MIRC imaging of two red supergiants from the Double Cluster

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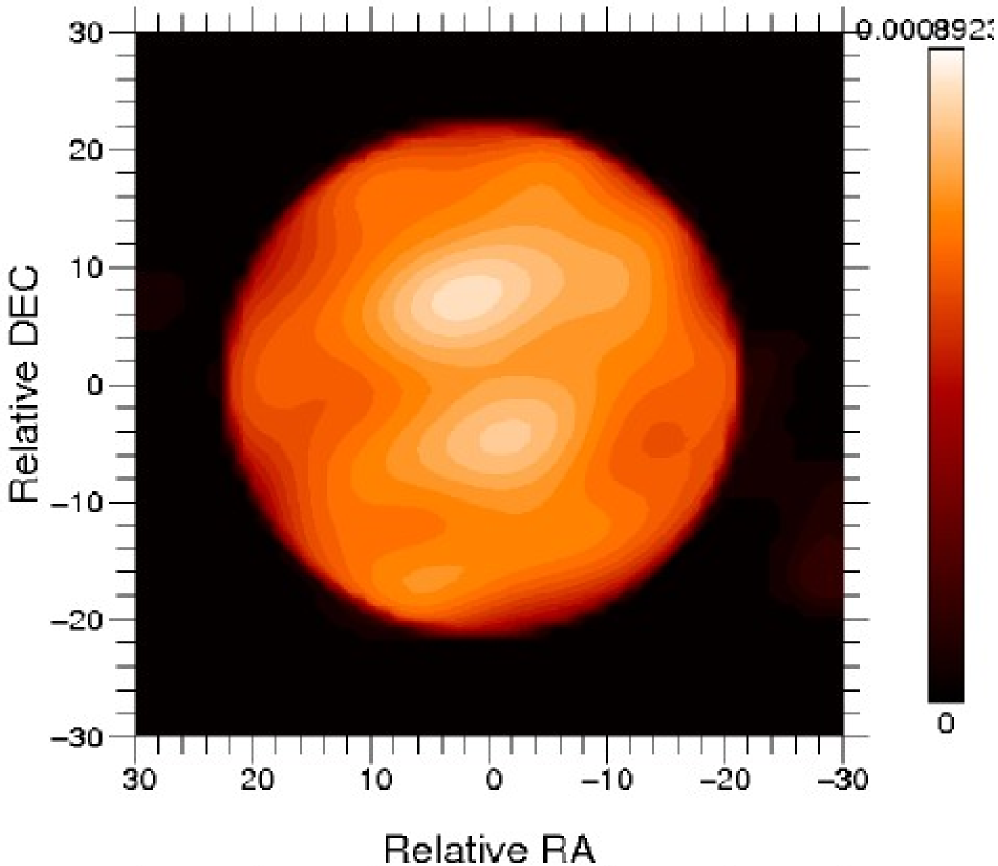
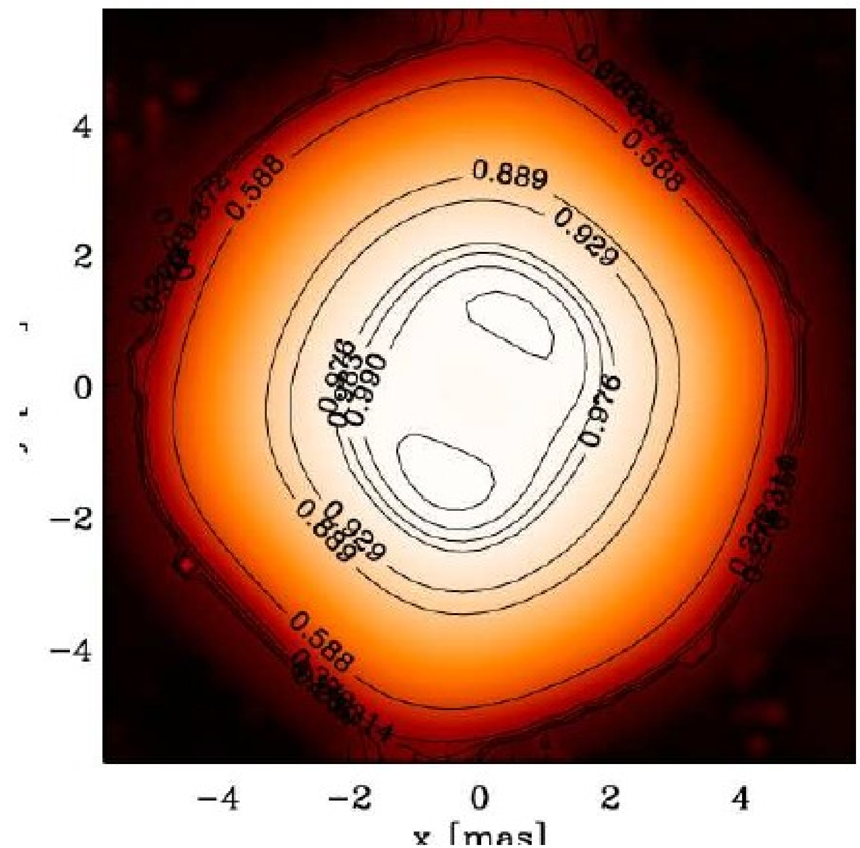
RSGs and long baseline interferometry

- Temperature scales
  - Before: Levesque 2005, SED fitted by MARCS models
  - van Belle 2009: SED fitted by RSG templates (Pickles 1998) + PTI angular diameters
- Only two model-independent images: Betelgeuse and VX Sgr
- Betelgeuse
  - Young 2000: spots in the V, but not in J
  - Haubois 2009: image, two spots, somewhat inconsistent with modeling
- VX Sgr
  - Monnier 2004: asymmetries detected
  - Chiavassa 2010: image but asymmetries barely resolved

RSG images so far...



Betelgeuse
Haubois 2009



VX Sgr
Chiavassa 2010

T Per and RS Per

	mV	mH	Spec type	D Cluster
T Per	8.54	3.02	M2Iab	h Per/chi Per
RS Per	8.73	2.11	M4Iab	chi Per

Date (UT)	Target	$N_{\rm block}$	Calibrators	Flux calibration
2007 Jul 28	T Per	2	HD 9022	Chopper
2007 Jul 29	T Per	1	υ And	Fiber
2007 Jul 30	RS Per	1	υ And	Chopper
2007 Jul 31	RS Per	1	37 And	DAQ
2007 Aug 2	RS Per	2	σ Cyg, υ And	DAQ

Note. — Calibrator diameters (mas):
HD 9022 = 1.05 ± 0.02 (Mérand et al. 2005).
υ And = 1.097 ± 0.009 (Zhao et al. 2011), UD model.
37 And = 0.676 ± 0.034, Kervella & Fouqué (2008).
σ Cyg = 0.542 ± 0.021 Mérand 2008, private comm.

