High-contrast imaging of exoplanets and disks with adaptive optics

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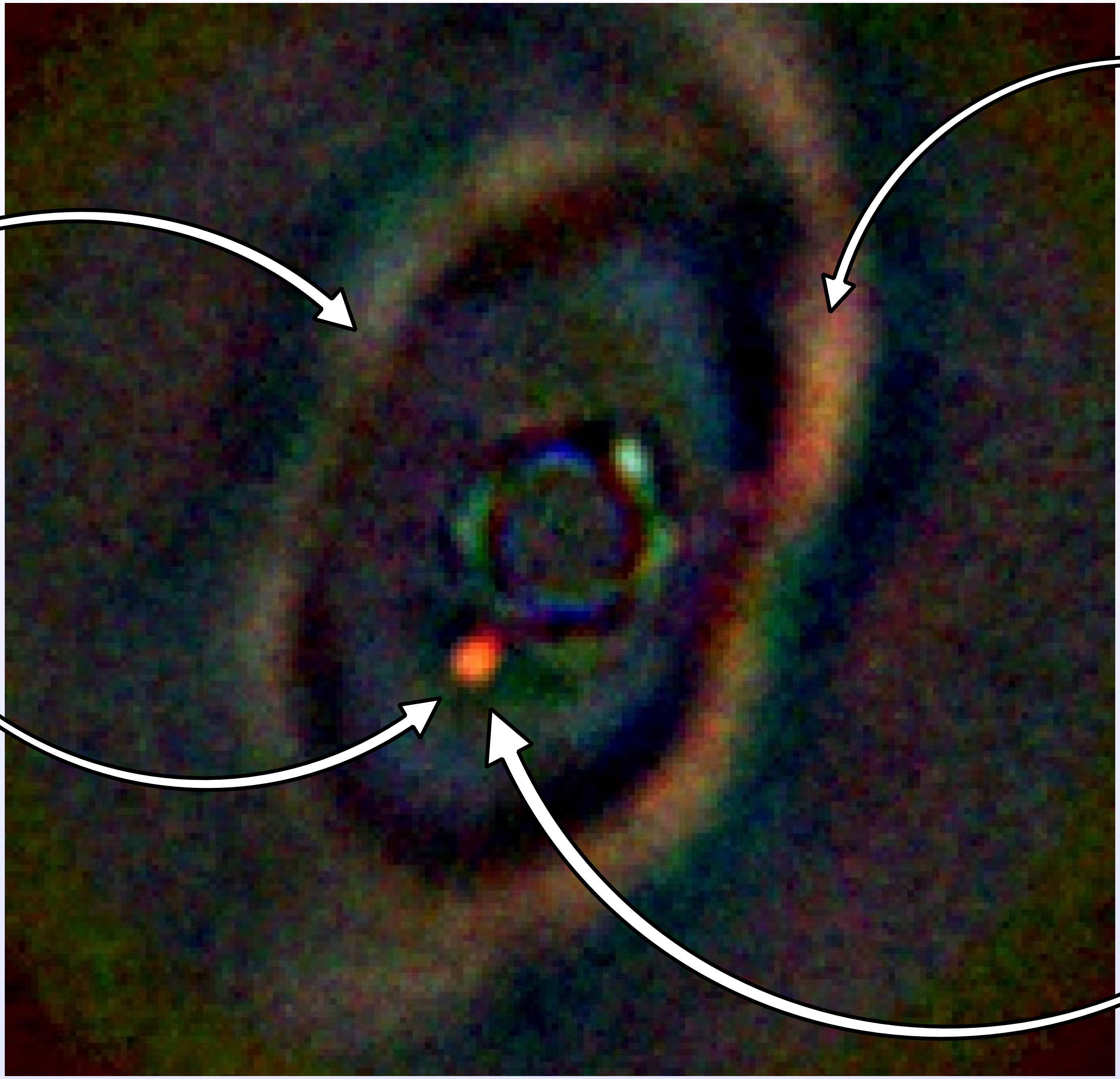
Direct imaging of circumstellar environments



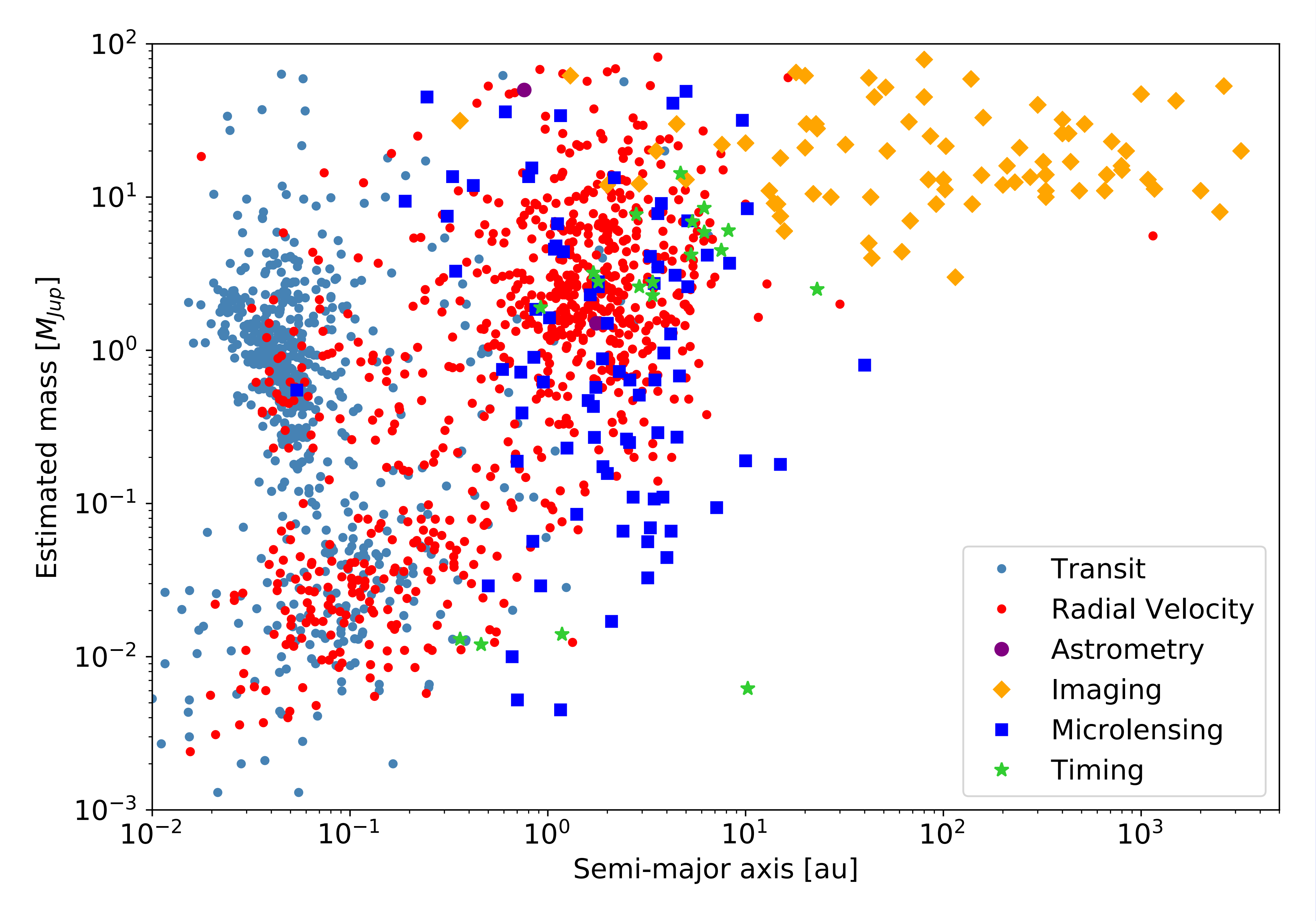
Dust properties

System architecture

Planet composition

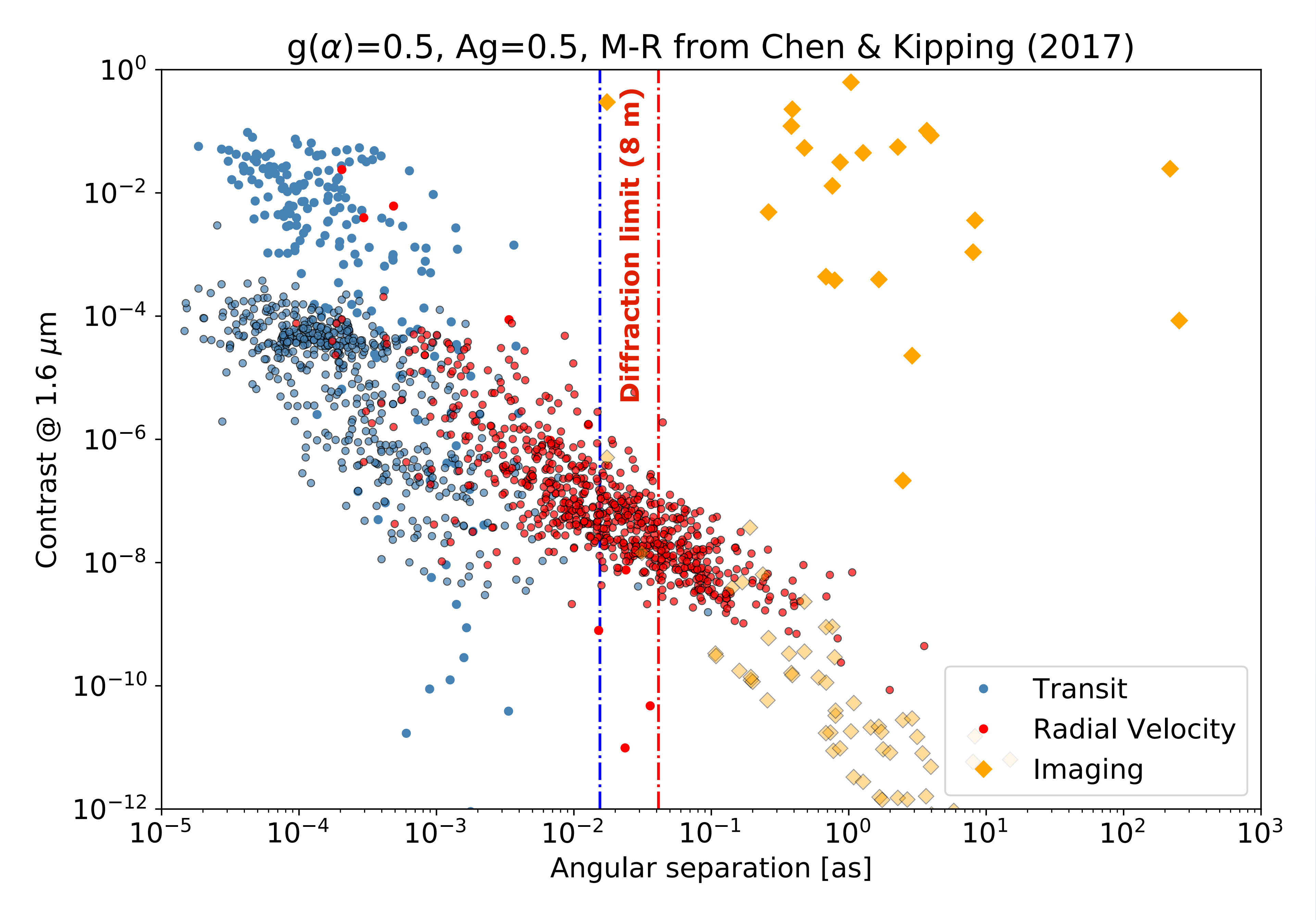
Direct imaging of exoplanets

Physical units

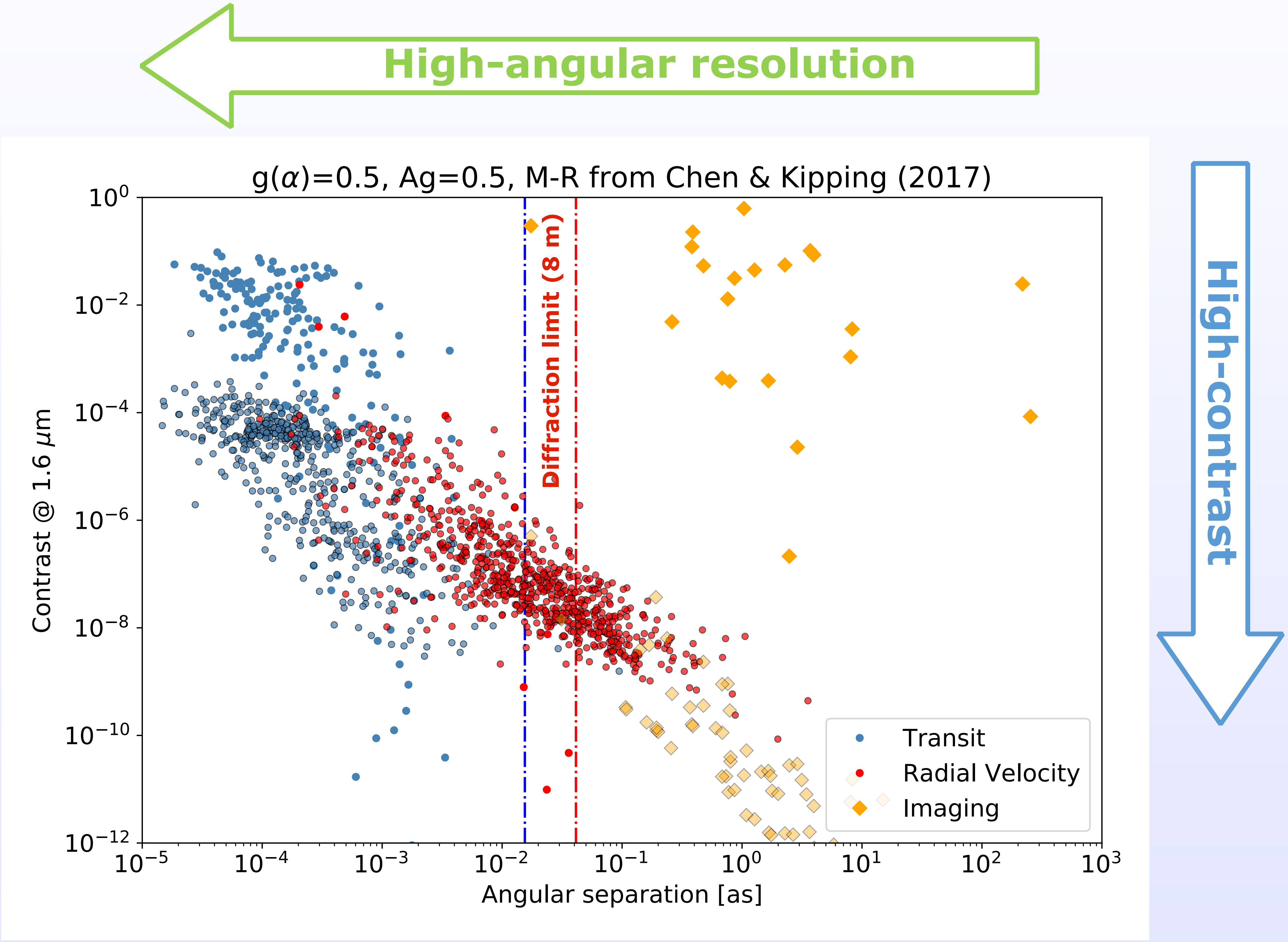


Direct imaging of exoplanets

Observables



Direct imaging of exoplanets



Large ground-based telescopes

<0.1" angular resolution → 8-10 m telescopes

LBT
FLAO + PISCES , LMIRCAM

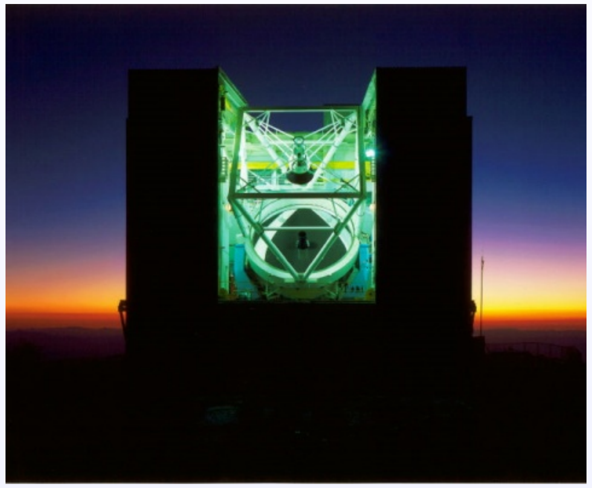
Subaru
AO188, SCExAO + CIAO, HiCIAO, CHARIS

Magellan: MagAO + VisAO-CLIO

Gemini: ALTAIR-NIRI, NICI, GPI

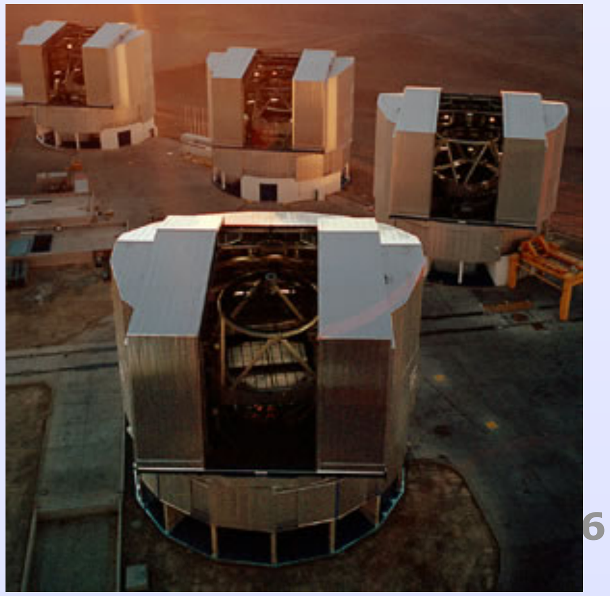
Keck: NIRC2, NIRSPEC, OSIRIS

MMT
MMT AO-2ndary + ARIES, CLIO



Palomar
PALAO/P3K + PHARO-P1640

VLT: NaCo, SINFONI, SPHERE



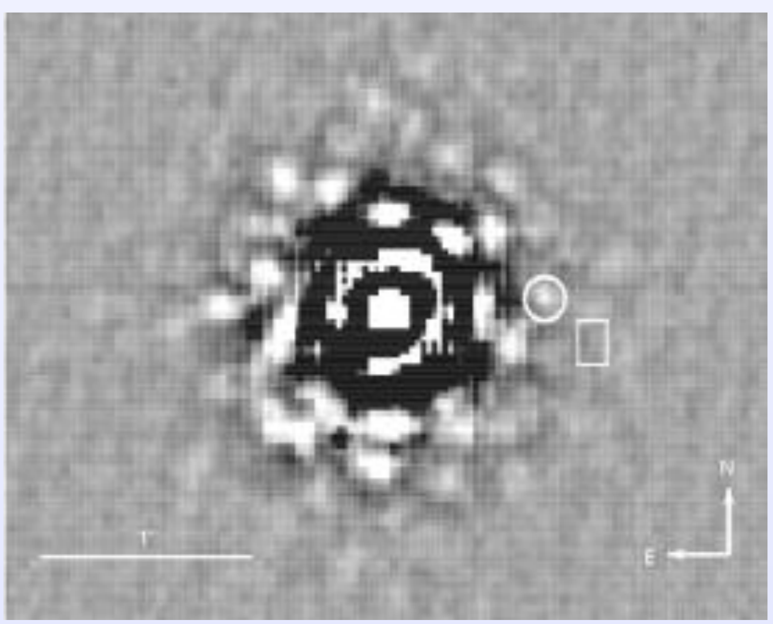
(Extreme) Adaptive optics systems

<0.1" angular resolution → 8-10 m telescopes + AO

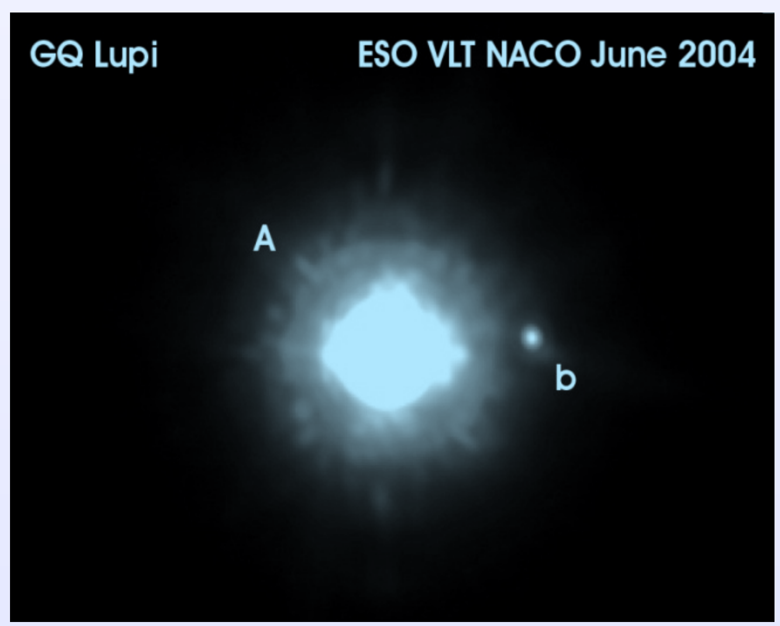
1990s
ESO3.6m/Come-On+
SH WFS; 62 actuators
Sr < 10% (NIR)

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

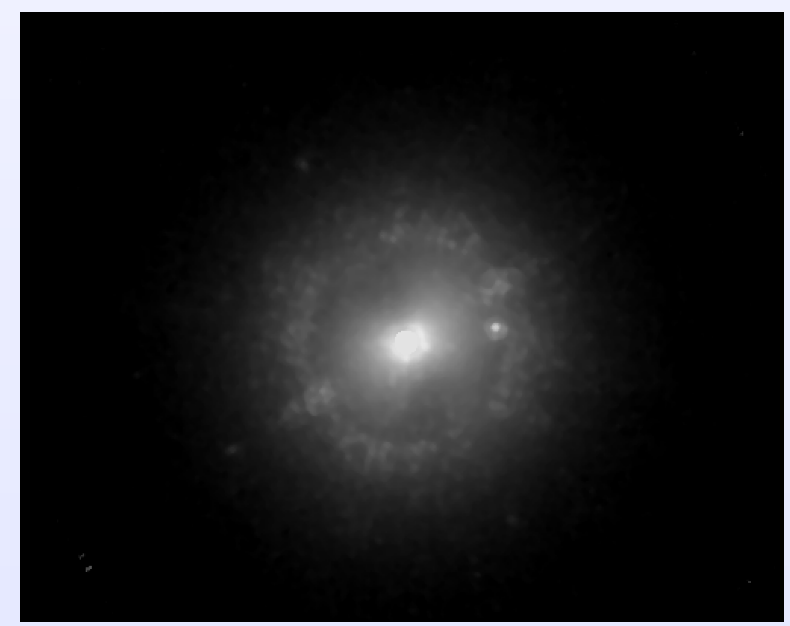
2010s
LBT/SPHERE/GPI
SH/Pyr WFS; 1200 actuators
Sr > 80% (NIR)
Sr = ~40% (VIS)



