DiskFM: A Forward Modeling Tool for Disk Analysis with Coronagraphic Instruments

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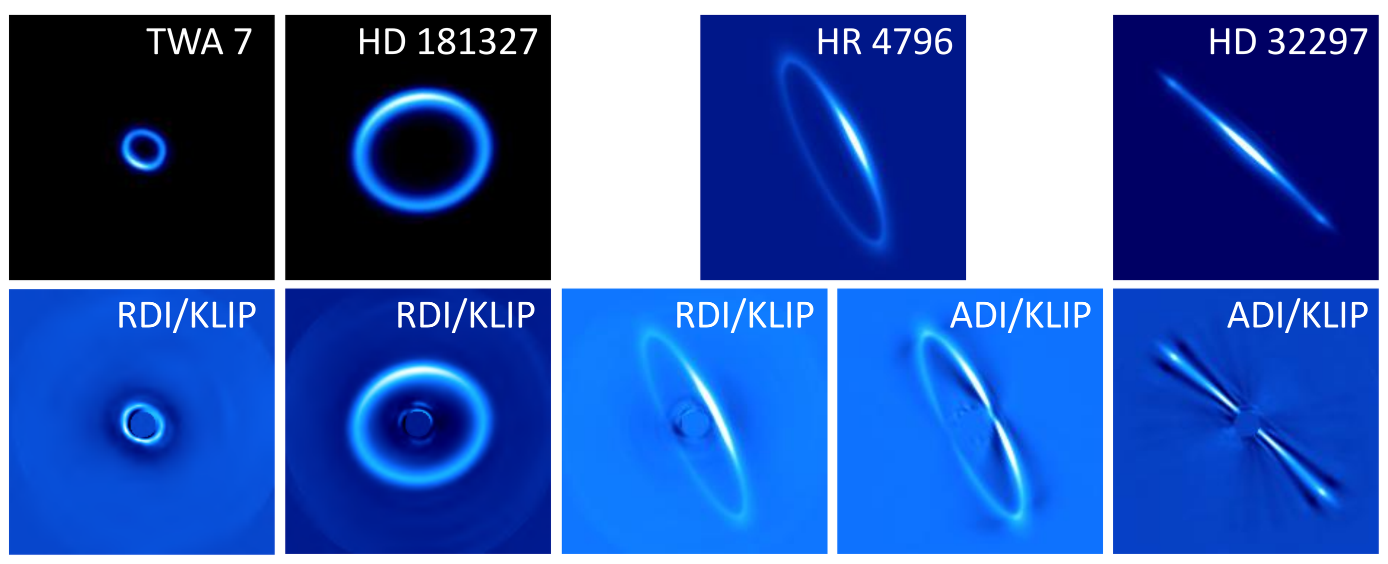
INTRODUCTION

Because of bright starlight leakage in coronagraphic raw images, faint astrophysical objects such as exoplanets can only be detected using powerful point spread function (PSF) subtraction algorithms. However, these algorithms have strong effects on faint objects of interest, and often prevent precise spectroscopic analysis and scattering property measurements of circumstellar disks. For this reason, **PSF-subtraction effects is currently the main limitations to the precise characterization of exoplanetary dust with scattered-light imaging.**

Forward modeling techniques have long been developed for point source objects (Pueyo 2016 [1]). However, Forward Modeling with disks is complicated by the fact that the disk cannot be simplified using a simple point source convolved by the PSF as the astrophysical model; all hypothetical disk morphologies must be explored to understand the subtle and non-linear effects of the PSF subtraction algorithm on the shape and local geometry of these systems. Because of their complex geometries, the forward-modeling process has to be repeated tens or hundred of thousands of times on disks with slightly different physical properties. All of these geometries are then compared to the PSF-subtracted image of the data, within an MCMC or a Chi-square wrapper.

We present here DiskFM, a new open-source algorithm included in the PSF subtraction algorithms package pyKLIP. This code allows to produce fast forward-modeling for a variety of observation strategies (ADI, SDI, ADI+SDI, RDI), that can be easily included in an MCMC wrapper to explore large disk parameter space. DiskFM has already been used for SPHERE/IRDIS [2] and GPI data [3]. It is readily available on all instruments supported by pyKLIP (SPHERE/IFS, SCExAO/CHARIS, …), and can be quickly adapted for other coronagraphic instruments.

