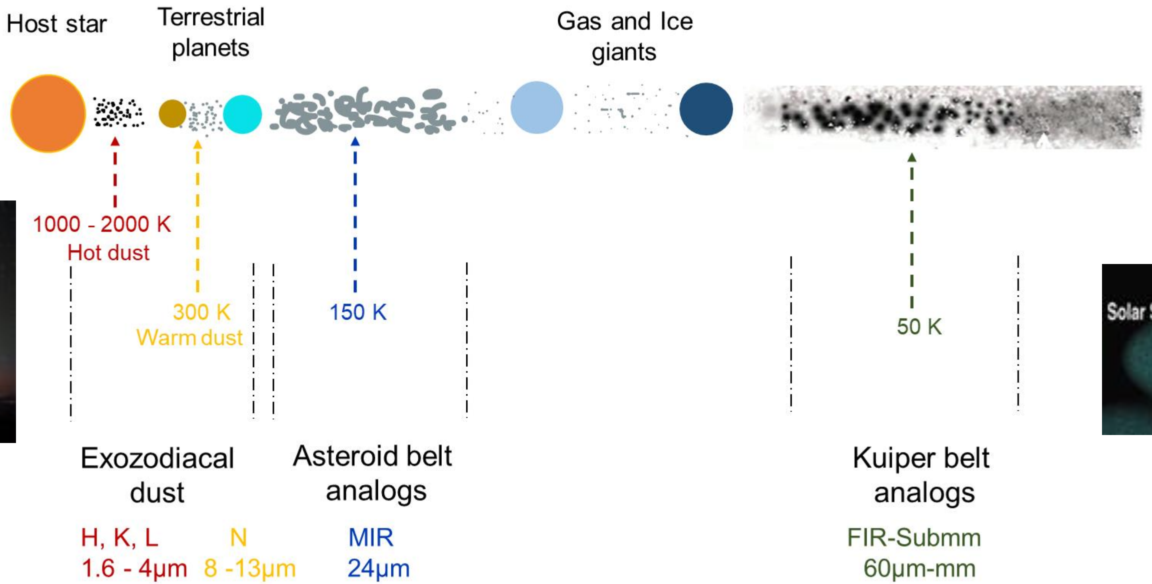
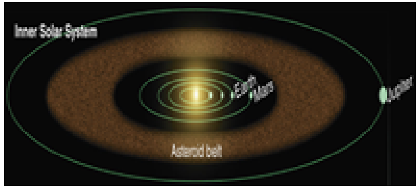
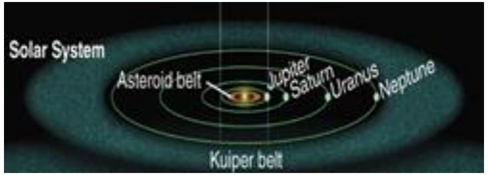
Roman Coronagraph School Europe 2026
Debris disks

Isa Rebollido and Ramya Anche

Anatomy of a Debris disk system







Asteroid belts
Located near the water-icelines, these belts are made up of mostly rocky bodies, likely shepherded by gas giants that formed at the ice-line

Kuiper belts
These belts of Icy planetesimals

Adapted from Gaspar et al. 2019; Youdin & Rieke 2015)

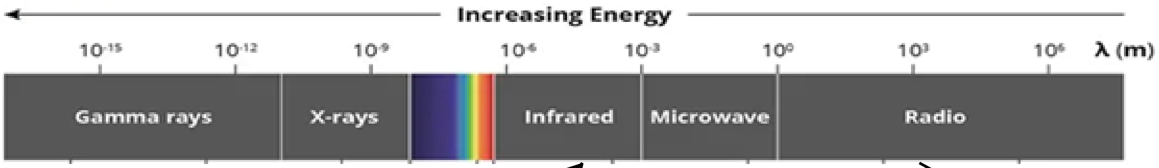
Dust in Debris disk

Dust in debris disk is seen in Scattered light and thermal emission

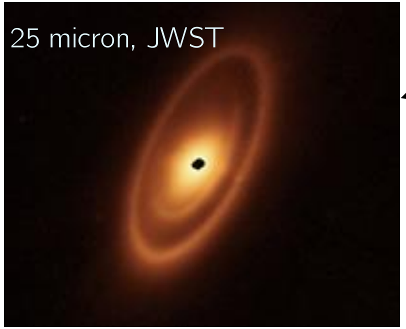
- Scattered light. This is where light from a star gets reflected off a dust grain. – Optical wavelengths
- Thermal emission. This is where a grain radiates heat as photons. – IR and Radio

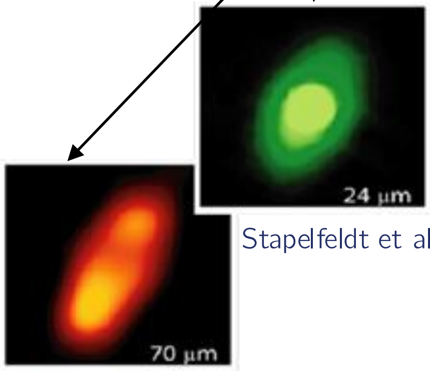
- ‘**Cold dust**’: dust at temperatures of order 30 K. Located in the outer regions of planetary systems, at 10s to 100s of au from stars.
- ‘**Warm dust**’: temperatures of order 300 K. Distances of order 1 au, which is near the habitable zone.
- ‘**Hot dust**’: temperatures of order 1000 K. Located very close to stars, at 0.1 au or less.

Observational Signatures of Debris Disks

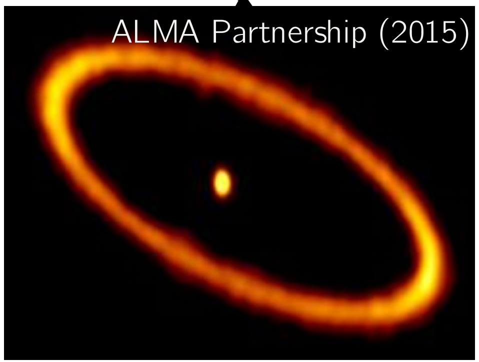


Gaspar et al. 2023





Stapelfeldt et al. 2004

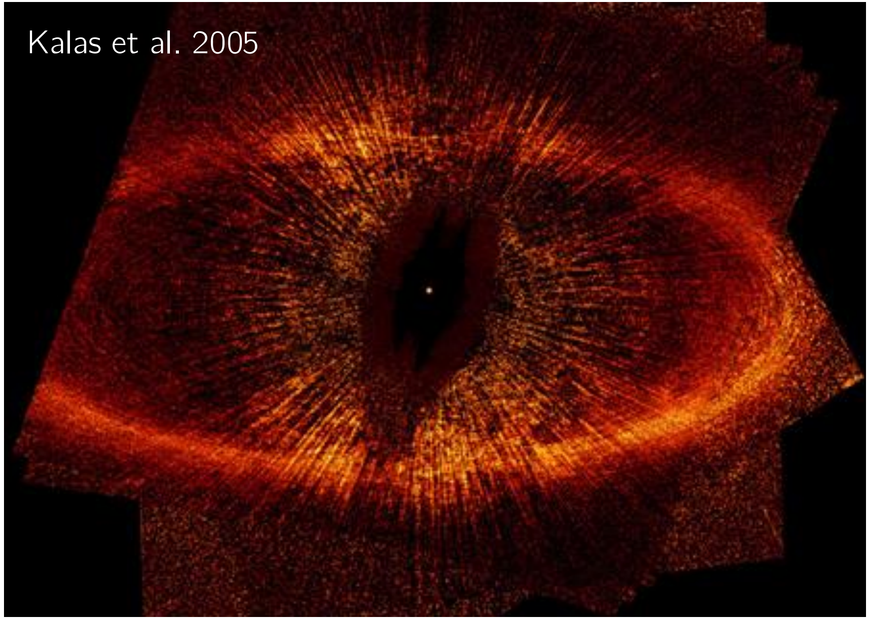


McGregor et al. 2017

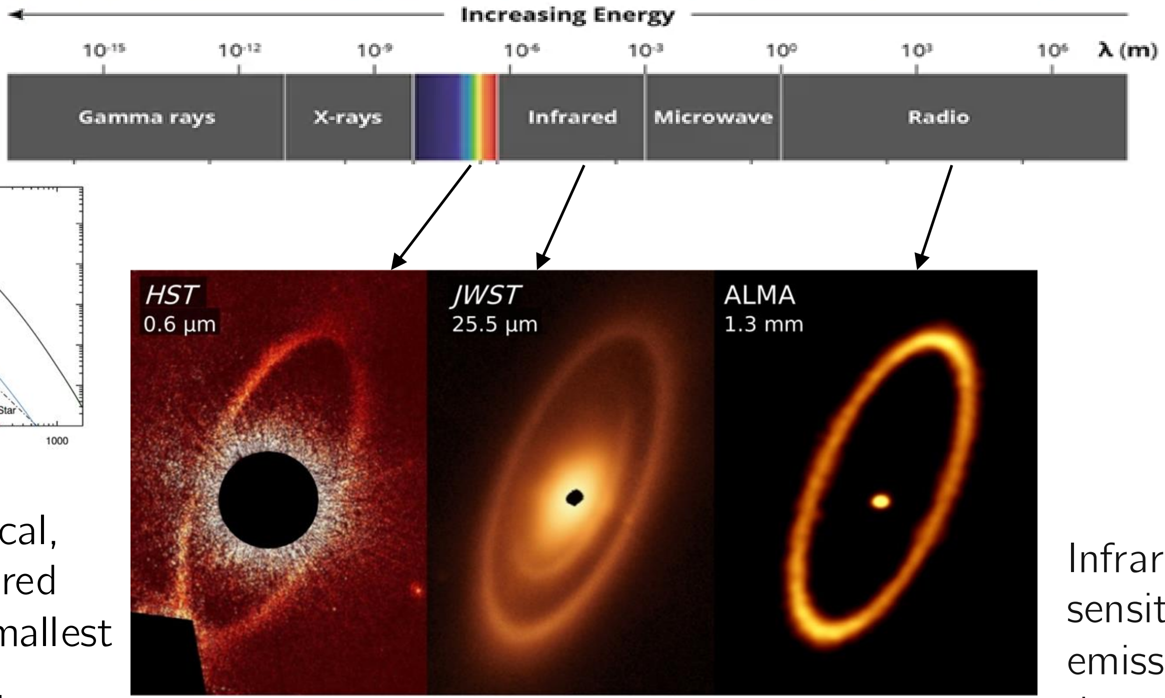
IR is sensitive to thermal emission from the dust grains

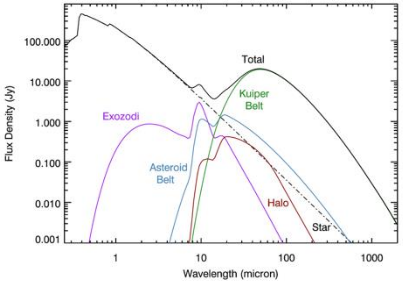
Observational Signatures of Debris Disks

In the Optical and NIR, we image light scattered off of the smallest dust grains.



Observational Signatures of Debris Disks

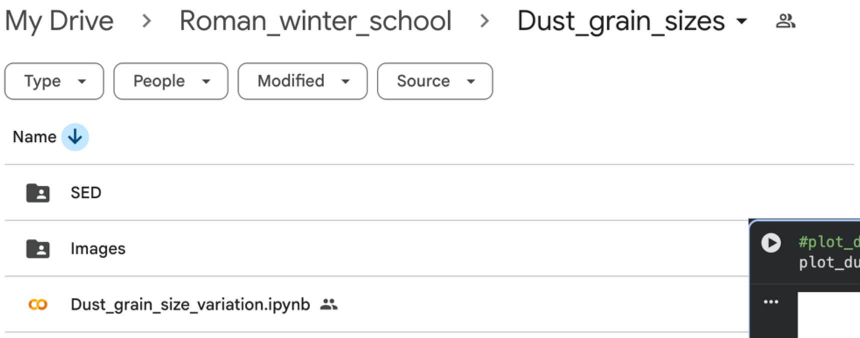




In the Optical, light scattered from the smallest dust grains.

Infrared and Radio is sensitive to thermal emission from the large dust grains

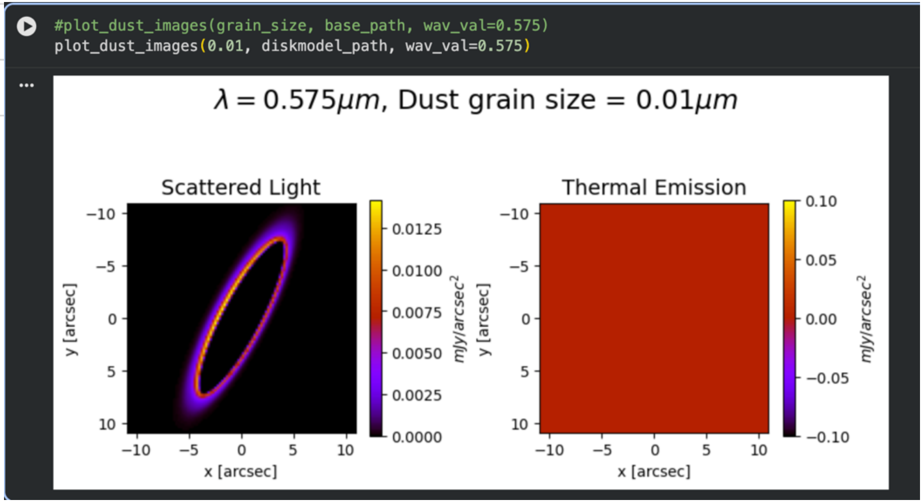
Google colab on scattered light and thermal emission



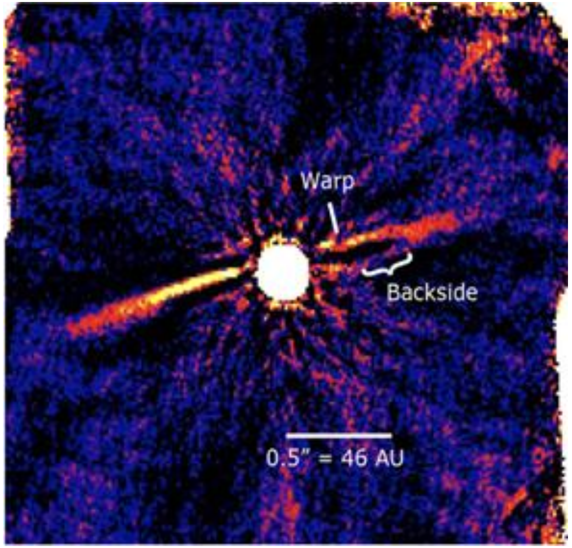
We vary the dust grain sizes and look at

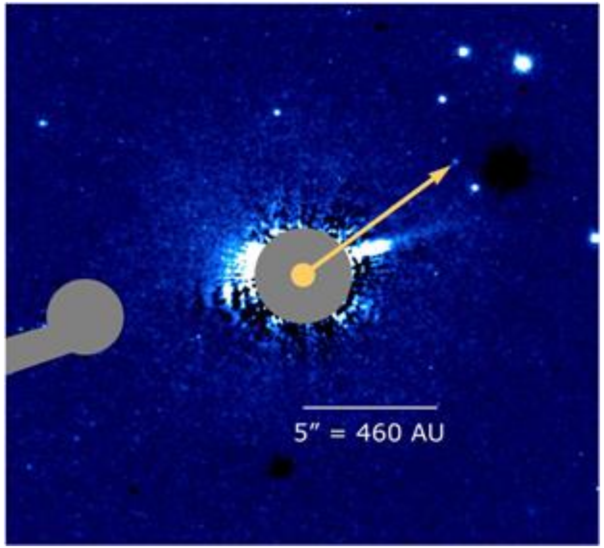
- Scattered light (0.575 microns)
- Thermal emission (100 microns)

- When is the disk brighter in scattered light? What kind of grain sizes?
- When is the disk brighter in thermal emission? What kind of grain sizes?



