Circumstellar Disks Around Rapidly-Rotating Be Stars:

An Observing and Modeling Study using Interferometry and Spectrophotometry

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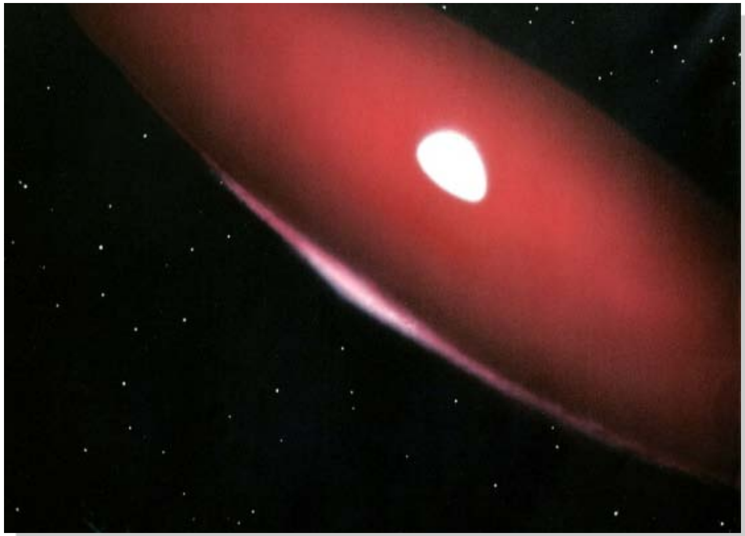
Nature of Be Stars

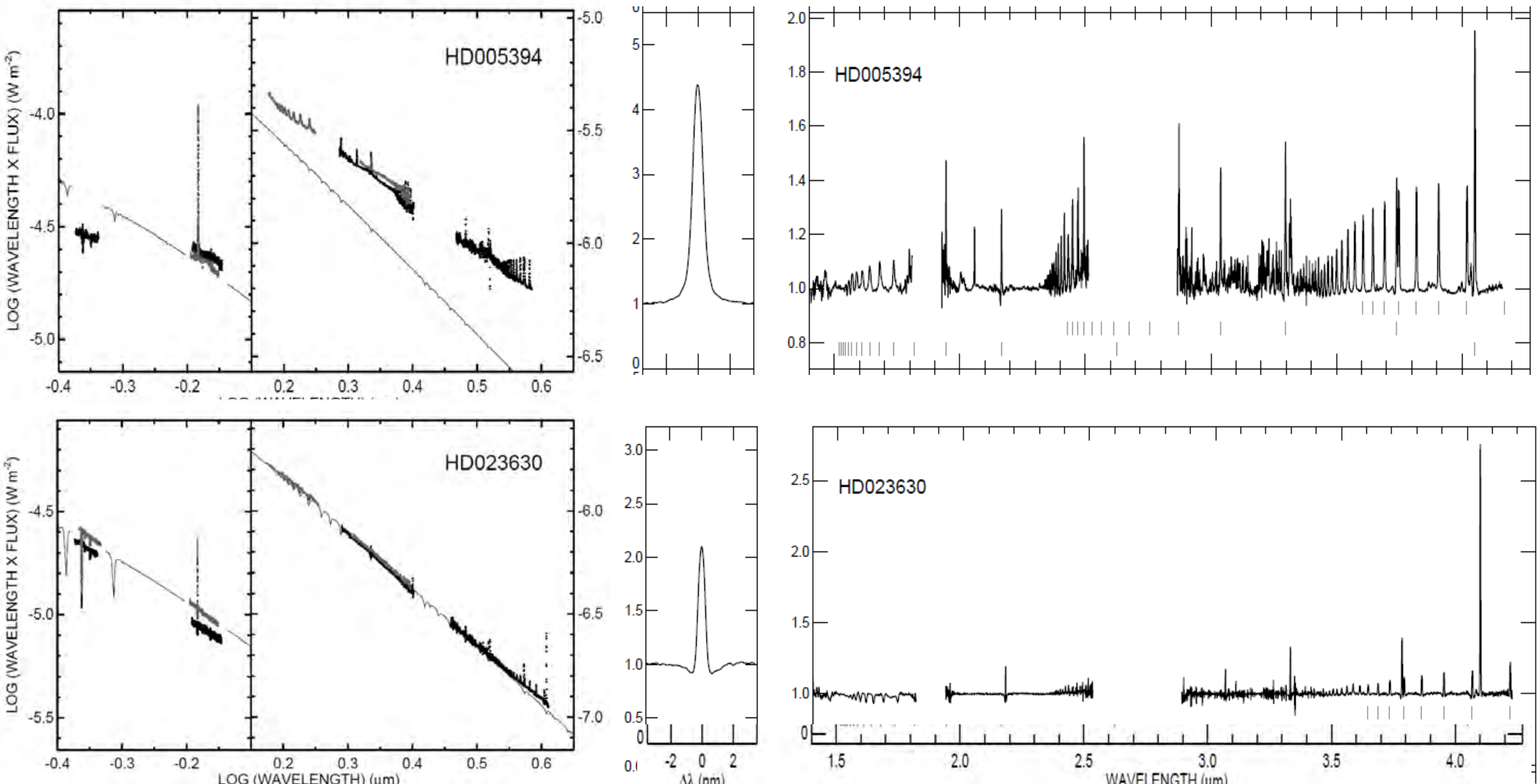
- Massive B-type Stars with prominent hydrogen emission lines and singly ionized metal lines
- Extreme rotation, close to critical
- Stellar gas ejected into a circumstellar, outflowing disk
- 15% of all Galactic B stars are Be stars
- Be disks are variable: Be → B → Be
- The disk density drops with distance from the star as r^{-n} with n ~ 2.5–4.0
- Testbeds for evolutionary models of rapidly rotating stars
- Closest examples of ionized gas disks



Our Mission

- How big are Be disks in the *K*-band?
- What are their geometries?
- What is a typical Be disk density profile?
- How do the *K*-band disk properties relate to the disk properties seen in Hα and in mid-infrared?
- How close to critical are Be stars rotating?

