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

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

SPHERE

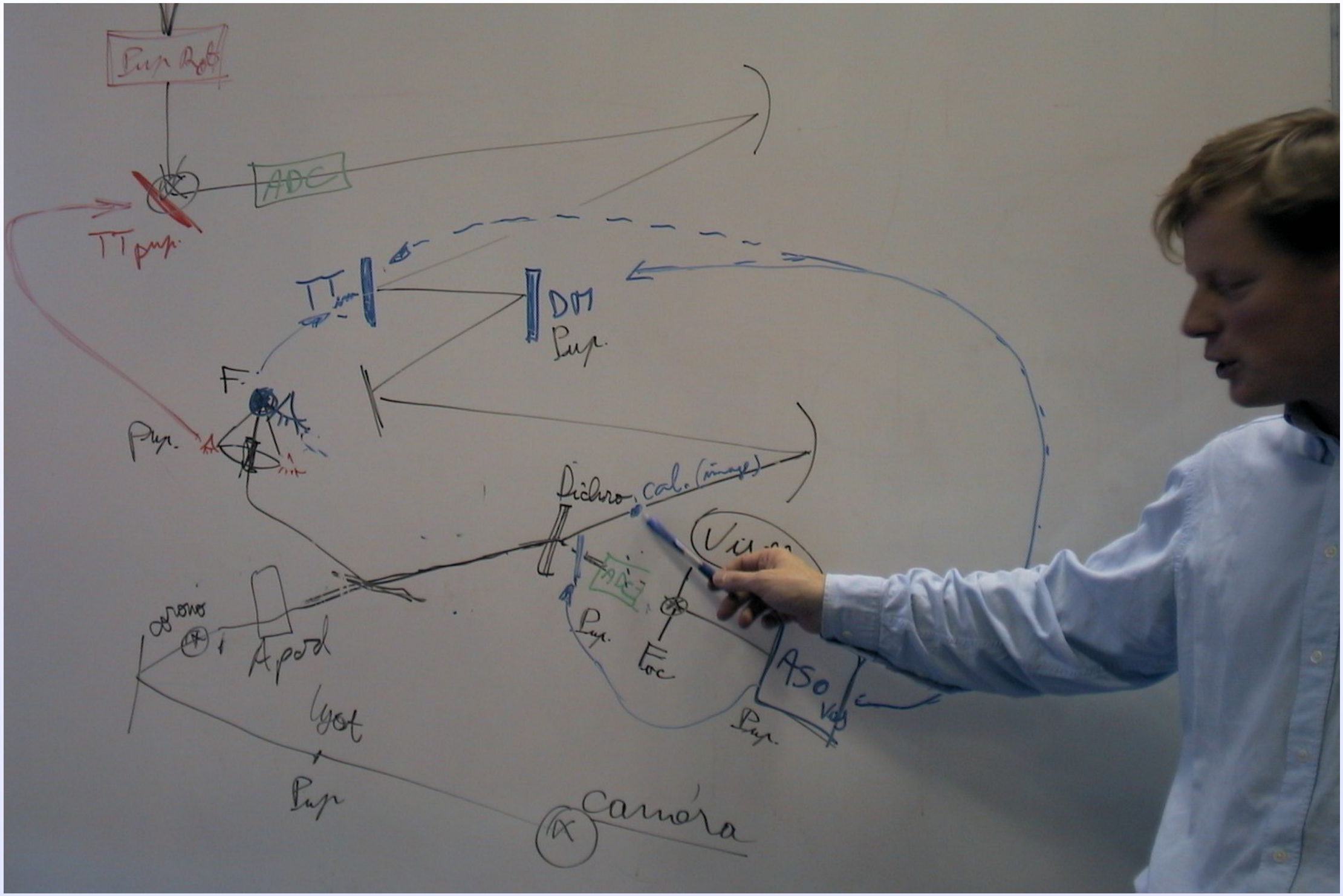
J.-L. Beuzit (PI), M. Feldt (Co-PI), D. Mouillet (PS), P. Puget (PM), K. Dohlen (SE), F. Wildi (AIT), T. Fusco (AO), M. Kasper (ESO responsible), Z. Wahhaj (current ESO IS) and numerous participants from 12 European institutes!

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!

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”

Fore optics

Extreme AO

Vis Coronagraph

ZIMPOL

IFS

IRDIS

NIR Coronagraph

Common Path

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

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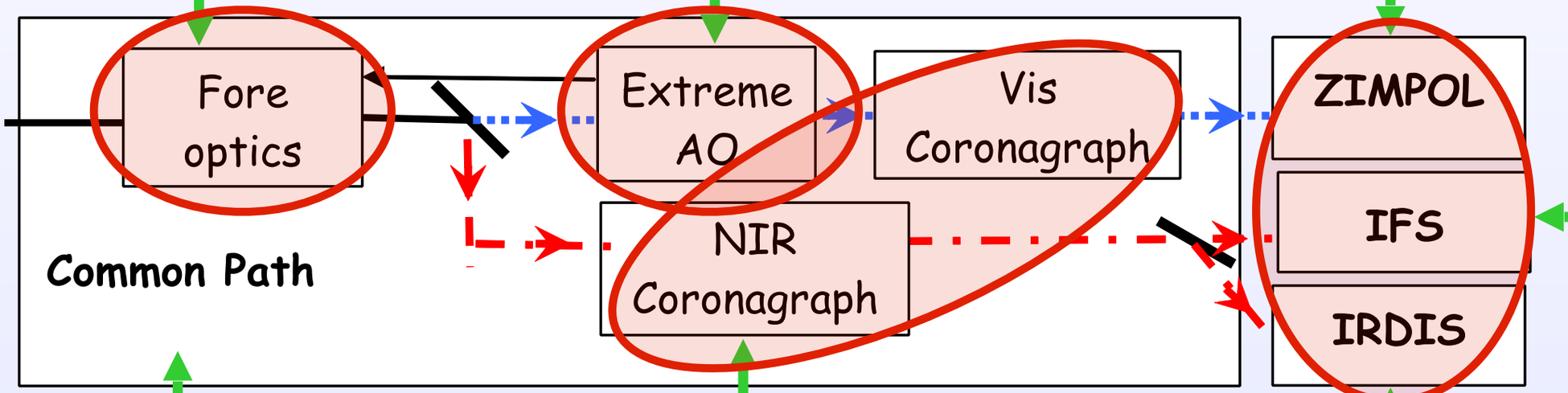

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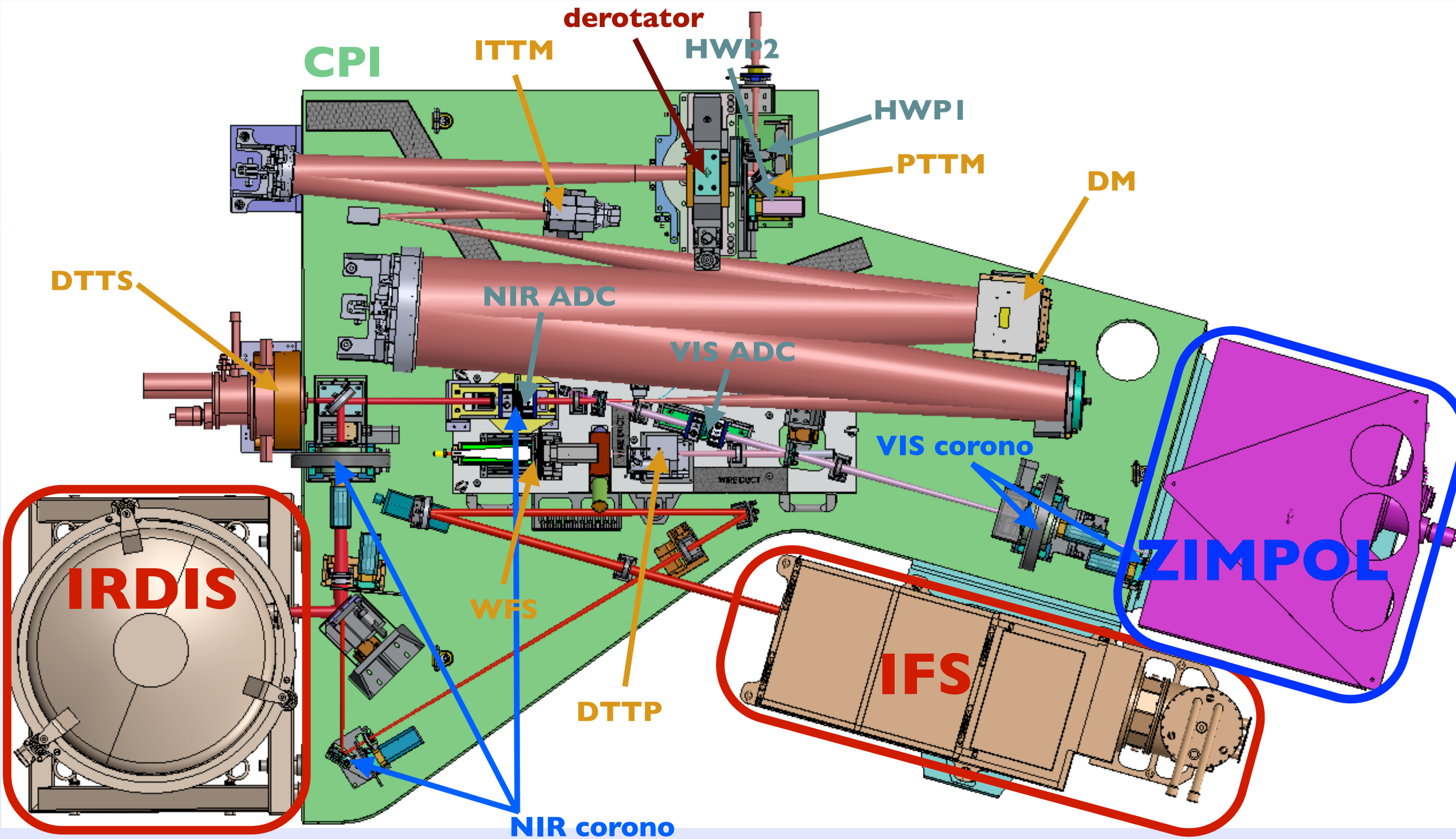
Implementation



2011-2013: integration in Europe

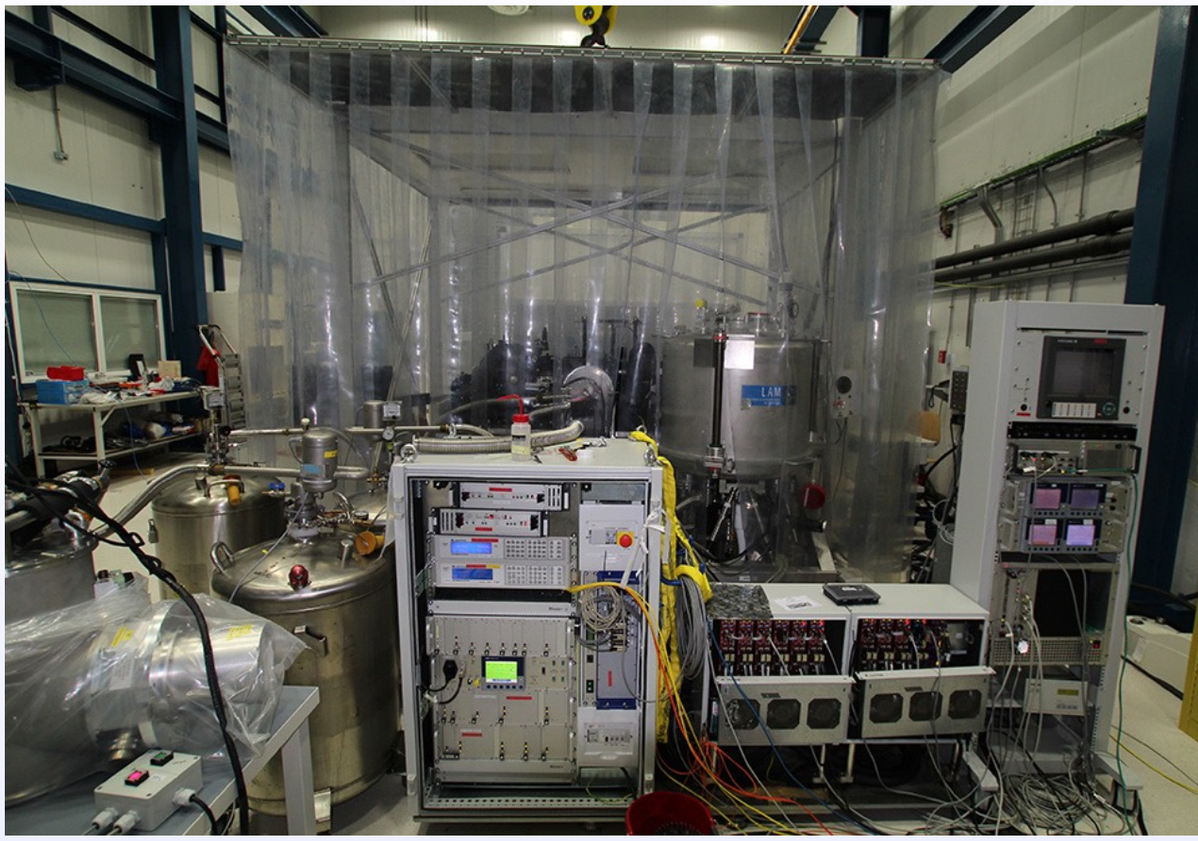
CPI during integrations

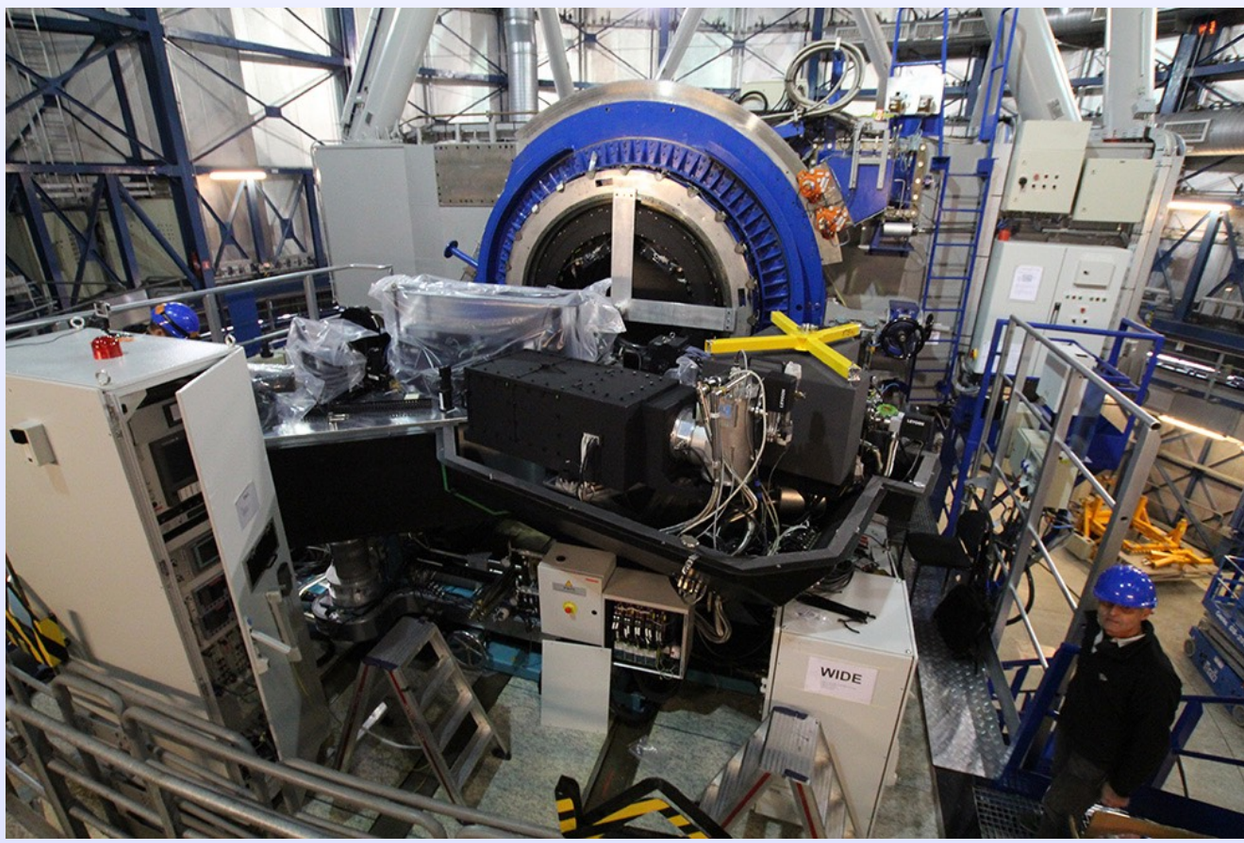
Installation on baseframe

SPHERE completed in 2013

IRDIS cryostat

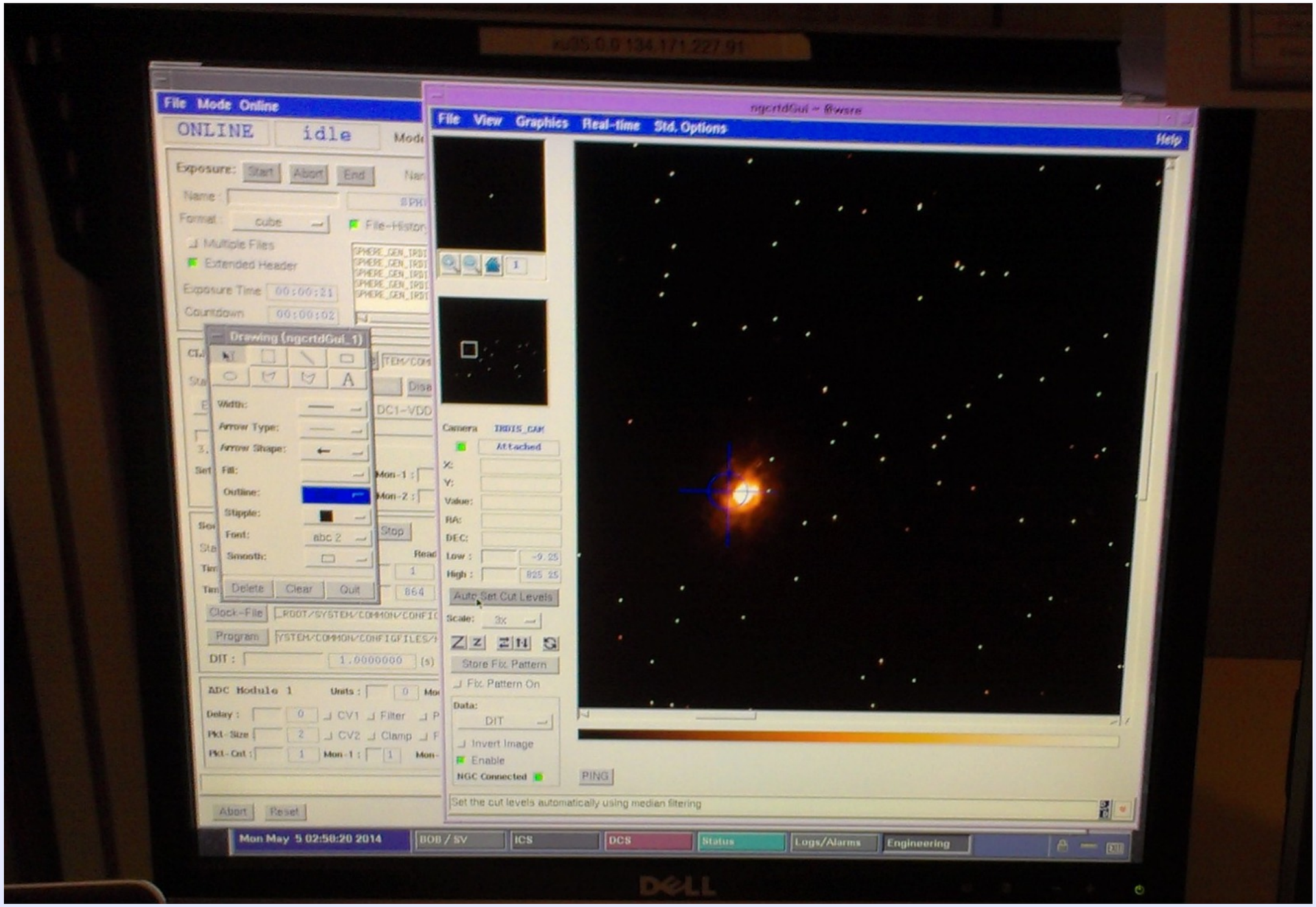
2014: shipment and reintegration





May 2015 @ UT3

May 6th 2014: first light



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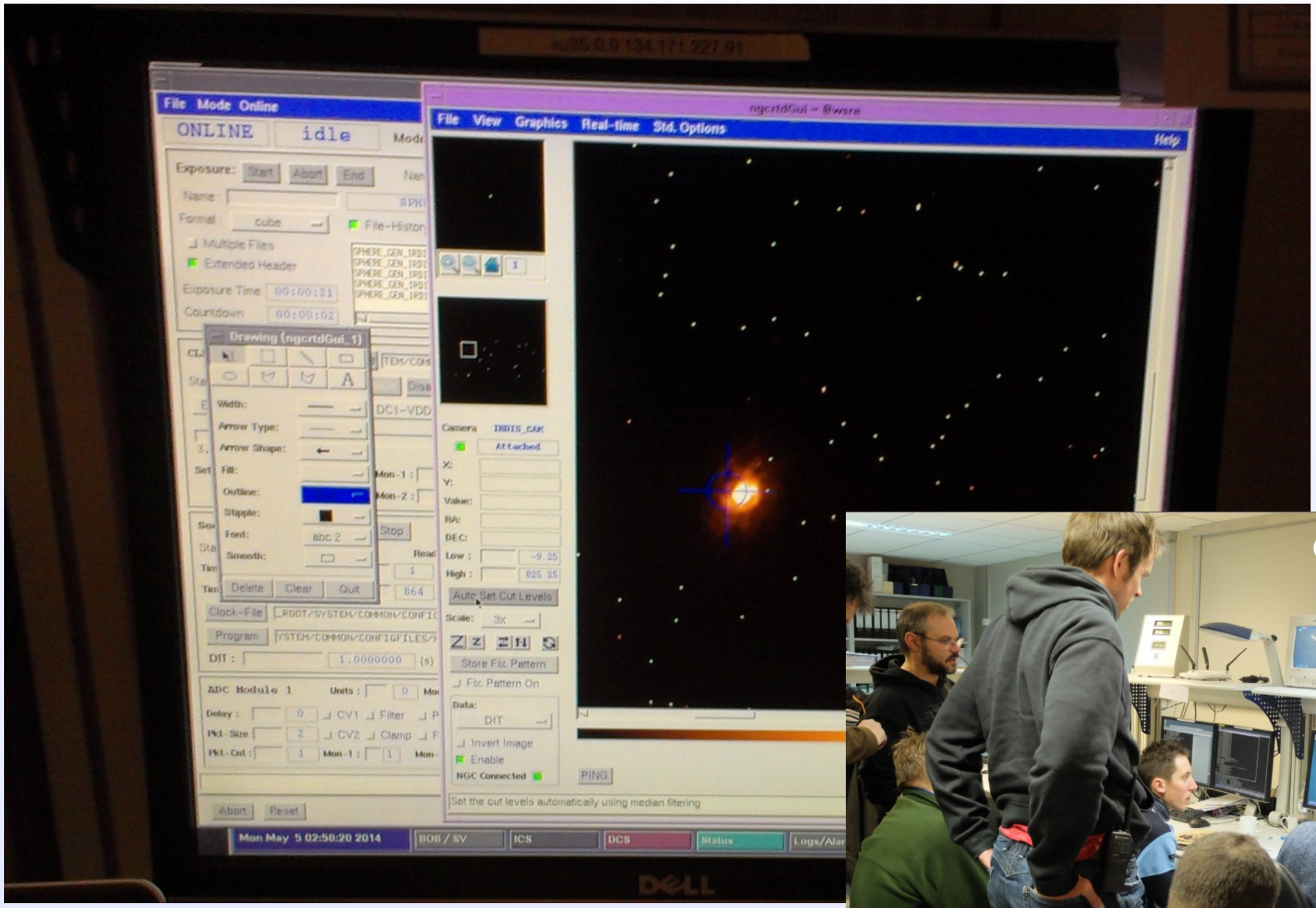
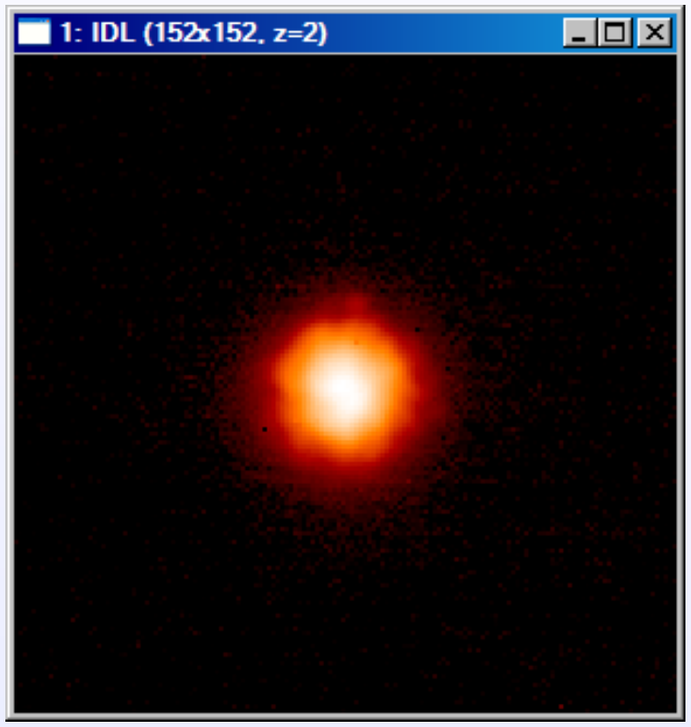
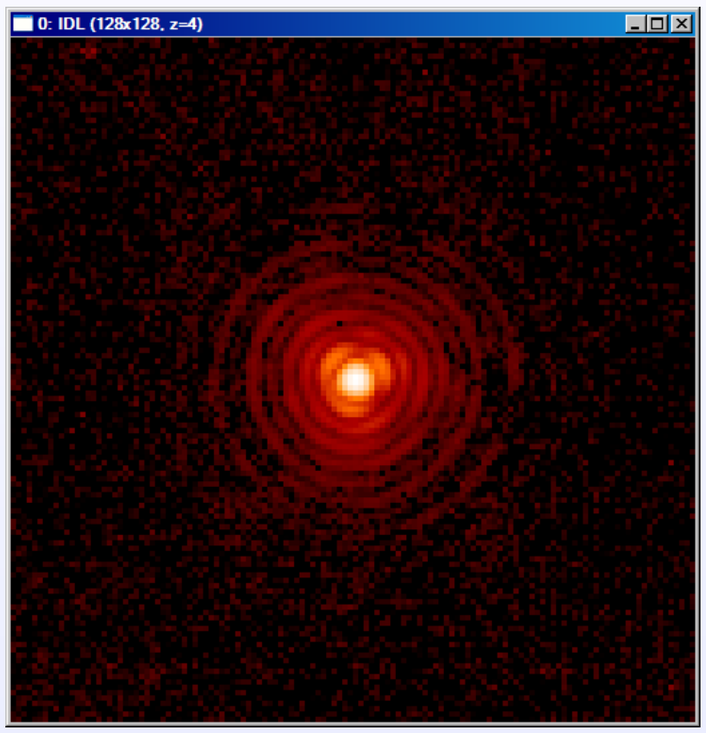


SPHERE asset #1: SAXO

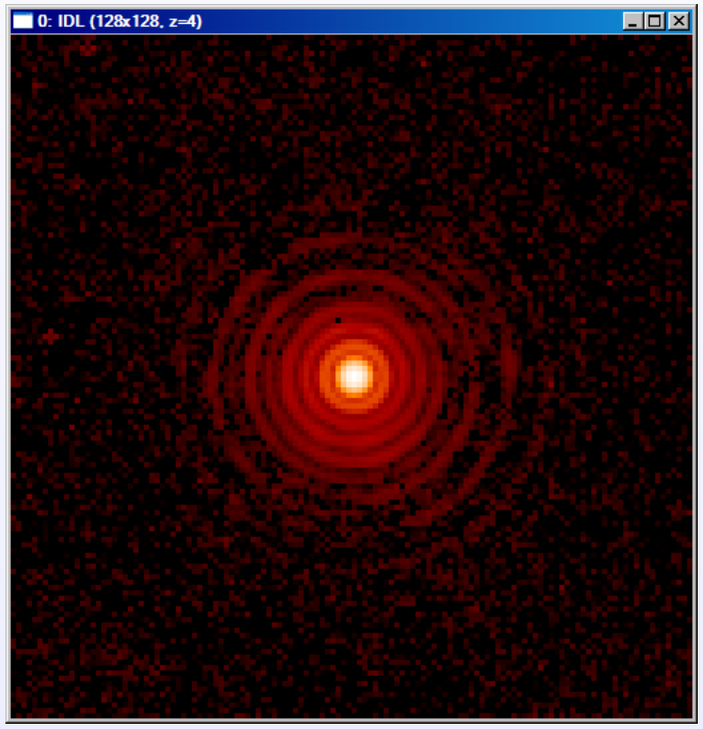
Open loop
Sr = ~5%

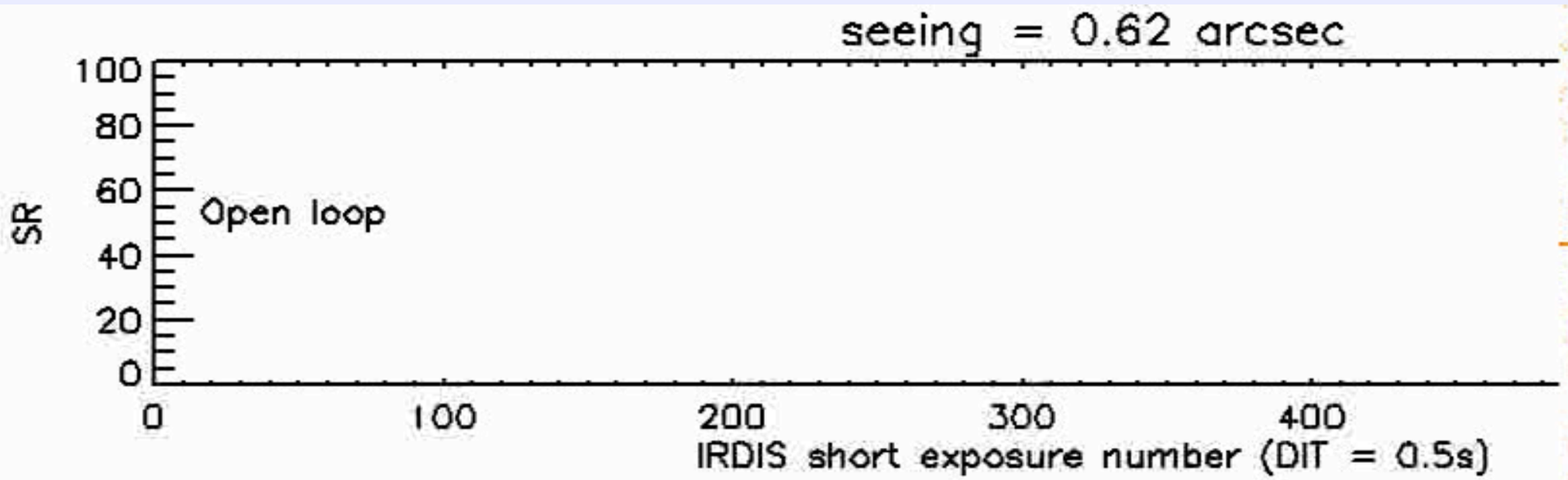


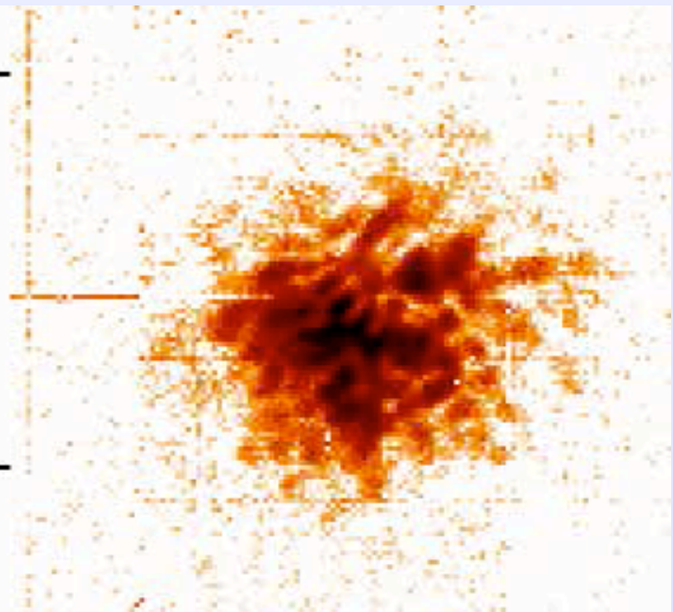
Closed loop
Sr = 85%



Closed loop + NCPA
Sr = 99%







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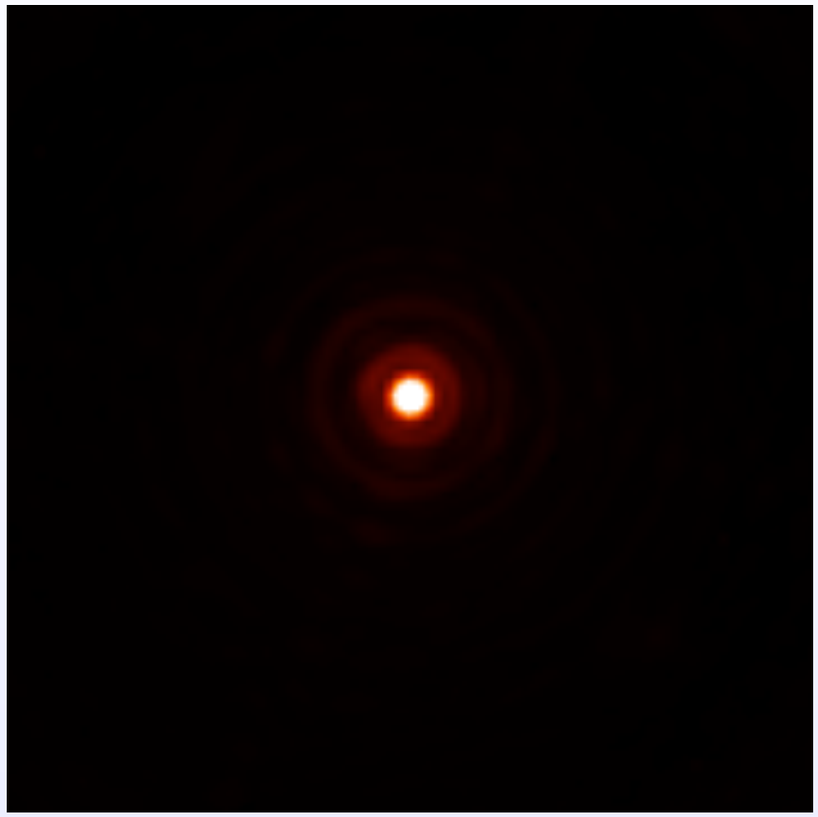
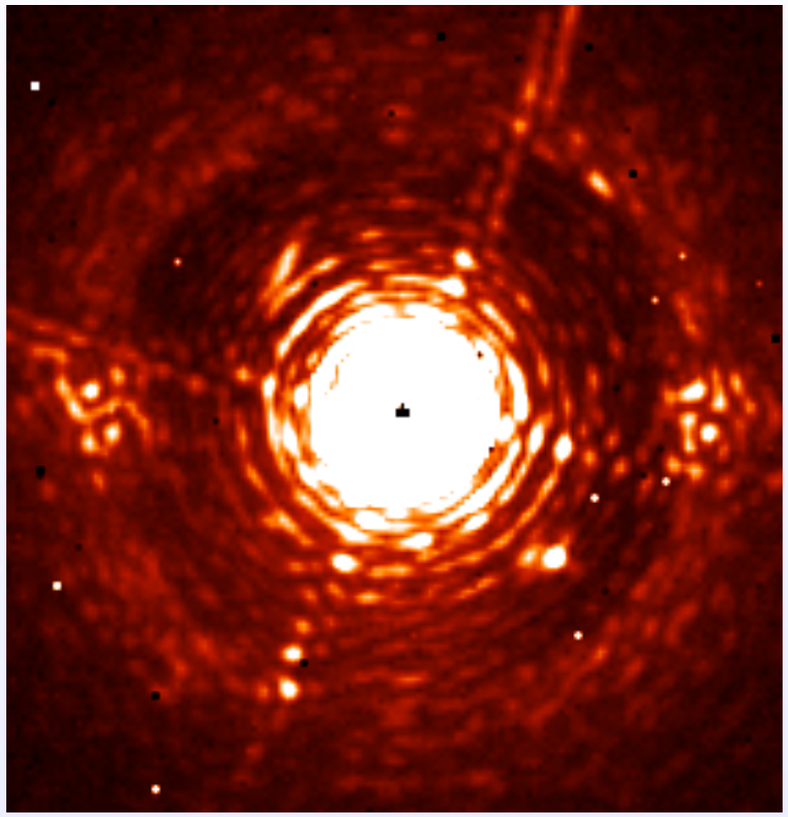
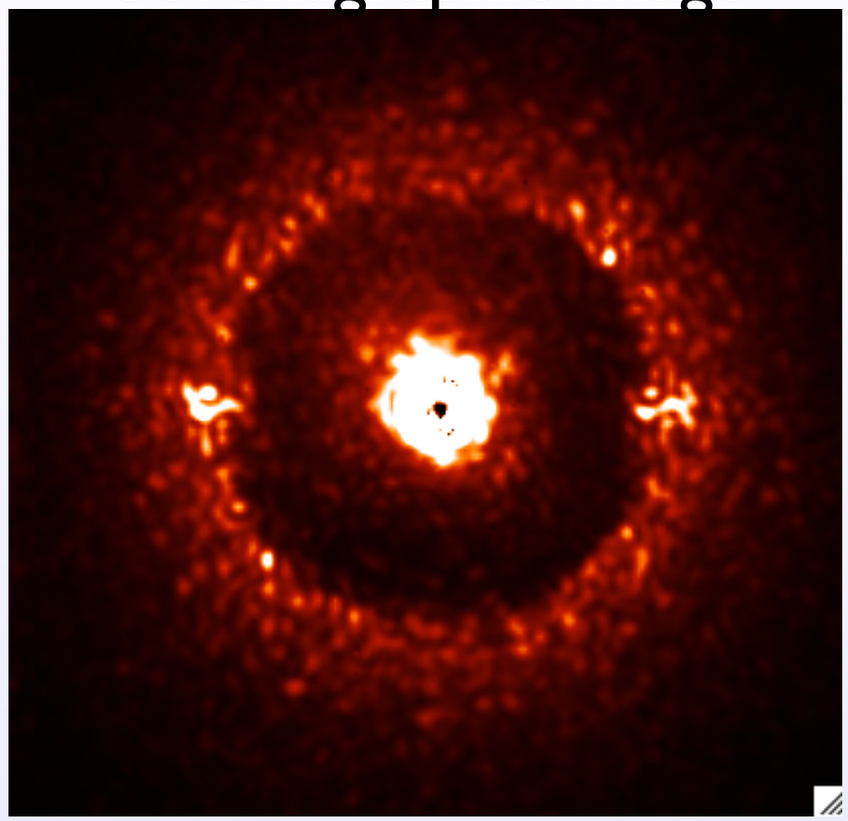
PSF



Saturated PSF



Coronagraphic image



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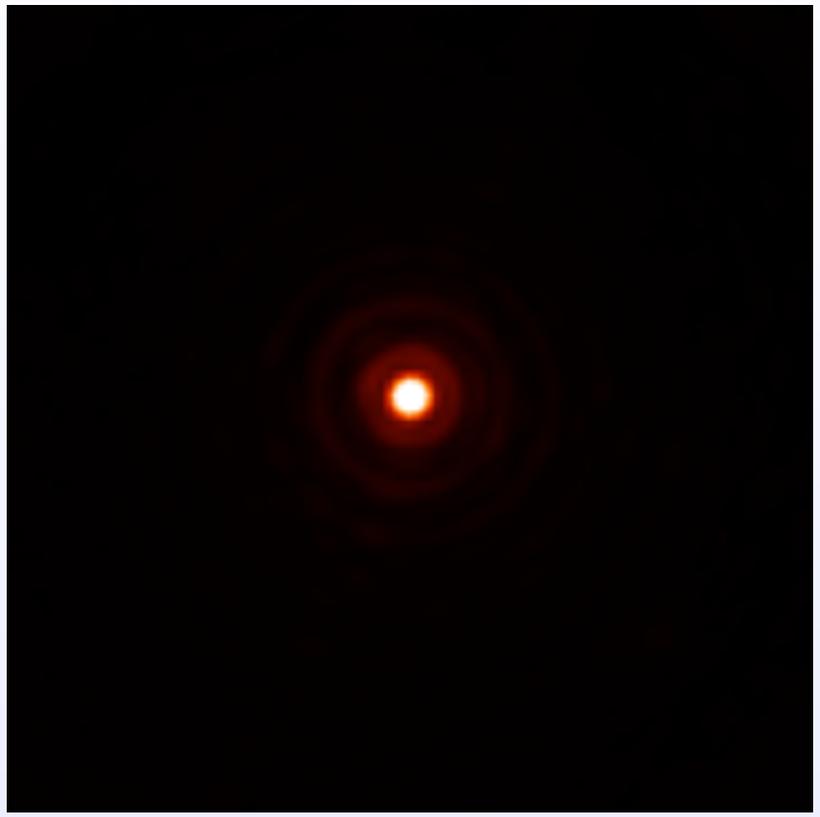

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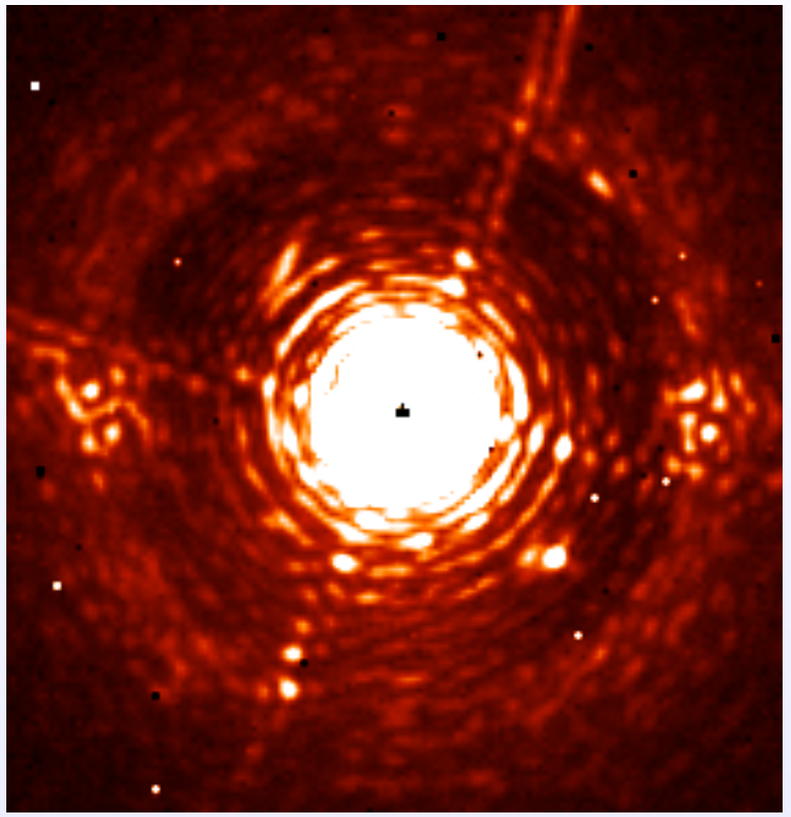