Double Cluster distance: $d = 2345 \pm 55$ pc

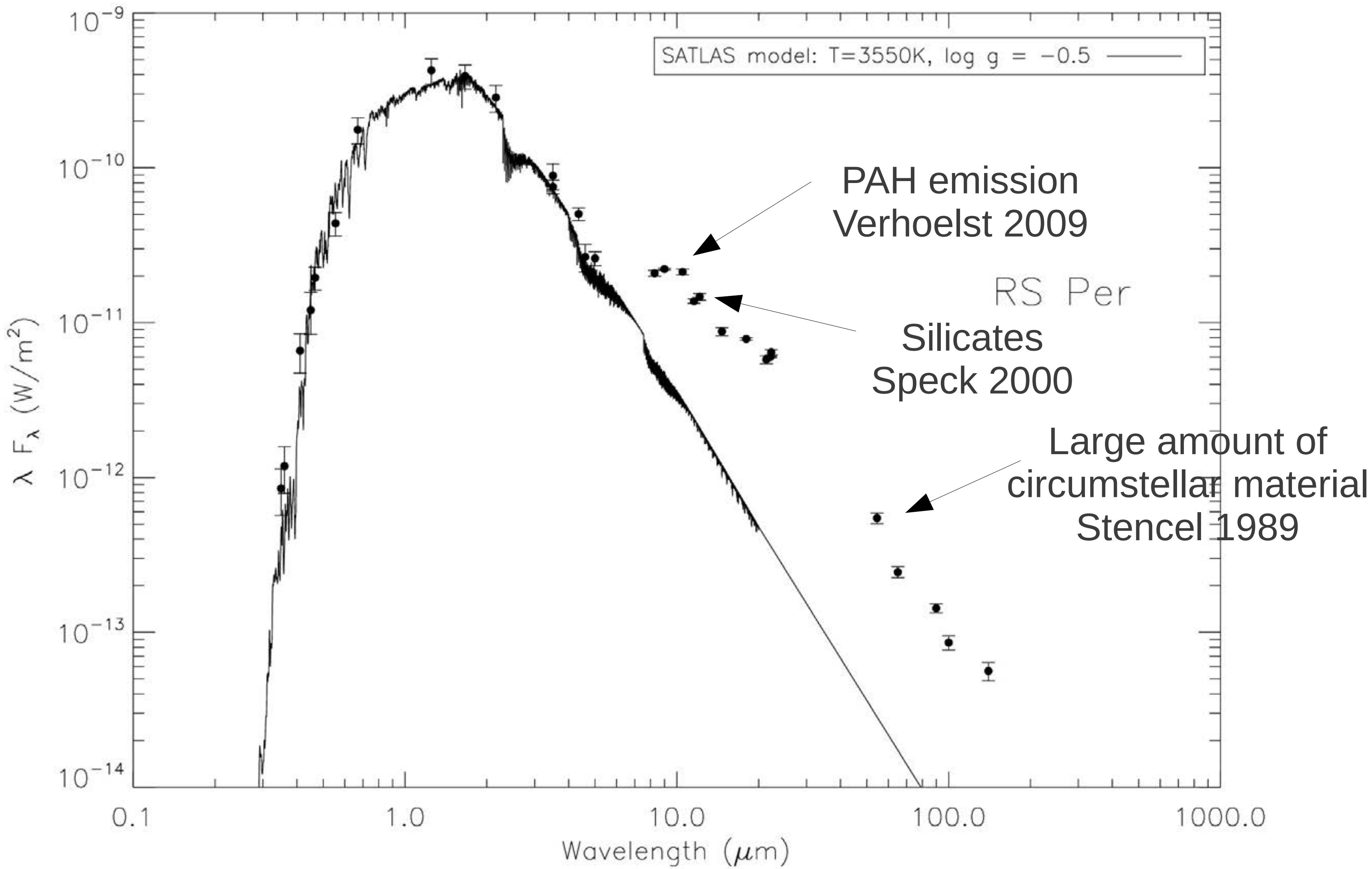
Main goals

- Bolometric flux and angular diameter will give the temperature

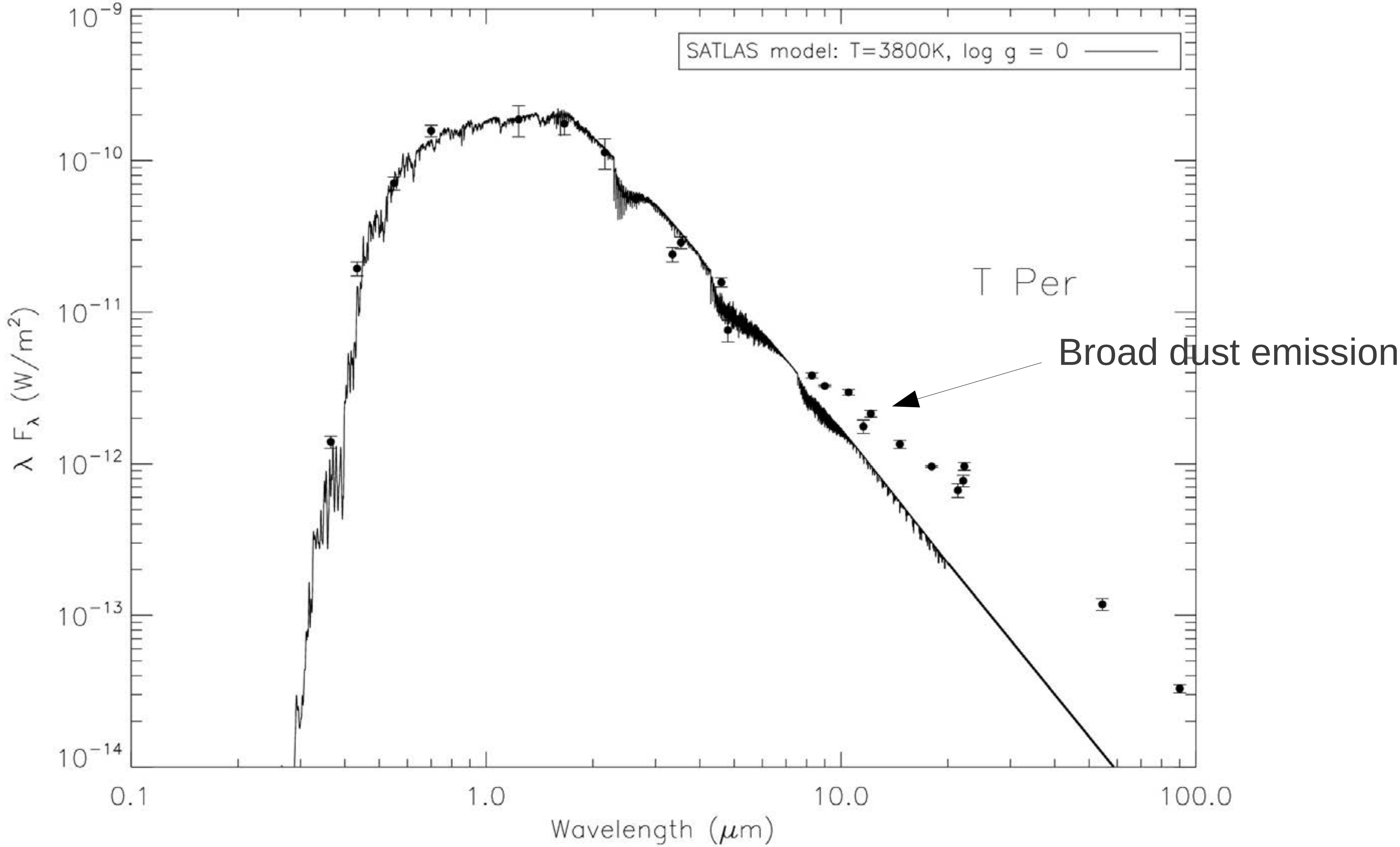
$$T_{\rm eff} = 4162 \left(\frac{f_{\rm bol}}{10^{-10}\mathrm{W.m}^{-2}} \right)^{\frac{1}{4}} \left(\frac{\theta}{1\ \mathrm{mas}} \right)^{-\frac{1}{2}} K$$

  – part of the bolometric flux does not arise from the photosphere, SED models needed
- Other physical parameters: size, mass, log g
- Model of the surface brightness: spots ?
- Model-independent images

SED – RS Per


SATLAS model: T=3550K, log g = −0.5
PAH emission
Verhoelst 2009
RS Per
Silicates
Speck 2000
Large amount of
circumstellar material
Stencel 1989
λ F_λ (W/m²)
10⁻⁹
10⁻¹⁰
10⁻¹¹
10⁻¹²
10⁻¹³
10⁻¹⁴
0.1
1.0
10.0
100.0
1000.0
Wavelength (μm)