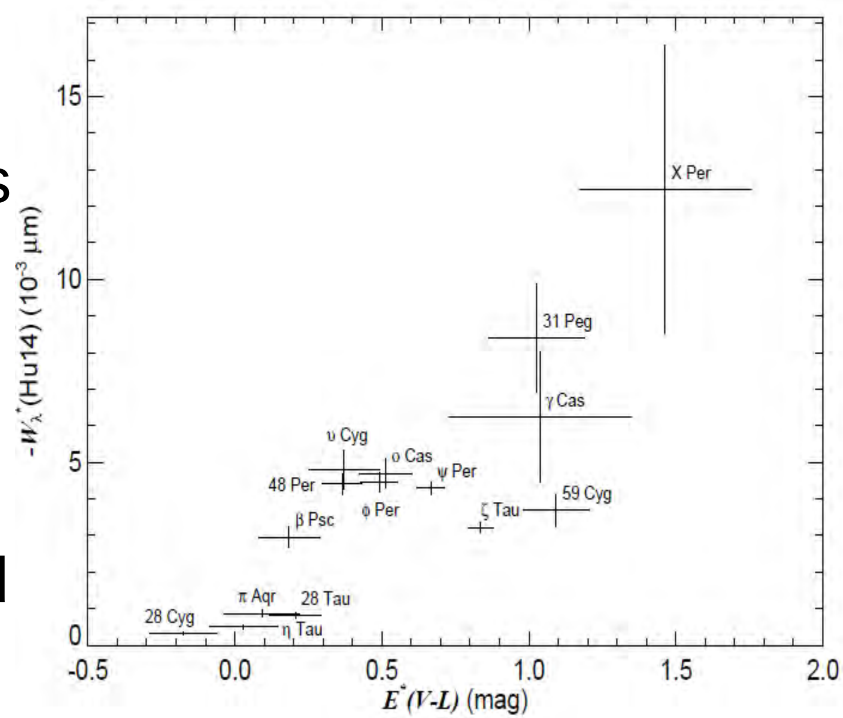
SEDs and Spectra



Touhami et al. (2010)

IR Excess and Emission Lines

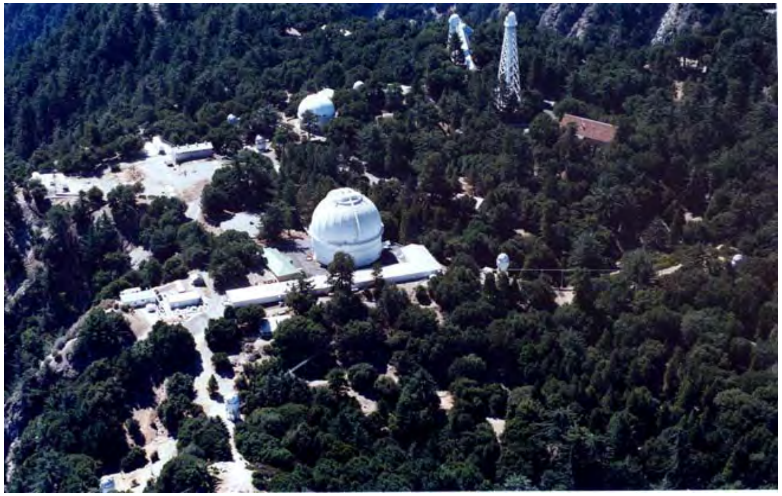
- The amount of the IR excess is correlated with the Hα Equivalent-width
- The amount of the IR excess is better correlated with the Equivalent-widths of high excitation transitions like Hu14
- The correlation suggests that the IR continuum emission and the high excitation line emissions both originate in the inner dense parts of the disk

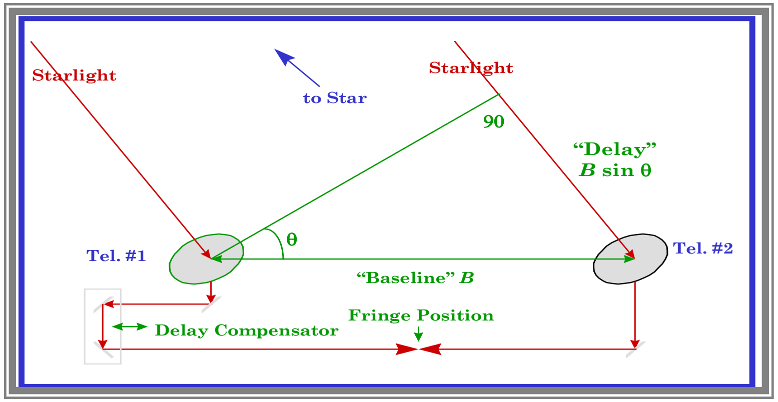


Touhami et al. (2010)