IMPACT OF PSF-SUBTRACTION



Because disks are extended structures, they are very sensitive to the effect of PSF-subtraction algorithms (over- and self-subtraction) [4,5]. Geometrical disk parameters (radius, inclination, …) are affected but can sometimes be extracted at a lower precision directly from the self-subtracted image.

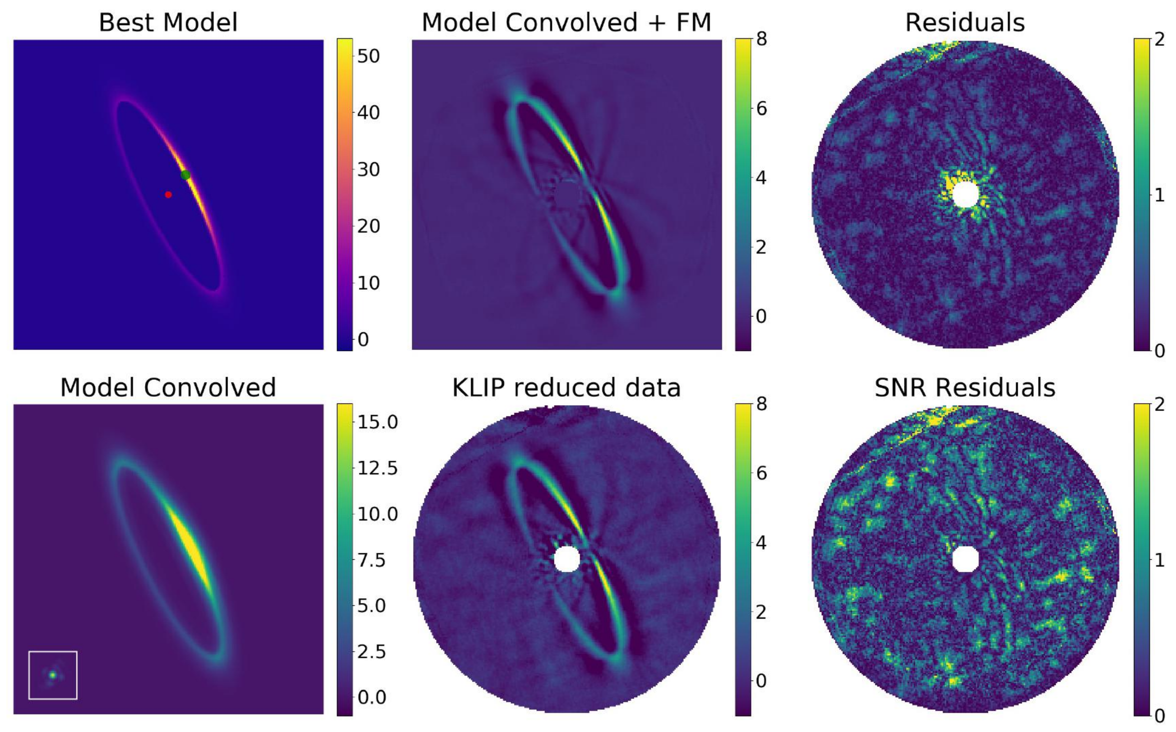
However, more subtle properties : the absolute photometry (and therefore spectroscopy) or local variations of the photometry as a function of the observing angle (scattering phase functions, or SPFs) cannot be reliably extracted in a self-subtracted disk images.

