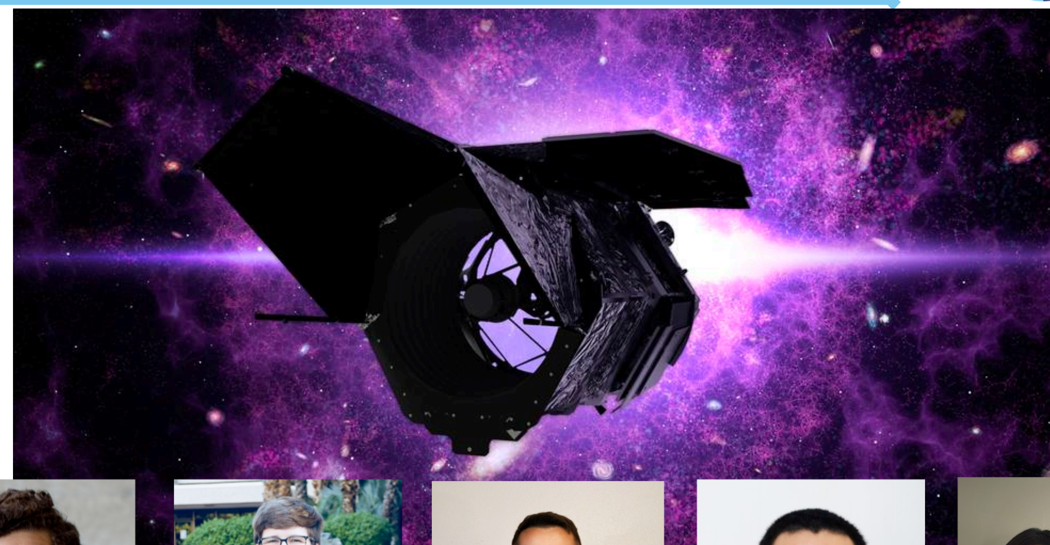
Prospects for polarimetry, exozodiacal,and debris disk observations with the Roman Space Telescope Coronagraph Instrument

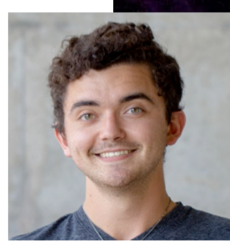
John Debes (STScI, debes@stsci.edu, @JohnDebes), Ewan Douglas (UArizona Steward Observatory, douglase@arizona.edu)
and Bertrand Mennesson (Jet Propulsion laboratory, California Institute of Technology)

With contributions from Jaren Ashcraft,
Bin Ren, Kian Milani, & Vanessa Bailey

The Disks Working Group: A Team Effort

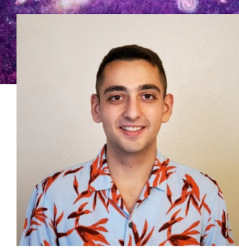
- Thanks to support from the SITs and the Project
- Thanks to support from early career researchers!



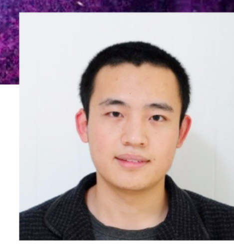


Jaren Ashcraft
(UA PhD Student)

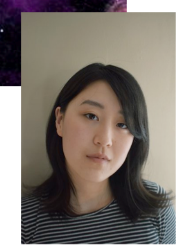
Erin Maier
(UA PhD Student)



Kian Milani
(UA PhD Student)



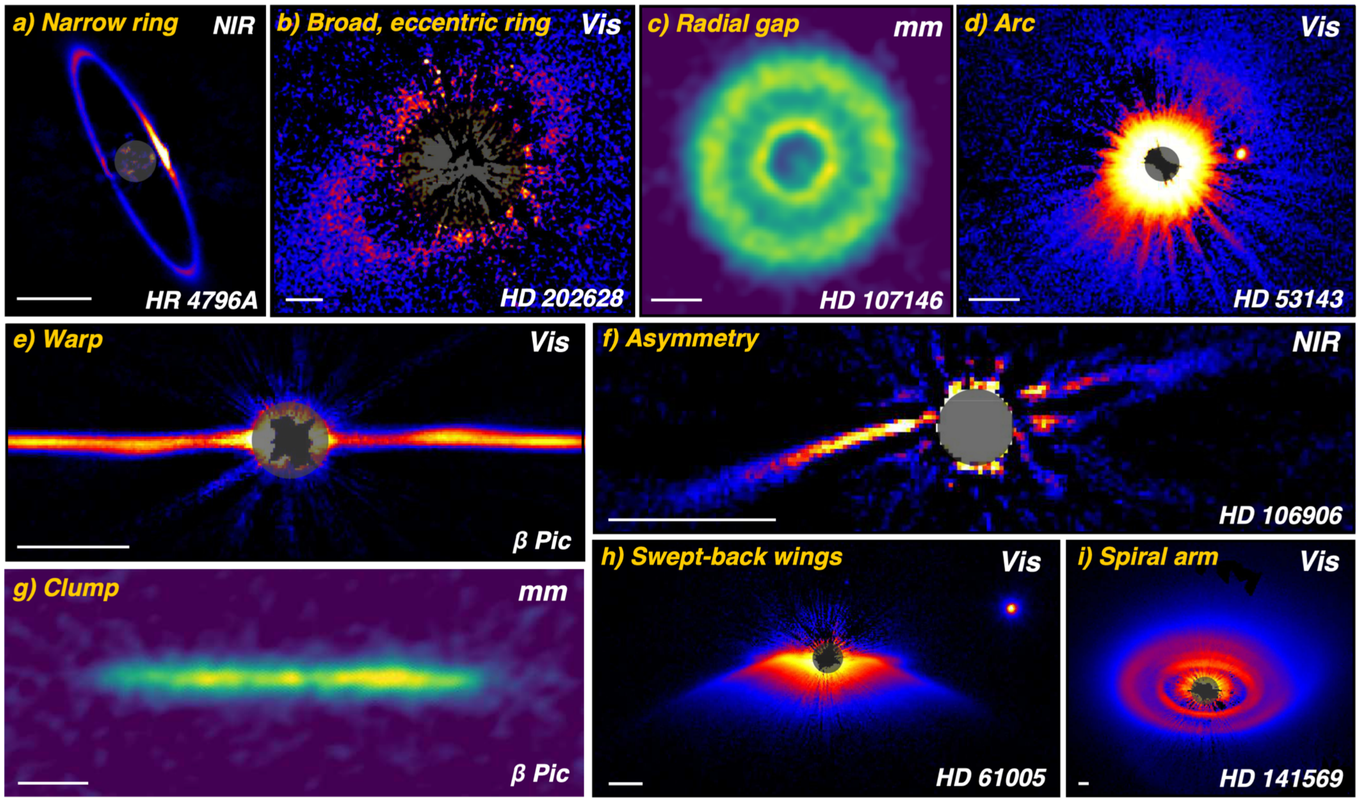
Bin Ren
(Caltech Postdoc)



Yinzi Xin
(Caltech
PhD Student)

Early Career Contributors to this work

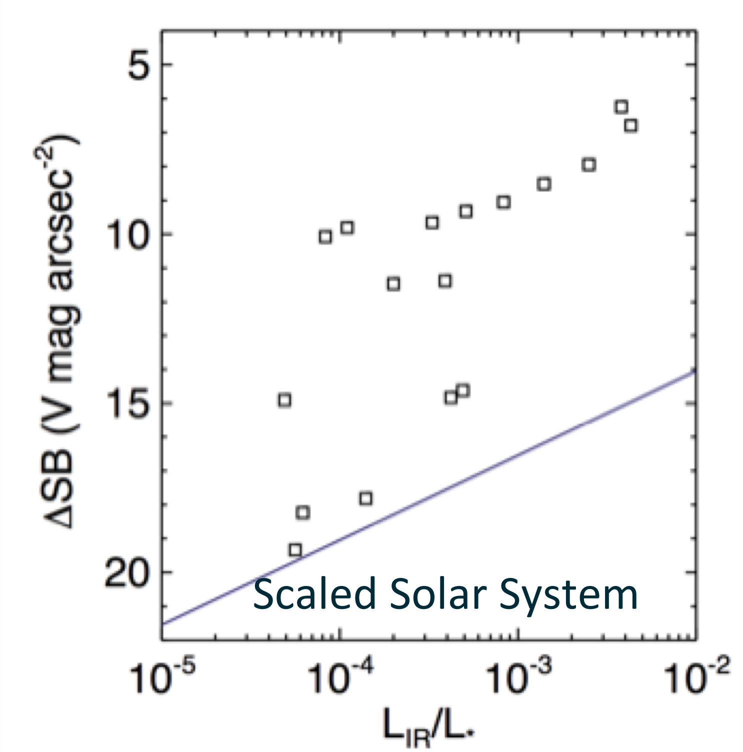
Vast Diversity in Known Disk Architectures

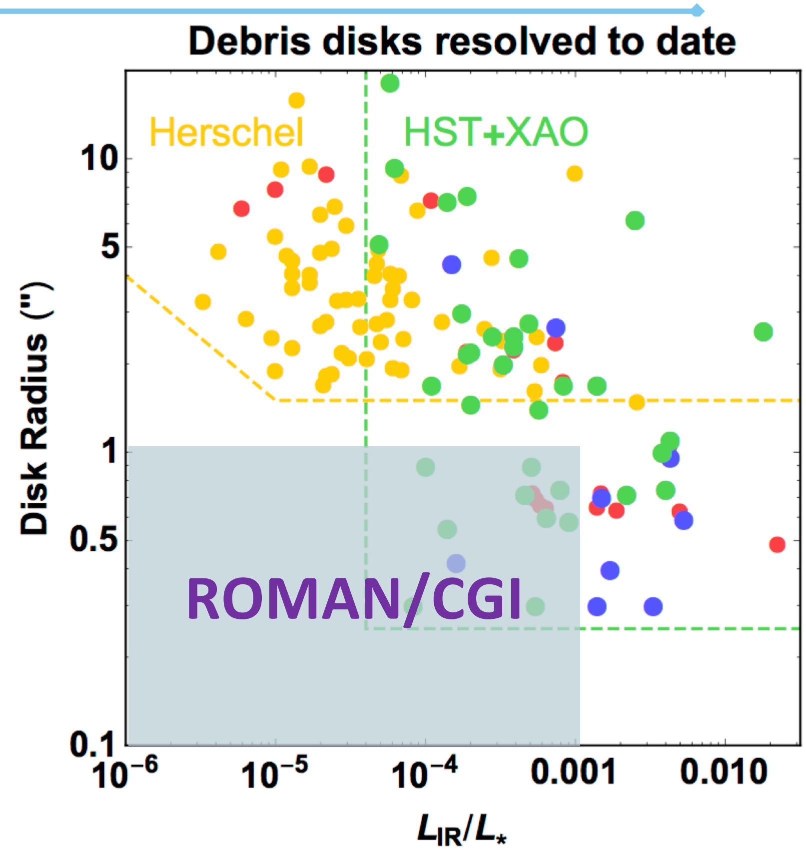


$L_{IR}/L_{*} \sim 10^{-3}$

Hughes, A. M. 2018. http://arxiv.org/abs/1802.04313.