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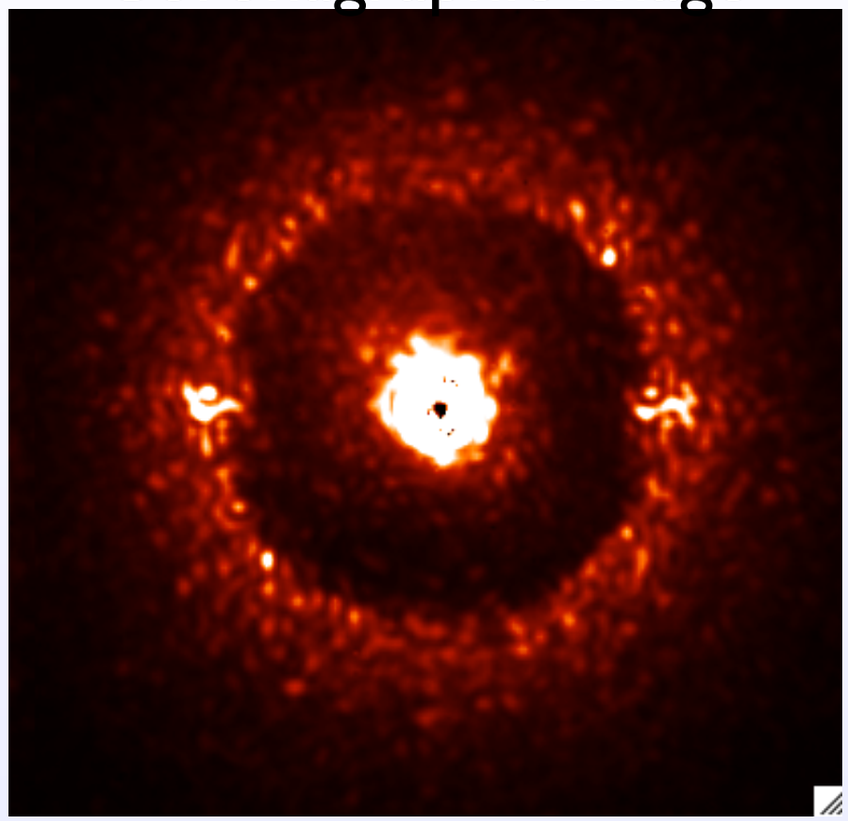
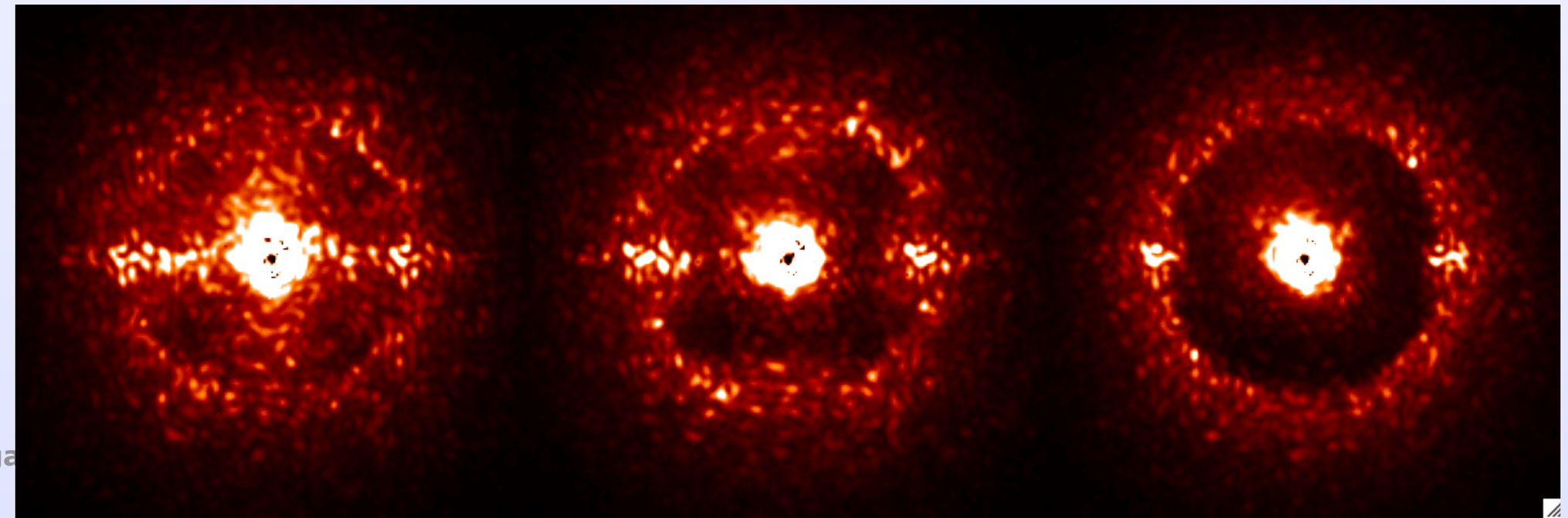
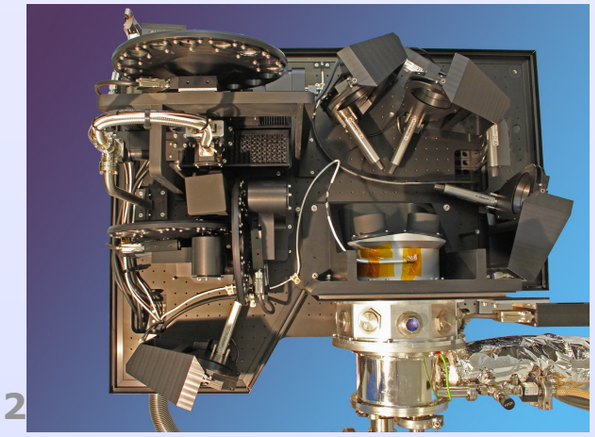


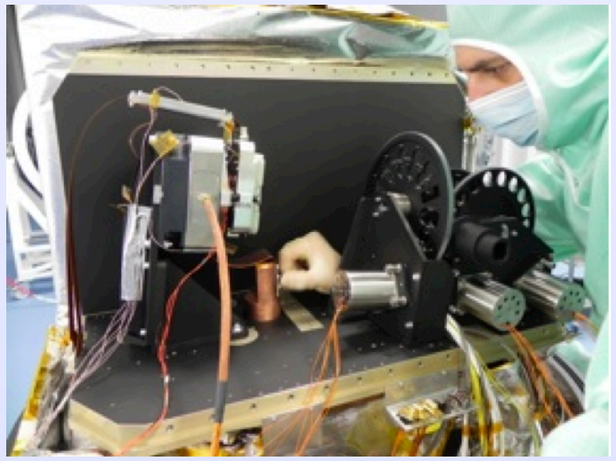
Spatially-filtered Shack-Hartmann for anti-aliasing

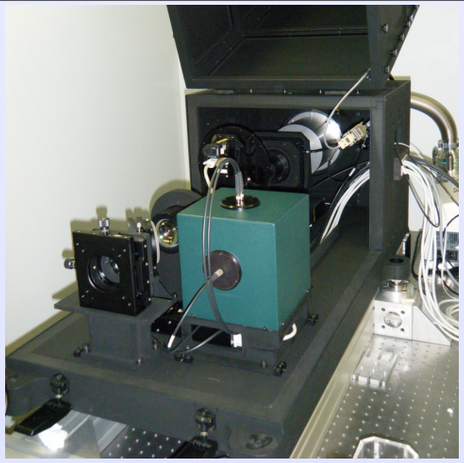


SPHERE asset #2: science instruments

	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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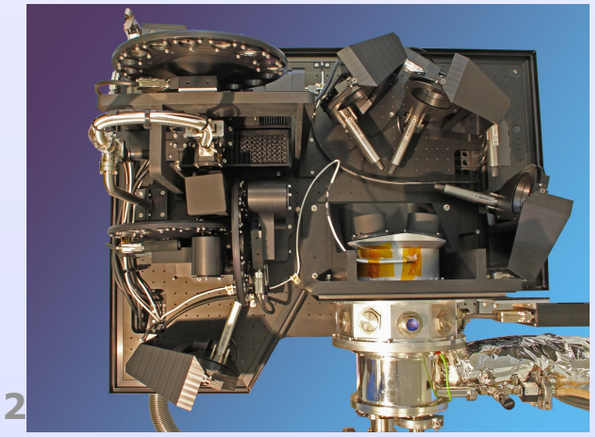
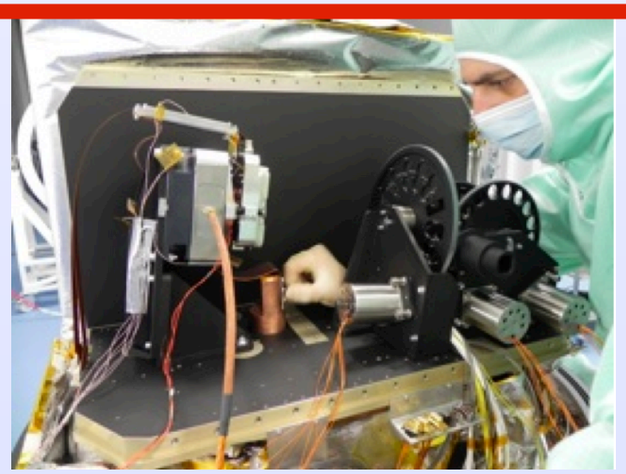
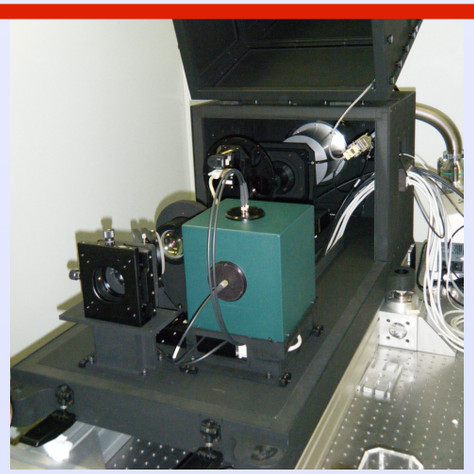
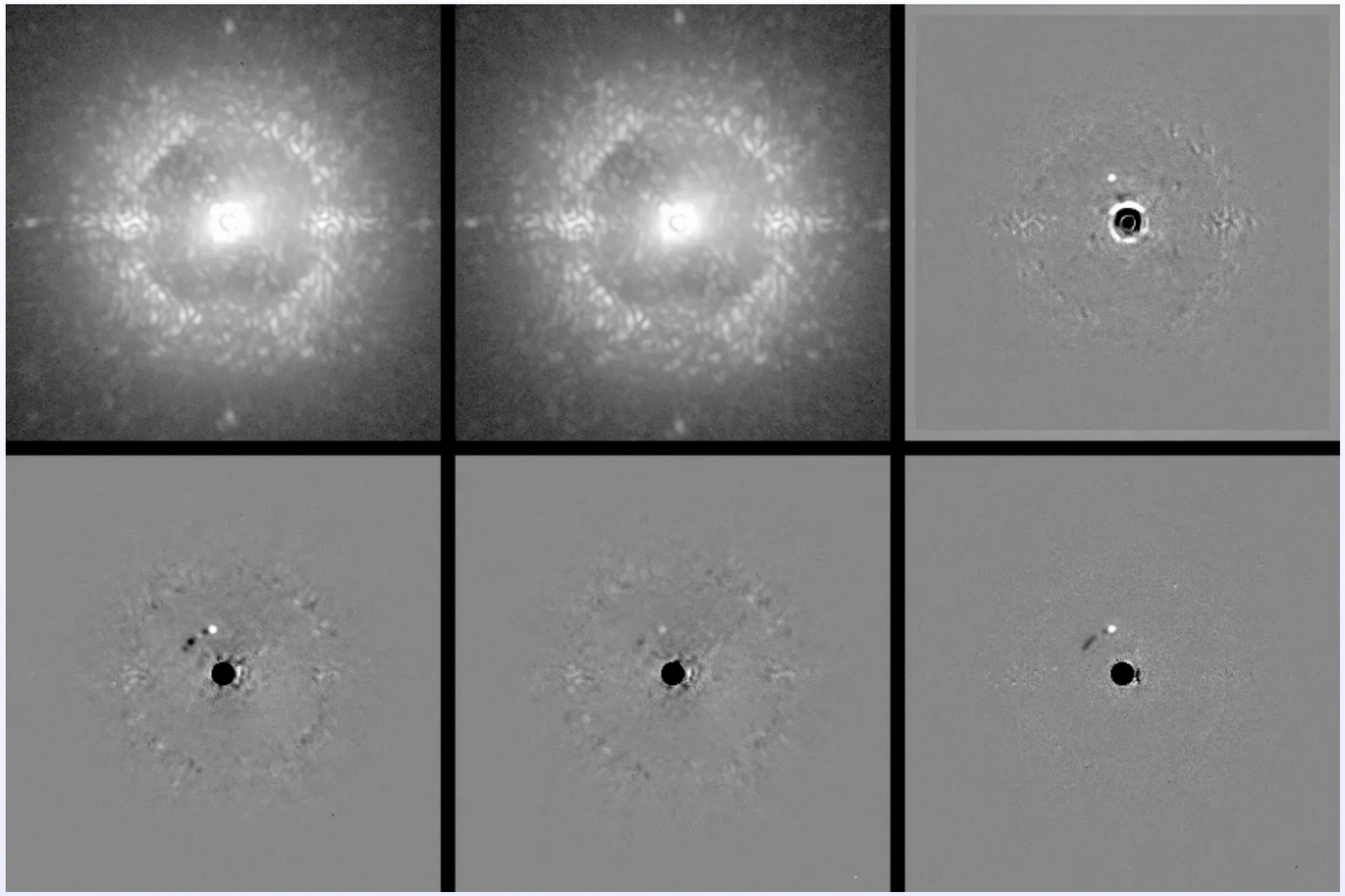




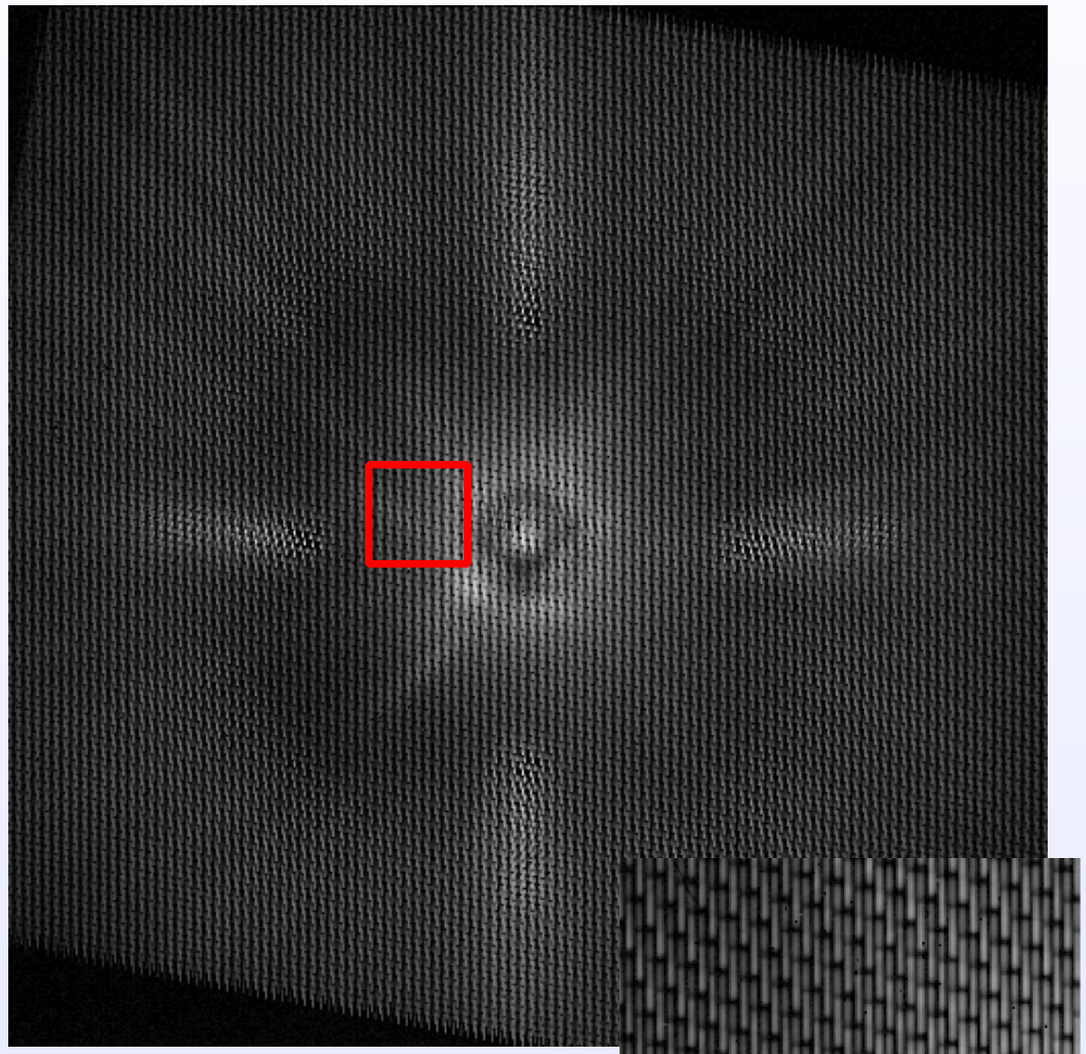


IRDIFS: the exoplanet hunting mode

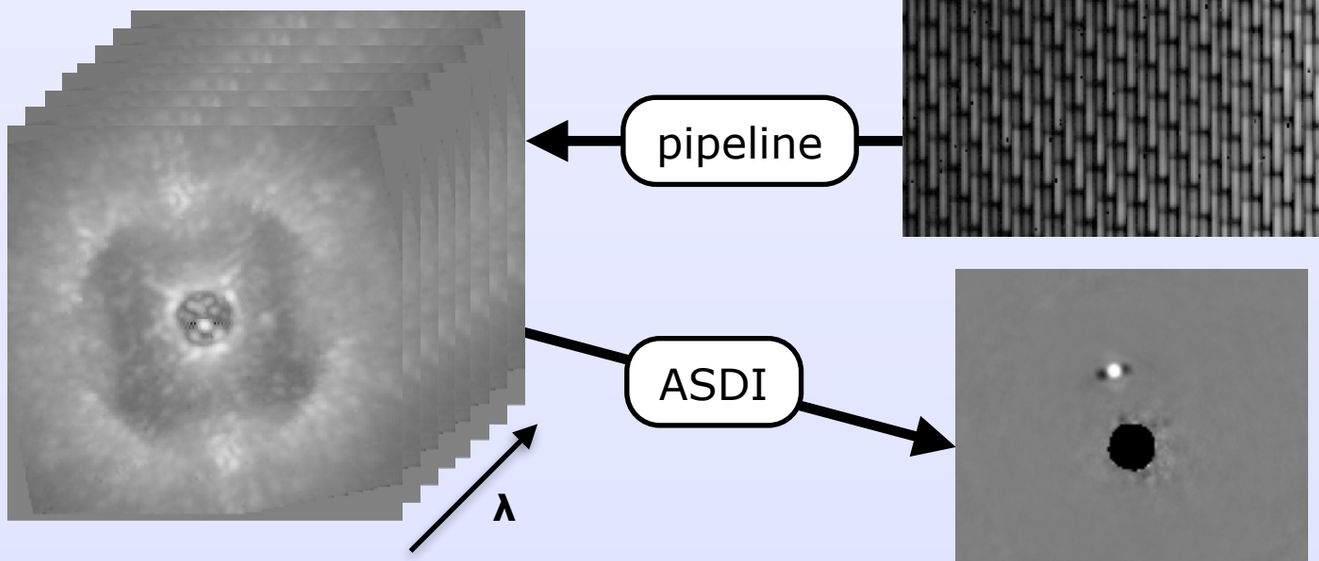
IRDIS



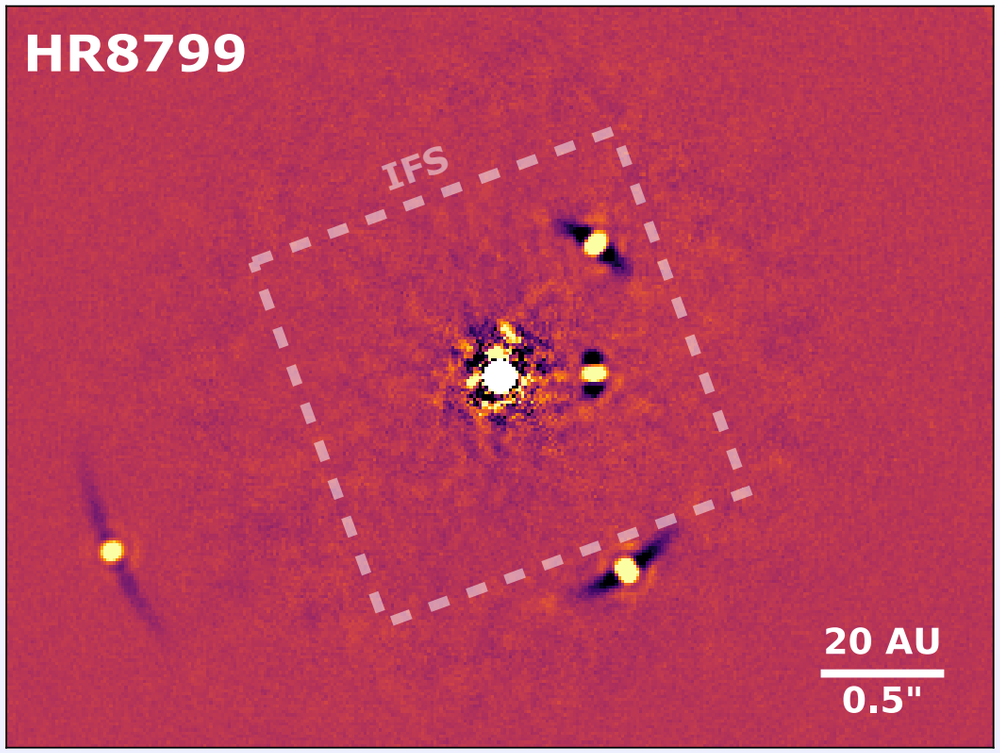
IFS



- 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

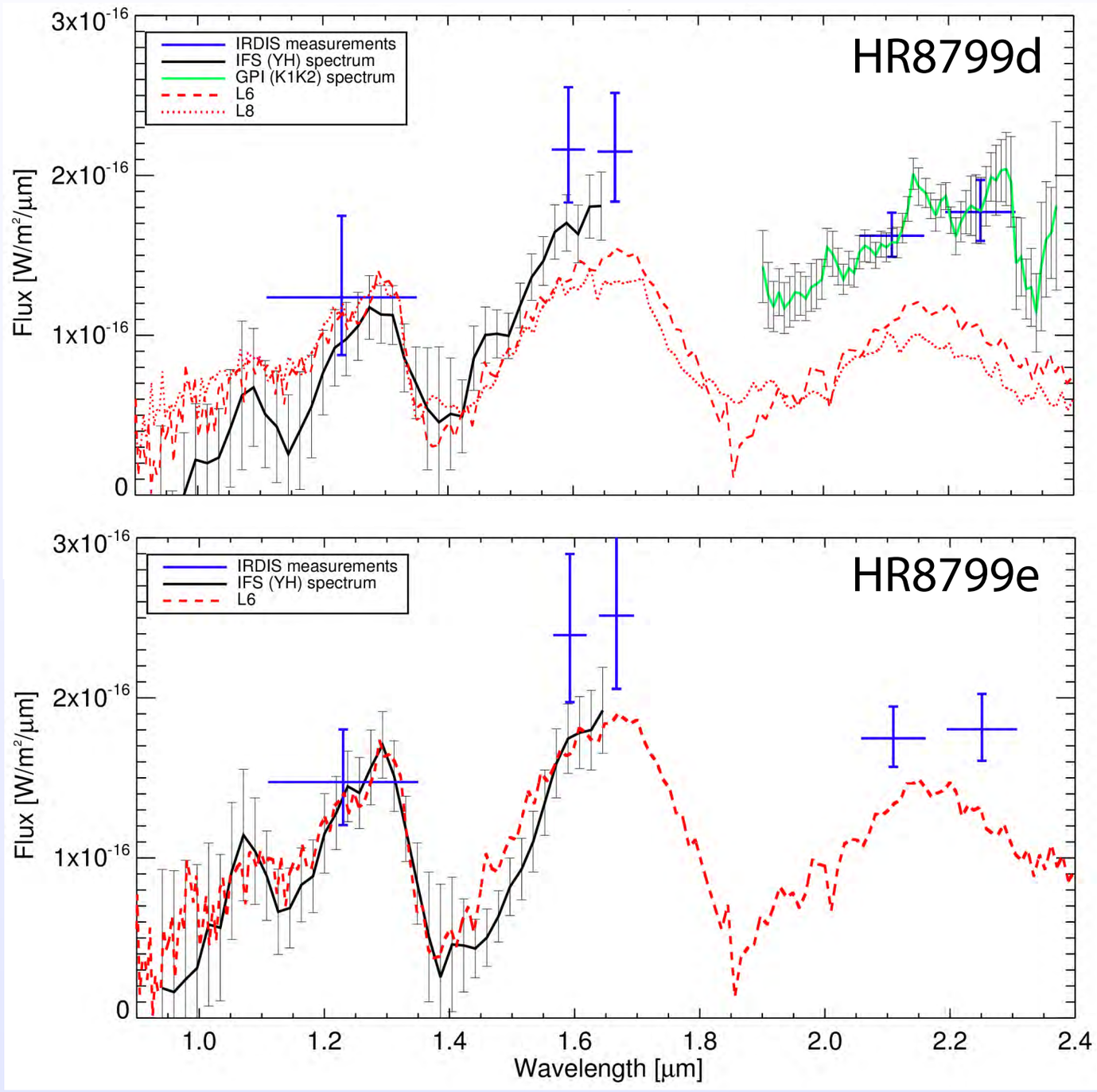


Commissioning & SVT: HR8799



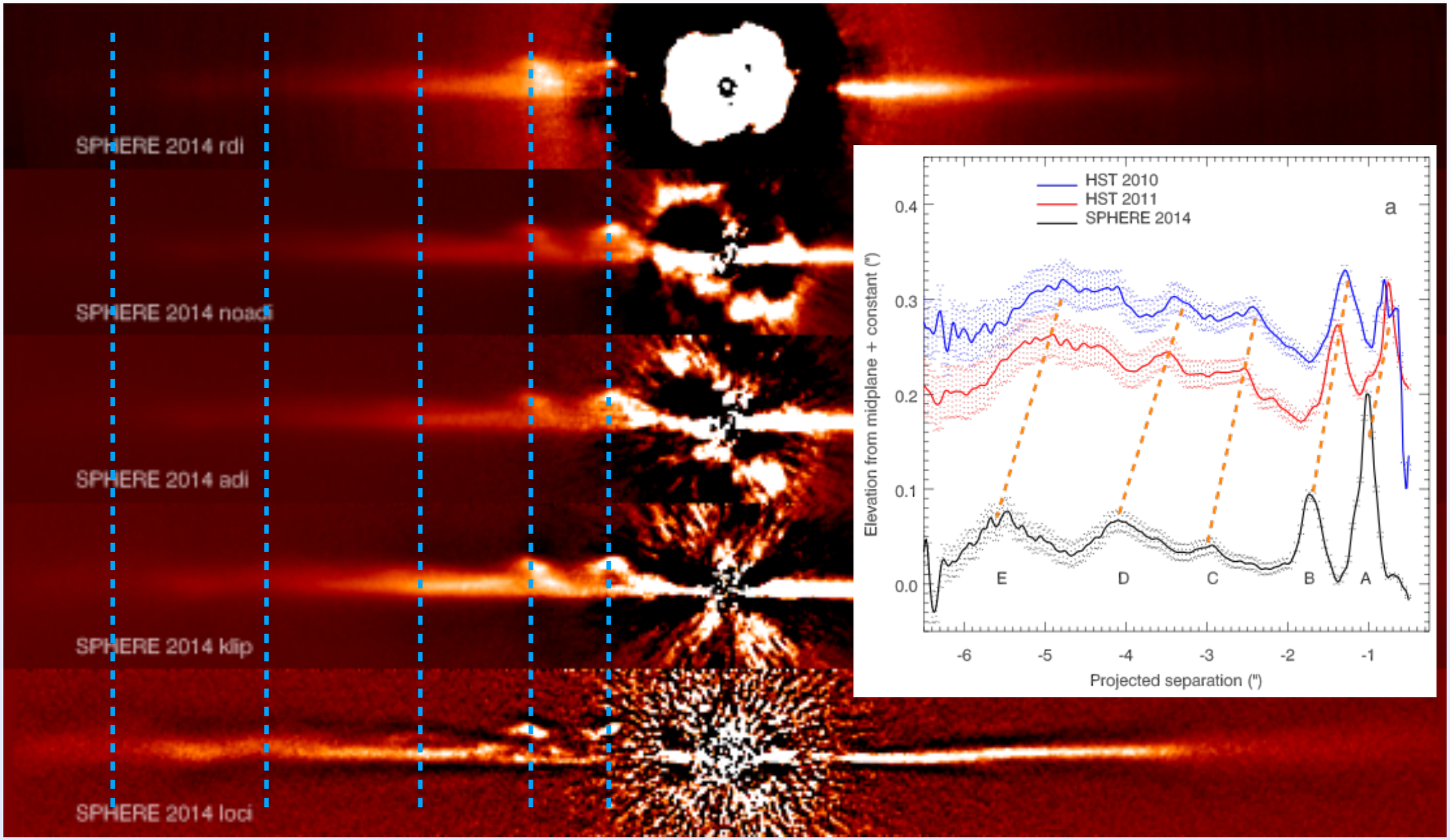
- First spectra for HR8799 c, d
- Spectral types ~L6-L8
- Redder colors than field BD and models
- Reddening well reproduced by submicron grains made of corundum, iron, enstatite, or forsterite

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



Commissioning & SVT: AU Mic

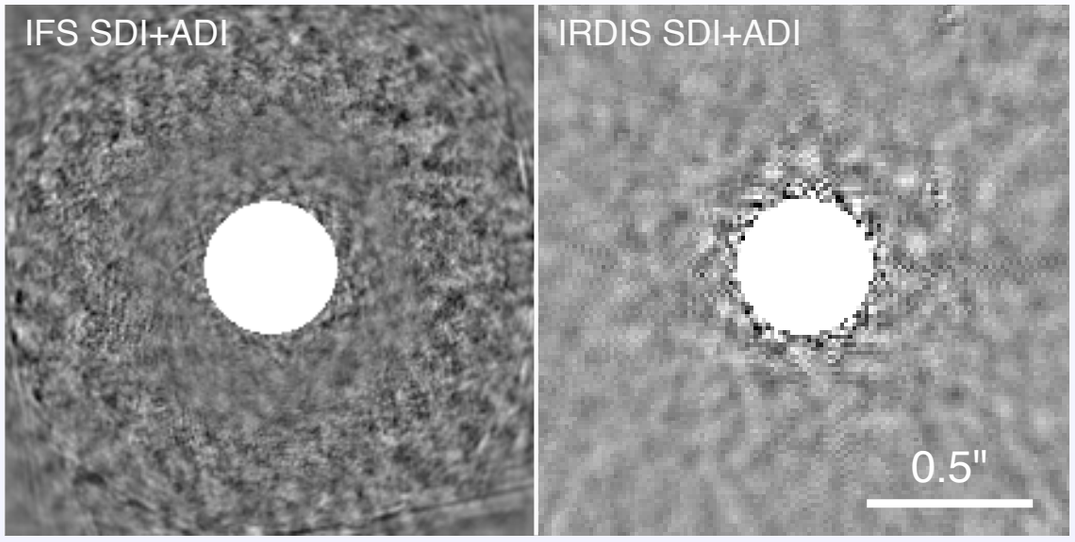
Boccaletti et al. (2015)

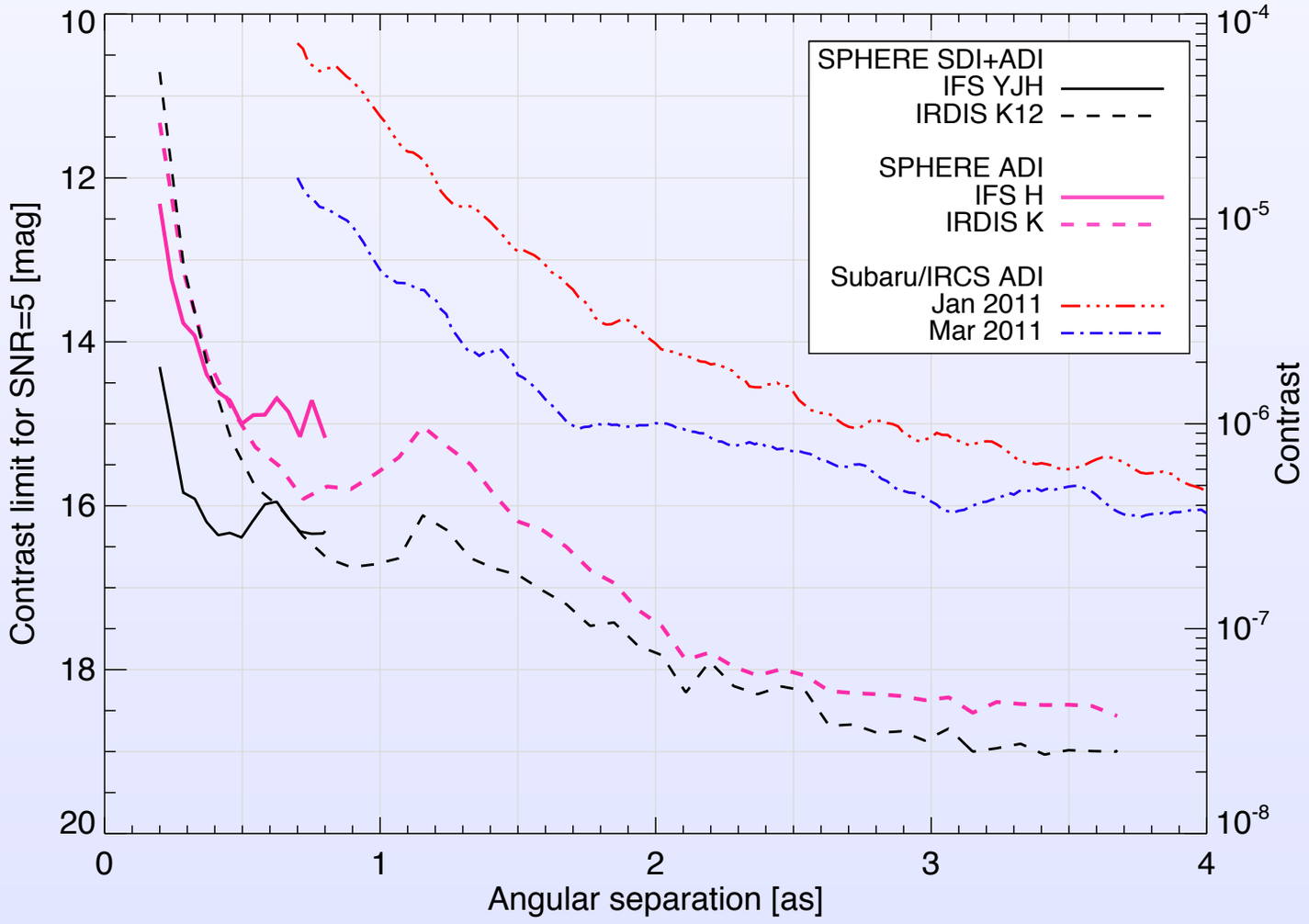


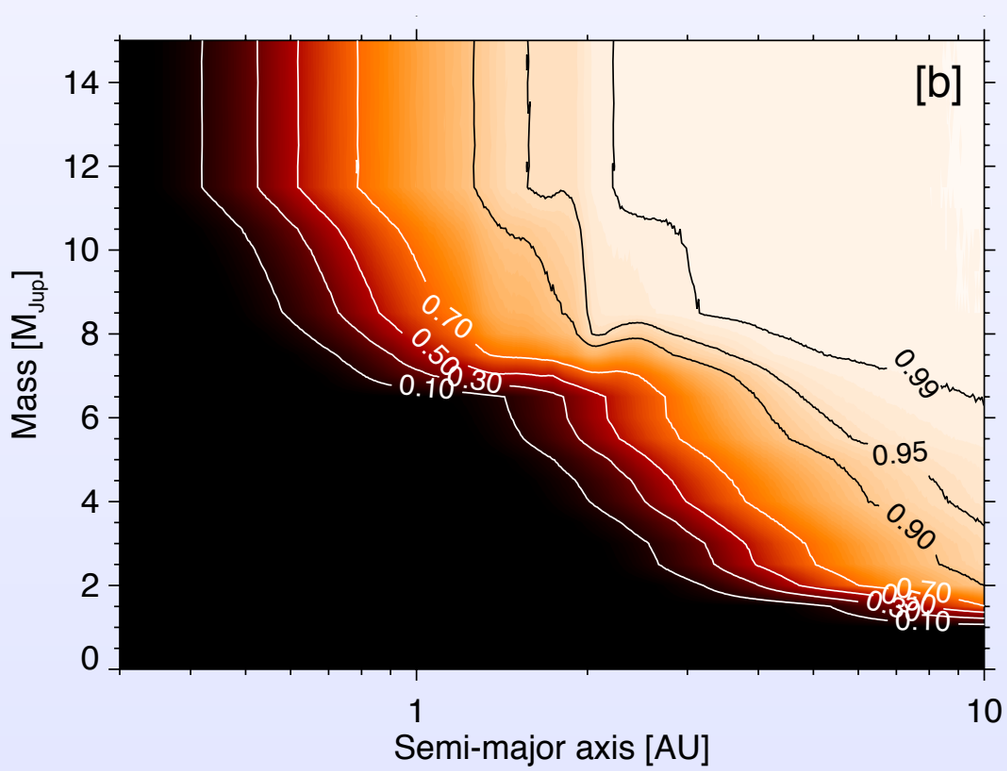
Commissioning & SVT: Sirius

Vigan et al. (2015)

- IRDIFS-EXT observations, APLC
- exceptional observing conditions: **0.3-0.5" seeing**
- long sequence divided in 4:
  - **T_{exp} = 2.5 hours**
  - **106° of field rotation**







Present

SHINE: SpHere Infrared survey for Exoplanets

200 nights of VLT/SPHERE over 5 years

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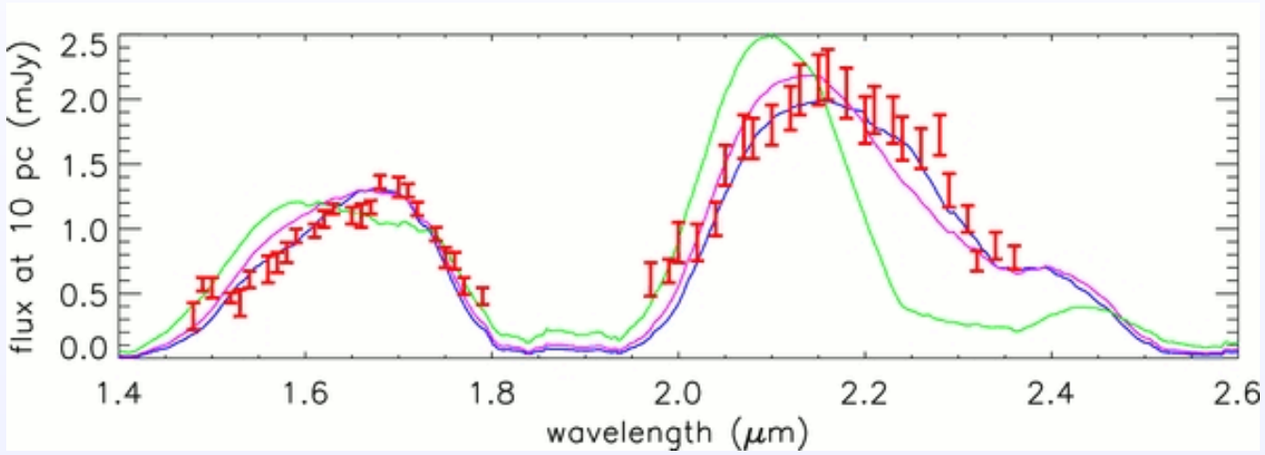
200 nights of VLT/SPHERE over 5 years

1/ Physics of giant exoplanets

Photometry & Spectroscopy

Atmosphere & physical properties



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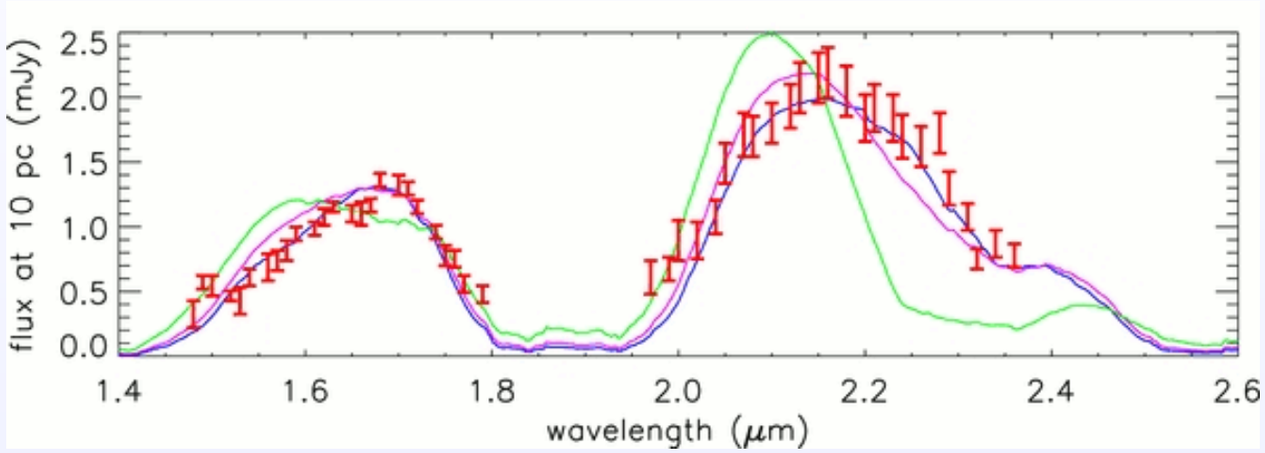
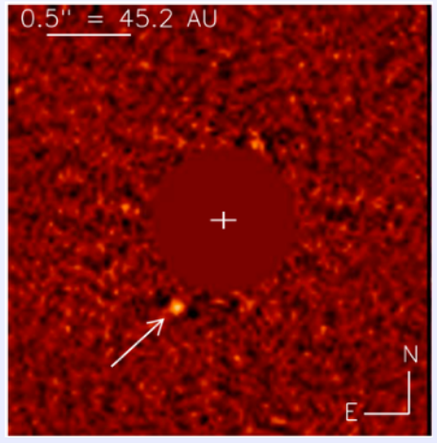
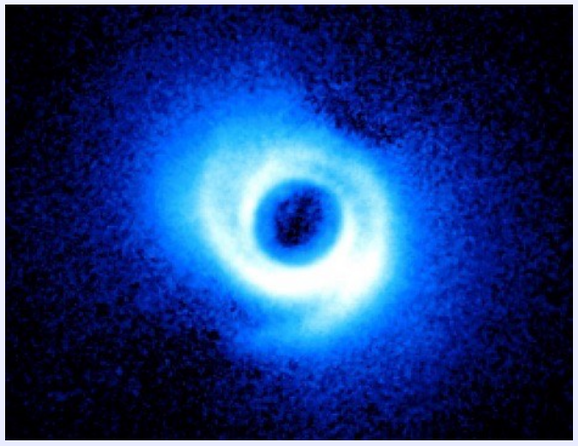


2/ Architecture & stability of planetary systems

Astrometry & Disk/Planet relative position

Orbits, dynamical interactions, resonances & long-term evolution





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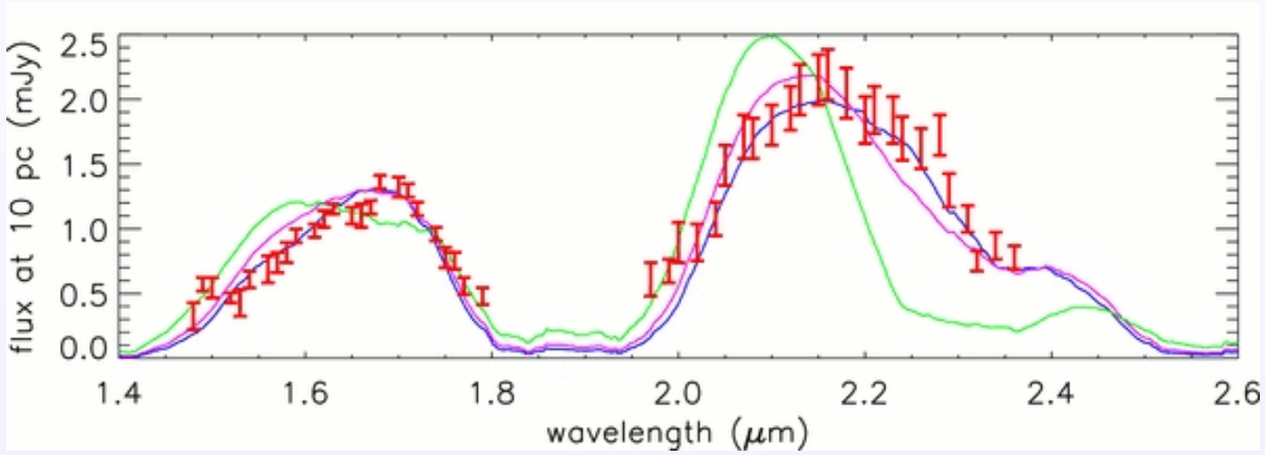

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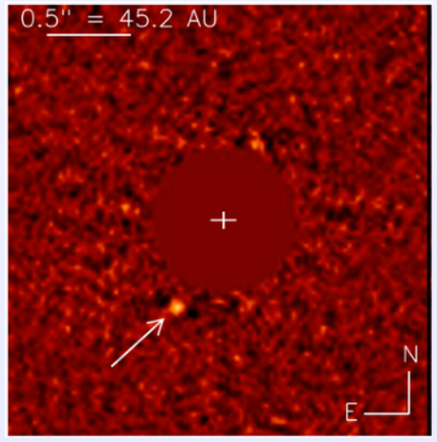
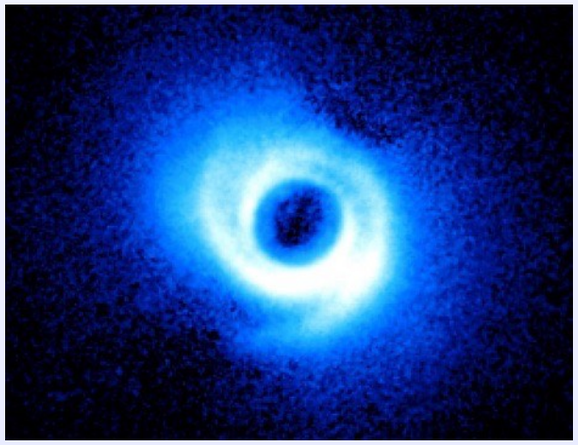
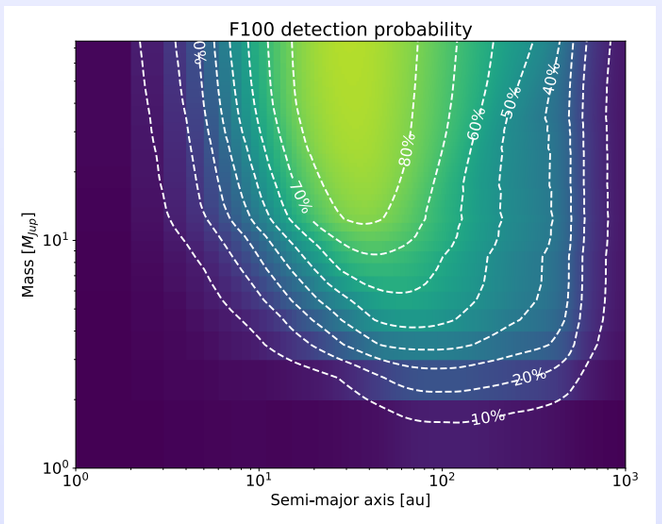




