Florida Institute of Technology

High-contrast Imaging of Massive Stars

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KU LEUVEN

Outline

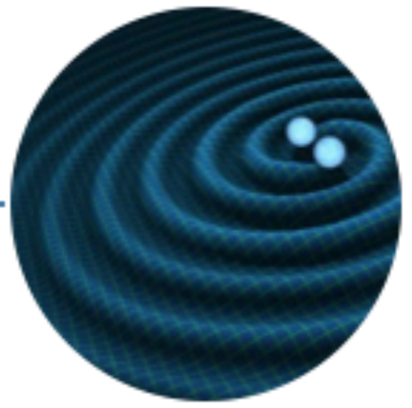
1. Scientific overview
2. High-contrast imaging: VIP, SHIPS, …
3. The CHIPS project
4. Published results: QZ Car, Tr14
5. Future of HCi

Scientific context

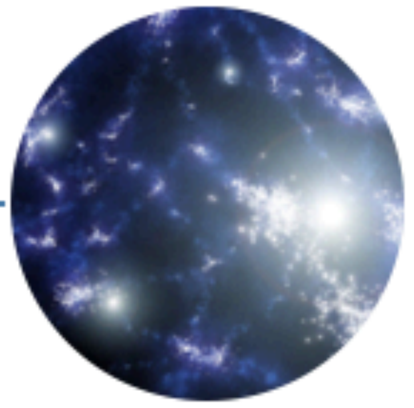

M101, ©STScI/NASA


2,700 K
3,500 K
5,000 K
6,000 K
7,500 K
10,000 K
25,000 K
M
K
G
F
A
B
O
©ESO/M. Kornmesser

M>8Mo

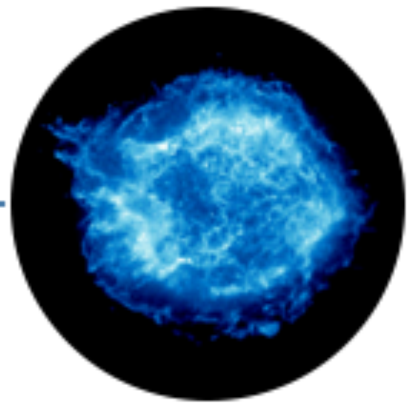


Gravitational
wave sources



First Stars & Galaxy
formation and evolution

>80% binaries



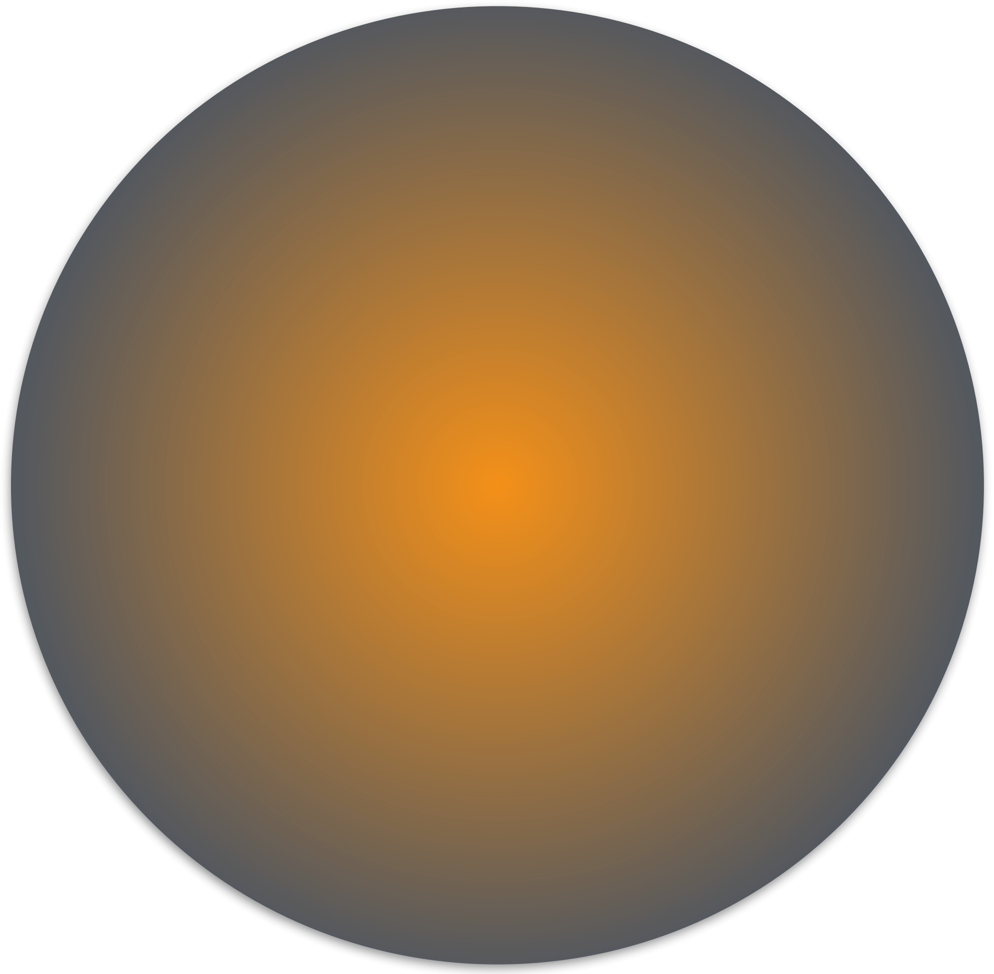
Supernova(progenitors)