Scattered light observations

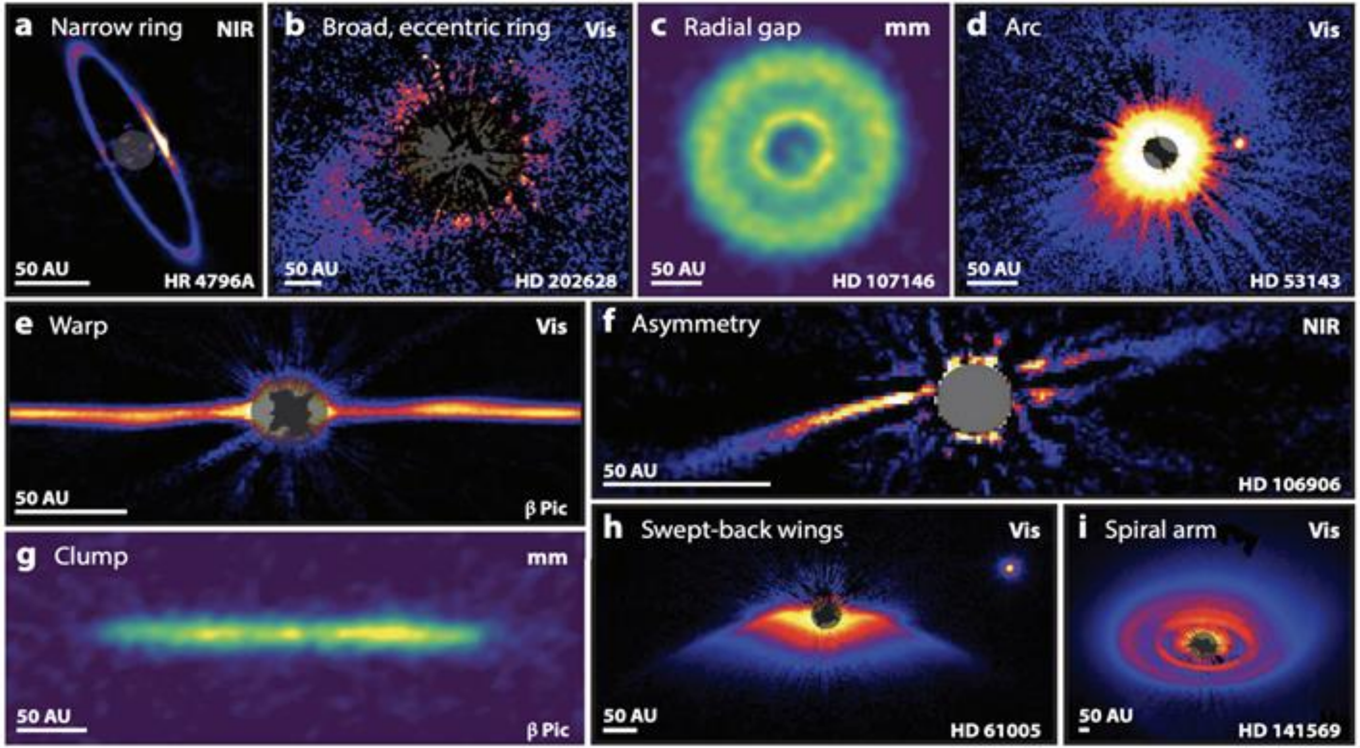




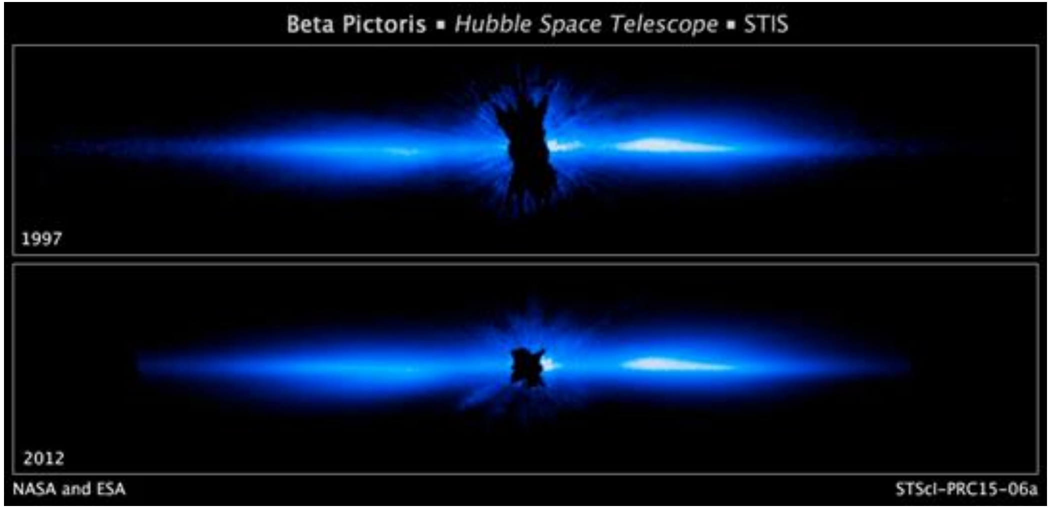
- Geometry
  - Ring inner and outer radii
  - Vertical structure
  - Asymmetries (Planets?)
- Dust Grain Properties
  - Disk brightness
  - Scattering phase function

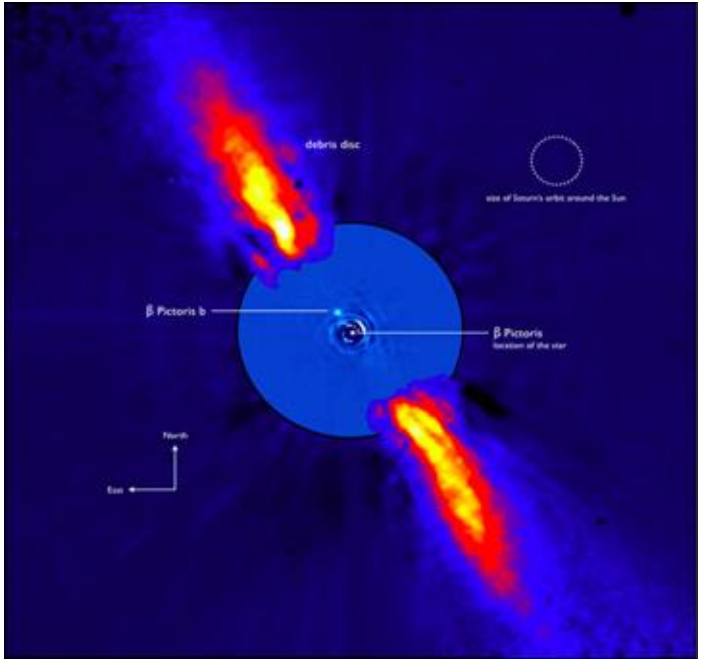
Credit: Kalas et al. (2015), Bailey et al. (2014)

Structural Diversity



Signs of planets

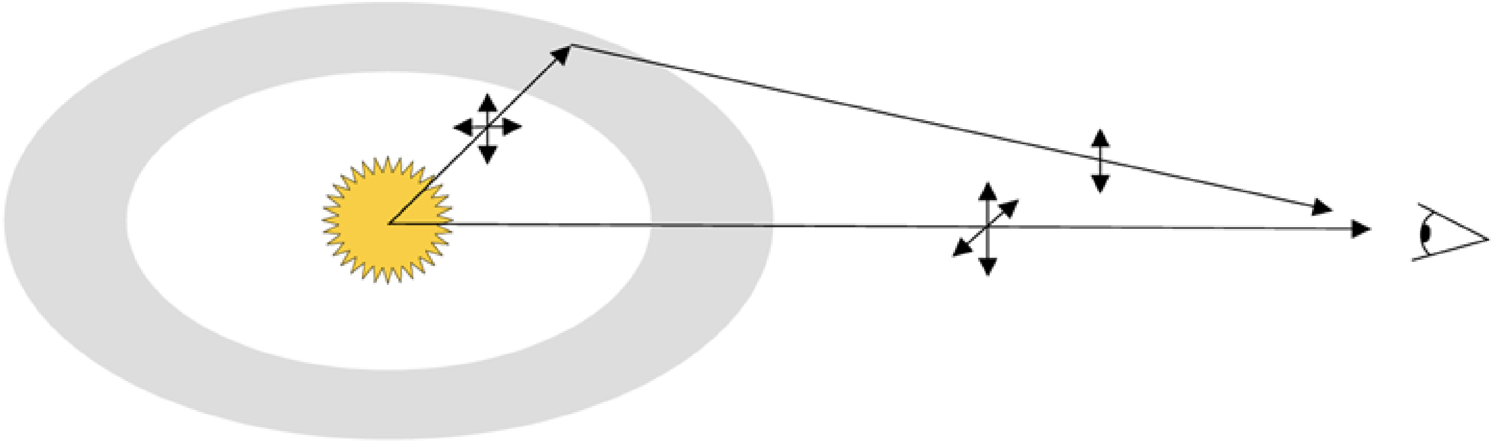




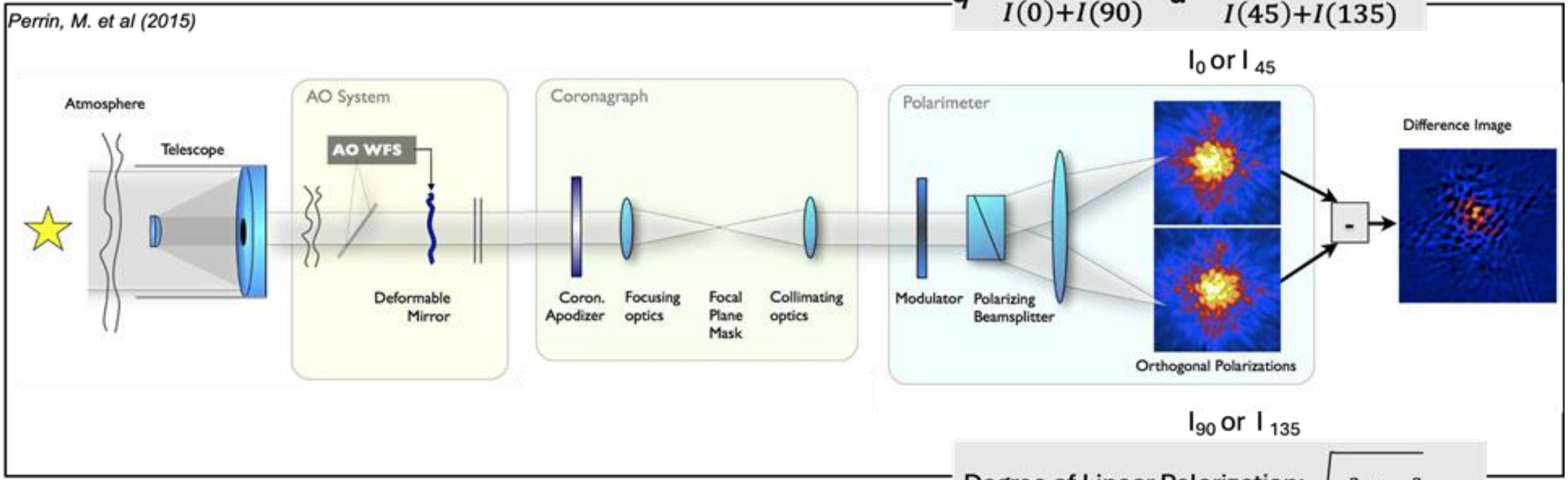
Debris disks are also polarized

Scattered light from debris disks is expected to be linearly polarized to some degree

