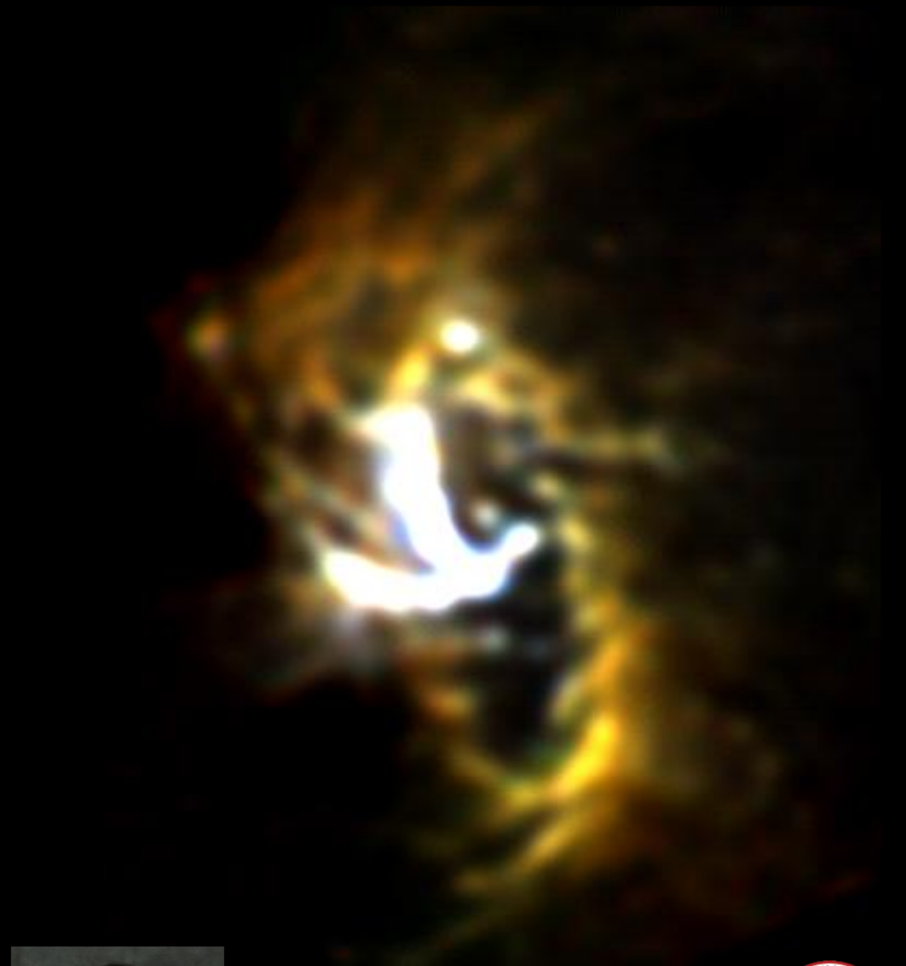
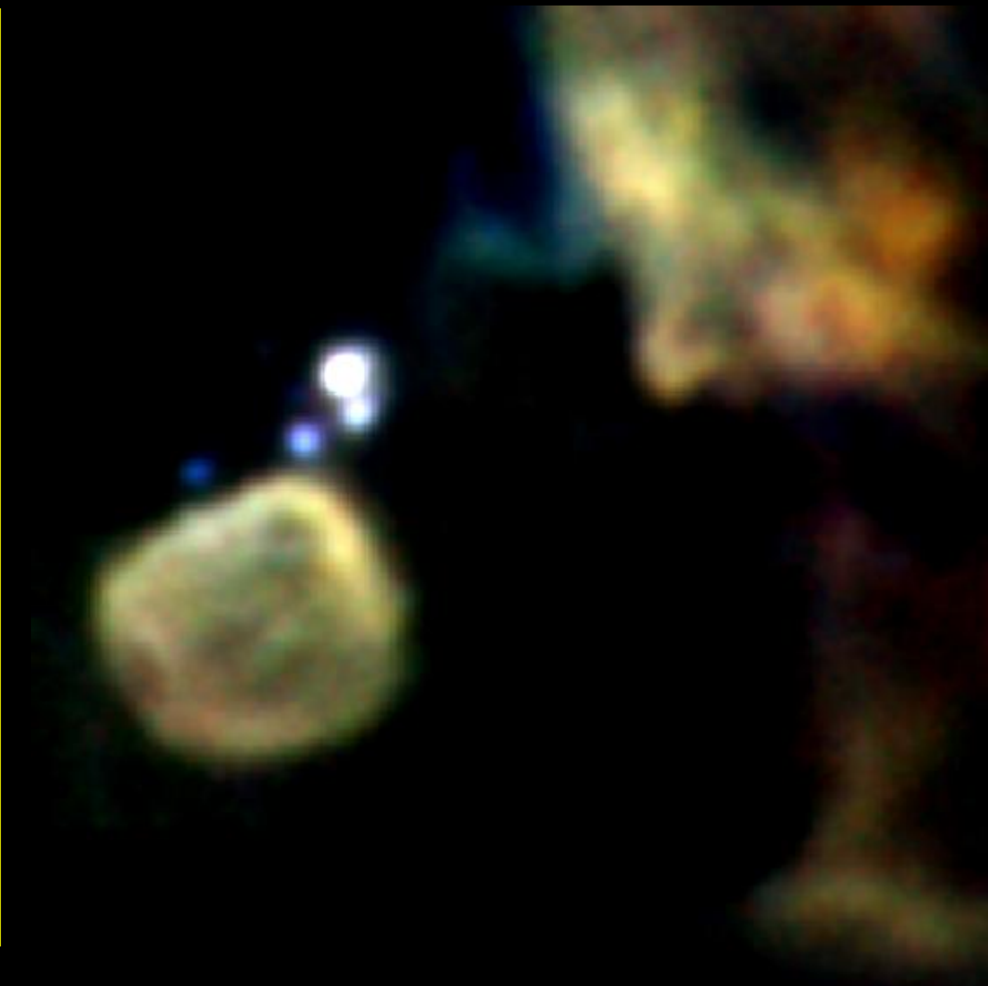
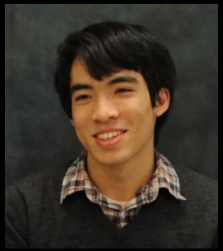
SOFIA/FORCAST Observations of the Galactic Center







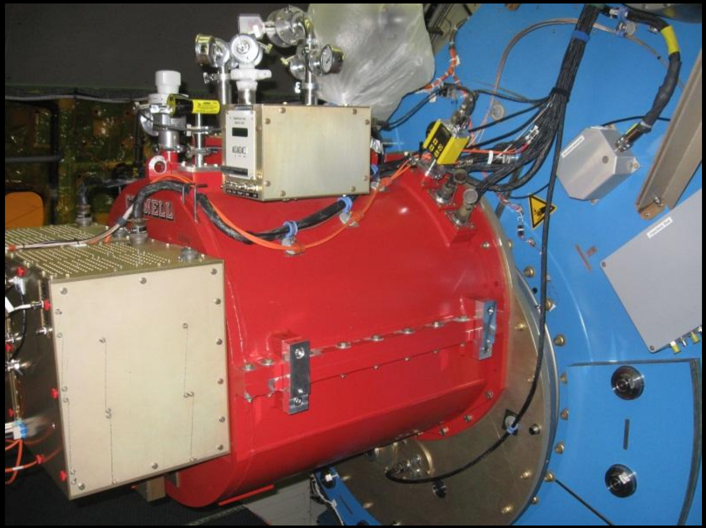
Ryan M. Lau

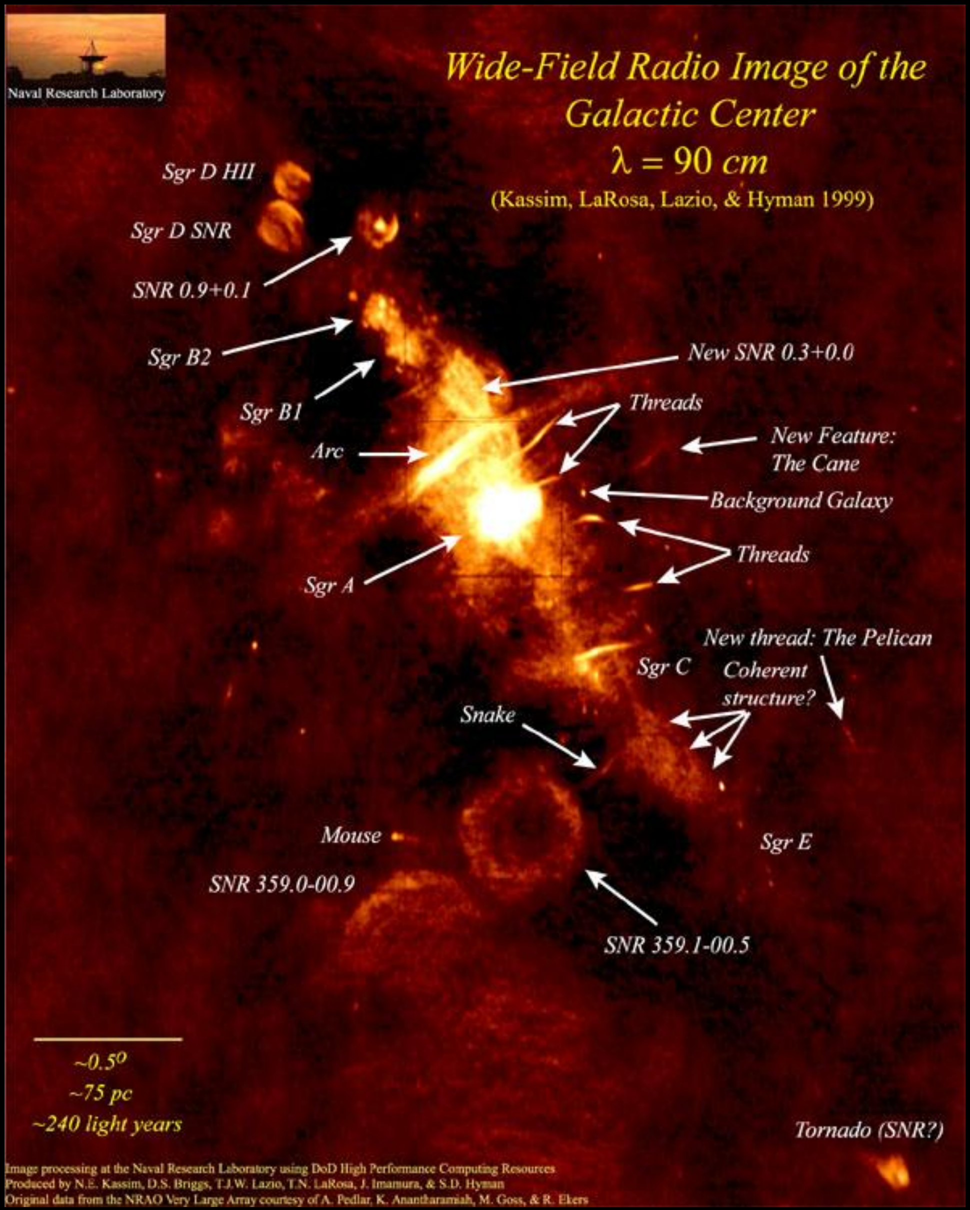
Collaborators: T. L. Herter, M. R. Morris, E. E. Becklin, M. J. Hankins, J. D. Adams, G. E. Gull, C. P. Henderson, J. Schoenwald

SOFIA Community Task Force Teletalks, February 6, 2013

Talk Outline

- Background
  - The Galactic Center
  - Observations
- Results and Science
  - The Circumnuclear Ring (CNR) (11 slides)
  - Quintuplet Proper Members (QPMs) (6 slides)
  - Pistol Nebula (10 slides)
- Further Work

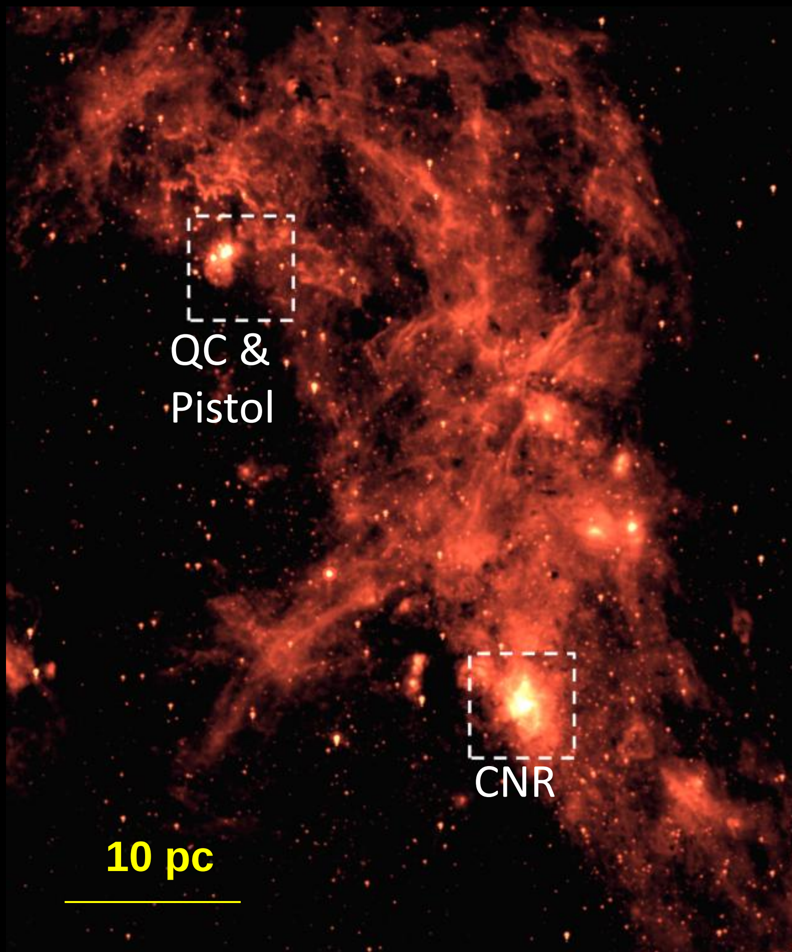




The Galactic Center

- ~500 pc unique region containing a 4,000,000 solar mass black hole, massive stars, supernovae, and star formation regions
- 10% of present SF activity in Galaxy occurs in GC yet only tiny fraction of a percent of volume in Galactic disk
- Contains ~4/12 of the LBVs and ~90/240 of Wolf-Rayet stars in galaxy