Nucleosynthesis
& Feedback

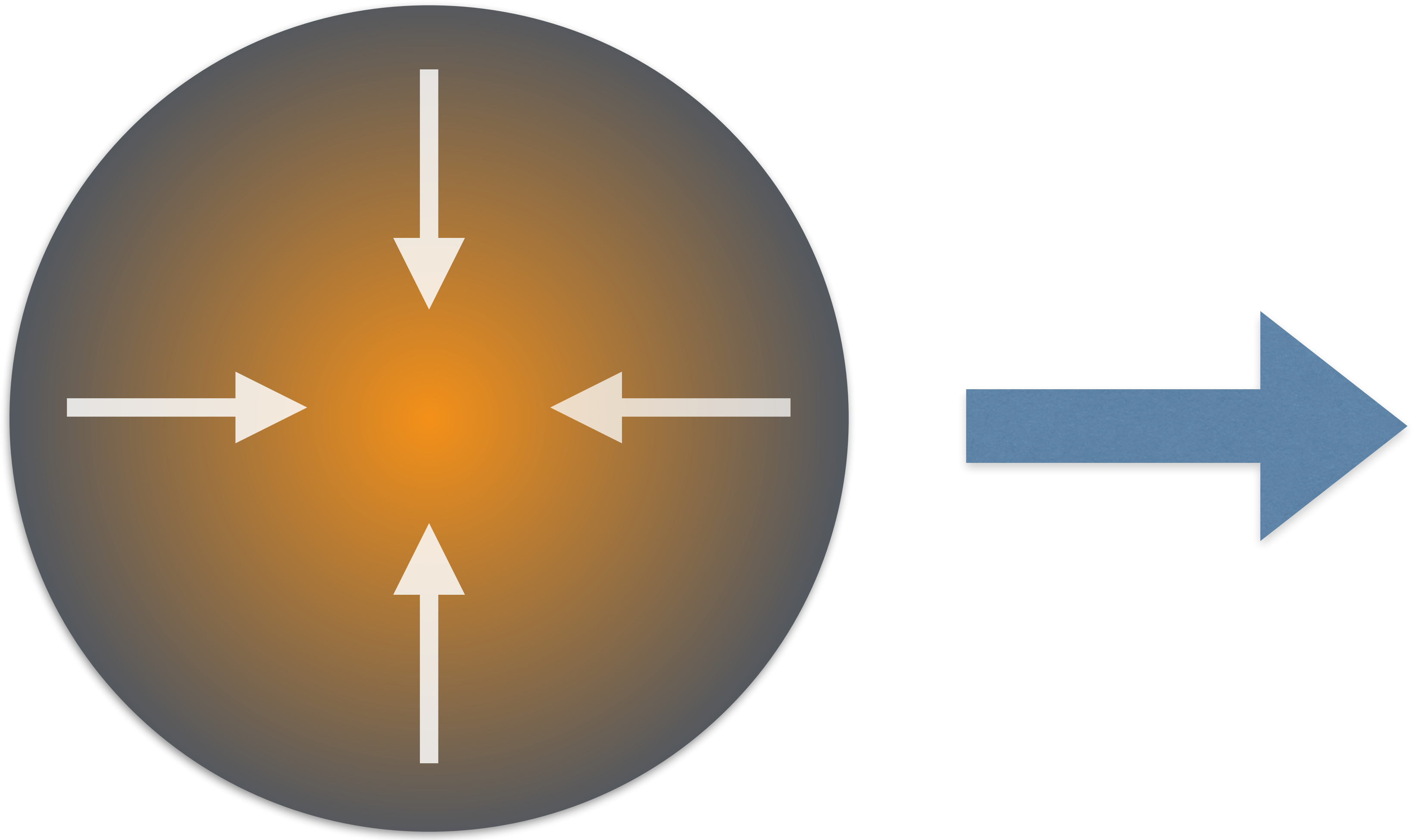
τ_{form}~10^5 years

MAESTRO/KUL

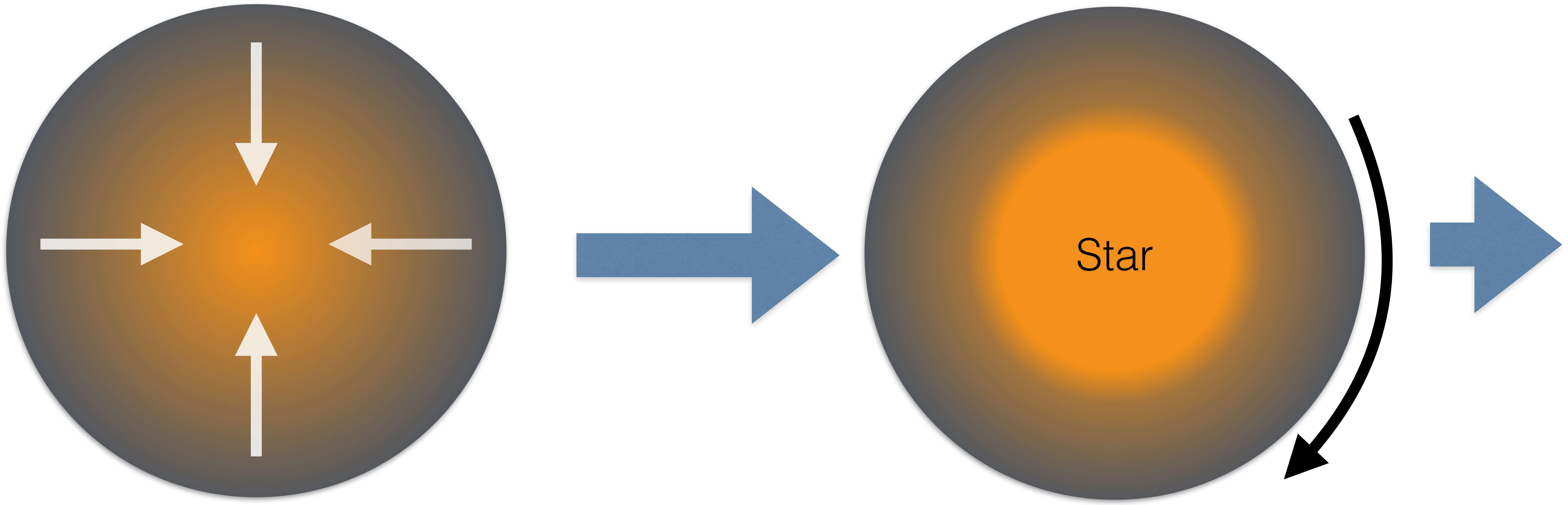
Massive Star Formation



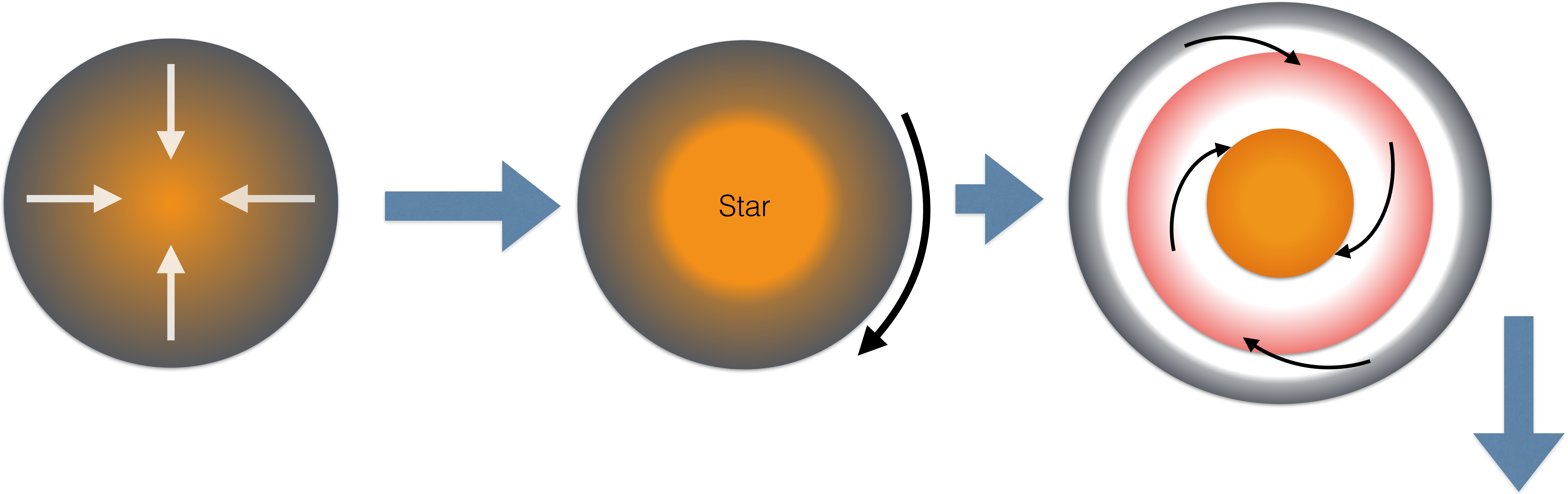
Massive Star Formation



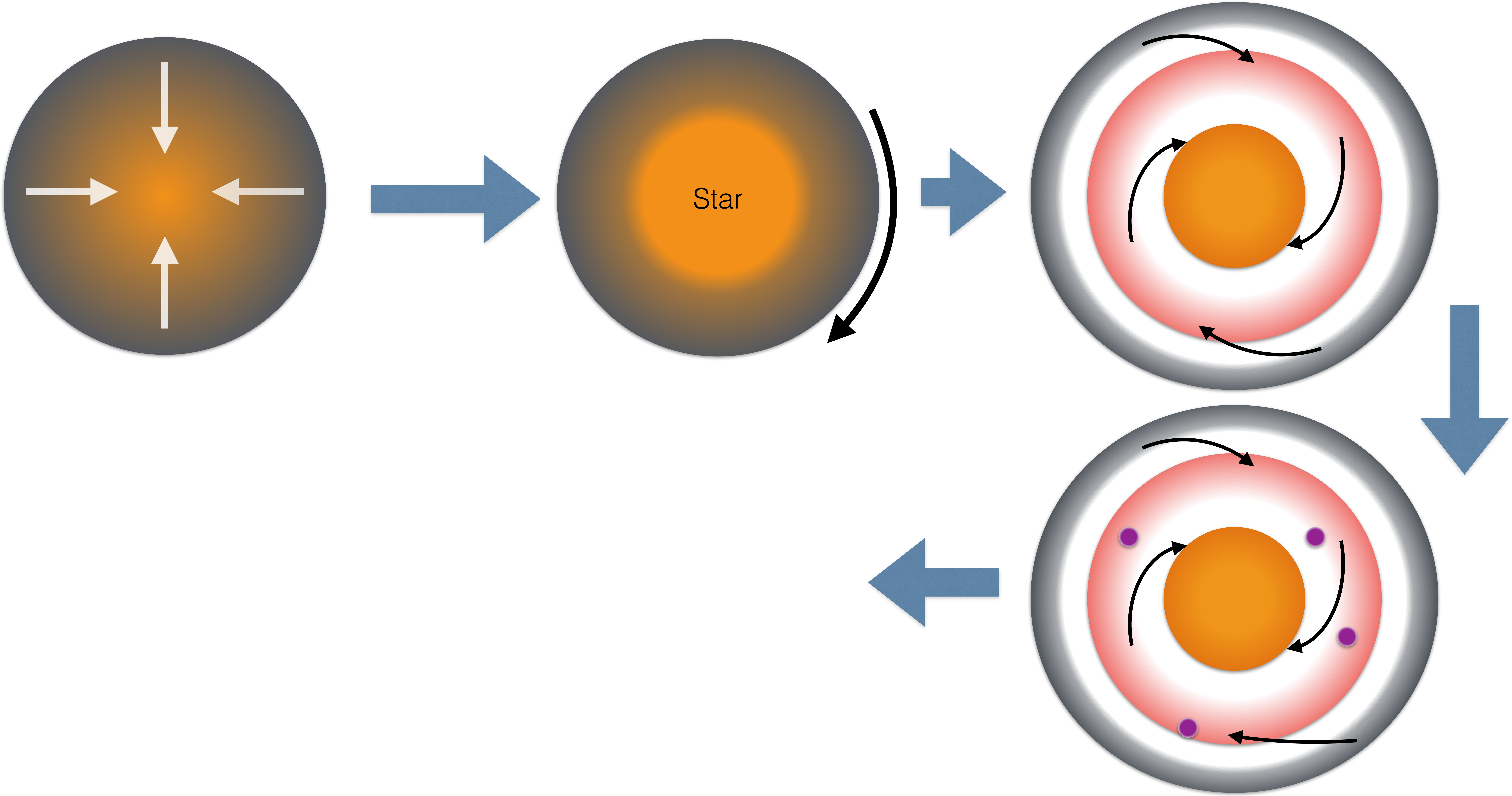
Massive Star Formation



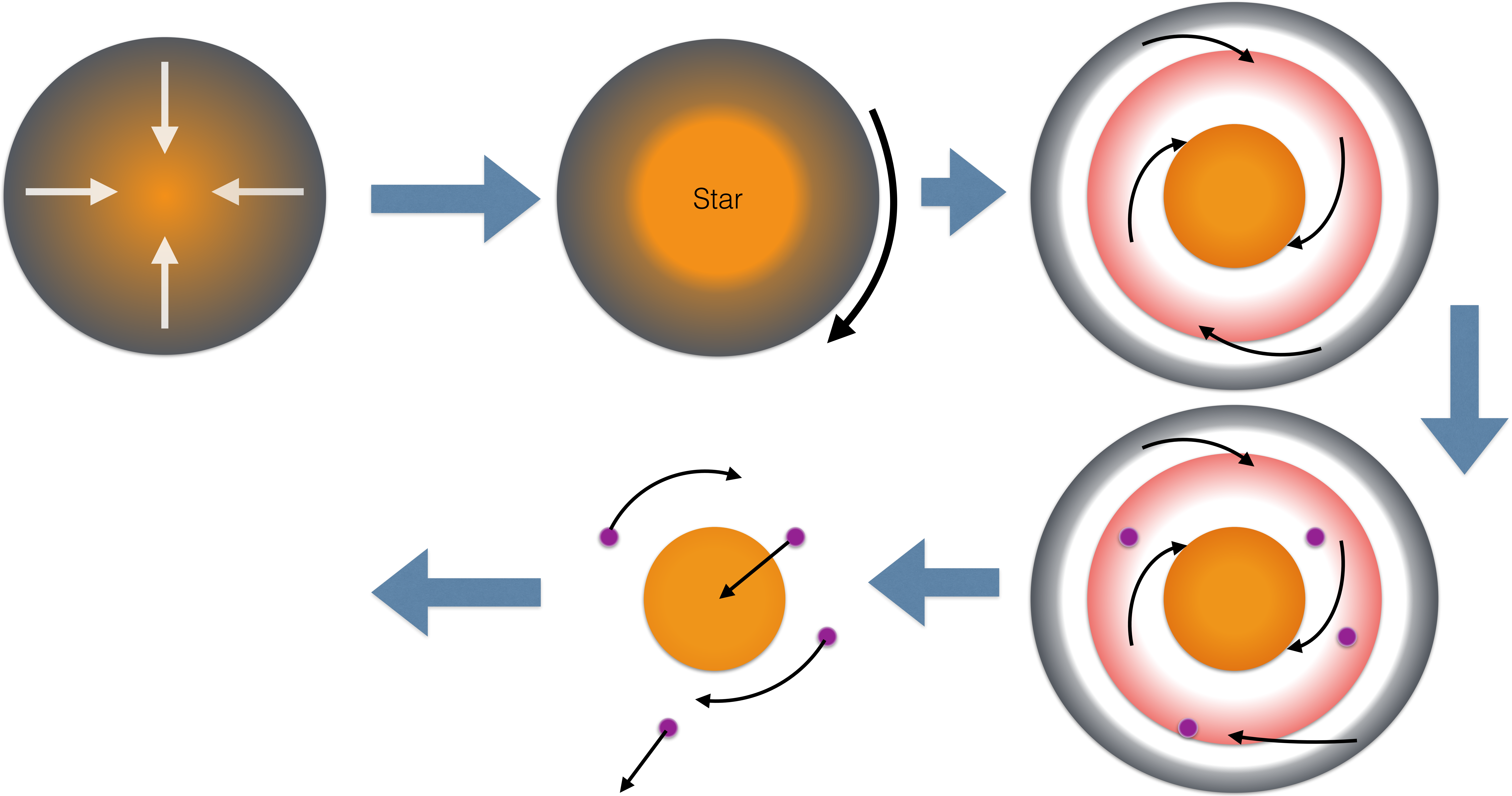
Massive Star Formation



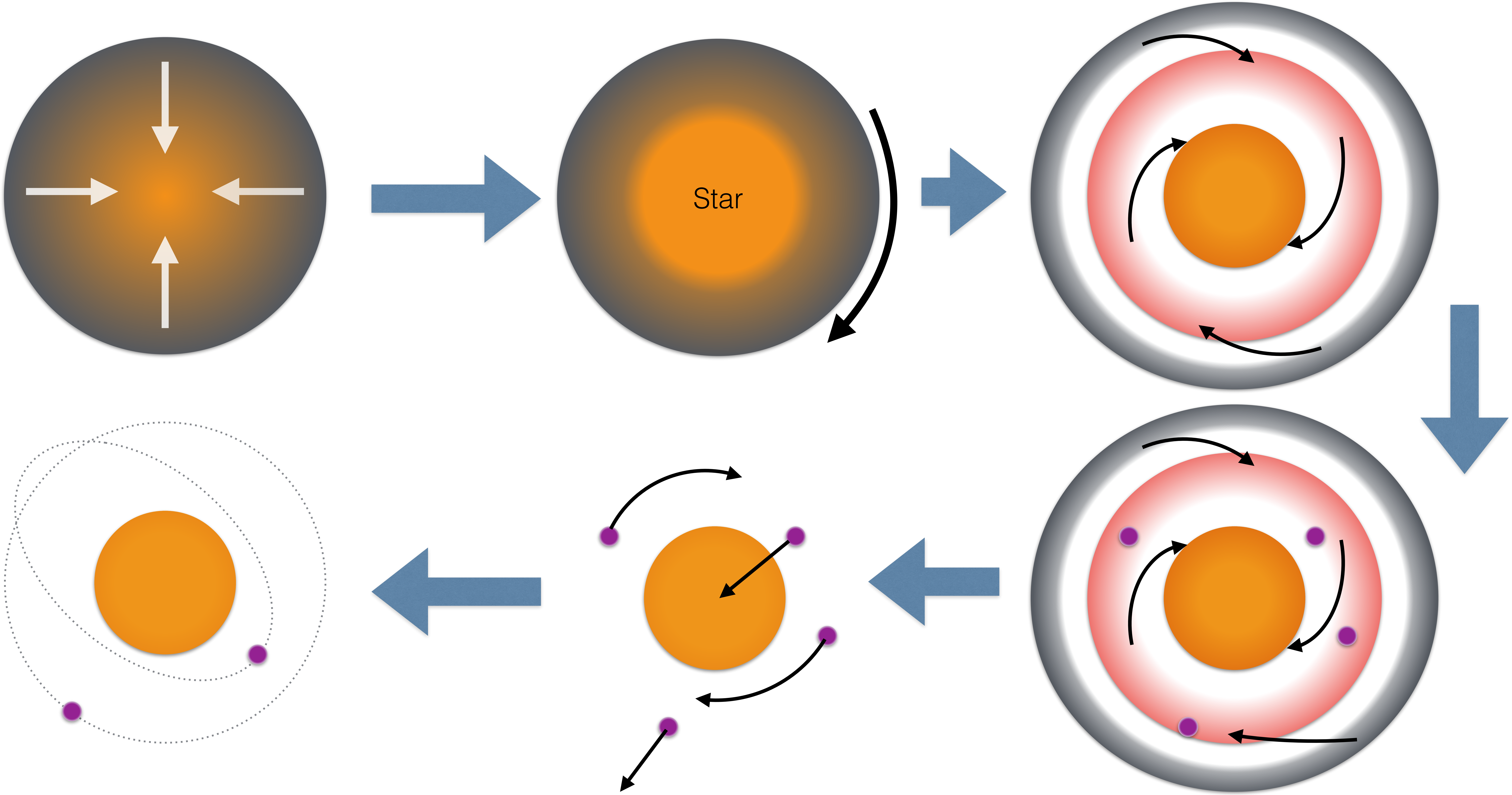
Massive Star Formation



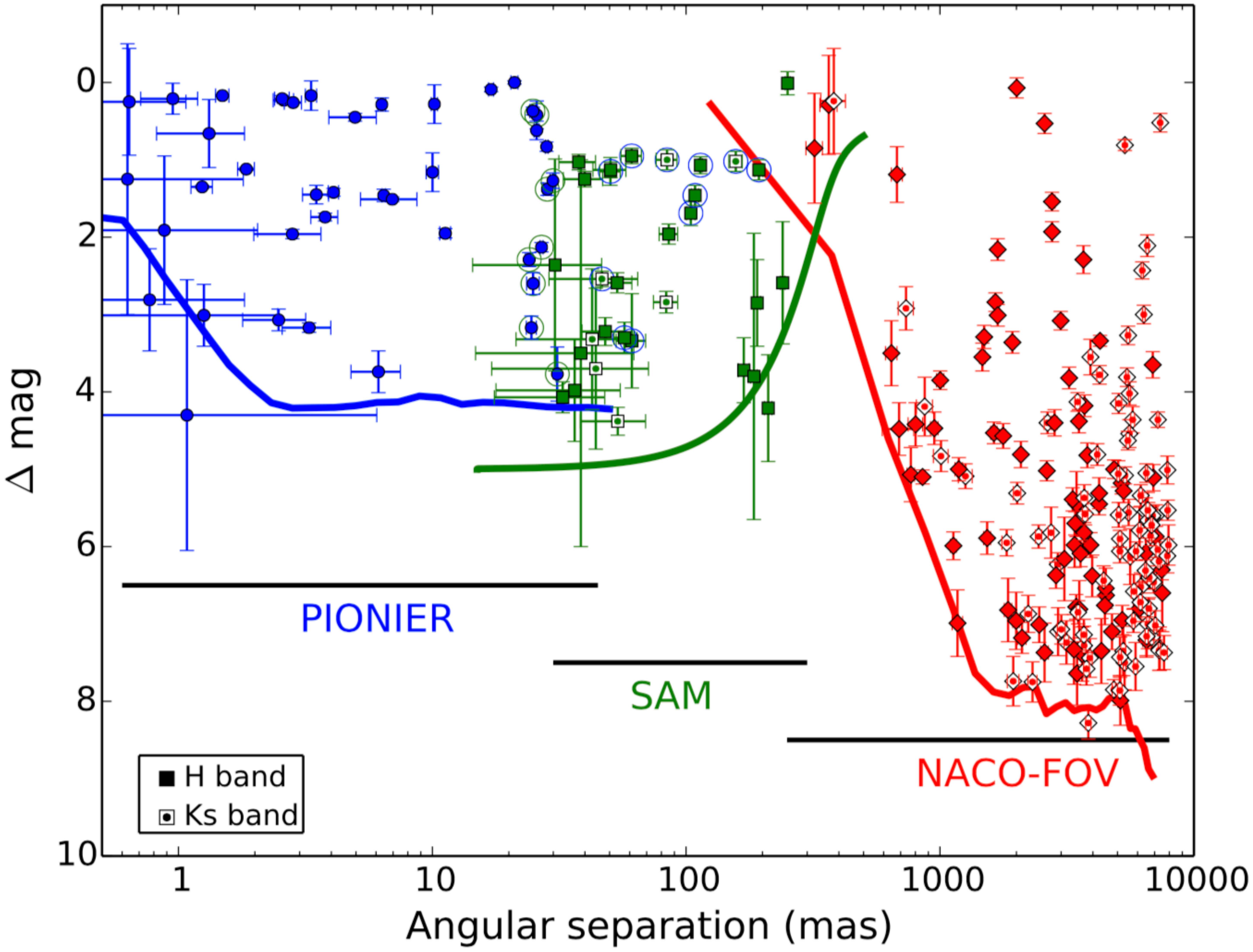
Massive Star Formation



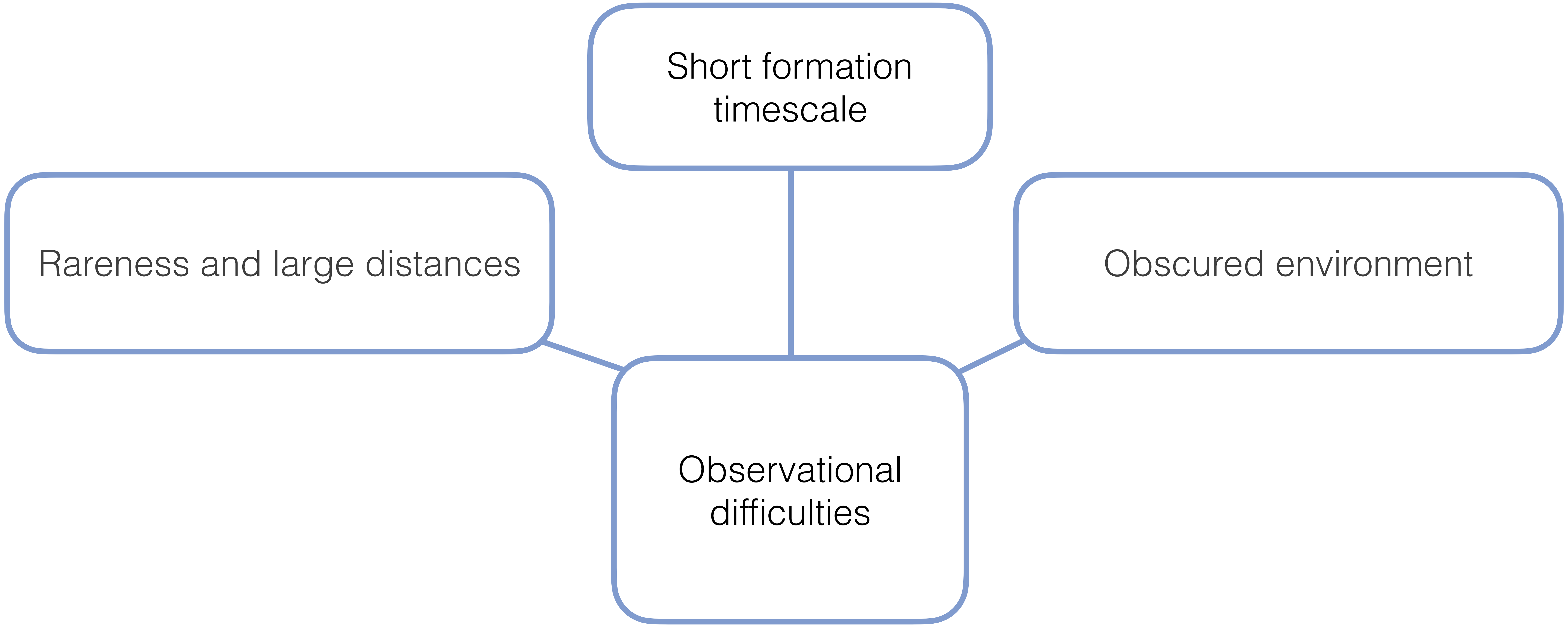
Massive Star Formation



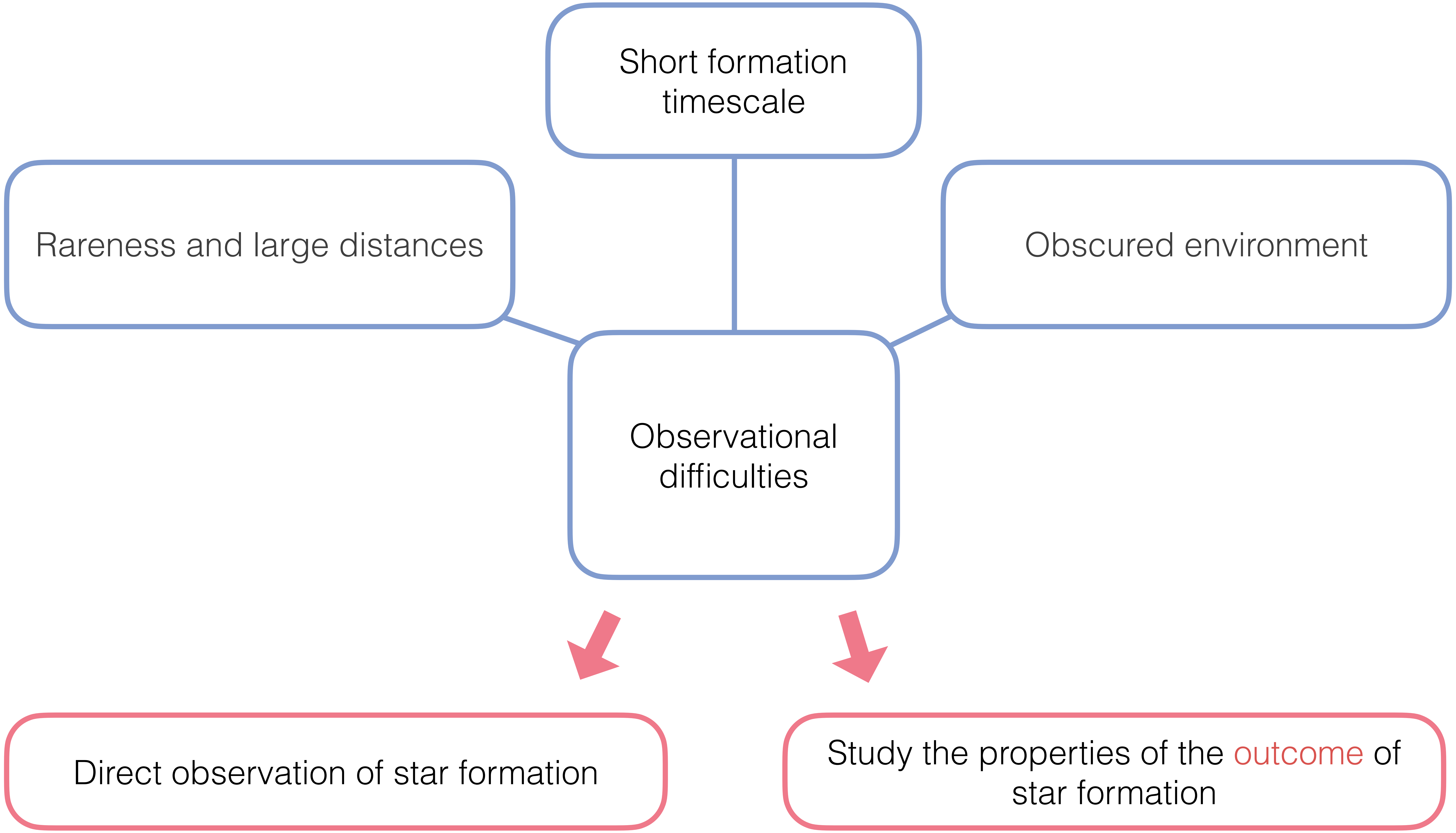
Companion detections (SMaSH+,Sana+,2014)



Massive Star Formation Problems



Massive Star Formation Problems

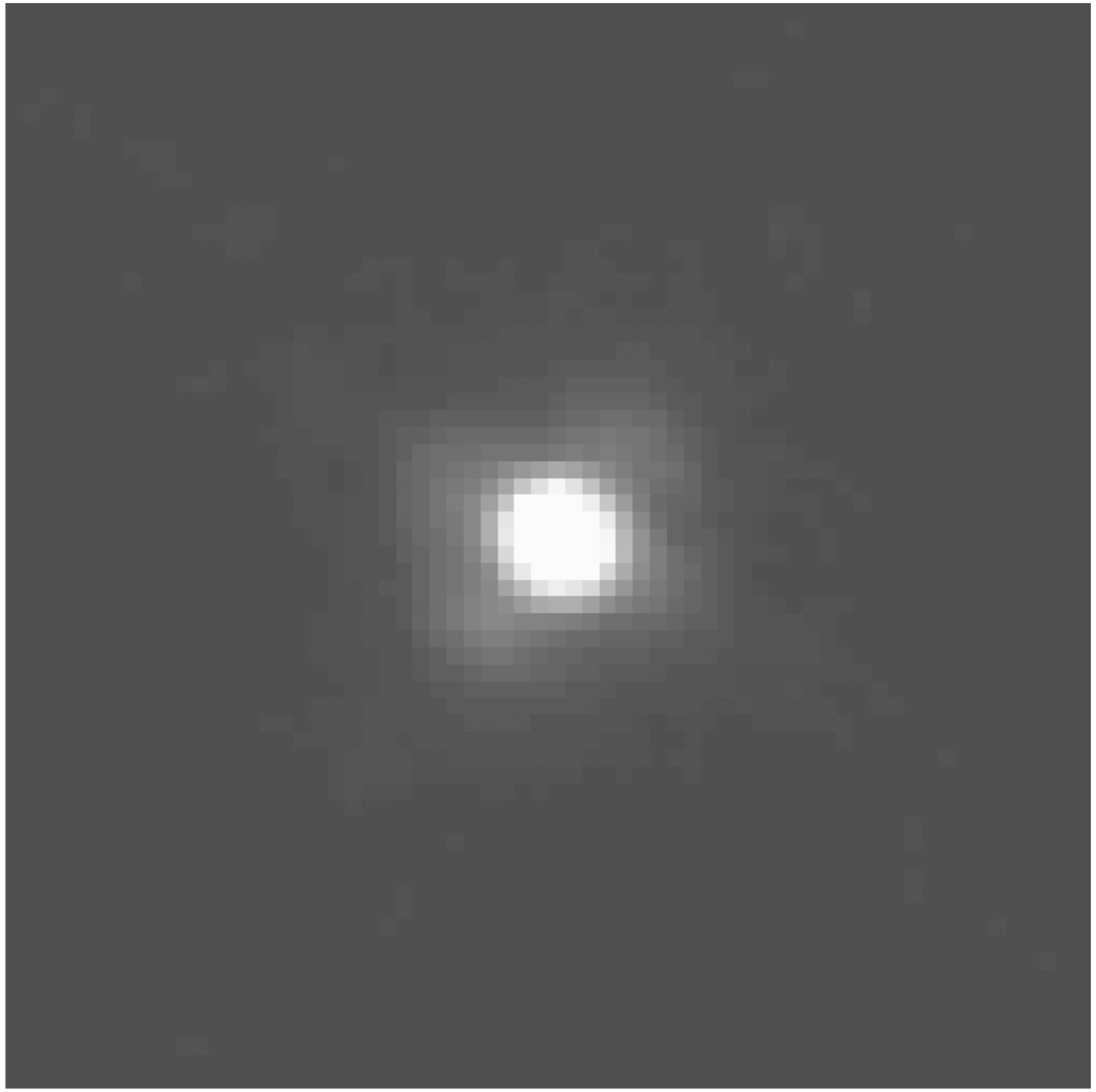


High-contrast imaging

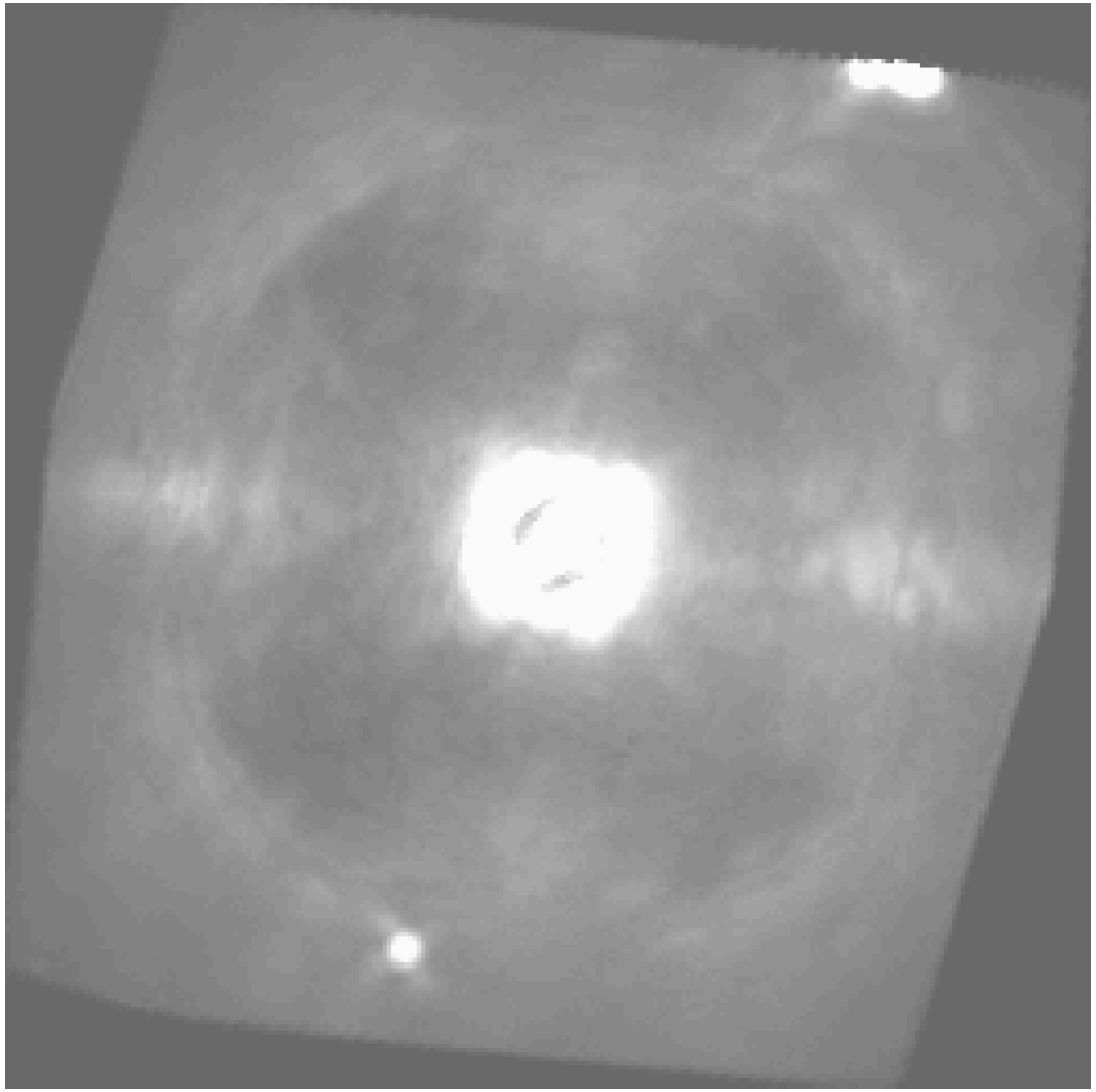
Raw

“Coronographed” image

Coronagraphy



Without coronagraph

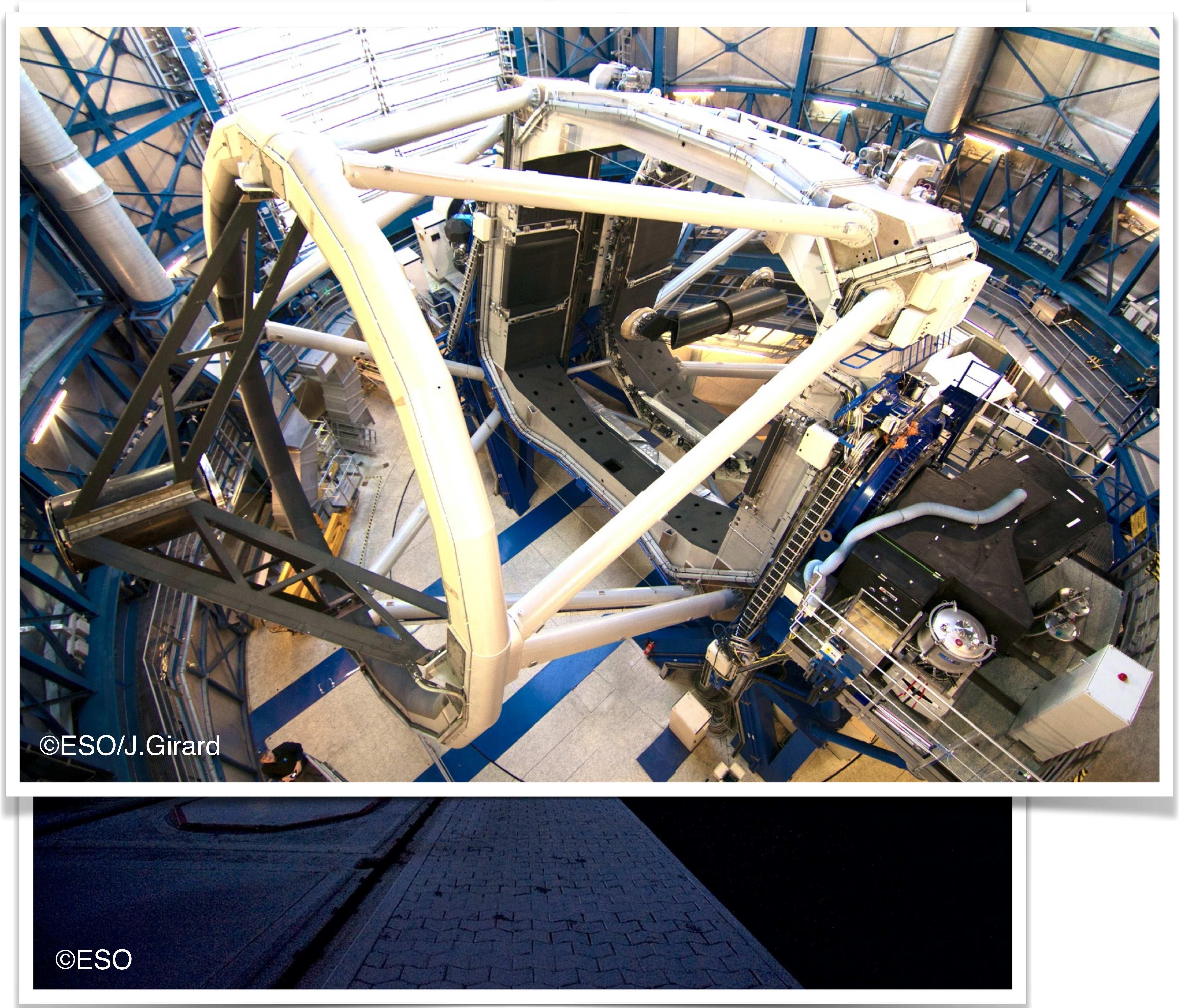


With coronagraph

Adaptive optics

©ESO/P. Weilbacher (AIP)/NASA, ESA, and M.H. Wong and J. Tollefson (UC Berkeley)

