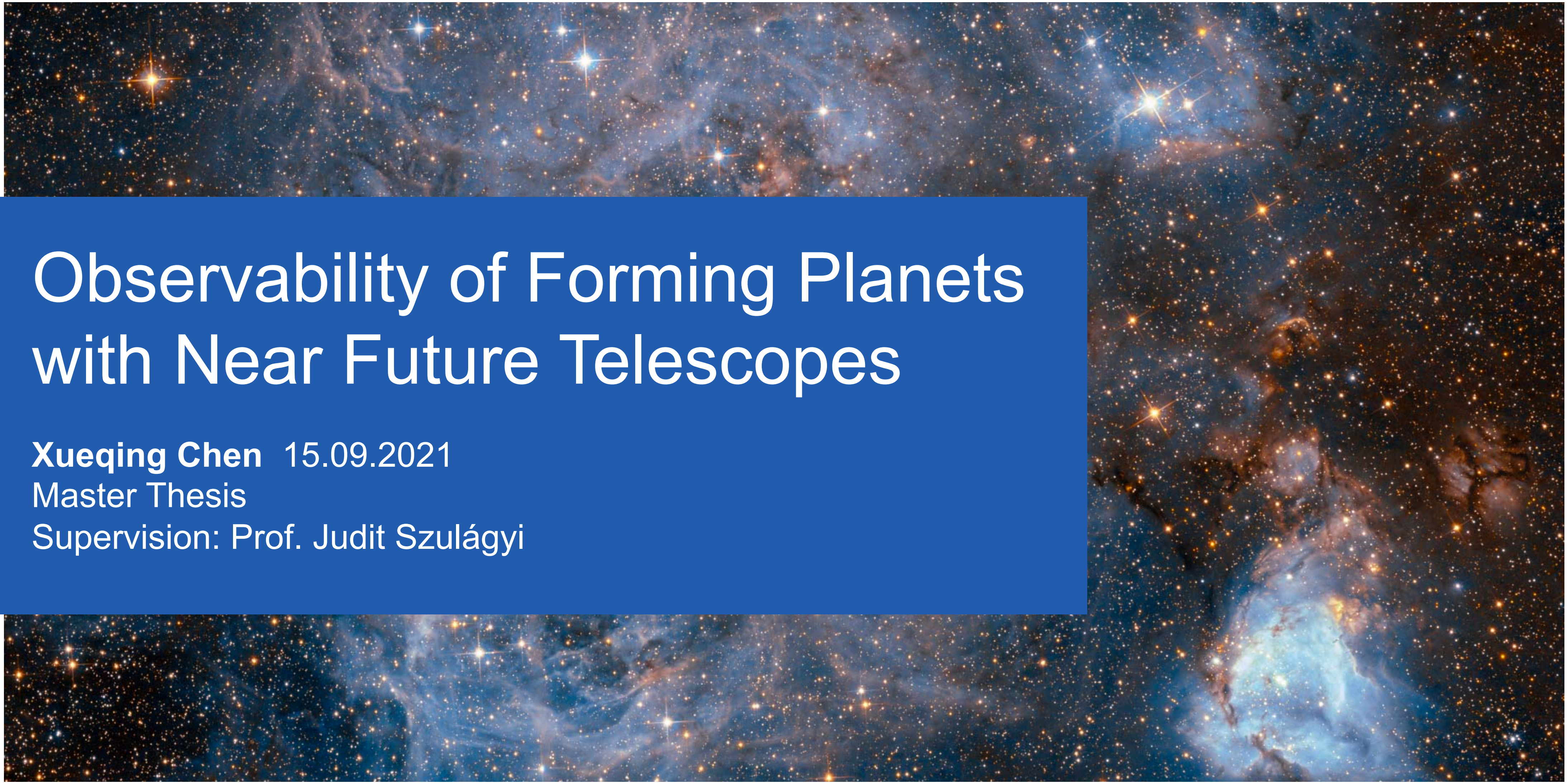


Observability of Forming Planets with Near Future Telescopes

Xueqing Chen 15.09.2021
Master Thesis
Supervision: Prof. Judit Szulágyi

Outline

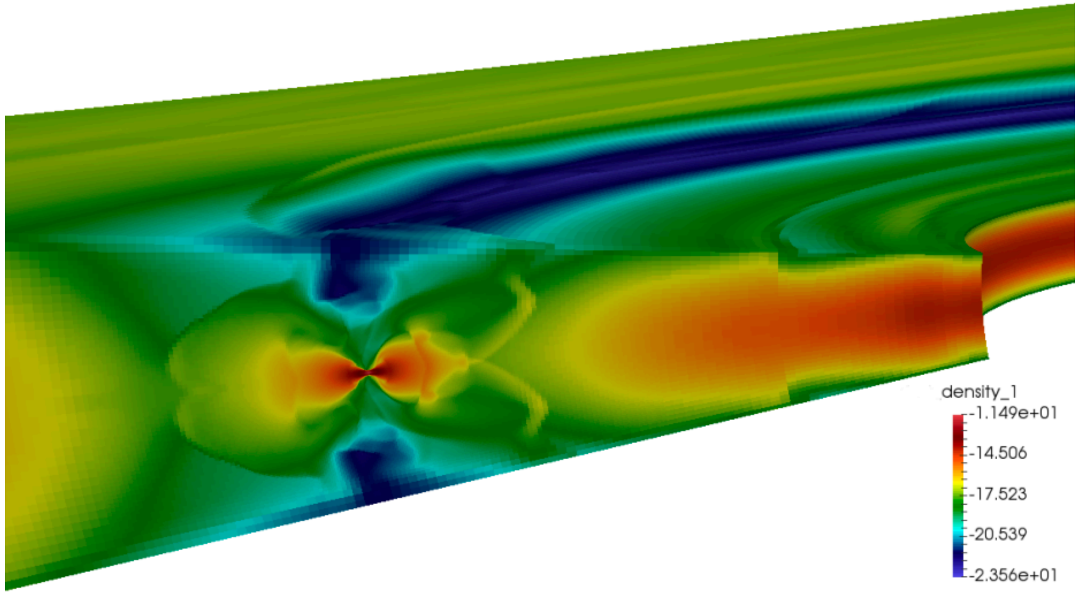
1. Background
2. Method
   i. Hydrodynamic simulation
   ii. RADMC3D radiative transfer
   iii. Instrument simulation
3. Results

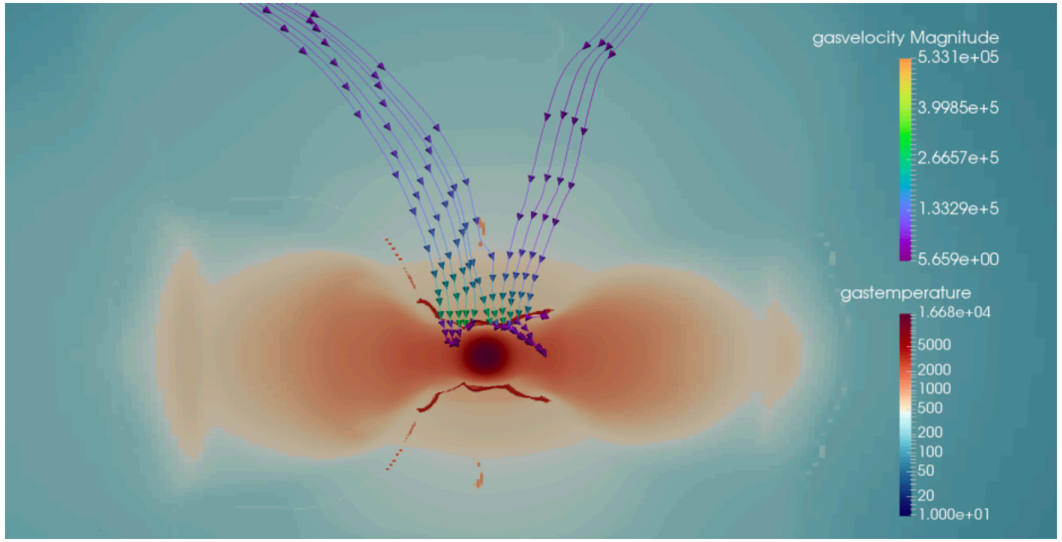
Backgrounds

Background

- Young planets are formed in circumstellar disks (CSD). Due to on-going accretion onto the forming planet, they also form a sub-disk around themselves, the so-called circumplanetary disks (CPD).

- Accretion from CSD to the CPD is dominated by a vertical inflow which creates a hot shock front above the CPD surface. Detecting a forming planet is actually detecting its CPD.

