The Mass Loss Histories of Warm and Cool Hypergiants

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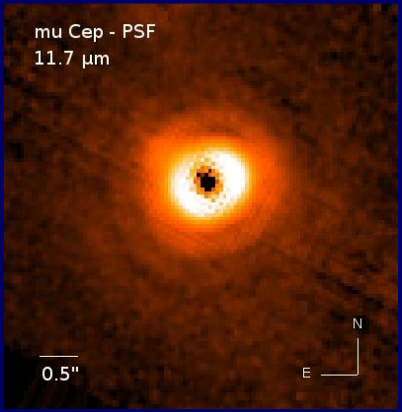
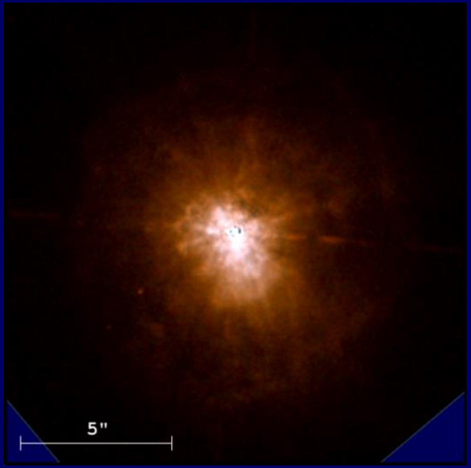
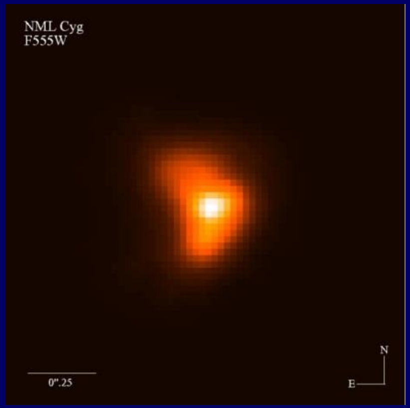
VY CMa



µ Cep



IRC +10420



NML Cyg

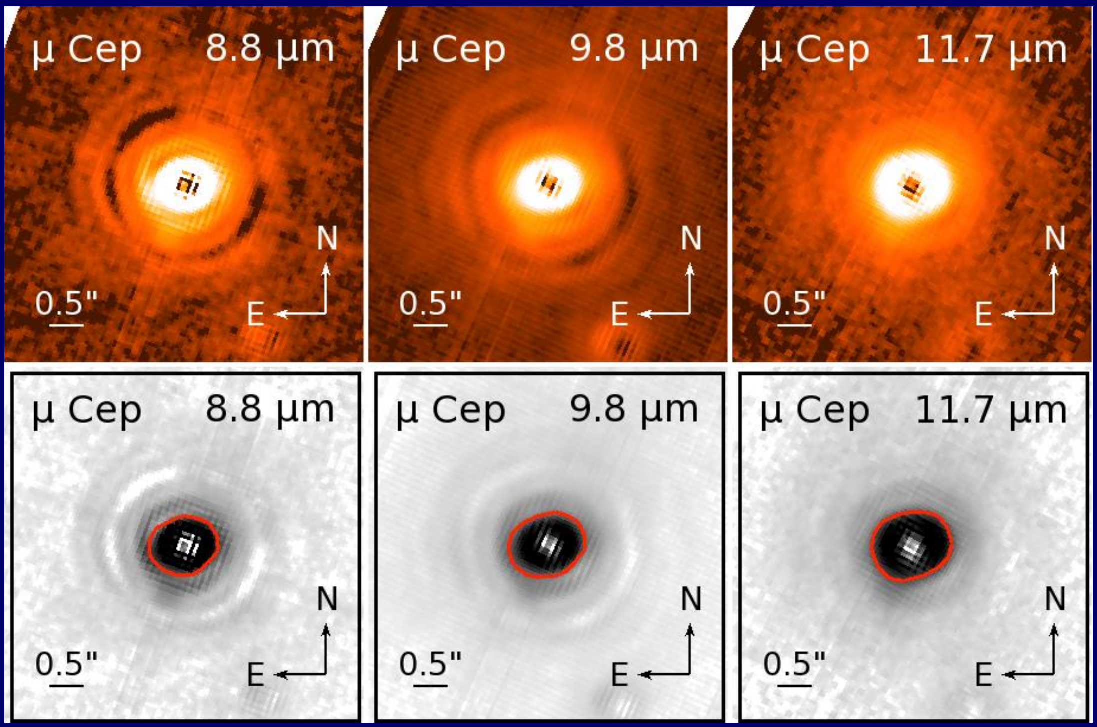
Betelgeuse Workshop --- Paris Observatory, Sept. 2016

With near- and mid-IR AO imaging with LMIRCam on the LBT and MIRAC on the MMT plus imaging polarimetry with MMT-POL we have mapped the geometry of the circumstellar material and reconstructed the mass loss histories over the past 1000 years for μ Cep, VY CMa and IRC+10420