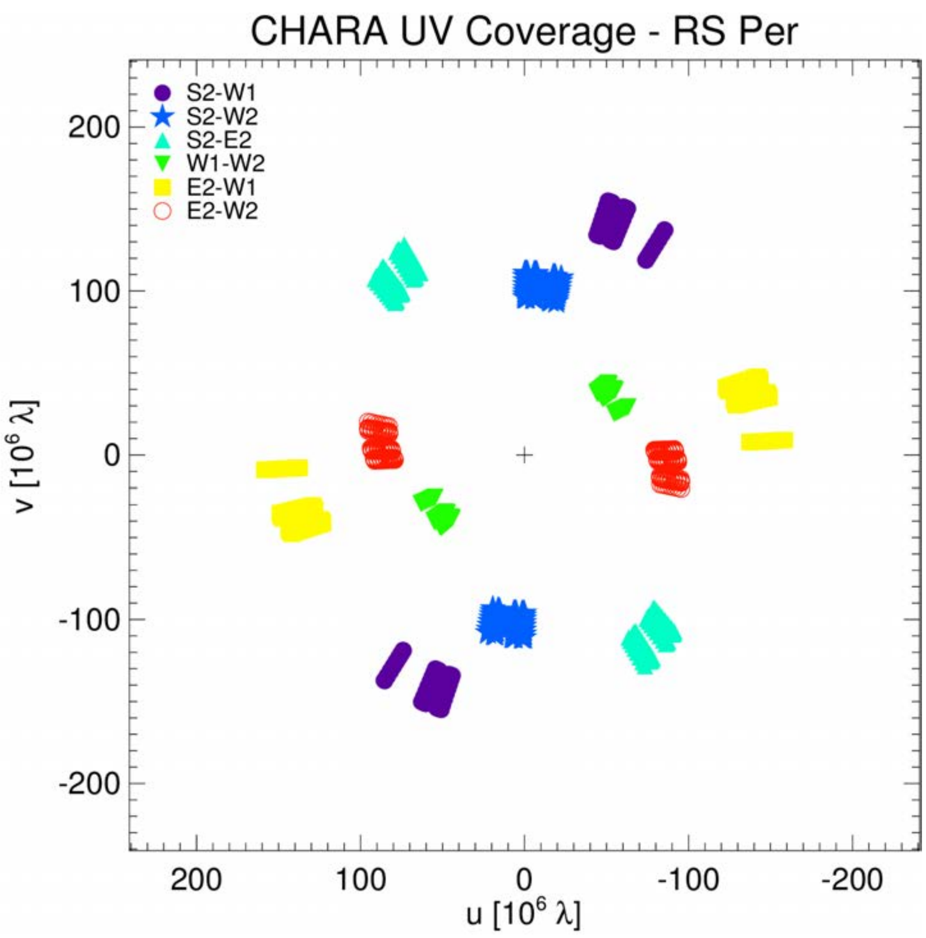
SED – T Per

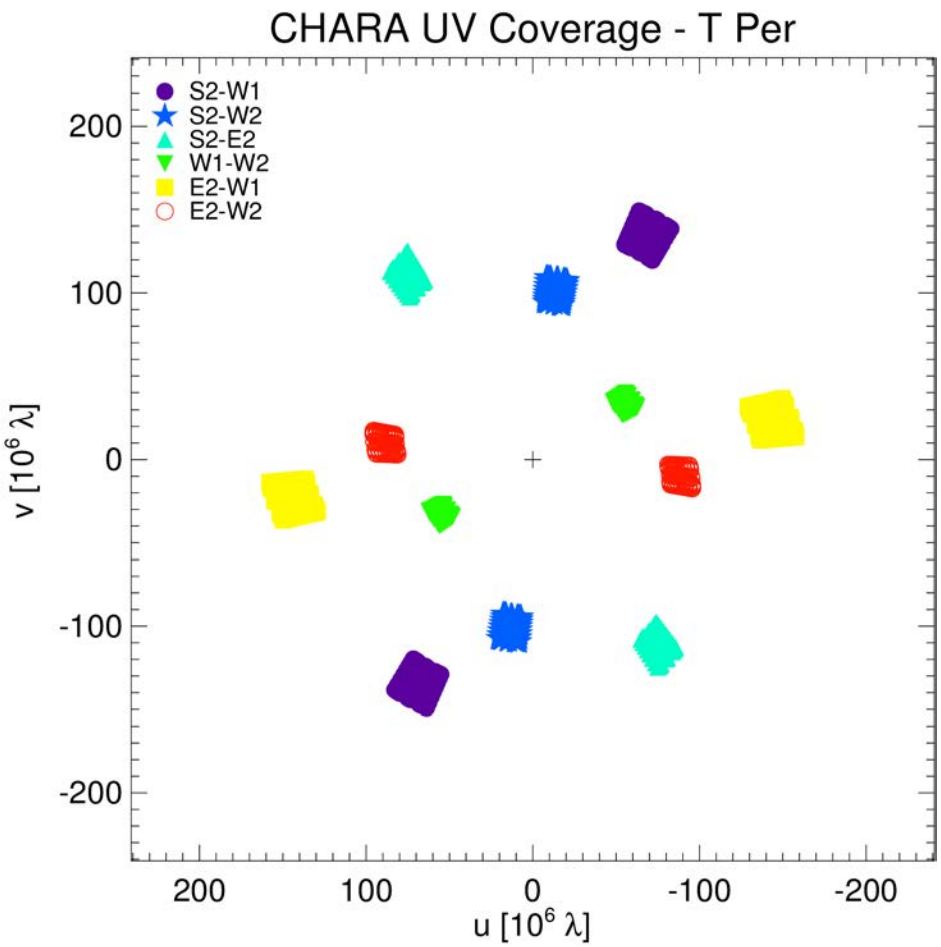

SATLAS model: T=3800K, log g = 0
T Per
Broad dust emission
λ Fλ (W/m²)
10⁻⁹
10⁻¹⁰
10⁻¹¹
10⁻¹²
10⁻¹³
10⁻¹⁴
0.1
1.0
10.0
100.0
Wavelength (μm)

SED fitting

- Spectra de-reddened using:
  - Castelli 1989 and Fitzpatrick 1999 with custom extinction laws for RSGs from Massey 2005
  - Distance estimate for the Double Cluster $d = 2345 \pm 55$ pc
- Atmosphere models:
  - Issue = RSGs have cool (lines) + extended (non-plane-parallel) atmospheres
- Latest SATLAS (Lester 2008) atmosphere code:
  - Temperature range $T = 3000 - 4000K$
  - Low metallicities (typical of Double Cluster)
  - Mass range $M = 7 - 25M_{\odot}$
  - Gravity $\log g = -0.5$ to 0.5
  - Turbulence $\chi_t = 3 - 5km/s$

