Update on Be stars and BA supergiants

R. Klement, A. Carciofi, R. Ignace, G. Hallinan, A. Meilland, D. Mourard, D. Faes, T. Rivinius, R. Vieira, L. Matthews, S. Štefl, ...

OUTLINE

- BA supergiants with CHARA/VEGA - Deneb
- Classical Be stars (CBes) with CHARA/VEGA – β CMi
- Outer disks of CBes probed by radio fluxes (JVLA, VLA, ATCA, APEX/LABOCA, CARMA, …)

- Spectral monitoring for Be star outbursts → ToO MIRC-X proposal
- MIRC-X program on imaging the surface of Deneb (to be observed in June 2019)
- Translating of hand-written diaries of czech astronomer and philosopher Karel Hujer (mentor of Hal McAlister) for upcoming books by Hal
- Lab duties – daily alignment

CHARA/VEGA

- VEGA 4T mode has previously worked when simultaneously using MIRC to stabilize the fringes (Mourard+2015)
- VEGA 4T + CLIMB 3T mode (most of my data) so far unsuccessful
- 2T & 3T mode works – final reduction still pending
    - Time series of 2T HR differential Hα data of **Deneb** 2017 – 2018
    - 2T data for Rigel, 6 Cas, μ Cep
    - 3T snapshots of P Cyg, HD 190603, 55 Cyg, 69 Cyg
    - 2T & 3T data for **Be stars β CMi** and **κ Dra**

BA supergiants with VEGA

- Massive stars evolving from MS to RSG phase (α Cyg variables) and possibly after RSG.
- Distance indicators via wind-momentum-luminosity relationship (WMLR)
- A.k.a. luminous blue variables (LBVs) if showing massive outbursts
- Variable **line-driven winds** with small-scale & large-scale asymmetries
    - P Cygni line profiles – strongest emission in **Hα** → high resolution spectroscopy and **spectro-interferometry** ideal to probe the wind → spectro-interferometric **imaging**
    - Bright spots/non-radial pulsations → localized time-dependent mass ejections → hints of corotating interaction regions (Chesneau+2010, 2014)
    - Signatures of large-scale magnetic confinement of wind not detected

Deneb with VEGA

- Deneb – α Cyg, A2Ia, UD diameter 2.4 mas, *R* = 1.14
    - Closest and most studied among BA supergiants, but huge uncertainty on the distance, mass loss rate, …
    - **Hα line** profile not yet reproduced by any model
    - Spherically symmetric wind with second order inhomogenities - **pioneering VEG data** (Chesneau+2010)
- Radiative transfer modeling with Monte Carlo radiative transfer code HDUST (Carciofi & Bjorkman 2006)
    - Used extensively on Be star disks – purely gaseous, tenuous
    - Full 3D capability – in principle ideal for exploring **structured hot star winds** in detail – modeling efforts underway

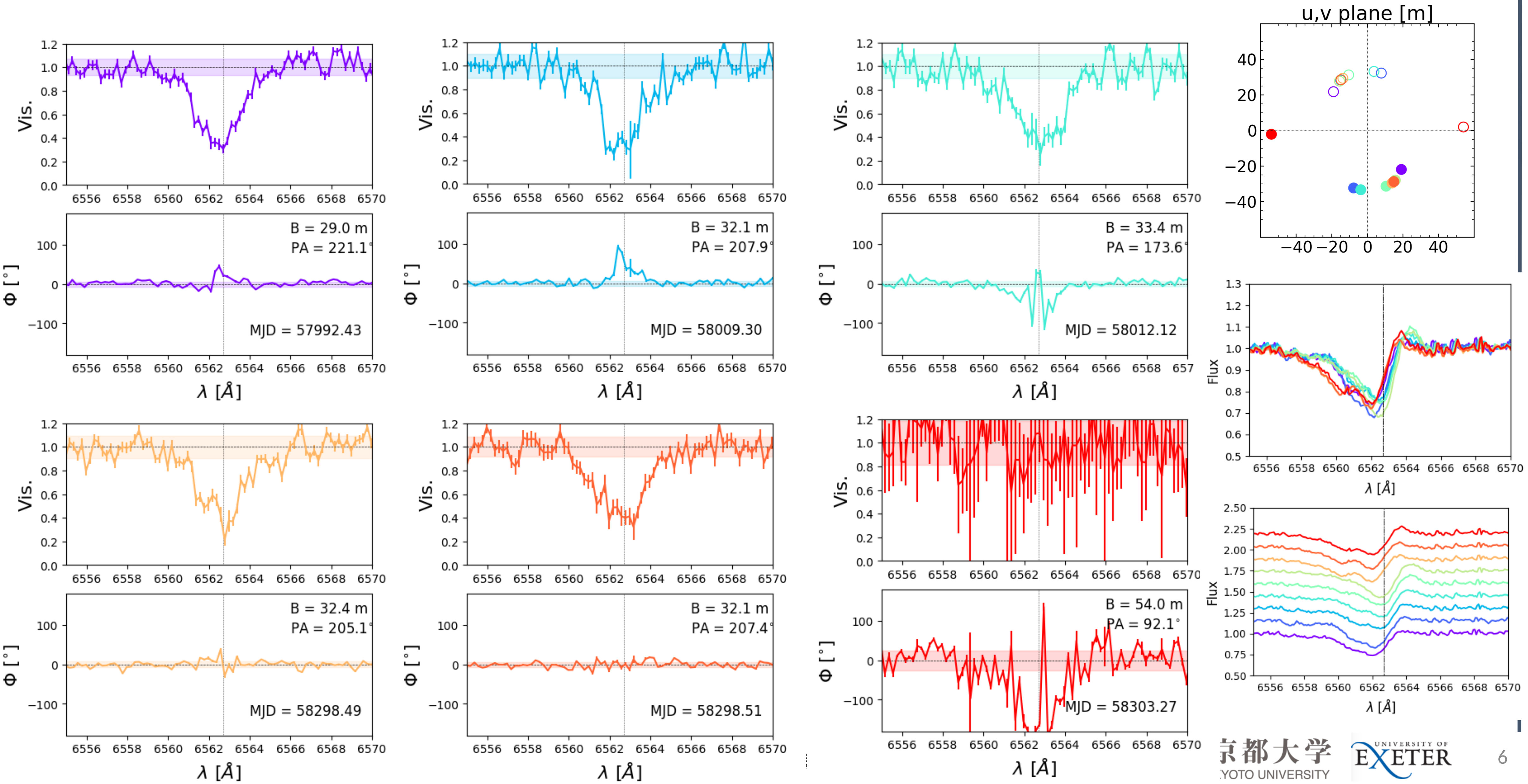
Table 2. Stellar parameters of Deneb.

Name	Deneb
Spectral type	A2 Ia
d	802 ± 66 pc
Radial velocity	2.50 km s^{-1}
Atmosphere	
$T_{\rm eff}$	8525 ± 75 K
$\log g$ (cgs)	1.10 ± 0.05
n(He) (number fraction)	0.11 ± 0.01
$[M/H]$	-0.20 ± 0.04
ξ	8 ± 1 km s^{-1}
ζ	20 ± 2 km s^{-1}
$v \sin i$	20 ± 2 km s^{-1}
Photometry	
V [a]	$1^{\rm m}.25$
$B-V$ [a]	$+0^{\rm m}.09$
$U-B$ [a]	$-0^{\rm m}.23$
$(B-V)_0$ [b]	$0^{\rm m}.05$
$E(B-V)$	$0^{\rm m}.04$
A_V	$0^{\rm m}.11$
$(m_V - M_V)_0$ [c]	$9^{\rm m}.52 \pm 0^{\rm m}.18$
M_V	$-8^{\rm m}.38 \pm 0^{\rm m}.18$
B.C. [b]	$-0^{\rm m}.11$
$M_{\rm bol}$	$-8^{\rm m}.49 \pm 0^{\rm m}.18$
Physical	
$\log L/L_\odot$	5.30 ± 0.07
$R/R_\odot$	203 ± 17
$M^{\rm spec}/M_\odot$	19 ± 4
$M^{\rm ZAMS}/M_\odot$	23 ± 2
$M^{\rm evol}/M_\odot$	18 ± 2
Wind parameters	
$\dot{M}$	3.1×10^{-7} $M_\odot$ yr^{-1}
v_∞ [d]	240 ± 25 km s^{-1}
β	3.0
$\xi_{{\rm H}\alpha}$	35 km s^{-1}

[a] Johnson et al. (1966); [b] calculated from the ATLAS9 model; [c] Humphreys (1978); [d] Hirsch (1998).

