The Interstellar Medium at the Galactic Center

Cornelia C. Lang (U Iowa)

E. Richards, J. Moon, M. Drout (U Iowa), E. Mills,

M. Morris (UCLA), Q.D. Wang (U Mass), J. Mauerhan,

S. Stolovy (IPAC) and A. Cotera (SETI), and others. . .

and of course W. Miller Goss (NRAO)

Outline

- Where it all began: the GC Sickle HII Region

- Stars, HII Regions and Molecular Gas in the GC

→ *The summer student, PhD student years in Socorro*

- Recent directions in GC Research

→ *Adding the IR perspective: HST Pα GC Survey*

- Looking Forward: GC ISM

→ *Recent projects and ideas for EVLA & ALMA*

Where in the world did *I* meet Miller?

Cornelia and father in PNG (1979)

Summer REU in 1994:
CCL Application details:

- Student at Vassar College: Kate Goss was about to begin there as a first year student

- Qualifications – has learned love for scientific research from biologist father and has lived in: ***South India; Sydney, Australia, Manchester, England***
→ Known for crocodilian research and also radio astronomy!

Little did we know then that CCL's mother Gretchen went to college and was friends with Libby Goss many years earlier – total chance! Just a few of the many connections between our families that we have found.

Our Galactic center: a deeply buried part of the Galaxy

GC region (Sagittarius) is obscured by 30 vis. magnitudes of extinction – no optical, UV

available: radio, near-IR, mid-IR, far-IR, hard X-rays, gamma rays

- Distance 25,000 ly from Sun

- Physical conditions different:
  - T ~ 70-100 K in mol. clouds
  - strong magnetic fields
  - strong tidal forces due to Gravitational potential (turbulence) – spectral lines have very wide profiles

$P_{turbulence} \sim 10^{-8}$ erg cm^{-3}
$P_{magnetic} \sim 4 \times 10^{-10}$ to 10^{-8} erg cm^{-3} for B=0.1 to 1 mG

- Can stars form in this arena?
- What is the interstellar environment like?

“WORST” image of GC SgrA Complex

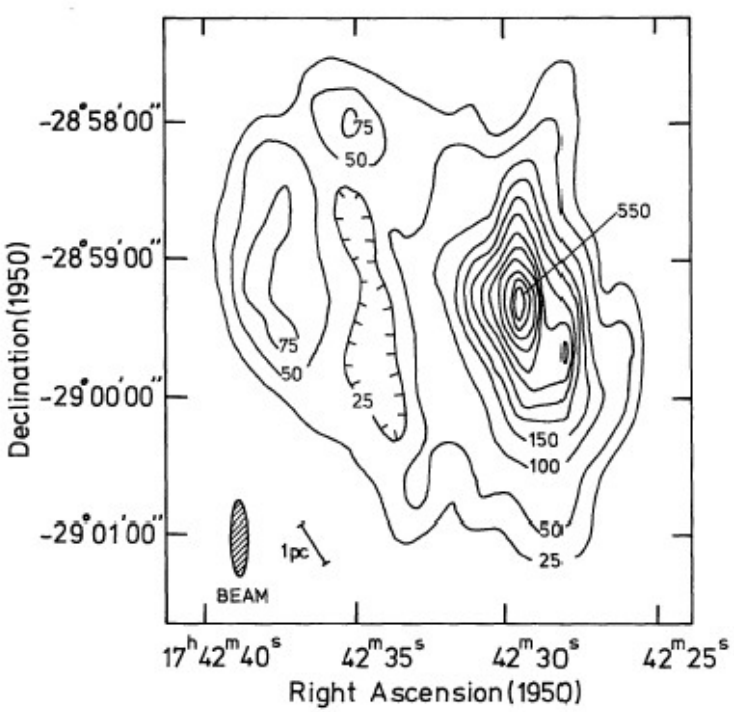


Fig. 4. “Cleaned” map of Sgr A made with combined data from the Westerbork and Owens Valley telescopes. The half-power widths of the synthesized beam are 6.3 × 34″ (R.A. × Dec.), and the contour unit is 1.2 K brightness temperature. The zero contour on this map corresponds approximately to the 60 K contour on the 5 GHz map by Whiteoak and Gardner (1973)

Caption provided by Ron Ekers:

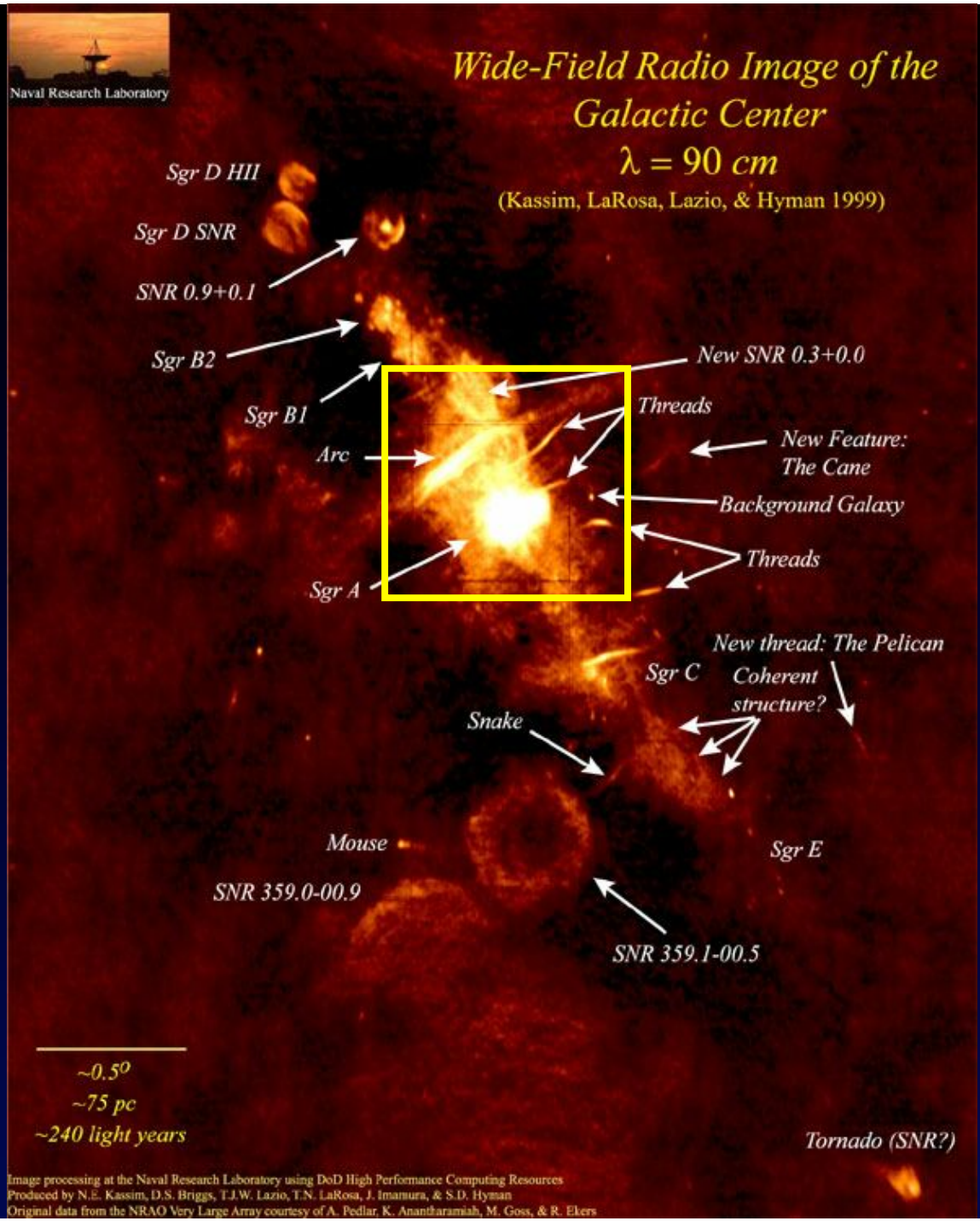
“Original "WORST" image of the Galactic Centre shown to the left. Authors are: Ekers, Goss, Schwarz, Downes and Rogstad.

It was probably the first aperture synthesis image combining data from more than one aperture and it was certainly a challenge for Miller's cat herding instincts to keep this group of individuals together!”