- Asymmetries in their structure
- Scattering/absorption by the dust grains



High-contrast polarimetry



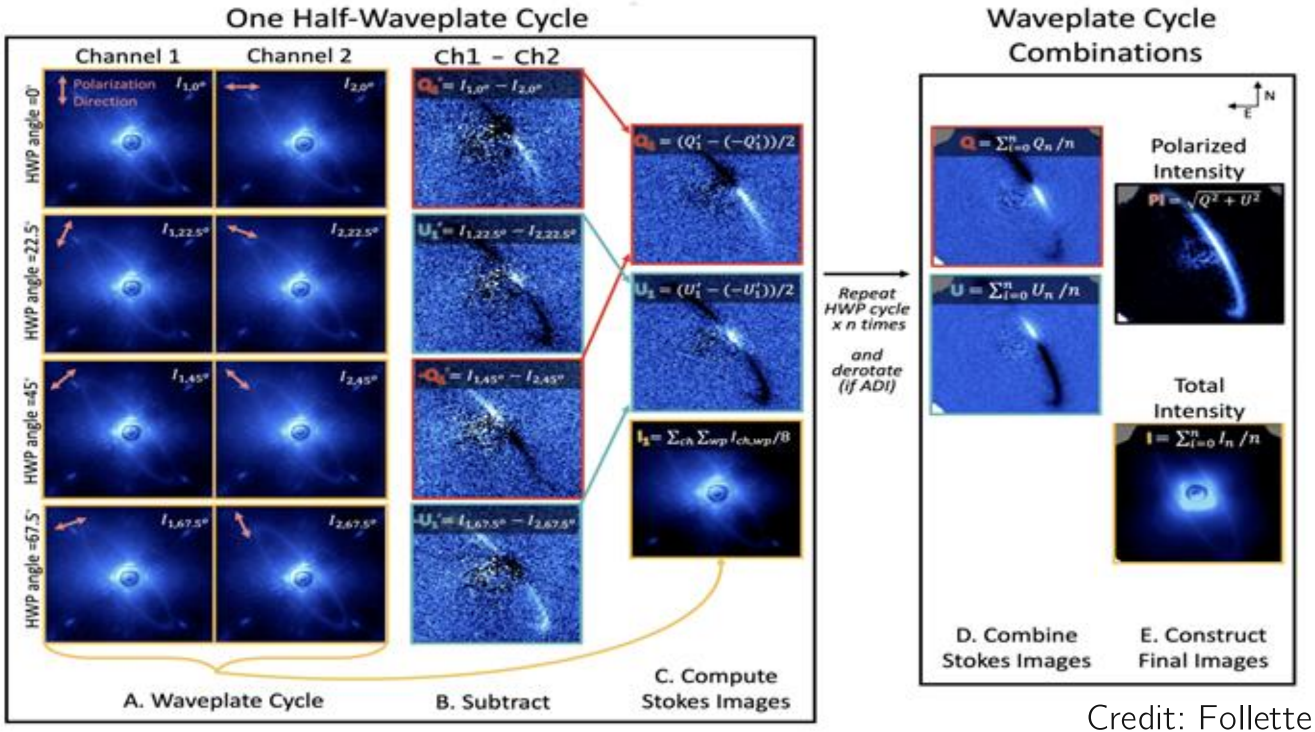
$$q = \frac{I(0) - I(90)}{I(0) + I(90)} \quad u = \frac{I(45) - I(135)}{I(45) + I(135)}$$

I_0 or I_{45}

I_{90} or I_{135}

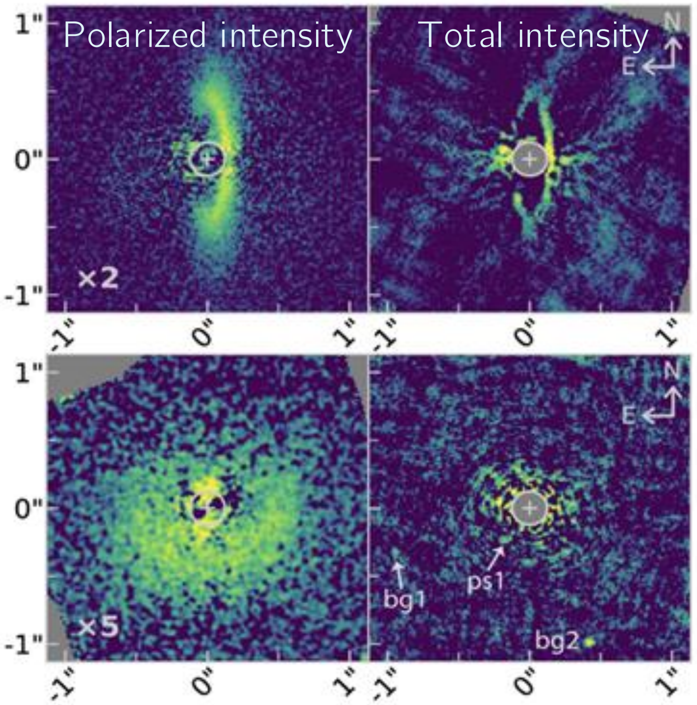
Degree of Linear Polarization: $\sqrt{q^2 + u^2}$

Polarized differential imaging

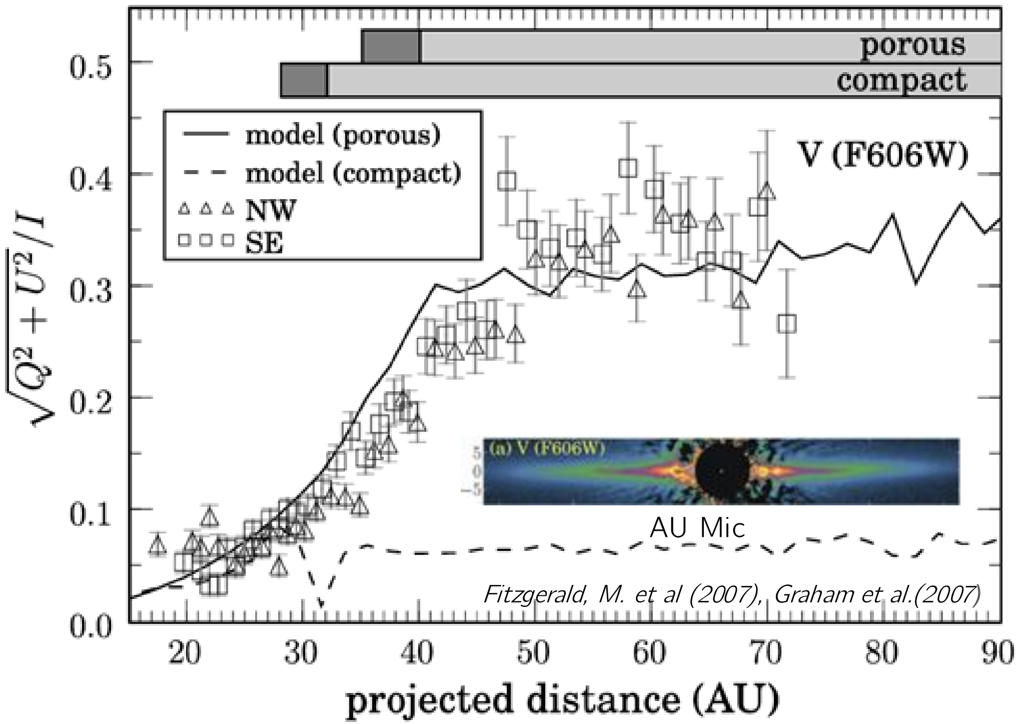


Credit: Follette 2023

Comparison of polarized and total intensity



Esposito, T et. al(2020)



Fitzgerald, M. et al (2007), Graham et al.(2007)

Debris disks imaged through HST

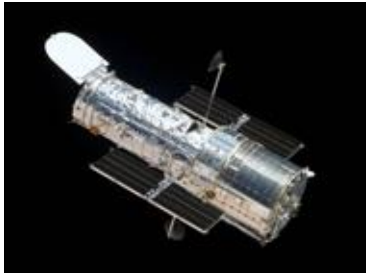
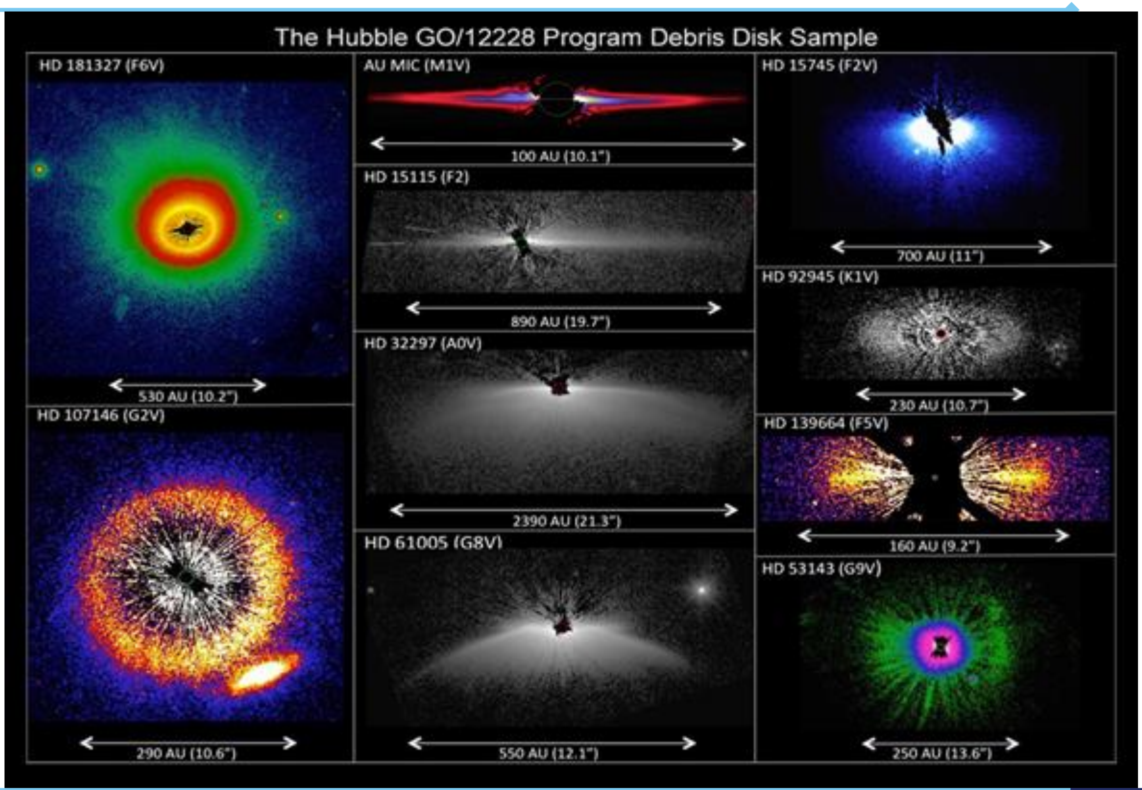
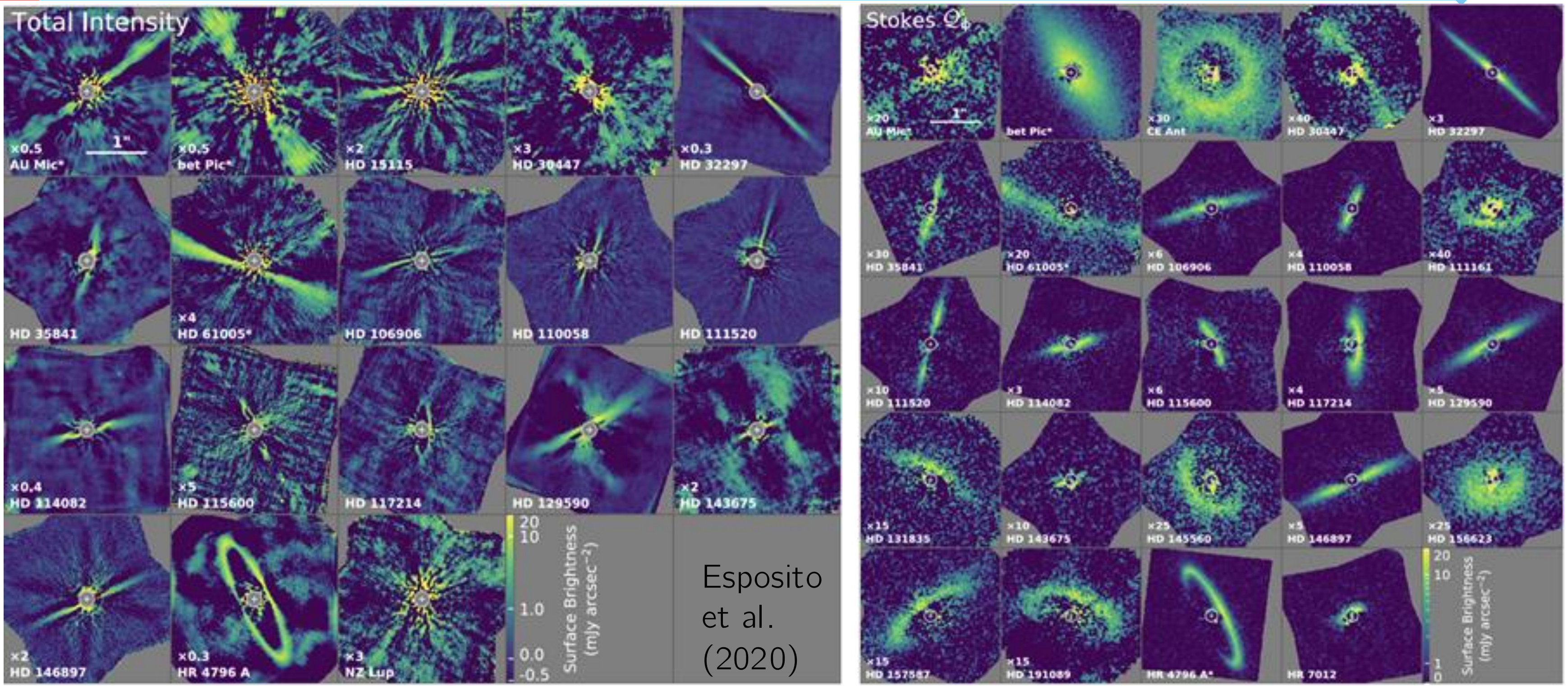


Image Credit: NASA, ESA, G. Schneider (University of Arizona), and the HST/GO 12228 Team.



