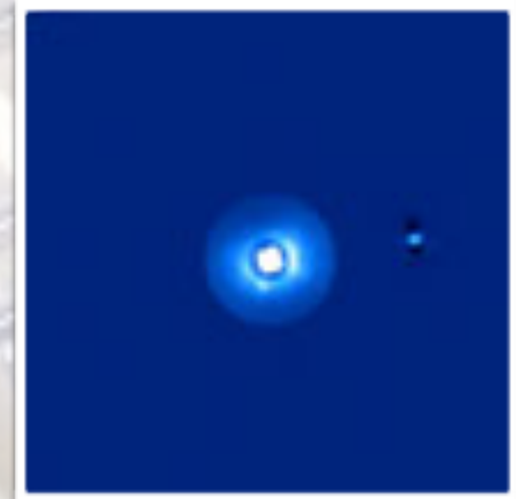
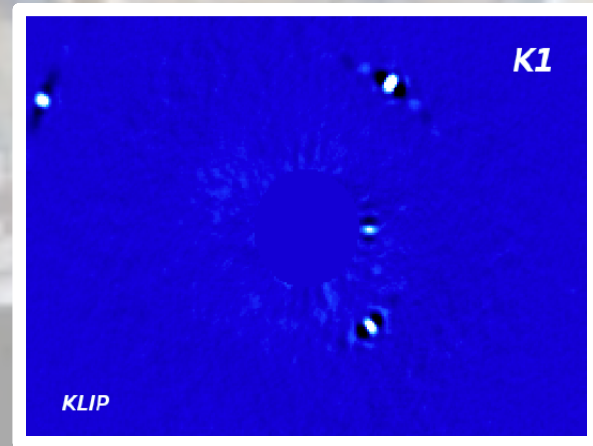
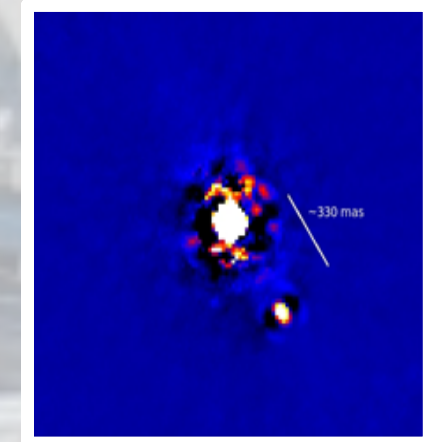
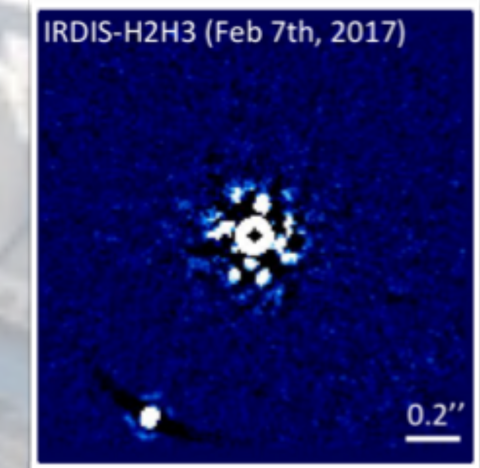
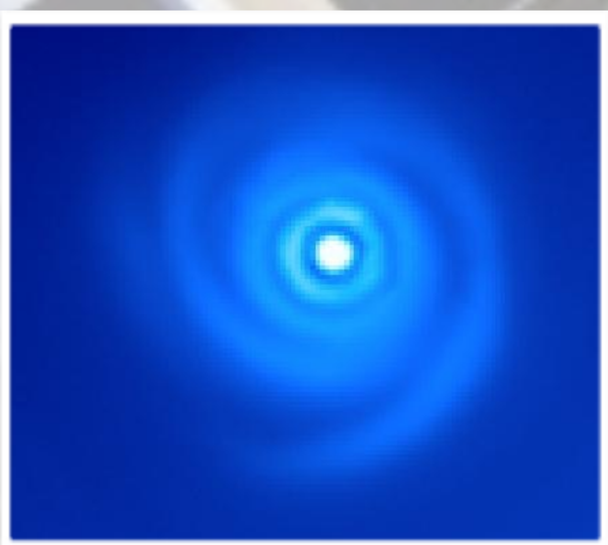


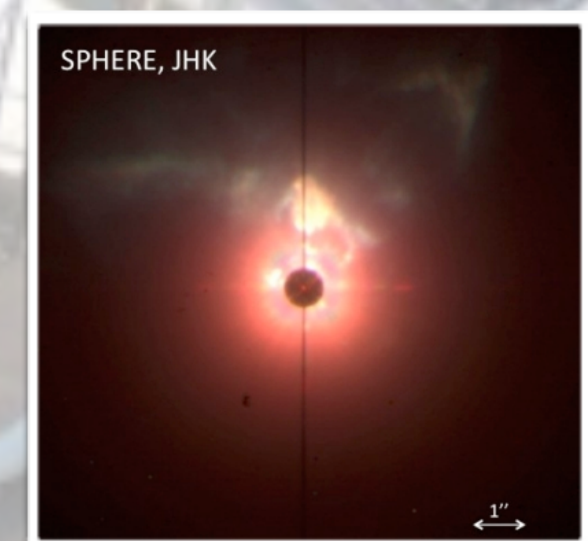






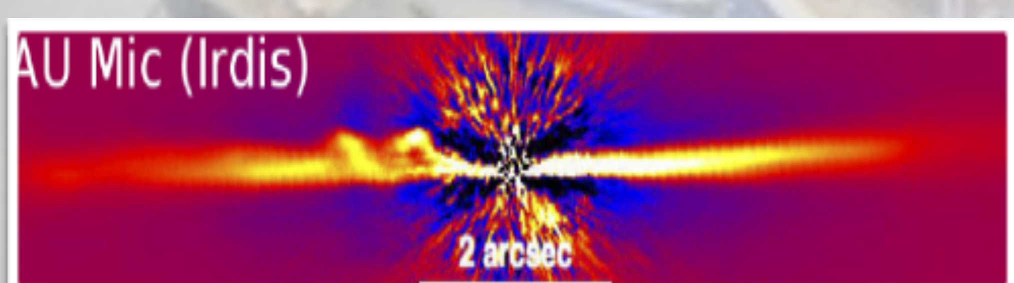
Future of Giant Planet Imaging: Requirements

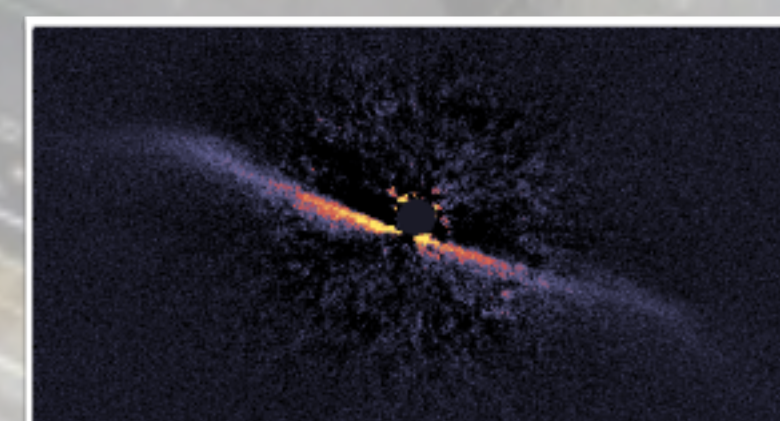




Anne-Marie Lagrange

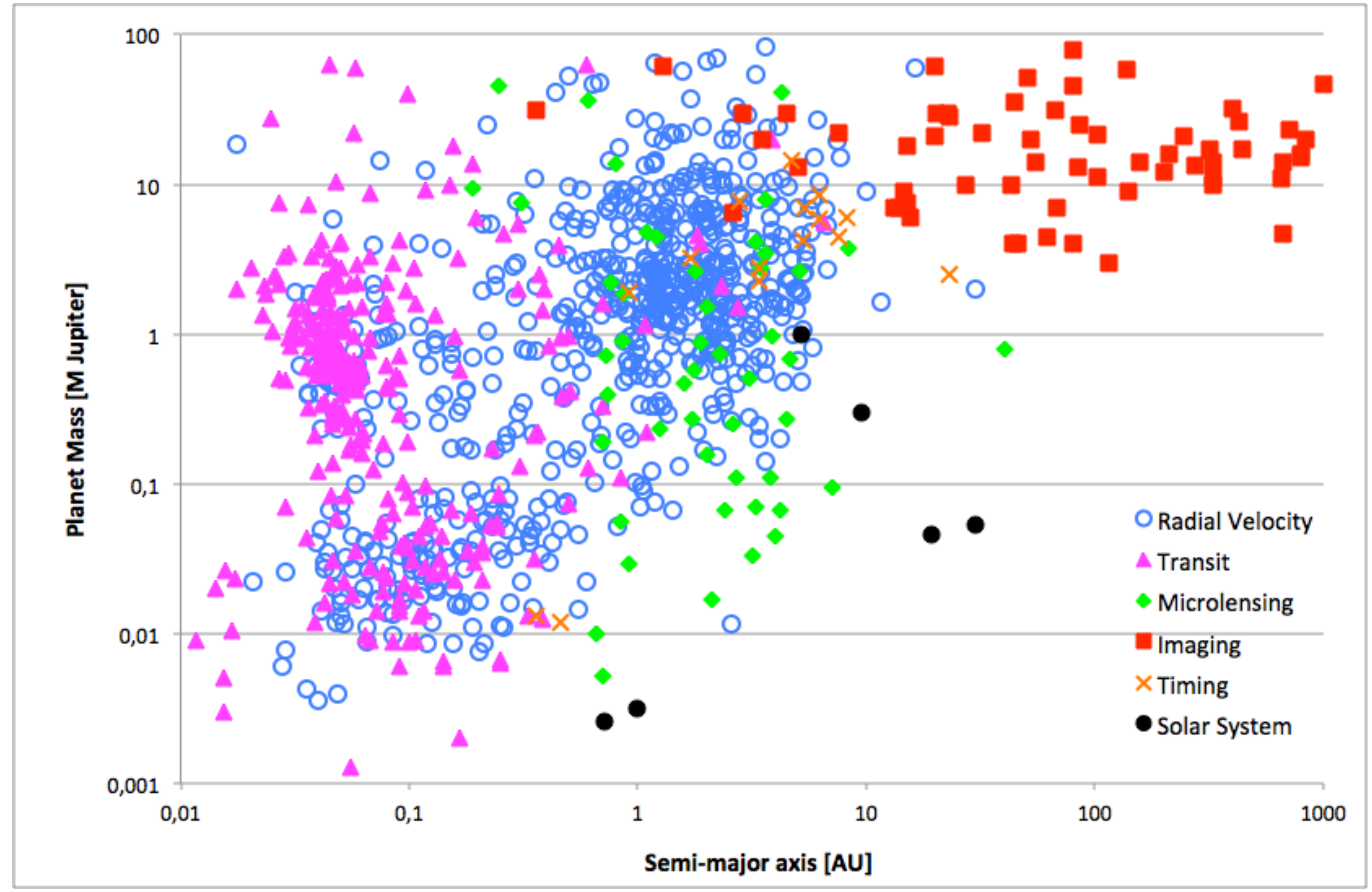
Institut de Planétologie et d'Astrophysique de Grenoble





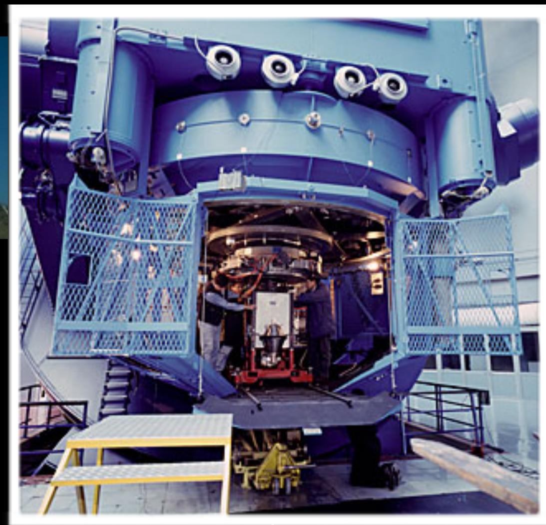
Pasadena, April 9th, 2018

Direct imaging of exoplanets



- Access to long period planets
- Rates of planets, systems architectures
- Planets properties : log(g), Teff, R, atmosphere composition (non-irradiated planets)

