Probing Hypergiant Mass Loss with Adaptive Optics Imaging and Polarimetry in the Infrared

Stellar End Products: The Low Mass - High Mass Connection
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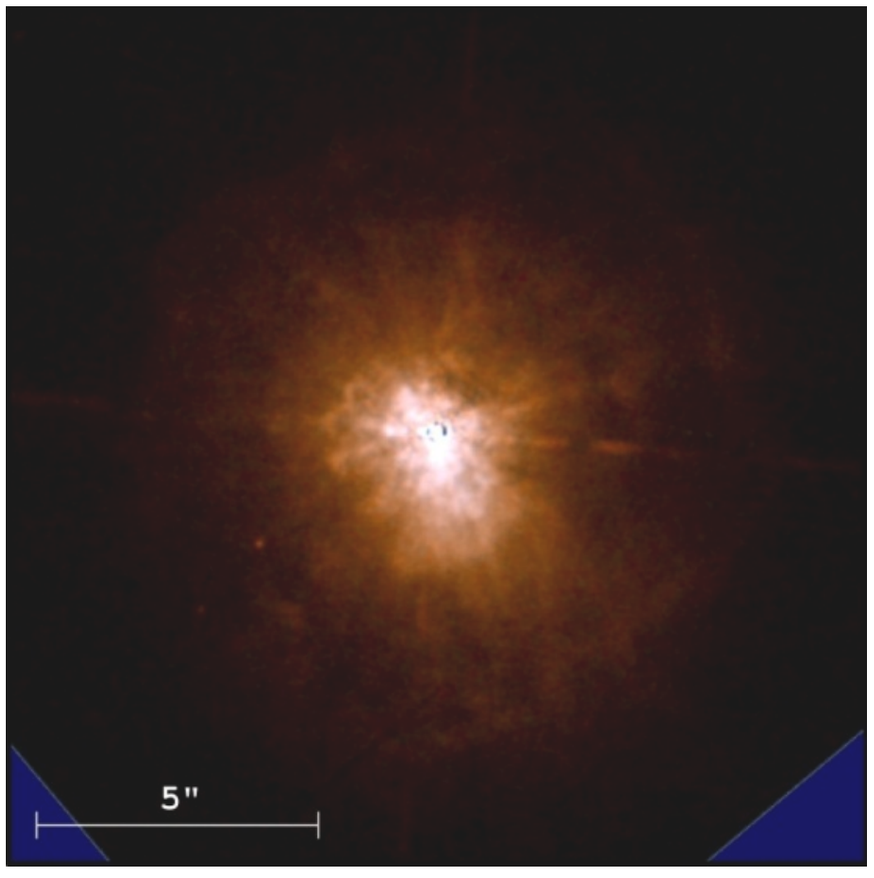
VY CMa: *HST* visual composite
(Smith et al., 2001 AJ 121, 1111)



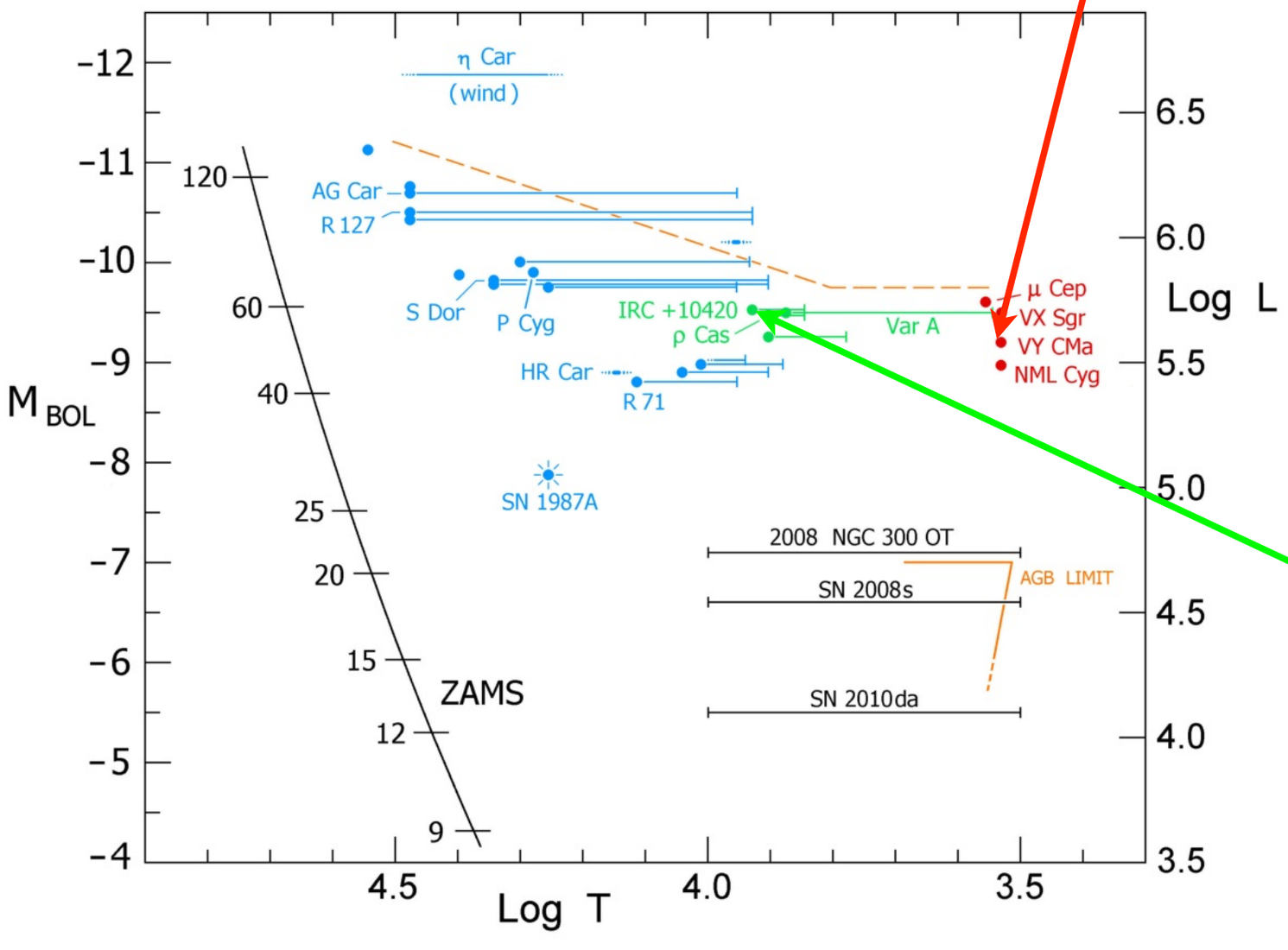
IRC +10420: *HST* visual composite
(Humphreys et al., 1997 AJ 114, 2778)

VY CMa

$L = 2.7 \times 10^5\ L_\odot$

D = 1.2 kpc

Sp Type: M4 − M5 Ia

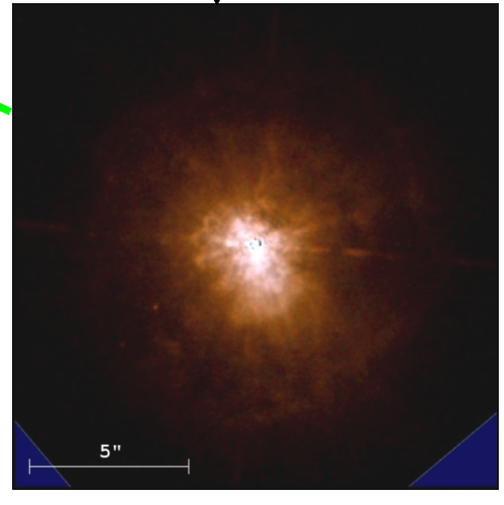


IRC +10420

$L = 5 \times 10^5\ L_\odot$

D = 5 kpc

Sp Type: A − F Ia

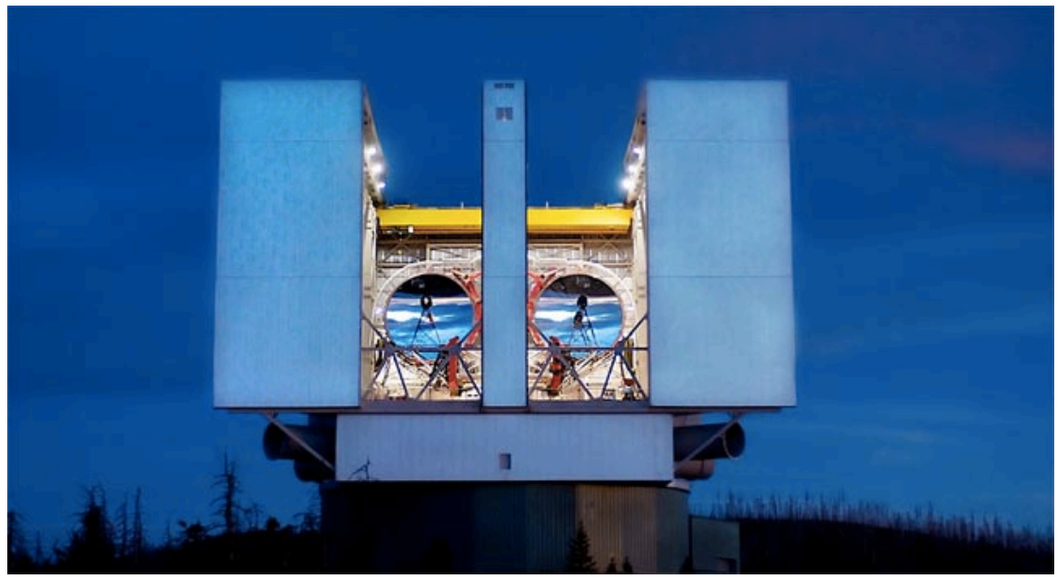


Motivations & Goals

- Mass Loss Mechanism in Evolved Stars: Convective Cells and/or Magnetic Origin?
- Probe geometry of hypergiant mass loss in the infrared, separate scattered vs. thermal emission & make mass-loss estimates

LBT / LMIRCam

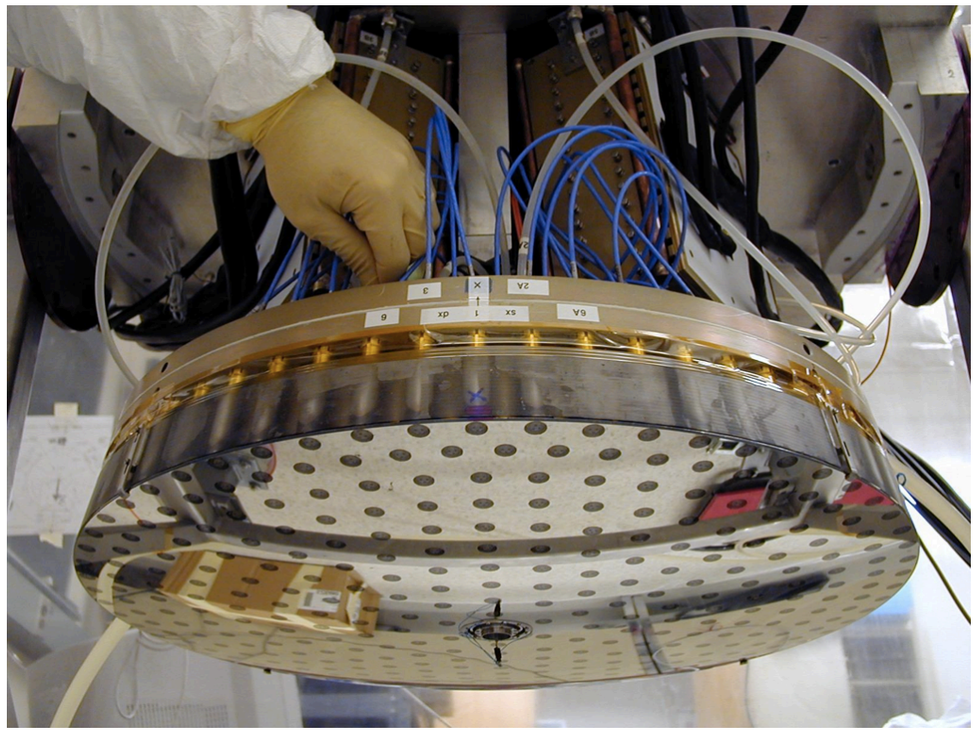
- Mt. Graham, Arizona, USA
- Two 8.2 m Primaries
- AO secondary
- **Filters: 2 - 5 μm**
- L′ (3.8 μm) PSF FWHM = 0.12″



