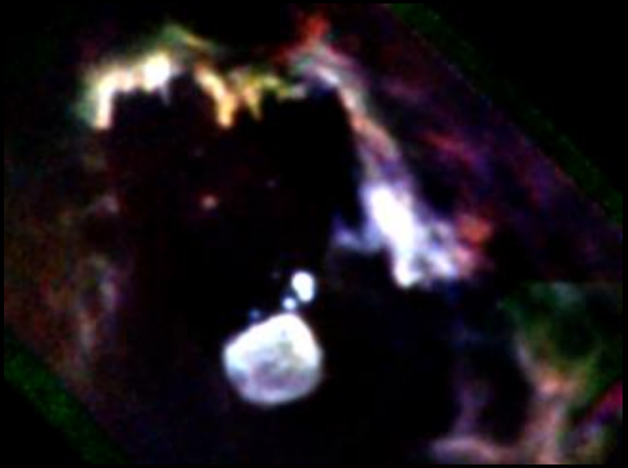
Infrared Observations of the Quintuplet Proper Members with SOFIA/FORCAST



SOFIA/FORCAST 25, 31, & 37 μm

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SOFIA community Tele-Talk

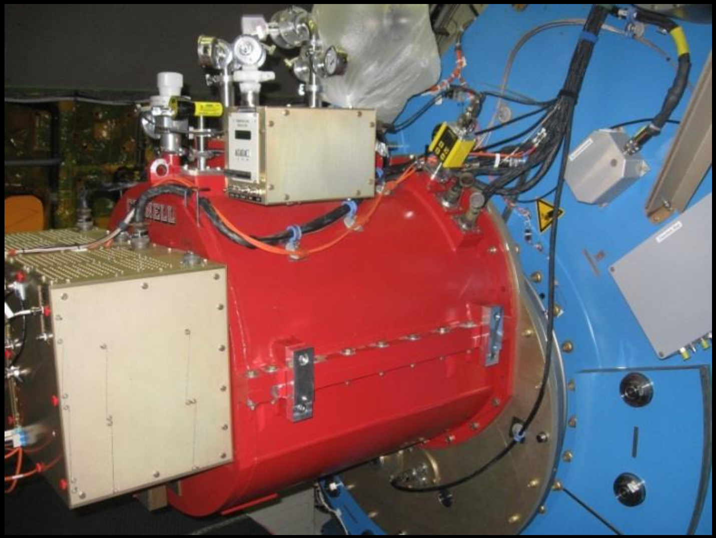
September 7, 2016

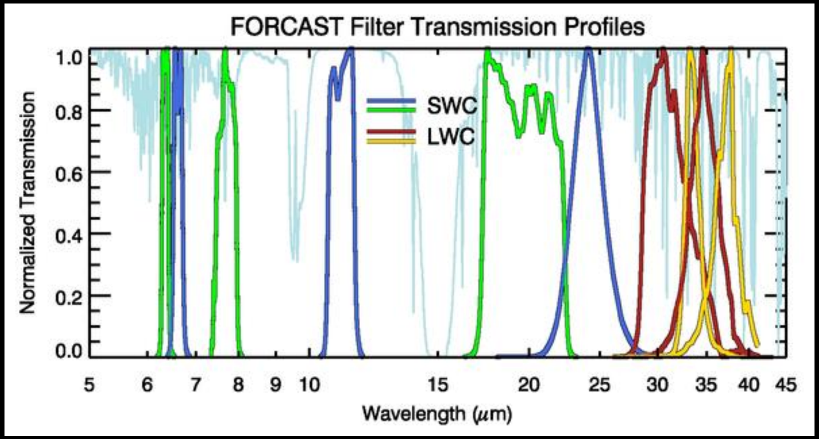
Outline

- Background & Motivation:
  - What are the Quintuplet Propter Members (QPMs) and why are they so interesting?
- This work:
  - Observations of the QPMs with SOFIA/FORCAST at 19.7, 25.2, 31.5, 37.1 μm
  - Characterizing the dust emission from the QPMs
  - Develop models to constraining the luminosities & dust masses of the QPMs
  - Comparing the QPMs with the population of similarly classified objects
- Future work:
  - Prospective observations with SOFIA & VLT