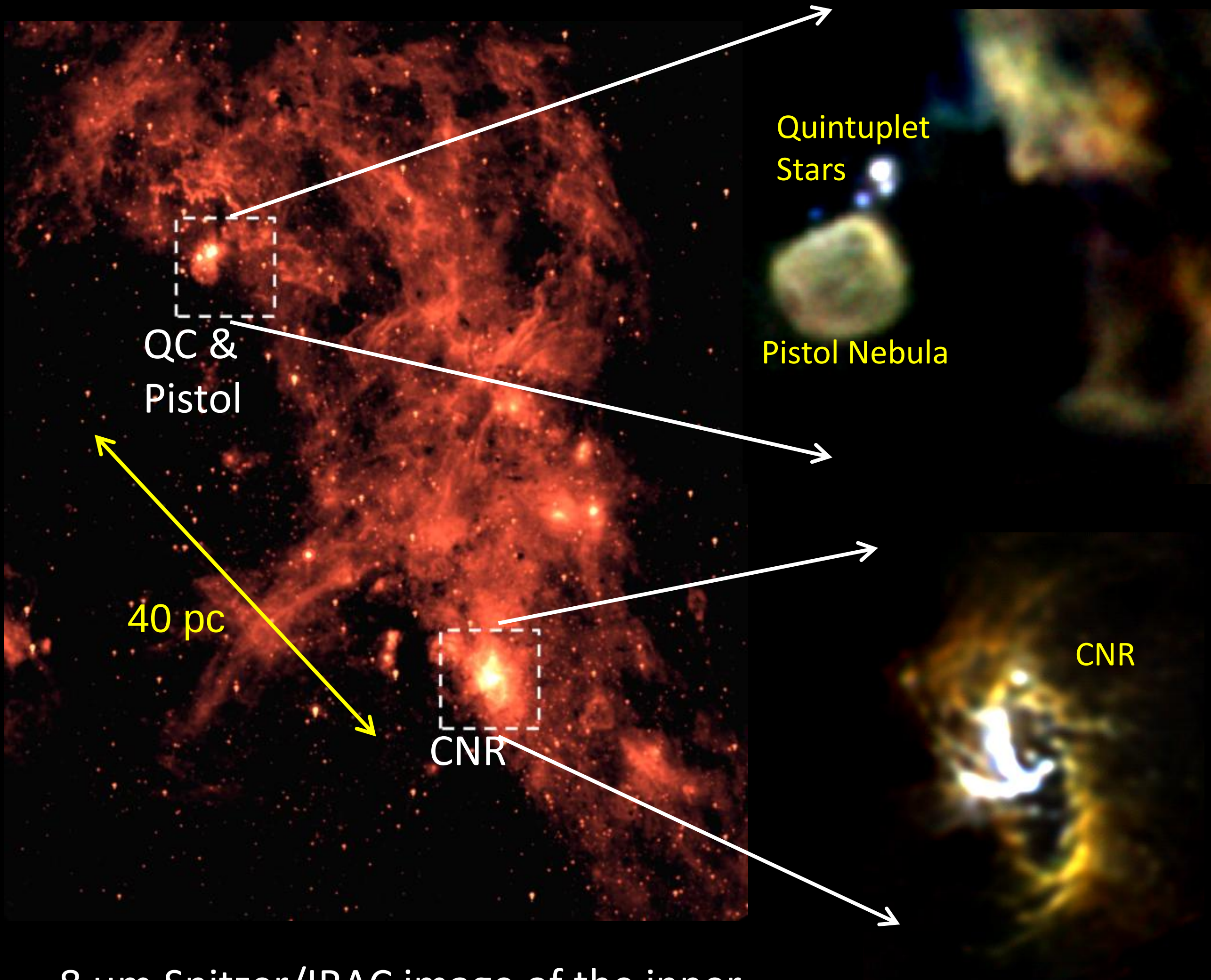
The Galactic Center: Inner 50 Pc



8 μm Spitzer/IRAC image of the inner 50 pc of the Galactic Center

- Circumnuclear Ring (CNR)
  - Dense ring of gas and dust surrounding Sgr A* by 1.4 pc
- Quintuplet Cluster (QC)
  - ~4 Myr cluster of hot, massive stars
  - Named after 5 bright IR sources within cluster (we observe 4 of them)
- Pistol Nebula
  - Asymmetric shell of dust and gas surrounding the Pistol star
  - Appears to be shaped by interaction with QC winds

Observations



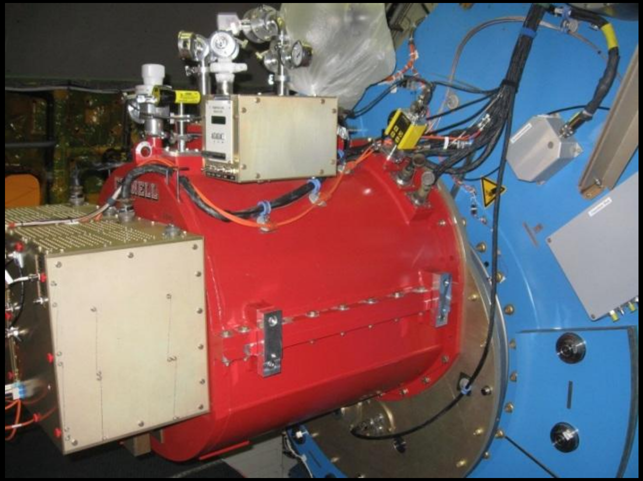
8 µm Spitzer/IRAC image of the inner 50 pc of the Galactic Center

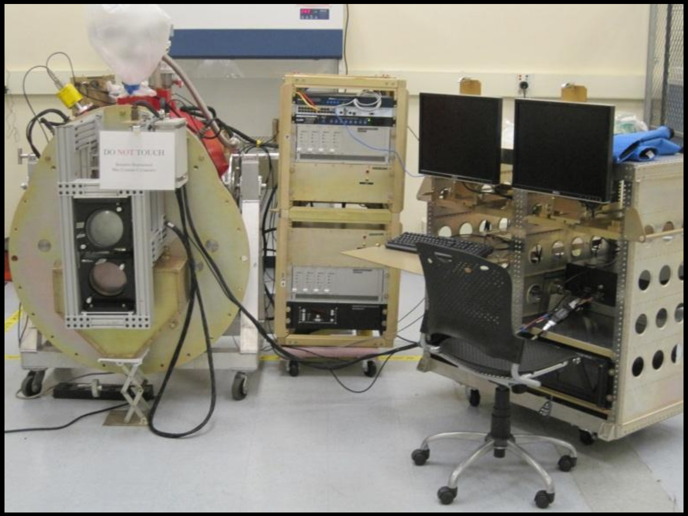
- SOFIA/FORCAST Galactic Center observations conducted during Basic Science flights 63 and 64 on June 4, 2011 and 8, 2011, respectively.

SOFIA/FORCAST images at 19.7 (blue), 31.5 (green), 37.1 (red) µm

FORCAST

- Facility Instrument
  - LHe cooled (4.2 K), 700 lbs
- Dual-Channel 256x256 Camera w/ Si BIB arrays
  - BIB: Blocked-Impurity-Band
  - 5-25 μm with Si:As array
  - 25-38 μm with Si:Sb array
- Plate scale: 0.75 arcsec/pixel
  - 3.2×3.2 arcmin FOV
- Selectable filters over the 5 - 38 μm range

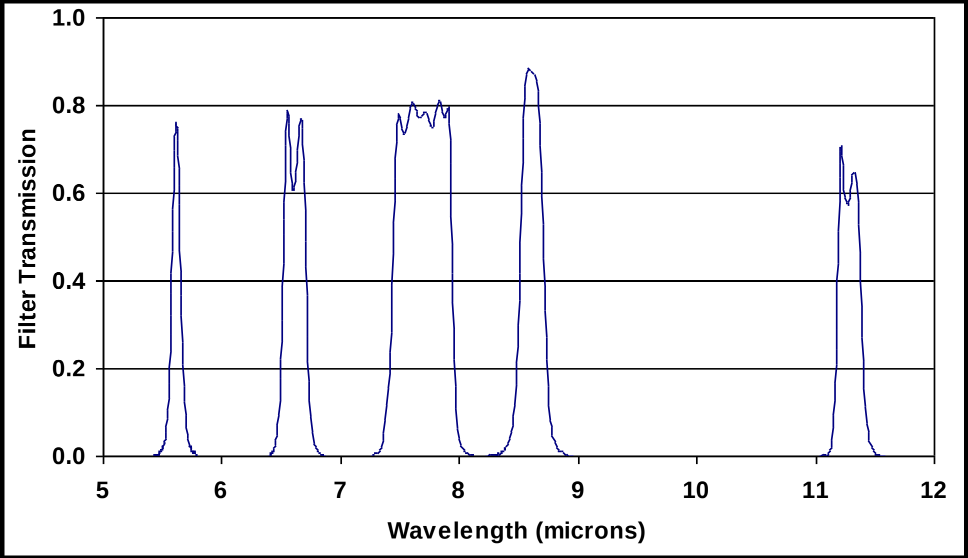


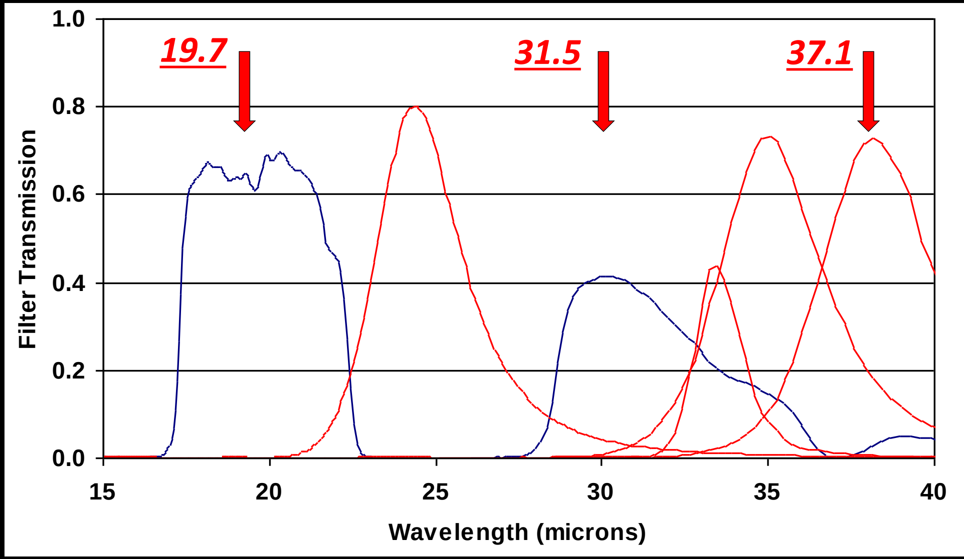


FORCAST commissioning in mid-March 2013 and available for Cycle 1B observations in early Summer 2013

Above: FORCAST mounted on the SOFIA Telescope
Below: FORCAST in the DAOF lab

FORCAST Filters

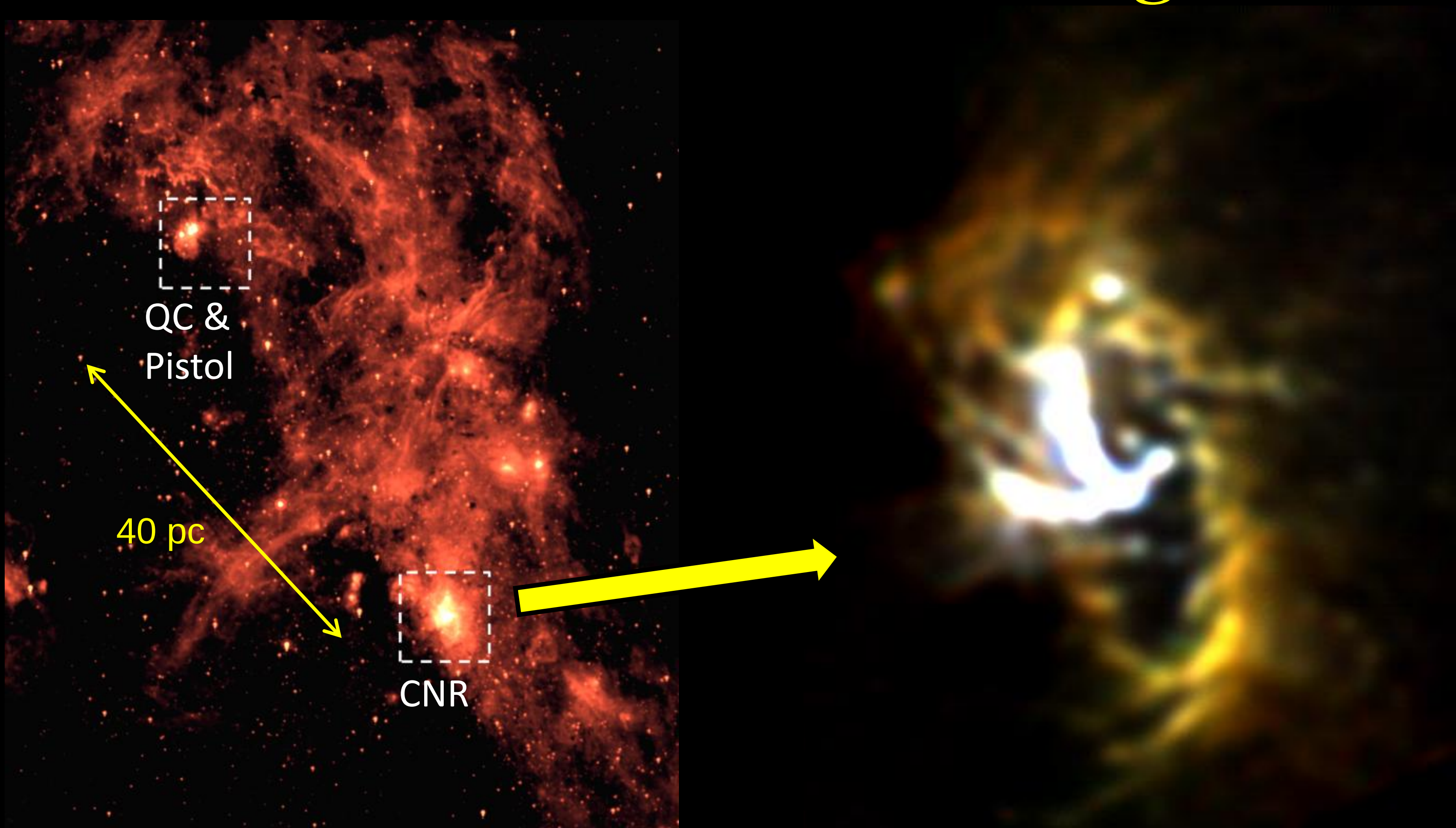




Filter (μm)	R (λ/Δλ)
5.3	33
6.3	48
6.6	34
7.6	15
8.6	42
11.0	12
11.28	56
19.5	3.8
24.4	7.5
30.6	5.7
33.4	18
34.8	8.3
37.1	8.8

Left: Representative FORCAST filter curves (not including atmospheric transmission or detector response). Arrows indicate filters used in GC observations.