Large Binocular Telescope, Mt Graham, AZ

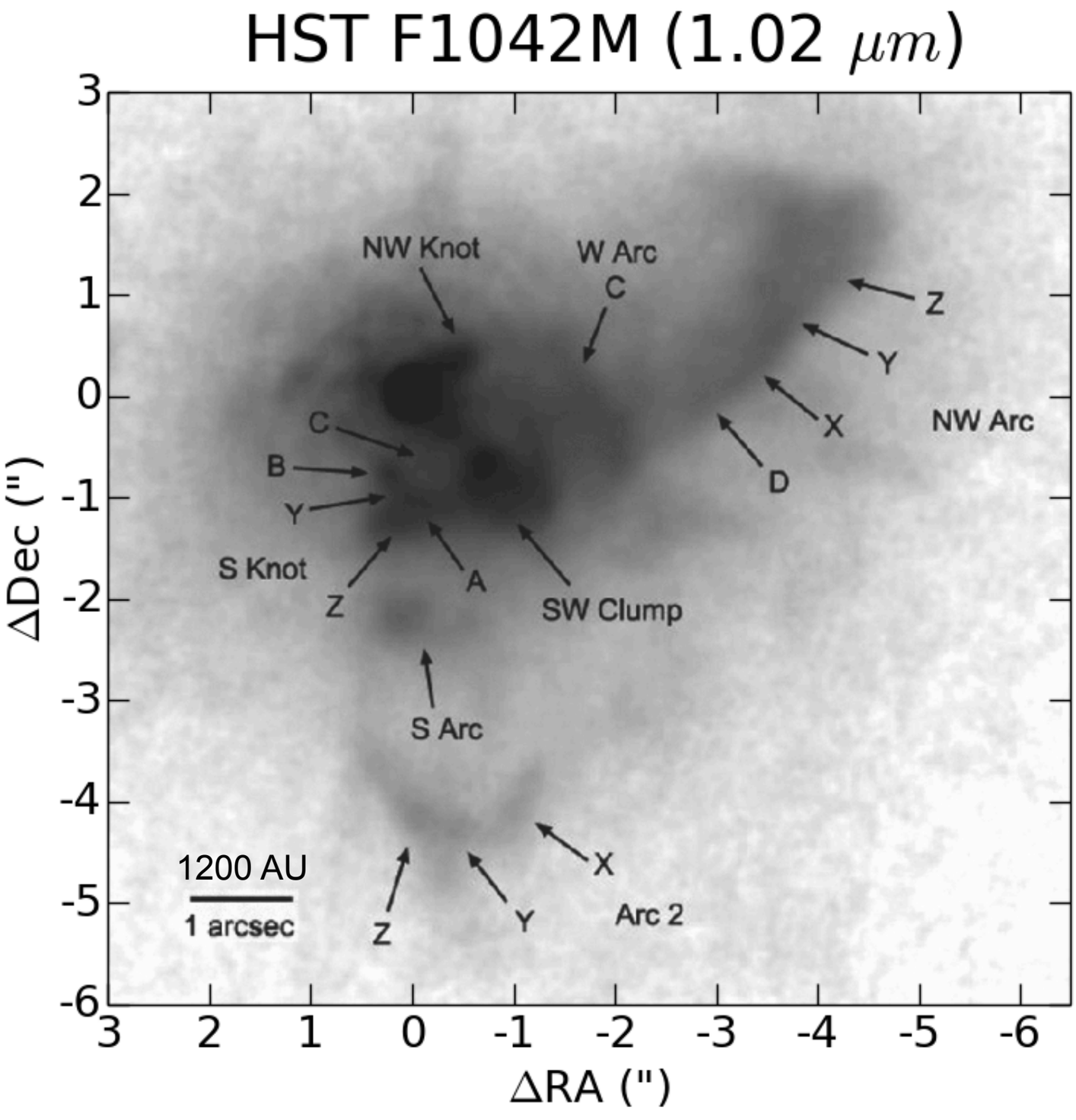
MMT / MMT-Pol

- Mt. Hopkins, Arizona, USA
- 6.5 m Primary
- AO secondary
- **Filters: 1 - 3 μm**
- MMT-Pol @ Cassegrain focus
- Instrumental $p \approx 0.05 \pm 0.03\%$



MMT Adaptive Optics Secondary Mirror

VY CMa (Context): *HST* Visual to 1 μm

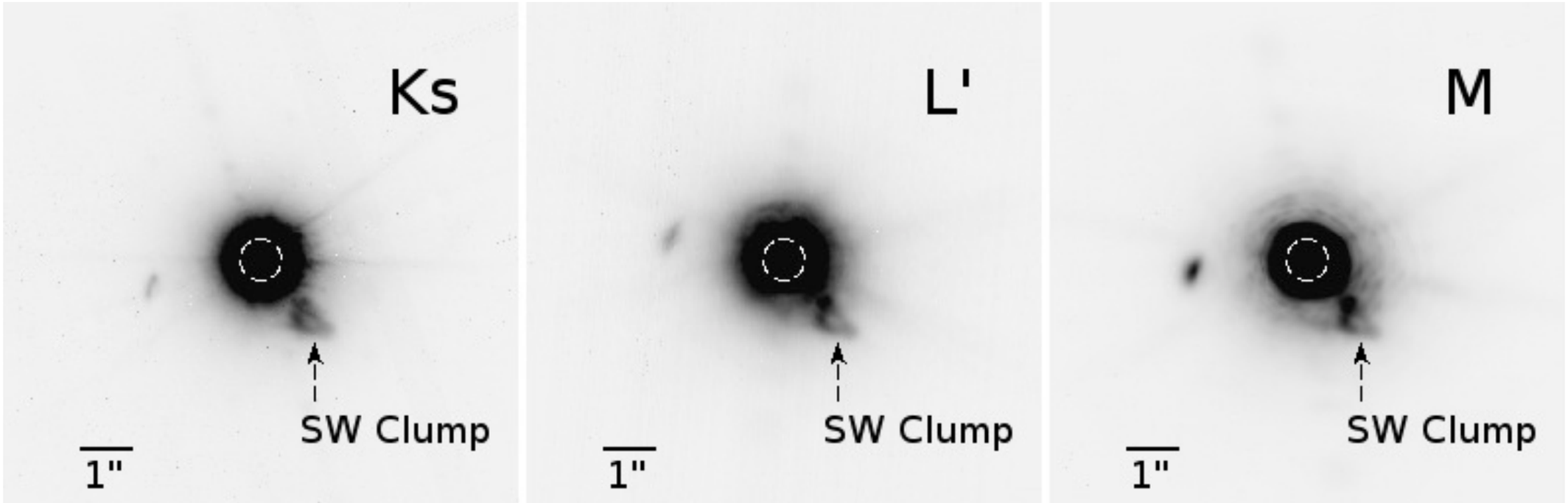


Humphreys, Helton & Jones (2007)

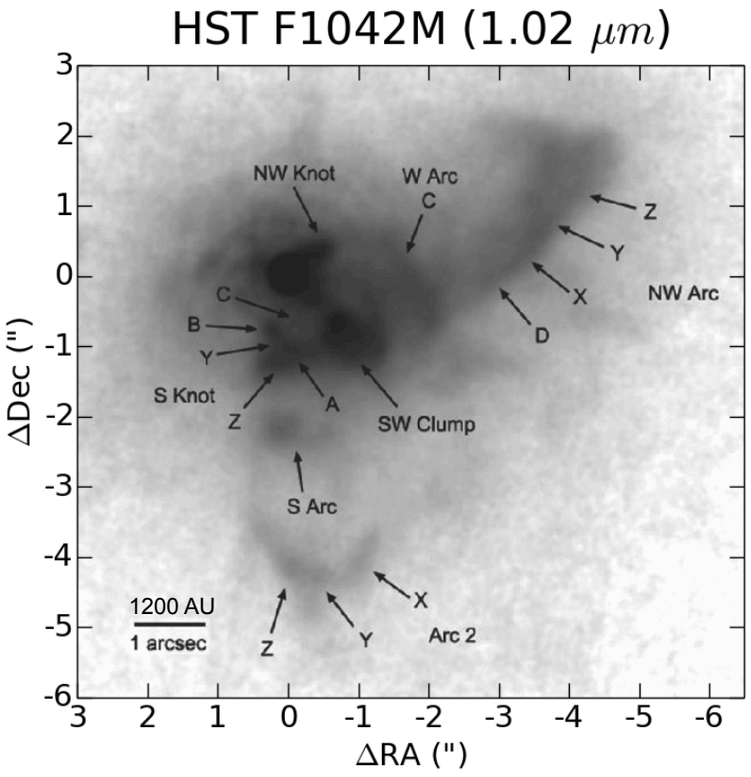
<u>NW Arc, Arc 1 Arc 2:</u>
each ~ 3×10^{-3} $M_\odot$

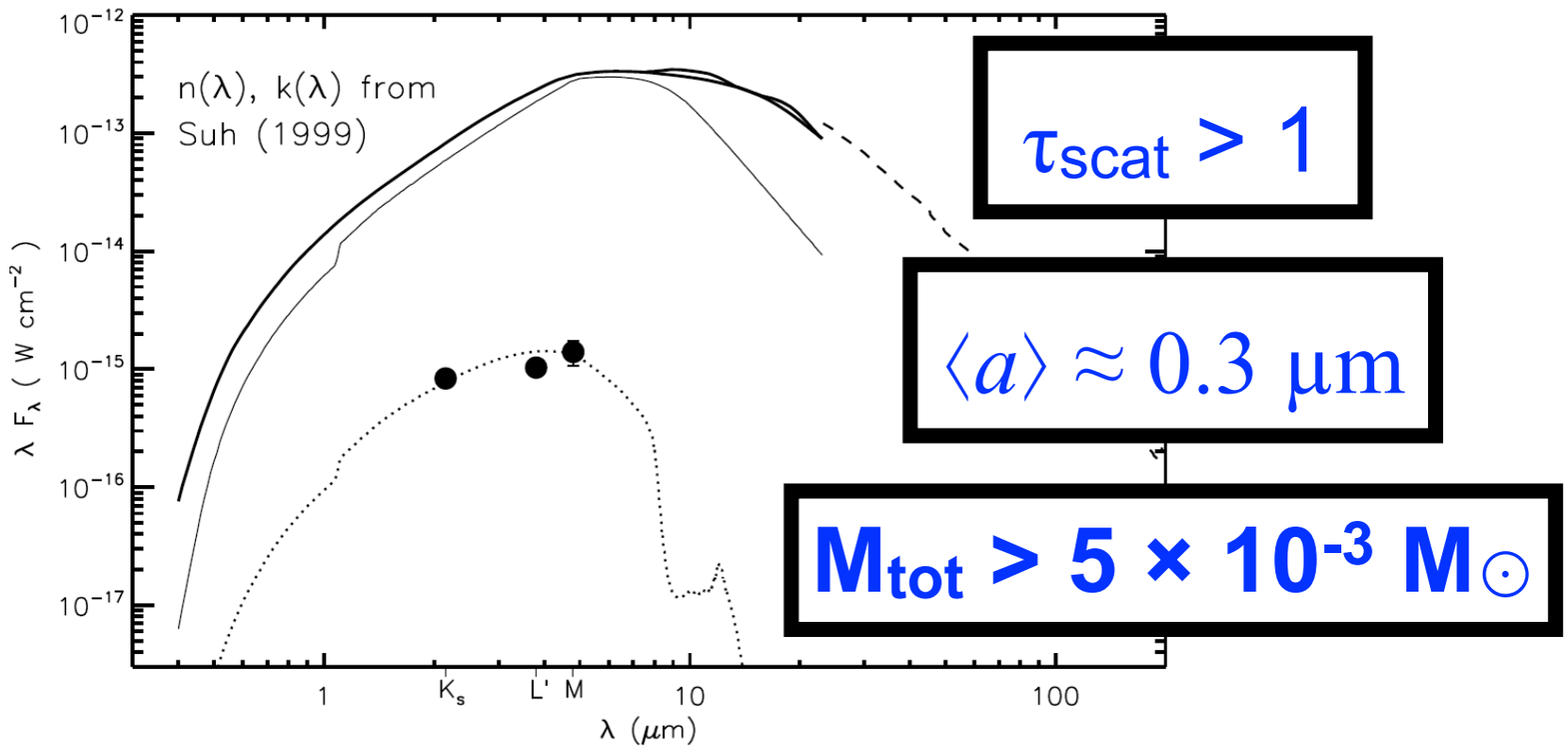
<u>SW Clump</u>:
- seen only $\lambda \geq 1$ μm
- ejected ~ 500 yr ago
- moving radially away

VY CMa with LMIRCam: 2 – 5 μm



Shenoy et al. (2013)



