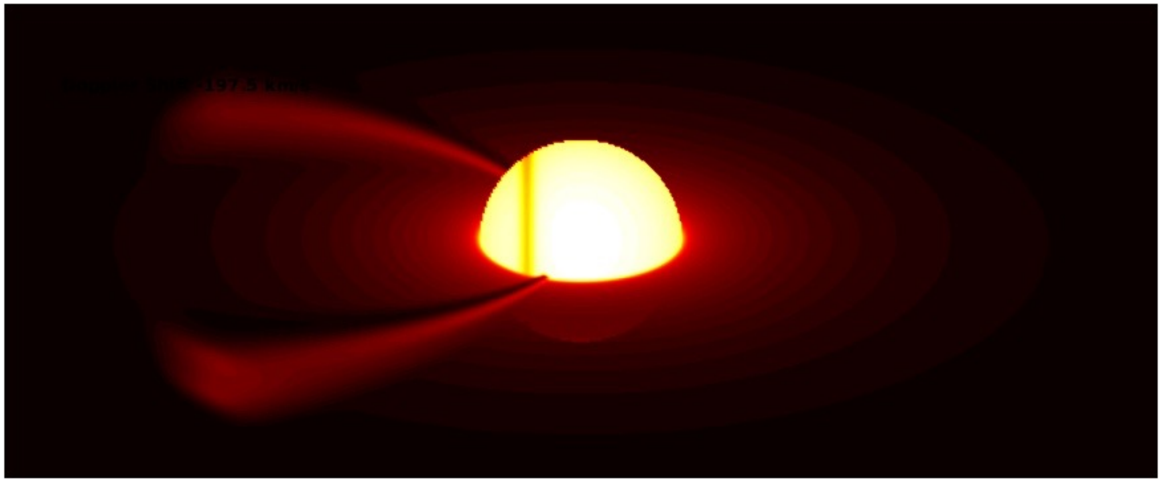
Constraining Be Star Disks with Combined Spectroscopy and Interferometry



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A Be star is defined as non-supergiant B star that has shown Hα emission *at least once* in its observational record.

Classical Be, B[e], sgB[e], Herbig Ae/Be, σ Ori E, ...

Definition suggests variability B ⇒ Be ⇒ B ...

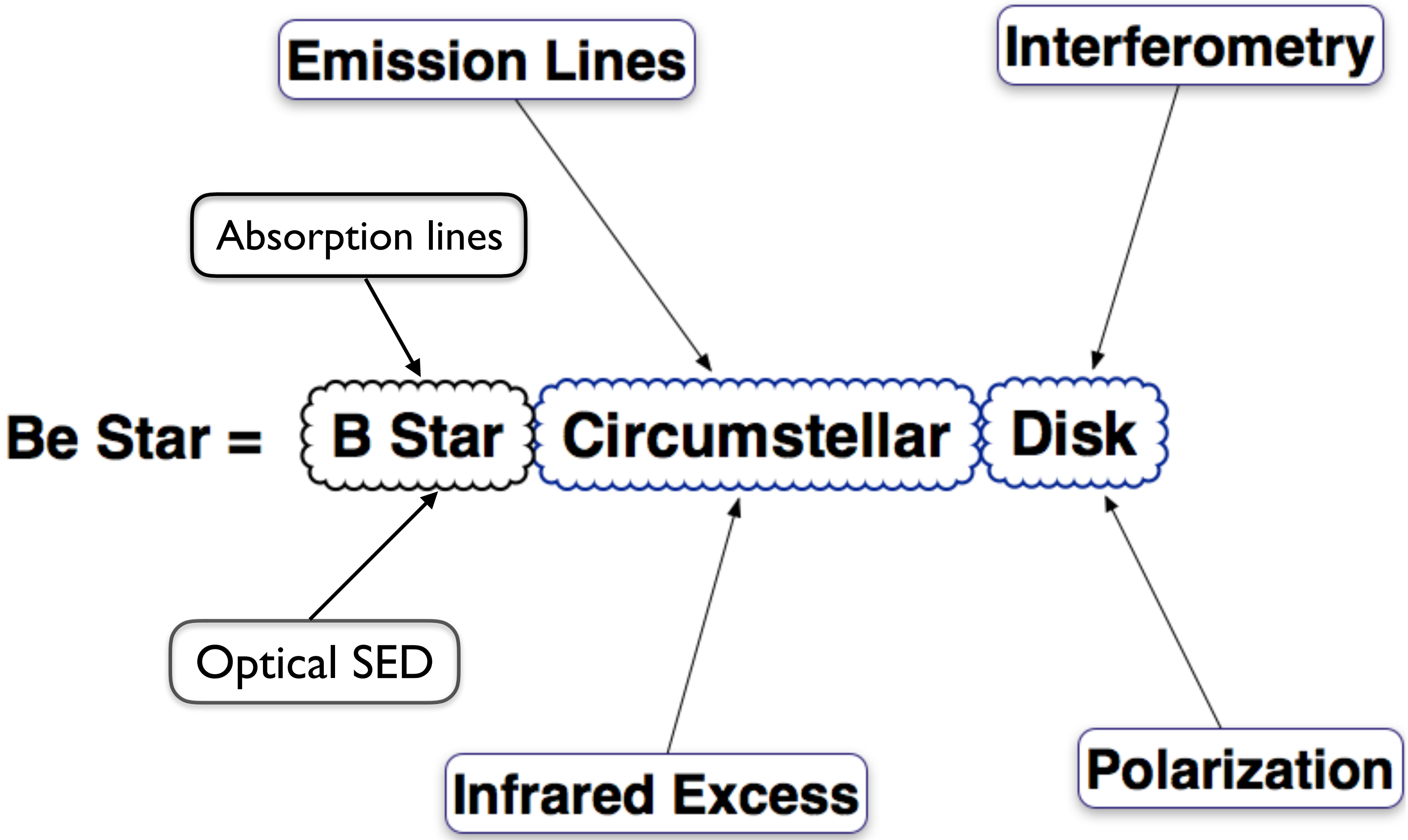
~20% of B stars are Be stars. Why?