DiskFM PERFORMANCE

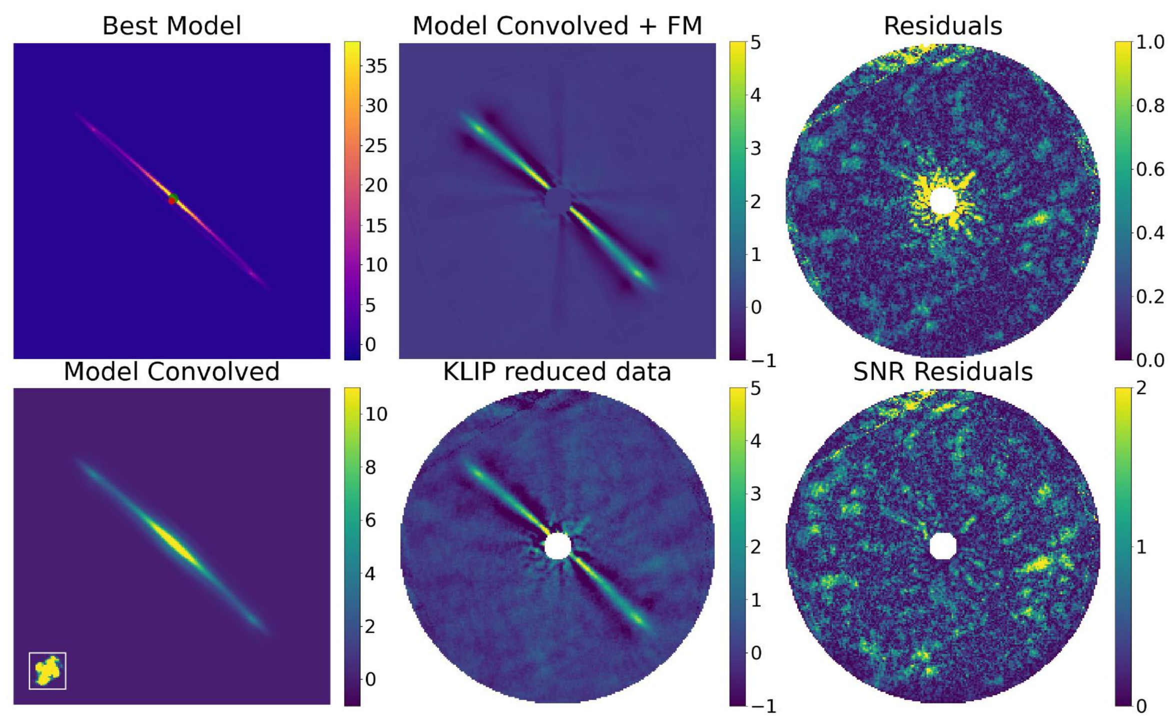
DiskFM allows the careful identification of the biases introduced by KLIP/ADI and KLIP/RDI using KLIP-FM formalism, optimized in speed and efficiency in order to be included in an MCMC wrapper.

We used a common approach in planet detection algorithms to show performance: inject a modeled disk[3] in an empty sequence and try to recover (within 1σ) its parameter with the smallest error bars. Using this method, we tested DiskDM in 30 different cases: different geometries (3), different photometries (one "bright" and one "faint"), different observation modes (ADI and RDI) and finally different reduction parameters (conservative to aggressive).

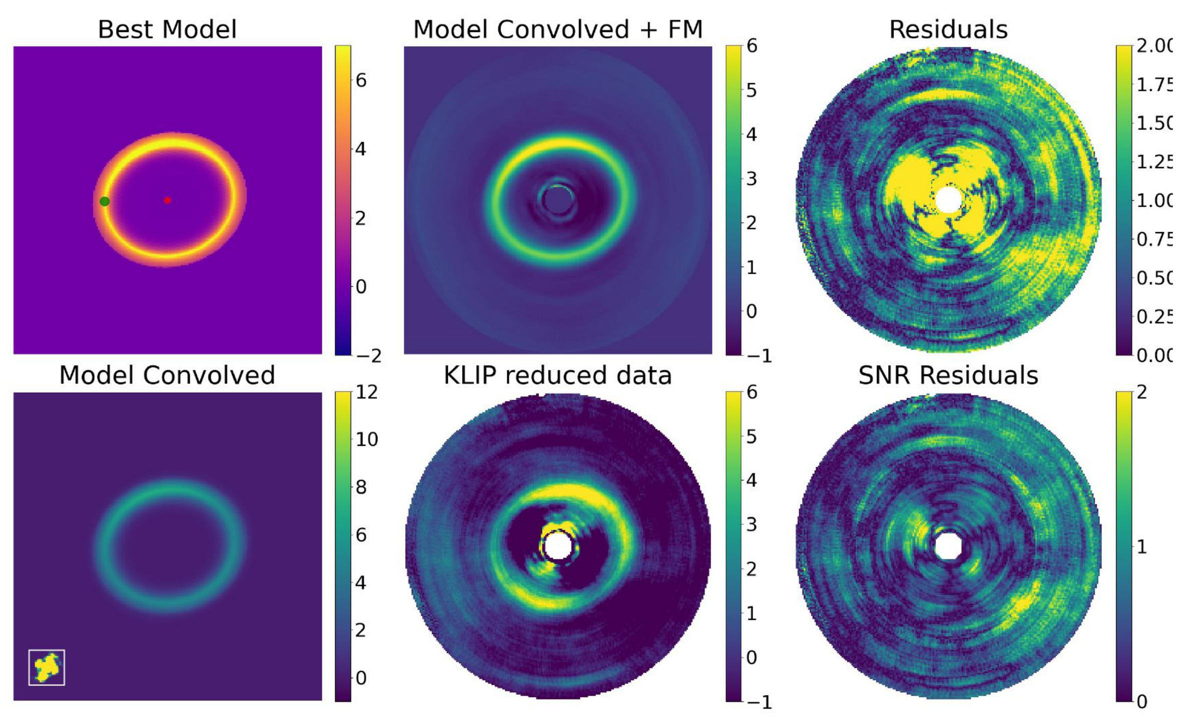
Injected Bright HR 4796 ADI (KL#: 10): Best Model and Residuals



