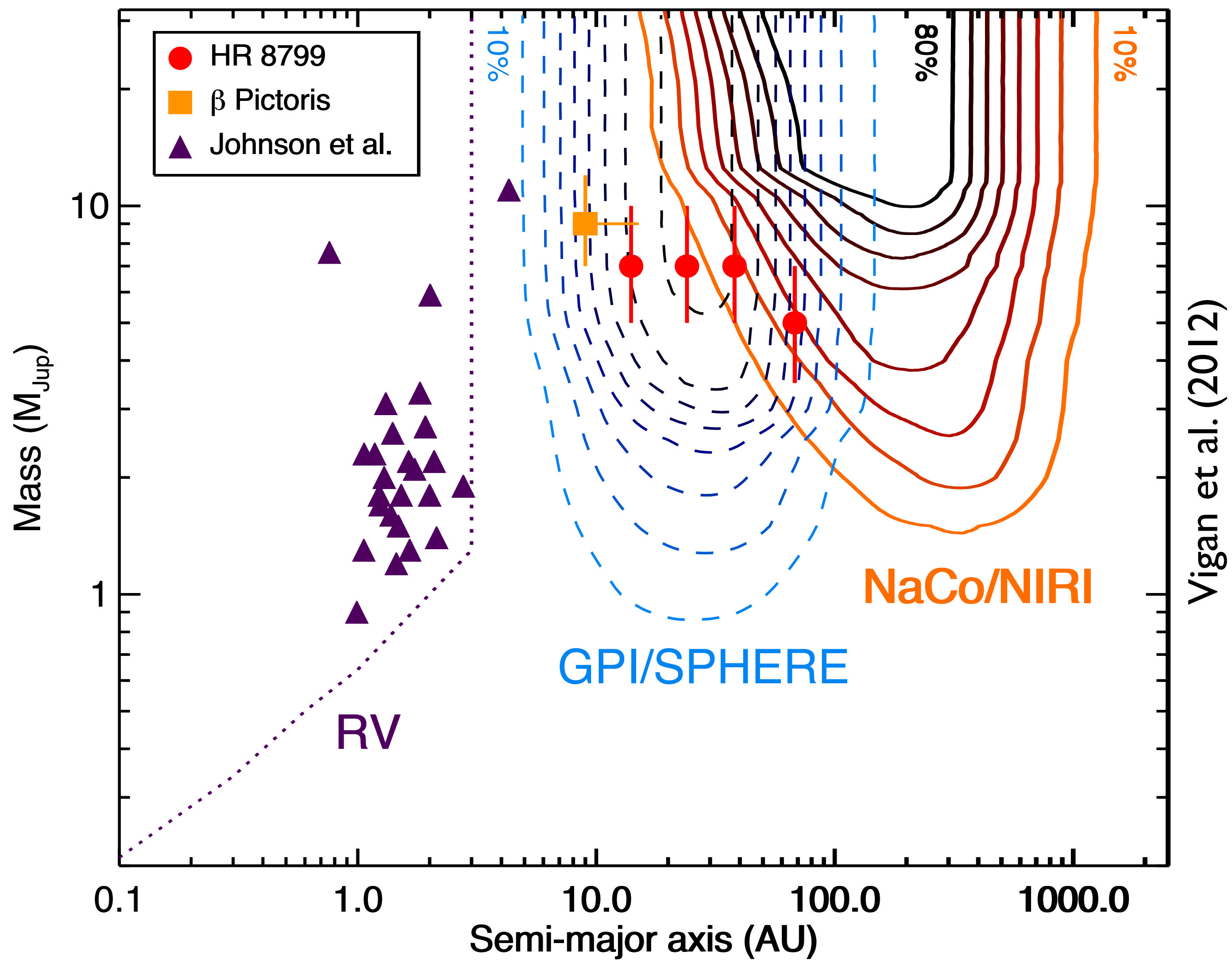
Statistical properties (occurrence, planetary host dependency, disk properties)

Formation Theories: CA, GI or CF

New generation of instruments

- What do we want?
  - get **closer in separation**
  - reach **higher contrast**
  - get spectral information

- What was missing?
  - **high-order AO** correction at fast rate
  - efficient coronagraphs with **small IWA**



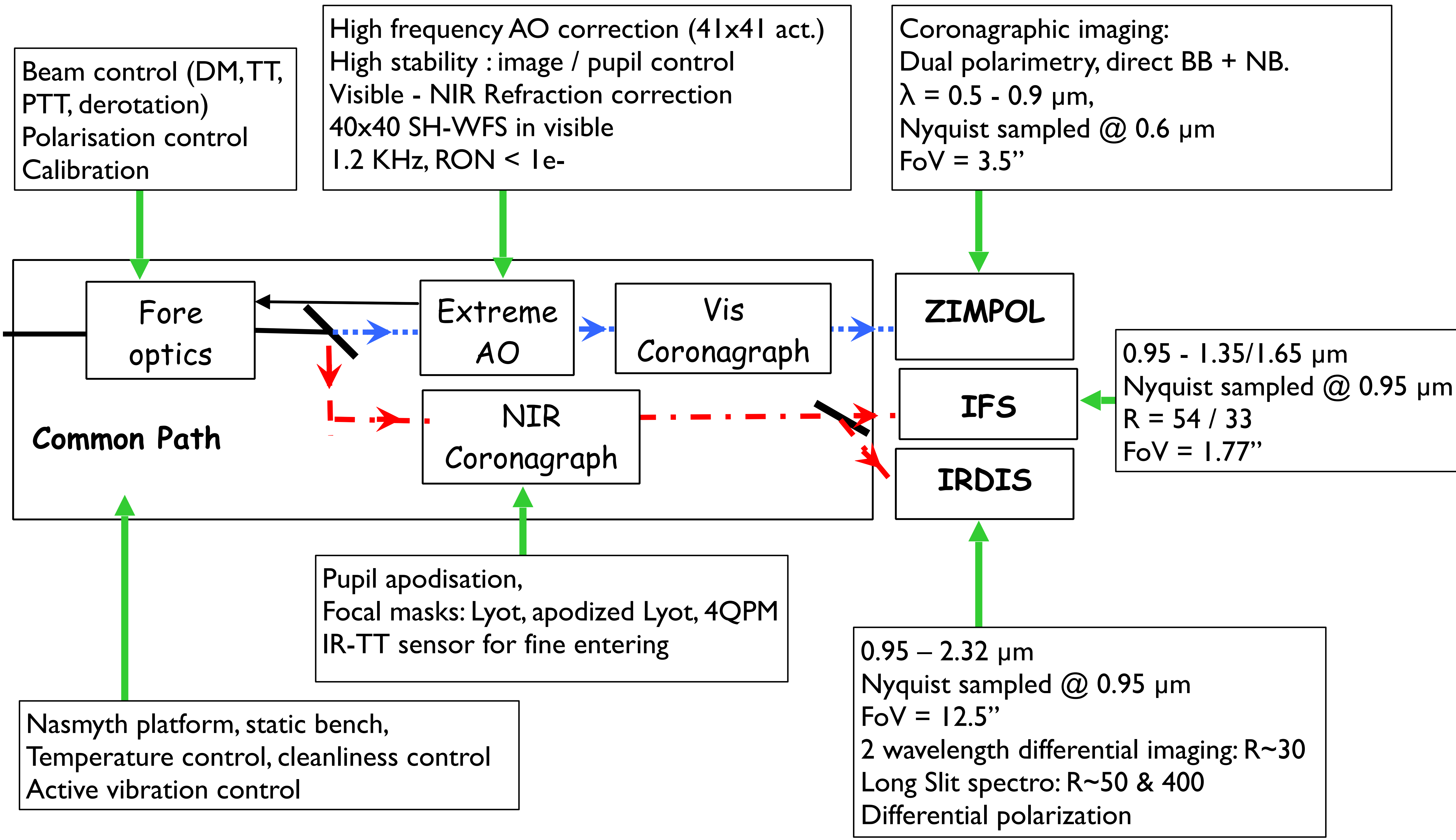
New generation of dedicated instruments

Two new instruments

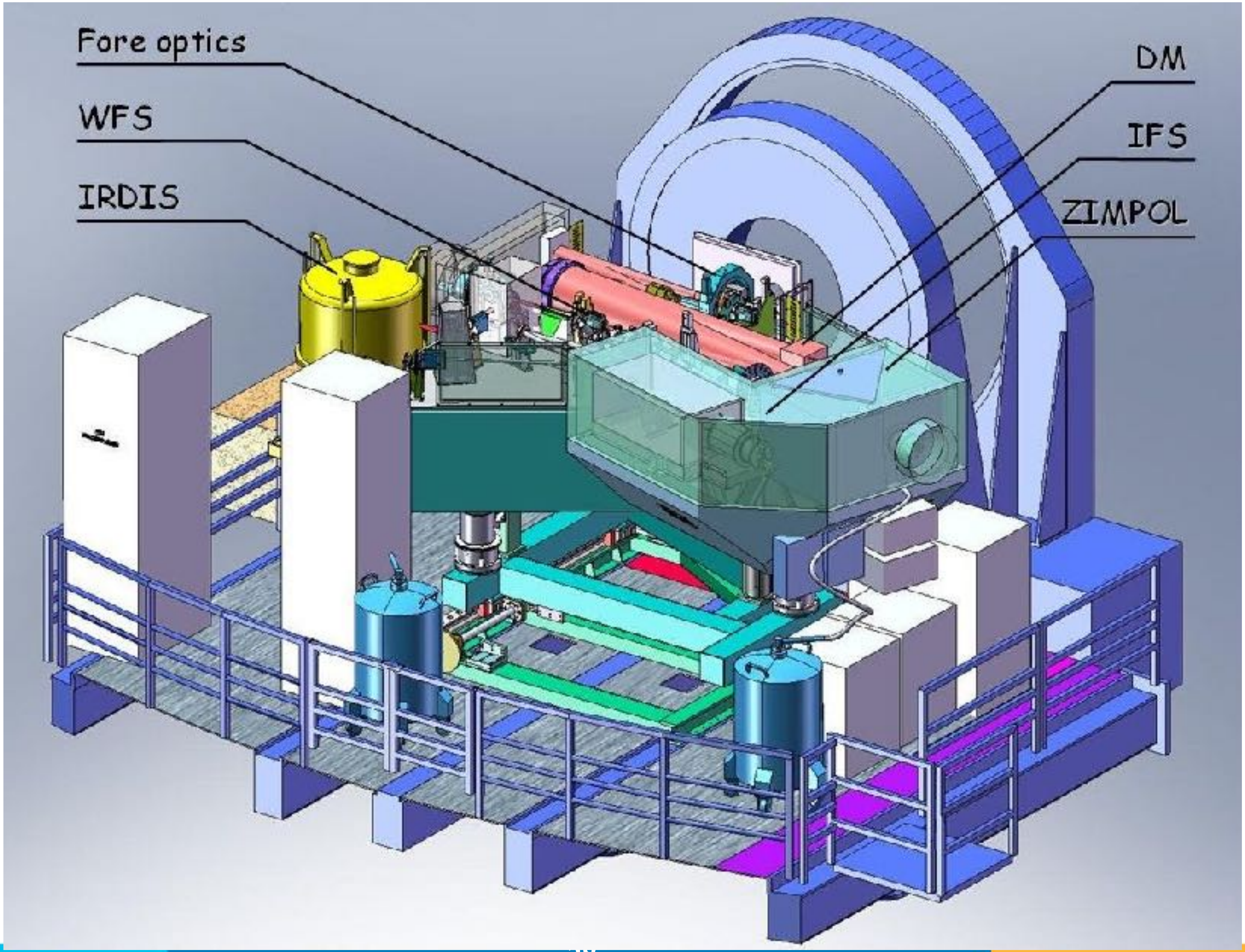
Gemini Planet Imager - GPI
Gemini South
North-American consortium
PI: Bruce Macintosh

Spectro-Polarimetric High-contrast Exoplanet REsearch
VLT-UT3
European consortium
PI: Jean-Luc Beuzit