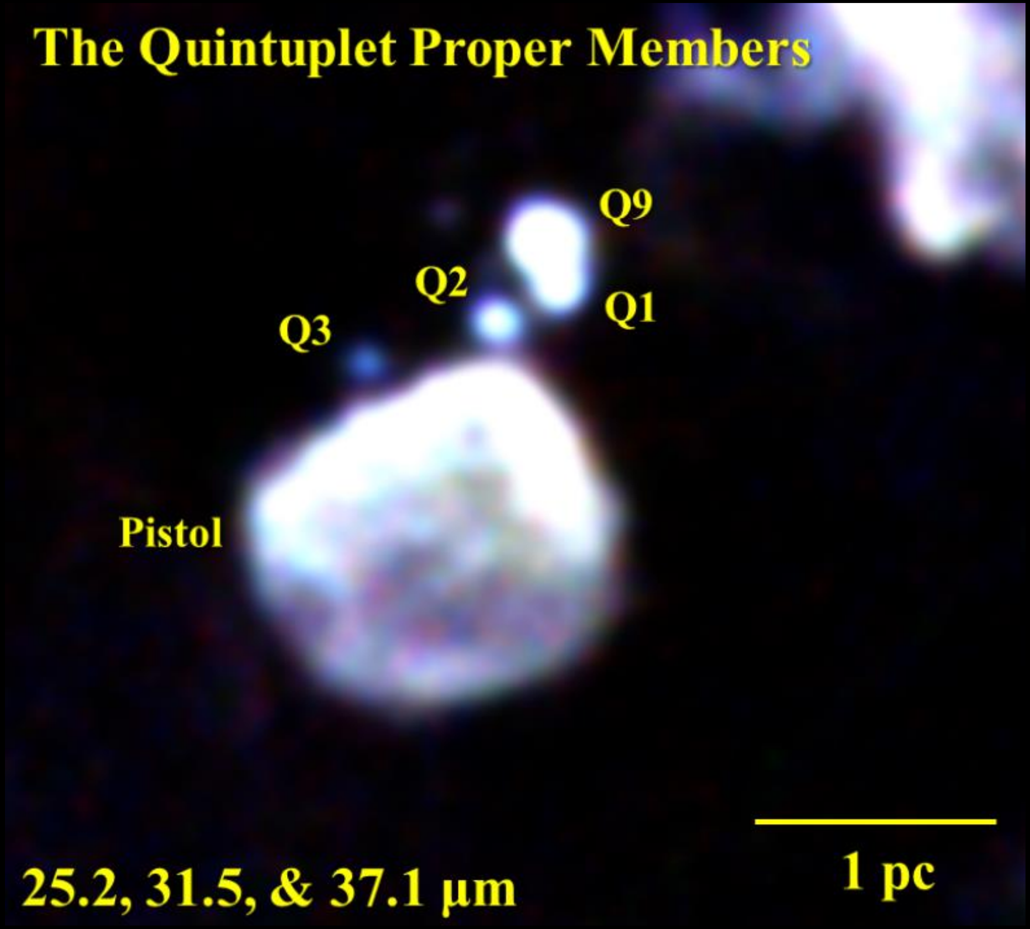
FORCAST

- Dual-Channel 256x256 Camera with Si BIB arrays
  - BIB: Blocked-Impurity-Band
  - 5-25 μm with Si:As array
  - 25-38 μm with Si:Sb array
- 3.2×3.2 arcminute FOV
  - Plate scale: 0.768”/pixel
- Selectable filters over the 6 - 37 μm range





The Quintuplet Proper Members (QPMs)



- Characteristics:
  - Bright mid-IR sources (L_{IR}~10^5 L_{sun})
  - Cool characteristic dust temperatures: 400-1000 K
  - Near featureless near-IR spectrum
- Uncertain Classification: YSO?, Evolved Star?, Other?

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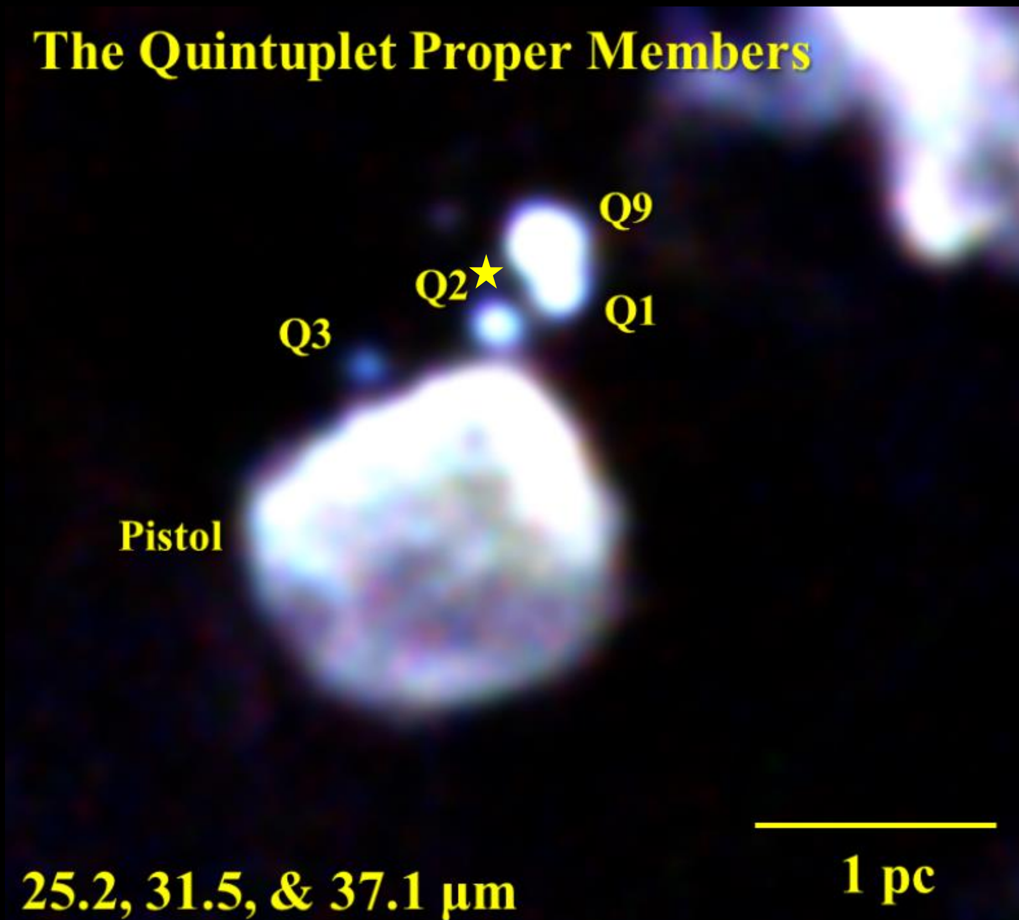