Injected Faint HD 32297 ADI (KL#: 10): Best Model and Residuals



Injected HD 181327 RDI (KL#: 25): Best Model and Residuals



EXTRACTING DISK PARAMETERS

Disk Type	Reduction	KL #	R1[au]	R2[au]	βin	βout	i[°]	PA[°]	dx[au]	dy[au]	N[ADU]
'HR 181327 like' disk	ADI	1	NC	NC	NC	NC	NC	NC	NC	NC	NC
		3	ND	ND	ND	ND	ND	ND	ND	ND	ND
		5	ND	ND	ND	ND	ND	ND	ND	ND	ND
	RDI	5	44 +1/-2	52 +2/-1	-8 +1/-2	8 +7/-4	32 +1/-1	98 +2/-3	0.2 +/-0.3	0.7 +/-0.4	98 +11/-13
		15	42 +/-1	52 +/-1	-13 +3/-5	5 +3/-2	31 +/-1	104 +/-2	0.0 +/-0.3	1.1 +/-0.3	103 +11/-12
		25	43 +/-1	51 +/-1	-12 +2/-4	6 +4/-3	30 +/-1	104 +2/-2	-0.3 +/-0.3	1.1 +/-0.3	107 +11/-13
Injected disk "true" parameters			45.0	52	-7	12.3	30.0	101.0	-0.9	1.37	100