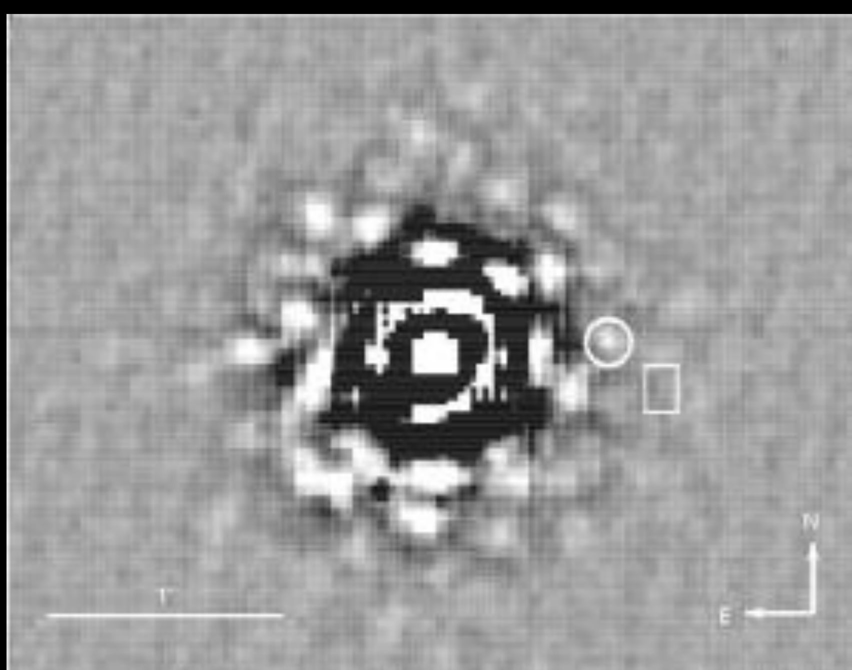
- Formation processes, link with disks



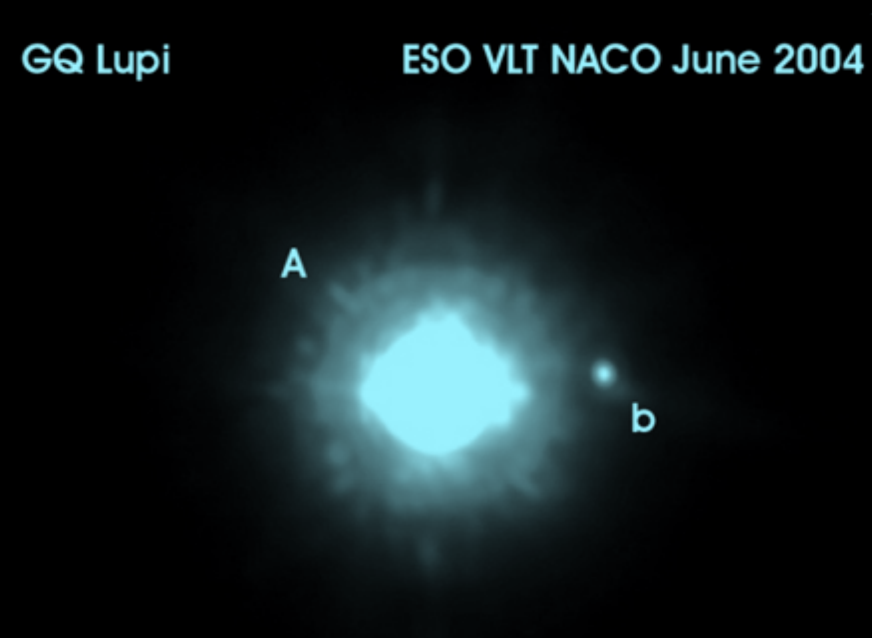
1990': Adonis
50 act., 60Hz
ESO T3.6m

2000': NaCo
185 act., upto400Hz
ESO VLT8.2m

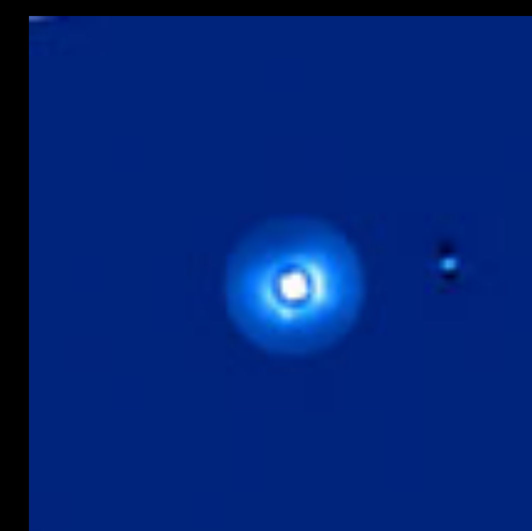
2015: SPHERE XAO
1600 act., 1.2 kHz
ESO VLT8.2m



Neuhaueser et al,1995



Neuhaueser et al, 2005



Beuzit et al, 2015

Classical AO on 3m
CFHT/PUE'O , etc

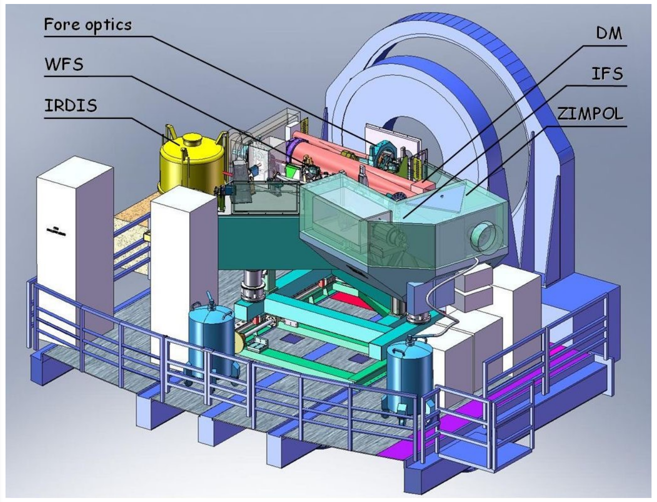
Classical AO on 10m nIR/LM
VLT, Keck, GEMINI, SUBARU, LBT, Magellan

XAO on 10m nIR/LM
SPHERE,GPI,SCEXAO
LBTAO, 1640 PALM
VLT/ERIS (project)

Extreme AO-fed instruments

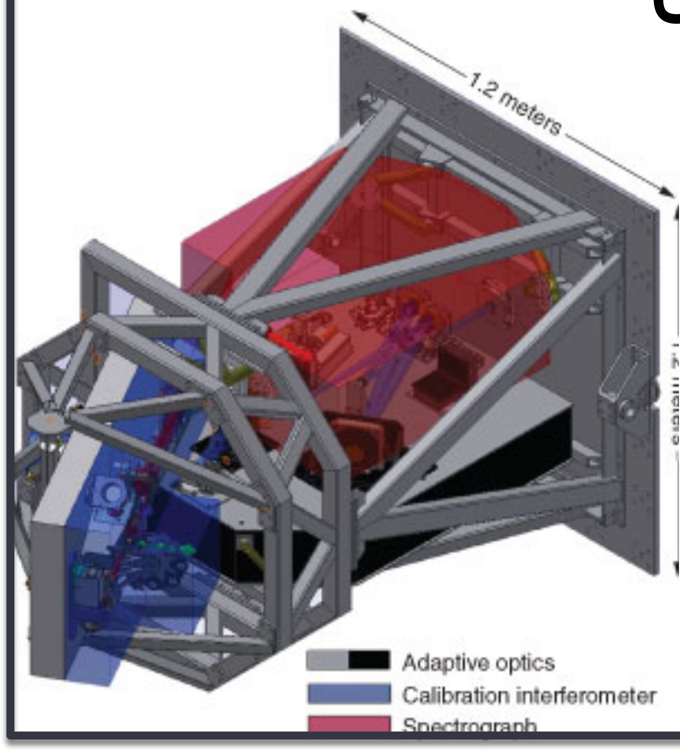
SPHERE (VLT)

*Spectro-Polarimeter High-contrast Exoplanet REsearch

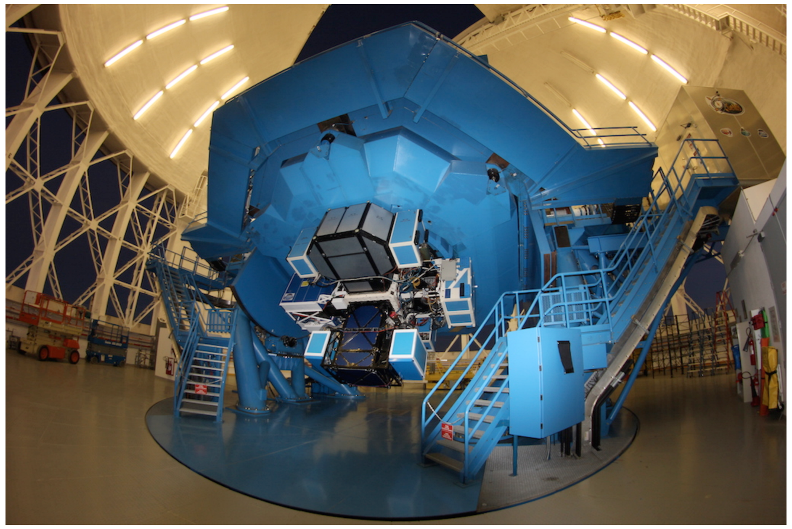


- Heavy & stable at Nasmyth
- HODM: 41*41 act (NAOS: 185)
- SH WFS 40x40 lensless at 1.38kHz, spatial filtering (NAOS: 180; 400Hz)
- Off-line phase diversity for NCPA
- Control ol star centering behind mask
- Near-IR Imager, IFS, optical imager/ polarimeter

GPI (Gemini South)



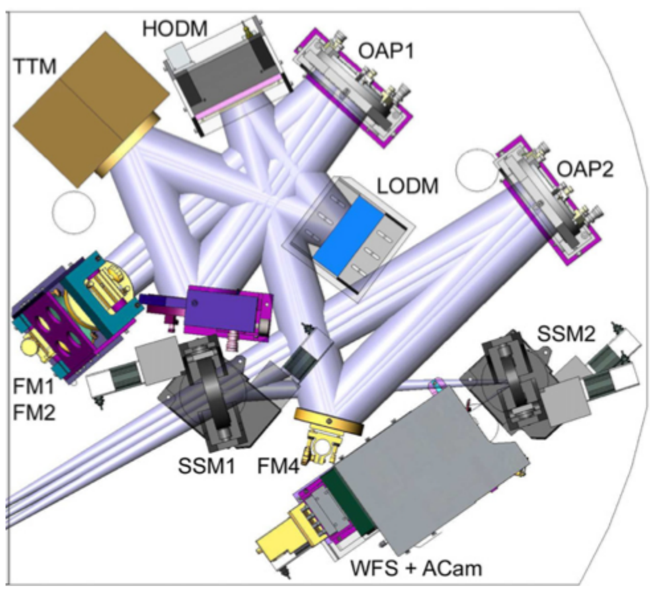
- Compact & light
- Cassegrain focus
- SH WFS at 2.5kHz max
- TTM +4096 act. MEMS DM
- IR interferometric cal. system for NCPA compensation
- IFS and integral field polarimeter



XAO-fed instruments

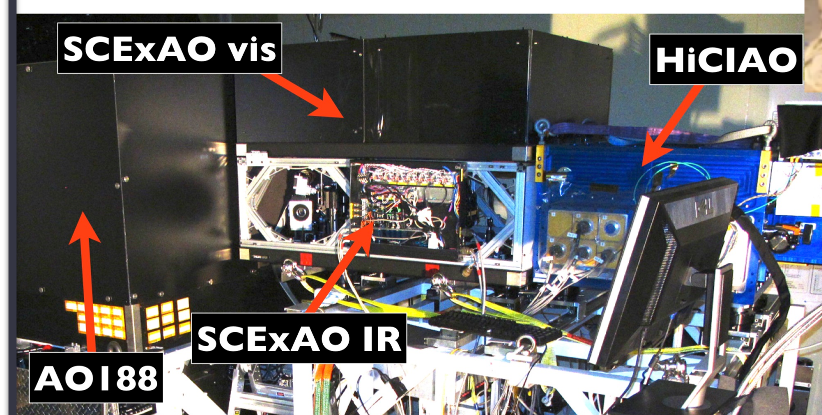
P3K- P1640 (Hales telescope, Palomar)

TTM + LODM + HODM of 3000 actuators
SH WFS at 2kHz

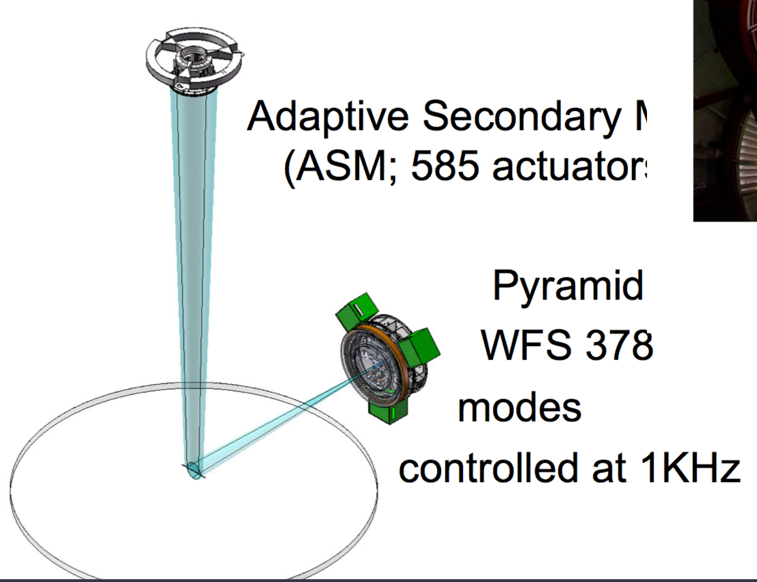


ScexAO (Subaru, Mauna Kea)

AO188 (Stacked array + curvature WFS)
+ MEMS DM of 1000 act.
pyramid WHS

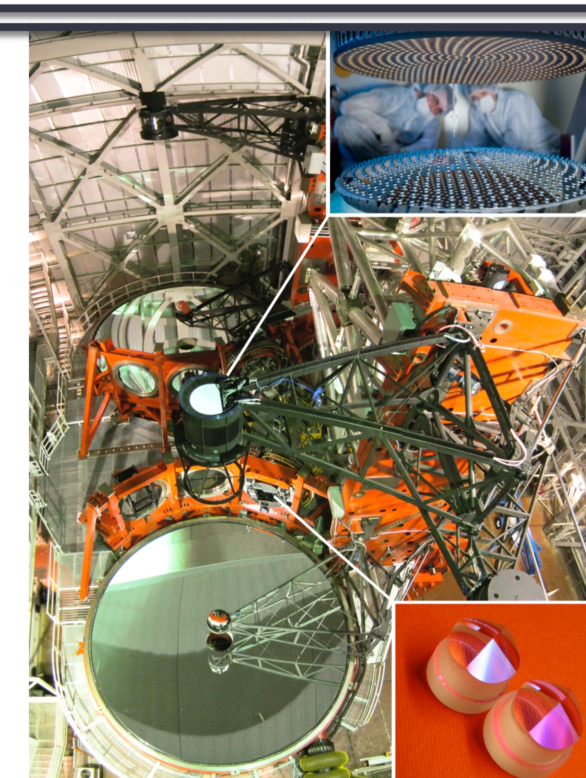


MagAO (Clay telescope)