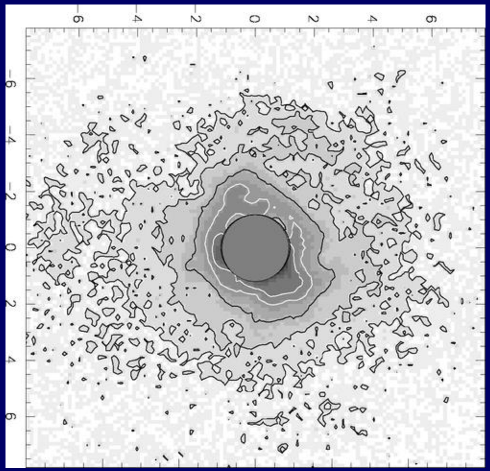
With imaging at much longer wavelengths with SOFIA, we can extend their mass-loss histories to several thousand years.

The iconic red supergiant – μ Cep

9 -12 μm imaging MMT/MIRAC/AO images its extended circumstellar ejecta

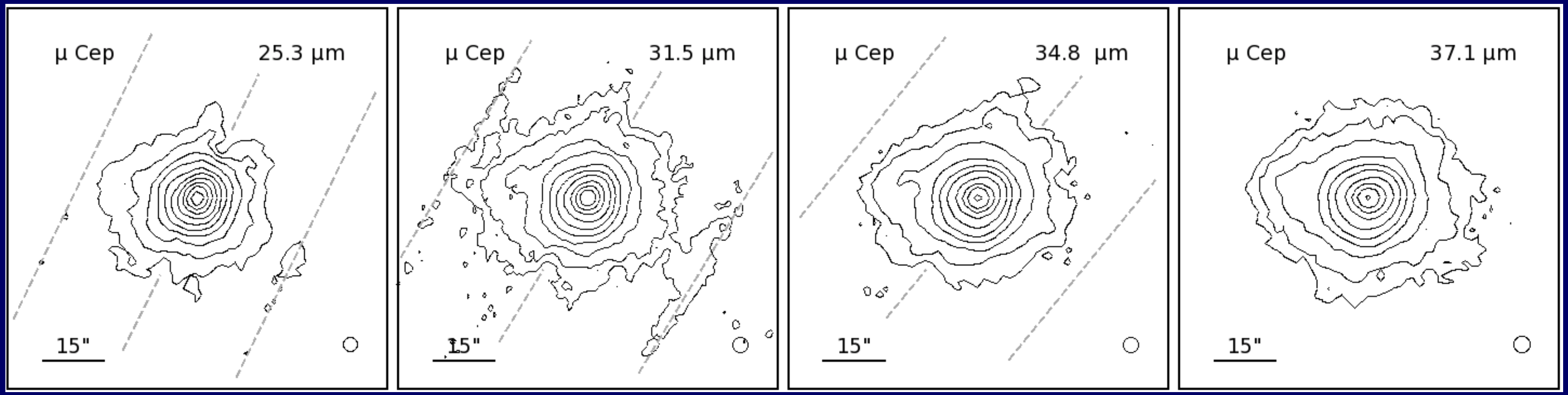


Shenoy et al. 2016

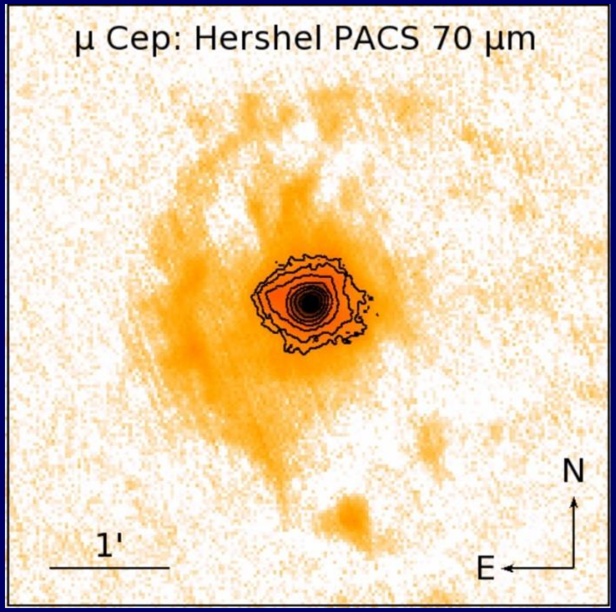


de Wit et al. 2008 25 μm image

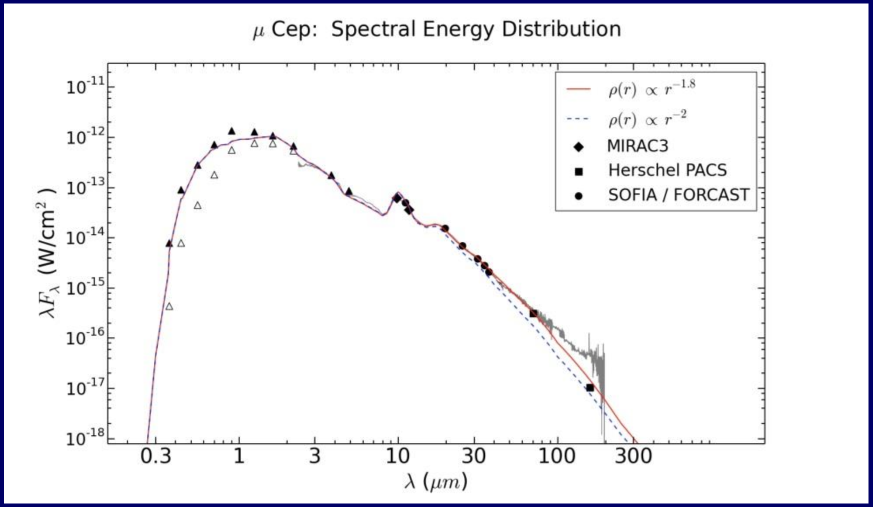
SOFIA 11- 37 μm Shenoy et al. 2016



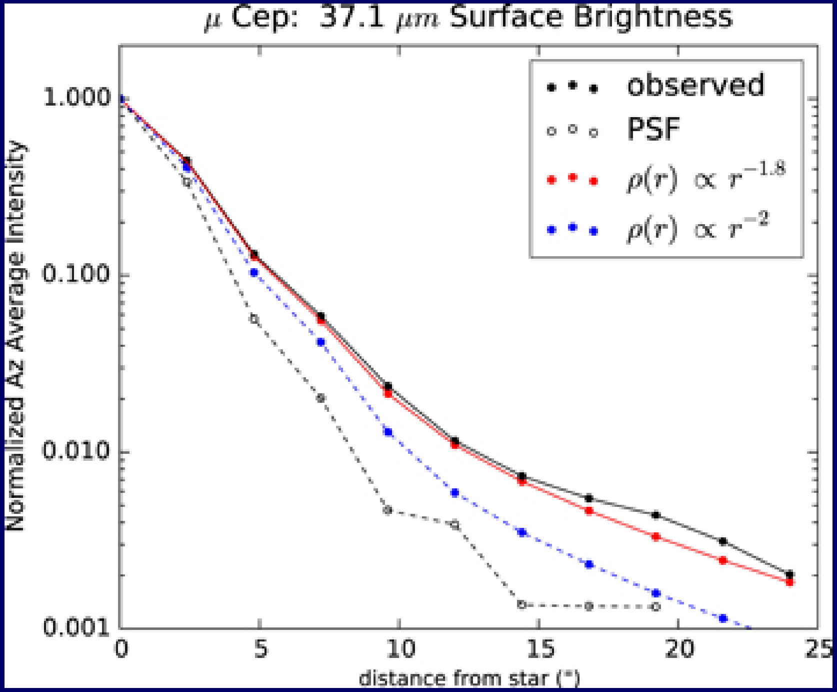
With an expansion velocity of 35 km/s, outer shell at 37 μm is ~ 13,000 yrs old.



Herschel 70μm (Cox et al 2012)



The blue dashed line is a DUSTY model for a constant mass-loss rate. A better fit to the observed SED is obtained for a distribution $\rho \sim r^{1.8}$ (red solid line).



The solid black line is the observed azimuthal average intensity in the 37 mm filter. A r^{-2} density distribution (blue dashed line) does not predict sufficient intensity to match the observed profile. A better fit is obtained assuming a dust density distribution $r^{-1.8}$ (red solid line).

Over 13,000 yrs mass loss rate decreased from ~ 5 x 10^{-6} to 10^{-6} Msun/yr

VY CMa -- the extreme red supergiant, powerful OH/IR source

10”

1” = 1500 AU

Two HST epochs 1999 and 2005, plus K I velocities HiRes

	exp Vel	orientation	age
NW arc	46	22	500 +/- 50
Arc 1	68	-33	800 +/- 50
Arc 2	64	-17	400 +/-15
West arc	44	~ 0	300 +/- 30
S arc	42	-22	480 +/- 25
SE loop	65	-21	320 +/- 20
S. knots	42	-27	157 +/- 25
SW knot	36	-25	250 +/- 50
SW clump	~ 18	8 :	~ 500

