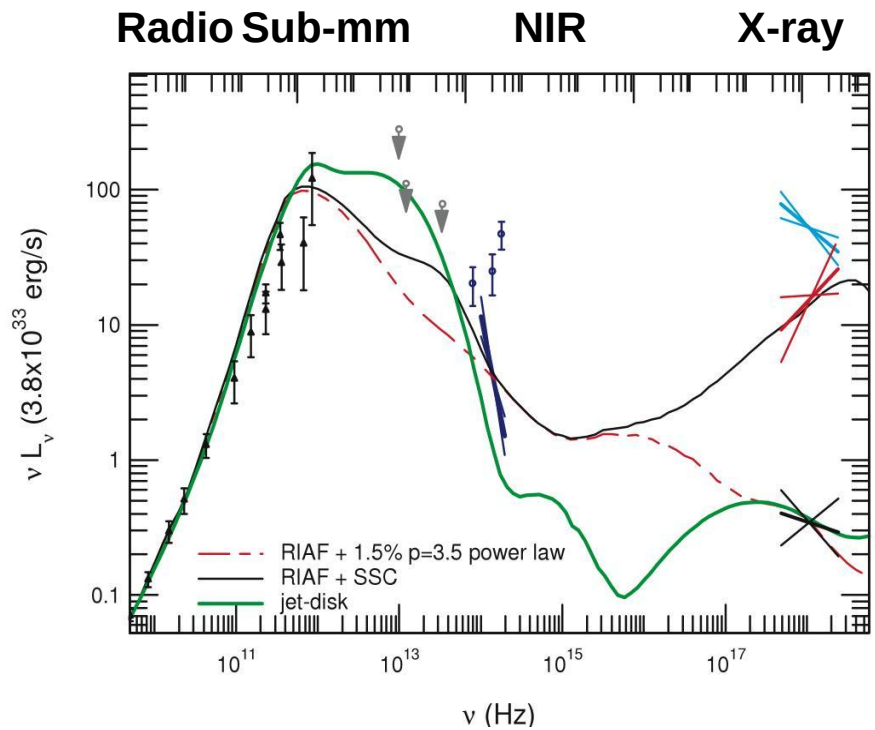
Sgr A* and Its Activity

Farhad Yusef-Zadeh
Northwestern University

- **Sgr A***
  1. Overview: Mass and SED
  2. Time Variability
     - Plasma Expansion Model
     - Jet Model
  3. Structural Details near Sgr A*
     - The mini-cavity
     - Blobs
     - Continuous Linear Feature (1pc)
     - Jet Outflow?
  4. Large Scale Streamers (15pc)
     - Starburst Driven Outflow?

Spectral Energy Distribution



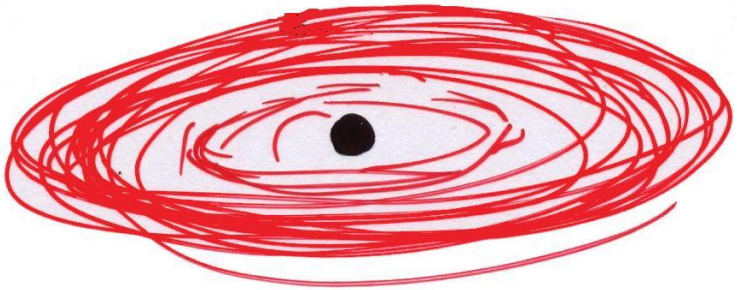
- Variable and Quiescent Components
- SED peaks in Submm

- Quiescent: Radio/ Submm (optically thick)
- Variable: IR/X-rays (optically thin)

- Underluminous:

$$\nu L_\nu \approx 100\,\mathrm{L}_\odot$$

$$L_{\rm bol} = \epsilon \dot{M} c^2 = 1.5 \times 10^7 \, \frac{\epsilon}{0.1} \left(\frac{\dot{M}}{10^{-5}\,\mathrm{M}_\odot\,\mathrm{yr}^{-1}} \right) \mathrm{L}_\odot$$

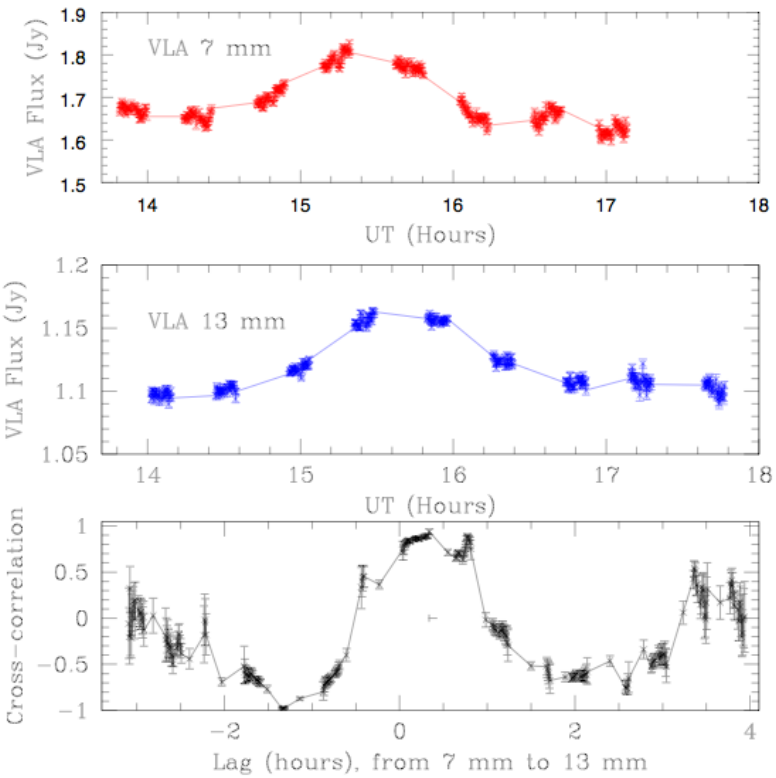


- The Steady Component: Two classes of Models
  - Accretion flow
  - Jet outflows