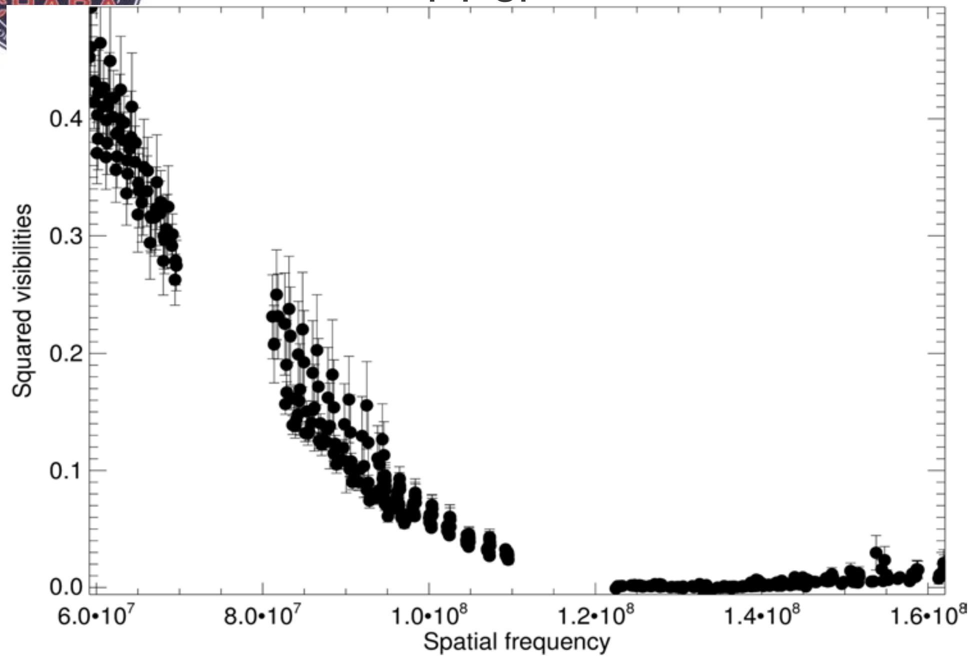
Model fitting - (*u*,*v*) coverage

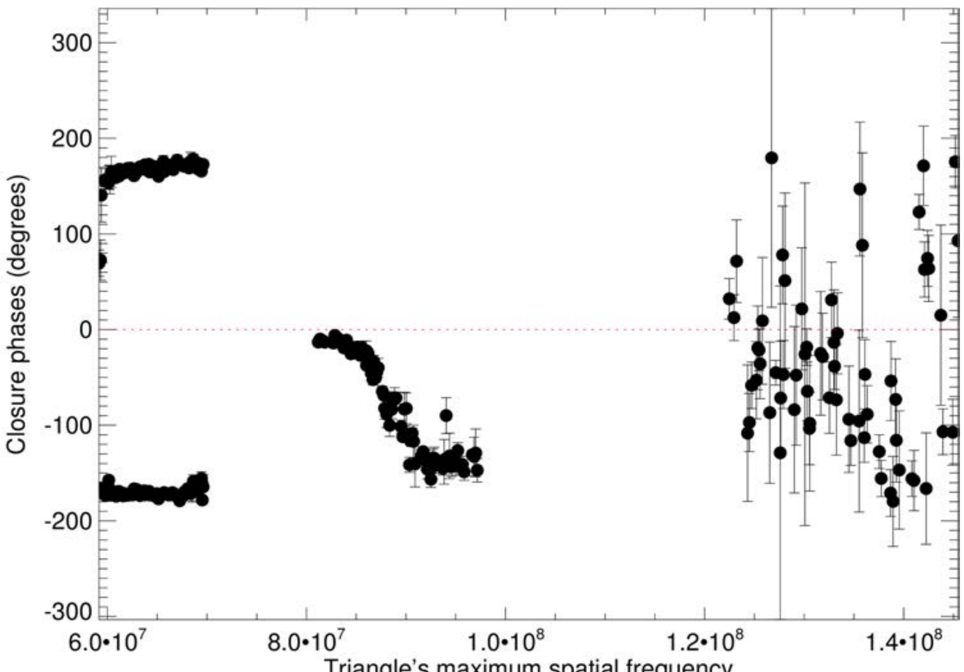




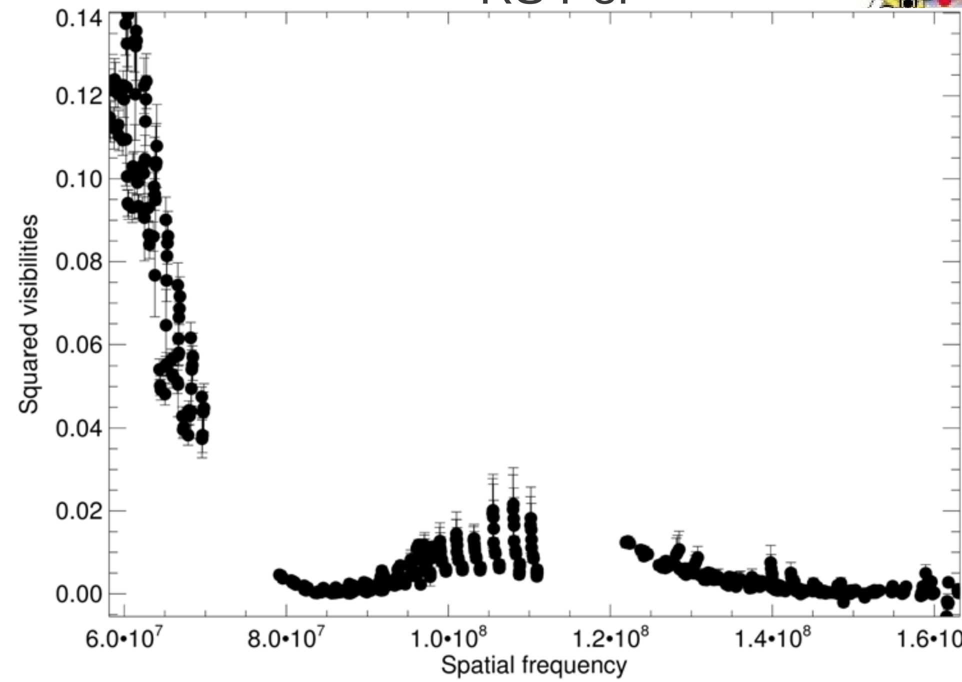
Data

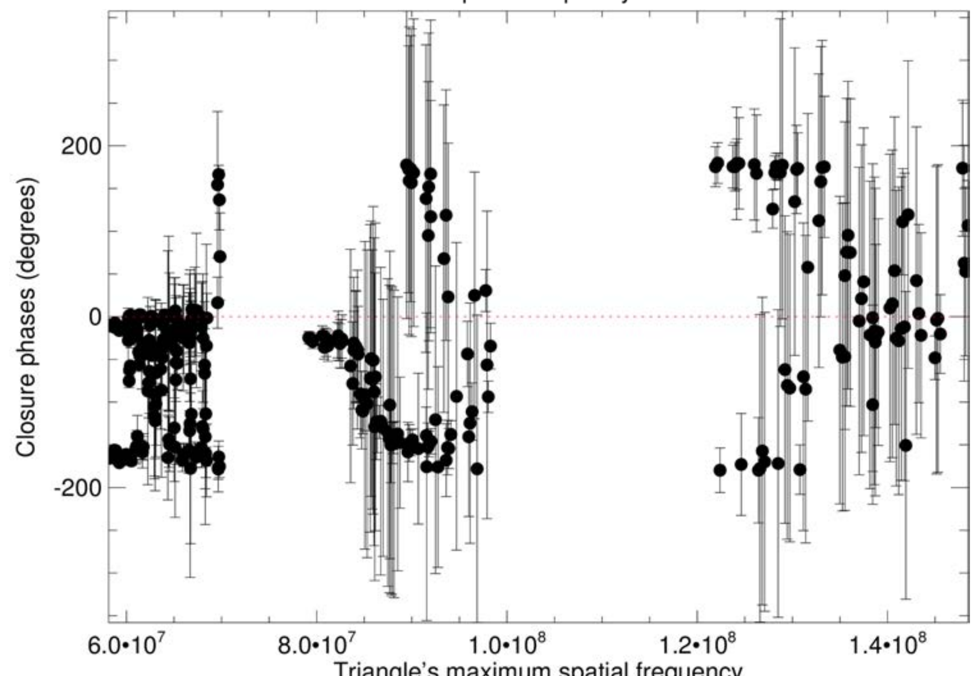
T Per



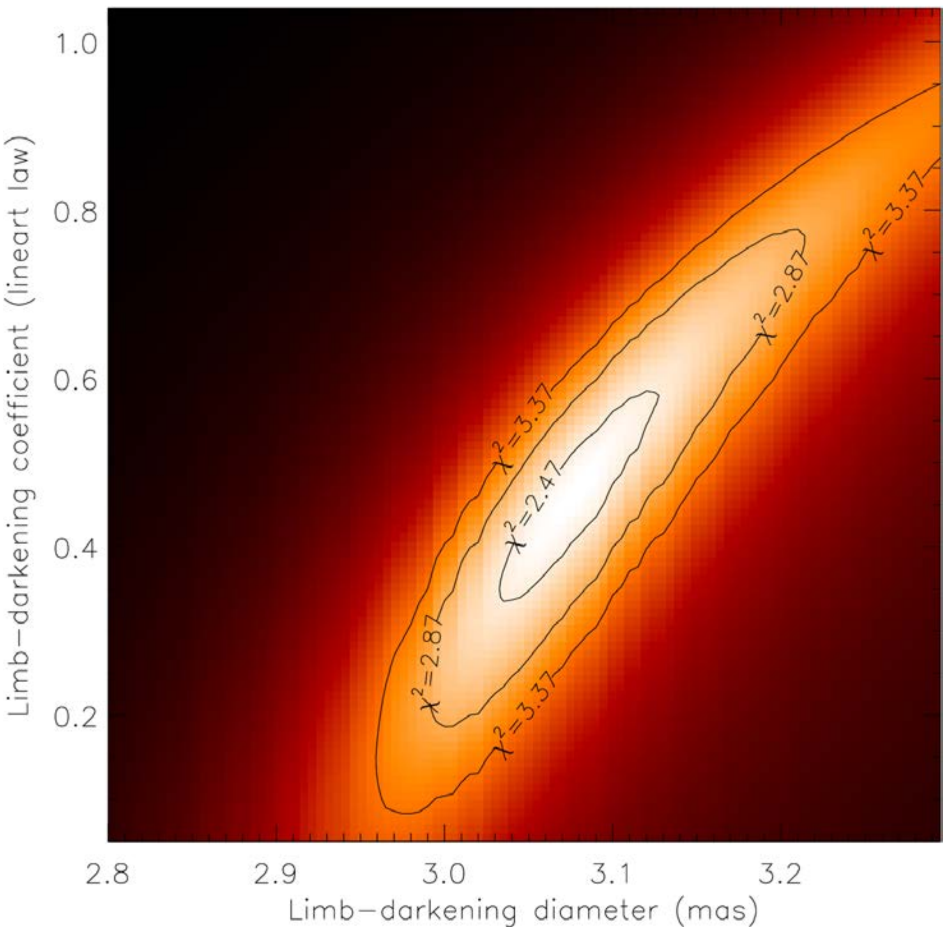


RS Per

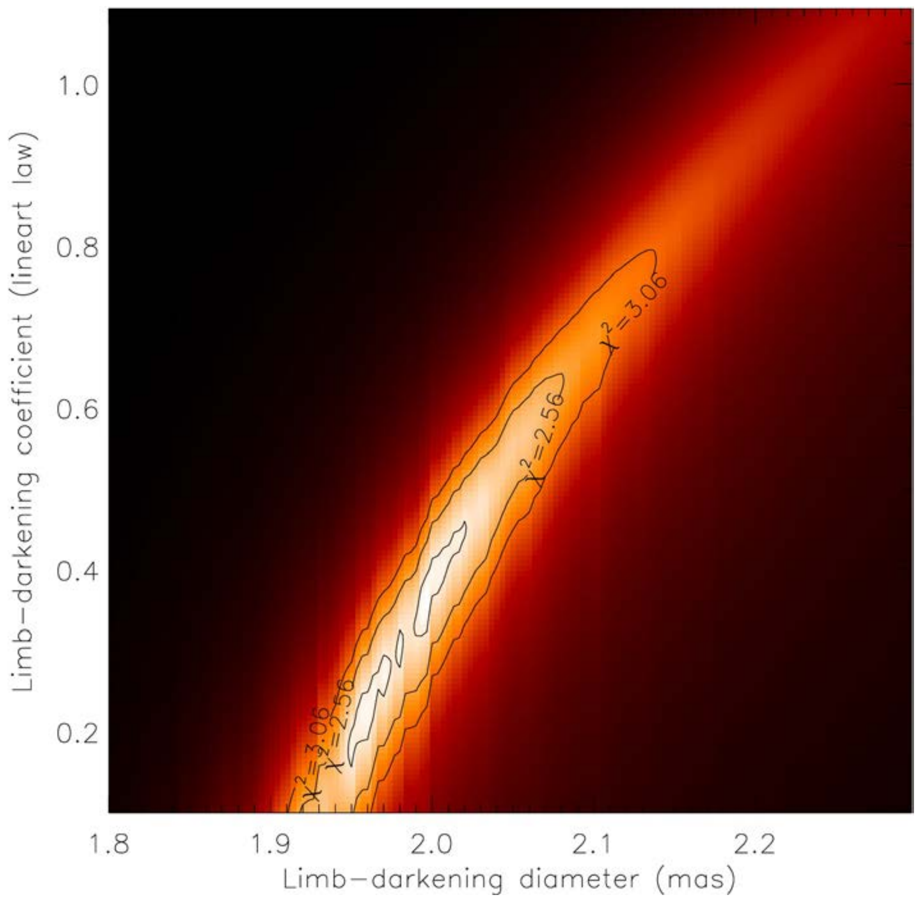




Model fitting – spotless model

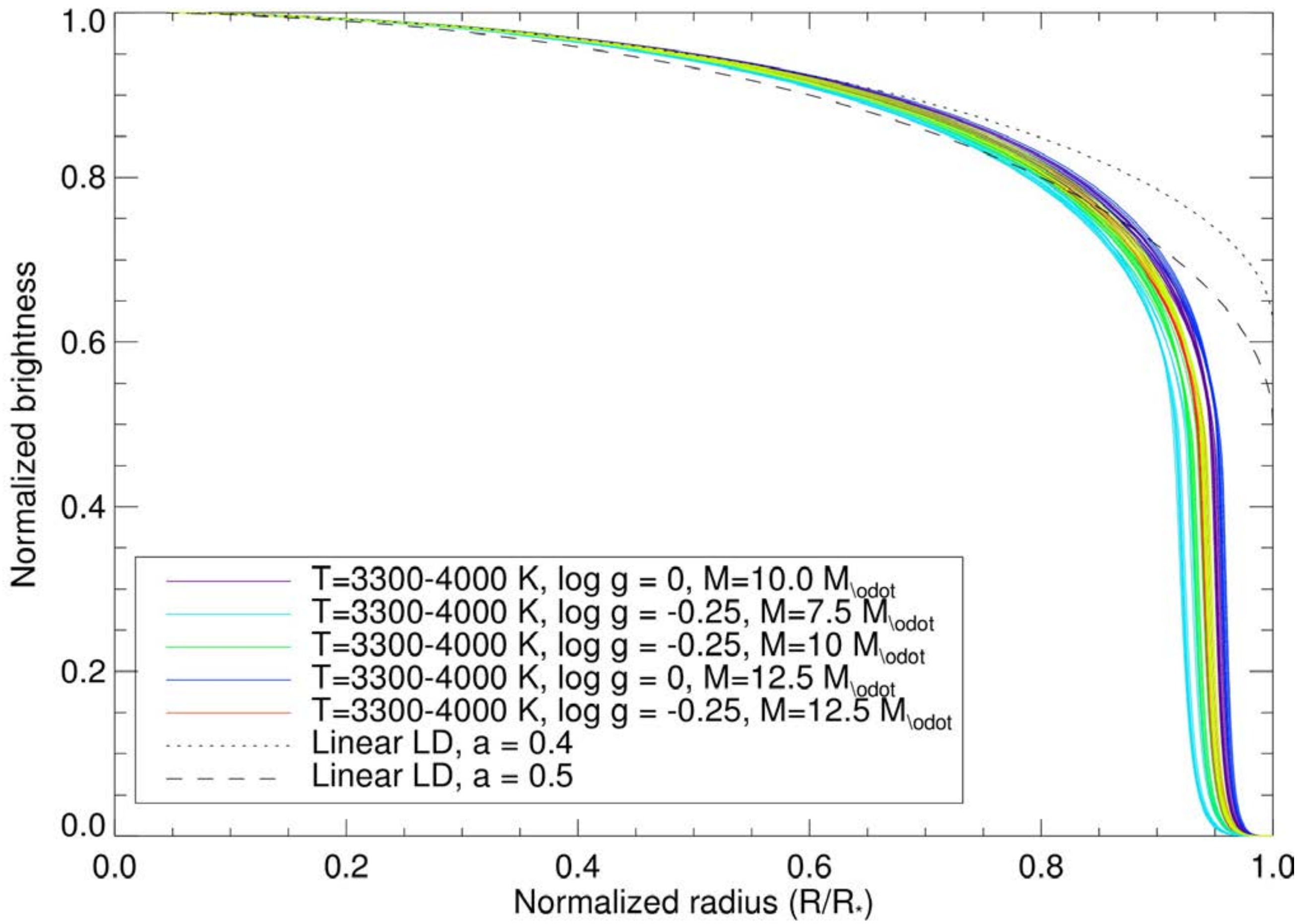


