Tombs and Wombs: Examining Supernova Remnant/Interstellar Medium Interactions in the Large Magellanic Cloud with WISE

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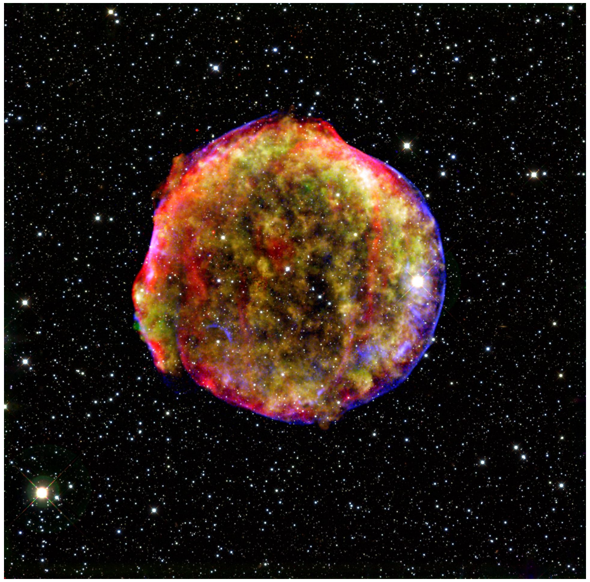


SN 1572 (Tycho Remnant)

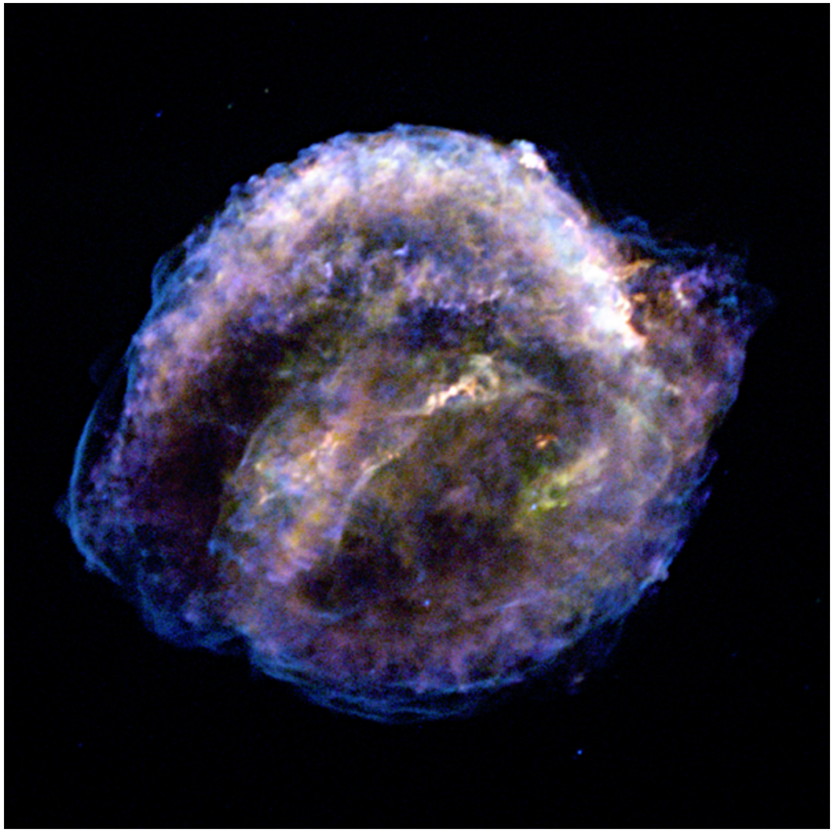
Credit: X-ray: NASA/CXC/SAO (Blue), Infrared: NASA/JPL-Caltech (Red); Optical: MPIA, Calar Alto (Yellow), O.Krause et al.

M16 (“Pillars of Creation”)

Credit: NASA HST; J. Hester, and P. Scowen (Arizona State University)

The Tomb: Supernova Remnants (SNR)

- What are SNR? Where do they come from?
  - Progenitor Supernova Event:
    - Type Ia: (Thermonuclear Reaction of a White Dwarf exceeding Chandrasekhar limit)
    - Type II: (Core Collapse of a Massive star)
- SNR material is:
  - Metal enriched – from fusion core of former star and nucleosynthesis during early expansion
  - Strongly shocked – expansion velocities greatly exceed local speed of sound
  - Superheated ~ 10^6 K plasma near shock boundary



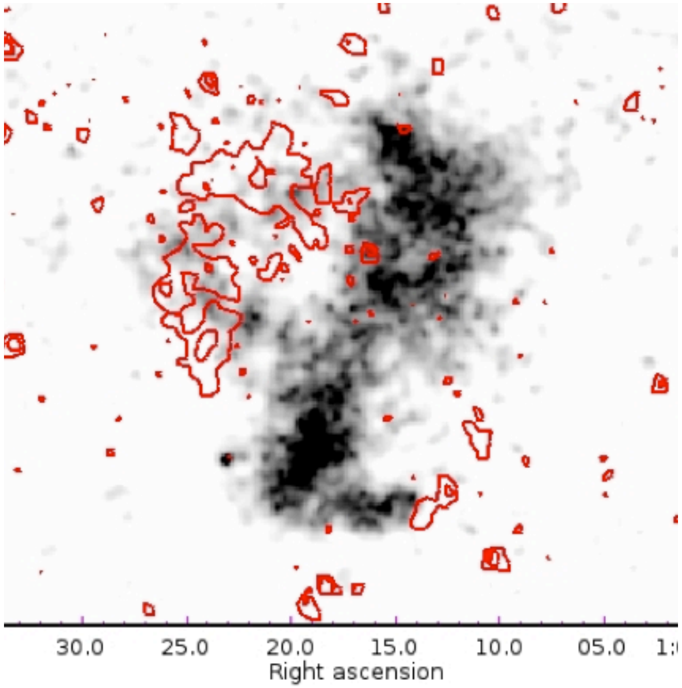
SN 1572 (Kepler Remnant)

Red: 0.3–0.72 keV; Green: 0.72–1.7 keV; Blue: 1.7–8 keV.

Image Credit: NASA/CXC/NCSU/Reynolds et al. 2007

The Womb: Interstellar Medium (ISM)

- As SNRs evolve, they interact with the surrounding ISM
  - Enrich the ISM with metals
    - Fusion products from progenitor star with surrounding medium, SNRs are the primary source of this enrichment
  - Drive ISM dynamics
    - Energy from SN event passed to gas/dust nearby, causes mixing and ISM turbulence, shocks dissociate PAHs locally
  - Presence of SNRs may also influence star formation
    - Observationally motivated (e.g. Herbst & Assousa 1977) but never conclusively observed

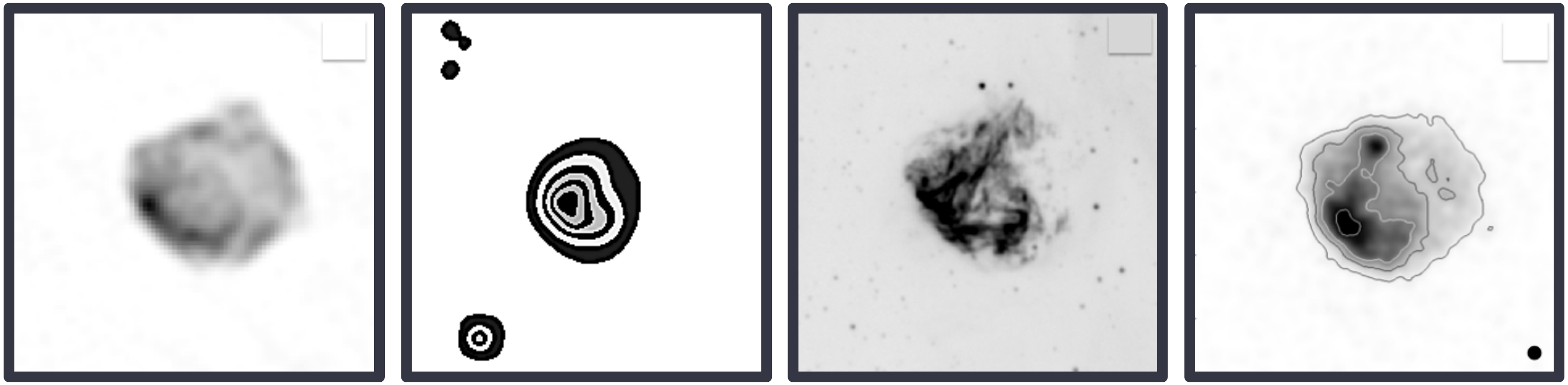


IKT 25 – An SMC SNR.
Grayscale: Chandra ACIS; Red Contours: Spitzer IRAC 8 μm.
Image Credit: Quentin Roper, UI

↳ Hence, SNRs play key roles in galactic evolution!

How can we probe SNR/ISM interactions?

