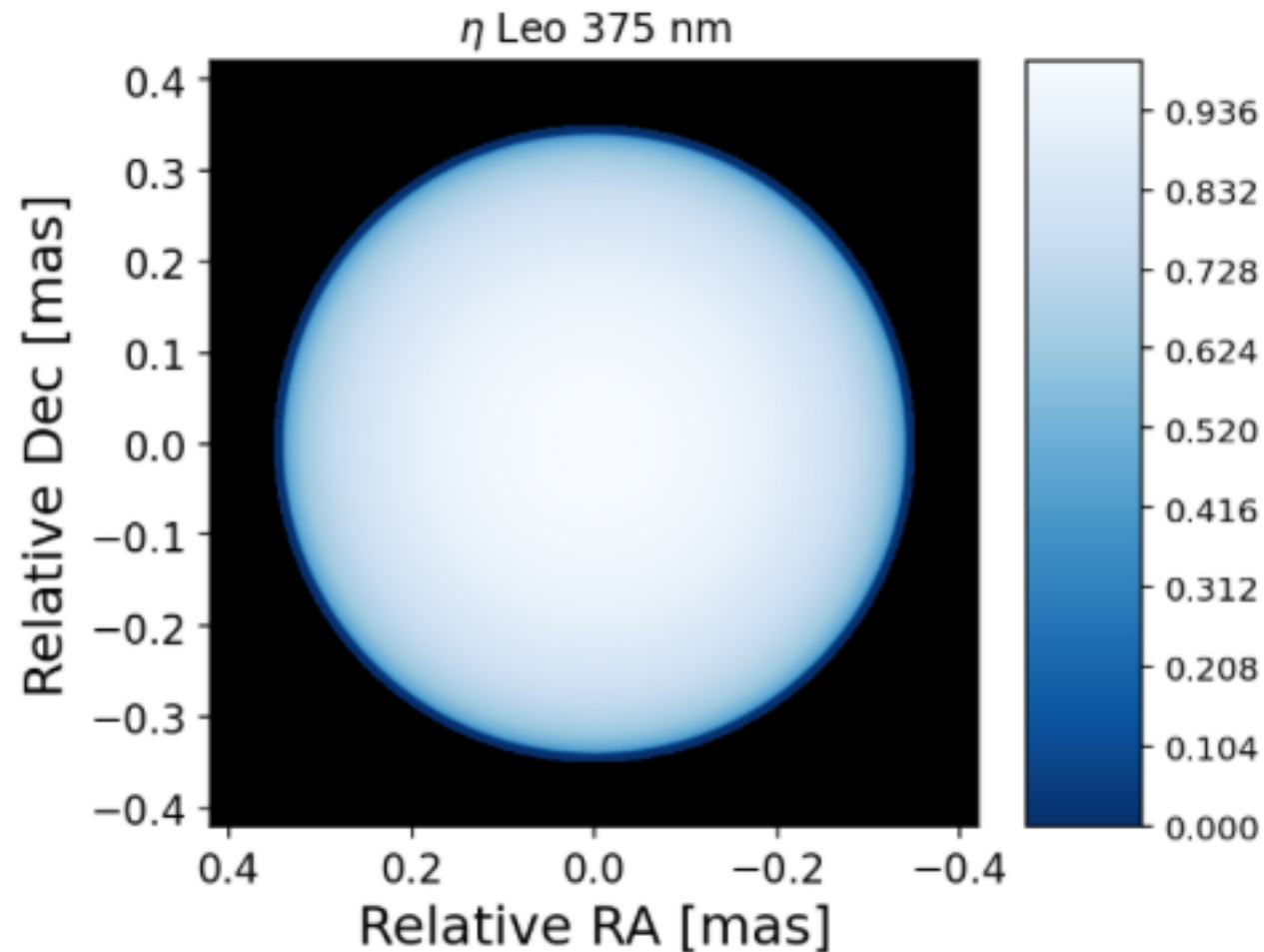


Probing stellar atmospheres and binary stars with Stellar Intensity Interferometry

Jason Aufdenberg

Embry-Riddle Aeronautical University (ERAU)



Jackson Sackrider for early contributions to the the stellar atmosphere to visibilty pipeline
Ben Katz for assistance with compiling stellar parameter data
Peter Hauschildt and PHOENIX code development team

What's to Come....

- **Limb darkening studies not requiring the 2nd lobe**

Probes temperature structure, tests atmosphere models

Short SII baselines needed for larger stars with near-IR diameters

- **SII within spectral lines: predictions for Balmer series $H\delta$ and higher**

- **Potential SII targets:**

A-type supergiants other than Deneb (α Cyg)

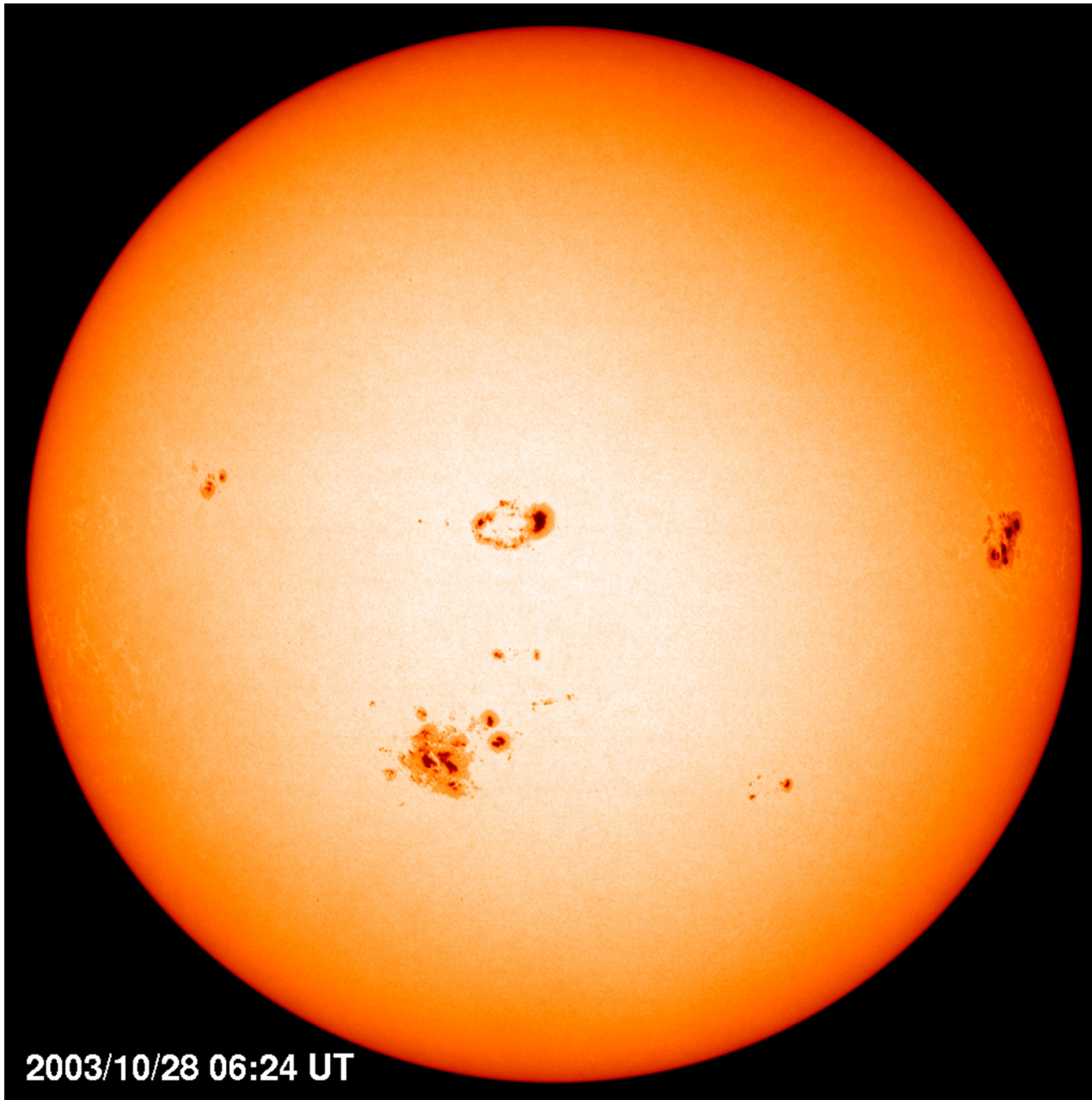
Radially pulsating Cepheid variables, the brightest five

A-type dwarfs with debris disks other than Vega (α Lyr)

More Be-type stars with disks

Bright, short-period binary stars

Limb Darkening Reveals Temperature Structure



2003/10/28 06:24 UT

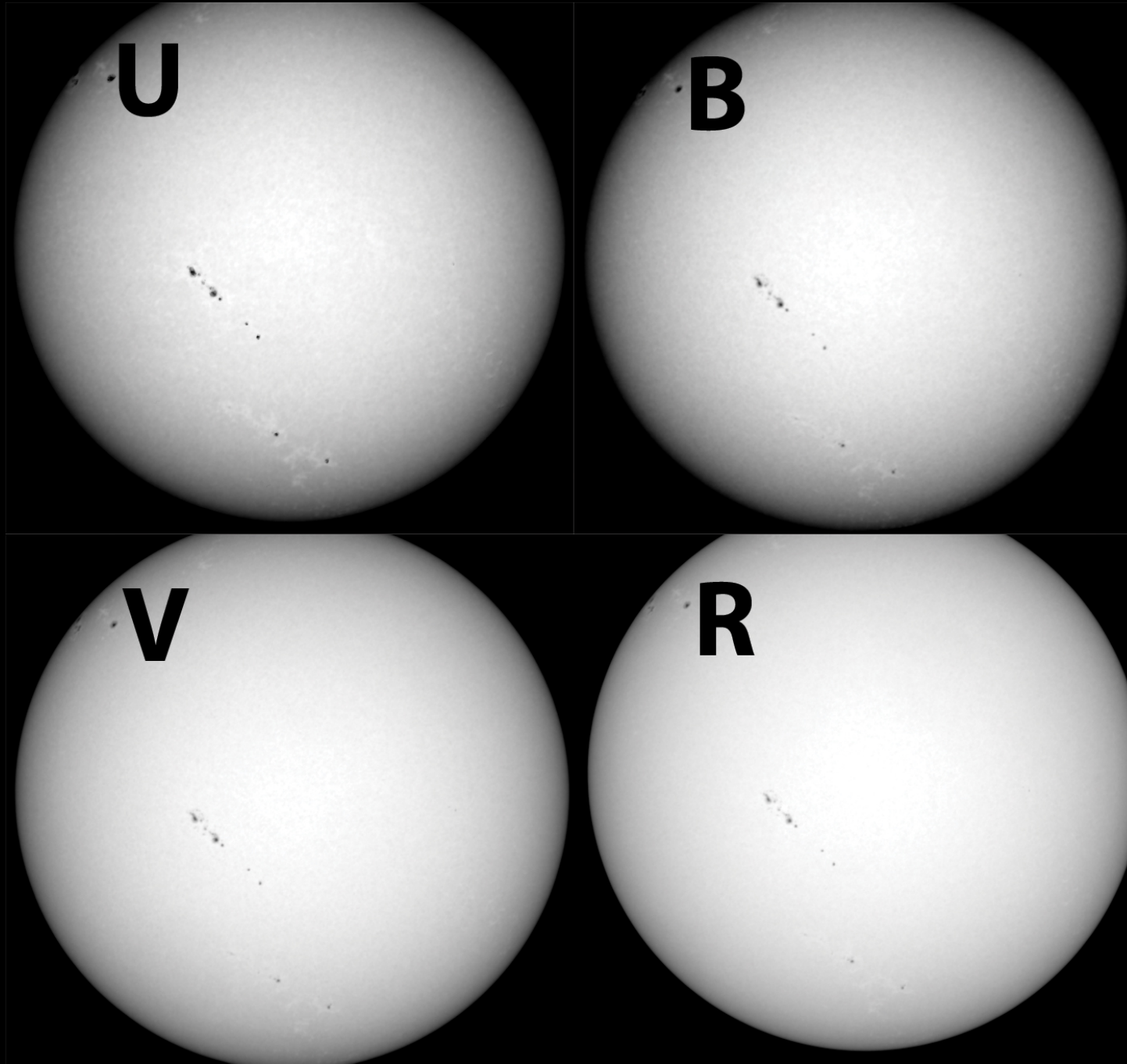
Solar and Heliospheric Observatory (SOHO), Michelson Doppler Imager (MDI)
Very narrow band at Ni I 6768 Å (sohowww.nascom.nasa.gov)

(a) Deeper, hotter layers are visible near the disk center

(b) Shallower, cooler layers are visible near the disk limb

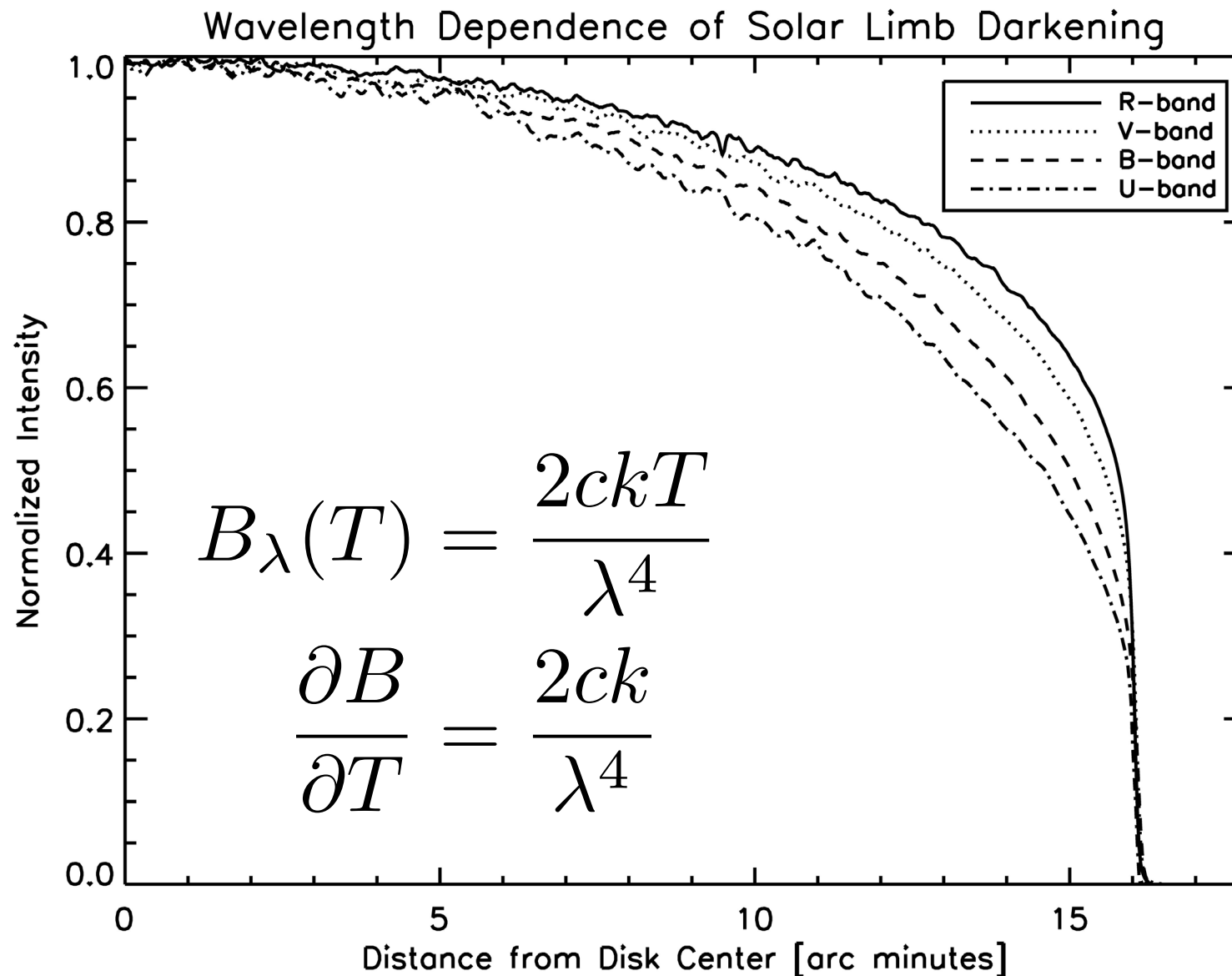
Isothermal atmospheres do not exhibit limb darkening

Intensity contrast stronger at bluer wavelengths



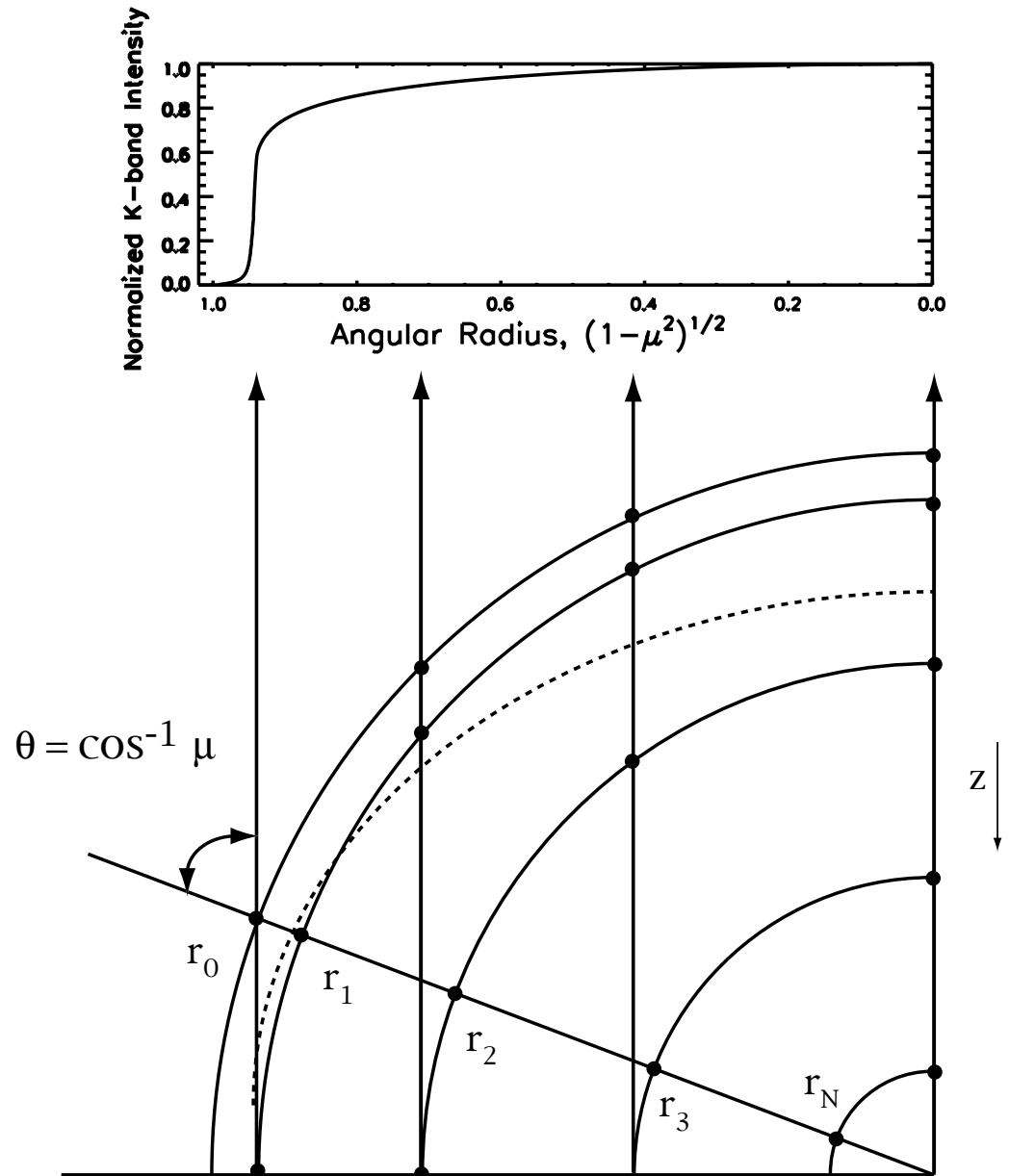
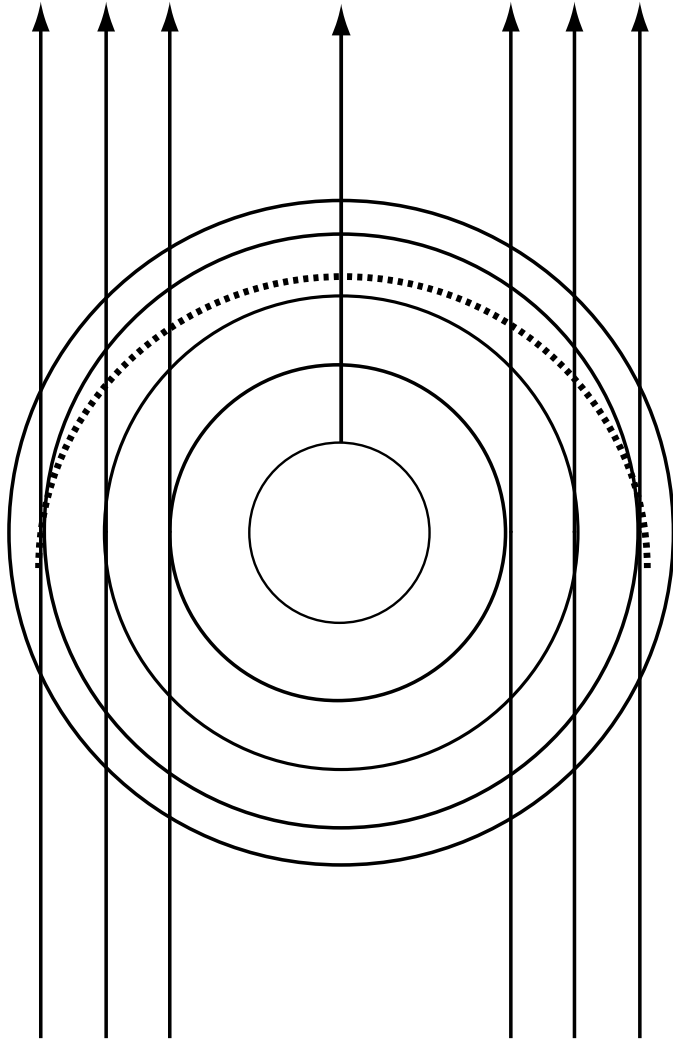
Credit: EP 425 Students Edward Muller and Keily Grubaugh

Limb Darkening Depends on Wavelength

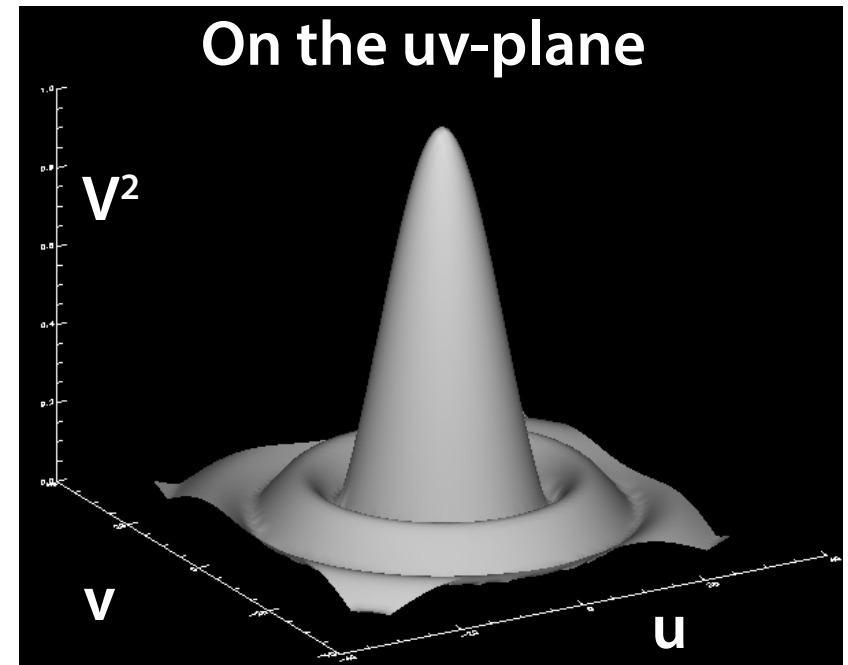
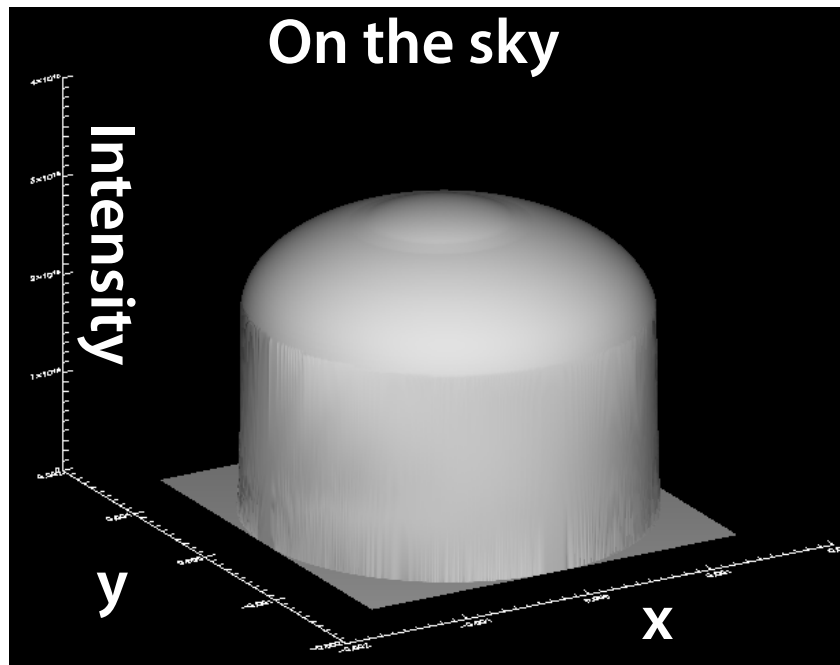


Credit to EP 425 (Observational Astronomy) students: Edward Muller and Keily Grubaugh