3/ Occurrence & formation

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

Formation Theories: CA, GI or CF



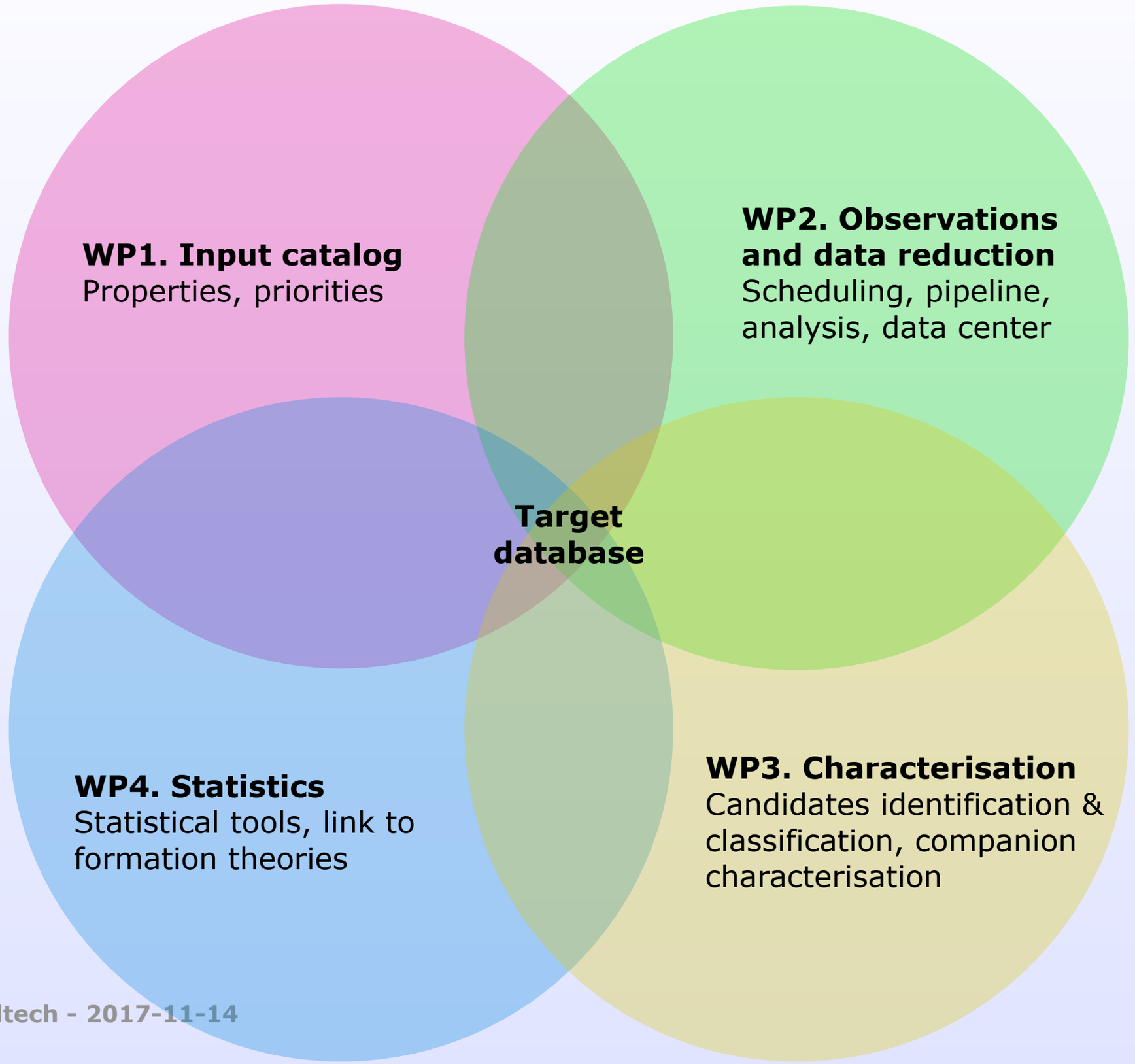
Arthur Vigan - Caltech - 2017-11-14

SHINE organisation

G. Chauvin, S. Desidera

S. Desidera
A. Cheetham

A.-M. Lagrange
R. Gratton
M. Langlois

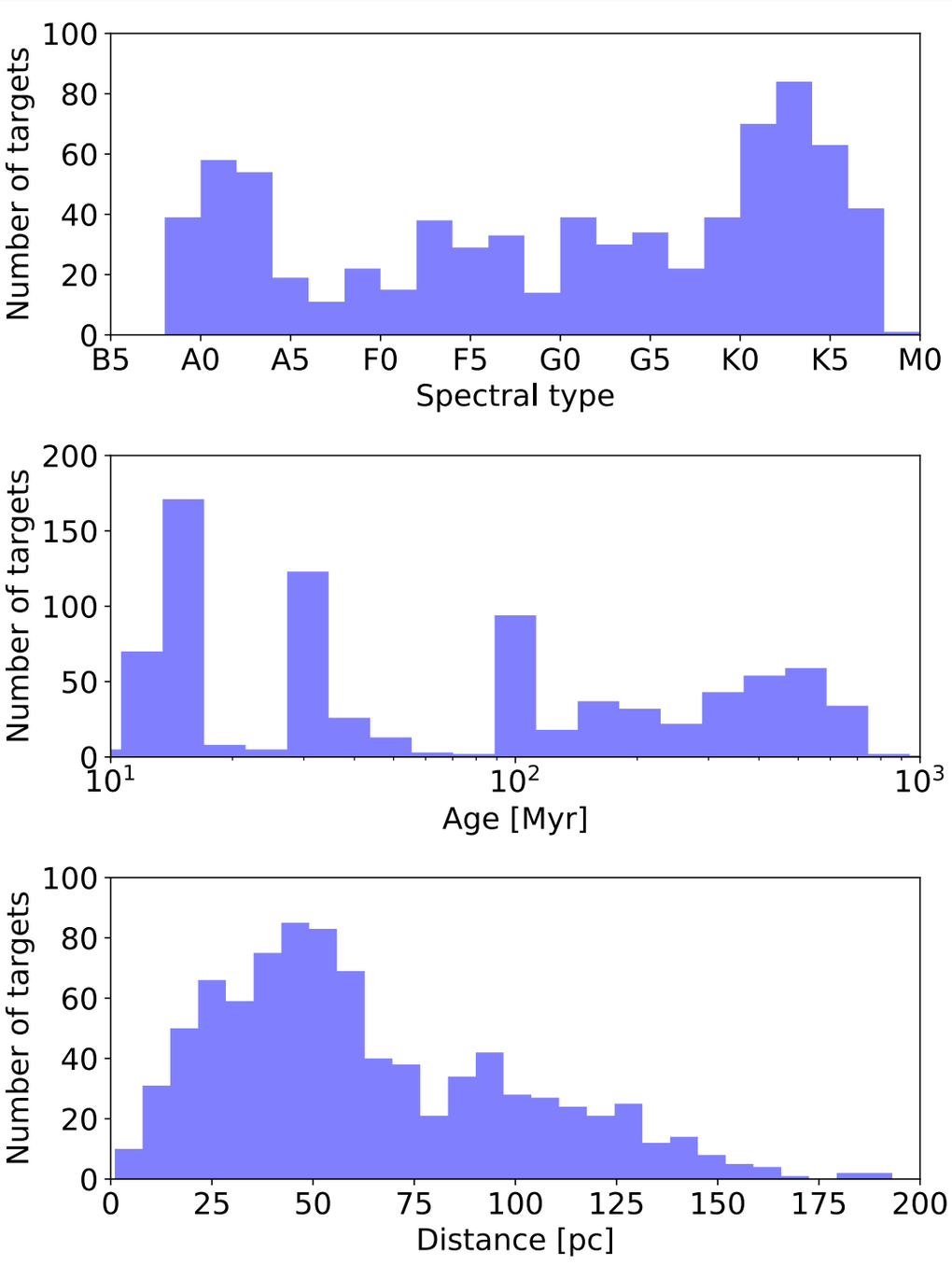


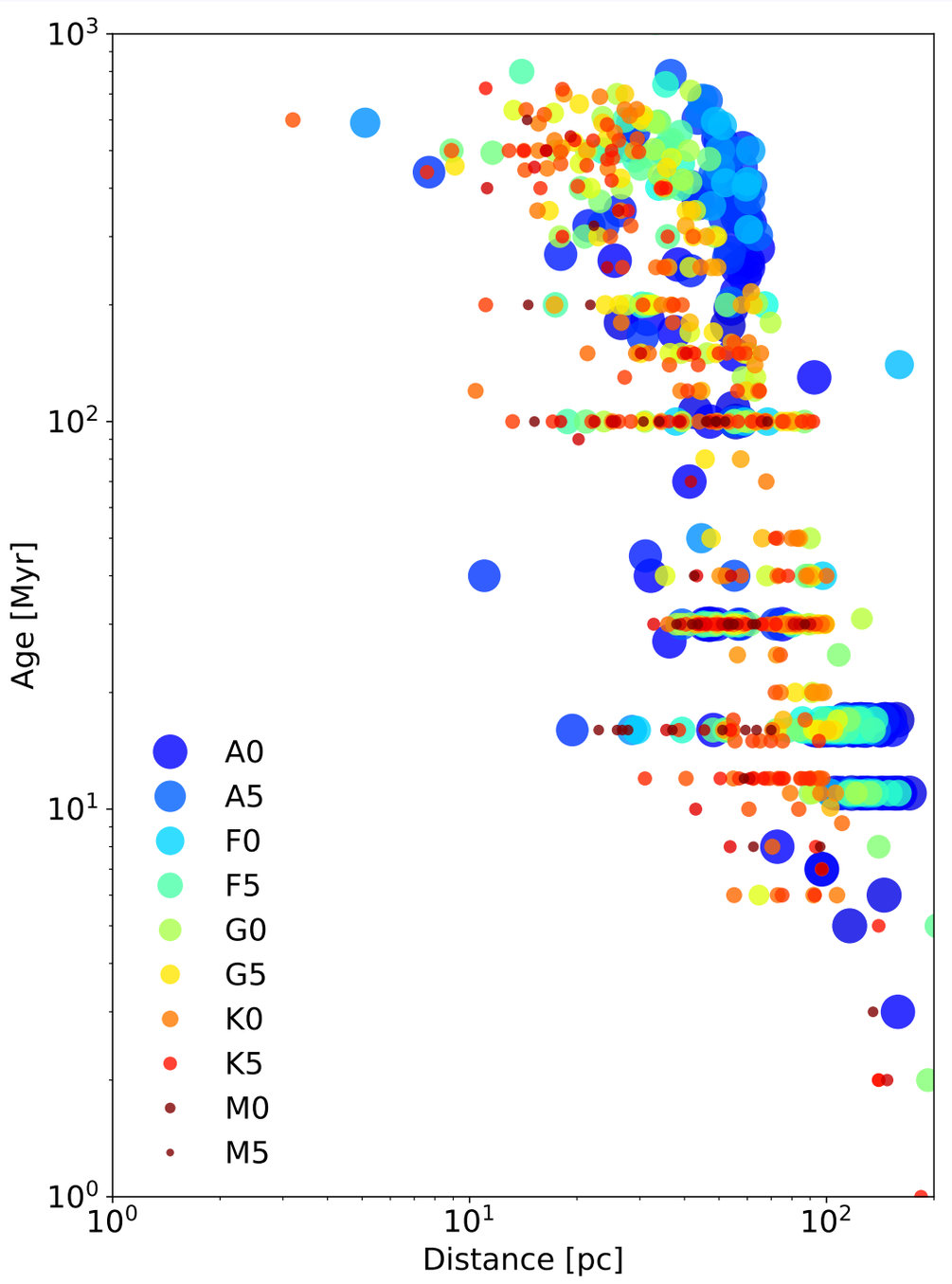
M. Feldt
M. Meyer

A. Vigan
M. Bonnefoy

Sample

600 stars + 400 backup, 4 priority bins





R<11

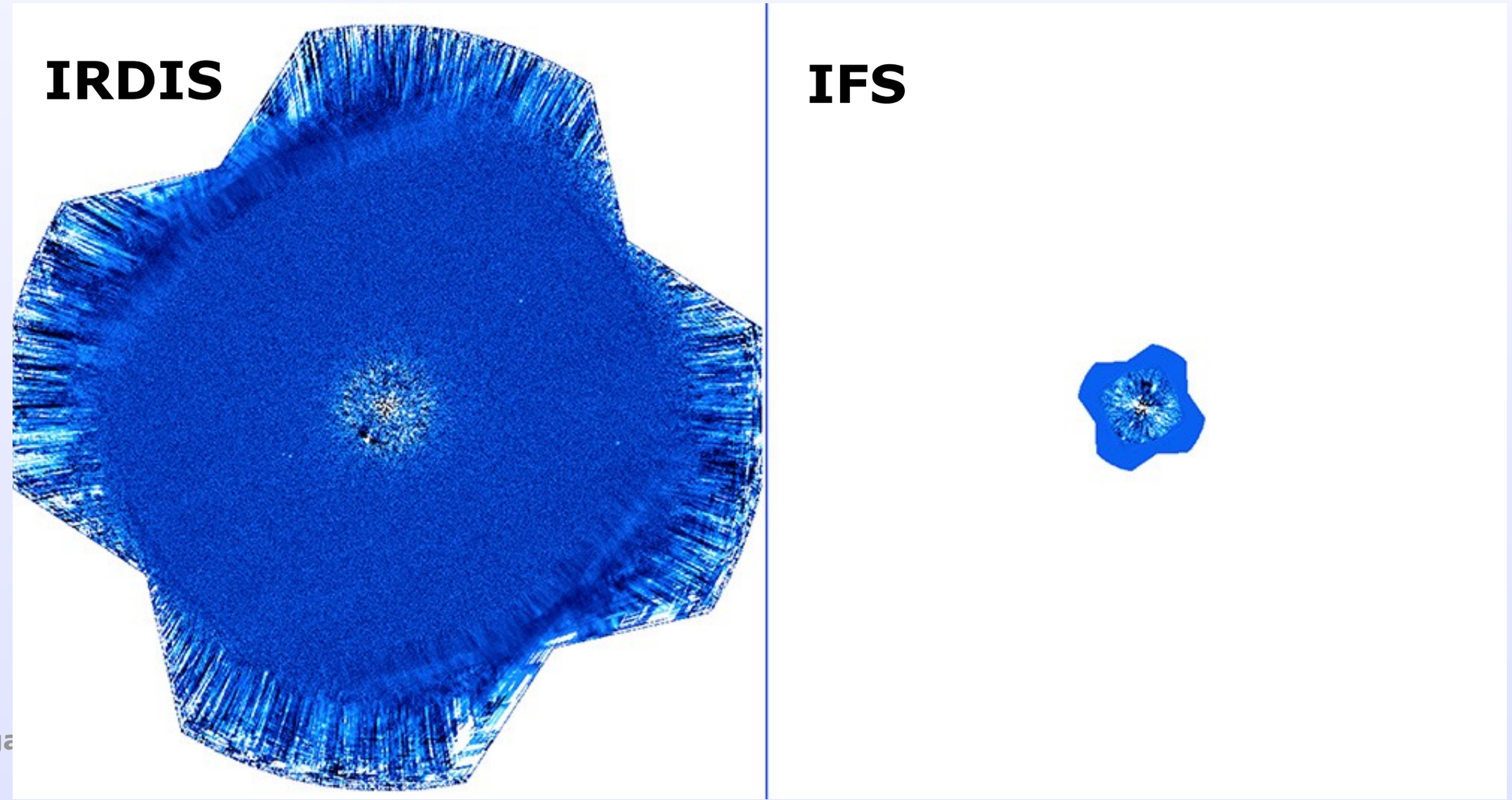
No binaries (spectro or visual <6")

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

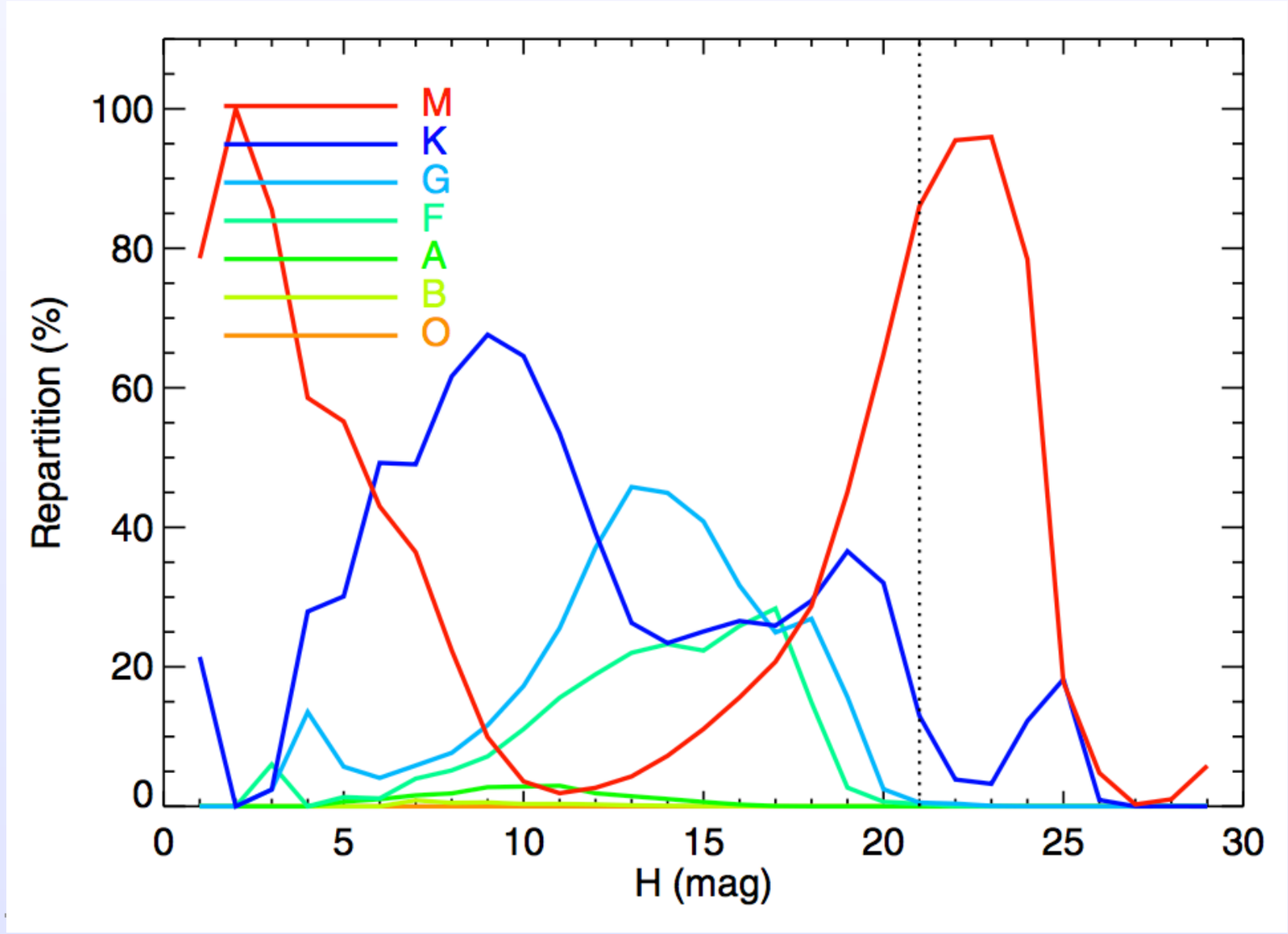
- SPHERE Data Center in grenoble:
  - almost fully automated pre-processing pipeline
  - SpeCal pipeline for ADI-processing (Galicher et al. in prep): **TLOCI**, PCA, cADI, RDI
  - Candidates astrophotometry derived after eye identification
- Observation manually validated by 2 people
- "Data Reduction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



The candidates nightmare

- contamination probability:
  - increases with FoV^2
  - 5% for IFS
  - 50% for IRDIS (measured to 30%)

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



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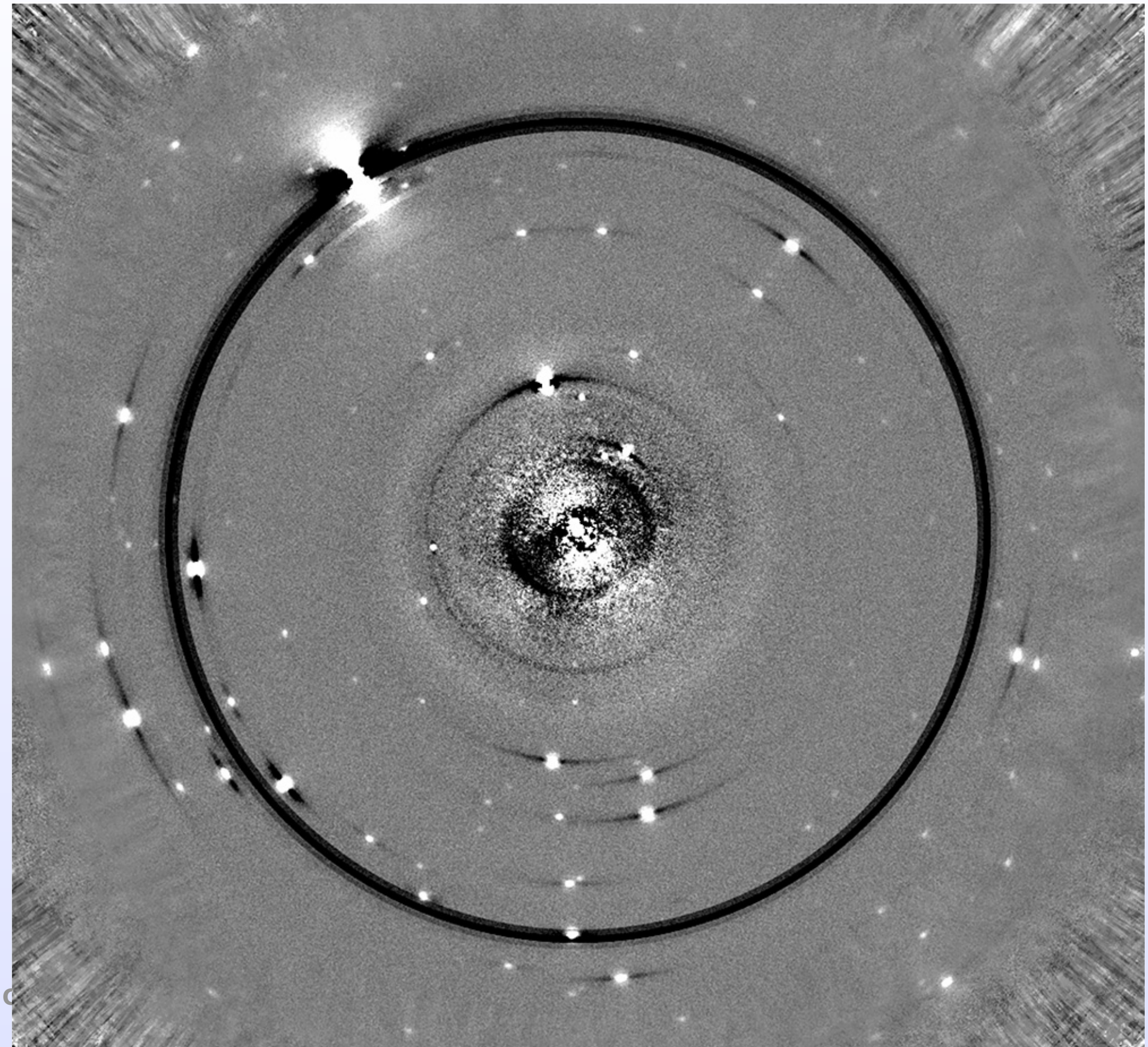

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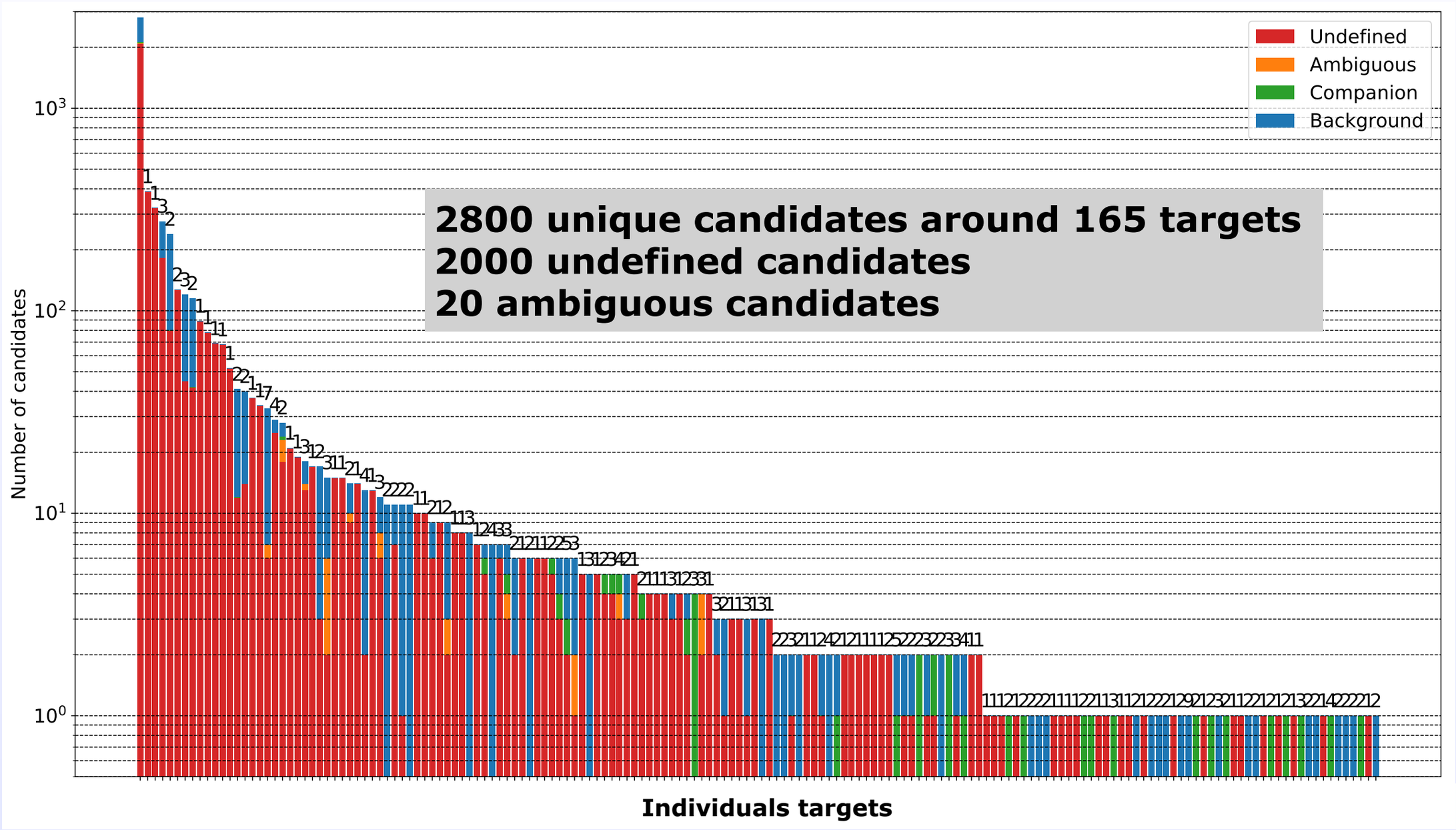
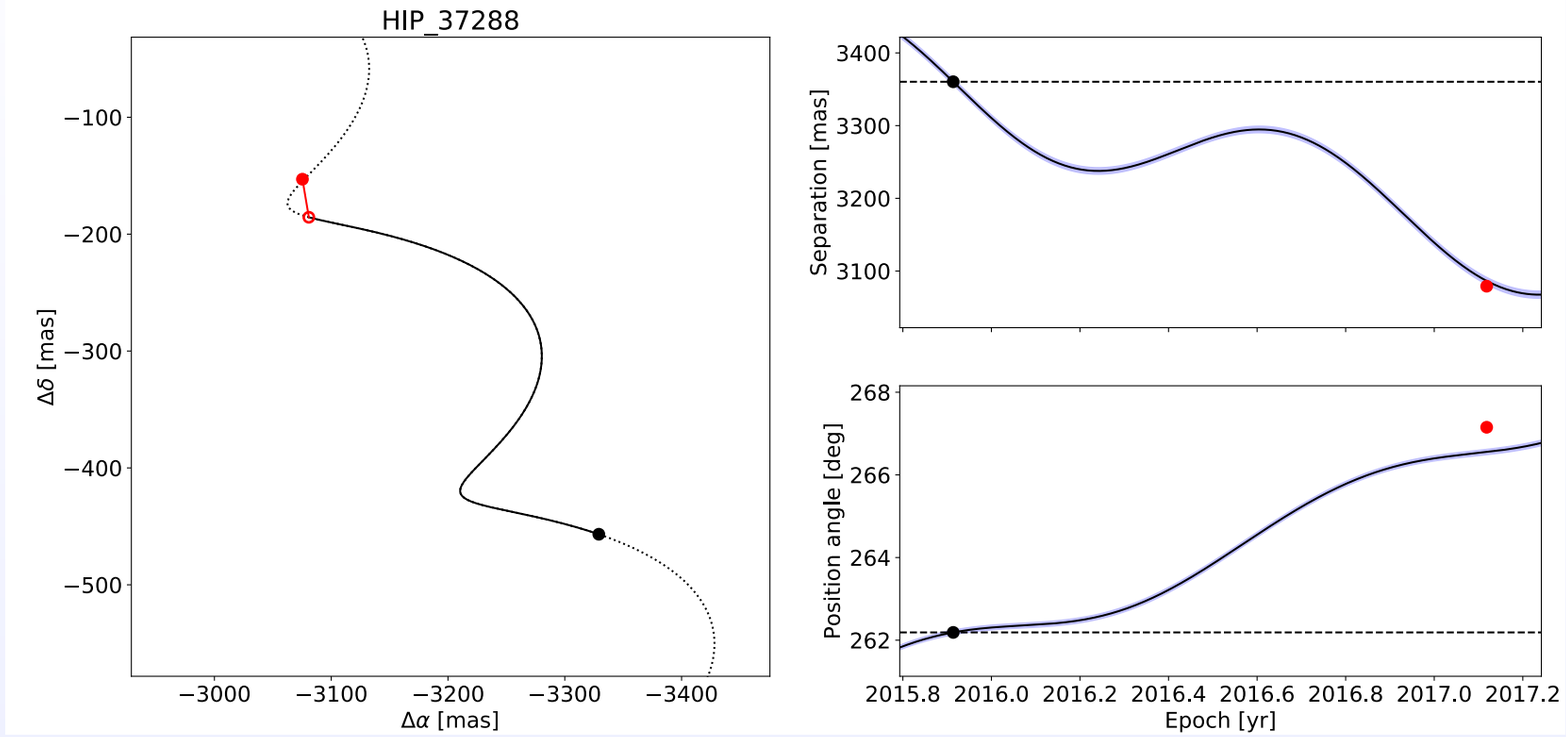


Reducing candidates: proper motion

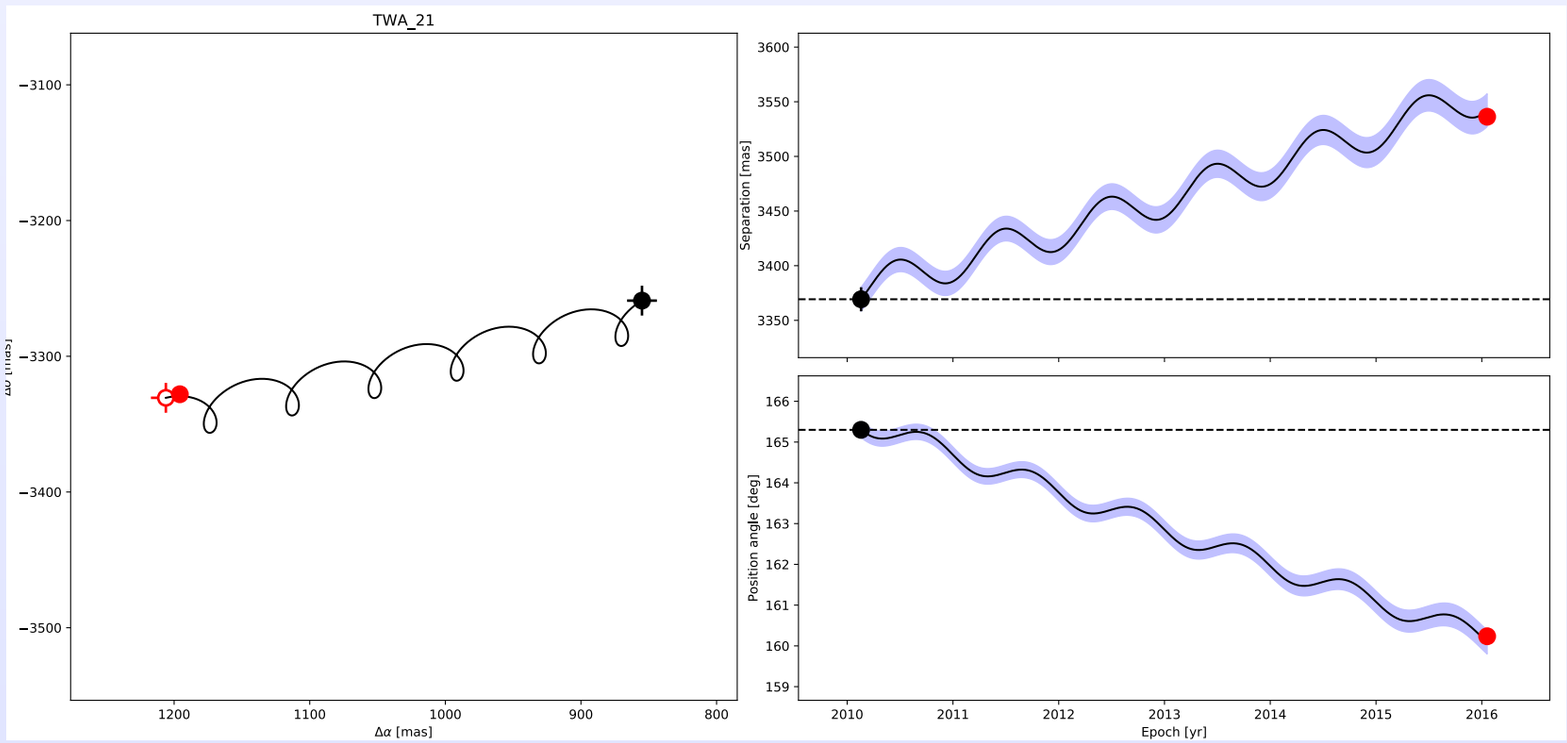
SHINE second epoch

- **Pros:**
  - fully consistent with first epoch
- **Cons:**
  - costly in telescope time
  - sometimes short baseline
  - possible issues with astrometric accuracy

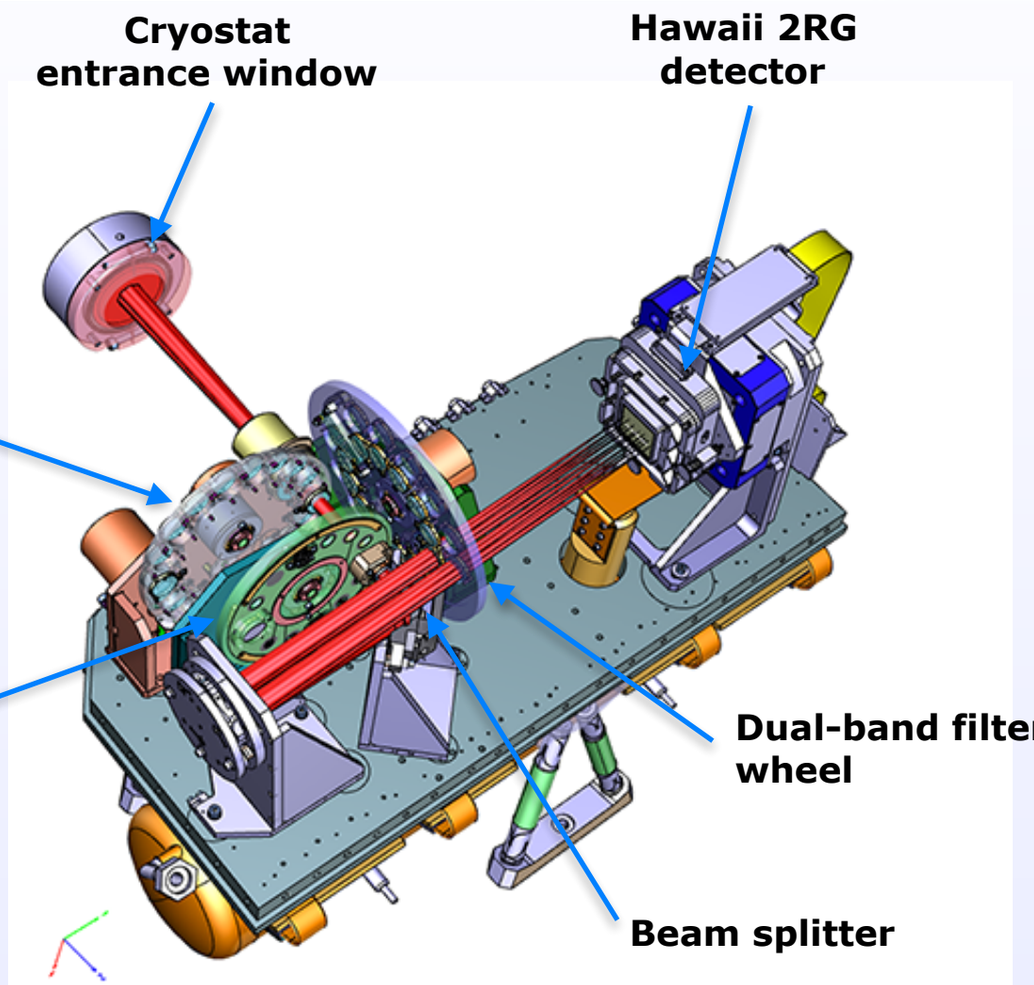


Archival data

- **Pros:**
  - sometimes very long baseline
  - good use of archival data
- **Cons:**
  - astrometric accuracy can be very bad
  - HUGE amount of work

