30-micron observations of circumstellar dust around Luminous Blue Variables

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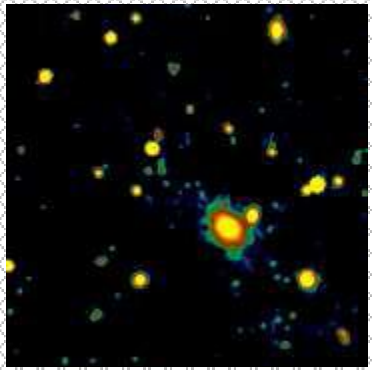
Dust formation on Massive Stars

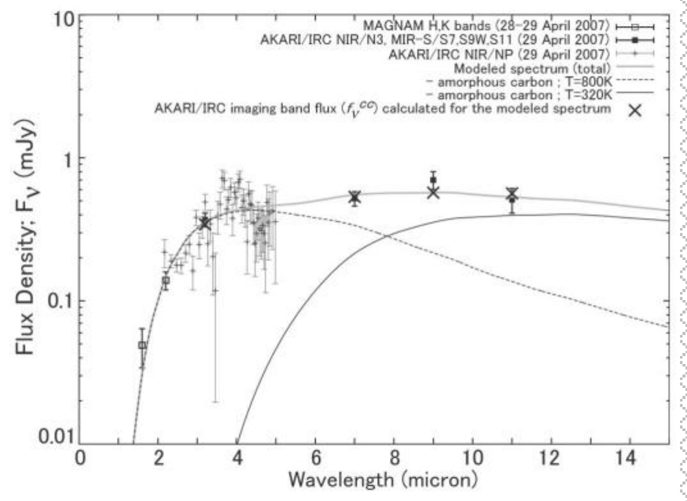
- Dust at high-z galaxies
  - z~6 (age: ~1Gyr); 10^8-$10^9 M_{sun}$ dust
  - Massive stars will be primary dust suppliers



QSO SDSS J1148+5251
(Bertoldi et al. 2003)

- When do massive stars form dust?
  - Prior to the SN explosion
  - In the SN ejecta

- SN2006jc
  - $7\times10^{-5} M_{sun}$@800K+$3\times10^{-3} M_{sun}$@320K
  - Pre-existing dust is dominant



(Sakon et al. 2009)

dust formation on massive mass-losing stars is important but little known

Massive stars' life

- Varying with changes in initial masses
- mass-losing phase duration: ~10^4-10^5year

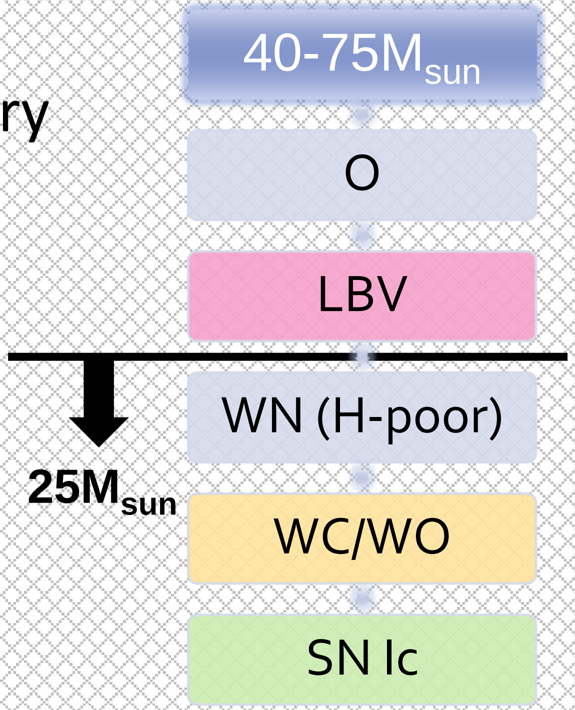
$>75M_{sun}$	$40\text{-}75M_{sun}$	$25\text{-}40M_{sun}$
O	O	O
WN (H-rich)	LBV	LBV/RSG
LBV	WN (H-poor)	WN (H-poor)
WN (H-poor)	WC/WO	SN Ib
WC/WO	SN Ic	
SN Ic		

Wolf-Rayet Stars

(Smartt, 2009)

Luminous Blue Variables

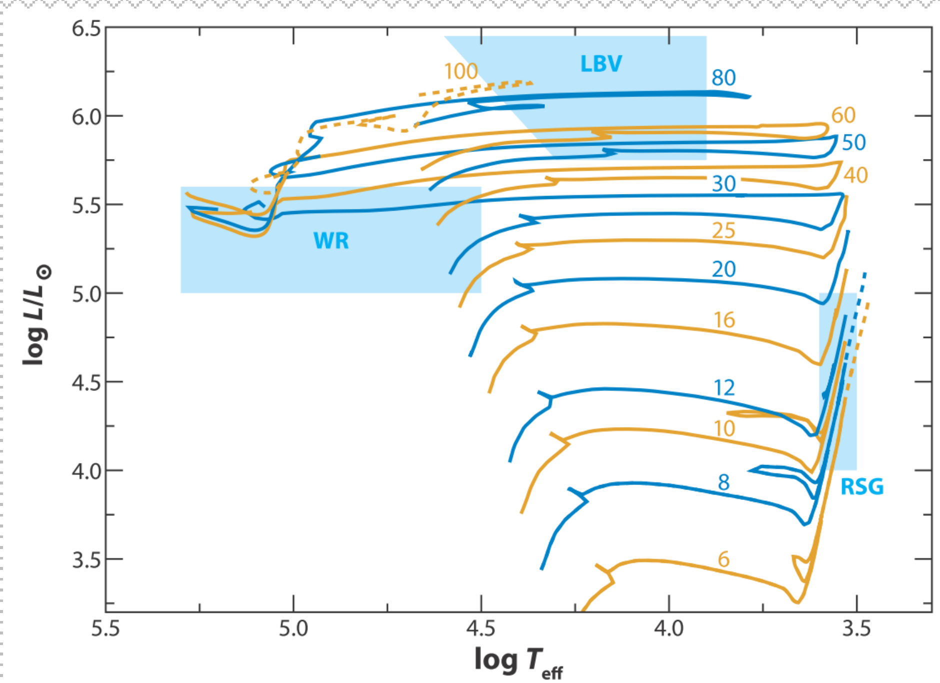
- The LBV phase is considered to be a primary mass loss phase of very massive stars.
  - observed (H-poor) WR stars have the mass of no more than $25M_{sun}$