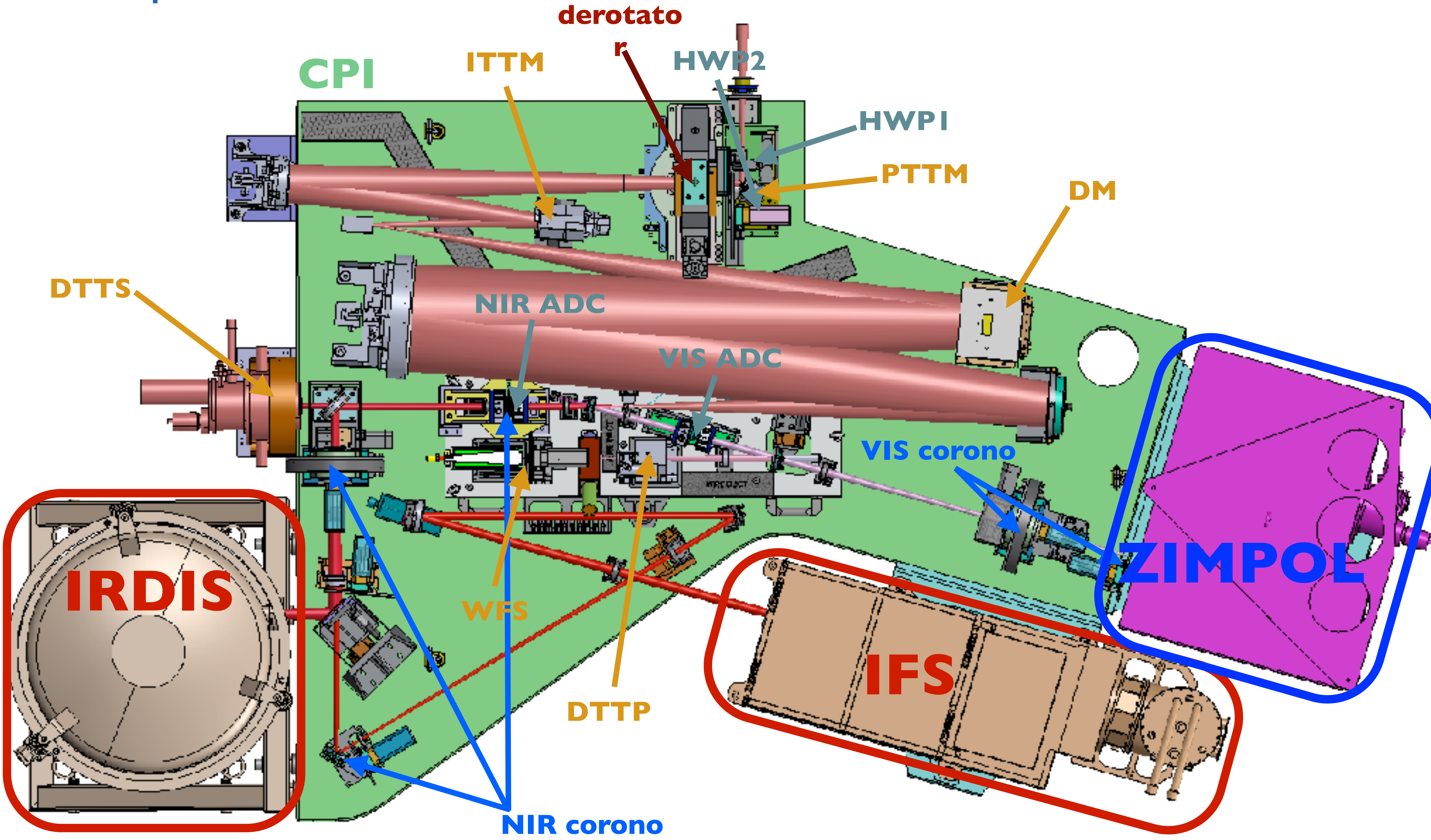
SPHERE concept overview



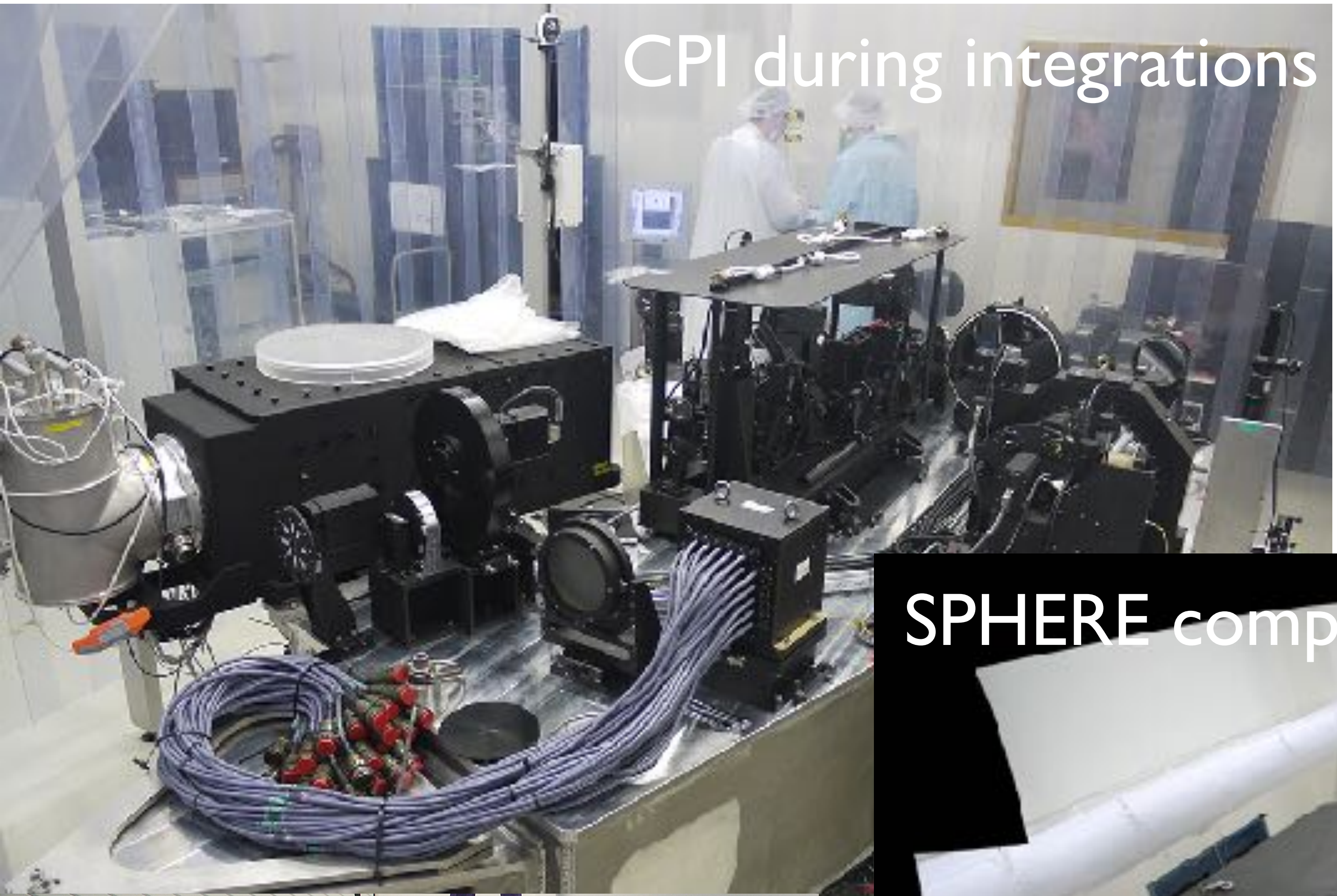
Interface with the telescope



Implementation

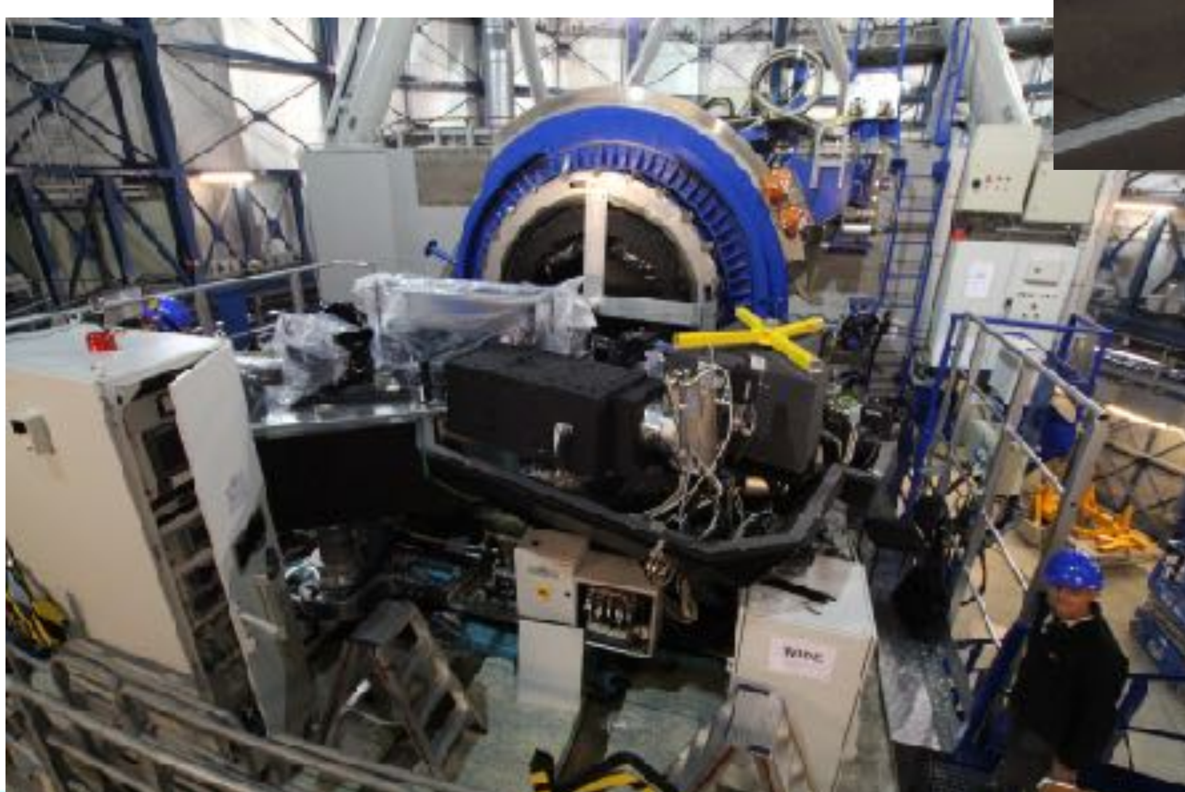


Integrations in Grenoble

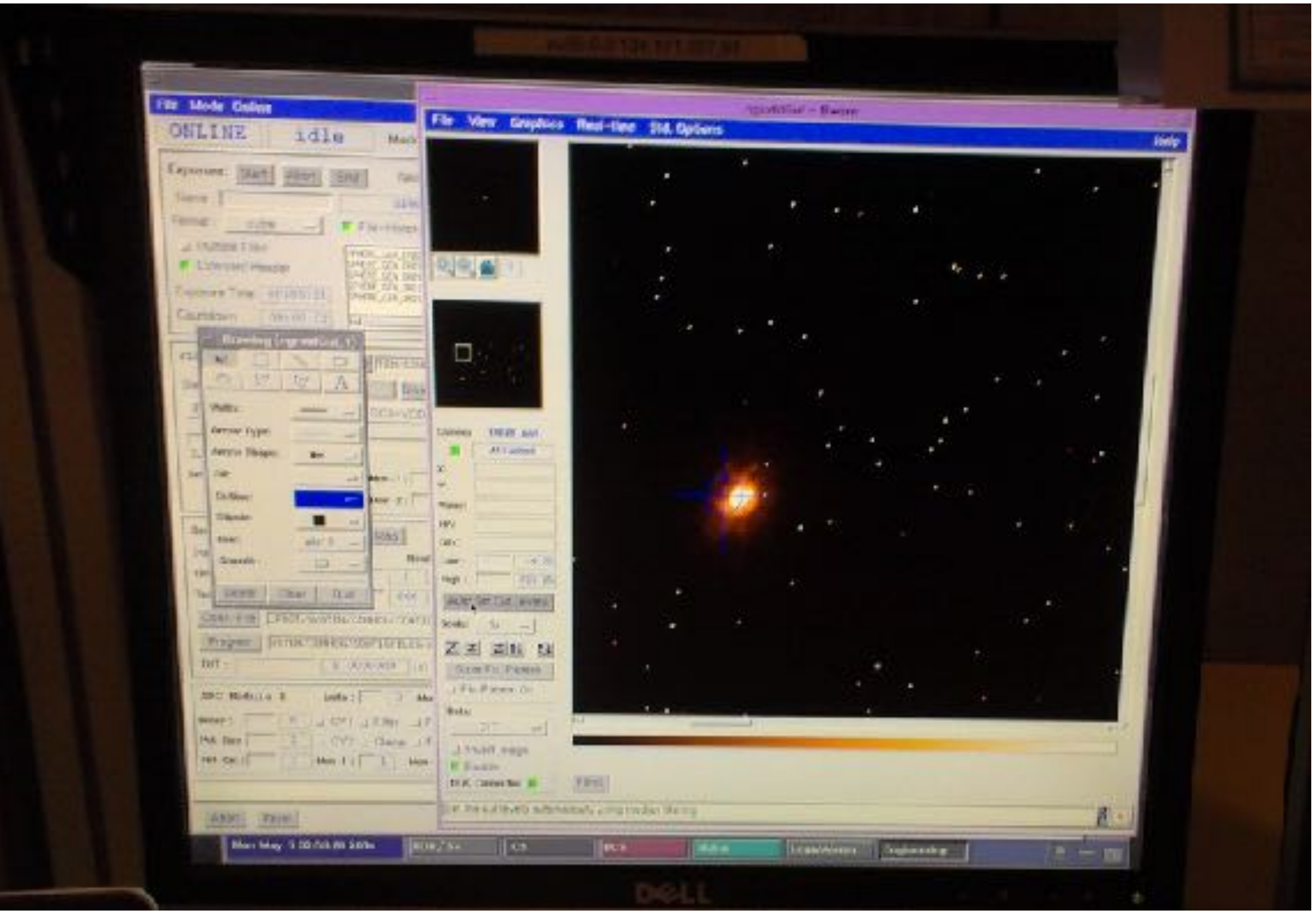


Reintegration in Paranal

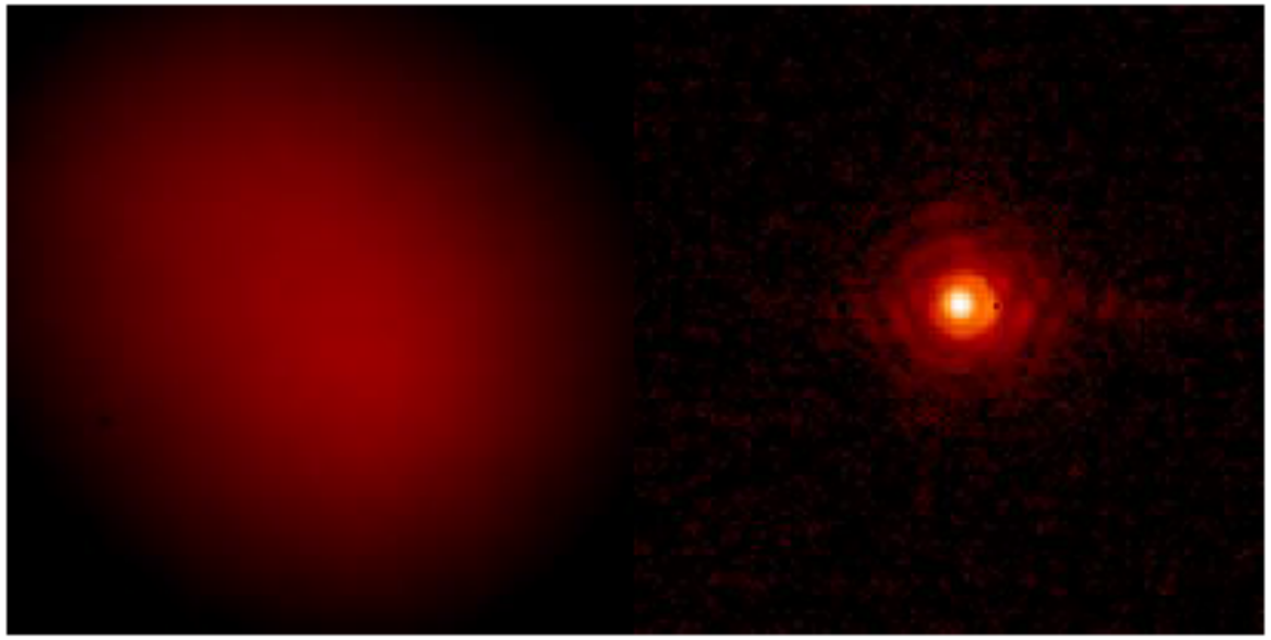
Transport and installation on UT3



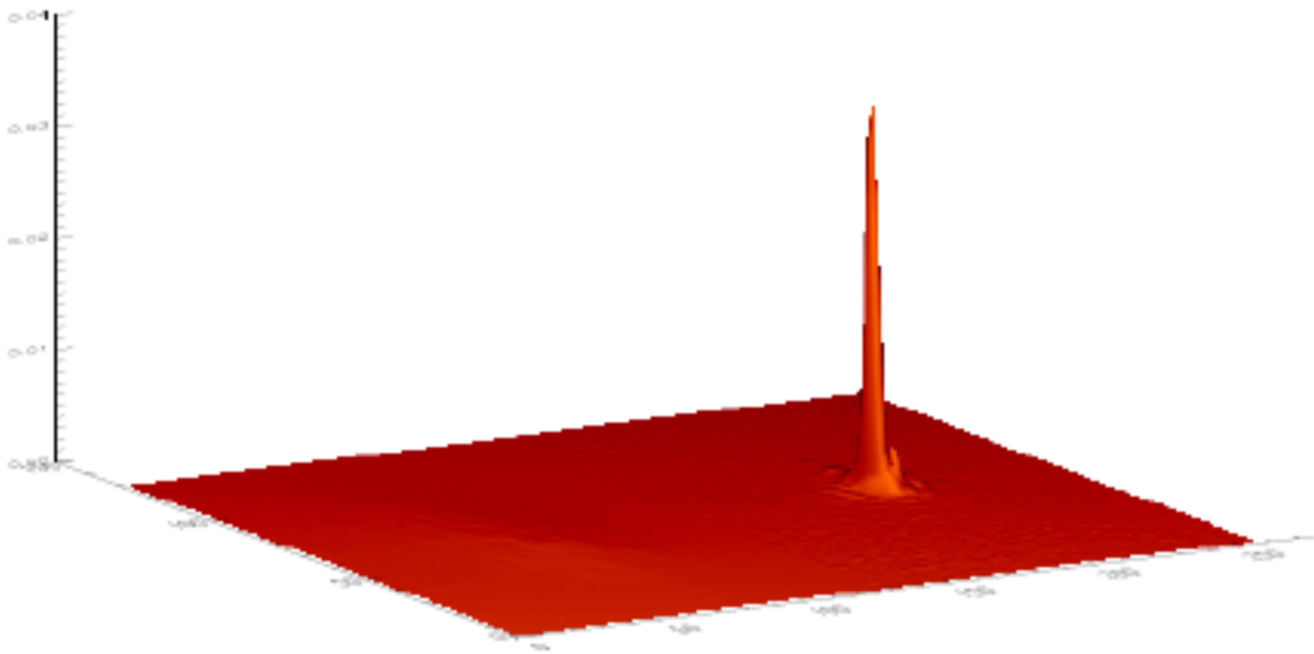
SPHERE first light (May 6th, 2014)



First close-loop (May 6th, 2014)