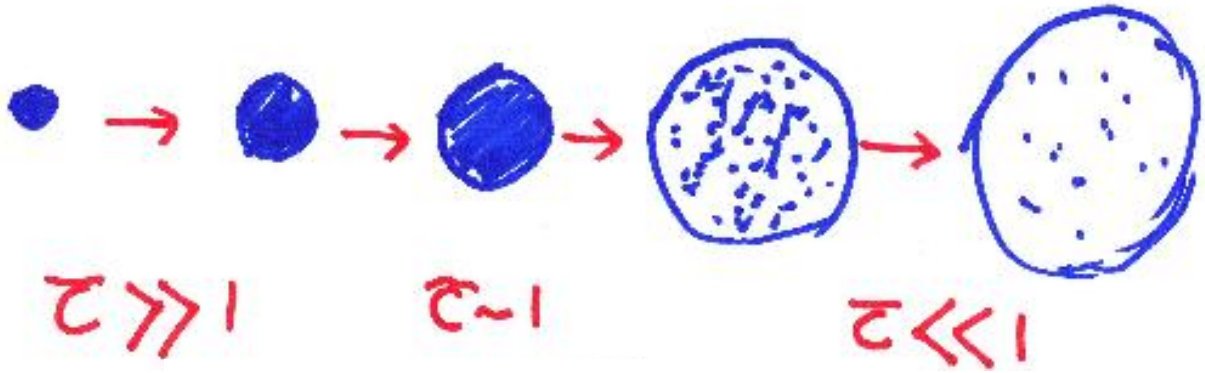
- Degeneracy

The Variable Component: Cross-Correlation

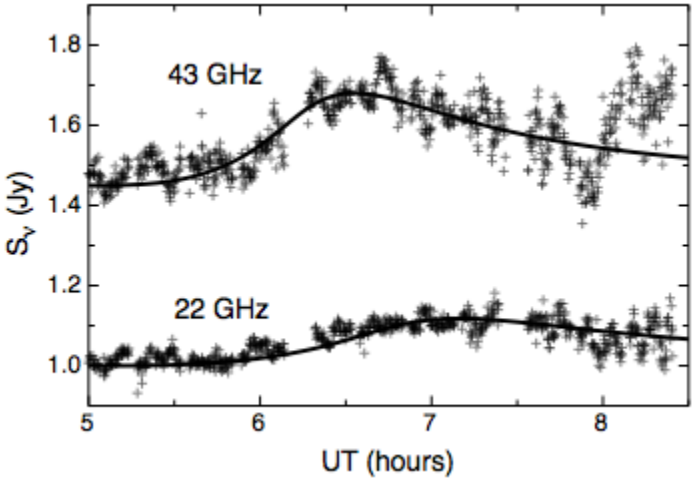
- Variability on Even Horizon length scale
- VLA Observations 43 and 22 GHz: Feb 2005, BnA array
- The cross correlation peaks:
  - 20-40 minute time delay led by 43GHz peak



Expanding Blob of Explain Synchrotron Light Curves



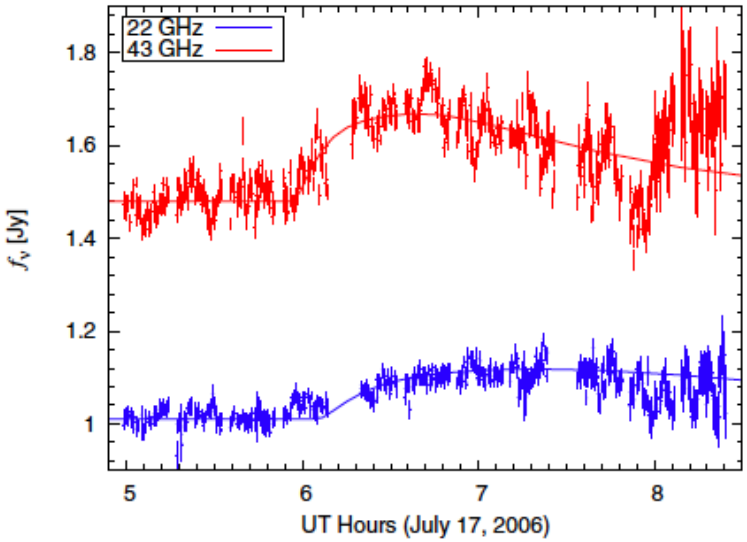
- Time delay is consistent with the expanding hot plasma model (Van der Laan 1964)
- Synchrotron optical depth $\tau \sim \nu^{-2.5}$
- Optically thick gas grows and then decays
- Particle spectrum E^{-3} corresponding to n_c=130 GHz

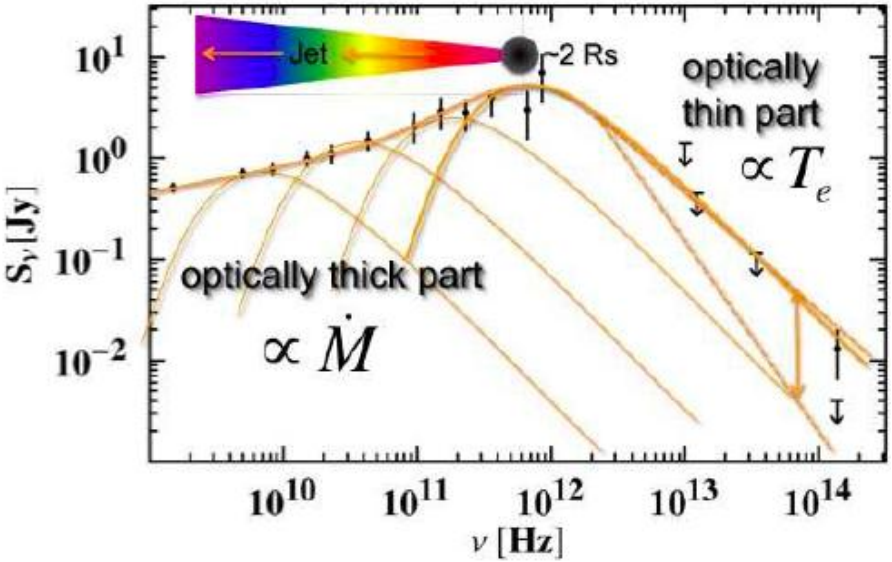


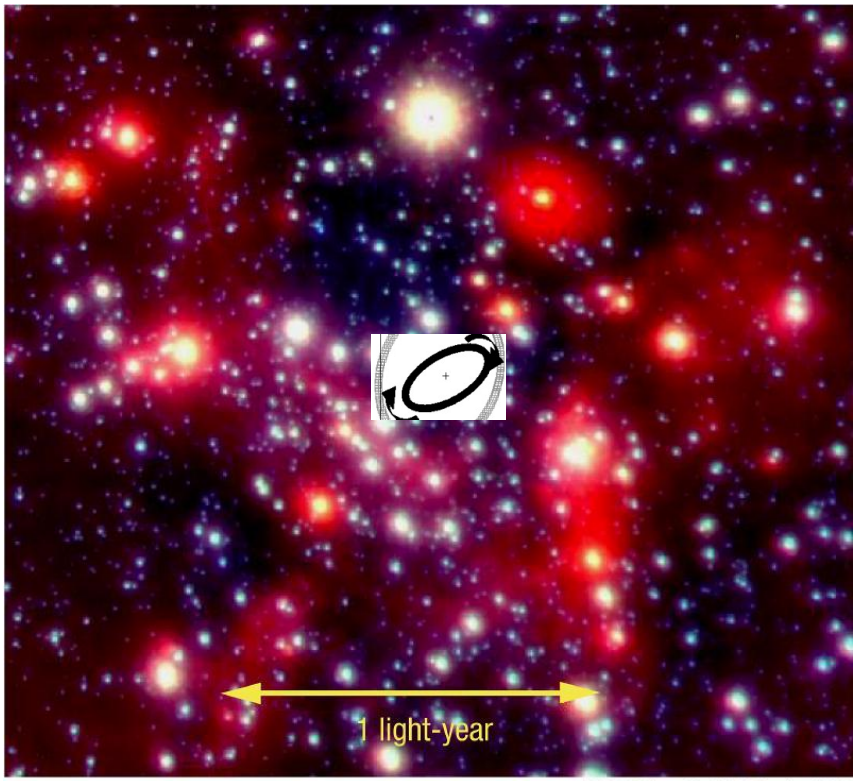
- v/c=-0.15
- B=11G
- Initial radius=2.2 R_s
- P=1