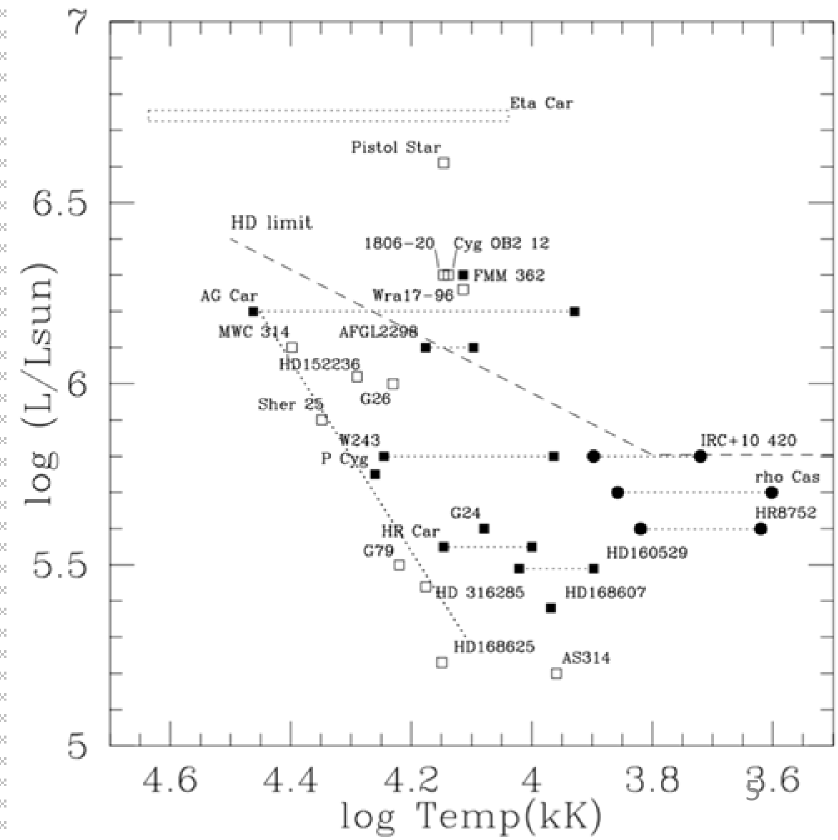


- Continuum-driven wind (Owocki et al. 2003)
  - Mass-loss rate : ~10^{-3} Msun/yr
  - Exceeding "Eddington-limit"
  - Independent of stellar metalicity

Luminous Blue Variables

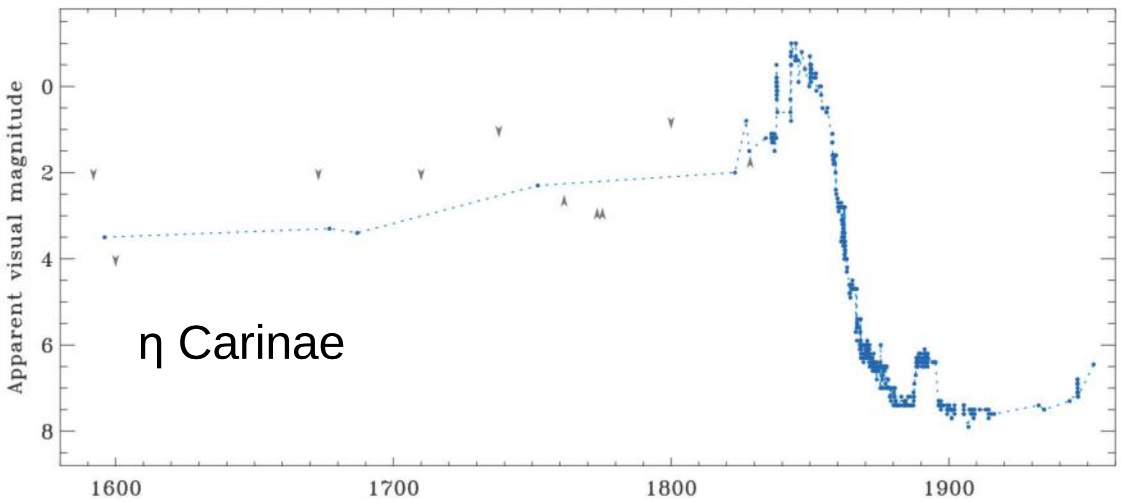
- Evolved, massive stars (initial mass: >30M_{sun})
- Luminous (~10^6 L_{sun}) and high mass-loss rate (~$10^{-3}M_{sun}$/yr)
- Very rare: 12 LBVs and 23 LBV candidates in our Galaxy (Clark+, 2003)

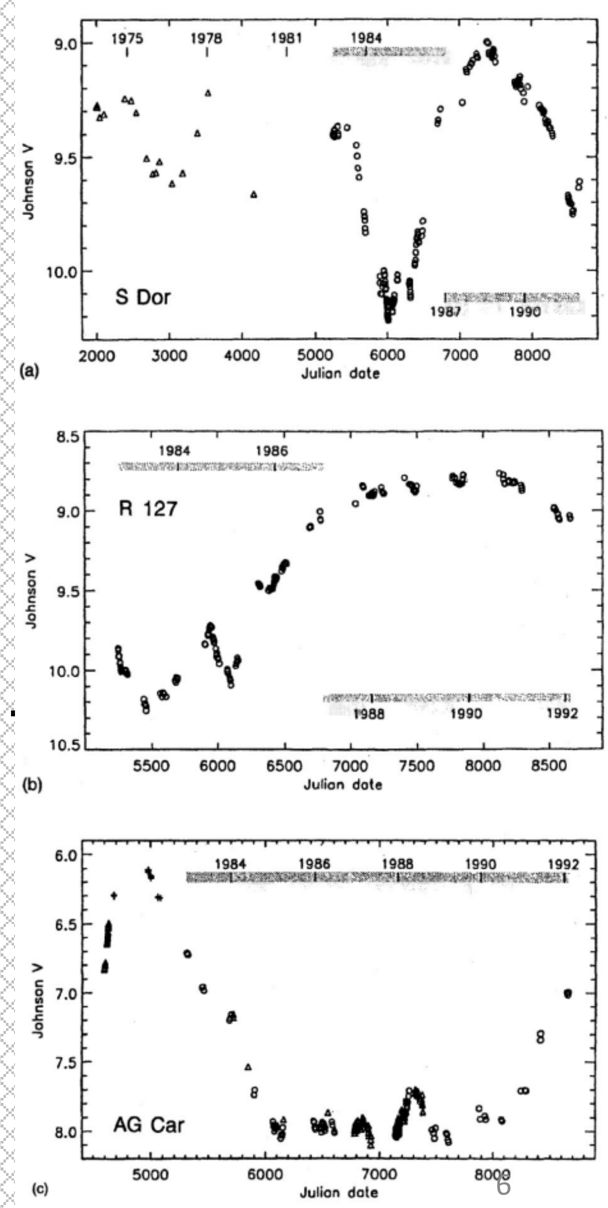




LBV variability

- Giant eruption
  - Variation of > 2 mag
  - Observed two times in the Galaxy （η Carinae, P Cygni）
- Eruption: variation of 1-2 mag
  - Timescale: ~10-40 years
- The origin of variation is still unknown
  - instability of stars, binary system, etc…