Spherical Geometry and Atmospheric Extension

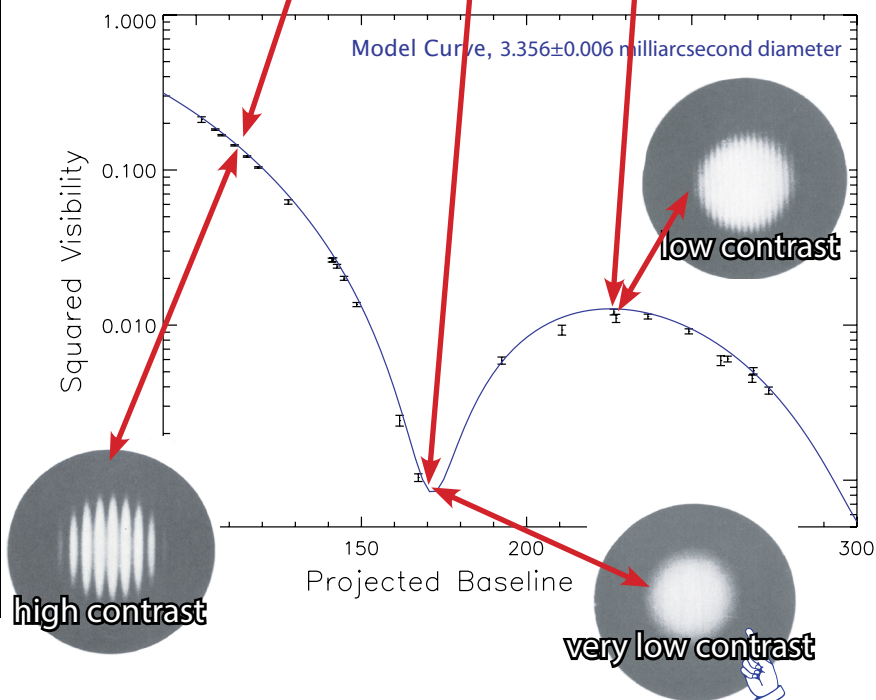
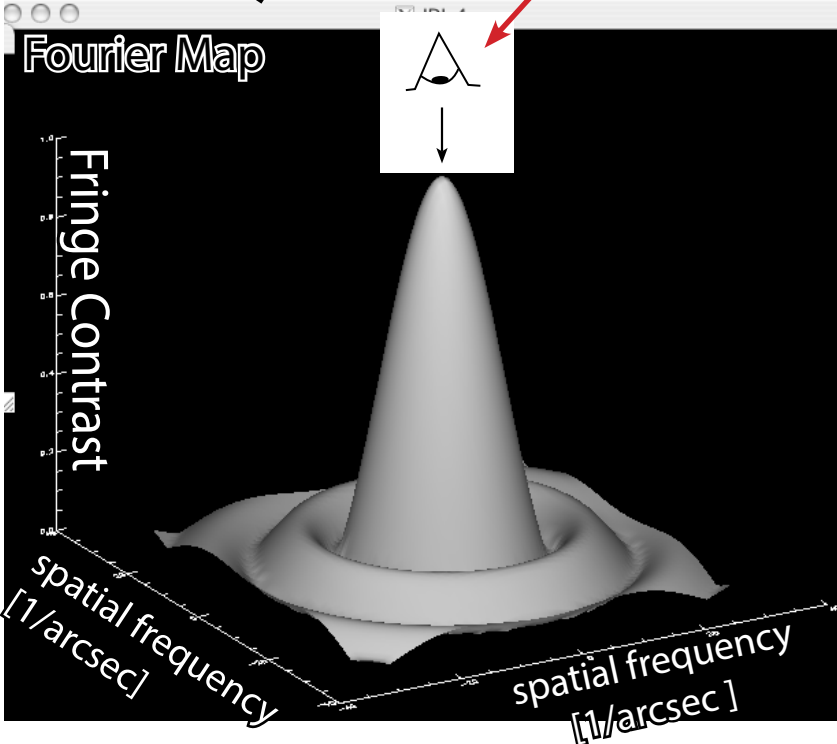
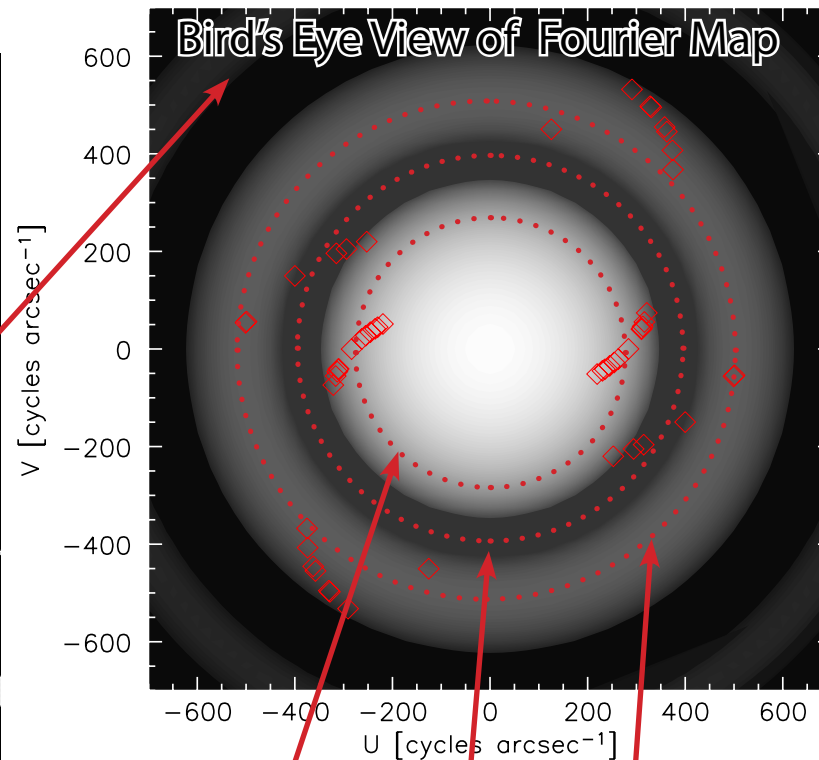
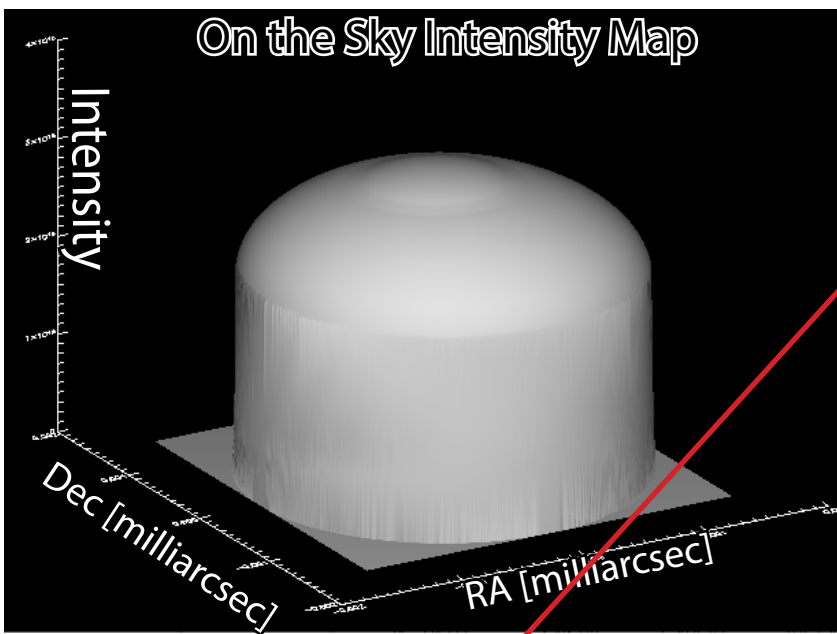


Intensity on the sky $\Rightarrow$ Visibility in the u-v plane



$$V_{\lambda}^2(u, v) = \left[\int_{-\infty}^{\infty} \int_{-\infty}^{\infty} S_{\lambda} I_{\lambda}(x, y) e^{i2\pi(u x + v y)} dx dy \right]^2$$

How Does an Interferometer See a Single Star?



Stellar example: Multi-Wavelength Diameters for Procyon (F5 IV-V)

ON THE LIMB DARKENING, SPECTRAL ENERGY DISTRIBUTION,
AND TEMPERATURE STRUCTURE OF PROCYON

J. P. AUFDENBERG¹

National Optical Astronomy Observatory, 950 North Cherry Avenue, Tucson, AZ 85719

H.-G. LUDWIG

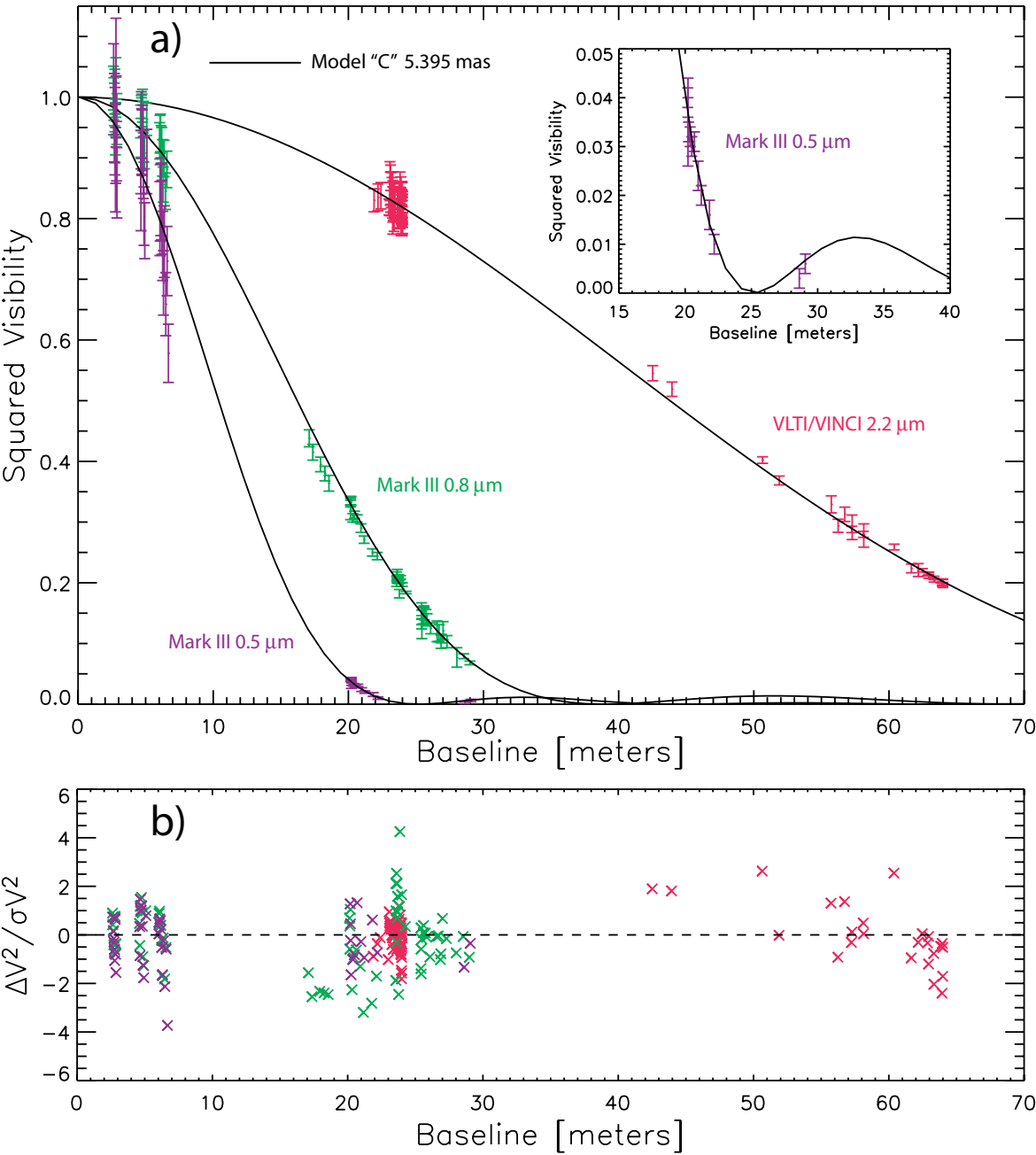
Lund Observatory, Lund University, Box 43, 22100 Lund, Sweden

AND

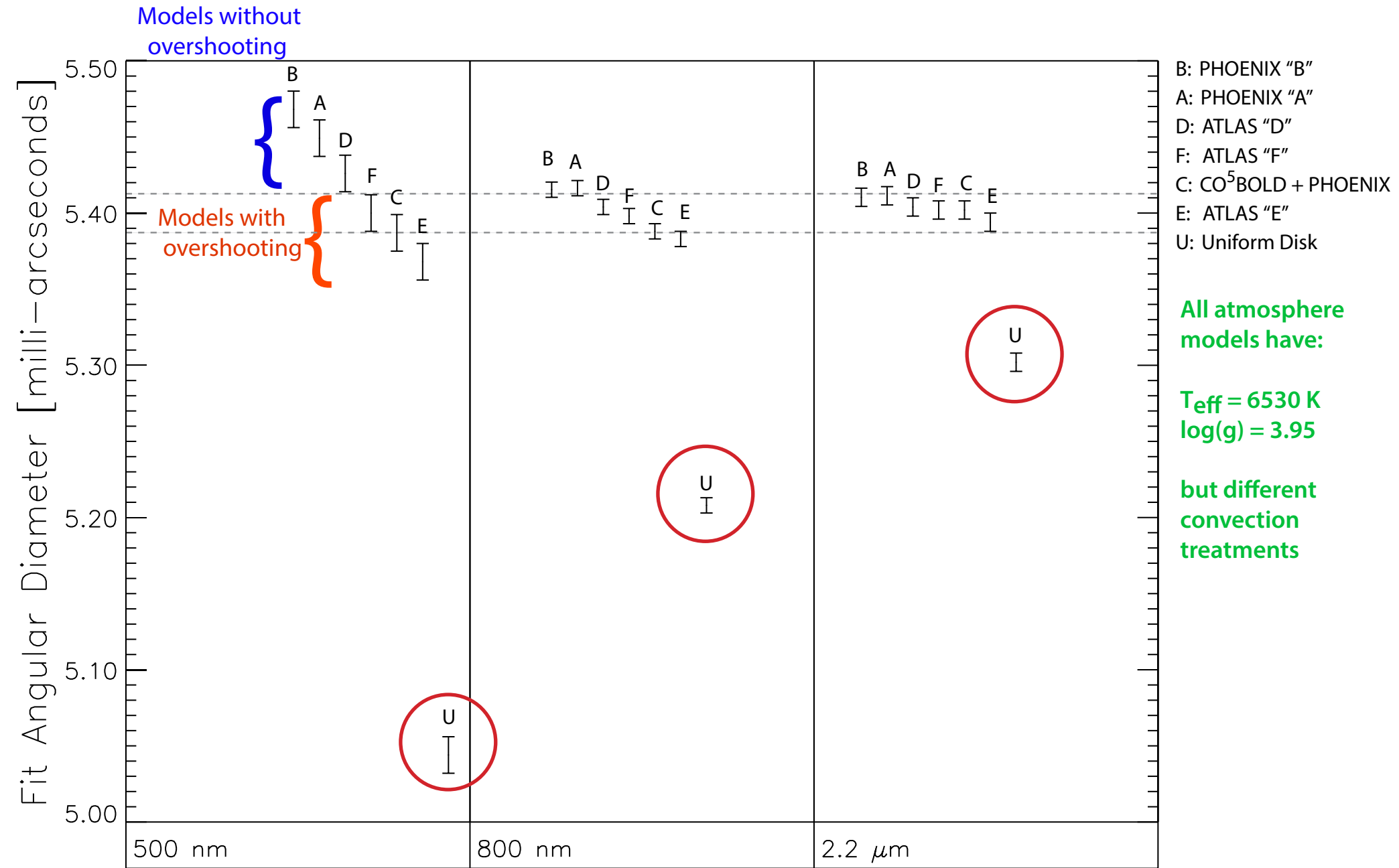
P. KERVELLA

LESIA, UMR 8109, Observatoire de Paris-Meudon, 5 place Jules Janssen, 92195 Meudon Cedex, France

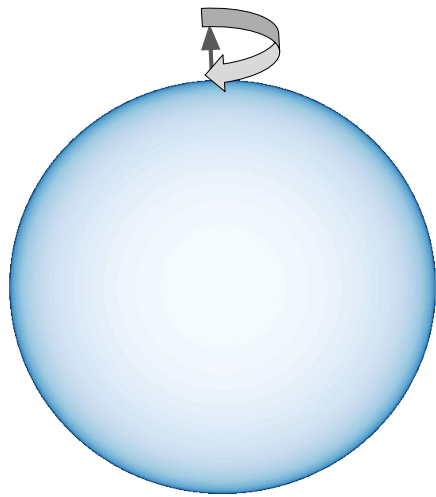
Received 2005 May 23; accepted 2005 July 13



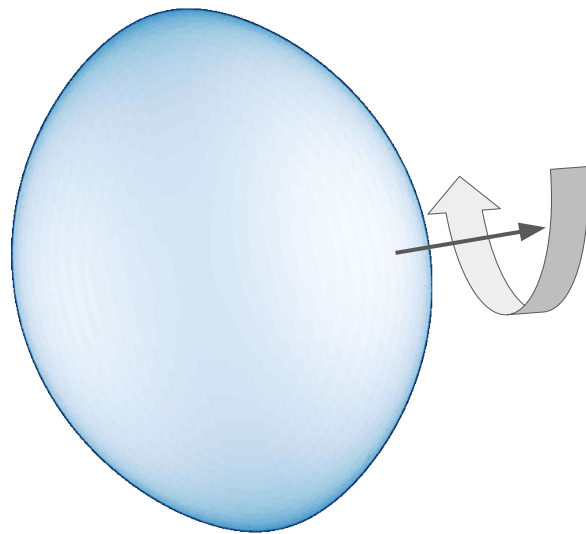
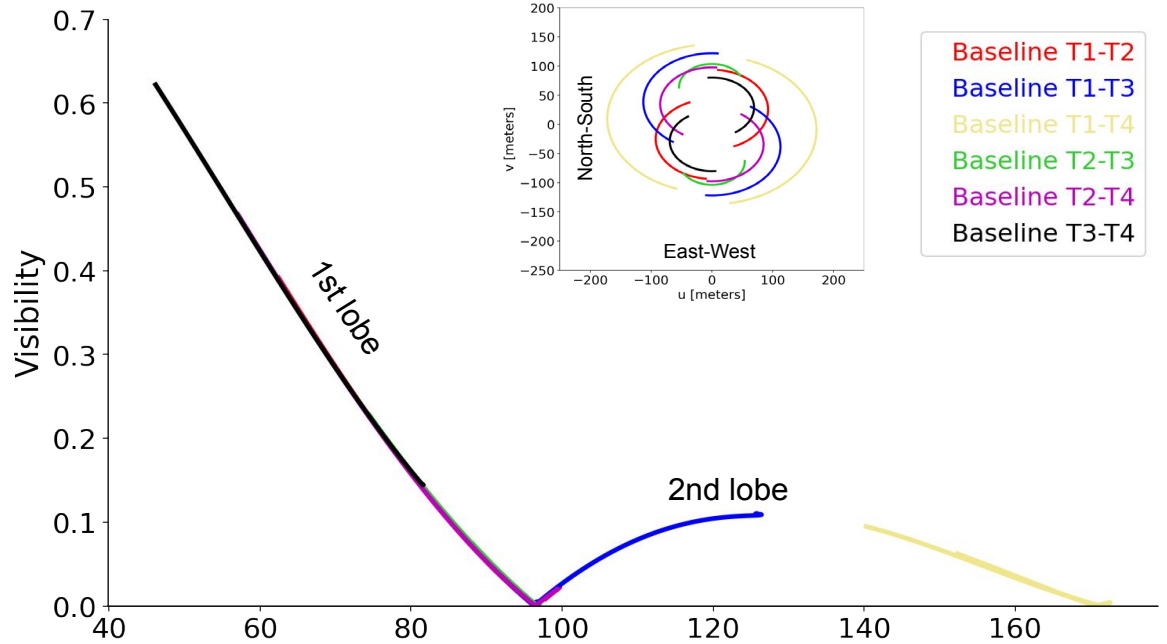
Fits most sensitive to model parameters at shortest λ



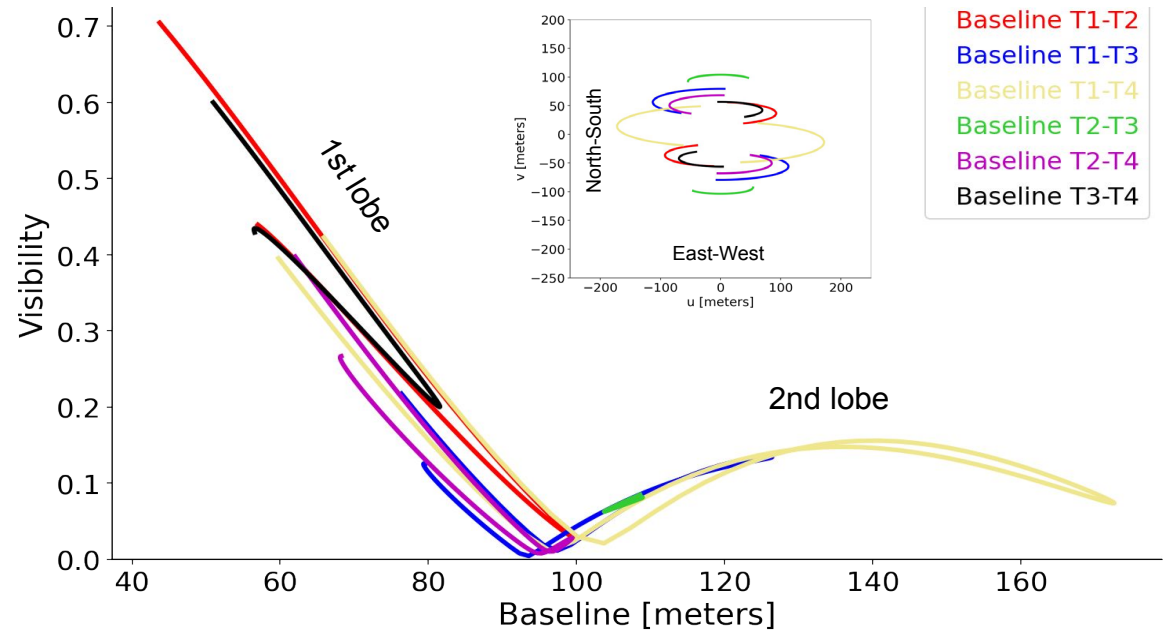
Symmetric β UMa vs asymmetric α Leo (Regulus) at 400 nm



β UMa ($v_{eq} = 46$ km/s)



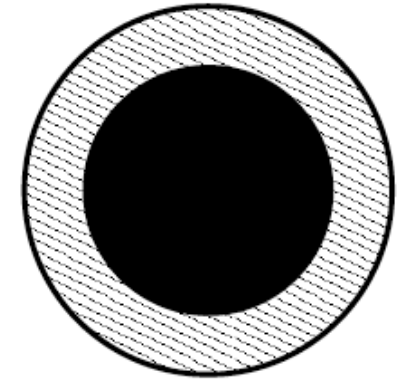
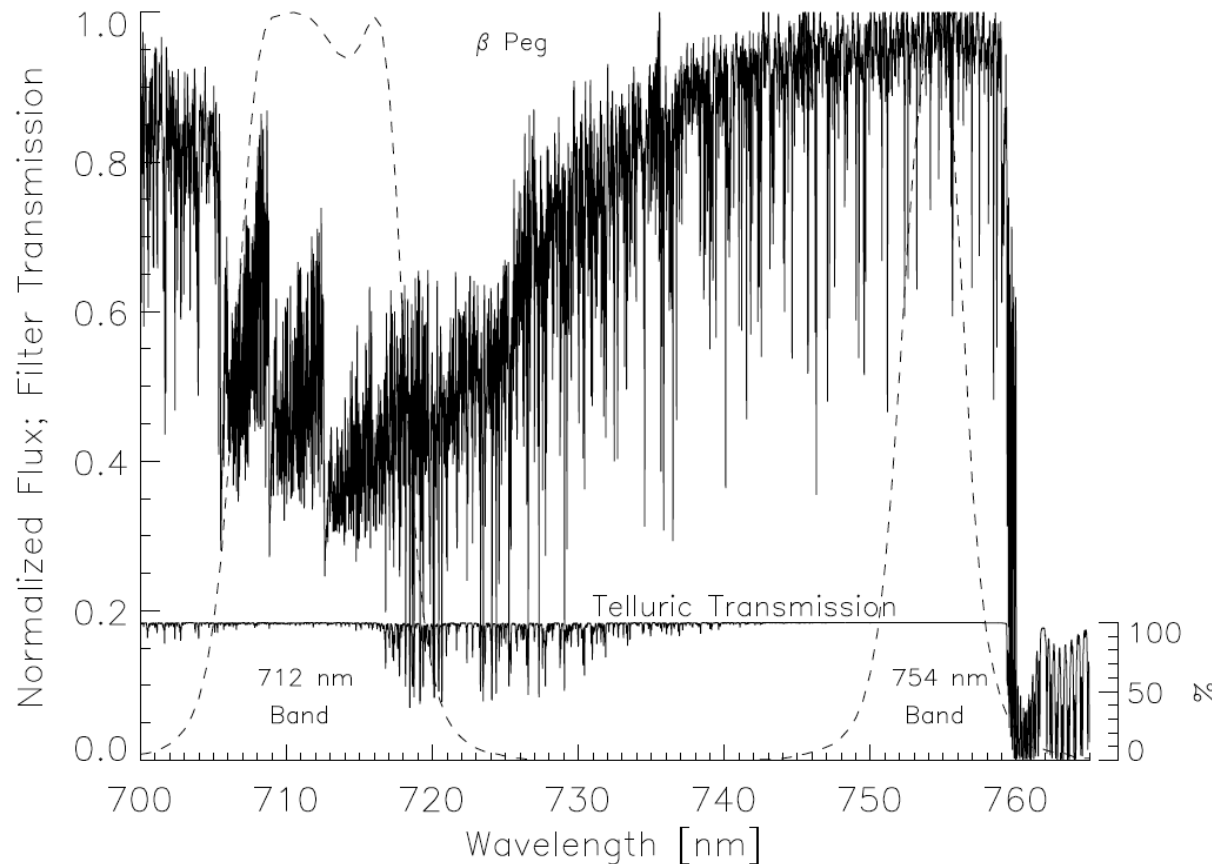
α Leo ($v_{eq} = 343$ km/s)



β UMa parameters from Adelman, S. J. (1996), MNRAS, 280, 130

α Leo parameters from Che, X., Monnier, J. D., Zhao, M., et al. (2011), ApJ, 732, 68.