Use radio interferometers like the Very Large Array (VLA) to obtain high spatial resolution to resolve stellar winds and the structures of HII regions

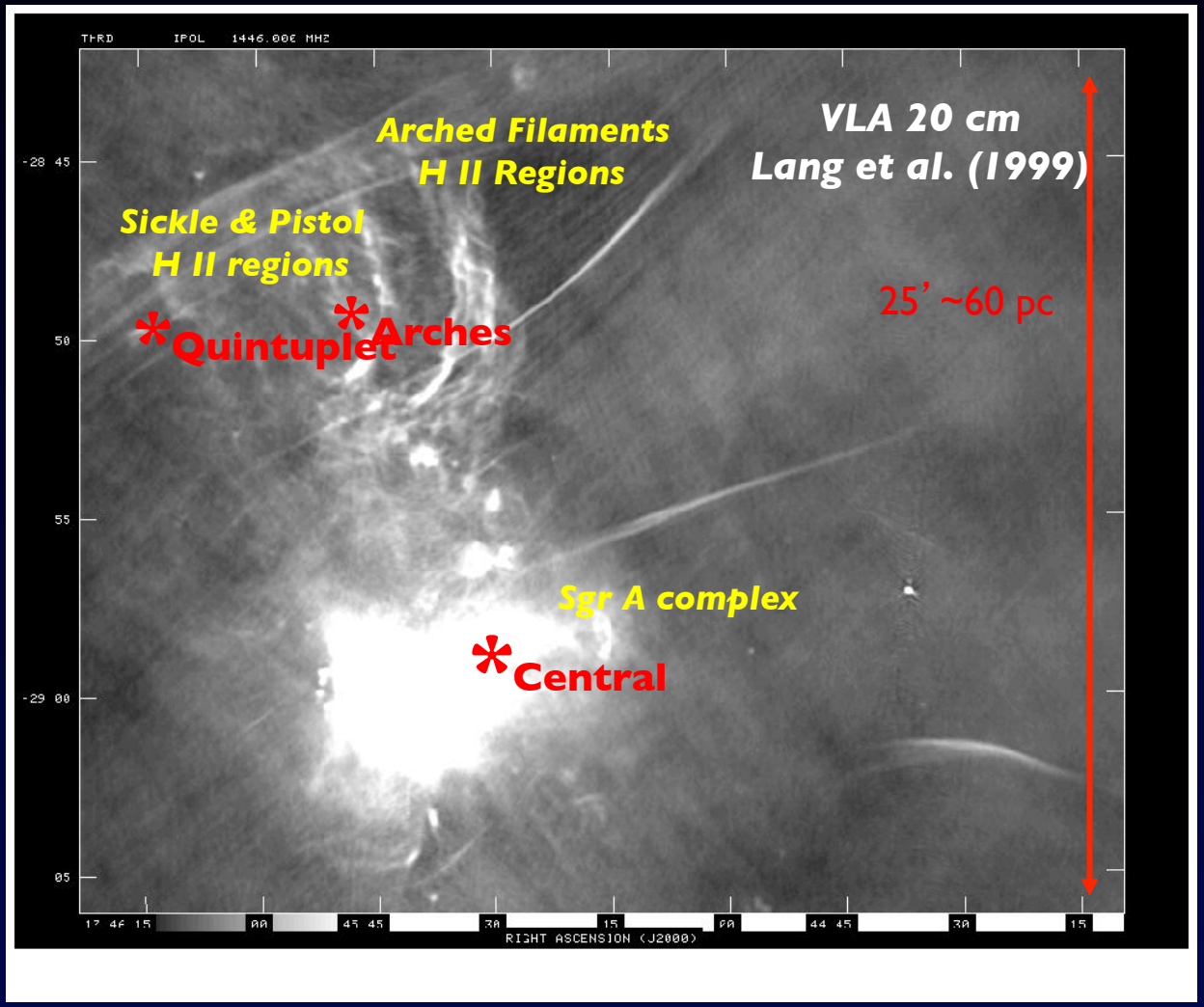
VLA west of Socorro, NM

Summer 1994: CCL as MG's REU


Naval Research Laboratory
Wide-Field Radio Image of the Galactic Center
λ = 90 cm
(Kassim, LaRosa, Lazio, & Hyman 1999)
Sgr D HII
Sgr D SNR
SNR 0.9+0.1
Sgr B2
Sgr B1
Arc
Sgr A
New SNR 0.3+0.0
Threads
New Feature: The Cane
Background Galaxy
Threads
New thread: The Pelican
Sgr C
Coherent structure?
Snake
Mouse
SNR 359.0-00.9
Sgr E
SNR 359.1-00.5
~0.5º
~75 pc
~240 light years
Tornado (SNR?)
Image processing at the Naval Research Laboratory using DoD High Performance Computing Resources
Produced by N.E. Kassim, D.S. Briggs, T.J.W. Lazio, T.N. LaRosa, J. Imamura, & S.D. Hyman
Original data from the NRAO Very Large Array courtesy of A. Pedlar, K. Anantharamiah, M. Goss, & R. Ekers

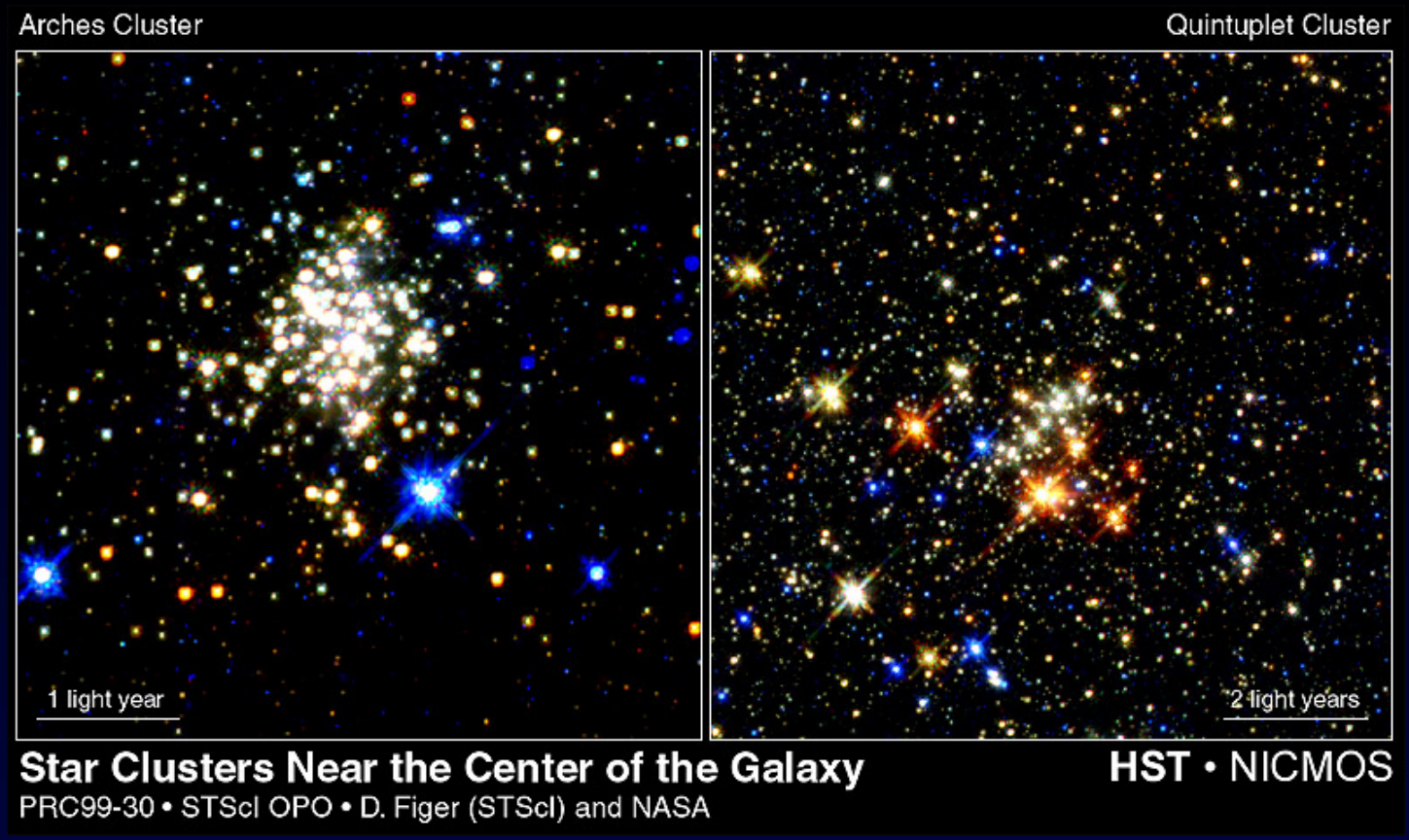
Massive Stars and the ISM in the Galactic Center

Unusual Thermal Filaments – due to Stars?



