Direct imaging of exoplanets: past, present and future

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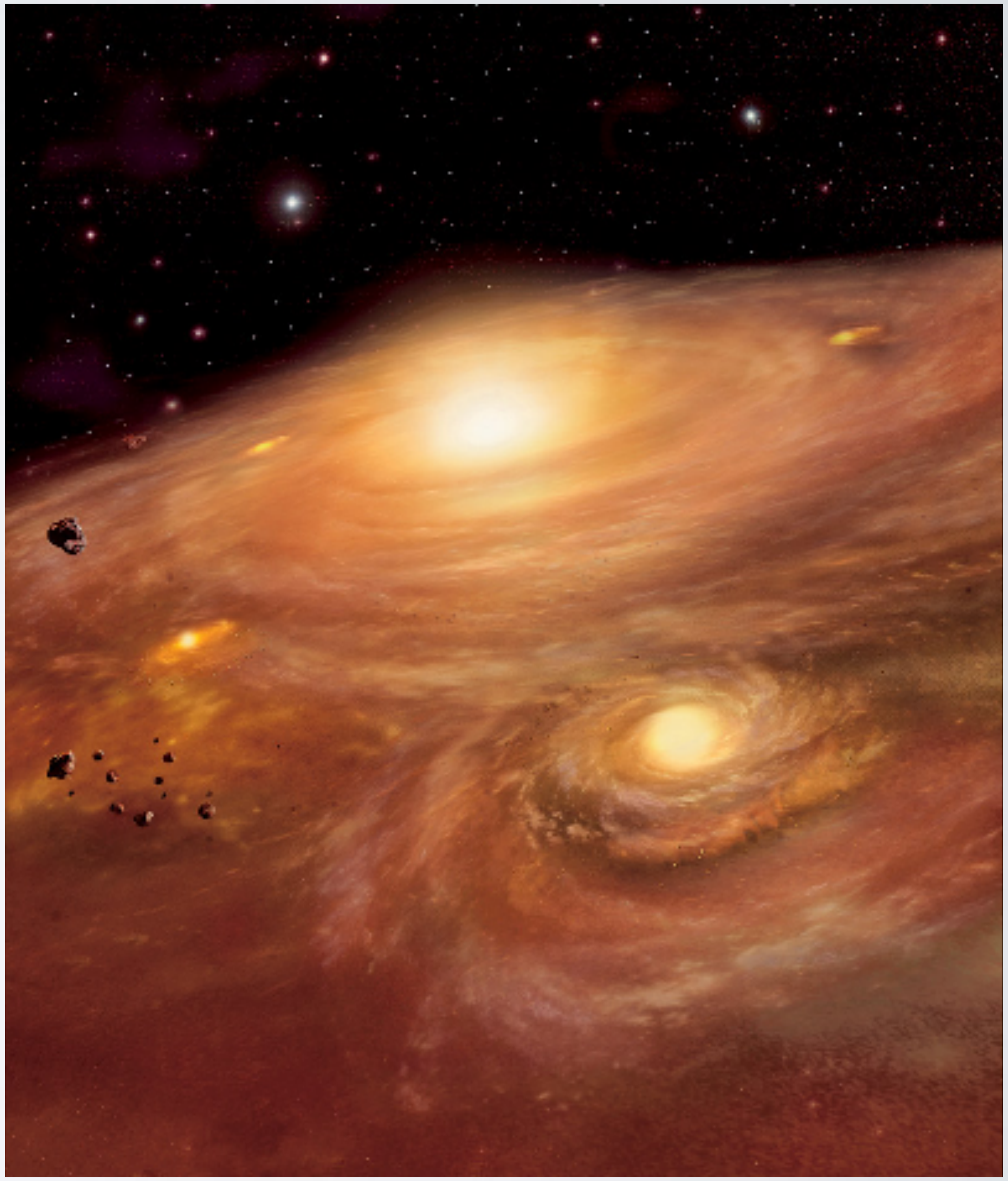
Outline

1. Direct imaging in context
2. Techniques for high-contrast imaging
3. Recent results from large imaging surveys
4. A new generation of instruments

Introduction

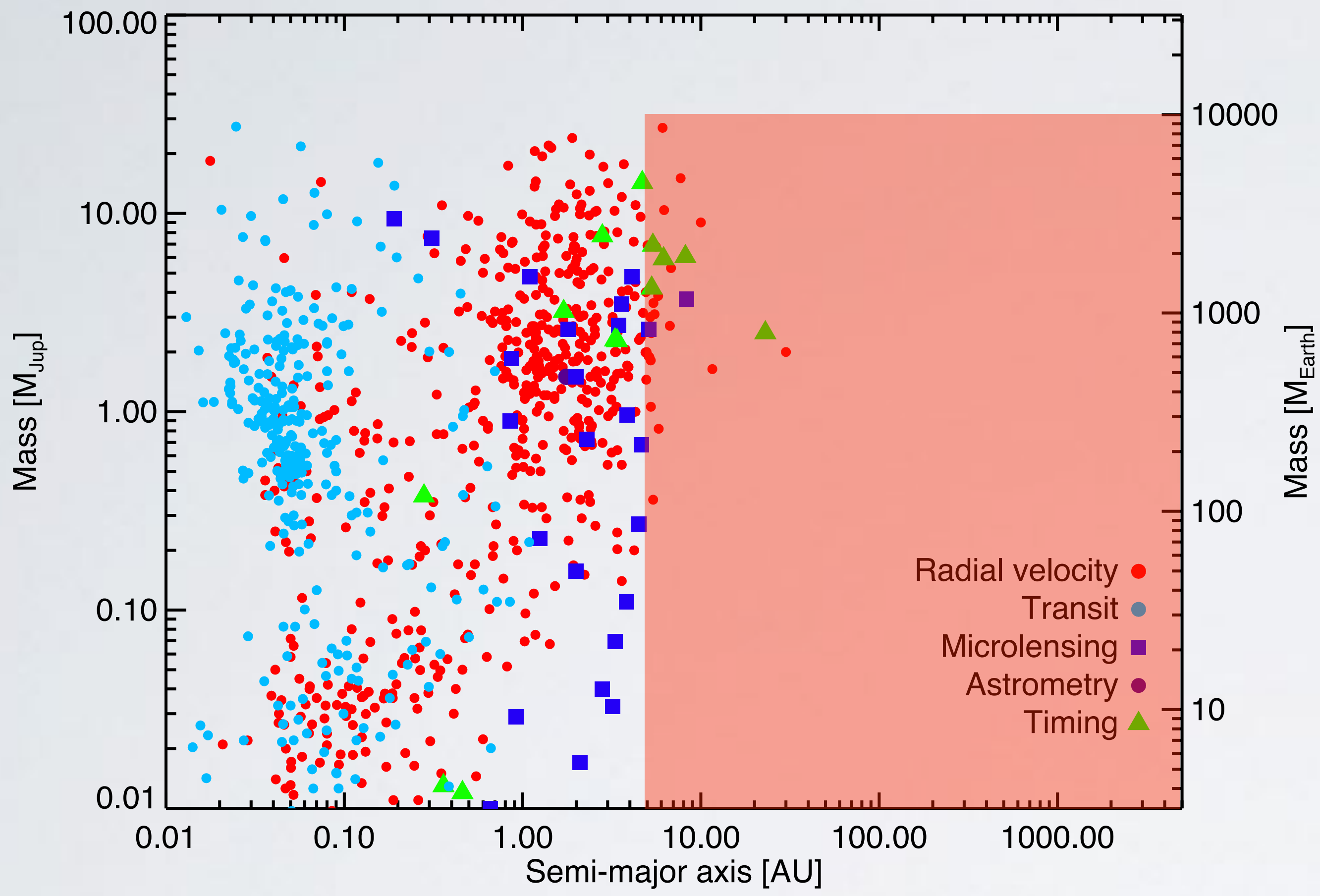
A multi-facet story

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



Artist view of planet formation

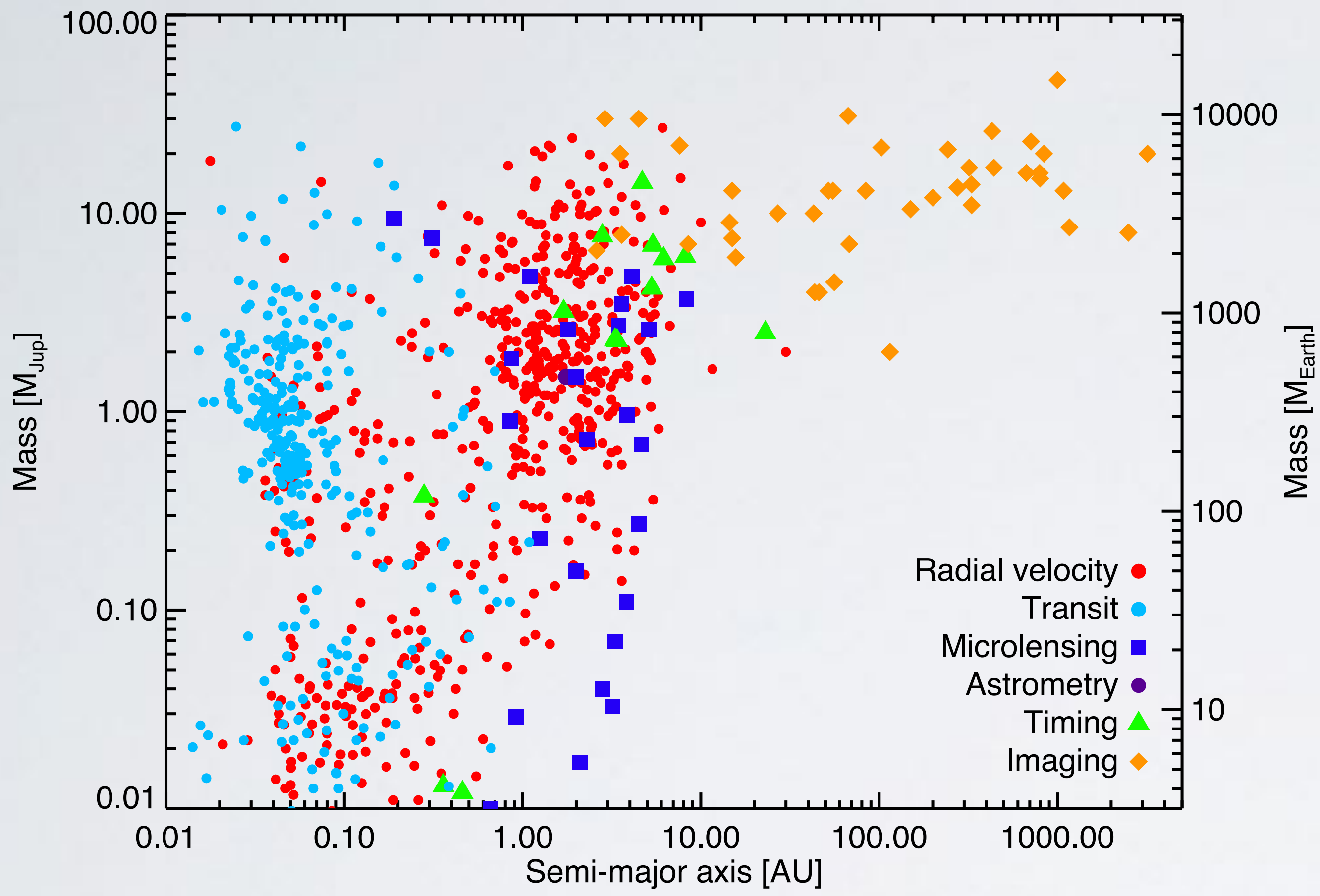
Direct imaging: context



- 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

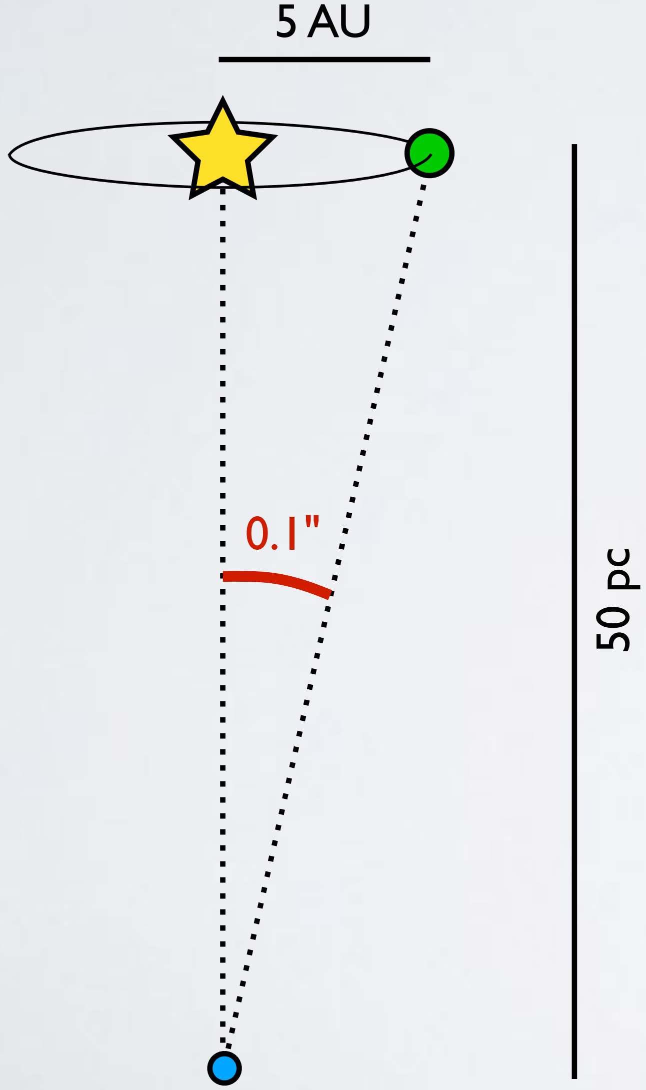


- Direct imaging measures **photons from the planet**
- Orbital and physical properties:
  - L, a, e, i, ω, t0
  - giant planets >1 M_{Jup} at wide-orbit >5 AU
  - system architecture & stability
  - planet-disk interactions
- Spectroscopy:
  - composition
  - cool, non-irradiated, atmospheres
  - low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

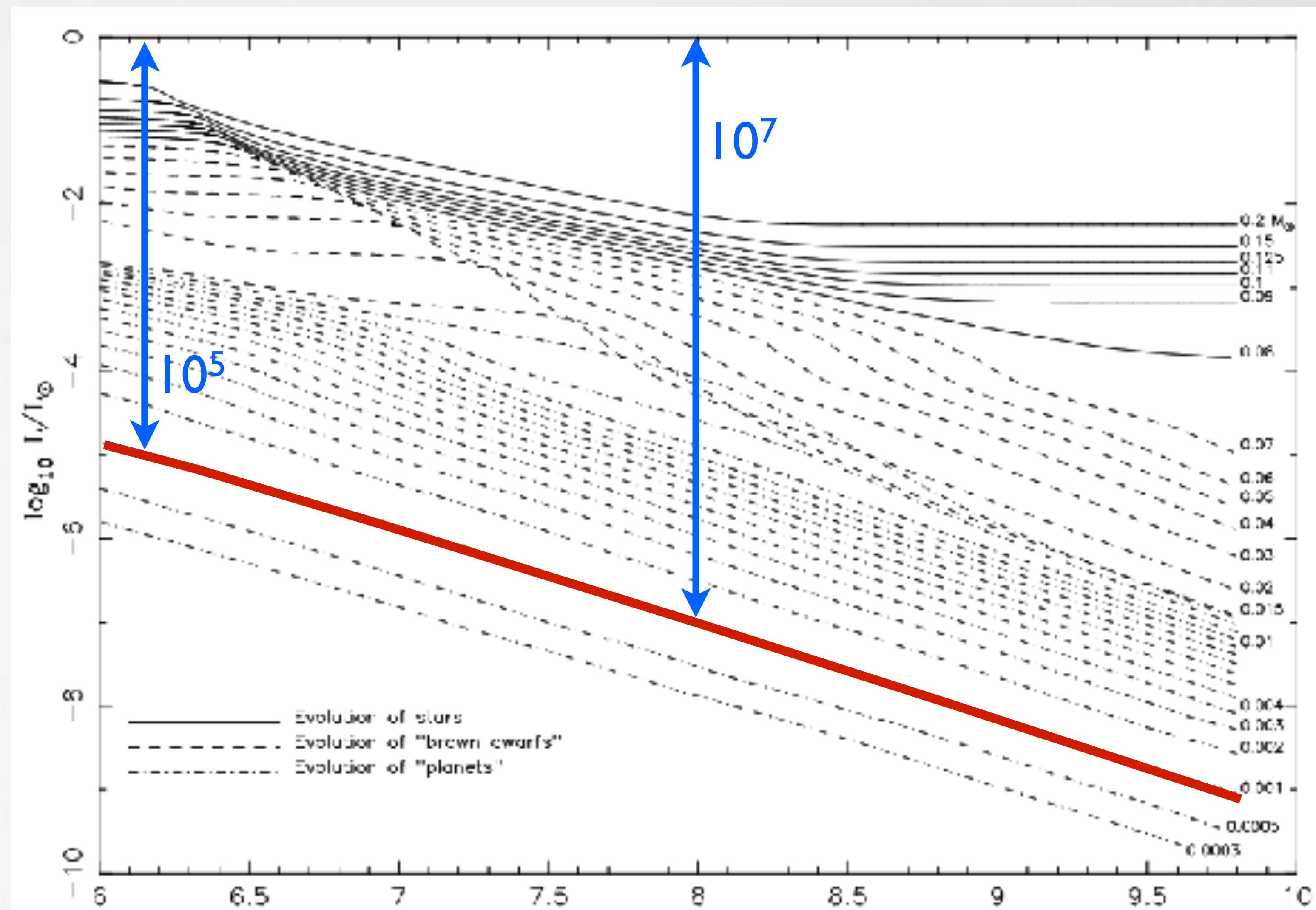
Observational challenge

Direct imaging has to overcome **2 difficulties**

High-angular resolution



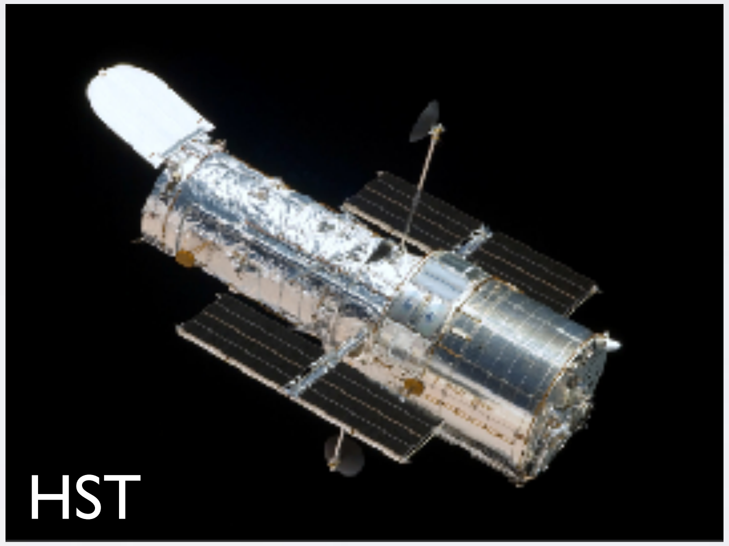
High-contrast

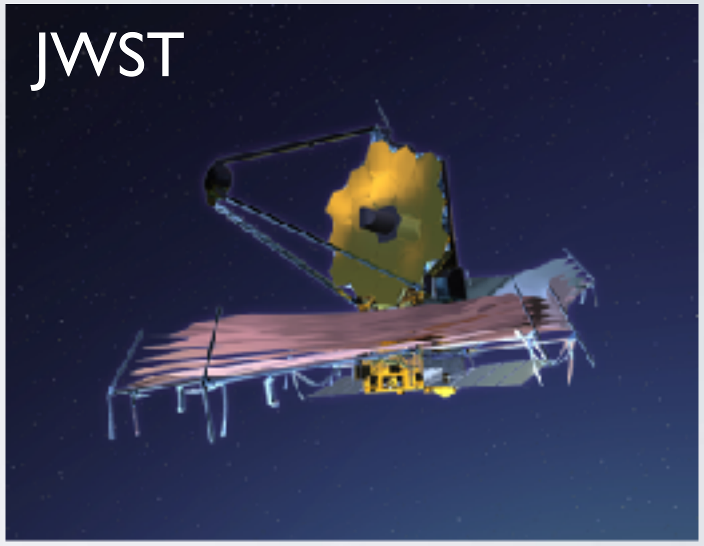


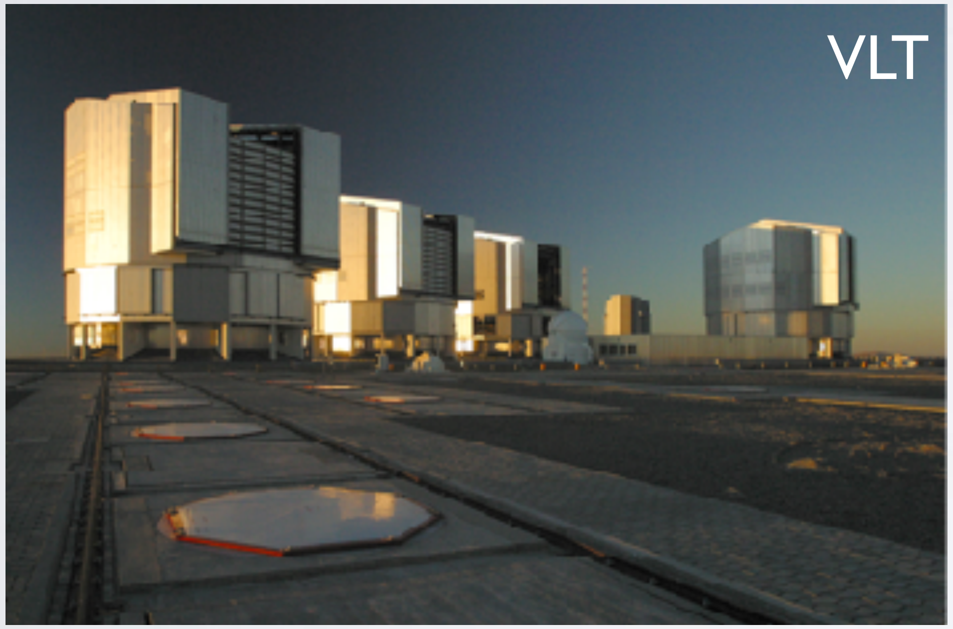
Burrows et al. (1997)

High-angular resolution

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



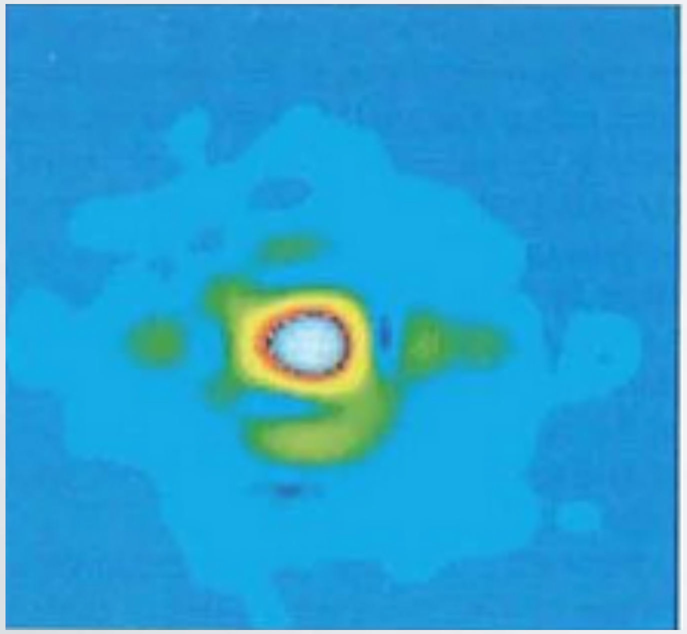




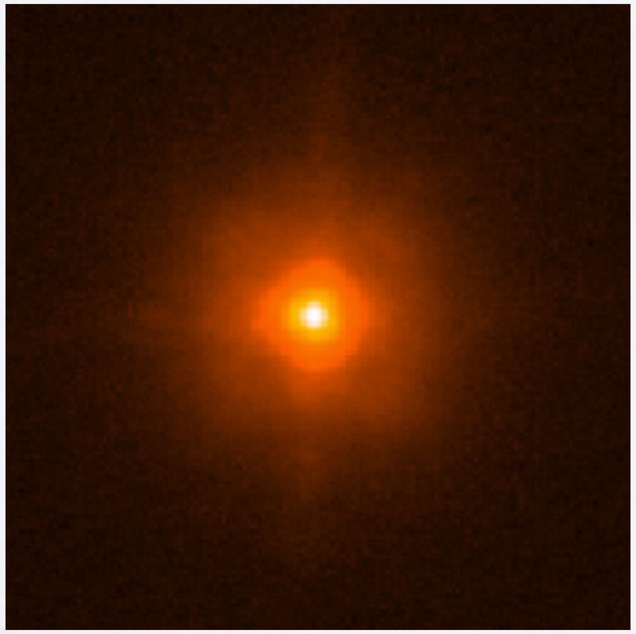
High-angular resolution: adaptive optics

- **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:

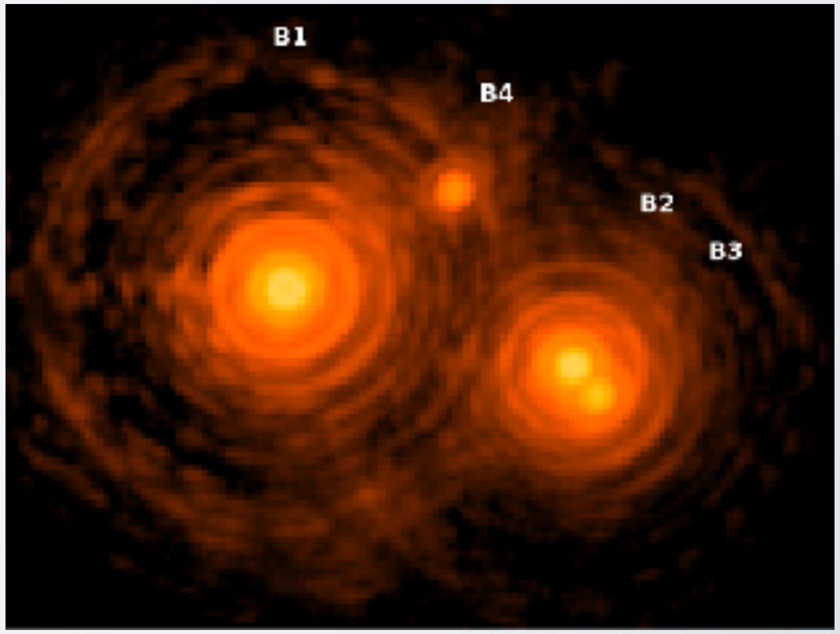
1990s
ESO3.6m/Come-On+
SH WFS; 52 actuators
Sr < 10%