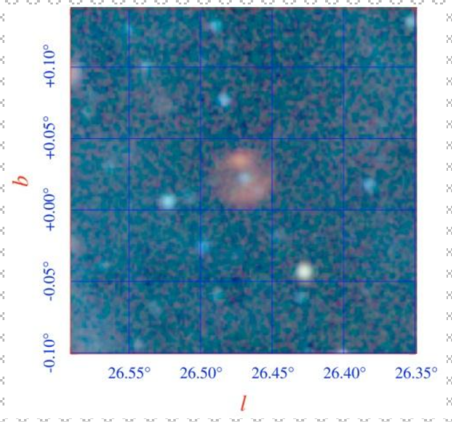


Dust formation in LBVs

- Many LBVs are associated with circumstellar dust
- The estimated amount of dust mass: ~0.01--0.1M_{sun}
  - Much larger than the other types of massive stars (WR, RSG, etc…)

Star	$\log(L/L_\odot)$	R_{neb} (pc)	M_{dust} ($M_\odot$)	M_{gas} ($M_\odot$)
η Car[a,b]	6.7	0.1	0.15	3–15
AG Car[c]	6.25	0.36→0.80	0.22	8.9
HR Car[d,e,f]	5.7	0.26	$<8\times10^{-4}$	0.8–2.1
Hen 3-519[g]	5.7	1.14	0.007	2.0
Wra 751[c]	5.7	0.17→0.34	0.017	1.7
HD 168625[1,h,i]	5.6	0.21 × 0.24	0.016	2.1
P Cyg[j,k]	5.8	0.4	0	0.01
AFGL 2298[l,m]	6.2	0.12→0.72	0.1	*10*
R 127[j,n]	6.1	1.05 × 0.8	–	10 ± 2
S 119[j,n]	6.0	1.0 × 0.9	–	2.6 ± 0.7
R 71[o]	5.85	0.12→0.18	0.02	*2*
Pistol Star[p,q]	6.6	1.5	0.004	11
G25.5+0.2[2,r,s,t]	>5.9	0.4 × 0.6	>0.06	5.4
S 61[j,u]	6.1	0.7 × 0.65	–	14 ± 3
G79.49+0.26[v,w]	5.5	0.8→3.6	0.15	15
Wra 17-96[x]	6.26	0.7→2.2	0.1	*10*
G24.73+0.69	5.6	0.7→1.7	0.0045	*0.45*
G26.47+0.02	6.0	1.4→2.4	0.019	*1.9*

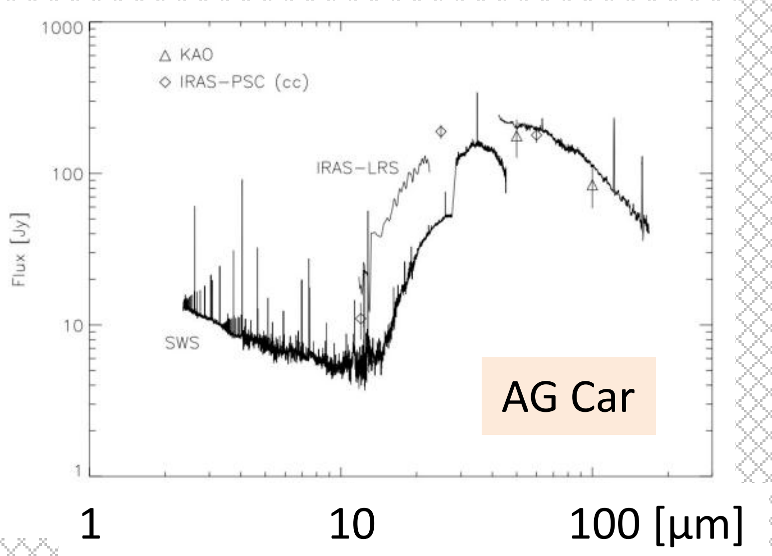
G26.47+0.02 (MSX)

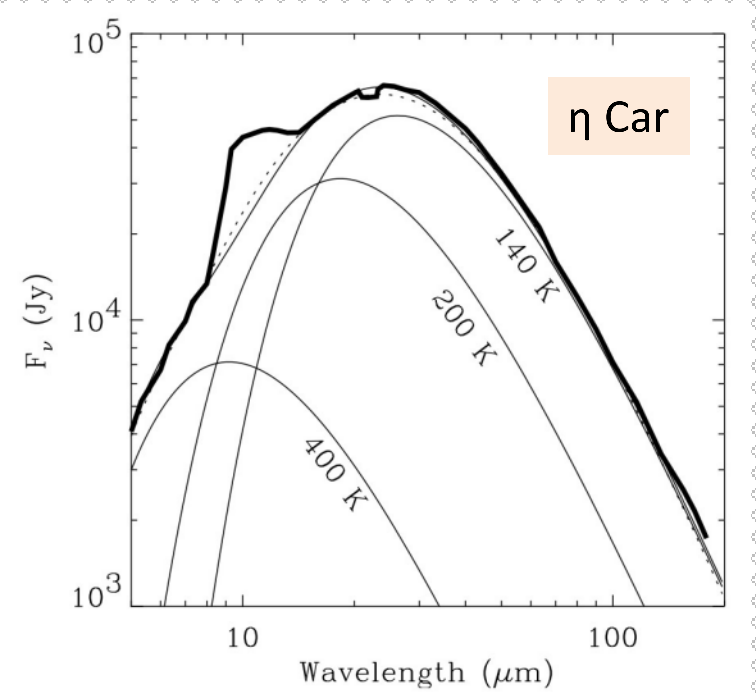


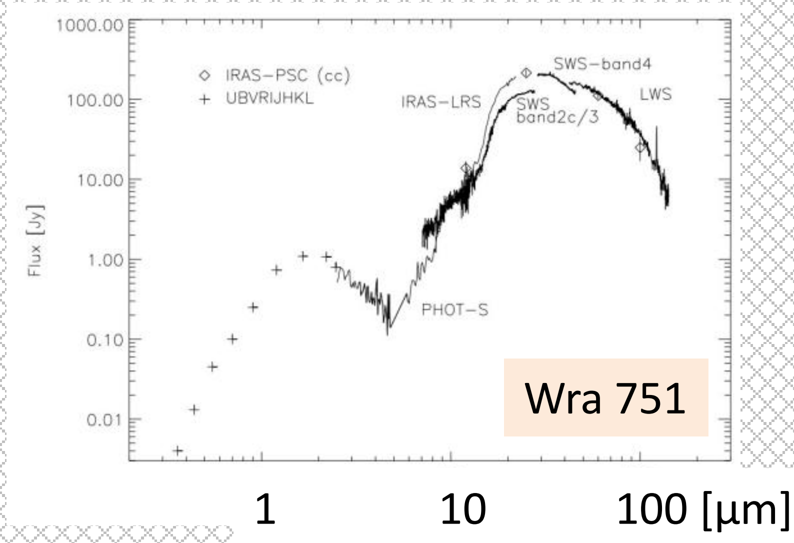
(Clark+, 2003)