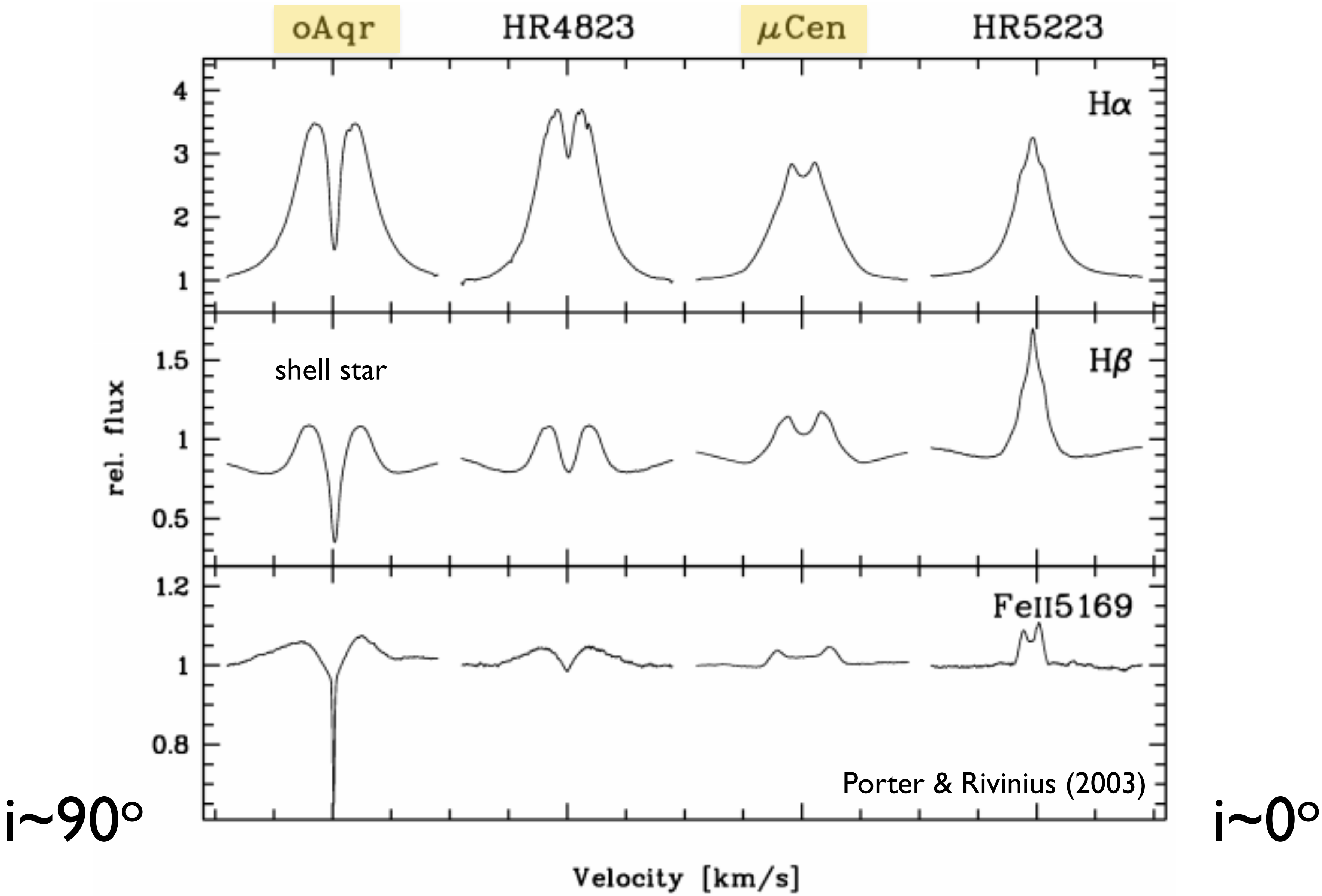
B Stars by the numbers

Mass 3.4 - 17.5 $M_\odot$

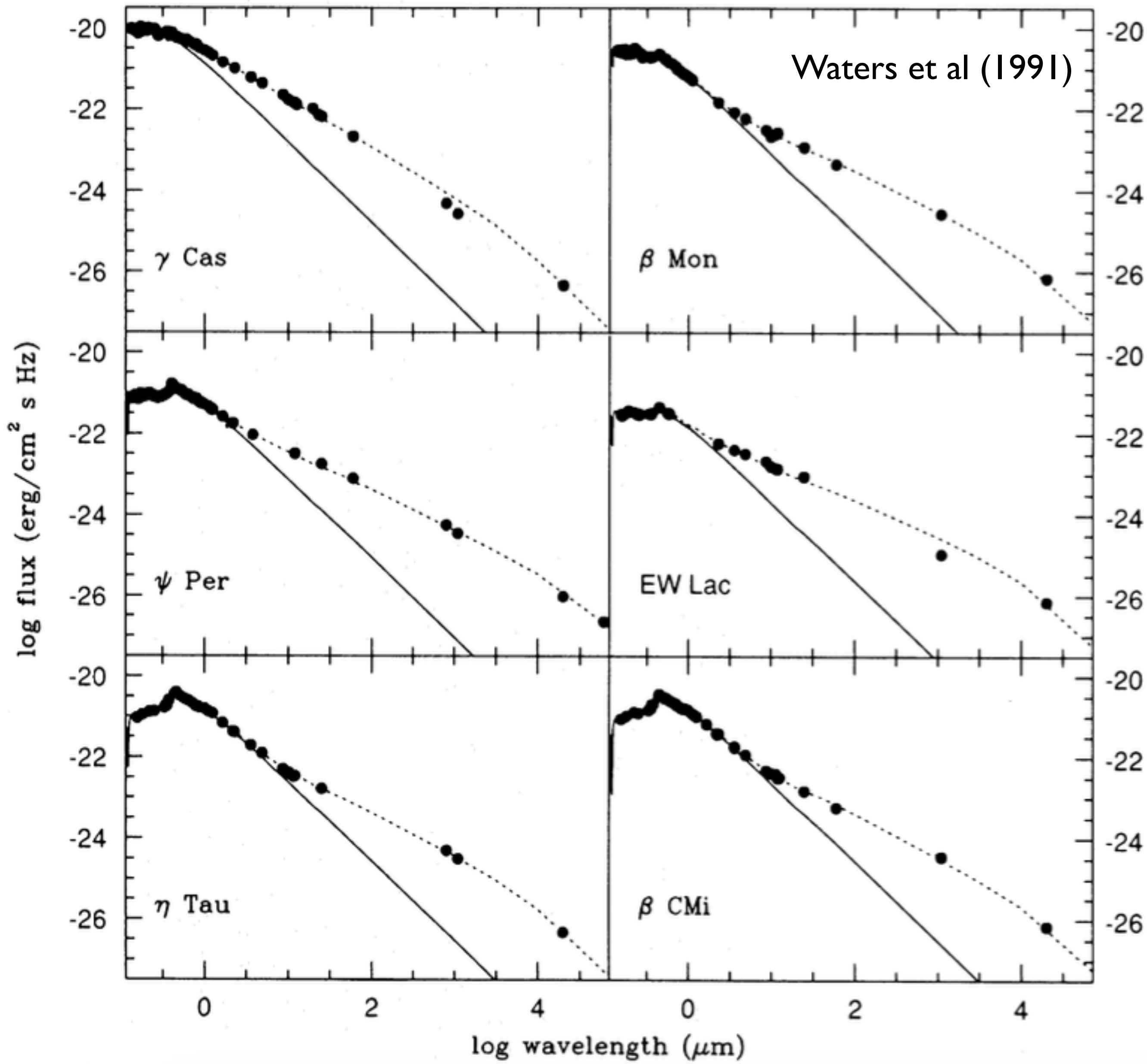
Radius 2.8 - 7.7 $R_\odot$

Luminosity 160 - 4.4 10^4 $L_\odot$


Emission Lines
Interferometry
Absorption lines
Be Star =
B Star
Circumstellar
Disk
Optical SED
Infrared Excess
Polarization



Viewing inclination (the *i* in vsin*i*) controls appearance of the spectrum...



IR excess consistent with free-free emission from an ionized disk

Why are Be Stars Interesting?

They are telling us important things about stellar rotation, in particular rapid rotation.

Be Stars are prime targets for optical and near-IR interferometry. Be stars are laboratories for disk dynamics.

Extra-galactic Be stars are known (SMC/LMC, M31) and are more common in lower metallicity environments like the LMC/SMC.

Struve (1931) *On the Origin of Bright Lines in the Spectra of Stars of Class B*

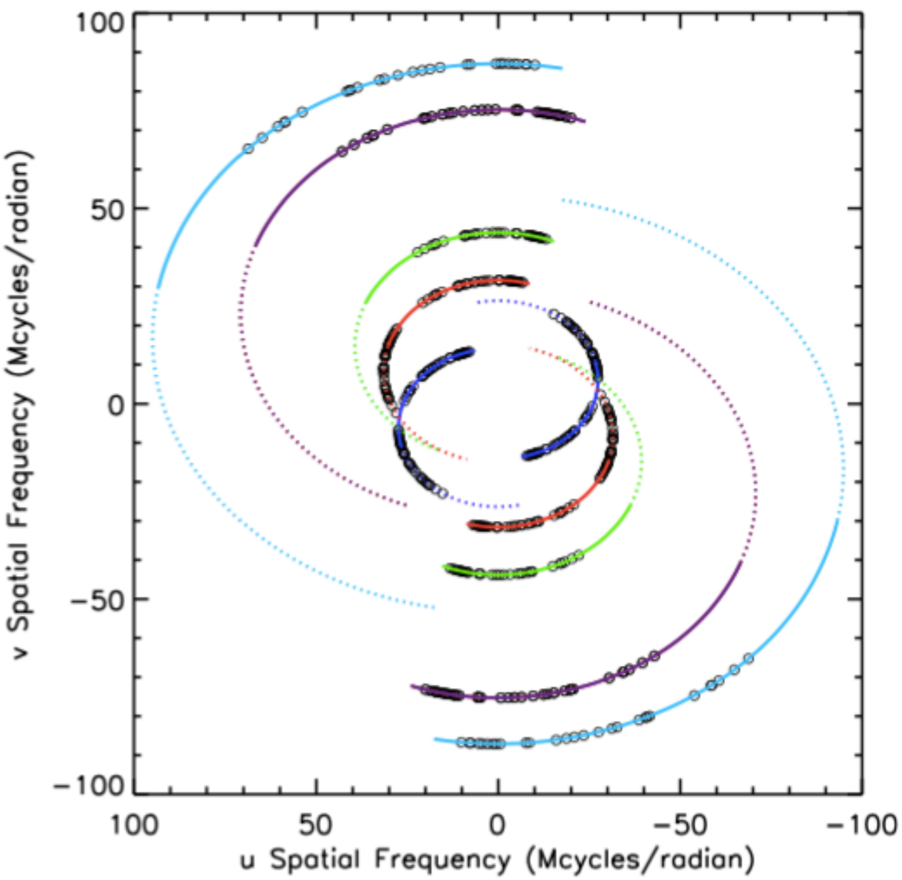
"Sir James Jeans has shown that under certain circumstances, a rapidly rotating, gaseous body may become lens shaped and throw off matter at its sharp equatorial edge."

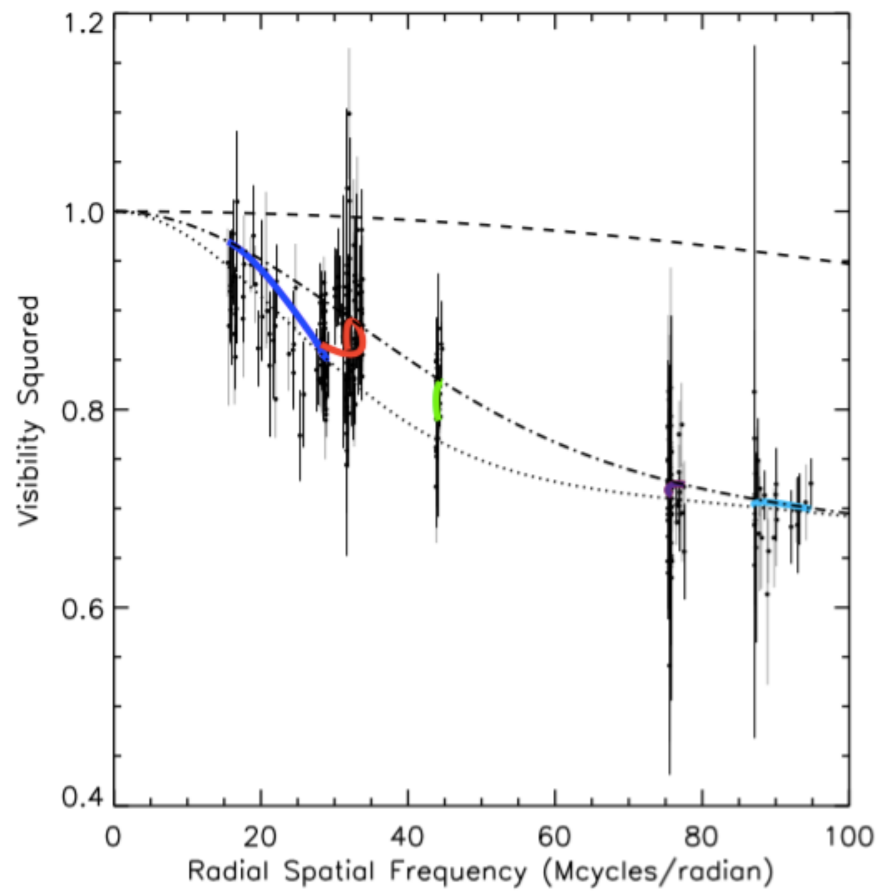
Interferometry of Be Stars

- There are many close, bright examples of Be stars— stars with names not numbers!
- A 5 solar radii B star at 150 pc has an angular diameter of ~0.3 mas. Typical disk radii are ~10 stellar radii making the disks ~3 mas on the sky.
- Good star-disk contrast can be achieved by observing either in a strong emission line (such as Hα) or in the near-IR (or radio).

