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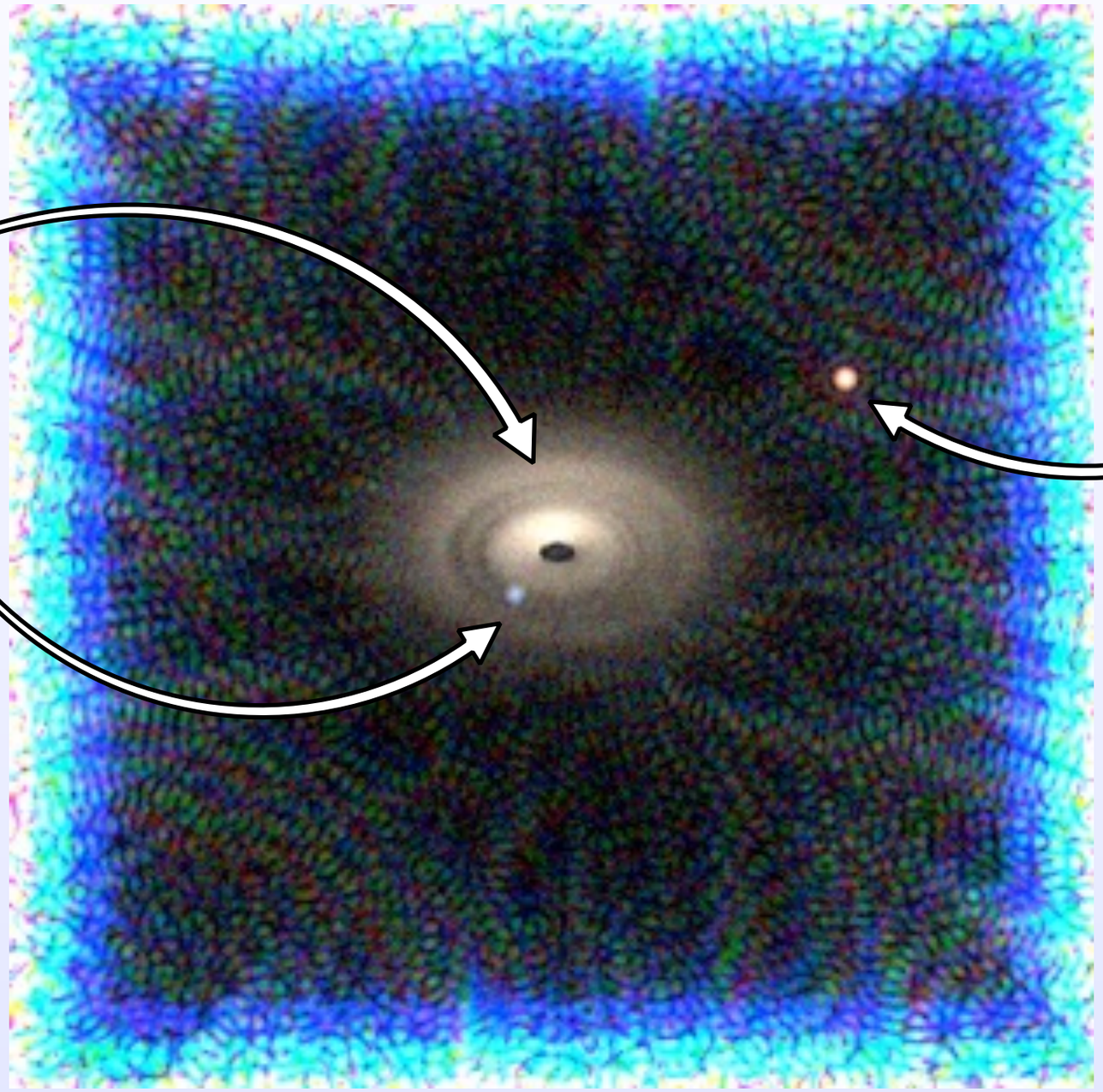
Direct Imaging and Characterisation of Exoplanets with VLT/SPHERE
Past, Present and Future

SPHERE
J.-L. Beuzit (PI), M. Feldt (Co-PI), D. Mouillet (PS), P. Puget (PM), K. Dohlen (SE),
F. Wildi (AIT), T. Fusco (AO), M. Kasper (ESO responsible), Z. Wahhaj (current ESO IS)
and numerous participants from 12 European institutes!

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, K. Dohlen, Y. Charles, M. Houllé, N. Tchoubaklian, M. Phillips, R. Pourcelot,
U. Seemann, J.-L. Beuzit, R. Dorn, M. Kasper, D. Mouillet, I. Baraffe, A. Reiners

Direct imaging of exoplanets

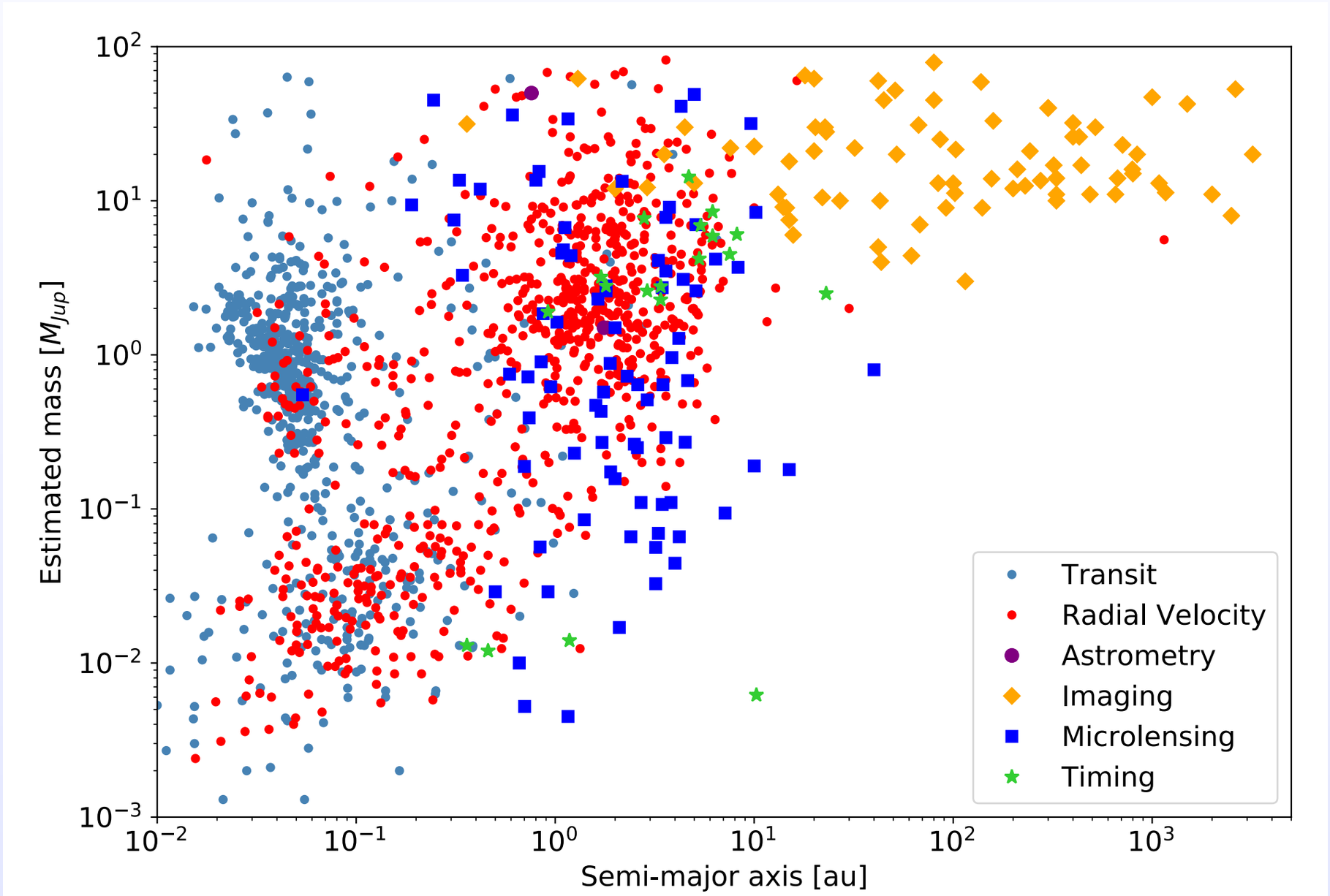


System architecture

Planets composition

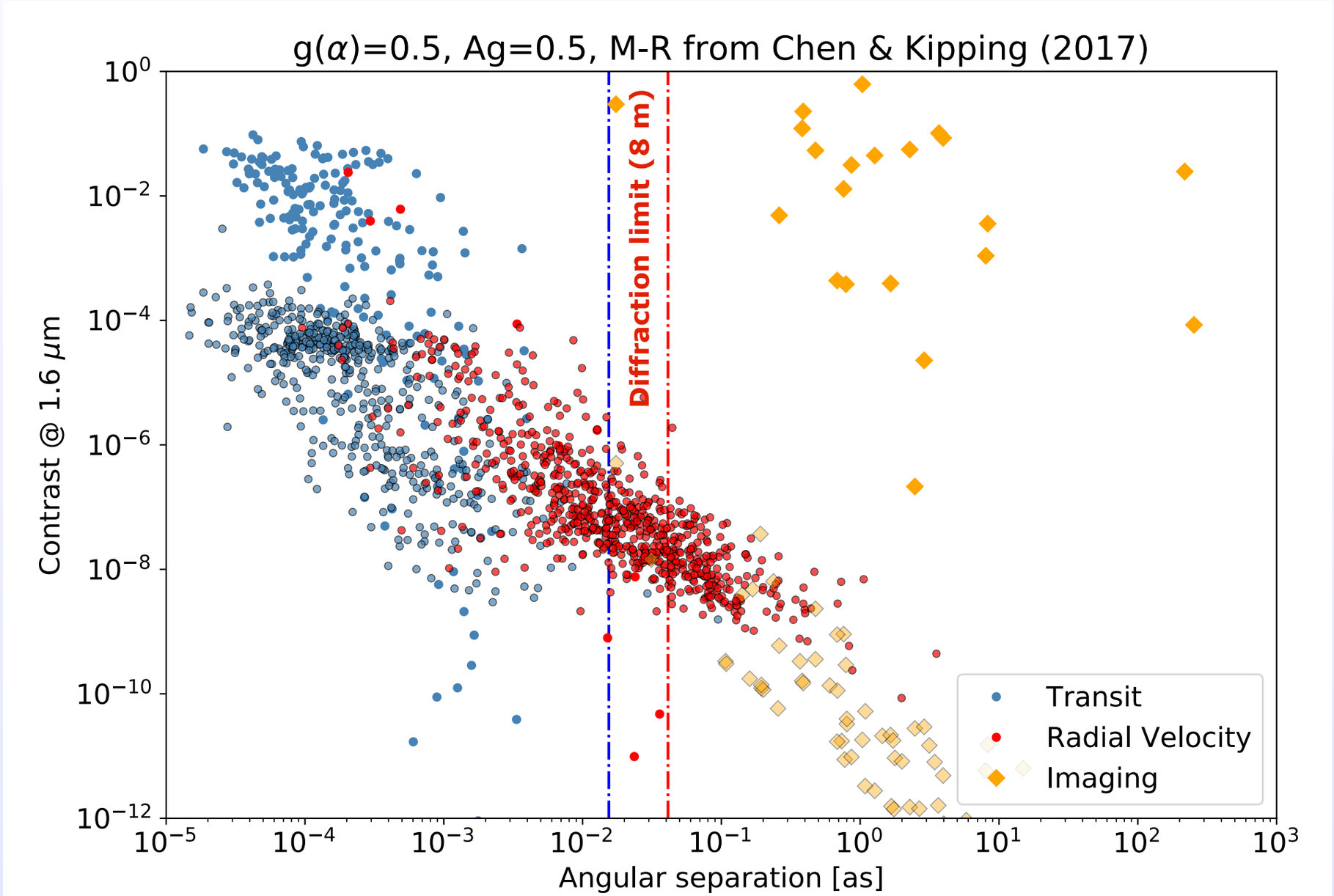
Direct imaging of exoplanets

Physical units



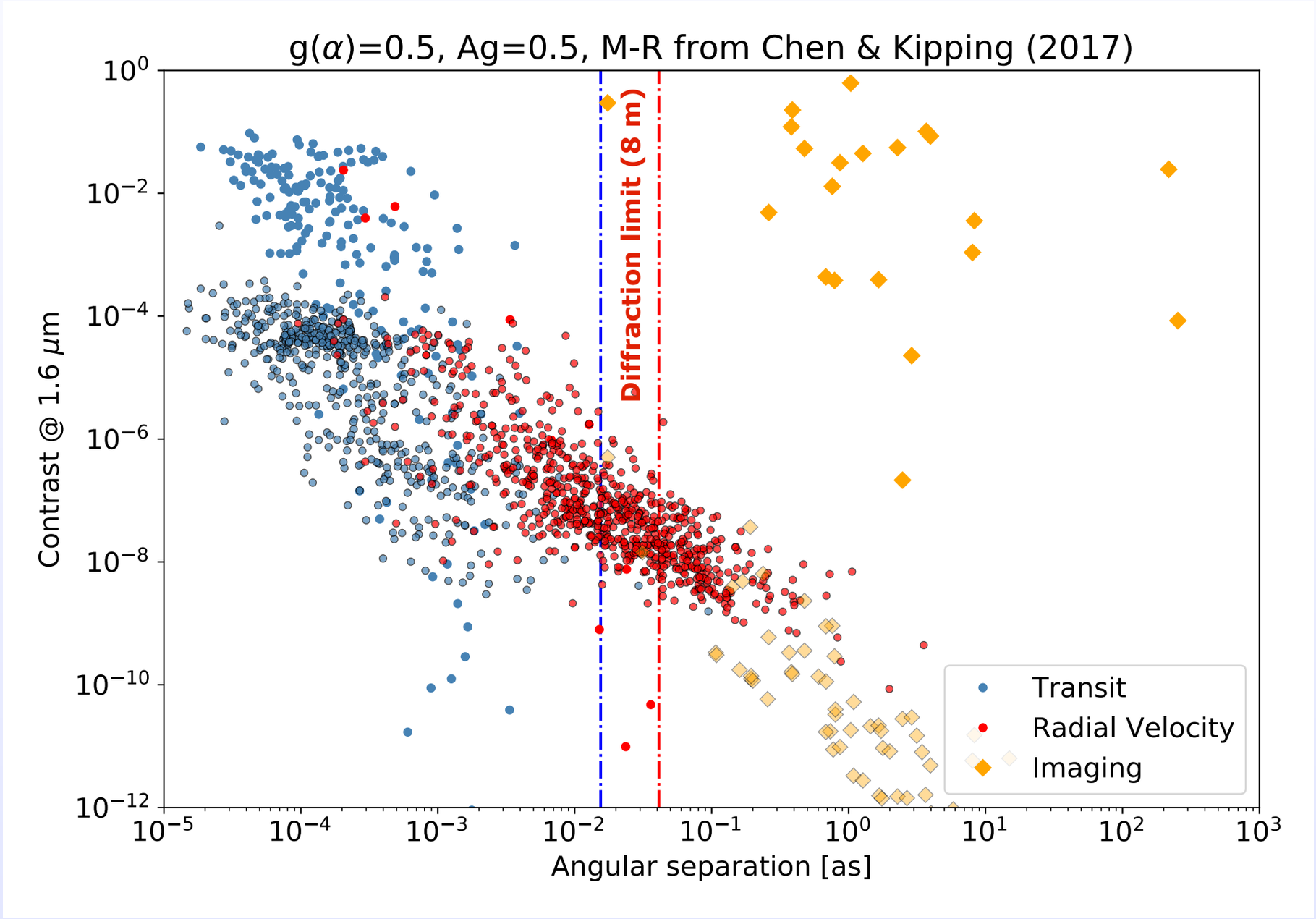
Direct imaging of exoplanets

Observables



Direct imaging of exoplanets

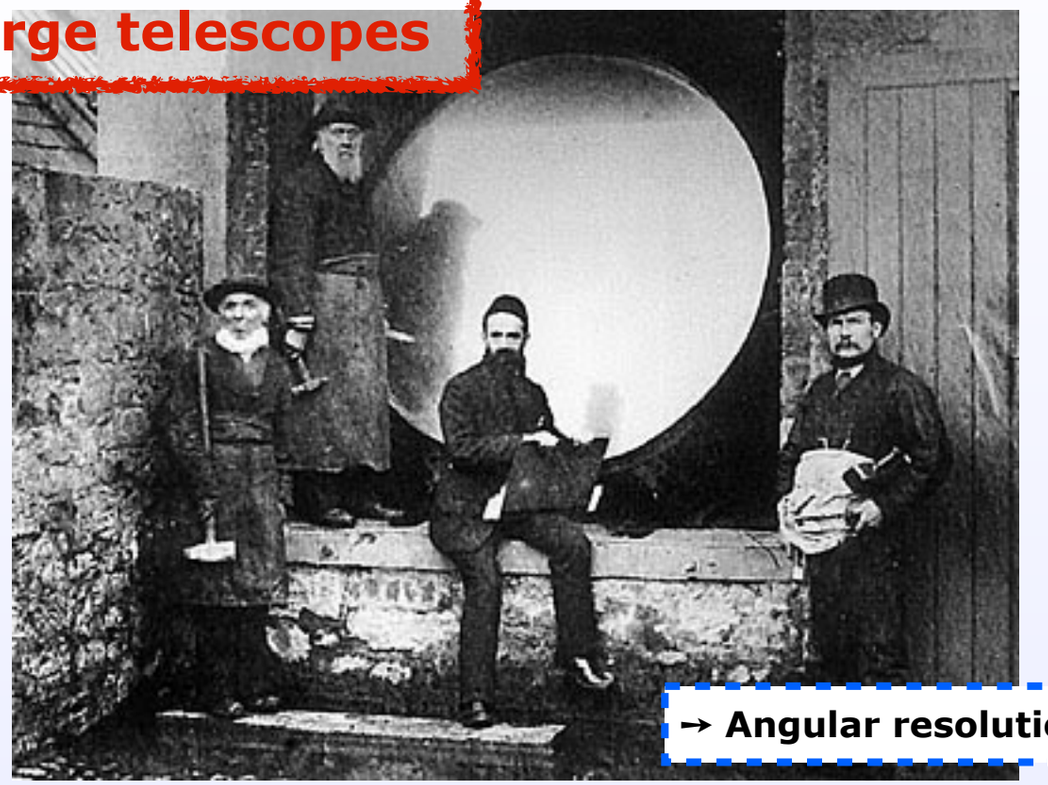
High-angular resolution



High-contrast

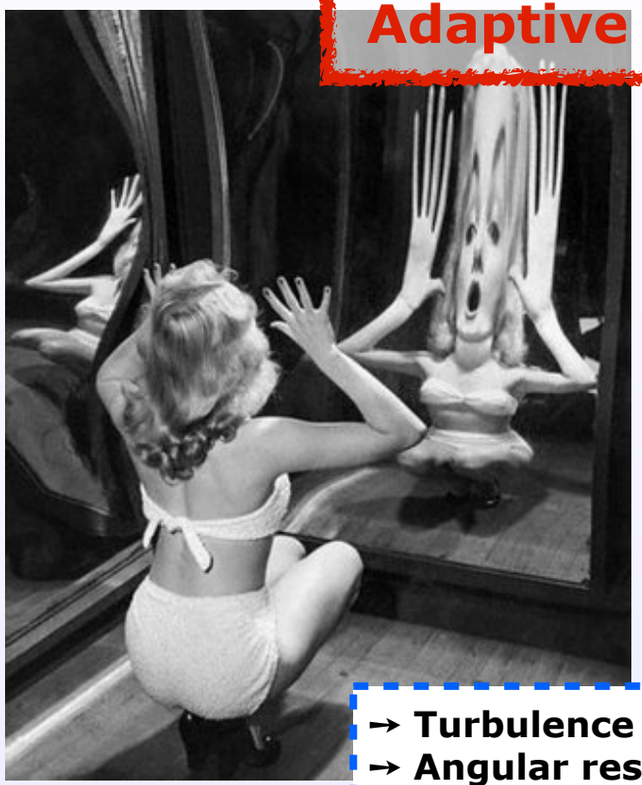
Direct imaging recipe

Large telescopes



→ Angular resolution

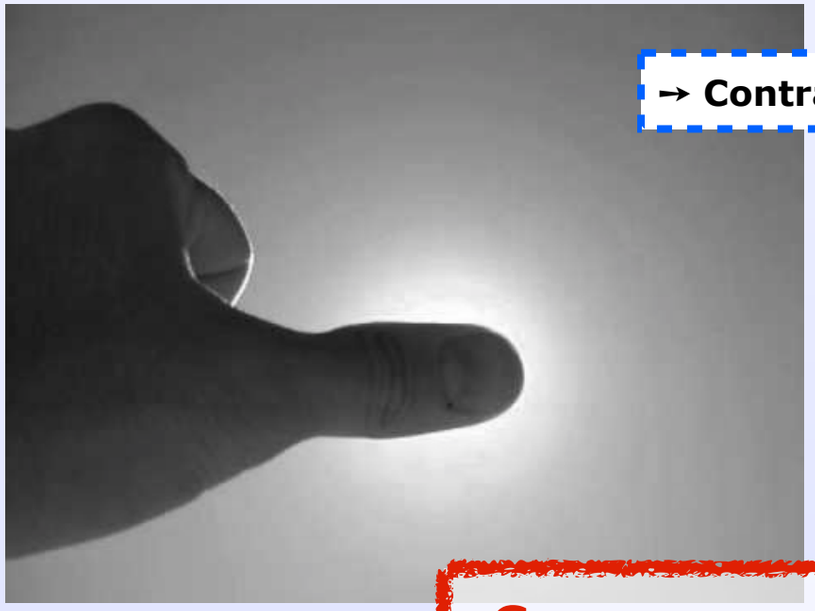
Adaptive optics



→ Turbulence correction
→ Angular resolution

→ Contrast

Algorithms



→ Contrast

Coronagraphs

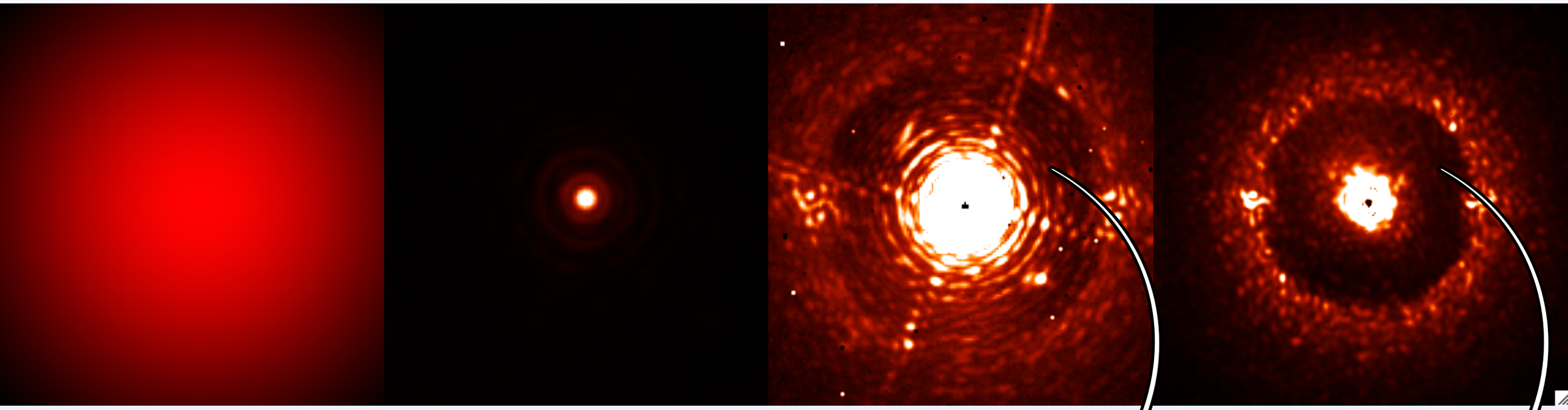
Direct imaging recipe

Seeing-limited PSF
✘ Adaptive optics
✘ Coronagraph

Diffraction-limited PSF
✔ Adaptive optics
✘ Coronagraph

Diffraction-limited PSF
✔ Adaptive optics
✘ Coronagraph

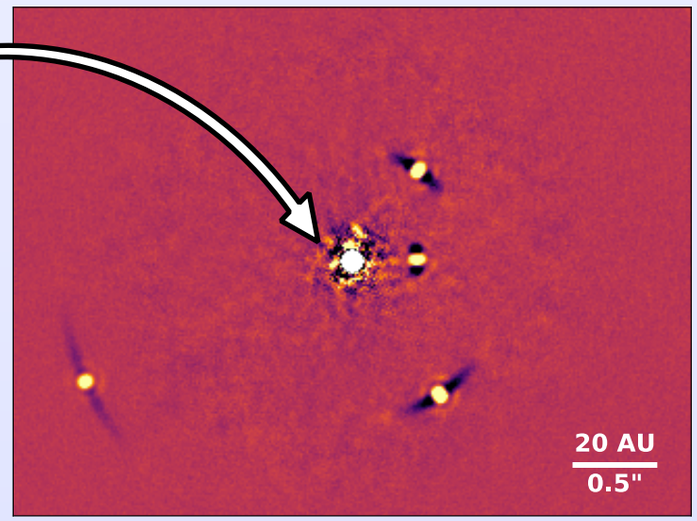
Coronagraphic image
✔ Adaptive optics
✔ Coronagraph



Diffraction limited within 20 λ/D

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

post-processing

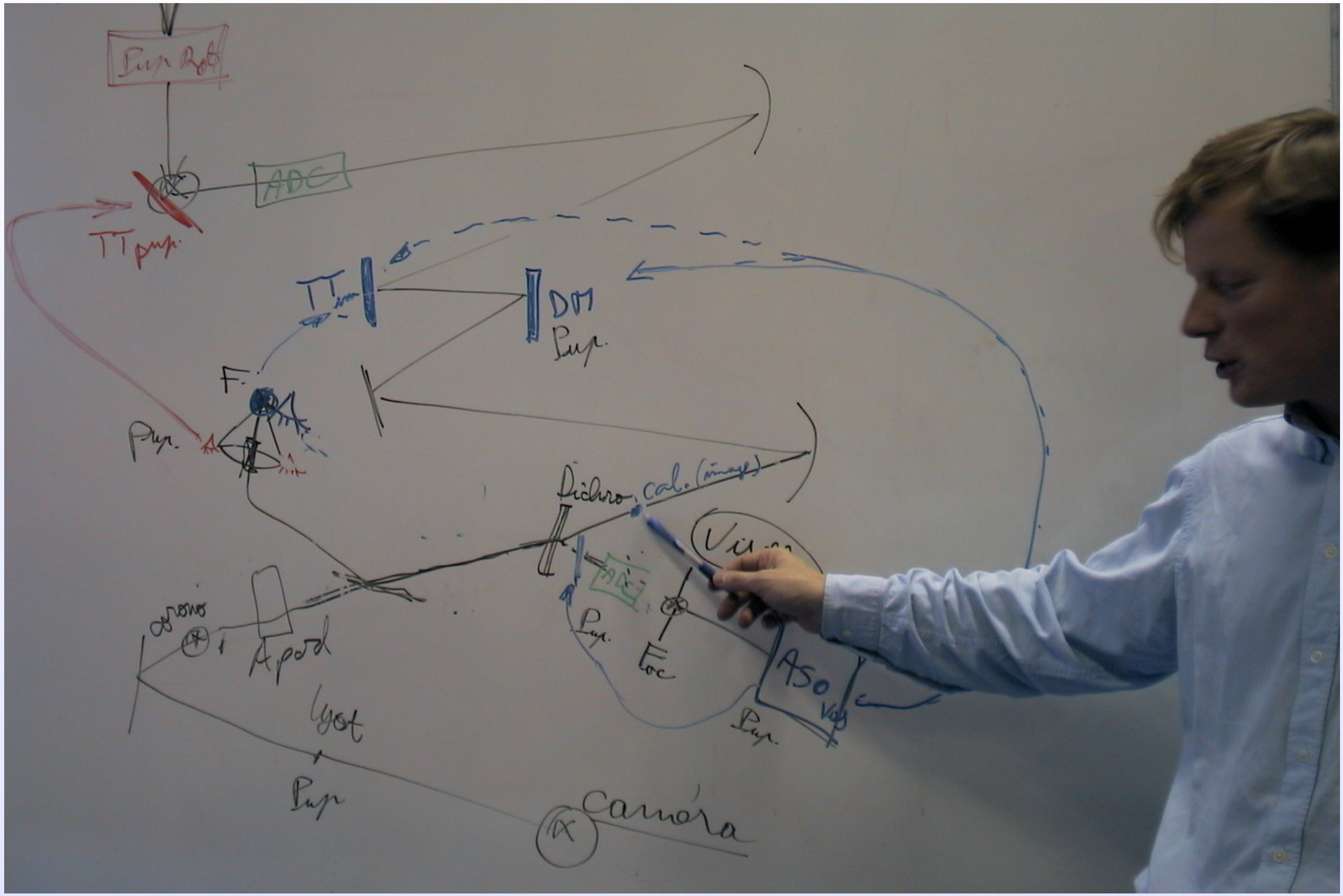


~10^{-5}-10^{-6} contrast down to 0.2"

Enough to detect young giant exoplanets of a few Jupiter masses

PAST

Where it all started

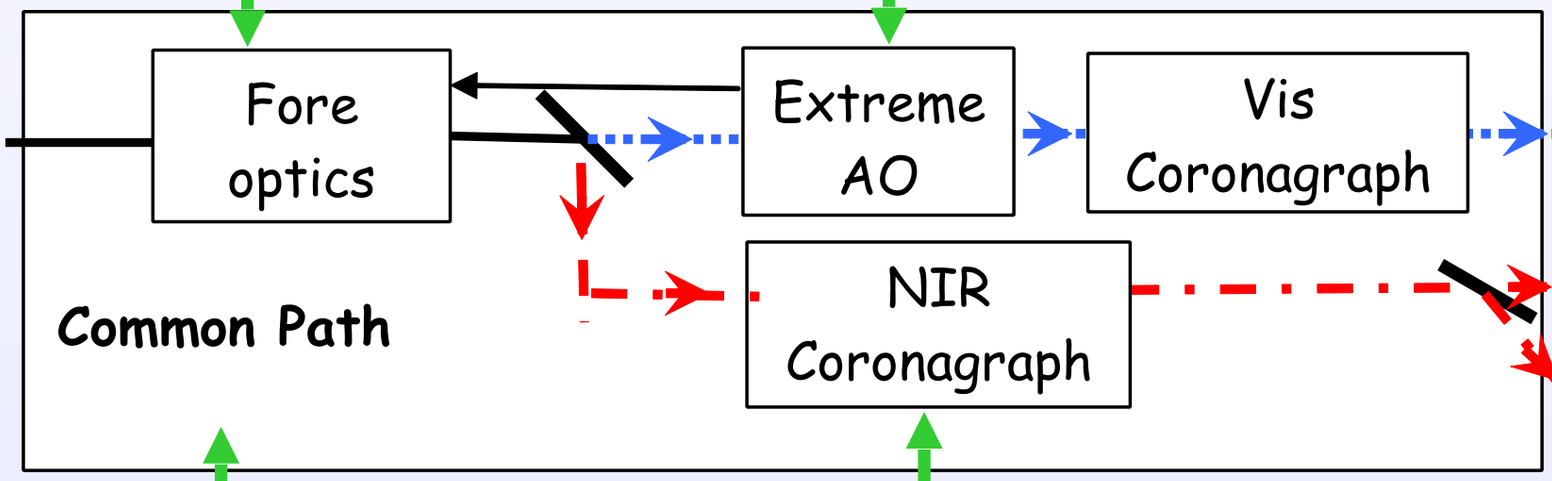


SPHERE system overview

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”



ZIMPOL

IFS

IRDIS

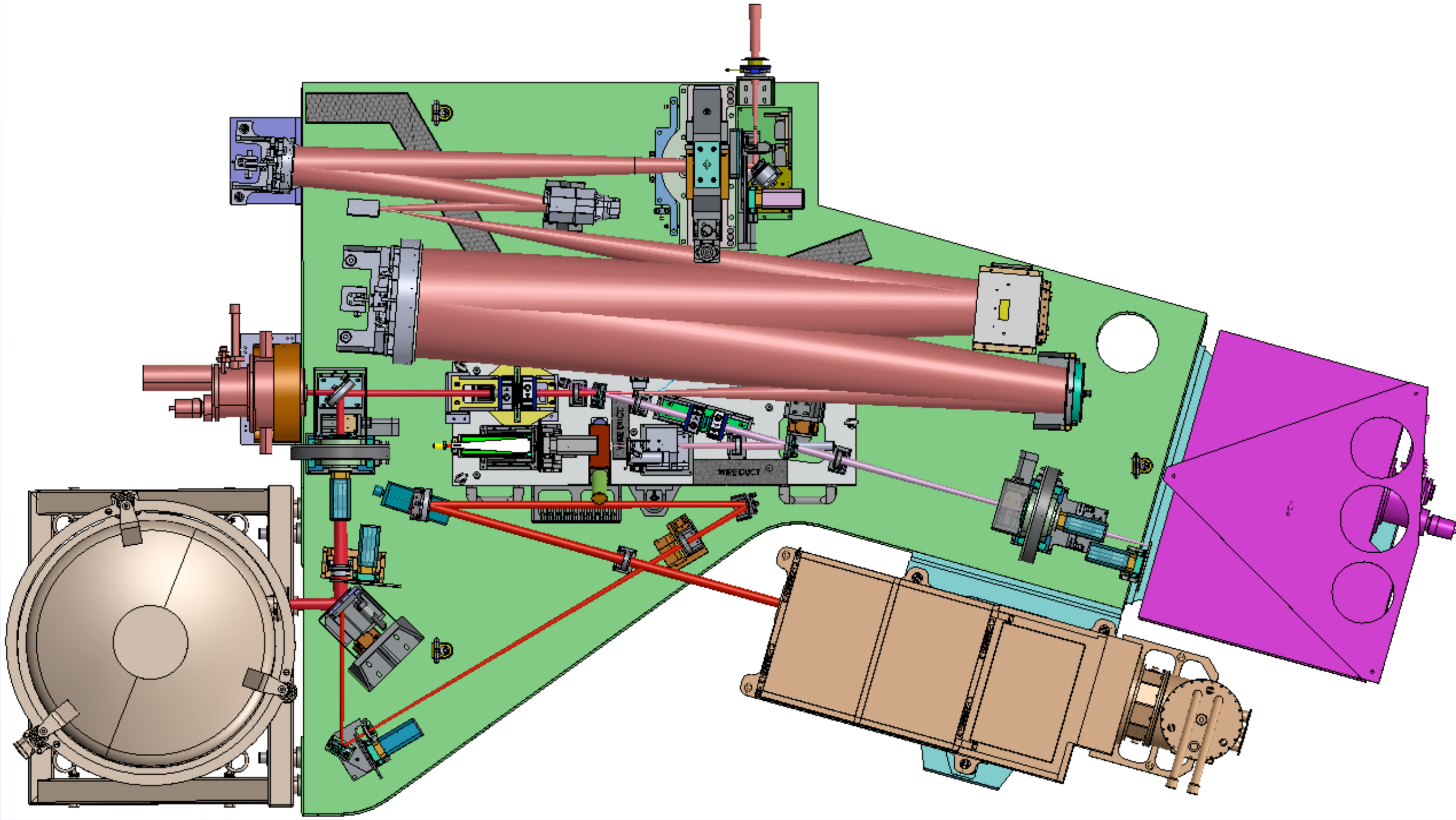
0.95 - 1.35/1.65 µm
Nyquist sampled @ 0.95 µm
R = 54 / 33
FoV = 1.77”

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

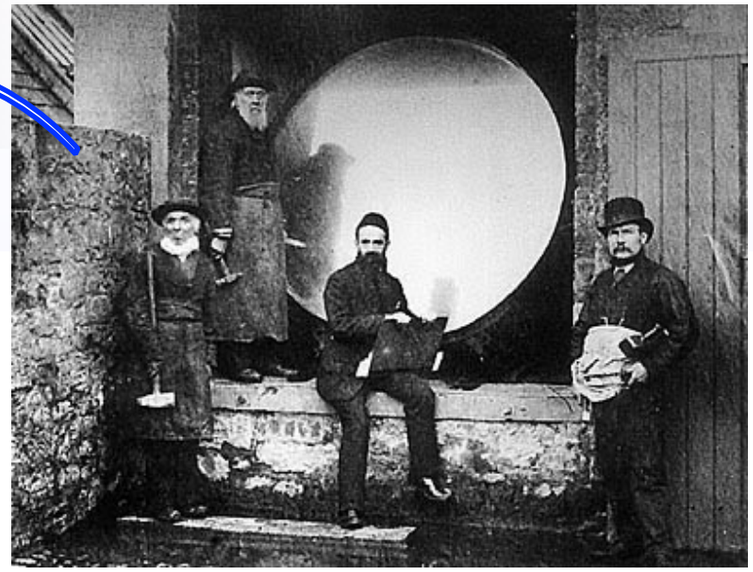
Nasmyth platform, static bench,
Temperature control, cleanliness control
Active vibration control