LBT

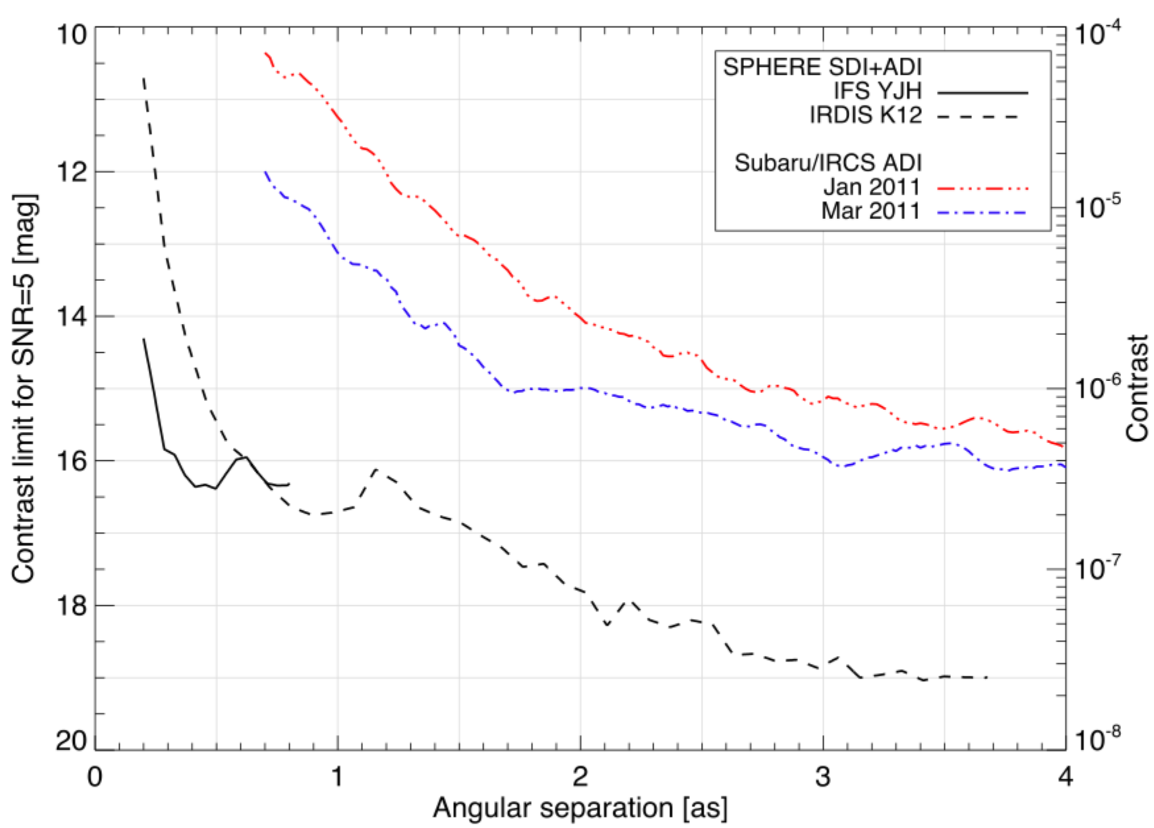
PyWFS
Secondary DM
672 actuators



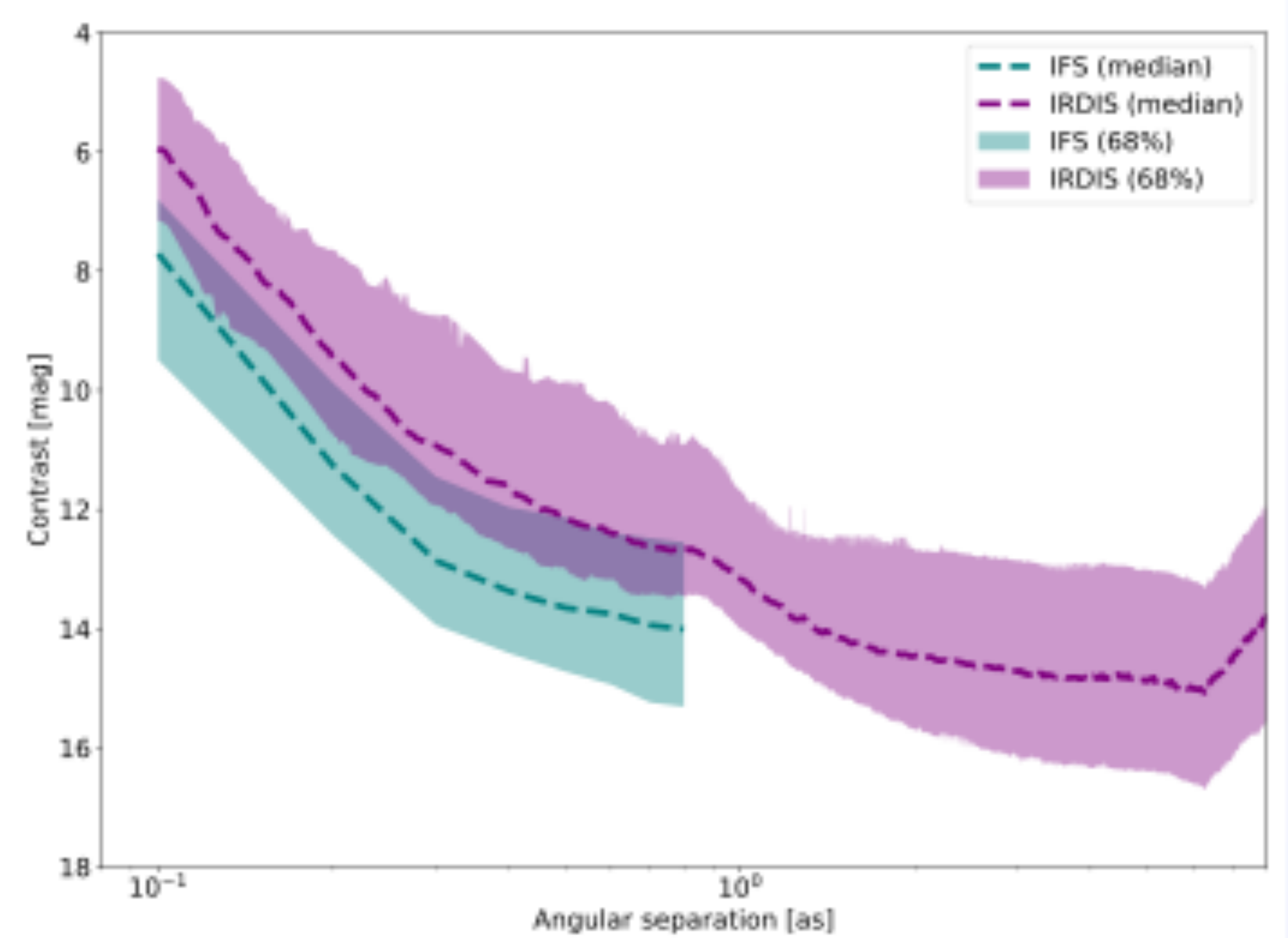
XAO Planet-imagers

- Improved AO
- Improved coronagraphs
- Improved algorithms for star halo subtraction

  => improved contrast performances % previous systems



best performances (not representative)
Vigan+ 2015



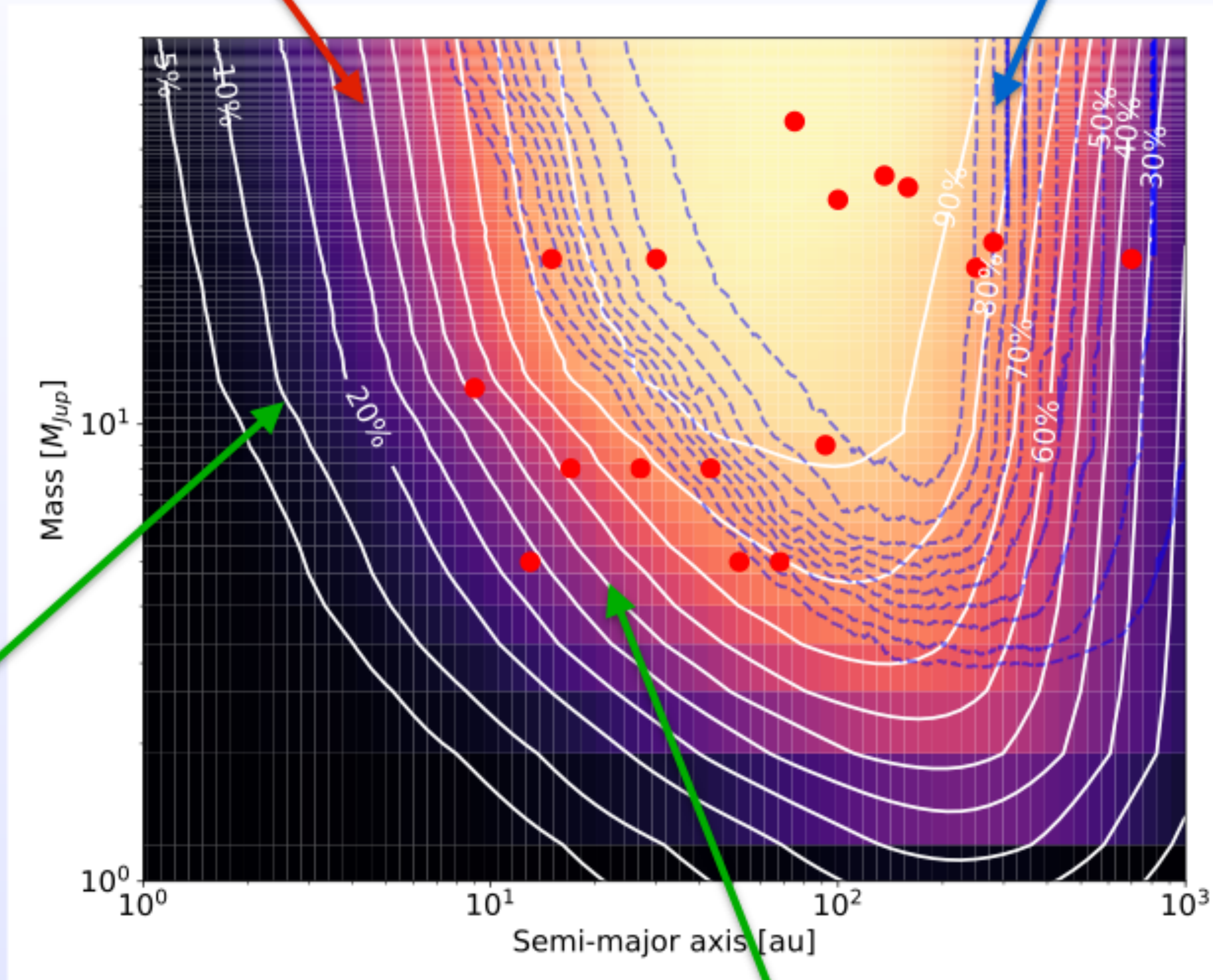
more representative (Langlois+, 2018)

Mass conversion with Baraffe et al. models

(Baraffe+ 2003, 2015)

+ Monte-Carlo analysis with MESS tool

(Bonavita+ 2013)



Direct Imaging Surveys Before XAO

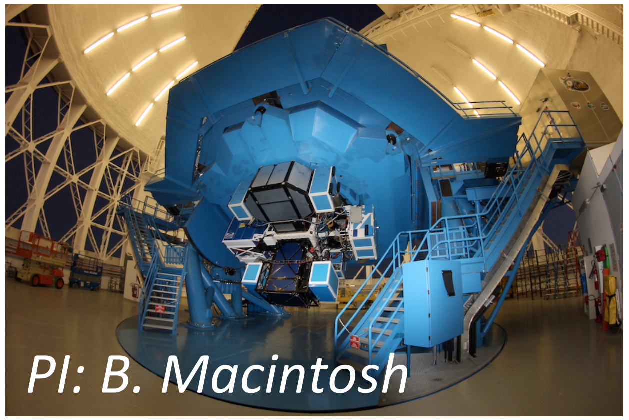
Reference	Telescope	Instr.	Mode	Filter	FoV	Number	SpT	Age
					('' '')	of targets		(Myr)
Chauvin et al. 2003	ESO3.6m	ADONIS	Cor-I	H, K	13*13	29	GKM	<~50
Neuh\"auser et al. 2003	NTT	Sharp	Sat-I	K	11*11	23	AFGKM	<~50
	NTT	Sofi	Sat-I	H	13*13	10	AFGKM	<~50
Lowrance et al. 2005	HST	NICMOS	Cor-I	H	19*19	45	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
Lafreni\`ere et al. 2007	Gemini-N	NIRI	ADI	H	22*22	85		10-5000
Apai et al. 2008	VLT	NaCo	SDI	H	3*3	8	FG	12-500
Metchev et al. 2009	Palomar	PALAO/PHARO	Cor-I	K	25.2*25.2	266	FK	3-3000
	Keck-II	NIRC2	Cor-I	K	40.6*40.6	-	-	-
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
Nielsen et al. 2013	Gemini-S	NICI	Cor-ASDI	H	18*18	70	BA	50-500
Wahhaj et al. 2013	Gemini-S	NICI	Cor-ASDI	H	18*18	57	AFGKM	100
Janson et al. 2013	Subaru	HiCIAO	ADI	H	20*20	50	AFGKM	<~1000
Brandt et al. 2014	Subaru	HiCIAO	ADI	H	20*20	63	AFGKM	<~500
Chauvin et al. 2015	VLT	NaCo	ADI	H	14*14	86	FGK	<~200
Bowler et al. 2015	Gemini-S	NICI	Cor-ASDI	H,K	18*18	122	M	<~620
Lannier et al. 2016	VLT&NaCo	NaCo	ADI	L'	28*28	58	M	<~120
Galicher et al. 2016	Gemini-N	NIRI	ADI	J,H,K,CH4	22*22	292	BAFGKM	<~100
	Gemini-S	NICI	ADI	CH4,K	18*18			
	KeckII	NIRC2	ADI	J,H,K,L',F2II,H2,CH4	10*10,40*40			

Table 1

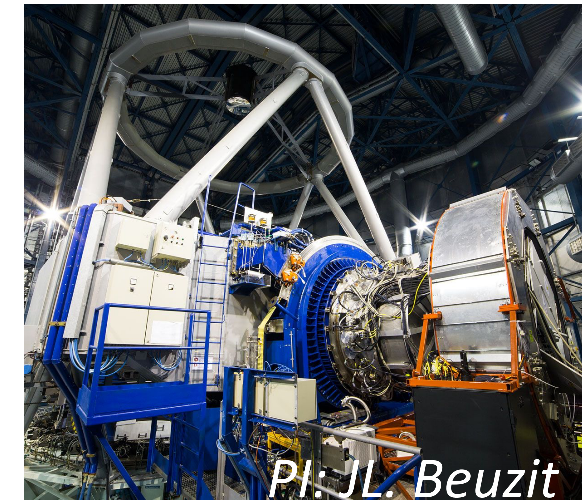
	Nb	Mass range	Sep range	Age	F	CL
	of targets	au	MJup			
Metchev et al. 2009	266	12-72	28-1590	3 Myr–3 Gyr	0.5-6.3 (FGK)	2 sigma
Galicher et al. 2016	356	0.5-14	20-300	< 200Myr	0.3-3.85 (BAFGKM) 0.25-4.95 (GM) 0.35- 7.15 (AF)	95 %
Bowler et al. 2016	384	1.-100	0.5-100	5-300 Myr	0.1-1.3 (BAFGKM) -0.5-6.5 BA <4.1% FGK (95%) <3.9% M (95%)	68 %
Vigan et al. 2016	199	5.-75	5.-300	< 200Myr	0.8-3.4 / 0.3-5.75	68/95 %
		5.-75	5.-300		1.6-4.4 / 0.85-6.45	68/95 %
		0.5-14	20-300		0.7-3.0 / 0.25-5.05	68/95 %
		0.5-75	20-300		1.4-3.85 / 0.75-5.7	68/95 %