Our approach is to combine constraints using radiative transfer modelling from spectroscopic line profile(s) (Hα), SED modelling, and interferometric visibilities from NPOI.

NPOI Observations of 48 Persei





Jones et al. (2017)

Radiative Transfer Modelling of Star-Disk Systems

Want to predict $I_\nu(x,y)$ on the sky:

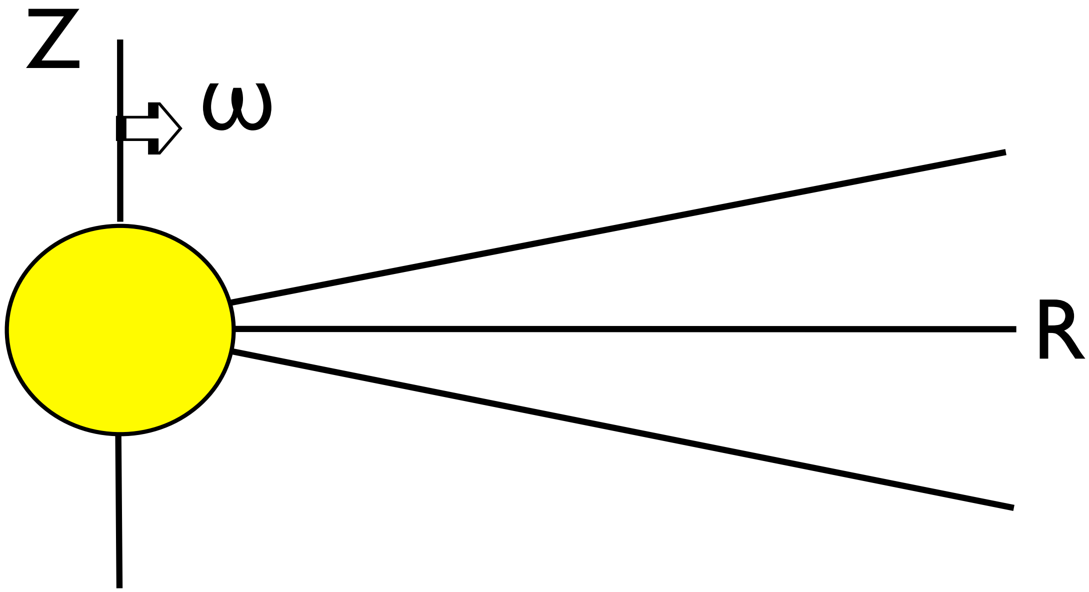
Radiative transfer problem requiring NLTE ε_ν and χ_ν

STAR: Model Photosphere(s): (T_{eff}, log g), Rotation

+

DISK: Density, velocity, temperature structure

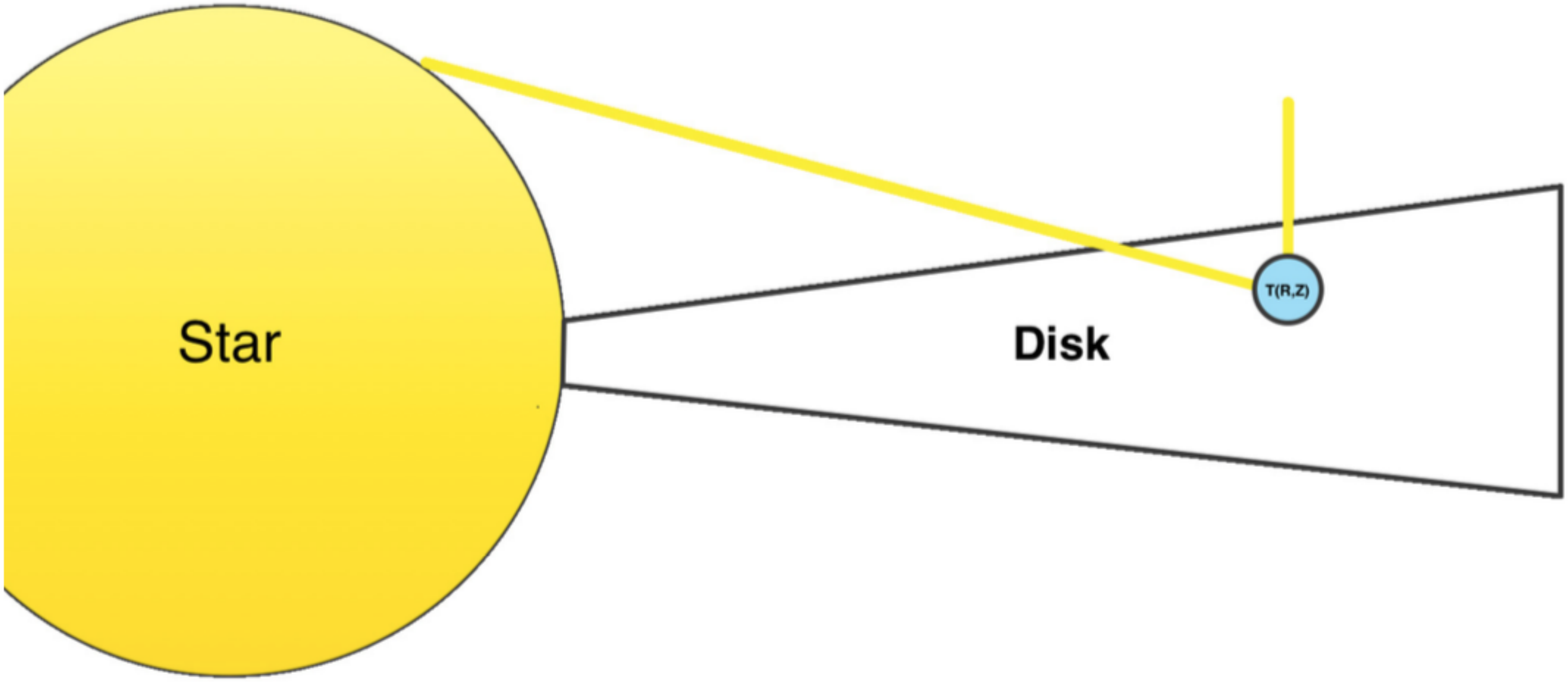
Disk Density Structure



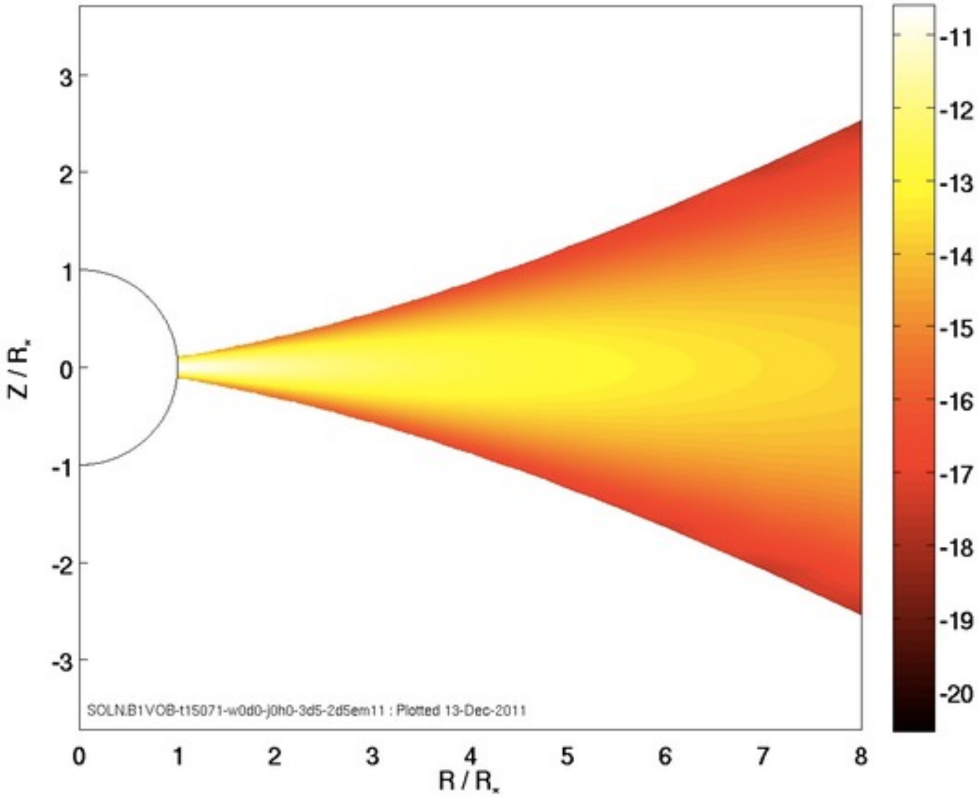
$$\rho(R,Z) = \rho_0 \left(\frac{R_*}{R}\right)^n e^{-(Z/H)^2} \qquad \frac{H}{R} = \frac{c_s}{V_K}$$

