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SHINE
The SPHERE infrared survey for exoplanets

SPHERE
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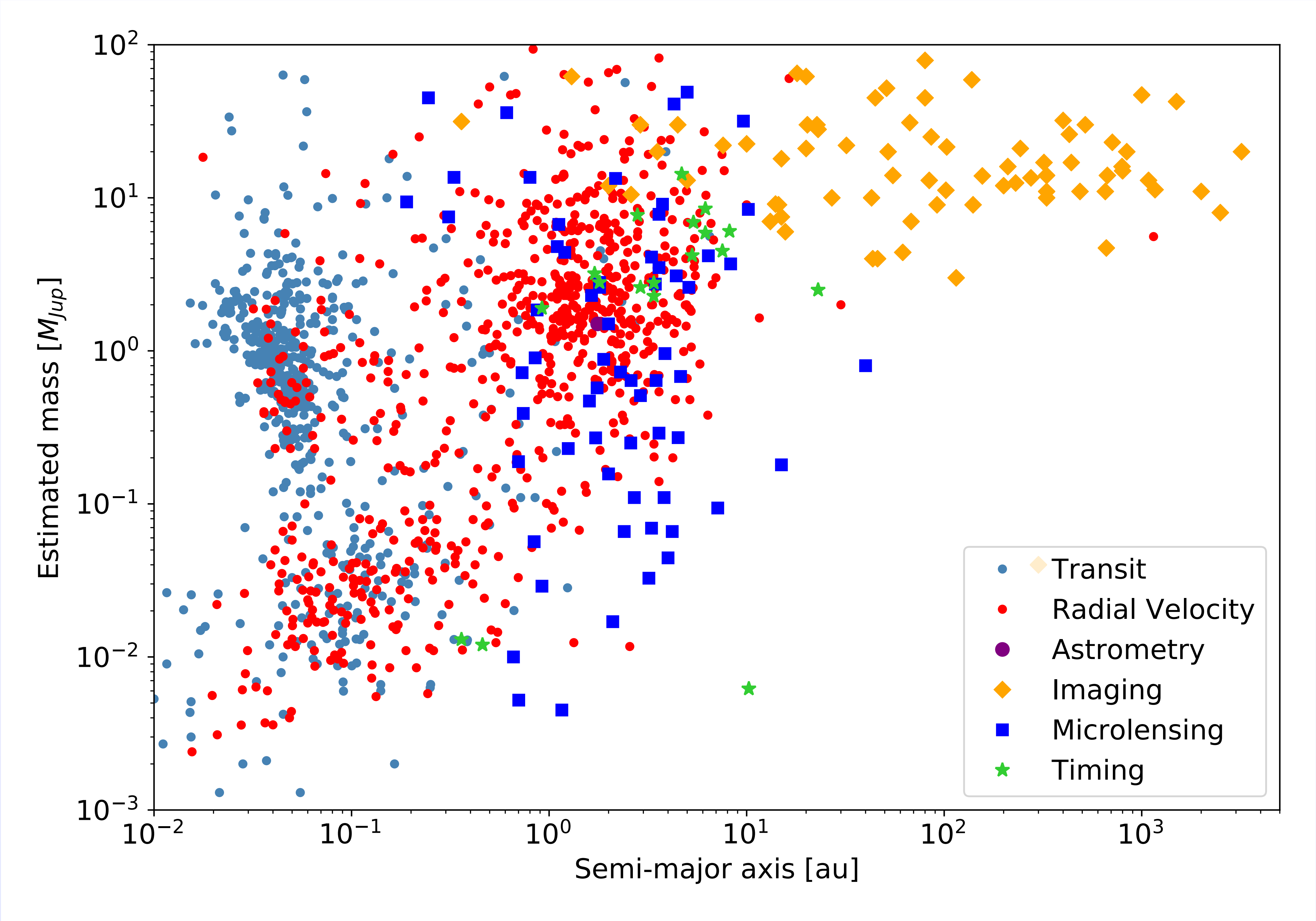
F. Wildi (AIT), T. Fusco (AO), M. Kasper (ESO responsible), Z. Wahhaj (current ESO IS)
and numerous participants from 12 European institutes!

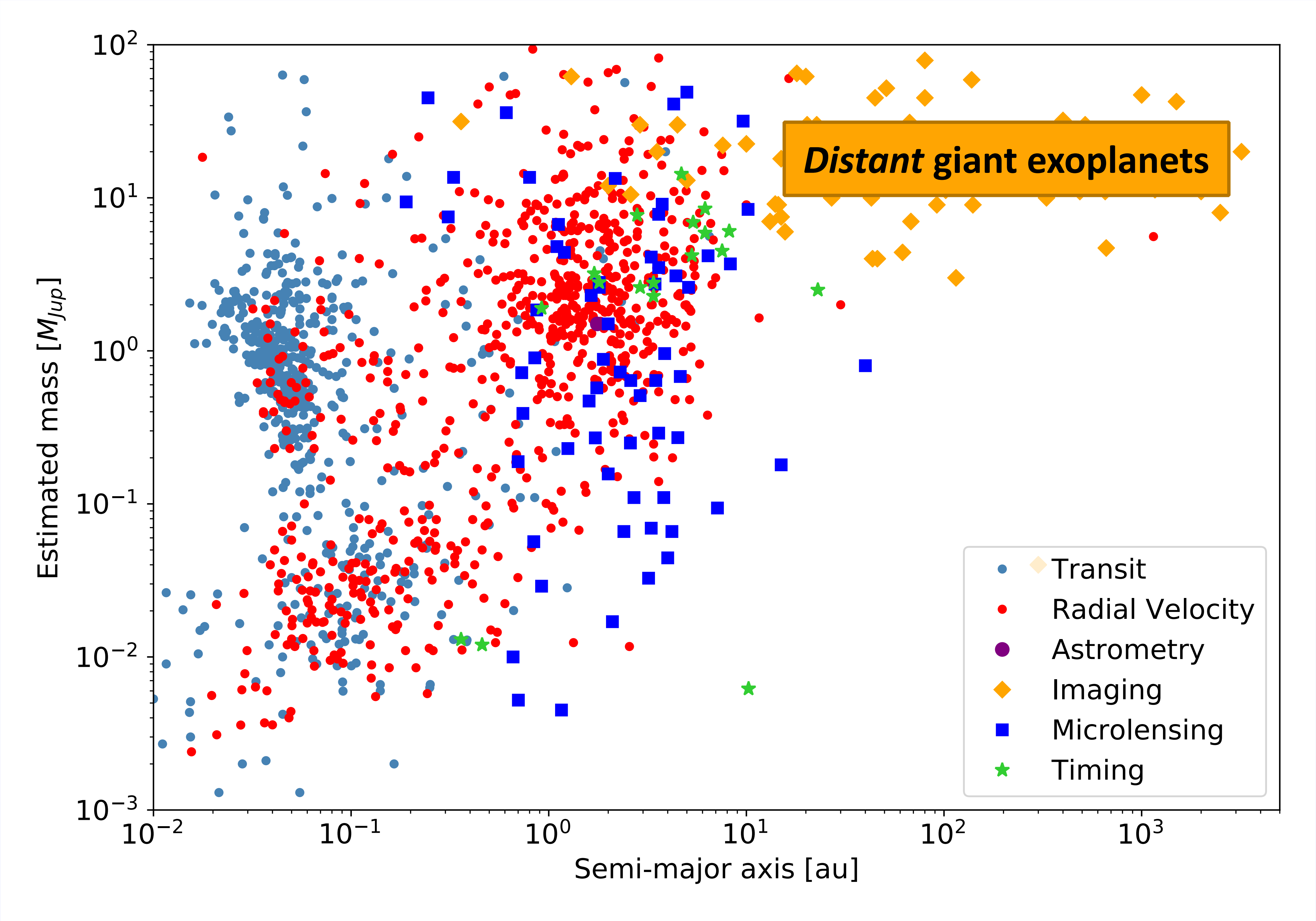
SHINE
G. Chauvin (SHINE coordinator), S. Desidera (SHINE+WP1 coordinator), A.Cheetham (WP1),
A.-M. Lagrange (WP2 coordinator), R. Gratton (WP2), M. Langlois (WP2), A. Vigan (WP3 coordinator), M. Bonnefoy (WP3), M. Feldt (WP4 coordinator), M. Meyer (WP4)
and numerous participants from 12 European institutes!

Context

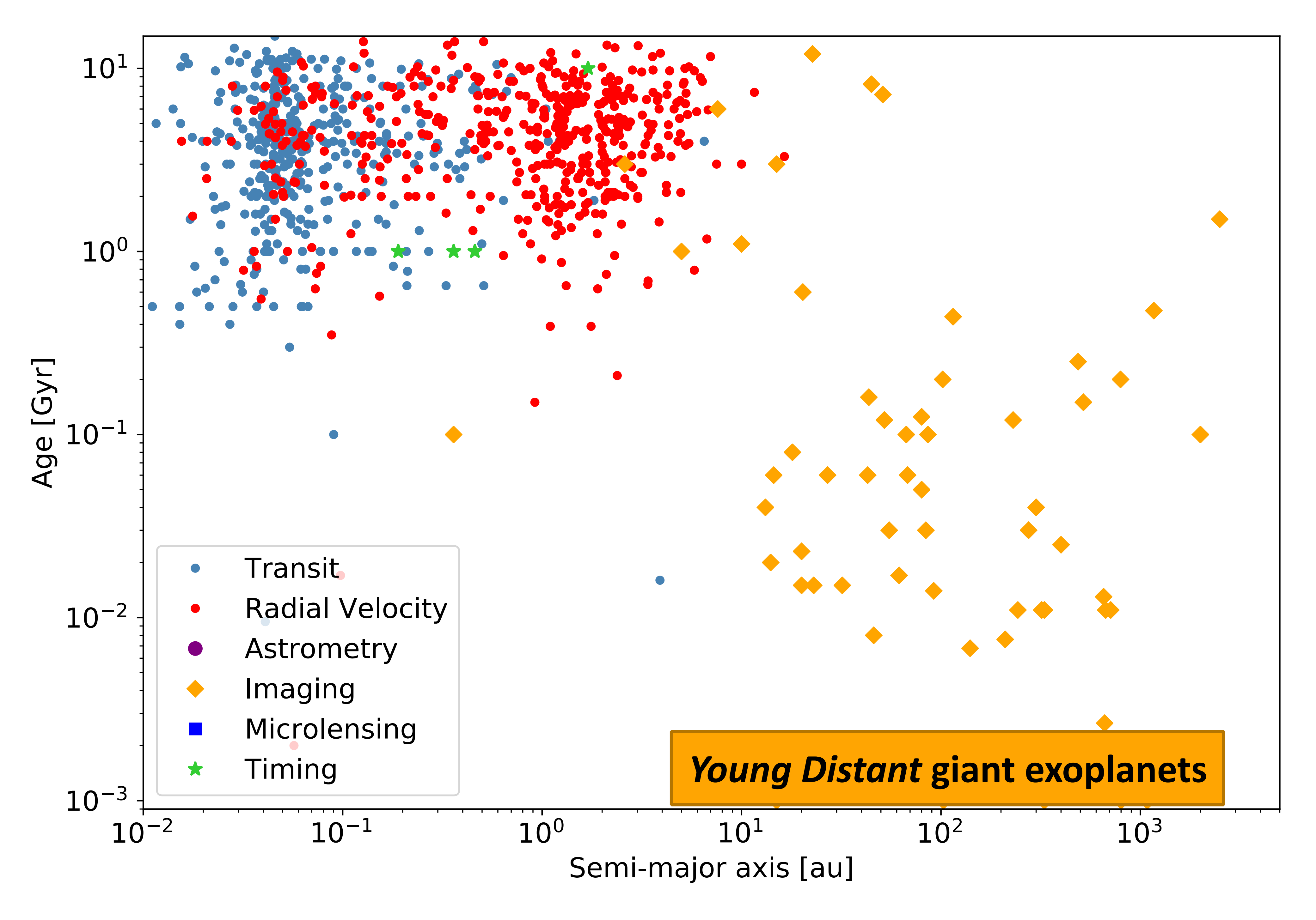
Imaging of low-mass companions



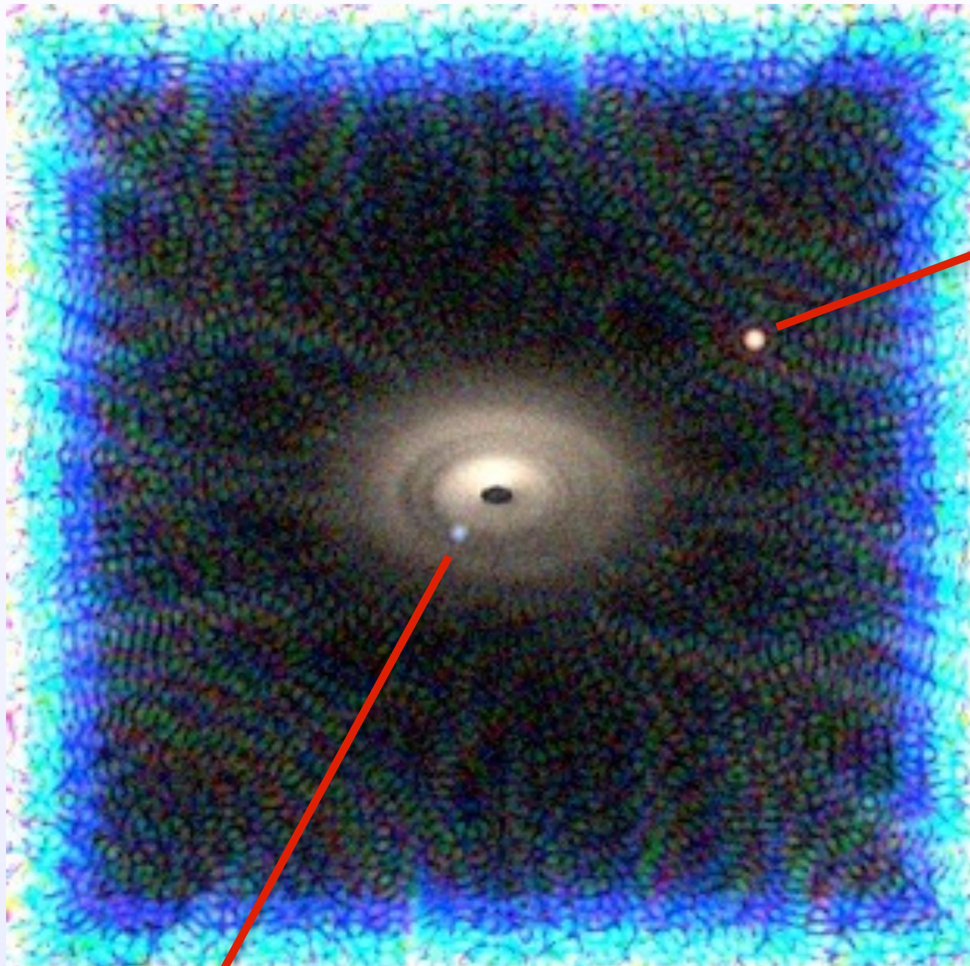
Imaging of low-mass companions

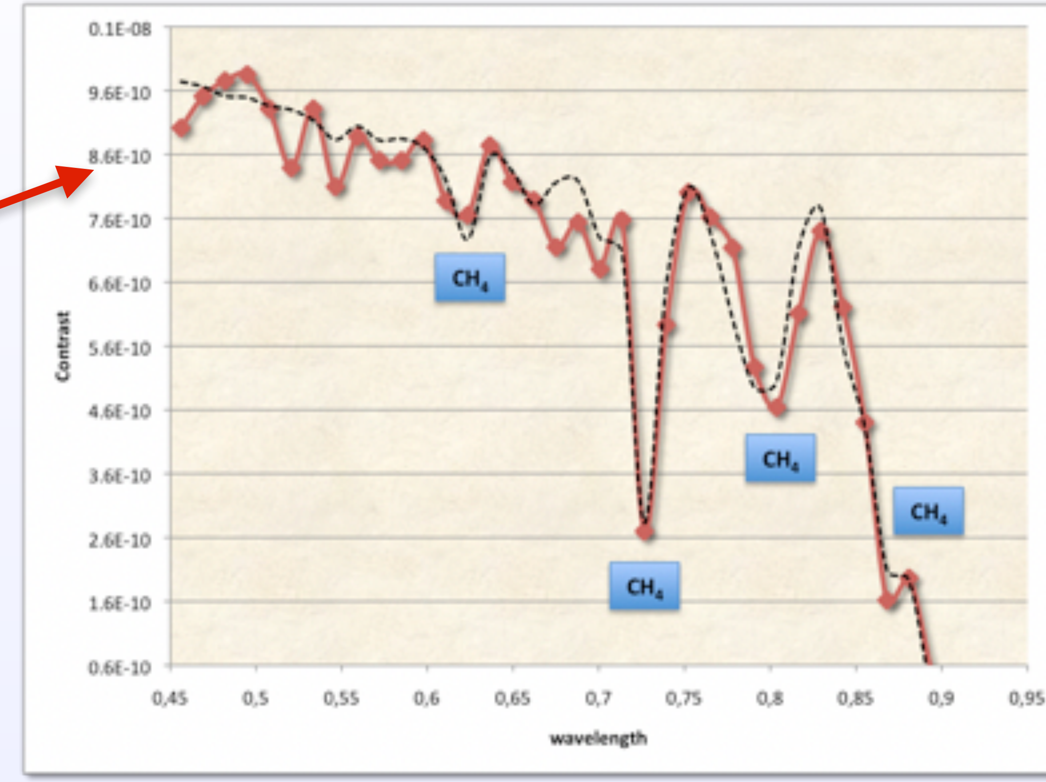


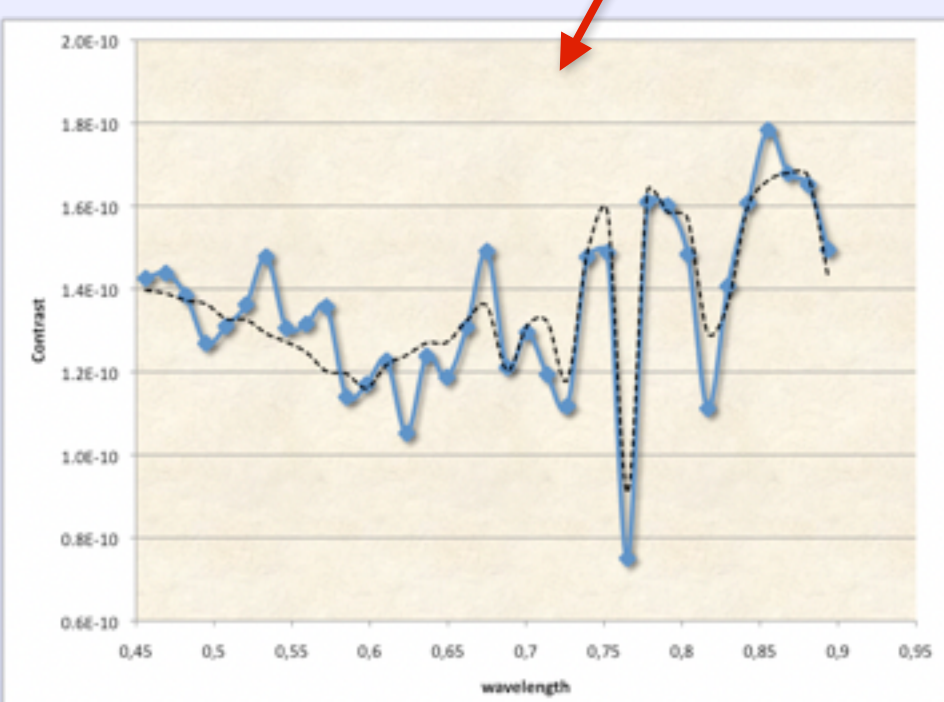
Imaging of low-mass companions



Why do imaging?



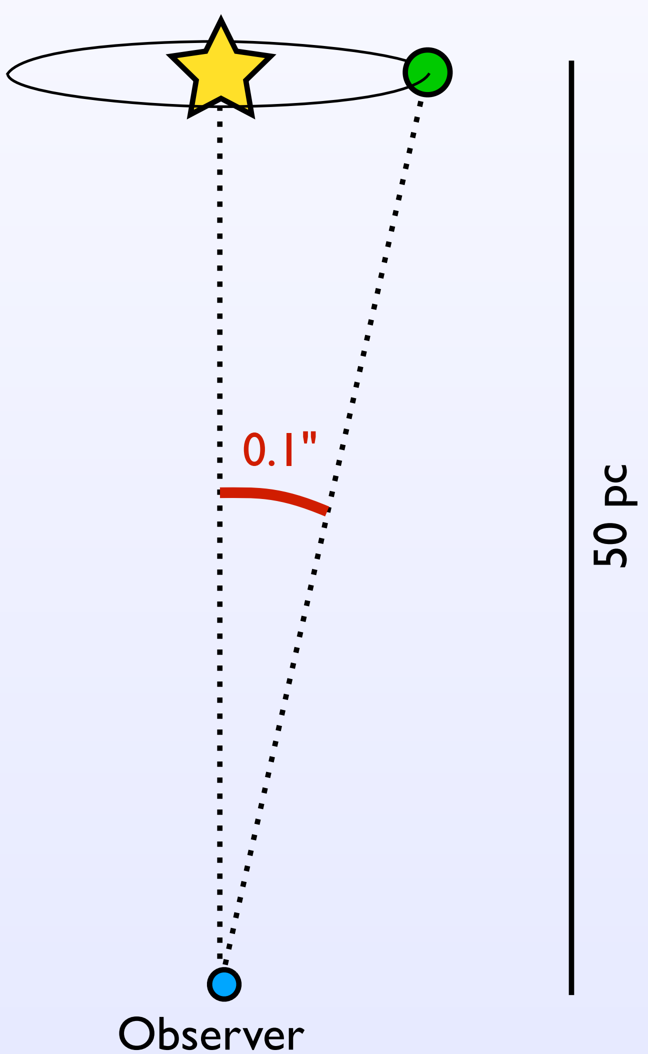




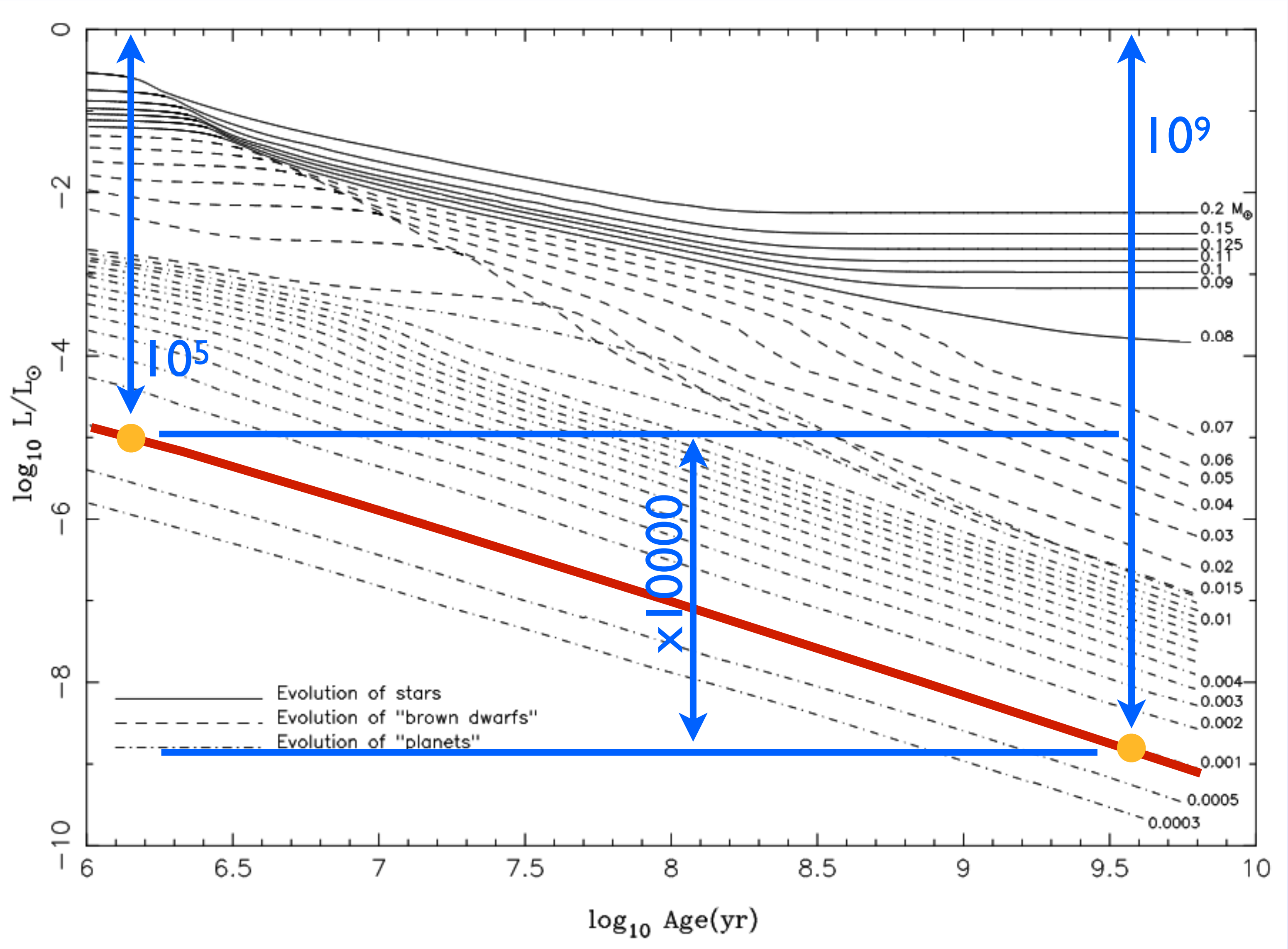
- sensitive to all spatial components: planets, disk
- direct access to:
  - architecture of systems
  - flux vs. wavelength (total and/or polarised)
- complementary with other methods:
  - mass, semi-major axis & age

Two major difficulties

High-angular resolution



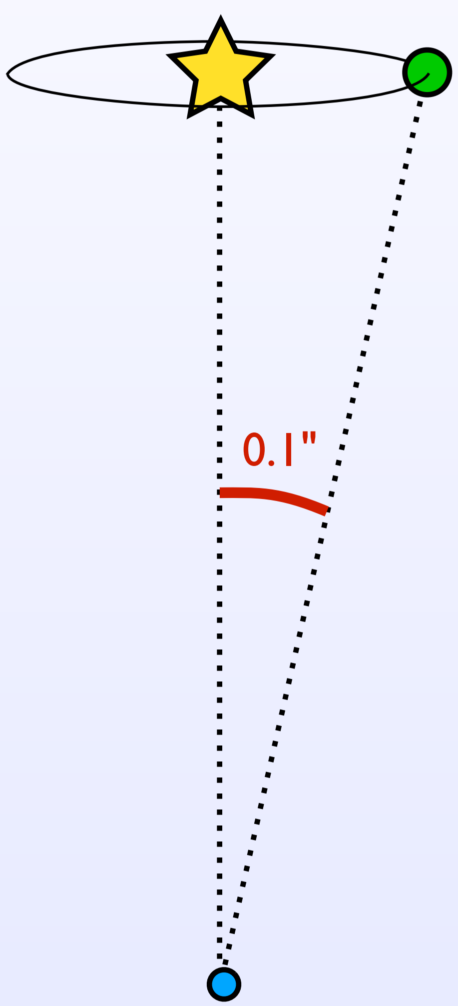
High-contrast



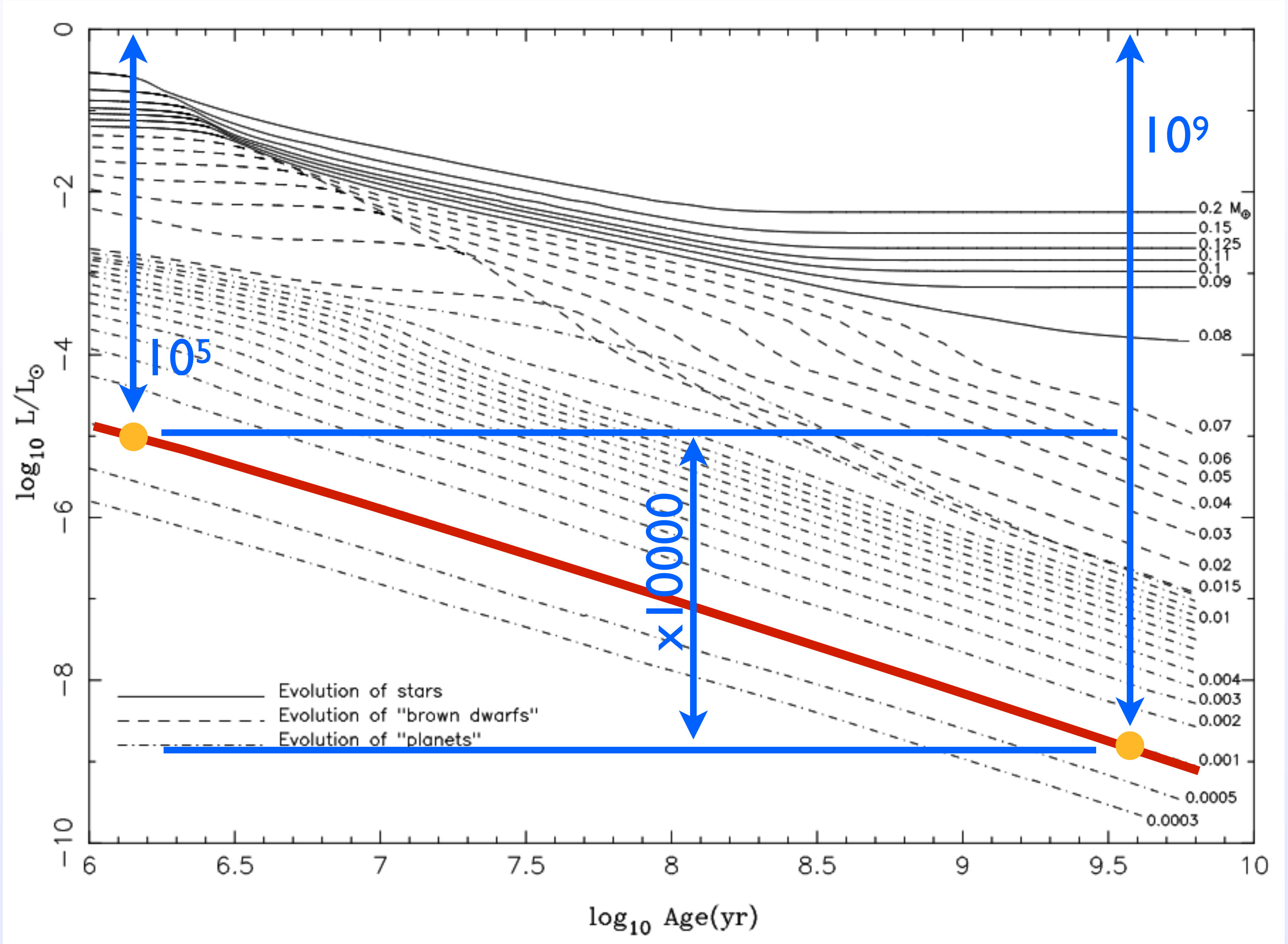
Burrows et al. (1997)

Two major difficulties

High-angular resolution



High-contrast

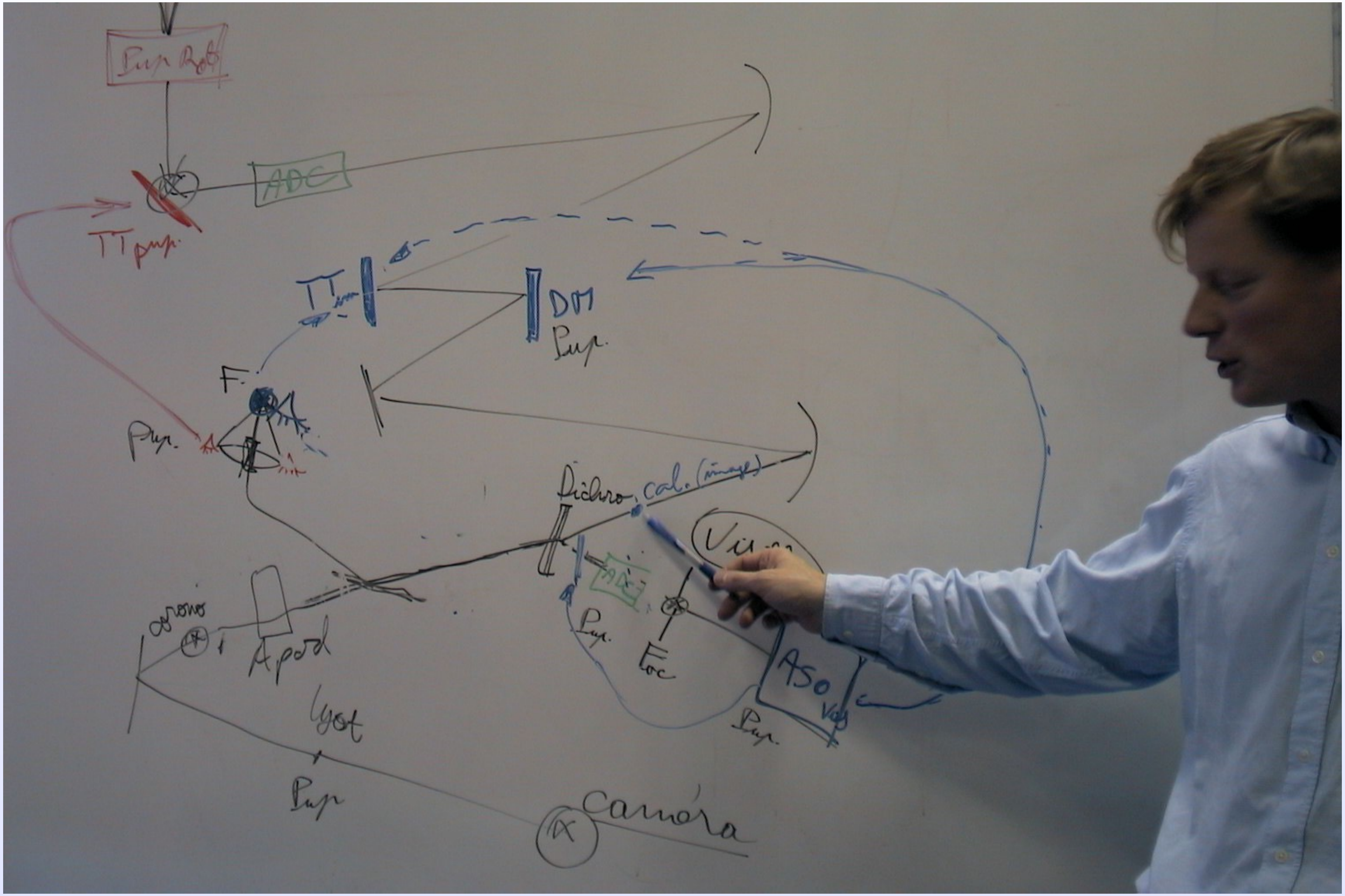


Burrows et al. (1997)

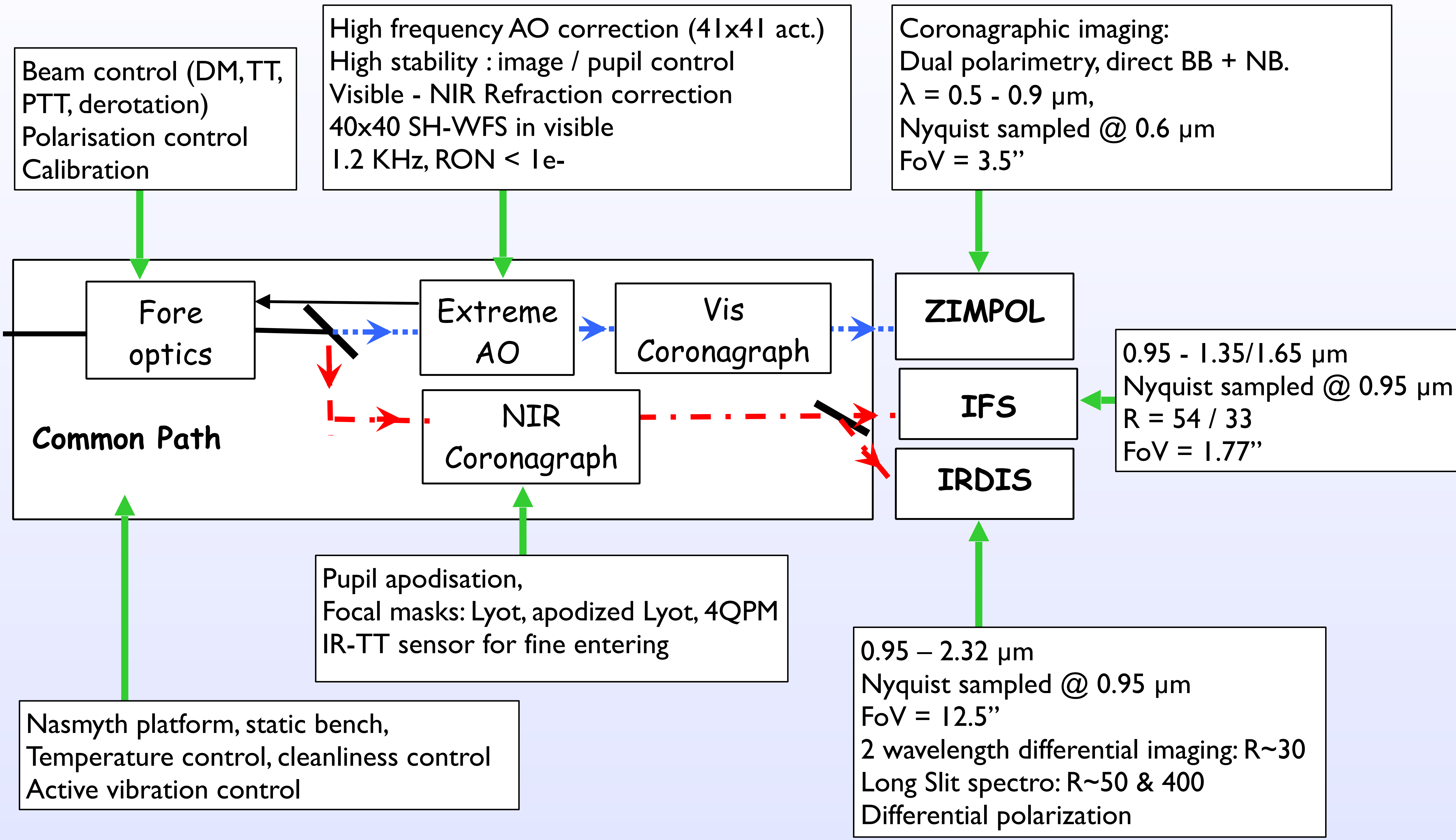
Need for dedicated, optimised instrumentation!