Open loop Closed loop



First SPHERE Closed loop image

(06/05/2014, 06:12 UT)

Mag = 7.5 - Seeing ~ 1.3''

EMCCD gain = 200 / AO loop gain = 0.4

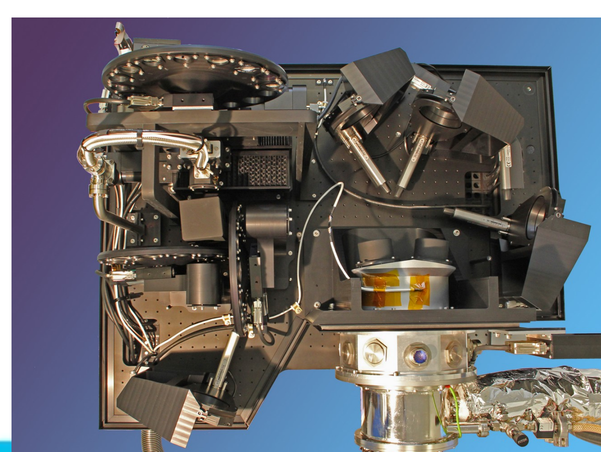
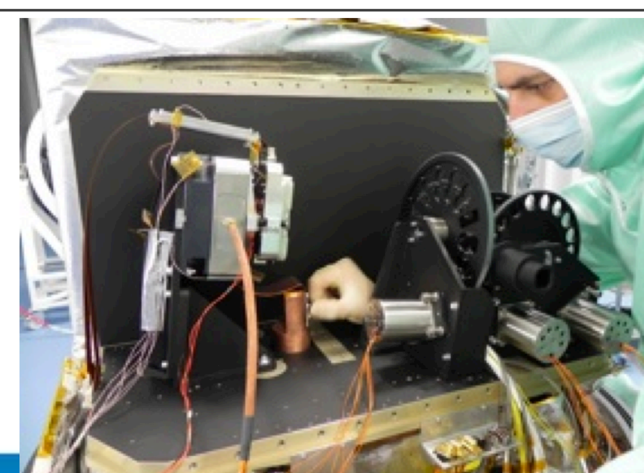
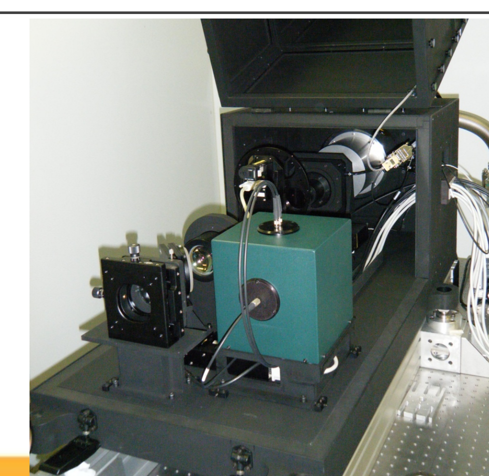
WFS Spatial filter = large

IRDIS filter : H2H3

SR ~ 62 %

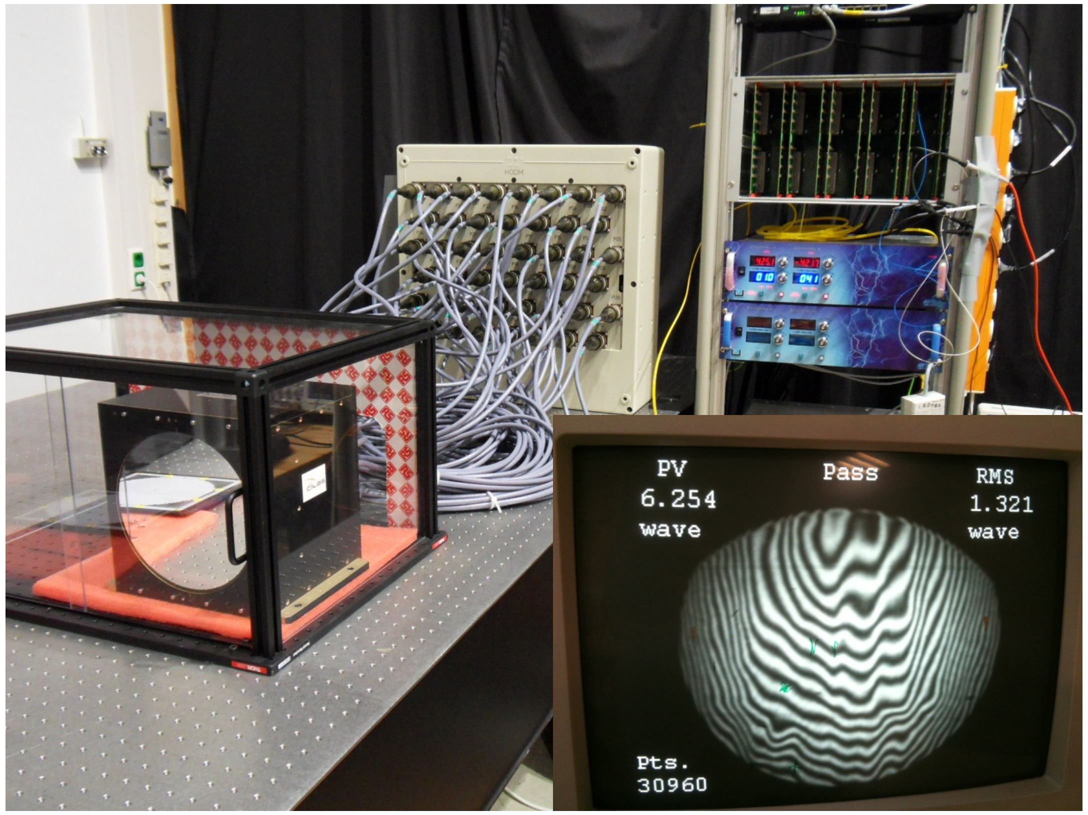
Scientific sub-systems

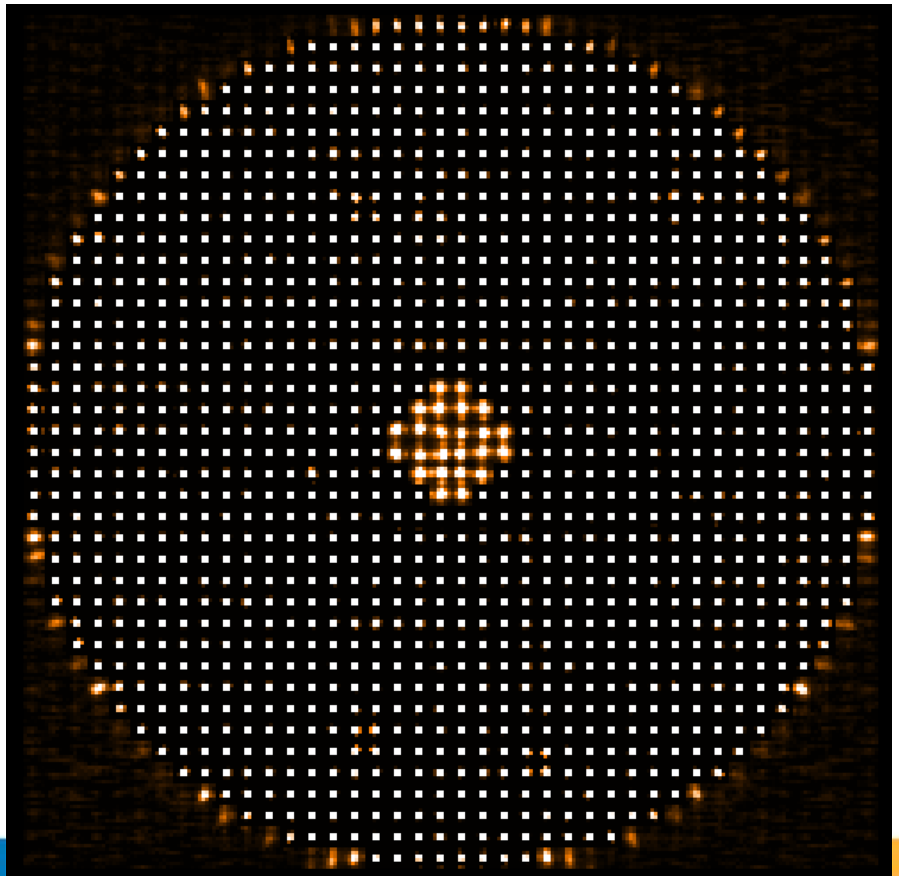
	ZIMPOL	IRDIS	IFS
FoV	3.5"	11"	1.77"
Spectral range	0.5-0.9 µm	0.95-2.30 µm	0.95-1.35 / 1.65 µm
Spectral information	BB, NB filters	BB, NB filters slit spectro @ R =	R = 50 / 30
Linear polarisation	Simultaneous	Simultaneous (dual-beam)	
Nyquist sampling	@ 0.6 µm	@ 0.95 µm	@ 0.95 µm

SAXO: the adaptive optics system

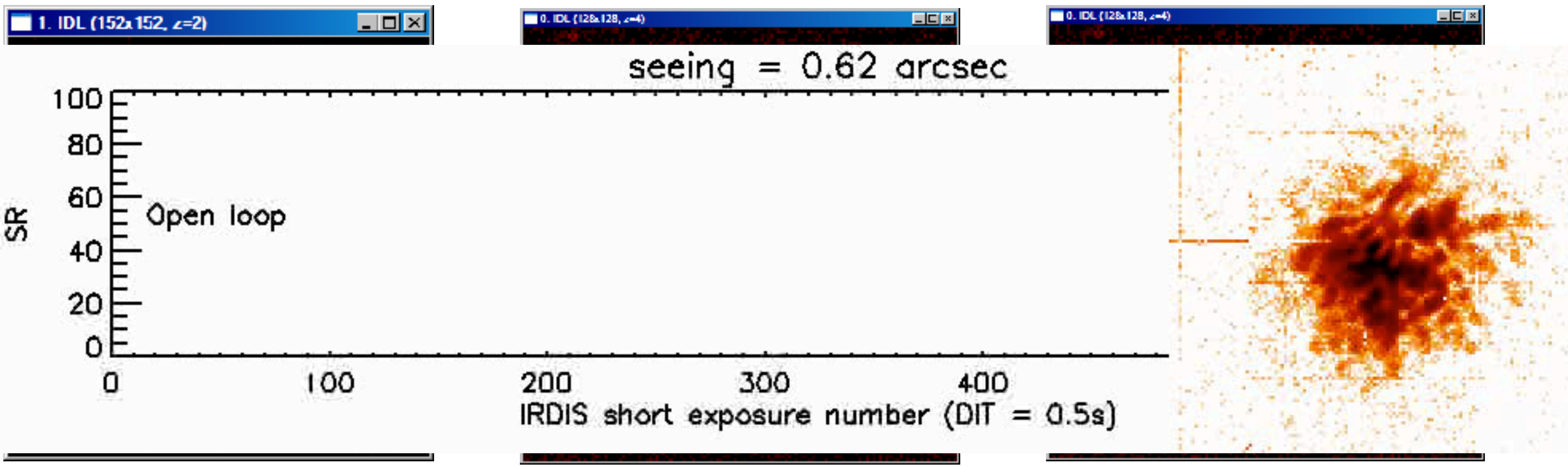
- deformable mirror built by CILAS
- wavefront sensor:
  - spatially filtered SH to reduce aliasing
  - E2V L3CCD detector
- control:
  - developed by ESO/ONERA
  - 1.2 kHz
  - HO loop, DTT loop, PTT loop
  - Kalman filtering
- NCPA calibration with phase diversity