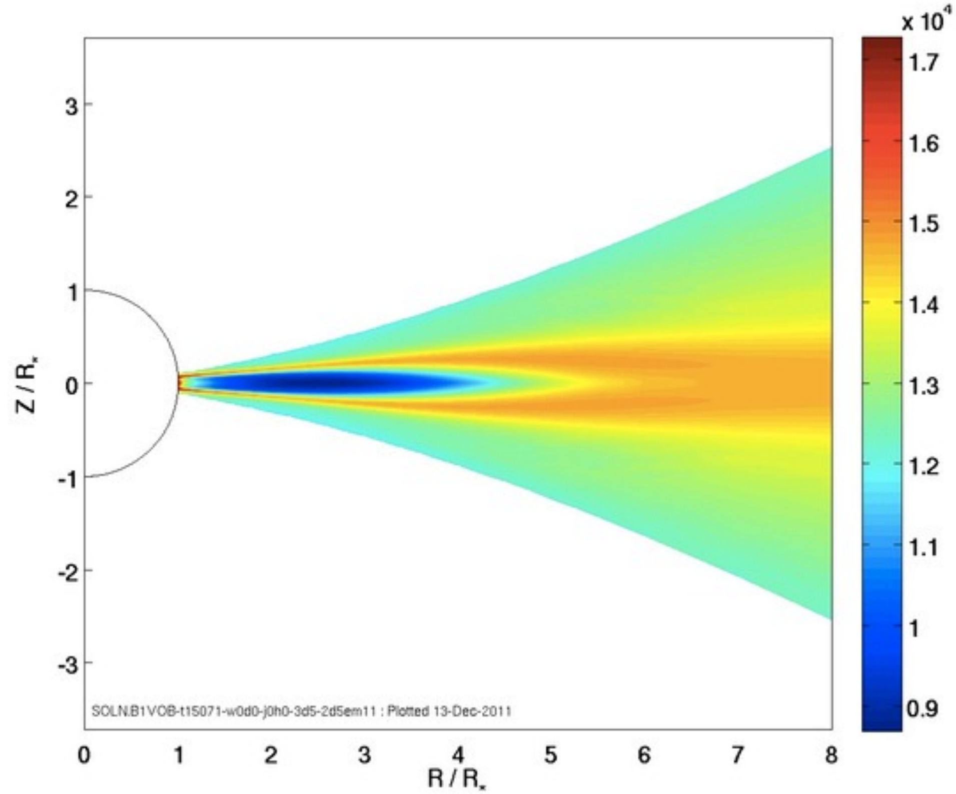
$$H(R) = H_0 \; (R/R_*)^{\frac{3}{2}}$$

Disk Temperature Structure: Bedisk



Disk temperatures found from radiative equilibrium in gas of solar composition:radiative transfer + statistical equilibrium (Sigut & Jones 2007)



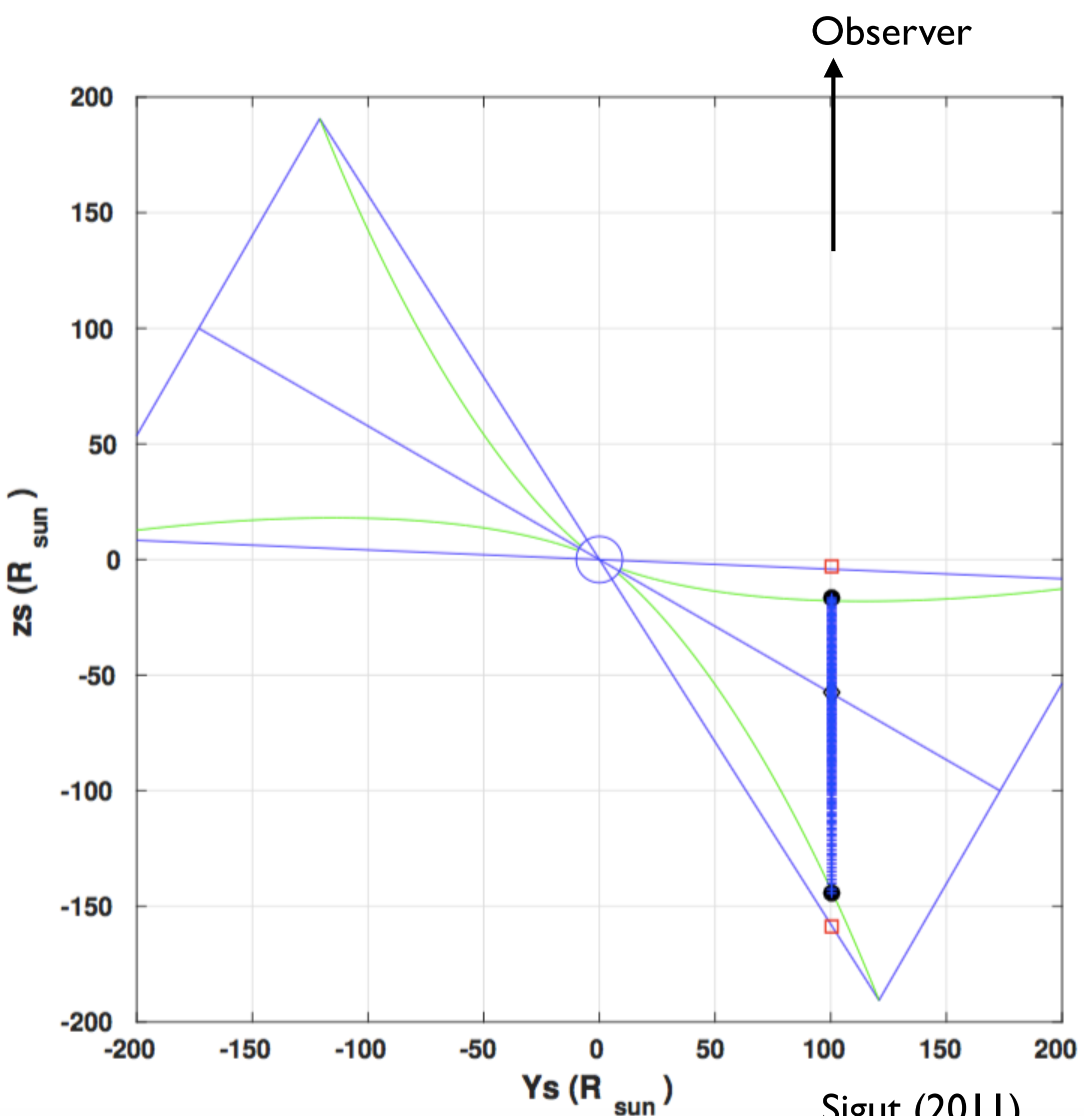


Bedisk

Density (assumed) ⟶ Temperature (R.E.)

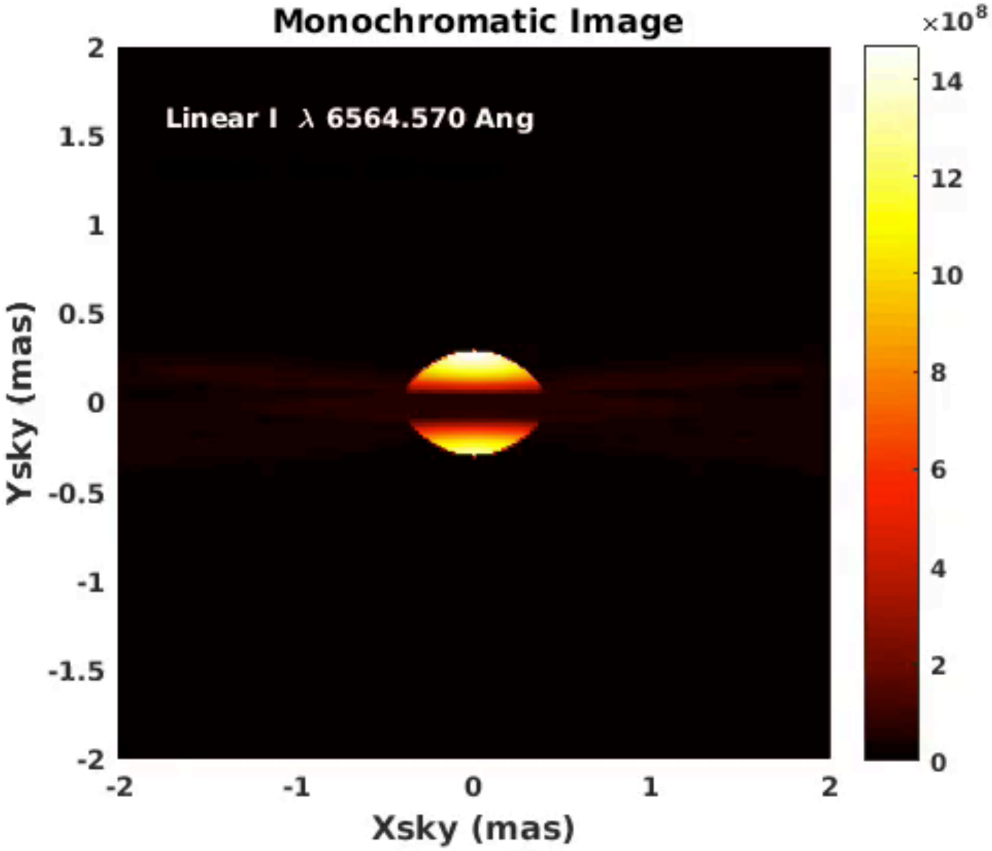
- As a by-product of this calculation, you obtain the atomic level populations of all atoms/ions ⇒ further formal solutions of RT

