Spatially Resolved Radio/mm Continuum Studies of Red Supergiants

Eamon O'Gorman
Chalmers University of Technology, Sweden

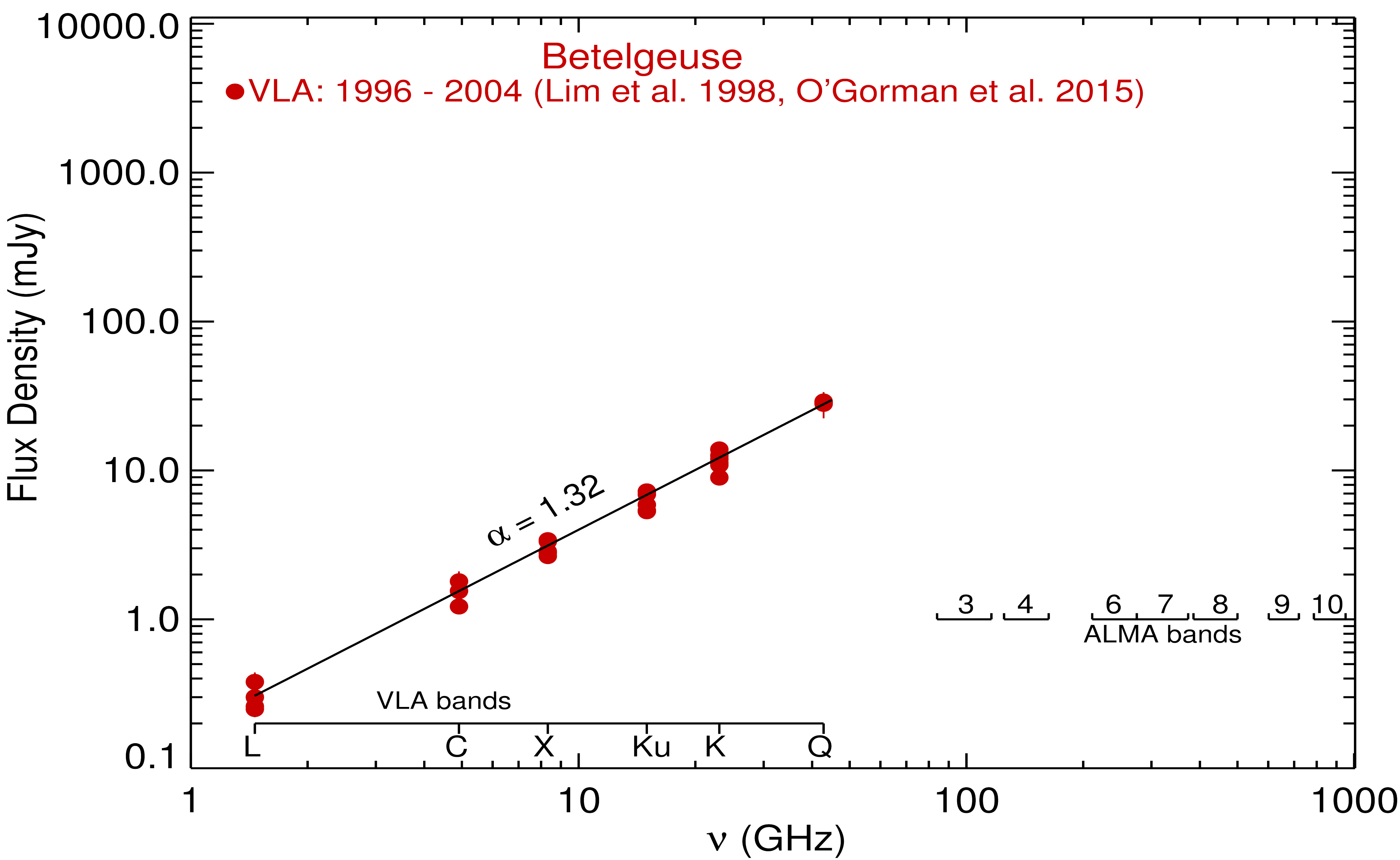
STEPS: ESO Garching, 6-10 July, 2015

W. Vlemmings, G. Harper, A. Richards, et al.

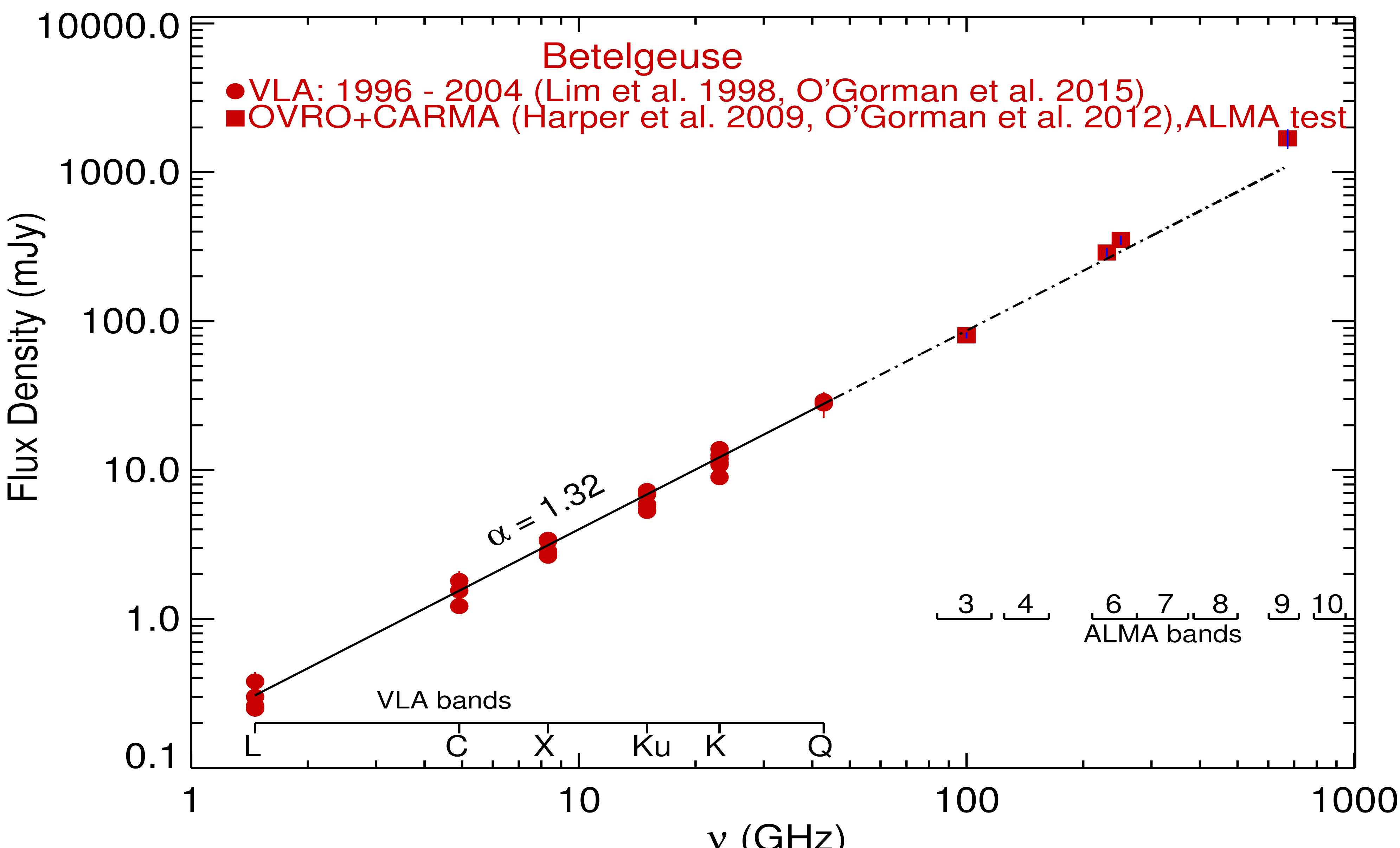
JVLA: Image courtesy of NRAO/AUI and NRAO

ALMA: Image courtesy of ESO

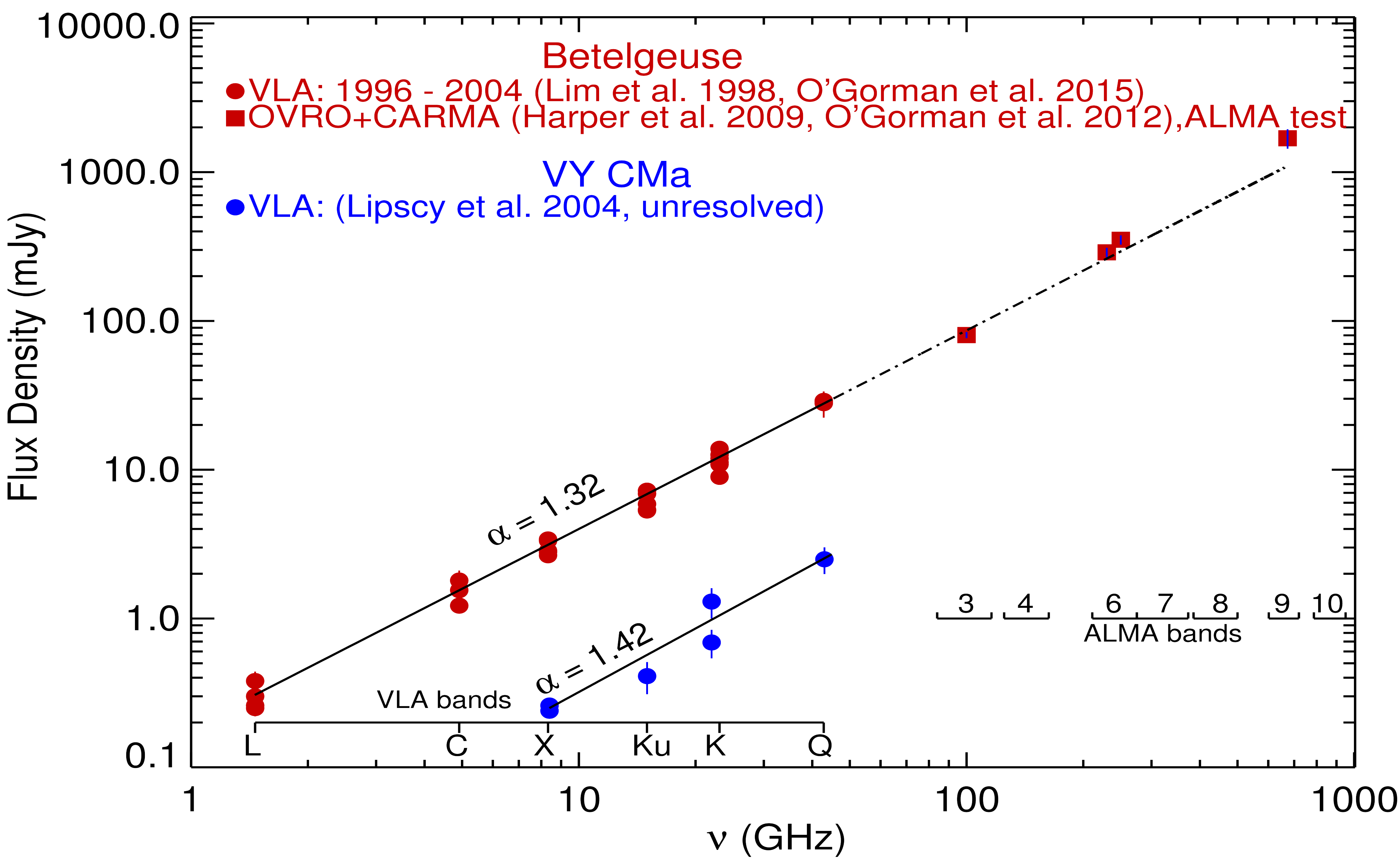
Betelgeuse & VY CMa: Radio/mm/sub-mm SED