Galactic Center Results: The Circumnuclear Ring

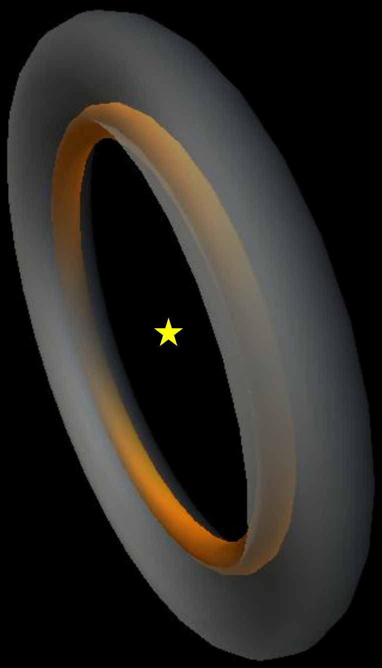


8 µm Spitzer/IRAC image of the inner 50 pc of the Galactic Center

SOFIA/FORCAST false color image of the inner 6 pc of the GC at 19.7 (blue), 31.5 (green), 37.1 (red) µm

The Ring around Sgr A*

Face-on view of CNR model

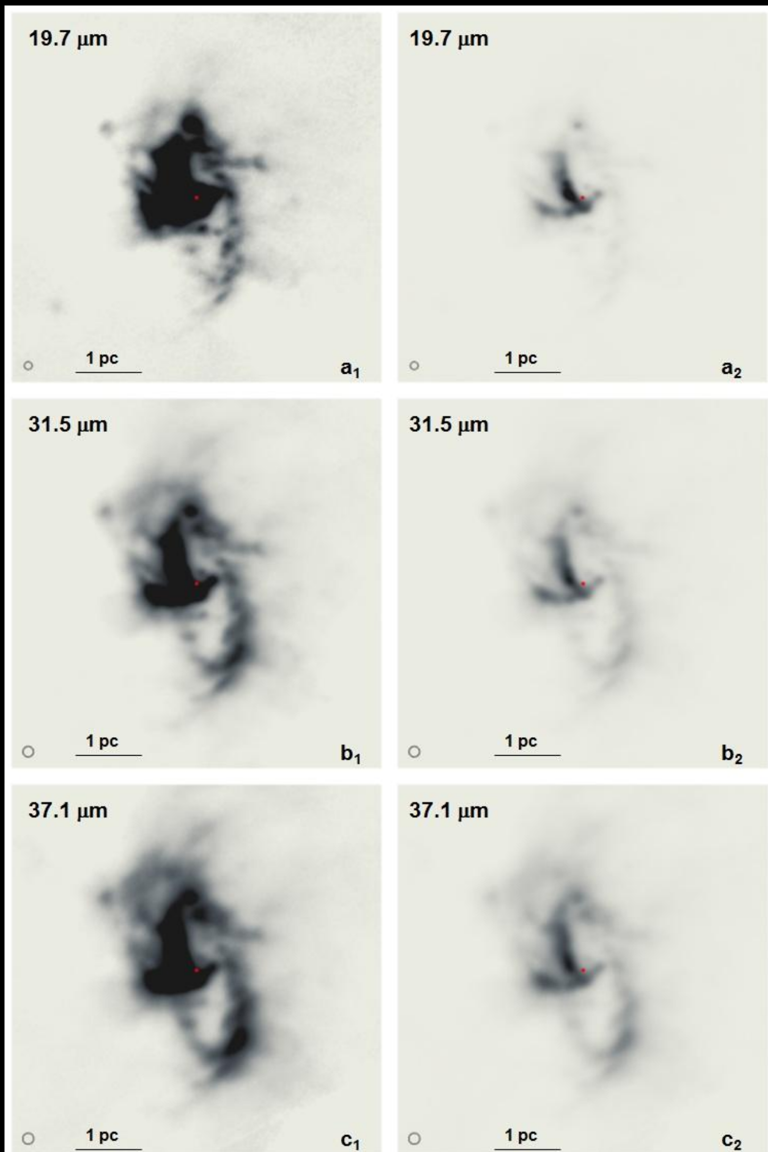


Observed view of CNR model

SOFIA/FORCAST false-color image of CNR

CNR inclined by ~67 degrees and has a radius of 1.4 pc

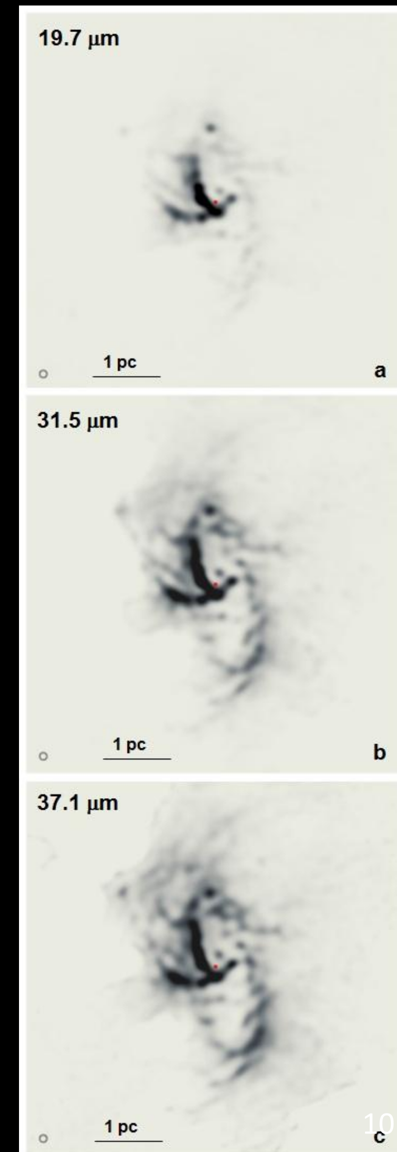
Observations of the CNR



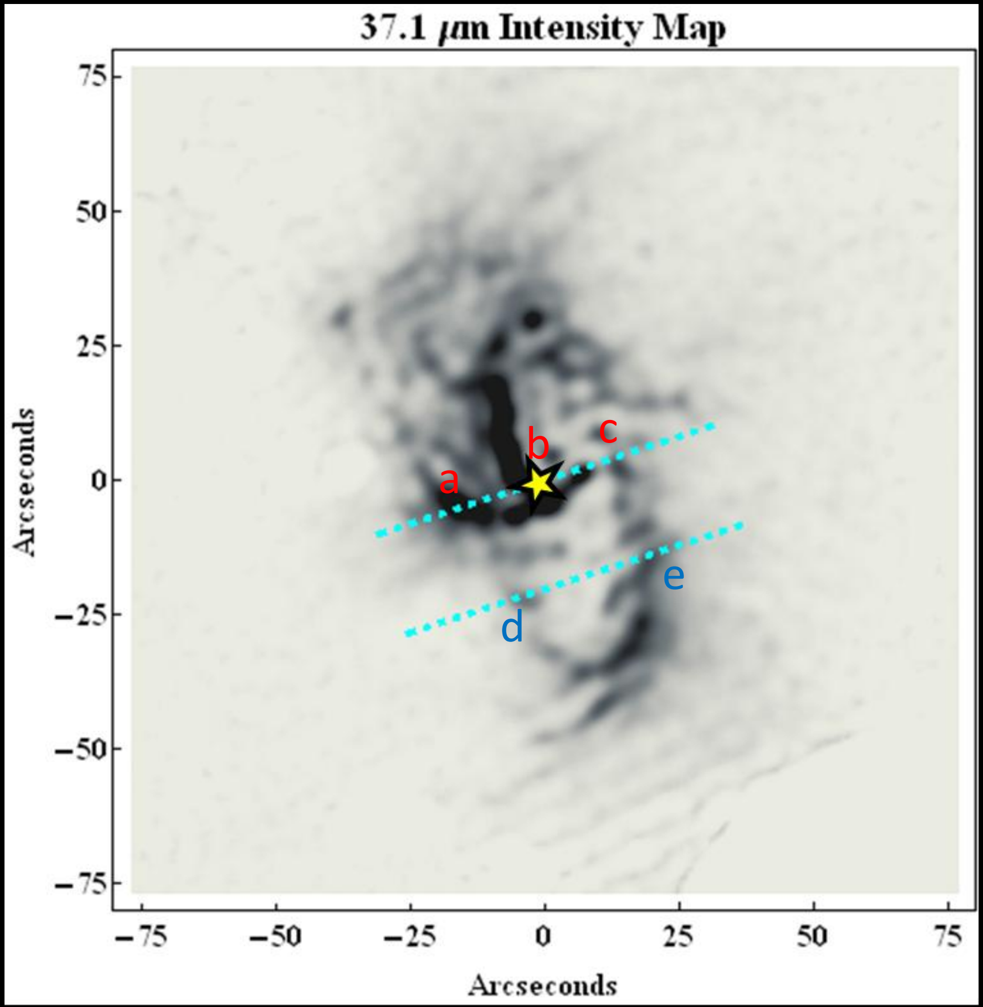
Deconvolved and reconvolved to 2.5'' beamsize

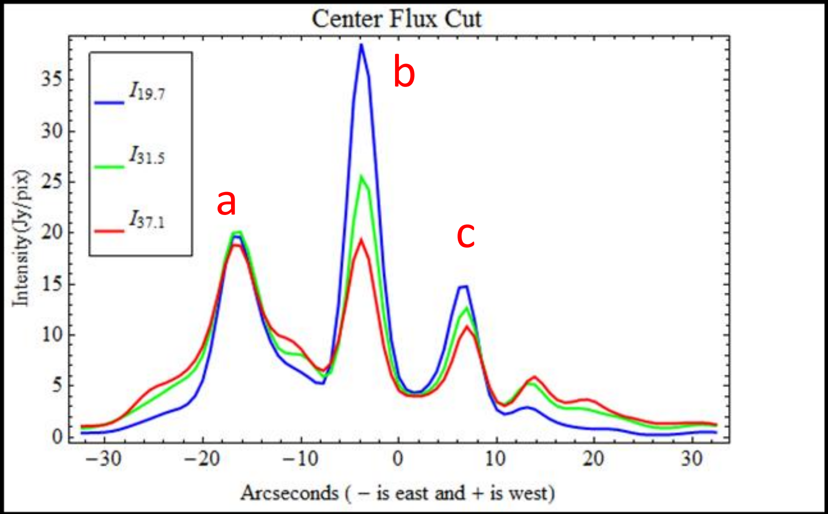
Left: Observed SOFIA/FORCAST images of the CNR at different intensity stretches

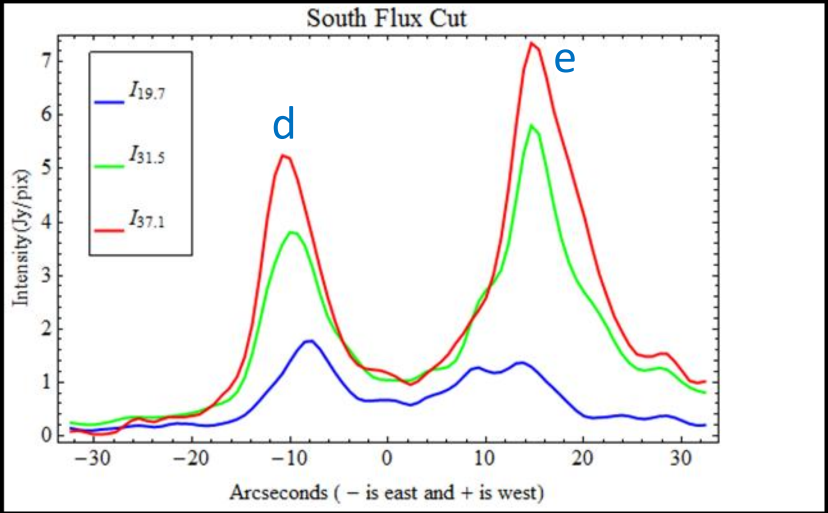
Right: Deconvolved and reconvolved CNR images



Evidence for Central Heating



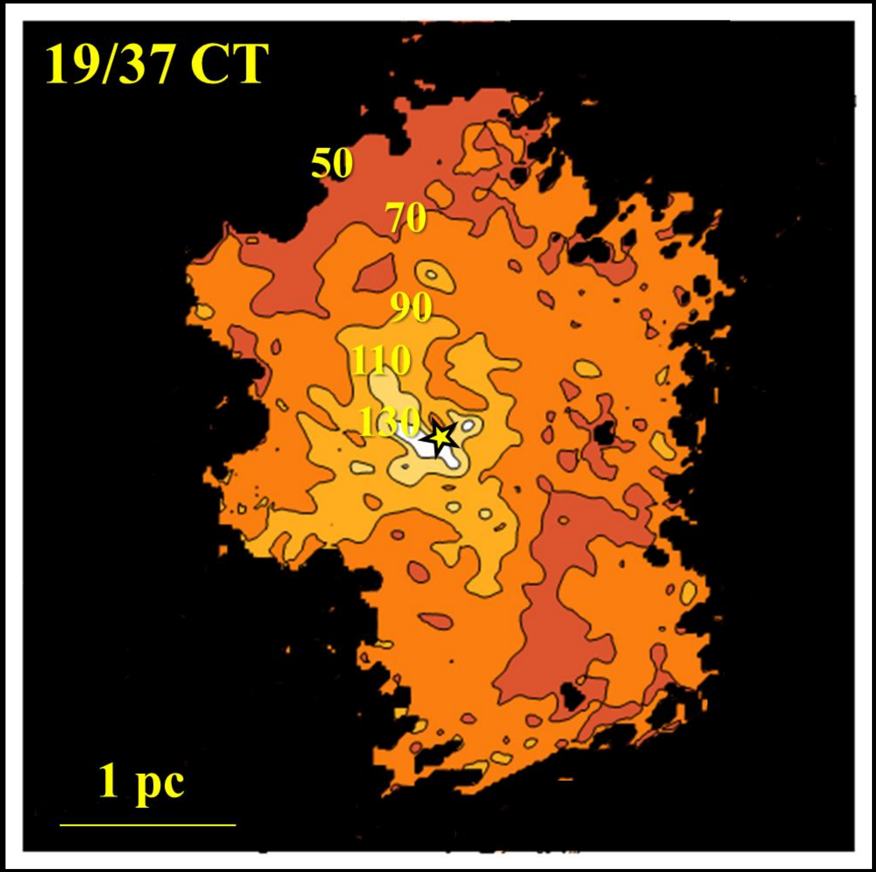




Above: 37.1 μm intensity map
Upper Right: Intensity line cut through center of ring
Lower Right: Intensity line cut through south of ring

Shifts in peaks across wavelengths indicate a radial temperature gradient and central heating