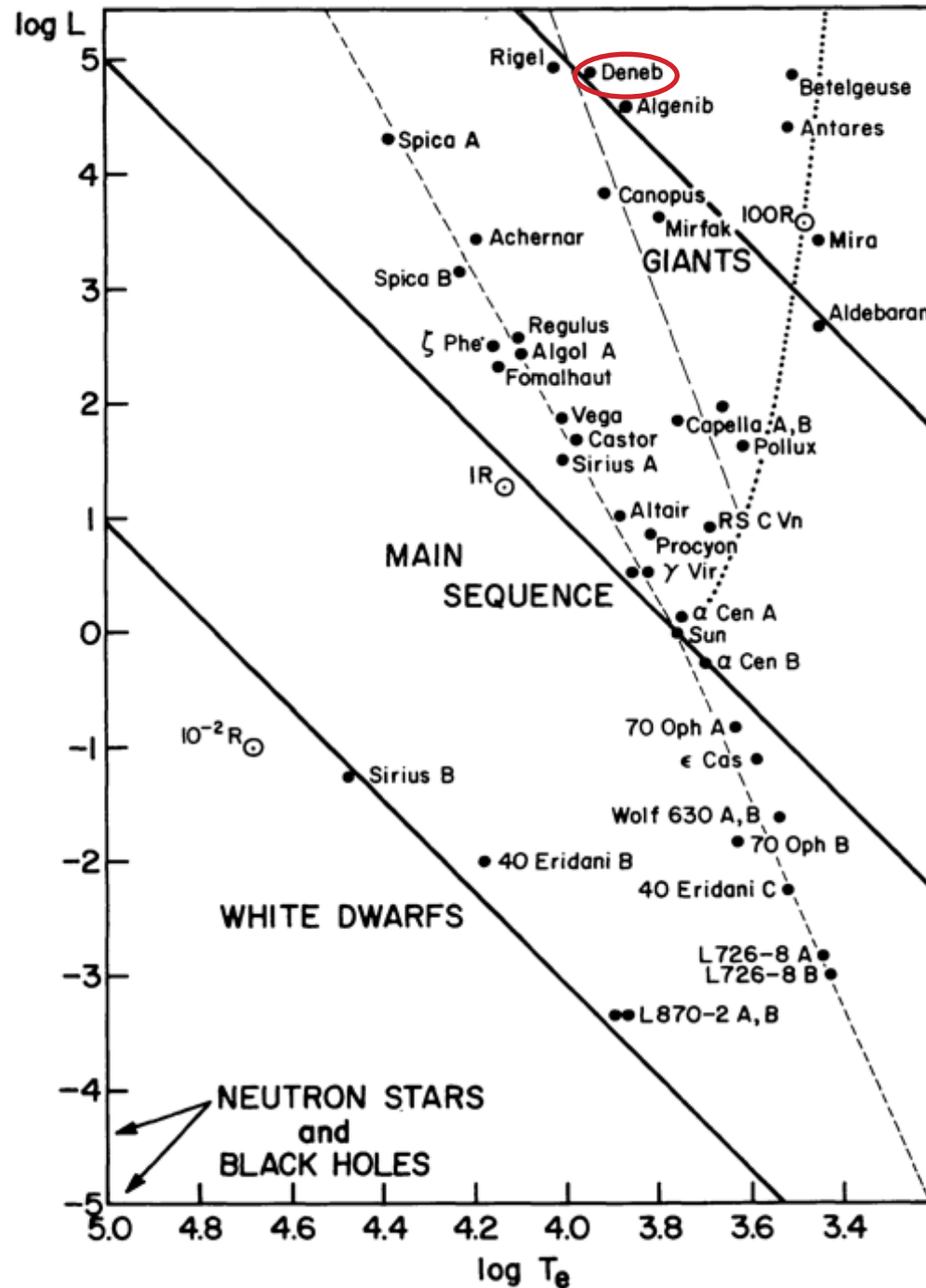
Probing atmospheric extinction in giants, angular diameter measurements in molecular bands, e.g. TiO



β Peg (M2 II-II) appears 1-2% larger in the 712 nm TiO band than the adjacent 754 nm band.

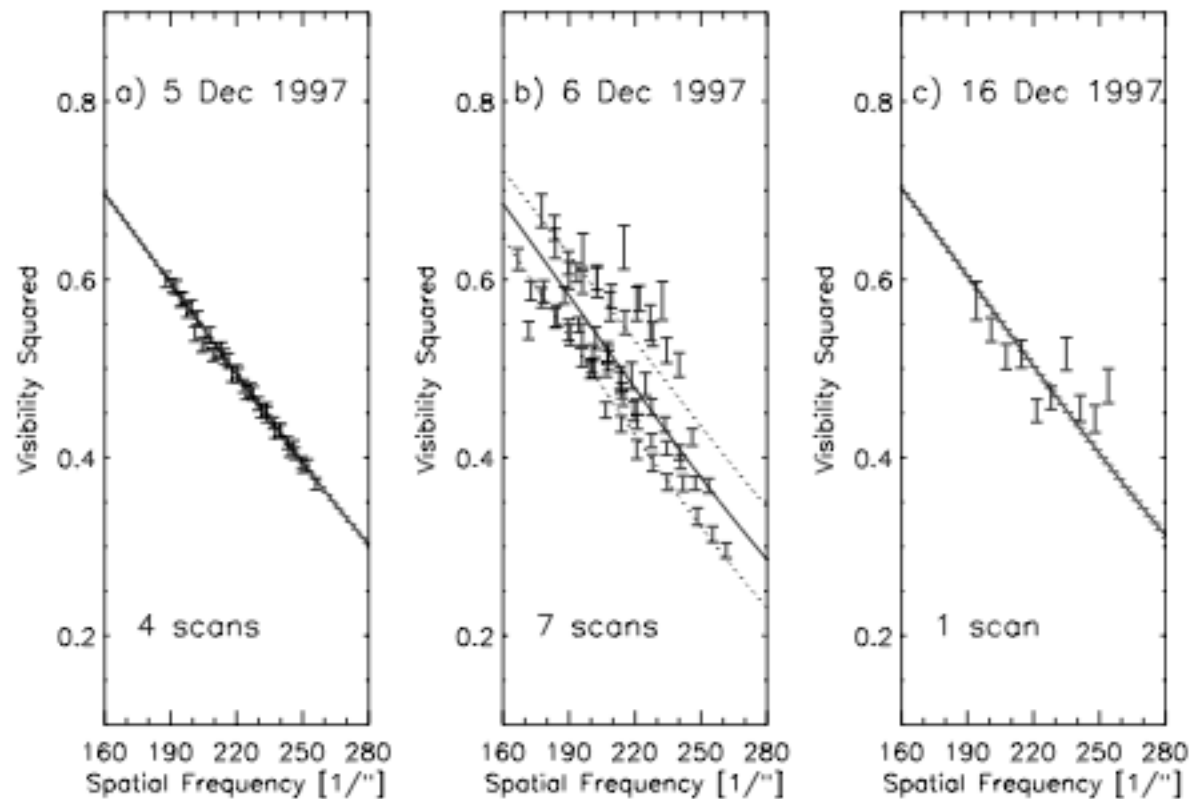
“Wavelength-Dependent Diameters of Cool Giant Stars”
Quirrenbach, A. and Aufdenberg, J. (2003)

A-type supergiants



Deneb - the brightest and only A-type supergiant with a measured angular size (2.4 mas)

Observations at 750 nm from Navy Prototype Optical Interferometer (NPOI)



“THE SPECTRAL ENERGY DISTRIBUTION AND MASS-LOSS RATE OF THE A-TYPE SUPERGIANT DENEb” Aufdenberg et al. (2006)

Of the next four-brightest A-type supergiants, two have parallaxes < 10%

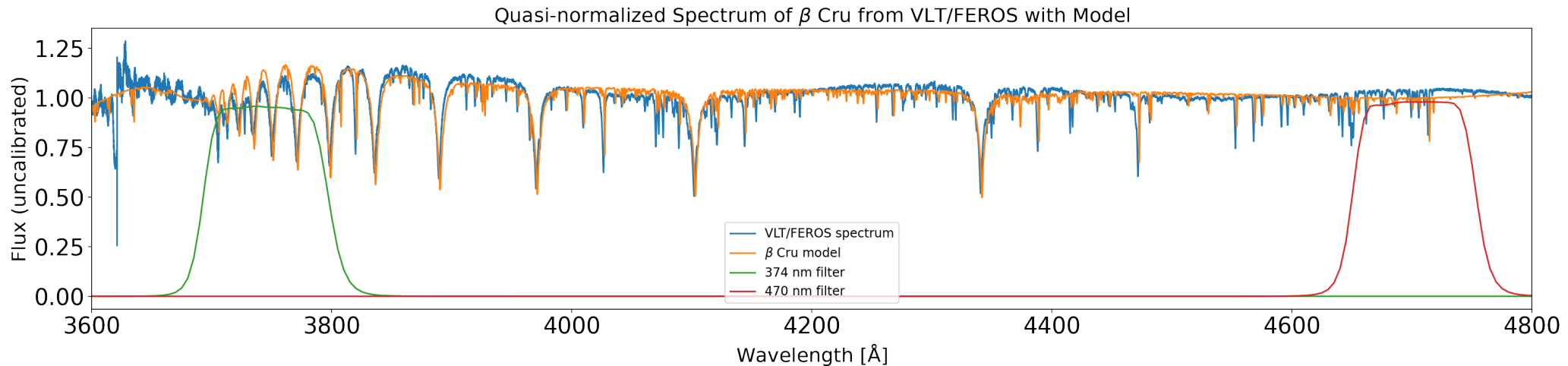
A-type supergiant	Spectral type	Est. Angular Size ¹ (mas)	U-band magnitude	V-band magnitude	Parallax (mas)	Dec.
η Leo	A0Ib	0.70	3.17	3.49	1.80±0.31	+17
ν Cep	A2Iae	0.89	4.29	4.94	0.93±0.09	+61
HD 92207	A0Ia	0.69	5.45	5.71	0.47±0.06	+58
HD 111613	A2Iabe	0.46	5.74	6.00	0.45±0.03	− 60

¹ Based on radii from Przybilla (2001), Przybilla (2006), Firnstein & Przybilla (2012)

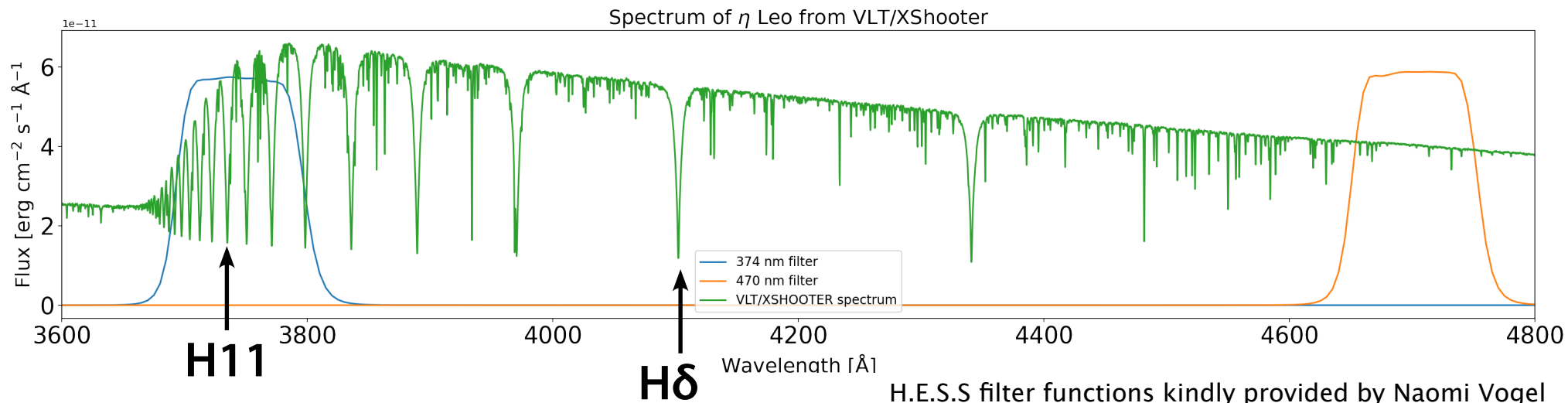
These supergiants have angular sizes comparable to their parallaxes.

A-type supergiants have low surface gravities, strong H Balmer lines, many near the limit

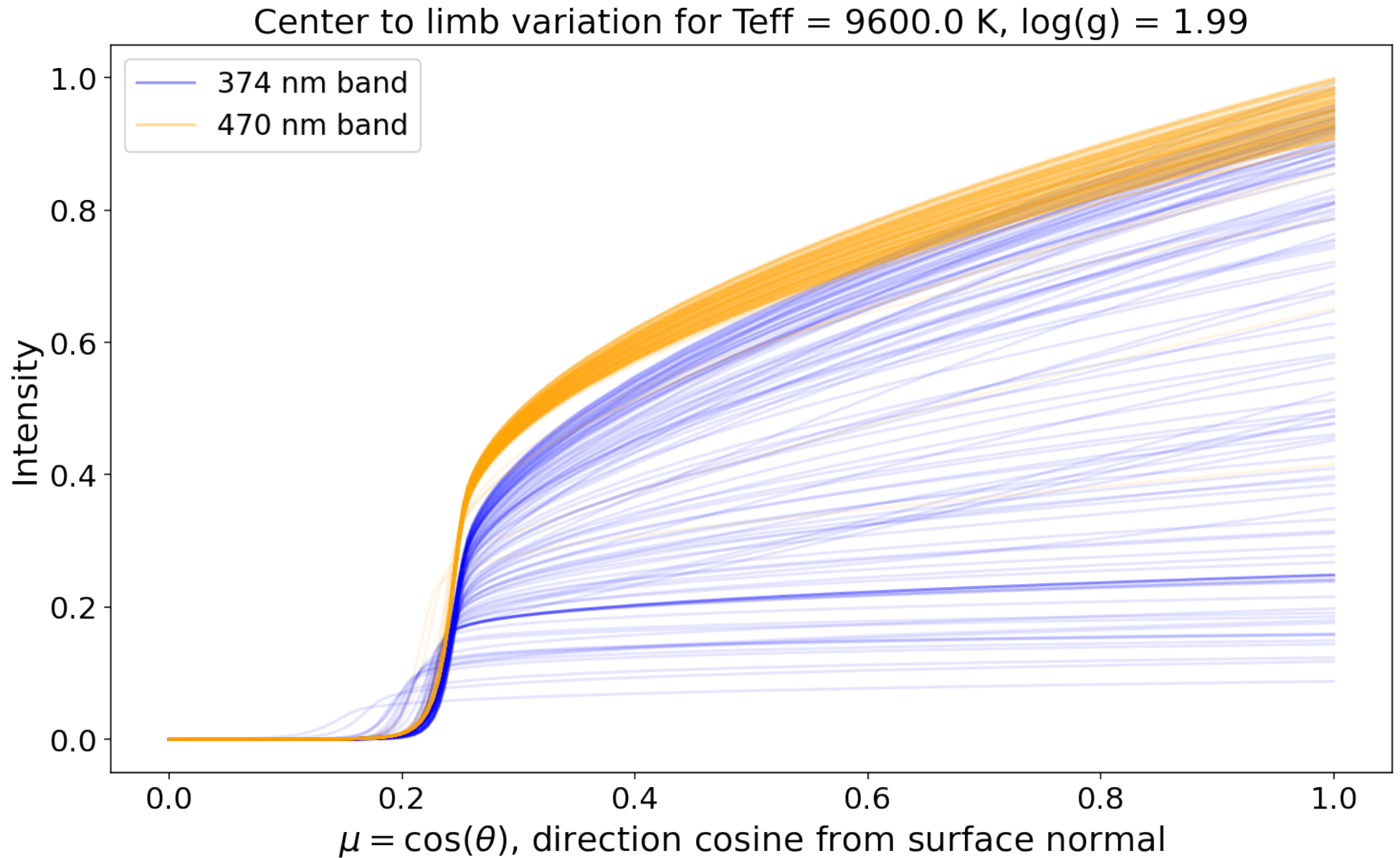
Spectrum of β Cru (B1IV) shows H-Balmer lines in 374 nm H.E.S.S filter and only weak lines in the 470 nm H.E.S.S filter.



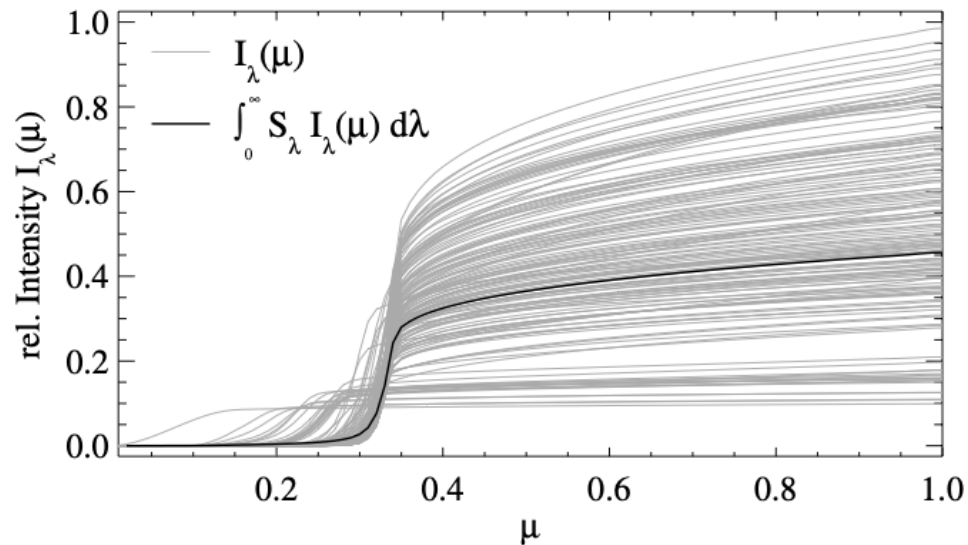
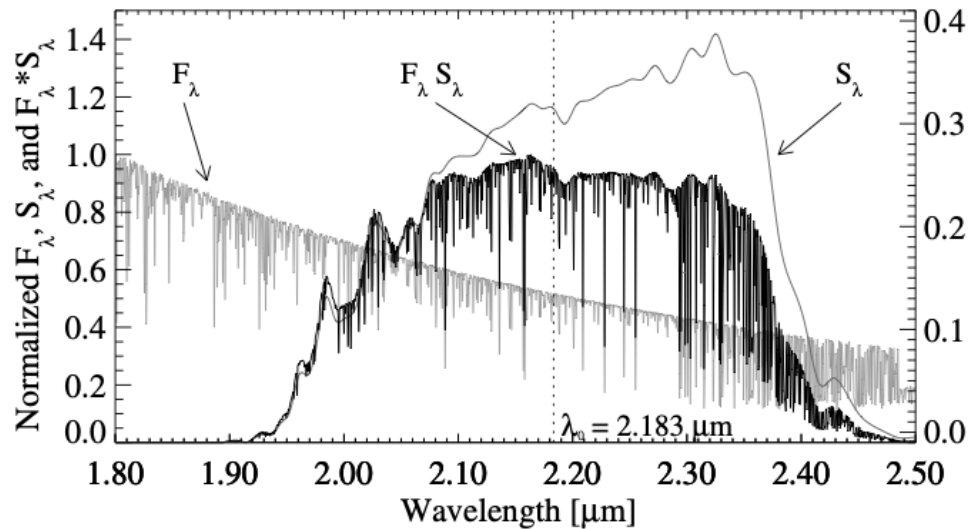
Spectrum of η Leo shows nine H-Balmer lines in the 374 H.E.S.S. filter



Center-to-limb variations for η Leo differ in the two H.E.S.S bands due to the Balmer lines



V² prediction example: the extended atmosphere of M-giant ψ Phoenicis (3550 K, $\log(g)=0.7$)



$$V_{\text{LD}}(\lambda) = \int_0^1 S_\lambda I_\lambda^\mu J_0 \left[\pi \theta_{\text{LD}} (B/\lambda) (1 - \mu^2)^{1/2} \right] \mu d\mu.$$

$$\lambda_0 = \frac{\int_0^\infty S_\lambda F_\lambda \lambda d\lambda}{\int_0^\infty S_\lambda F_\lambda d\lambda}$$

with F_λ being the stellar flux at wavelength λ :

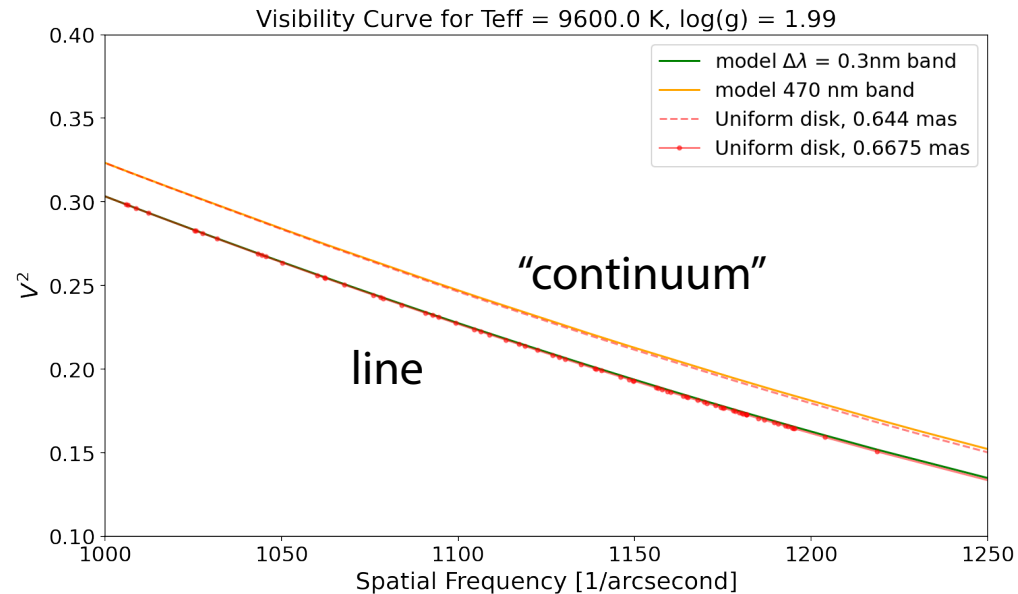
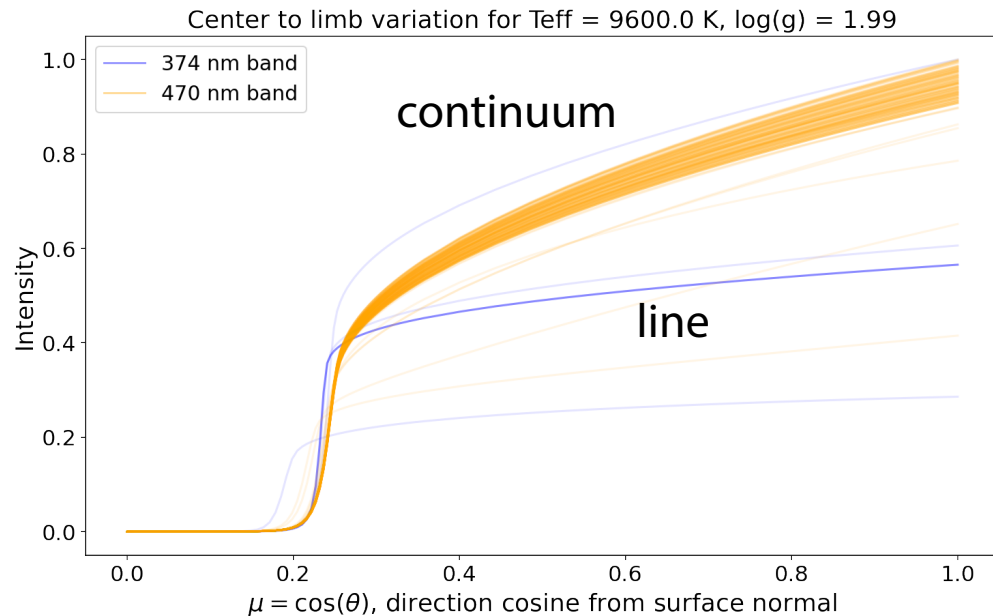
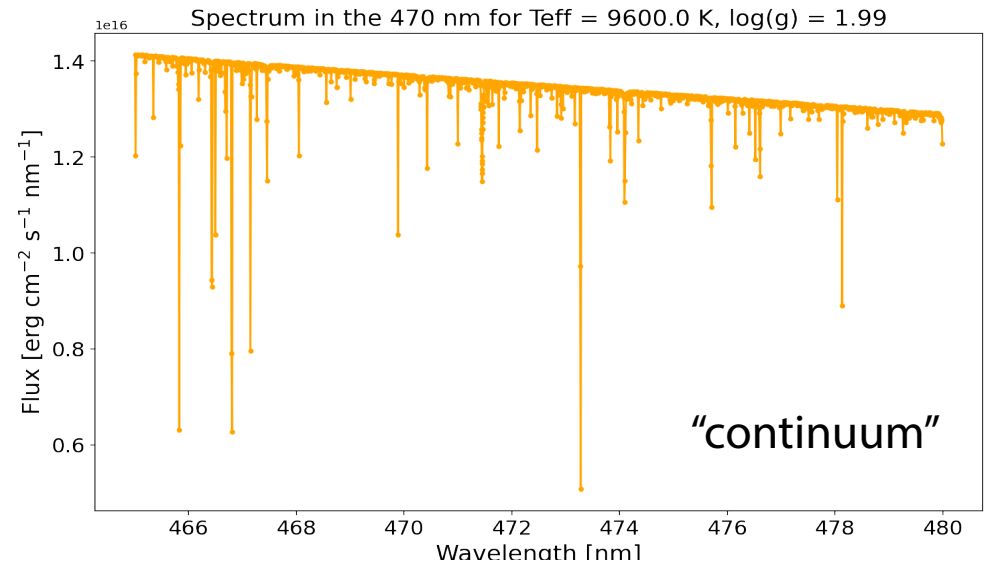
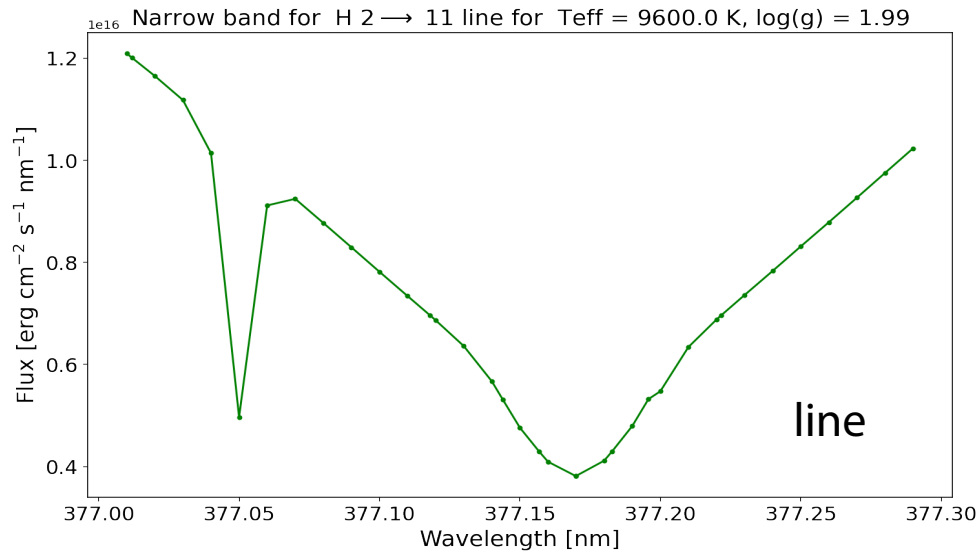
$$F_\lambda = \int_0^1 I_\lambda(\mu) \mu d\mu.$$