SPHERE

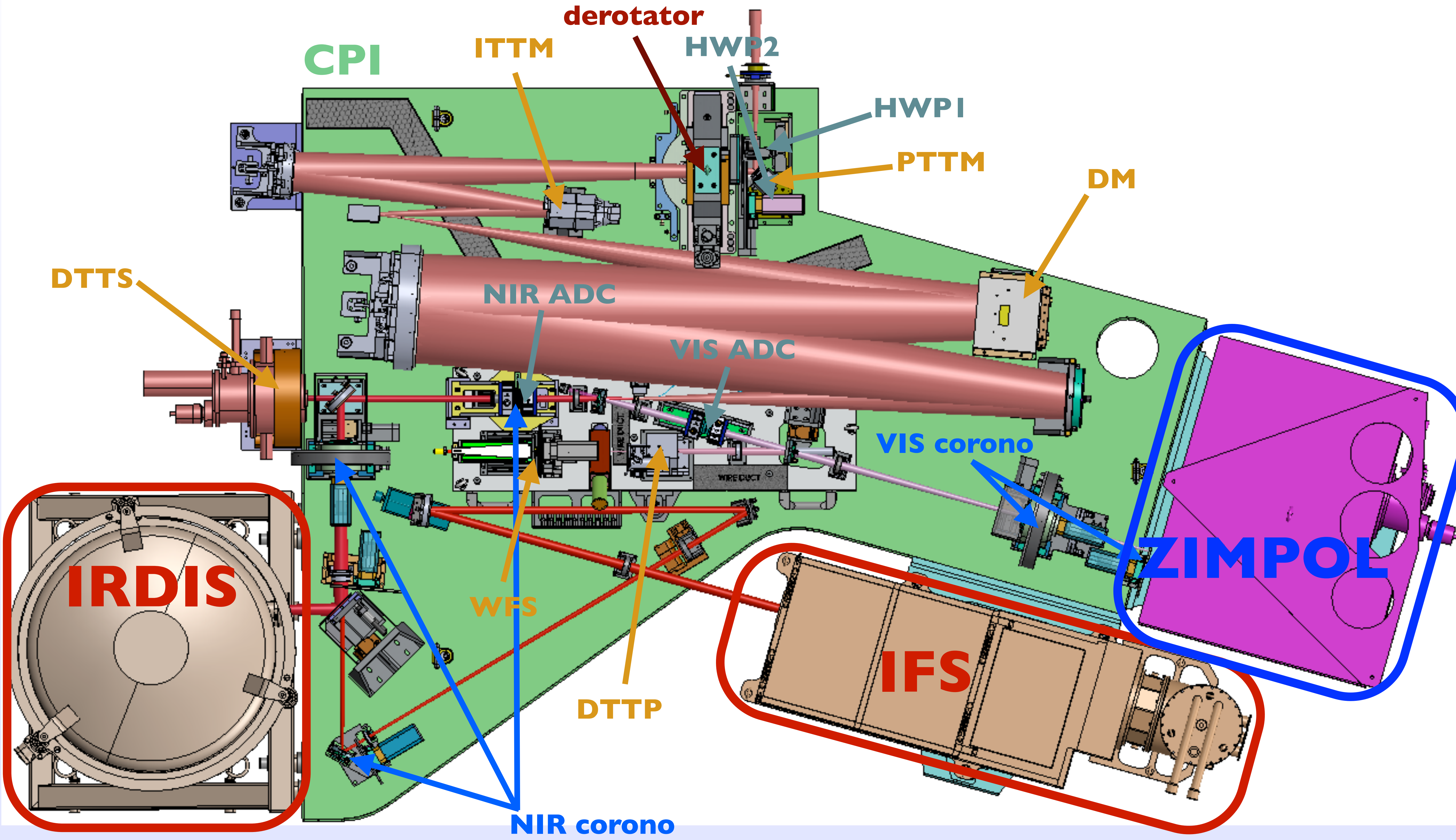
Where it all started



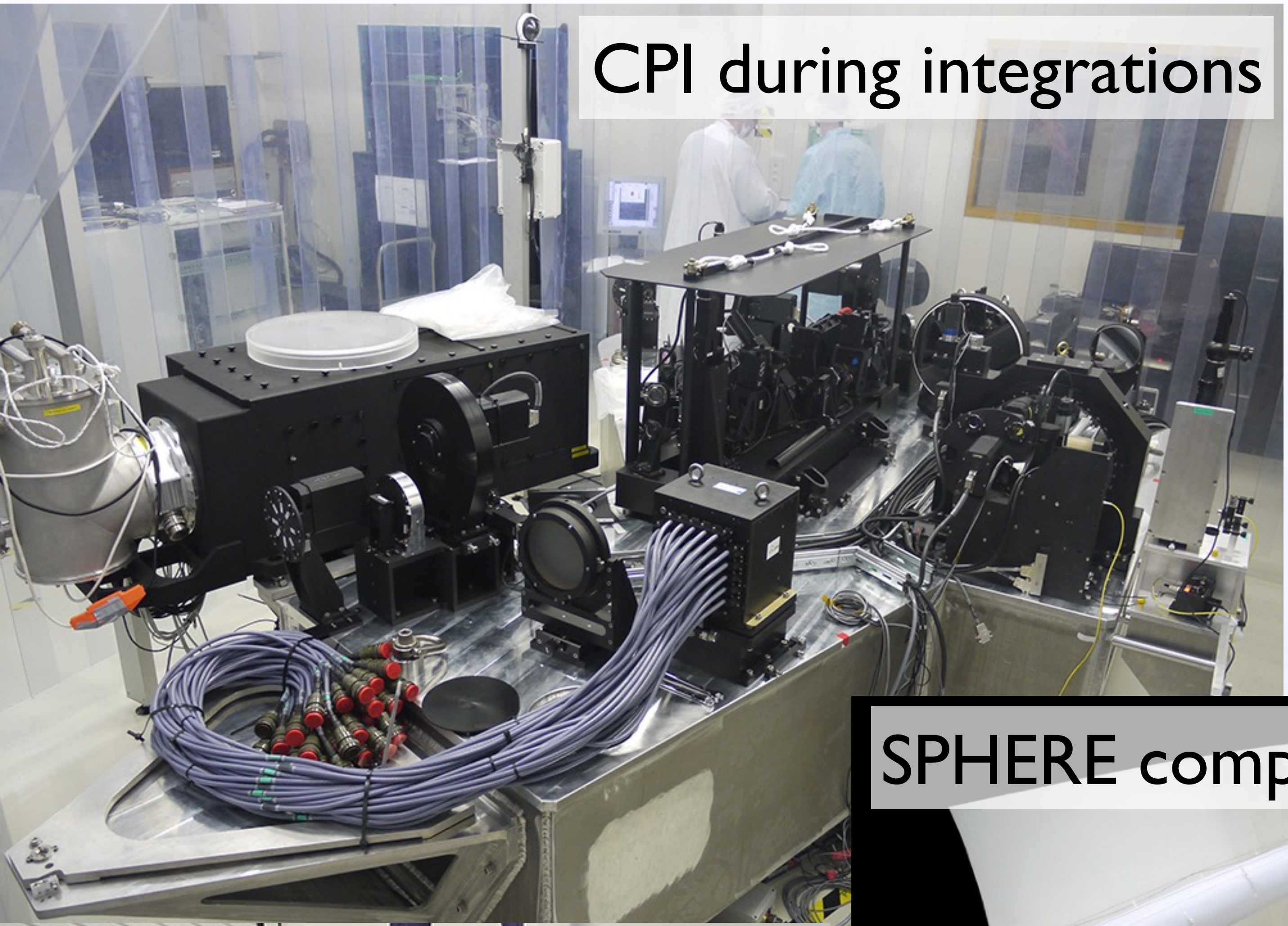
SPHERE system overview

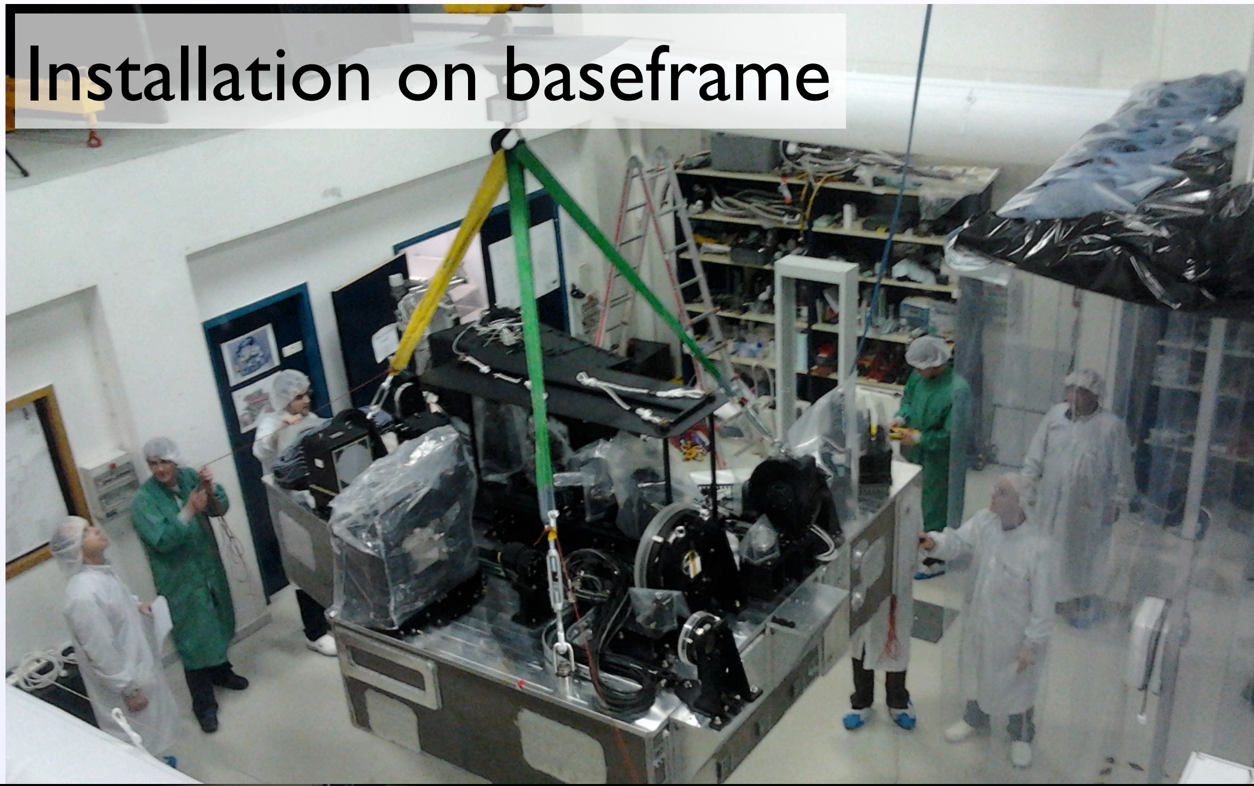


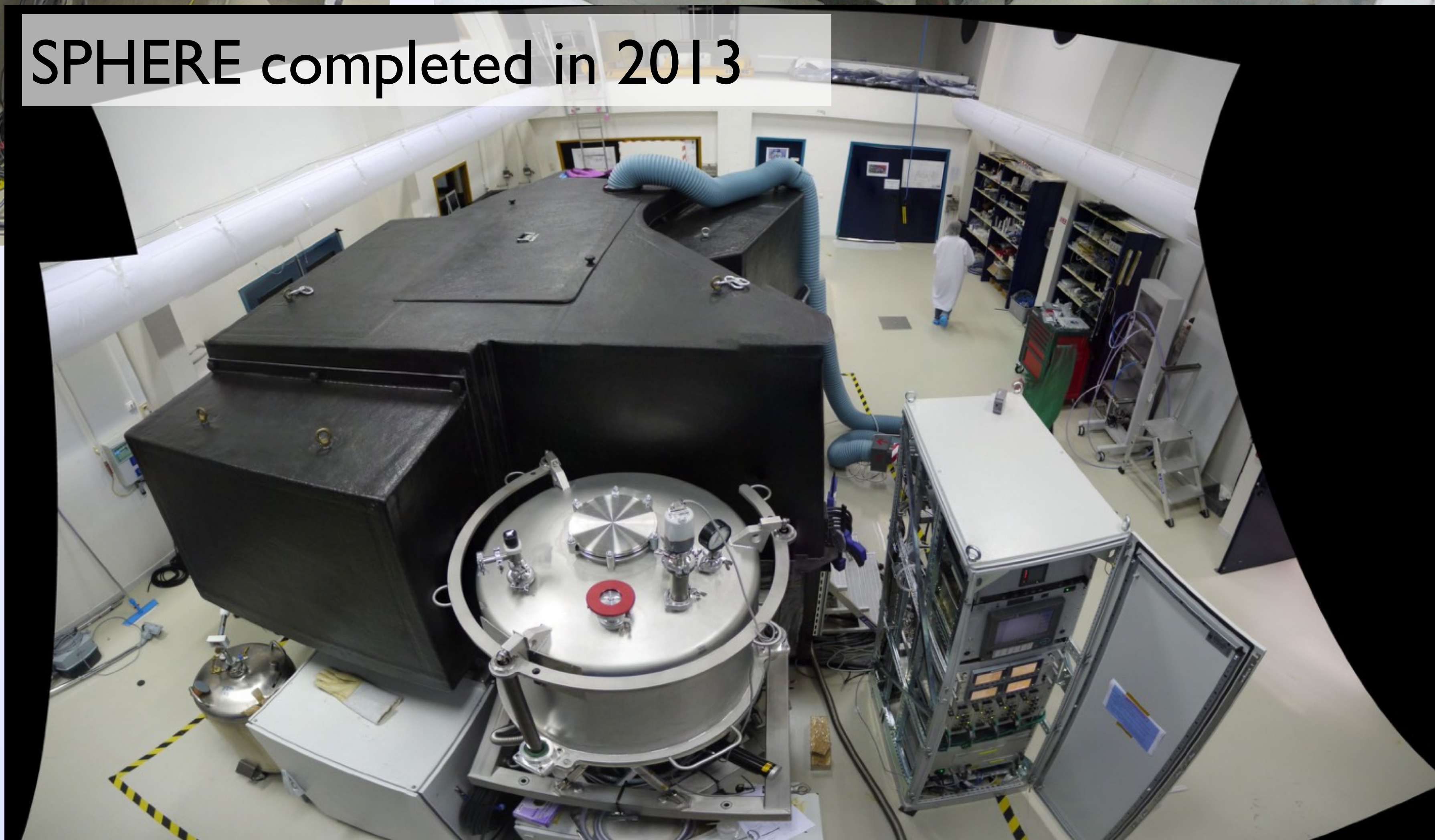
Implementation



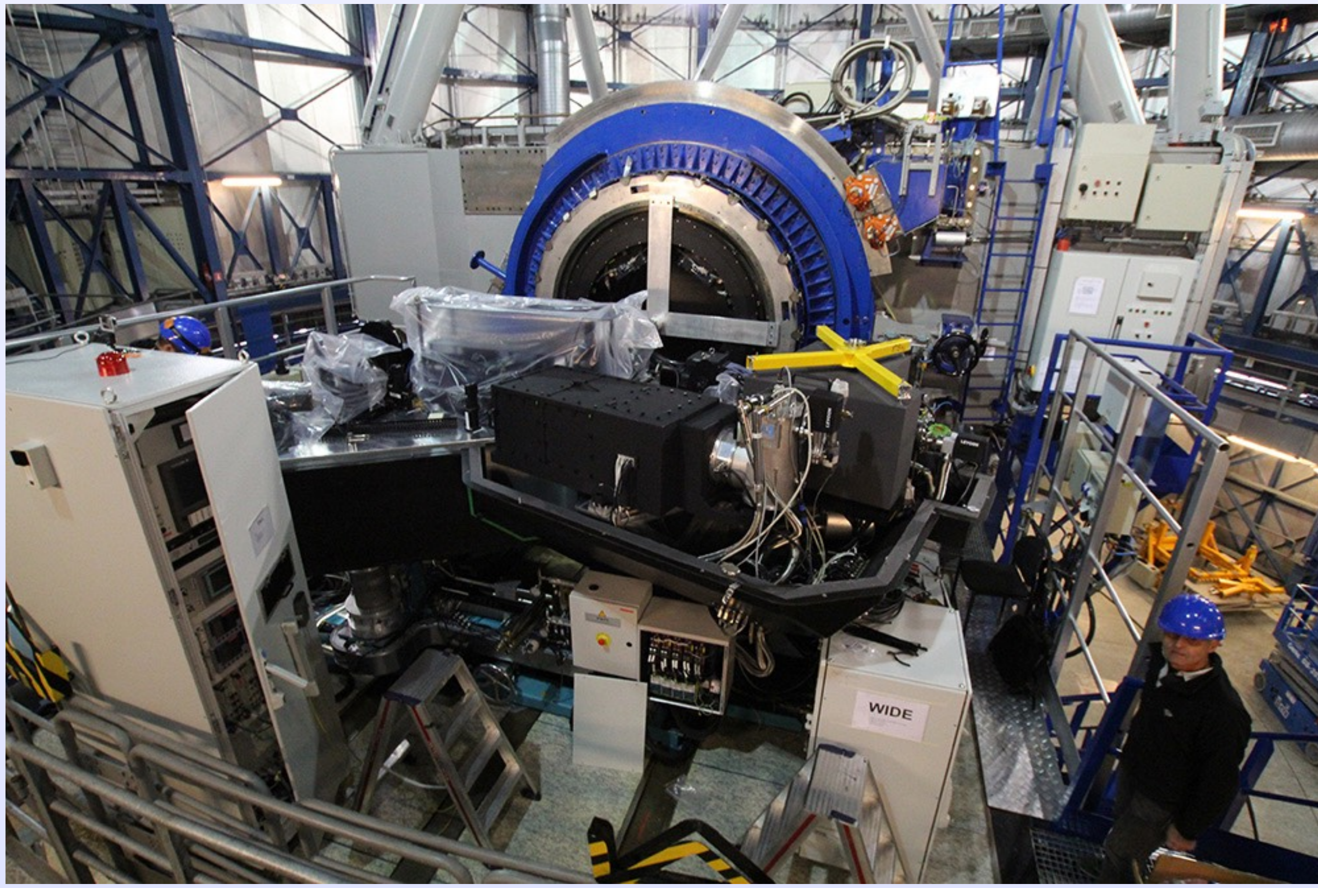
2011-2013: integration in Europe

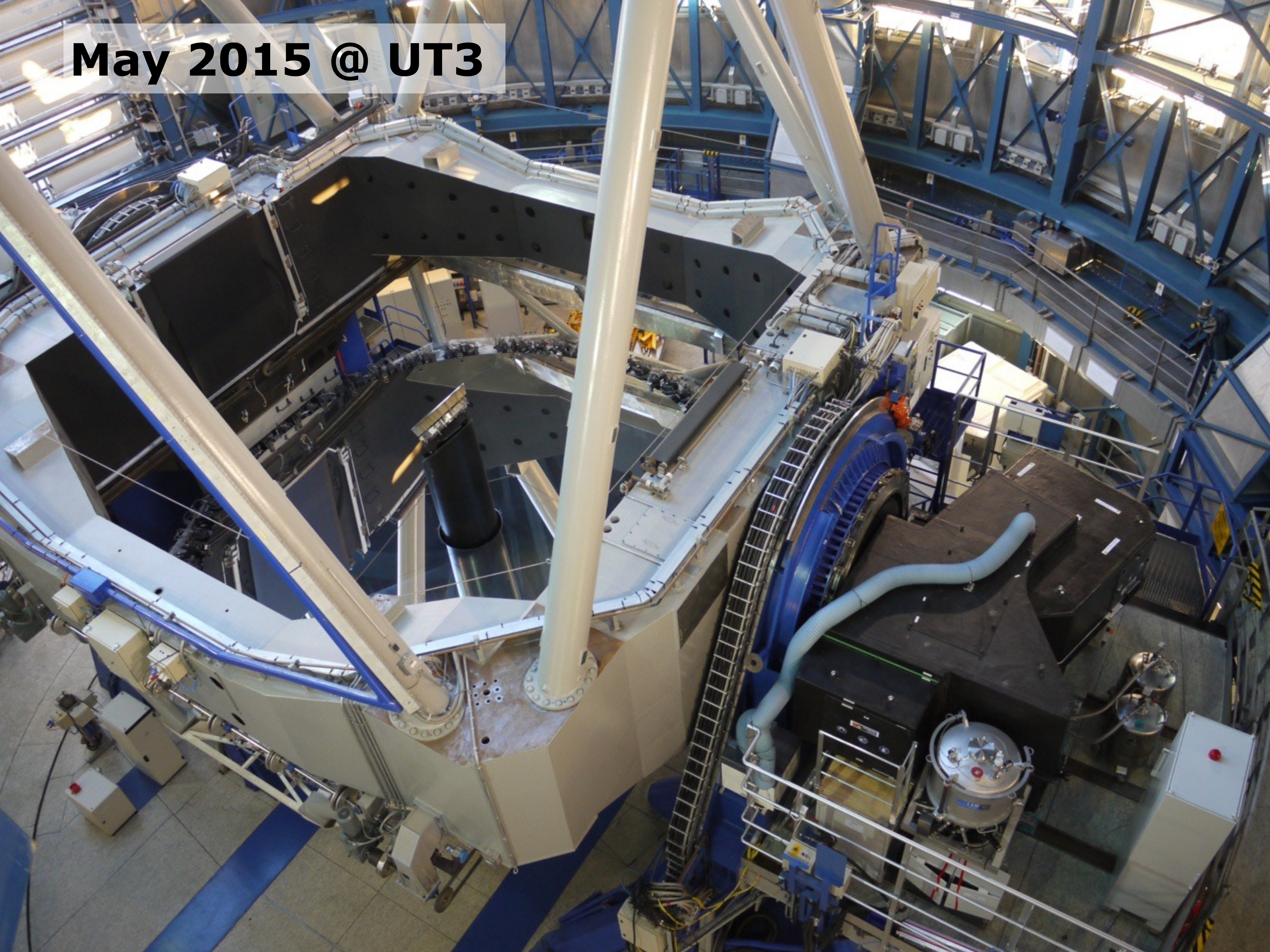




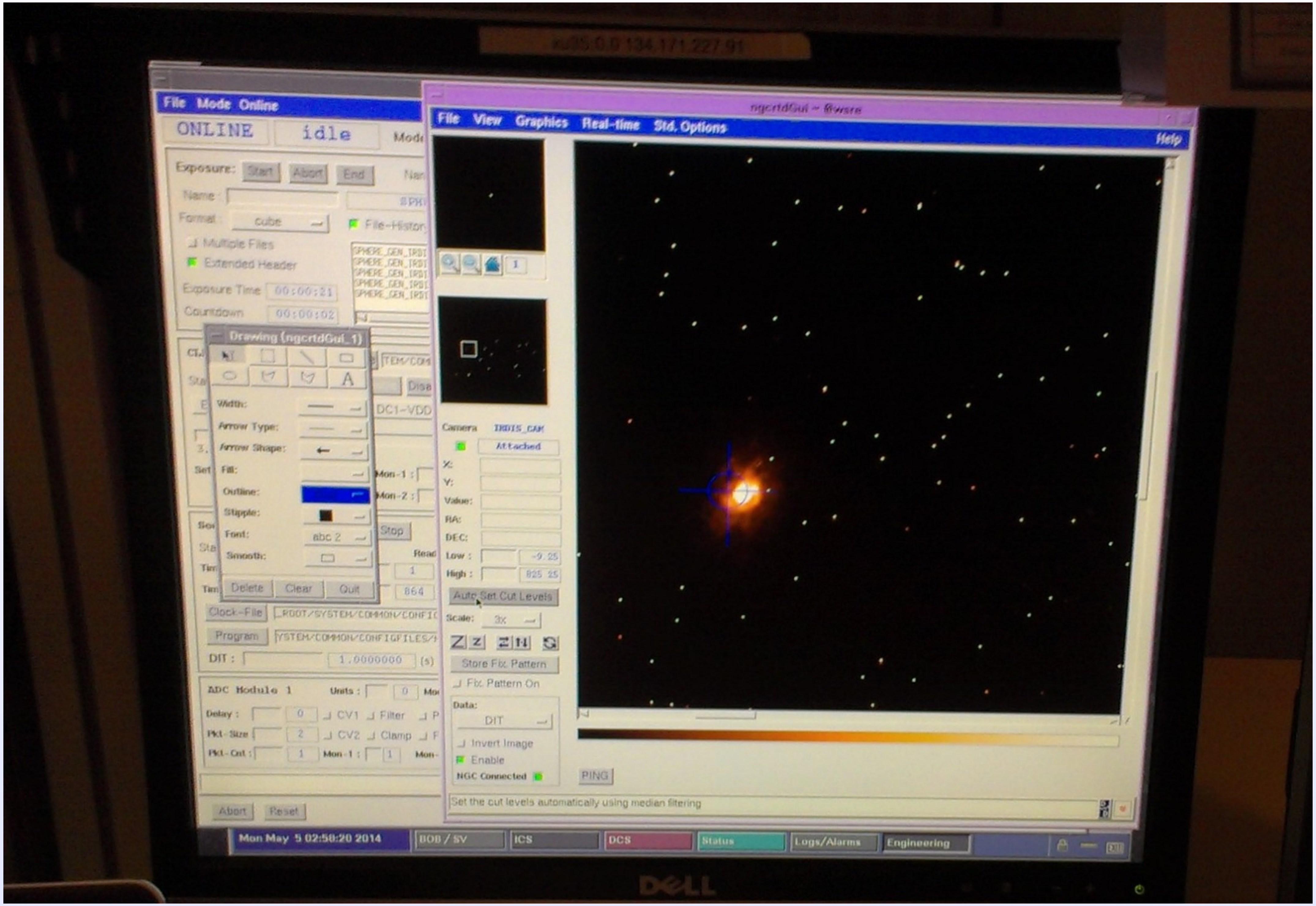


2014: shipment and reintegration




May 2015 @ UT3

May 6th 2014: first light



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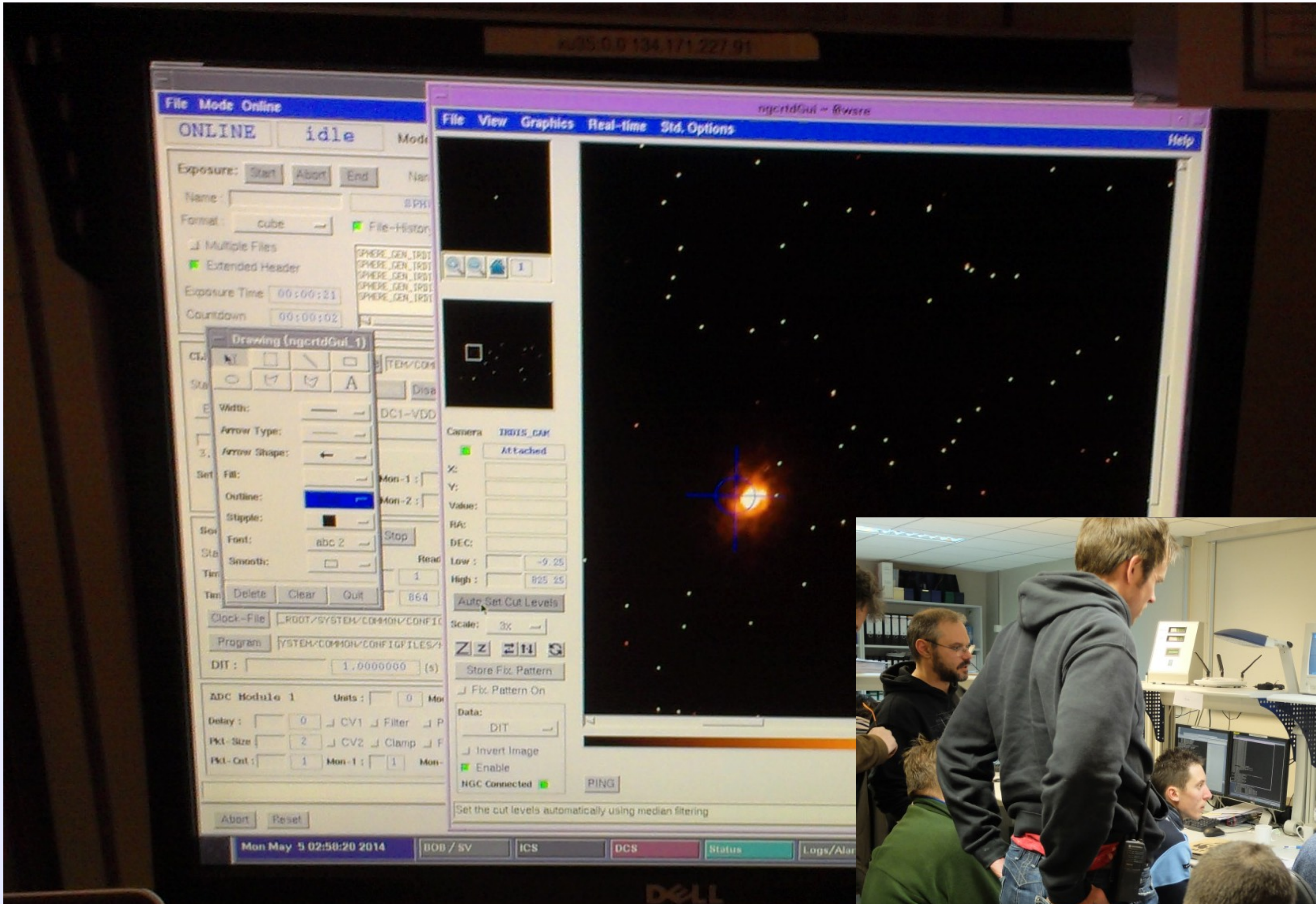
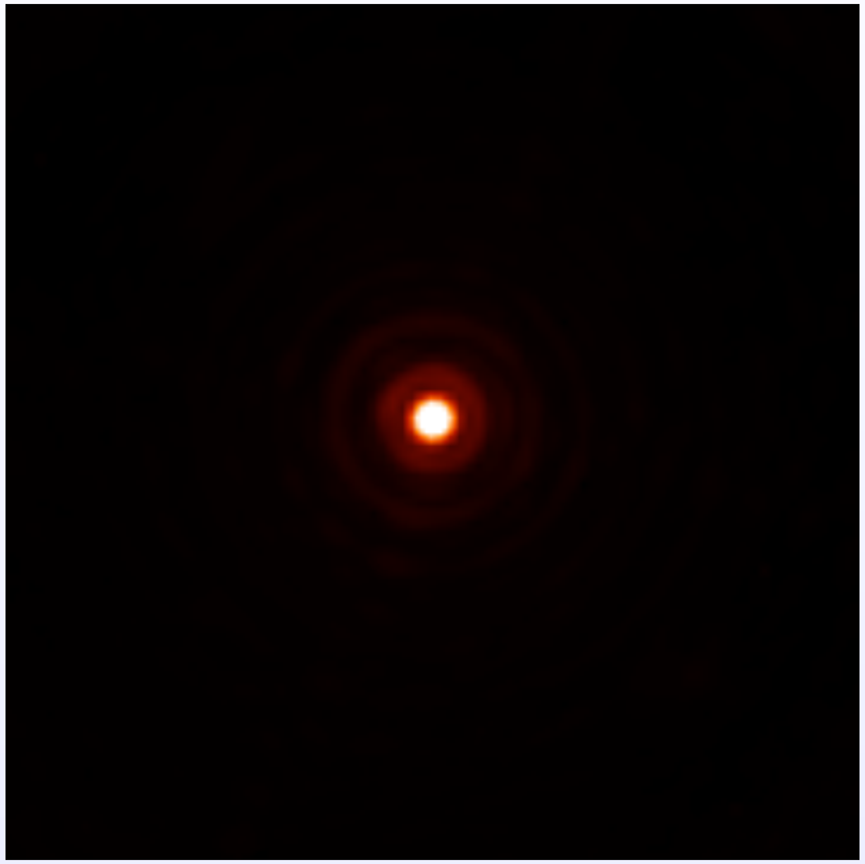
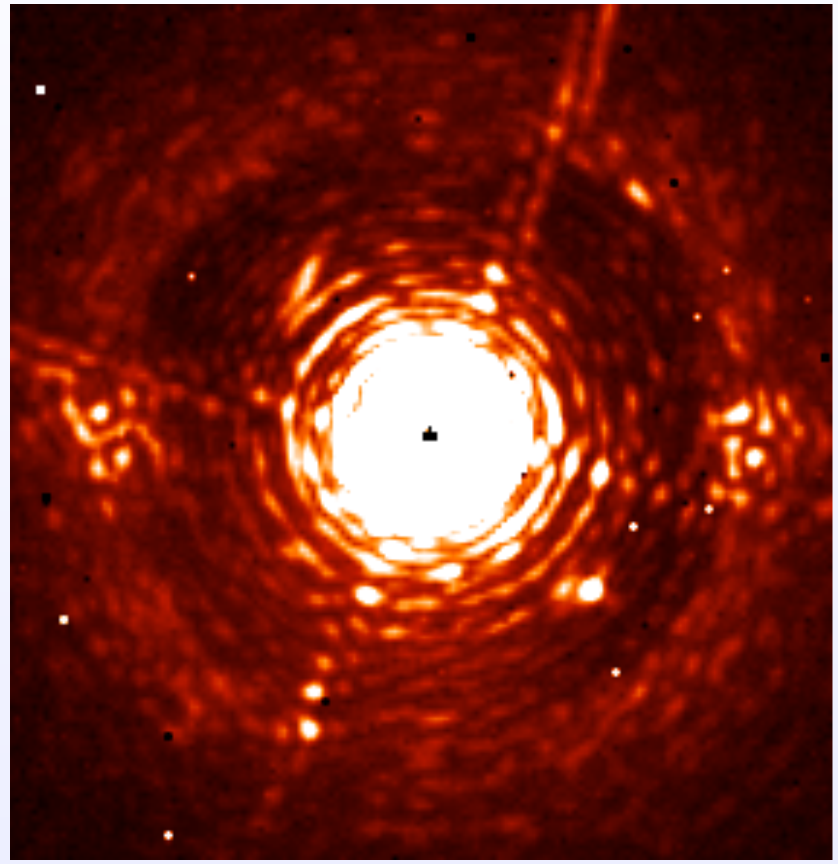


SPHERE asset #1: SAXO

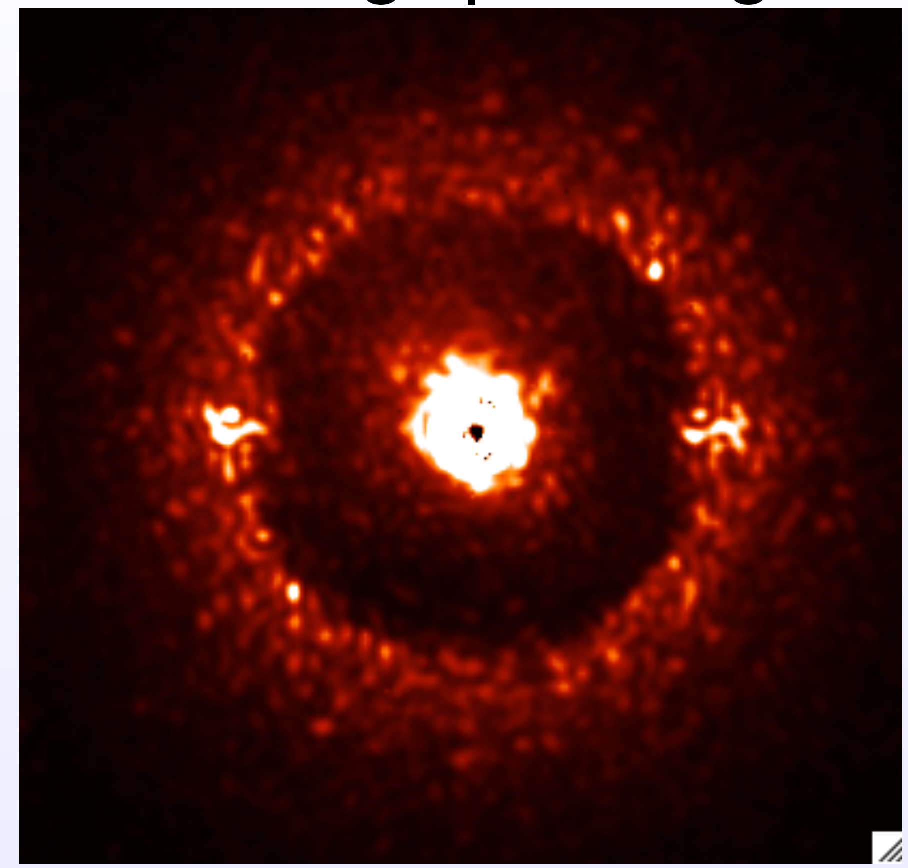
PSF



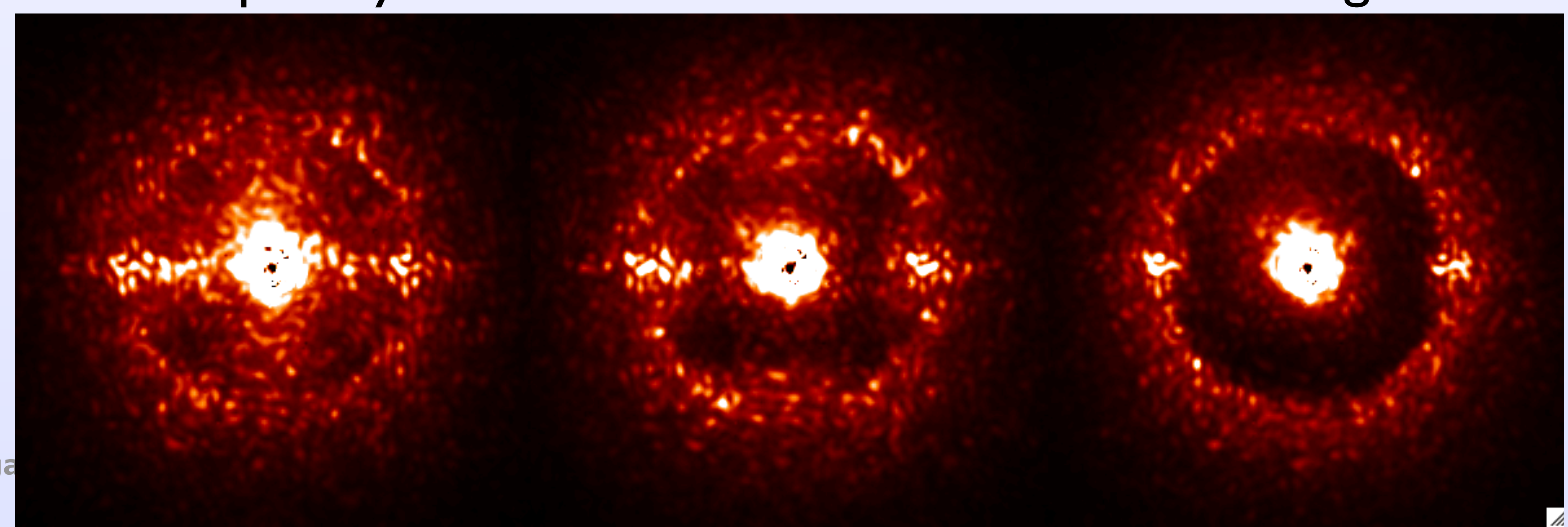
Saturated PSF



Coronagraphic image

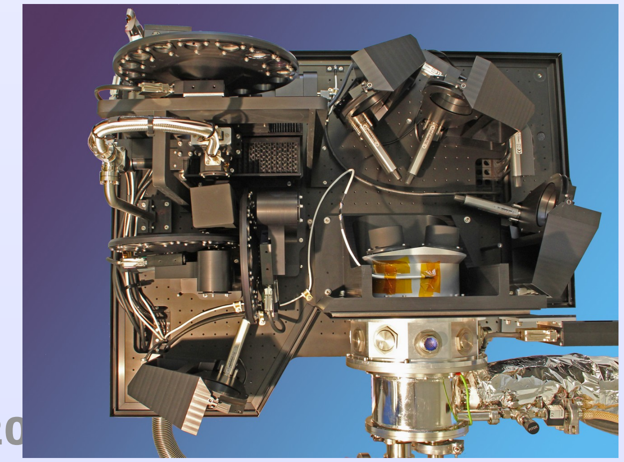


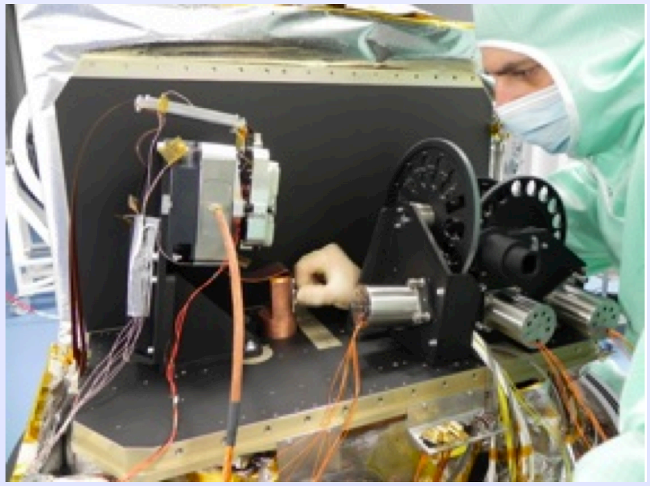
Spatially-filtered Shack-Hartmann for anti-aliasing

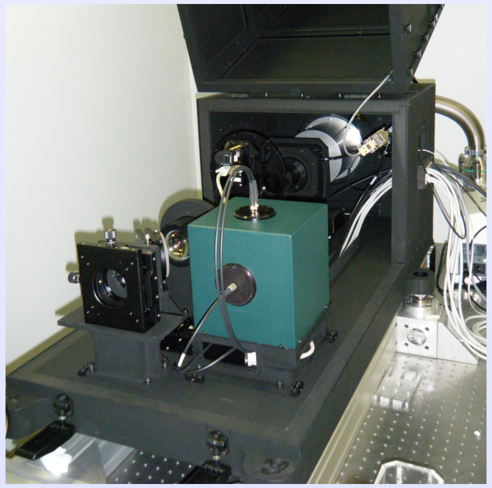


SPHERE asset #2: science instruments

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







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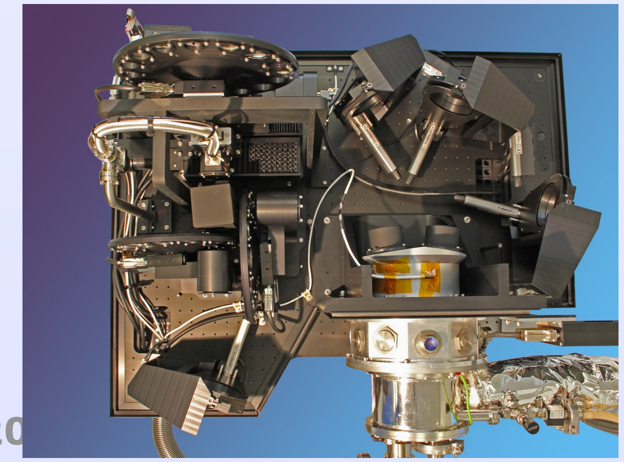
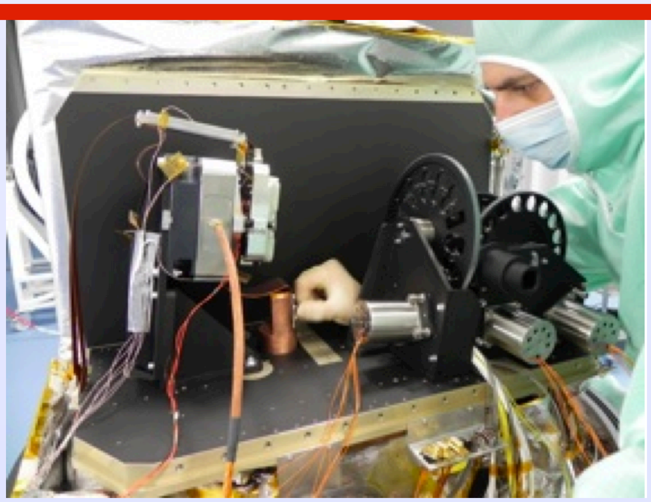
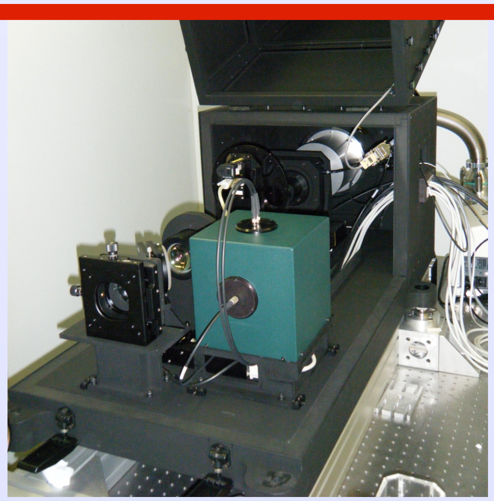
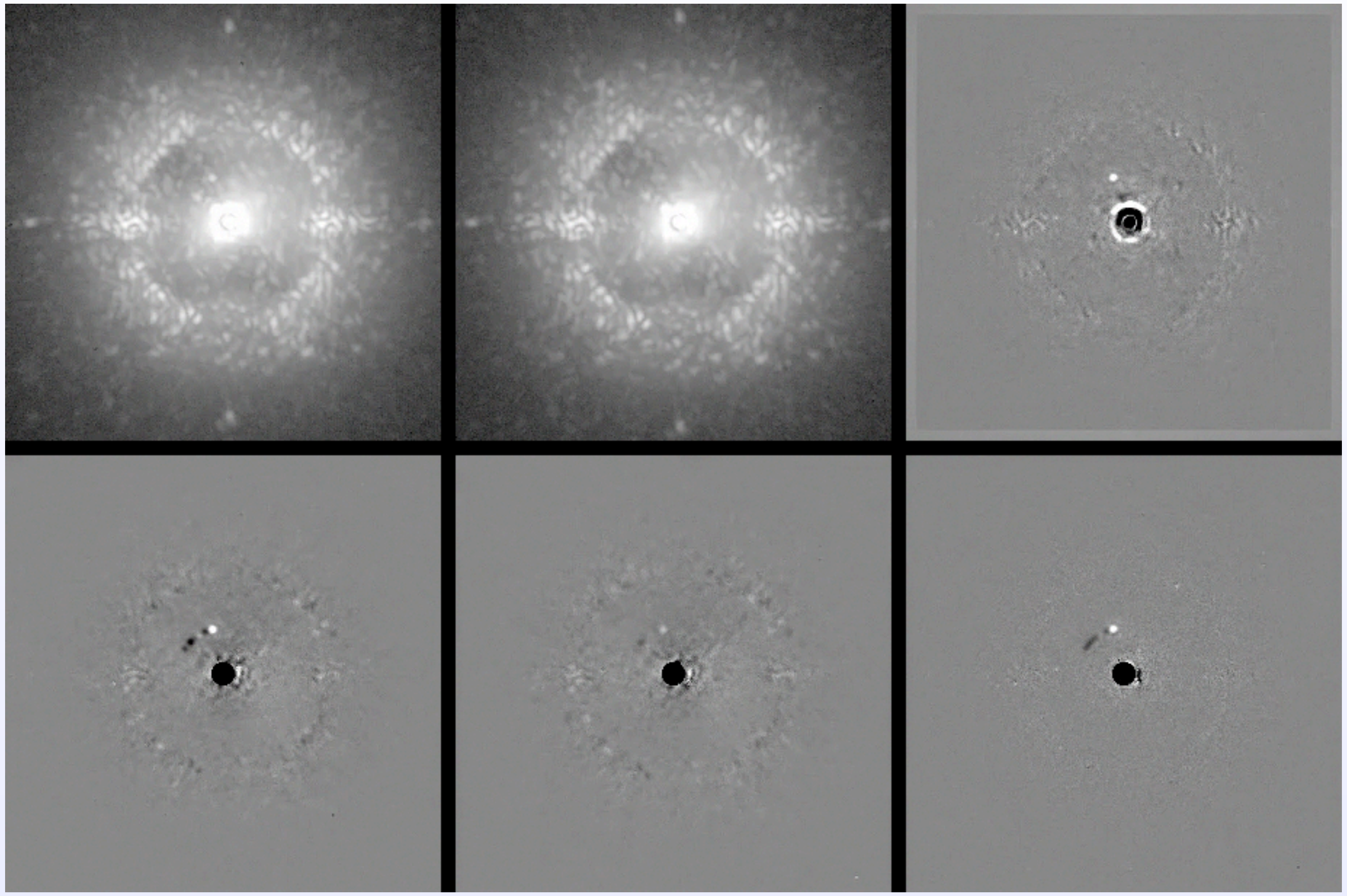




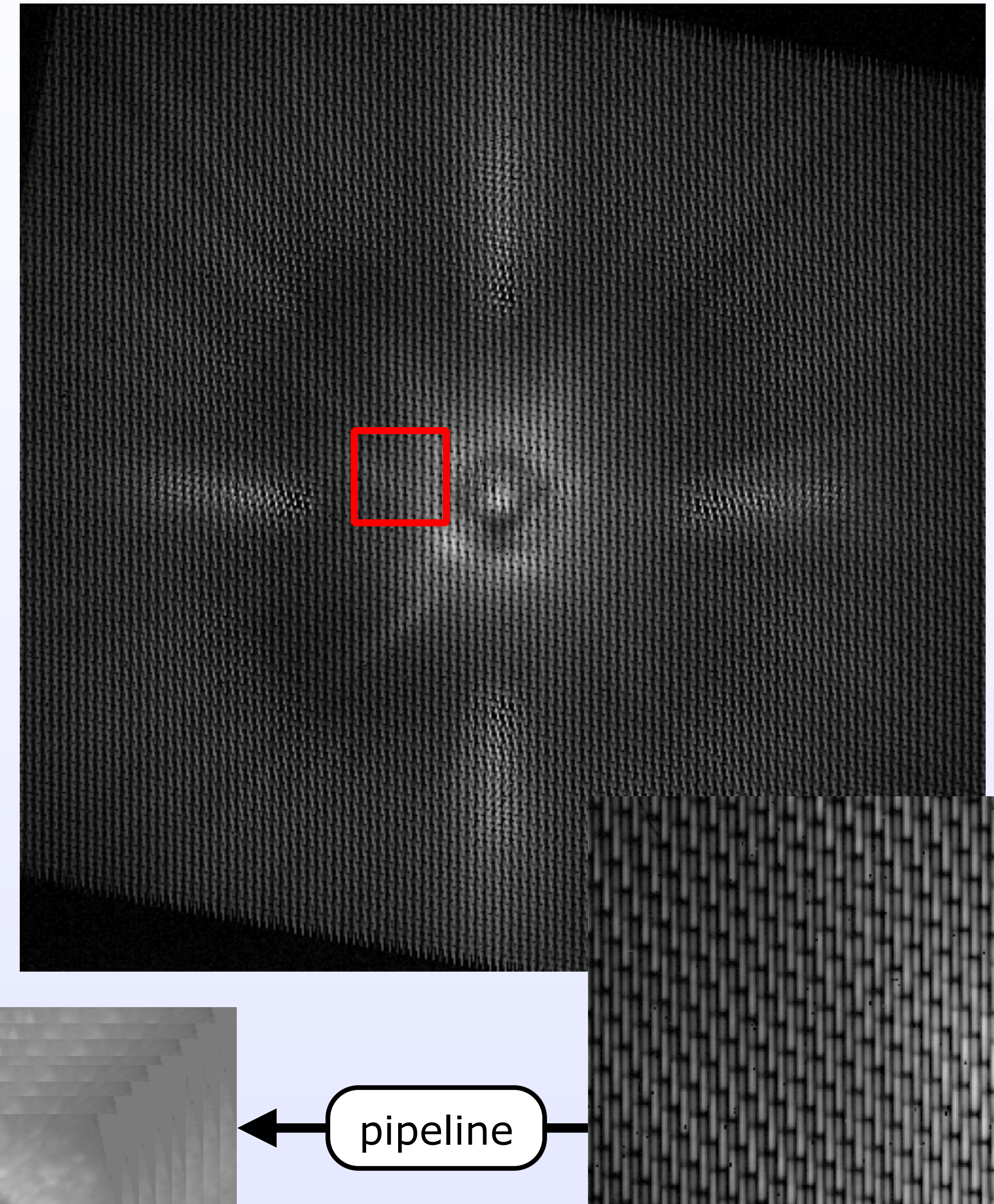


IRDIFS: the exoplanet hunting mode

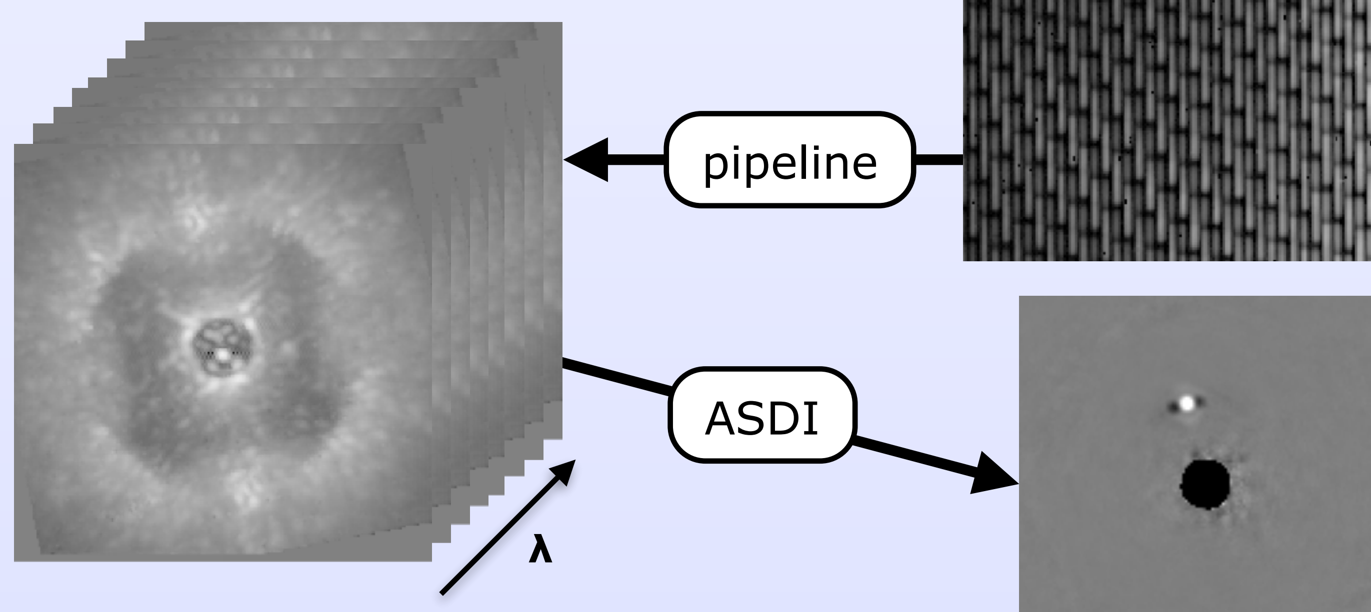
IRDIS



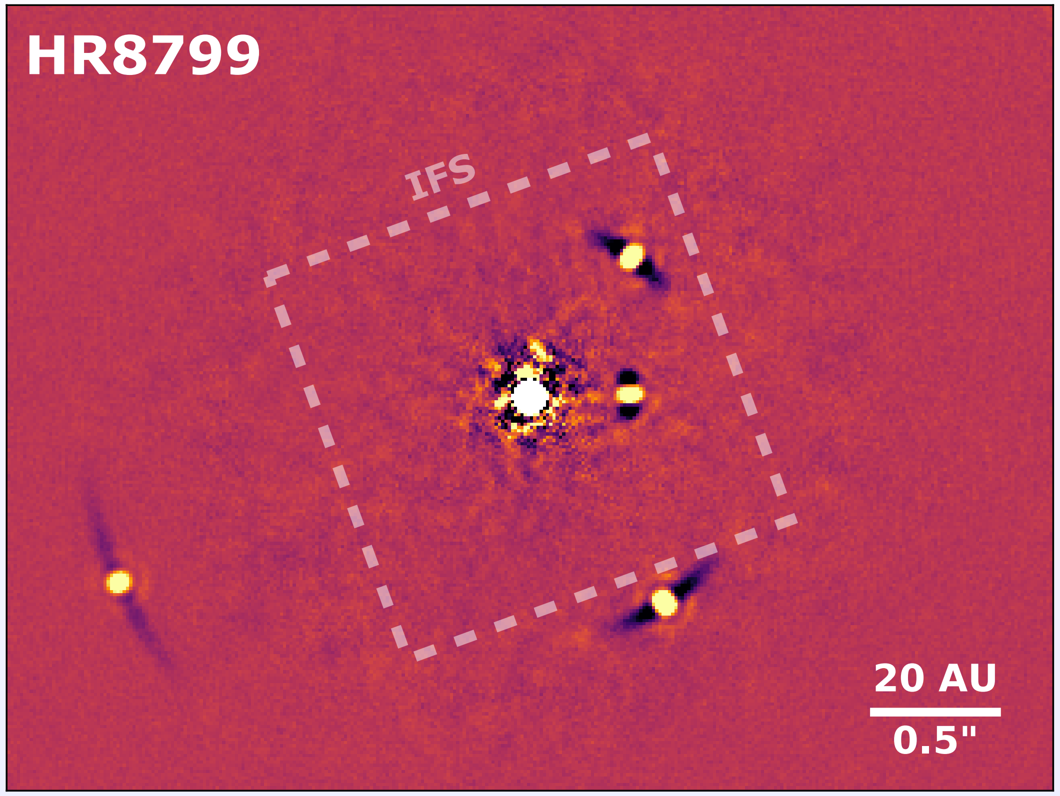
IFS



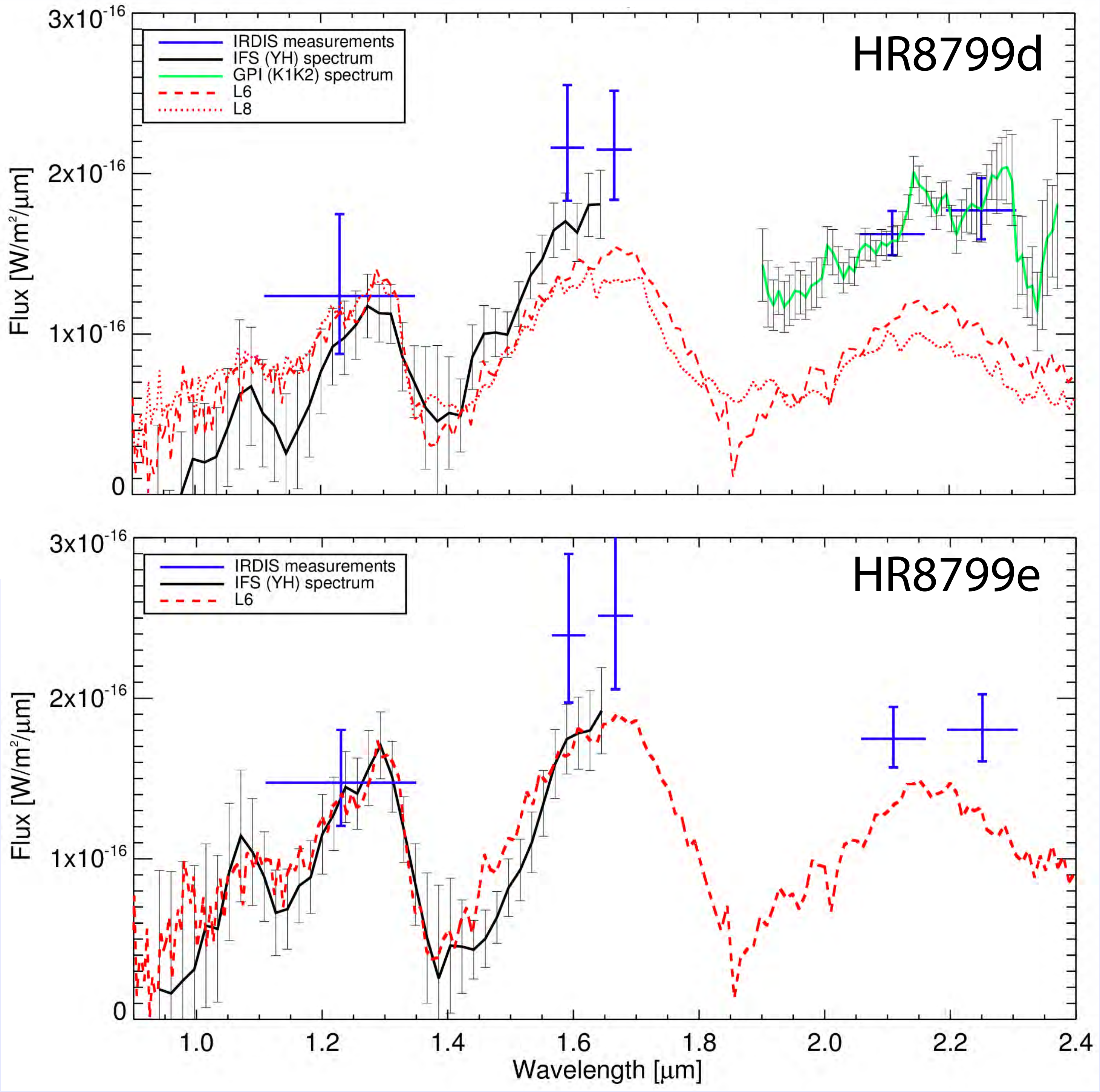
- SPHERE designed to be a **survey instrument**
- "near-infrared survey" observing mode
    - IRDIFS: IFS in YJ + IRDIS in H
    - IRDIFS_EXT: IFS in YJH + IRDIS in K_s
- extremely efficient for planet hunting