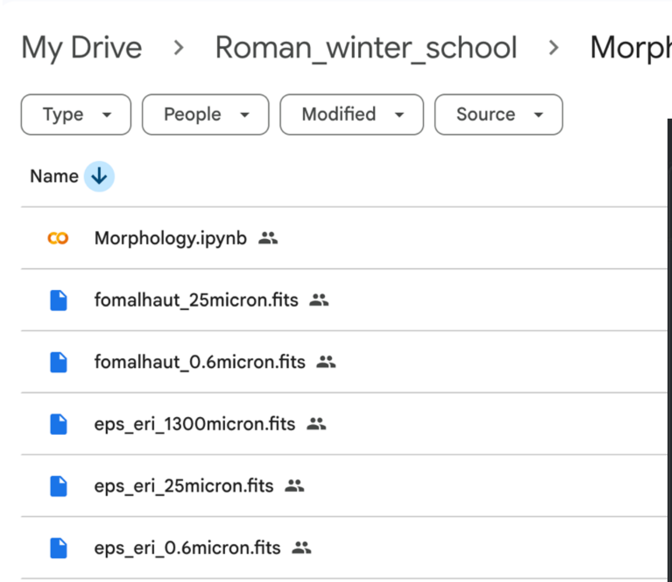
Debris disks images through GPI

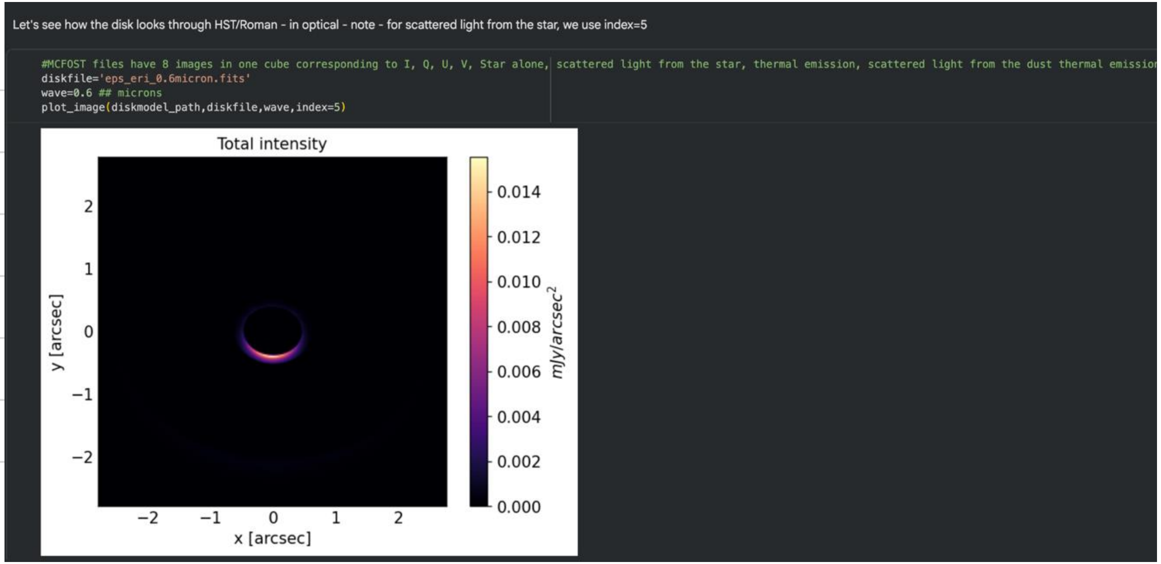


Esposito et al. (2020)

Google colab on Morphology

We will look at observations in Optical, Mid IR and radio to understand how the disk morphology varies

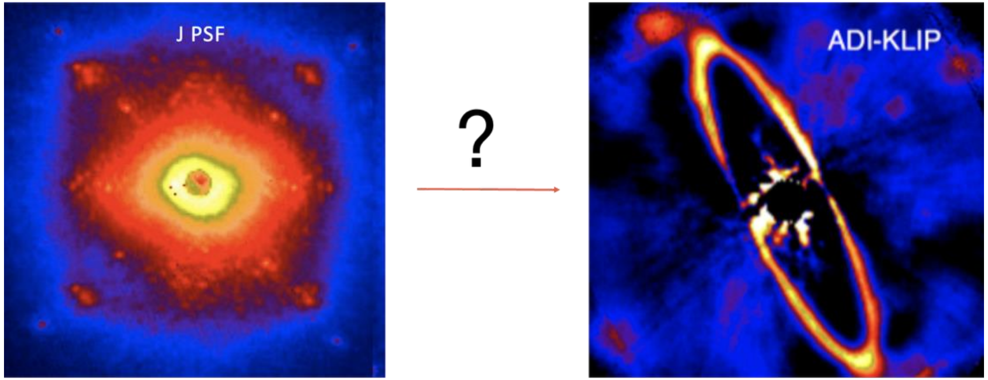




- What features can you understand from these multi wavelength observations?

Disk images require post-processing

The challenge = removing starlight to see the fainter disk



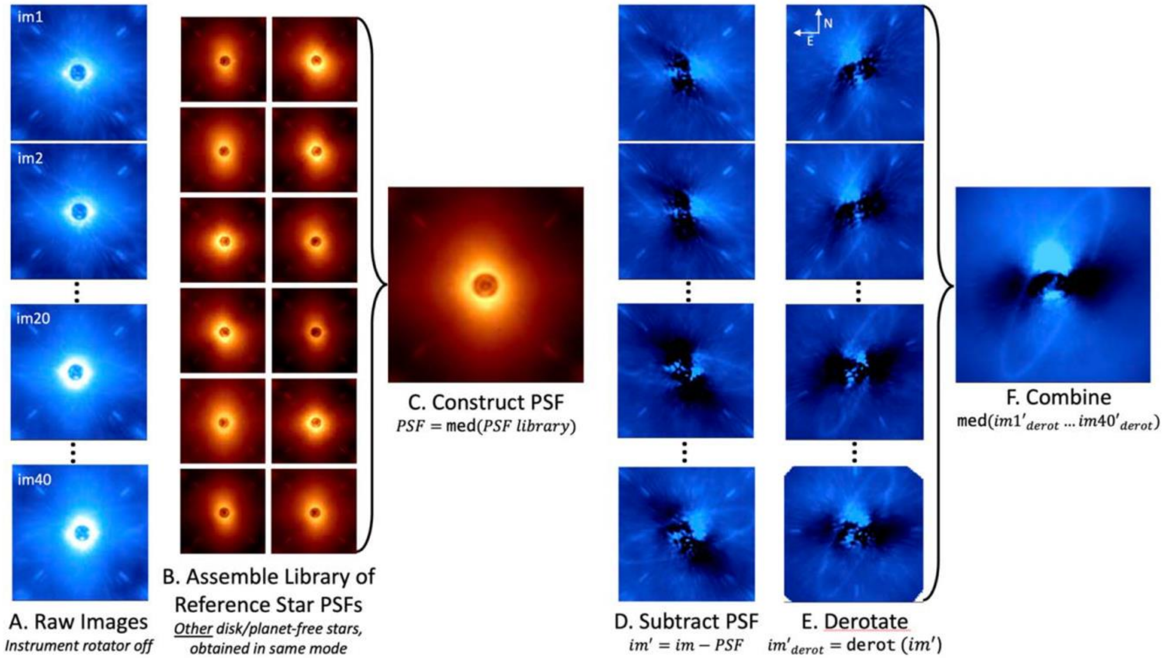
The (common) solution = PSF (point spread function) subtraction using a differential imaging technique:

Reference Differential Imaging (RDI) → Requires reference star observations

Angular Differential Imaging (ADI) → Requires on-sky rotation

Reference Differential Imaging (RDI)

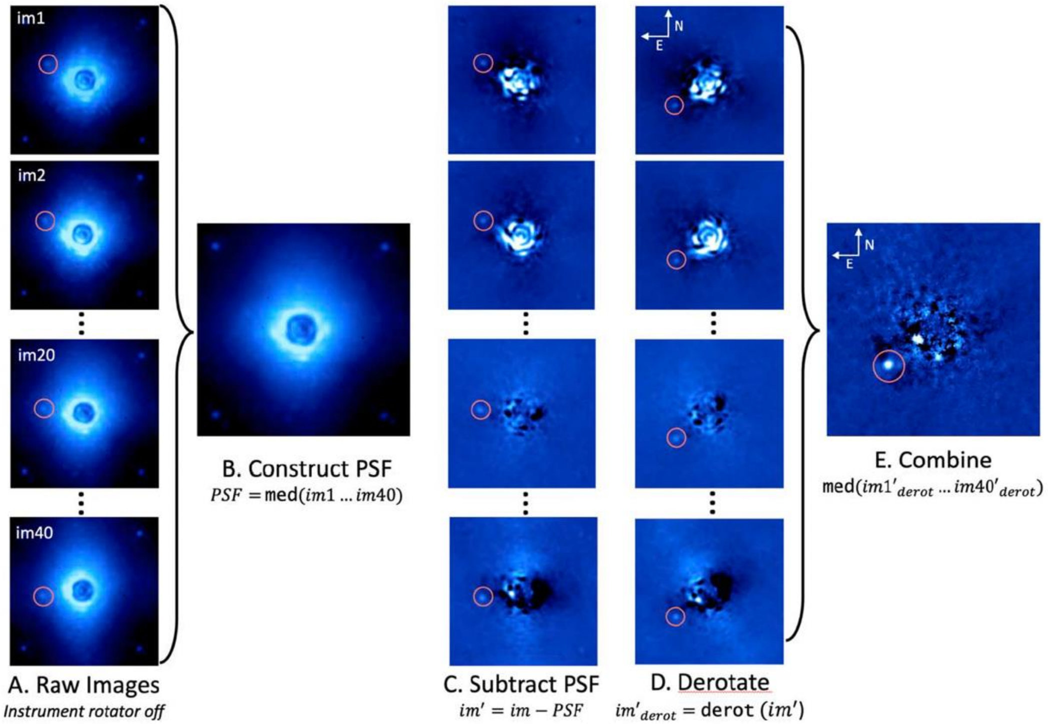
- RDI utilizes a library of images of stars other than the science target (Column B) obtained in the same observing mode.
- Generally, stars without any known disk or planet signal are chosen as reference
- PSF estimate is subtracted (Column D) to remove starlight in the image.



Credit: Follette 2023

Angular Differential Imaging (ADI)

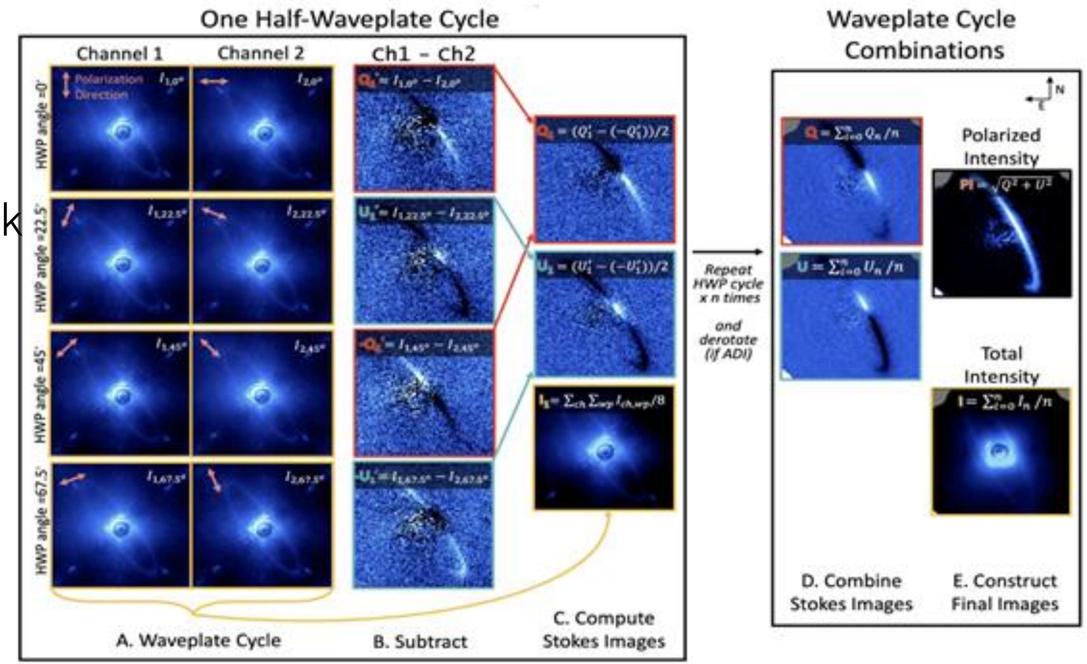
- Images are collected with the instrument rotator off.
- The instrumental PSF (including any quasi-static speckles) remains relatively stable in the instrument frame throughout the sequence, while real sources rotate with the sky



Polarized differential imaging

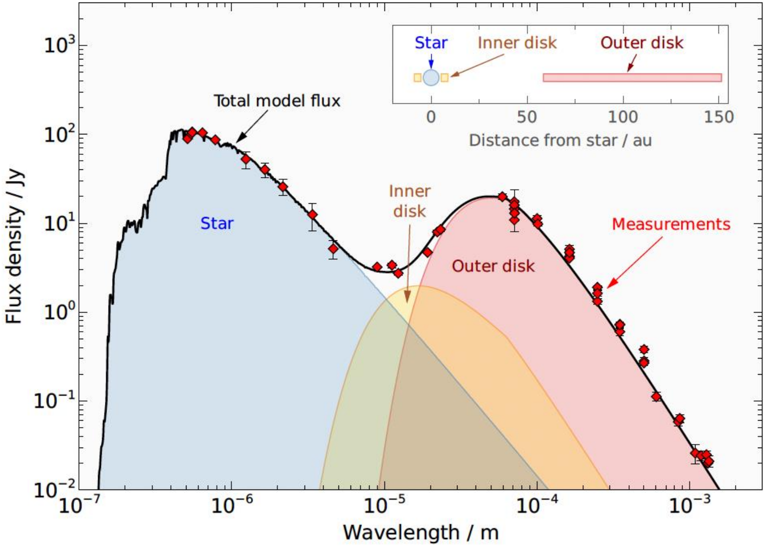
- The "Polarized Intensity" (PI) image (Column E) easily isolates the (polarized) light of the disk from the (unpolarized) starlight.

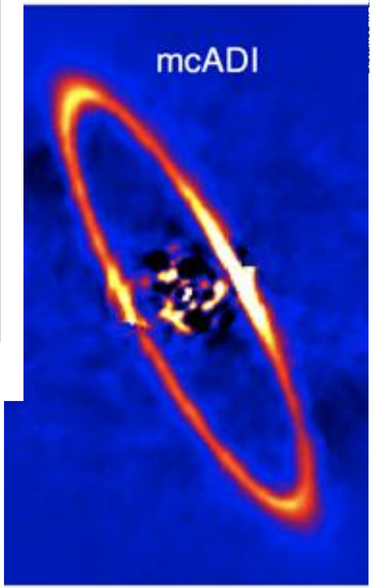
- The combined total intensity image, on the other hand (Column E, bottom), is dominated by starlight.