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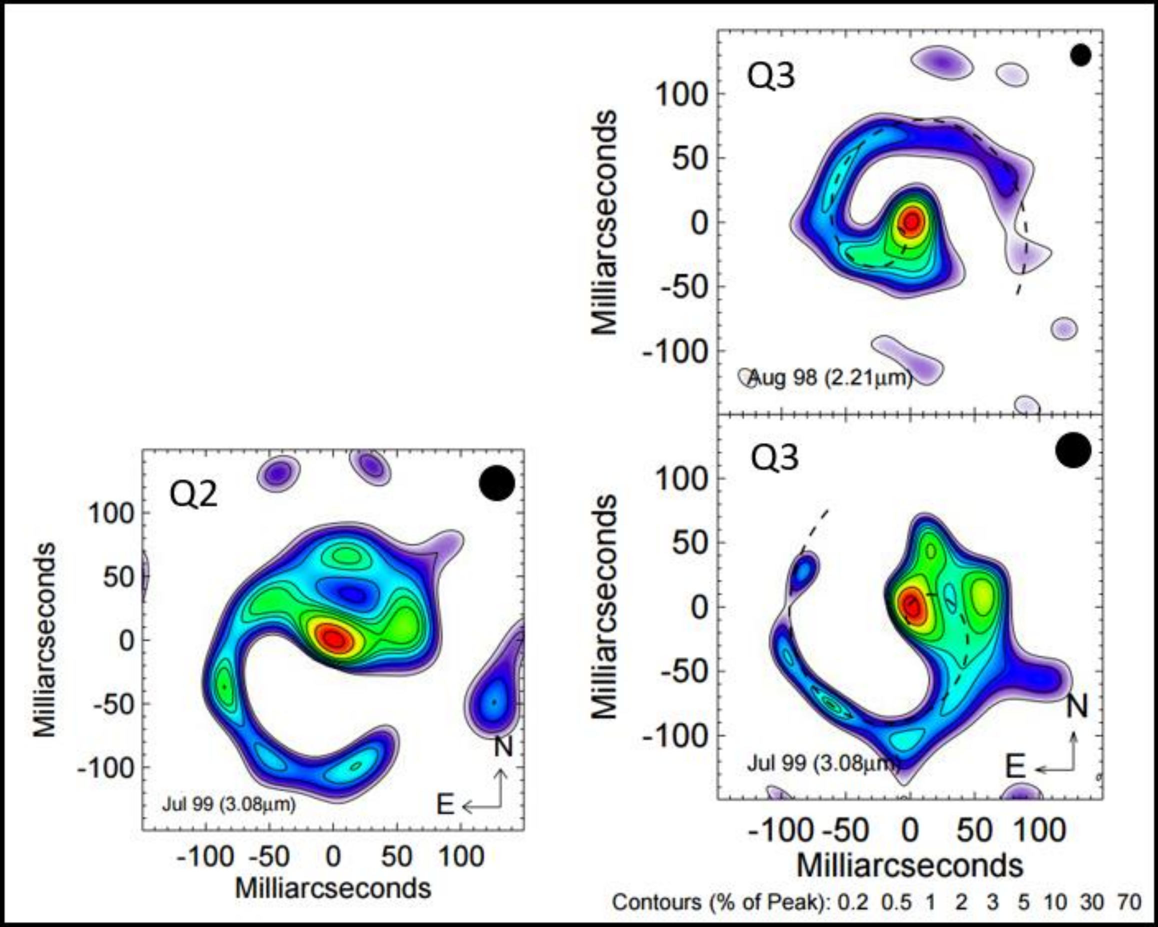
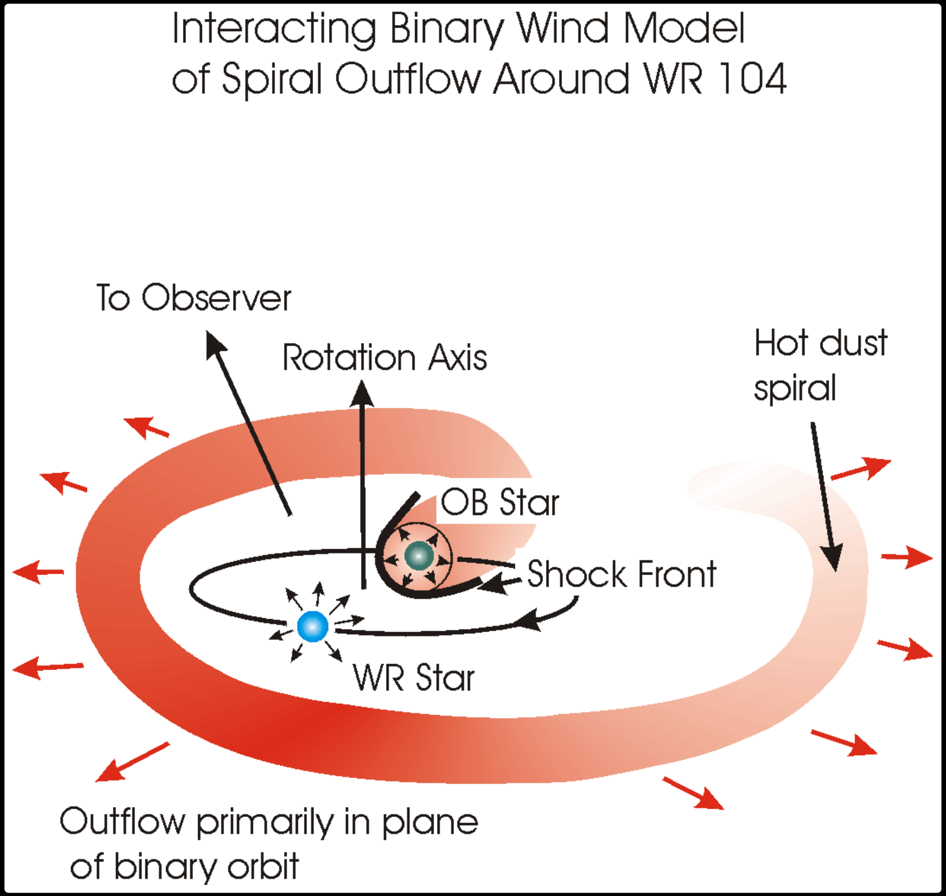
Dusty ‘Pinwheels’ in the Quintuplet Cluster (Tuthill+ 2006)