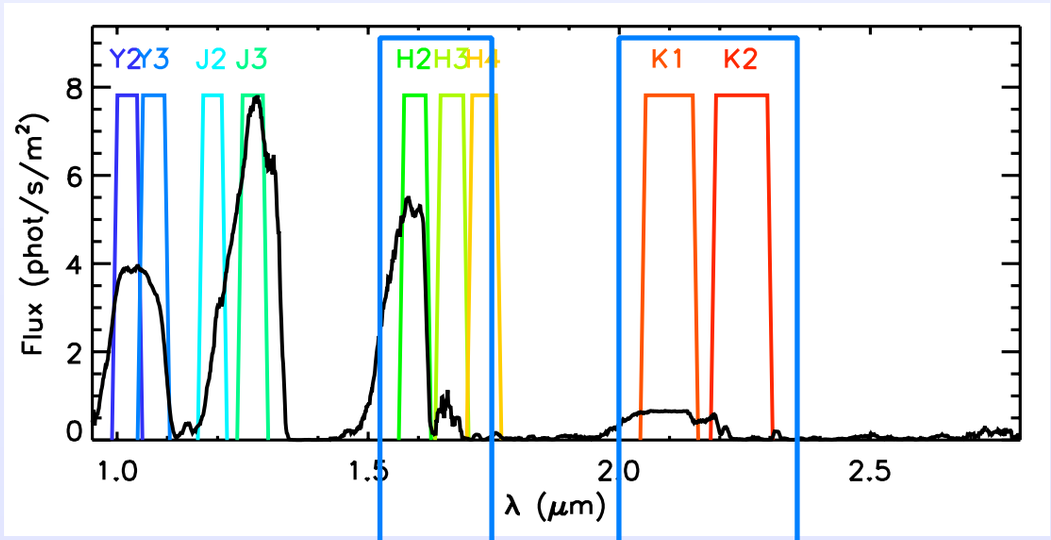


Reducing candidates: color-mag diagrams

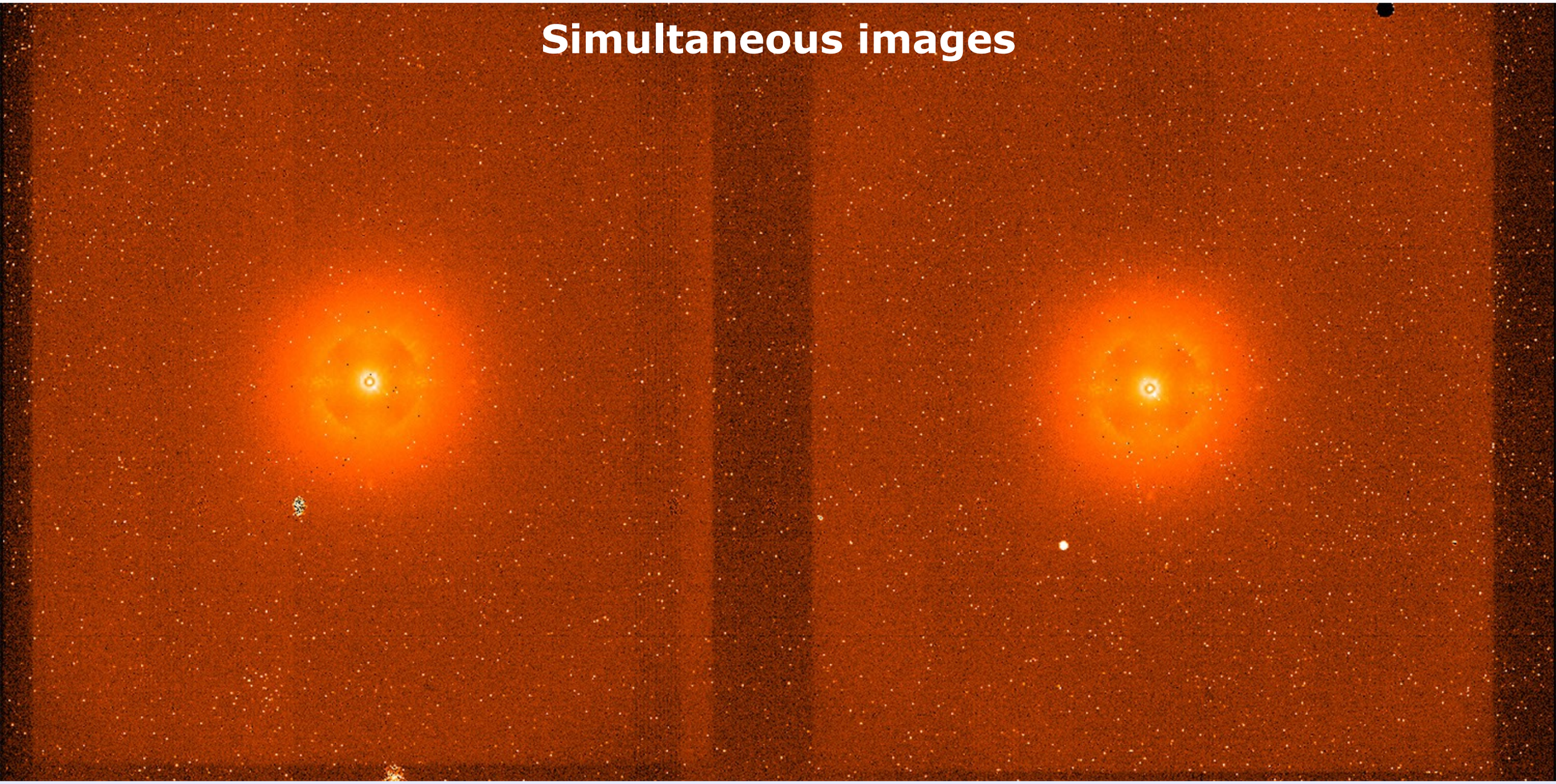


IRDIS
Dual-band imaging

Dual-band filters



Reducing candidates: color-mag diagrams



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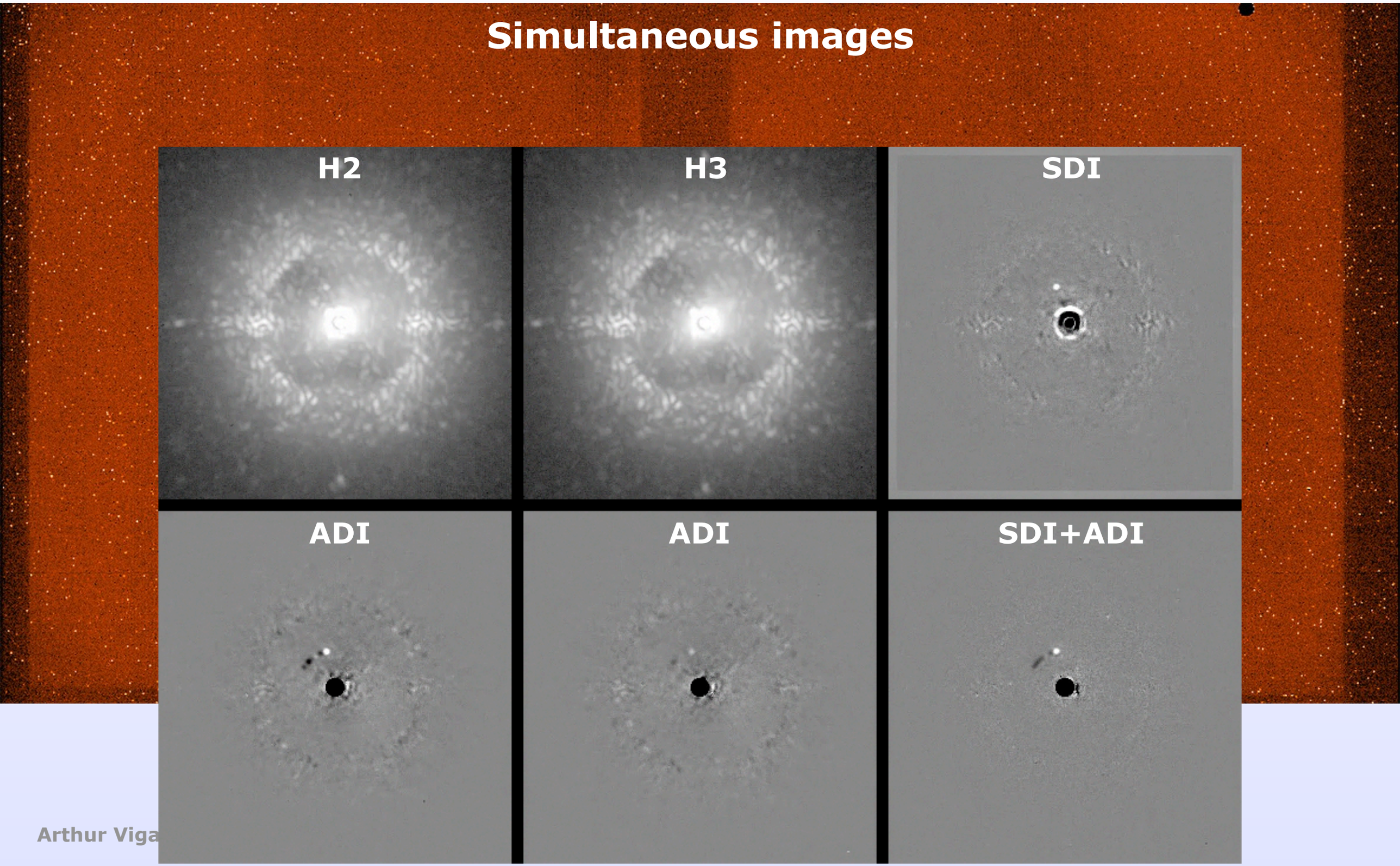
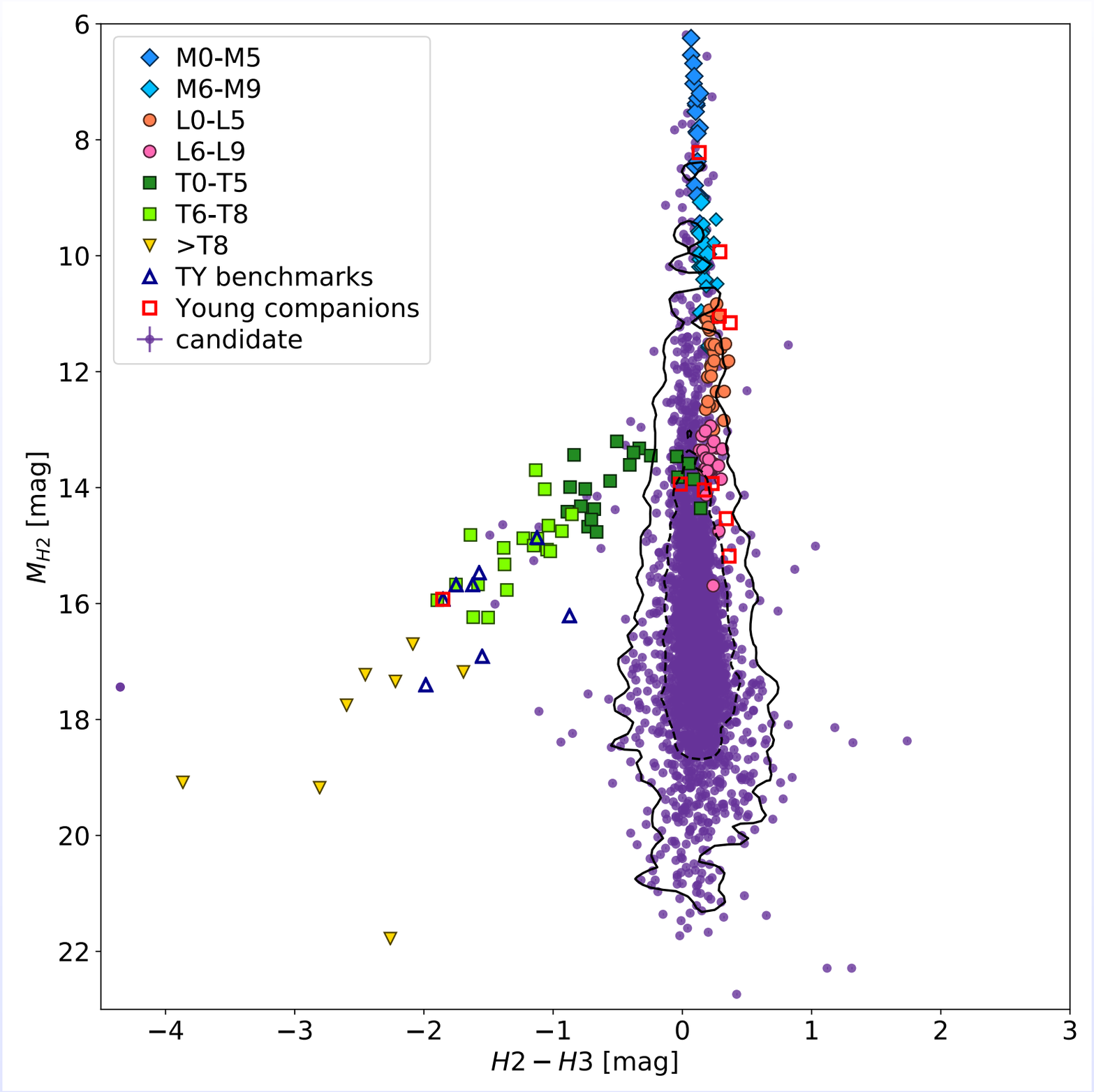
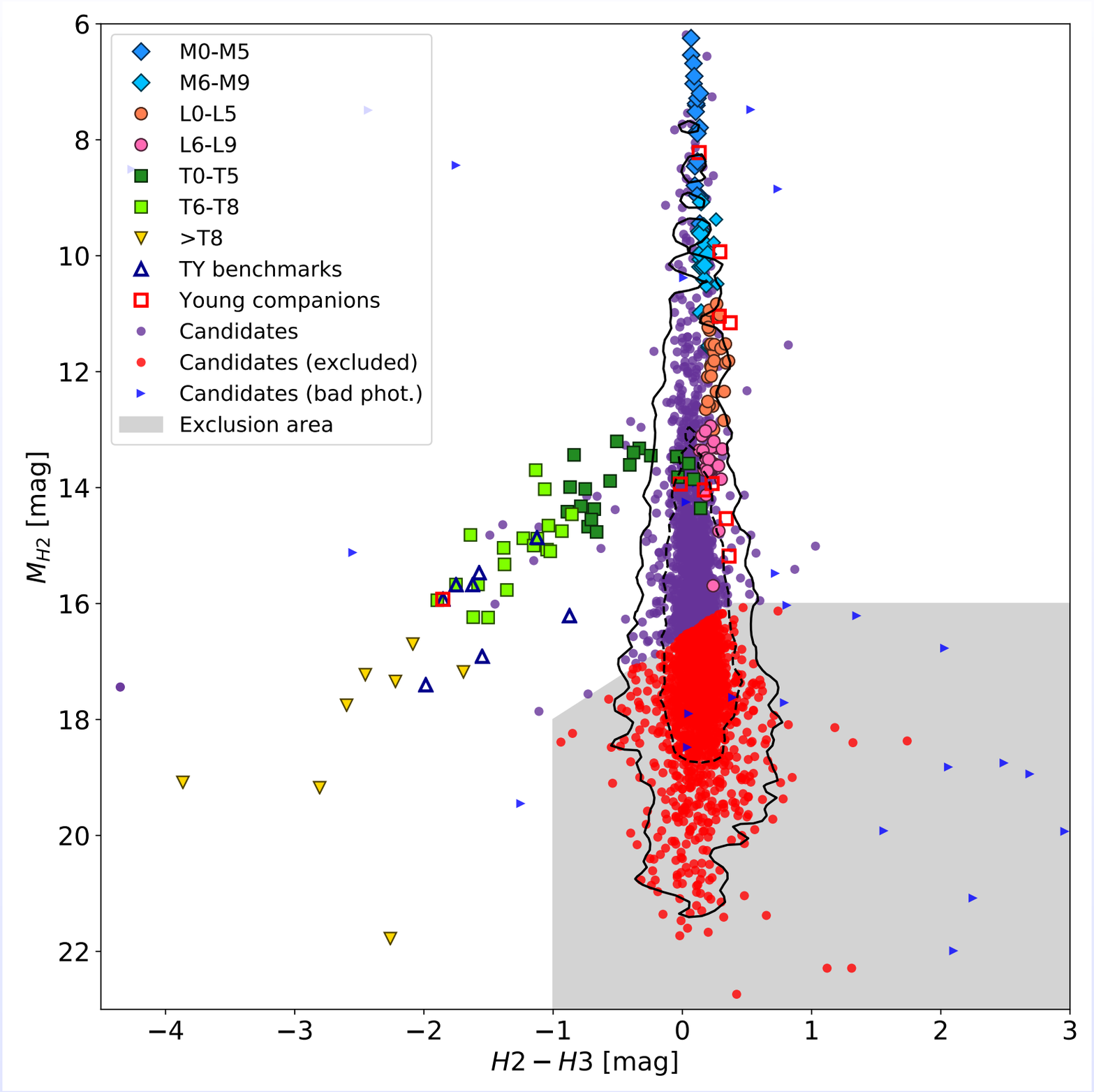


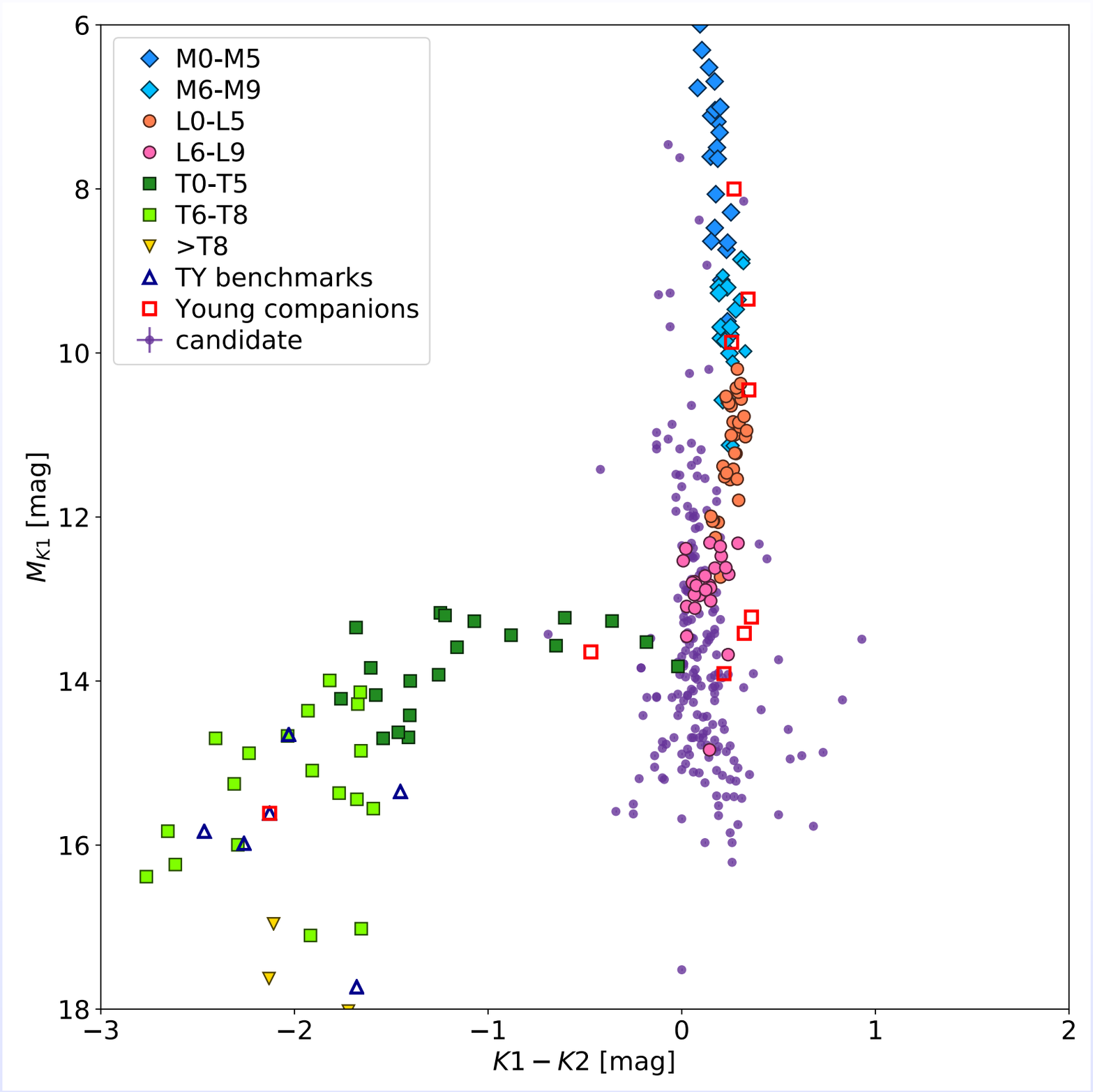
Reducing candidates: color-mag diagrams



Reducing candidates: color-mag diagrams



Reducing candidates: color-mag diagrams



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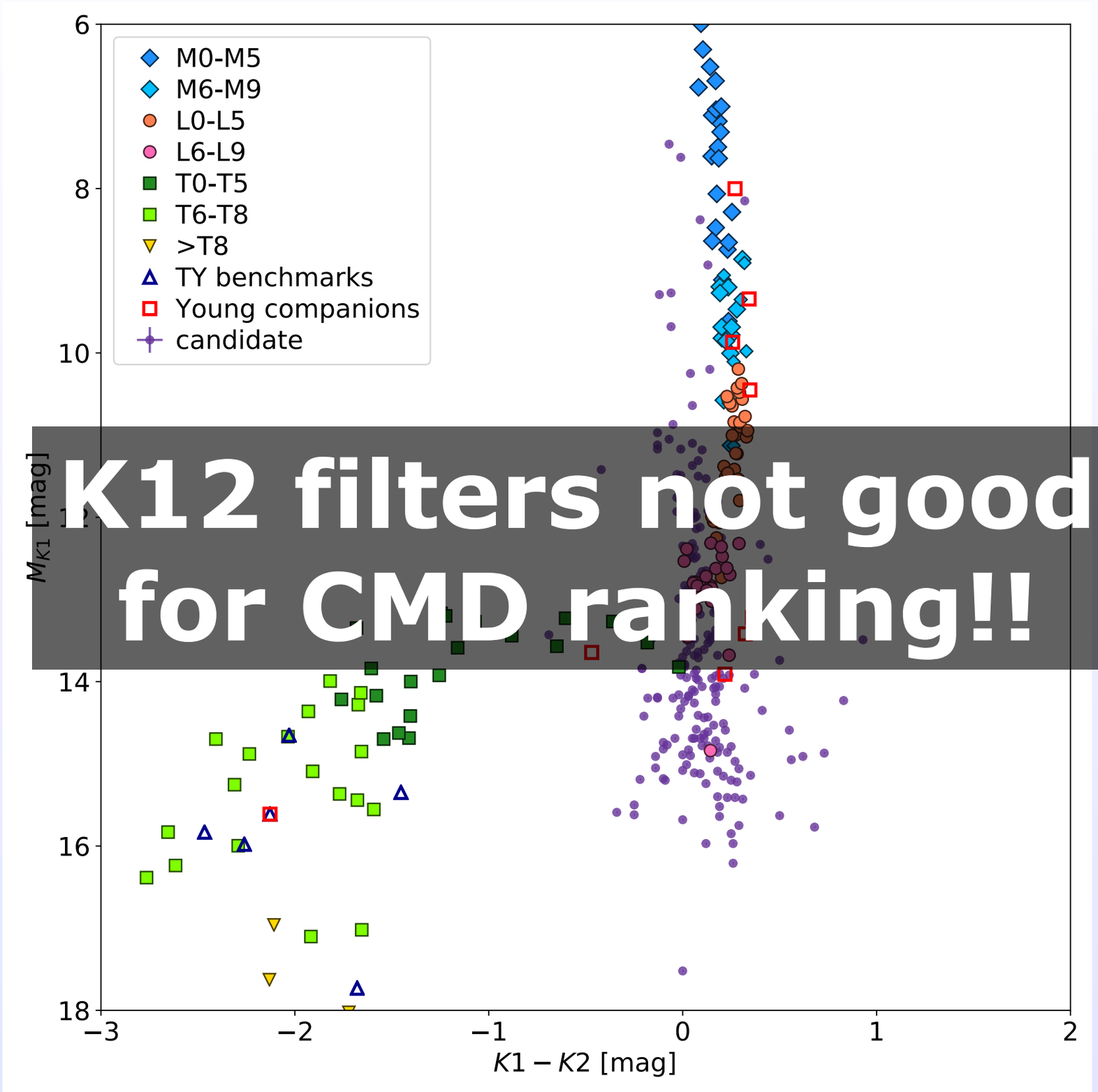
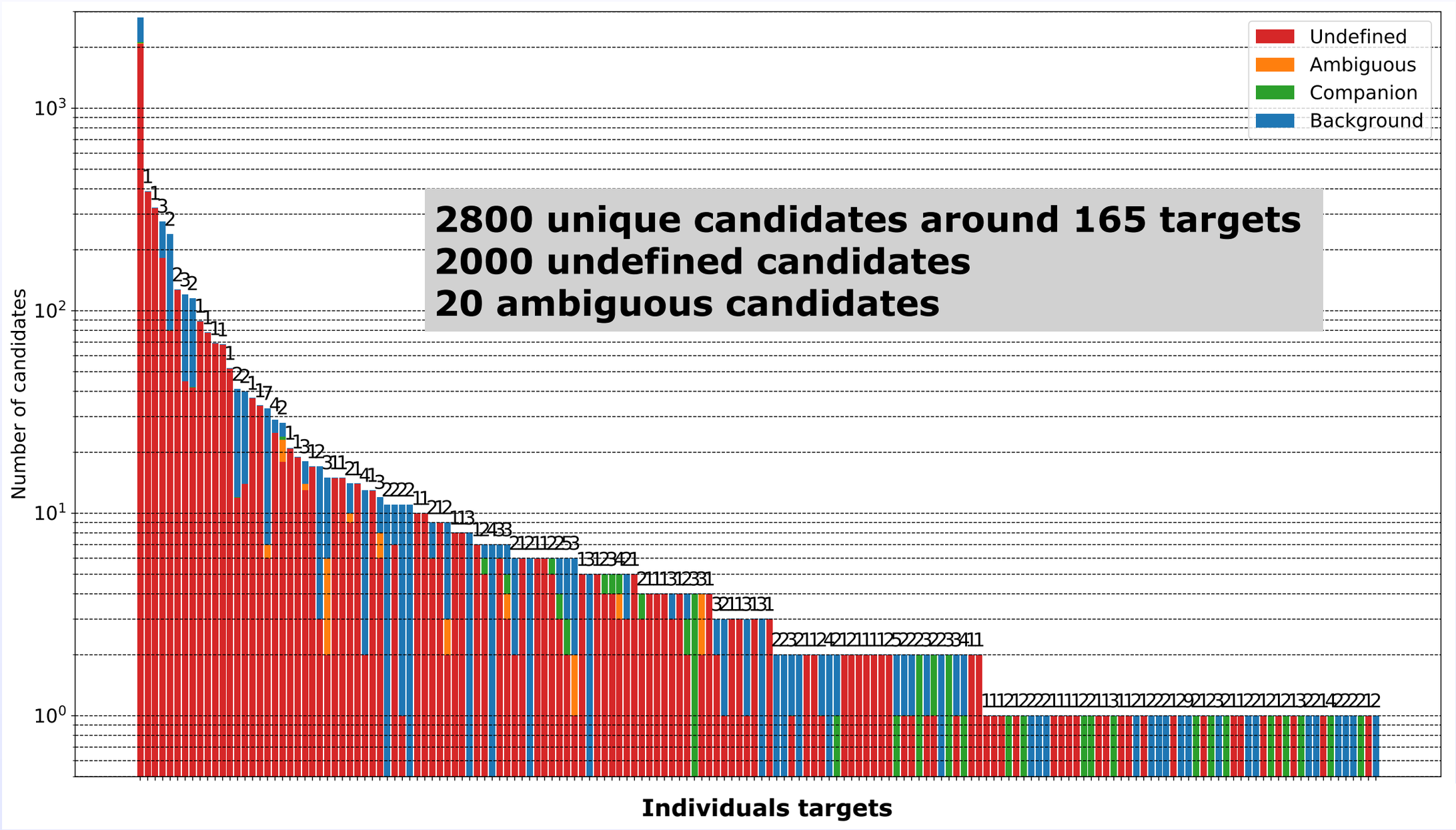
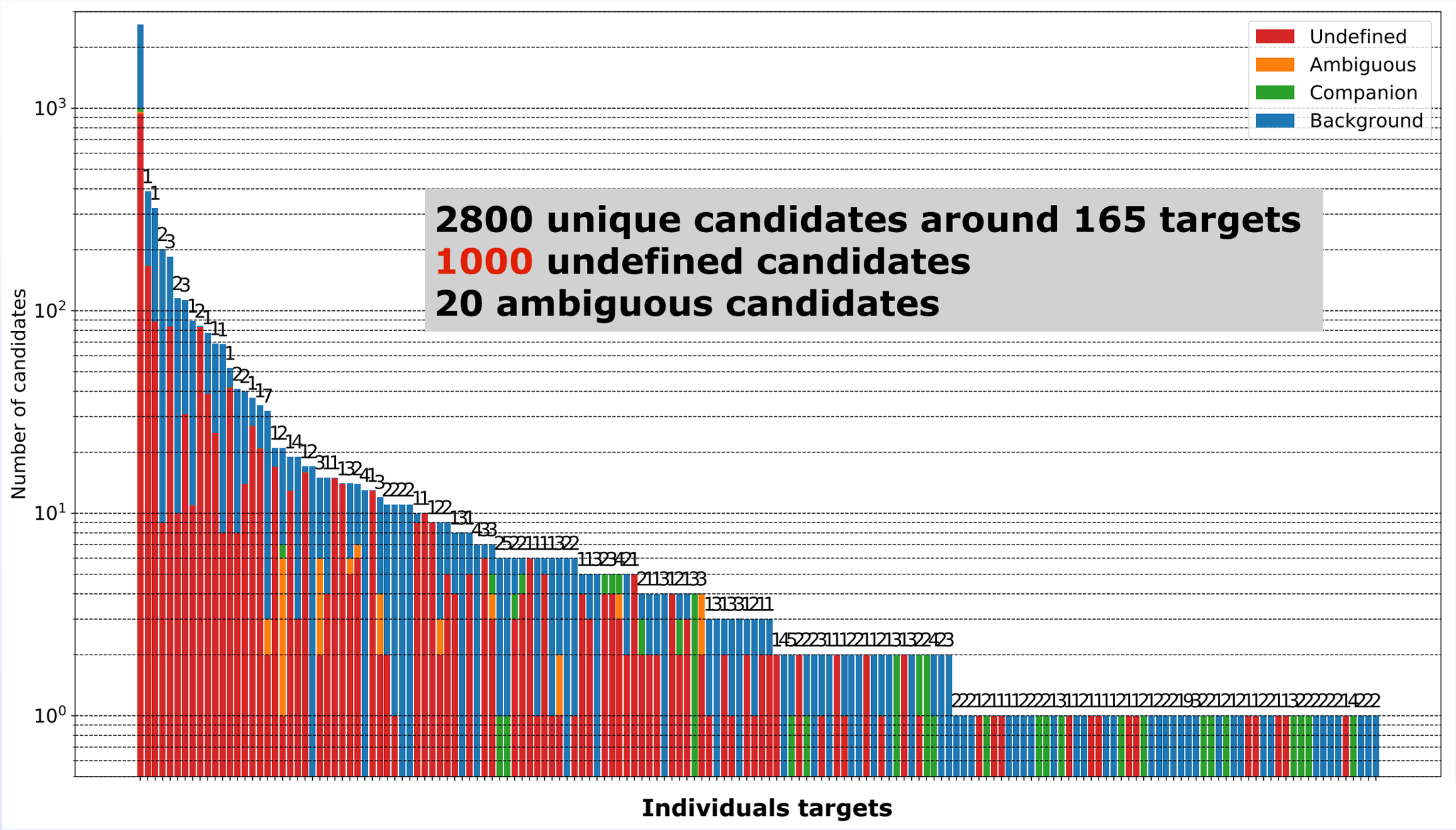


K12 filters not good for CMD ranking!!

The candidates nightmare



The candidates ~~nightmare~~ very bad dream



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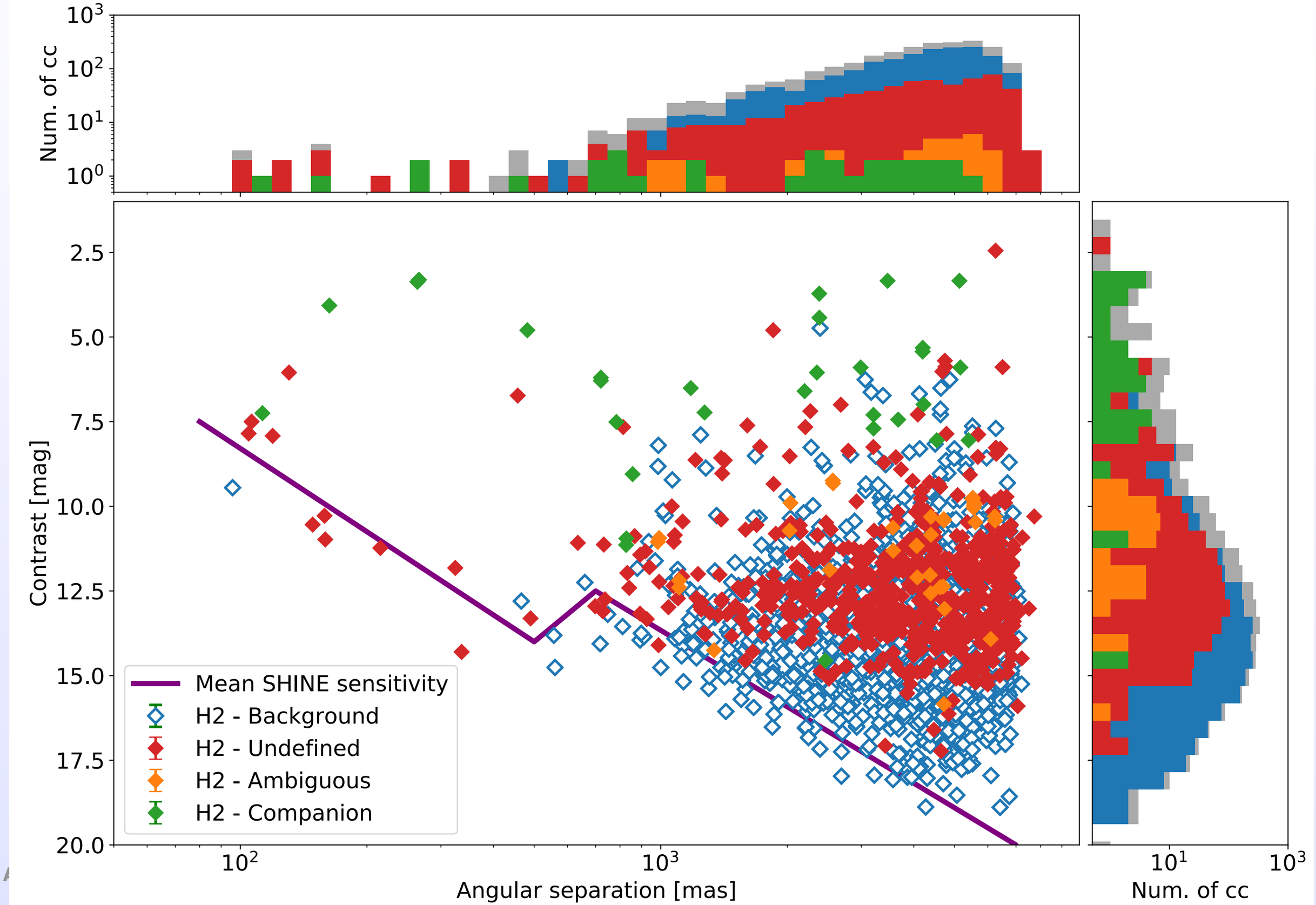

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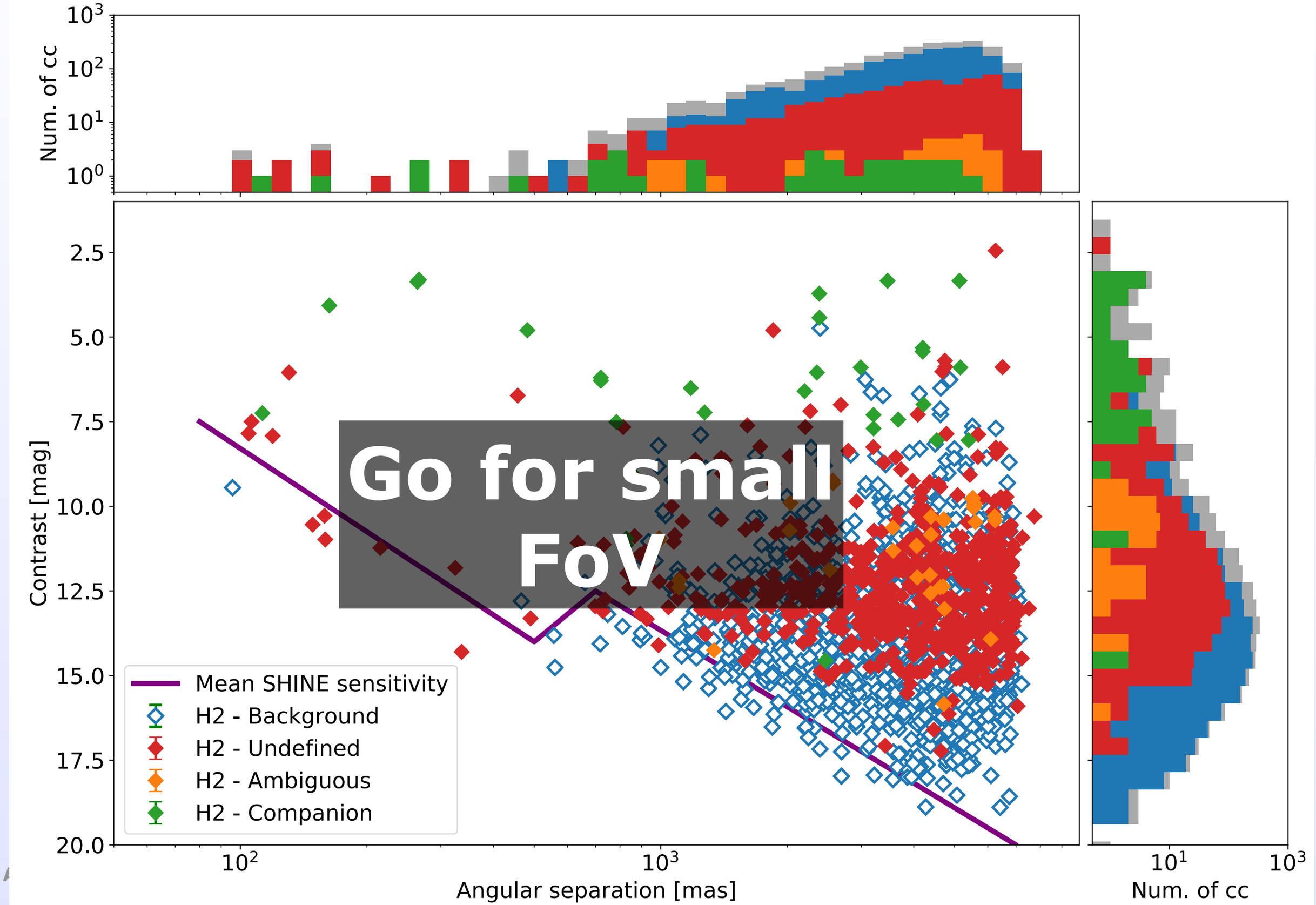

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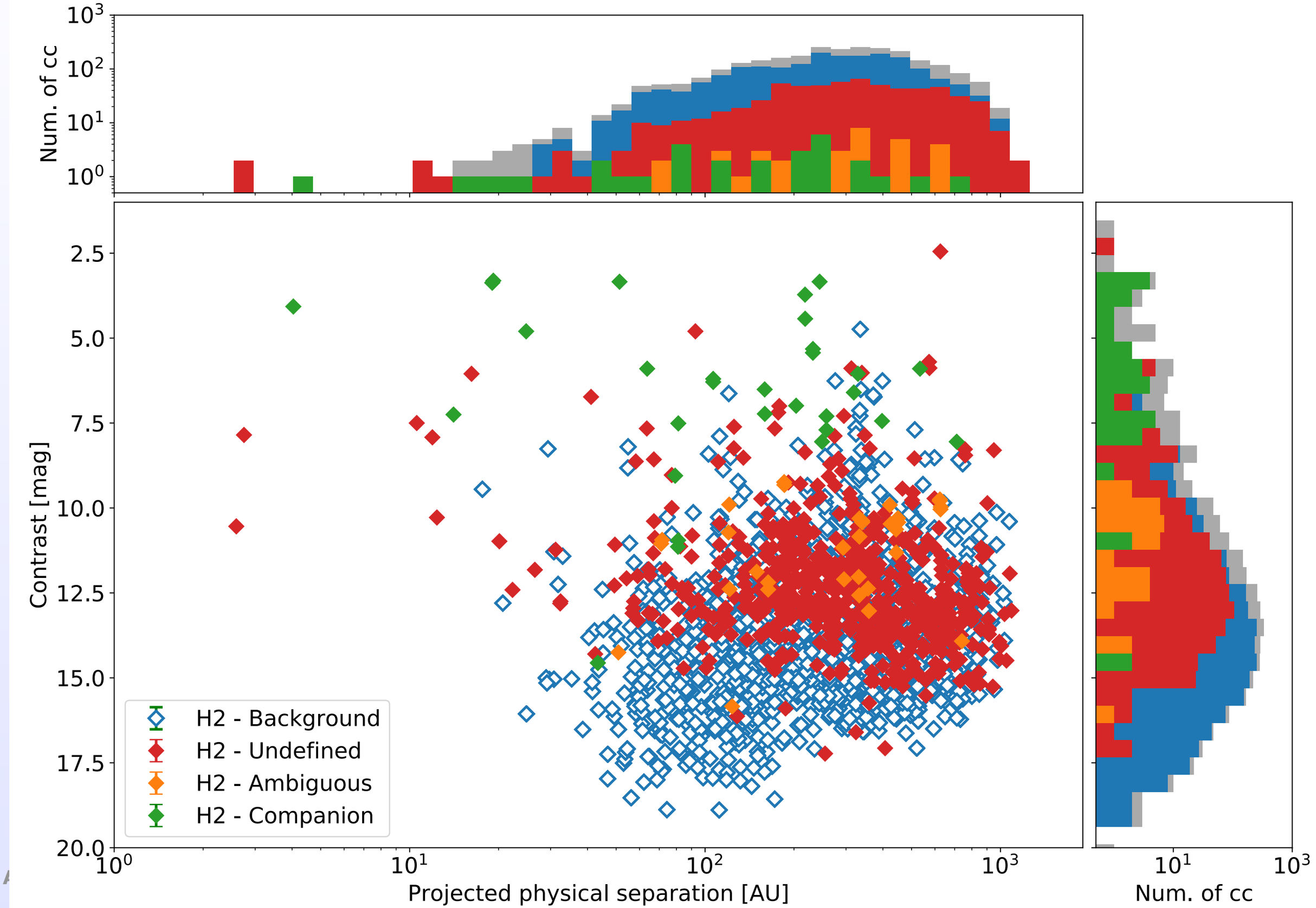

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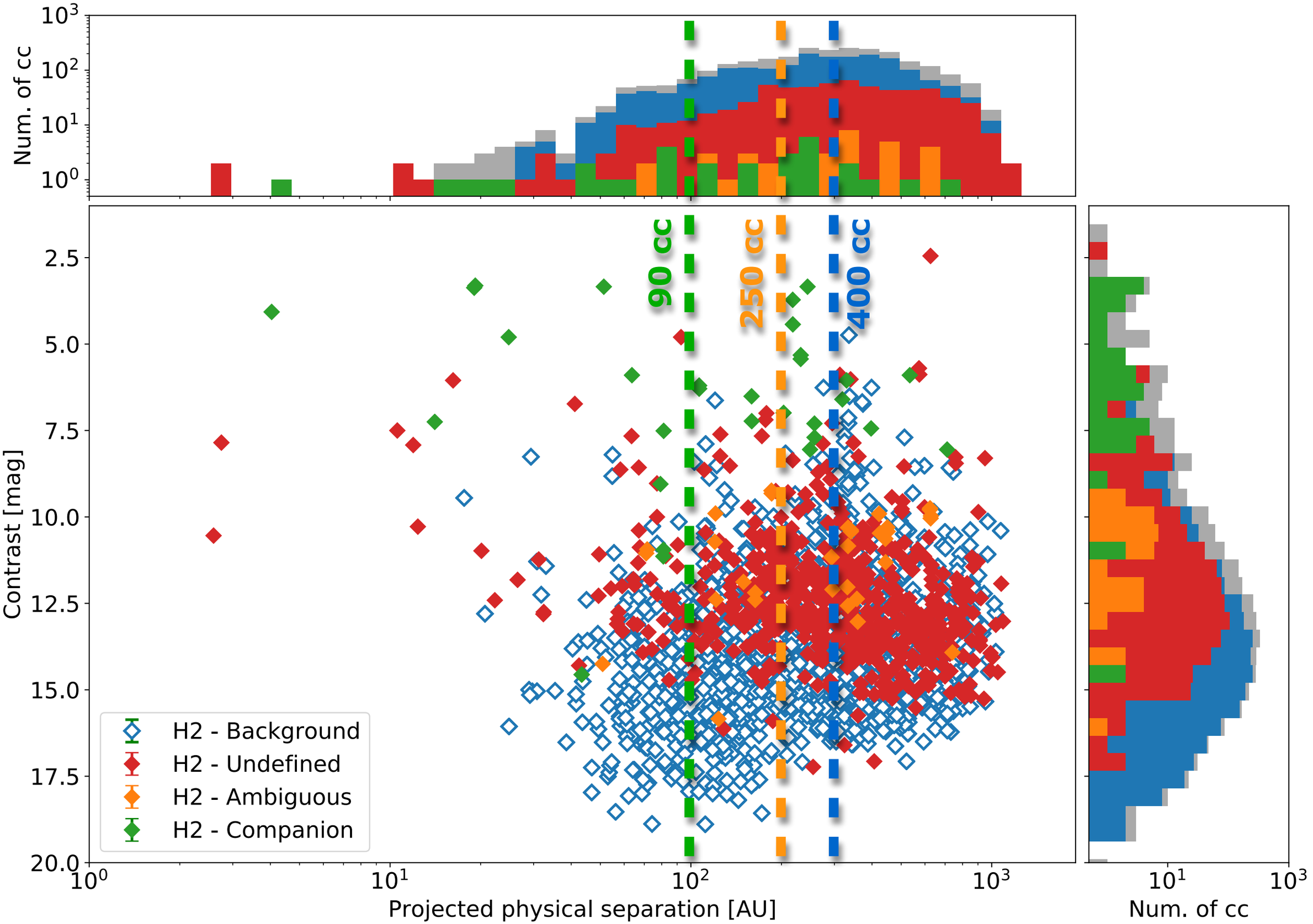


The (real) SPHERE planet: HIP 65426 b

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

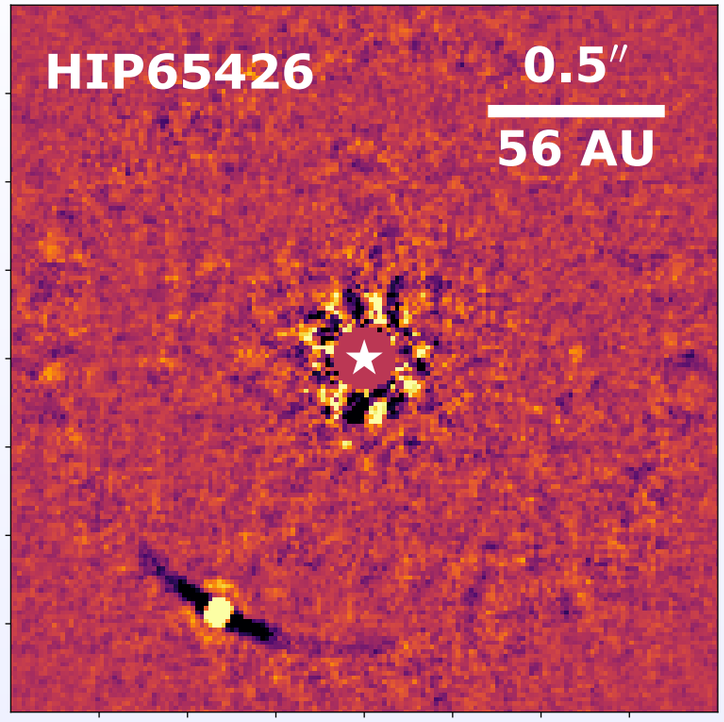
Sep. = 830 mas / 92 AU

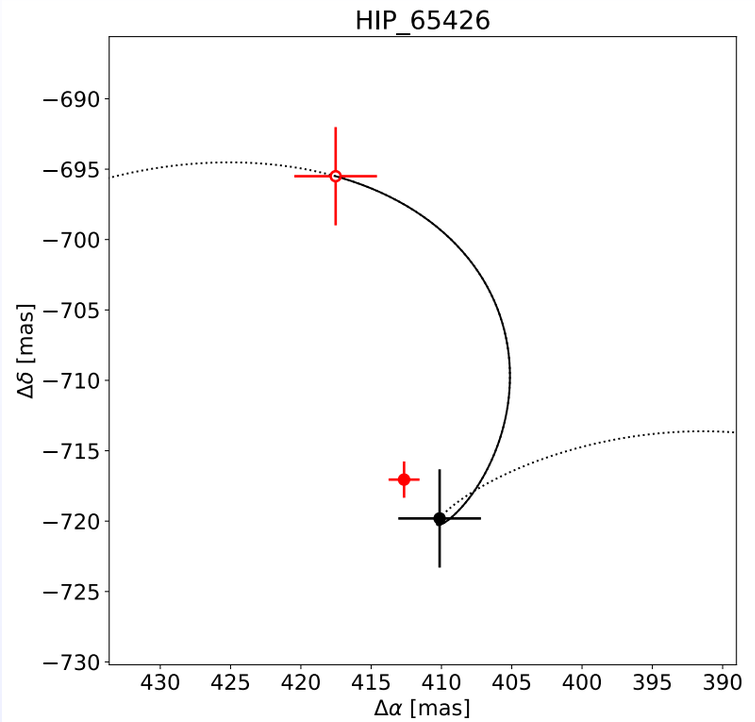
ΔH2 = 11 ± 0.1 mag

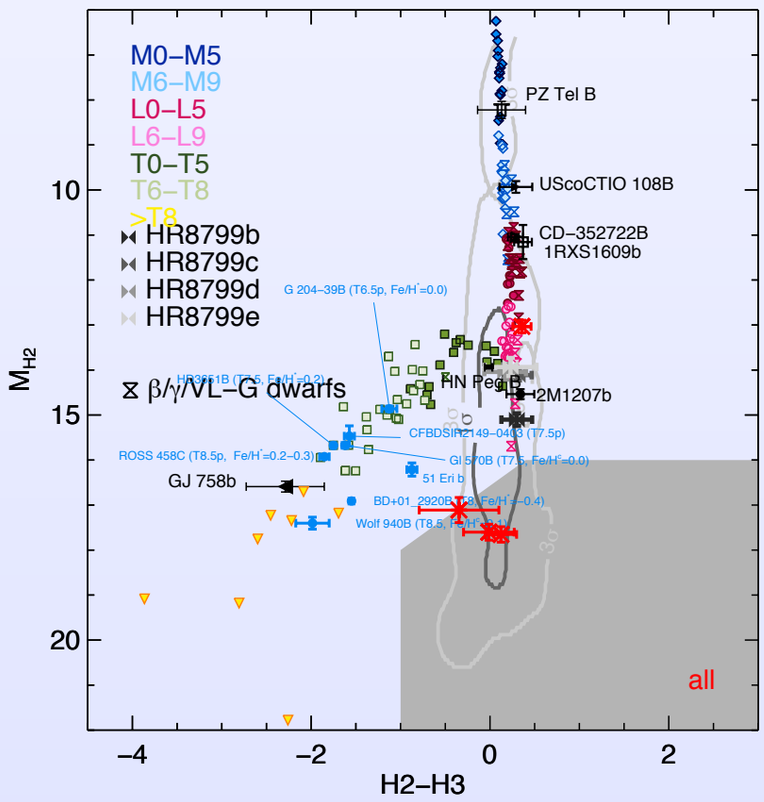
Mass = 6-12 M_{Jup}

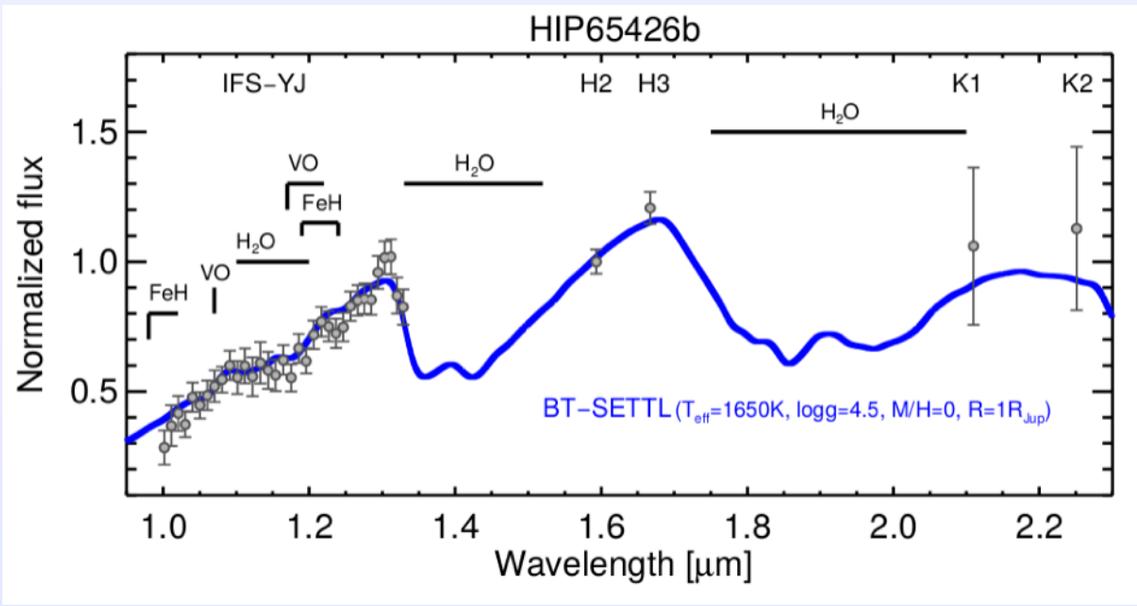
Teff = 1300 – 1600 K

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
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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
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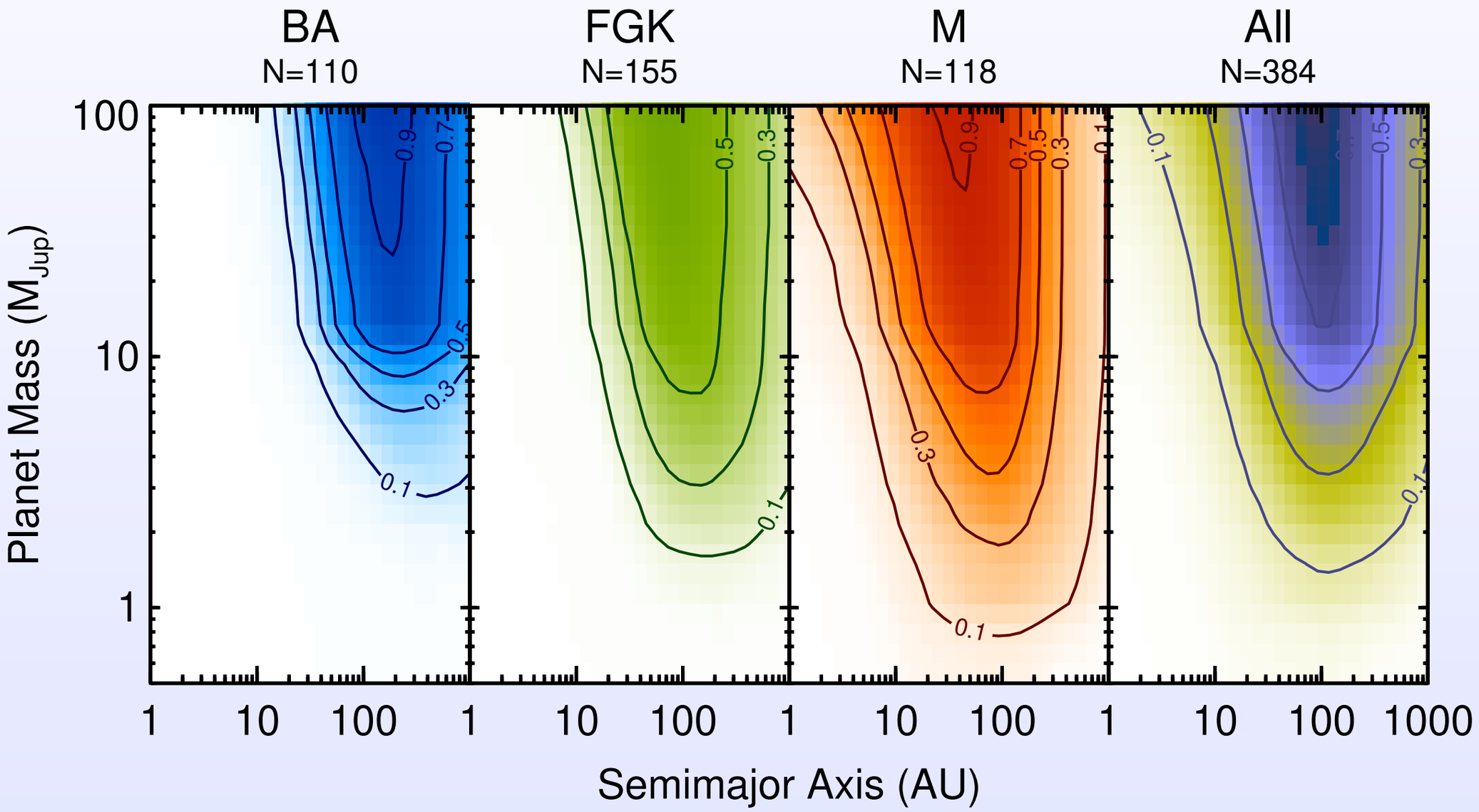