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

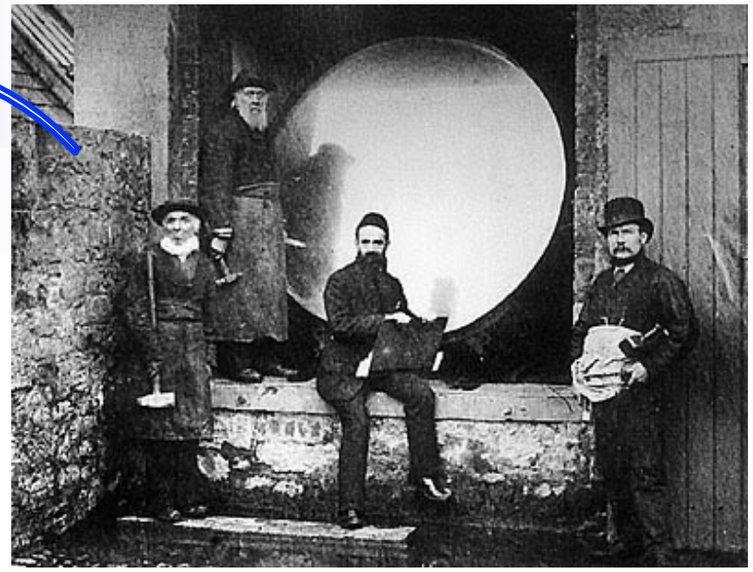
VLT/SPHERE



VLT/SPHERE



VLT/SPHERE



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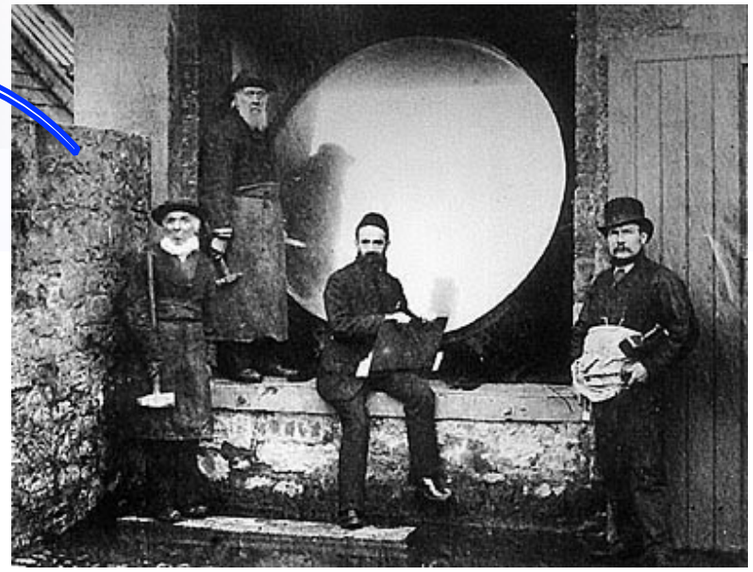
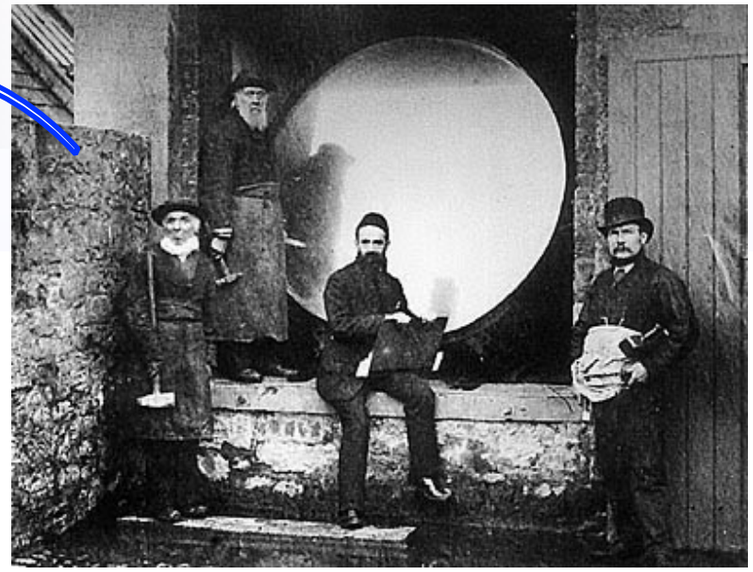


VLT/SPHERE



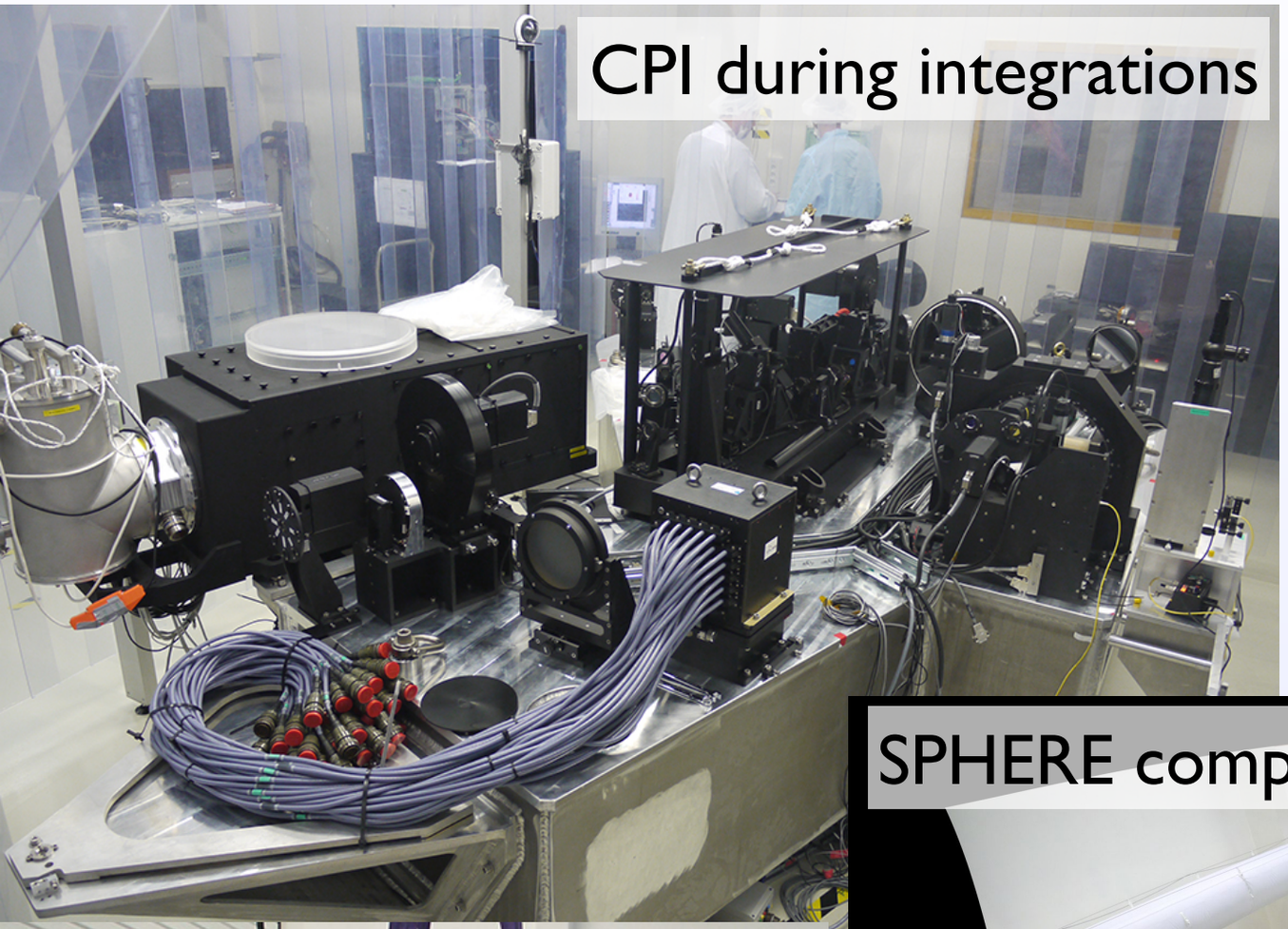
IRDIS

IFS

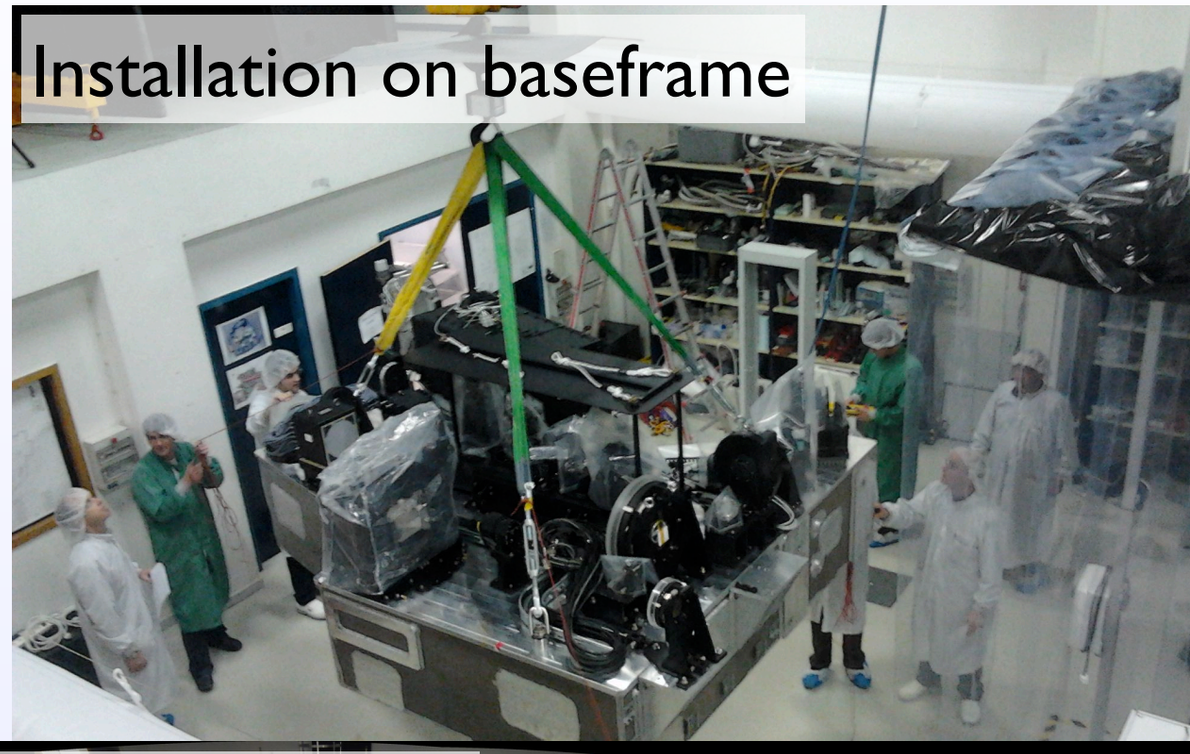
ZIMPOL

2011-2013: integration in Europe

CPI during integrations

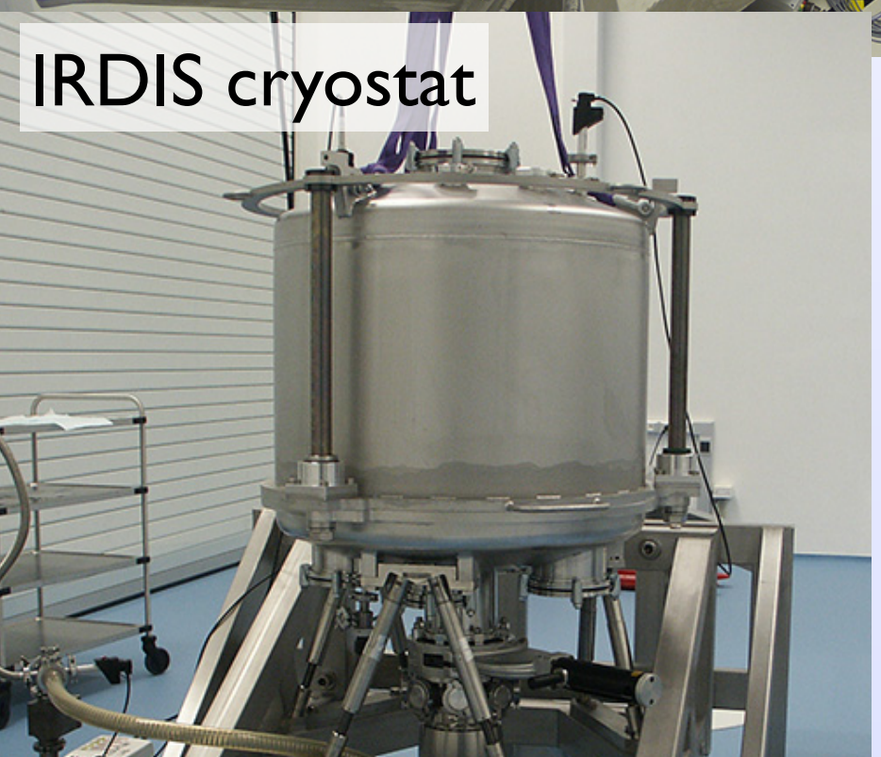


Installation on baseframe

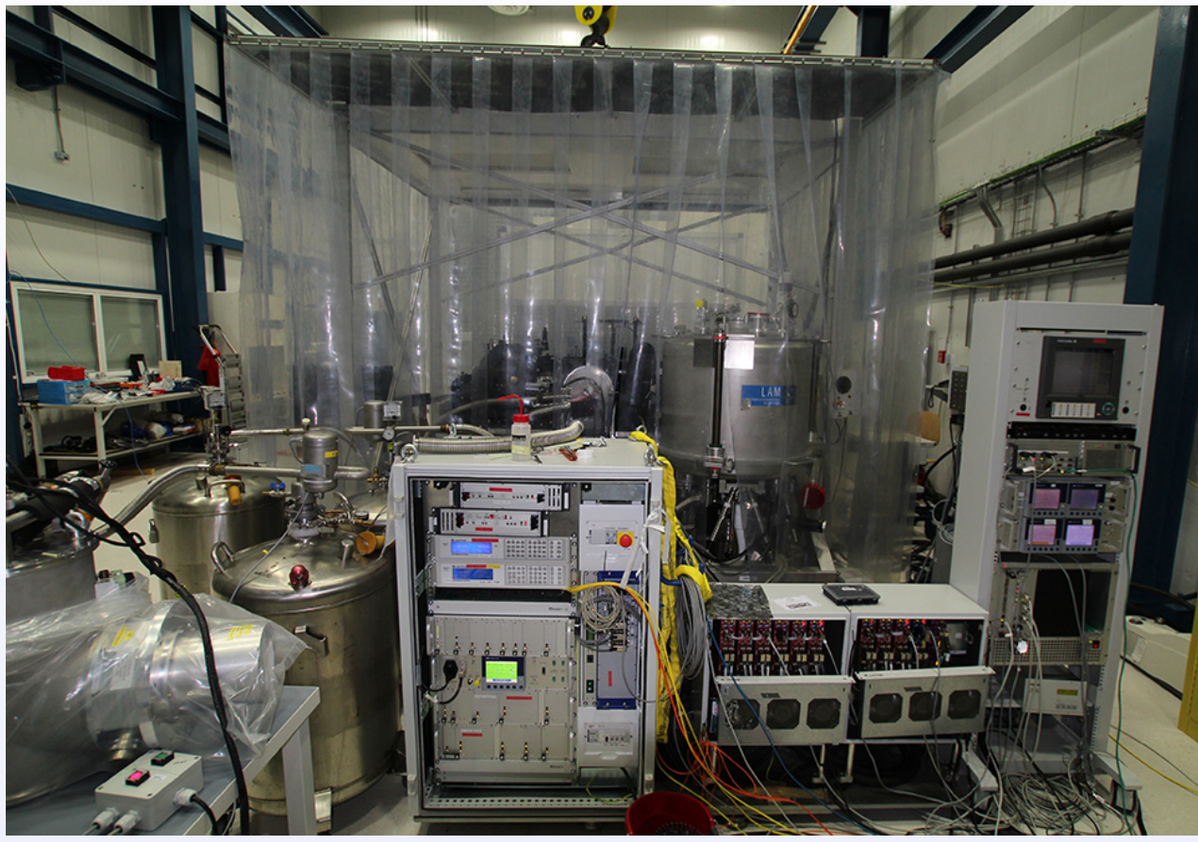


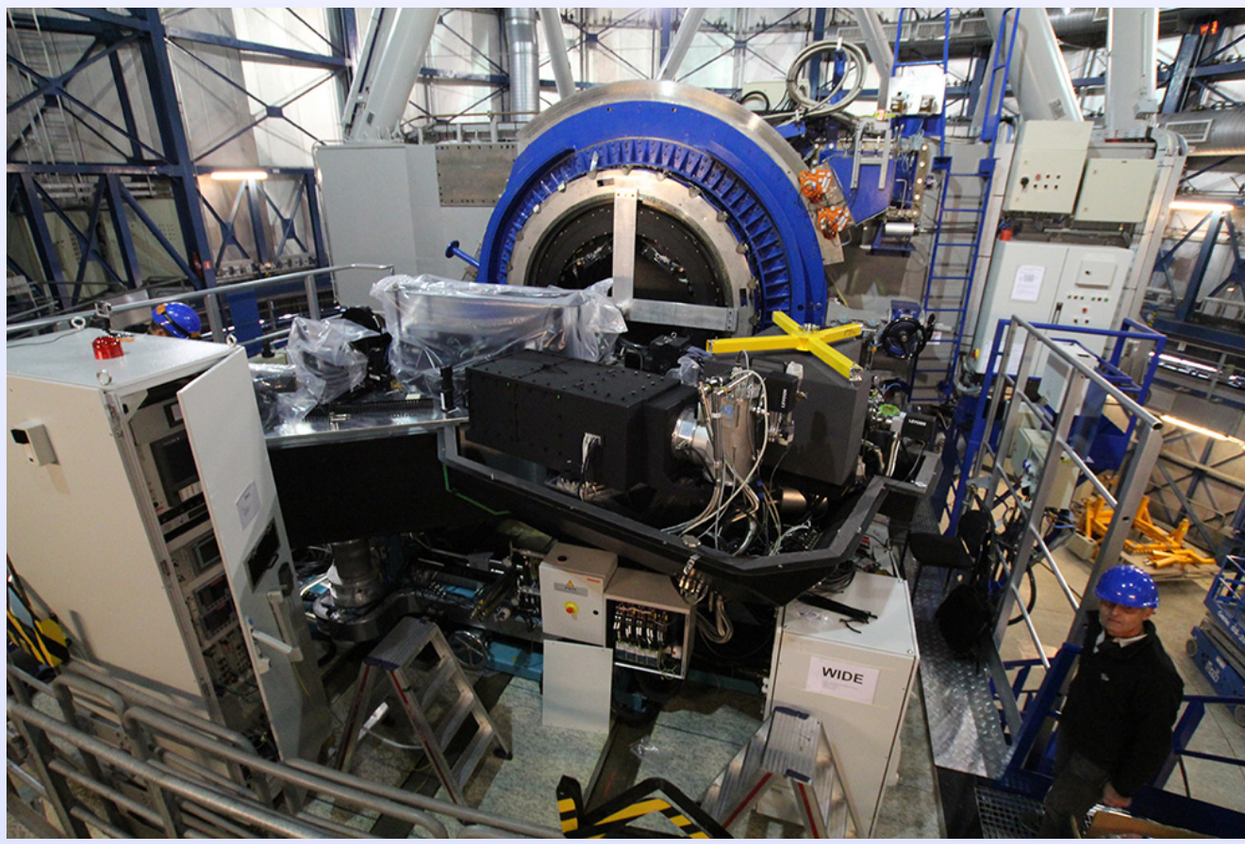
SPHERE completed in 2013

IRDIS cryostat



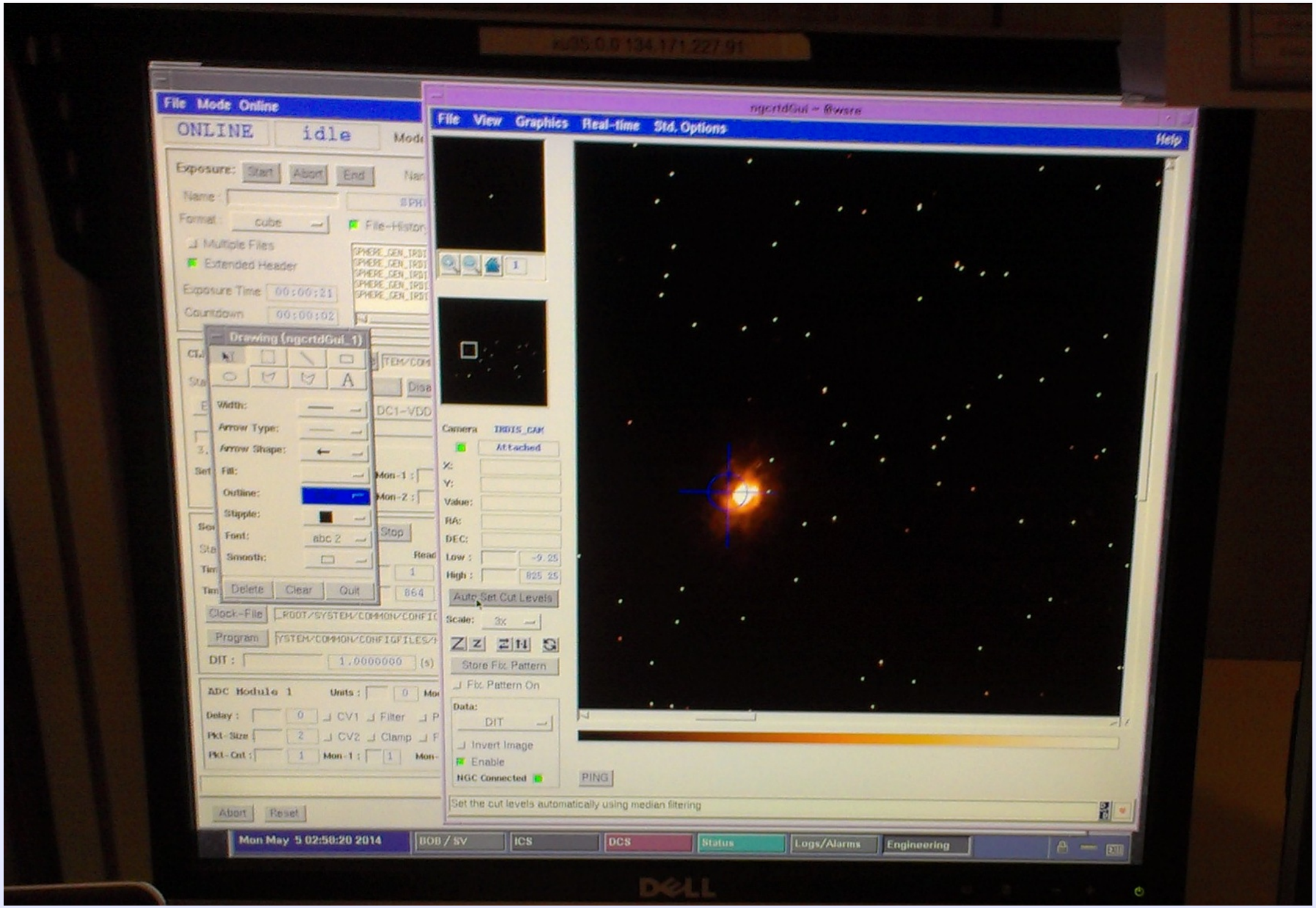
2014: shipment and reintegration





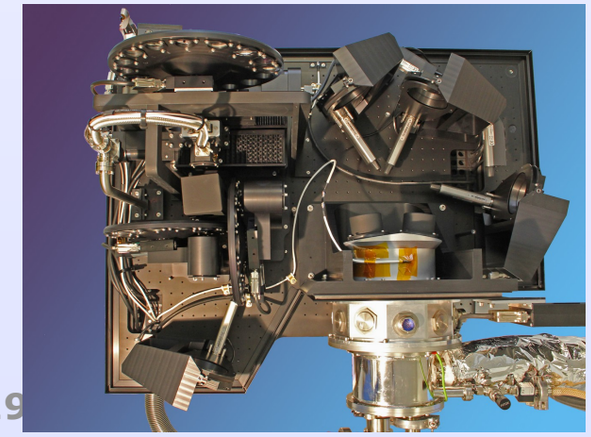
May 2015 @ UT3

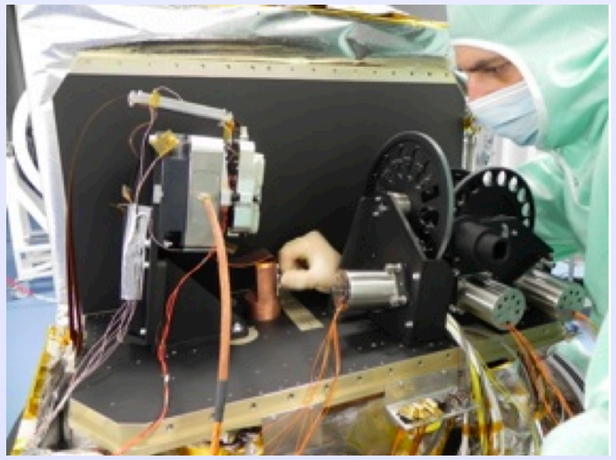
May 6th 2014: first light

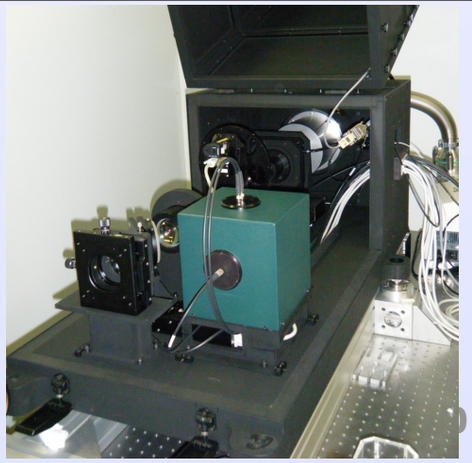


SPHERE science instruments

	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







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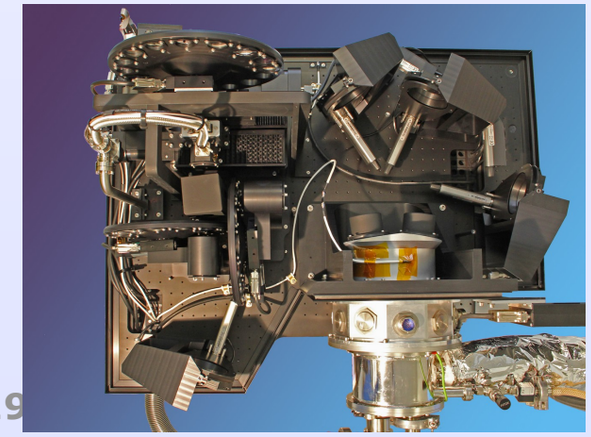
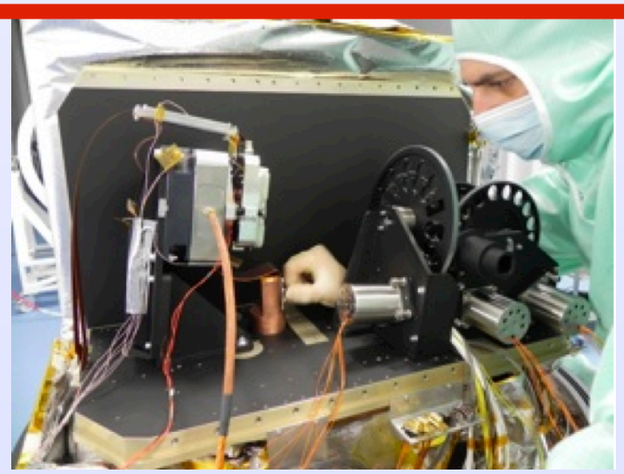
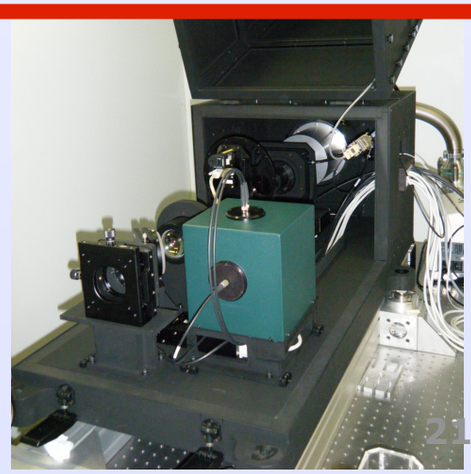
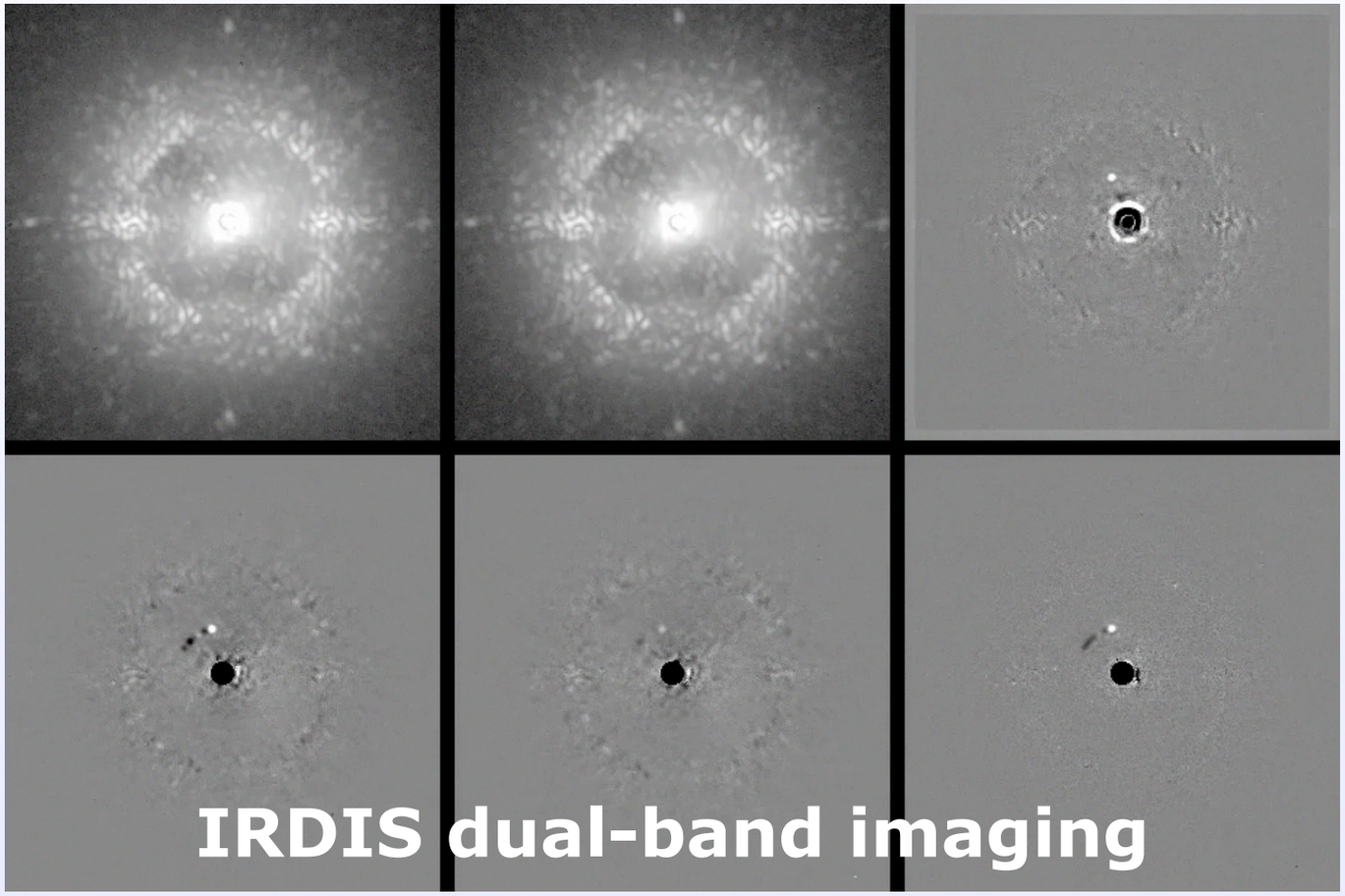