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



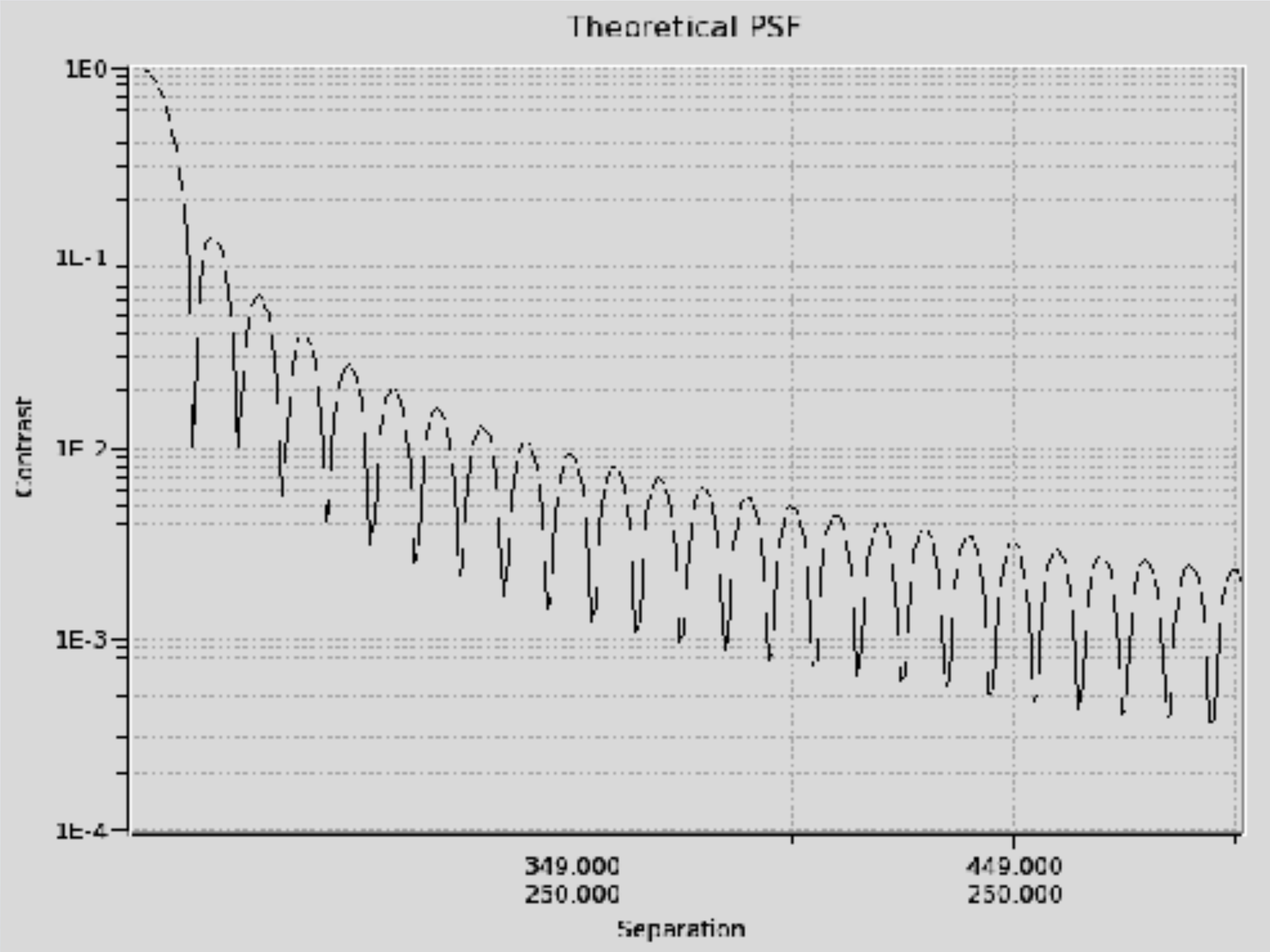
2010s
LBT/SPHERE/GPI
SH/Pyr WFS; >1000 actuators
Sr > 80%



High-contrast

Sensitivity limited by the star/planet luminosity difference

- **long integration times**

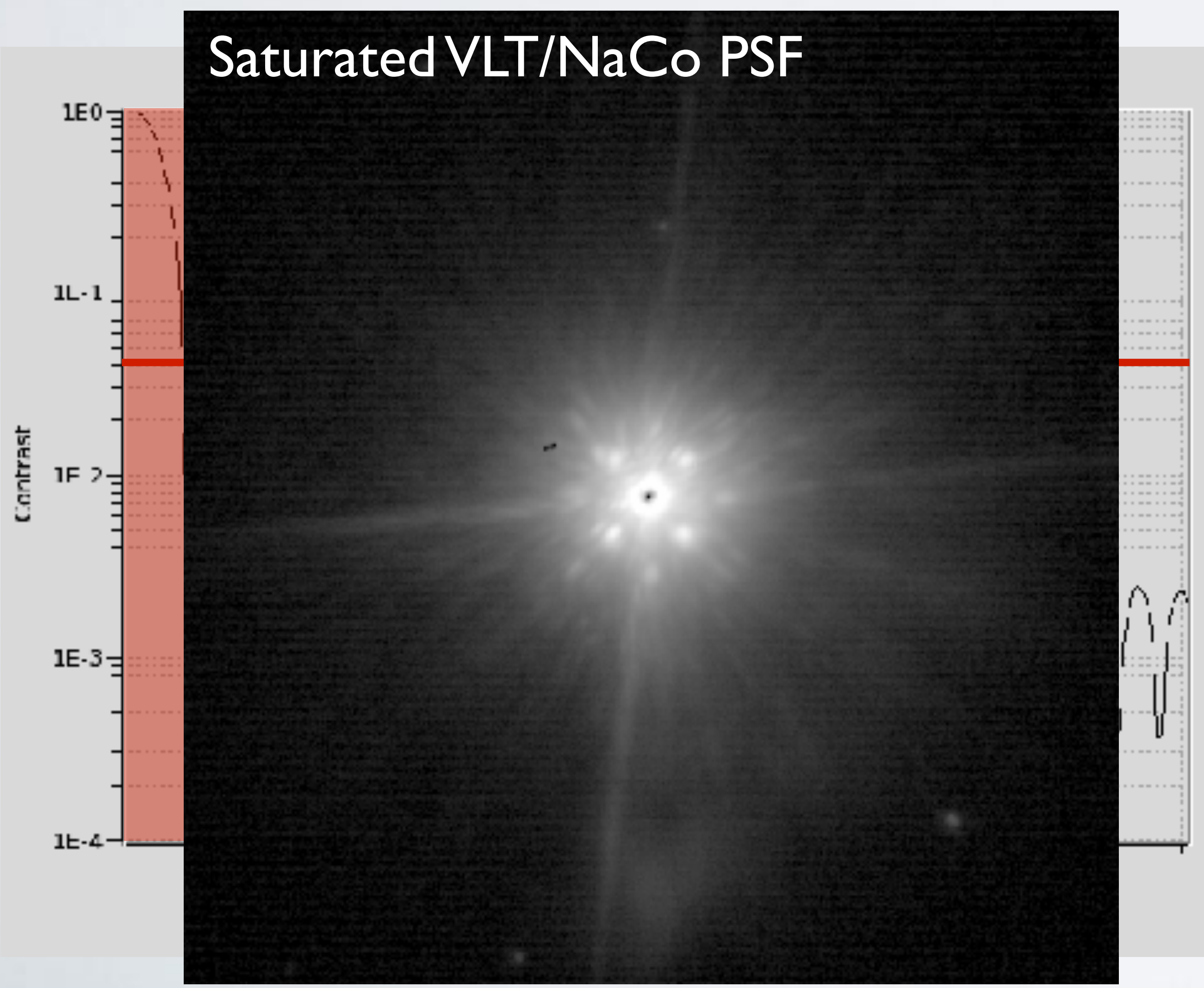


- Advantages:
  - ?
- Drawbacks:
  - extremely long integration times
  - limited by detector overheads
  - ultimately limited by diffraction

High-contrast

Sensitivity limited by the star/planet luminosity difference

- long integration times
- **saturated imaging**

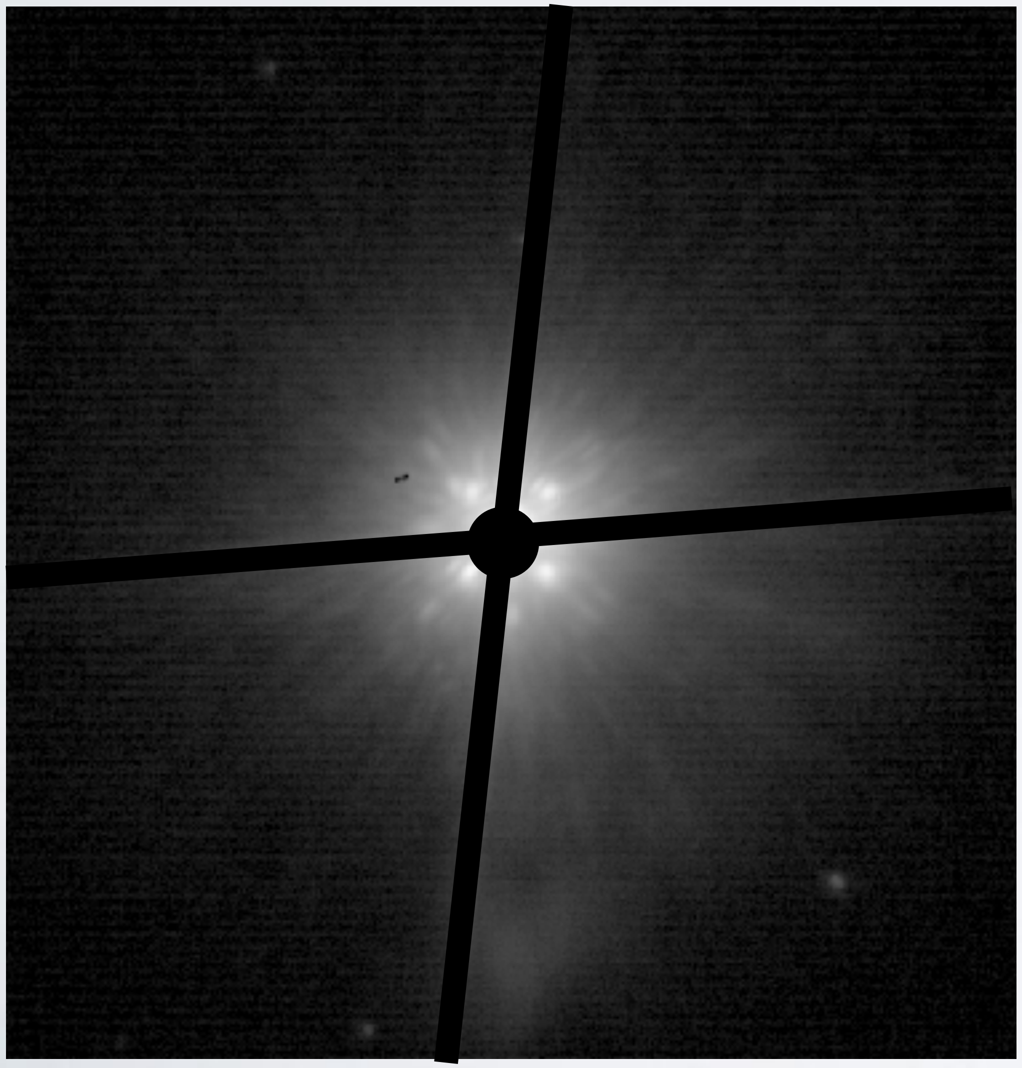


- Advantages:
  - increased sensitivity in PSF wings
  - improved SNR
- Drawbacks:
  - loss of angular resolution
  - remanence effects on detectors
  - ultimately limited by diffraction

High-contrast

Sensitivity limited by the star/planet luminosity difference

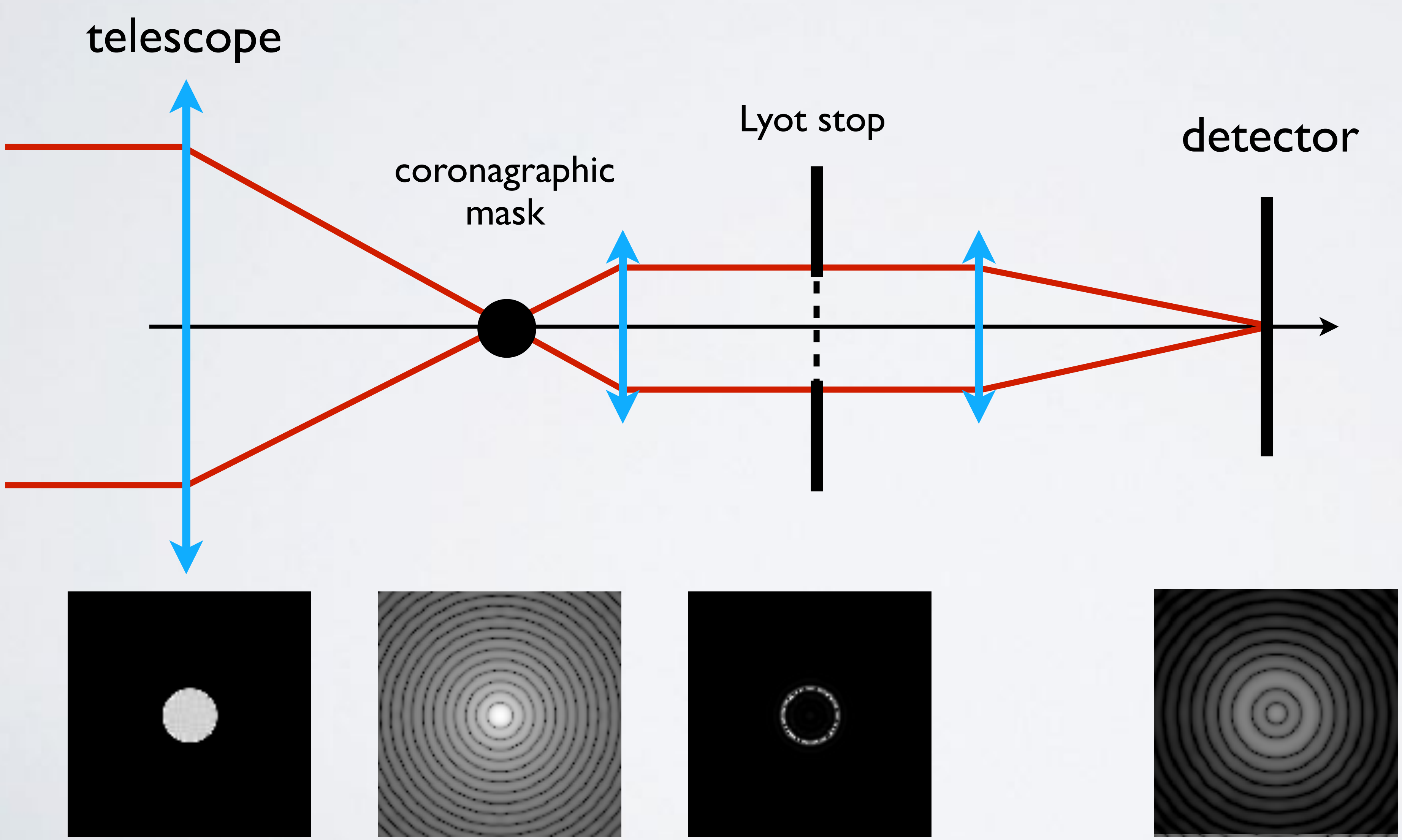
- long integration times
- saturated imaging
- **coronagraphy**

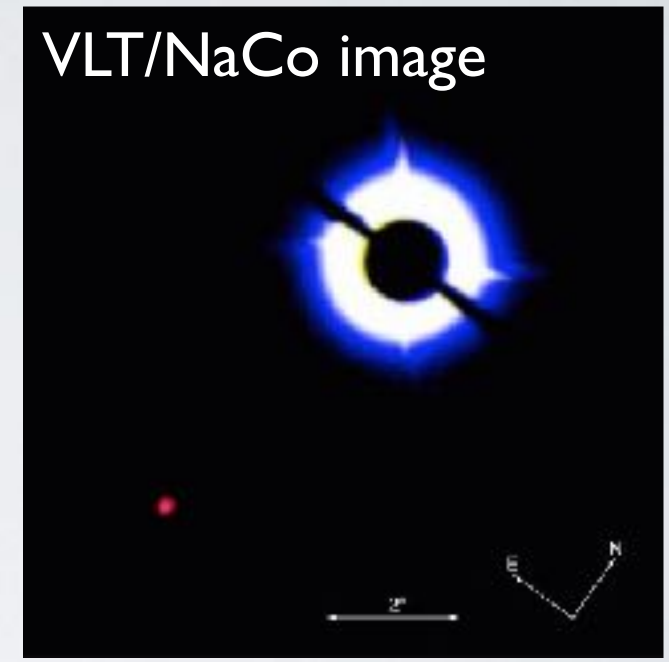


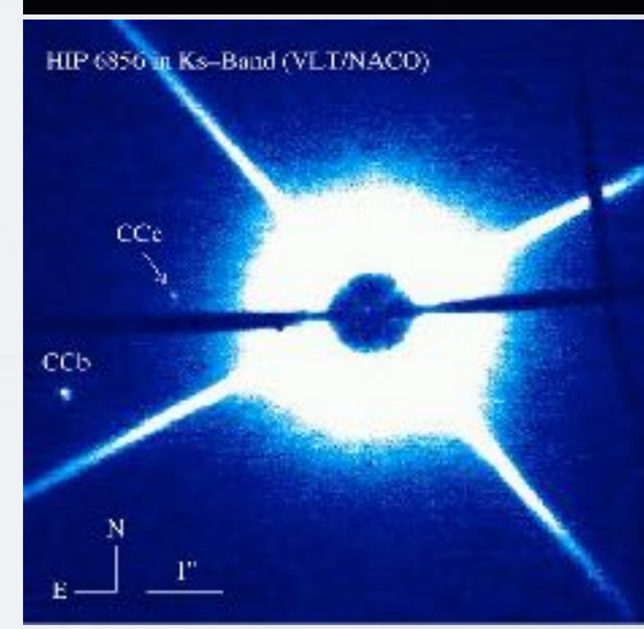
- Advantages:
  - suppress diffraction
  - improved SNR
- Drawbacks:
  - possible loss of angular resolution
  - increased system complexity
  - high Strehl ratio required

High-contrast: coronagraphy

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



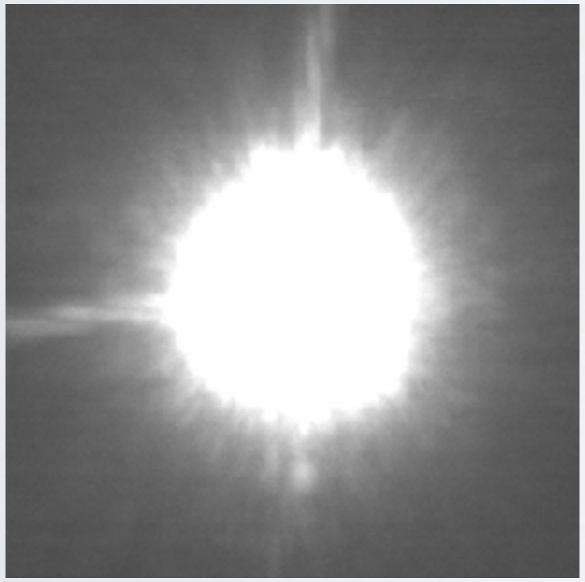


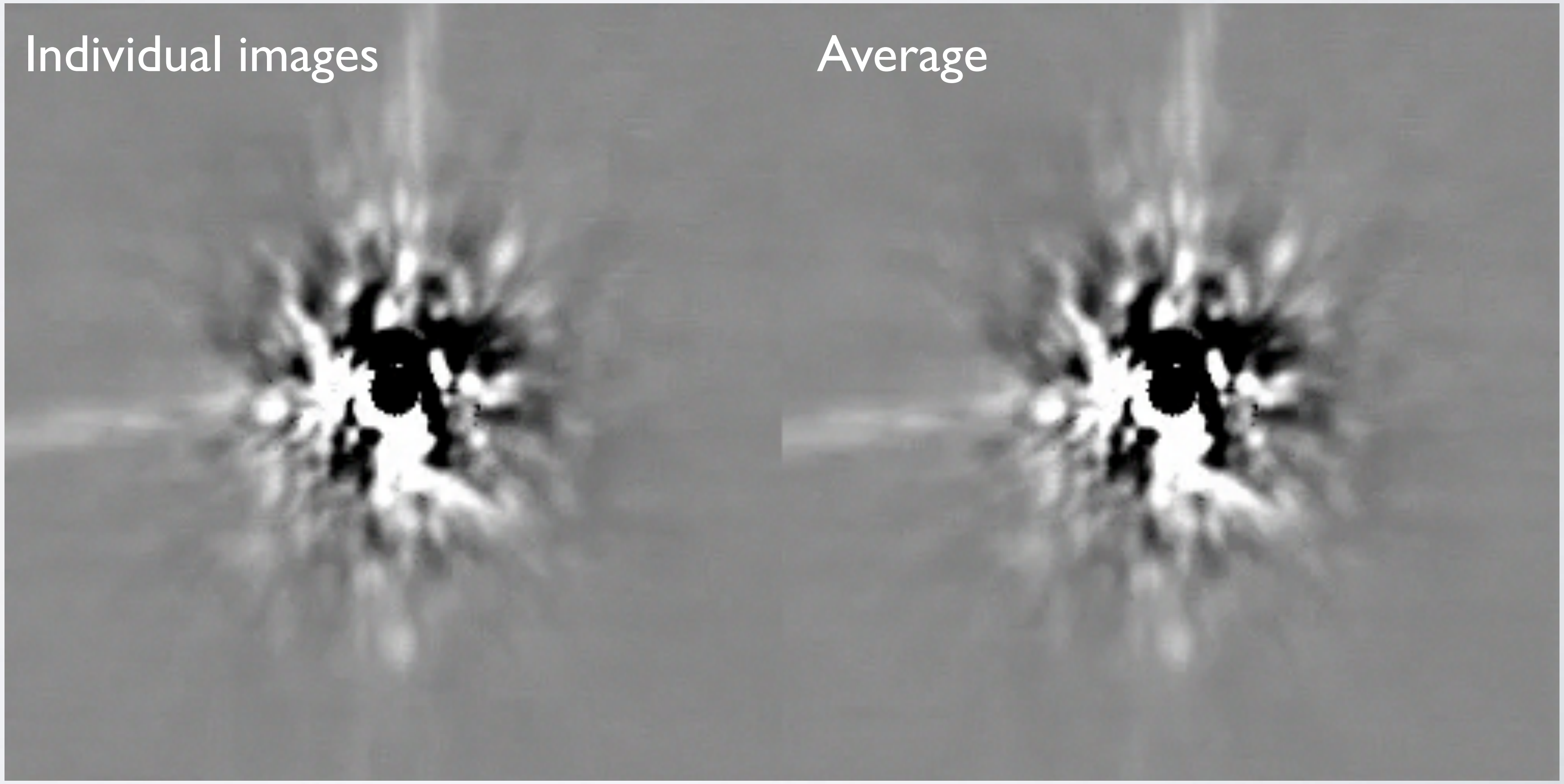


Quasi-static speckles

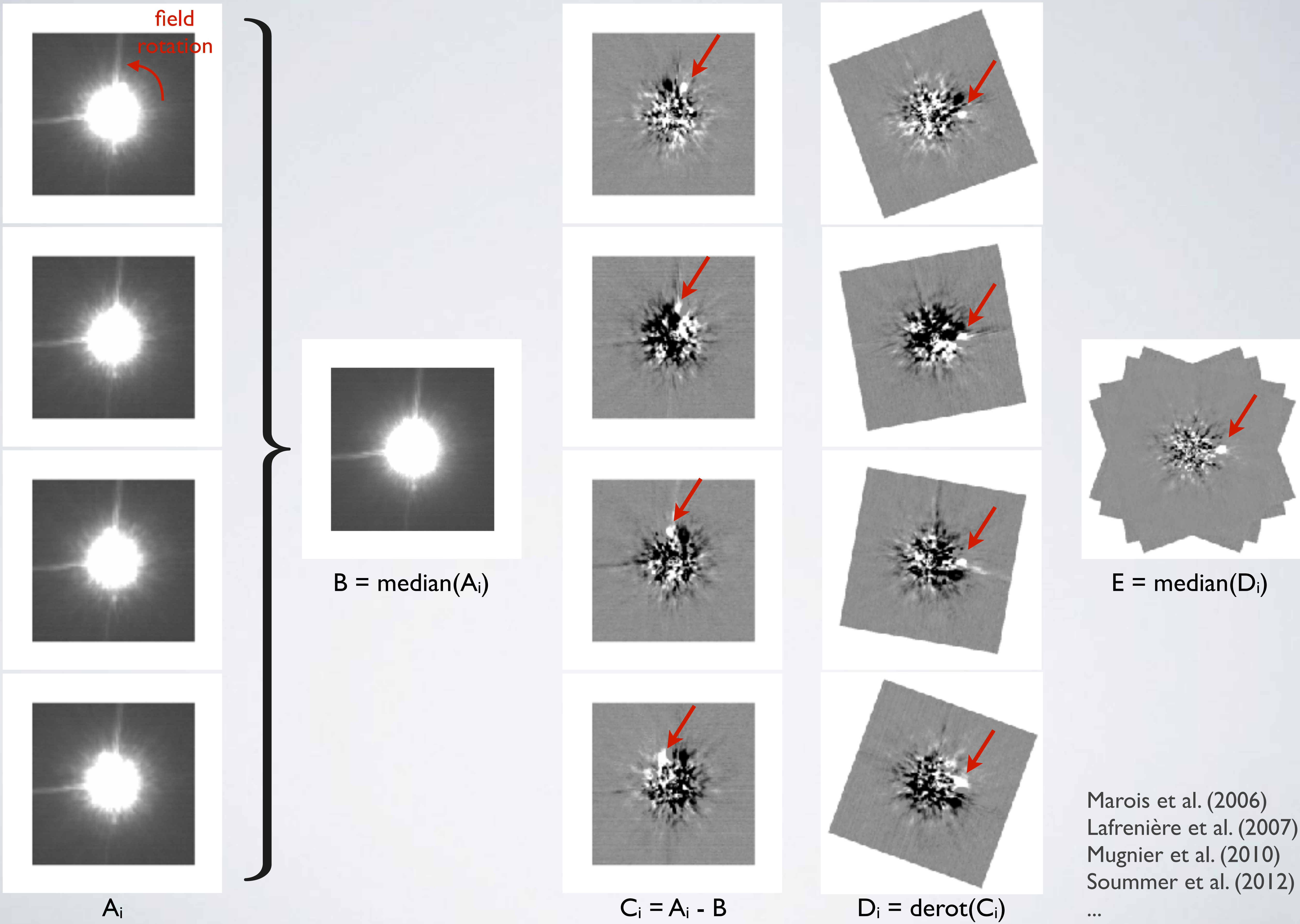
- high-angular resolution + high-contrast → **not enough!**
  - limitations: atmospheric and instrumental **speckles**
  - speckles are **not static**, but definitely **not random**
- optimized **observing strategy**, **data analysis** and **target selection**