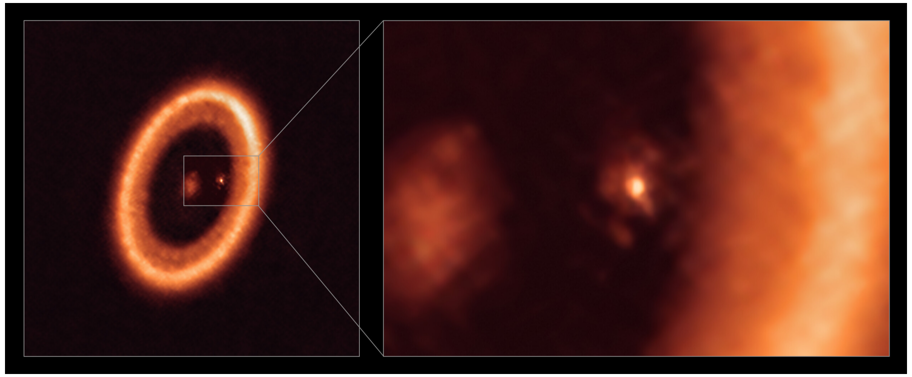




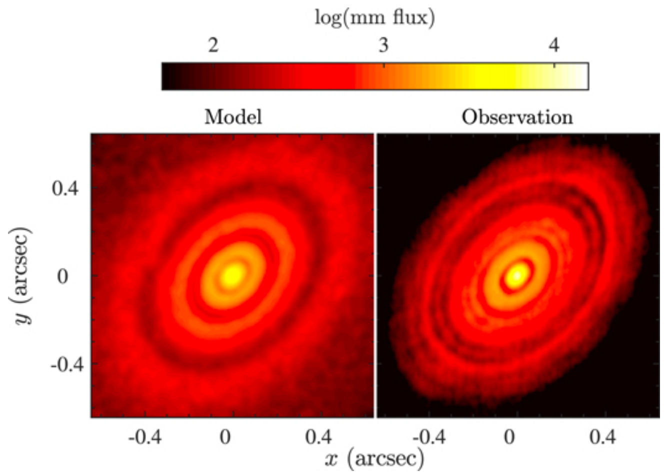
Credit: Judit Szulágyi

Background

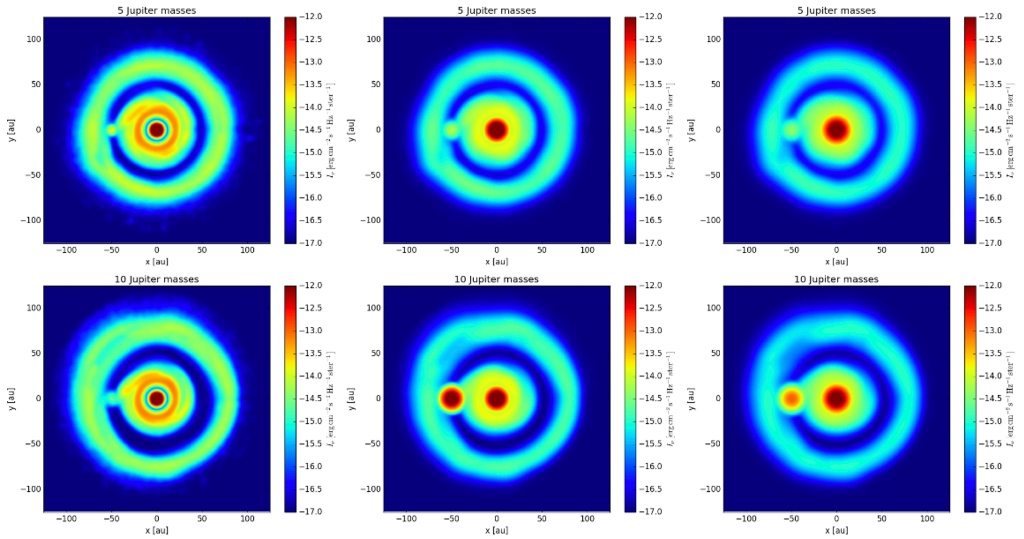
- Only few observations of CPD to date
- Numerical simulations can bridge the gap between theory & observation
- Synthetic observations are made to interpret or predict observations



CPD around PDS 70 c, Benisty et al. 2021



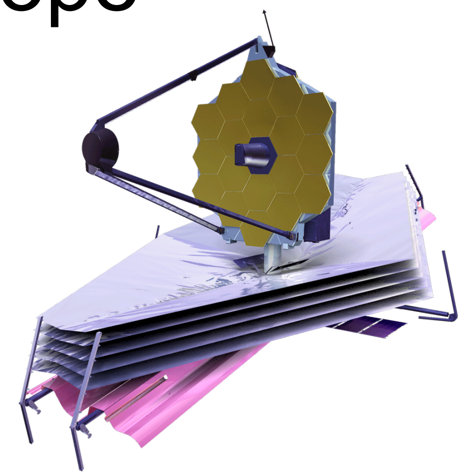
Comparison between model and ALMA observation of HL Tau, Dong et al. 2015



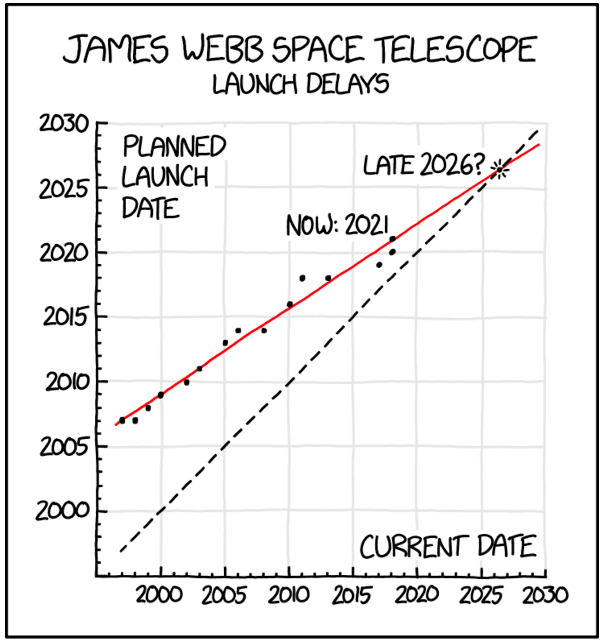
Synthetic VLT/NaCo images in Ks, L', M band, Szulágyi et al. 2018

<u>Aim: How well can future telescopes like JWST, ELT and GMT image forming planets?</u>

Background – JWST: James Webb Space Telescope



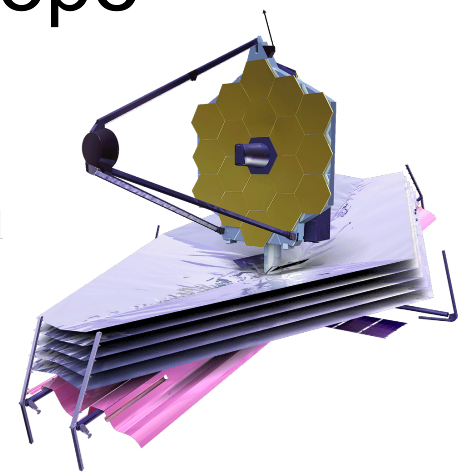
- Planned to launch in Dec 2021
- To be deployed at the Sun-Earth L2 Lagrange point
- 6.5 m primary mirror composed of 18 hexagonal segments
- Imaging in near and mid infrared

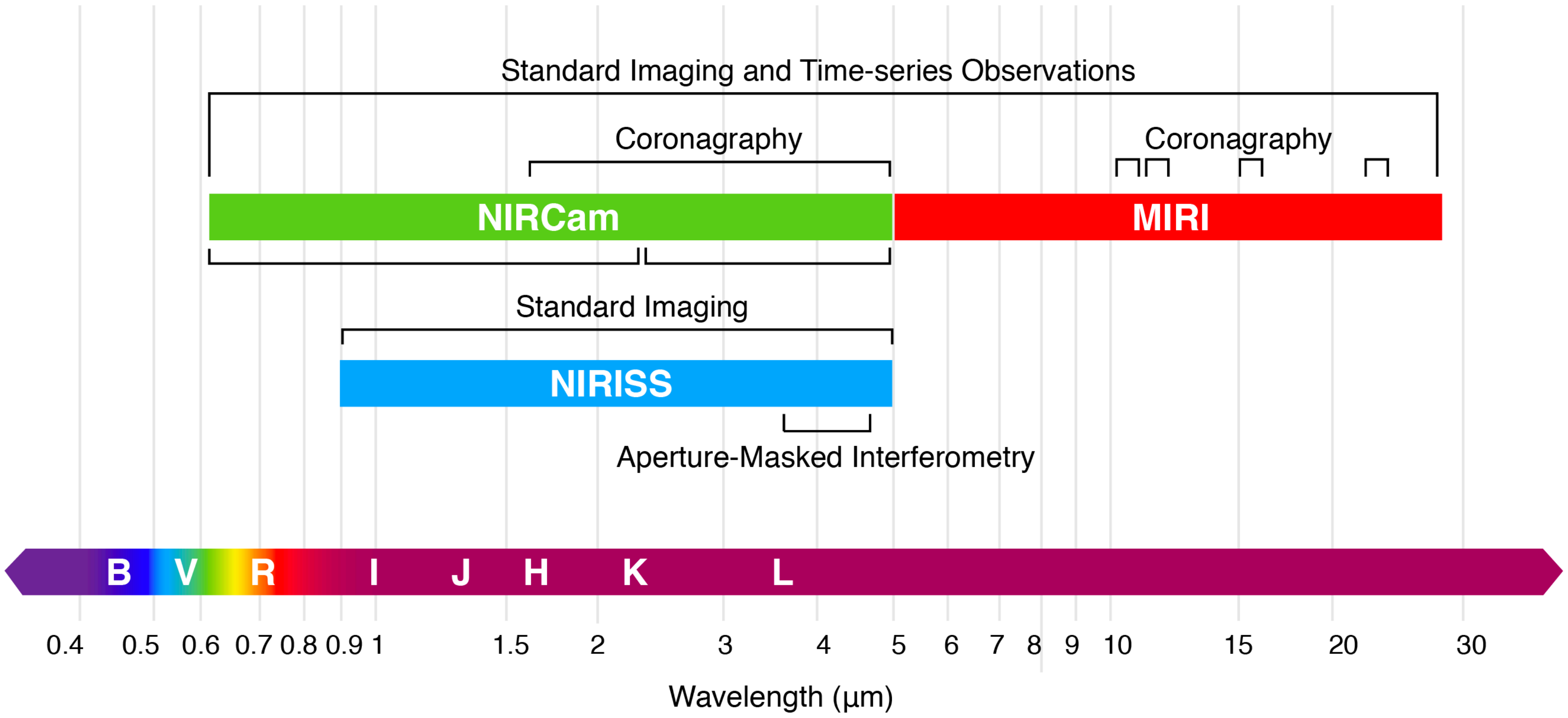


LOOK, AT LEAST THE SLOPE IS LESS THAN ONE.