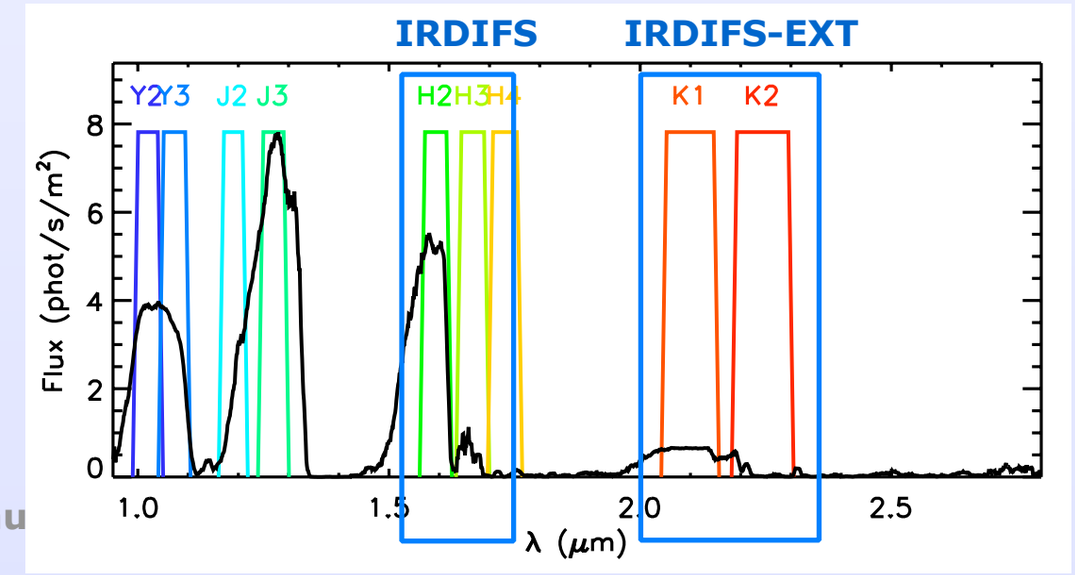


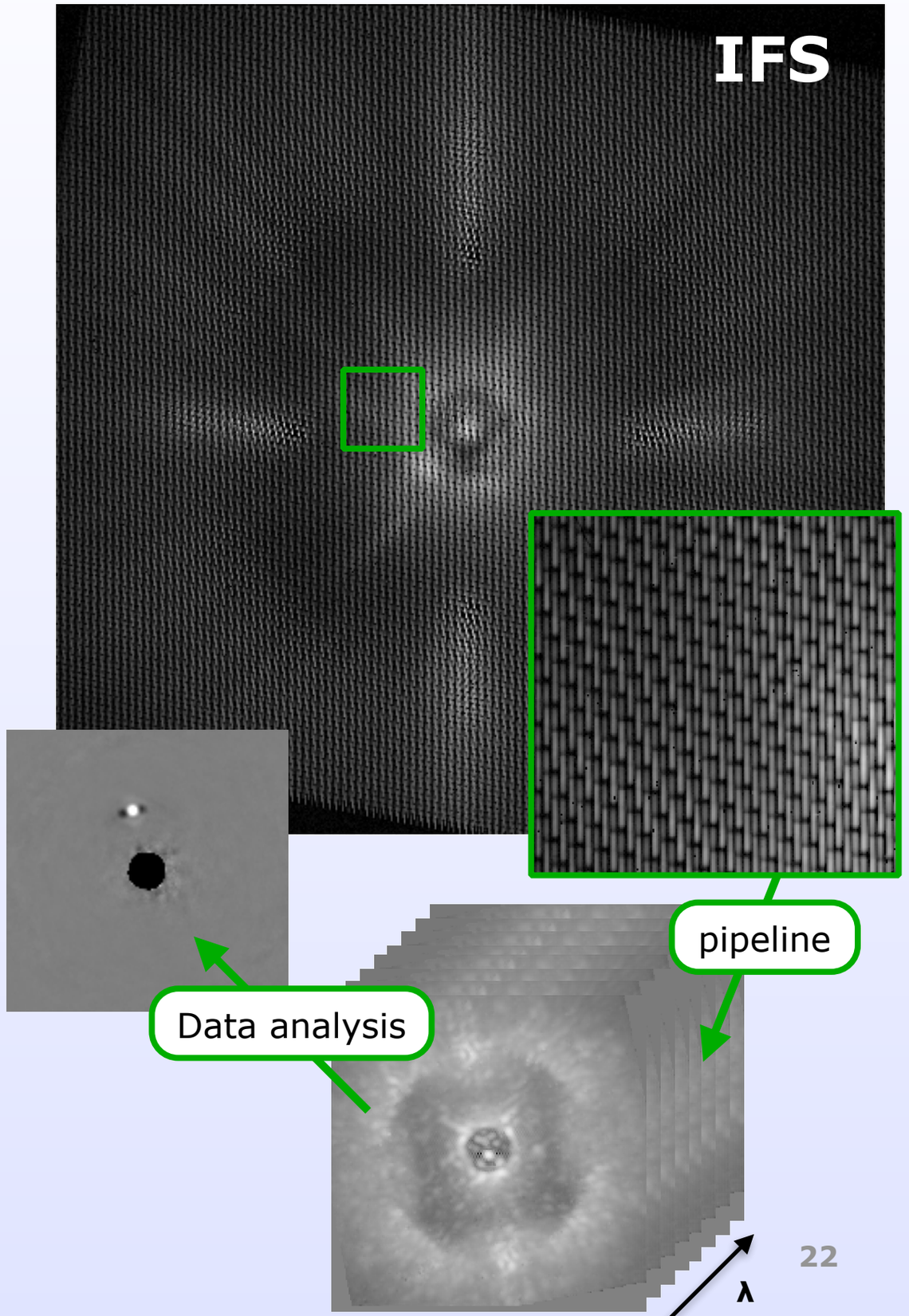


IRDIFS: the exoplanet hunting mode

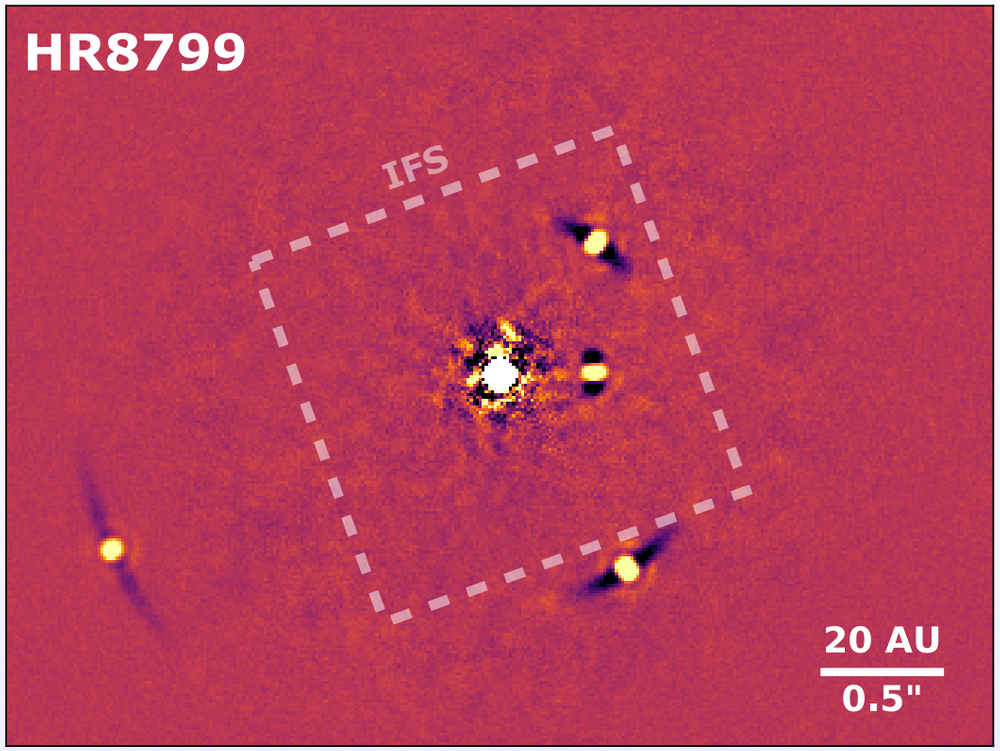
SPHERE designed as a <u>survey instrument</u>



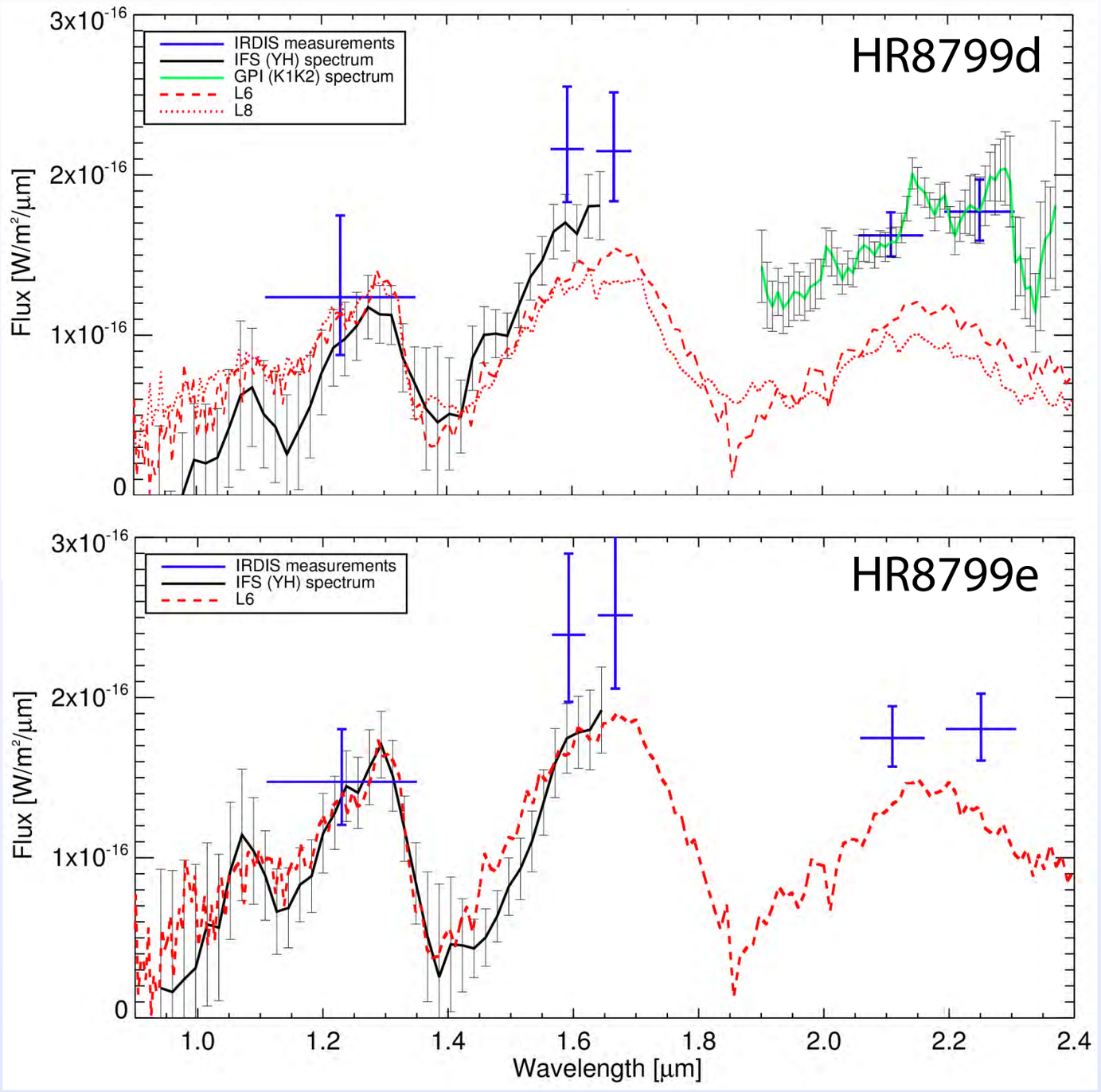




IRDIFS power illustrated: HR8799



- 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

Maire+ 2016

Stolker+ 2016

Ginski+ 2016

Lagrange+ 2016

Maire+ 2017

Keppler+ 2018

Feldt+ 2017

Van Boekel+ 2017

Peretti+ 2018

Sissa+ 2018

Samland+ 2017

Mesa+ 2016

Boccaletti+ 2015

Bonavita+ 2017

Sissa+ 2018

Müller+ 2018

Avenhaus+ 2017

Lazzoni+ 2018

Benisty+ 207

Pohl+ 2017

Mesa+ 2016

Rodet+ 2018

Garufi+ 2016

Milli+ 2017

de Boer+ 2016

Delorme+ 201

Mesa+ 2018

Cheetham+ 2018

Thalmann+ 2016

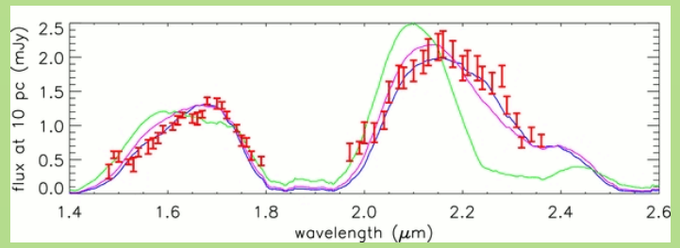
Olofsson+

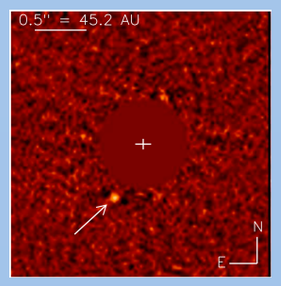
SHINE: SpHere Infrared survey for Exoplanets

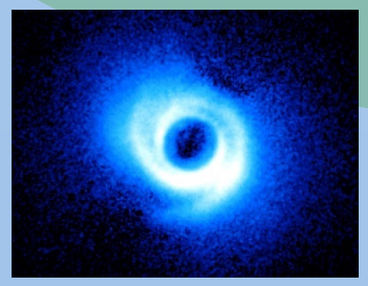
1/ Physics of giant exoplanets

Photometry & Spectroscopy

Atmosphere & physical properties



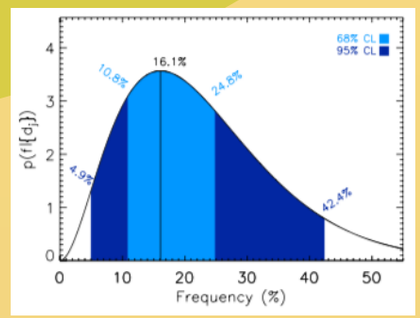




2/ Architecture & stability of planetary systems

Astrometry & disk/planet position

Orbits, dynamical interactions, resonances & long-term evolution



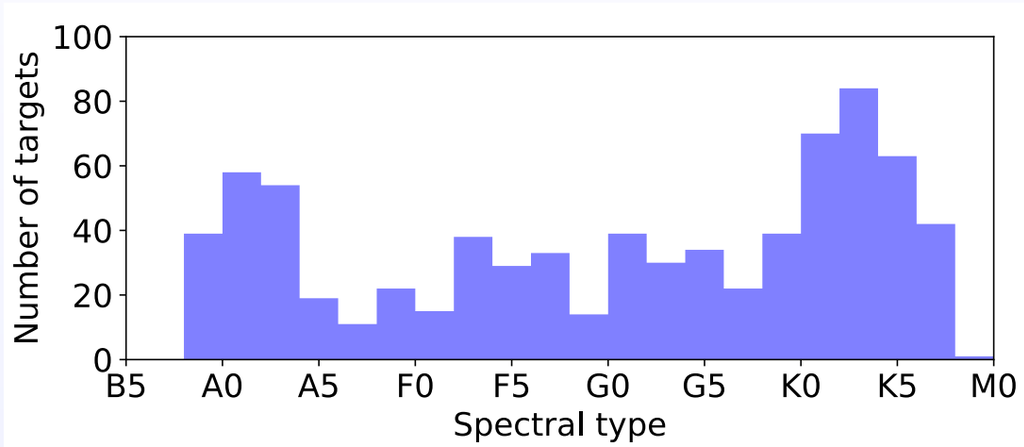
3/ Occurrence & formation

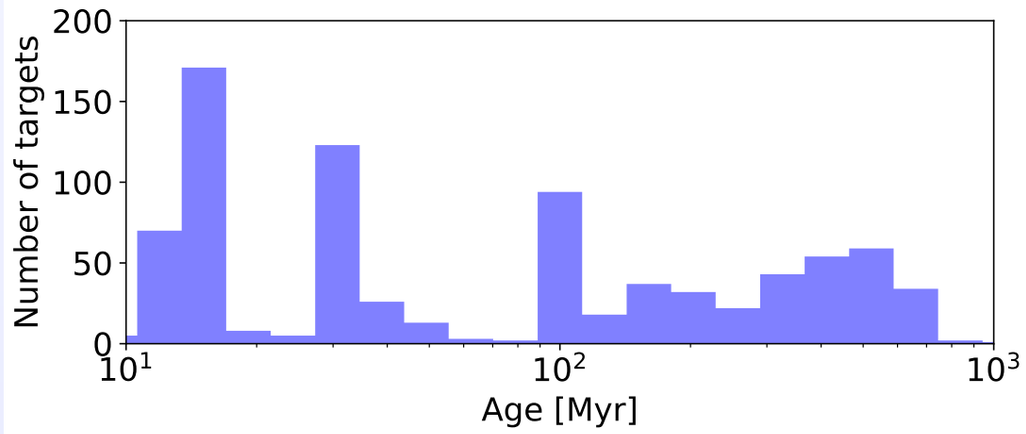
Statistical properties (occurrence, stellar host dependency, disk properties)

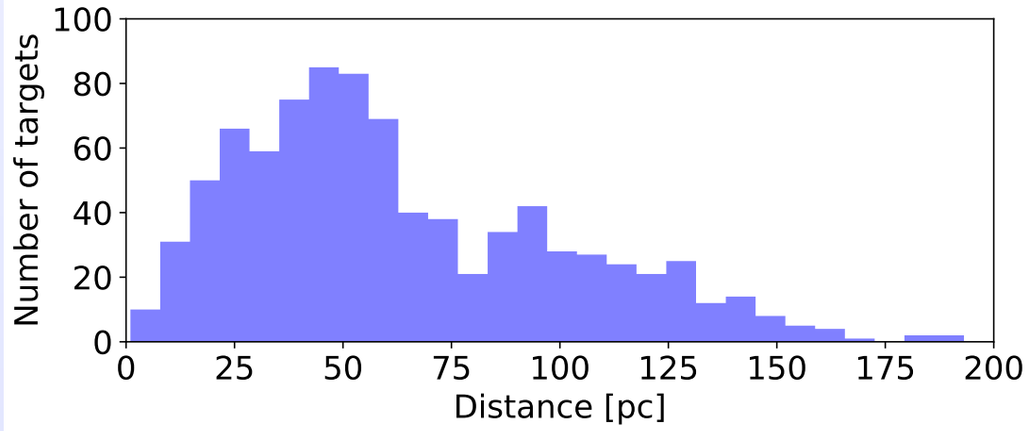
Formation theories

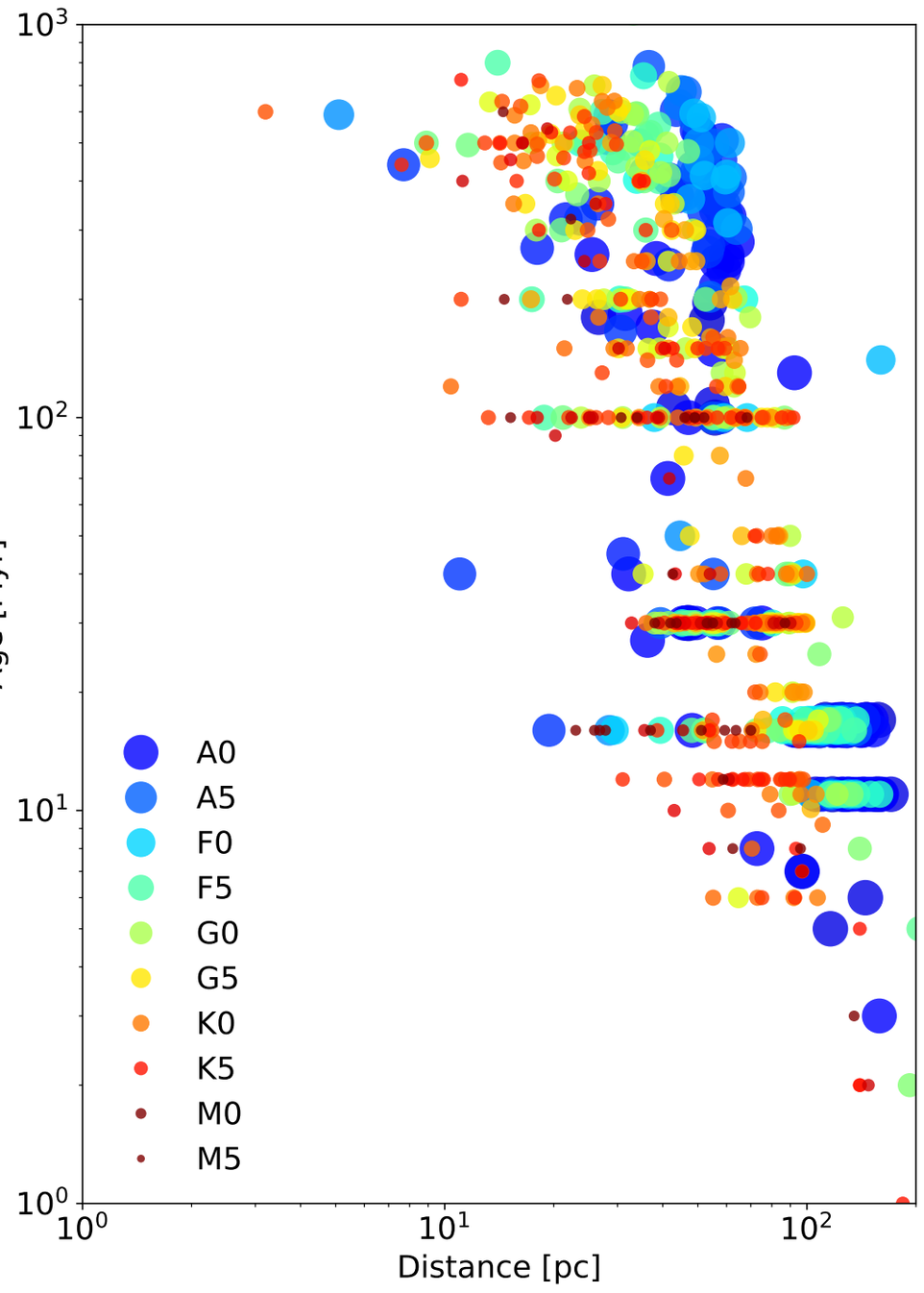
Sample: all young stars within 130 pc

600 stars + 400 backup, 4 priority bins









R<11

No binaries (spectro or visual <6")

Observations

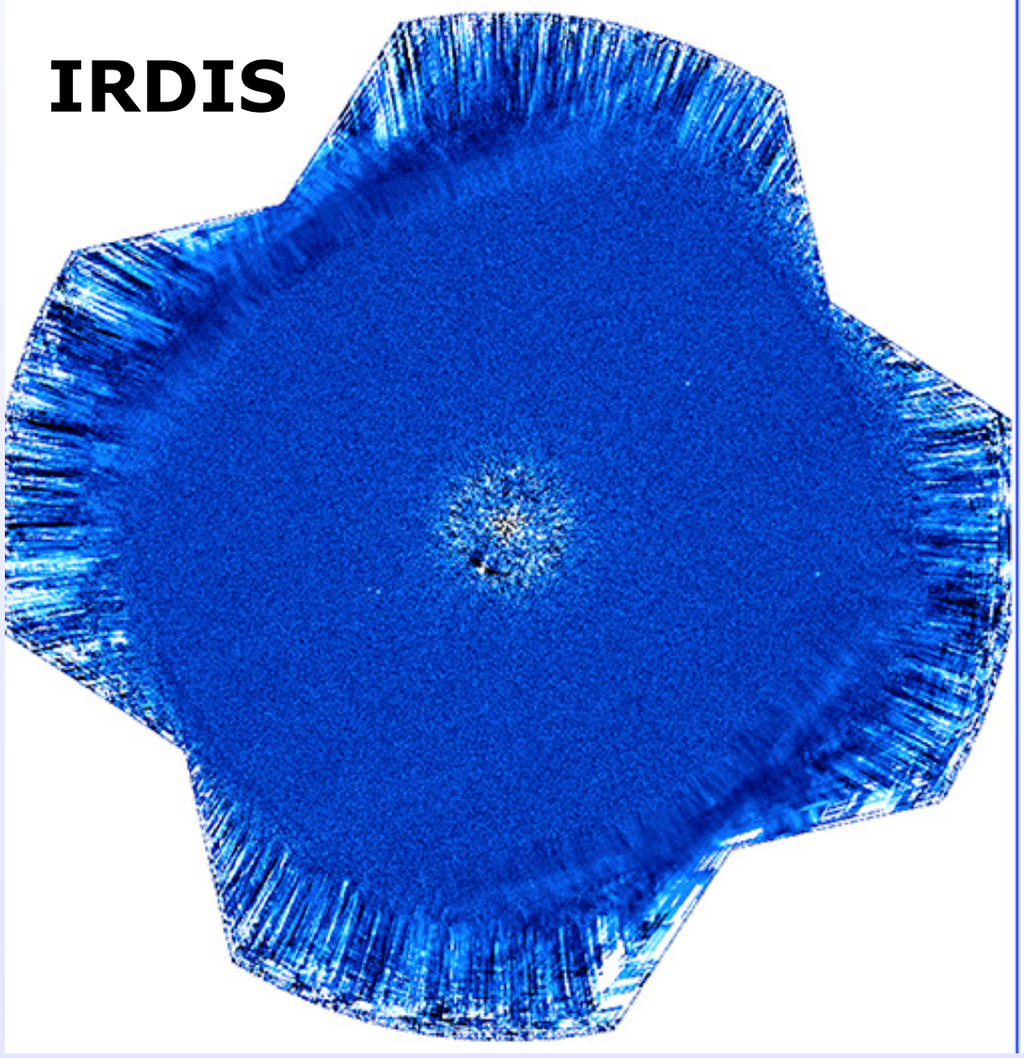
200 nights of VLT/SPHERE over 5 years

- ~160 nights already done (80%)
- **GTO done in Visitor Mode**
- Statistics:
  - 25% bad weather loss
  - 5% technical loss
- Strategy:
  - IRDIFS or IRDIFS-EXT
  - ADI
  - ~1.5 hour/target
- scheduling tool (SPOT) to optimise the survey on the long-term

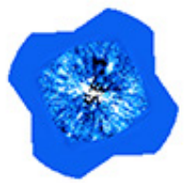
Data analysis

- SPHERE Data Center hosted @ IPAG:
  - **fully automated** pre-processing pipeline
  - SpeCal pipeline for ADI-processing (Galicher et al. in 2018): **TLOCI**, PCA, cADI, RDI
  - Candidates astrophotometry derived after **eye identification**

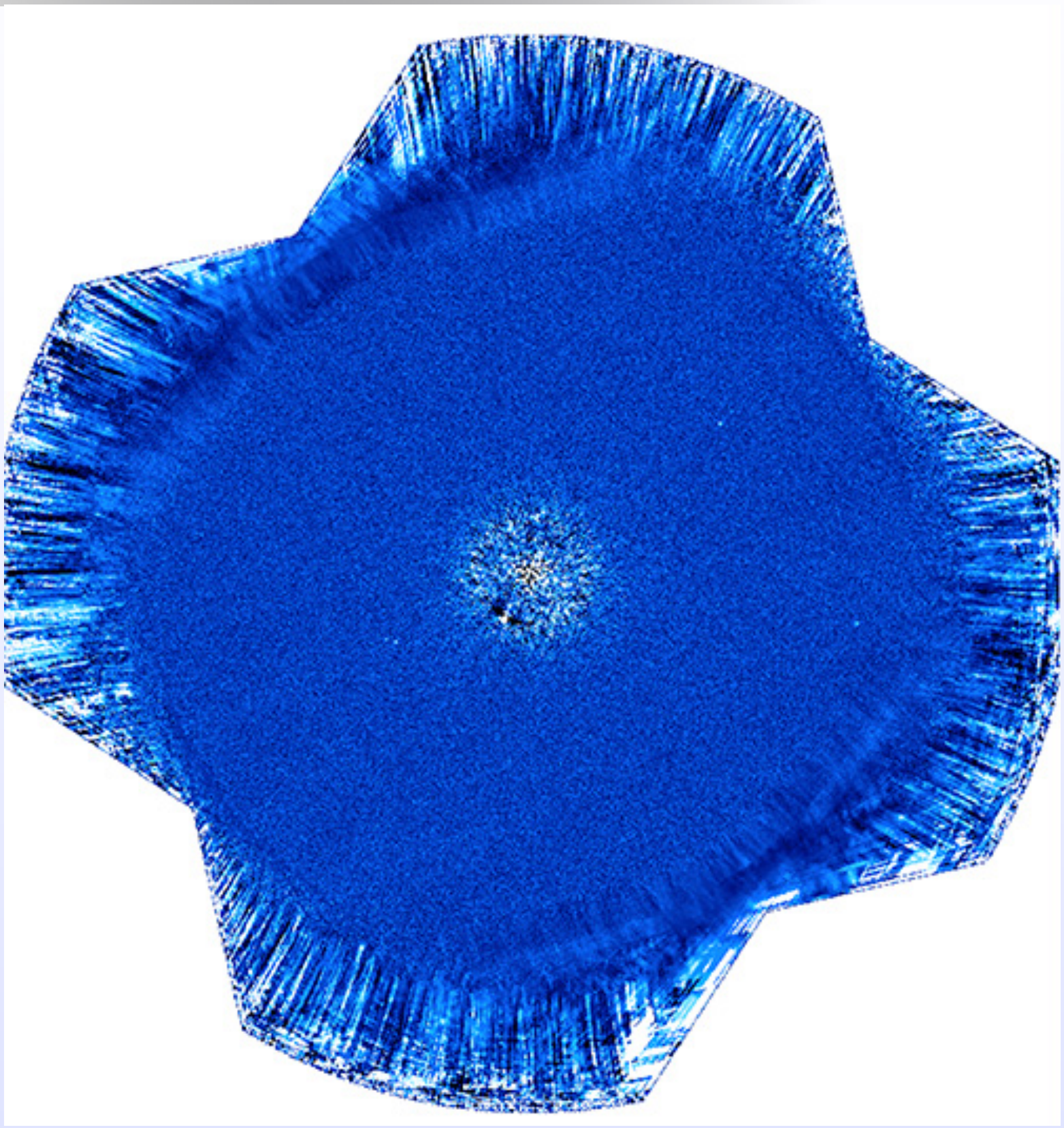
IRDIS



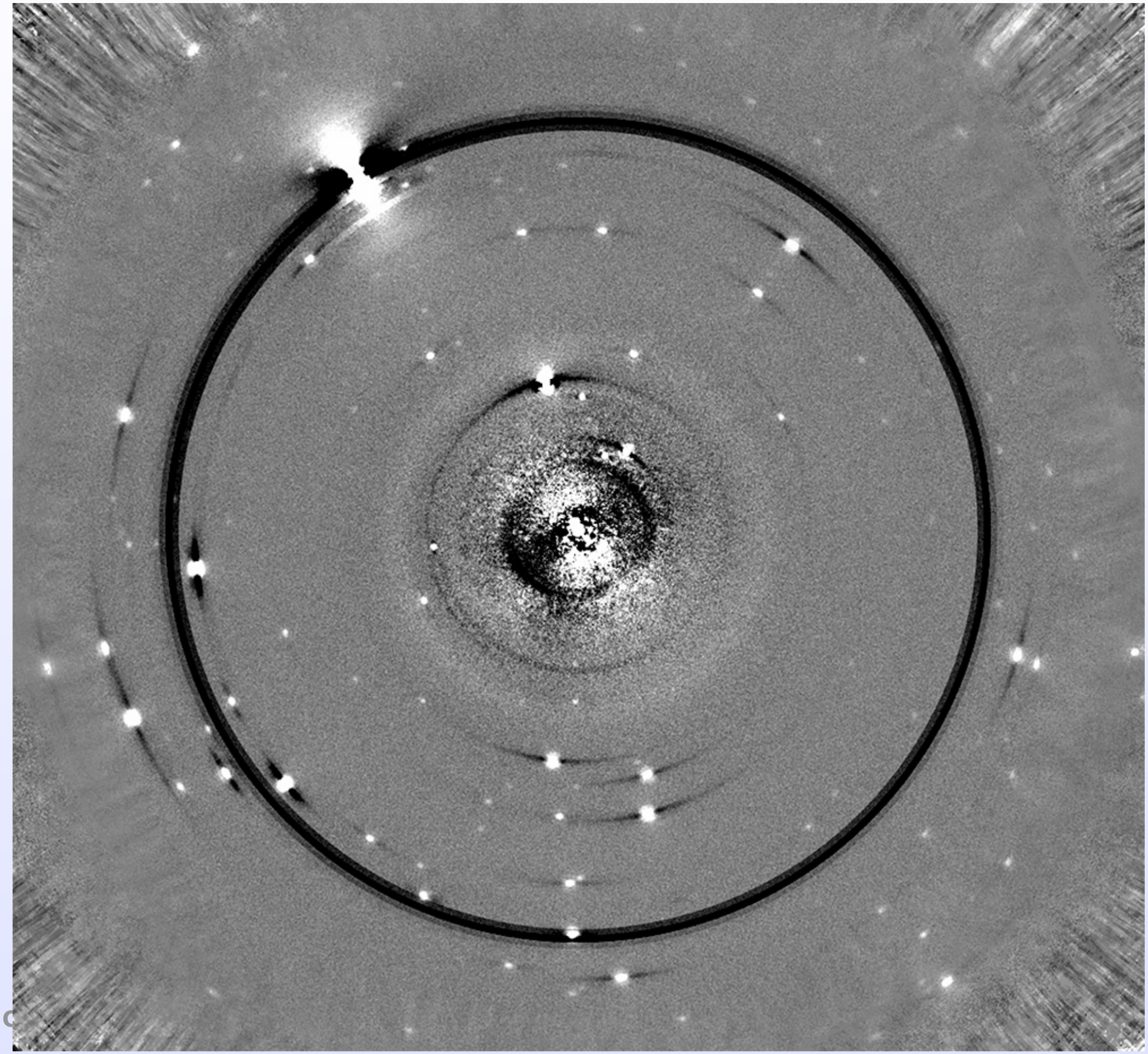
IFS



The candidates nightmare

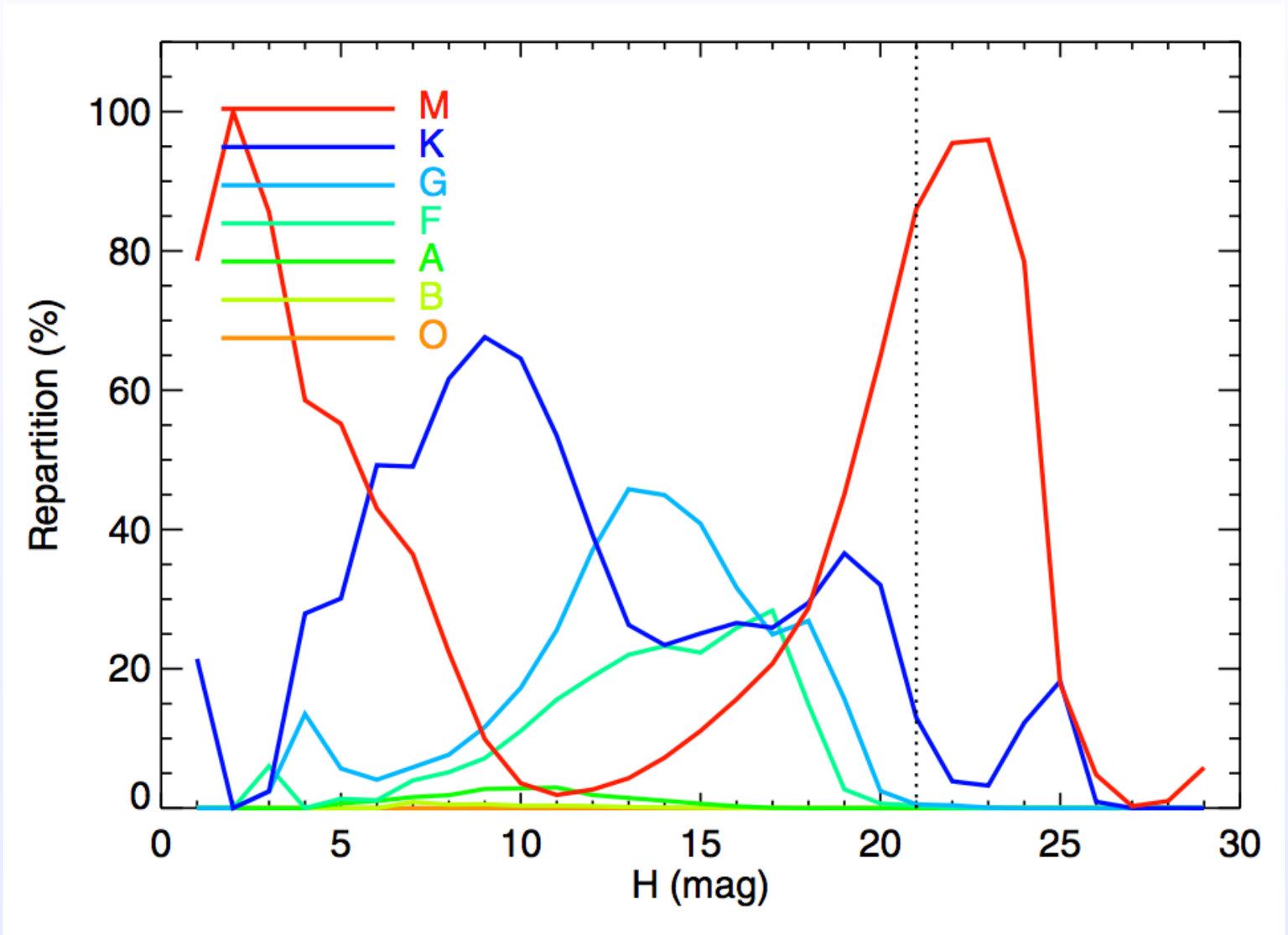


The candidates nightmare



Background stars contamination

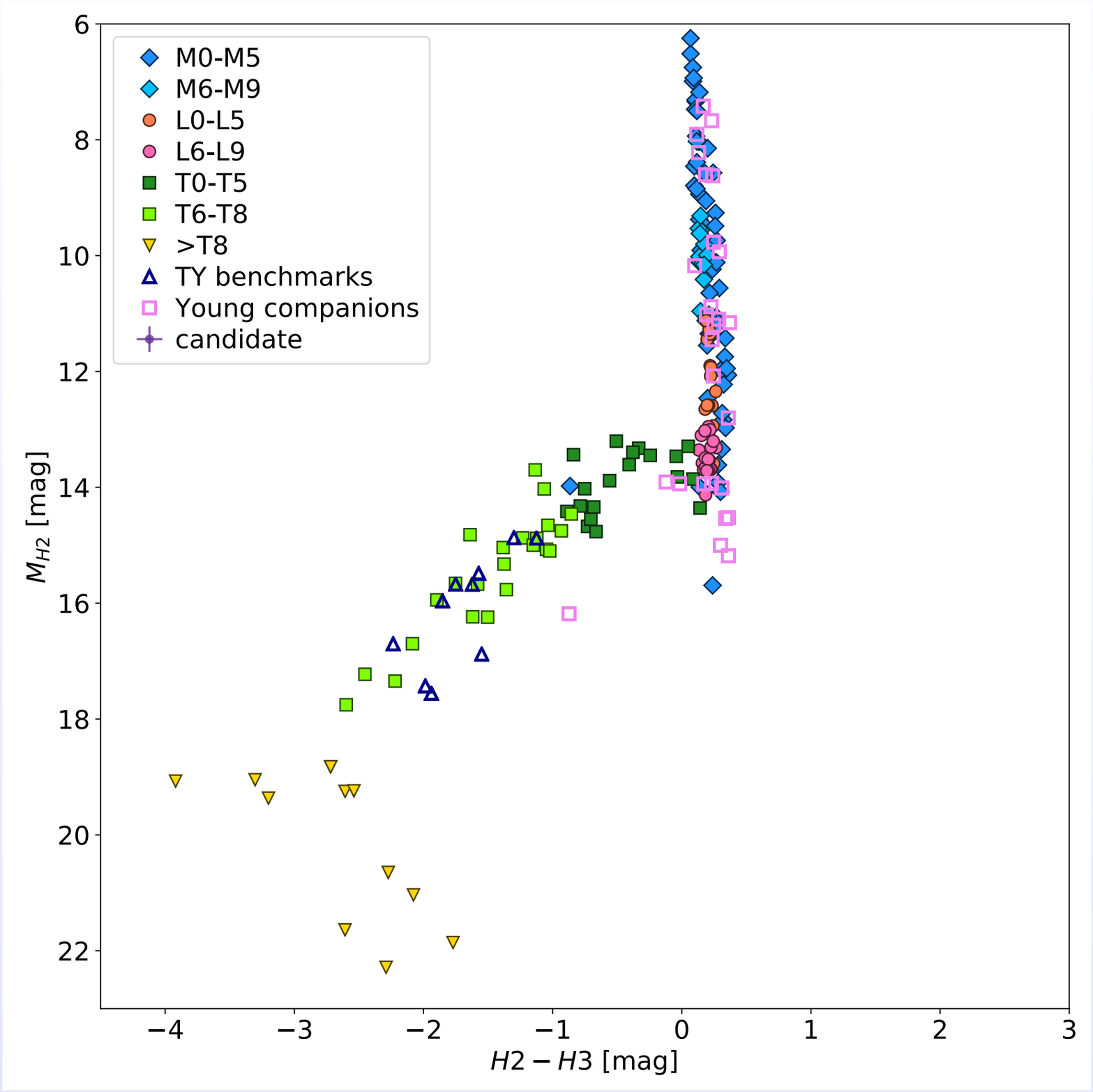
Besançon models, 13" FoV, H-band (Chauvin et al. 2015)