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





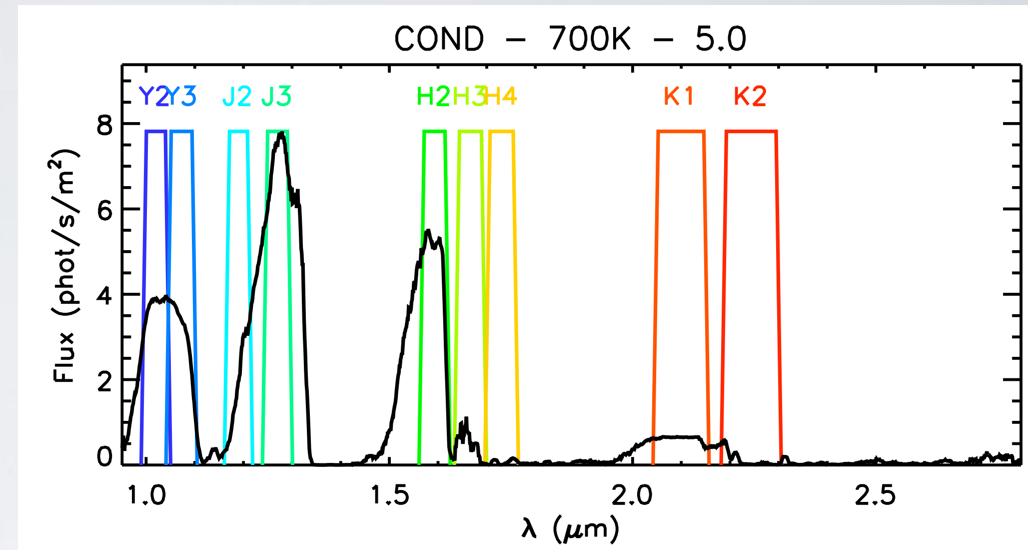
Angular Differential Imaging



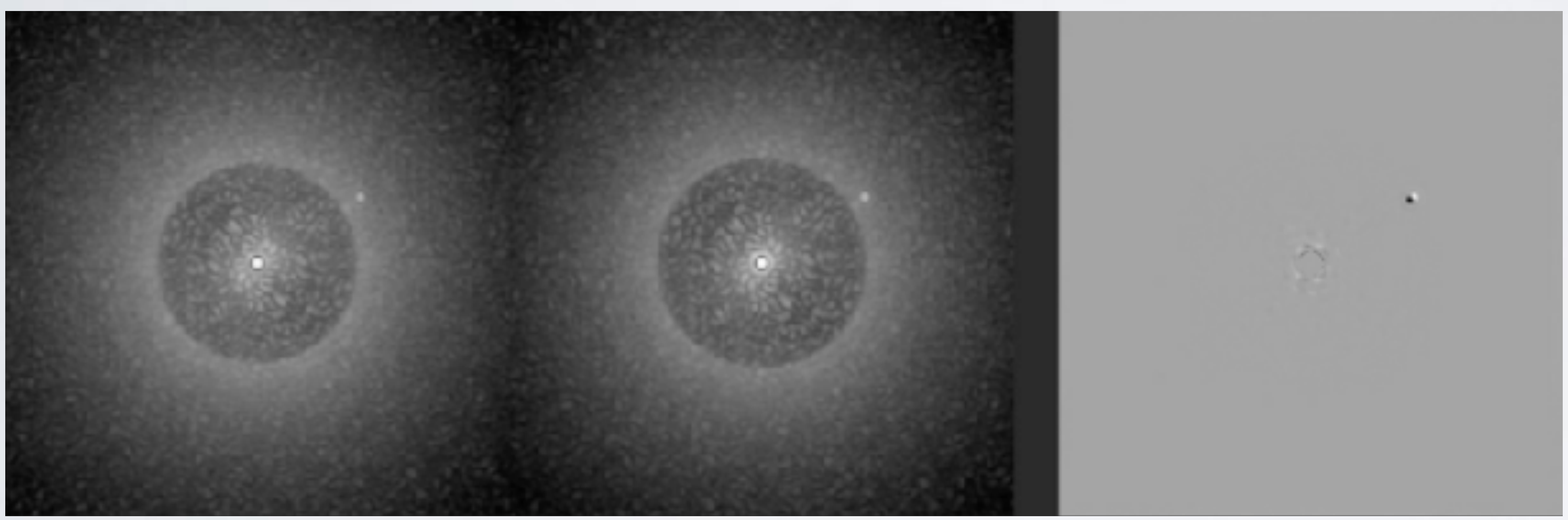
Marois et al. (2006)
Lafrenière et al. (2007)
Mugnier et al. (2010)
Soummer et al. (2012)
...

Spectral Differential Imaging

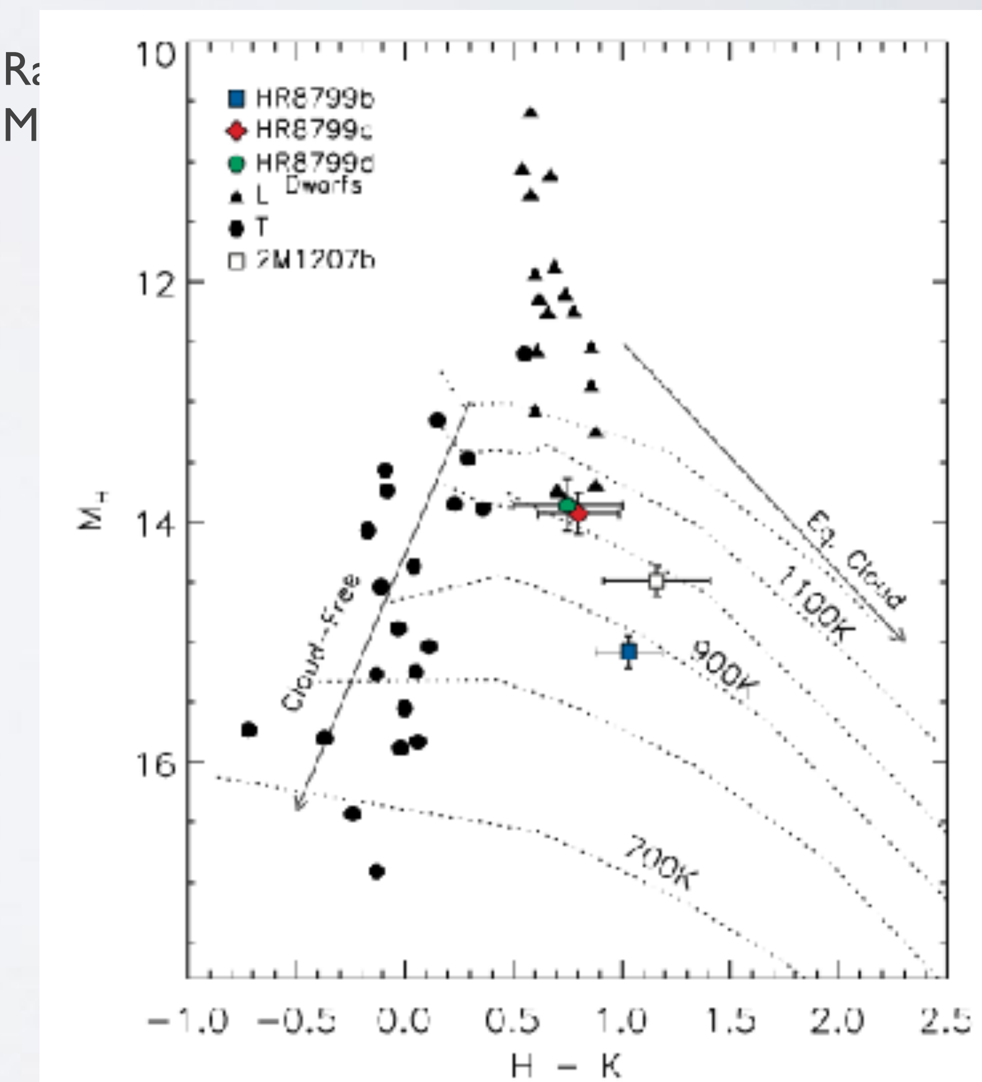
- Based on **expected spectral features** of the planets vs. flat stellar spectrum
- CH_4 / H_2O absorptions expected for cold, low-mass planets



λ_0 λ_1 $\lambda_0-\lambda_1$



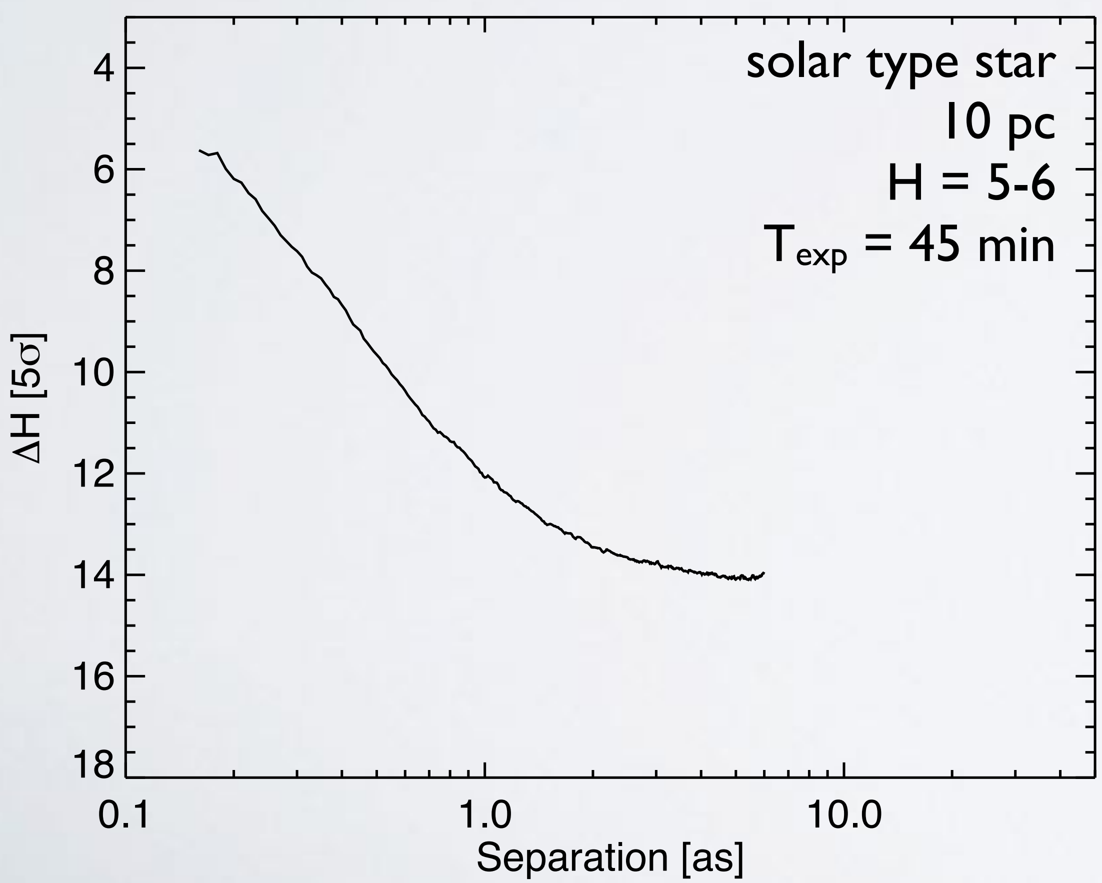
- Caveat: know cold objects don't show CH_4 abs.
  - HR8799b and 2M 1207b
  - unexpected role of CO/CH_4 non-equ. chemistry

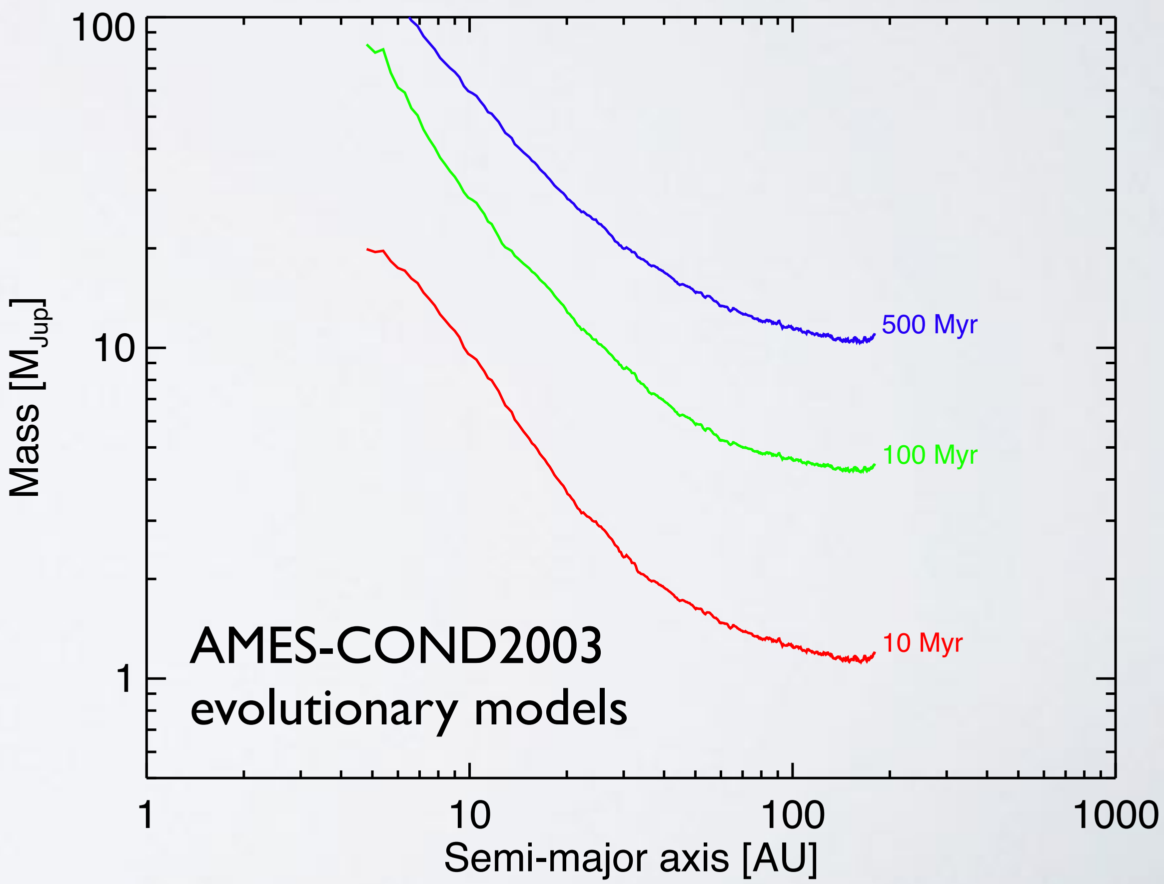


Barman et al. (2011); Konopacky et al. (2012); ...

Target selection

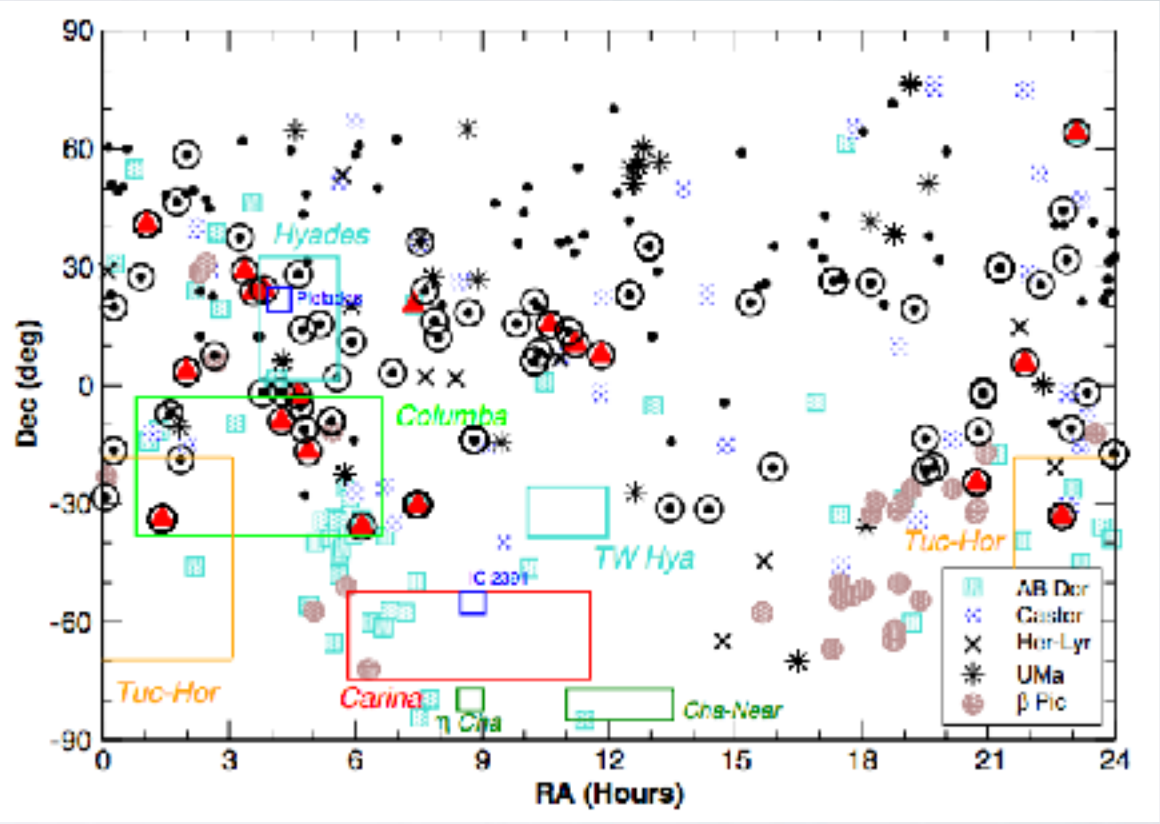
- high-angular resolution + high-contrast + obs. strategy + data analysis
  - ➙ increased sensitivity at small separation (0.1"-0.2")
- what about physical units: semi-major axis [AU] and mass [MJup]?
  - ➙ significant role of **target selection**



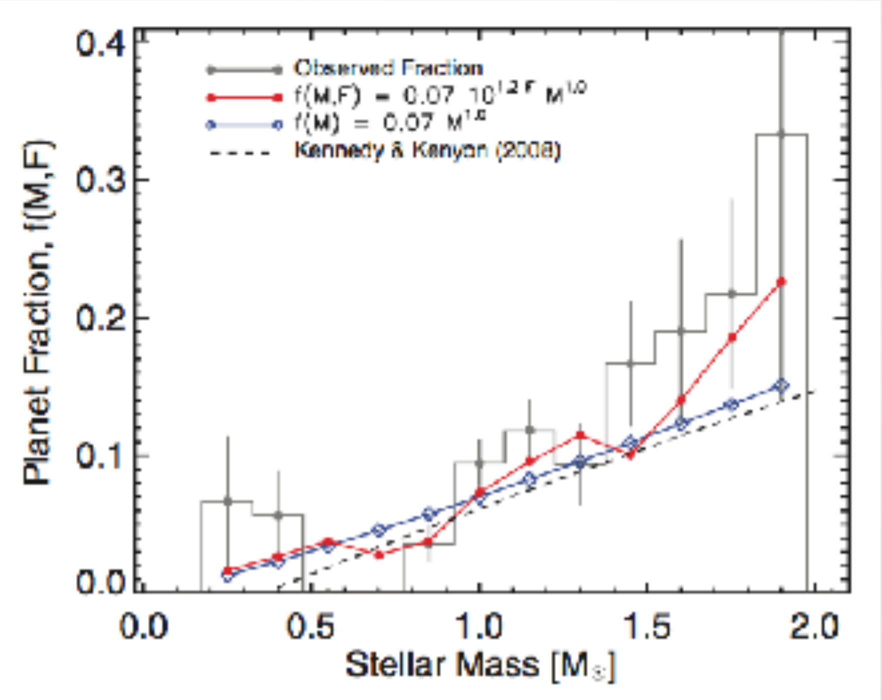


Target selection

- 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)

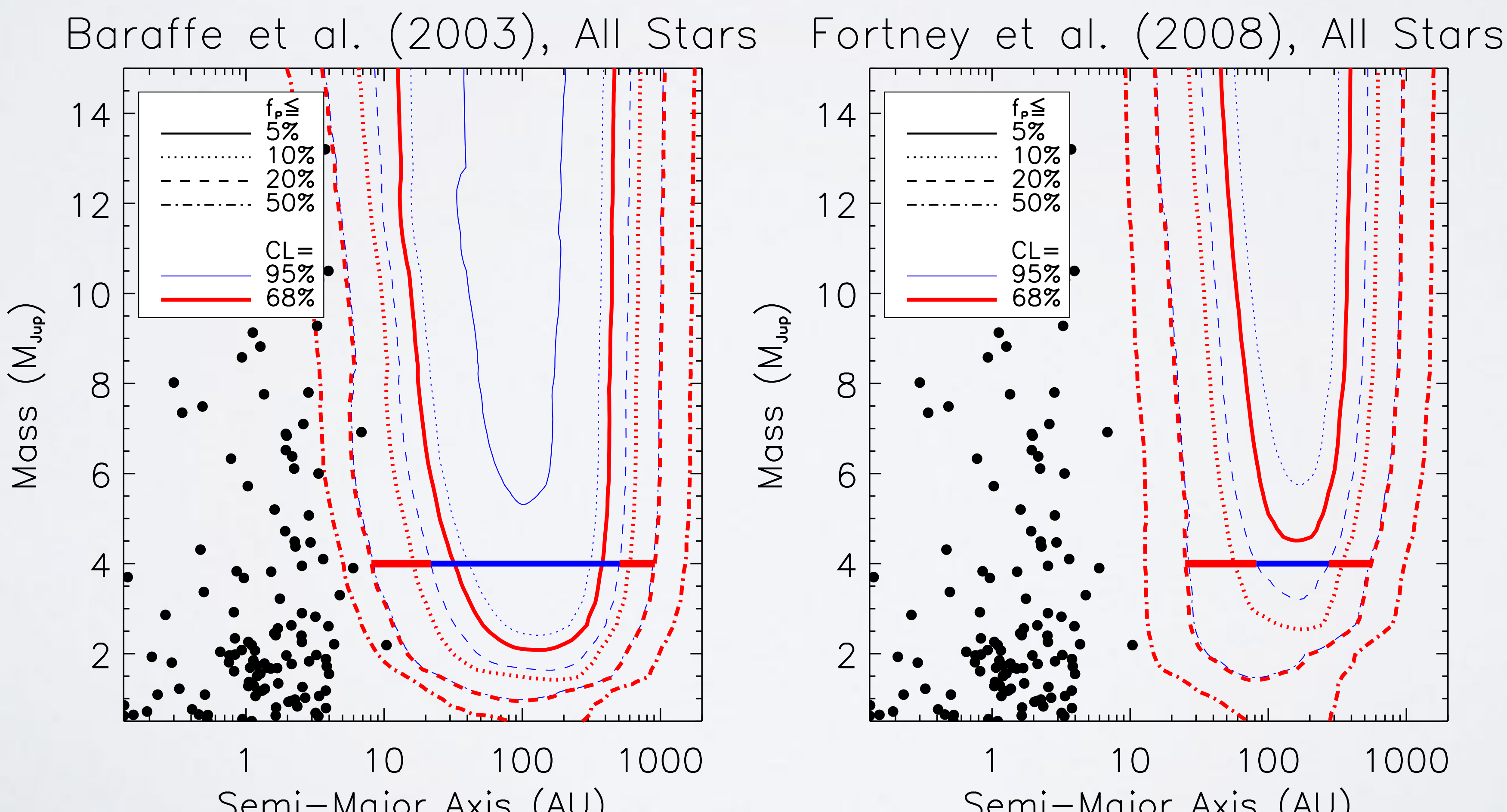
Direct imaging surveys

Census of all published direct imaging surveys:

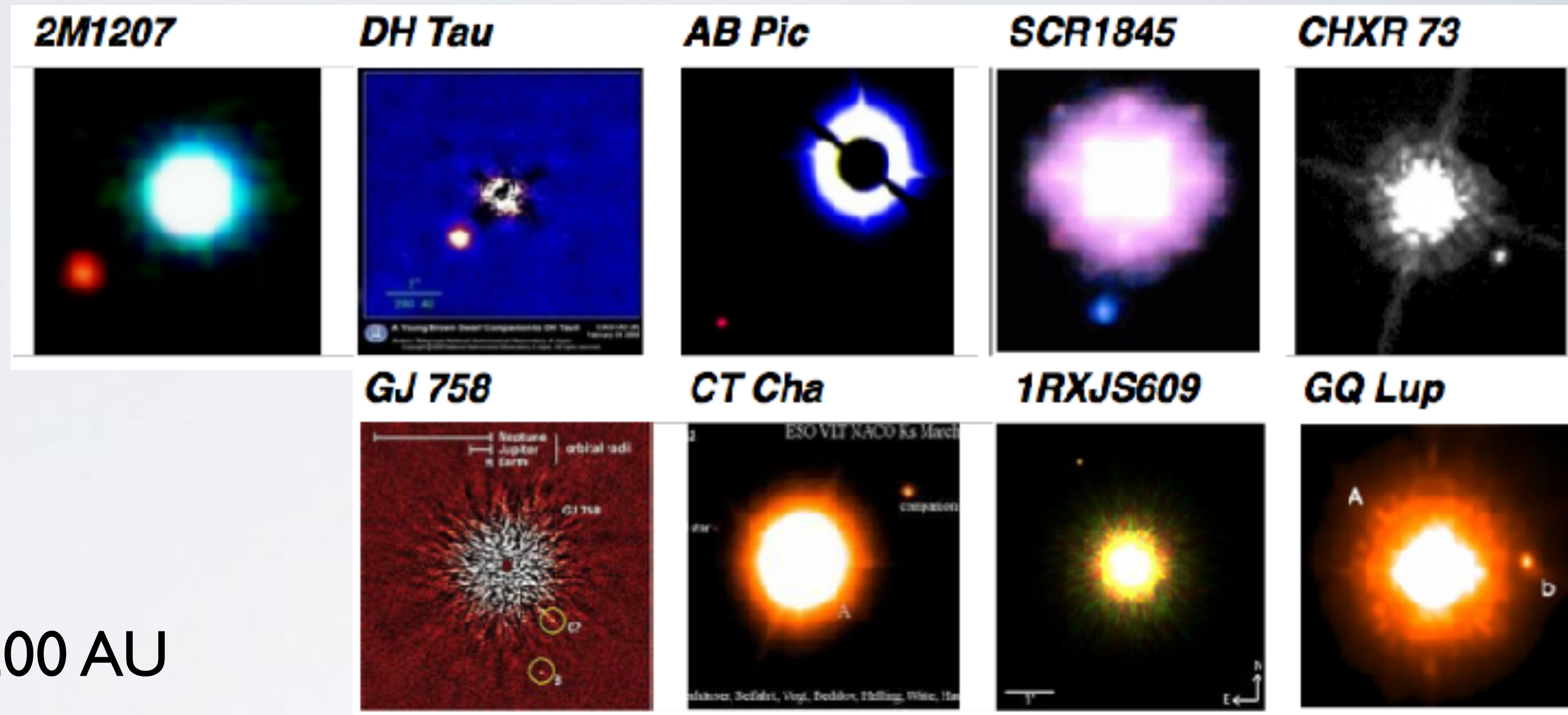
Reference	Telescope	Instr.	Mode	Filter	FoV (″×″)	#	SpT	Age (Myr)
Chauvin et al. 2003	ESO3.6m	ADONIS	Cor-I	H, K	13 × 13	29	GKM	≤ 50
Neuhäuser et al. 2003	NTT	Sharp	Sat-I	K	11 × 11	23	AFGKM	≤ 50
	NTT	Sofi	Sat-I	H	13 × 13	10	AFGKM	≤ 50
Lowrance et al. 2005	HST	NICMOS	Cor-I	H	19 × 19	45	AFGKM	10 − 600
Masciadri et al. 2005	VLT	NaCo	Sat-I	H, K	14 × 14	28	KM	≤ 200
Biller et al. 2007	VLT	NaCo	SDI	H	5 × 5	45	GKM	≤ 300
	MMT		SDI	H	5 × 5	-	-	-
Kasper et al. 2007	VLT	NaCo	Sat-I	L'	28 × 28	22	GKM	≤ 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	≤ 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	≤ 200
Rameau et al. 2013c	VLT	NaCo	ADI	L'	28 × 28	59	AF	≤ 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	≤ 200
Brandt et al. 2013[b]	Subaru	HiCIAO	ADI	H	20 × 20	63	AFGKM	≤ 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	≤ 1000
Chauvin et al. 2014	VLT	NaCo	ADI	H	14 x 14	80	FGK	< 300

Information on the population

- Actually very little information, **based on non-detections**
- Study by Nielsen et al. (2010):
  - giant planets around solar-type stars are rare
- based extrapolations of RV population studies (e.g. Cumming et al. 2008)
- extremely model-dependent



Family portrait



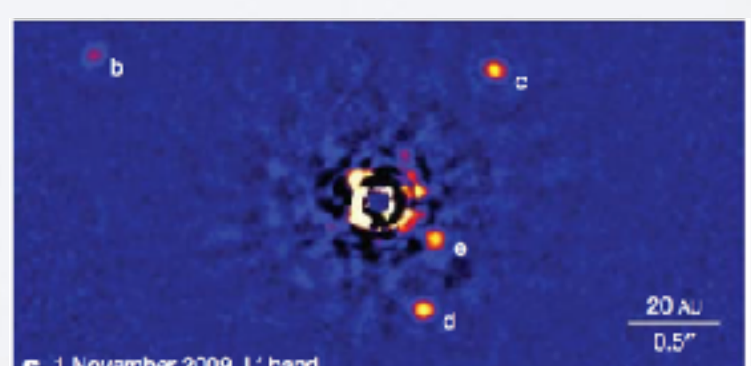
Wide orbit

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

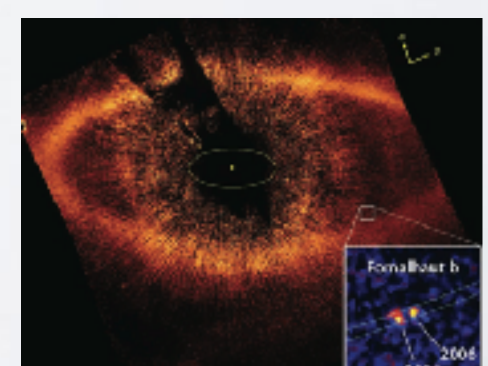
Close(r) orbit

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

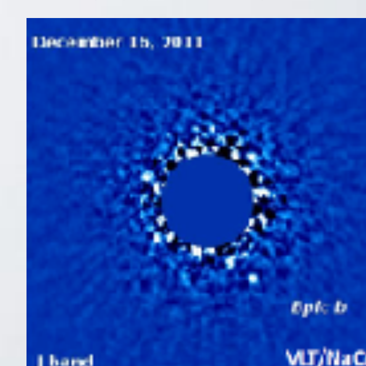
HR8799



Fomalhaut



Beta Pic



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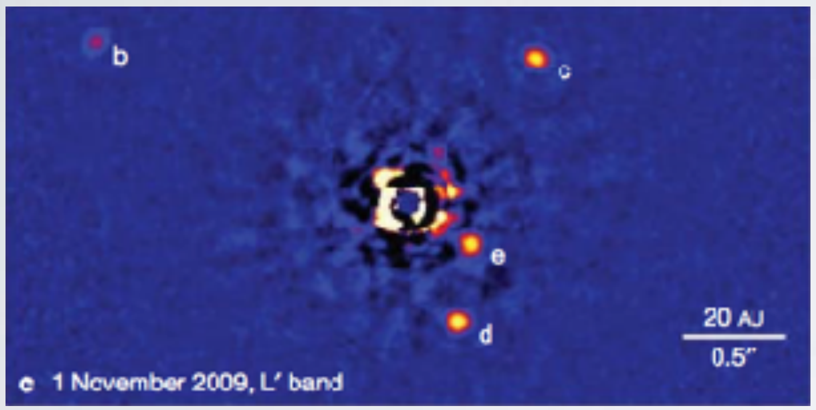
IDPS survey: context

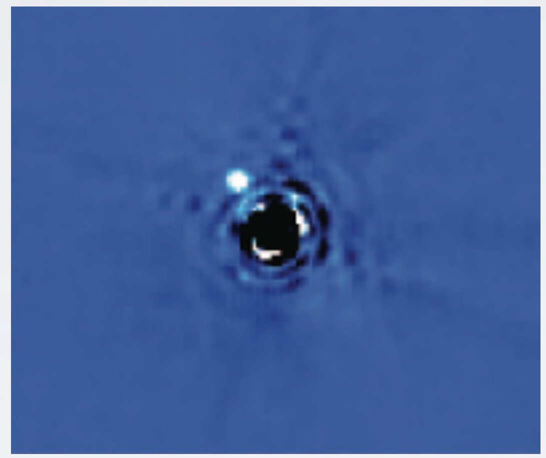
- Recent breakthrough discoveries around young A stars

HR 8799 - 30 Myr



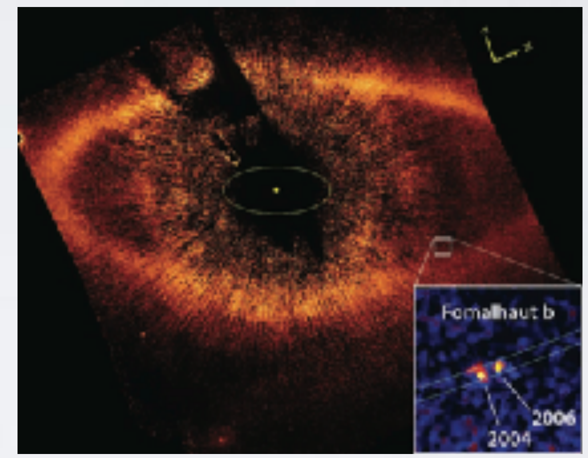
Marois et al. (2008, 2010)

β Pictoris - 12 Myr



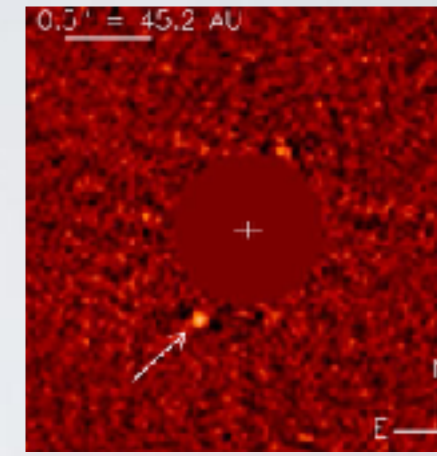
Lagrange et al. (2010)

Fomalhaut - 100-300 Myr



Kalas et al. (2008, 2013)

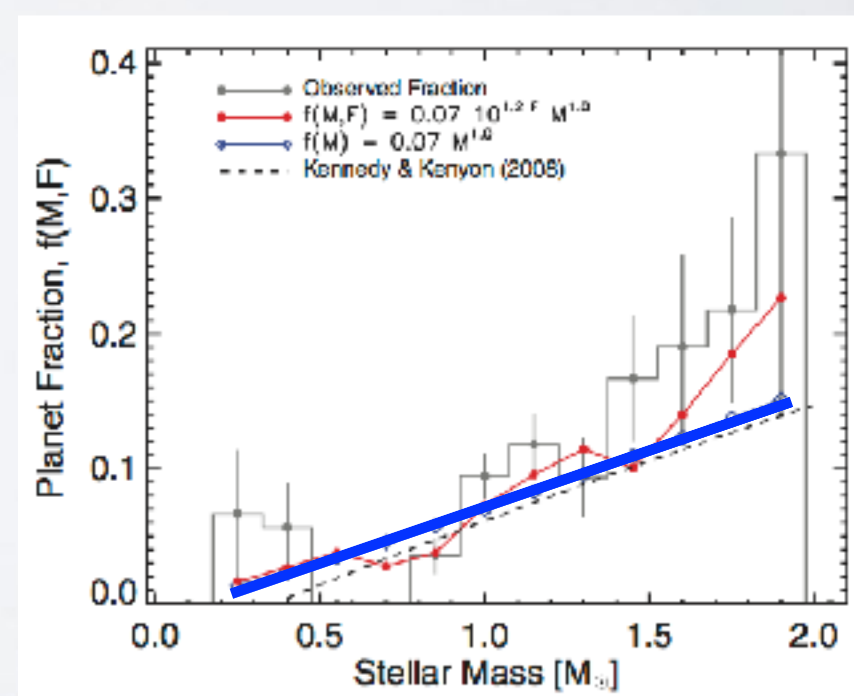
HD 95086 - 17 Myr



Rameau et al. (2013)

- Recent discoveries of RV planets around old A stars
  Lick and Keck subgiant surveys
  (Johnson et al. 2010, 2011; Bowler et al. 2010)

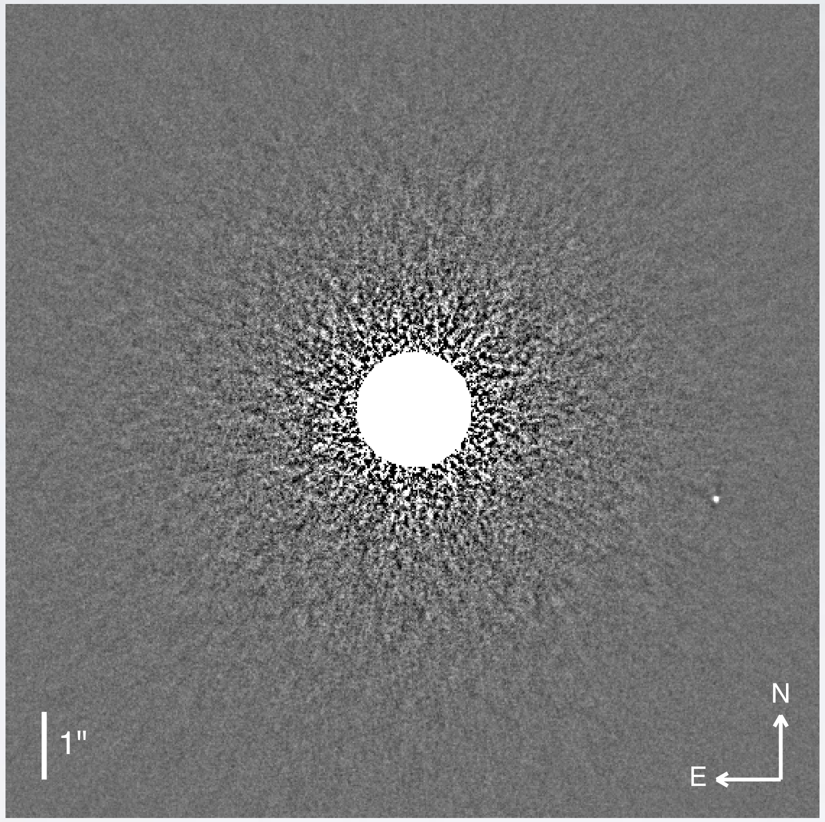
→ strong correlation between stellar mass and planet mass

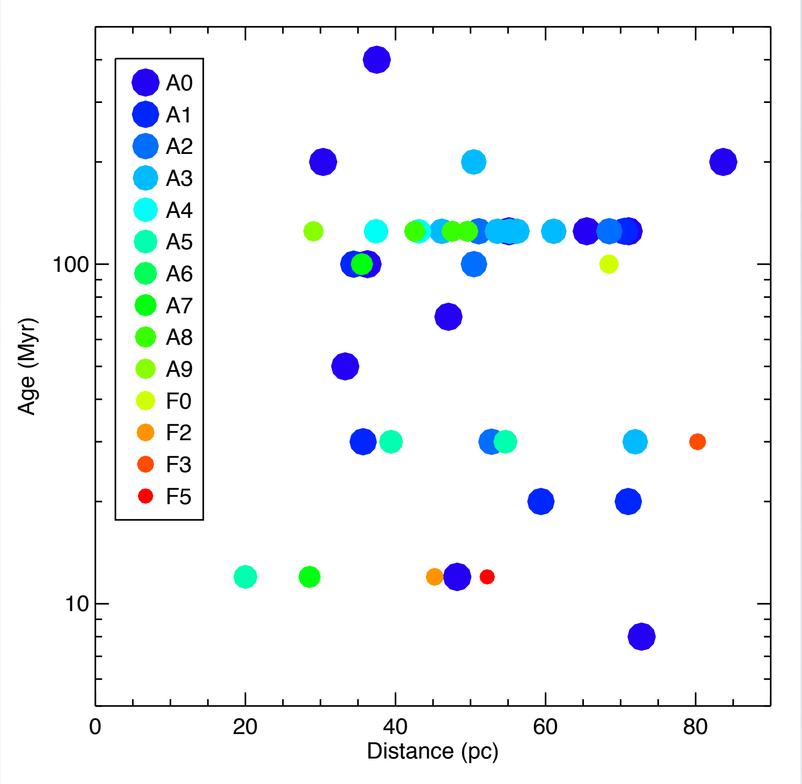


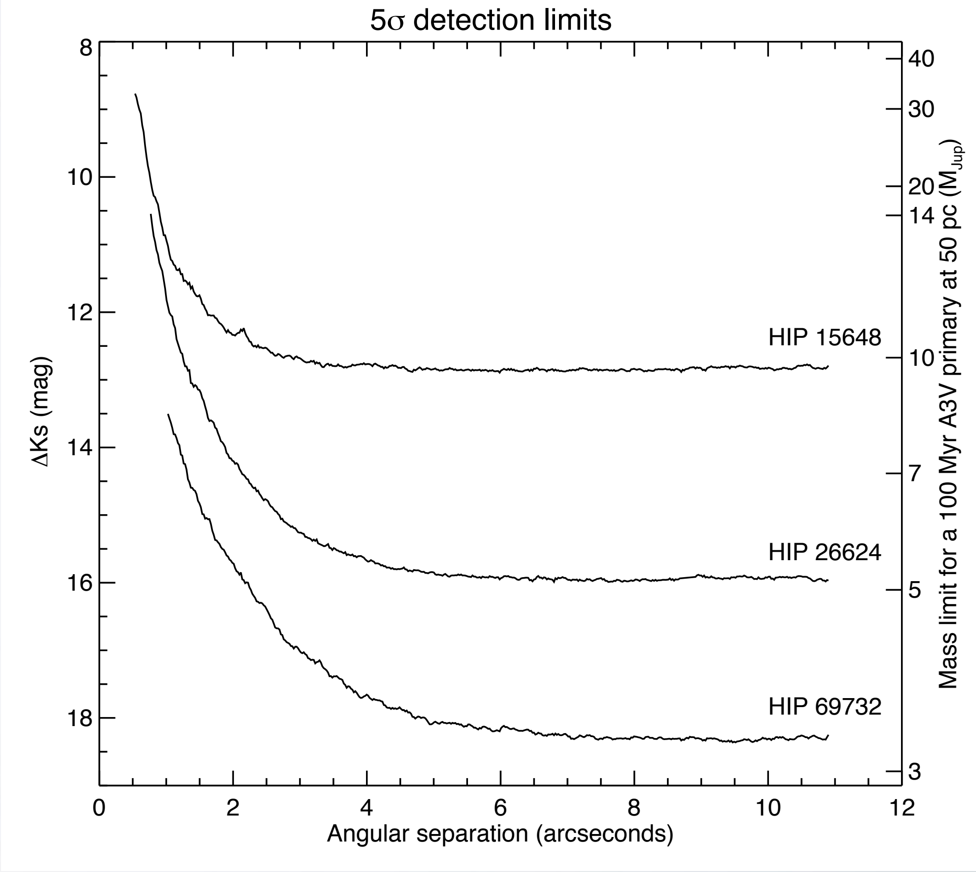
Johnson et al. (2010b)

IDPS survey: sample, observations, analysis

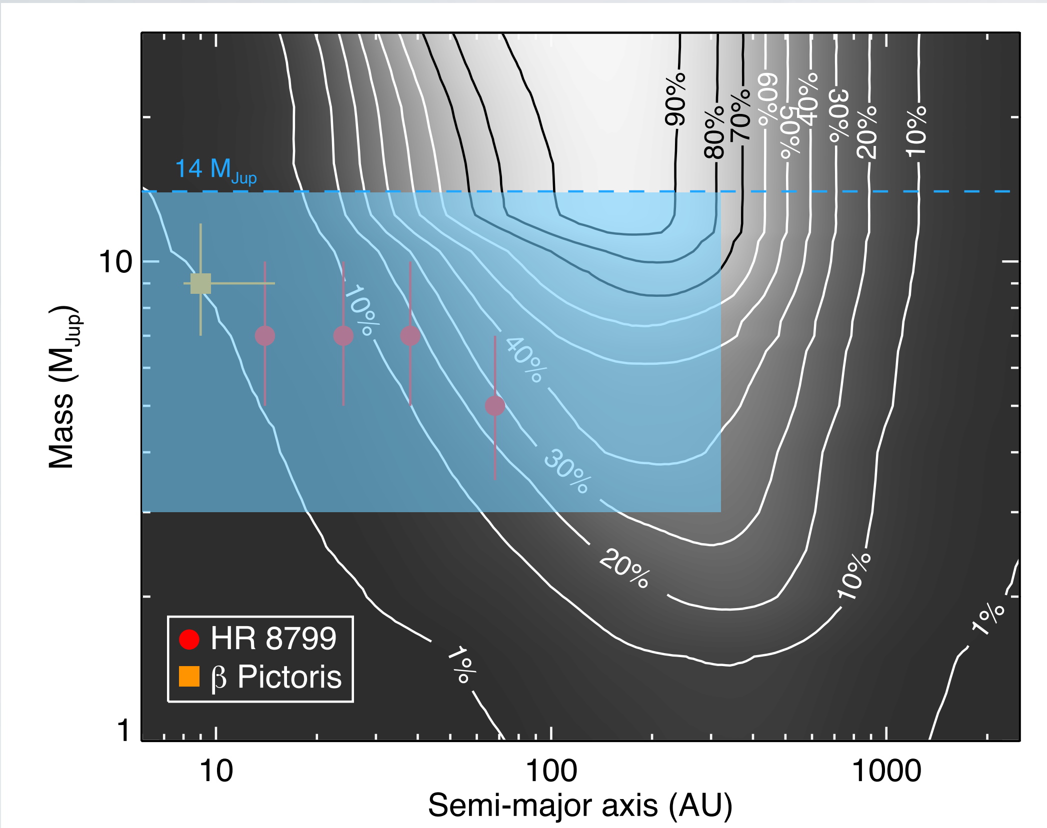
- sample of **38 young A-stars + 4 F-stars**
  - β Pic
  - HR8799
- observations:
  - 2007-2012
  - NACO, NIRI
  - ADI
  - H- and K-band
  - saturated imaging
- data analysis with LOCI
- **no new substellar companions**

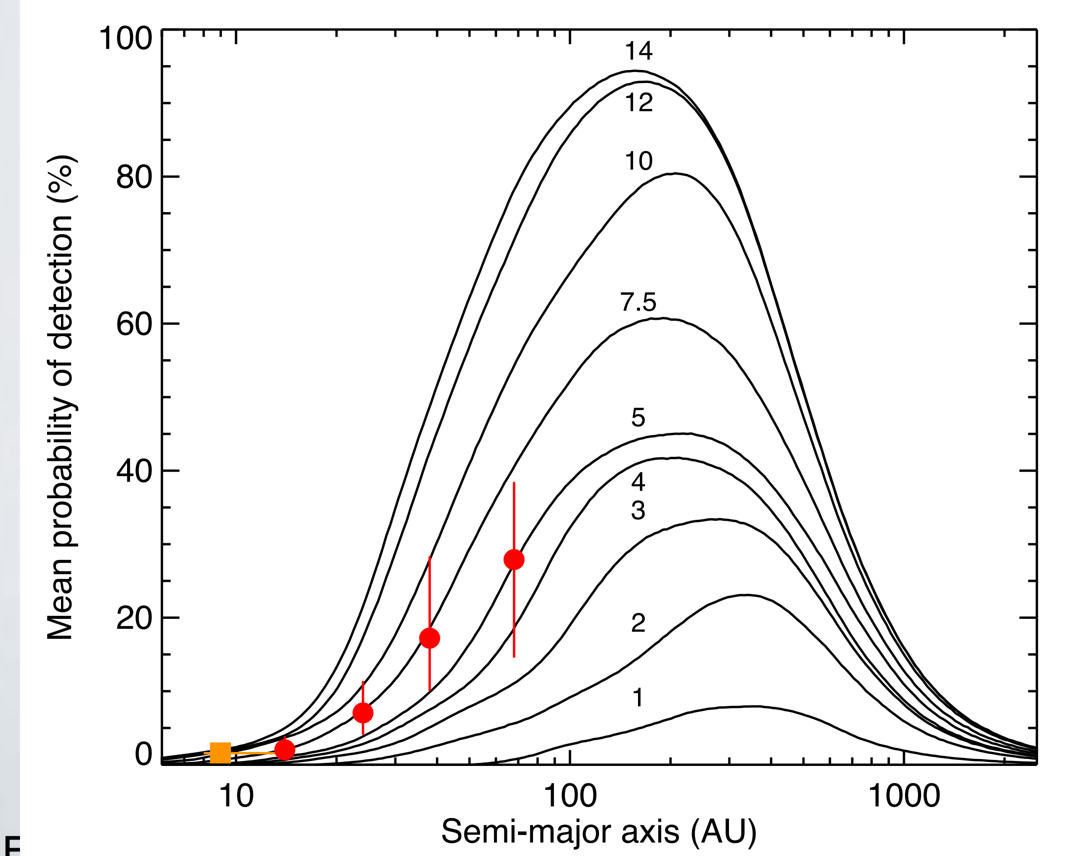


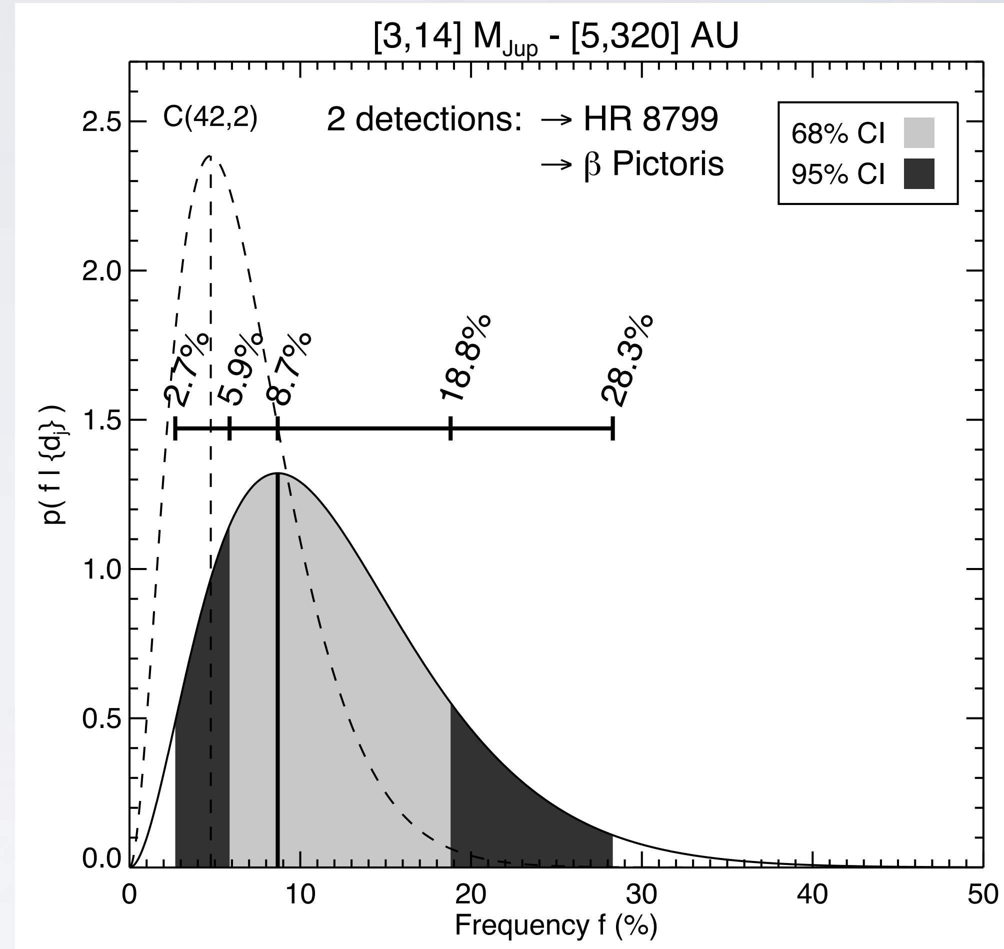




IDPS survey: results







Vigan et al. (2012)