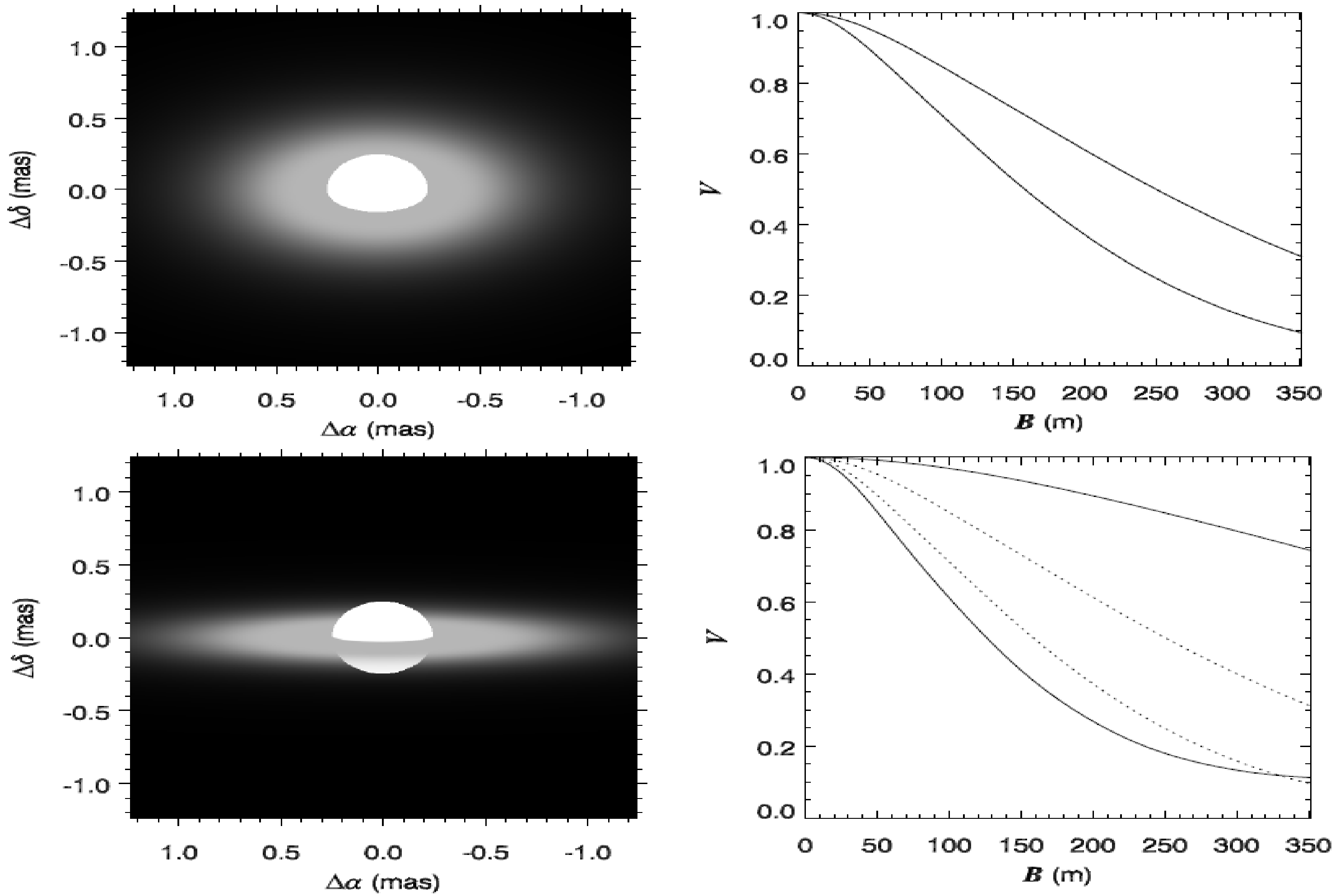
An Interferometric Survey

- A survey of 24 bright Be stars in the *K*- band to determine size and orientation of Be disks.
- Project started in 2007 and reached the completion stage in Fall 2011
- CHARA CLASSIC beam combiner
- FLUOR beam combiner in some cases
- Intermediate to Long baselines (330 meters) of the CHARA Array interferometer