Background – JWST: James Webb Space Telescope

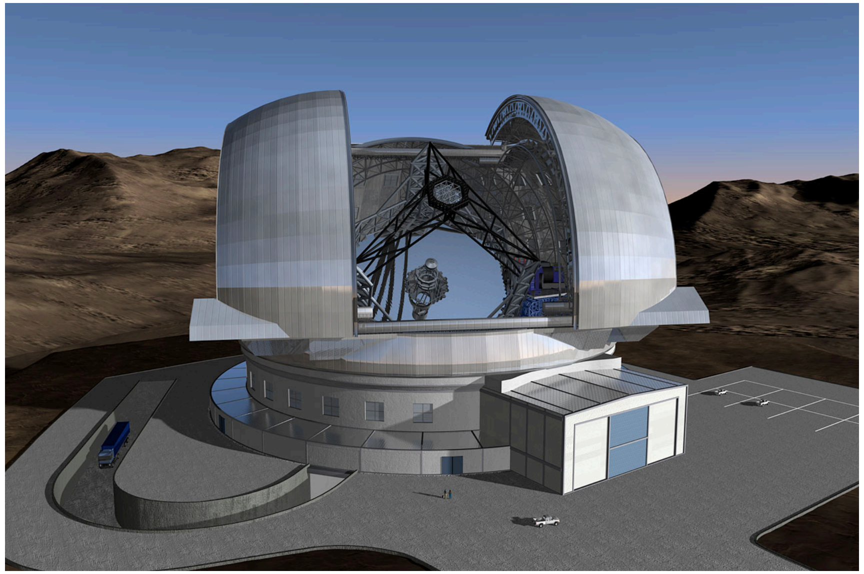
- JWST imaging instruments

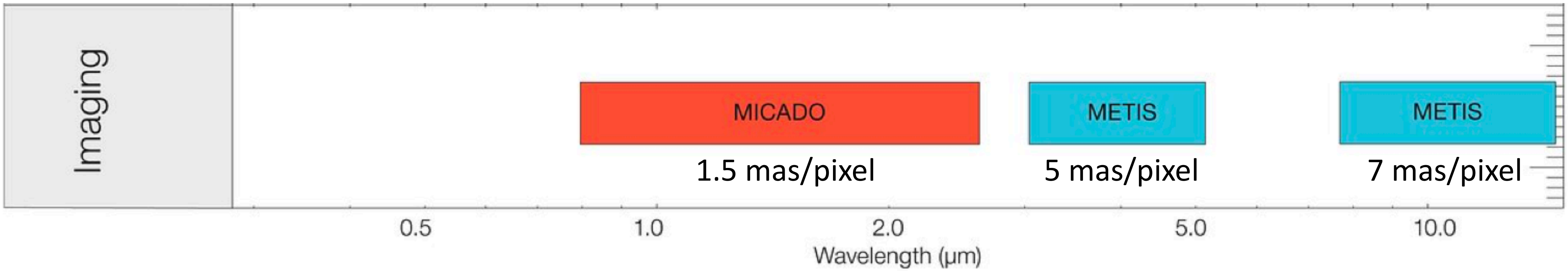




Background – ELT: Extremely large telescope

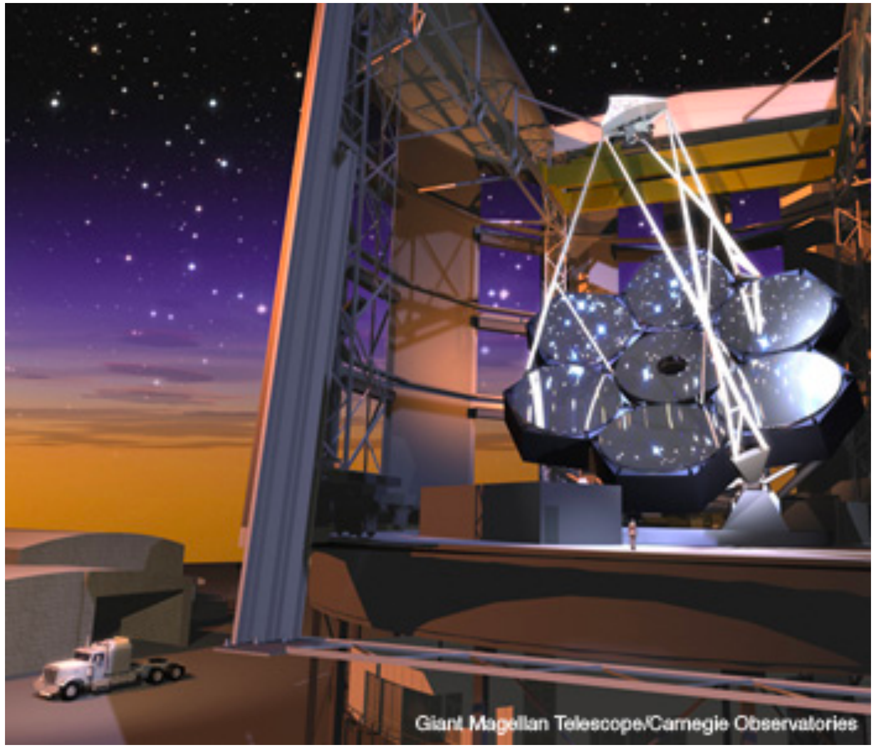
- Under construction in Cerro Armazones, Chile
- First light in late 2020s (2027?)
- 39 m primary mirror diameter





Background – GMT: Giant Magellanic Telescope

- Located in Las Campanas, Chile
- First light in late 2020s (2029?)
- Seven 8.4 m diameter primary segments, effective diameter of 25 m
- Imager – GMTIFS
- Imaging at 0.9 - 2.5 μm (J H K bands)



Methods

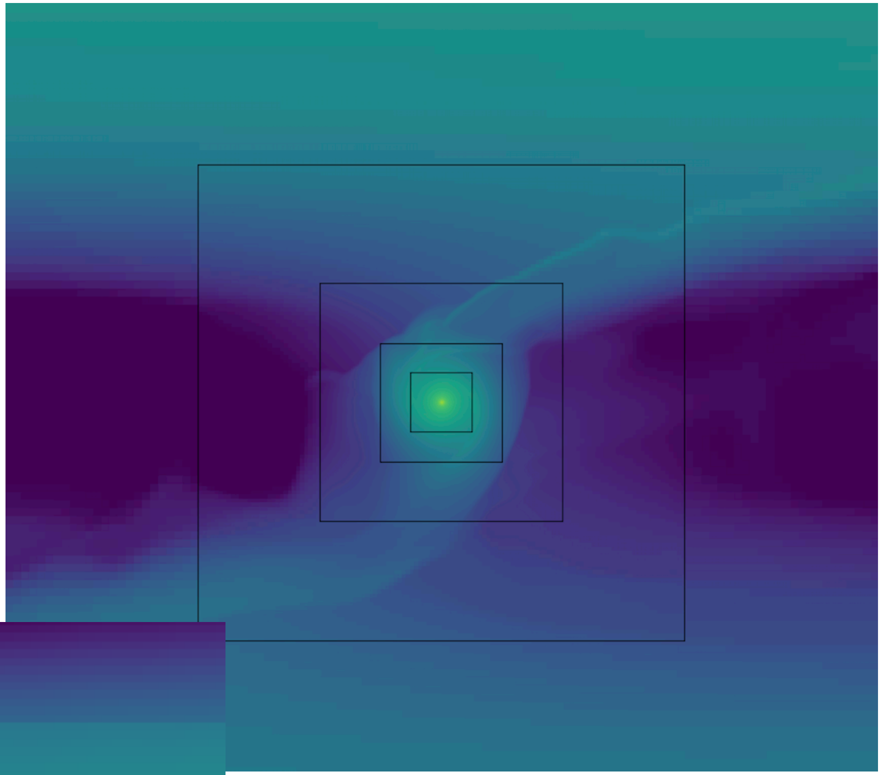
i. Hydrodynamic simulation

ii. RADMC3D radiative transfer

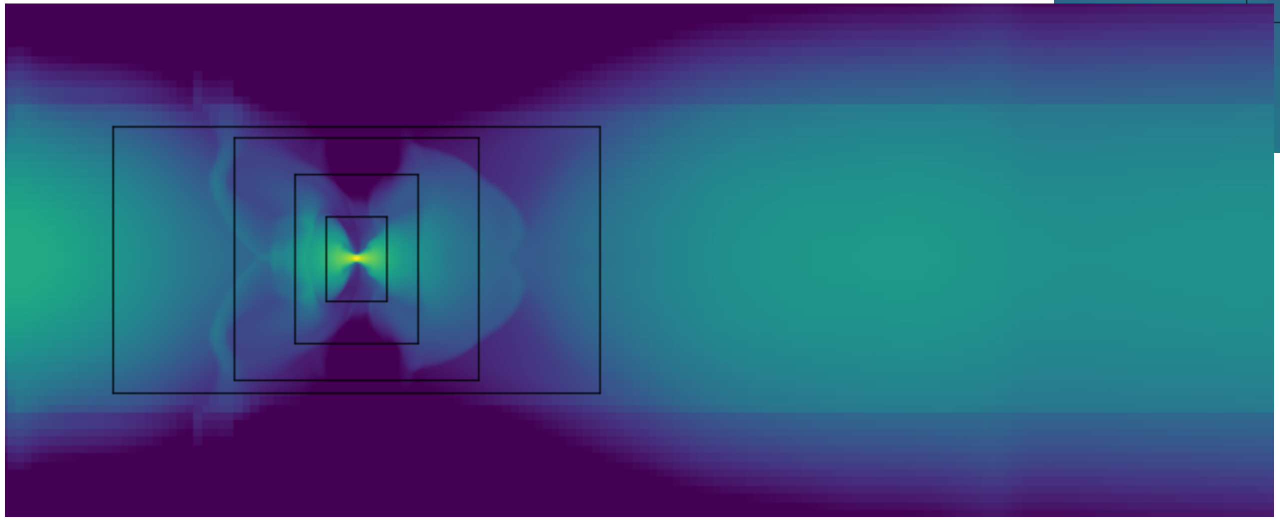
iii. Instrument simulation

Step 1: Hydrodynamic simulation

- JUPITER – a 3D grid-based hydrodynamic code with radiative module by F. Masset and J. Szulágyi
- Adaptive mesh refinement
- simulation for 2 separations (30 AU & 50 AU), 4 masses (10Mjup, 5Mjup, 1Mjup, 1Msat)



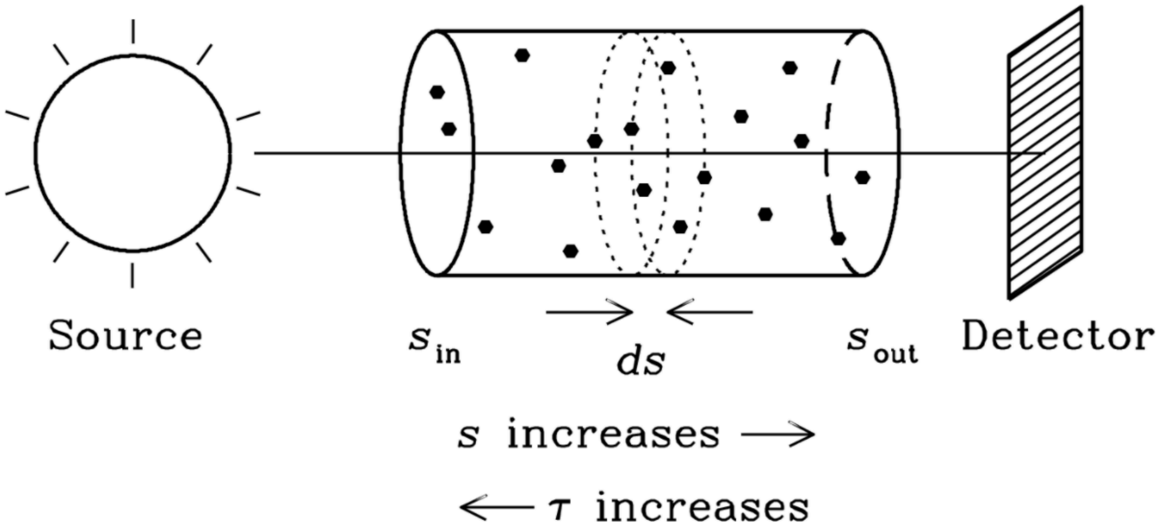
dust density slice at midplane



dust density slice at meridional plane

Step 2: Radiative transfer

- Wavelength-dependent intensity images from a specific viewing angle are needed for mock observations
- Radiative processes included are: absorption, emission, scattering