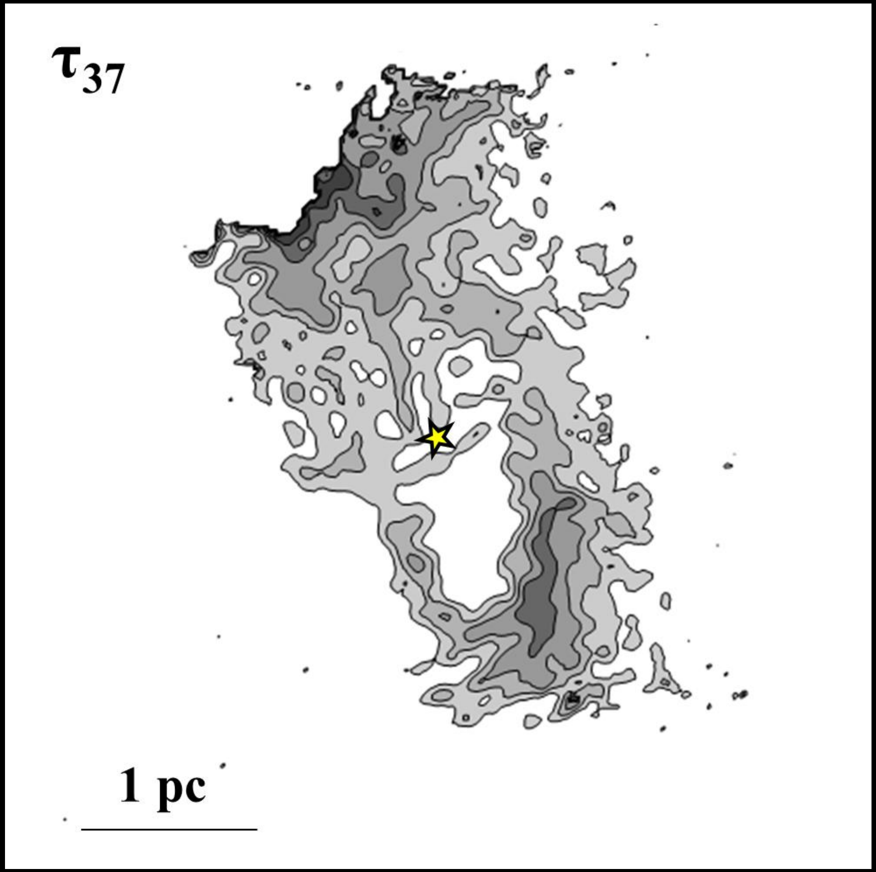
Temperatures Across the Ring



Color temperature map of the inner 6 pc of the GC derived from 19.7 and 37.1 μm intensity maps

- Temperatures range from 70 - 85 K
  - Consistent with temperature calculations assuming central $L \sim 2 \times 10^7 L_{sun}$ heating source.
- Fairly uniform temperature around ring
  - Heating dominated by radiation from central cluster
  - No star formation occurring in rung

CNR Column Density



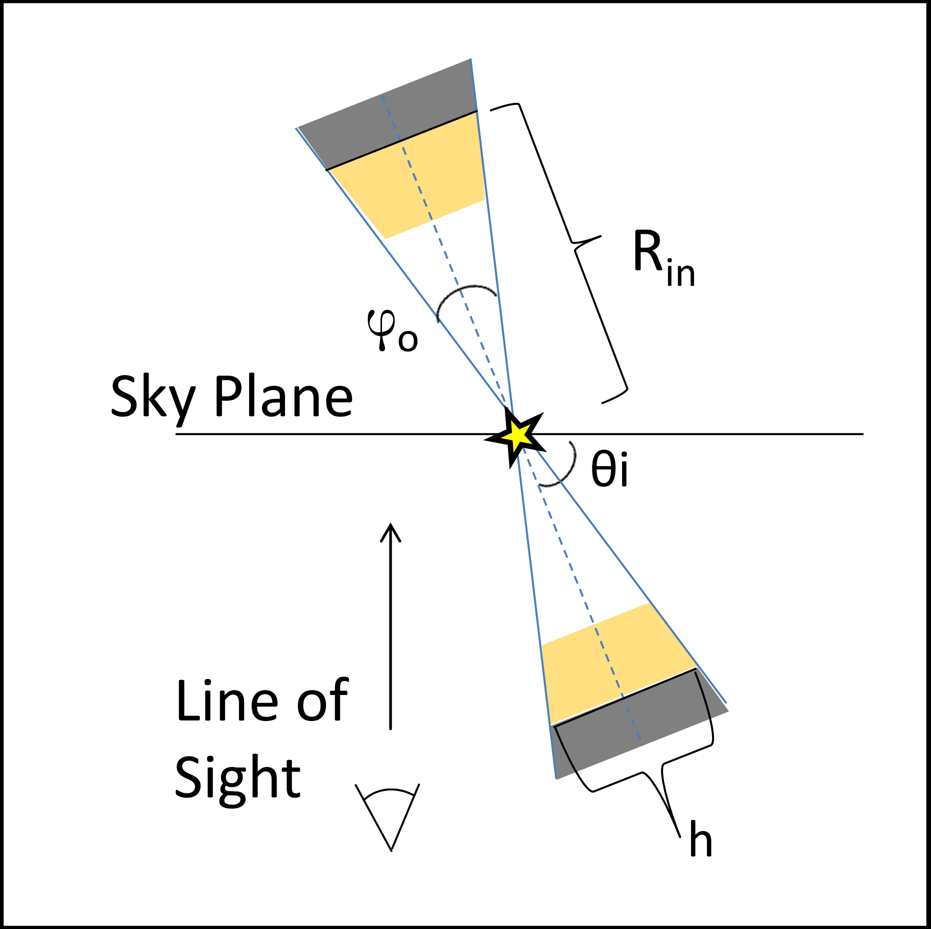
Optical depth map at 37.1 μm of the inner 6 pc of the GC. Contours at 0.025, 0.05, 0.1, 0.2, and 0.4 (dark)

- Column densities range from 0.025 – 0.4
  - They peak at the northern and southern clumps
- A majority of the material in this region lies in the ring (not the Northern arm or East-West bar)
- *Total CNR gas mass is ~450 Solar masses**

*Assuming dust to gas mass ratio of 1/100

Ring Morphology

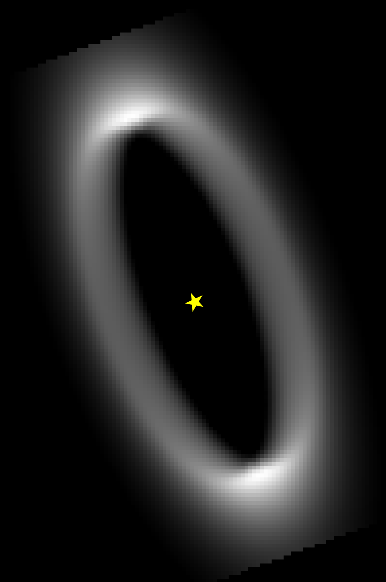
- We can determine the width of the CNR given our 2.5'' resolution images
  - We can also find the inclination angle θi (67°), and inner radius *R_{in} (1.4 pc)*
- From the width we determine the opening angle φ_o (14°) and ring height h (0.35 pc)



Cross section through CNR. The orange regions indicate the illuminated region of the ring

CNR Intensity Model

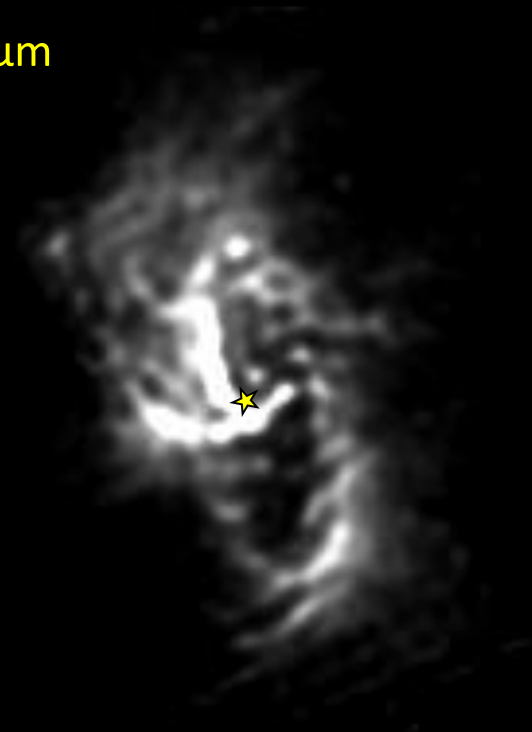
37.1 µm
MODEL



Model 37.1 µm Intensity map of CNR
Density at inner edge is n = 10^4 cm^{-3}

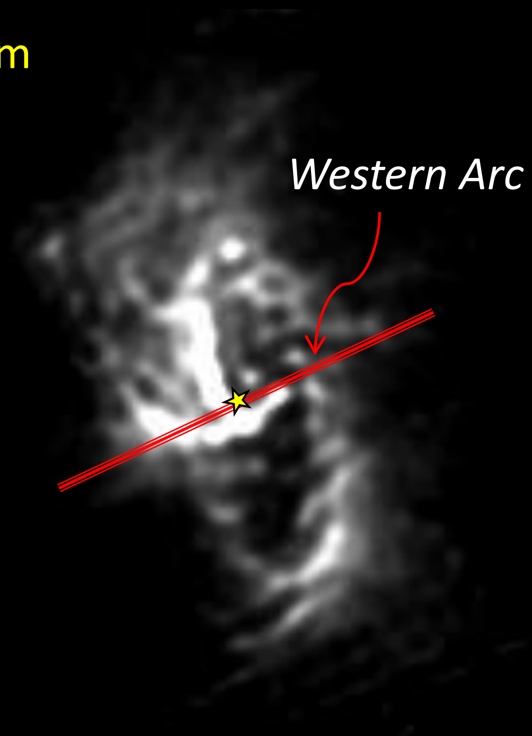
Model has been convolved with 2.5’’ Gaussian to match beamsize of the observed image

37.1 µm
OBS

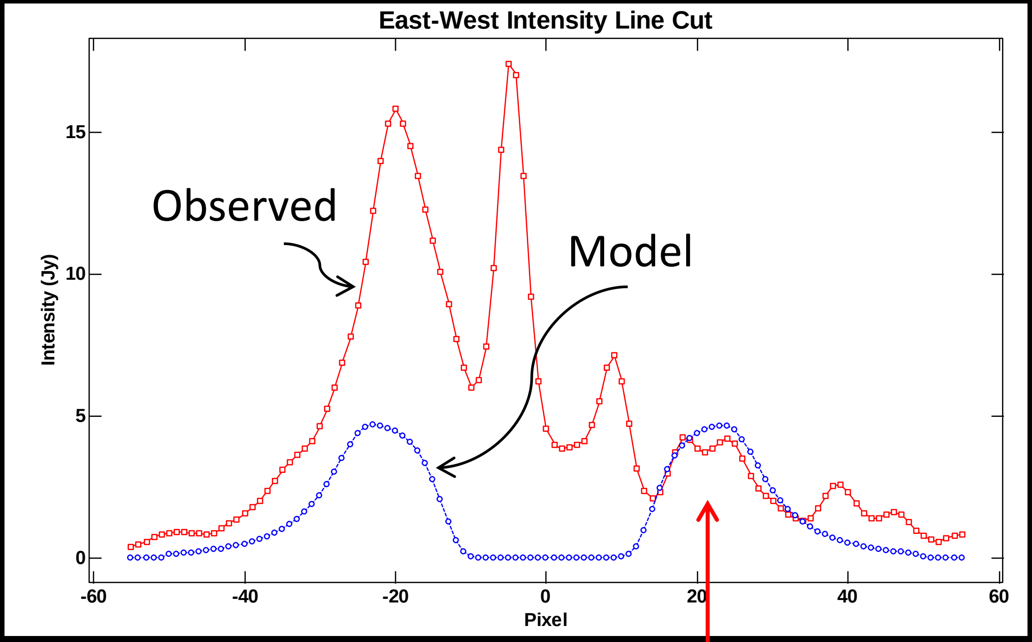


Observed 37.1 µm Intensity map of the inner 6 pc of the GC

Model vs Observed 37.1 Intensity Map Radial Line Cuts: East-West



Observed 37.1 μm Intensity map of the inner 6 pc of the GC with East-West cut overlaid

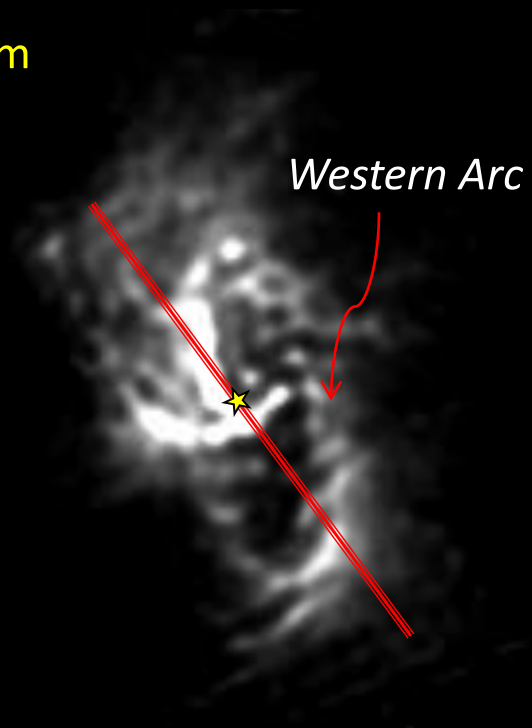


Model vs. Observed 37.1 μm intensity line cut through CNR

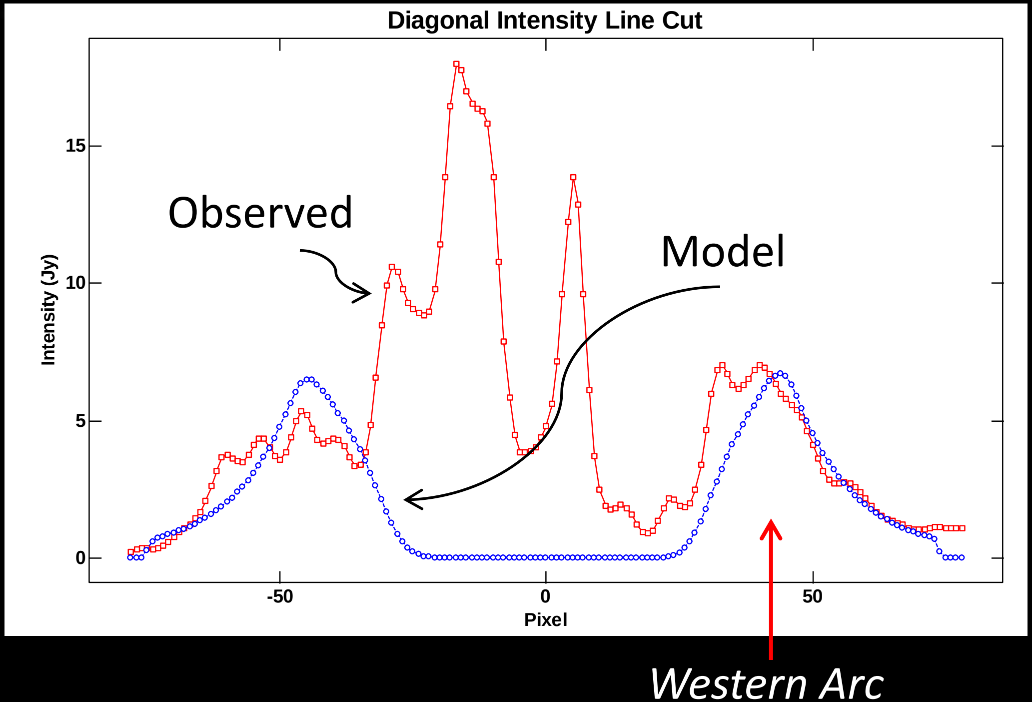
Model intensity peak location, width, and value at Western arc are consistent with observed data

