Arthur Vigan
Laboratoire d'Astrophysique de Marseille (LAM)
Centre National de la Recherche Scientifique (CNRS)

Direct Imaging and Characterisation of Exoplanets with VLT/SPHERE
Past, Present and Future

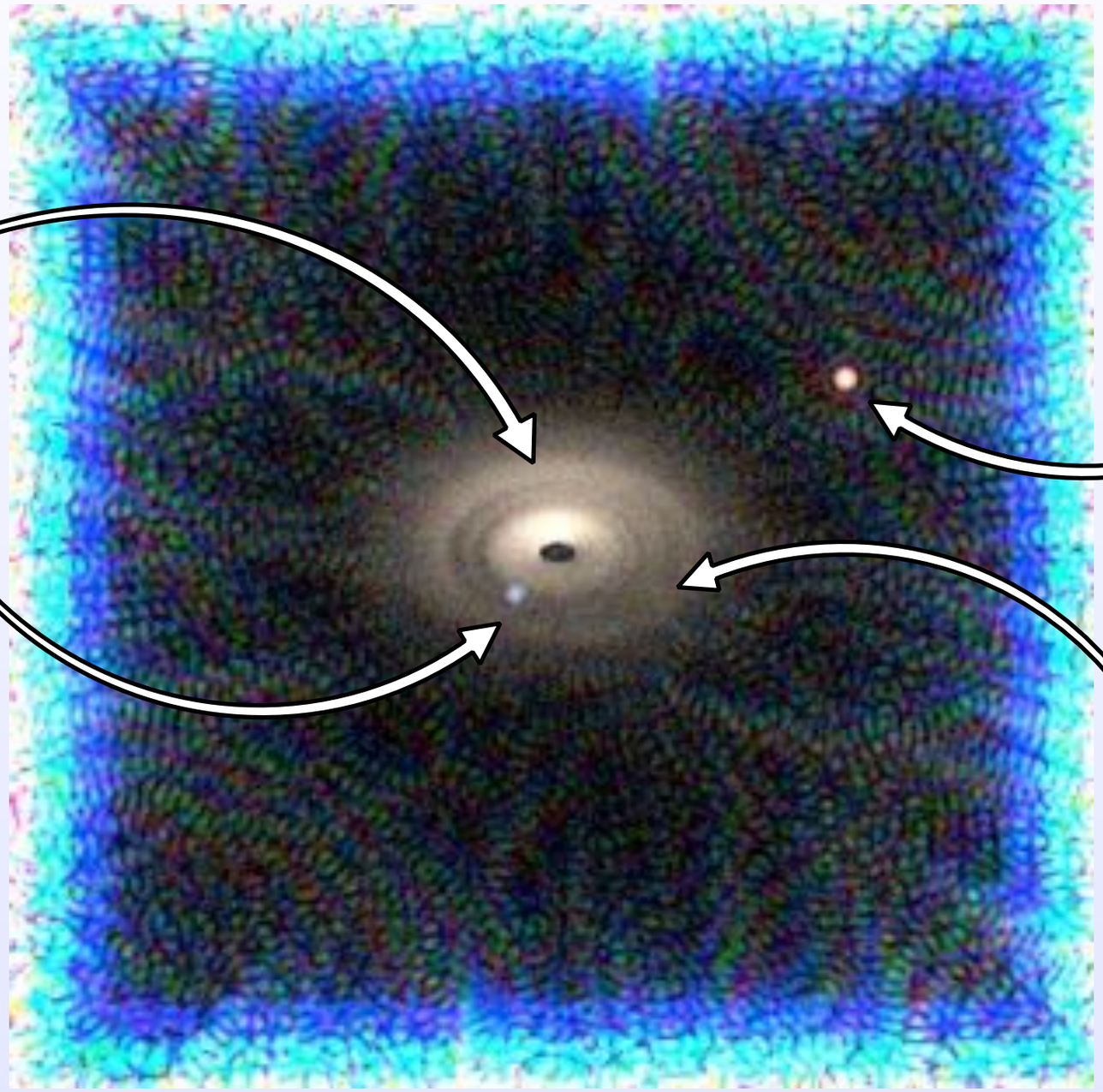
SHINE

G. Chauvin (SHINE coordinator), S. Desidera (SHINE+WP1 coordinator), A.Cheetham (WP1), A.-M. Lagrange (WP2 coordinator), R. Gratton (WP2), M. Langlois (WP2), A. Vigan (WP3 coordinator), M. Bonnefoy (WP3), M. Feldt (WP4 coordinator), M. Meyer (WP4)
and numerous participants from 12 European institutes!

HiRISE

G. Otten, E. Muslimov, M. Lopez, M. El Morsy, K. Dohlen, M. Houllé, M. Phillips, E. Choquet, R. Pourcelot, U. Seemann, J.-L. Beuzit, R. Dorn, M. Kasper, I. Baraffe, A. Reiners, Y. Charles, N. Tchoubaklian, ...

Direct imaging of exoplanets...



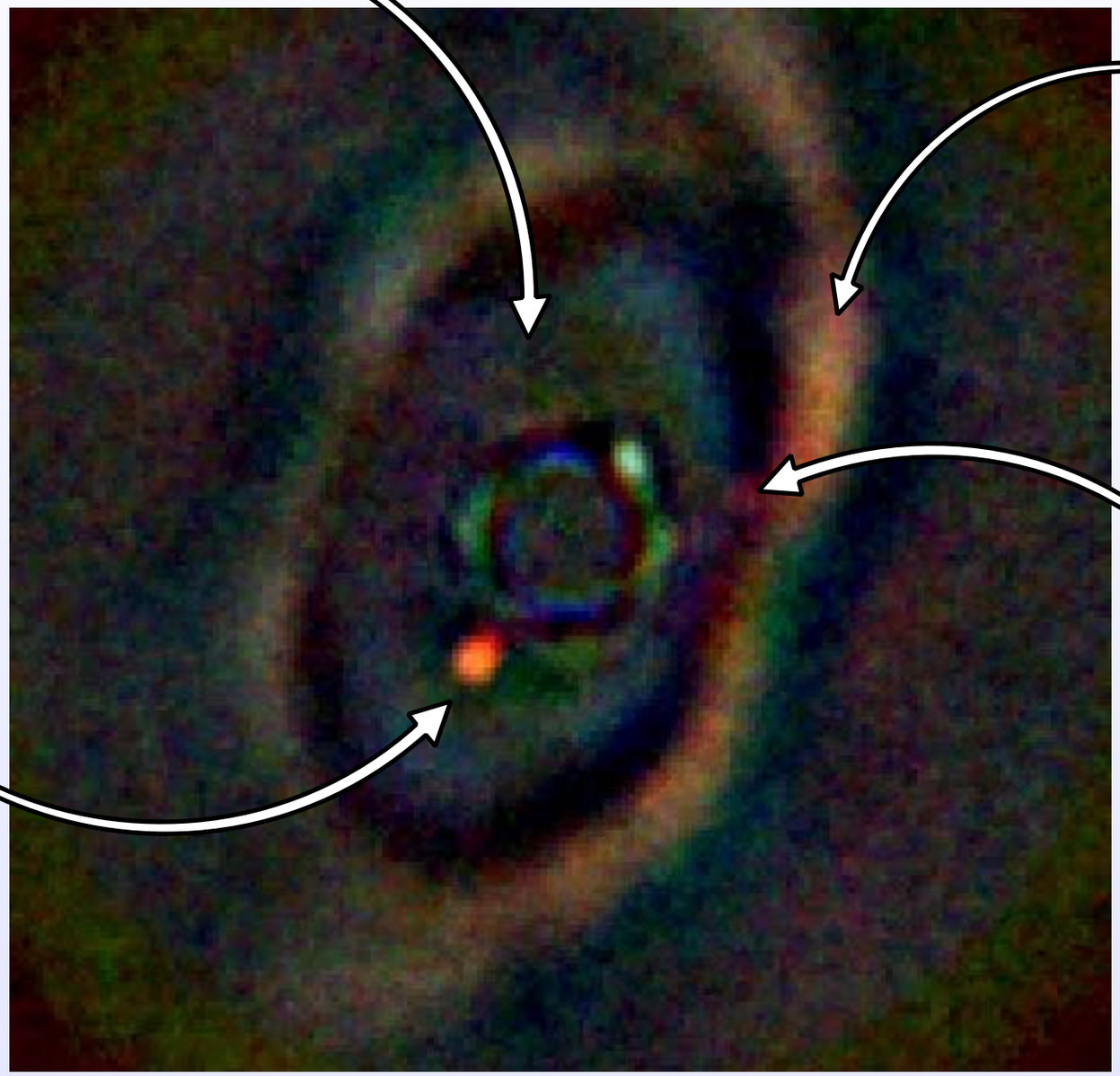
System architecture

Planet composition

Dust properties

Simulation

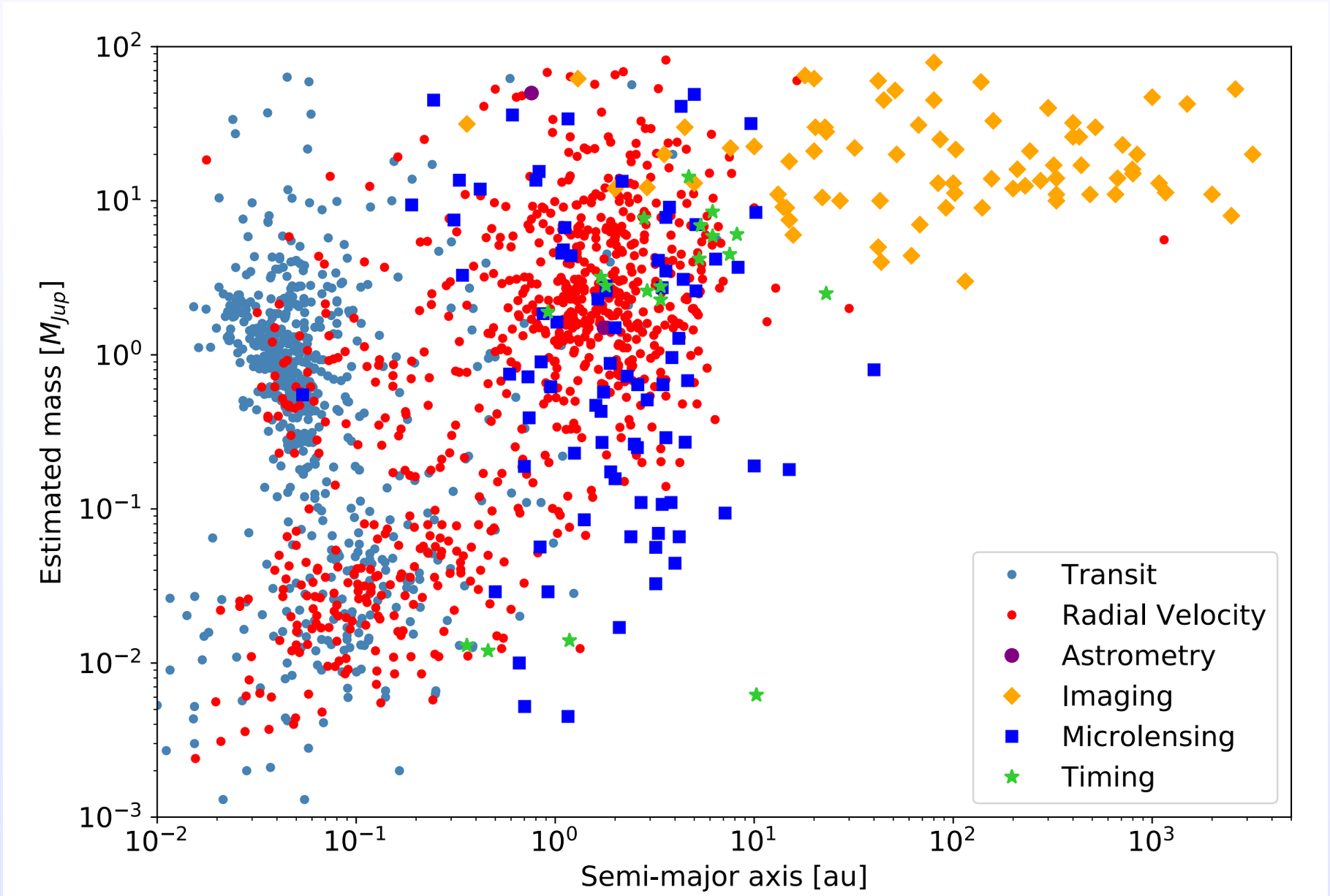
Direct imaging of exoplanets… is real



PDS 70 - Keppler et al. (2018)

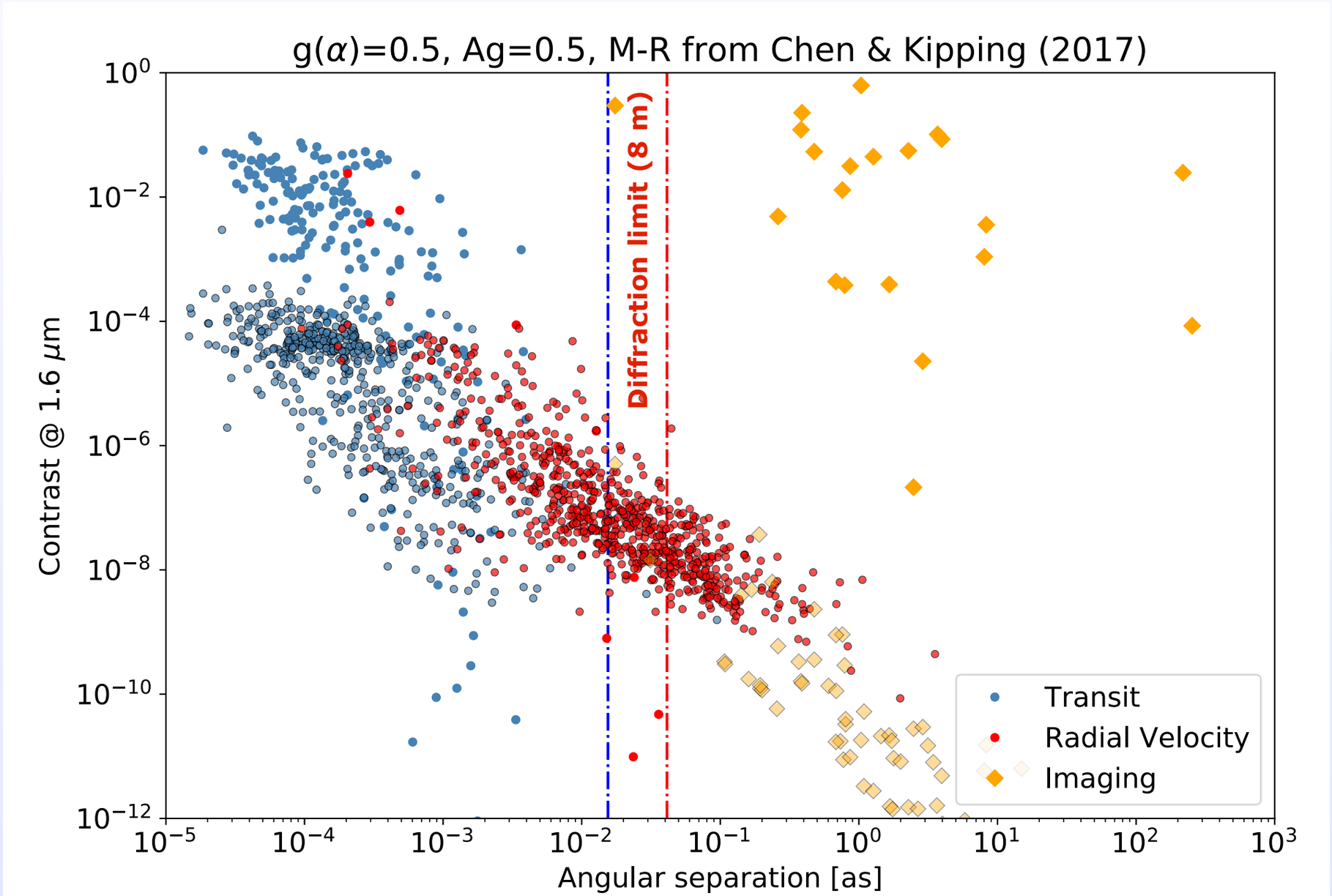
Direct imaging of exoplanets

Physical units



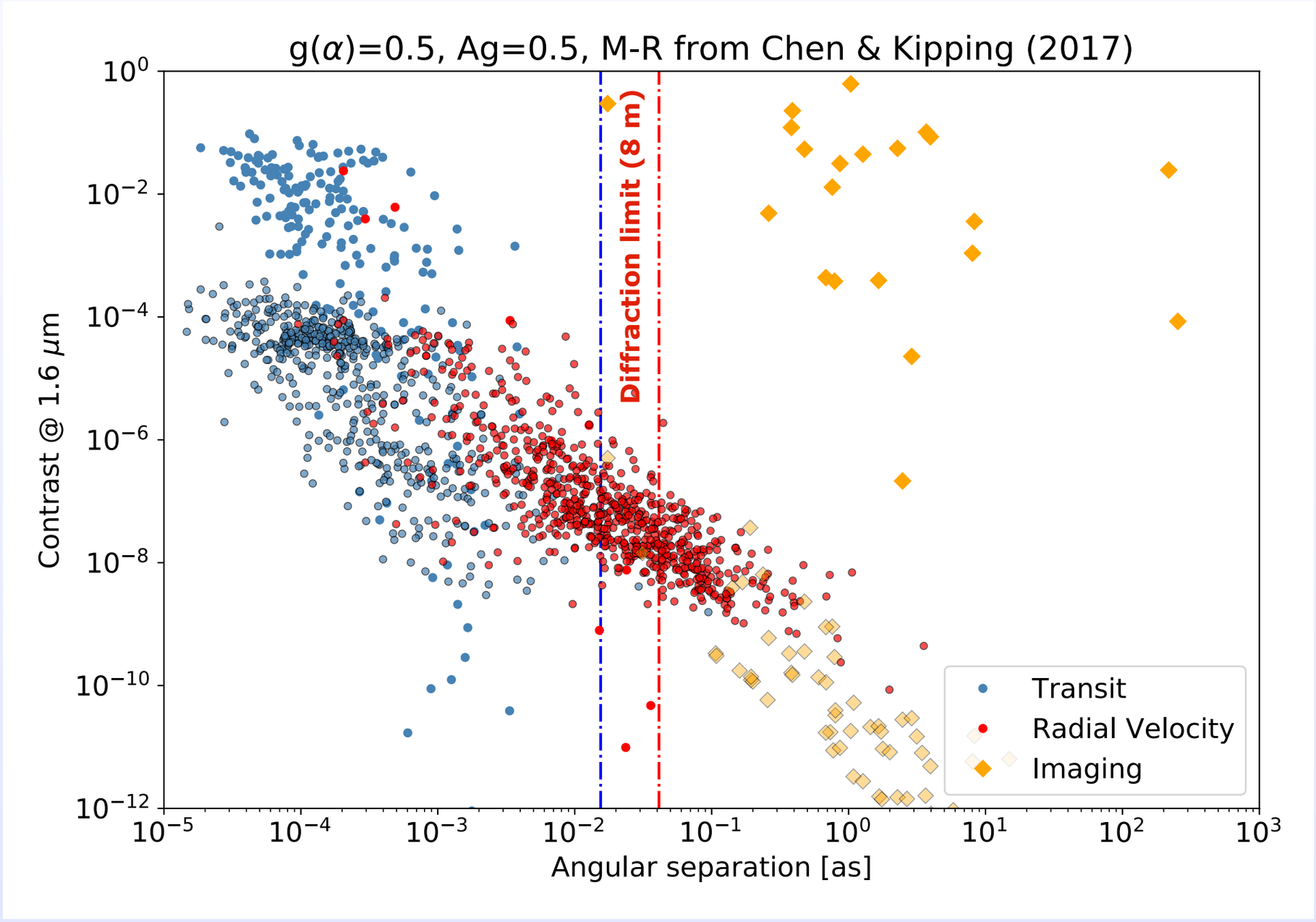
Direct imaging of exoplanets

Observables



Direct imaging of exoplanets

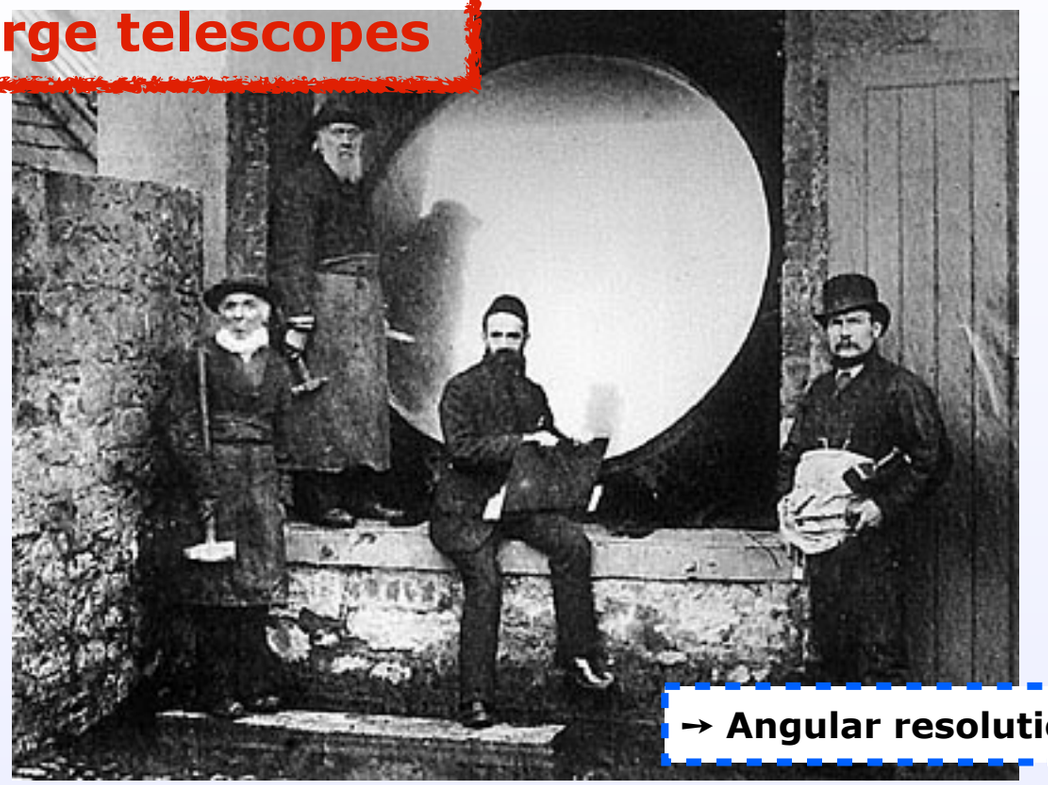
High-angular resolution



High-contrast

Direct imaging recipe

Large telescopes



→ Angular resolution

Adaptive optics

→ Turbulence correction
→ Angular resolution

→ Contrast

Post-processing

→ Contrast

Coronagraphs

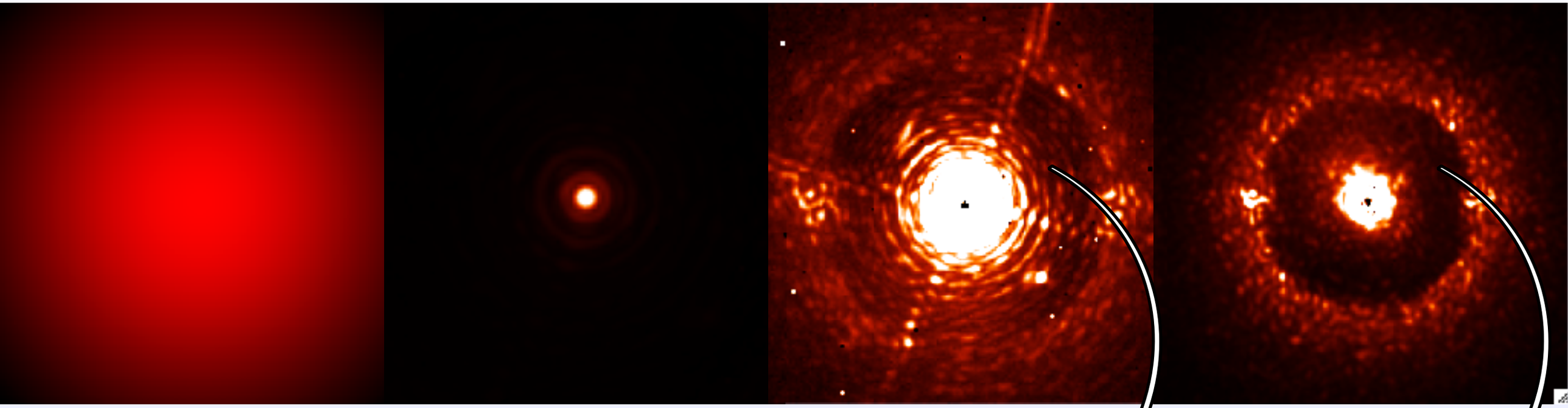
Direct imaging recipe

Seeing-limited PSF
✘ Adaptive optics
✘ Coronagraph

Diffraction-limited PSF
✔ Adaptive optics
✘ Coronagraph

Diffraction-limited PSF
✔ Adaptive optics
✘ Coronagraph

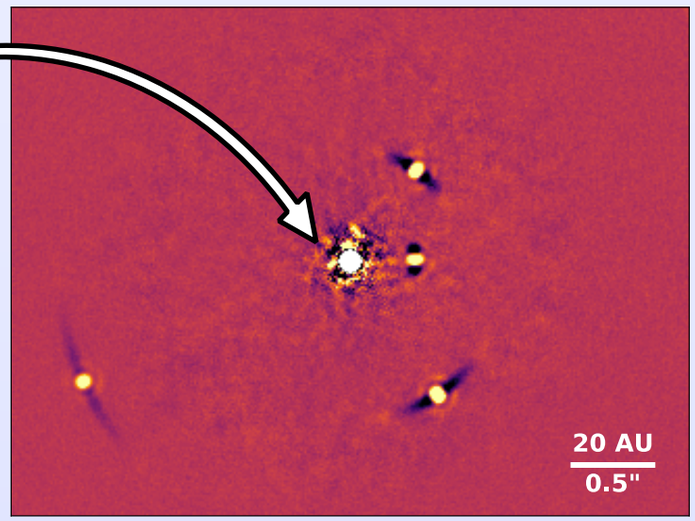
Coronagraphic image
✔ Adaptive optics
✔ Coronagraph