- Contamination probability:
  - $\propto$ FoV^2
  - 5% for IFS / 40-50% for IRDIS

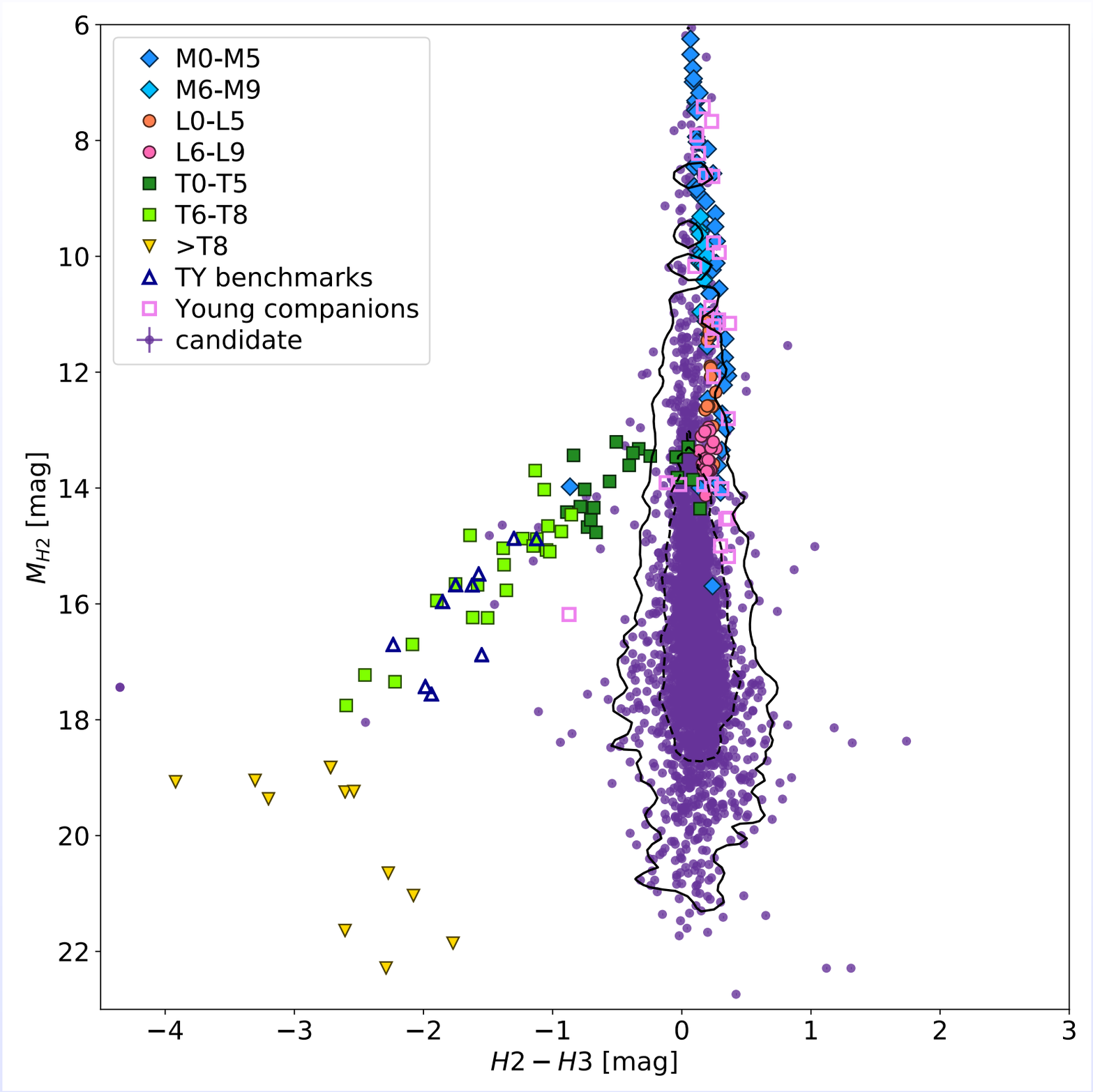
SHINE candidates

IRDIS H23 photometry



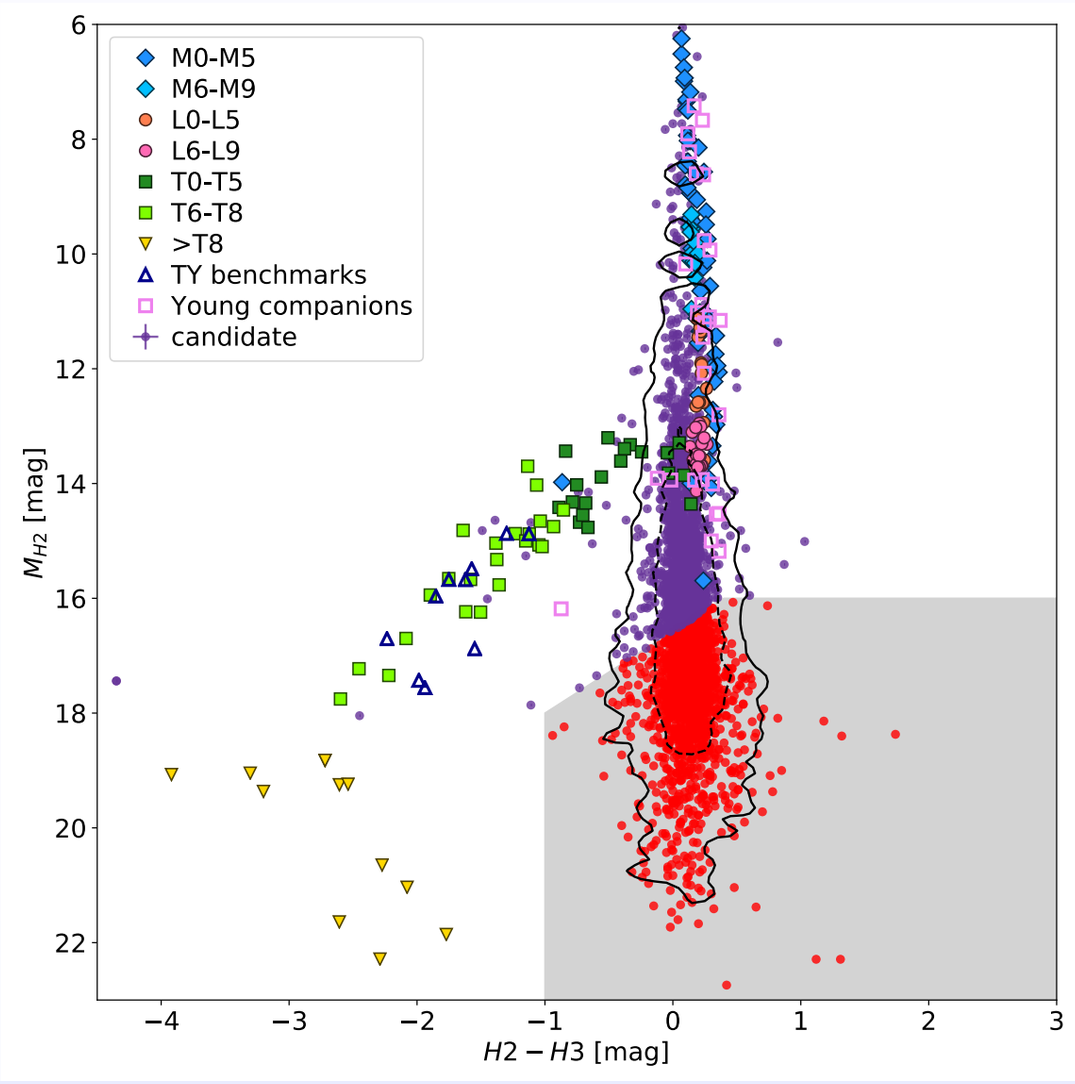
SHINE candidates

IRDIS H23 photometry



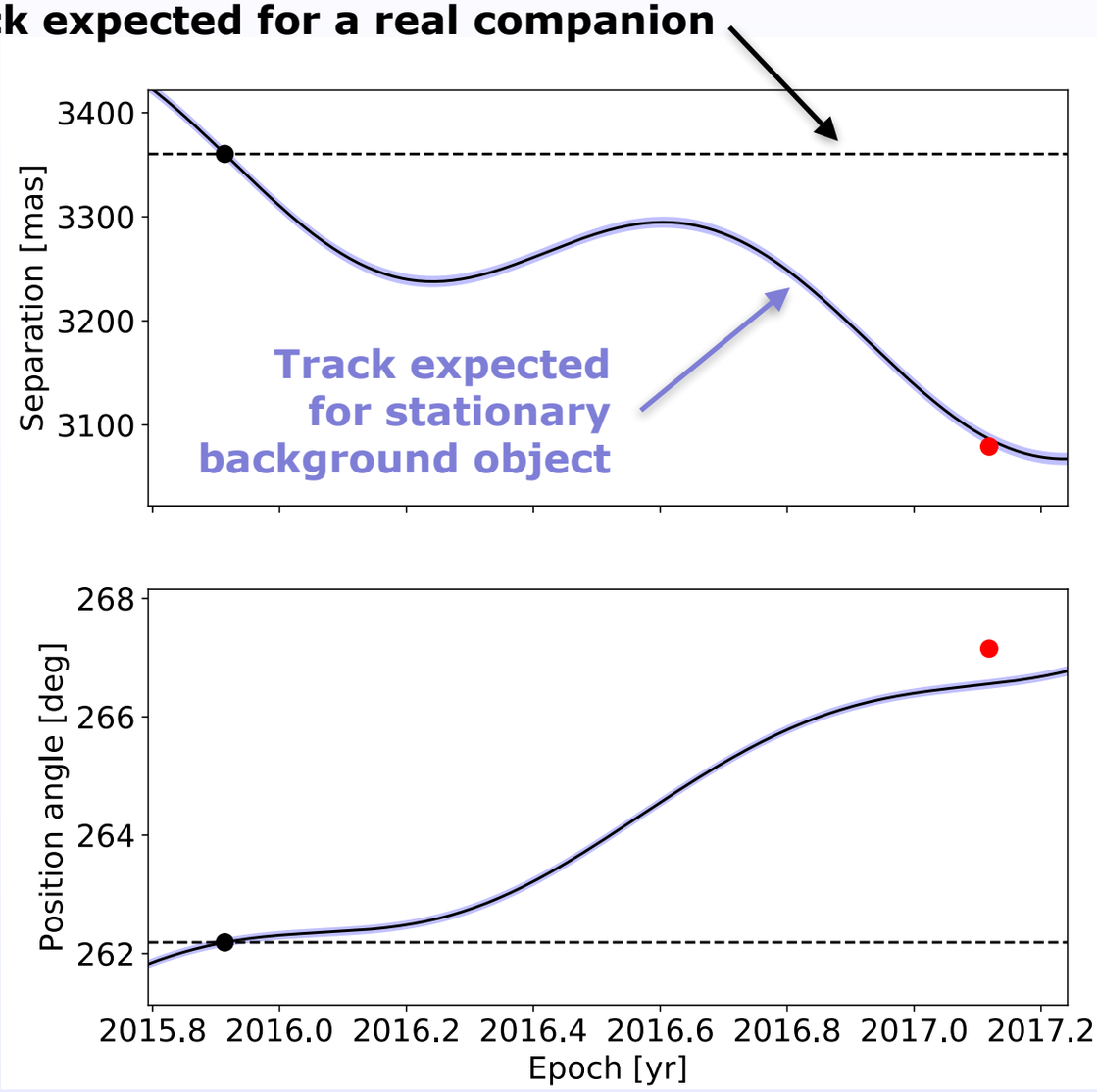
>2900 undefined candidates!

Reducing candidates



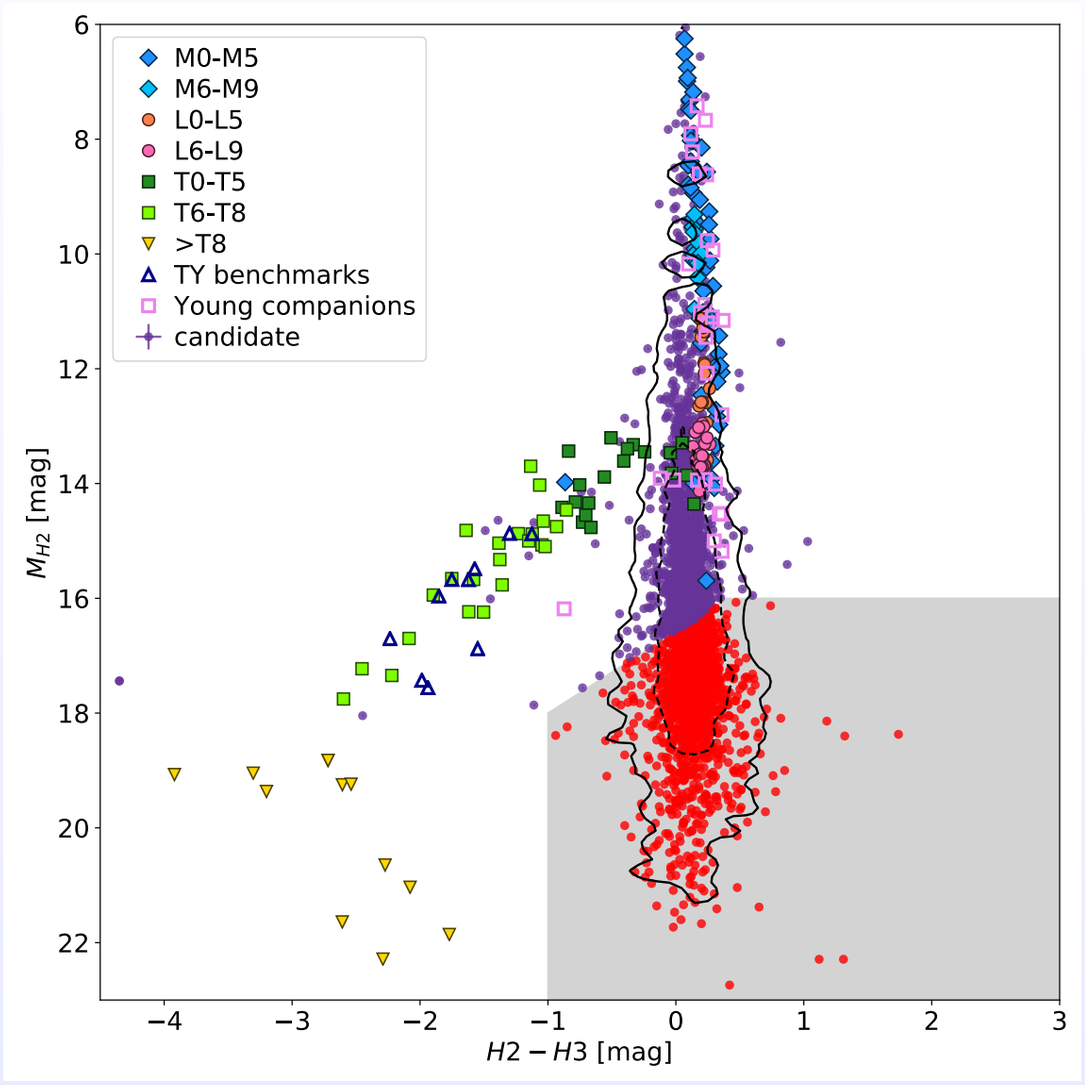
Color-mag diagram rejection

Track expected for a real companion



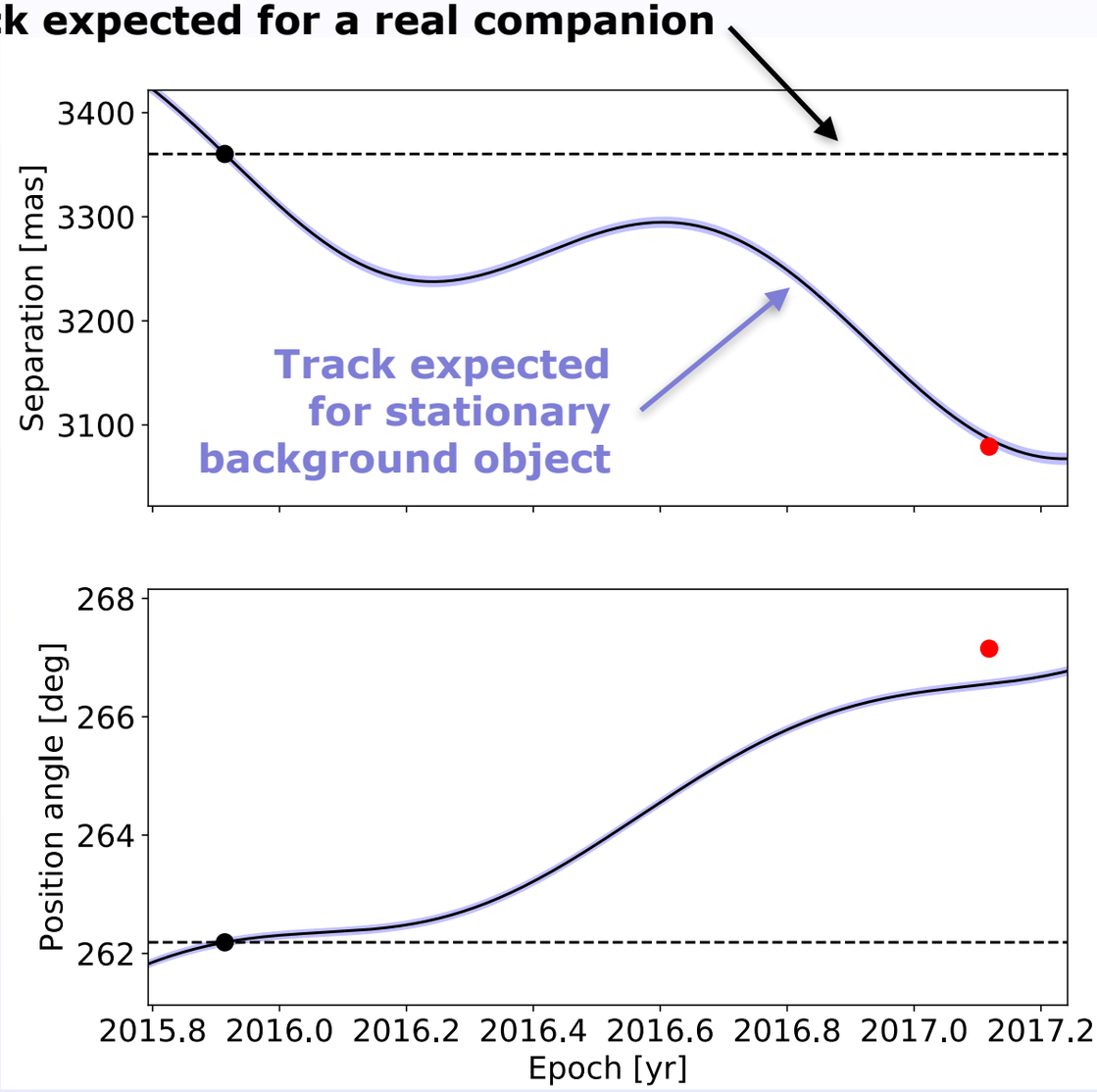
Second epoch astrometry

Reducing candidates



Color-mag diagram rejection

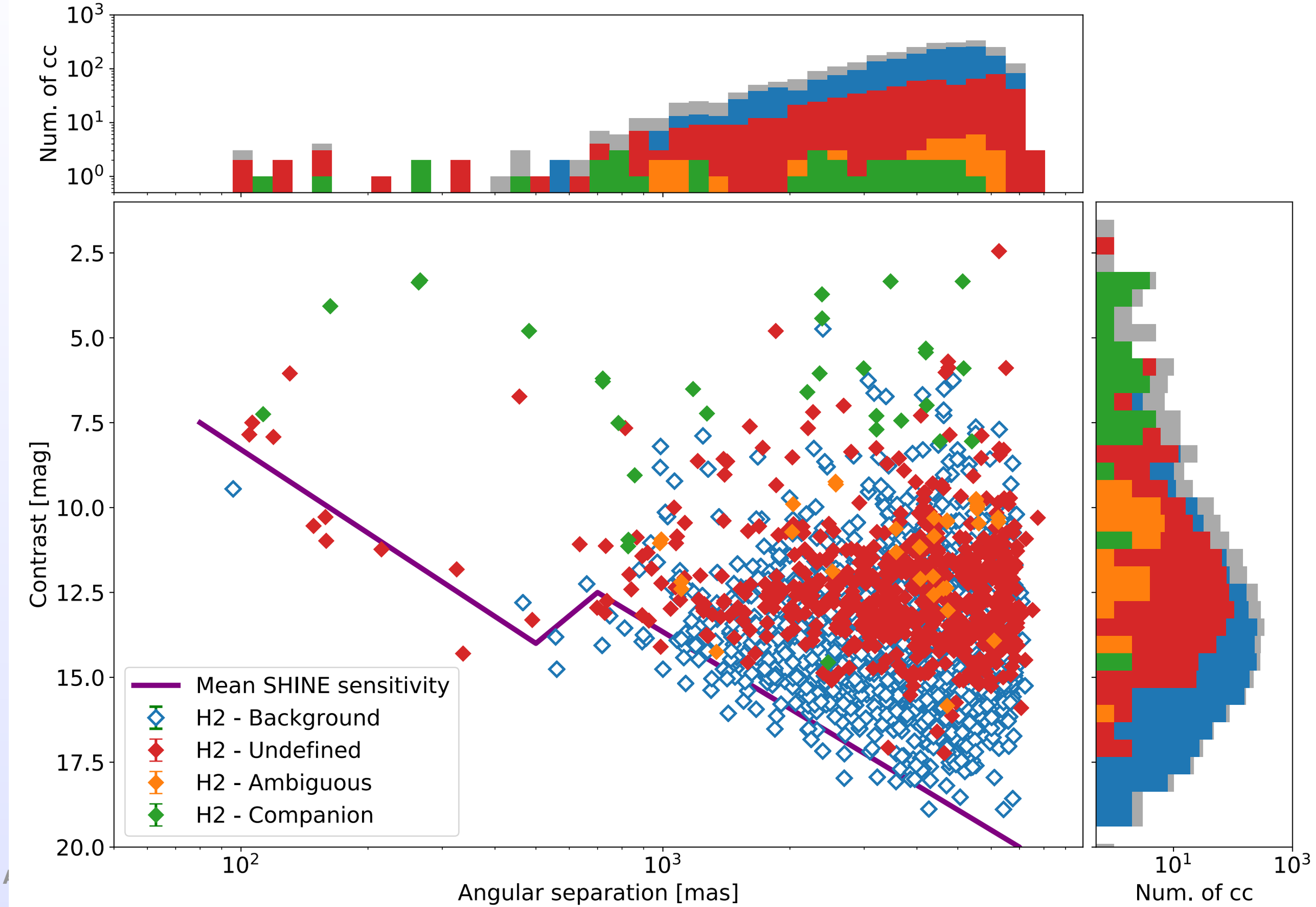
Track expected for a real companion



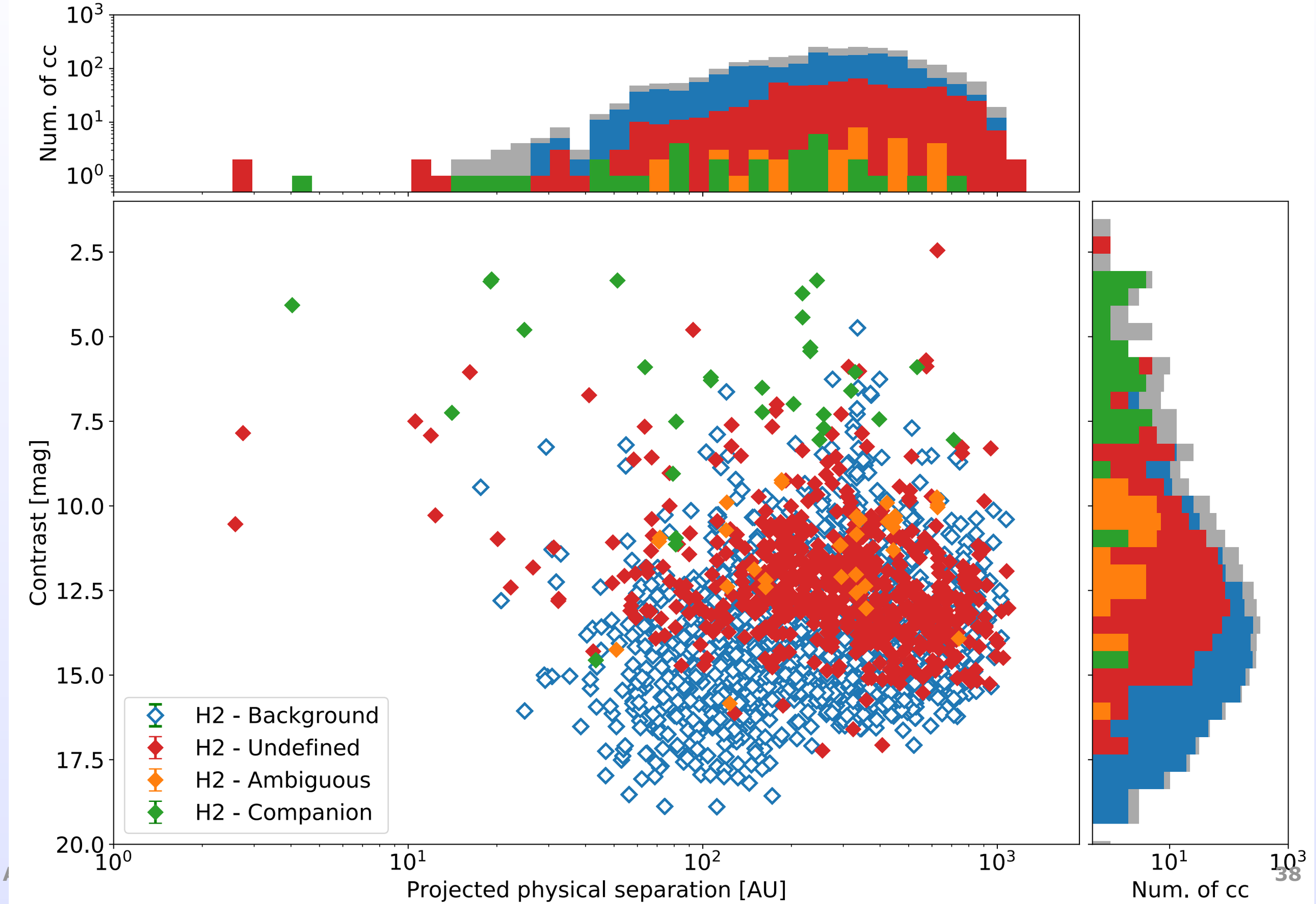
Second epoch astrometry

~40 companions
>1800 background
~800 undefined candidates

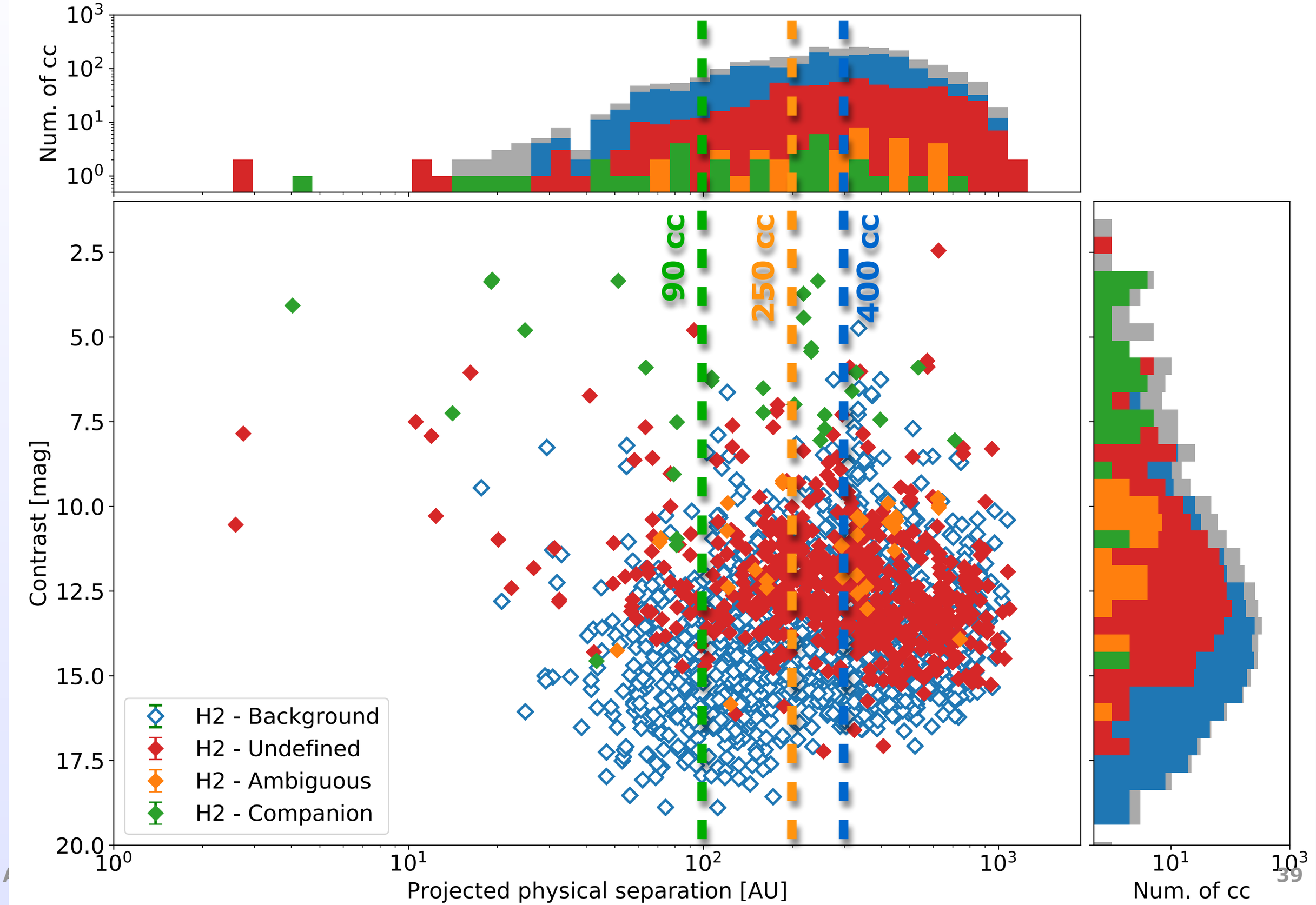
Reducing candidates



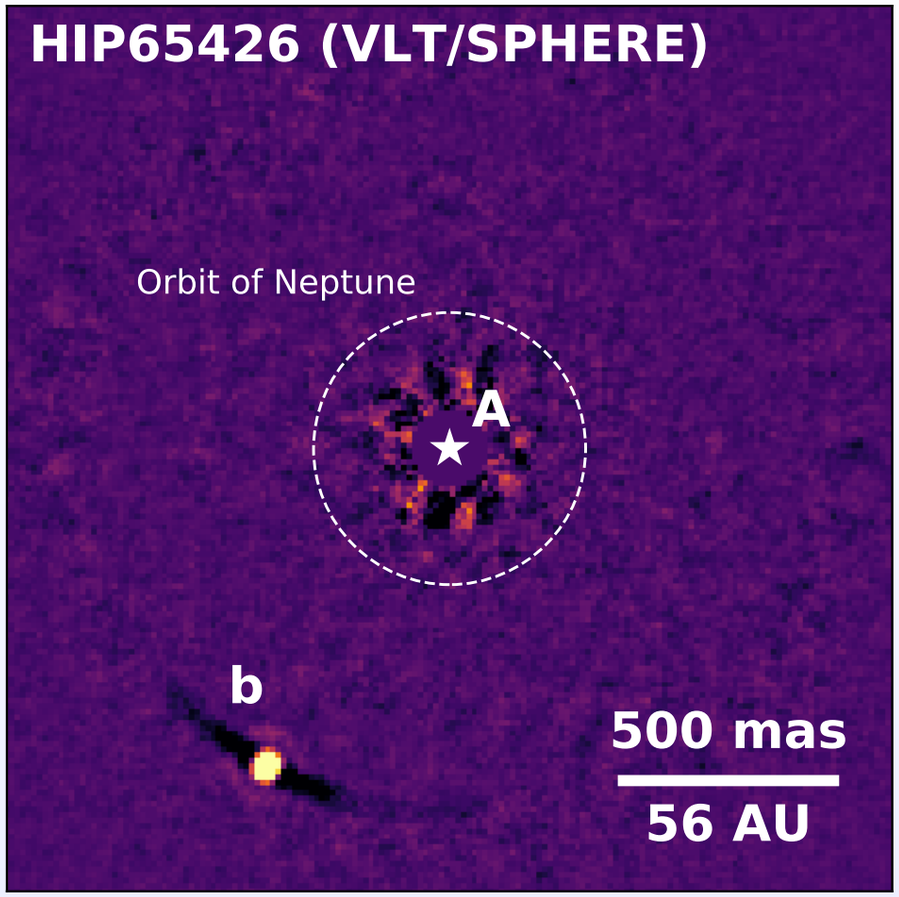
Reducing candidates



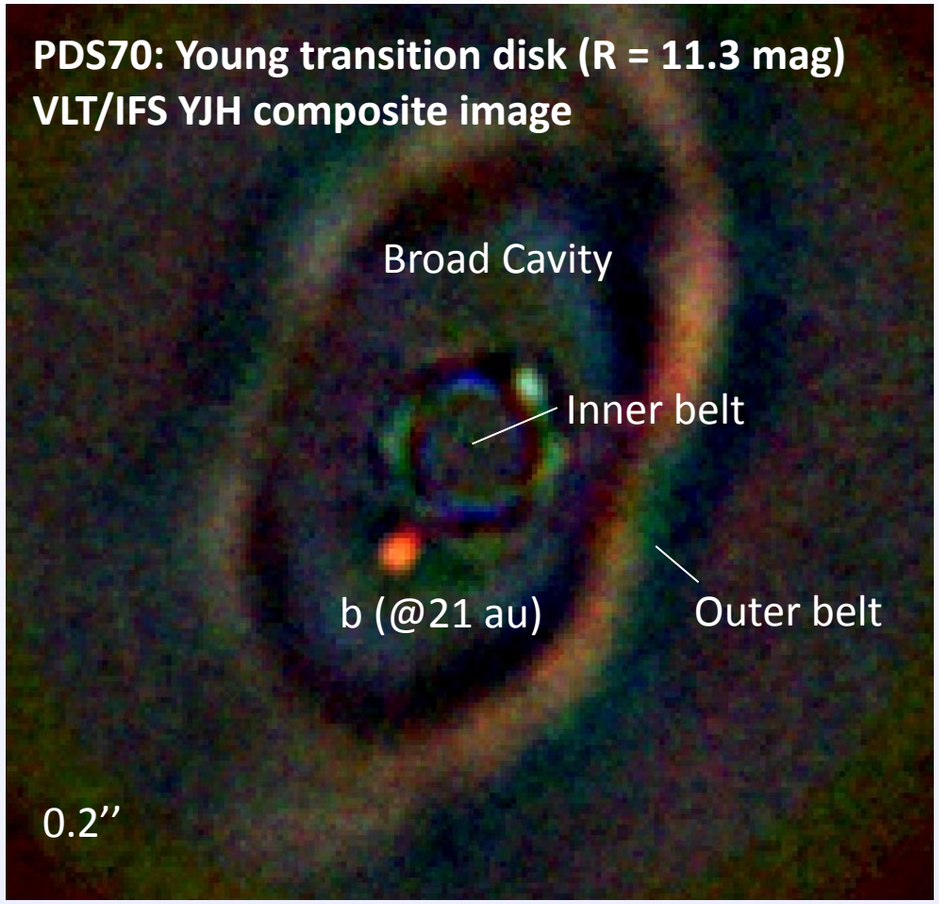
Reducing candidates: semi-major axis cutoff



SPHERE detections



Chauvin et al. 2017



Keppler et al. 2018

HIP 65426

A2V, 111.4pc
LCC member, 14 Myr,
No IR excess; fast-rotator (300 m/s)

HIP 65426 b

Separation = 830 mas (92 au)
$\Delta H2 = 11 \pm 0.1$ mag
Mass = 6-12
Teff = 1300 – 1600 K

PDS 70

K7, 113.4pc
UCL member, 5 Myr,
Transition disk with cavity

PDS 70 b

Separation = 195 mas (21 au)
$\Delta H2 = 9.3 \pm 0.2$ mag
Teff = 1000 – 1600 K
Large radius

Giant exoplanets occurence rate

What is the frequency of young giant exoplanets on wide orbit?