N 49

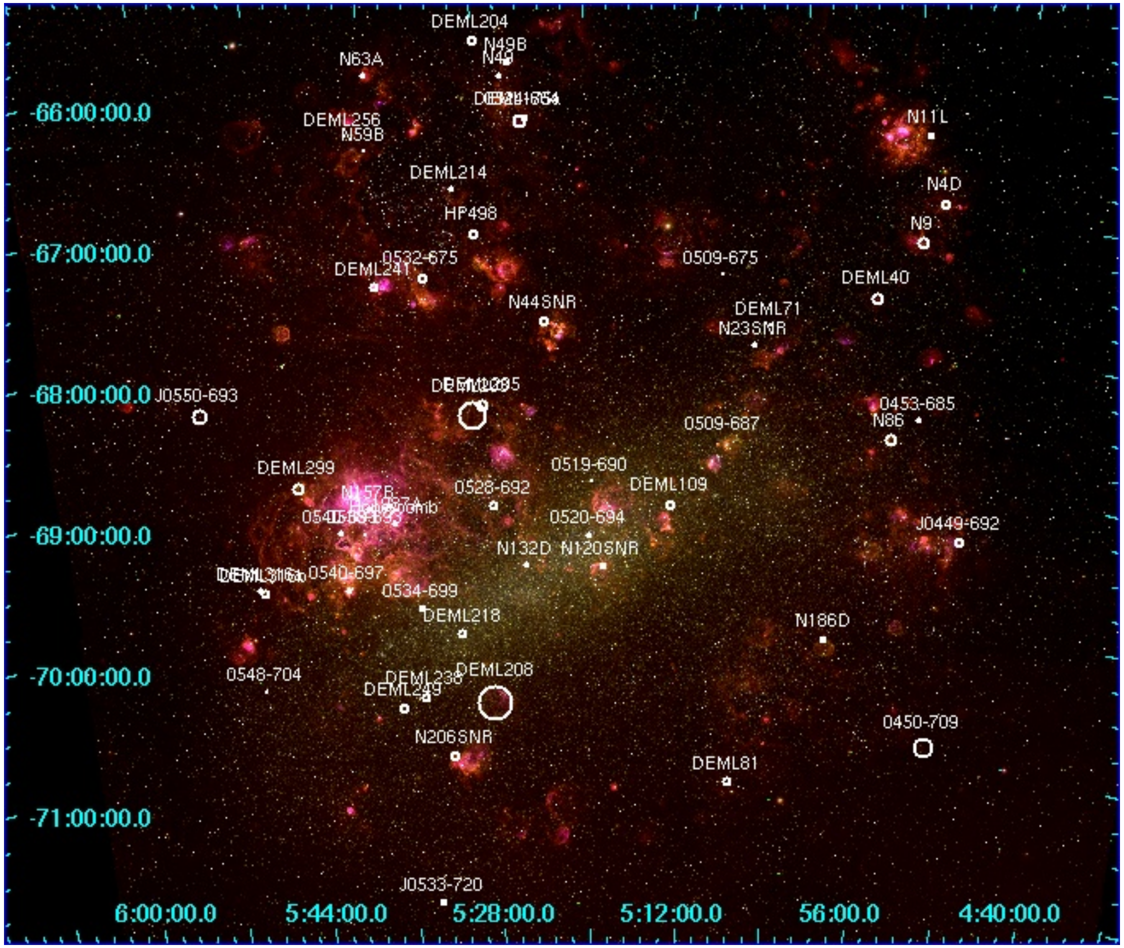


Radio (20cm) IR (22μm) Hα X-ray

- Observe coincident emission in multiple wavelength regimes
  - Turbulent shocks produce X-ray
  - Pressure driven shell is seen in optical
  - Cooling interior hydrogen gas emits radio
  - Heated dust radiates in IR
  - A survey of wavelengths probes different densities and temperatures

Cool story, bro – but where do you look?

- Check out the Large Magellanic Cloud (LMC)!
  - LMC is analogous to a younger Milky Way
    - lower metal content (0.6 solar metallicity)
  - Low LoS absorption at a known distance (~ 50 kpc)
  - 45 known SNRs (location and extent provided by Desai et al. 2010)
  - LMC SNRs are already studied in a variety of wavelengths (x-ray, radio, optical)

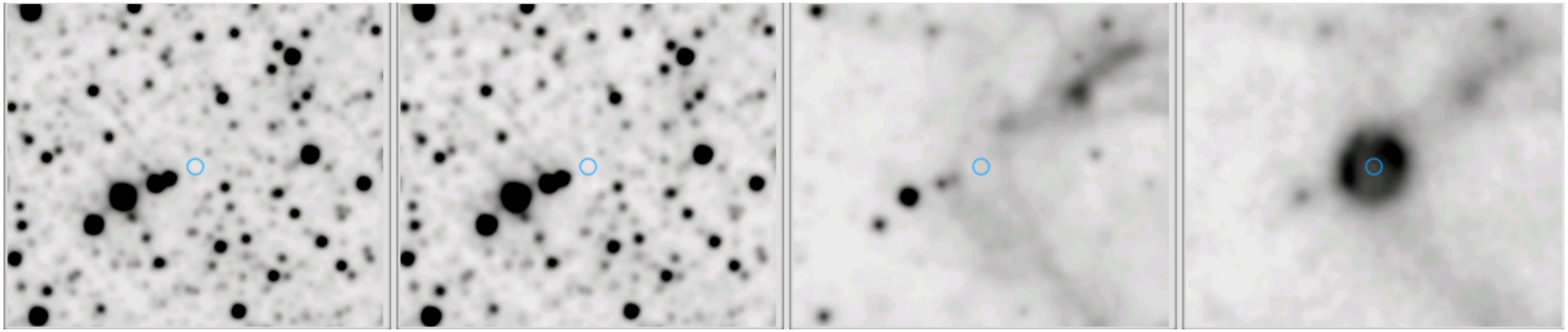


The Magellanic Cloud Line Emission Survey (MCELS) – View of the LMC Supernova Remnant Locations
Image Credit: Rosa Williams and the MCSNR Database Team

Our Project: A LMC SNR Survey

- Detailed multi-wavelength morphology for a large population of SNRs difficult – beyond the scope of this project
- What are we going to do?
  - Instead, correlate bulk properties of the remnant related to SNR/ISM interaction
    - bulk properties: age, total luminosity (X-ray, 22 µm), broad morphological classifications
  - Incorporate recent infrared observations – WISE – to pre-existing data
  - Identify Young Stellar Objects (YSOs) near LMC SNRs to examine the possibility of shock-triggered star formation
- How are going to do this?
  - Computing total luminosities:
    - IR/Optical: integrate over SNR extents
    - Radio/X-ray: Use pre-existing data sets to get total count rates/fluxes
  - Classify SNRs for analysis:
    - Estimate ages
    - IR morphology in relevant WISE bands

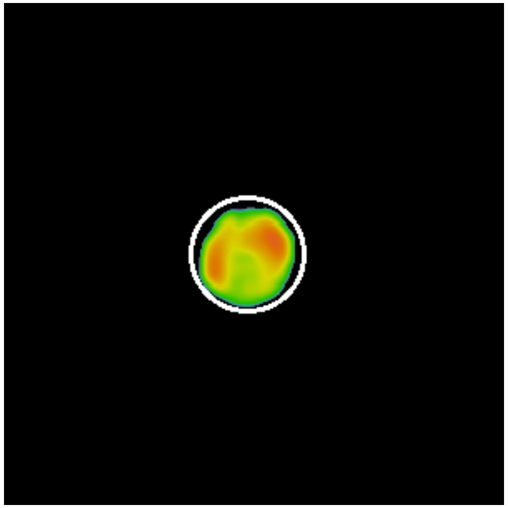
WISE Source Classification System



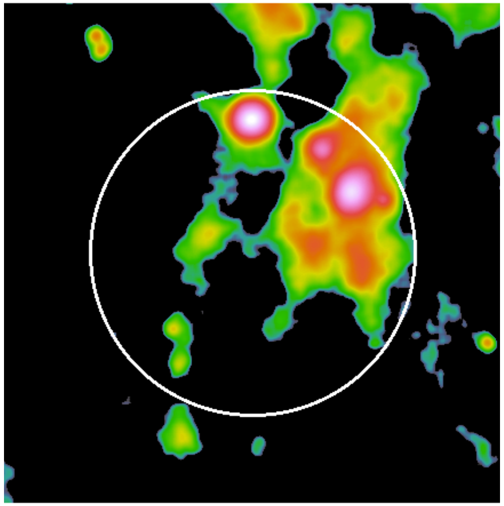
DEM L71

- Not all known LMC remnants are detected by WISE
  - Most remnants have no significant observable emission in 3.4 (W1), 4.6 (W2) µm
  - 12 µm (W3) emission is often faint, and traces predominantly PAH emission (Wright et al. 2010, §4.4.3)
  - 22 µm (W4) includes thermal continuum from small grains and the Wien tail of large grains – traces dust heating
- Even in 22 µm, not all SNRs appear bright compared to background
  - Division into three IR categories: “Detected” (D), “Possible Detection” (P), and “Not Detected” (N)

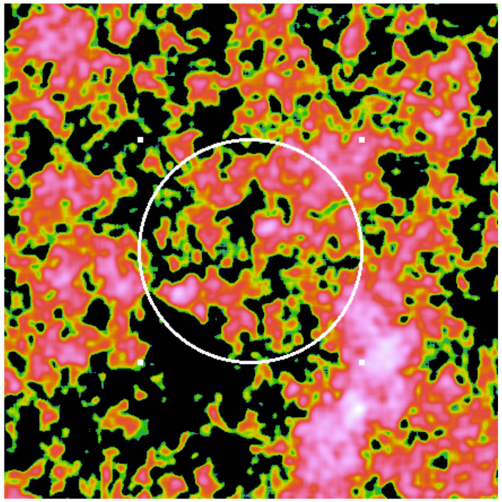
WISE Source Classification System (cont.)