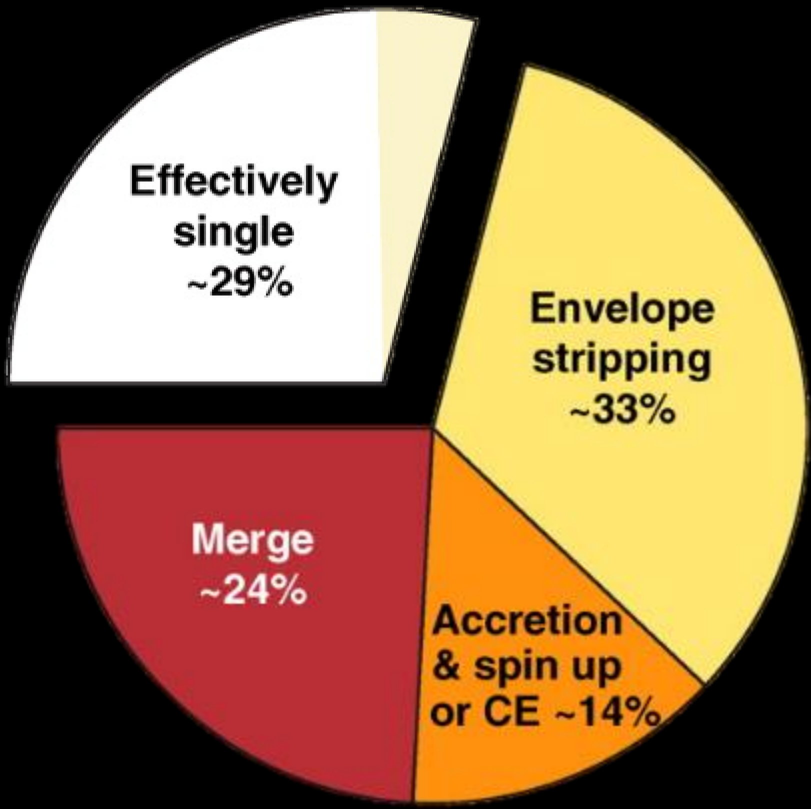
The Anatomy of a Dusty 'Pinwheel' Star



Tuthill+ 1999

- Binary Wolf-Rayet+O/B systems
  - Carbonaceous Chemistry
  - High Densities in wind-wind collision zone
  - Dust formed and shielded in wake of companion's orbit
  - 'Pinwheel' traced by binary orbit

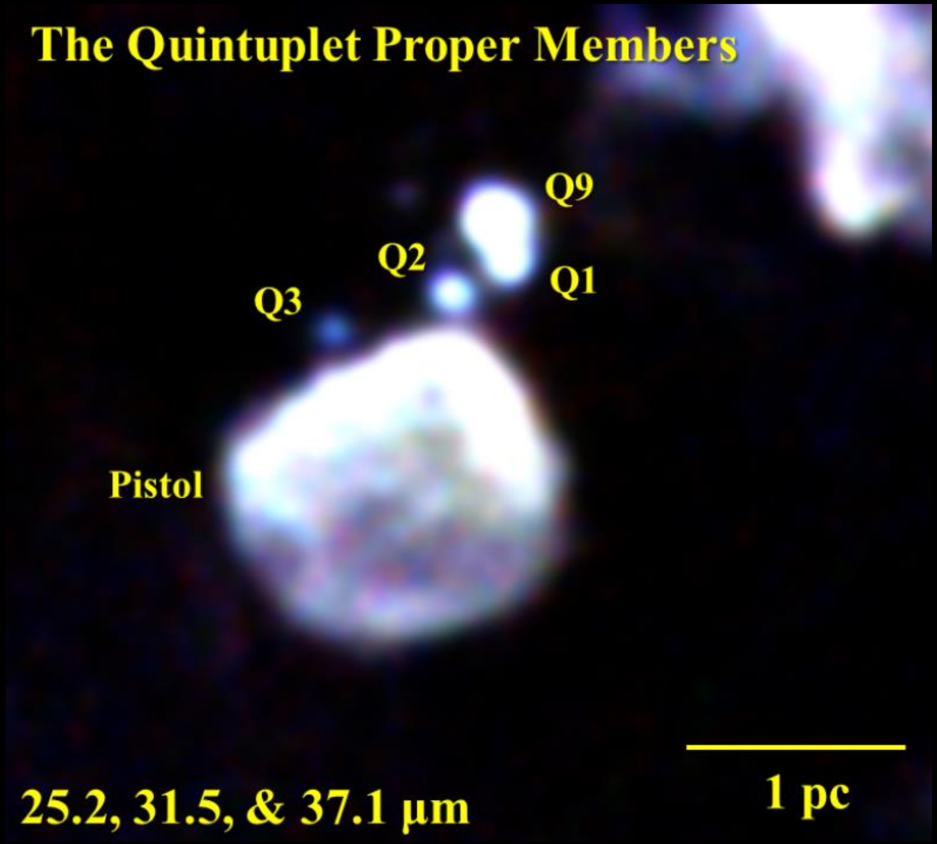
Evolution of Massive Stars: Binary Influence (Sana+ 2012)



Sana+ 2012

- >70% of all massive stars are expected to exchange mass with a companion
  - Mass exchange will effect stellar luminosity & mass-loss rates
  - Binary interaction greatly impacts the evolution of massive stars!