Model vs Observed 37.1 Intensity Map Radial Line Cuts: Diagonal

37.1 µm
OBS



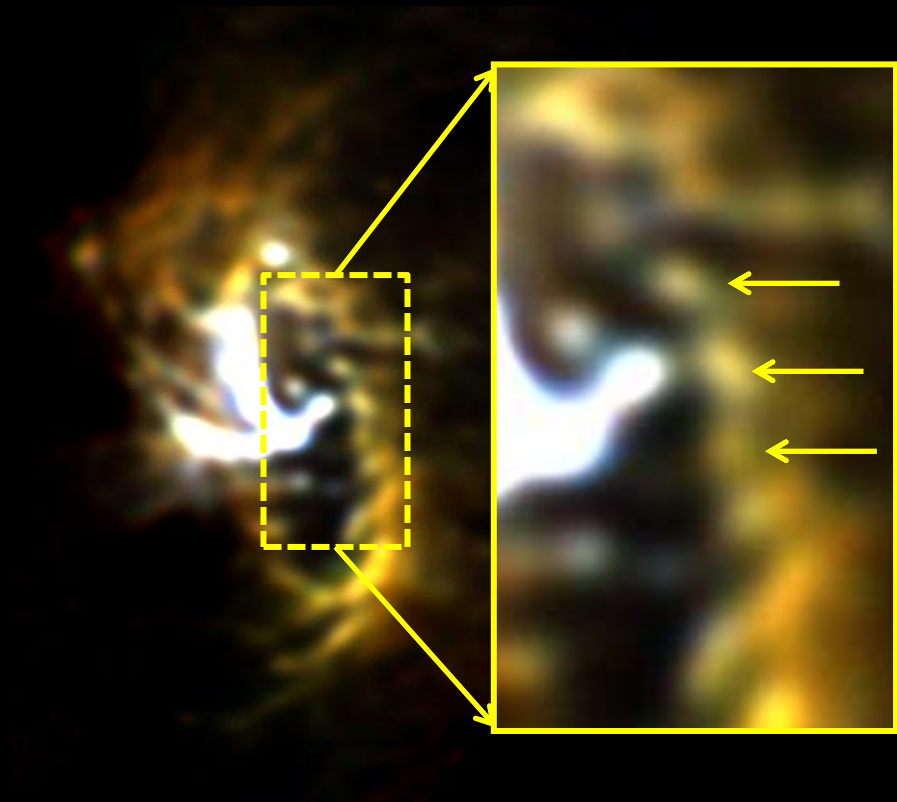
Observed 37.1 µm Intensity map of the inner 6 pc of the GC with diagonal cut overlaid



Model vs. Observed 37.1 µm intensity line cut through CNR.

Model intensity peak location, width, and value at Western arc are consistent with observed data

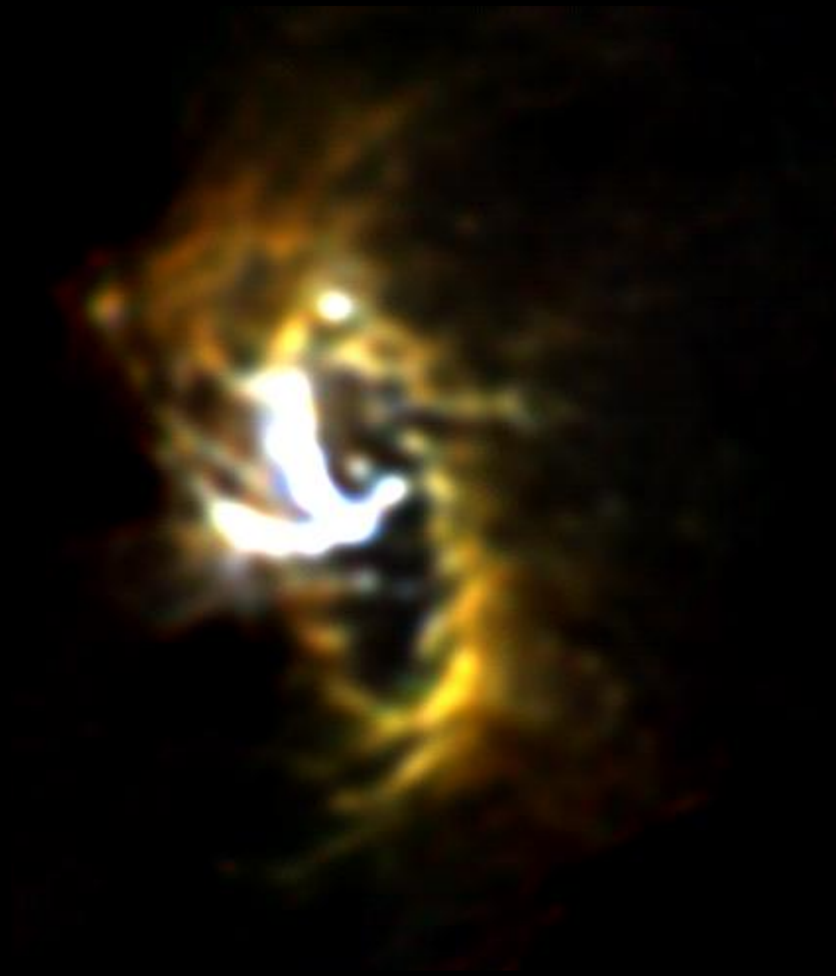
Inner Edge "Clumps"



SOFIA/FORCAST false color image of the inner 6 pc of the GC at 19.7 (blue), 31.5 (green), 37.1 (red) µm. Inset shows zoom of inner edge "clumps"

- We resolve "clumps" at the inner edge of the CNR
- "Clumps" due to density enhancements (not embedded sources)
  - *$n \sim 2\text{-}3 \times 10^4\ cm^{-3}$*
- Periodic?

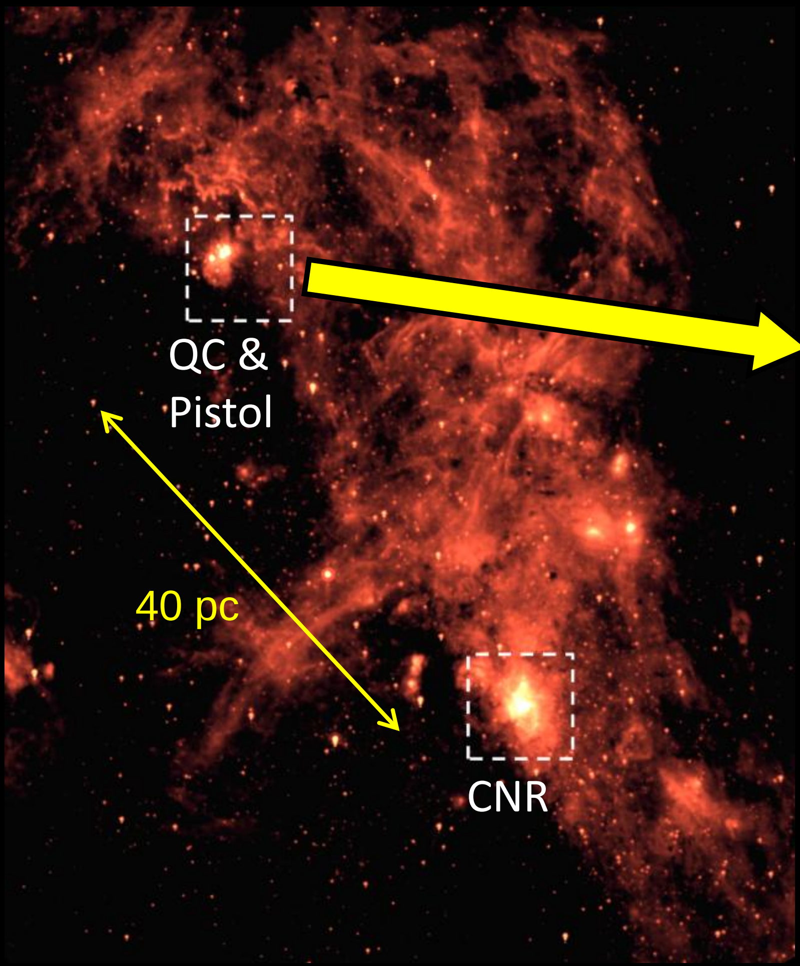
CNR Results Summary



SOFIA/FORCAST false color image of the inner 6 pc of the GC at 19.7 (blue), 31.5 (green), 37.1 (red) μm

- The CNR is heated by central cluster of stars
- Observed temperatures consistent with heating by central source with total luminosity $L \sim 2 \times 10^7 L_{sun}$
- No star formation occurring in CNR
- Dust emission from CNR can be modeled as an inclined ring
- Possibly periodic "clumps" occur in the inner edge of the CNR

Galactic Center Results: The Quintuplet Proper Members*



8 µm Spitzer/IRAC image of the inner 50 pc of the Galactic Center

*Work lead by Matt Hankins, senior undergrad at UCA

SOFIA/FORCAST false color image of the Quintuplet cluster at 19.7 (blue), 31.5 (green), 37.1 (red) µm

The Quintuplet Proper Members (QPMs)

SOFIA/FORCAST false color image of the Quintuplet cluster at 19.7 (blue), 31.5 (green), 37.1 (red) μm

- Quintuplet cluster age ~4 Myrs
  - Cluster of hot, massive stars
  - Coeval formation
- QPMs very luminous ($L \sim 10^5$ L_{Sun}), cool (600-1200 K) sources with featureless K-band spectra
  - Extremely dusty
- Late-type dusty Wolf-Rayet stars (DWCL) (Figer et al. 1999)

*we barely observe Q4

Are the QPMs "Pinwheels"?

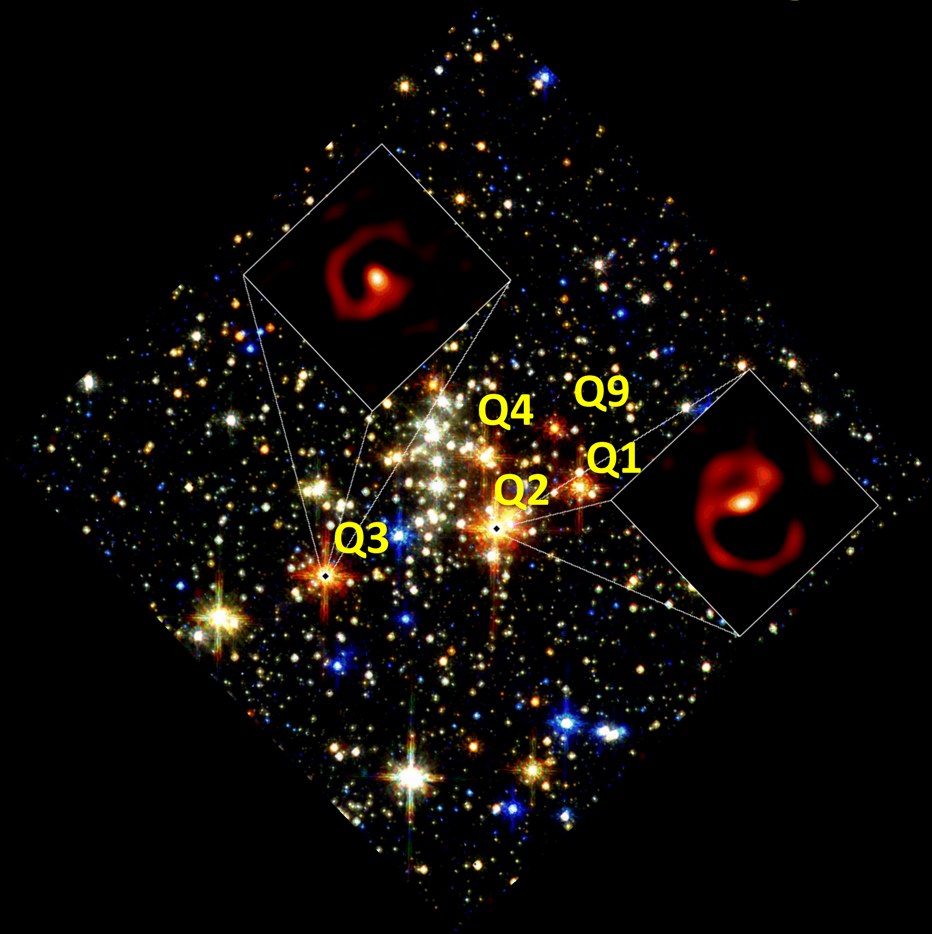
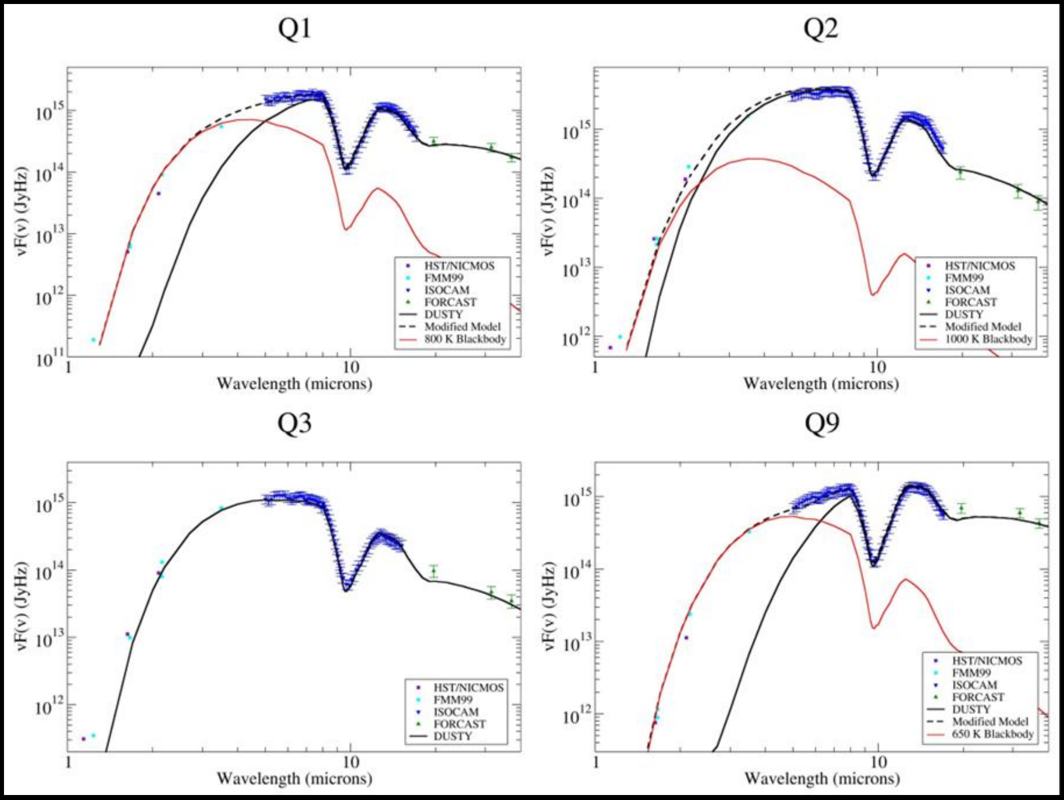