Dust formation in LBVs

- Typical LBV spectrum has a peak around 30μm
  - Cool dust (~100K) emission
- High-resolution >30μm imaging is important to investigate the cool dust components

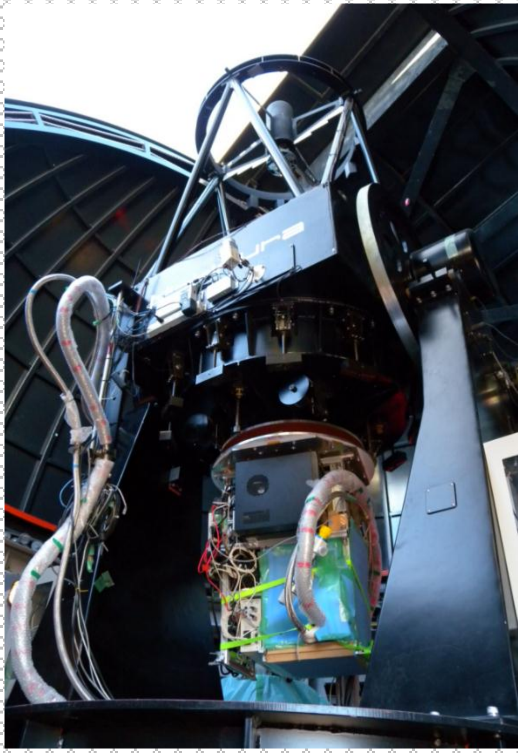




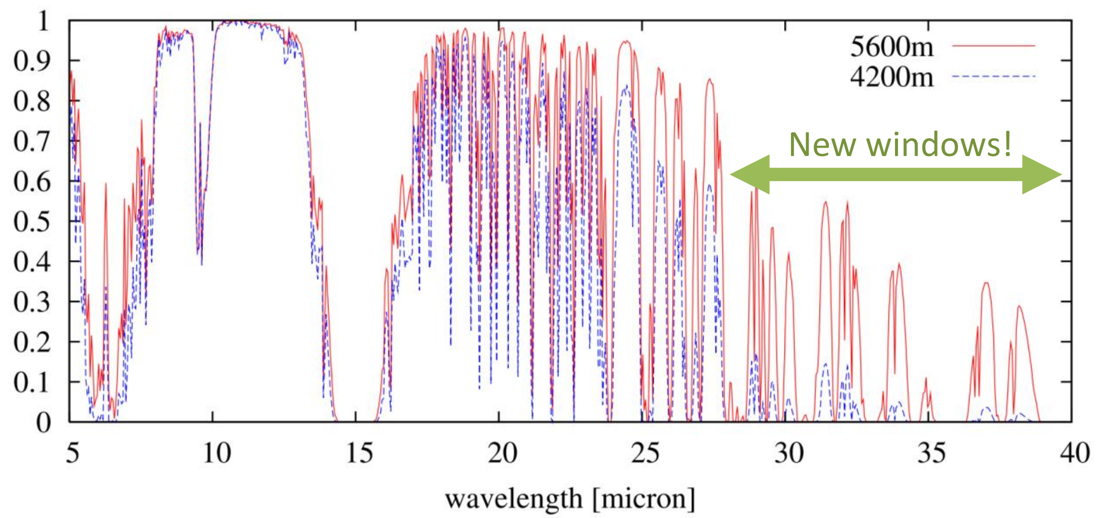


miniTAO/MAX38 observations

- The top of Co. Chajnantor (5640m)
- Atmospheric windows at 30μm band are available
  - miniTAO/MAX38 has a unique capability for 30μm observations from the ground!



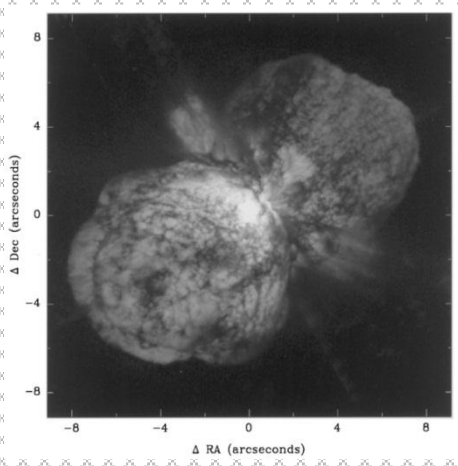
Object	λ (μm)	T_{exp} (sec)	reference star
η Carinae	18.7	50	VY CMa
	31.6	50	
	37.3	50	
AFGL 2298	18.7	40	IRC +10420
	31.6	1000	
HD 168625	18.7	500	V1185 Sco
	31.6	3500	



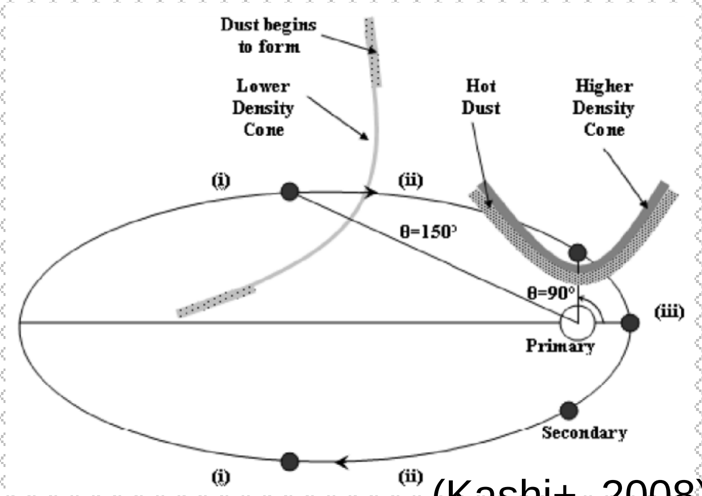
η Carinae

- The most intensely observed LBV
- Remarkable circumstellar nebula called the “Homunculus” Nebula

- Giant eruption in 1843
  - Formed the Homunculus Nebula
- Binary interaction
  - LBV+O binary (5.54years)
  - periodic dust formation occurred



(HST/WFPC3)