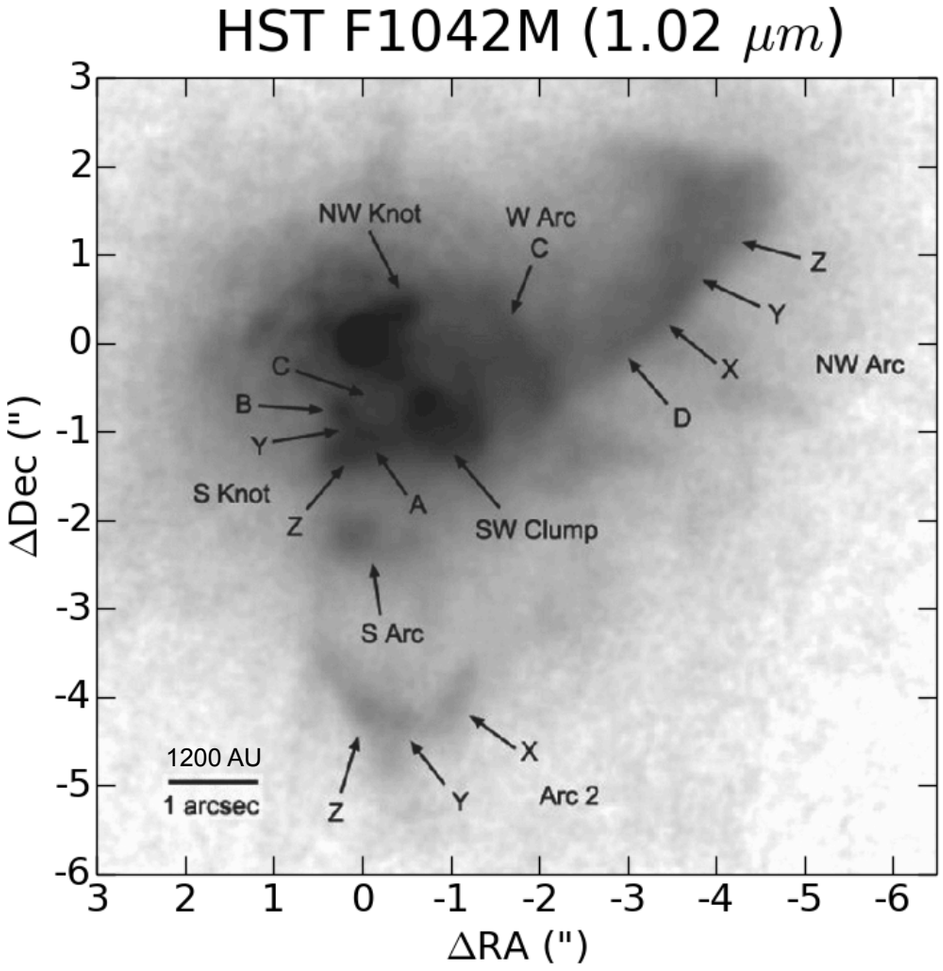


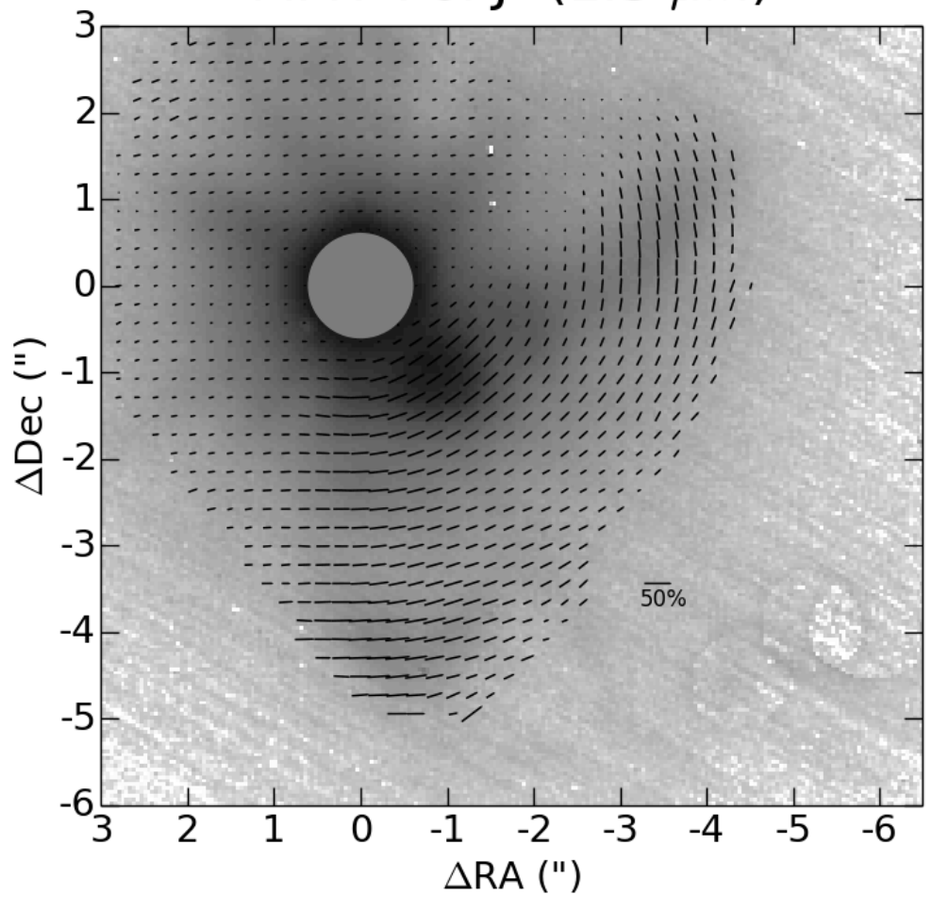
$\tau_{scat} > 1$

$\langle a \rangle \approx 0.3$ μm

$M_{tot} > 5 \times 10^{-3}\ M_\odot$

VY CMa with MMT-Pol: 1.3 μm

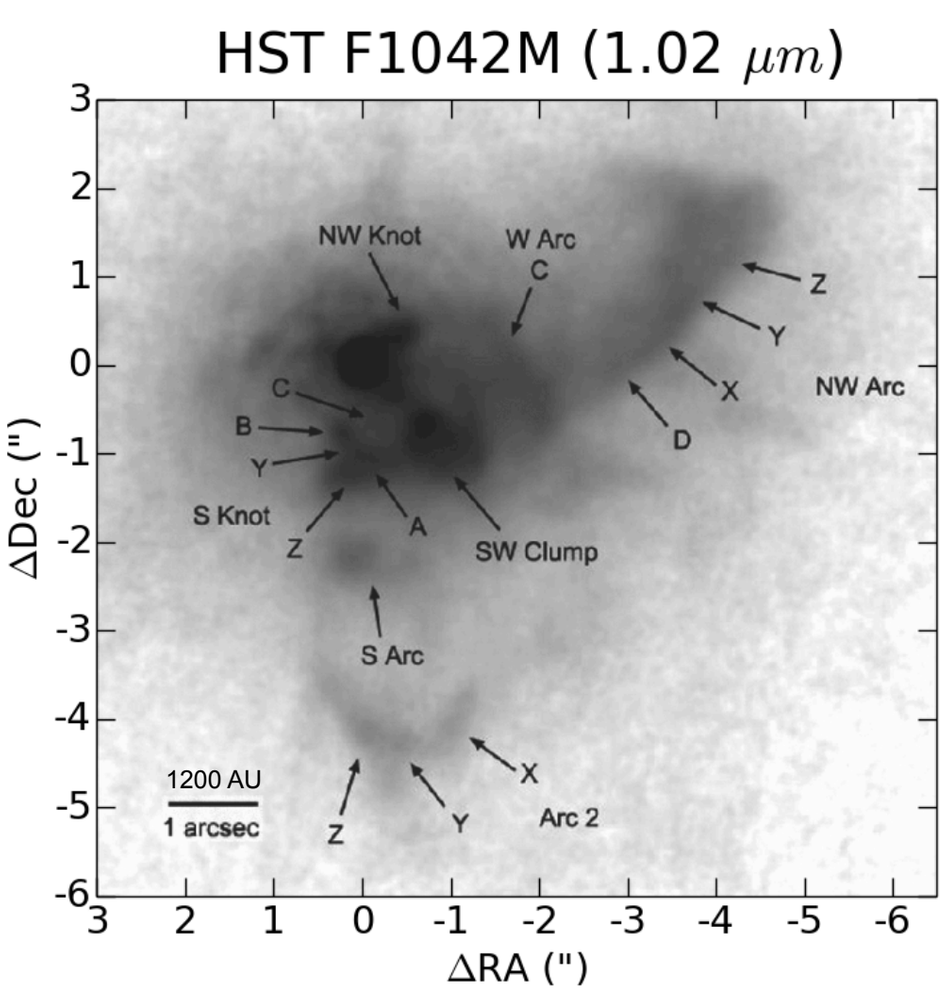


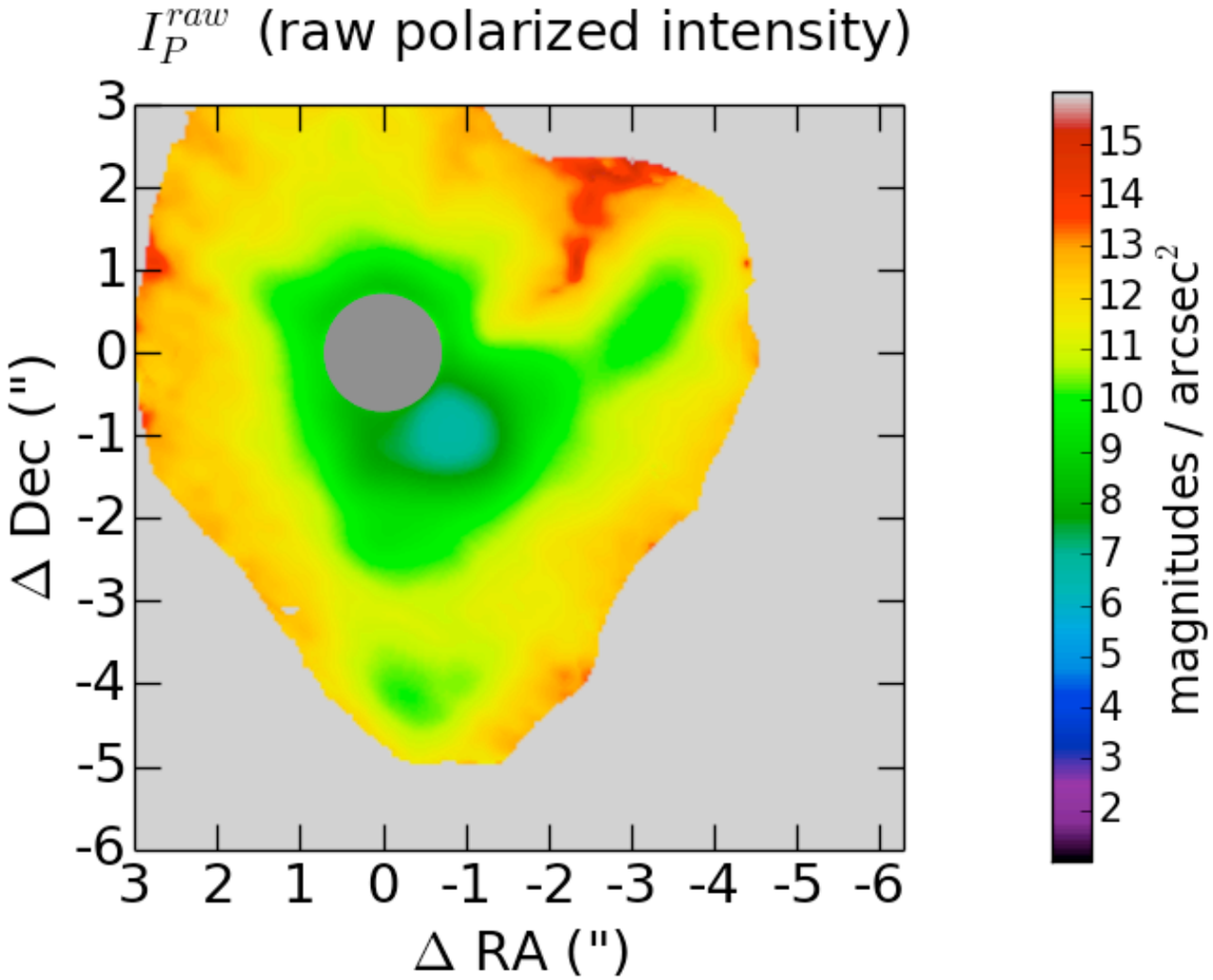


Shenoy et al. (2015)