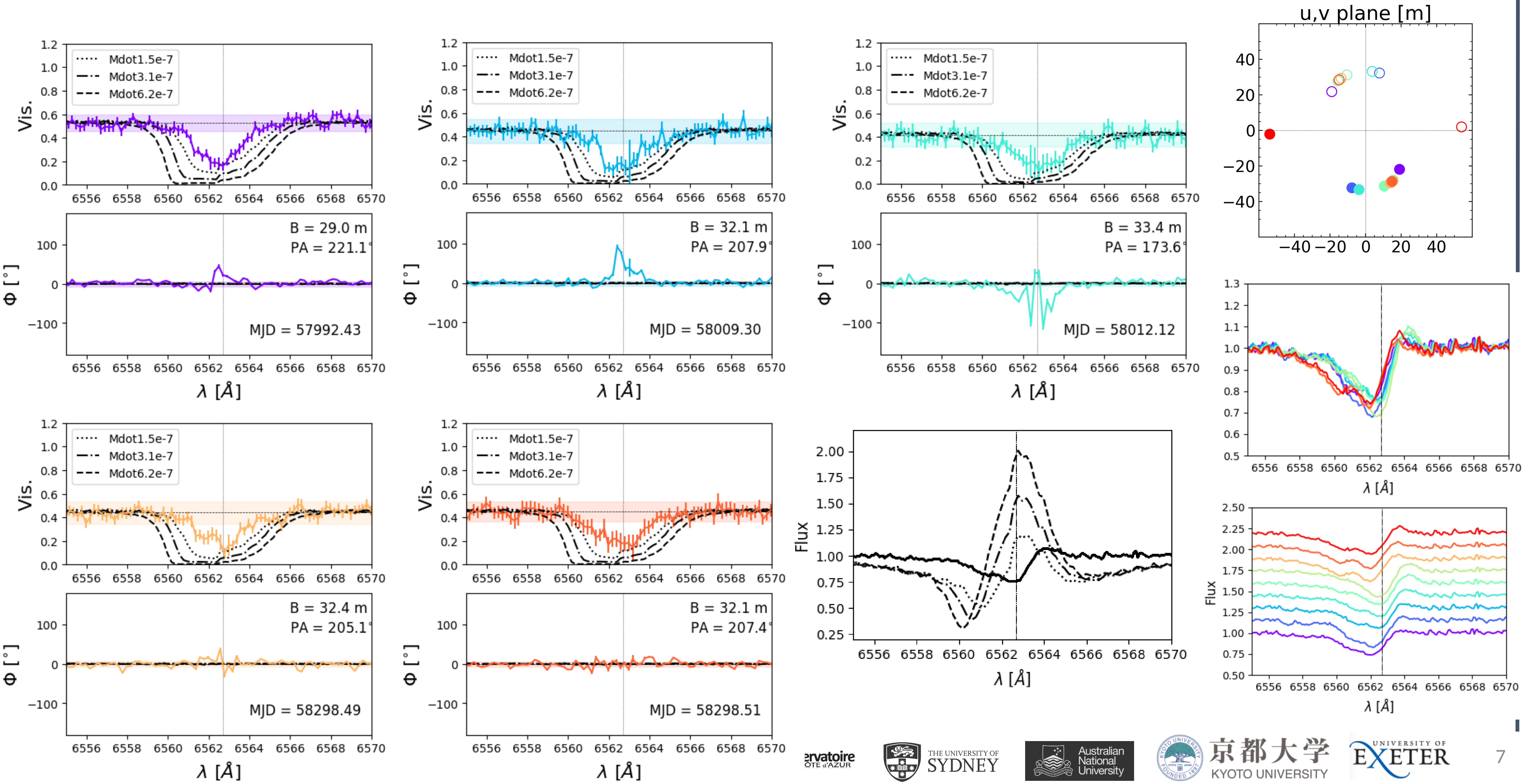
Schiller & Przybilla (2008)

Deneb with VEGA



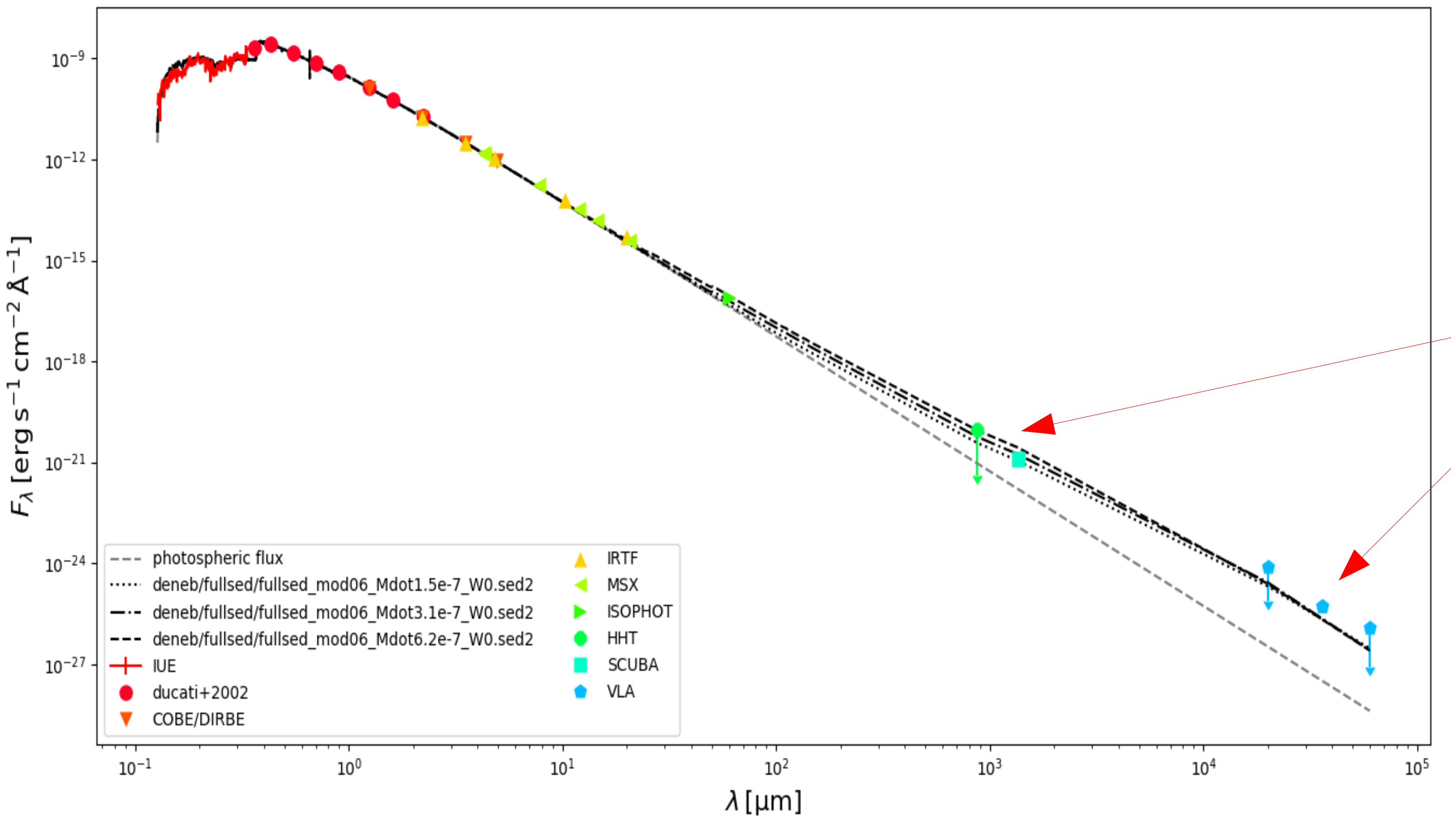
Deneb – HDUST model

(wind parameters from Chesneau+2010)



