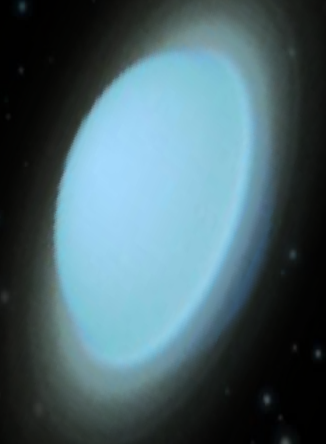
Revealing the structure of the outer disks of classical Be stars



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Introduction – Classical Be stars

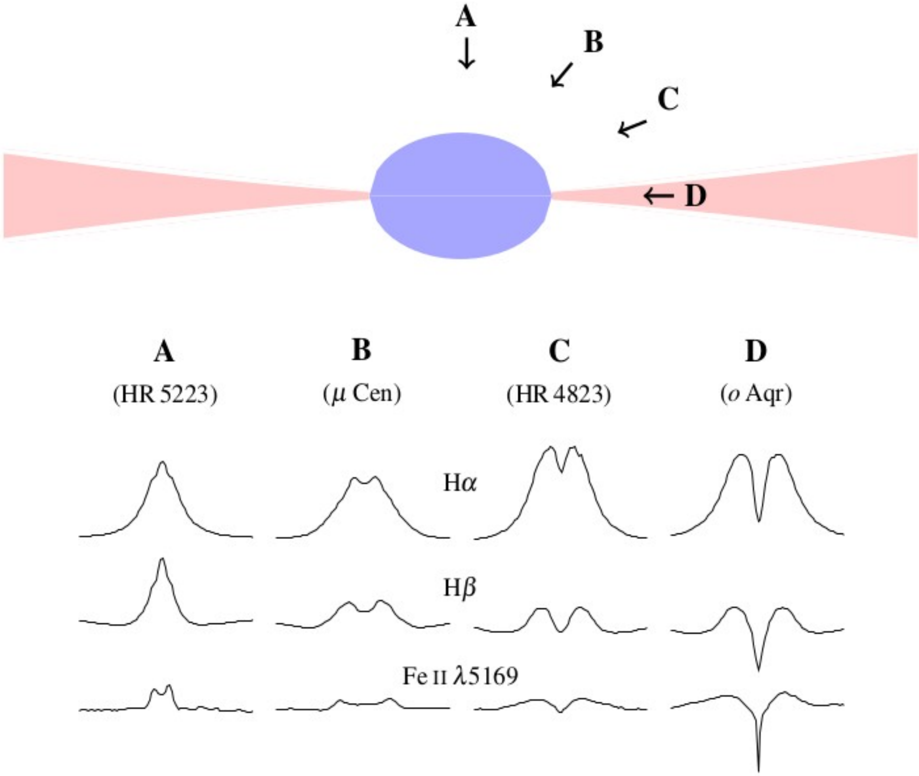
- Stars of spectral type **B**
  - Effective temperatures: **10000 – 30000 K**
  - Emit UV radiation that can photoionize circumstellar gas

- B**e** stars
  - Sufficiently dense gas (> 10^{-13} gcm^{-3}) around a B-type star leads to **line emission –** hydrogen recombination lines

- **Classical** Be stars
  - Emission formed in **circumstellar disks** that are **formed by mass loss from the rotating central star**
  - Disks are supported rotationally – **Keplerian rotation**

Classical Be stars

- **Rapidly rotating,** non-radially pulsating, **main sequence B stars** forming **purely gaseous, ionized, outflowing disks** rotating close to **Keplerian** (Rivinius+ 2013)
  - Evolutionary context
  - Structure of fast rotating stars
  - **Disk physics**



Schematic picture of Struve (1931); Fig. taken from Rivinius+ 2013

Classical Be stars

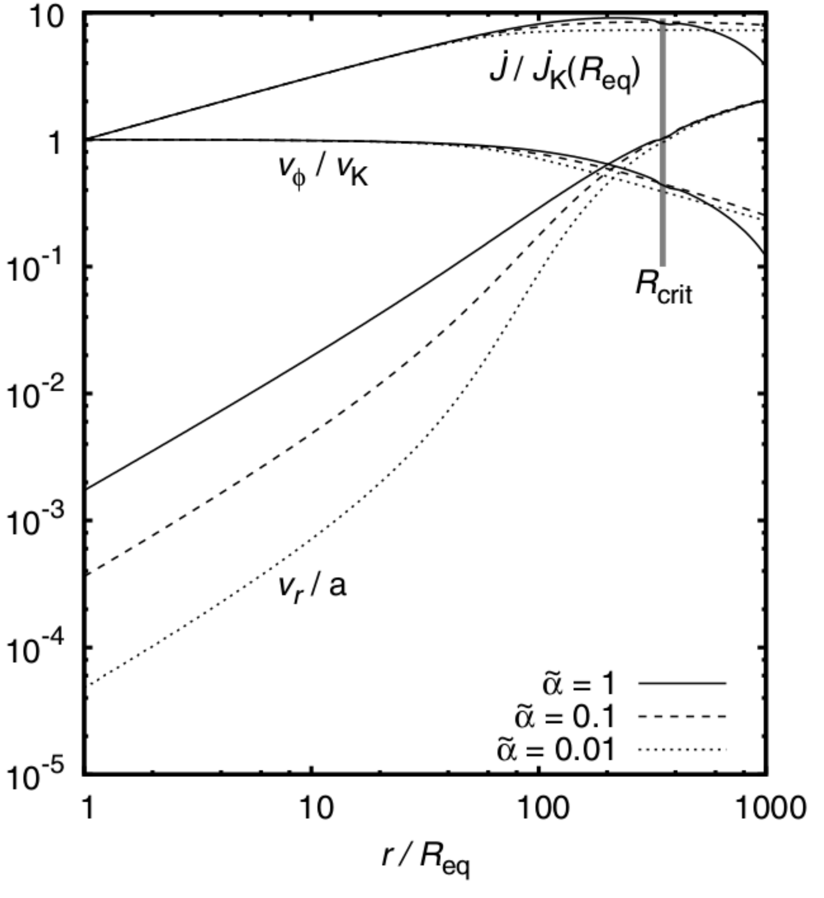
- **Keplerian disk** can be formed if:
  - Star generates **excess angular momentum** → continuous or episodic ejection of material from the stellar equator
  - Some mechanism **transfers angular momentum outwards**
    - **Turbulent viscosity** - first introduced to explain AM transport in accretion disks (Shakura & Sunyaev 1973)

- **The viscous decretion disk (VDD) model** (Lee+ 1991)
  - Radial structure governed by viscous transport
  - Vertical structure by hydrostatic equilibrium

- **VDD density structure**
  - Isothermal, steady-state, **isolated** VDD, inner few hundred R_e
    - power law → $\rho(\mathrm{r}) = \boldsymbol{\rho_0}\,(r/R_\mathrm{e})^{-\boldsymbol{n}}$, where $\boldsymbol{n} = 3.5$