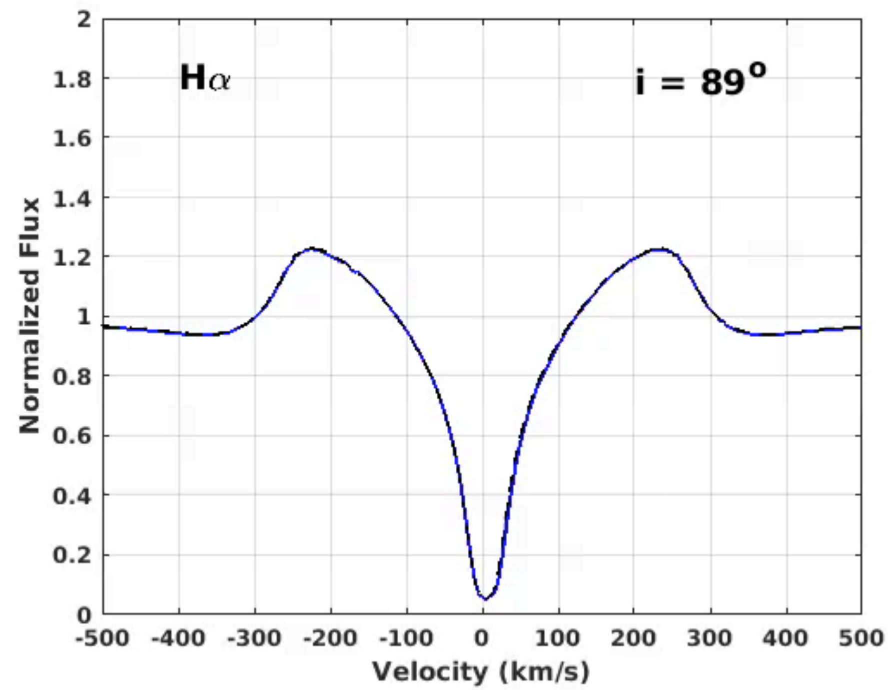
Spectra, SEDS, Images on Sky: Beray



Sigut (2011)

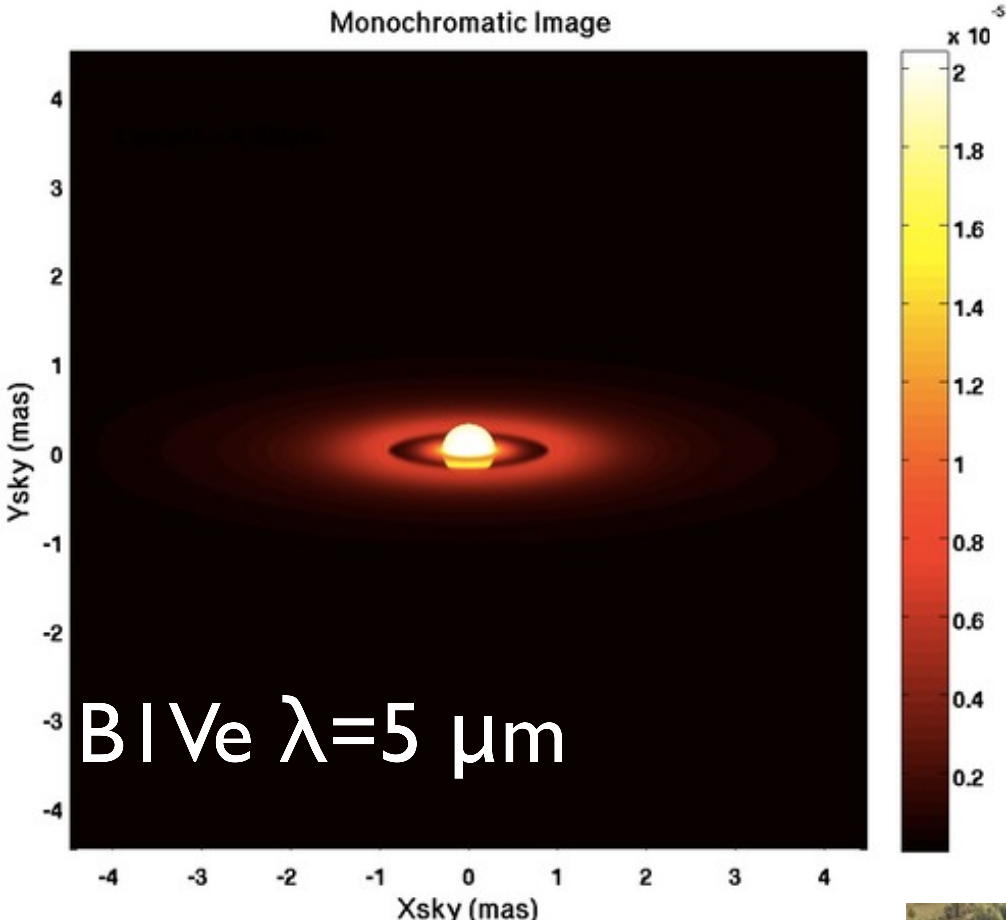
Solve radiative transfer equation along a series of rays directed at the observer.