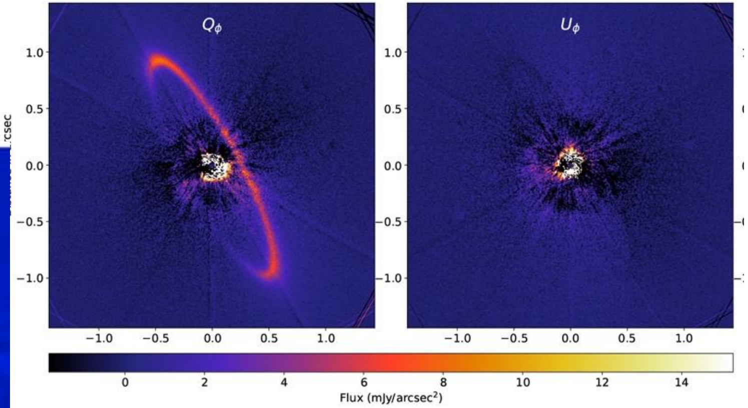


Credit: Follette 2023

SED, total intensity, polarization observations





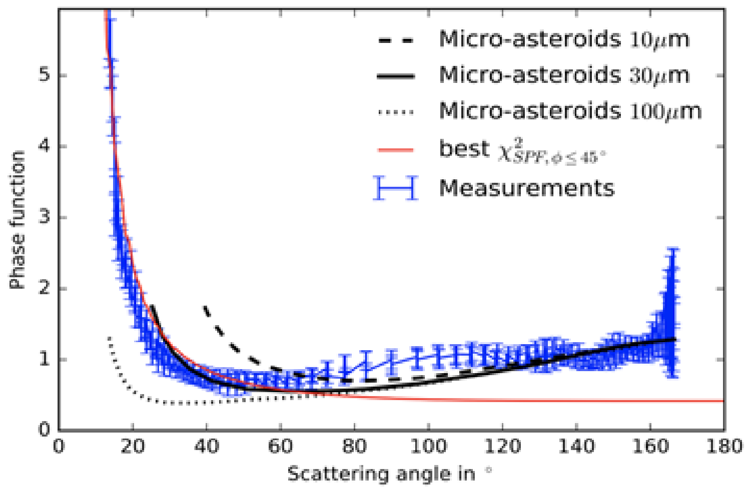


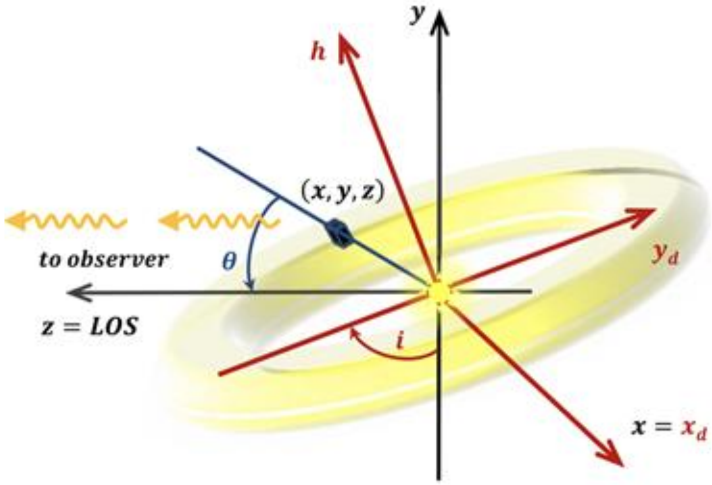
Scattering phase function (SPF)

Describes amount of light scattered by a dust grain at various scattering angles

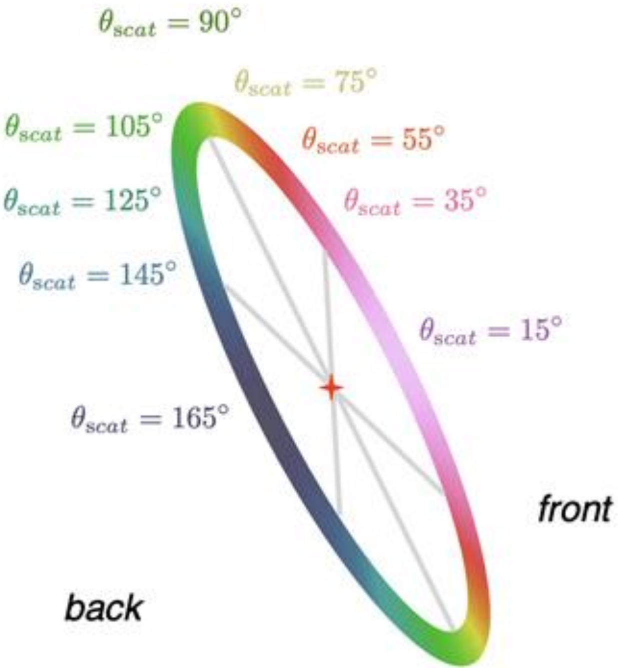
180° = back scattering

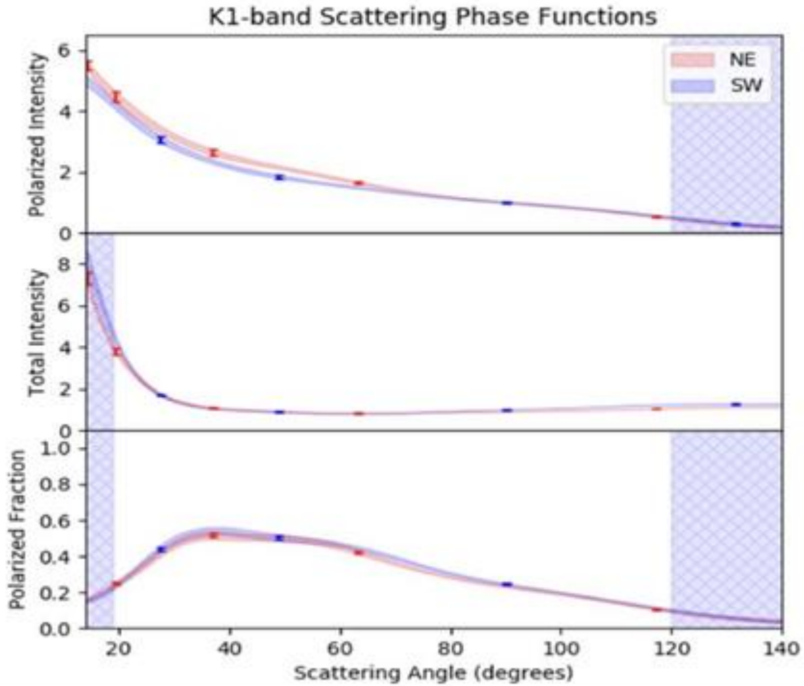
0° = forward scattering



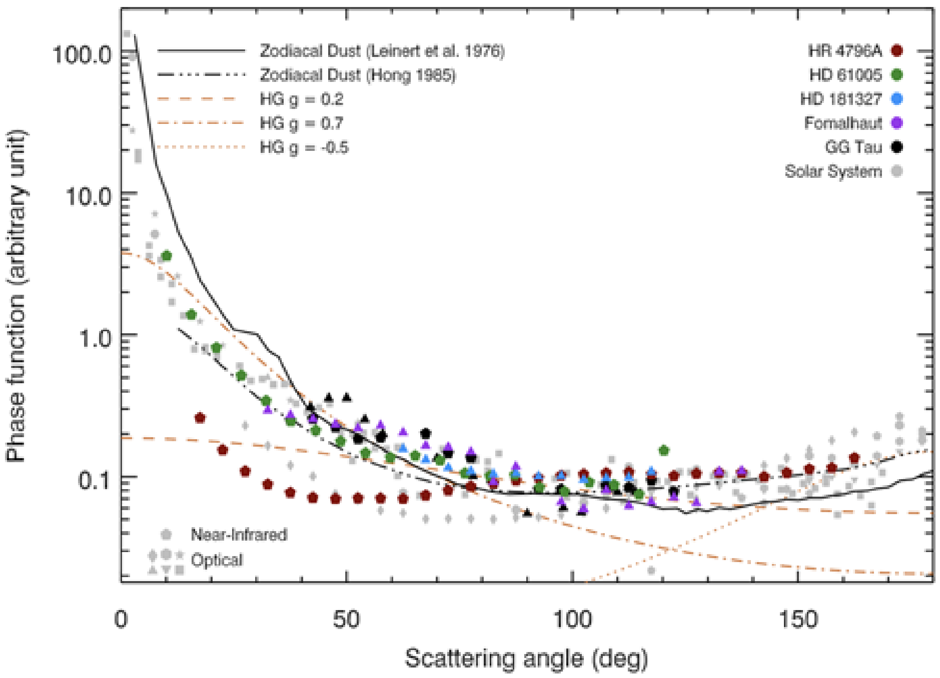


pSPF or polarization fraction





Henyey-Greenstein Functions



The Henyey-Greenstein phase function (1941):

$$p(\theta) = \frac{1}{4\pi} \frac{1 - g^2}{[1 + g^2 - 2g \cos(\theta)]^{3/2}}$$

Asymmetry Parameter:

$$g = < \cos(\boldsymbol{\theta}) >$$

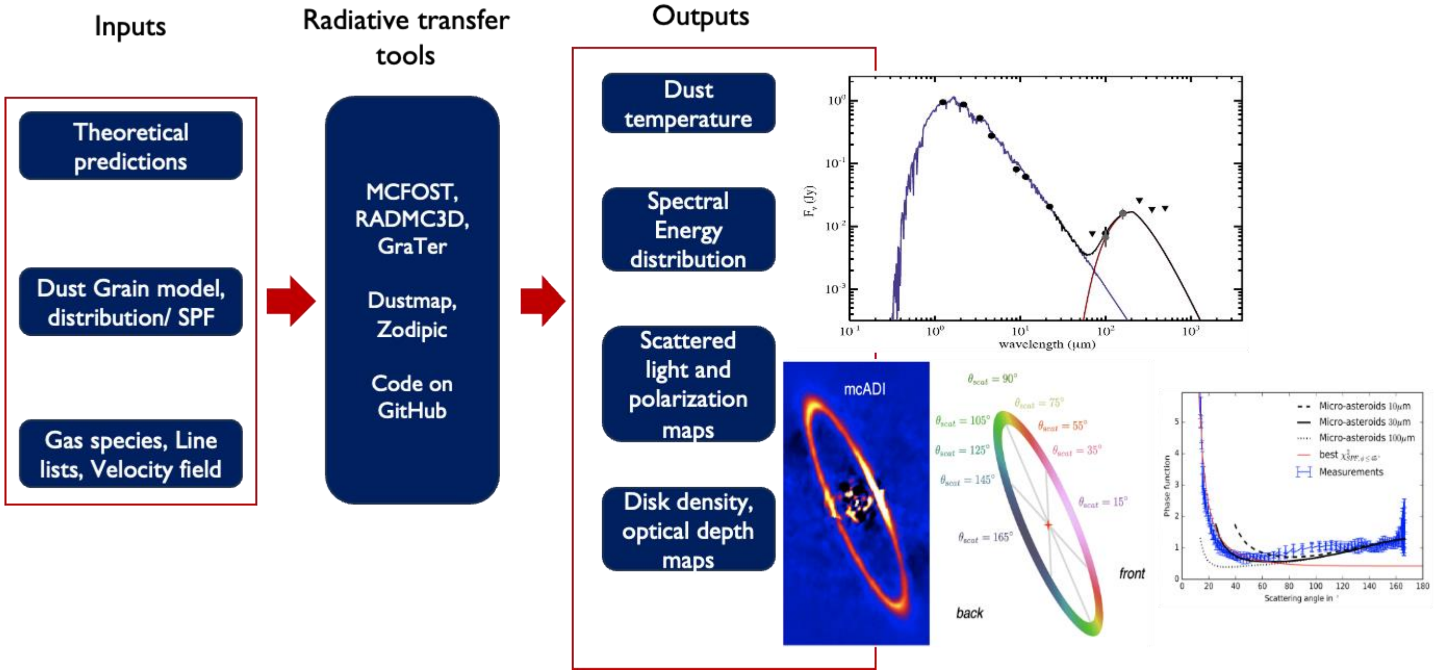
g > 0 : Forward Scattering

g < 0 : Backward Scattering

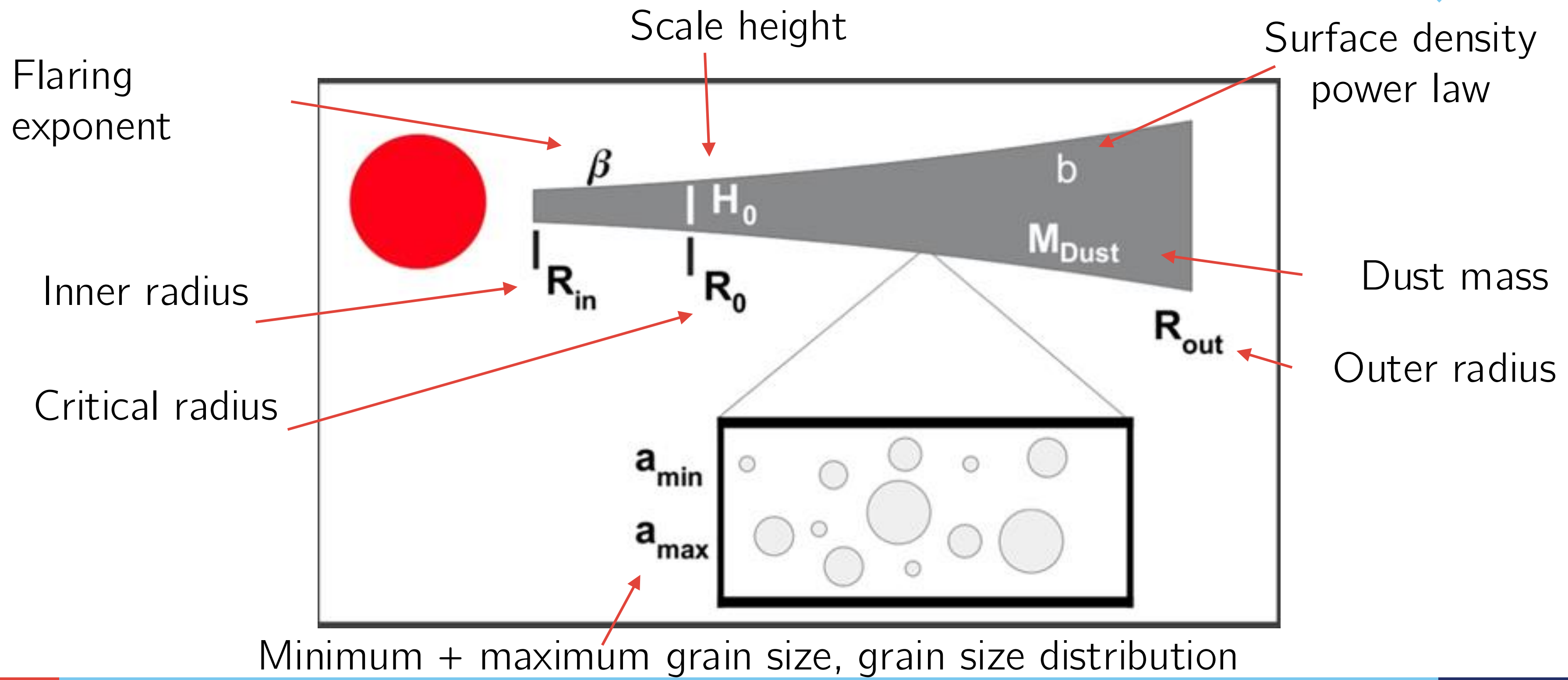
g = 0 : Isotropic Scattering

Radiative transfer modeling and disk properties

Radiative transfer describes how electromagnetic radiation is transmitted through a planetary atmosphere.