Massive (> 5 MJup) GPs further than ~10-20 au are not common

GPs more common around early type stars than late-type stars



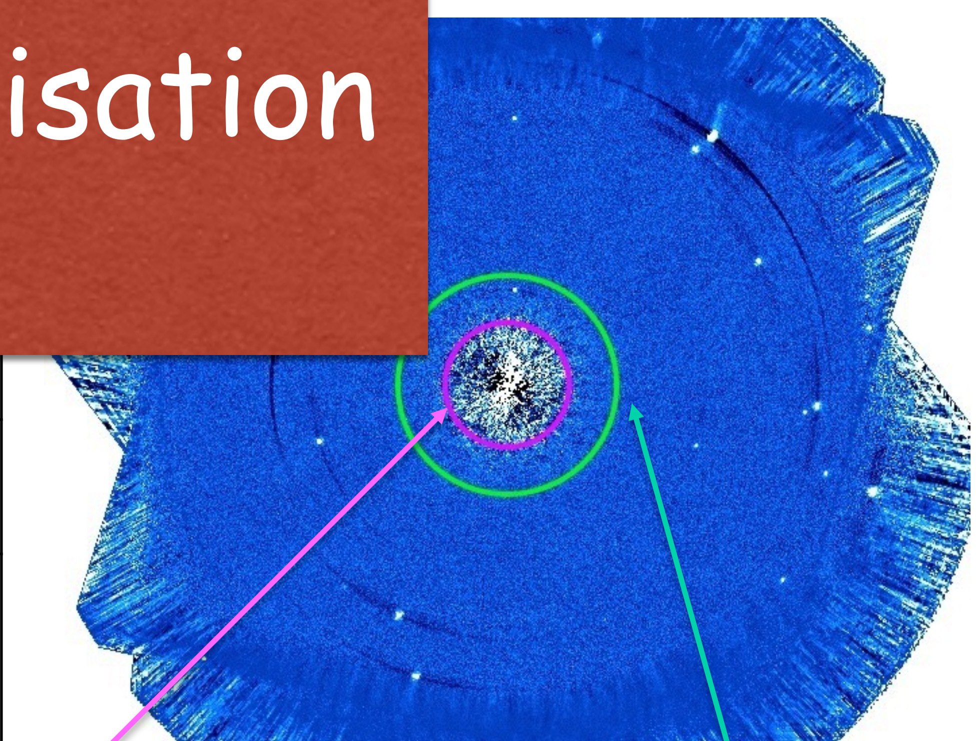
GPIES & SPHERE/SHINE planet surveys



GEMINI/GPI	VLT/SPHERE
IFS Y-K (+polar)	
890 hours over 3 y (GPIES)	
600 stars	~800
Young (<100 Myr), Close <75 pc	Young (< 150 pc) + <1 Gyr < 100 pc V upto 13.5
A to M stars	A to M stars
Started: nov 2014	Started: Feb 2015

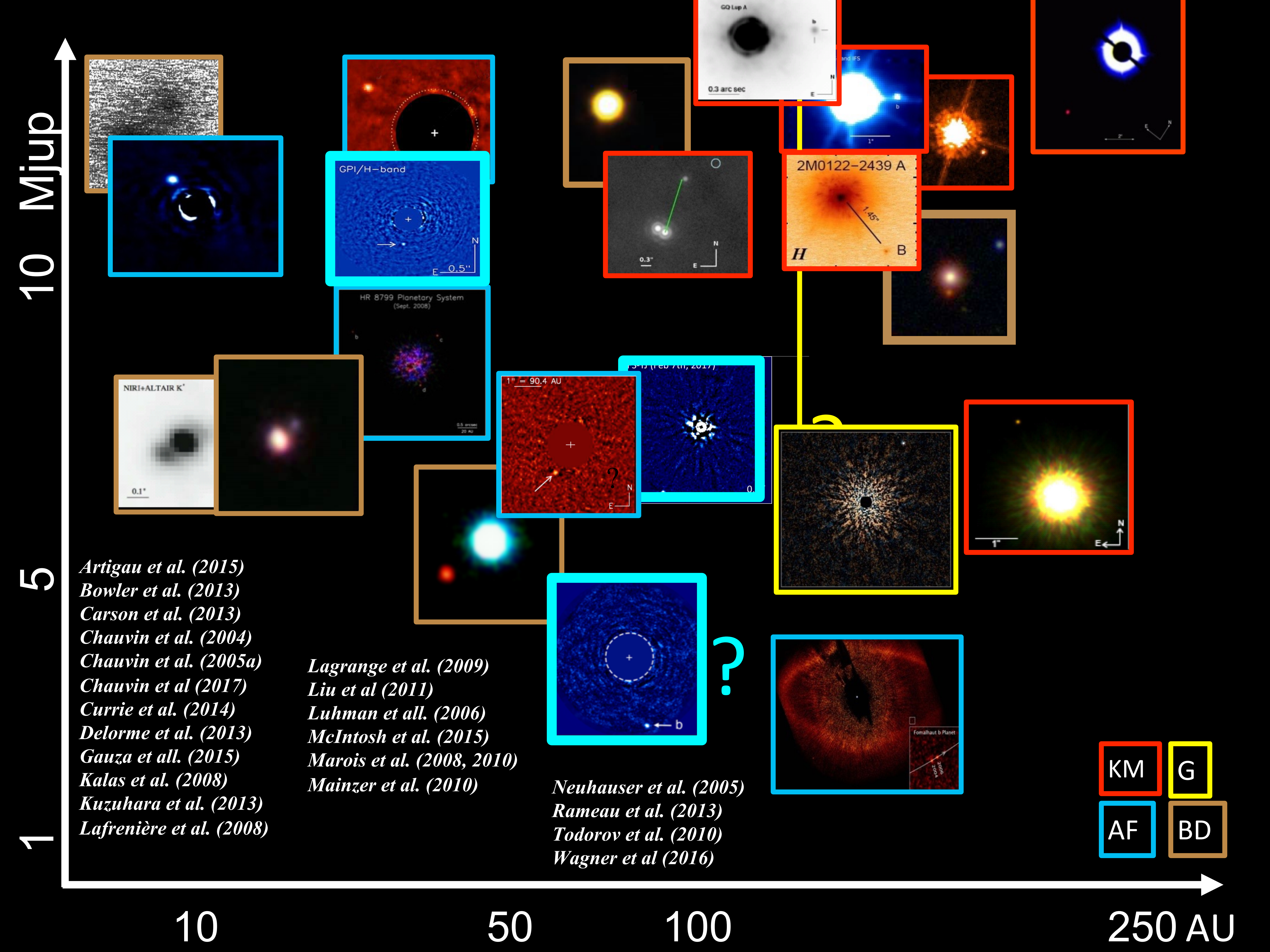
- 2 new planets
- planets characterisation
- several new disks

SPHERE/IRDIS Image *12’’



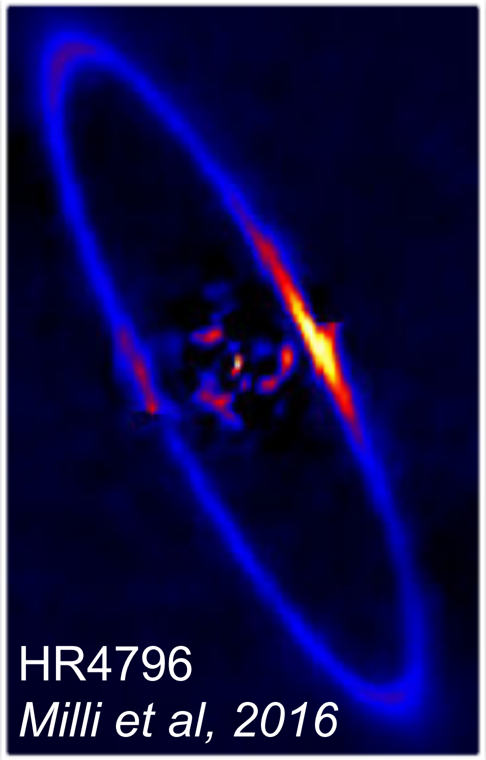
SPHERE/IFS FoV 1.7*1.7’’

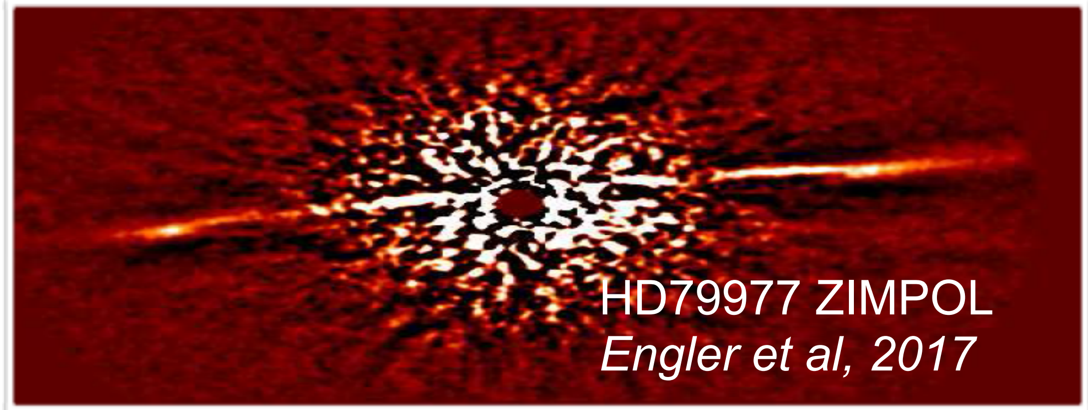
GPI FoV (2.7*2.7’’)

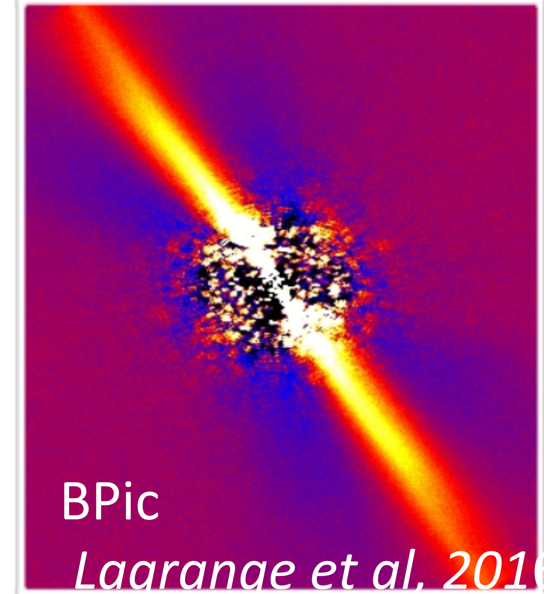


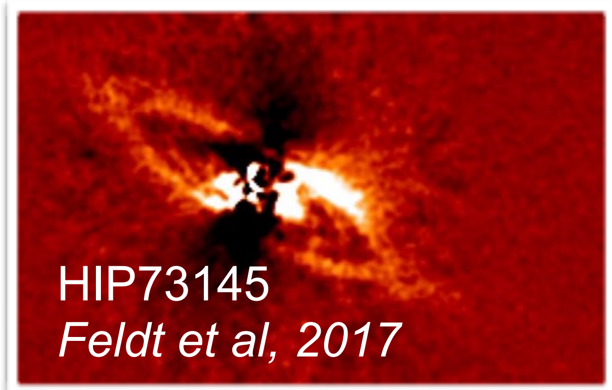
Mjup
10
5
1
10
50
100
250 AU
GQ Lup A
0.3 arc sec
GPI/H−band
0.5''
HR 8799 Planetary System
2M0122−2439 A
1.45''
B
H
NIRI+ALTAIR K'
0.1''
1'' = 90.4 AU
?
?
b
Fomalhaut b Planet
Artigau et al. (2015)
Bowler et al. (2013)
Carson et al. (2013)
Chauvin et al. (2004)
Chauvin et al. (2005a)
Chauvin et al (2017)
Currie et al. (2014)
Delorme et al. (2013)
Gauza et all. (2015)
Kalas et al. (2008)
Kuzuhara et al. (2013)
Lafrenière et al. (2008)
Lagrange et al. (2009)
Liu et al (2011)
Luhman et all. (2006)
McIntosh et al. (2015)
Marois et al. (2008, 2010)
Mainzer et al. (2010)
Neuhauser et al. (2005)
Rameau et al. (2013)
Todorov et al. (2010)
Wagner et al (2016)
KM
G
AF
BD

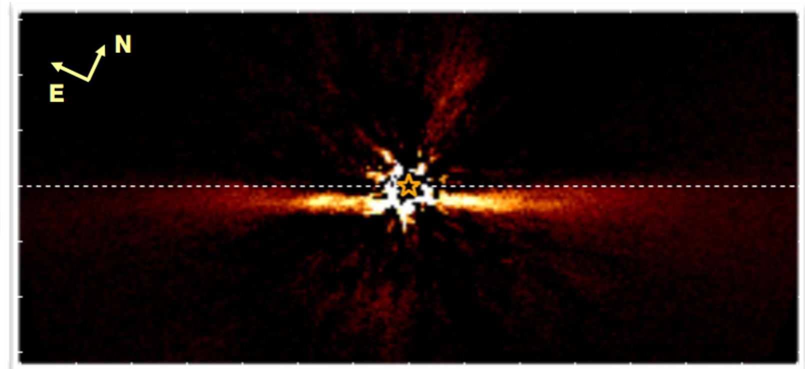
Known bright young debris disks with SPHERE