intrinsic fractional polarizations of 35% - 60%

VY CMa with MMT-Pol: 1.3 μm



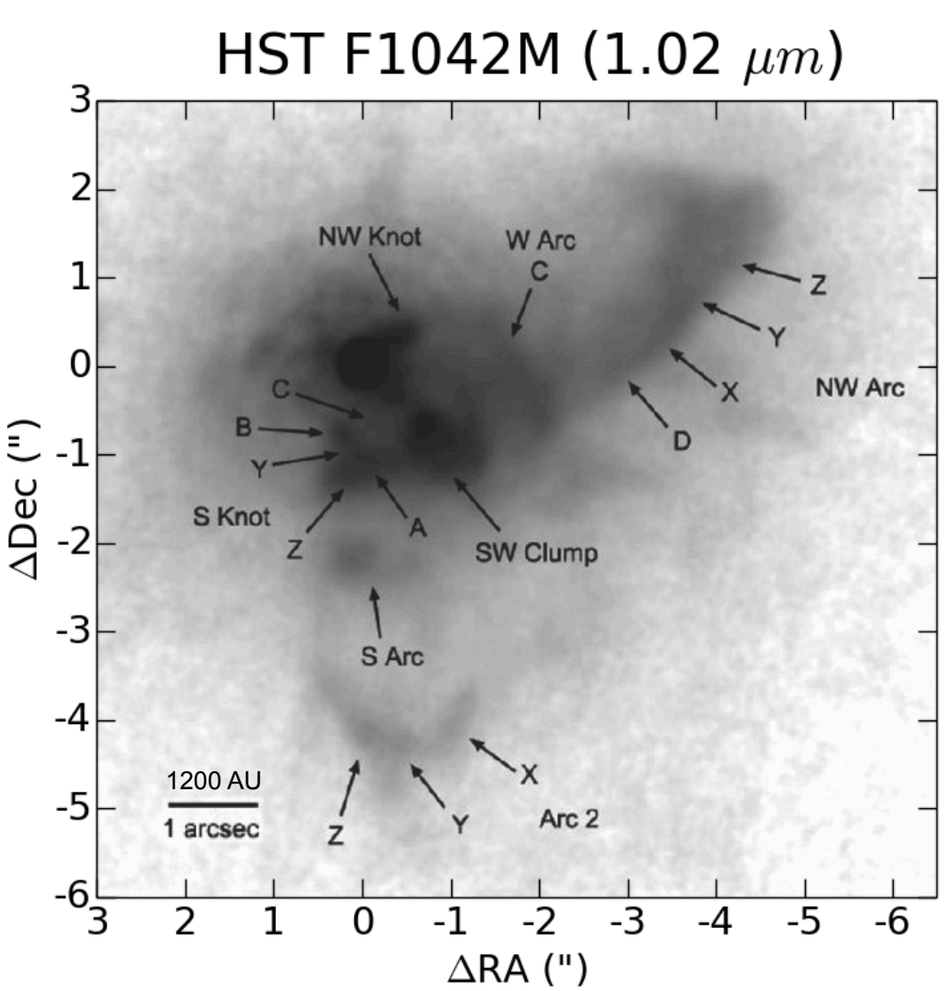


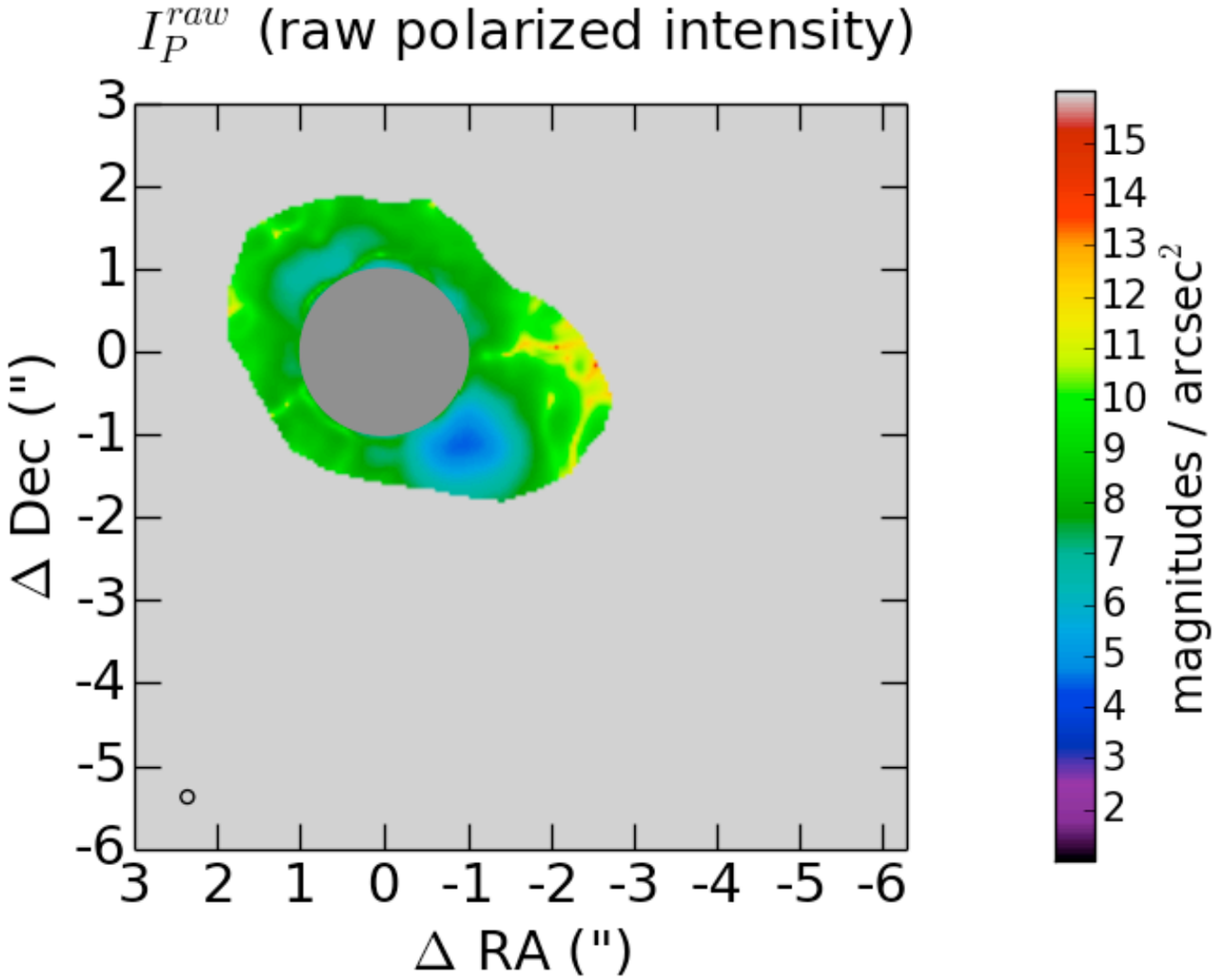
Shenoy et al. (2015)

polarized intensity ≤ total scattered light intensity

$\tau_{scat,\ pol.\ intens.} \leq \tau_{scat}$

VY CMa with MMT-Pol: 3.1 μm





Shenoy et al. (2015)

polarized intensity ≤ total scattered light intensity

$\tau_{scat,\ pol.\ intens.} \leq \tau_{scat}$

Intrinsic Polarization vs. Minimum τ_{scat}

Feature	λ (μm)	intrinsic p (%)	minimum τ_{sc}
VY CMa			
NW Arc	J′ (1.3)	35%	0.7
Arc 2	J′ (1.3)	45%	1.0
S Knot	J′ (1.3)	60%	0.8
S Arc	J′ (1.3)	60%	0.5
SW Clump	J′ (1.3)	40%	1
SW Clump	3.1	40%	0.3
IRC +10420			
Nebula Az. Avg.	2.2	30%	0.4

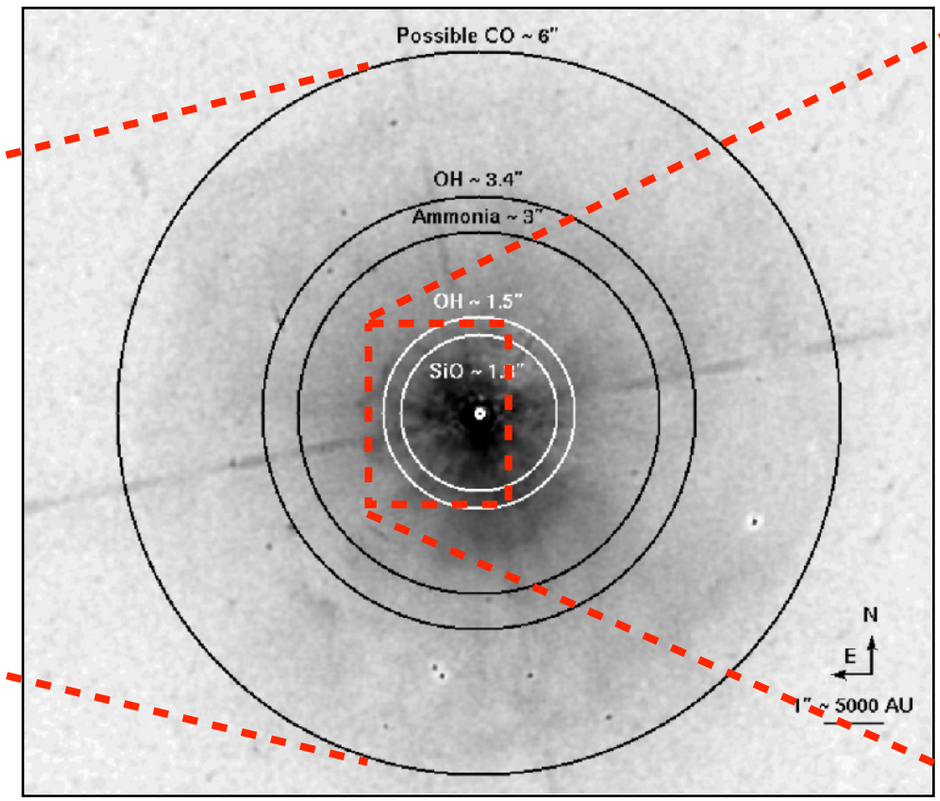
Reconciled if ω ≲ 0.4 (White 1979: $p_{opt\ thick} \approx 0.7\ p_{single\ scat}$)

IRC +10420 (Context)

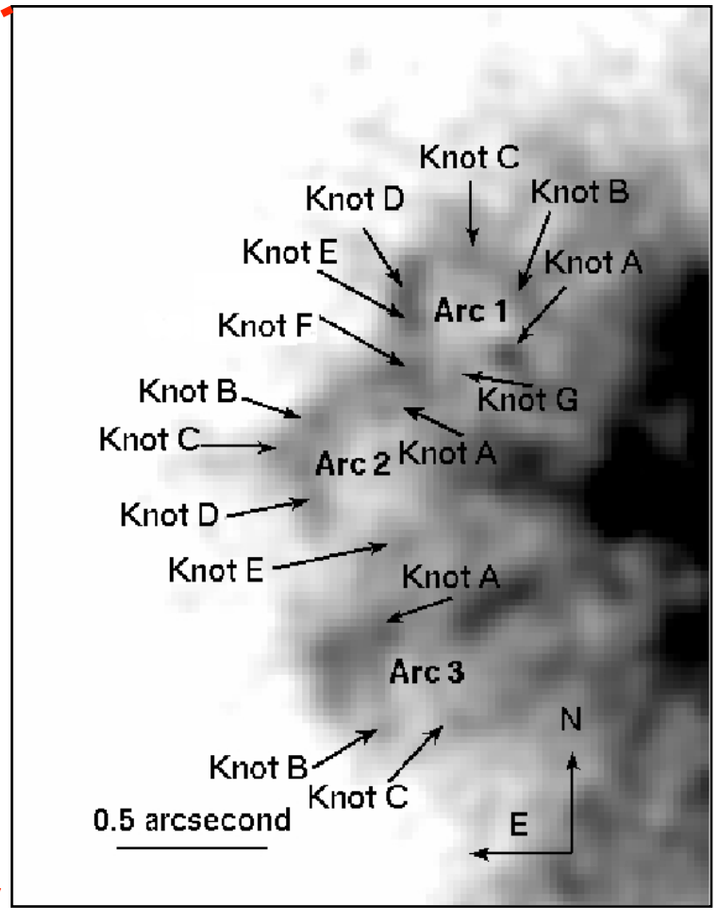
HST & spectra: Numerous arcs & loops ejected at different times in different directions→ associated with surface activity?