- location, orientation of stellar heating sources unclear, unusual
- interactions between magnetic fields/clouds proposed for ionization
- radio obs. showed no indications of interactions; consistent with UV-ioniz.
- extraordinary stellar clusters resolved in 90s in Radio Arc: Cotera 1995 Figer 1995, Nagata, Okuda (many other references)

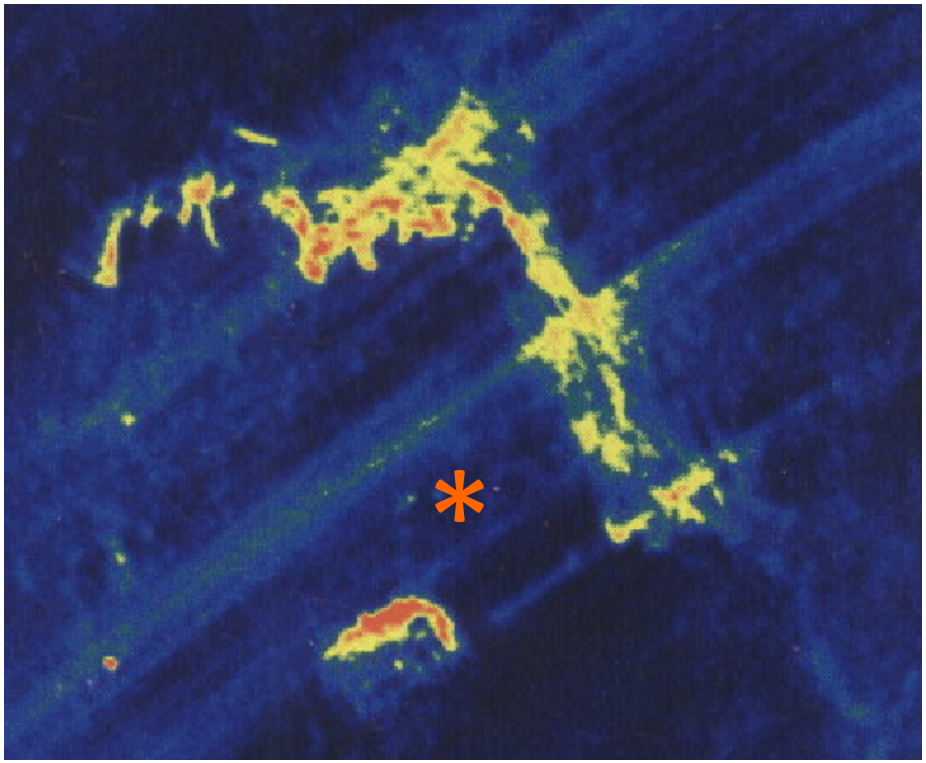
Arches & Quintuplet Clusters

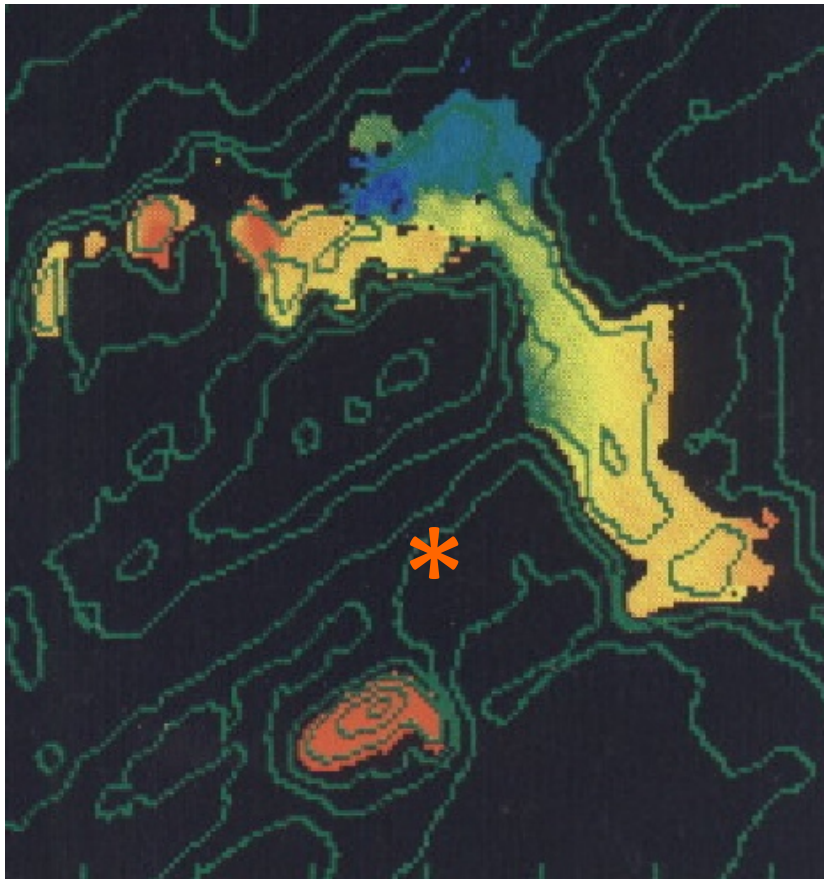


- > 100 OB supergiants, dozen Wolf-Rayet stars in each cluster, 2-5 Myr old
- ionizing fluxes of $N_{Lyc} \sim 10^{50\text{-}51}$ photons s^{-1}
- dense: central density of Arches cluster ~ 5 x 10^5 M_o pc^{-3} (like globular cluster!)
- near-IR observations: Nagata et al. 1995, Cotera 1996, Figer 1995, Figer et al. 1998; Figer et al. 1999ab, 2002, Serabyn et al. 1998

What are the Physical Properties of the Sickle HII Region?

→ *Is it photoionized by Quintuplet?*





- Sickle in fact is a very typical GC HII region
- Unusual and striking velocity gradients (due to infall and grav. potential of GC)

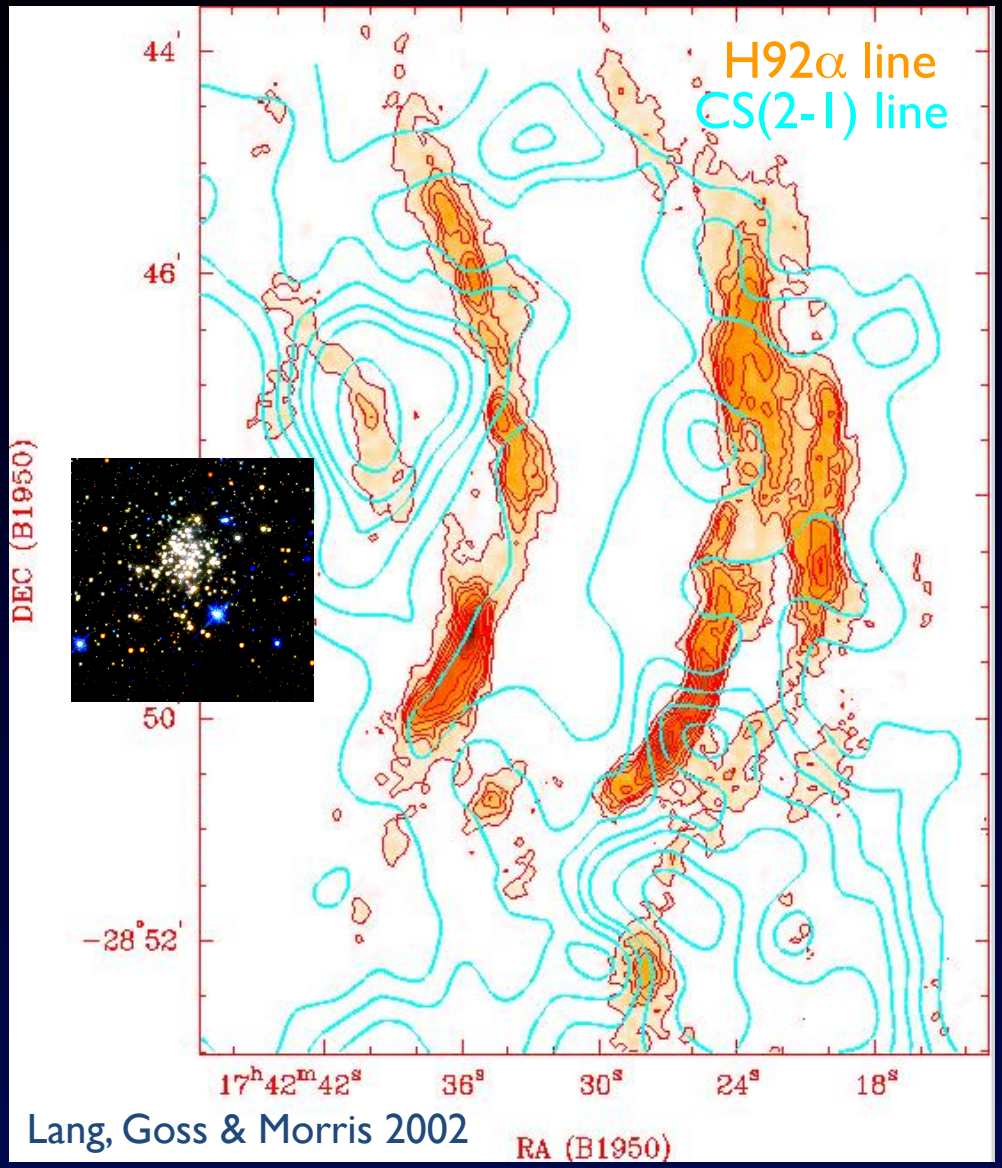
(Lang, Goss & Wood 1997)

the Sickle, an expanding shell of photoionized gas is a possible explanation of the double profiles; however, if this were the case, double lines would be expected in the center of the Pistol, and narrower profiles at the edges. This pattern is not observed. The profiles are single and narrow across the entire W portion of the source (regions H3, H4) and the double profile is located at the E edge (region H1). The extreme width (ΔV_{FWHM} ~60 km s^{-1}) of the profile for region H2 (Figure 7b) is due to fitting a single component to a complex spectrum. Figure 11 shows a profile from a smaller area of this region (H2), in which a double peaked profile is fit. The single lines have widths similar to those elsewhere in the Pistol, ΔV_{FWHM} ~25 and 47 km s^{-1}. In addition, the components in H2 have velocities similar to those in the adjacent region H1, V_1~140 km s^{-1}, and V_2~85 km s^{-1}. It may be that the V_{LSR}~130 km s^{-1} feature in regions H1 and H2 is associated with the main portion of the ionized gas centered at V_{LSR}~115 km s^{-1}, but the origin of the feature near ~80 km s^{-1} is uncertain. Despite the asymmetry of the double profiles on a larger scale, the ionized gas in this small part of the Pistol (near H1 and H2) may be expanding outwards from the central SE edge.

the continuum emission. The T_{eC}^{*} (the corrected electron temperatures) in column 8 were calculated using the corrected continuum intensity. The T_e^{*} derived from integrated profile of the Sickle (Figure 4a, Table 5) is ~6200 K. The T_e^{*} is fairly uniform across the smaller regions of the Sickle, with an average T_e^{*} ~4800 K. This temperature is somewhat lower than that found in most Galactic HII regions where T_e^{*} is 7000-10000 K. Similar low values for T_e^{*} have been observed in the Galactic Center HII region, Sgr B1 (T_e^{*}~5050 K) (Mehringer et al. 1992), and in Sgr B2 (T_e^{*}~7150 K) (Mehringer et al. 1993). Previously, Pauls et al. (1976) derived a T_e^{*}~7000 K for the Sickle from observations of the H85α recombination line. Non-LTE effects, therefore, may not be significant in the Sickle, since the T_e^{*} from the H92α line (~6200 K) is comparable to the H85α derived electron temperature.