SPHERE:
Spectro-Polarimetric High-contrast Exoplanet REsearch



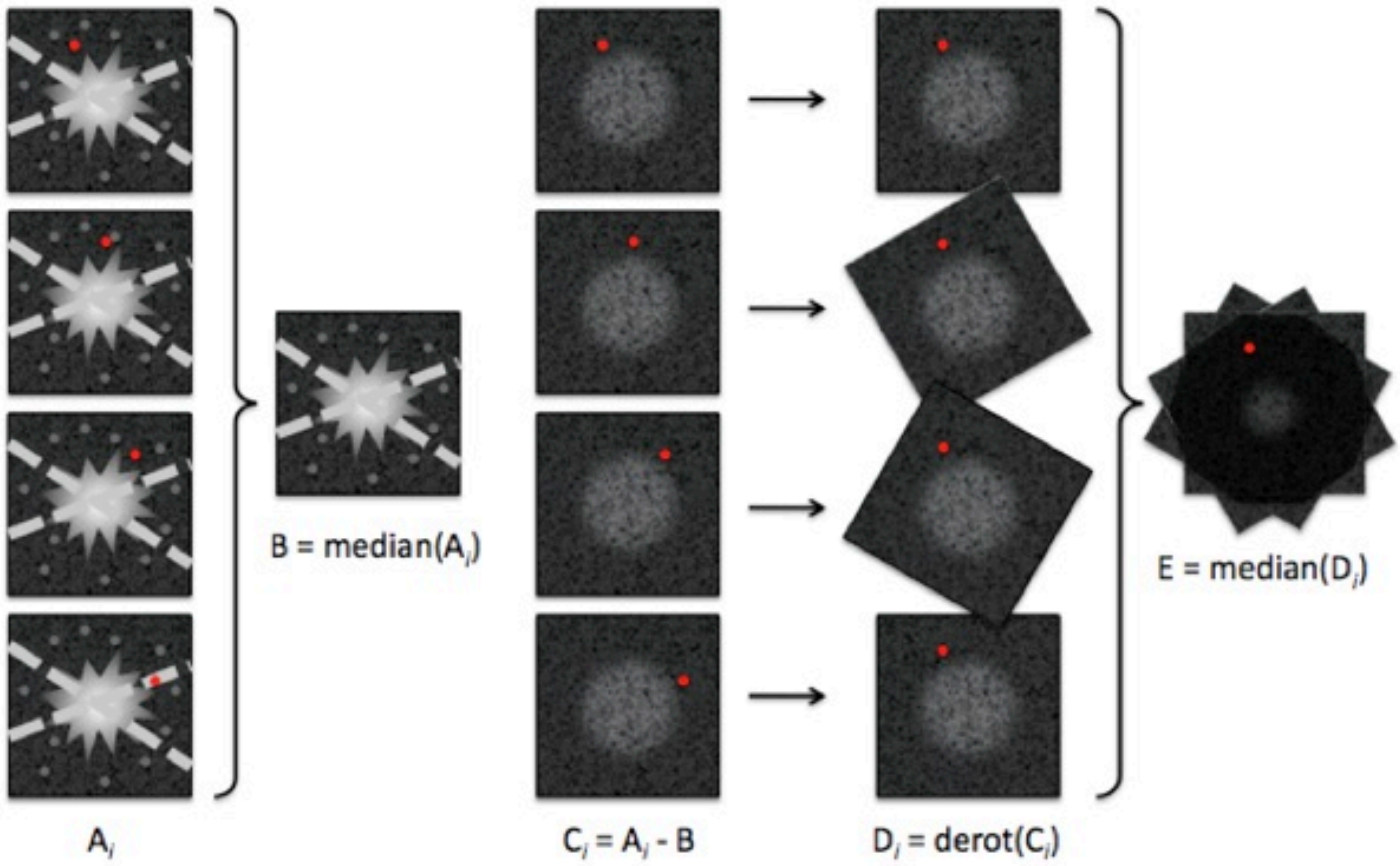
SPHERE	IFS	IRDIS
Spectral Range (μm)	0.95-1.75	0.95-2.32
FOV (arcsec²)	1.73	11
Pixel Scale (marcsec)	7.4	12.25
Bands	Y-J-H	K (1&2)

Observing strategy

Observing strategy

- ADI: Angular Differential Imaging

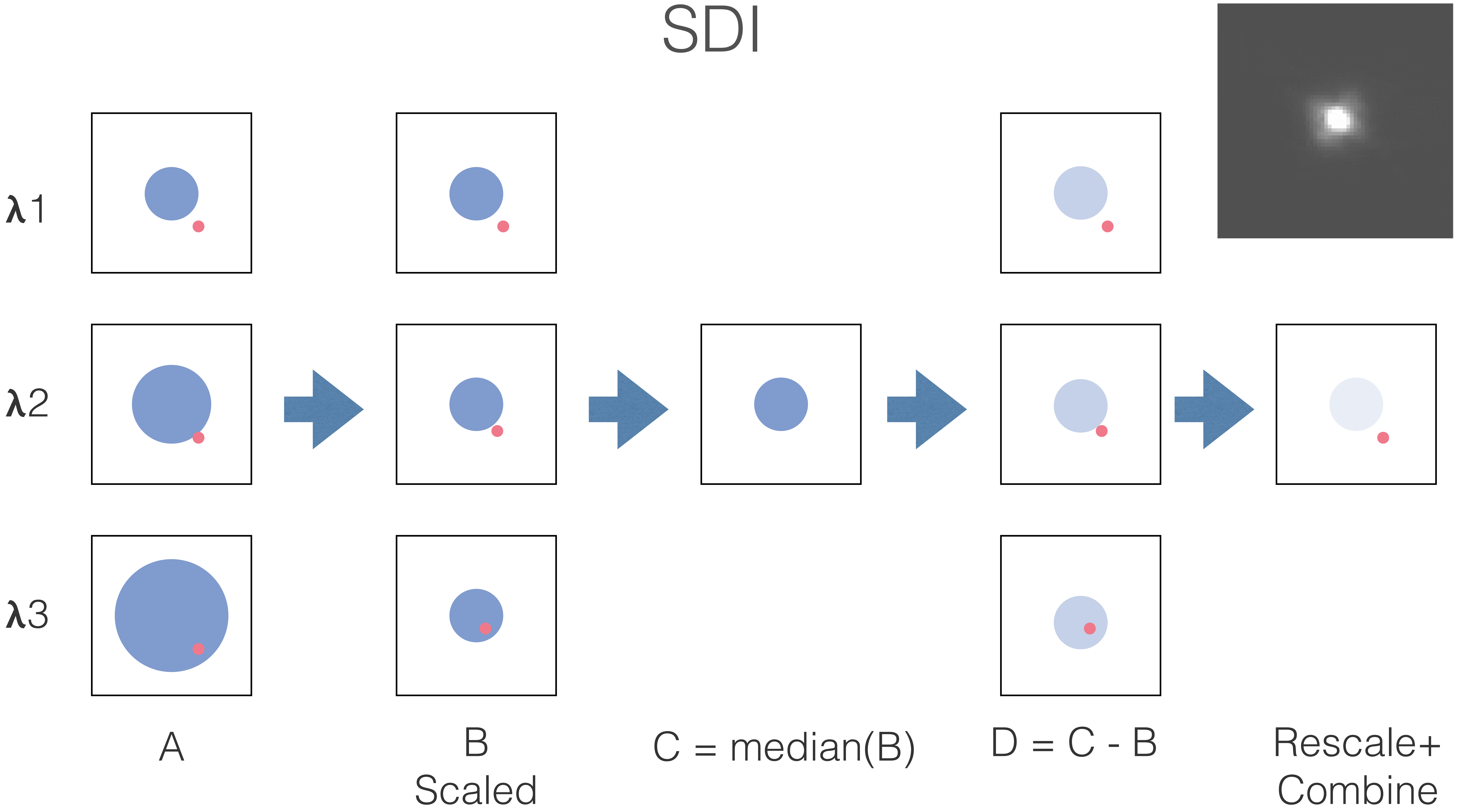
ADI (Marois et al., 2006)



Observing strategy

- ADI: Angular Differential Imaging
- SDI: Spectral Differential Imaging

SDI



Observing strategy

- ADI: Angular Differential Imaging
- SDI: Spectral Differential Imaging
- RDI: Reference star Differential Imaging

➡ Vortex Image Processing (VIP) Package: Gomez-Gonzalez et al. 2017

➡ pyKLIP: Wang et al. 2015

★ Star 44

VIP's documentation

Table of Contents

Quick search

Go

VIP - Vortex Image Processing package

pypi package 0.9.11 | Python 3.6, 3.7 | build failing | license MIT | arXiv 1705.06184 | docs passing | codecov 45%

```
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            oooooo     oooo ooooo ooooooooo.
             `888.     .8'  `888' `888   `Y88.
              `888.   .8'    888   888   .d88'
               `888. .8'     888   888ooo88P'
                `888.8'      888   888
                 `888'       888   888
                  `8'       o888o o888o
    ---------------------------------------------------
             Vortex Image Processing package
    ---------------------------------------------------
```
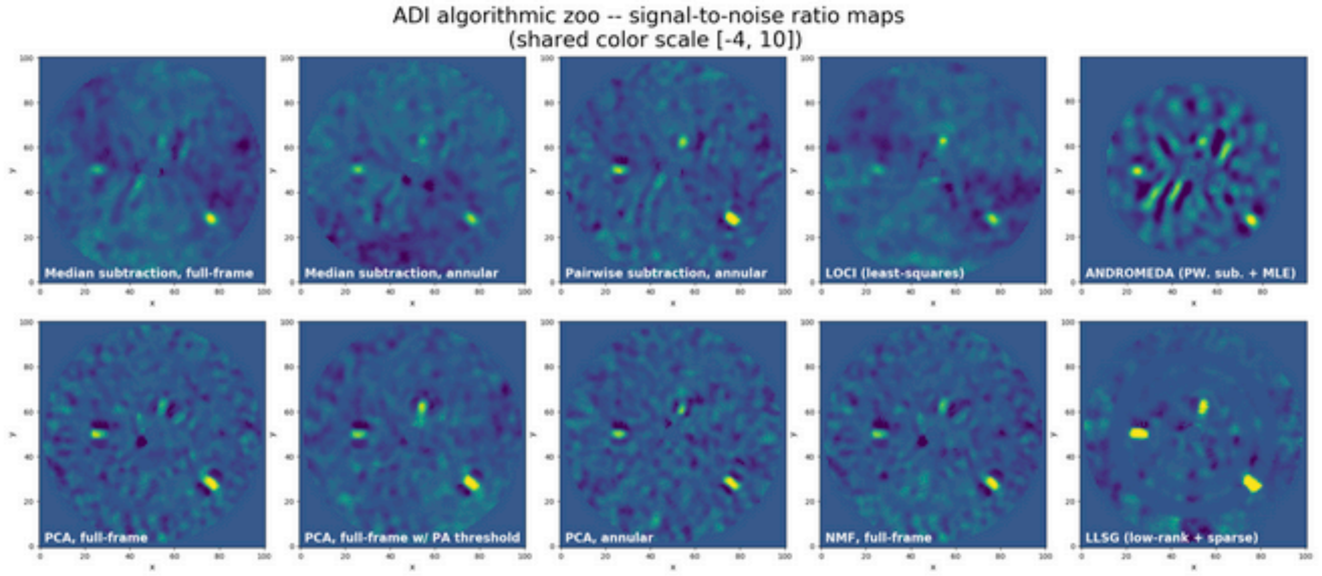

Introduction

`VIP` is a python package for angular, reference star and spectral differential imaging for exoplanet and disk high-contrast imaging. `VIP` is compatible with Python 3 (Python 2 compatibility dropped with `VIP` 0.9.9).



https://vip.readthedocs.io

__pycache__	Code cleanup	8 months ago
LICENSE	Initial commit	2 years ago
PSFfitting.py	Bug fixes	7 months ago
__init__.py	V1.0 release	8 months ago
__init__.pyc	Added basic + contrast curve functionality	2 years ago
readme.rst	Update readme.rst	8 months ago
ships_ifs.py	Added ability to save contrast curve	7 months ago
ships_irdis.py	Added ability to save contrast curve	7 months ago

readme.rst

SHIPS - SPHERE High-contrast Imaging Pipeline for massive Stars

Introduction

SHIPS is a high-contrast imaging pipeline specialising in the study of massive stars. It includes all necessary routines to fully analyse high-contrast imaging frames taken with SPHERE: it enables the detection and position of potential companion candidates and their spectrum extraction.

SHIPS bridges the gaps between the image processing algorithms from the state-of-the-art software VIP (https://github.com/carlgogo/vip-tutorial) and the scientific user. It aims to be a simple to use reduction pipeling to analyse and process images.

It is still under active development and is modified daily. Currently at version 1.0.

VIP is a package/pipeline for angular, reference star and spectral differential imaging for exoplanet/disk detection through high-contrast imaging. VIP is being developed in Python 3+.

Documentation

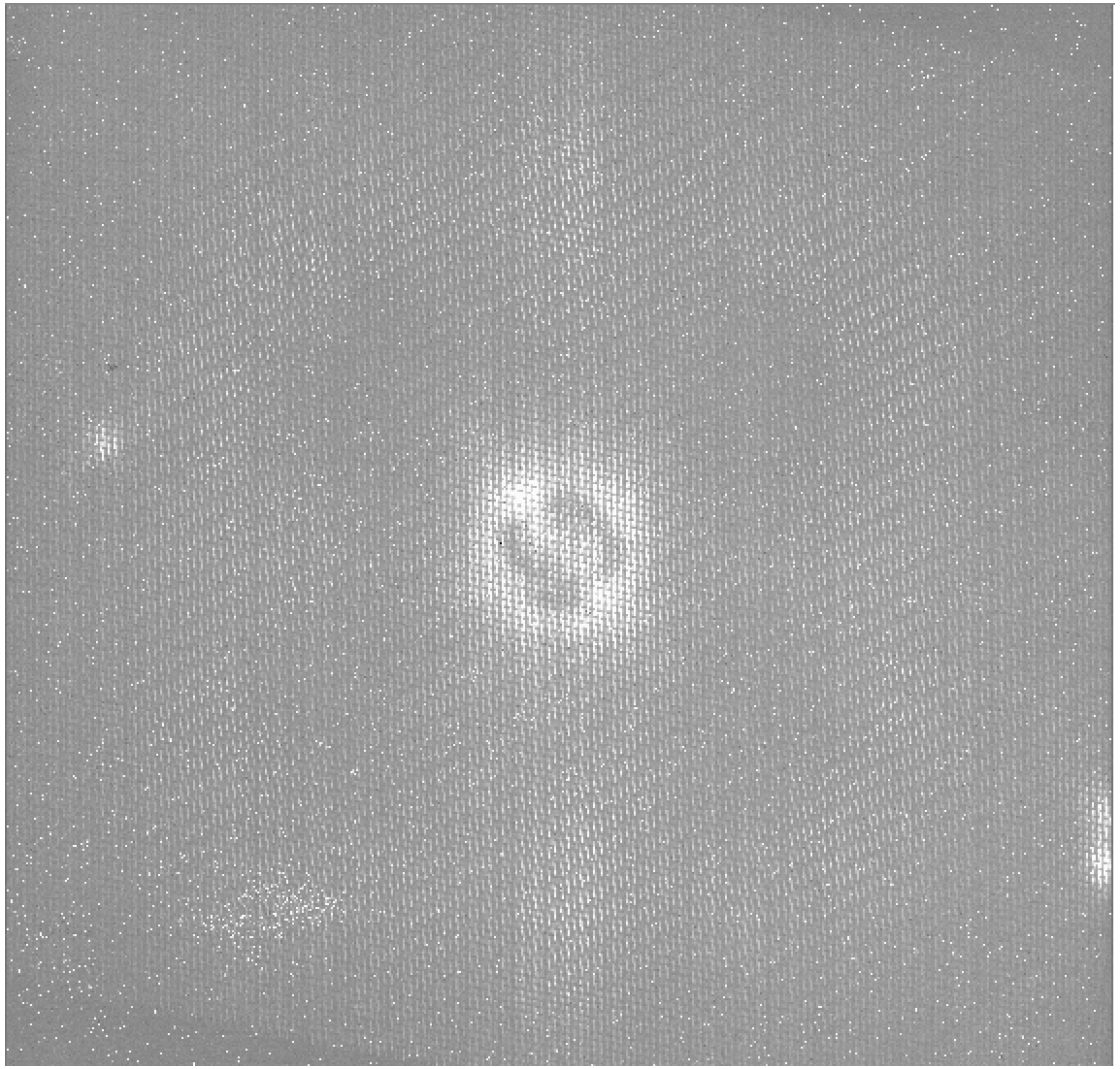
Documentation for VIP can be found in http://vip.readthedocs.io/.

https://github.com/arainot

```python
############################
# Date: 07/08/2019
# Title: Running script for SHIPS for IFS data
# Description: Use this script to run SHIPS for IFS data. In this script you'll find all the necessary parameters to run SHIPS. ONLY SPHERE-DC DATA FOR NOW. VIP are used.
# VIP version: 0.9.11 (Rainot edit.)
# Python version: 3 ONLY
############################

# Set up your parameters

## Define images to analyse
cube_filepath = '/home/alan/data/Backup_macbook/SPHERE/IFS/QZCardone/ifs_sortframes_dc-IFS_SCIENCE_REDUCED_SPECTRAL_MASTER_CUBE_SORTED-center_im_sorted.fits'
cube_filepath = '/home/alan/data/Backup_macbook/SPHERE/IFS/QZCardone/cube_free_Ad.fits'
wavelength_filepath = '/home/alan/data/Backup_macbook/SPHERE/IFS/QZCardone/ifs_sortframes_dc-IFS_SCIENCE_LAMBDA_INFO-lam.fits'
angles_filepath = '/home/alan/data/Backup_macbook/SPHERE/IFS/QZCardone/ifs_sortframes_dc-IFS_SCIENCE_PARA_ROTATION_CUBE_SORTED-rotnth_sorted.fits'
psf_filepath = '/home/alan/data/Backup_macbook/SPHERE/IFS/QZCardone/psf_corrected_final.fits'
# wavelength_filepath = '/home/alan/data/Backup_macbook/SPHERE/IFS/HD93403/ifs_sortframes_dc-IFS_SCIENCE_LAMBDA_INFO-lam.fits'
# cube_filepath = '/home/alan/data/Backup_macbook/SPHERE/IFS/HD93403/ifs_sortframes_dc-IFS_SCIENCE_REDUCED_SPECTRAL_MASTER_CUBE_SORTED-center_im_sorted.fits'
# angles_filepath = '/home/alan/data/Backup_macbook/SPHERE/IFS/HD93403/ifs_sortframes_dc-IFS_SCIENCE_PARA_ROTATION_CUBE_SORTED-rotnth_sorted.fits'
# psf_filepath = '/home/alan/data/Backup_macbook/SPHERE/IFS/HD93403/ifs_sortframes_dc-IFS_SCIENCE_PSF_MASTER_CUBE-median_unsat.fits'

## Photometry
comp_pos = (110.,54.) # Companion position in pixels from the center of the frame (X,Y)
psf_pos = (32, 32) # PSF position in pixels (X,Y)
frame_cent = (145,145) # Center of the frame
radial_dist = 98 # Radial distance of companion in pixels
position_angle = 159.  # Position angle of companion in degrees
noise_aperture_pos_comp = (92,104) # Position in pixels of the circular annulus aperture for noise measurement in the case of the companion
noise_aperture_pos_psf = (12,22) # Position in pixels of the circular annulus aperture for noise measurement in the case of the PSF
size_psf = 31 # What size PSF would you like to use? ODD VALUE ONLY!!


## Computing power
ncores = 4 # Number of cores you are willing to share for the computation

## Do you want to see the image?
see_cube = False # Original cube
see_collapsed_cube = False # Collapsed cube
see_psf_norm = False # Normalised PSF
see_cube_centre = False # Check if the image is centered correctly

## PCA
ncomp_pca = 0 # Number of principal components for PCA
opti_pca = False # Optimise the number of PCA components?
source_pca = (82.,116.) # Source where to optimise the PCA

## SNR maps
snr_maps = False # Would you like to make and save an SNR map to disk?
snr_map_file = '/home/alan/data/Backup_macbook/SPHERE/IFS/QZCardone/SNRmap_VIP11.fits' # Finish the file with .fits

## Detection
adi_frame = False # Would you like to apply ADI on the frame?
adi_plot = False # Would you like to see the resulting plot?
adi_min_scale = -1 # Minimum colour scale for the ADI plot
adi_max_scale = 1 # Maximum colour scale for the ADI plot
detection = False # Would you like the algorithm to detect sources for you? !! WARNING: this is a simple detection !!

detect_sigma = 5 # What sigma limit would you like for the detection?

## Contrast curves
```