Janson et al. 2007



Neuhaüser et al. 2005



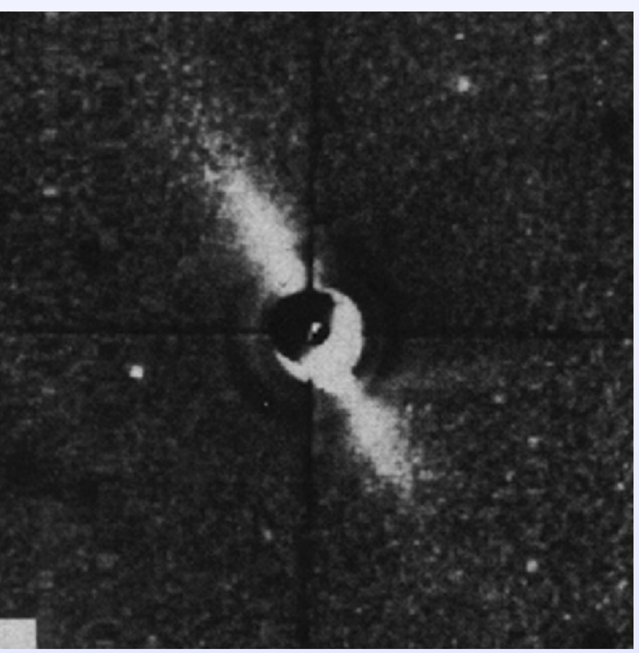
SPHERE consortium

Coronagraphy

Contrast > 10^4 at separation < 2" → coronagraphs

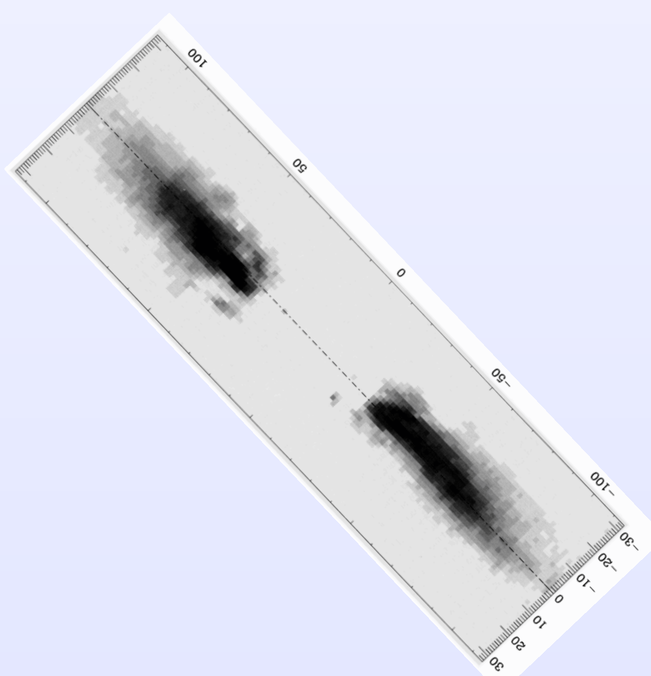
1980s

Las Campañas Obs.
7" mask
VIS



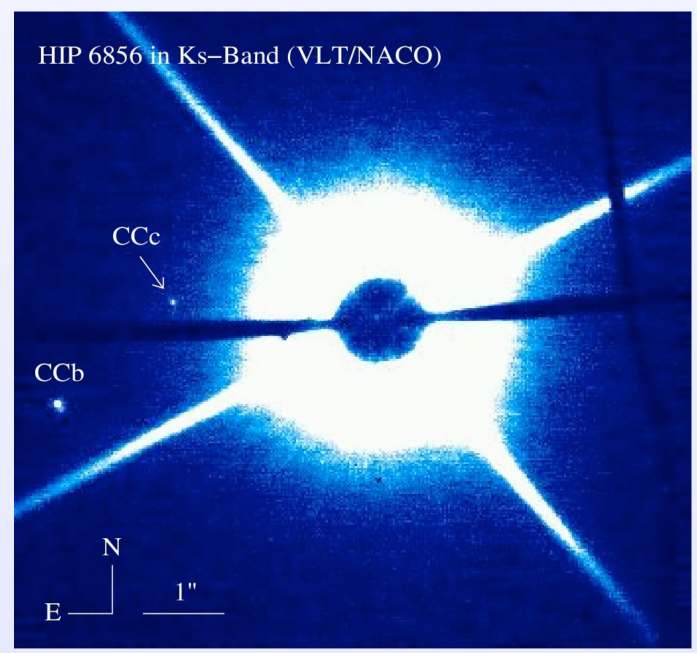
1990s

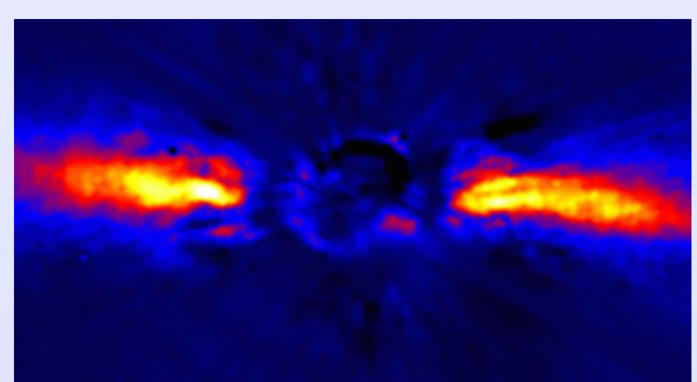
3-5 m telescopes
1" mask
NIR detectors
First AO systems



2000s

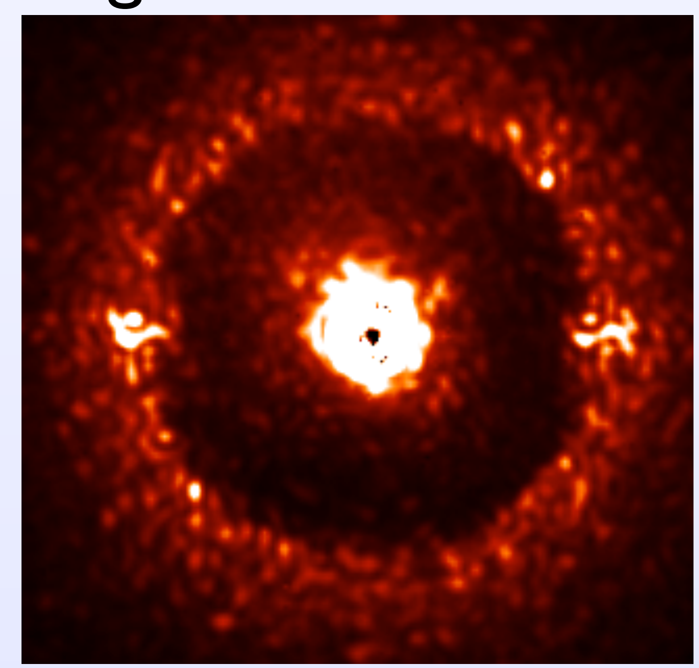
8-10 m telescopes
<1" mask
NIR detectors
Low order AO

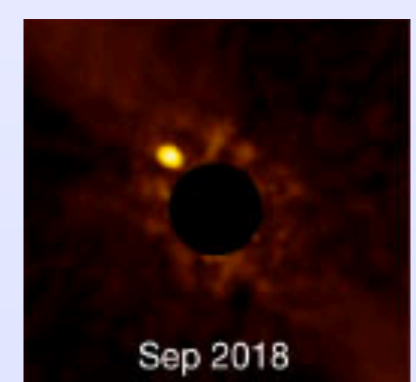




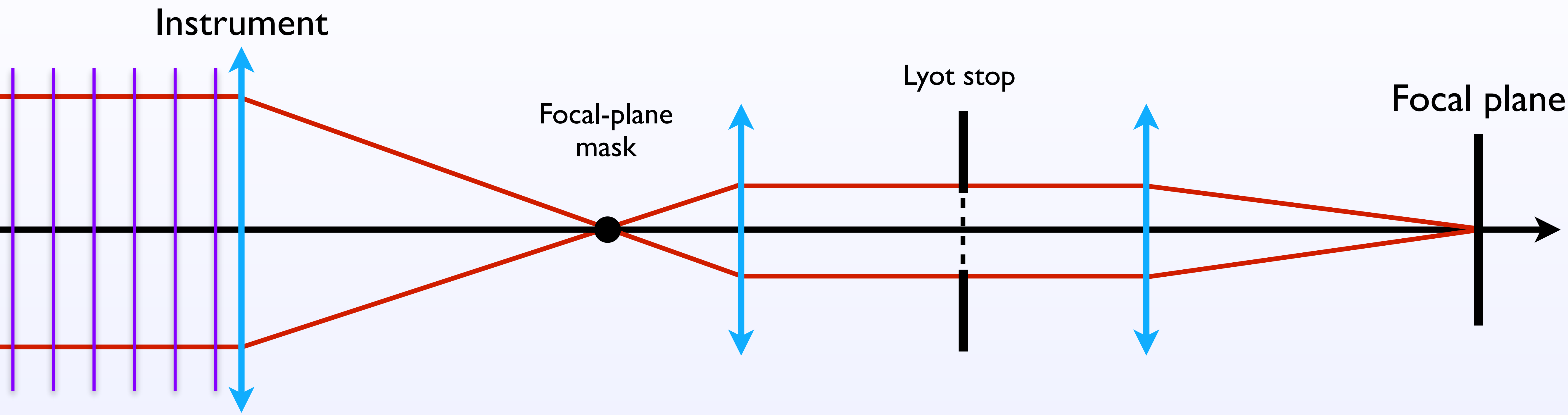
2010s

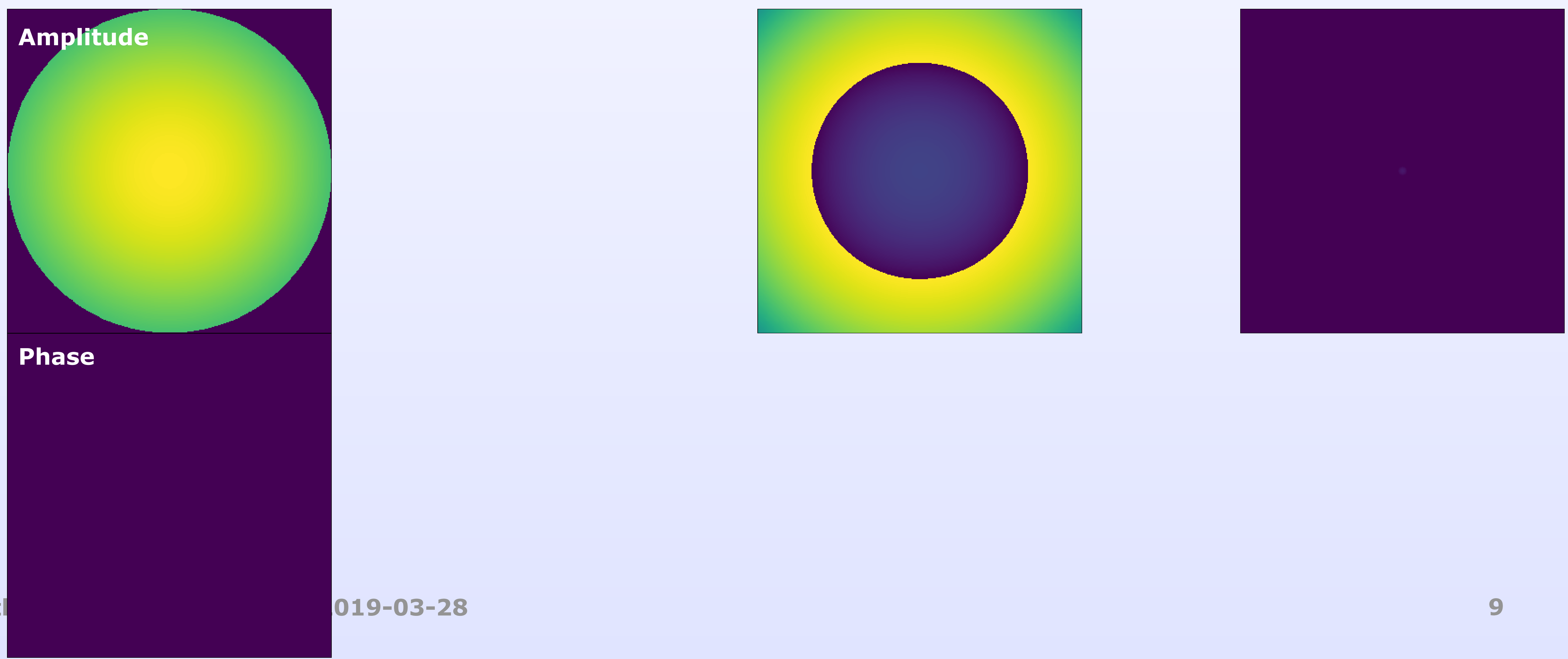
8-10 m telescopes
<0.1" mask
NIR or VIS
High-order AO





Real coronagraphy requires AO!





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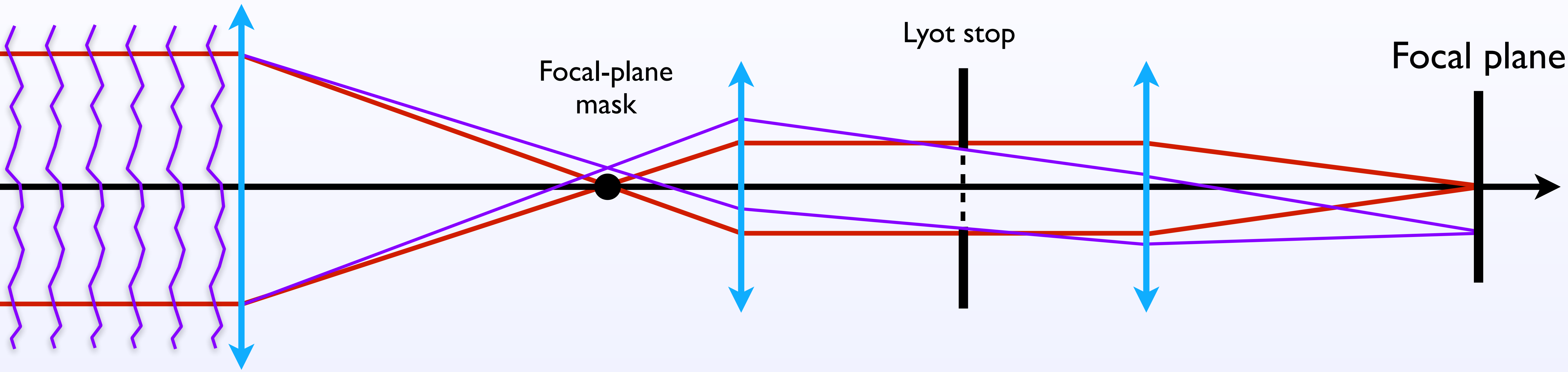
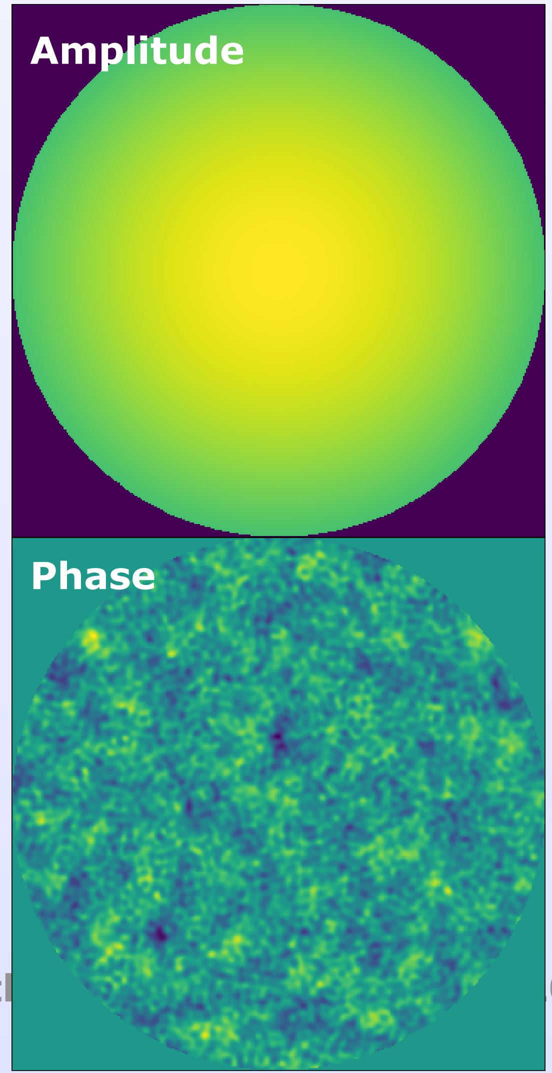
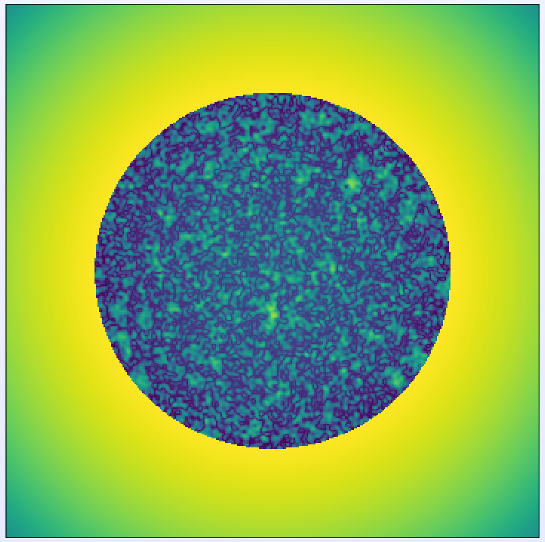
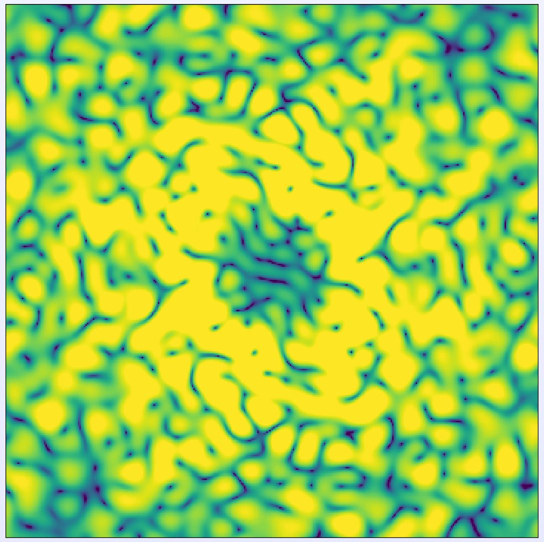


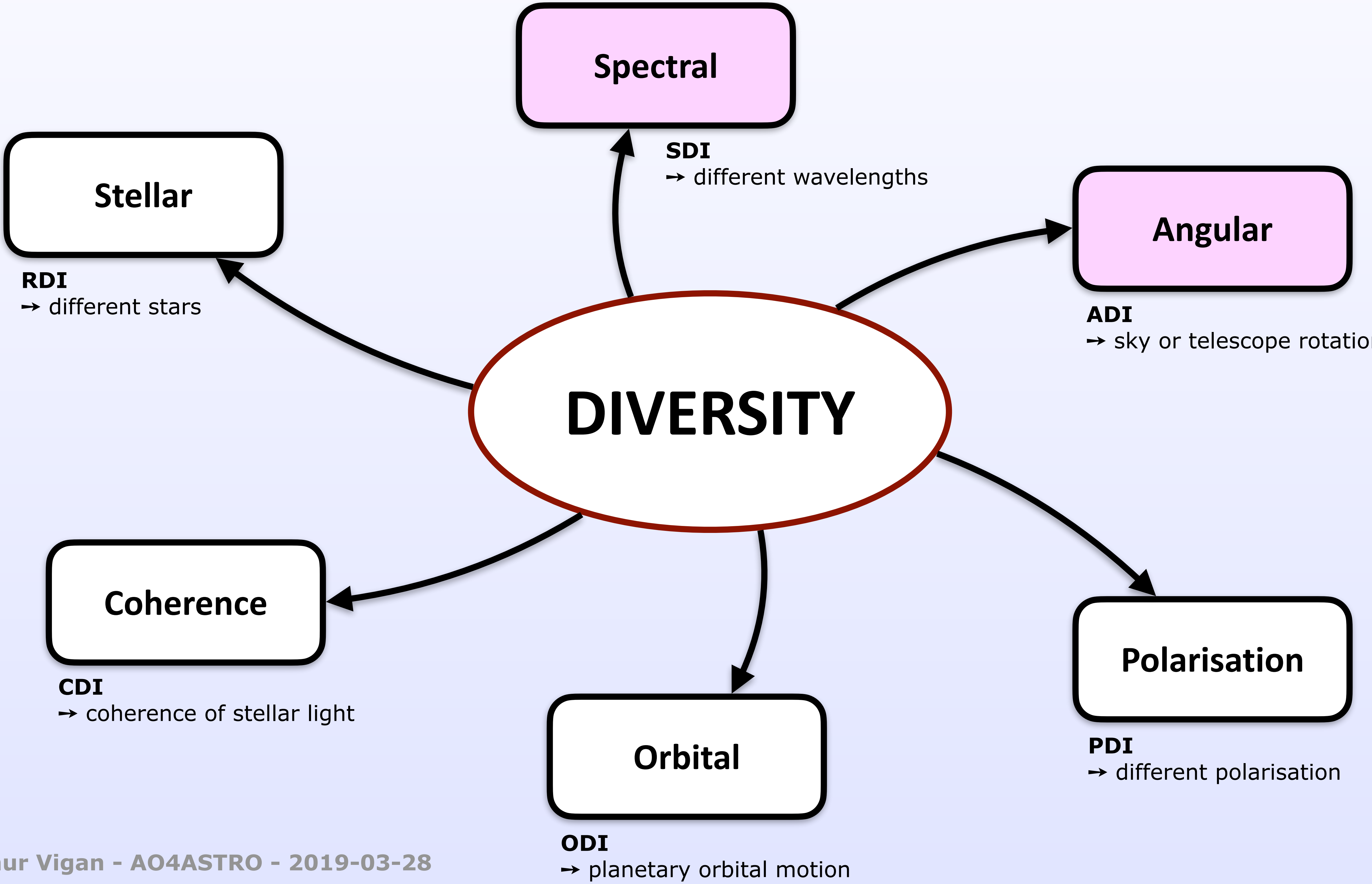






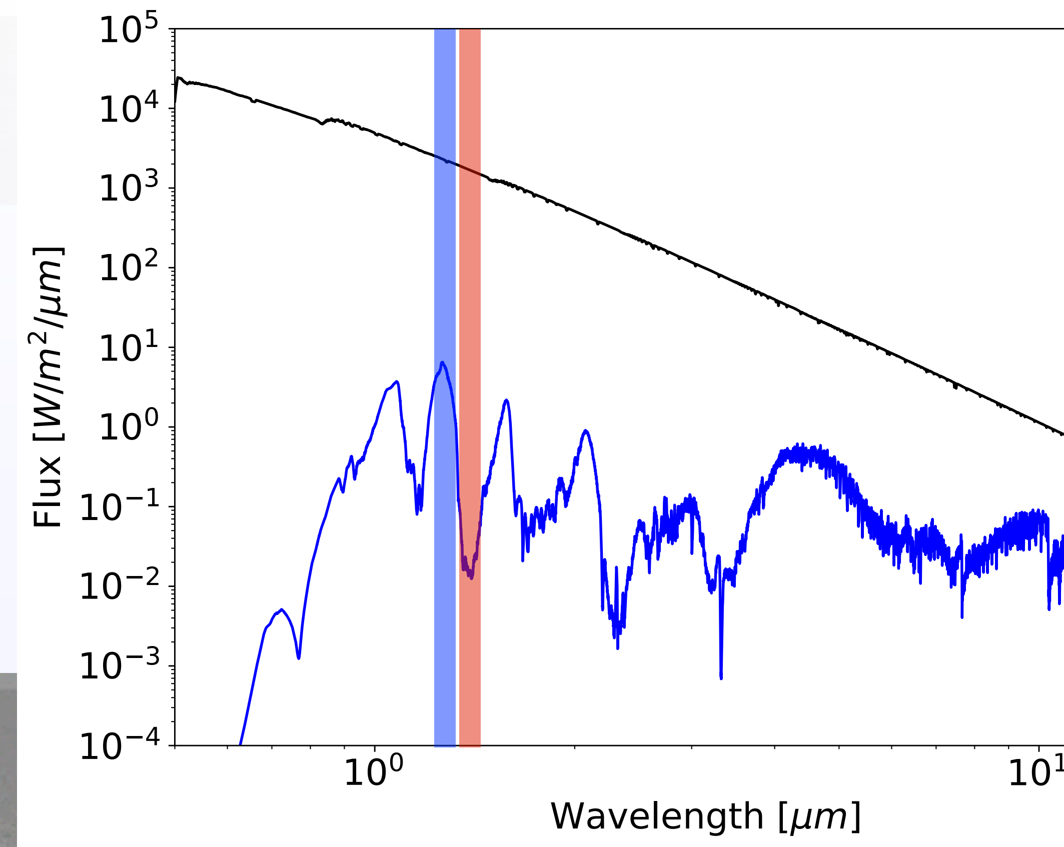
Post-processing

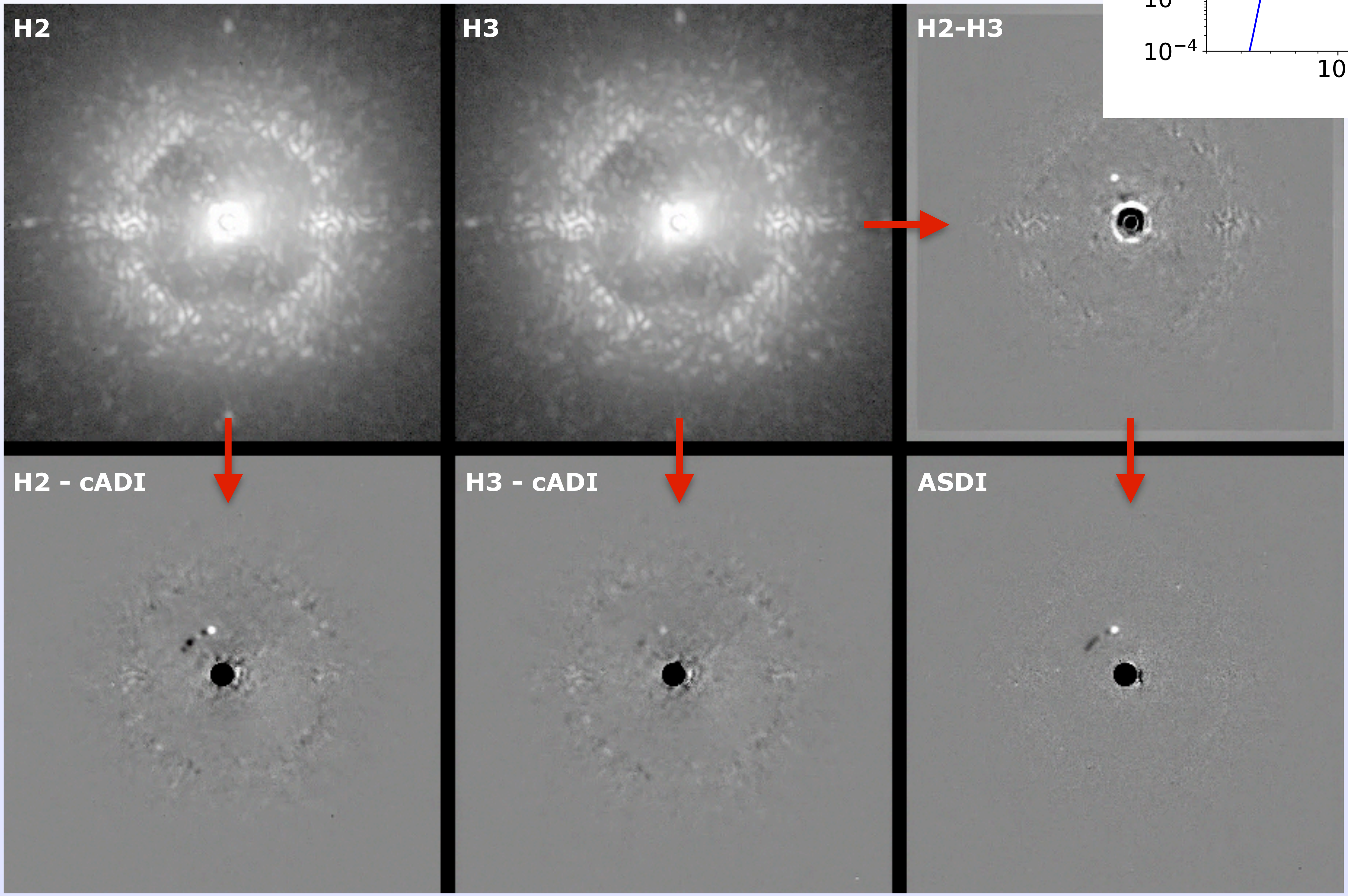
Contrast > 10^6 at separation < 2" → post-processing



Post-processing: ADI, SDI

Racine et al. (1999) - SDI
Sparks & Ford (2002) - Spectral Deconvolution
Marois et al. (2006) - Classical ADI
Lafrenière et al. (2007) - LOCI
Mugnier et al. (2009) - ANDROMEDA
Soummer et al. (2012) - KLIP
... etc ...