Early SPHERE results: the HR8799 system



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

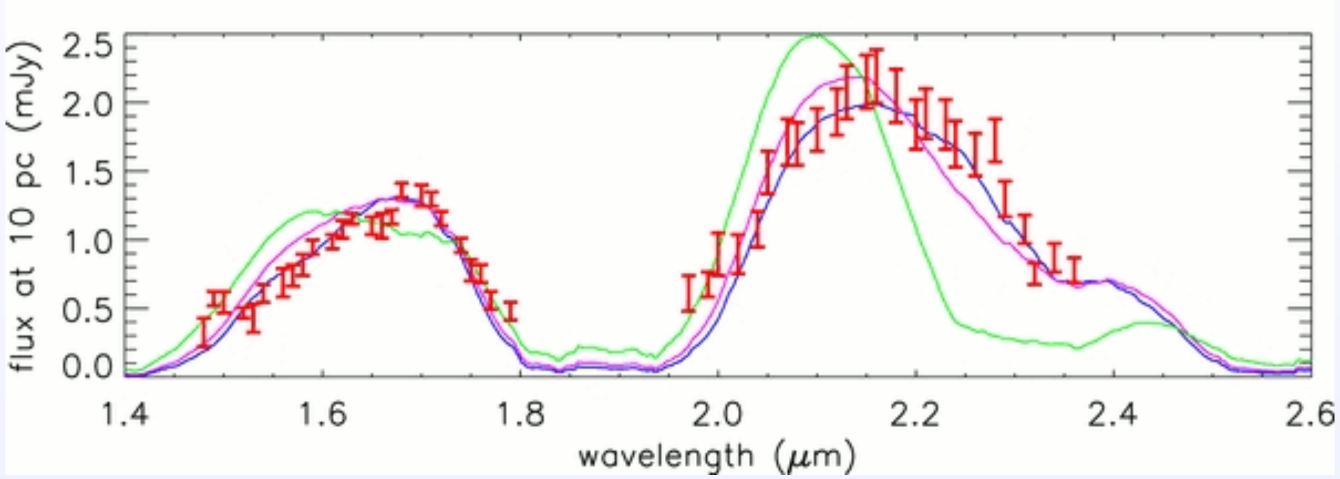


- First spectra for HR8799 c, d
- Spectral types ~L6-L8
- Redder colors than field BD and models
- Reddening well reproduced by submicron grains made of corundum, iron, enstatite, or forsterite

SHINE

SHINE: SpHere Infrared survey for Exoplanets

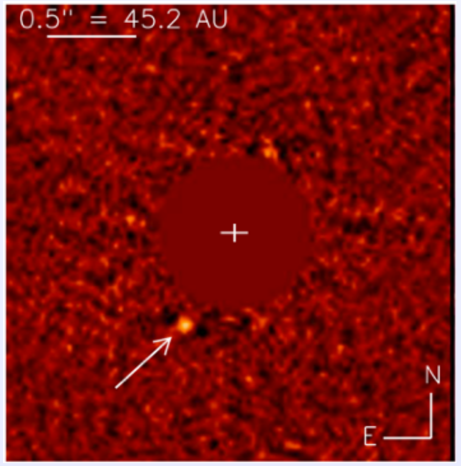
200 nights of VLT/SPHERE over 5 years

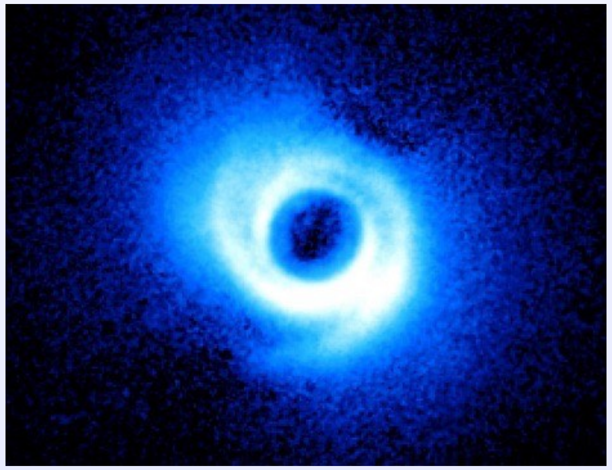


1/ Physics of giant exoplanets

Photometry & Spectroscopy

Atmosphere & physical properties





2/ Architecture & stability of planetary systems

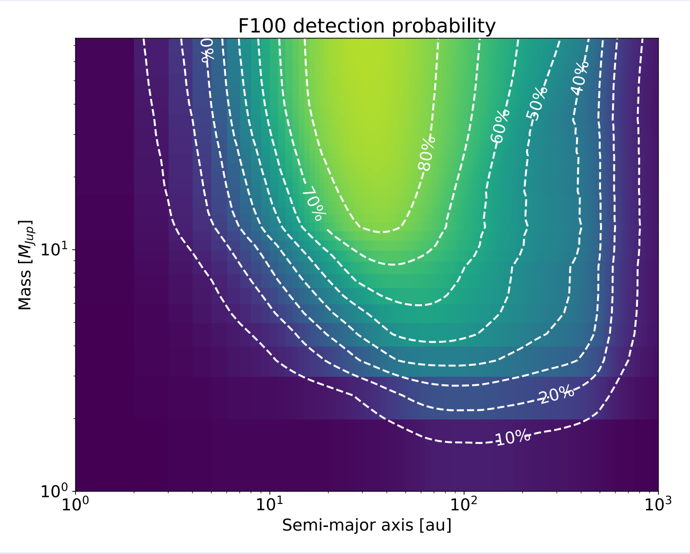
Astrometry & Disk/Planet relative position

Orbits, dynamical interactions, resonances & long-term evolution

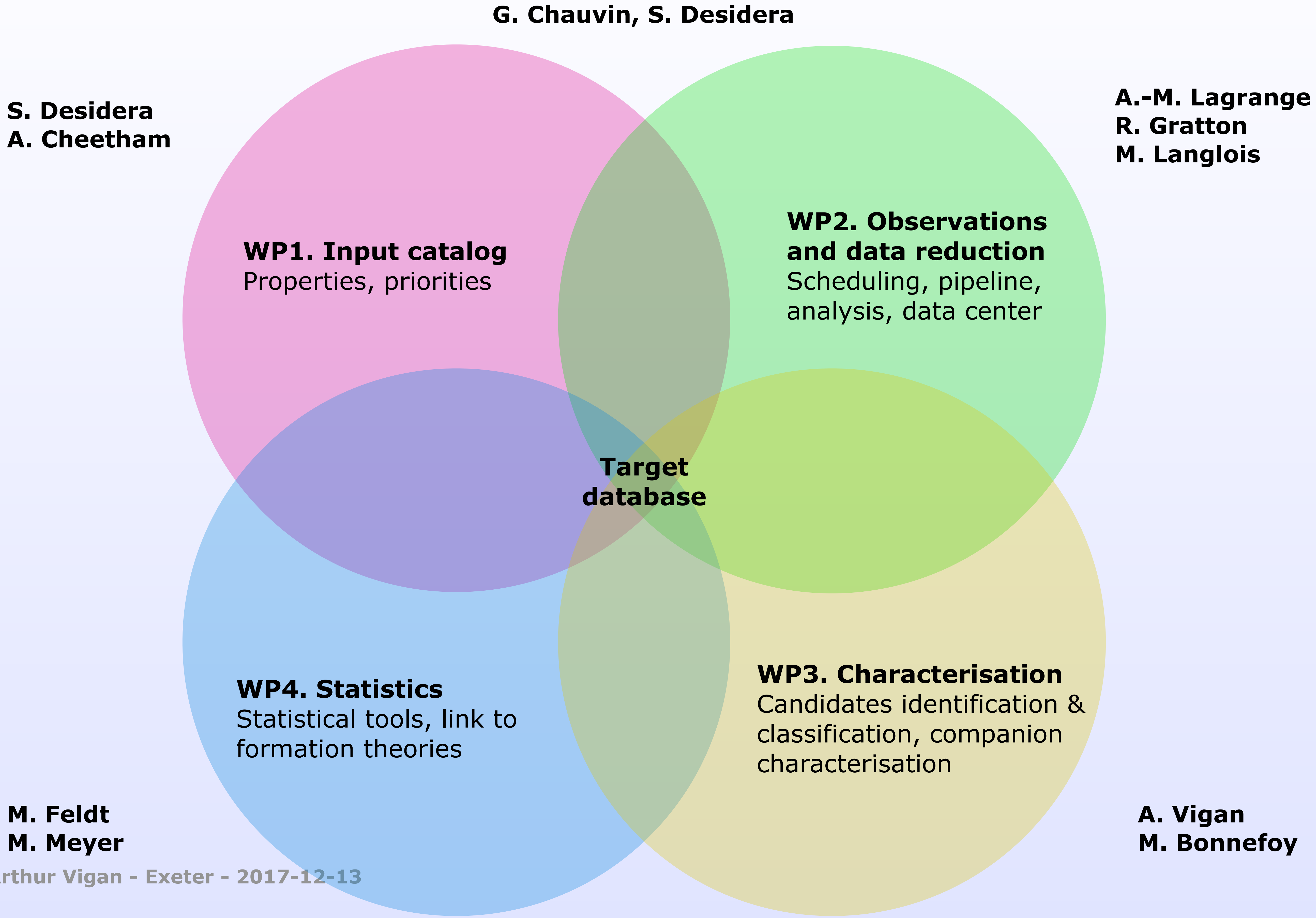
3/ Occurrence & formation

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

Formation Theories: CA, GI or CF

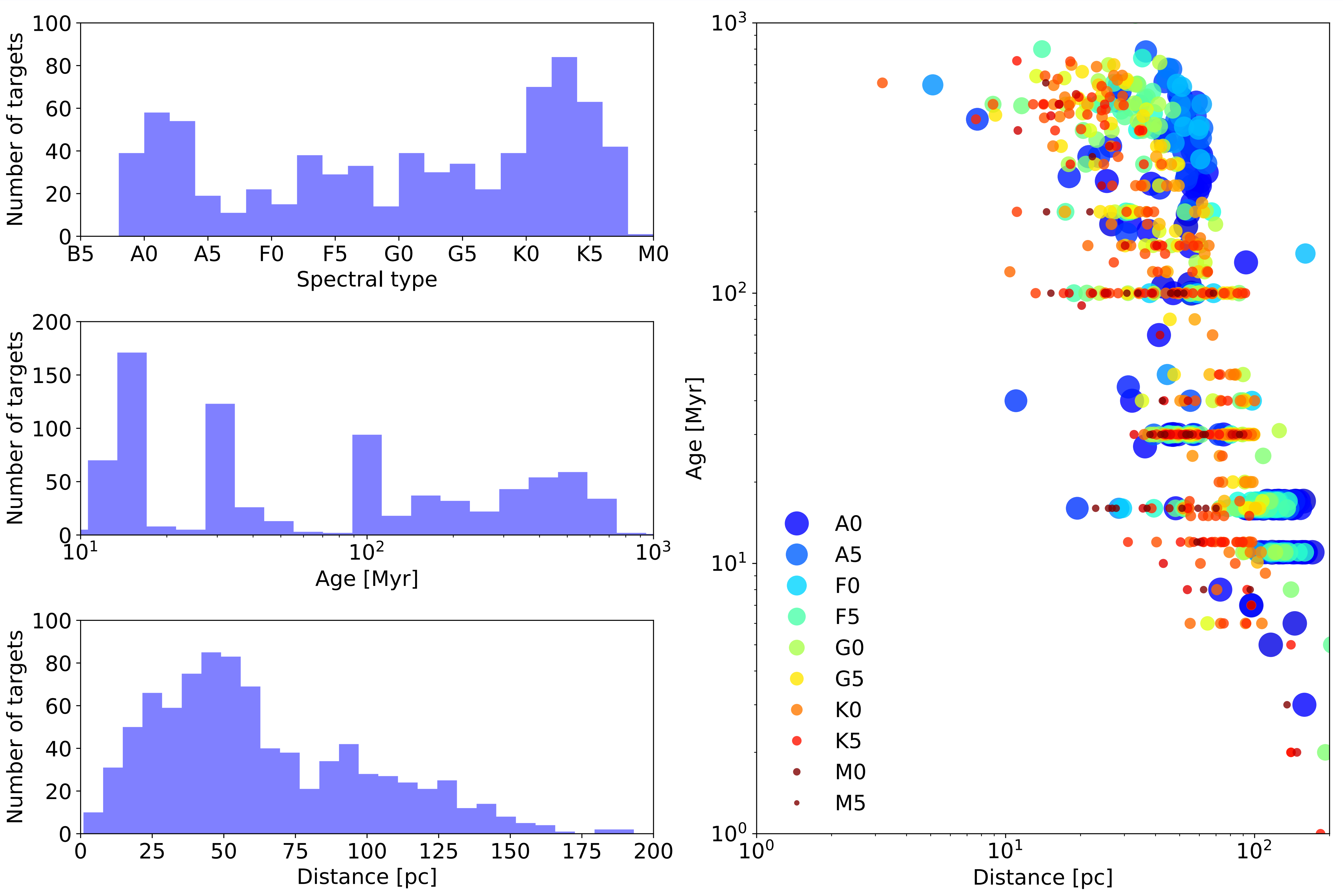


SHINE organisation



Sample

600 stars + 400 backup, 4 priority bins



R<11

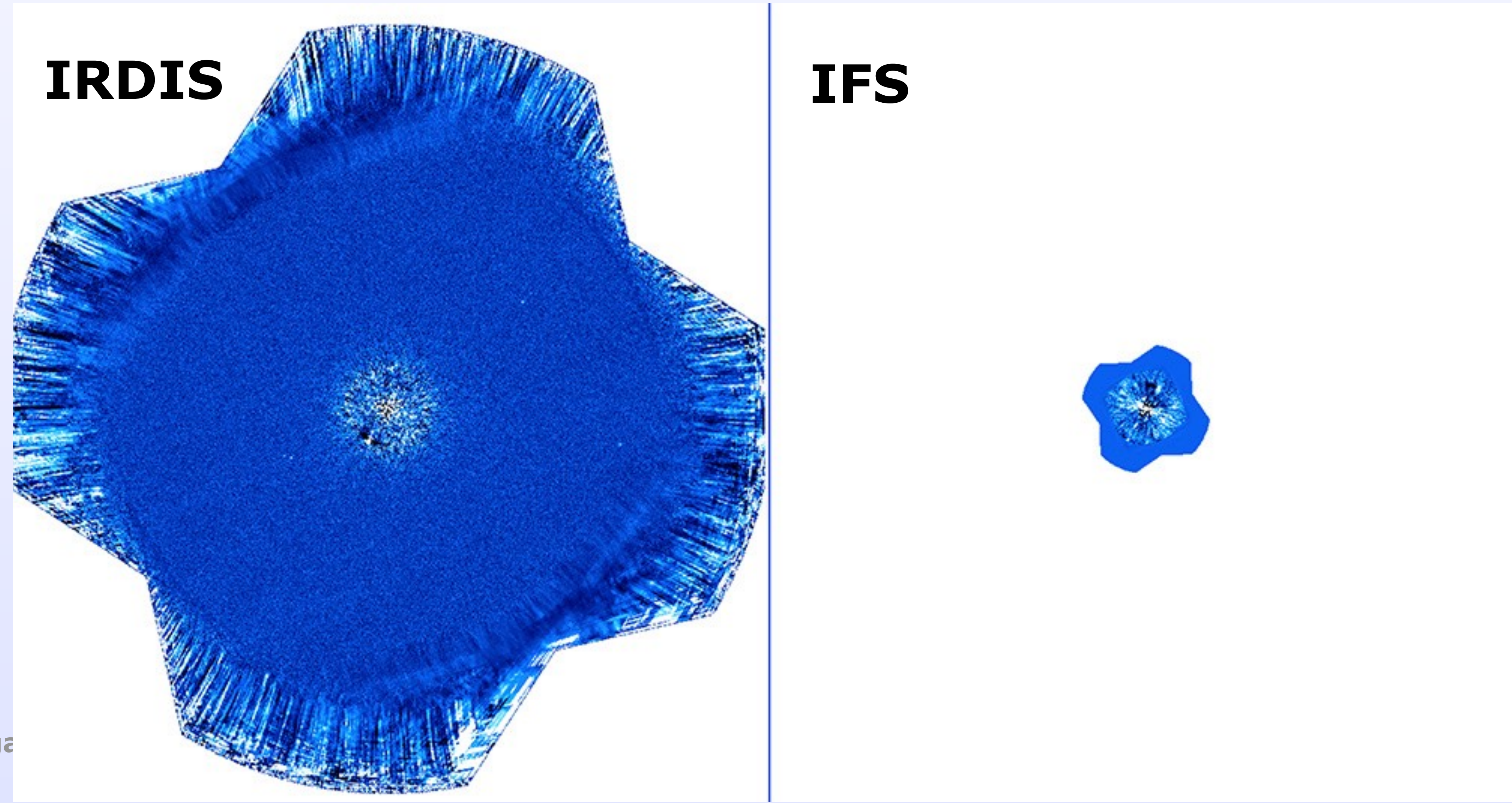
No binaries (spectro or visual <6")

Observations

- **200 nights over 2015-2019**
  - ~135 already done (68%)
- **GTO done in Visitor Mode**
  - usually two visitors
- Statistics:
  - 25% bad weather loss
  - 5% technical loss
- **~500 individual observations**
  - ~400 validated
- Strategy:
  - IRDIFS or IRDIFS-EXT
  - ADI
  - ~1.5 hour/target
- scheduling tool (SPOT) to optimise the survey on the long-term

Data analysis

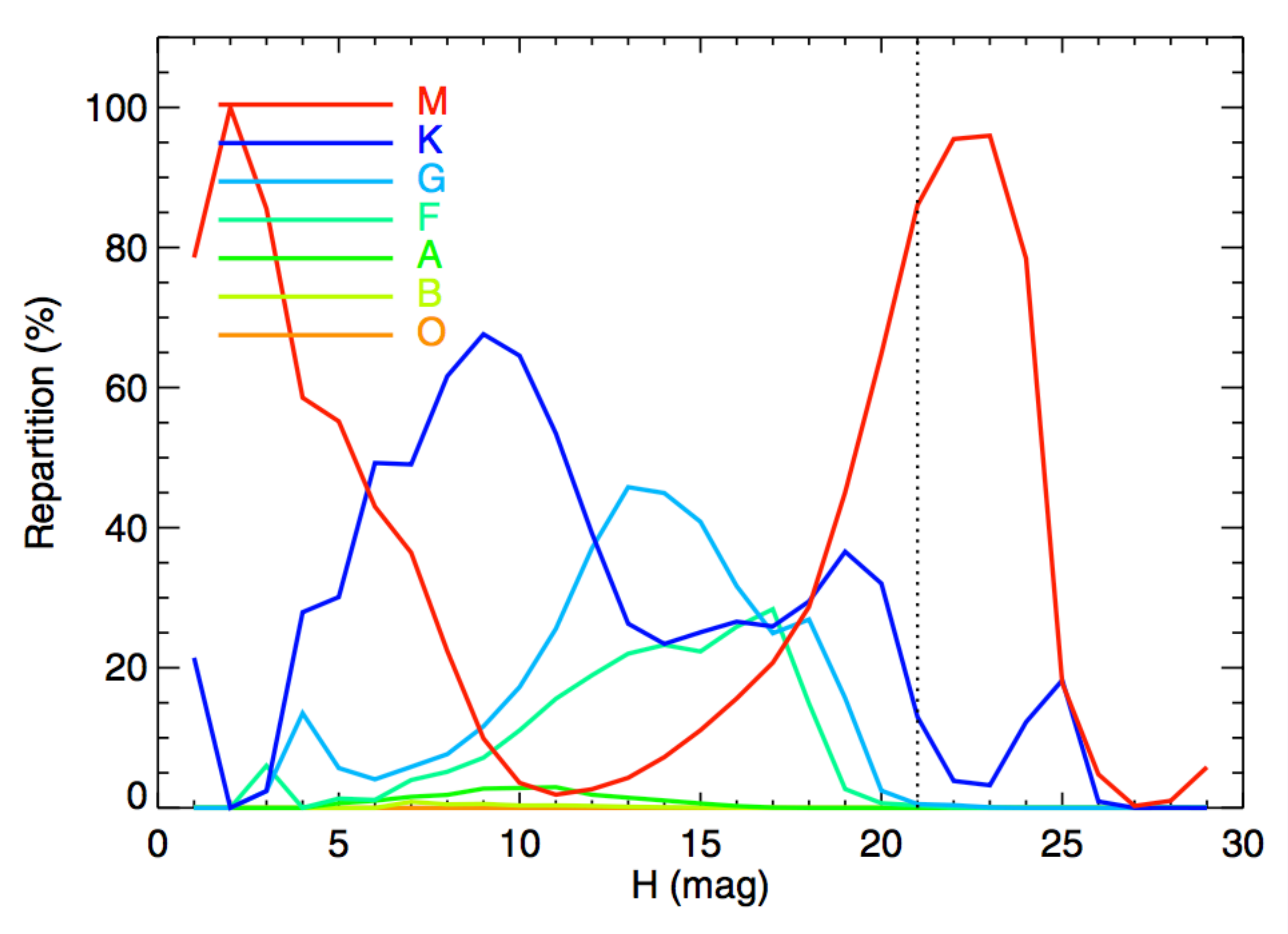
- SPHERE Data Center in grenoble:
  - **almost fully automated** pre-processing pipeline
  - SpeCal pipeline for ADI-processing (Galicher et al. in prep): **TLOCI**, PCA, cADI, RDI
  - Candidates astrophotometry derived after **eye identification**
- Observation manually validated by 2 people
- **Data Reduction Teams** on call during all observing run



The candidates nightmare

- **contamination by remote background stars**
- probability
  - increases with FoV^2
  - 5% for IFS
  - 40-50% for IRDIS

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



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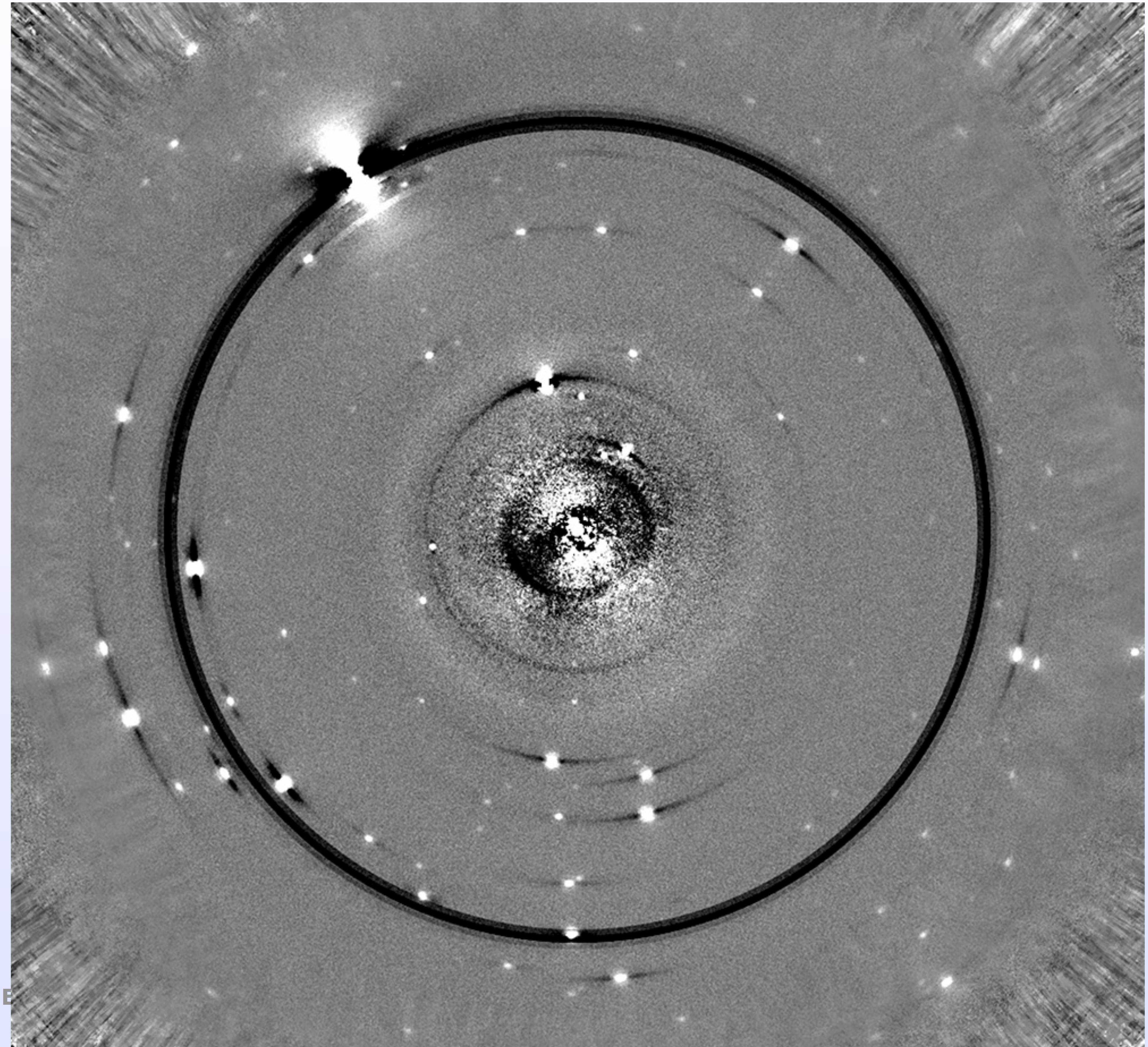

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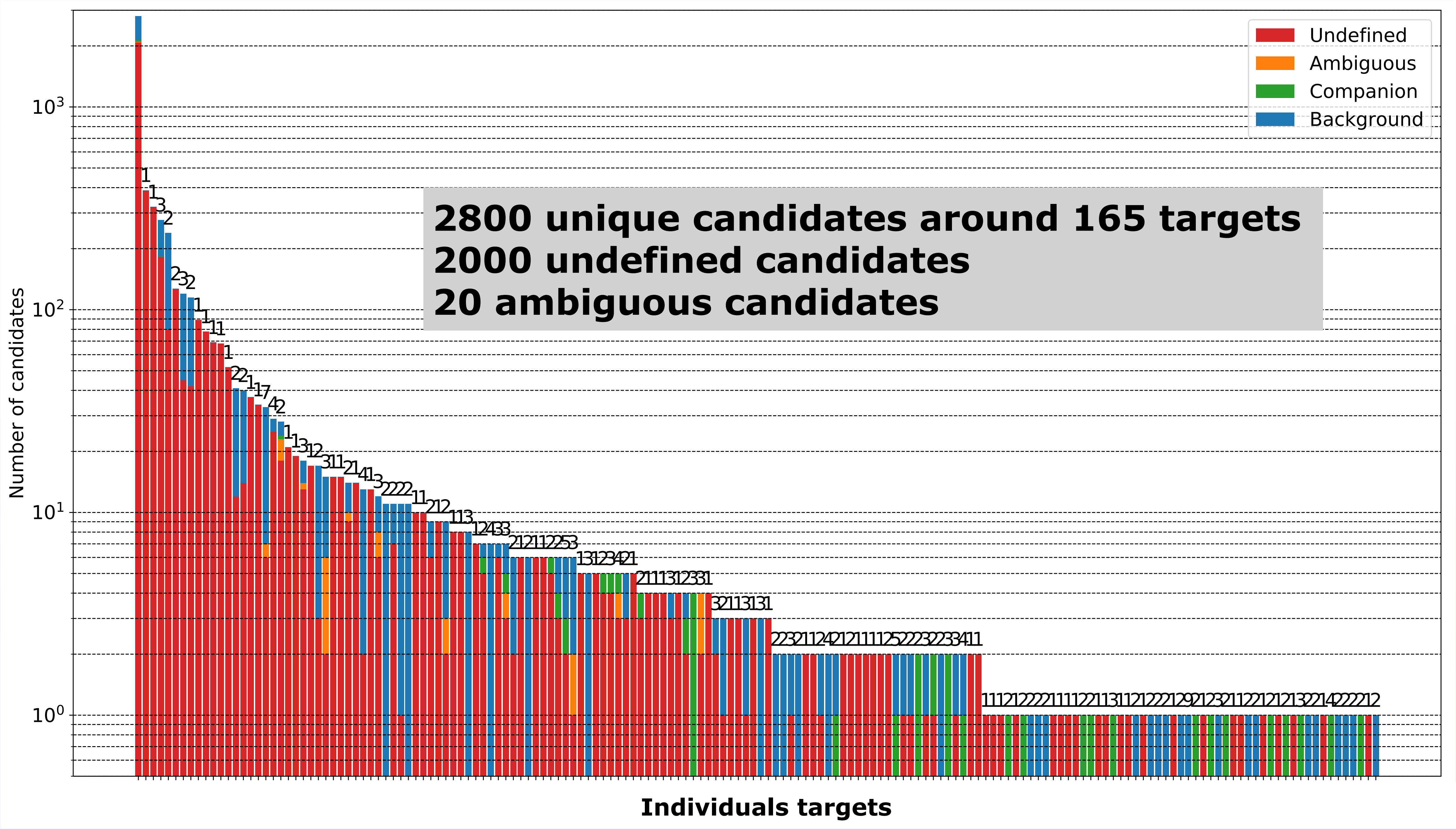
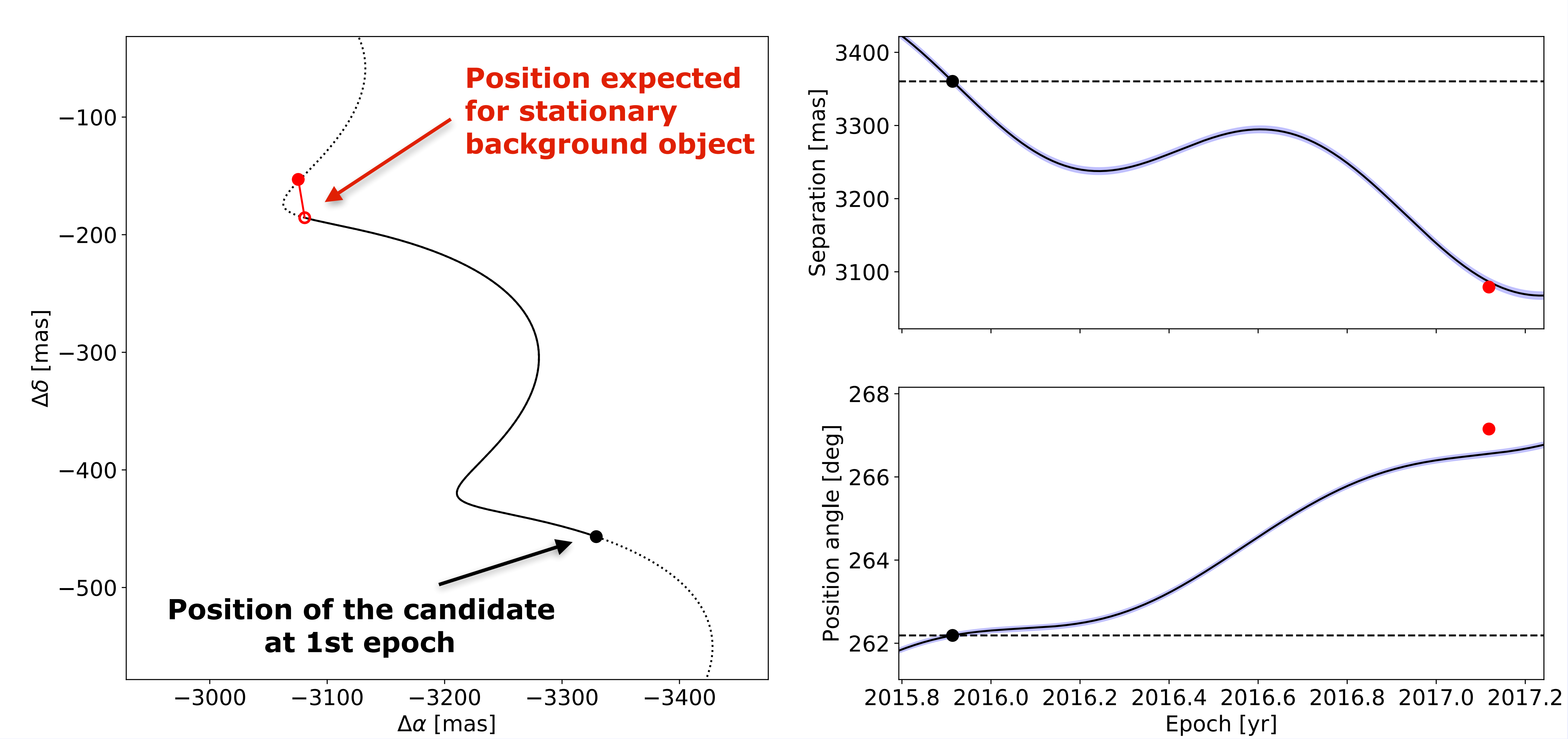


2800 unique candidates around 165 targets
2000 undefined candidates
20 ambiguous candidates

Reducing candidates: proper motion



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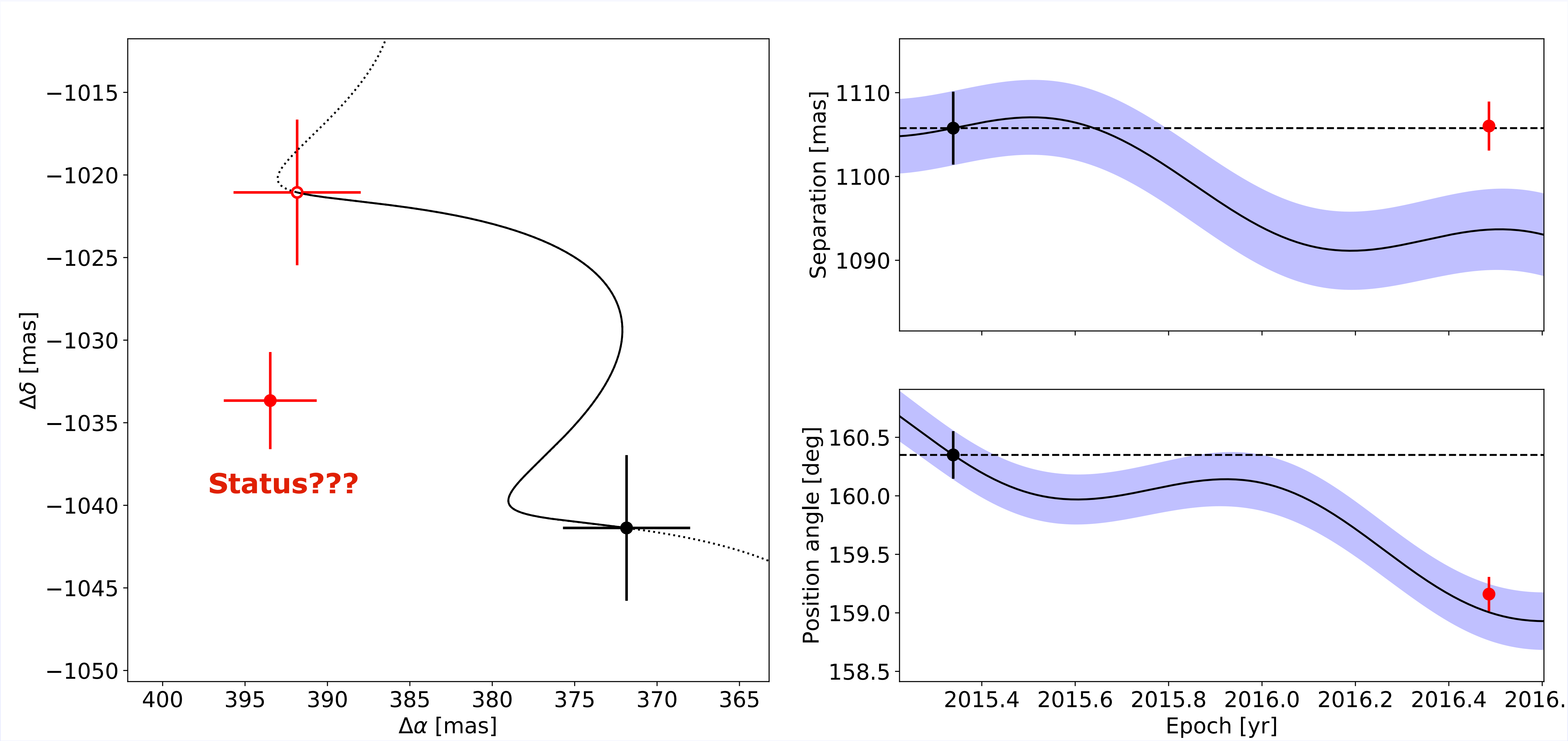
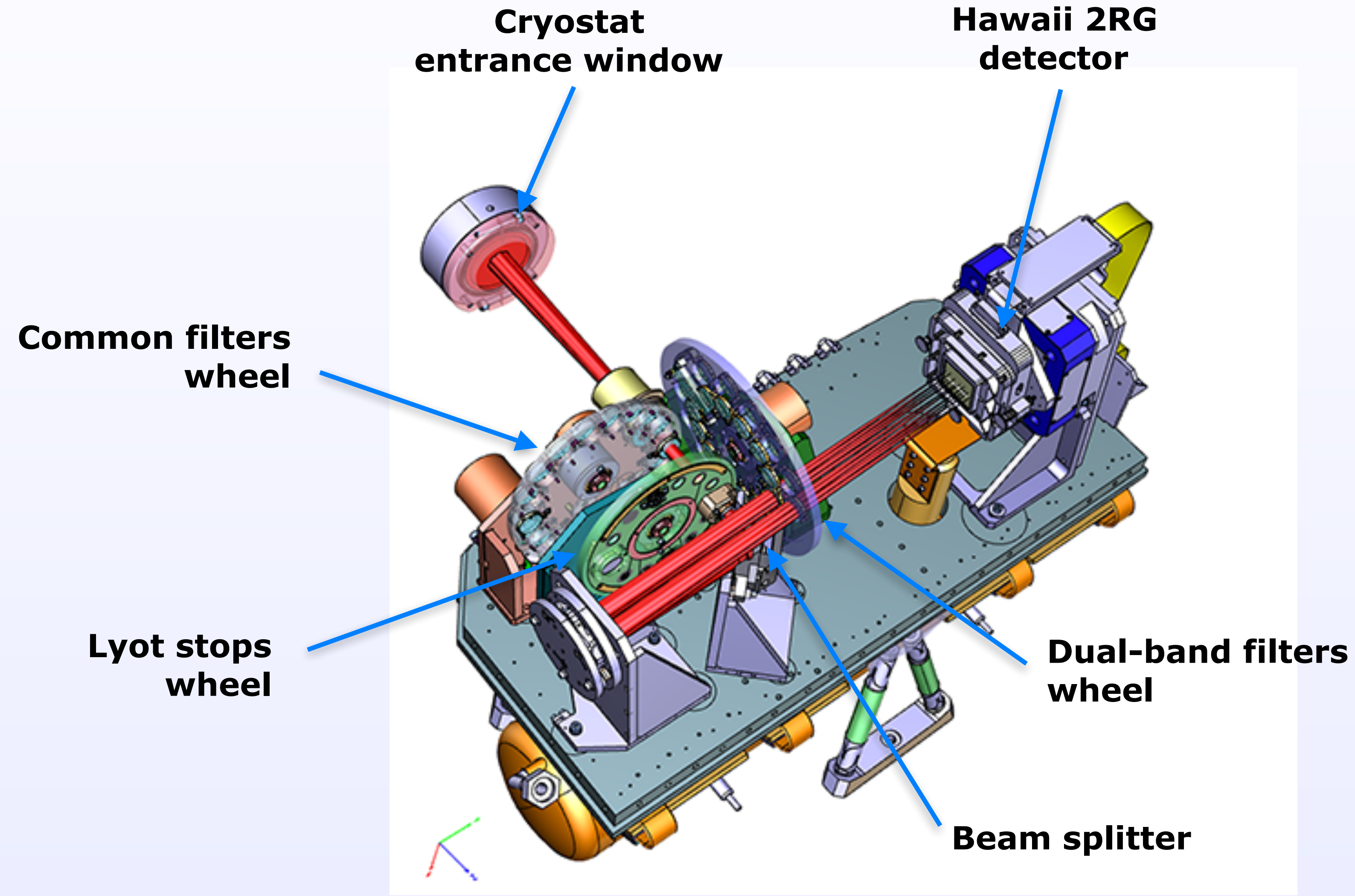
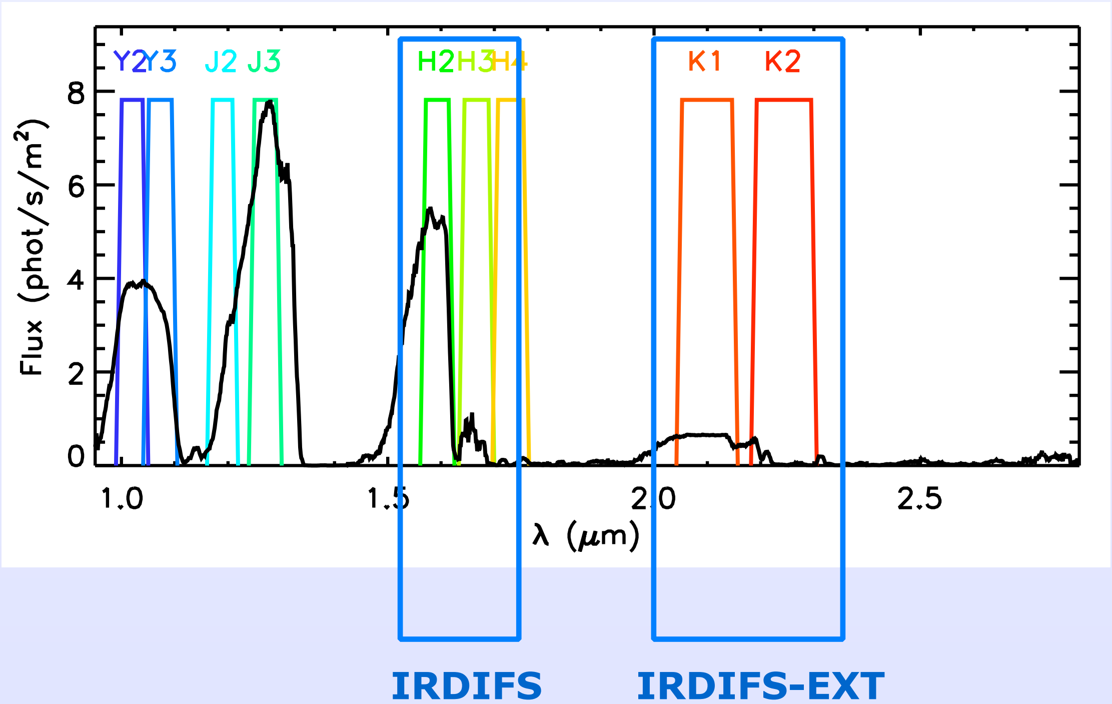