https://www.youtube.com/watch?v=xWo-Ii730rY

https://www.youtube.com/watch?v=fs4-oq8Umhc



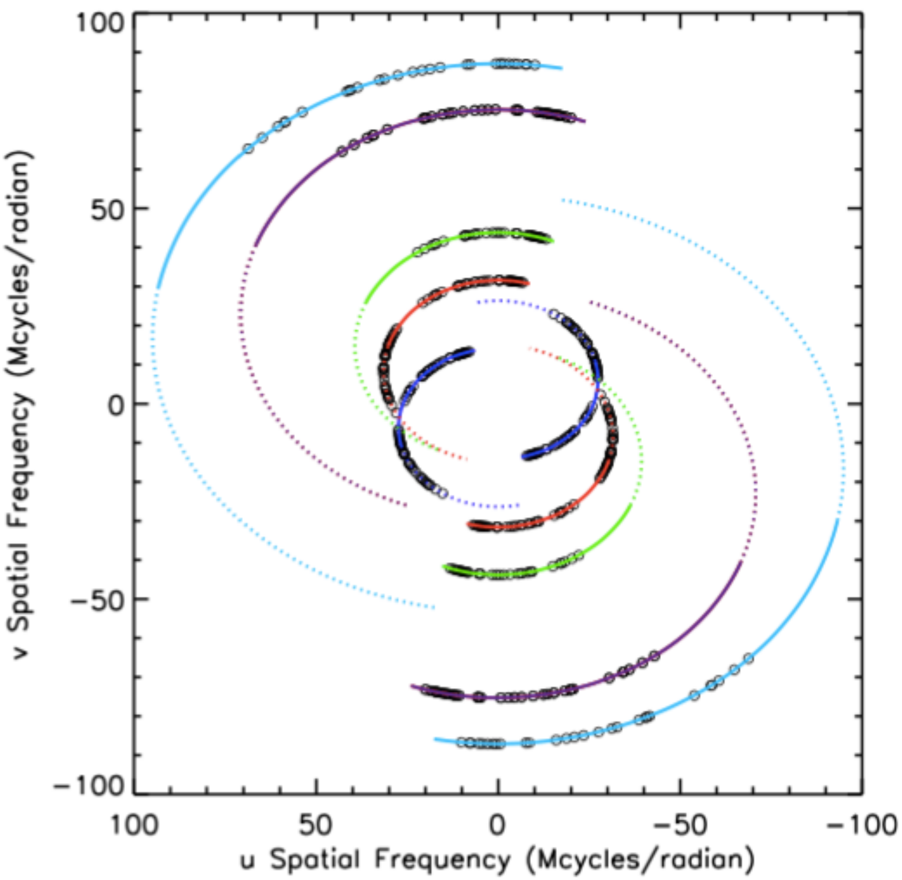
$$\int I(x,y)\frac{dxdy}{D^2}$$

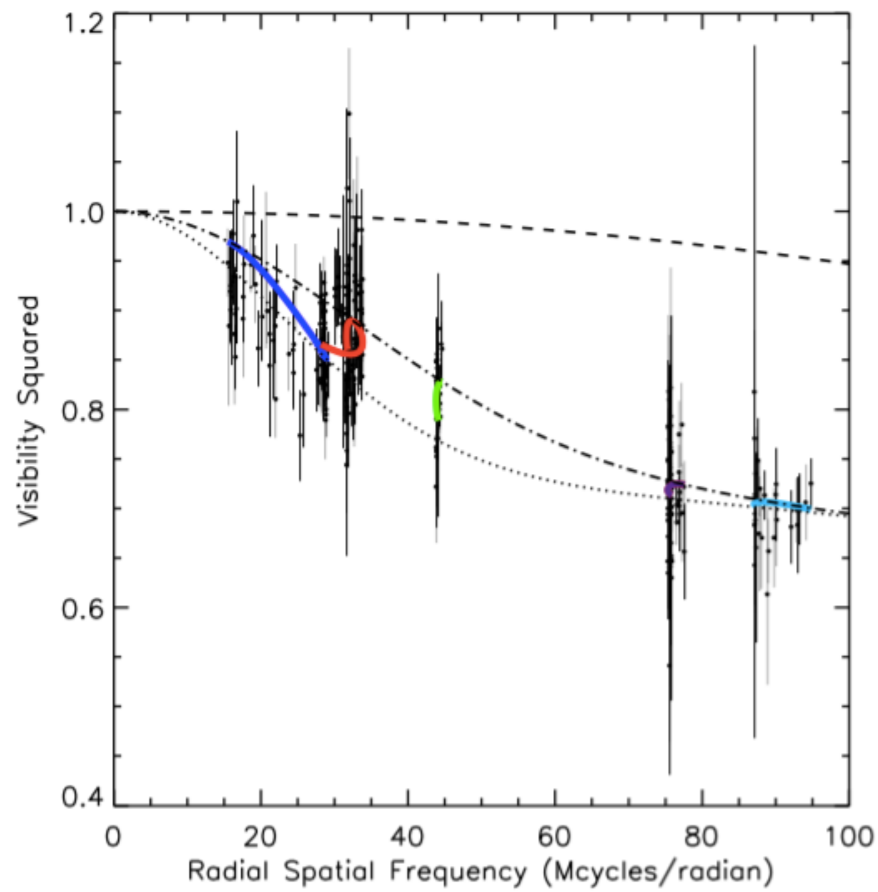
⇒Hα line profile, SED

$$\mathcal{FT}[I(x,y)]$$

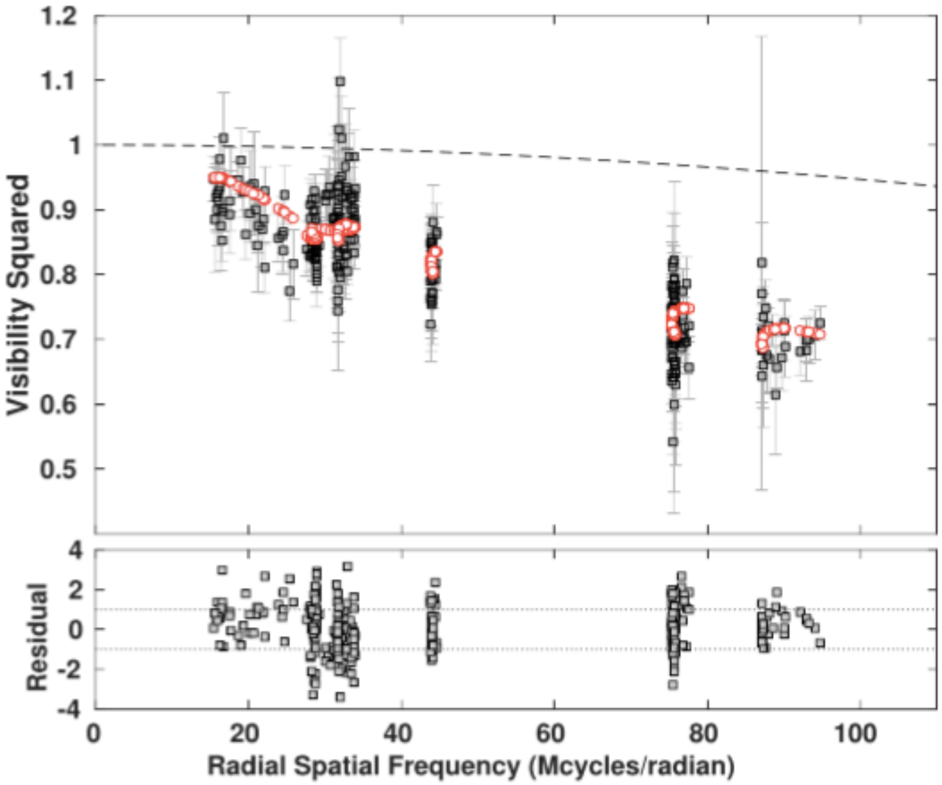
⇒Visibilities (phases)

NPOI Observations of 48 Persei



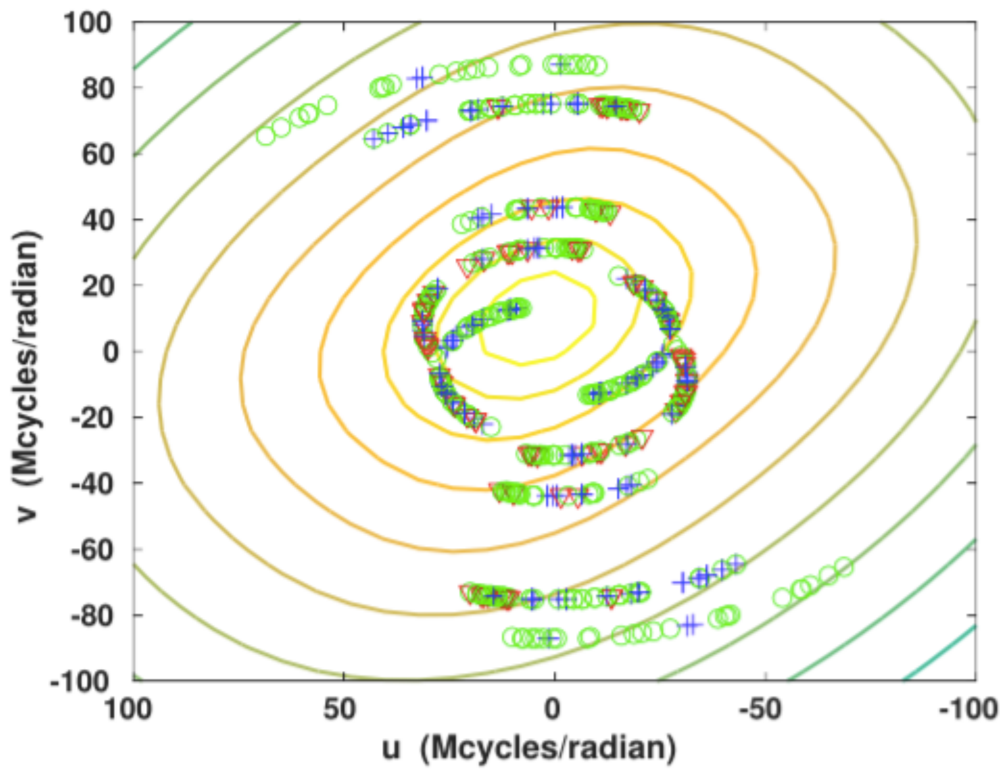


Jones et al. (2017)