Giant exoplanets occurence rate

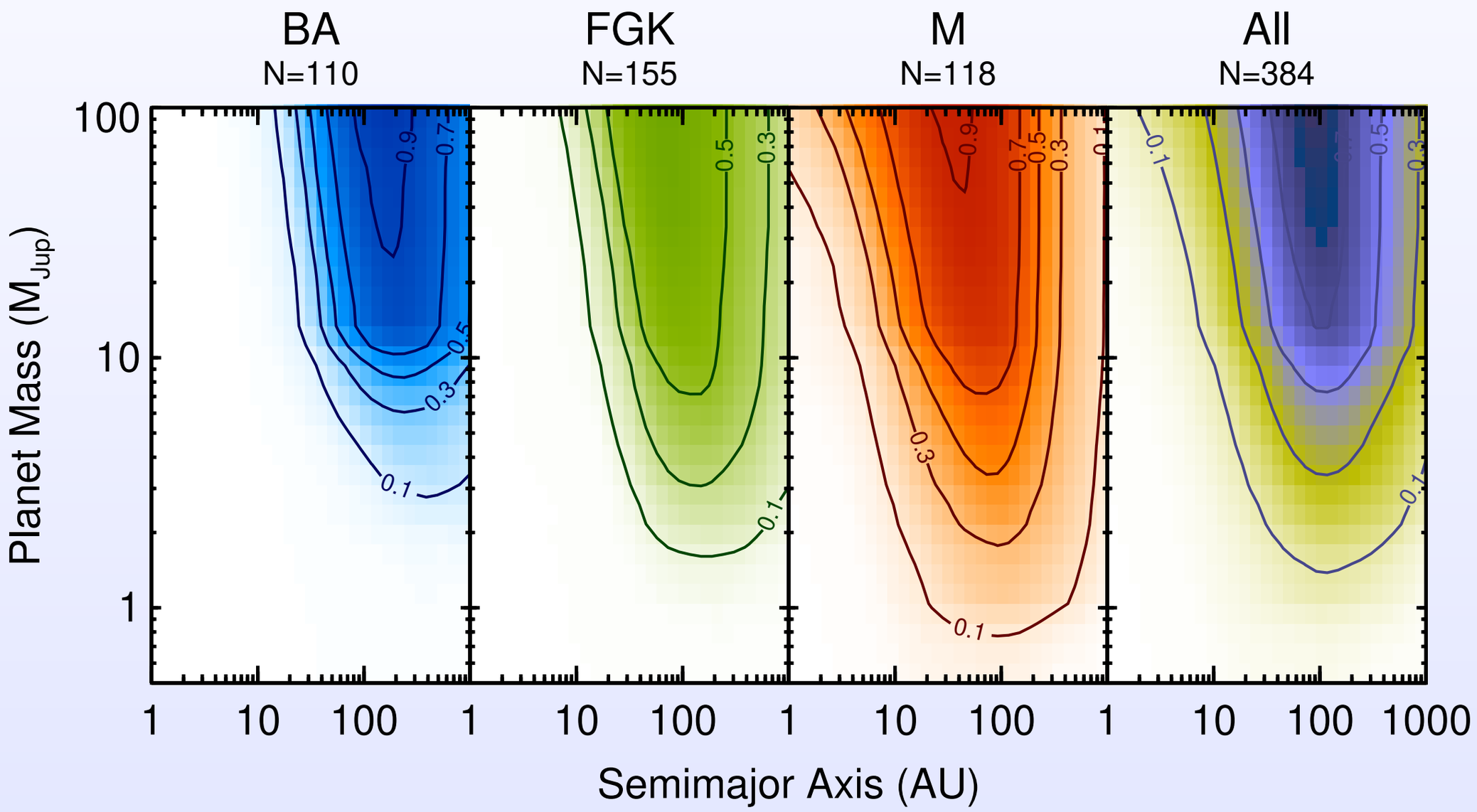
What is the frequency of young giant exoplanets on wide orbit?

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), …

Giant exoplanets occurence rate

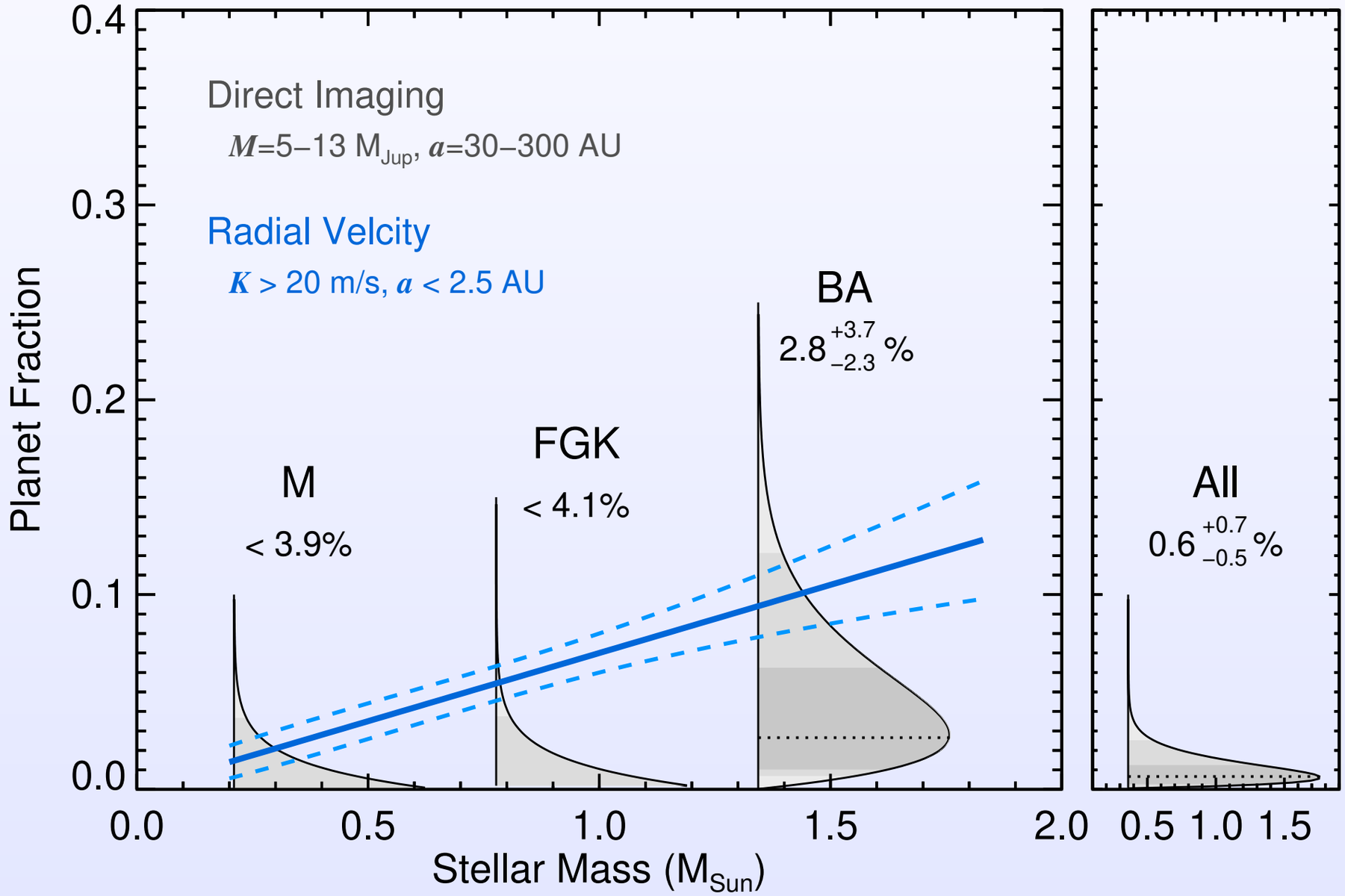
What is the frequency of young giant exoplanets on wide orbit?



Bowler (2016)

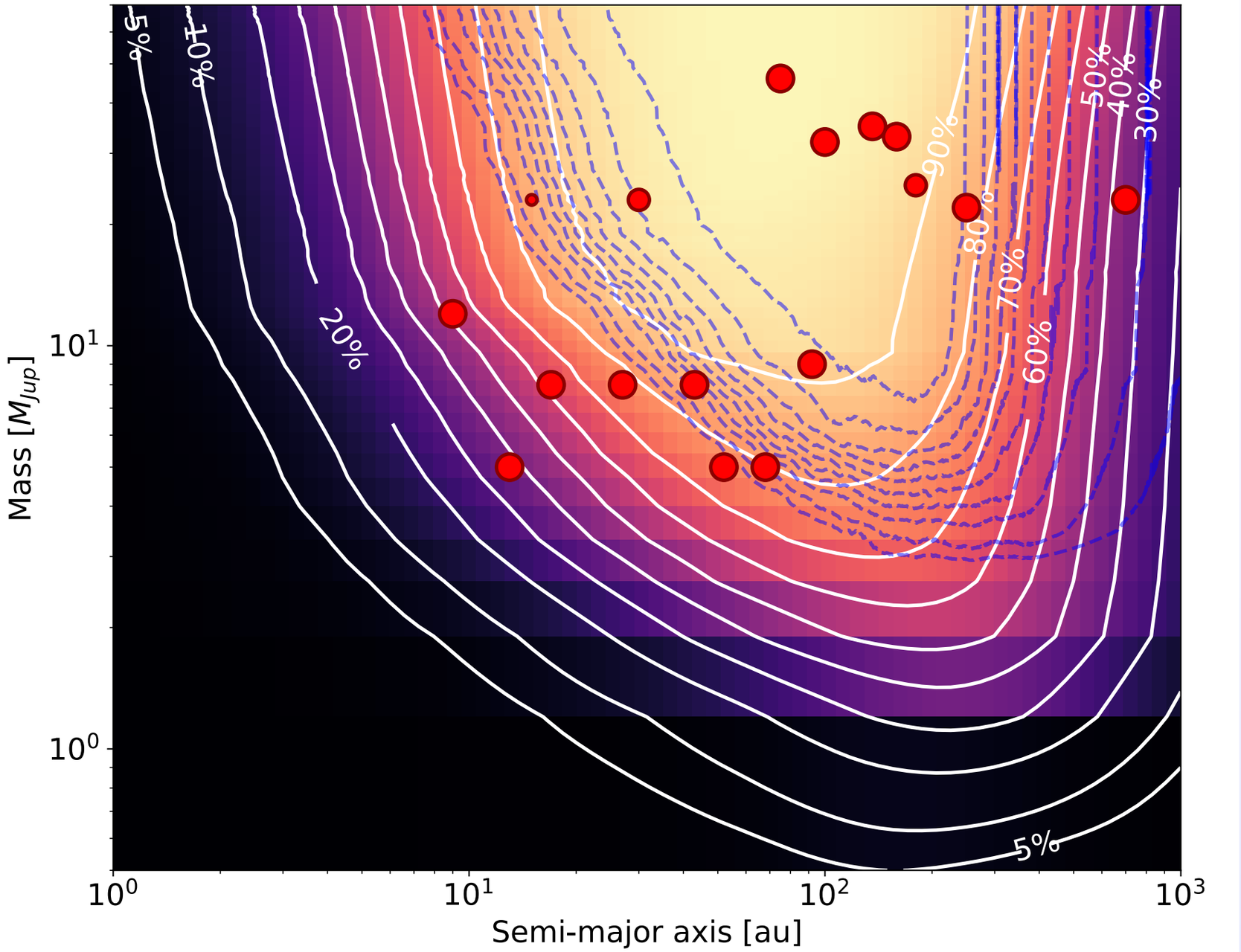
Giant exoplanets occurence rate

What is the frequency of young giant exoplanets on wide orbit?



Bowler (2016)

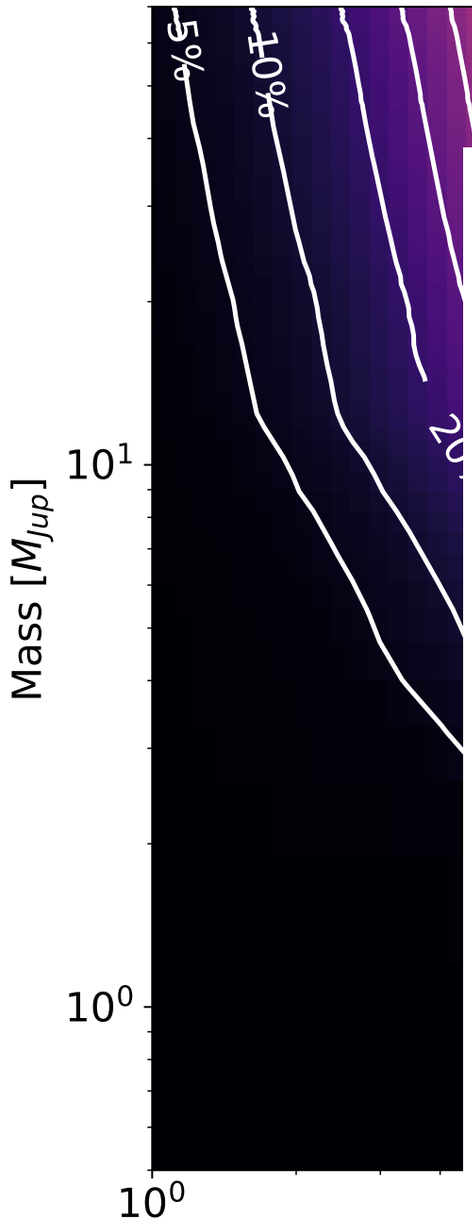
Occurence rate from SHINE

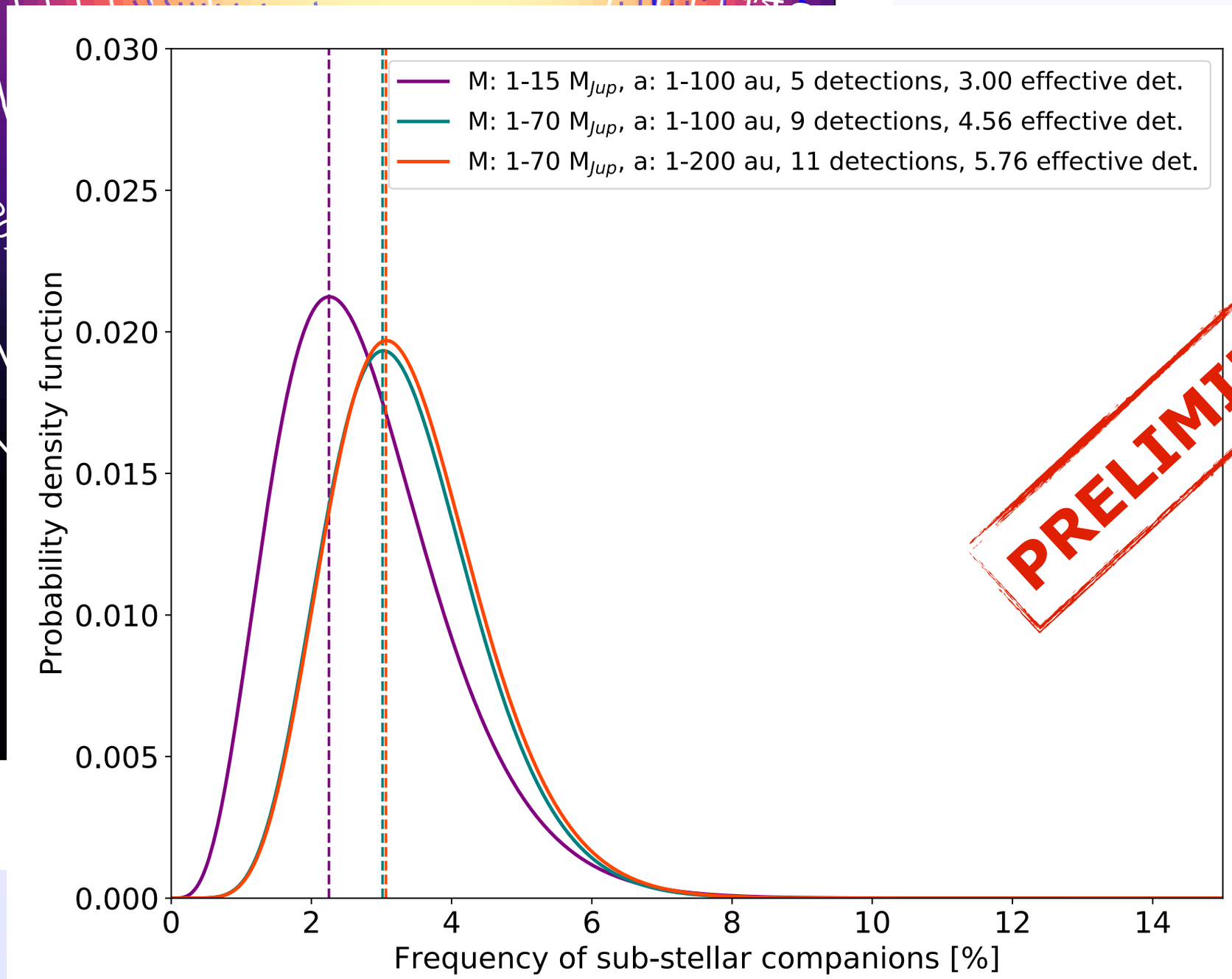


~160 stars, all spectral types

Vigan et al. (in prep)

Occurence rate from SHINE





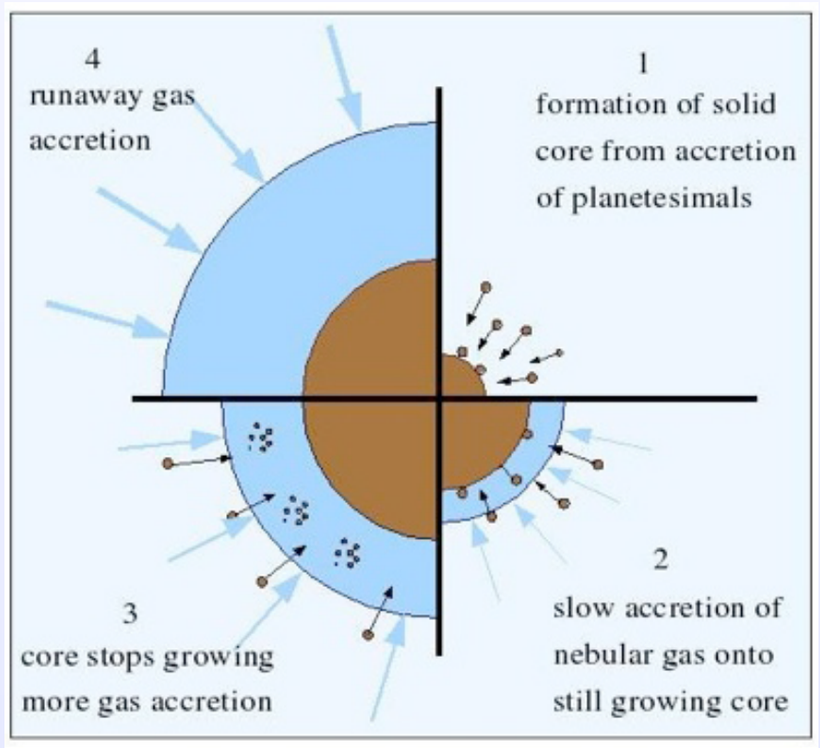
PRELIMINARY

Vigan et al. (in prep)

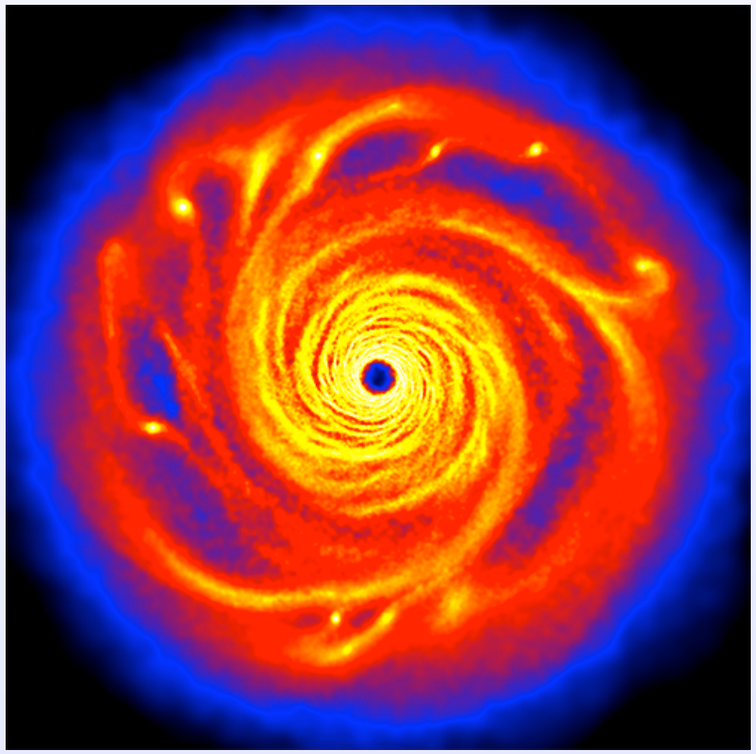
Link to formation models

Can direct imaging observations constrain formation models?

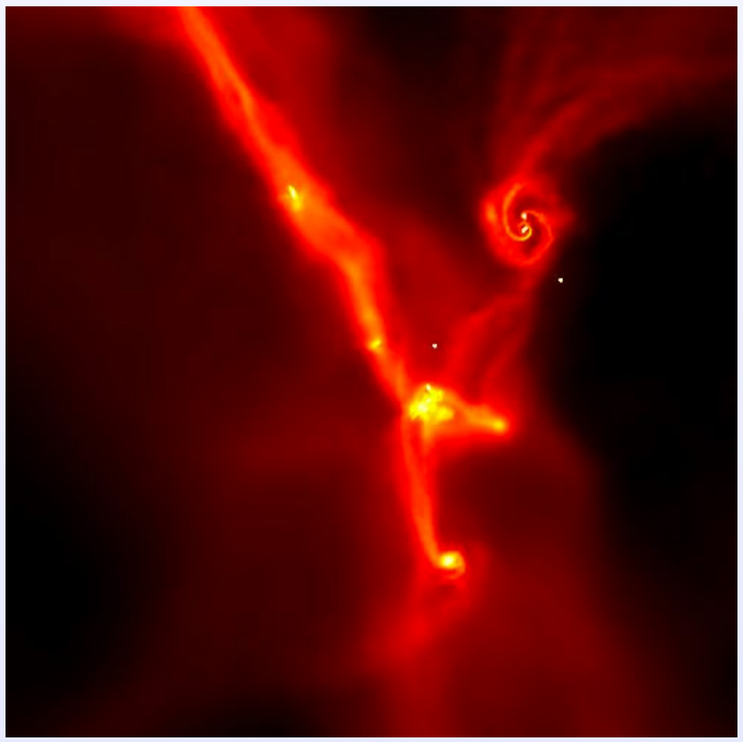
Core Accretion
Pollack et al. 1994



Gravitational Instability
Cameron 1978

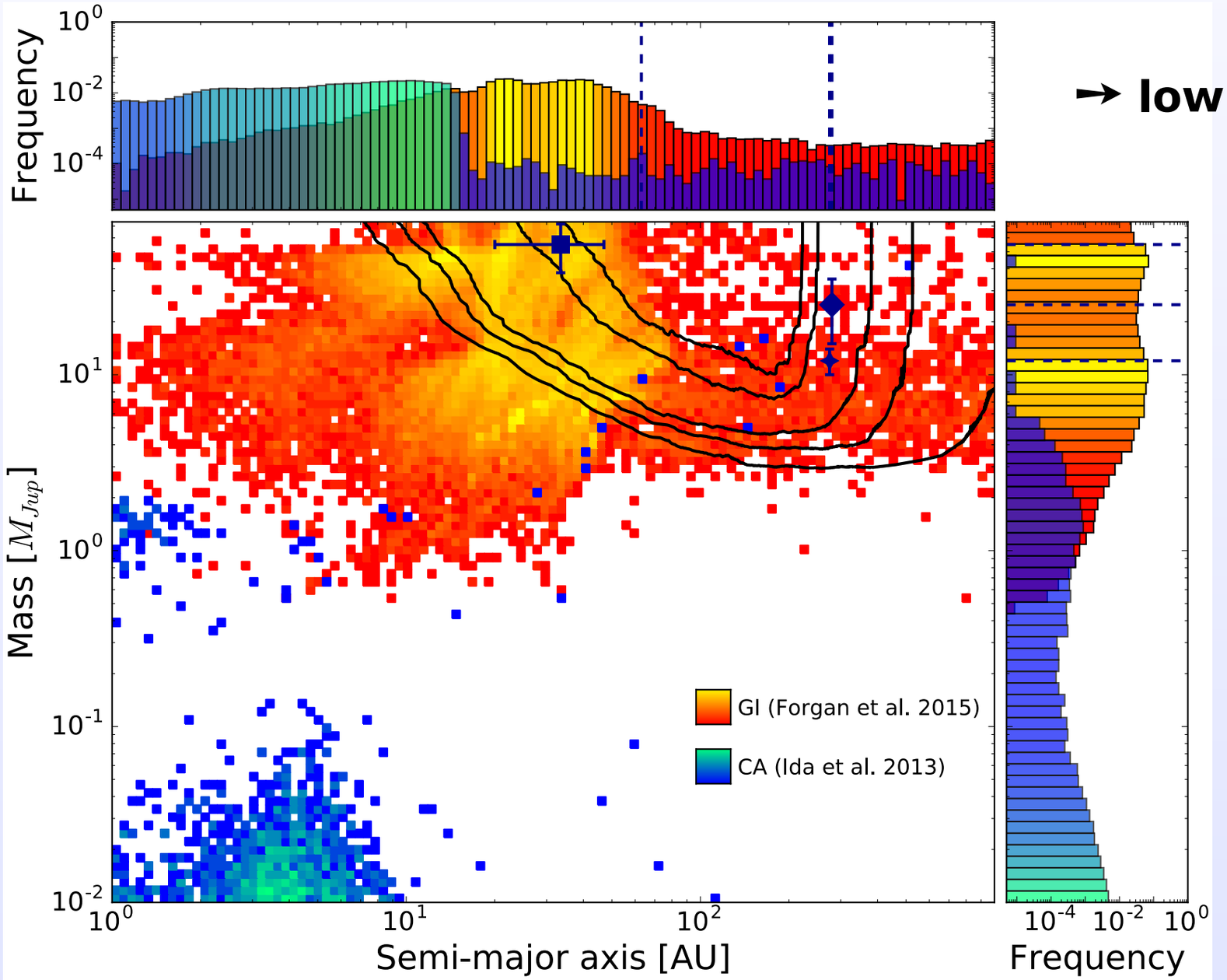


Gravo-turbulent fragmentation
Hennebelle & Chabrier 2011



Link to formation models: NaCo-LP

- VLT/NaCo large programme (2009-2012)
- 200 FGK stars, 3 detections
- Comparison to population synthesis models by Forgan et al. ➙ gravitational instability



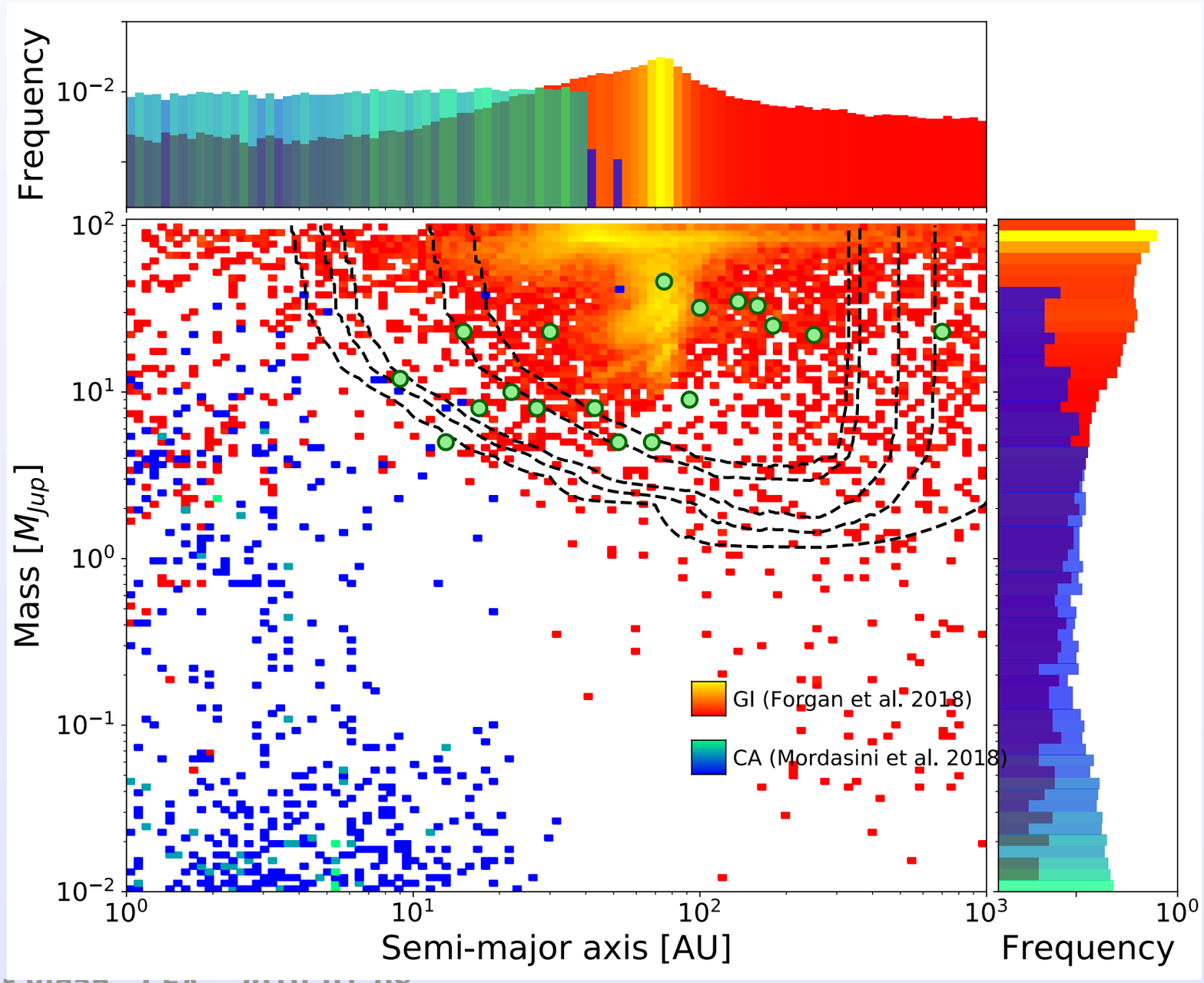
➙ **low occurence rate: <4%**

- **GI not dominant!**
- CA not accessible
- Alternatives?
  - multi fragmentation GI
  - pebble accretion
  - dynamical evolution

Vigan et al. (2017)

Link to formation models: SHINE

- First sub-sample of the SHINE survey
- 160 AFGKM stars, 14 detections
- State-of-the-art CA models (Mordasini et al.) and GI models (Forgan et al.)



On-going

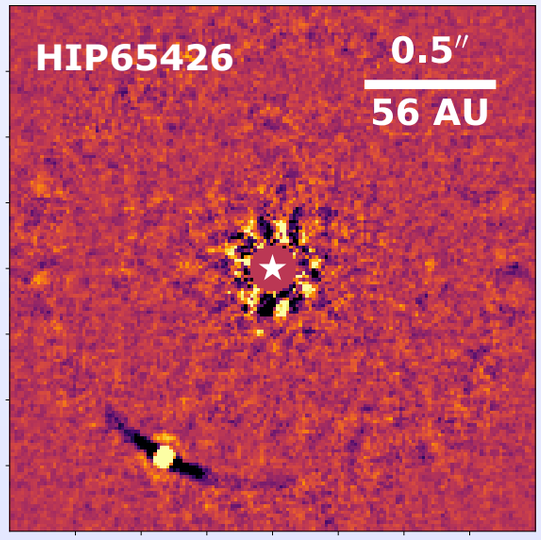
Vigan et al. in prep.

Future

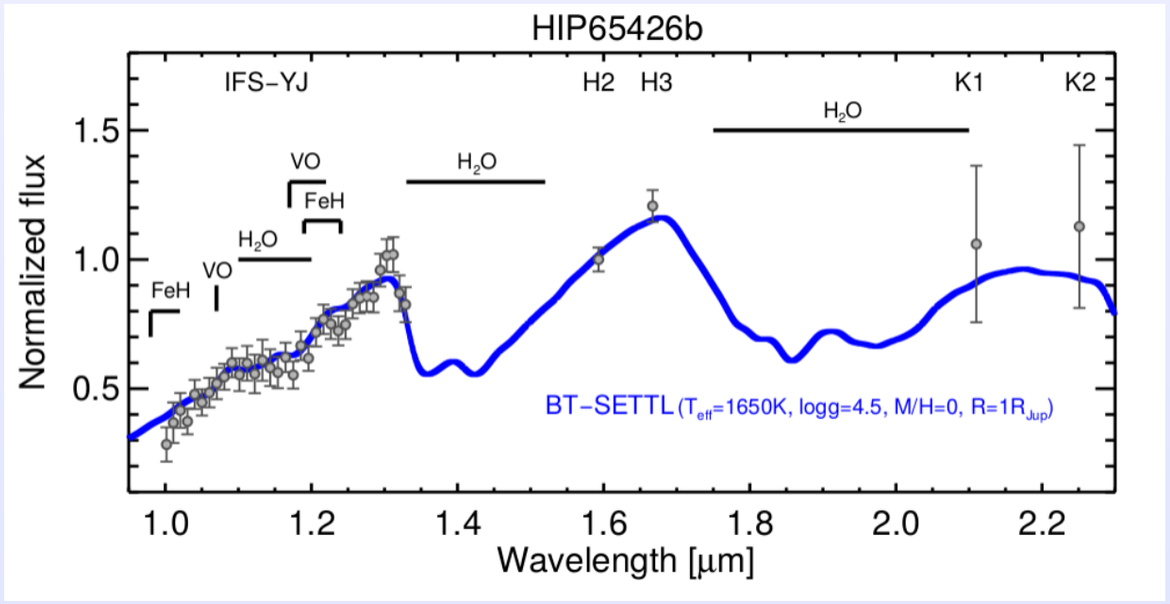
So… what's next? What do we want?