Deneb – HDUST model

(wind parameters from Chesneau+2010)



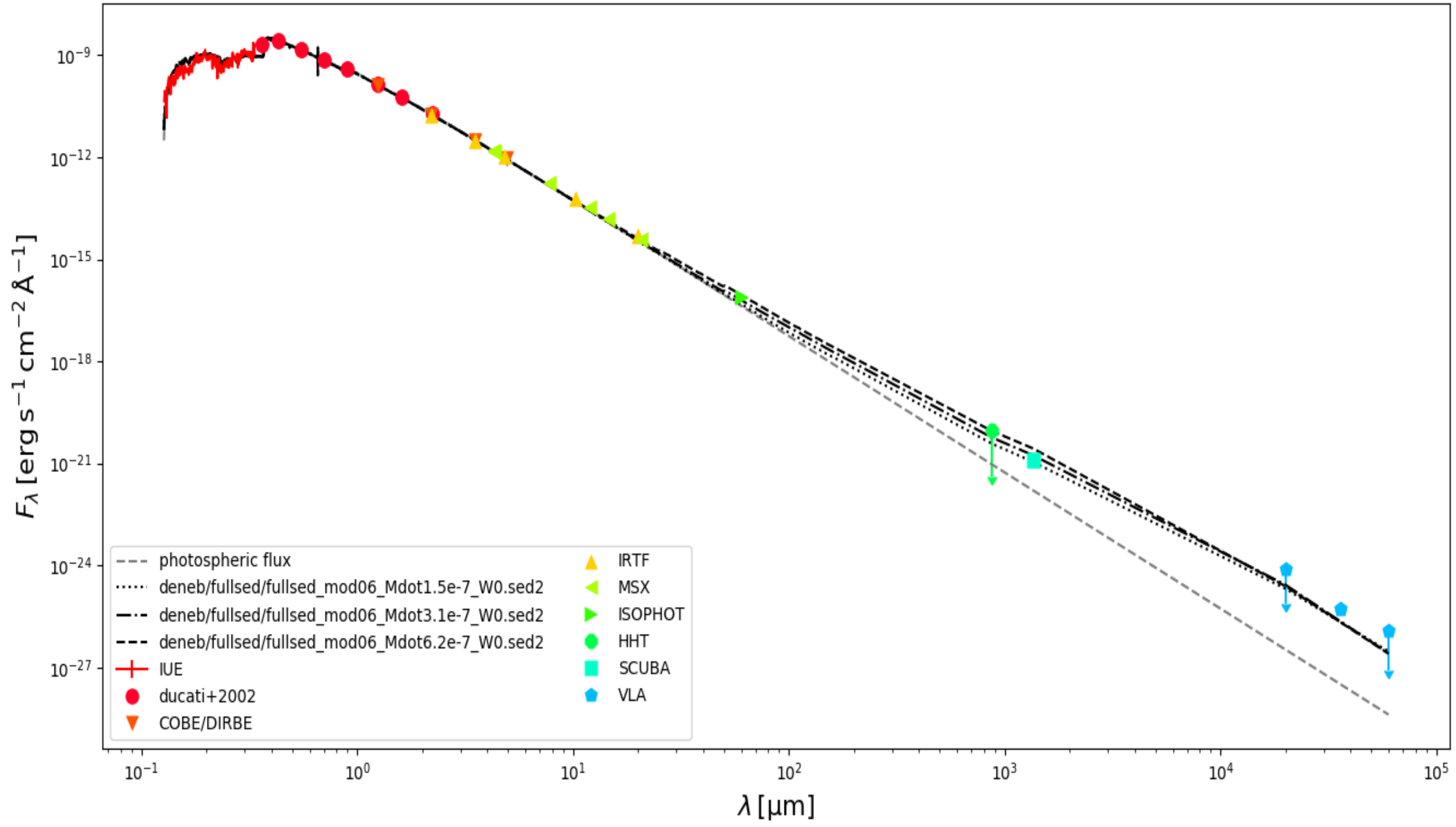
- Computed for **envelope size of 10 stellar radii** only (truncated env.)
- Free-free emission – longer wavelengths probe outer parts

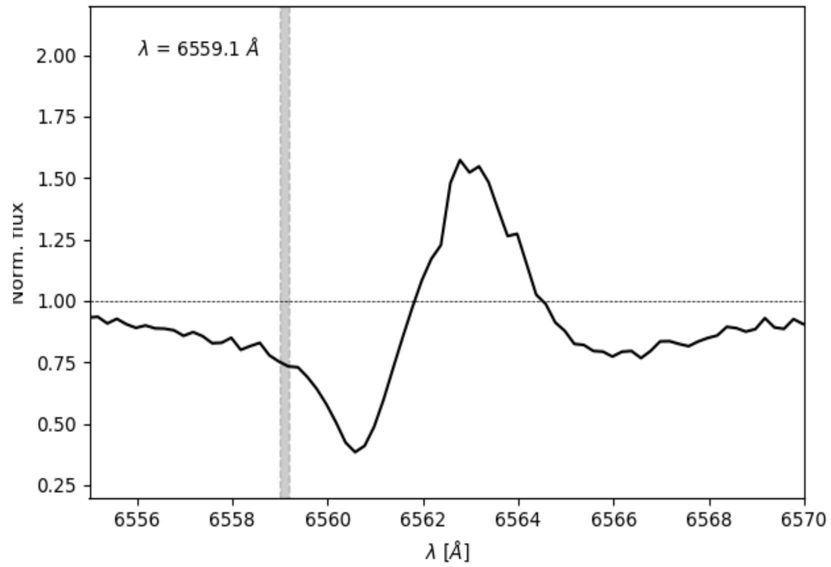
mm fluxes come from within 10 stellar radii

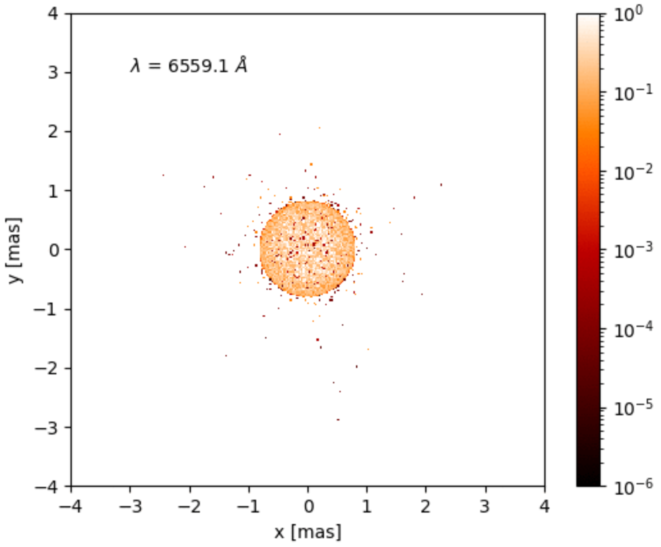
cm fluxes come from >10 stellar radii

Deneb – HDUST model

(wind parameters from Chesneau+2010)