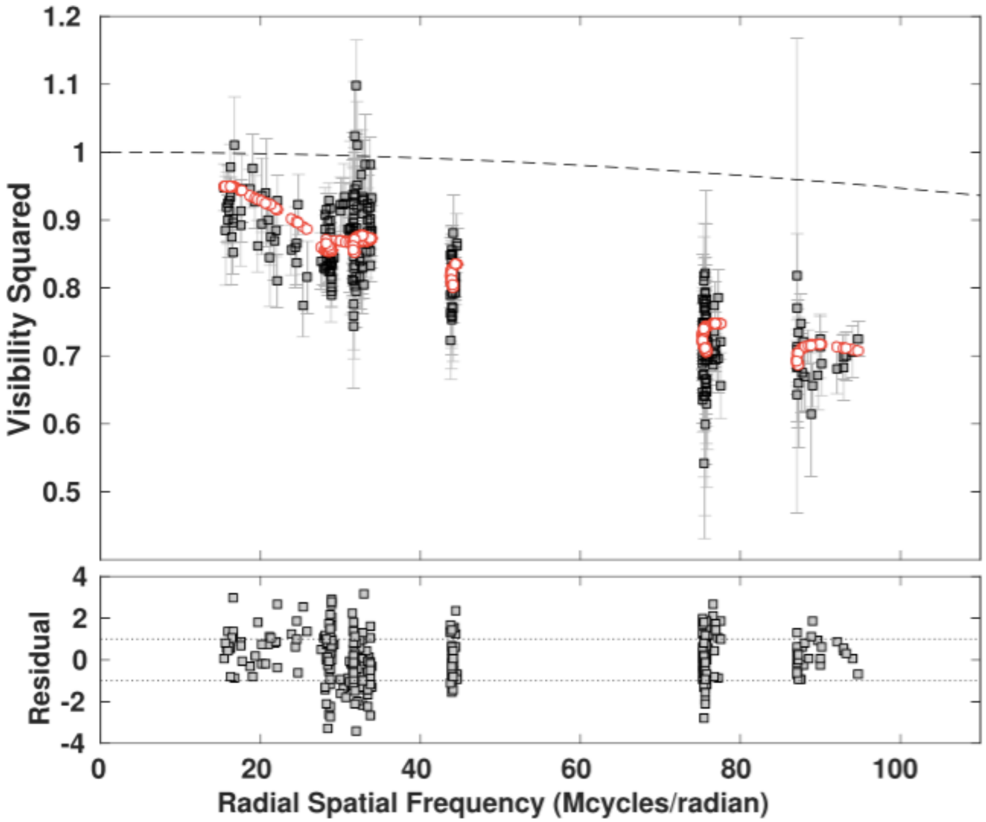


Model parameters are:
ρ, n, Rd, i

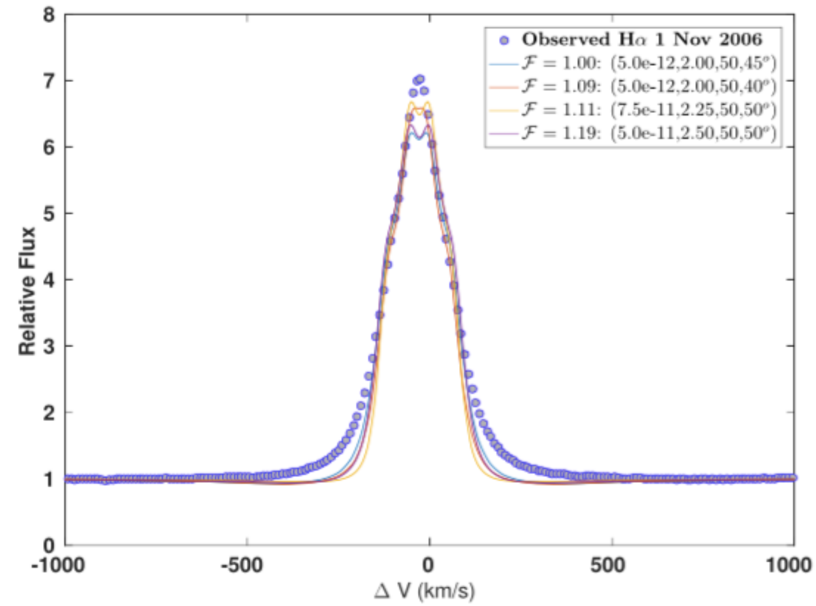
$X^2/\nu \sim 1.4$

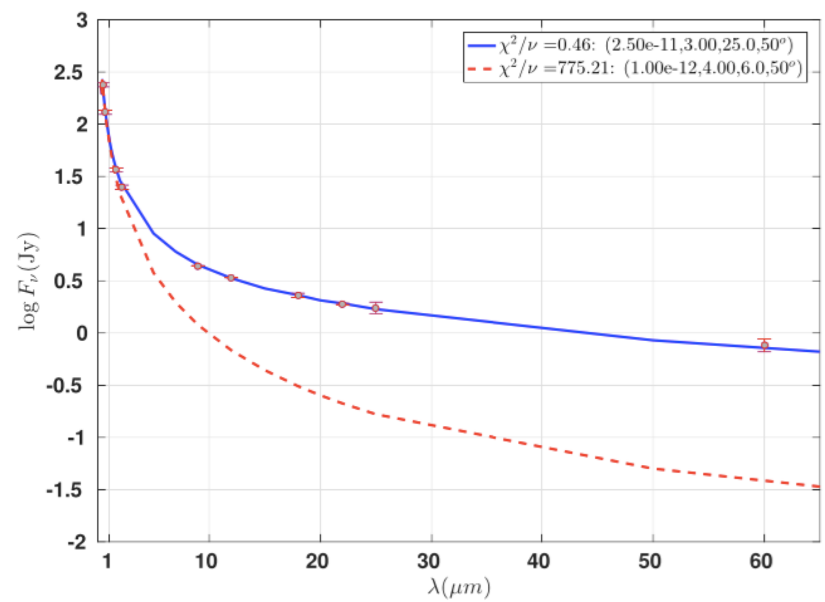


48 Per, B3Ve (146 pc)



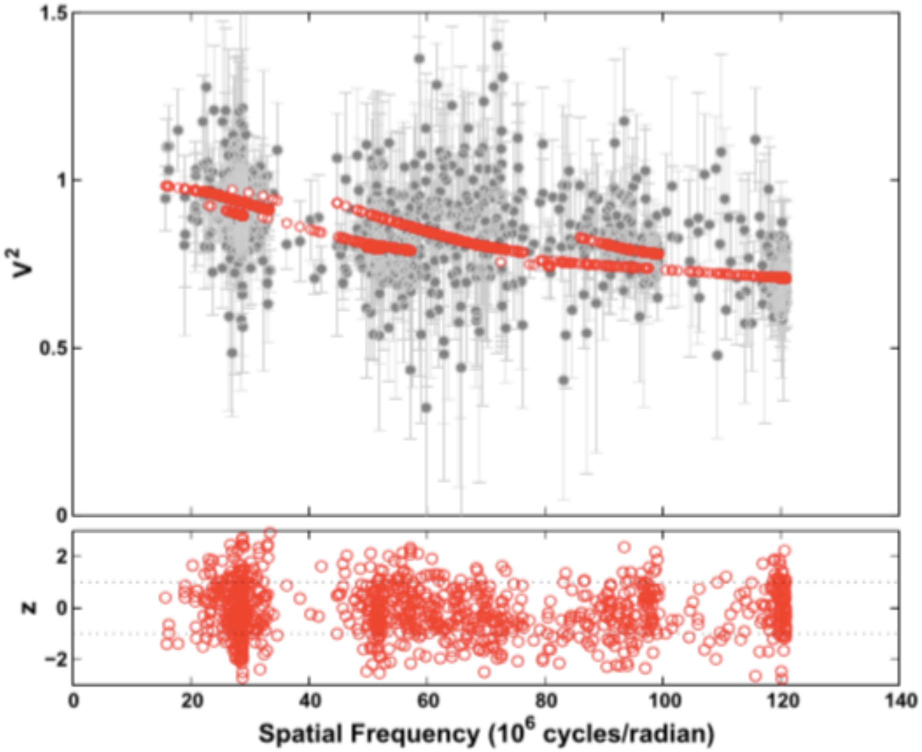
$$\rho(R, Z) = \rho_0 \left(\frac{R_*}{R}\right)^n e^{-(Z/H)^2}$$

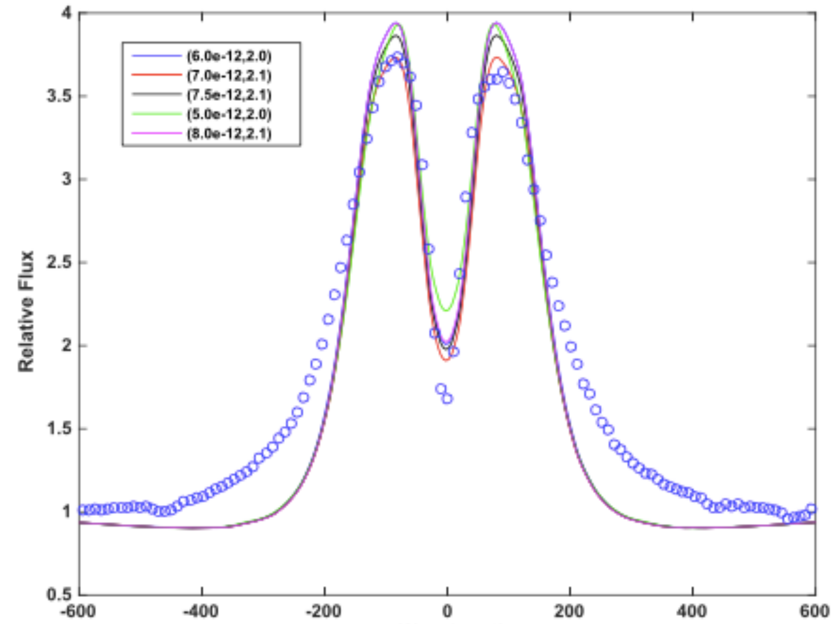


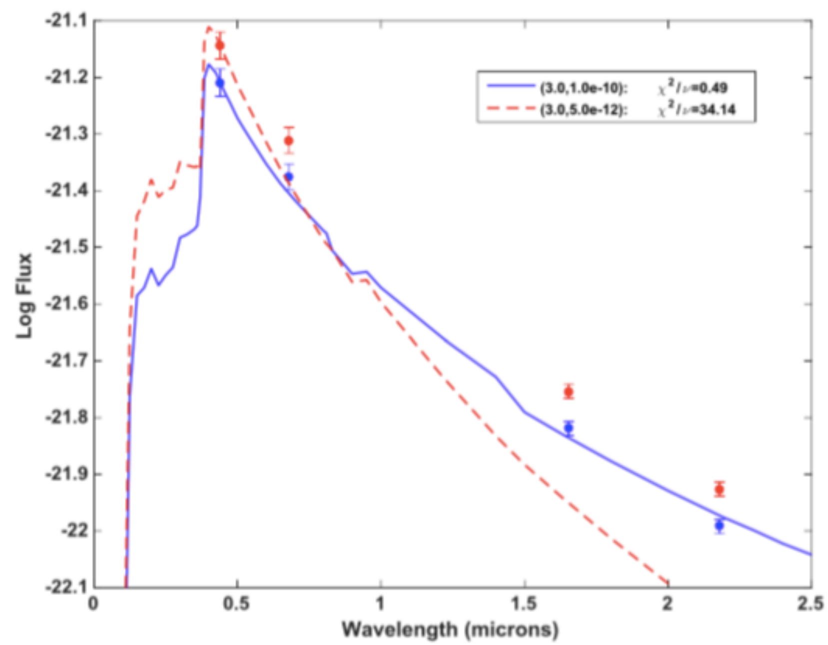


Jones et al (2017)