Modelling Debris disks in scattered light

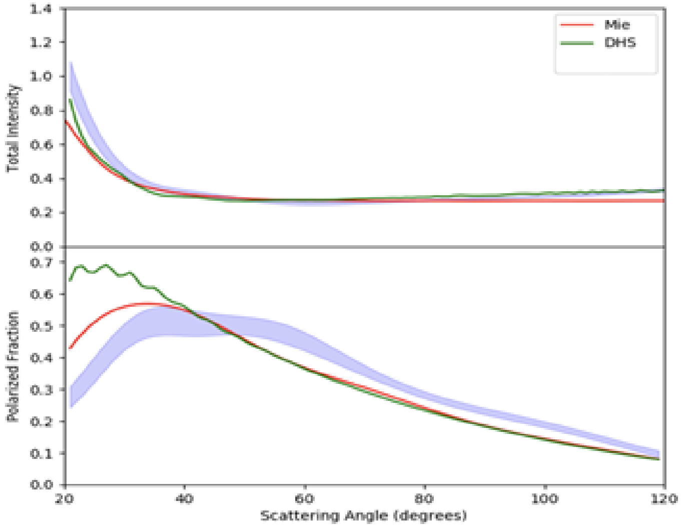


Dust scattering properties

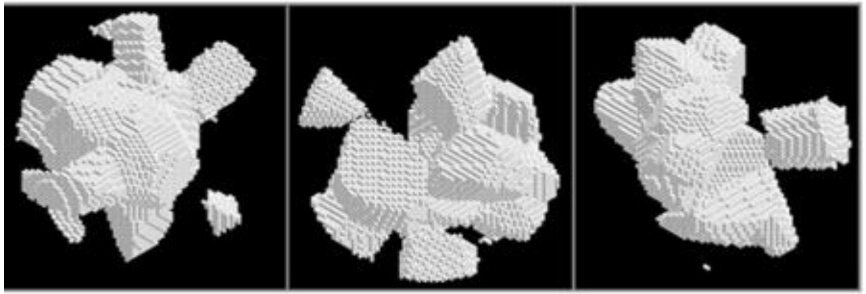
- Size (+size distribution), shape, porosity and composition dictate the material and timescales for planet formation!
- Scattering efficiency depends on grain size
- We often use Mie scattering to model dust in debris disks as solid homogenous spheres, but it's not necessarily a great assumption!

What limits our scattered light observations? Future directions

- Understanding of grain scattering theory: Observations are becoming incompatible with Mie theory/spherical grains. We need more sophisticated grain models to understand the scattering properties

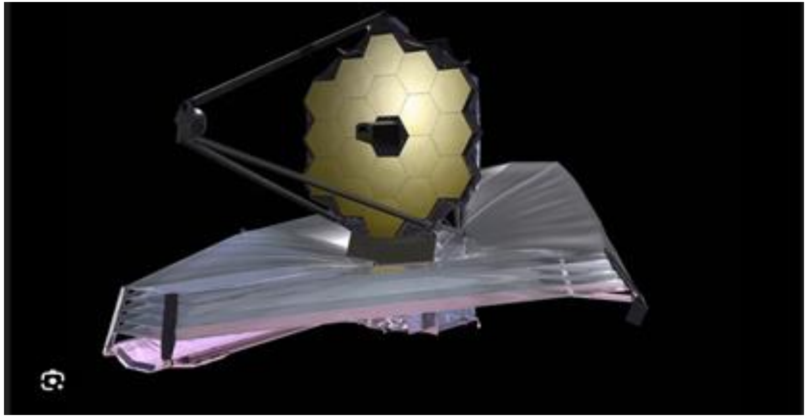


Irregular compact particles



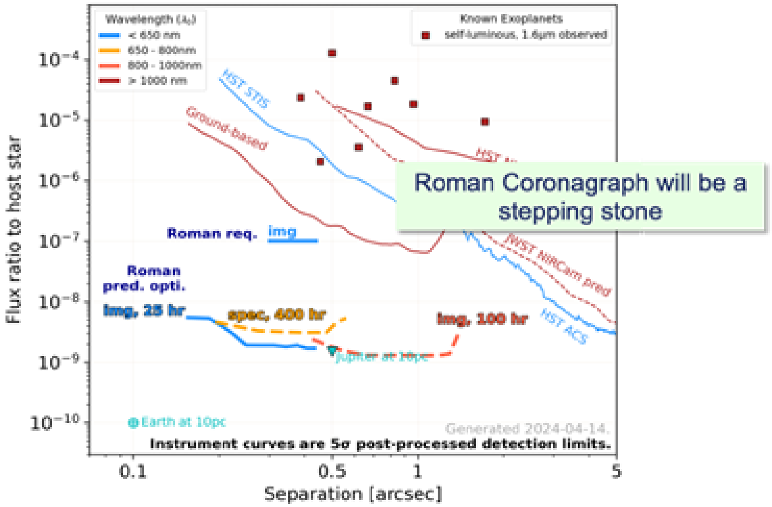
What limits our scattered light observations? Future directions

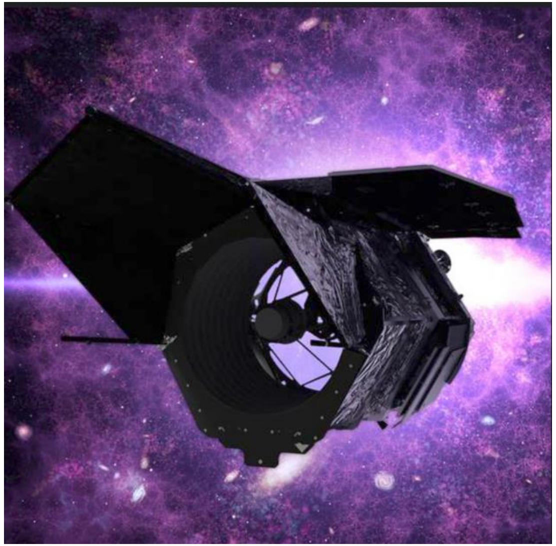
- Chemistry? – dust grain composition and optical constants
- **Laboratory measurements** of scattering dust grain Mueller matrices should inform, develop, and complement theories of dust grain scattering
- ALMA is helping to probe gas chemistry and JWST provide MIR spectroscopy probing water, silicates etc.



What limits our scattered light observations? Future directions

- Contrast limitations: Better contrast with Roman and Polarimetry!!!!!!





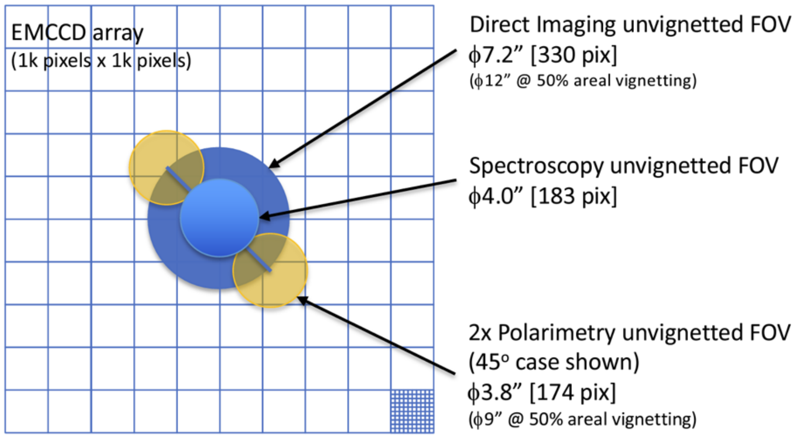
1 fully supported mode

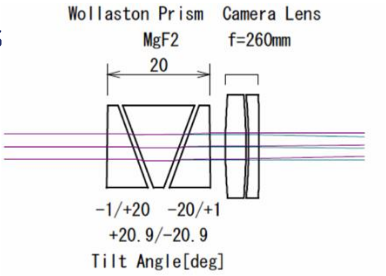
Additional "best effort" modes: spectroscopy & polarimetry

Band	λ_{center}	BW	Mode	FOV radius	FOV Coverage	Pol?	Coronagraph Mask Type	Support
1	**575 nm**	**10%**	**Narrow FOV Imaging**	**0.15" – 0.45"**	**360°**	**Y ****	**Hybrid Lyot**	**Req'd**
1	**575 nm**	10%	"Wide" FOV Imaging	0.45" – 1.4"	360°	Y	Hybrid Lyot	Best Effort
2	**660 nm**	17%	Slit + R~50 Prism Spectroscopy	0.17" – 0.52"	2 x 65°	-	Shaped Pupil	Best Effort
3	**730 nm**	17%	Slit + R~50 Prism Spectroscopy	0.18" – 0.55"	2 x 65°	-	Shaped Pupil	Best Effort
4	**825 nm**	11%	"Wide" FOV Imaging	0.45" – 1.4"	360°	Y	Shaped Pupil	Best Effort

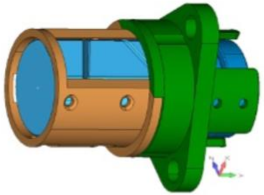
Polarimetry with Roman Coronagraph

Roman CGI field of view for different observing modes



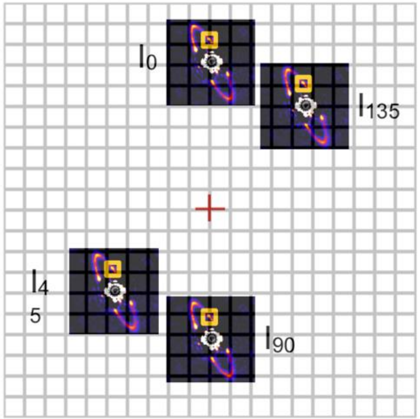


JAXA Polarization Module (2X)
Courtesy of Motohide Tamura



One of 2 identical assembled modules.
Courtesy of Tyler Groff, GSFC

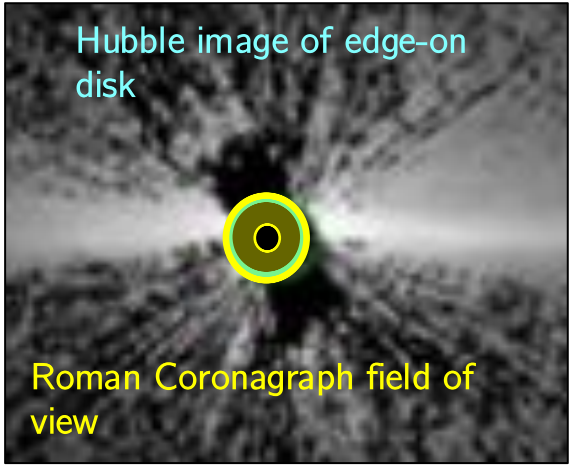
Each of the 2 polarization modules produces two orthogonally polarized images separated by 7.5" on the sky



Debris disks through Roman

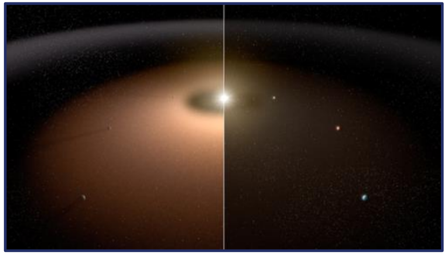
- Kuiper belt analogs
  - **SOTA:** Hubble imaging
  - **Roman**: **Observe closer to the star**

    (Mennesson+2018)



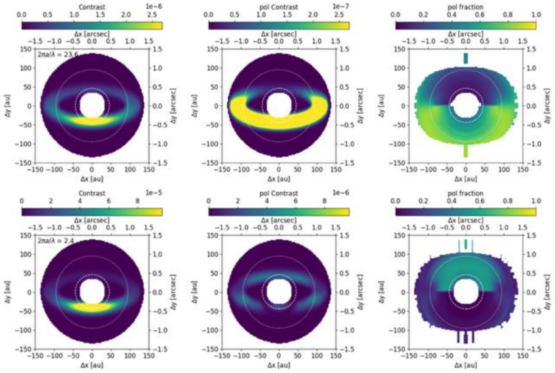
- Exozodi disks (terrestrial zone dust)
  - **SOTA:** IR excesses
  - **Roman**: ***potential* for first visible-light image**
    - Are any HWO high-priority systems too dusty?

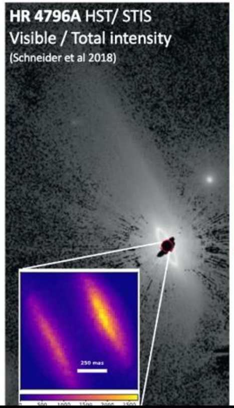
    (Douglas+2022)

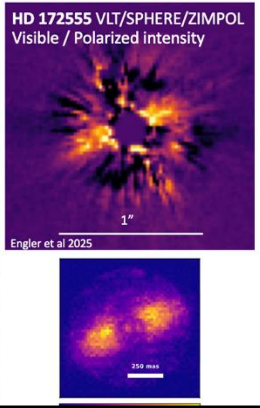


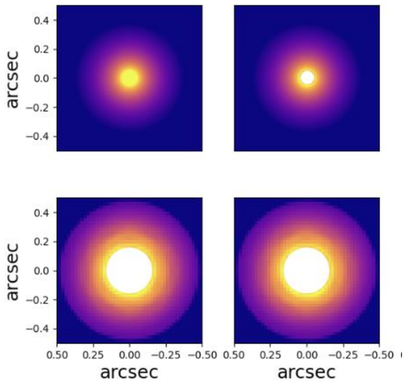
Debris disks through Roman

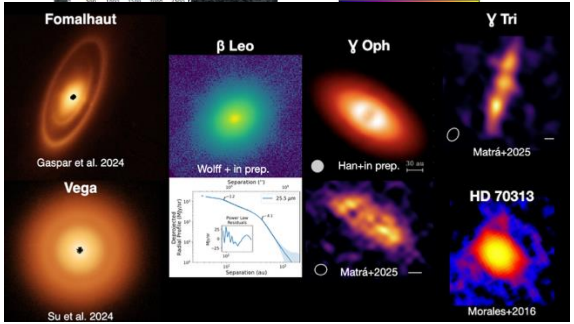
- Exozodi survey
- Dust transport survey
- Sco Cen survey
- Polarization and scattering phase function measurement