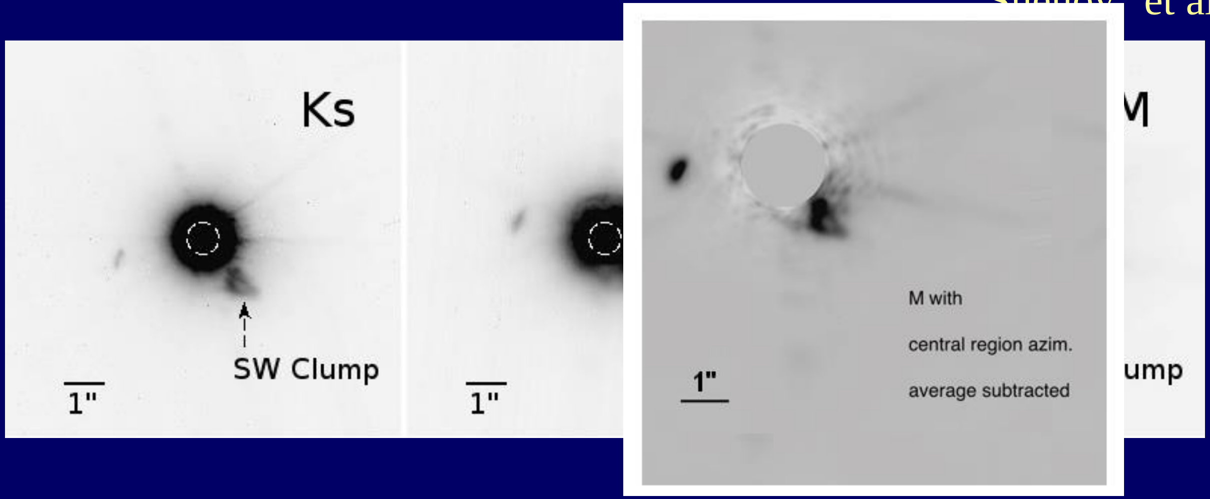
Spatially and kinematically distinct

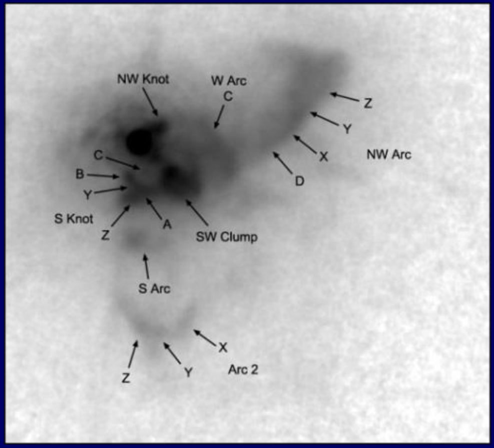
Large scale surface activity -- magnetic fields?