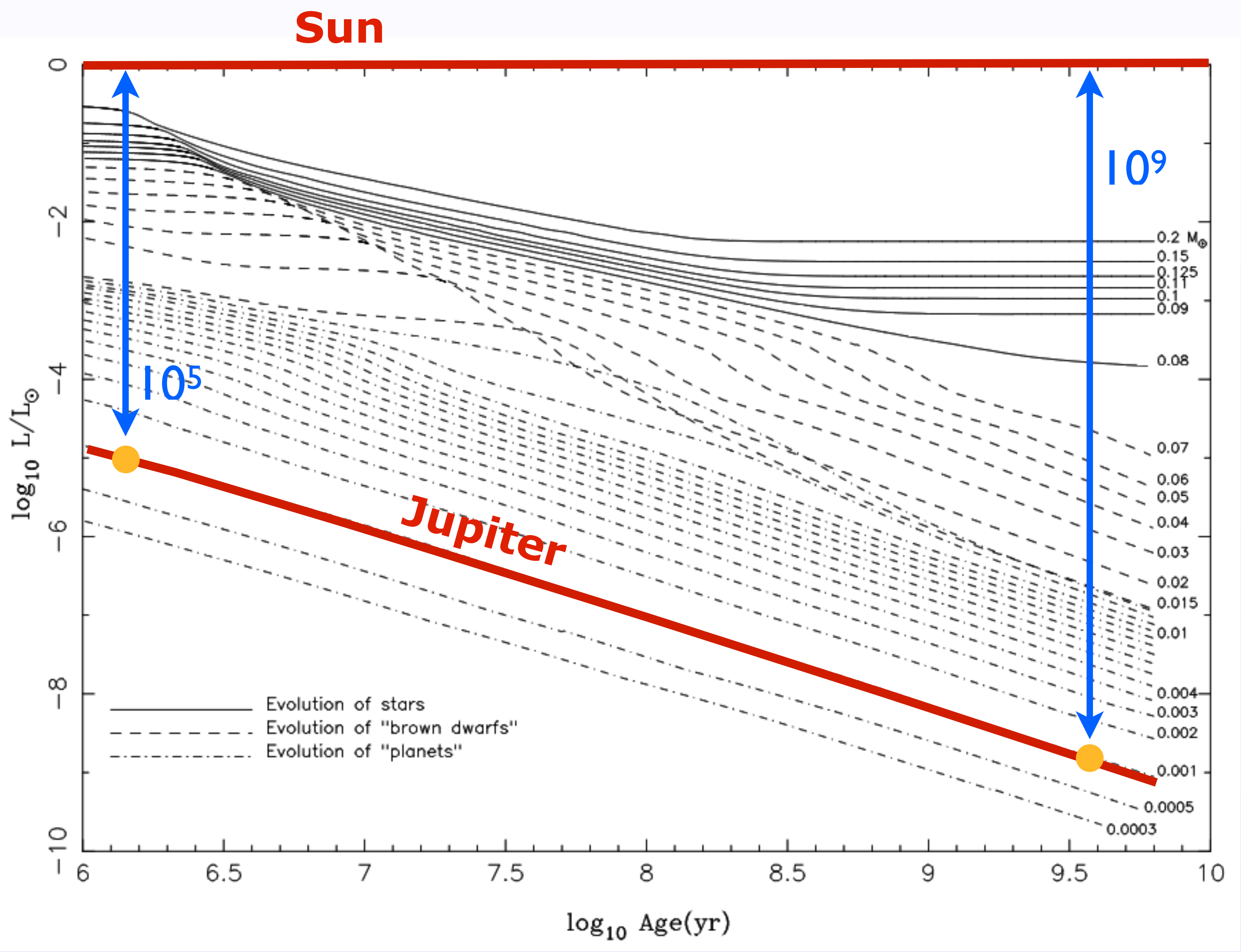


- Assumes:
  - chromaticity of speckles is $\ll 1$
  - speckles lifetime is $\gg 1$
- Strong assumptions!

Target selection

Sensitivity to planetary-mass

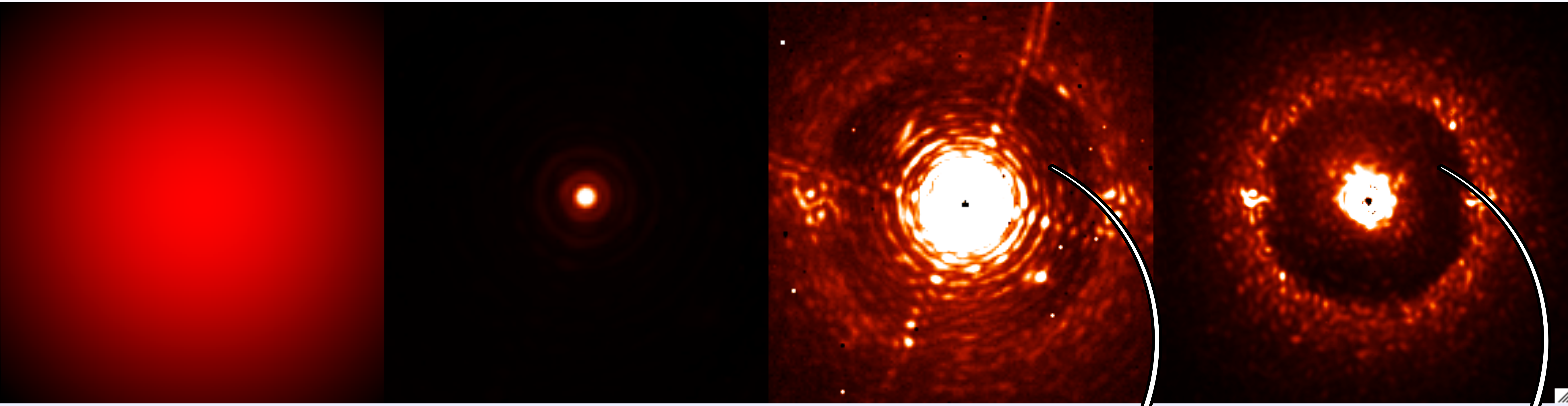
→ young nearby stars



- Identification of nearby young stars: ischrones, Li, Hα, X-ray, kinematics, ...
  - ***1980s:*** TW Hydra (Rucinski & Krautter 1983)
  - ***1990s:*** Additional members of TW Hya assoc.
  - ***2000s:*** 10 new young associations
  - ***2010s:*** extension to low-mass stars, intermediate-old (<1 Gyr), more distant associations

Mixing ingredients: the direct imaging recipe

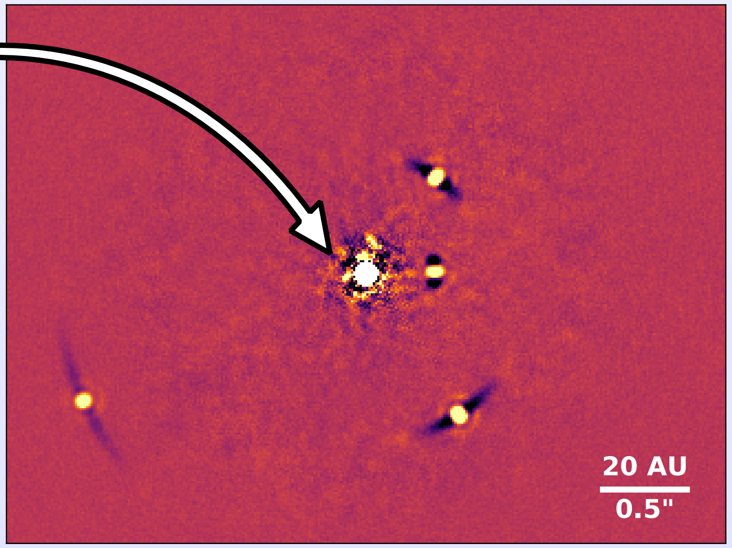
Seeing-limited PSF	Diffraction-limited PSF	Diffraction-limited PSF	Coronagraphic image
✘ Adaptive optics	✔ Adaptive optics	✔ Adaptive optics	✔ Adaptive optics
✘ Coronagraph	✘ Coronagraph	✘ Coronagraph	✔ Coronagraph



Diffraction limited within 20 λ/D

10^{-4}-10^{-5} contrast in dark zone

post-processing



~10^{-5}-10^{-6} contrast down to 0.2"

Enough to detect *young* giant exoplanets of a few Jupiter masses around young nearby stars

Census of direct imaging surveys

Reference	Telescope	Instr.	Mode	Filter	FoV (as)	#	SpT	Age (Myr)	
Nakajima+94	Palomar	AOC	Cor-I	$I - band$	60	24	GKM	Field	
...									
Chauvin+03	ESO3.6m	ADONIS	Cor-I	H, K	13	29	GKM	$\lesssim 50$	
Neuhäuser+03	NTT	Sharp/Sofi	Sat-I	K/H	33	23/10	A–M	$\lesssim 50$	
Lowrance+05	*HST*	NICMOS	Cor-I	H	19	45	A–M	$10 - 600$	
Masciadri+05	VLT	NaCo	Sat-I	H, K	14	28	KM	$\lesssim 200$	
Biller+07	VLT/MMT	NaCo/ARIES	SDI	H	5	45	GKM	$\lesssim 300$	
Kasper+07	VLT	NaCo	Sat-I	L'	28	22	GKM	$\lesssim 50$	
Lafrenière+07	Gemini-N	NIRI	Sat-ADI	H	22	85	FGK	10-5000	
Apai+08	VLT	NaCo	SDI	H	3	8	FG	12-500	
Chauvin+10	VLT	NaCo	Cor-I	H, K	28	88	B-M	$\lesssim 100$	
Heinze+10ab	MMT	Clio	Sat-ADI	L', M	15.5	54	FGK	100-5000	
Janson+11	Gemini-N	NIRI	Sat-ADI	H, K	22	15	BA	20-700	
Vigan+12	Gemini-N/VLT	NIRI	Sat-ADI	H, K	22/14	42	AF	10-400	
Delorme+12	VLT	NaCo	Sat-ADI	L'	28	16	M	$\lesssim 200$	
Rameau+13c	VLT	NaCo	Sat-ADI	L'	28	59	AF	$\lesssim 200$	
Yamamoto+13	Subaru	HiCIAO	Sat-ADI	H, K	20	20	FG	125 ± 8	
Biller+13	Gemini-S	NICI	Cor-ASDI	H	18	80	B-M	$\lesssim 200$	
Nielsen+13	Gemini-S	NICI	Cor-ASDI	H	18	70	BA	50-500	
Wahhaj+13	Gemini-S	NICI	Cor-ASDI	H	18	57	A-M	~ 100	
Janson+13	Subaru	HiCIAO	Sat-ADI	H	20	50	A-M	$\lesssim 1000$	
Brandt+14	Subaru	HiCIAO	Sat-ADI	H	20	63	A-M	$\lesssim 500$	
Chauvin+15	VLT	NaCo	Sat-ADI	H	14	86	FGK	$\lesssim 200$	
Meshkat+15ab	VLT	NaCo	APP-ADI	L'	28	20	AF	$\lesssim 200$	
Bowler+15	Keck/Subaru	NIRC2/HiCIAO	Cor-ADI	H	10/20	78	M	$\lesssim 200$	
Galicher+16	Keck	NIRC2	Cor-ADI	H, K	10	229	A-M	$\lesssim 200$	
	Gemini-N/S	NIRI/NICI							
Durkan+16	*Spitzer*	IRAC	I	4.5 μm	312	73	A-M	$\lesssim 200$	
GPIES Macintosh et al.	Gemini-S	GPI	ALC-ASDI	JHK	3.5	600	A-M	1 - 1000	started in 2014
SHINE Chauvin et al.	VLT	SPHERE	ALC-ASDI	JHK	10	600	A-M	1 - 1000	started in 2015

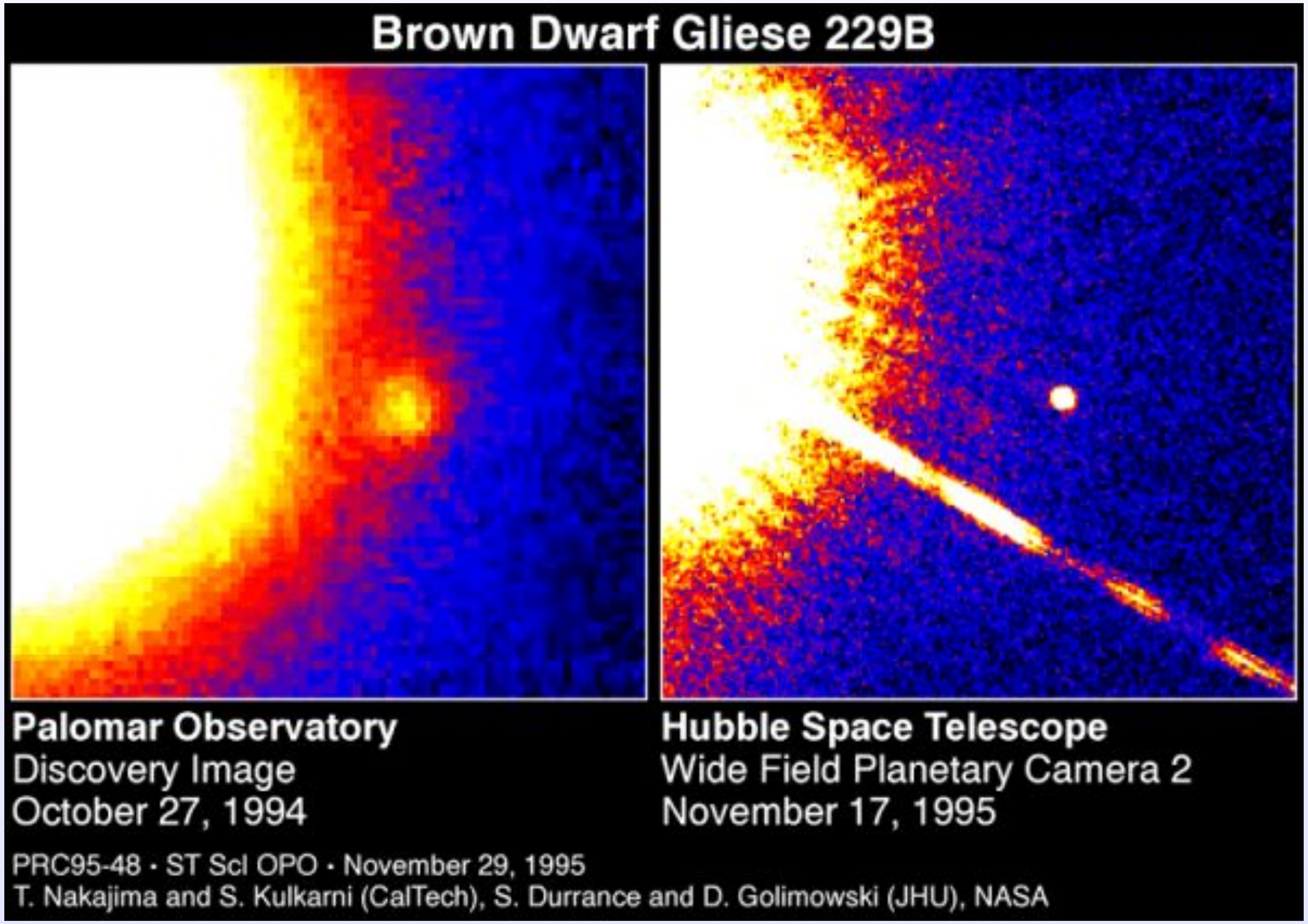
A short timeline of discoveries...

1990 — ***1994*** — 2000 — 2010 — 2020

Coronography

Gl229 B discovery *(Nakajima et al. 1995)*

First imaged substellar companion
- Palomar AOC camera:
  image stabilizer + coronograph
- First T-dwarf discovery with strong CH4 absorptions



A short timeline of discoveries…

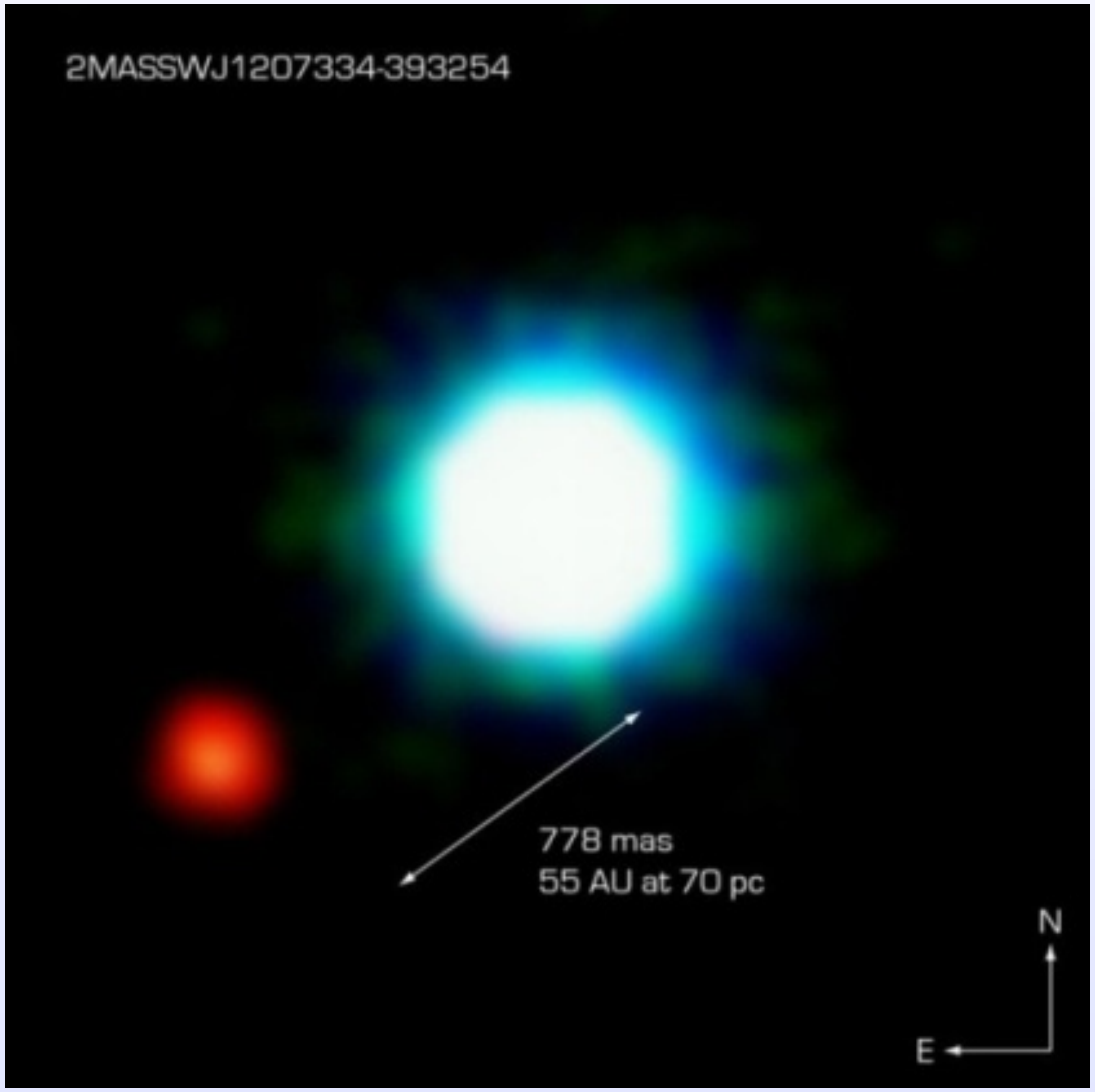
1990 — *Coronography*
2000 — *+IR detectors* *+8-m telescopes with AO*
2004
2010
2020

Gl229 B discovery *(Nakajima et al. 1995)*

2M1207 b *(Chauvin et al. 2004)*

First imaged planetary-mass companion
- VLT/NaCo
- 3-5 MJup object
- L5 spectral type, dusty/cloudy atmosphere

Followed by many on wide orbits (>100 au)
- DH Tau b (Itoh et al. 05)
- AB Pic b (Chauvin et al. 05)
- CHXR73 b (Luhman et al. 05)
- GQ Lup b (Neuhauser et al. 05)
- RXJ1609 b (Lafrenière et al. 08)
- …
- HD106906 b (Su et al. 2013)
- HD203030 b (Miles-Paez et al. 2017)
- …



A short timeline of discoveries…

1990 — *Coronography*

2000 — *+IR detectors* *+8-m telescopes with AO*

2008 — *+differential imaging*

2010 2020

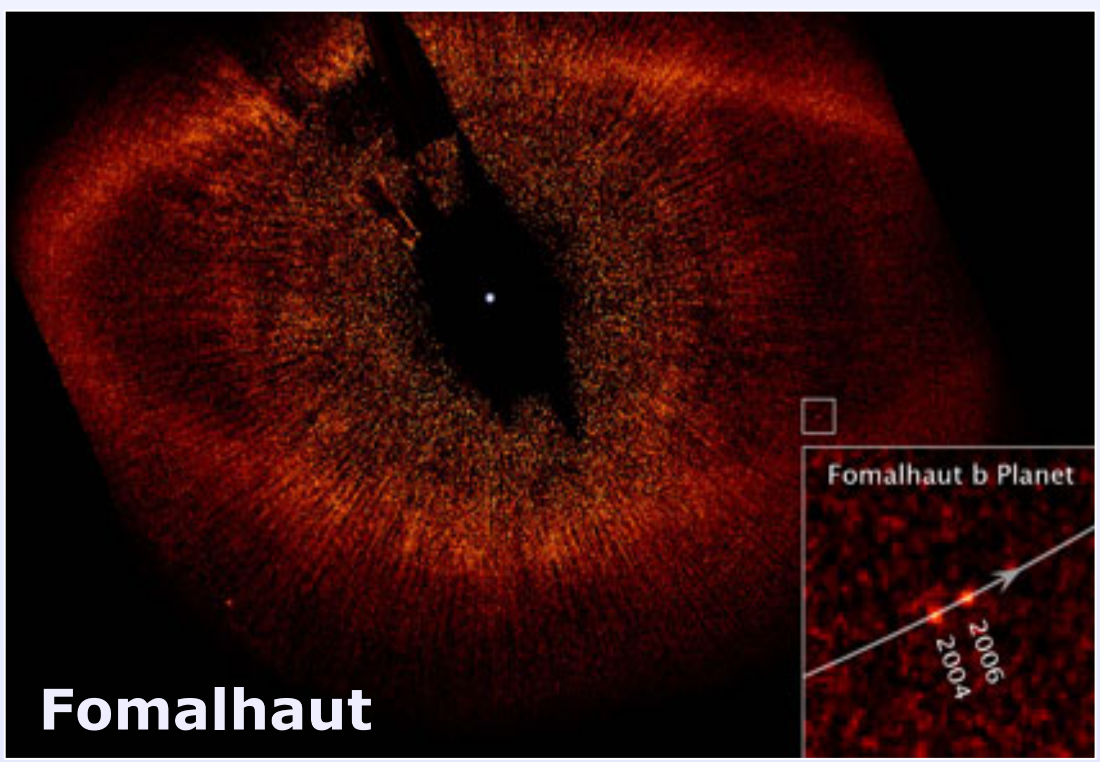
Gl229 B discovery *(Nakajima et al. 1995)*