Data Reduction

Raw frame



26-01-2016

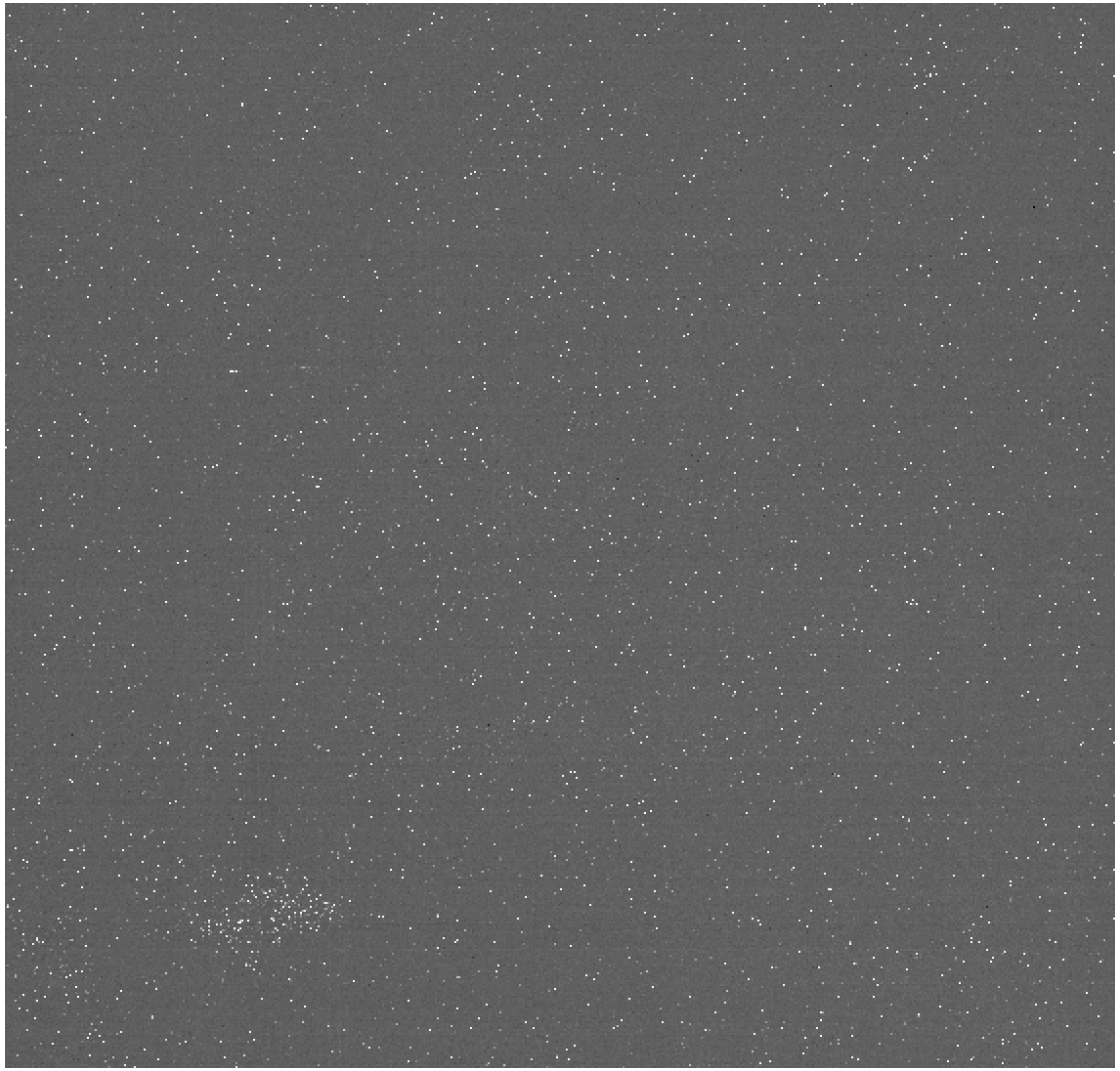
Dark frame

Detector flat-field

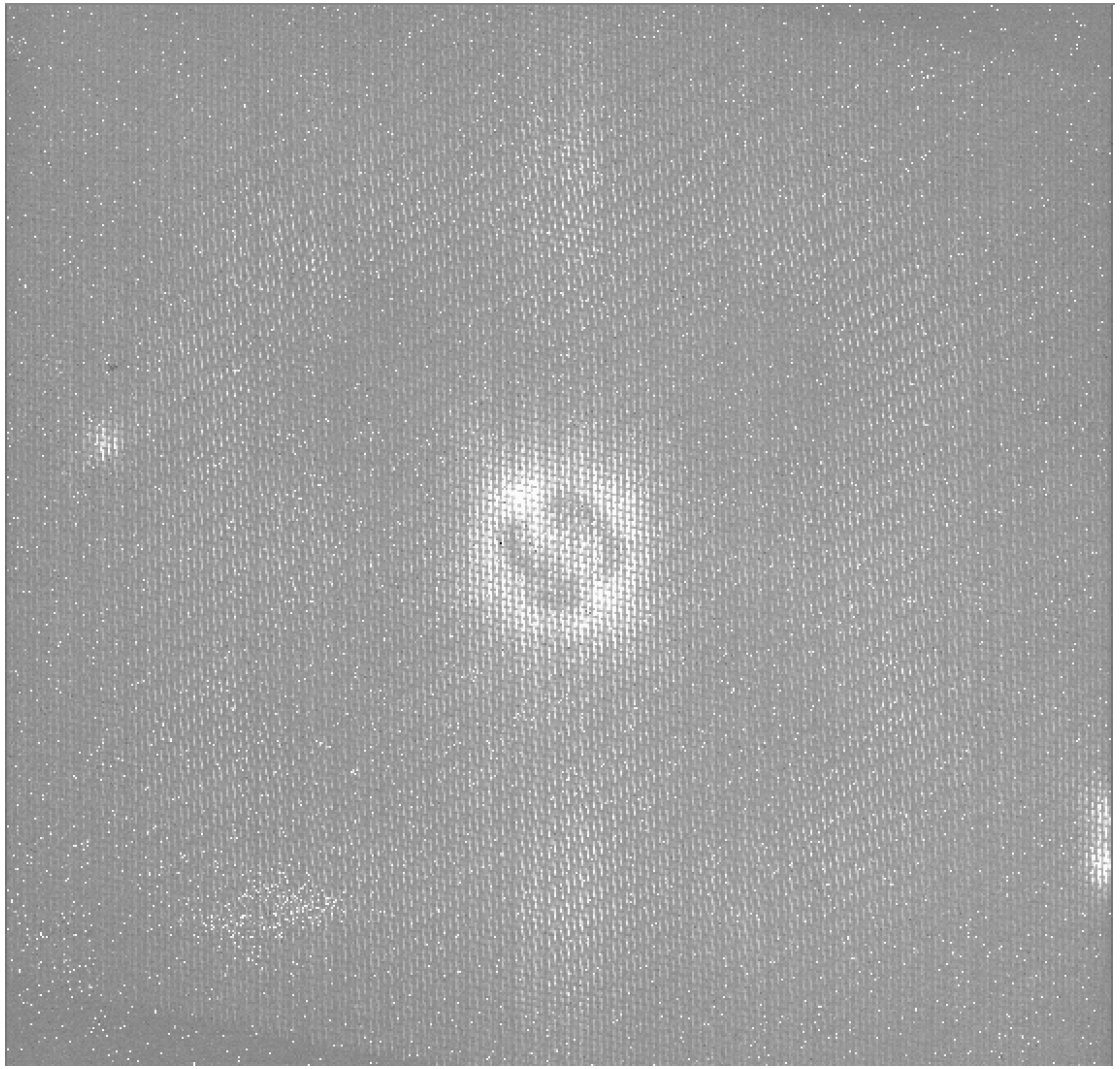
Wavelength calibration

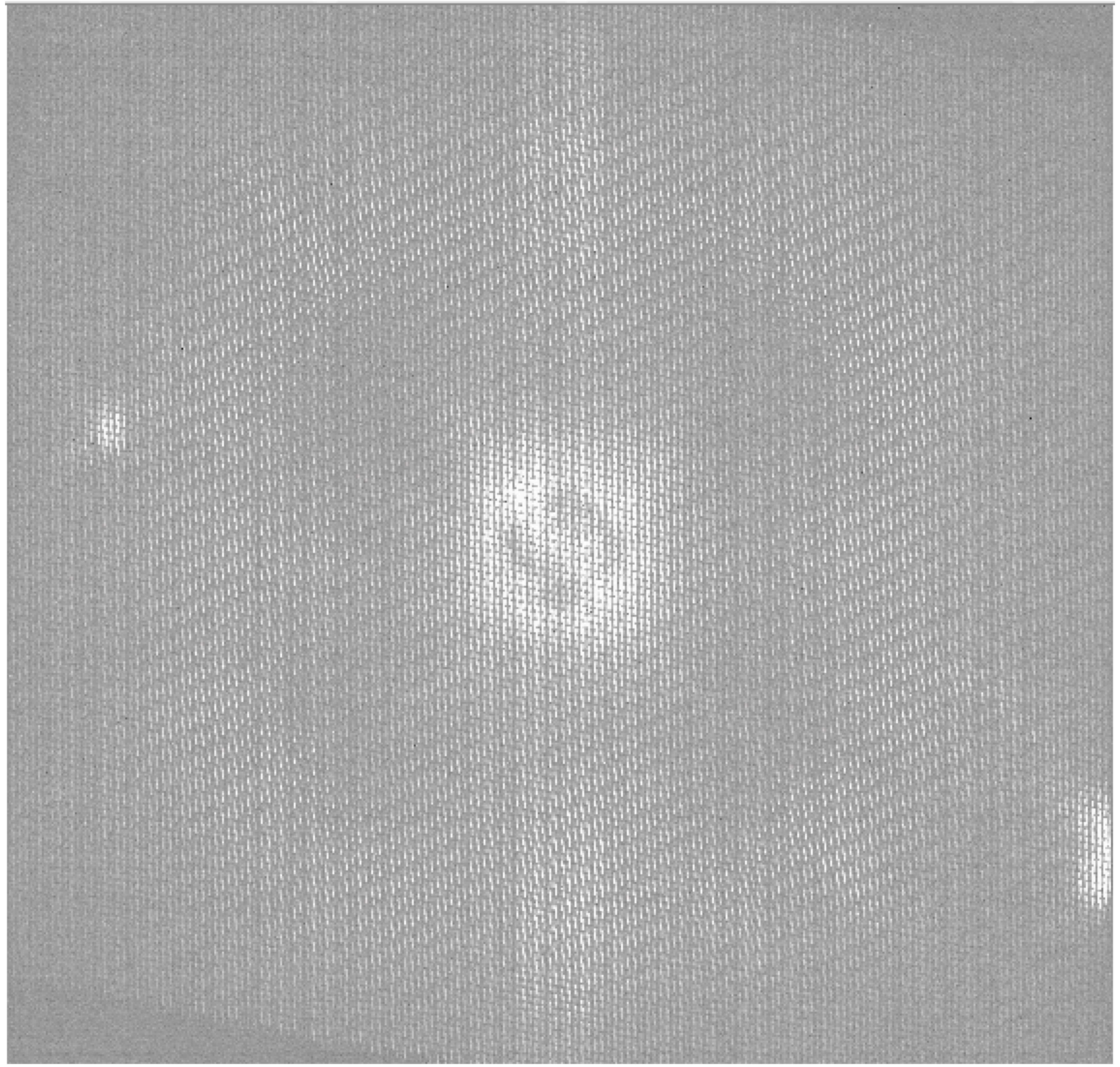
Combination of input frames

Dark frame



Bad pixel + dark correction





Dark frame

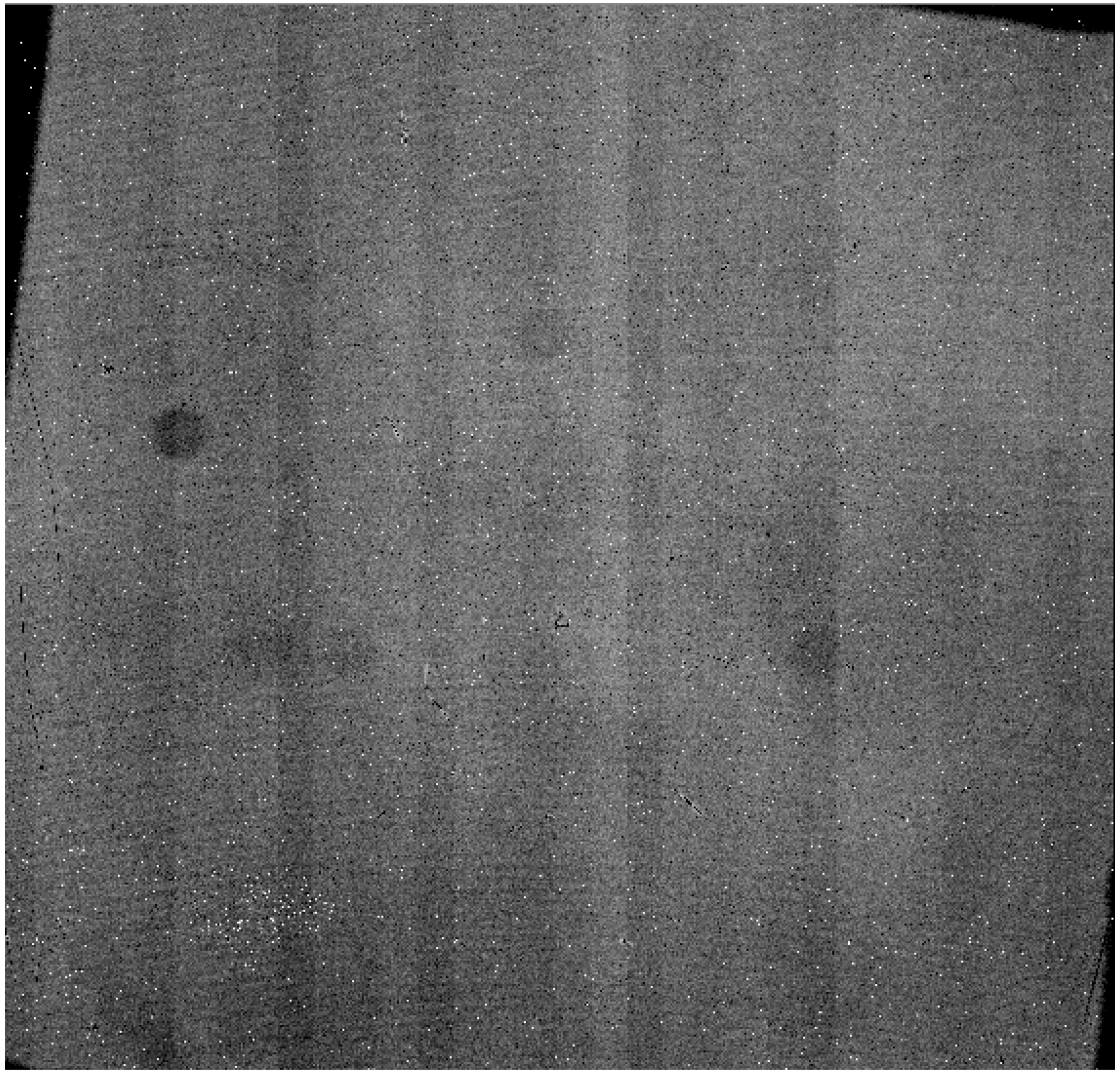
↓

Detector flat-field

Wavelength calibration

Combination of input frames

Flat-field



Dark frame

↓

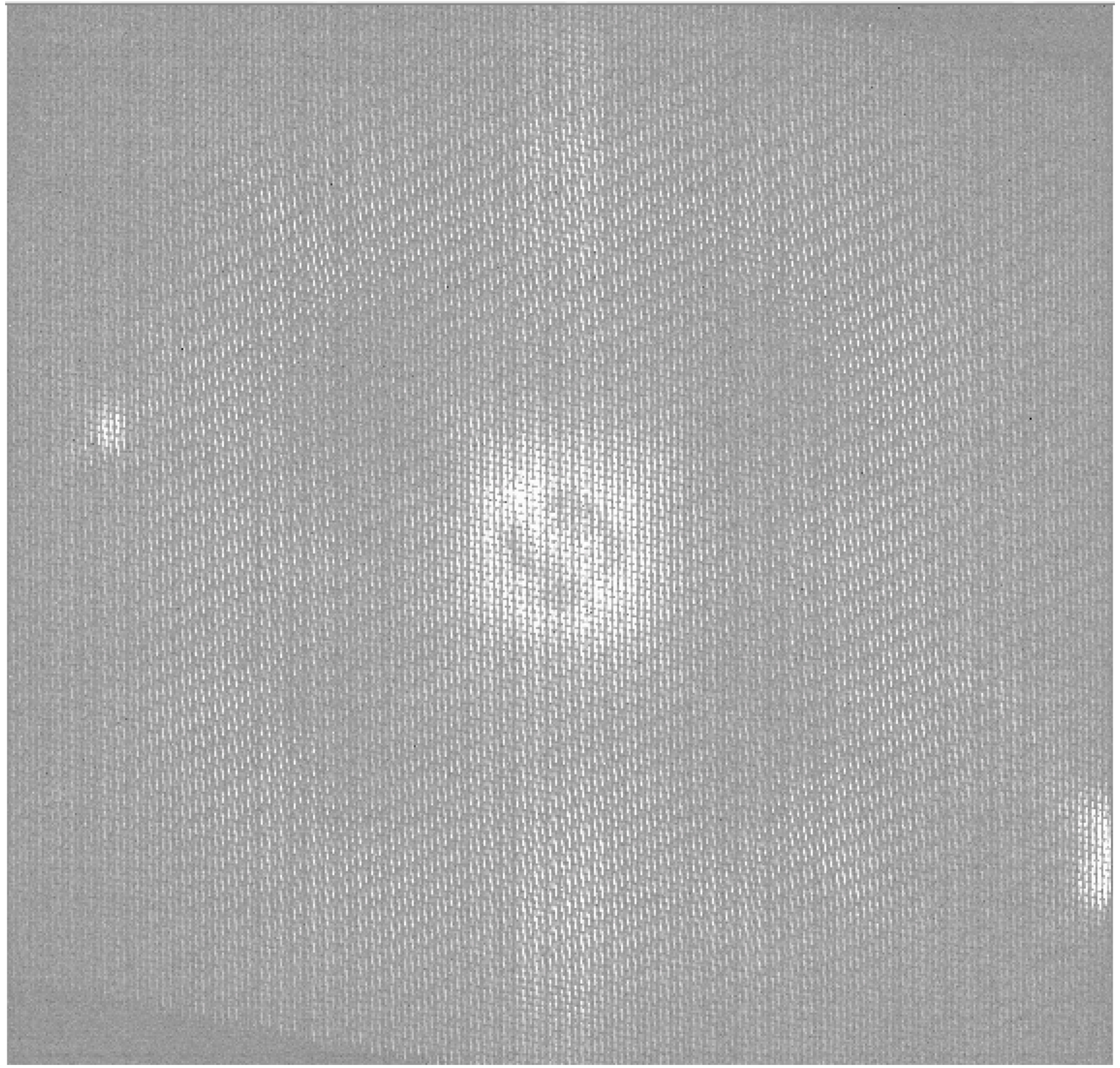
Detector flat-field

↓

Wavelength calibration

Combination of input frames

Wavelength calibration



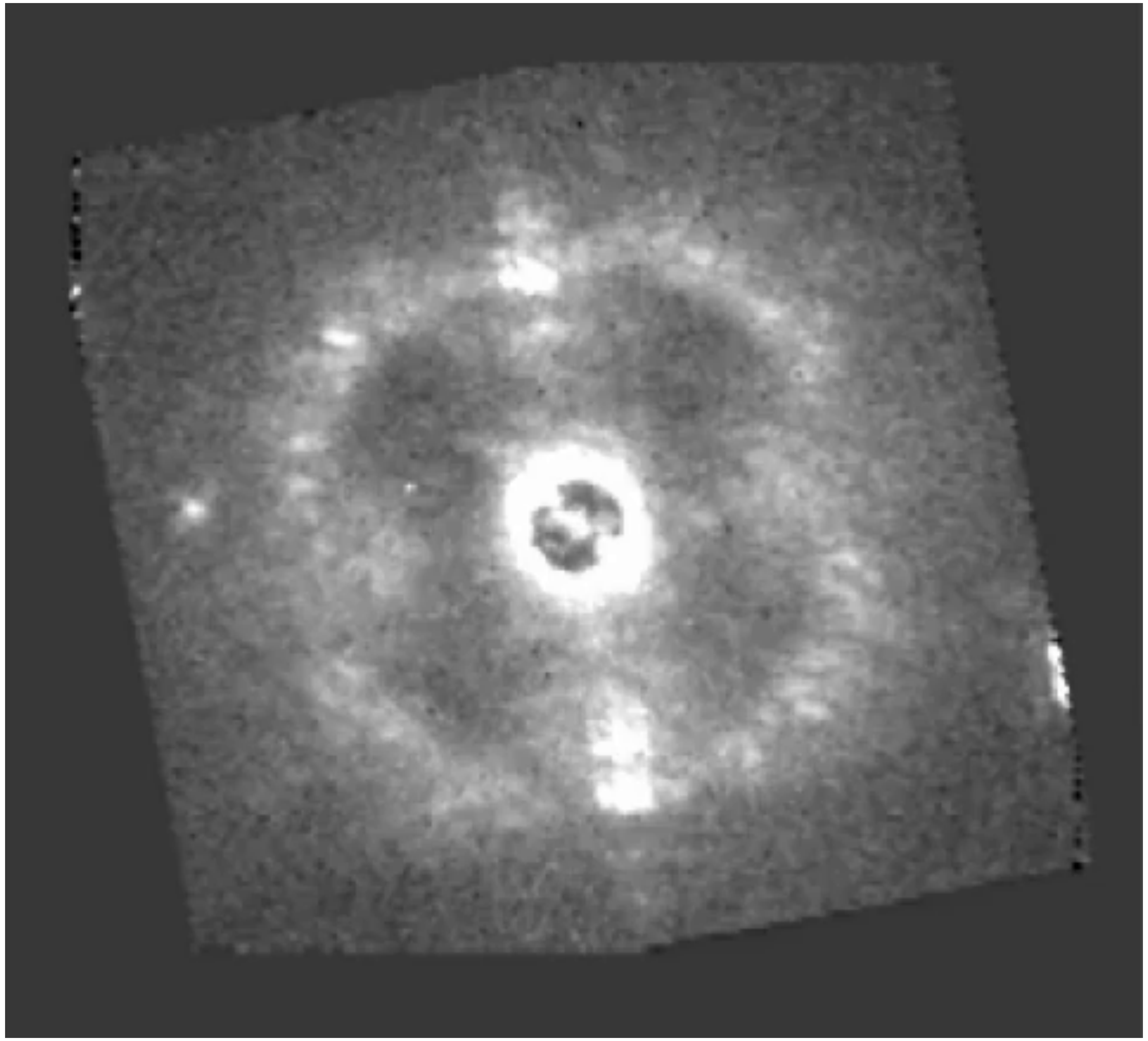
Dark frame

Detector flat-field

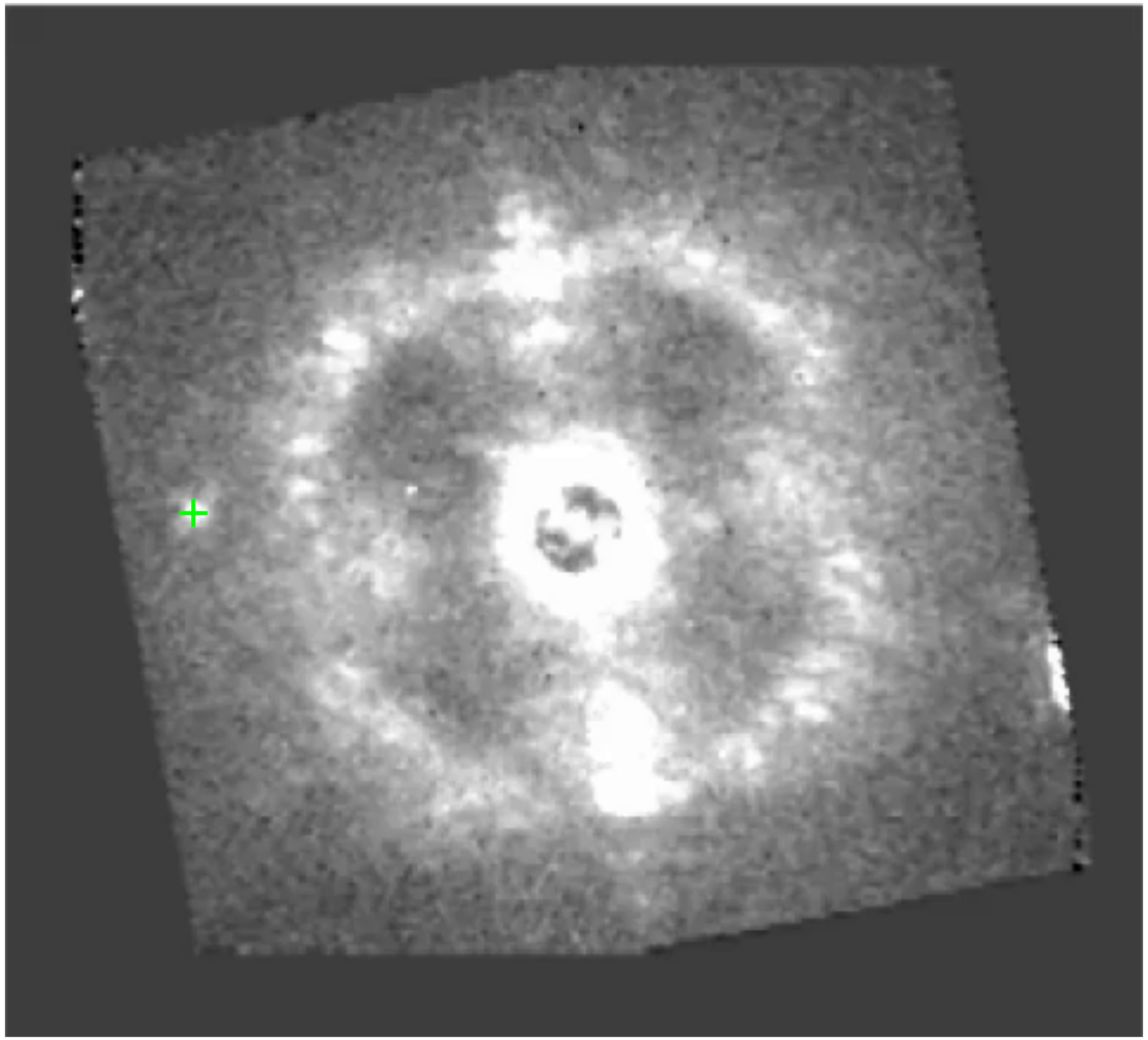
Wavelength calibration

Combination of input frames

Reduced IFS data



39 Wavelengths



48 rotations

Data Analysis

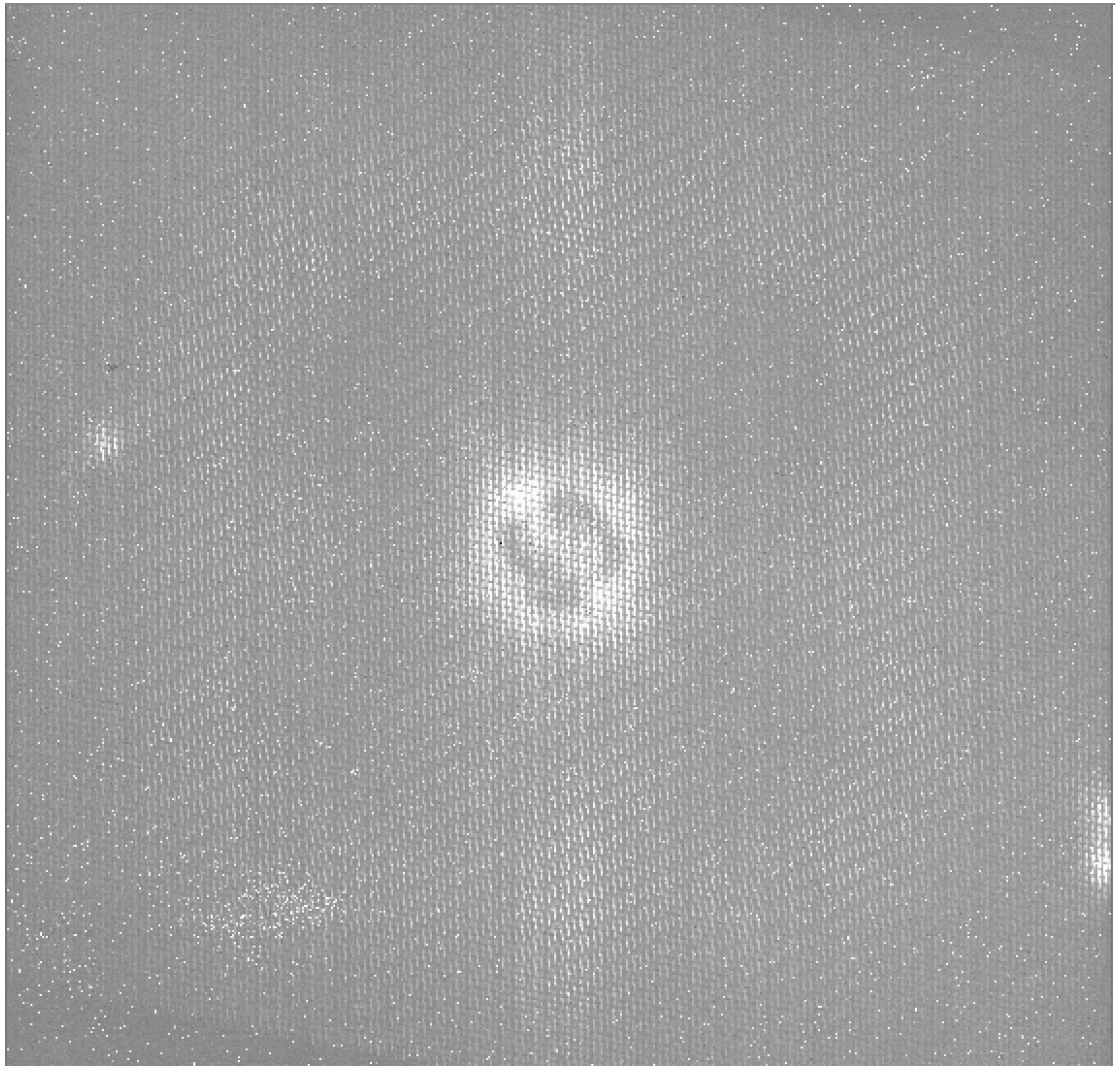
Analysis Techniques

- ADI: Angular Differential Imaging
- SDI: Spectral Differential Imaging
- RDI: Reference star Differential Imaging
- PCA: Principal Component Analysis