Back to the QPMs…

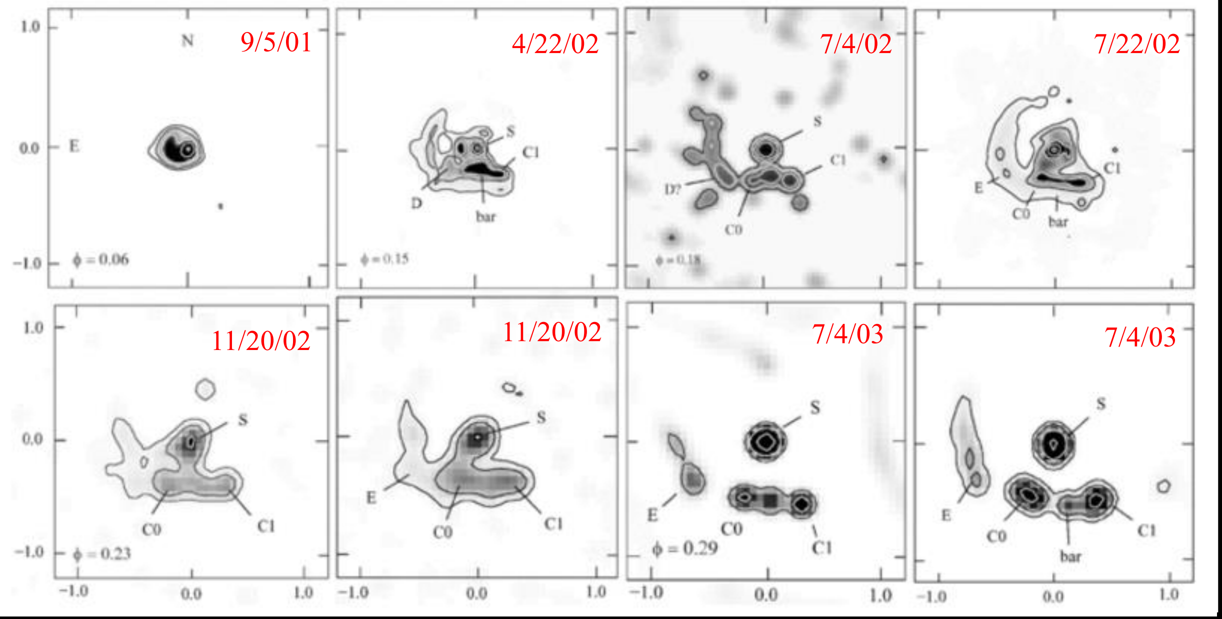


- Goals of Study:
  - SED Models
    - Dust Temperatures
    - Luminosities
    - Dust Masses
  - High spatial resolution imaging
    - Study Morphology
- Improvements over previous studies:
  - Improved wavelength coverage
  - Better spatial resolution

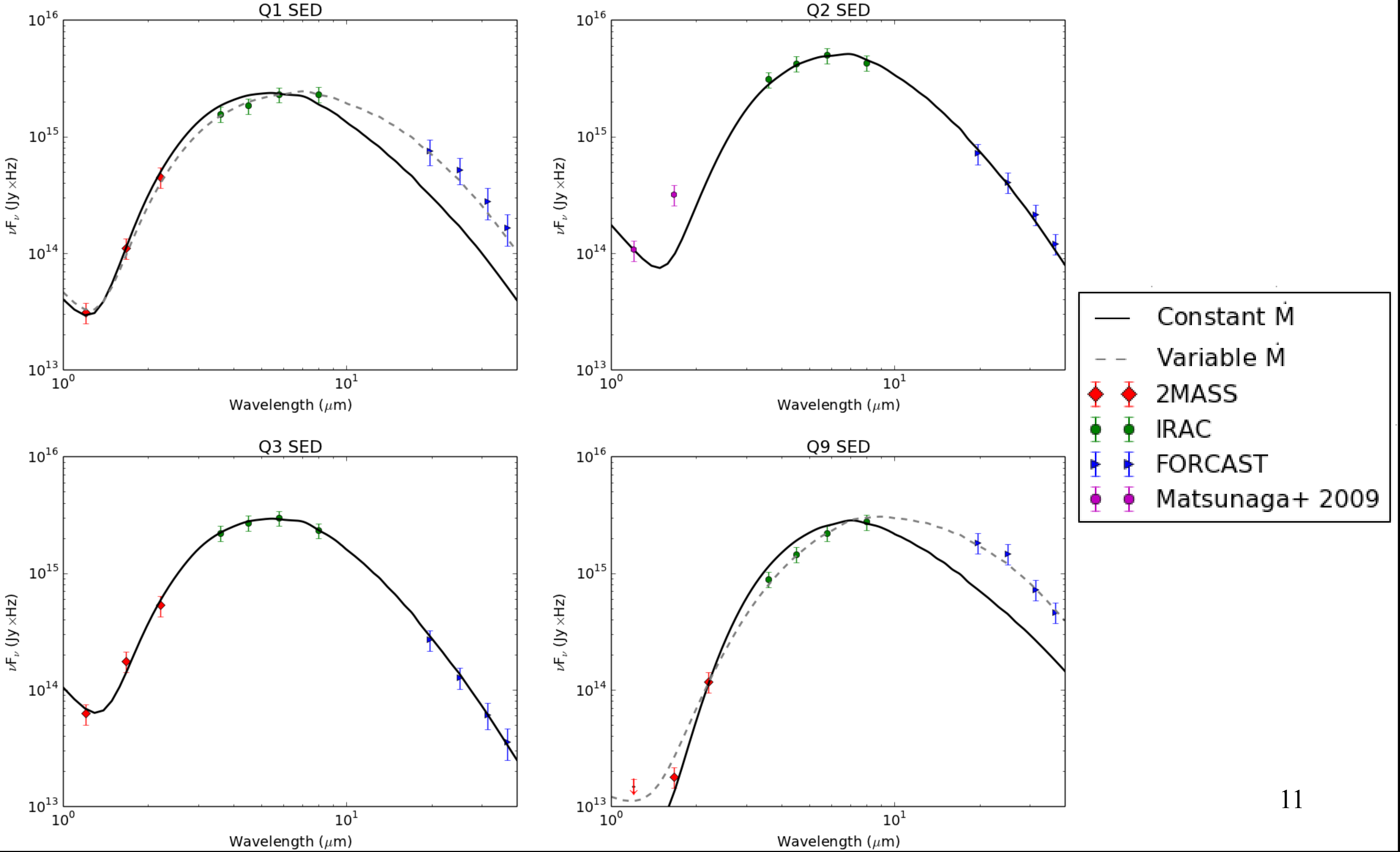
Constructing SEDs: Near-IR Variability of Dusty Wolf-Rayet Stars