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

More planets

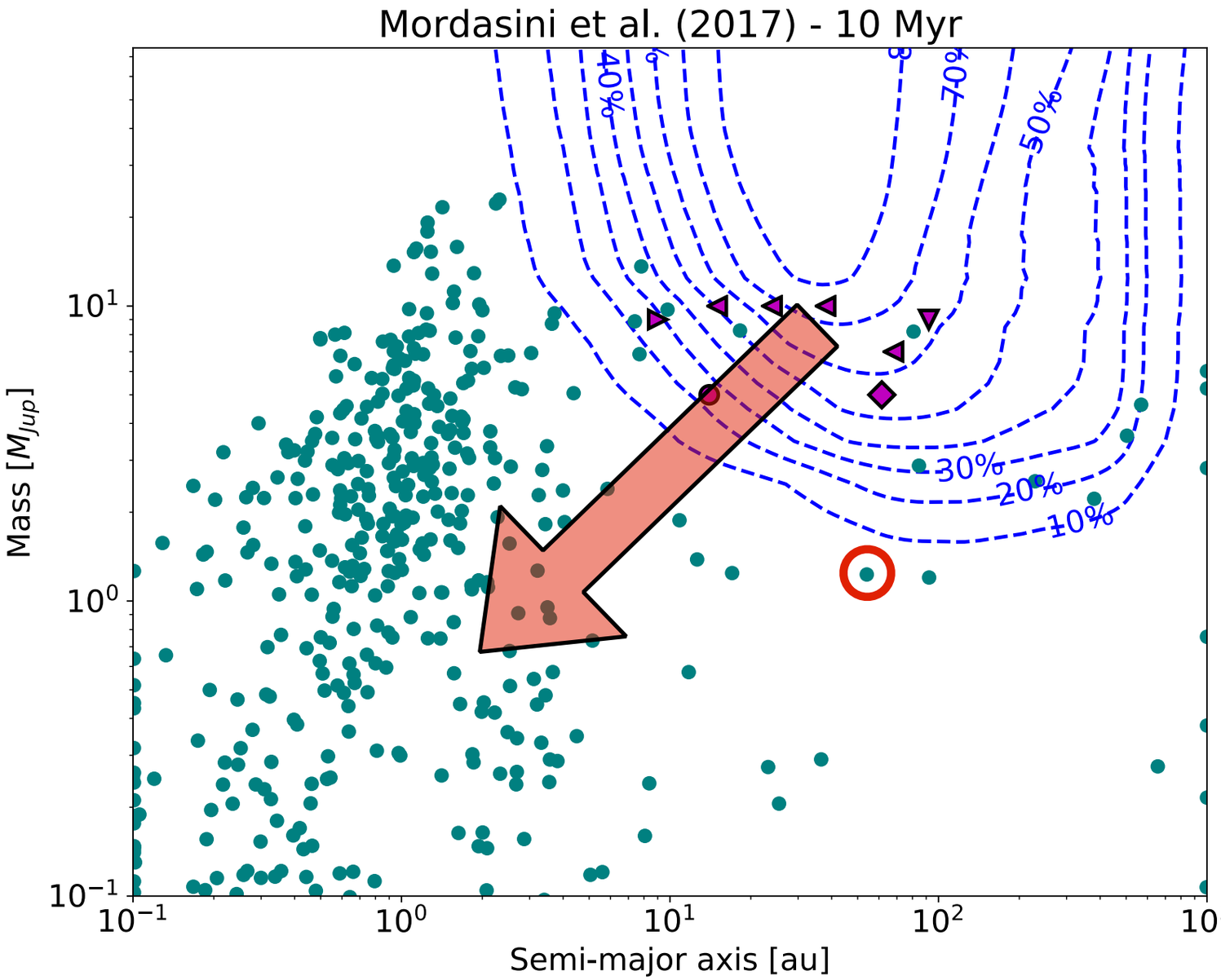


Improved characterization



More planets: closer, deeper

High-angular resolution



High-contrast

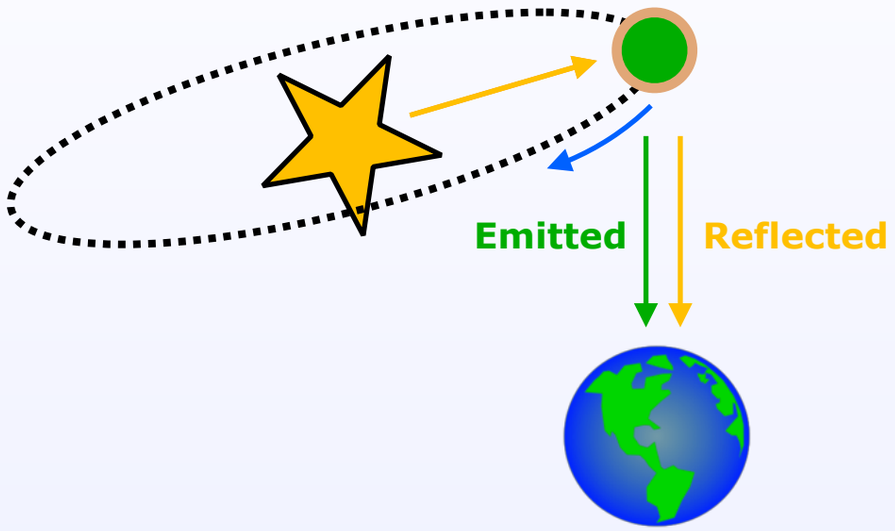
Going to higher spectral resolution

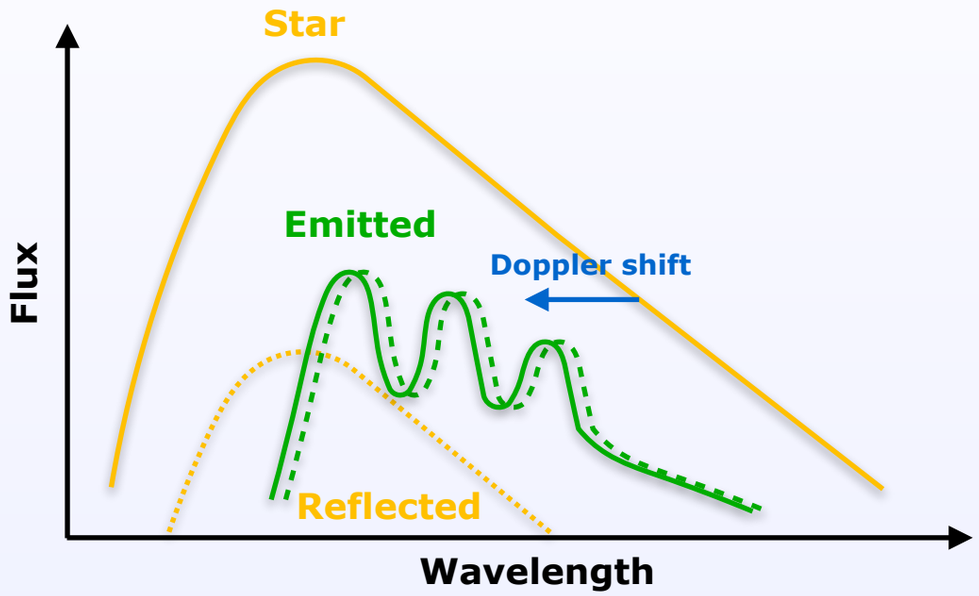
Detection

Characterization

Going to higher spectral resolution

Detection

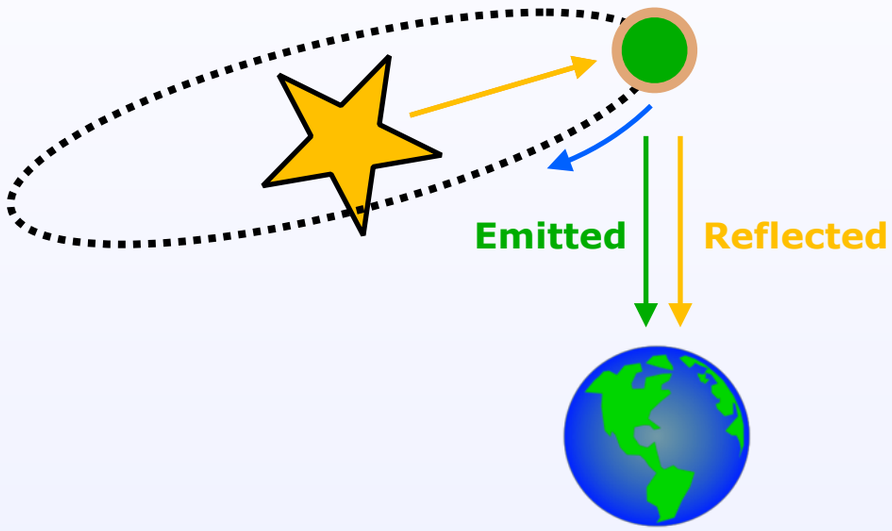


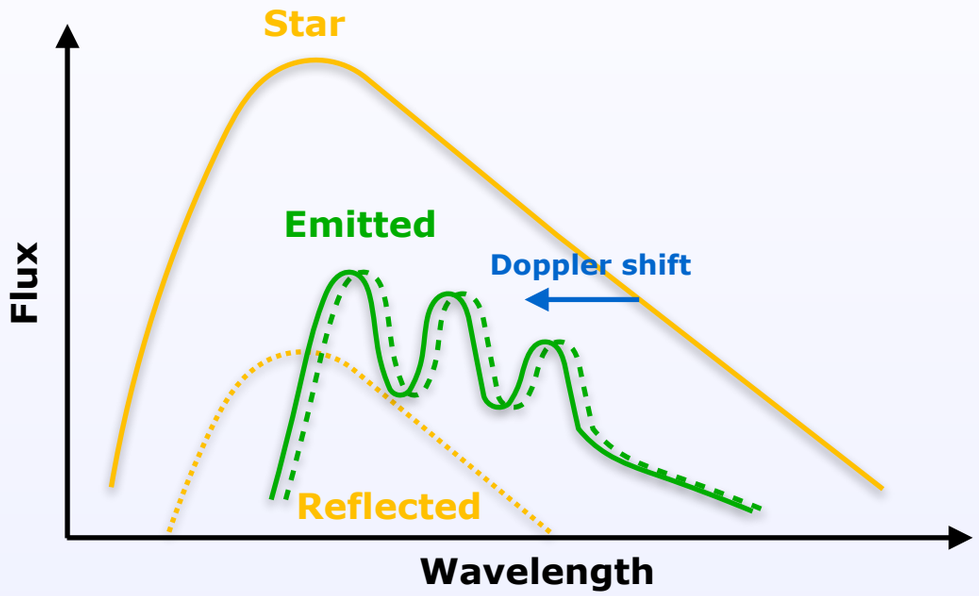


Characterization

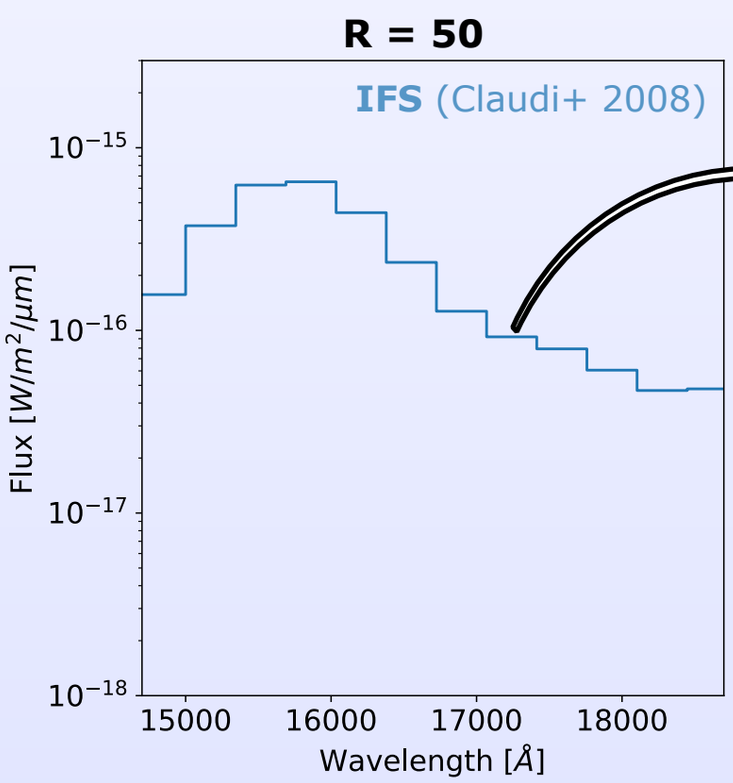
Going to higher spectral resolution

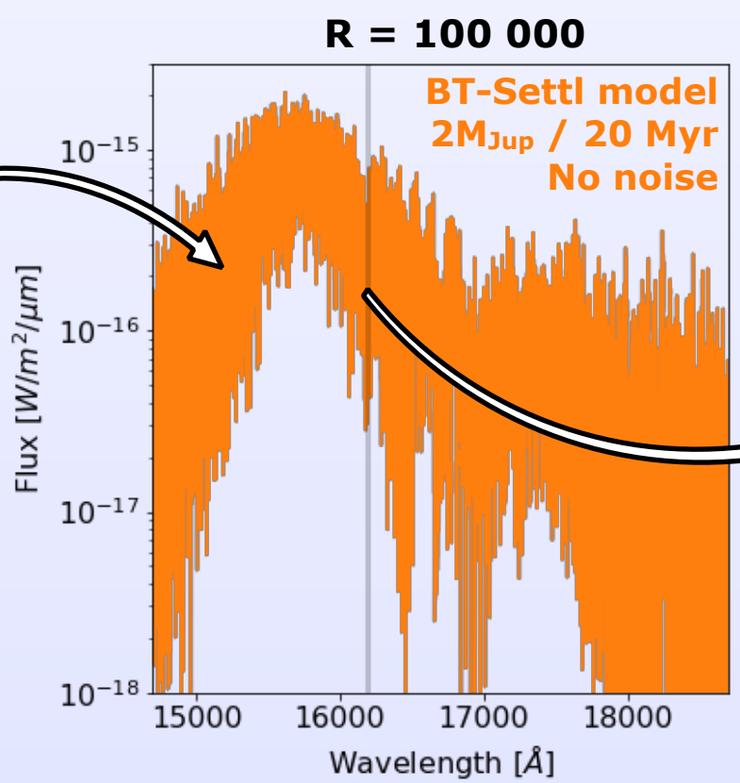
Detection

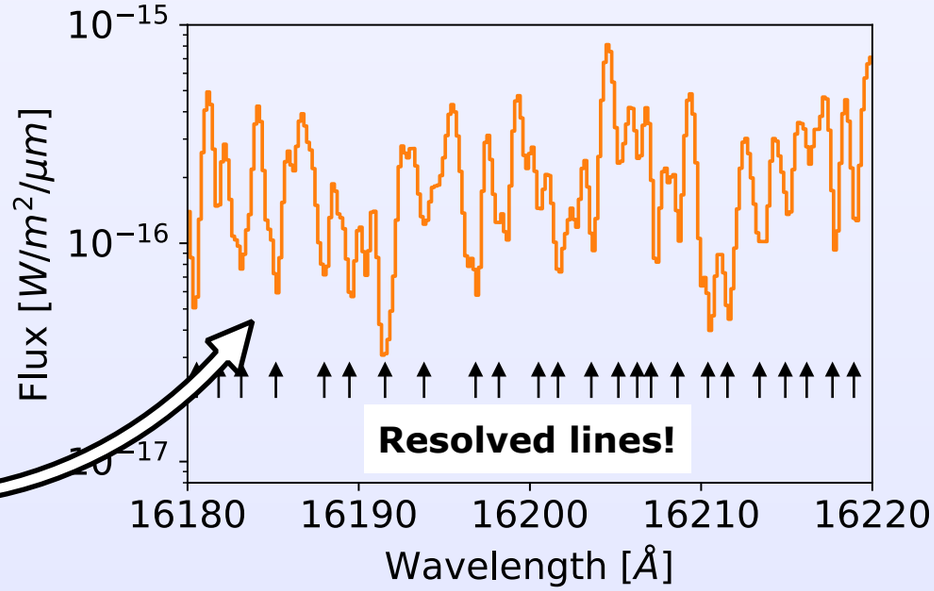




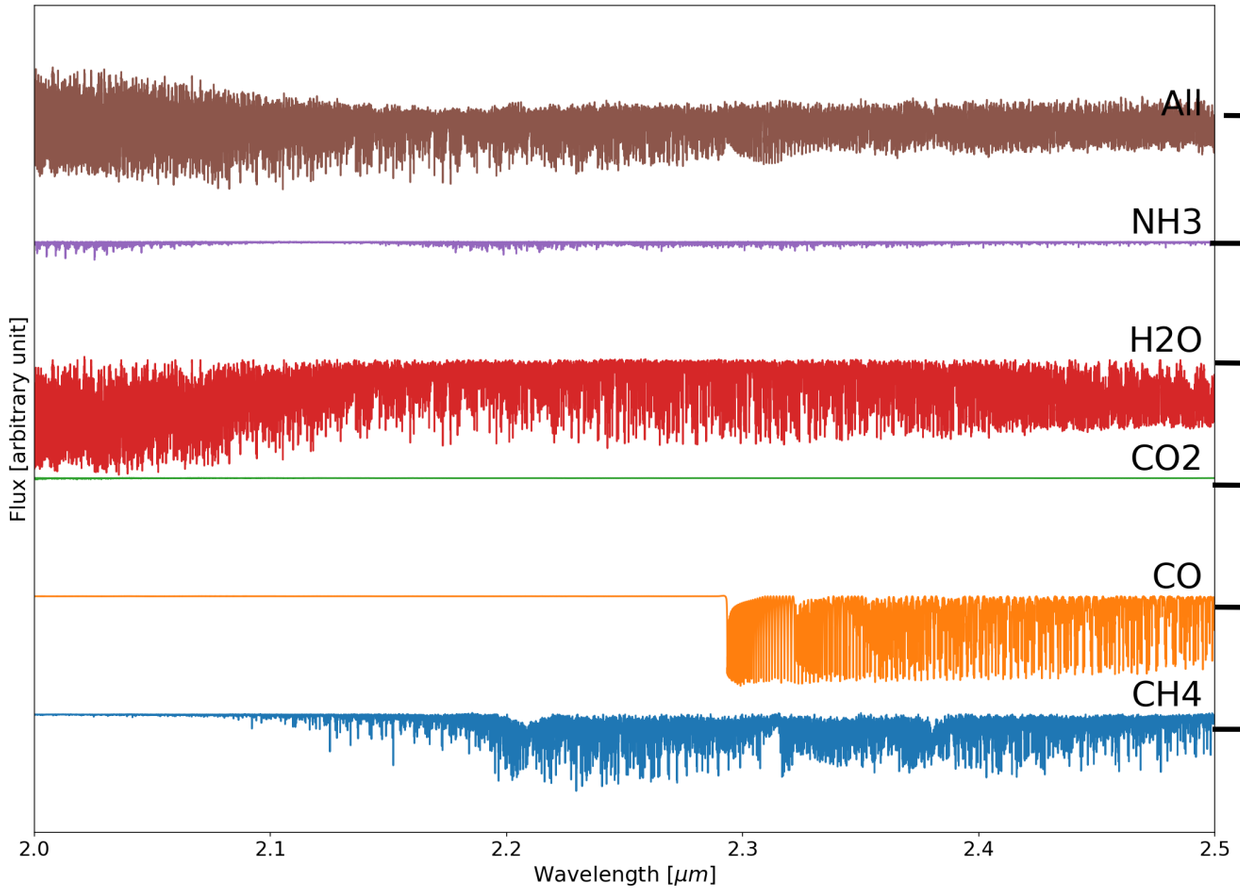
Characterization





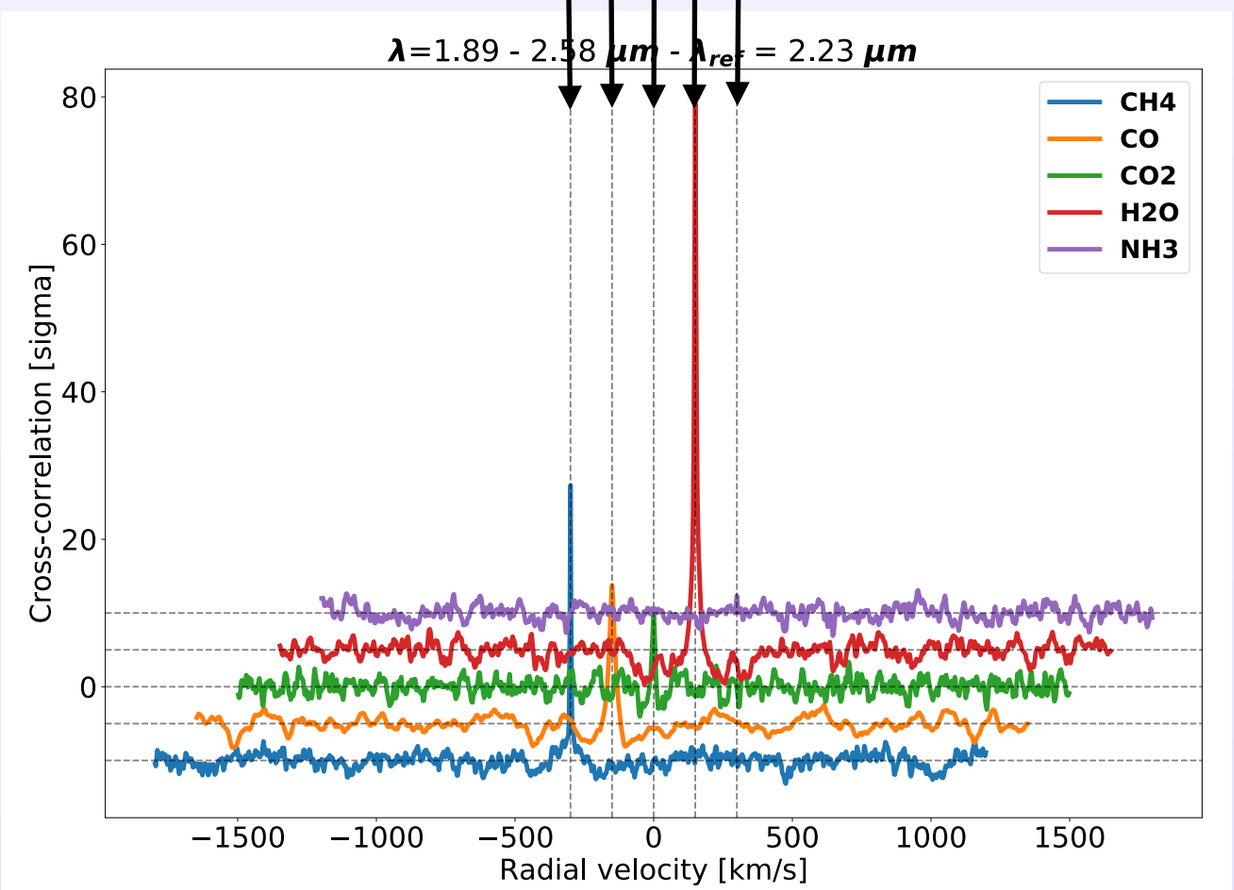


Boosting the SNR

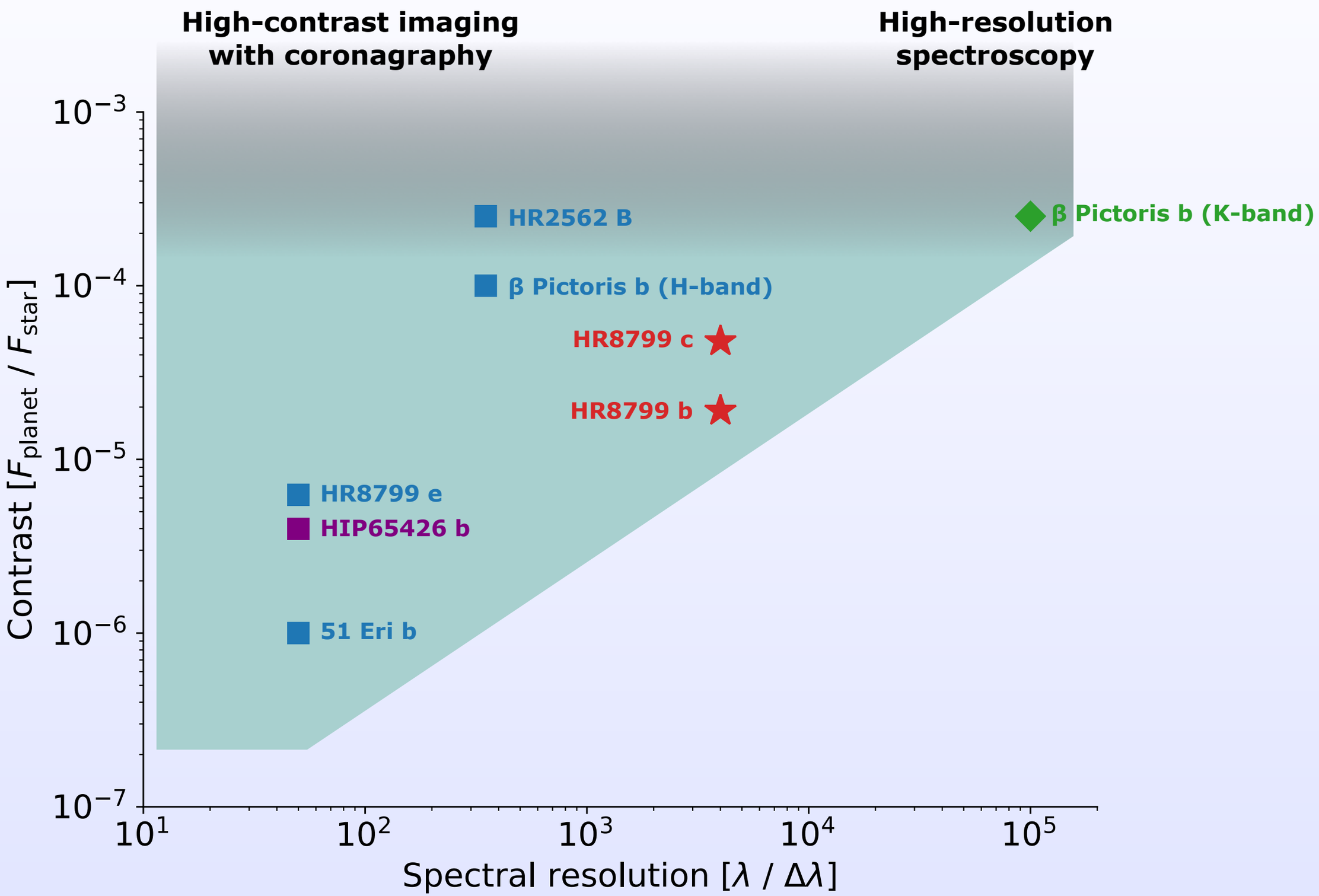


Standard CCF approach

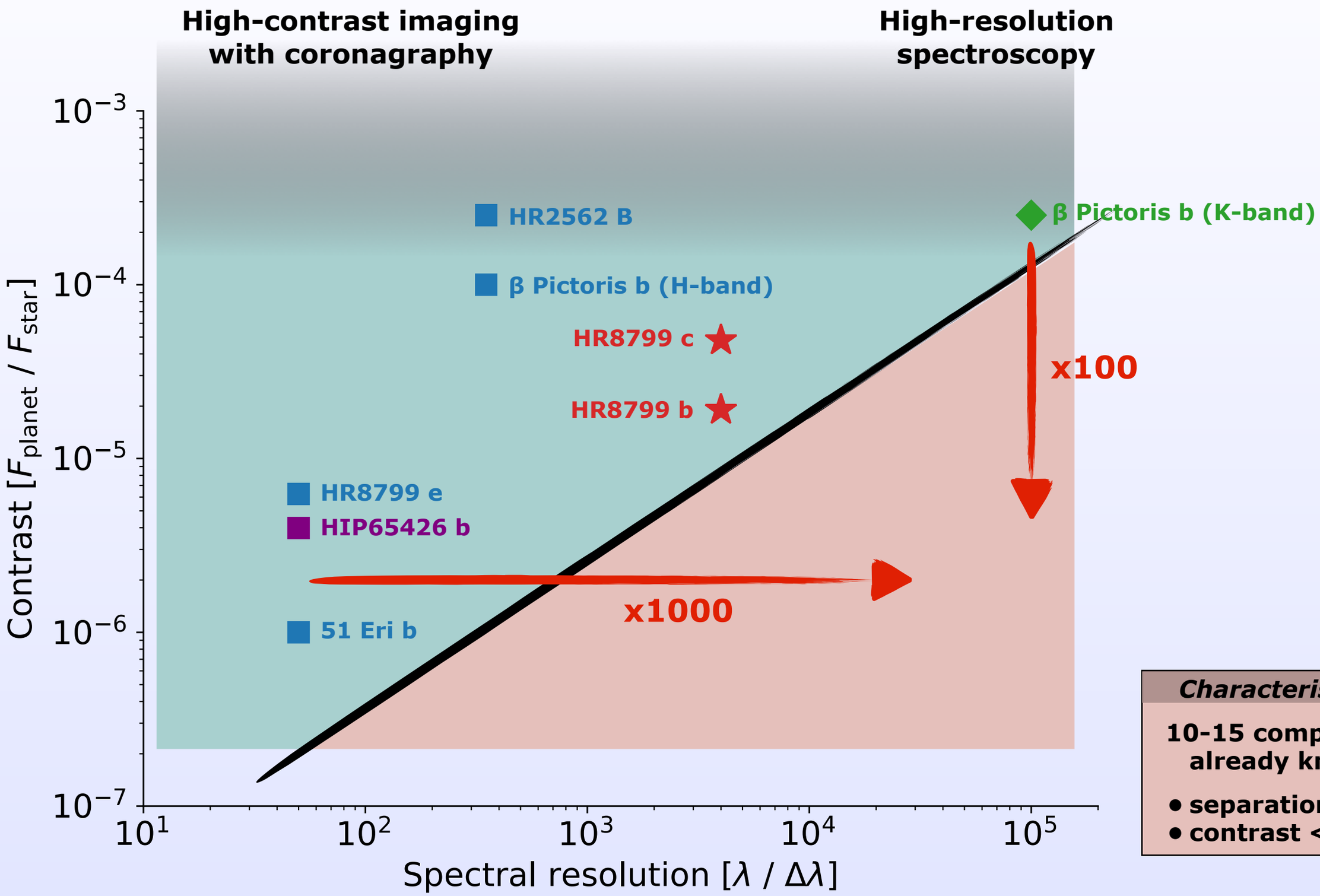
ATMO models
Tremblin et al. (2015)
Philipps et al. in prep.



Very high spectral resolution



Very high spectral resolution



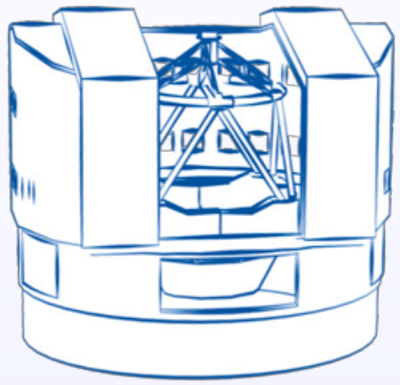
Characterisation

10-15 companions already known

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

A unique window of opportunity

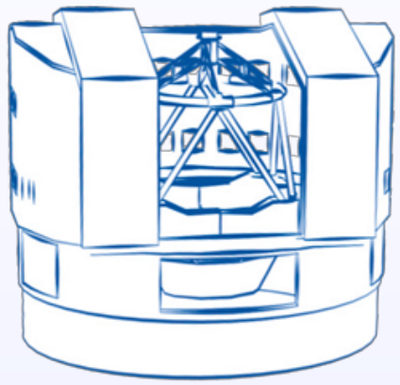
VLT/UT3



High-contrast exoplanet imager		High-resolution spectrograph
SPHERE		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

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

HiRISE

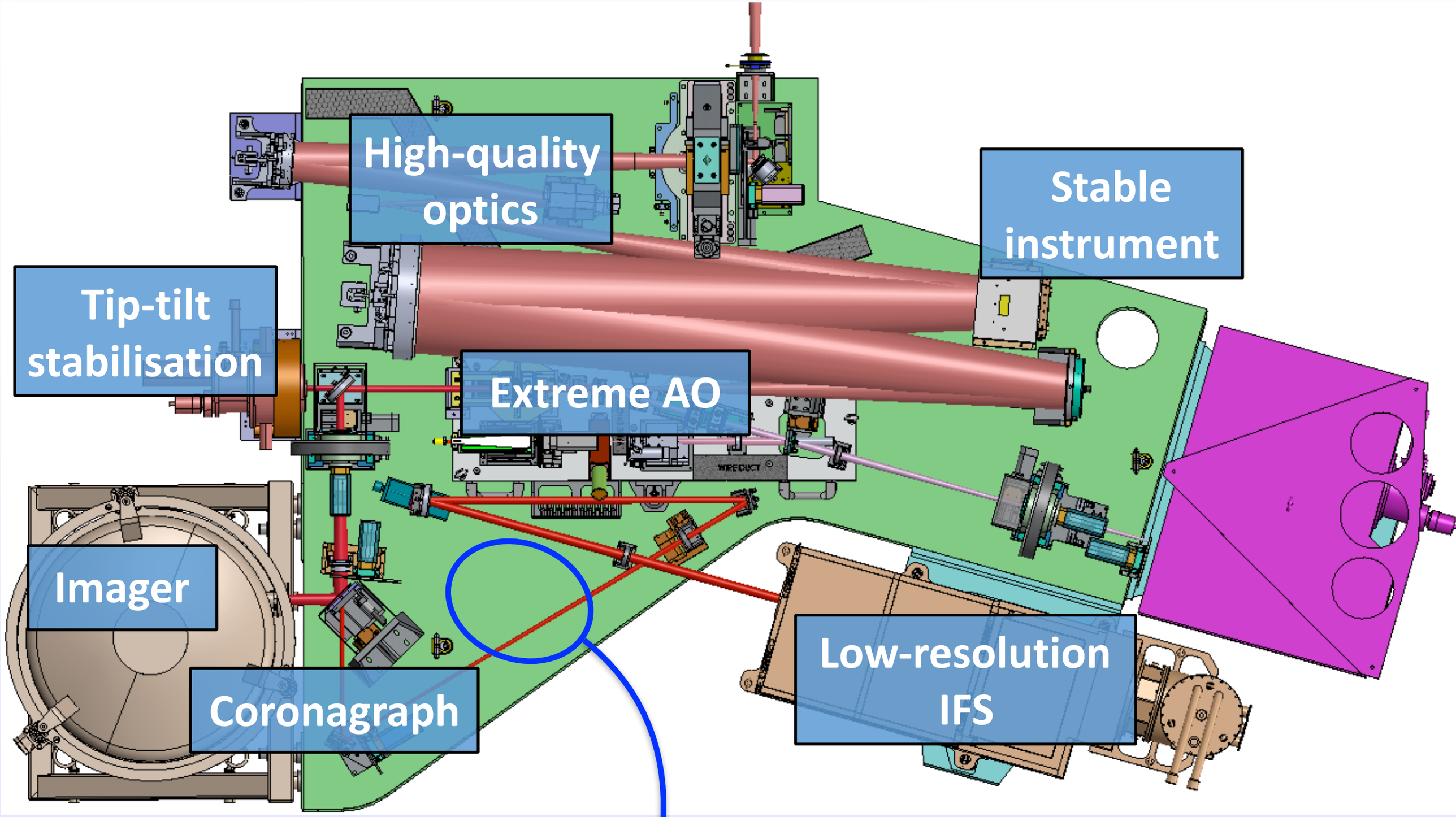
Fiber coupling

Supported by ESO

erc

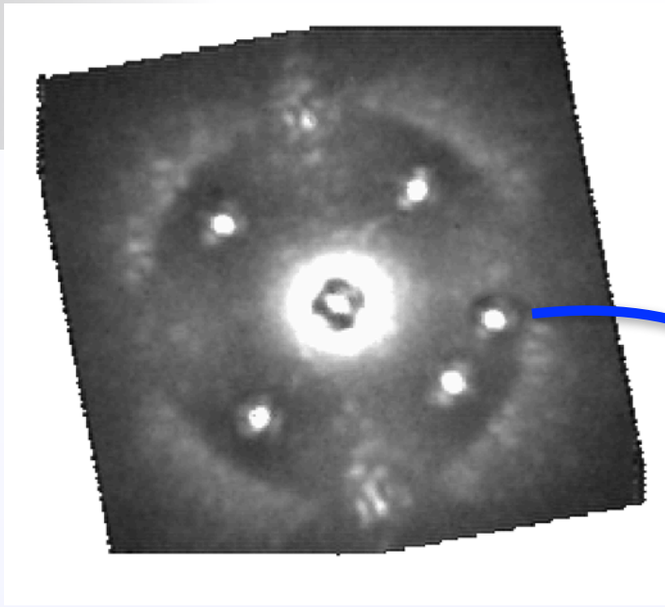
Supported by CRIRES+

HiRISE fiber injection in SPHERE



Conceptual design

- Removable pick-off mirror
- Tip-tilt in closed loop for positioning
- Long wavelengths to single-mode fibre
- At least 2 fibres
  - science
  - reference