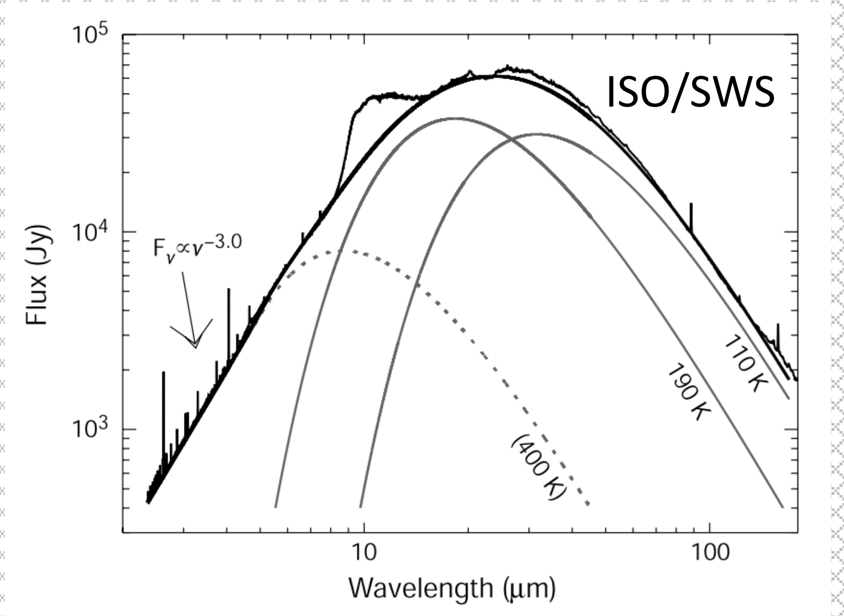


(Kashi+, 2008)

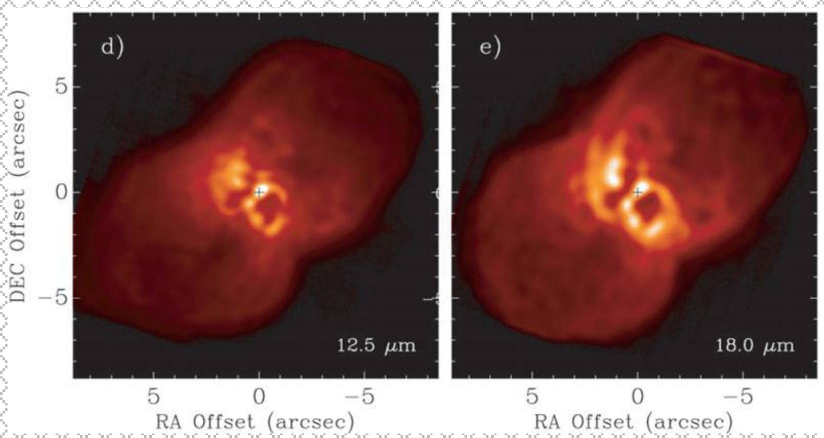
η Carinae

- The Homunculus Nebula is considered to be consists of ~100K, 0.1〜0.15M_{sun} dust, but the distribution of the cool dust components is poorly understood
  - Morris+99: in the equatorial torus
  - Smith+03: in the polar lobes

30-micron observations can reveal the cold dust distribution of η Carinae



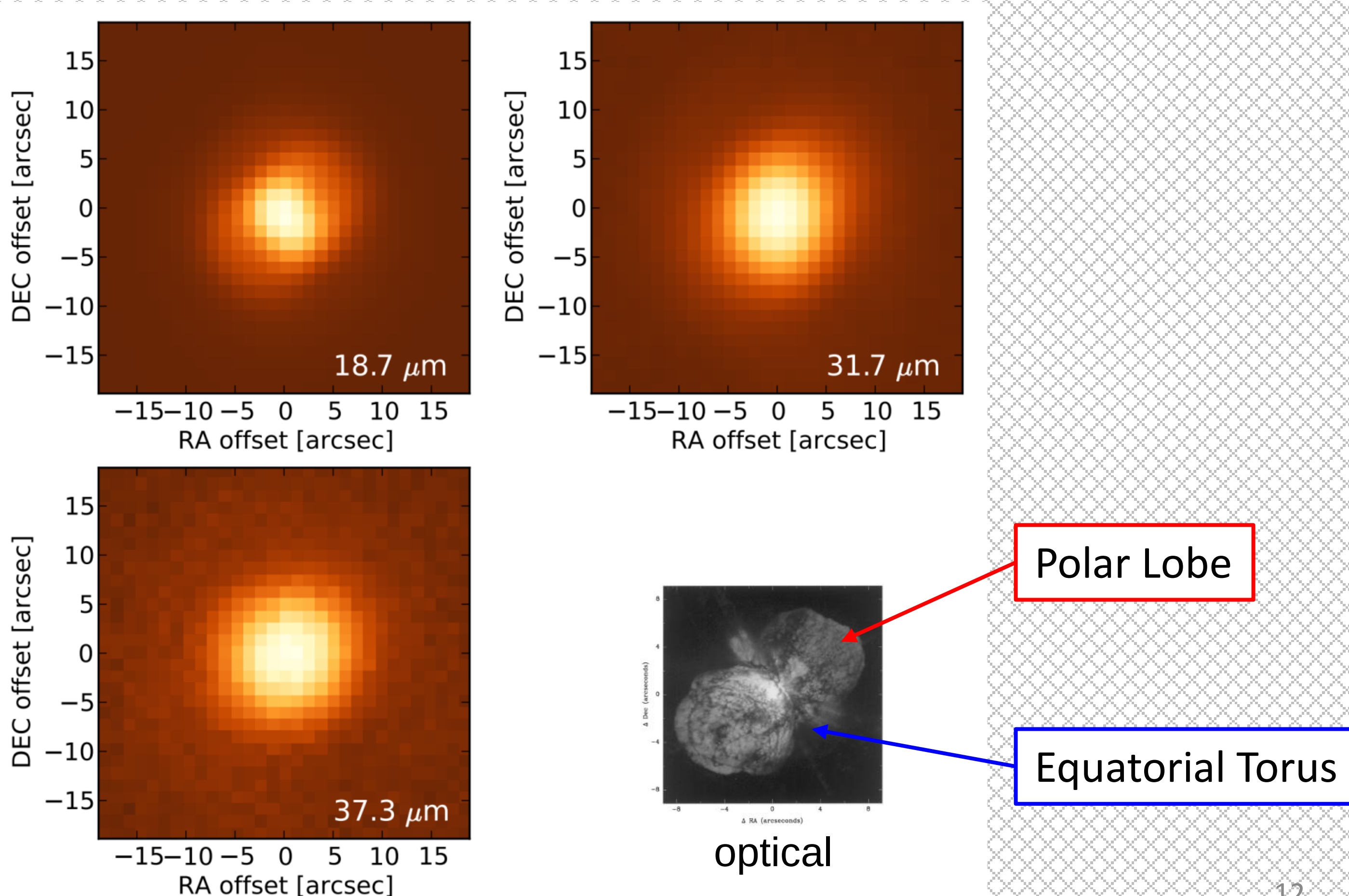
(Morris el al, 1999)



(Morris el al, 1999)