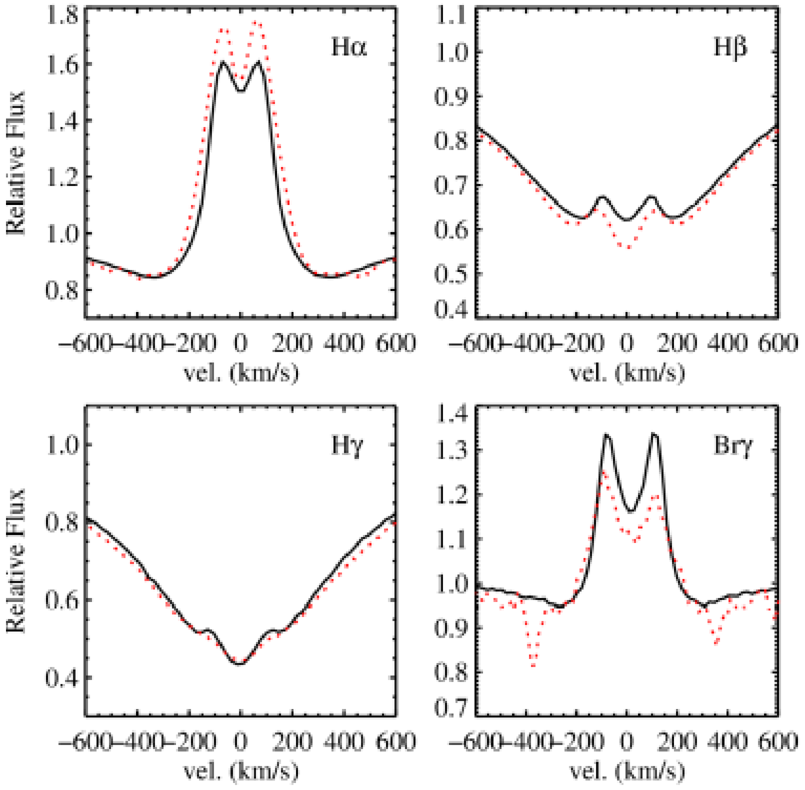


Classical Be stars

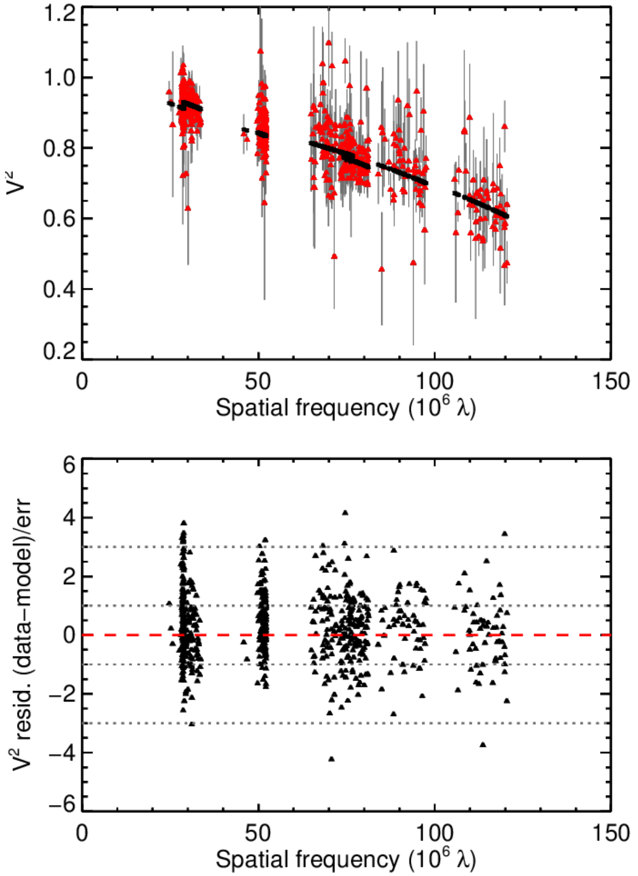
- Rapidly rotating **B** stars showing line **e**mission from circumstellar decretion disks
- Favorite targets for (spectro-)interferometry
    - Disk-like geometry (Quirrenbach+1994)
    - Keplerian rotation (Meilland+2007)
    - One-armed density waves (Carciofi+2009)

Classical Be stars with VEGA – β CMi

- Previous multi-technique study (Klement+2015) – VLTI, CHARA, and NPOI data
- Stable disk – ideal for spectro-interferometric imaging – what about HR across Hα?

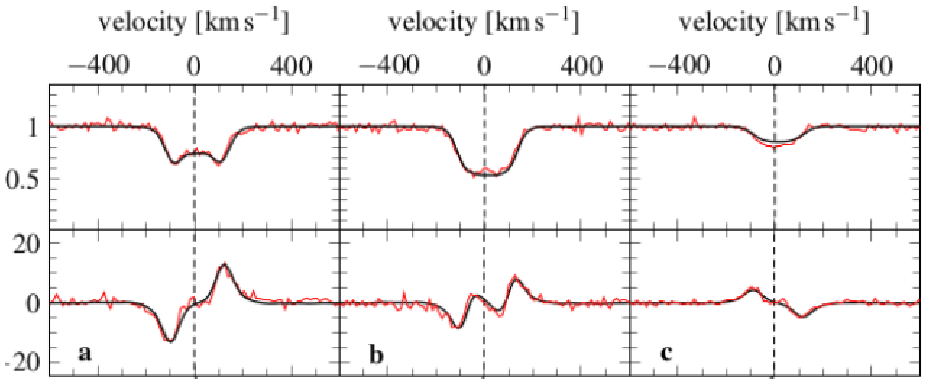


Hydrogen line profiles



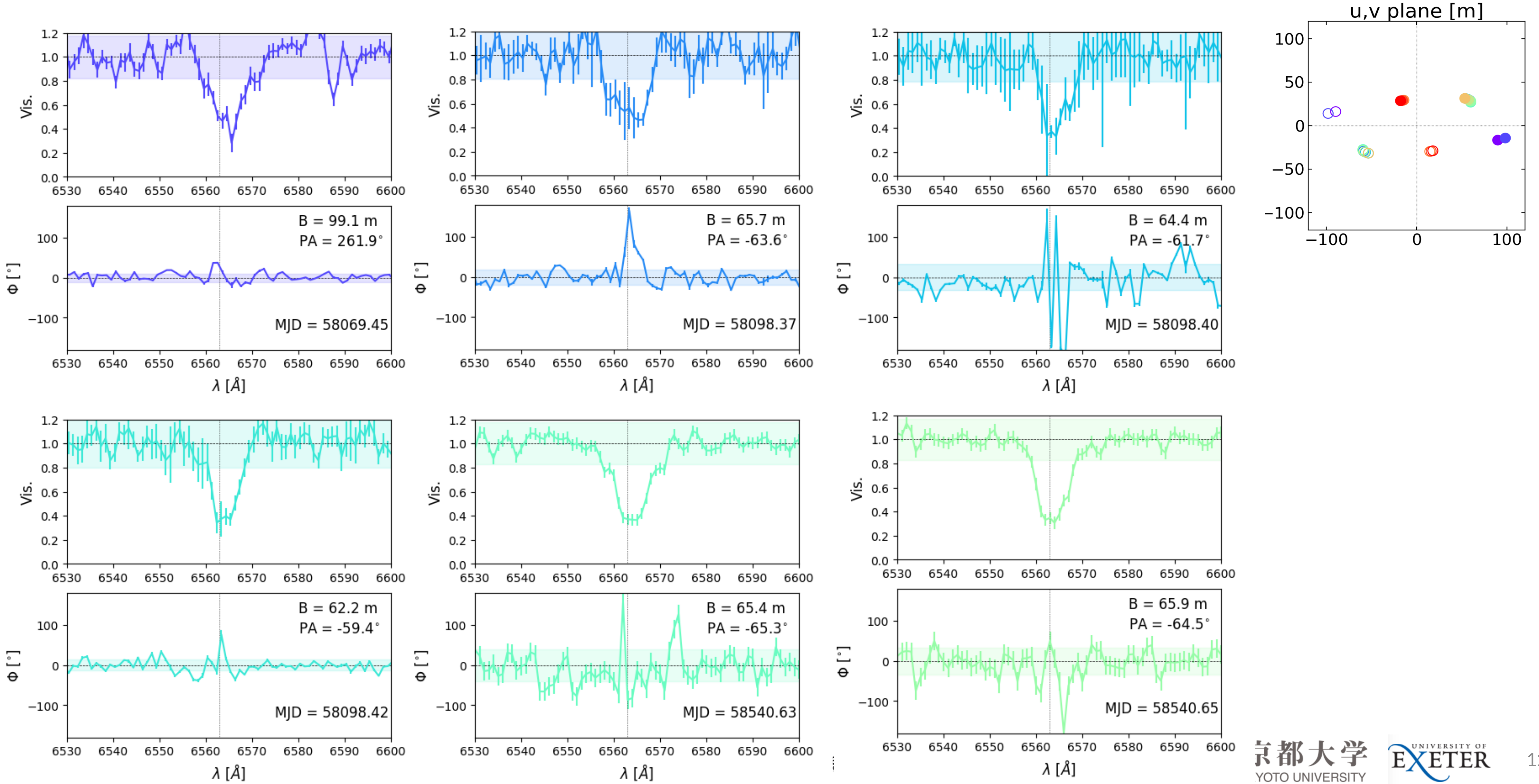
NPOI (Hα)