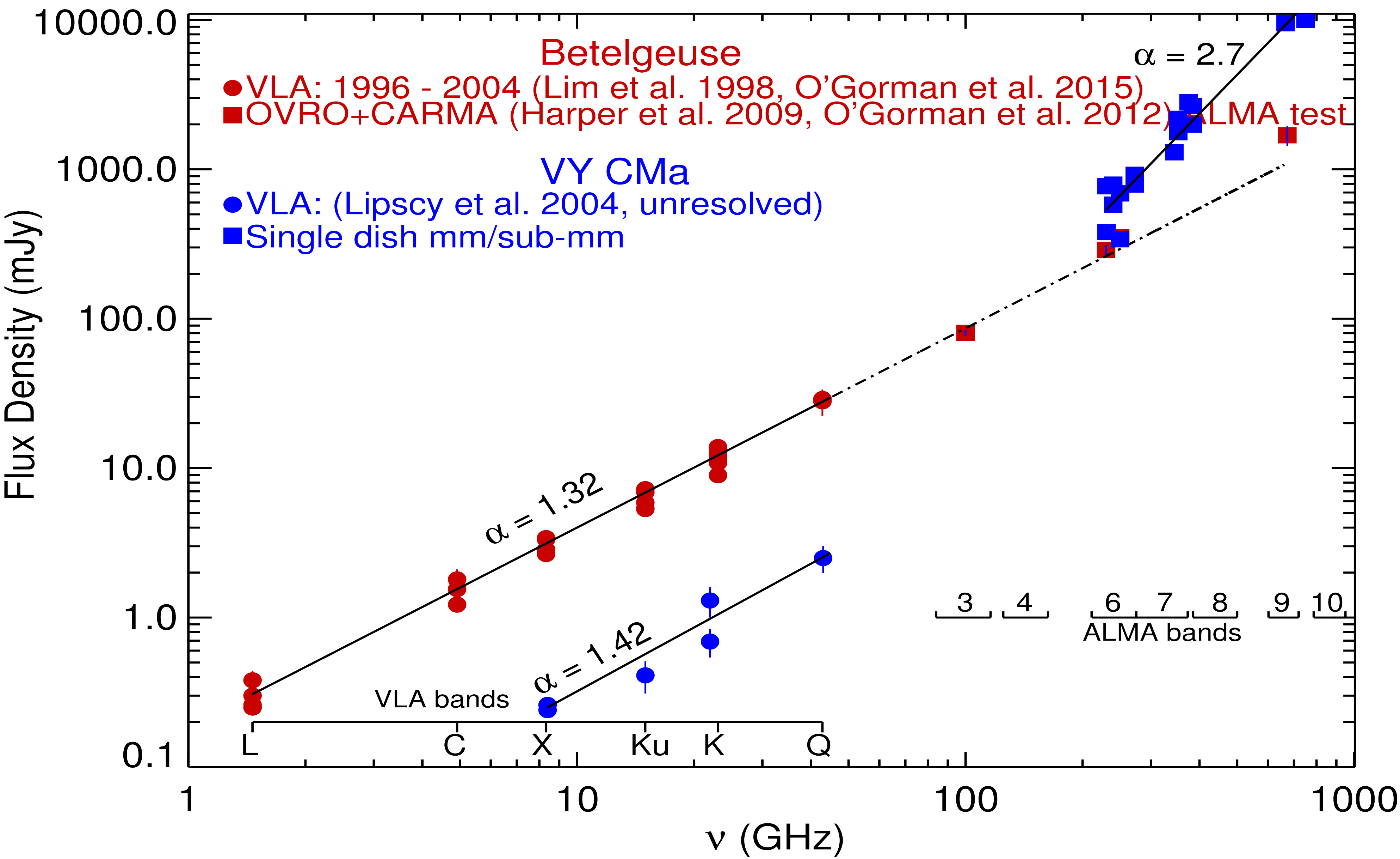
Betelgeuse & VY CMa: Radio/mm/sub-mm SED



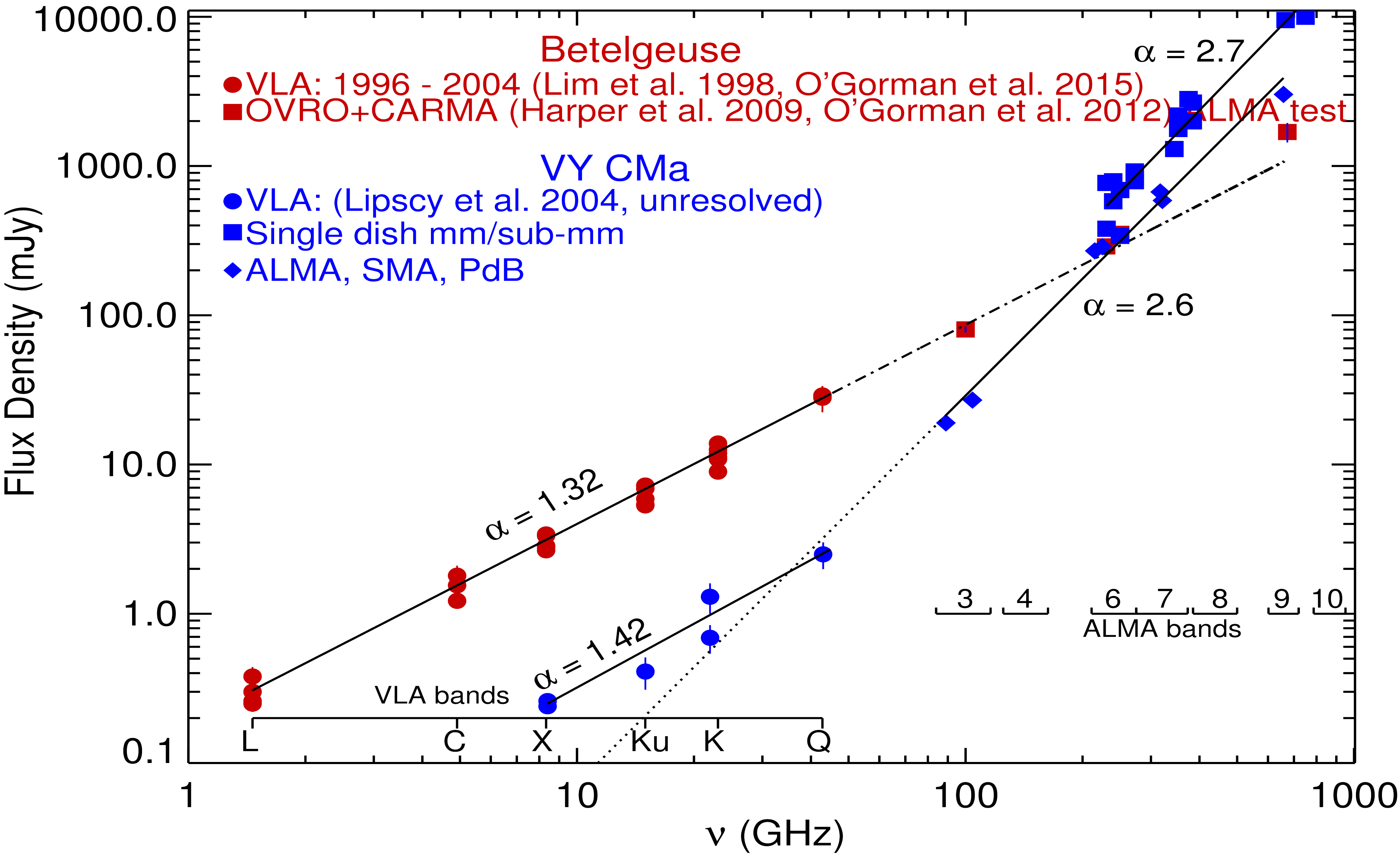
Betelgeuse & VY CMa: Radio/mm/sub-mm SED