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

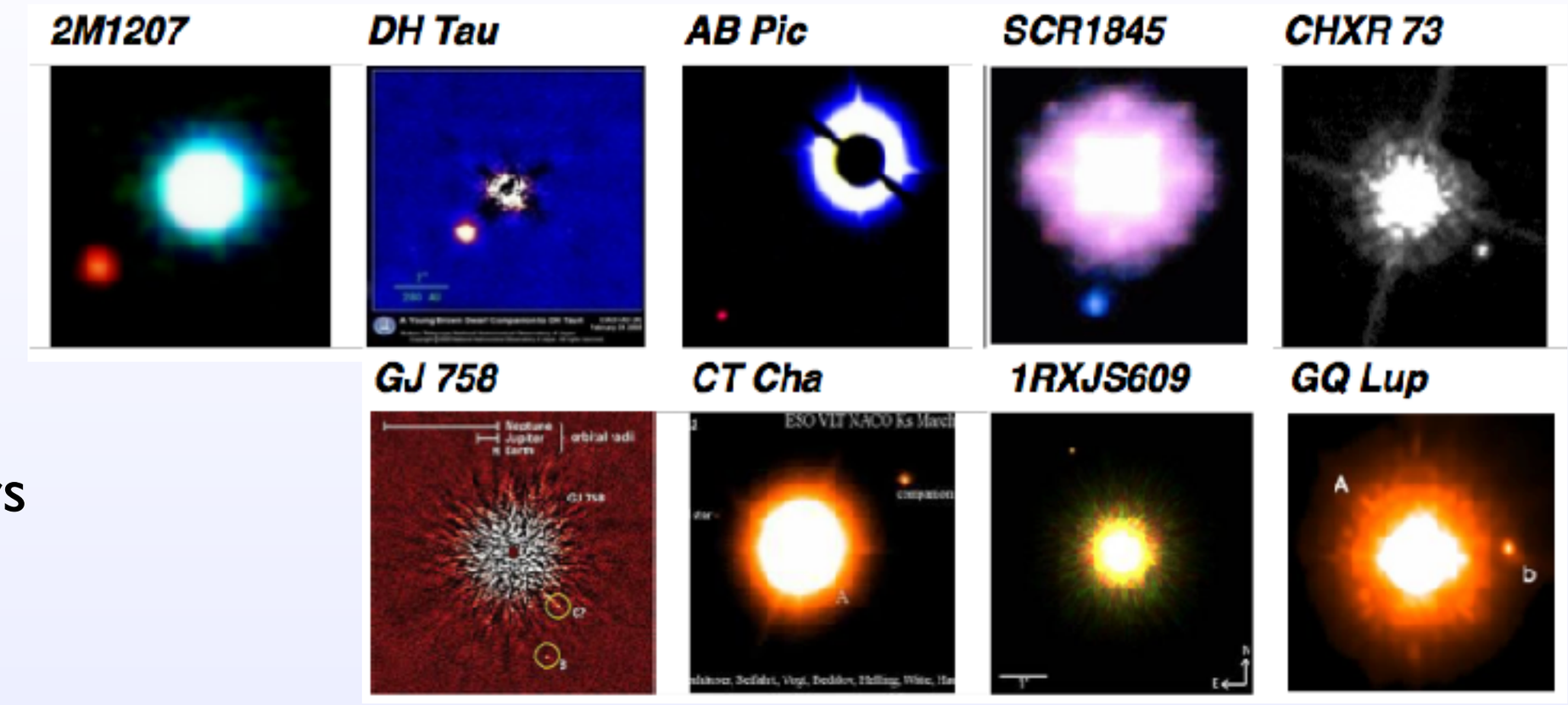
PAST

Imaged companions in 2015

$$q = \frac{M_p}{M_\star}$$

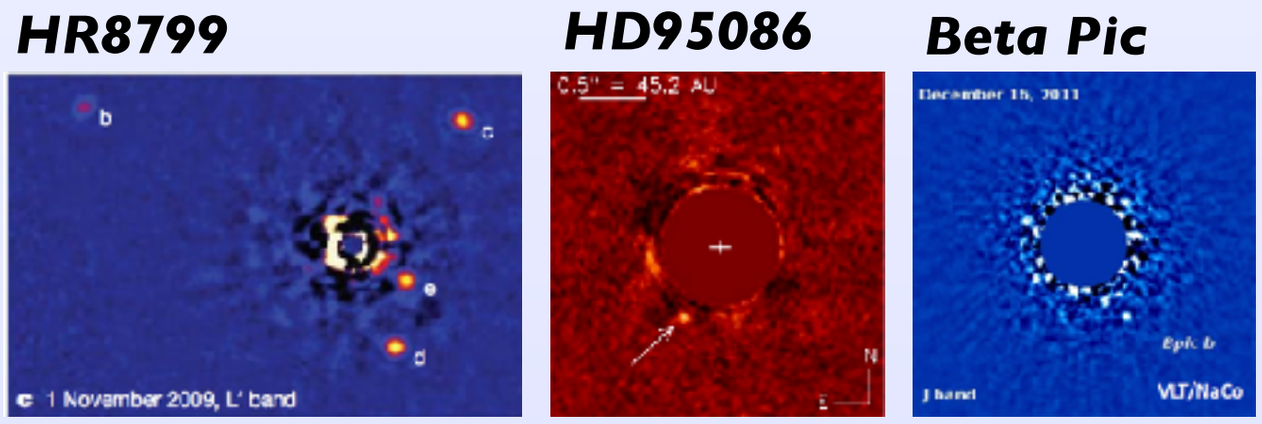
Wide orbit

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



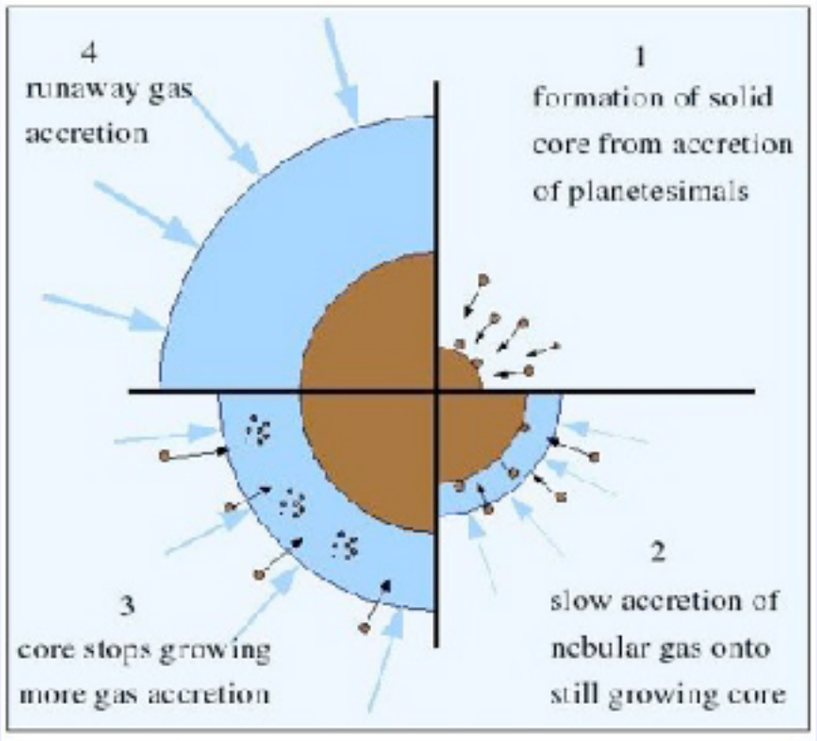
Close(r) orbit

- Early-type stars
- q = 0.5%
- a < 120 AU
- disk signatures/detections

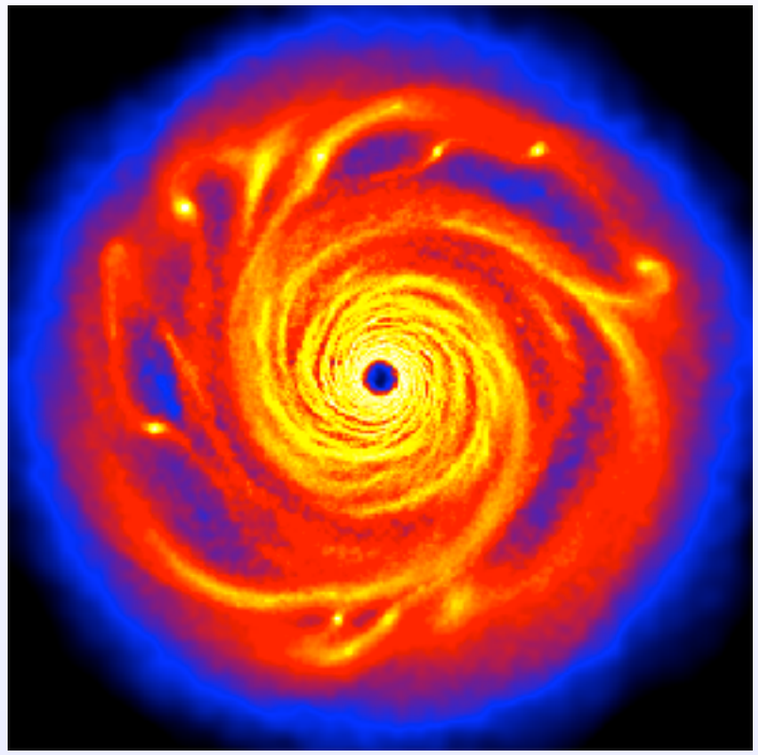


Link to formation models

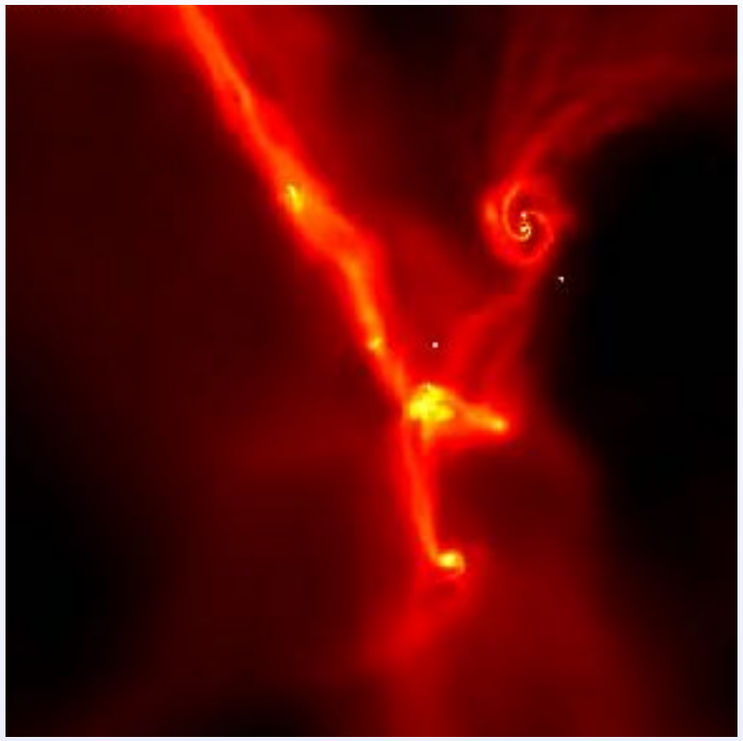
Core Accretion
Pollack et al. 1994



Gravitational Instability
Cameron 1978



Gravo-turbulent fragmentation
Hennebelle & Chabrier 2011



Different formation pathways will induce:

- ➙ *Different physical and orbital parameter distributions*
- ➙ *Different occurence rates*
- ➙ *Different compositions*
- ➙ *Different luminosities*

Can direct imaging observations constrain formation models?

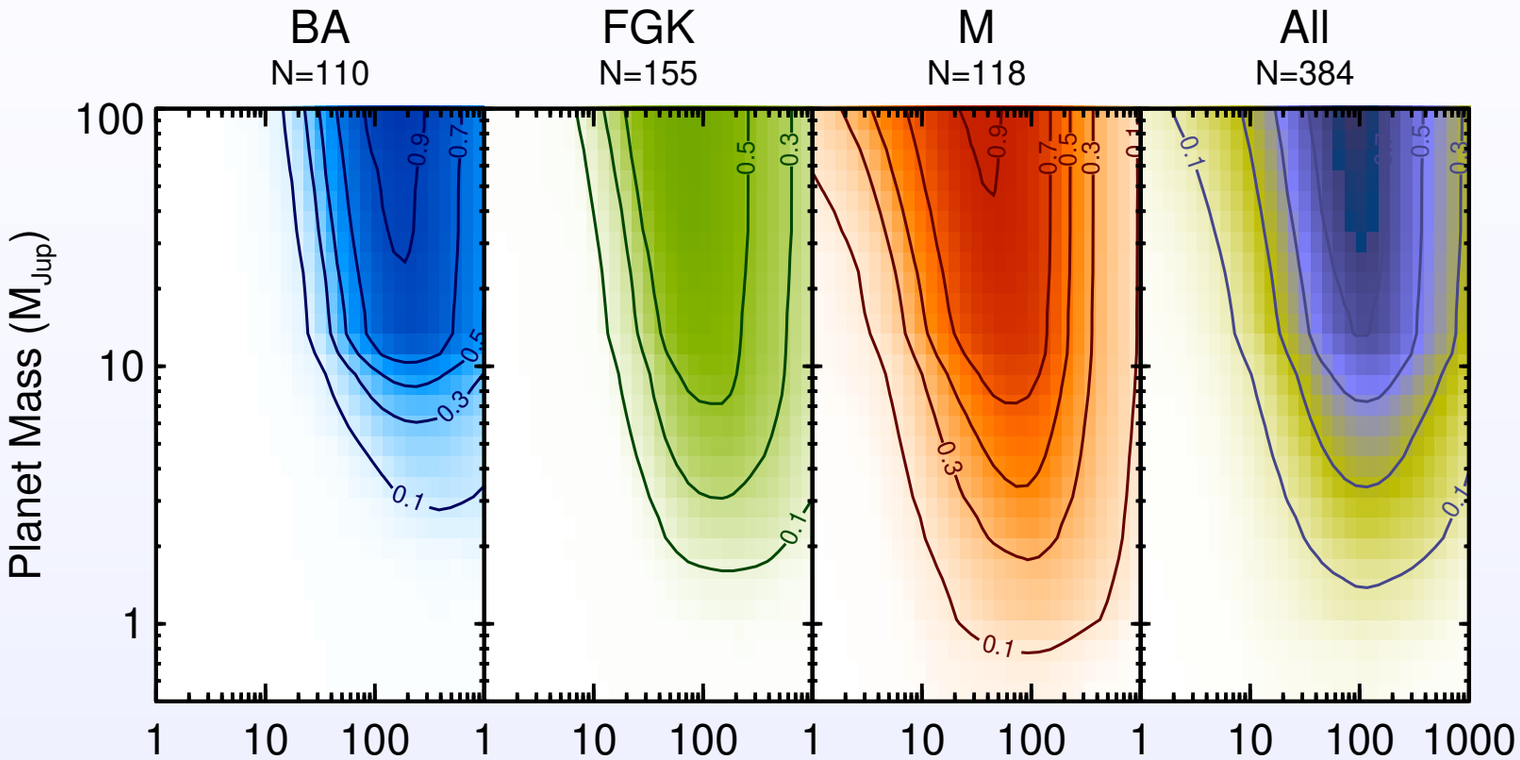
Frequency of giant exoplanets on wide orbits?

An old question that led to many 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. (2010a,b)	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)	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

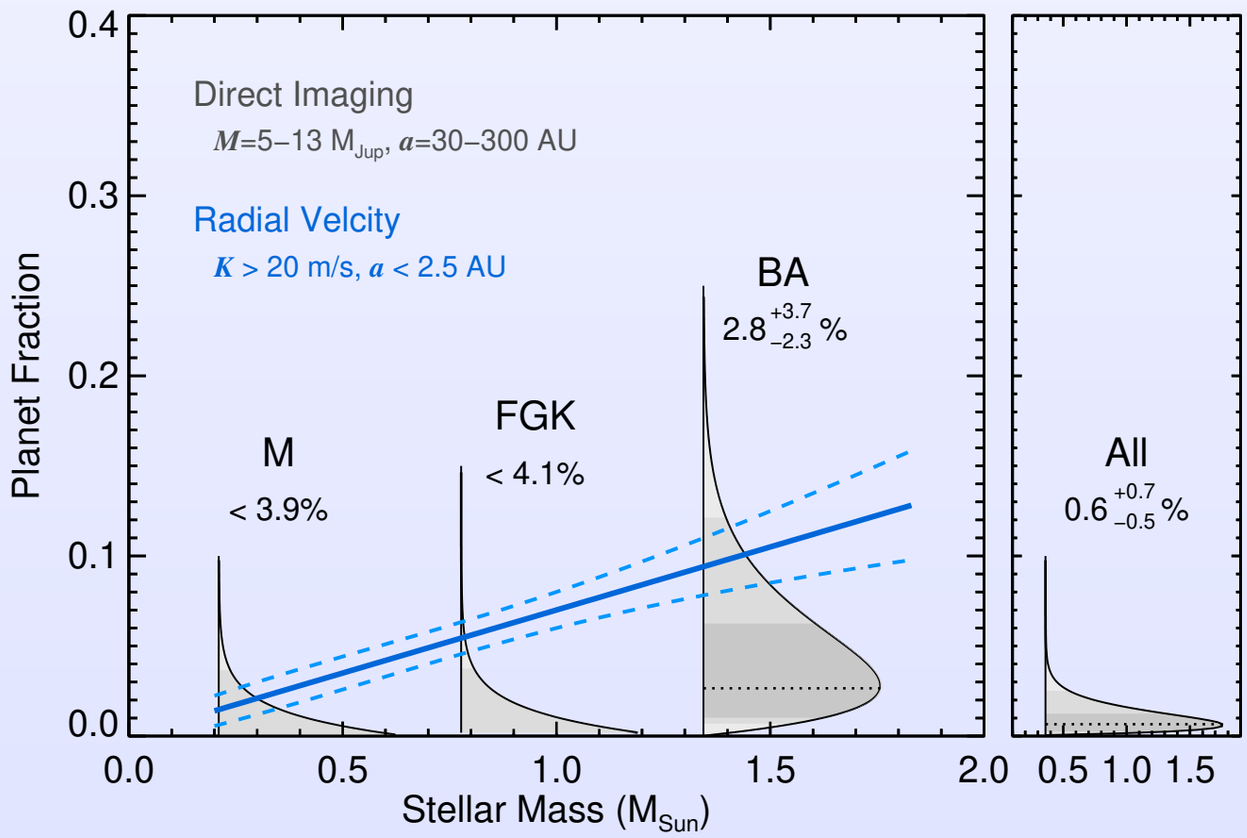
+ Galicher et al. (2016), Vigan et al. (2017), Meshkat et al. (2016, 2017), Durkan et al. (2016), …

Frequency of giant exoplanets on wide orbits?



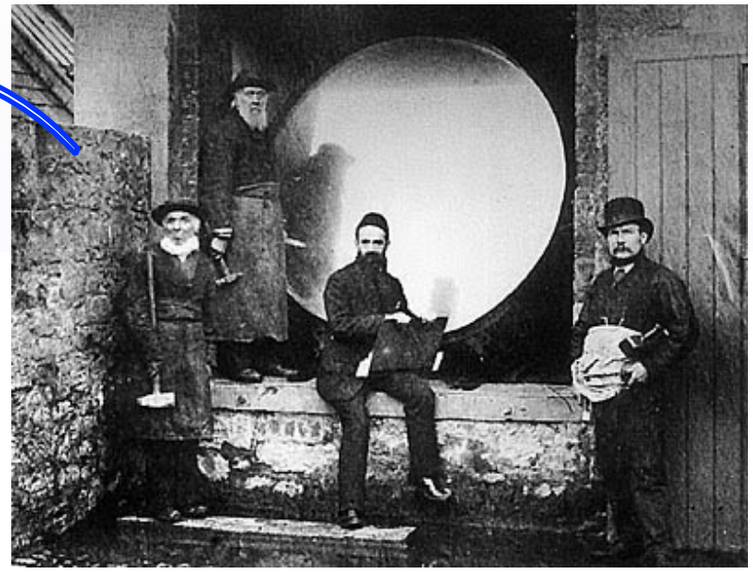
Meta-analysis by Bowler (2016)

- Mixing various surveys
- Very large sample
- Heterogeneous selection
- Low sensitivity at small sma/masses



SPHERE @ VLT/UT3

VLT/SPHERE - 2009



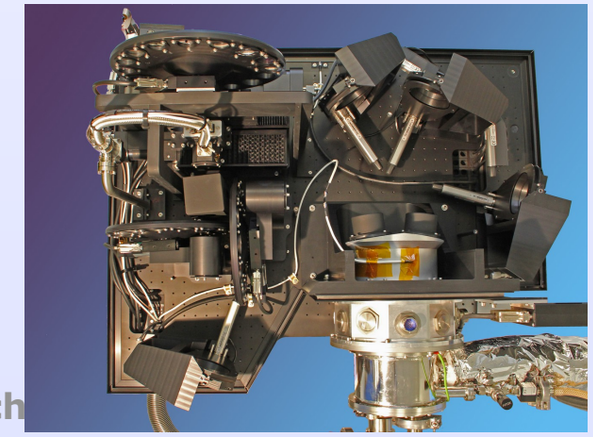
IRDIS

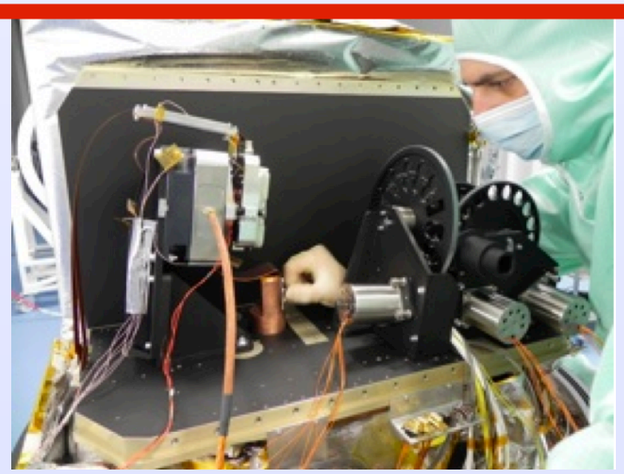
IFS

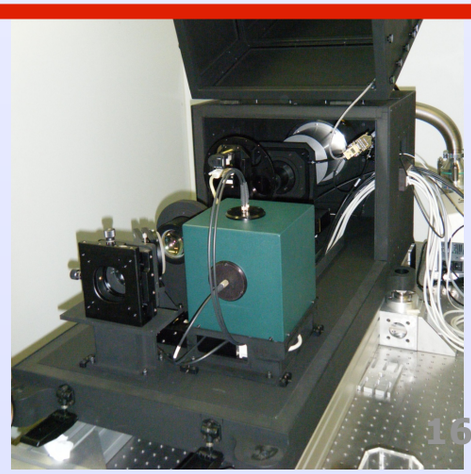
ZIMPOL

SPHERE science instruments

	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 = 50/350	R = 50 / 30
Linear polarisation	Simultaneous	Simultaneous (dual-beam)	
Nyquist sampling	@ 0.6 µm	@ 0.95 µm	@ 0.95 µm