RS Per



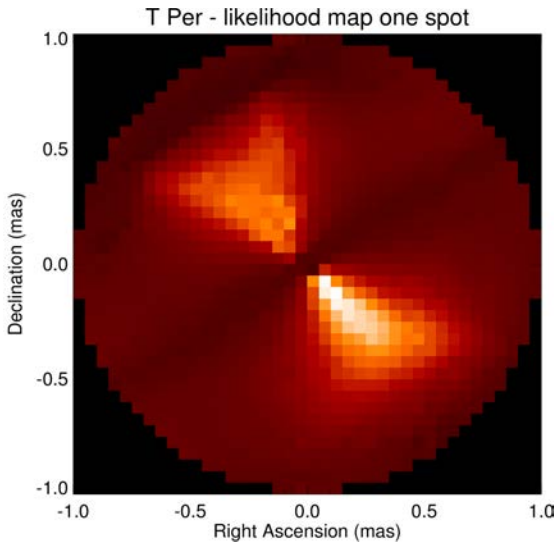
T Per

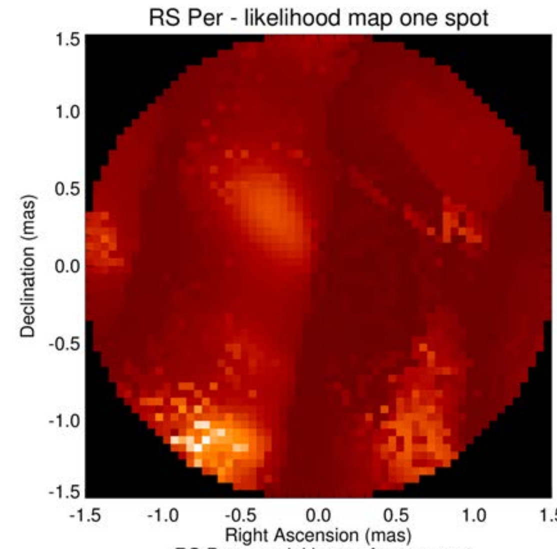
SATLAS models

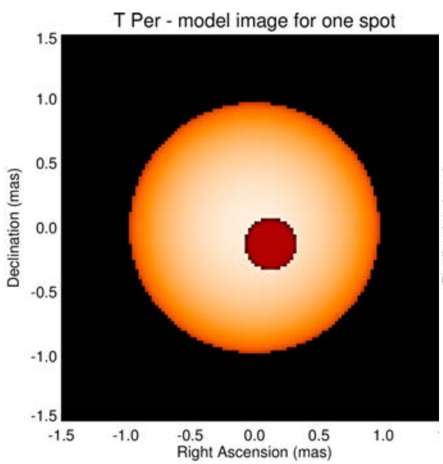


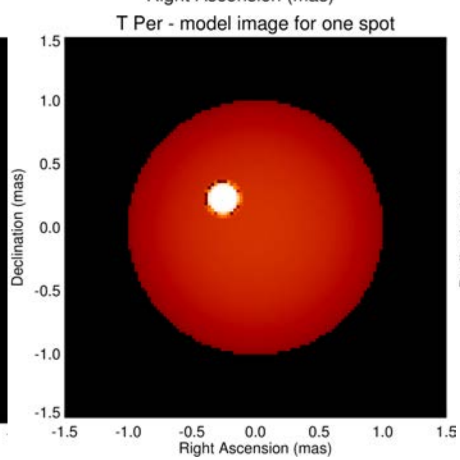
Model fitting – spot models

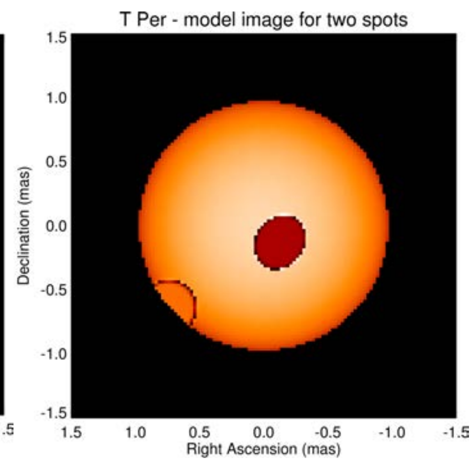
- Spot modeled as uniform ellipses
- Grid search on spot position + Levenberg on other parameters (LDD and spot shape and flux)