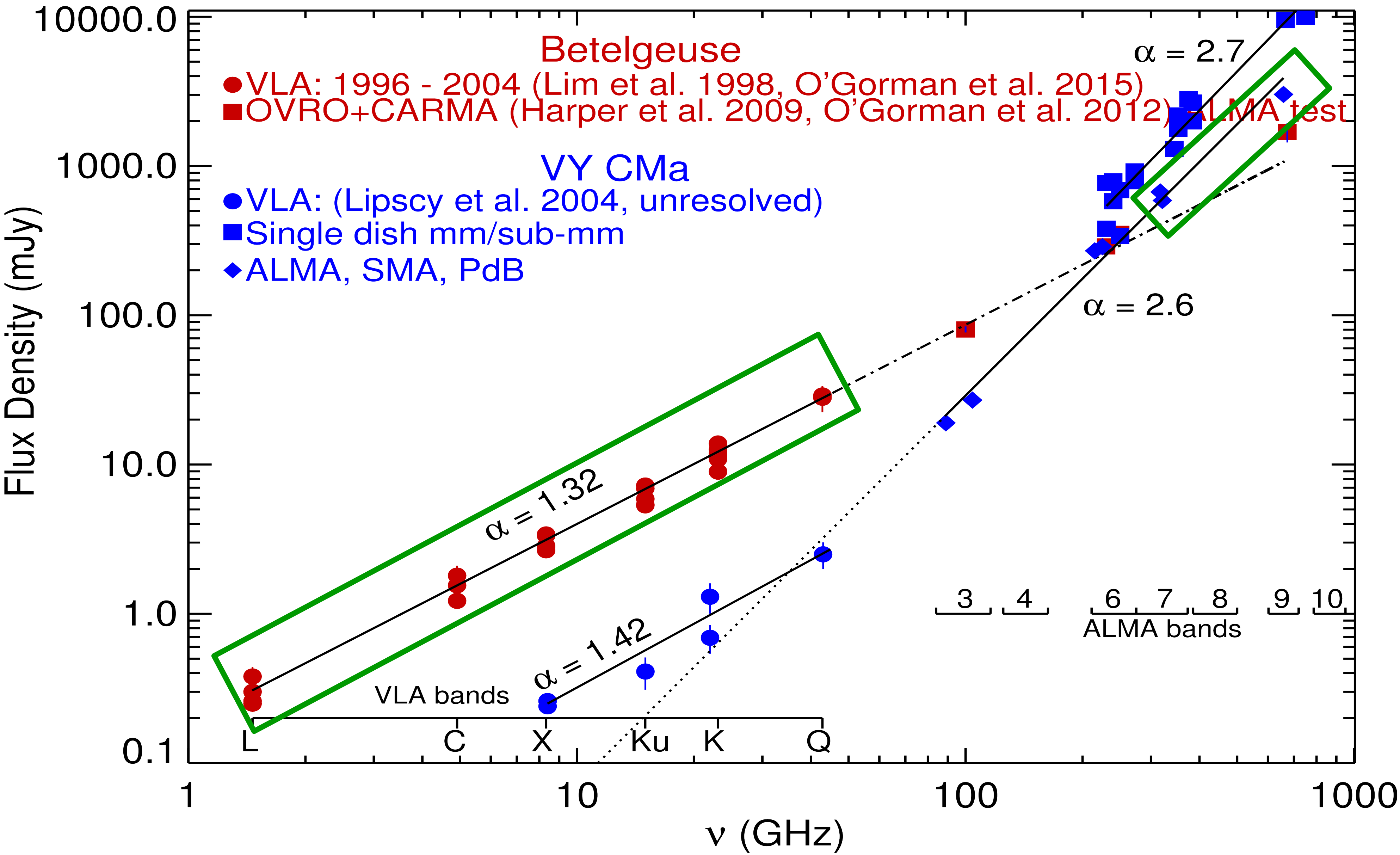
Betelgeuse & VY CMa: Radio/mm/sub-mm SED



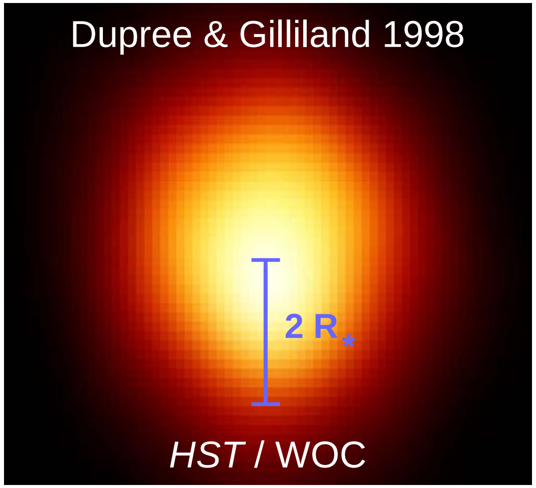
Betelgeuse & VY CMa: Radio/mm/sub-mm SED

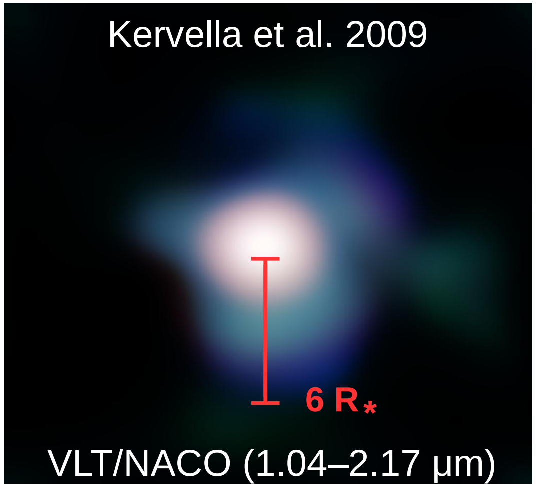


Betelgeuse & VY CMa: Radio/mm/sub-mm SED

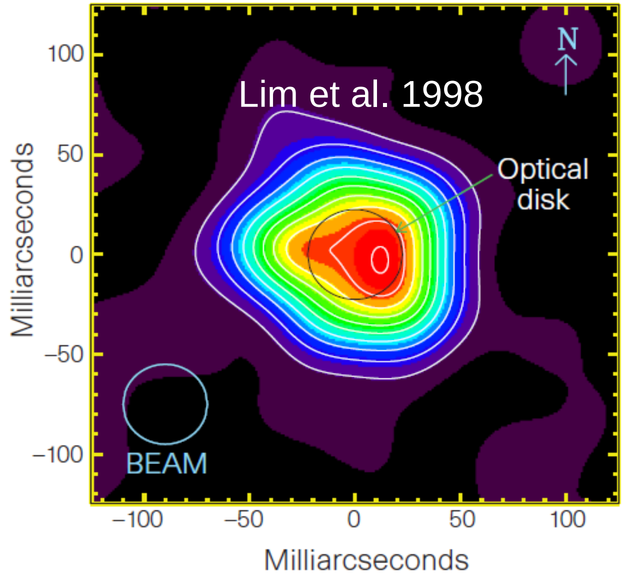


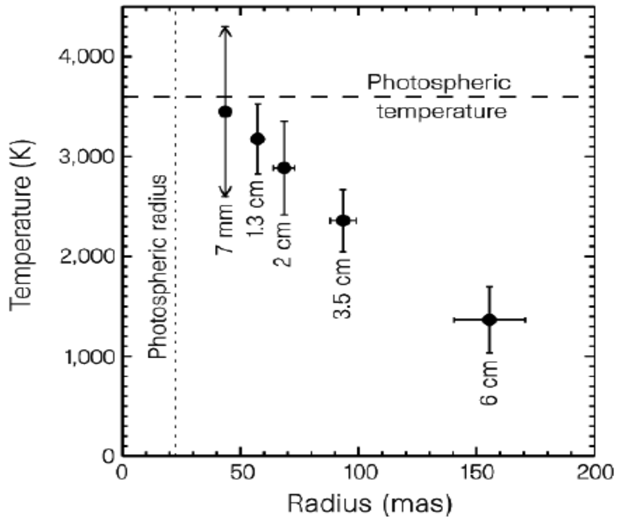
Betelgeuse: Extended atmosphere resolved





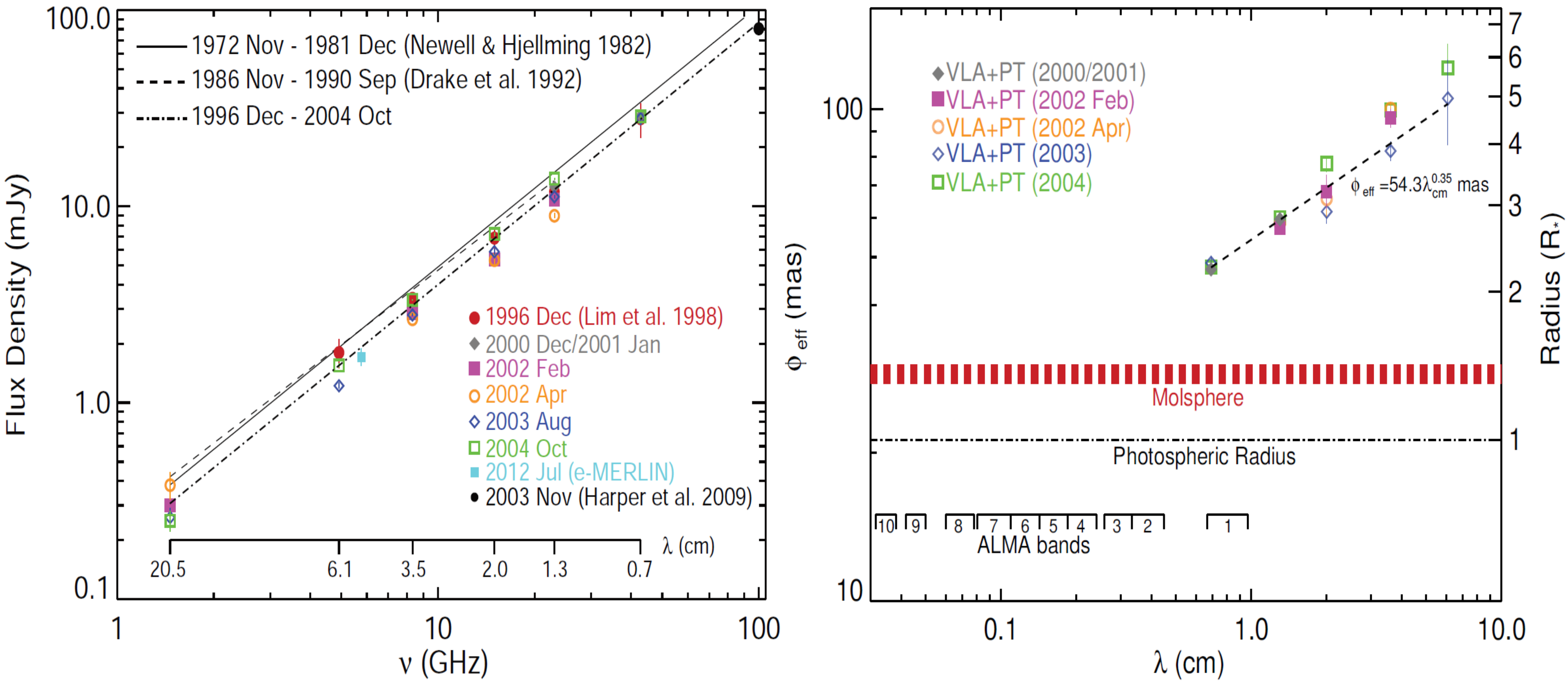
$$S_{\mathrm{mJy}} = \frac{T_{\mathrm{B}}\theta^2_{\mathrm{mas}}}{2.0\lambda^2_{\mathrm{cm}}}$$