- Variability is a sign of eccentric binary system with variable dust production
  - Q2 is the only QPM that shows significant near-IR variability

WR 140 (Williams+ 2008)



DUSTY Models of QPMs



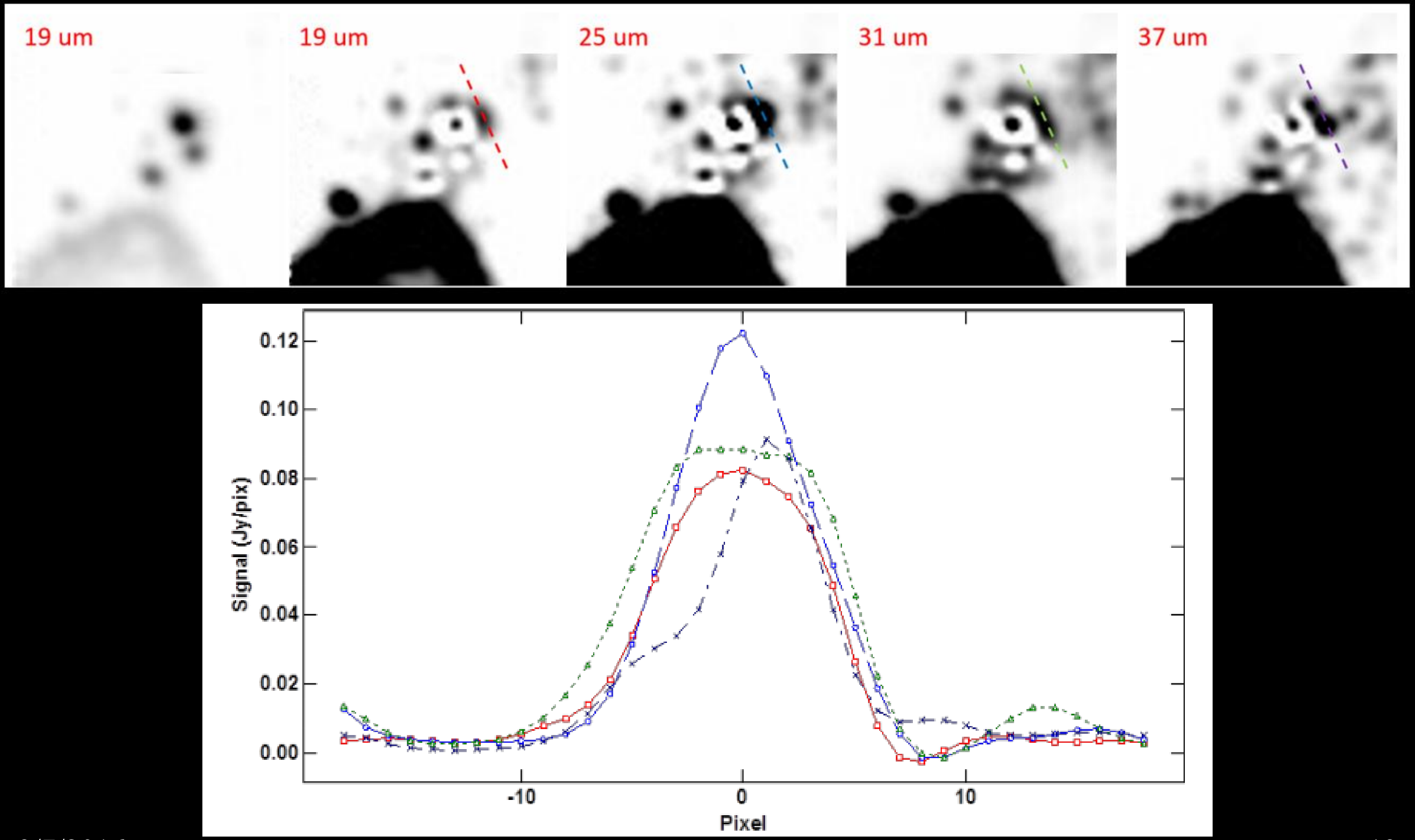
Best-Fit Model Parameters

Best-fit DUSTY Model Parameters

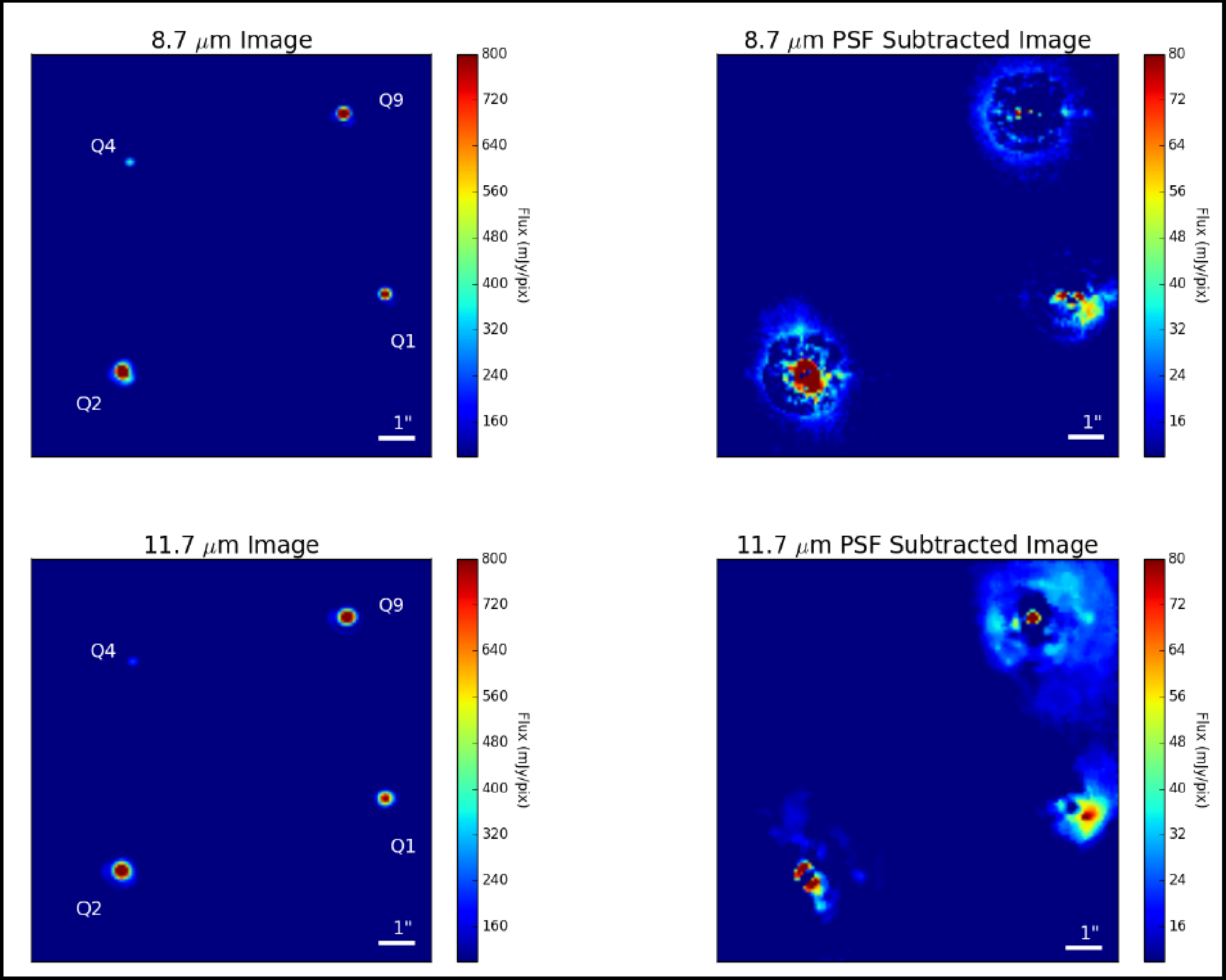
ID	T_0 (K)	α ($r^{-\alpha}$)	M_d ($M_\odot$)	Log($L_{IR}/L_\odot$)	Log($L_\star/L_\odot$)	$L_{IR}/L_\star$
Q1	800±50	1.±0.5	$3.8^{+1.1}_{-1.5} \times 10^{-4}$	4.9	5.2	~0.5