The H92α line profiles for regions L9 and L10 are shown in Figures 6i and 6j. The source in L10, G0.21-0.00, has V_{LSR} ~45 km s^{-1}, in agreement with previous studies which suggest that it is associated with the V_{LSR} ~50 km s^{-1} Galactic center molecular cloud (Yusef-Zadeh 1986, Serabyn & Güsten 1991). Region L9, a more diffuse component, shows line emission centered at V_{LSR} ~5 km s^{-1}.

Is the Arches Cluster responsible for Arched Filaments?



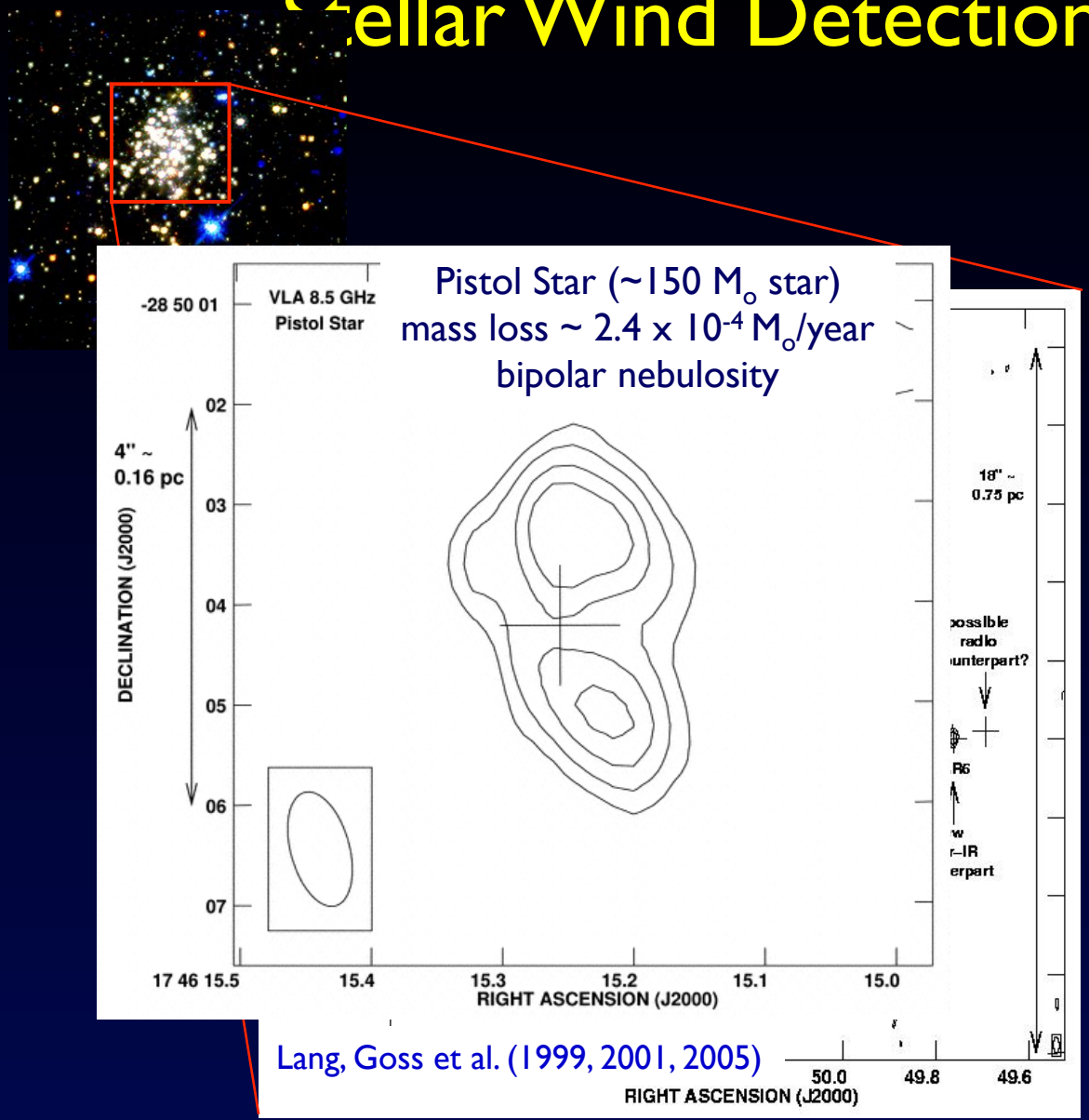
Lang, Goss & Morris 2002

- HII regions represent ionized edge of "-30 km/s cloud", heated by Arches

- N_{Lyc}(cluster)~4×10^{51} ph. s^{-1}
- N_{Lyc} (radio continuum) ~ 3×10^{50} photons s^{-1}

- Arches cluster could be as far away as ~20 pc (60 ly) from the molecular gas and still ionize the cloud! (Lang, Goss & Morris 2001,02)

Stellar Wind Detections in the GC



Pistol Star (~150 M_o star)
mass loss ~ 2.4 x 10^{-4} M_o/year
bipolar nebulosity

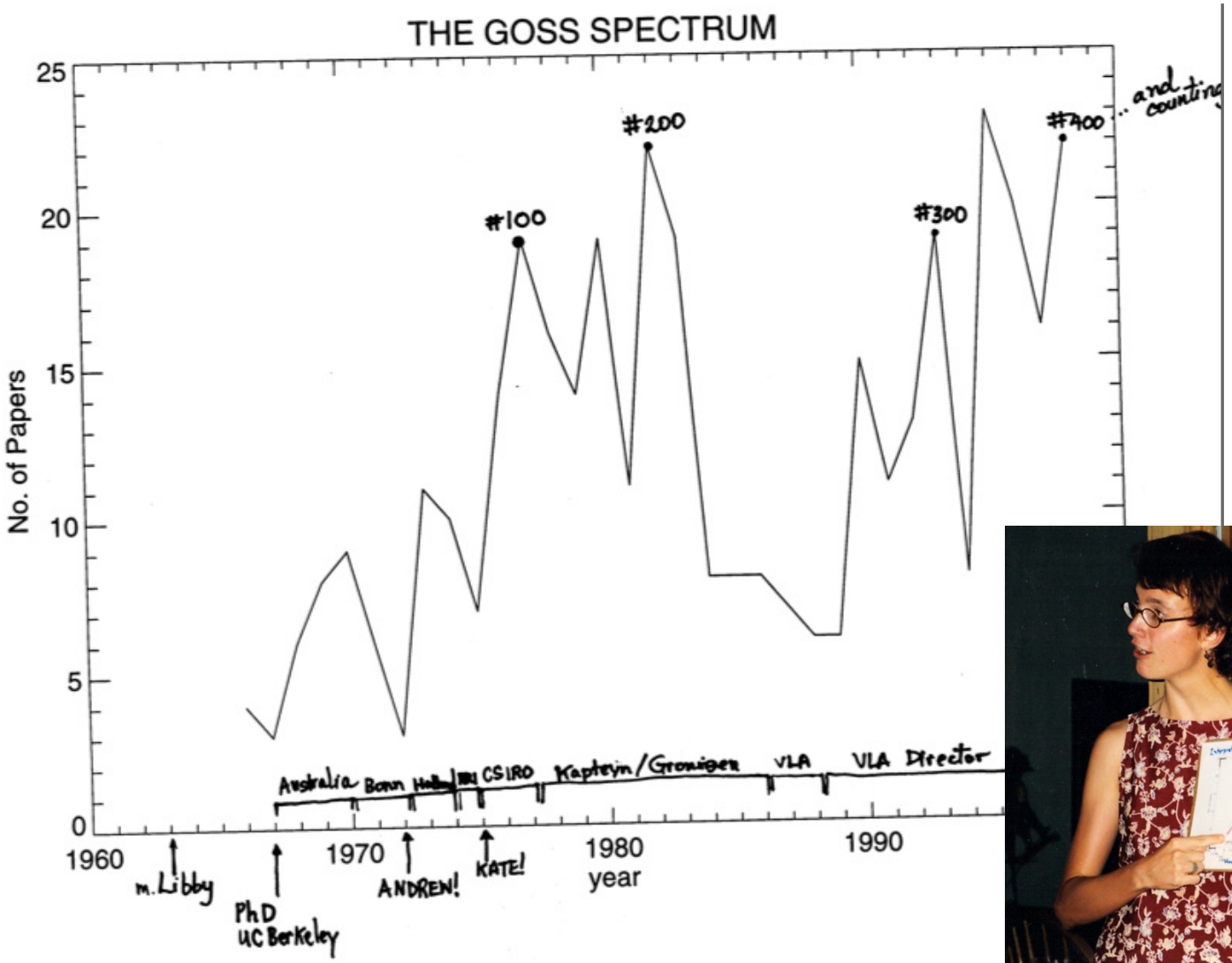
Lang, Goss et al. (1999, 2001, 2005)