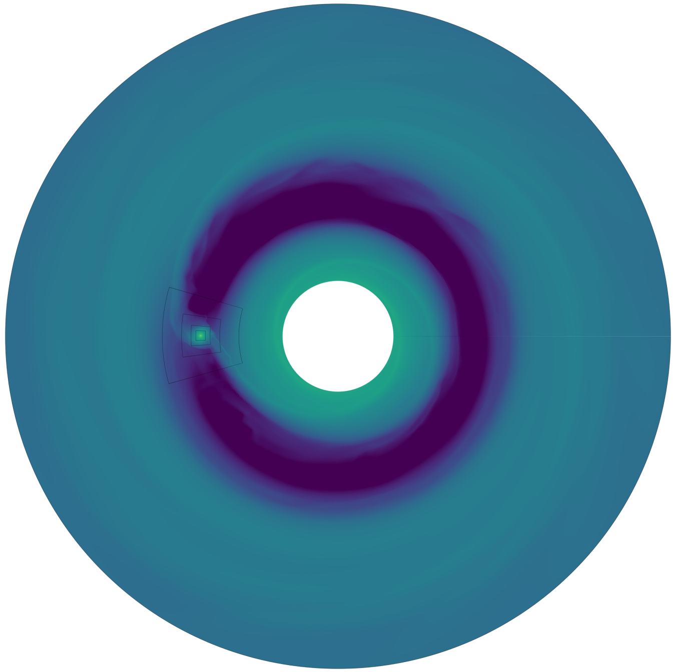


$$\frac{dI_\nu}{ds} = j_\nu^{\text{therm}} + j_\nu^{\text{scat}} - \left(\alpha_\nu^{\text{abs}} + \alpha_\nu^{\text{scat}}\right) I_\nu$$

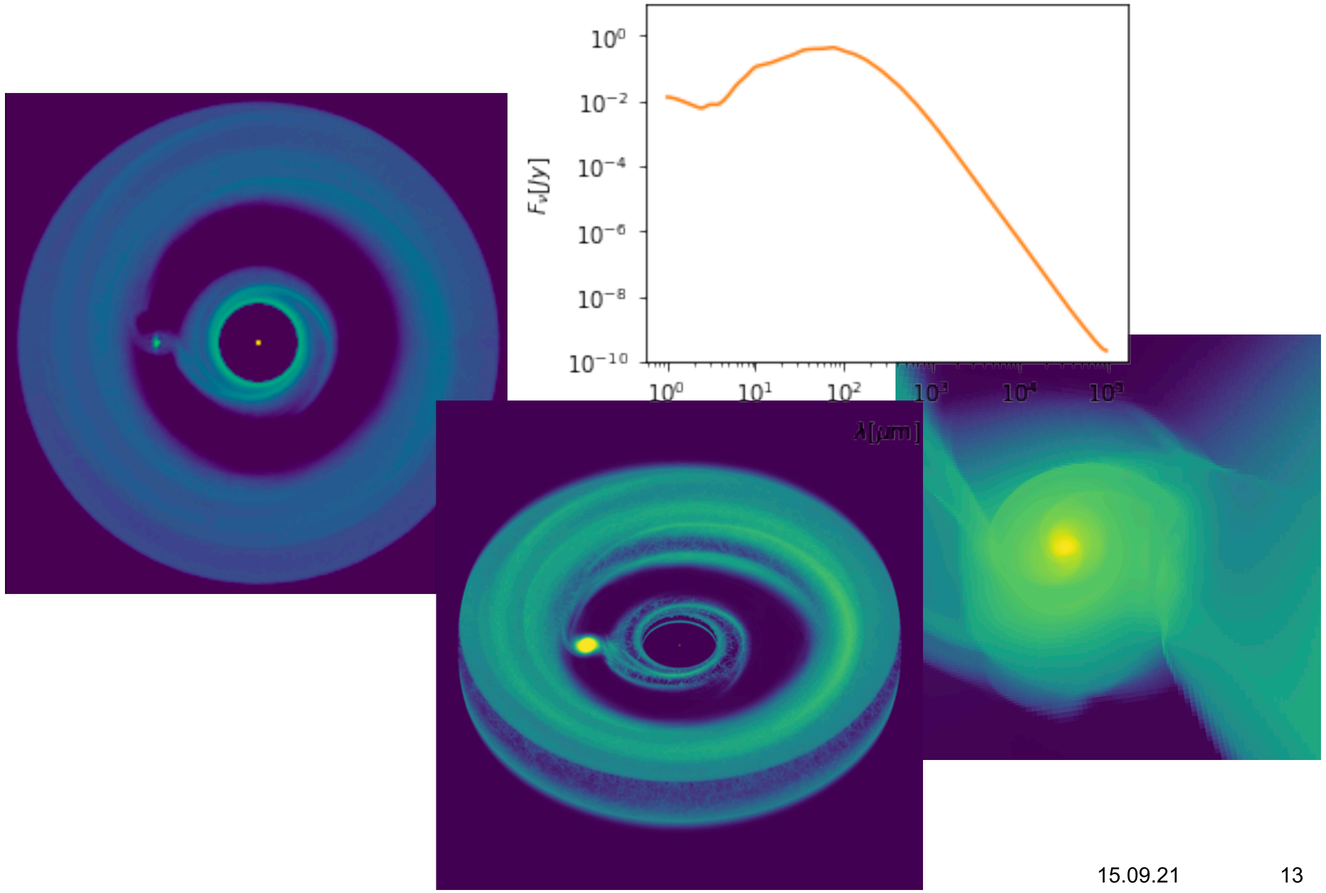
where
$$\alpha_\nu^{\text{abs}} = \rho\kappa_\nu^{\text{abs}}$$
$$\alpha_\nu^{\text{scat}} = \rho\kappa_\nu^{\text{scat}}$$
$$j_\nu^{\text{therm}} = \alpha_\nu^{\text{abs}} B_\nu(T)$$

Step 2: RADMC3D (by C. P. Dullemond)

- Calculates what a 3D density distribution of gas/dust look like from a specific viewing angle in a specific wavelength – an intensity image
- Calculates the spectral energy distribution (SED) of that gas/dust model – many intensity images



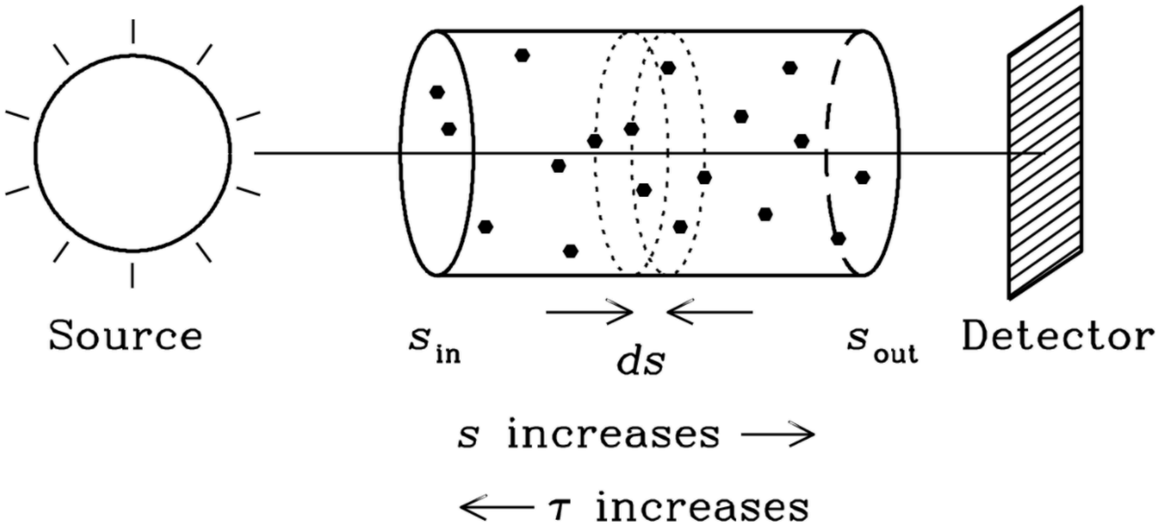
gas density distribution at disk mid-plane



Step 2: RADMC3D

- Inputs: dust density+temperature, dust opacity table, star info, wavelength table, other command options ...

- Automatized processing and parallelization is important!



$$\frac{dI_\nu}{ds} = j_\nu^{\rm therm} + j_\nu^{\rm scat} - \left(\alpha_\nu^{\rm abs} + \alpha_\nu^{\rm scat}\right) I_\nu$$

$$\text{where} \quad \alpha_\nu^{\rm abs} = \rho \boxed{\kappa_\nu^{\rm abs}}$$

$$\alpha_\nu^{\rm scat} = \rho \boxed{\kappa_\nu^{\rm scat}}$$

$$j_\nu^{\rm therm} = \alpha_\nu^{\rm abs} B_\nu(T)$$

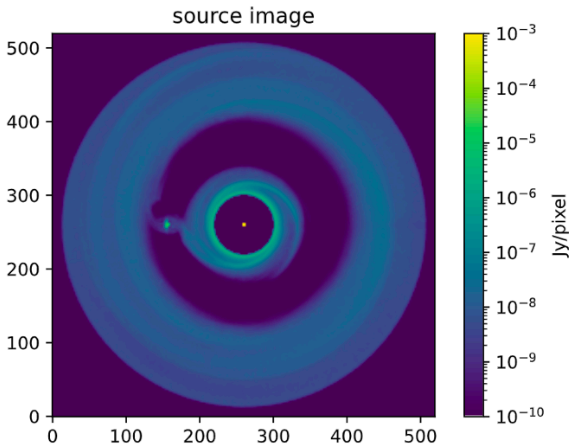
opacities

Step 3: Instrument simulation

- Open source simulators for JWST and ELT
- GMT simulator not public
- Other python packages for optics propagation: e.g. poppy
- Limitation: lack of coronagraphy simulation
  solution: mask the brightness of central star to 1%