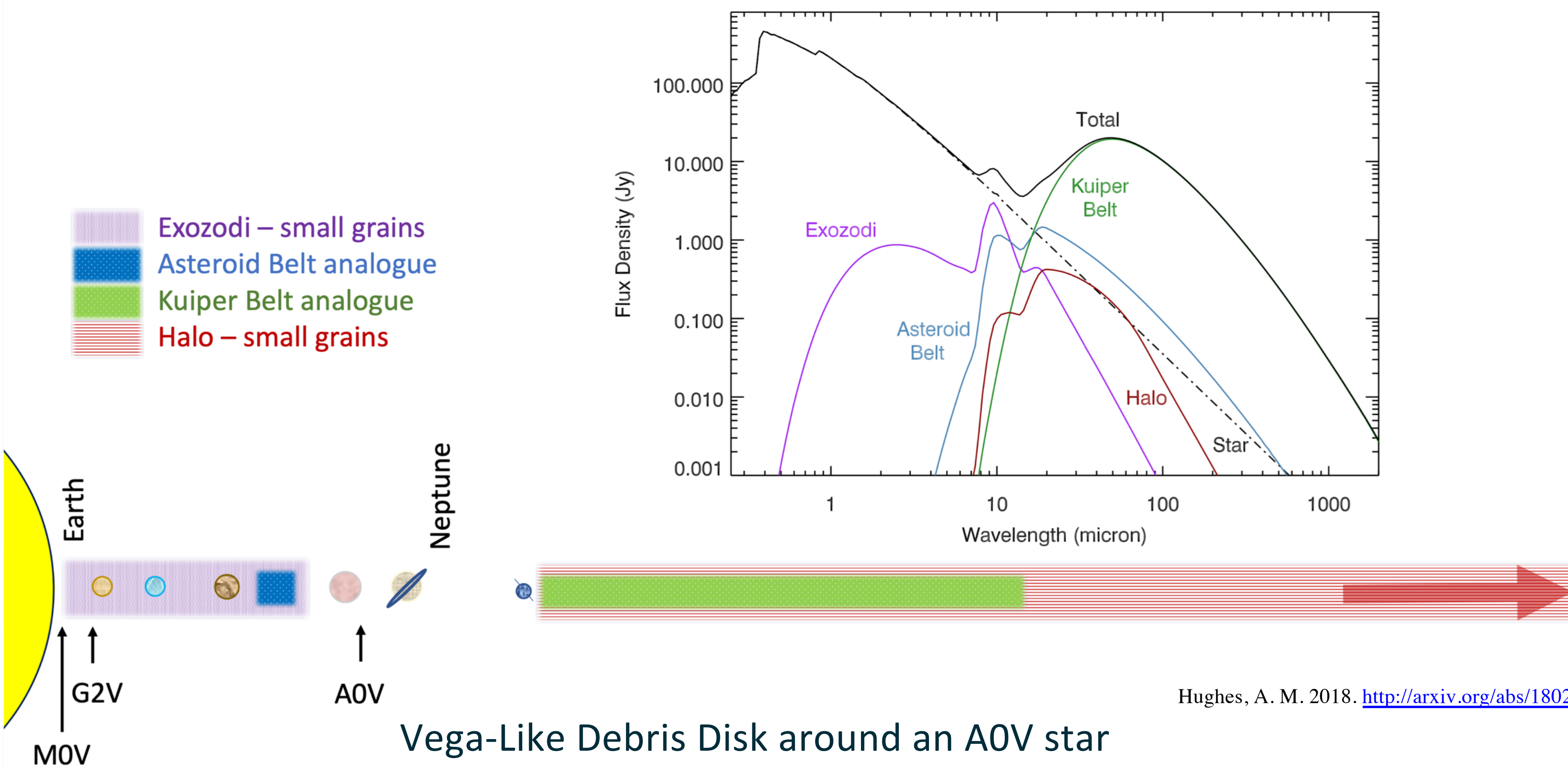
Known Cold Debris Disks





Debes et al. 2019, BAAS, 51, 566

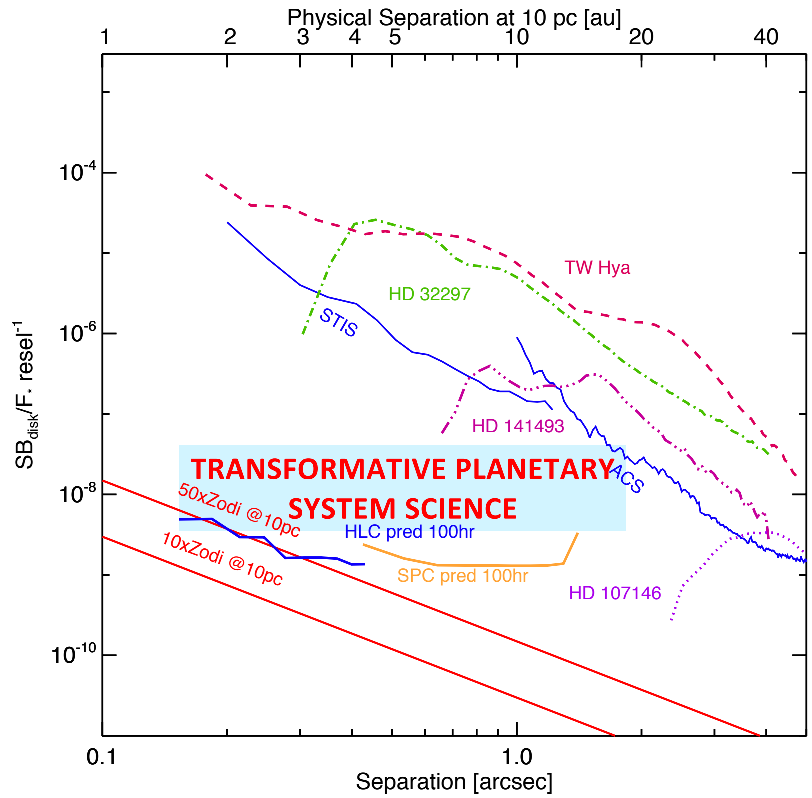
Cold Debris Disk Architecture/Solar System Architecture



Hughes, A. M. 2018. http://arxiv.org/abs/1802.04313.

Vega-Like Debris Disk around an A0V star

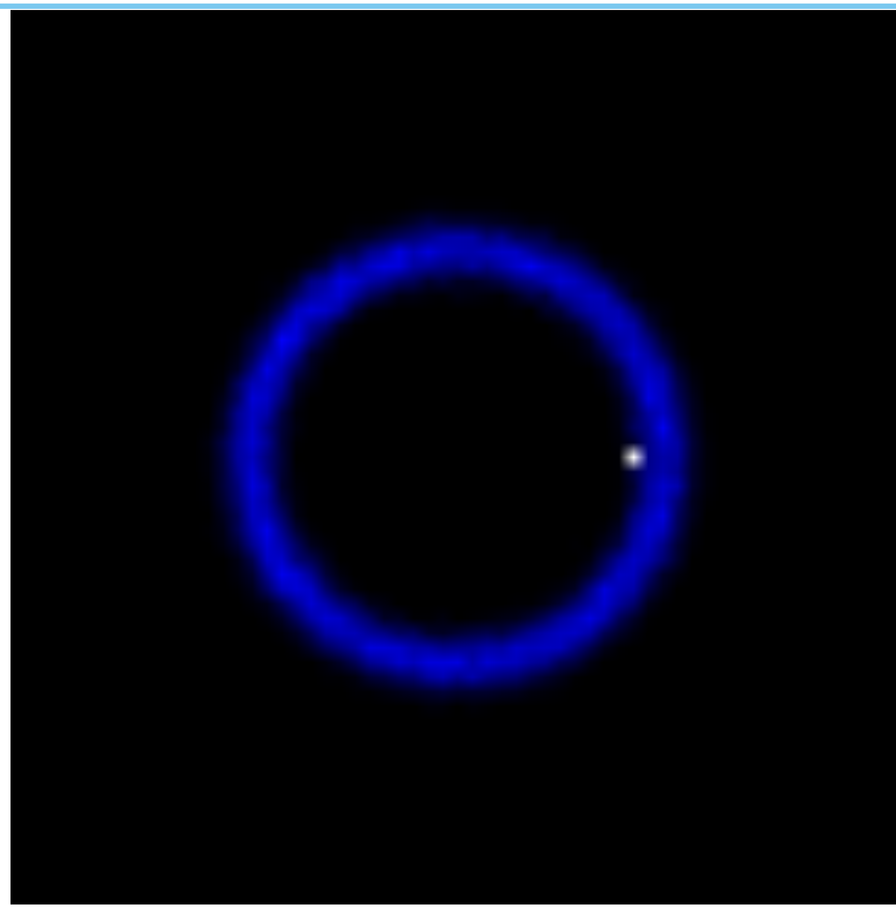
Surface brightness sensitivity



J. Debes (STScI)

Why disk morphology can matter

V=5 star
3e-9 Companion at 2.5 AU
5 Zodi disk at 3 AU



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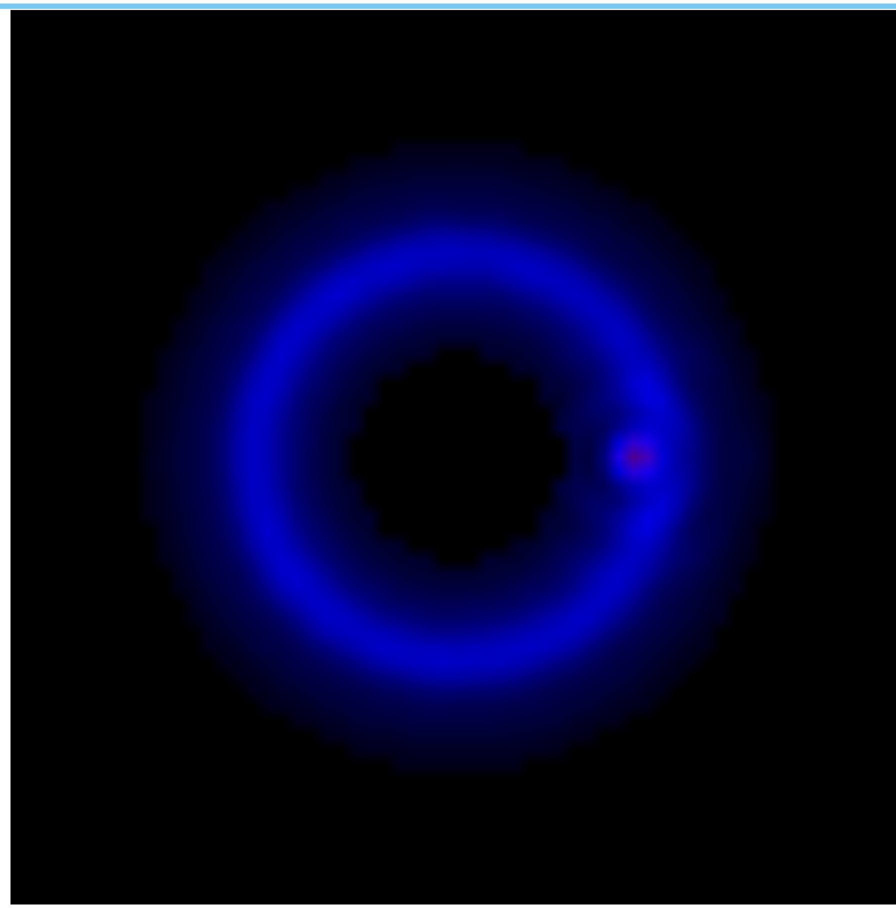
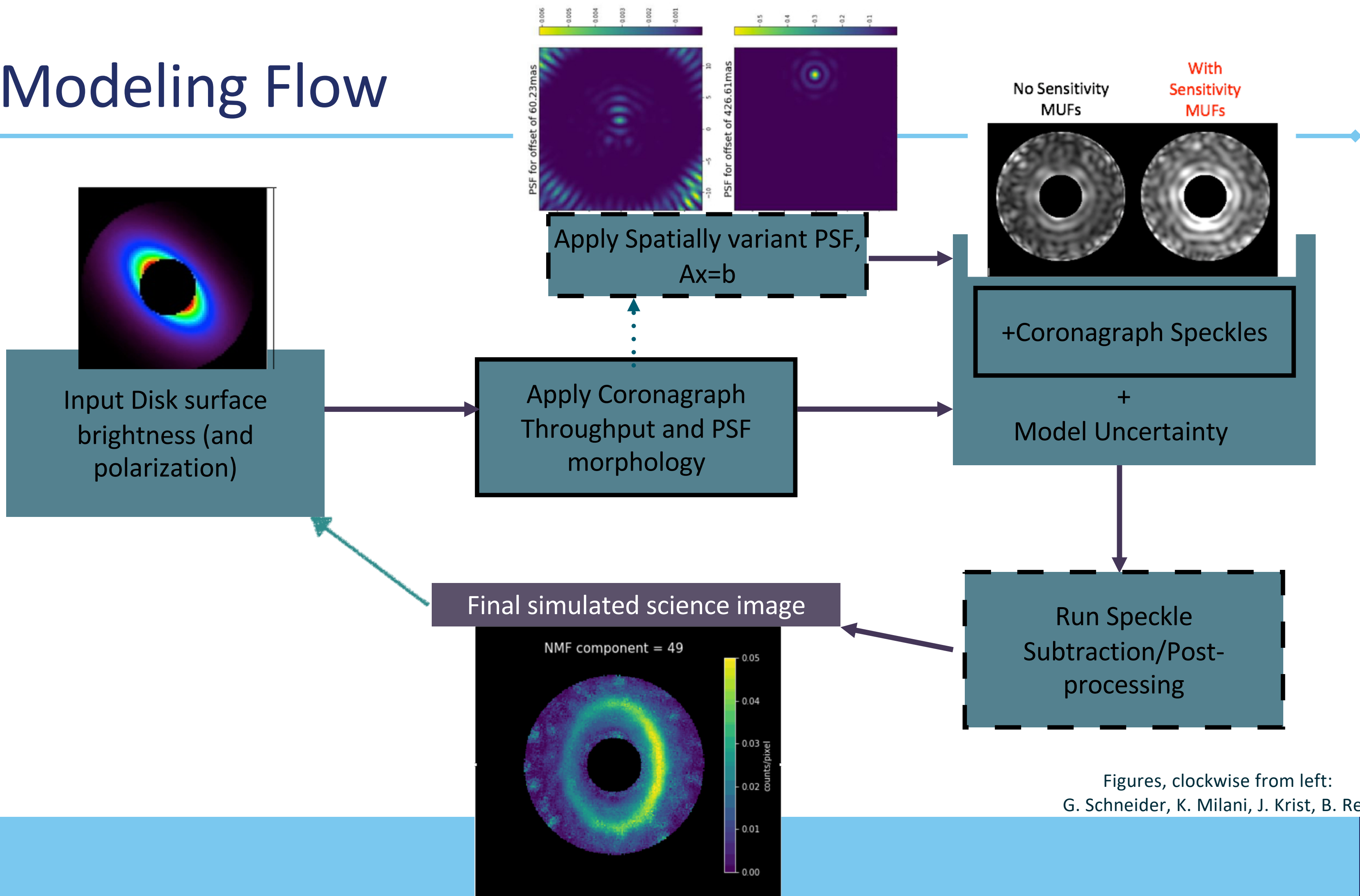