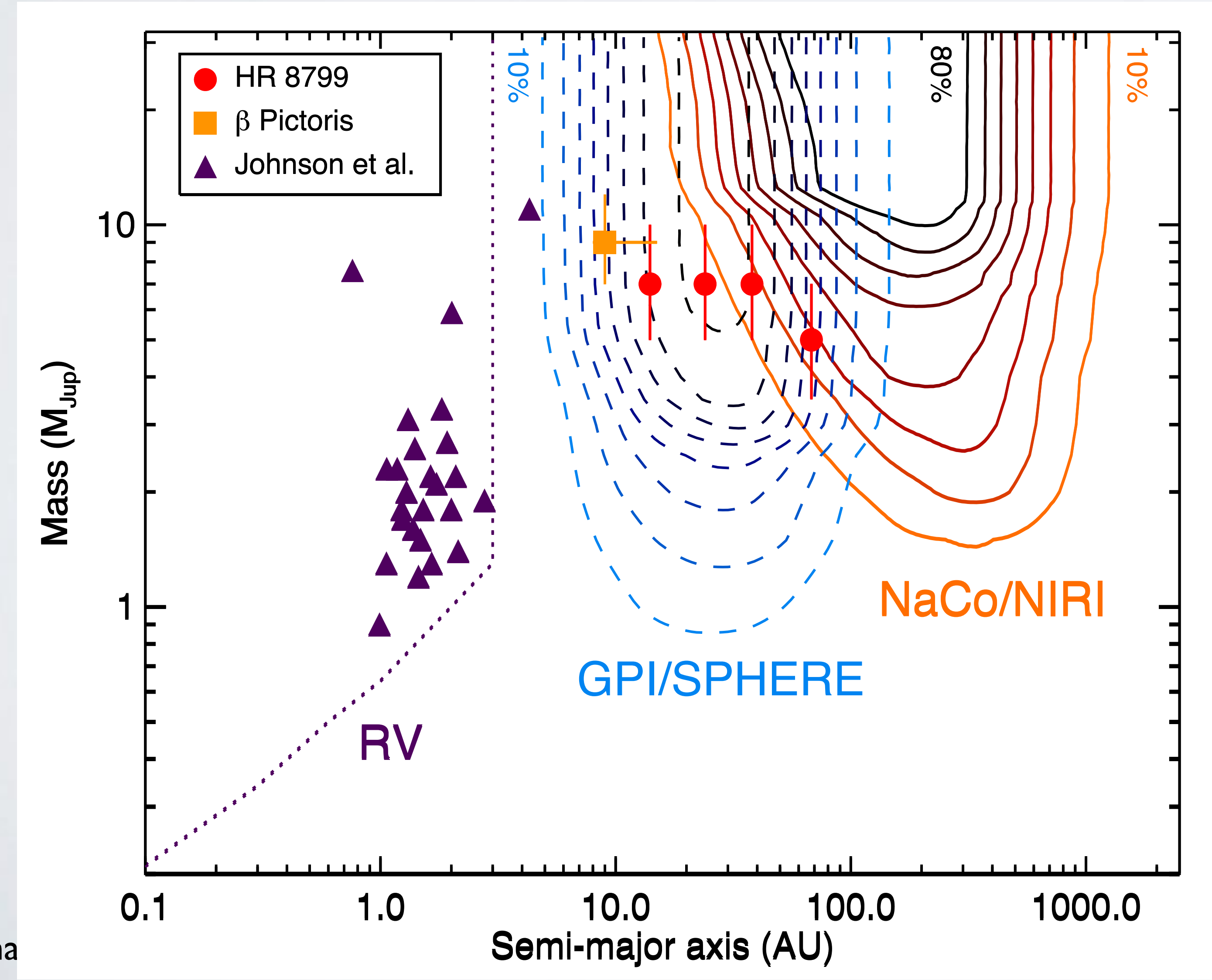
$f \in [5.9\%, 18.8\%]$ at 68% confidence

- 3 $M_{Jup} \leq$ mass $\leq$ 14 M_{Jup}
- 5 AU $\leq$ a $\leq$ 320 AU

Result confirmed by Rameau et al. (2013)
In agreement with NICI survey (Nielsen et al. 2013)

New generation of instruments

- What do we want?
  - get **closer in separation**
  - reach **higher contrast**
  - get spectral information
- What is currently missing?
  - **high-order AO** correction at fast rate (>1 kH
  - efficient coronagraphs with **small IWA**



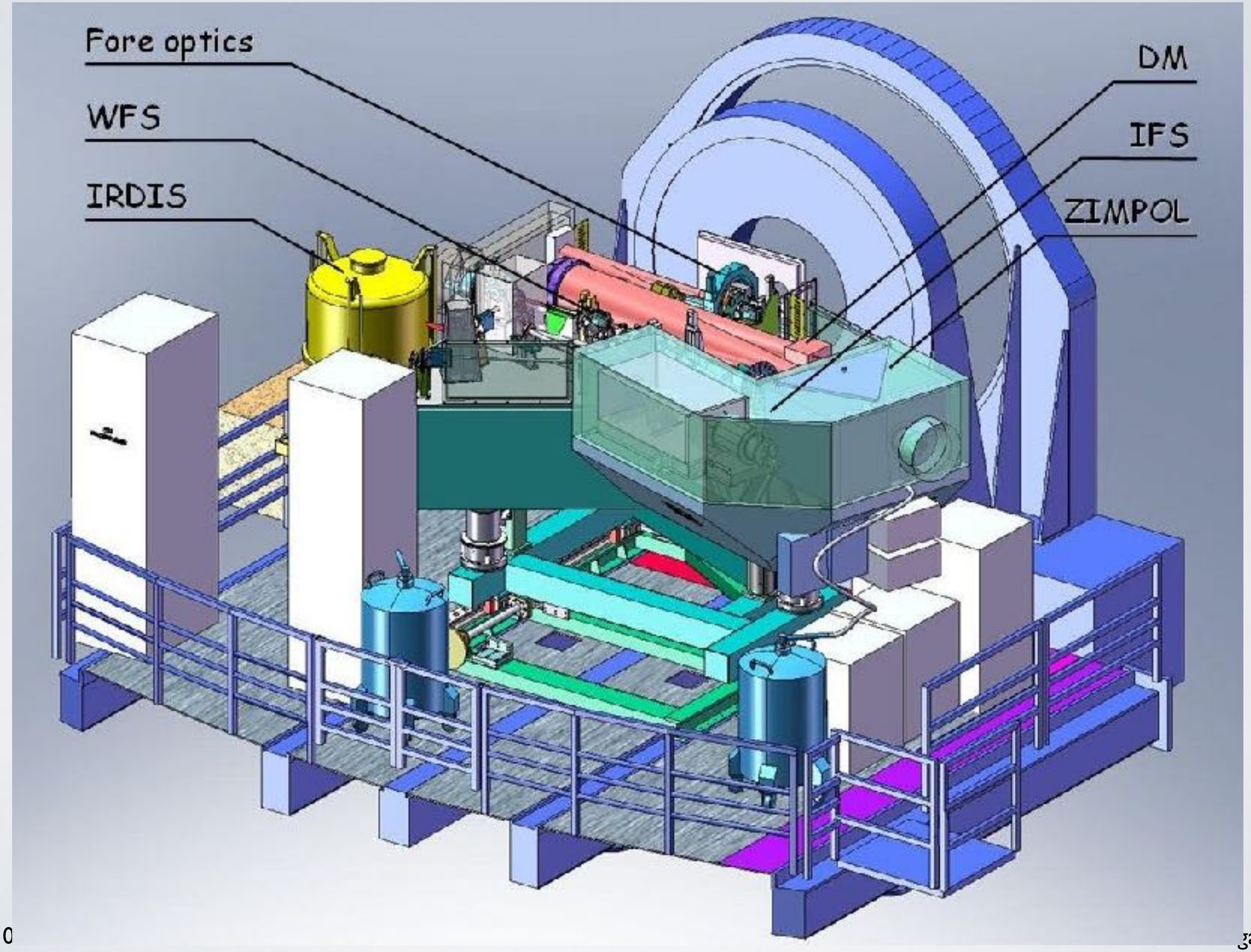
New generation of dedicated instruments

Two main contenders

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: telescope interface

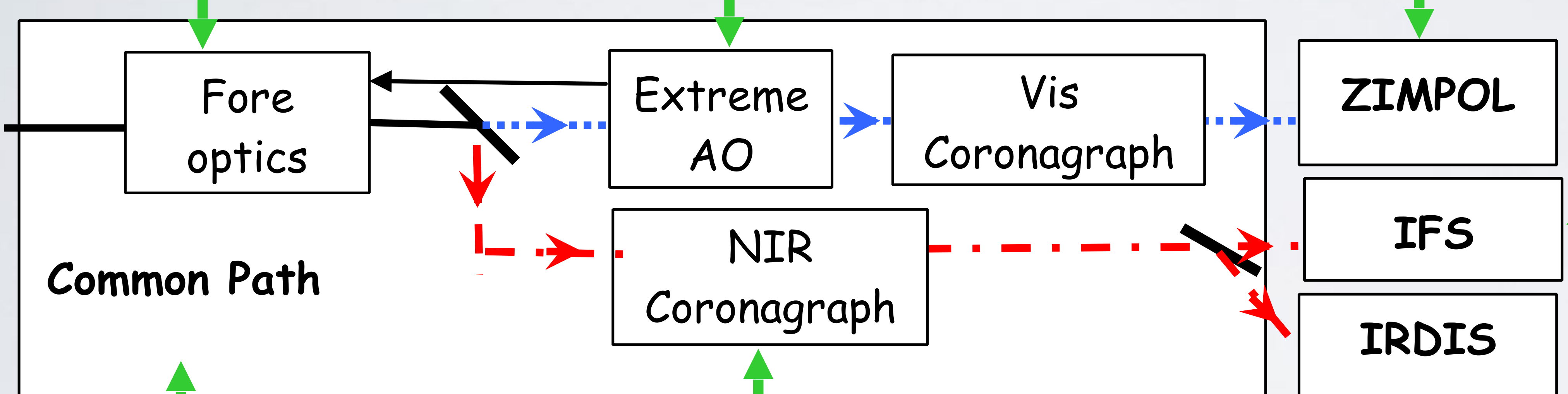


SPHERE: concept overview

Beam control (DM, TT, PTT, derotation)
Polarisation control
Calibration

High frequency AO correction (41x41 act.)
High stability : image / pupil control
Visible - NIR Refraction correction
40x40 SH-WFS in visible
1.2 KHz, RON < 1e-

Coronagraphic imaging:
Dual polarimetry, direct BB + NB.
λ = 0.5 - 0.9 μm,
Nyquist sampled @ 0.6 μm
FoV = 3.5”



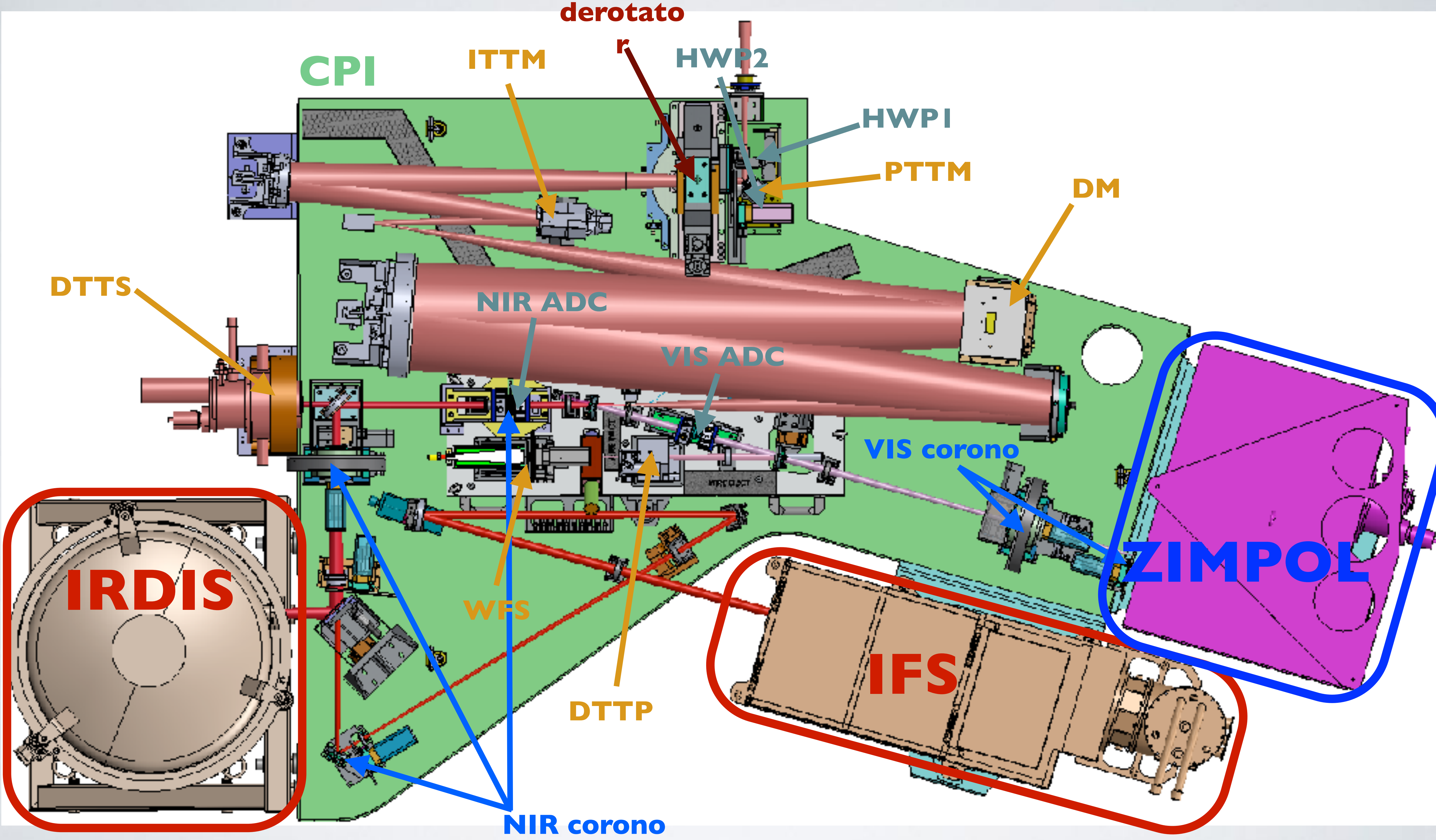
0.95 - 1.35/1.65 μm
Nyquist sampled @ 0.95 μm
R = 54 / 33
FoV = 1.77”

Pupil apodisation,
Focal masks: Lyot, apodized Lyot, 4QPM
IR-TT sensor for fine entering

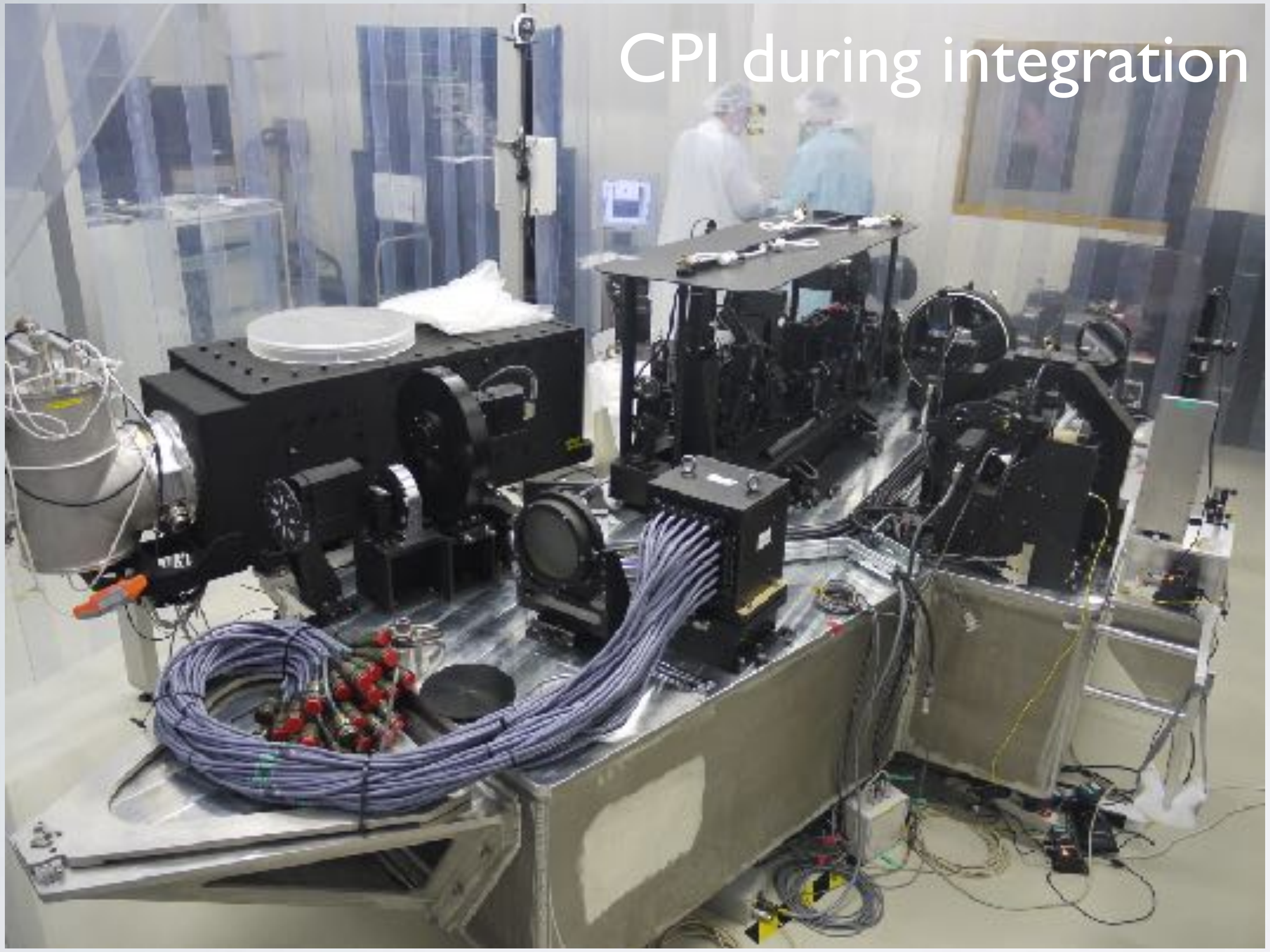
Nasmyth platform, static bench,
Temperature control, cleanliness control
Active vibration control

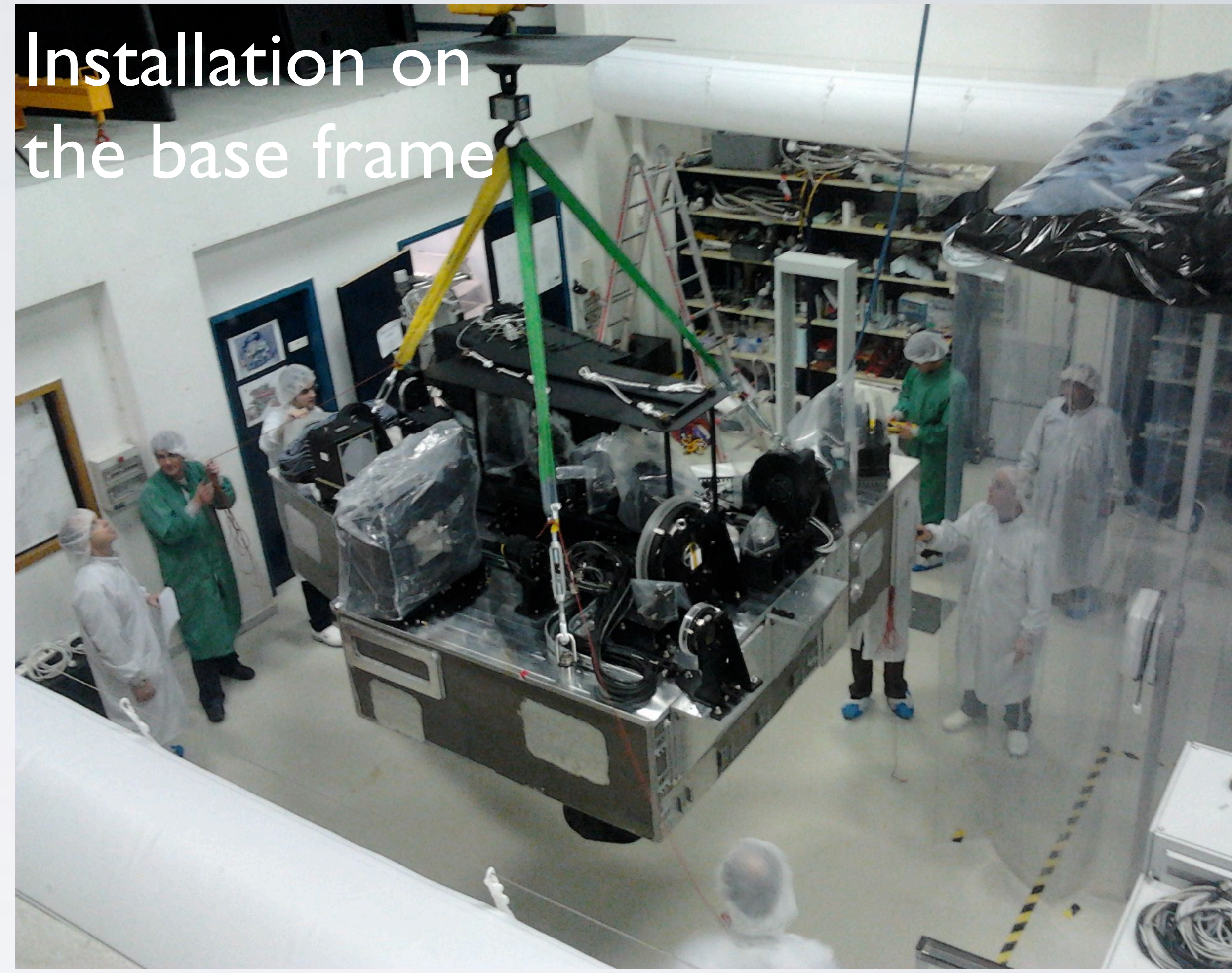
0.95 – 2.32 μm
Nyquist sampled @ 0.95 μm
FoV = 12.5”
2 wavelength differential imaging: R~30
Long Slit spectro: R~50 & 400
Differential polarization