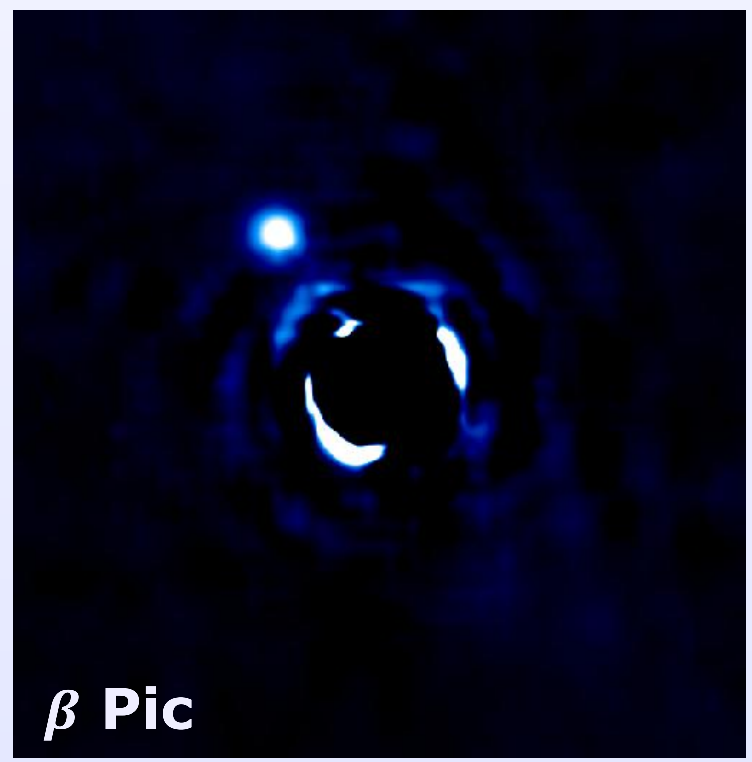
2M1207 b *(Chauvin et al. 2004)*

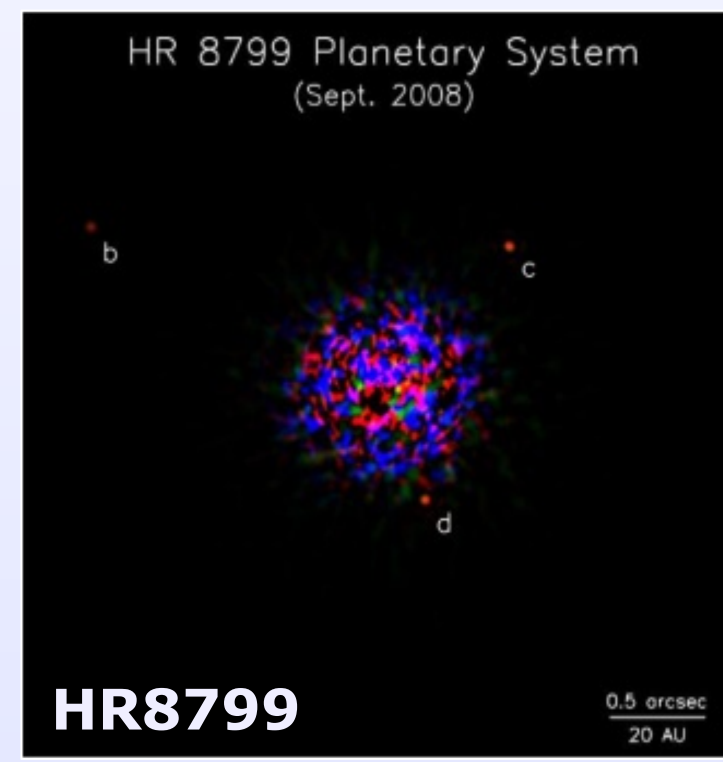
HR8799 bcd, Fomalhaut b, β Pic b
(Marois+ 2008; Kalas+ 2008; Lagrange+ 2008)

First low-mass ratio companions

- Stars with debris-disk
- Mp/M* < 1%
- Semi-major axis < 100 au







A short timeline of discoveries…

1990 — ***2000*** — ***2010*** — ***2013*** — *2020*

Coronography | ***+IR detectors*** | ***+8-m telescopes with AO*** | ***+differential imaging***

***Gl229 B discovery** (Nakajima et al. 1995)*

***2M1207 b** (Chauvin et al. 2004)*

HR8799 bcd, Fomalhaut b, β Pic b
HR8799 e, HD95086 b, GJ504 b
(Marois+ 2010; Rameau+ 2013; Kuzuhara+ 2013)

First low-mass ratio companions

- Stars with debris-disk
- Mp/M* < 1%
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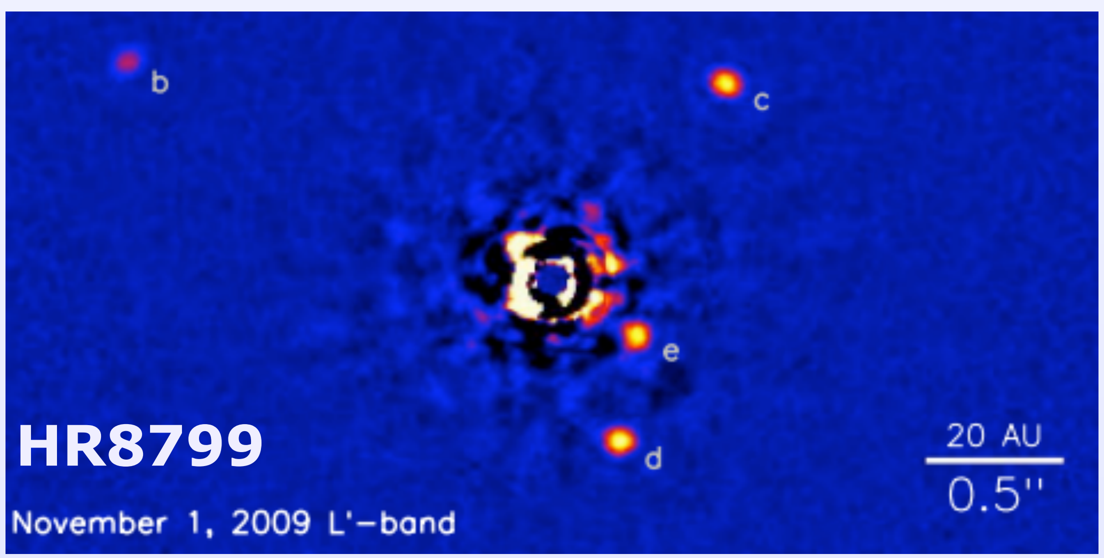
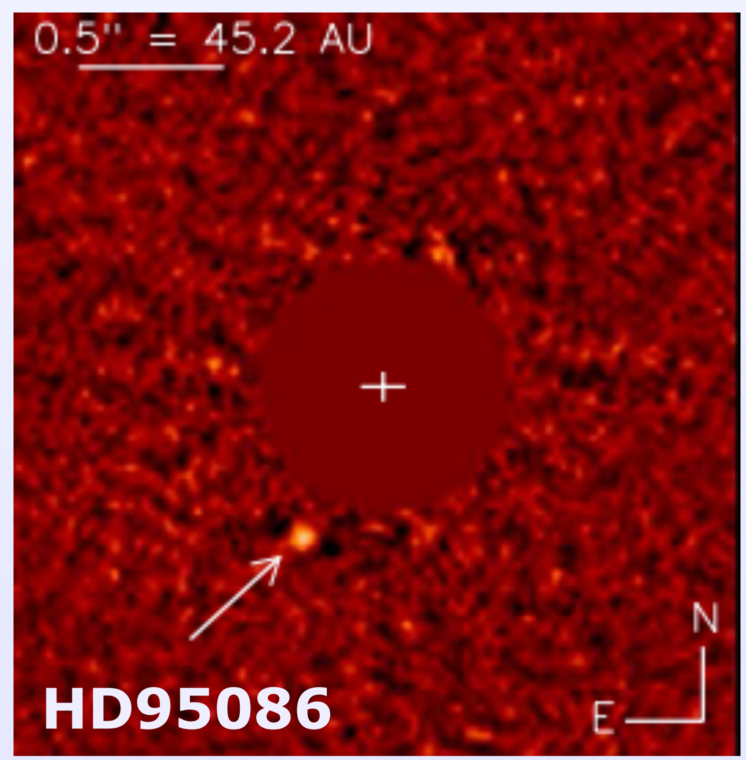
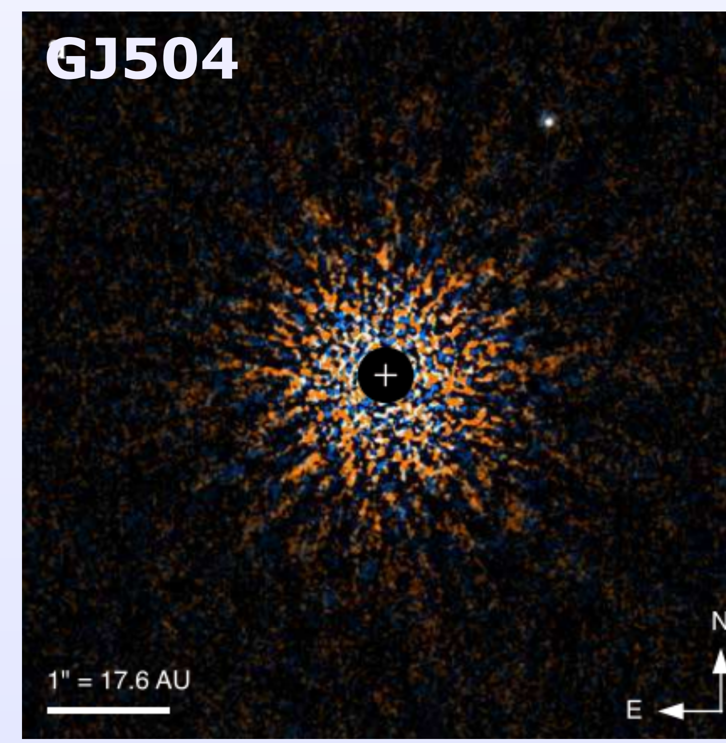






A short timeline of discoveries…

1990 — **2000** — **2010** — **2015** — 2020

Coronography · *+IR detectors* · *+8-m telescopes with AO* · *+differential imaging* · *+ExAO +dedicated instruments*

Gl229 B discovery *(Nakajima et al. 1995)*

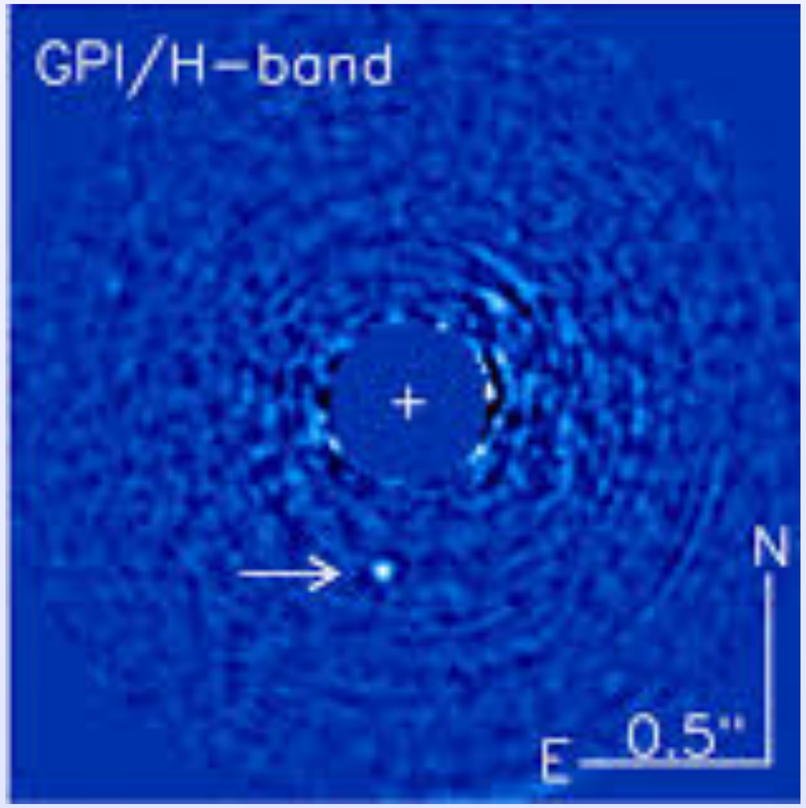
2M1207 b *(Chauvin et al. 2004)*

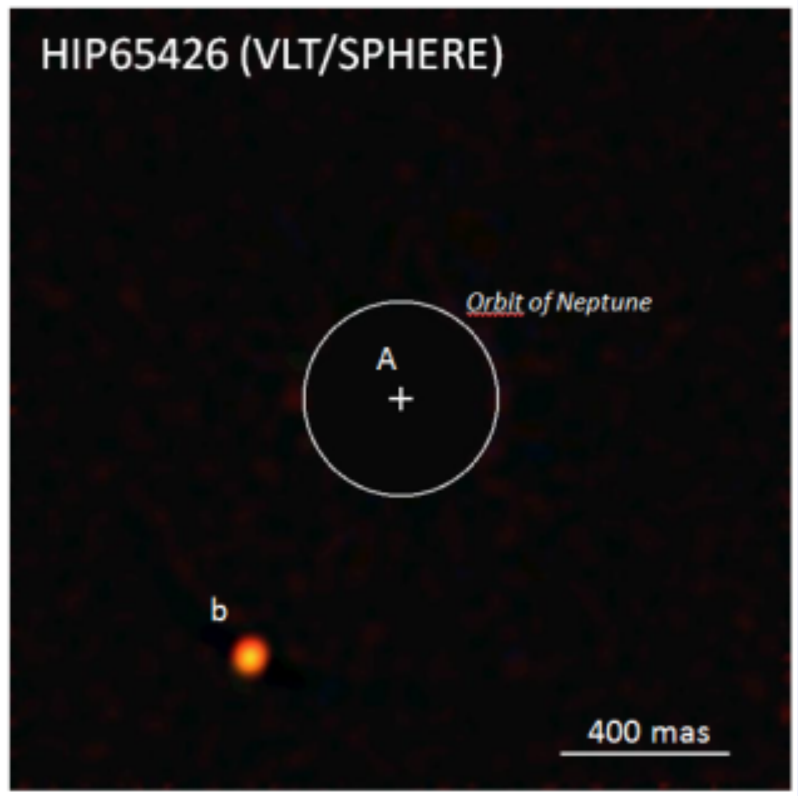
HR8799 bcd, Fomalhaut b, β Pic b
HR8799 e, HD95086 b, GJ504 b
(Marois+ 2010; Rameau+ 2013; Kuzuhara+ 2013)

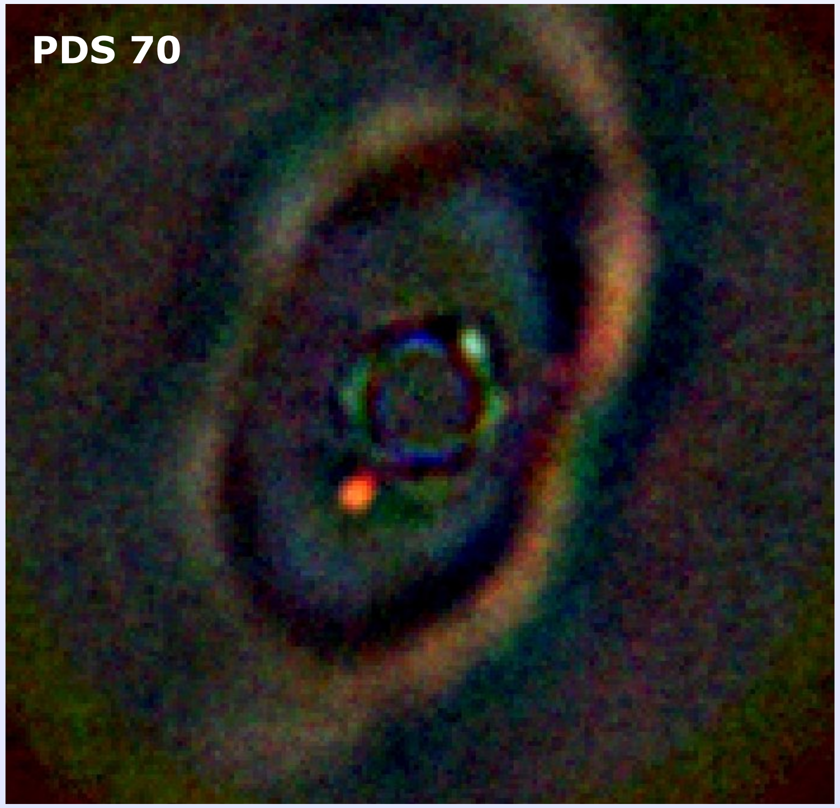
51 Eri b, HIP65426 b, PDS 70 b
(Macintosh+ 201; Chauvin+ 2017
Keppler+ 2018)

First exoplanet imagers detections

- *51 Eri b:* GPI, T3 dwarf with CH4
- *HIP 65426 b:* SPHERE, L7 dusty dwarf
- *PDS 70 b:* SPHERE, L dusty dwarf, transition disk





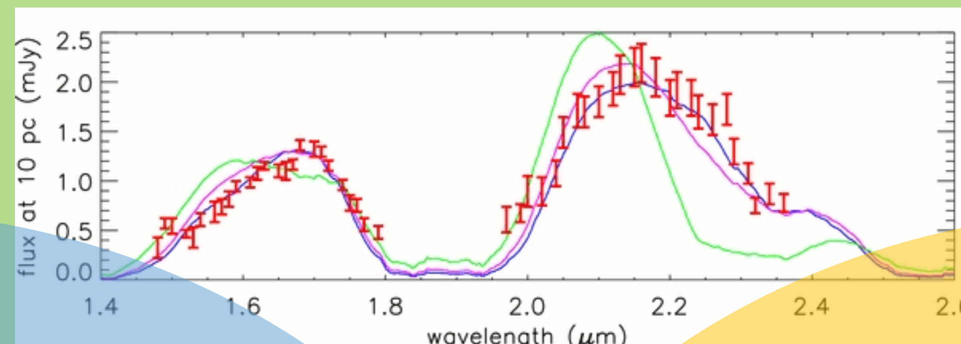


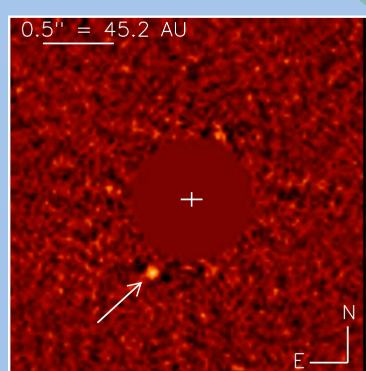
Science with direct imaging

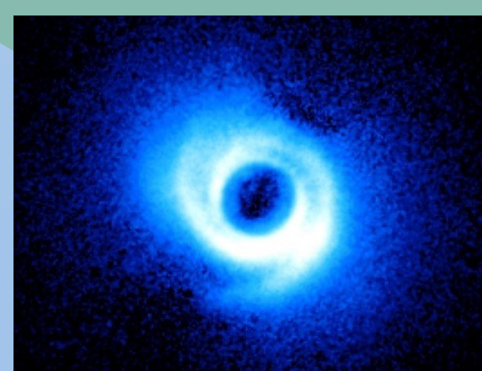
1/ Physics of giant exoplanets

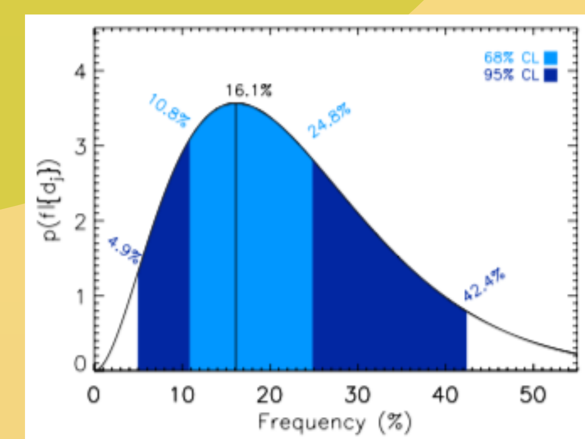
Photometry & Spectroscopy

Atmosphere & physical properties









2/ Architecture & stability of planetary systems

Astrometry & disk/planet position

Orbits, dynamical interactions, resonances & long-term evolution

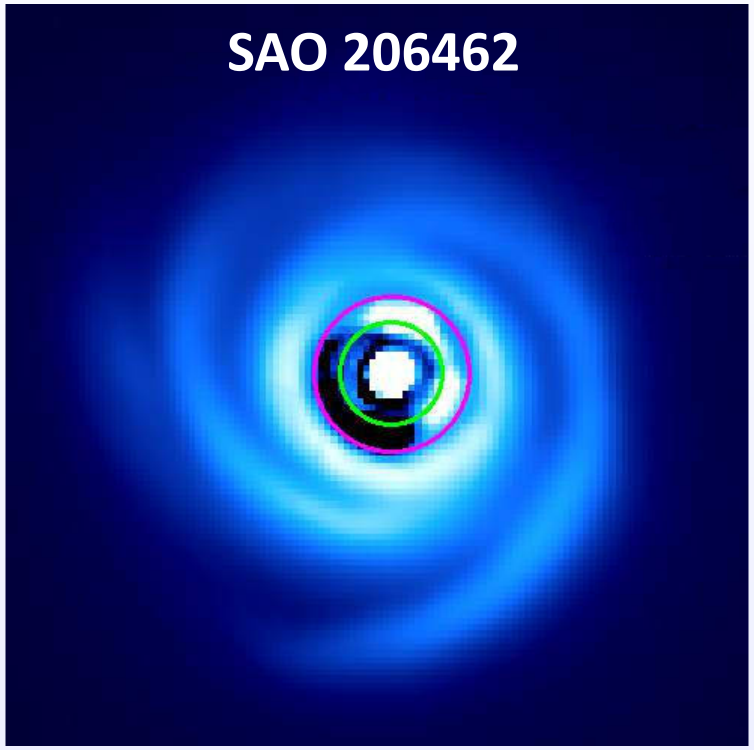
3/ Occurrence & formation

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

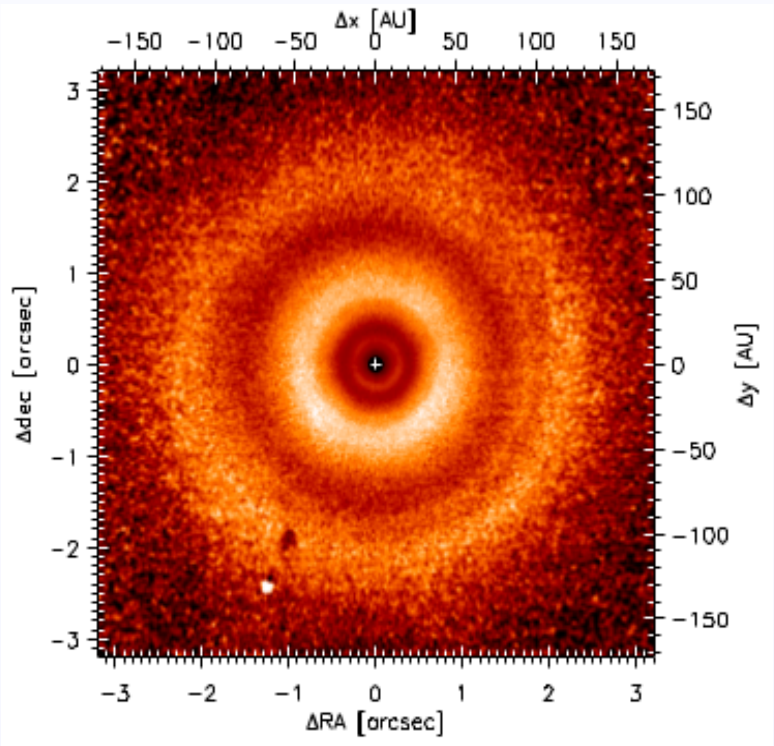
Formation theories

Planetary formation in real-time

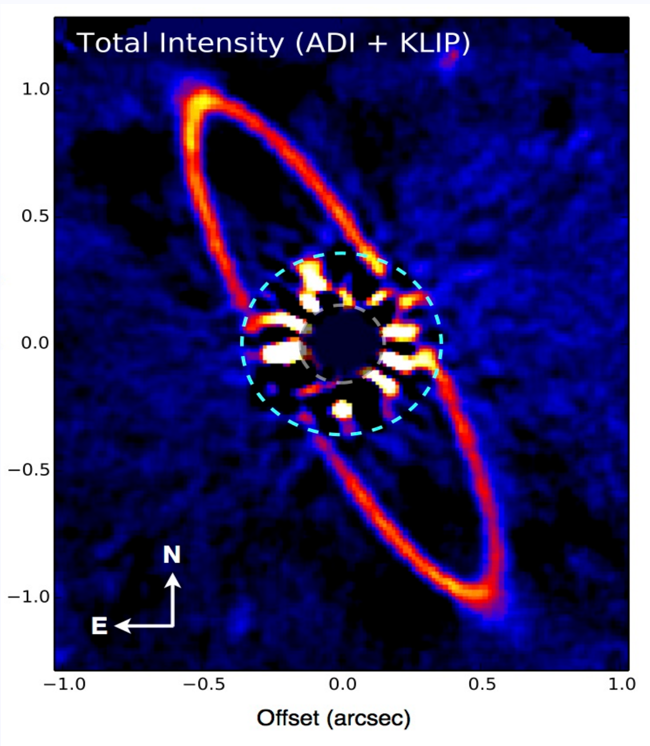
Detection of fine structures in circumstellaire disks: spirals, gaps, rings, ...