Reducing candidates: color-mag diagrams



IRDIS
Dual-band imaging

Dual-band filters



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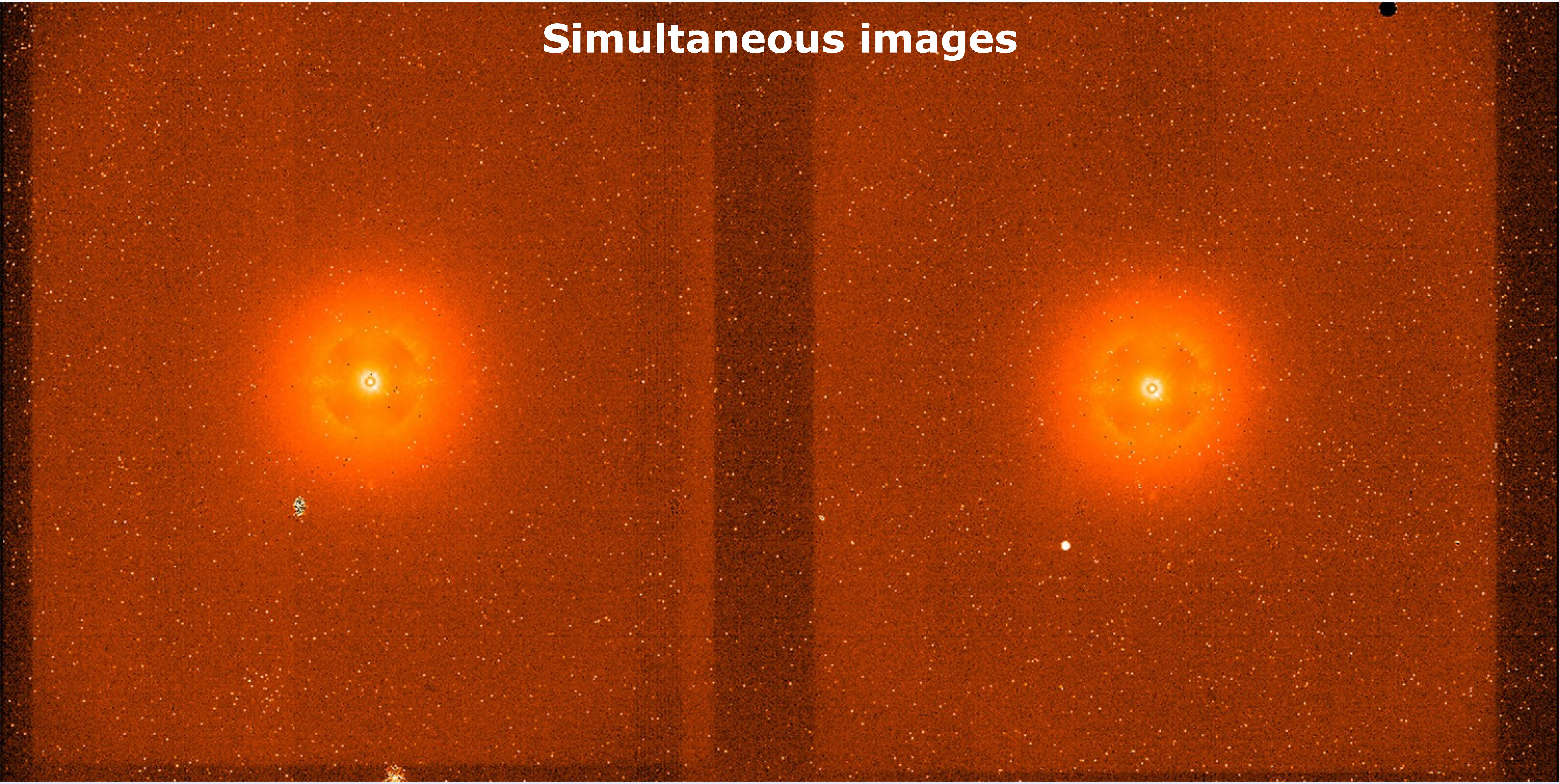

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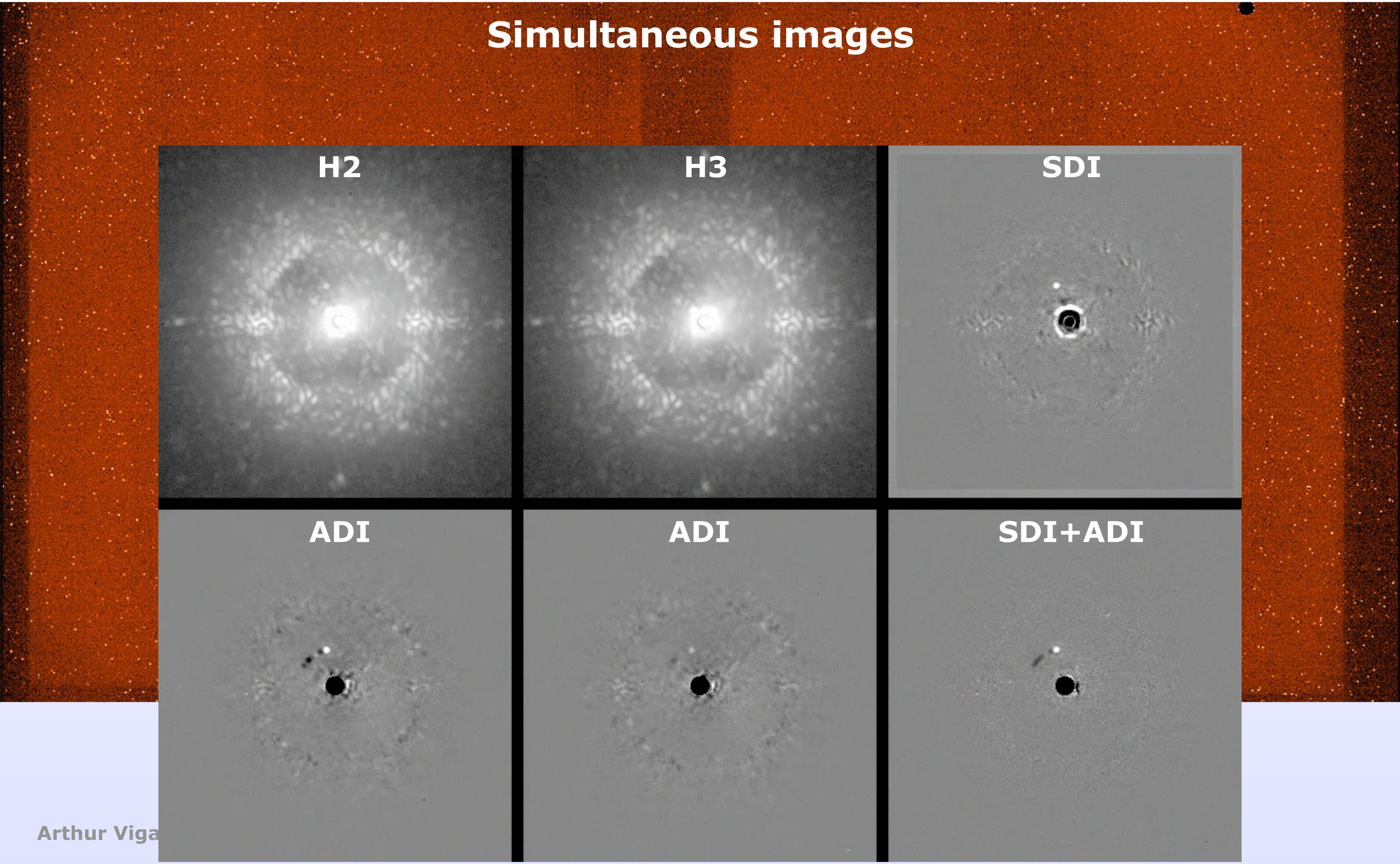

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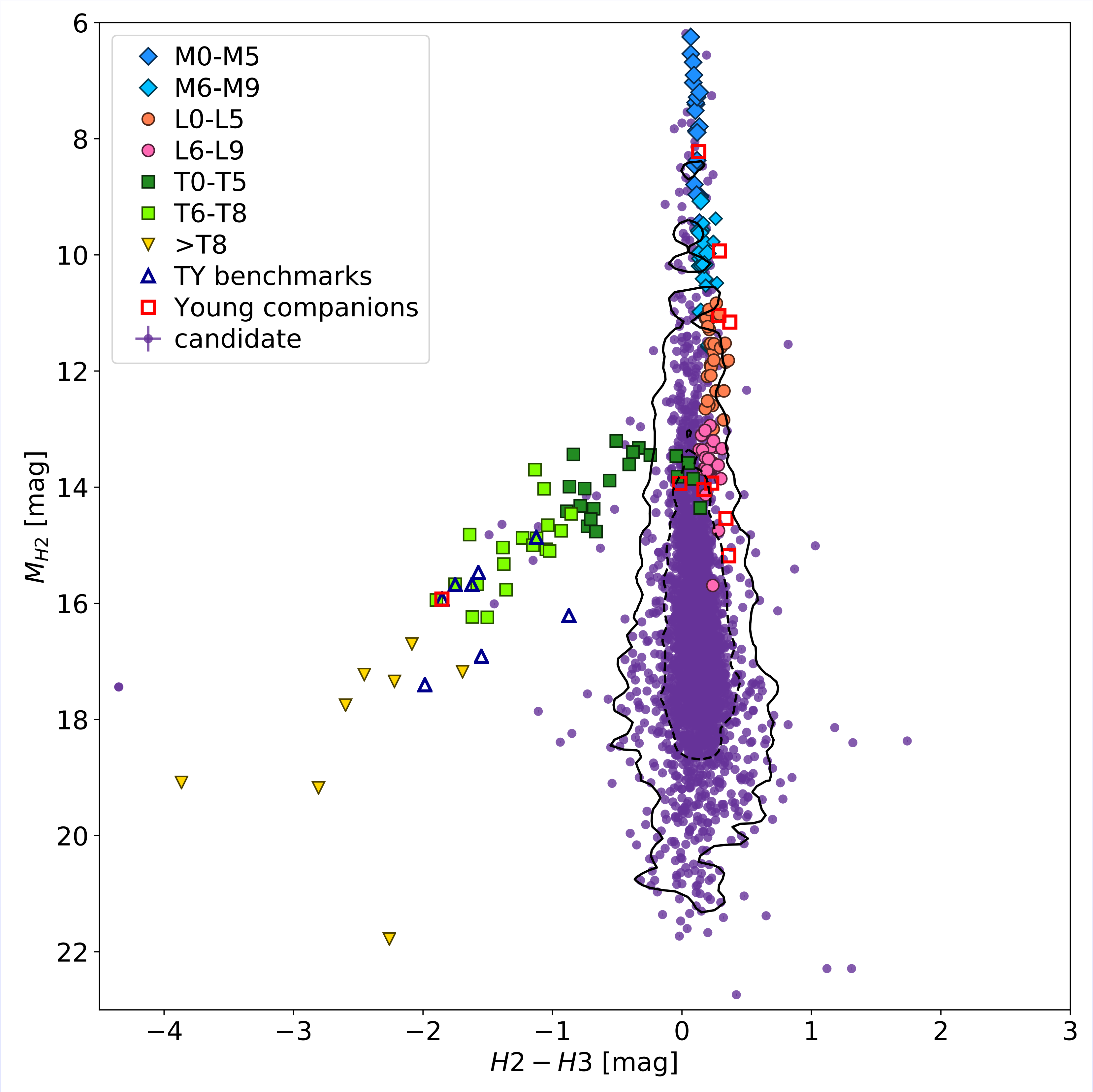

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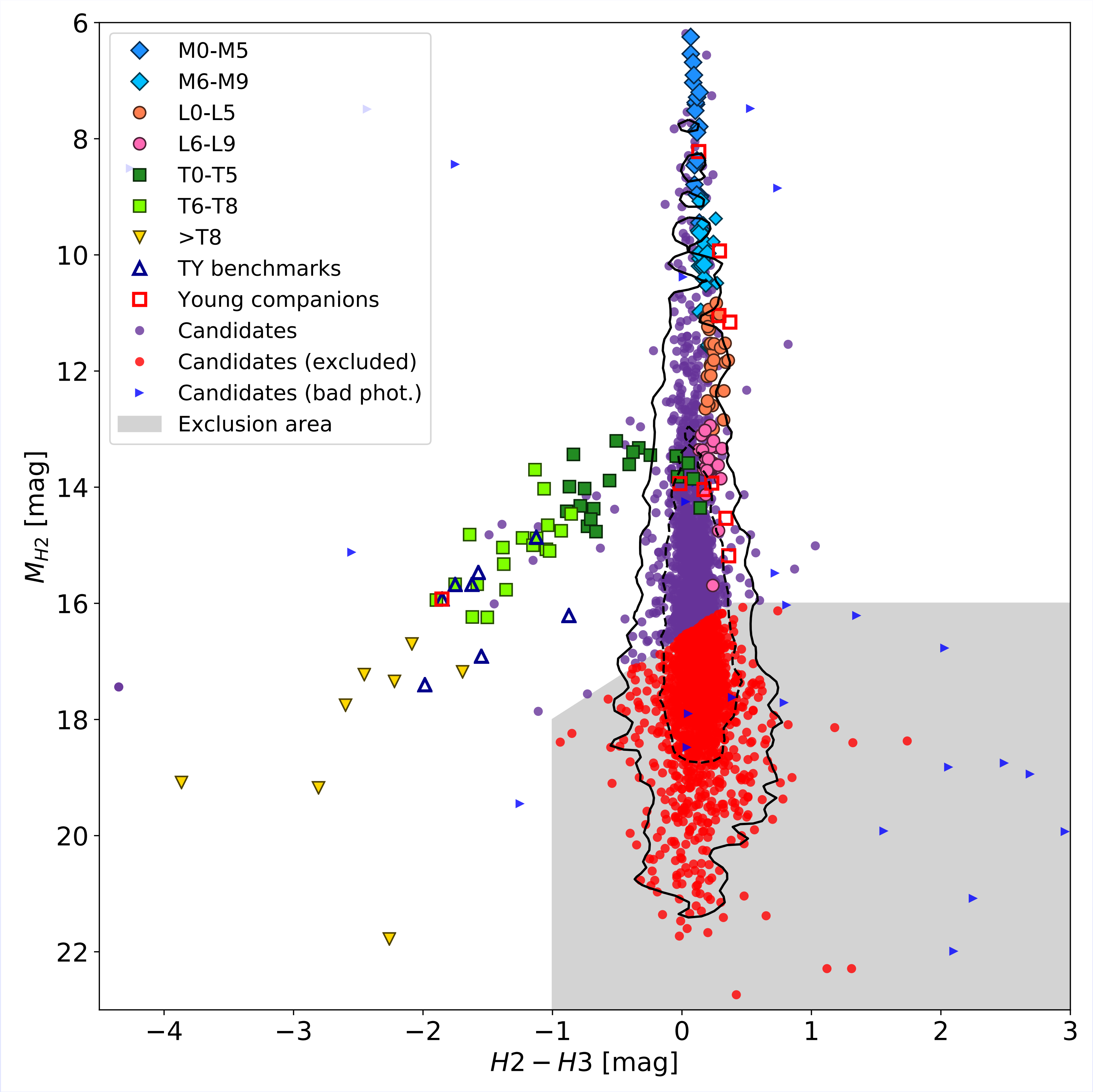

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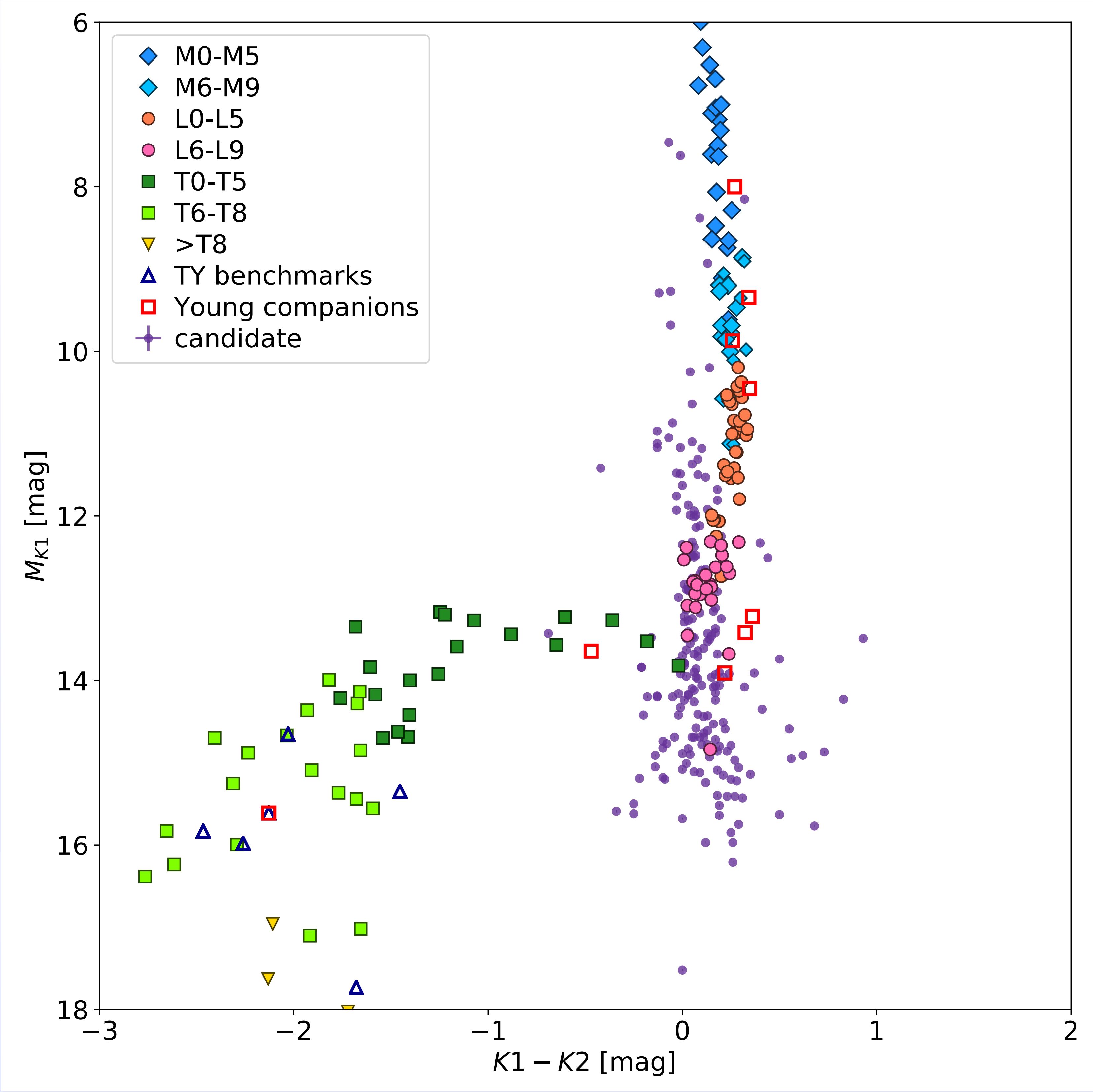
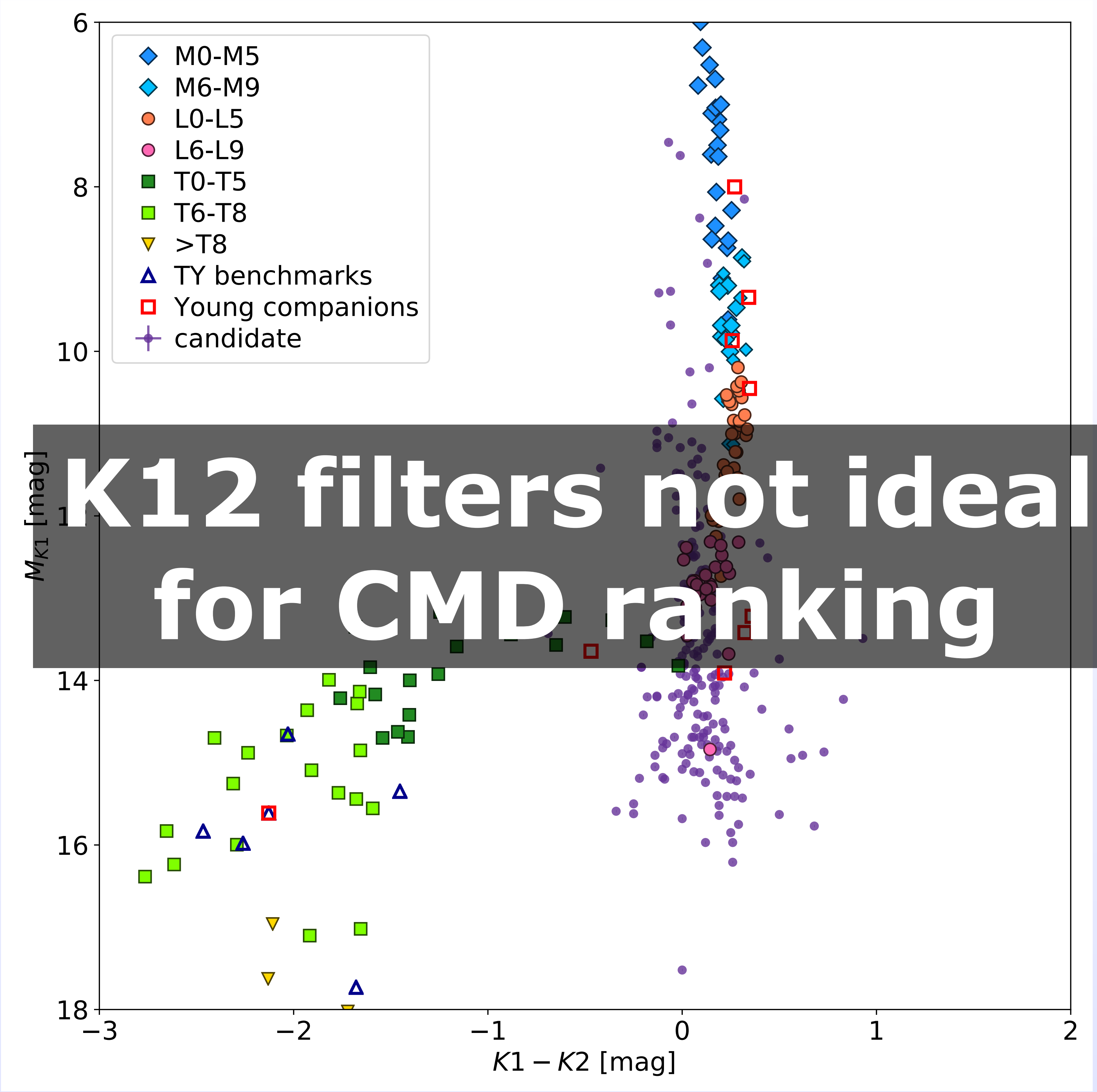
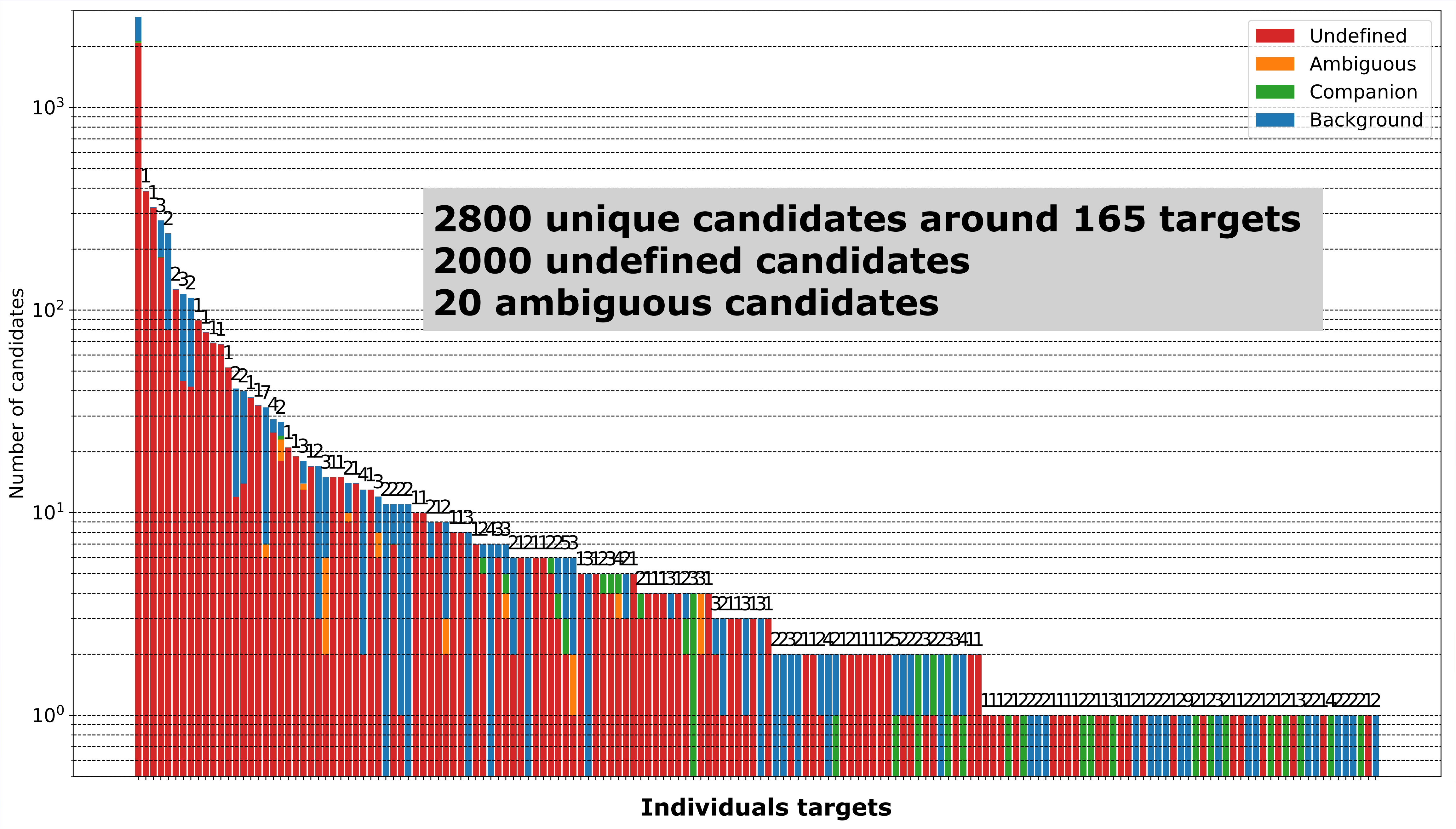


Reducing candidates: color-mag diagrams

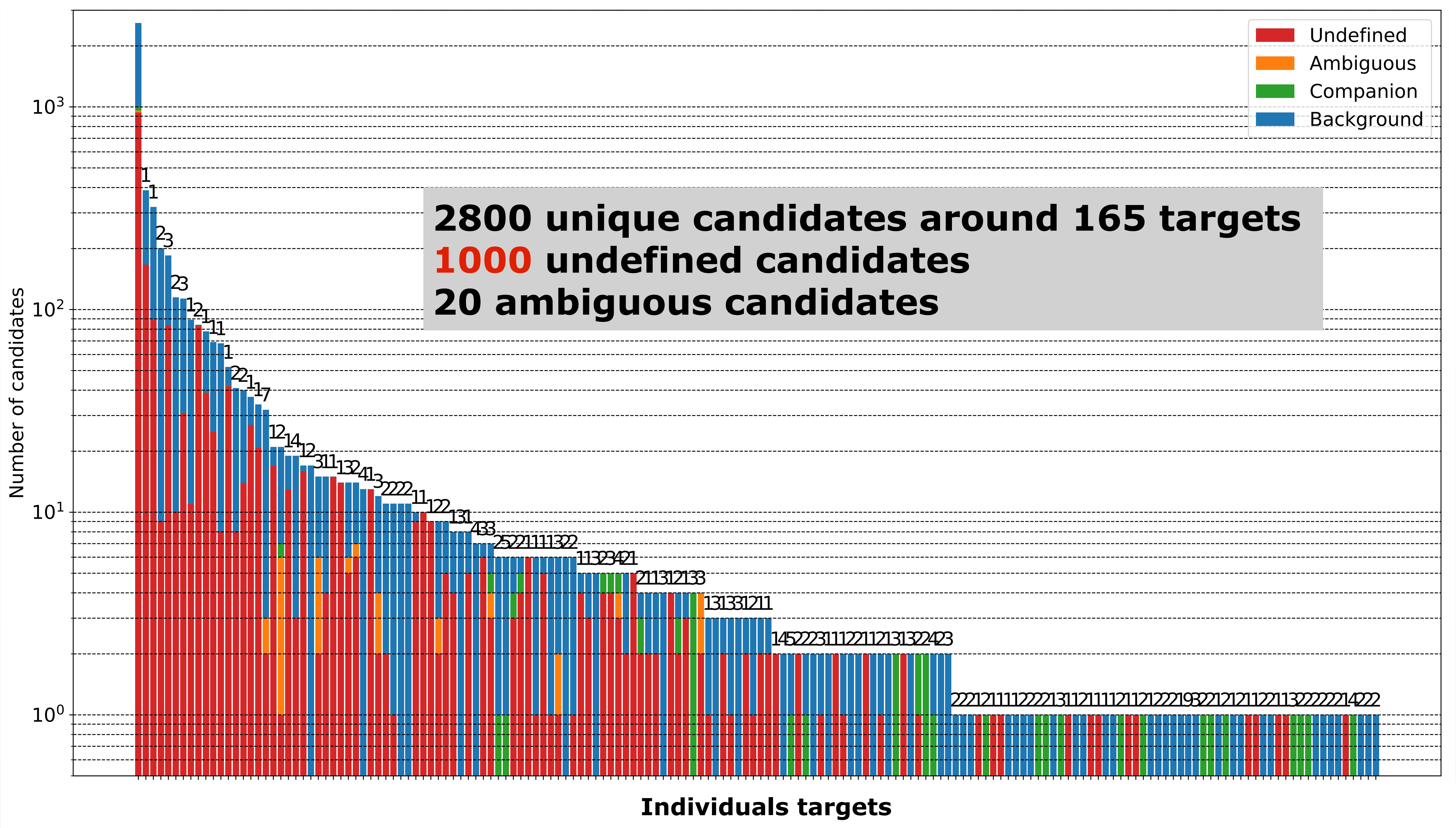


K12 filters not ideal for CMD ranking

The candidates nightmare



The candidates ~~nightmare~~ very bad dream



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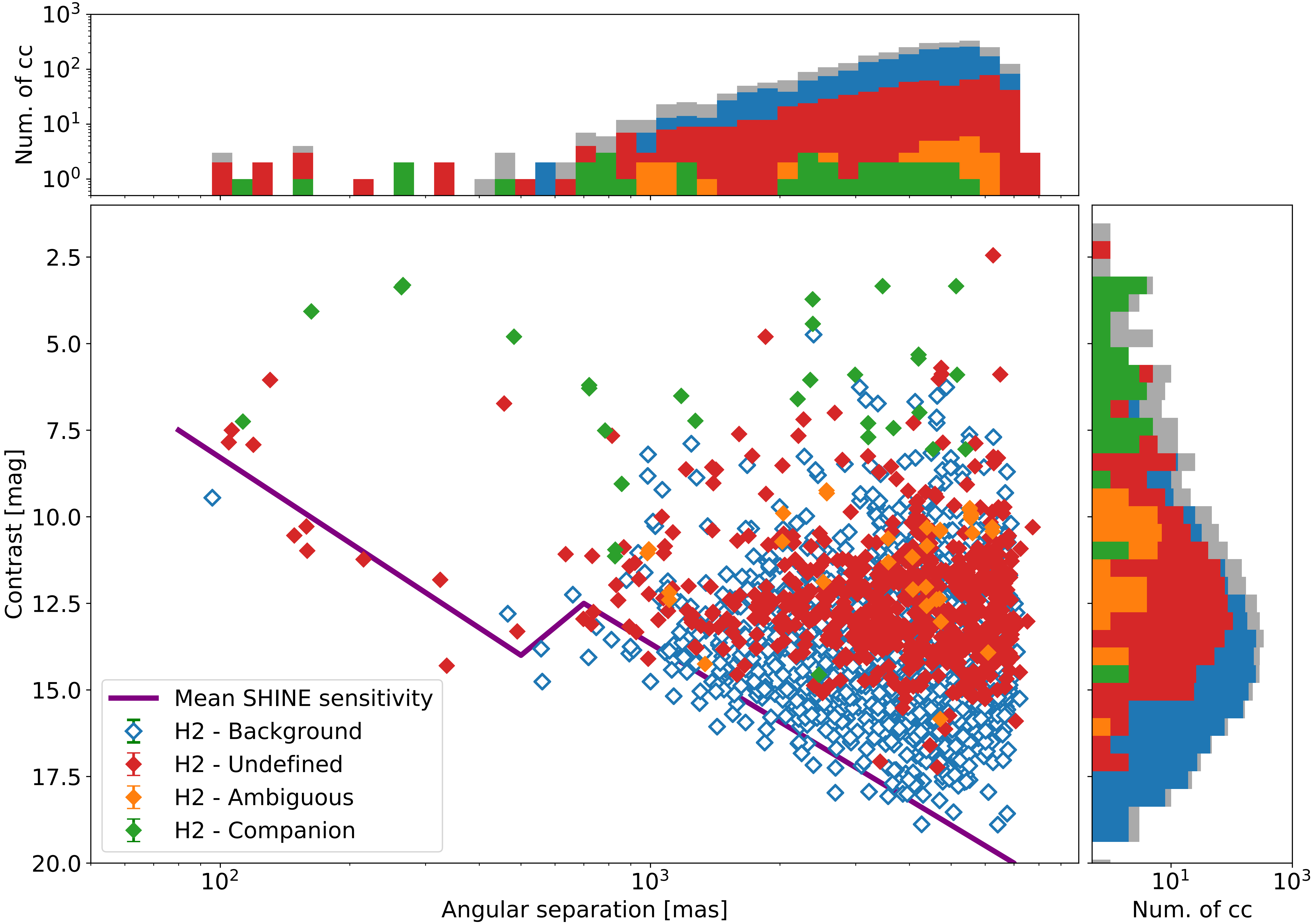

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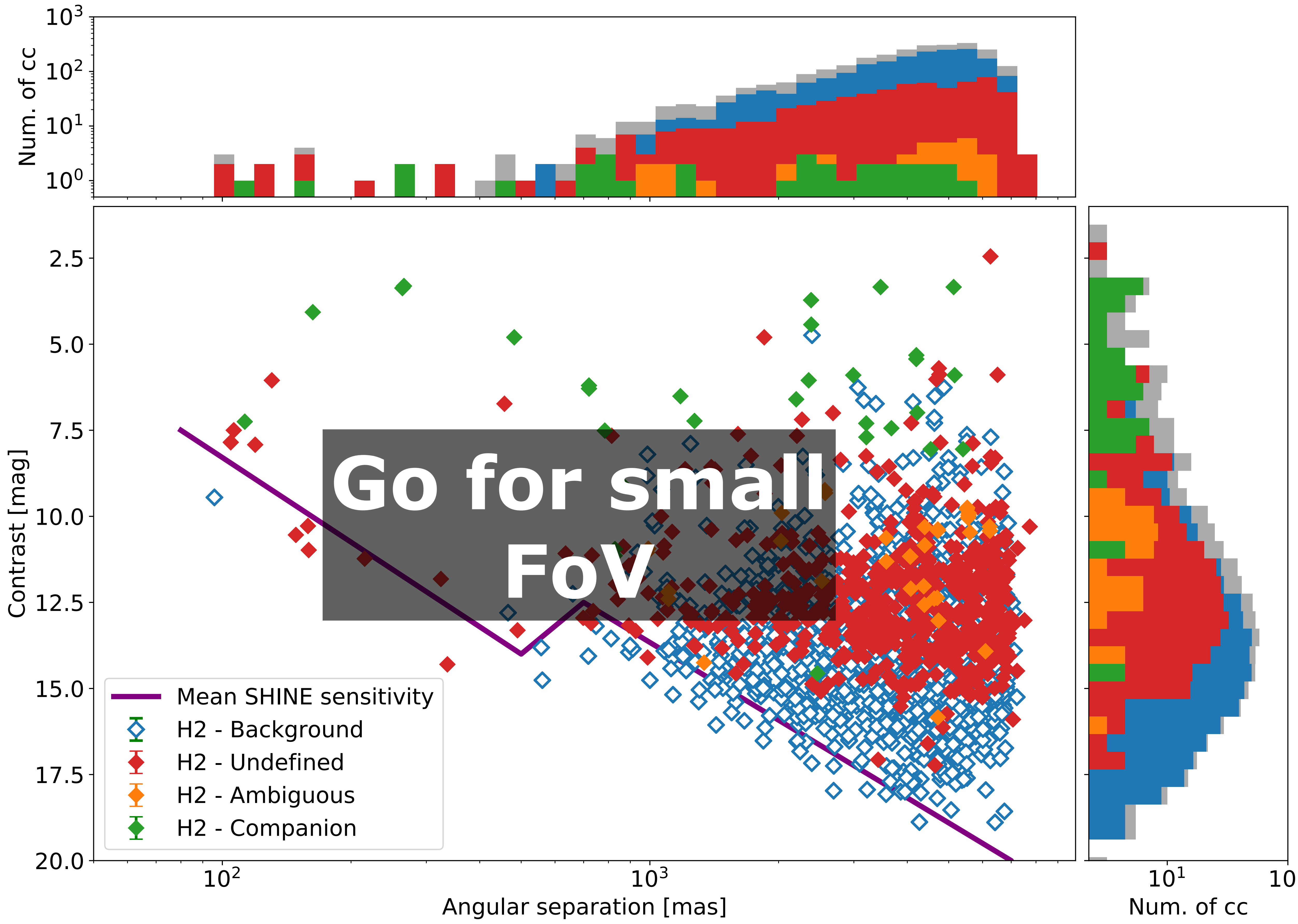
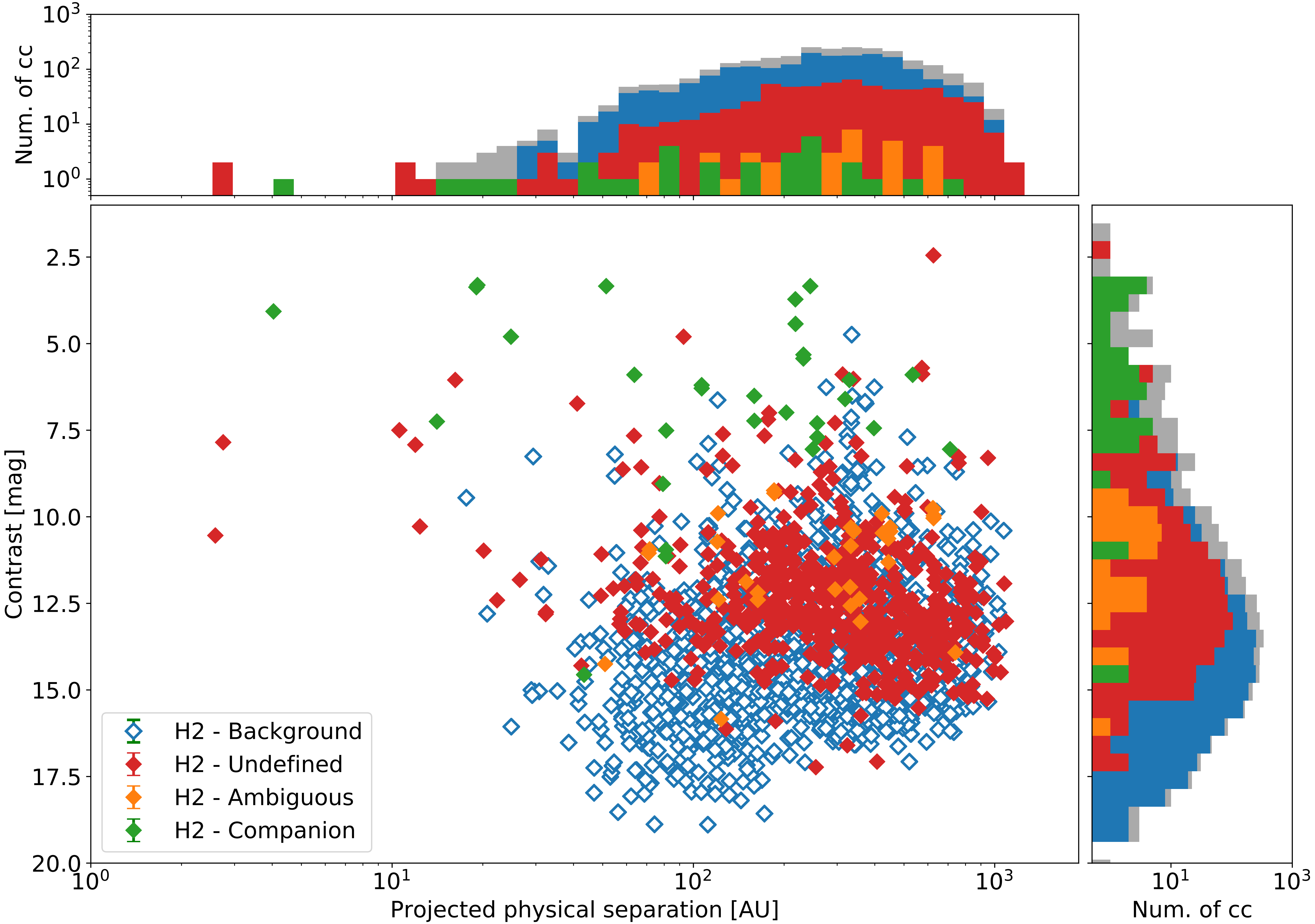


Go for small FoV

The candidates very bad dream



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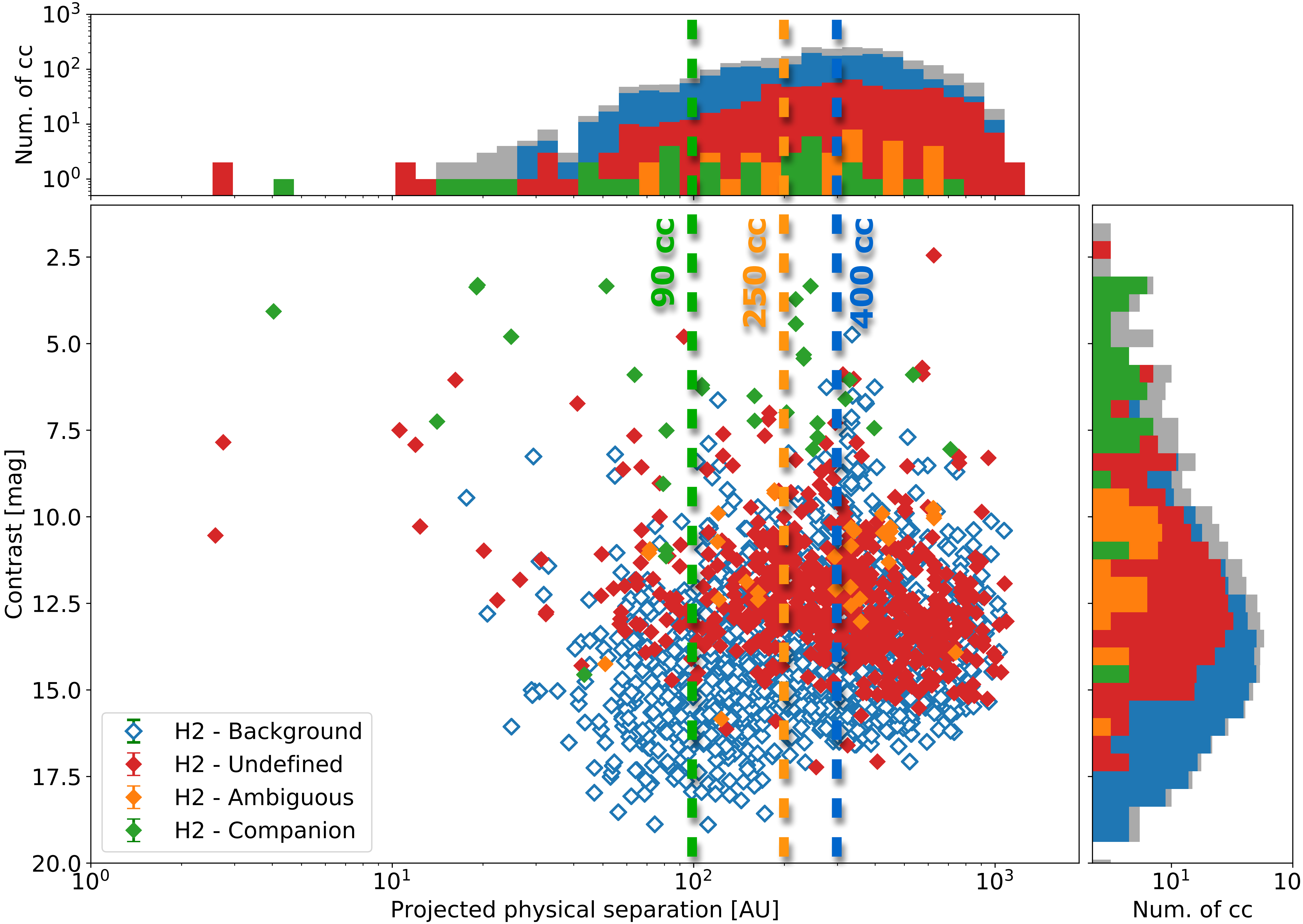
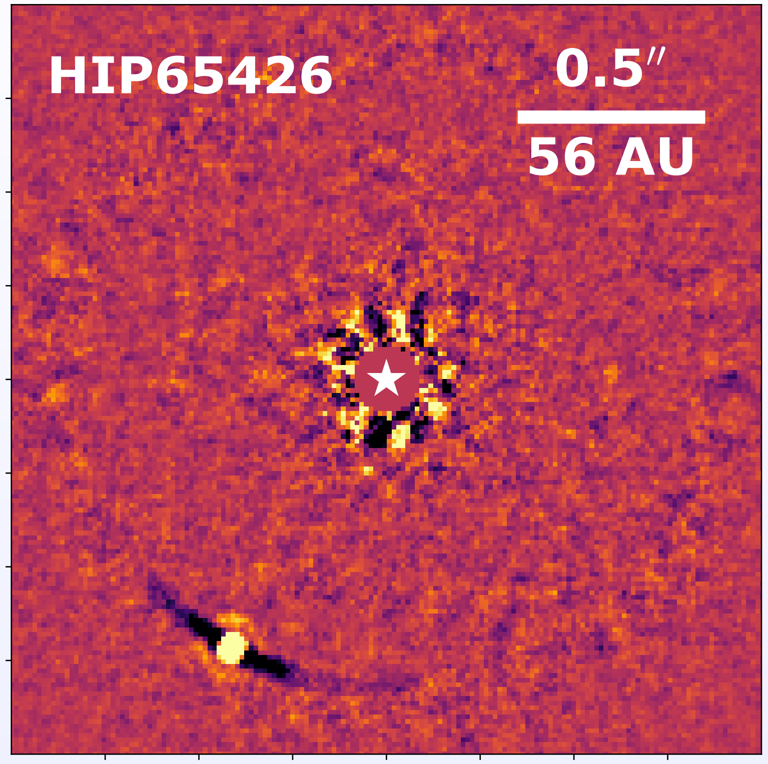
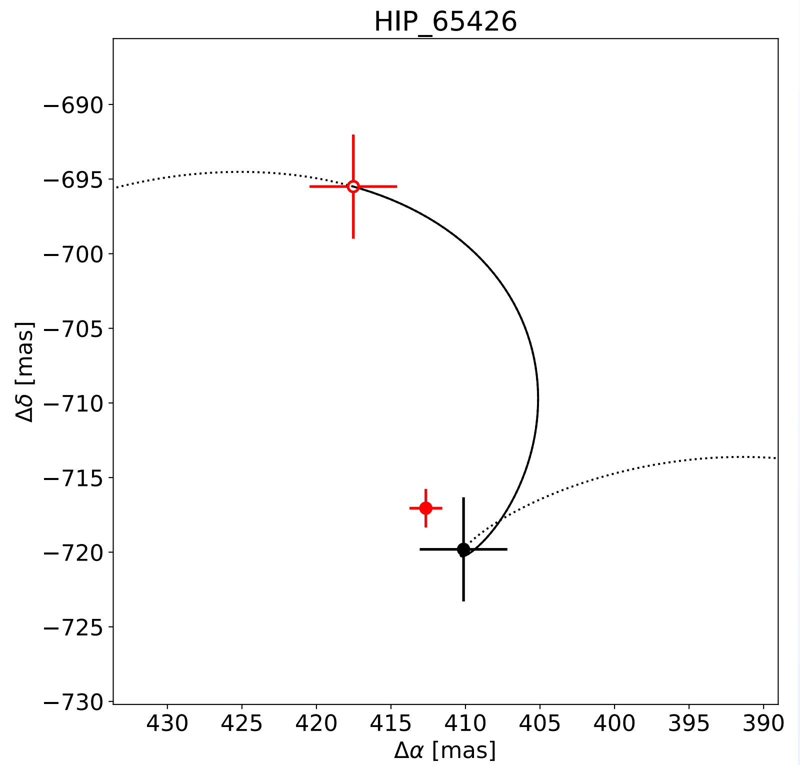