(Very bright) **planet!**

Tracking camera

Tip-tilt mirror

J

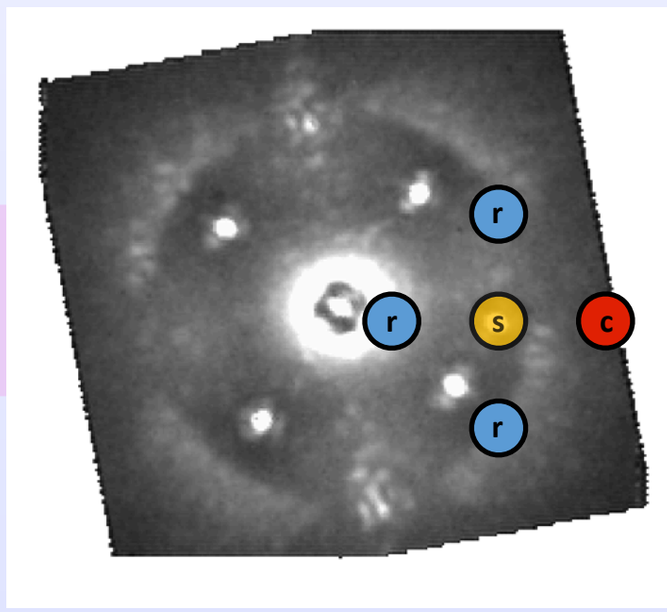
H+K

Fibre bundle

Dichroic

IFS beam

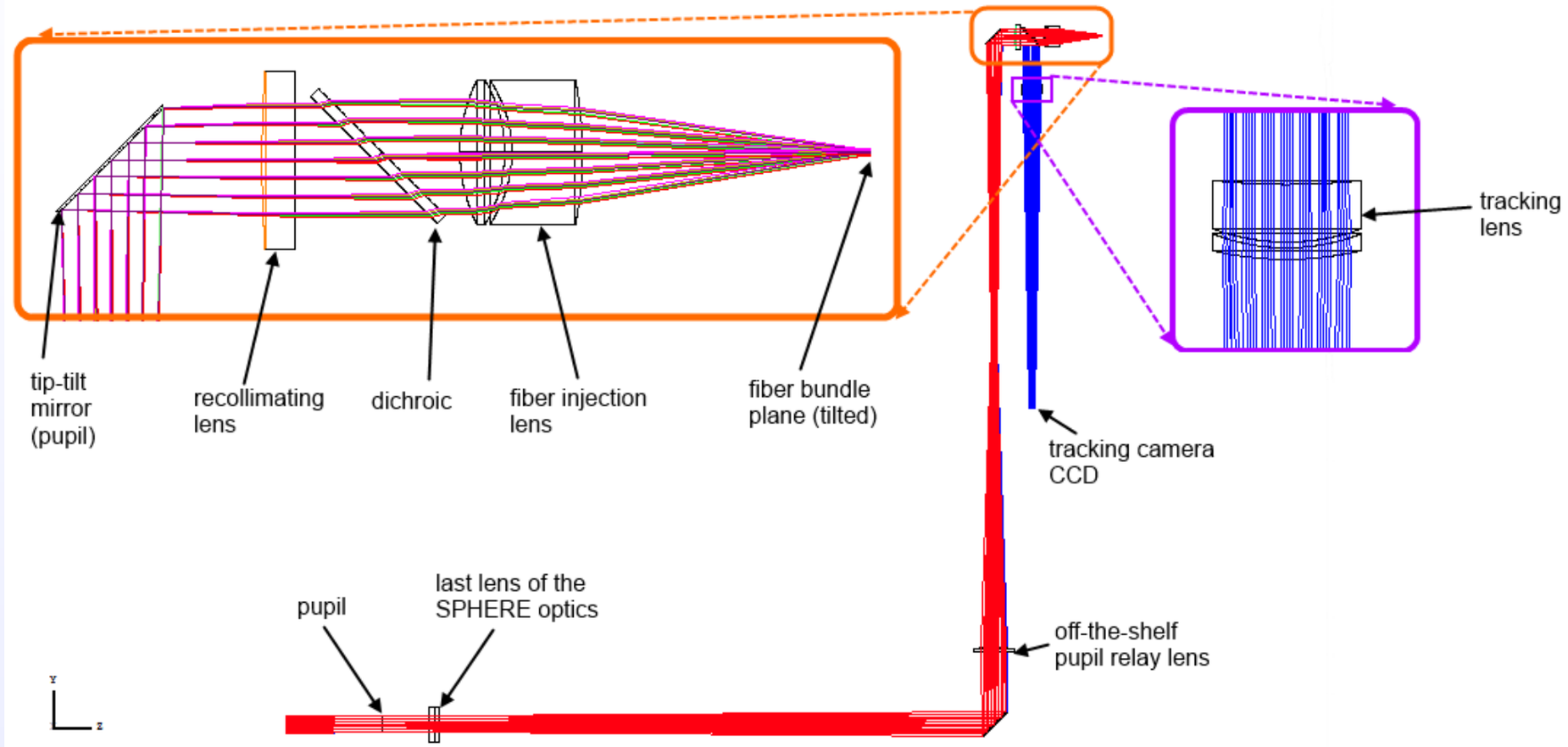
Retractable pick-off mirror

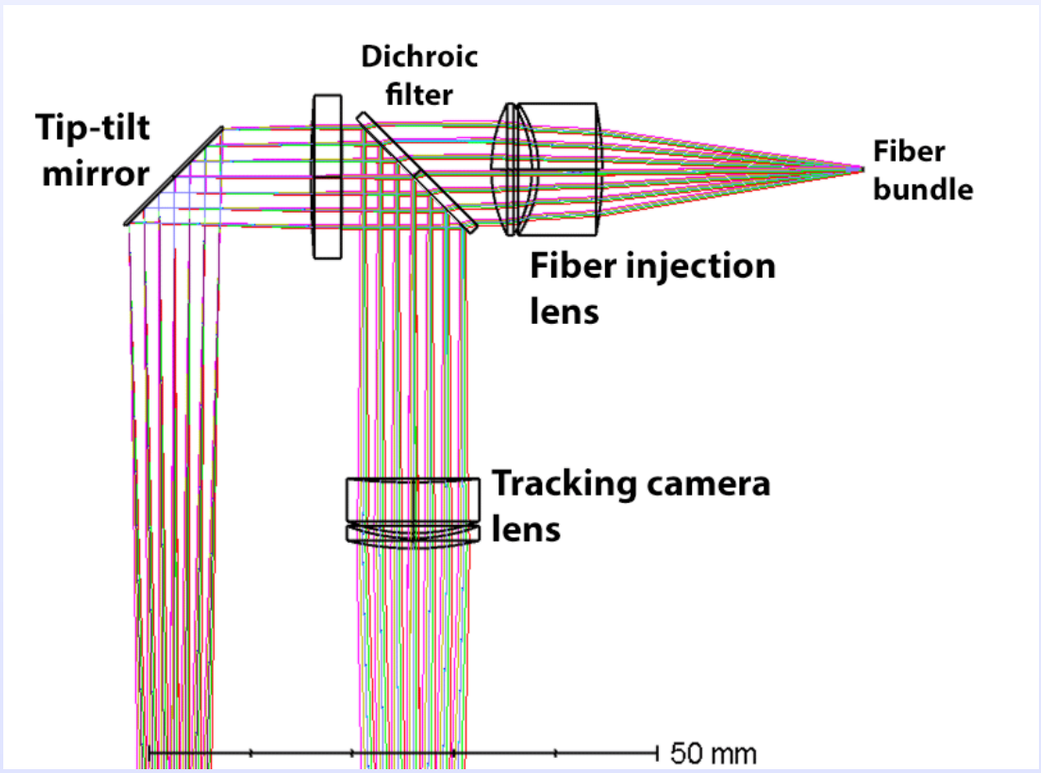


Inspired by Mawet et al. (2017)

Opto-mechanical design

Optical design: E. Muslimov

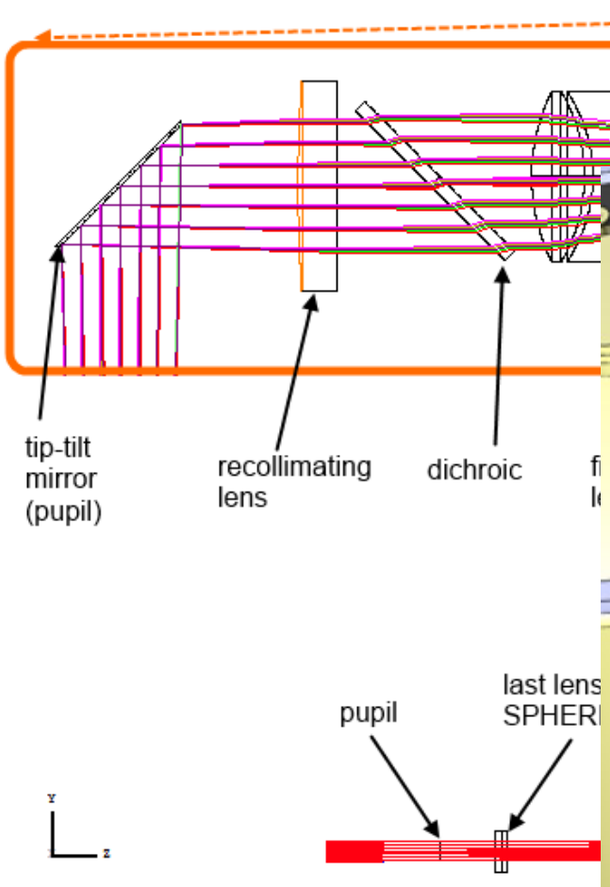


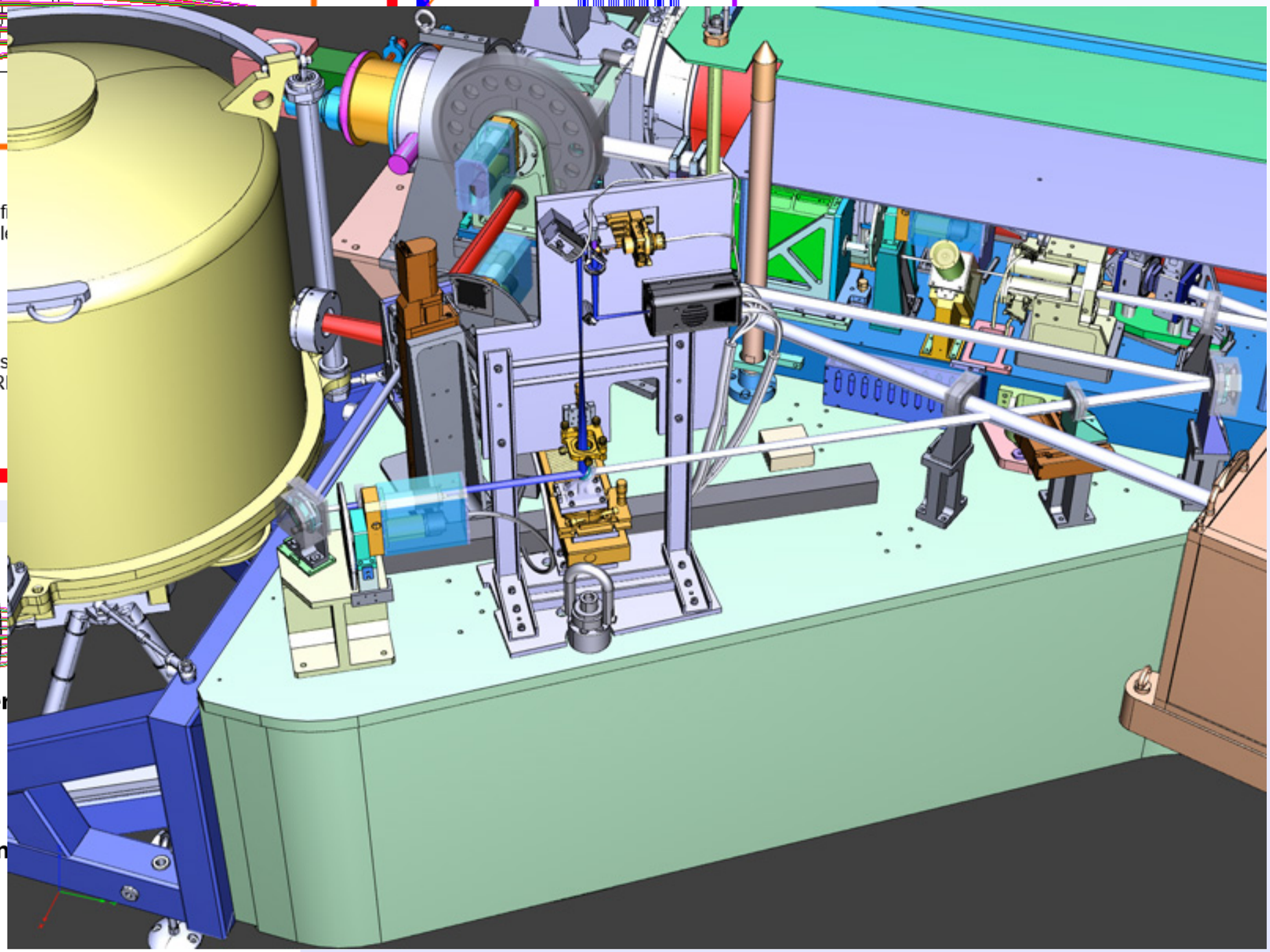


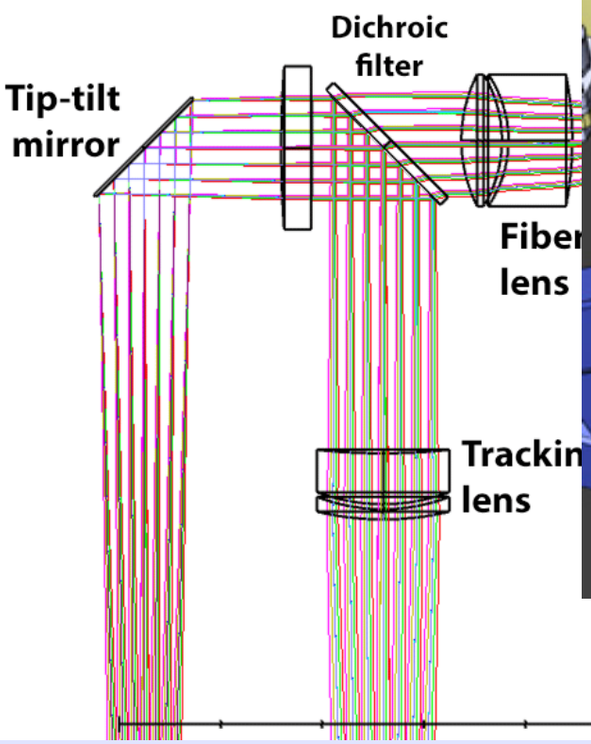
Vigan et al. (2018)

Opto-mechanical design

Optical design: E. Muslimov
Mechanical design: N. Tchoubaklian, Y. Charles

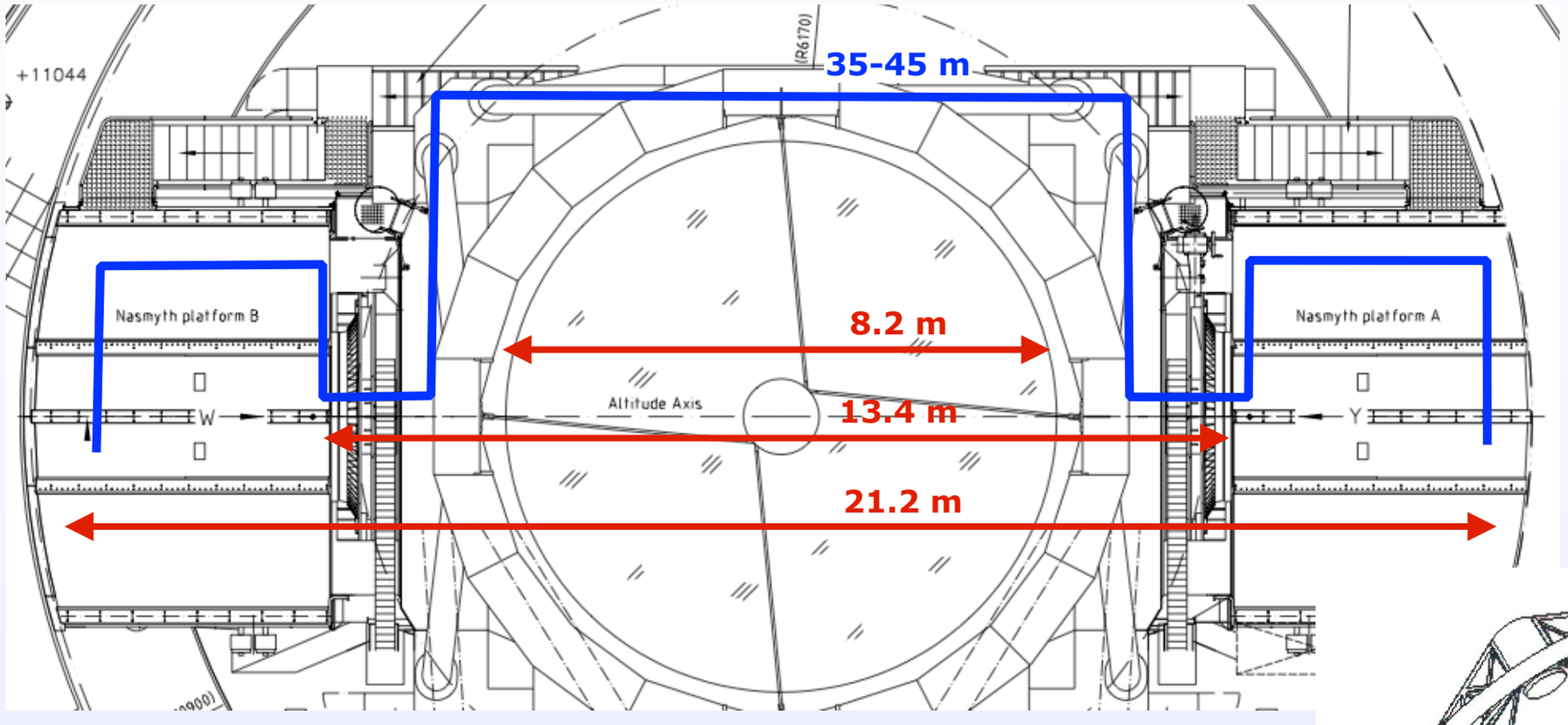




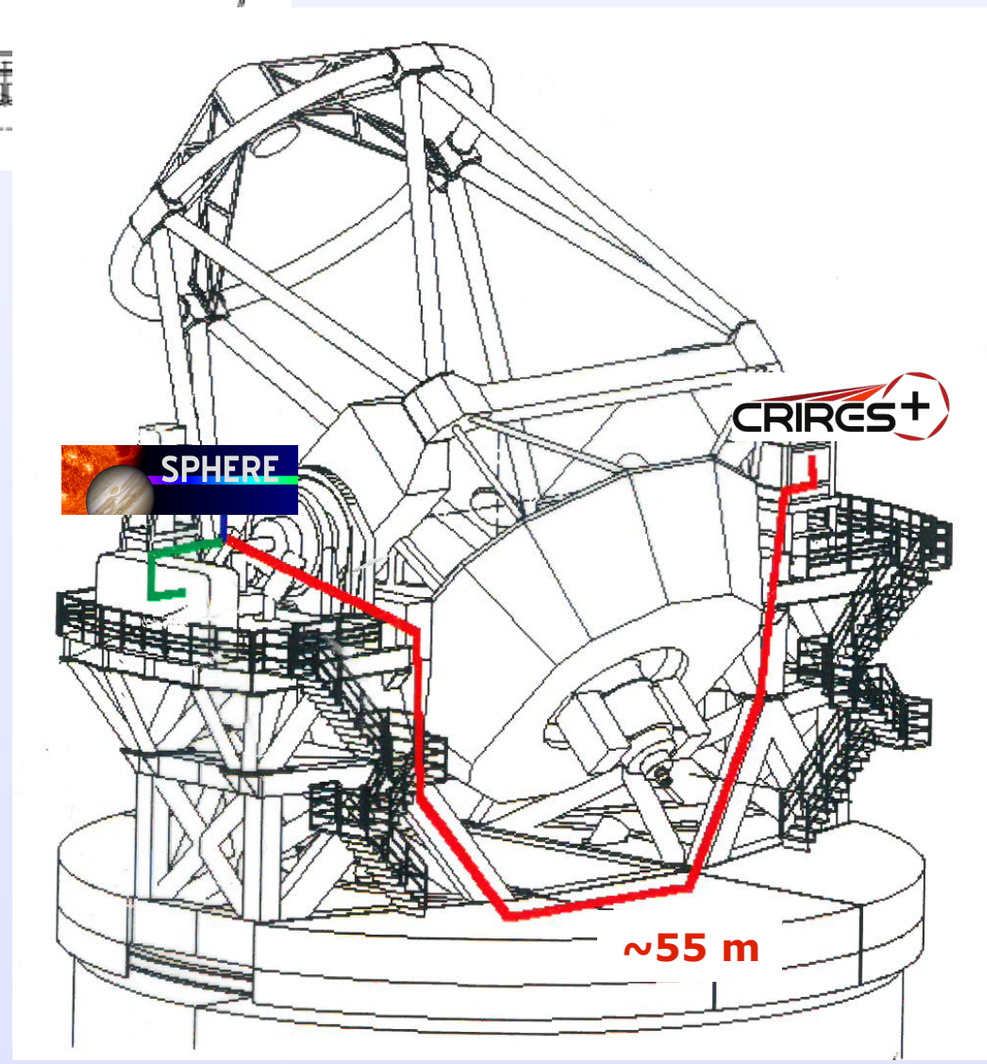


Vigan et al. (2018)

NIR fibers between SPHERE and CRIRES+

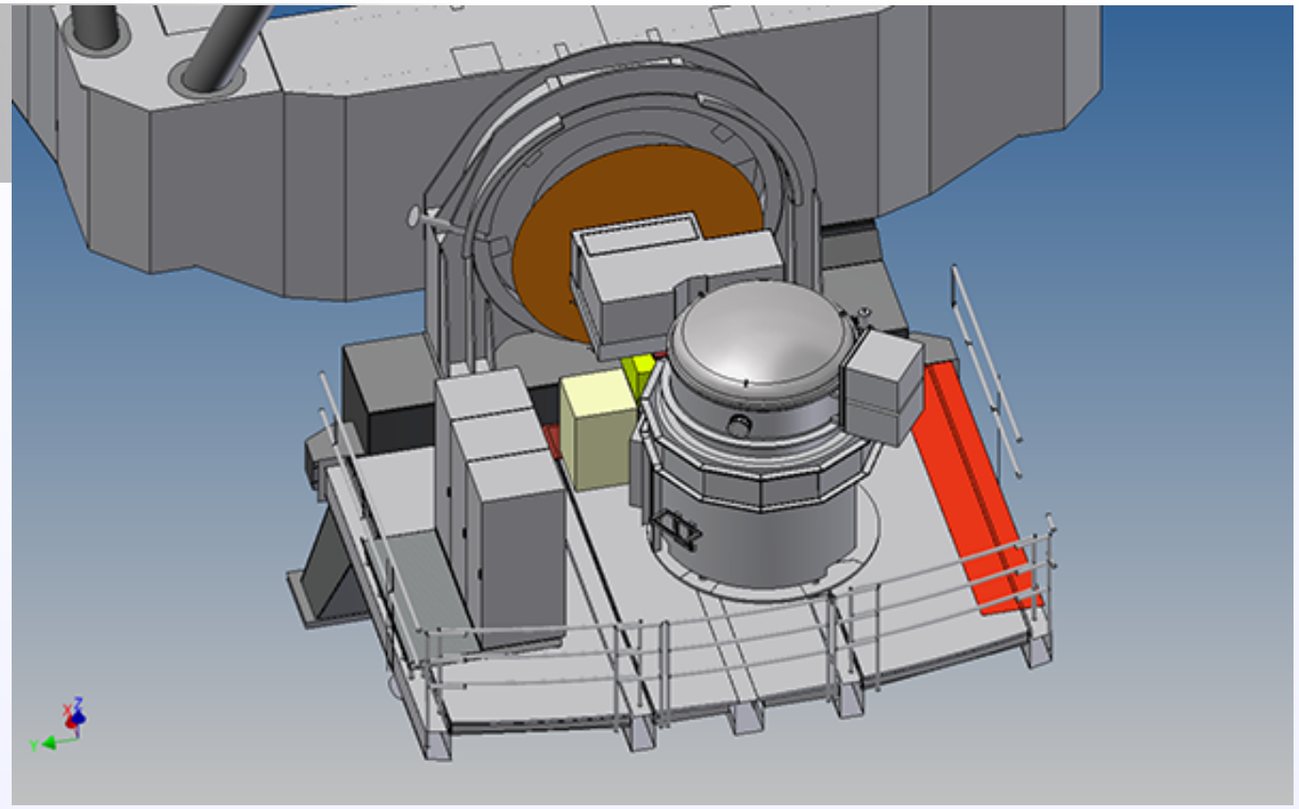


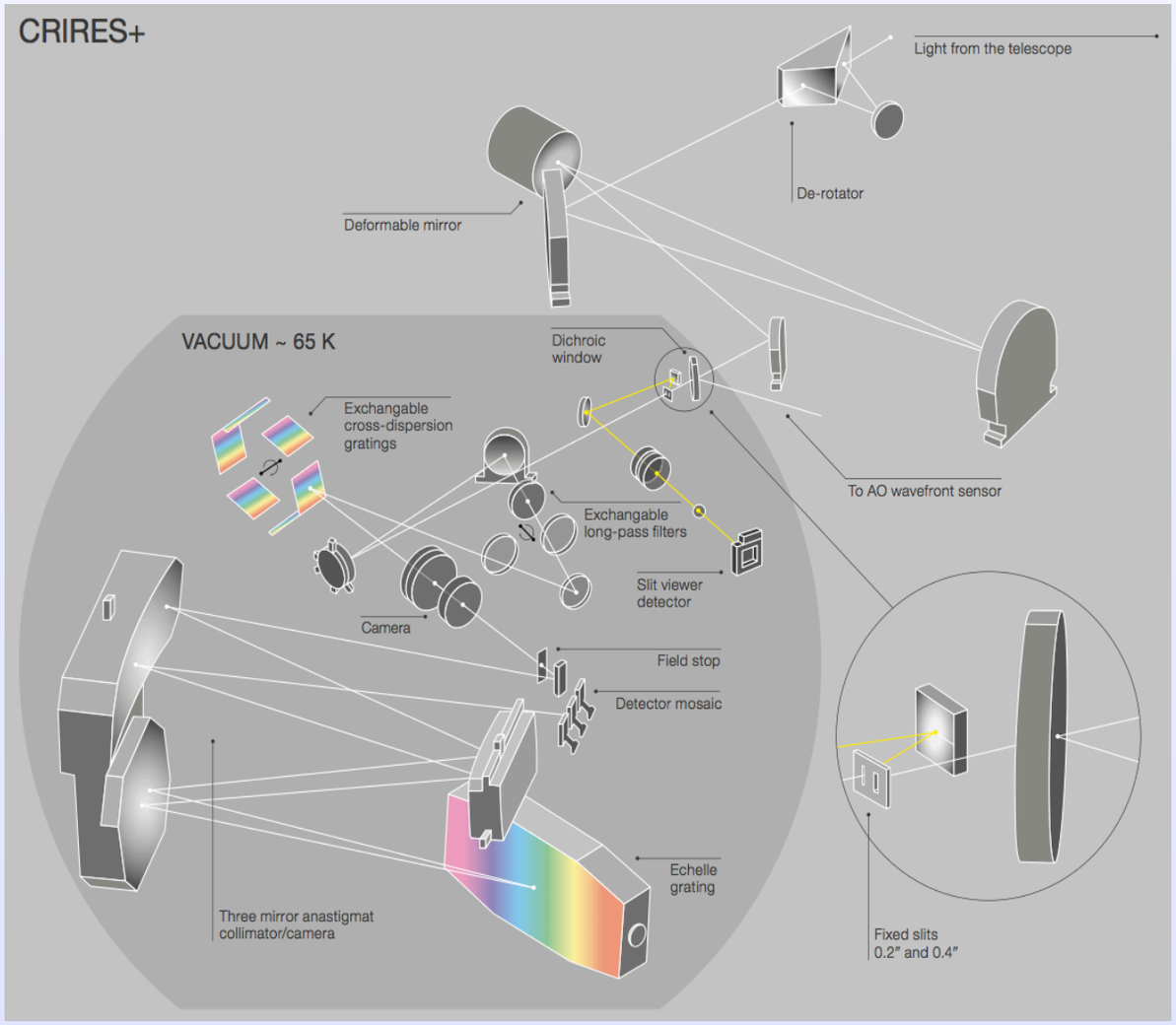
- ZBLAN fibers optimised for near-infrared
- Fibre bundle must go from Nasmyth A to Nasmyth B
- Similar setup already implemented for FLAMES
  - fibre length ~55 m

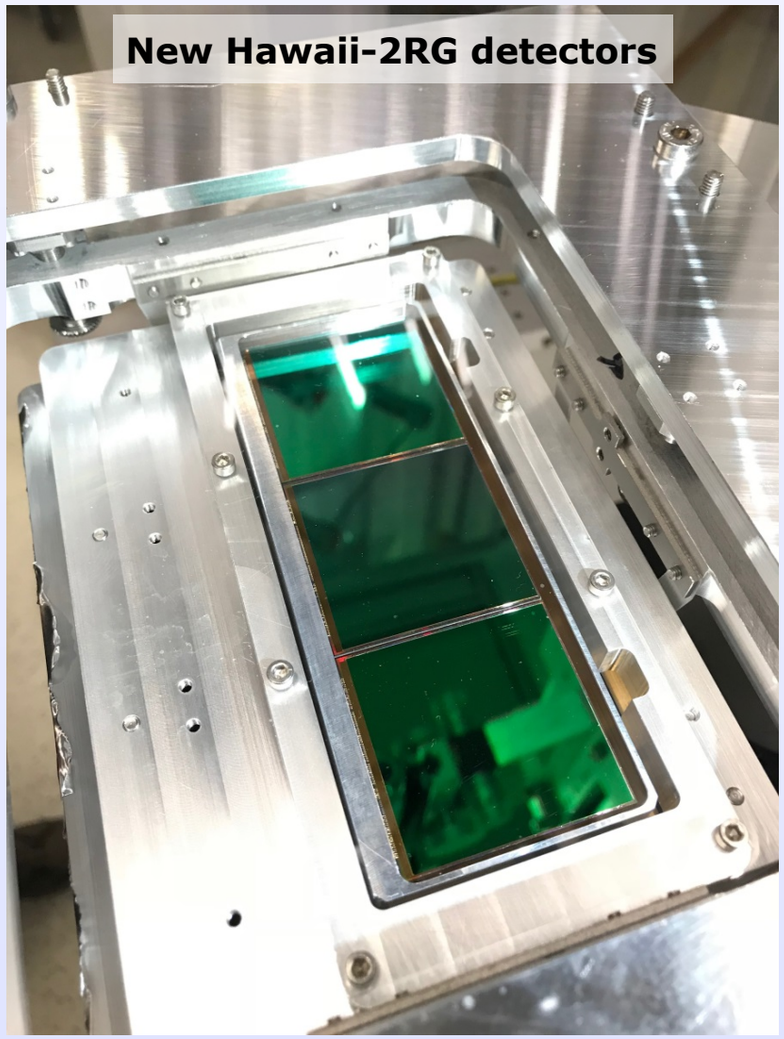


CRIRES+

- NIR infrared echelle spectrograph
- Being upgraded to a cross-dispersed spectro.
  - new cross-dispersion gratings stage
  - new detectors
  - slit reduced from 40" to 10"

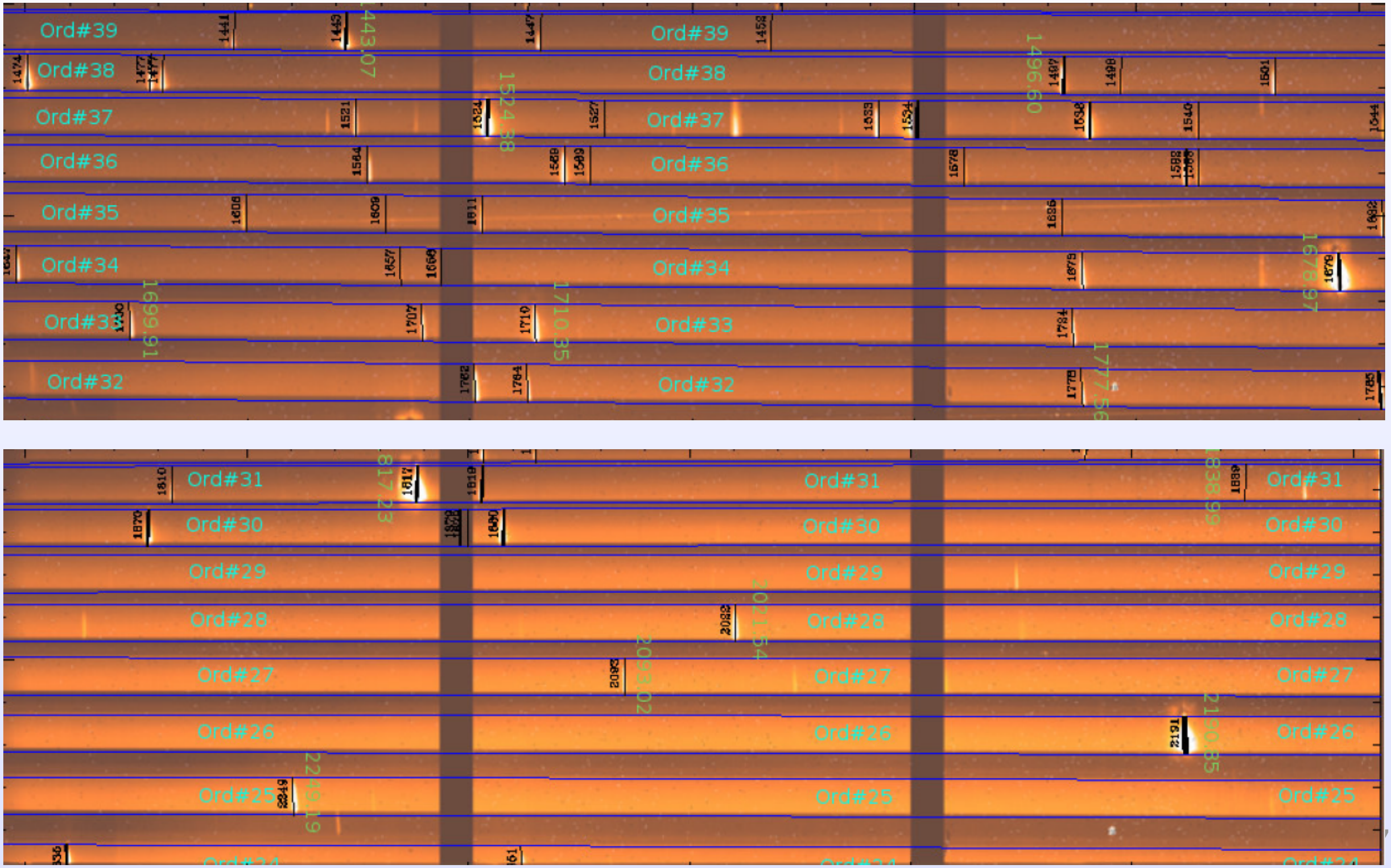






CRIRES+ wavelength coverage

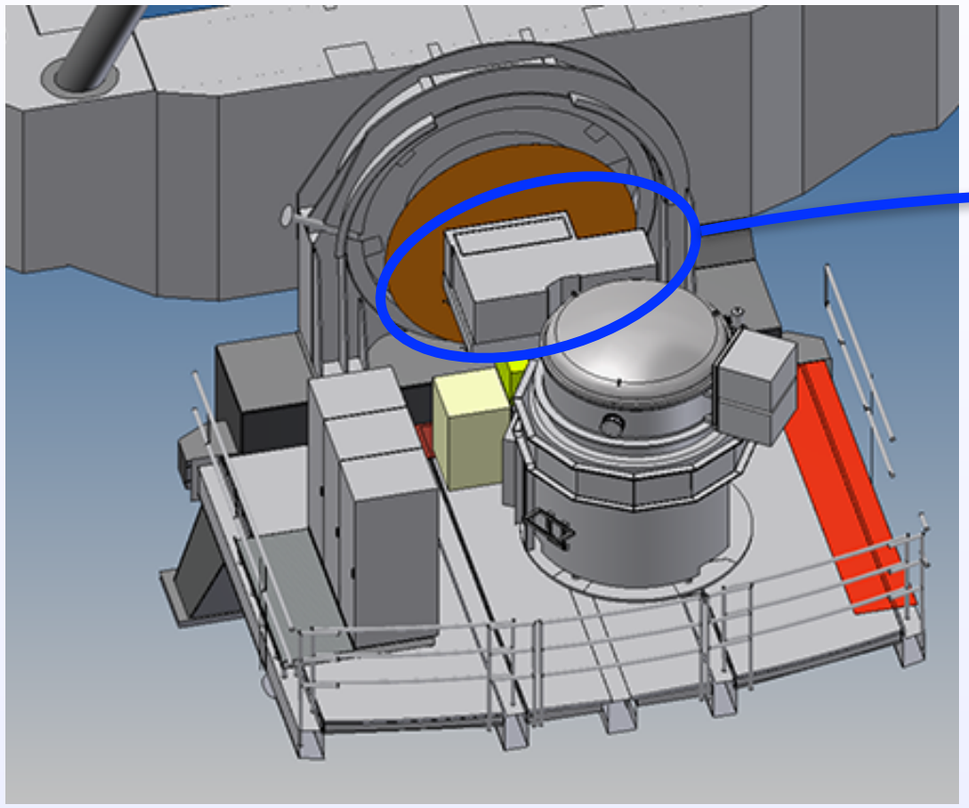
Almost a full band in a single observation!