- very high resolution radio observations: can resolve individual stars with mass-loss
- ~10 sources in each cluster (Arches/Quint)
- high mass loss rates ~ 3 – 17 x 10^{-5} M_o yr^{-1}
- several sources are strong X-ray emitters: indicates wind-wind binary systems

Miller's 400th Paper: July 1999

CCL and Anantha presenting the "scientific program" at the party

The Goss Spectrum: July 1999



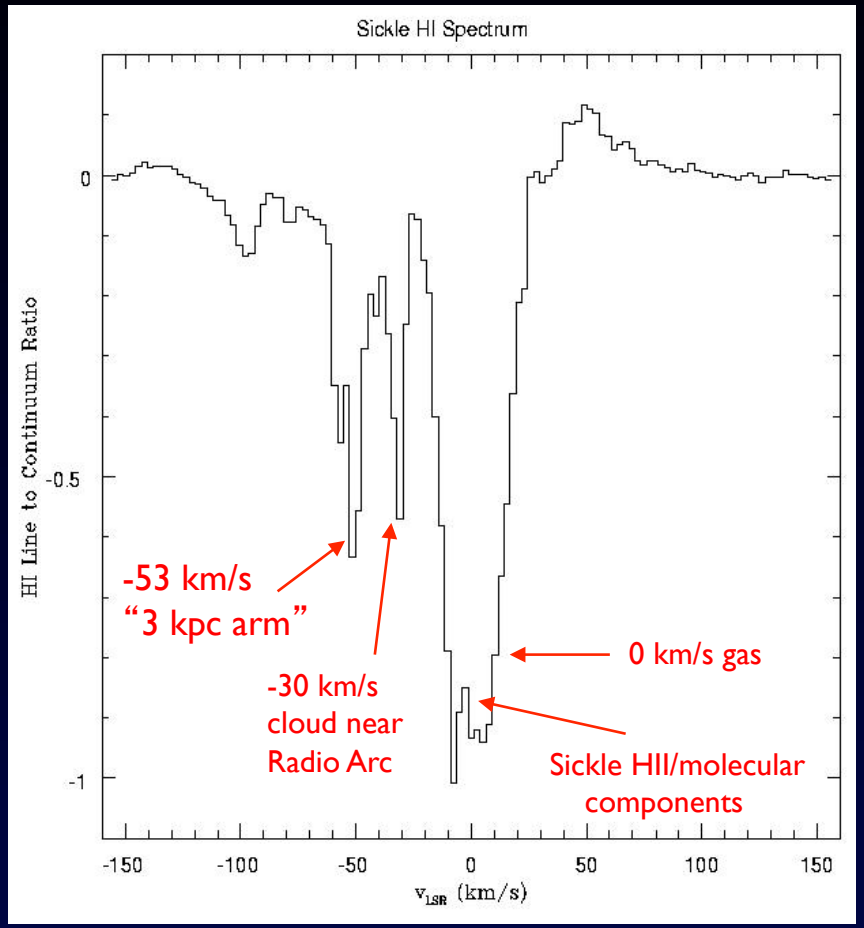
Fitting a "Gossian" profile to the data

The Galactic Center Club:
Regular Meetings in Socorro 1998-2000

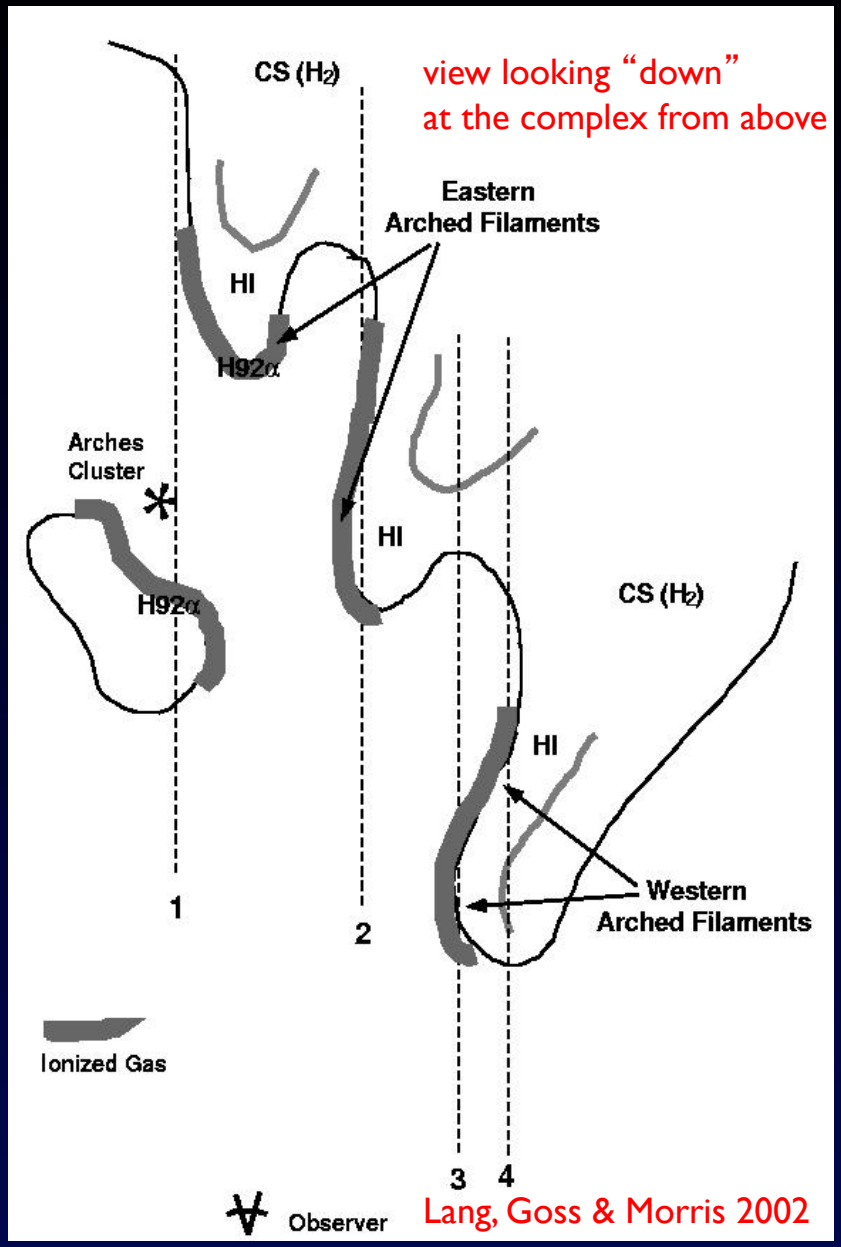
Local members wearing GC hats.

CCL PhD Exam: September 2000

HI Absorption toward the GC (~200 pc)



Lang, Goss, Cyganowski et al. (2010)



How many such massive clusters or stars are located in the GC?

- May be as many as 50 such massive clusters in the GC:
Portegies-Zwart (2001), Bica, Dutra (2000, 2001, 2003)