Preparing for CGI via disk modeling

- Assist in defining requirements for CGI
- Simple model disk grids convolved with field dependent mask PSFs
- Assess observing implications of field dependent PSF
  - Quantifying "effective throughput" for extended sources
  - Quantifying post processing gains for extended sources
  - Quantifying noise from dust "under the mask" or exterior to dark hole
- Predict performance for extended sources during Tech Demonstration
- Assess scientific returns for known debris disks with filters/polarization
- Assess performance without dark hole over full field of view
- Assess ultimate sensitivity of CGI to extended sources (i.e. exo-zodis)

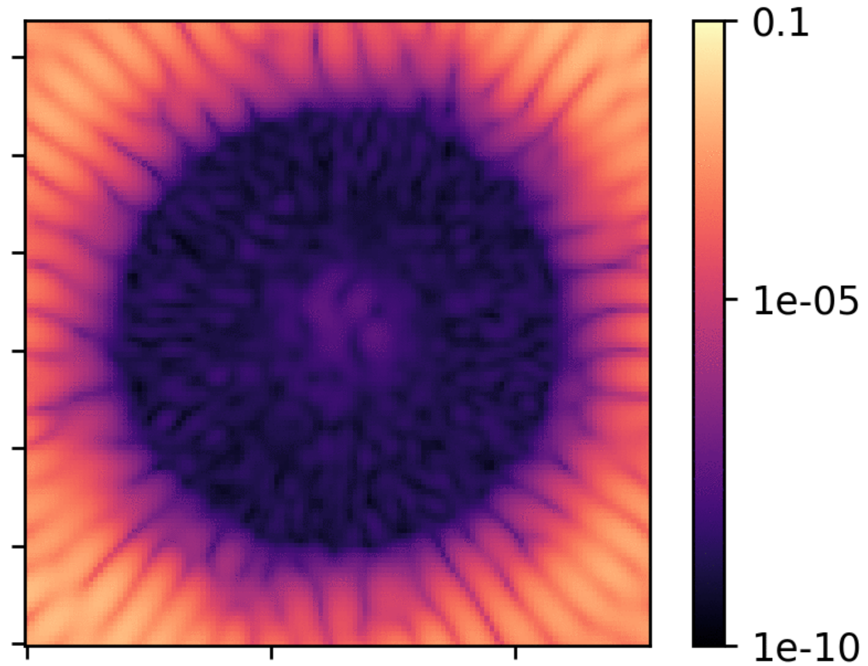
See my Lyot 2019 talk for more: https://stsci.box.com/v/Roman-CGI-DISKS

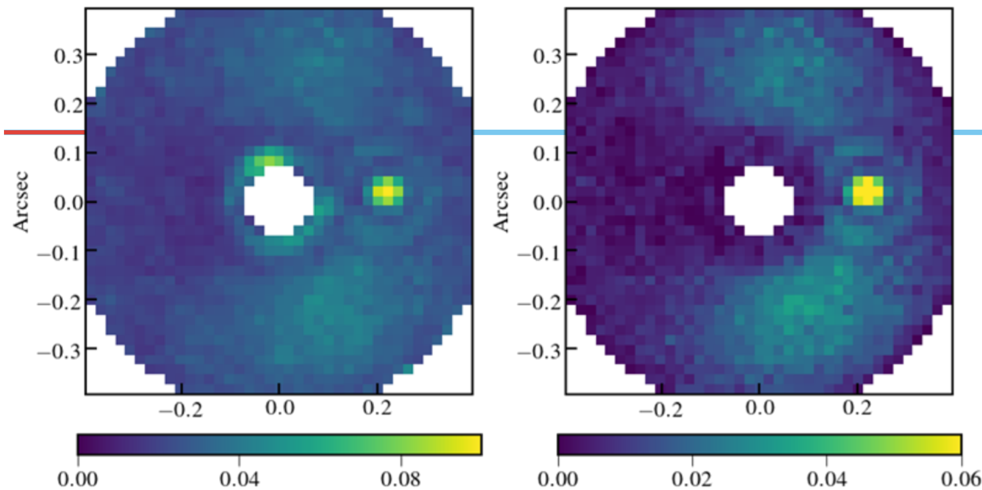
Modeling Flow



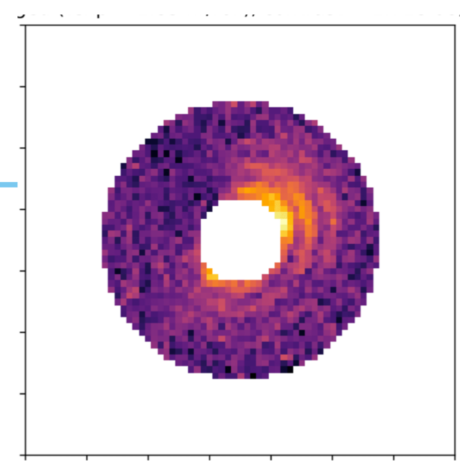
Figures, clockwise from left:
G. Schneider, K. Milani, J. Krist, B. Ren

PSF has complex dependency on angle

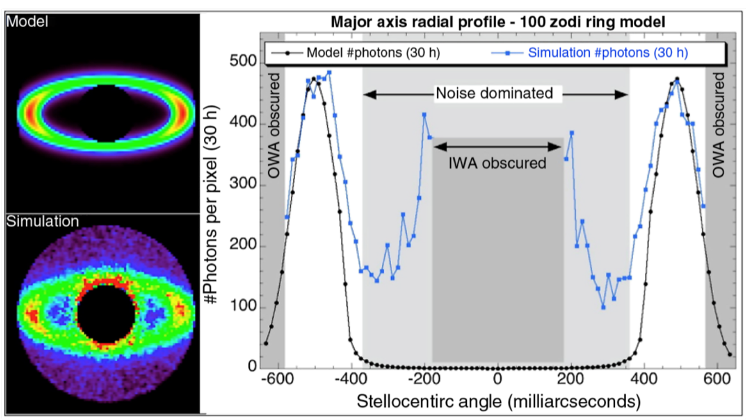




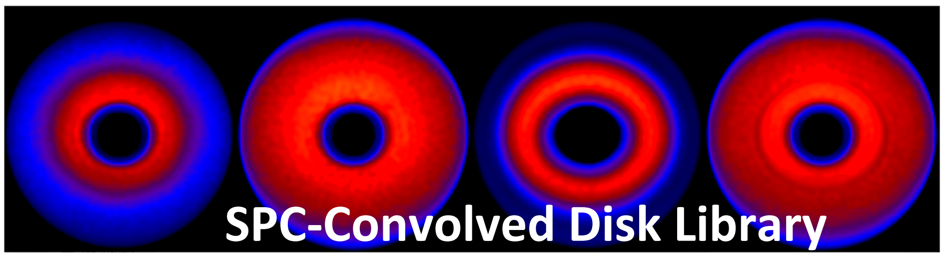
M. Rizzo, Haystacks Team (PI: Aki Roberge).
https://asd.gsfc.nasa.gov/projects/haystacks/haystacks.html



Christine Chen WFIRST Preparatory Science: 61 Vir, eps Eri, HD 10647, HD 69830, HD 95086, HR 8799, and tau Ceti, also include hypothetical ice/giant planets,
https://roman.ipac.caltech.edu/sims/Chen_WPS.html