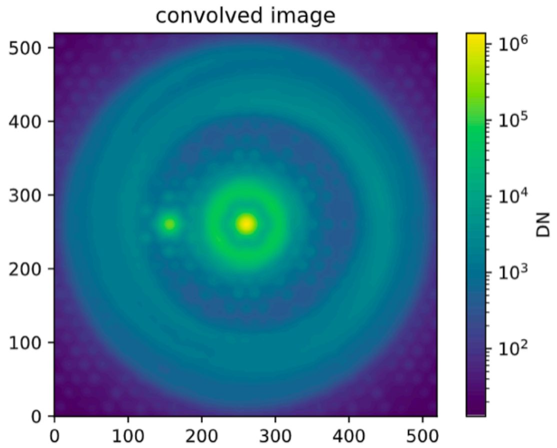
Step 3 - GMT Simulation Routine

RADMC3D intensity image

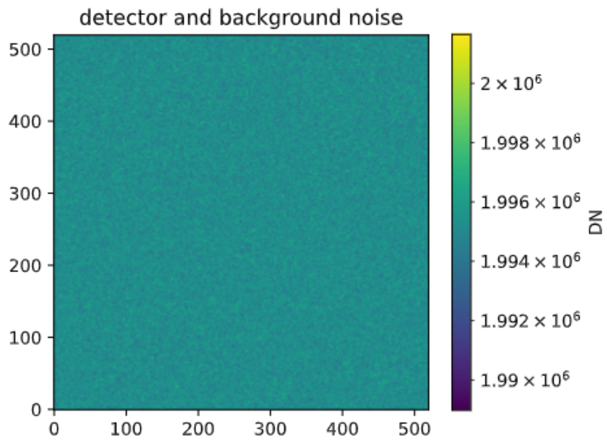


+

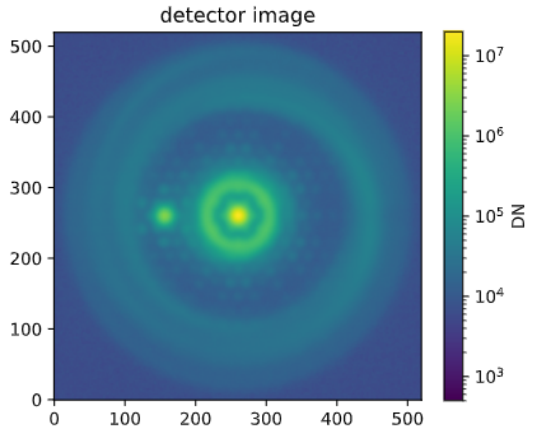
convolution



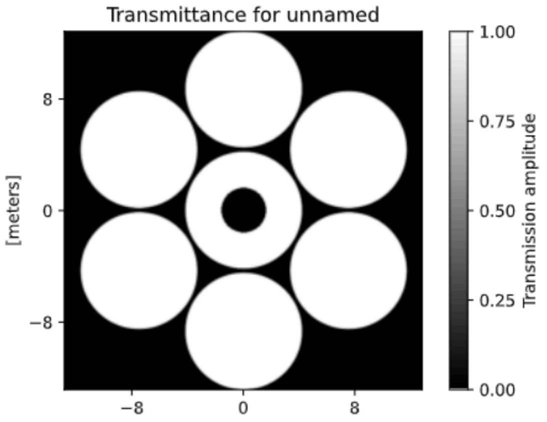
+



random Poisson noise

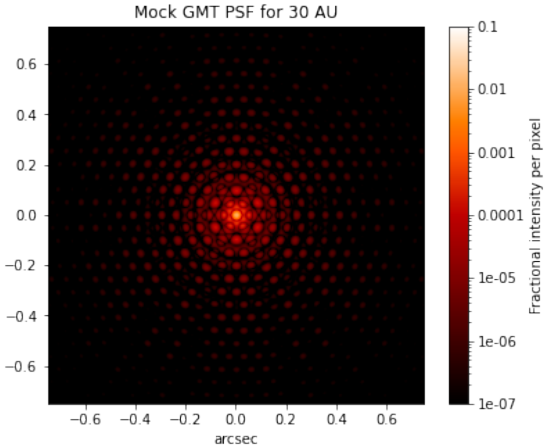


final image



telescope pupil generated by poppy

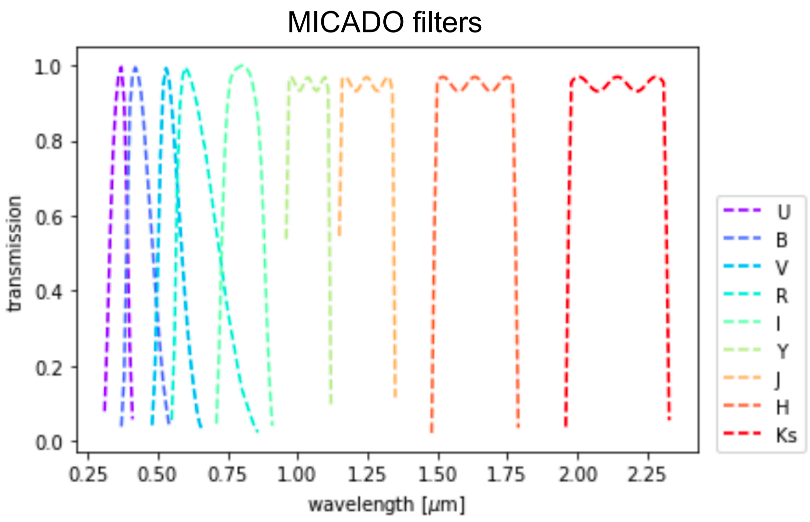
F.T.

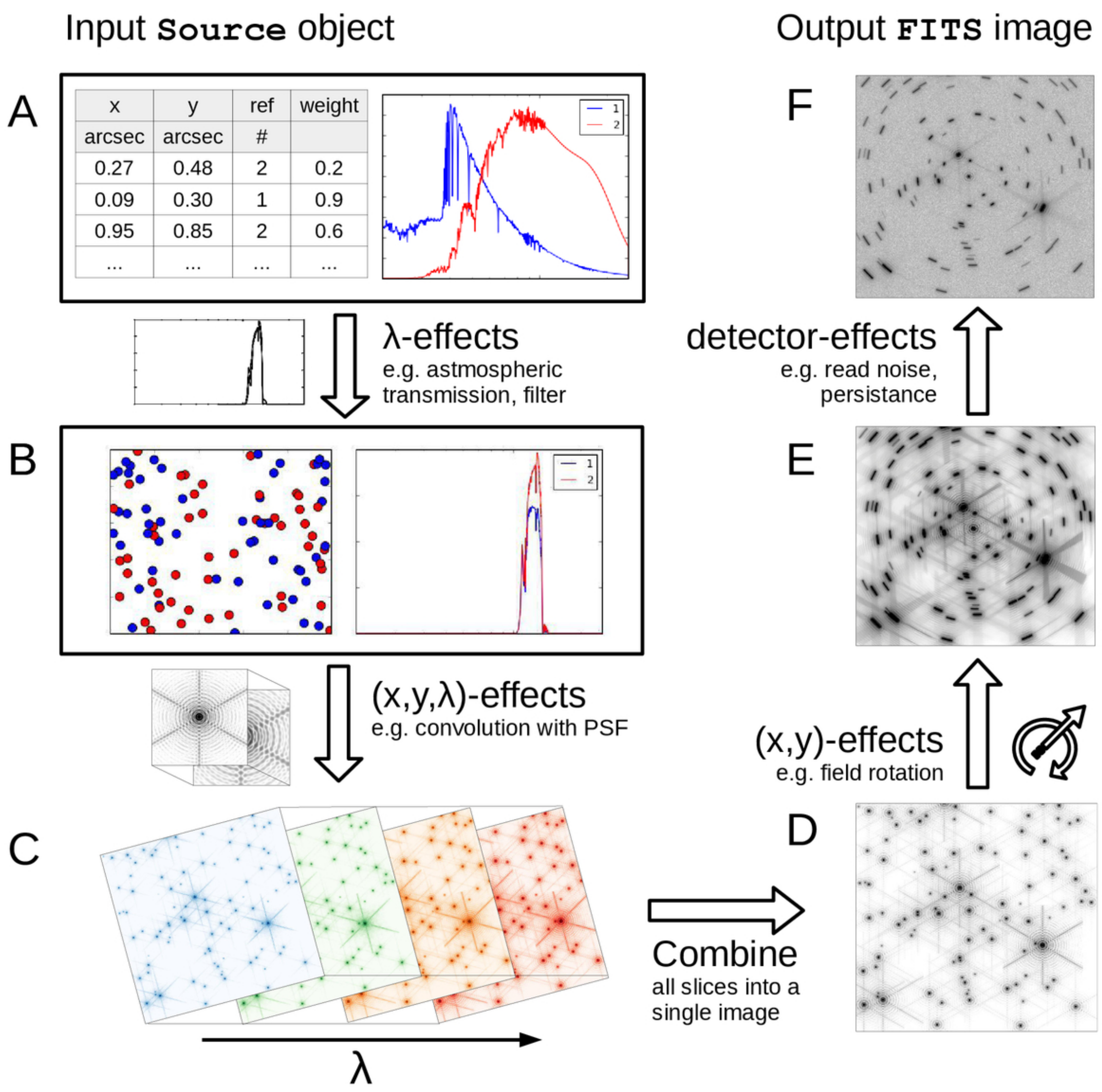


mock GMT PSF (point spread function) calculated by poppy

Step 3 – ELT MICADO/METIS: `SimCADO` / `SimMetis`

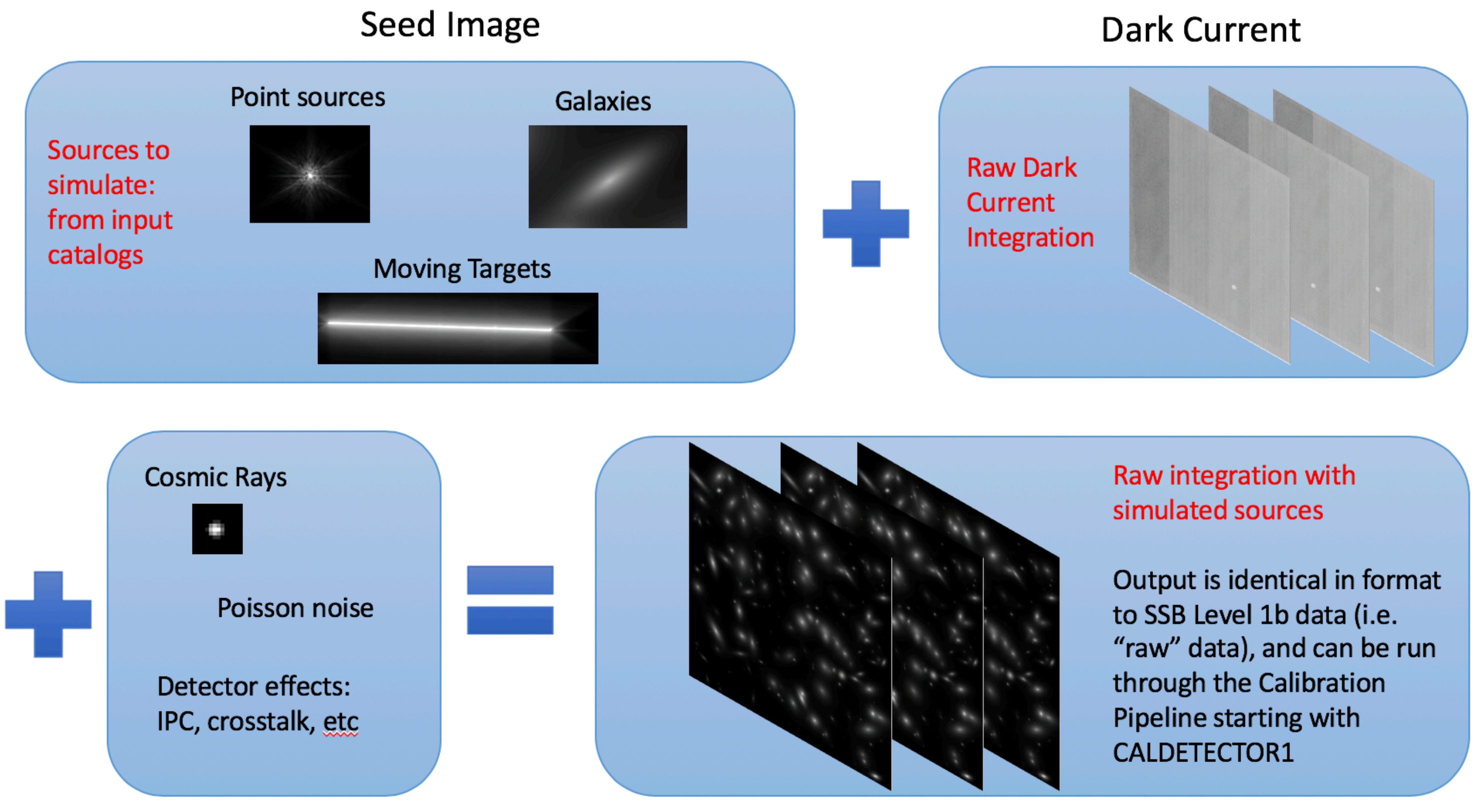
- Applies wavelength-dependent effects, PSF convolution, detector effects (noise, distortion, etc.)...
- Inputs: source image, source spectrum, simulation config file