SAO 206462
Herbig Ae/Be star, ~9 Myr
SPHERE/IRDIS RDI
Maire et al. (2017)

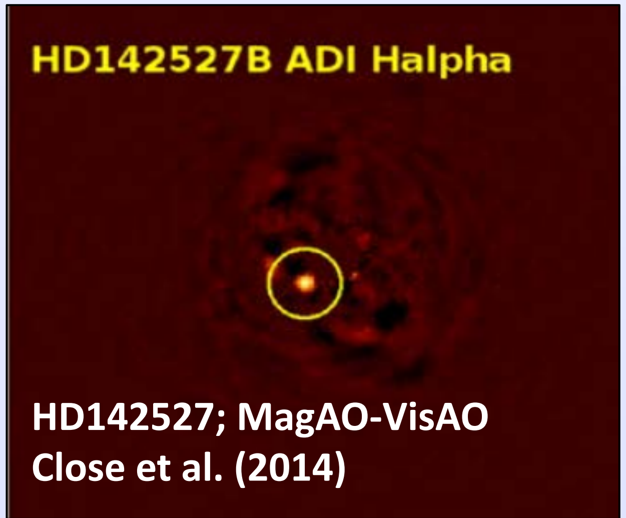


TW Hya
T Tauri K6Vs star, TWA, 8 Myr
SPHERE/IRDIS DPI
Van Boekel et al. (2016)

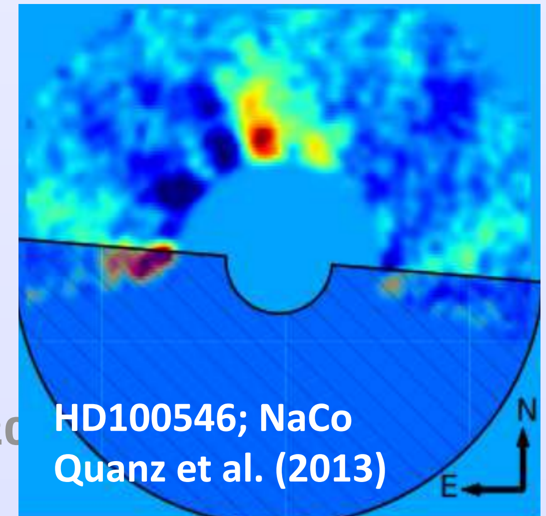


HR4796
A0V star, TWA, 8 Myr
GPI H-band ADI
Perrin et al. (2014)

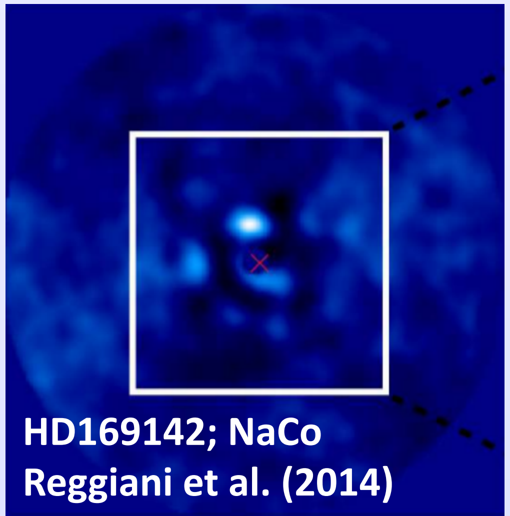
Candidate embedded proto-planets: importance of gas accretion



HD142527; MagAO-VisAO
Close et al. (2014)

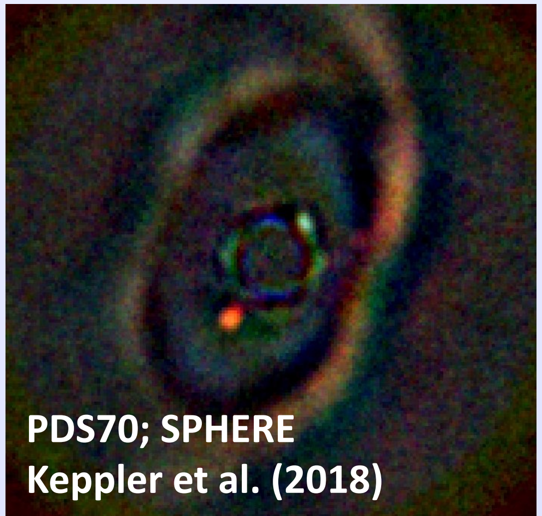


HD100546; NaCo
Quanz et al. (2013)



HD169142; NaCo
Reggiani et al. (2014)

First confirmed proto-planet!

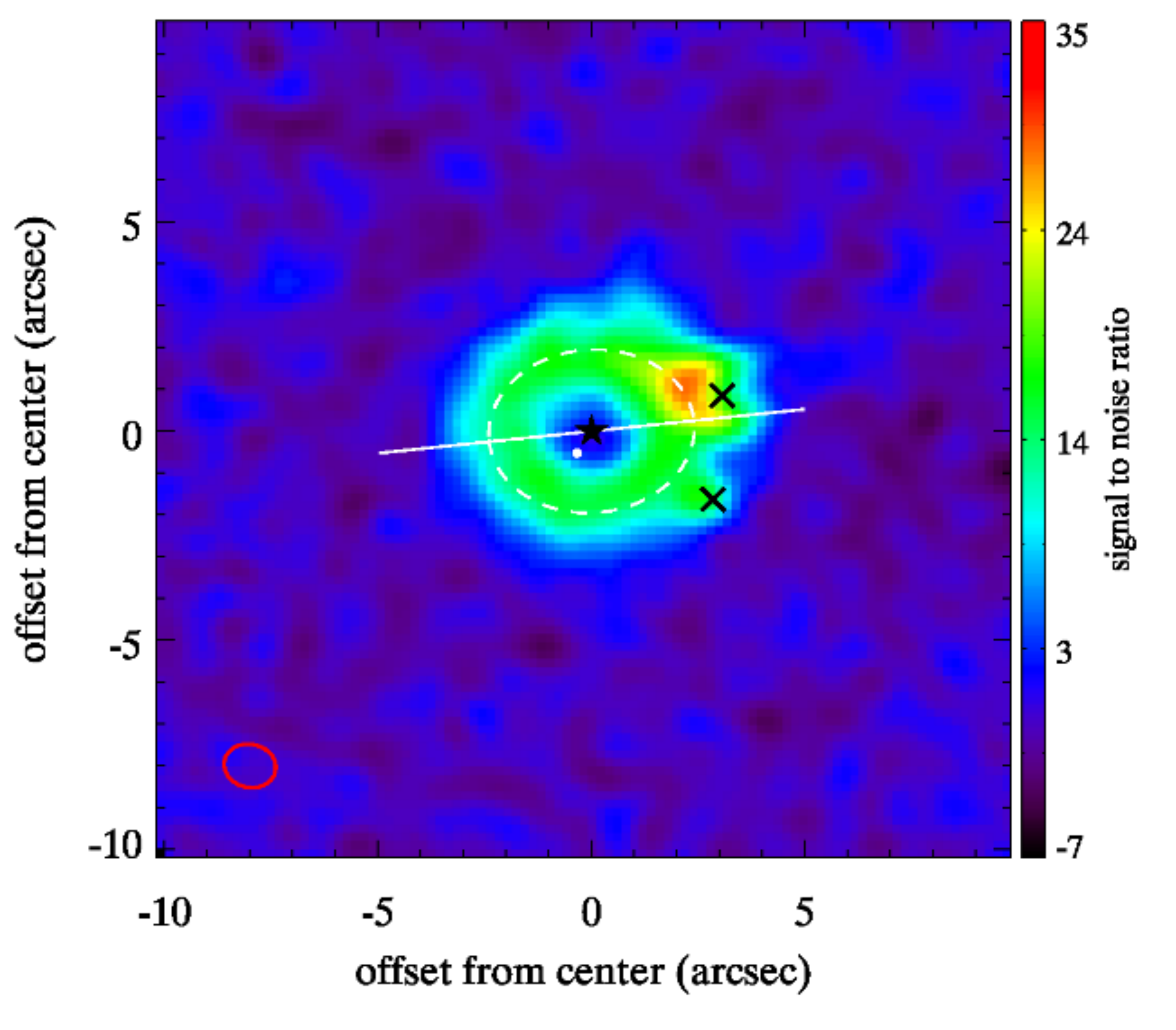


PDS70; SPHERE
Keppler et al. (2018)

Study of planetary systems

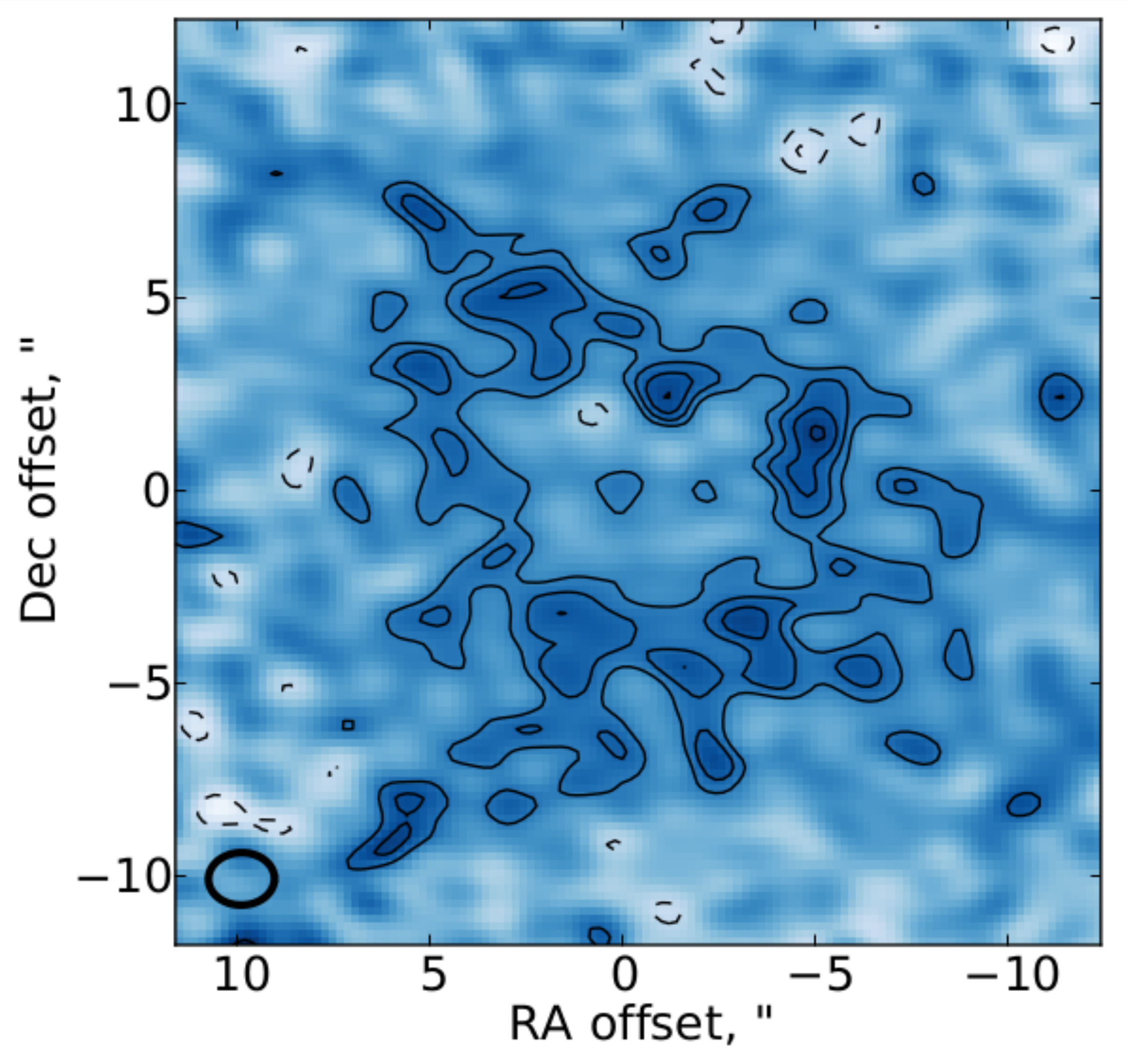
Planets and multi-belt architectures

HD95086
A8, ScoCen, 17 Myr, 83.8pc
Warm, inner belt: 7-10 au, 175K (SED)
Cold, outer belt: 106-320 au, 55K



Su et al. (2017)

HR8799
A5, Colunba, 30 Myr, 39.4pc
Warm, inner belt: 6-16 au, 150K (SED)
Cold, outer belt: 145-425 au, 45K



Booth et al. (2016)

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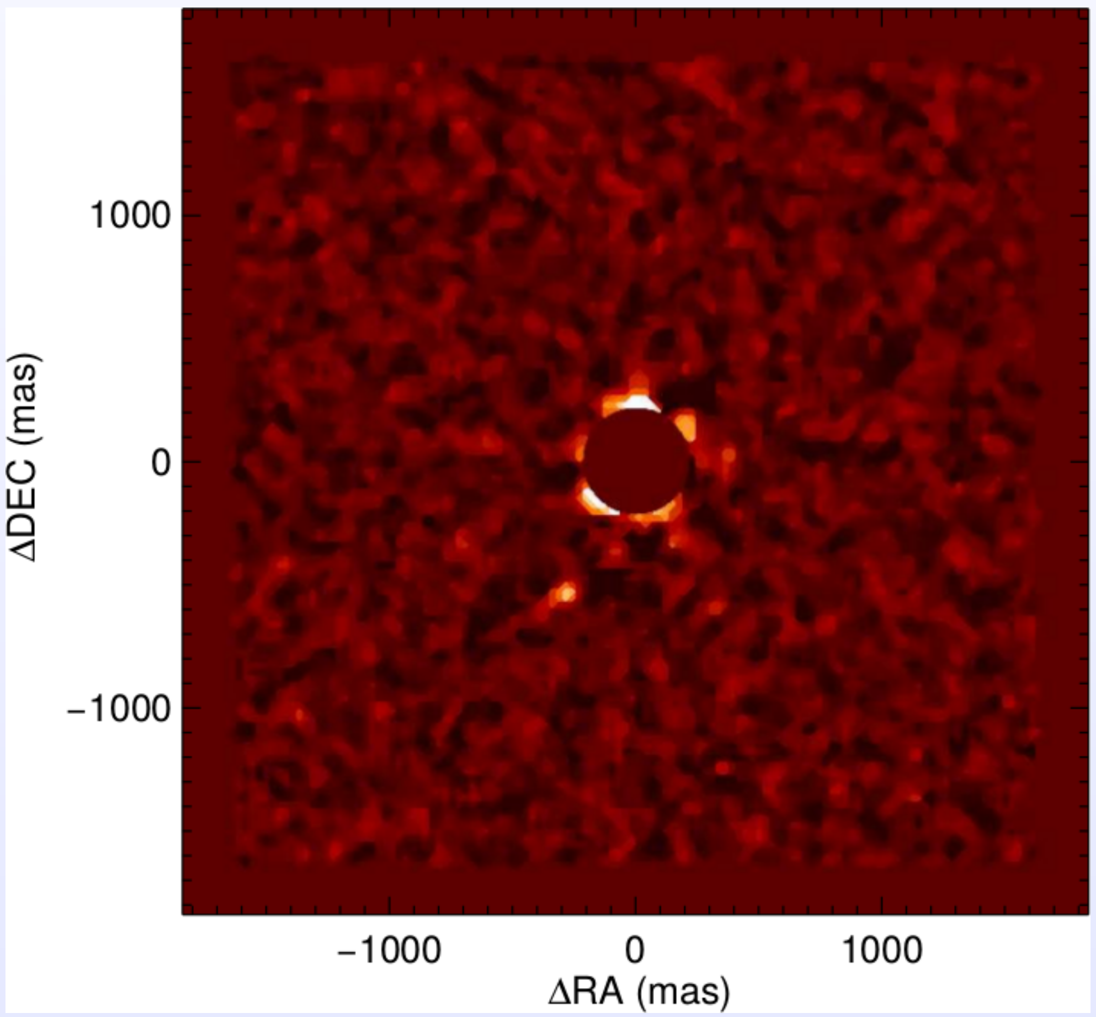

Rameau et al. (2013)

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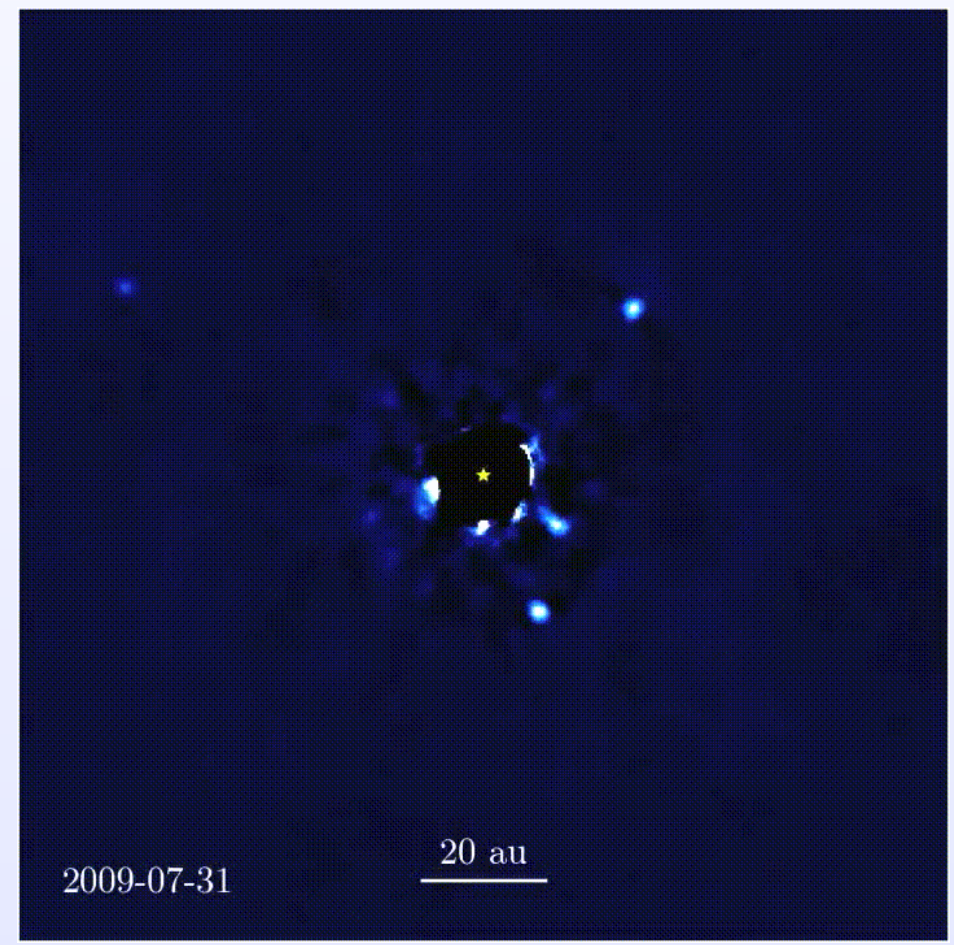

Marois et al. (2008, 2018)

Study of planetary systems

Planets and multi-belt architectures

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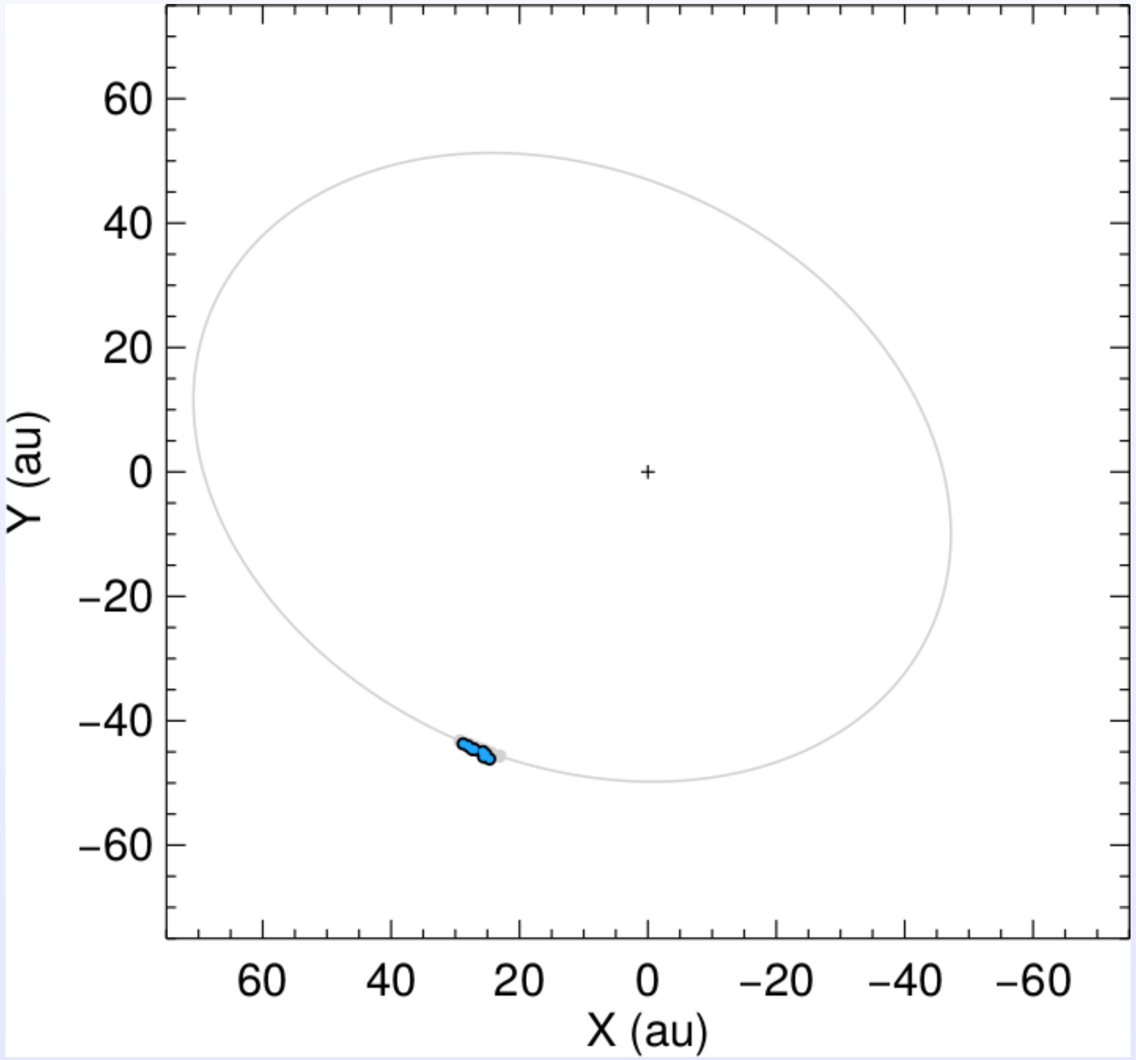