OH masers: imply *B* ~ 100 G @ surface
(compare Vlemmings 2002, 2005 for VY CMa & other RSGs)

HST image

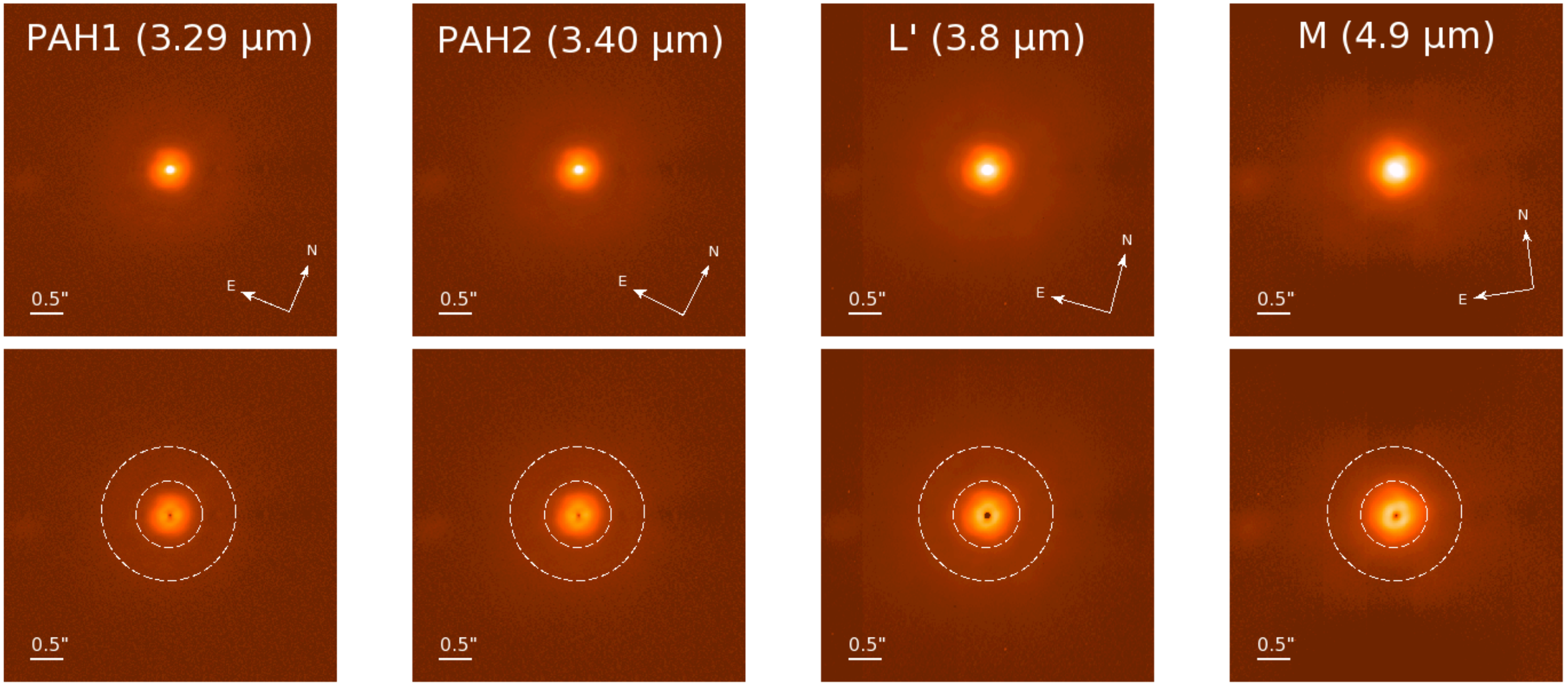


locations of masers



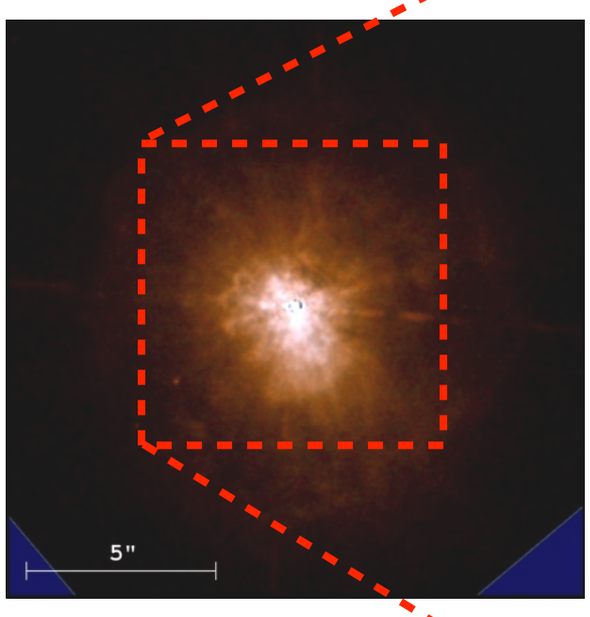
We view IRC +10420 nearly pole-on: Tiffany et al. 2010 (visual); Oudmaijer & de Wit 2013 (2.166 μm Br-ɣ).

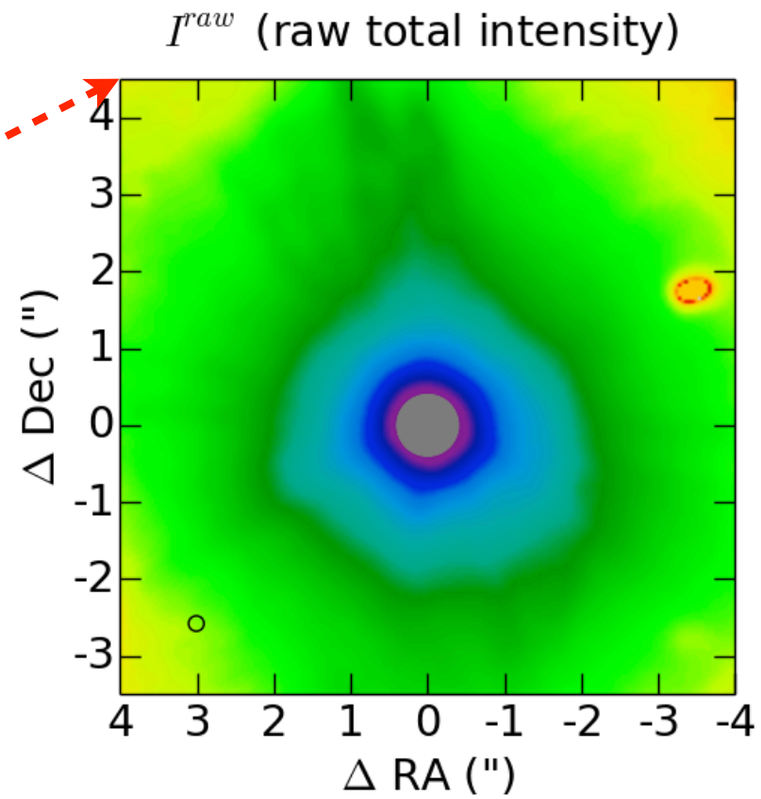
IRC +10420 with LMIRCam: 3 – 5 μm

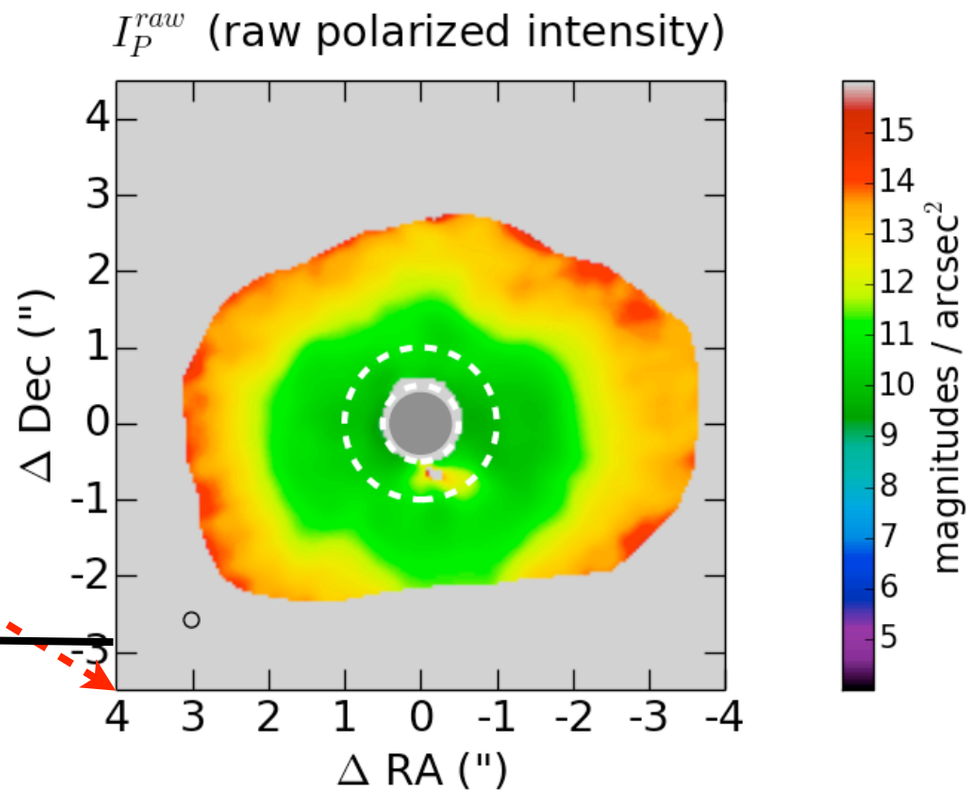


Shenoy et al. (2015)

IRC +10420 with MMT-Pol: K′ (2.2 μm)

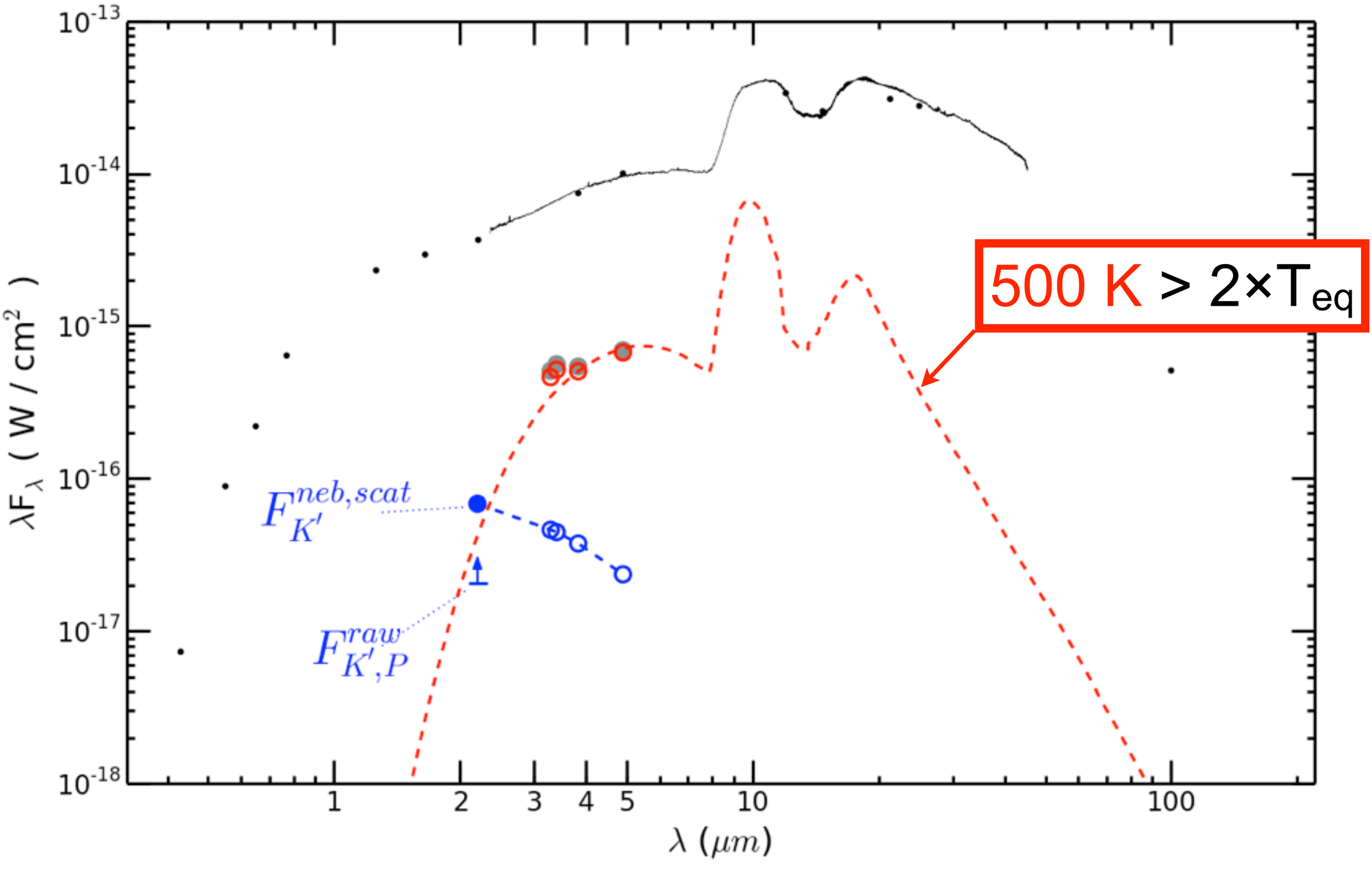






View: pole-on
Minimum τ_{scat} ~ 0.4

IRC +10420: Nebula from 2 – 5 μm



Summary

In general

• high intrinsic *p* (35 - 60%) optically thick scattering.