Schneider & Hines 2016

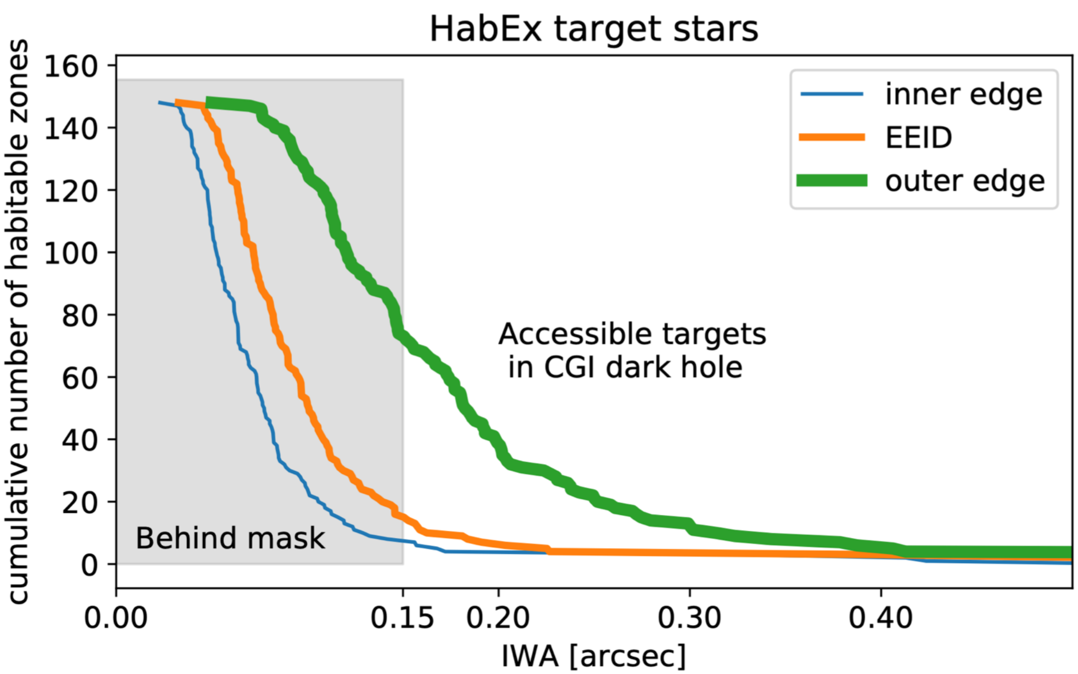


John Debes, https://roman.ipac.caltech.edu/sims/Circumstellar_Disk_Sims.html

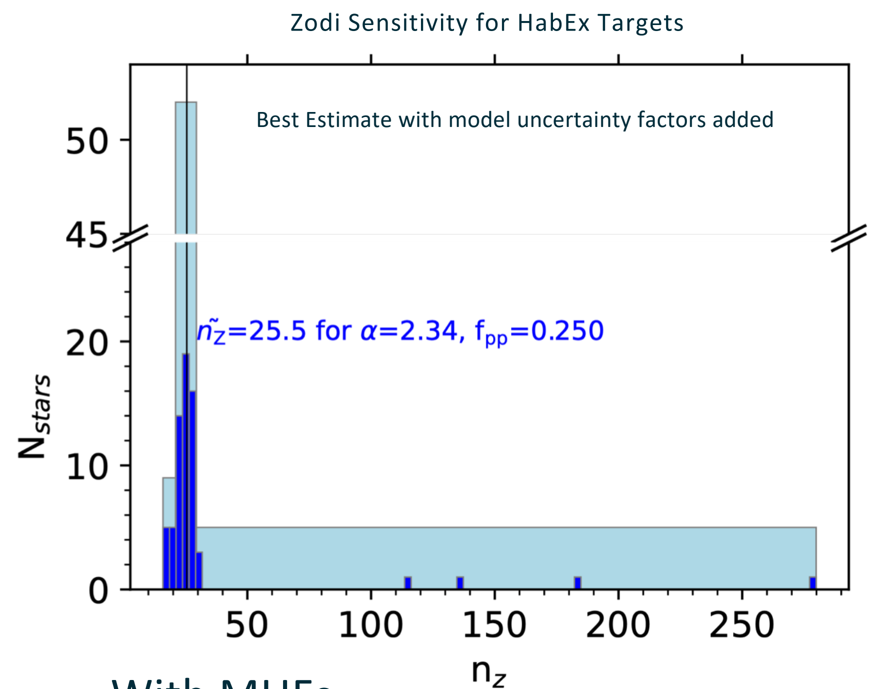
ZODIACAL LIGHT

VLT, Yuri Beletsky (ESO), http://apod.nasa.gov/apod/ap110509.html

Analytic EXOZODI Sensitivity



74 stars have part of HZ available

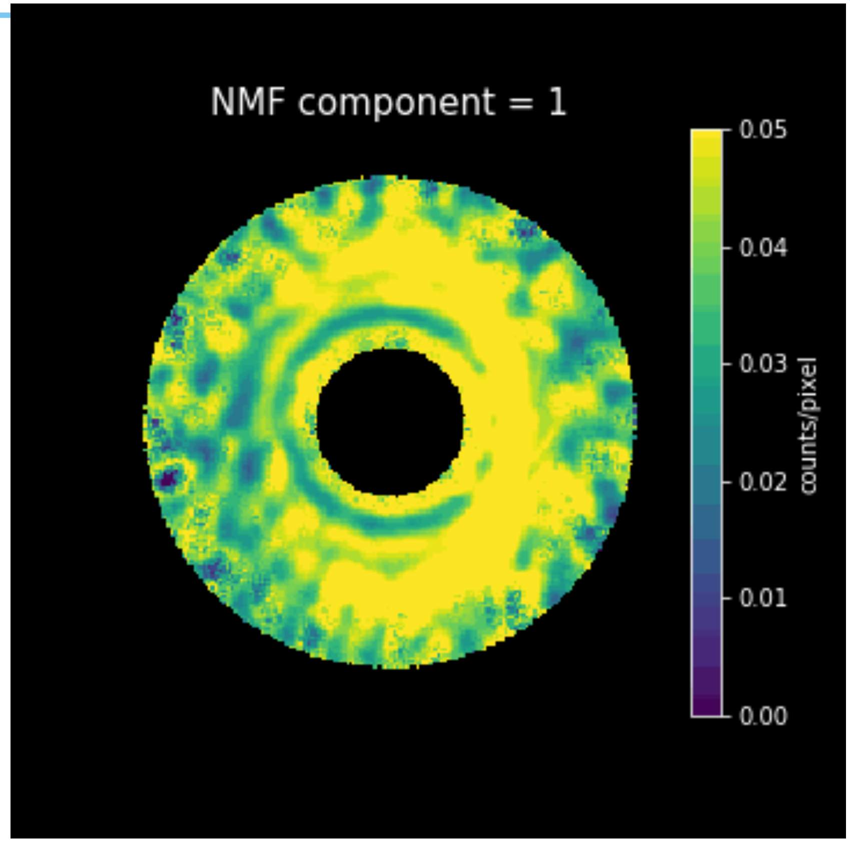


With MUFs

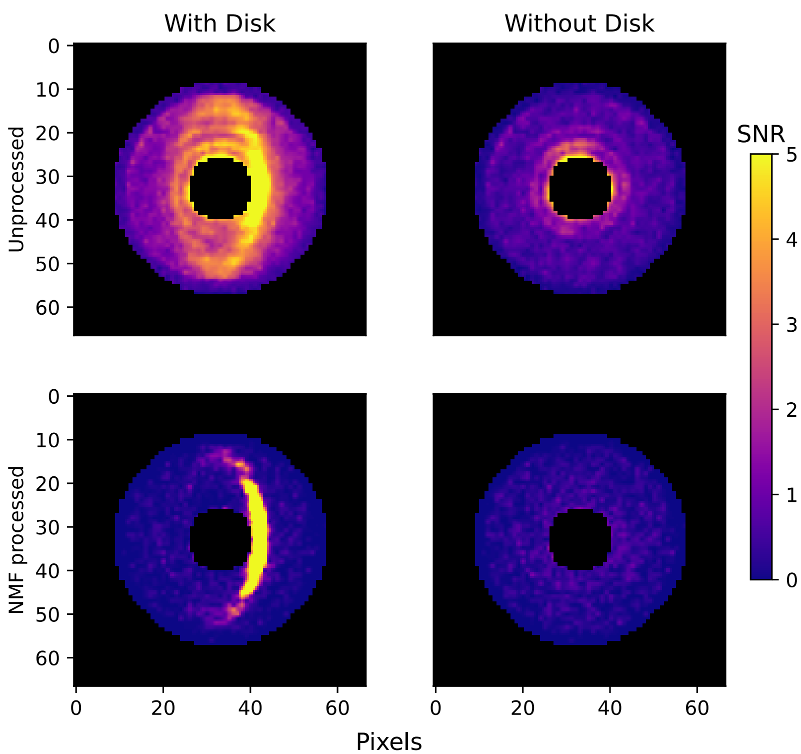
Douglas et al, submitted

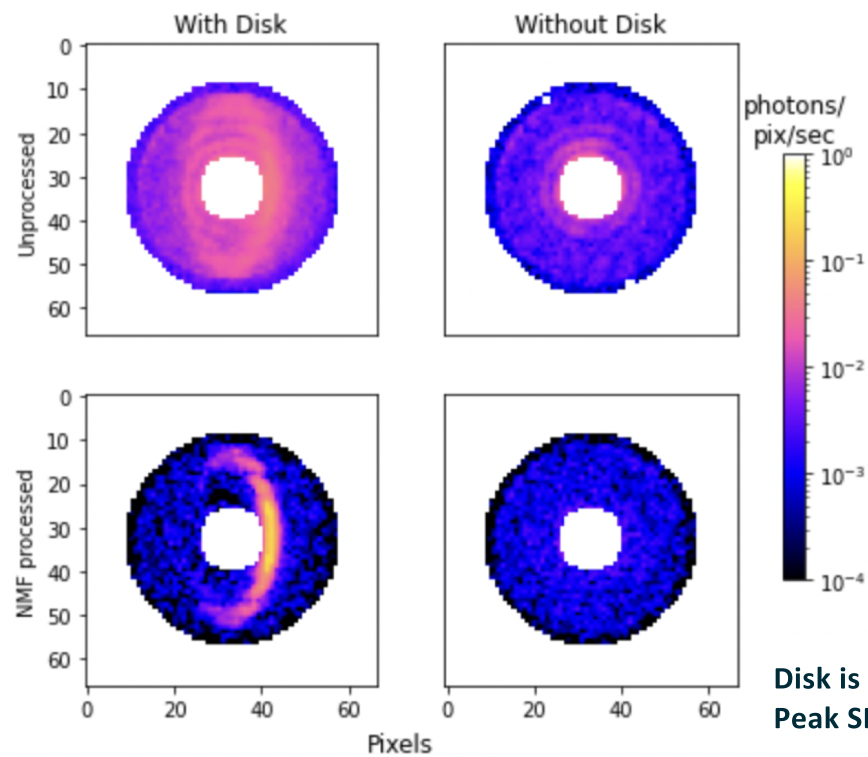
POST-PROCESSING

- NMF recovery of disk near OS6 speckle noise floor (video)



Post-processing: similar gains to point sources



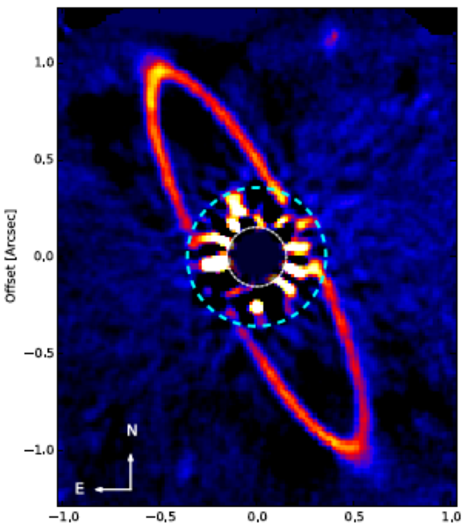


Disk is 13x Zodi SB disk
Peak SB~260 Zodi SB

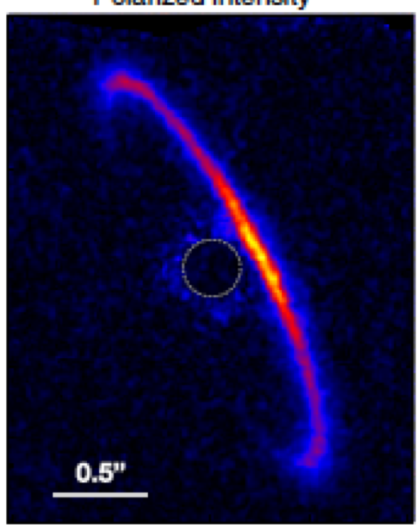
Polarimetry with the Roman Coronagraph

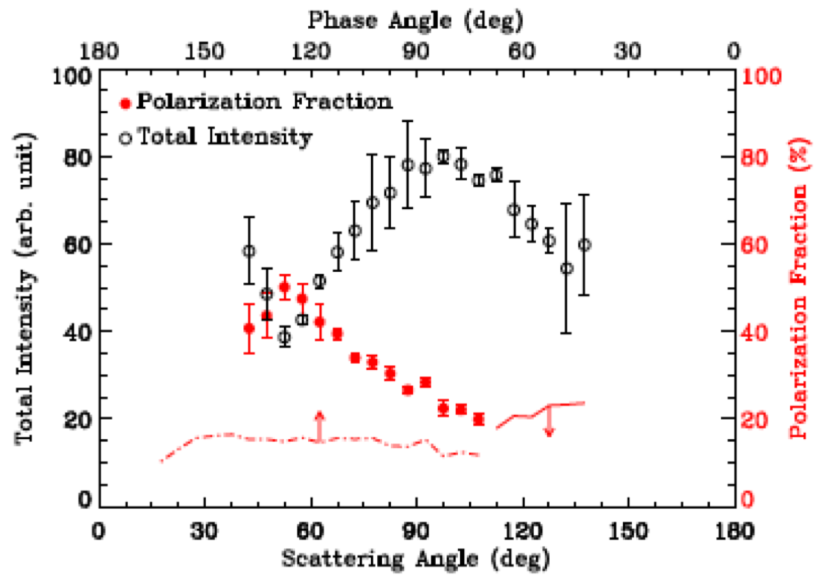
- Total intensity and polarized images of high inclination – optically thin- debris disks or rings give access to the grains scattering phase function (and breaks some degeneracies)
  - Can in principle inform grain size and shape, and even composition if SPF measured at different λ's

Total intensity



Polarized intensity



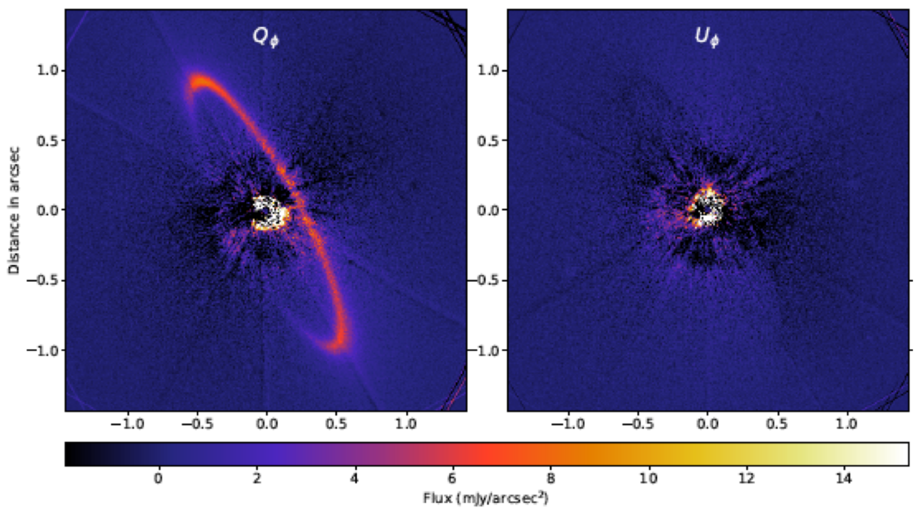


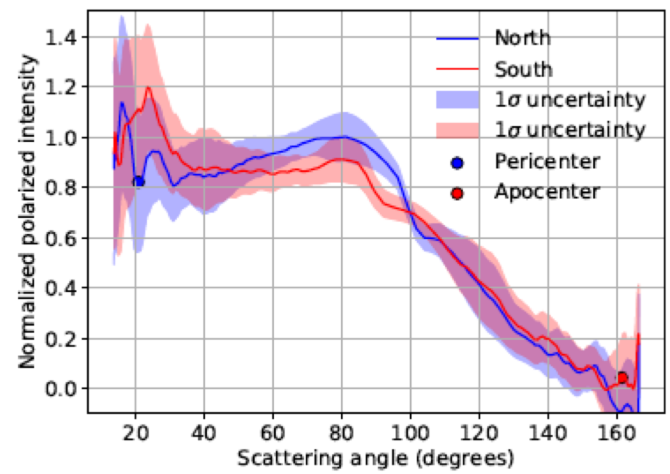
e.g. GPI K band total intensity and polarized images of the HR 4796A ring (Perrin et al. 2015)