Jet Model Fitting of Light Curves

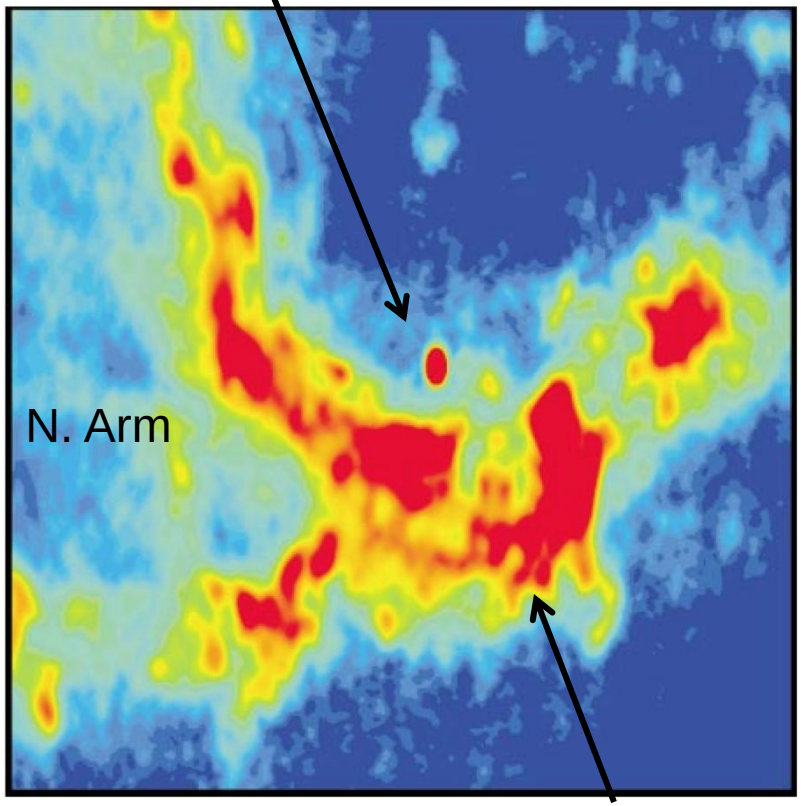
- Time Dependent Jet Model
  (Maitra, Markoff and Falcke 2009)
- But. there is no evidence for a Jet on a VLBI scale
- Degeneracy again
- Is there a large scale Jet?





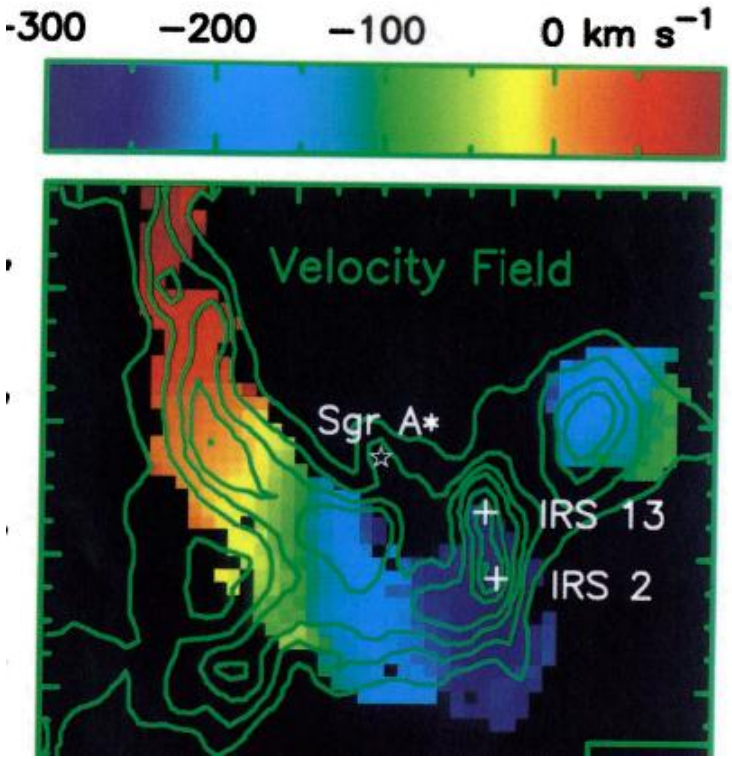


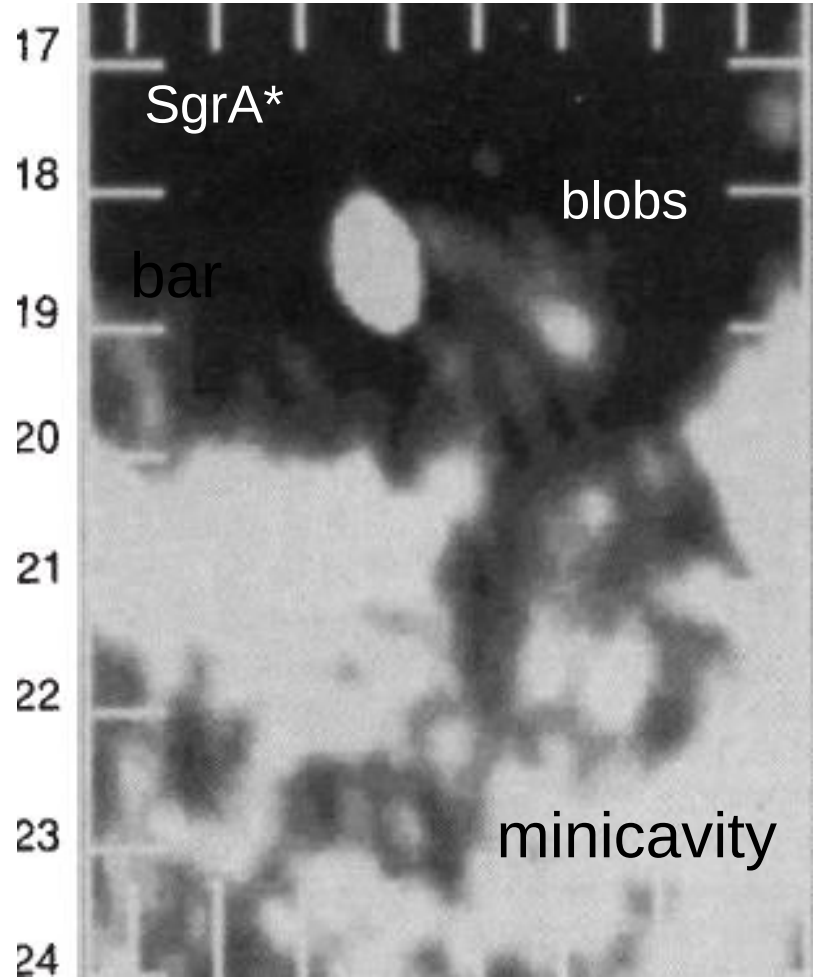
ESO PR Photo 23a/02 (9 October 2002)



- Ionized mini-spiral structure (Sgr A West)
- A couple of light years across
- 2cm Continuum
- Young and evolved stellar clusters