Isolated VDD

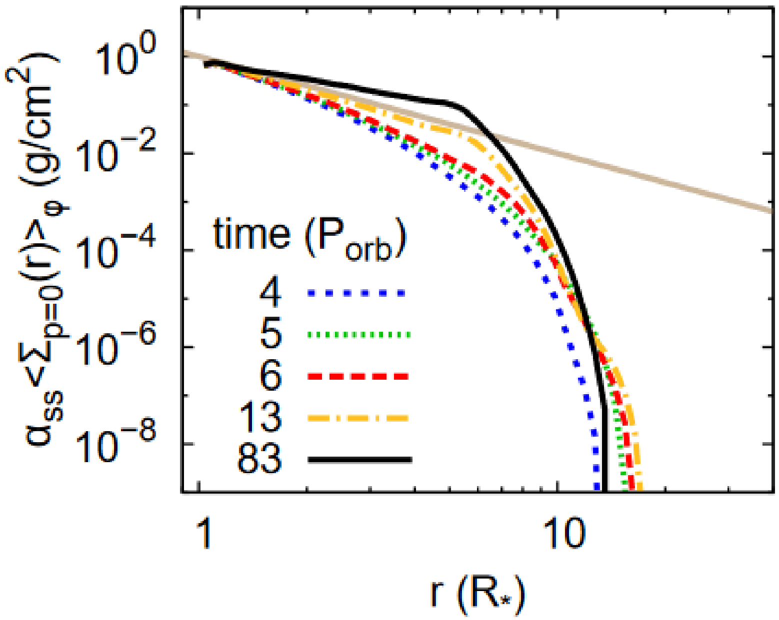
- **Disk regime transition when $v_r \approx c_s$**
  - Critical radius - $R_c / R_{eq} \approx 3/10\ (v_{orb} / c_s)^2$
    - B9V: $R_c = 430\ R_{eq}$
    - B0V: $R_c = 350\ R_{eq}$
  - $R_c \approx$ outer edge of the disk

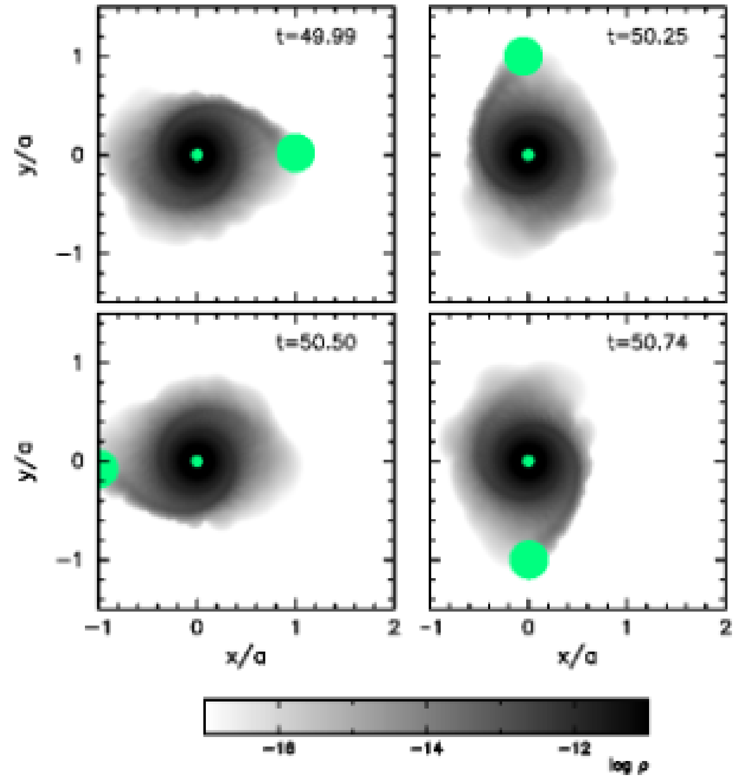


Krtička+ 2011, A&A 527, 84

VDD in binary system

- **Truncation** of the disk at orbital resonance
- Spiral density structure locked with the binary orbit – outer disk variability?
- **Accumulation** of material inwards of the truncation
- binary companions: **sdB/sdO** stars (UV), compact stars (X-rays), late-type main sequence stars (hardest to detect)