Instrument	Spectral band	χ^2 ($n = 2.9$)
NPOI	R (Hα)	1.37
MIRC	H	2.17
FSU-A	K	0.89
AMBER	K (Brγ)	1.52
CLIMB	K'	1.48
MIDI	N	1.83

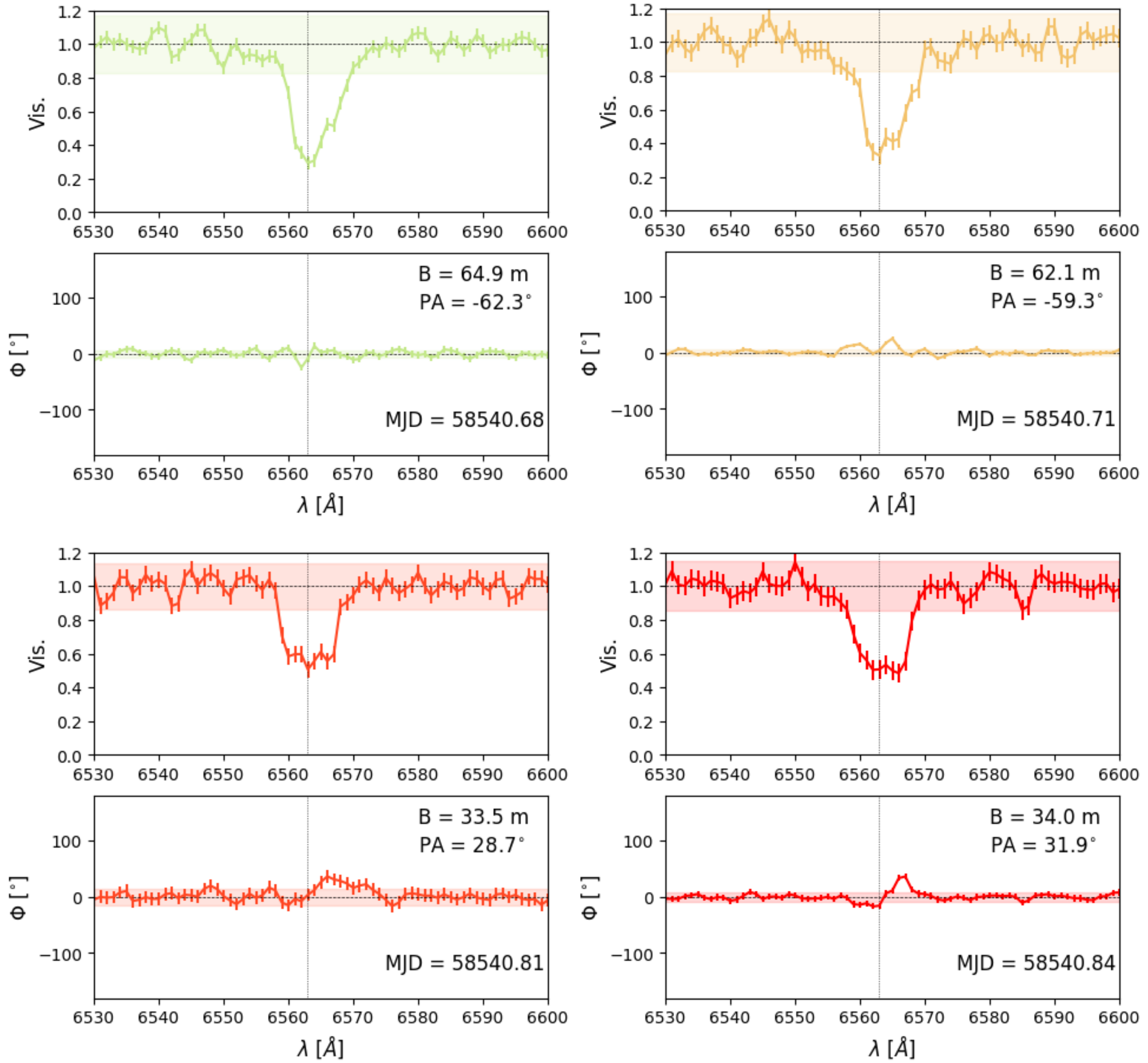


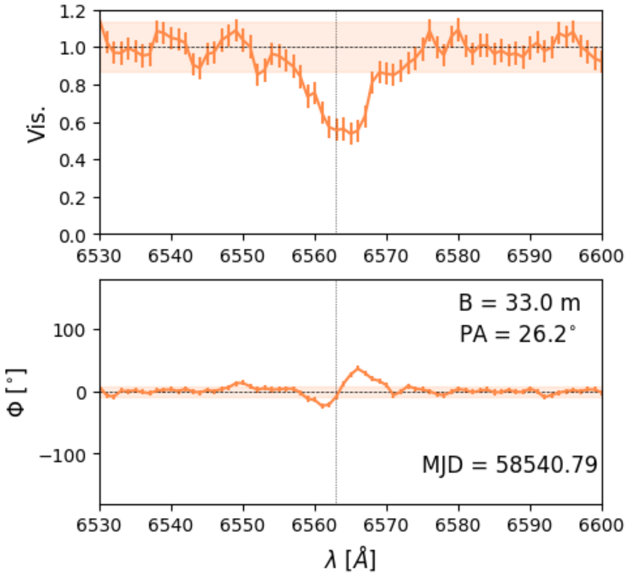
VLTI/AMBER (Brγ, R = 12000)