x <1σ
1σ < x < 2σ
2σ < x < 3σ
x > 3σ
No converge
No detection

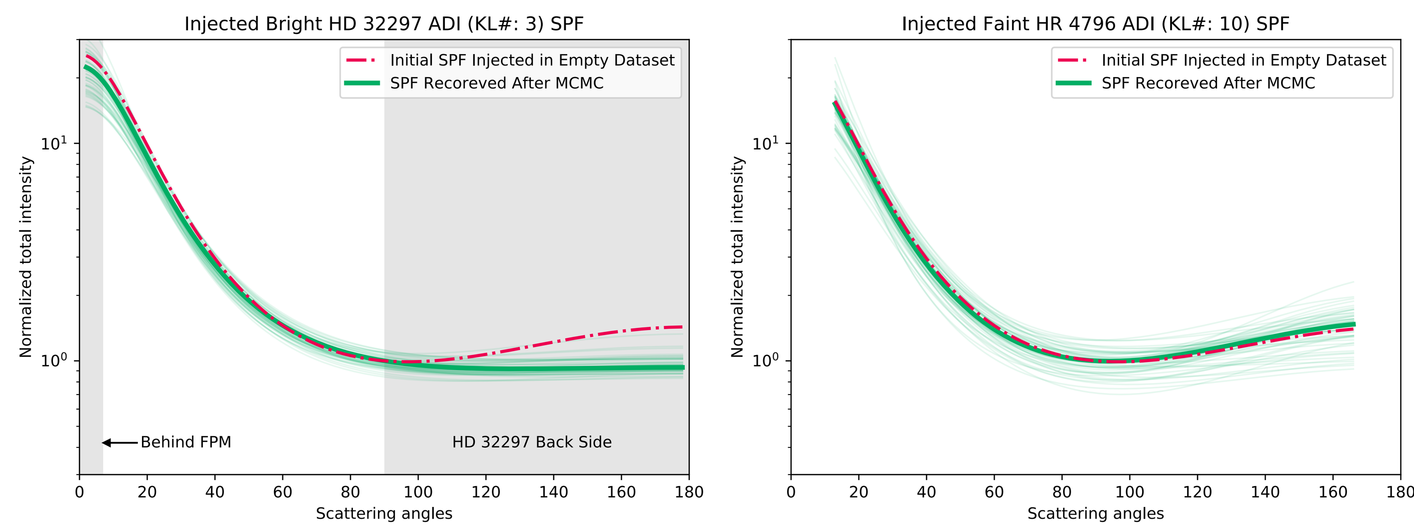
Disk Type	Reduction	KL #	R1[au]	R2[au]	βout	i[°]	PA[°]	dx[au]	dy[au]	N[ADU]	g1	g2	α
Faint 'HD 32297 like' disk	ADI	3	70.1 +/-0.6	89 +6/-4	13 + /-3	88.5 +/- 0.2	47.7 +/- 0.1	1 +5/-4	0.7 +/-0.4	17 +/-3	80 +7/-14	-8 +3 / -6	69 +/- 7
		10	69.2 +/-0.6	89 +5/-3	10 + /-2	88.3 +/- 0.1	47.7 +/- 0.1	-4 +/-4	0.6 +/-0.4	17 +/-3	70 +/- 3	-8 +5 / -7	64 +/- 3
		20	69.2 +/-0.6	89 +5/-3	10 +2 /-3	88.3 +/- 0.1	47.7 +/- 0.1	-3 +/-4	0.6 +/-0.4	17 +/-3	71 +/- 3	-9 +5 / -7	64 +/- 3
	RDI	5	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC
		15	69 +/- 3	81 +12/-7	NC	89 +3/-1	47.6+0.6/-0.5	NC	2 +/-2	15 +8/6	NC	NC	NC
		25	70 +/- 2	84 NC/-7	NC	89 +2/-1	47.6 +/-0.4	NC	2 +/-2	16 +8/7	NC	NC	NC
Injected disk "true" parameters			70.0	90.0	12.4	88.3	47.6	-2.0	0.94	20	70	-20	66

Disk Type	Reduction	KL #	R1[au]	R2[au]	βout	i[°]	PA[°]	dx[au]	dy[au]	N[ADU]	g1	g2	α
Brigth 'HD 32297 like' disk	ADI	3	69.9 +/-0.2	90 +/-2	11.6 +/-0.9	88.38+/-0.06	47.64+/-0.03	-1 +/-2	0.74 +/-0.14	64 +/- 4	70 +2/-3	-7 NC/-3	69 +/- 7
		10	69.7 +/-0.2	90 +2/-1	10.9 +/-0.8	88.36+/-0.03	47.64+/-0.02	-2 +1/-2	0.72 +/-0.12	66 +/- 4	68 +/-1	-14 +/-3	66 +/- 1
		20	69.7 +/-0.2	89 +/-1	10.5+0.8/-0.9	88.38+/-0.03	47.64+/-0.02	-1 +2/-1	0.75 +/-0.13	65 +/- 4	68 +/-1	-16 +/-3	66 +/- 1
	RDI	5	70.4 +/- 0.4	85 +5/-3	15 +/-3	88.4+/-0.1	47.61+/-0.06	-1 +/-3	0.5 +/-0.2	68 +/- 10	69 +4/-5	-6 NC/-2	61 +/- 4
		15	70.0 +/-0.7	84 +8/-4	15 +6/-7	88.3+/-0.1	47.61+/-0.08	-1 +4/-5	1.0 +/-0.4	70 +/- 20	68 +4/-5	-7 NC/-2	68 +5/- 4
		25	70.1 +/-0.6	84 +6/-3	14 +5/-6	88.3+/-0.1	47.61+/-0.08	-3 +/-4	0.8 +/-0.3	71 +19/-18	64 +/-5	-8 NC/-4	70 +5/- 4
Injected disk "true" parameters			70.0	90.0	12.4	88.3	47.6	-2.0	0.94	70	70	-20	66