Polarimetry with the Roman Coronagraph

- Total intensity and polarized images of high inclination – optically thin- debris disks or rings give access to the grains scattering phase function (and breaks some degeneracies)
  - Can in principle inform grain size and shape, and even composition if SPF measured at different λ's

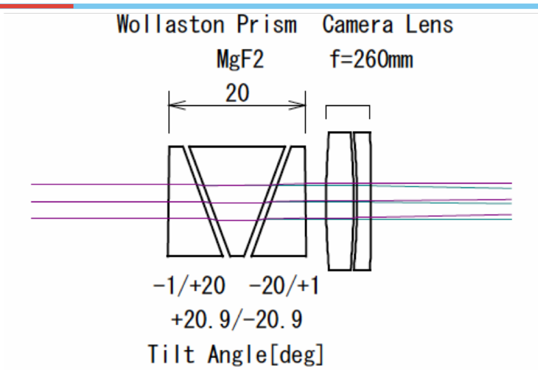
Polarized intensity in the visible



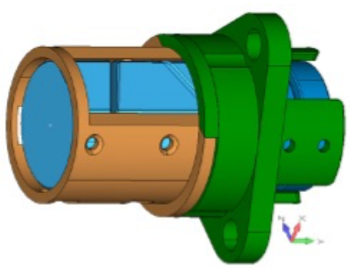


e.g. SPHERE/ZIMPOL polarized visible images of the HR 4796A ring (Milli et al. 2020).
Observed SPF physical interpretation remains challenging though ! (Olofsson et al. 2020)

Polarimetry with the Roman Coronagraph

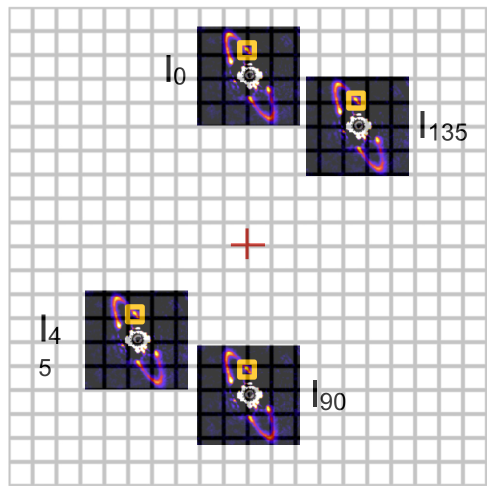


JAXA Polarization Module (2X)
Courtesy of Motohide Tamura

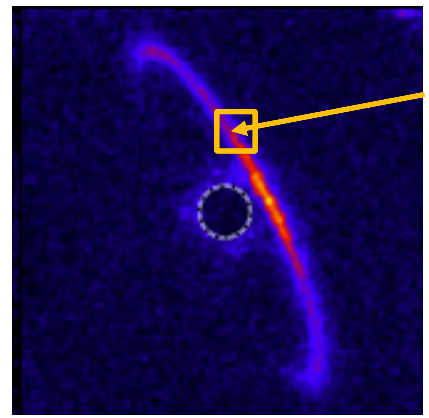


One of 2 identical assembled modules.
Courtesy of Tyler Groff, GSFC

- Each of the 2 Polarization modules produces two orthogonally polarized images separated by 7.5" on the sky, each 3.2" in diameter:



- Linear polarized fraction (LPF) shall be measured in CGI bands 1 & 4 with an rmse < 3% ***per resel***



Resel:
- *3x3 pixels in band 1*
- *4x4 pixels in Band 4*

LPF = sqrt $\{(I_0 - I_{90})^2 + \{(I_{45} - I_{135})^2\}$ / I_{tot} = sqrt $(Q^2 + U^2)$ / I_{tot}

More polarization information

- Roman Virtual Lecture Series:

https://www.stsci.edu/contents/events/roman/2021/june/prospects-for-polarimetry-exozodiacal-and-debris-disk-observations-with-romans-coronagraph

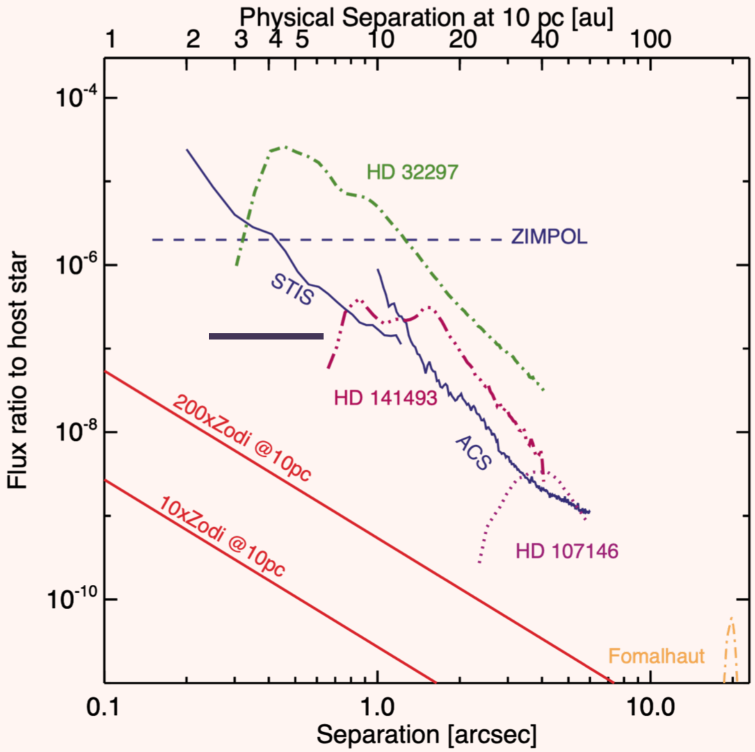
Future Opportunities

- Determining science cases for the WFOV mode
- Studying science cases for polarimetry modes
- Faint stars with protoplanetary disks (including narrowband searches for accreting protoplanets?)
- Material around other astrophysical objects (quasars, massive stars, giant stars)
- High contrast imaging without dark holes

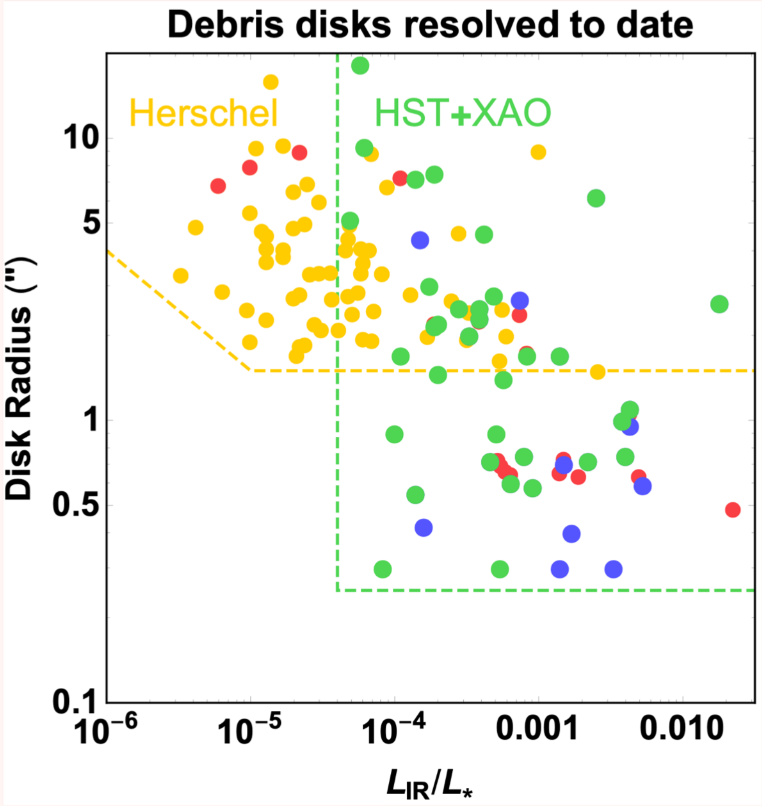
Resources

- https://roman.ipac.caltech.edu/sims/Circumstellar_Disk_Sims.html
- https://roman.ipac.caltech.edu/sims/Chen_WPS.html
- https://github.com/kian1393/faster-imaging-simulation-hlc
- https://roman.ipac.caltech.edu/mtgs/AAS231/maxime_rizzo_2018Rizzo_AAS.pdf
- Debes J. et al (2019). Pushing the Limits of the Coronagraphic Occulters on HST/STIS. https://arxiv.org/abs/1905.06838
- Douglas, E. S. et al. (2019). Simulating the effects of exozodiacal dust in WFIRST CGI observations. Proc SPIE. https://doi.org/10.1117/12.2529488
- Mennesson, B., et al. (2019). The Potential of Exozodiacal Disks Observations with the WFIRST Coronagraph Instrument. http://arxiv.org/abs/1909.02161
- Milani, K., & Douglas, E. S. (2020). Faster imaging simulation through complex systems: a coronagraphic example. Proc SPIE. https://doi.org/10.1117/12.2568204
- Rén, B., et al (2018). Non-negative Matrix Factorization: Robust Extraction of Extended Structures. *The Astrophysical Journal*, *852*(2), 104. https://doi.org/10.3847/1538-4357/aaa1f2
- Schneider, G. (2014). A Quick Study of Science Return from Direct Imaging Exoplanet Missions: Detection and Characterization of Circumstellar Material with an AFTA or EXO-C/S CGI. ArXiv:1412.8421 [Astro-Ph]. Retrieved from http://arxiv.org/abs/1412.8421

Questions?



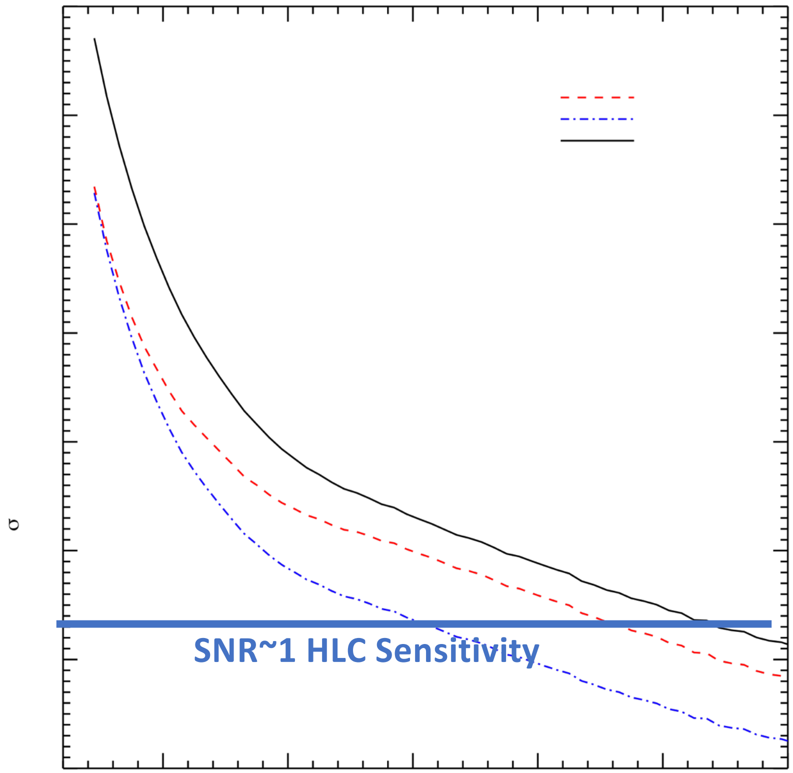
Physical Separation at 10 pc [au]
1
2
3
4
5
10
20
40
100
HD 32297
ZIMPOL
STIS
HD 141493
ACS
HD 107146
200xZodi @10pc
10xZodi @10pc
Fomalhaut
Flux ratio to host star
10^-4
10^-6
10^-8
10^-10
0.1
1.0
10.0
Separation [arcsec]



Debris disks resolved to date
Herschel
HST+XAO
Disk Radius (")
10
5
1
0.5
0.1
10^-6
10^-5
10^-4
0.001
0.010
L_IR/L_*

What can HLC do without a dark hole? Close or better than STIS

Published in JATIS (https://arxiv.org/abs/1905.06838)



Predicted SB sensitivity for 24hr exposure time on V=5 star

STIS currently approaches SB limits for HLC dark hole beyond 2-3”

J.Debes (STScI)