Bowler (2016)

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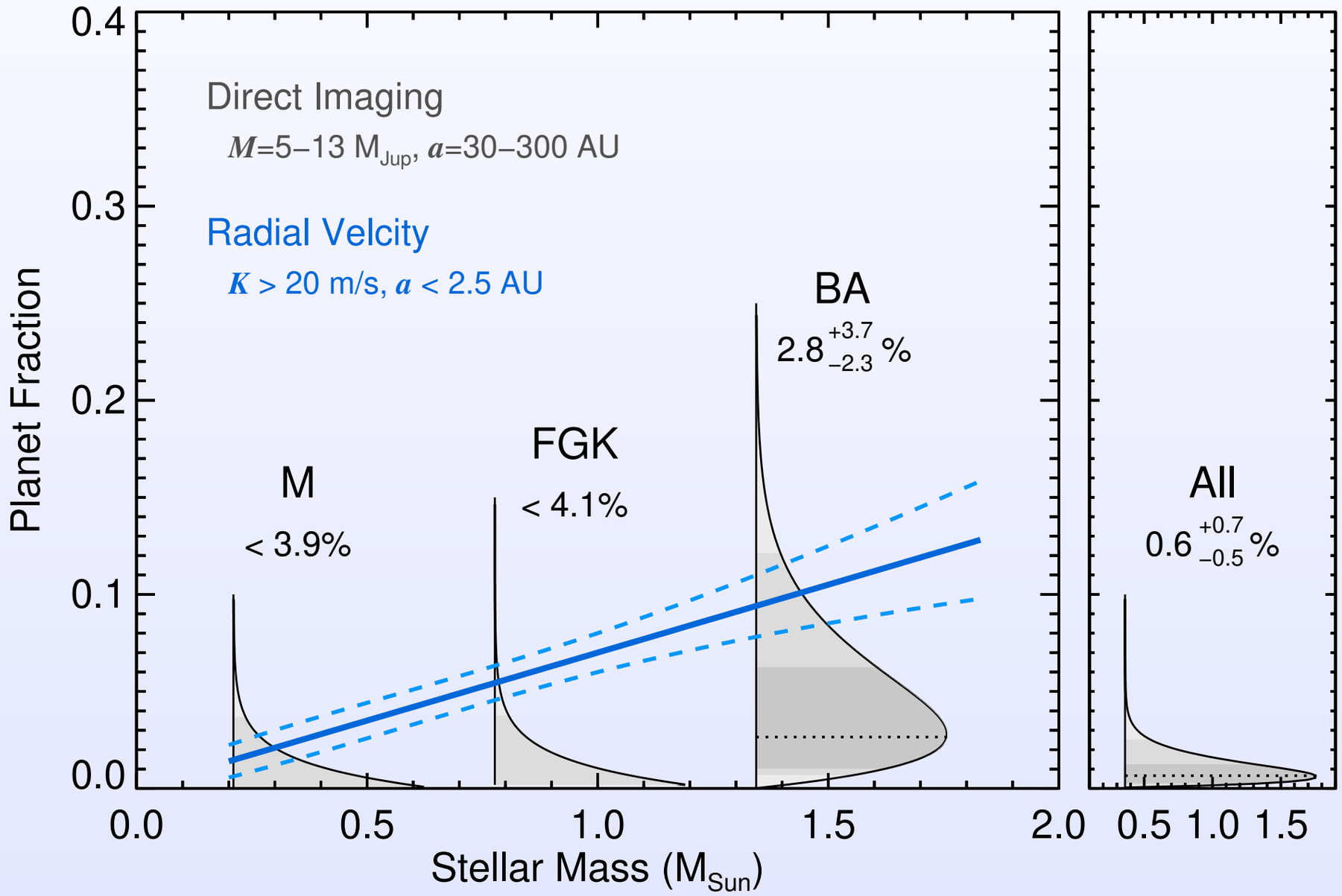
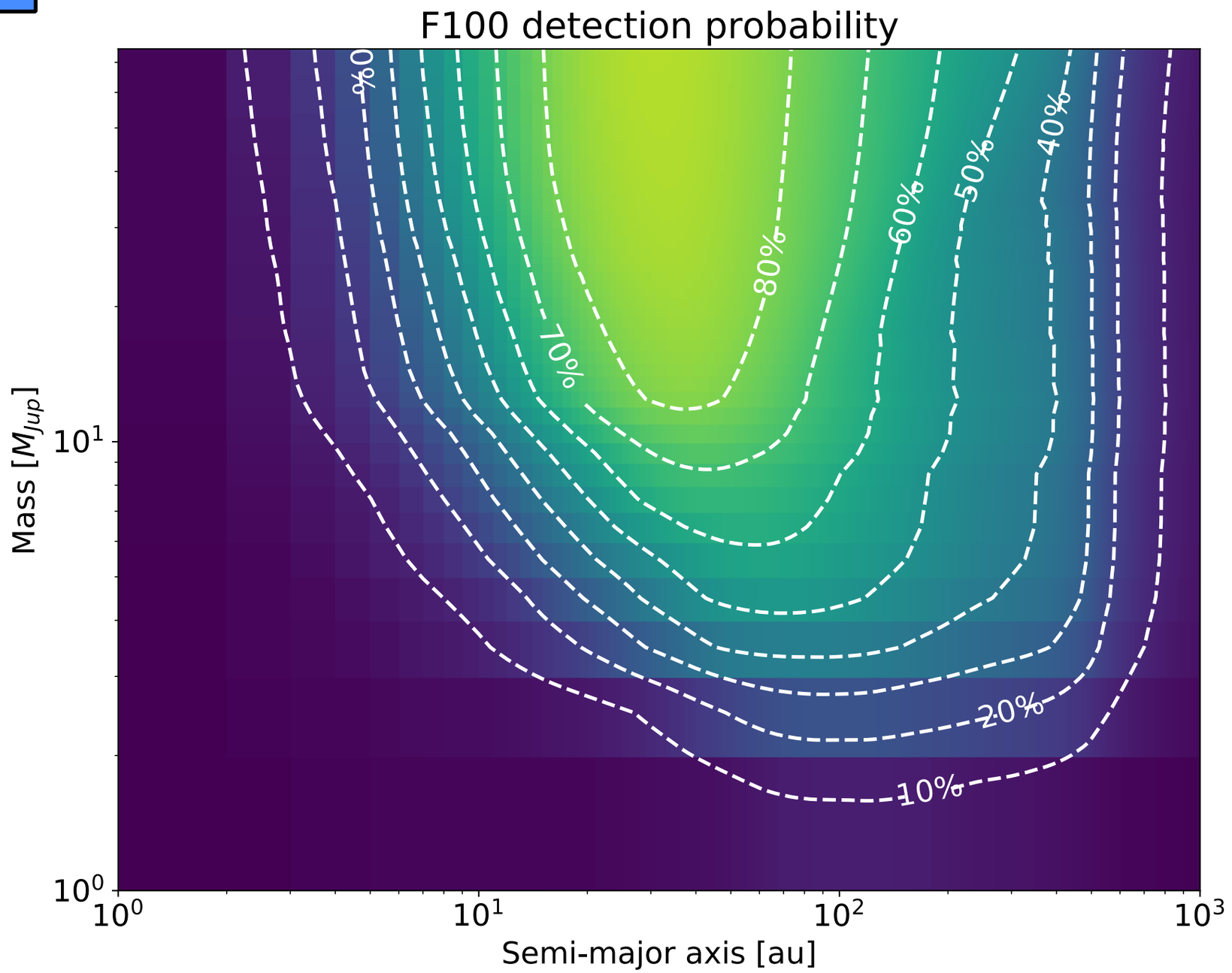


Bowler (2016)

Occurence rate from SHINE

IFS only!

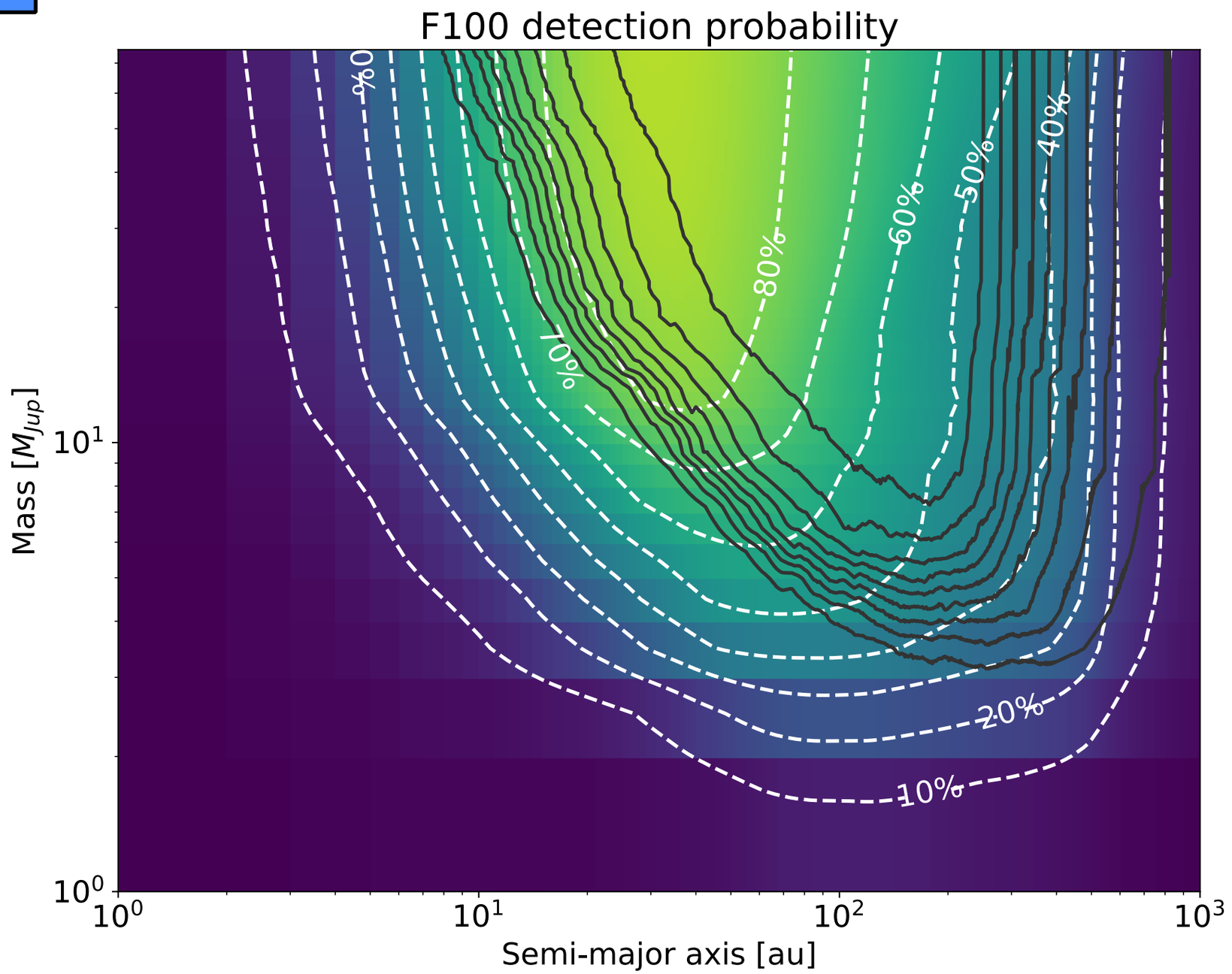


~150 stars, all spectral types

Vigan et al. (in prep)

Detection probability from SHINE

IFS only!



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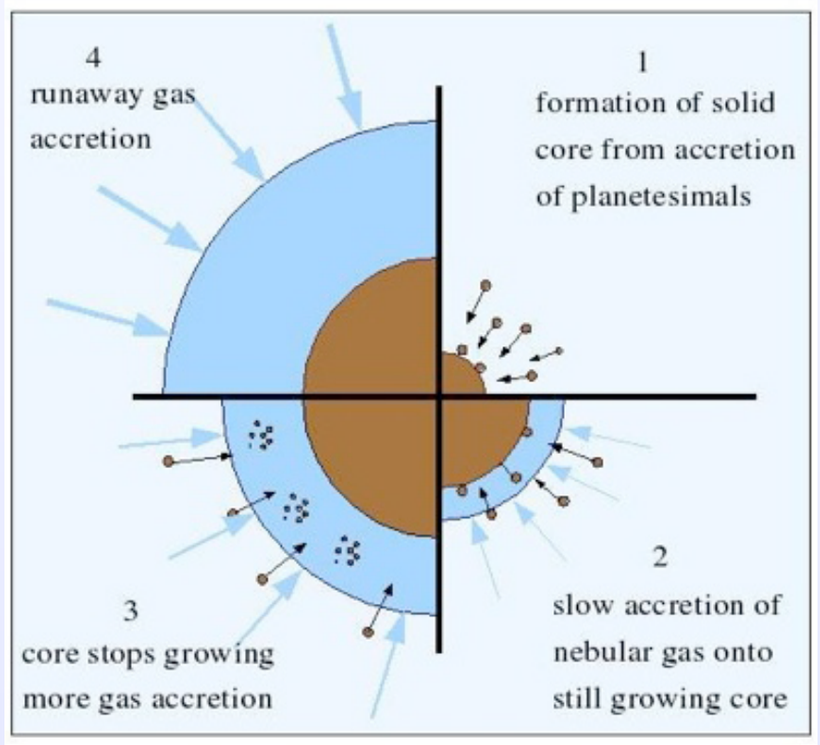
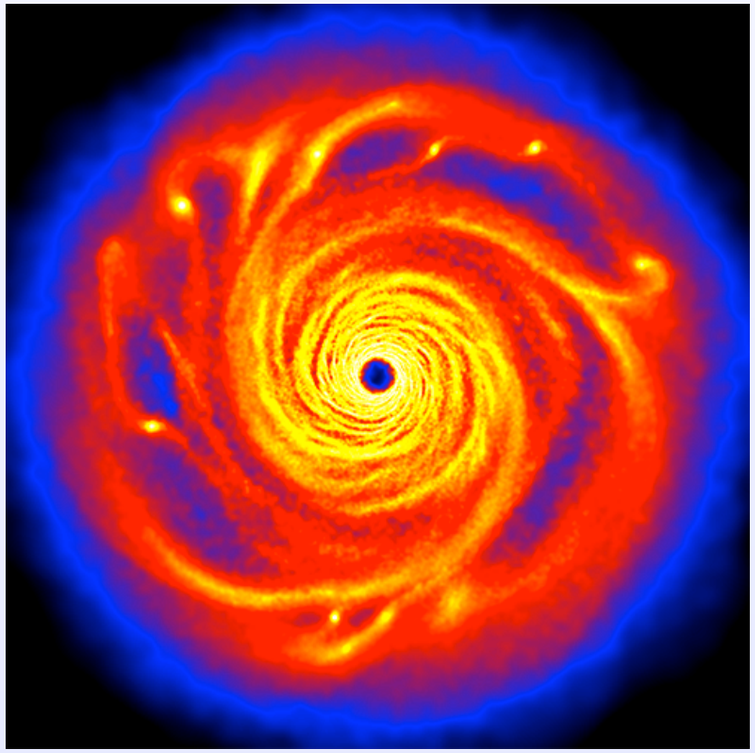
Link to formation models

Can direct imaging observations constrain formation models?

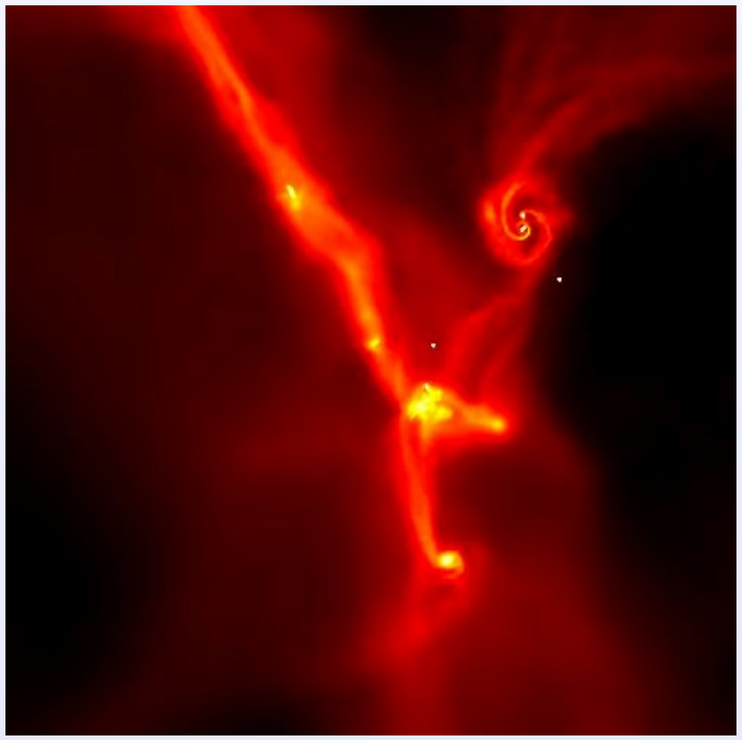
Core Accretion
Pollack et al. 1994



Gravitational Instability
Cameron 1978

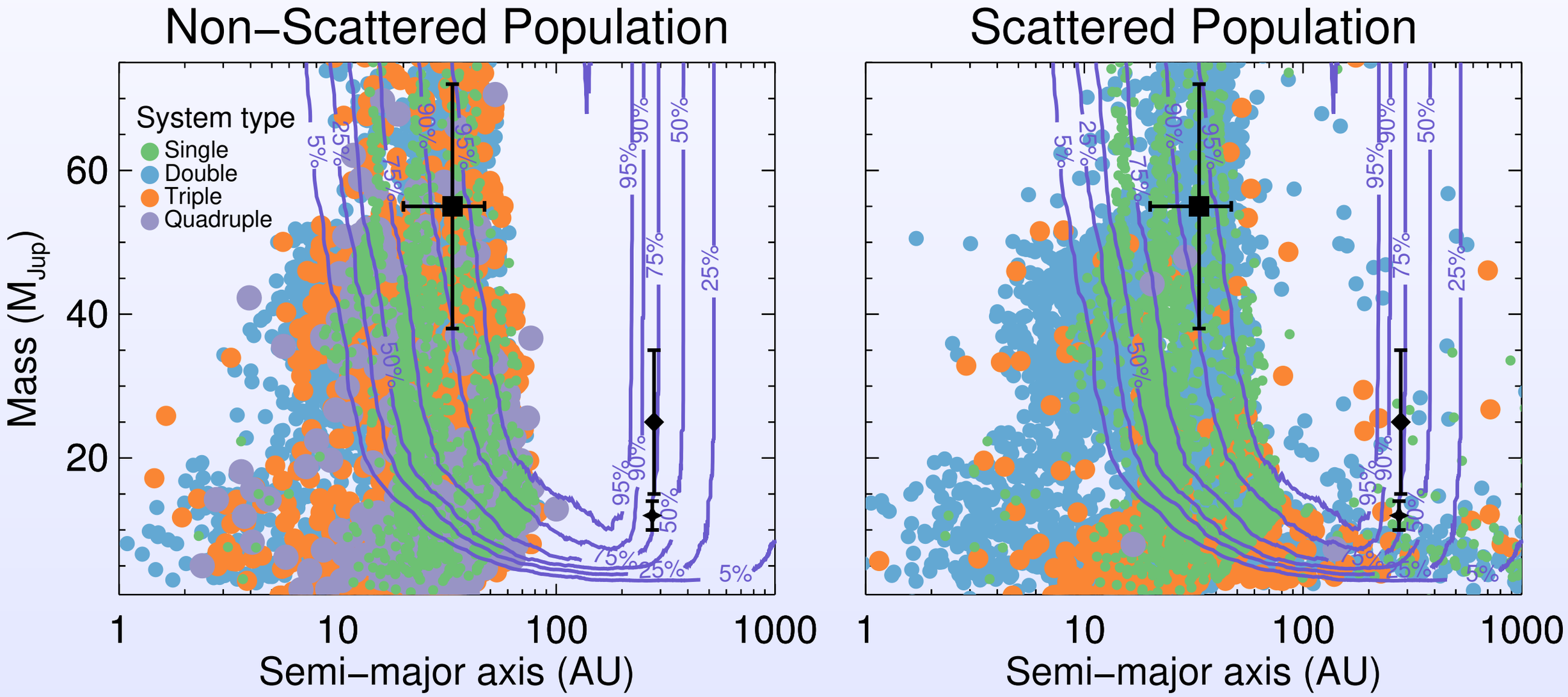


Gravo-turbulent fragmentation
Hennebelel & Chabrier 2011



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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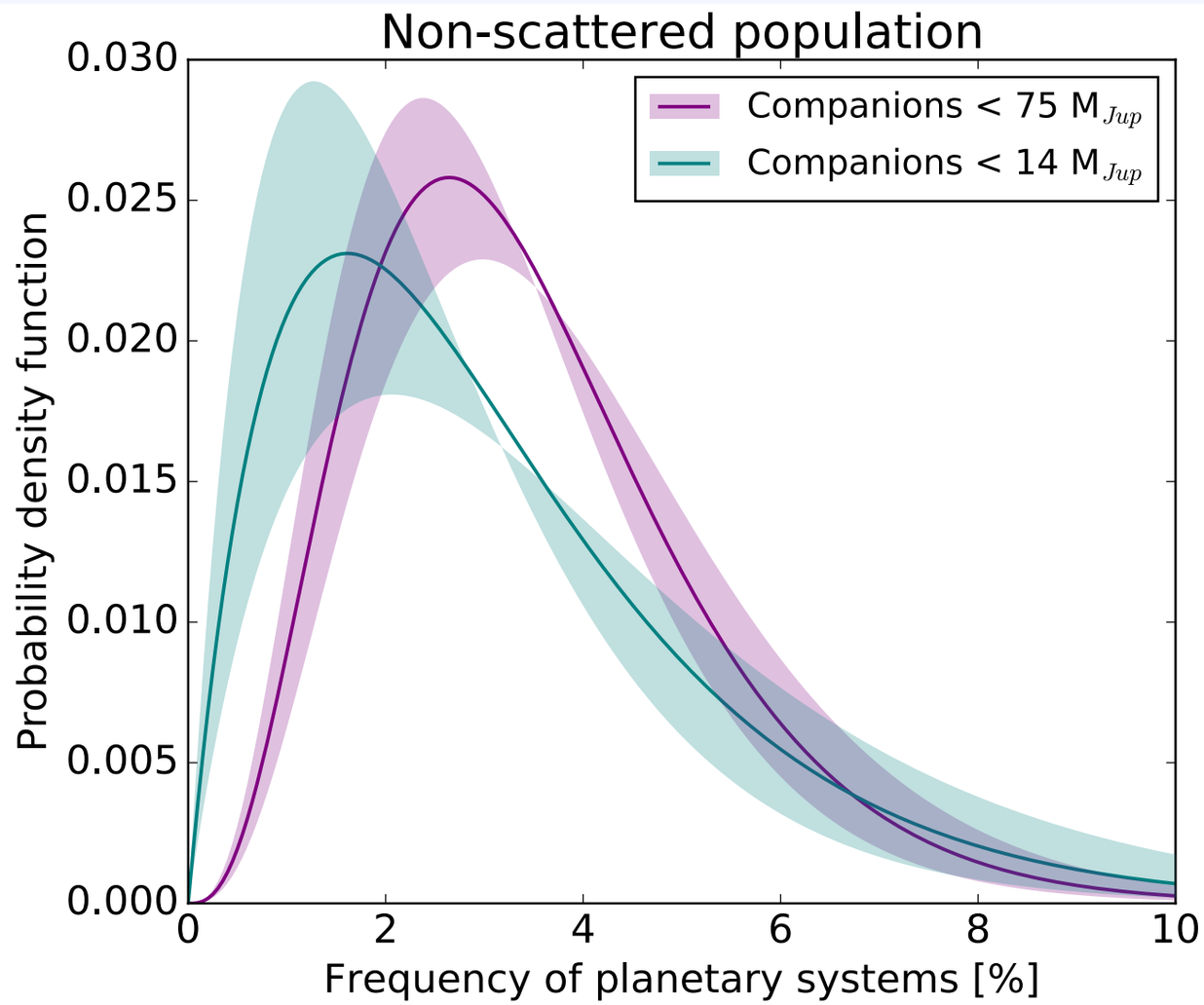

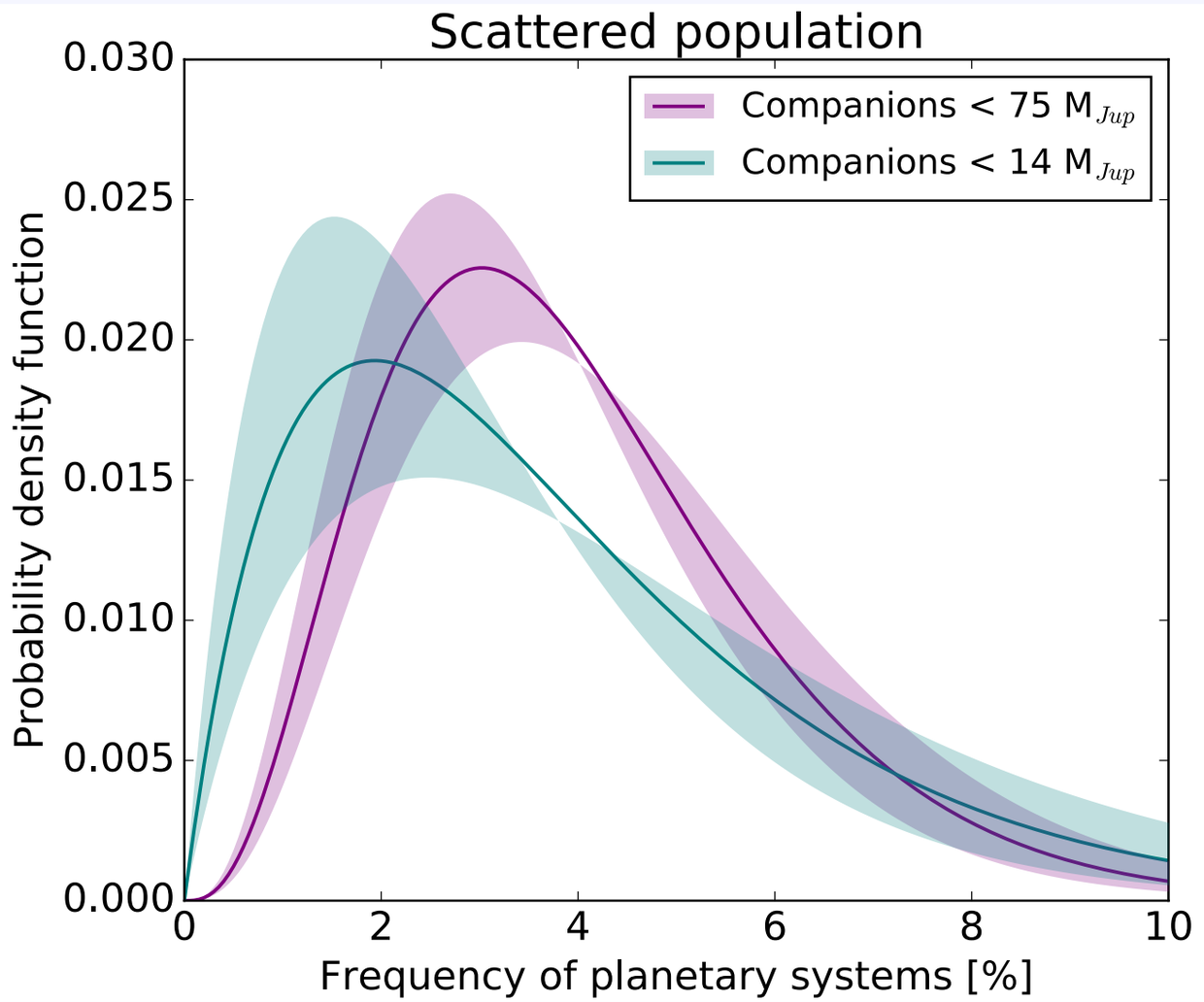

Vigan et al. (2017)

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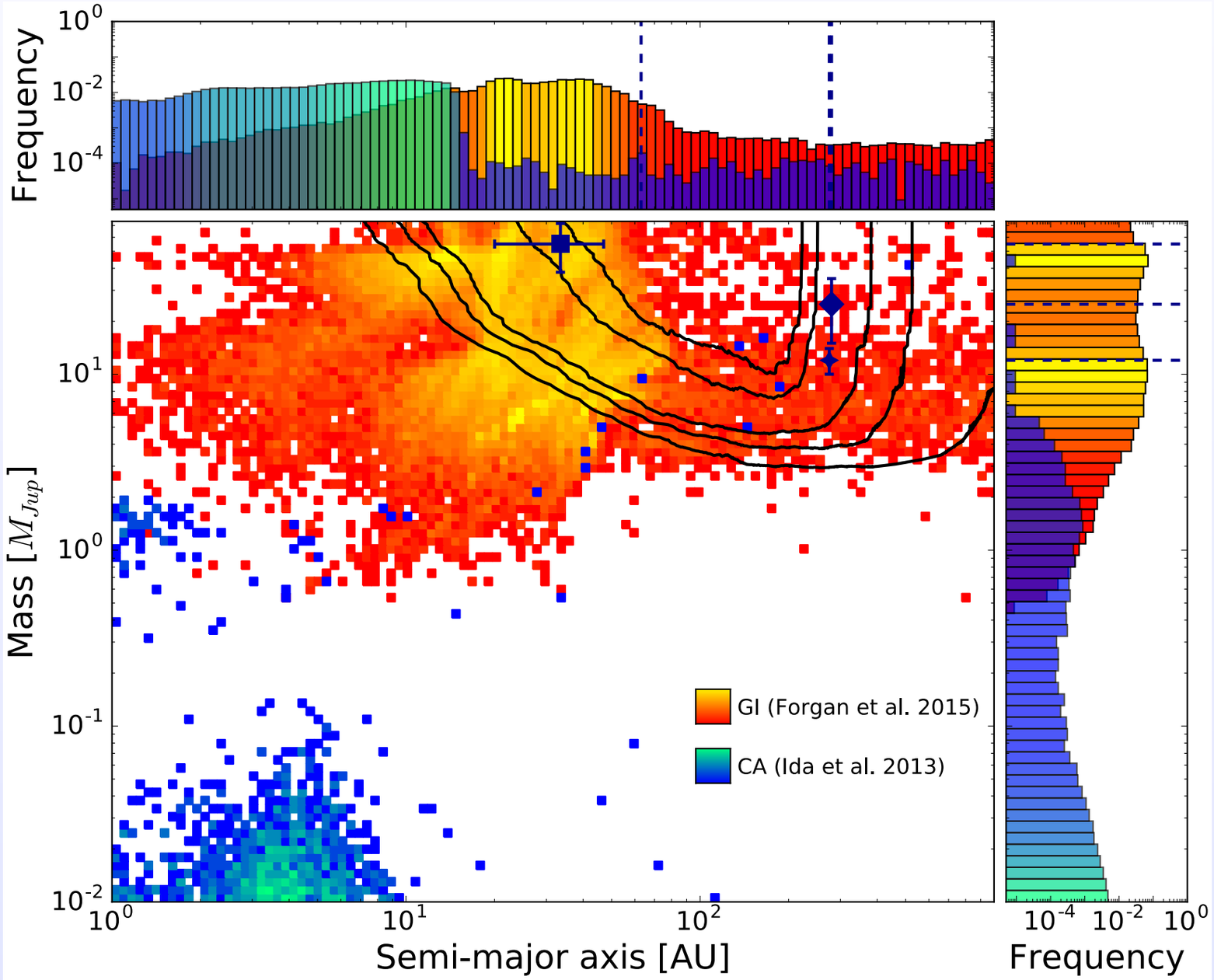
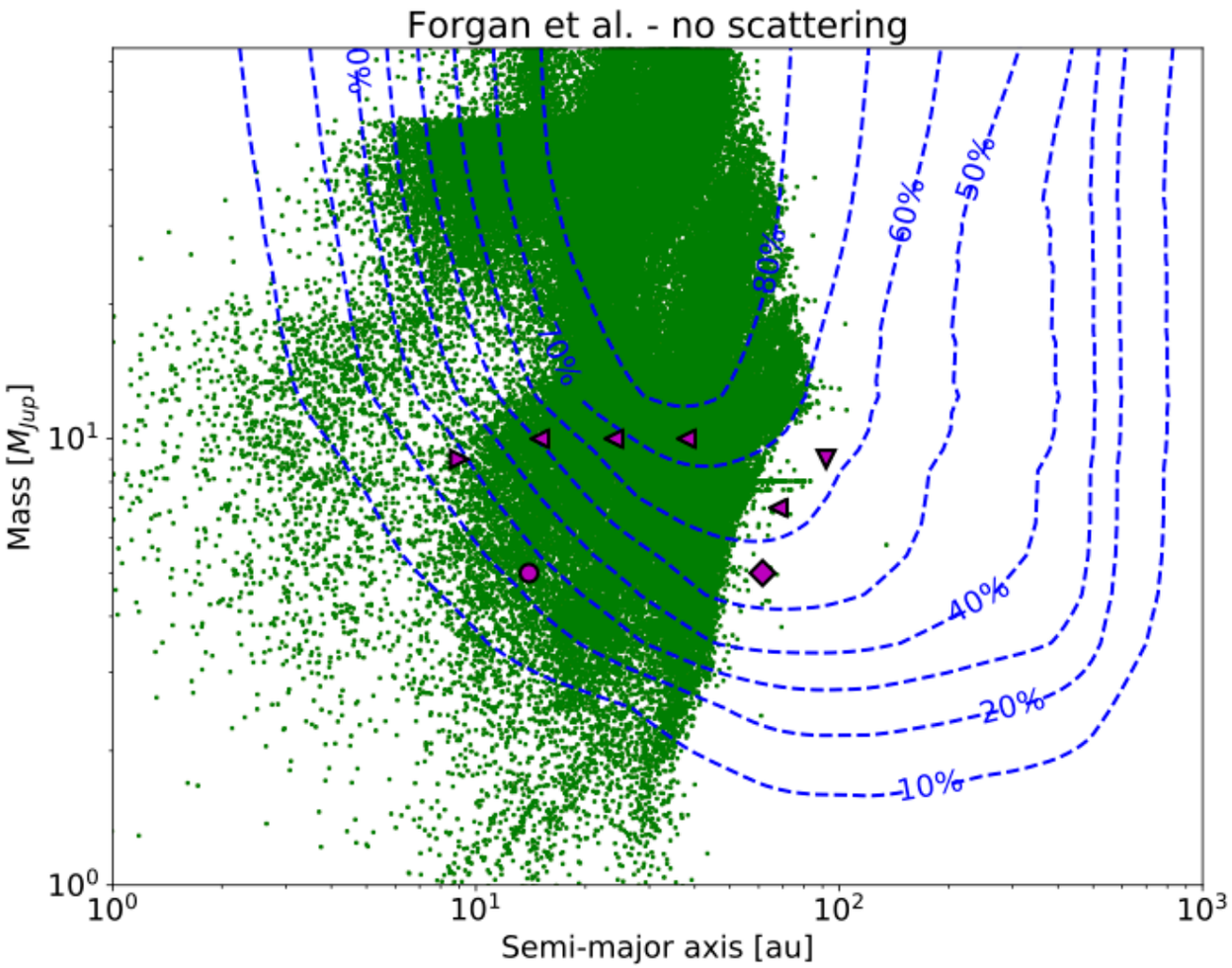


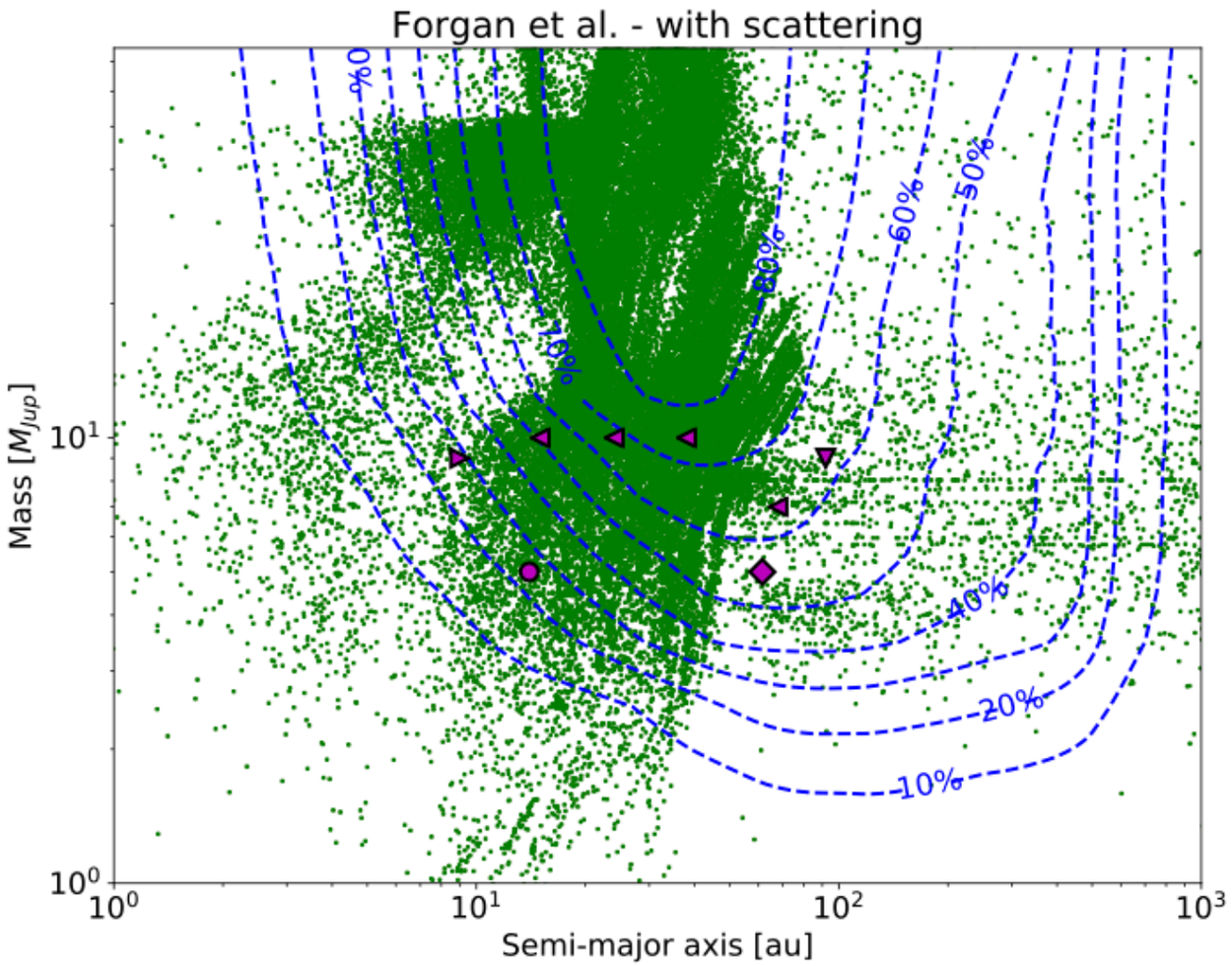
- GI not dominant!
- CA accretion not accessible
- Alternatives?
  - multi fragmentation GI
  - pebble accretion
  - dynamical evolution

Vigan et al. (2017)

Link to formation models: SHINE

Gravitational instability



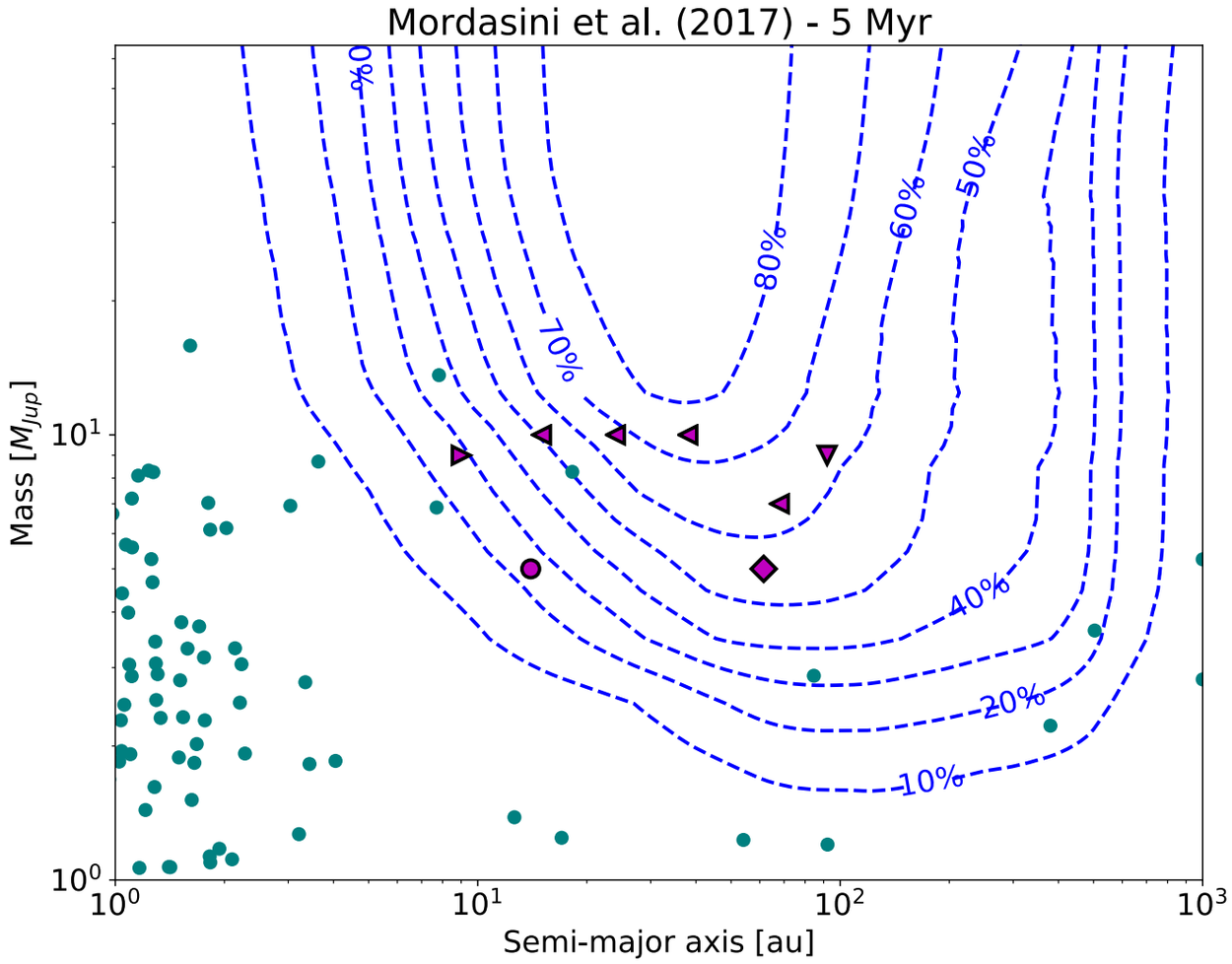


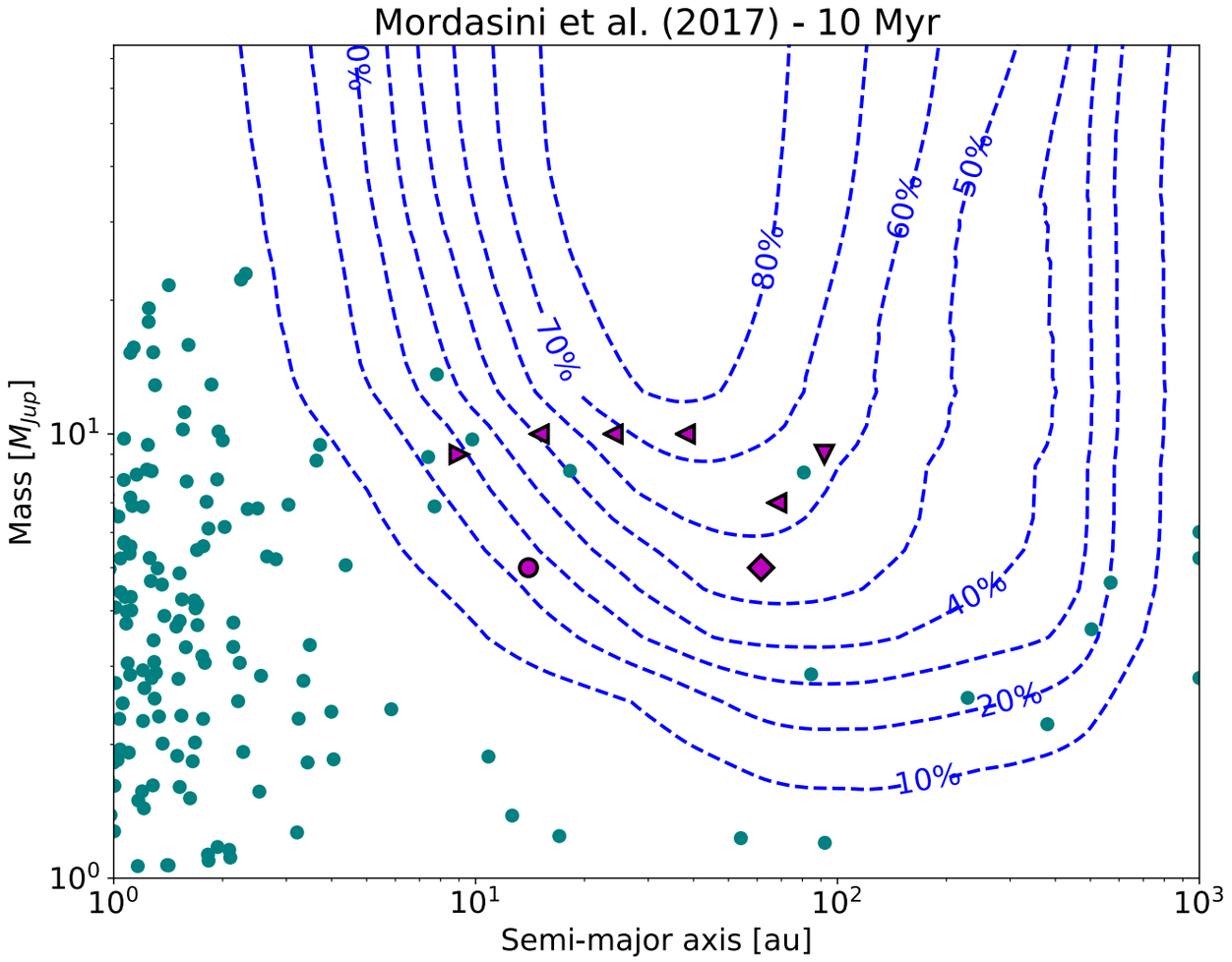
- State-of-the-art GI models by Forgan et al.
- Solar-type stars
- Semi-analytical scattering with systems up to 5 planets

Vigan et al. (in prep)

Link to formation models: SHINE

Core accretion



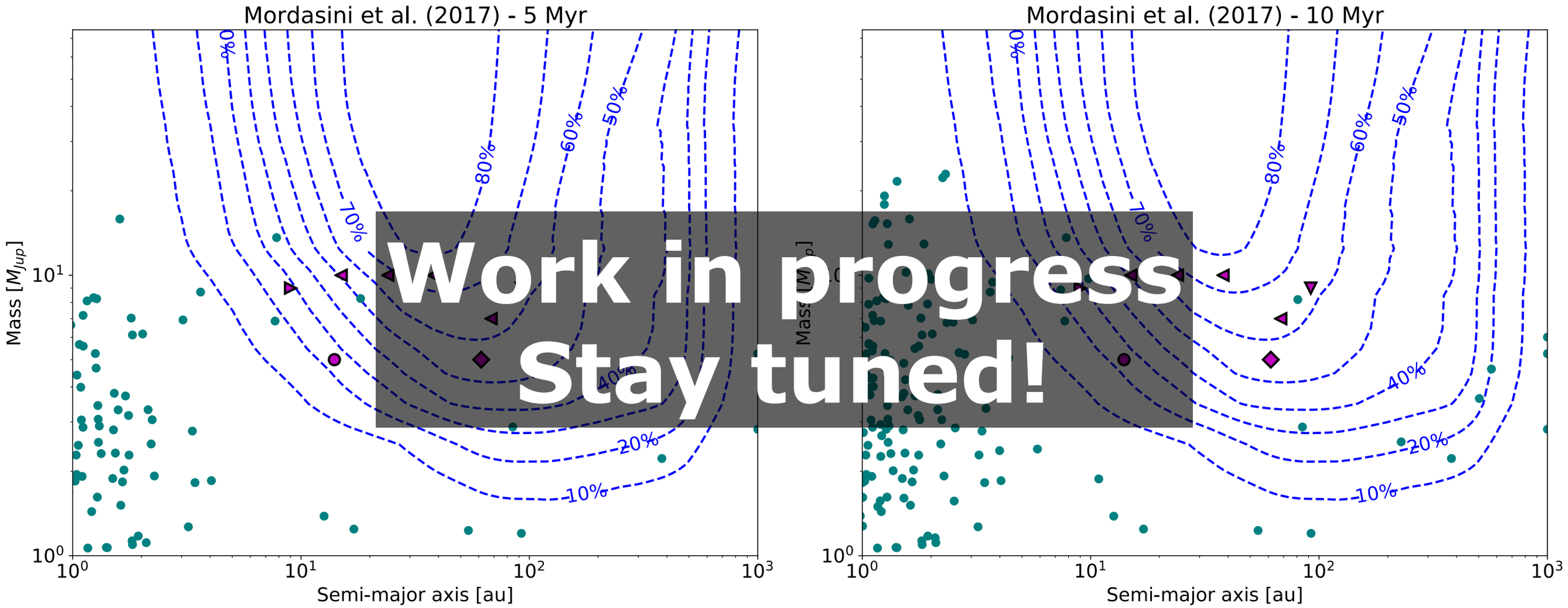


- State-of-the-art CA models by Mordasini et al.
- 0.5, 1.0, 2.0 M_{Sun}
- 10 embryos/disk, evolution from 0 to 1 Gyr

Vigan et al. (in prep)

Link to formation models: SHINE

Core accretion



Work in progress

Stay tuned!