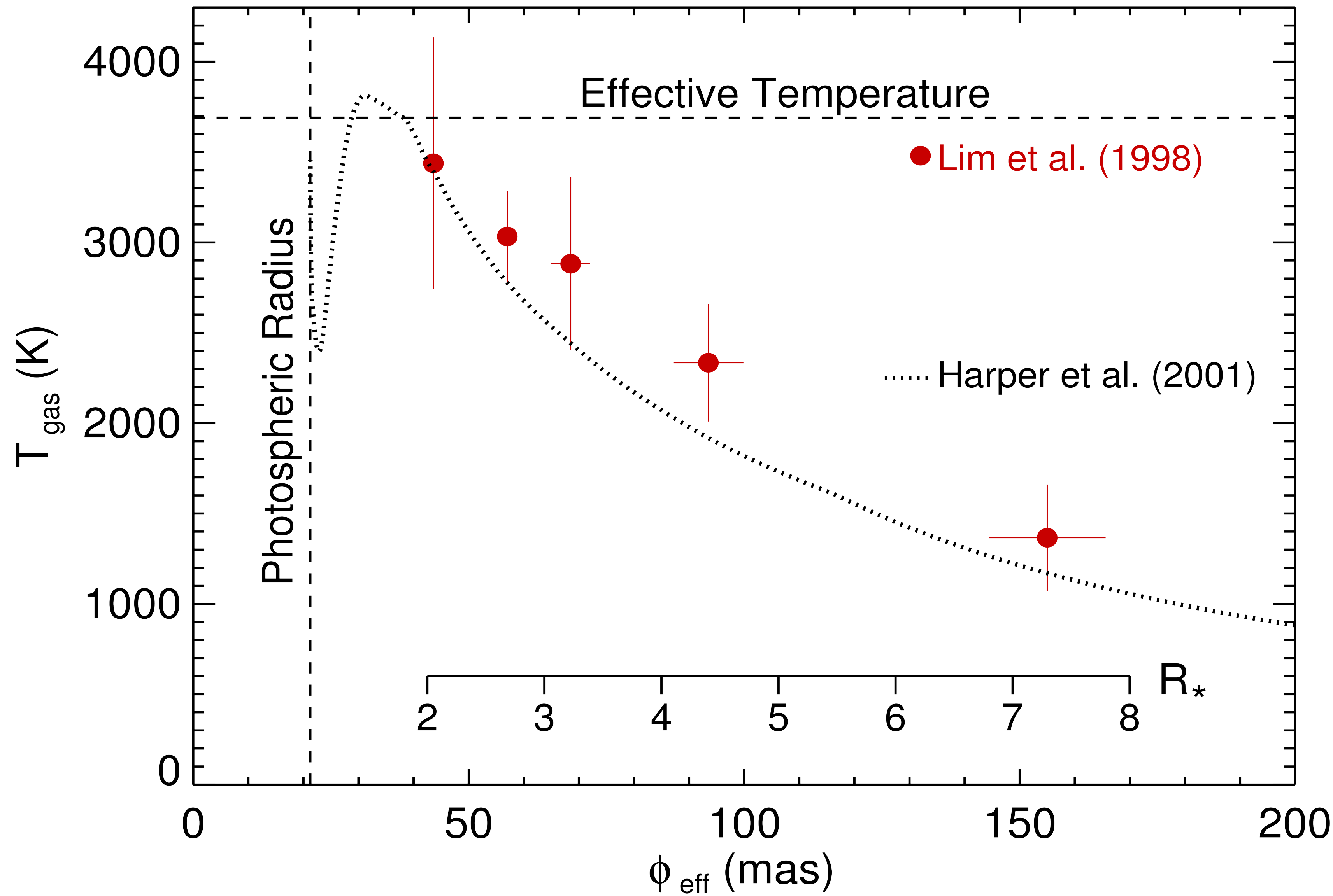


Betelgeuse with VLA + Pie Town

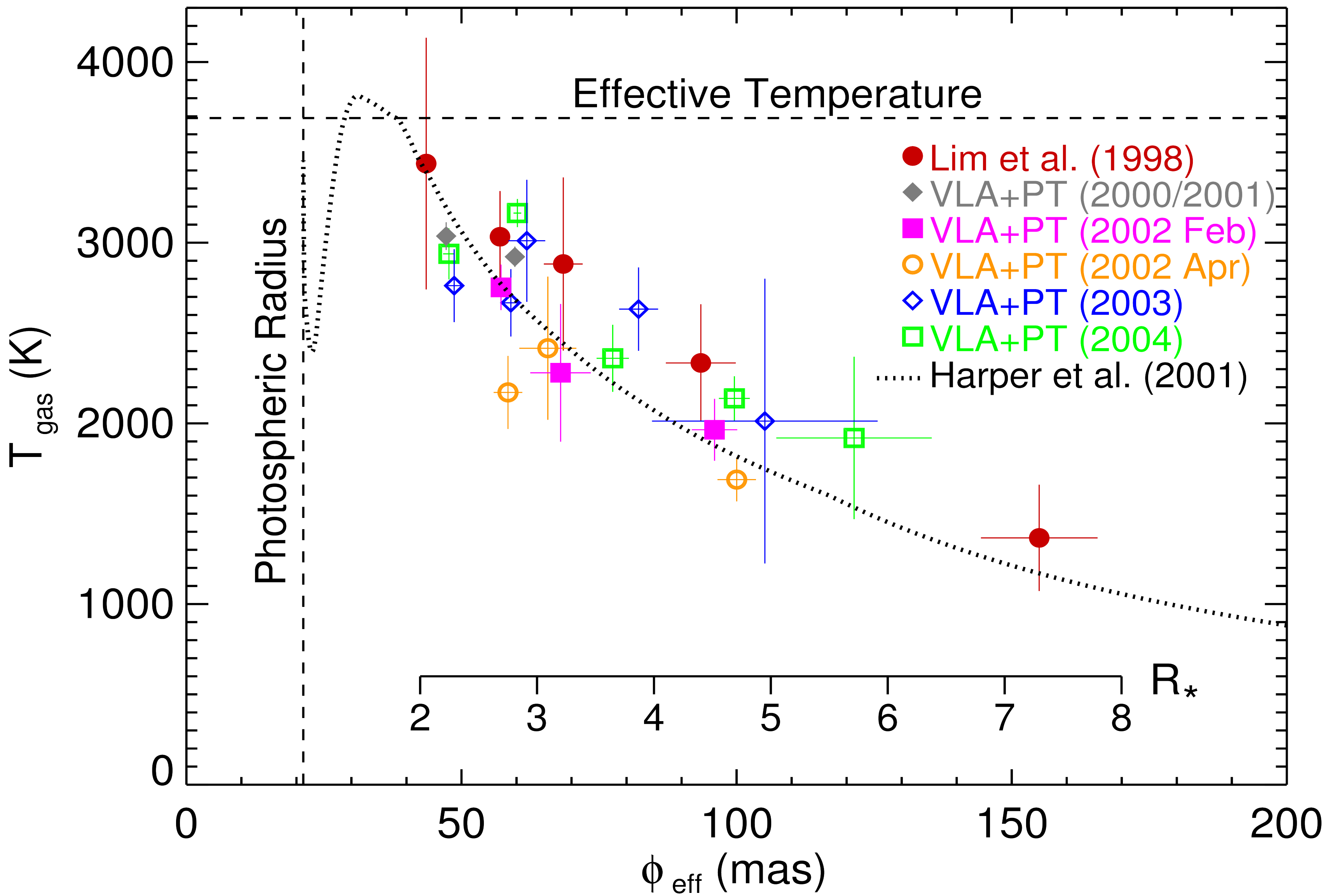
- Observations spanning 2000,2001,2002,2003,2004 – 0.7, 1.3, 2, 6, 20 cm