VY CMa

• Optically thick scattering with *minimal* thermal emission

• SW Clump: optically thick 2 − 5 μm → $M_{gas+dust} > 5 \times 10^{-3}\ M_{\odot}$

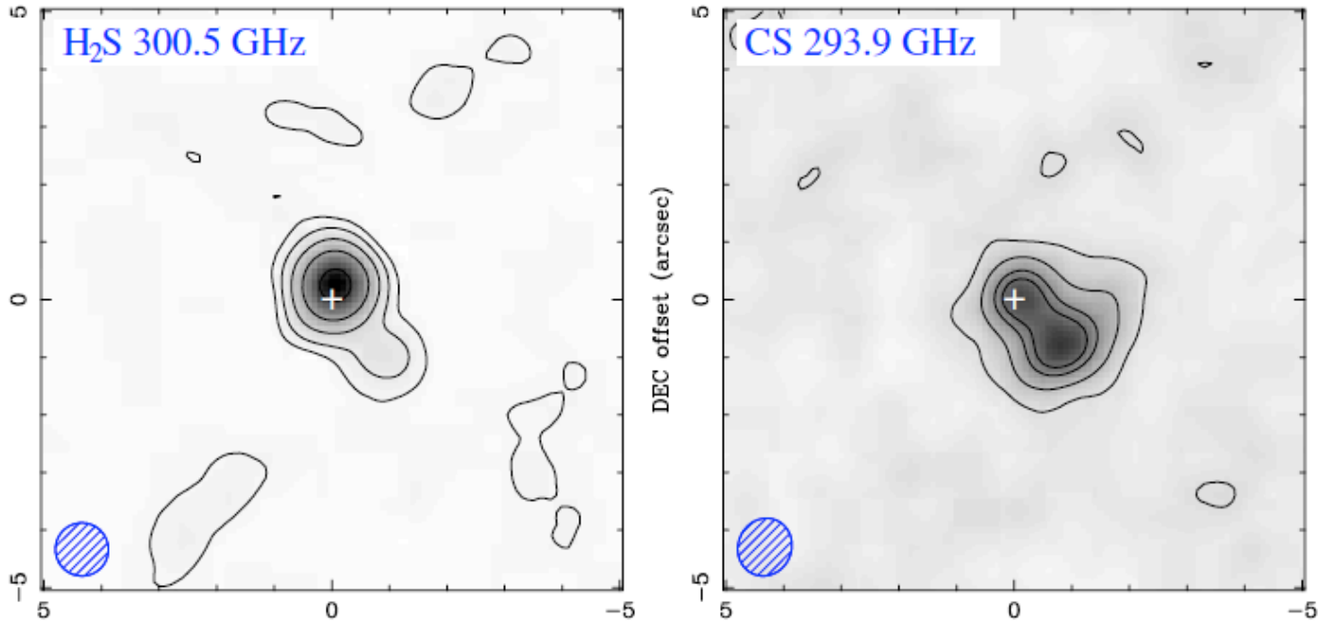
IRC +10420

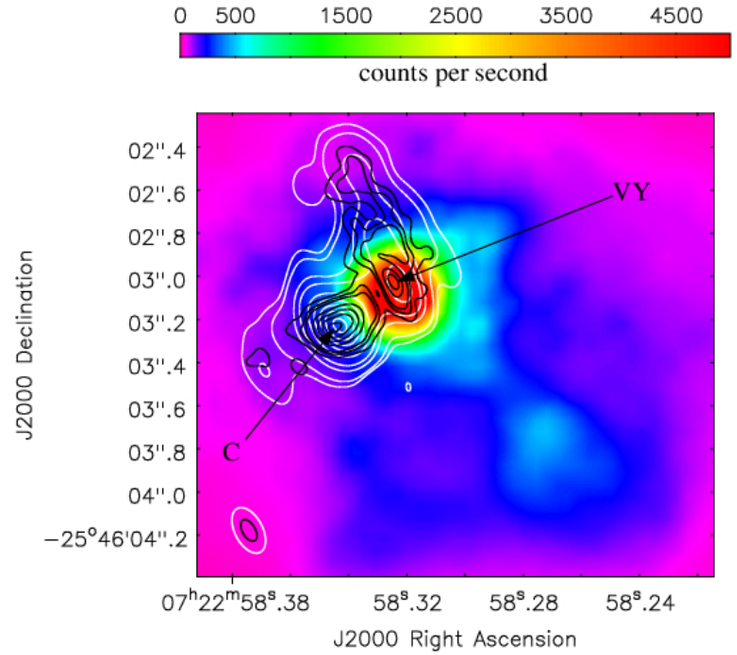
• Polarimetry: 2.2 μm nebula consistent with pole-on view of star

• Optically thick scattering is *mostly* thermal emission (> 2 × T_{eq})

(SUPPLEMENTARY SLIDES)

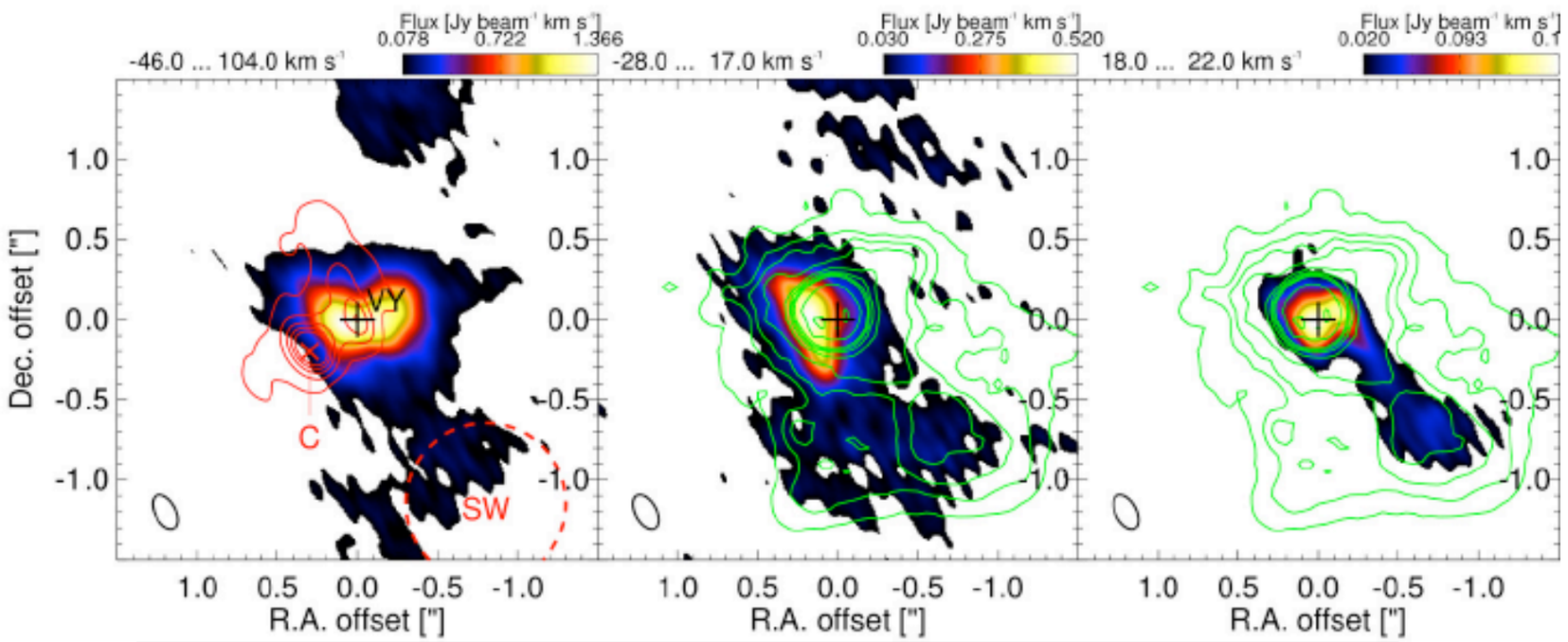
VY CMa: SW Clump in Sub-MM and Molecules





H_2S & CS: Kaminski et al. (2015), ApJS 209, 38

321 & 658 GHz: O'Gorman et al. (2015), A&A 573, L1



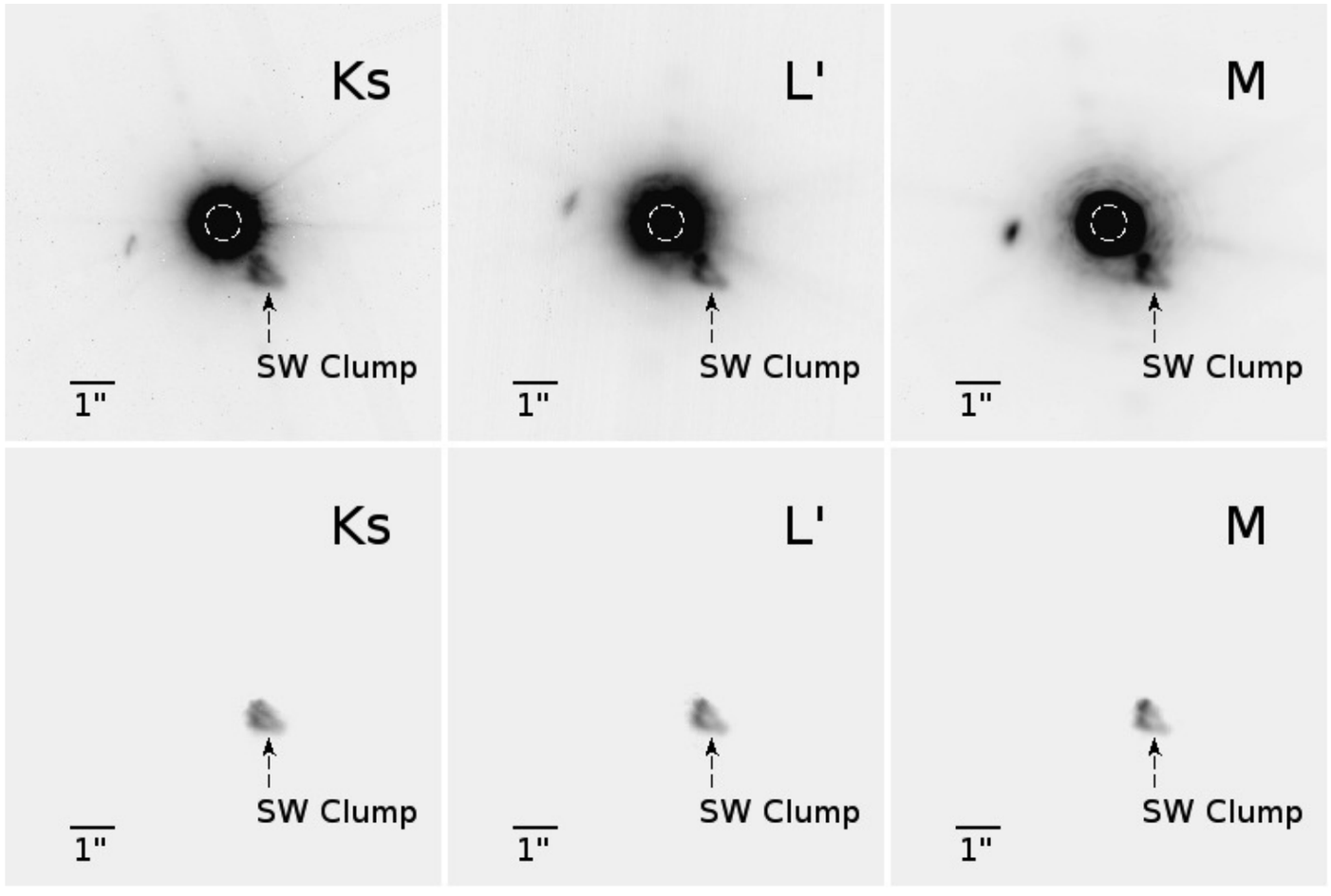
TiO_2 @ 312 - 314 GHz: de Beck et al. (2015), arXiv:1506.0081v1

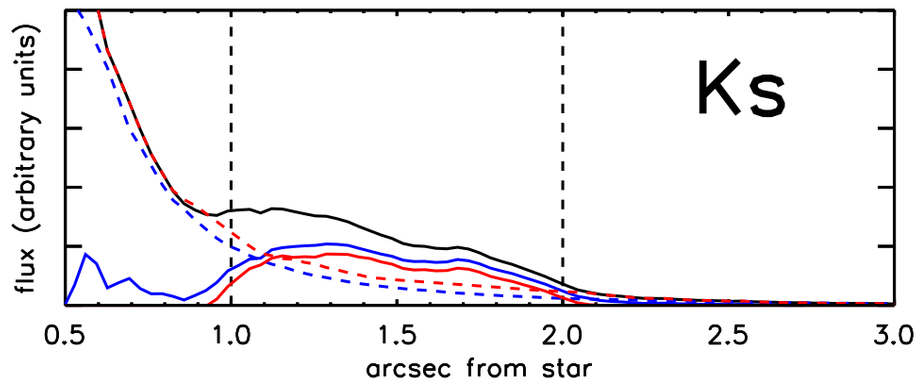
Polarimetry: Formulae

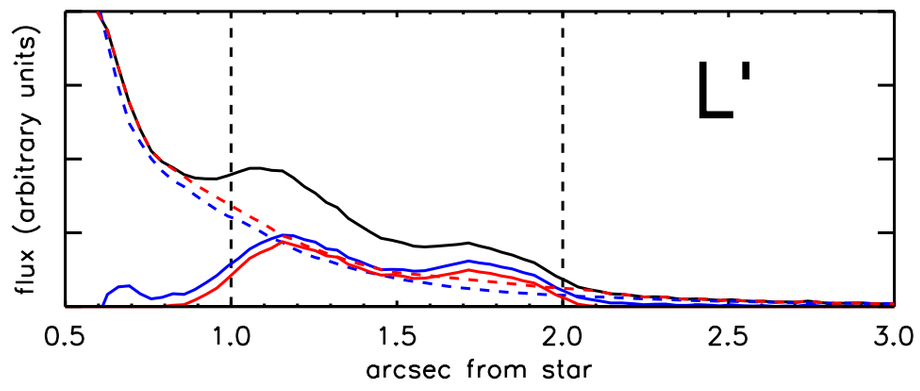
$$p = \frac{I_P^{raw}}{I_{tot}^{raw}} \quad ; \quad \theta = \frac{1}{2}\tan^{-1}\left(\frac{Q}{U}\right)$$