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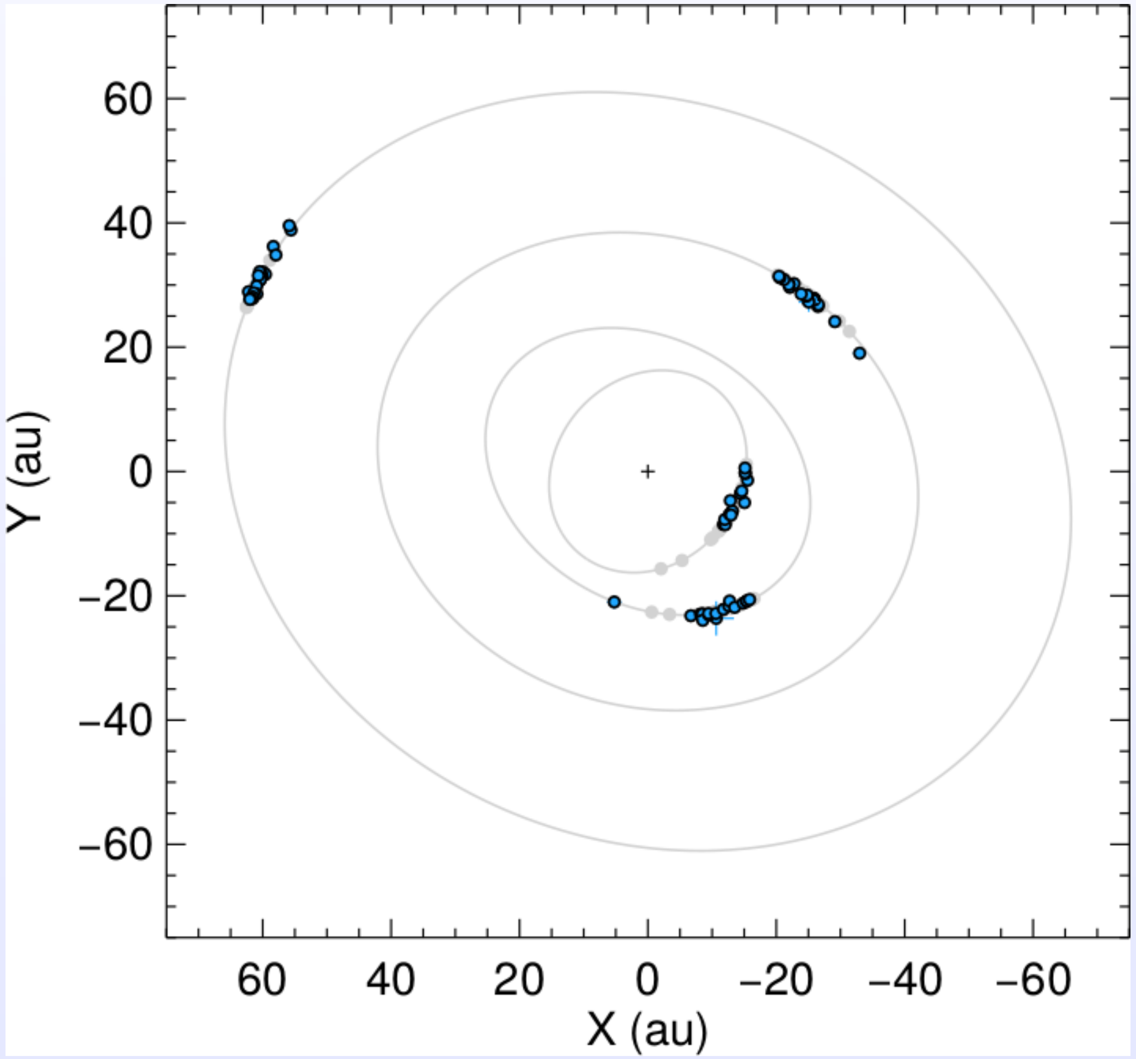
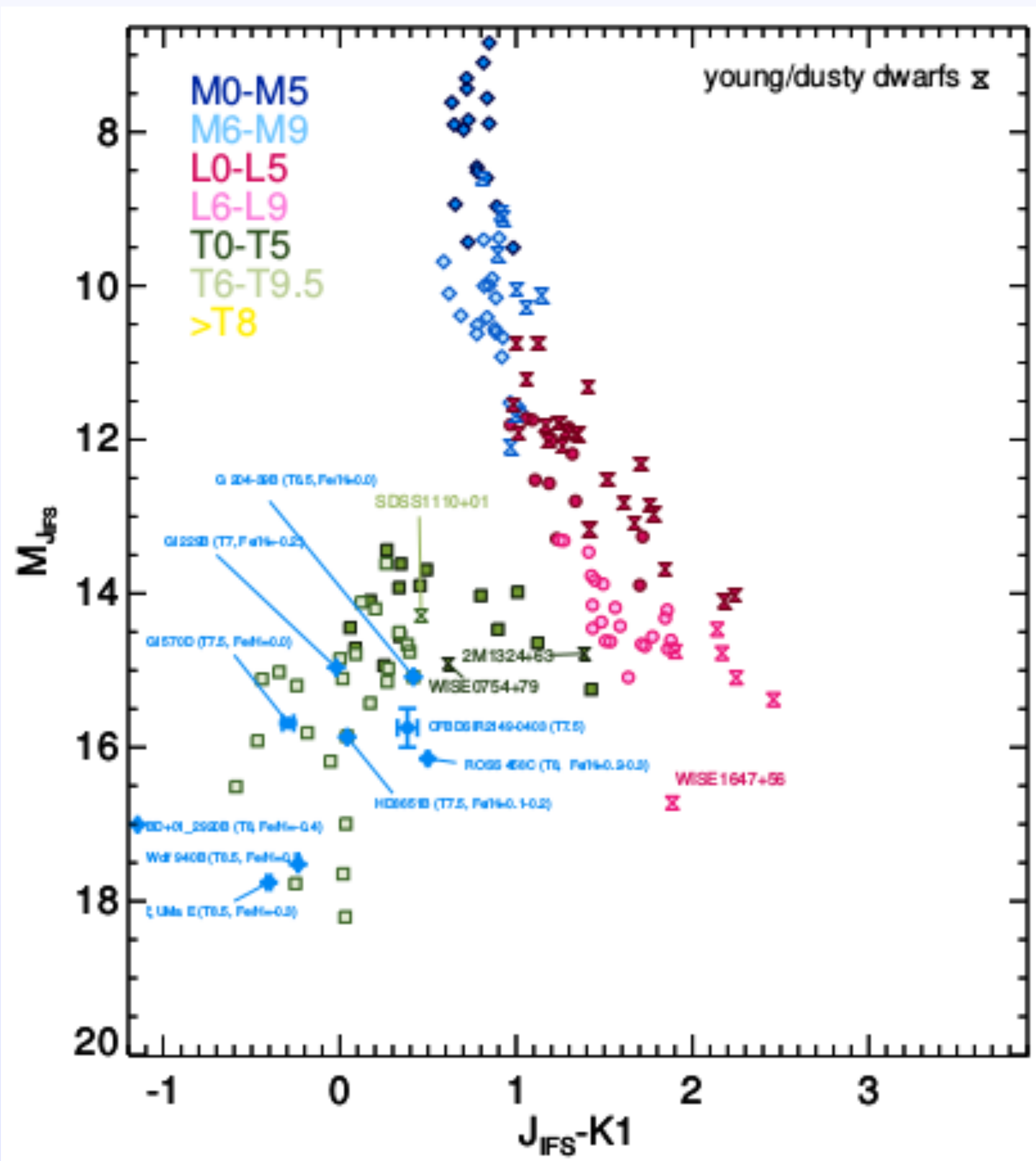


Architecture of planetary systems, dynamical stability, migration/ejection...

Physics of giant exoplanets

Measuring the photons from the planets: physics of their atmospheres

- temperature
- gravity
- clouds
- non-equilibrium chemistry



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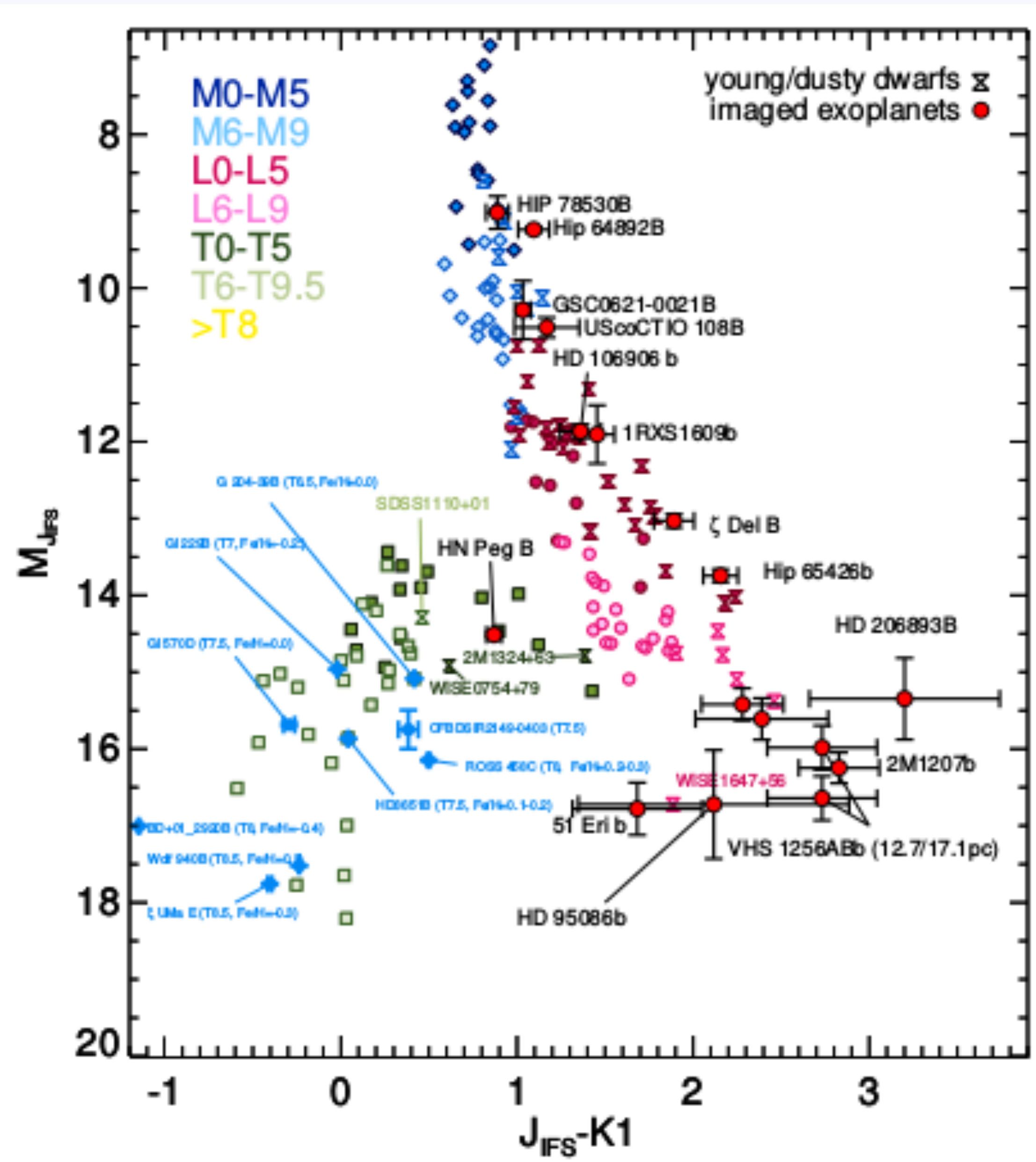
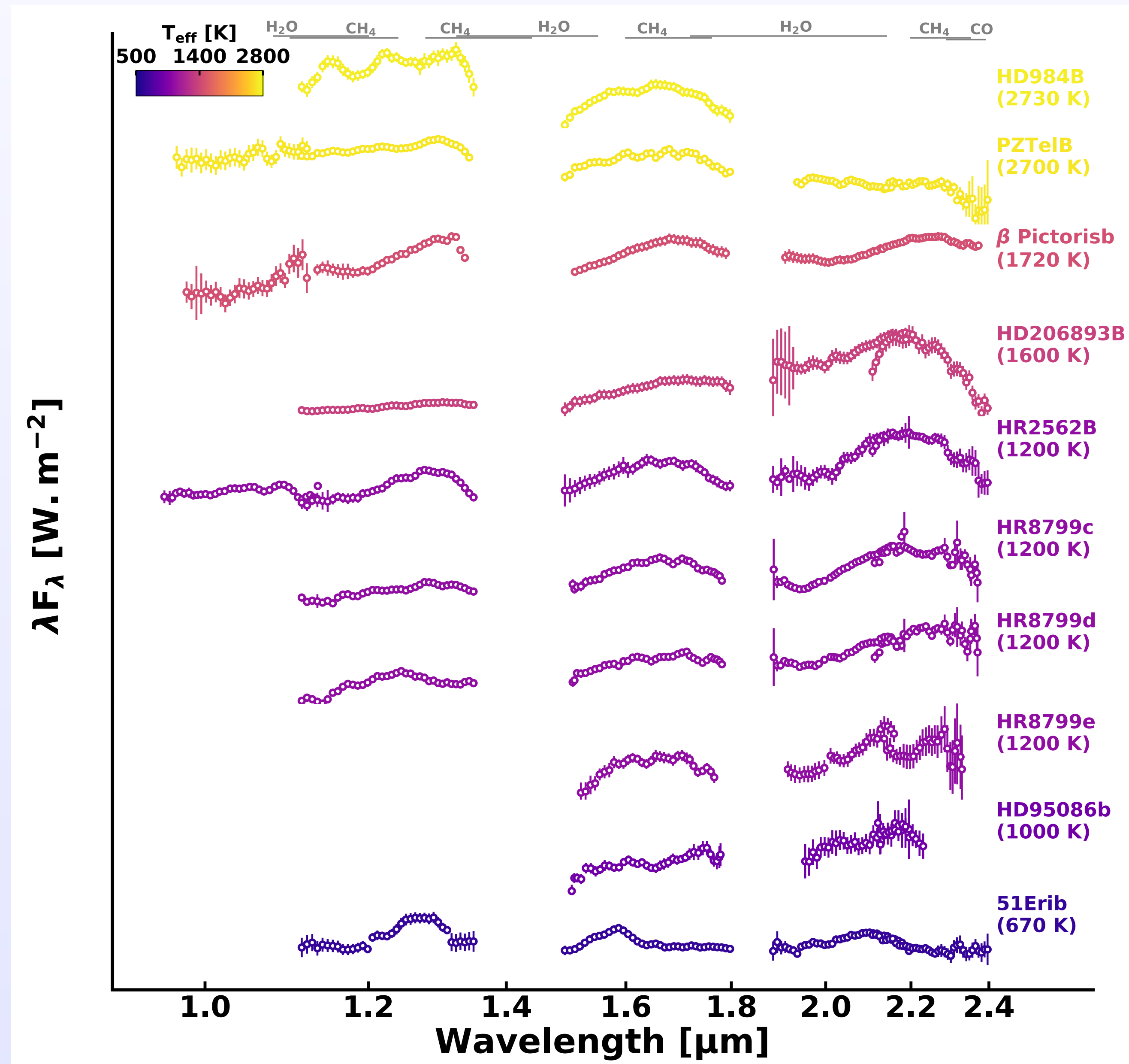
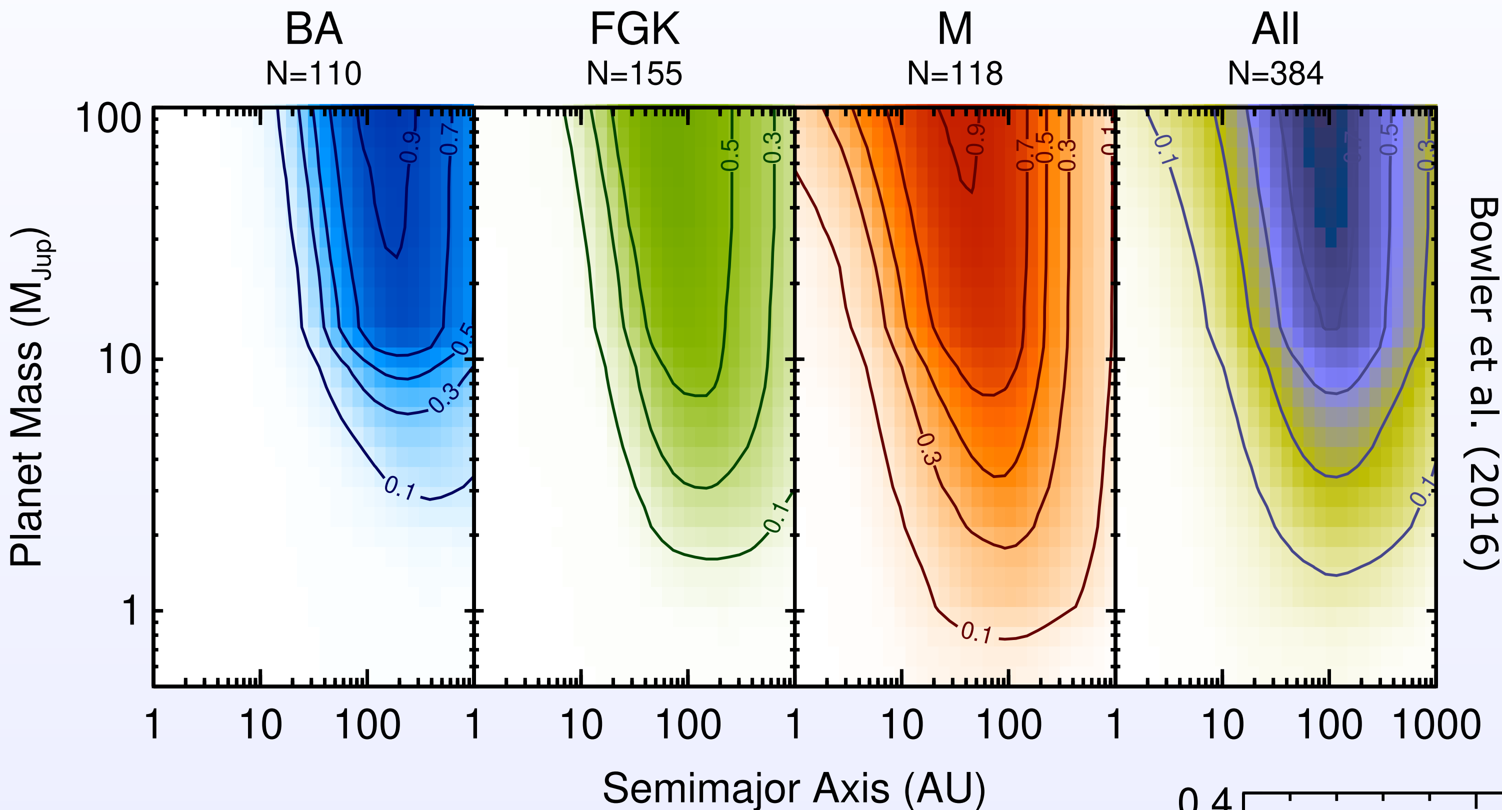




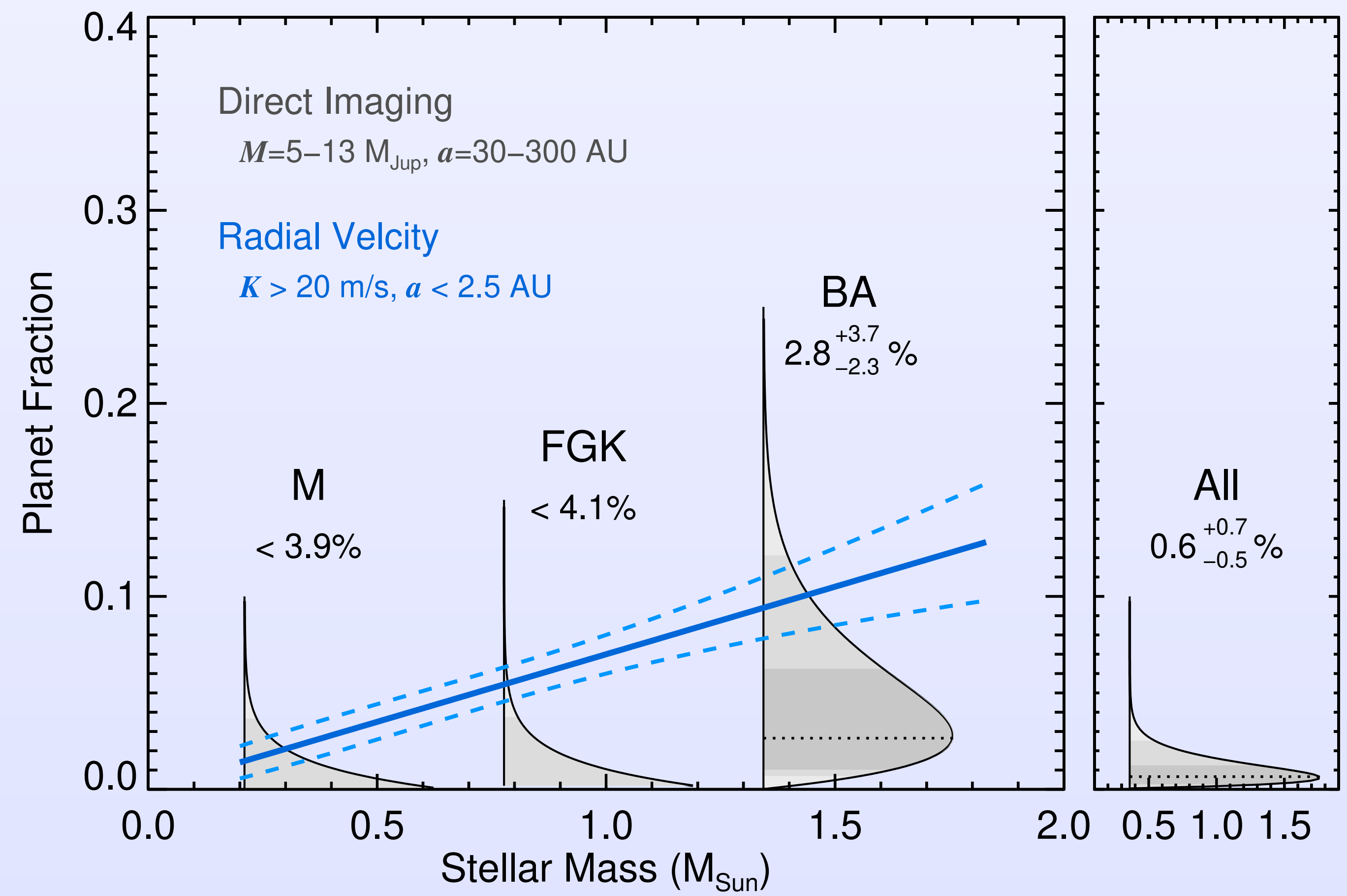
Rameau et al., GPIES collaboration

Occurence and formation of giant planets

How frequent are giant gaseous exoplanets?



- Low occurence rate: <10%
- Lower than RV for semi-major axes < 2.5 UA
  - Indication of a different formation process?

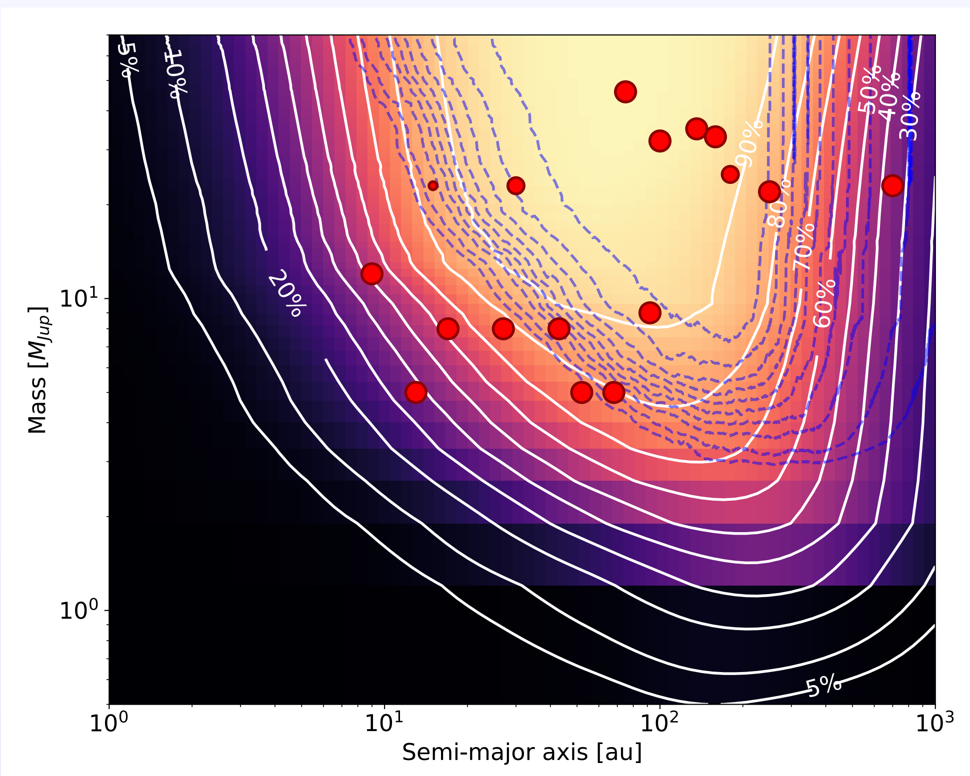


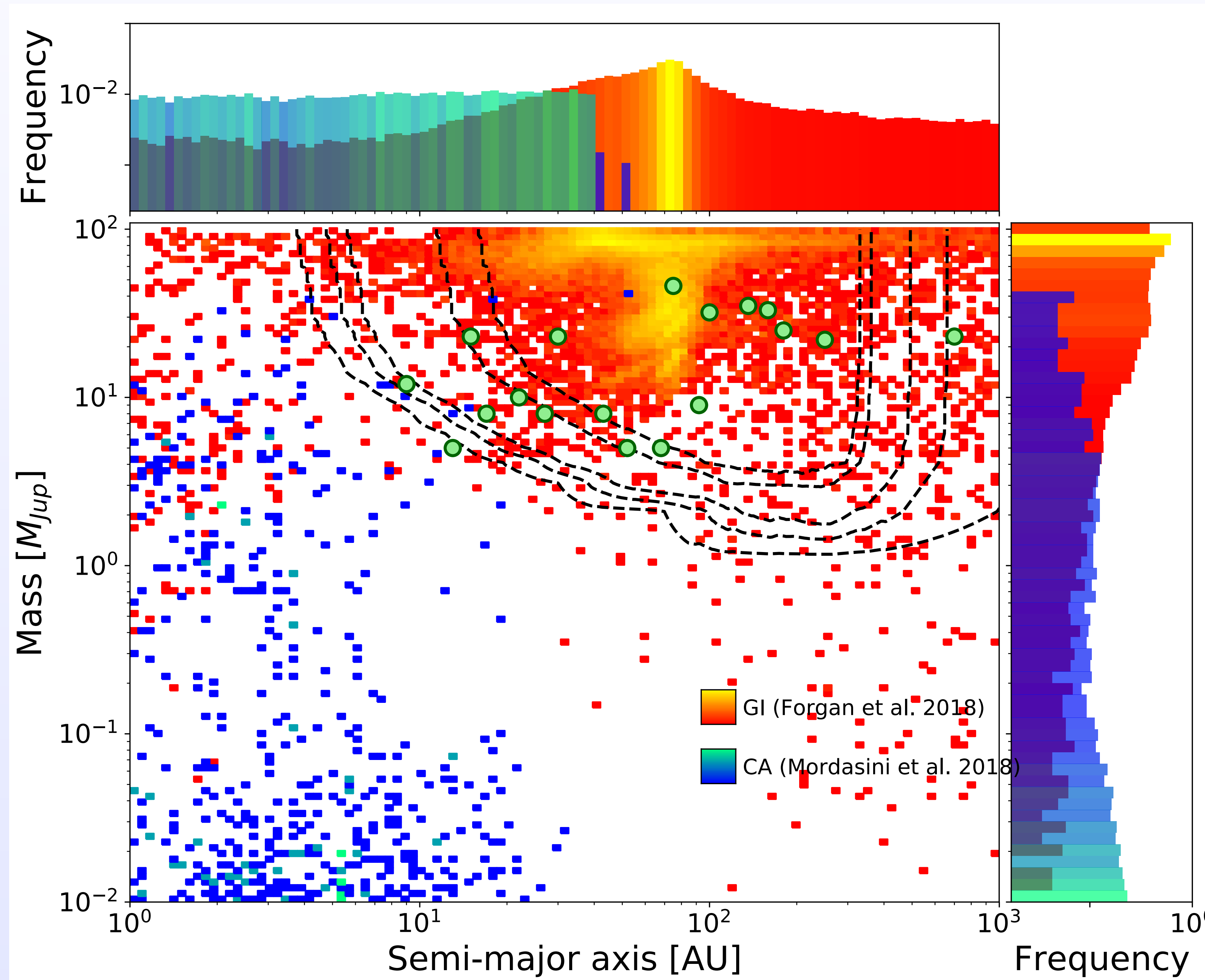
Occurence and formation of giant planets

Can we infer what is the most common formation scenario from observations?