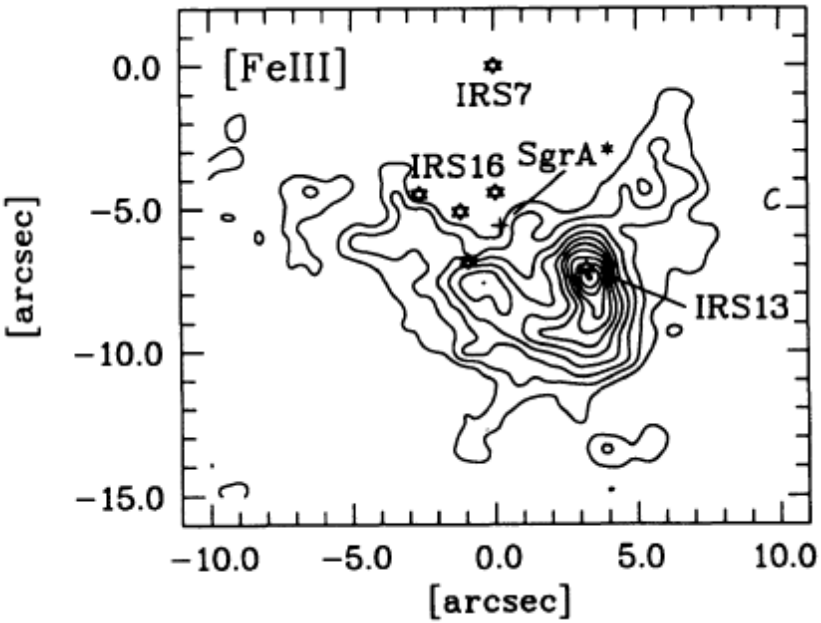
Min-cavity: Morphology & Kinematics

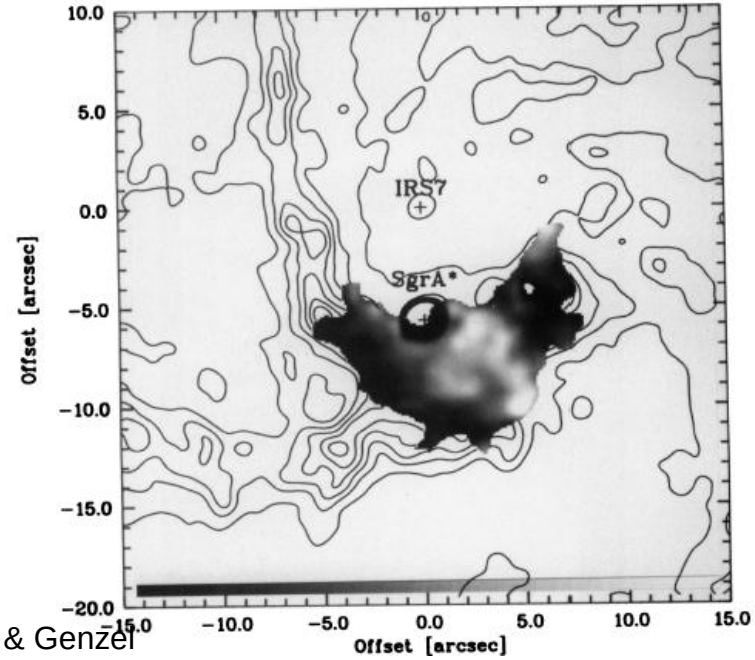




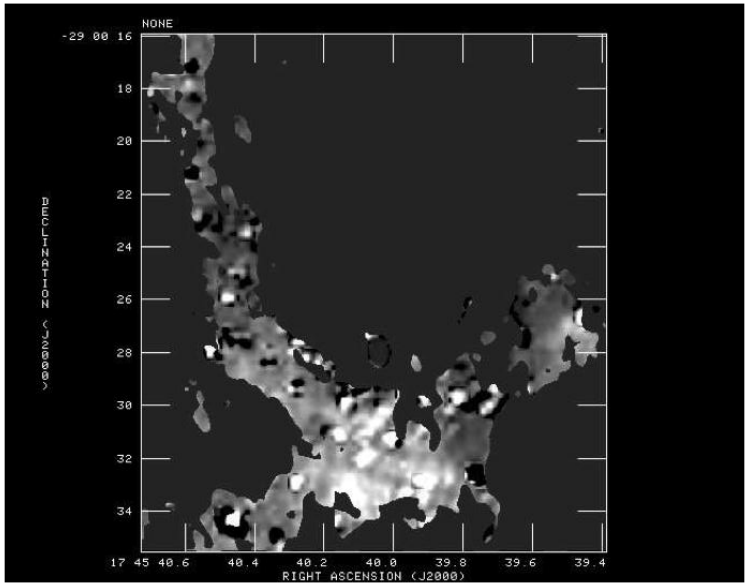
- Radio observations at 3.6cm
- Chain of blobs
- Cavity of ~2” diameter
- Ridge of emission
- Kinematically disturbed
- Low L/C ratio

Mini-cavity: Shocked gas





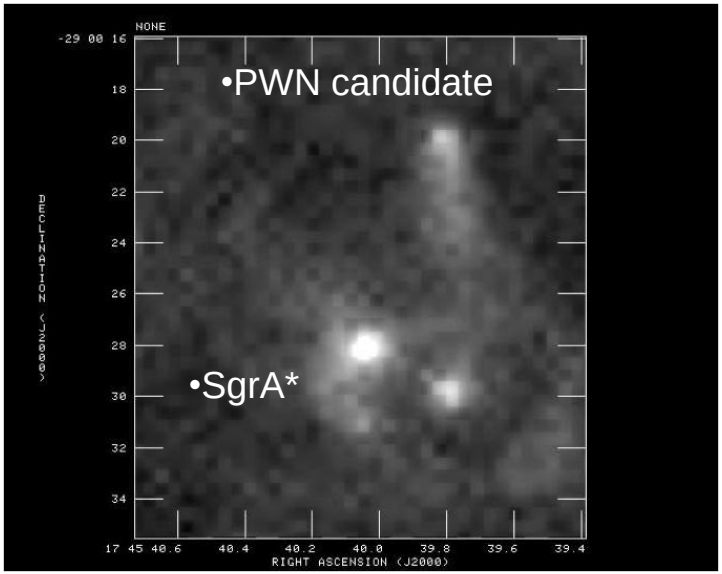
Lutz, Krabbe & Genzel 1993



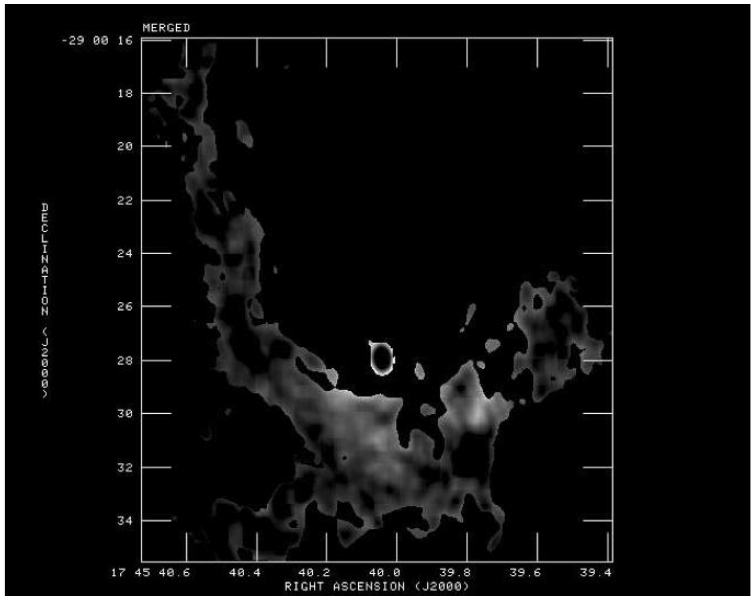
- FeII and FeIII emission from the mini-cavity
- Bow-shock structure
- High FeIII/ratio
- Shocks to enhance Fe abundance
- Photoionized by UV photons