Vlemmings et l -> 300 – 400 G surface

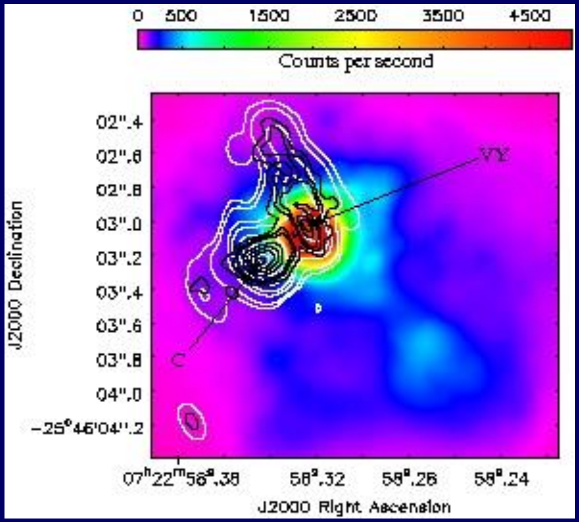
LMIRCam (2 – 5μm) on the LBT with AO

Shenoy et al. 2013

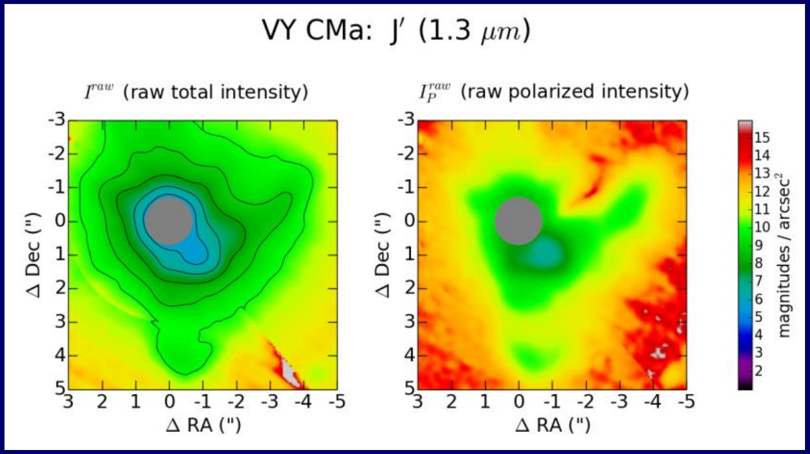




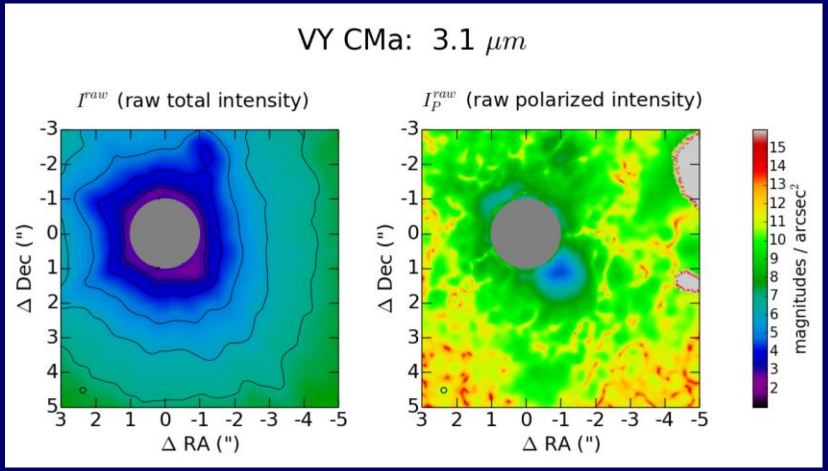
Clump is optically thick.
Mass lost > 5 x 10^{-3} Msun



MMT-POL polarized intensity images

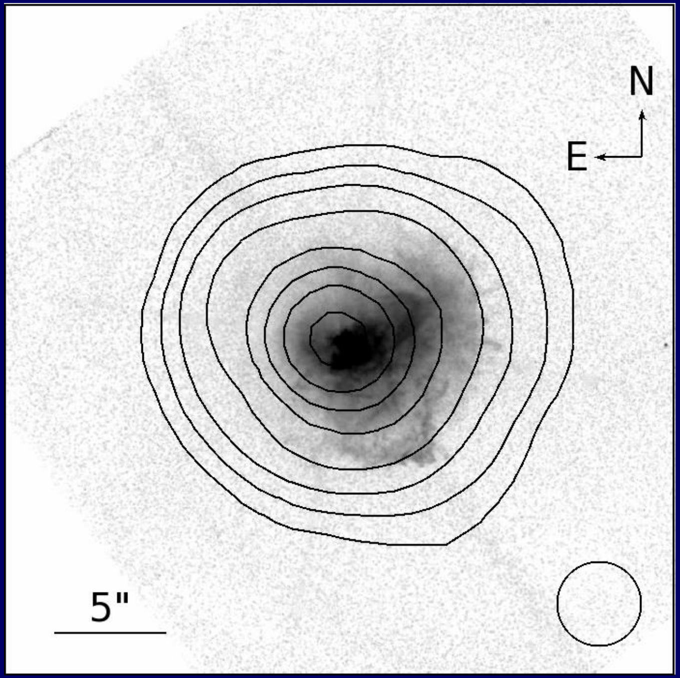


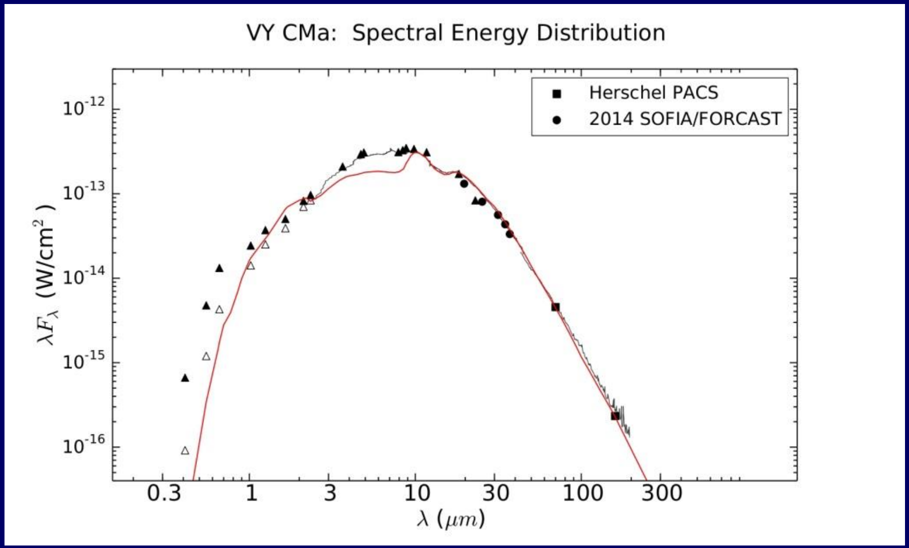
The PSF is sufficiently low that the fractional polarization of scattered light can be measured and discrete features identified.



Very high fractional polarization 40 % at 1.3 and 3.1 μm with respective minimum optical depths of 1 and 0.3 due to scattering for SW Clump, confirms clump is optically thick.