Fig. S1 from Tuthill et al. (2006). Background field is from HST/NICMOS near-IR imaging. Inset images of Q2 and Q3 were taken by Keck in the K-band

- Tuthill et al. (2006) find QPMs are likely WR + O/B binary systems
  - Box scale: ~2400 AU x 2400 AU
- Q1, Q9, and Q4 were only partially resolved, Tuthill et al. claims they have tighter winding angles or have different orientations

Spectral Energy Distribution Model Fits



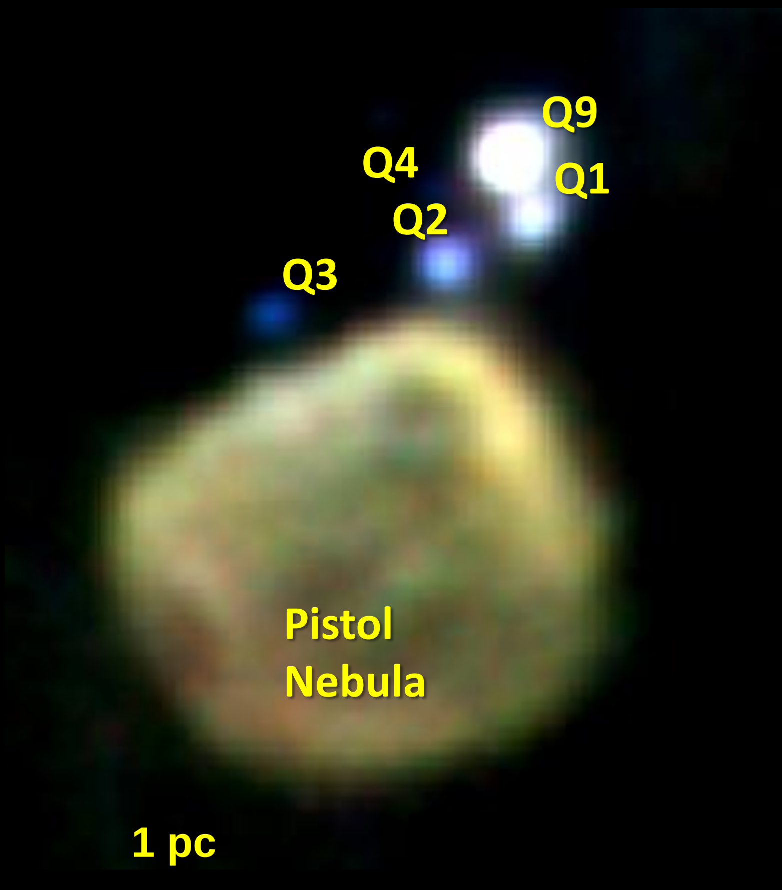
- Models generated by the DUSTY radiative transfer code assuming spherical geometry
- Cool Blackbodies (650-1000K) added to fit the near-IR for Q1, Q2, and Q9.
- *Q1 and Q9 models exhibit different physical properties from Q2 and Q3 models*

DUSTY Parameters

Object ID	Density Power Law	Inner Radius	Inner Temp.	Outer Radius	Outer Temp.	Half Intensity Radius	Shell Luminosity
Q1	$\rho(r) \sim r^{-0.6}$	1,885 AU	450 K	15,080 AU	91 K	3,054 AU	$10^{5.0}$ L_{Sun}
Q2	$\rho(r) \sim r^{-2.4}$	613 AU	700 K	15,325 AU	100 K	760 AU	$10^{5.4}$ L_{sun}
Q3	$\rho(r) \sim r^{-1.8}$	267 AU	950 K	13,370 AU	111 K	366 AU	$10^{5.0}$ L_{sun}
Q9	$\rho(r) \sim r^{-0.4}$	5,415 AU	300 K	43,320 AU	57 K	8,718 AU	$10^{5.0}$ L_{Sun}

DUSTY models and model parameters

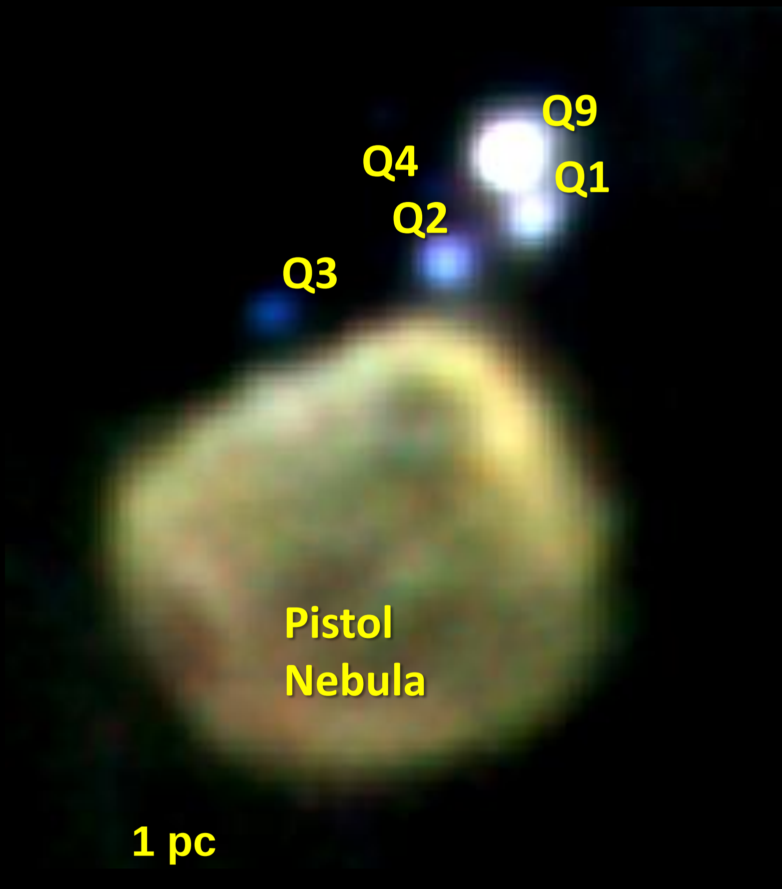
Implications



SOFIA/FORCAST false color image of the Quintuplet cluster at 19.7 (blue), 31.5 (green), 37.1 (red) μm

- Given the models, QPMs appear to be quite different from each other
  - A shallower density power law for Q1 and Q9 indicate a *decreasing* mass loss rate
- Differences in morphological properties indicate the QPMS are in different evolutionary phases?

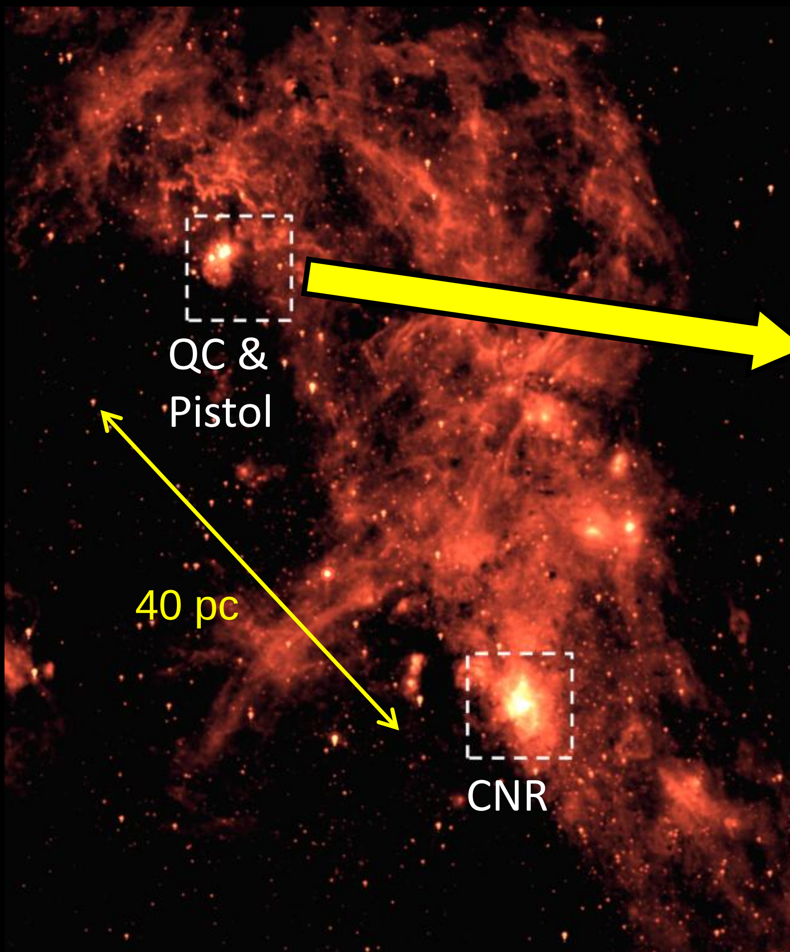
Quintuplet Results Summary



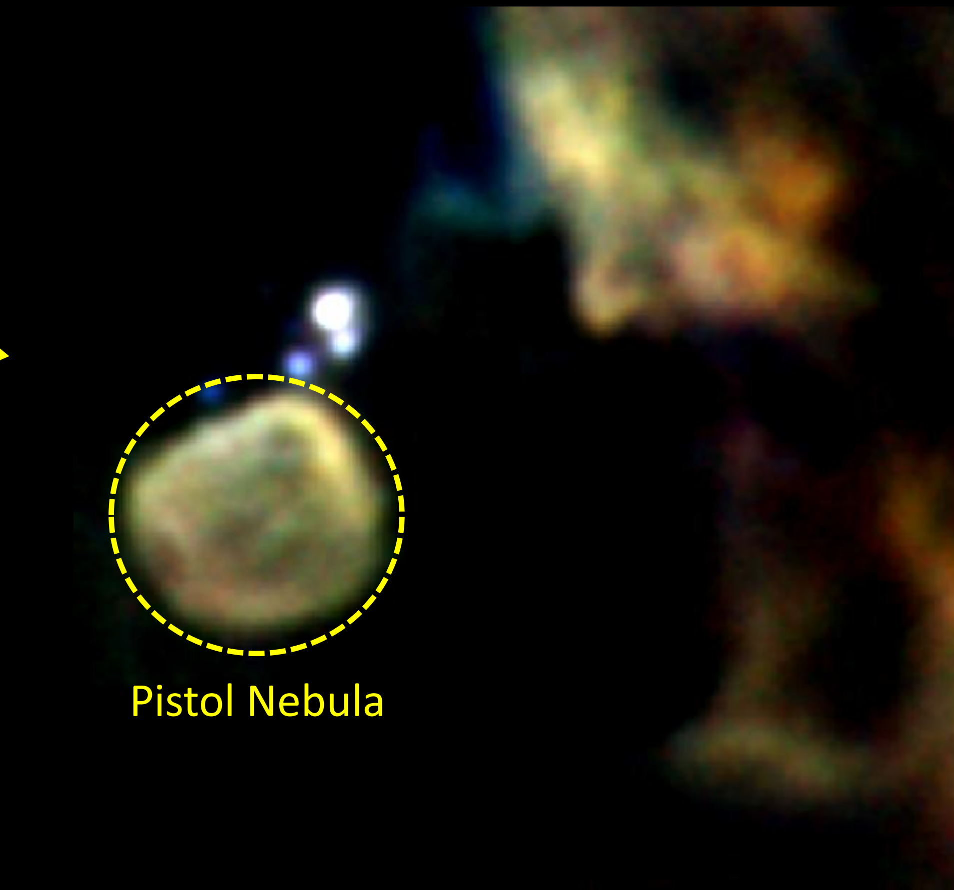
SOFIA/FORCAST false color image of the Quintuplet cluster at 19.7 (blue), 31.5 (green), 37.1 (red) μm

- Spectra reveal different morphological properties amongst QPMs
- DUSTY model of Q1 and Q9 require an additional cool blackbody to fit near-IR part of observed spectra
  - Are we looking through "holes" in the dust shell?
- Some work still needs to be done to check robustness of model fits

Galactic Center Results: The Pistol Nebula



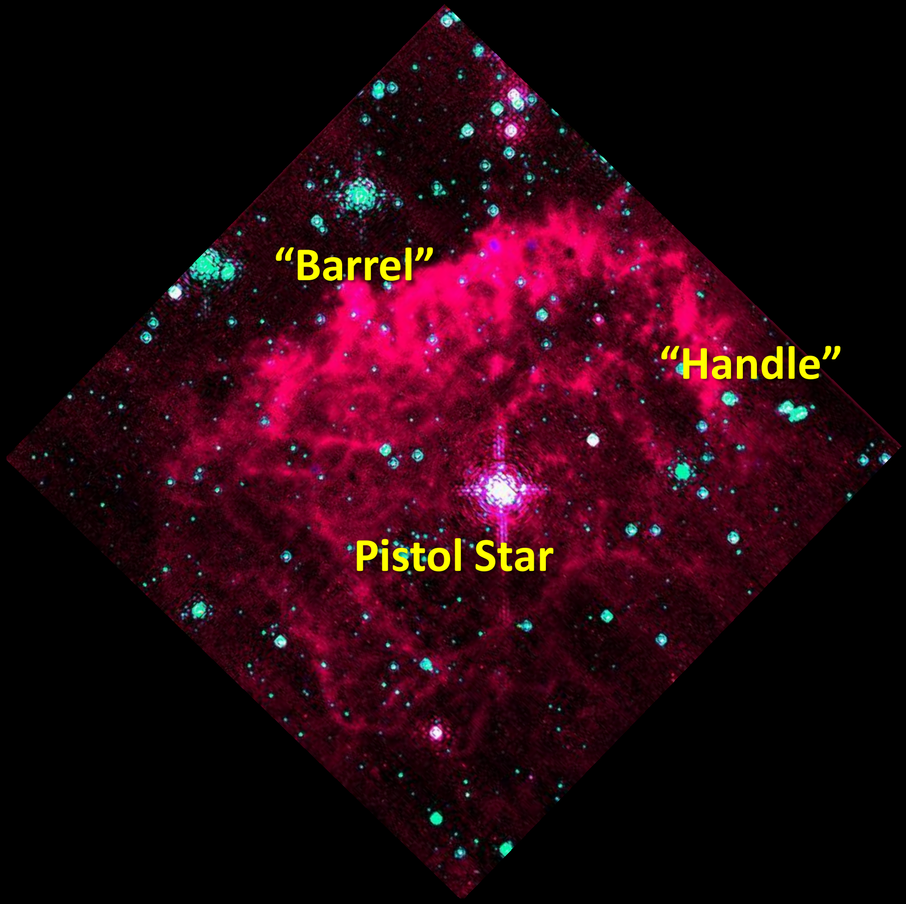
8 µm Spitzer/IRAC image of the inner 50 pc of the Galactic Center