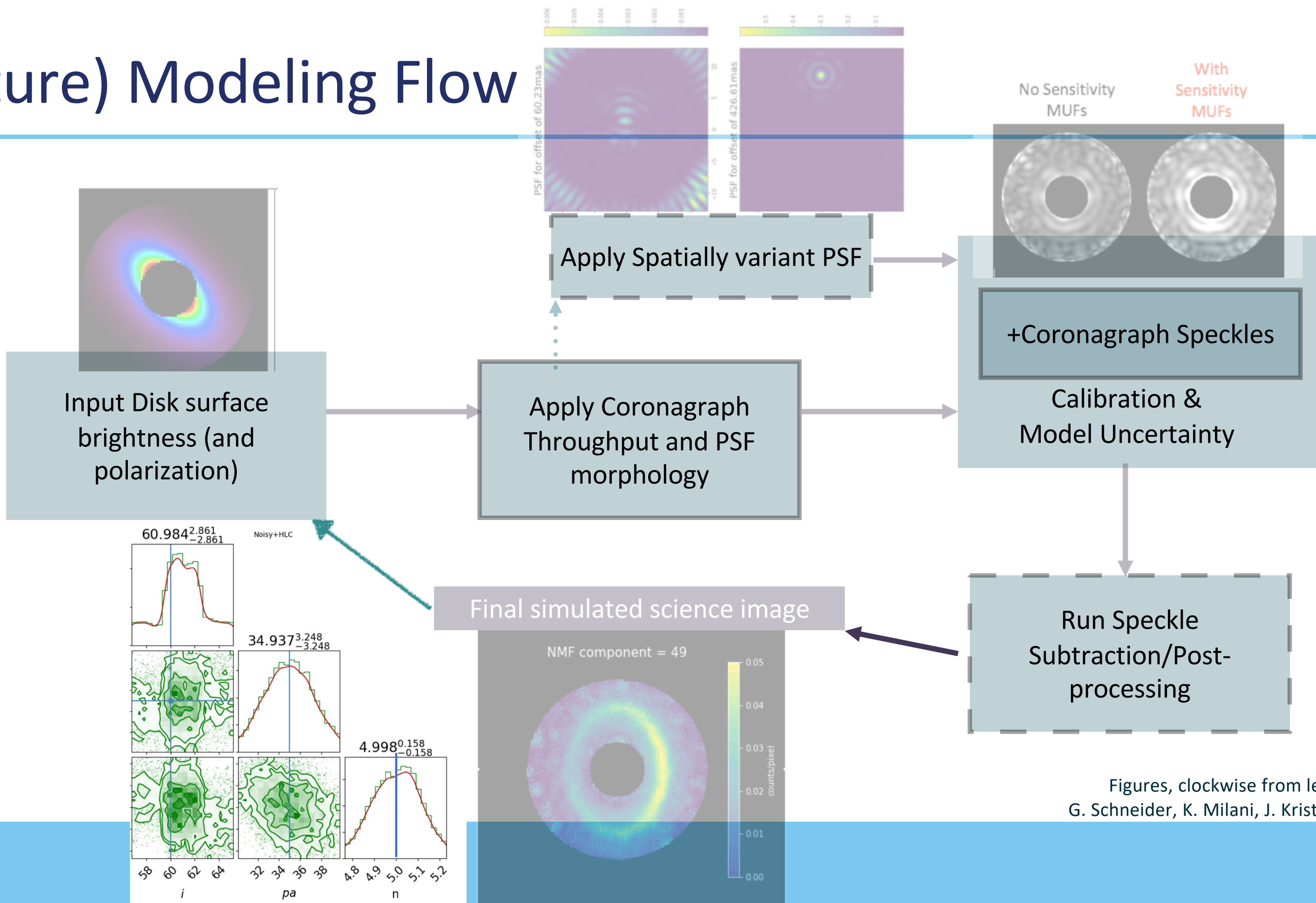
Future work

Exozodi survey DRM

Updated post-processing with OS9

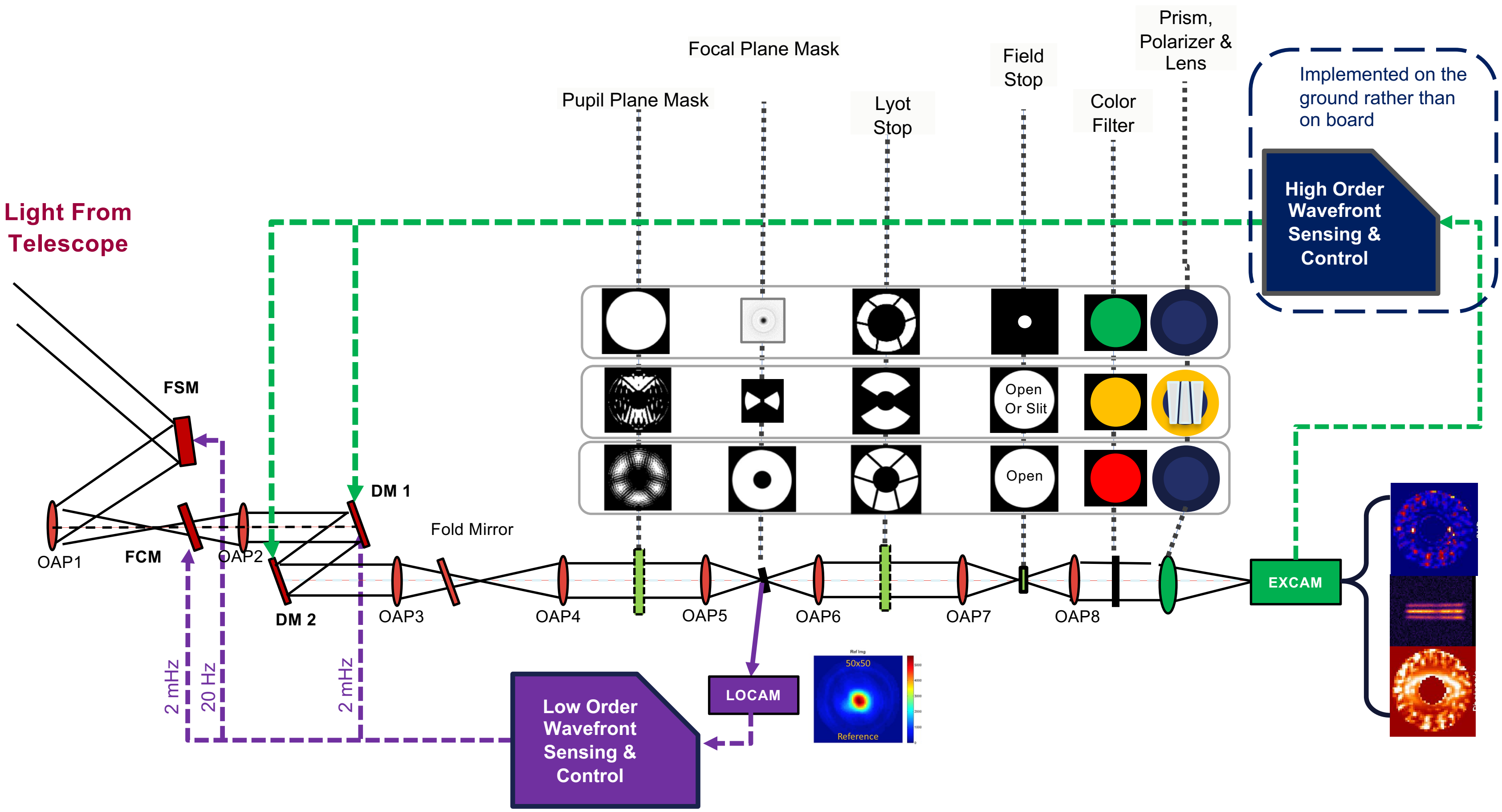
Proto-planetary accretion sensitivity with slit

(Future) Modeling Flow



Figures, clockwise from left:
G. Schneider, K. Milani, J. Krist, B. Ren

Key technologies work together as a system to deliver high performance



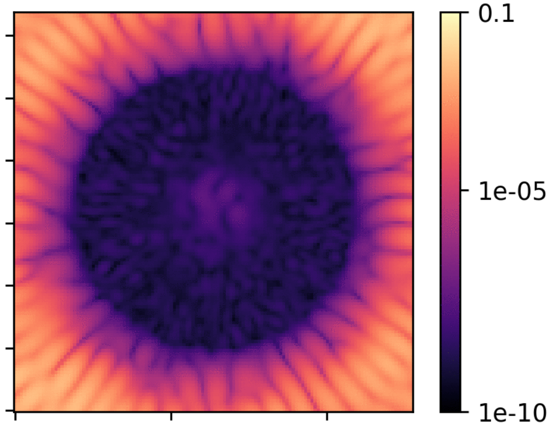
OAP = Off-Axis Parabolic [Mirror]

FAST COMPUTATION OF CROWDED FIELDS

Milani et al 2020 showed that a matrix multiplication approach using pre-computed PSFs speeds up simulation of crowded scenes by orders of magnitude

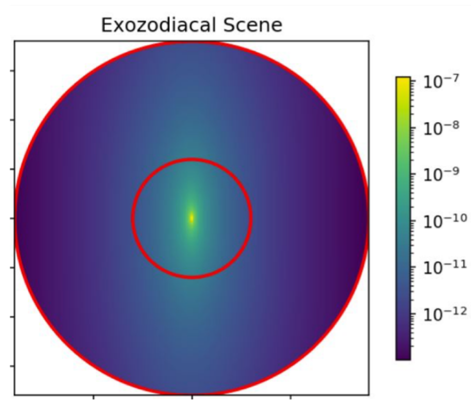
A x = b

2D matrix of coronagraphic PSFs

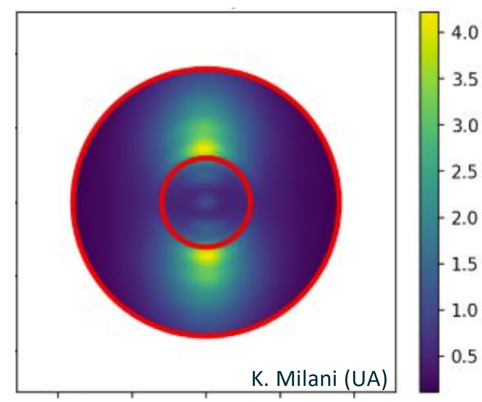


(small subset shown)

Input image



Post coronagraph simulation

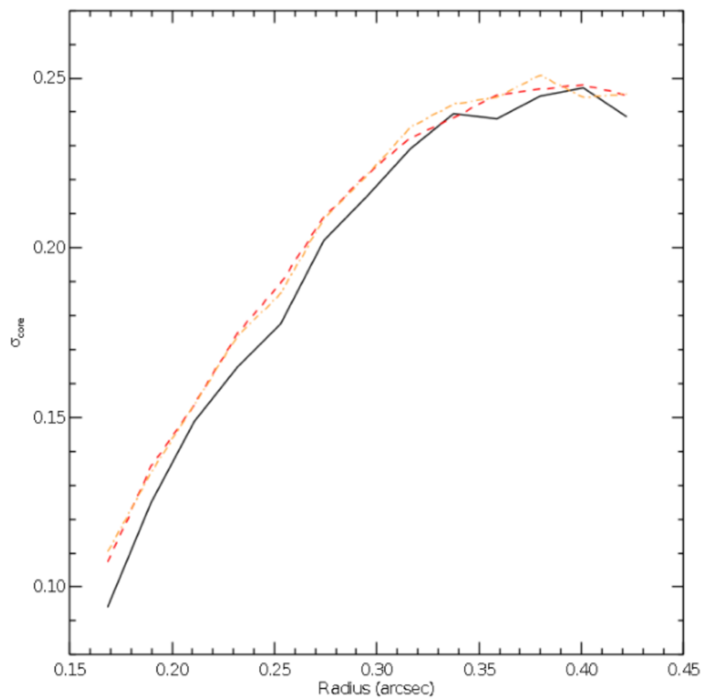


Runs in <0.2 seconds

BACKUP

Radial dependence for a zodi-analog mostly invariant to how photometric aperture is defined