passband-averaged squared visibility amplitude

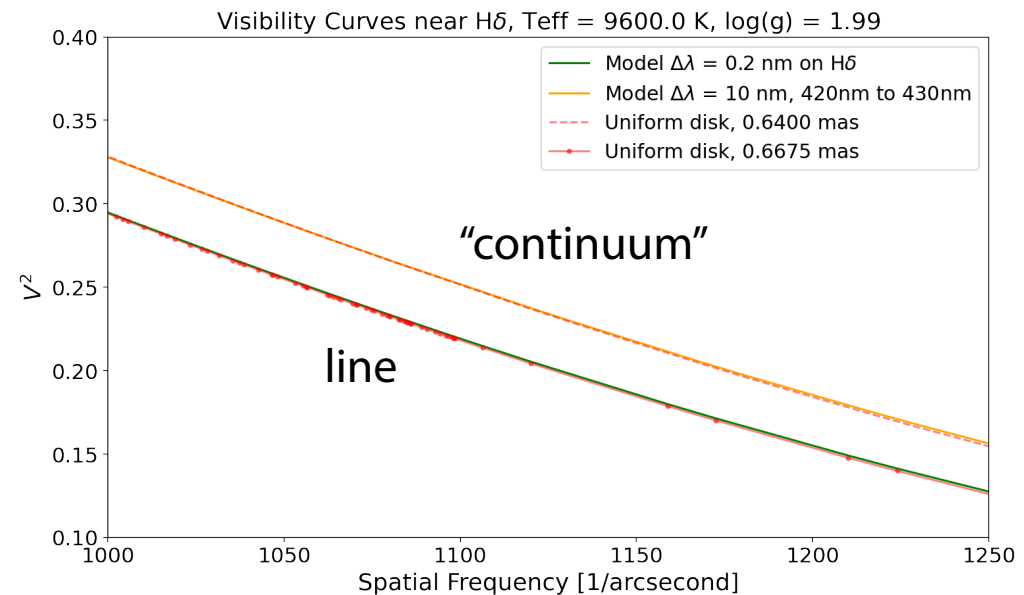
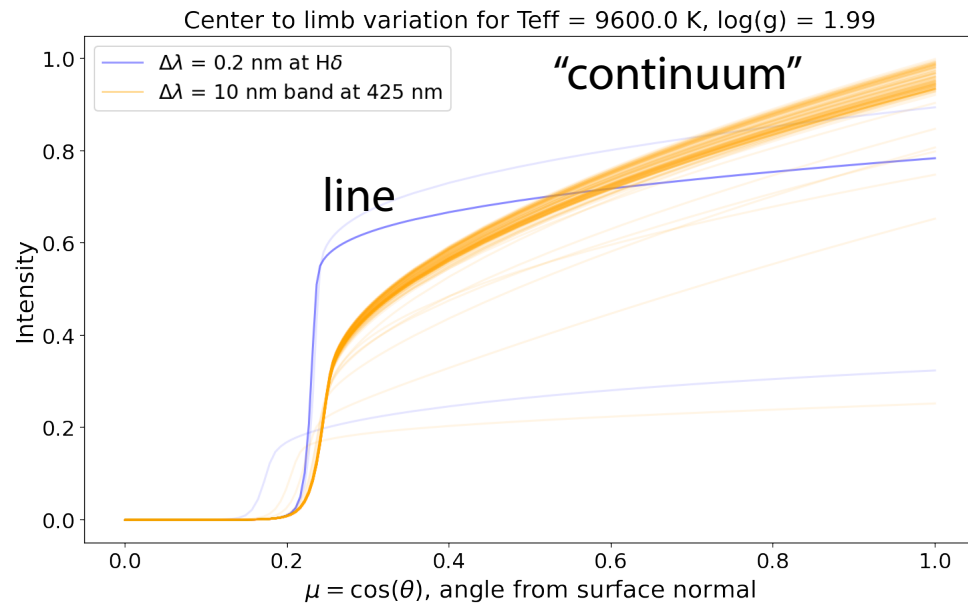
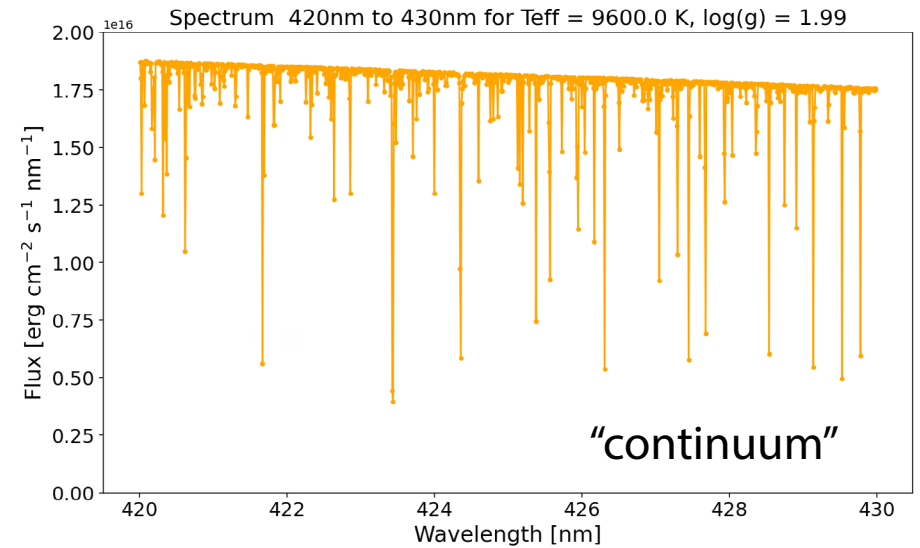
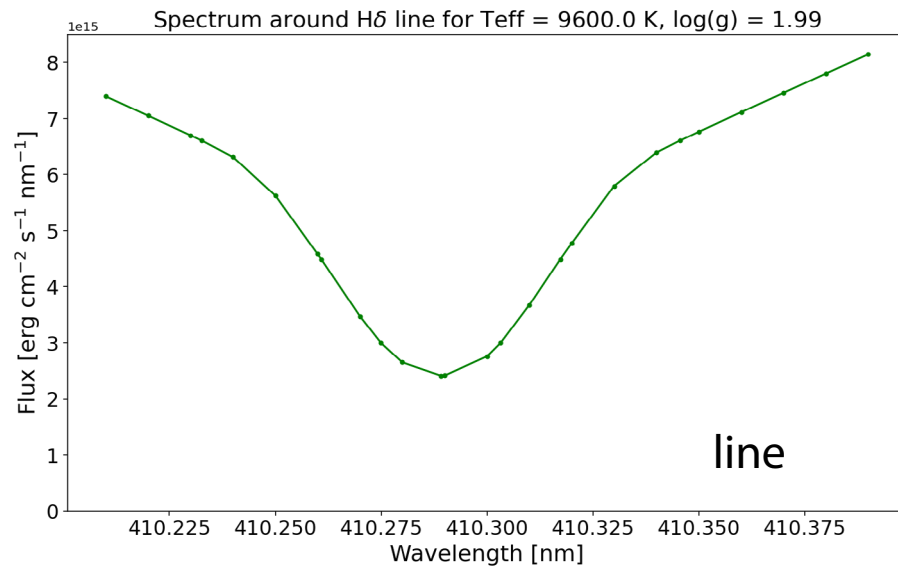
$$|V_{\text{LD}}|^2 = \frac{\int_0^\infty |V_{\text{LD}}(\lambda)|^2 d\lambda}{\int_0^\infty S_\lambda^2 F_\lambda^2 d\lambda},$$

“Tests of stellar model atmospheres by optical interferometry
VLT/VINCI limb-darkening measurements of the M4 giant ψ Phe”
M. Wittkowski, J. P. Aufdenberg, and P. Kervella (2004)

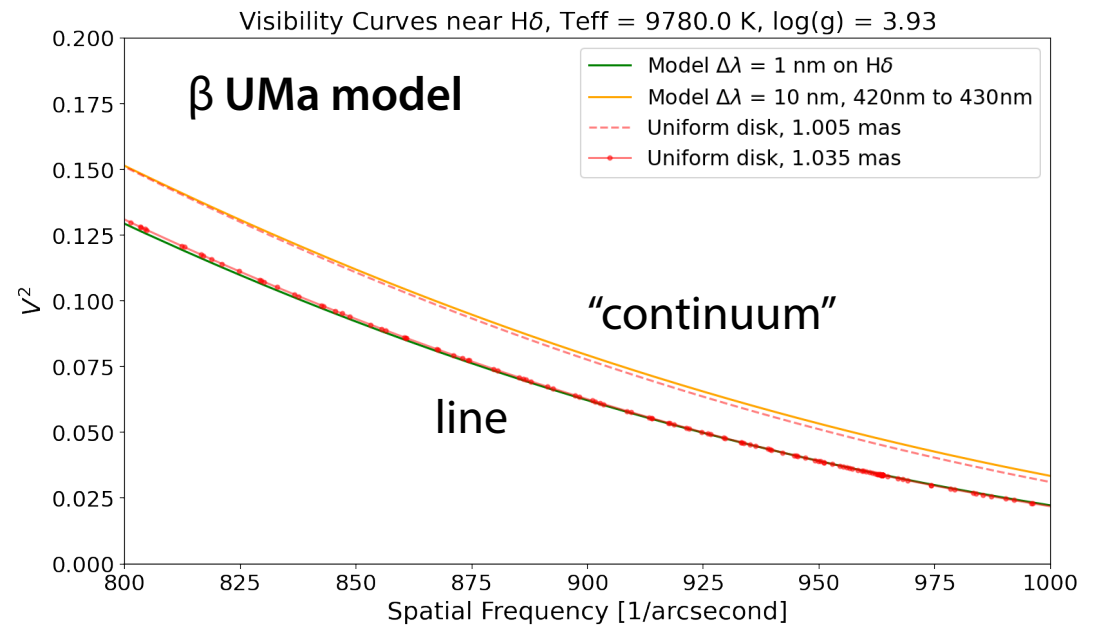
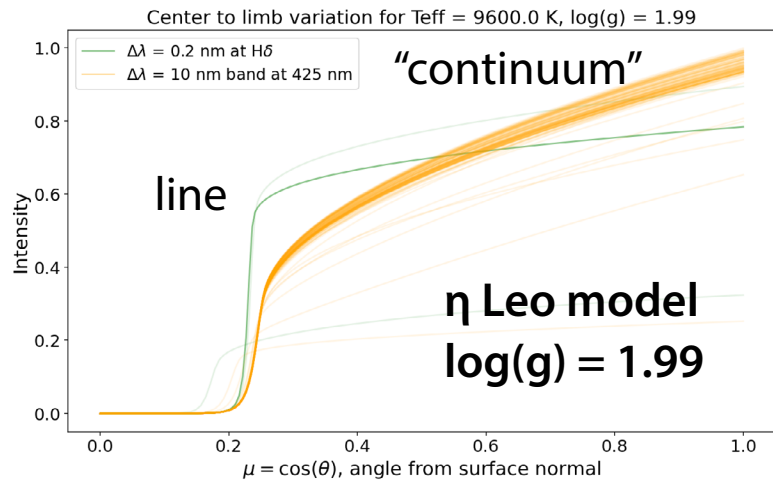
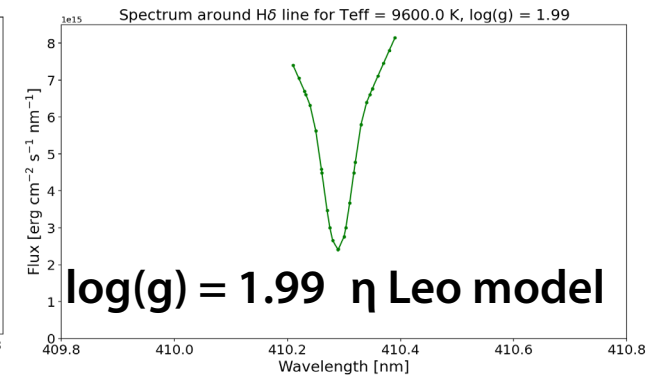
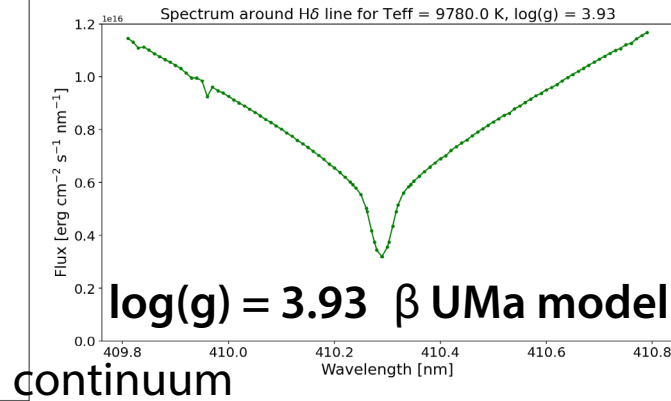
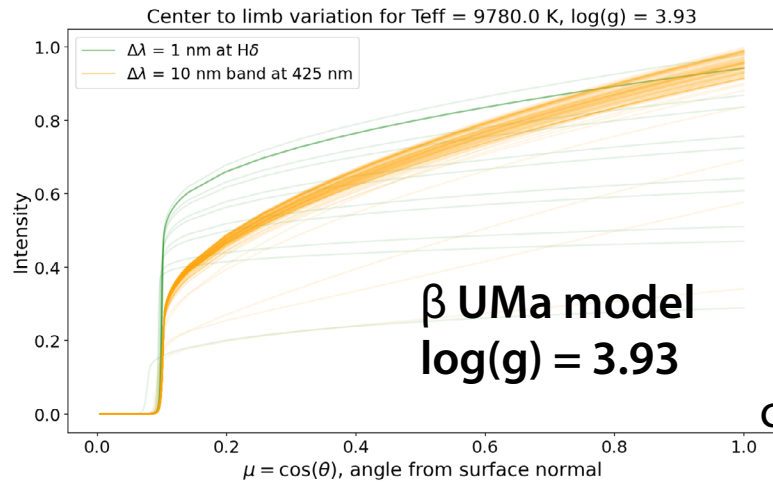
Very narrow band (0.3 nm) required to see 2.5% larger UD diameter in the H 11 Balmer line in η Leo



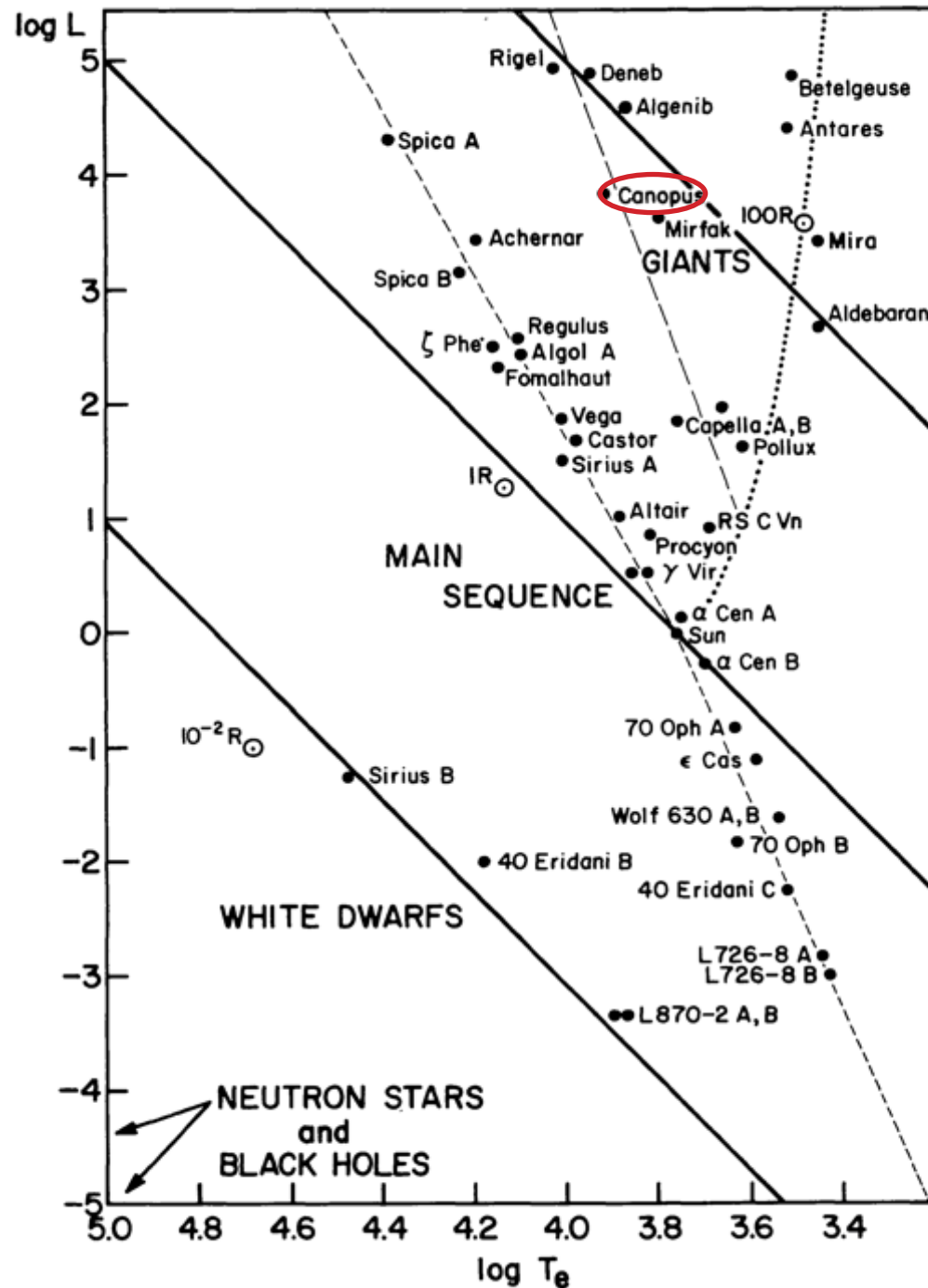
Very narrow band (0.2 nm) required to see 4.3% larger UD diameter in the H δ Balmer line



Model H δ Stark wings, for the A-type subgiant β UMa, yield larger 3% UD diameter in 1-nm band

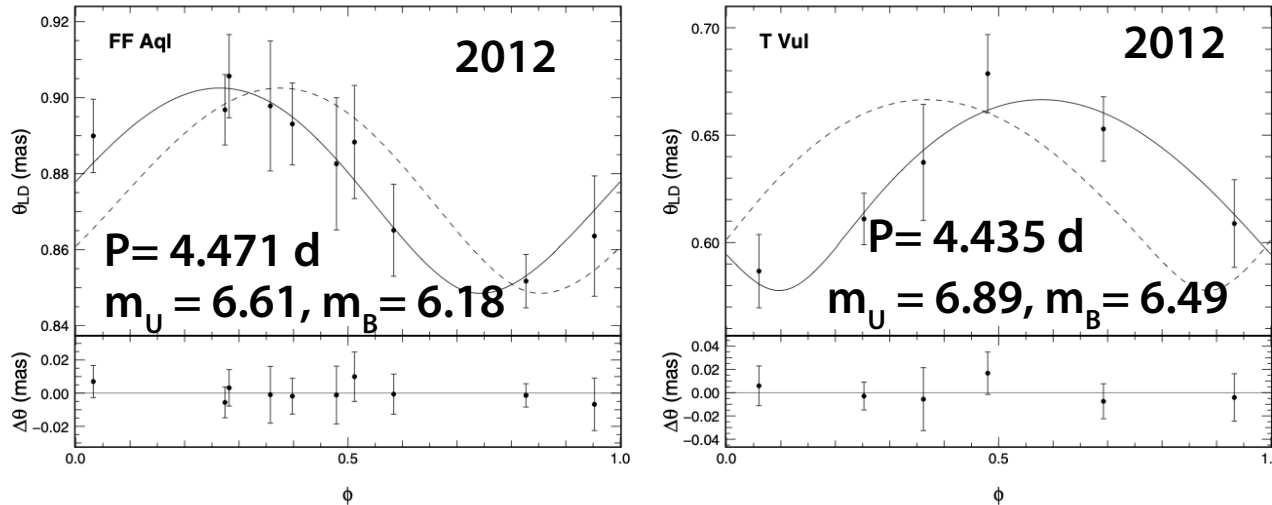


F-type supergiants/Cepheids

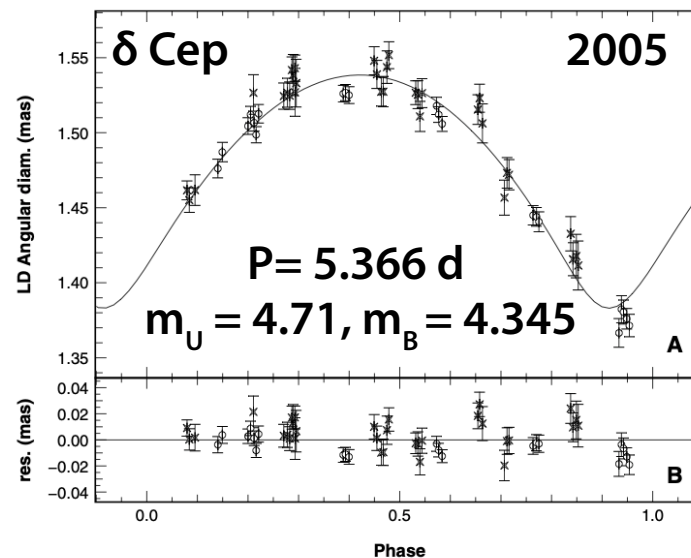


Brightest Cepheids below 1 mas: FF Aql & T Vul, but they are faint...