Q2	650±50	2	$1.3^{+0.6}_{-0.5} \times 10^{-4}$	5.1	5.7	~0.25
Q3	750±50	2	$2.4^{+1.3}_{-0.8} \times 10^{-5}$	4.9	5.5	~0.25
Q9	750±80	-1.5±0.5	$1.3^{+0.8}_{-0.4} \times 10^{-3}$	5.0	5.0	~1.0

- Q9 and Q1 show departures from a constant mass loss rate
- Q9 and Q1 have large dust covering fractions compared to expected value for disks
- Dust reservoir present in Q9 is quite massive!

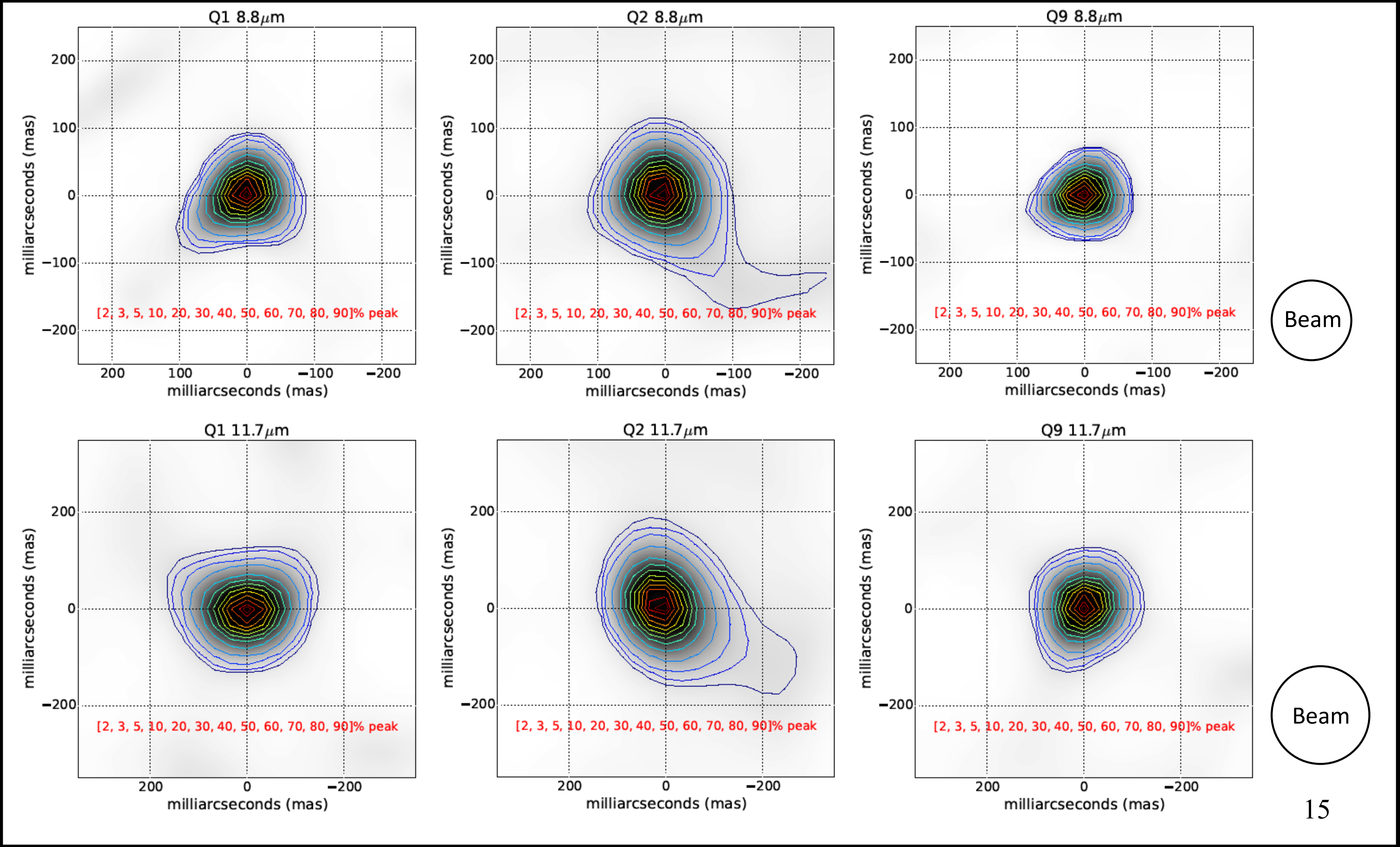
Morphology of the QPMS: The Extended Nature of Q9