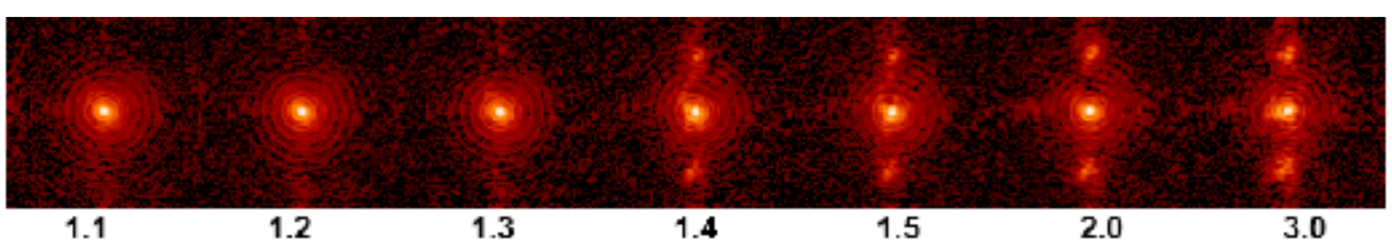




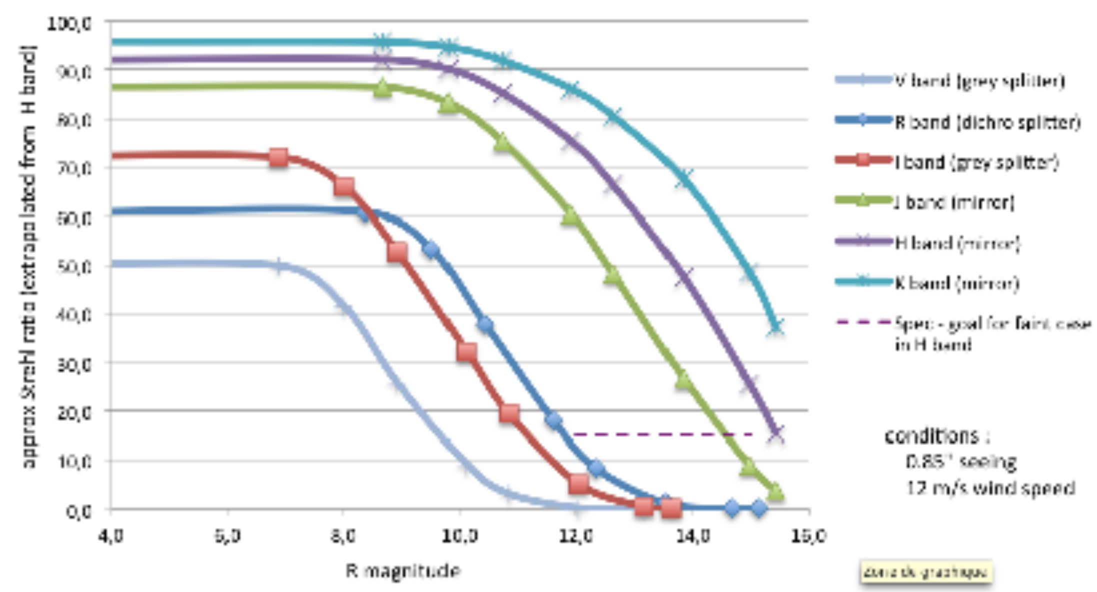
SAXO: the adaptive optics system

Open loop	Closed loop	Closed loop + NCPA
Sr = ~5%	Sr = 85%	Sr = 99%

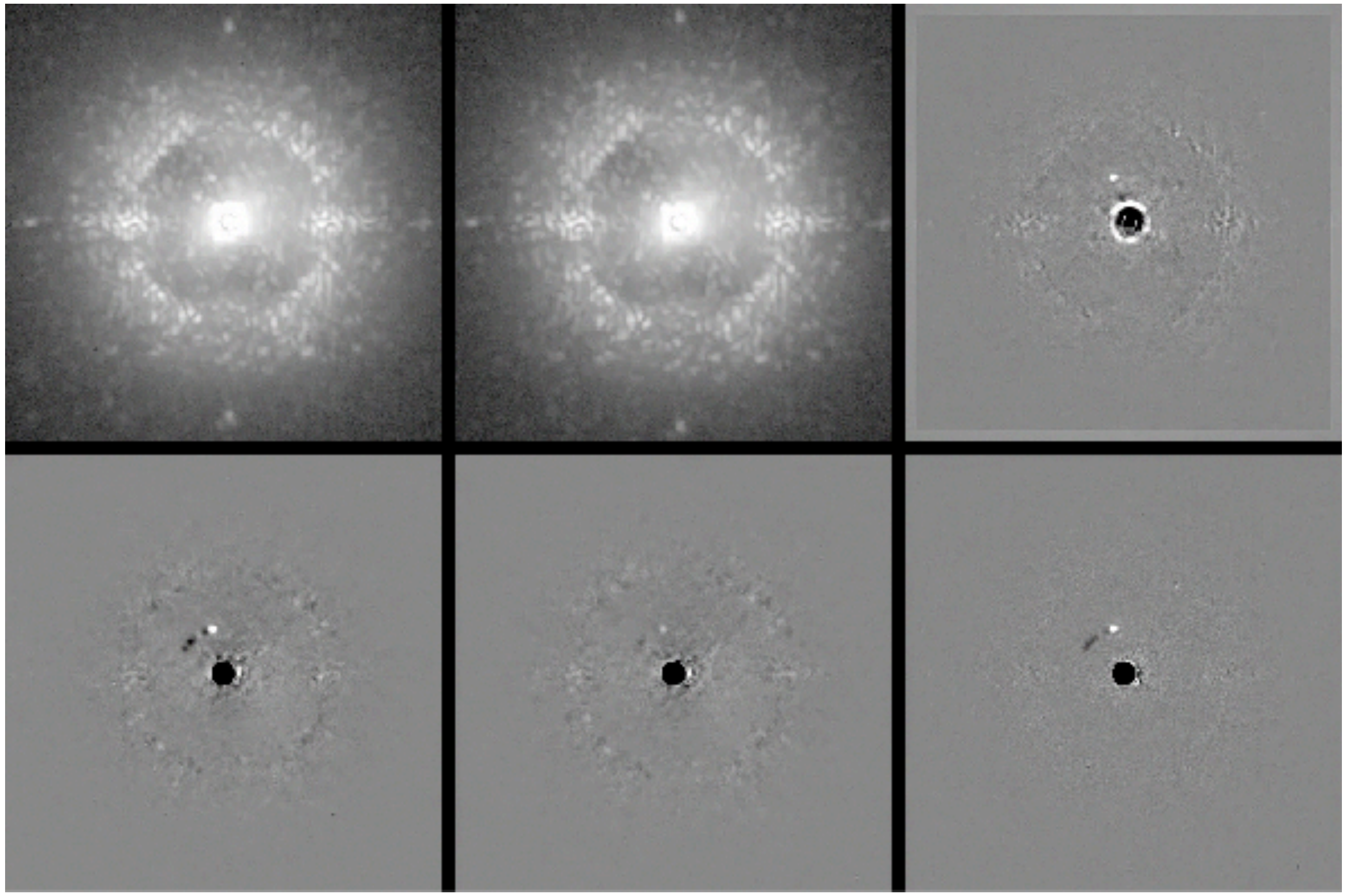


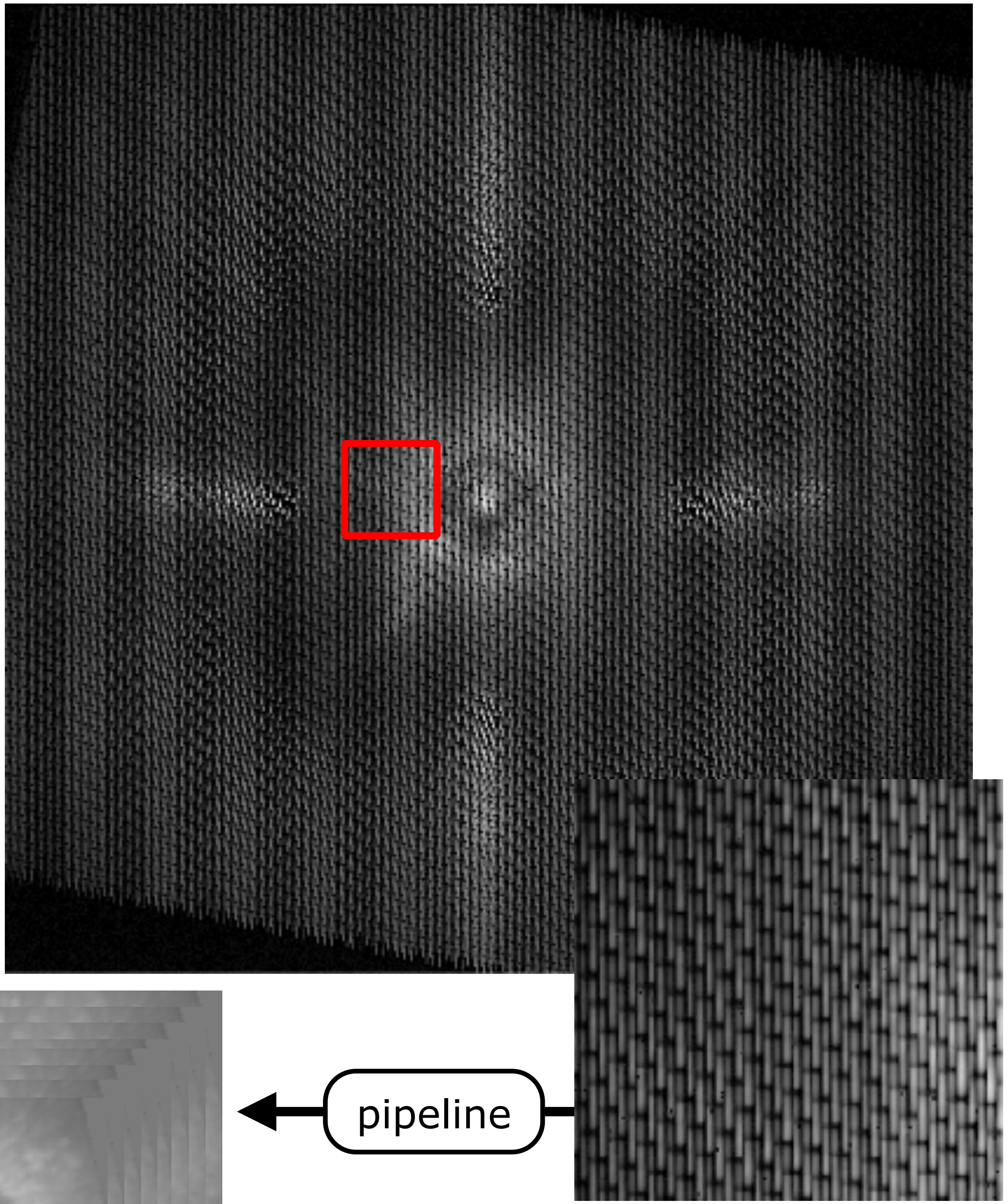


Spatial filtering for anti-aliasing

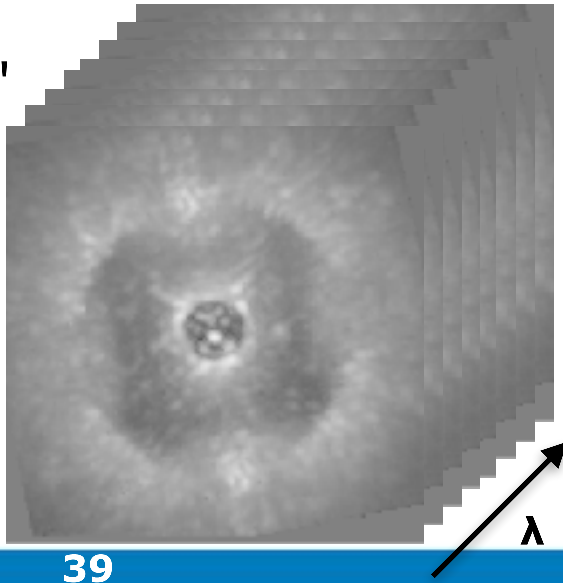


IRDIFS: the planet-hunting mode



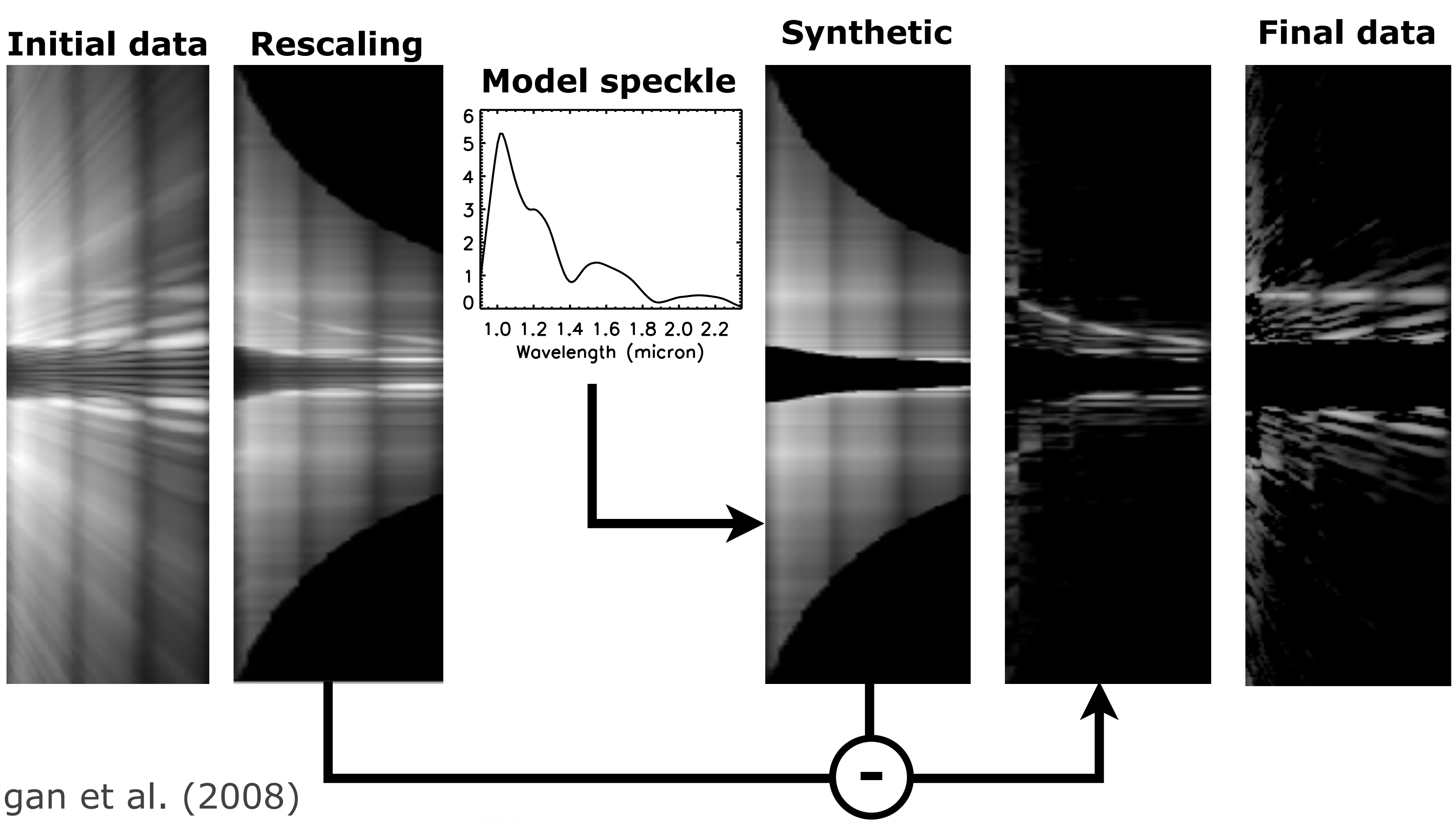


- SPHERE designed to be a **survey instrument** from the start
- implementation of the "near-infrared survey" observing mode
  - IRDIFS: IFS in YJ + IRDIS in H
  - IRDIFS_EXT: IFS in YJH + IRDIS in Ks
- extremely efficient for planet hunting

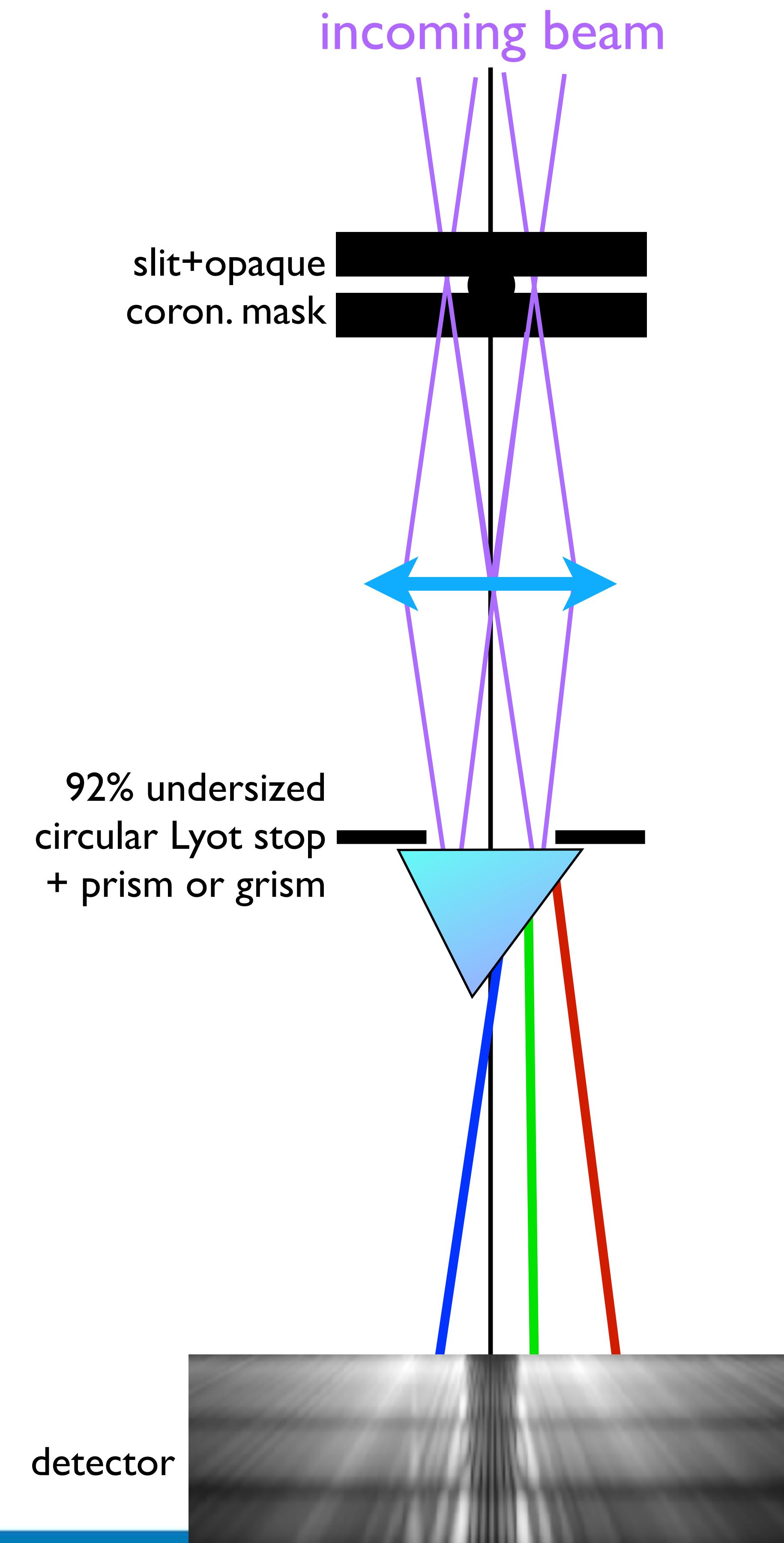


IRDIS long-slit spectroscopy

- Dedicated to characterization of planets detected in DBI
- Two observing modes:
  - Low resolution (LRS) → R=50 over YJHKs
  - Medium resolution (MRS) → **R=350 over YJH**
- Limitations:
  - not optimal Lyot stop
  - field-stabilized observations → no ADI!