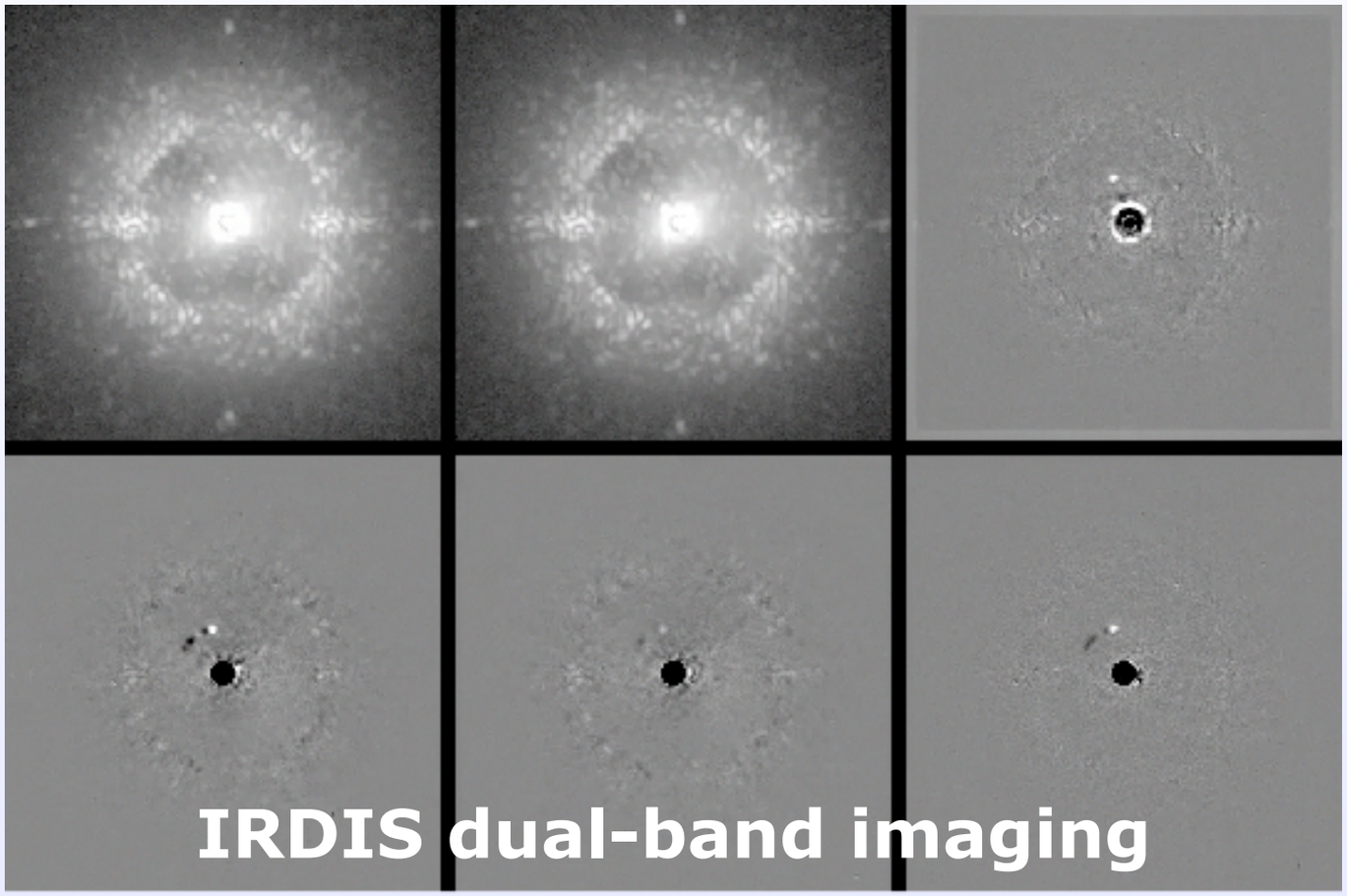


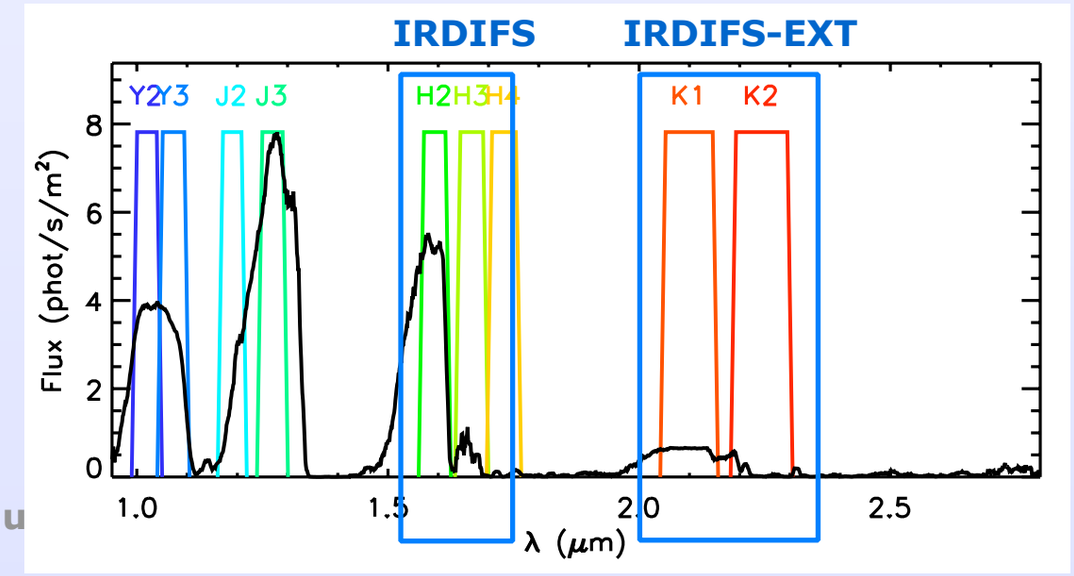


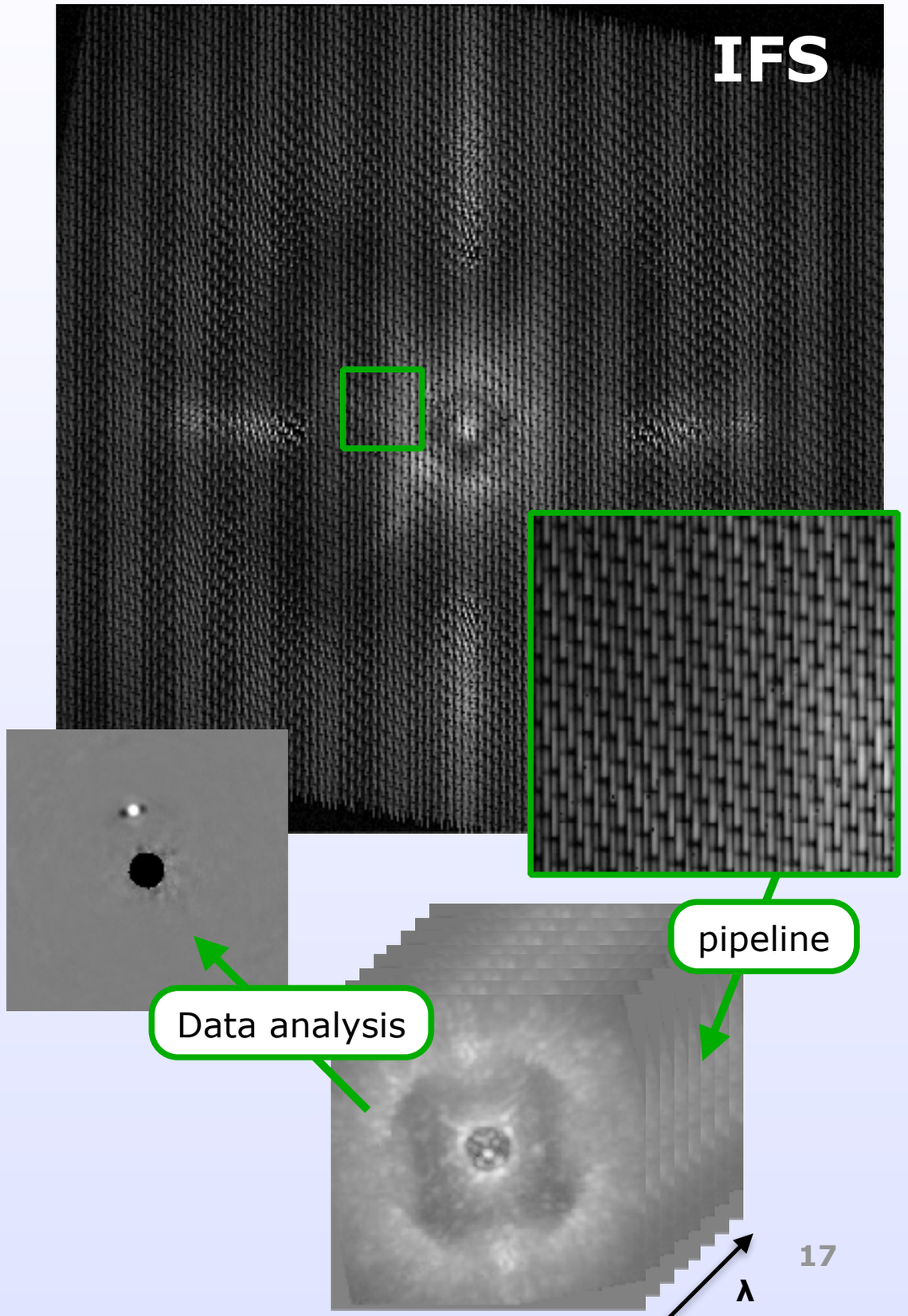


IRDIFS: the exoplanet hunting mode

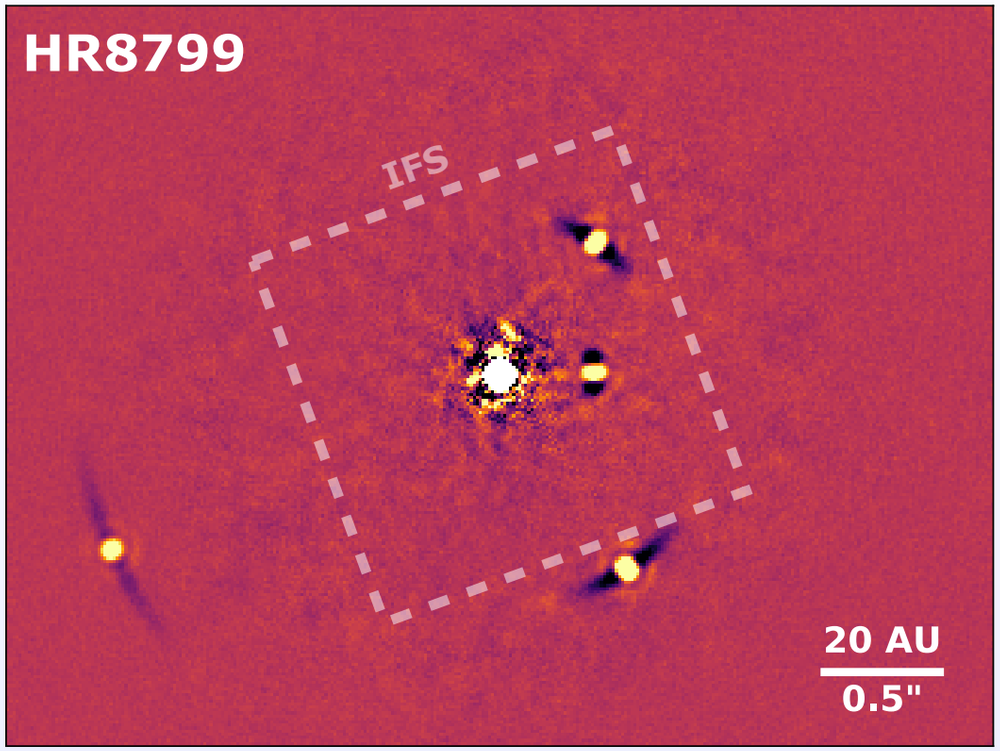
SPHERE designed as a <u>survey instrument</u>



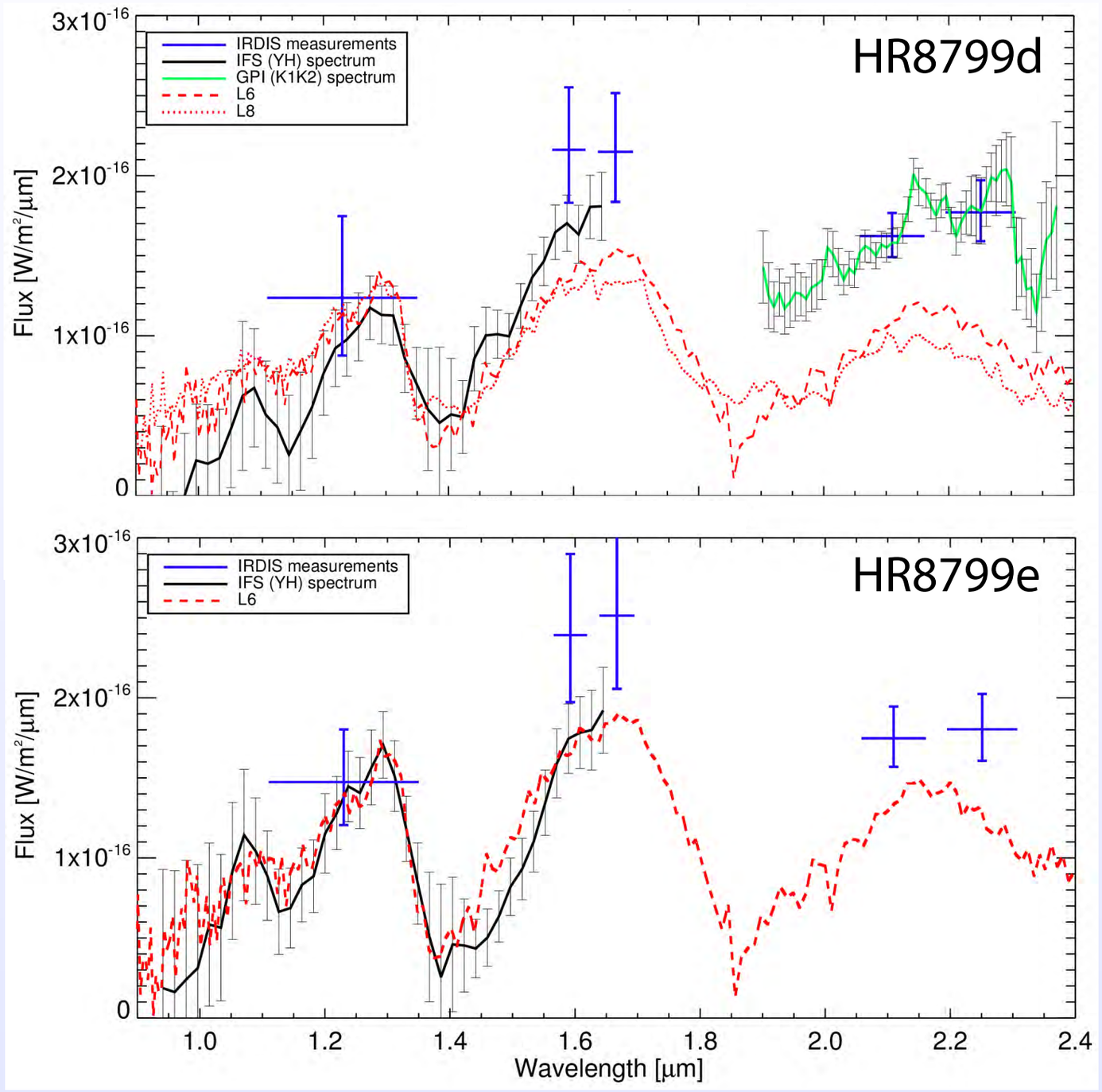




IRDIFS in action: the HR8799 system



- First spectra for HR8799 c, d
- Spectral types ~L6-L8
- Redder colors than field BD and models
- Reddening well reproduced by submicron grains made of corundum, iron, enstatite, or forsterite



Zurlo et al. (2016)
Bonnefoy et al. (2016)

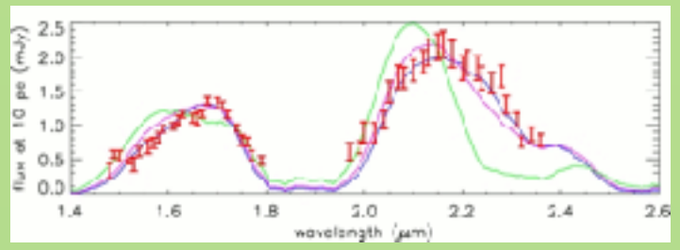
PRESENT

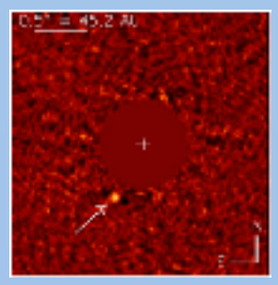
SHINE: SpHere Infrared survey for Exoplanets

1/ Physics of giant exoplanets

Photometry & Spectroscopy

Atmosphere & physical properties

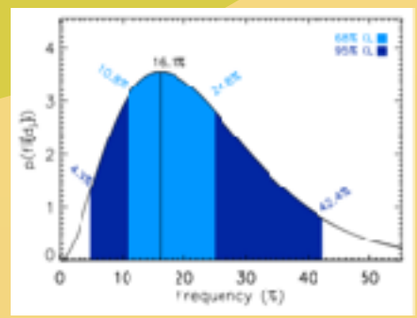




2/ Architecture & stability of planetary systems

Astrometry & disk/planet position

Orbits, dynamical interactions, resonances & long-term evolution



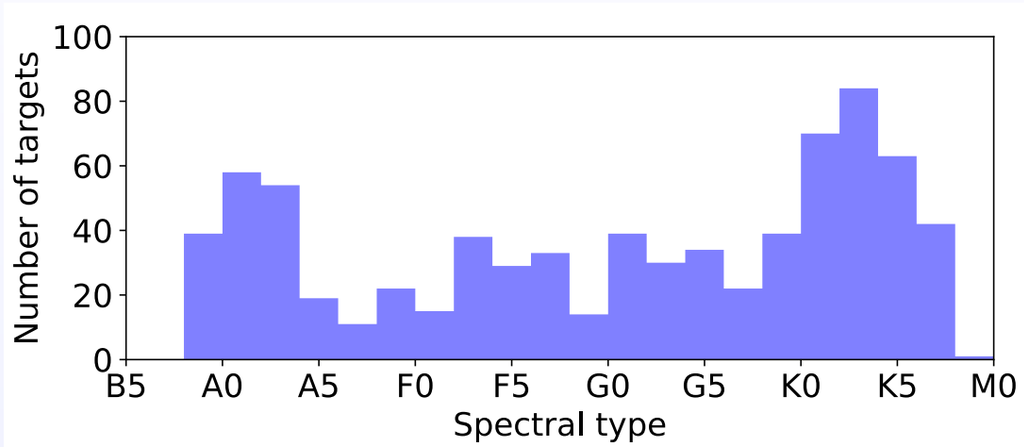
3/ Occurrence & formation

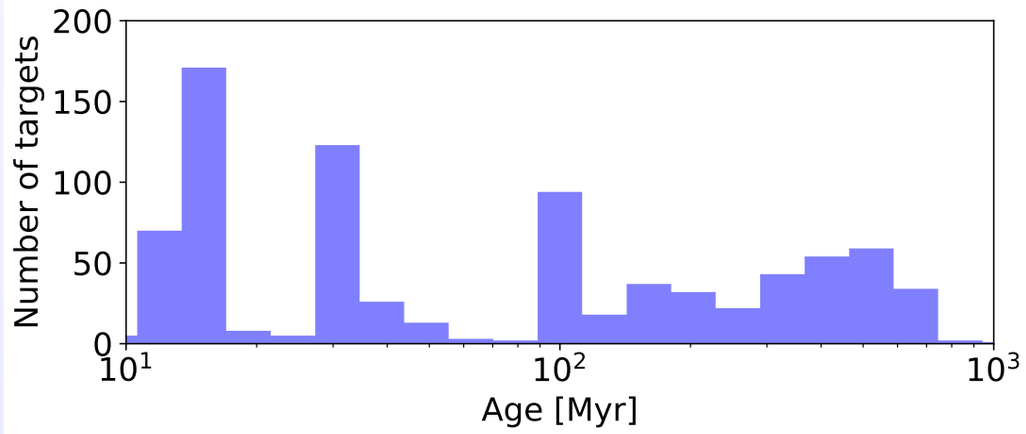
Statistical properties (occurrence, stellar host dependency, disk properties)

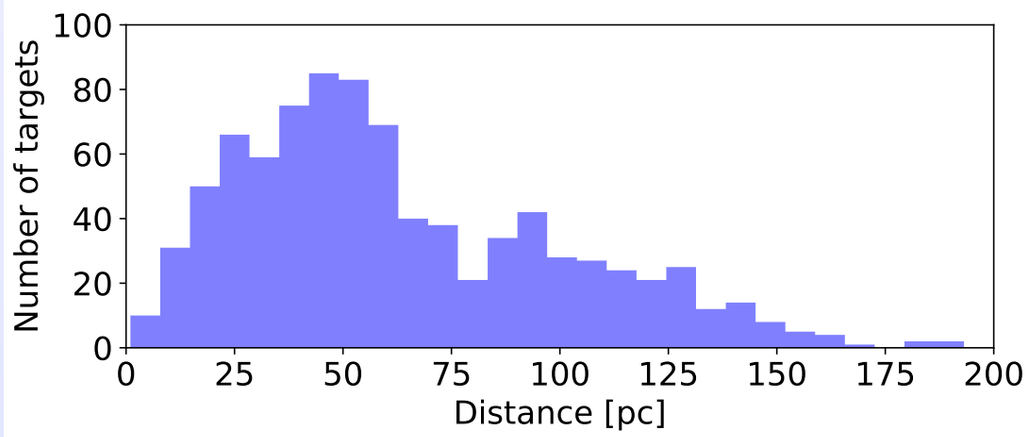
Formation theories

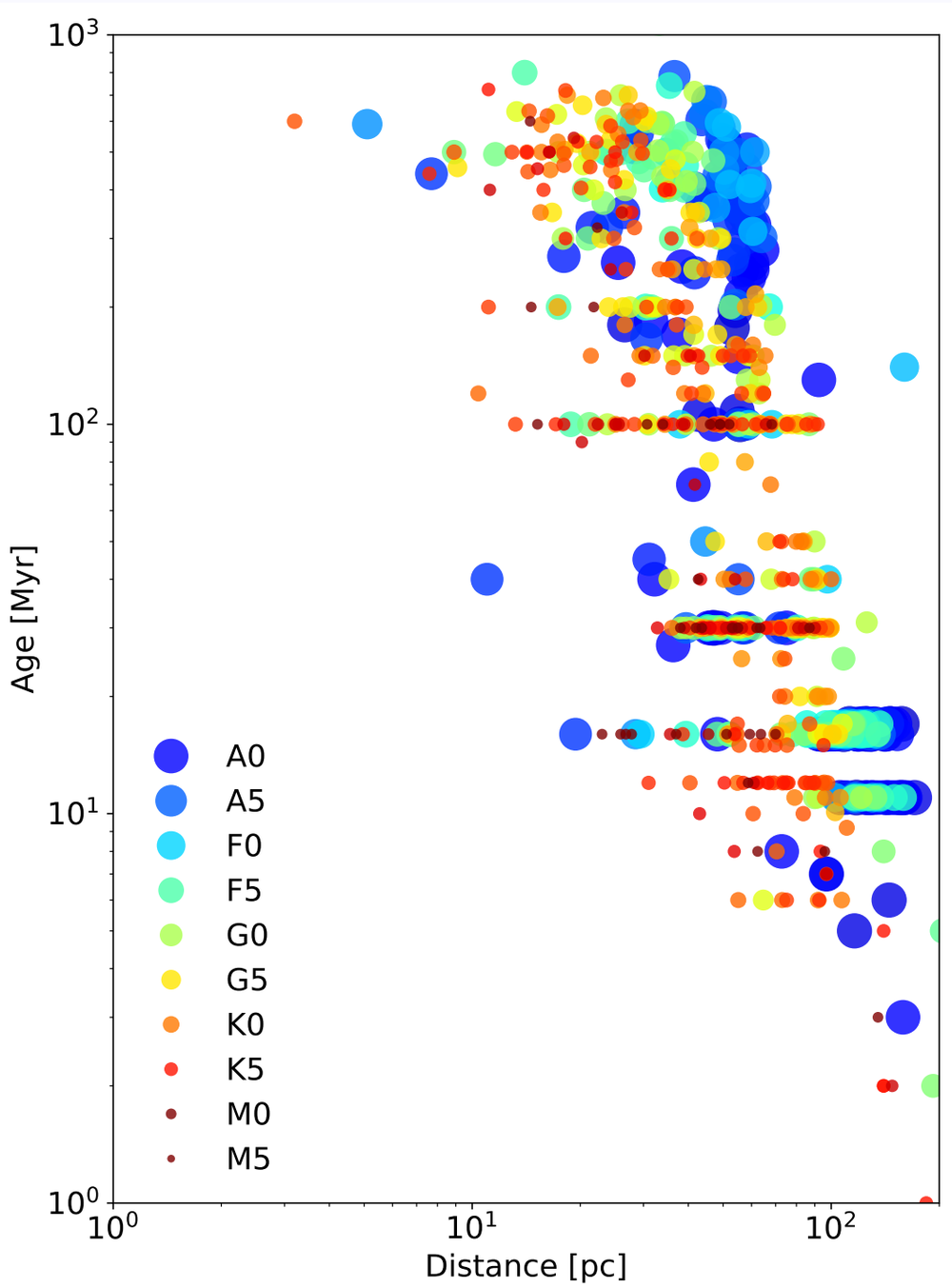
SHINE sample: all young stars within 130 pc

500 stars + 400 backup, 4 priority bins









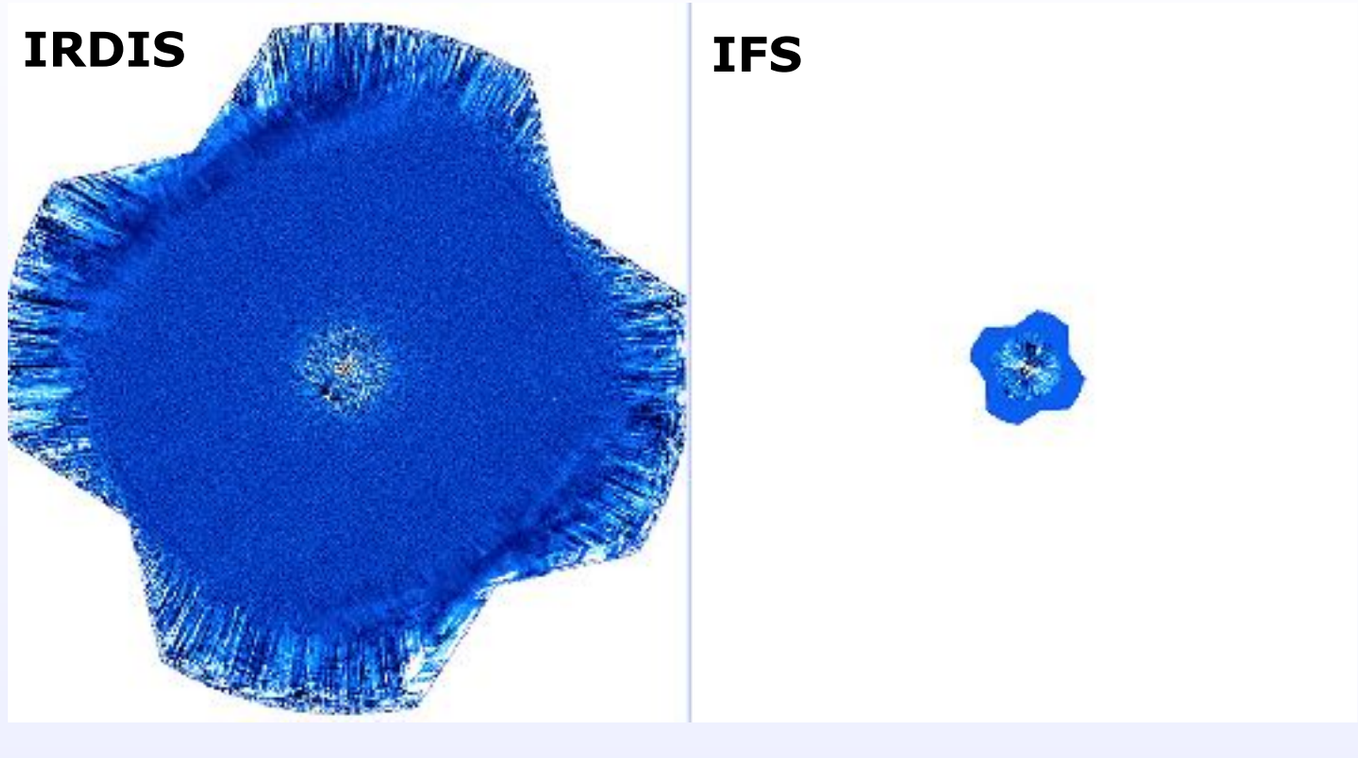
R<11

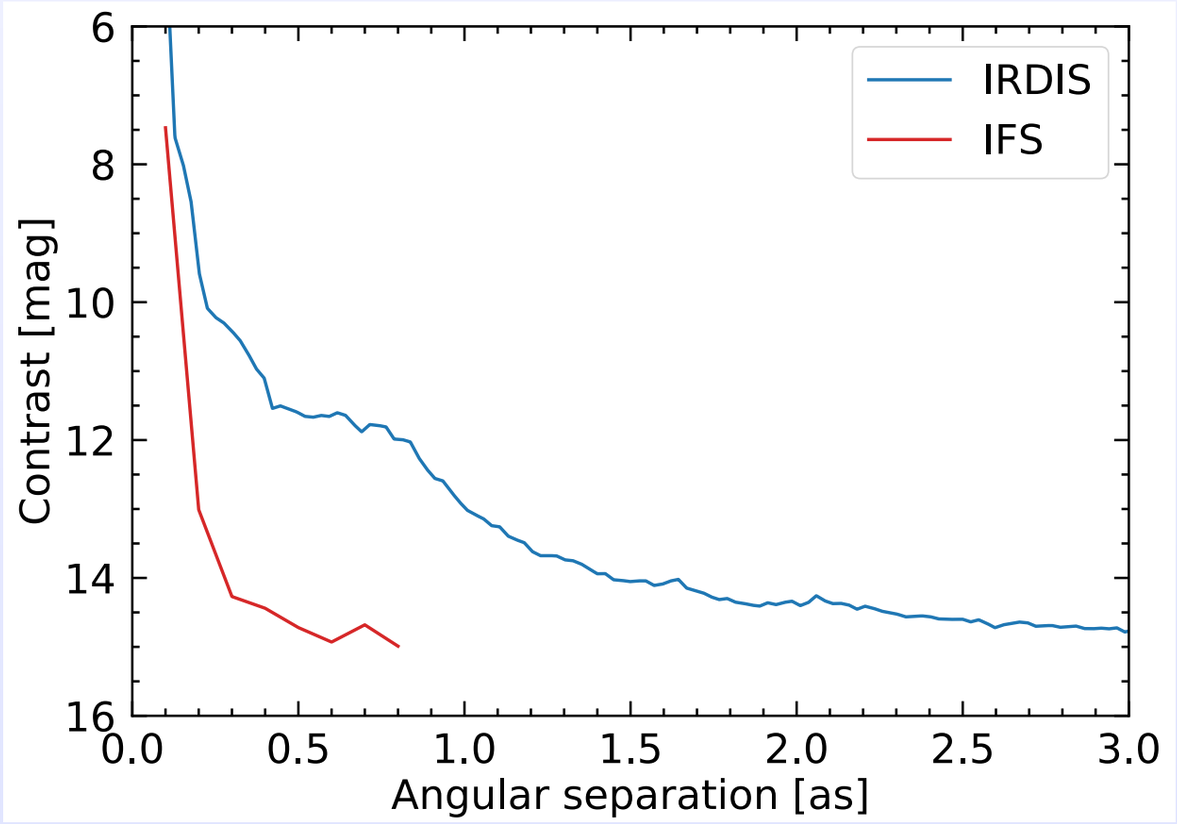
No binaries (spectro or visual <6")