DEM L71 (D)



N86 (P)



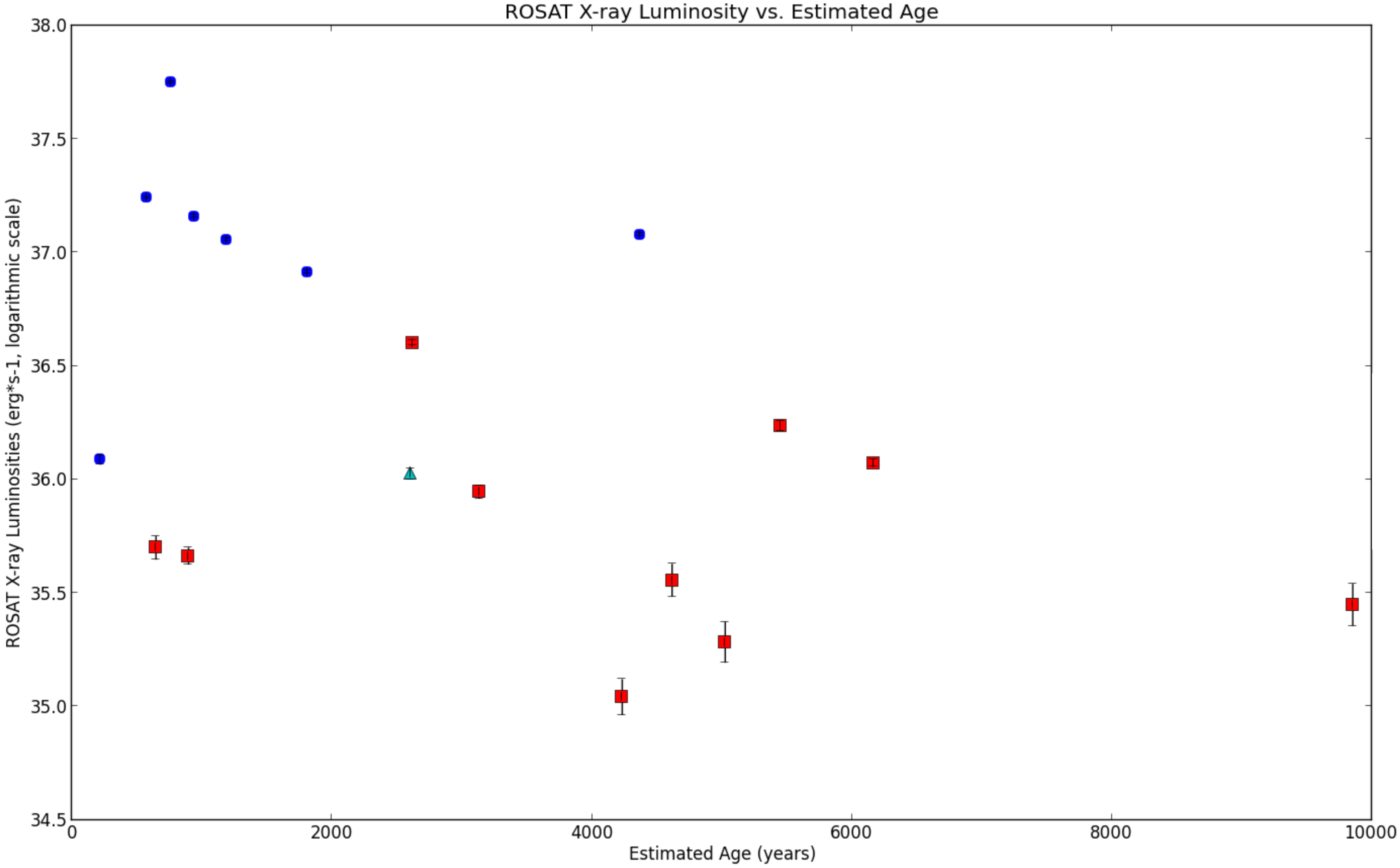
MCELS J0448-6659 (N)

- “Detected” (D):
  - Roughly spherical, “filled-in” morphology
  - Fraction of Overall Survey: 10 of 45
- “Possible Detection” (P):
  - Structured, peripheral emission, unclear if associated with SNR
  - Fraction of Overall Survey: 6 of 45
- Not Detected (N):
  - No emission or emission not associated with SNR
  - (Large) Fraction of Overall Survey: 28 of 45

X-ray, Radio, Optical Observations – Holy Multi-wavelength Analysis, Batman!

- X-ray: Archival *ROSAT* data as analyzed by Williams et al. 1999
  - 31 LMC SNRs detected, classified sources by X-ray morphology, measured total count rates (we converted this to a luminosity)
- Radio: CSIRO Parkes radio telescope, observed by Filipović et al. 1998
  - Used empirical relation to relate 4.75 GHz flux to dynamical age of SNR
- Optical: Magellanic Cloud Line Emission Survey (MCELS)
  - Narrow band filters centered on [O III] (5007 Å), Hα (6563 Å), [S II] (6724 Å)
  - Identify SNRs by large [SII]/Hα ratio