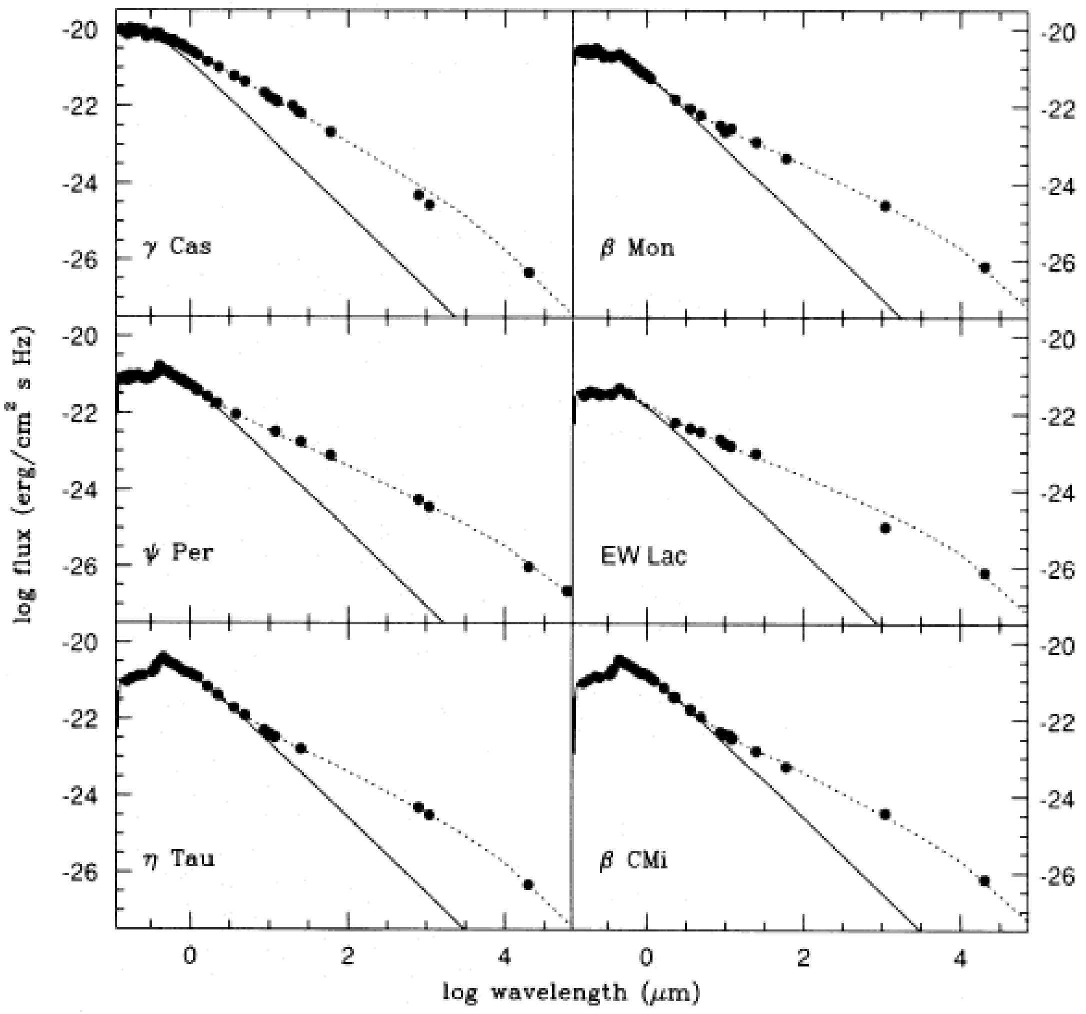




Panoglou+ 2016

VDD continuum emission

- **CONTINUUM EXCESS EMISSION**

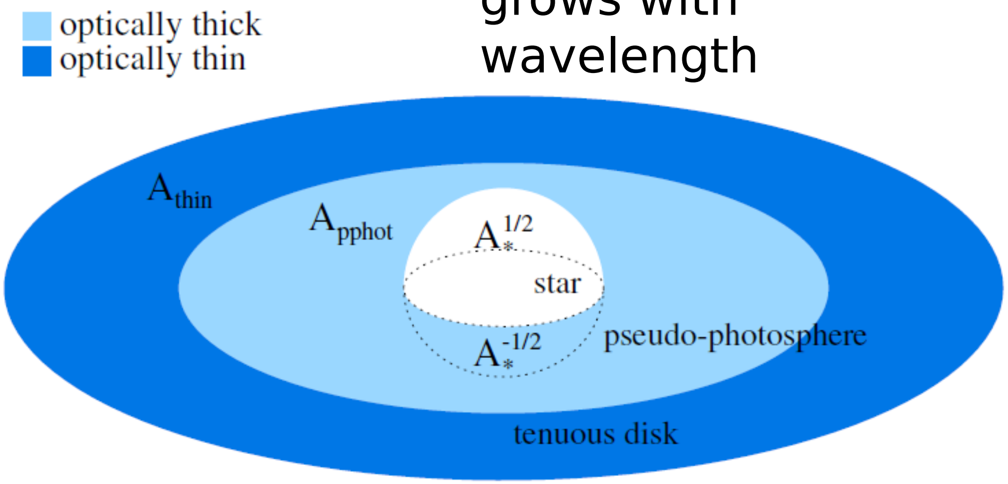


Waters+ 1991, A&A, 244, 120

VDD continuum emission

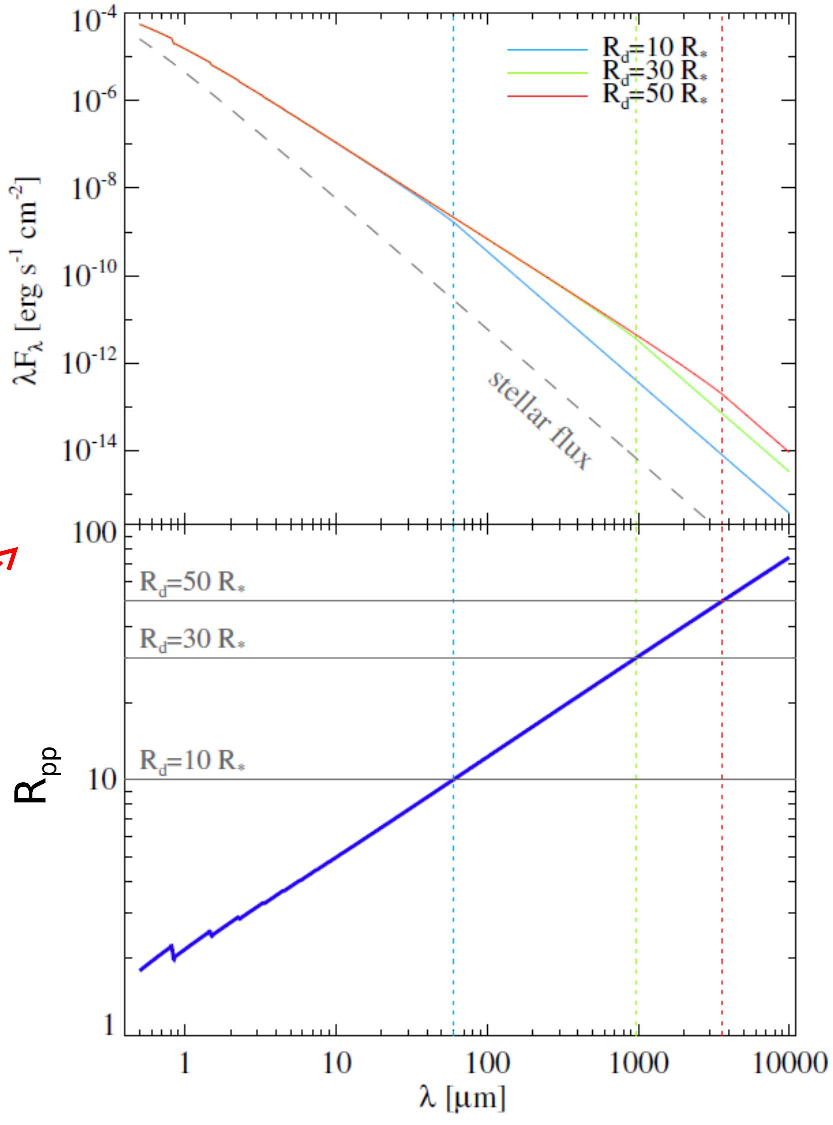
Optically thick part (pseudo-photosphere) + optically thin part (tenuous disk)

grows with wavelength



(a) general case

(b) tenuous disk (c) truncated pseudo-photosphe



Vieira+ 2015

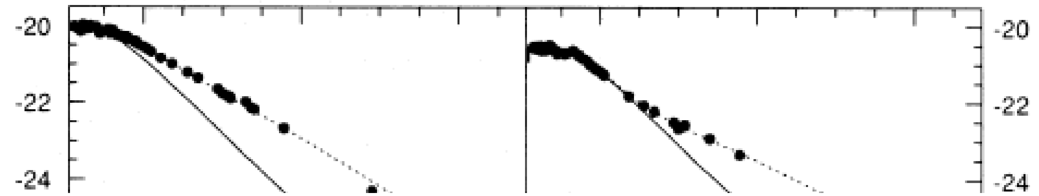
Modeling procedure

- Solve the tranfer of stellar radiation through the disk
  - Monte Carlo radiative transfer code HDUST (Carciofi & Bjorkman 2006) – computes temperature and ionization in the disk, subsequently the outgoing **polarized spectrum** and **intensity maps** for specific observer positions
- Compare the synthetic observables with multi-technique & multi-wavelength observations sensitive to different parts of the system: central star → inner disk → **outer disk**

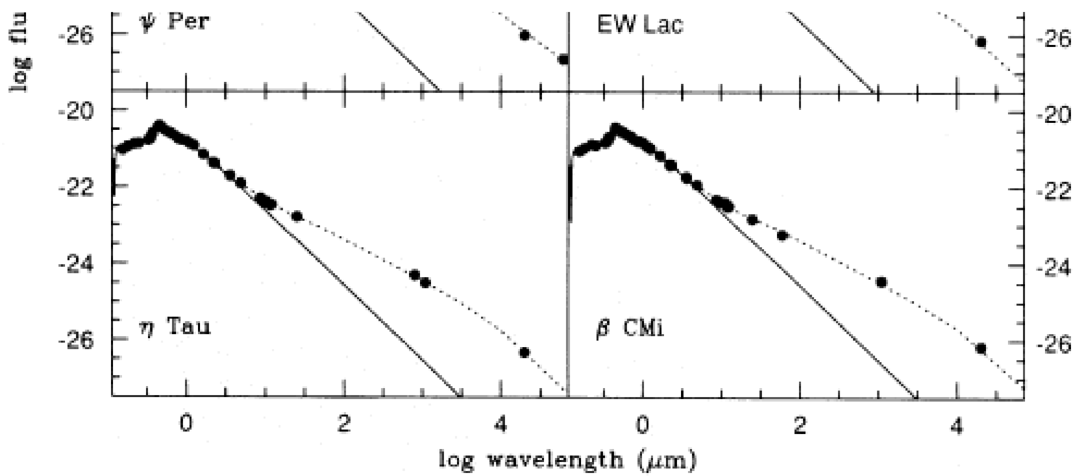
- **OUTER DISKS -** parts beyond ~20 Re observable only in the radio
  - What is the physical extent of the disk? Can we detect the outer boundary?
    - Transonic transition
    - Truncation by (unseen) **binary companions**?