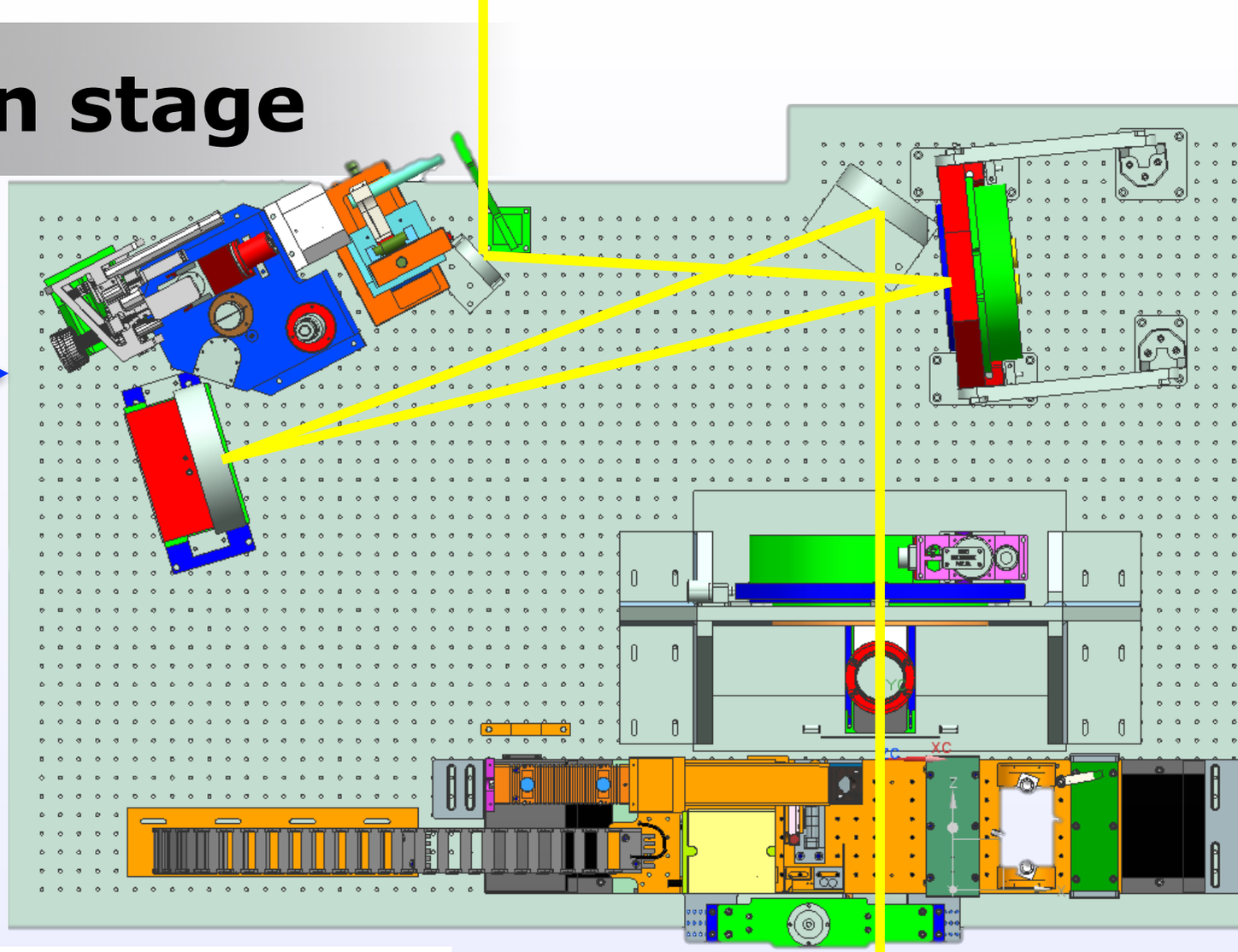


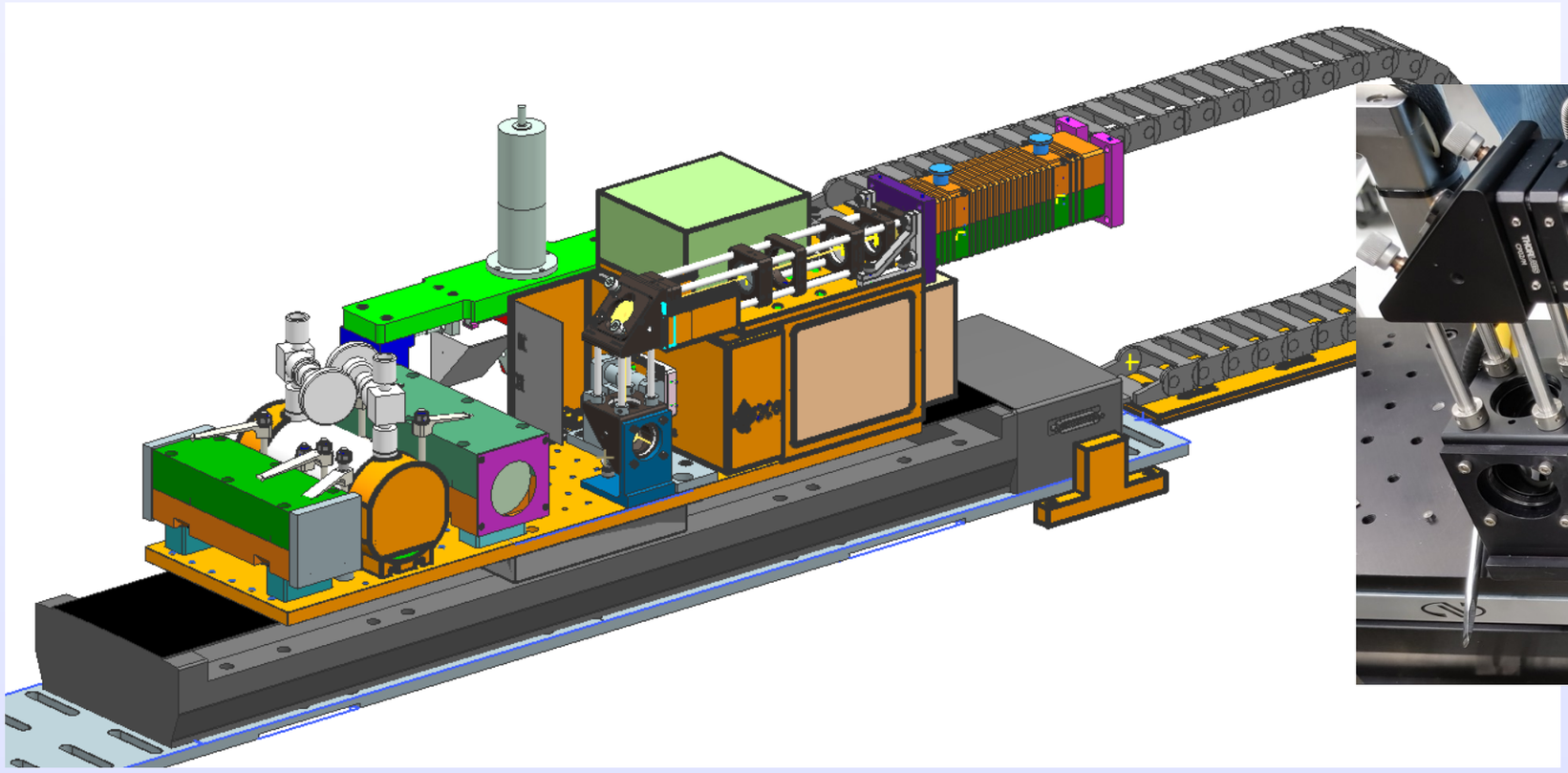
H

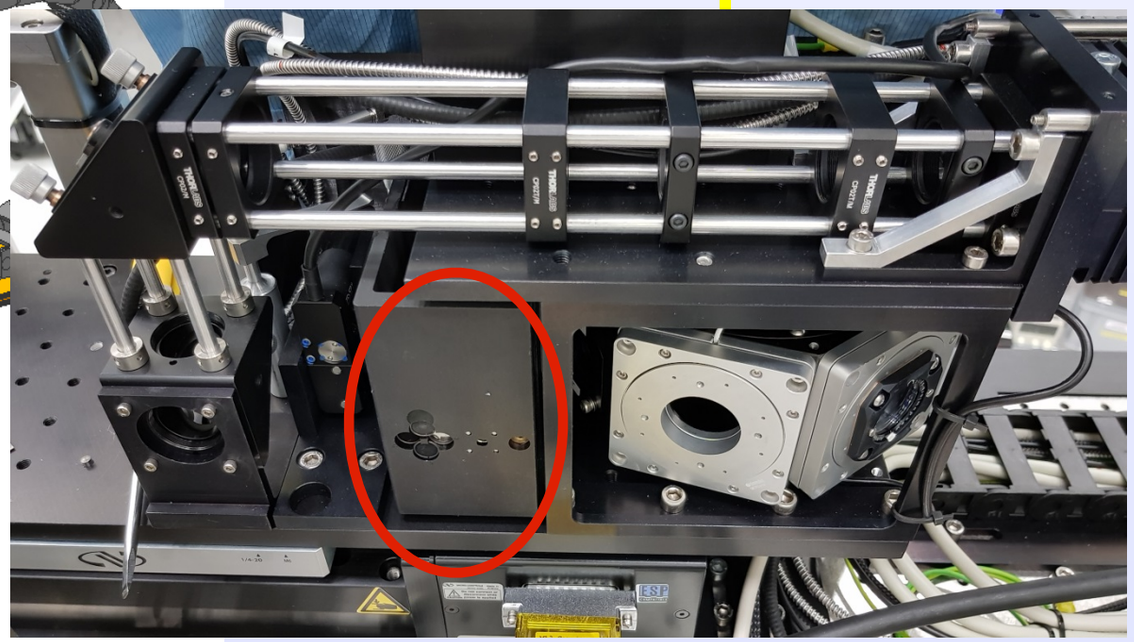
K

CRIRES+ calibration stage





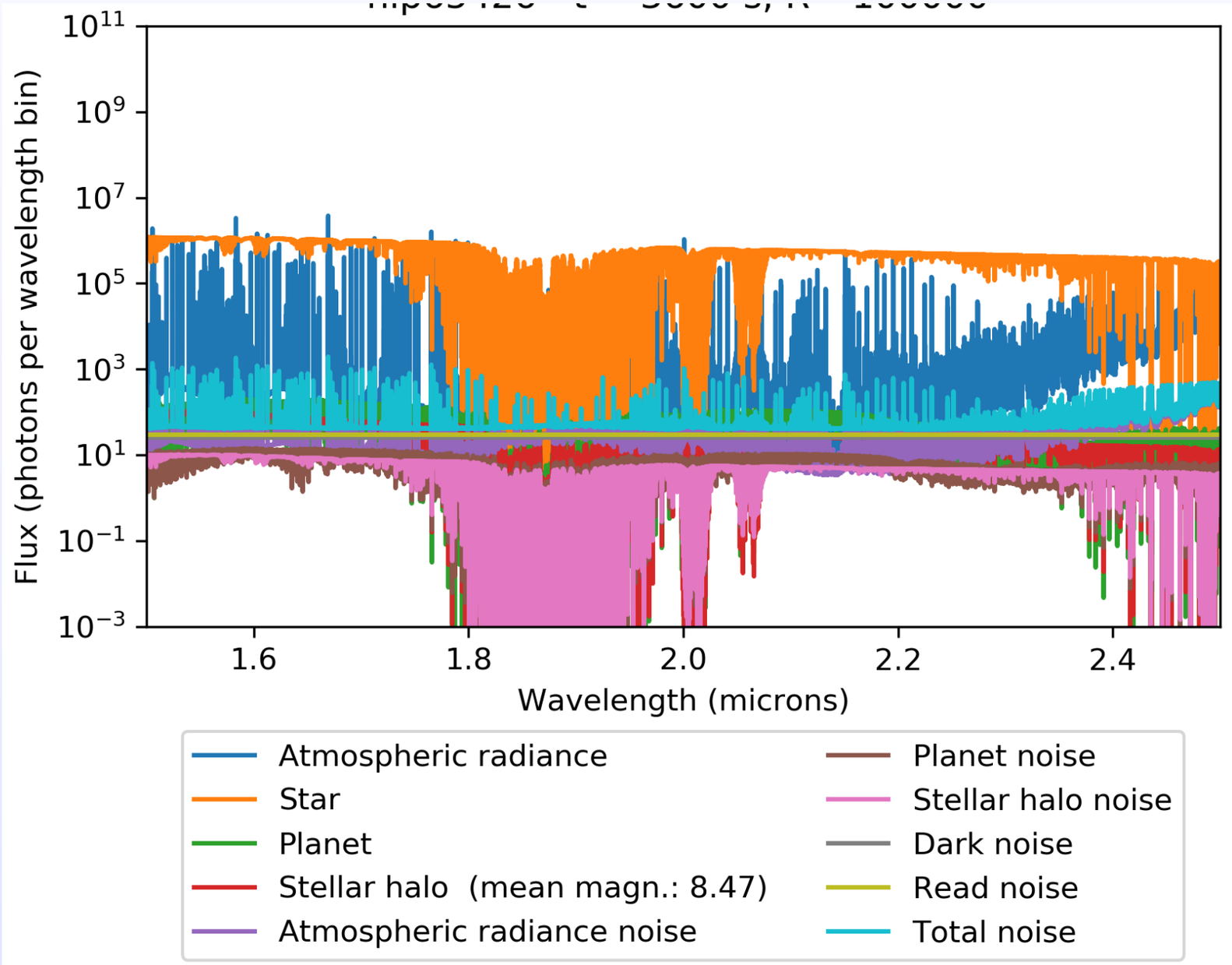




Performance simulations: results

Simulations: G. Otten

- End-to-end photometric model developed for performance estimation
- Realistic transmissions and instrumental noises
- Study of most directly-imaged companions



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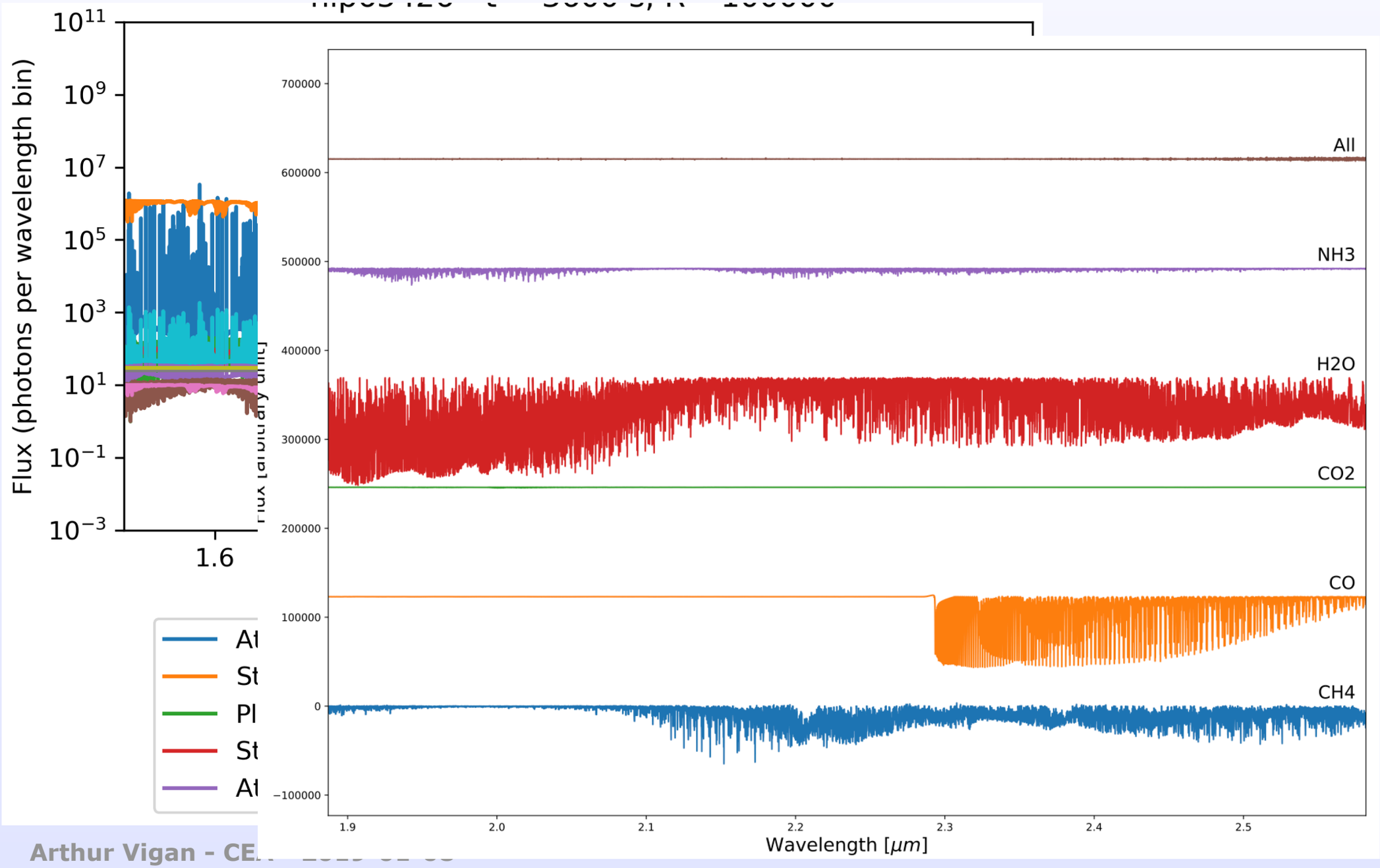

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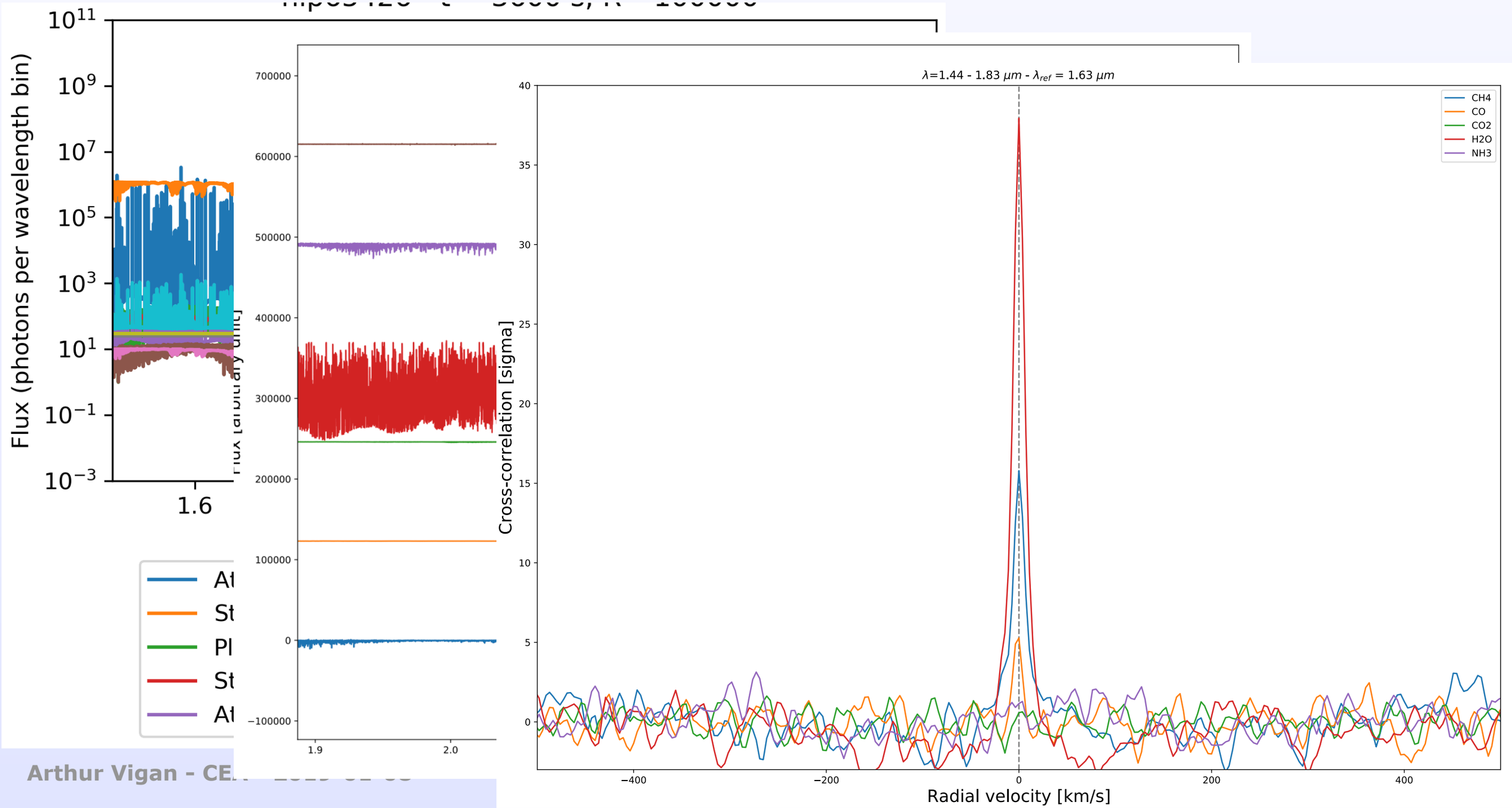

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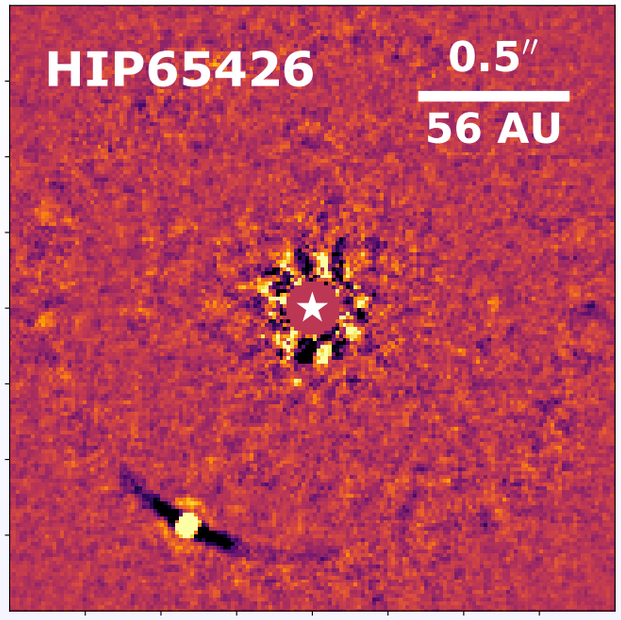
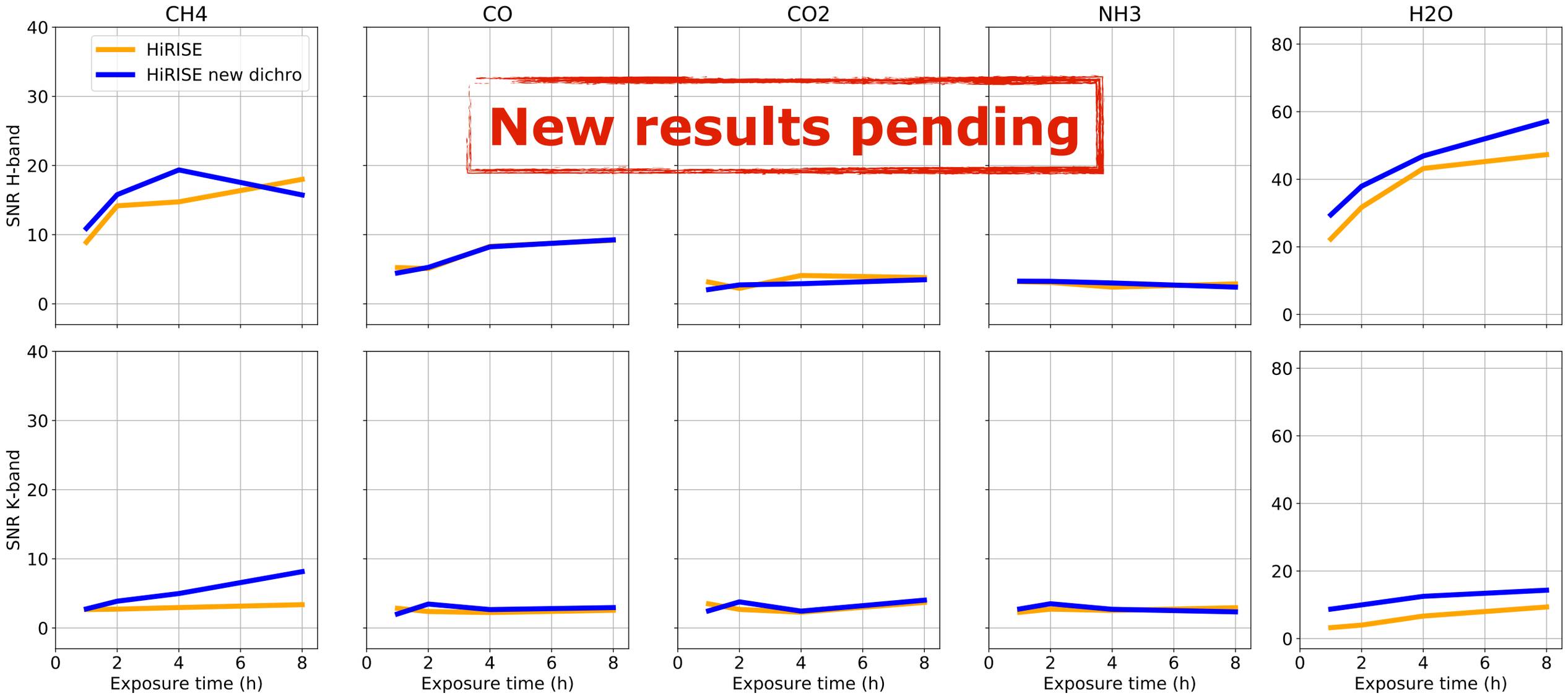
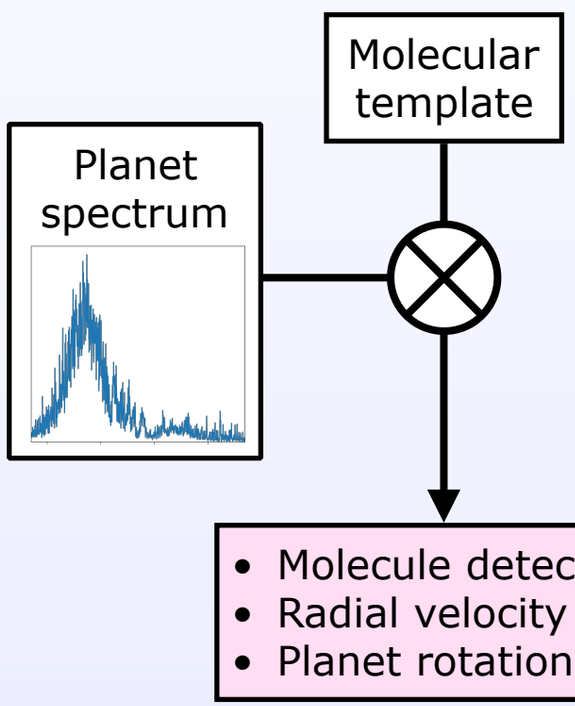




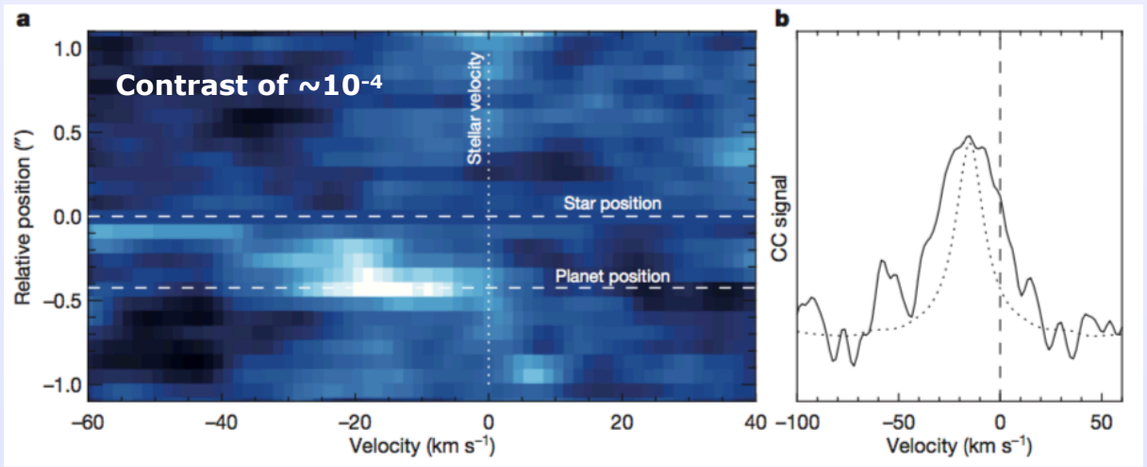
New science at high-spectral resolution

Classical approach
(e.g. Snellen et al. 2014)



- Molecule detection
- Radial velocity
- Planet rotation

Molecular lines shape



ß Pictoris b (Snellen et al. 2014)

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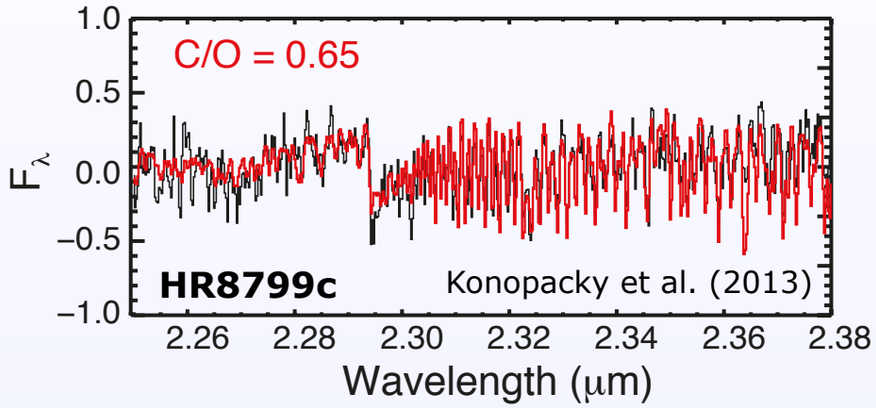
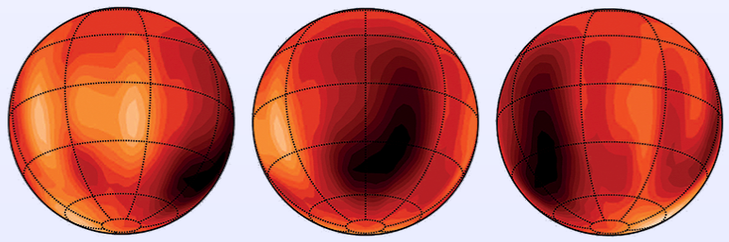


- formation scenario
- migration in the disk
- detailed composition

Time-resolved Doppler imaging



- rotational period
- temporal variability
- cloud and winds

Luhman 16B (Crossfield et al. 2014)

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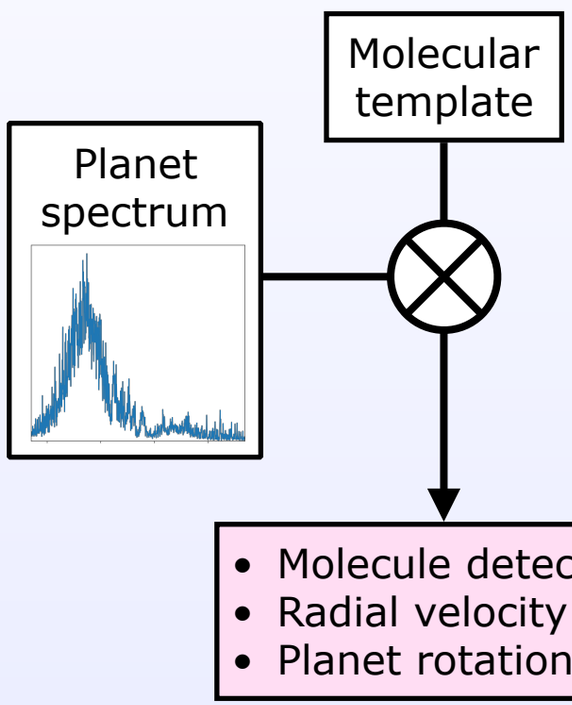

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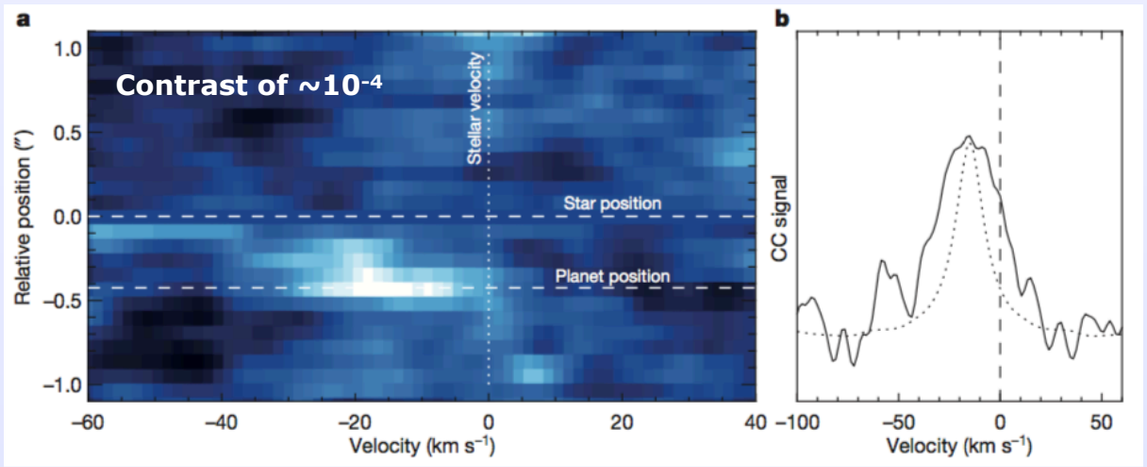

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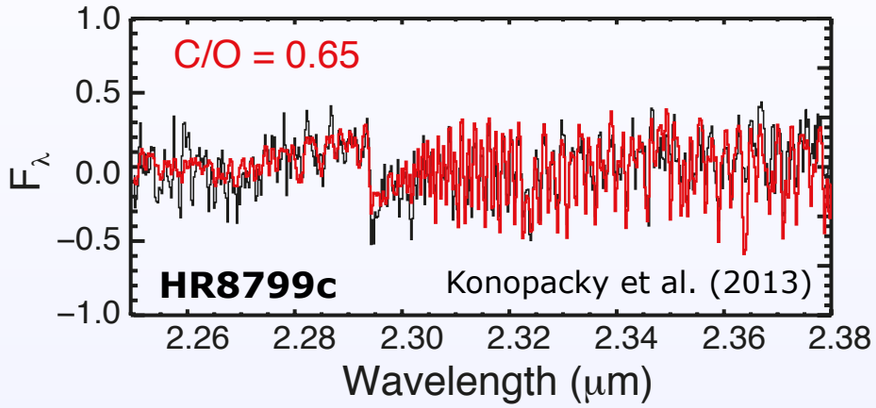

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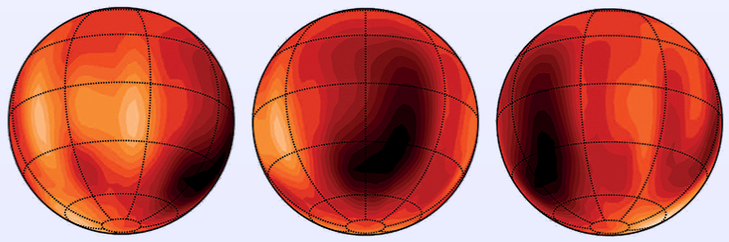

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Stay tuned for more…

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
- 80% of the survey done, 2 planets
- many, many, many disk results + some companions characterisation

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

- Couling between SPHERE and CRIRES+
- Phase A on-going at LAM with ERC funding
- First light... early 2020?