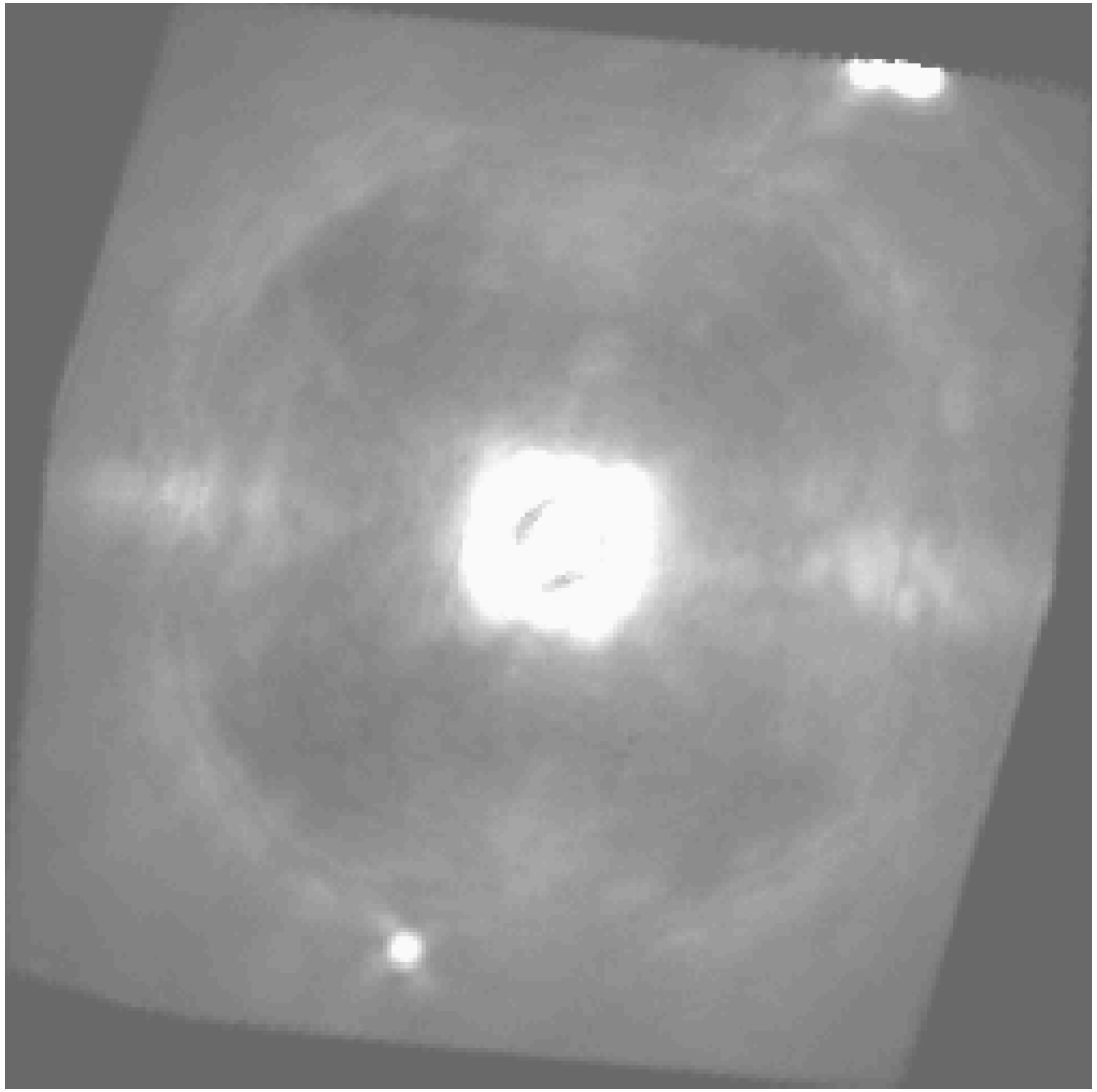
➡ Reference PSF subtraction

➡ Spectrum Extraction

IFS

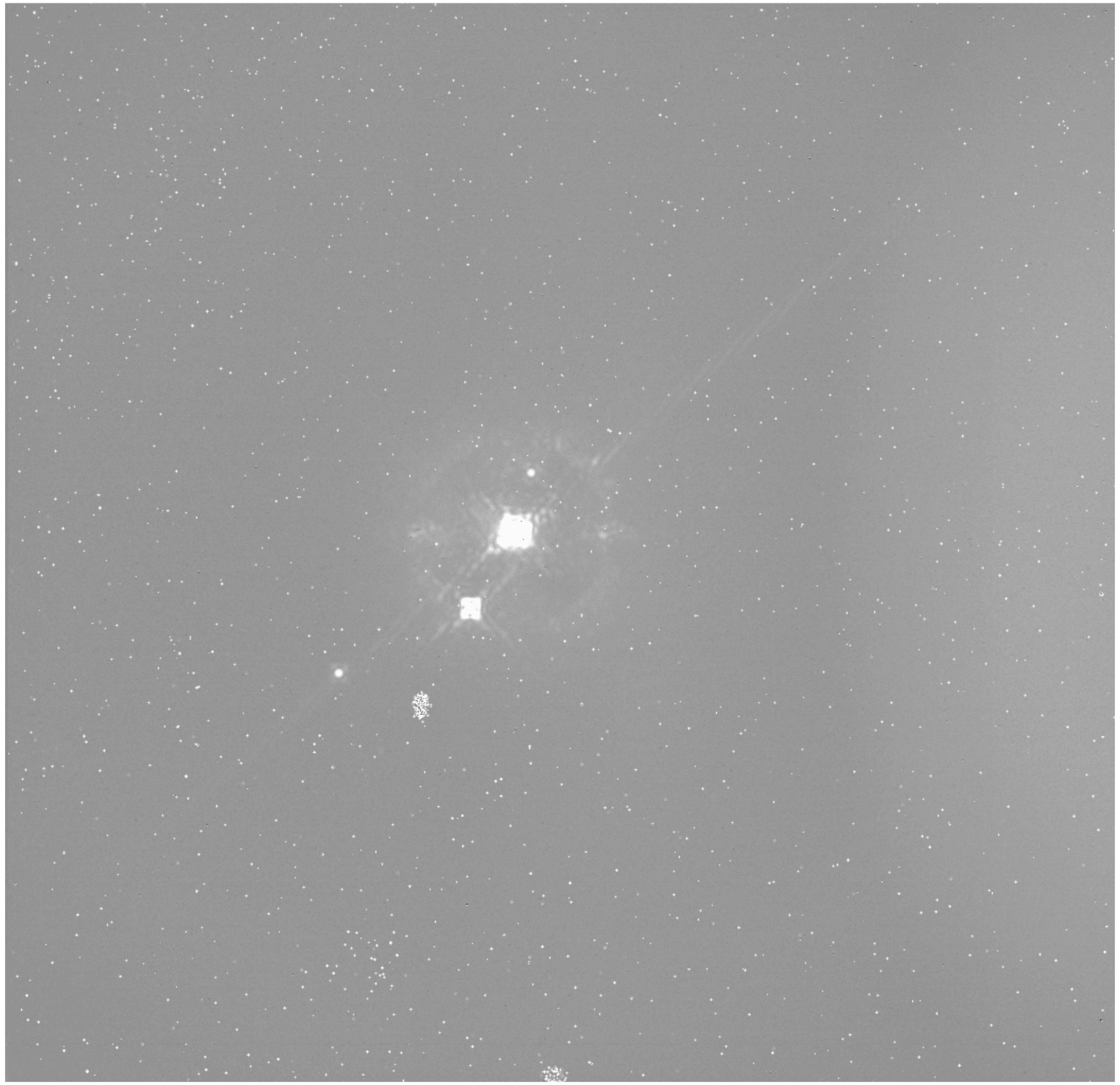


Raw image

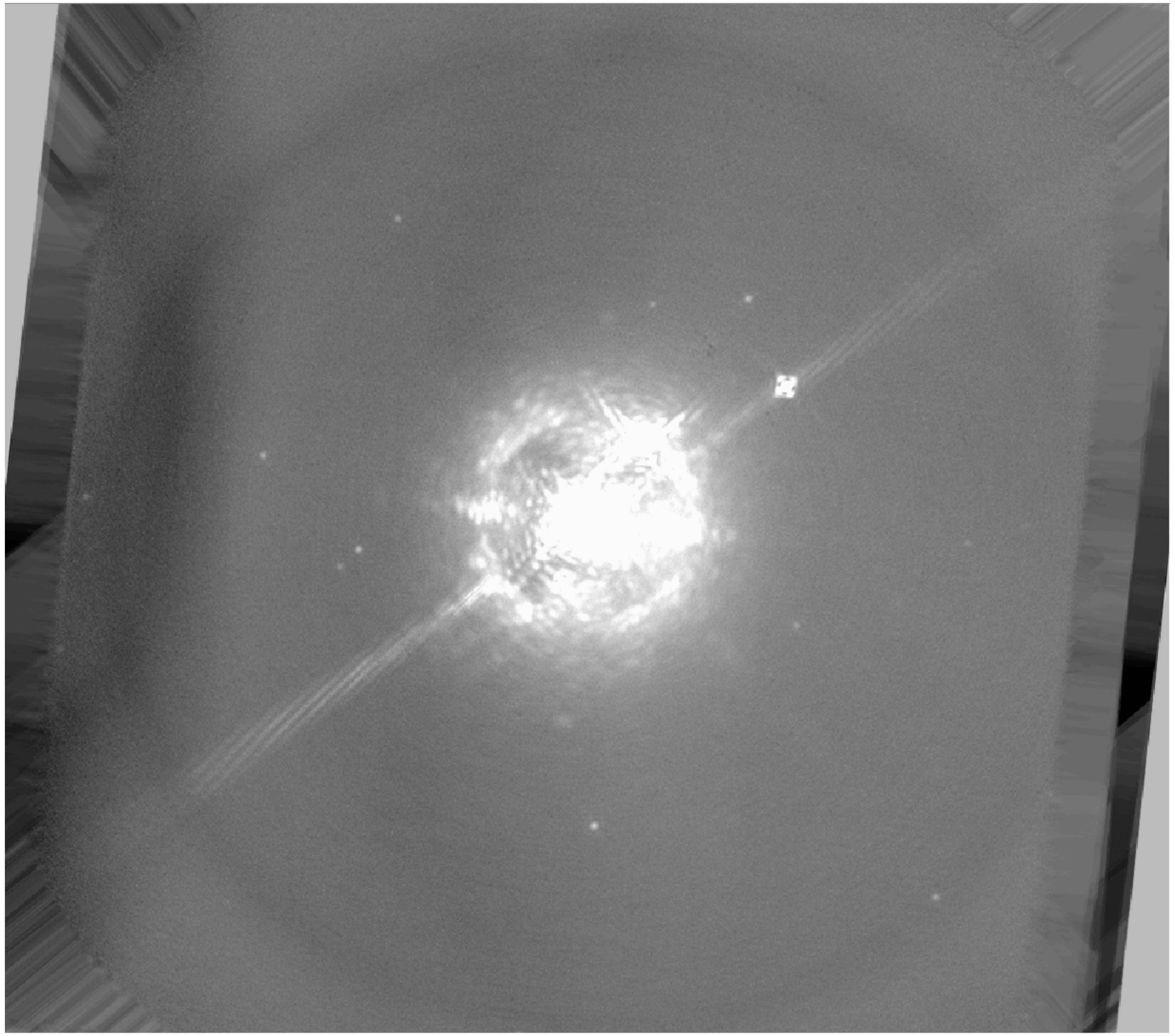


Post-processed image

IRDIS



Raw image



Post-processed image

C H I P S

C H I P S

Carina **H**igh-contrast **I**maging **P**roject of massive **S**tars

C H S

Carina

close massive star region

C H I P S

High-contrast **I**maging

VLT/SPHERE
@ESO

46 stars already reduced

47 stars planned

C H I **P** **S**

Multiplicity properties of 93 massive stars

faint and low-mass companions

Project of massive **S**tars

A&A 640, A15 (2020)
https://doi.org/10.1051/0004-6361/201936448

Astronomy & Astrophysics

Carina High-contrast Imaging Project for massive Stars (CHIPS)

I. Methodology and proof of concept on QZ Car (≡ HD 93206)

A. Rainot[1], M. Reggiani[1], H. Sana[1], J. Bodensteiner[1], C. A. Gomez-Gonzalez[2], O. Absil[3,⋆], V. Christiaens[3,4,5], P. Delorme[6], L. A. Almeida[7,8], S. Caballero-Nieves[9], J. De Ridder[1], K. Kratter[10], S. Lacour[11], J.-B. Le Bouquin[6], L. Pueyo[12], and H. Zinnecker[13]

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[4] Departamento de Astronomía, Universidad de Chile, Casilla 36-D, Santiago, Chile
[5] School of Physics and Astronomy, Monash University, VIC 3800, Australia
[6] Université Grenoble Alpes, CNRS, IPAG, 38000 Grenoble, France
[7] Departamento de Física, Universidade do Estado do Rio Grande do Norte, Mossoró, RN, Brazil
[8] Departamento de Física Teórica e Experimental, Universidade Federal do Rio Grande do Norte, CP 1641, Natal, RN 59072-970, Brazil
[9] Department of Aerospace Physics & Space Sciences, Florida Institute of Technology, 150 West University Blvd, Melbourne, FL 32901, USA
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[11] LESIA, (UMR 8109), Observatoire de Paris, PSL, CNRS, UPMC, Université Paris-Diderot, 5 place Jules Janssen, 92195 Meudon, France
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[13] Universidad Autonoma de Chile, Avda Pedro de Valdivia 425, Providencia, Santiago de Chile, Chile

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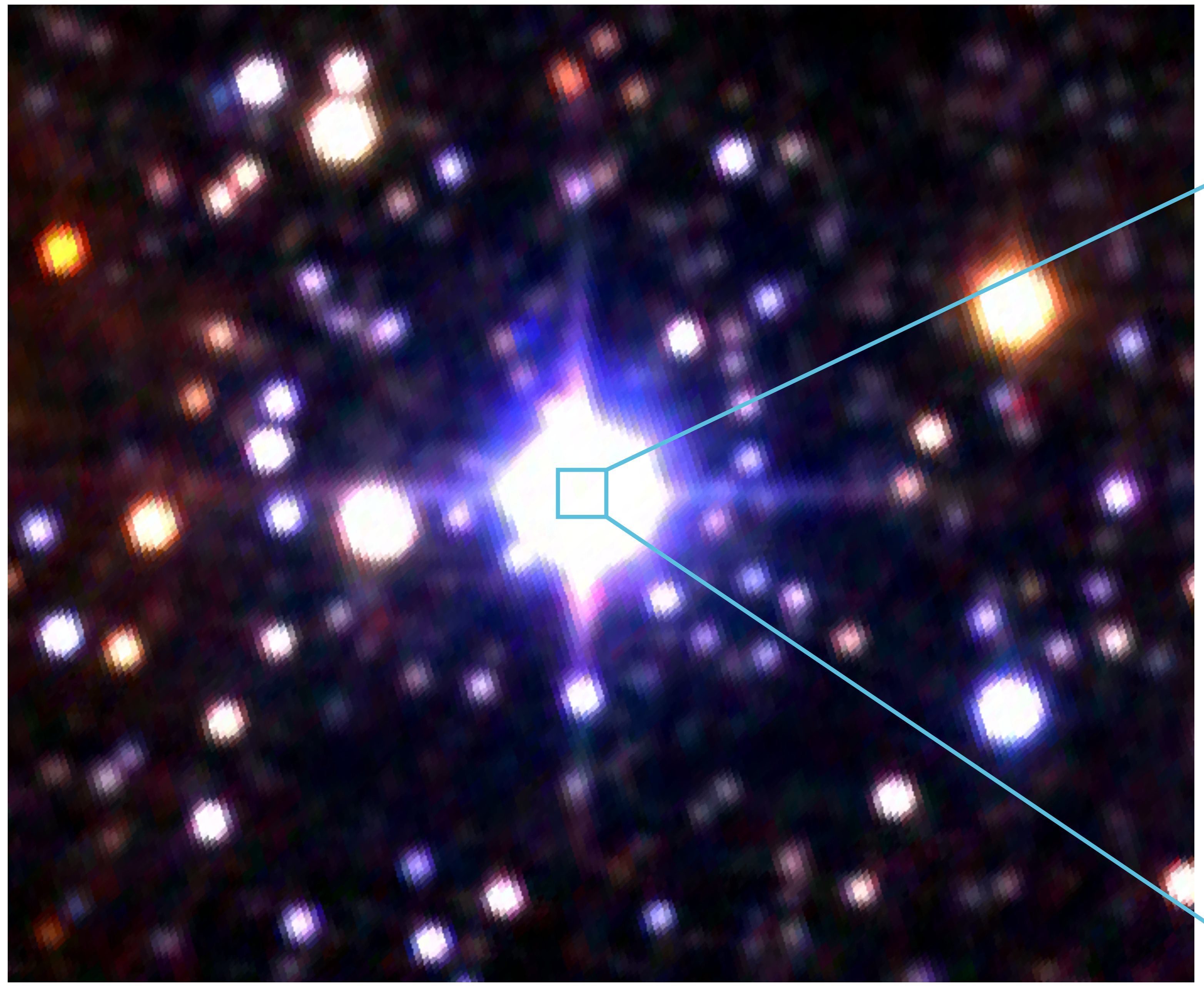
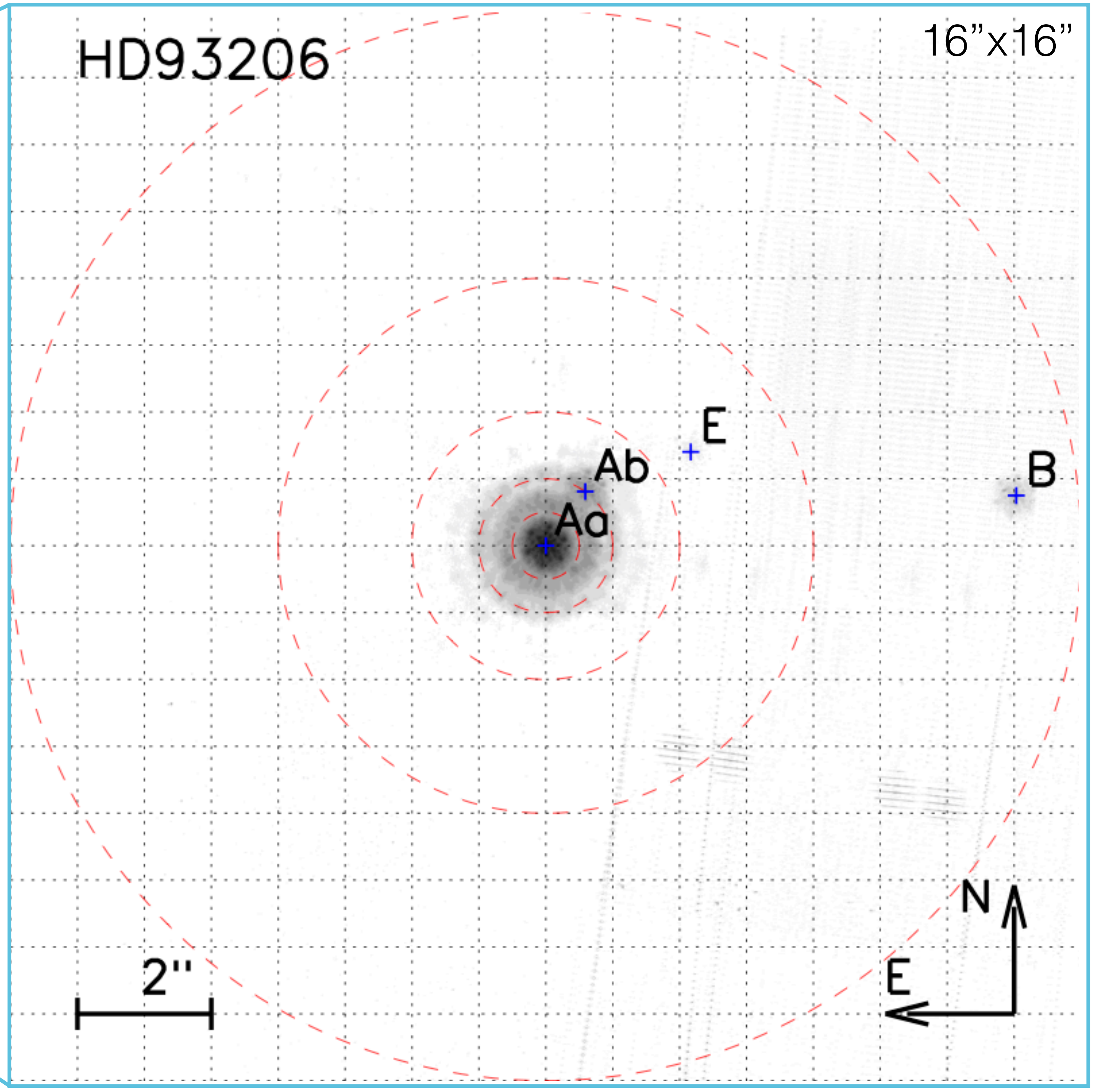
ABSTRACT

Context. Massive stars like company. However, low-mass companions have remained extremely difficult to detect at angular separations (ρ) smaller than 1″ (approx. 1000–3000 au, considering the typical distance to nearby massive stars) given the large brightness contrast between the companion and the central star. Constraints on the low-mass end of the companions mass-function for massive stars are needed, however, for helping, for example, to distinguish among the various scenarios that describe the formation of massive stars.
Aims. With the aim of obtaining a statistically significant constraint on the presence of low-mass companions beyond the typical detection limit of current surveys (Δmag $\lesssim 5$ at $\rho \lesssim 1''$), we initiated a survey of O and Wolf-Rayet stars in the Carina region using the Spectro-Polarimetric High-contrast Exoplanet REsearch (SPHERE) coronagraphic instrument on the Very Large Telescope (VLT). In this, the first paper of the series, we aim to introduce the survey, to present the methodology and to demonstrate the capability of SPHERE for massive stars using the multiple system QZ Car.