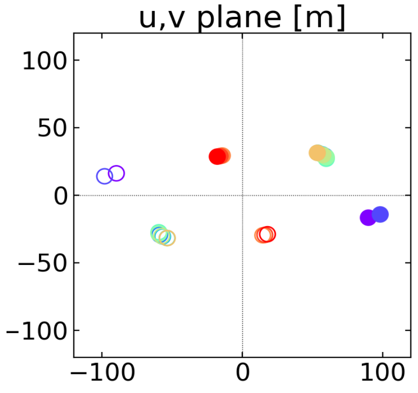
Classical Be stars with VEGA – β CMi



Classical Be stars with VEGA – β CMi





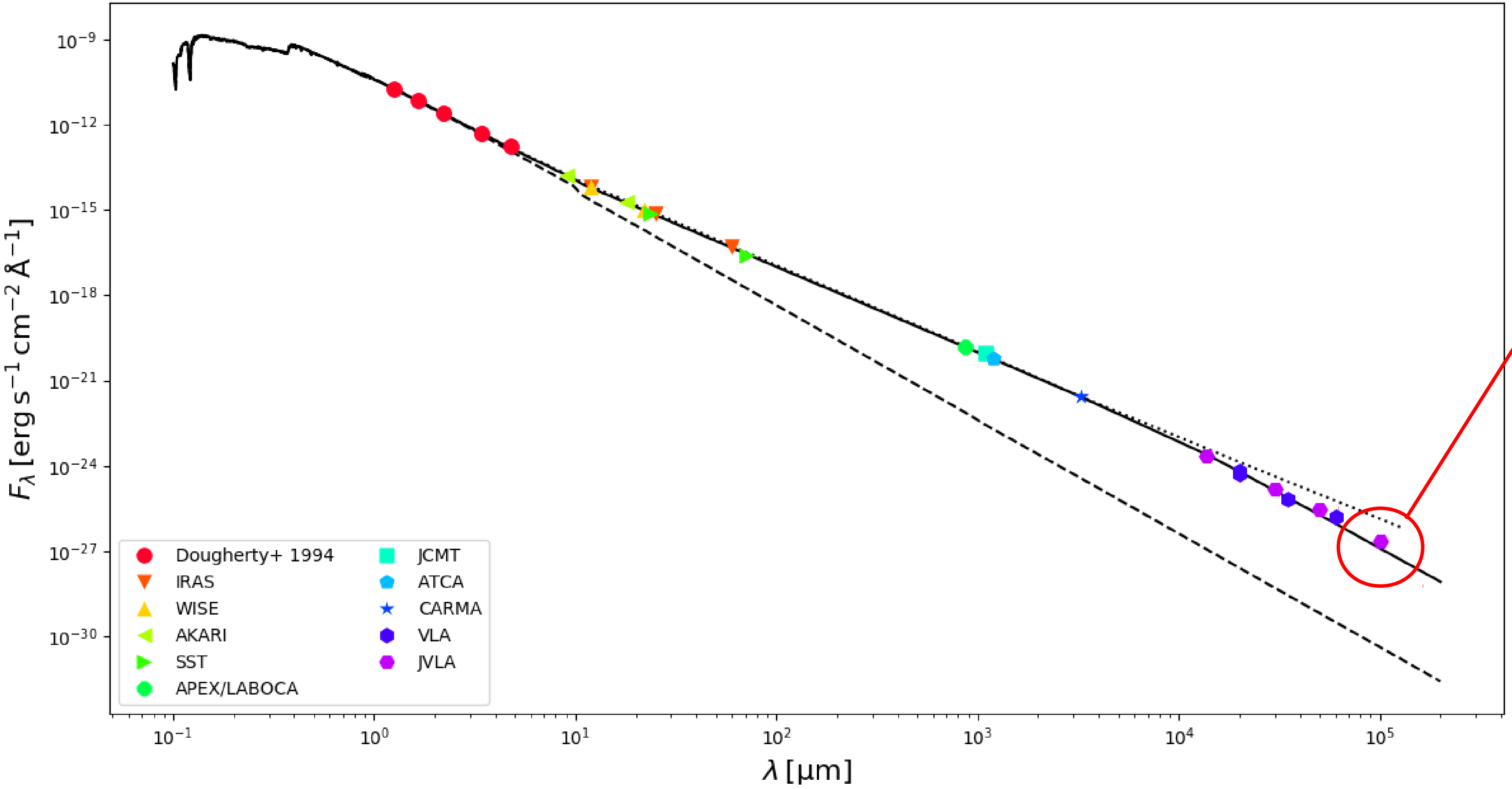


Data taken on 2/26/2019 (!)
reduced by A. Meilland

Outer disks of Be stars probed by radio fluxes

- Are Be disks truncated by binary companions?
  - Spectral energy distribution (SED) **turndown** evident at long wavelengths when data of sufficient quality available (Waters+1991, Klement+2017) – most likely caused by **truncation due to** (unseen) **companions**
  - Presence of **sdO/sdB** companions could explain why Be stars rotate so fast and consequently form decretion disks (Wang+2017)
  - Centimeter fluxes from upgraded VLA suggest that Be disks might be **circumbinary** with small companion carving a gap (like planets in protoplanetary disks?)

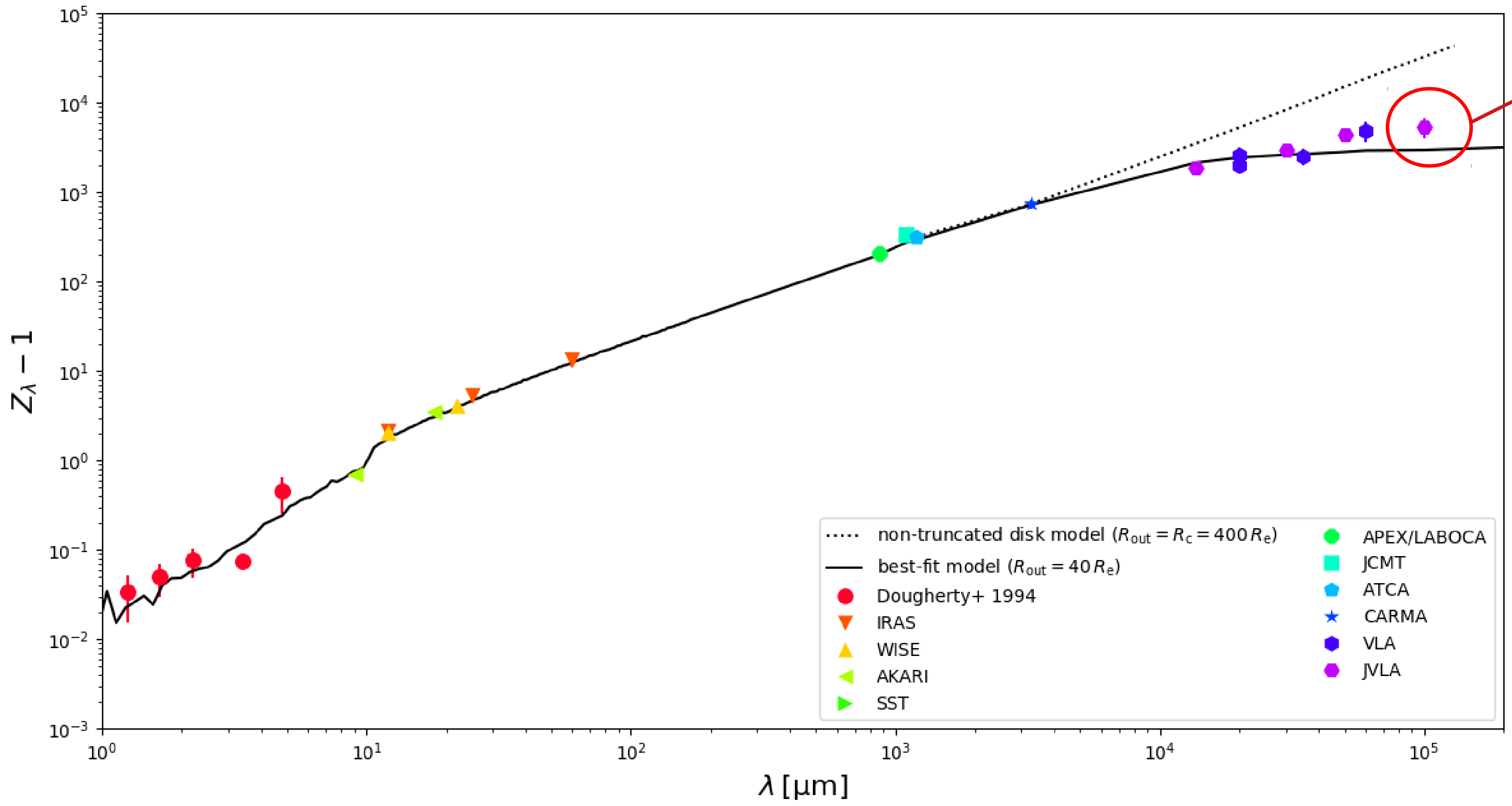
Outer disks of Be stars probed by radio fluxes – β CMi



First detection of a classical Be star at 10 cm!