Mini-Cavity: Hot Gas

- X-ray Emission from the mini-cavity
- Hot million degree gas
- Shocked gas with v~1000 km/s
- Lx ~10^{34} ergs/s



X-rays

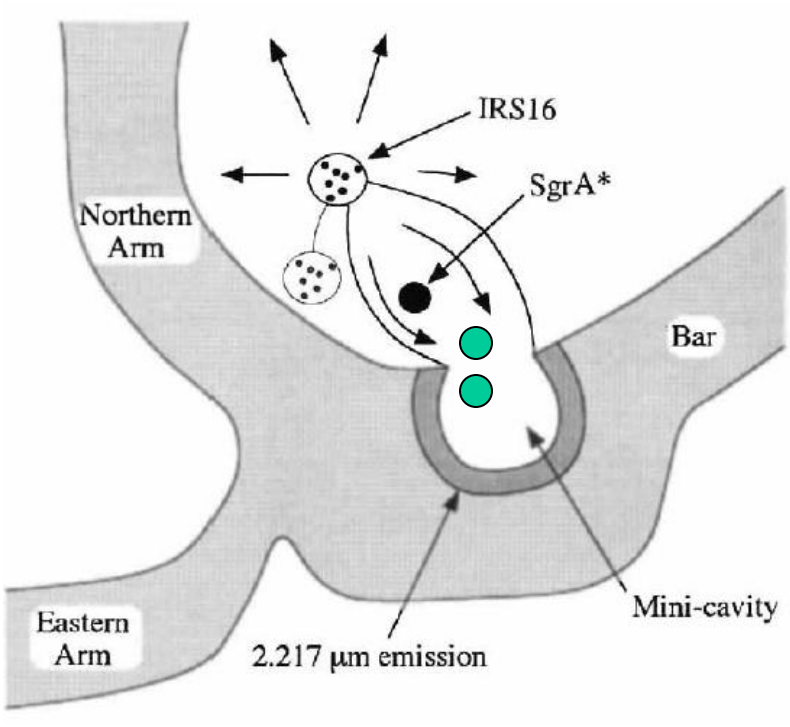


X-ray/2cm

Mini-cavity and Blobs: Origin and Formation

- Morphology
- Kinematically disturbed
  - Expanding bubble
- Thermal
  - High L/C ratio in RRL
  - High Fe abundance
  - Low 12micron/2cm
  - X-rays
  - High FeII/2cm

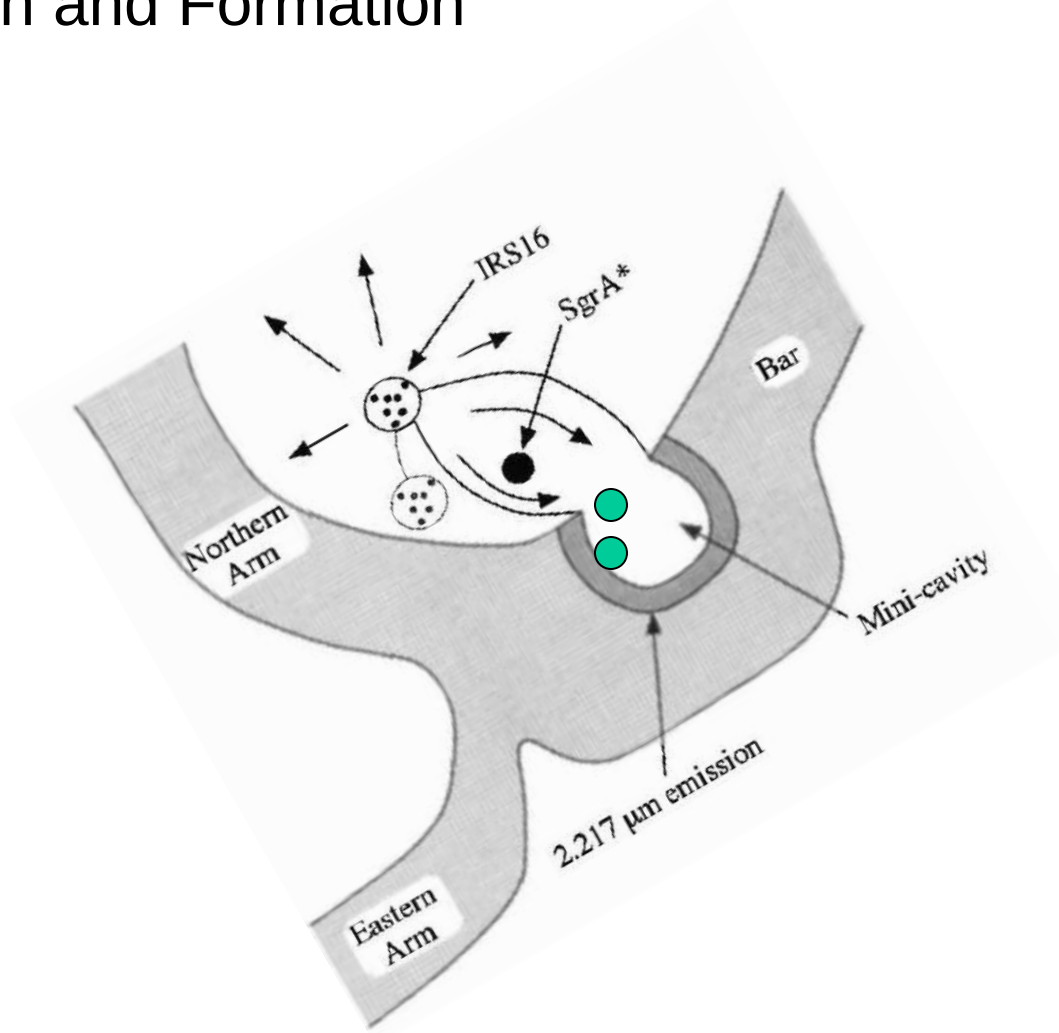
- Focused Winds vs, Jet outflow from Sgr A*?