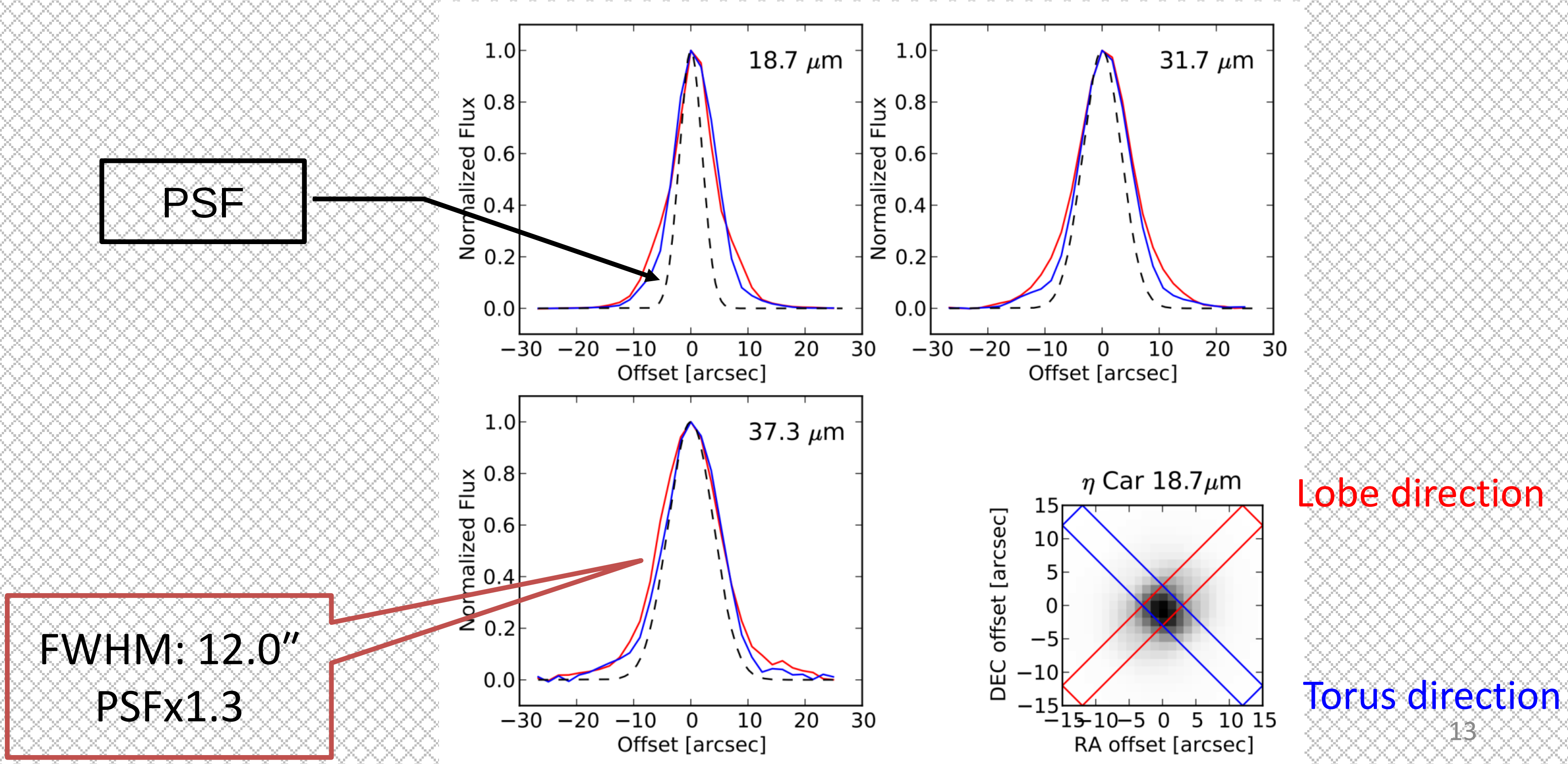
30-micron imaging

- Obtained the diffraction-limited images at each band
- Resolved the Homunculus Nebula at 31.7um for the first time



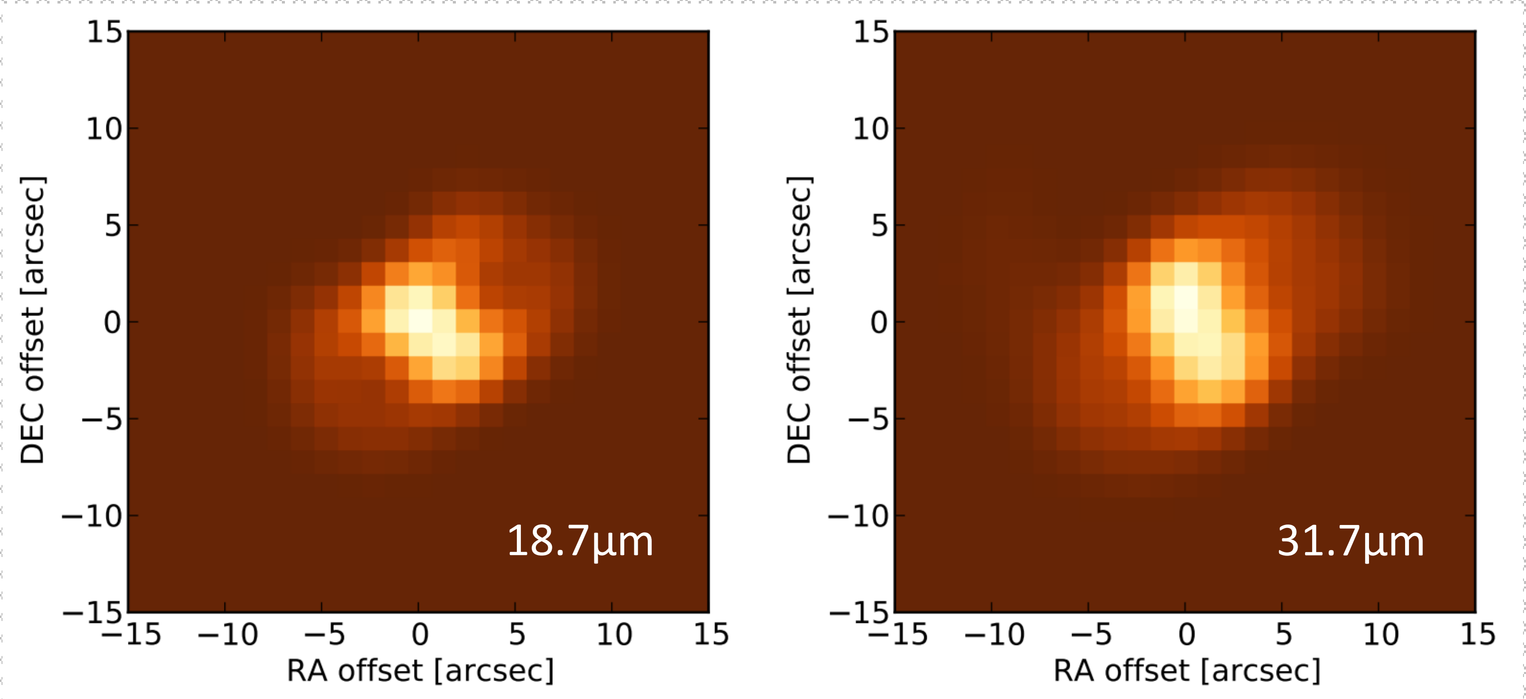
spatial profiles of Homunculus Nebula

- comparing spatial profiles between two directions
- extended structure along both of the directions
  - However, most of the infrared source is concentrated in the central core