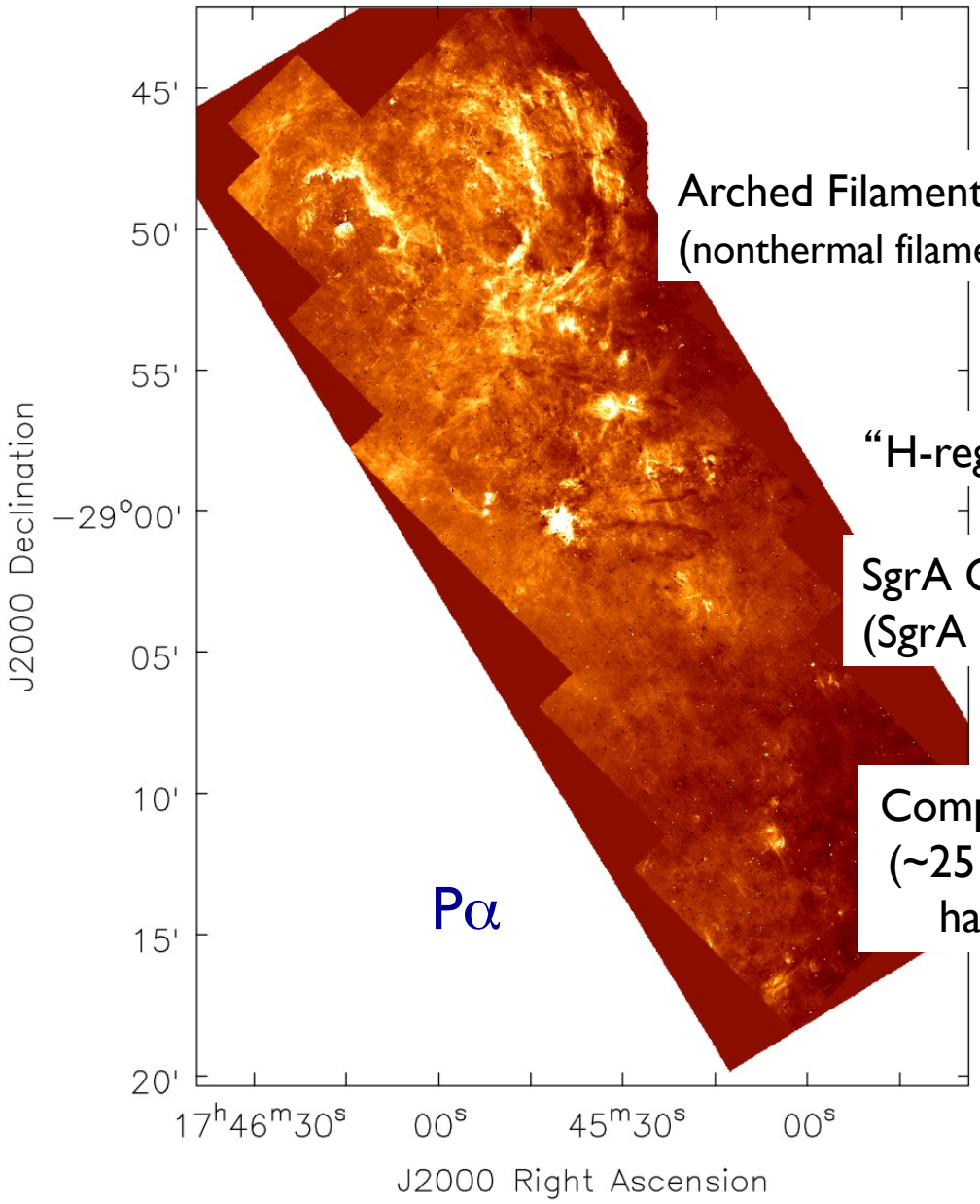
-Observations reveal candidates: *Chandra* (Mauerhan 2008, 2009), *Spitzer* (Stolovy et al. 2006, 2009), radio continuum (4.9 GHz survey by Lang et al. (2011))

HST/NICMOS Pa α (recomb line at 1.9 μm)

Can trace ionized gas from HII regions and massive stellar winds at very high resolution in the GC; first HST survey of GC

(Wang, Stolovy, Lang & Cotera et al. 2009, 2010)

Comparison of Paschen-Alpha and Radio Emission

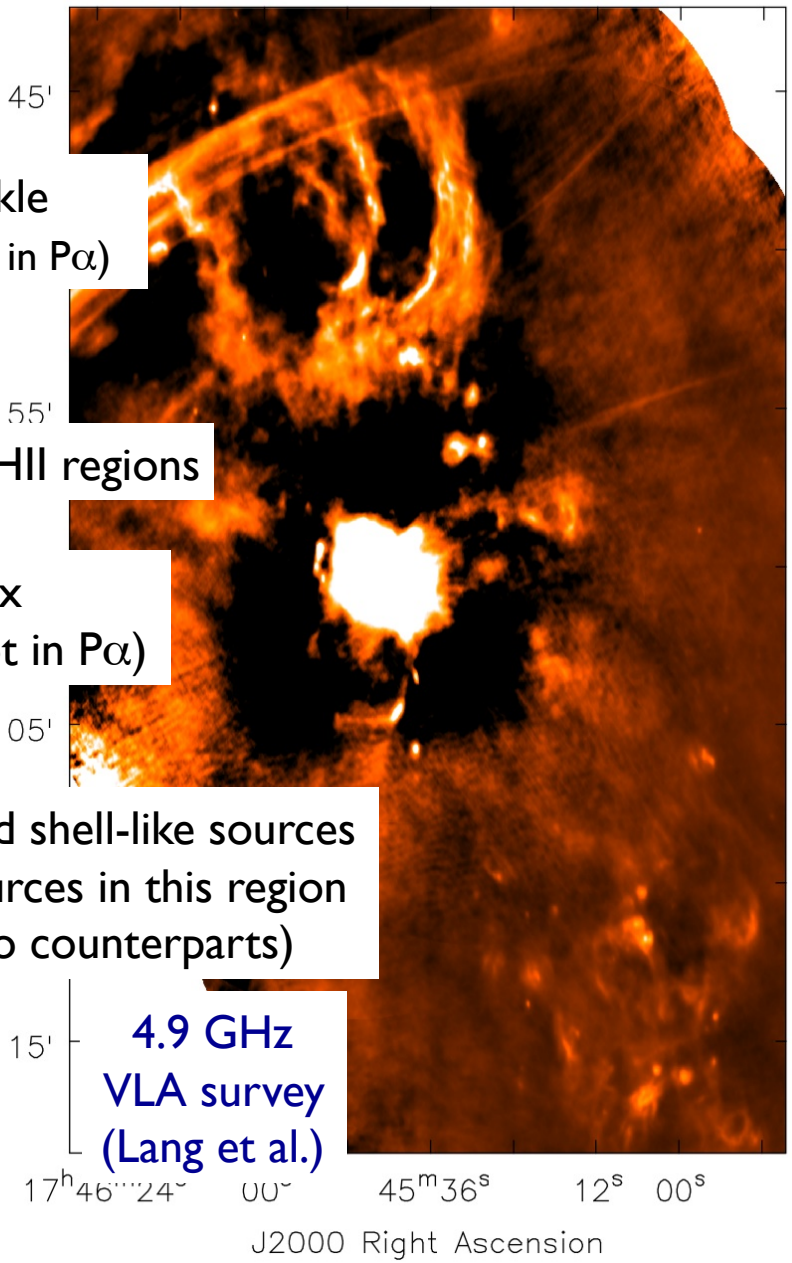


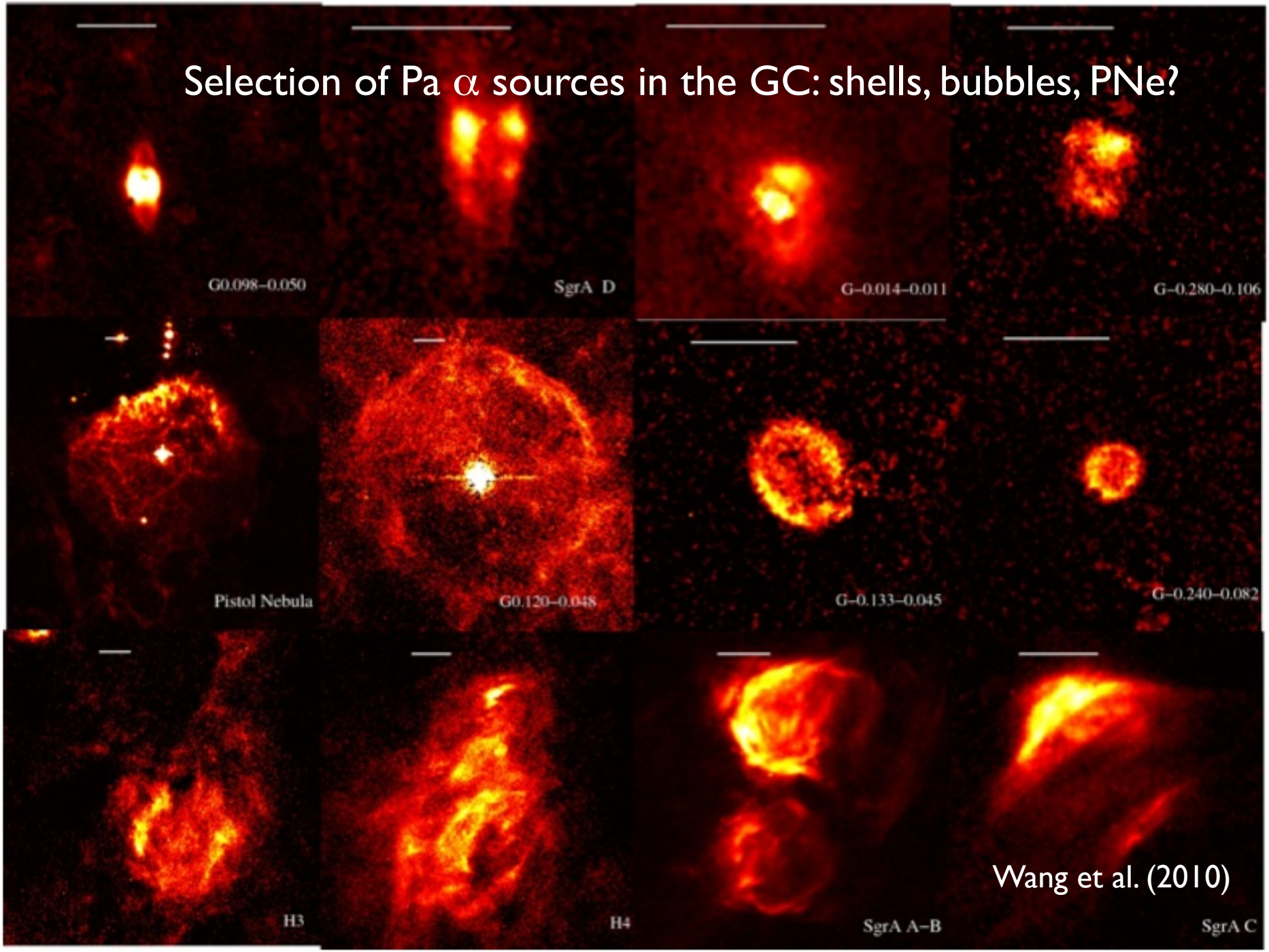
Arched Filaments & Sickle
(nonthermal filaments not in Pα)