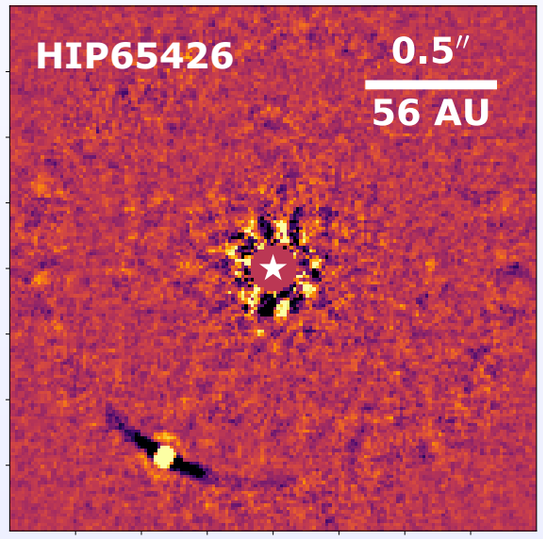
- State-of-the-art CA models by Mordasini et al.
- 0.5, 1.0, 2.0 M_{Sun}
- 10 embryos/disk, evolution from 0 to 1 Gyr

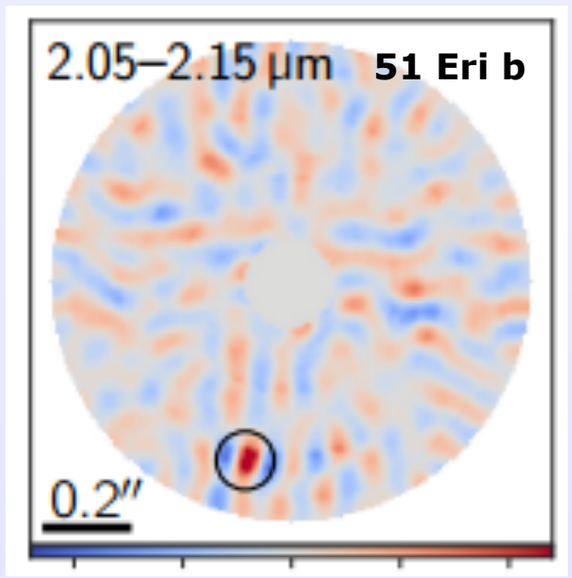
Vigan et al. (in prep)

Future

2 main directions

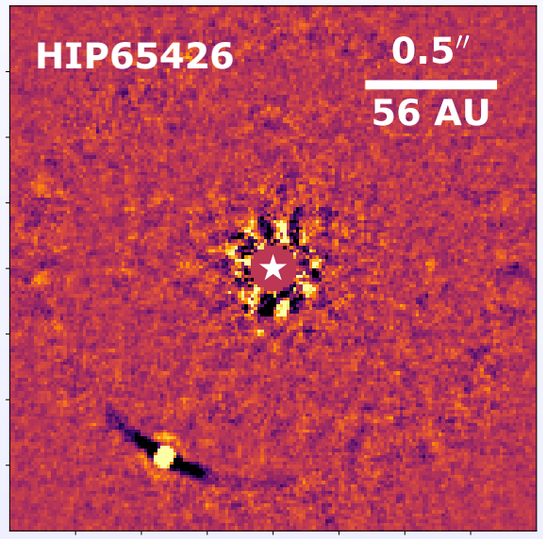
1. More planets!!

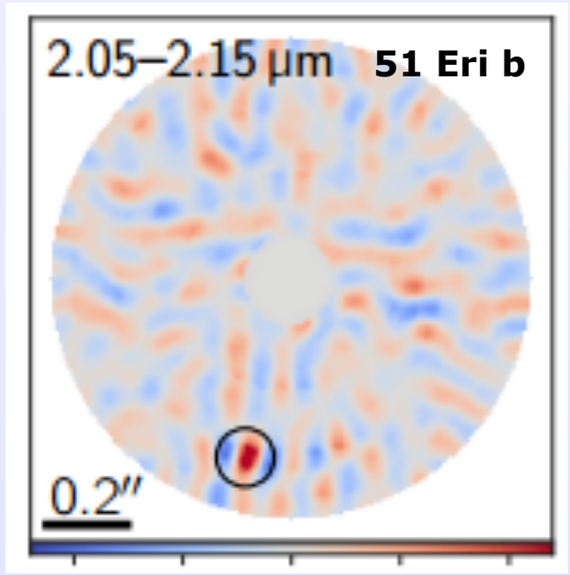




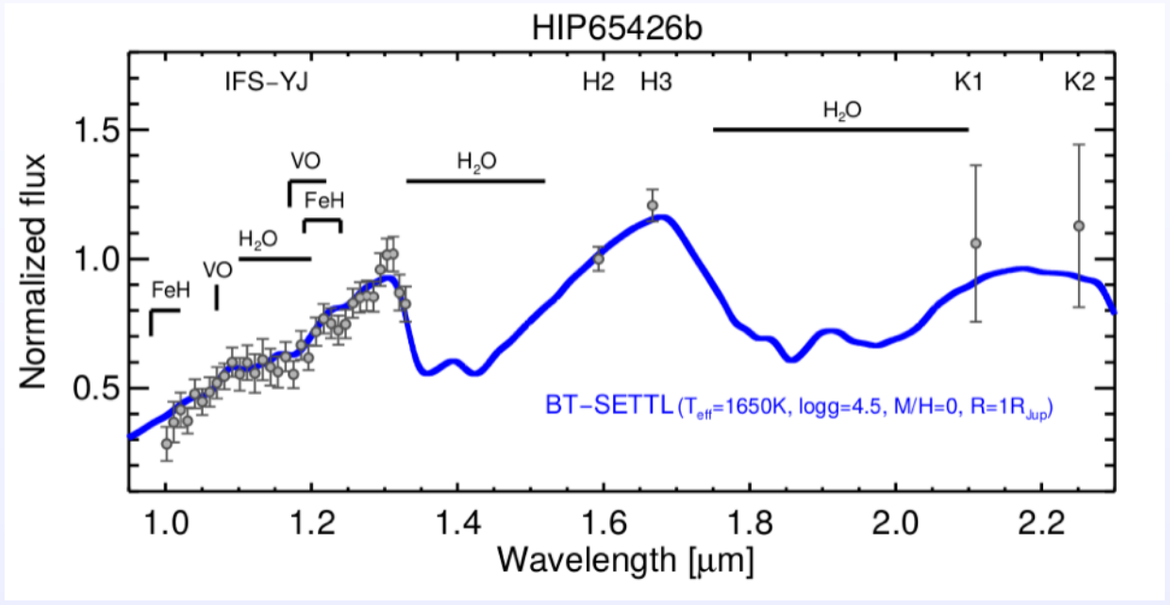
2 main directions

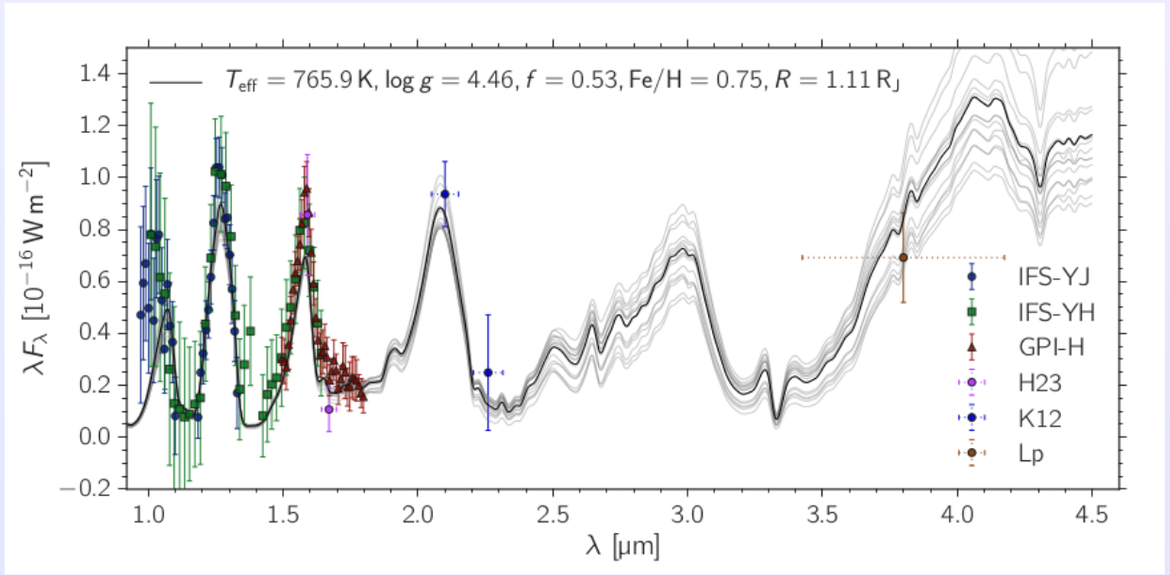
1. More planets!!



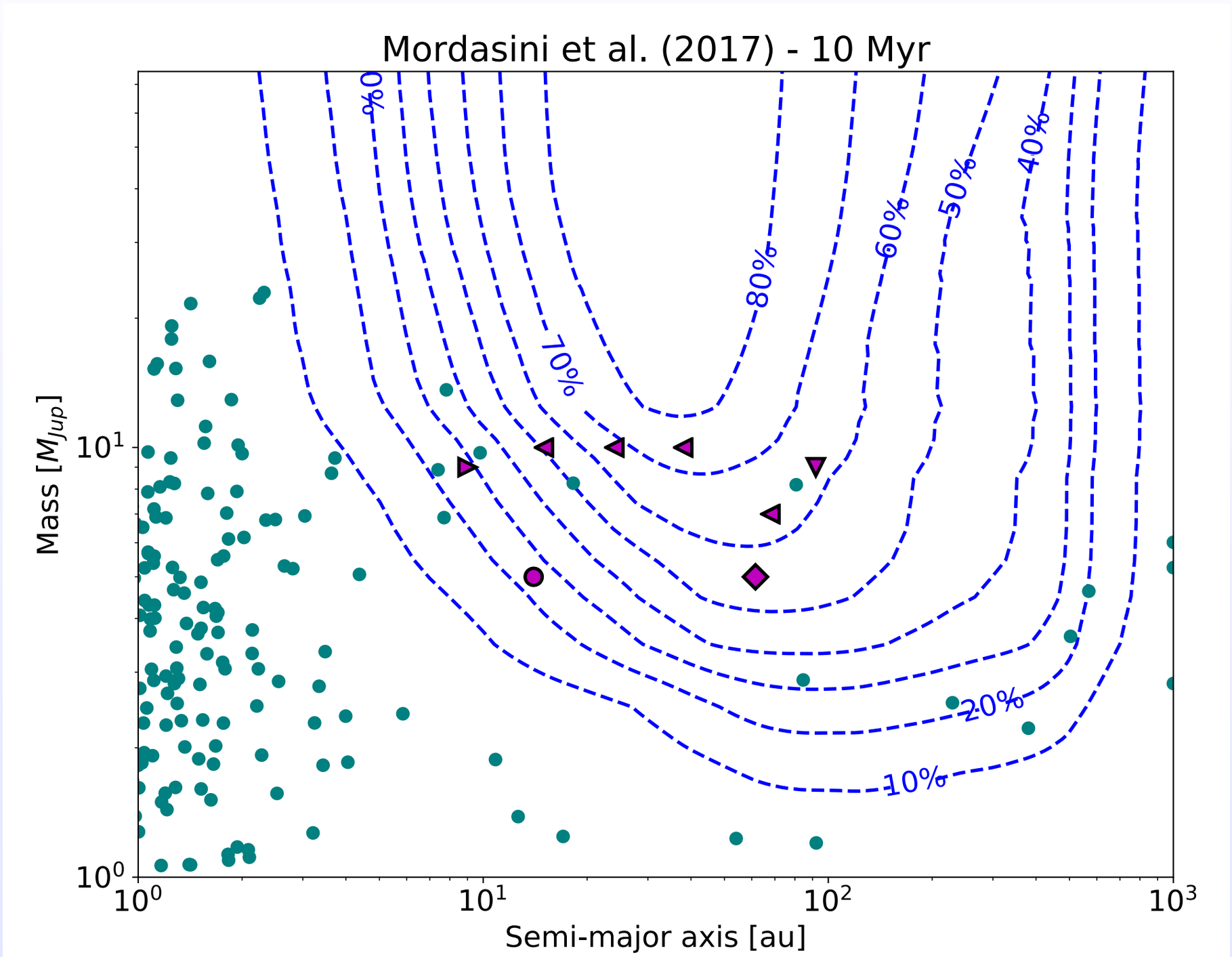


2. Better characterization

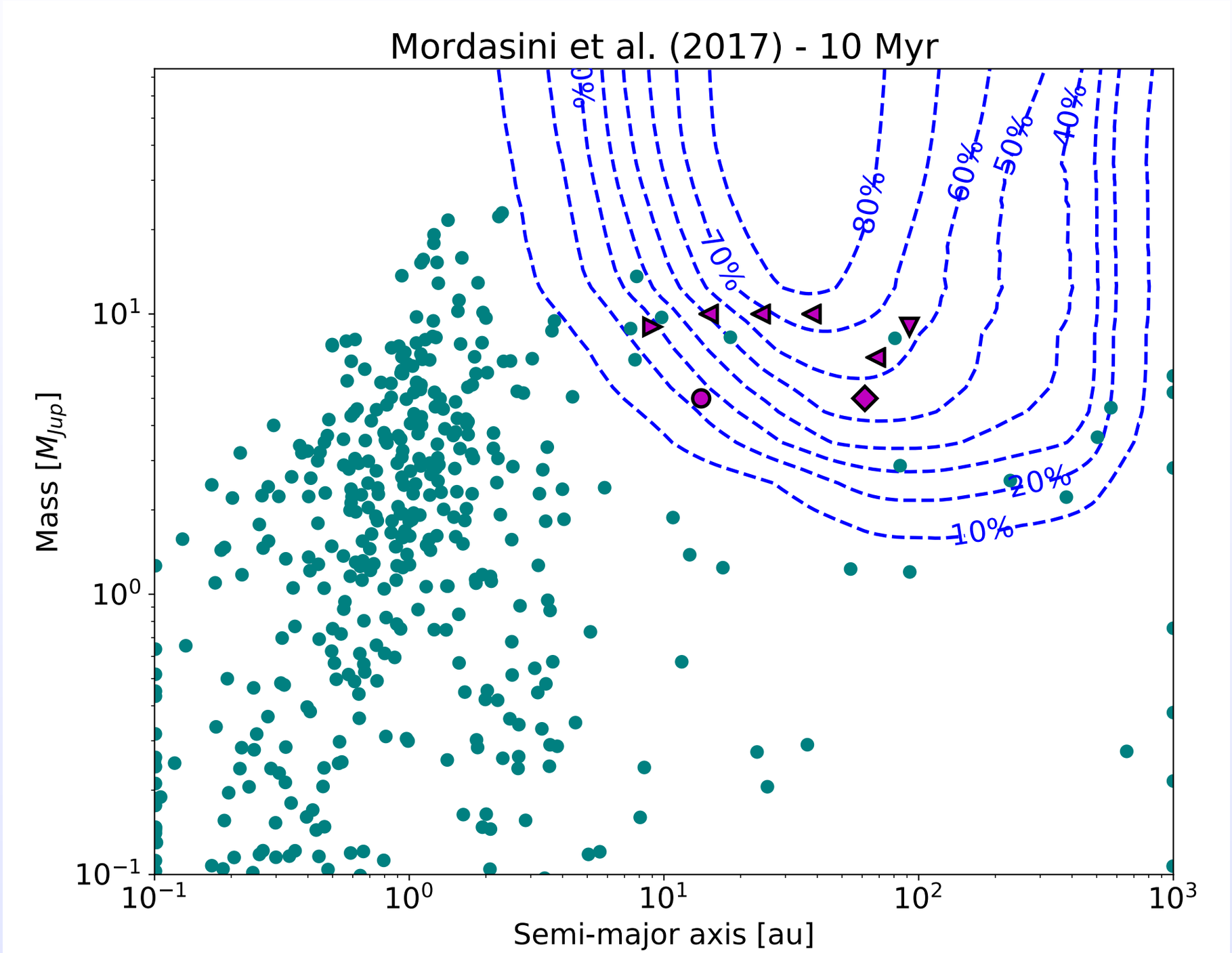




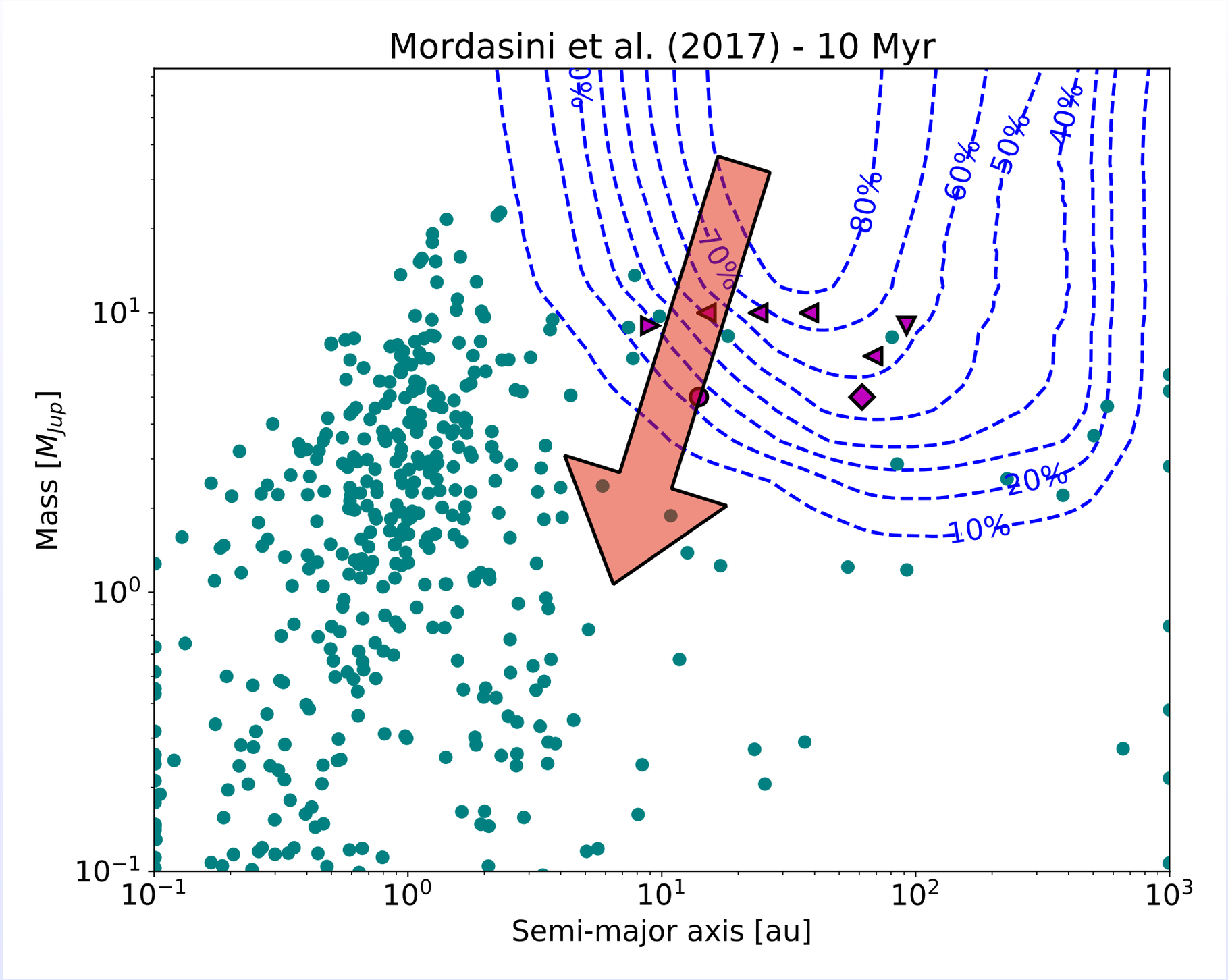
More planets: closer, deeper



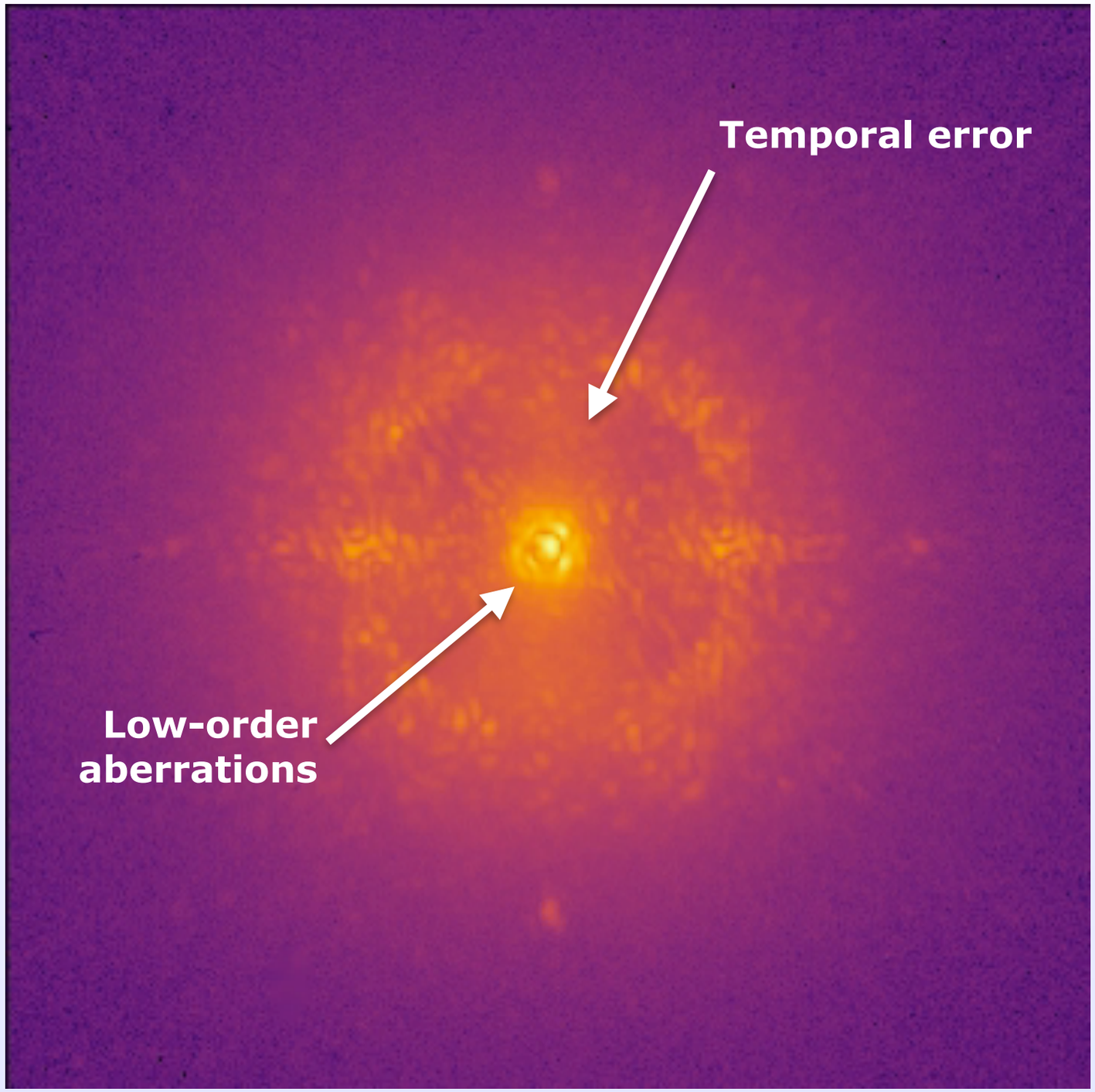
More planets: closer, deeper



More planets: closer, deeper



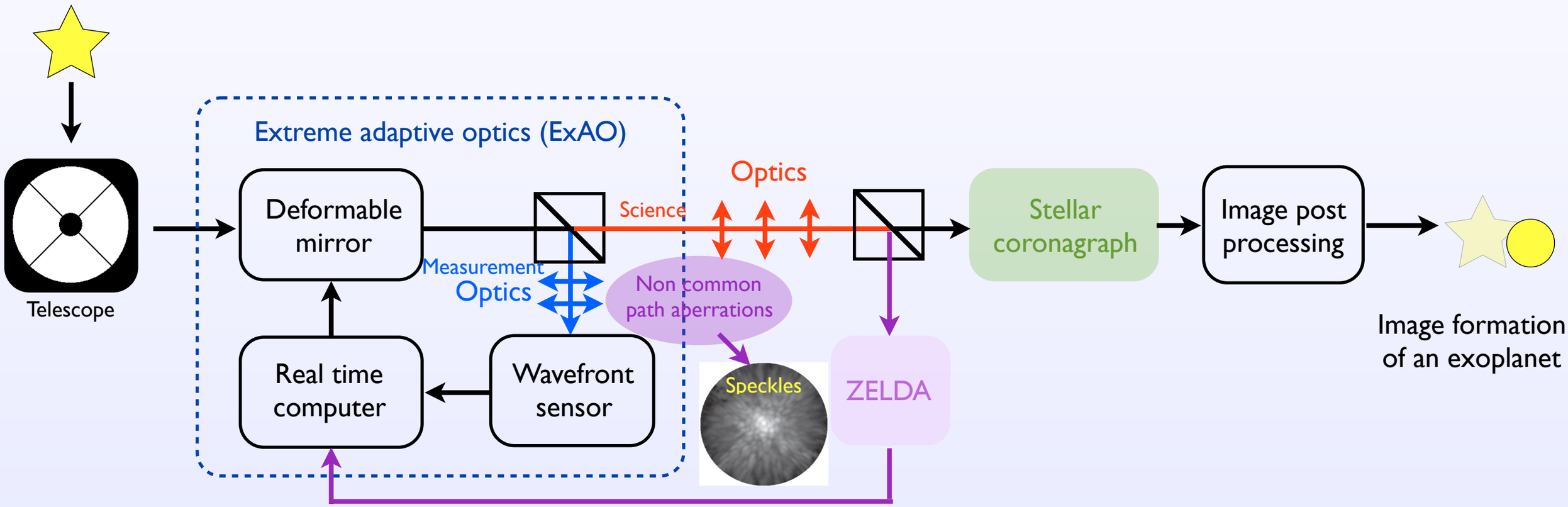
Current limitations



ZELDA: Zernike wavefront sensor

ZELDA

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

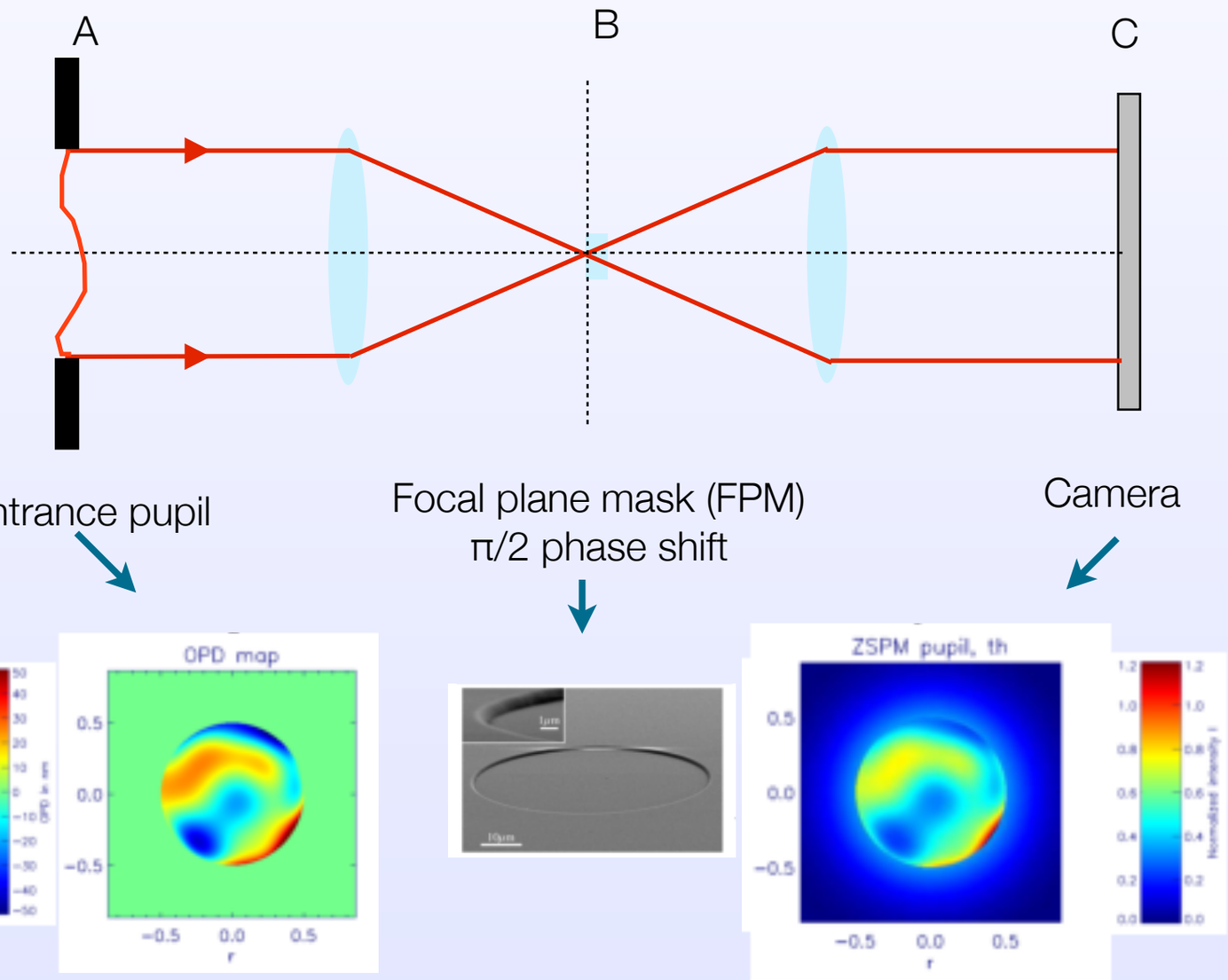


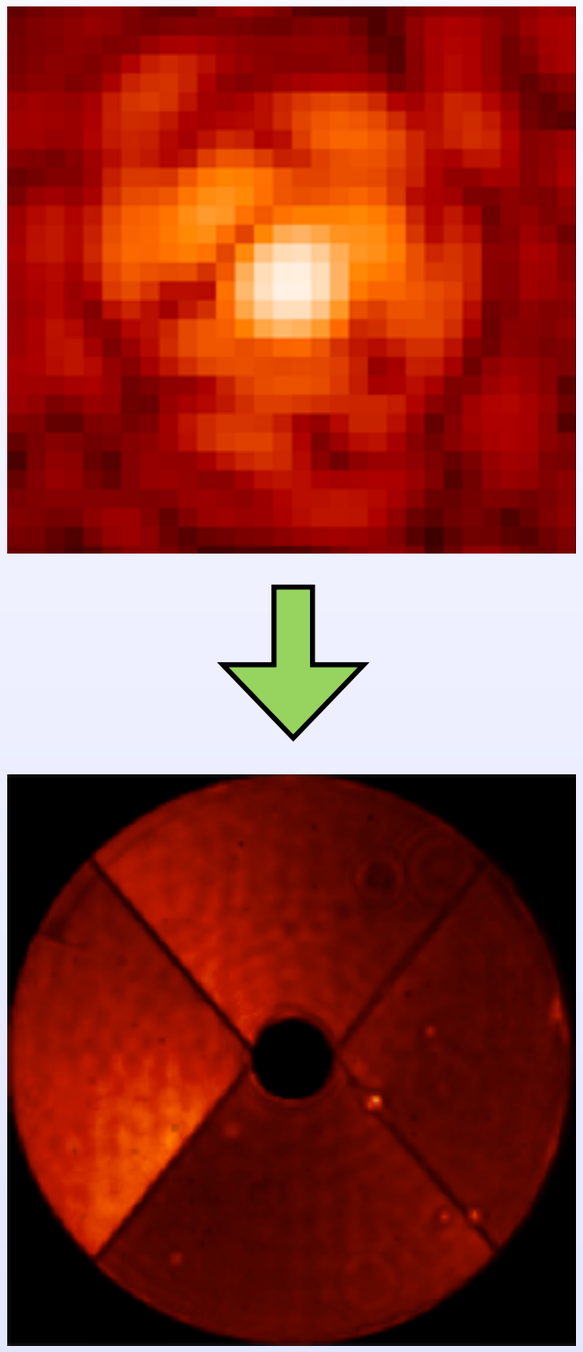
- Original measurement strategies:
  - VLT/SPHERE: off-line phase diversity
  - GPI: Mach-Zehnder interferometer behind coronagraph