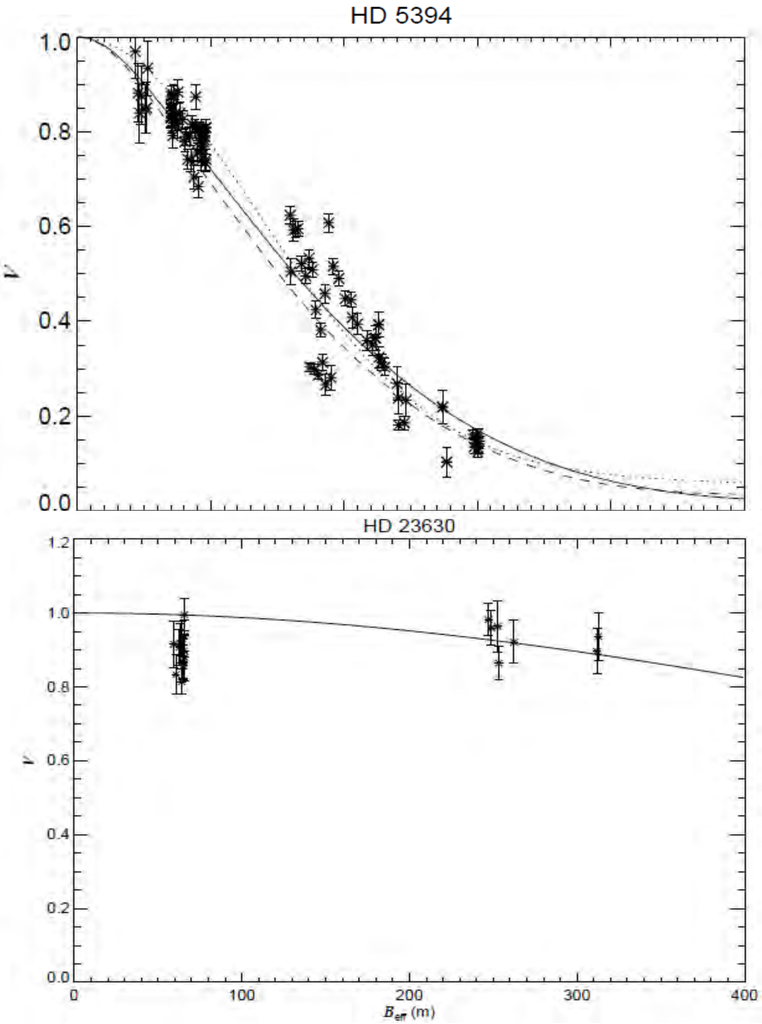


Visibility Function

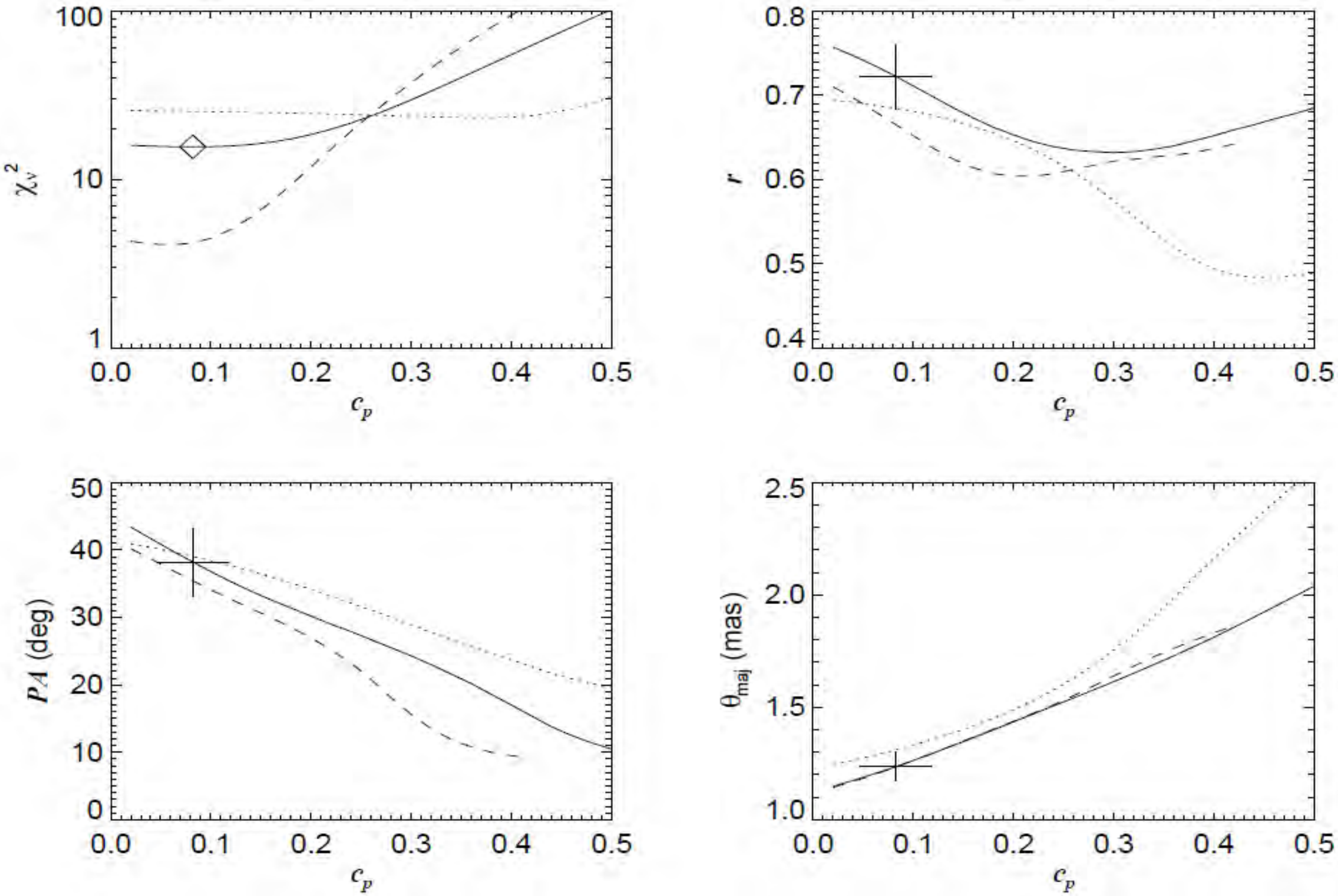


Survey Results

Star Name	r_{fit}	ϕ_{fit} (degrees)	c_p	FWHM (mas)	χ^2	Corr. c_p	Corr. $\frac{R_d}{R_s}$
HD 004180	0.51±0.06	156±11	0.69±0.04	1.18±0.05	4.3	0.71	4.12
HD 005394	0.48±0.11	38±8	0.18±0.06	1.74±0.09	8.4	0.26	3.96
HD 010516	0.32±0.12	118±6	0.58±0.04	1.09±0.06	4.5	0.63	4.20
HD 022192	0.35±0.09	131±6	0.61±0.05	1.34±0.07	2.3	0.66	3.75
HD 023630	0.71[a]	24[b]	0.89±0.04	0.81±0.05	2.2	0.95	1.46
HD 023862	0.42[a]	159[b]	0.77±0.06	0.62±0.09	2.9	0.83	2.38
HD 025940	0.78[a]	20[b]	0.85±0.05	1.18±0.08	2.5	0.86	3.12
HD 037202	0.07±0.06	121±8	0.44±0.06	1.73±0.06	4.8	0.61	3.13
HD 058715	0.71±0.09	134±7	0.73±0.09	0.91±0.08	3.5	0.86	1.57
HD 109387	0.64[a]	102[b]	0.71±0.08	0.89±0.06	2.2	0.77	2.38
HD 138749	0.18[a]	177[b]	0.89±0.05	0.51±0.05	2.2	0.96	1.67
HD 142926	0.28[a]	70[b]	0.76±0.05	0.66±0.07	1.6	0.80	3.61
HD 142983	0.38[a]	72[b]	0.69±0.08	0.82±0.09	1.5	0.73	3.43
HD 148184	0.94[a]	140[b]	0.55±0.09	1.16±0.07	1.7	0.58	3.42
HD 164284	0.67[a]	18[b]	0.93±0.06	0.41±0.06	4.8	0.96	1.69
HD 166014	0.86[a]	89[b]	0.91±0.05	0.61±0.08	4.3	0.95	1.48
HD 198183	0.81[a]	30[b]	0.93±0.08	0.42±0.04	5.2	0.96	1.72
HD 200120	0.31±0.05	75±8	0.62±0.08	1.05±0.05	1.6	0.68	3.64
HD 202904	0.48±0.09	110±11	0.53±0.09	0.81±0.06	3.7	0.59	3.37
HD 203467	0.71±0.09	62±7	0.78±0.06	0.76±0.08	2.3	0.81	3.32
HD 209409	0.63±0.06	105±9	0.71±0.05	1.02±0.07	3.2	0.74	3.51
HD 212076	0.95[a]	148[b]	0.82±0.04	0.63±0.05	1.8	0.83	3.49
HD 217675	0.22±0.11	18±8	0.92±0.05	0.51±0.07	3.4	0.97	1.62
HD 217891	0.91 ± 0.04	34 ± 6	0.77±0.08	0.94±0.06	2.2	0.78	3.43