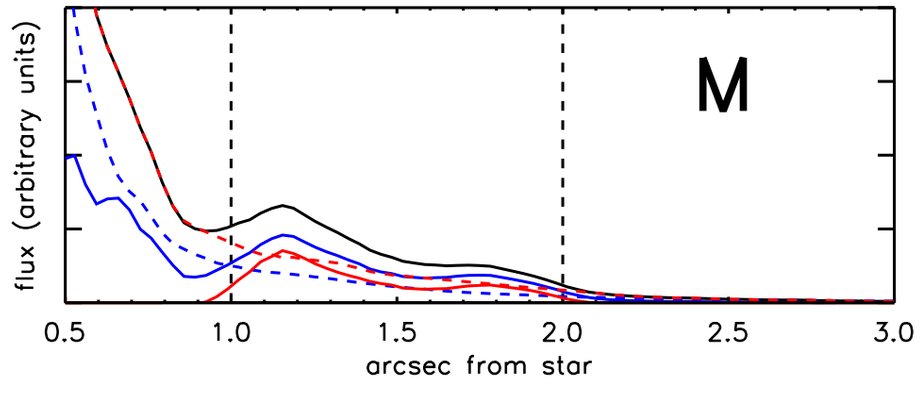
$$Q = I_0 - I_{90} \quad ; \quad U = I_{45} - I_{135} \quad \longrightarrow \quad I_P^{raw} = \sqrt{Q^2 + U^2}$$

VY CMa / LMIRCam: Removing Star's Light Profile

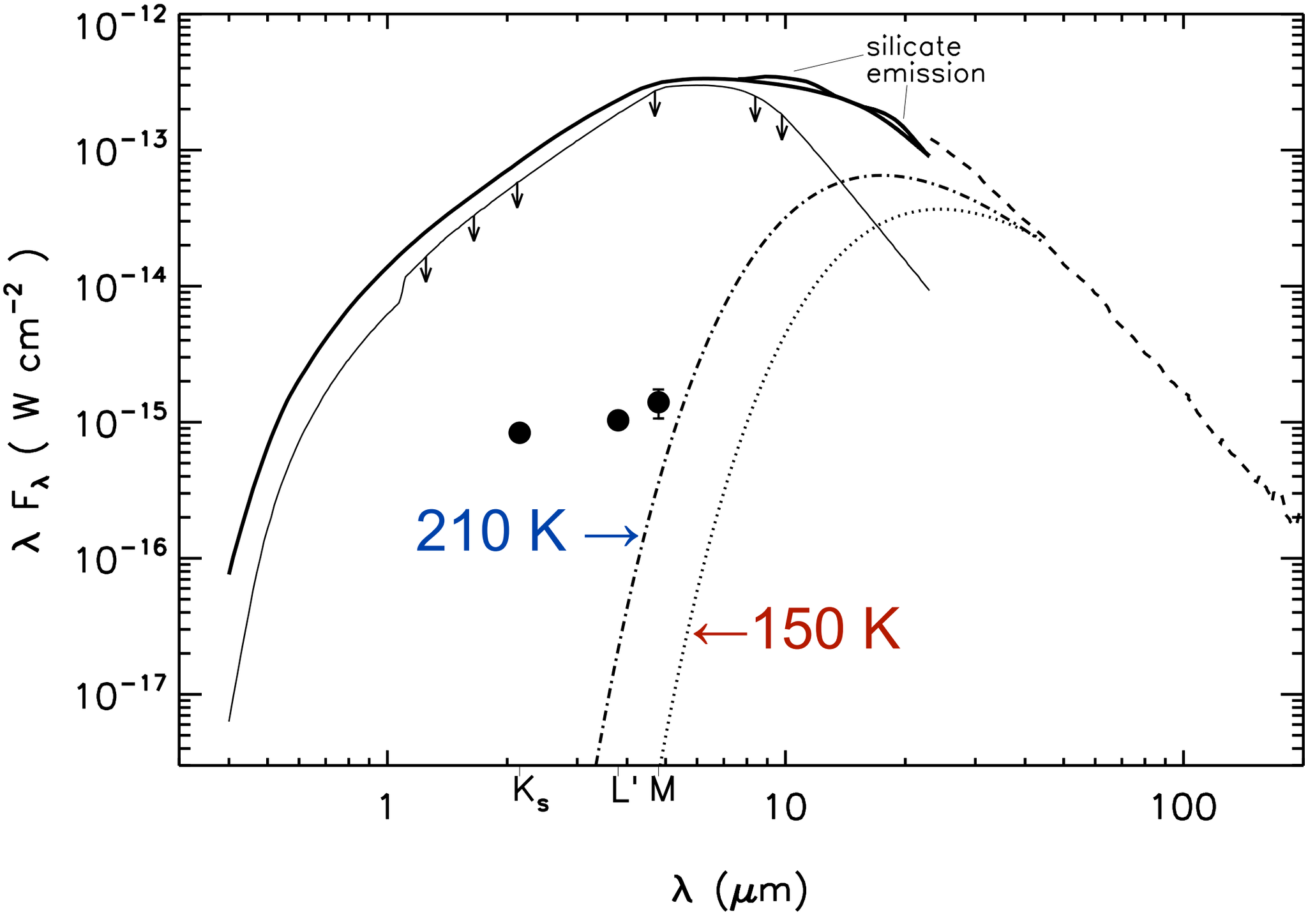




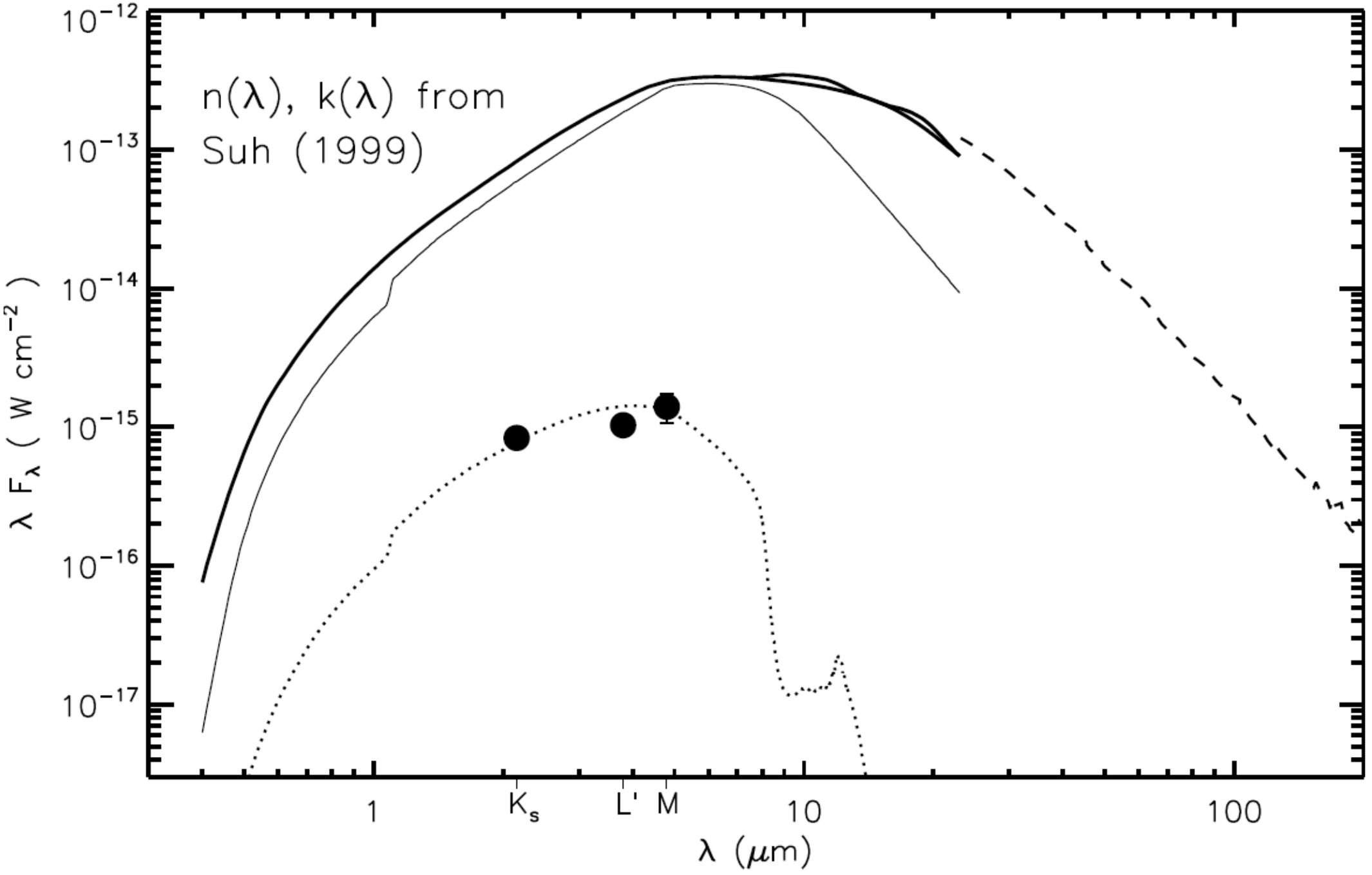




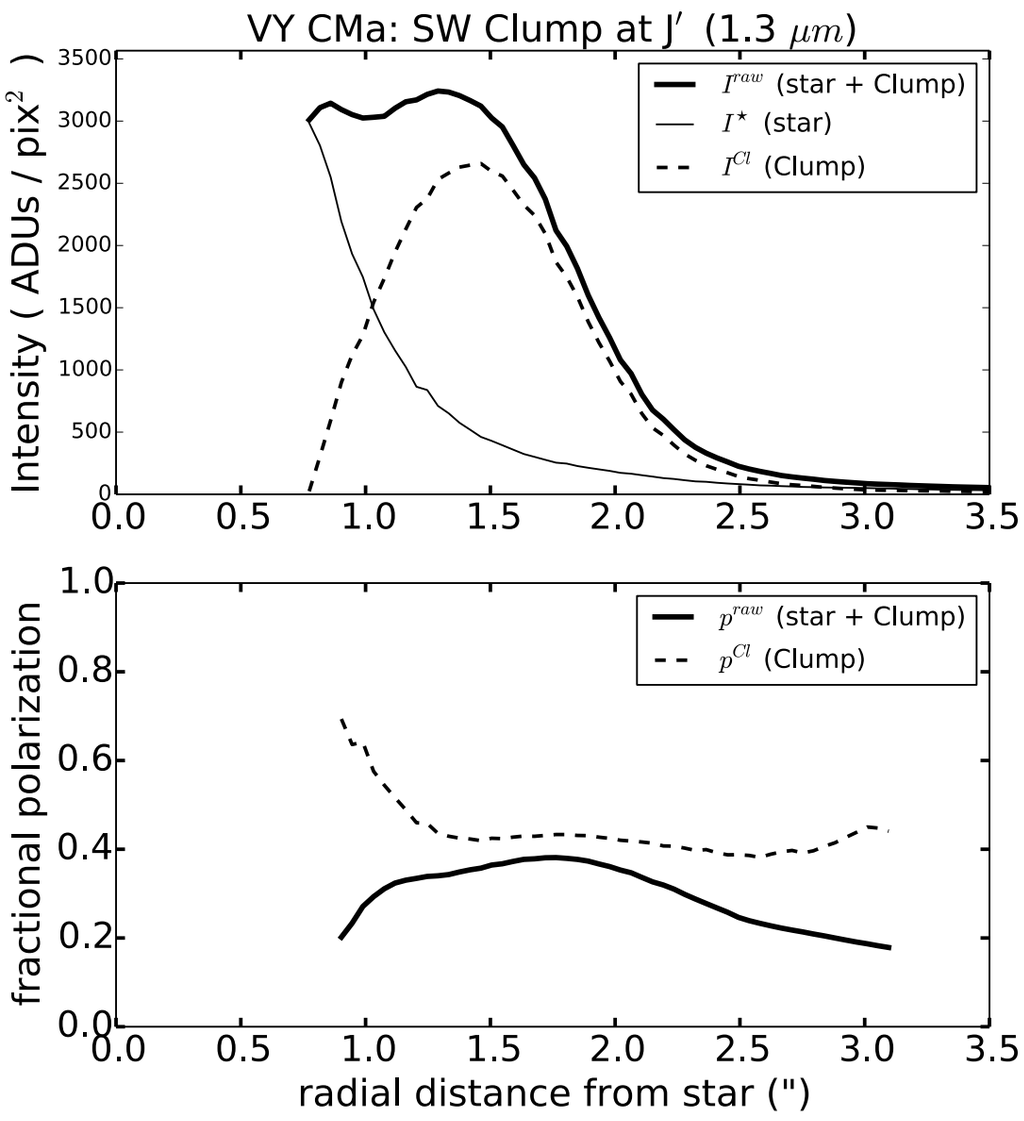
VY CMa: SW Clump's Flux Must Be Scattered Light