➞ core-accretion (CA) vs. gravitationnel instability (GI) vs. gravo-turbulent fragmentation

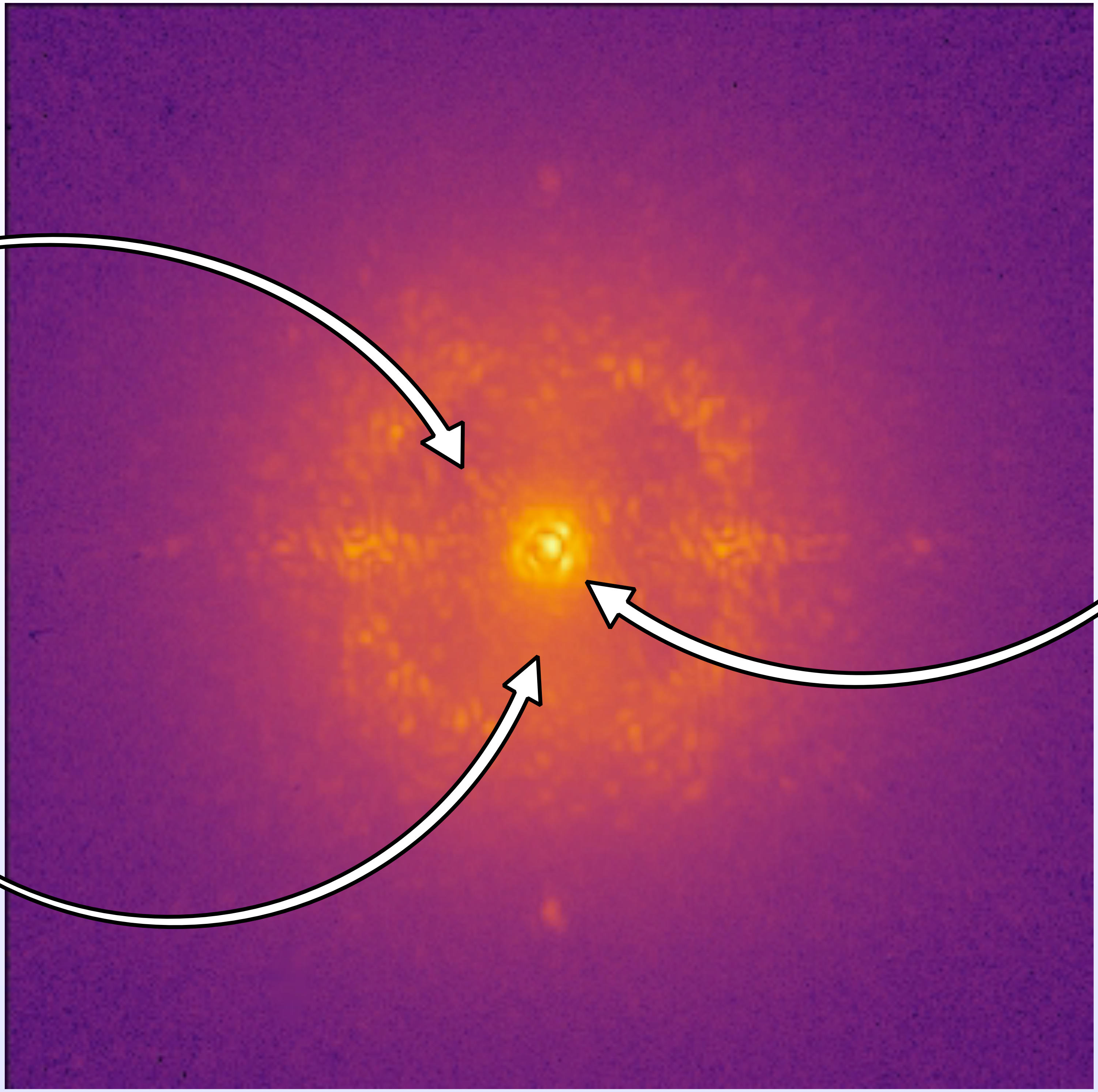
NaCo-LP - Vigan et al. (2017)
SHINE - Vigan et al. (in prep.)





- GI not dominant process based on current data
- CA population difficult to probe, even with SPHERE/GPI

What are our limitations today?

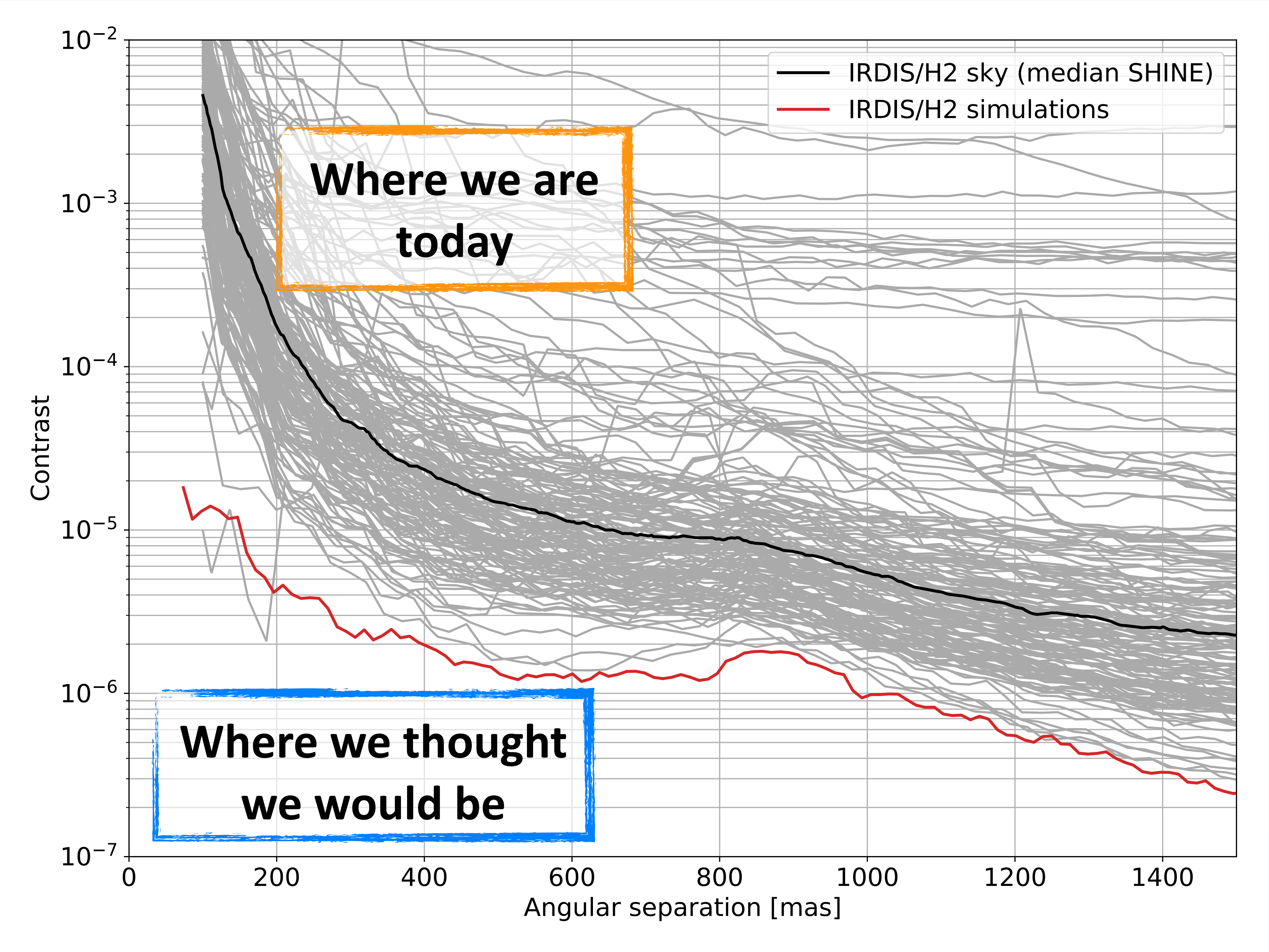


Quasi-static speckles

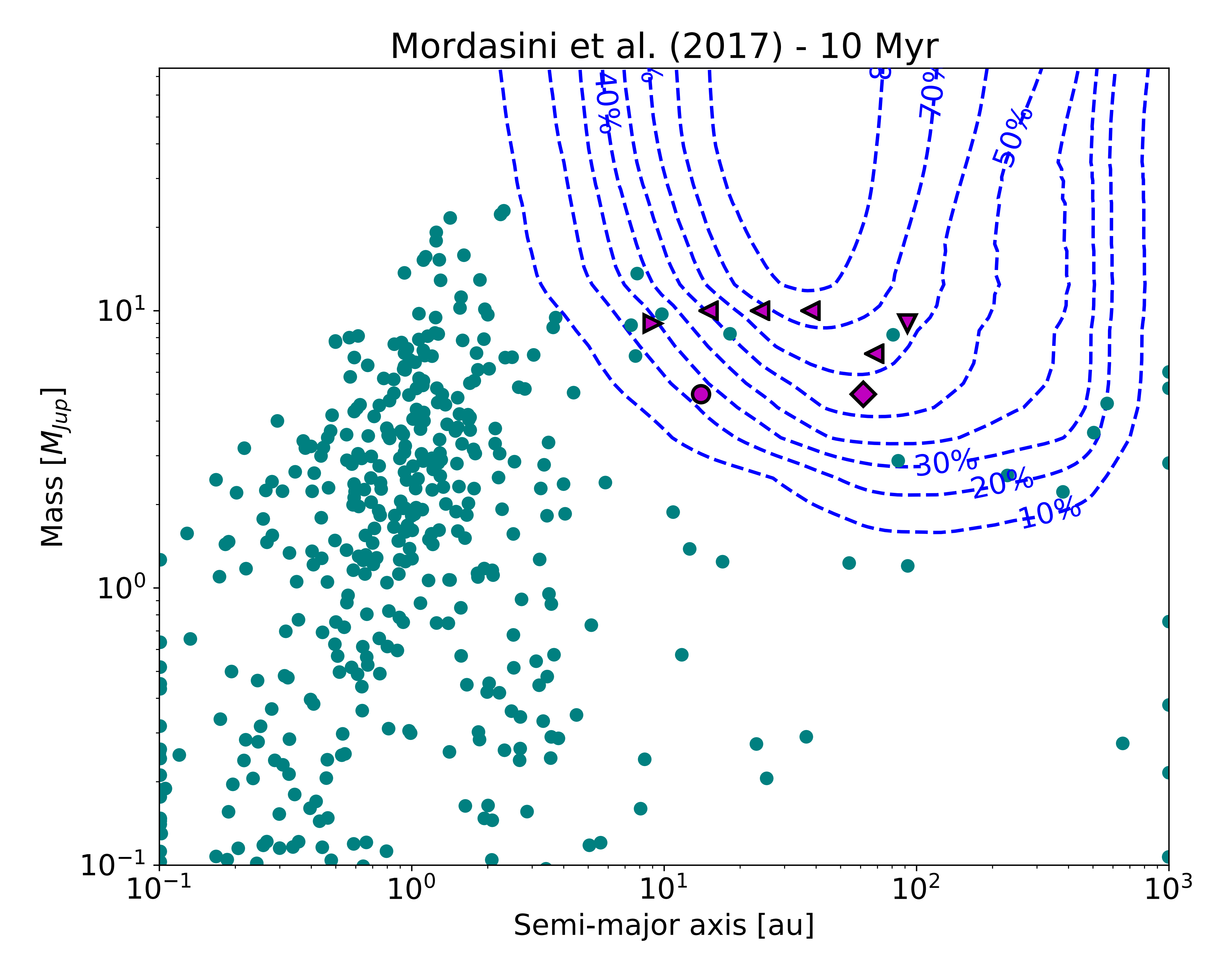
Low-order residuals

AO temporal error

Expected vs. observed contrast performance

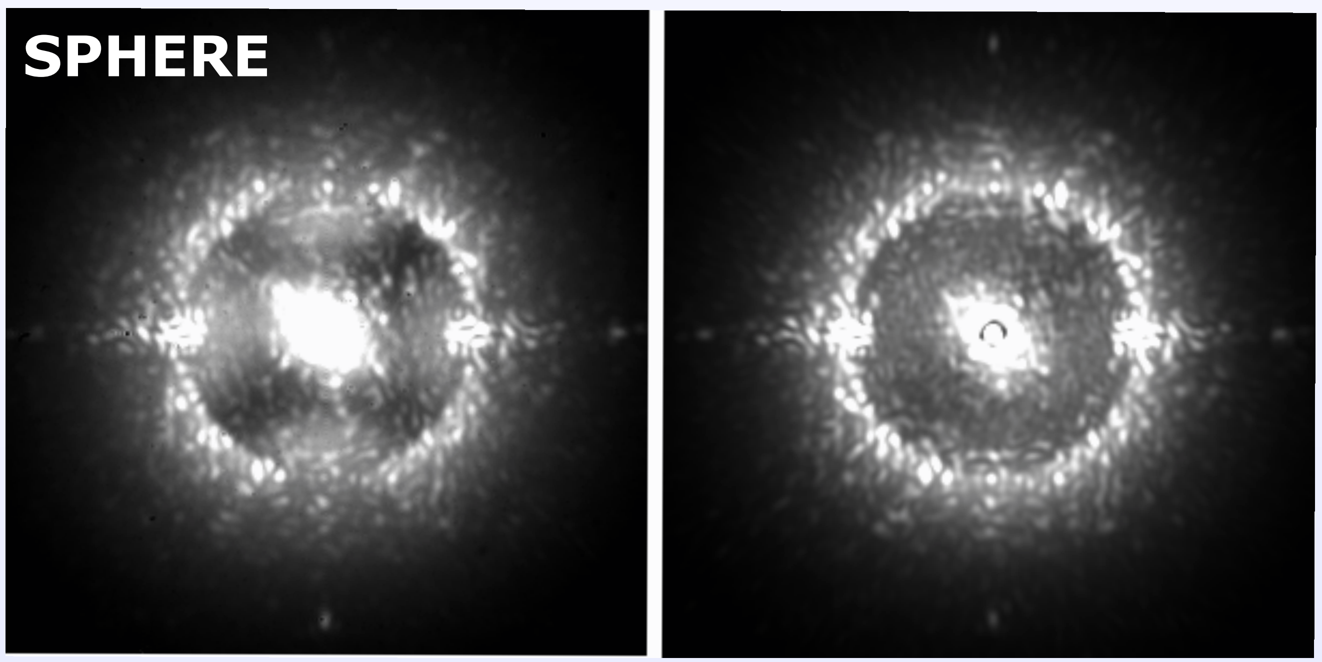


Exoplanet sensitivity

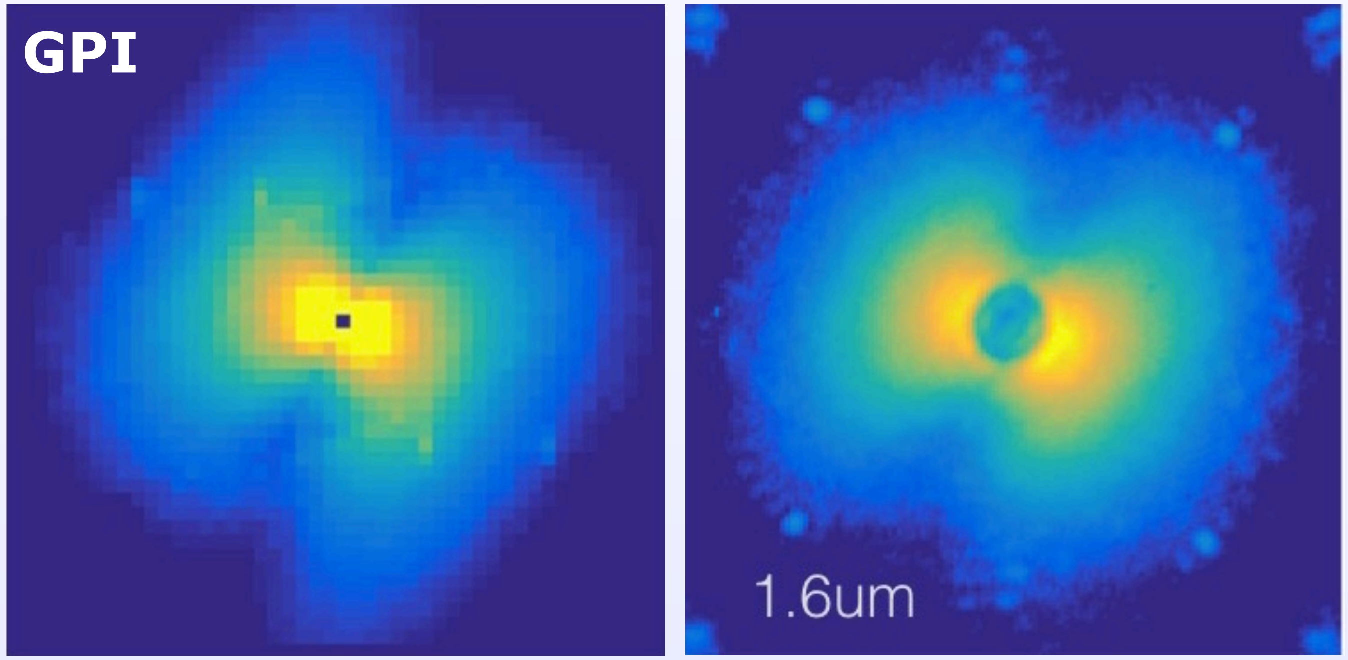


Some new directions?

- Higher-order, faster AO
- Visible AO for detection of Hα emission
- **Image reconstruction from AO telemetry**
- Improved NCPA control
- Higher spectral resolution



Vigan et al. (in prep.)
Cantalloube et al. (in prep.)



Bailey et al. (2016)

- Wind-driven halo often dominates at 1 kHz: $\tau_0 \lesssim 1$ ms
- Not major issue for point-sources ➙ filtering + ADI
- Major issue for disks!

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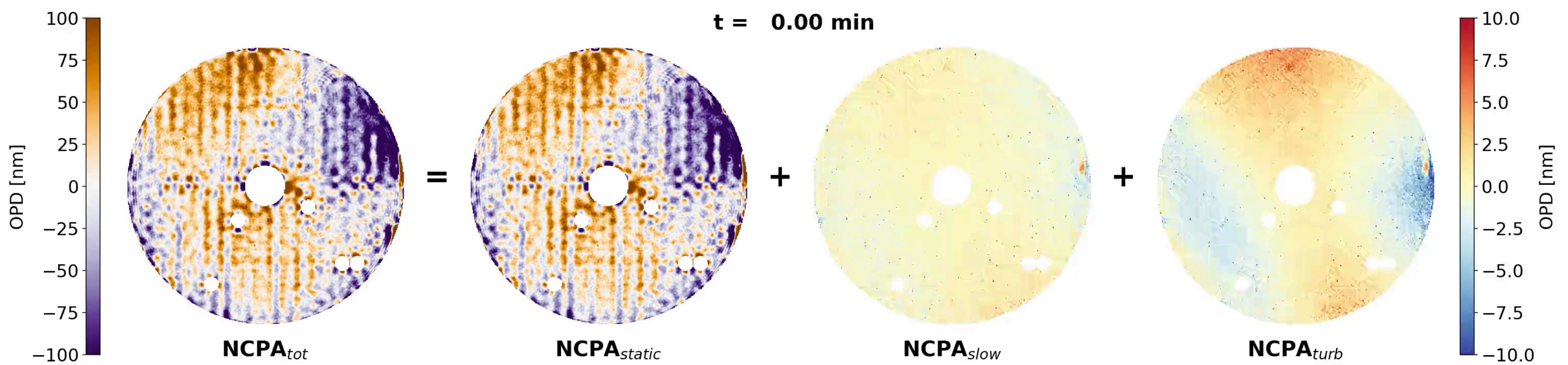
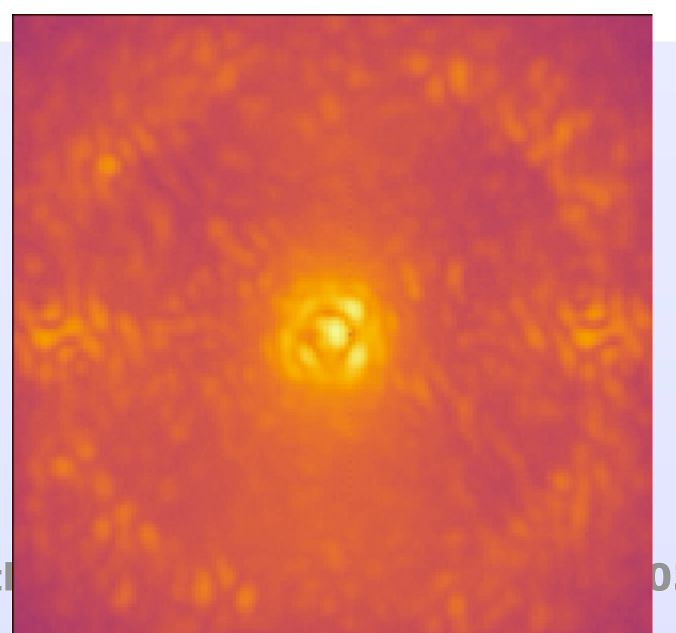


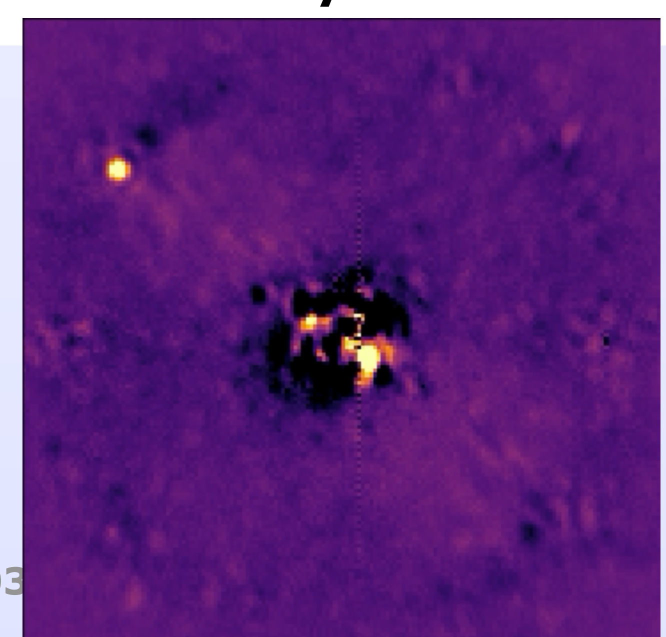
50 nm rms

49 nm rms
t = days

5 nm rms
t = 5-10 min

3 nm rms
t = 2-3 sec





- NCPA control affects coronagraph rejection
  - Raw contrast
  - Processed contrast (stability of speckles)
- Many NCPA control strategies... few implemented and in operation