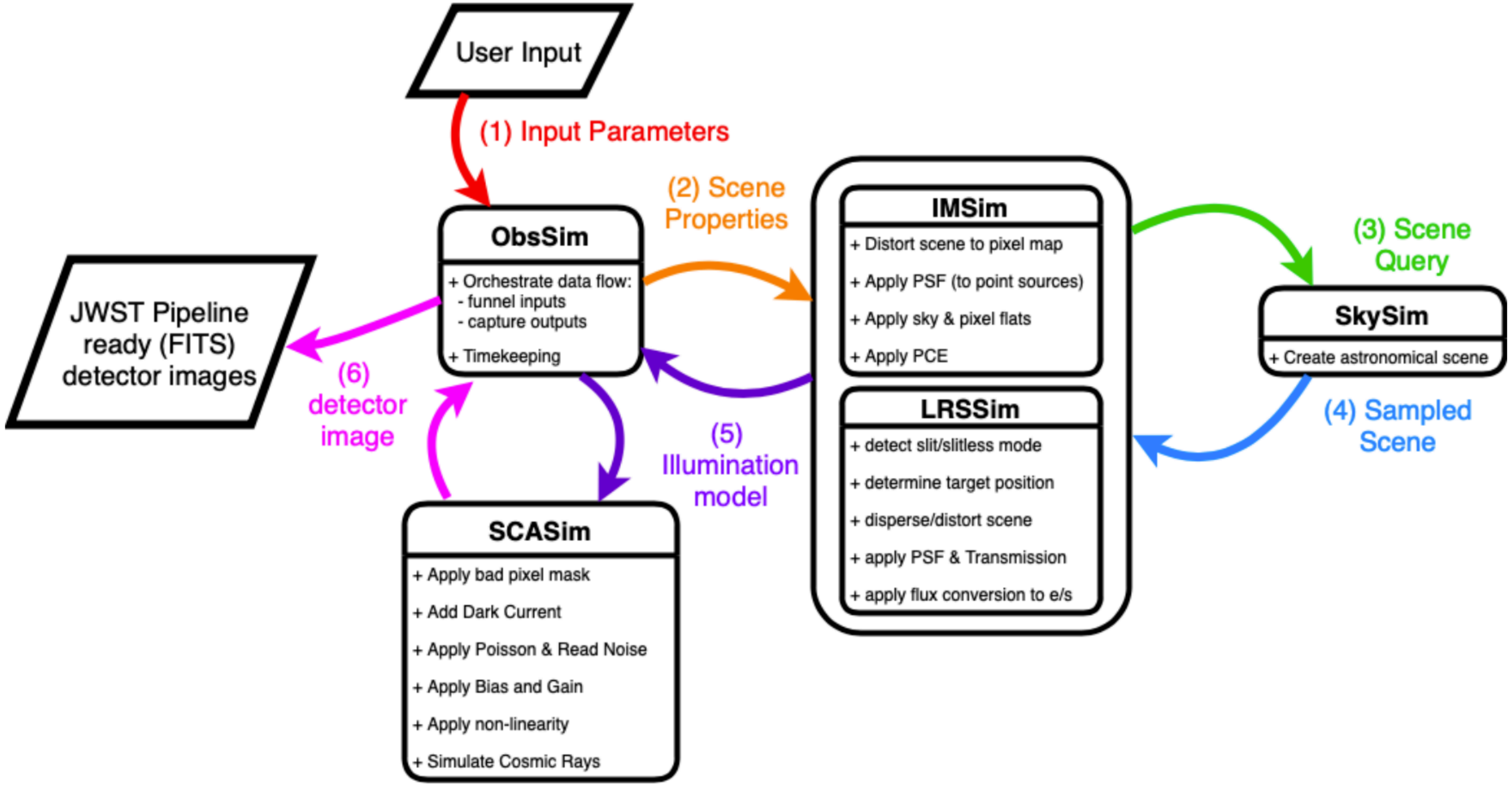
Step 3 – JWST NIRCam/NIRISS: `Mirage`

- Produce JWST pipeline-ready detector images
- Inputs: source catalog file (convert from Jy to ADU/s), observation planning file from APT, simulation config file



Step 3 – JWST MIRI: `MIRISim`

- Create image scene -> create illumination model with convolved PSF -> apply detector effects (dark current, noise...)
- Inputs: source image cube (with an spectral dimension), simulation configs



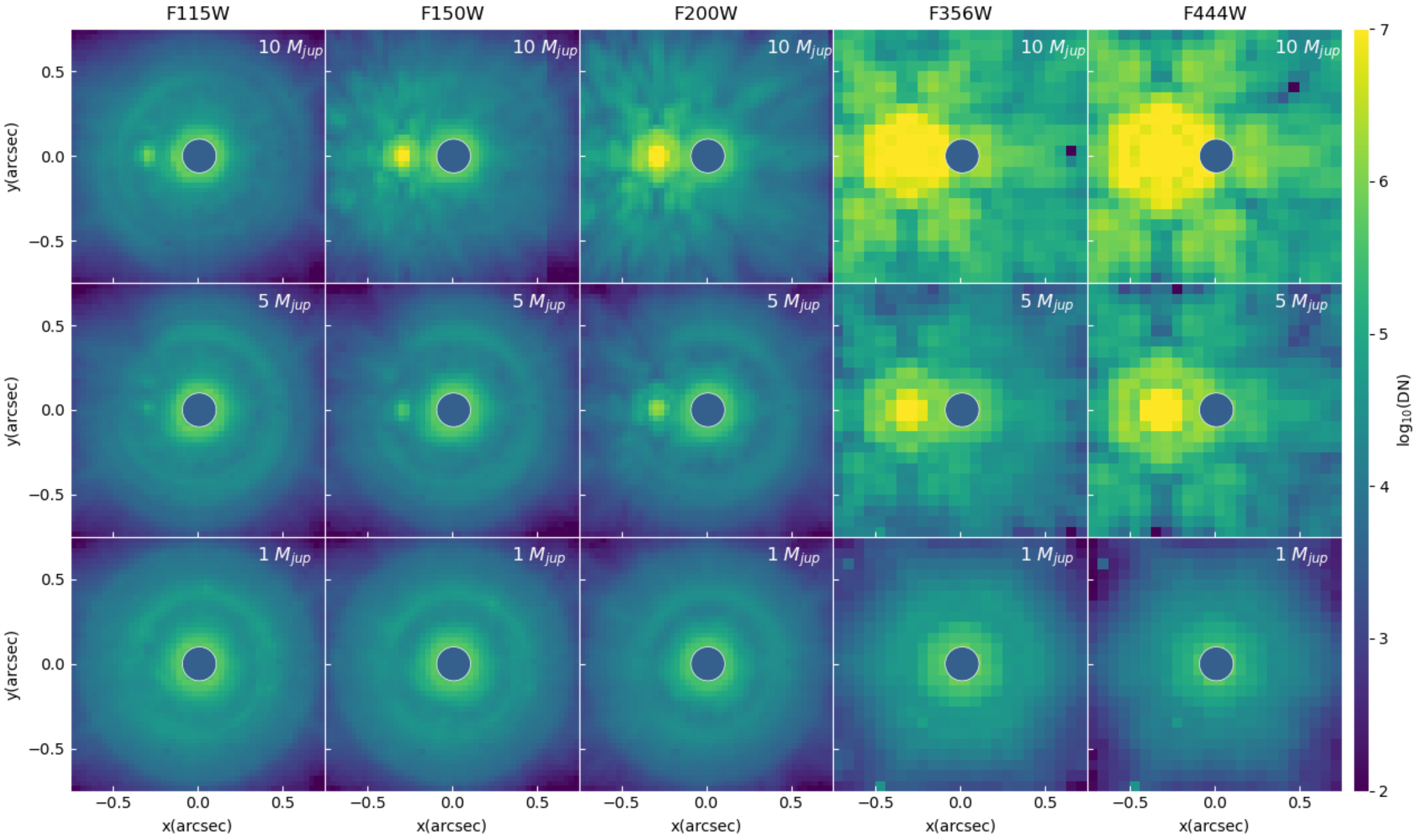
Step 3 – Summary

Photometric bands of interest and corresponding instrument filters,
with their central wavelength presented in microns

Instrument/Band		J	H	K	L	M	N	Q
ELT	MICADO	J=1.25	H=1.64	Ks=2.14	/	/	/	/
	METIS	/	/	/	L=3.79	Mp=4.88	N2=11.8	/
JWST	NIRCAM	F115W=1.15	F150W=1.50	F200W=1.98	F356W=3.59	F444W=4.43	/	/
	NIRISS	F115W=1.15	F150W=1.50	F200W=1.98	F356W=3.59	F444W=4.43	/	/
	MIRI	/	/	/	/	/	F1000W=10.0	F1500W=15.0 F2100W=21.0
GMT/GMTIFS		hJ=1.23	hH=1.64	hK=2.27				