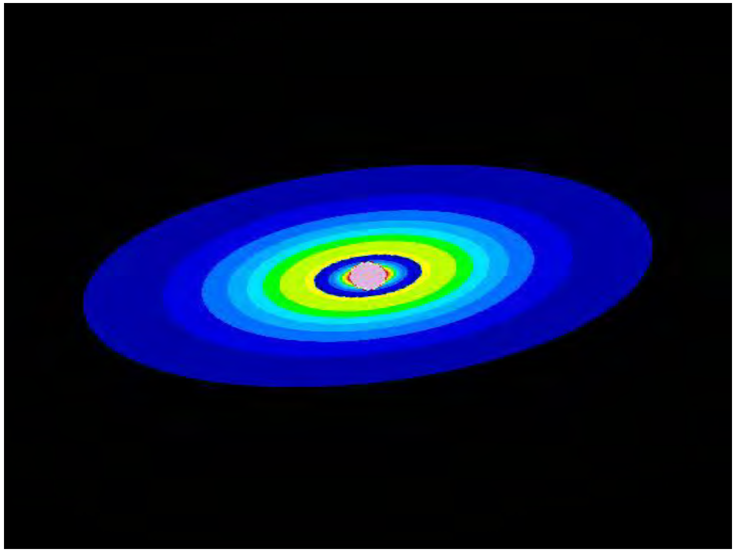
Gaussian Elliptical Model Degeneracy



Physical Model of The K-band Visibility

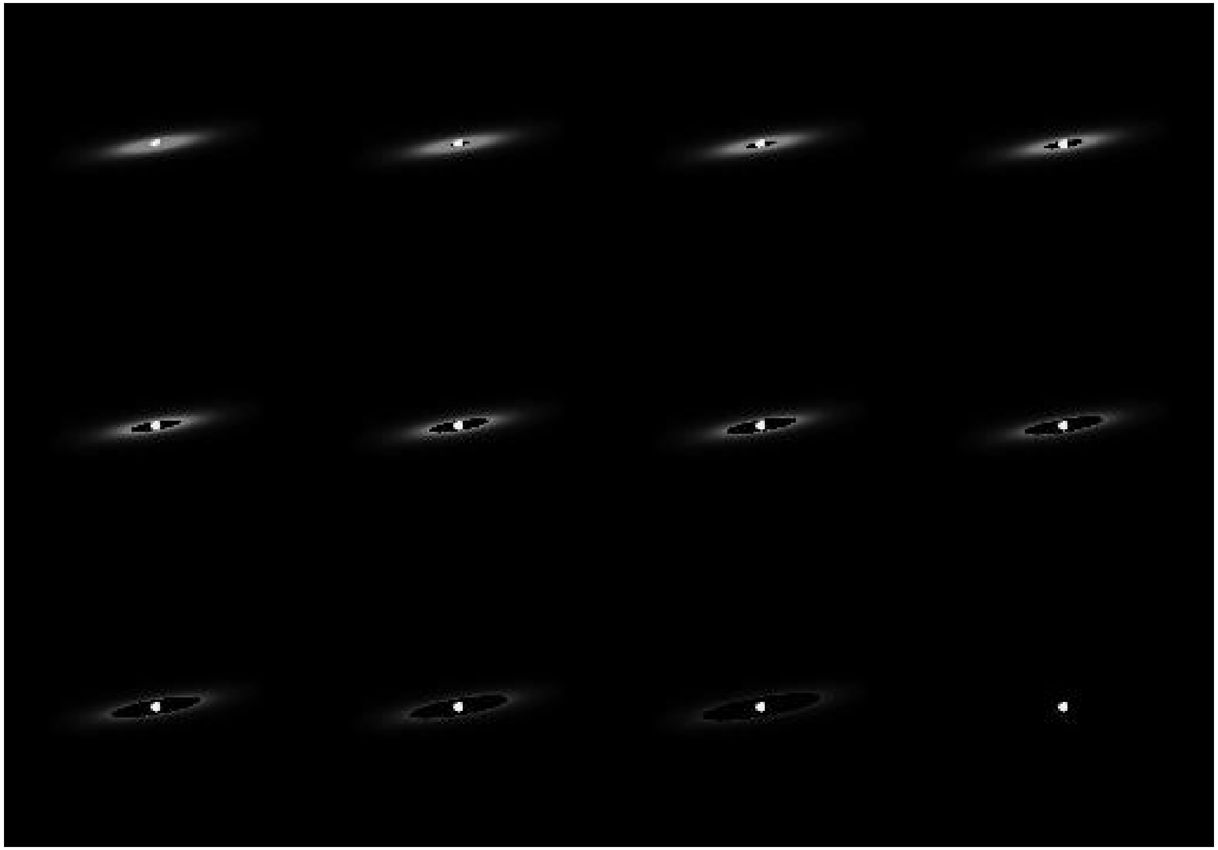
- Uniform disk star with a set of initial physical parameters: (M_s , R_s , T_{eff} , π)
- Disk geometry (Hummel & Vrancken 2000)

$$\begin{cases} \rho(\mathrm{r},\mathrm{z}) = 0, & r < r_0 \\ \rho(\mathrm{r},\mathrm{z}) = \rho_0 (r/r_o)^{-n} \exp(-1/2(\mathrm{z}/H)^\wedge 2), & r > r_0 \end{cases}$$