Classical Be stars in radio

- Historic radio observations of Be stars – only 8 detections at cm (until 2010)!
  - VLA (cm) – 6 stars detected – ψ Per resolved (Dougherty & Taylor 1992)
  - ATCA (cm) – 2 stars

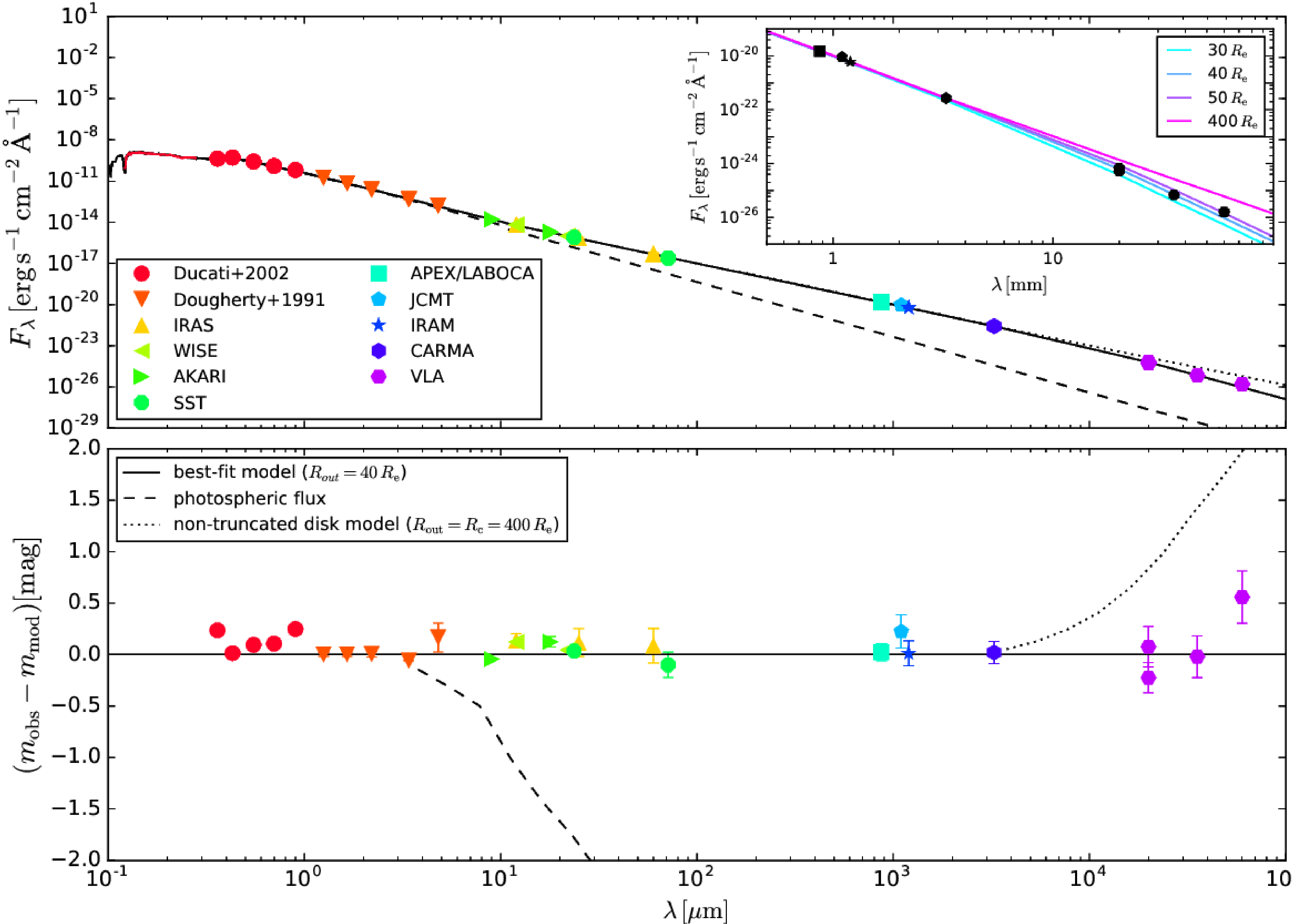


Star	F at 0.7 cm [mJy]	F at 1.3 cm [mJy]	F at 3.5 cm [mJy]	F at 6.0 cm [mJy]
η Tau	2.09 ± 0.30	0.852 ± 0.090	0.237 ± 0.024	0.1432 ± 0.0098
EW Lac	<0.83 (3σ)	0.351 ± 0.077	0.133 ± 0.023	0.089 ± 0.012
γ Cas	1.65 ± 0.15	0.710 ± 0.057	0.201 ± 0.016	0.128 ± 0.011
ψ Per	3.47 ± 0.26	1.284 ± 0.083	0.435 ± 0.022	0.241 ± 0.012