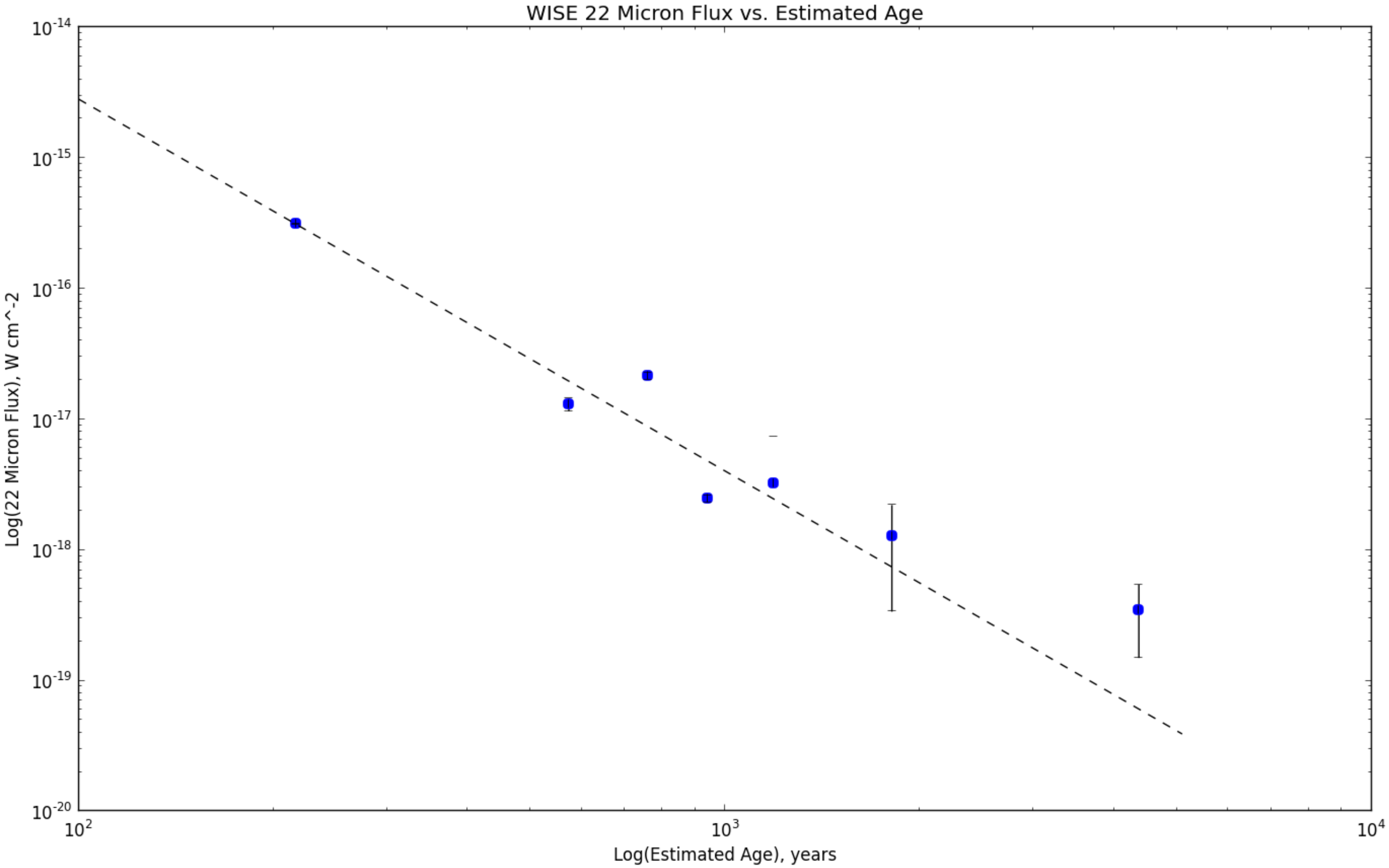
Results – ROSAT X-ray vs. Radio Age



Color Key:
Blue: Detected,
Red: Not Detected,
Green: Possible Detection

- IR classification scheme shows significance outside of IR wavelengths!
- 22 μm detections: most X-ray luminous, tend to be younger
- Williams morphology classifications: largely “Diffuse Face” or “Shell”

Results – 22 μm vs. Radio Age



Color Key: Blue: Detected, Dashed Line: Best Fit Model to power-law model:

$$f_{22\mu m} = c \ (T/1000 \text{ years})^{-a}$$

Best fit parameters:

c = 4.02 ± 1.67 (W cm^{-2})

a = 2.84 ± 0.27

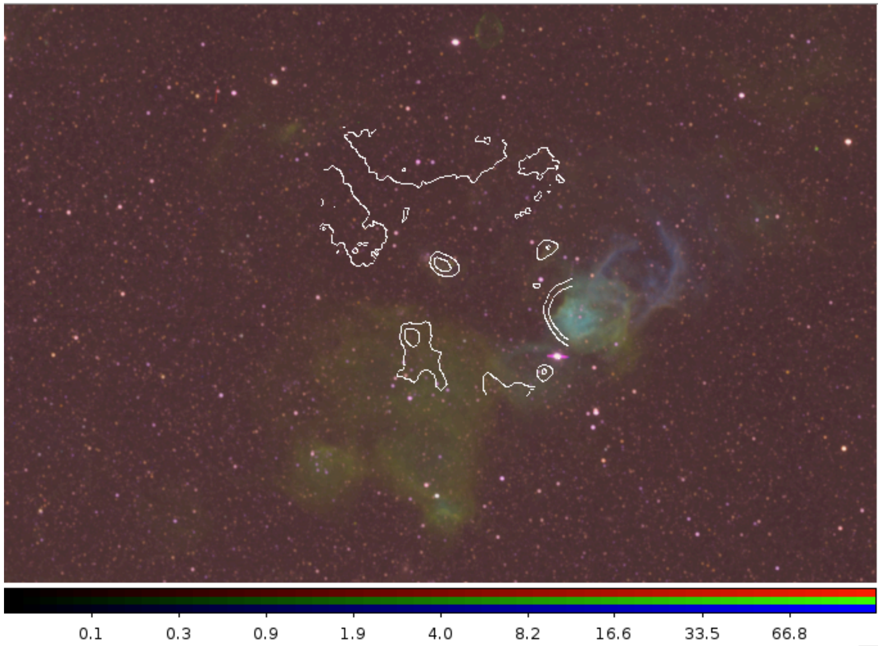
- Only look at detections (D) – only IR emission we can associate with SNR
- Clear turn-over: 22 μm bright at younger ages, 22 μm emission no longer as efficient on timescales T ~ 4000 years
- Cooling dust? Or large grain destruction?
  - Dust grain destruction more likely on physical grounds – expect dust to be reheated through reverse shock, power-law size distribution of large dust grains

WISE Detected SNRs – Characterization

- All WISE detected SNRs appear in complicated optical regions (Hα bright)
- 3.4, 4.6 μm not observed in most cases, faint 12 μm emission

Conclusion: D-class SNRs are young remnants in a dense ambient medium (SFRs?) with strong shocks

- X-ray luminosity – superheated material at shock front, young SNR = strong shocks
- Dense medium – shocked ISM dust fills inner region, radiates thermally
- Strong shocks – dissociate PAHs, small grains for most remnants
  - Faint emission in 3.4, 4.6, 12 μm
  - Diminishing 22 μm emission with age makes a case for destruction



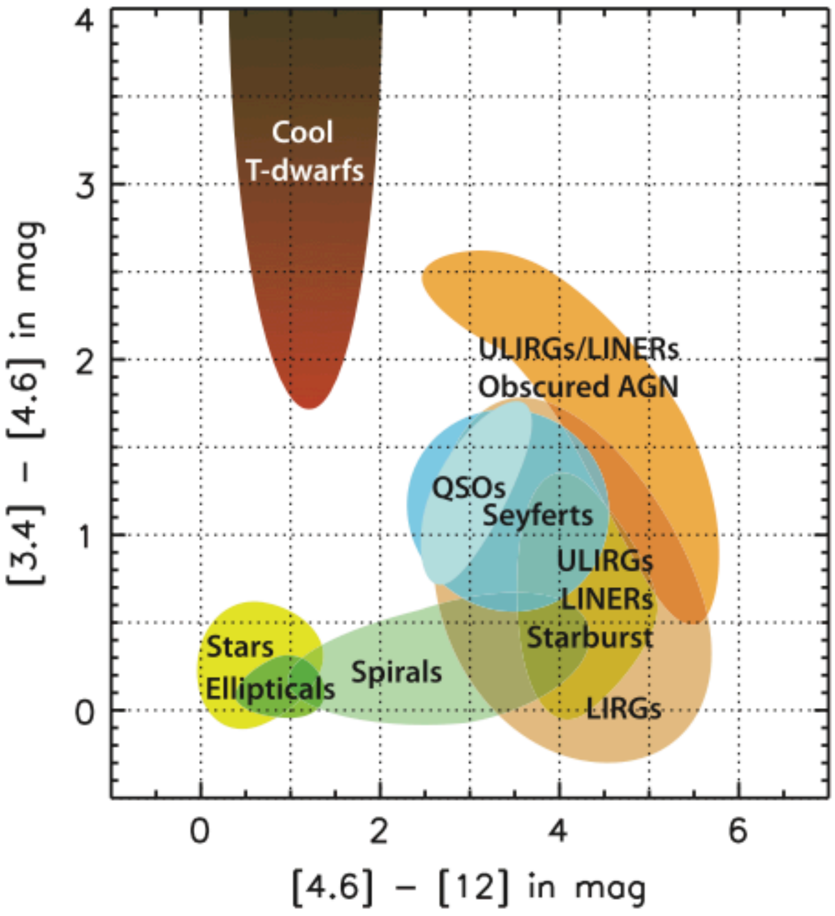
N23 (SNR 11): MCELS RGB (Red [SII], Green Hα, Blue [OIII]) with WISE 22 μm contours

SNR and Nascent Stars

- Hypothesis: Shocks from SNRs can trigger star formation (SF)
- Desai et al. 2010 – optical study of SNRs in the LMC to detect any spatial association with young stellar objects (YSOs) and molecular clouds (MCs):
  1. Most cases for induced star formation were rejected
  2. Proximity does not guarantee causality
  3. Need confirmation of surrounding molecular structure
- Our criteria for observing shock-triggered star formation:
  - YSOs are spatially associated with an SNR
  - SNR needs to be older in order for shock velocities to be slow enough not to dispel molecular cloud core
  - Visible 12, 22 μm emission forming “trunk-like” structures nearby, associated with star formation regions