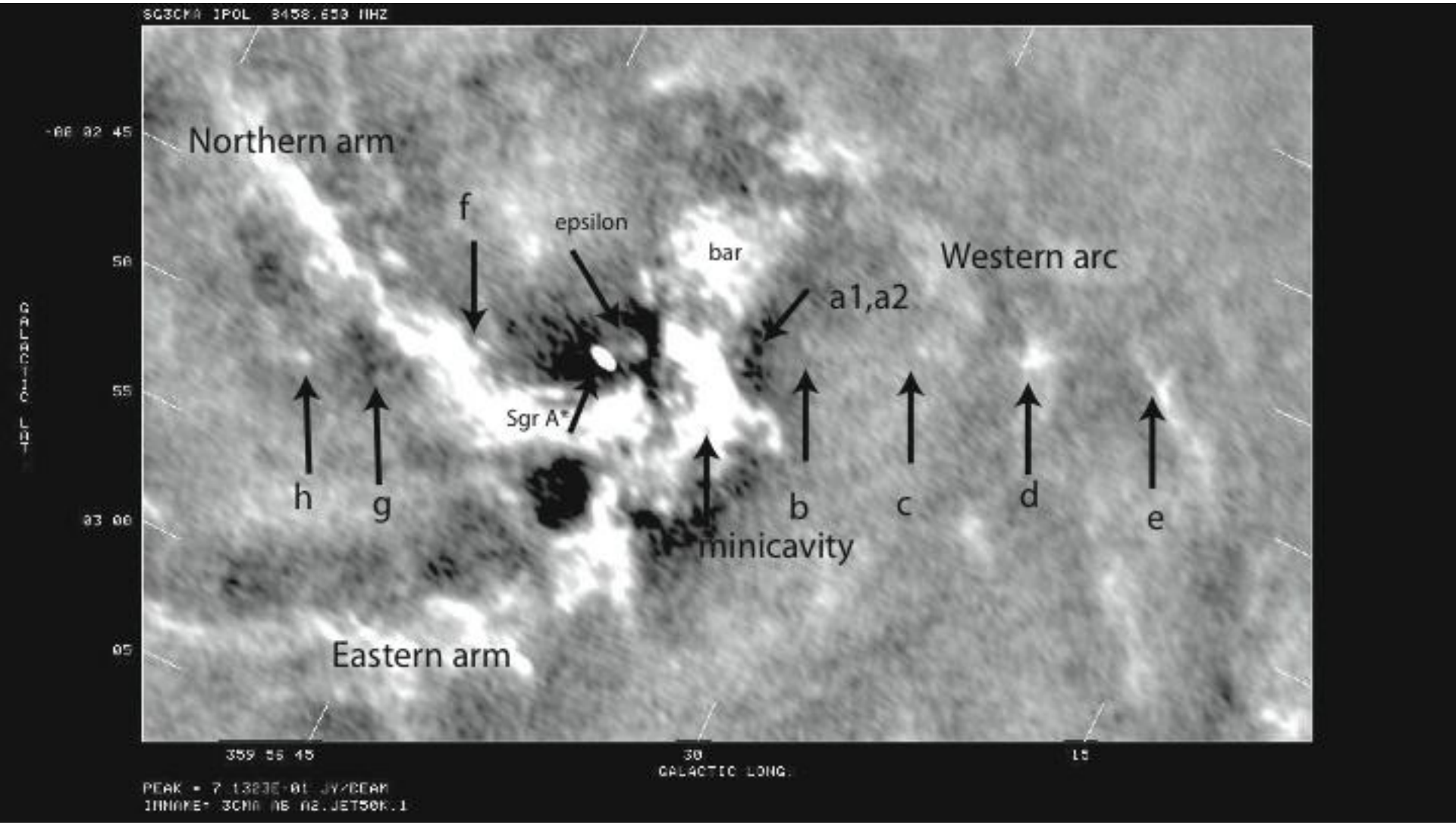
Mini-cavity and Blobs: Origin and Formation

- Morphology
- Kinematically disturbed
  - Expanding bubble
- Thermal
  - High L/C ratio in RRL
  - High Fe abundance
  - Low 12micron/2cm
  - X-rays
  - High FeII/2cm

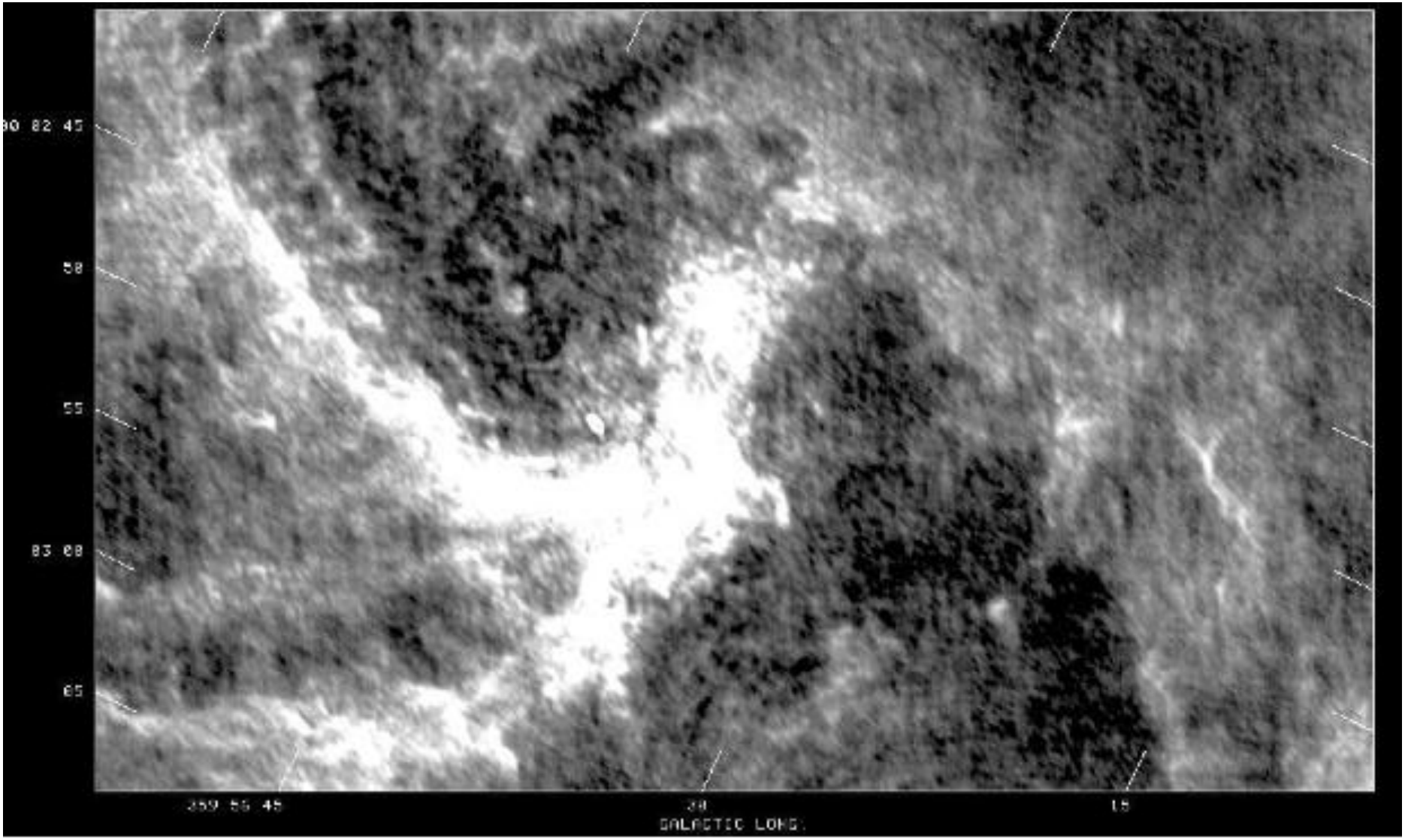
- Focussed Winds vs, Jet outflow from Sgr A*?