CHARA/FLUOR observations (2012, 2005)

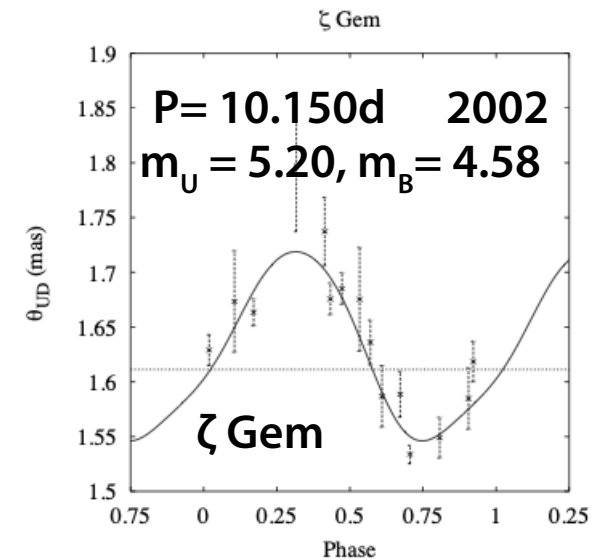
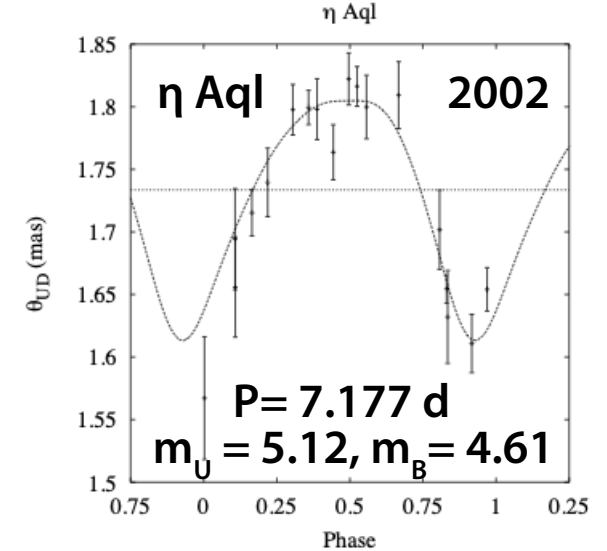


“Mean angular diameters, distances, and pulsation modes of the classical Cepheids FF Aquilae and T Vulpeculae...” Gallenne, A. (2012)



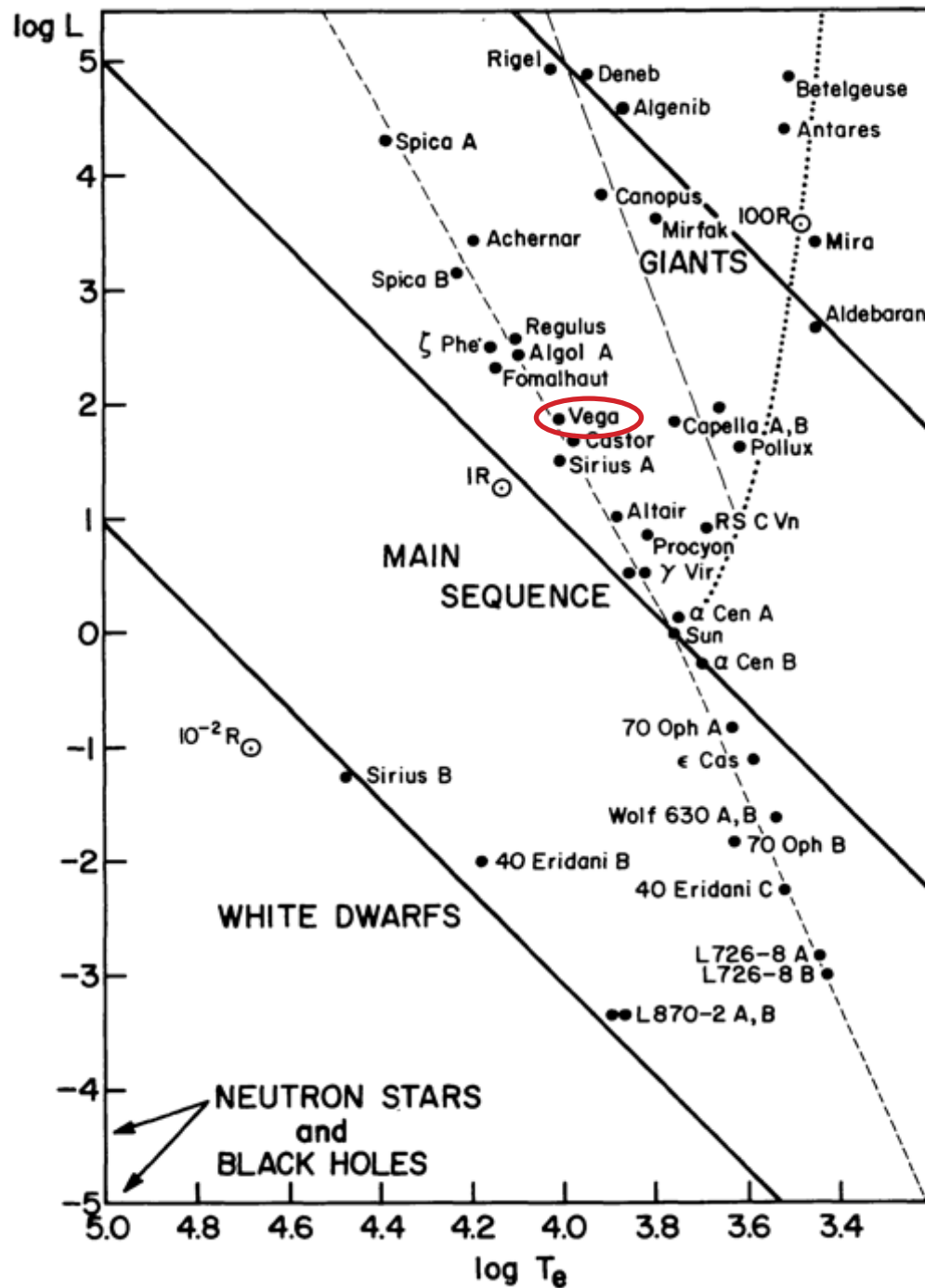
“The projection factor of δ Cephei. A calibration of the Baade–Wesselink method using the CHARA Array” Mérand, A. et al. (2005)

PTI observations (2002)



“LONG-BASELINE INTERFEROMETRIC OBSERVATIONS OF CEPHEIDS”, Lane, B. et al. (2002)

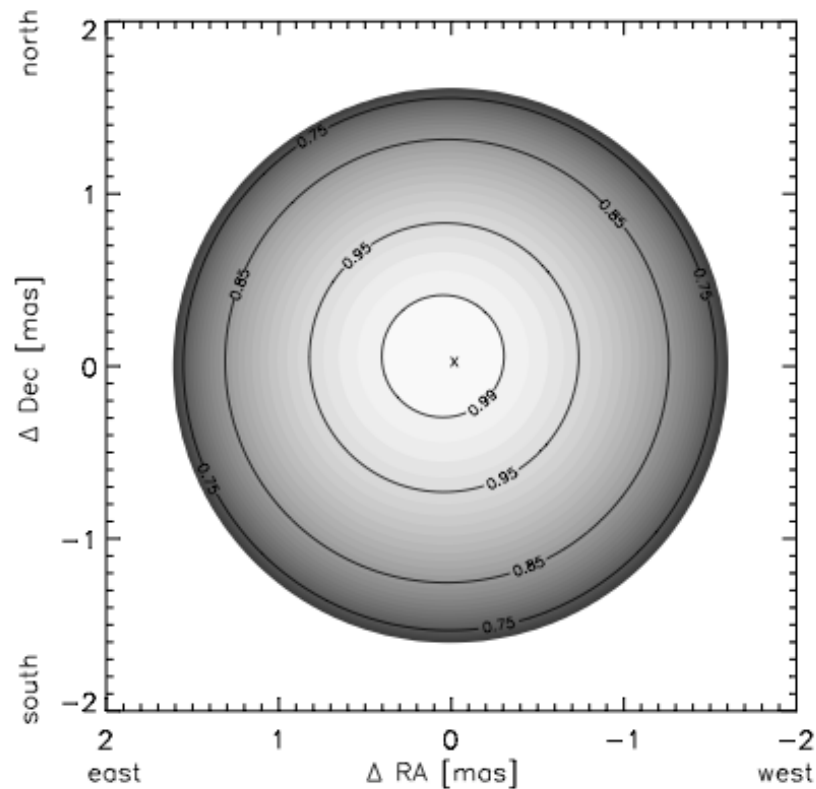
A-type dwarfs and subgiants



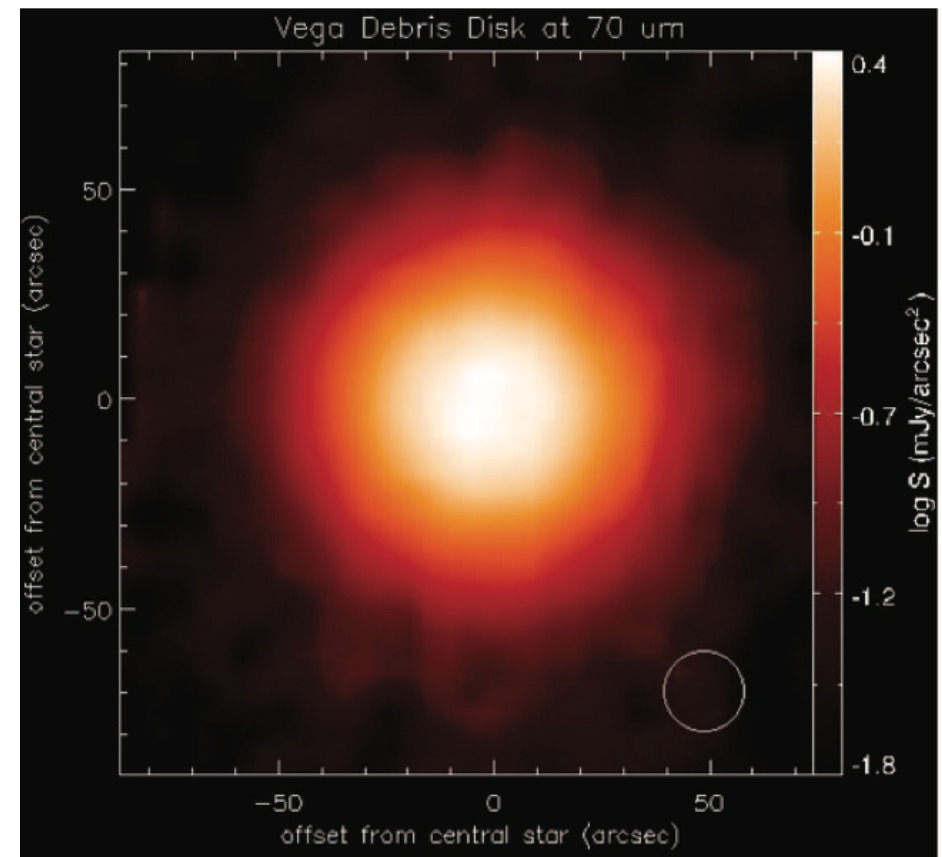
Iben, I (1991) ApJ (Russel Lecture)

Vega - a rapid rotator with debris disk

Stellar disk 3.3 mas, debris disk 100'' at 70 μm



"FIRST RESULTS FROM THE CHARA ARRAY. VII. LONG-BASELINE INTERFEROMETRIC MEASUREMENTS OF VEGA CONSISTENT WITH A POLE-ON, RAPIDLY ROTATING STAR" Aufdenberg et al. (2006)

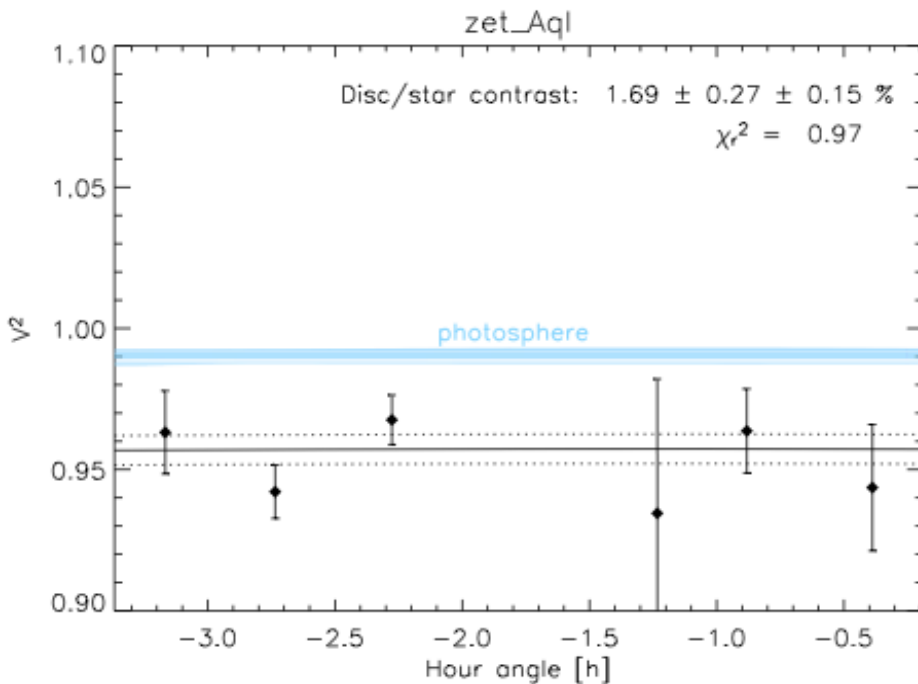


"THE VEGA DEBRIS DISK: A SURPRISE FROM SPITZER"
Su, K. Y. L., et al. (2005)

Unresolved rapid rotators with a debris disks:

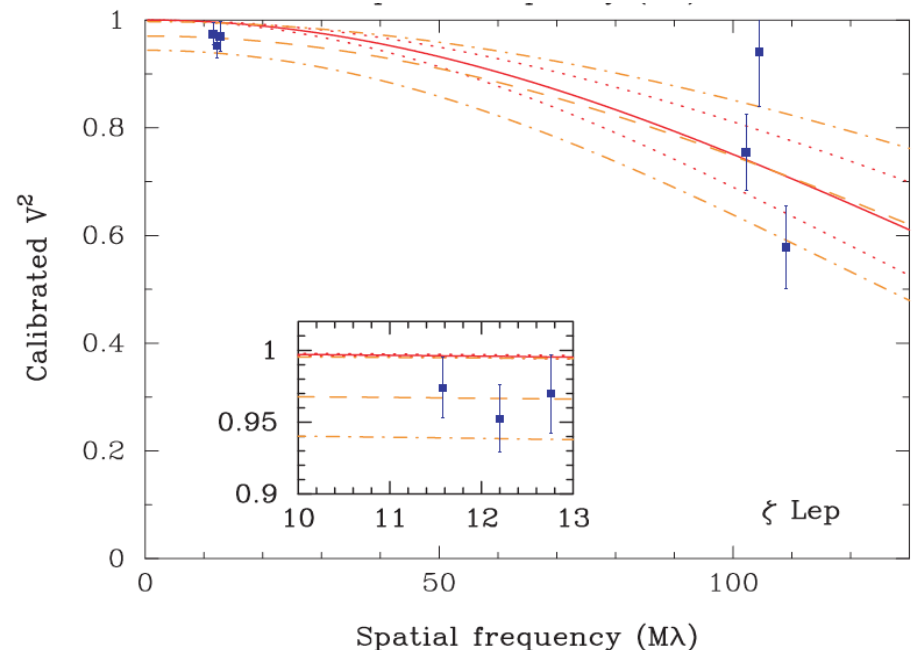
1. ζ Aquilae, $V=3.0$, $\theta_{\text{minor}} \sim 0.77$ mas, $\theta_{\text{major}} \sim 1$ mas

A0IV-Vnn, $v \sin(i) = 317$ km/s, an edge-on Vega



"A near-infrared interferometric survey of debris disc stars II. CHARA/FLUOR observations of six early-type dwarfs"
Absil, O. et al. (2008)

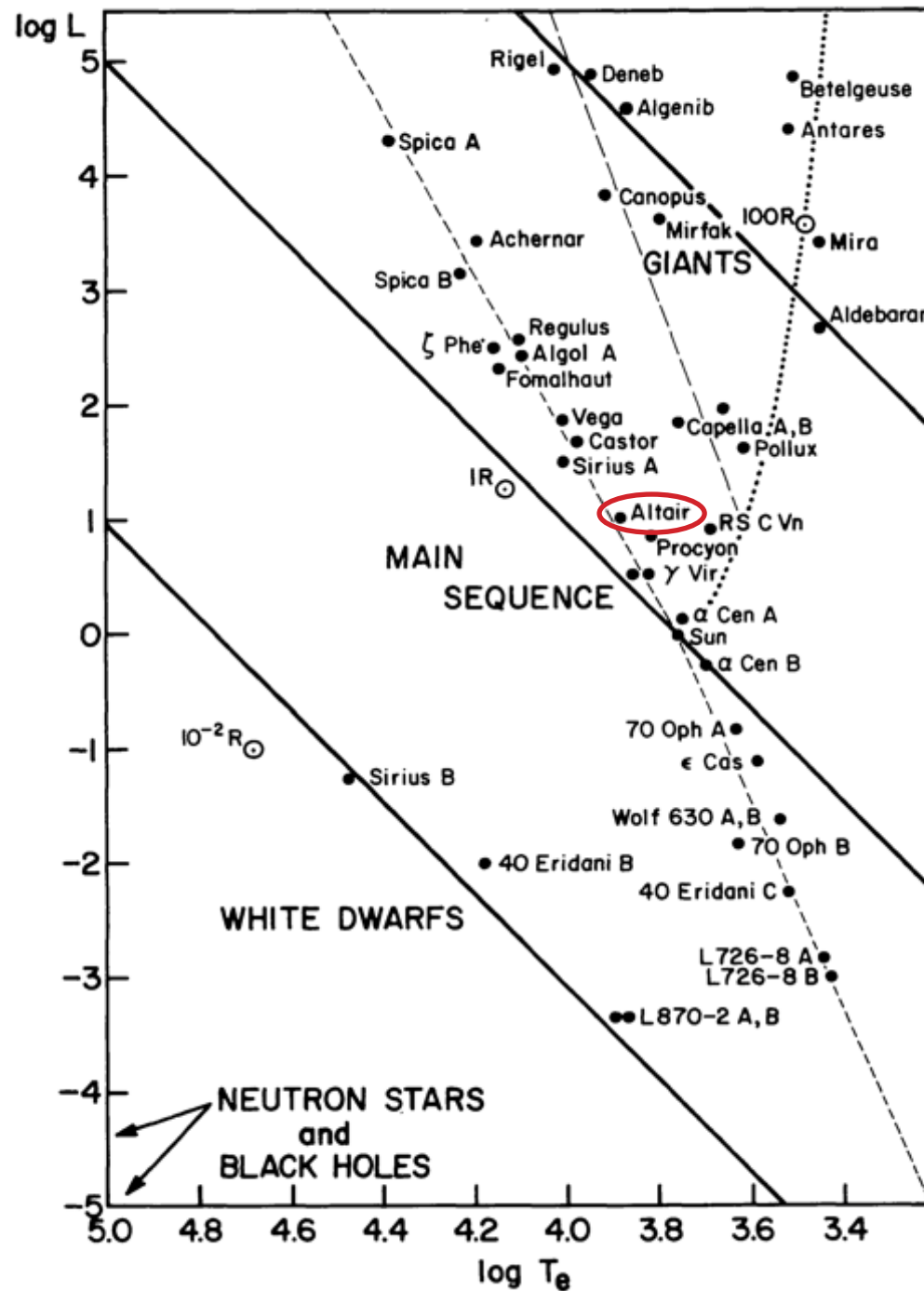
2. ζ Lep, $V=3.5$, $\theta \sim 0.70$ mas
A2IV-V(n), $v \sin(i) = 259$ km/s



"DUST IN THE INNER REGIONS OF DEBRIS DISKS AROUND A STARS"
Akeson, R. et al. (2009)

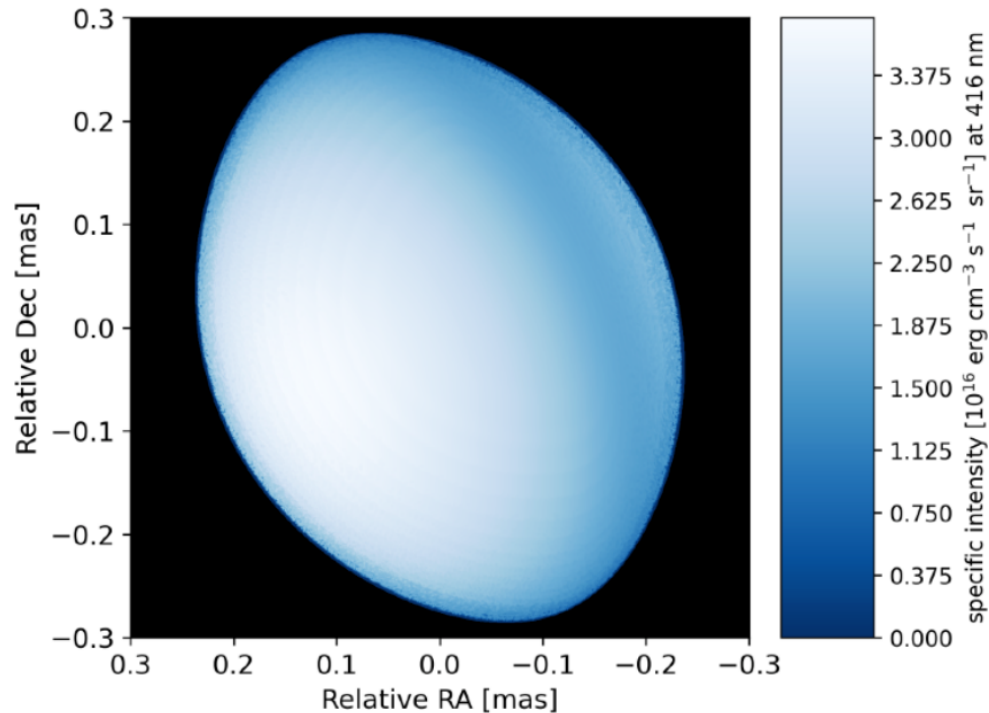
SII with 150 m baseline at 400 nm reaches 375 $M\lambda$

Be Stars with disks

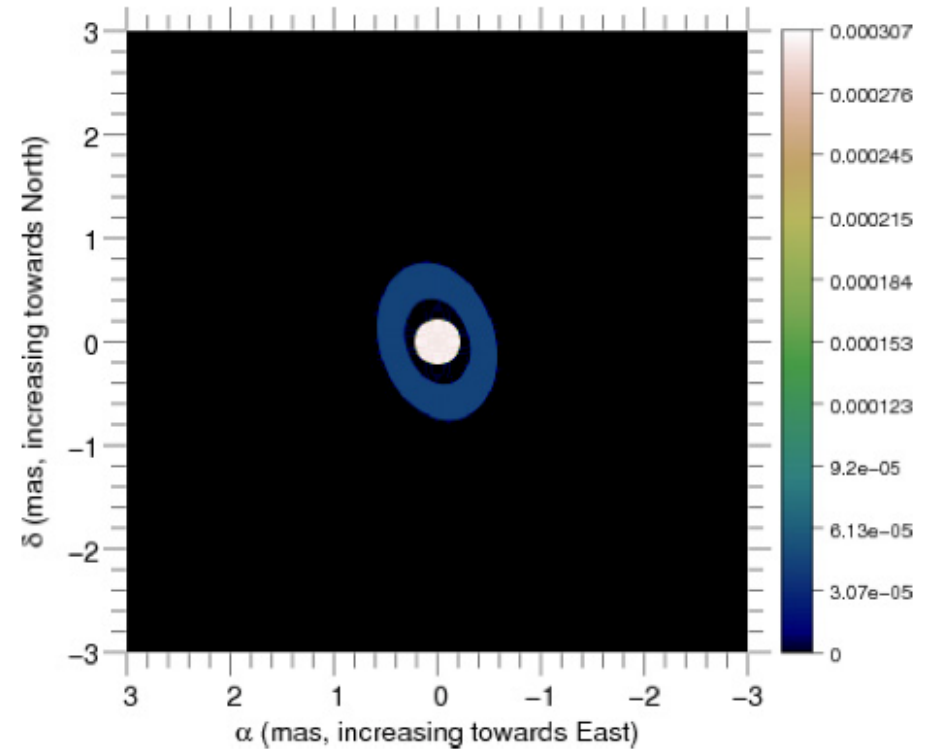


Fully resolving the stars with resolved disks

γ Cas resolved by VERITAS, disk by CHARA



Measurement of the photosphere oblateness of γ Cassiopeiae via Stellar Intensity Interferometry with the VERITAS Observatory
Archer et al. (2025, in press)



“The relationship between γ Cassiopeiae’s X-ray emission and its circumstellar environment
II. Geometry and kinematics of the disk from MIRC and VEGA instruments on the CHARA Array” Stee et al. (2012)

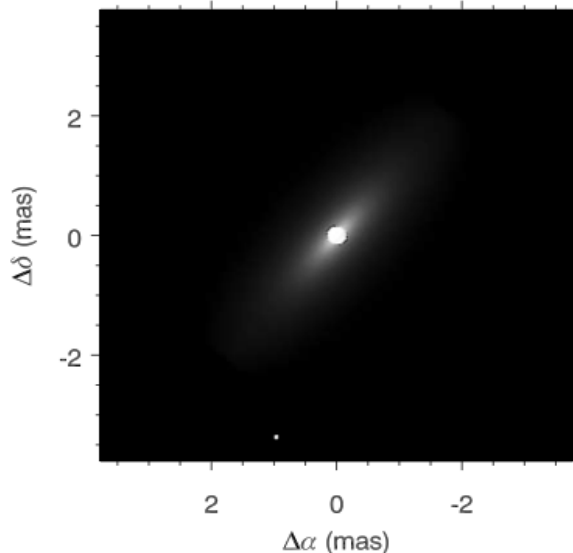
Other bright Be stars with disks

Be-stars	Spectral type	Est. Angular Size ¹ (mas)	U-band magnitude	V-band magnitude	Parallax (mas)	Dec.
β CMi	B8Ve	0.50 ²	2.42	2.89	20.2 $\pm$ 0.20	+8
φ Per	B1.5Ve	0.30	3.10	4.06	5.40 $\pm$ 0.20	+50
ζ Tau	B1IVe	0.40	2.22	3.03	7.33 $\pm$ 0.82	+21
κ Dra	B6 IIIe	0.39	3.18	3.89	7.01 $\pm$ 0.30	+70

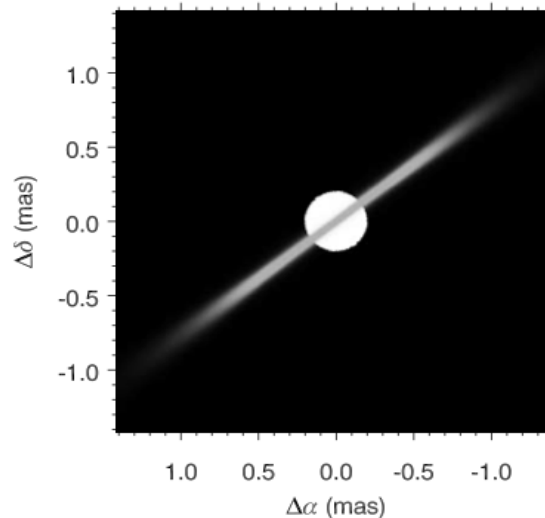
1 From "CHARA Array K'-Band Measurements of the Angular Dimensions of Be Star Disks" Geis et al. (2007)

2 From "Gas Distribution, Kinematics, and Excitation Structure in the Disks around the Classical Be Stars β Canis Minoris and ζ Tauri" Kraus et al. (2012)