Multi-partisan Candidates

- Sample suffers serious source contamination

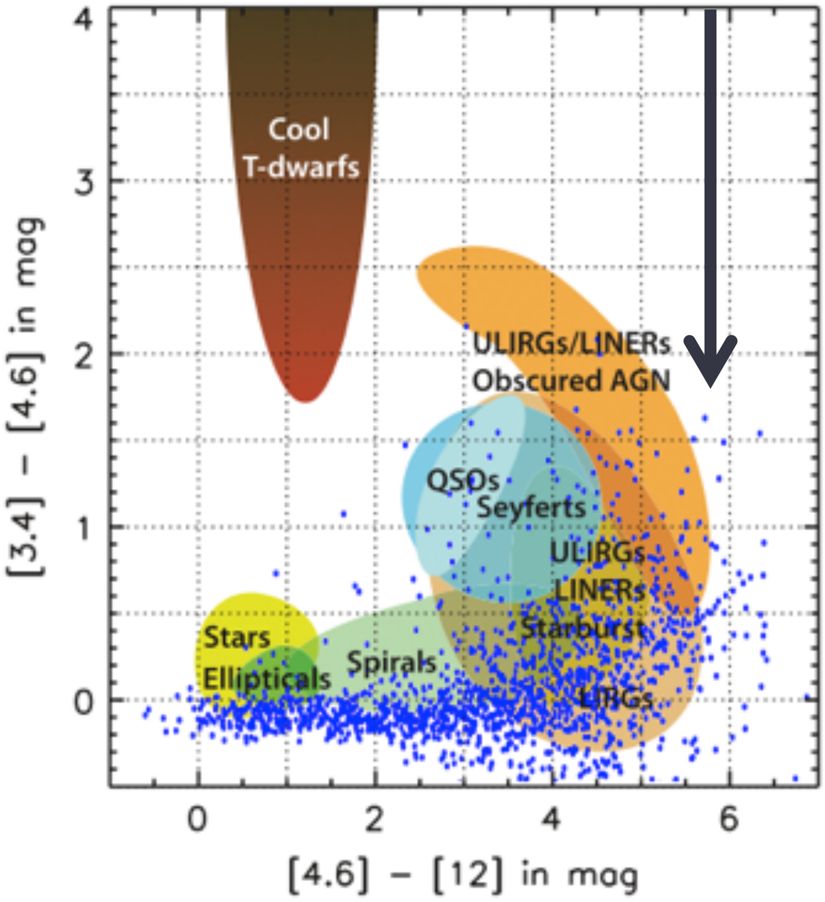


WISE Projected Color-Color Diagram
Image Credit: Wright et al. 2010

Multi-partisan Candidates

- Sample suffers serious source contamination
- We utilize a photometric color-cutoff scheme developed by Koenig et al. 2012 to identify YSOs based solely on WISE data

Point Sources



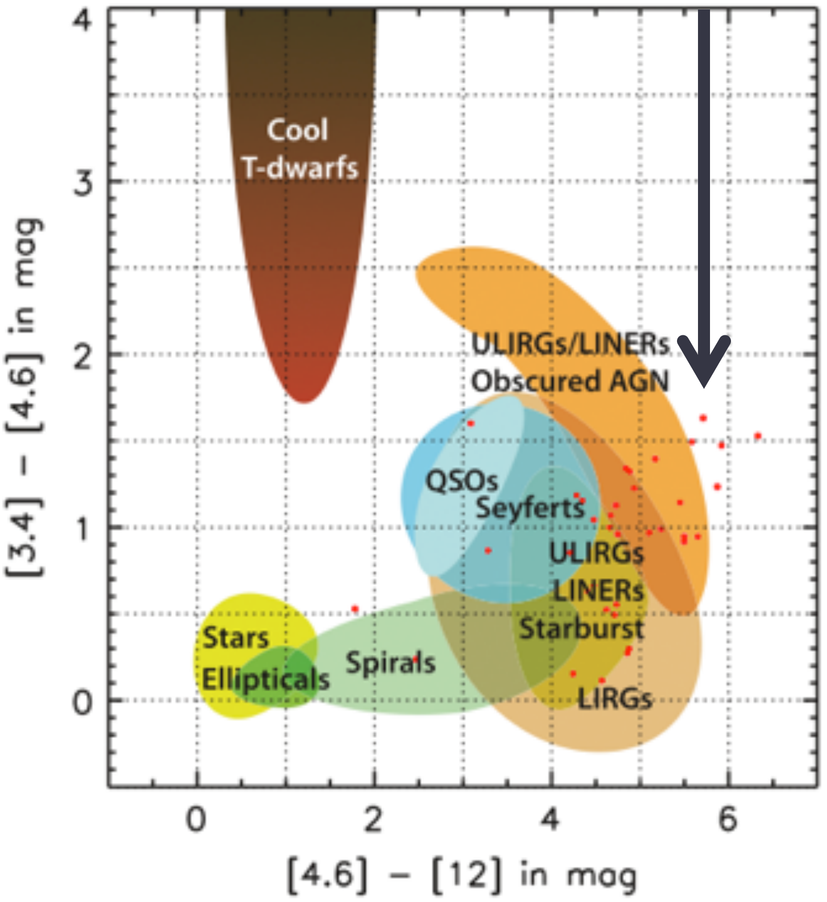
WISE Projected Color-Color Diagram
Image Credit: Wright et al. 2010

Multi-partisan Candidates

- Sample suffers serious source contamination
- We utilize a photometric color-cutoff scheme developed by Koenig et al. 2012 to identify YSOs based solely on WISE data

- We eliminate:
  - Red star forming galaxies
  - Broad-line AGNs
  - Shock emission knots
  - Structured PAH emission

Surviving YSOs

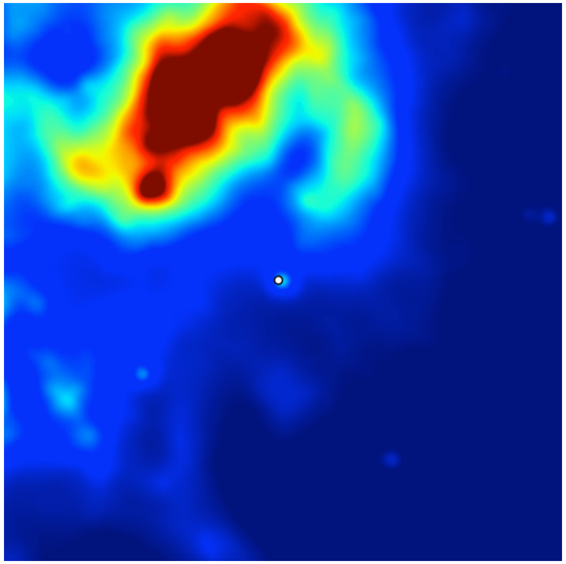


WISE Projected Color-Color Diagram
Image Credit: Wright et al. 2010

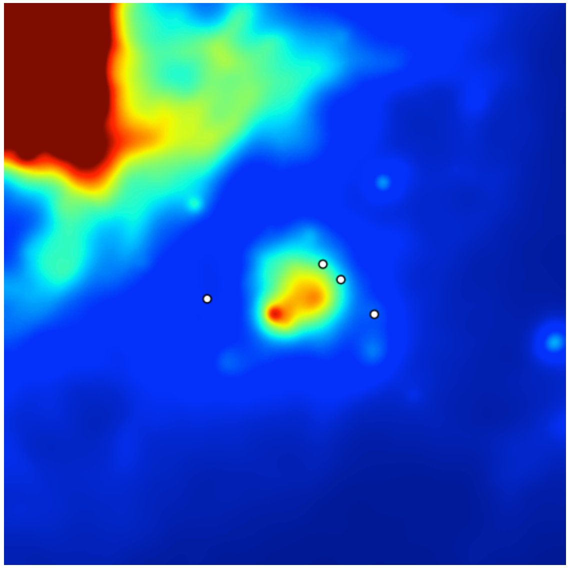
Criteria 1: Spatial Association

- Surviving YSO candidates are distributed among 17 observed SNR, including all 10 SNR-YSO candidates considered by Desai et al. 2010.
- Examples of nearby SNR-YSO candidate associations are shown below:

SNR 1987A

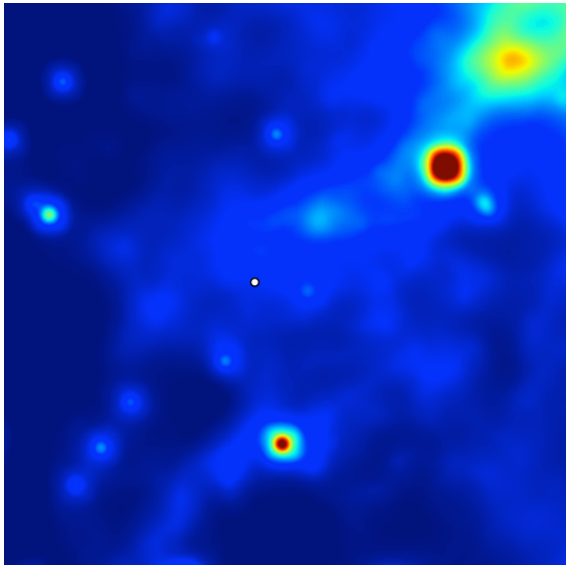


N157B



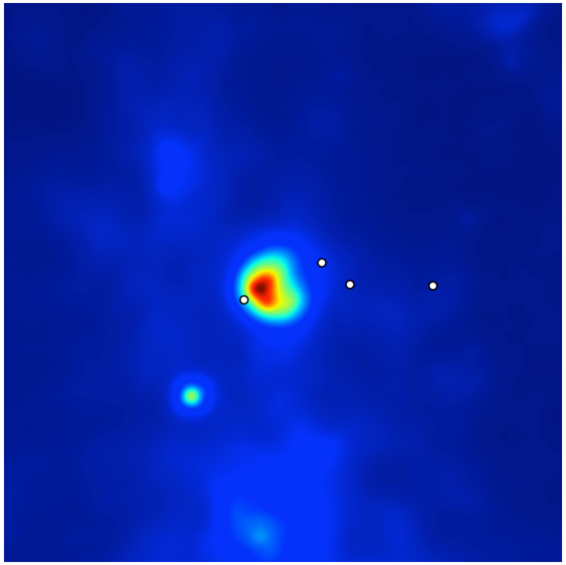
~200 yrs

N158A



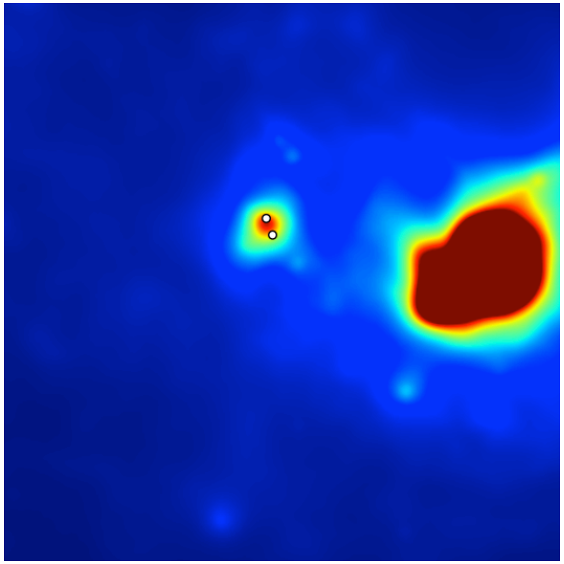
Criteria 2: Temporal Plausibility

N49



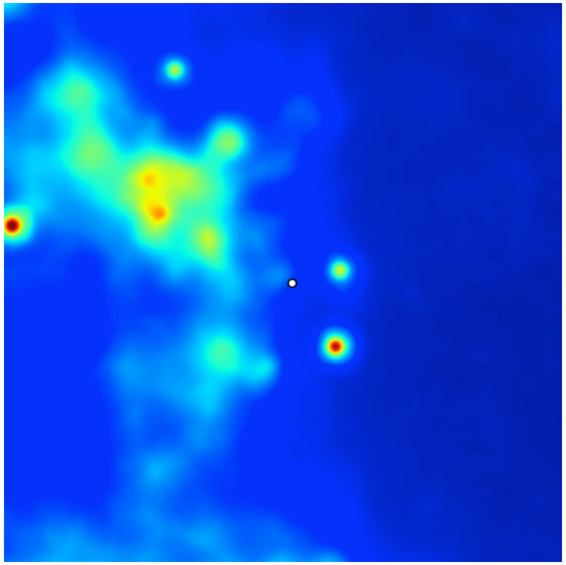
~600 yrs

DEM L241



~2700 yrs

N57

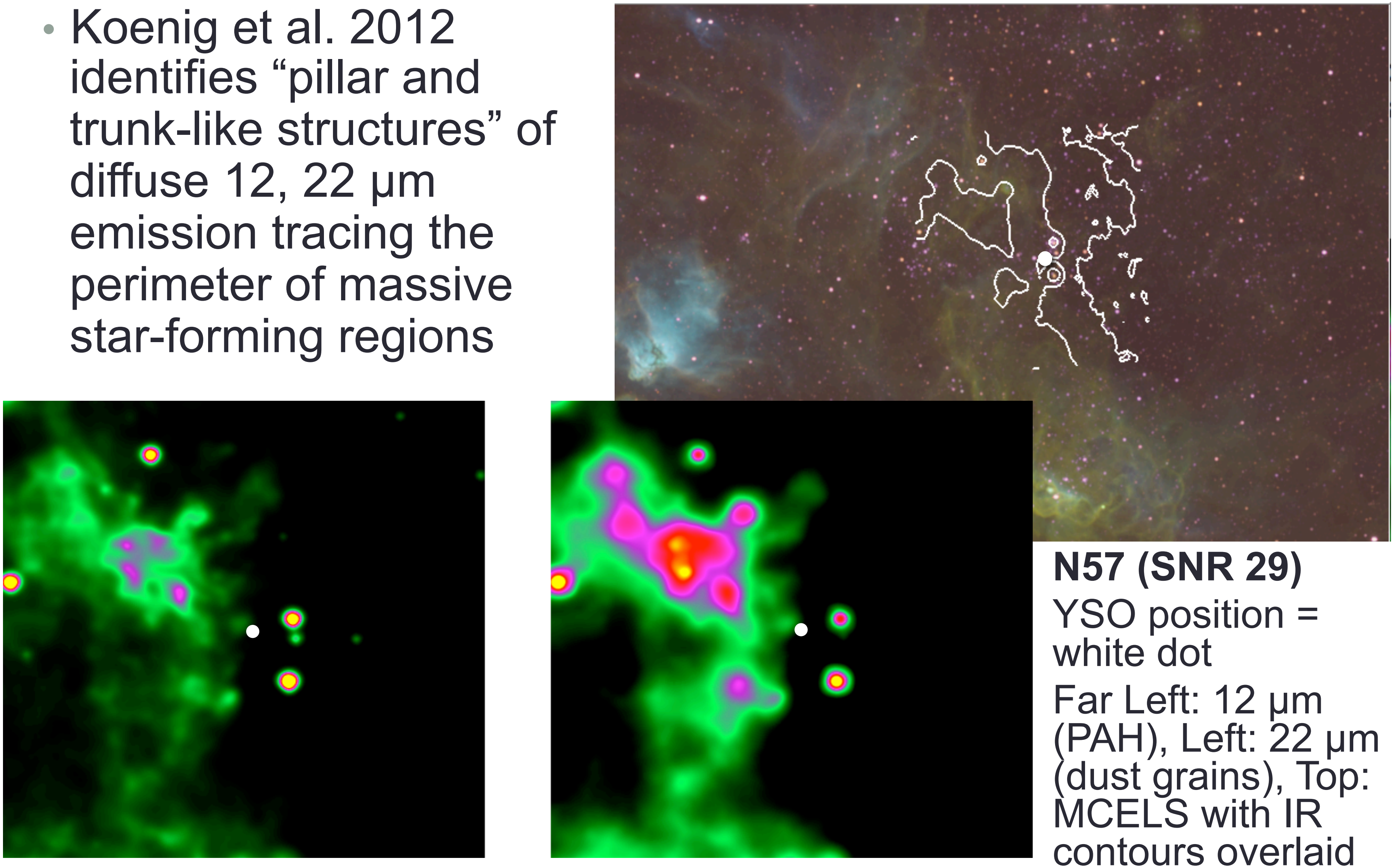


~3600 yrs

- Only those SNRs with older radio ages (~ 10^4 years or more) will have shocks slow enough ($v \approx 20 - 45\ \mathrm{km\ s^{-1}}$) to perturb (not destroy) nearby molecular cloud cores

Criteria 3: Molecular Environment

- Koenig et al. 2012 identifies “pillar and trunk-like structures” of diffuse 12, 22 µm emission tracing the perimeter of massive star-forming regions



N57 (SNR 29)