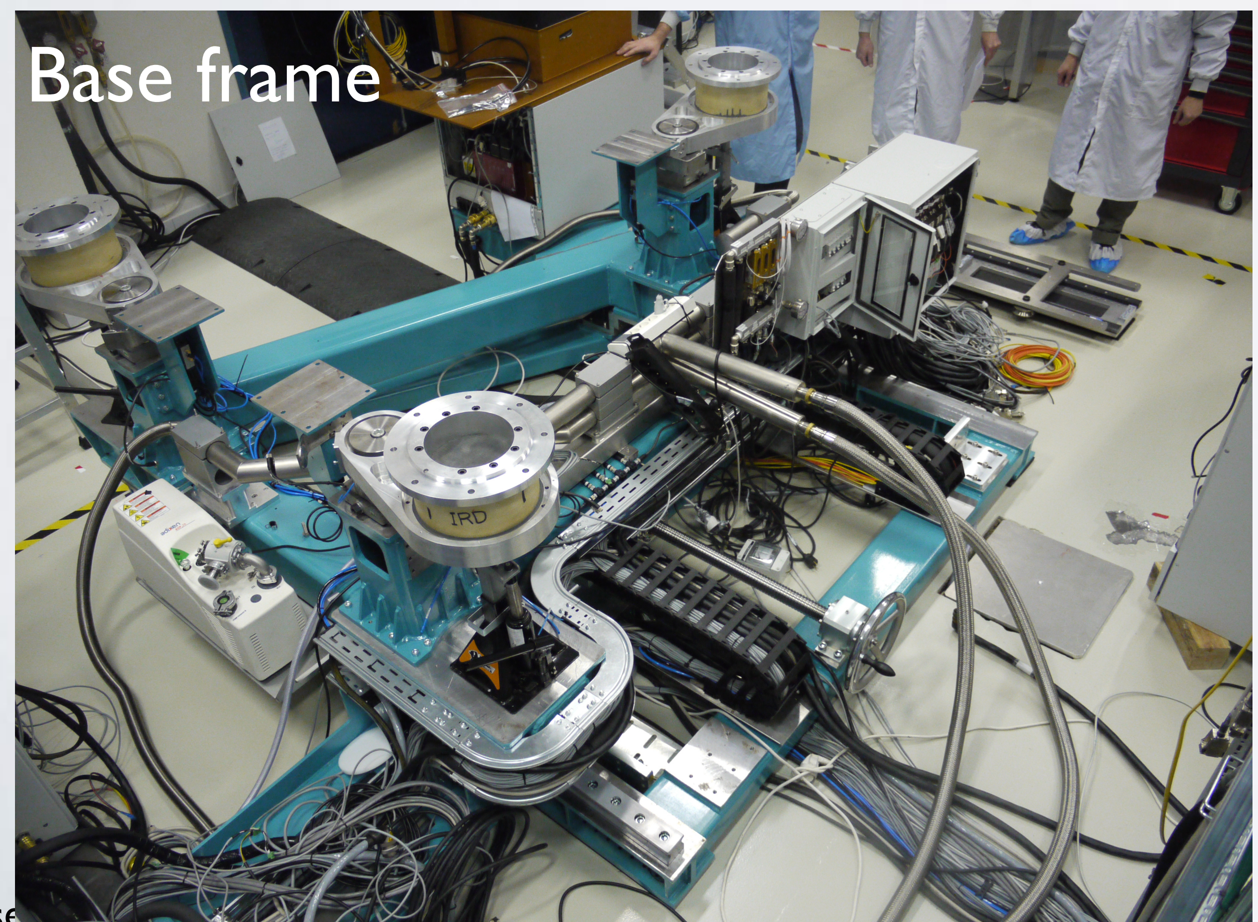
SPHERE: implementation



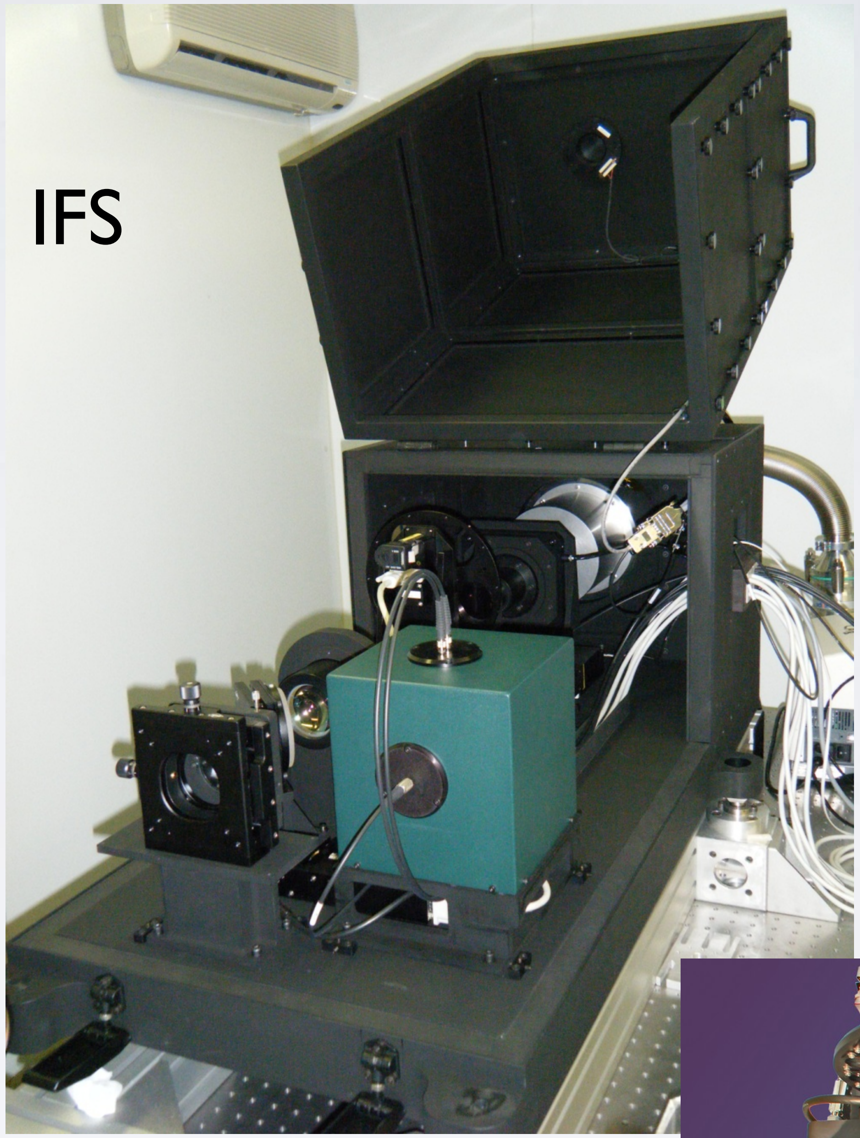
SPHERE in pictures

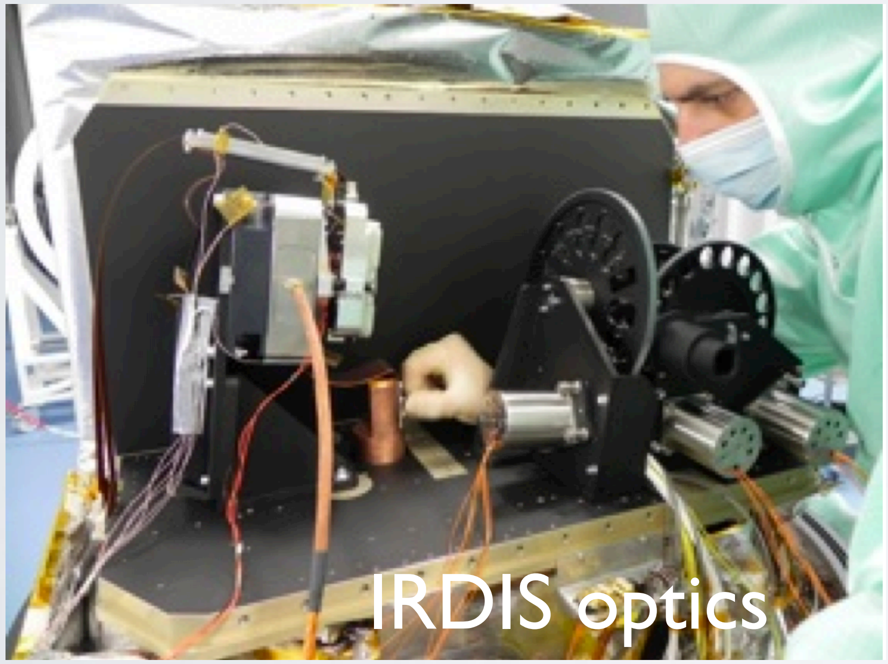


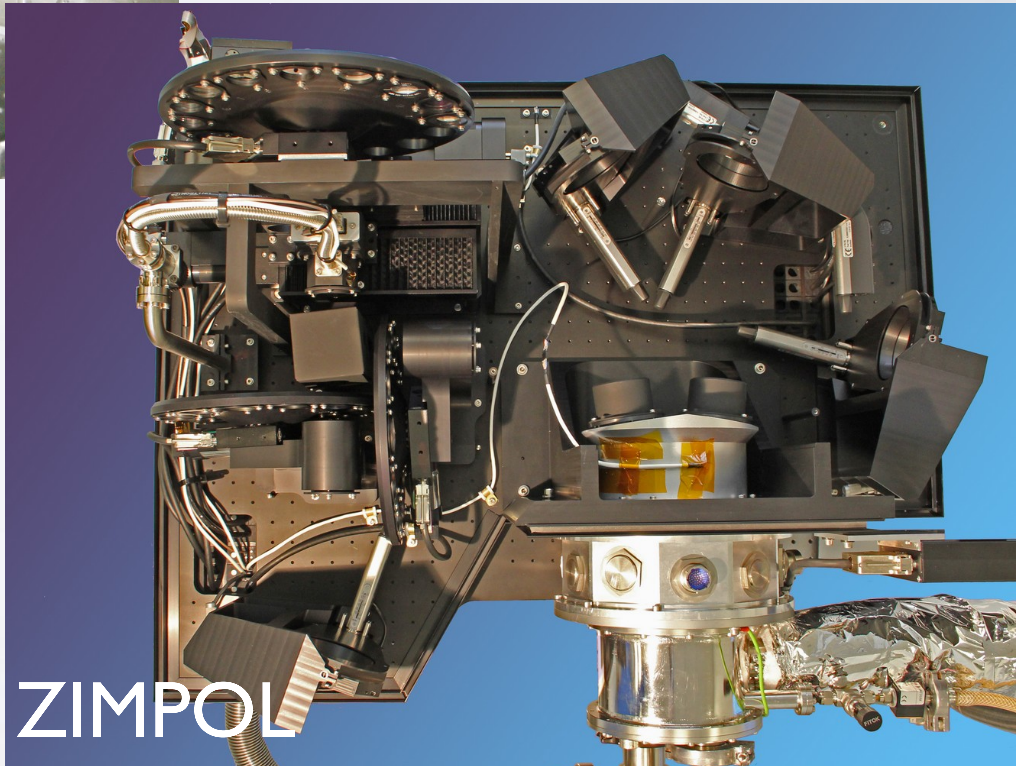




SPHERE in pictures

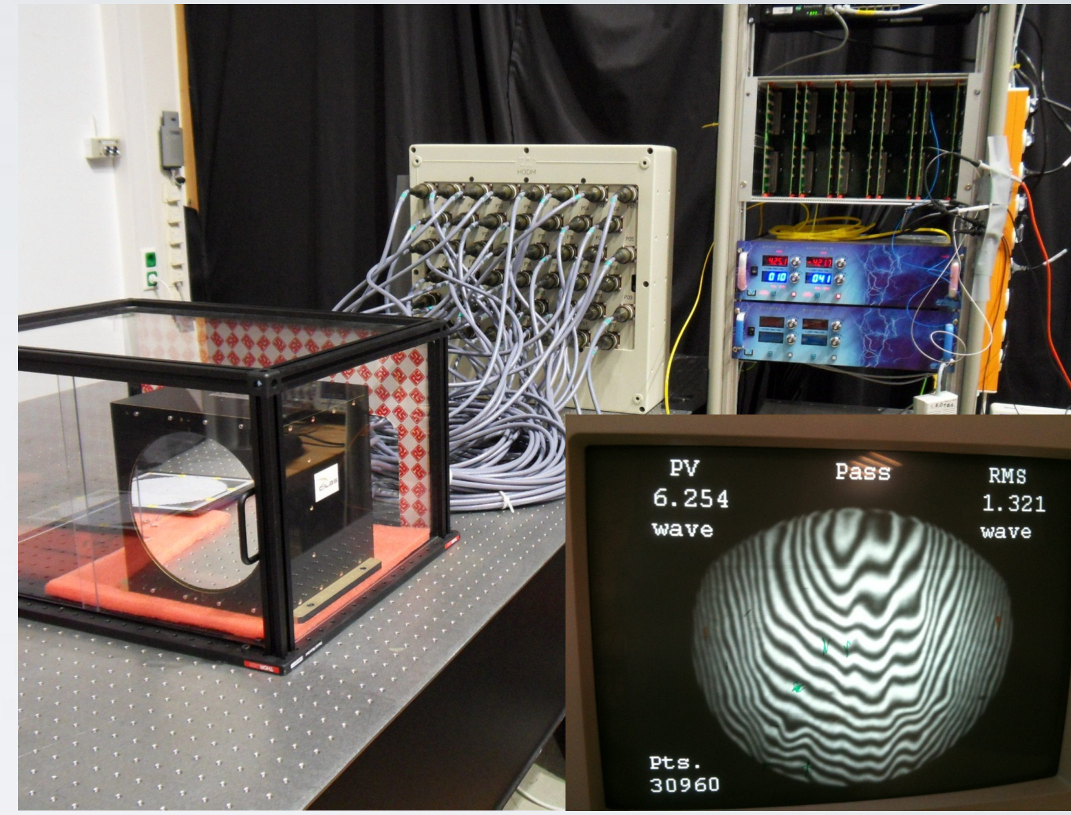


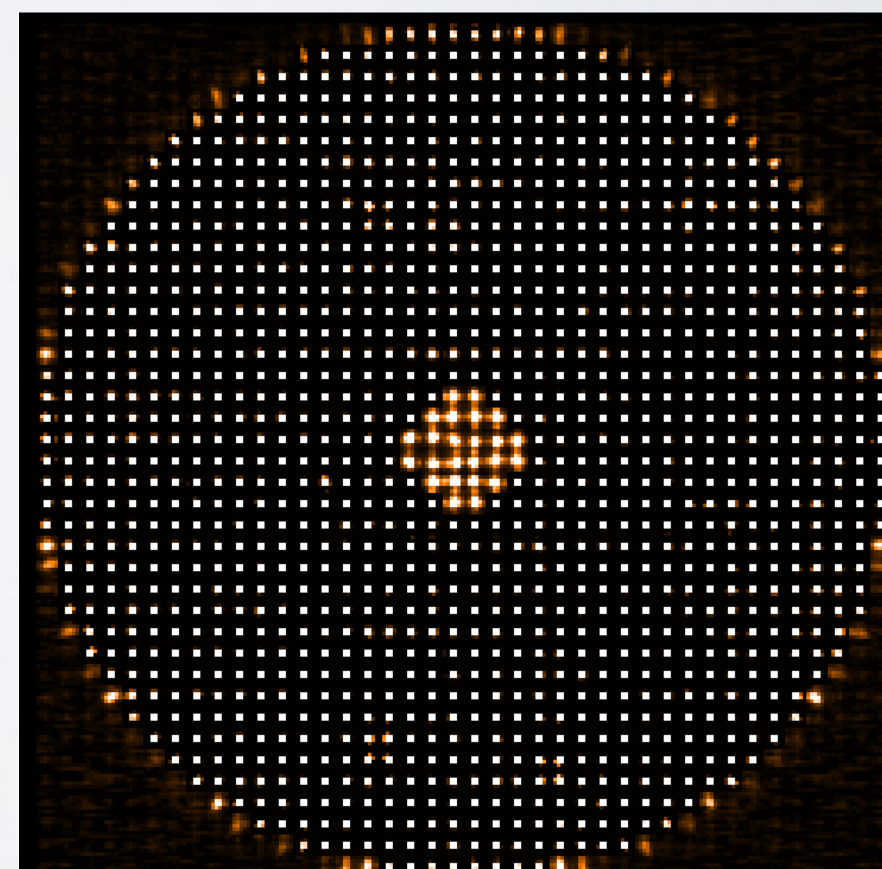




SAXO: overview

- 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



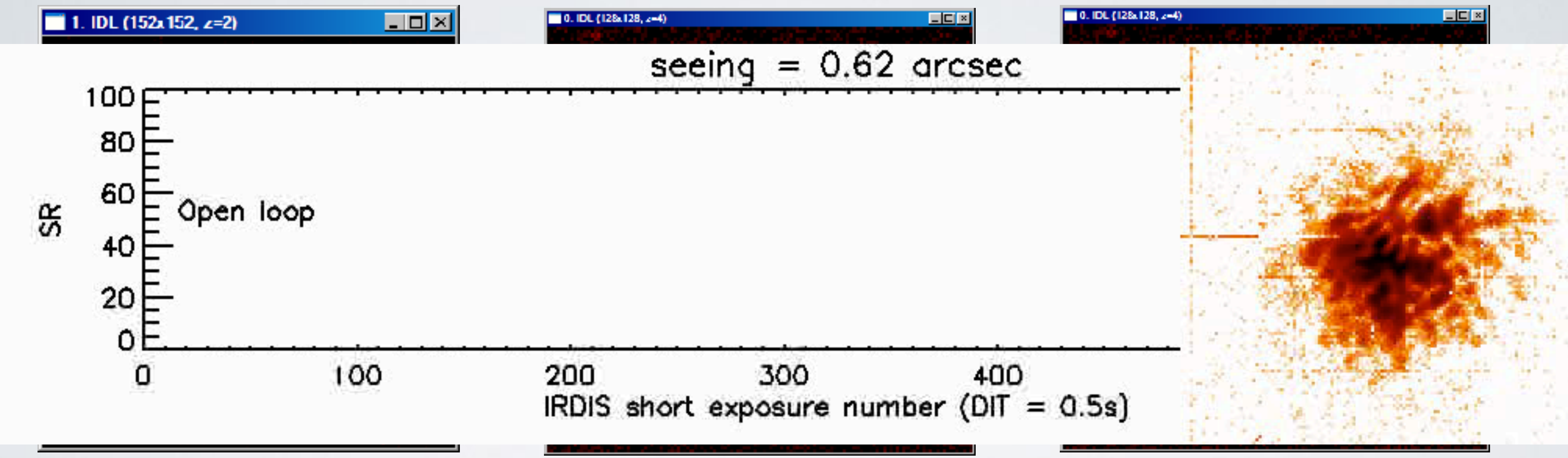


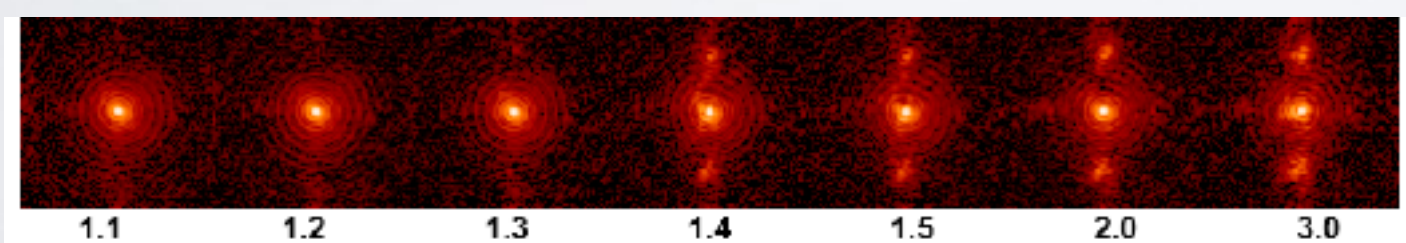
SAXO: results

Open loop
Sr = ~5%

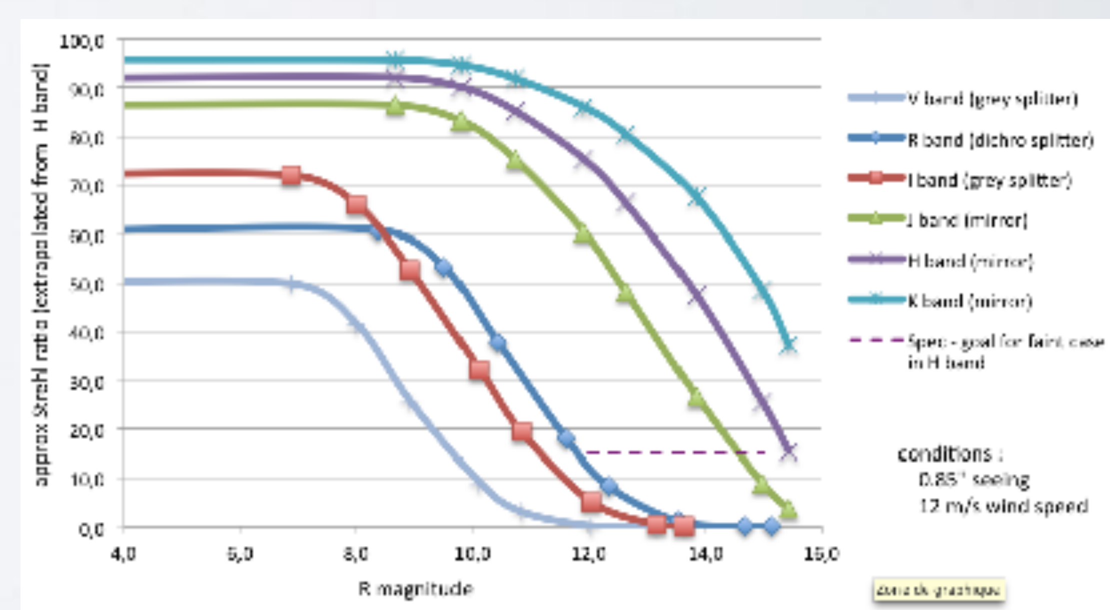
Closed loop
Sr = 85%

Closed loop + NCPA
Sr = 99%





Spatial filtering for anti-aliasing

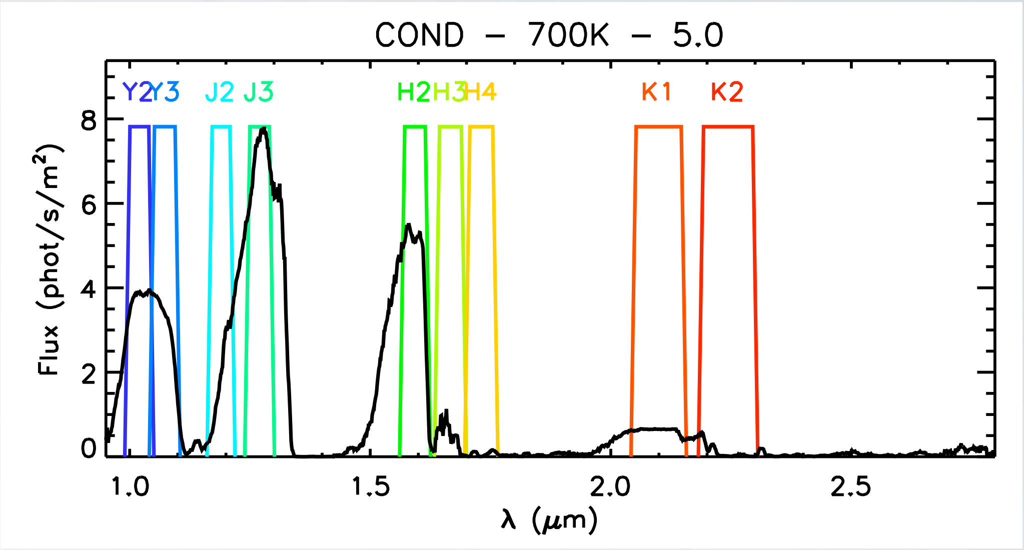


Science sub-systems

	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 = 50/400**	**R = 50 / 30**
Linear polarisation	**Simultaneous**	**Simultaneous (dual-beam)**	
Nyquist sampling	**@ 0.6 µm**	**@ 0.95 µm**	**@ 0.95 µm**

IRDIS: dual-band imaging

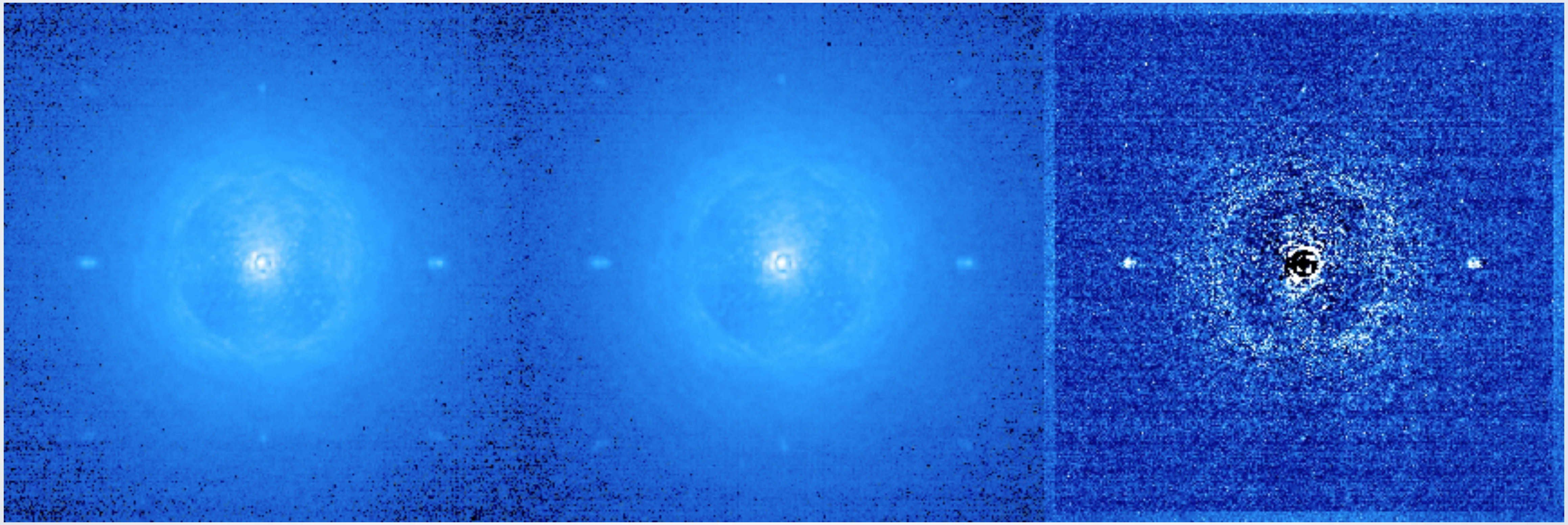
- **4 observing modes**
- main mode is **dual-band imaging (DBI)**
  - two images acquired simultaneously at close wavelength
  - 5 pairs of filters covering YJHKs