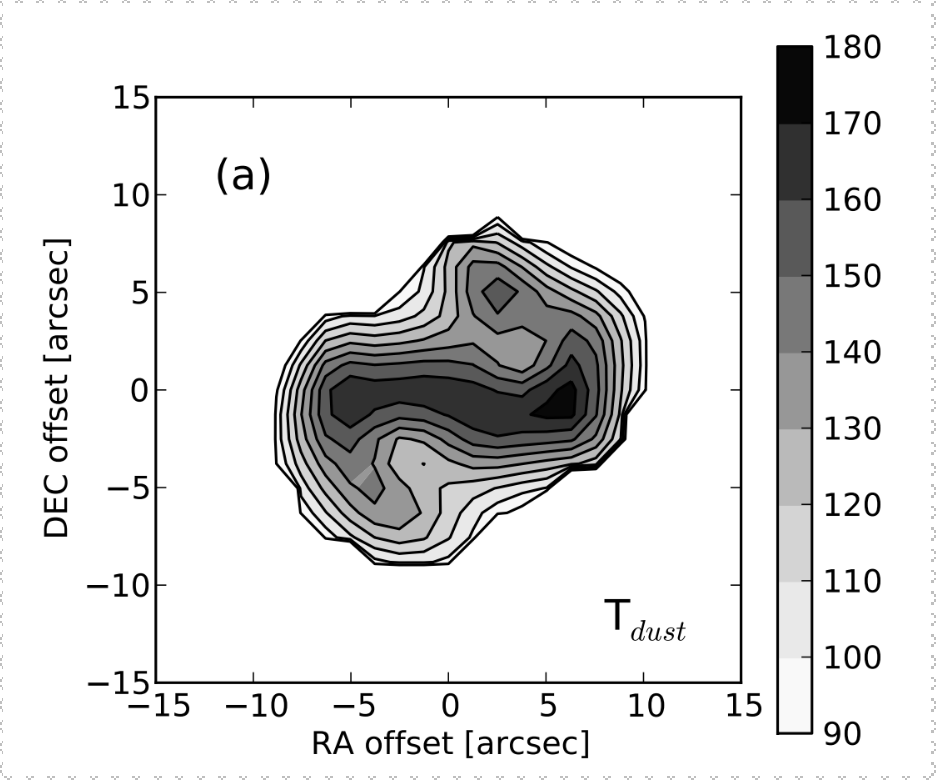
Deconvolution

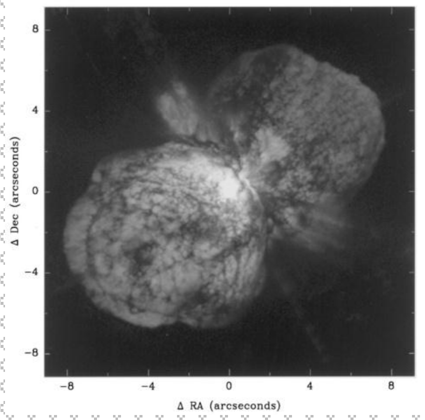
- Obtained the deconvoluted image at 18.7/31.7μm
  - IRAF STSDAS/Lucy task
- FWHM of deconvoluted images became approximately 3 arcseconds at each image



Temperature map

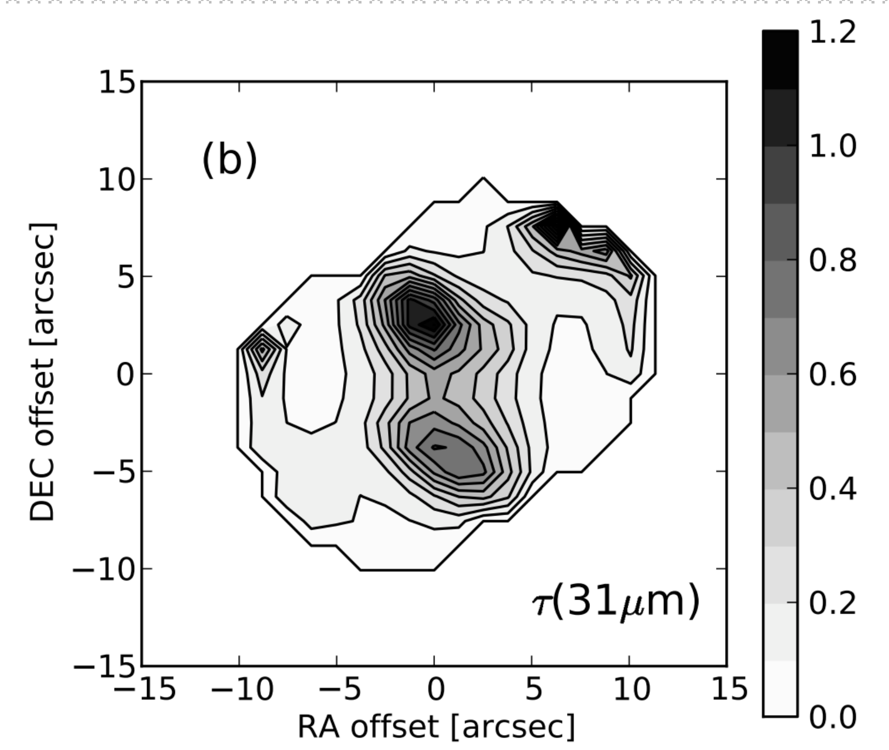
- Calculate the temperature map from 18.7/31.7um
  - grain emissivity is proportional to λ^{-1} (cf. Morris+, 1999)
  - warmer dust (140〜180K): central region, polar lobes
  - cooler dust (90〜130K): equatorial torus, inside the lobes