Core
Throughput

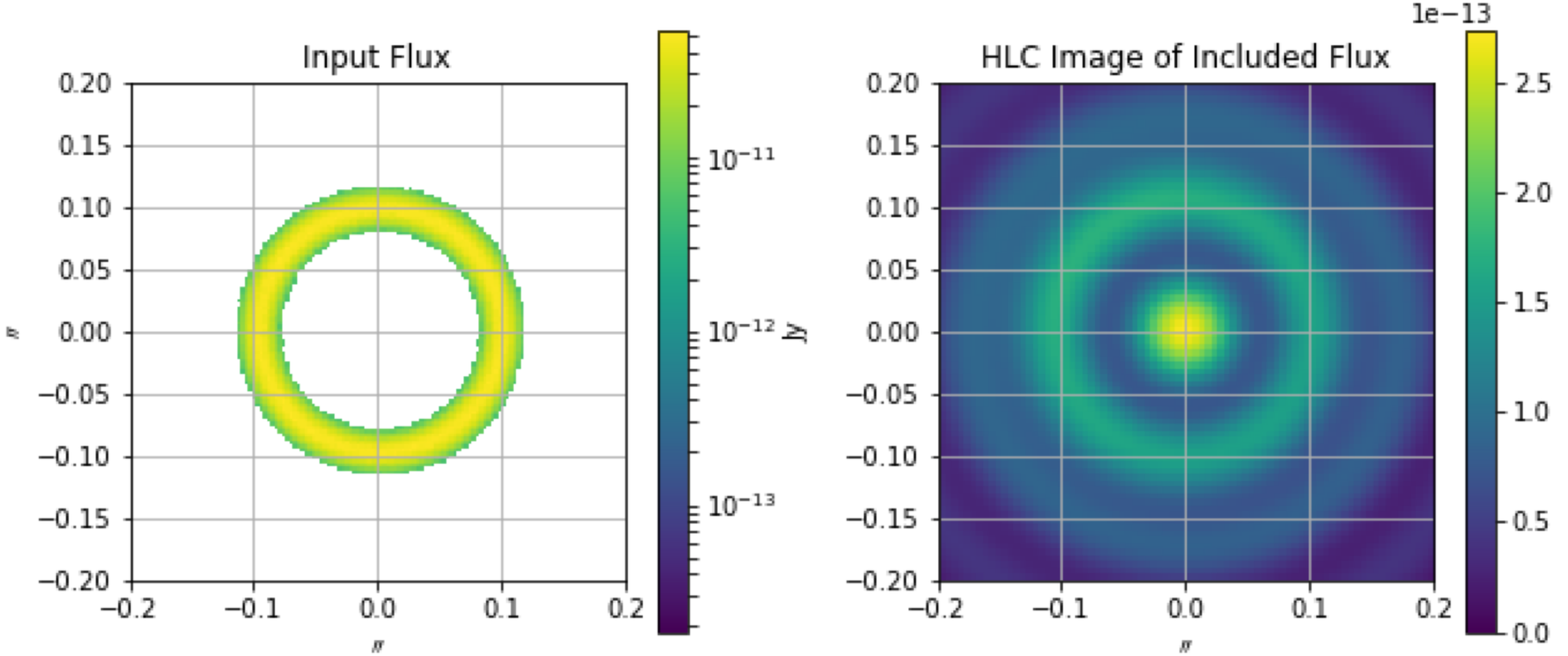


Arcseconds

PS core throughput=0.046

J. Debes (STScI

Dust ring inside the IWA

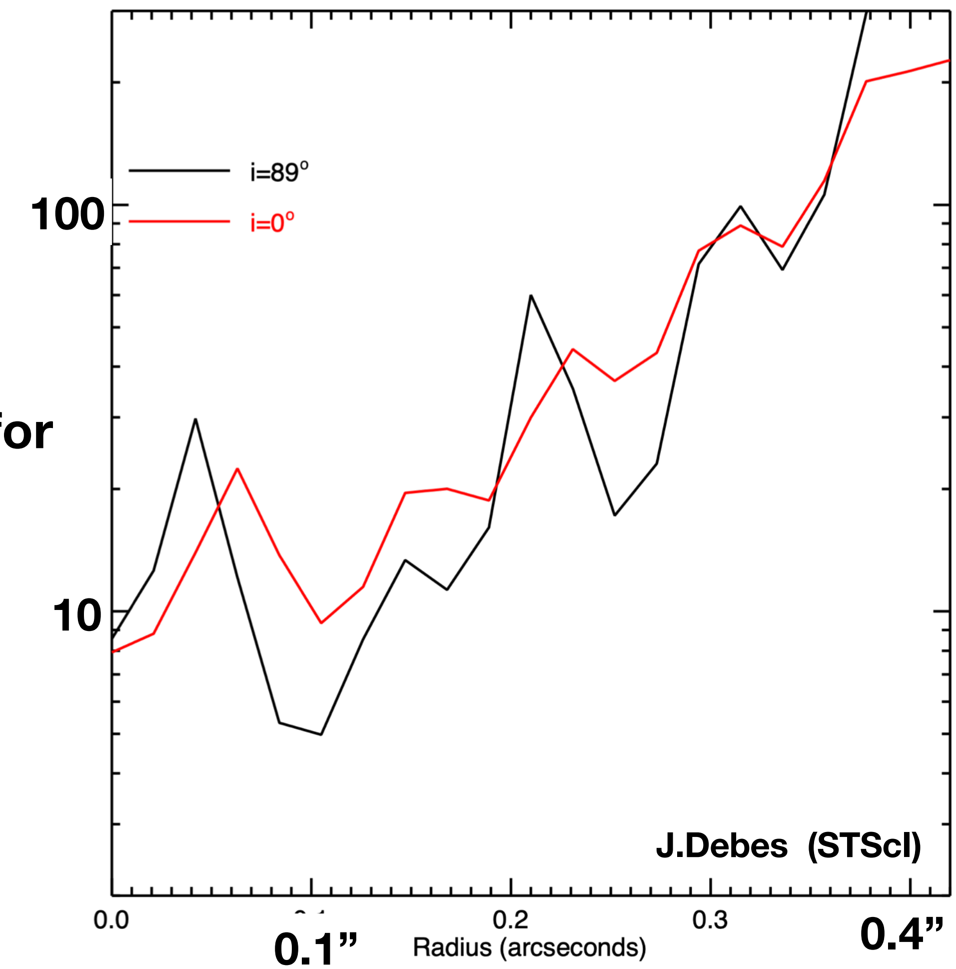


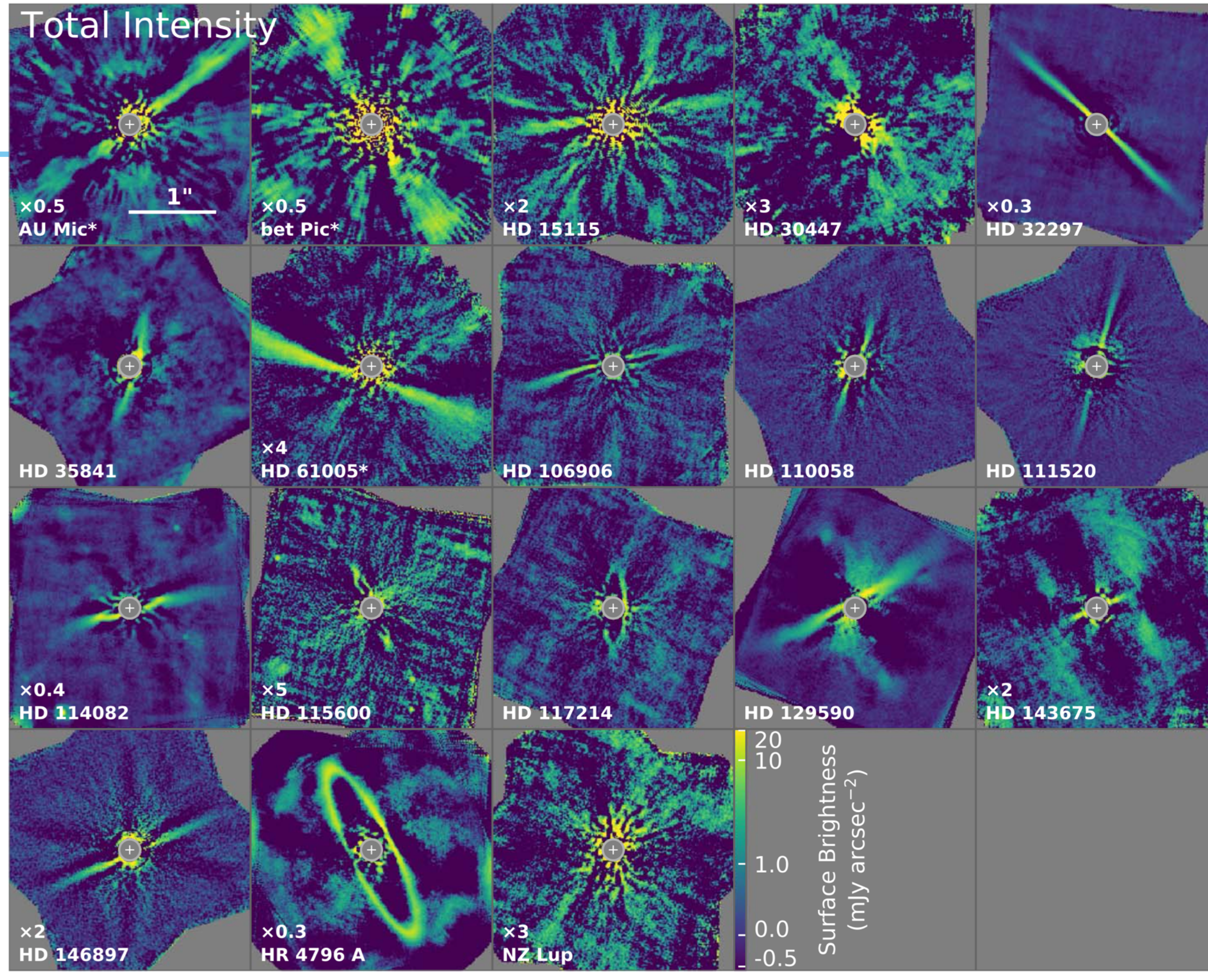
Douglas et al 2019

Quantifying Leakage from interior disks

10-100x exoZodi leakage can cause
~1 exoZodi of background for HLC

Disk at 0.1” required for 1 Zodi of leakage

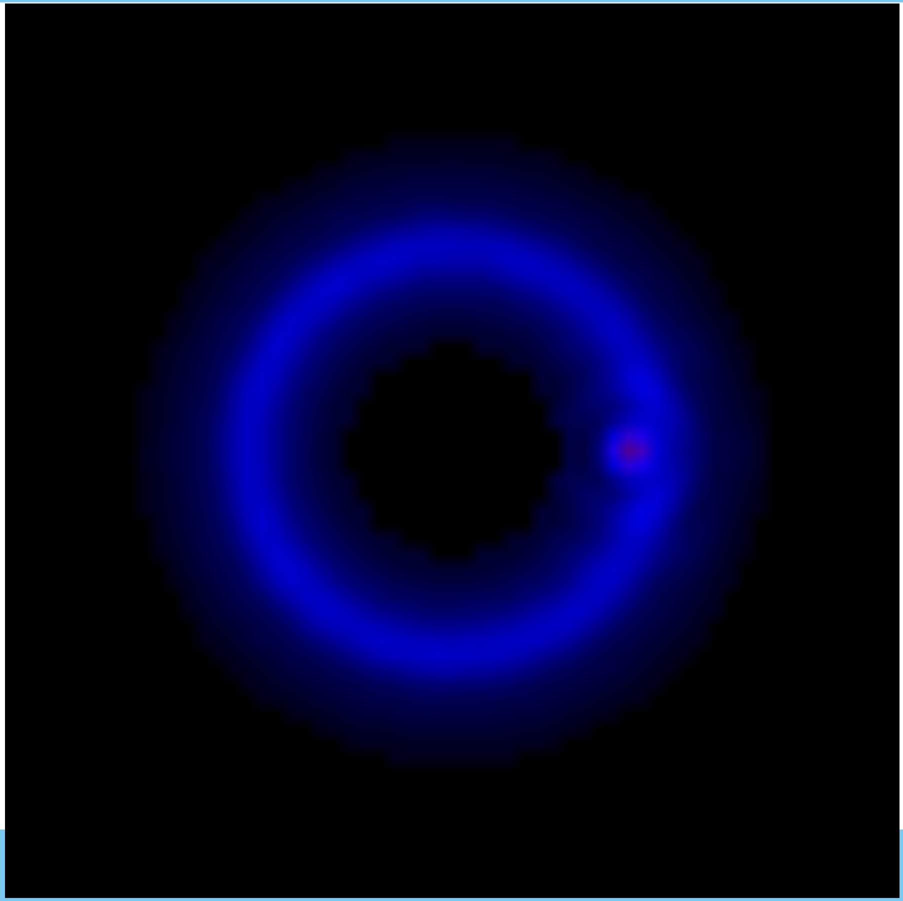



Total Intensity
×0.5
1"
AU Mic*
×0.5
bet Pic*
×2
HD 15115
×3
HD 30447
×0.3
HD 32297
HD 35841
×4
HD 61005*
HD 106906
HD 110058
HD 111520
×0.4
HD 114082
×5
HD 115600
HD 117214
HD 129590
×2
HD 143675
×2
HD 146897
×0.3
HR 4796 A
×3
NZ Lup
20
10
1.0
0.0
-0.5
Surface Brightness
(mJy arcsec^{-2})