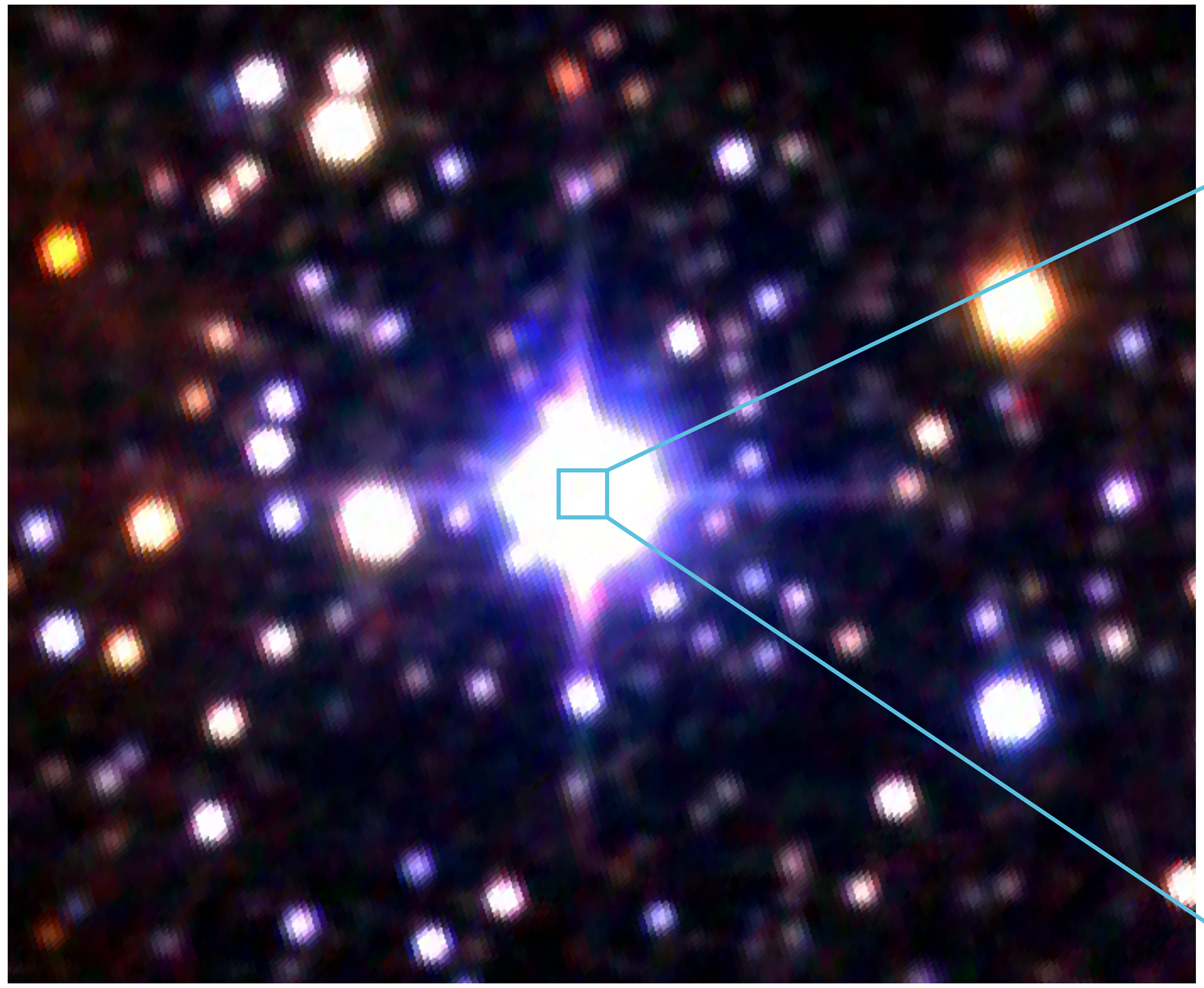
FOV = 5’, 2MASS



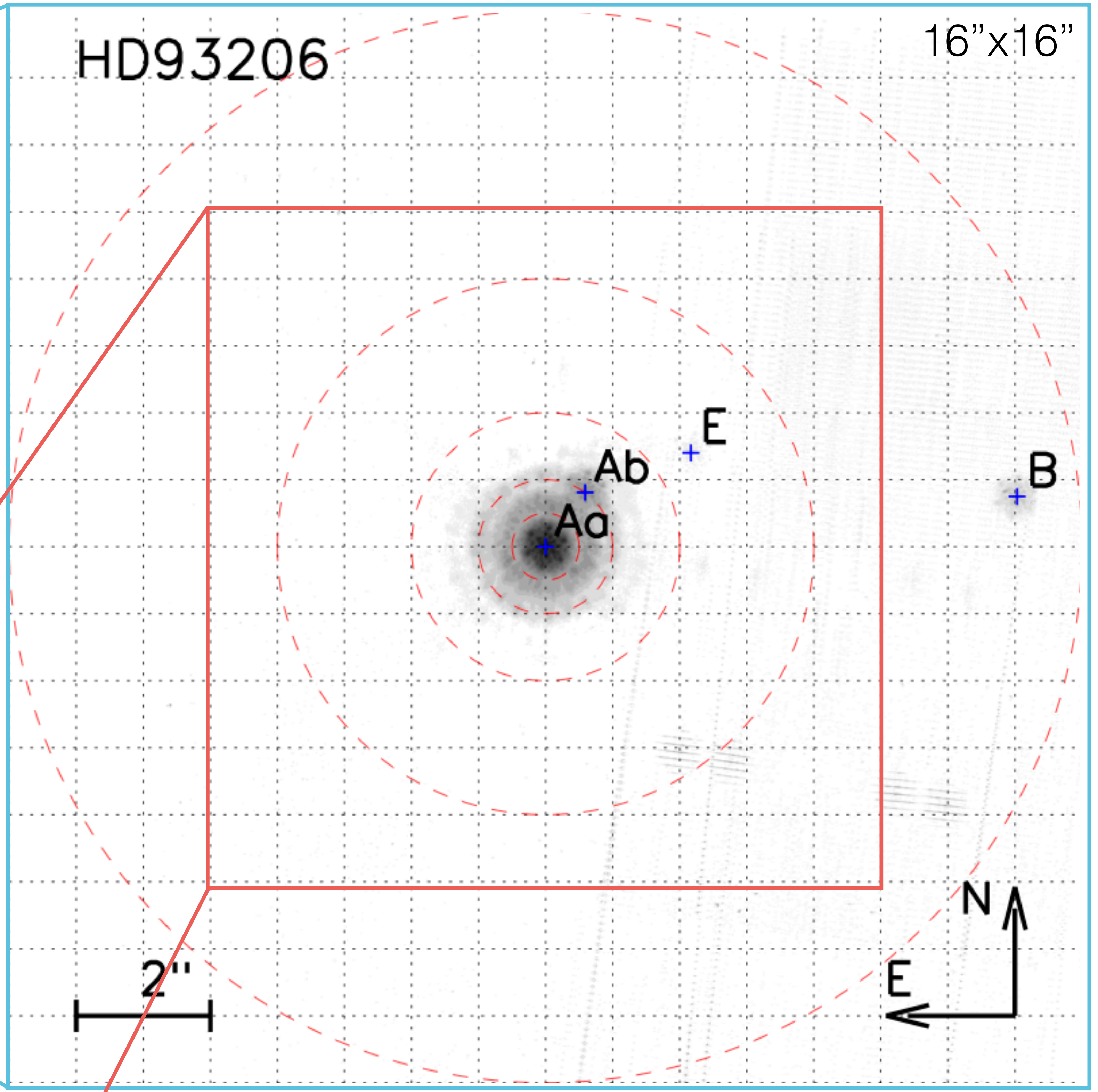
FOV = 5’, 2MASS



SMaSH+ Image
Sana et al, 2014

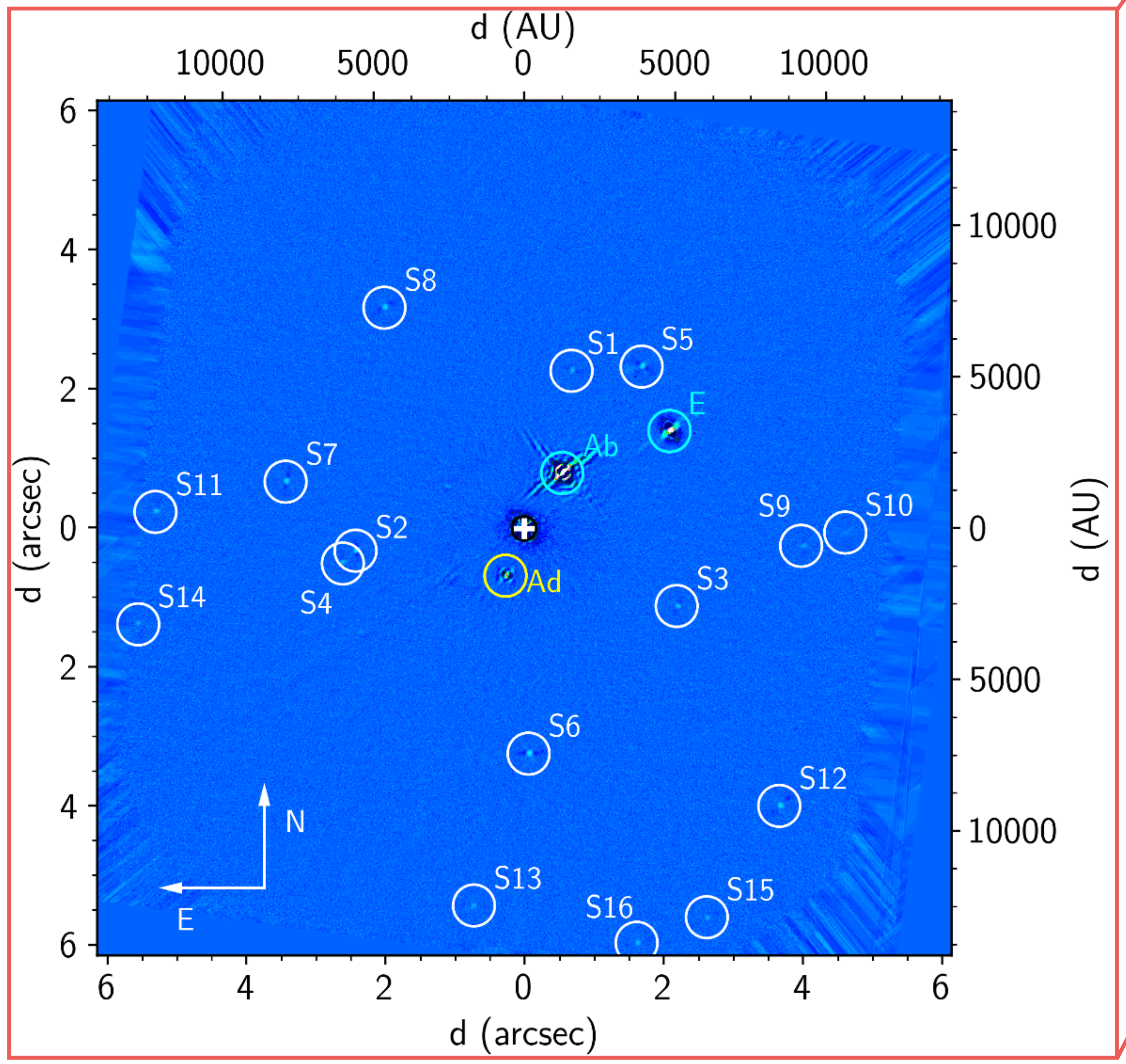


FOV = 5’, 2MASS

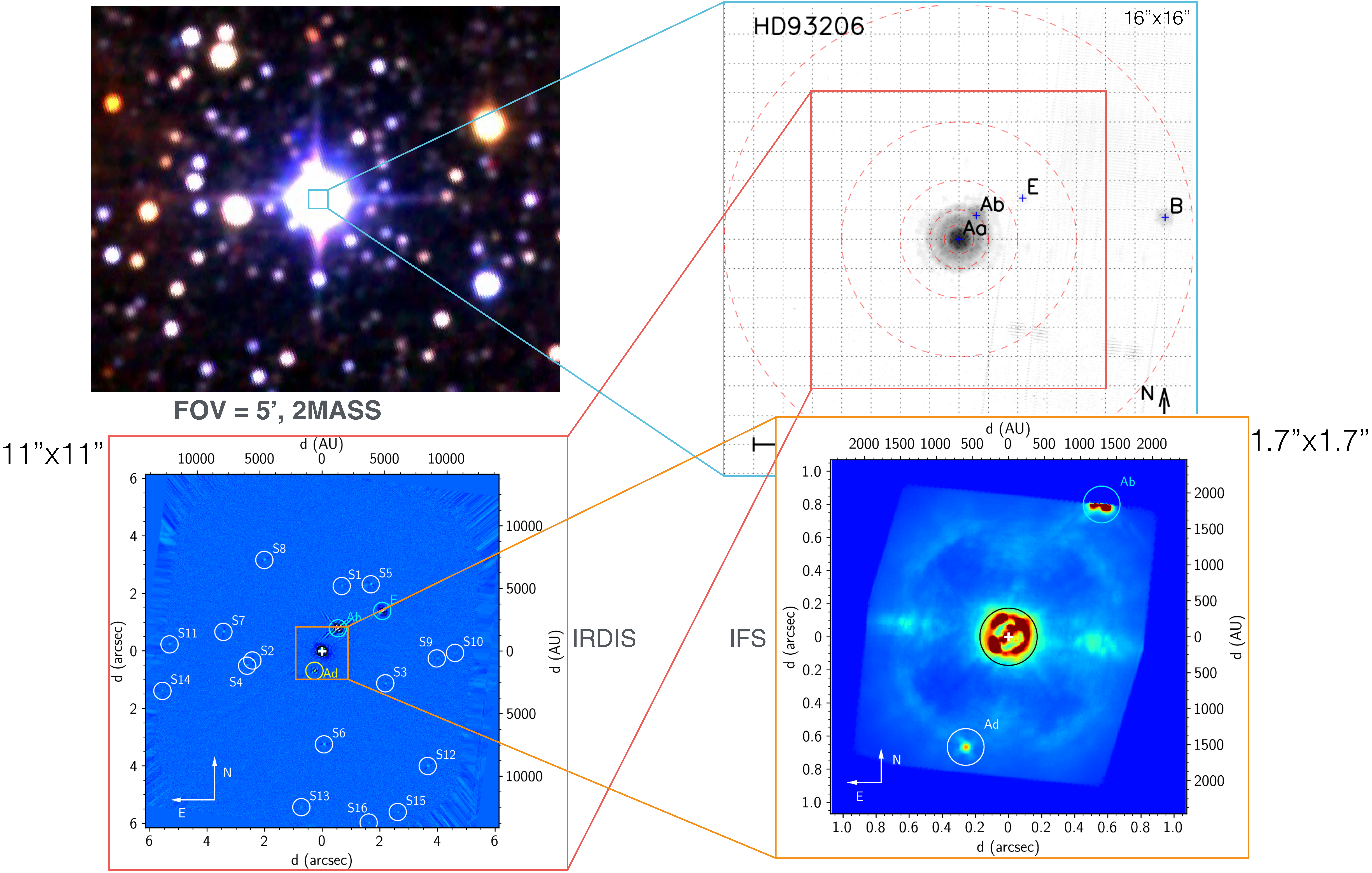


SMaSH+ Image
Sana et al, 2014

11”x11”

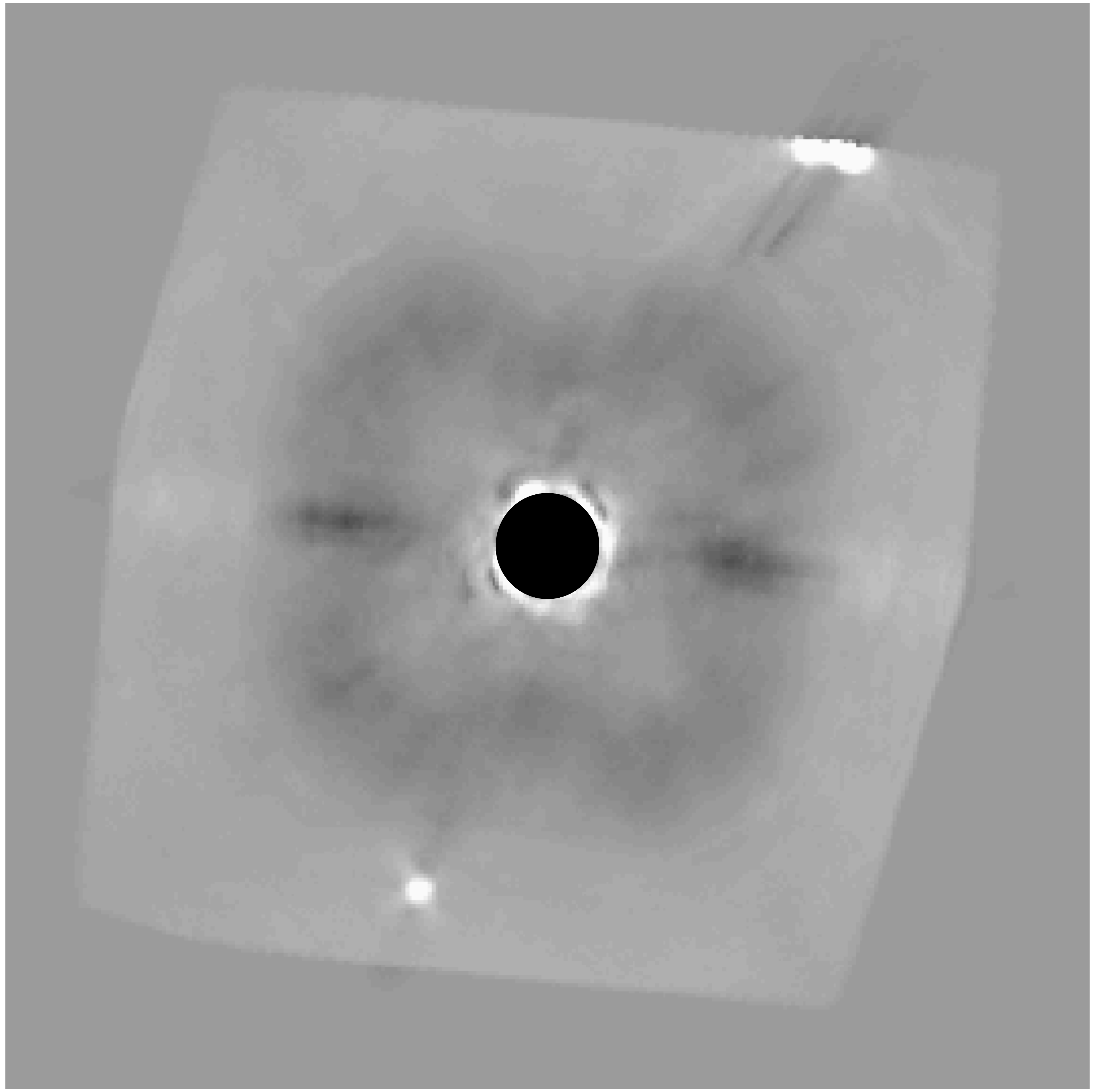


IRDIS

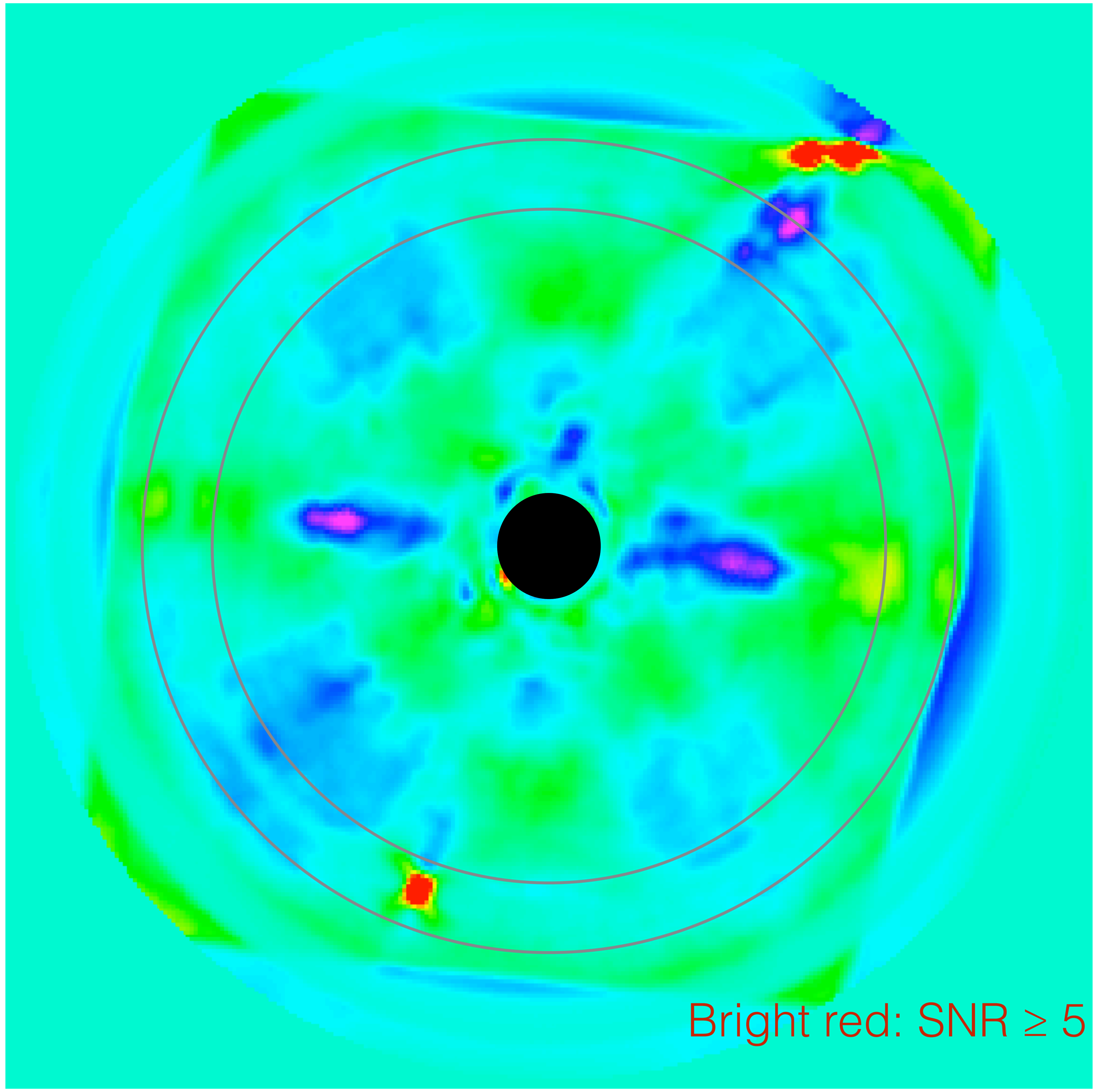


FOV = 5', 2MASS
HD93206
16"x16"
Ab
Aa
E
B
N
11"x11"
d (AU)
10000 5000 0 5000 10000
d (arcsec)
d (AU)
S8
S1
S5
F
S7
Ab
S11
S2
S9
S10
S4
Ad
S3
S14
S6
S12
N
E
S13
S16
S15
IRDIS
IFS
1.7"x1.7"
d (AU)
2000 1500 1000 500 0 500 1000 1500 2000
Ab
Ad
N
E
d (arcsec)
d (AU)