76 ± 20 µJy

Outer disks of Be stars probed by radio fluxes – β CMi

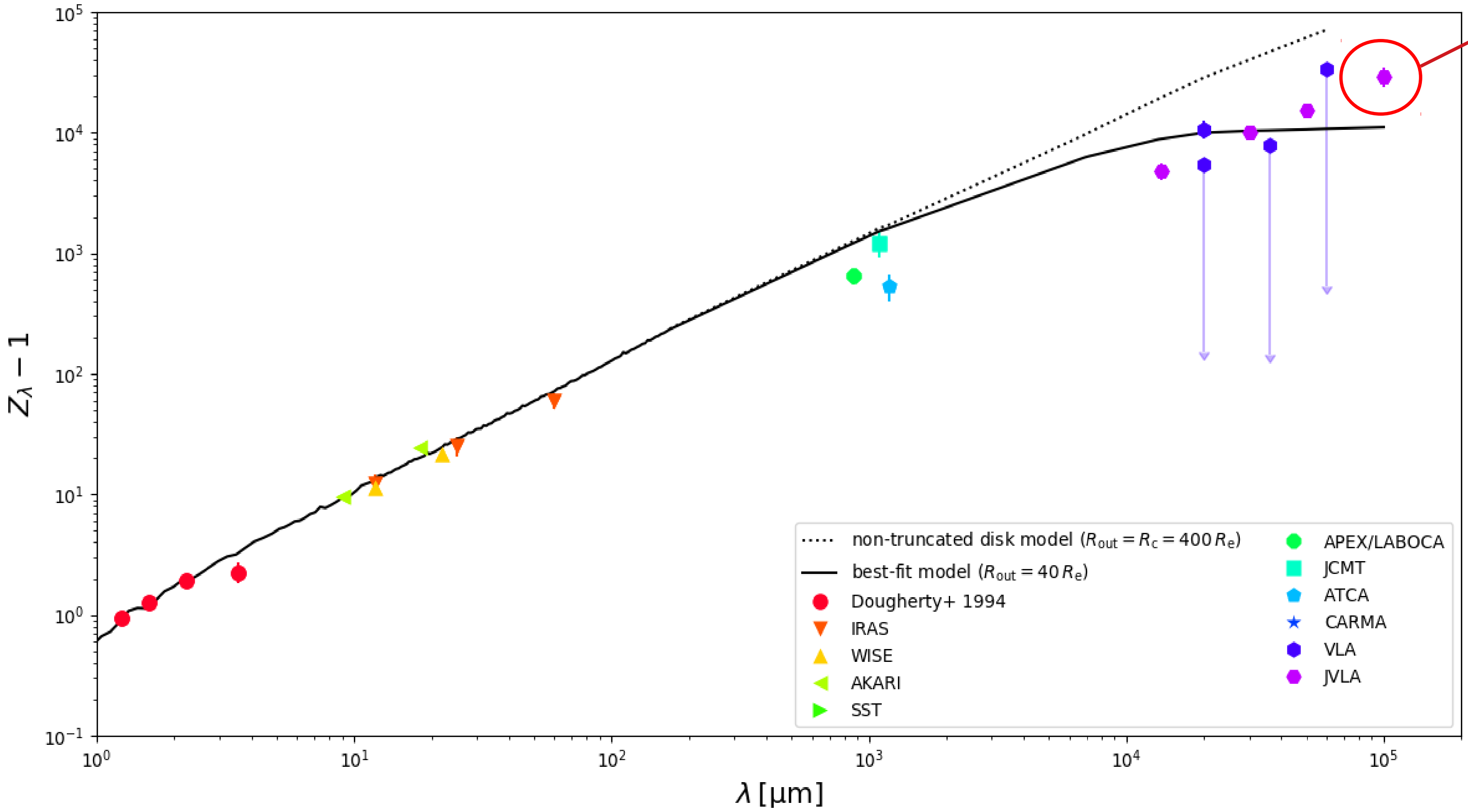


First detection at 10 cm!

76 ± 20 µJy

Truncation not sharp – circumbinary disk? (Bratcher+ in prep.)

Outer disks of Be stars probed by radio fluxes - β Mon A



Second detection at 10 cm!

80 ± 15 μJy

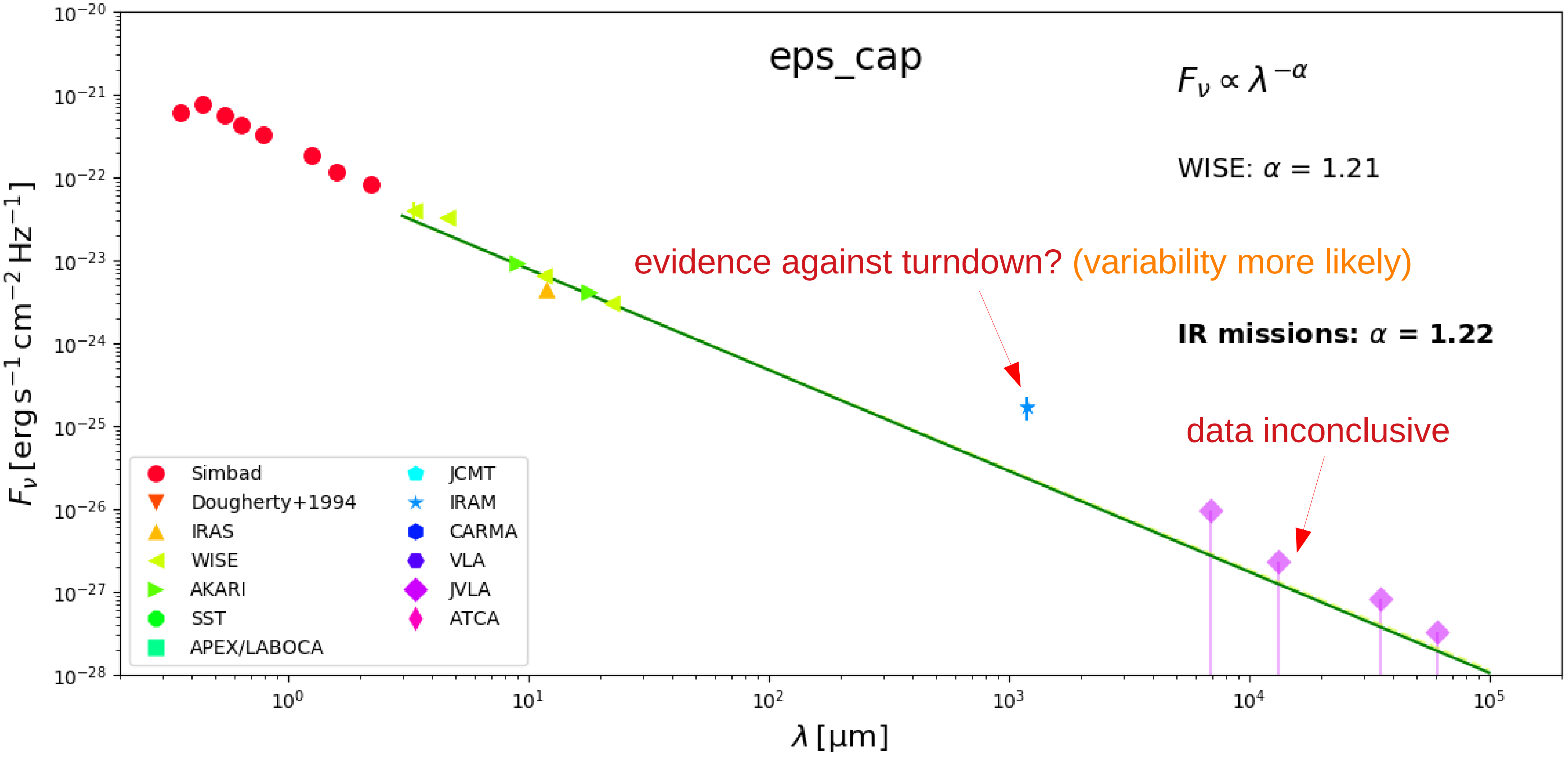
Truncation not sharp – circumbinary disk? (Bratcher+ in prep.)