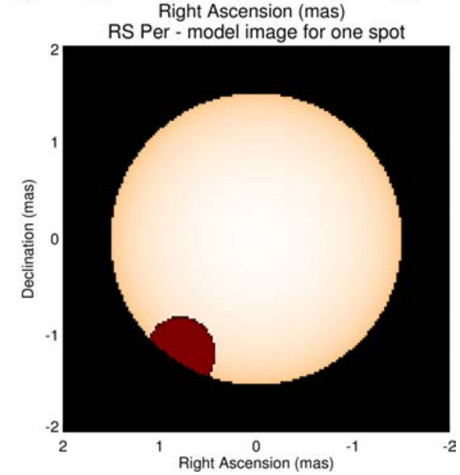












Bayesian model selection

Model coefficients

Model i

Data

- Classic model fitting: $p(\boldsymbol{C}|\boldsymbol{M}_i) \propto p(\boldsymbol{C}|\boldsymbol{D},\boldsymbol{M}_i)p(\boldsymbol{C}|\boldsymbol{M}_i)$

Posterior

Likelihood / χ^2

Priors

- True Bayes equation: $p(\boldsymbol{C}|\boldsymbol{M}_i) = \dfrac{p(\boldsymbol{C}|\boldsymbol{D},\boldsymbol{M}_i)p(\boldsymbol{C}|\boldsymbol{M}_i)}{p(\boldsymbol{D}|\boldsymbol{M_i})}$

Evidence

- Model selection: $\dfrac{p(\boldsymbol{M_1}|\boldsymbol{D})}{p(\boldsymbol{M}_2|\boldsymbol{D})} = \dfrac{p(\boldsymbol{M}_1)}{p(\boldsymbol{M}_2)}\dfrac{p(\boldsymbol{D}|\boldsymbol{M_1})}{p(\boldsymbol{D}|\boldsymbol{M_2})}$

1 if no preference

Bayes factor = ratio of evidences

- Nested sampling (MULTINEST, Feroz 2008) can evaluate:

$$\log Z(\boldsymbol{M_i}) = \log p(\boldsymbol{D}|\boldsymbol{M_i})$$

Bayesian Interpretation

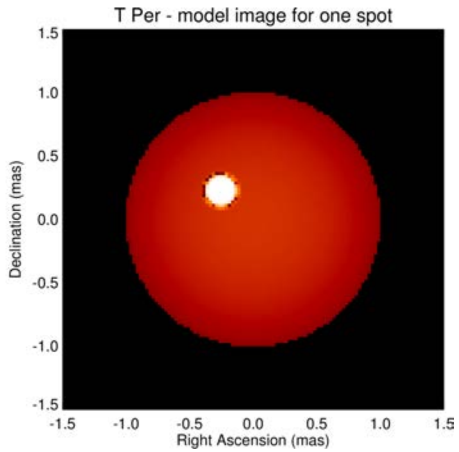
T Per results

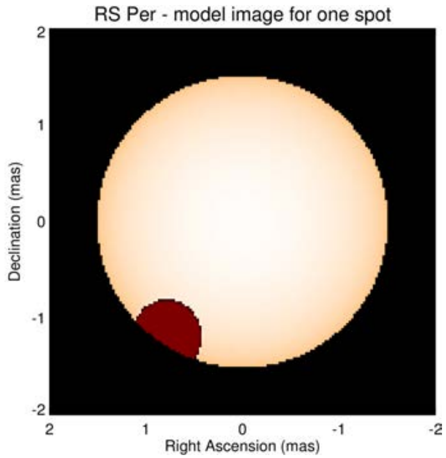
Fit results	No spot	Dark spot	Bright spot	Two spots
χ^2	9.4	2.24	2.64	1.95
$\log Z(\pm 0.02)$	-0.35	0.87	1.23	0.20
$\theta_\star$	2.01	2.03	2.05	2.04
$f_{\rm spot}$	...	4 %	5%	3%, 4%

Interpretation of differences of log Z (Jeffreys 1961, Kass & Raftery 1995)

$\log_{10}(B_{10})$	B_{10}	Evidence against H_0
0 to 1/2	1 to 3.2	Not worth more than a bare mention
1/2 to 1	3.2 to 10	Substantial
1 to 2	10 to 100	Strong
>2	>100	Decisive