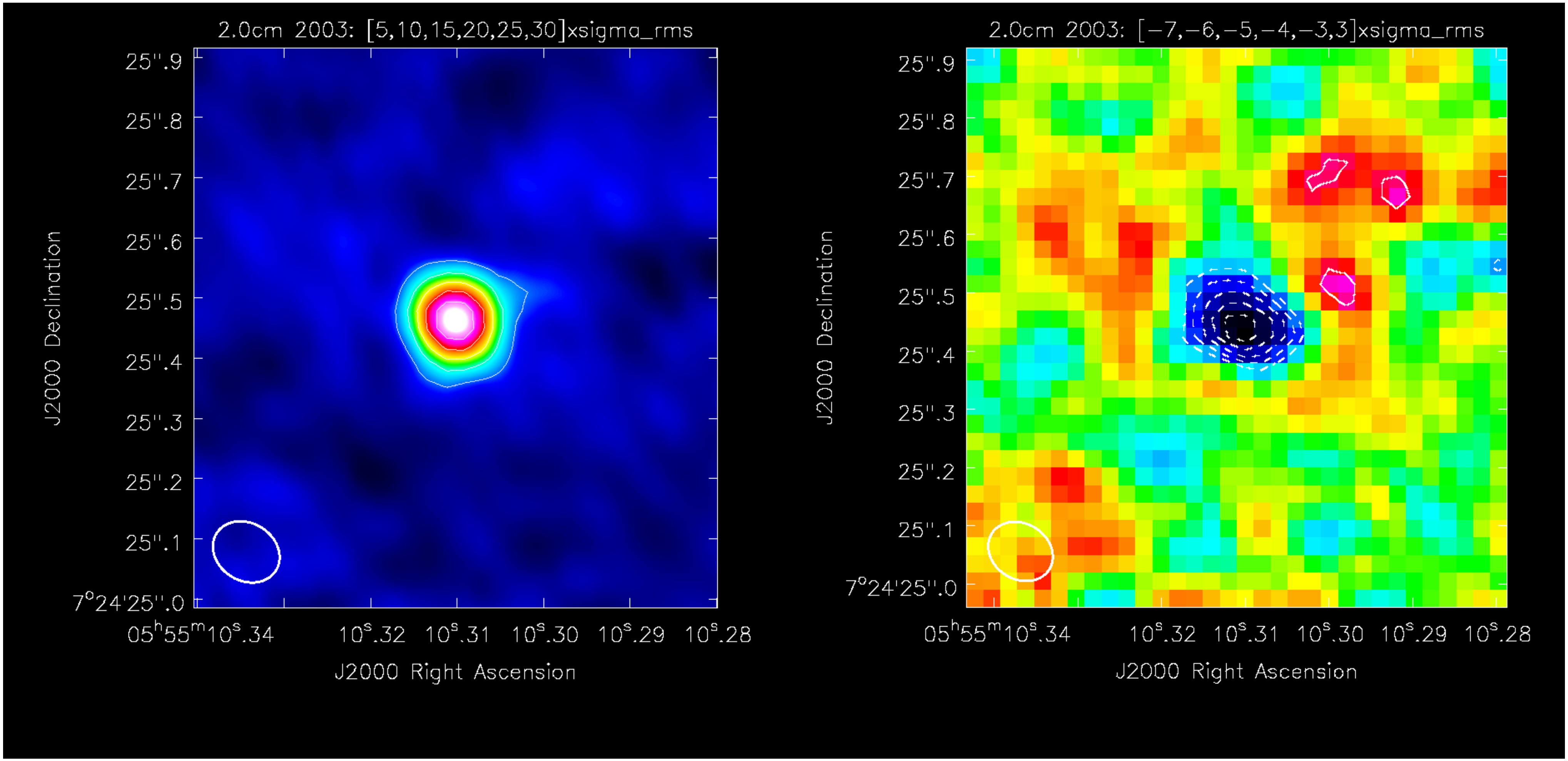
Thermal continuum tomography



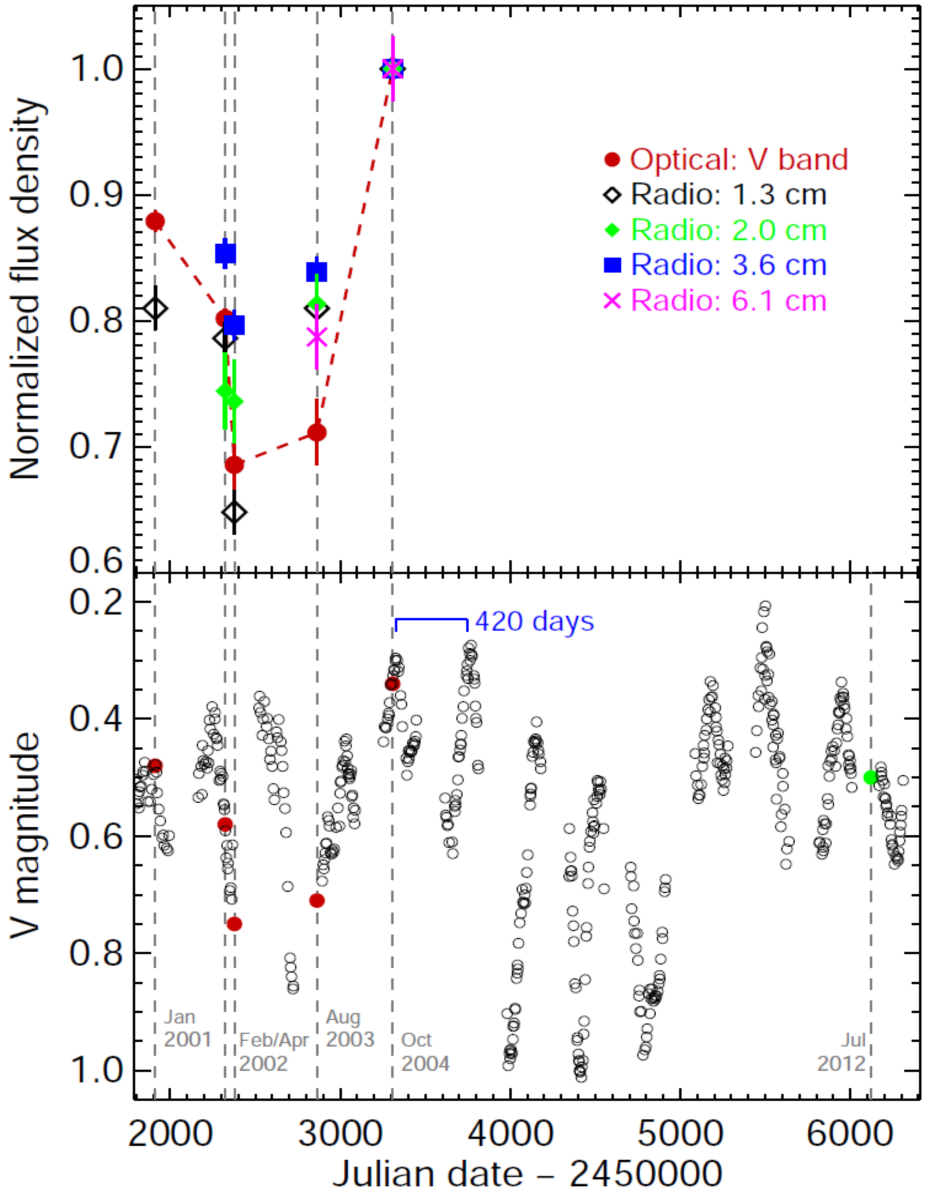
Thermal continuum tomography



Non-uniform brightness



Betelgeuse V band photometry



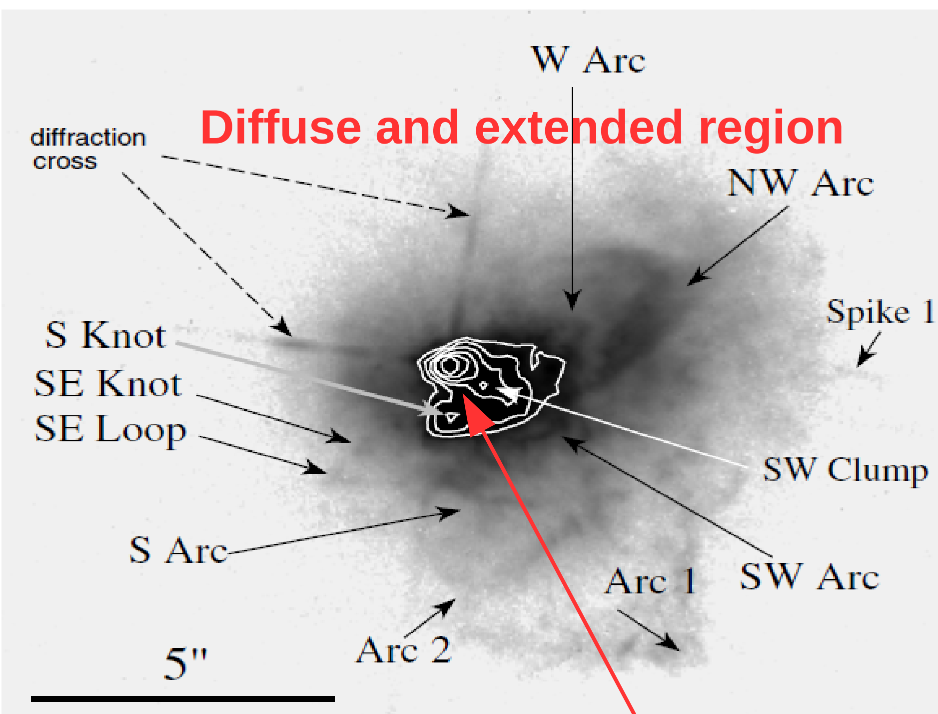
- Two prominent periods (radial velocity and photometry)
  - Secondary period ~2000 days
  - Primary period ~400 days
- Overlaps well with radio data
- Photometry and radio change together
- Pulsation/shocks: source of radio variability

1) Betelgeuse: conclusions from VLA/PT

- Radio continuum emission probes the extended atmosphere between 2 → 6 R_*.
- The global mean temperature of RSGs extended atmospheres are cool (< 3000 K)
- Possible non-uniformities in brightness distribution (cooler features) but no evidence for radio hotspots between 2 → 6 R_*.
- Radio variability associated with pulsation/shocks

2) VY Canis Majoris: Overview

	VY CMa	Alpha Ori
Spectral type	M5e Ia	M2 Iab
d (pc)	1200 ± 100	197 ± 45
Angular diameter (mas)	11	41
dM/dt ($M_{\odot}\,yr^{-1}$)	$3x10^{-4}$	$3x10^{-6}$