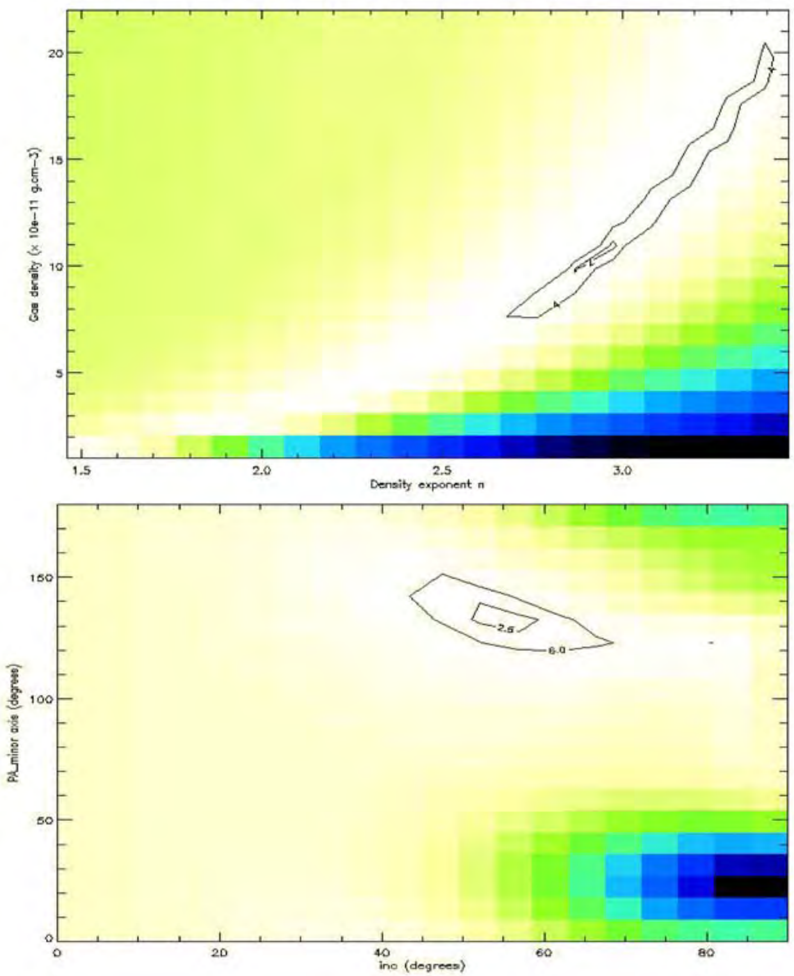


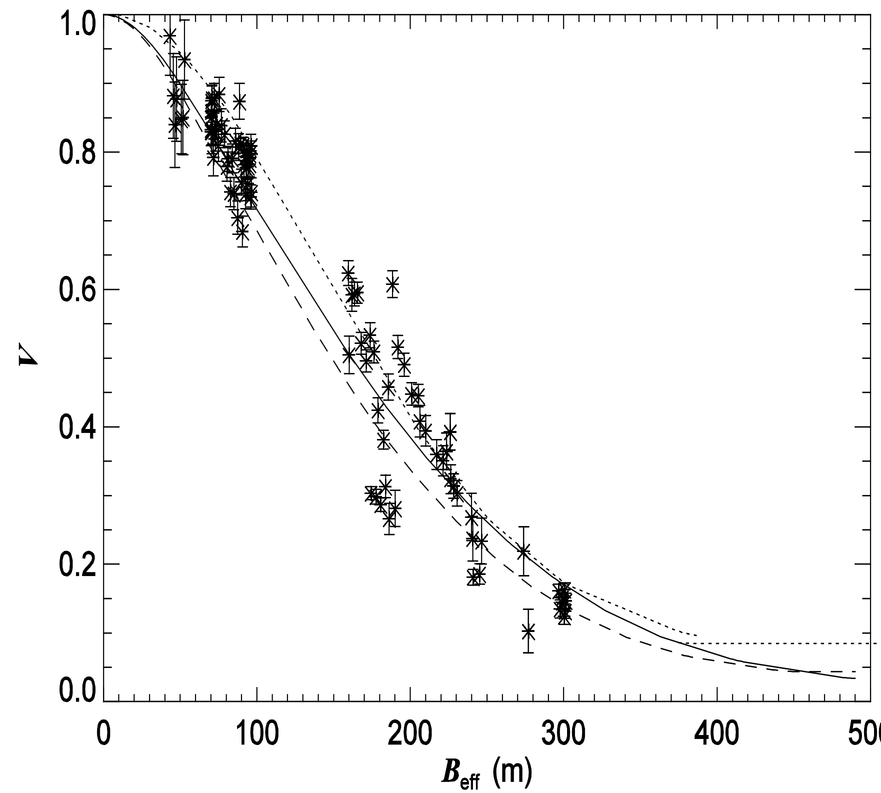
- r_0 = inner disk radius (R_0)
  ρ_0 = base density (g cm^{-3})
  n = radial density exponent
  $H(R) = R^{3/2}\, C_s / V_K$ = disk scale height
- Observer parameters:
- i = inclination of disk normal
  α = position angle
- Output: infrared images, infrared excess, and visibility as a function of (u,v)