SOFIA imaging 20 – 37 μm





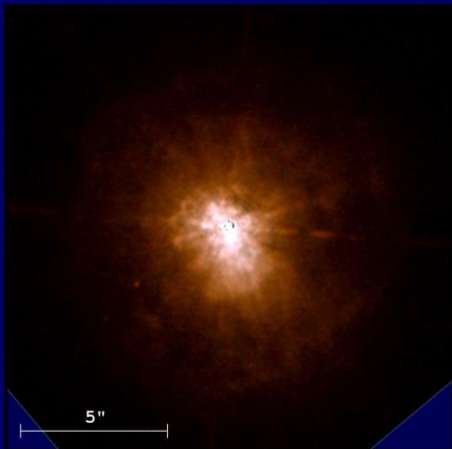
37μm contours on HST visual image

Note asymmetric shape. **There is no extended cold dust much beyond 10″ from the star, corresponding to the lack of ejecta from more than 1200 yrs ago**

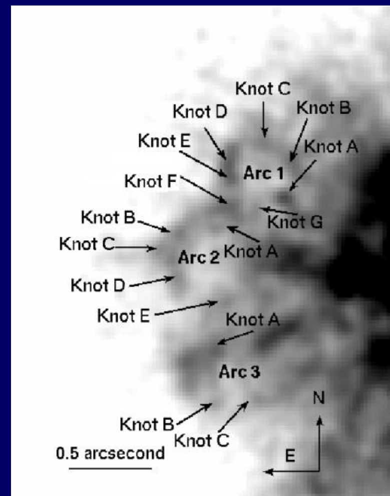
Shenoy et al. 2016

We use DUSTY to fit its SED but are unable to fit it with a single mass loss rate. The best fit to longer wavelengths yields an average of 6 x 10^{-4} $M_{\odot}$/yr over 1200 yrs. Since this is an average rate, it does not capture the higher short term rates on the order of 10^{-3} $M_{\odot}$/yr associated with prominent arcs and clumps

The Post-RSG IRC+10420

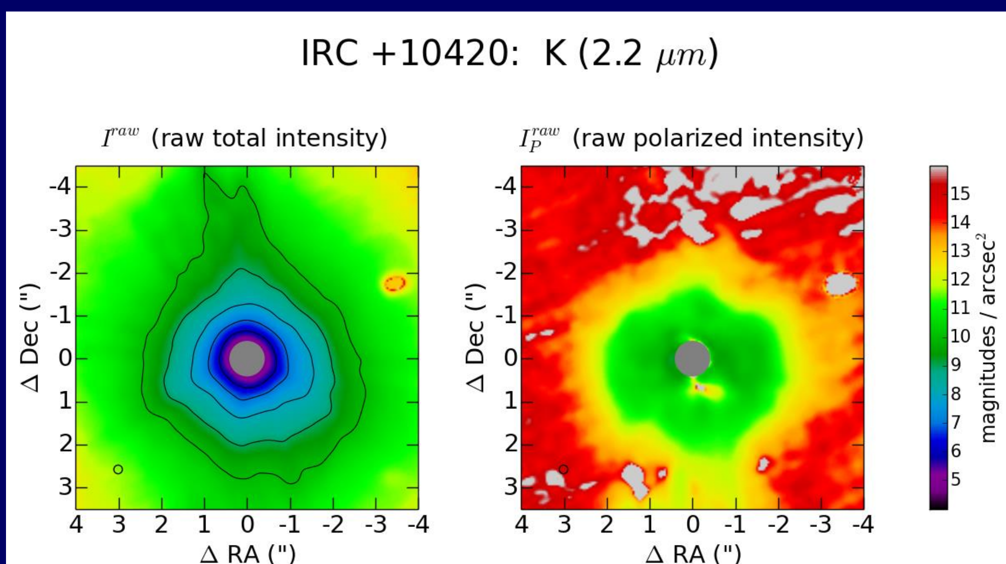


1 arcsec ~ 5000AU



Earlier work – multi-epoch imaging plus velocities from spectra showed viewing ejecta pole-on