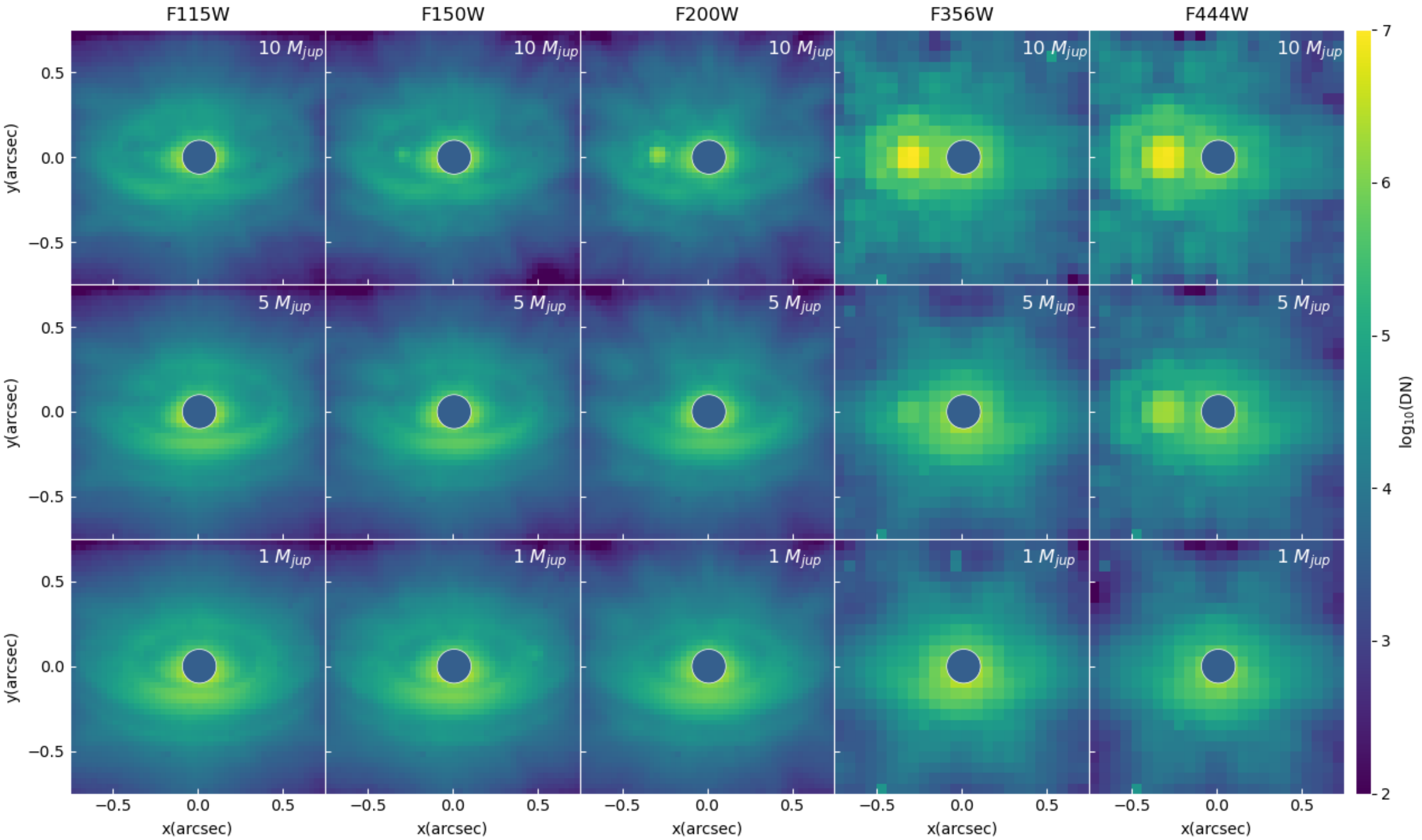
Selected results

JWST NIRCam



0º inclination, planet at 30 AU separation

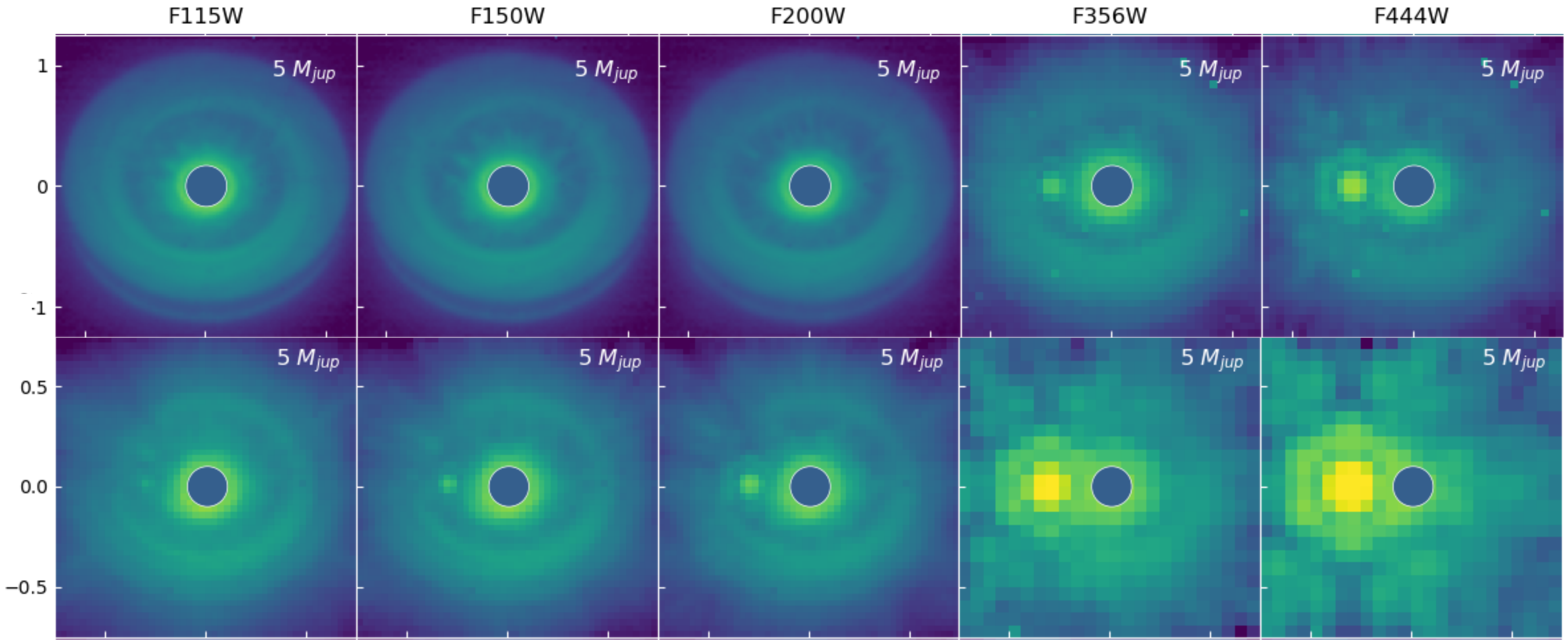
JWST NIRCam



60º inclination, planet at 30 AU separation

JWST NIRCam

Comparison of different planet separation



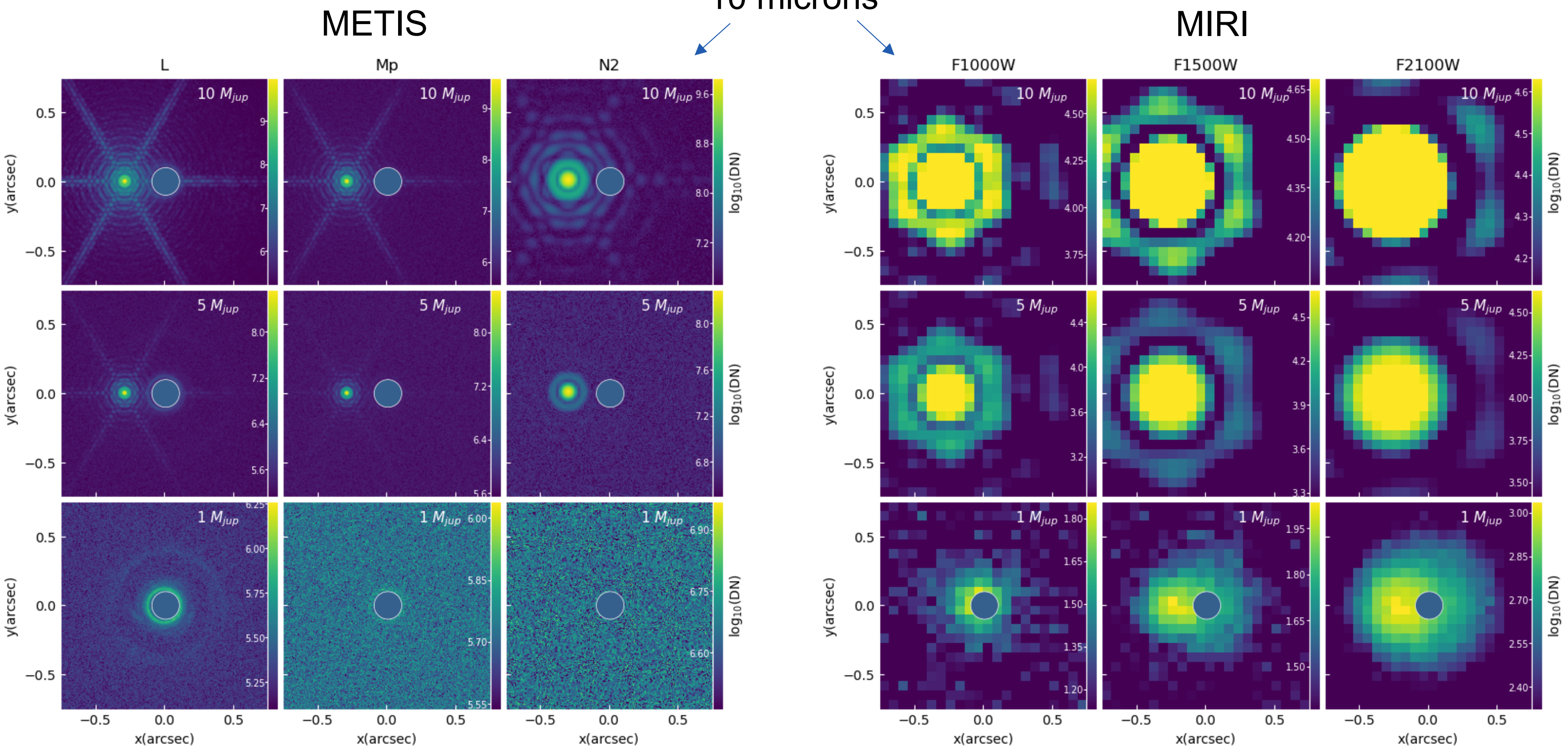
50 AU

30 AU

30º inclination

ELT/METIS vs JWST/MIRI

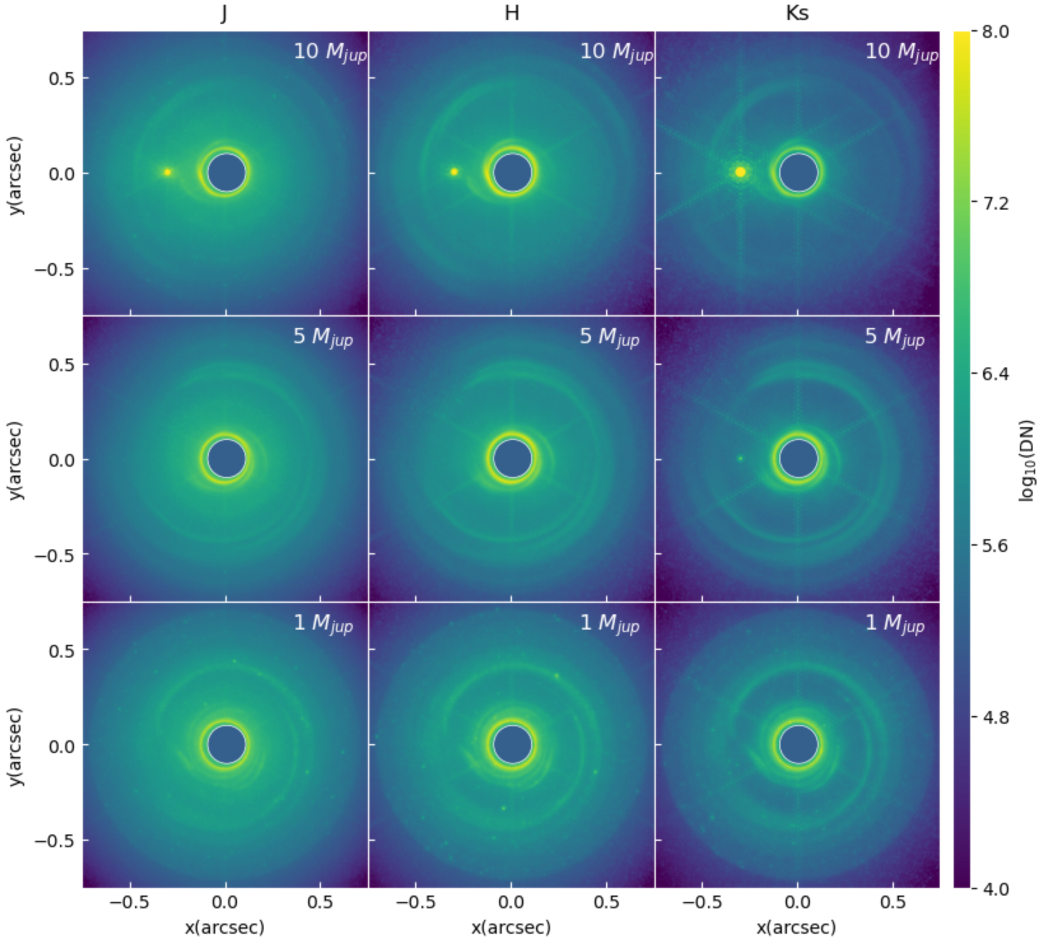
10 microns



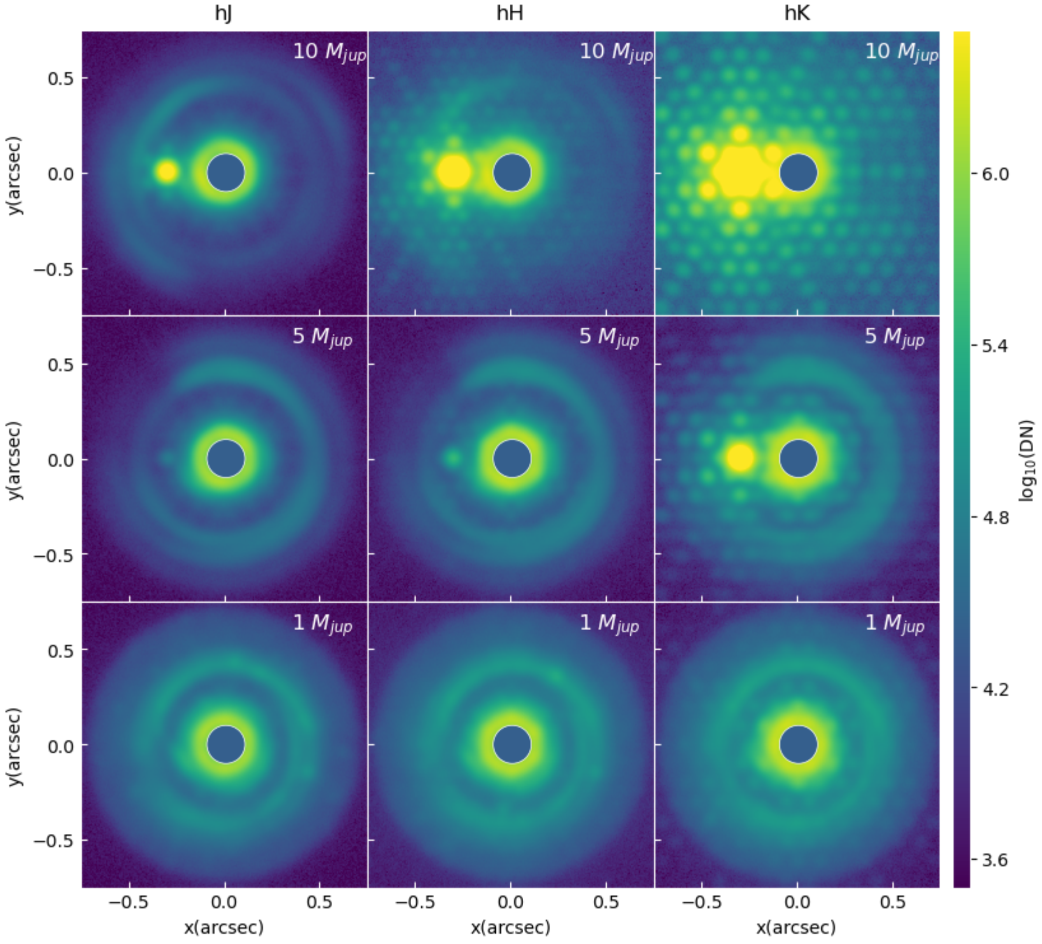
planet at 30 AU separation

ELT/MICADO vs GMT/GMTIFS

MICADO J, H, Ks

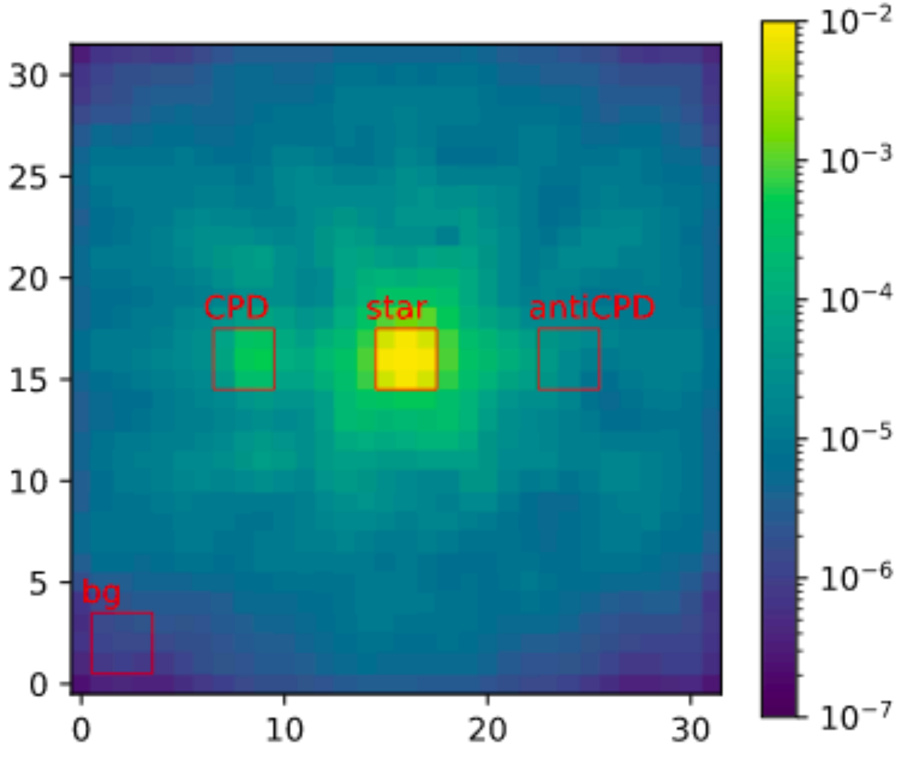


GMTIFS hJ, hH, hK



planet at 30 AU separation

Aperture photometry and predicted magnitudes



SNR = F_{CPD} / $F_{antiCPD}$

Table 5.5: Circumplanetary disk fluxes and magnitudes at 100 pc as imaged by ELT/MICADO.

model	filter	CPD (Jy)	CPD only (Jy)	CPD (mag)	CPD only (mag)	$\mathrm{SNR}_{\mathrm{CPD}}$
	J	1.09e-05	4.41e-07	20.41	23.89	1.04
10jup50au	H	3.32e-03	3.31e-03	13.77	13.78	304.30
	Ks	1.79e-02	1.79e-02	11.40	11.40	1881.39
	J	1.10e-05	1.43e-07	20.40	25.11	1.01
5jup50au	H	1.19e-05	1.58e-08	19.89	27.08	/
	Ks	1.33e-05	1.68e-07	19.23	23.97	1.01
	J	1.20e-05	/	20.31	/	/
1jup50au	H	1.33e-05	/	19.77	/	/
	Ks	1.51e-05	/	19.09	/	/
	J	1.28e-05	/	20.23	/	/