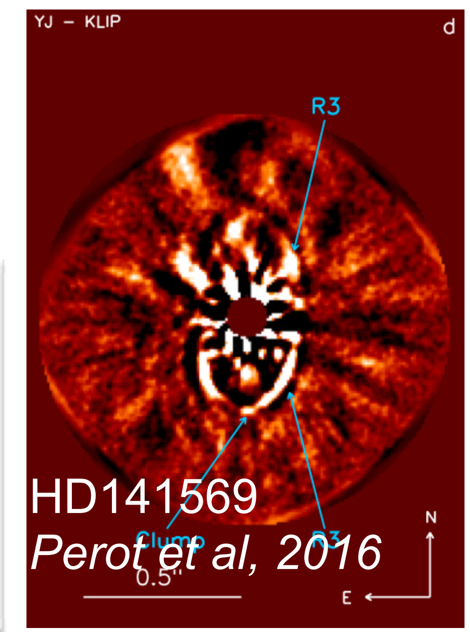


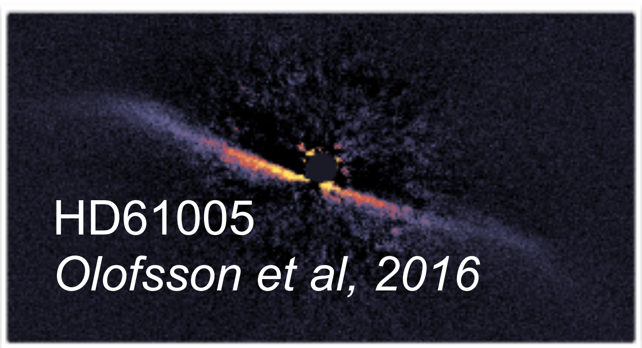


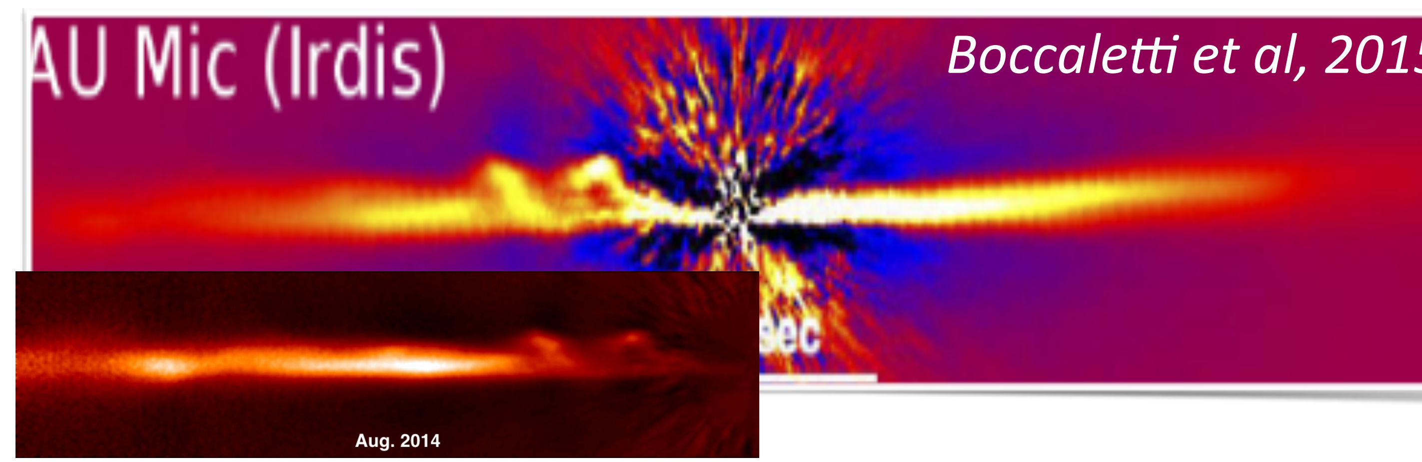






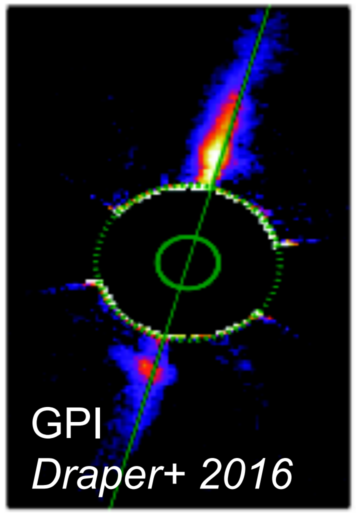


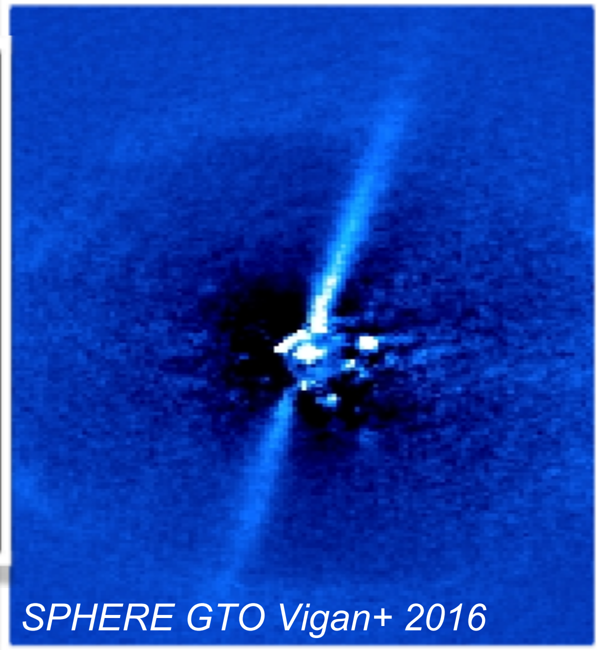




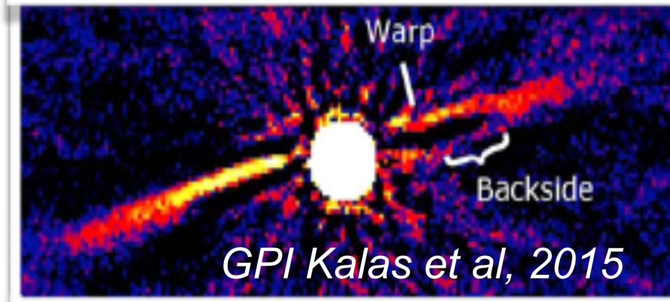
Disks close to the stars — morphology at sub-AU scale — multiple belts — asymmetries

New young debris disks with SPHERE - The Sco Cen 'niche'

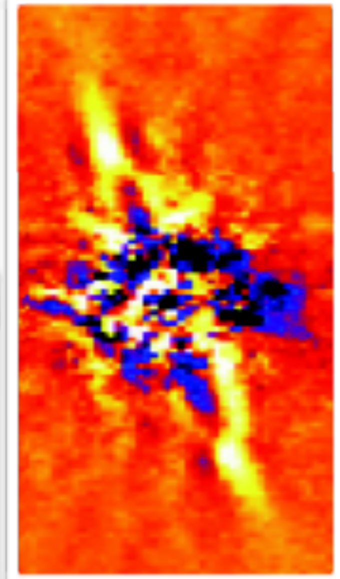




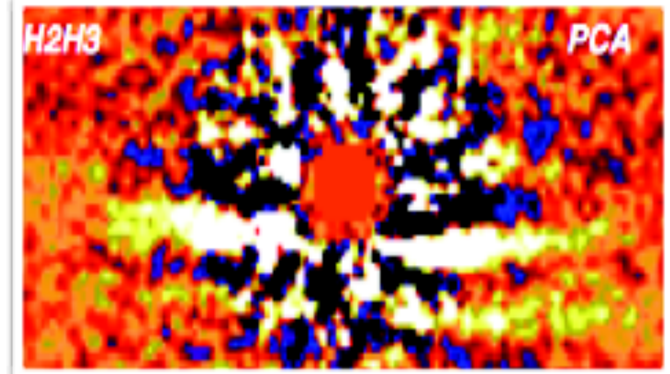
HD111520
LCC, F5; Ld/L* ~ 1e-3
30-100AU



HD106906
LCC, F, Ld/L*~ 1.e-3
~ 65 AU

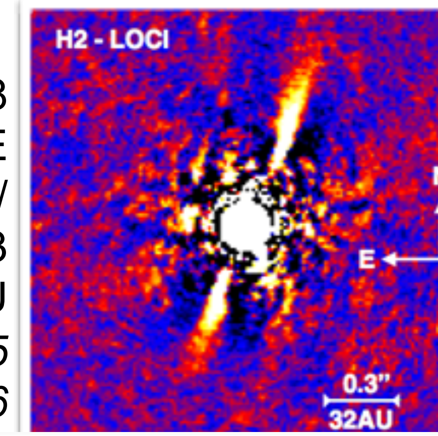


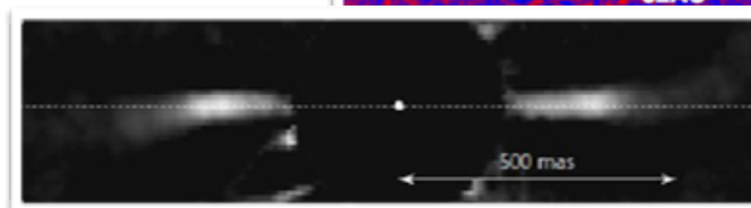
XXX
SPHERE GO
LCC
~ 40AU

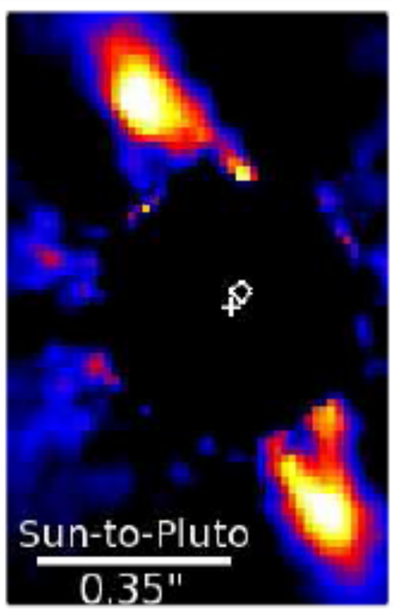


HIP 67497 SPHERE GO
UCL; Ld/L* ~1e-3
Bonnefoy+ 2017

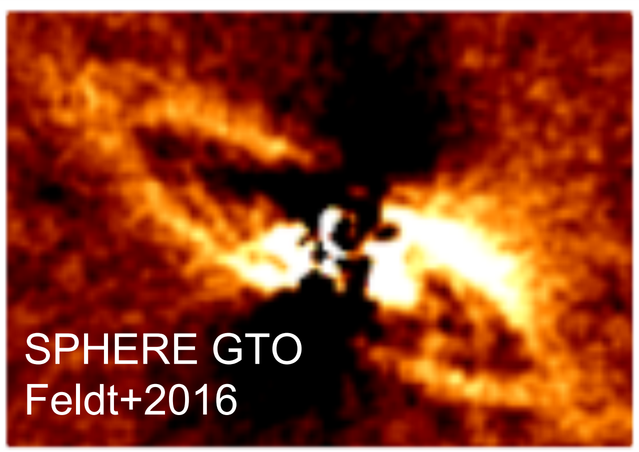
HD110058
SPHERE
LCC, A0V; Ld/L*=2e-3
Up to 65 AU
Kasper+ 2015
Milli+2016