H2 = 1.593 μm

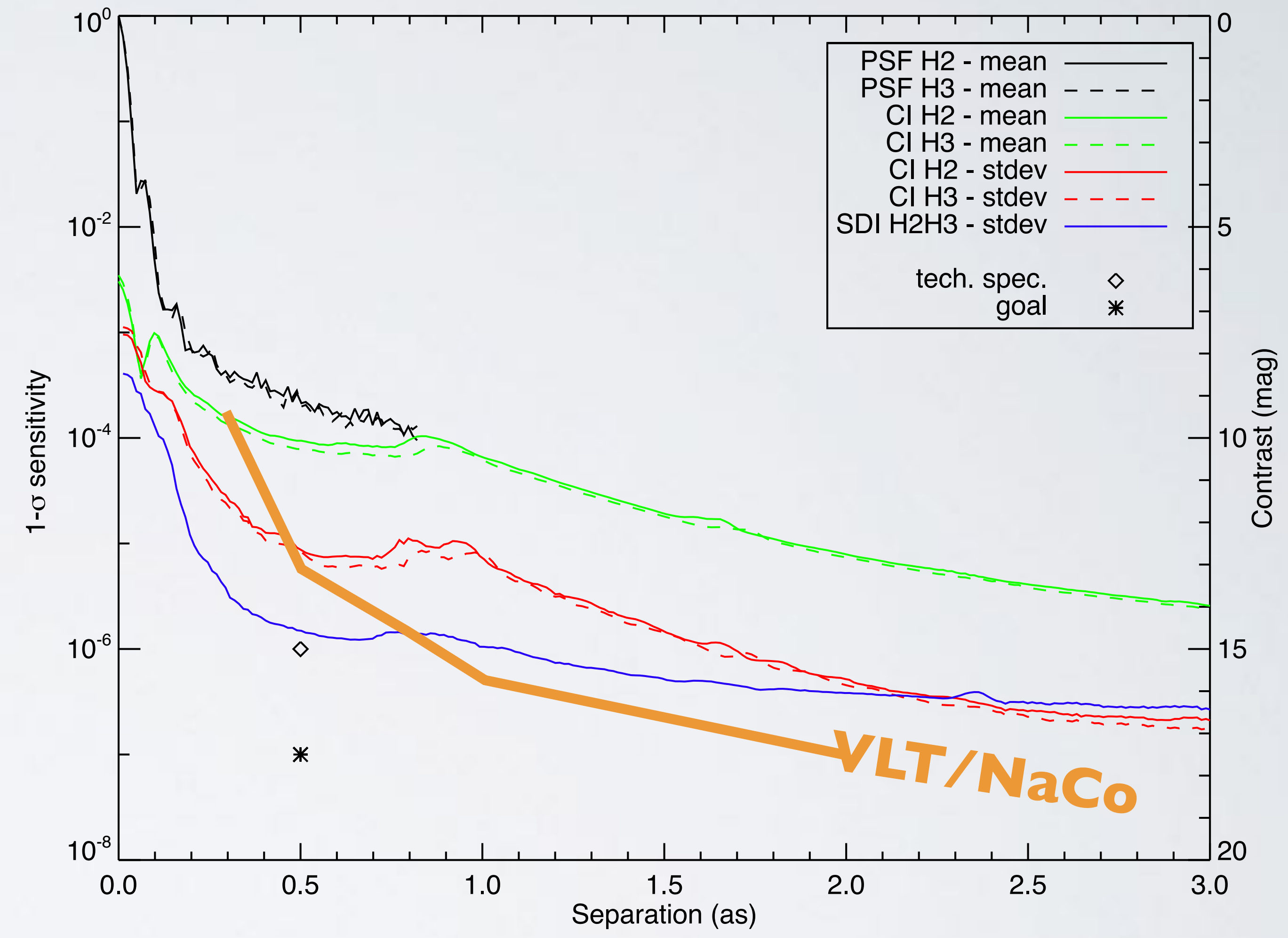
H3 = 1.667 μm

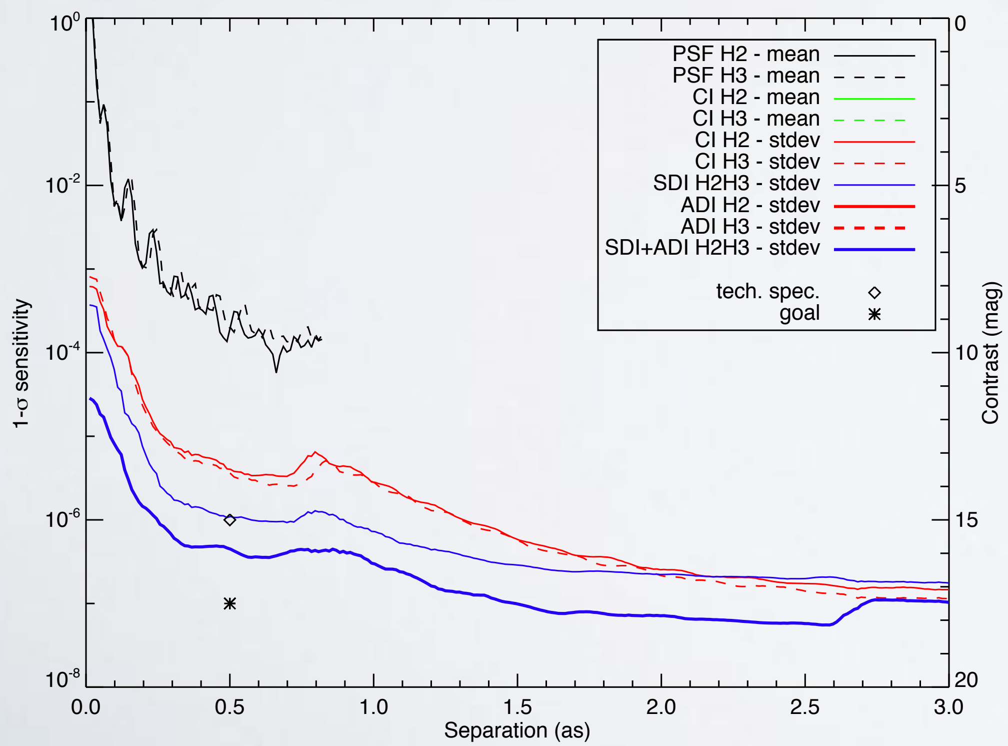
H2-H3



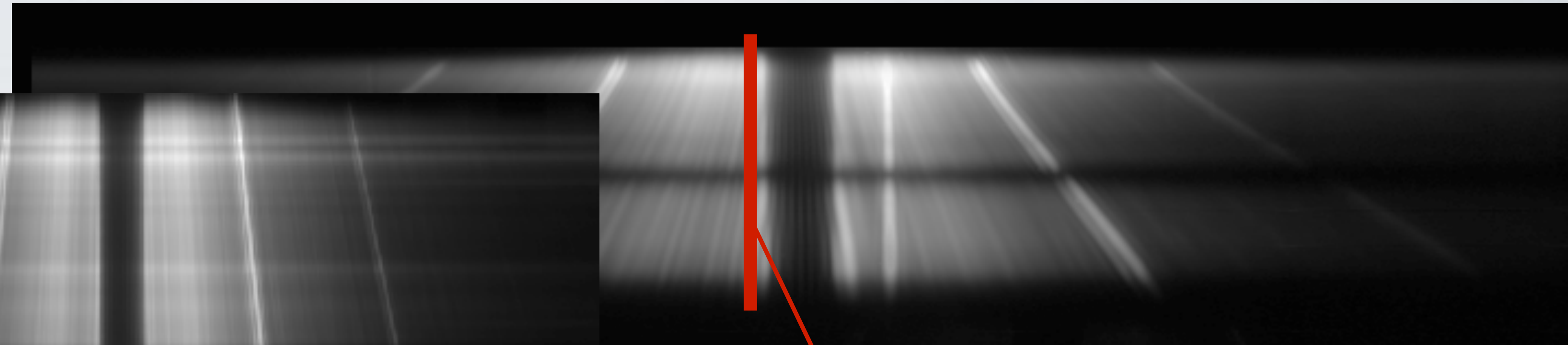
IRDIS: performance in DBI

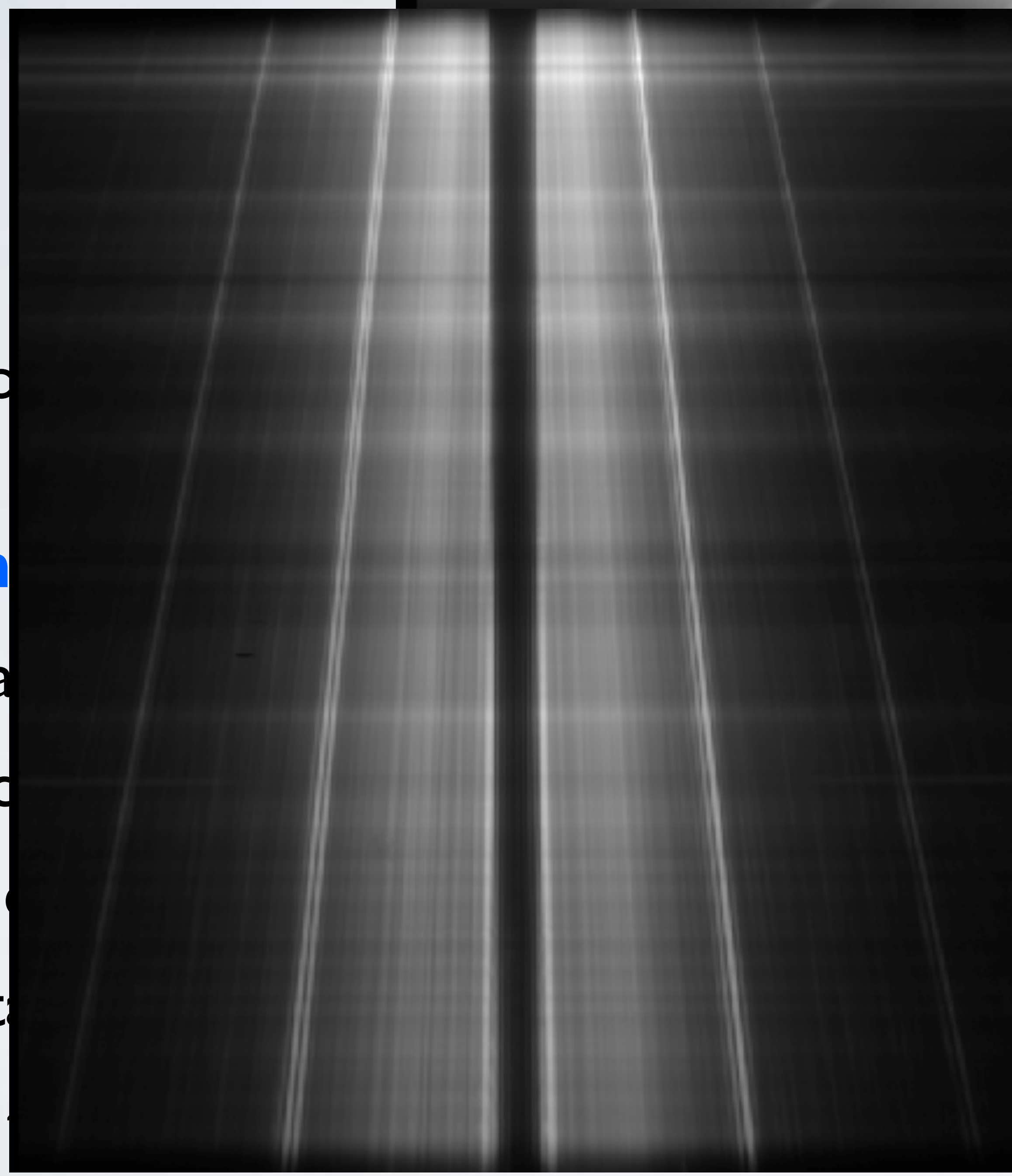
- Performance estimated in **SDI only**
- ADI cannot be simulated in the lab
  - fixed pupil outside of the instrument
  - wobble of the derotator
- **simulated ADI** with discrete derotator positions:



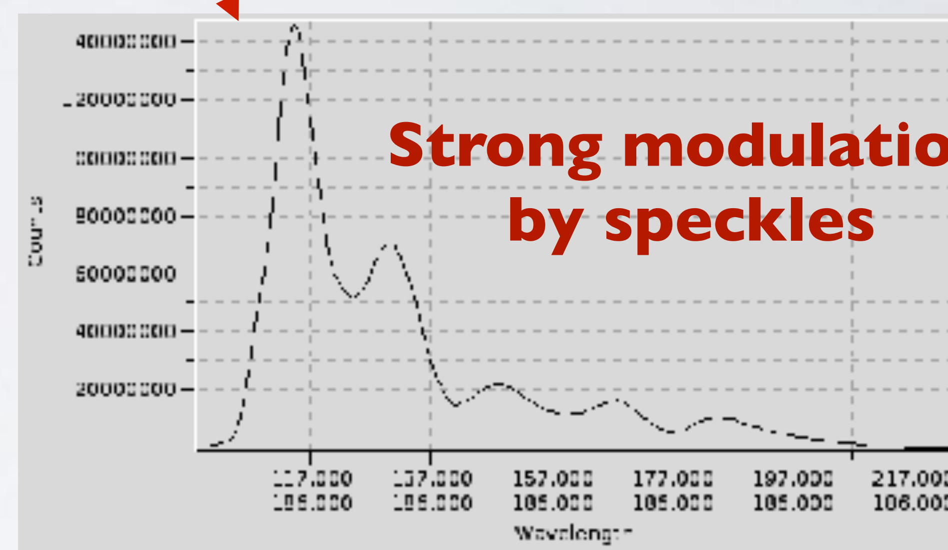


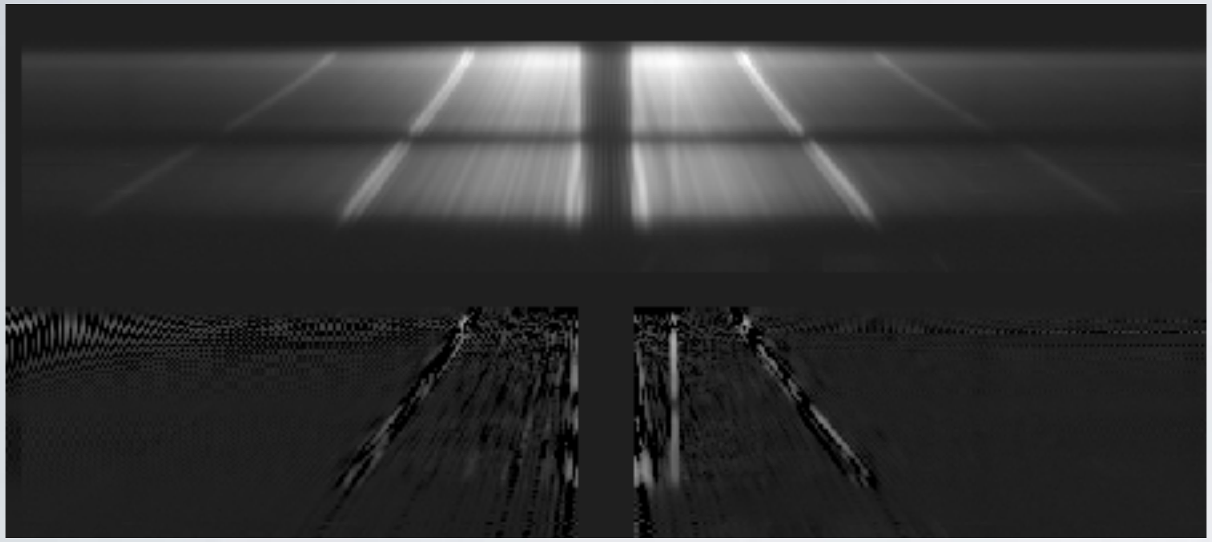
IRDIS: long slit spectroscopy





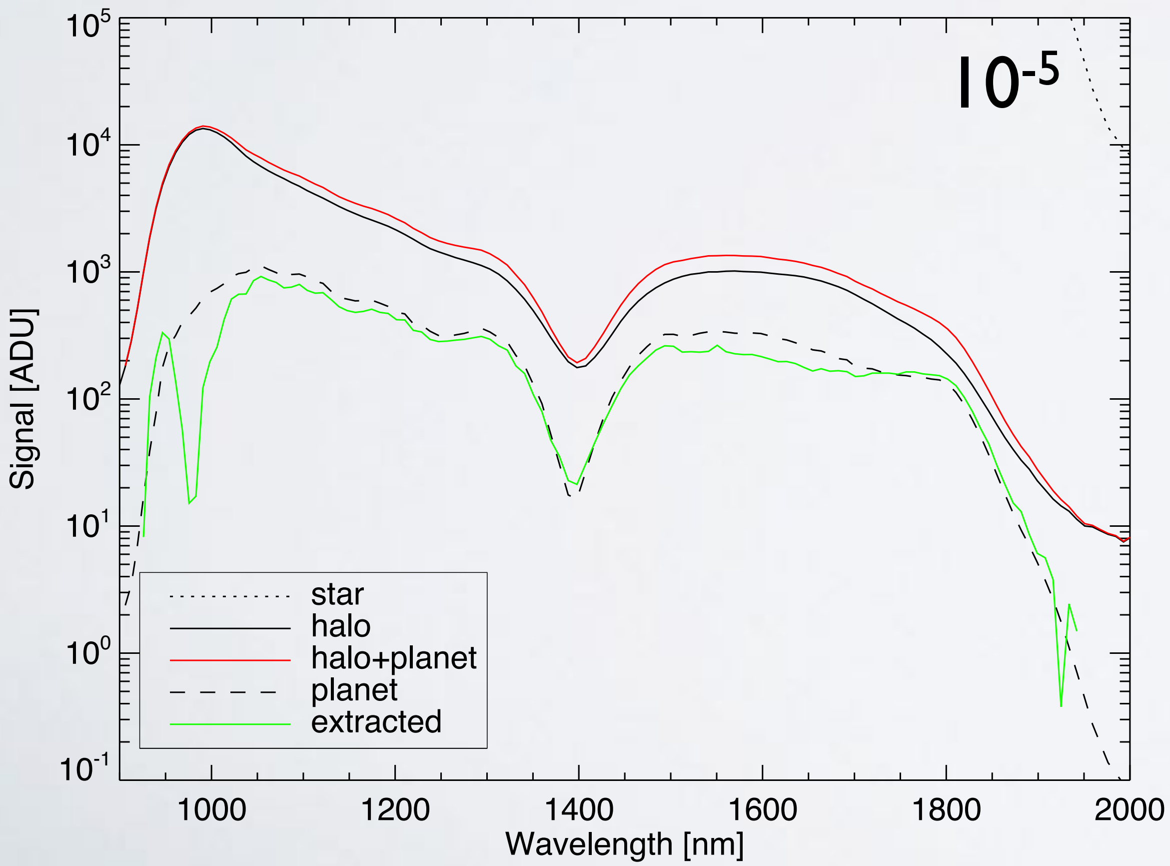
- LSS mo
- unique
  coron
- not rea
- specific
- possibl 3)
- import
  - R =
  - unique instrument at this level of contrast

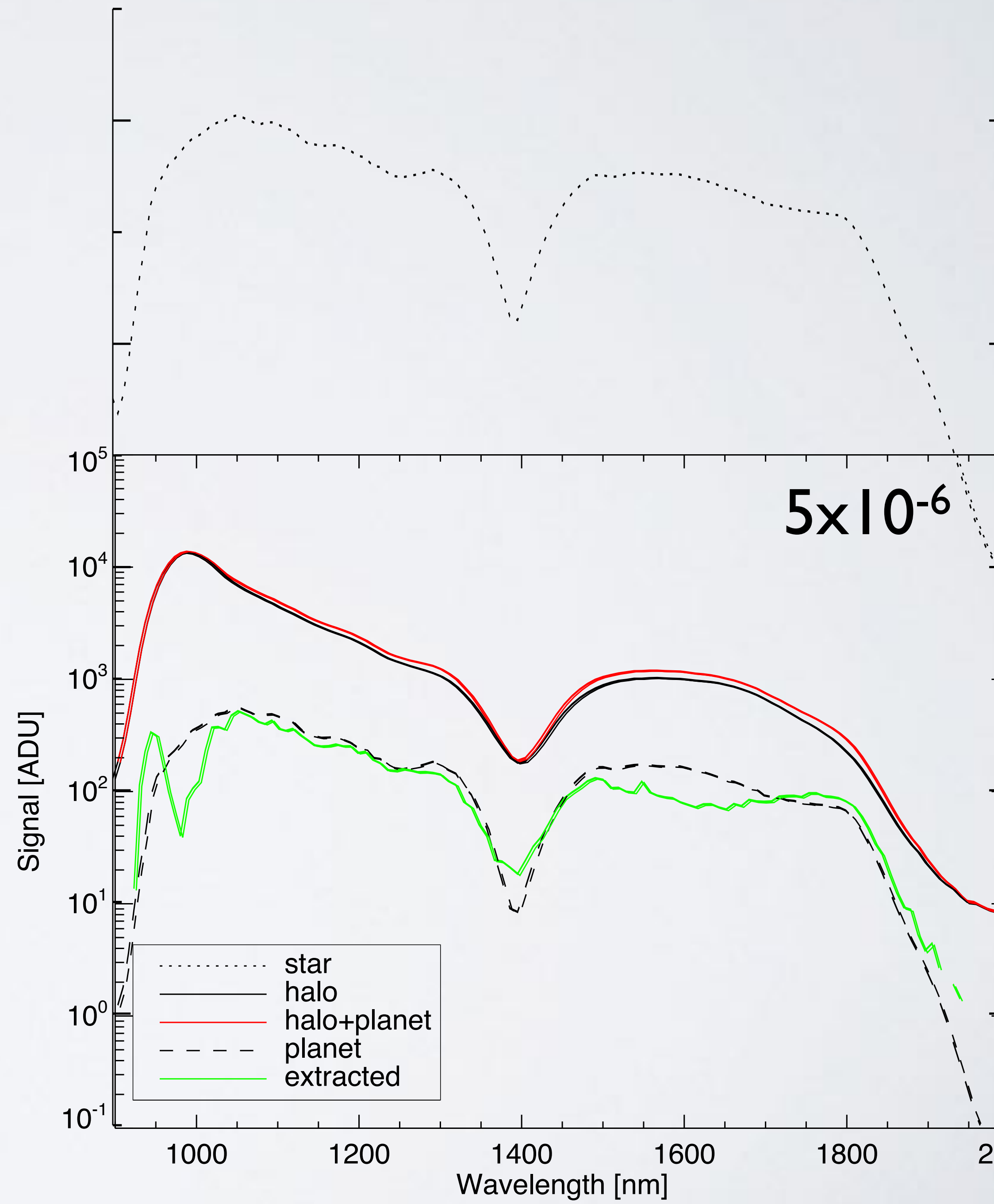




IRDIS: LSS performance

- fake planet inserted at 0.5"
- optimized speckle subtraction
- on-going work to improve data analysis



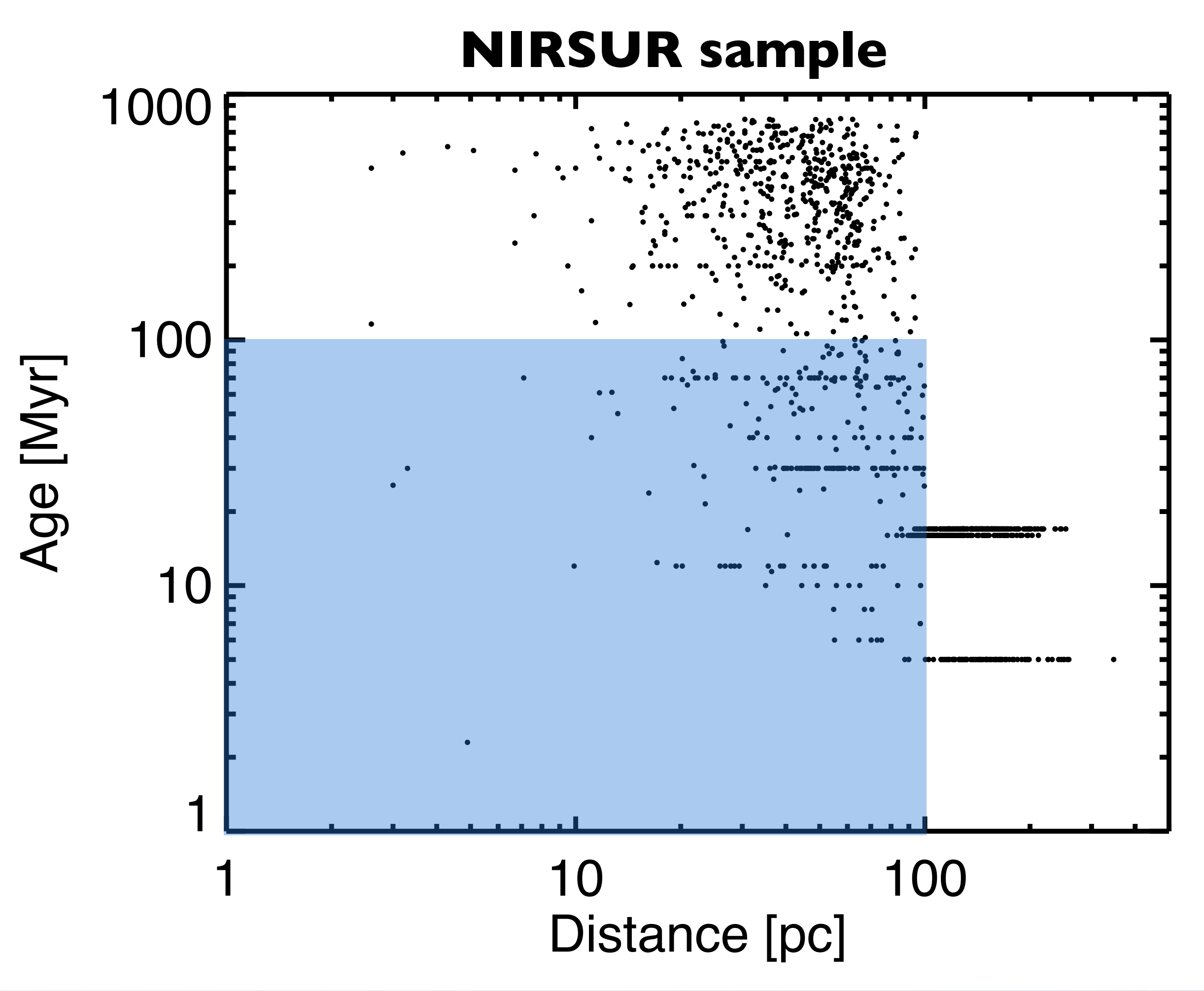


SPHERE: schedule

Preliminary acceptance in	mid-December 2013
Instrument packing	January 2014
Reintegration in Paranal, standalone tests	March 2014
First technical nights	mid-April 2014
First commissioning	May 2014
First call for proposal	September 2014
End of all commissionings	October 2014
Science Verification Time	end-2014
First operations in open time	March 2015

SPHERE: guaranteed time

- **260 nights of GTO** over 5-6 years
- 20% for ZIMPOL+other science
- 80% dedicated to **NIRSUR**:
  - simultaneous IRDIS+IFS obs
  - Y-H coverage
  - 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



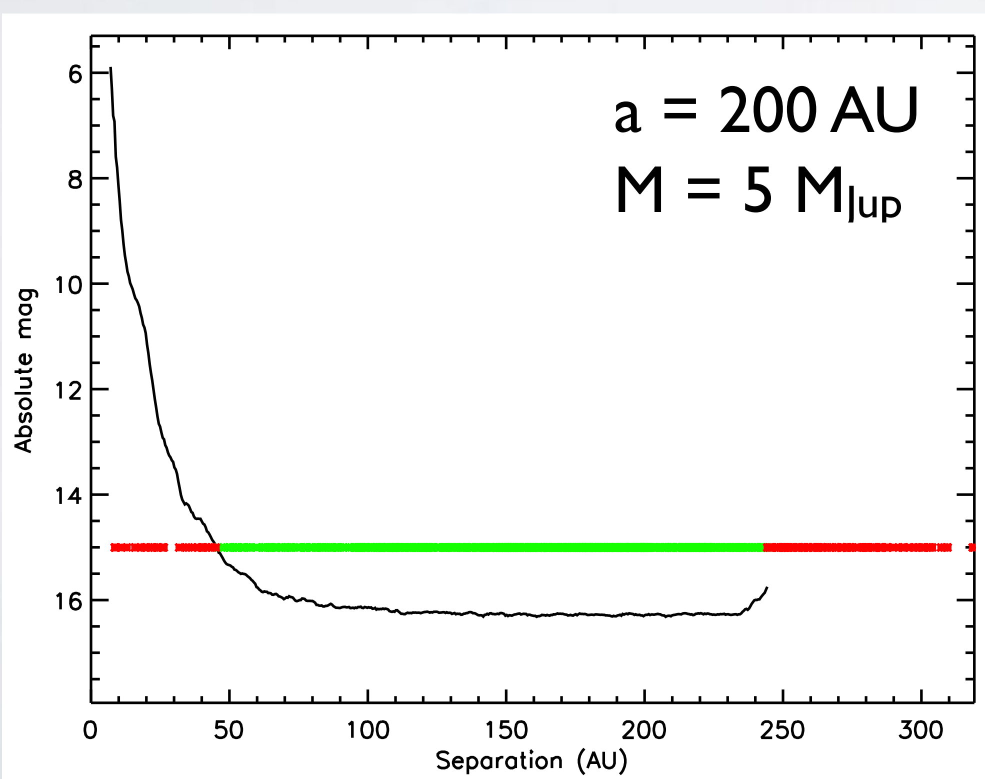
Comparison to GPI:
- GPIES
- 900 hrs ~100 nights
- 2013-2015
- all in queue mode

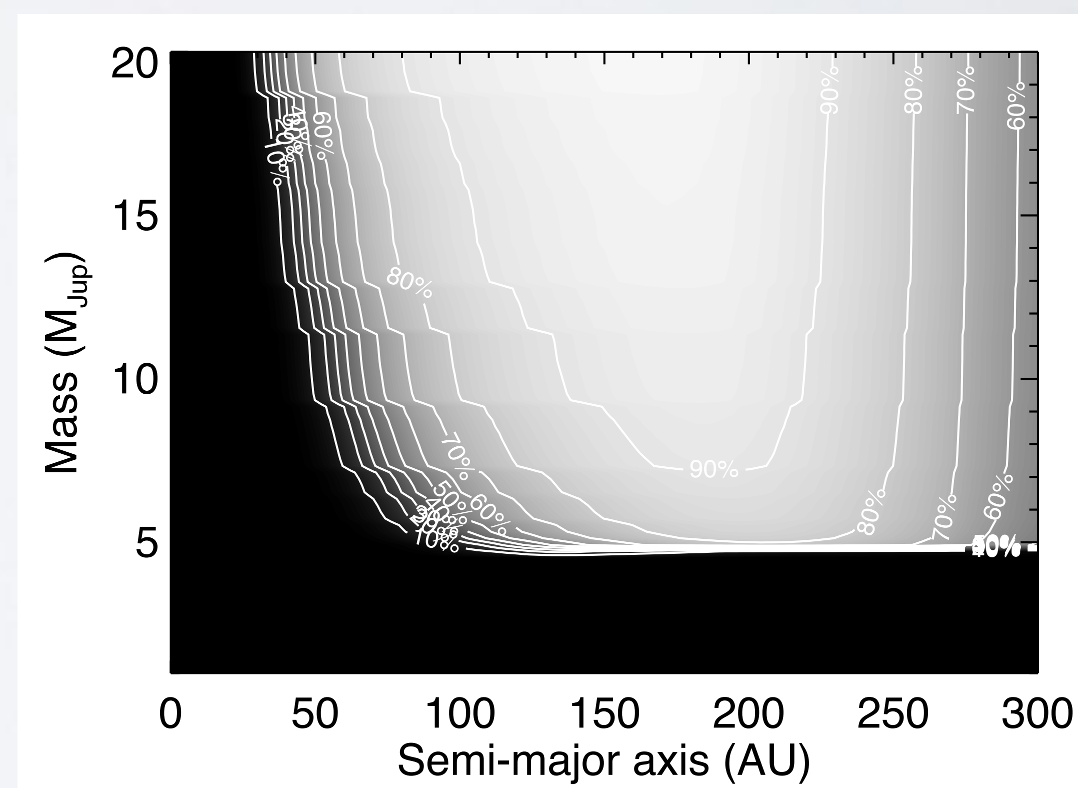
Conclusions

- This is just the beginning!