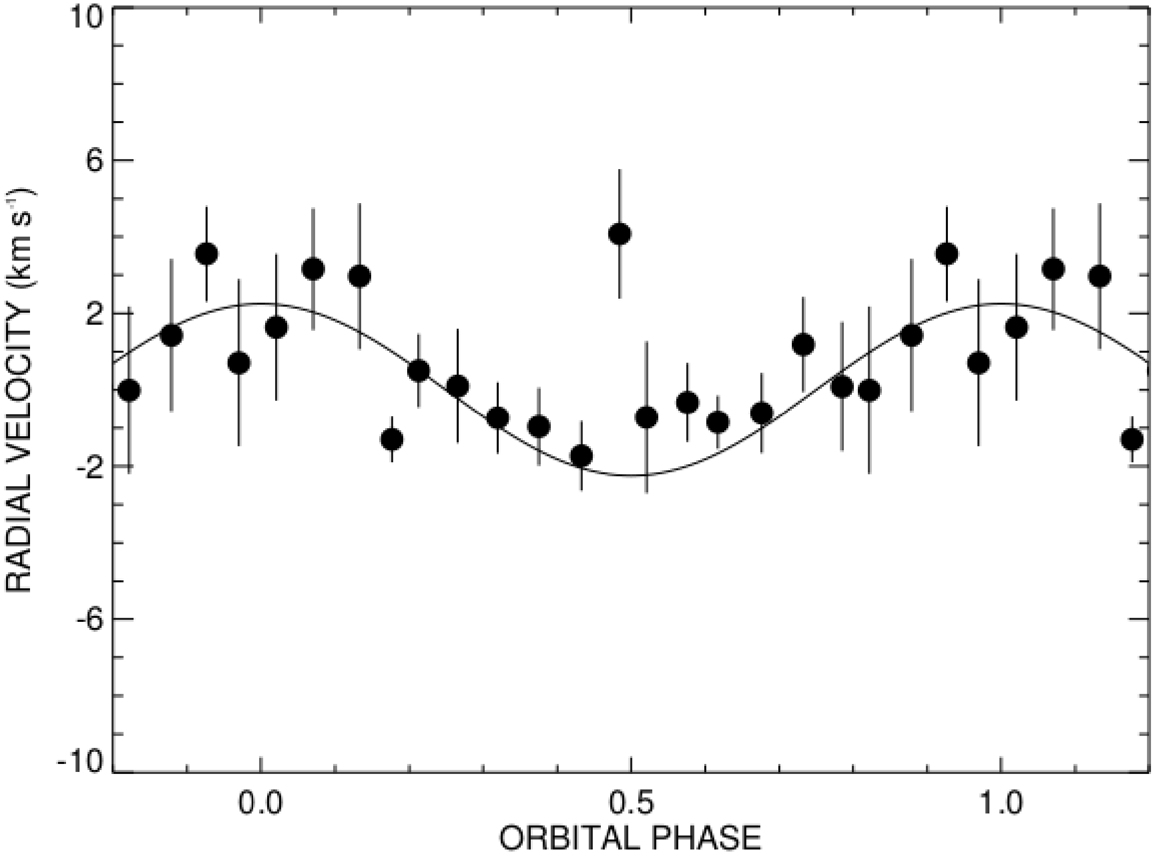
Waters et al. 1991, A&A, 244, 120

β CMi – full SED from UV to radio



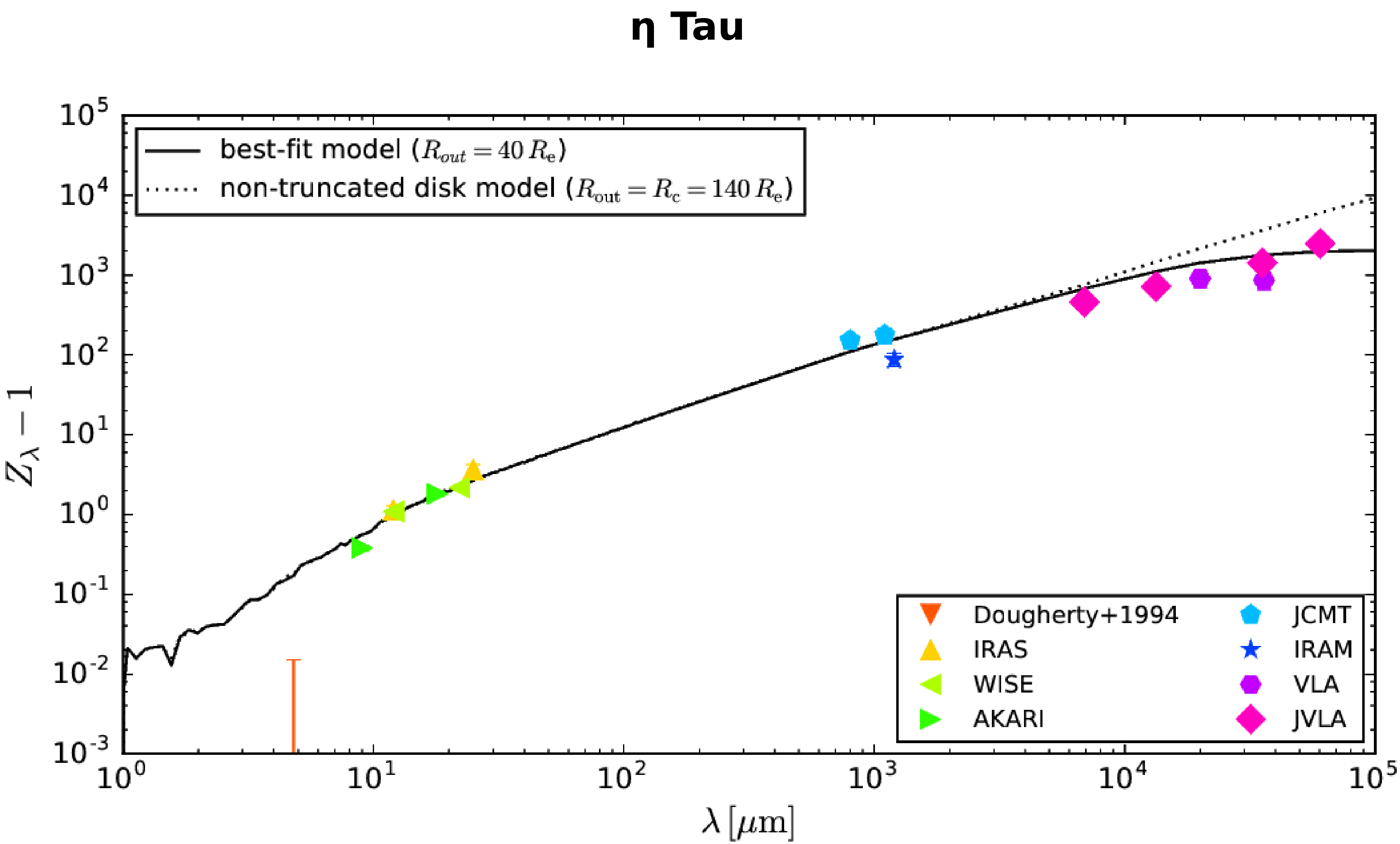
Spectroscopic search for the predicted companion

- RV variations of Hα wings with P = 170 d; K = 2.25 kms^{-1}
- small companion with M ~ 1 M_{sun} → the disk is truncated close to the 3:2 resonance with the binary orbit