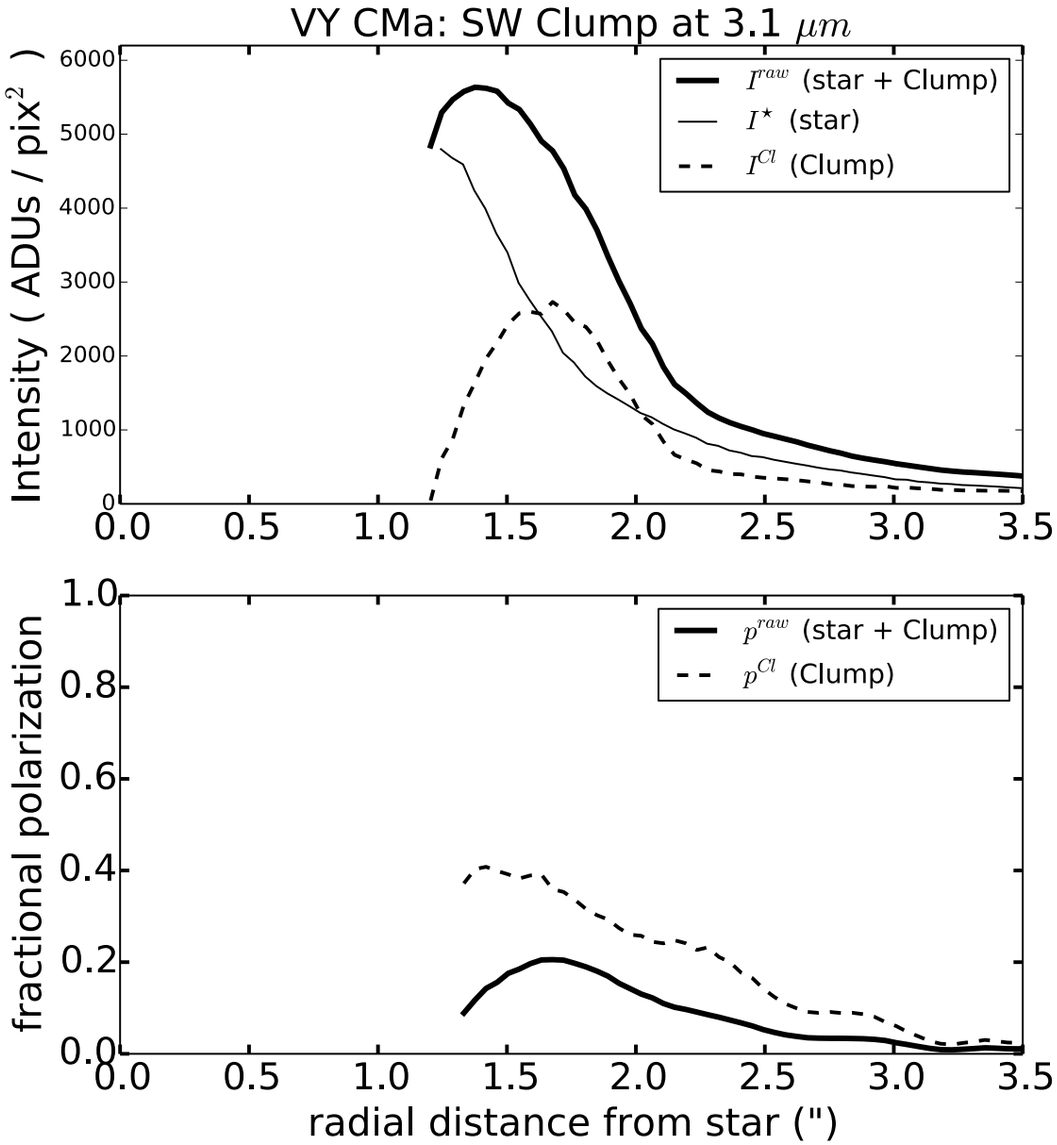


VY CMa SW Clump: Scattered Light Requires $a \approx 0.3\ \mu m \rightarrow M > 5 \times 10^{-3}\ M_{\odot}$

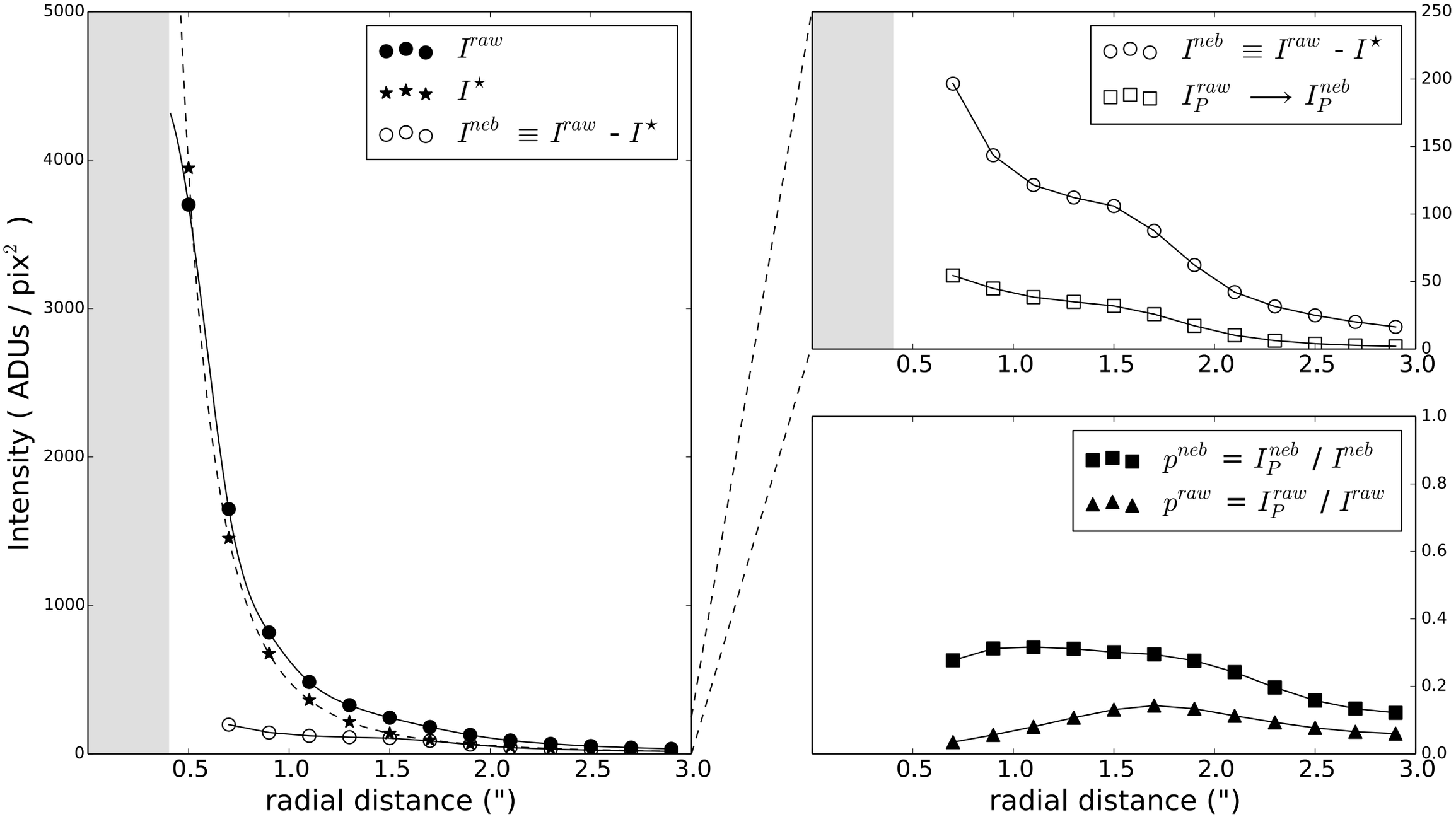


VY CMa / MMT-Pol: Removing Star's Light

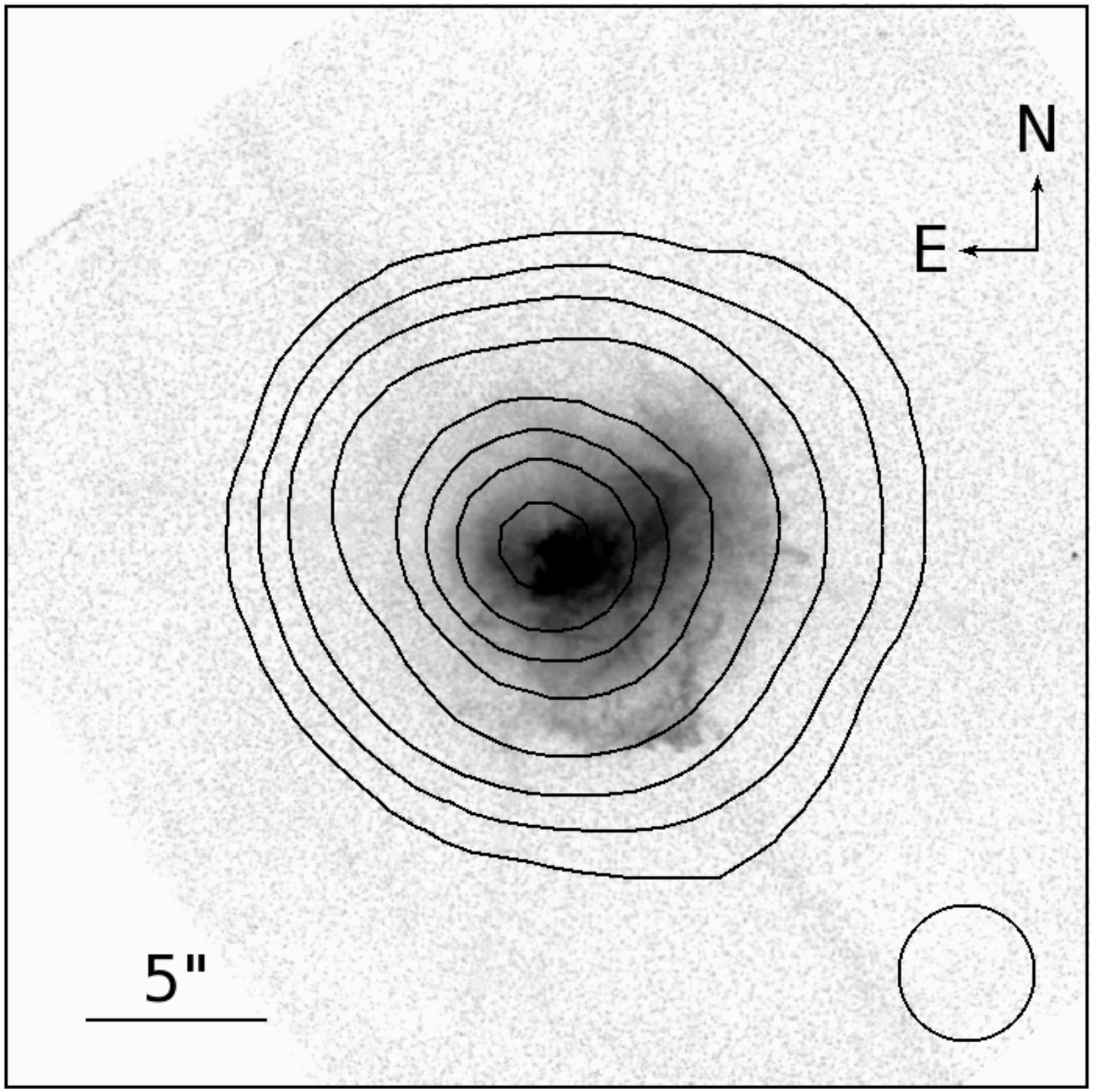




IRC +10420 / MMT-Pol: Removing Star's Light



Future Work: Arc 1, NW Arc Sweeping Up?



Shenoy et al., 2015 (submitted)