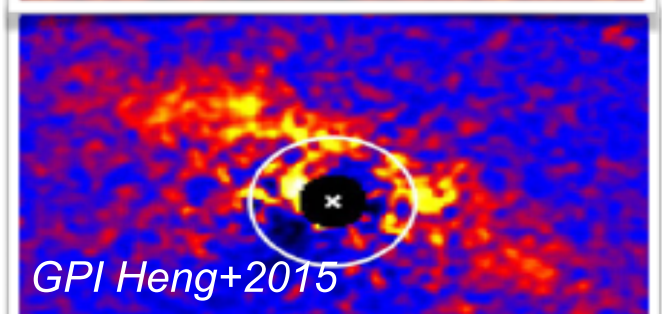




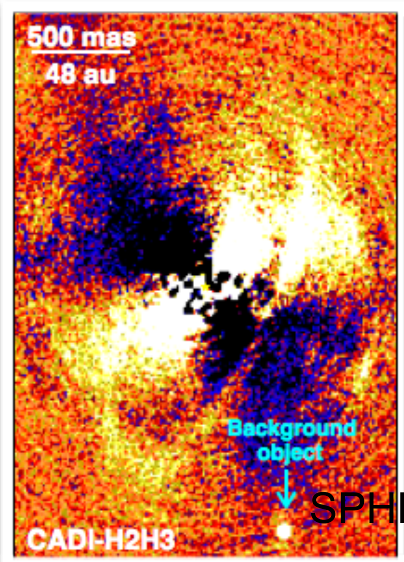


HD115600 GPI
LCC, F2V; Ld/L*=1.3e-3
22-48 AU
Currie+ 2015

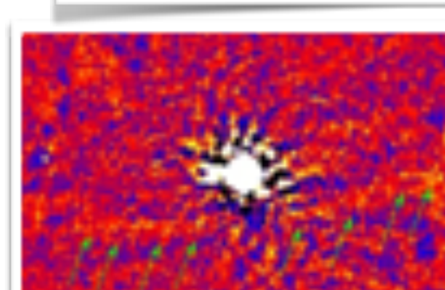




HD131835
UCL, A2V; Ld/L*>1.e-3
75-210 AU



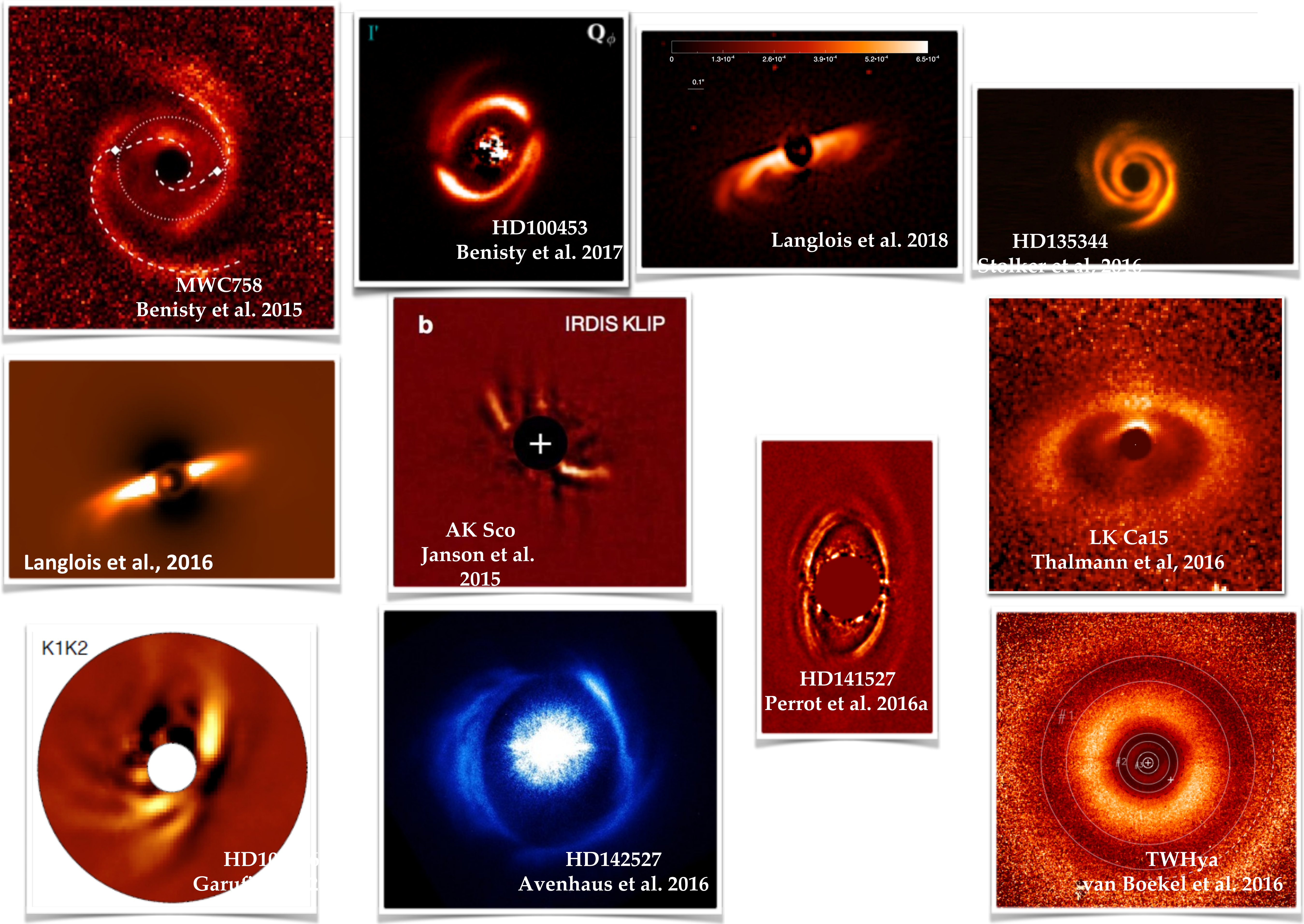
SPHERE GO
LCC
~ 40AU
Bonnefoy+ 2017



SPHERE
LCC
Milli et al, 2016

Tens of AU scales -- ring structures – side asymmetries

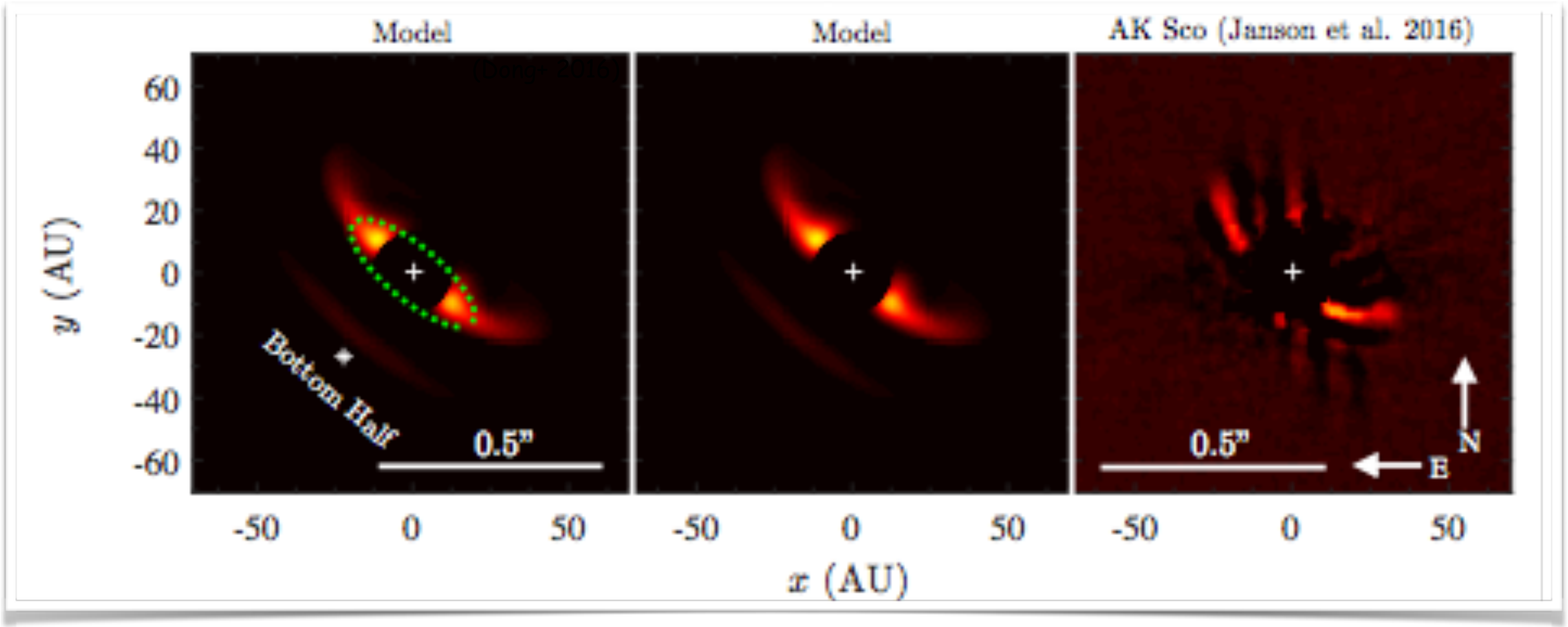
More to come



Protoplanetary disks with SPHERE

Spirals & gaps

Planets to explain spirals in transition disks ?

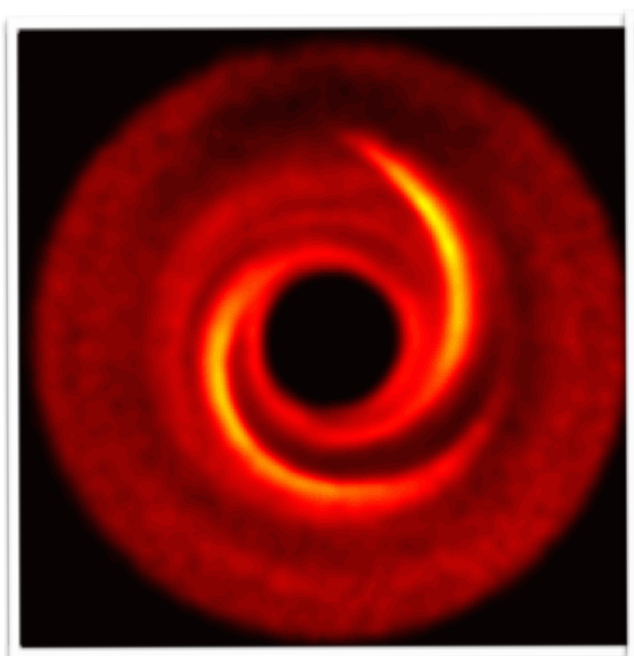


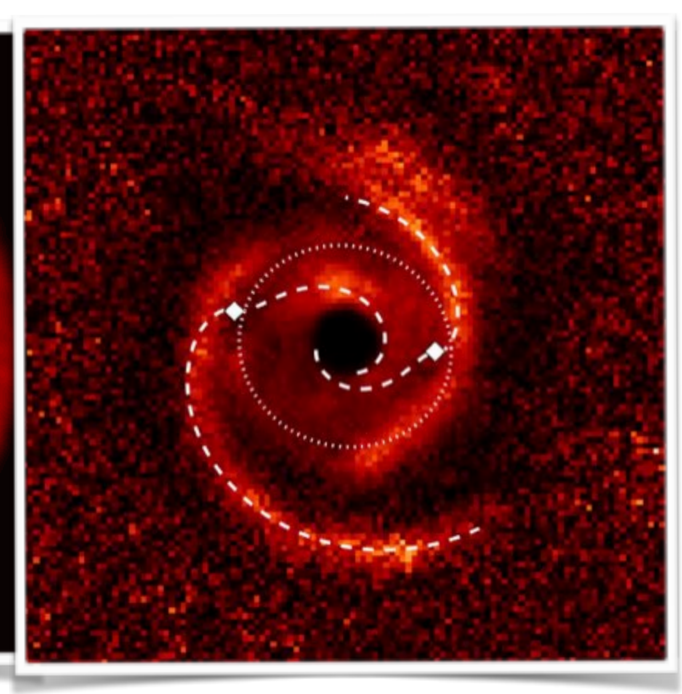
HD model (6MJ)
Dong +2015

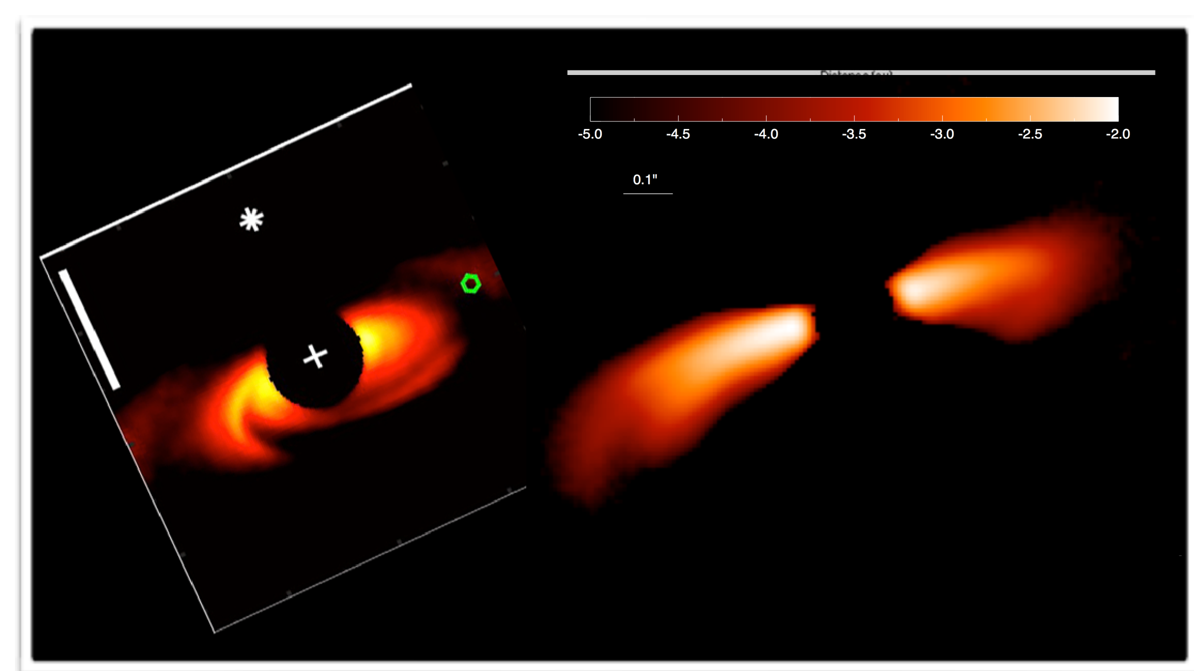
Observations
Benisty +2015

HD model
Dong+ 2016

Observations
Langlois+, 2018

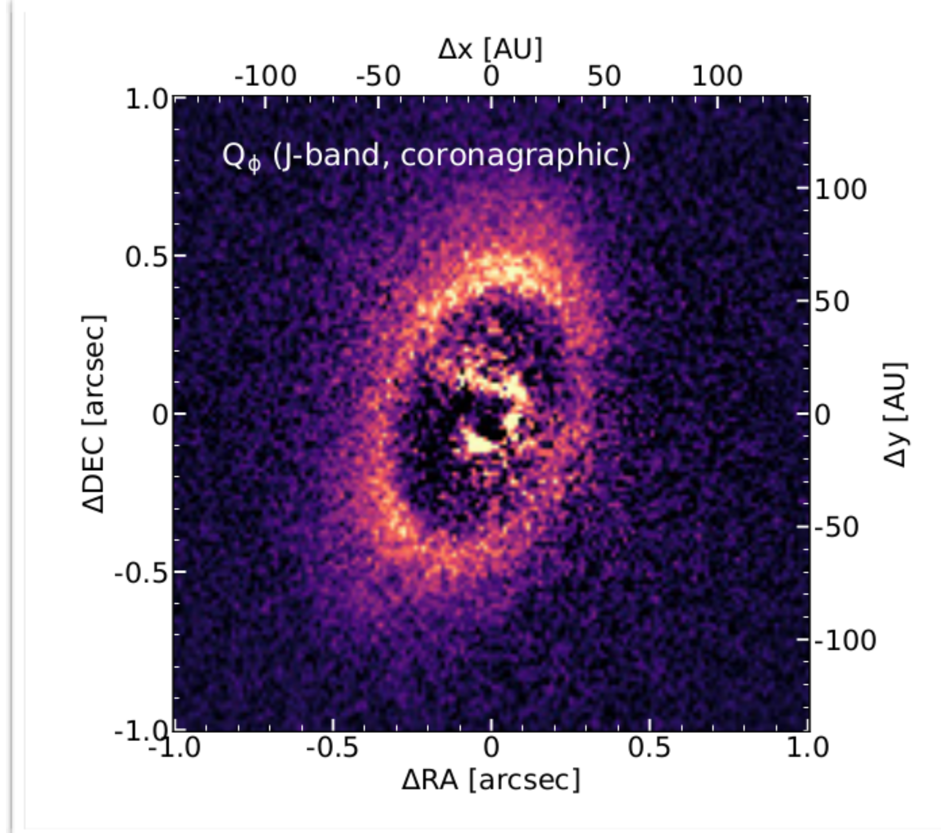


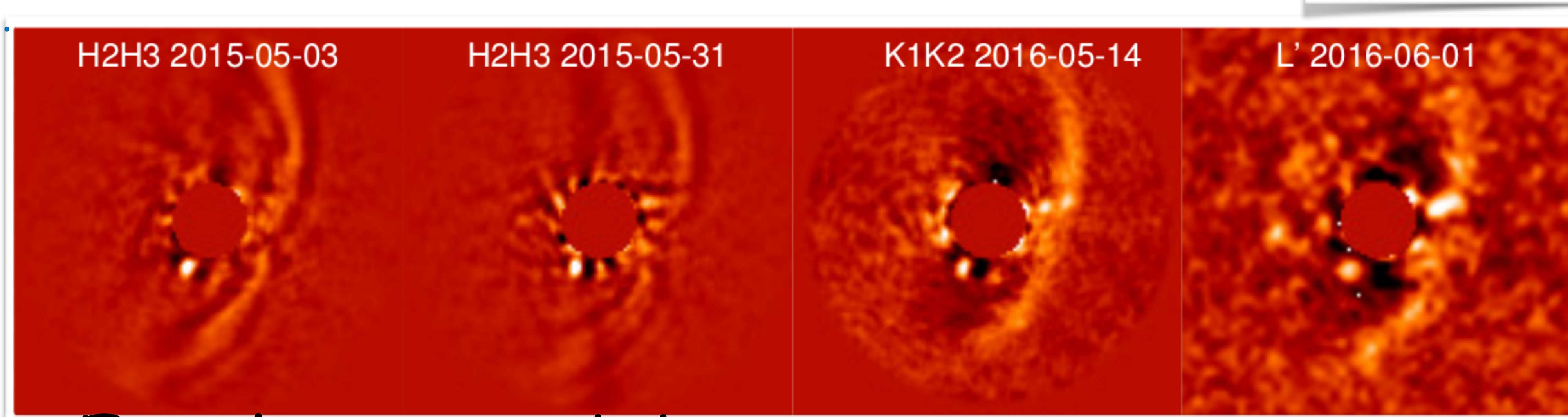




PDS70

- SPHERE/IRDIS DPI observations
  - Young transition disk
  - Inner and outer belts detected
  - Large 65 au sized gap; Flared Geometry;