IDPS survey: Monte Carlo simulations

- Monte-Carlo simulations to estimates the planets potentially detectable
- MESS code (Bonavita et al. 2012)
- result: probability of detections map for each target
- assumptions:
  - evolutionary models assumptions: COND2003 (Baraffe et al. 2003)
  - planet population distribution in mass and semi-major axis





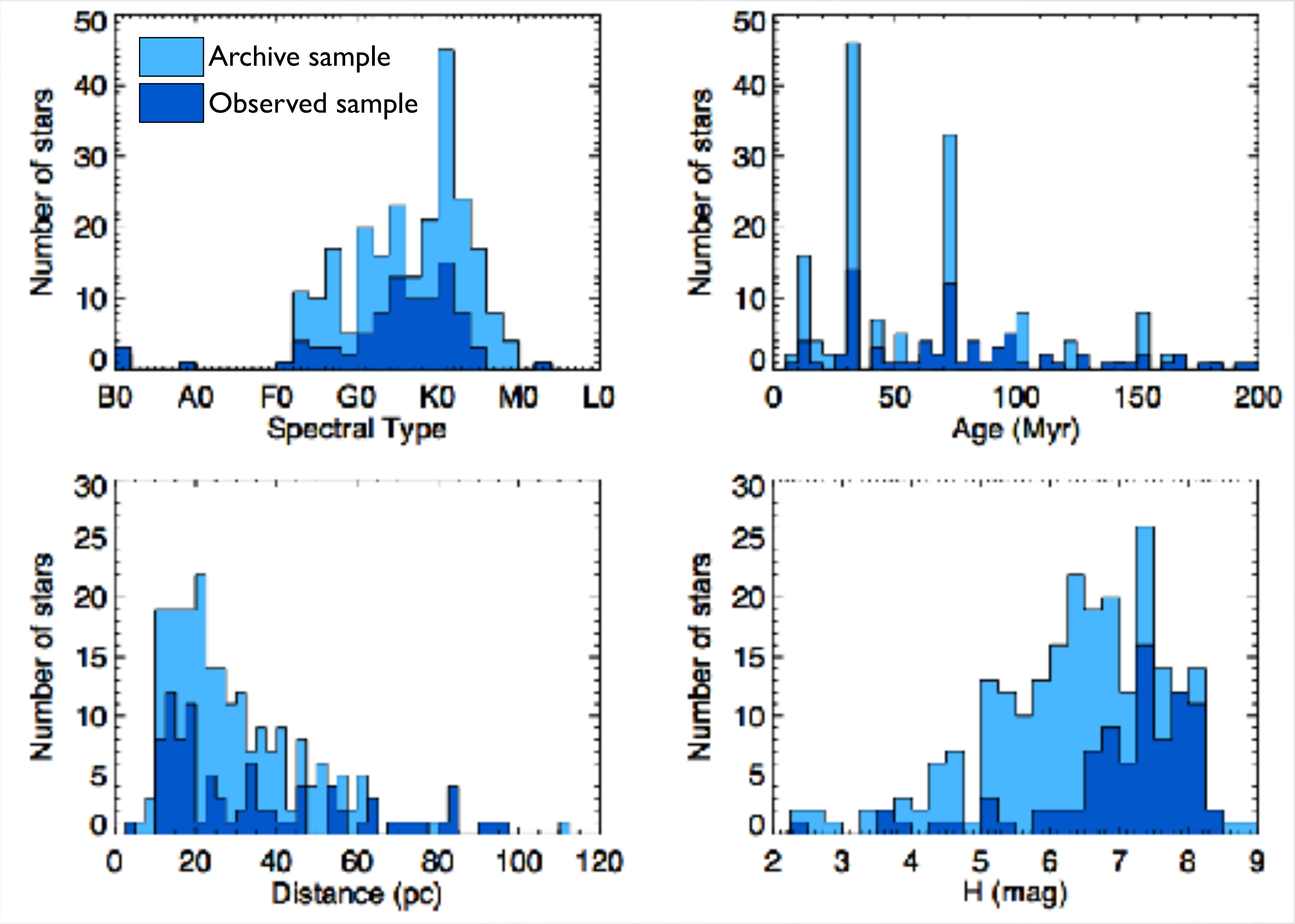
Direct imaging surveys

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	≤ 50
Neuhäuser et al. 2003	NTT	Sharp	Sat-I	K	11×11	23	AFGKM	≤ 50
	NTT	Sofi	Sat-I	H	13×13	10	AFGKM	≤ 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	≤ 200
Biller et al. 2007	VLT	NaCo	SDI	H	5×5	45	GKM	≤ 300
	MMT		SDI	H	5×5	-	-	-
Kasper et al. 2007	VLT	NaCo	Sat-I	L'	28×28	22	GKM	≤ 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	≤ 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	≤ 200
Rameau et al. 2013c	VLT	NaCo	ADI	L'	28×28	59	AF	≤ 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	≤ 200
Brandt et al. 2013[b]	Subaru	HiCIAO	ADI	H	20×20	63	AFGKM	≤ 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	≤ 1000
Chauvin et al. 2014	VLT	NaCo	ADI	*H*	14 x 14	80	FGK	< 300

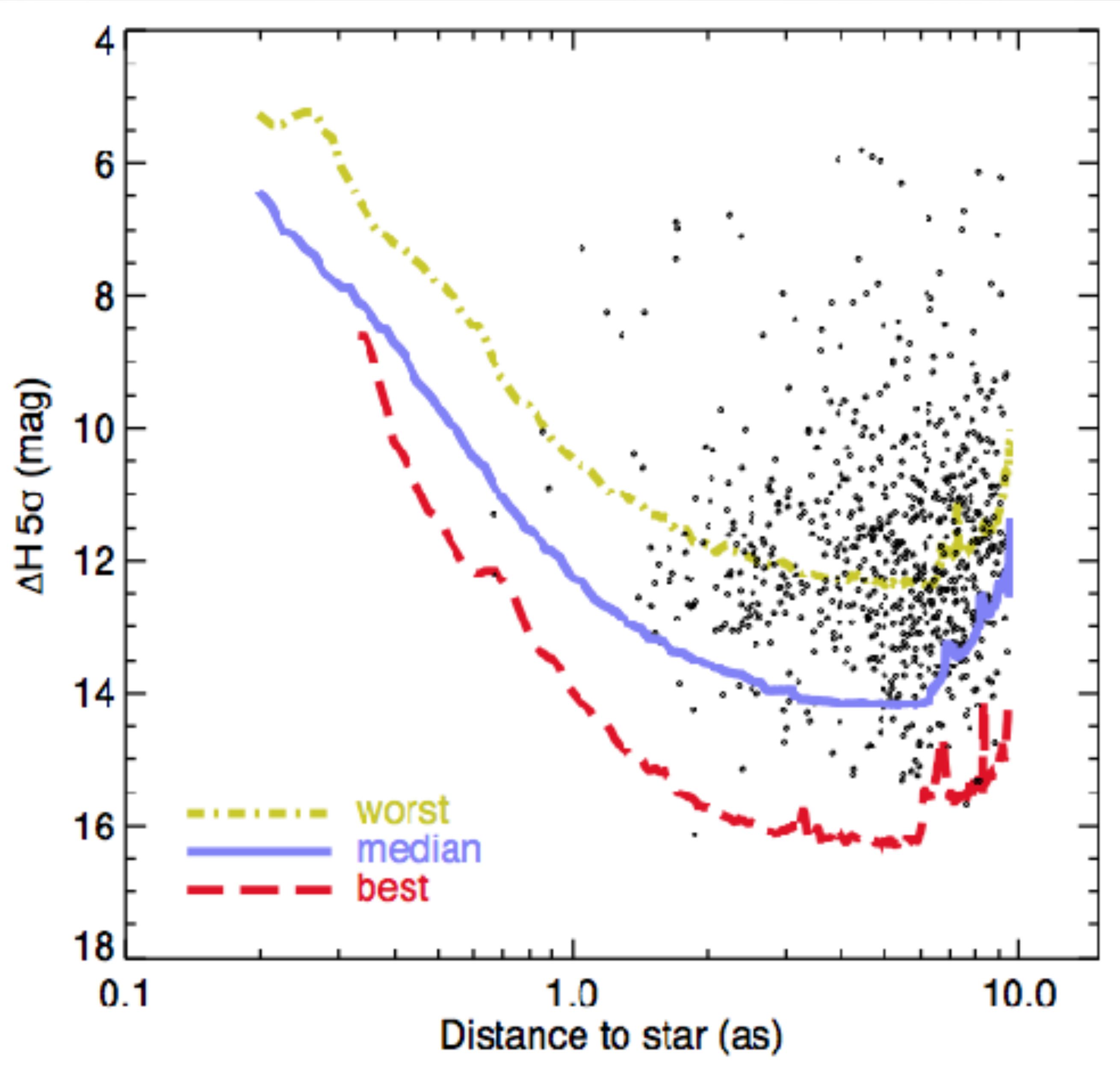
NaCo LP survey: sample

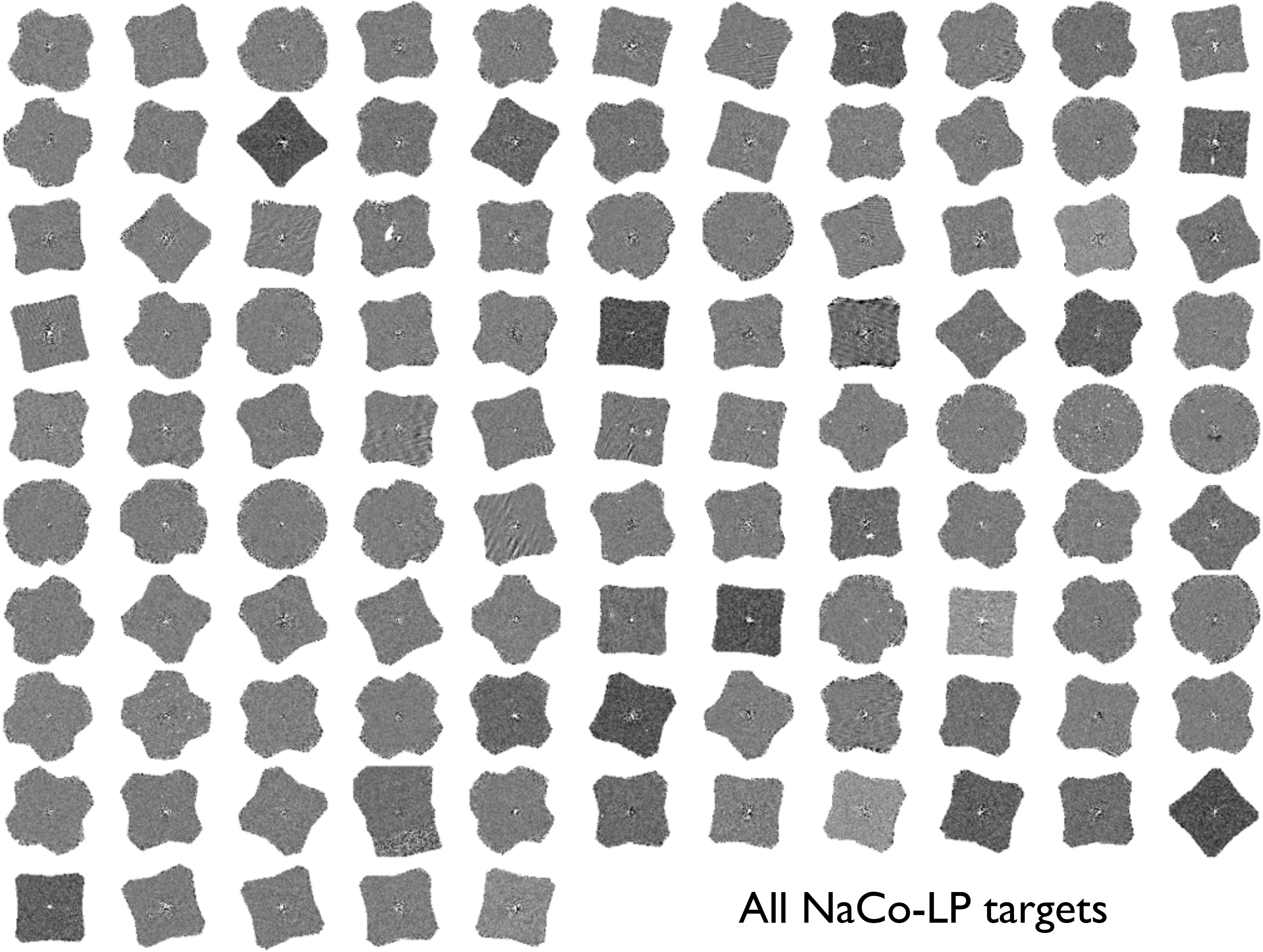
- project started in 2009
- SPHERE collaboration
- based on **exhaustive compilation of young stars** done for SPHERE
- sample divided in two groups:
  - **solar-type stars** (0.4 < B-V < 1.2)
  - *obs sample:* $\delta \leq 25°$, age $\leq$ 200 Myr, d $\leq$ 100 pc, R $\leq$ 9.5, no binaries (SB or <6"), **never observed at high-contrast**
  - *archive sample:* stars from previous surveys matching the same criteria



NaCo LP: observations, analysis

- Large program + open time for follow-up over P84-P90
- total of **16.5 nights** (visitor: 10.5; service: 6.0)
- instrumental setup:
  - broadband H
  - ADI
  - Lyot 0.7" coronagraph (run 1+2), saturated imaging (for subsequent observations)
  - T_{exp} = 35-40 min/target
- analysis with 4 pipelines

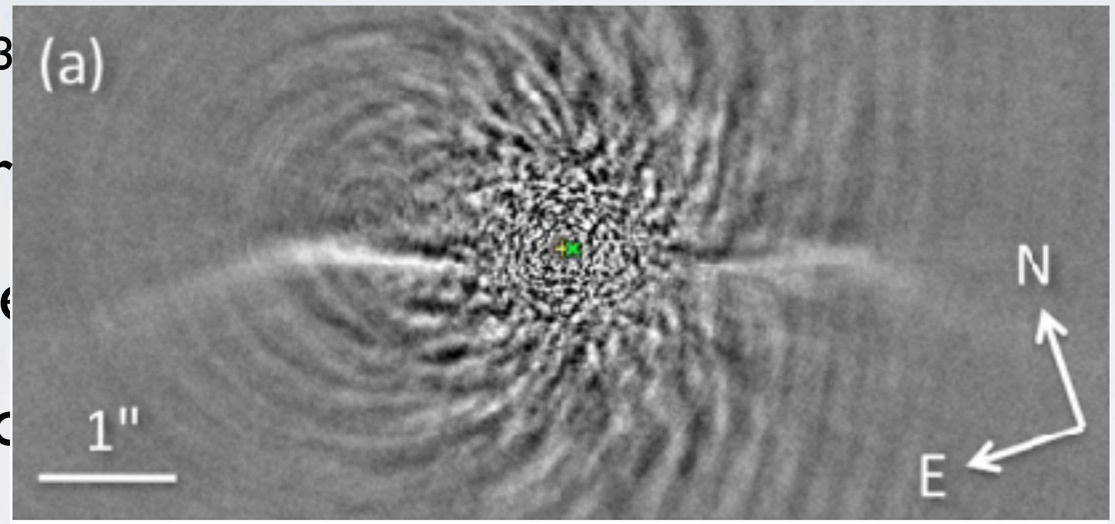




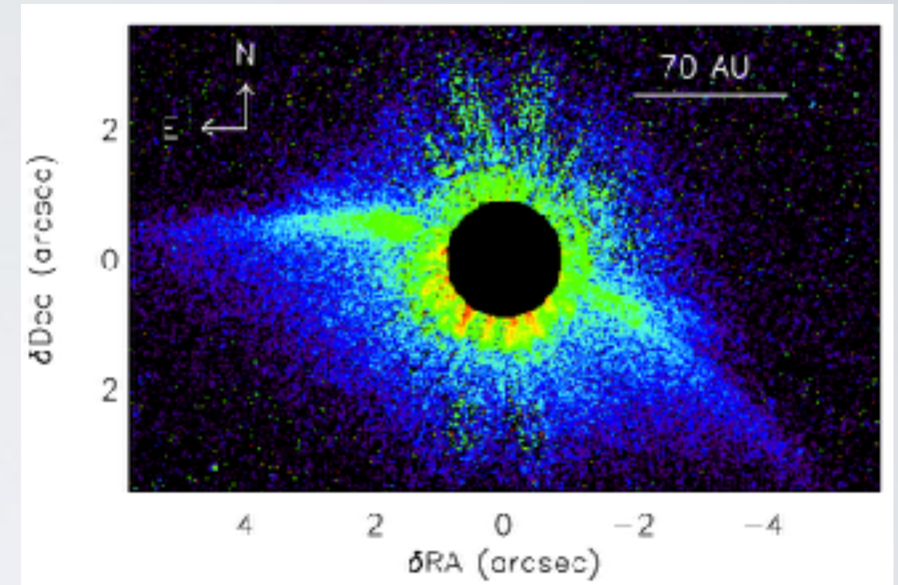
All NaCo-LP targets

NaCo LP: results

- **no new substellar companions**
- HD61005 (G8V, 3
  - debris disk r
  - very asymme
  - ring center c

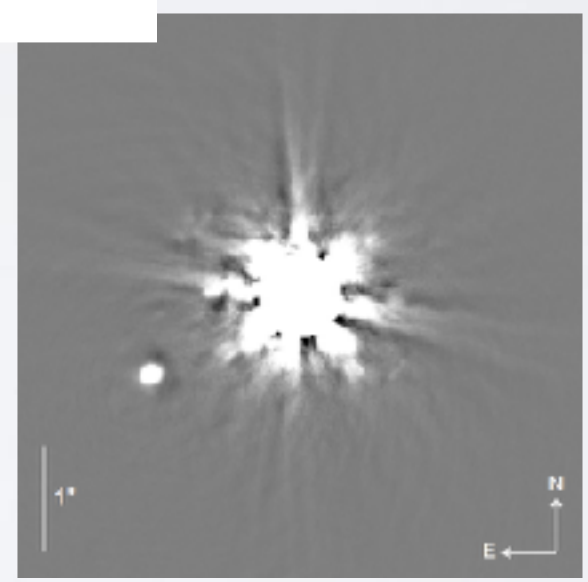


VLT/NaCo image, Buenzli et al. (2010)



HST/ACS image, Maness et al. (2009)

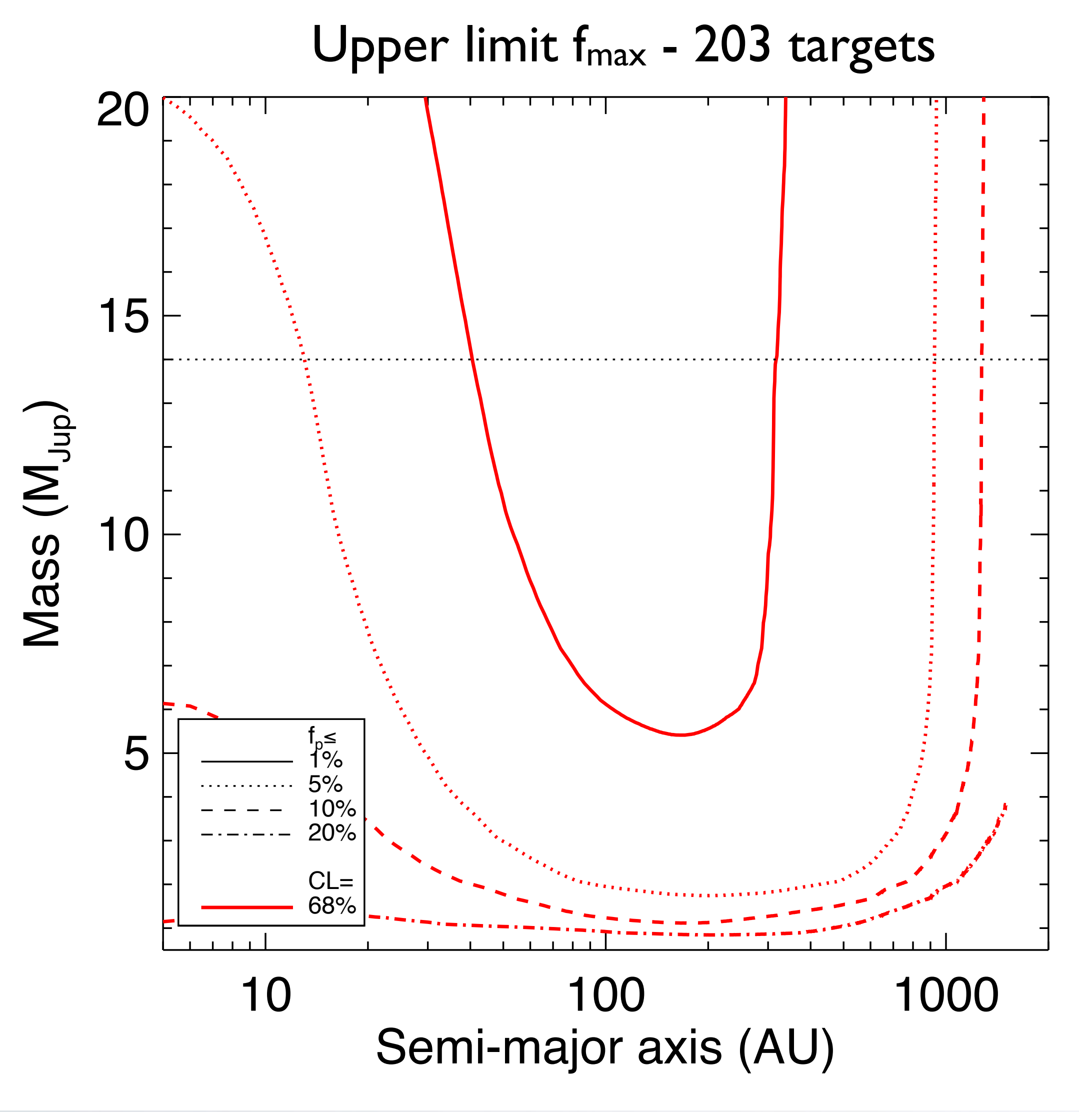
- HD8049 (K2, 34 p
  - interesting case of false positive:
  - age estimated to 100-400 Myr from stellar activity ➞ brown dwarf
  - contradiction with other indicators
  - RV only compatible with WD
  - WD confirmed with SINFONI spectroscopy



Indicator	Measure	Ref	Age (Myr)
Li EW (mA)	0	1,2	>500
log R_{HK}	-4.25 ± 0.05	1,3	90
log L_X/L_{bol}	-4.24	1	182
P_{rot} (d)	8.3 ± 0.1	1	360
P_{rot} (d)			380 ± 30
U, V, W (km/s)	18, −47, −28	6	old (few Gyr)

NaCo LP: statistical analysis

- analysis similar to IDPS, but without detection
- strength of the analysis is the **large size of the sample**



Population of Mordasini et al. (2012)