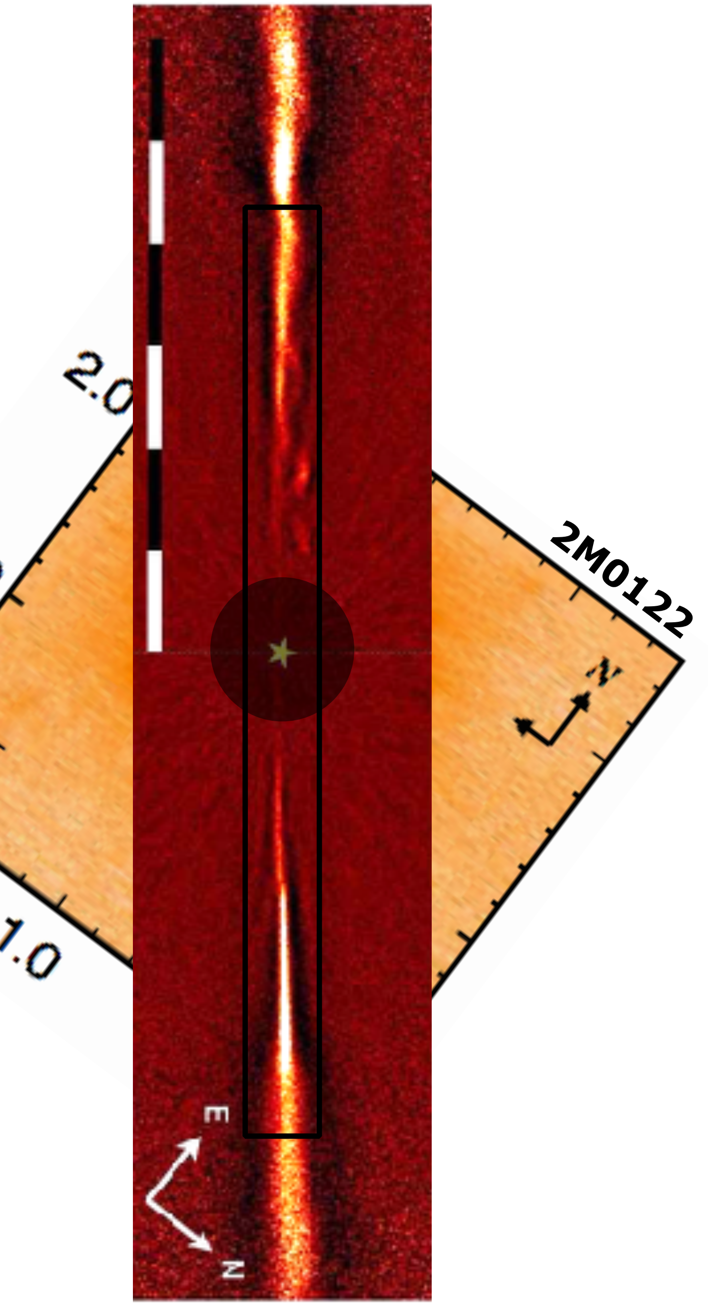


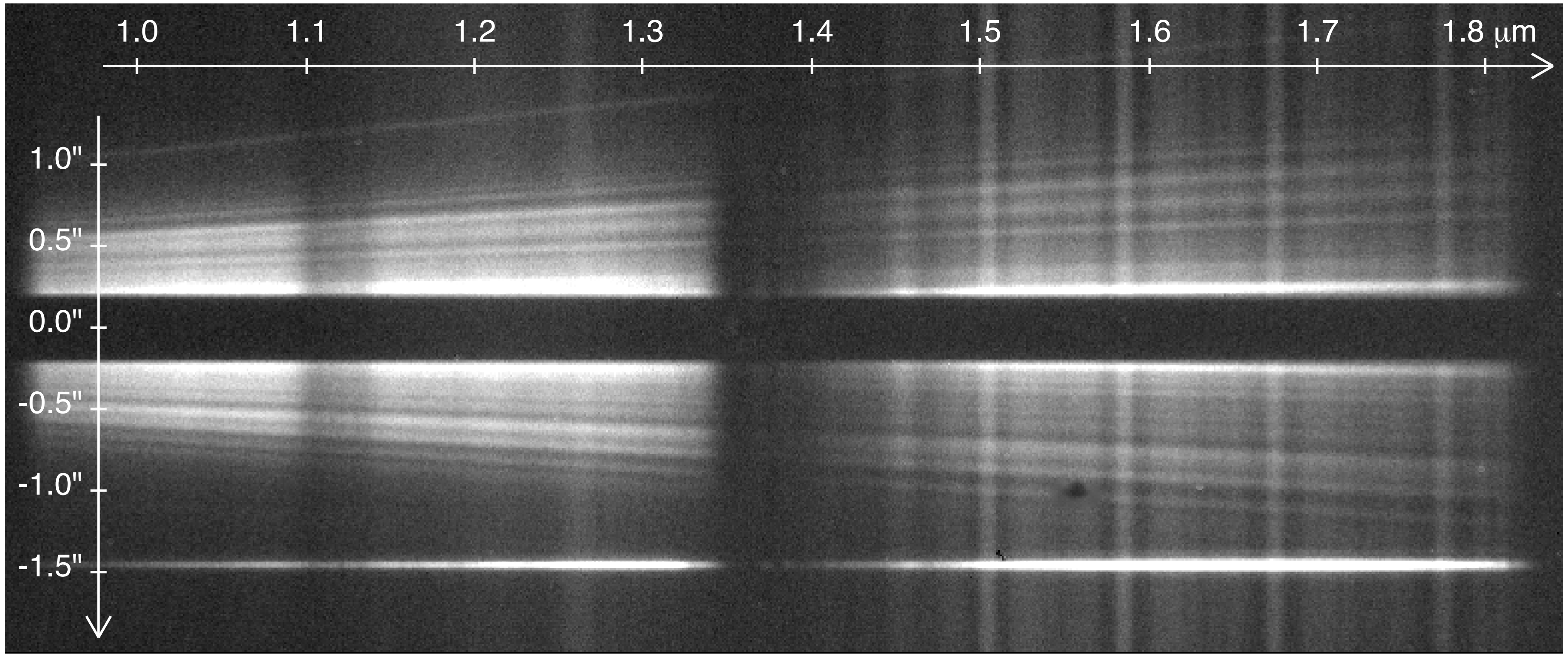
Vigan et al. (2008)



IRDIS long-slit spectroscopy

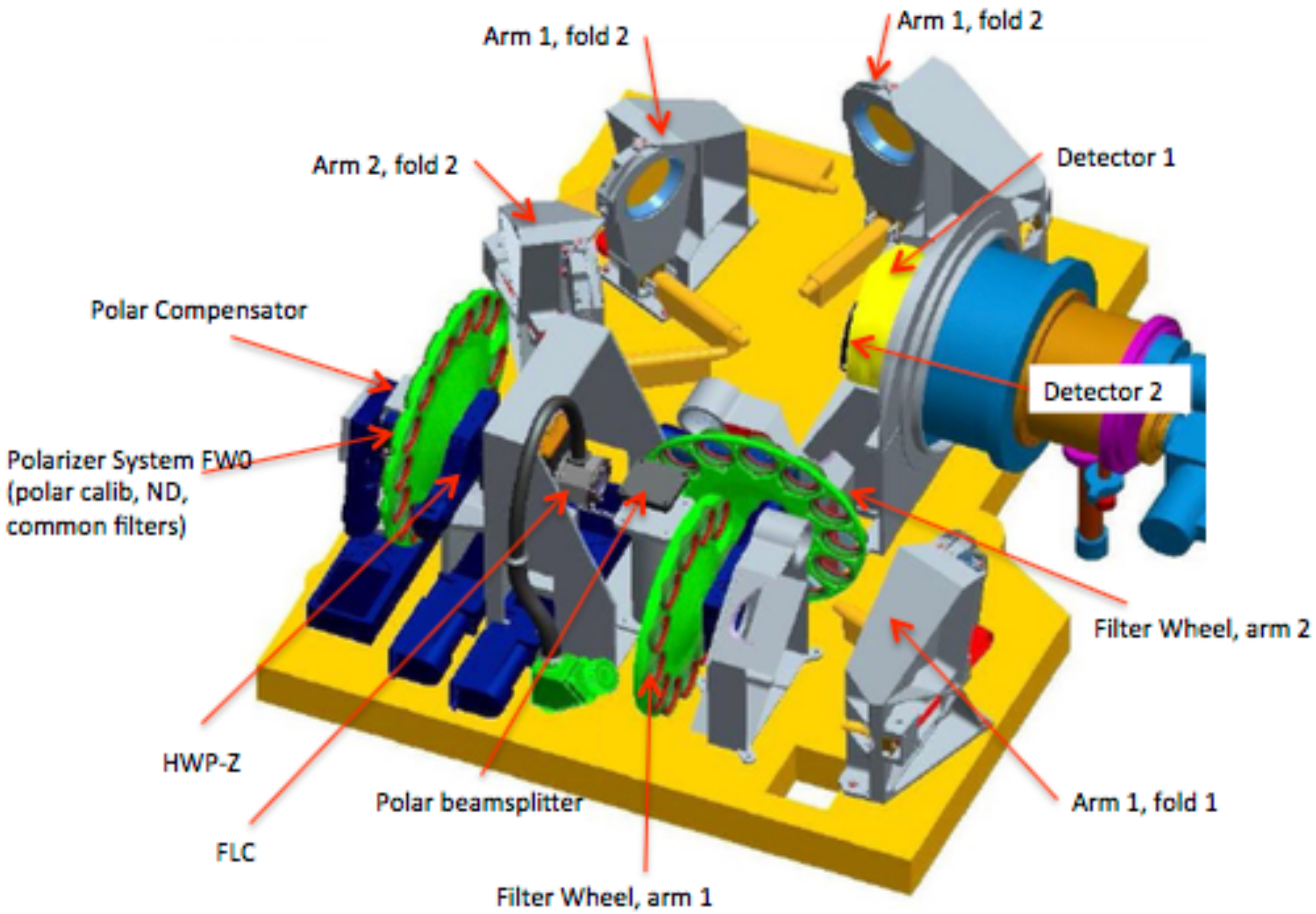
AU Mic

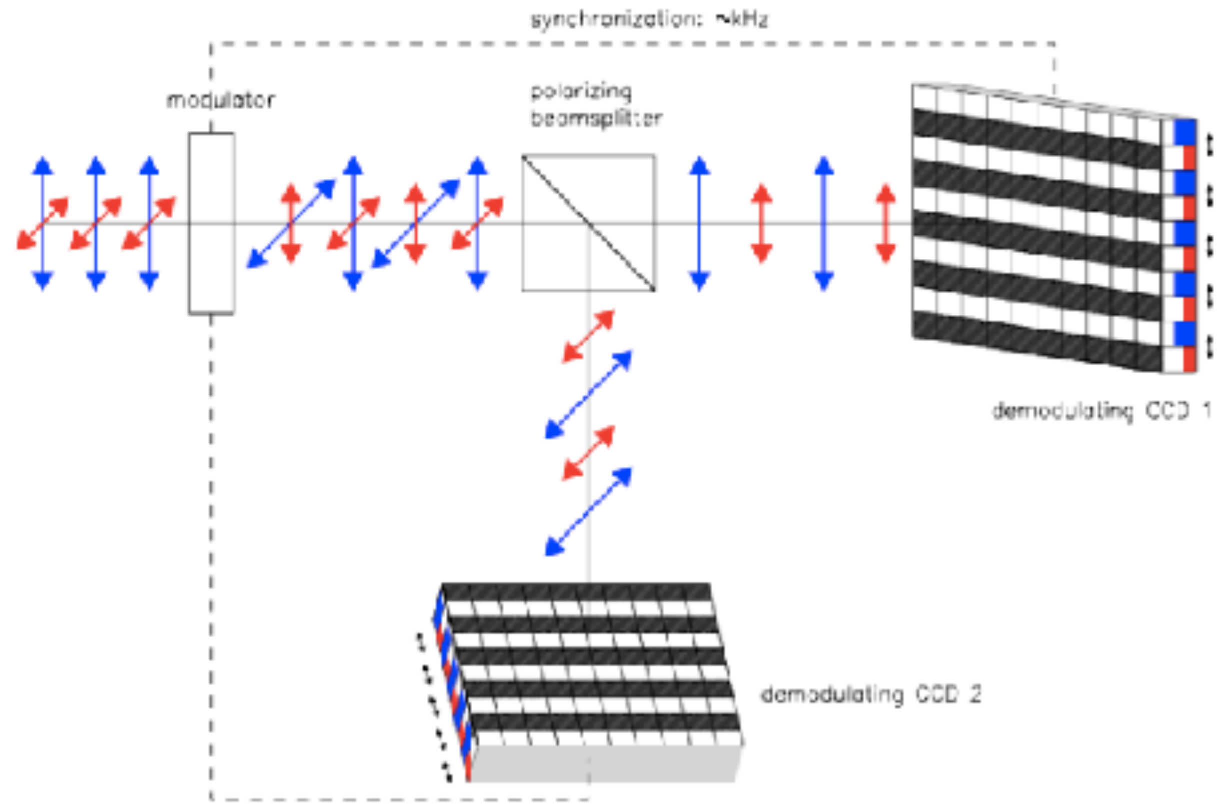




Hinkley et al. (2015)

ZIMPOL: visible imager and polarizer





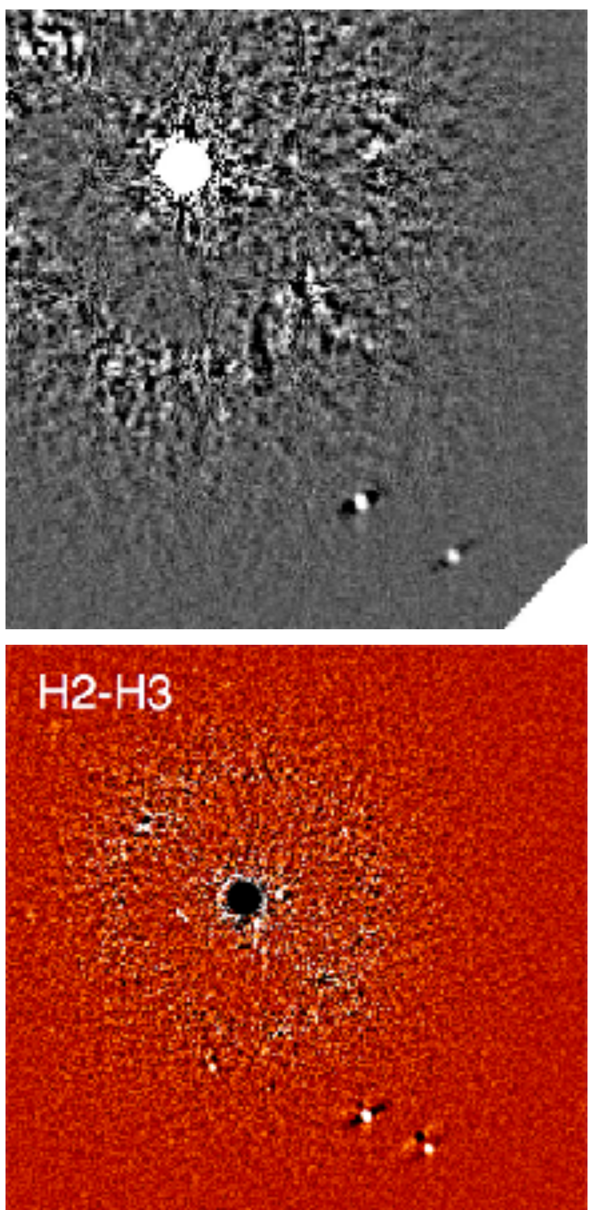
- classical imager with 2 arms in parallel
- efficient dual-polarisation imager:
  - optimized for extremely high-contrast thanks to dedicated CCD
  - modulation at >1 kHz
  - records simultaneously the two polarisation