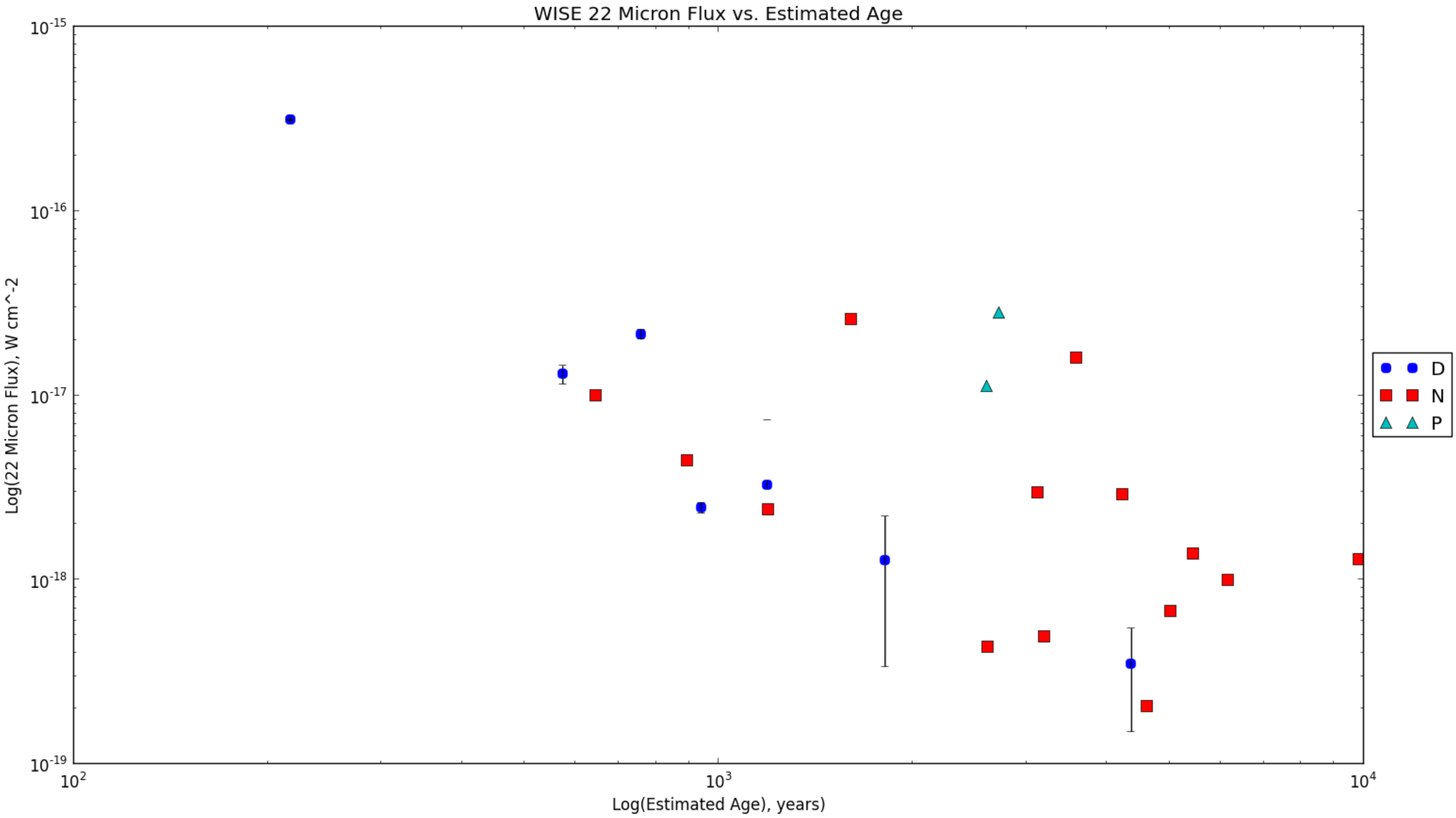
YSO position = white dot

Far Left: 12 µm (PAH), Left: 22 µm (dust grains), Top: MCELS with IR contours overlaid

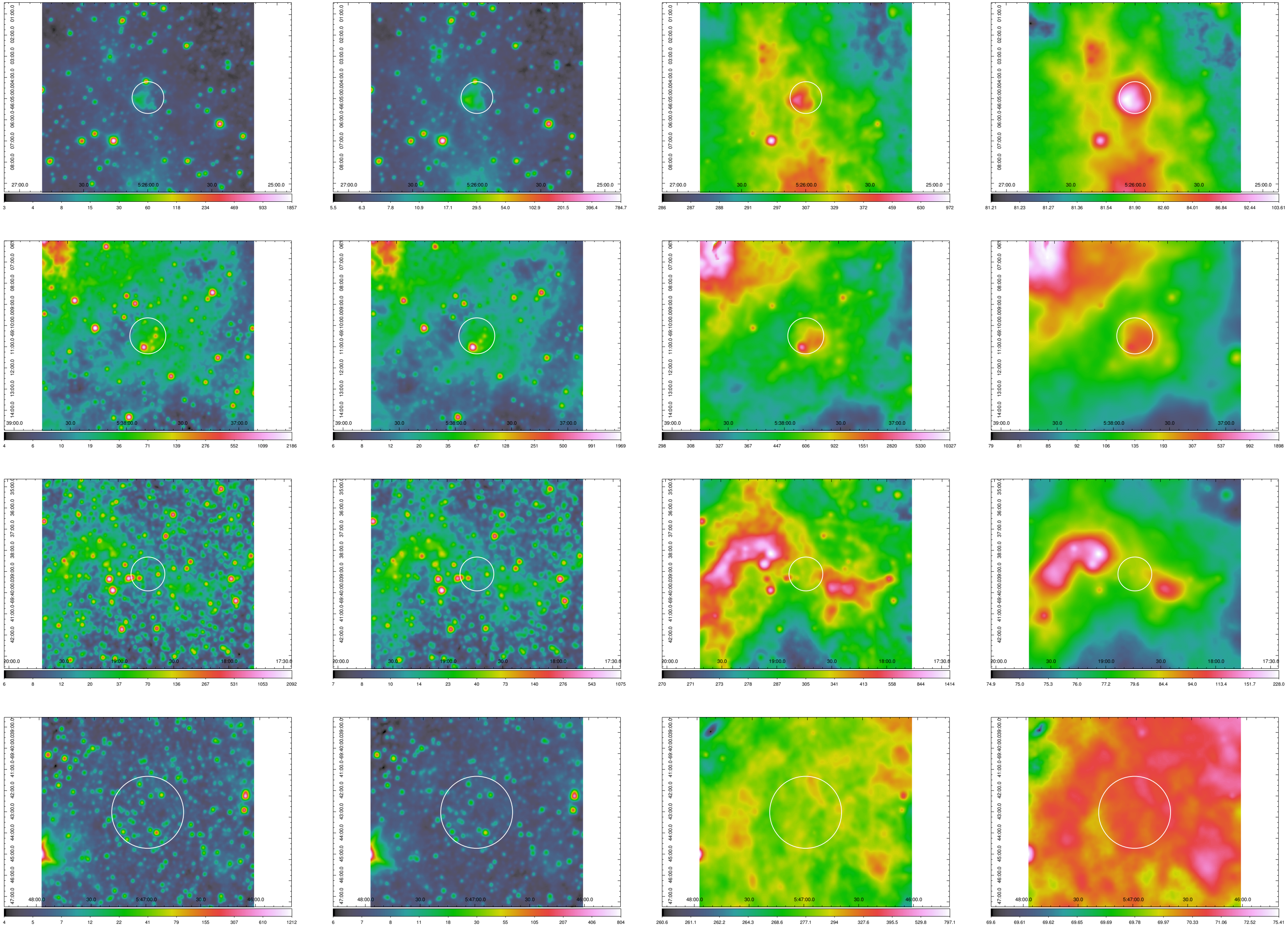
Examining ISM/SNR Interaction – Conclusions

- Surrounding medium can be important in explaining observed emission, even outside of IR wavelengths
  - WISE 22 μm morphology classification - basis for characterizing a type of LMC SNRs
  - Witnessing dust destruction?
    - Faint emission in 3.4, 4.6, 12 μm for most remnants – LMC SNRs destroying PAHs and small grains
    - Diminishing 22 μm emission with age makes a case for destruction rather than cooling
    - Detailed simulations of dust/shock interactions needed to determine which process is predominant
- Like Desai et al. 2010, we observe no evidence of shock-triggered star formation
  - No LMC SNR has sufficient age to have slow enough shock velocities
  - Shock-triggered SF may not be an important mechanism, even in regions of heavy star formation
  - Possible selection bias (older remnants dim, difficult to identify)