SOFIA/FORCAST false color image of the Quintuplet cluster at 19.7 (blue), 31.5 (green), 37.1 (red) µm

The Pistol Star and Nebula

- Pistol Star is a Luminous Blue Variable (LBV)
  - One of the most luminous stars in the Milky Way (L~1.6 x 10^6 L_{Sun})
  - Fairly cool (T_{eff} = 11800 K)
- Nebula formed from Pistol star ejecta
  - Shaped like a pistol due to interaction with QC winds



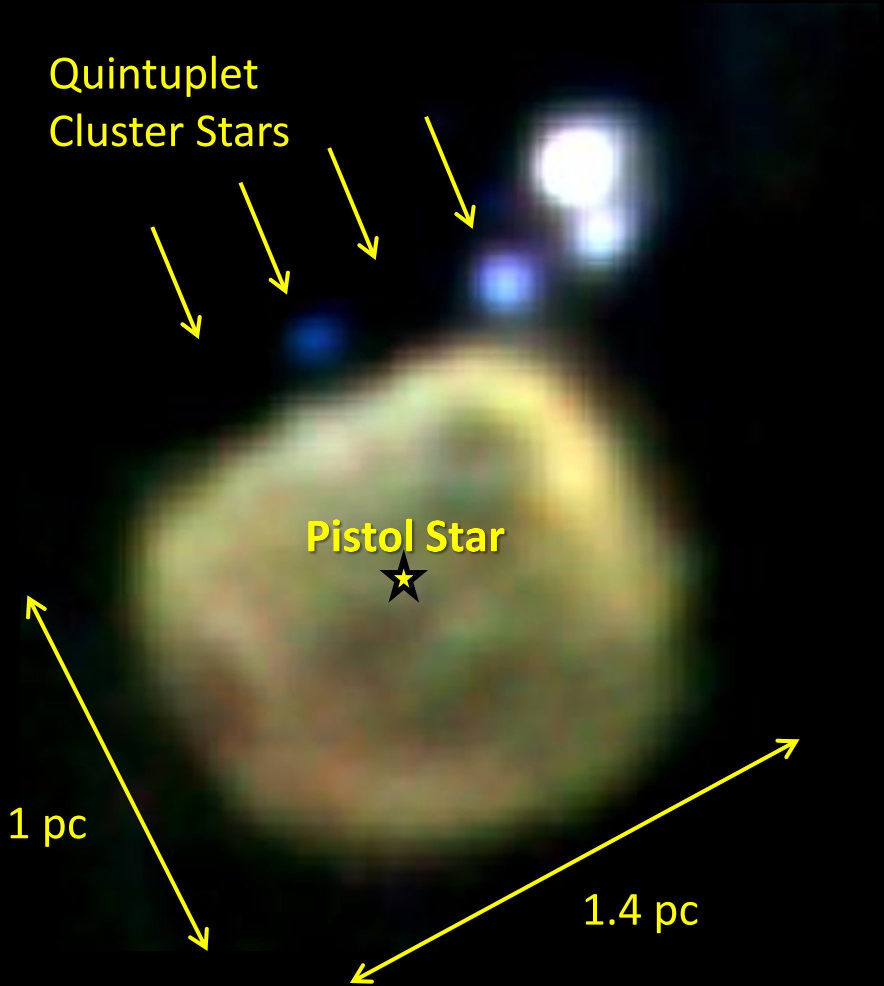
HST/NICMOS image of the Paschen-alpha emission from the Pistol star and nebula

Not Quite a "Pistol" in the Mid-IR…

"Baseball Diamond?"
"Ballpark?"
"Home Plate?"

"Home Plate" on Mars taken by HiRISE

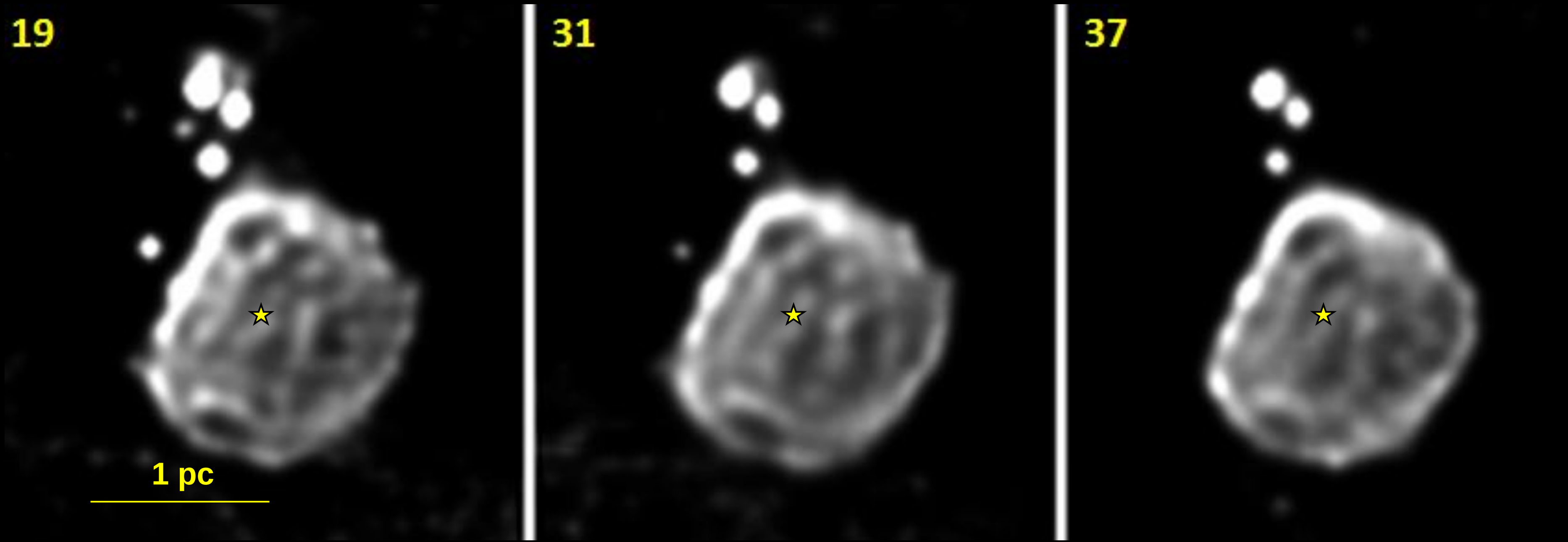
Morphology of the "Pistol" Nebula



SOFIA/FORCAST false color image of the Pistol Nebula at 19.7 (blue), 31.5 (green), 37.1 (red) μm

- Optically thin, asymmetric shell
  - Pistol star displaced from center of nebula
- Northern edged likely shaped by interaction with QC winds based on projected location
- Also shaped by the ambient magnetic field (Figer et al. 1999)?

Consistency Across Wavebands

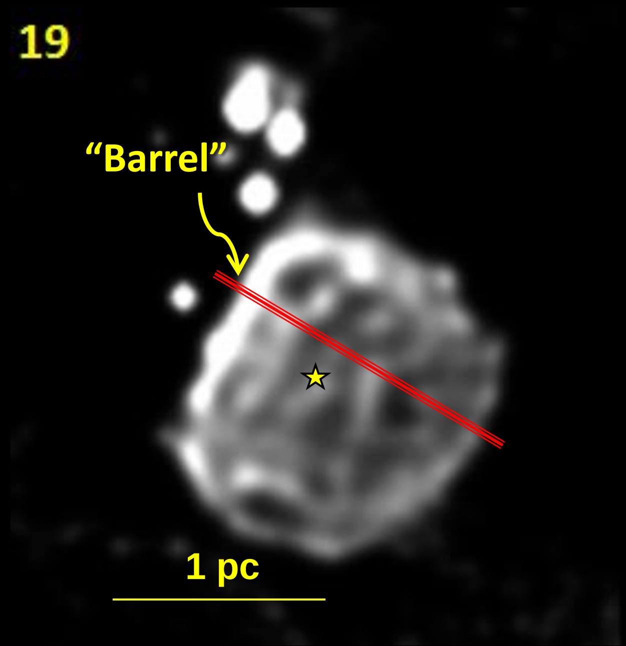


SOFIA/FORCAST deconvolved images of the Pistol nebula at 19.7, 31.5, and 37.1 μm

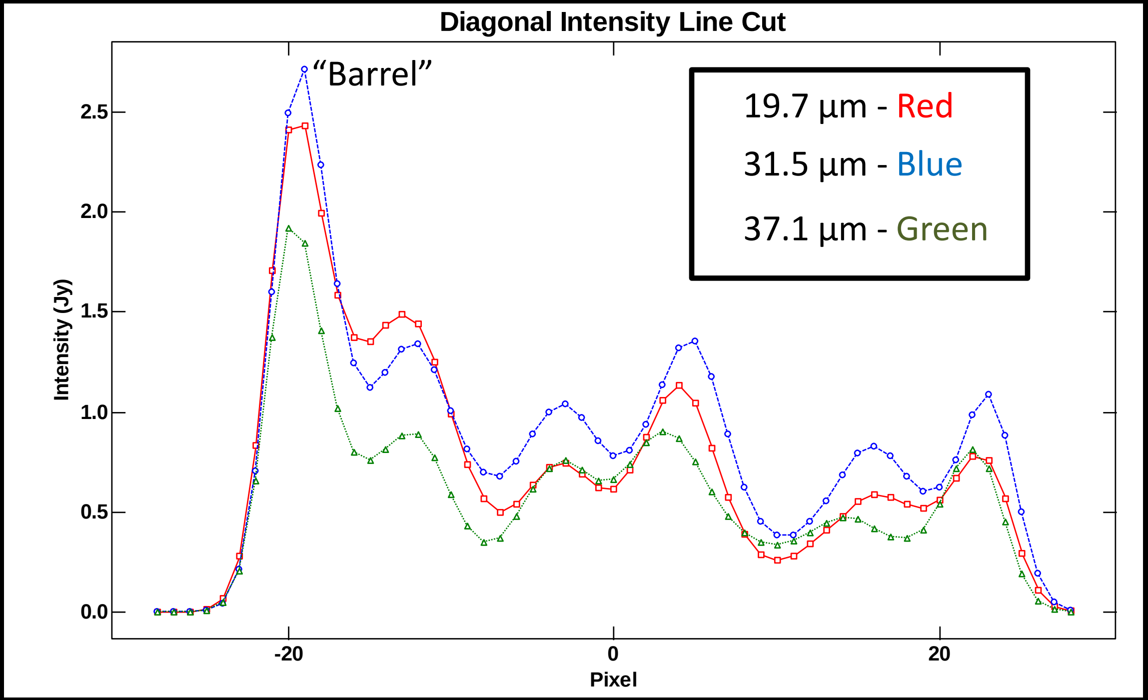
Apparent morphology extremely consistent across 19.7, 31.5, and 37.1 μm images
(note the filamentary structures within the nebula)

NOT like a classic HII region (compare to the CNR!)

Similarity of Intensity Profiles

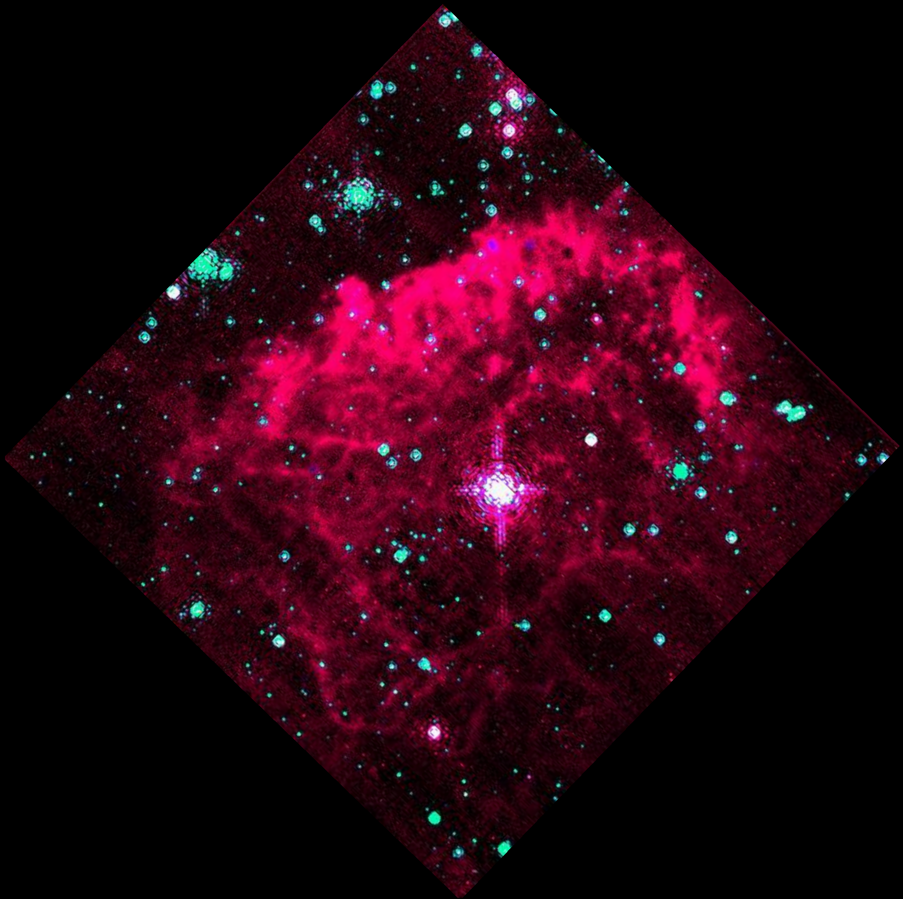


SOFIA/FORCAST deconvolved image of the Pistol nebula at 19.7 μm



Similar intensity line profiles across wavebands indicate uniform temperature throughout nebula

How is the Pistol Nebula Heated?