- Exoplanet candidate
  - Separation = 200 mas (25 au)
  - ΔH2 = 9.2 ± 0.2 mag
  - Mass = 5-10 M_{Jup}; Teff = 800 – 1100 K
  - IRDIS H2, H3, K1 and K2 + NaCo L'

Keppler et al. 2018, submitted

cf Beth's Talk

Status

- Very few planet-mass companions detected despite XAO
- Distribution of giant planets :
  - massive giant planets are not numerous, at separations > 5-10au
  - directly imaged planets so far belong to a small category of planets
- Many disks detected
- Planets in protoplanetary disks still debated
- Studies of individual cases very informative : confirms that DI is a powerful tool for planet characterisation and studies of planet-disk interactions

GP Exploration in Direct Imaging

- Detection
  - Still very limited in (mass, sep) : ~5 MJup, 10 au

we still lack most of the 5-10 Mjup in the 5-10 au range and by far the SS young GP analogs

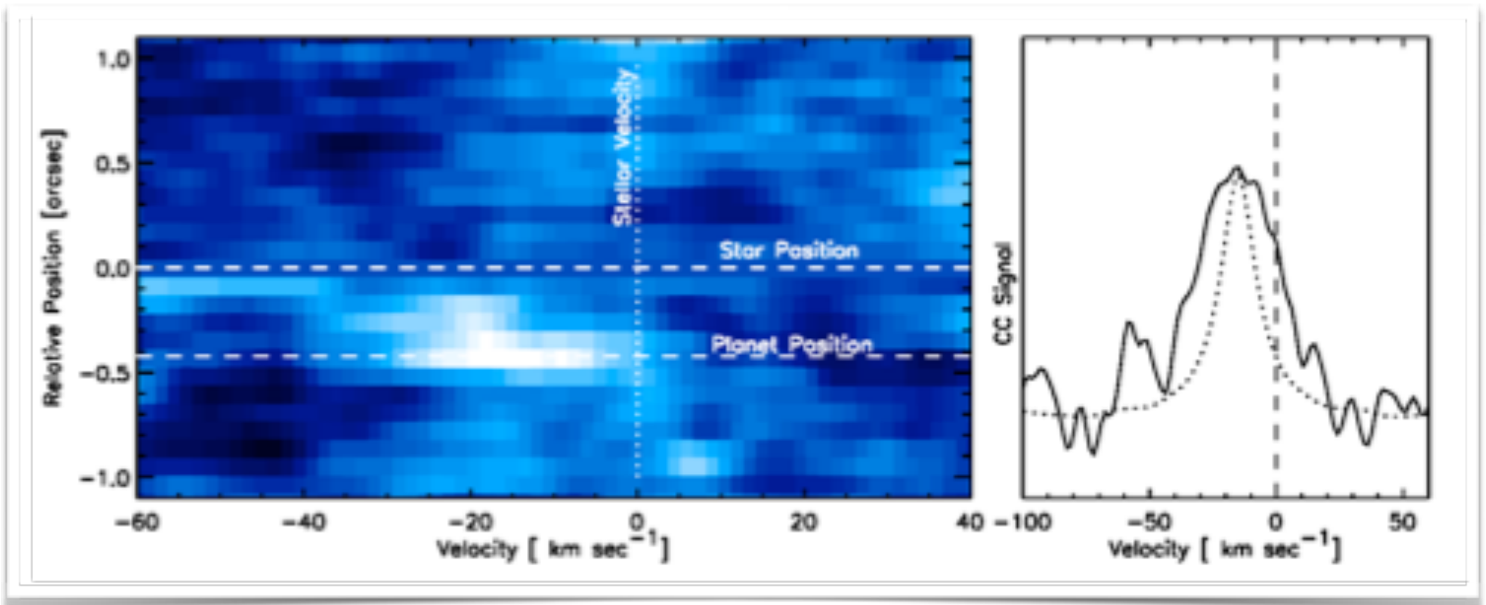
  - Still very limited in age (a few 10-100 Myr)

=> Need to improve contrast, sensitivity, IWA

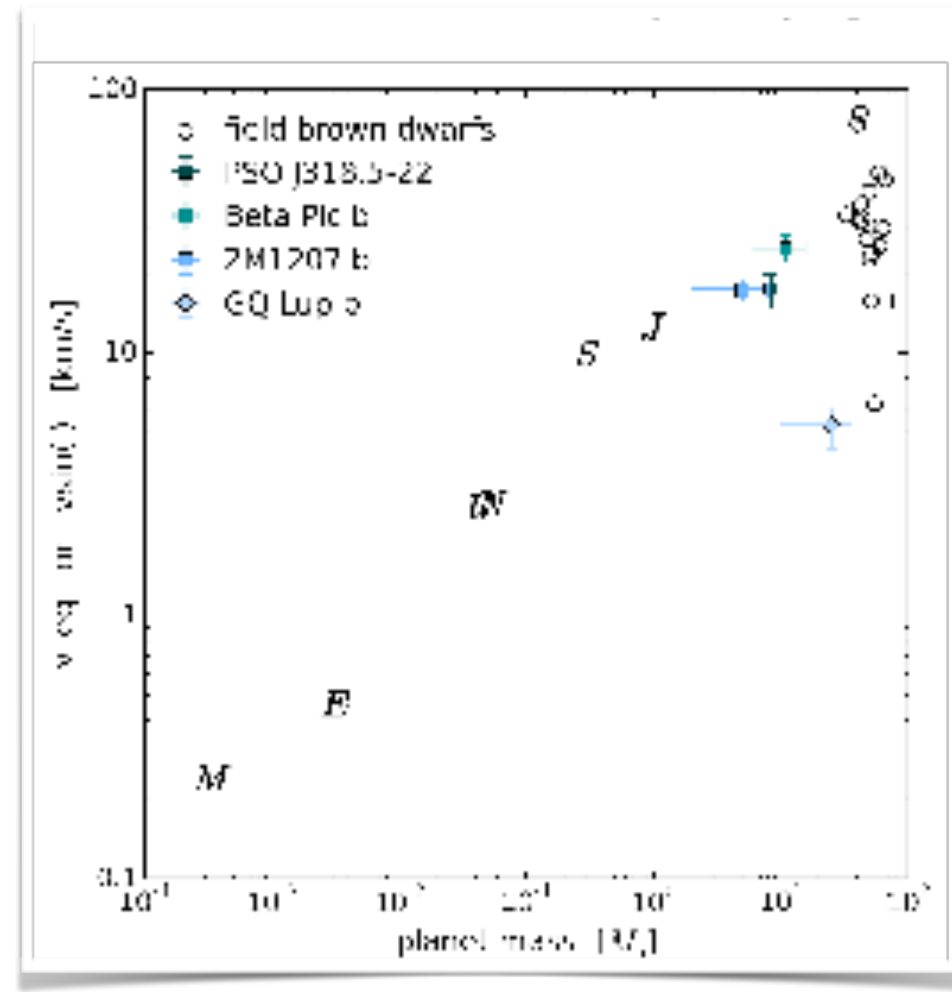
- Spectral characterisation
  - Mostly limited to R<100
  - Few cases of "molecular" detections and velocity-based measurements (Planet rot, orbital vel) (Snellen et al) with no/moderate AO correction

Coupling (high resolution) spectroscopy and AO

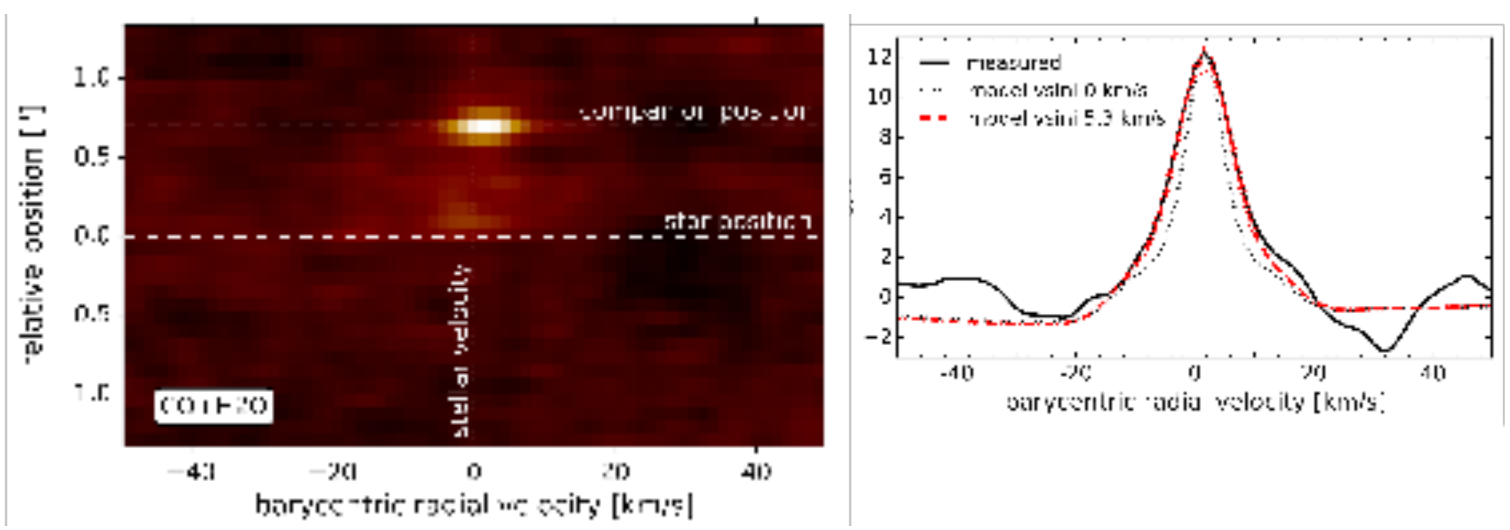
- Beta Pic b rotation period (Snellen et al, 2014)



CRIRES (no AO)



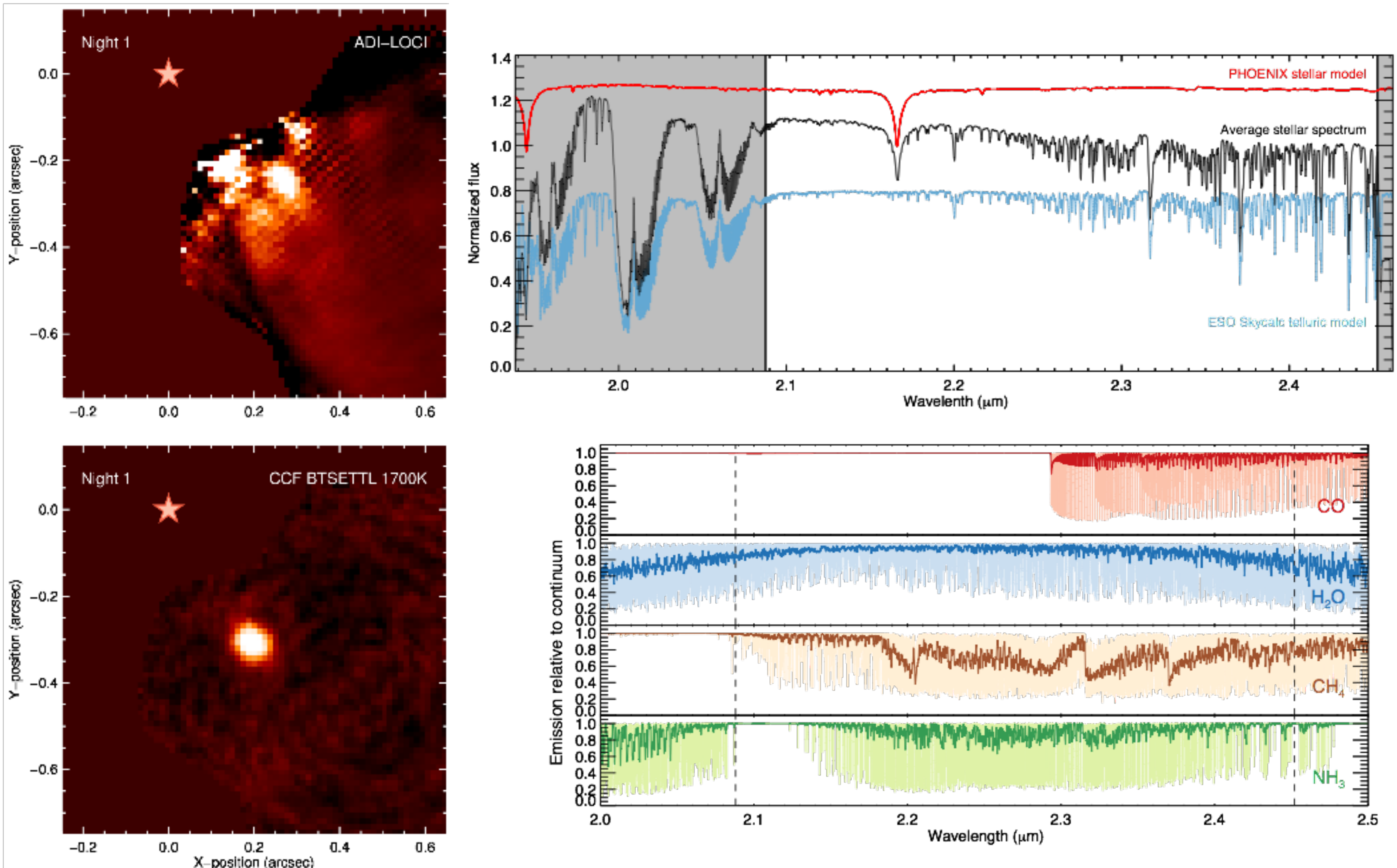
- GQ Lup B rotation period (Schwarz et al, 2016)