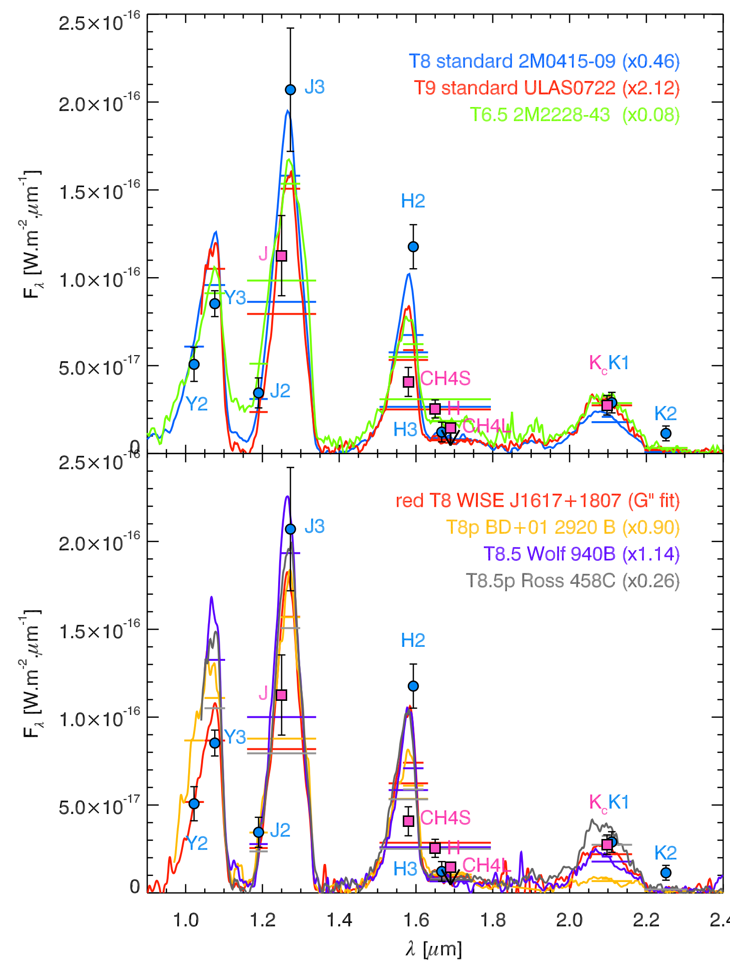
Thalman et al. (2008)

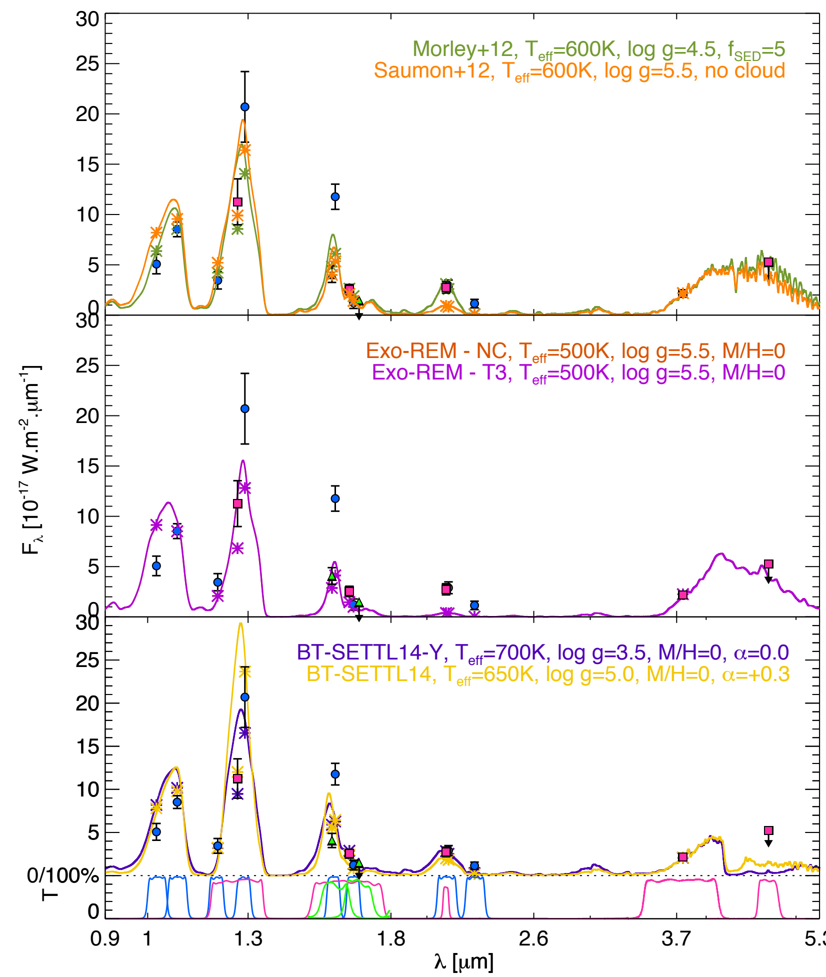
IRDIFS: commissioning results

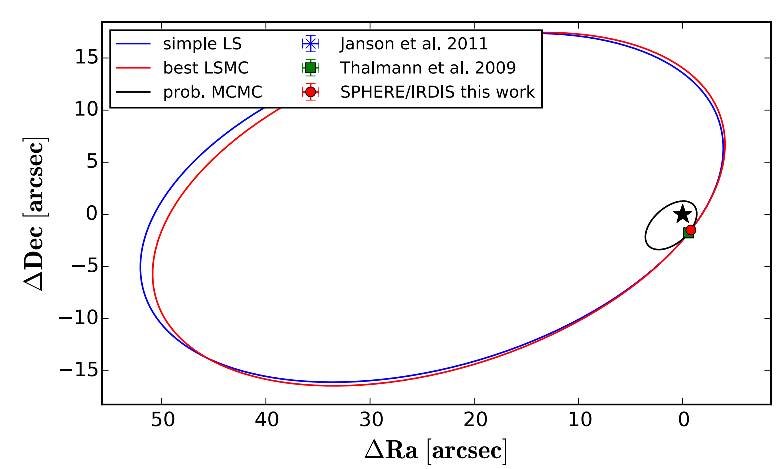
- Lots of data acquired during commissioning (~40 nights in 2014)
- Many results submitted/accepted

GJ758







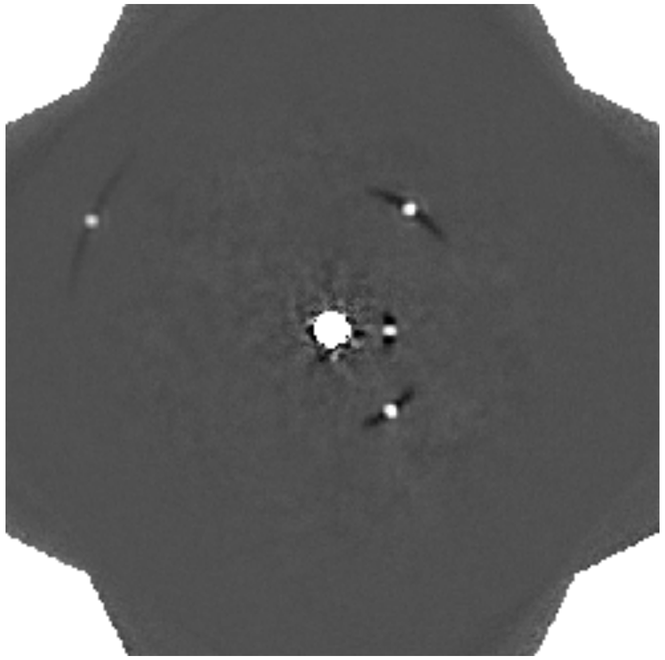


Vigan et al. (submitted)

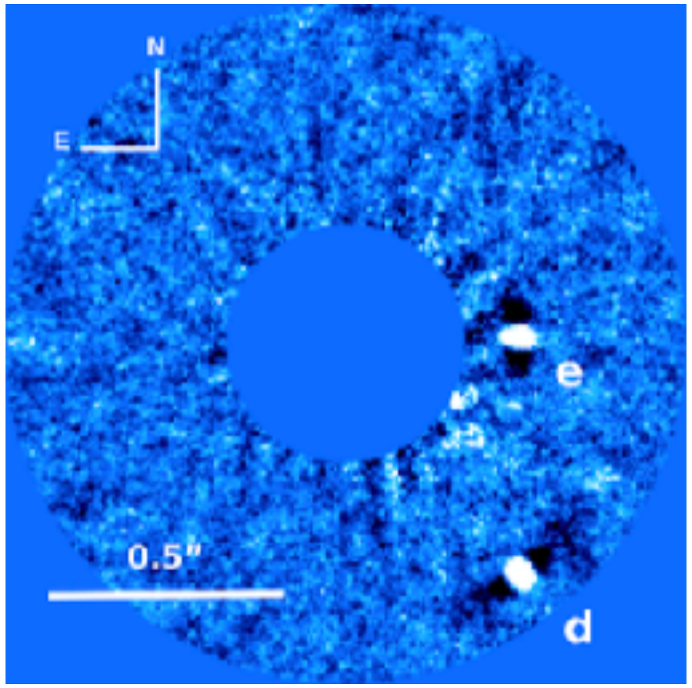
Commissioning results

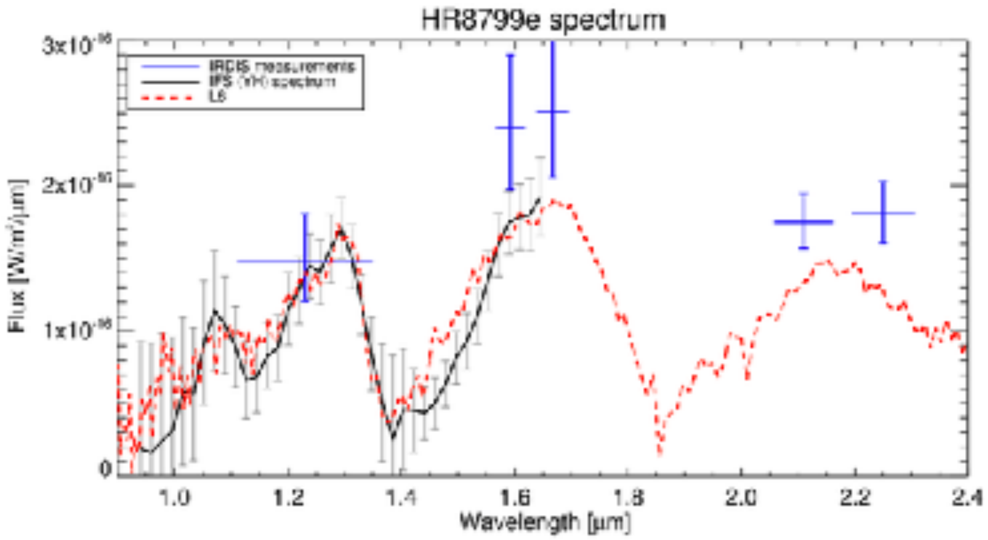
- revisiting the HR8799 system (Zurlo et al. submitted, Bonnefoy et al. accepted)