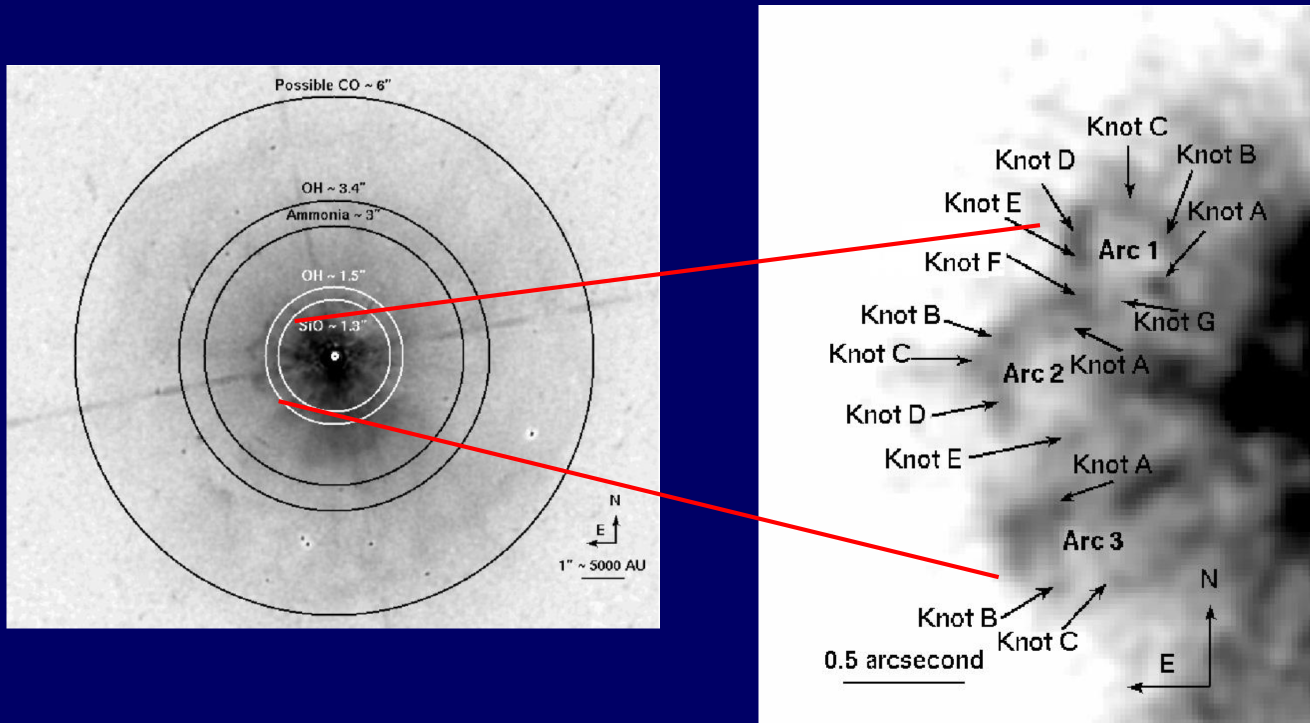
LMIRCam 3- 5μm AO imaging revealed a smooth distribution



MMT-POL at 2.2μm

The uniform distribution and high fractional polarization 30% consistent with pole-on view