Observations and data analysis

200 nights of VLT/SPHERE over 5 years

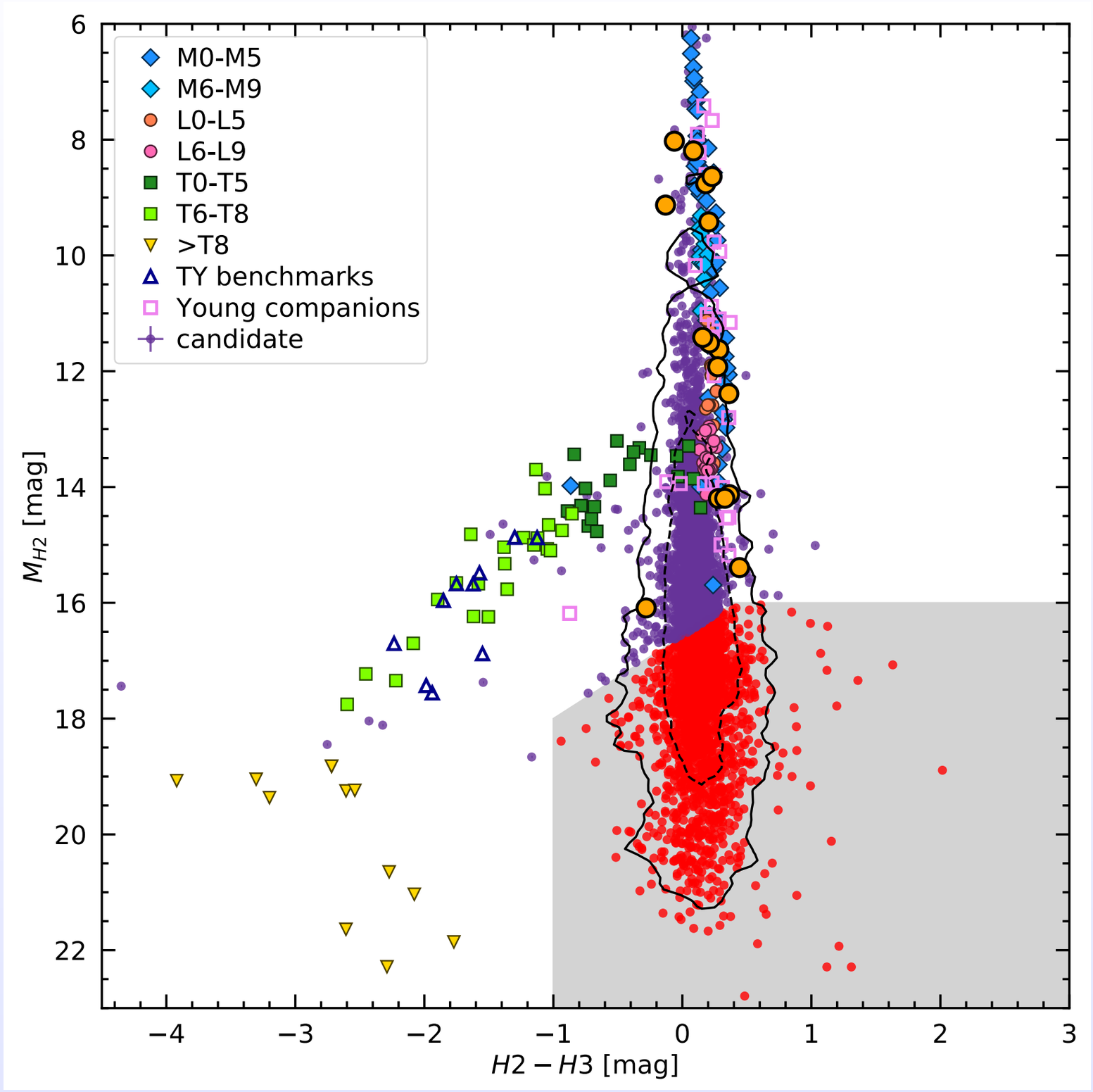
- >90% already done
- GTO done in **visitor mode**
  - Lots of bad weather!
- IRDIFS or IRDIFS-EXT, ADI, ~1.5 hour/target
- Finalisation pending the reopening of Paranal...
- SPHERE Data Center hosted @ IPAG:
  - **fully automated** pre-processing pipeline
  - SpeCal pipeline (Galicher et al. in 2018): **TLOCI**, PCA, cADI, RDI, ...
  - **Visual identification** of candidates





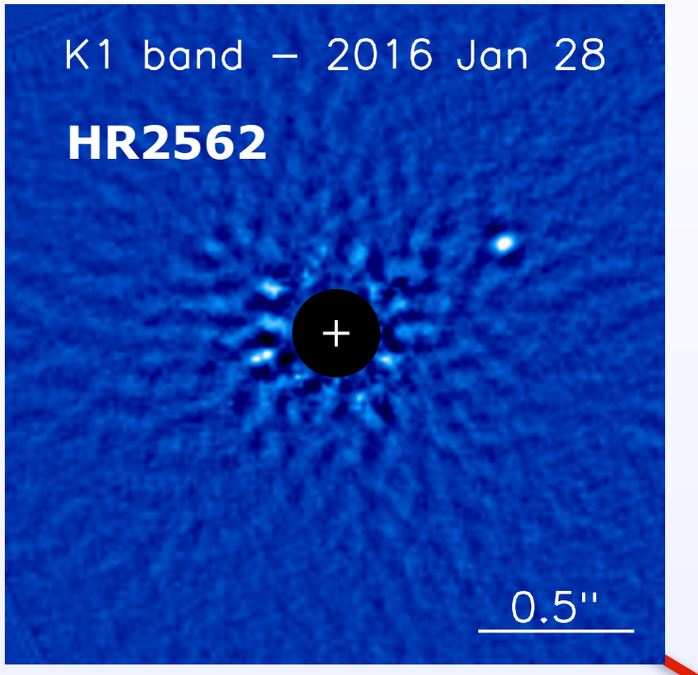
SHINE candidates

IRDIS H23 photometry

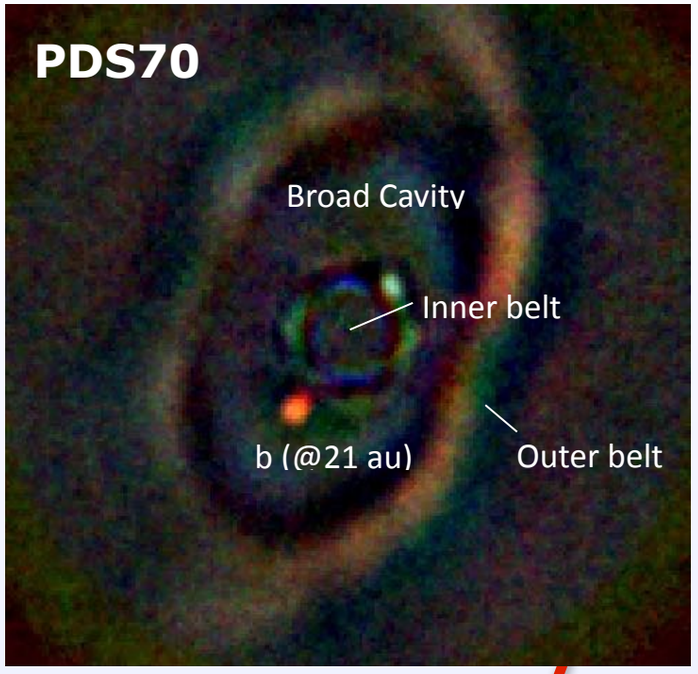


>2900 undefined candidates!

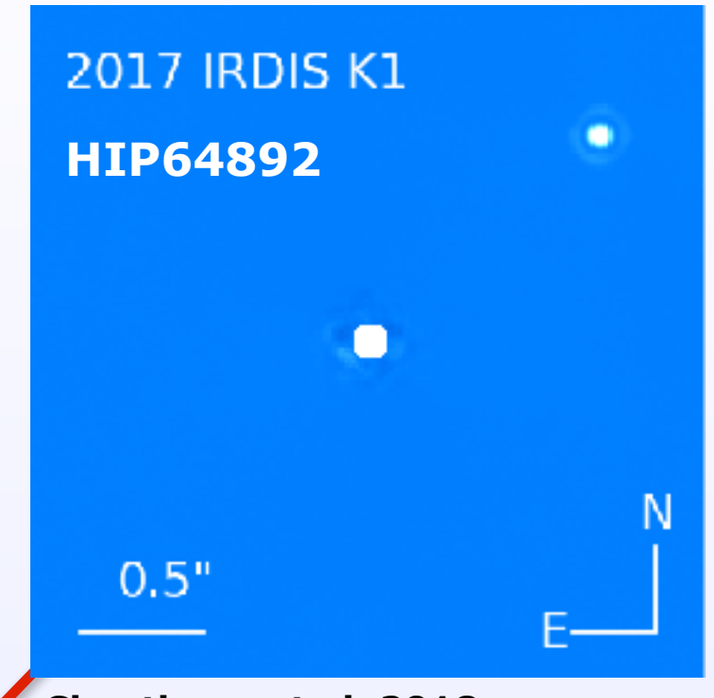
New SPHERE + GPI detections



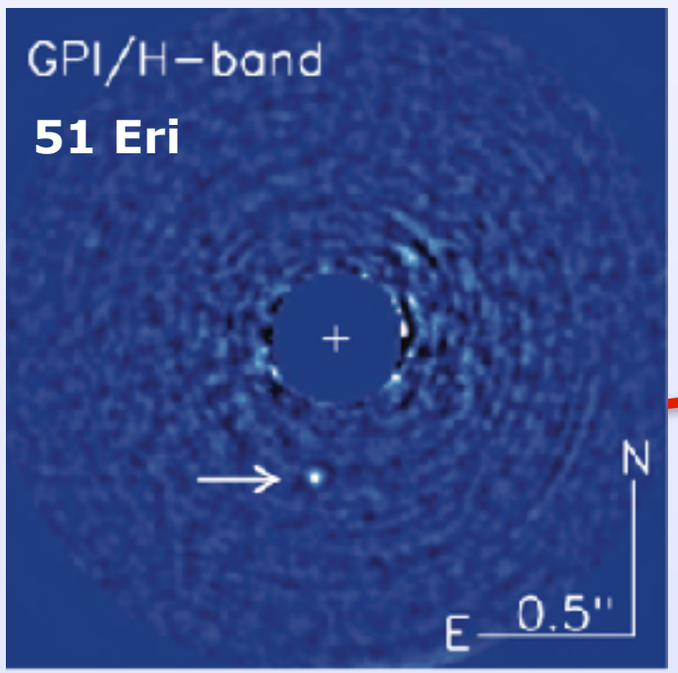
Konopacky et al. 2016



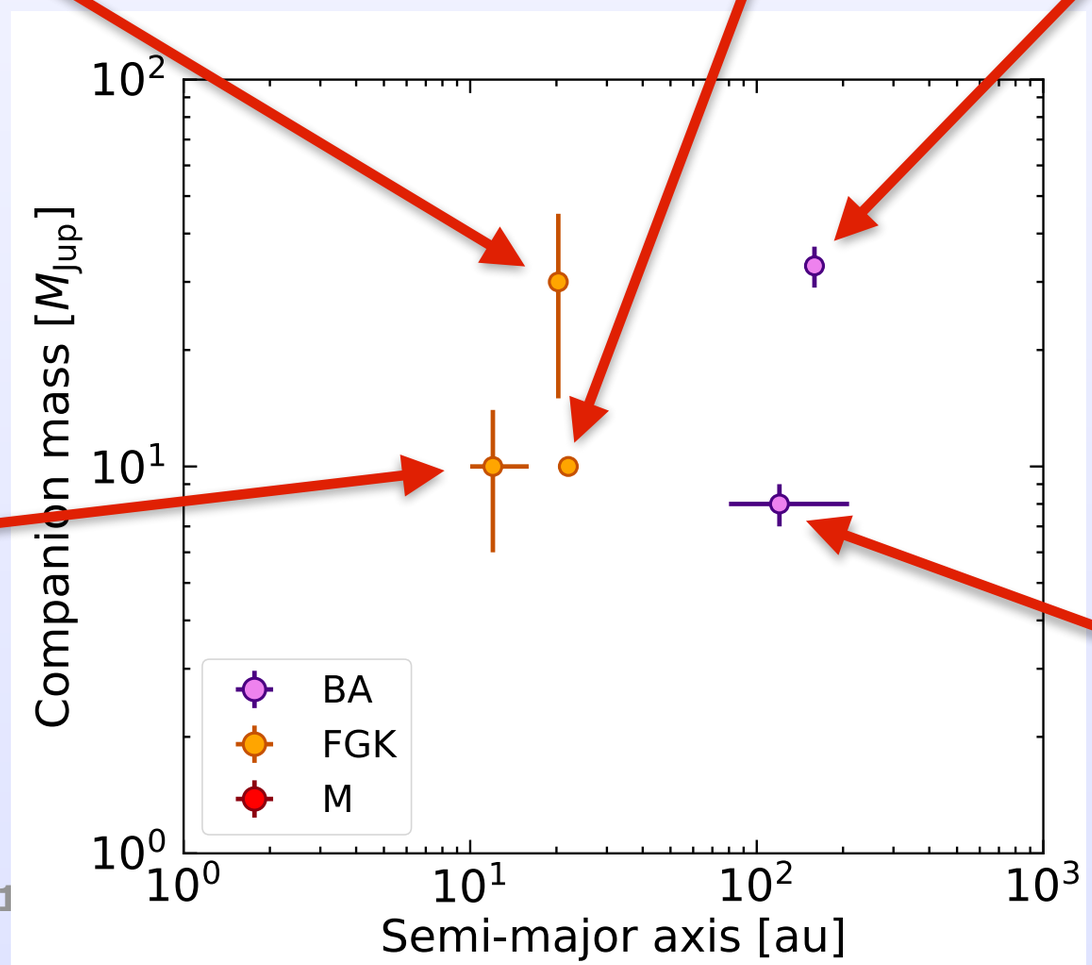
Keppler et al. 2018

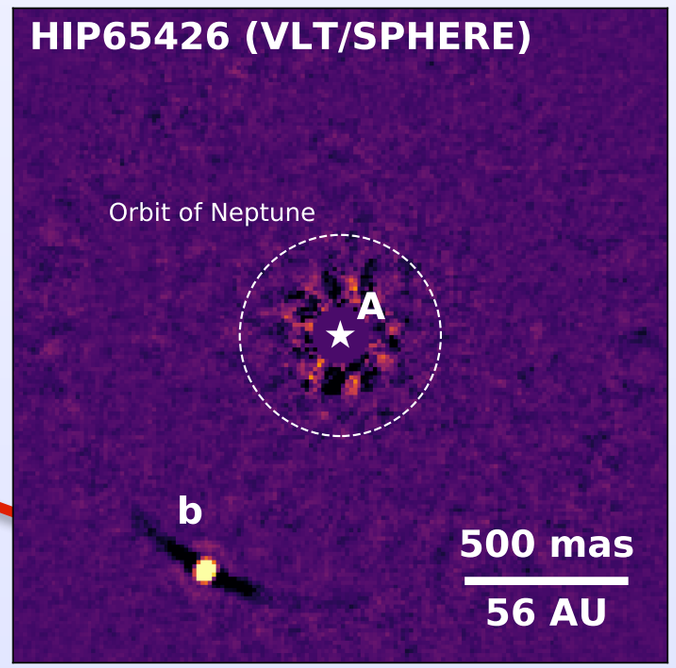


Cheetham et al. 2018



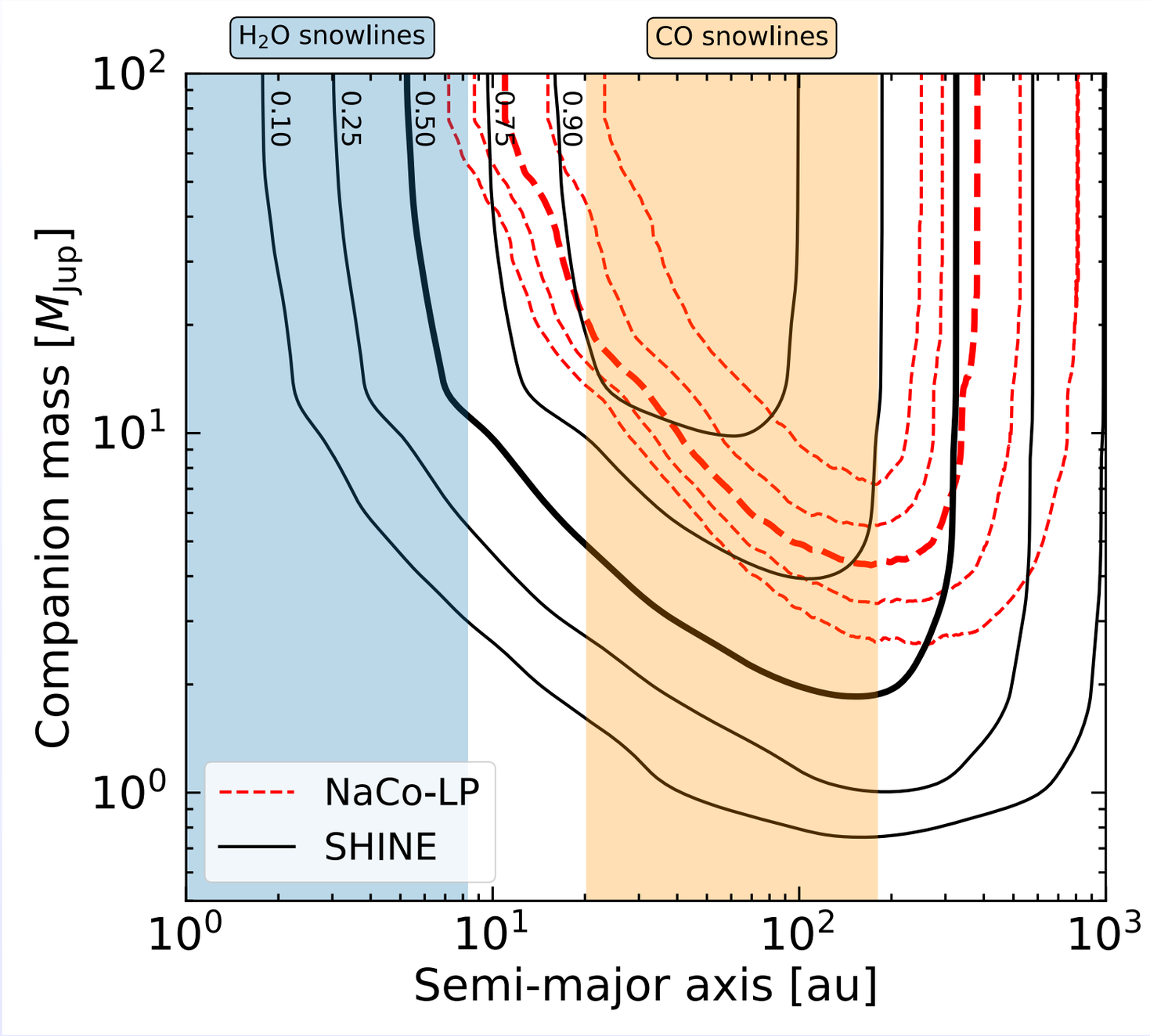
Macintosh et al. 2015





Chauvin et al. 2017

SHINE sensitivity



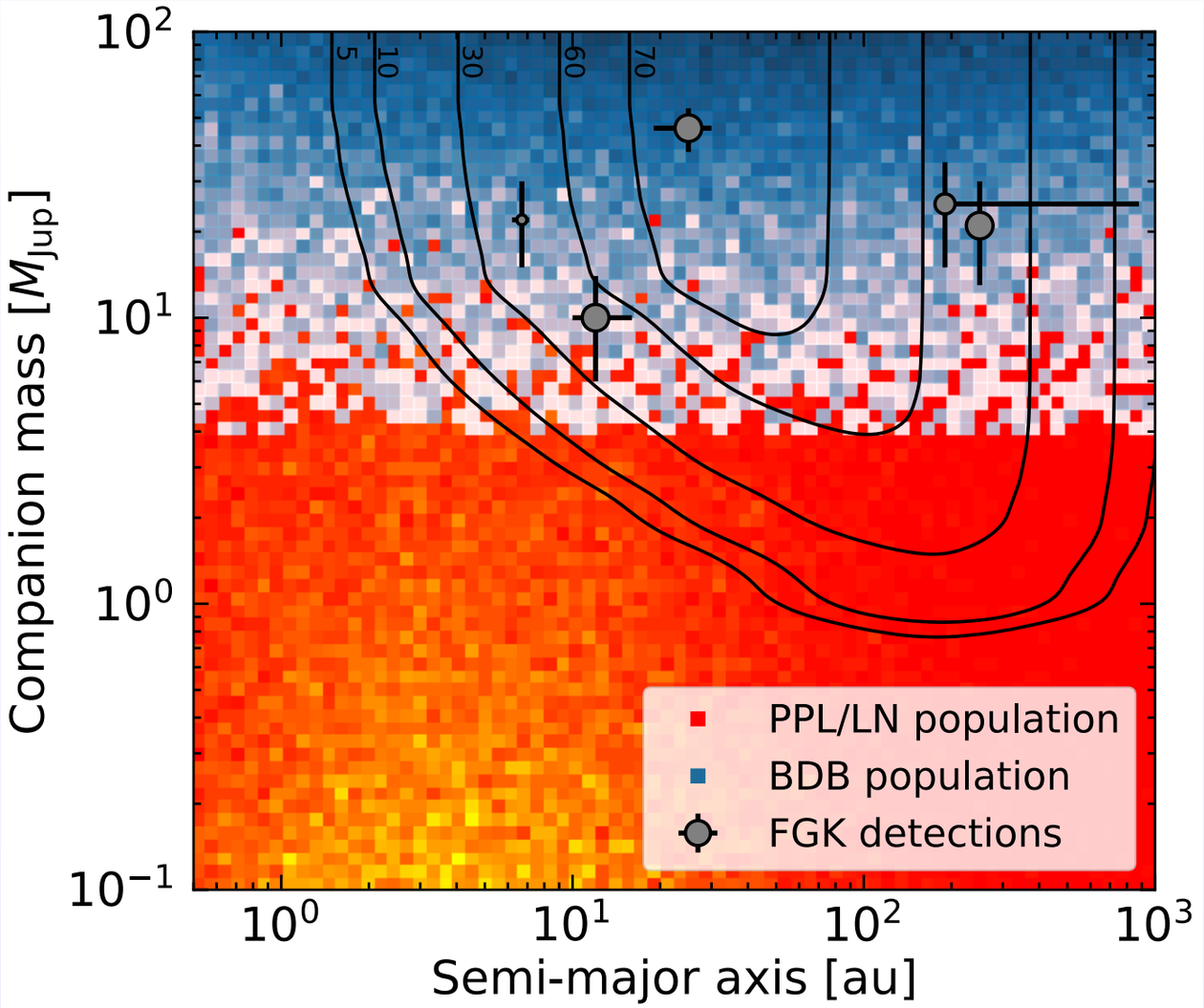
Vigan et al. (2020)

- 150 stars
- 16 detections
- IRDIS + IFS detection limits
- BEX-COND-hot evolutionary models

Exoplanet population modeling

Parametric model (p-model)

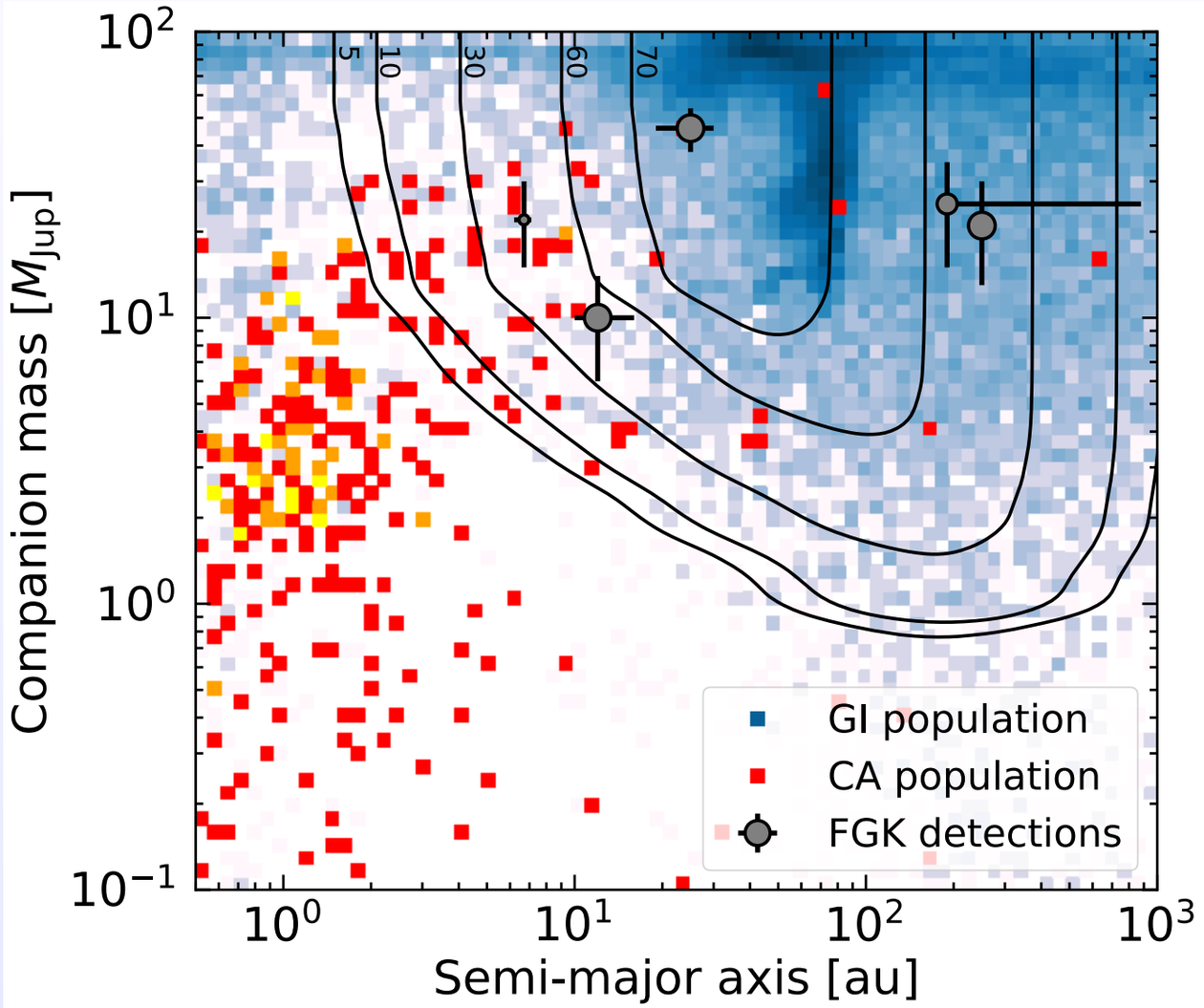
Meyer et al. (2018 + in prep.), Reggiani et al. (2016)



- **Top-down part:** brown dwarf binary (BDB)
- **Bottom-up part:** planet power law, log-normal (PPL/LN)

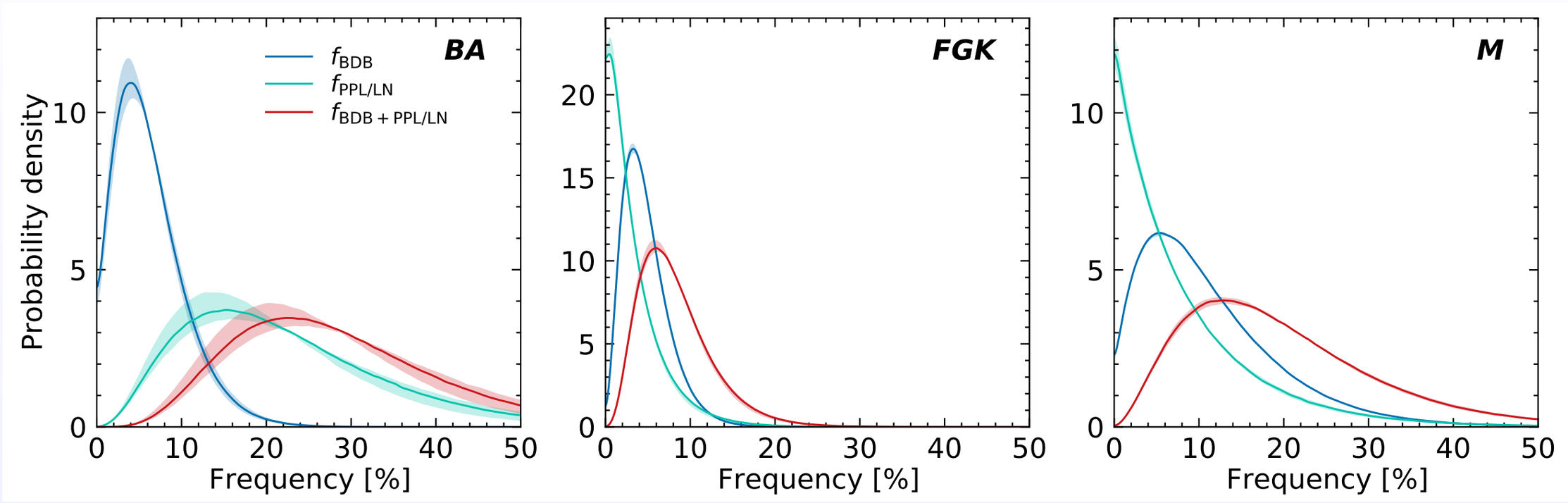
Population synthesis model (s-model)

Mordasini et al., Forgan et al.