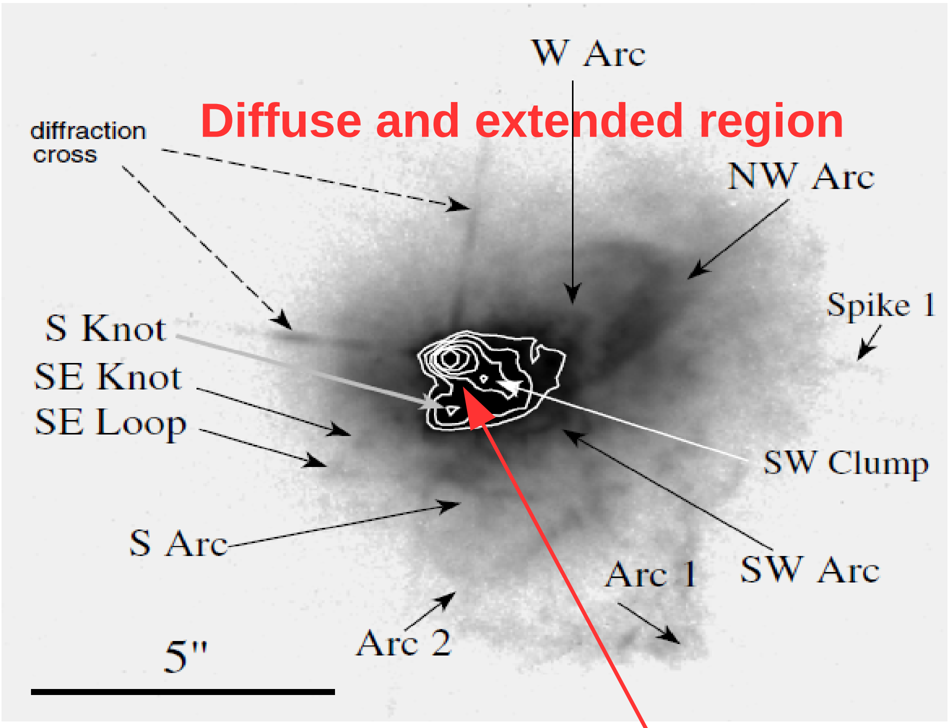


Humphreys et al. (2007)

Dense & dusty core

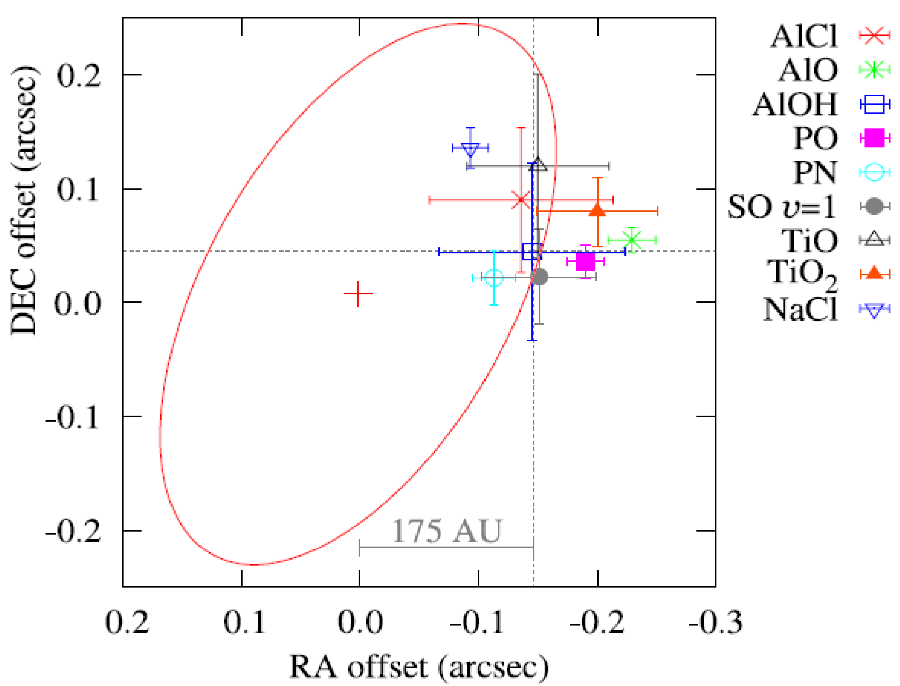
2) VY Canis Majoris: Overview

	VY CMa	Alpha Ori
Spectral type	M5e Ia	M2 Iab
d (pc)	1200 ± 100	197 ± 45
Angular diameter (mas)	11	41
dM/dt ($M_\odot$ yr^{-1})	3×10^{-4}	3×10^{-6}



Humphreys et al. (2007)

Submillimeter Array (SMA): ν ~ 300 GHz,Beam = 0.9"



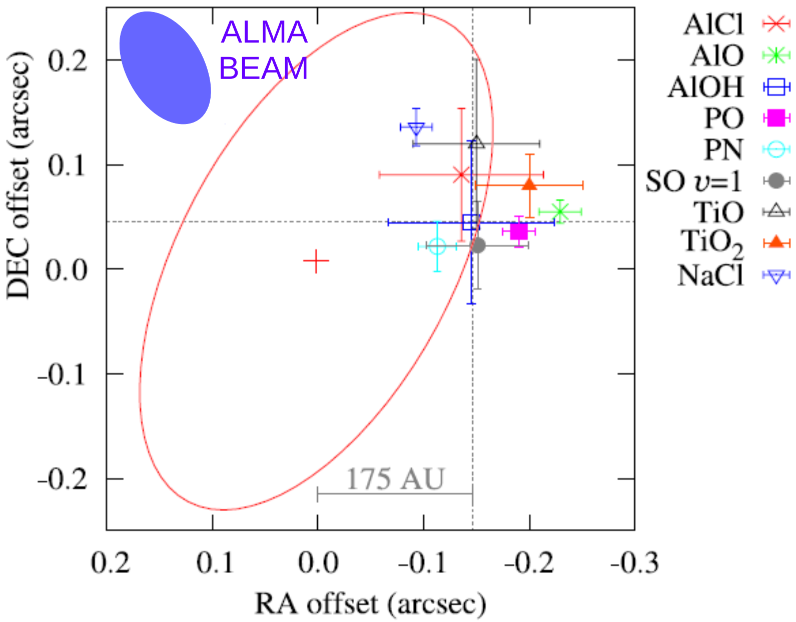
Kaminski et al. (2013)

Observations

- Science Verification, Observed August 2013, Released September 2014
- 16-20 antennas of the main array, Projected baselines ranging from 14m to 2.7 km
- 1.74 GHz line free continuum channels around 321 GHz (Band 7)
- 0.4 GHz at 658 GHz (Band 9)

Table 1. ALMA continuum observations of VY CMa.

ν (GHz)	Synthesized Beam ($'' \times ''$, PA)	rms noise (mJy beam^{-1})	MRS ($''$)	Total S_ν (mJy)
321	0.229×0.129, 28°	0.6	8.3	587
658	0.110×0.059, 30°	6	4.0	3017



Initial Results

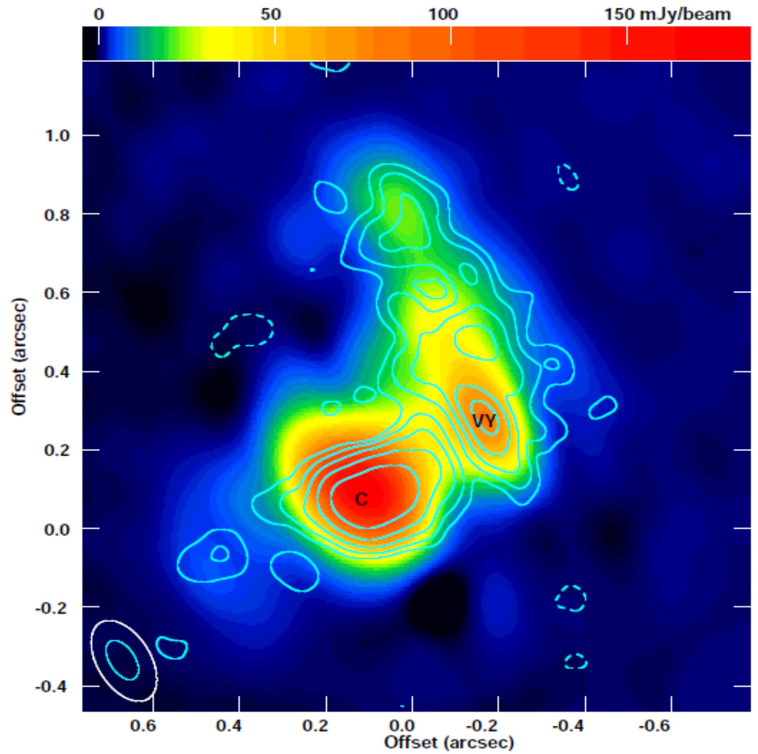


Fig. 1. Continuum emission: 321-GHz colour scale, 658-GHz contours at (–1,1,2,4,8,16)×10 mJy beam^{-1}. Synthesized beams shown at lower left for 321 GHz (white), 658 GHz (blue). (0, 0) at R.A. 07 22 58.33454 Dec. –25 46 03.3275 (J2000). **C** marks the continuum peak. **VY** is identified as the star, at the centre of water maser expansion.