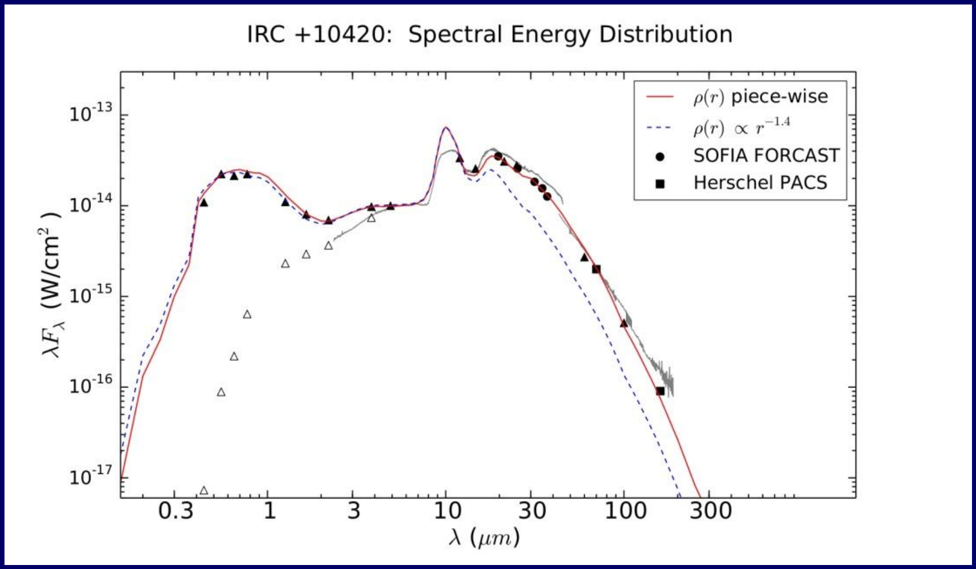
Maser distribution

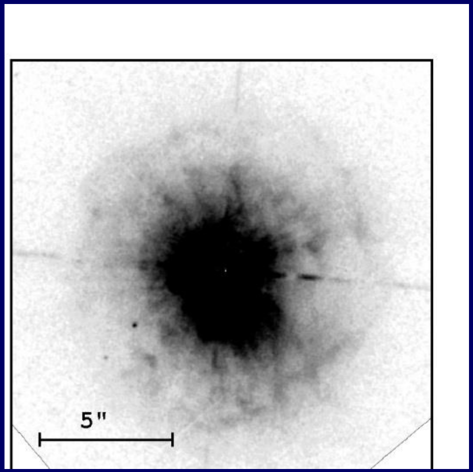


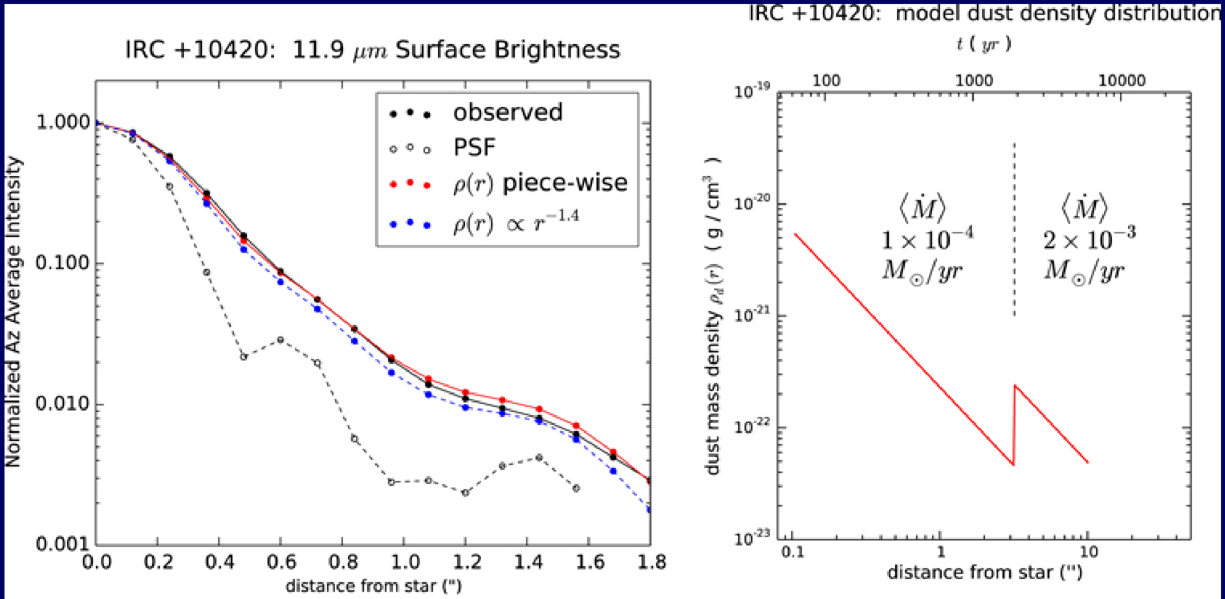
IRC +10420 -- circular polarization of OH (Nedoluha & Bowers 1992)

-> 300 – 400 G at the star (based on Vlemmings 2008)

Arcs and loops associated with surface activity





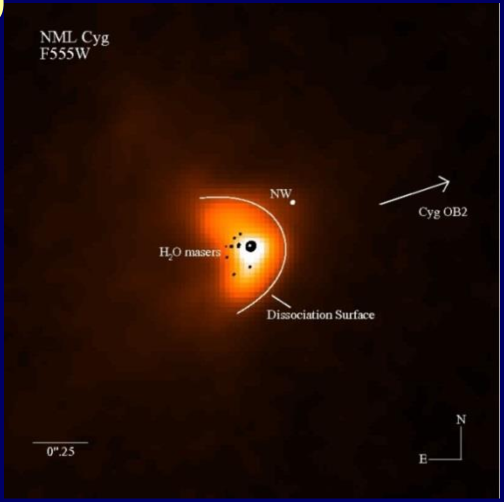


(a) (b)

The best fit DUSTY model with a factor of 5 enhancement in density at a radius of 3” to account for the long-wavelength flux on the SED.

Other red supergiants

NML Cyg (M6 I, OH/IR) -- extended CS ejecta (HST, MIRAC, SOFIA)
S Per (M4 Ia, OH/IR) -- extended CS ejecta (HST/MIRAC/SOFIA)
VX Sgr (M4 Ia –M8 , OH/IR) -- extended CS ejecta (HST,SOFIA)
W Per (M3 Iab) -- null
RW Cep (K0: Ia +) -- extended CS ejecta (MIRAC)
RW Cyg (M3-4 Ia) -- extended CS ejecta (MIRAC)
BD +24 3902 (M1 Ia+) -- extended CS ejecta (MIRAC)
T Per (M2 Iab) -- extended CS ejecta (MIRAC, SOFIA)
RS Per (M4 Iab) -- extended CS ejecta (SOFIA)



Evidence for increased mass loss, CS ejecta with higher luminosity and cooler temperatures .

Do RSGs evolve through the red supergiant stage getting apparently cooler, more extended envelopes and high mass loss episodes?

Like lower mass stars, could there be more than one RSG stage?
→ warm hypergiant → RSG again – extreme RSG (VY CMa) ?

Note – peculiar chemistry of VY CMa, C and Si compounds in ejecta, and high C^{12}/C^{13} ratio. (Ziurys et al 2007, 2009)