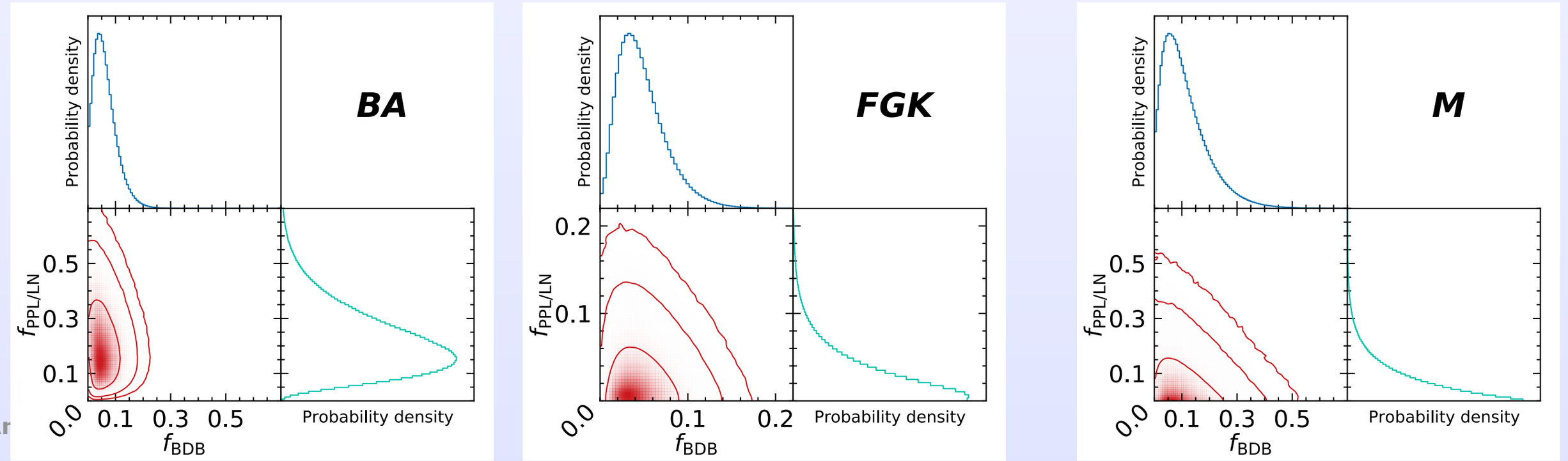


- **Top-down part:** gravitational instability (GI)
- **Bottom-up part:** core accretion (CA)

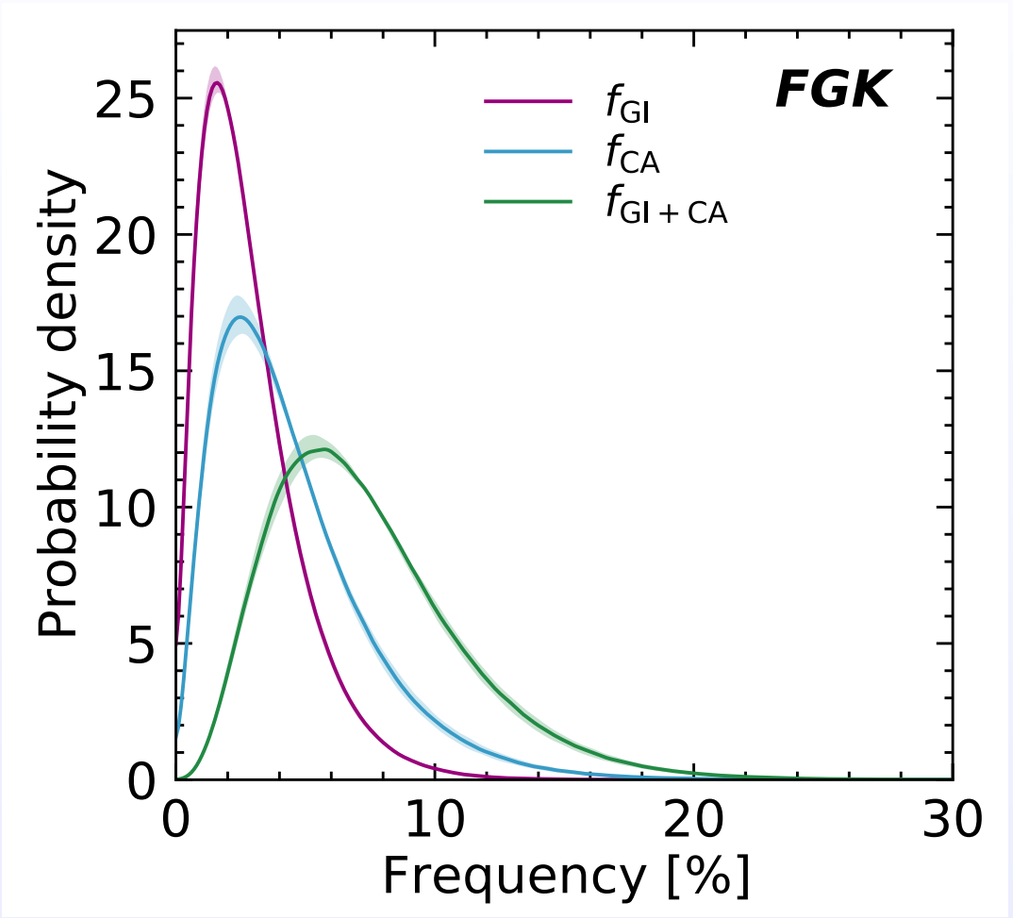
p-model: planet frequency vs. host star mass

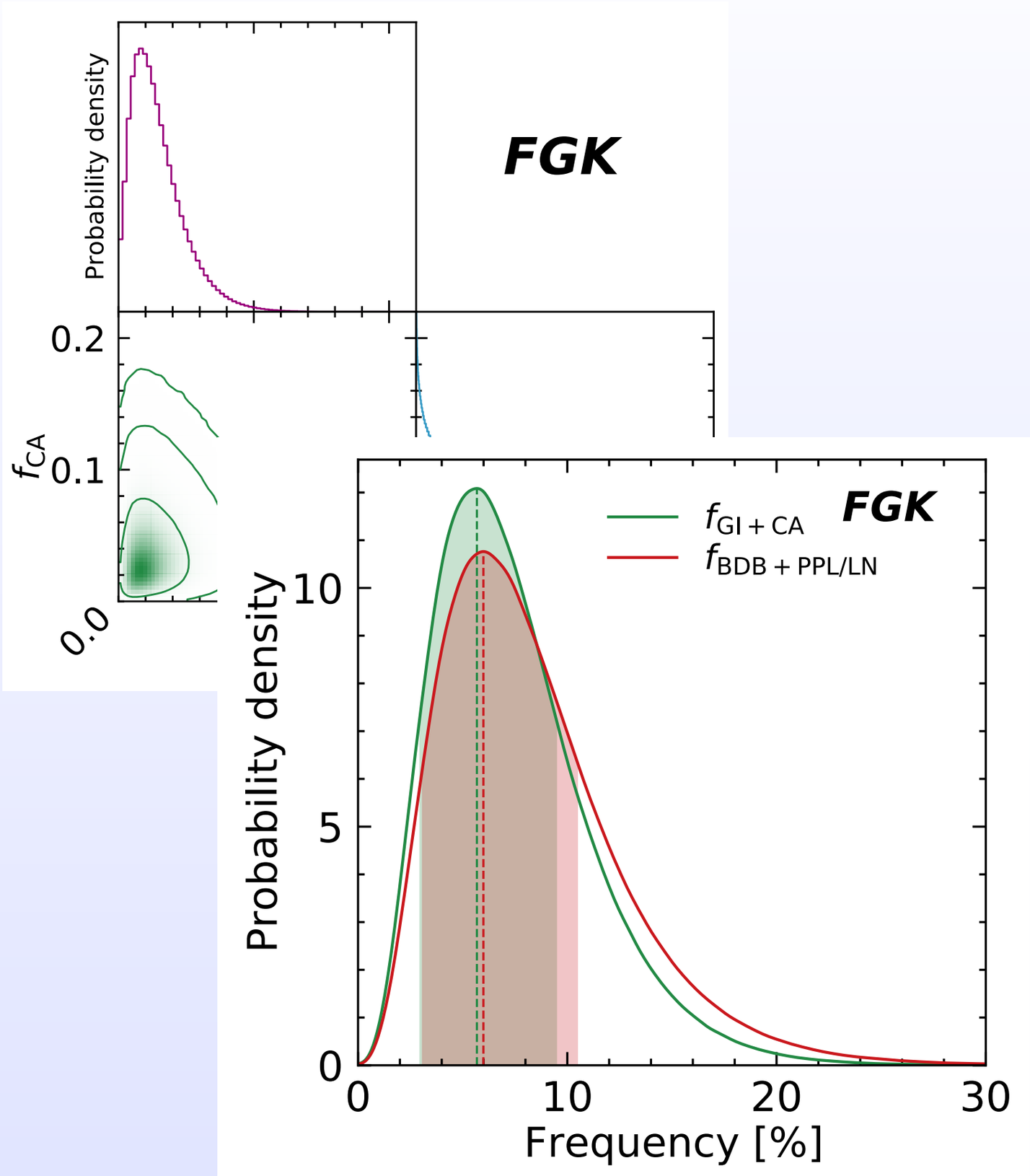


Change in formation paradigm (TBC on full SHINE sample)



s-model: planet frequency around FGK stars





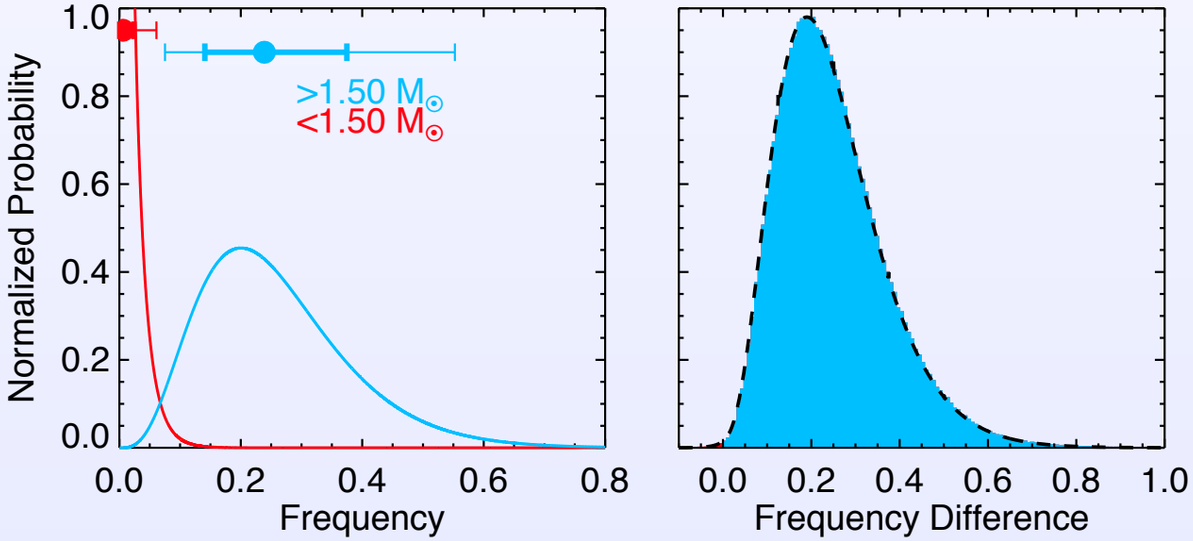
Comparison to other works

- Occurence rates compatible with previous large scale studies
- ***Highlight for GPIES (Nielsen et al. 2019):*** 300 targets, 45% of SHINE sub-sample in GPIES

✔ SHINE

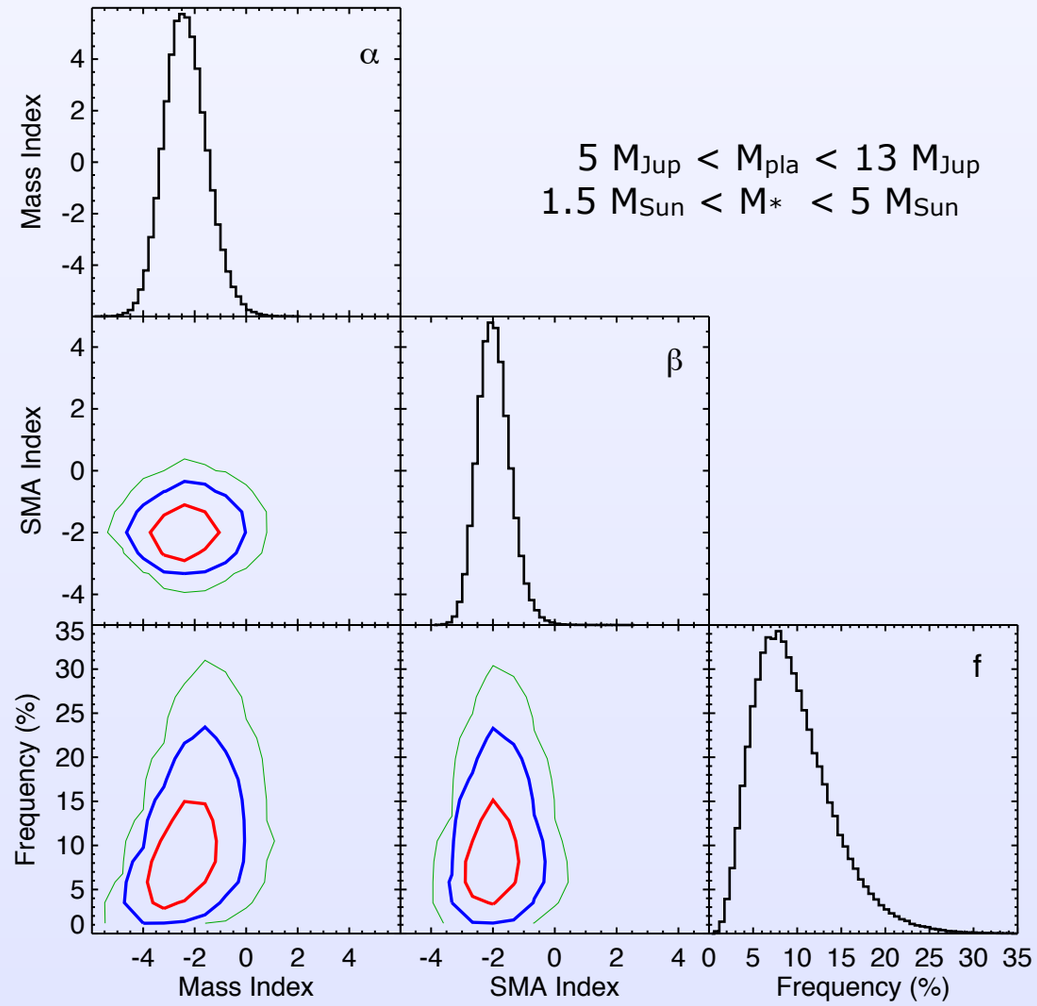
Giant planets more common around more massive stars

→ Indicative of a change in formation



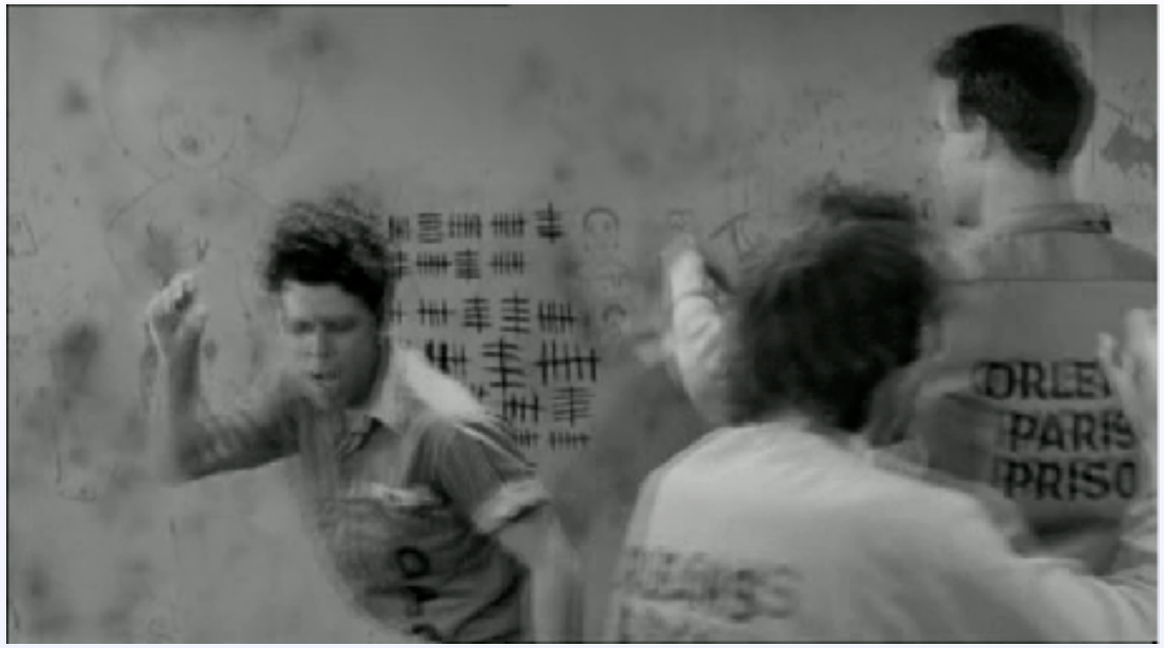
✔ SHINE

Occurence rate around BA stars is ~8.9%



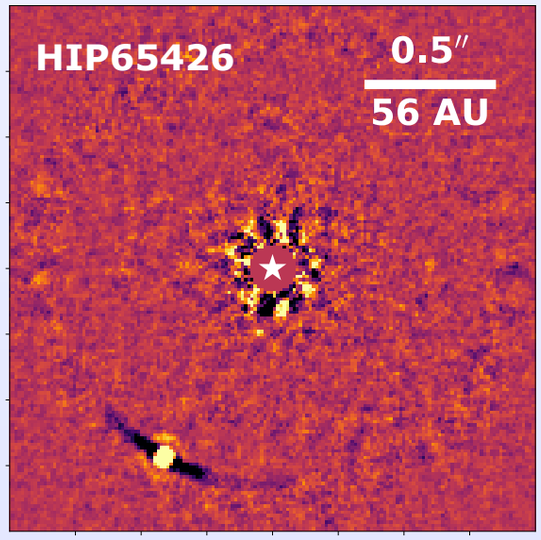
Future

So… what's next? What do we want?

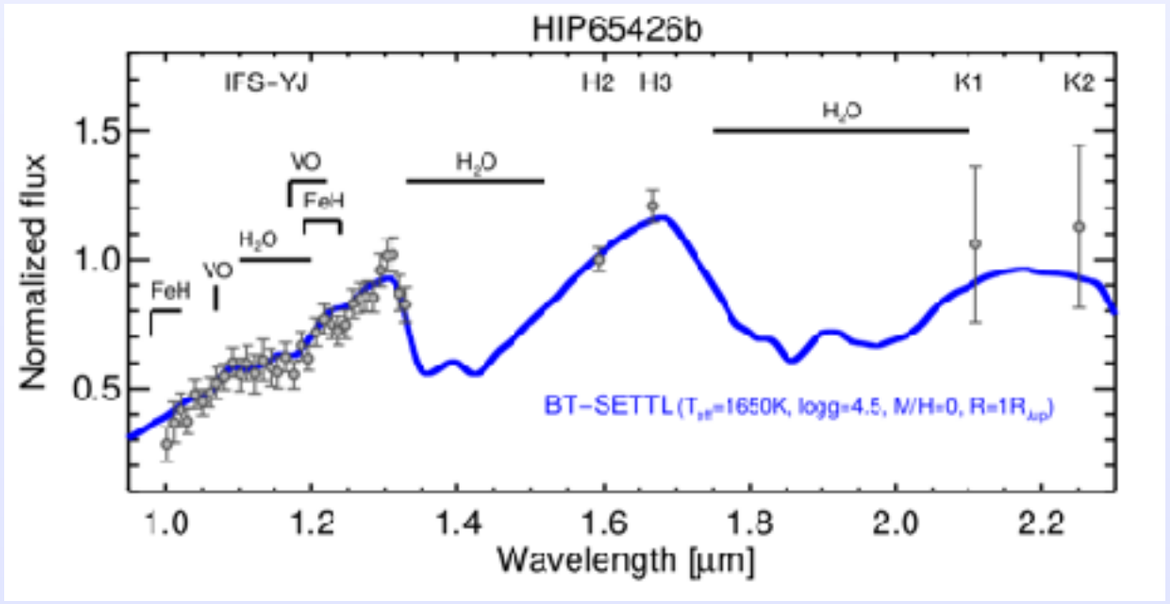


Astronomers desperately screaming for more directly imaged exoplanets (circa 2020)

More planets

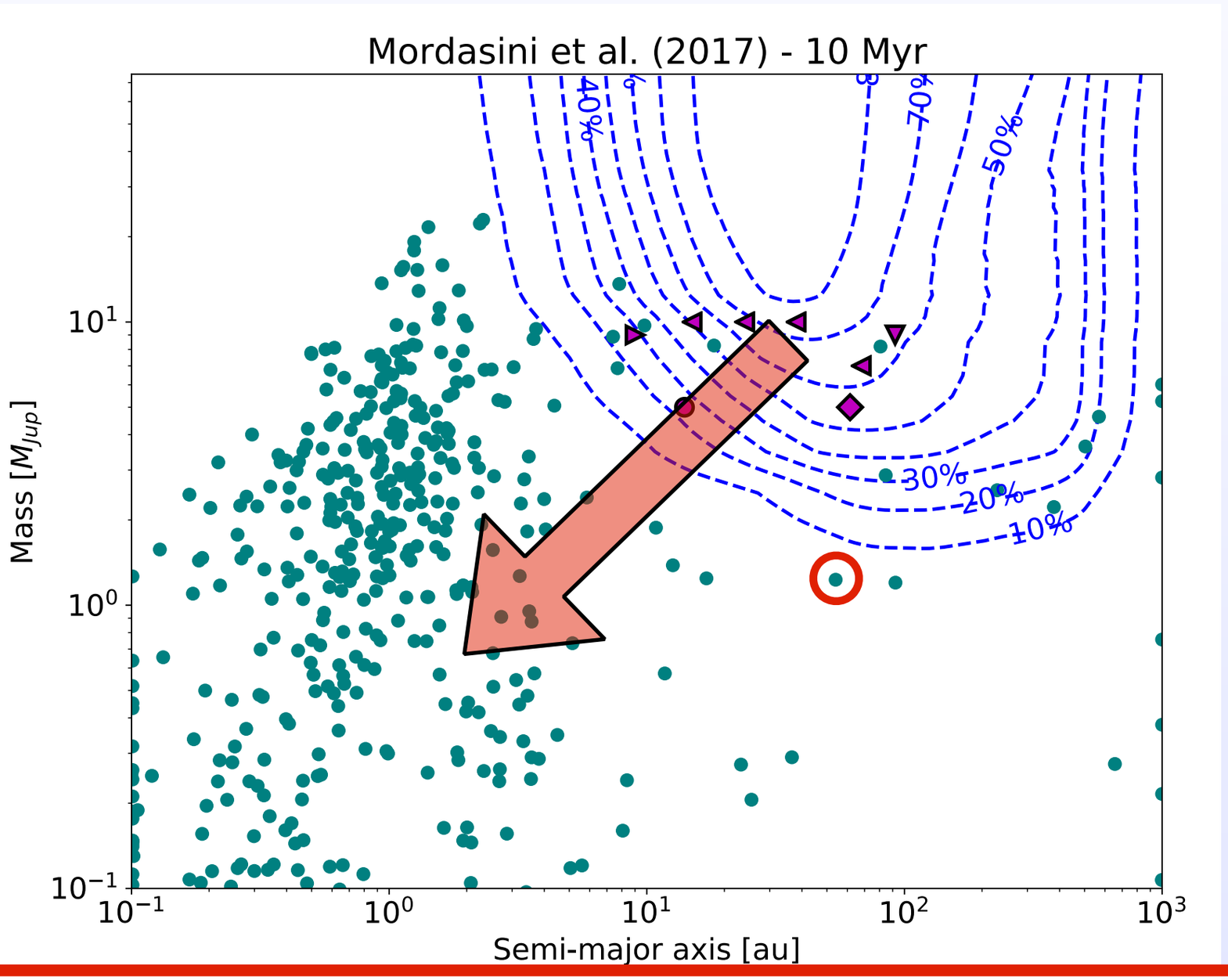


Improved characterization



More planets: closer, deeper

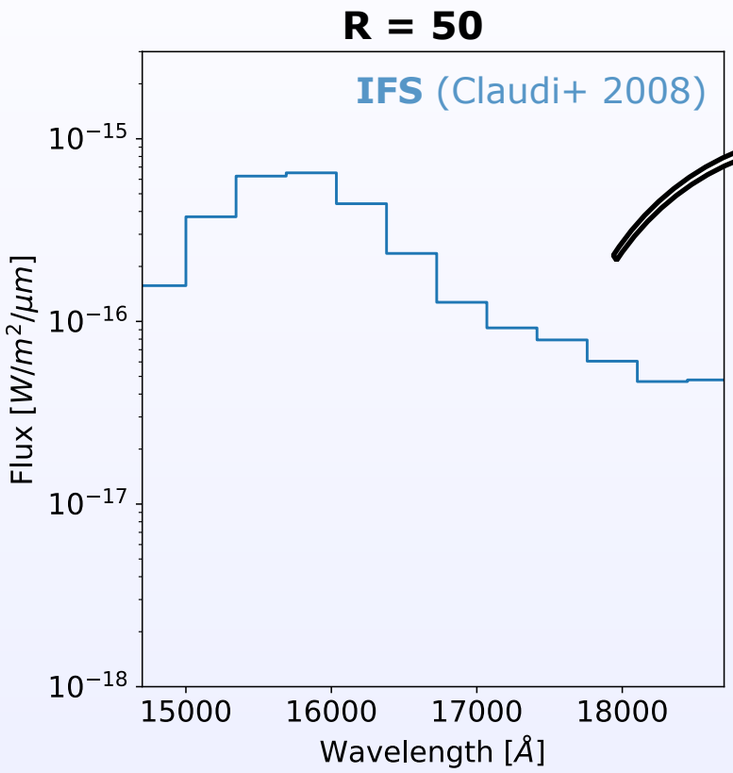
High-angular resolution

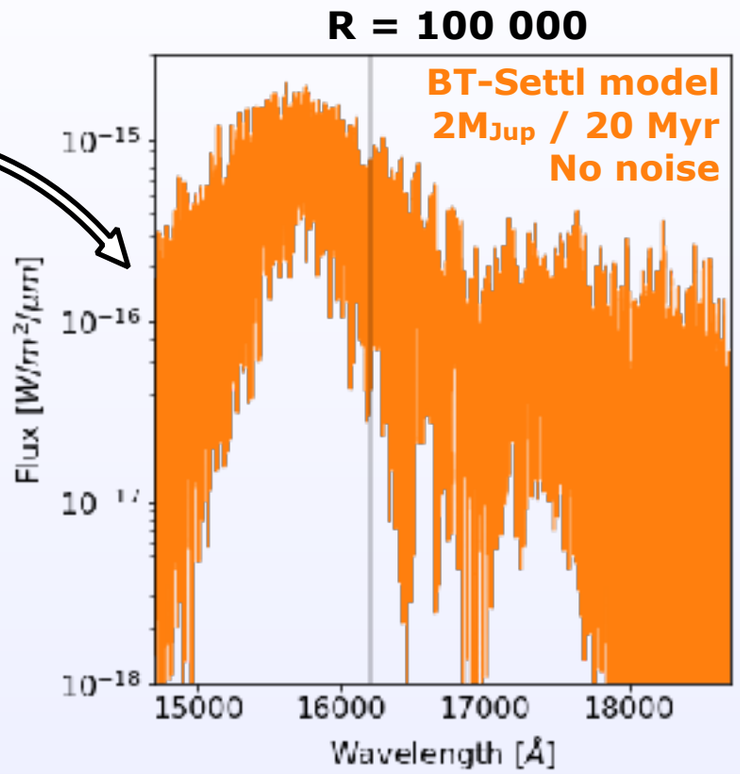


High-contrast

Go for high spectral resolution!