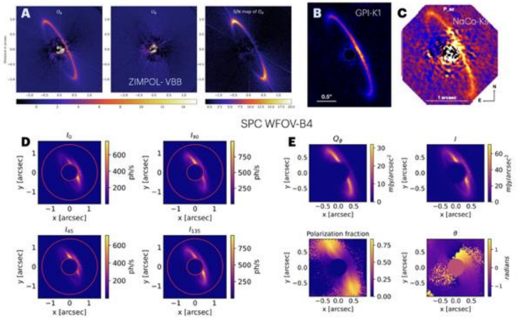






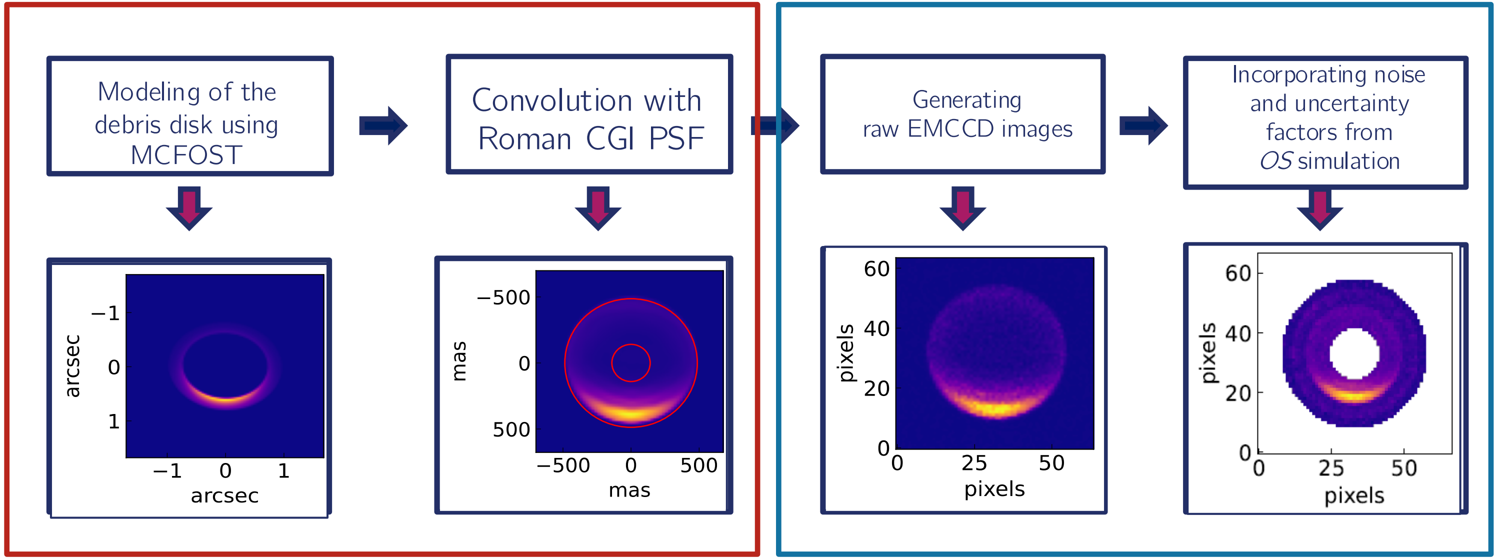






Afternoon Hands-on session

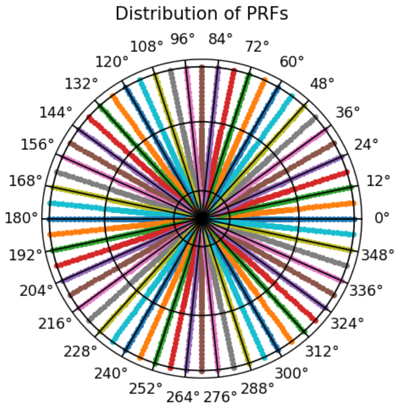
- Simulation of Disks through Roman CGI – 2-4 PM
- Time series observation sequence and perform RDI – 4.30-6.30 PM

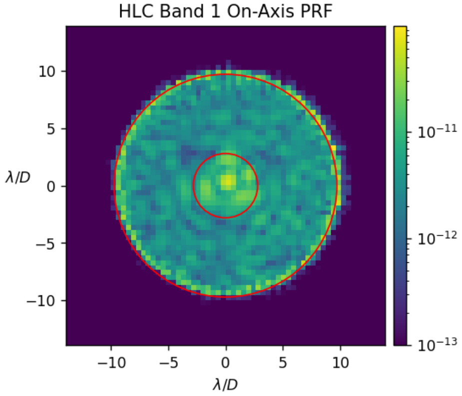


Disk Hands-on session- Simulation of Disks through Roman CGI

HLC

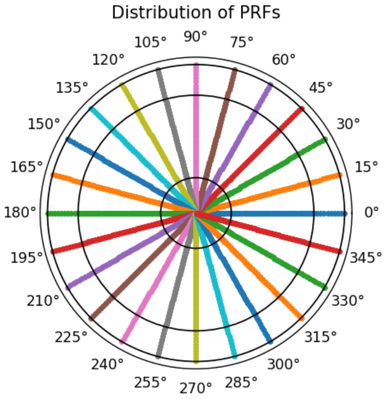
IWA = 140.52 mas and OWA = 486.83 mas

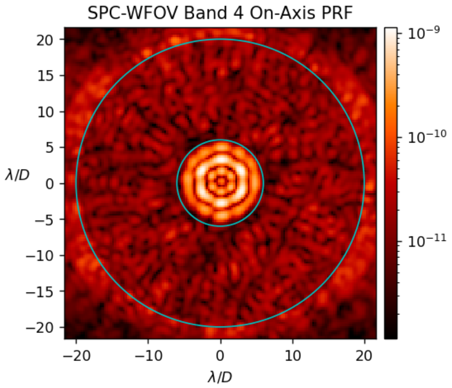




SPC

IWA=432.06 mas and OWA=1440.21 mas

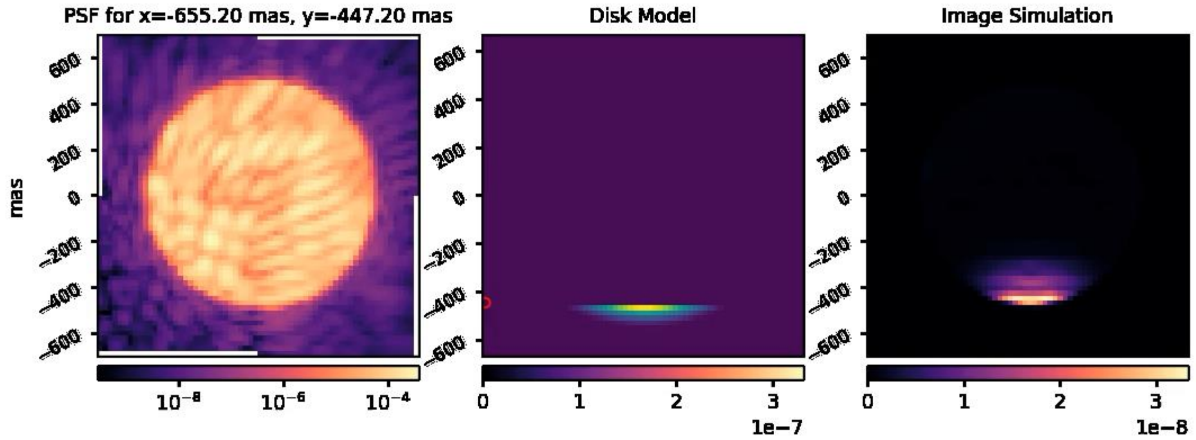




Disk Hands-on session

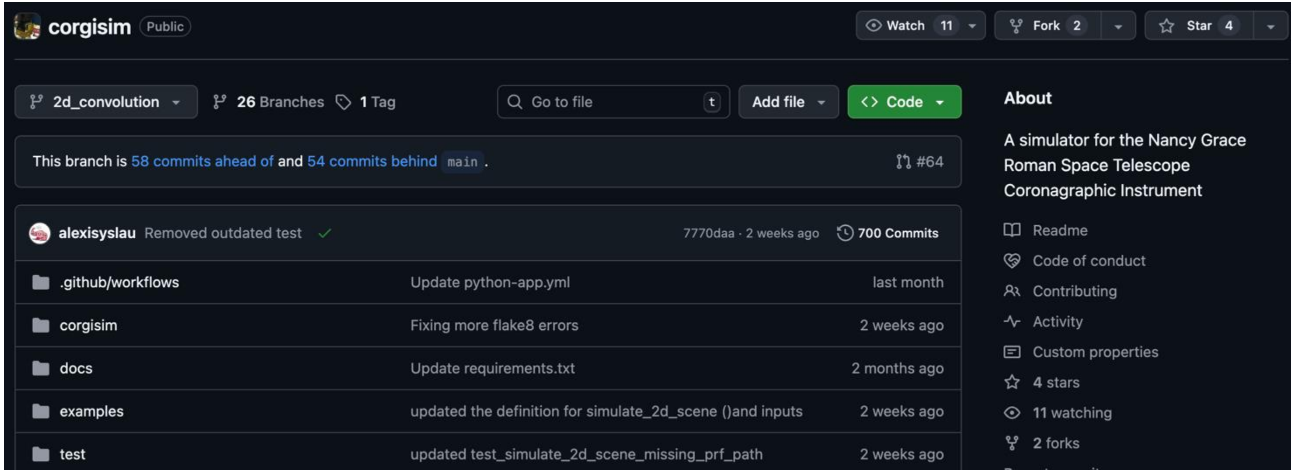
- Convolve debris disk model with Roman Coronagraph PRF – using corgisim

PRFs generated using the end-to-end CGI propagation models in romanphasec-proper



Disk Hands-on session- Simulation of Disks through Roman CGI

https://github.com/roman-corgi/corgisim/tree/2d_convolution



On your terminal

git status *On branch main*

git switch 2d_convolution

git pull

Disk Hands-on session- Simulation of Disks through Roman CGI

- Open disk_sim_demo notebook

This branch is 58 commits ahead of and 54 commits behind `main` .

Name	Last commit message
..	
disk_sim_demo.ipynb	updated the definition for simulate_2d_scene ()and inputs
polarimetry_demo.ipynb	add output to polarimetry notebook to speed up the documentation build
prf_build_demo.ipynb	Removed path definition at the top, and add explaination to output_di...
spc-wide_demo.ipynb	Merge branch 'main' into 101-website-should-have-the-tutorial-notebooks
spec_slit_prism_demo.ipynb	Merge branch 'main' into add_roll_angle_new
tutorial1_corgisim.ipynb	Merge branch 'main' into add_roll_angle_new

Disk Hands-on session- Simulation of Disks through Roman CGI

- Disk models are in HLC and SPC folder
- Off-axis prfs are in prfs folder

SPC

prfs

HLC

Disk Hands-on session- Simulation of Disks through Roman CGI

Pick a disk model – from HLC or SPC folders
If HLC – use the PRF for HLC – prf_cube_HLC_B1.fits and if SPC use prf_cube_SPC_B4.fits

2D scene inputs: disk model + PRF cube

For an extended scene (star + disk), we provide:

- a **disk model FITS** file (2D image of the disk brightness distribution), and
- a **PRF cube** (pre-computed PRF/PSF cube).

We collect these paths and scaling parameters in a dictionary (`twoD_scene_info`) that is passed into the extended-scene simulation.

```
# --- Disk path ---
main_path='/Users/polaris/Roman_winter_school/Corgisim_sims/fomalhaut/'
disk_model_path =main_path+'fomalhaut_disk_SPC_B4F.fits'  # Path to the FITS file

# --- PRF path ---
prf_path = '/Users/polaris/Roman_winter_school/Corgisim_sims/corgisim_2D_convolution/prf_cube_SPC_B4F.fits' # Path t

# --- info needed for the extended scene simulation --?-
twoD_scene_info = {
        'disk_model_path': disk_model_path,
        'prf_path': prf_path,
        'contrast': 10.0 # scaling factor for the disk model
        # 'flux unit': str, # to be added by Chen
    }
```

Disk Hands-on session- Simulation of Disks through Roman CGI

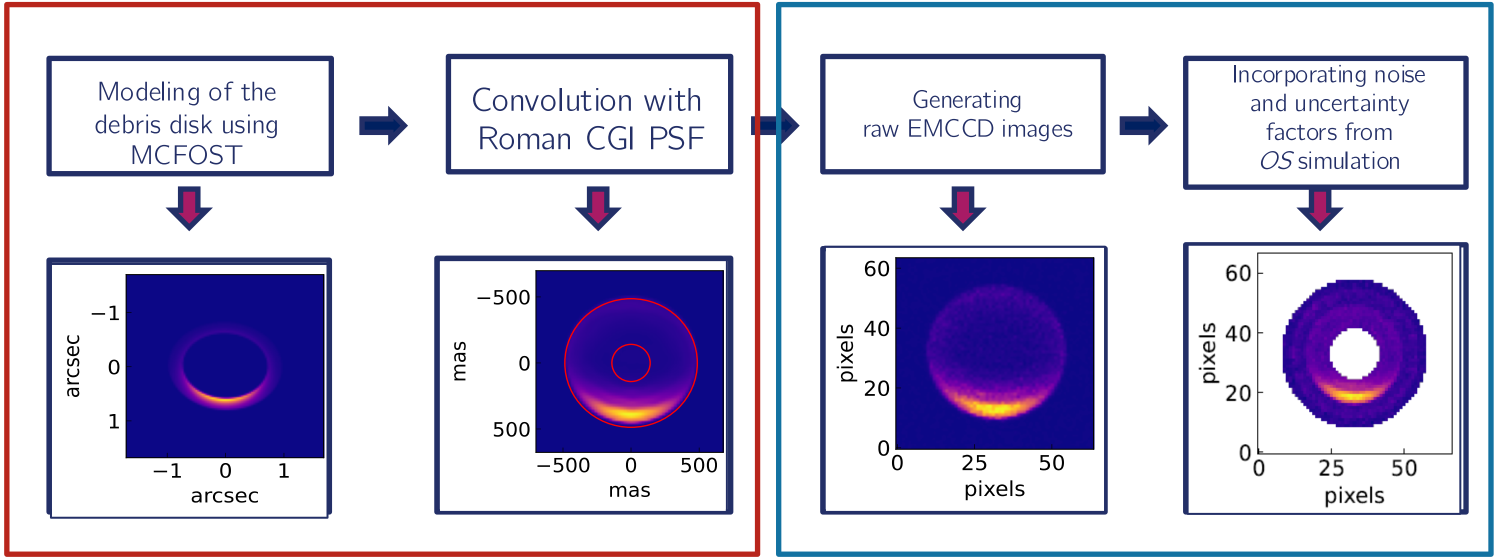
1. Follow the notebook – simulate the disk through the Coronagraph
2. Change the host star properties (look up Simbad) simulated image
3. For the same disk increase the contrast/scaling factor and see when the disk is not detectable

```
# --- Host star properties ---
Vmag = 1                                        # V-band magnitude
sptype = 'G0V'                                   # Spectral type of
ref_flag = False                                 # if the target is
host_star_properties = {'Vmag': Vmag,
                        'spectral_type': sptype,
                        'magtype': 'vegamag',
                        'ref_flag': False}
```