The (real) SPHERE planet: HIP 65426 b





HIP 65426

A2V, 111.4pc

LCC member, 14 Myr,

No IR excess

Fast-rotator (300 m/s)

Observations

IRDIFS + IRDIFS-EXT

2016-06-26

2017-02-07 + 2017-02-09

HIP 65426 b

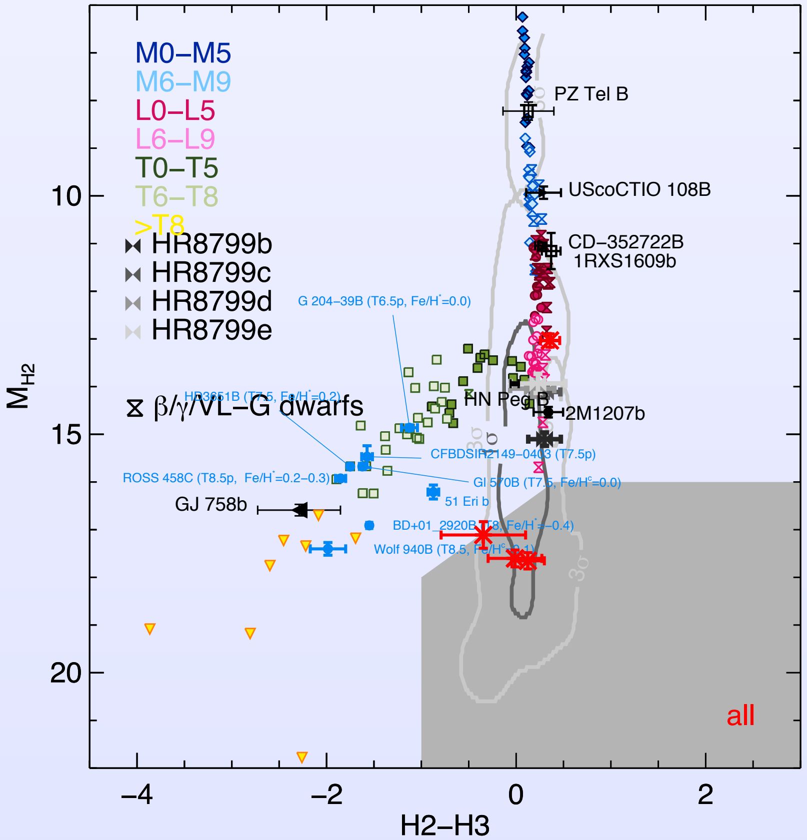
Sep. = 830 mas / 92 AU

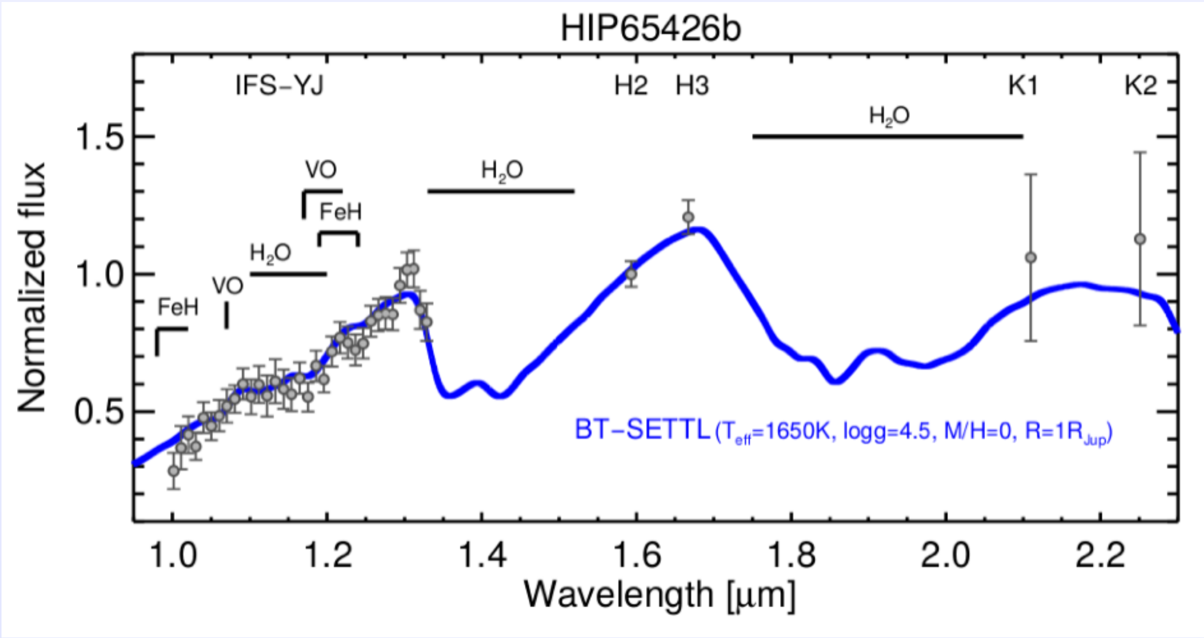
ΔH2 = 11 ± 0.1 mag

Mass = 6-12 M_{Jup}

Teff = 1300 – 1600 K

R = 1.5 ± 0.1 R_{Jup}





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), …

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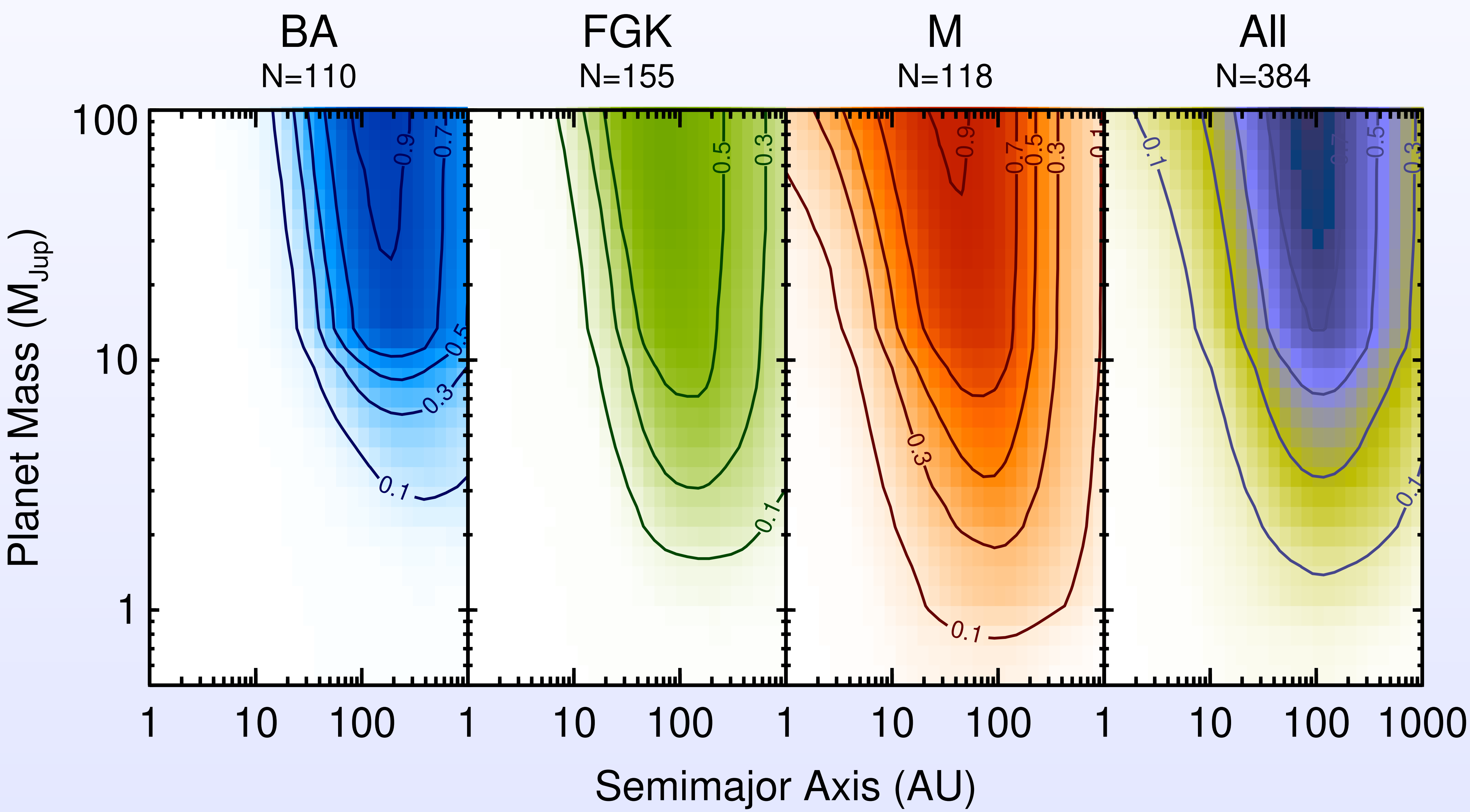
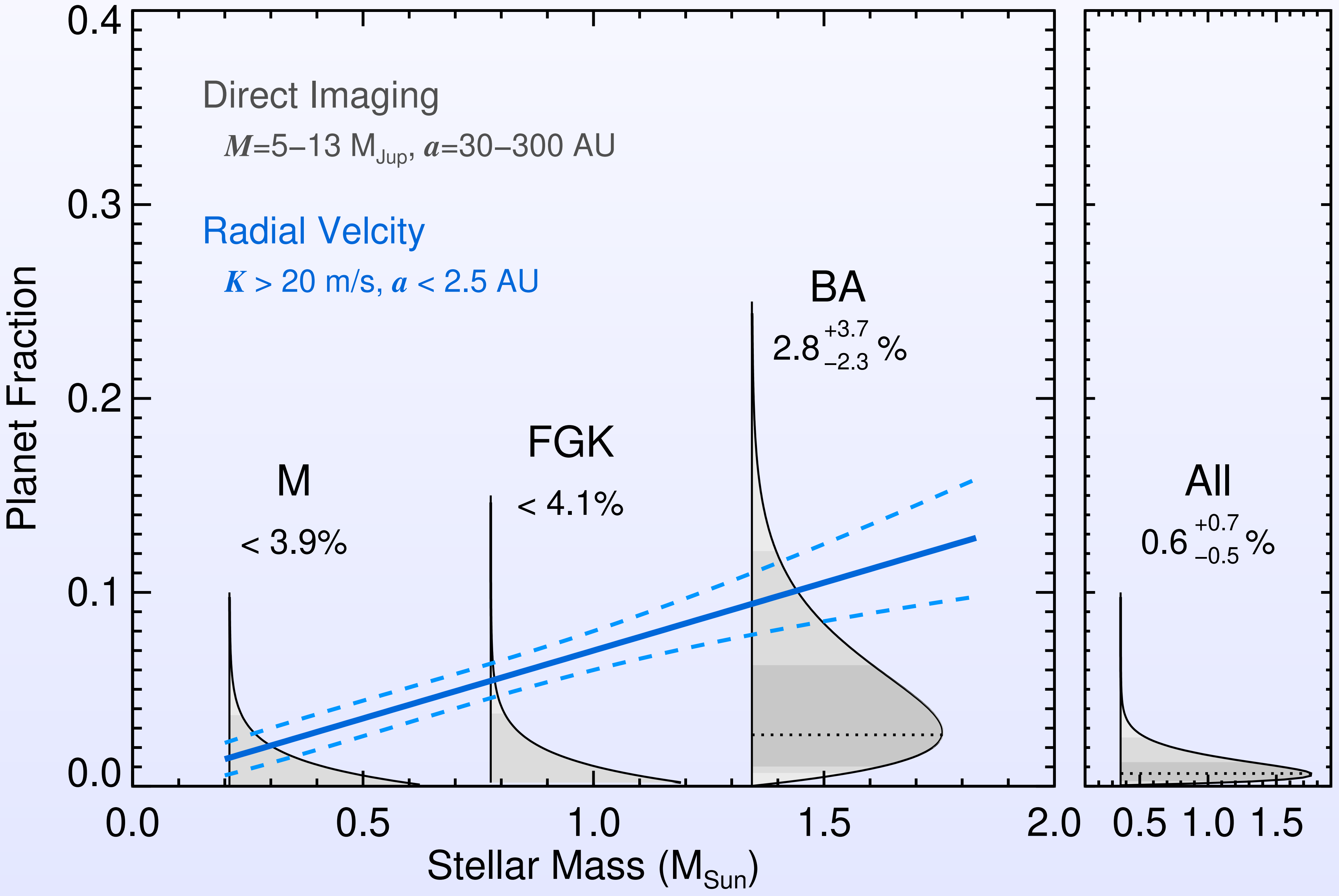


Bowler (2016)

Giant exoplanets occurence rate

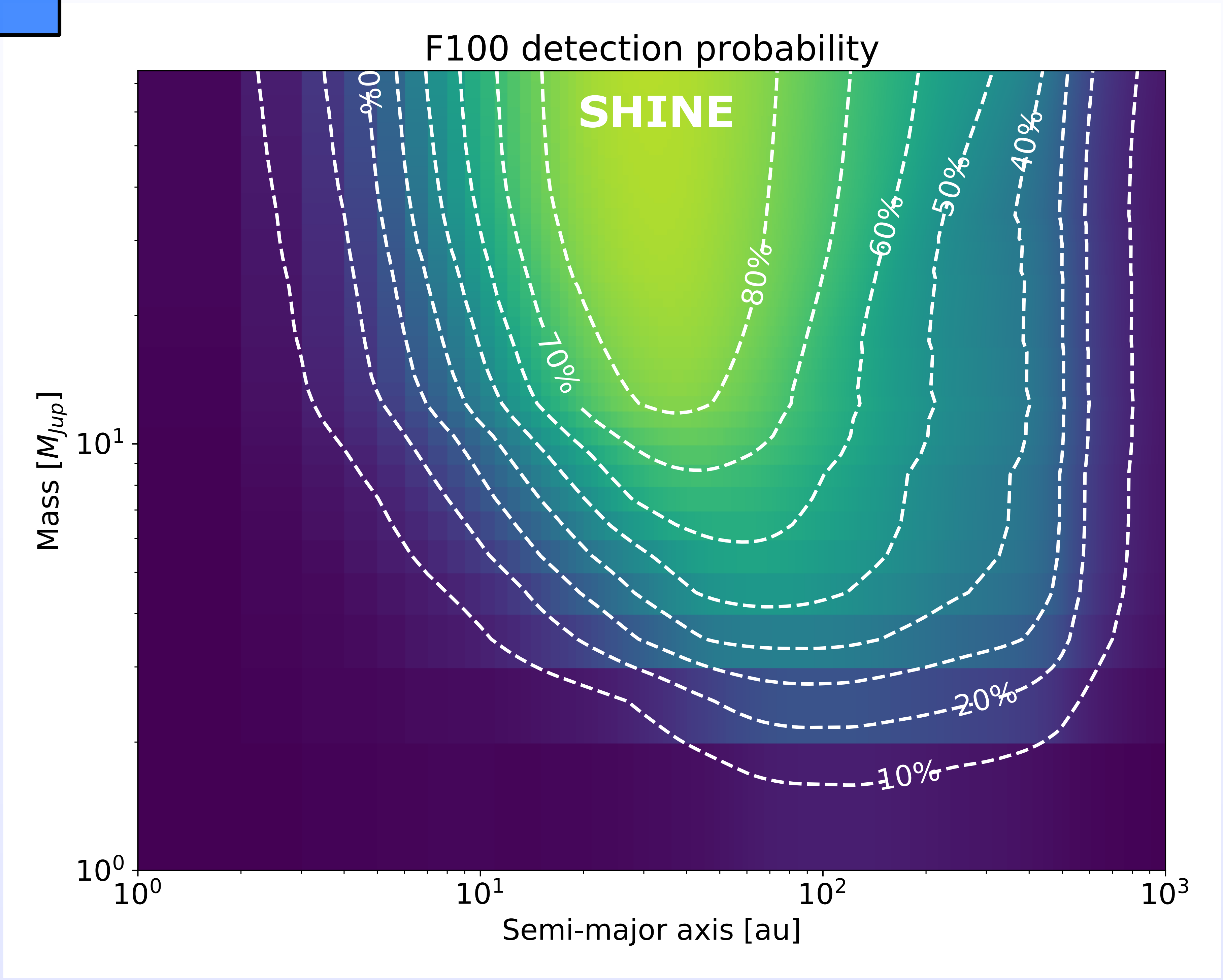
What is the frequency of young giant exoplanets on wide orbit?



Bowler (2016)

Occurence rate from SHINE

IFS only!

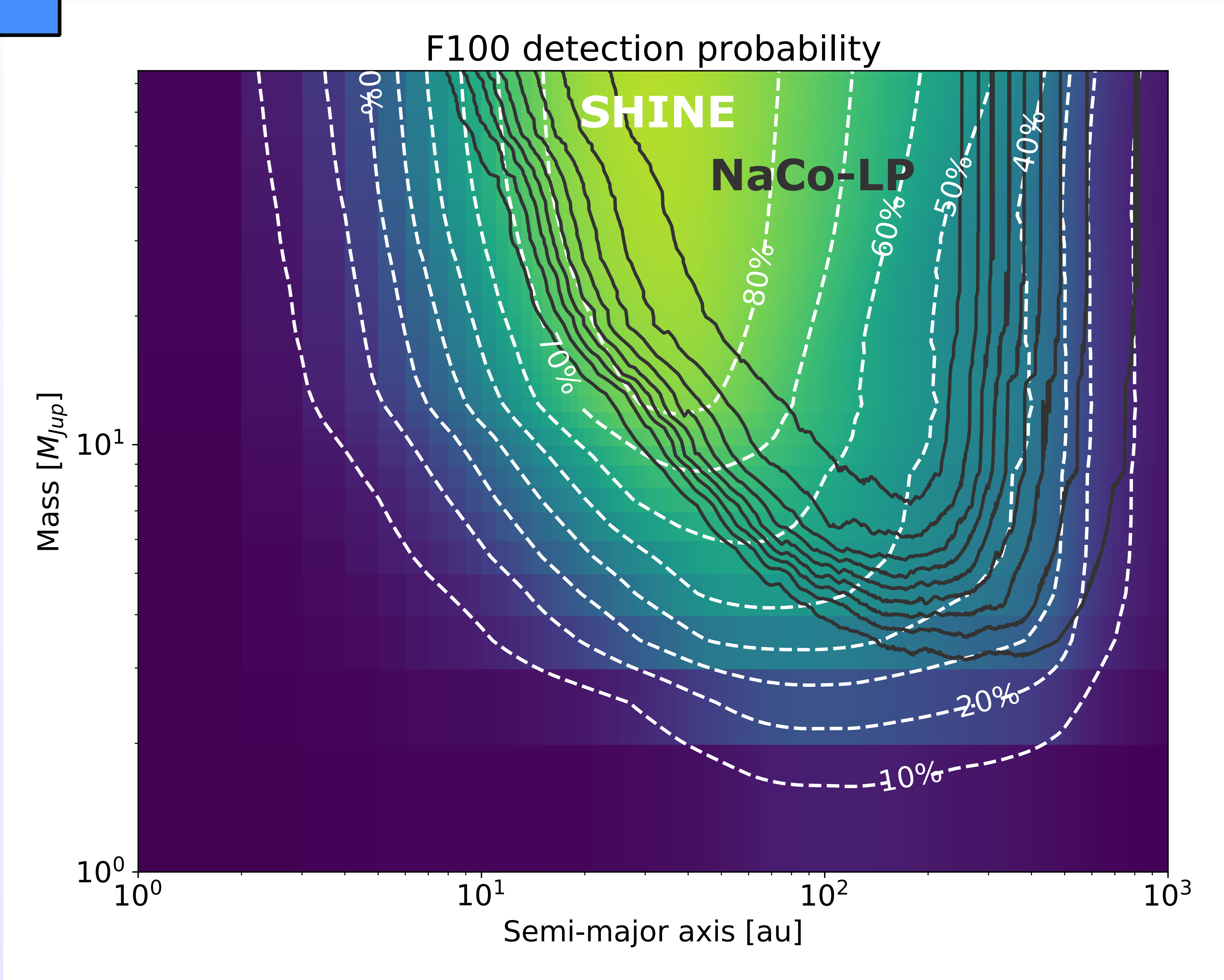


~150 stars, all spectral types

Vigan et al. (in prep)

Detection probability from SHINE

IFS only!



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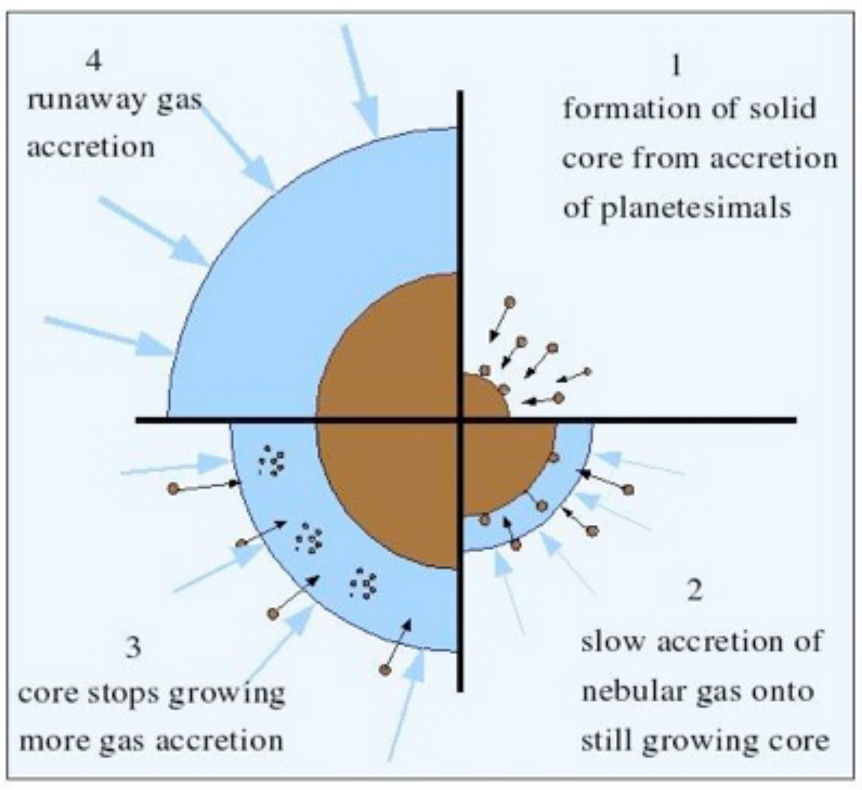
Vigan et al. (in prep)

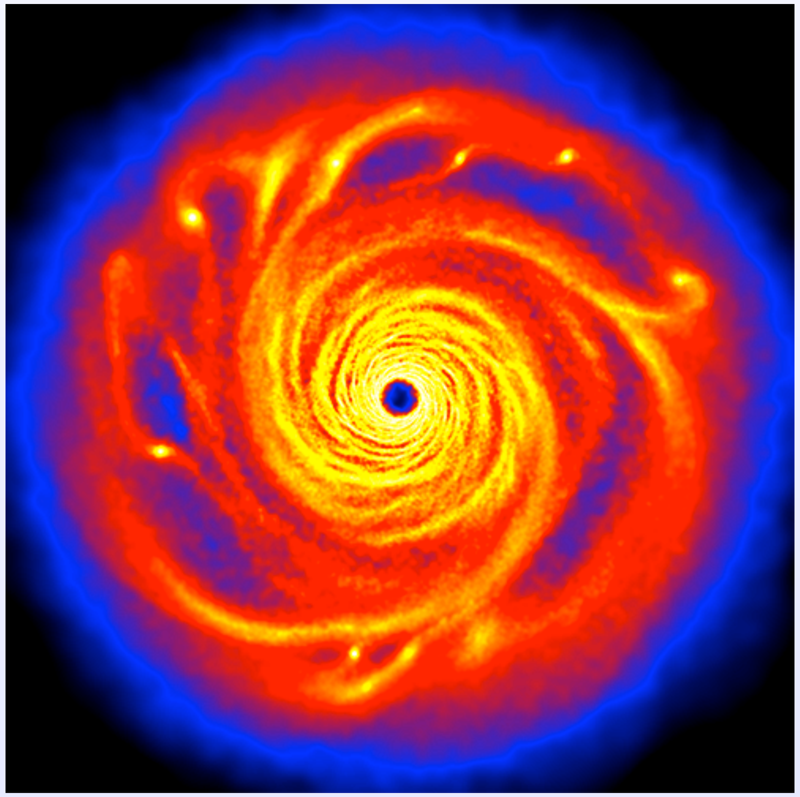
Link to formation models

Can direct imaging observations constrain formation models?

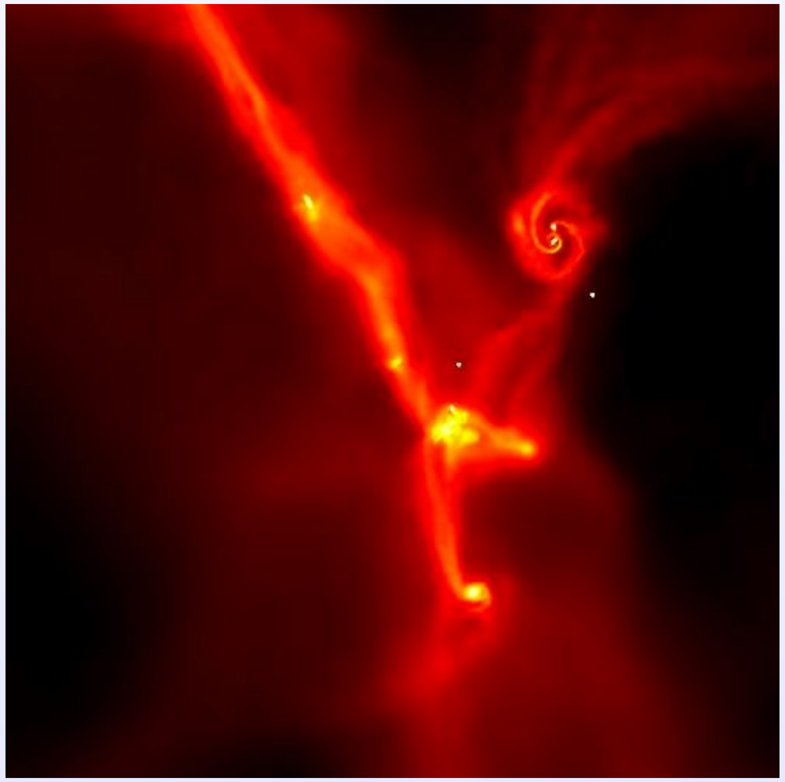
Core Accretion
Pollack et al. 1994



Gravitational Instability
Cameron 1978

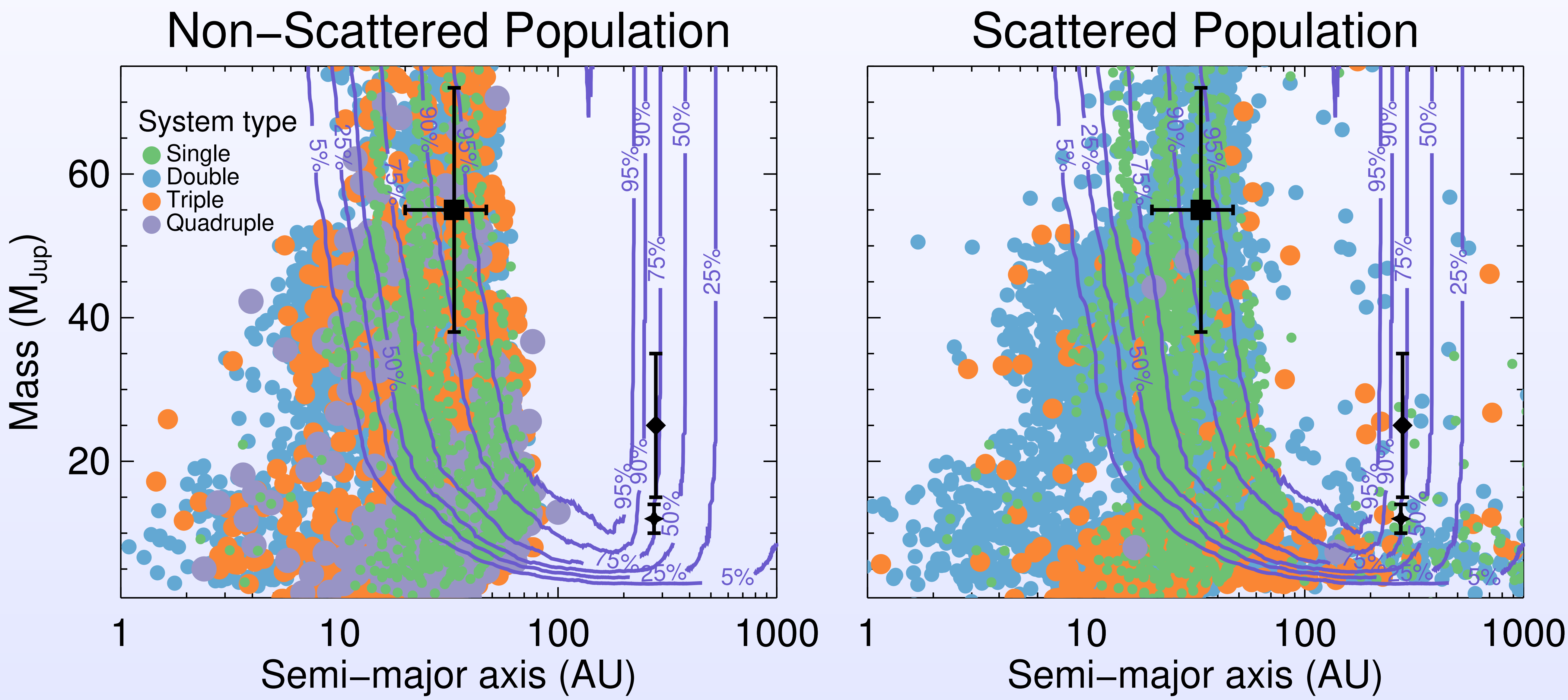


Gravo-turbulent fragmentation
Hennebelel & Chabrier 2011



Link to formation models: NaCo-LP

- NaCo-LP: 200 FGK stars, 3 detections
- Comparison to population synthesis models by Forgan et al. ➙ gravitational instability



Vigan et al. (2017)

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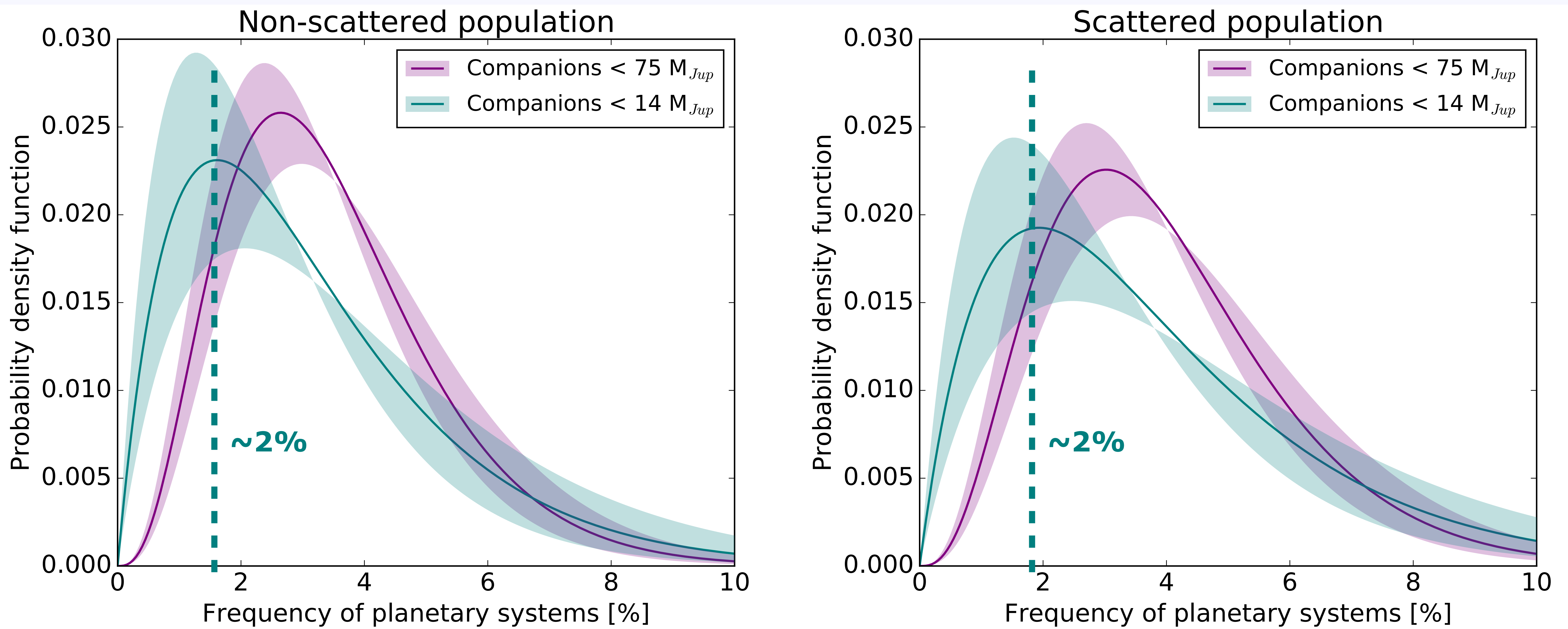

➙ low occurence rate with or without scattering: <5-6%

Vigan et al. (2017)

Link to formation models: NaCo-LP

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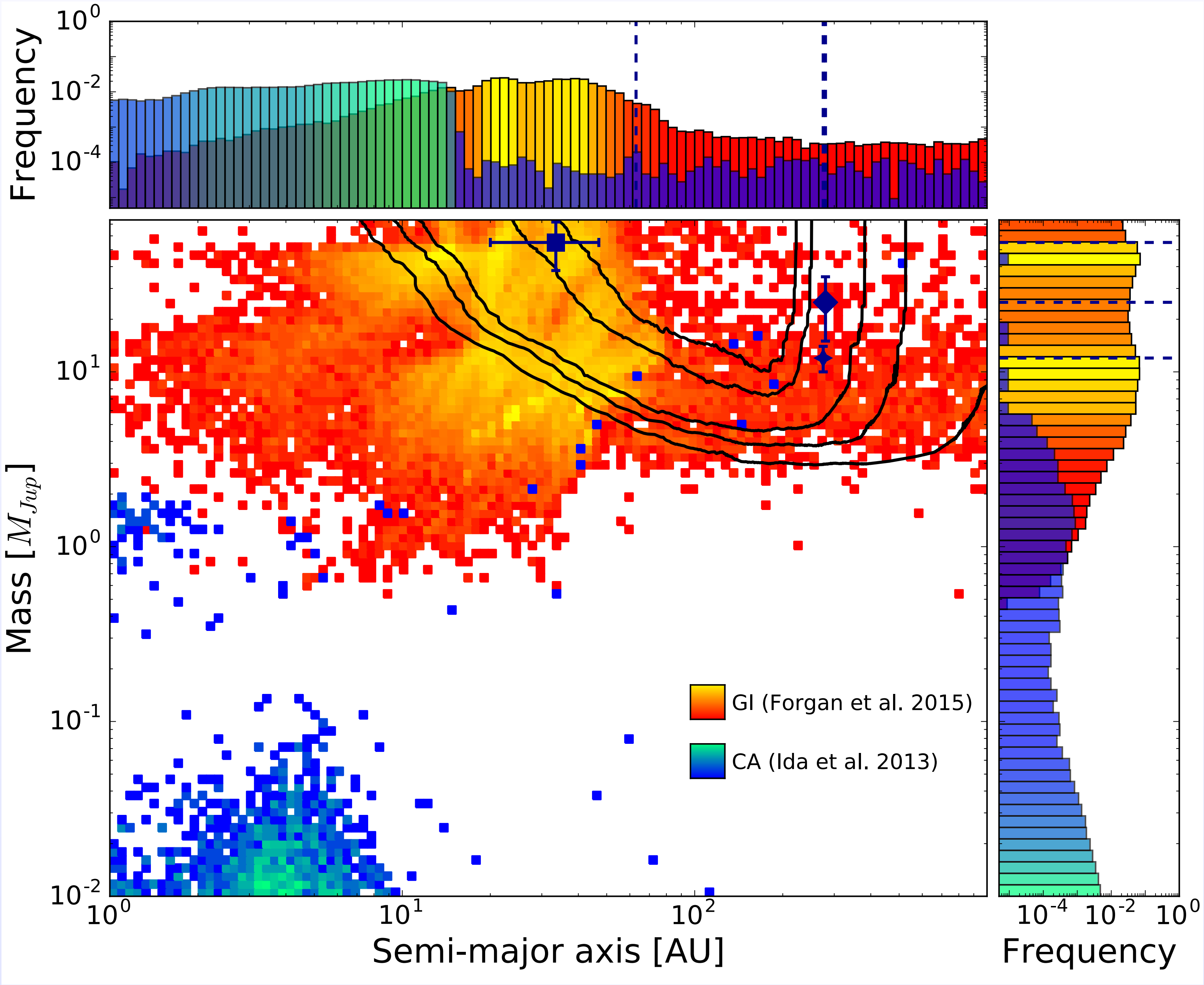
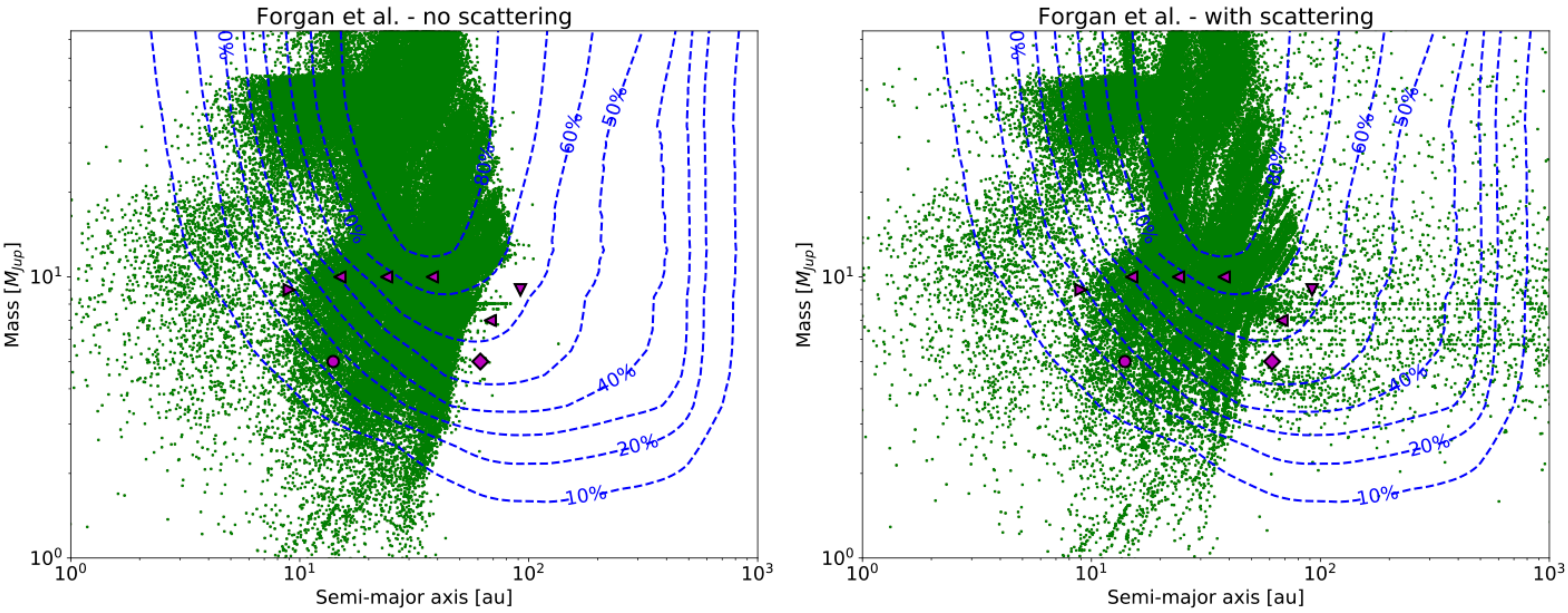


- **GI not dominant!**
- CA accretion not accessible
- Alternatives?
  - multi fragmentation GI
  - pebble accretion
  - dynamical evolution

Vigan et al. (2017)