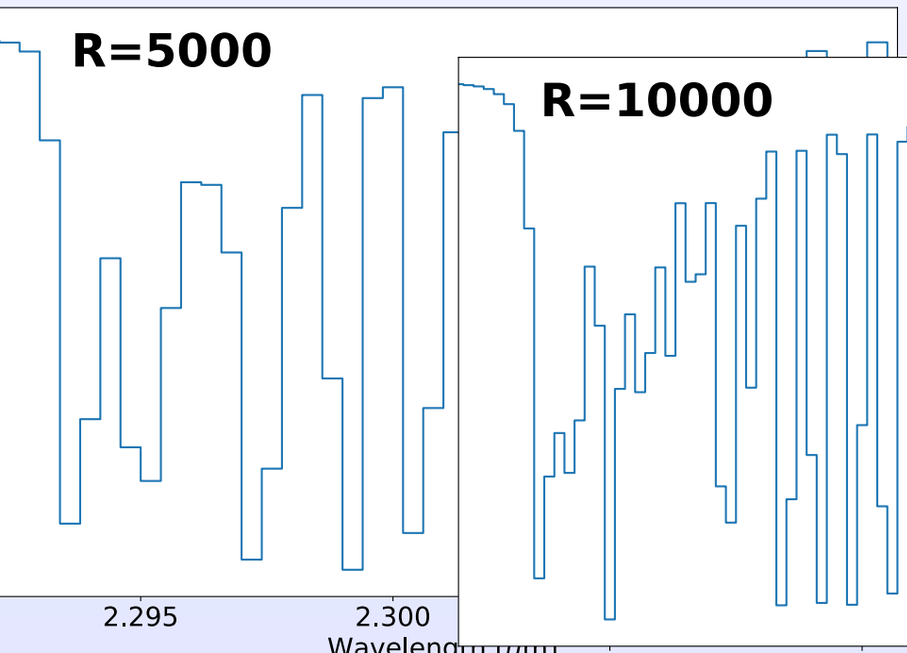
Characterisation at high-spectral resolution

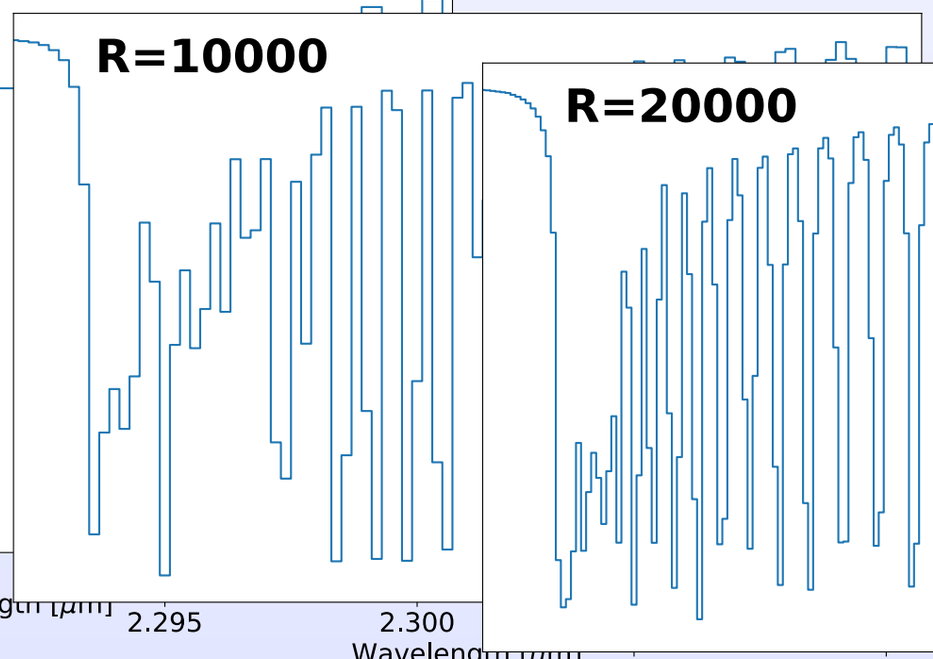


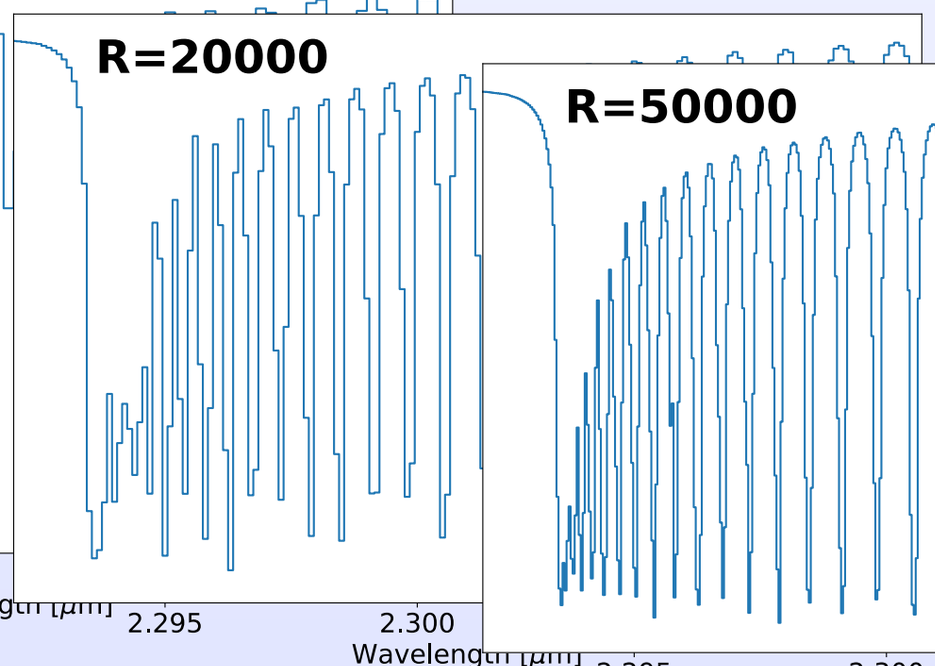


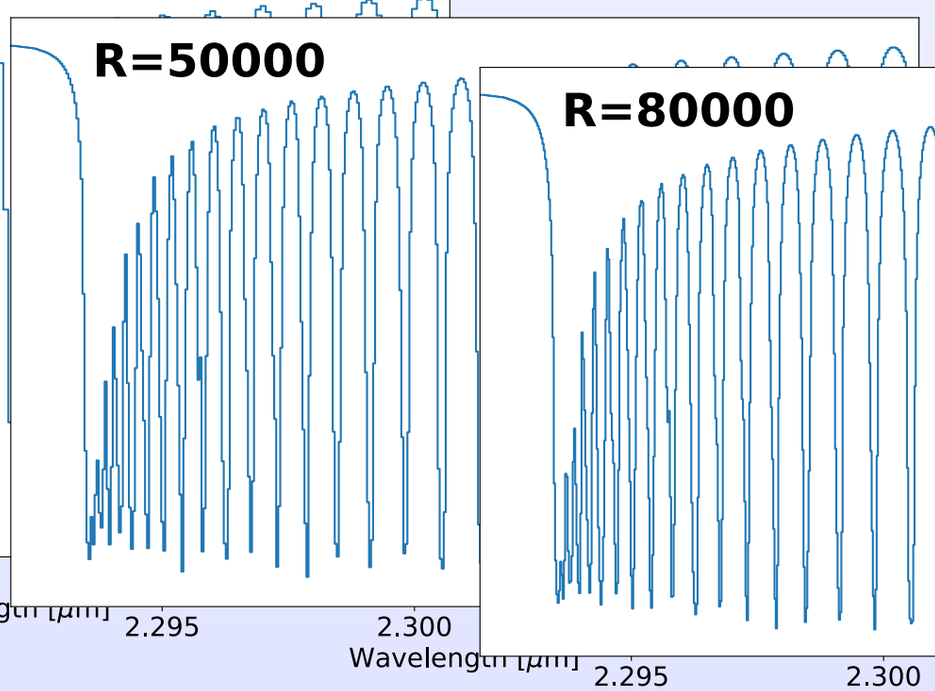
Requires
R ≫ 10 000

CO features / K-band

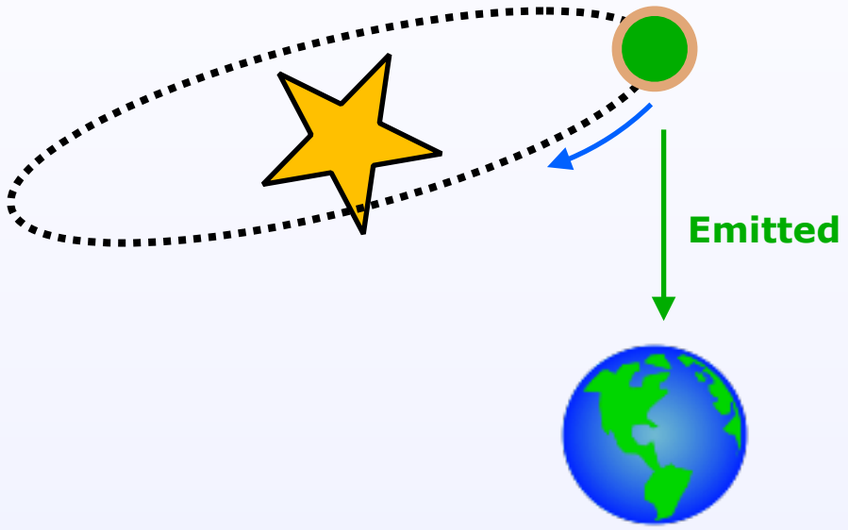


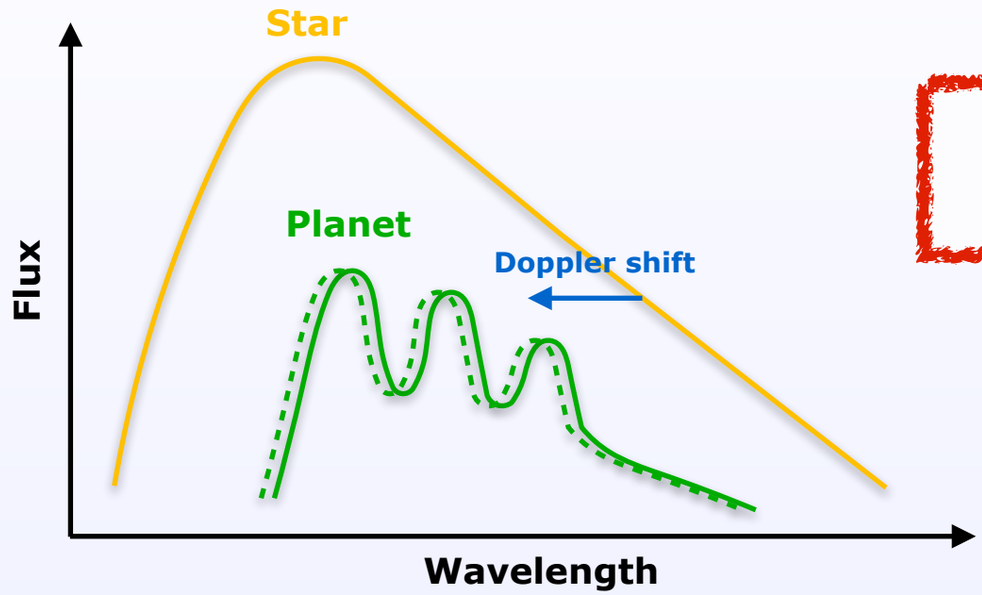






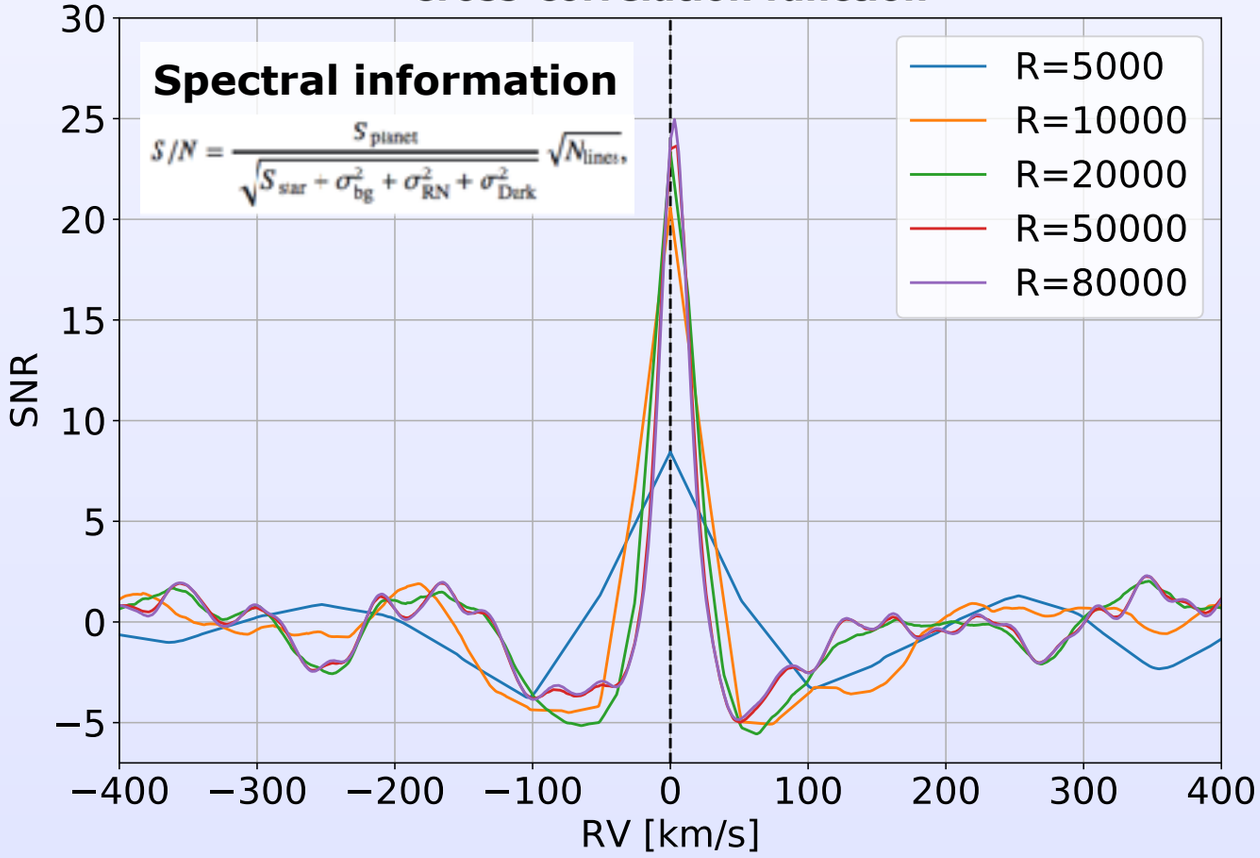
Detection boost at high-spectral resolution