Supplemental Slide – 22 µm Flux for all LMC SNR

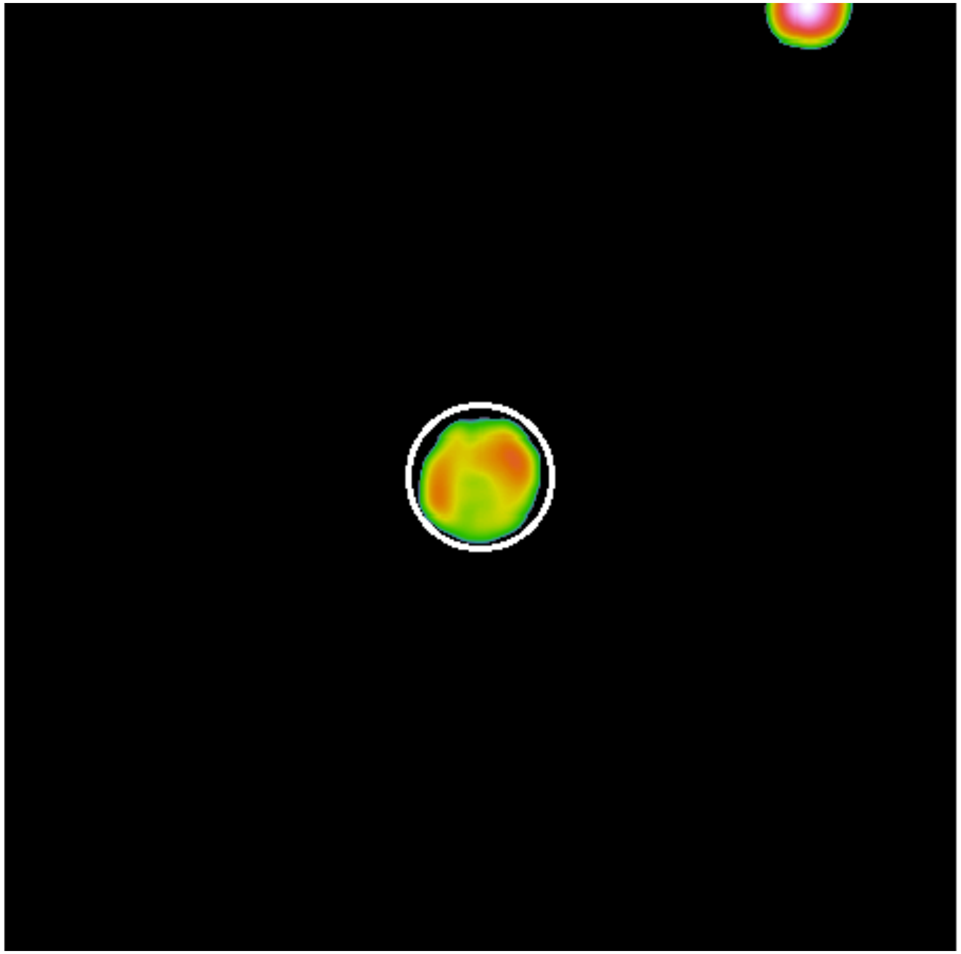


Supplemental Slide – 3.4, 4.6, 12 µm Emission in LMC SNR



0525-66.1 (N49, top row), 0538-69.1 (N157B, center top row), 0519-69.7 (SNR in N120, center bottom row), and 0547-69.7 (DEM L316B, bottom row)

WISE Source Classification System – Detected

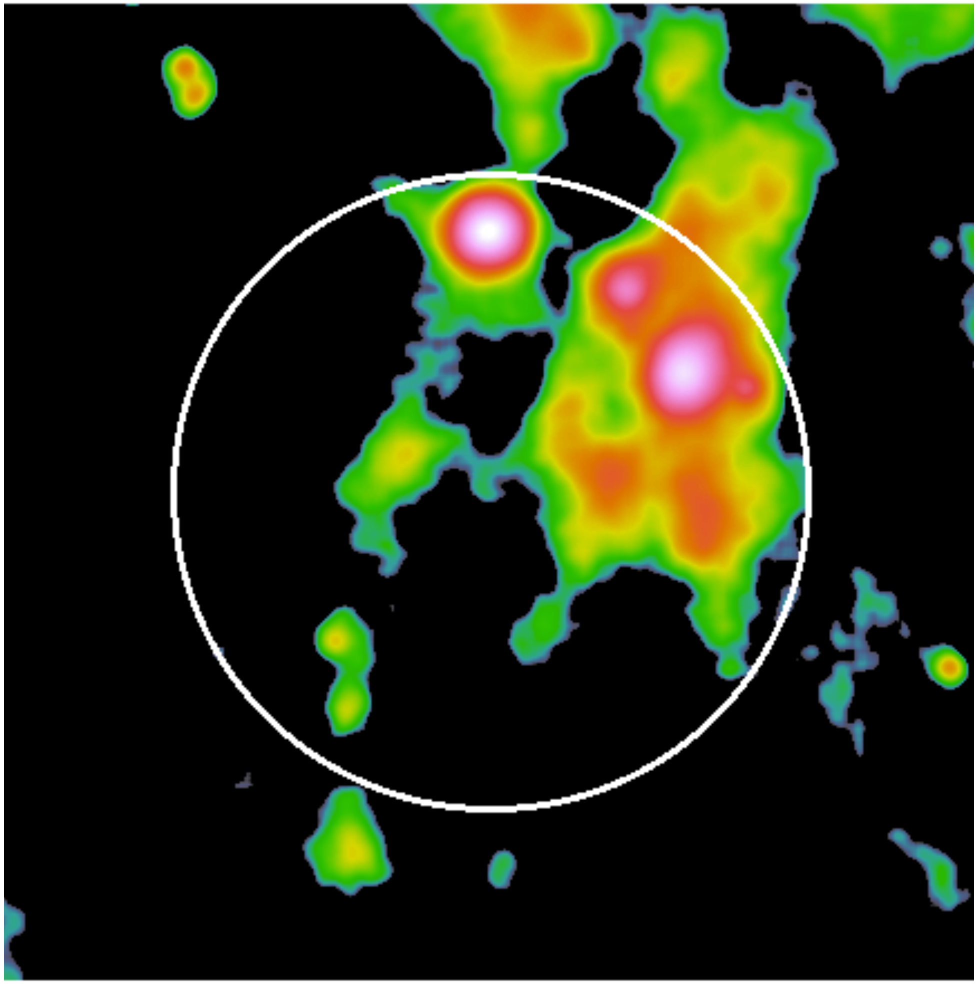


"Detected" (D) Example: DEM L71 (SNR 10)

- White circle = source region, as identified by Desai et al. 2010

- "Detected" (D) Characteristics:
  - Clear emission above background at all contrast levels (i.e. easiest to classify)
  - Roughly spherical, "filled-in shell" morphology
  - Optical/X-ray identified remnant locations and extents of Desai et al. 2010 completely coincide with IR emission
- Fraction of Overall Survey: 10 of 45

WISE Source Classification System – Possible Detection

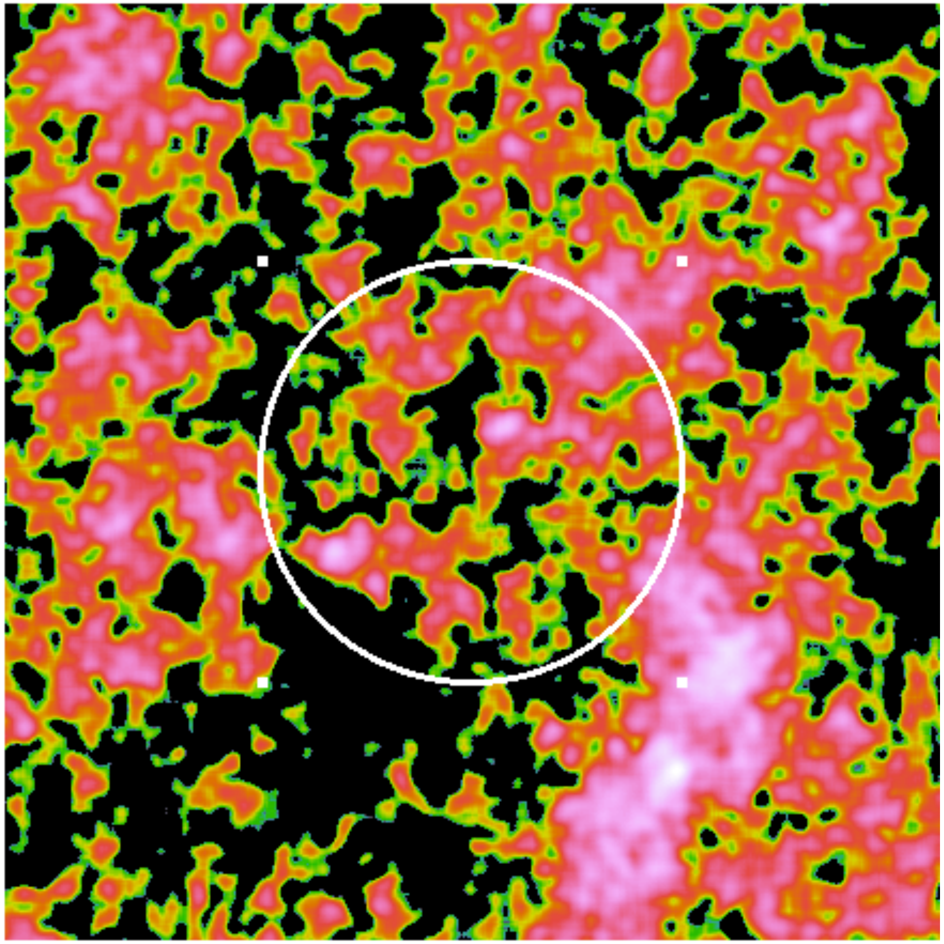


“Possible Detection” (P) Example: N86 (SNR 8)

- Clumpy emission on the outskirts of source region
- Psuedo-spherical or shell-like
- Unclear if point sources or diffuse with regions of higher intensity

- “Possible Detection” (P) Characteristics:
  - IR emission above background structure present in the image
  - 22 μm emission often present on the periphery of source region
  - Unclear if associated with SNR or background
  - Hardest to classify
- Fraction of Overall Survey: 6 of 45

WISE Source Classification System – Not Detected



"Not Detected" (N) Example: MCELS J0448-6659 (SNR 1)

- Source region indistinguishable from background

- "Not Detected" (N) Characteristics:

  Three Possibilities:

  1) 22 μm emission from source region indistinguishable from background
  2) Diffuse emission extends into source region, but clearly originates from point-like source outside
  3) Point-like sources contained inside the source region, point sources can be seen in 3.4, 4.6 μm
- (Large) Fraction of Overall Survey: 28 of 45