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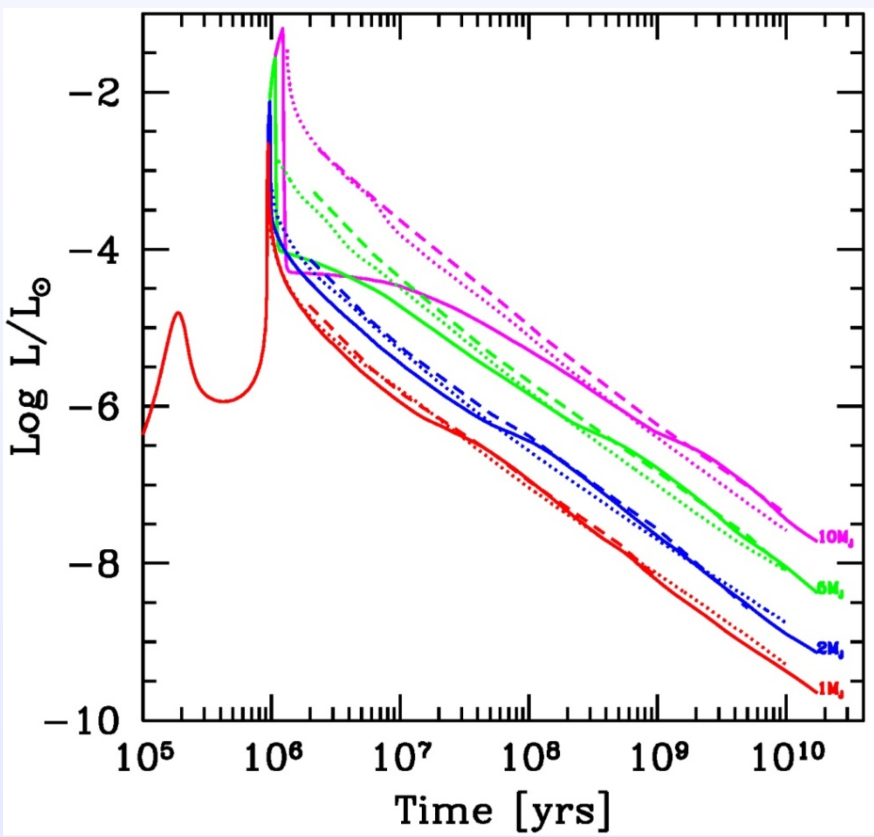
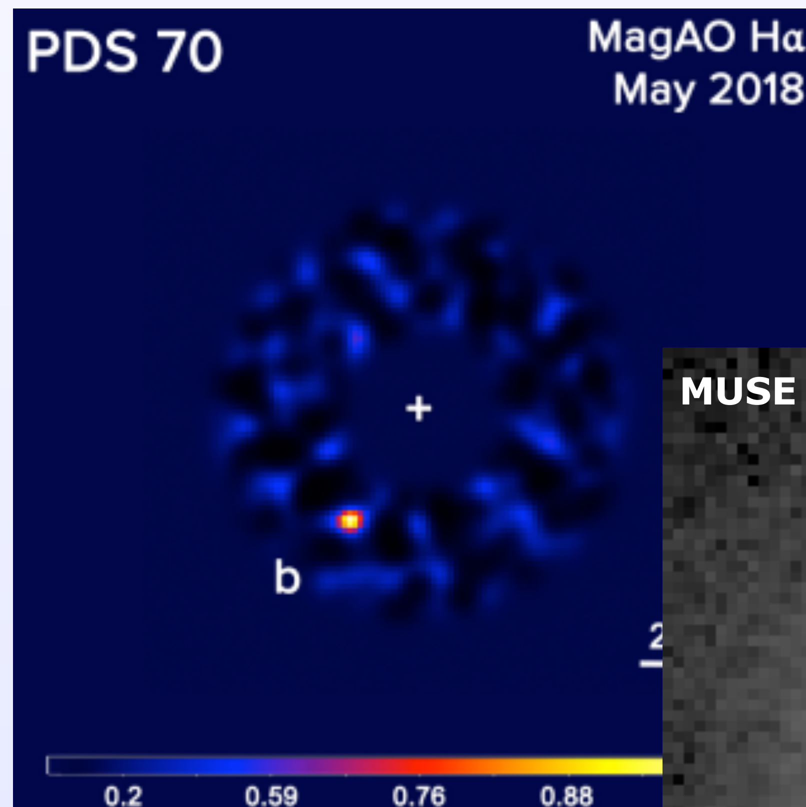
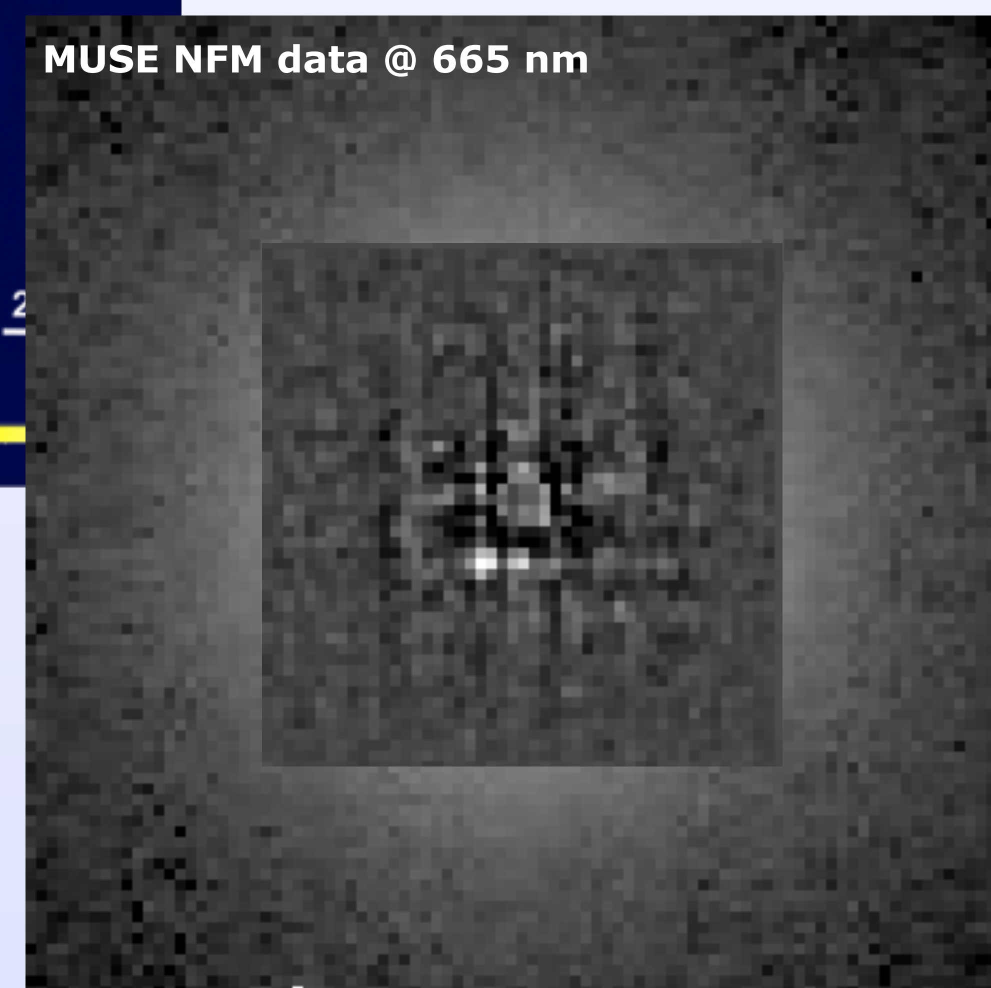
Mordasini et al. (2012)





Haffert et al. (submitted)



- High-potential for very young accreting companions
- Gain with better AO to be quantified

Some new directions?

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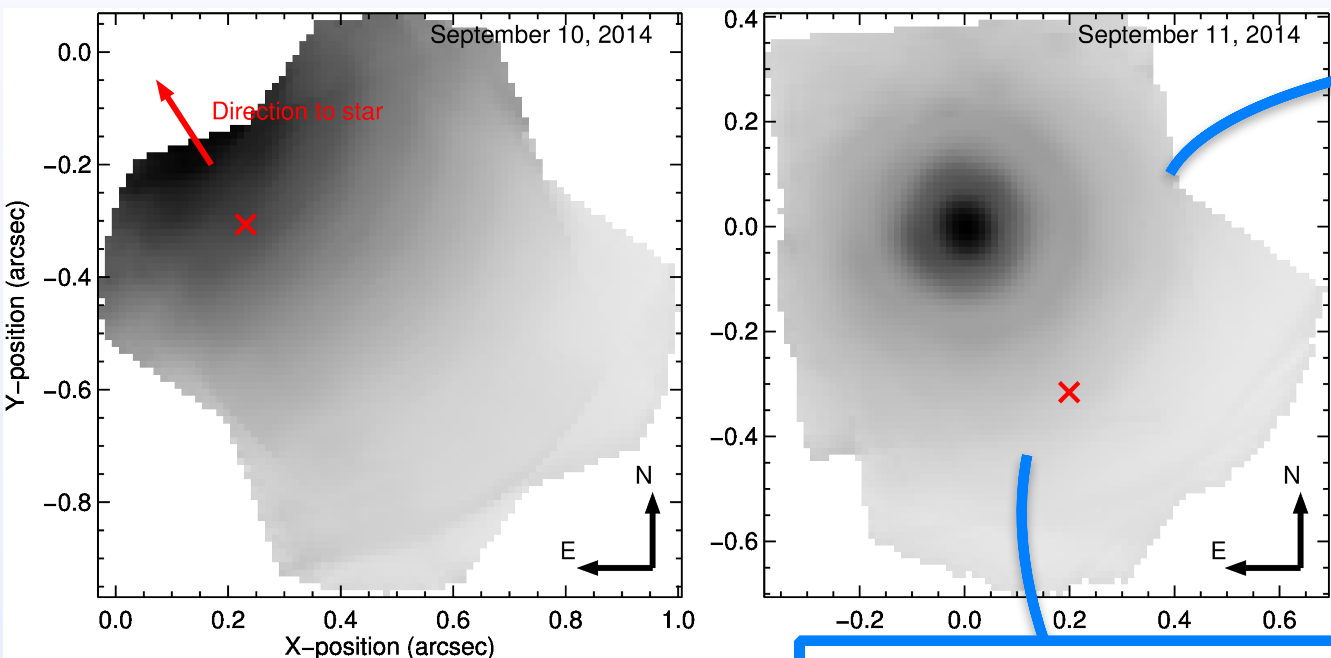
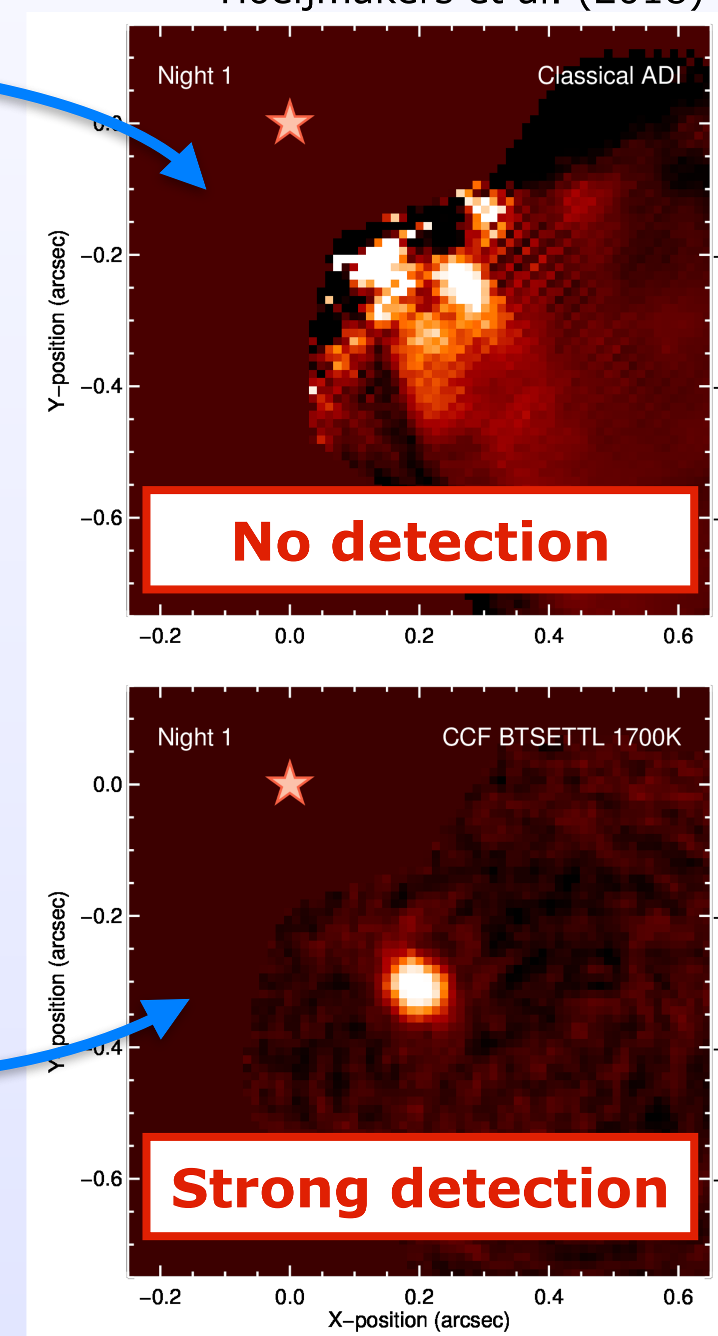
- **Higher spectral resolution**

Hoeijmakers et al. (2018)

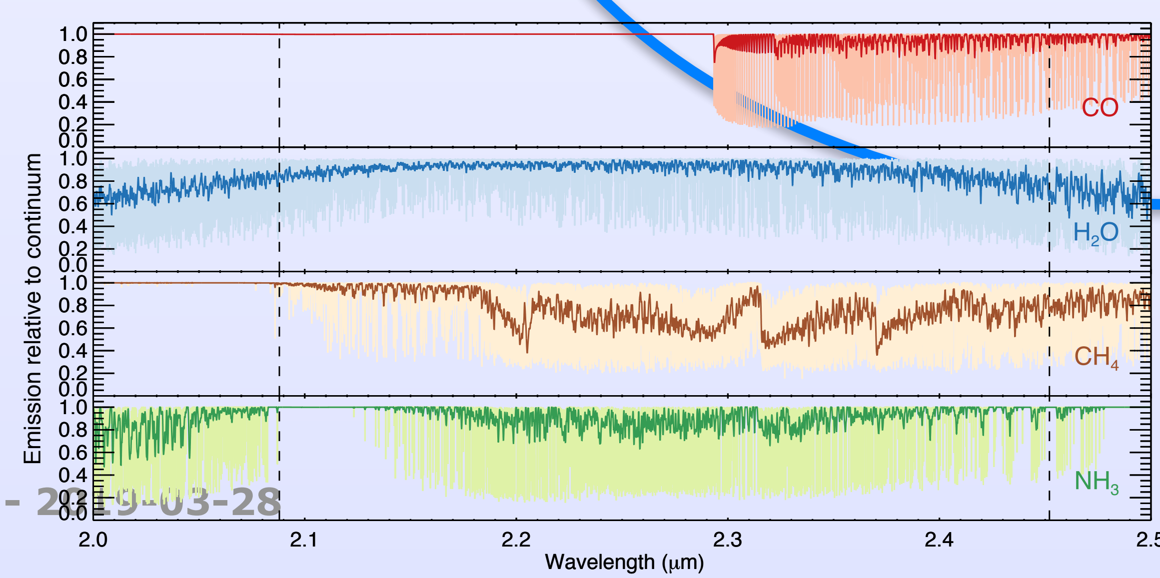


ADI



"Molecular mapping"

Spectral correlation with templates



Sparks & Ford (2002)
Riaud & Schneider (2007)

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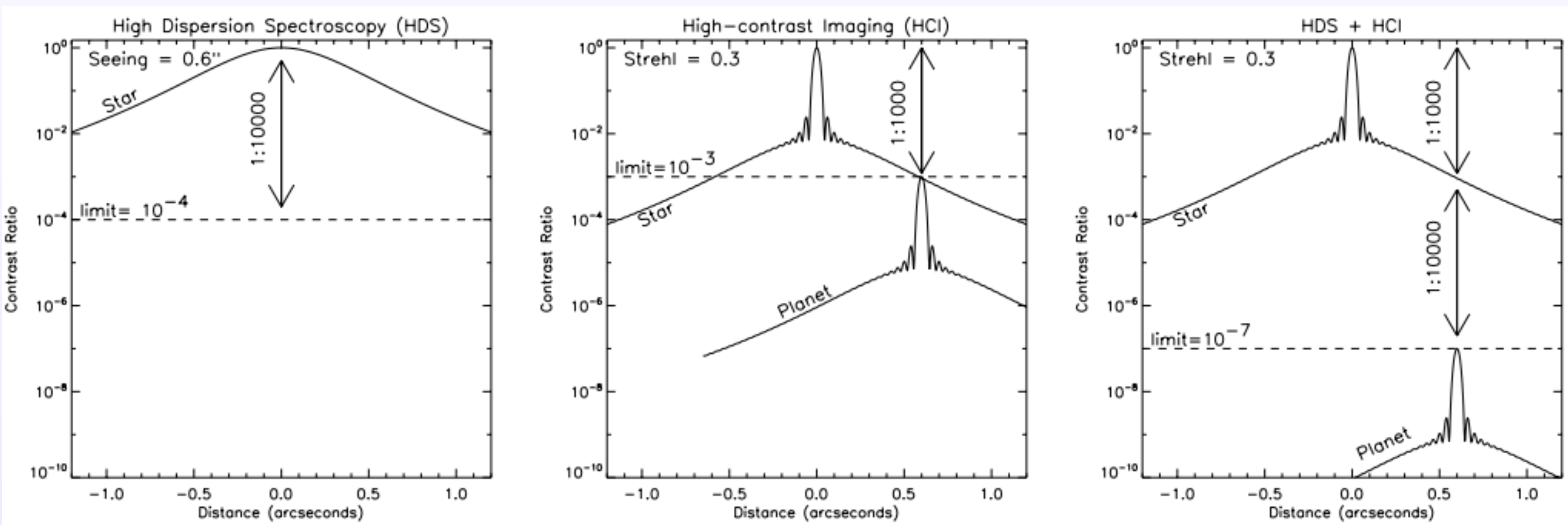
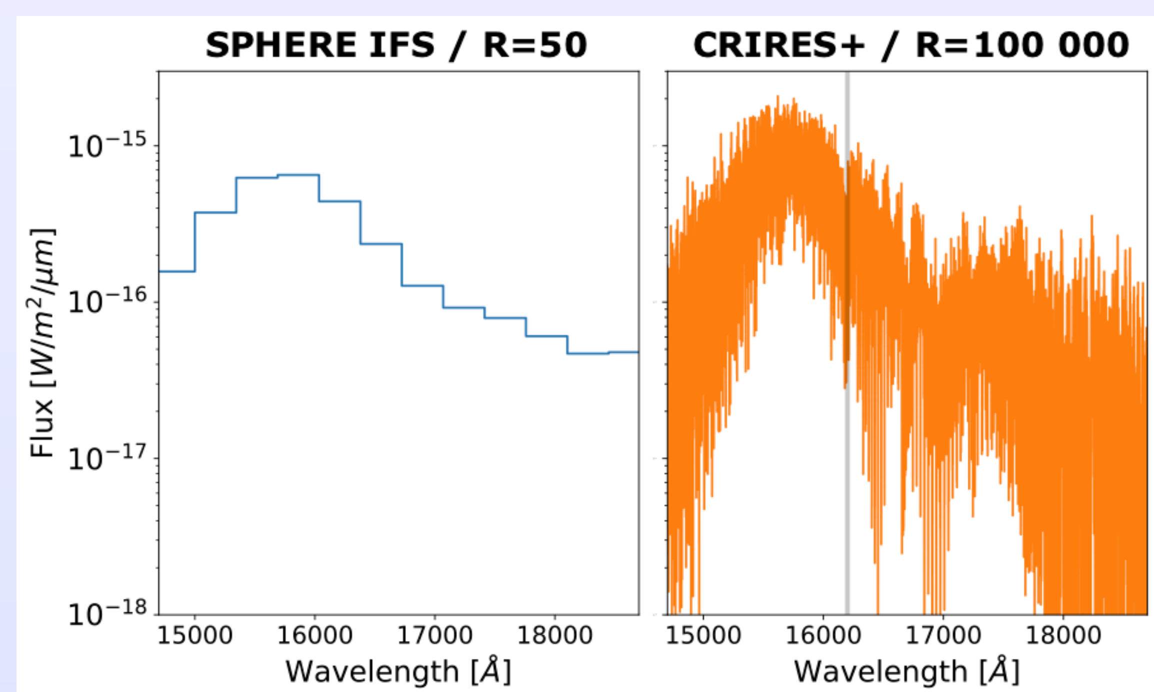


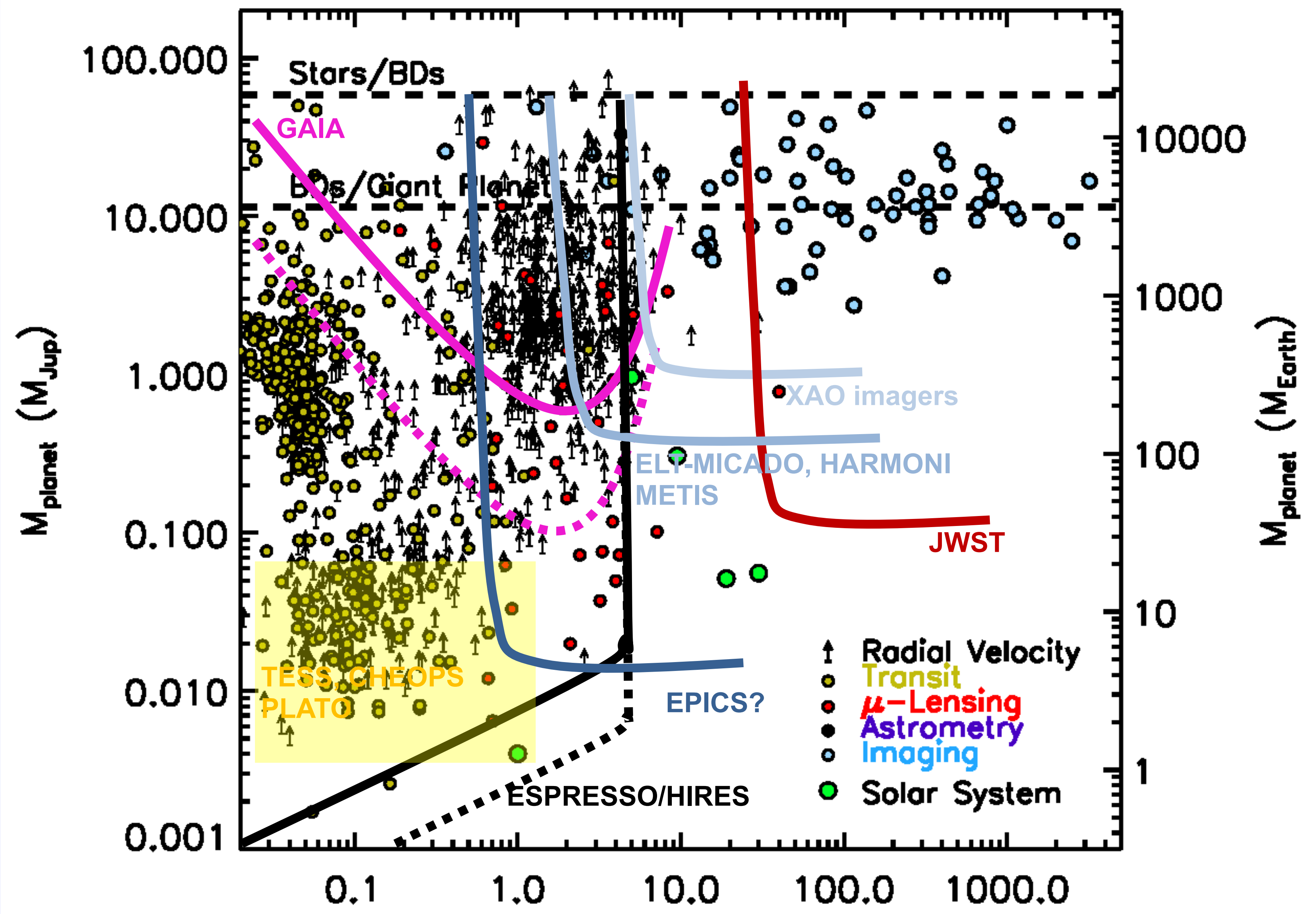
Snellen et al. (2015)

- Possibly improved characterization
- Detection boost for medium and high-resolution
- New science from RV information: rotation speed, orbital motion
- Possible detection of unseen companions (Gaia, RV) or confirmation of candidates



Conclusions: *a bright future for imaging!*

- Tremendous progress in 20 years with (Ex)AO and coronagraphy
- New generation of instruments can really help to address many science cases:
  - Atmospheric physics & chemistry, formation, occurence
- Synergies with other methods pave the way for the next 20 years!



Credit G. Chauvin