Disk Type	Reduction	KL #	R1[au]	R2[au]	βout	i[°]	PA[°]	dx[au]	dy[au]	N[ADU]	g1	g2	α
Faint 'HR 4796 like' disk	ADI	3	70.0 +/- 0.5	93 NC/-5	11 +/-2	77.0 +/- 0.3	26.6 +/- 0.2	-2 +/-1	0.8 +/- 0.4	21 +/- 3	66 +6/-7	-11 NC/-7	55 +/- 6
		10	70.1 +/- 0.4	91 +7 /-4	12 +/-2	76.8 +/- 0.2	26.7 +/- 0.1	-1.8 +/-0.5	1.0 +/- 0.3	21 +/- 2	71 +/- 4	-20 +/-7	64 +/- 3
		20	70.0 +/- 0.4	89 +6 /-3	12 +/-2	76.8 +/- 0.2	26.7 +/- 0.1	-1.7 +/-0.5	1.1 +/- 0.3	21 +/- 3	71 +/- 4	-18 +6/-7	62 +/- 3
	RDI	5	67 +3 /-5	80 -6/NC	NC	72 +/-2	26 +/ 2	NC	NC	7 +4/-2	83 +/-8	NC	96 NC/-8
		15	67 +3/-4	83 +11/-7	16 +/-9	75 +/-1	25 +/ 1	-3 +5/-4	3 +3/-4	9 +5/-4	83 +/-7	NC	94 NC/-8
		25	67 +/- 3	86 +9/-7	13 +9/-7	75 +/-1	25 +/ 1	-3 +5/-4	3 +/-4	10 +6/-4	76 +/-7	NC	94 NC/-7
Injected disk "true" parameters			70.0	90.0	12.4	76.8	26.64	-2.0	0.94	20	70	-20	66

Disk Type	Reduction	KL #	R1[au]	R2[au]	βout	i[°]	PA[°]	dx[au]	dy[au]	N[ADU]	g1	g2	α
Bright 'HR 4796 like' disk	ADI	3	70.0 +/- 0.2	93 +/-4	12.0 +/- 0.9	76.9 +/- 0.1	26.67+/-0.07	-1.9 +/-0.3	0.8 +/- 0.1	72 +4/-5	70 +/-2	-14 +/-4	62 +/- 2
		10	69.9 +/- 0.1	98 +2/-3	11.08+/- 0.5	76.80+/-0.06	26.67+/-0.04	-2.0 +/-0.2	0.8 +/- 0.1	73 +/-2	70 +/-1	-17 +/-2	64 +/- 1
		20	69.7+/-0.1	98 +1/-3	11.08+/- 0.4	76.81+/-0.06	26.71+/-0.04	-2.0 +/-0.2	0.8 +/- 0.1	73 +/-2	68 +/-1	-17 +/-2	62 +/- 1
	RDI	5	70.7+0.4/-0.5	80 +4/-1	22.0 +6/- 9	76.0 +/- 0.2	26.4+/-0.2	-2.2 +/-0.7	0.75 +/- 0.25	76 +15/-20	65 +/-3	-10 NC/-6	76 +/- 4
		15	70.3+0.5/-0.7	81 +7/-3	21 +6 /-9	76.2 +/- 0.3	26.5+/-0.2	-2.3 +/-0.9	1.2 +/- 0.4	72 +17/-22	72 +/-2	-22 +/-9	79 +/- 3
		25	70.3+0.6/-0.7	83 +8/-4	20 +6 /-8	76.2 +/- 0.3	26.5+/-0.2	-2.2 +/-0.9	1.1 +/- 0.4	71 +17/-20	71 +/-2	-22 +/-9	80 +/- 3
Injected disk "true" parameters			70.0	90.0	12.4	76.8	26.64	-2.0	0.94	70	70	-20	66

RECOVER SCATTERING PHASE FUNCTIONS



CONCLUSIONS

DiskFM is a powerful tool to extract physical parameters from a coronagraphic image of a disk in ADI, RDI or SDI, already used for SPHERE and GPI . This proceeding shows that DiskFM can sometimes gives under-estimated error bars, which encourage us to estimate more carefully uncertainty maps. We encourage developers of other disk post-processing techniques to reproduce this analysis with their own methods. **The planet imaging community is now organizing blind imaging challenges that could be imported in the circumstellar disk community, following the method that is shown in this paper, with the goal of aligning our metrics and goals.**

REFERENCES

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[3] Arriaga et al. 2020 AJ
[4] Milli et al. 2012 A&A
[5] Esposito et al. 2014 ApJ
[6] Millar-Blanchaer et al. 2016 AJ

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