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

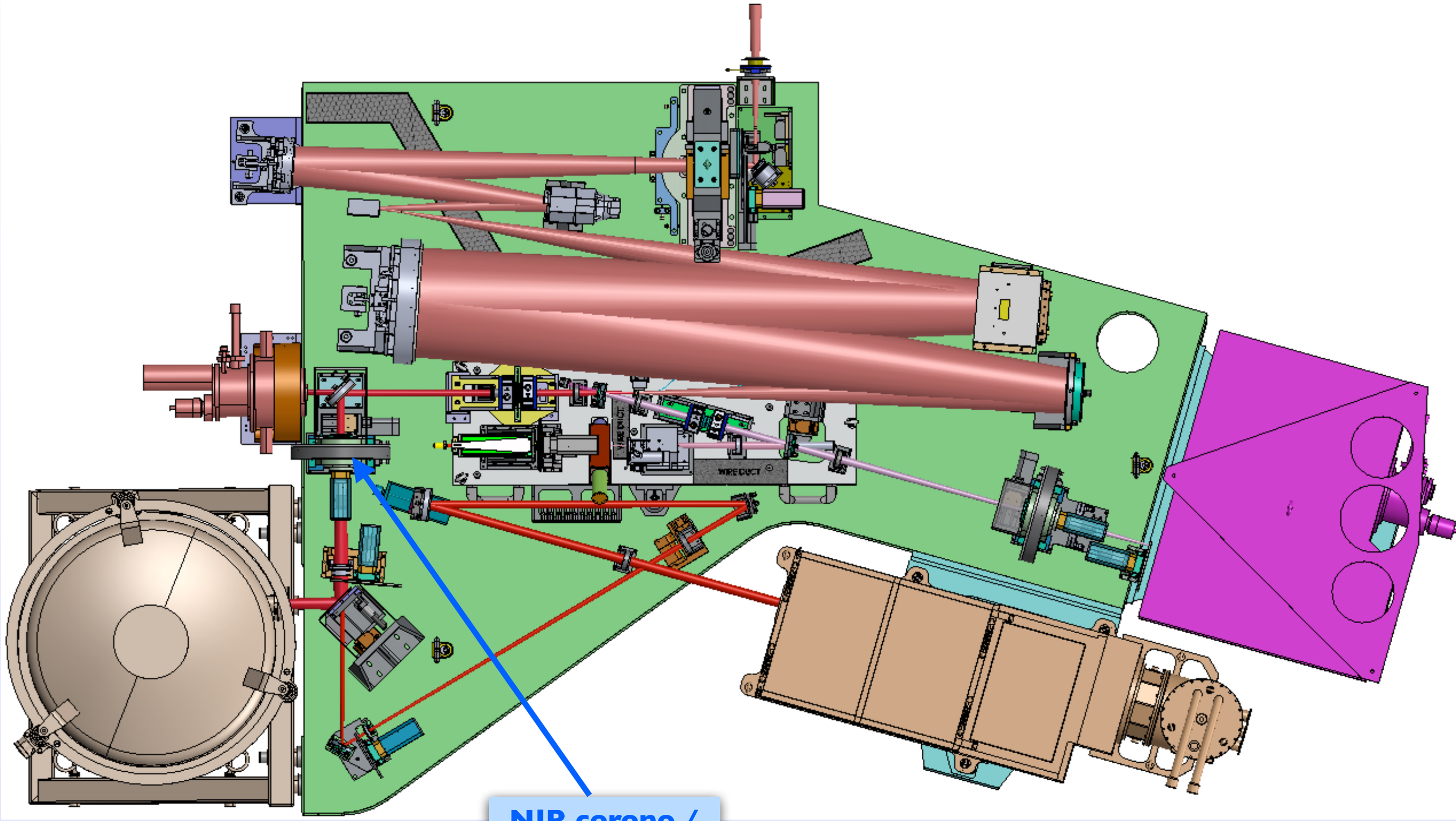
ZELDA: Zernike wavefront sensor

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



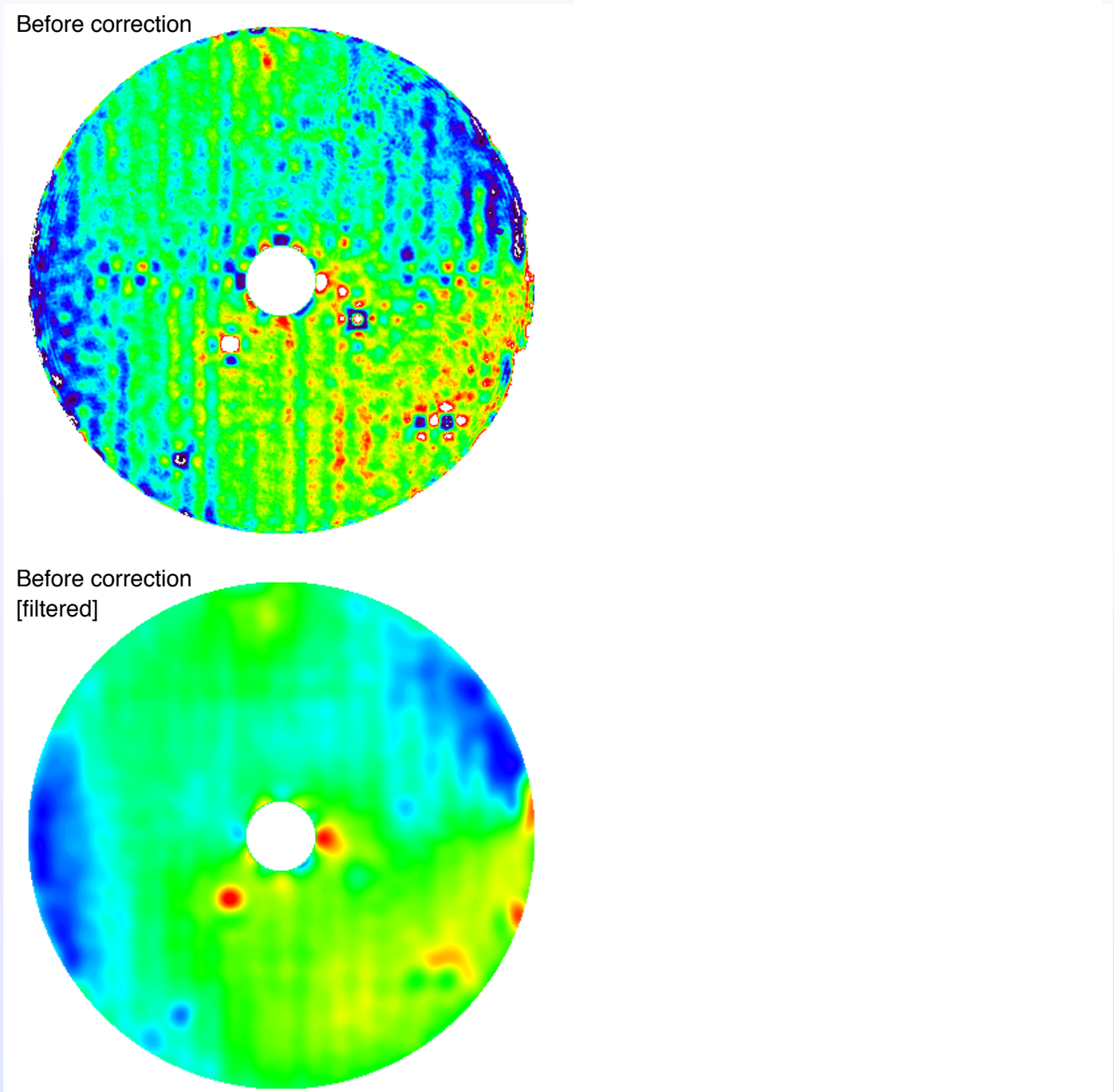


ZELDA in SPHERE



NCPA compensation in SPHERE

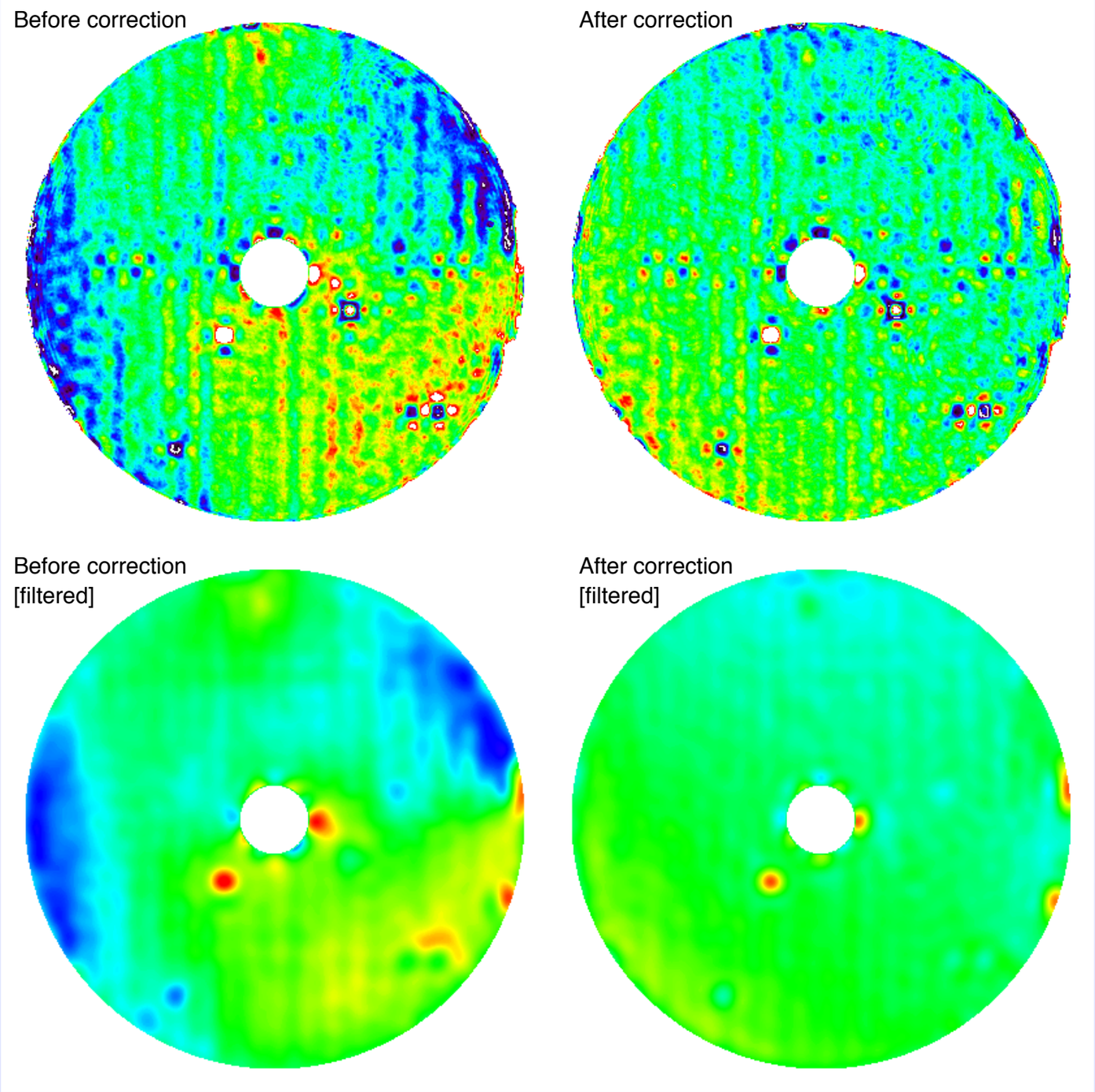
45 nm RMS



30 nm RMS

NCPA compensation in SPHERE

45 nm RMS



35 nm RMS

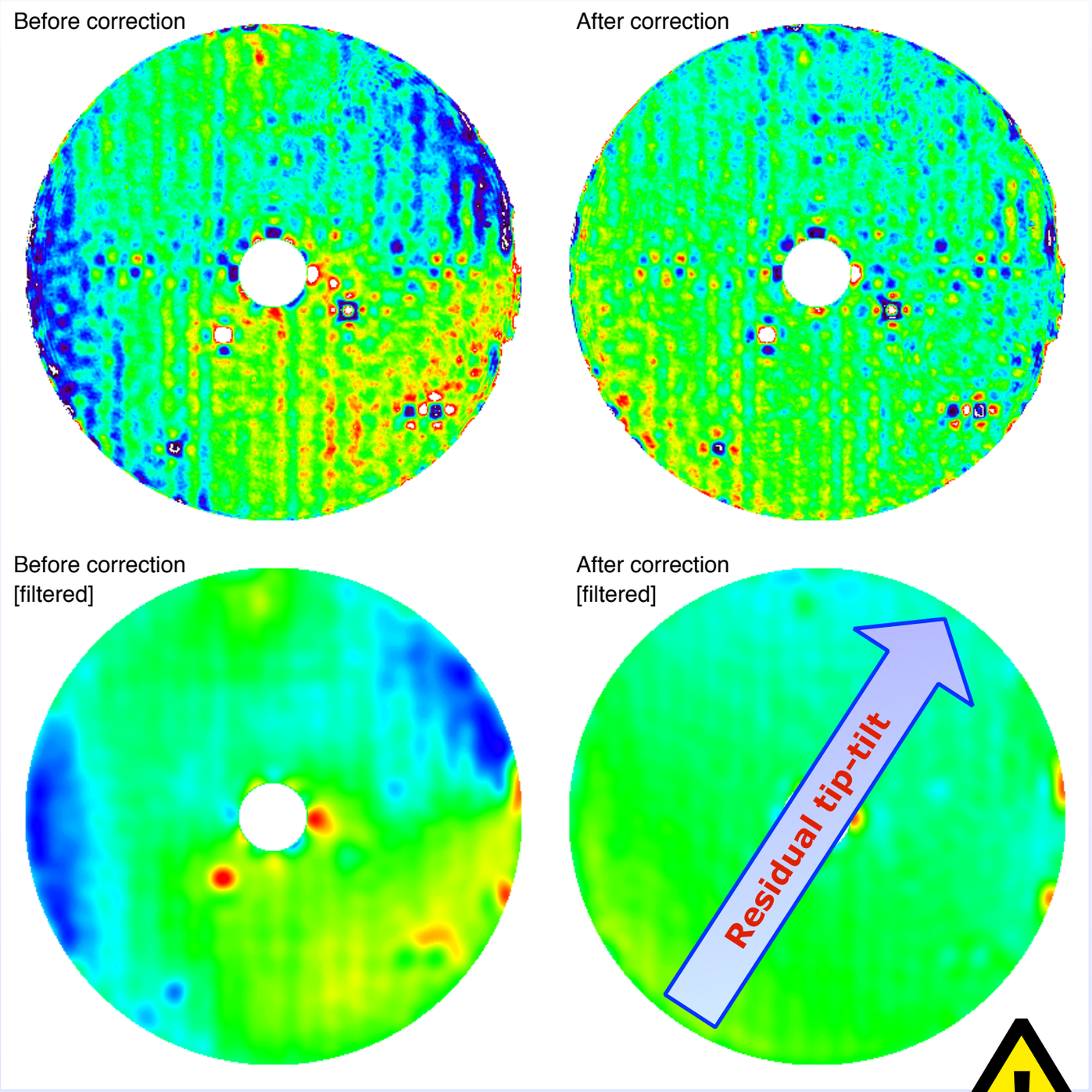
30 nm RMS

16 nm RMS

Tip-tilt:
~12 nm RMS

NCPA compensation in SPHERE

45 nm RMS



35 nm RMS

30 nm RMS

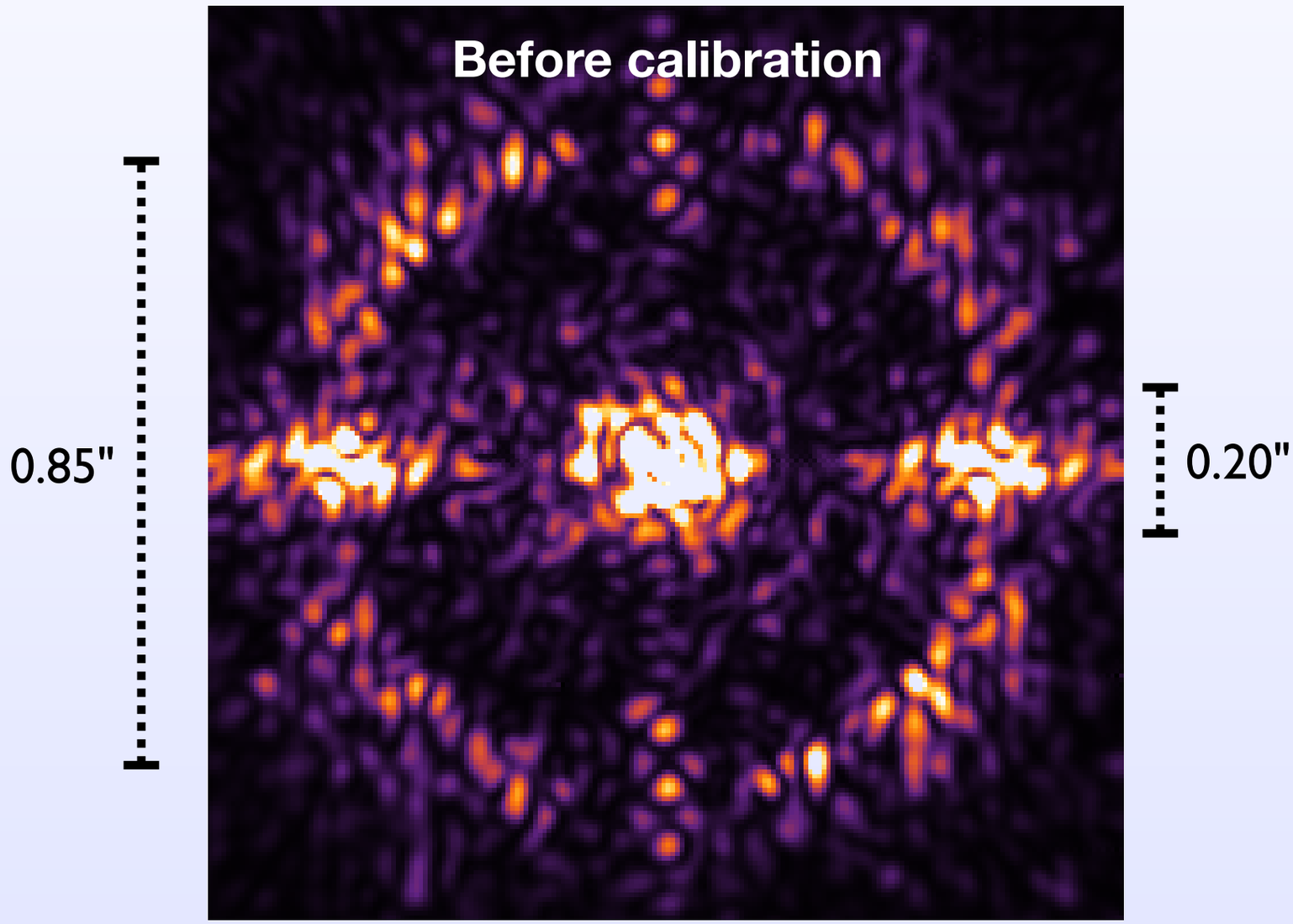
16 nm RMS

Tip-tilt:
~12 nm RMS

Manual centering + tip-tilt closed loop

NCPA compensation in SPHERE

Apodised pupil Lyot coronagraph, H-band



NCPA compensation in SPHERE

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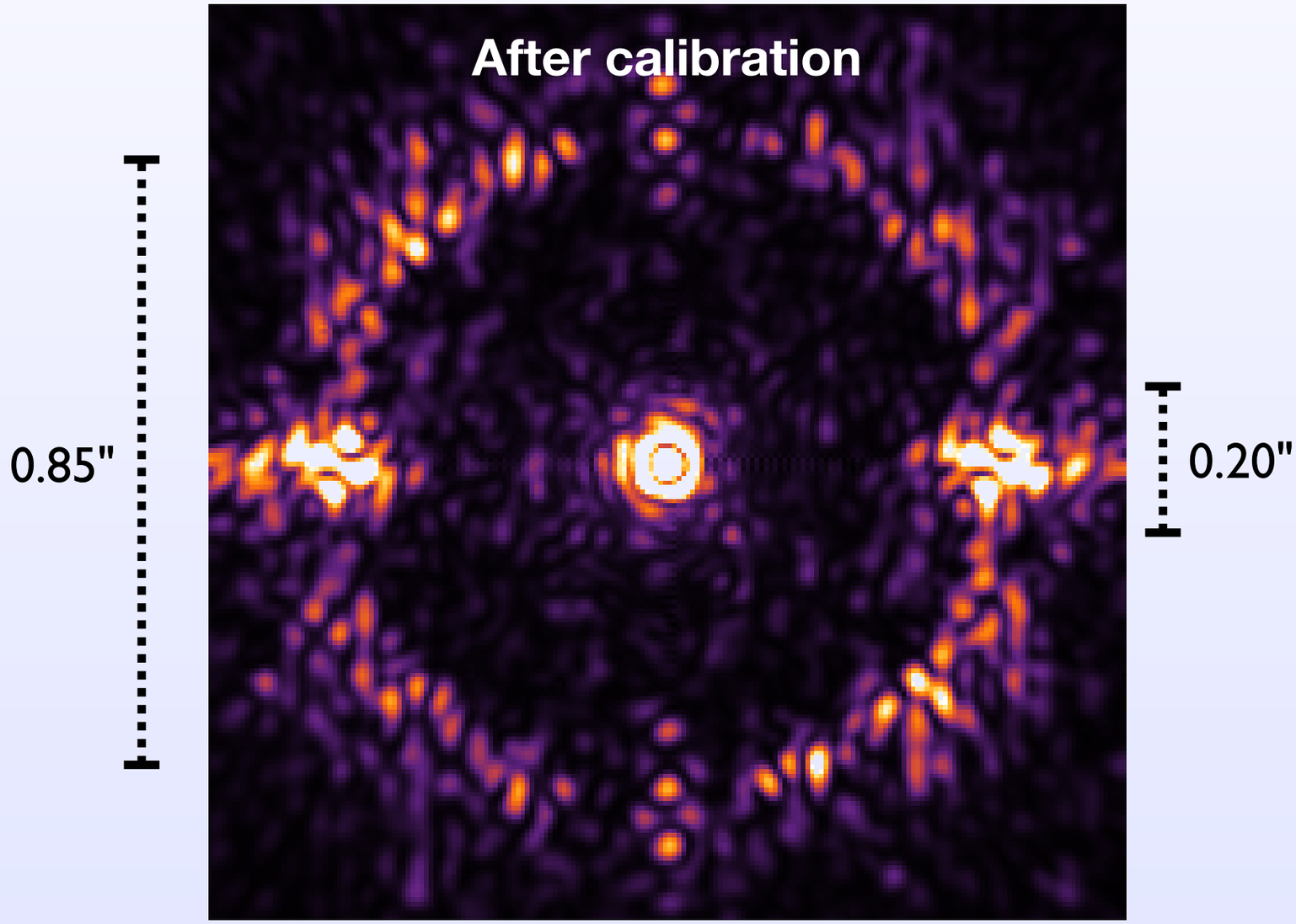
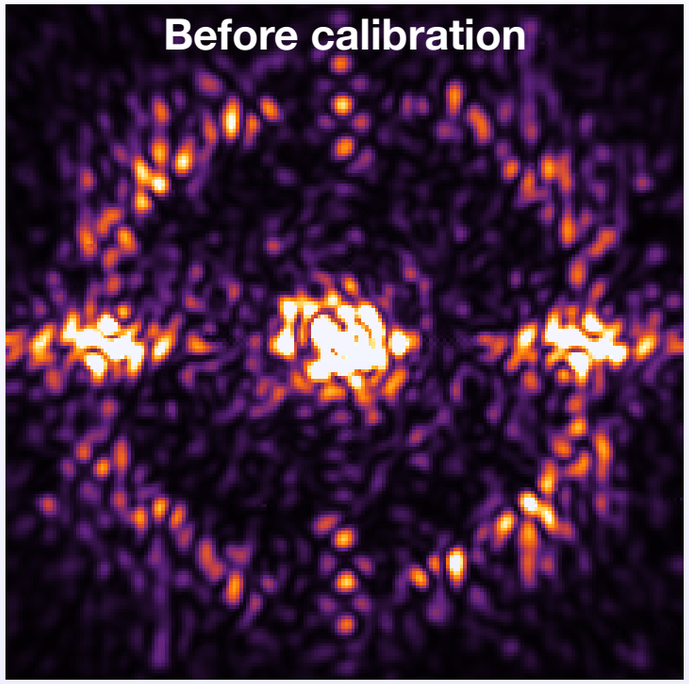
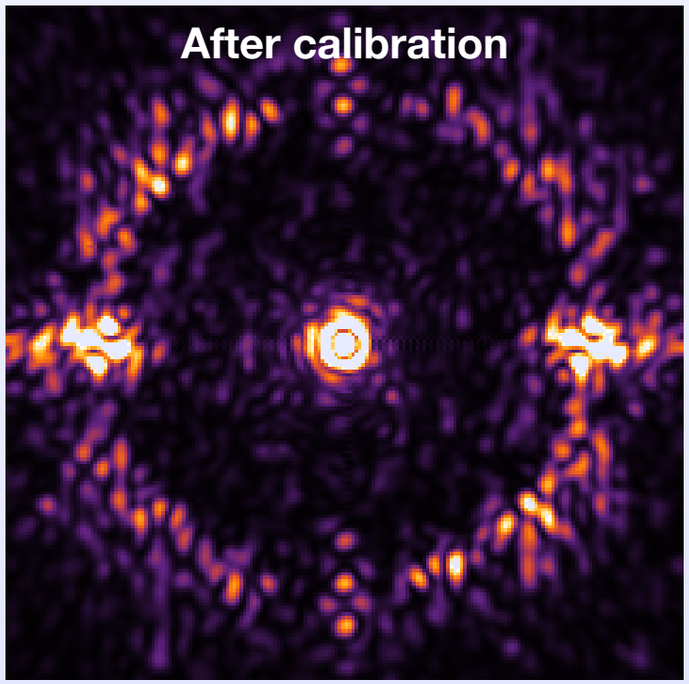
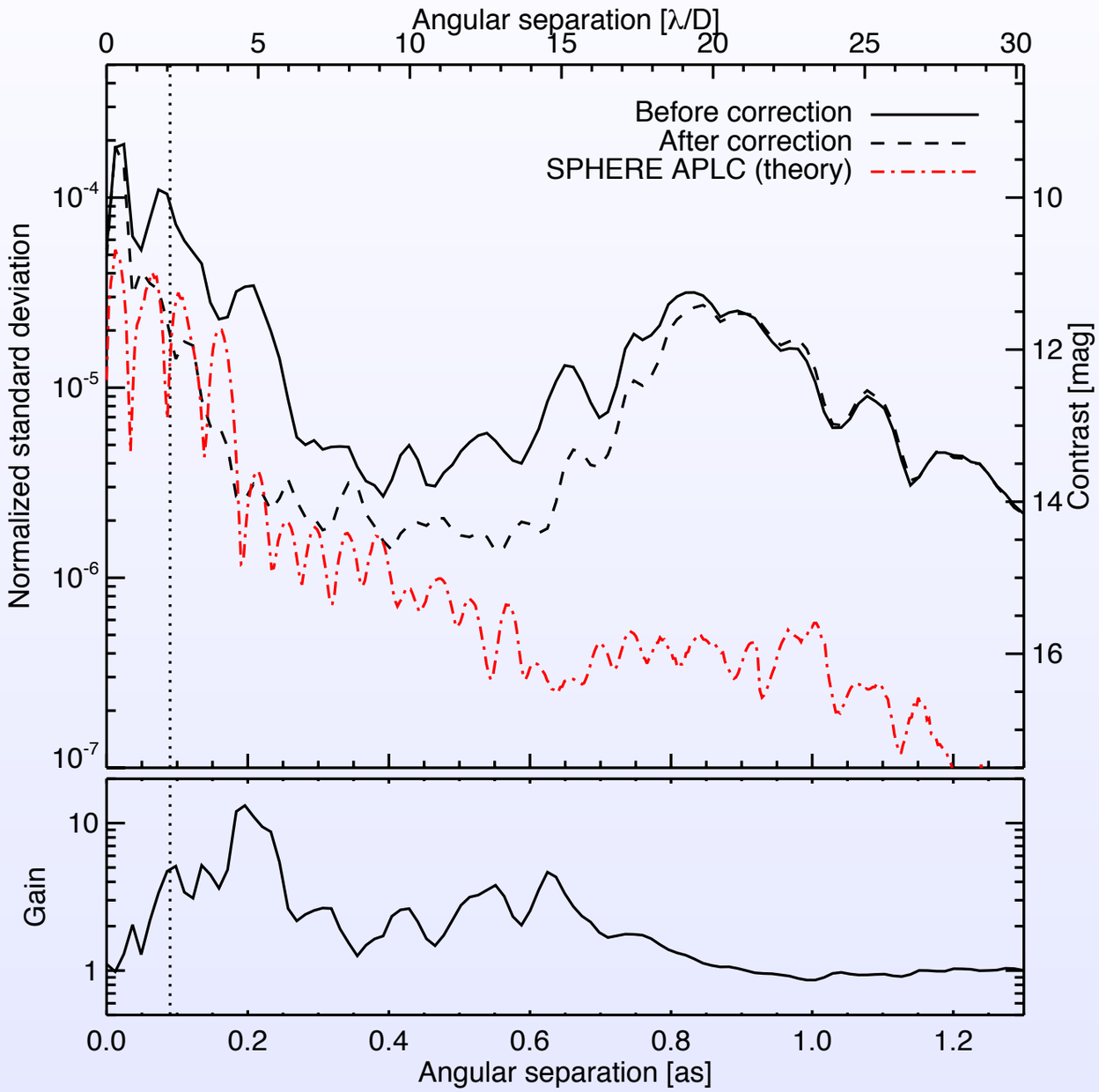


NCPA compensation in SPHERE







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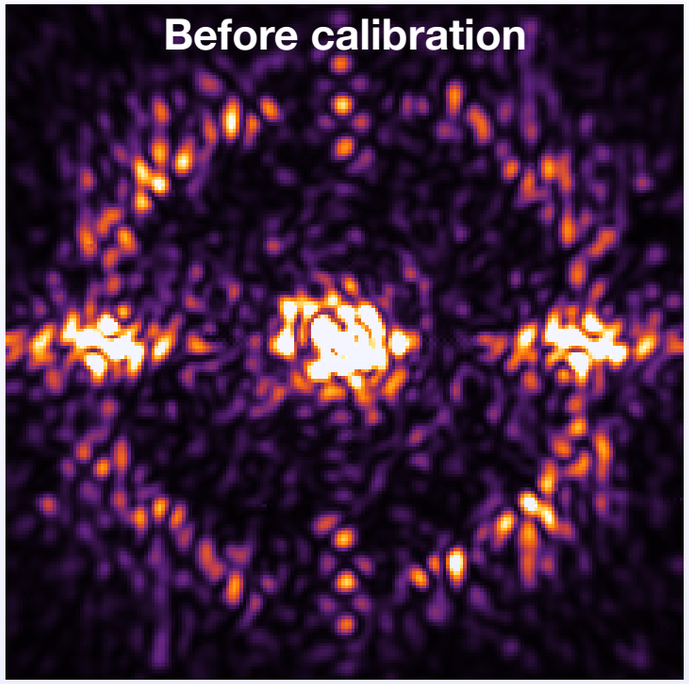
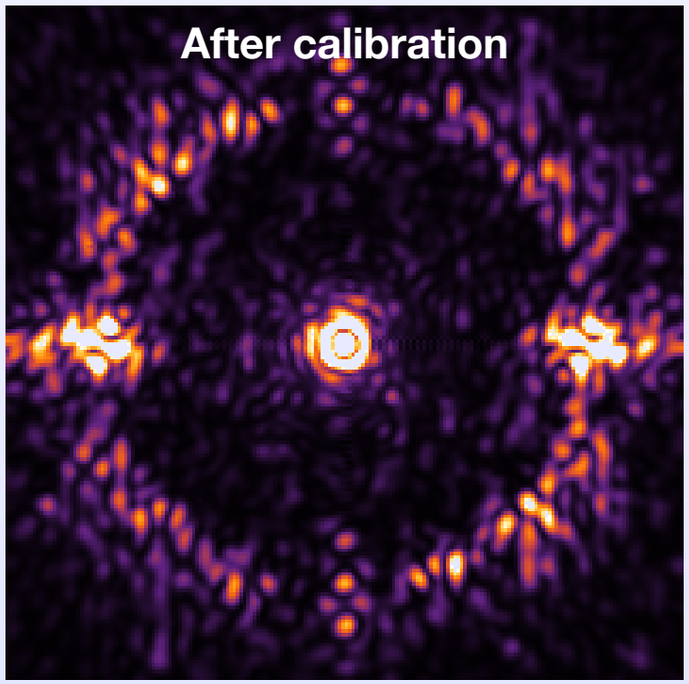
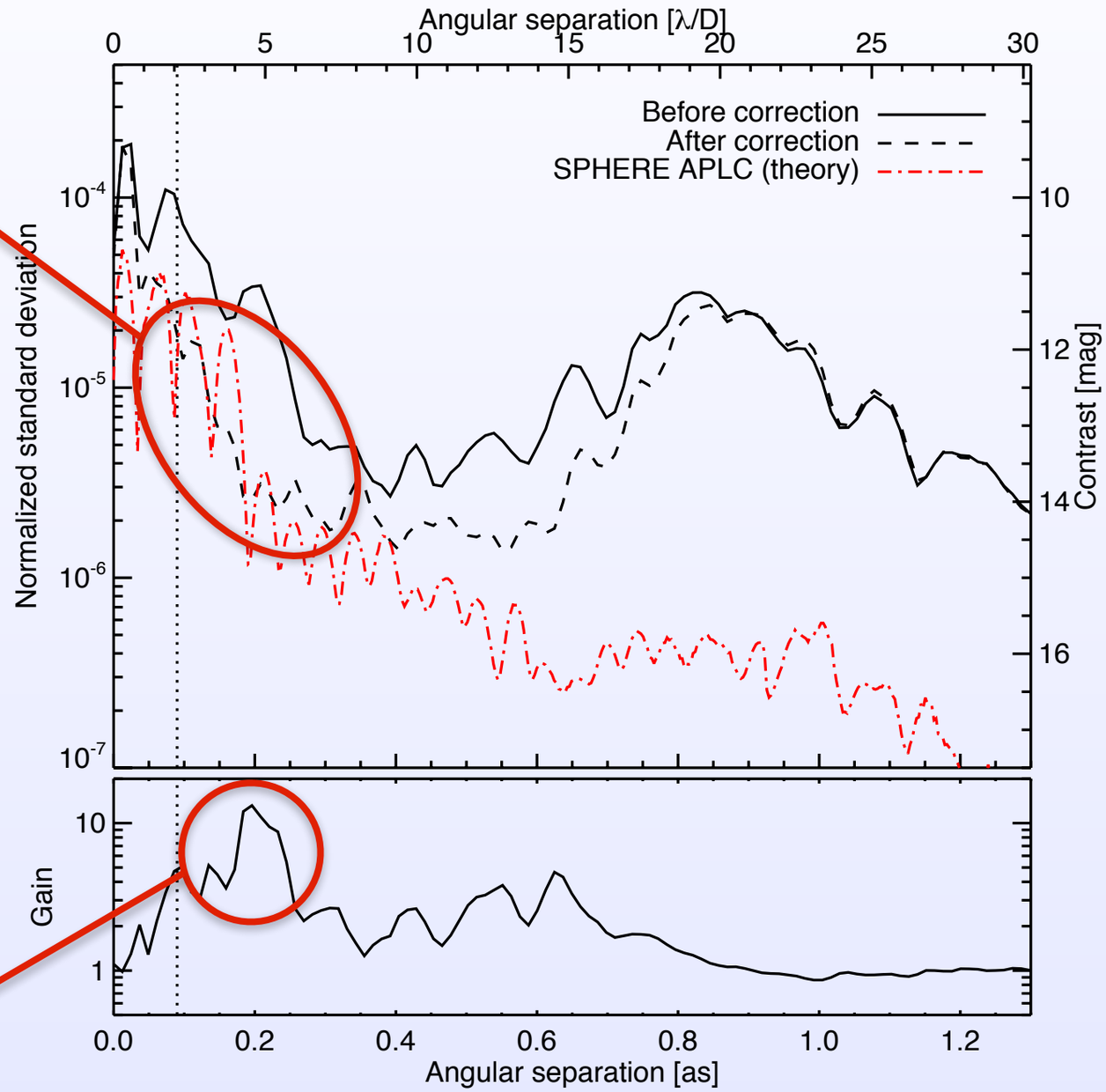




perf. limit of SPHERE coronagraph

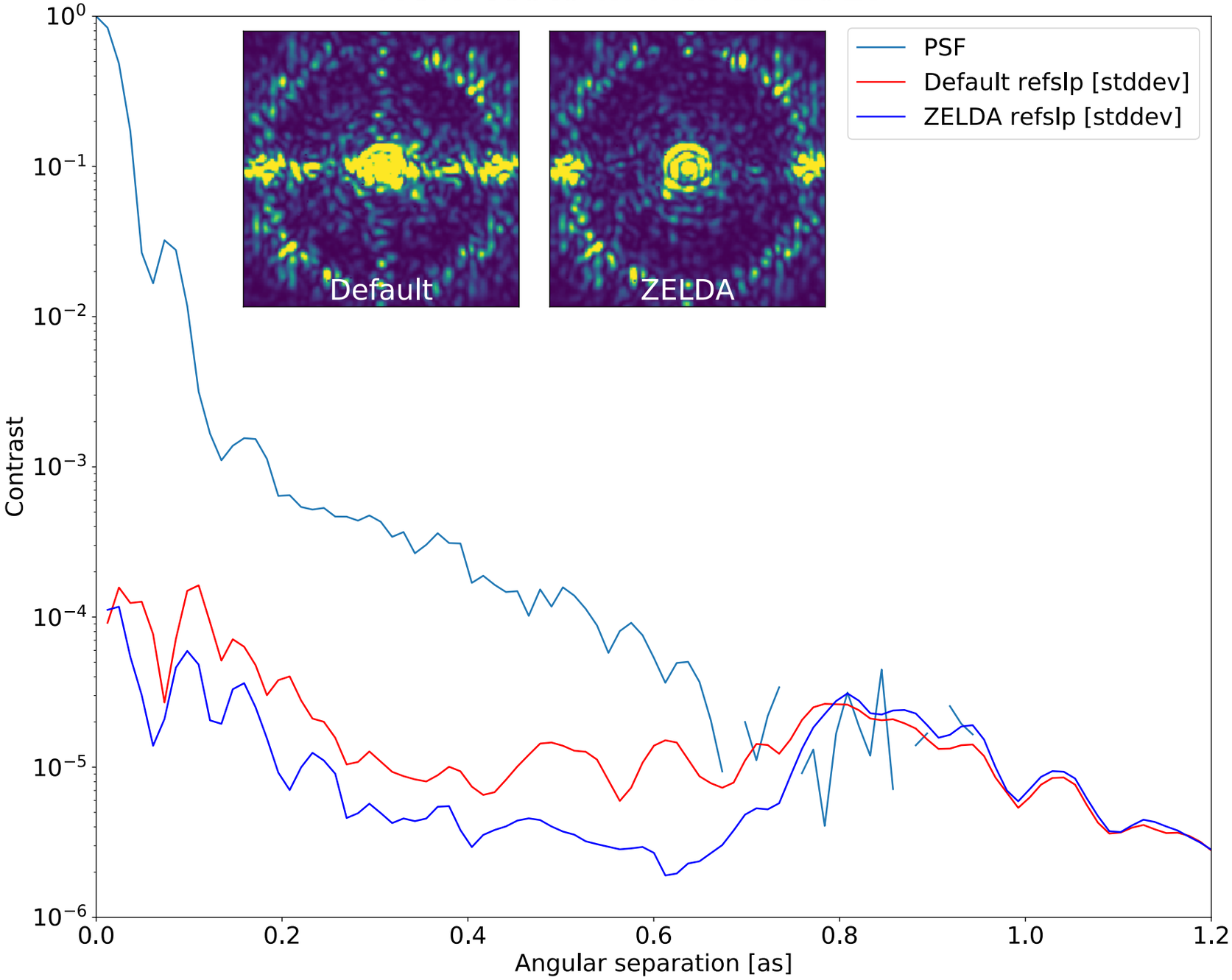


x10 gain @ 0.2"

➙ ZELDA now used to monitor NCPA in SPHERE

Towards NCPA compensation on-sky

New tests in March 2017



Procedure

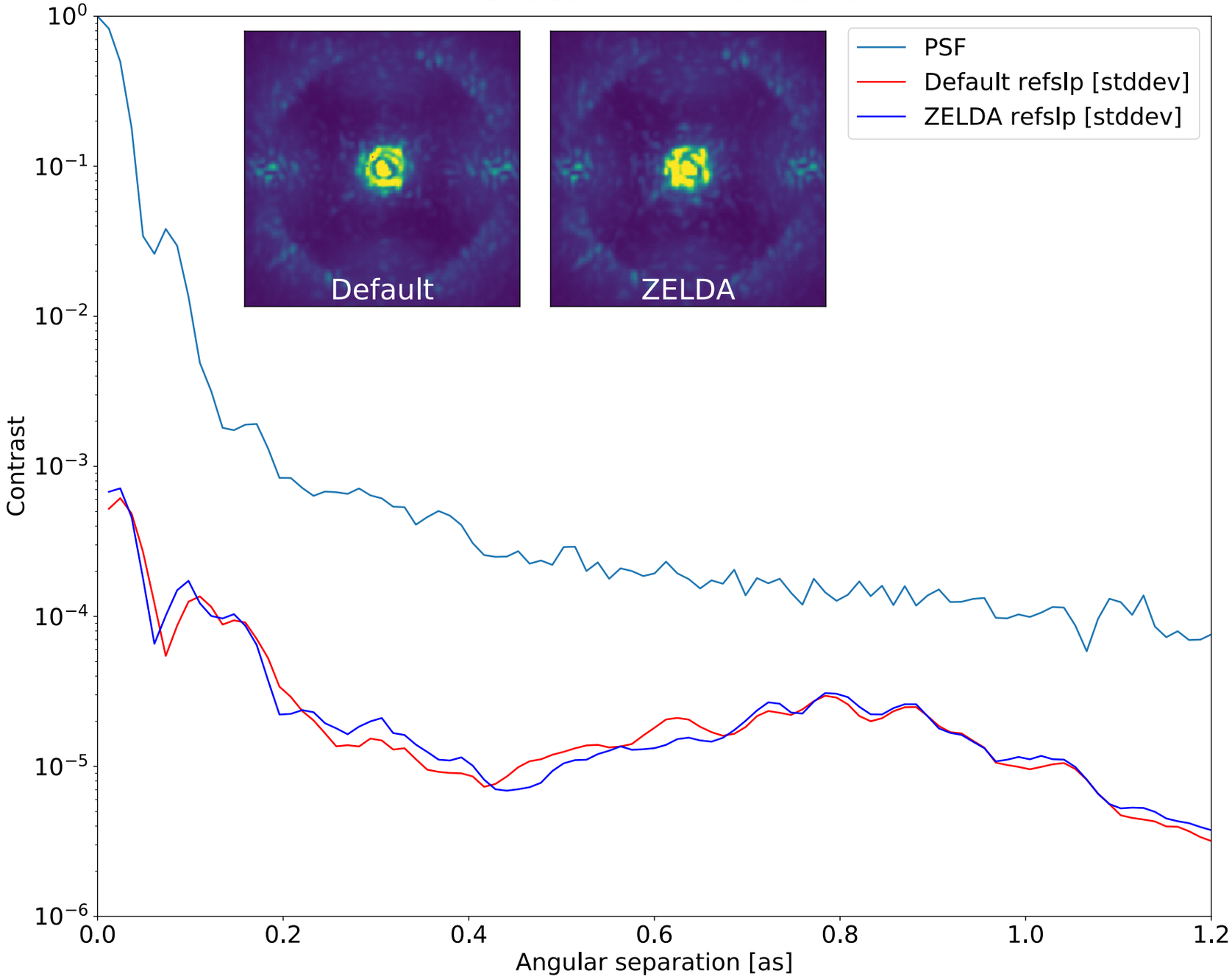
- internal NCPA calibration
- calibrated reference slopes applied on-sky

Internal performance

- **on-par with 2015**
- 5-10 contrast gain

Towards NCPA compensation on-sky

New tests in March 2017



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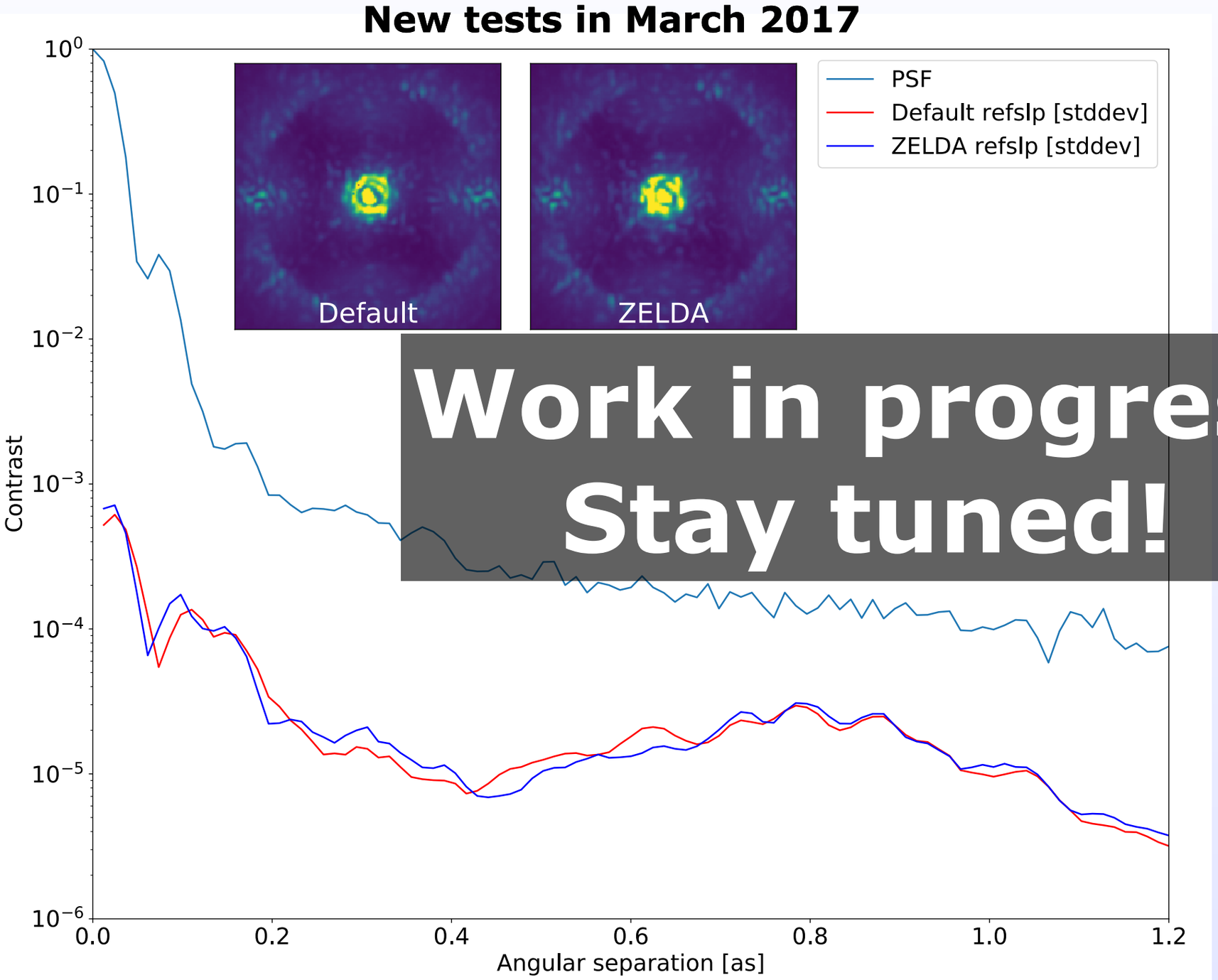
On-sky performance

- **no contrast gain yet!**
- reason unknown:
  - chromatic beam-shift?
  - near-IR ADCs?
  - amplitude aberrations?