Richards et al., 2014

Initial Results

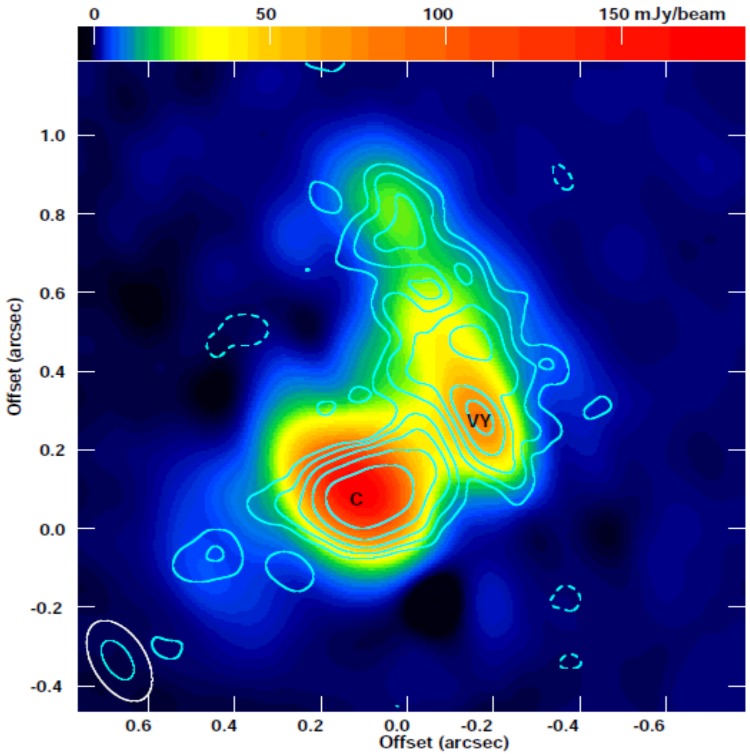
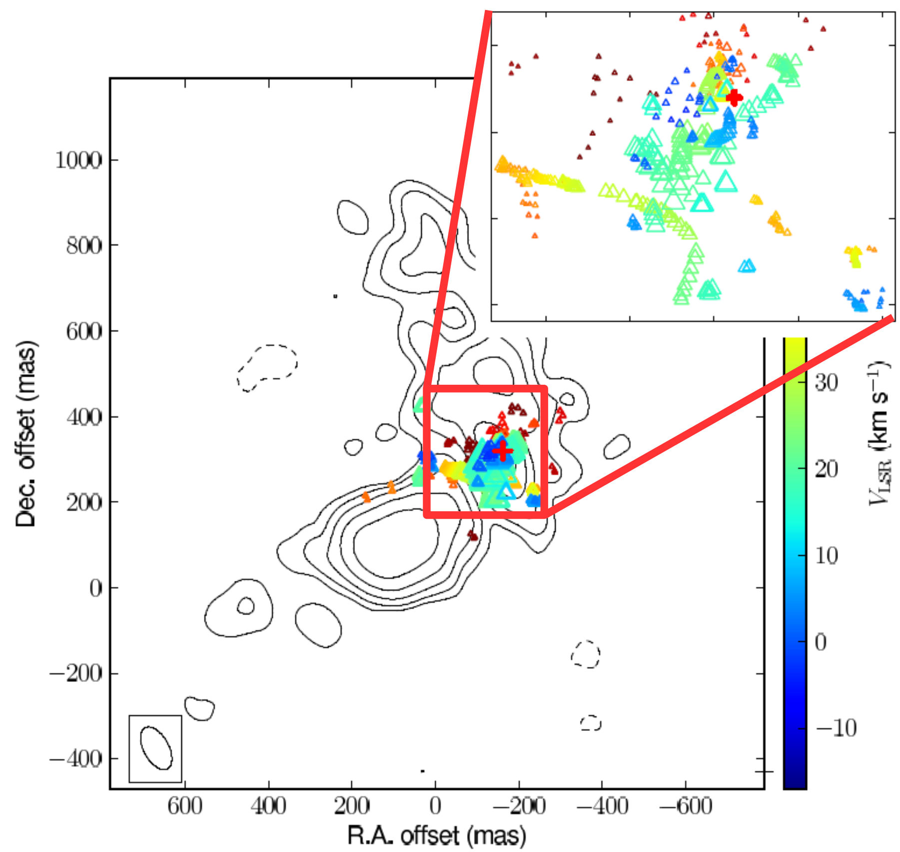
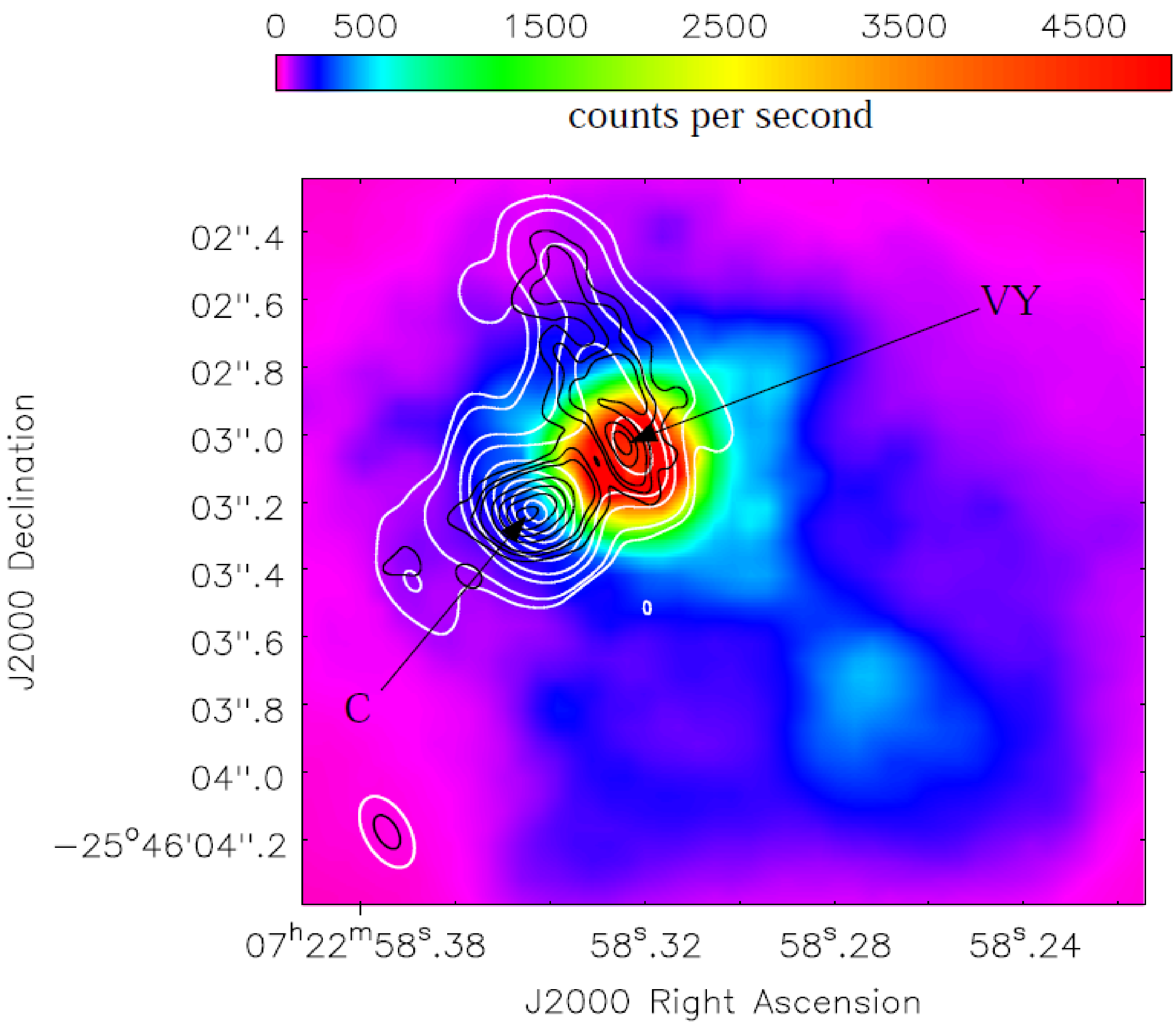


Fig. 1. Continuum emission: 321-GHz colour scale, 658-GHz contours at (–1,1,2,4,8,16)×10 mJy beam^{-1}. Synthesized beams shown at lower left for 321 GHz (white), 658 GHz (blue). (0, 0) at R.A. 07 22 58.33454 Dec. –25 46 03.3275 (J2000). **C** marks the continuum peak. **VY** is identified as the star, at the centre of water maser expansion.



Richards et al., 2014

ALMA vs *HST*



- SW *HST* feature not apparent
- VY and C components resolved at both frequencies

<u>C component</u>

- 321 and 658 GHz: 35 R_* x 20 R_*

<u>VY component</u>

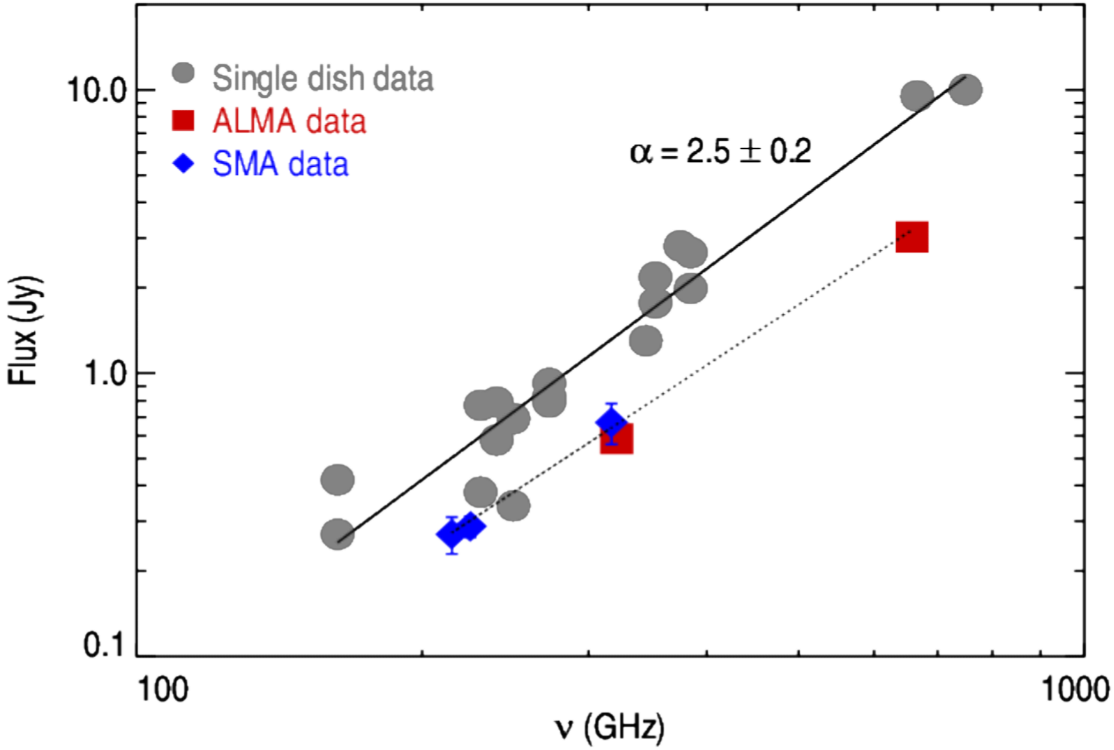
- 321 GHz: 40 R_* x 26 R_*
- 658 GHz: 27 R_* x 13 R_*