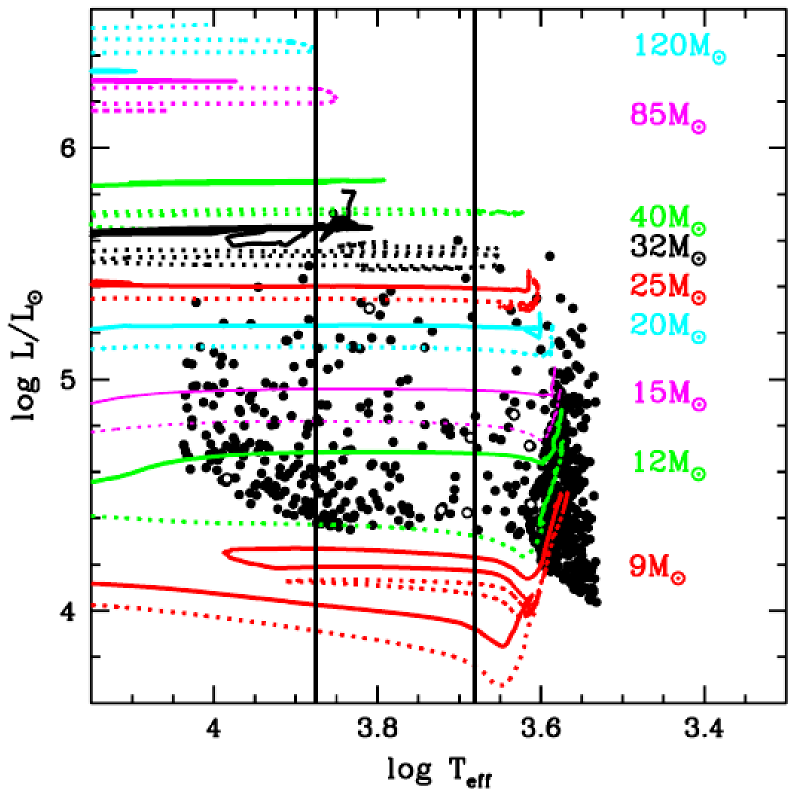
Best models



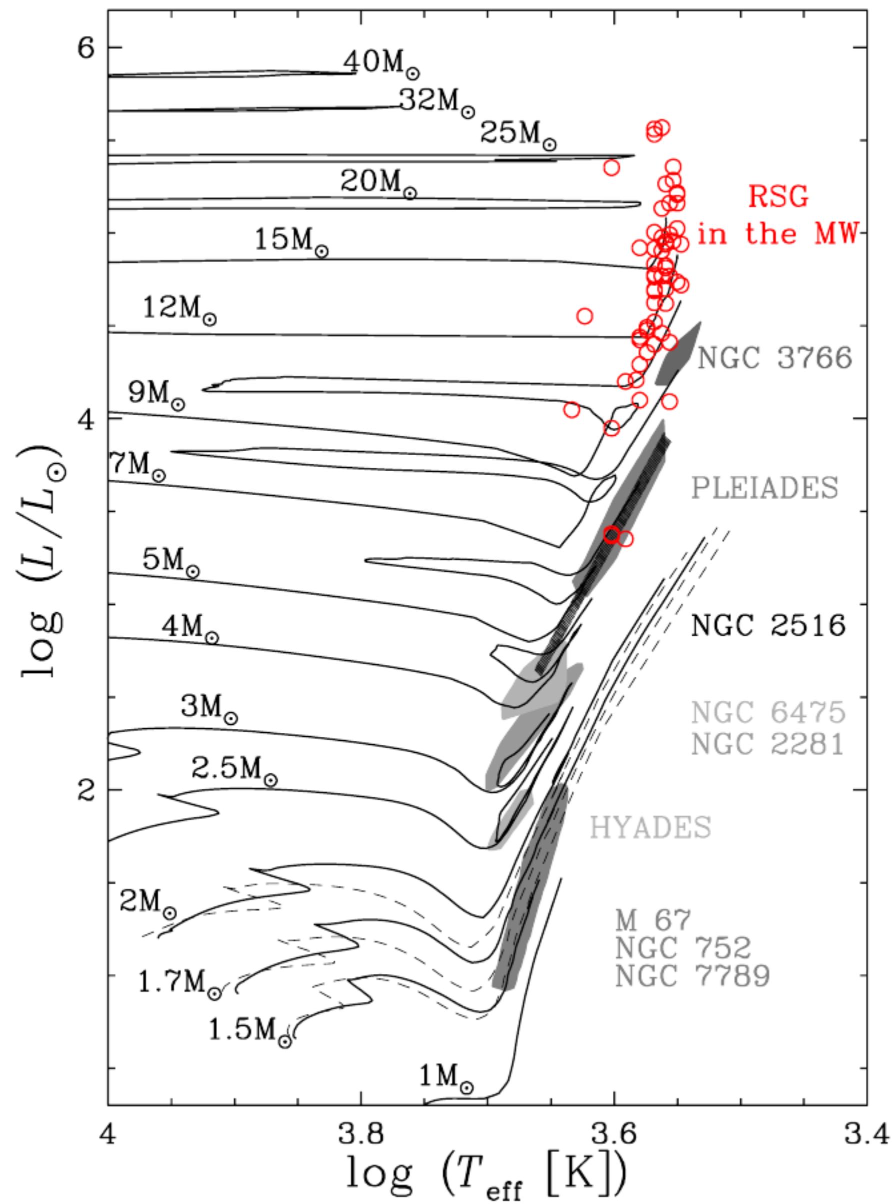


Final estimated parameters

	T Per	RS Per
$R_{\rm ross}$ $(R_\odot)$	510 ± 20	730 ± 30
$M_{\rm bol}$	$-6.82 \pm 0.12.$	-7.58 ± 0.13
$T_{\rm eff}\,(K)$	3850 ± 95	3560 ± 110
$M_\star(M_\odot)$	9-12	12-15
$\log L/L_\odot$	4.63 ± 0.05	4.94 ± 0.05
$\log g$ (cgs)	0.05 ± 0.15	-0.15 ± 0.15



Chomienne 2013, in prep.



Eckström 2012

RSG temperature scales

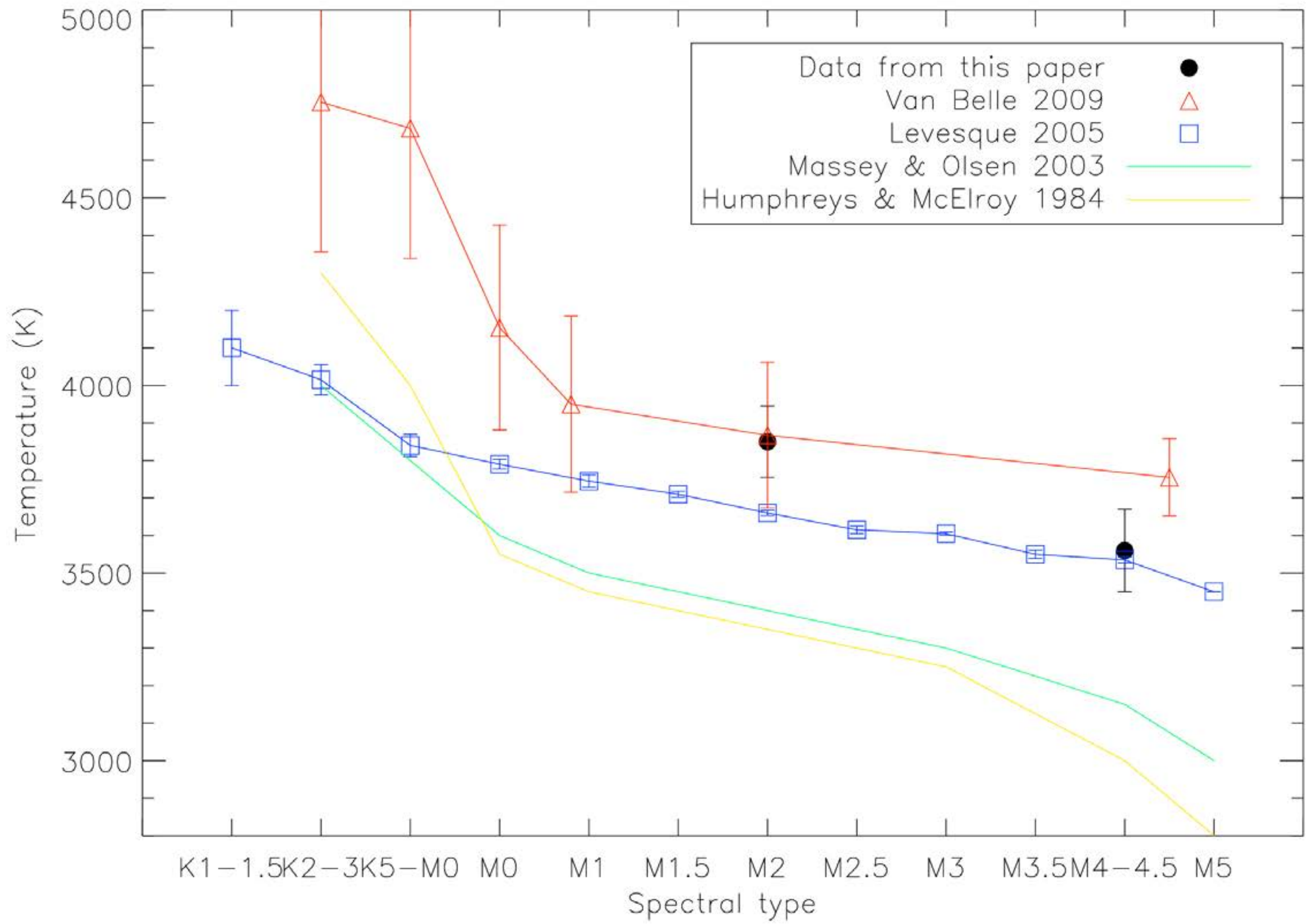


Image reconstruction

- A reminder of the principle

$$\widehat{\boldsymbol{i}} = \underset{i \in \mathbb{R}^n}{\operatorname{argmin}} \left\{ \chi^2(\boldsymbol{i}) + \sum_{k=1}^{K} \mu_k R_k(\boldsymbol{i}) \right\}$$

regularizer weight　regularizer

- We use the SQUEEZE image reconstruction code (Baron 2010)
  - MCMC, parallel tempering
  - Tries to find the global minima
  - Not as sensitive to initialization as simulated annealing
  - Multi-threaded + SSE optimizations

Regularization - regularizers

- Multiplicity/Maximum entropy (Sutton et al., 2006)

$$R_\Gamma(\boldsymbol{i}) = \sum_n \log \Gamma(i_n + 1)$$

- Total variation (Rudin 1992, Renard et al., 2011)

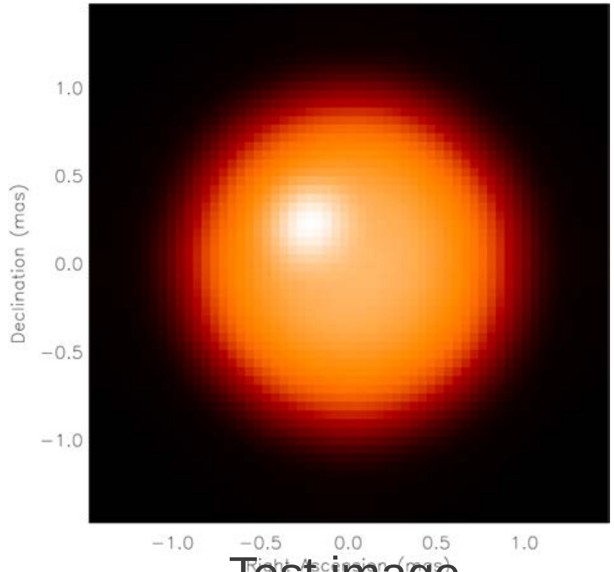
$$R_{\mathrm{TV}}(\boldsymbol{i}) = \ell_1(\boldsymbol{g}) = \sum_n |g_n|$$

$$g_{n,m}(\boldsymbol{i}) = \sqrt{|i_{n+1,m} - i_{n,m}|^2 + |i_{n,m+1} - i_{n,m}|^2}$$

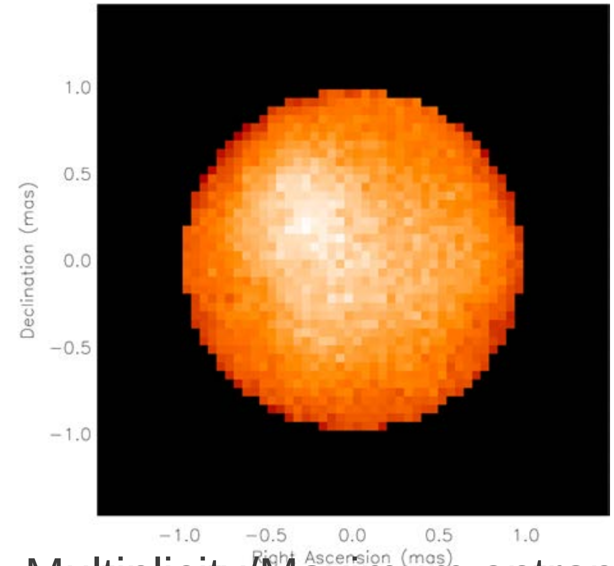
- Spot regularizer (Baron et al., 2013)

$$R_{\mathrm{spot}}(\boldsymbol{i}) = \ell_{\frac{1}{2}}(\boldsymbol{g}) = \left(\sum_n \sqrt{|g_n|}\right)^2$$