Outer disks of Be stars probed by radio fluxes – 57 Be stars

- Radio fluxes or upper limits available for 57 Be stars
- **How prevalent is SED turndown among classical Be stars?**
  - $F_\nu \propto \lambda^{-\alpha}$ - extrapolate IR power law to radio, compare **α** in IR and radio if available
  - 21 stars – data inconclusive, however, at least 7 of these are known binaries (e.g. 59 Cyg, 60 Cyg)
  - 5 stars – evidence against SED turndown, however, at least 2 of these are known binaries (e.g. α Eri) – SED variability
  - **31 stars - evidence of SED turndown** (at least 6 known binaries) – for 8 radio SED slope/shape can be recovered thanks to new JVLA data

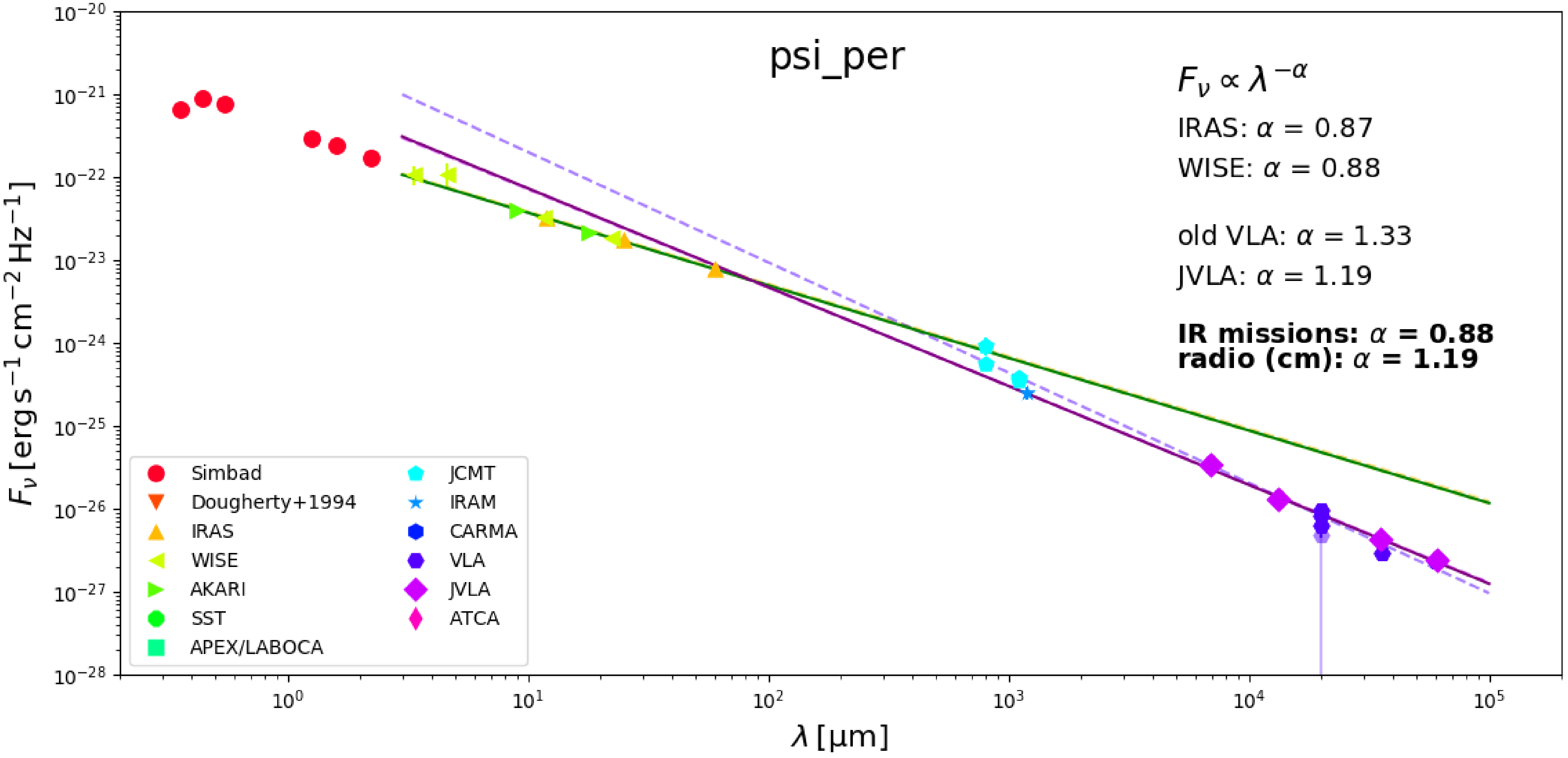
57 Be stars with radio data

example of no turndown



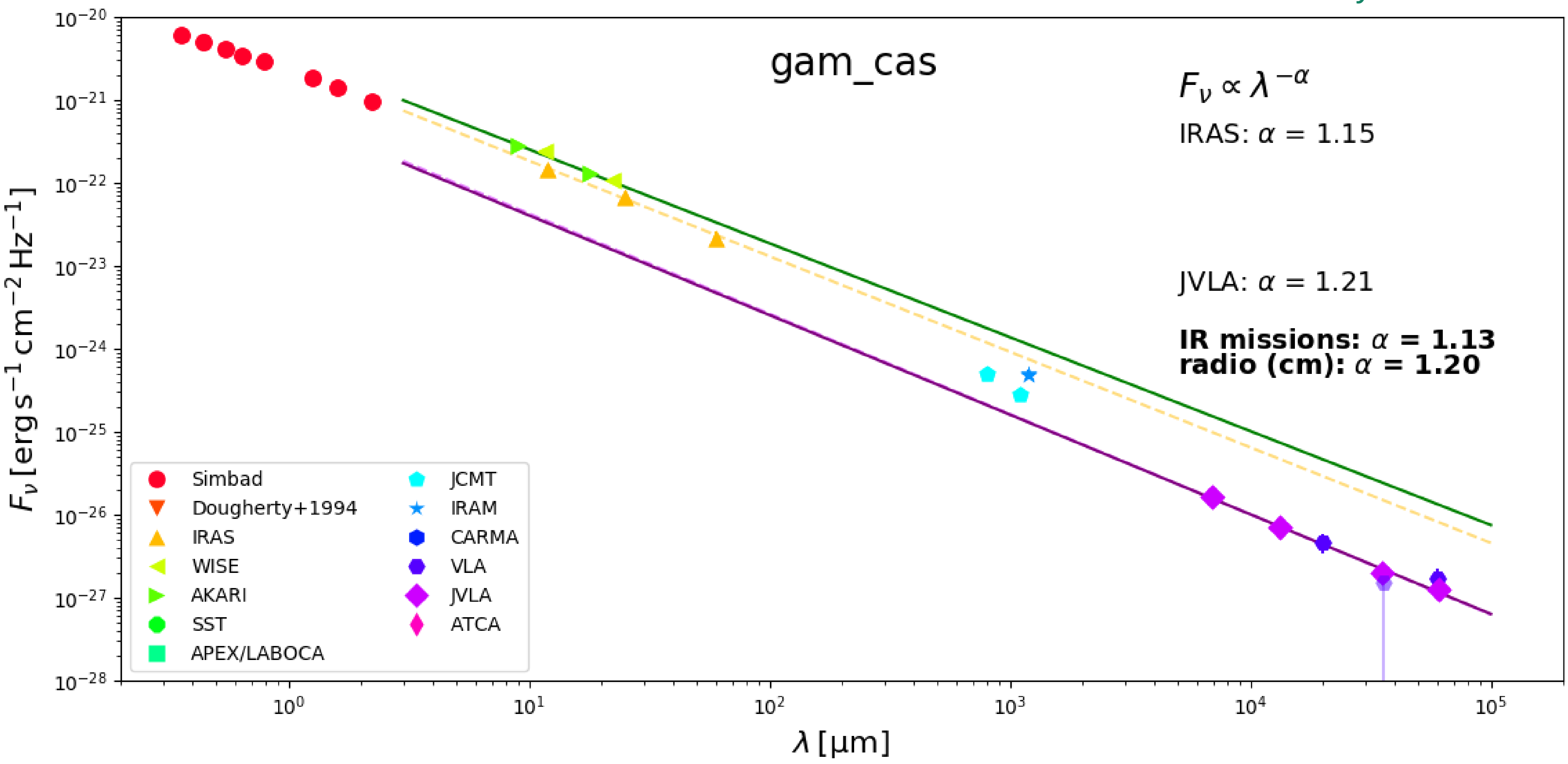
31 Be stars with SED turndown

example of a rich dataset



31 Be stars with SED turndown

example of a rich dataset
-data suggesting
circumbinarity



31 Be stars with SED turndown - all stars