Towards NCPA compensation on-sky



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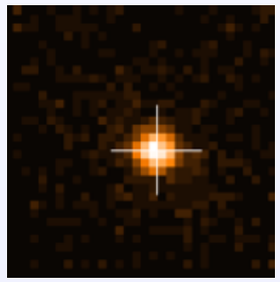
Arthur Vigan - Caltech - 2017-11-14

Arthur Vigan - Caltech - 2017-11-14

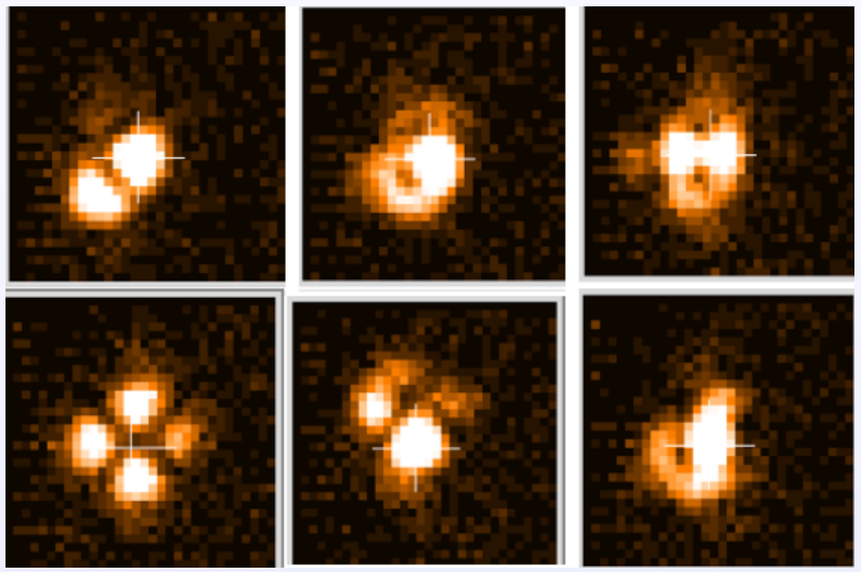
ZELDiAgnostic: low-wind effect

- effect identified during the SPHERE commissioning on DTTS images

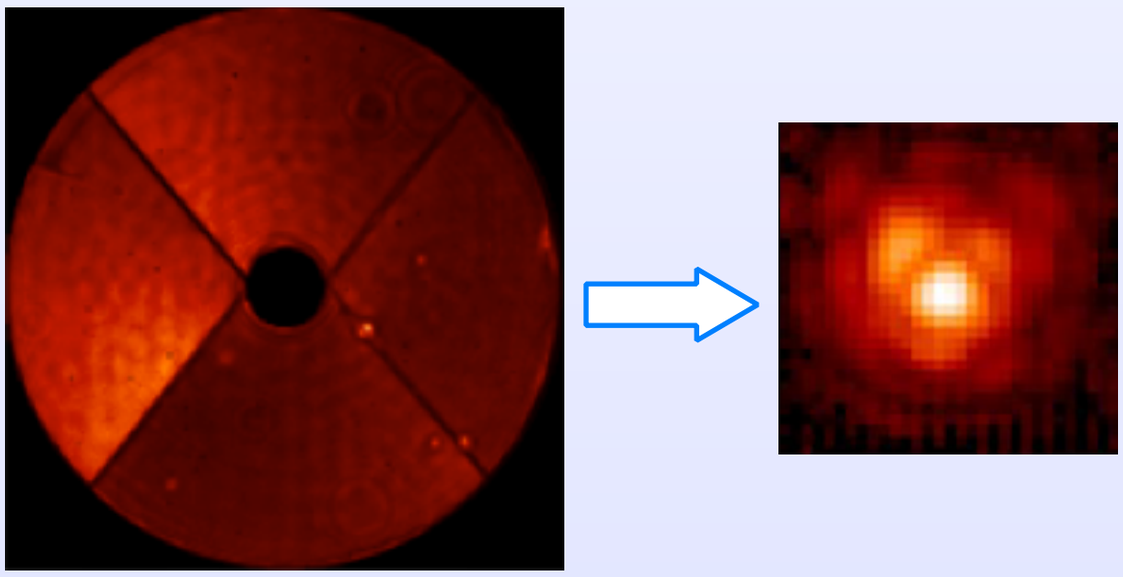
Normal DTTS image



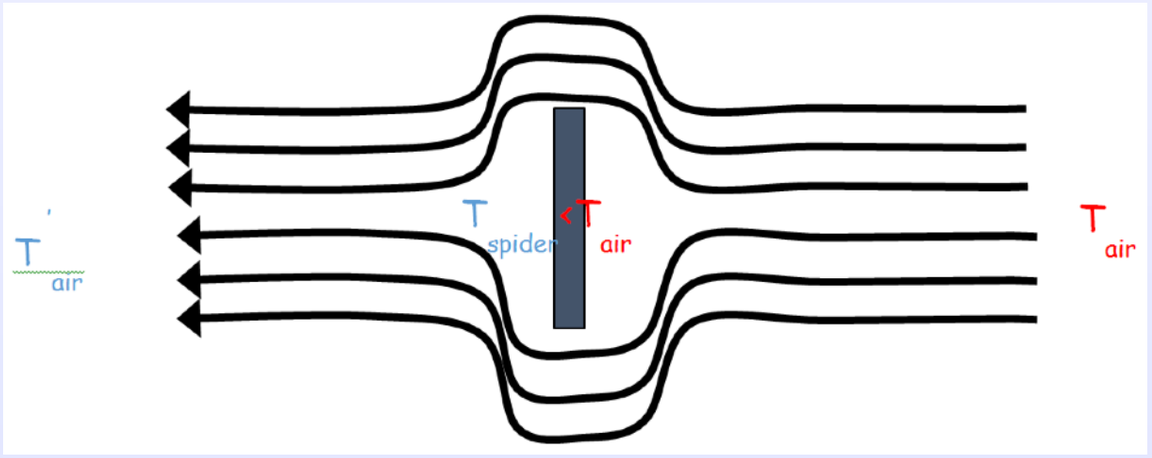
Abnormal DTTS images



- ZELDA identified a differential piston across the pupil:

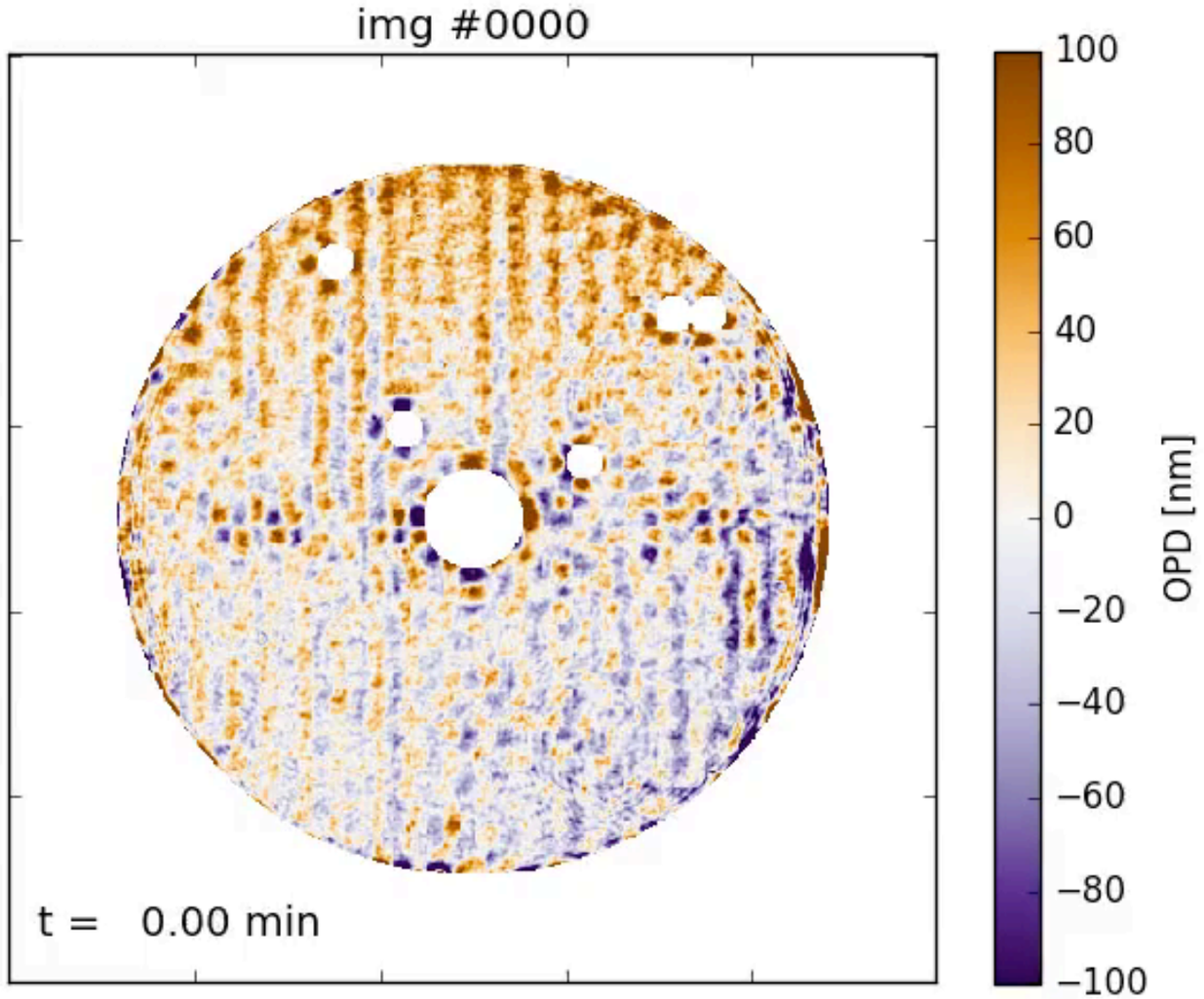


Radiative cooling of the spider structure

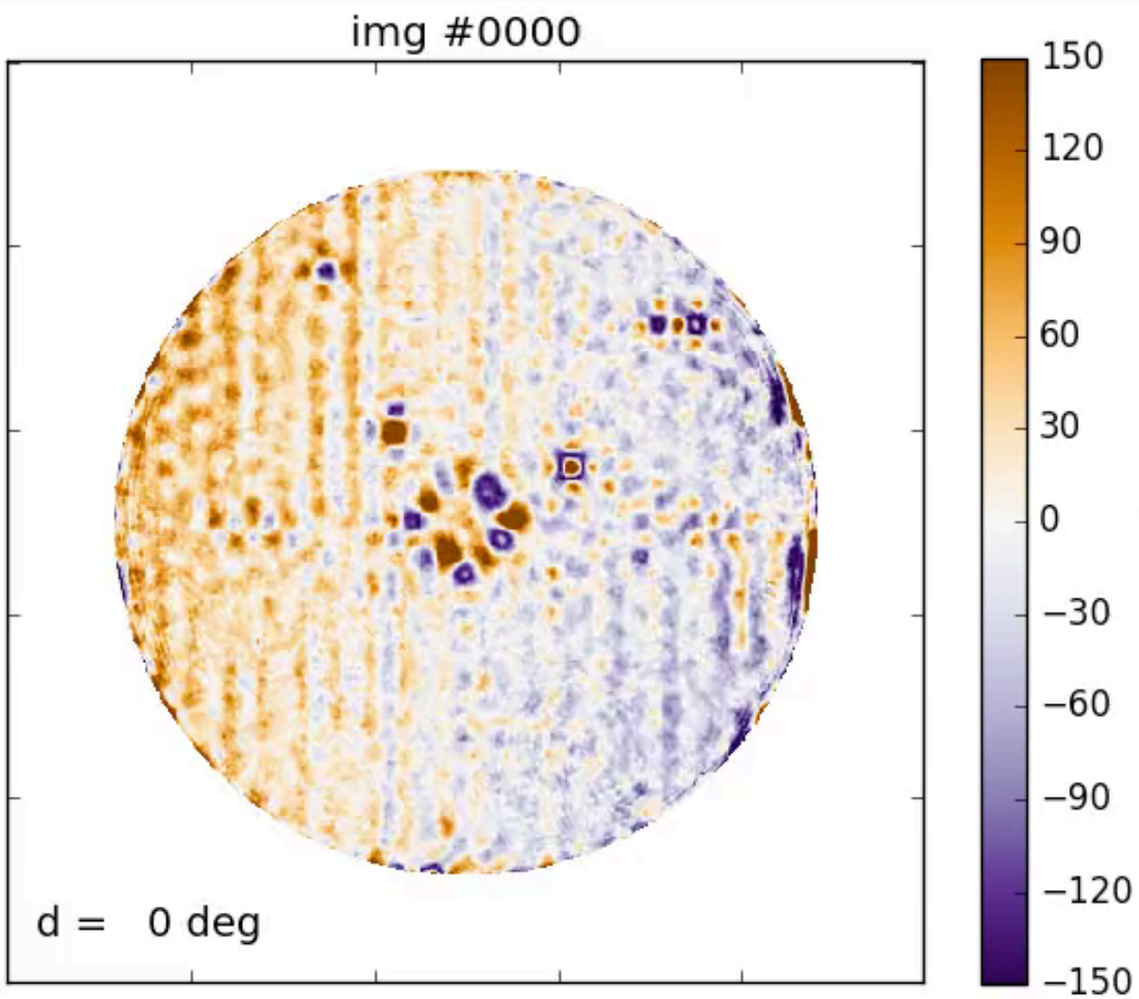


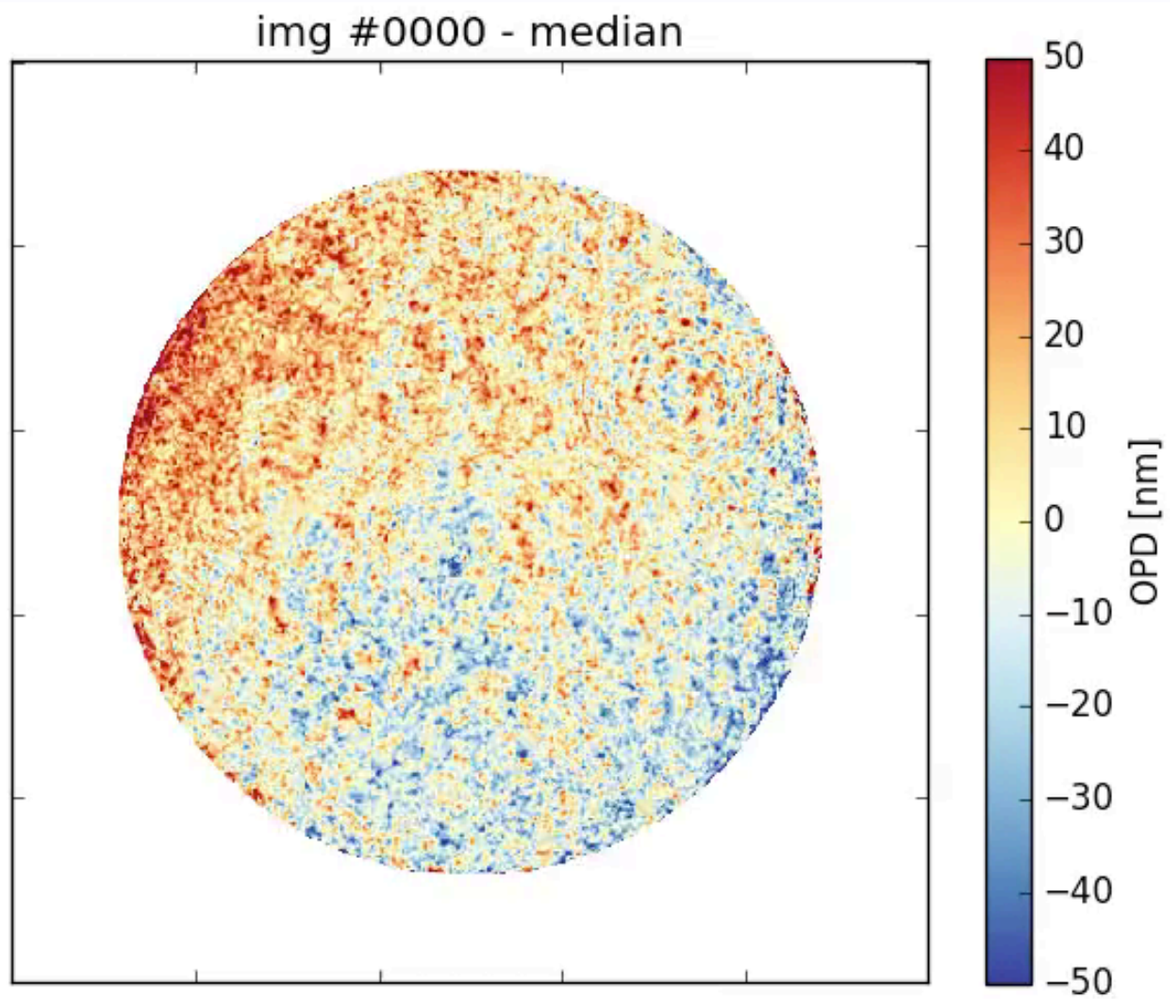
ZELDiAgnostic: NCPA variation

Internal turbulence with decorrelation timescale of 4-5 sec

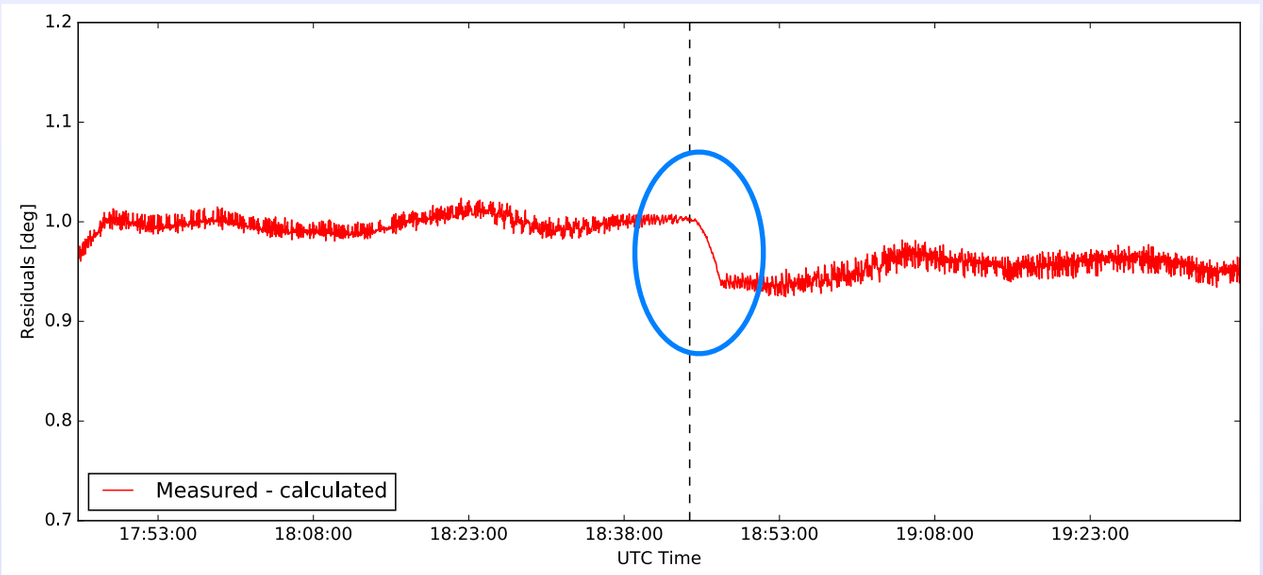


ZELDiAgnostic: derotator behaviour

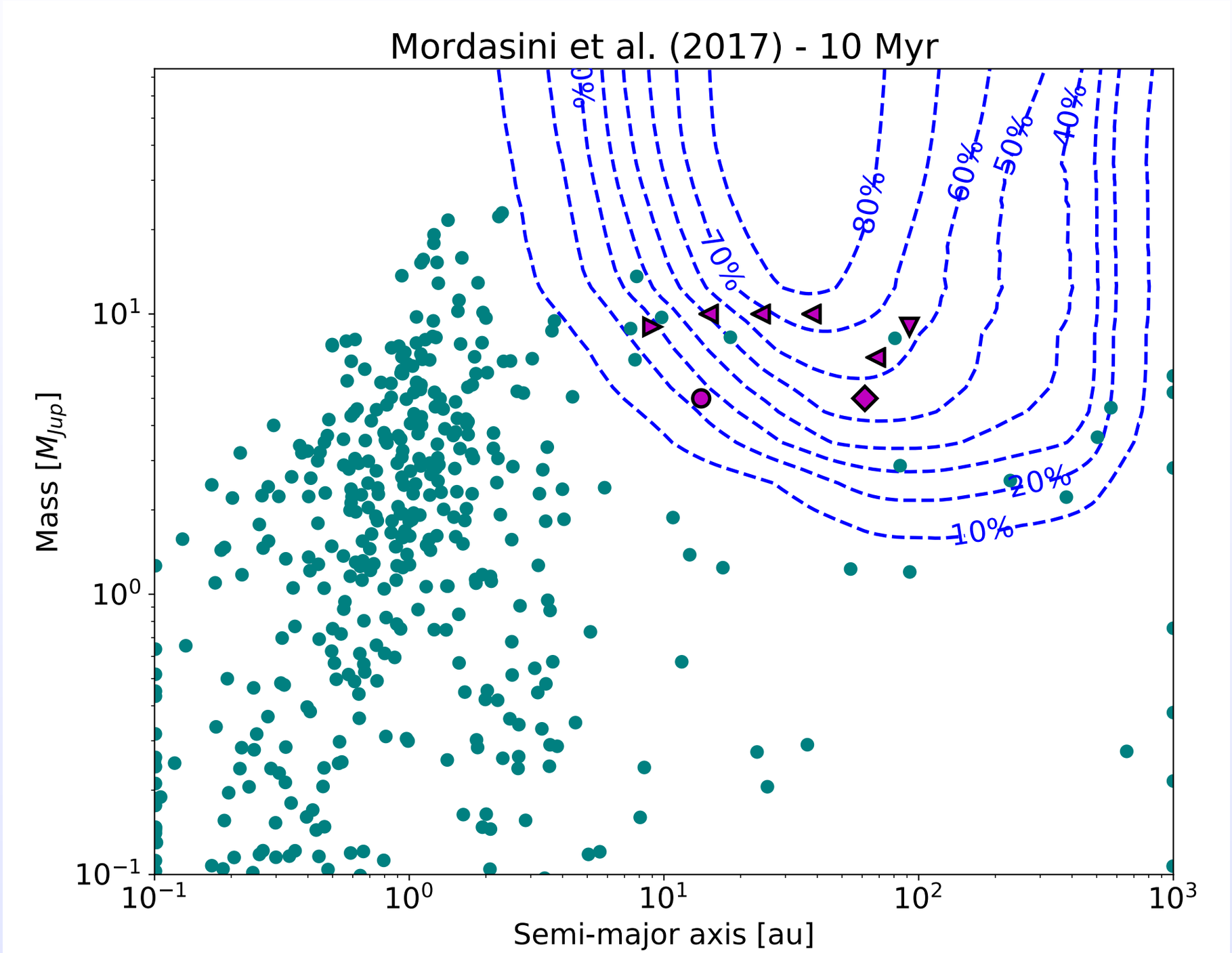




Derotator backlash

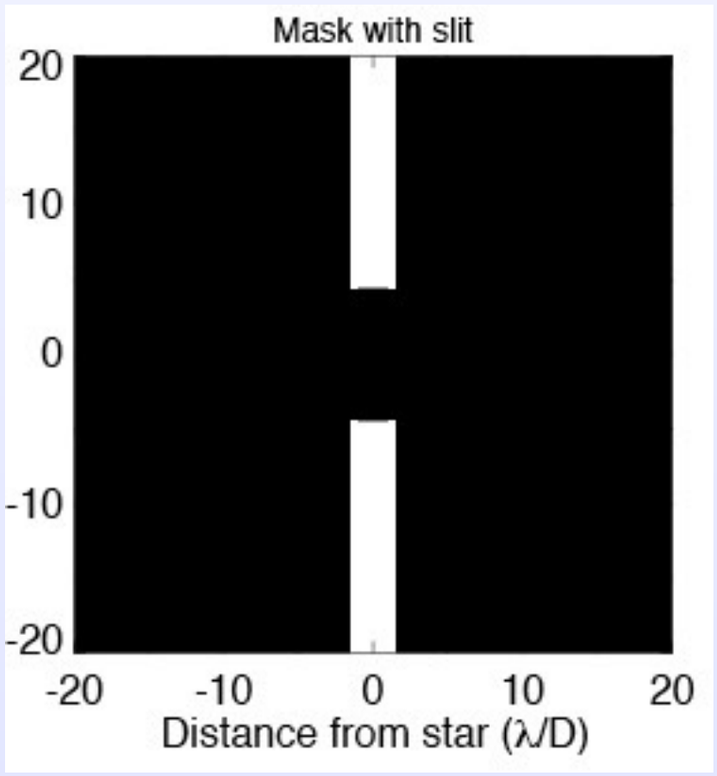


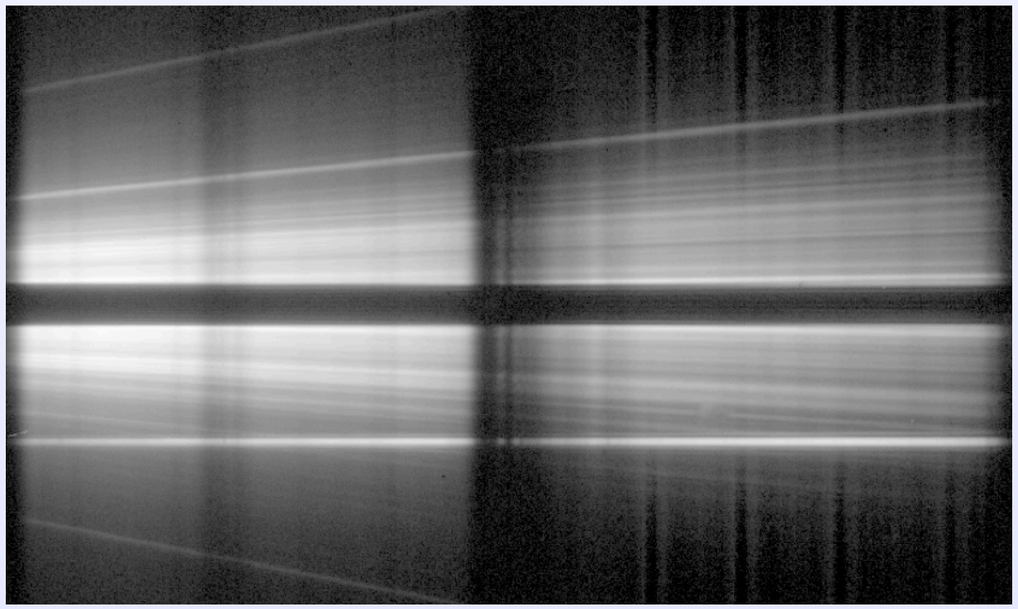
More planets: closer, deeper

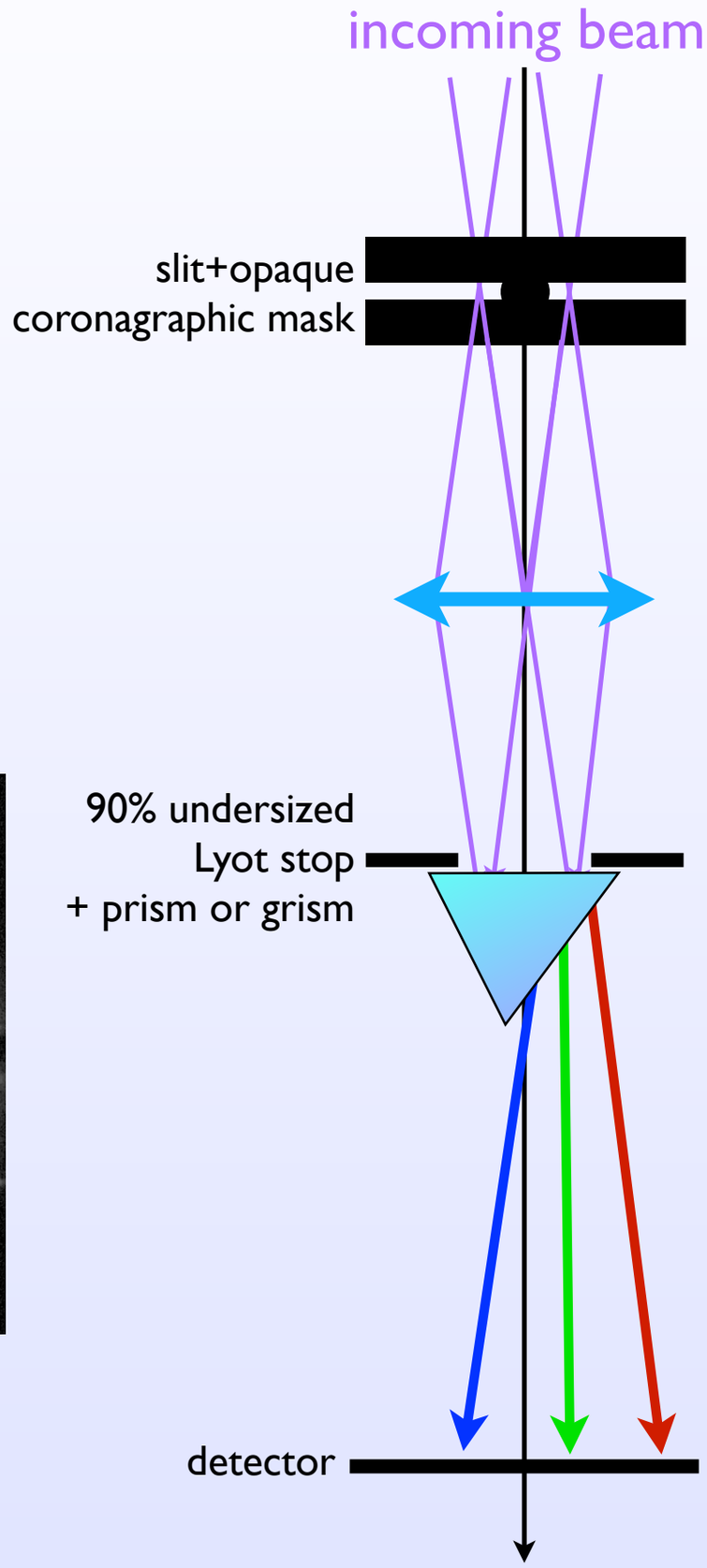


Higher spectral resolution

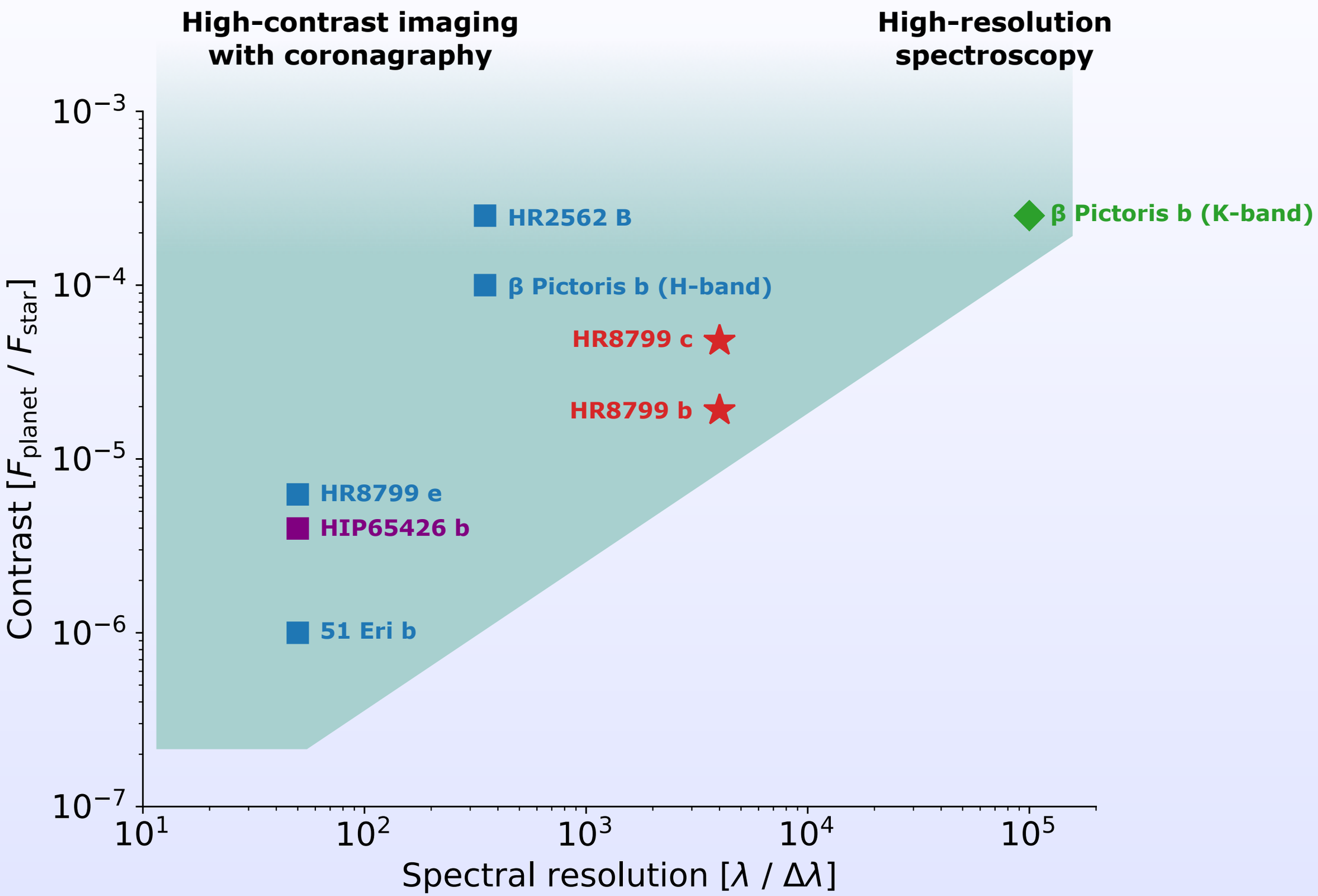
- IRDIS long slit spectroscopy mode
- LSS + Lyot coronagraph
  - low resolution: R~50, YJHKs in one shot
  - **medium resolution: R~330, YJH in one shot**



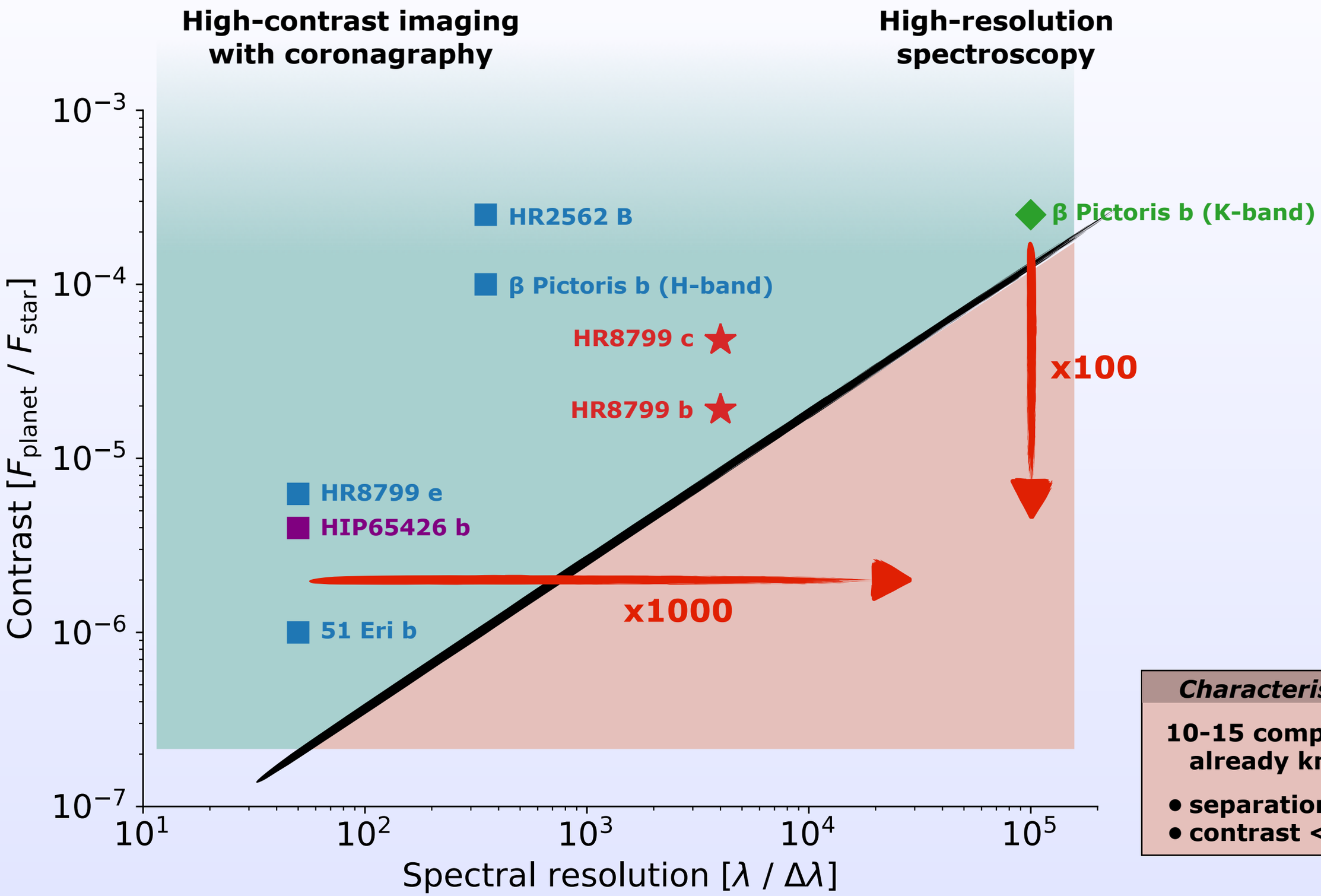




Very high spectral resolution



Very high spectral resolution



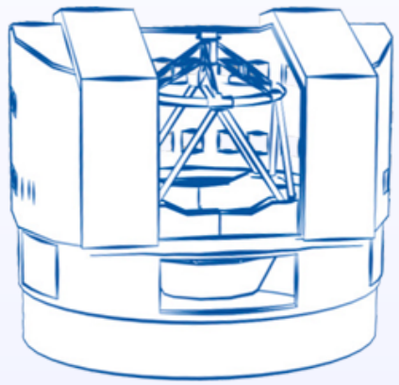
Characterisation

10-15 companions already known

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

A unique window of opportunity

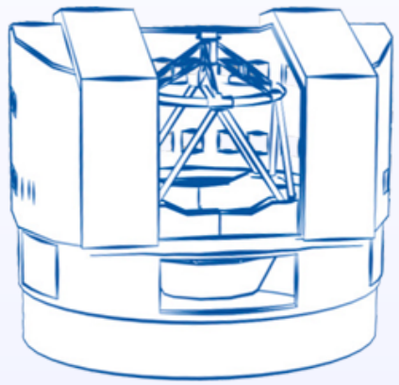
VLT/UT3



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

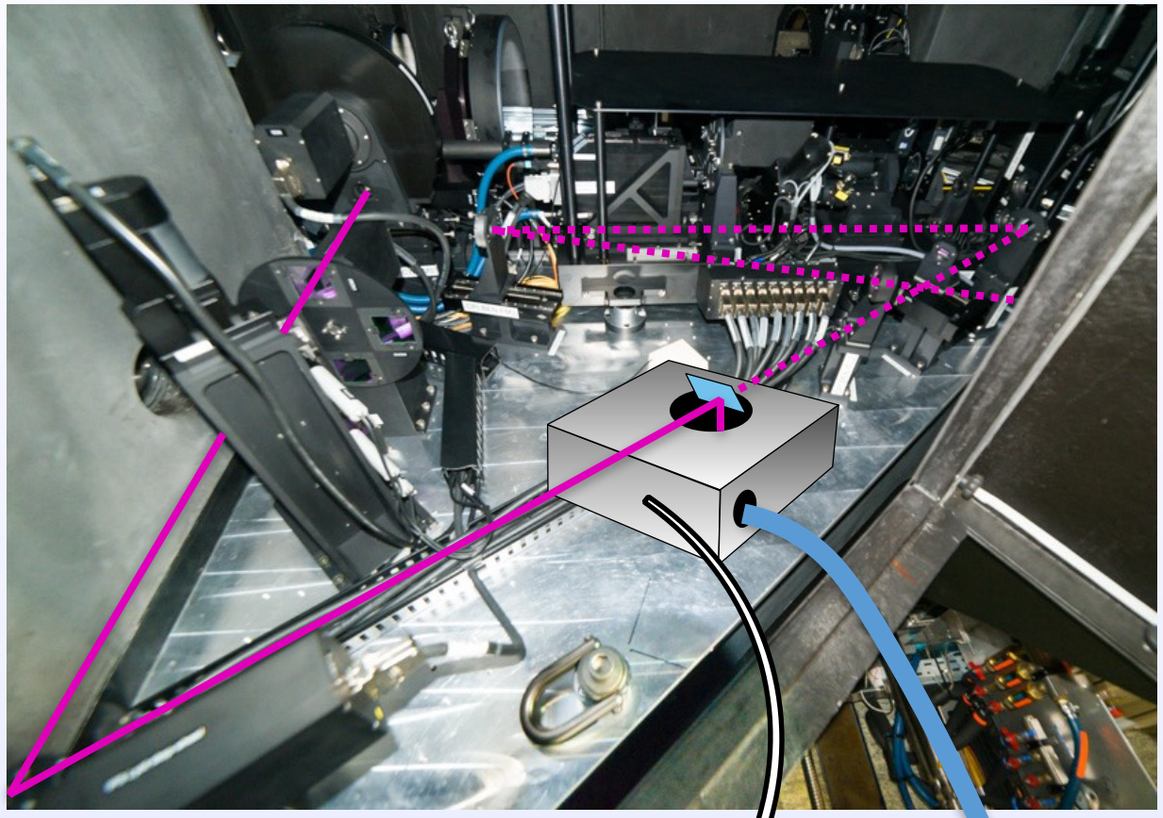
Fiber coupling

Supported by ESO

Supported by CRIRES+

A prototype fiber injection in SPHERE

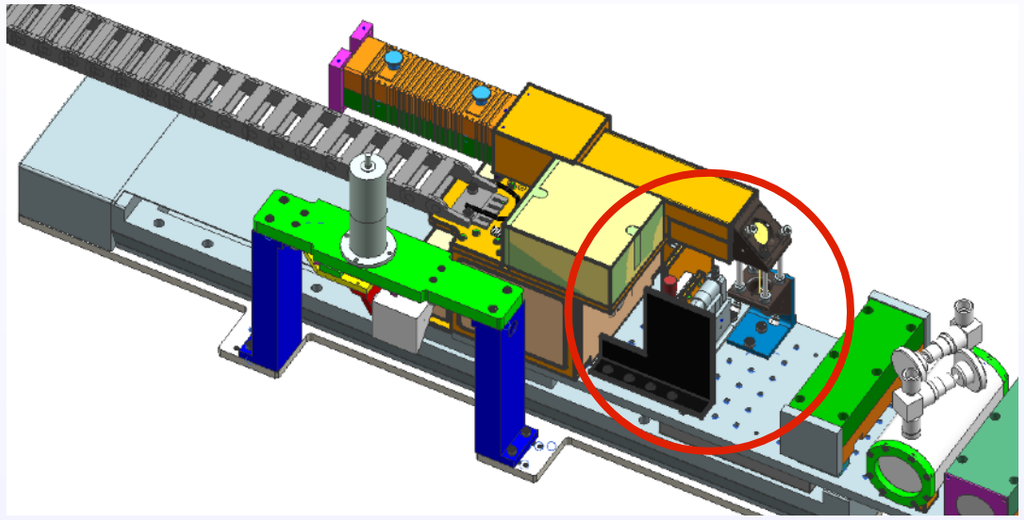
SPHERE near-infrared arm



Fiber injection unit

No show-stopper for implementation

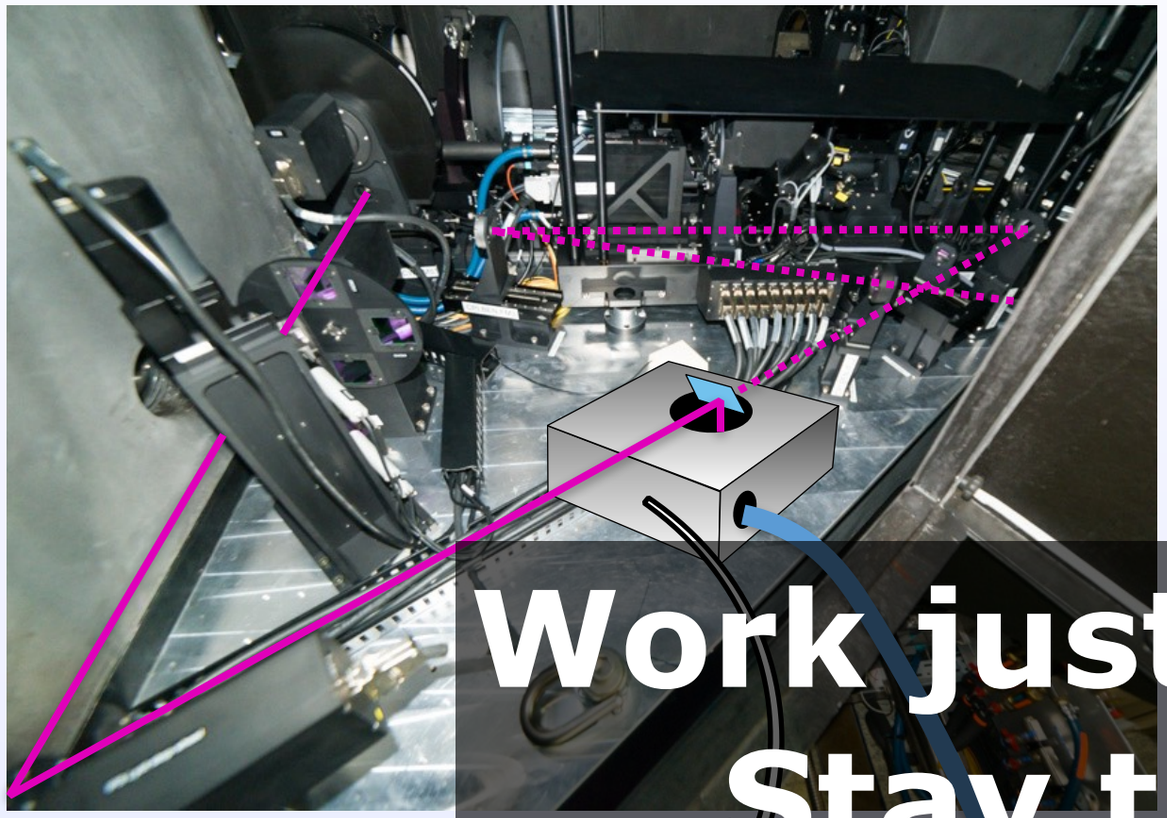
Fiber link



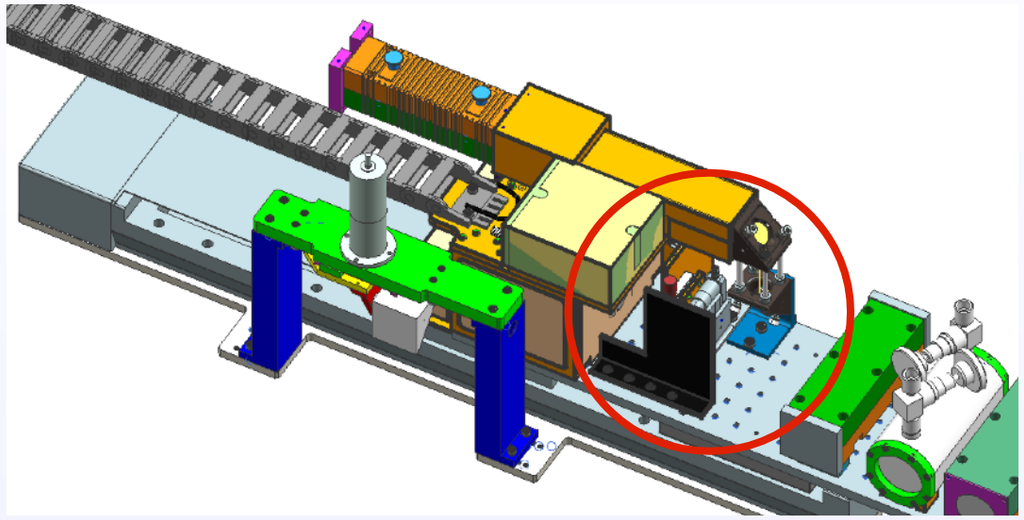
CRIRES+ calibration unit stage

A prototype fiber injection in SPHERE

SPHERE near-infrared arm



CRIRES+ calibration unit stage



Work just starting
Stay tuned!

Fiber injection unit

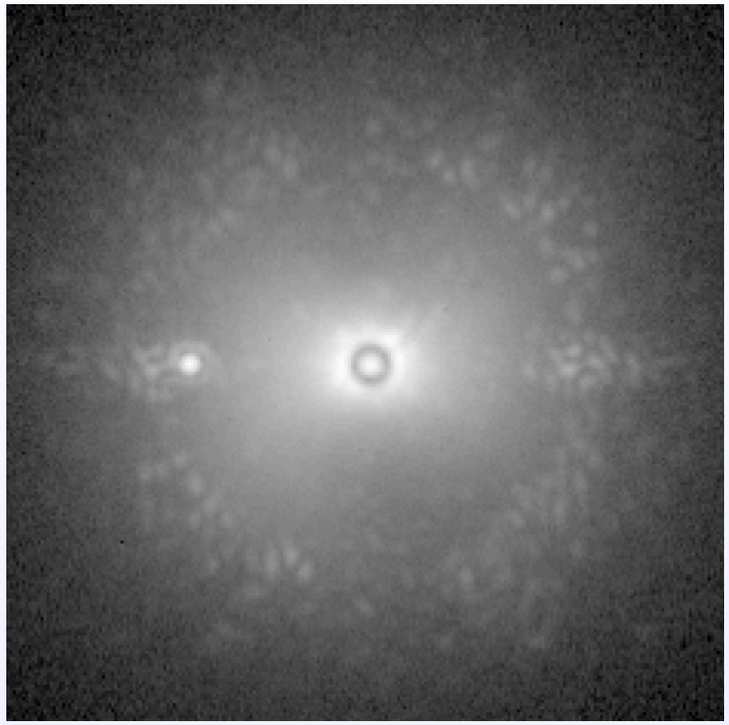
No show-stopper for implementation

Fiber link

Fiber entrance **already available** in CRIRES+

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?
- ...



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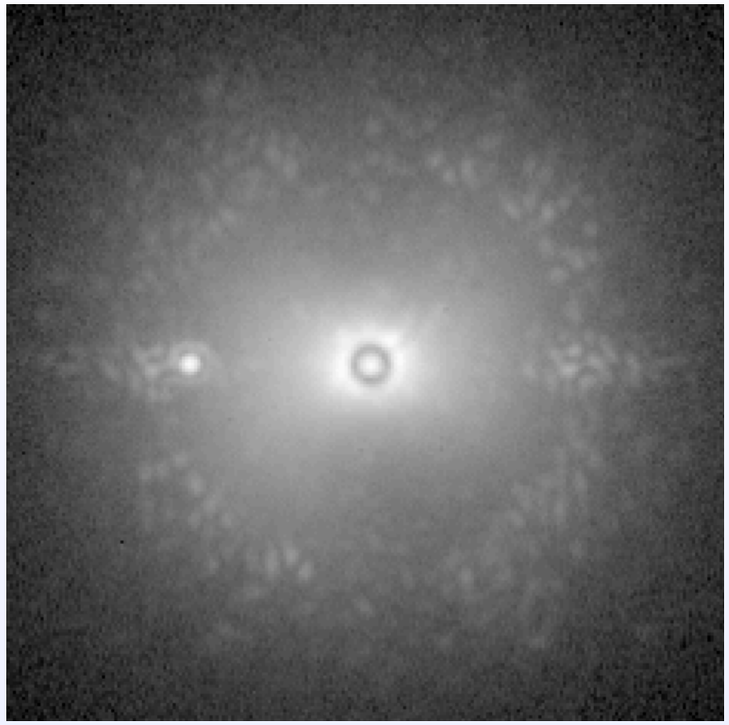
  - new ZIMPOL optimised for fainter targets?
- ...



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