Detection method

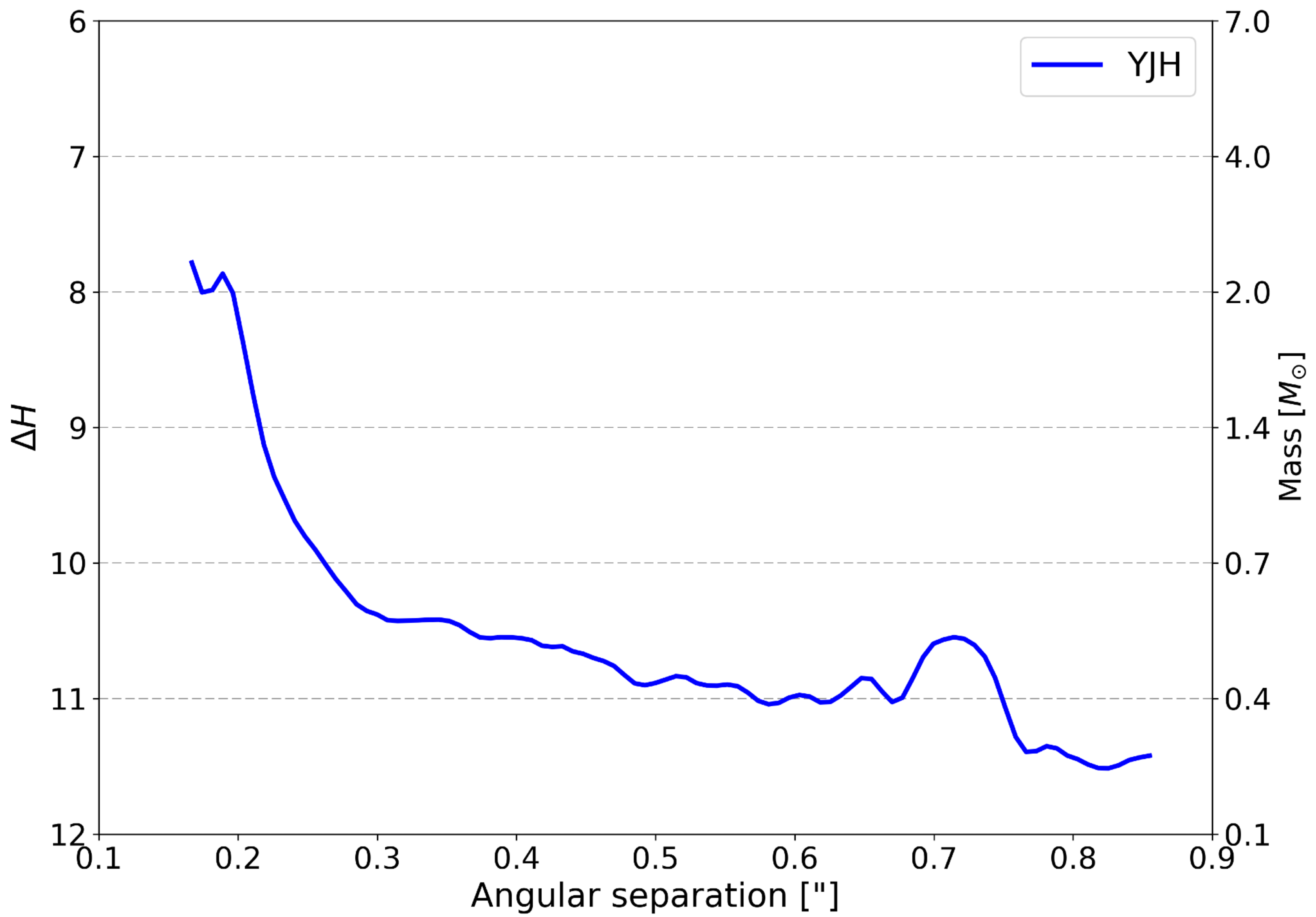


Post-processed image

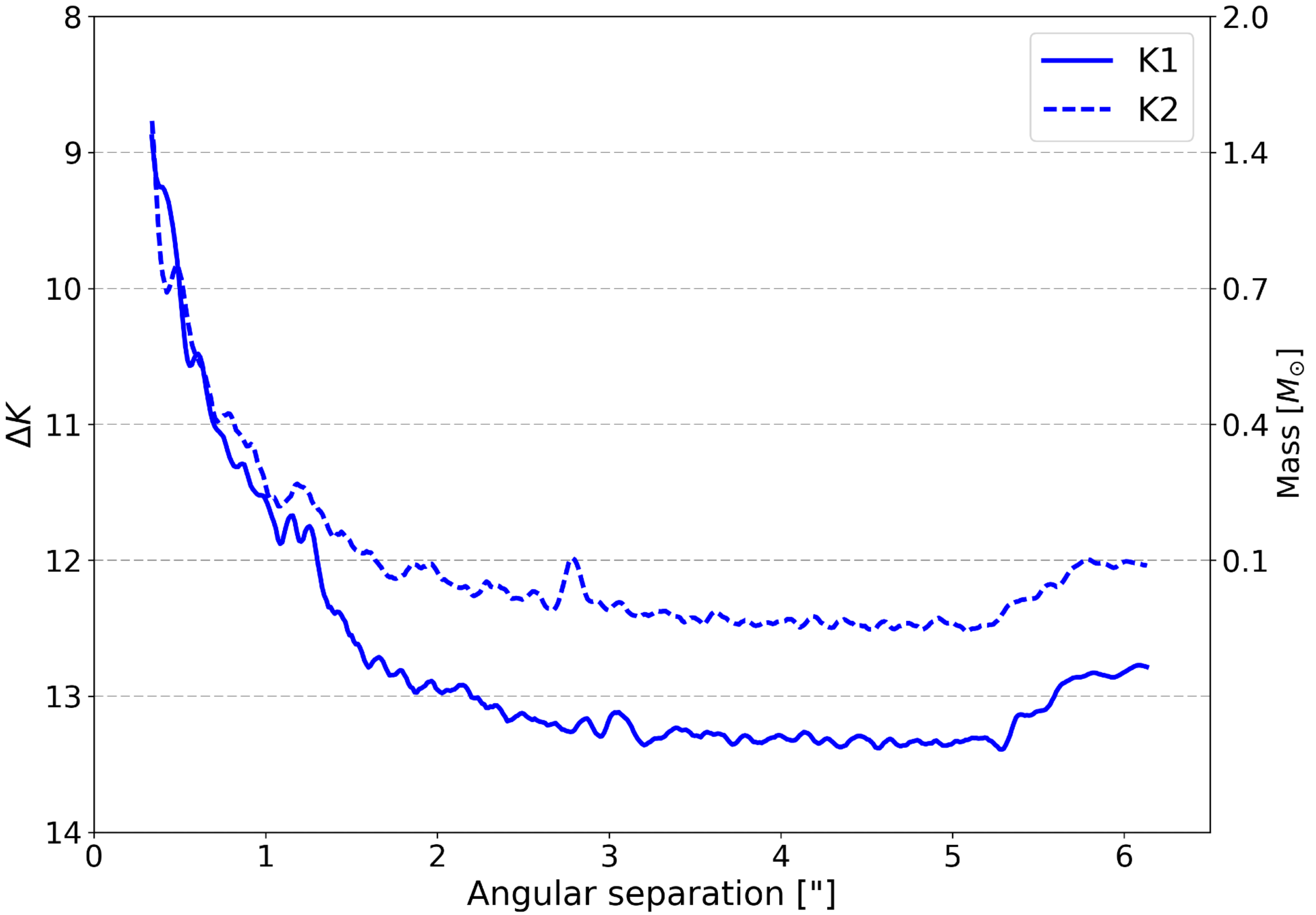


Signal-to-Noise Ratio map

Detection limits



IFS

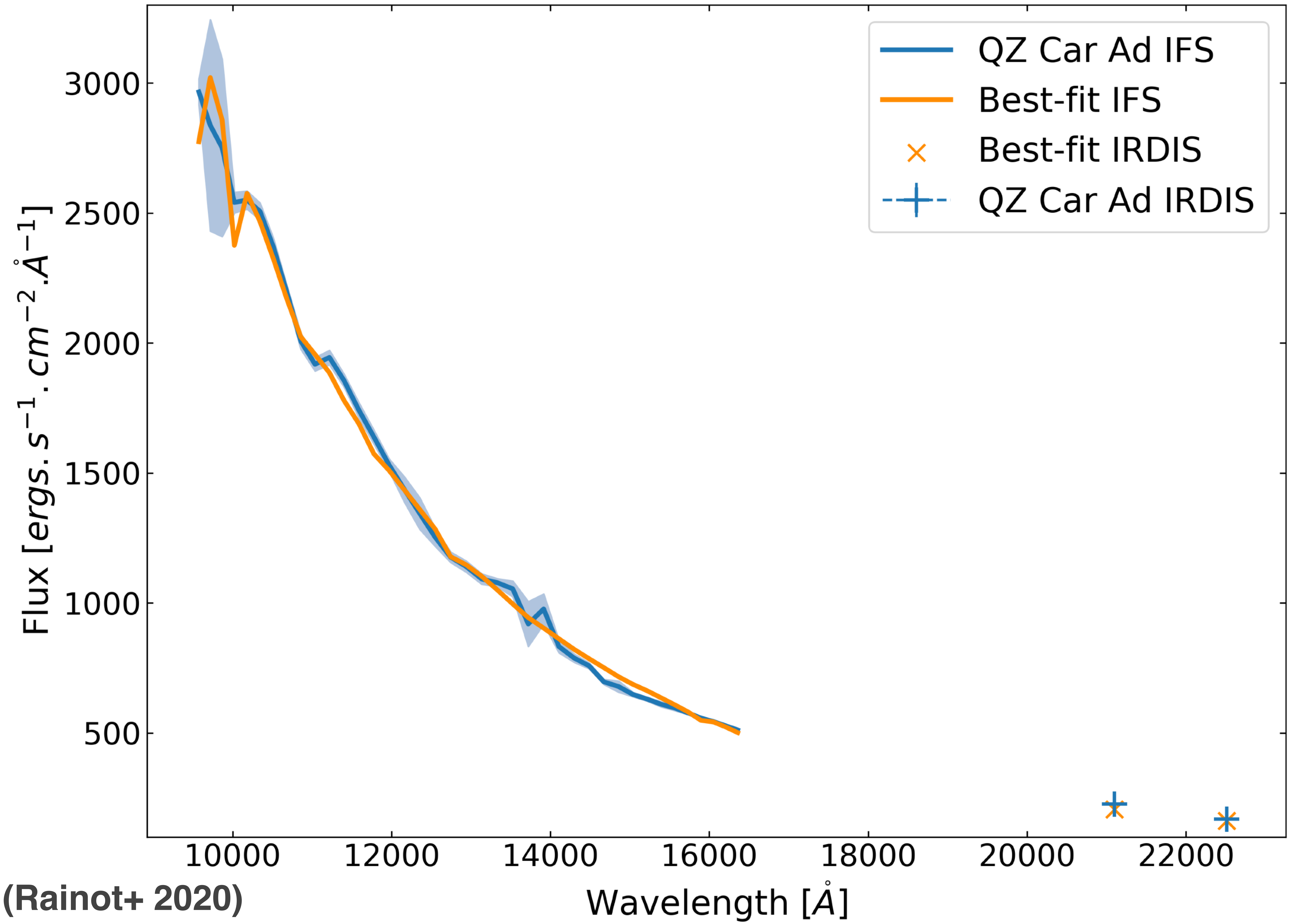


IRDIS

(Rainot+ 2020)

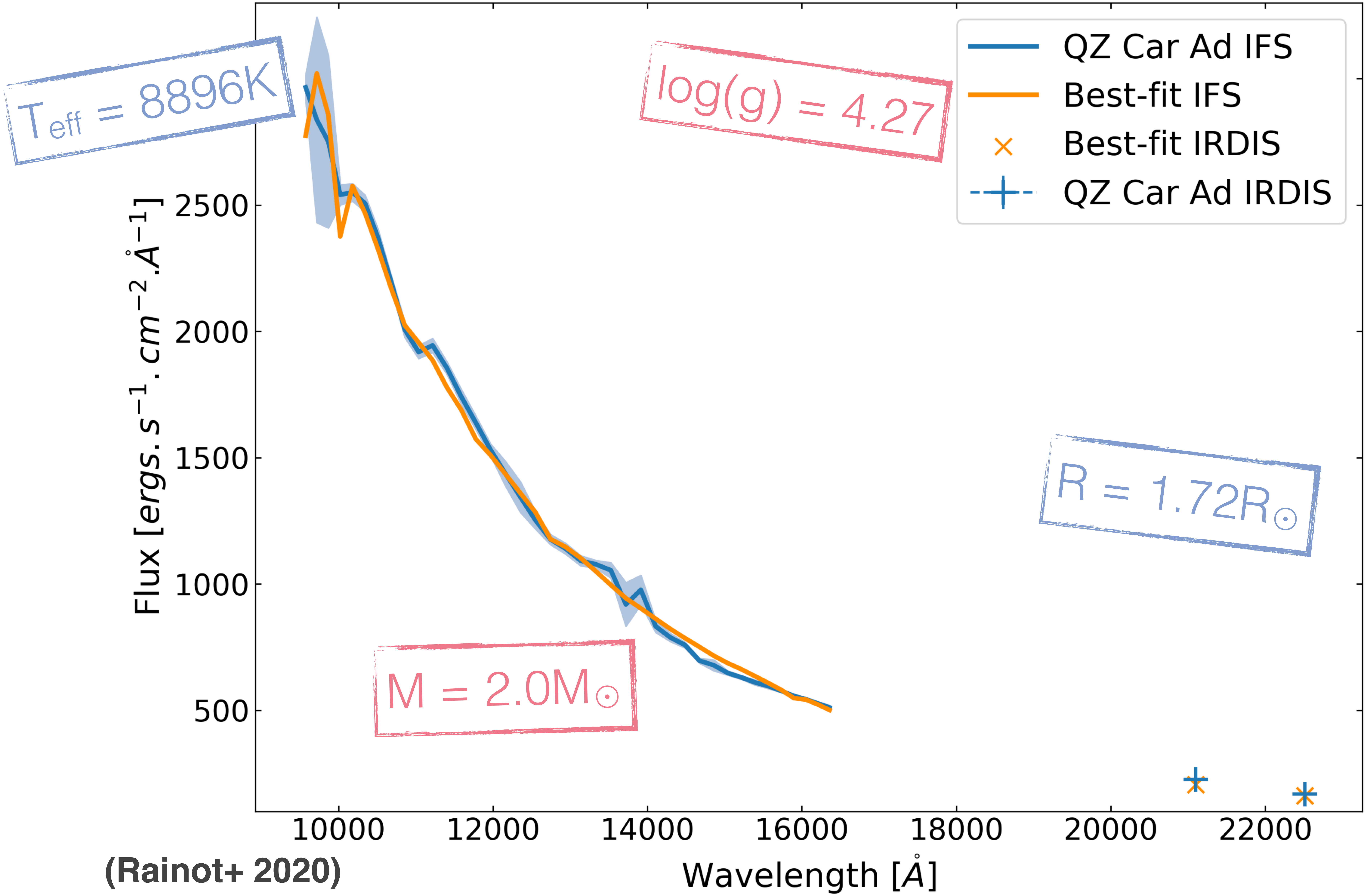
Stellar characterisation

IFS - QZ Car Ad



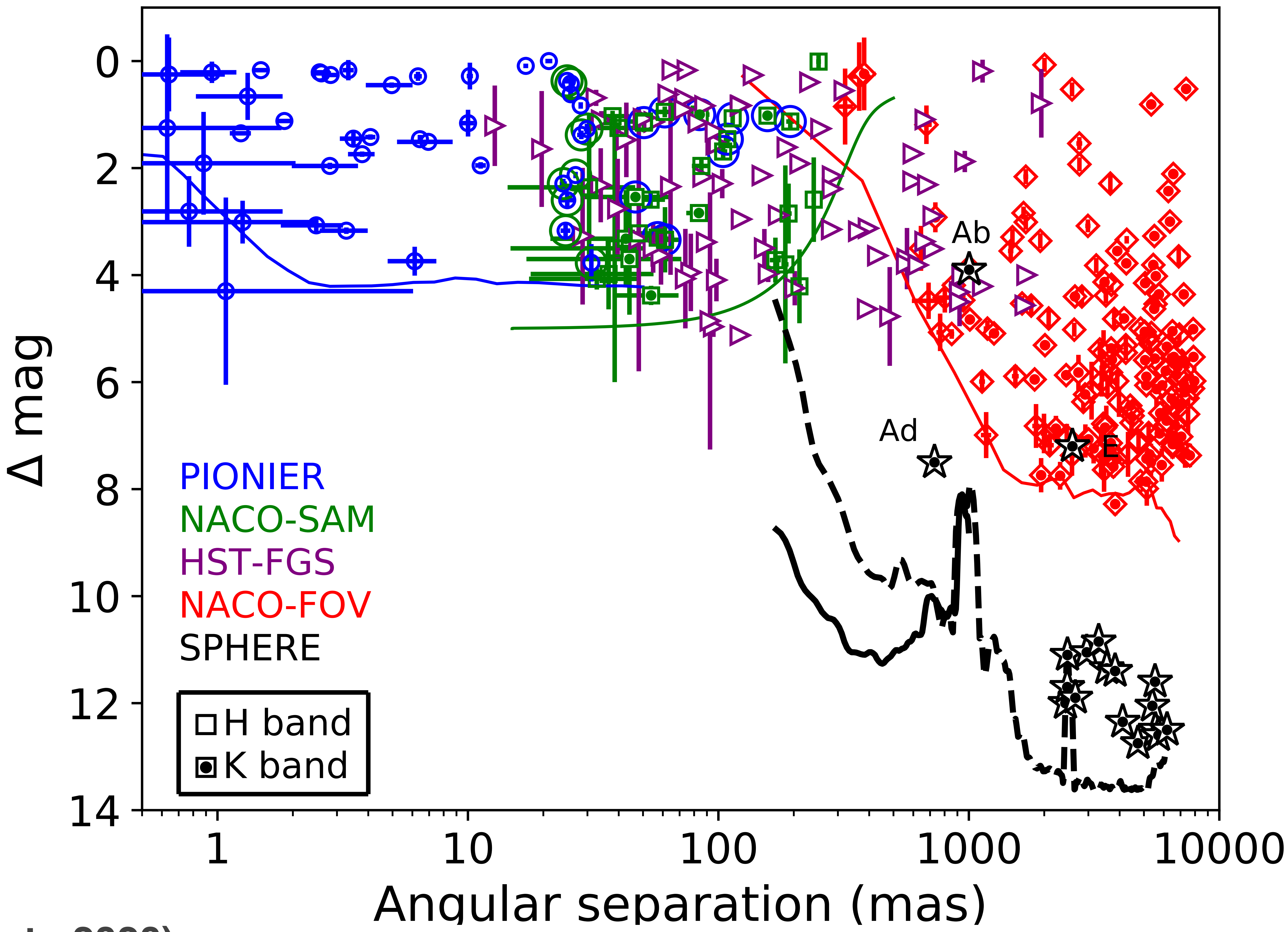
(Rainot+ 2020)

IFS - QZ Car Ad



(Rainot+ 2020)

SMaSH+ (Sana+,2014) & HST-FGS (Aldoretta+,2015)



(Rainot+ 2020)

Astronomy & Astrophysics manuscript no. output
November 25, 2020

Carina High-contrast Imaging Project for massive Stars (CHIPS)

II. A study of the close Trumpler 14 cluster

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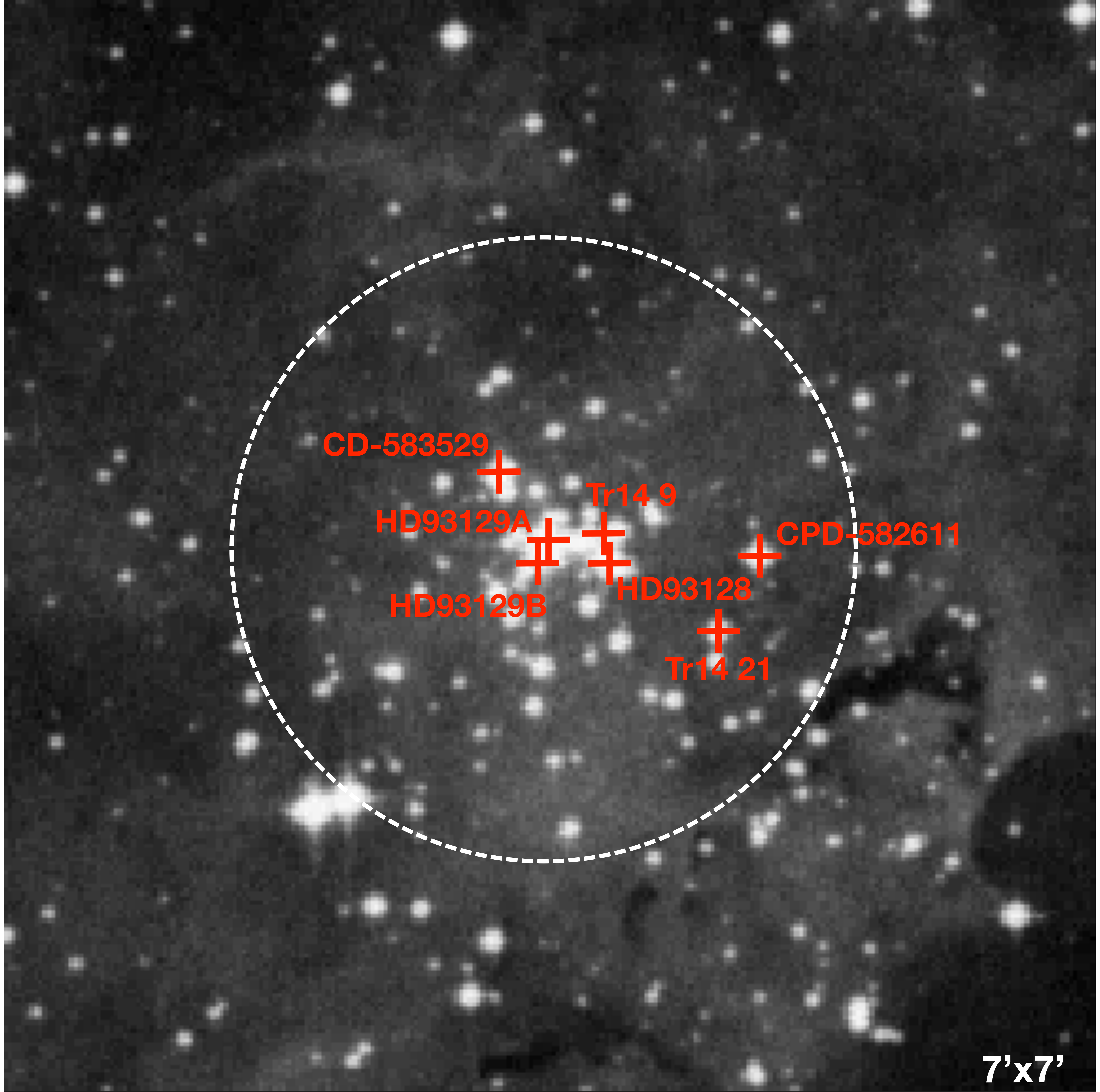
November 25, 2020

ABSTRACT

Context. Being single is not the way of massive stars. Understanding the formation of massive stars is a key issue in astrophysics today and to help constrain the different formation scenarios that exist, obtaining insights on the low-mass end of the companion mass-function of such stars is crucial. Unfortunately, this is a challenging endeavour as low-mass companions at angular separations (ρ) below 1″ (approx. 1000–3000 au) have been difficult to detect due to their brightness contrast with the central star.
Aims. With the Carina High-contrast Imaging Project of massive Stars (CHIPS), we aim to obtain statistically significant constraints on the presence of low-mass companions around massive stars at a previously unreachable observable window ($\Delta mag \lesssim 10$ at $\rho \lesssim 1''$) for the 92 O and Wolf-Rayet stars known in the Carina region using the Spectro-Polarimetric High-contrast Exoplanet REsearch (SPHERE) coronagraphic instrument on the Very Large Telescope (VLT). In the first paper of this series, we introduced the survey and presented the methodology as well as some first results with the star OZ Car. As the second paper in the series, here we aim to