Spectral Index

$$S_\nu \propto \nu^\alpha$$ Spectral index

$$\alpha = 2 + \beta$$ Dust emissivity Spectral index

- ISM: α = 3.8 ± 0.2
- VY CMa: α = 2.0 → 3.0



Spectral Index

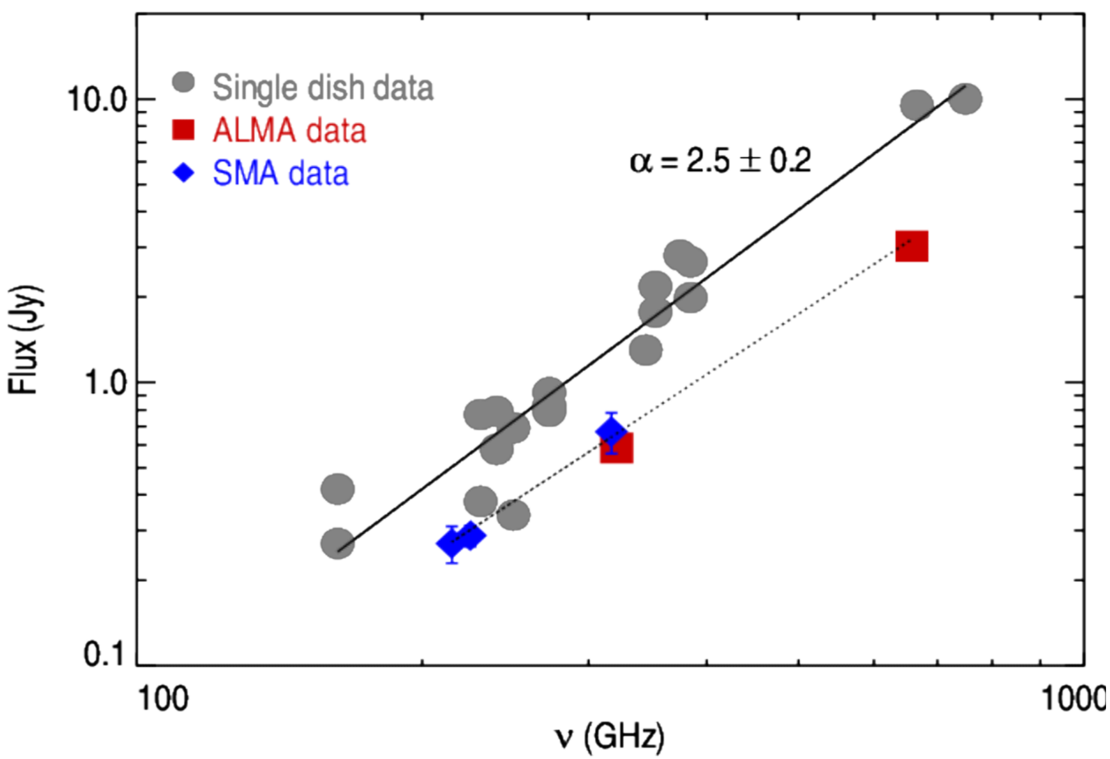
$$S_\nu \propto \nu^\alpha$$

Spectral index

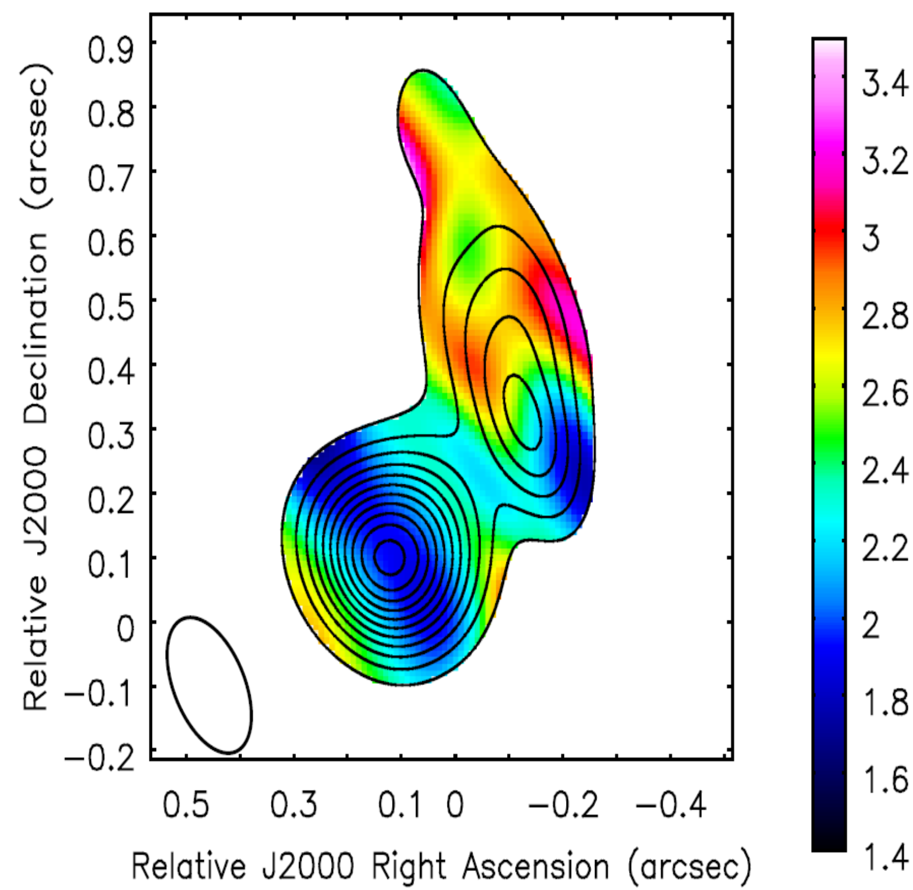
$$\alpha = 2 + \beta$$

Dust emissivity Spectral index

- ISM: $\alpha = 3.8 \pm 0.2$
- VY CMa: $\alpha = 2.0 \rightarrow 3.0$



Spectral index map



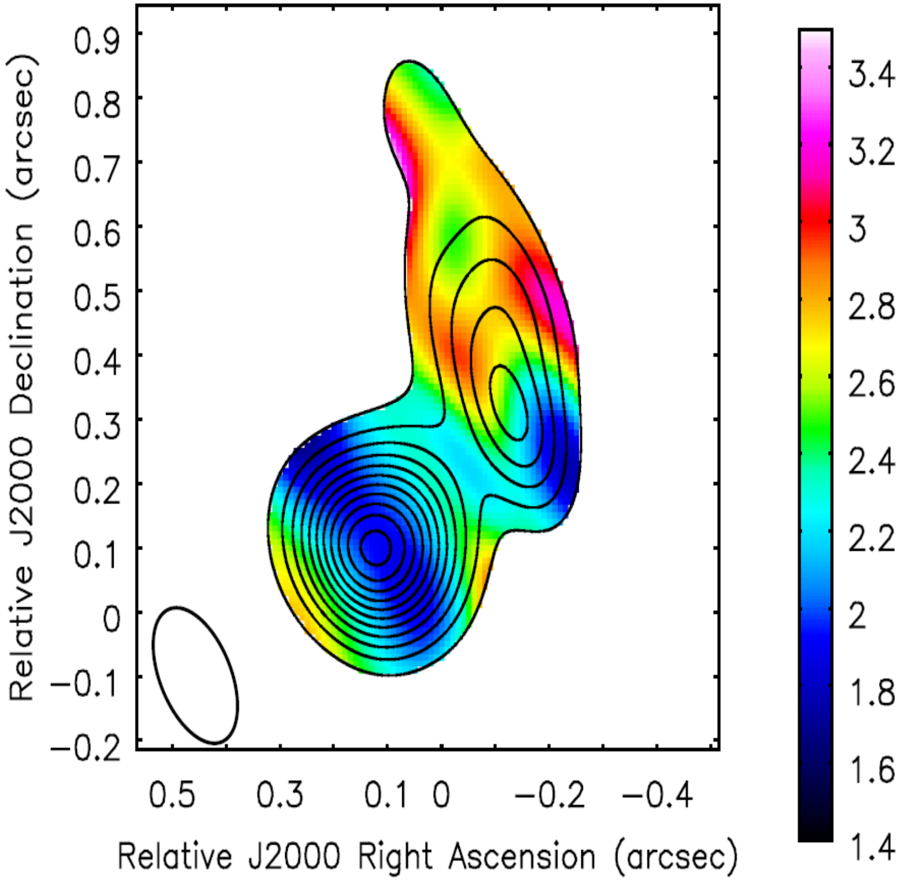
Dust Properties

	T_d (K)	M_d ($M_\odot$)
C	< 450 (T_d=200 K)	> 3 x 10^{-4}
VY	1000	3 x 10^{-5}

- At least 17% of dust mass in clumps ejected within a more quiescent stellar wind

- <u>C component:</u>
Low temperature and high optical depth → low excitation and/or freeze-out of thermal molecular lines

Spectral index map



2) VY CMa: conclusions from ALMA

- Most detailed view of thermal dust emission around a RSG
- Continuum emission allows derivation of dust properties (temperature, mass, density)
- Directed dust mass-loss over a few decades. Localized but much more stable over time.

2) VY CMa: conclusions from ALMA

- Most detailed view of thermal dust emission around a RSG
- Continuum emission allows derivation of dust properties (temperature, mass, density)
- Directed dust mass-loss over a few decades. Localized but much more stable over time.

Spatially resolved continuum observations with ALMA, JVLA, e-MERLIN are powerful tools to study evolved stars.