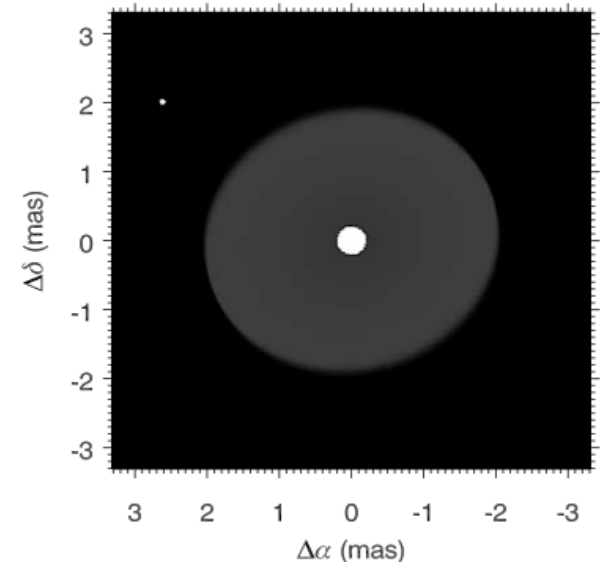
φ Per



ζ Tau



κ Dra



Binary Stars: Spectroscopy provides the projected separation; interferometry provides the inclination --> masses, distance

9th Catalogue of Spectroscopic Binary Orbits (Pourbaix+ 2004-2014) VizieR Query
Declination > -20°
Primary V magnitude < 5
Period < 20 days
Double-line systems

SC9 Catalog number	Bayer/ Flamsteed name	Primary V mag	Sp Type 1	Sp Type 2	Period (d)	eccentricity	K ₁ (km/s)	K ₂ (km/s)	M2/M1 = K1/K2	Parallax (mas) (simbad)	Projected angular semi-major axis $a \sin i$ (mas)	Notes (Diameter estimates from Cruzalèbes, P. 2019)
47	ν And	4.53	B5 V	B6.5	4.2827	0.03	72	102	0.71	5.7858	0.384	0.34 mas size est, HR 266 = HD 4727
107	γ ² And	4.84	B9.5 V	A0V	2.67	0.29	113	141	0.8	12.0724	0.488	Triple system: WDS0239+4220/ STT 38 BC, “B” is γ ² inclination est: 62° Docobo and An- drade (2006).
211	λ Tau A	3.47	B3 V	A4 IV	3.9529	0.00	57	216	0.27	8.0397	0.789	triple system, eclipsing
366	β Aur	1.909	A2 IV	A2 IV	3.96	0.00	108	112	0.96	40.21	3.22	eclipsing system
766	α Vir	0.96	B1 V	B3 V	4.0145	0.18	120	189	0.63	13.06	1.19	0.87 mas size est.
1268	57 Cyg	4.77	B5 V	B5 V	2.585	0.15	112	126	0.89	5.8088	0.275	0.25 mas size est.
1370	2 Lac	4.57	B6 IV	B6 V	2.616	0.04	80	110	0.73	5.2687	0.231	0.32 mas size est.

$$a \sin i = 13751(1 - e^2)P[\text{d}](K_1[\text{km s}^{-1}] + K_2[\text{km s}^{-1}]) \text{ km}$$

$$\alpha \sin i = \frac{a \sin i}{d}$$

$$m_1 + m_2 = \frac{P}{2\pi G} \frac{(K_1 + K_2)^3}{\sin^3 i}$$

$$\frac{m_2}{m_1} = \frac{K_1}{K_2}$$

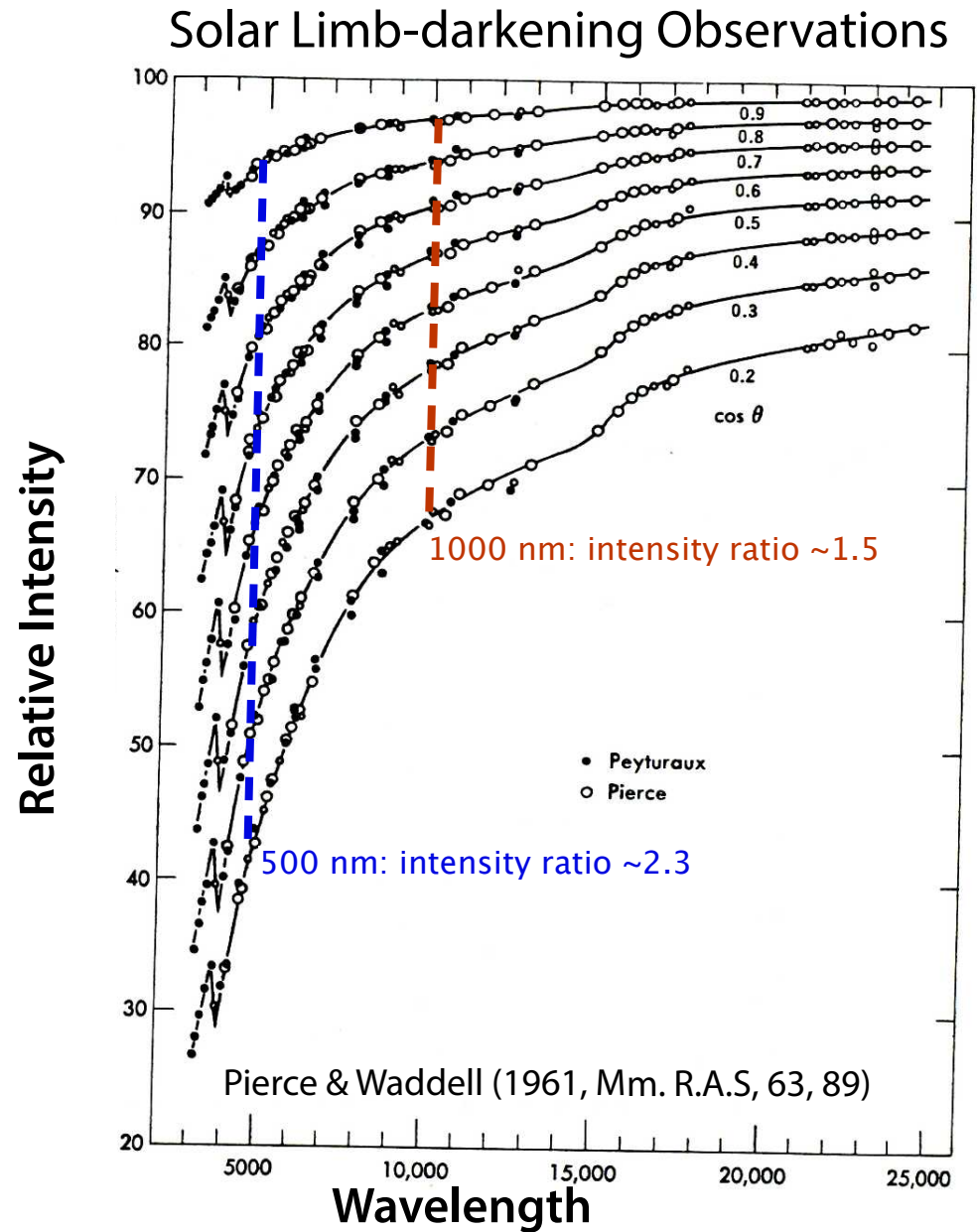
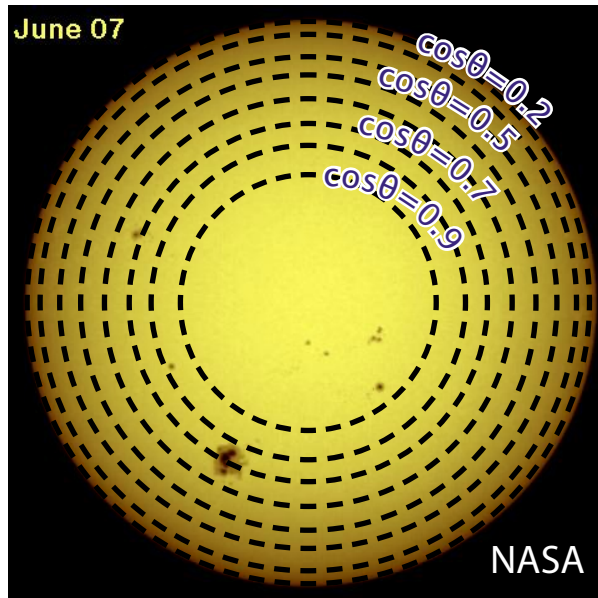
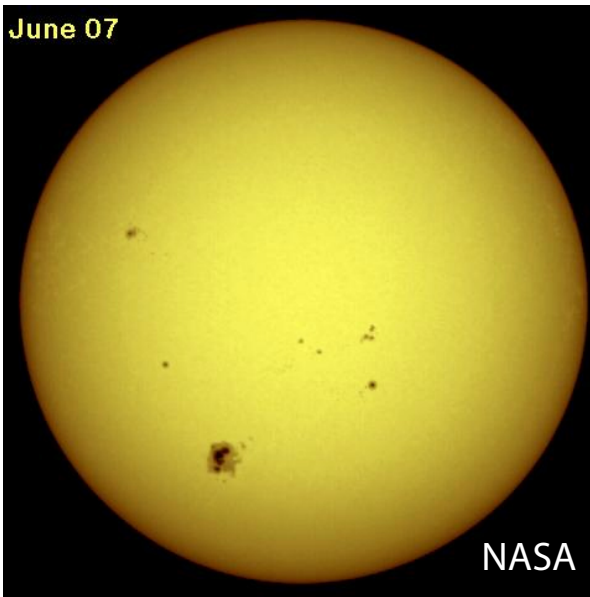
A few take-away ideas!

- Don't need the 2nd lobe measurements to study limb darkening: compare SII blue observations with H- and K-band observations
- Blue SII measurements test models where they are more sensitive
- SII measurements inside spectral lines will be challenging, very narrow band widths required: $\leq 1\text{nm}$
- SII measurements of angular diameters for central stars in debris disk and Be star disk systems is promising. A-supergiants and Cepheids are fainter targets.
- SII should excel at bright, short-period binary systems.

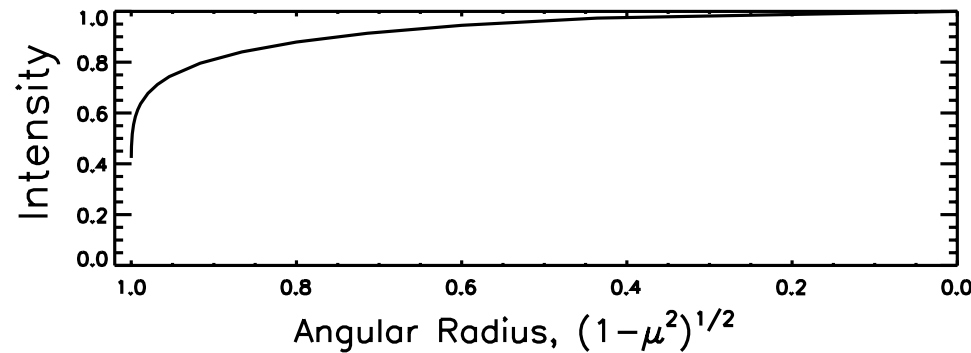
Thank you for your attention!

Extra slides from my 2023 talk at the
Columbus workshop.

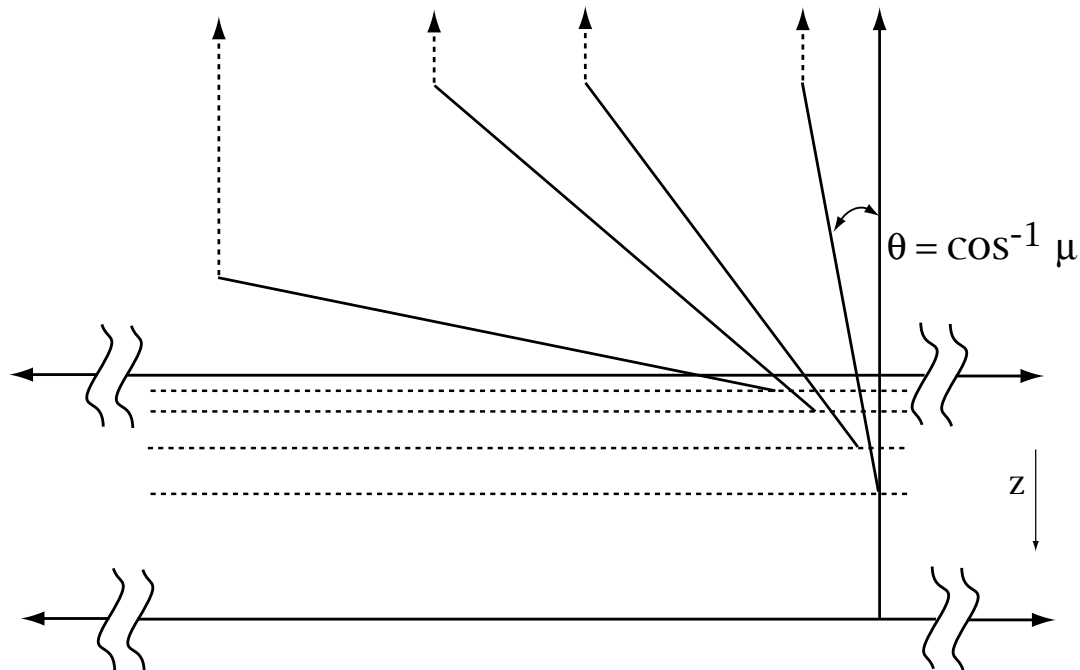
Limb Darkening weakens as wavelength increases



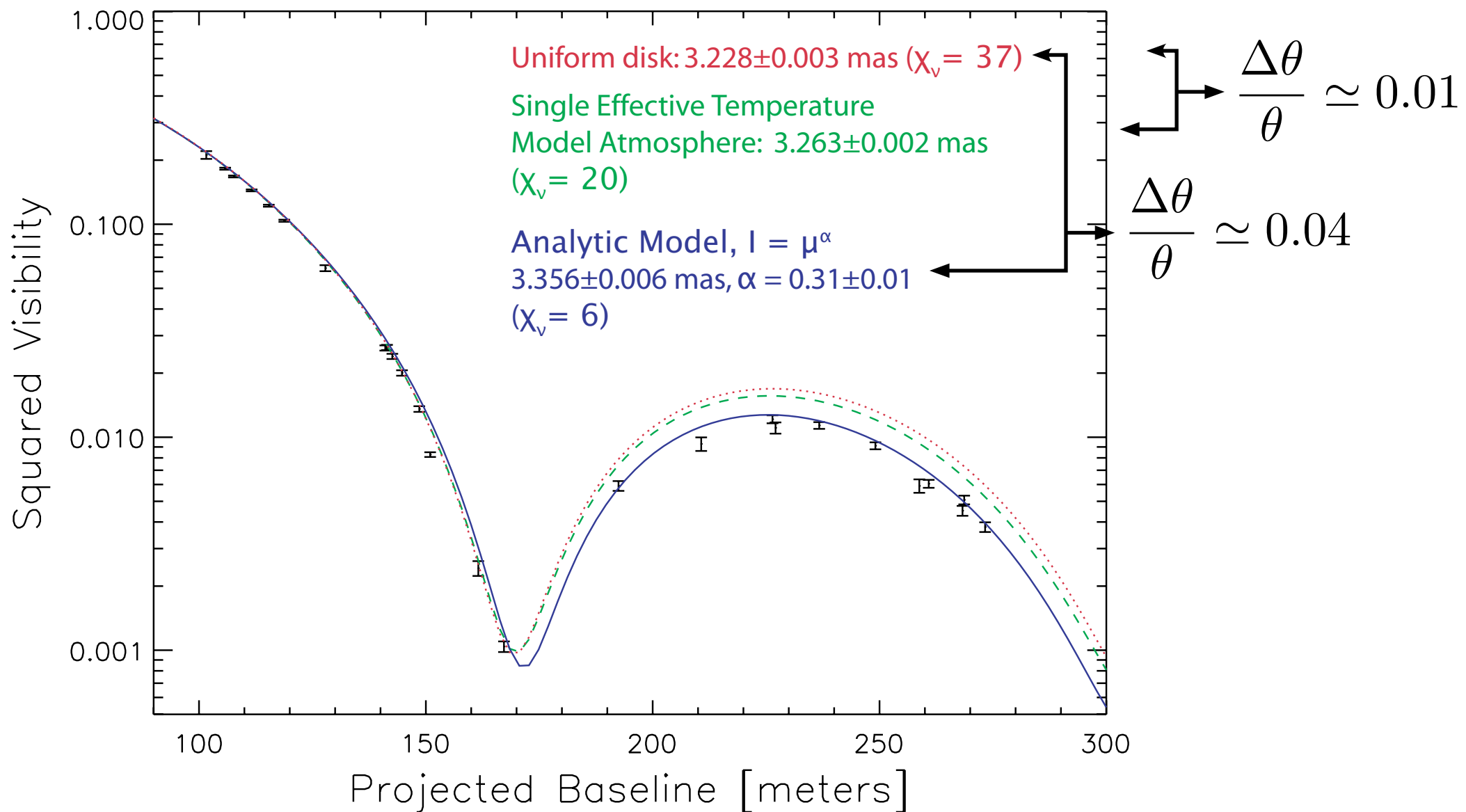
Stellar Limb Darkening: Geometry with a plane-parallel atmosphere



0.1% of
stellar
radius

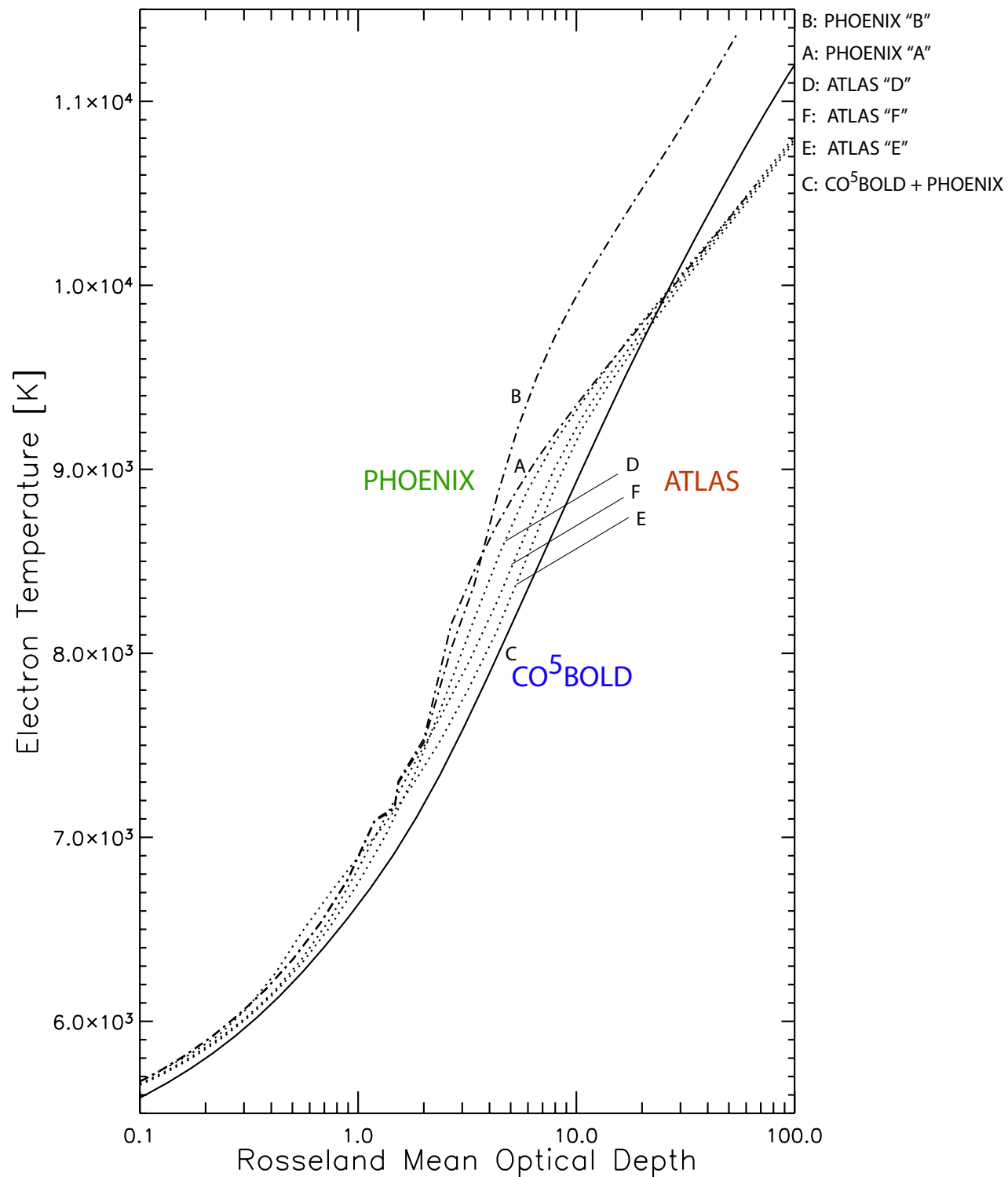


At a single wavelength, details are in the 2nd lobe



Vega (α Lyr), K-Band, CHARA/FLUOR (Aufdenberg et al., 2006)

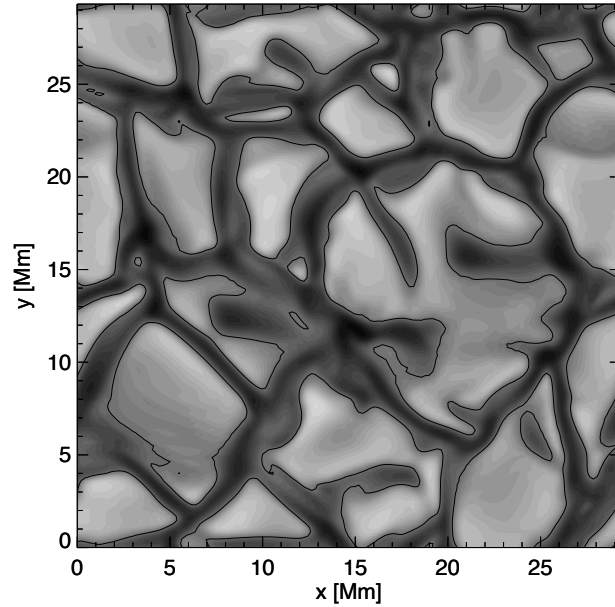
Temperature Structure Constrained by Interferometric Diameters



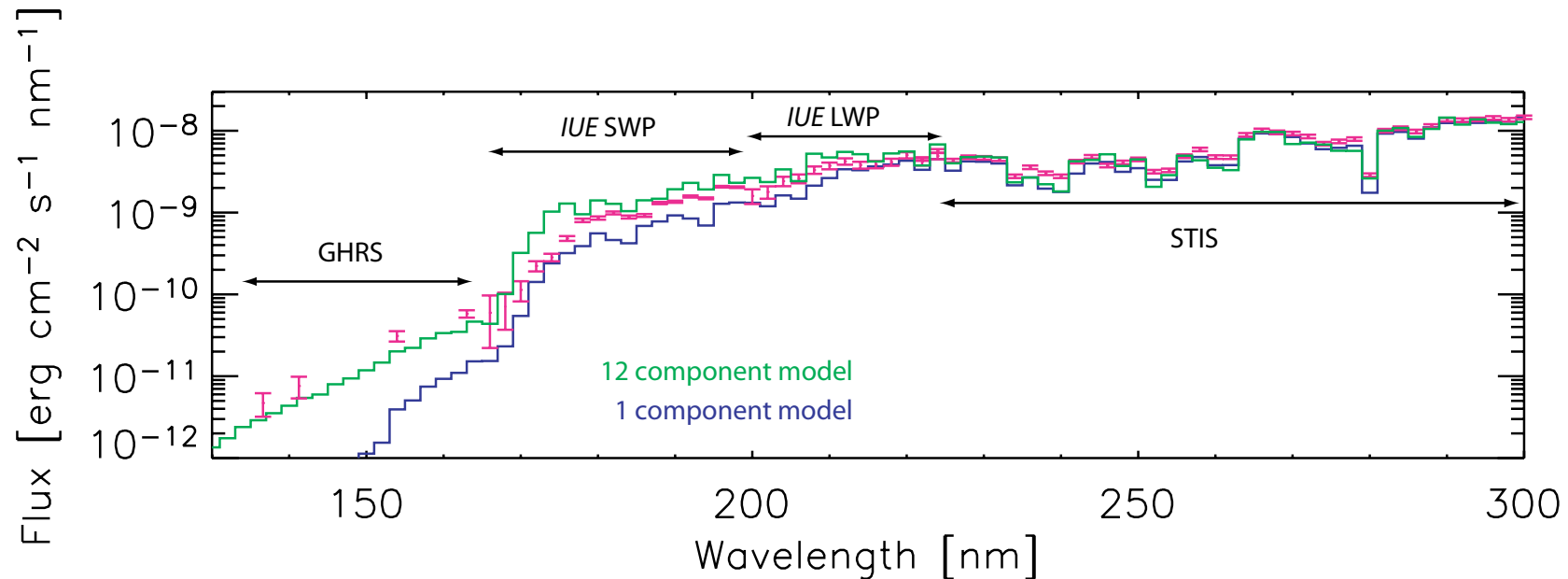
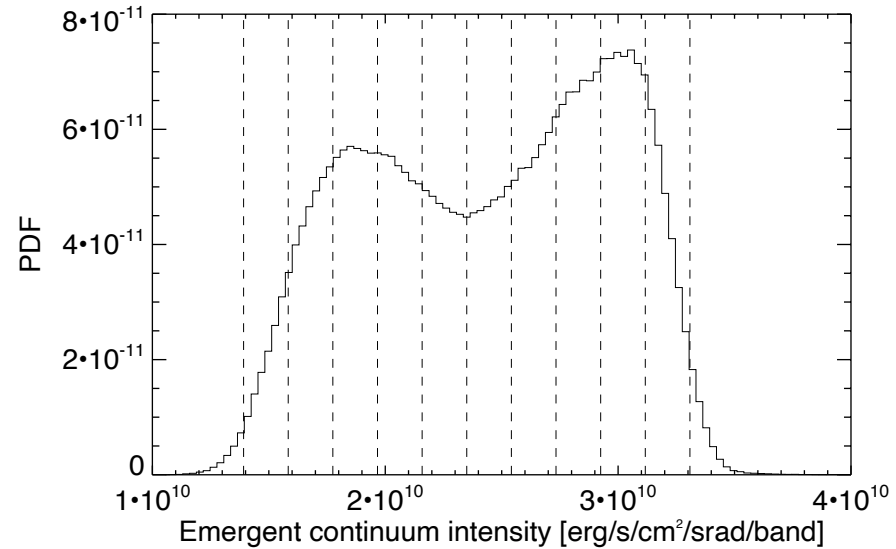
Aufdenberg, Ludwig & Kervella
(2005) ApJ, 633, 424