Gemini/TReCs Observations of the QPMs



High-Resolution Gemini/TReCs SAM Observations



Constraining Dust Sizes in the QPMs

Best-fit Gaussian Model

Parameters	Q2 8.8μm	Q2 11.7μm	Q9 8.8μm	Q9 11.7μm	Q1 8.8μm	Q1 11.7μm
FWHM [mas]	105$\pm$4.45	128$\pm$7.29	58$\pm$6.39	88$\pm$6.02	73$\pm$3.48	126$\pm$5.01
V_0^2 (zero-spacing)	0.81$\pm$0.01	0.69$\pm$0.02	0.89$\pm$0.01	0.71$\pm$0.01	0.9$\pm$0.01	0.78$\pm$0.01

- DUSTY provides measurements of the expected physical size of emitting region for each model (dependent on dust grain size):
  - Can exclude grains as small as 0.01 μm for Q1 and Q2
  - Poor fits to the small & large size scales measured for Q9
    - Likely an issue with optical depth effects

Characterizing the Sources

Best-fit DUSTY Model Parameters

ID	$\mathrm{Log}(L_{IR}/L_{\odot})$	$\mathrm{Log}(L_{\star}/L_{\odot})$	$L_{IR}/L_{\star}$	M_d ($M_{\odot}$)	$\dot{M}$ ($M_{\odot}$/yr)
Q1	4.9	5.2	∼0.5	$3.8^{+1.1}_{-1.5} \times 10^{-4}$	9.5×10^{-4}
Q2	5.1	5.7	∼0.25	$1.3^{+0.6}_{-0.5} \times 10^{-4}$	3.2×10^{-4}
Q3	4.9	5.5	∼0.25	$2.4^{+1.3}_{-0.8} \times 10^{-5}$	6.0×10^{-5}
Q9	5.0	5.0	∼1.0	$1.3^{+0.8}_{-0.4} \times 10^{-3}$	3.2×10^{-3}

- Stellar luminosities are consistent with carbon Wolf-Rayet (WR) stars (Crowther+ 2006)
- Dust covering factors for Q1 and Q9 are larger than most dusty WR stars (~0.1; Williams+ 1987)
- Dust reservoir in Q9 is more massive than any other dusty WR star in the literature
- Estimated mass loss rates are large for typical WR stars, but the estimates are within a factor of ~3 for radio measurements of Q2 (Lang+ 2005).

Is Q9 Just an Incredibly Dusty WR Star?

- Pros:
  - Classification is similar to the other QPMs which are confirmed WR stars
- Cons:
  - Mass-loss mechanism may be different than other dusty WR stars
    - Large dust covering factor is inconsistent with a disk-like geometry
- Alternative Classifications:
  - LBV?- Unlikely since the dust in Q9 appears purely carbonaceous (Moneti+ 2001)
  - RSG?- Unlikely since the dust in Q9 isn't oxygen rich
  - AGB?- Unlikely based on cluster age (~4 Myr; Leirmann+ 2012)

QPM Summary

- Q2 & Q3 have characteristics that are typical for dusty WR stars
- Q1 & Q9 show large extended structures (~1”) in high-resolution mid-IR imaging
  - Also have density profiles which indicate greater mass-loss rates in the past
- Q9 is fairly atypical for a dusty WR star
  - Mass reservoir is close to an order of magnitude larger than others
    - Imaging and fitted density profile suggests the dust is oriented in shell of material from a previous high mass-loss phase
      - Large mass loss ‘hiccups’ are unknown in the population of dusty WR stars
      - High wind velocity in these systems (1000+ km/s) could quickly sweep away evidences of these types of past outbursts

Future Work: Following up on the QPMs

- SOFIA observations:
  - HAWC+ observations to trace more of the cool dust in the QPMs
  - FIFI-LS observations to better sample the FIR continuum with the chance of detecting fine-structure lines which would constrain the terminal wind velocities
- VLT/VISIR observations
  - Spatially resolved N & Q band observations of Q9 to study the heating & spatial extent of the nebula

Future Work: Searching for Massive Dust Reservoirs Around Other WR Stars

- Future plans to observe additional dusty WR stars with FORCAST & HAWC+ to characterize the dust reservoirs in these types of systems:
  - SOFIA's ability to observe wavelengths longer than 20 μm is invaluable to constraining the nature of warm (~100 K) dust in these kinds of sources
- Planned observations with VLT/VISIR to study the systems with better spatial resolution
  - Current program investigating WR 112 and WR 48a

Thanks For Listening!

Questions?