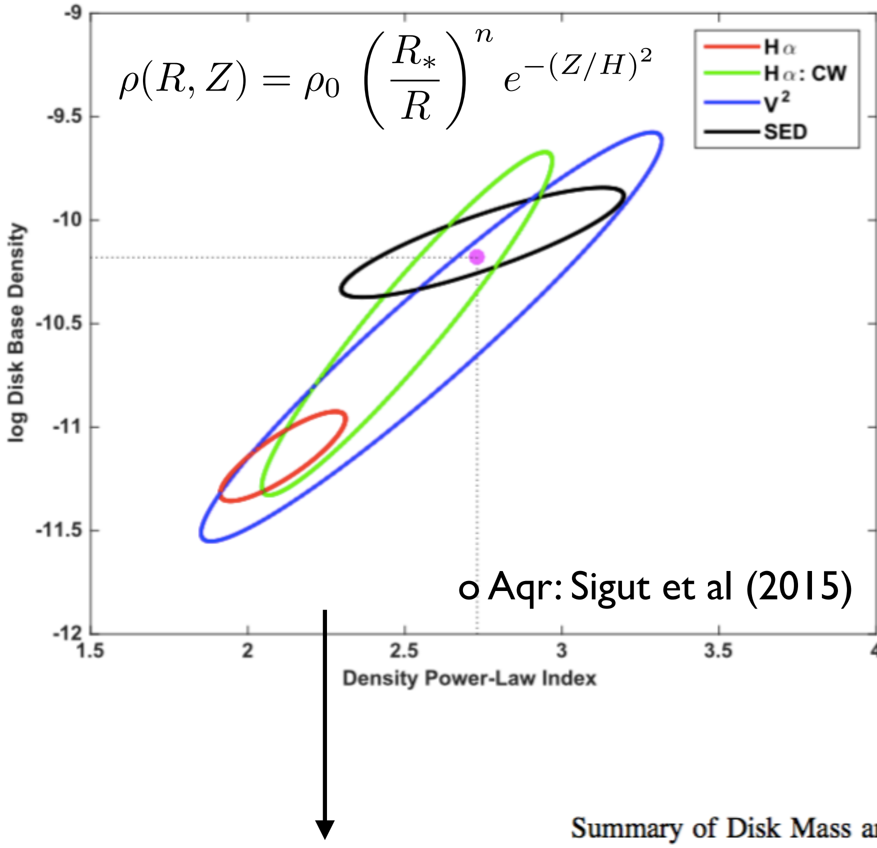
o Aqr, B7IVe (134 pc)







Sigut et al (2015)



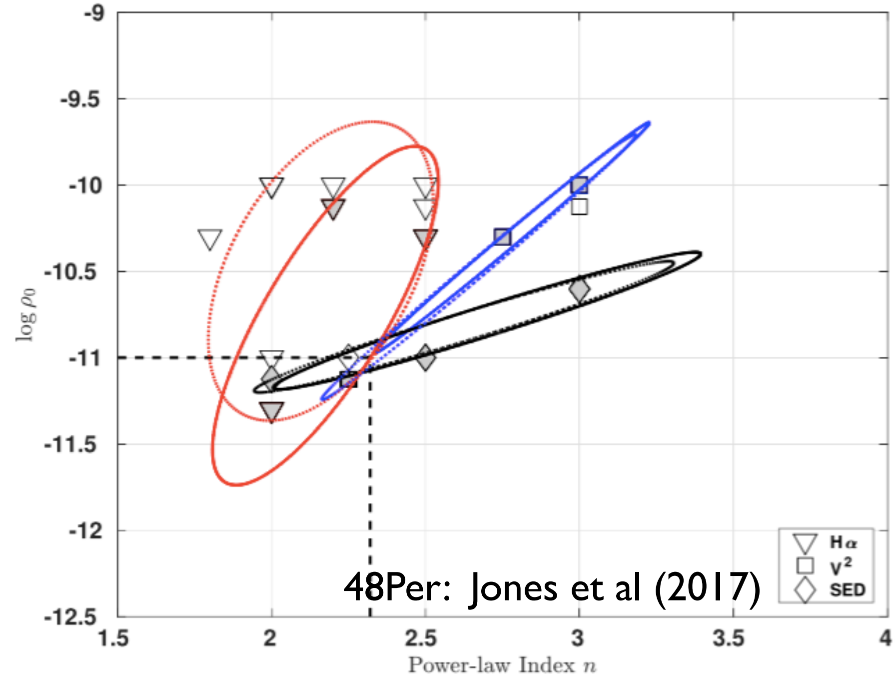
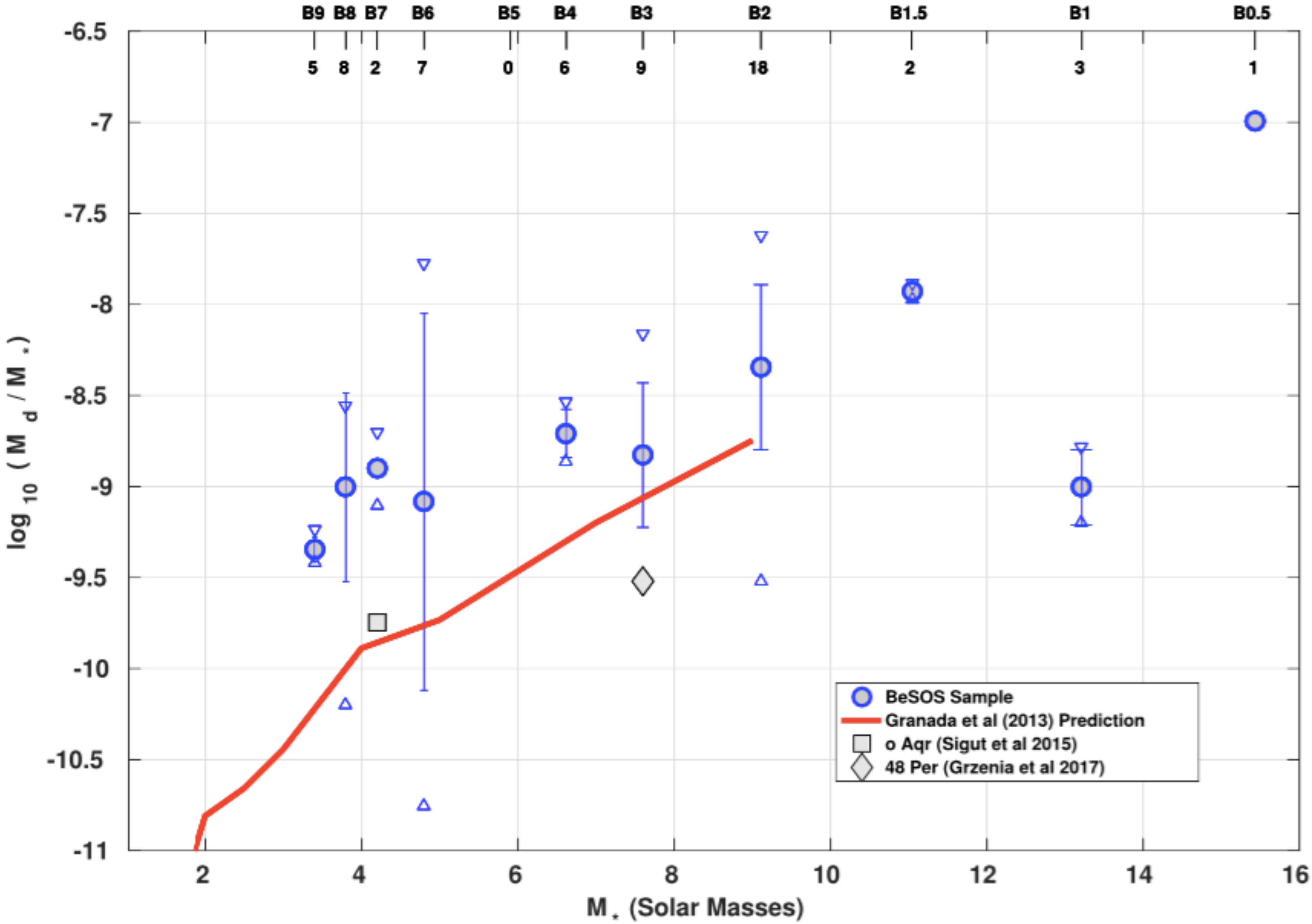


Table 5
Summary of Disk Mass and Total Angular Momentum Content

Diagnostic	(R_{90}/R_*)[a]	M_d (g)	M_d/M_*	J_d (g cm^2 s^{-1})	J_d/J_*
Hα ($\mathcal{F}$)	19.5	$1.0 \times 10^{+24}$	1.2×10^{-10}	$3.7 \times 10^{+43}$	1.7×10^{-8}
Hα ($\mathcal{F}_{CW}$)	8.3	$2.0 \times 10^{+24}$	2.3×10^{-10}	$4.4 \times 10^{+43}$	2.0×10^{-8}
V^2	19.5	$1.0 \times 10^{+24}$	1.2×10^{-10}	$3.7 \times 10^{+43}$	1.7×10^{-8}
near-IR SED	3.3	$5.8 \times 10^{+23}$	6.9×10^{-11}	$9.0 \times 10^{+42}$	4.2×10^{-9}
Adopted[b]	9.5	$1.5 \times 10^{+24}$	1.8×10^{-10}	$3.5 \times 10^{+43}$	1.6×10^{-8}

Notes.
[a] R_{90} is the disk radius that encloses 90% of the integrated Hα light.
[b] This is the best-fit model to all three constraints (Hα ($\mathcal{F}_{CW}$), V^2, and near-IR SED) shown in Figure 12.



Arcos et al (2017)

Take-Aways

Radiative transfer modelling of spectroscopic and interferometric observations of nearby Be stars allows estimates of the Hα masses of their disks. These can be compared to the predictions of stellar evolution with rotation.

We are working our way through a large data set of NPOI observations: Psi Per, 48 Lib, Zeta Tau, …

NPOI Closure phases for these data sets are now available and are being added to the modelling.

- Arcos et al (2017) ApJ 842, A48
- Granada et al (2013) A&A 553, A25
- Jones et al (2017) ApJ 843, A24
- Porter & Rivinius (2003) PASP 115, 1153
- Sigut et al (2015) ApJ 814, A159
- Sigut & Jones (2007) ApJ 668, 481
- Sigut (2011) in IAU 272 "Active OB Stars", 426
- Struve (1931) ApJ 73, 94