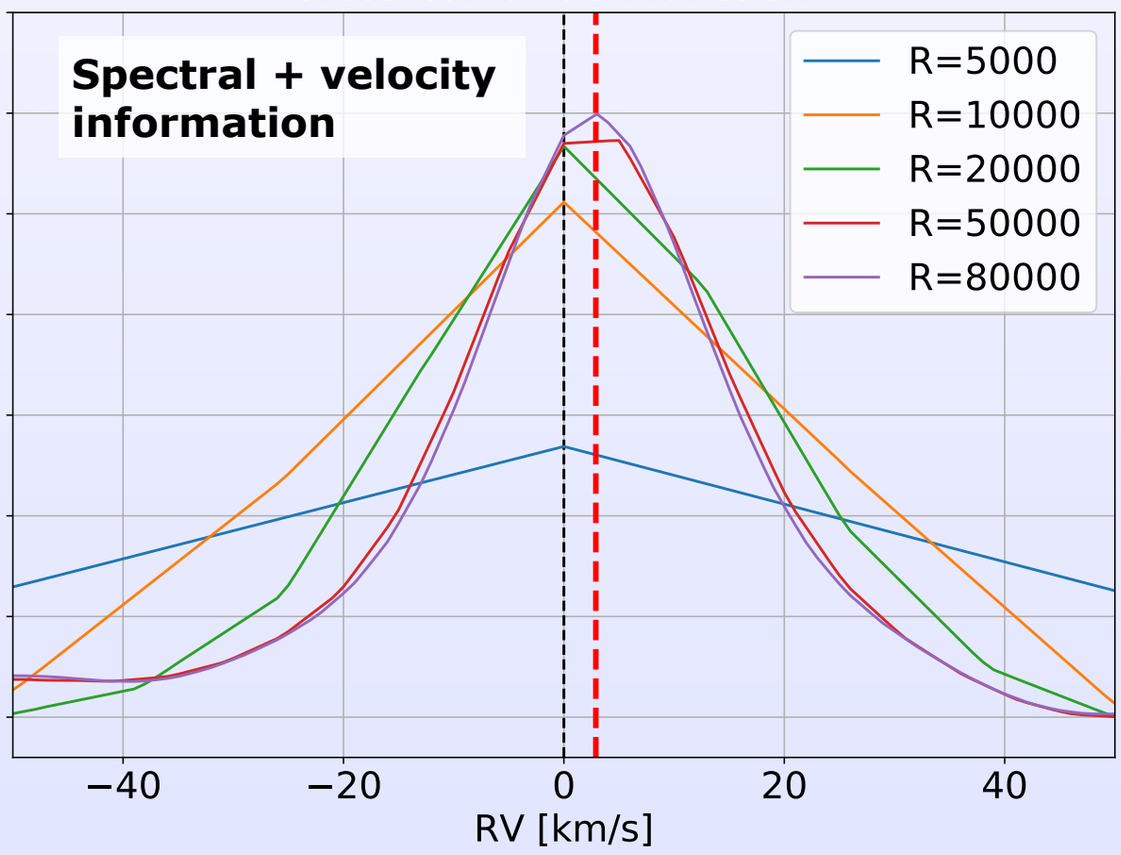


Requires
$R \gg 50\,000$

Cross-correlation function

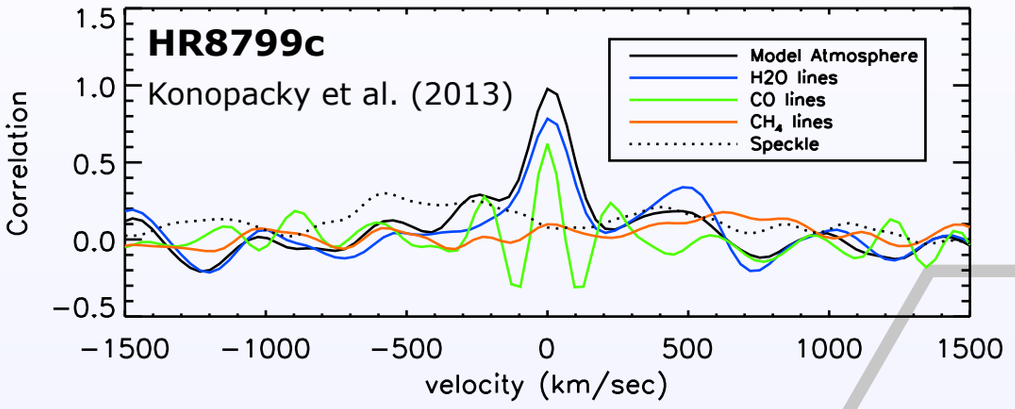


Cross-correlation function

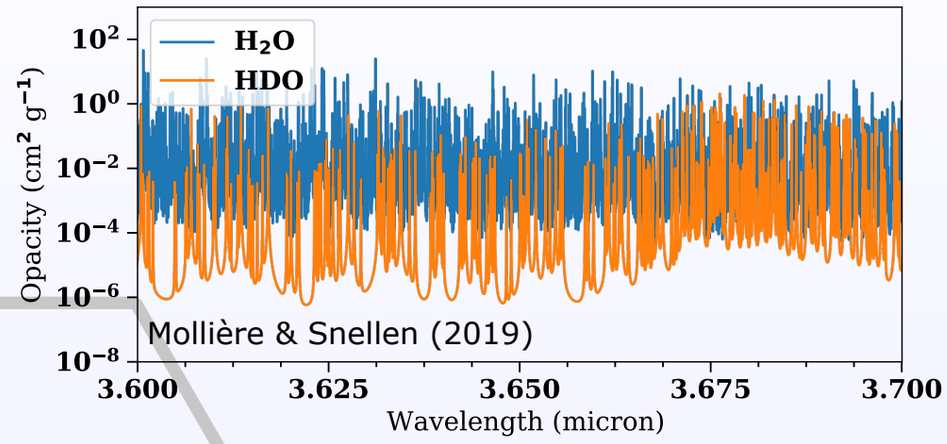


Exoplanet science at high resolution

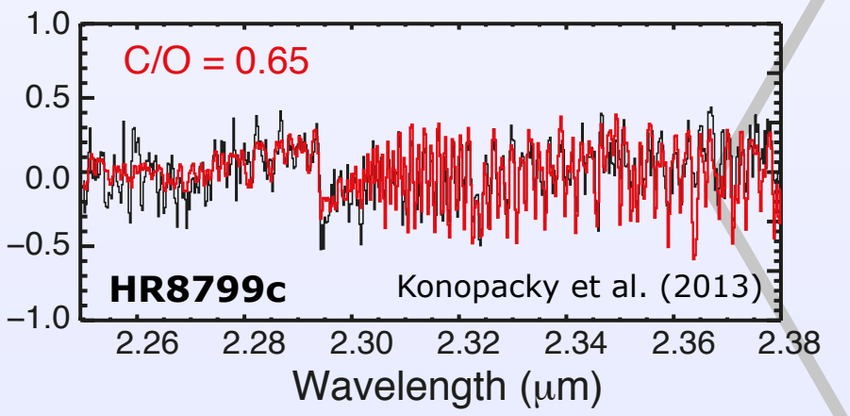
Molecules detection



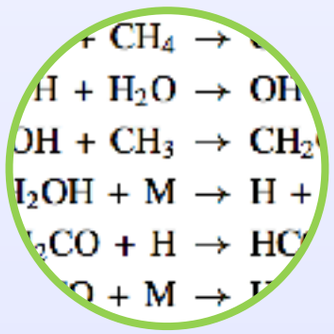
Isotopologues detection



Abundances determination

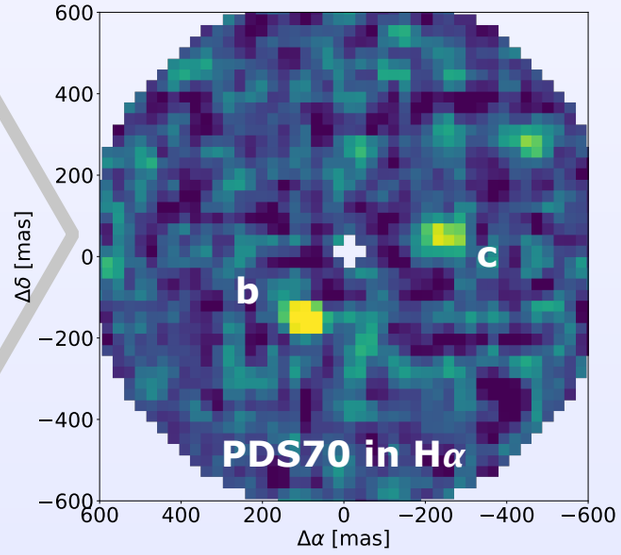


Formation, migration & evolution

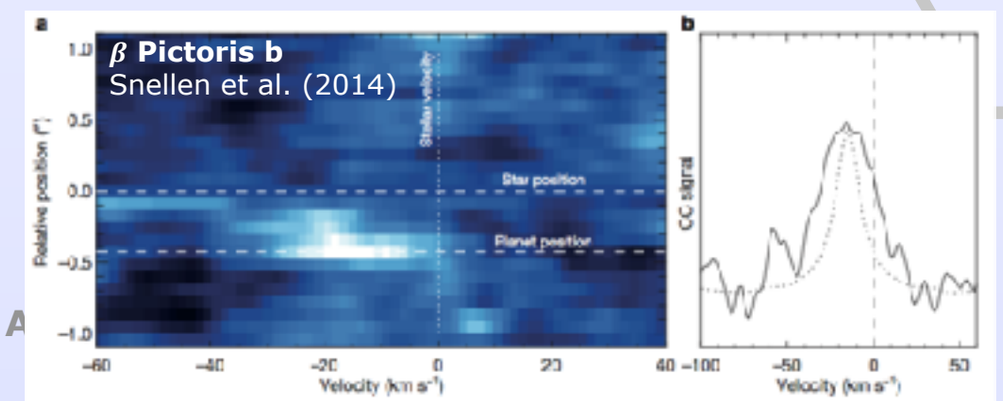


Atmospheric chemistry & dynamics

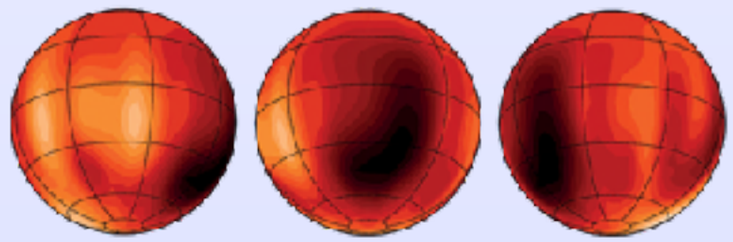
Accretion lines



Orbital and rotational velocity

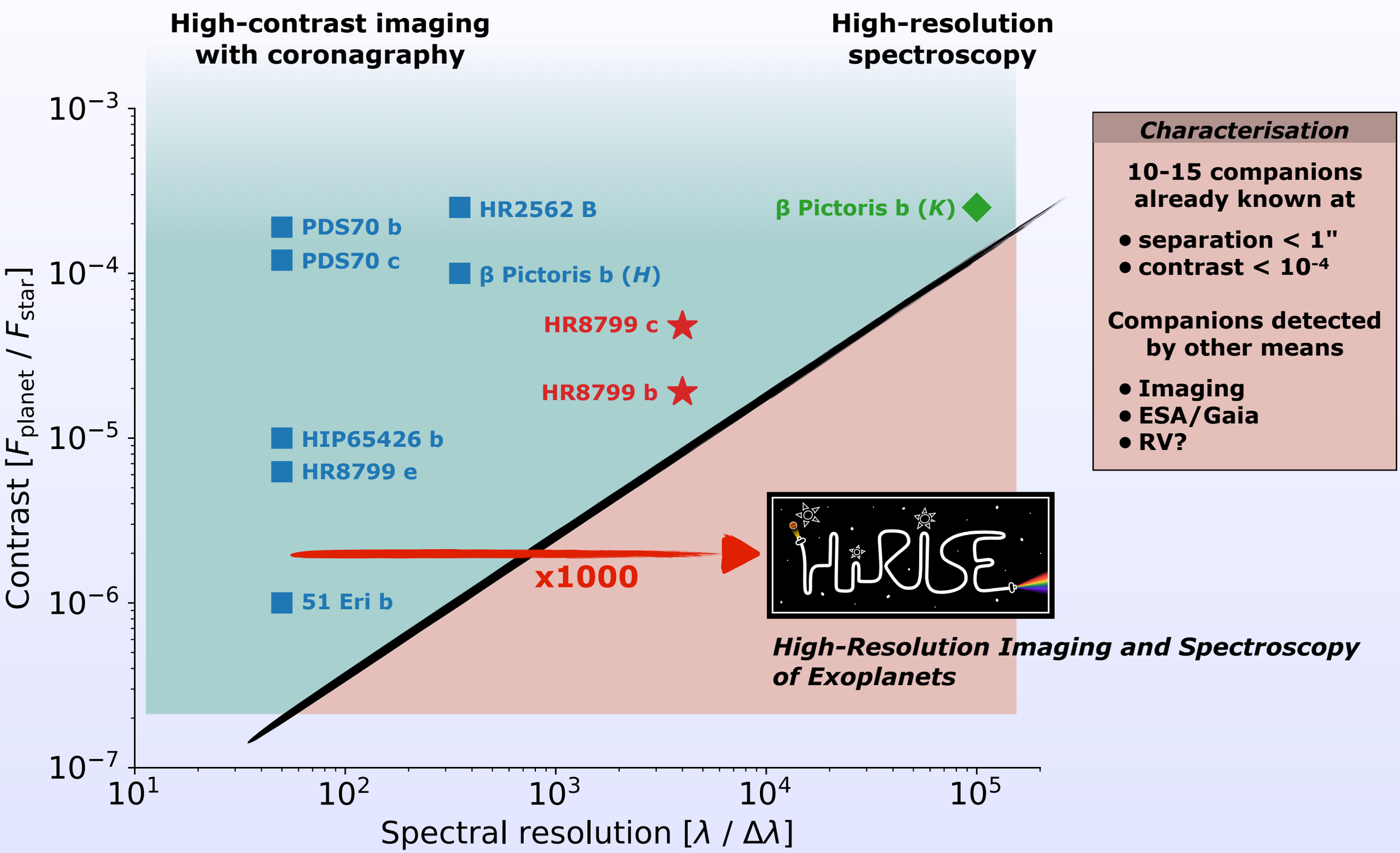


Variability & Doppler imaging



Luhman 16B (Crossfield et al. 2014)

Young exoplanets characterisation in near-IR



Characterisation

10-15 companions already known at

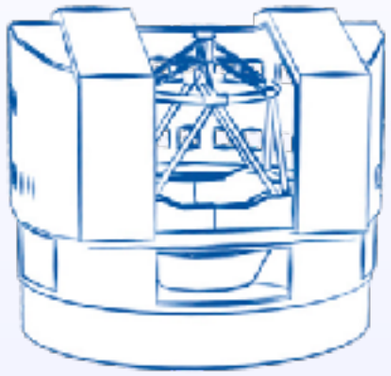
- **separation < 1"**
- **contrast < 10^{-4}**

Companions detected by other means

- **Imaging**
- **ESA/Gaia**
- **RV?**

A unique window of opportunity

VLT/UT3



High-contrast exoplanet imager

SPHERE

High-resolution spectrograph

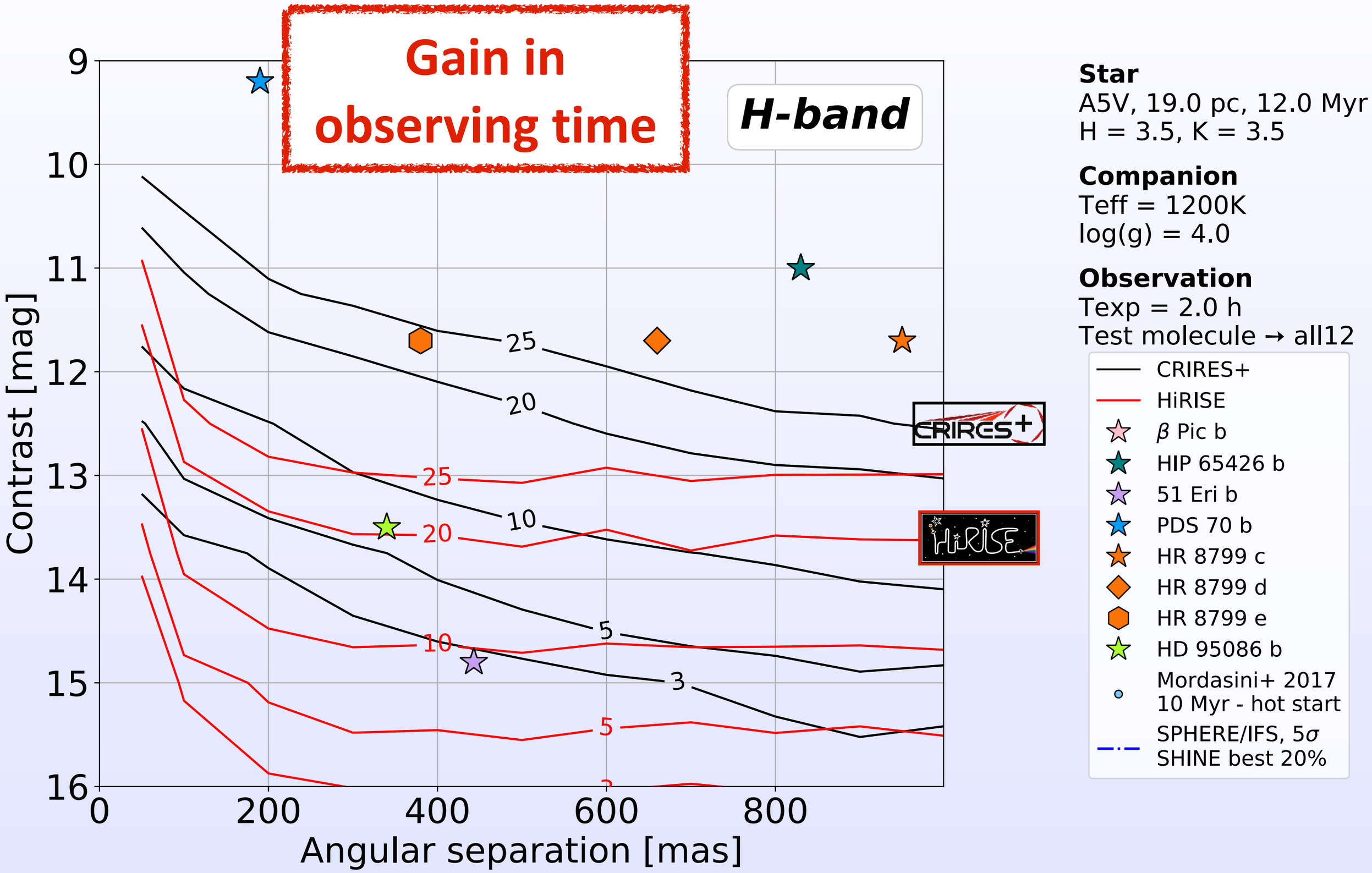
CRIRES+

✔	**Extreme adaptive optics**	✘
✔	**Coronagraphy**	✘
Y J H K	**Spectral coverage**	**Y J H K L M**
50 - 350	**Spectral resolution**	**50 000 - 100 000**

Fiber coupling

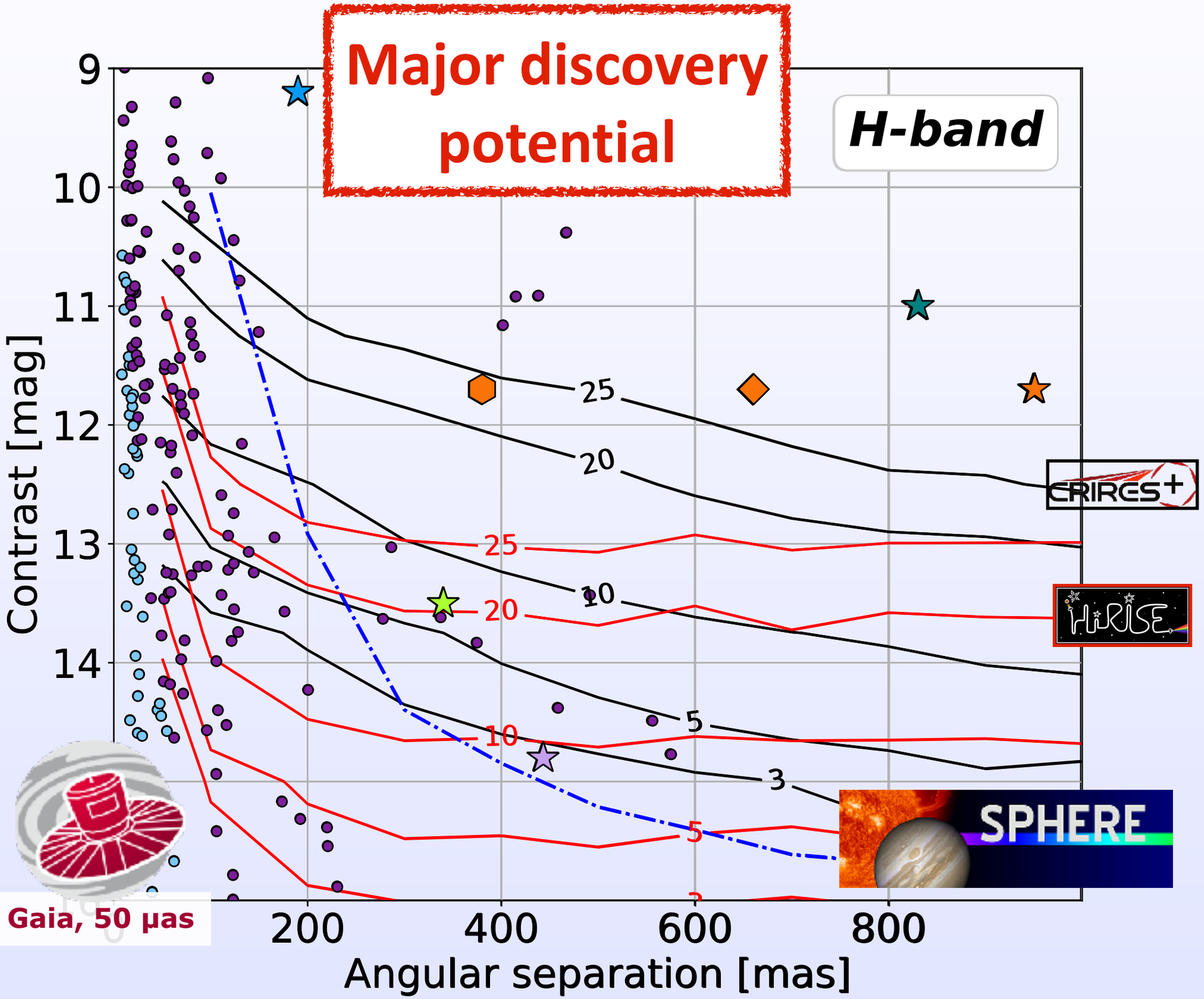
HiRISE

Expected performance



Otten, Vigan et al. (2020)

Expected performance



Star
A5V, 19.0 pc, 12.0 Myr
H = 3.5, K = 3.5

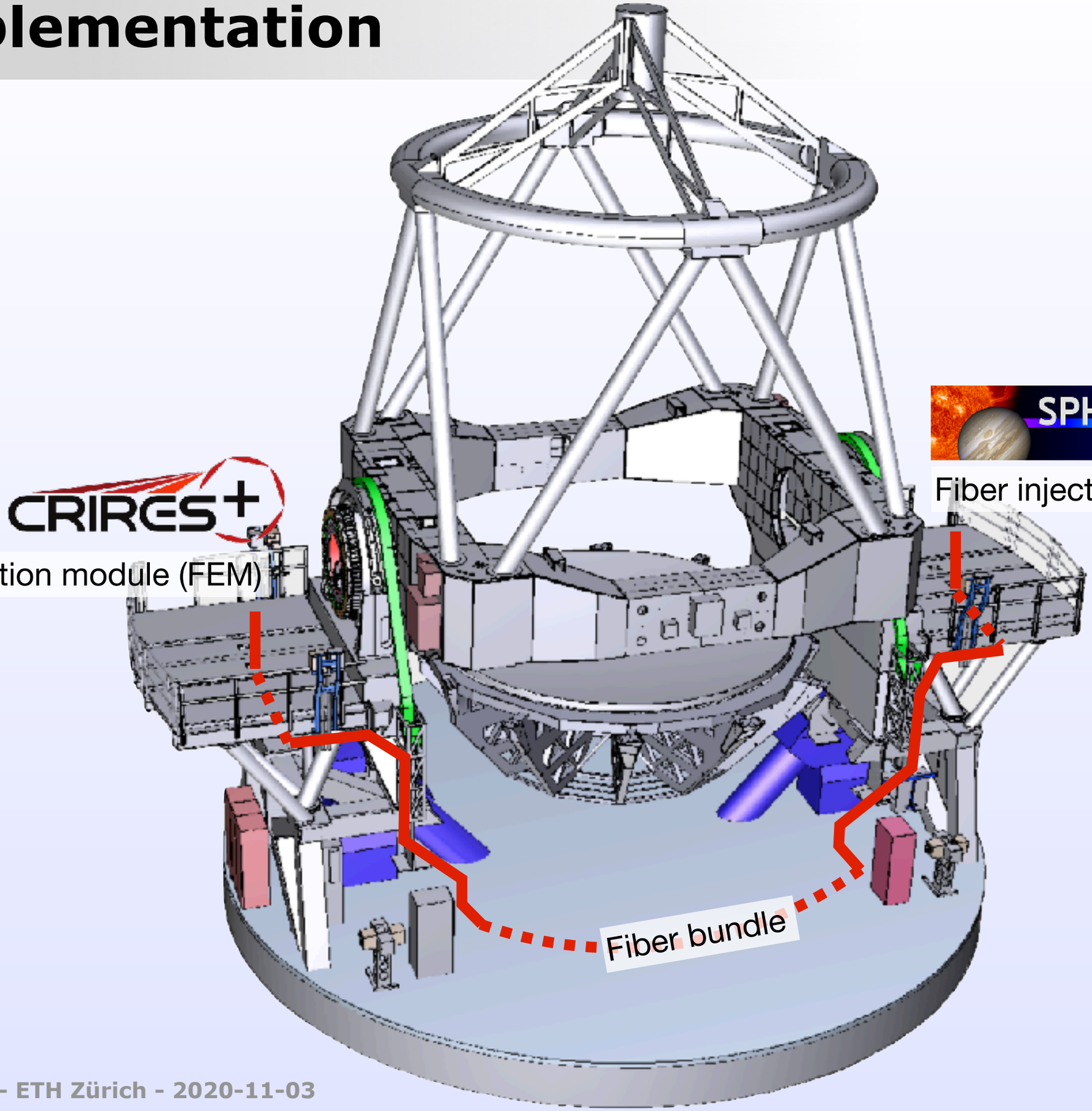
Companion
Teff = 1200K
log(g) = 4.0

Observation
Texp = 2.0 h
Test molecule → all12

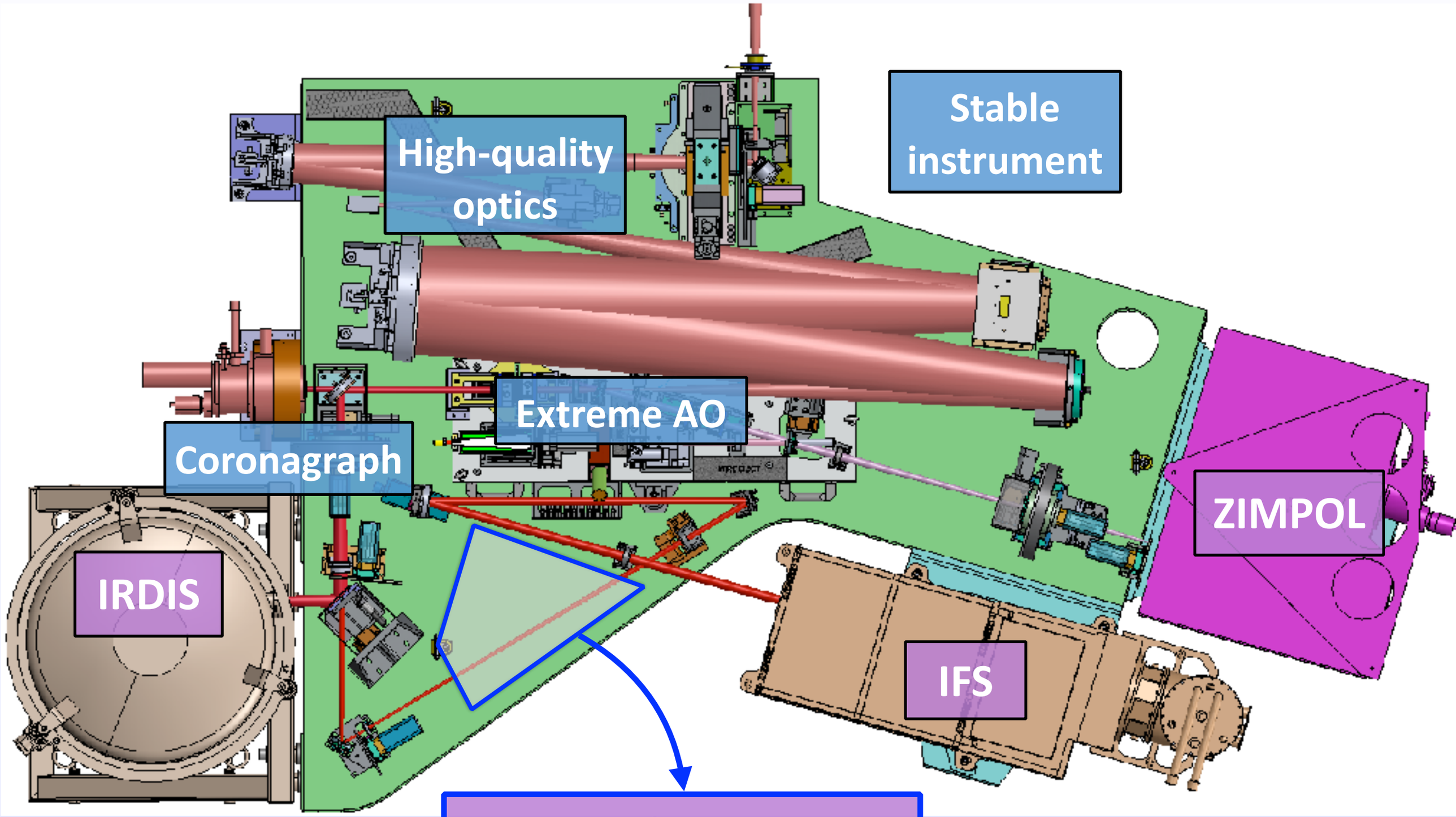
- CRIRES+
- HiRISE
- β Pic b
- HIP 65426 b
- 51 Eri b
- PDS 70 b
- HR 8799 c
- HR 8799 d
- HR 8799 e
- HD 95086 b
- Mordasini+ 2017 10 Myr - hot start
- SPHERE/IFS, 5σ SHINE best 20%

Otten, Vigan et al. (2020)