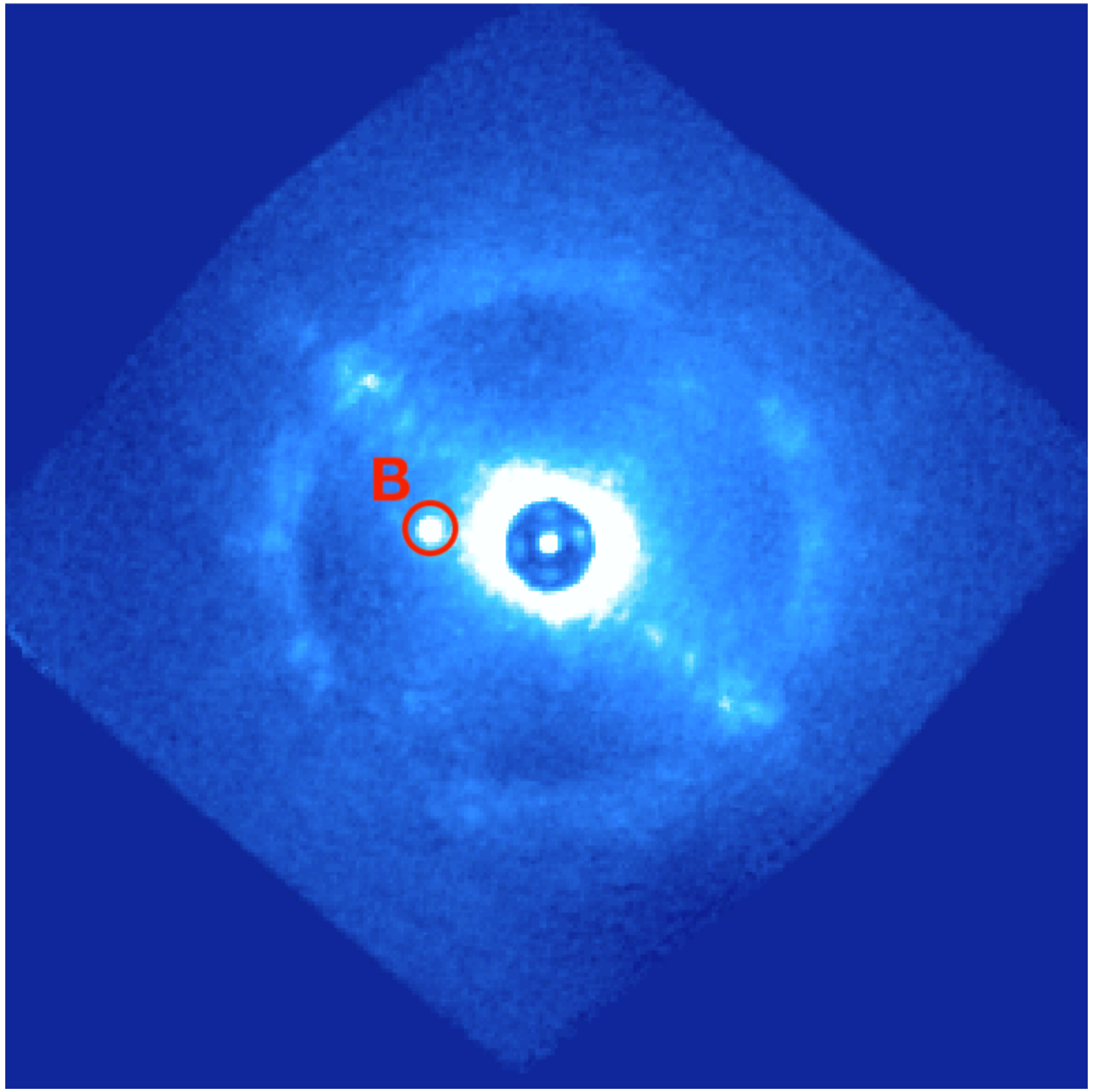
DSS2

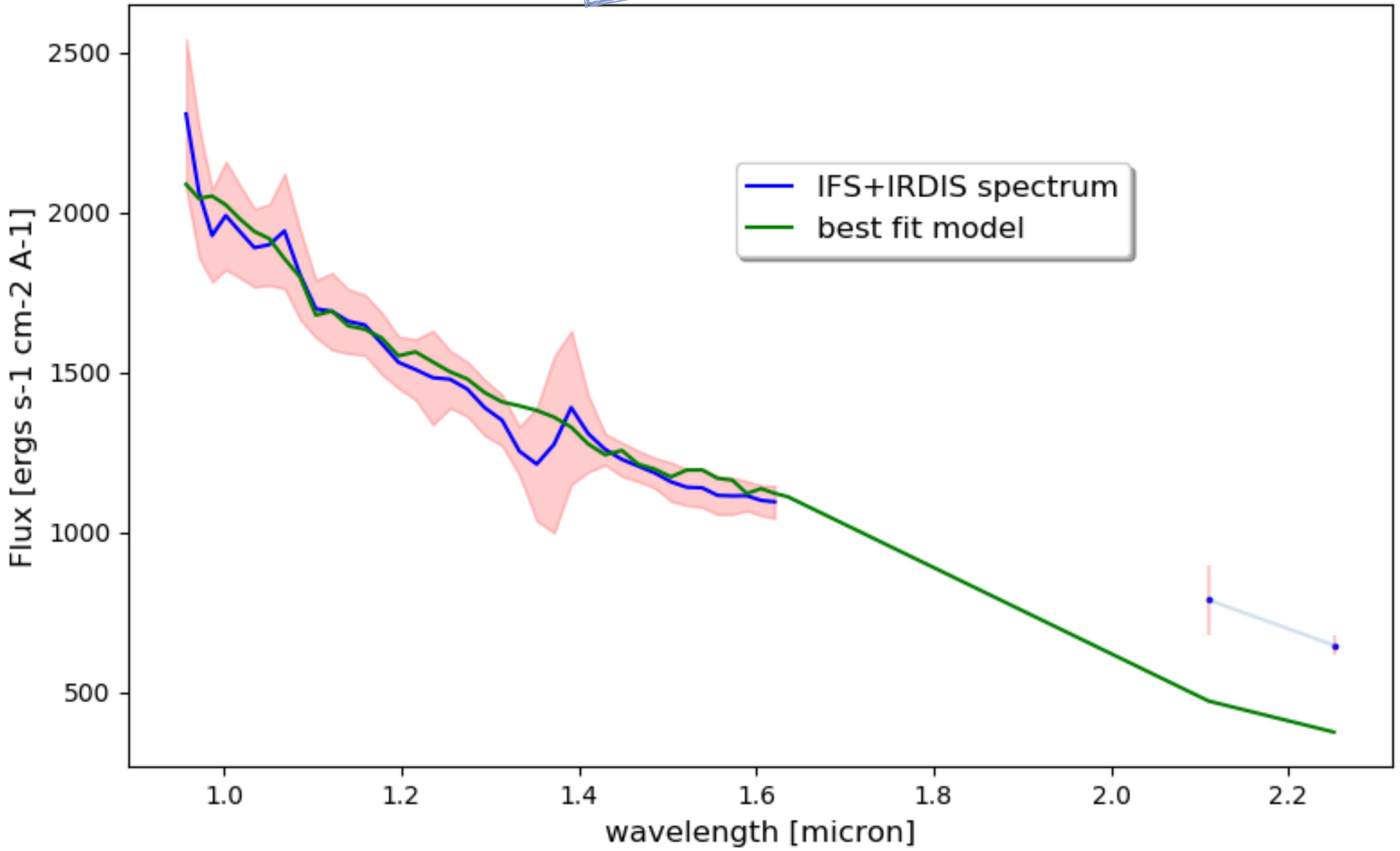
(Rainot+ in prep.)


1A
1B
2
21
8
9
20
S5
302,819
S4
757,766
S7
50,540
S1
305,526
S3
811,544
S2
369,330
S6
588,139

CD-583529

T_{eff} = 4408K

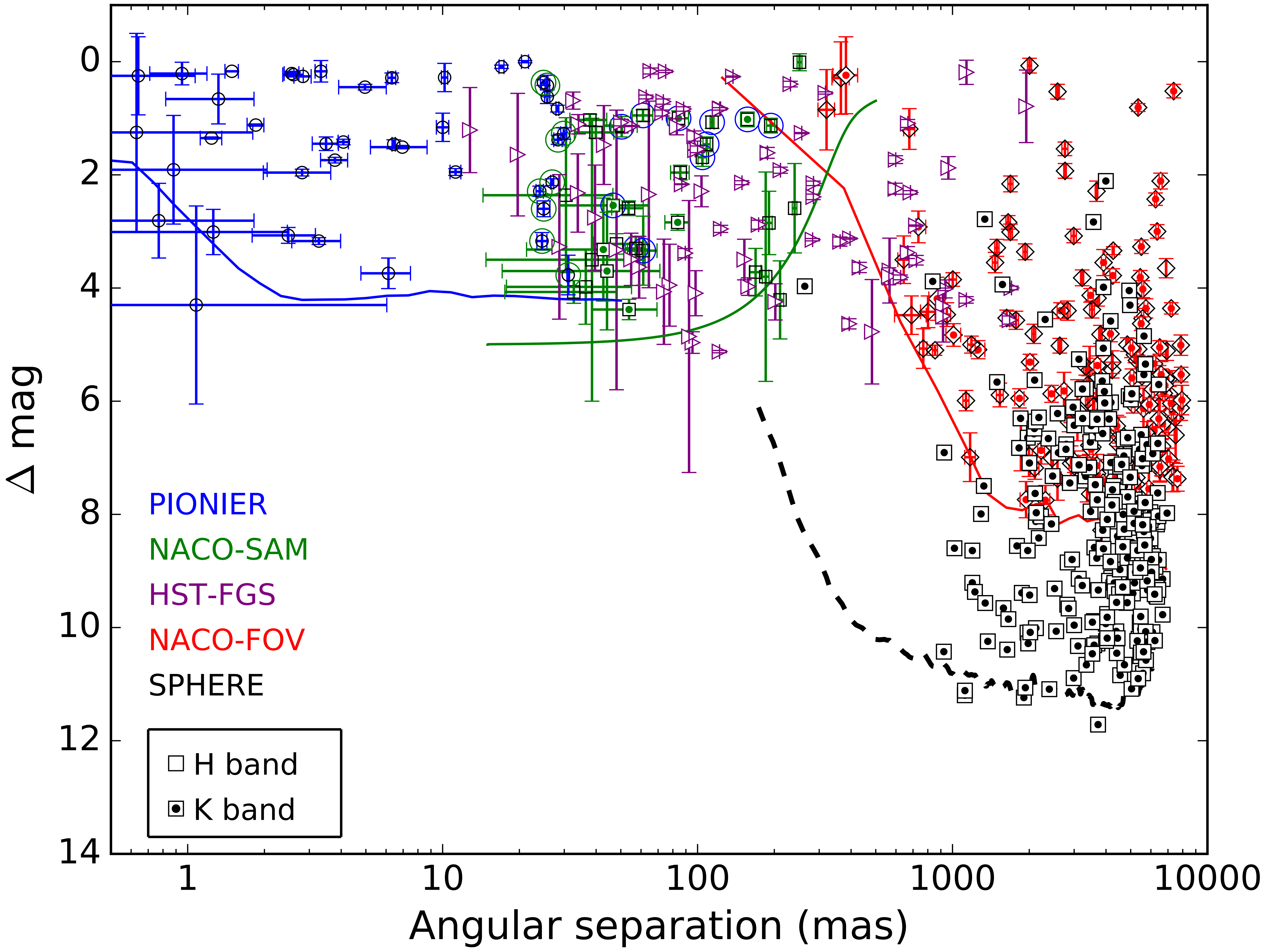




$M = 1.3M_{\odot}$

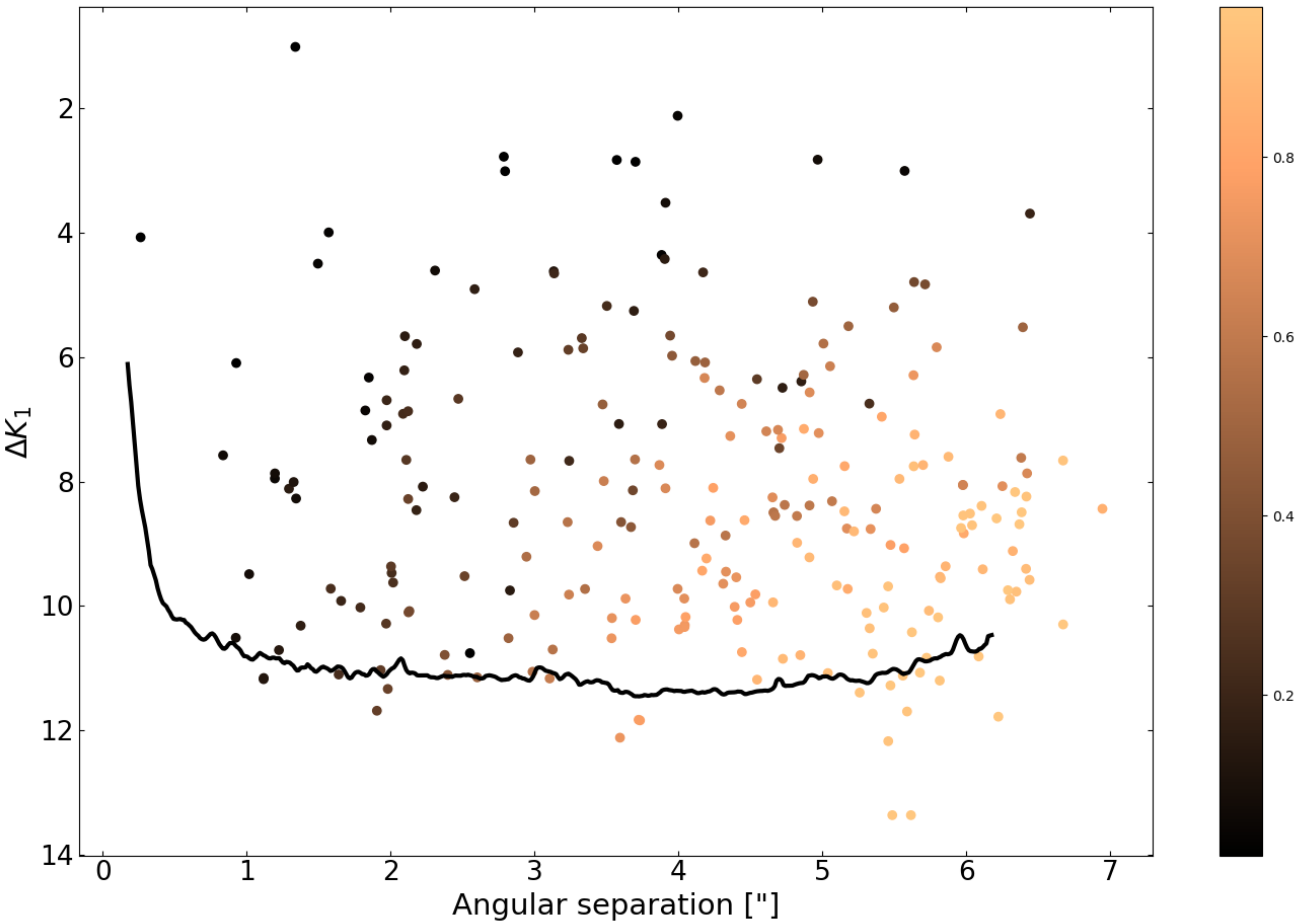
$5.37x10^5$yrs

SMaSH+ (Sana+,2014) & HST-FGS (Aldoretta+,2015)



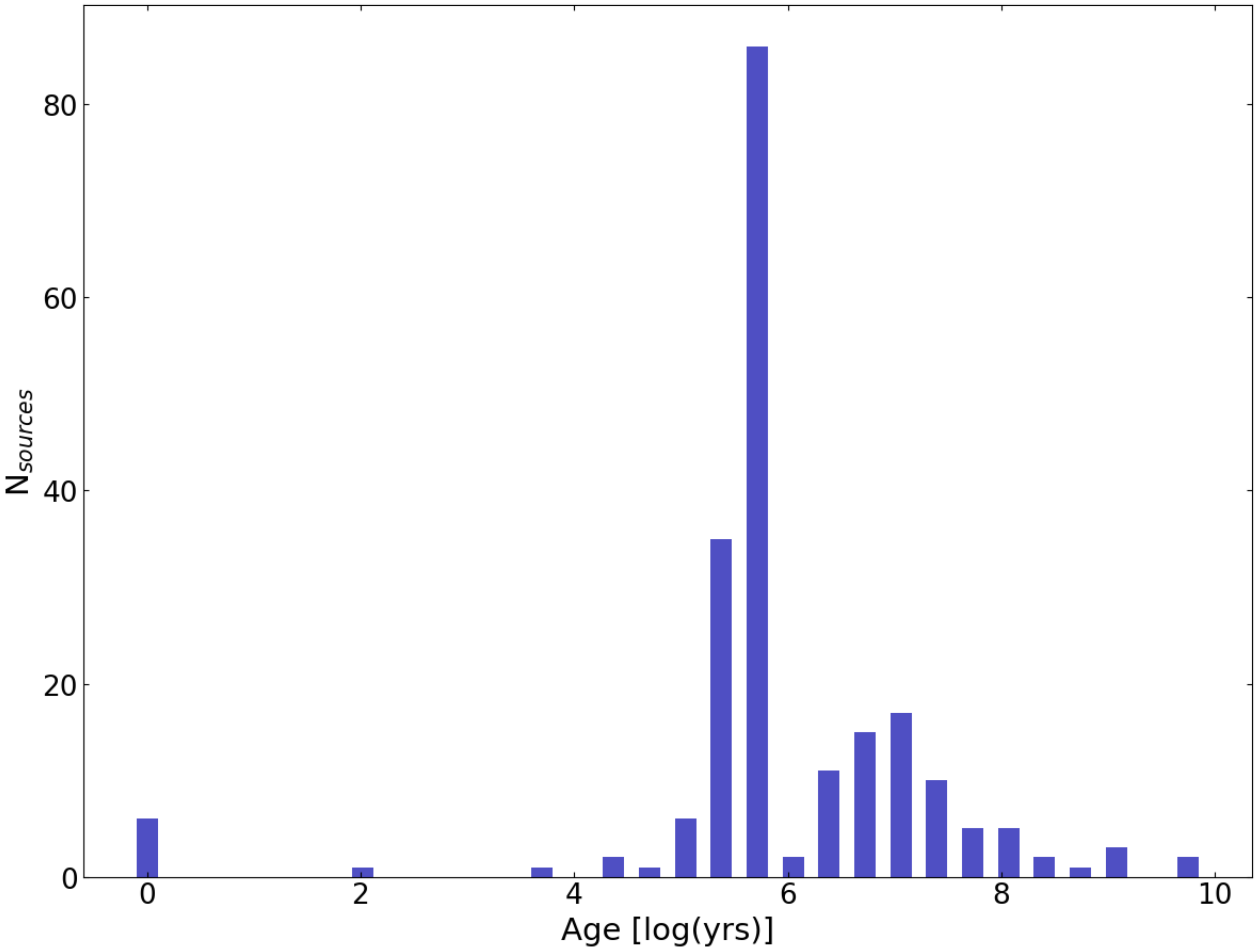
(Rainot+ in prep.)

Δmag vs radial separation



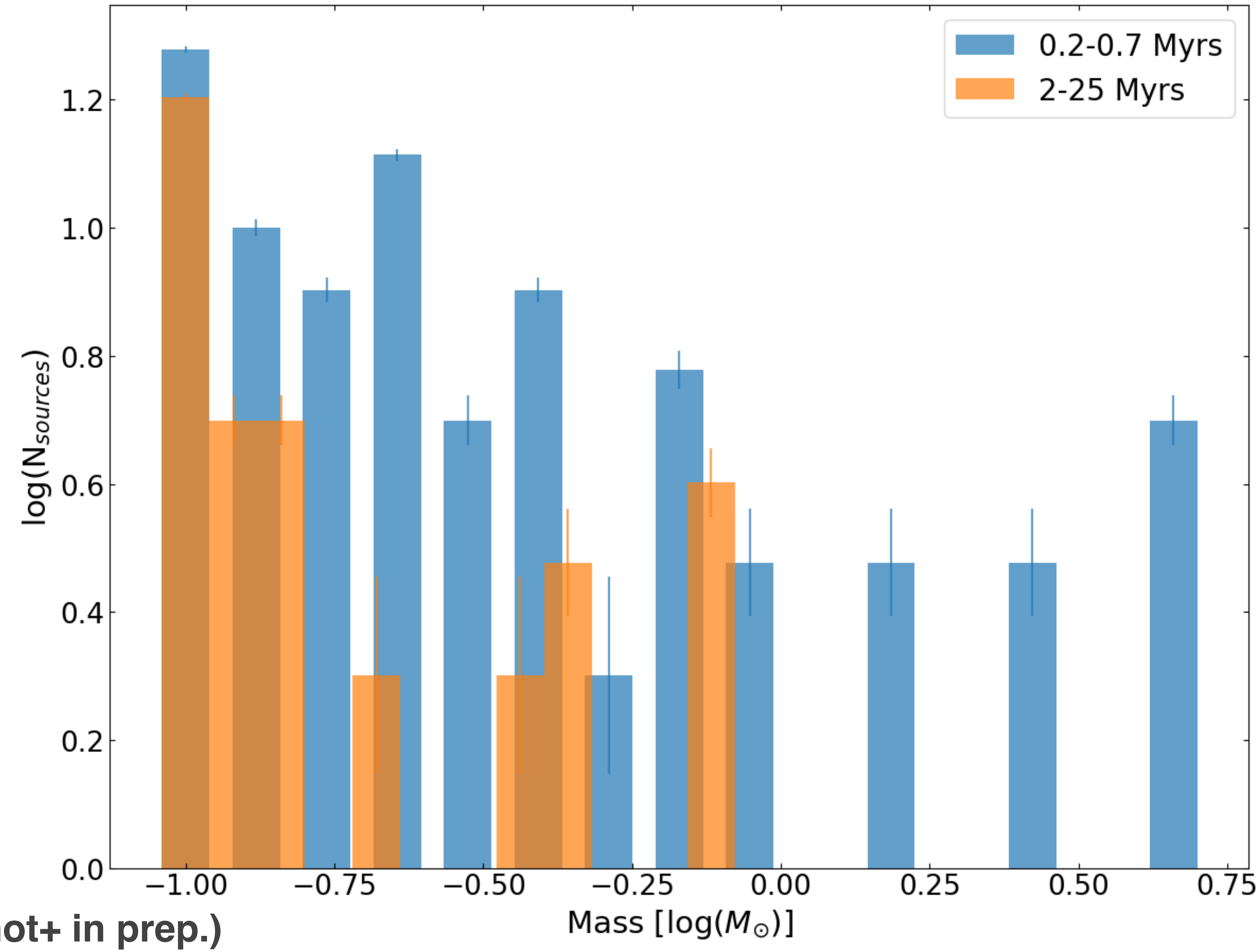
(Rainot+ in prep.)

Age distribution



(Rainot+ in prep.)

Mass distribution



(Rainot+ in prep.)

Trumpler 14

- 210 sources detected
- 50 highly likely to be bound
- Most sources have an age of ~5×10^5 yrs
- Mass range between 0.1 and 0.3 $M_\odot$
- No apparent over-density
- ~0.14 multiplicity fraction in IFS FoV

Sco. OB1

- Older (6-8Myrs) population of O-stars and B supergiants
- 39 stars: 15 observed, 14 in the future
- Lower IFS multiplicity than CHIPS: 0.20 companions/ star vs 0.43 for CHIPS
- Aim: Evolution study of multiplicity with age

Multiplicity Results - IFS

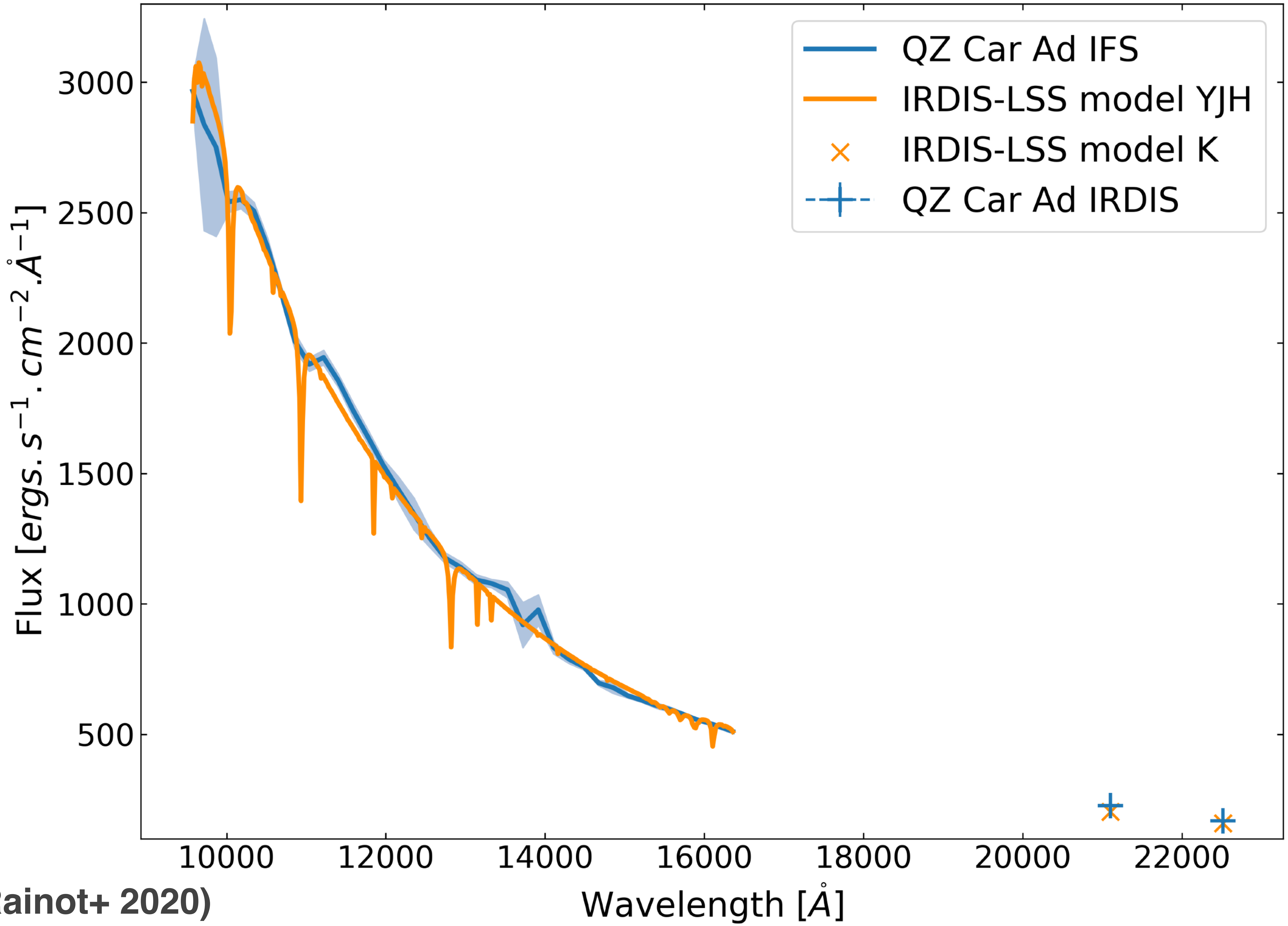
Images	Visible companions (SNR > 5σ)	Candidates (5σ > SNR > 3σ)
46	15	19

- Detection ratio ≃ 0.42 companions/star
- Expected ≃ 40 companions / 93 images

Future work

- 85 stars to analyse including 47 to observe
- Bias correction using the whole sample
- Development of SHIPS
- Complementary observations with high-resolution spectrographs

With better spectroscopy



(Rainot+ 2020)

Conclusion

- Detect and analyse stars at previously unobserving windows
- Reach contrast magnitudes of $\Delta m \sim 14$
- Obtain masses, ages, and other stellar parameters
- Larger sample yet to be analysed

Thank you!

https://arainot.github.io

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