Spectral Energy Distribution from 3-D Stellar Surfaces

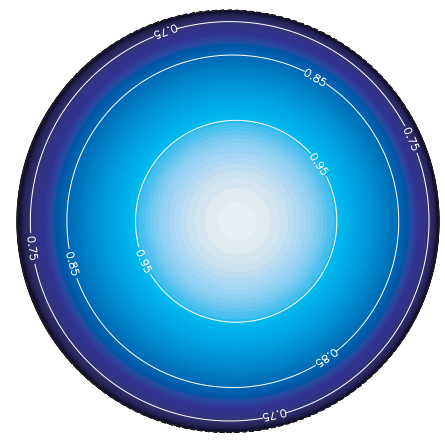
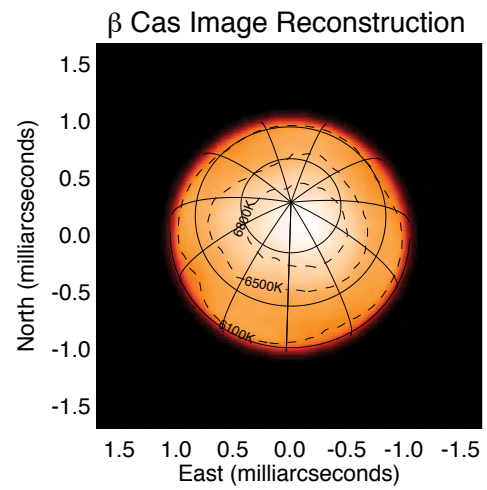
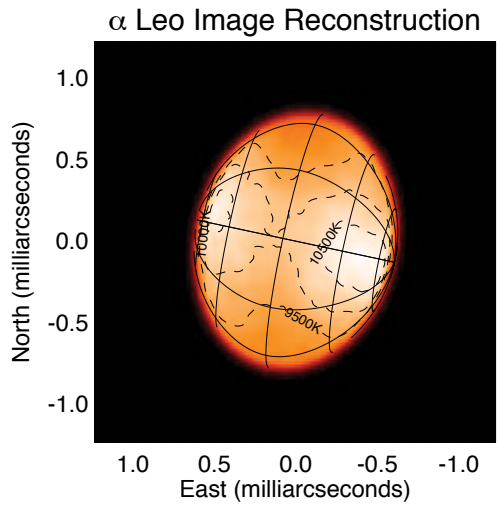
3-D Model Surface Intensity Map



Intensity Histogram



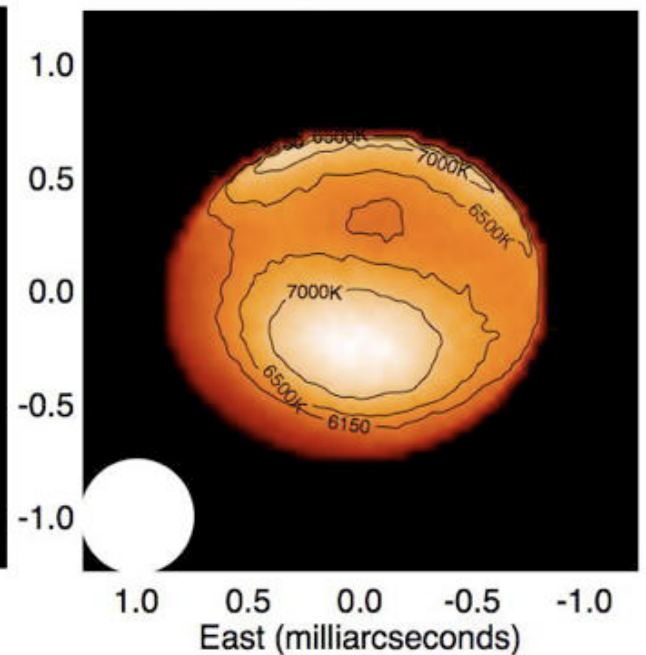
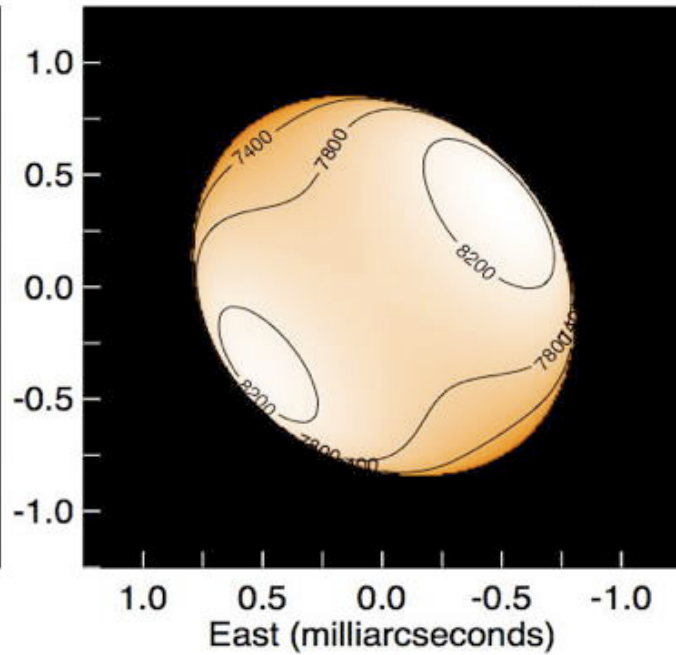
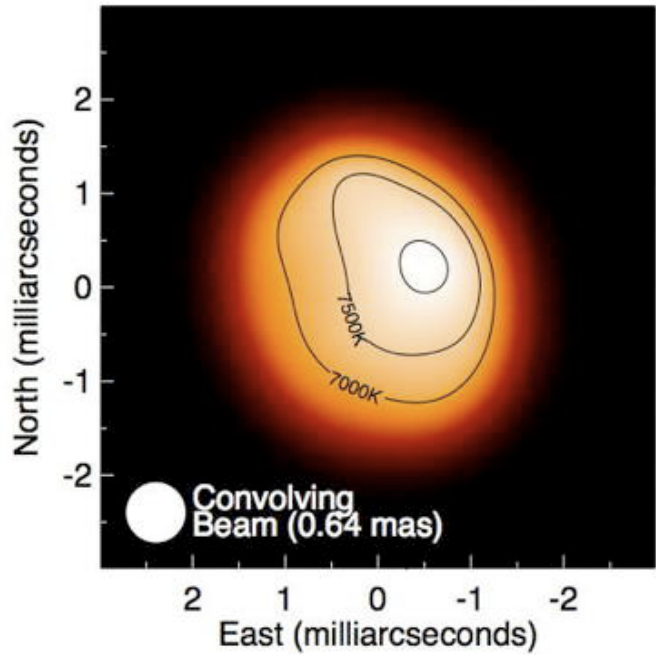
Resolved Rapidly Rotating Stars in the near-infrared, what about ~400 nm?



*Disk of **Regulus** (B7 V) resolved as ellipsoid by CHARA (McAlister et al. 2005, Che et al. 2011).

*Disk of **Caph** (F2 IV) resolved as ellipsoid by CHARA/MIRC (Che et al. 2011).

*Pole of **Vega** (A0 V) resolved by CHARA (Aufdenberg et al. 2006).

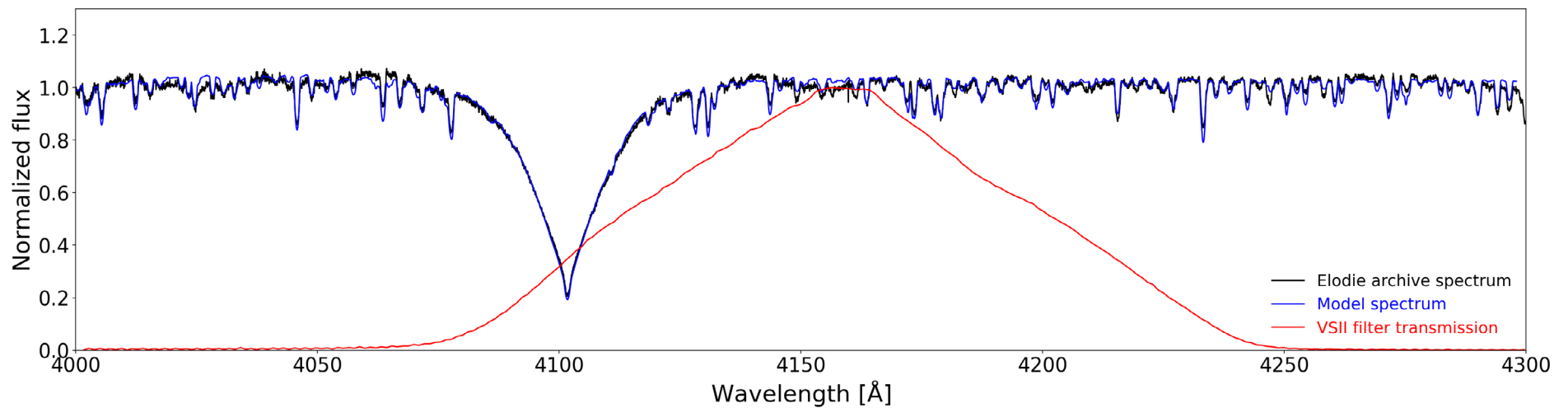
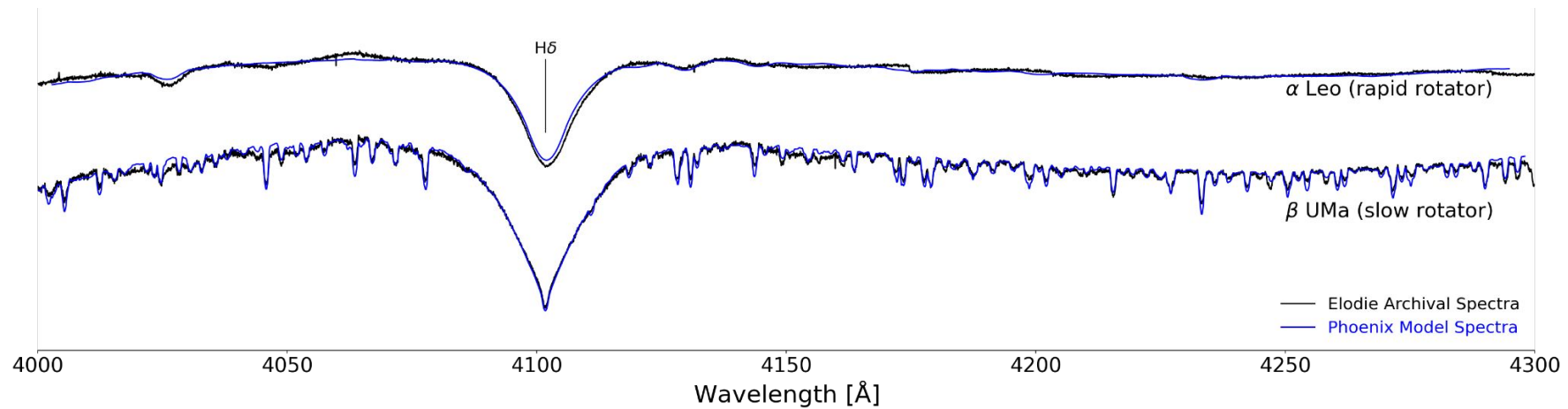


*Disk of **Altair** (A7 V) resolved by CHARA (J. Monnier et al. 2007).

*Disk of **Alderamin** (A7 V) resolved by CHARA (M. Zhao et al. 2009).

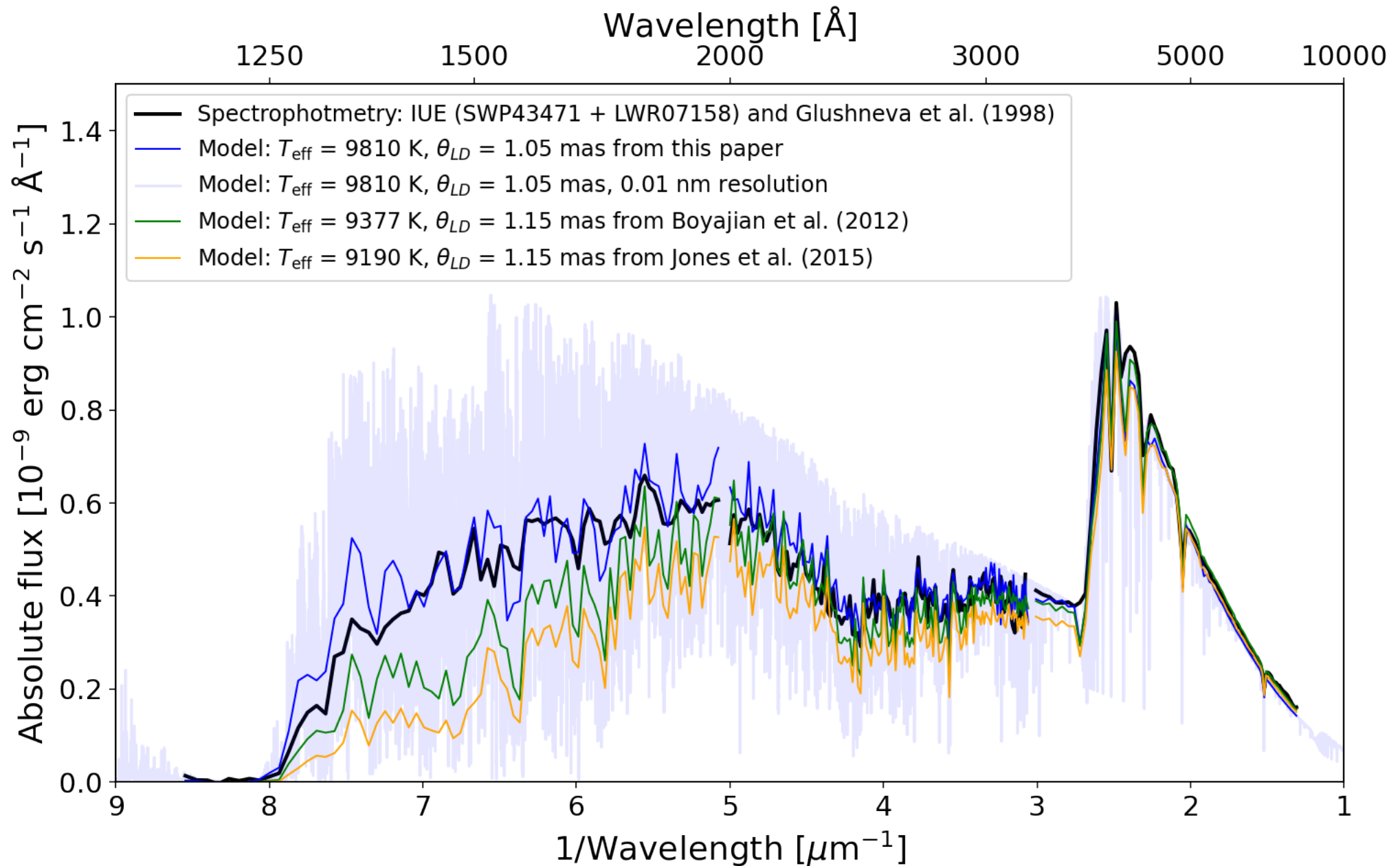
*Disk of **Rasalhague** (A5 III) resolved by CHARA (M. Zhao et al. 2009).

Check that synthetic spectra match archival spectra in the VERITAS SII band

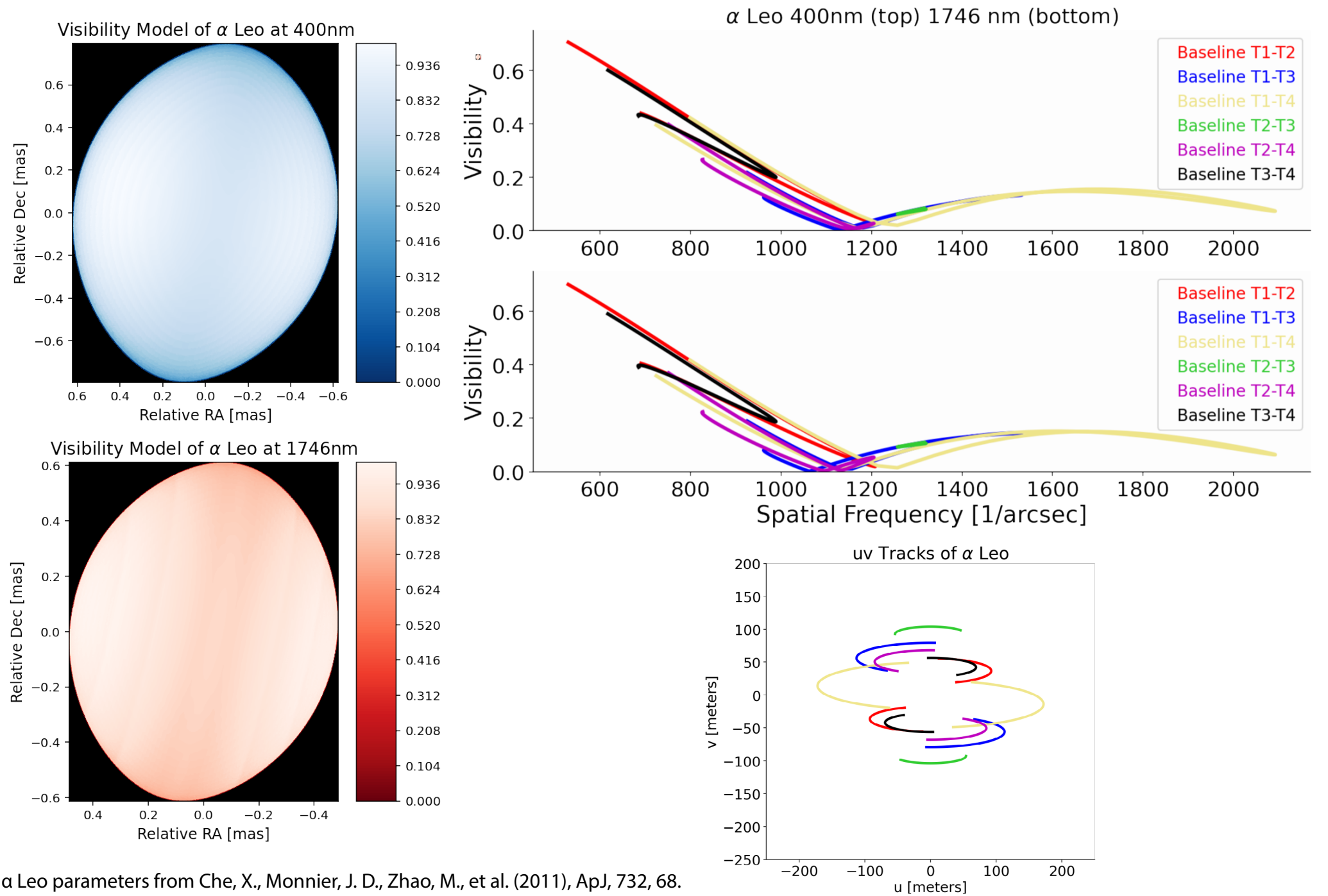


Filter transmission courtesy of Tugdual LeBohec (University of Utah)

Check spectral energy distribution for β UMa

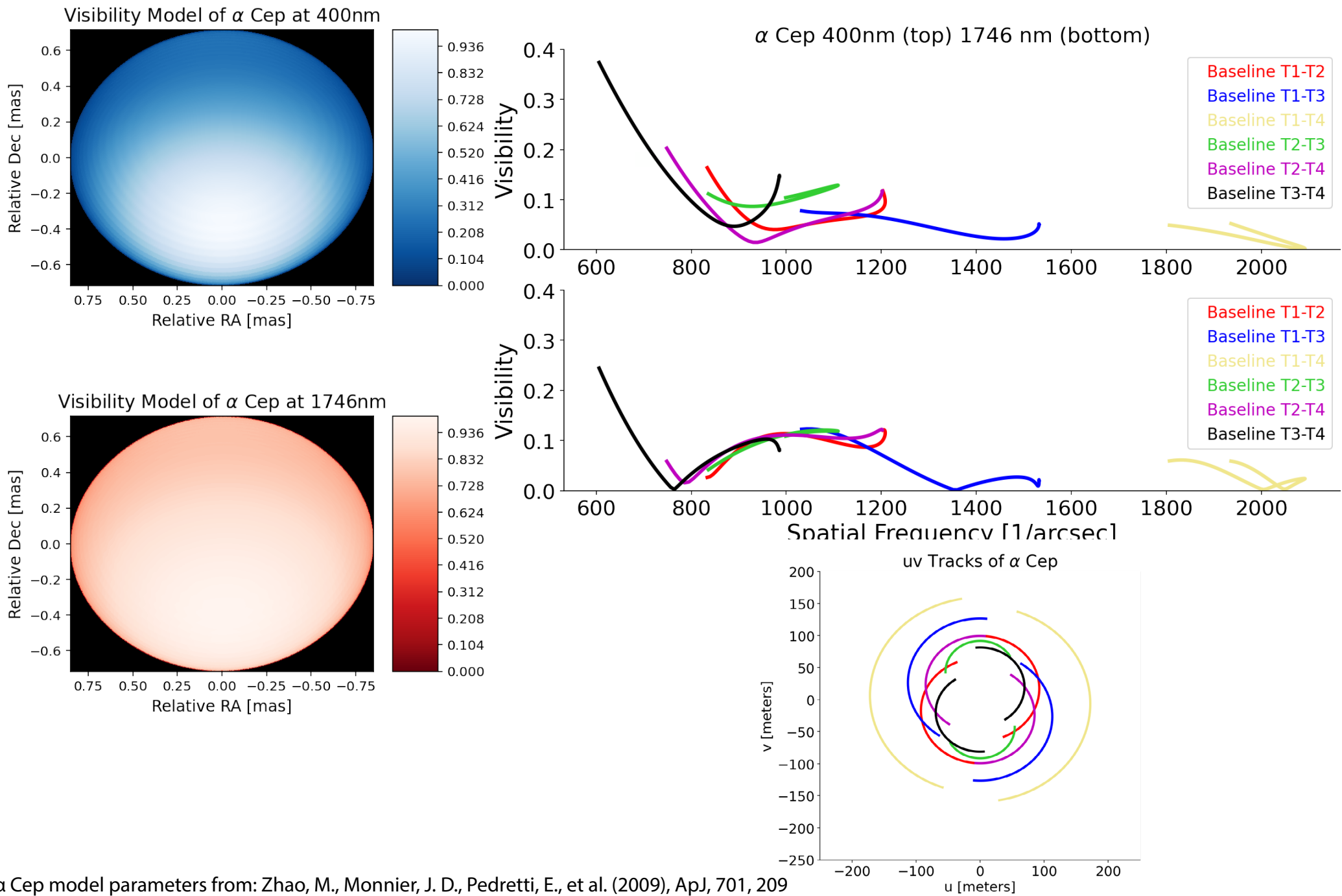


For equator-on ($i=86^\circ$) α Leo, its limb darkening *works against* gravity darkening, with less contrast between 400 nm and 1746 nm.