R~100000 CRIRES + MACAO

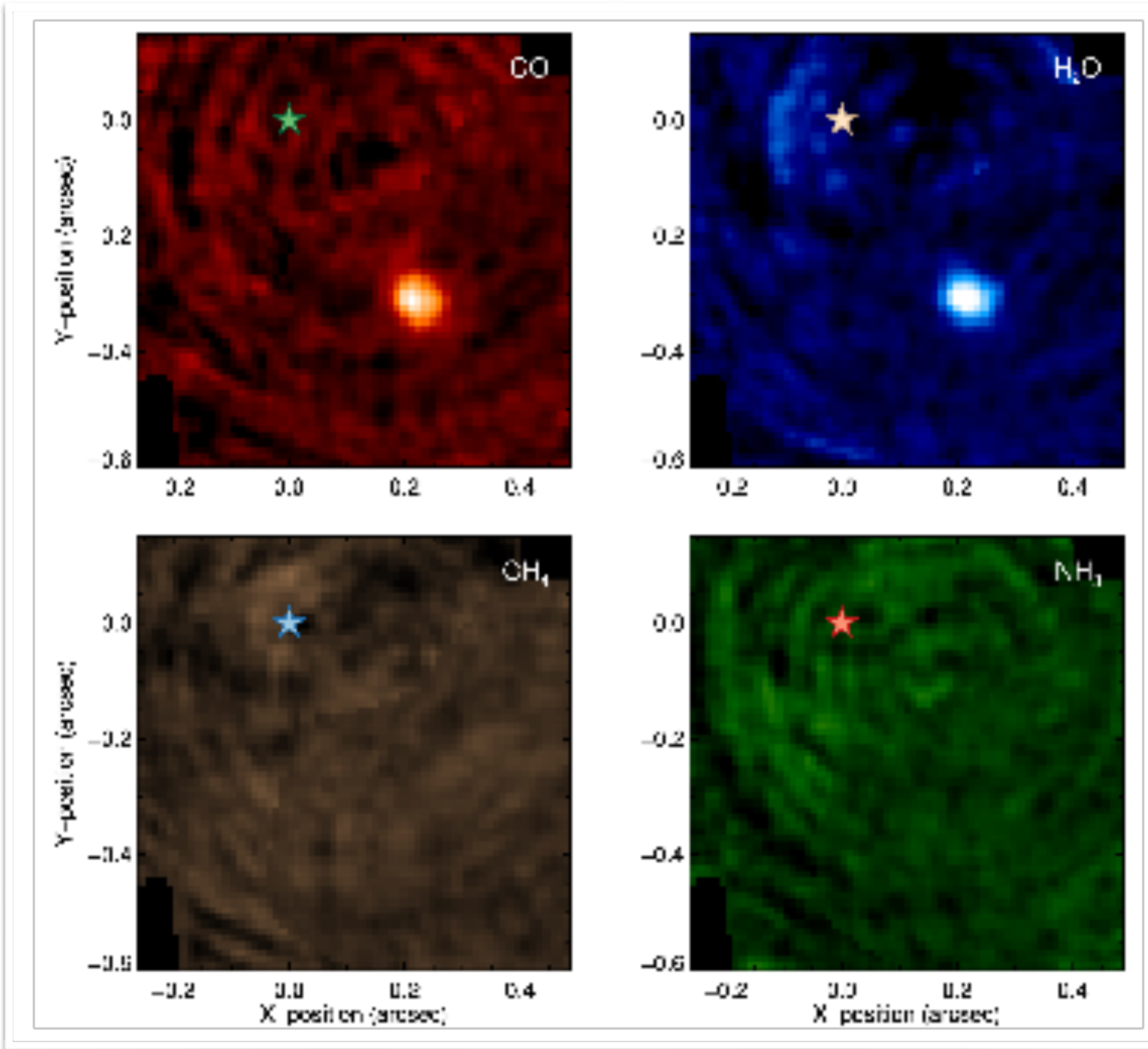
- Coupling ESPRESSO+SPHERE for aCen b (Pepe+ 2018)

Spectroscopy coupled with AO



Hoeijmaker+, 2018, subm

Coupling (high resolution) spectroscopy and AO



R5000 SINFONI

(Hoeijmaker+, 2018, subm.)

Future

Improve XAO
10m class telescopes
near-mid-IR

Disks & lighter young GP
around ~ 5 AU

E-ELT 1st gen. instruments
MICADO, HARMONI, METIS

Disks & young GP tens of AU in SFR
Inner components of disks
sub-Jup GP a few AU

XAO on the ELT

Super Earth in HZ ?

2018

2025

2030

JWST (mid-IR)

Light (0.2MJ) young GP, 10au
>2MJ GP around < 2Gyr close M

GP typ > 1"

?

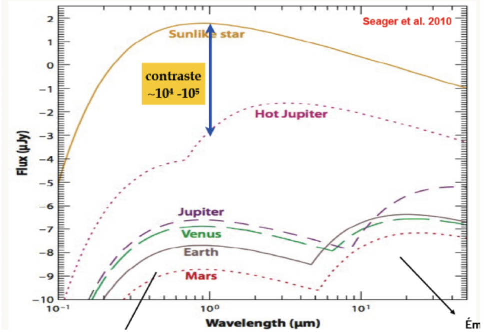
WFIRST (optical)

Detection down to super Earths
LR spectra
Disks

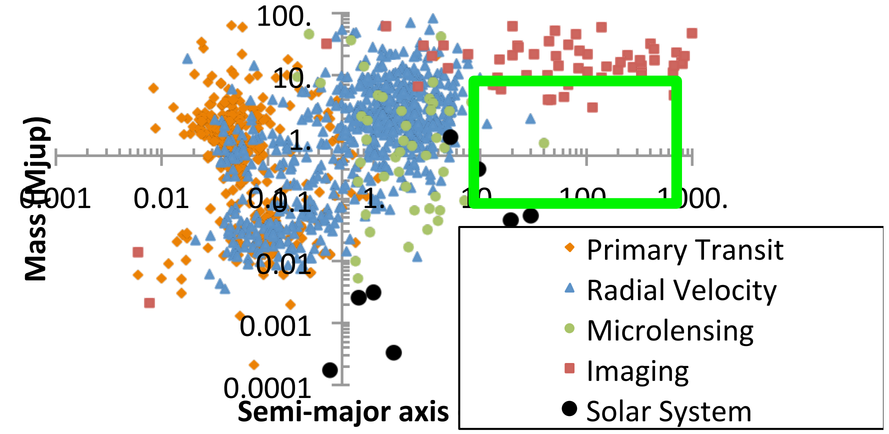
?

LUVOIR, HabEX

Earth in HZ
atmospheres,
Habitability

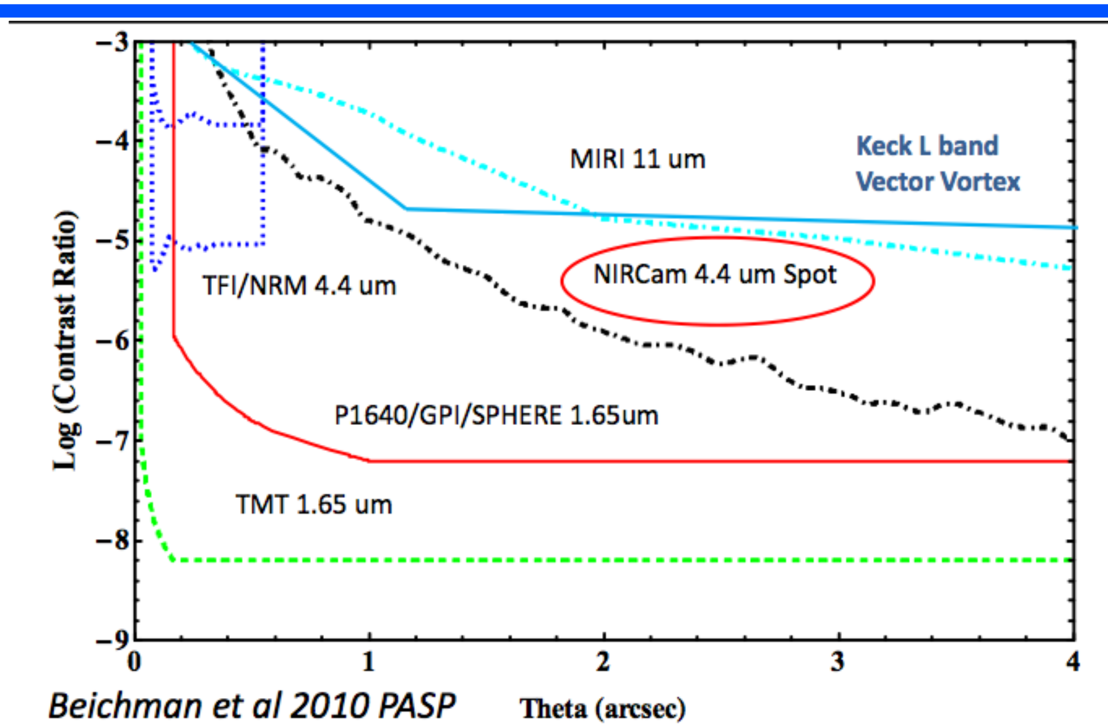


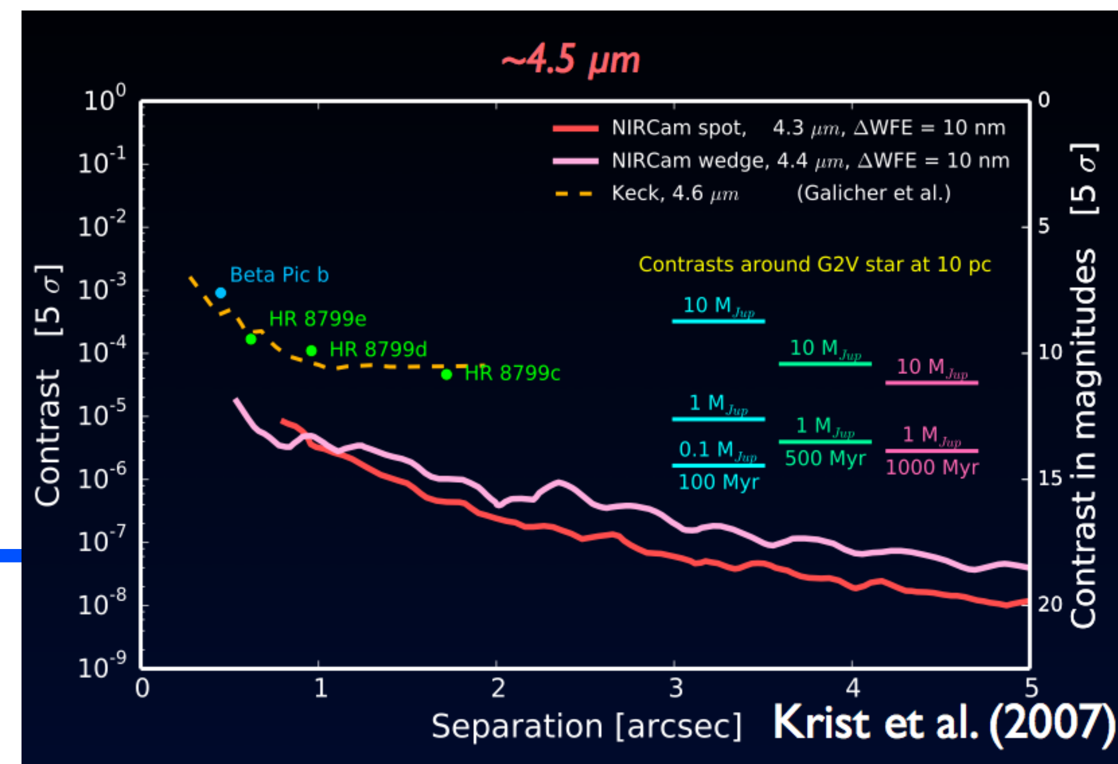
Exoplanets Imaging withJWST



Complementarity ground & space

- JWST : light planets further than 1″
- Ground AO : planets within 1″





Niche for JWST

- **Light**, young giant planets (0.2 MJup, 10 AU)
- >2MJup planets few au from **<2Gyr, close (<10pc) M dwarfs**

Beichman, 2010

Improving current systems on 10m

There is a spectrum of possibilities, with different levels of complexity and costs

- More sensitive WFS
- Faster correction
- Improved correction of NCPA
- Improved instrumental stability
- Improved coronagraphs (Vortex, APP and derivatives are not yet used routinely !)
- Coupling spectroscopy and XAO (various flavors)

Such improvements will serve as test benches for ELTs

Improving current systems on 10m
Basic Requirements

- IWA down to 0.1"
- $C=10^{-5}$ (goal a few 10^{-6}) at 0.1-0.2" (5-20 au at 50-100 pc: e.g. Sco -Cen) under median conditions
- Spectral Resolutions : 2 interesting domains: 5000-10000 for detection and 100000 for Doppler charac.
- Wavelength domains : H, K, (L-M)
- For targets brighter than R~13 (// Sphere)

- Access targets fainter than R~13 (P2)