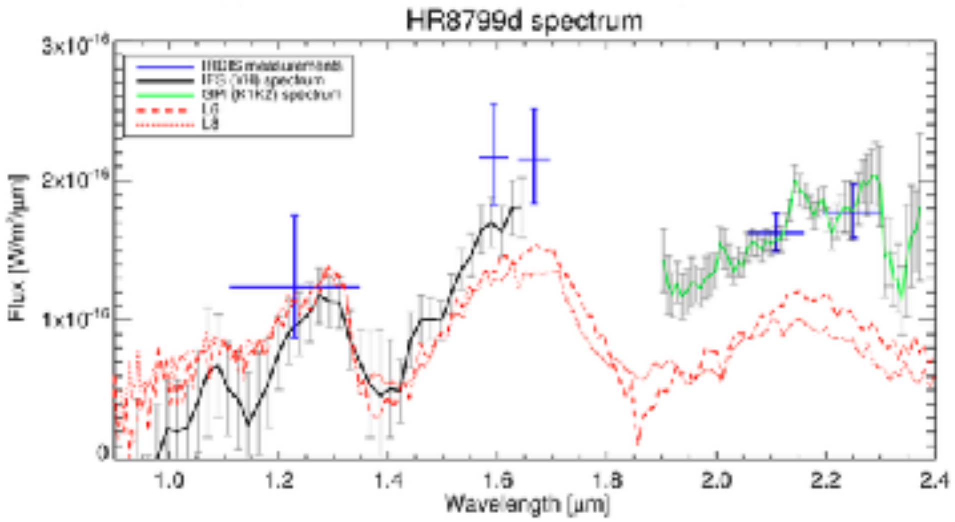
IRDIS-K12



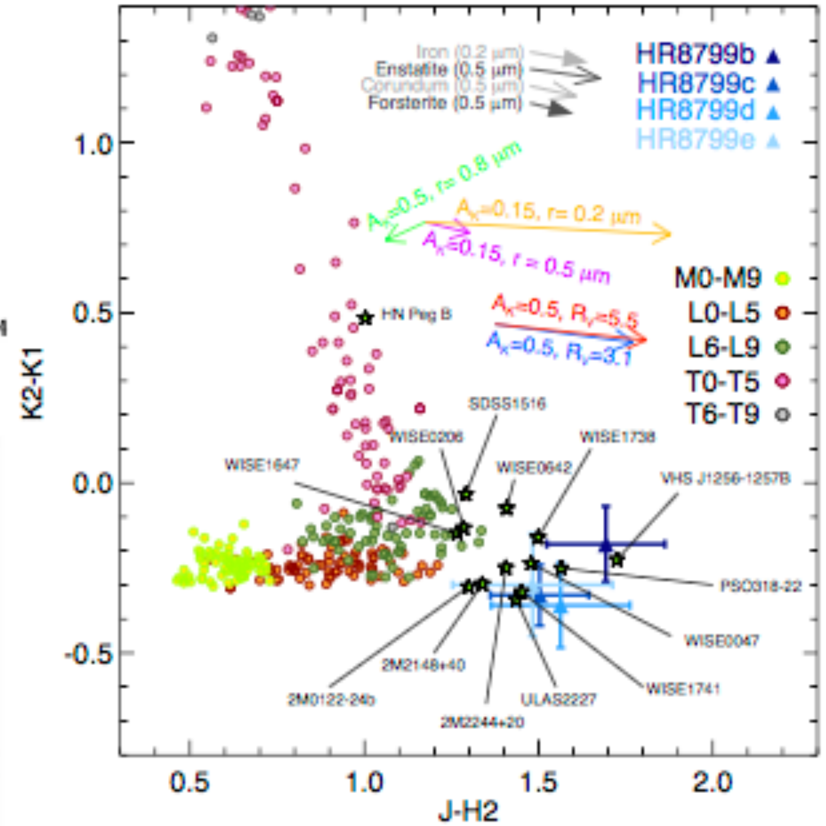
IFS-YJH







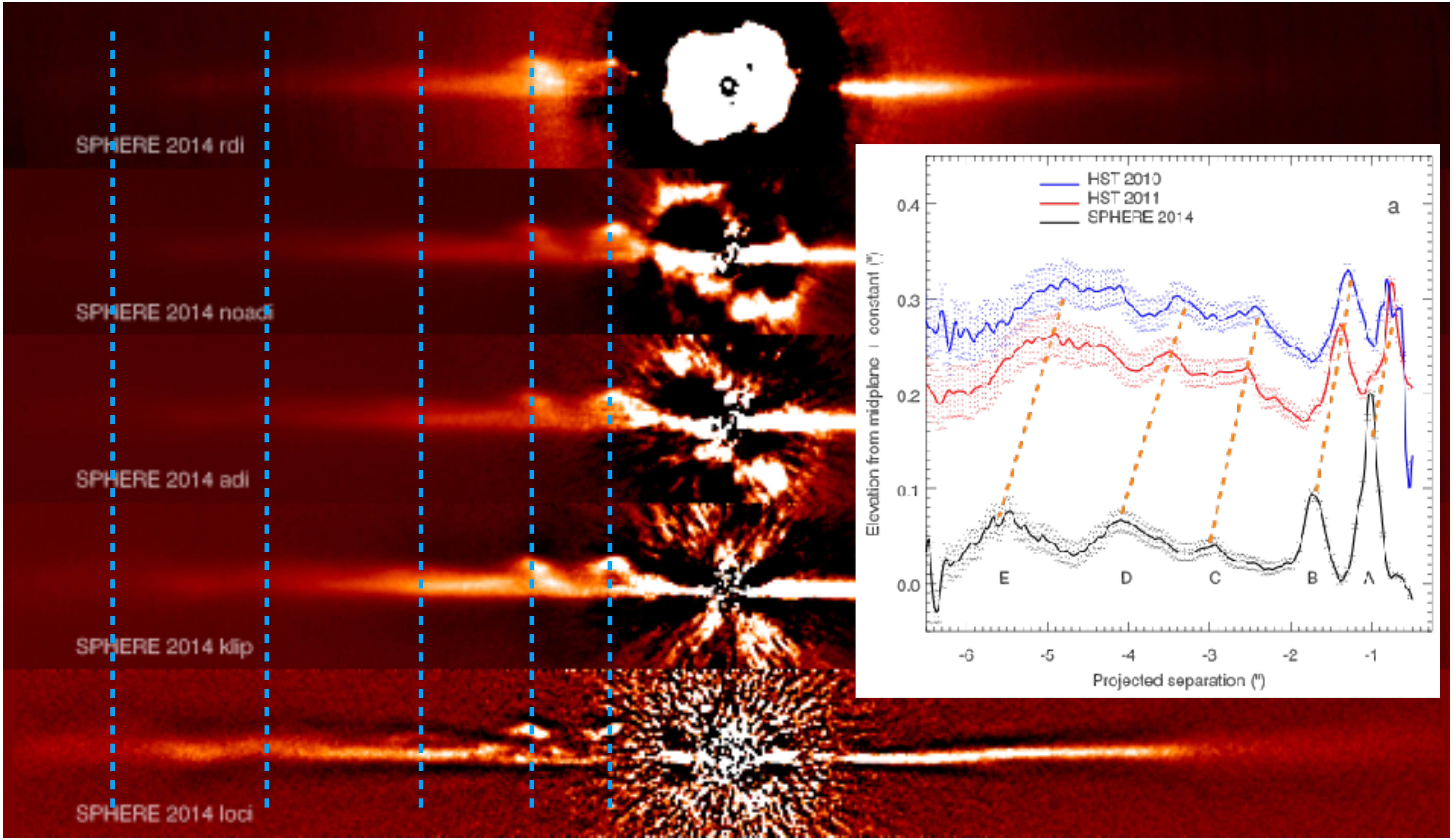
These planets might not be so peculiar after all!



Marois et al. (2008)
Marois et al. (2010)
Barman et al. (2011)
Konopacky et al. (2013)
...

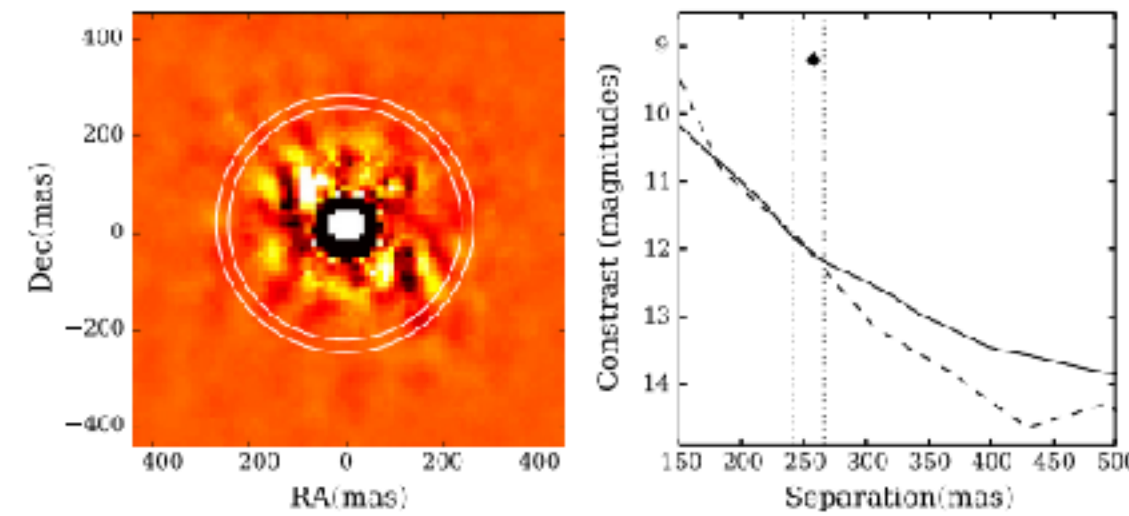
Commissioning results

- Intriguing structures in AU Mic (Boccaletti et al., accepted in Nature)

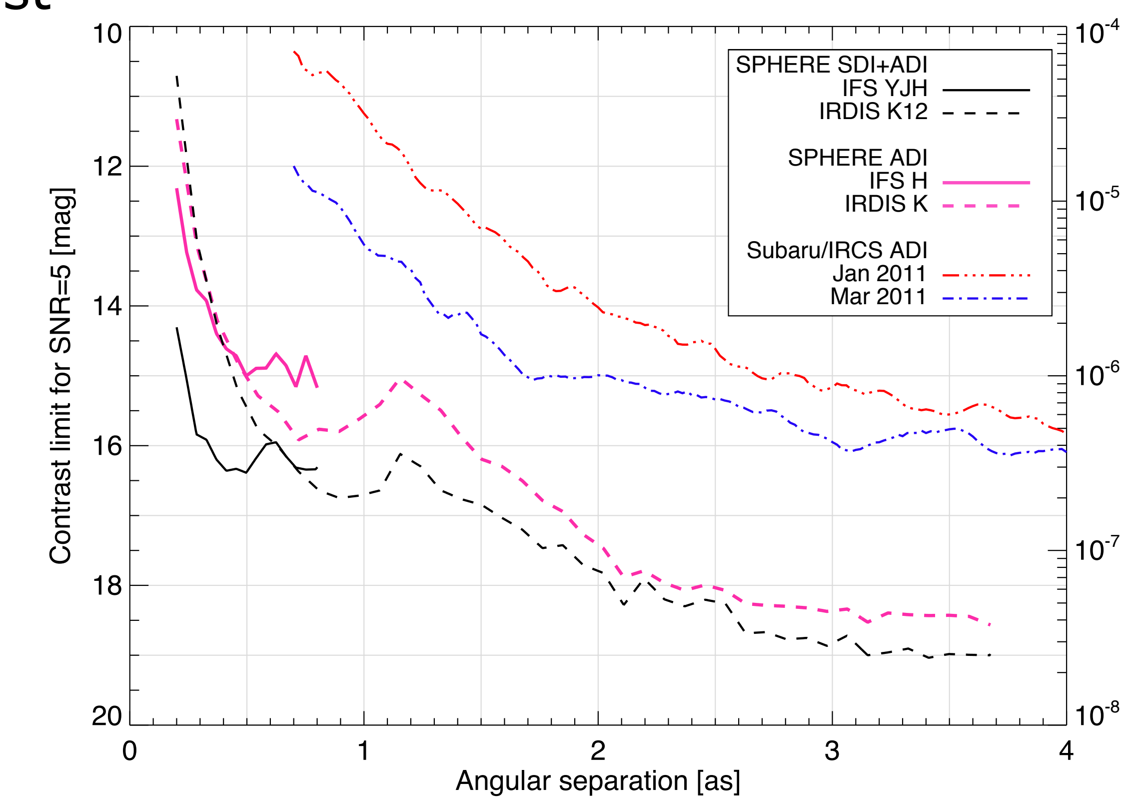


Science verification results

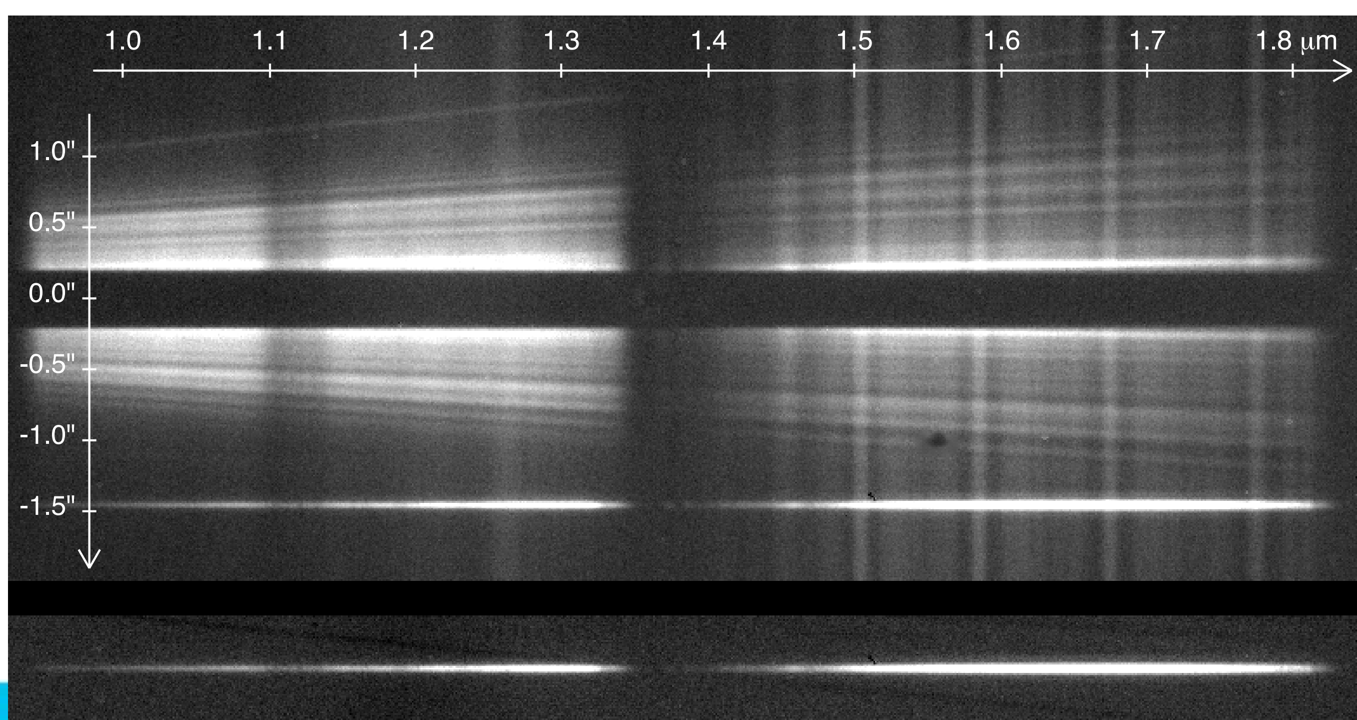
- 40 programs accepted for science verification
- many results already published:
  - non-detection of a brown dwarf around V471 Tau (Hardy et al. 2015)



  - non-detection around Sirius A, best on-sky contrast ever reported (Vigan et al. 2015)



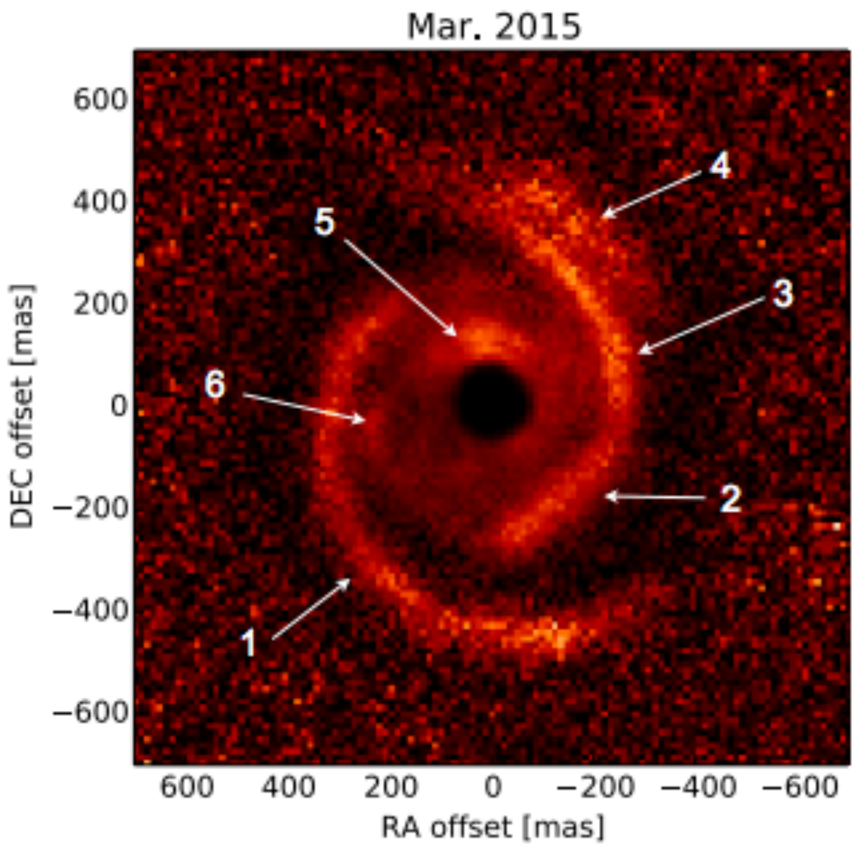
  - characterization of a low-mass companion with IRDIS/LSS (Hinkley et al. 2015)

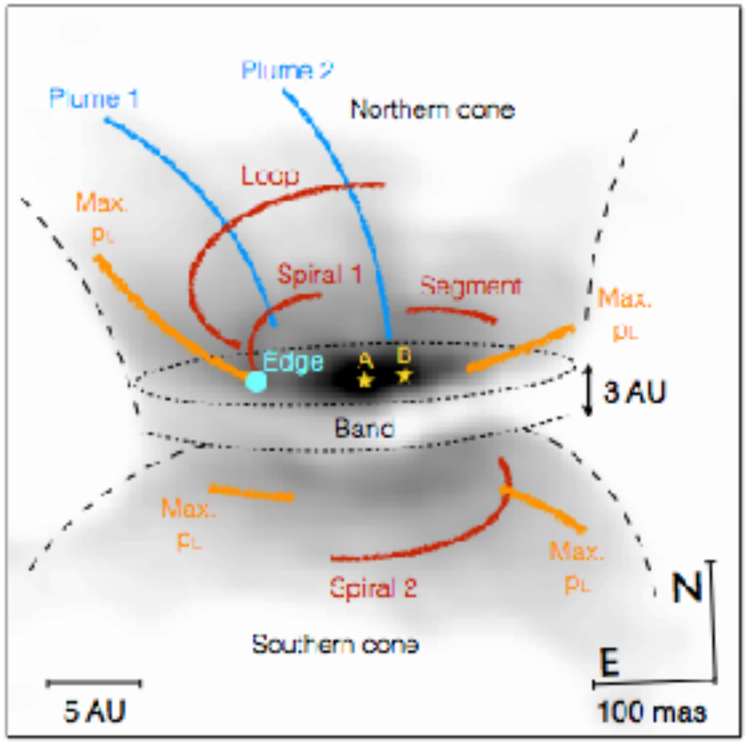


Science verification results

- asymmetric features in the protoplanetary disk MWC 758 (Benisty et al. 2015)

- dust disk and companion of the nearby AGB star L2 Puppis (Kervella et al. 2015)