"H-regions" HII regions

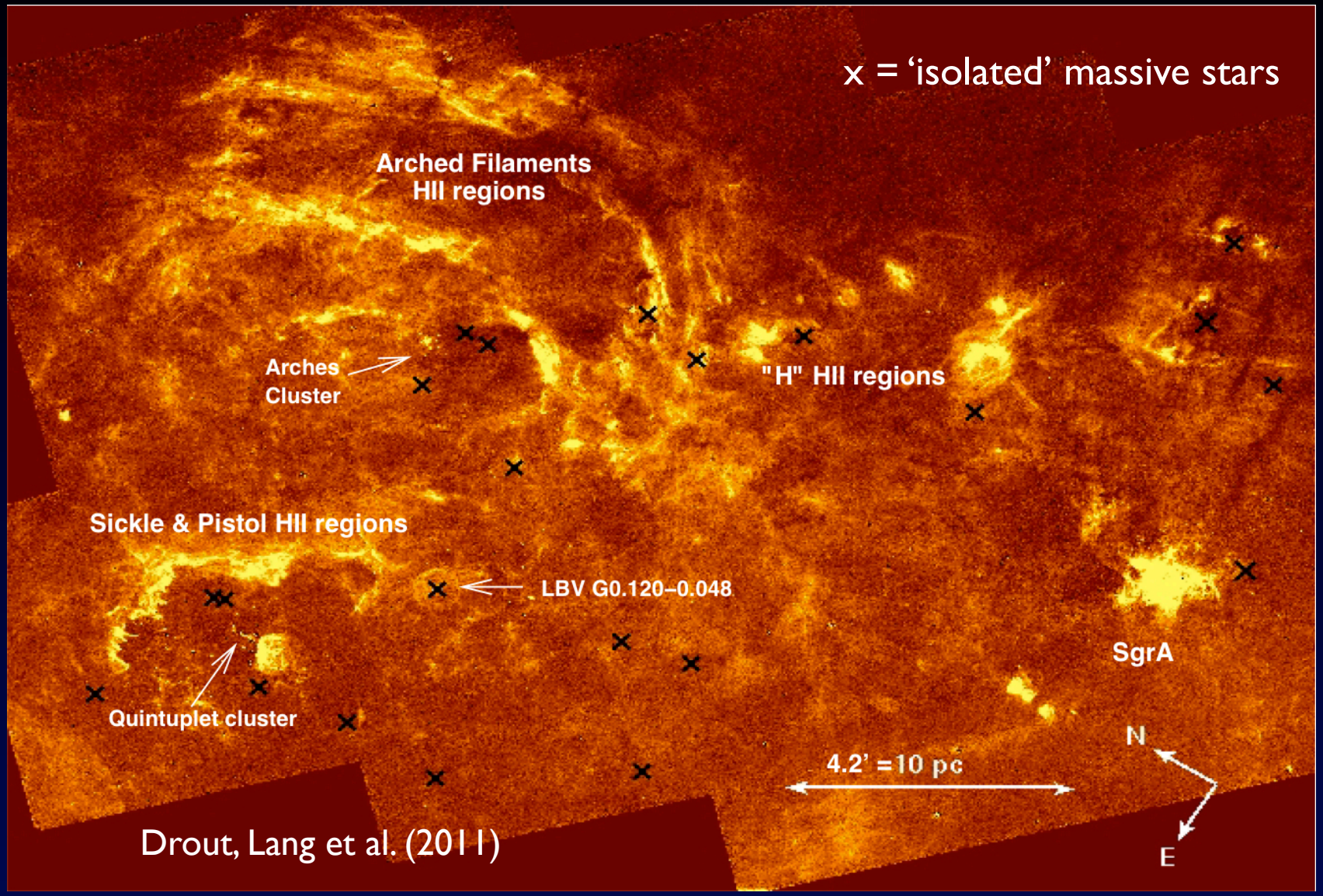
SgrA Complex
(SgrA East not in Pα)

Compact and shell-like sources
(~25 Pα sources in this region
have radio counterparts)

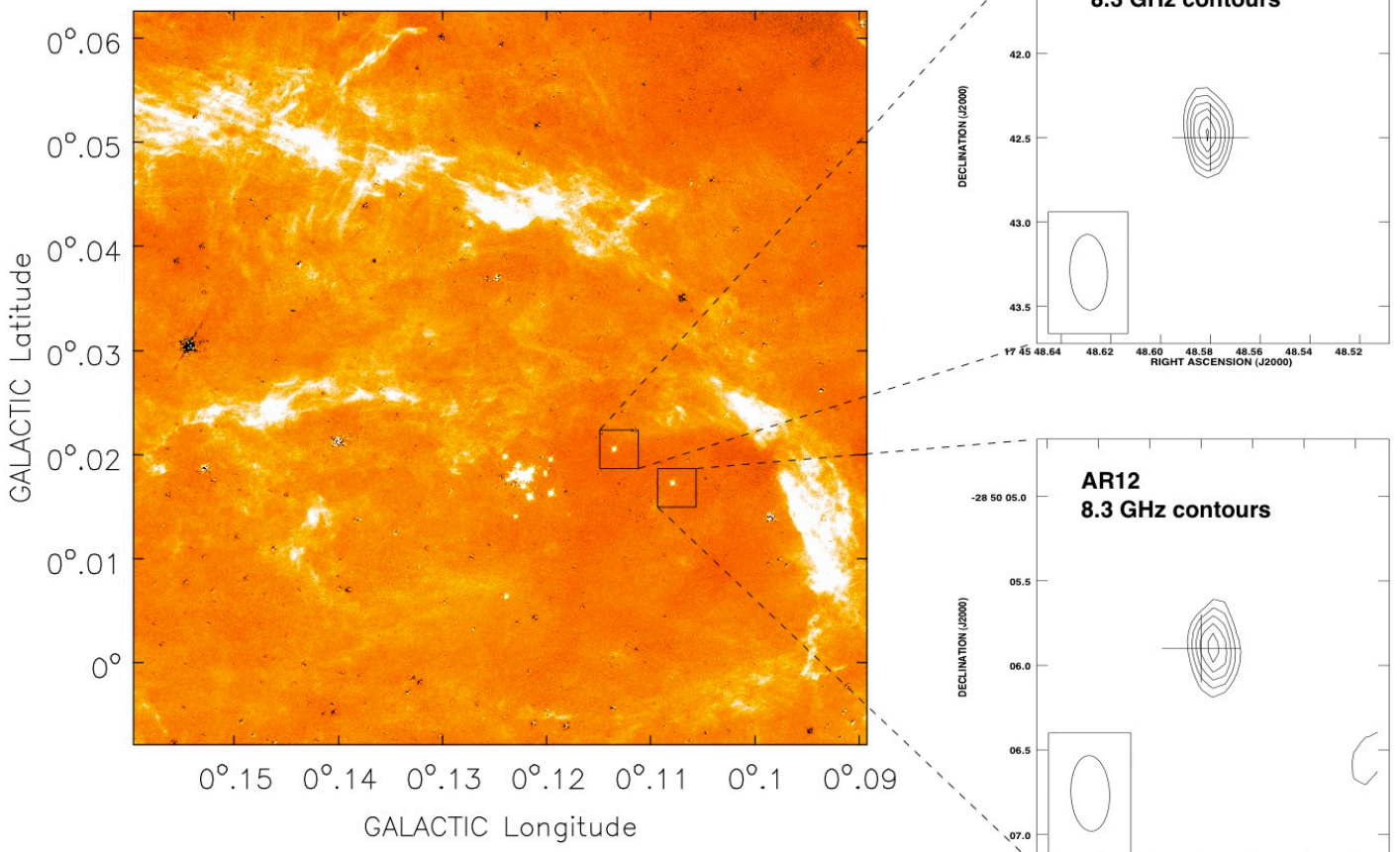



Selection of Pa α sources in the GC: shells, bubbles, PNe?
G0.098–0.050
SgrA D
G–0.014–0.011
G–0.280–0.106
Pistol Nebula
G0.120–0.048
G–0.133–0.045
G–0.240–0.082
H3
H4
SgrA A–B
SgrA C
Wang et al. (2010)