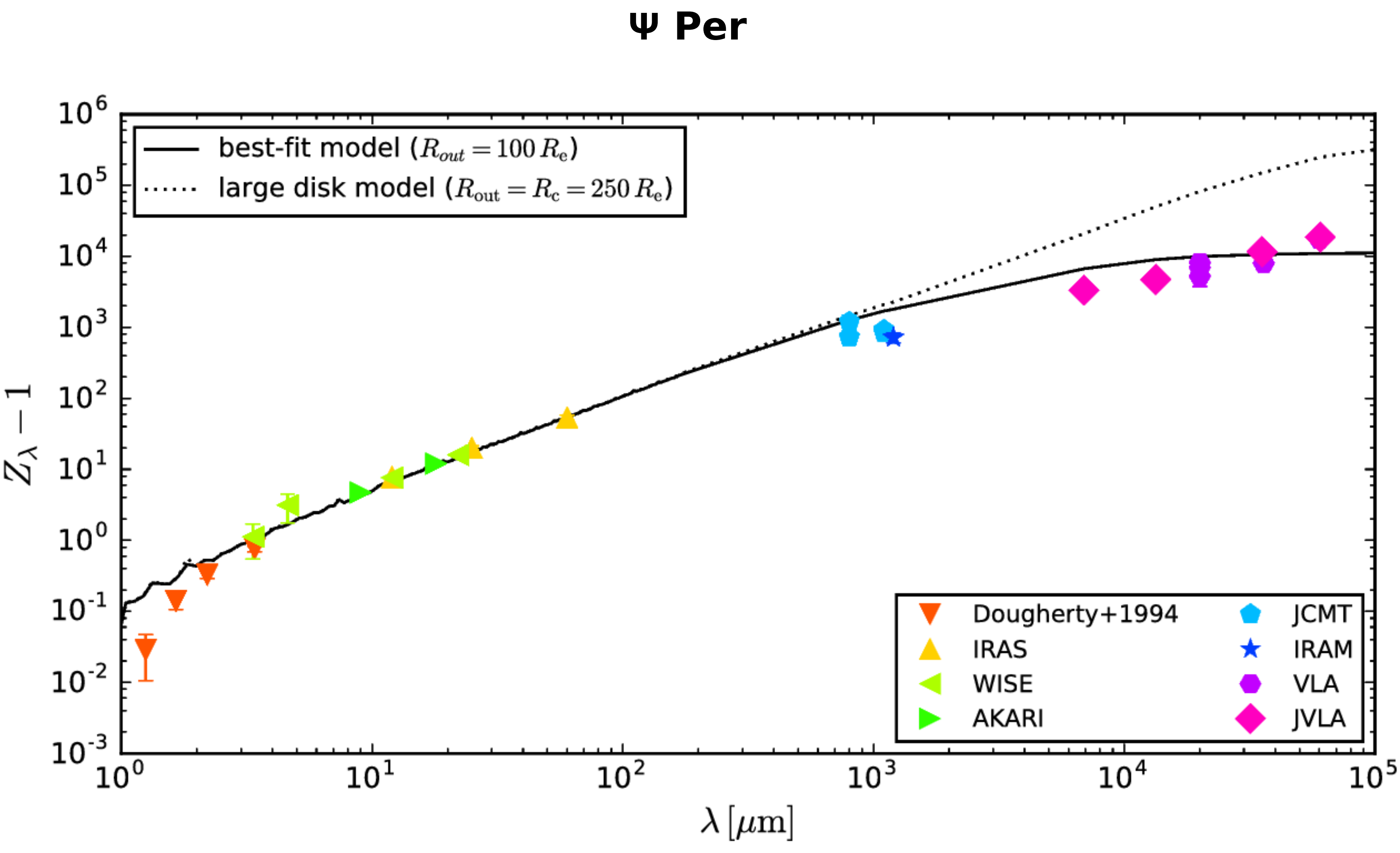


Dulaney+ 2017

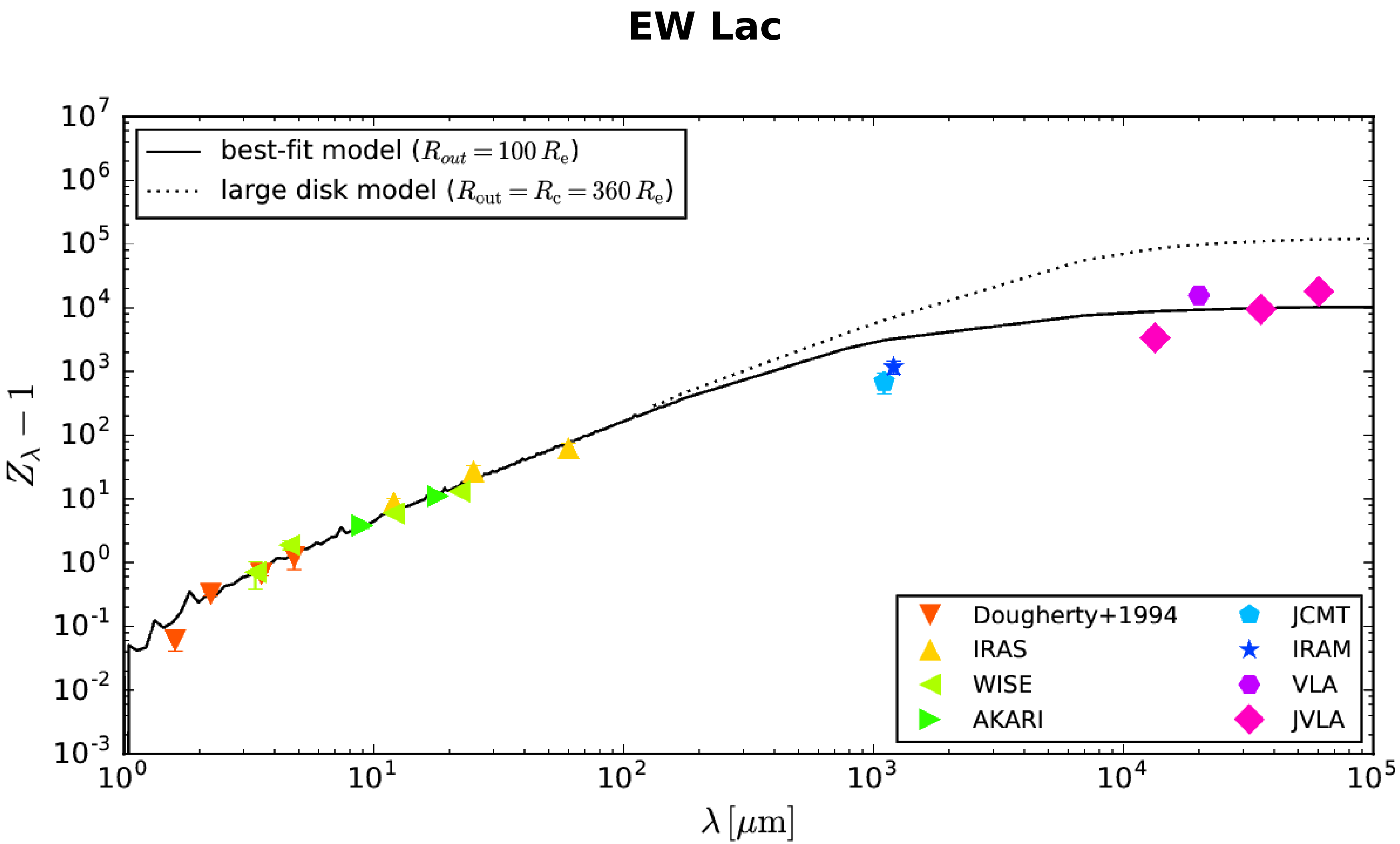
Revealing the structure of outer disks



Revealing the structure of outer disks

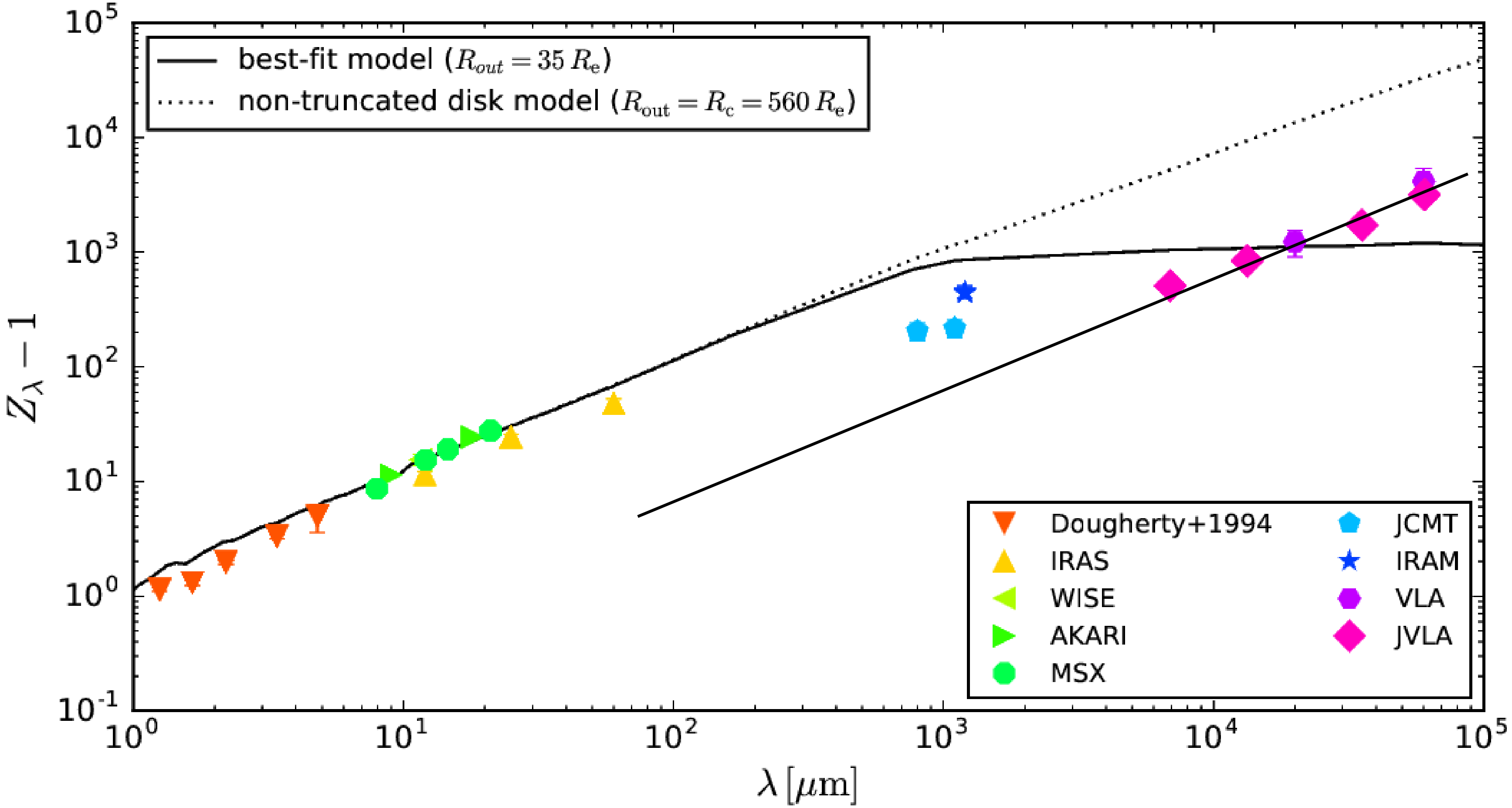


Revealing the structure of outer disks



Revealing the structure of outer disks

γ Cas - the only well-known binary from the sample



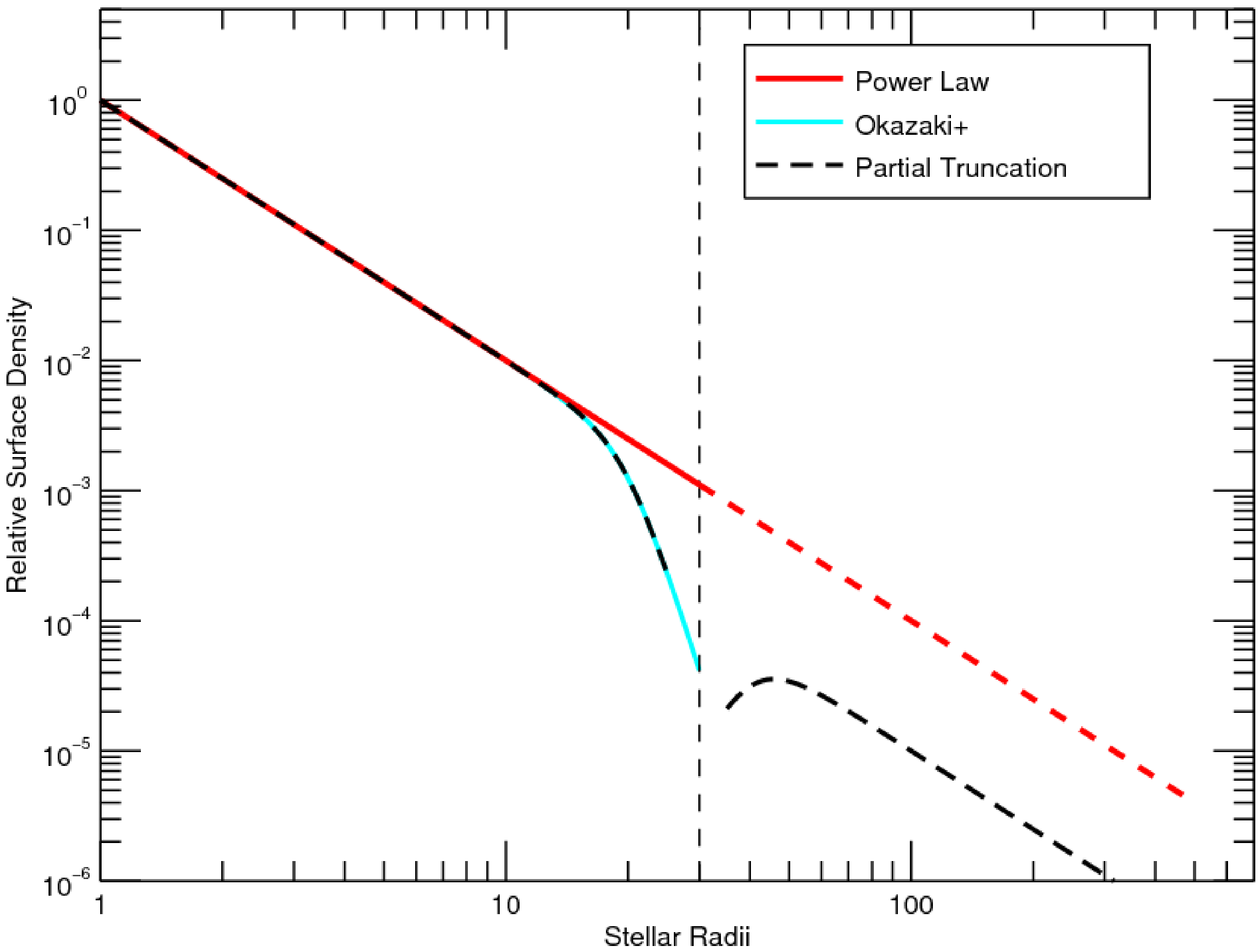
Revealing the structure of outer disks

- Disk **truncation by binary companions** offers the most plausible explanation of the radio SED structure (**in a first approximation**) - 2 out of 6 targets are now confirmed **binaries**

- **How to explain the shallow slope of the radio SED?**
  - Sharp truncation can be ruled out
  - Double power-law (Okazaki+ 2002)
  - Partial accretion on the companion and **extension of the disk beyond the companion‘s orbit** – **are Be disks circumbinary**?
    - Other evidence for circumbinarity: Peters+ 2016