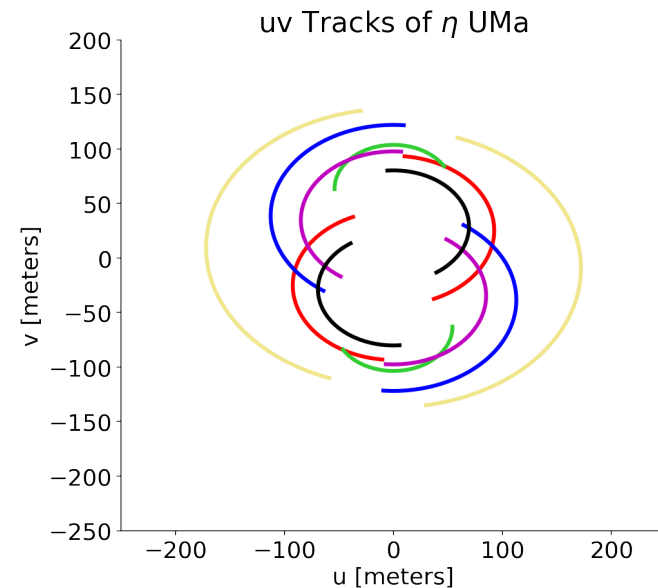
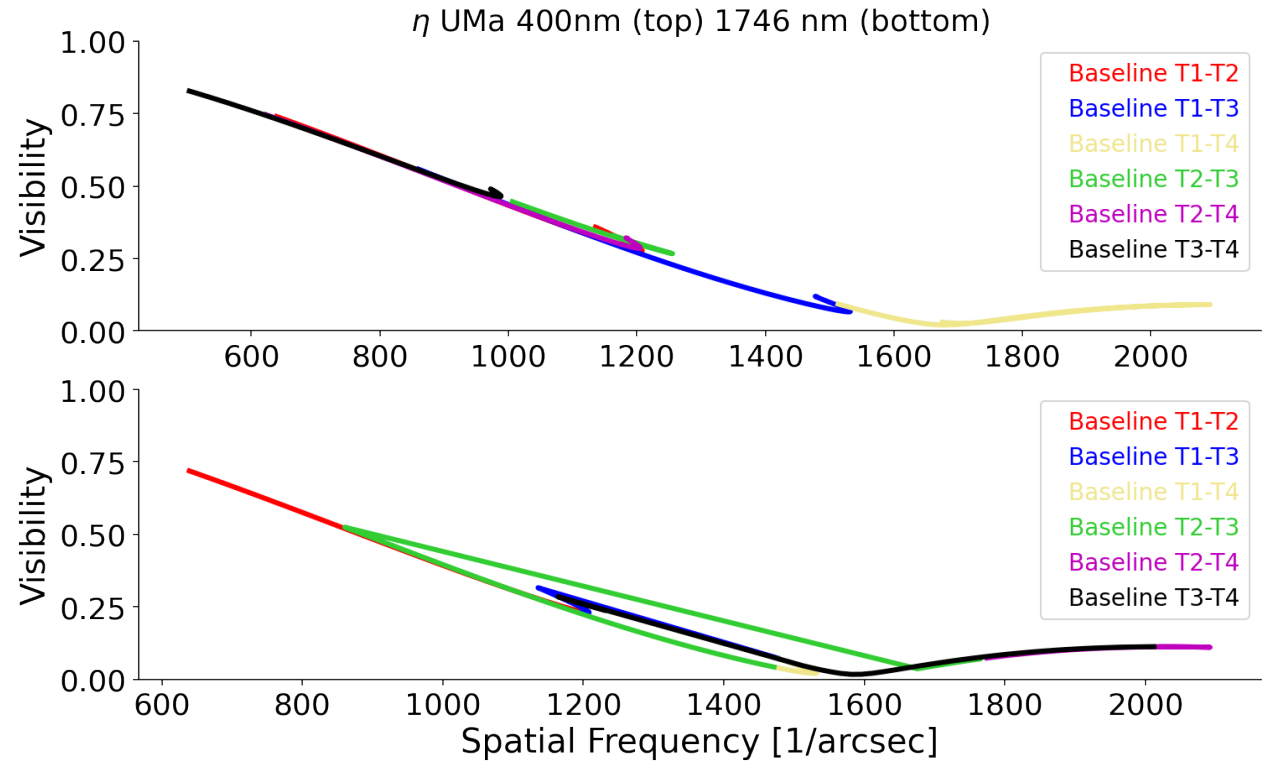
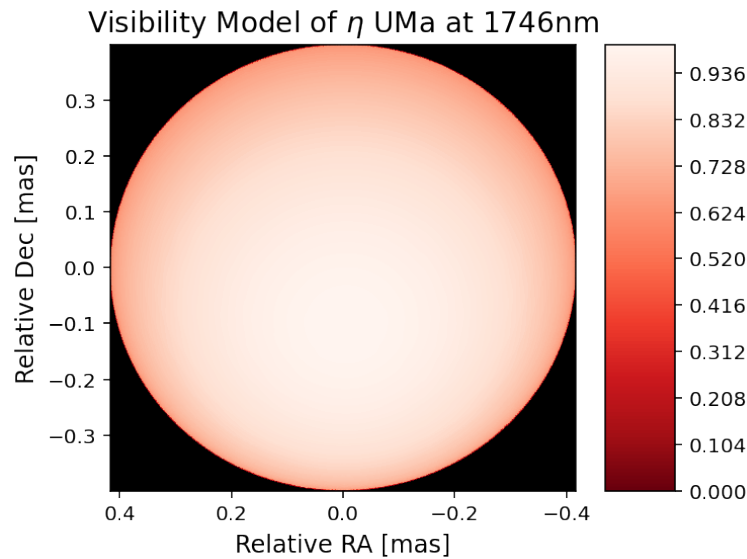
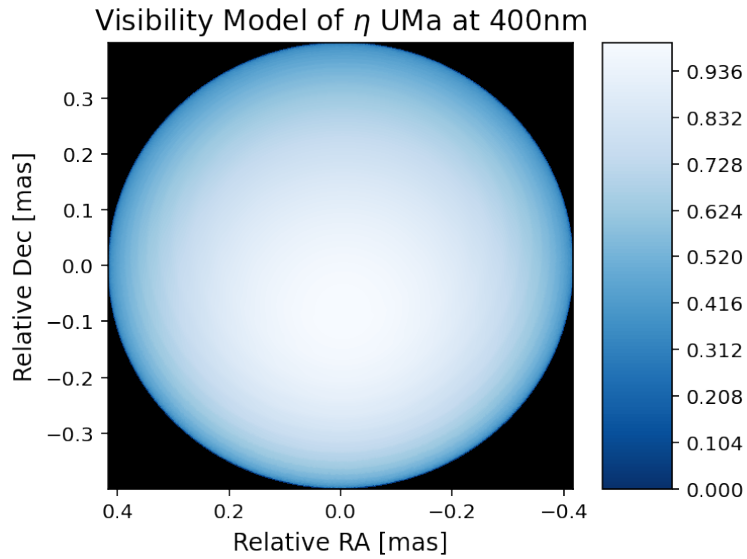


α Leo parameters from Che, X., Monnier, J. D., Zhao, M., et al. (2011), ApJ, 732, 68.

α Cep ($i = 56^\circ$) at 400 nm looks significantly smaller in the 1st lobe and the nulls are subdued.

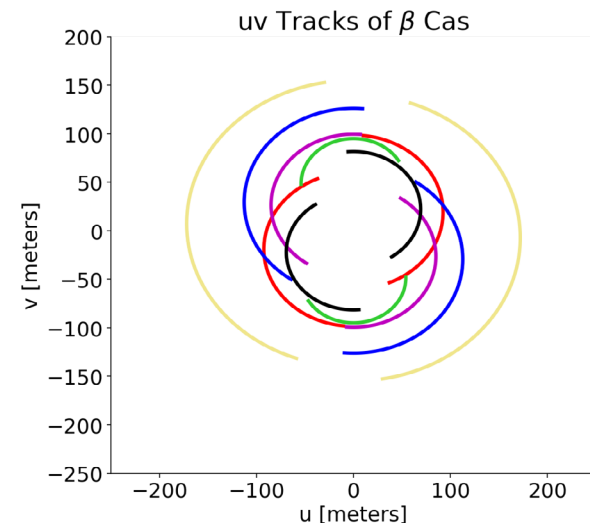
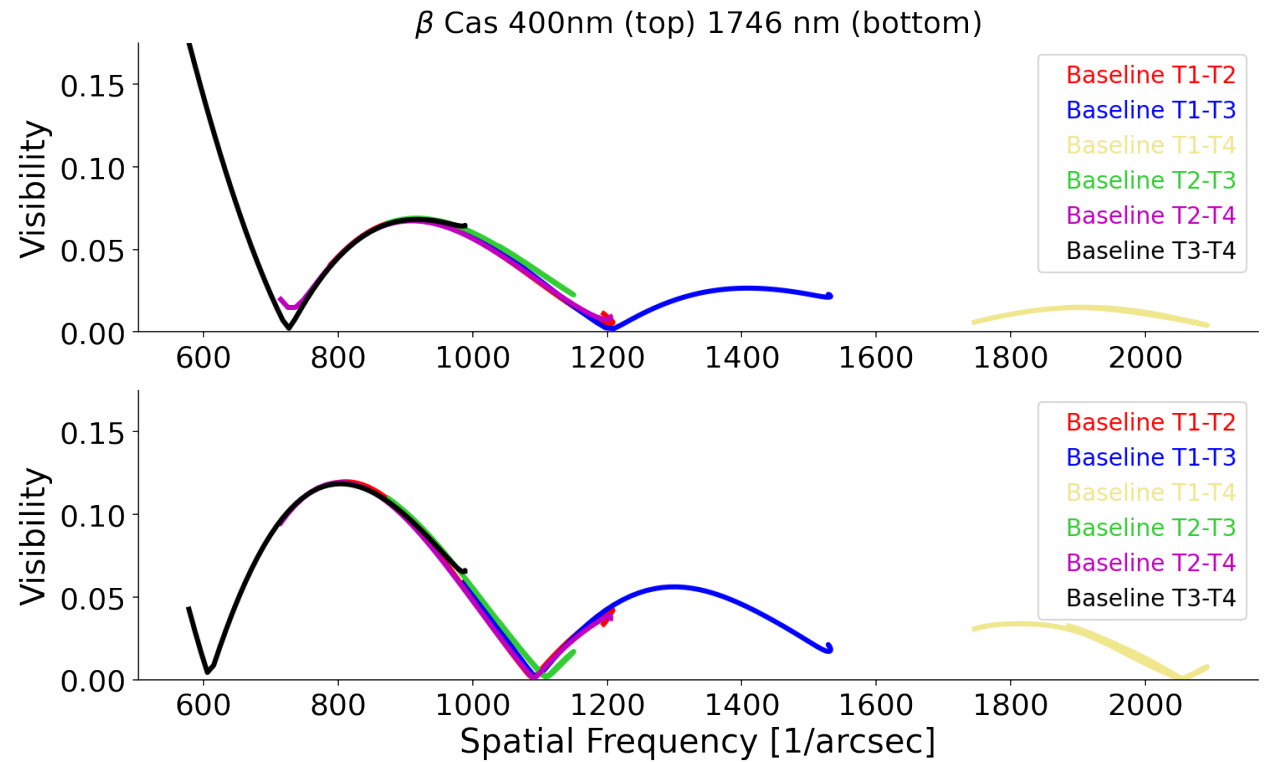
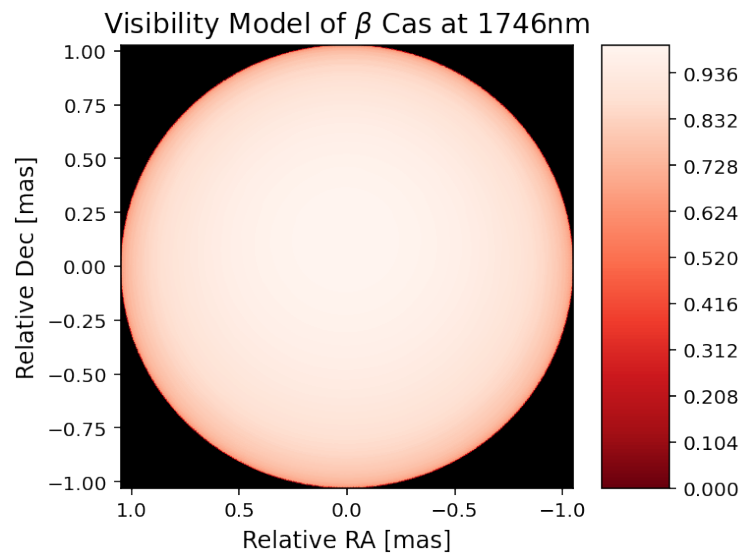
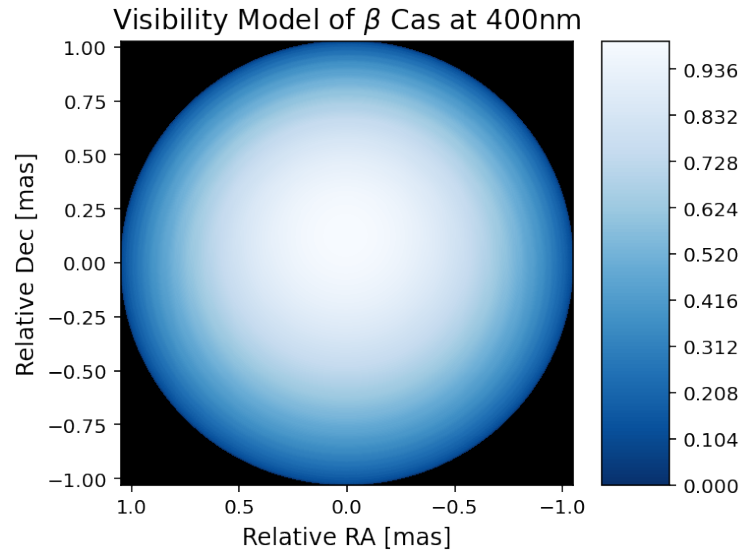


η UMa ($i = 23^\circ$) looks smaller and less oblate at 400 nm than 1746 nm (position angle of the pole, not well constrained)

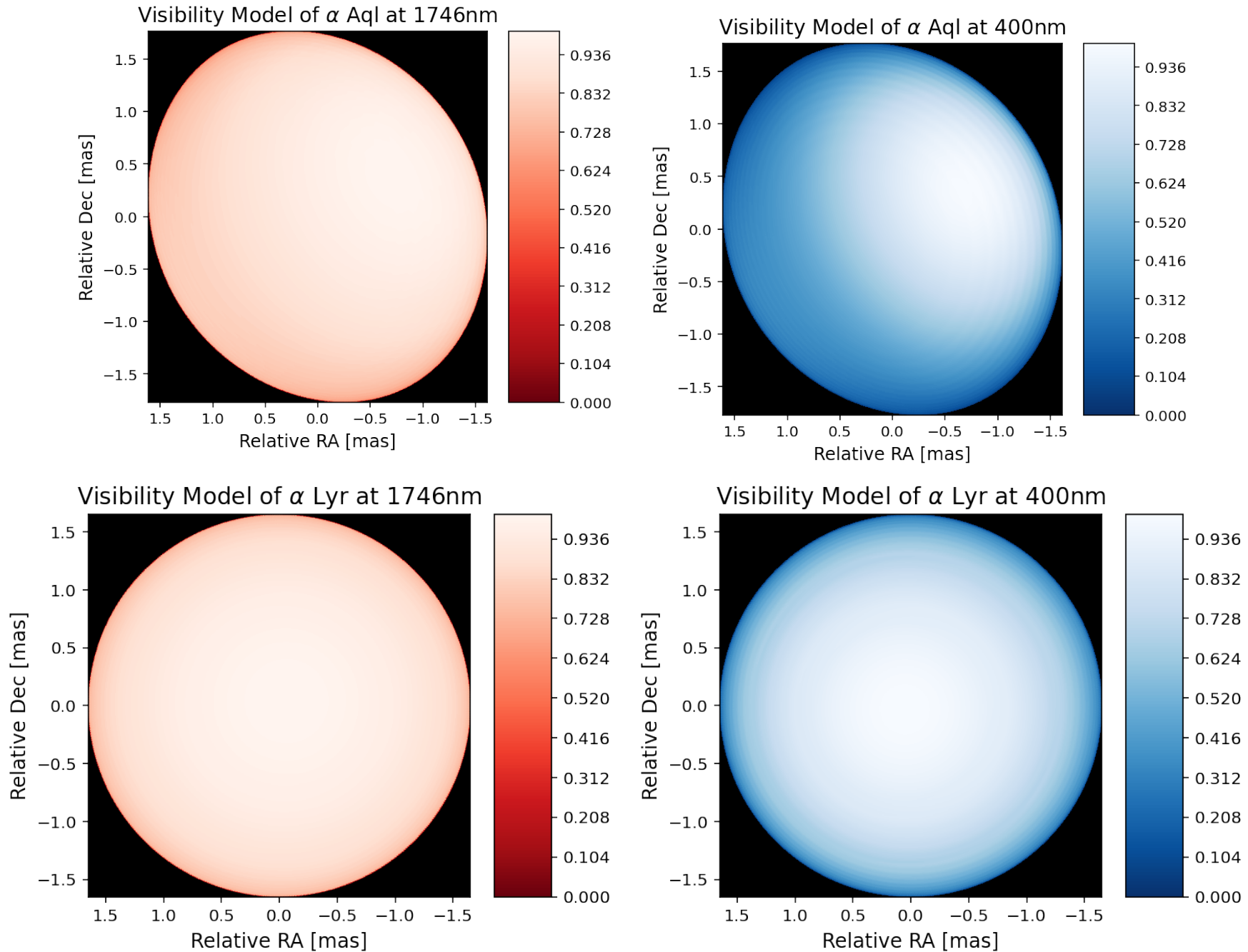


η UMa parameters from Stoeckley, T. R. & Buscombe, W. (1987), MNRAS, 227, 801

For more pole-on β Cas ($i = 18^\circ$), limb darkening *reinforces* gravity darkening, with more contrast between 400 nm and 1746 nm



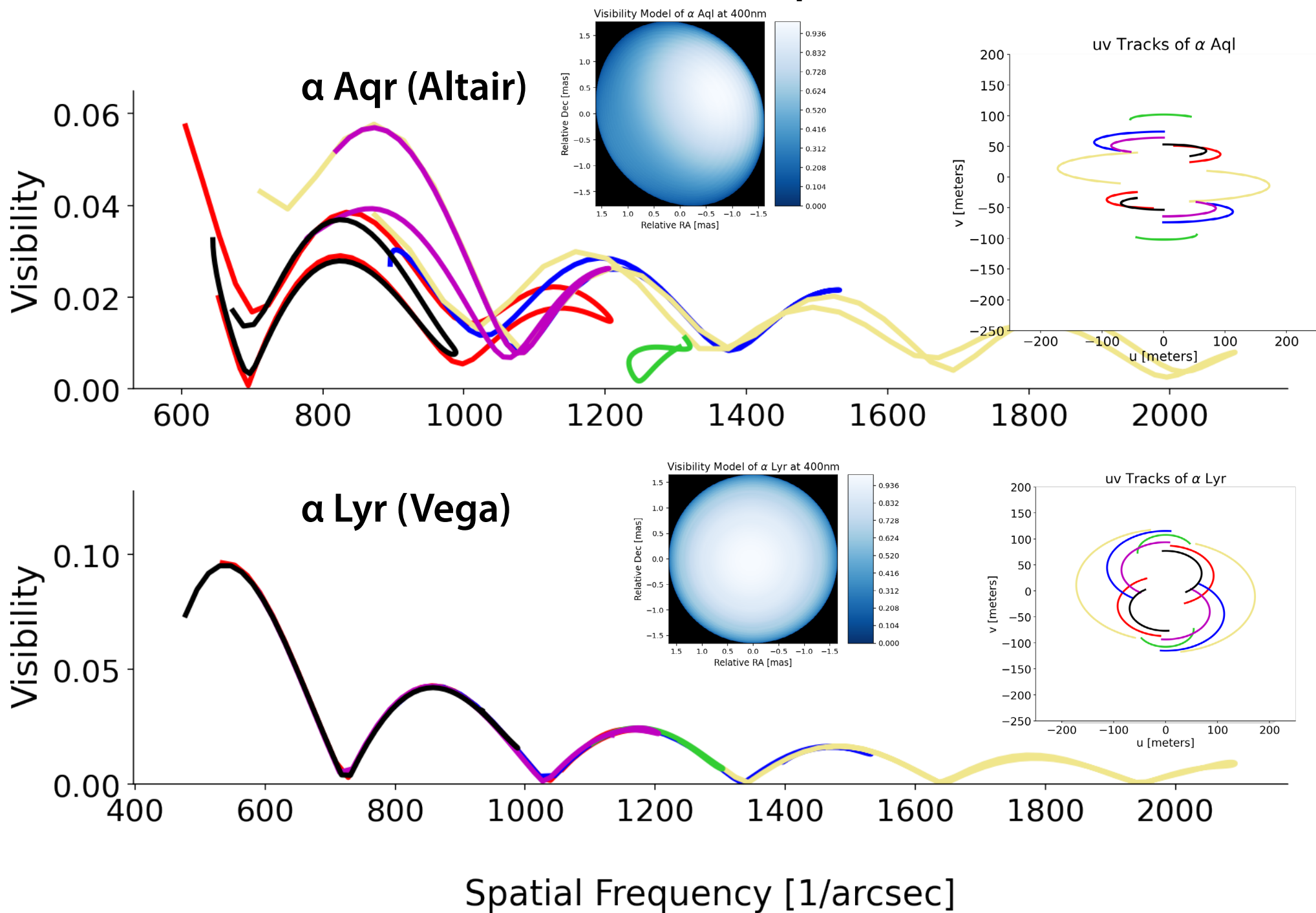
With ~ 3 mas angular diameters, α Aql (Altair) and α Lyr (Vega) are over-resolved by VERITAS SII



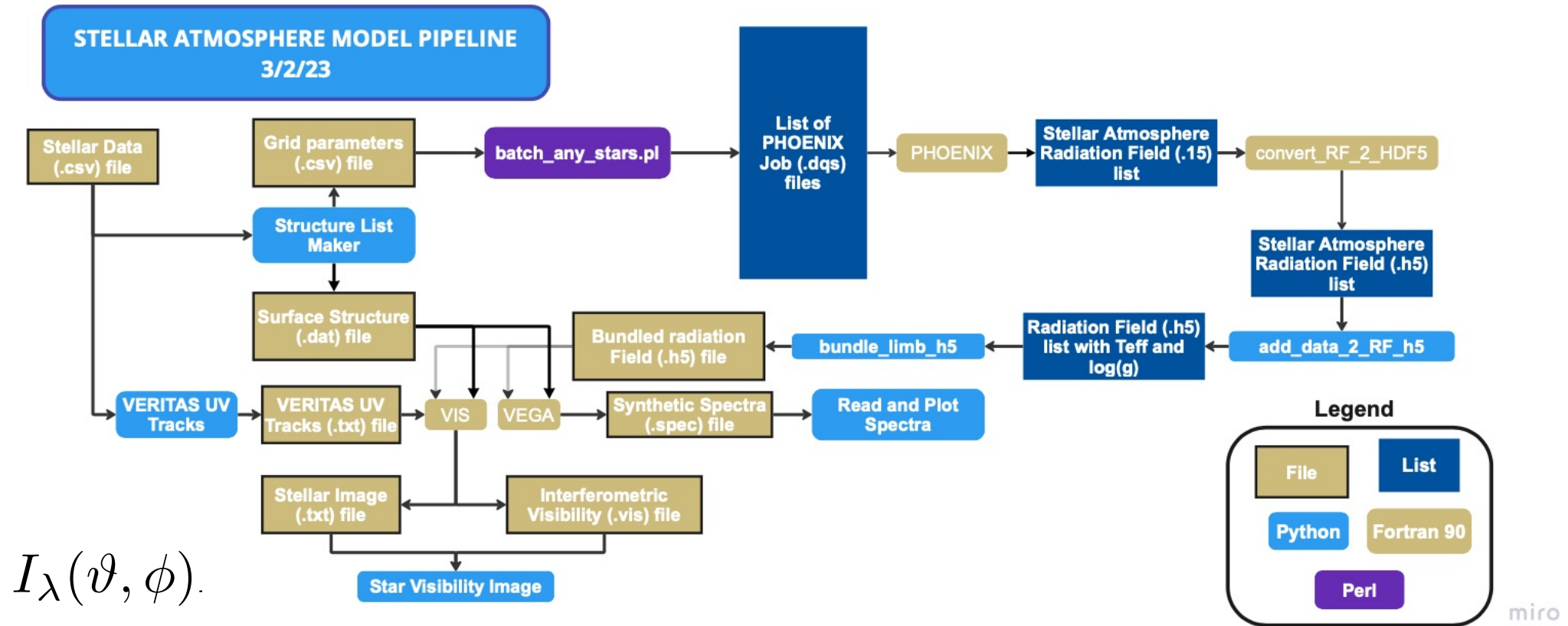
α Aql model parameters from: Monnier, J. D., Zhao, M., Pedretti, E., et al. (2007), Science, 317, 342.

α Lyr model parameters from: Monnier, J. D., Che, X., Zhao, M., et al. (2012), ApJL, 761, L3

Shorter baselines (< 40 m) needed to sample 1st lobes at 400 nm



A mixture of Perl, Python and Fortran codes (with help from ksh, awk and egrep) can generate images, spectra and visibilities in ~ 24 hours.

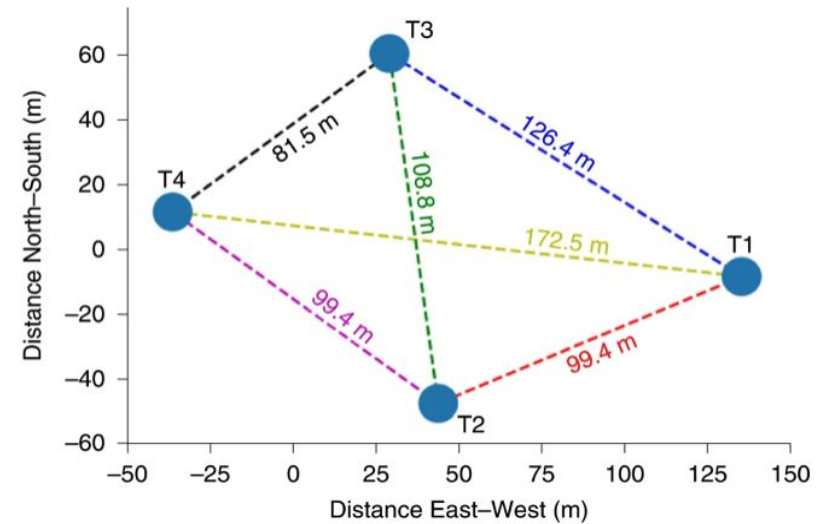


miro

1. Converge atmospheric structure for each T_{eff} , $\log(g)$ pair (24 min each)
2. Compute radiation field for each structure & each λ range (1-2 min each)
3. Compute visibilities for 276 λ s at 25 u,v points (13 min each on 36 CPUs)
4. Compute spectral energy distribution 23,000 λ s (23 min on 56 CPUs)
5. Compute high-resolution spectrum near 400nm 3,000 λ s (21 min on 7 CPUs)

Imaging Atmospheric Cherenkov Telescopes (IACTs) that also perform stellar intensity interferometry (SII) at wavelengths near 400 nm

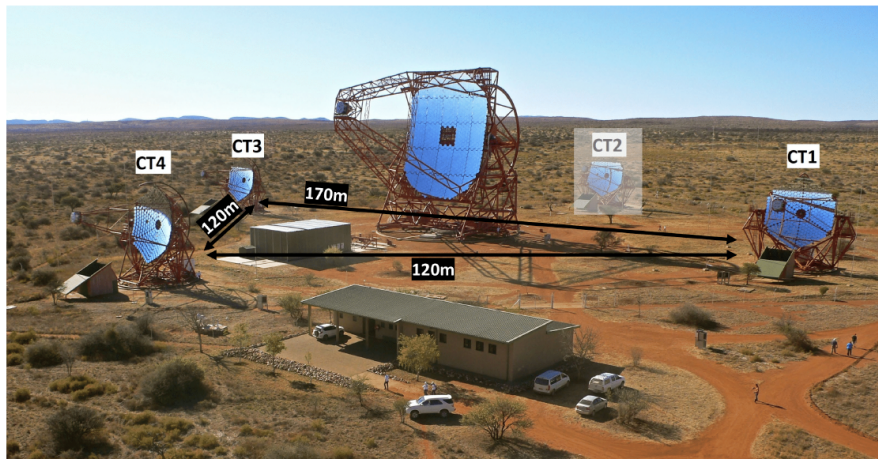
VERITAS (Very Energetic Radiation Imaging Telescope Array System) in Arizona



Abeysekara et al. (2020) in Nature Astronomy, 4, 1164

Davis, Matthews and Kieda (2020) in Journal of Astronomical Telescopes and Systems, 6, 3

H.E.S.S. (High Energy Stereoscopic System) in Namibia



Zmija A., et al. (2023) in Monthly Notices of the Royal Astronomical Society, 527, 12243–12252