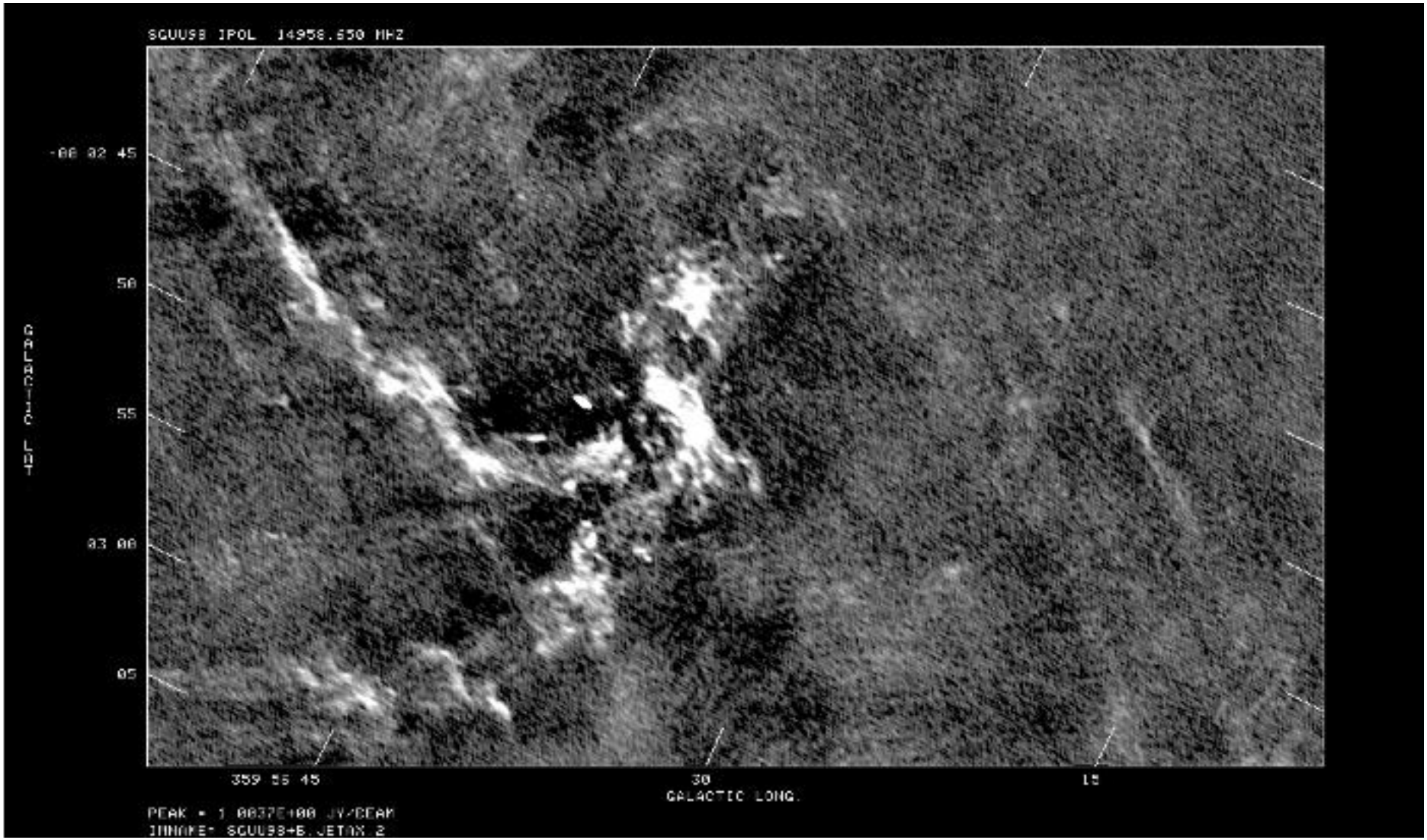
3.6cm Continuum: Blobs of Emission



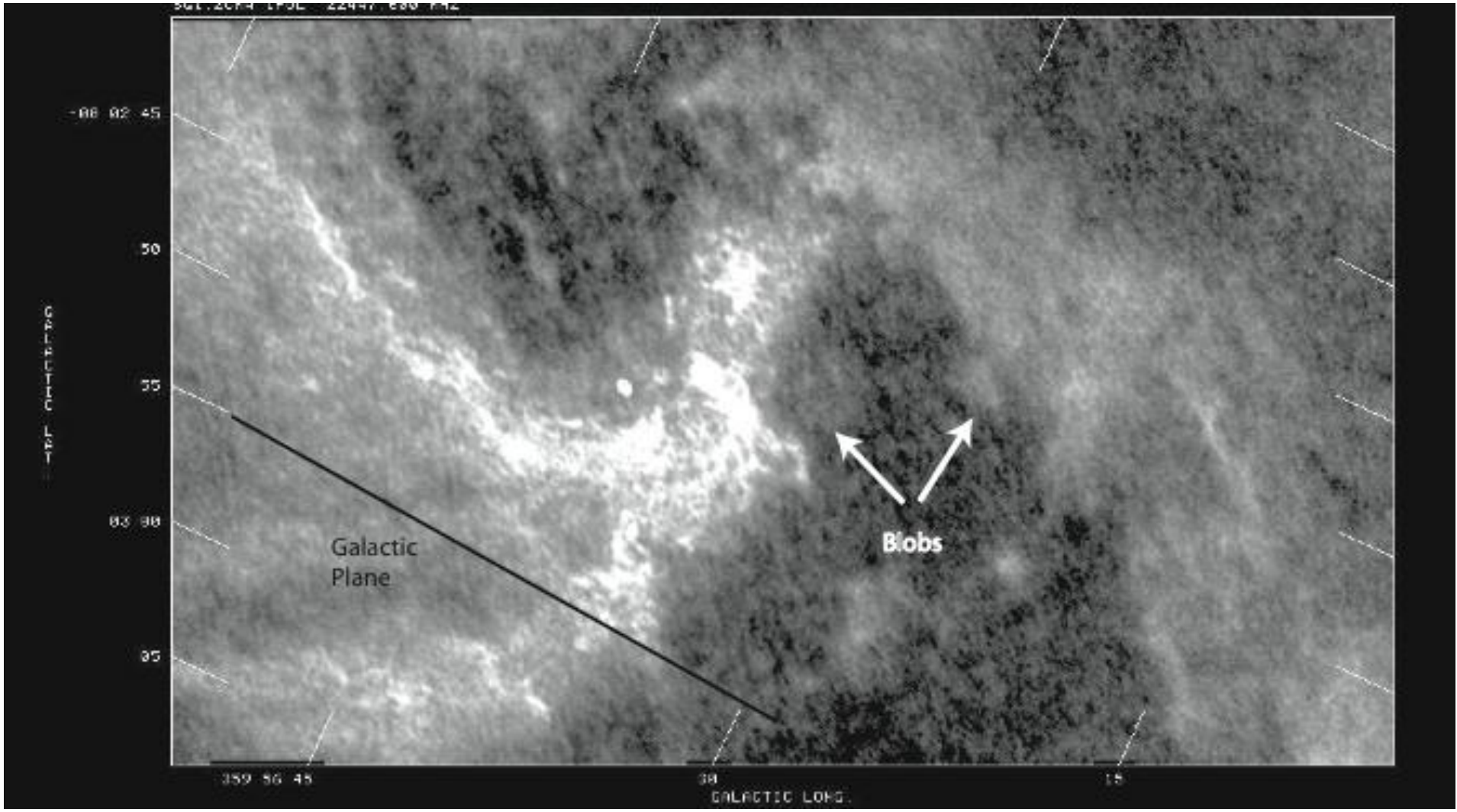
2cm Continuum: Blobs of Emission