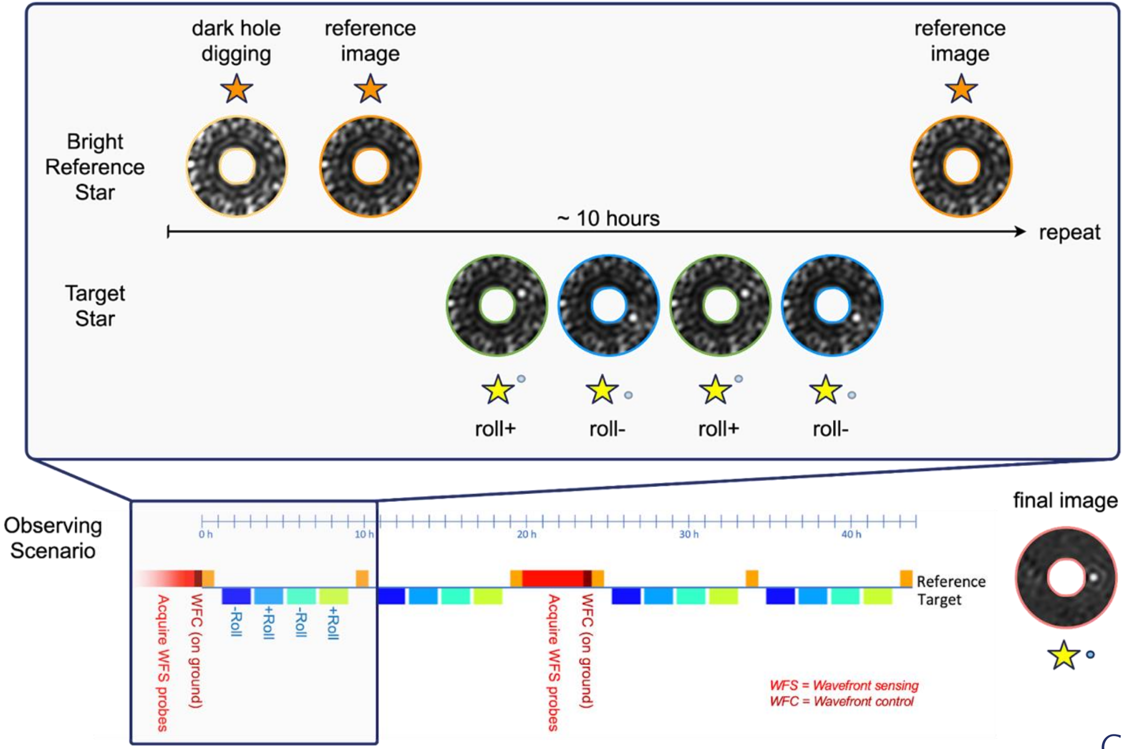
```
# --- info needed for the extended scene simulation --?-
twoD_scene_info = {
        'disk_model_path': disk_model_path,
        'prf_path': prf_path,
        'contrast': 10.0 # scaling factor for the disk model
        # 'flux unit': str, # to be added by Chen
    }
```

Afternoon Hands-on session

- Simulation of Disks through Roman CGI – 2-4 PM
- Time series observation sequence and perform RDI – 4.30-6.30 PM



Disk Hands-on session- Time series observation sequence and perform RDI



Credit: Julien Girard

Disk Hands-on session- Time series observation sequence and perform RDI

My Drive > Roman_winter_school > Os11images_with disks

Type | People | Modified | Source

Name ↓

- Time series simulations
- spc_wfov_os11_true_flux_maps.fits
- spc_wfov_os11_polx_darkhole_noiseless.fits
- spc_wfov_os11_frames_with_disk.fits
- spc_wfov_os11_frames_with_disk_muf.fits
- spc_wfov_os11_flux_maps.fits
- spc_wfov_os11_example.py
- spc_wfov_os11_batch_info.txt
- example_target_roll_plus_image.fits
- example_target_roll_minus_image.fits
- example_reference_image.fits
- example_rdi_roll_plus_image.fits
- example_rdi_roll_minus_image.fits

Adapted from an original script by John Krist, JPL

spc_wfov_os11_batch_info.txt

Batch ID	Start Hours	Star ID	Roll Deg	Sec/ Frame	EM Gain	Num Frames
0	170.000000	2	0.0	14.0	5000.0	184
100	171.350000	1	13.0	10.0	5000.0	78
101	173.350000	1	-13.0	10.0	5000.0	78
102	175.350000	1	13.0	10.0	5000.0	78
103	177.350000	1	-13.0	10.0	5000.0	78
1	179.600000	2	0.0	10.0	5000.0	159
104	180.850000	1	-13.0	10.0	5000.0	78
105	182.850000	1	13.0	10.0	5000.0	78
106	184.850000	1	-13.0	10.0	5000.0	78
107	186.850000	1	13.0	10.0	5000.0	78
2	189.100000	2	0.0	14.0	5000.0	159
3	194.000000	2	0.0	14.0	5000.0	184
108	195.350000	1	13.0	10.0	5000.0	78
109	197.350000	1	-13.0	10.0	5000.0	78
110	199.350000	1	13.0	10.0	5000.0	78
111	201.350000	1	-13.0	10.0	5000.0	78
4	203.600000	2	0.0	10.0	5000.0	159
112	204.850000	1	-13.0	10.0	5000.0	78
113	206.850000	1	13.0	10.0	5000.0	78
114	208.850000	1	-13.0	10.0	5000.0	78
115	210.850000	1	13.0	10.0	5000.0	78
5	213.100000	2	0.0	14.0	5000.0	159

Disk Hands-on session- Time series observation sequence and perform RDI

- *spc_wfov_os11_frames_with_disk.fits:* Temporal resampling spc_wfov_os11_*darkhole*.fits for 14.0 sec reference star images and 75.0 sec target star images; flux units remain e-/sec (no gain). 0.3 sec separation between frames allocated for readout time.

- *spc_wfov_os11_batch_info.txt:* Text file listing parameters corresponding to entries, in sequence, in the file spc_wfov_os11_frames_with_disk.fits for each batch: batch ID, batch start time, star ID, roll, seconds per frame, gain, and number of frames.

Time series simulations notebook - illustrating how to process images through emccd_detect and PhotonCount. Takes as inputs the files listed above, adds EMCCD noise, converts to flux maps, and then does simple RDI to create post-processed planet/disk images. You can generate your own image stacks with different gain and exposure times, scenes, etc. Note that cosmic rays are NOT added.

Disk Hands-on session- Time series observation sequence and perform RDI

1. Look at the reference star, disk images at different rolls

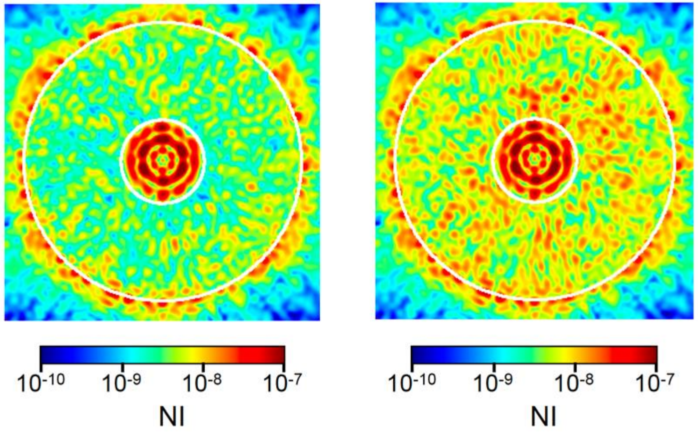
spc_wfov_os11_frames_with_disk.fits	R me
spc_wfov_os11_frames_with_disk_muf.fits	R me

2. Run the notebook without MUFs and see the reduced disk images
3. Run the notebook with MUFs and see the reduced images

Disk Hands-on session- Time series observation sequence and perform RDI

Current Modeling Uncertainty Factors (MUFs)

- STOP model (MUF always included)
  - 2x structural deformation MUF
    - increases beam shear, wavefront error drift by 2x
- Dynamic (vibration) model (MUFs always included)
  - Frequency-dependent jitter MUFs
    - 3x (<20 Hz), 4.27x (40-100 Hz), 8x (>100 Hz)
- Diffraction model (only when MUF is indicated)
  - Degraded dark hole contrast (uses the DM patterns from a few EFC iterations prior to the final solution)
  - Higher polarization-dependent aberrations
    - 1.5x higher aberrations
    - 2x higher contrast sensitivity to them
  - Higher pointing error sensitivity
    - 2x in contrast sensitivity (obtained by multiplying jitter by 1.6x)



Extra slides

Disk model parameters

The updated surface density profile $\eta(r,z)$ follows a smoothly connected two power-law structure described in more detail in Augereau et al. (1999) and given in Equation 1:

$$\eta(r,z) \propto R(r)Z(r,z) \quad (1)$$

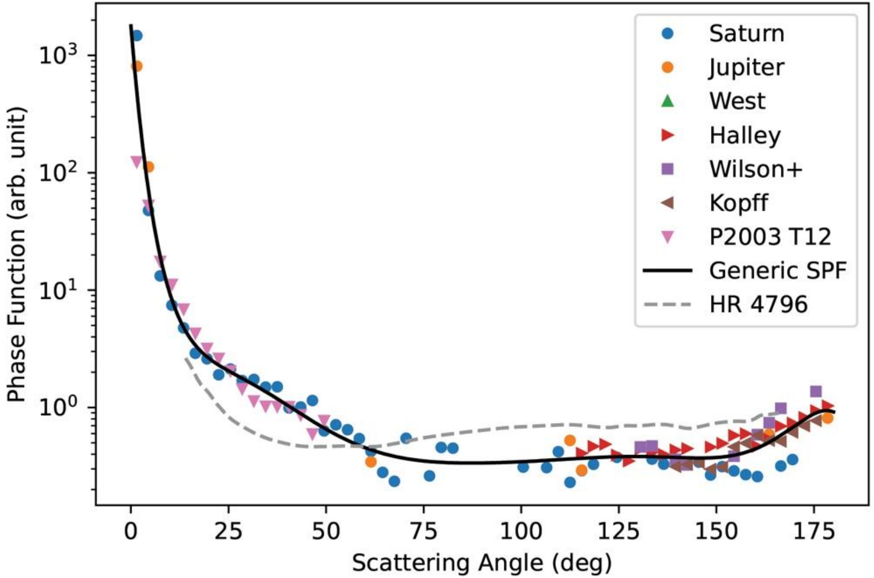
where $R(r)$ is given as:

$$R(r) \propto \left\{ \left(\frac{r}{R_C}\right)^{-2\alpha_{in}} + \left(\frac{r}{R_C}\right)^{-2\alpha_{out}} \right\}^{-\frac{1}{2}} \quad (2)$$

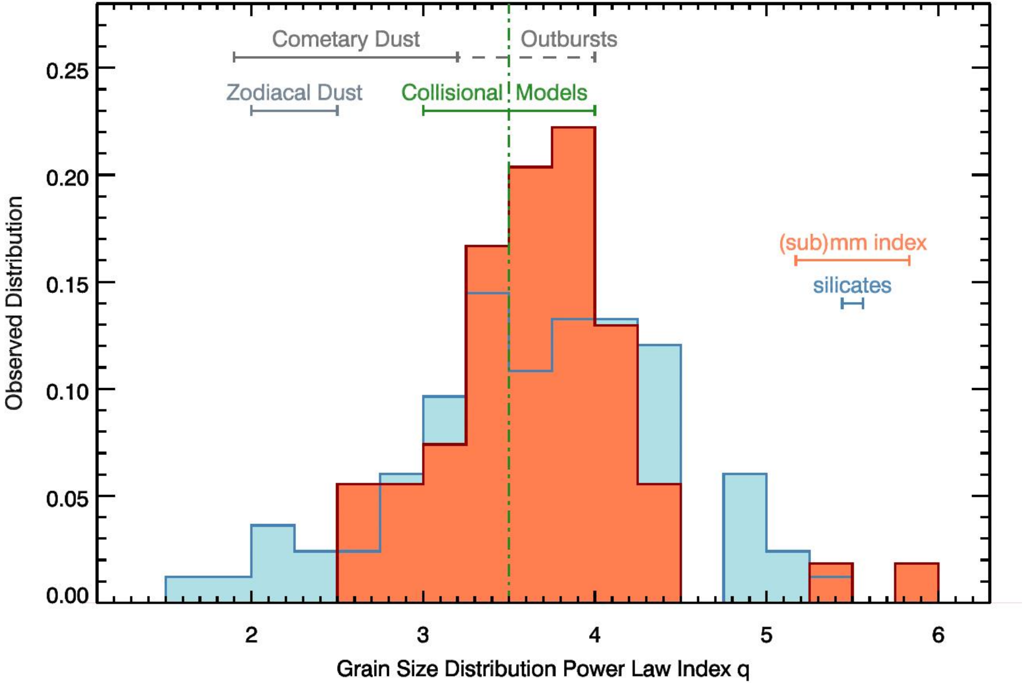
where r is the radial distance from the host star and R_C is the critical radius where a transition between two power law density regimes occurs. The indices of these power law density regimes are given as $\alpha_{in} > 0$ and $\alpha_{out} < 0$ for the inner and outer regions of the disk respectively. $Z(r,z)$ is given as

$$Z(r,z) \propto \exp\left(-\left(\frac{|z|}{h(r)}\right)^{\gamma_{vert}}\right) \quad (3)$$

where z is the distance from the disk midplane, γ_{vert} dictates the shape of the vertical density distribution, and $h(r)$ is the height above the disk midplane as a function of r. The Augereau et al. (1999) dust density profile was selected as it is more commonly used in dust density distribution analyses and therefore facilitates more consistent comparisons of our results to previous studies. For our analysis, we set $\gamma_{vert} = 2$ for a Gaussian vertical profile and $h(r)$ is given by $a_r \times r$ where a_r is the constant aspect ratio h/r, assuming a "bow-tie" shape for every disk. Both inner (R_{in}) and outer (R_{out}) cutoff radii define where the dust density $\eta(r,z)$ is treated as zero; only R_{in} is treated as a free parameter. All disks except for HD 110058 have evidence of extensive halo



Power law index



Extra Slides