Why disk morphology can matter

-]

V=5 star
3e-9 Companion at 2.5 AU
5 Zodi disk at 3 AU



J.Debes (STScI)

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V=5 star
3e-9 Companion at 2.5 AU
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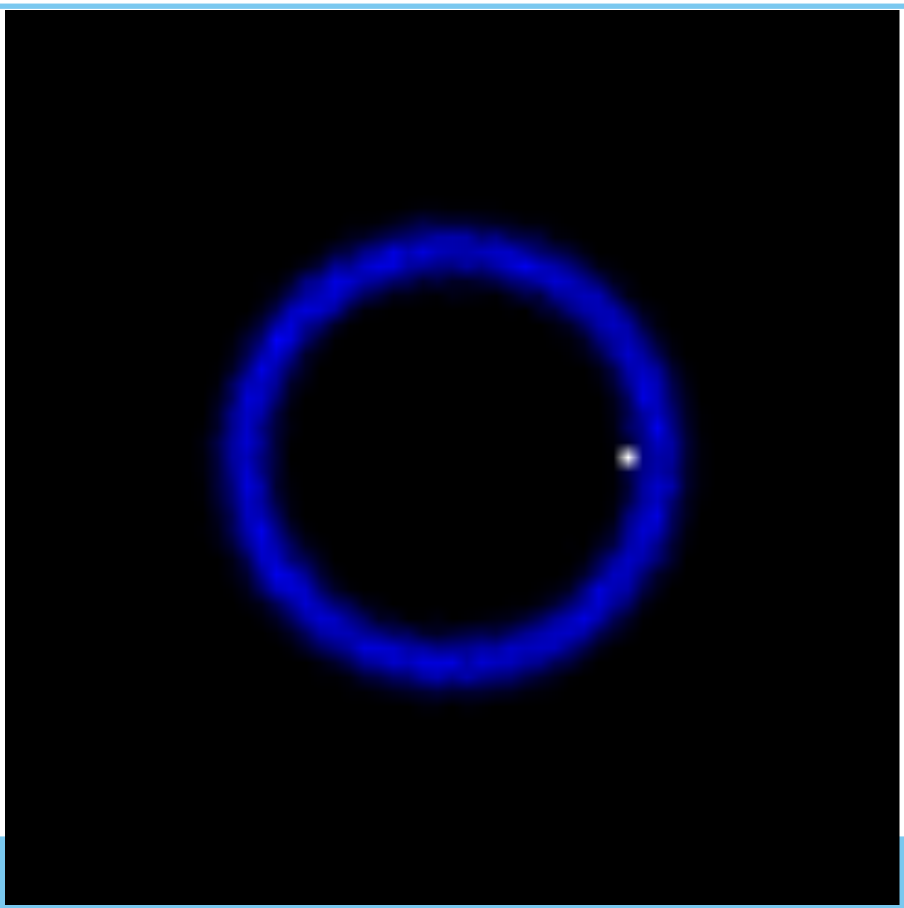
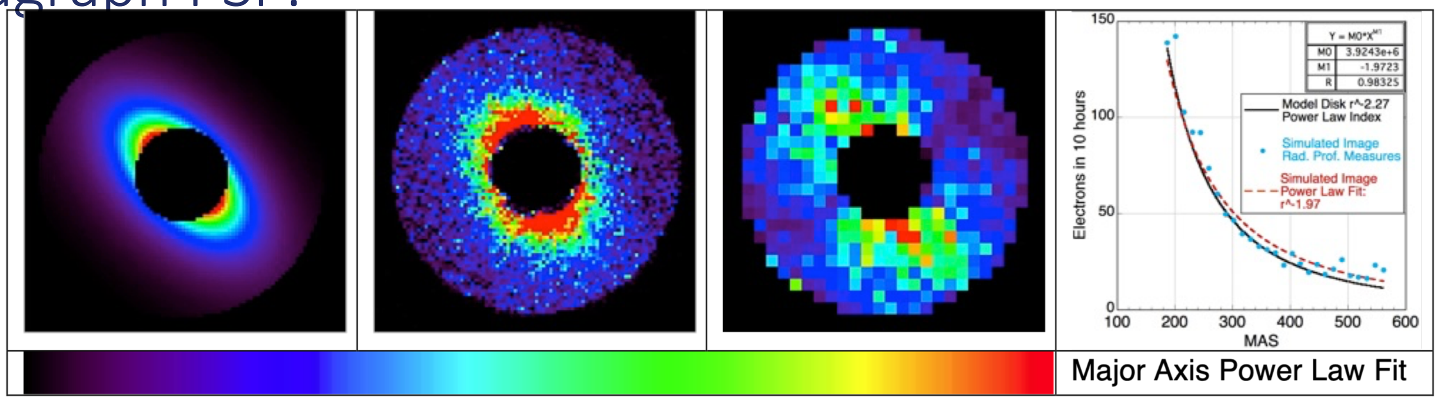


J.Debes (STScI)

Early Modeling Efforts

- Schneider 2014, 47 Uma (and other disks) convolved with coronagraph PSF:



Full Scene Modeling

- Haystacks (PI Aki Roberge)
- Includes dynamics and planet impact on morphology
- https://asd.gsfc.nasa.gov/projects/haystacks/haystacks.html

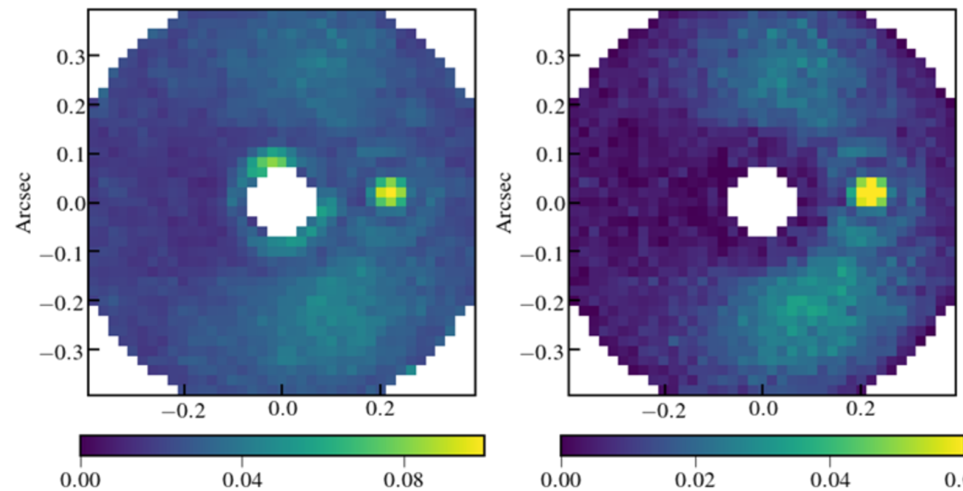


Figure 2: Simulated WFIRST CGI observations (HLC 575 nm imaging mask) of a nearby sunlike star (1 Ori, spectral type F6V at ~8 pc) hosting an exozodi dust cloud 10× denser than in the solar system, showing resonant structures due to a hypothetical jovian planet located at 1.6 AU. Flux scale is square-root stretch in units of photoelectrons/s. Simulated exposure time is 2.8 h. (Courtesy of M. Rizzo, N. Zimmerman and the “Haystacks” team). The right image shows the contrast enhancement provided by PSF subtraction (speckles removal) using observations of a reference star. The field of view diameter is 0.8” in both images.

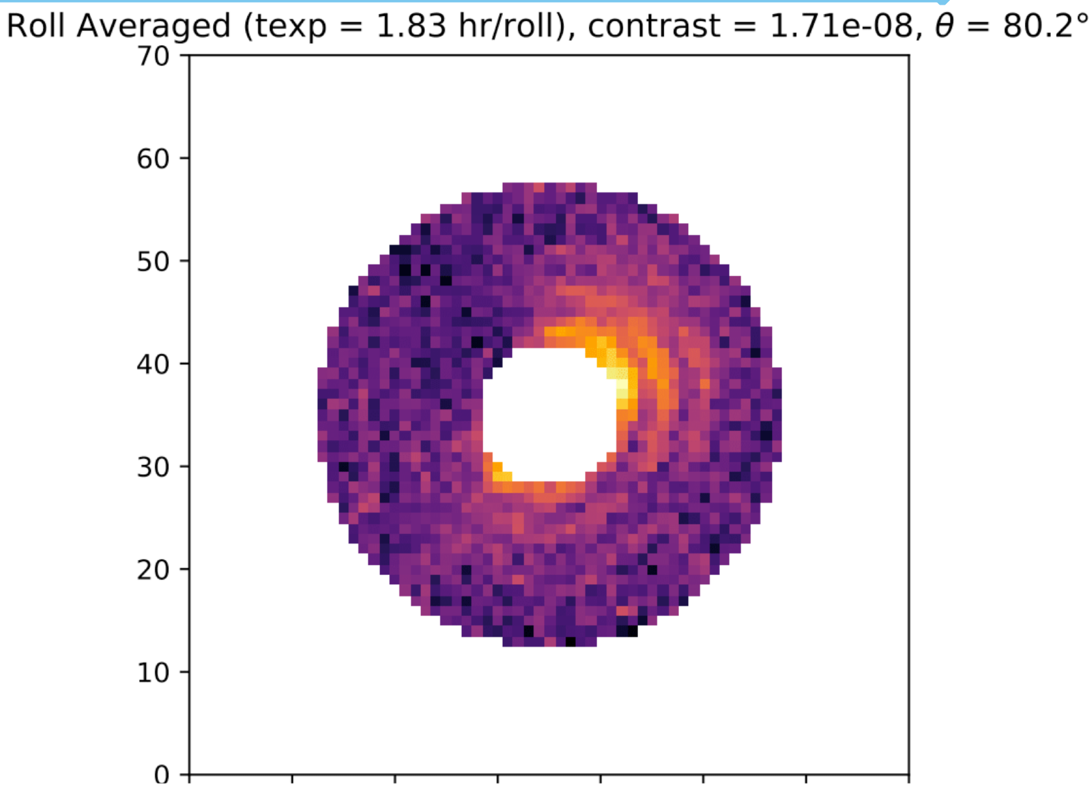
Christine Chen's WPS Team:

- HLC 575 nm models

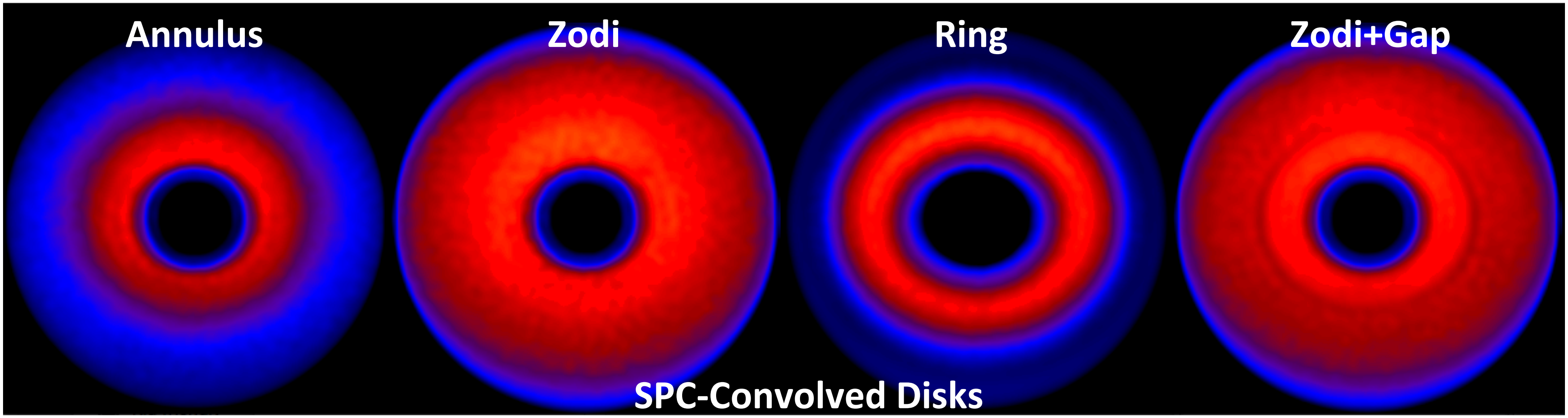
- 61 Vir, eps Eri, HD 10647, HD 69830, HD 95086, HR 8799, and tau Cet

- also include hypothetical ice/giant planets

https://roman.ipac.caltech.edu/sims/Chen_WPS.html



A Grid of Disk Models for the HLC and SPC



https://roman.ipac.caltech.edu/sims/Circumstellar_Disk_Sims.html

J.Debes (STScI)

POST-PROCESSING

- NMF recovery of disk near OS9 s