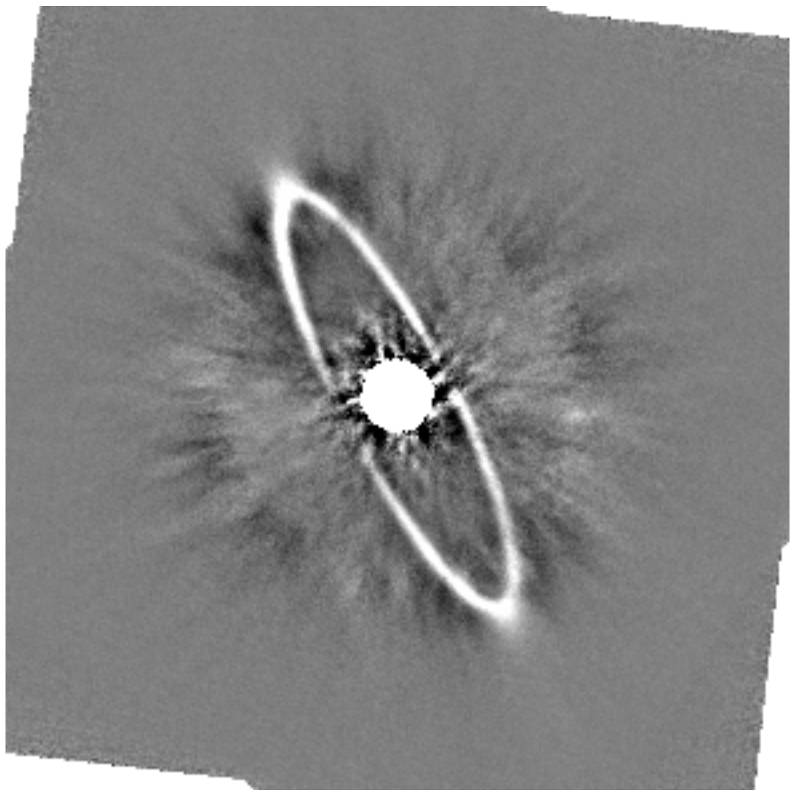


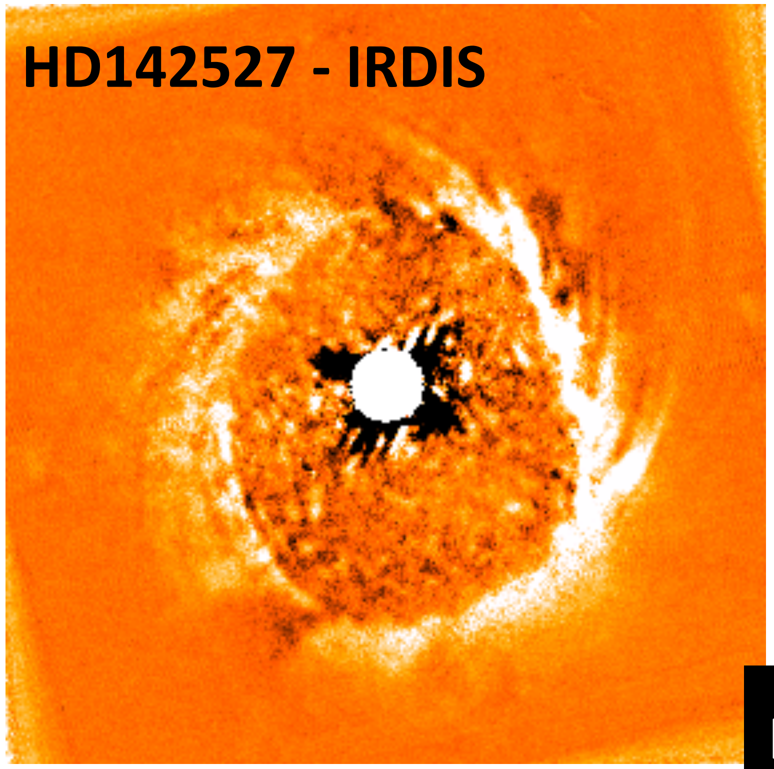


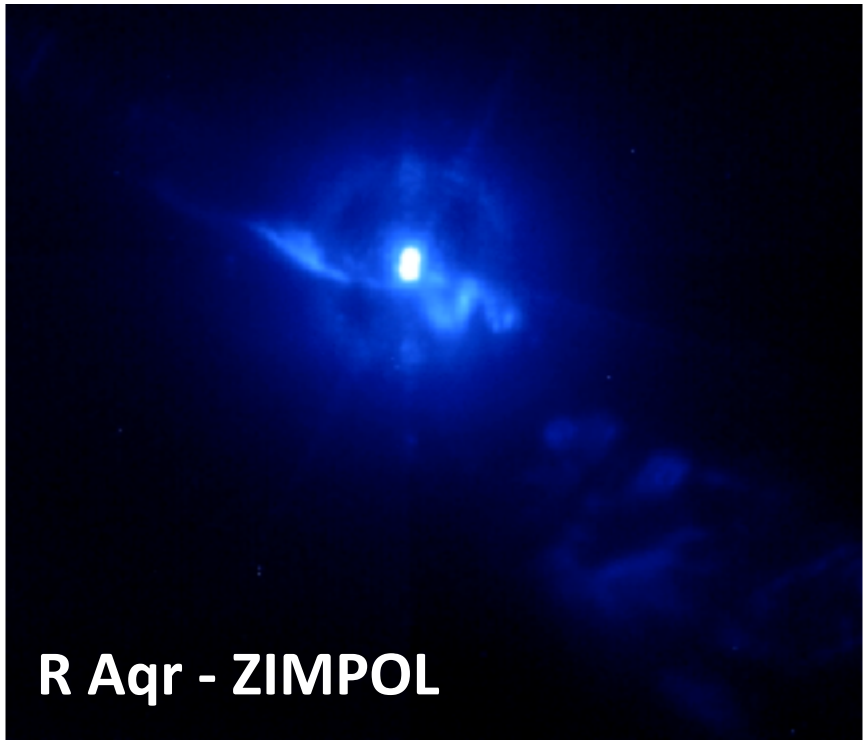
- Csépány et al. (2015), Thalmann et al. (2015), Xu et al. (2015), ...

And more results to come soon

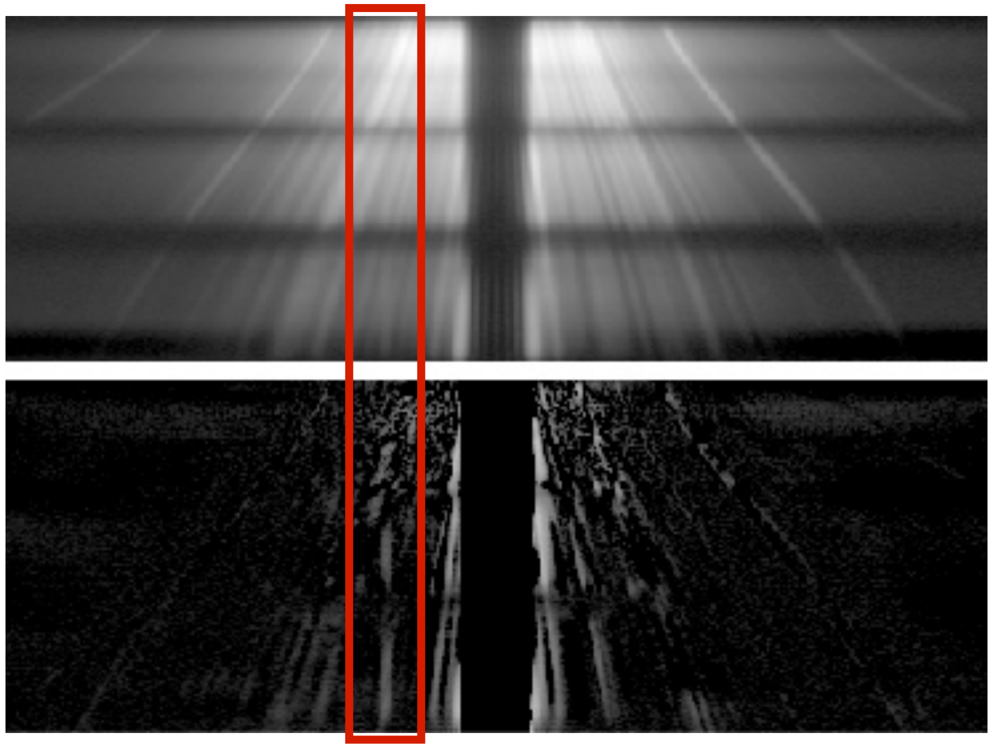
HR4796 - IRDIS

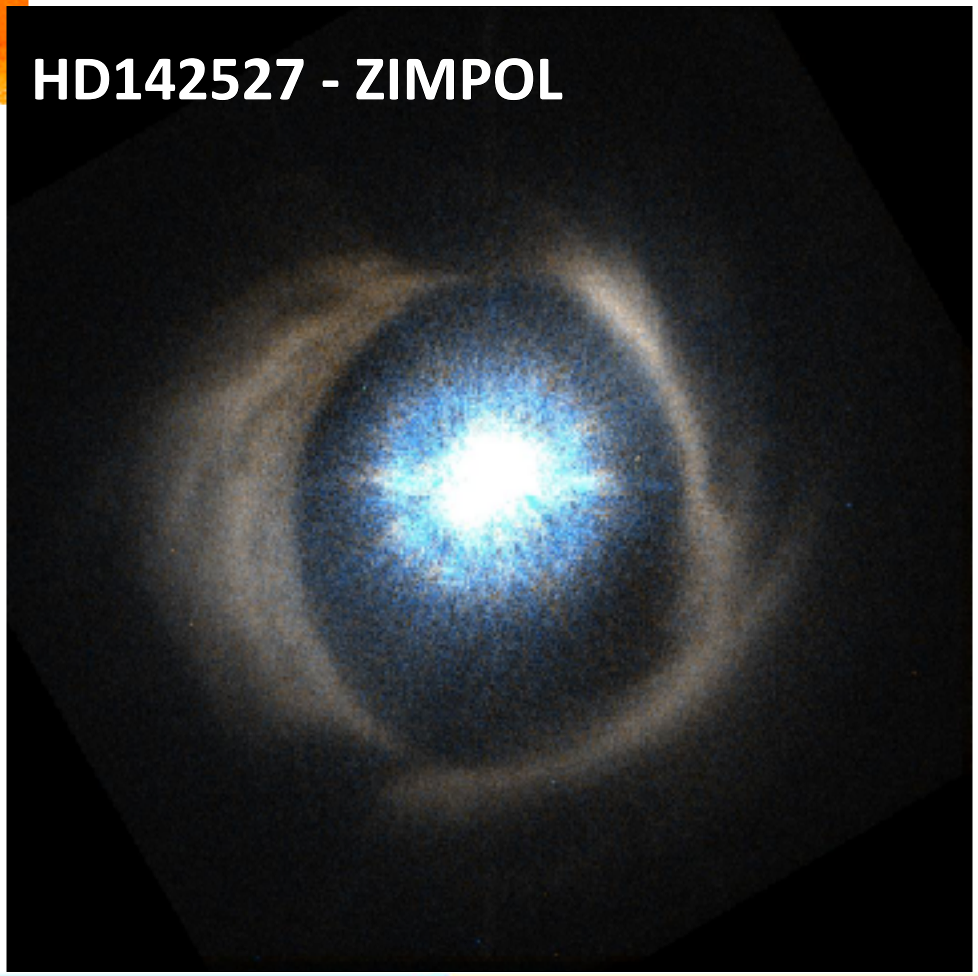






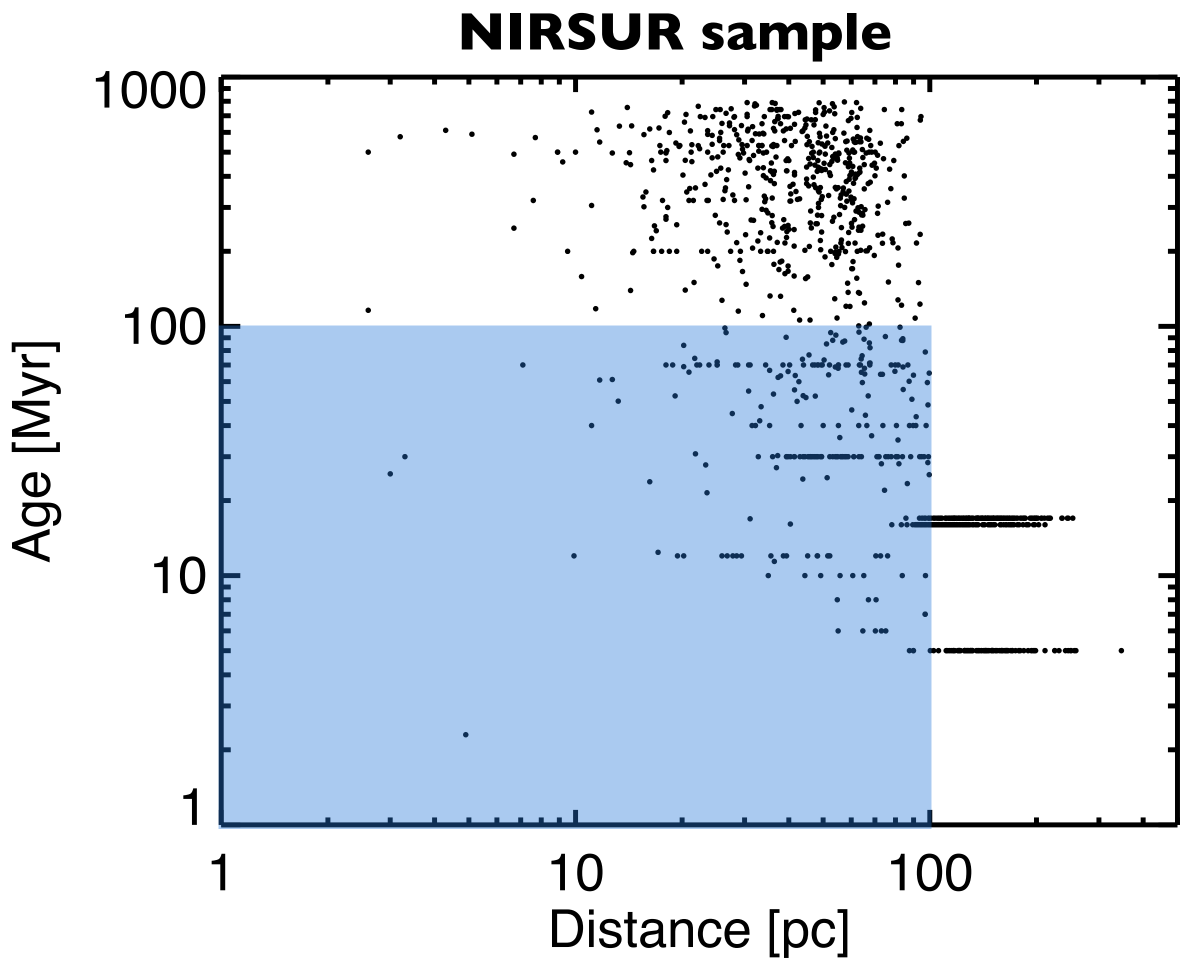
HR8799c - IRDIS





SPHERE guaranteed time of observation

- **260 nights of GTO** over 5-6 years
- 20% for ZIMPOL+other science
- 80% dedicated to **NIRSUR**:
  - simultaneous IRDIS+IFS obs.
  - look for planetary-mass companions
  - several **100s of targets**
  - large range of age/distance/spectral type
  - putting strong constraints on the population of giant planets at wide-orbit
  - all in visitor mode
  - already ~60 stars observed



Comparison to GPI:
- GPIES
- 900 hrs ~100 nights
- 2013-2015
- all in queue mode

Conclusions

- Direct imaging of exoplanets is extremely challenging
- High-contrast and high-angular resolution can be achieved with
  - large ground-based telescopes with extreme AO
  - coronagraphy
  - clever target selection
  - optimised observing strategy
  - advanced data analysis methods
- SPHERE is part of a new generation of direct imaging instruments
  - large scale european project since 2005
  - commissioned at VLT in 2014
  - already many first light and science verification results (>20 papers accepted, submitted or in preparation)
- Many results to come:
  - 260 nights of GTO time
  - many open-time programs