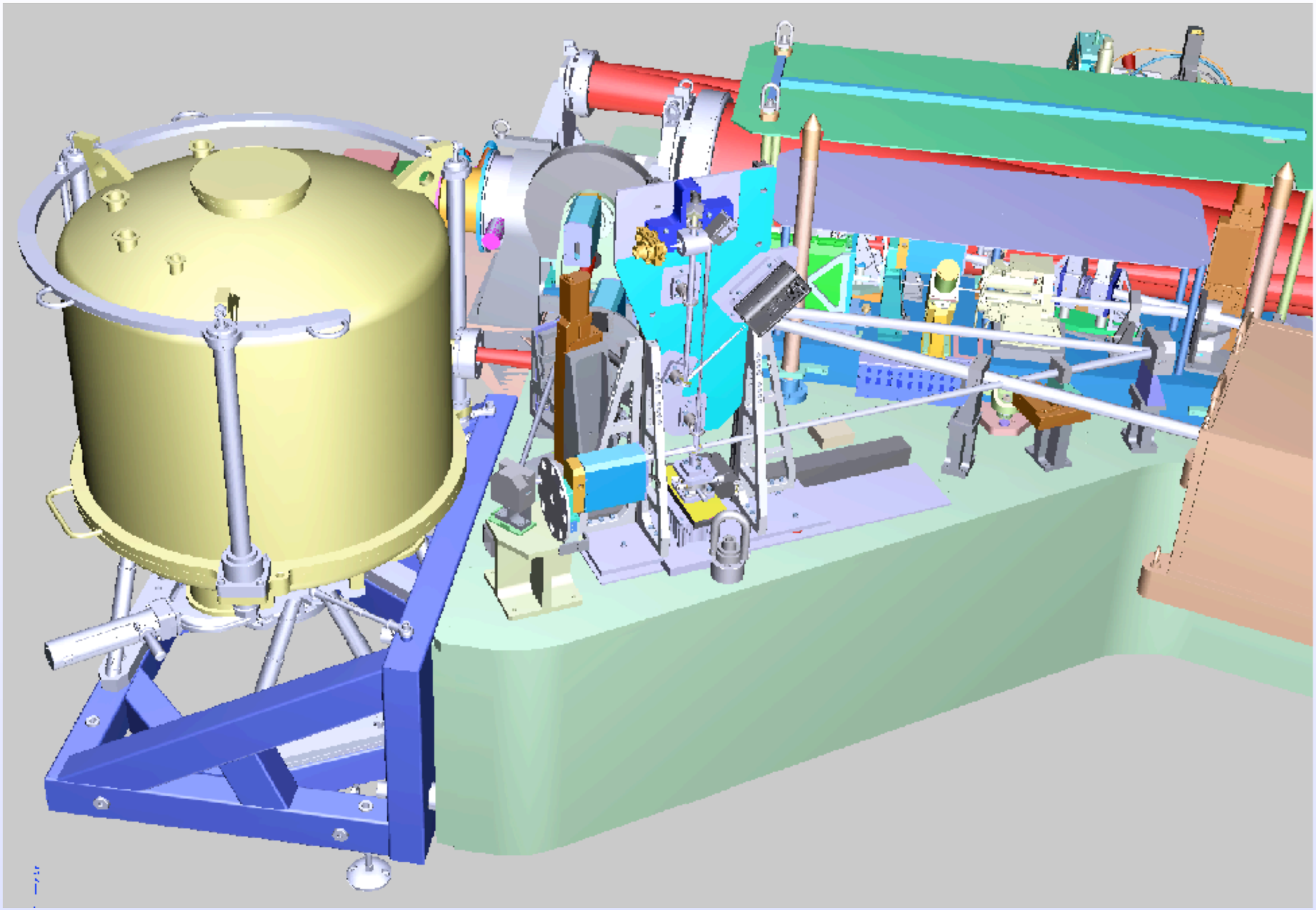
Implementation

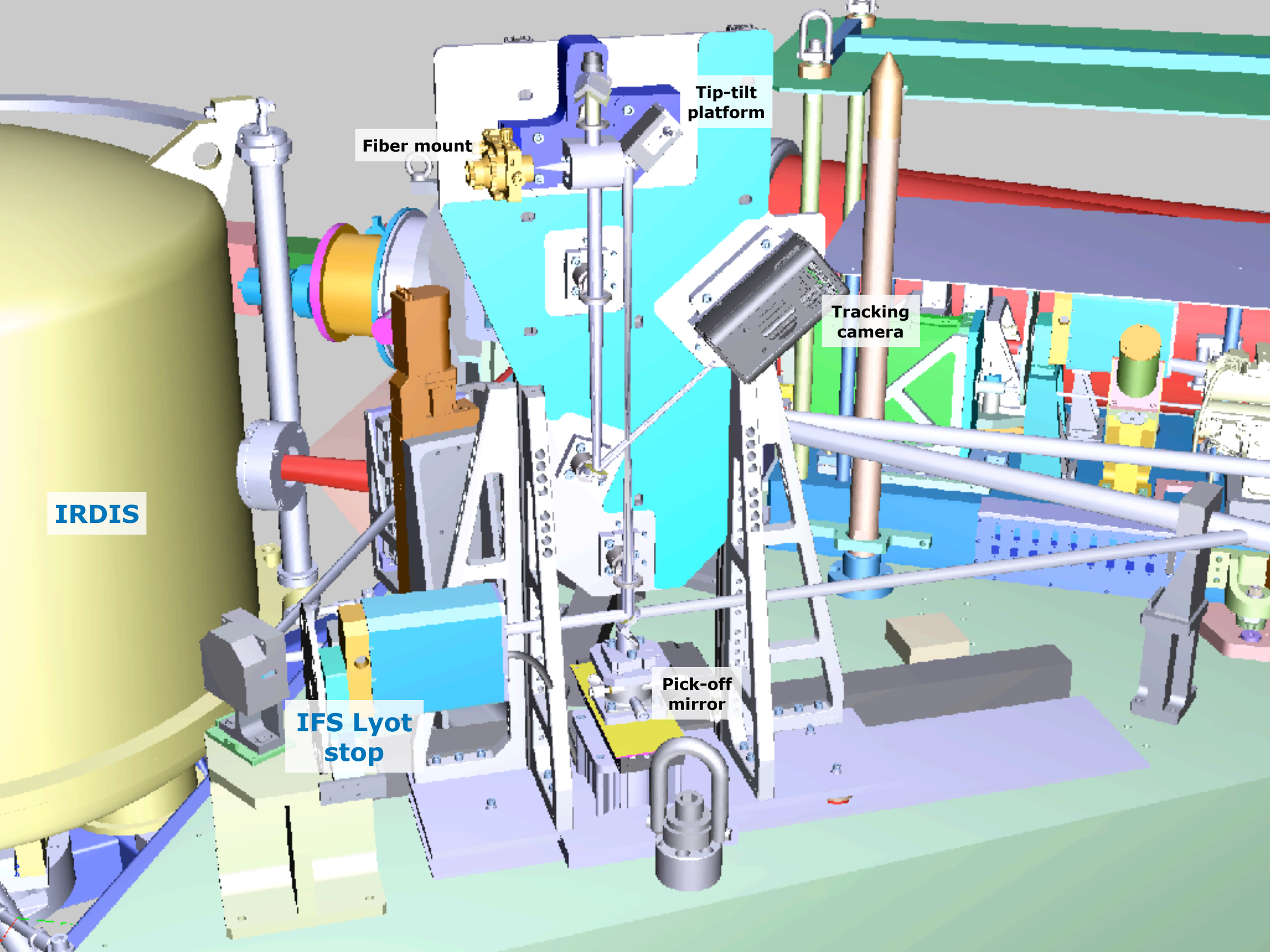


Fiber injection module in SPHERE

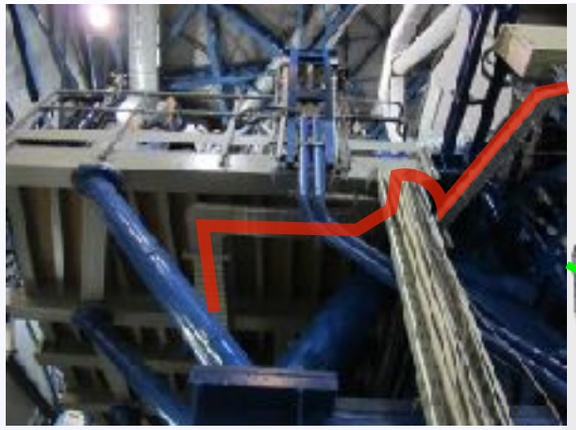


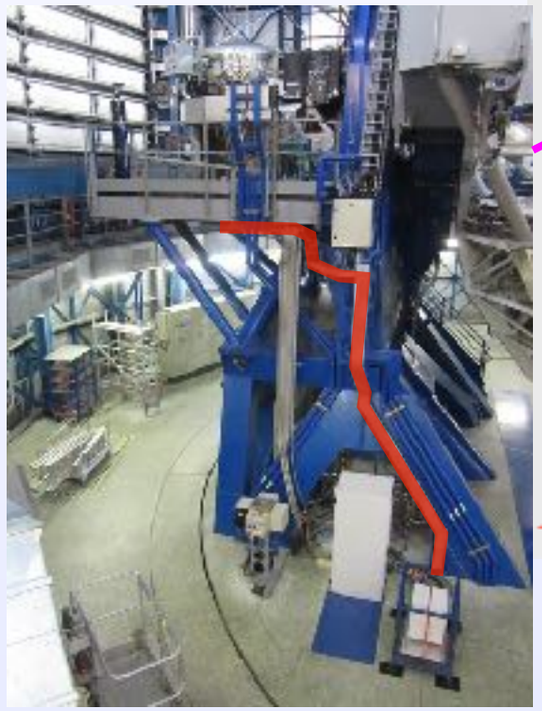
Fiber injection module in SPHERE

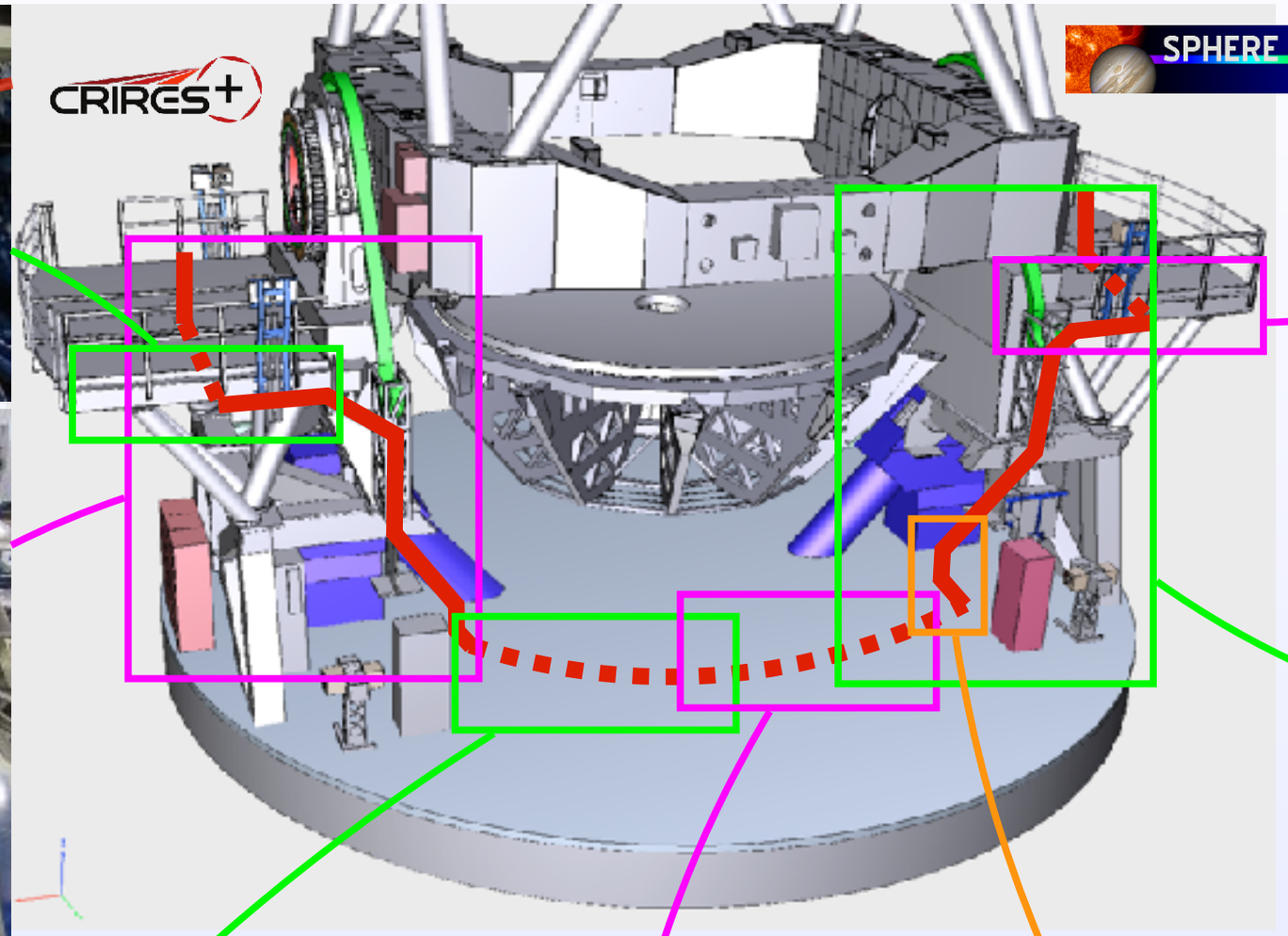


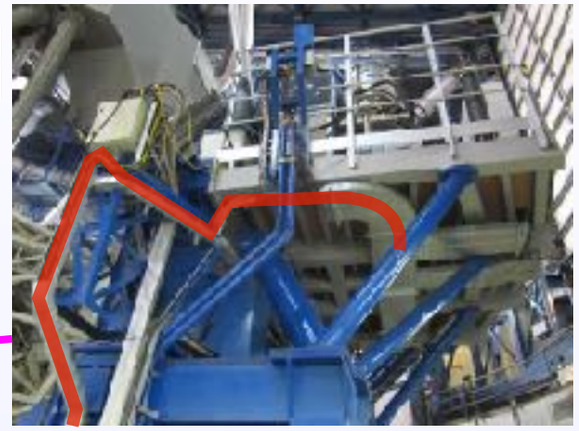

Tip-tilt platform
Fiber mount
Tracking camera
IRDIS
IFS Lyot stop
Pick-off mirror

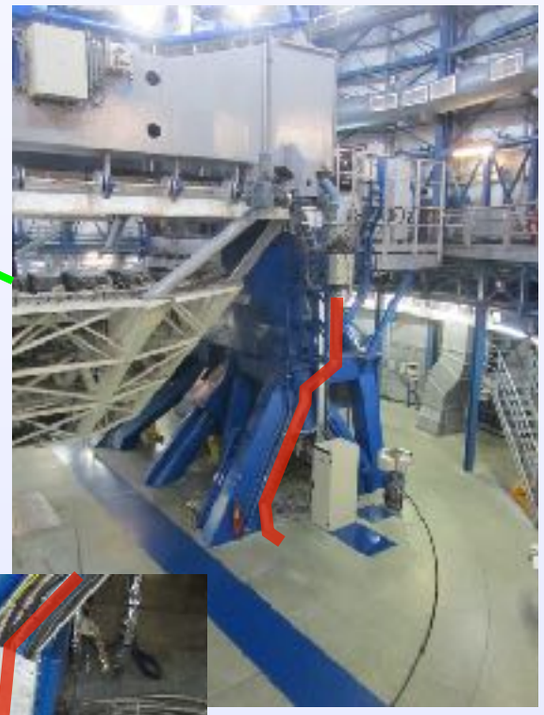
Fiber bundle around UT3





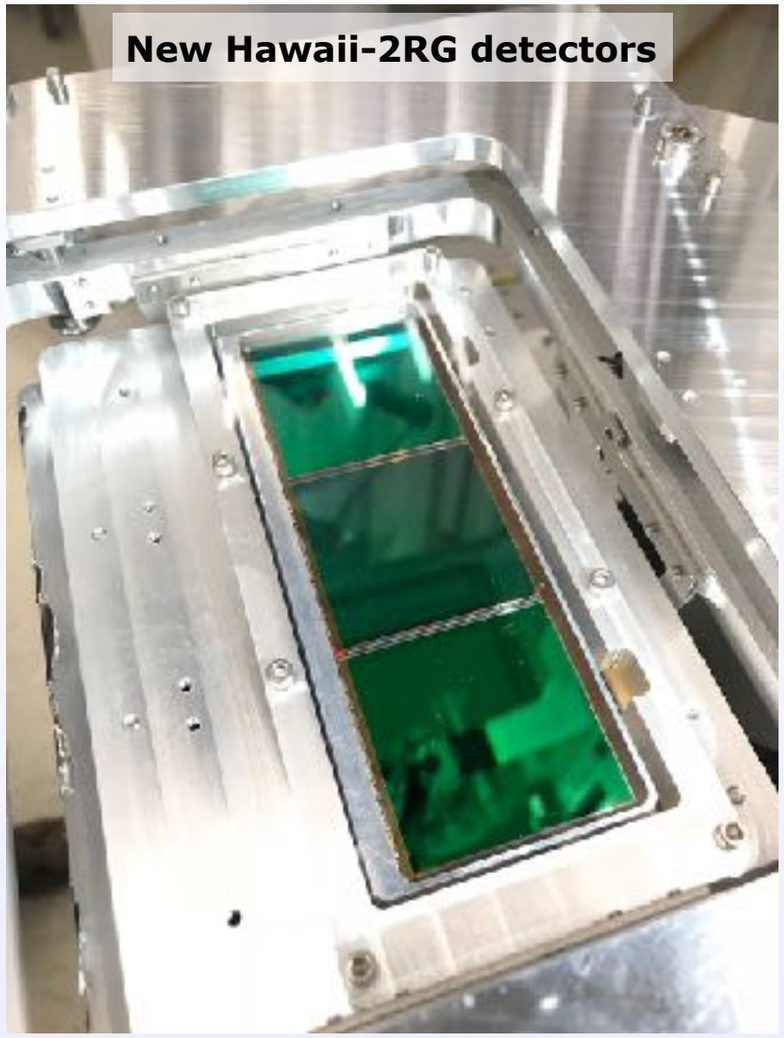


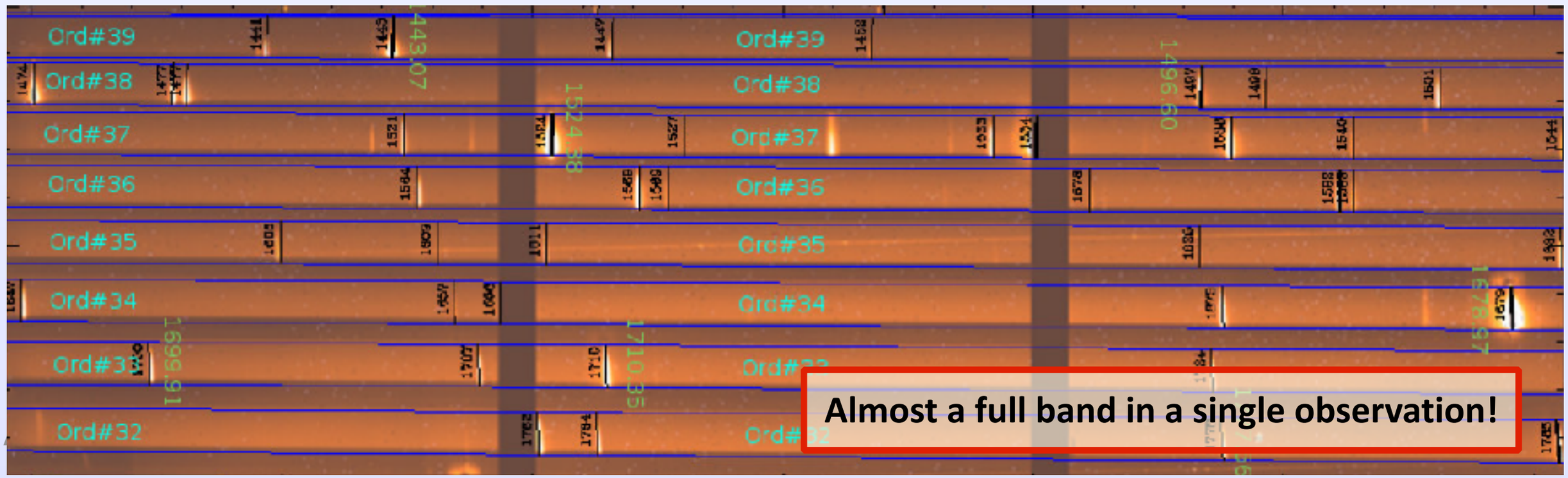




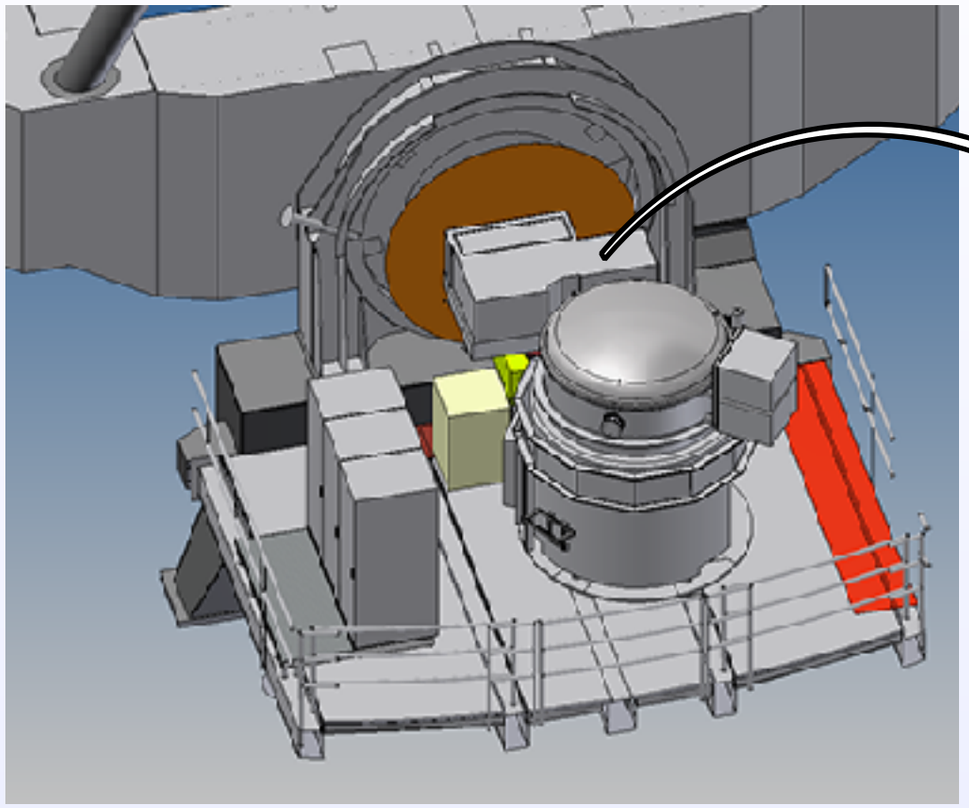
CRIRES+: improving CRIRES

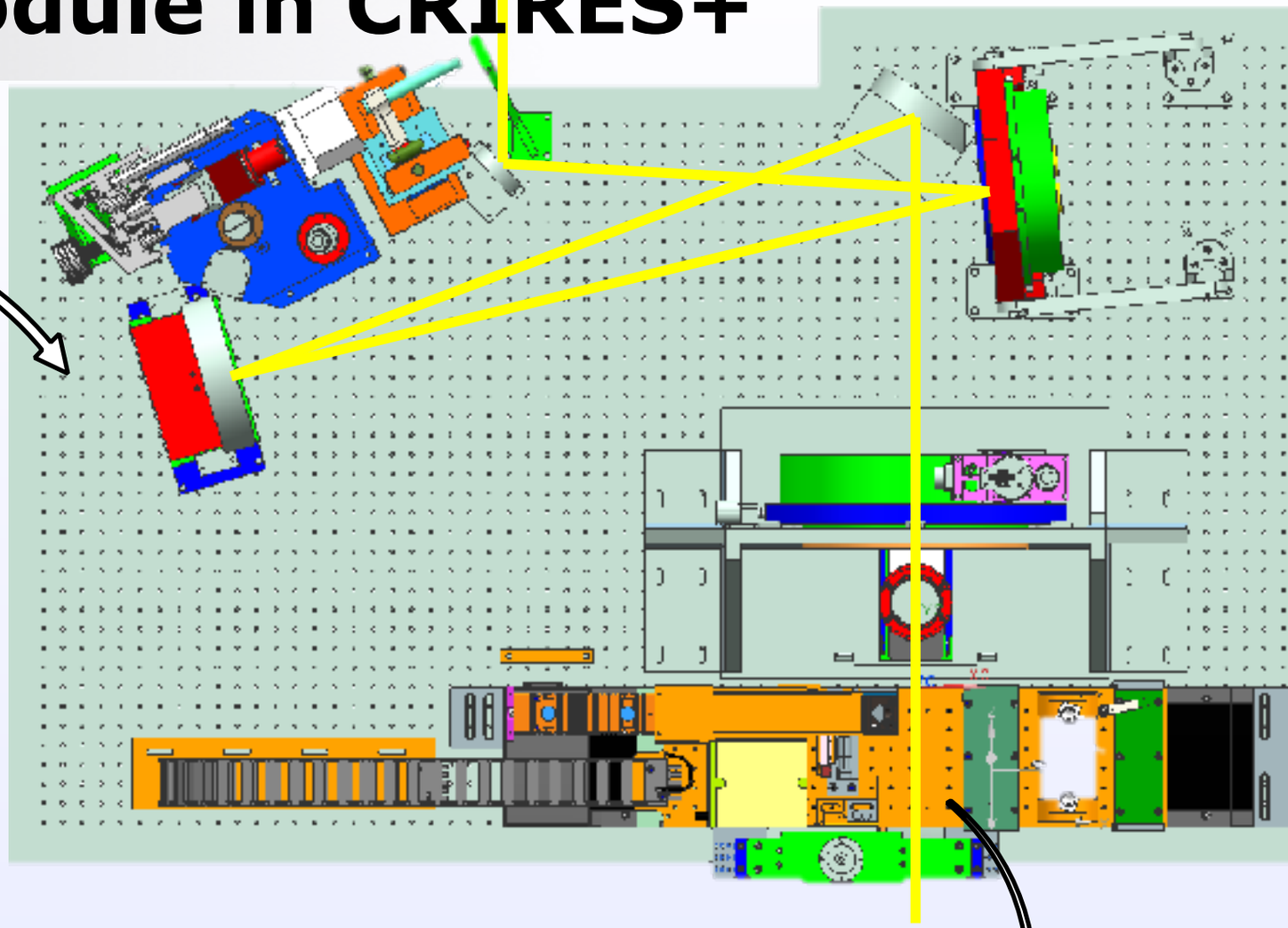
- NIR infrared echelle spectrograph
- New cross-dispersion gratings stage
- New Hawaii-2RG detectors

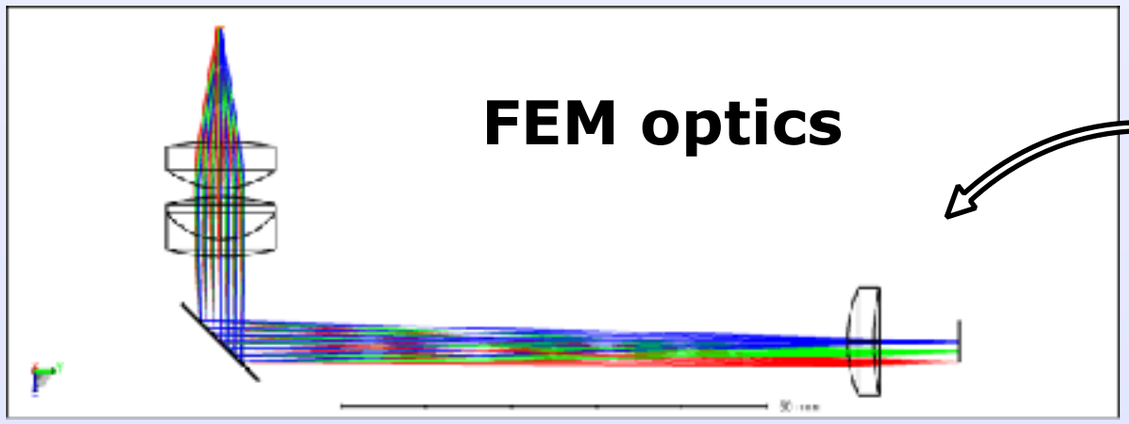




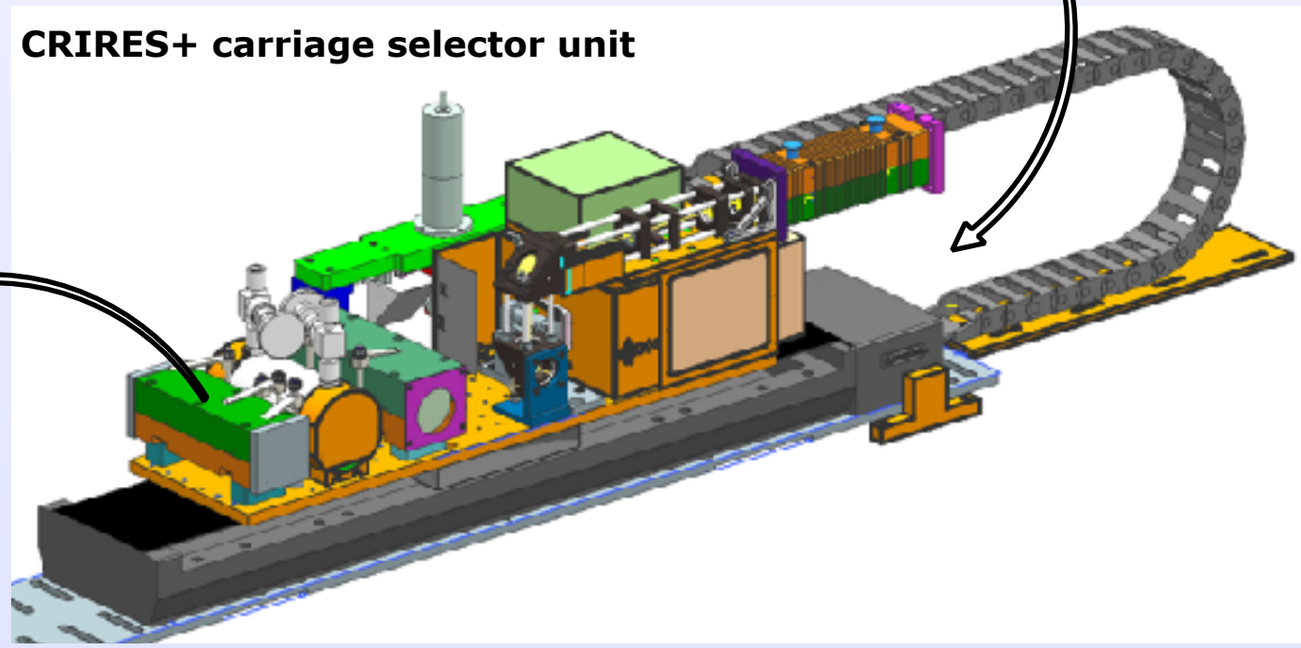
Fiber extraction module in CRIRES+







CRIRES+ carriage selector unit



Status of HiRISE

- Many discussions with ESO over the past 2 years
- Science case validated by the OPC: **strong support!**
- Technical proposal submitted to ESO to implement HiRISE as a visitor instrument
  - STC met **last week** to discuss the proposal (among many many other things)

Stay tuned for more in the coming months...

Conclusions

1. VLT/SPHERE: a high-contrast imaging instrument

- Powerful and versatile instrument
- Benefit from a great ExAO system and 3 complementary science instruments

2. SHINE: looking young giant exoplanets in imaging

- 400-600 stars survey over 5 years
- Survey almost completed, 2 planets
- Early statistical results show:
  1. An increased occurence rate of giant planets around BA stars
  2. A possible change of formation paradigm for companions around BA and FGKM stars

3. HiRISE: high-spectral resolution of directly-imaged exoplanets

- Couling between SPHERE and CRIRES+
- Final design on-going based on ERC funding
- Advanced discussions with ESO for installation as a visitor instrument