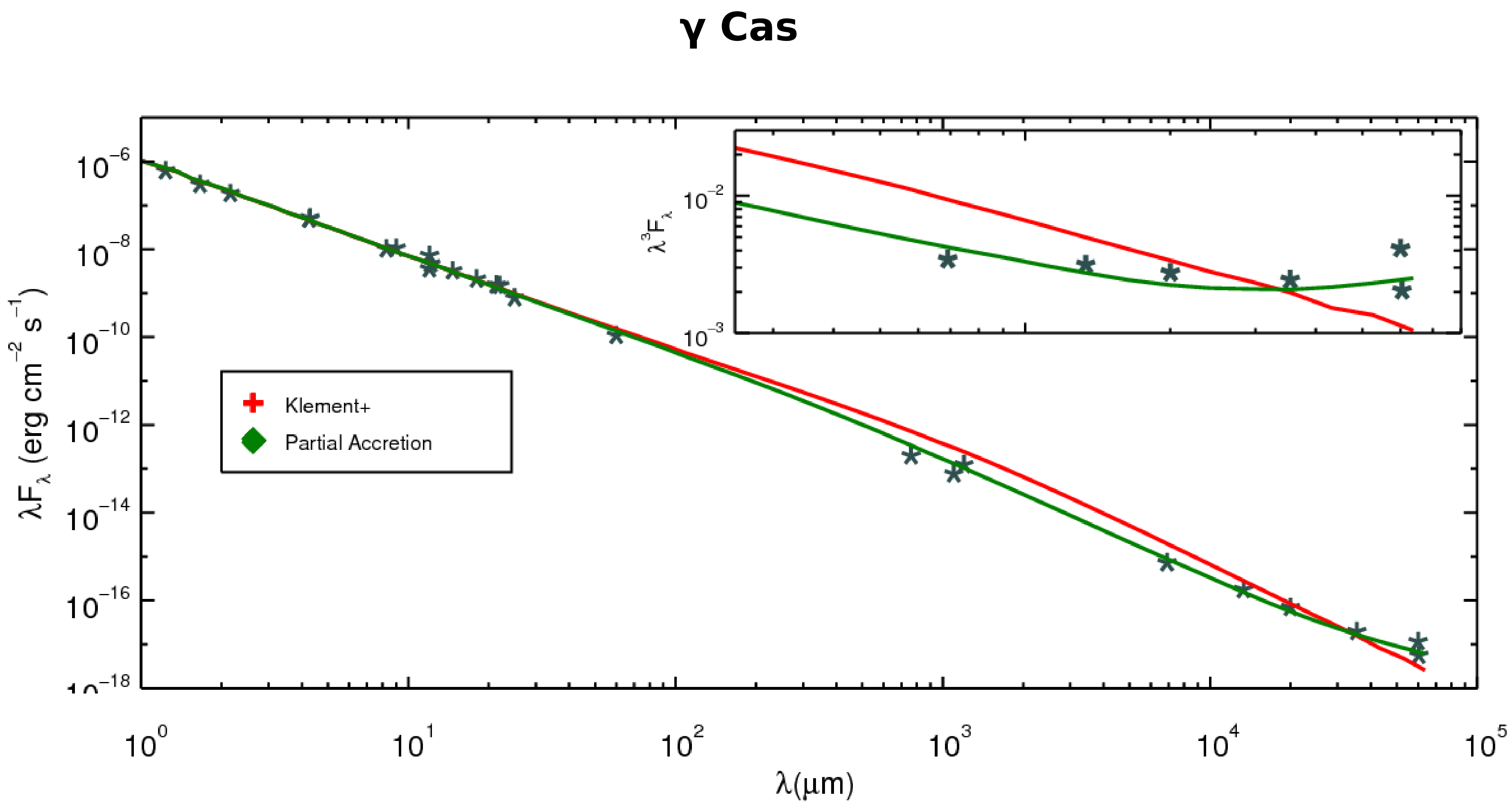
$$\Sigma = \begin{cases} \Sigma_0 \frac{(\frac{r}{R_{t1}})^{-n}}{1+(\frac{r}{R_{t1}})^{m-n}}, & r < R_i \\ (1 - A_{frac})\Sigma_0 \frac{(\frac{r}{R_{t2}})^{-n}}{1+(\frac{R_{t2}}{r})^{m-n}}, & r > R_o \end{cases}$$

Revealing the structure of outer disks



Bratcher+ in prep.

Revealing the structure of outer disks



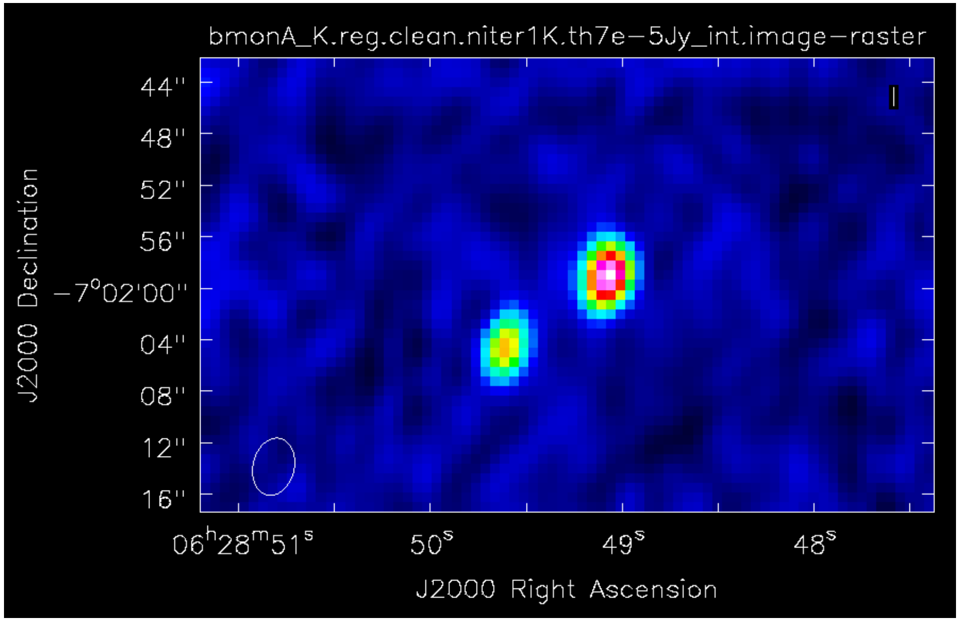
Bratcher+ in prep.

Revealing the structure of outer disks

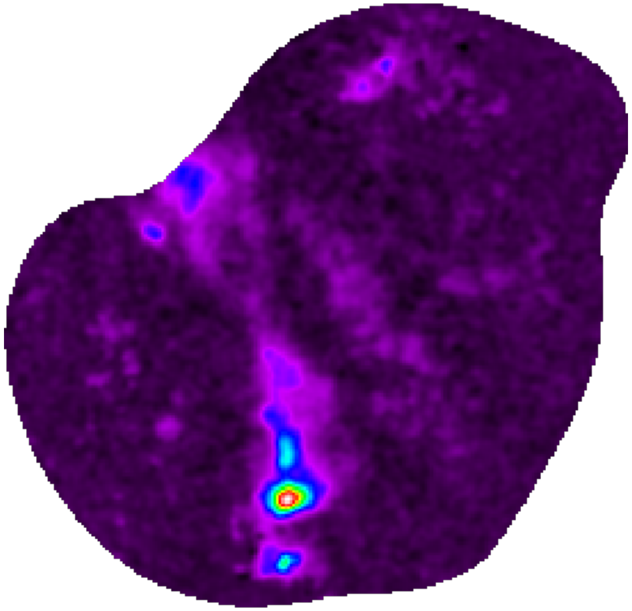
Looking ahead

- Ongoing radio observational campaign – APEX/LABOCA & VLA
- 56 classical Be stars with radio data (including upper limits & literature)

β Mon – A and C components detected (VLA)



P Car – strange structure detected not corresponding to the Be star (APEX/LABOCA)



Open access to the CHARA array

- CHARA received funding from NSF/MSIP to
  - provide open access to the community for 50 – 75 nights per year
  - provide an online data pipeline and archive of CHARA observations
- Time allocated through NOAO TAC review: 2018B (Aug – Dec 2018)
- Proposals welcome from the US and the international community
- Community workshops to help guest observers develop programs and analyze data – next one in January in Washington, DC

Open access to the CHARA array