Link to formation models: SHINE

Gravitational instability

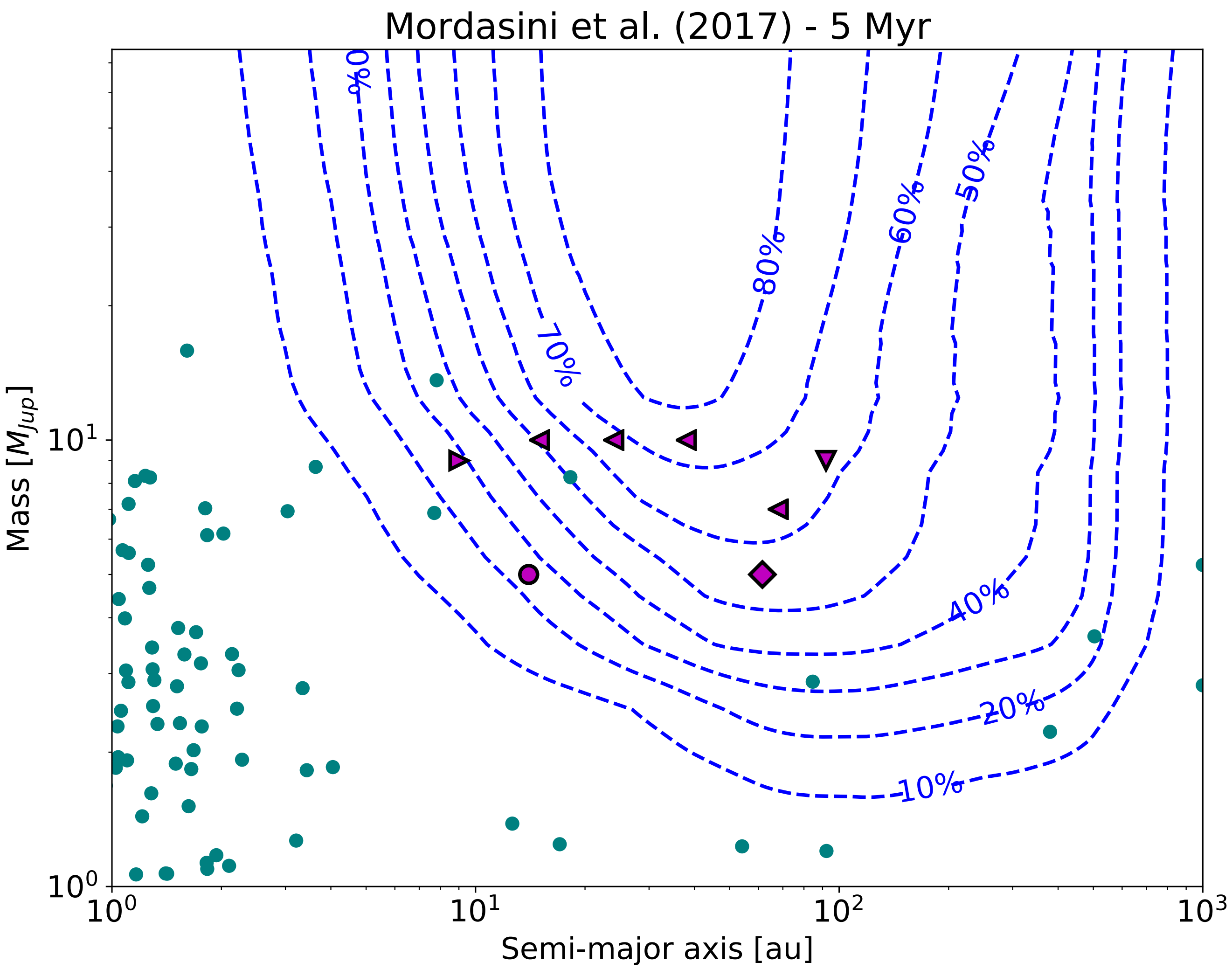


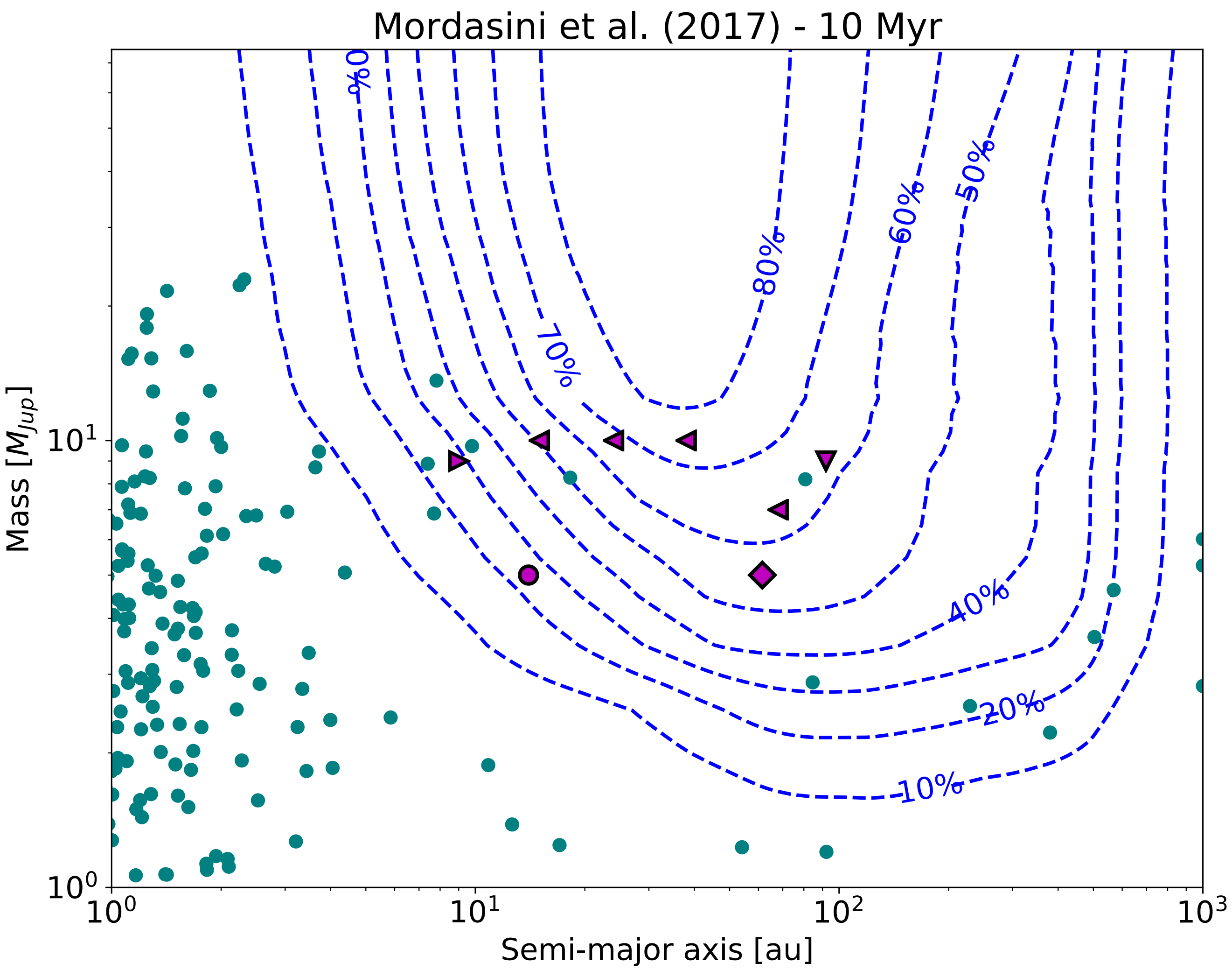
- State-of-the-art GI models by Forgan et al.
- Solar-type stars
- Semi-analytical scattering with systems up to 5 planets

Vigan et al. (in prep)

Link to formation models: SHINE

Core accretion



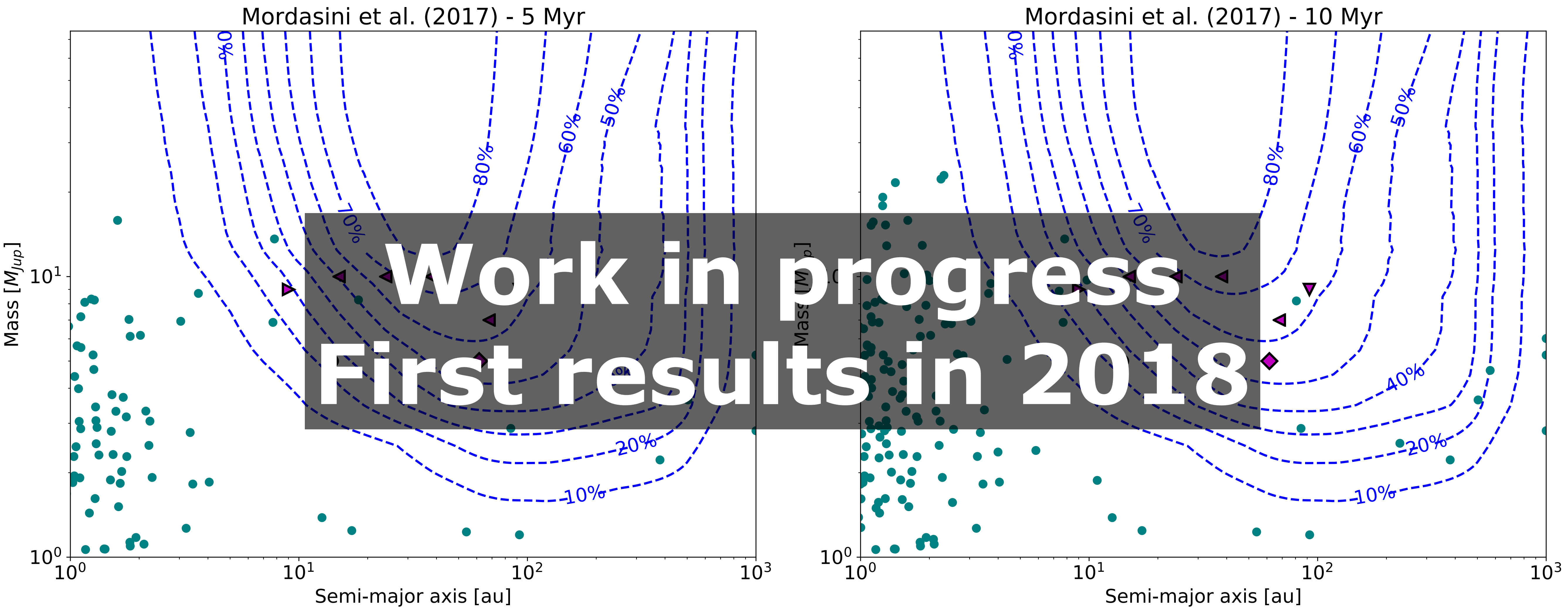


- State-of-the-art CA models by Mordasini et al.
- 0.5, 1.0, 2.0 M_{Sun}
- 10 embryos/disk, evolution from 0 to 1 Gyr

Vigan et al. (in prep)

Link to formation models: SHINE

Core accretion



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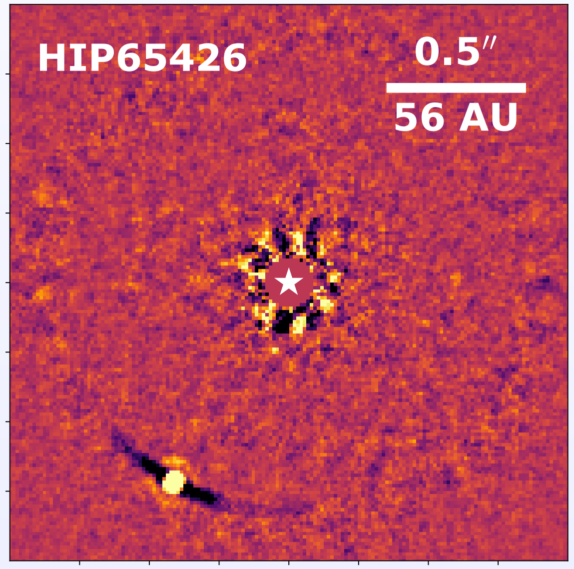
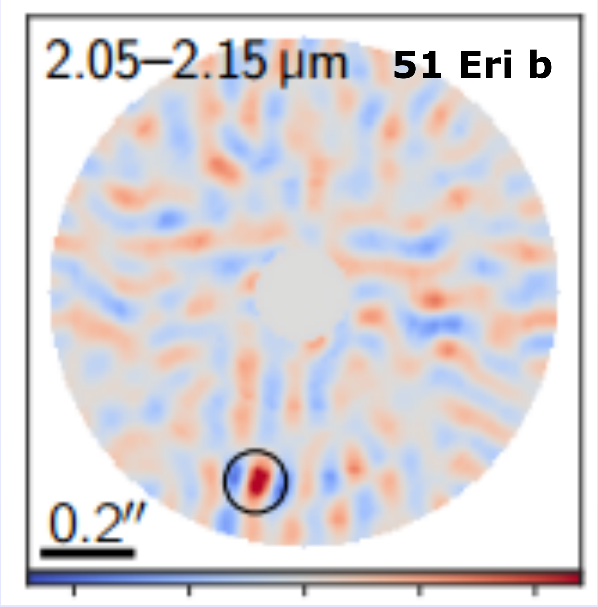
Future

2 main directions

1. More planets!!





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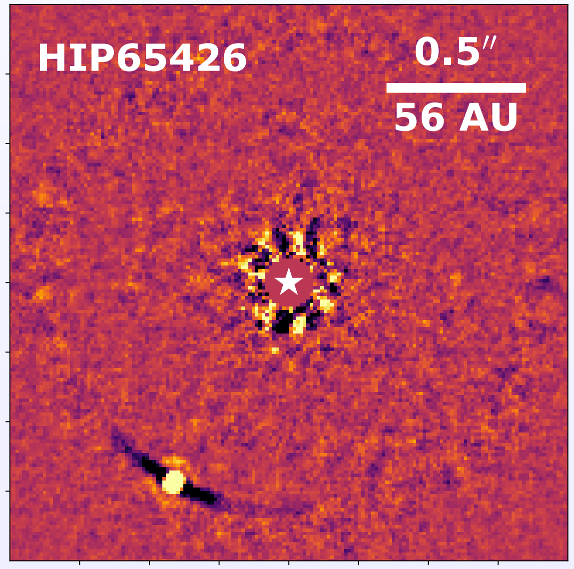
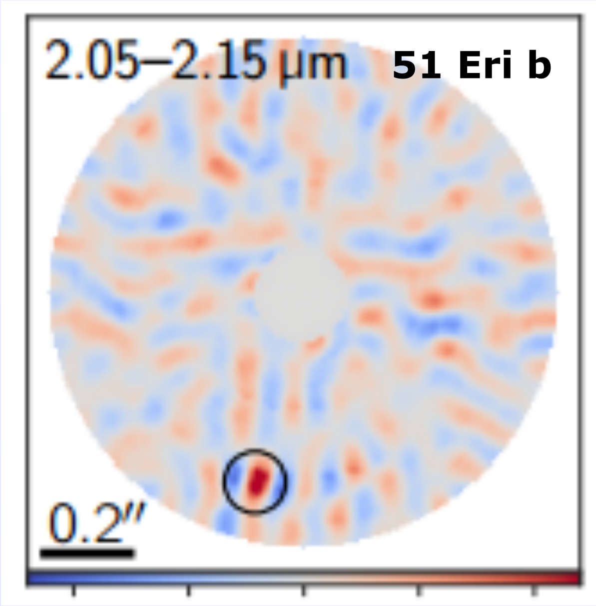
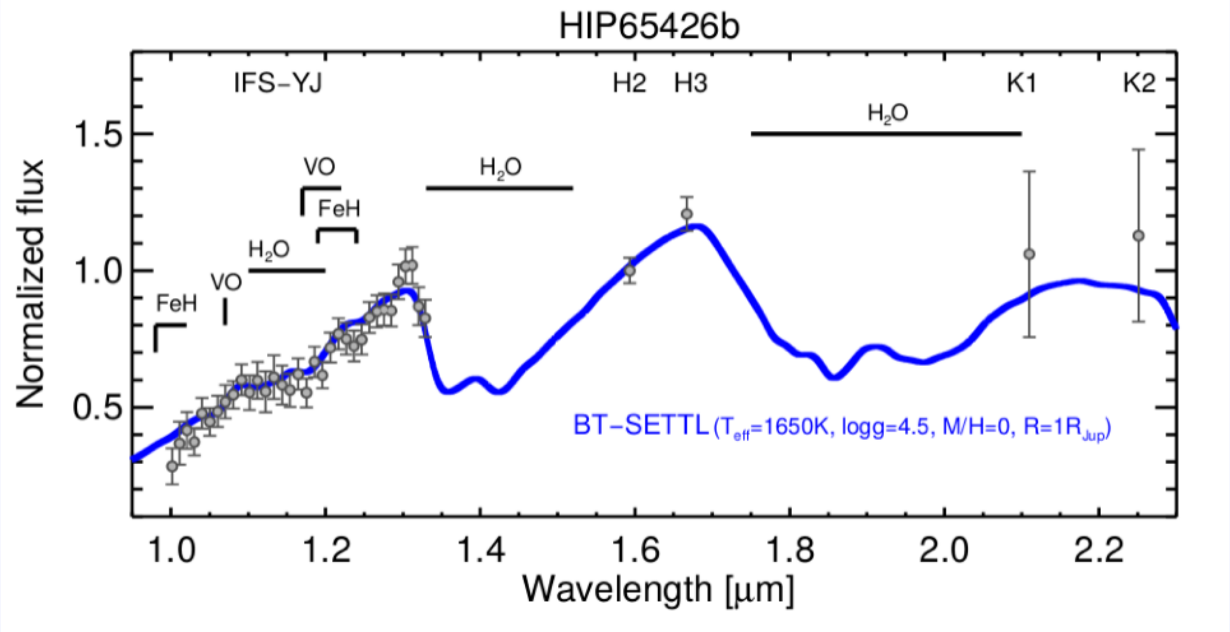
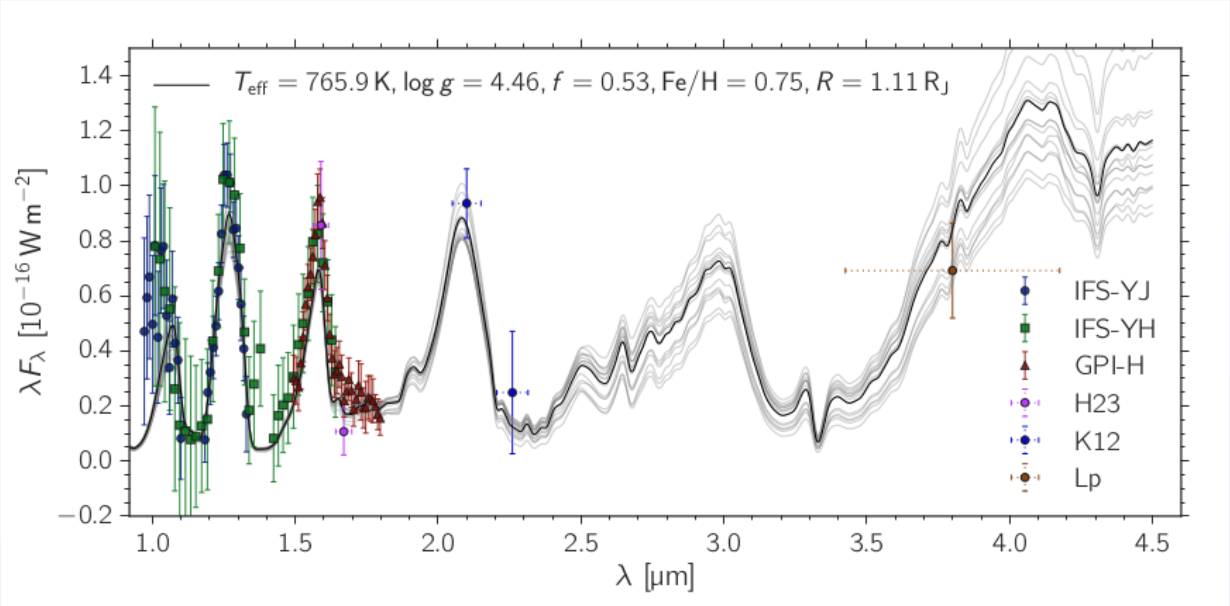


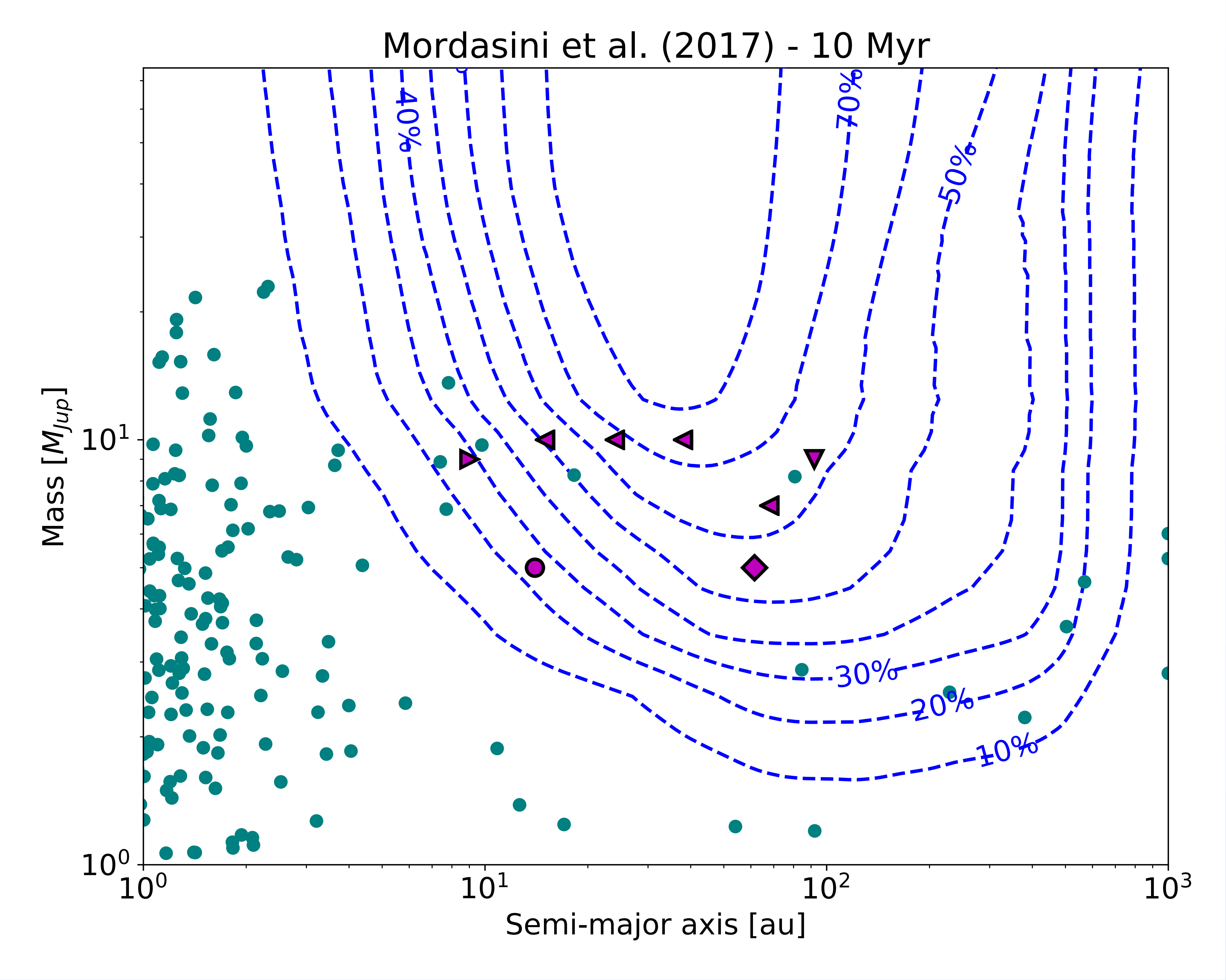


2. Improved characterization





More planets: closer, deeper



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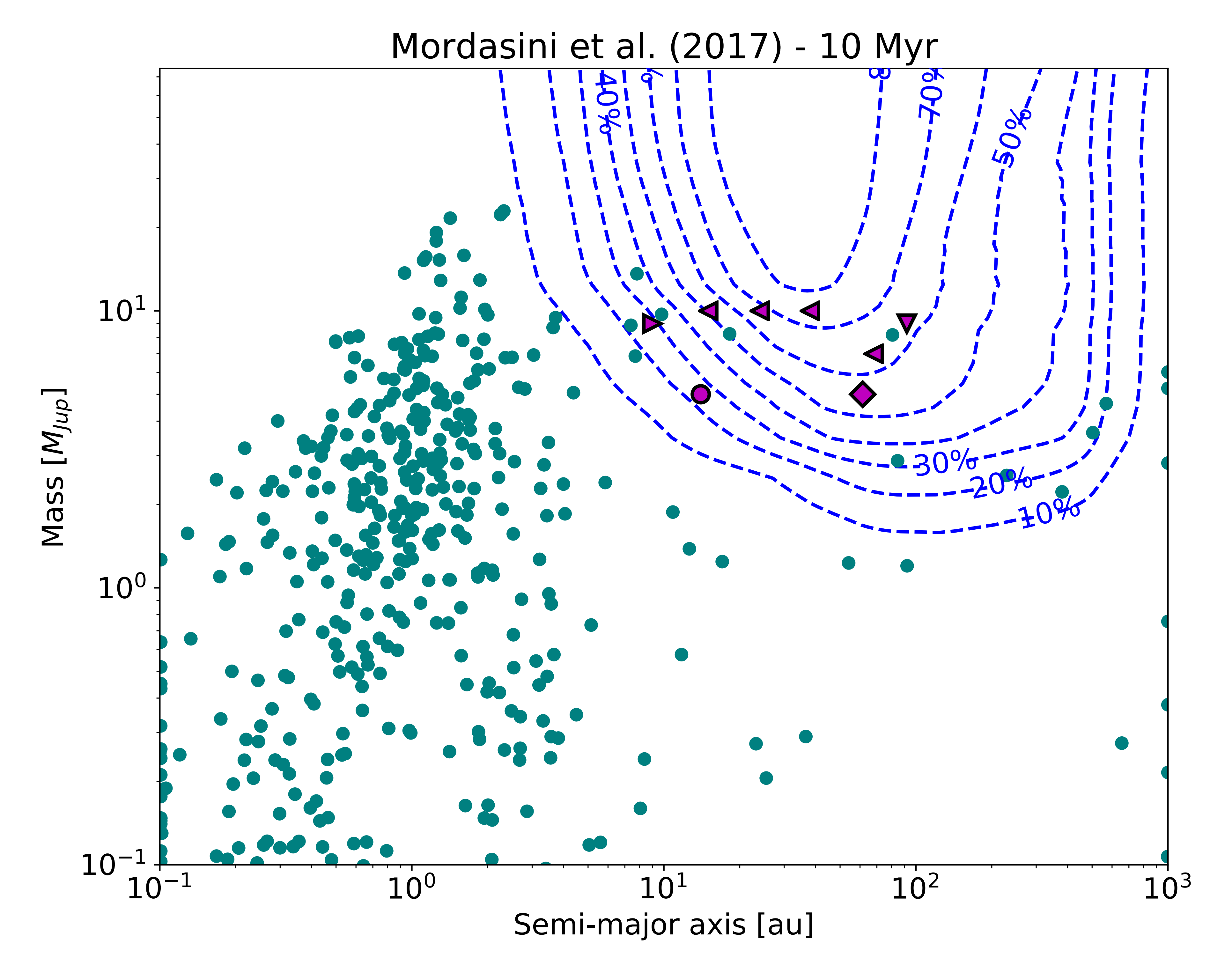

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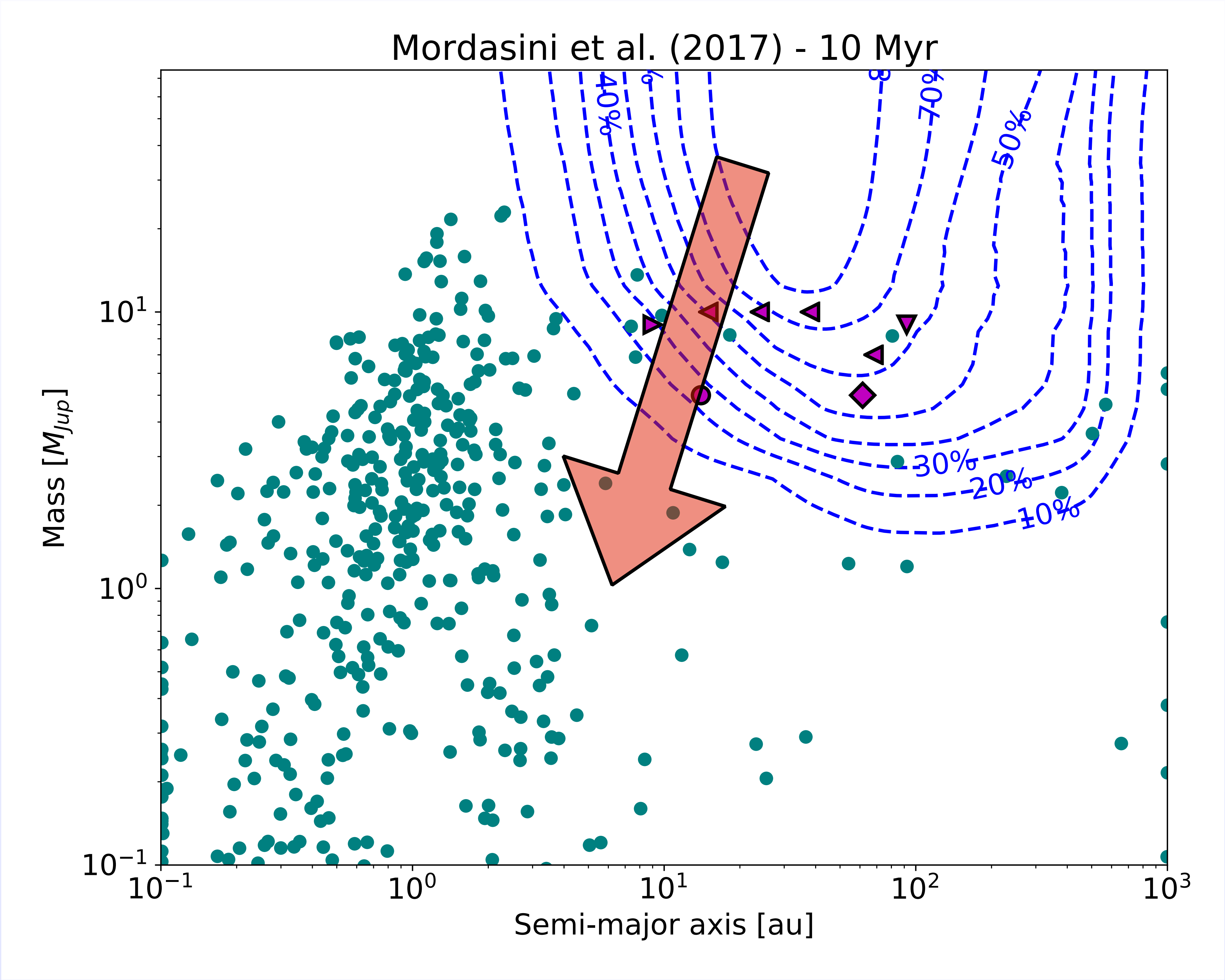
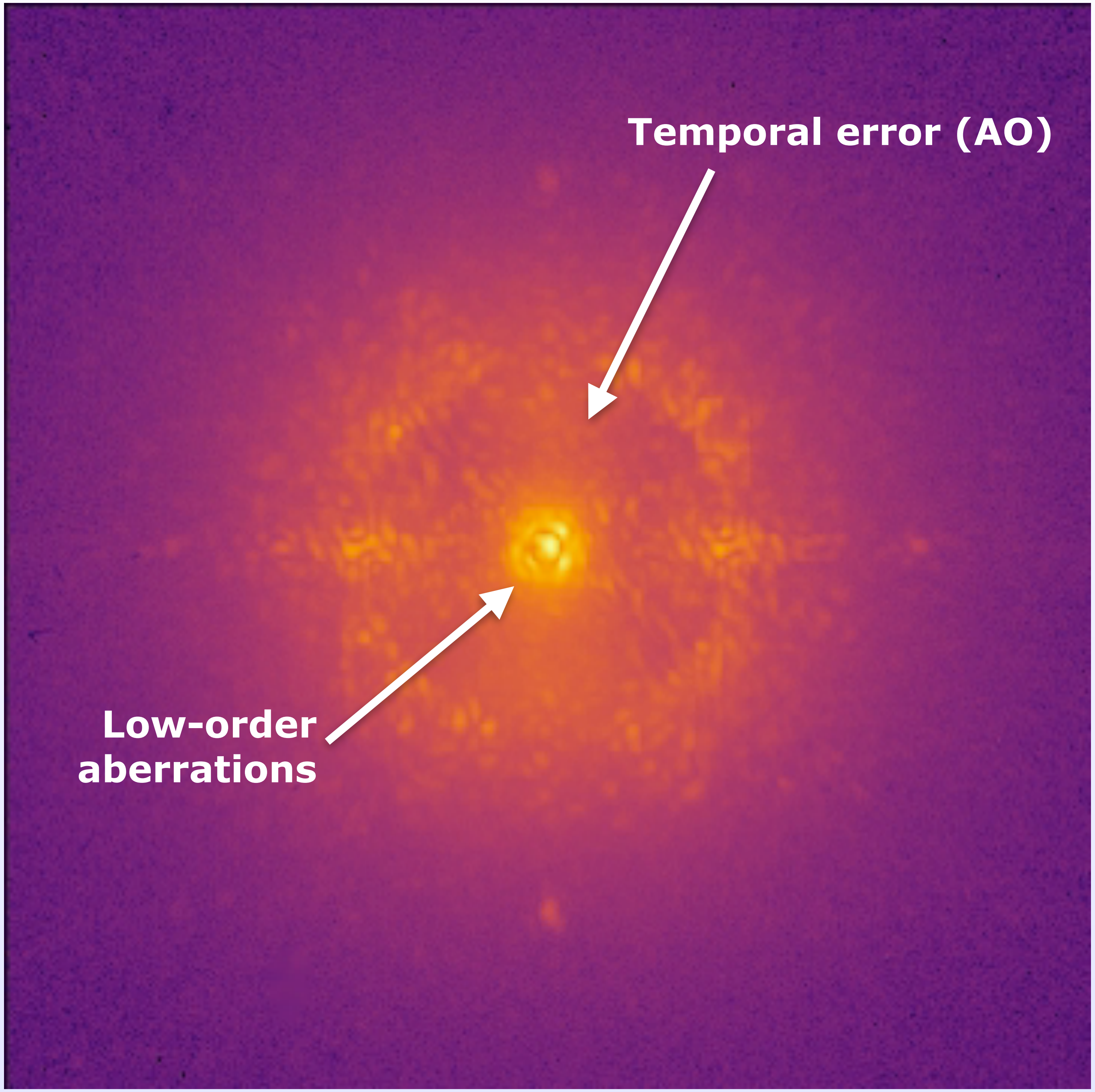


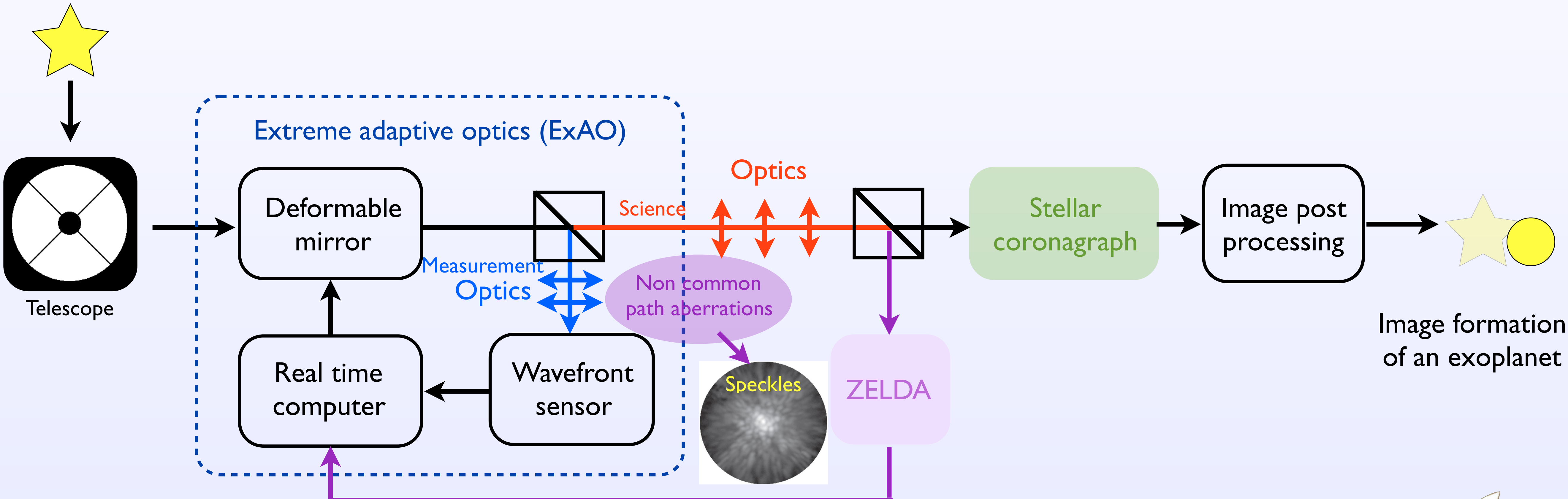
Current limitations



ZELDA: Zernike wavefront sensor

ZELDA

Zernike sensor for Extremely accurate measurements of Low-level Differential Aberrations

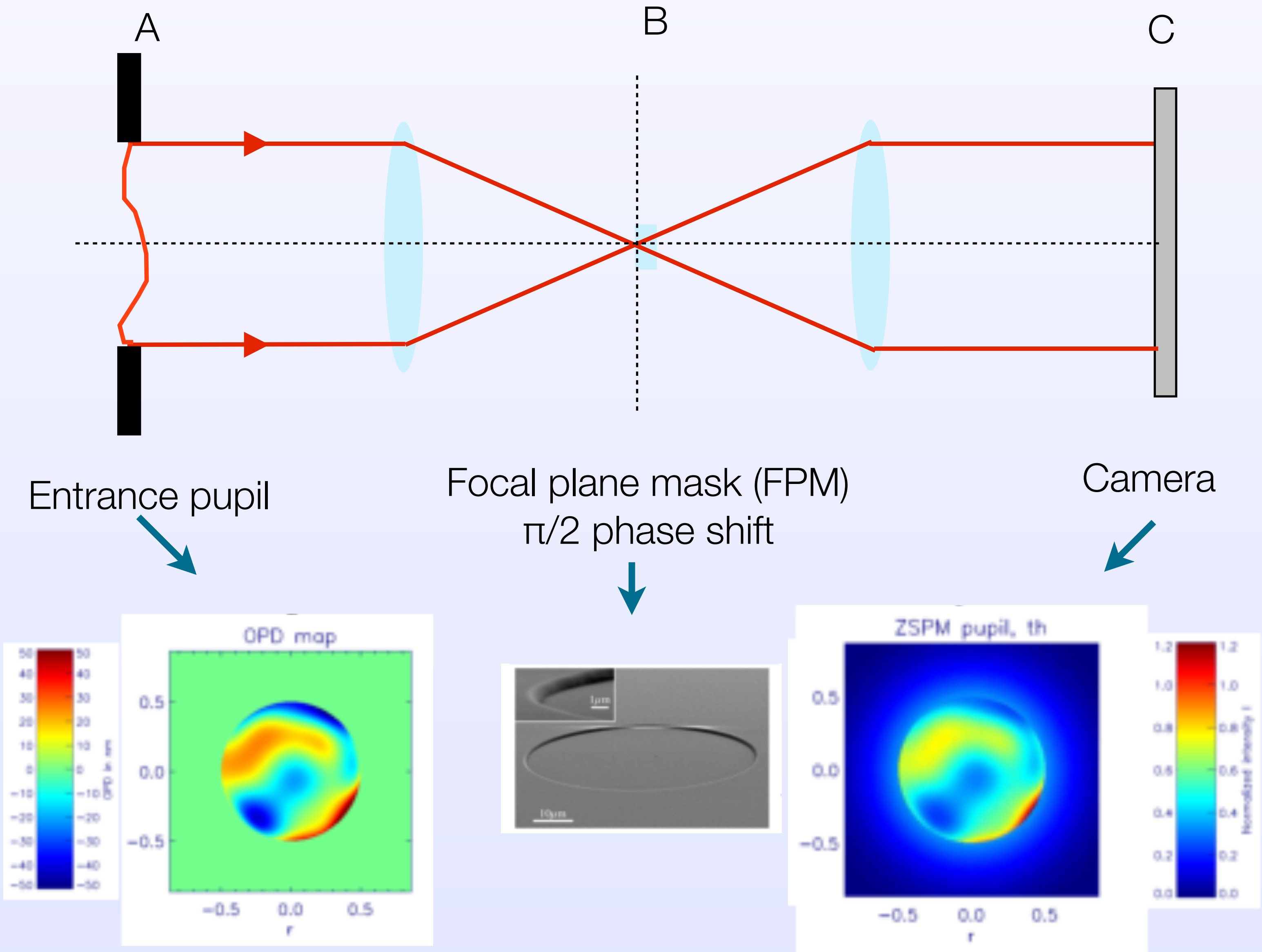


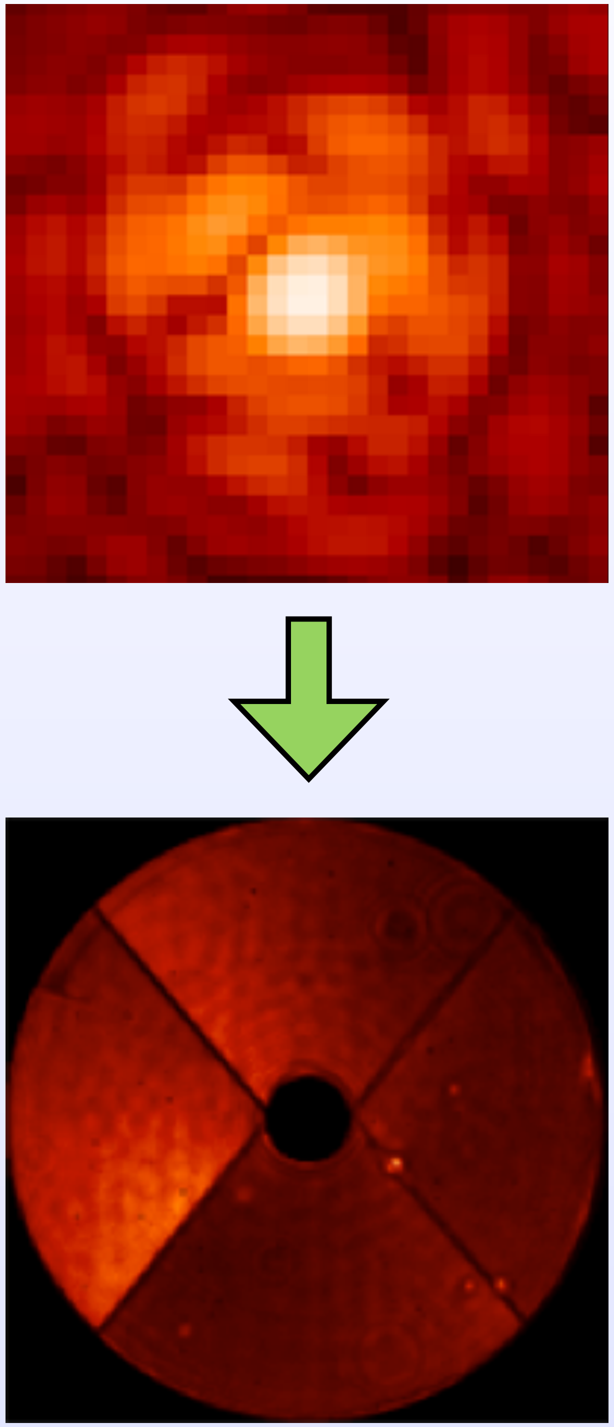
- Original measurement strategies:
  - VLT/SPHERE: off-line phase diversity
  - GPI: Mach-Zehnder interferometer behind coronagraph

- Our proposal:
  - ZELDA a concept based on phase-contrast technique

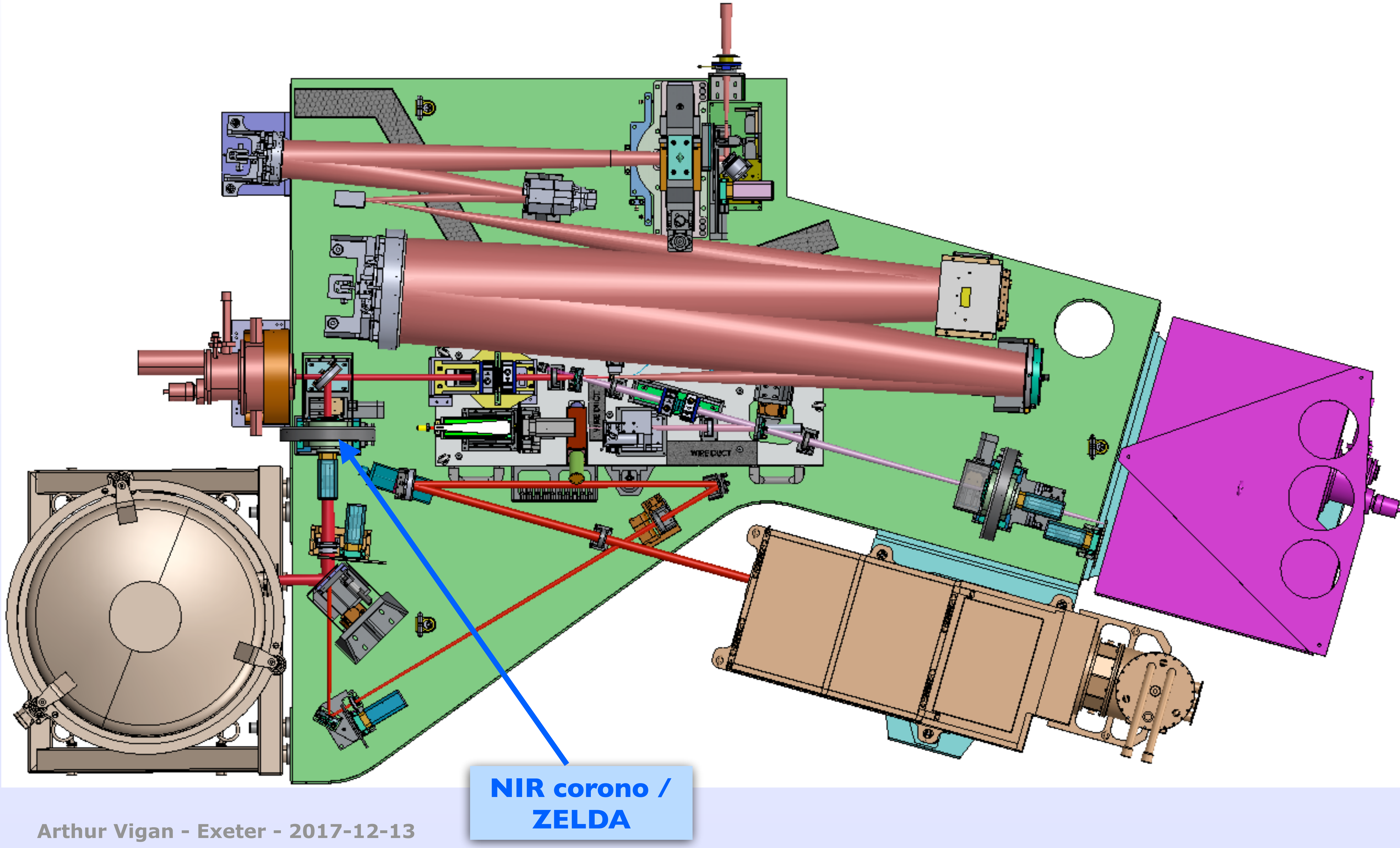
ZELDA: Zernike wavefront sensor

- Conversion of the phase aberrations into intensity variations
  - Ic=α sin φ + β
  - Small aberrations: Ic =αφ + β