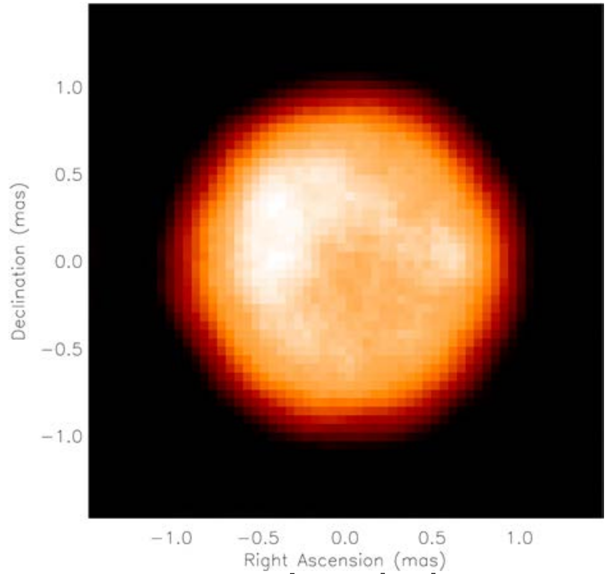
Regularization - simulations



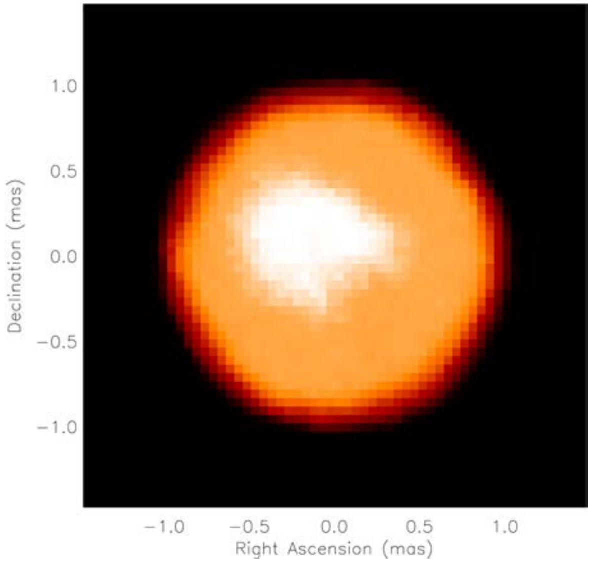
Test image
Convolved to 3x array resolution



Multiplicity/Maximum entropy
with strong prior on stellar shape

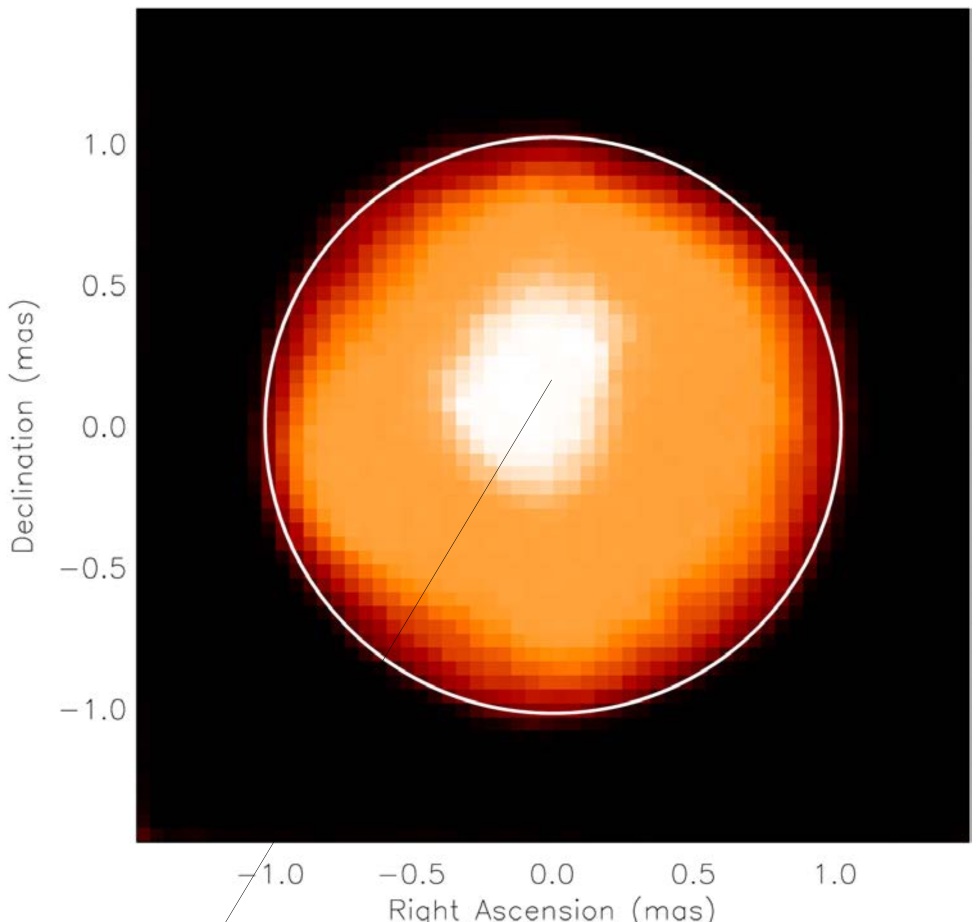


Total variation



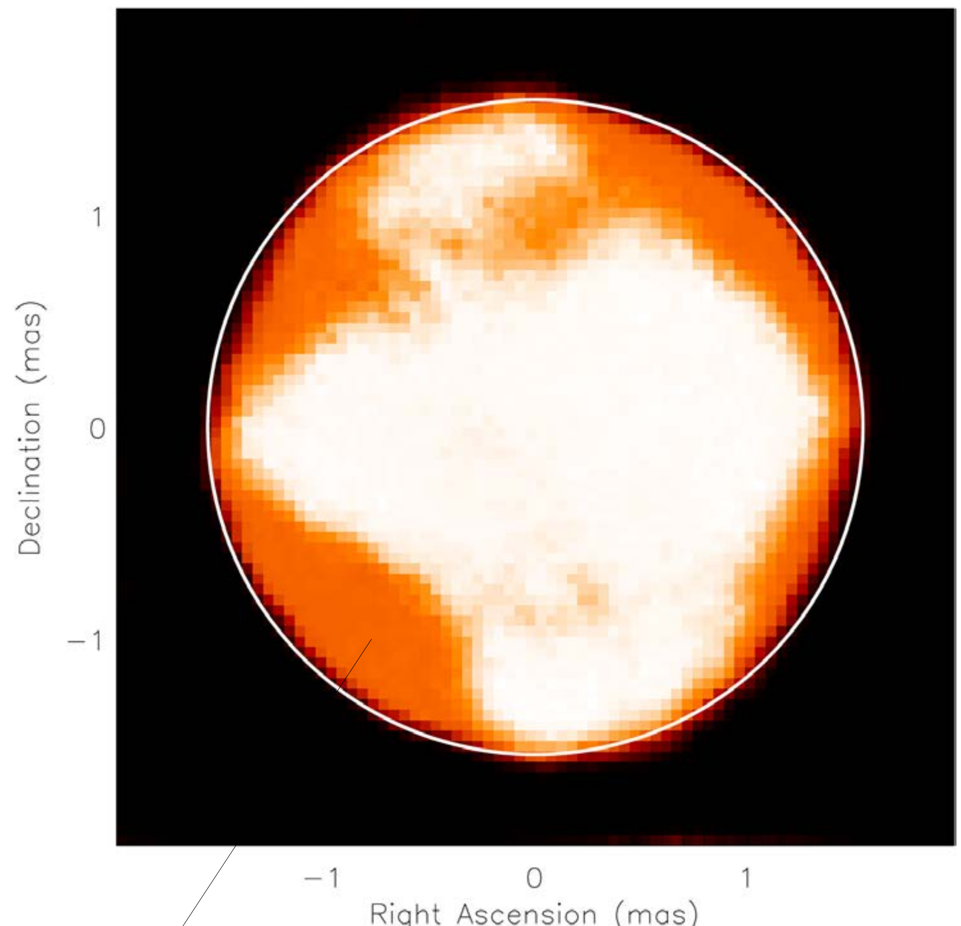
Spot regularizer

Final reconstructions



T Per

Spot !



RS Per

Dark spot ?

Note: artifact tests were successful, i.e spotless disks were reconstructed spotless
https://github.com/bkloppenborg/oifits-sim

Conclusion

- Bayesian model selection and Compressed Sensing regularizer were required to extract all information from the data
- This constitutes more evidence for spots in near-infrared
- Considering the opacity minimum in H band
  - these spots should be close to the photosphere...
  - contrast cannot be explained readily by opacity...
- More observations required
  - link between circumstellar activity and spots ?
  - work ongoing on AZ Cyg