Pα Image of the Central 30 pc of GC

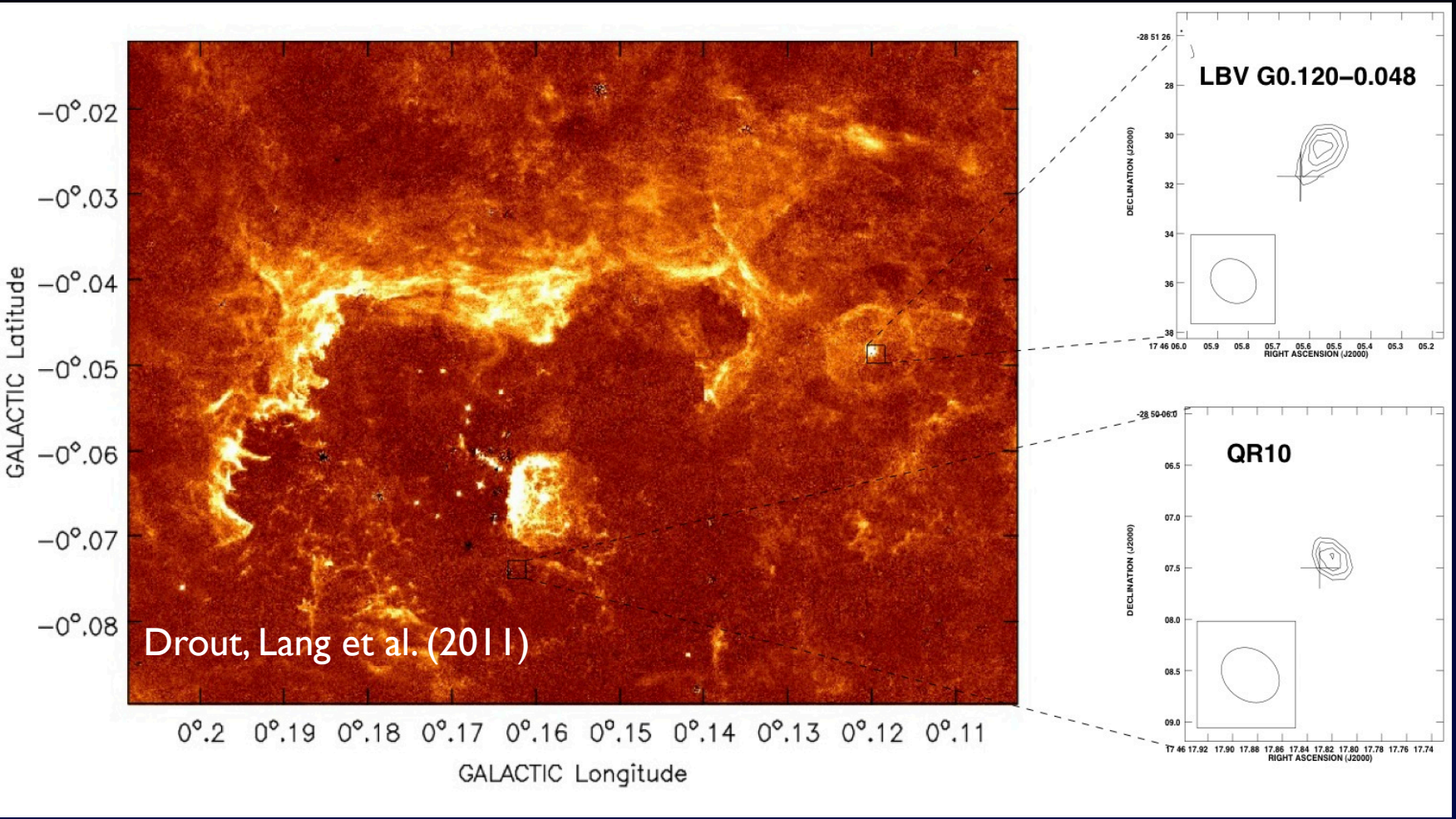


Massive Stars Near Arches Cluster: Radio and Pa α

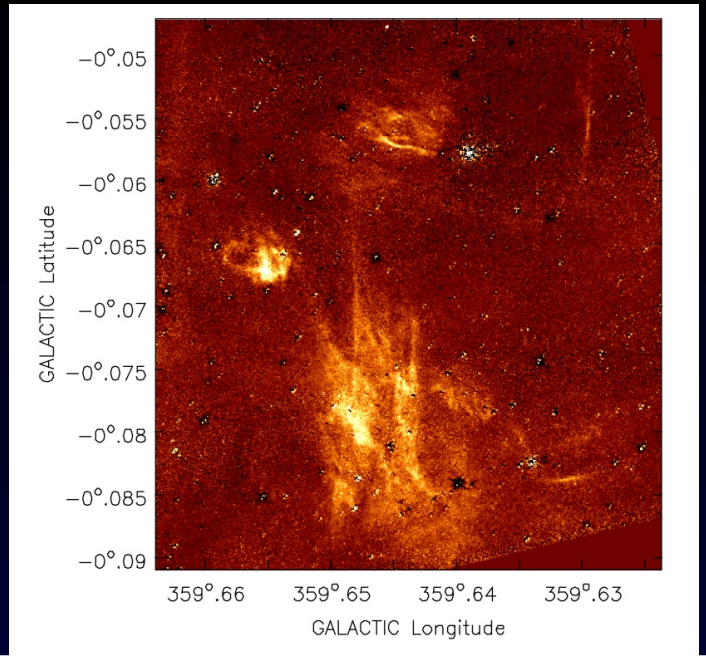


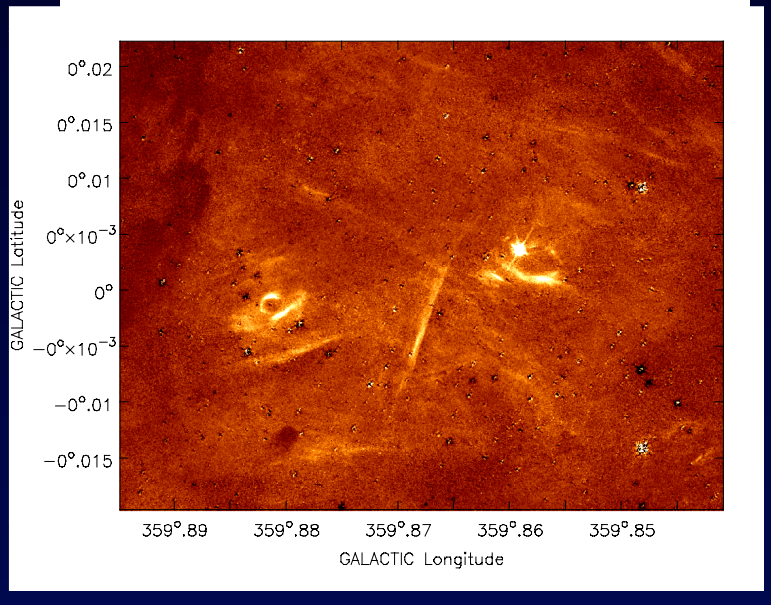
Drout, Lang et al. (2011)

Massive Stars near Quintuplet: Radio/Pa α



Pa α Thermal Filamentation





- Striking across all HII regions: Arches & Sickle

- Very striking isolated filaments elsewhere in the Pα image
  → identified ~50 Pα filaments
  → many in small groups

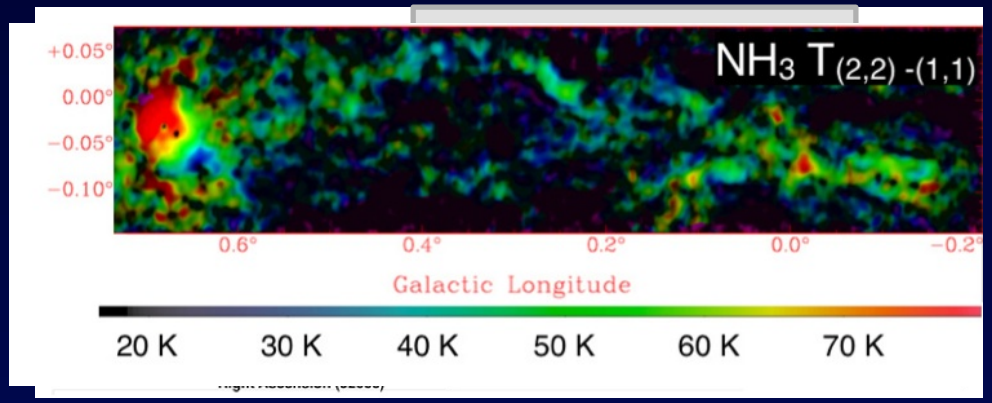
- Pα filament properties:
  → typical lengths ~26" (~1 pc @ 8 kpc)
  → typical widths ~5" (0.2 pc @ 8 kpc)
  → variety of position angles
  → majority (95%+) w/ radio counterparts
- Need to establish relationship to radio "streaks" detected in sensitive radio images of the GC

Multiwavelength view of massive star activities in the GC

Red = Spitzer IRAC 8 μm (Stolovy et al.2006)
Yellow = HST/NICMOS (Wang et al. 2010)
White/Blue = Chandra X-ray (Wang, Gotthelf & Lang 2002; Muno et al. 2009)

Looking forward….

- What is heating GC molecular clouds?
  - Local vs. global: stars, shocks, Bfields, CRs, ?
- High transitions of NH_3 have shown clouds with T > 500 K!
- How and why do stars form in this extreme environment?
- How many embedded massive clusters/stars in the GC?



EVLA and ALMA:
Simultaneous transitions of molecules like ammonia, recomb lines, shock tracers and deep continuum

Congratulations Miller !!!

Thanks for introducing me to the Galactic Center many moons ago... thanks for all the collaborations and support over the years, and for sharing your family and friends with mine.
Here's to many more adventures together!