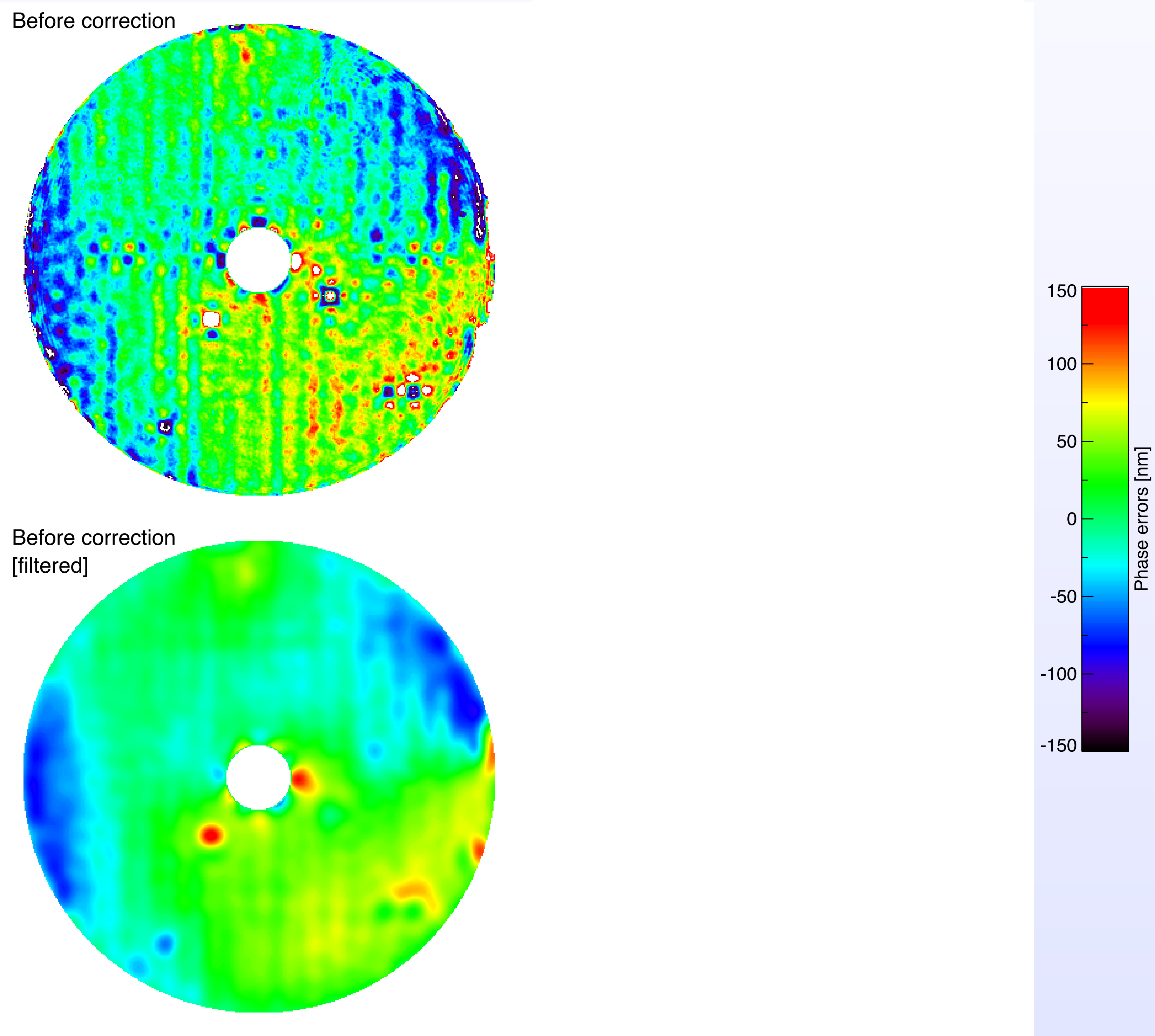
ZELDA in SPHERE



NCPA compensation in SPHERE

45 nm RMS

30 nm RMS



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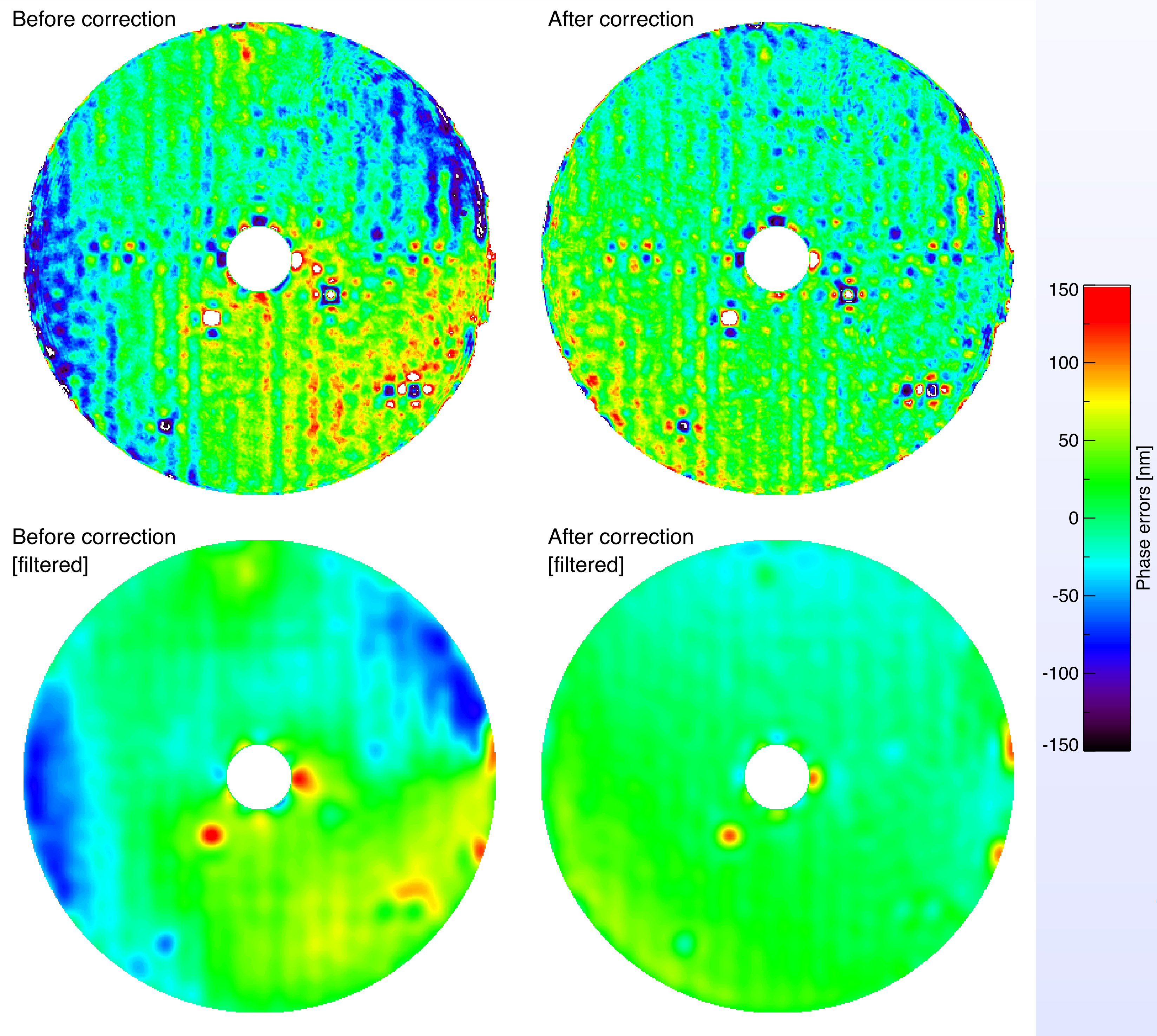


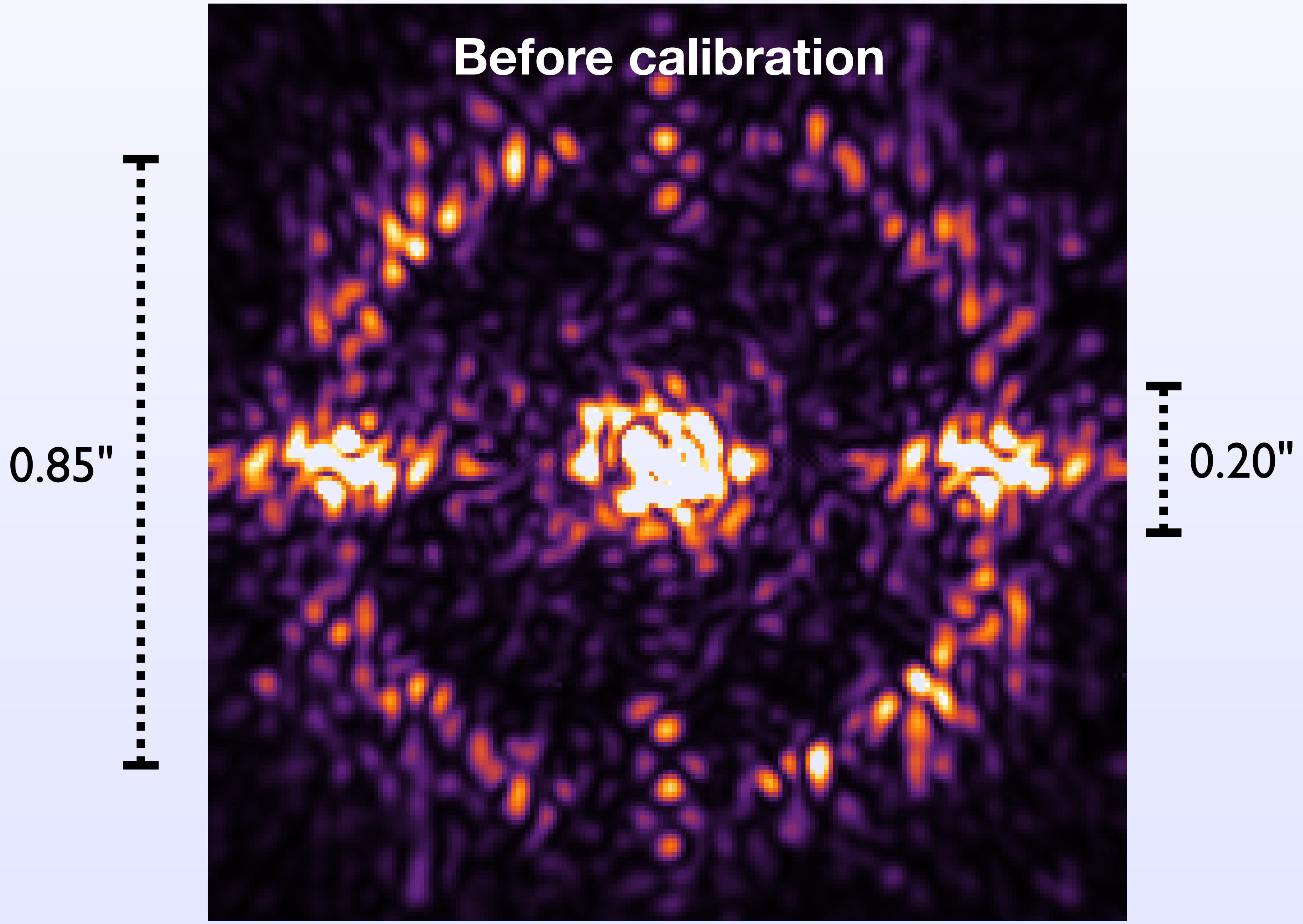
35 nm RMS

16 nm RMS

Tip-tilt:
~12 nm RMS

NCPA compensation in SPHERE

Apodised pupil Lyot coronagraph, H-band



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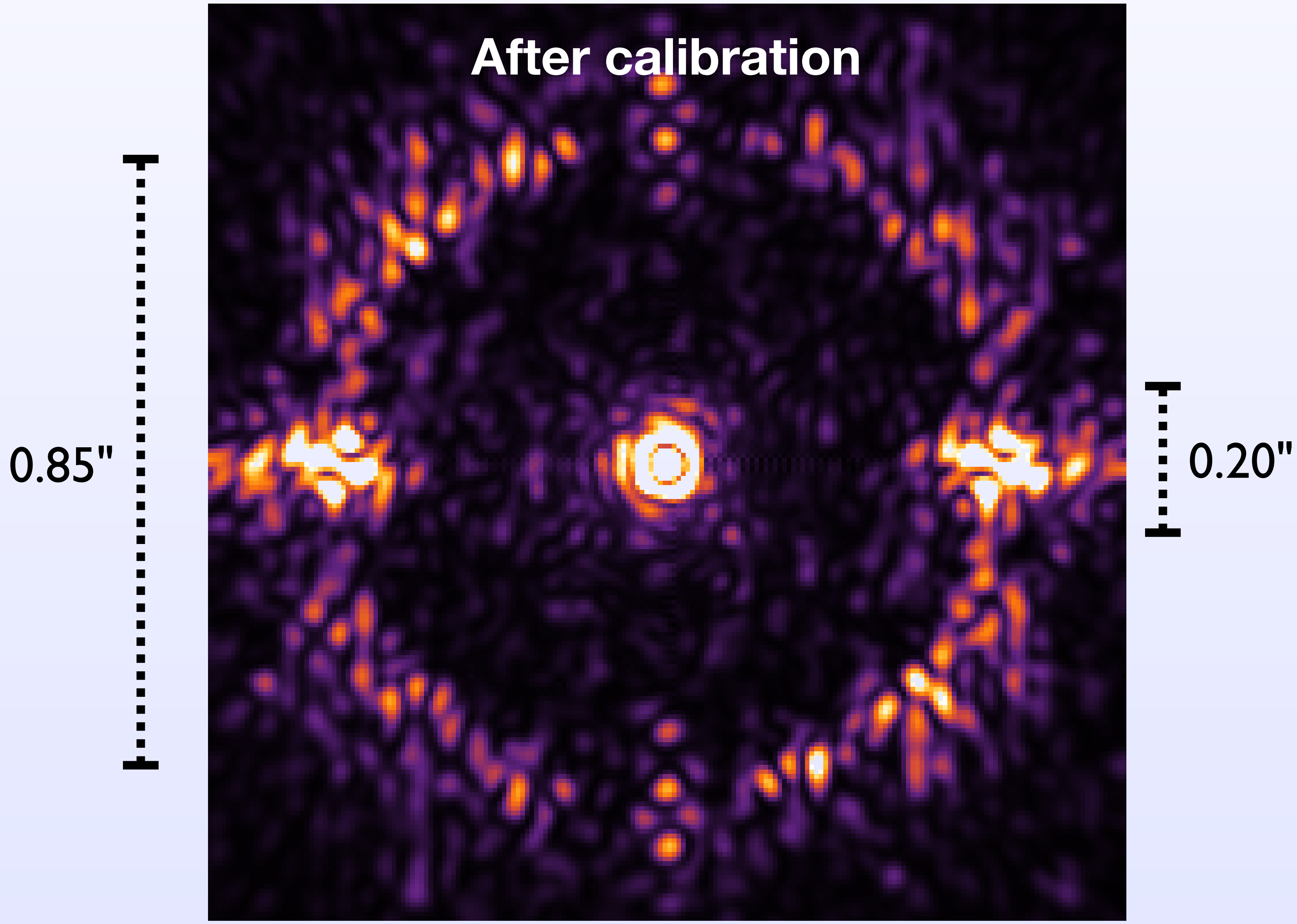

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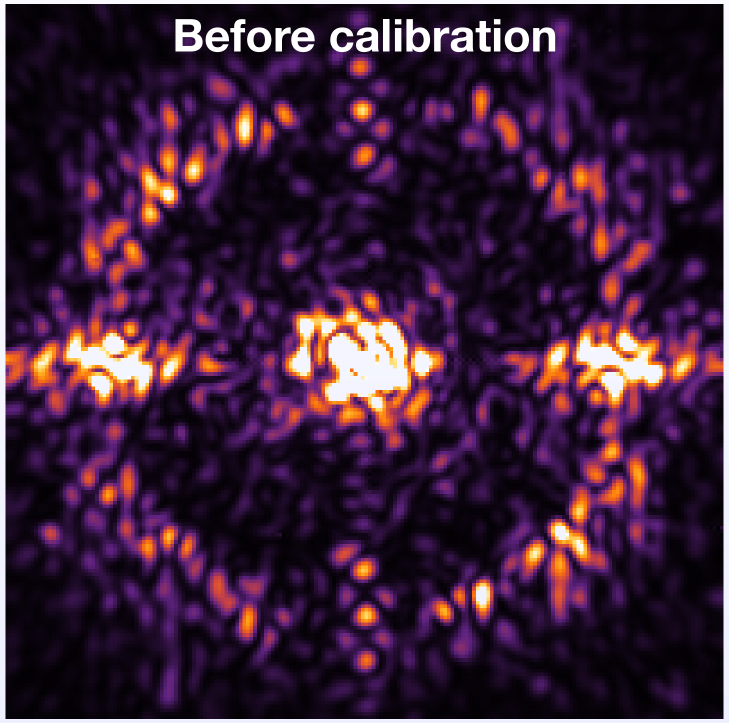

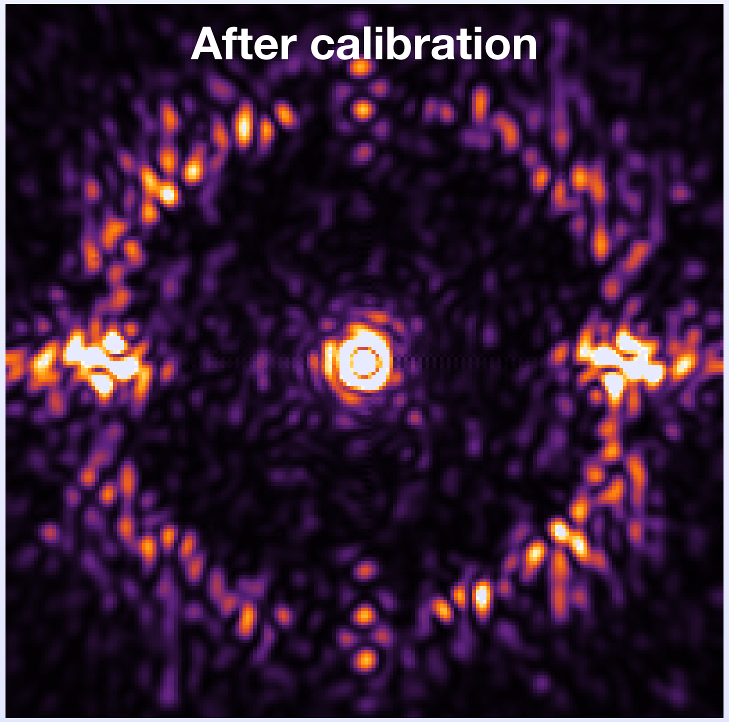

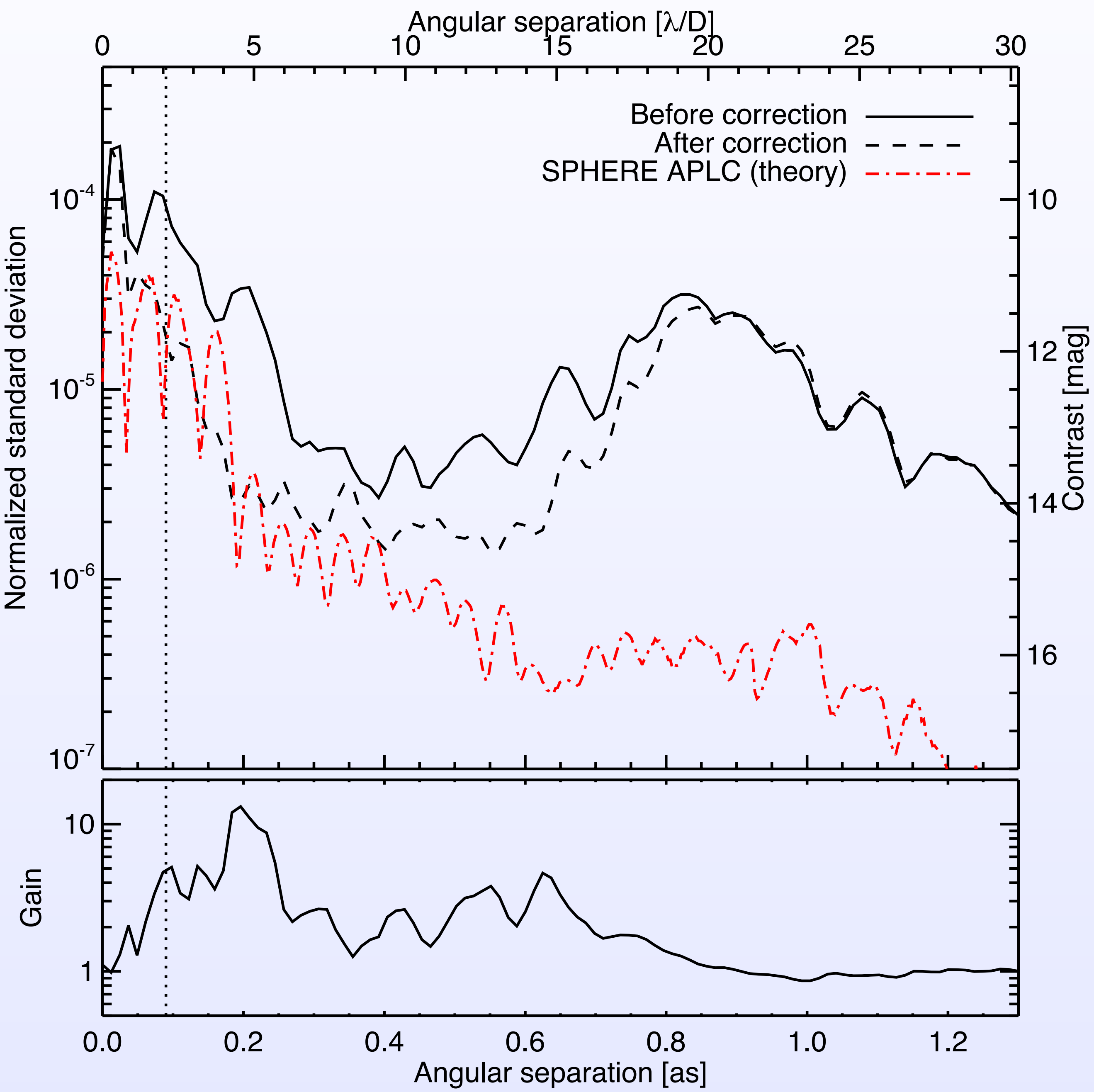

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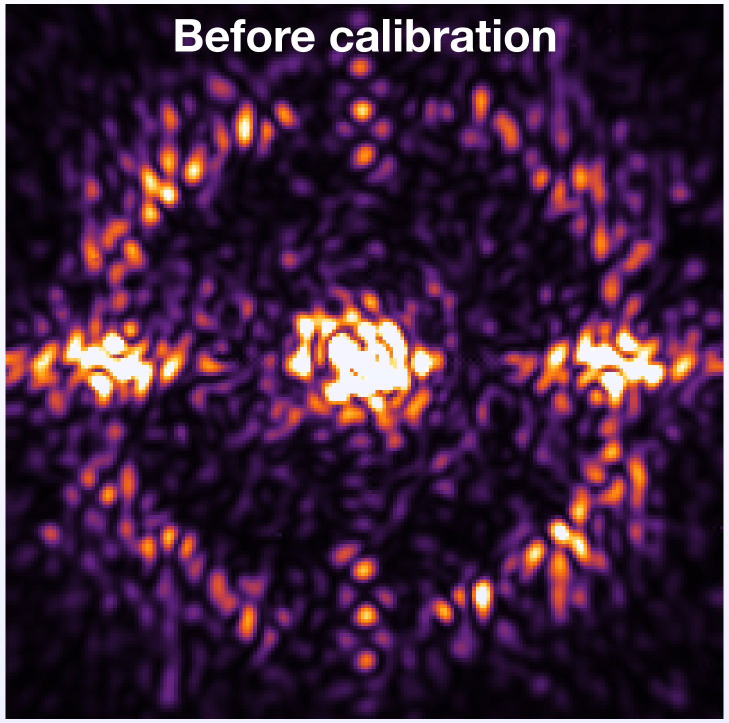
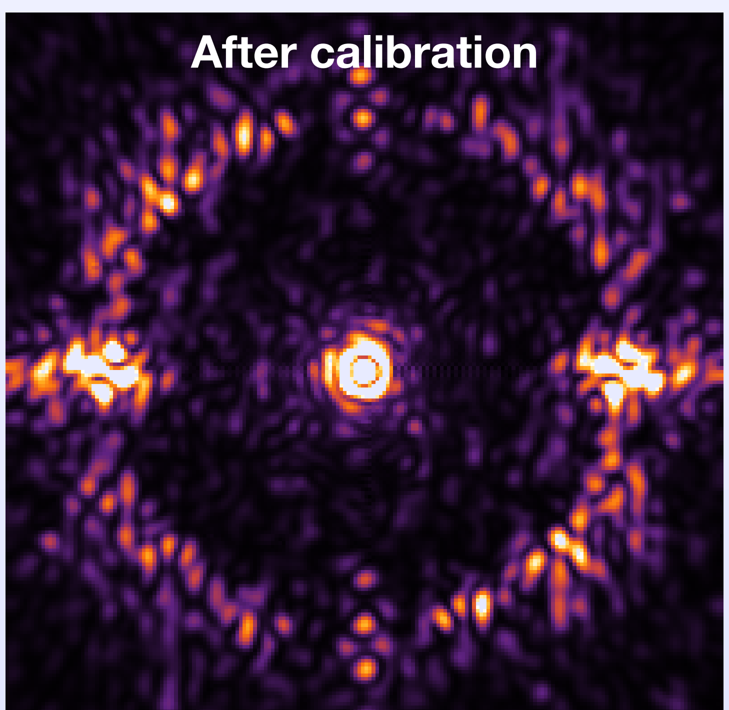
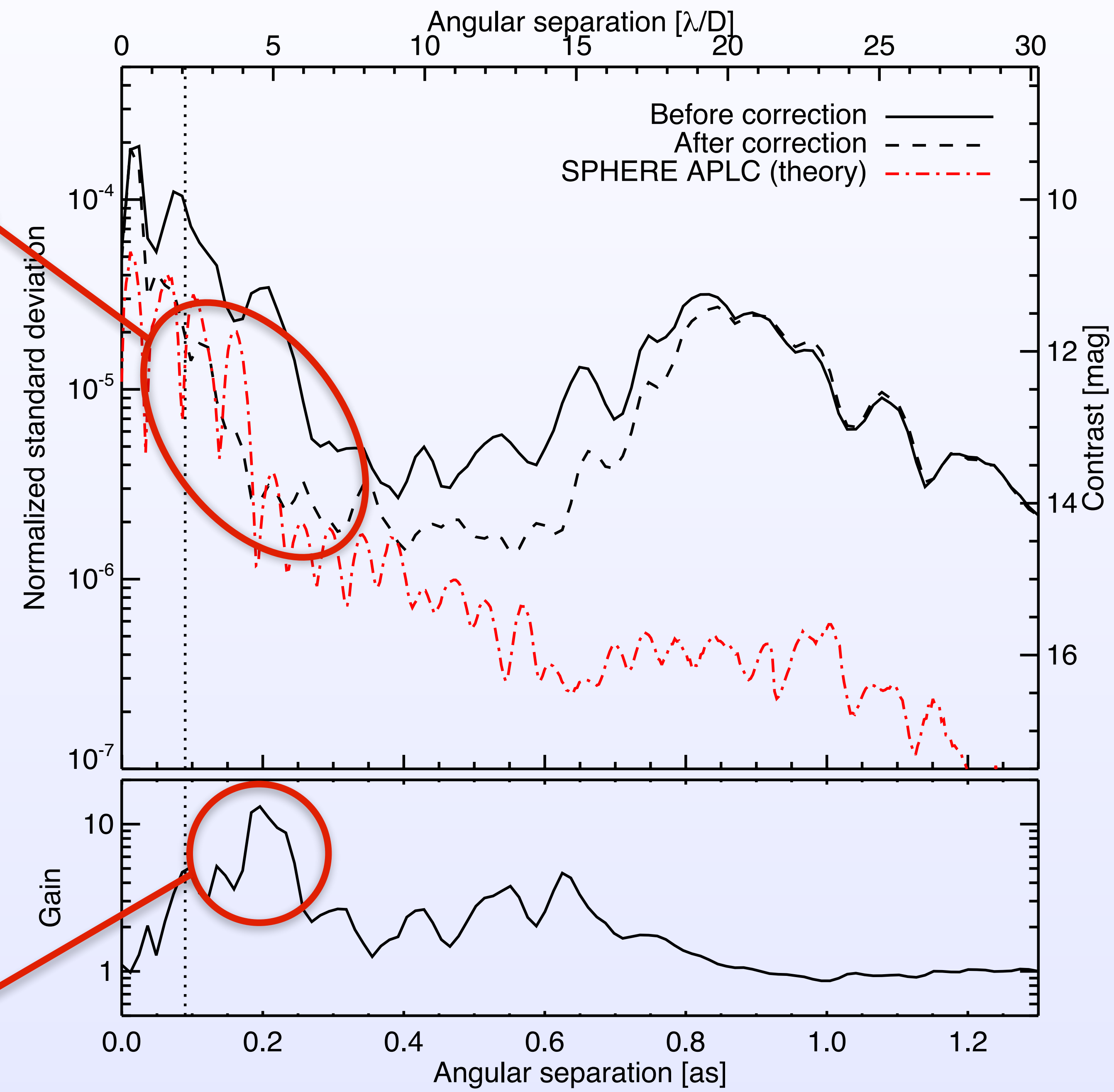




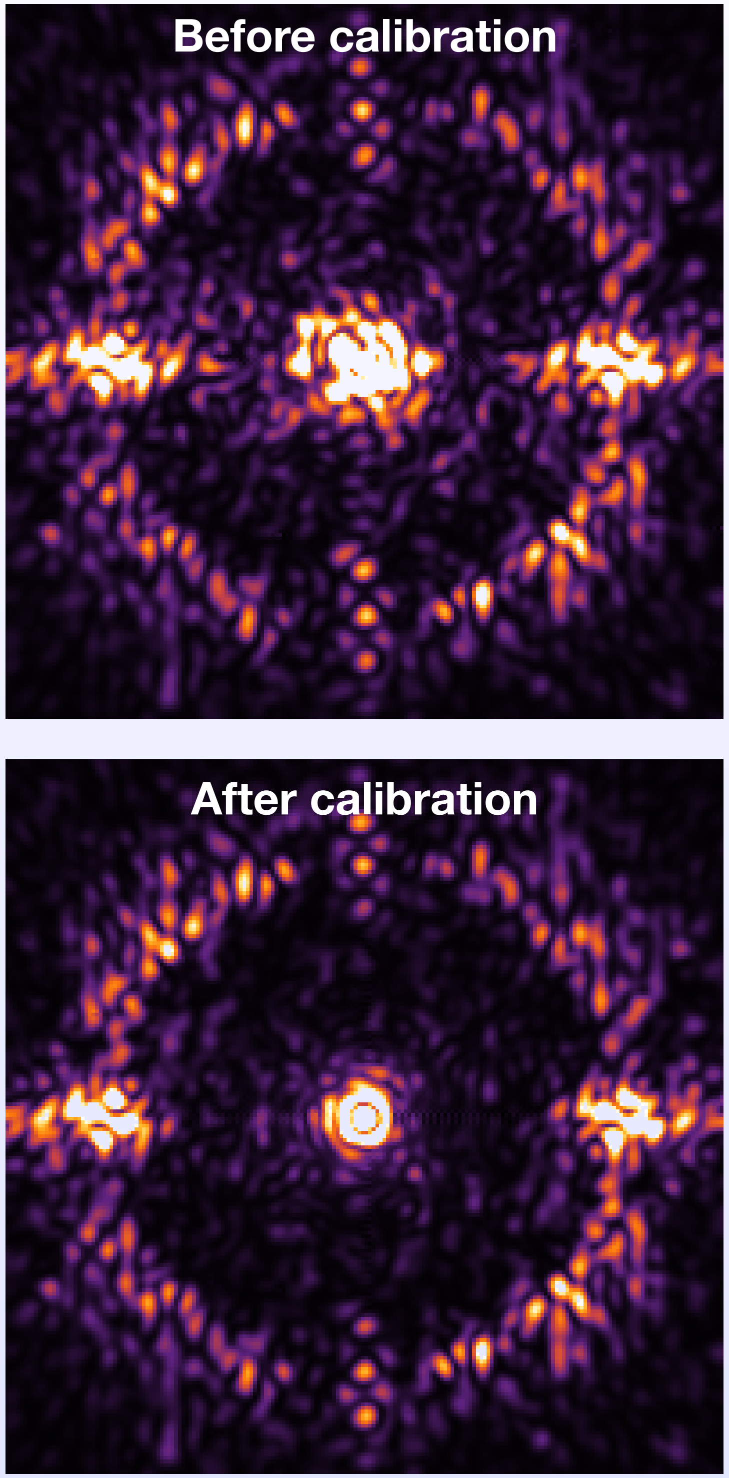
performance limit of SPHERE coronagraph



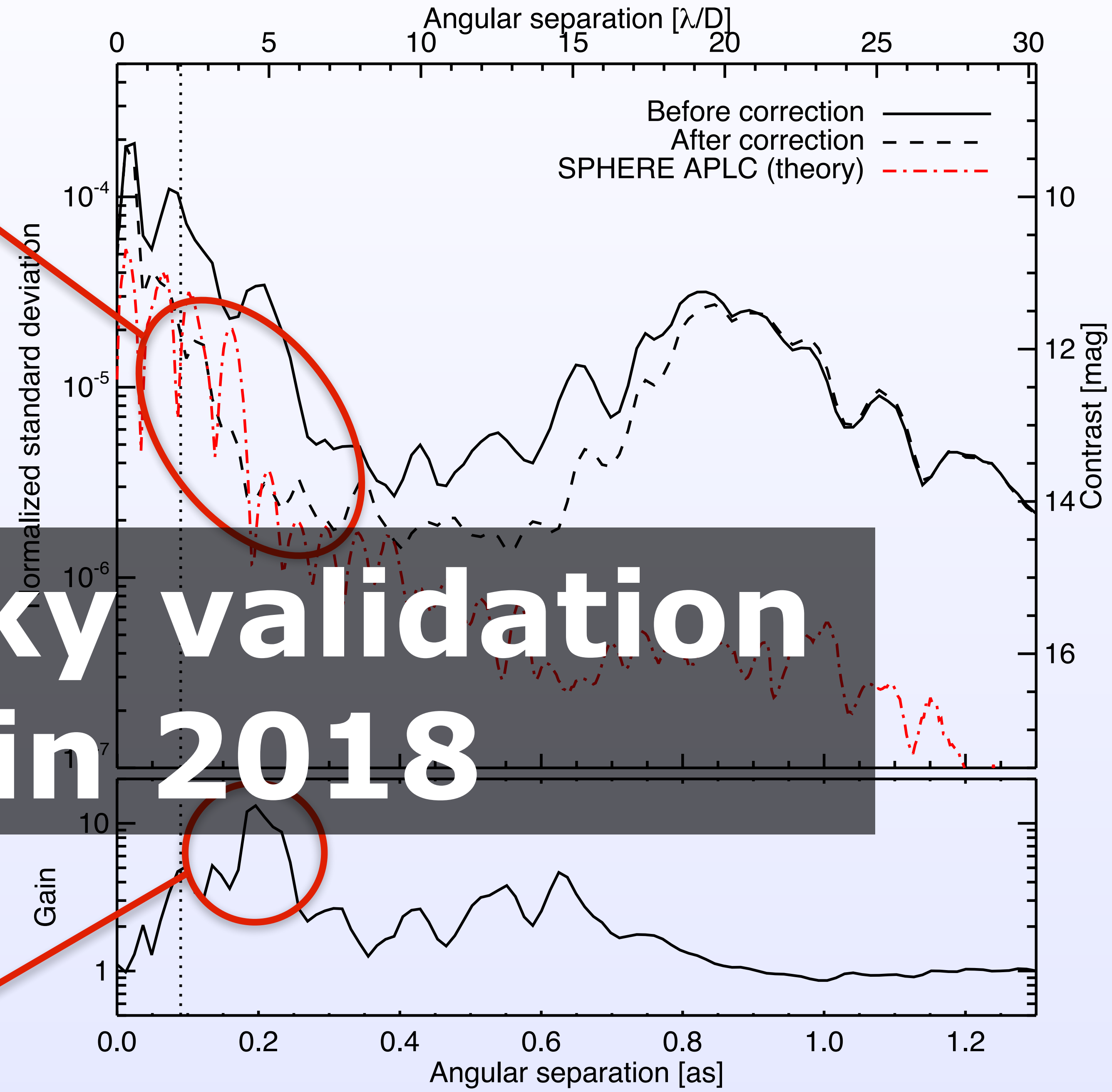
x10 gain @ 0.2"

→ ZELDA now used to monitor NCPA in SPHERE

NCPA compensation in SPHERE



performance limit of SPHERE coronagraph

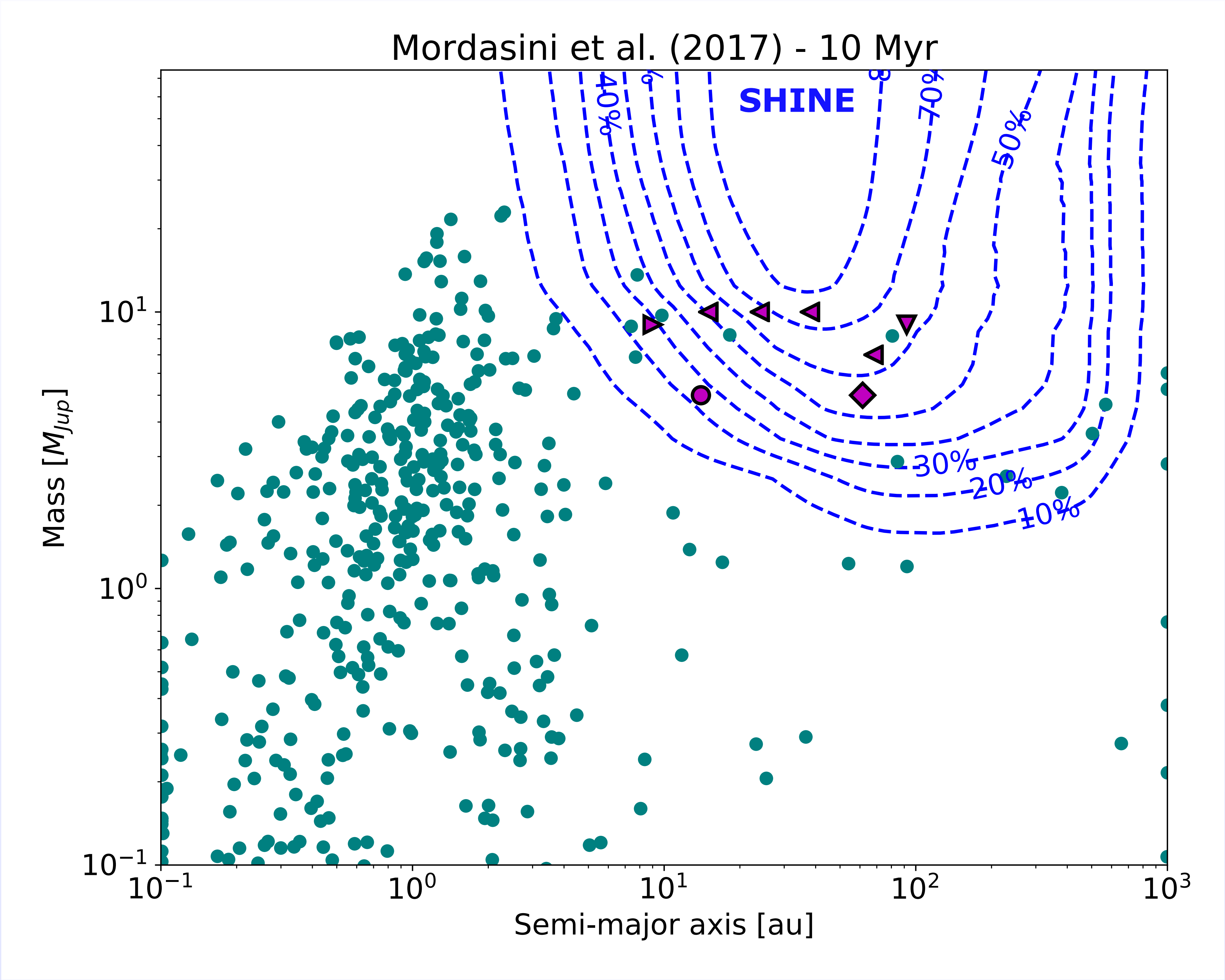


On-sky validation in 2018

x10 gain @ 0.2"

→ ZELDA now used to monitor NCPA in SPHERE

More planets: closer, deeper



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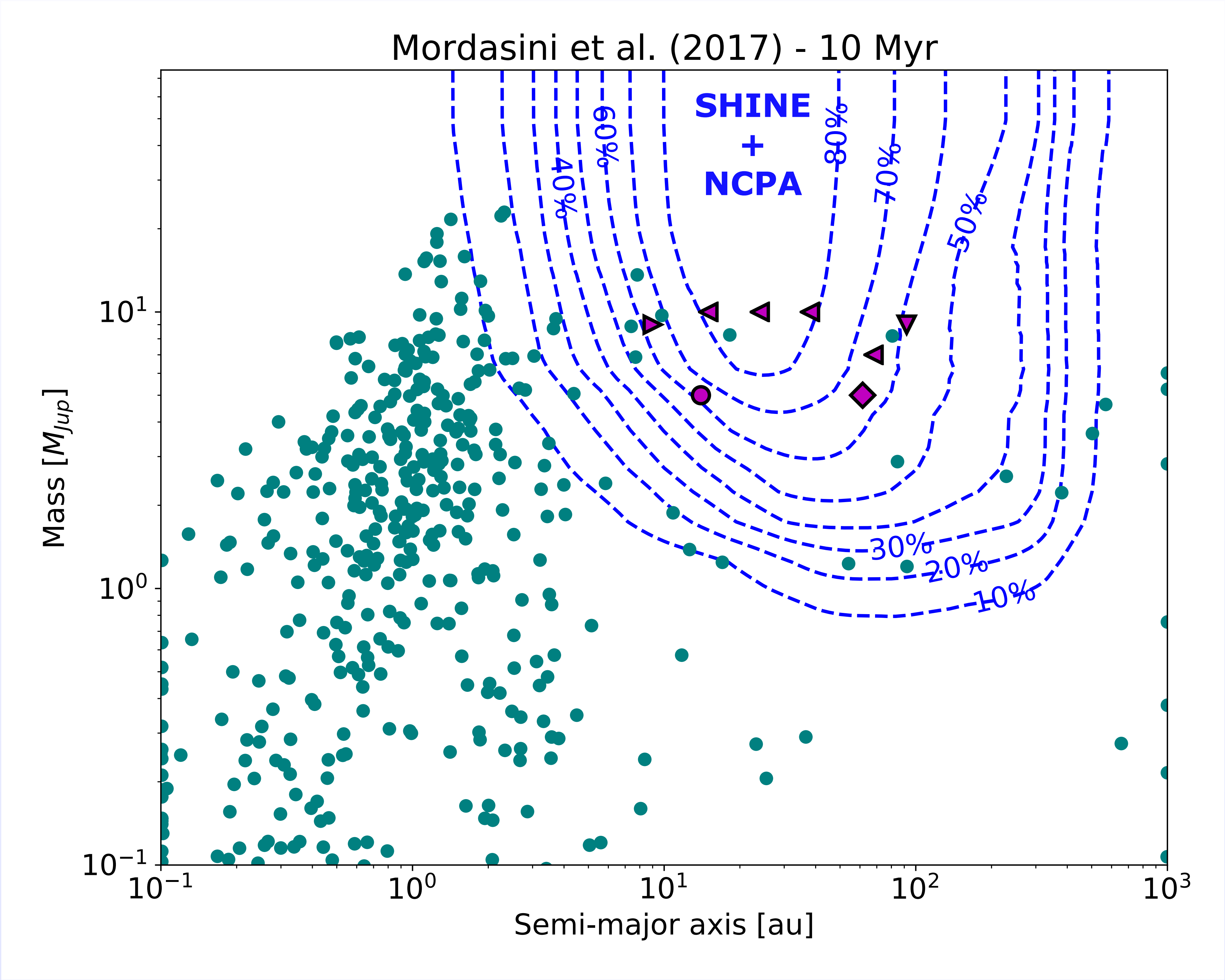
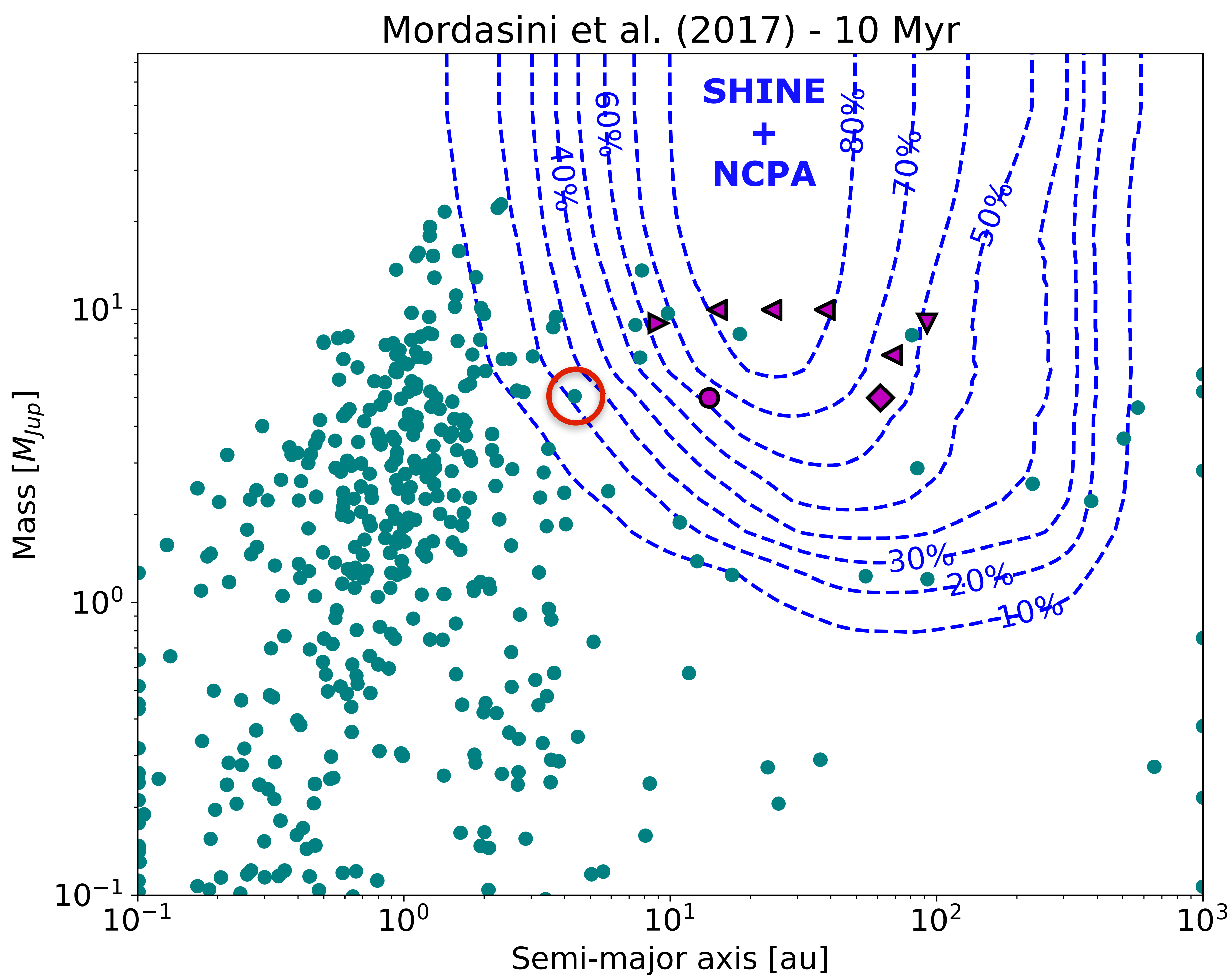
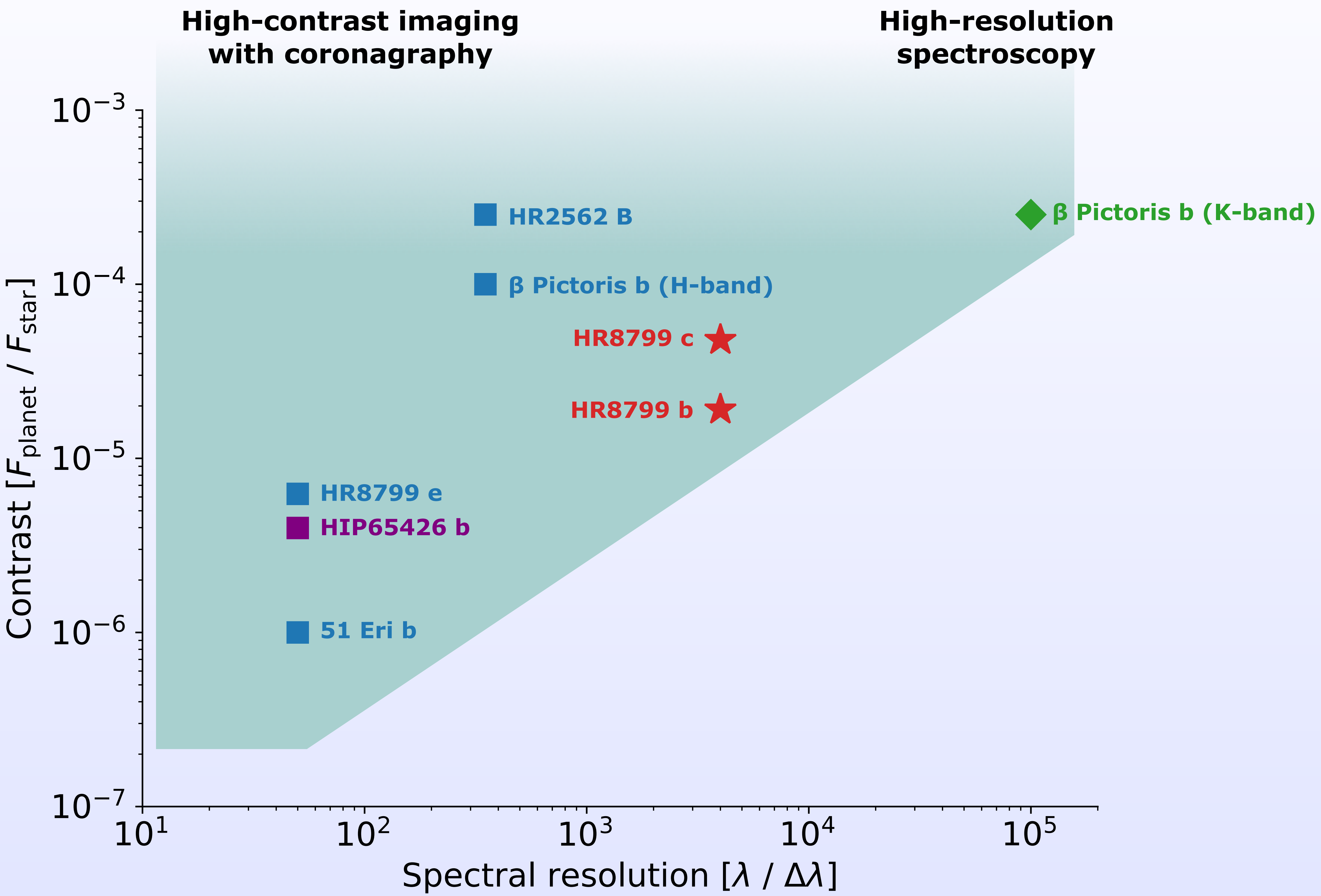