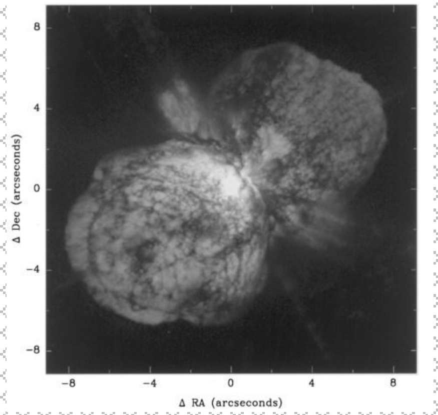




Optical depth map

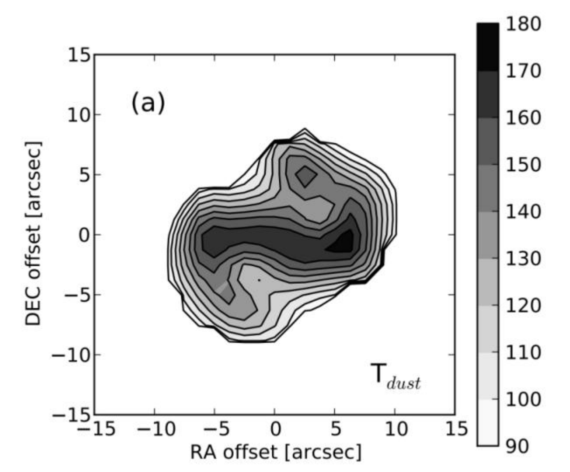
- Calculated the optical depth map from 31μm brightness distribution
- Large optical depth at the edge of the polar lobes and the equatorial torus (up to 1.2)

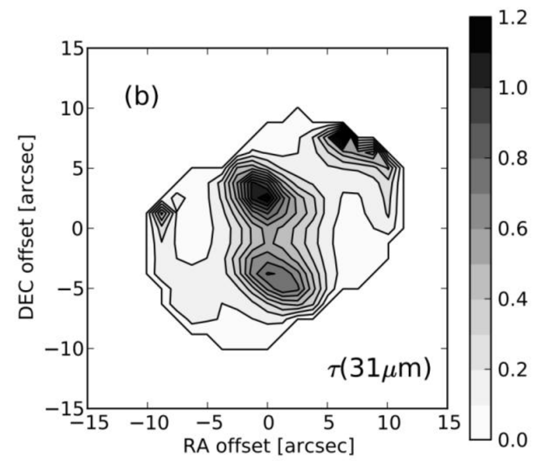




Distribution of cool dust components

- The distribution of cool dust components has been controversial:
  - Morris+99: in the equatorial torus
  - Smith+03: in the polar lobes
- <u>Our observations clearly showed the cool dust components mainly resides in the equatorial torus</u>



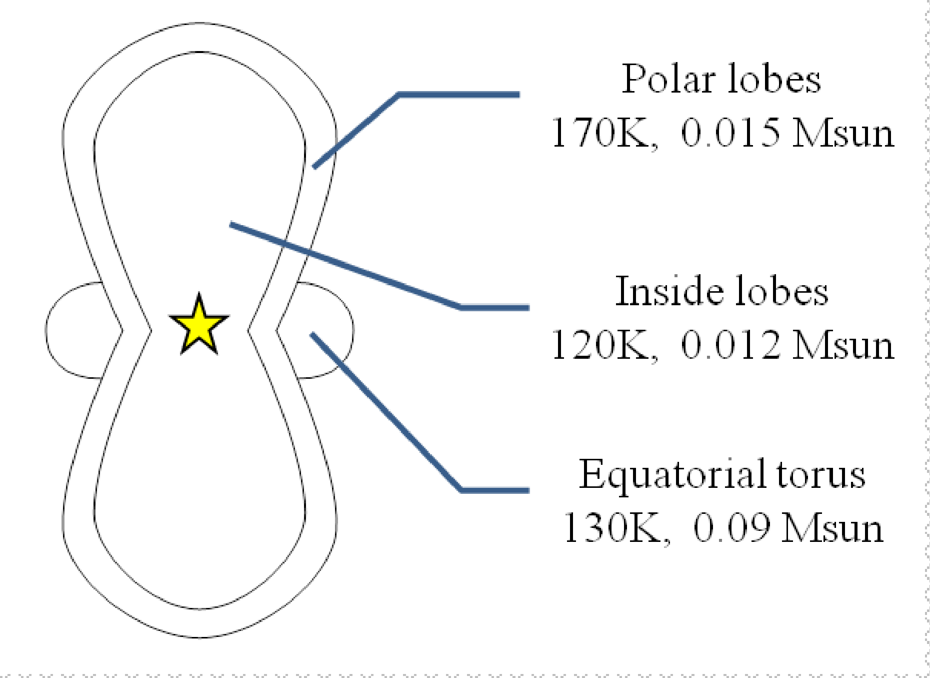


- In addition, the cool dust components *inside* the lobes are found
  - this component is in thermal equilibrium

17

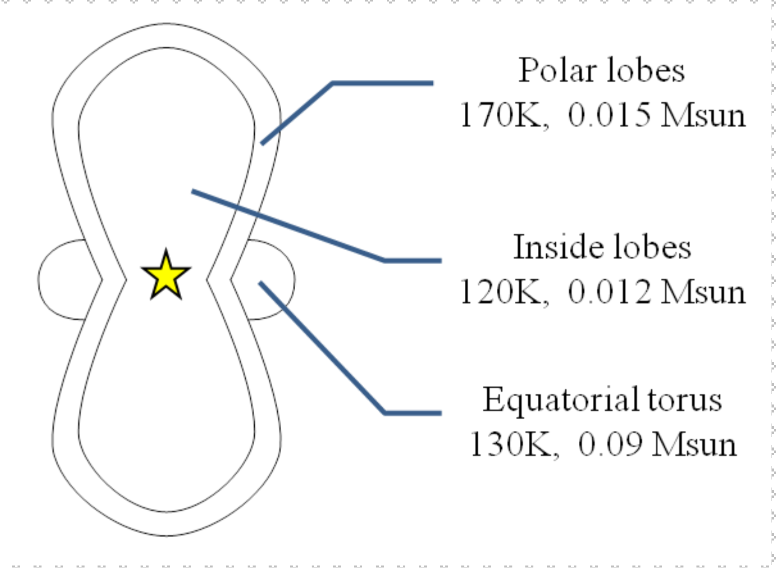
Cool Dust Mass in the Homunculus Nebula

- Estimation of the dust mass at each part
  - $\rho \simeq 3 g/cm^3$, $a \simeq 1 \mu m$
  - A total of $0.12 M_{sun}$ dust :
    consistent with Morris+ (1999) and Smith+ (2003)
  - 80% of the dust exists in equatorial torus
  - $> 0.015 M_{sun}$ of dust formed at the giant eruption



Cool Dust Mass in the Homunculus Nebula

- 0.012 M_{sun} dust in the Polar lobes
  - corresponds 10% of the total amount of dust in the Homunculus Nebula
- Assuming that this dust formed after the giant eruption, the dust formation ratio is 7×10^{-5} Msun/yr
  - Much higher rate than the typical WR binary (10^{-7}～10^{-6} Msun/yr)



The active dust formation occurred at binary interaction in LBV binaries

Conclusion

- We carried out the observations of Luminous Blue Variables with miniTAO/MAX38
- 30 micron imaging observations of η Carinae
  - Spatially resolved the cool dust components of the Homunculus Nebula for the first time
  - Both of the giant eruption and the binary interaction make significant contributions to the dust formation at η Carinae
  - The active dust formation occurred at binary interaction in LBV binaries