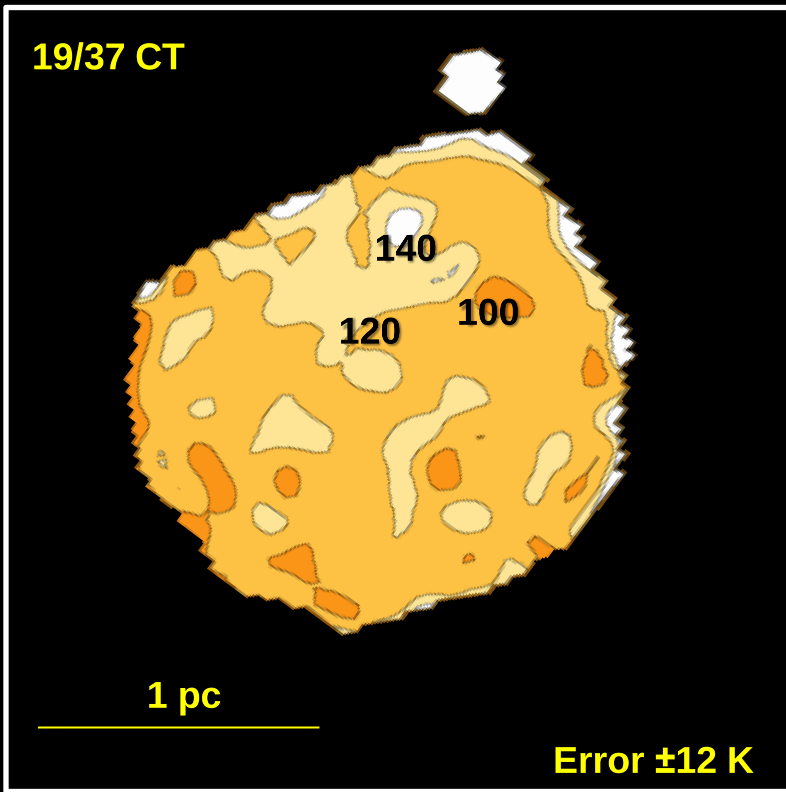
Gas Emission

Because the Pistol star is relatively cool, the gas is primarily ionized by hot O and B Quintuplet cluster stars to the North-East of the Pistol (Figer et al. 1999)

Dust Emission

The Pistol star will contribute much more to heating the dust than it does for ionizing the gas

Pistol Nebula Temperature Map



Color temperature map of Pistol nebula derived from 19.7 and 37.1 μm intensity maps

- Pistol nebula exhibits almost uniform temperature distribution (~100 K)
  - Slight decreasing gradient from east to west
  - Gradient is consistent with heating by both Pistol and hot QC stars

- *However, the color temperature is higher than what calculations predict for typical silicate grains (~ 70 K)*

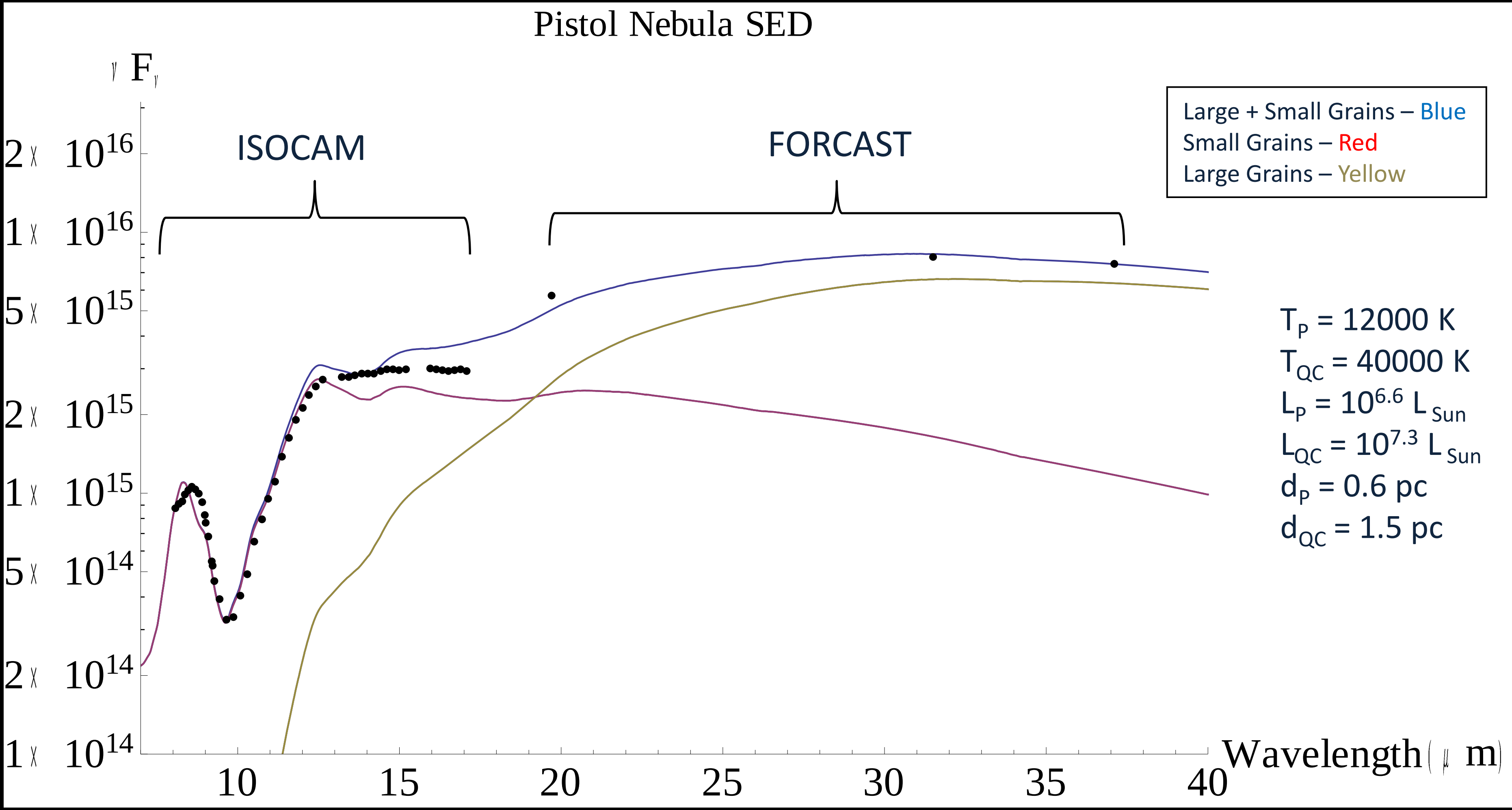
Introducing a Small Grain Component

Grain Size (SGs): 3.25 – 210 Ang

Grain Size (LGs): 2.2e4 – 8e4 Ang

Dual grain size distribution (small grains & large grains)

Models generated using DustEM radiative transfer code



T_P = 12000 K

T_{QC} = 40000 K

$L_P = 10^{6.6} L_{Sun}$

$L_{QC} = 10^{7.3} L_{Sun}$

d_P = 0.6 pc

d_{QC} = 1.5 pc

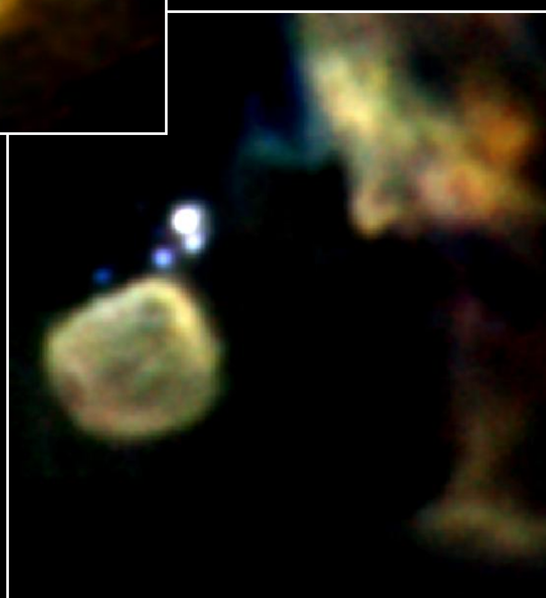
Pistol Nebula Results Summary

SOFIA/FORCAST false color image of the Pistol Nebula at 19.7 (blue), 31.5 (green), 37.1 (red) μm

- Pistol nebula is an asymmetric shell composed of ejecta from the Pistol star
  - Likely being shaped by interactions with QC winds
- Dust in nebula heated by hot QC stars and the Pistol star, itself
- Requires dual grain size components (large AND small grains) to fit SED

Further Work

SOFIA/FORCAST false color image of the inner 6 pc of the GC at 19.7 (blue), 31.5 (green), 37.1 (red) µm



SOFIA/FORCAST false color image of Quintuplet Cluster at 19.7 (blue), 31.5 (green), 37.1 (red) µm

- Circumnuclear Ring
  - Explore the hydrodynamics in the CNR environment to explain "clumps" and striations.
- Quintuplet Proper Members
  - Study the formation and evolution of dusty, binary WR systems
- Pistol Nebula
  - Draw comparison to 2nd LBV nebula in region (Mauerhan et al. 2010), which appears much more spherically symmetric than the Pistol Nebula.

Thanks!

Extra Slides

CNR Properties

Object Name	Luminosity (10^6 L_{Sun})	Ratio with Central Luminosity $\sim 2 \cdot 10^7$ L_{Sun} [4]	Temperature (K)	Optical Depth at 37.1 µm	Gas Mass* (M_{Sun})
CNR	3.3	16 %	65 – 85	0.025 (W. Arc) – 0.4 (Northern Clump)	460
Northern Arm	2.1	11%	100 - 150	0.05	50
East-West Bar	1.9	10%	100 - 150	0.033	120

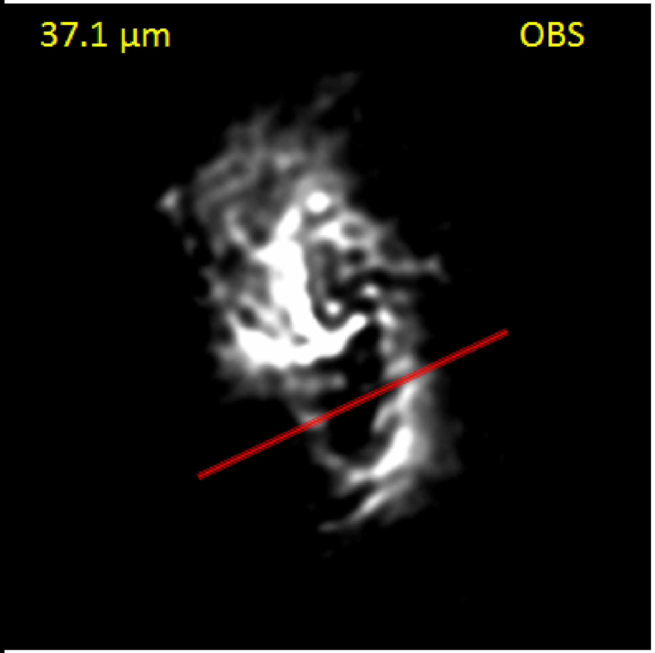
Ring Radius (R)	Inclination Angle (θi) [5,6]	Opening Angle (φ_o)	Ring Height (h)	$\tau_V = 1$ Length (t)
1.4 pc	67°	14°	0.35 pc	~0.3 pc

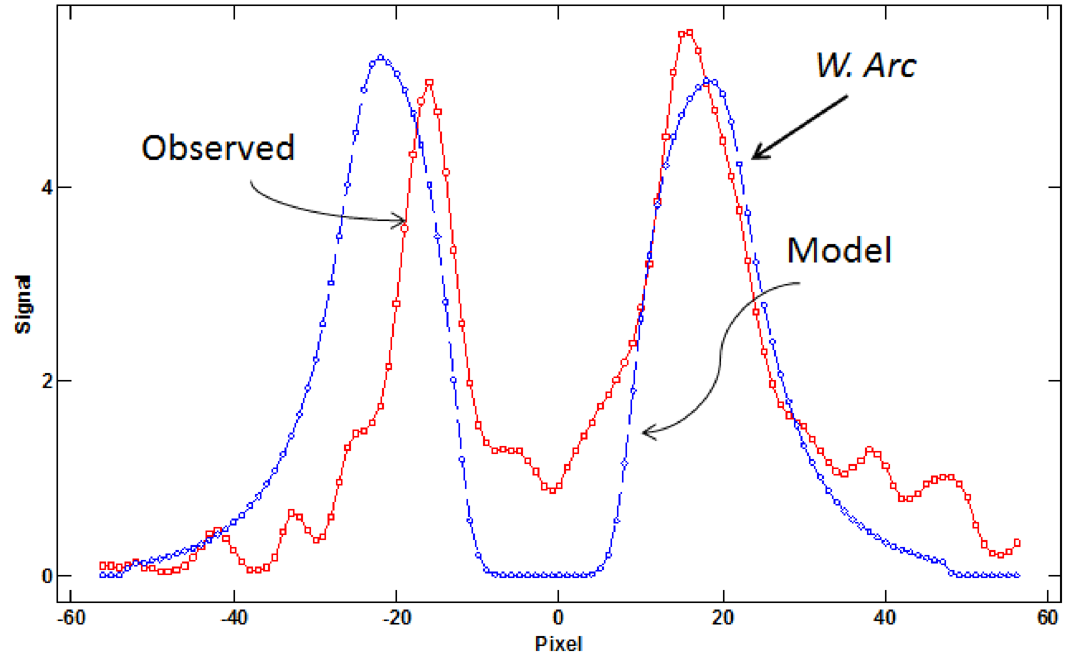
Model Parameters: Dust Properties

- 53% Silicate and 47% Graphite type dust grains (dust to gas mass ratio of 1/100)
- Grain Size dist: amin – 0.1 µm, amax – 2 µm
- Dust density profile: n(r) = n0 (r/Rin)^q
  - n0 = 10^4 cm^-3
  - q = -1.5
- Dust temperature profile: T(r) = T0 (r/Rin)^m
  - T0 = 80 K
  - m = -1

These dust properties are checked with DUSTY in comparison with our temperature map from observations

Model vs Observed 37.1 Intensity Map Line Cut: East-West





Observed 37.1 μm Intensity map of the inner 6 pc of the GC with Southern East-West overlaid

Model vs. Observed 37.1 μm intensity line cut through CNR.

Eastern arm of CNR lies slightly inward of model

Pistol Nebula Spectral Energy Distribution and Model Fit Attempts