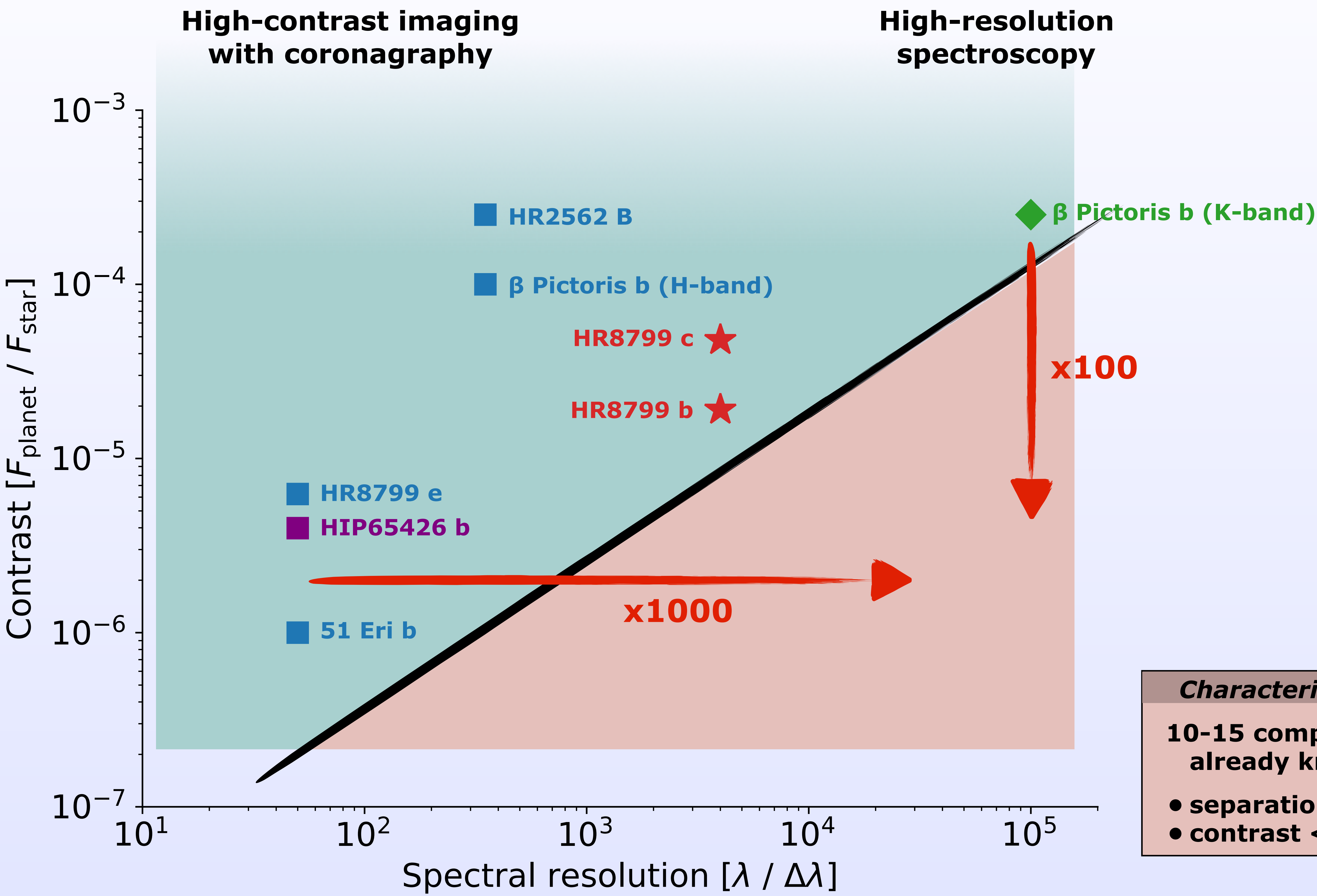
Improved characterization



Very high spectral resolution



Very high spectral resolution



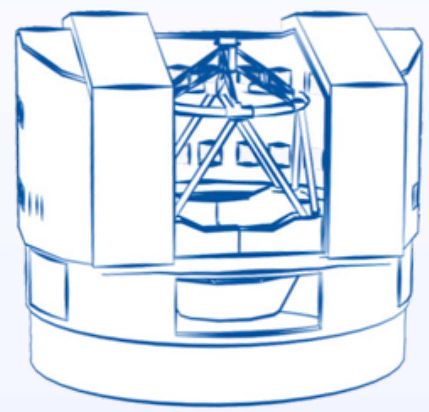
Characterisation

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

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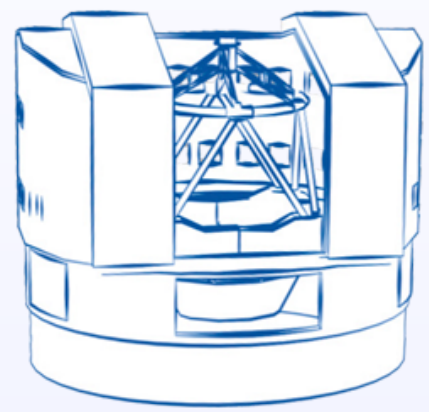

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Y J H K	Spectral coverage	Y J H K L M
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HiRISE

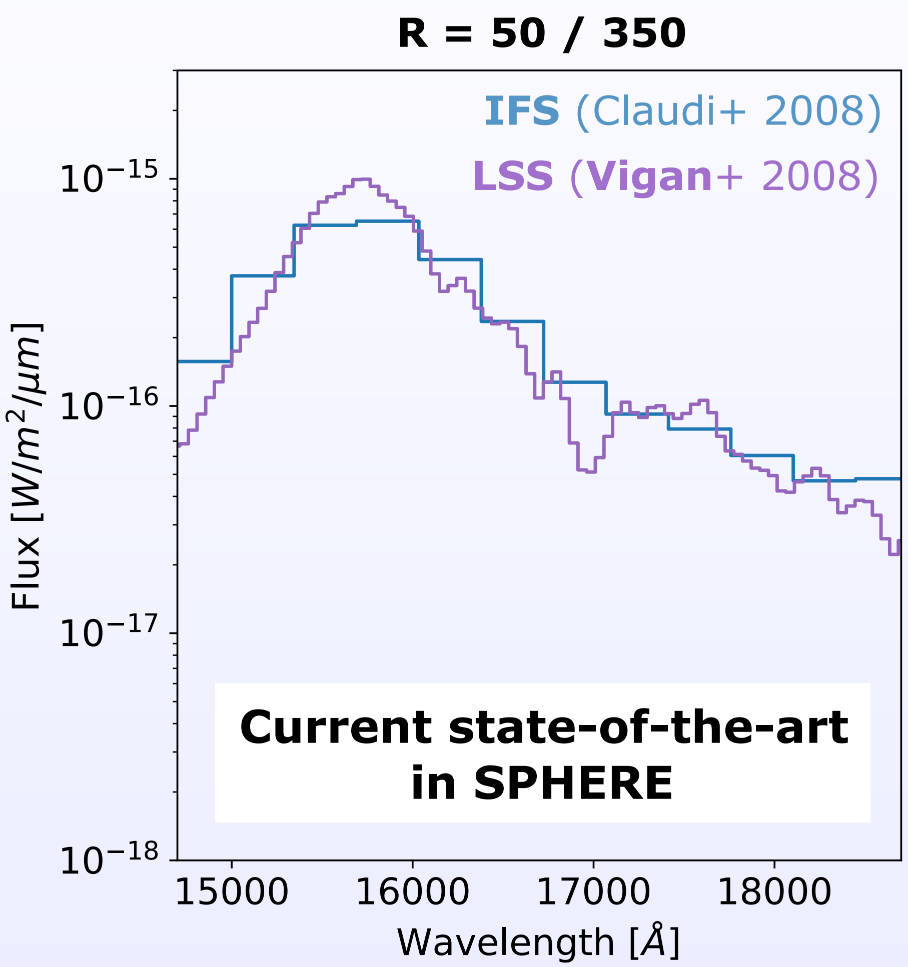
Fiber coupling

Supported by ESO

erc

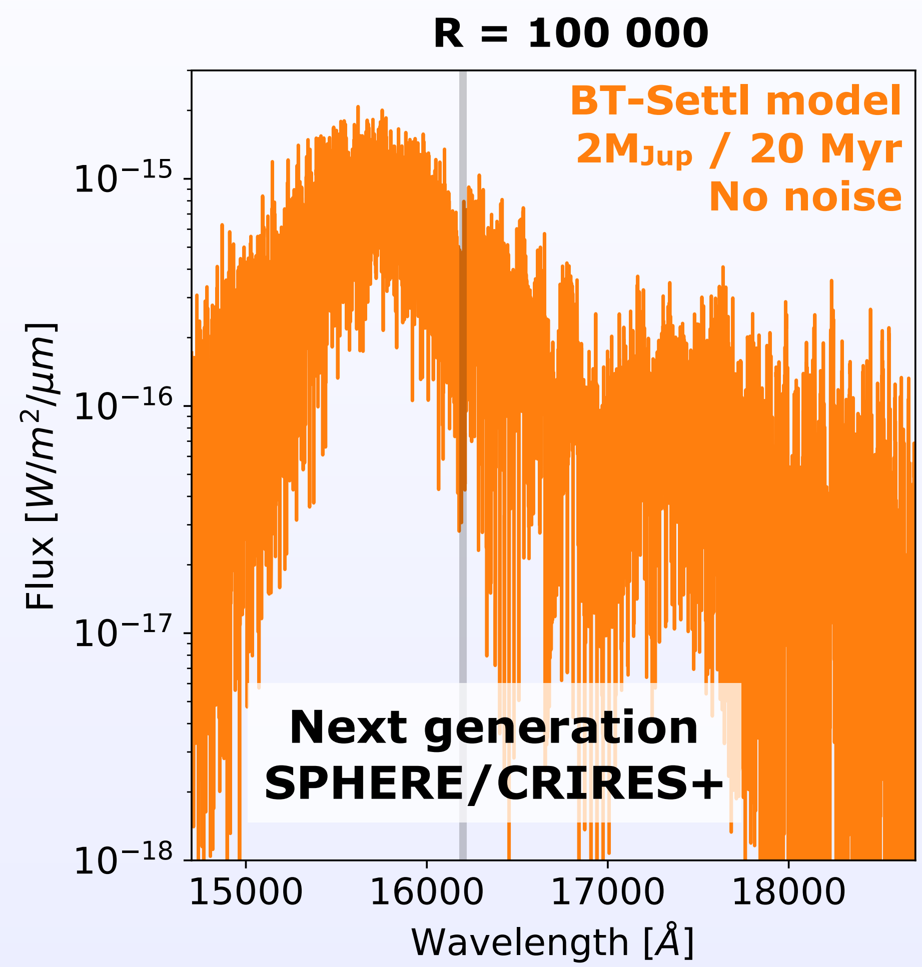
Supported by CRIRES+

New science at high-spectral resolution



HiRISE

Resolution x300 to x2000



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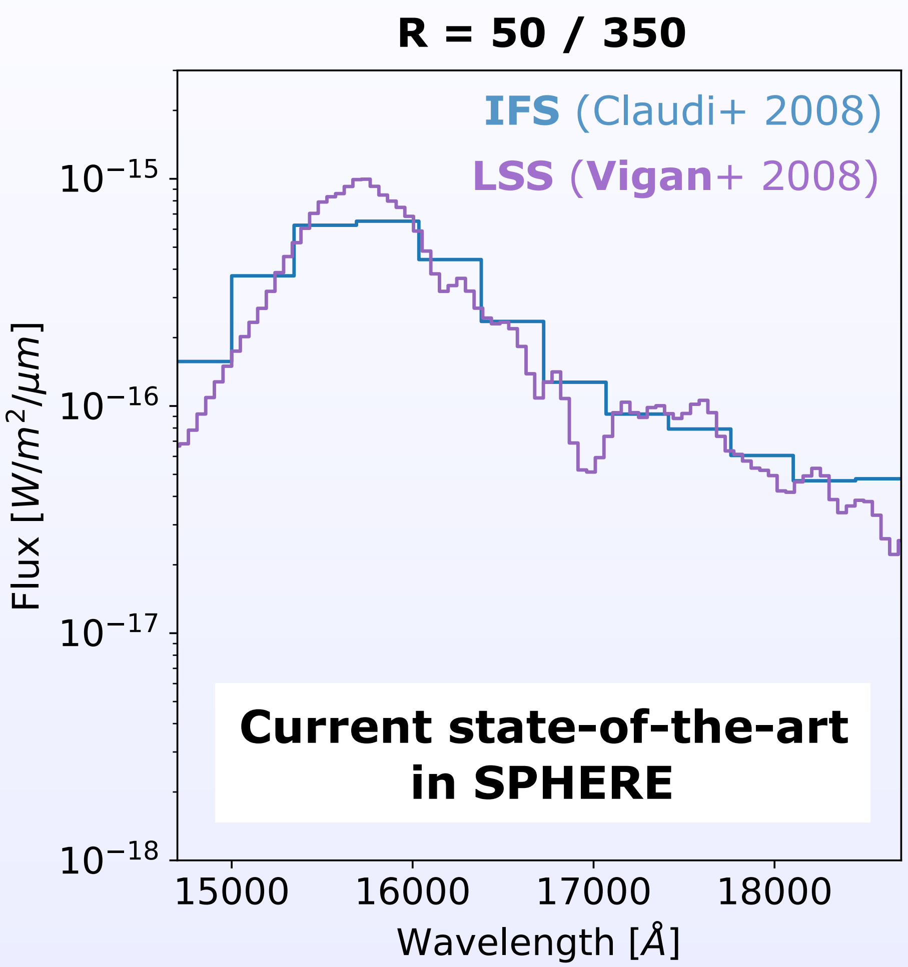

HiRISE

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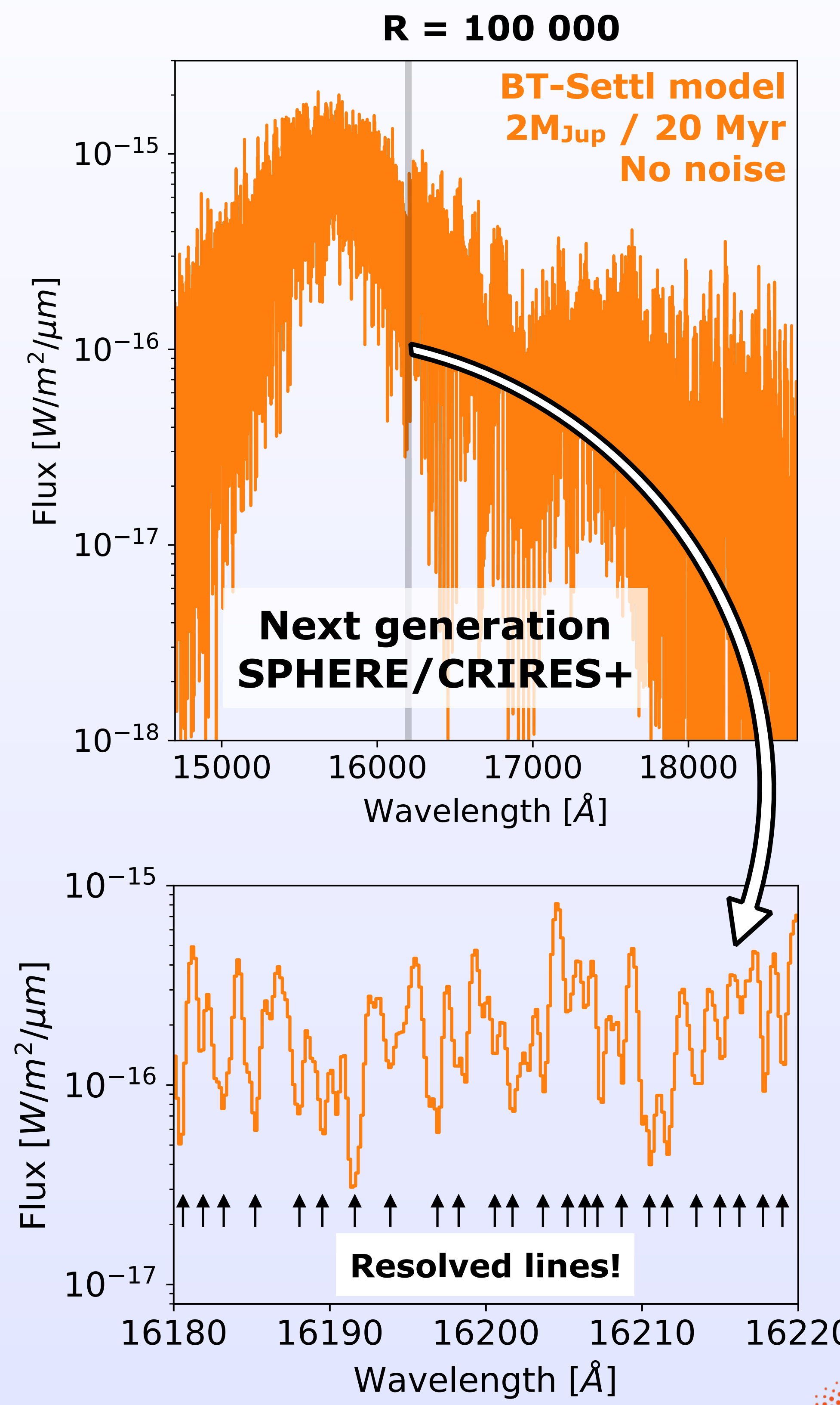
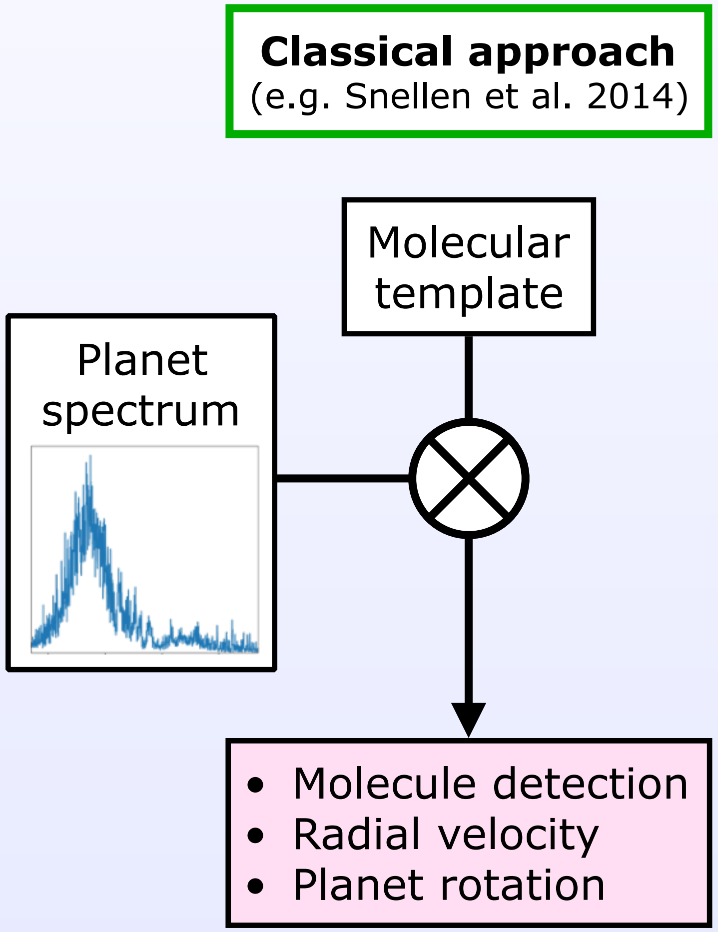


New science at high-spectral resolution

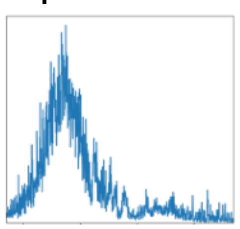


New science at high-spectral resolution

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

Molecular template

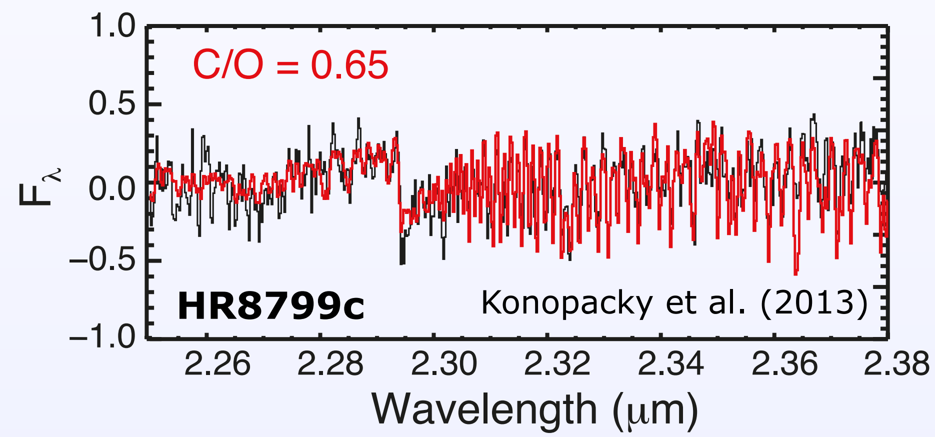
Planet spectrum



- Molecule detection
- Radial velocity
- Planet rotation

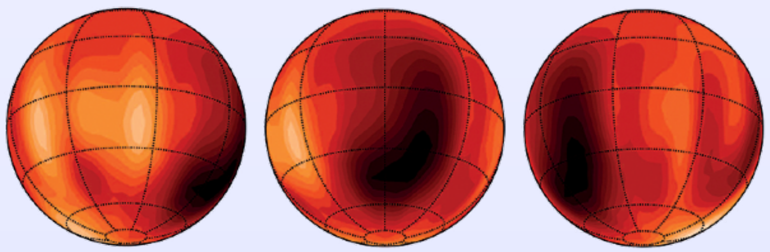
Molecular lines shape

Abundances determination



- formation scenario
- migration in the disk
- detailed composition

Time-resolved Doppler imaging



Luhman 16B (Crossfield et al. 2014)

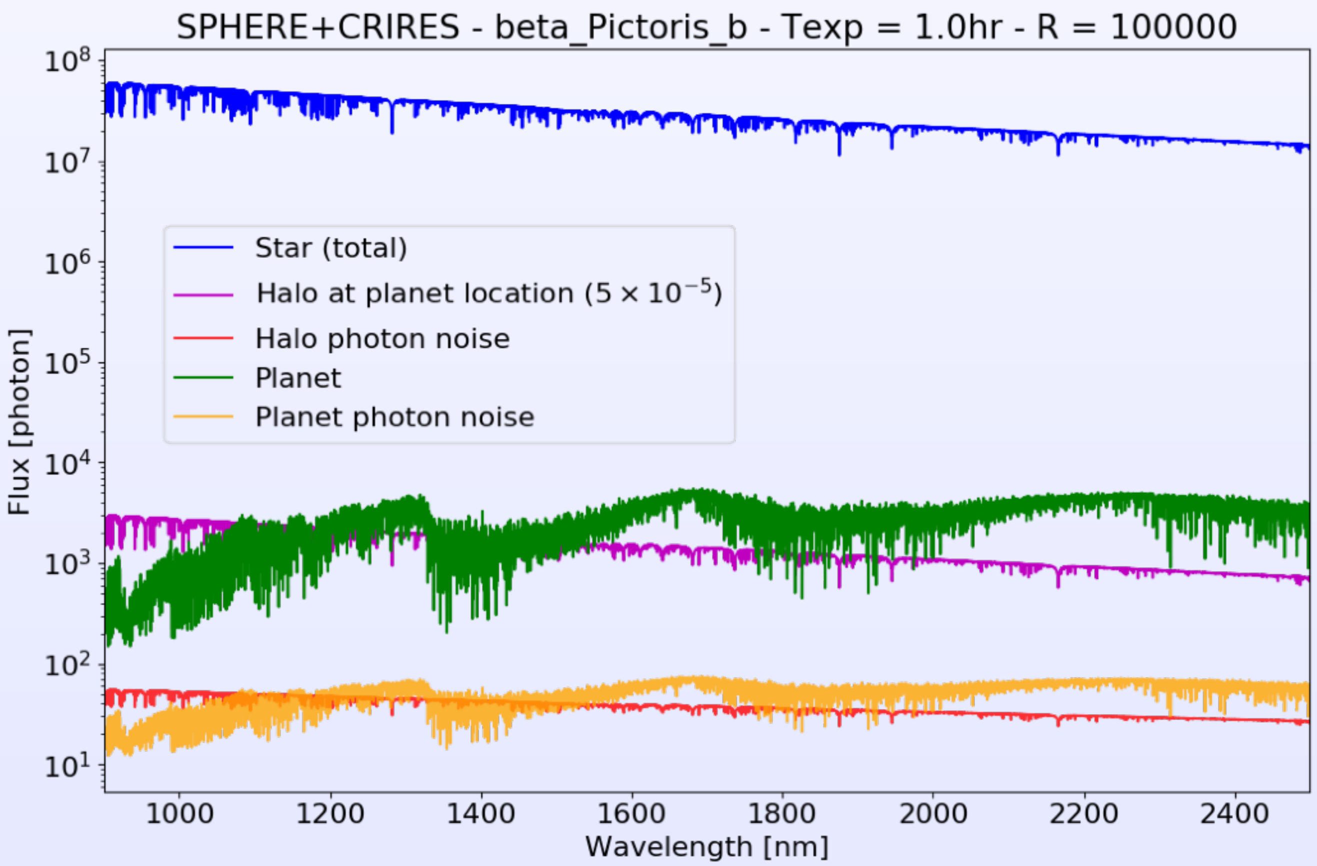
- rotational period
- temporal variability
- cloud and winds

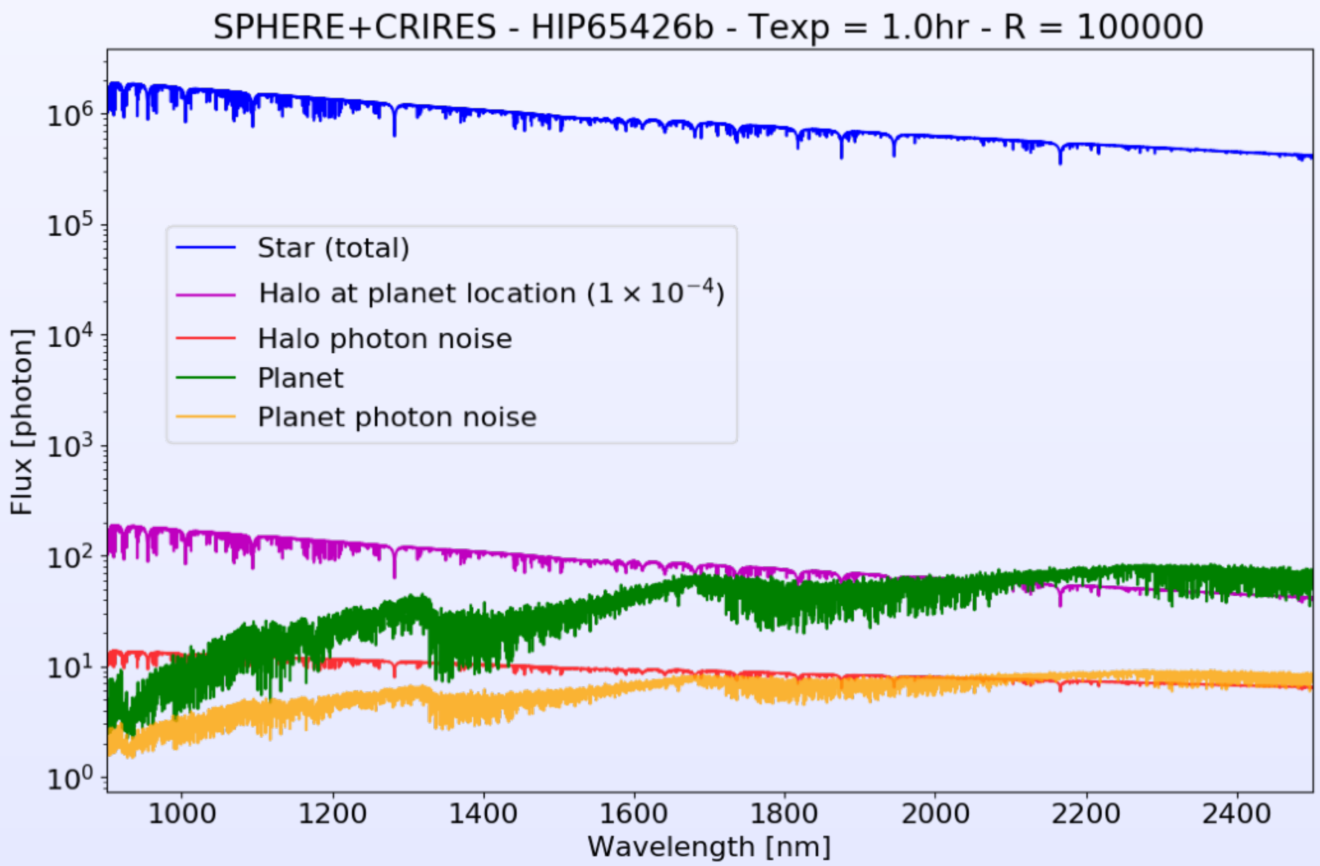
Preliminary simulations

- BT-NextGen model for the star
- BT-Settl model for the planet
- Magnitudes from the literature

- Texp = 1 hr
- $R=10^5$
- no spectral binning
- Realistic values for transmission

	Transmission
SPHERE	15 %
Injection	70 %
Fiber	99 %
CRIRES+	15 %



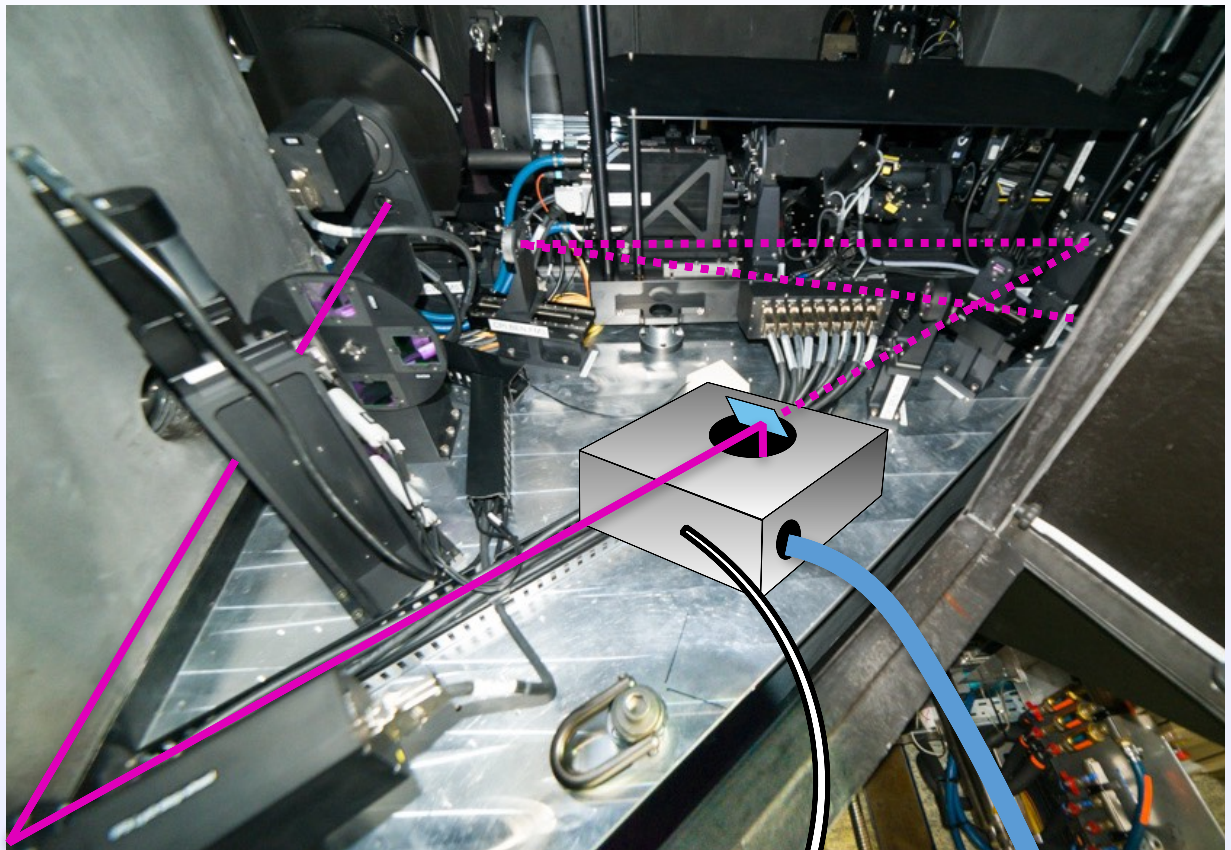


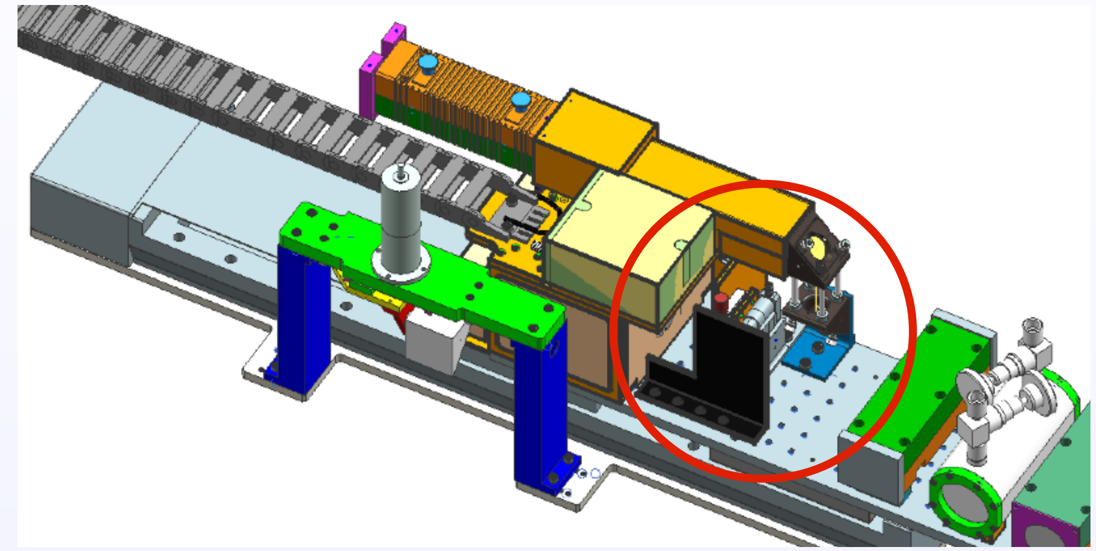
>1000 photon/channel
SNR > 100

>100 photon/channel
SNR > 10

A prototype fiber injection in SPHERE

SPHERE near-infrared arm





CRIRES+ calibration unit stage

Fiber link

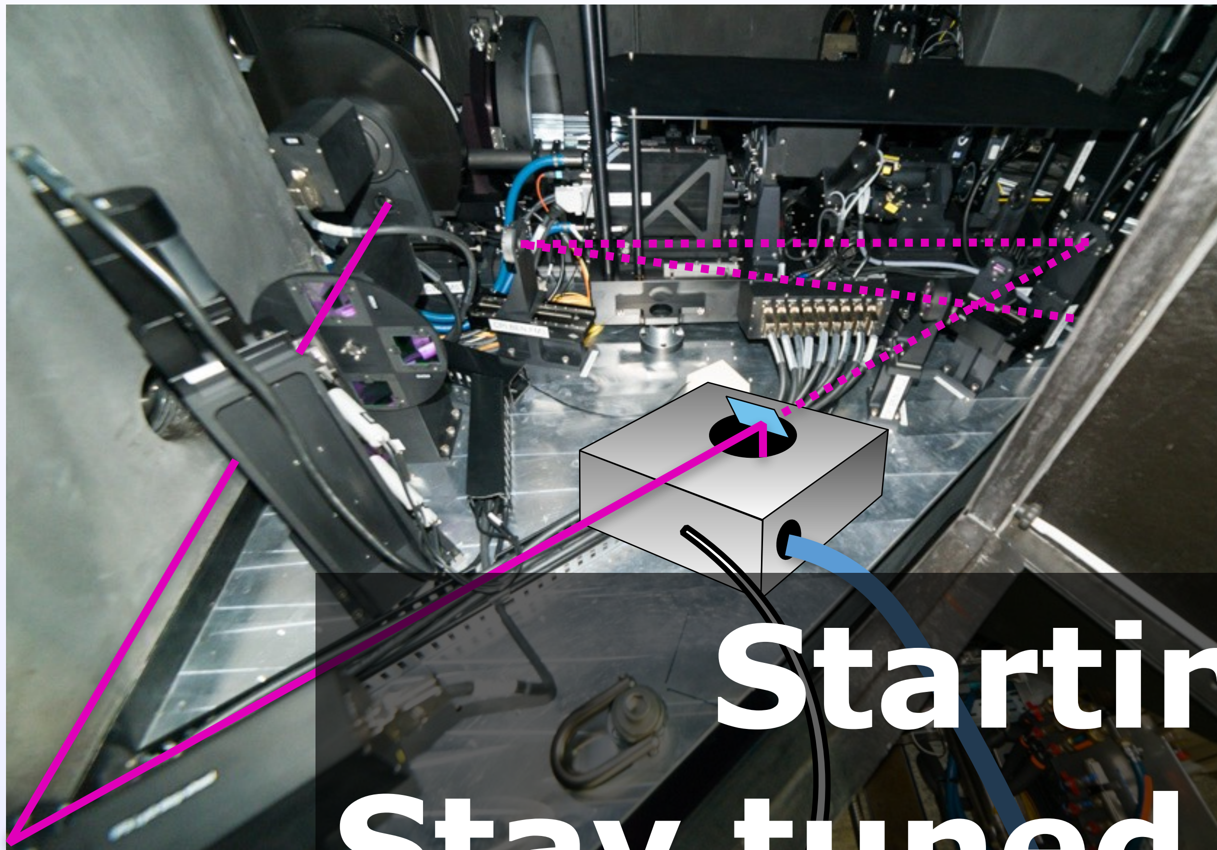
Fiber injection unit

↓

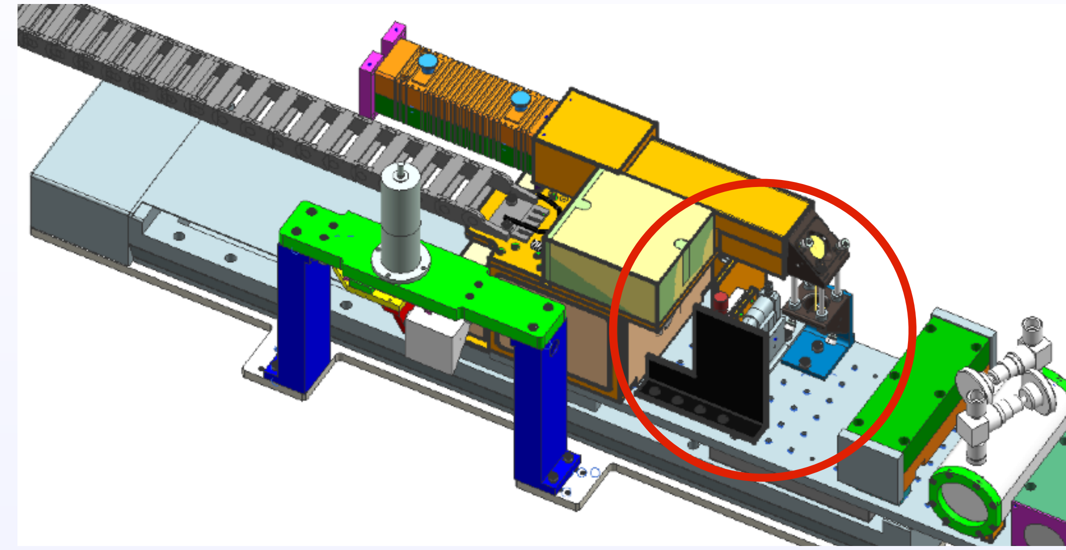
No show-stopper for implementation

A prototype fiber injection in SPHERE

SPHERE near-infrared arm



CRIRES+ calibration unit stage



Fiber entrance **already available** in CRIRES+

Starting now
Stay tuned for results!

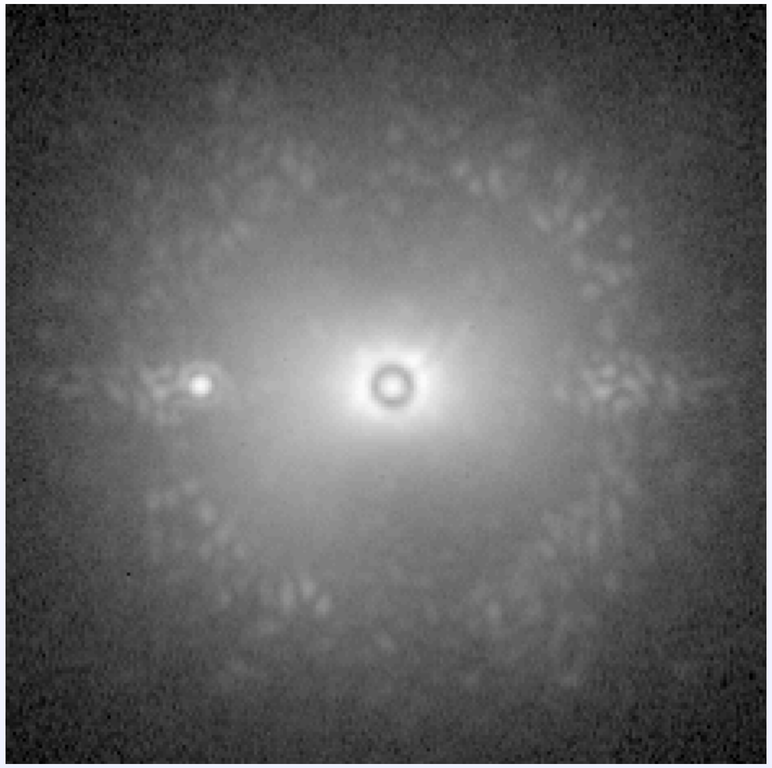
Fiber injection unit

No show-stopper for implementation

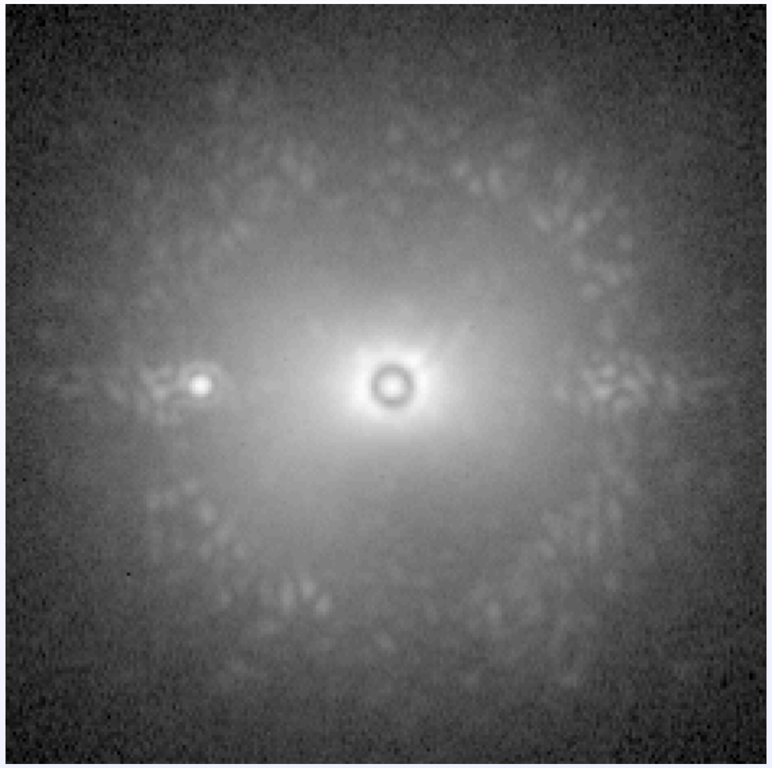
Fiber link

Other updates

- Many other ideas in the pipeline
- Adaptive optics:
  - NCPA correction
  - faster turbulence correction: factor 2 to 4 increase
  - infrared pyramid WFS
  - improved predictive control
- Coronagraphy:
  - better IWA: vortex? other?
- Science:
  - HRS coupling in NIR with CRIRES+ or dedicated spectro
  - HRS coupling in VIS with ESPRESSO
  - new ZIMPOL optimised for fainter targets?
- ...



Other updates



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Upgrade path under study. Again, stay tuned...

Conclusions

Conclusions

1. SPHERE

- powerful and versatile instrument
- benefit from a great ExAO system and 3 complementary science instruments

2. SHINE

- 400-600 stars survey over 5 years
- 2/3 of the survey done, 1 planet
- many, many, many disk results + some companions characterisation

3. SPHERE upgrades

- NCPA calibration and compensation with ZELDA
- HRS coupling with CRIRES+
- many other upgrades in the pipeline, include AO