Decreting Disks of Be Stars

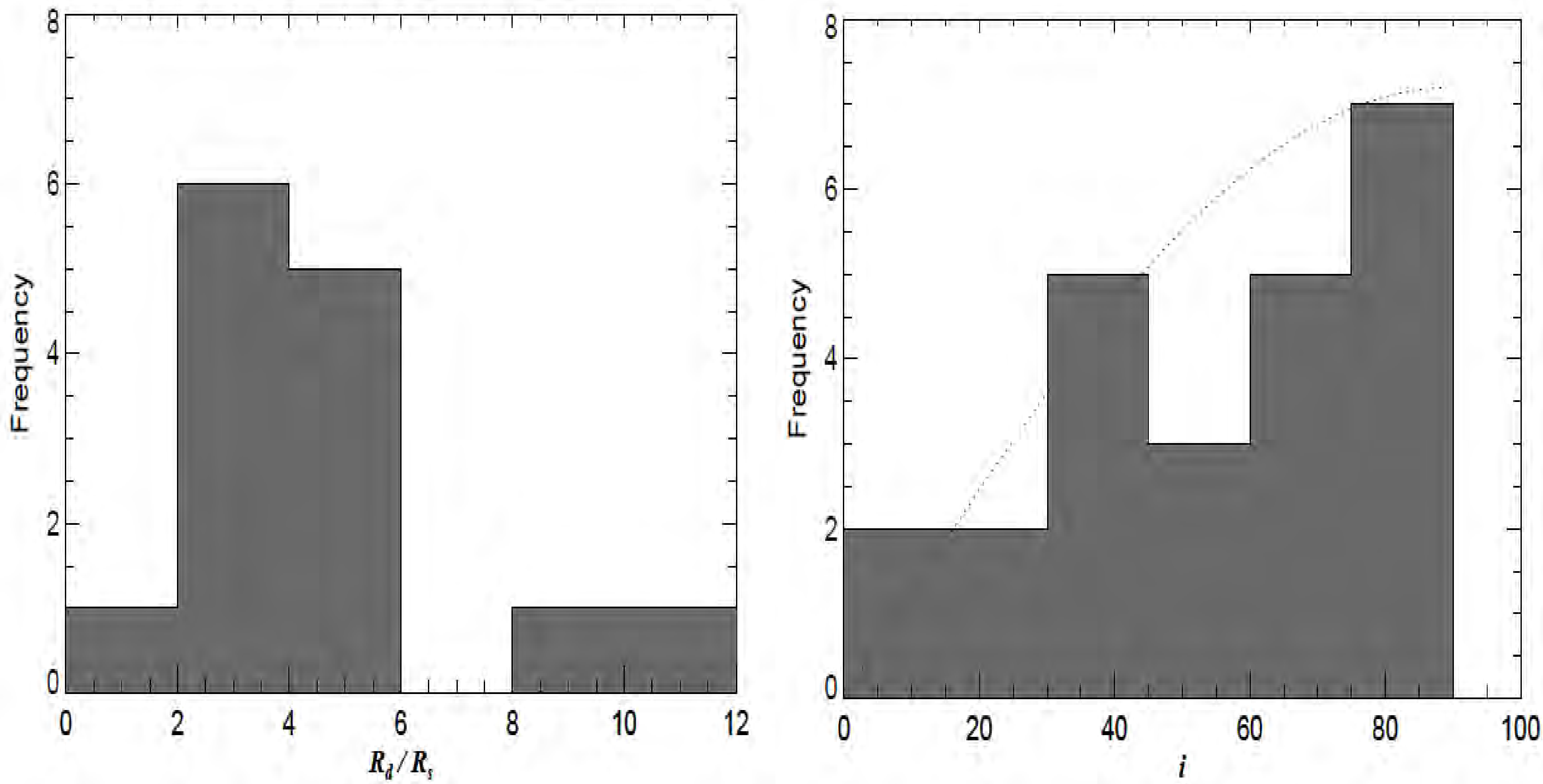


Model Parameter Space

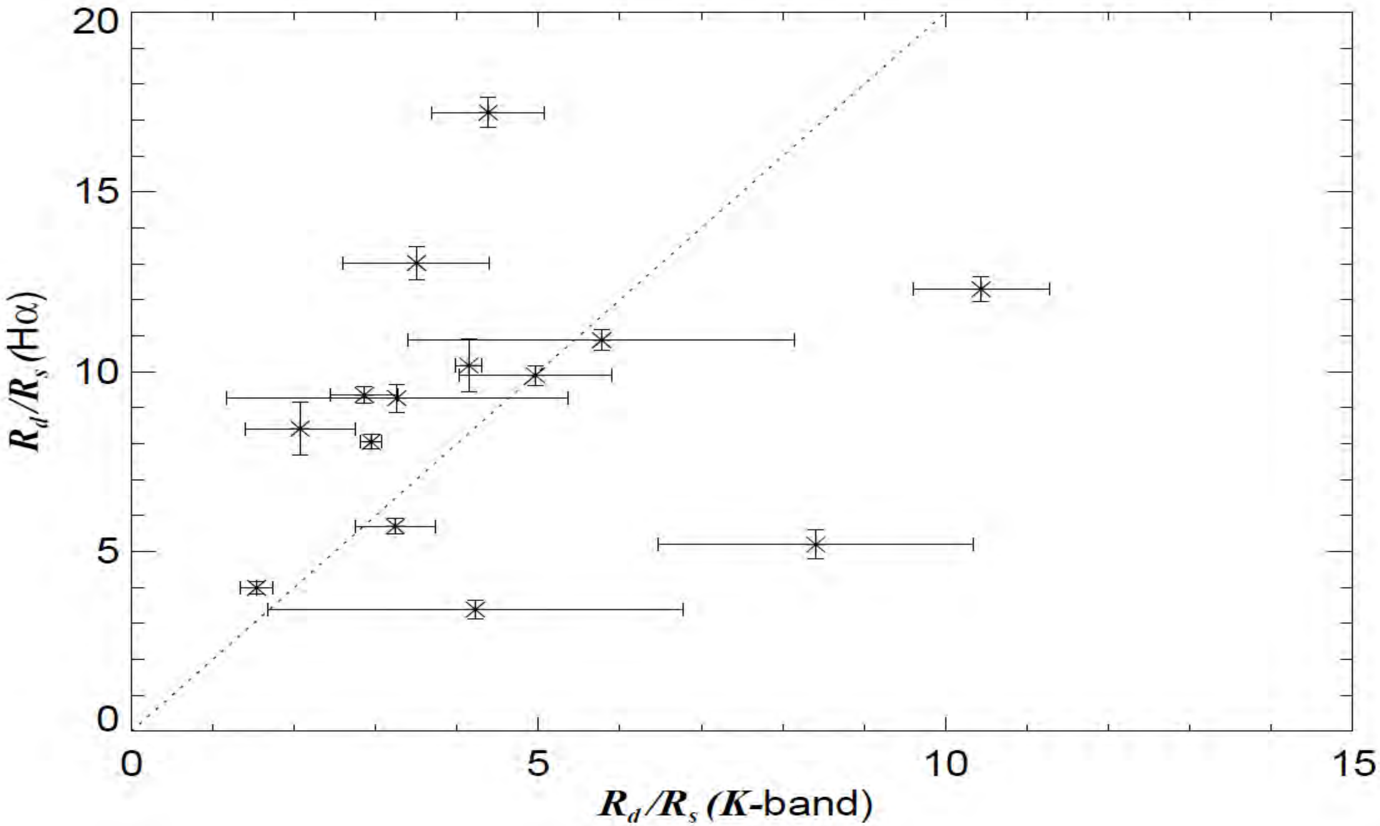




Typical Be Disk Geometry & Density

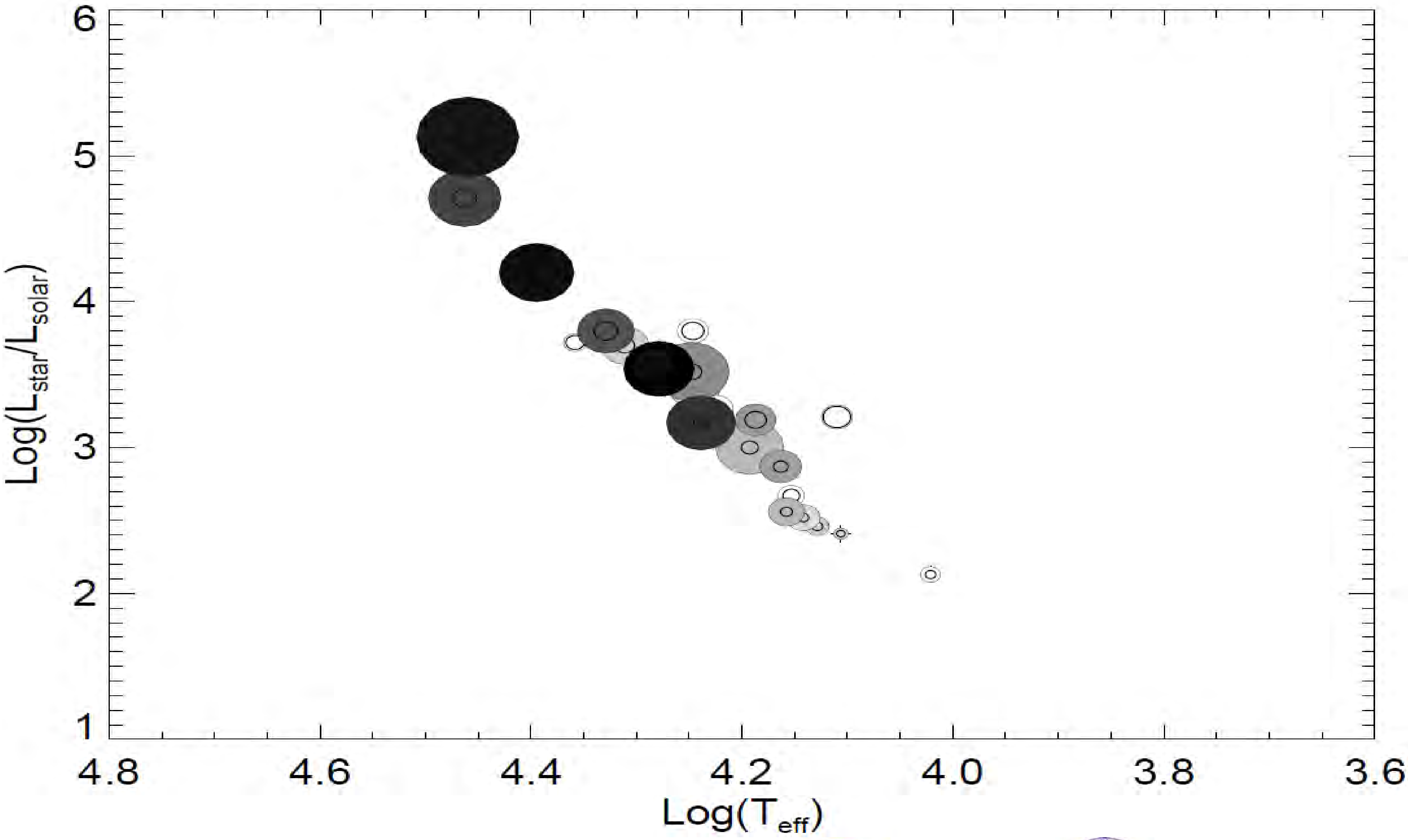


Disk Sizes in K-band and Hα



Hα disk sizes measured with the NPOI interferometer (Tycner et al. 2005, 2008)

HR Diagram for Be Stars



Summary

- We resolved circumstellar disks surrounding 24 relatively nearby Be stars using CHARA
- Simultaneous interferometry and spectrophotometry help constrain the geometry and the density of Be disks
- The *K*-band sizes of Be disks are few stellar radii
- The disk density exponent ***n*** ranges between 2.5 - 3.5
- Disk sizes increase at longer wavelengths
- Using disk inclinations and *vsini*, the actual rotational velocity of Be stars is found to be close to critical

Thank you..