1sat50au	H	1.52e-05	/	19.62	/	/
	Ks	1.76e-05	2.32e-07	18.92	23.63	1.01
	J	7.69e-03	7.66e-03	13.29	13.29	279.55
10jup30au	H	4.95e-03	4.92e-03	13.34	13.35	181.85
	Ks	2.69e-02	2.69e-02	10.96	10.96	1697.78
	J	3.13e-05	/	19.26	/	/
5jup30au	H	2.96e-05	/	18.90	/	/
	Ks	1.63e-04	1.37e-04	16.51	16.69	6.29
	J	3.45e-05	1.84e-06	19.16	22.34	1.06
1jup30au	H	3.51e-05	4.79e-06	18.71	20.88	1.16
	Ks	3.49e-05	7.55e-06	18.18	19.84	1.28

Summary

- We simulated observation of planet forming disks with various future instruments in a wide range of wavelengths in near and mid IR.
- Planets with high planetary mass (> 5 Mjup) are observable by all instruments in most filters, even some cases with 60° inclination.
- Planet brightness increases with longer wavelength and closer separation from its star.
- For the near-IR instruments, the best observability of forming planets is achieved towards longer wavelengths, which are F356W and F444W for NIRCam & NIRISS, and K band for MICADO and GMTIFS.
- In the mid IR, METIS will provide high resolution imaging that allows resolved CPD detection around 10 μm, and MIRI will offer unique chance to image planet forming disks beyond 15μm, where the contrast of lower-mass giant planets is better.

ETH zürich

Thank you!