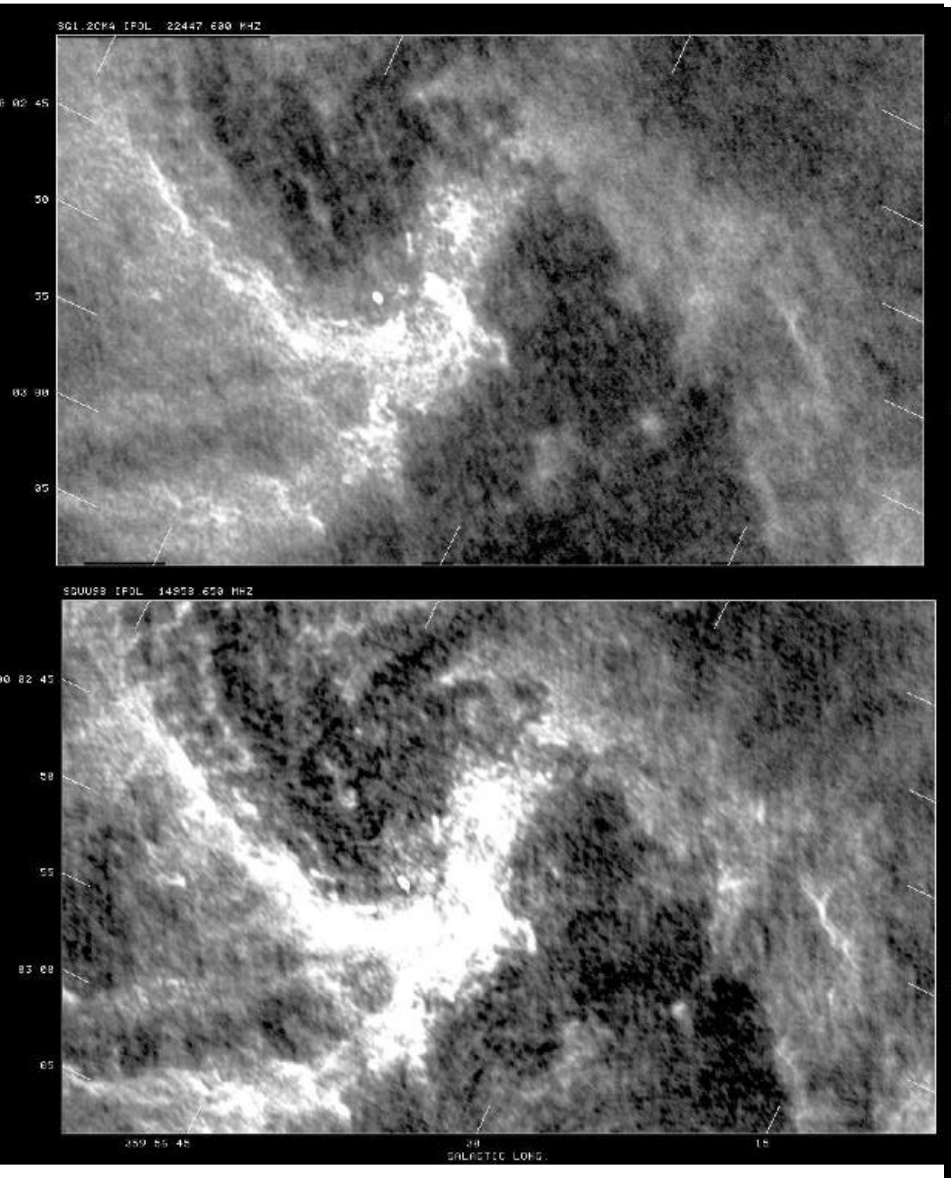
1.3cm Continuum: Blobs of Emission

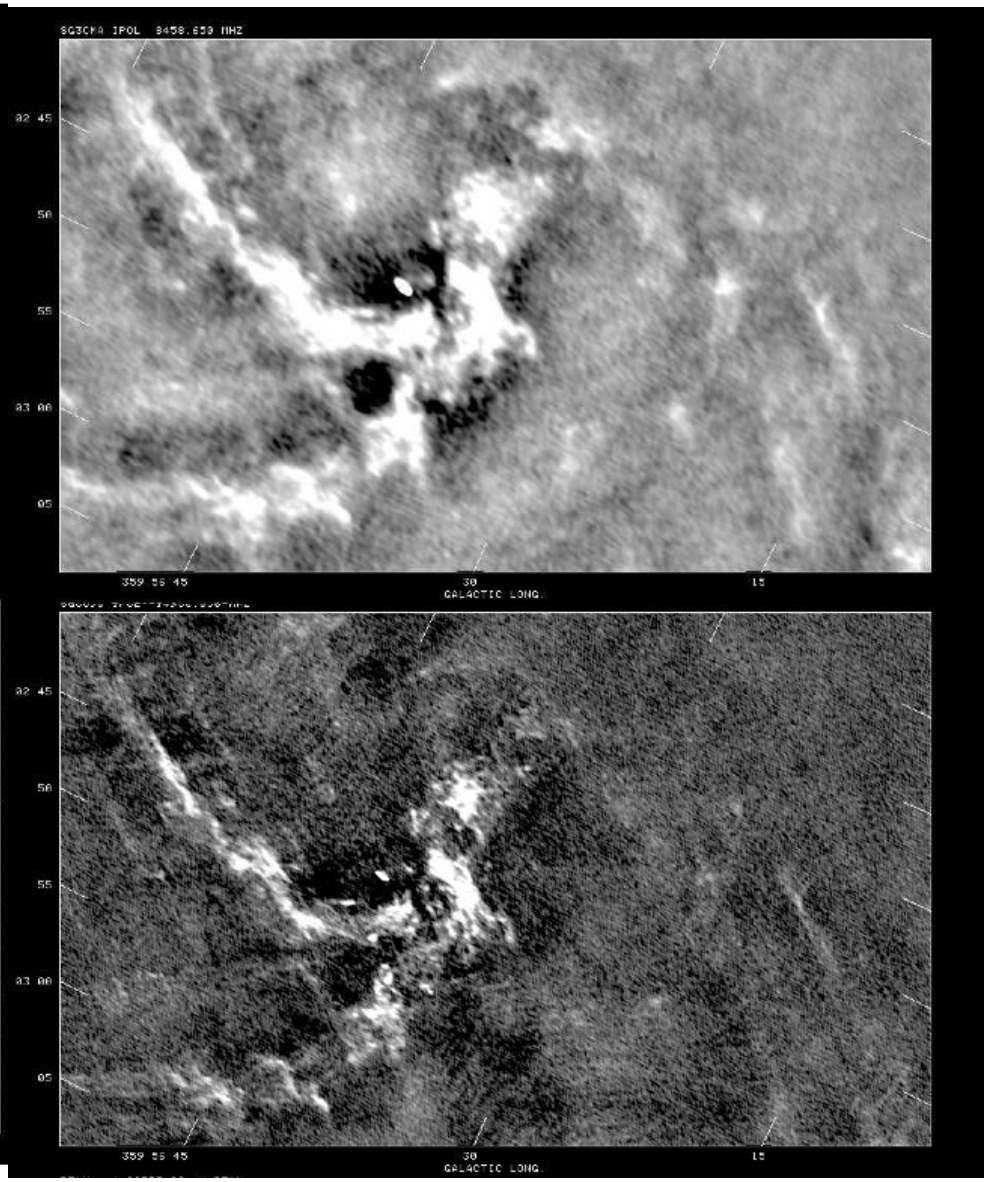


1.3cm Continuum: Blobs of Emission



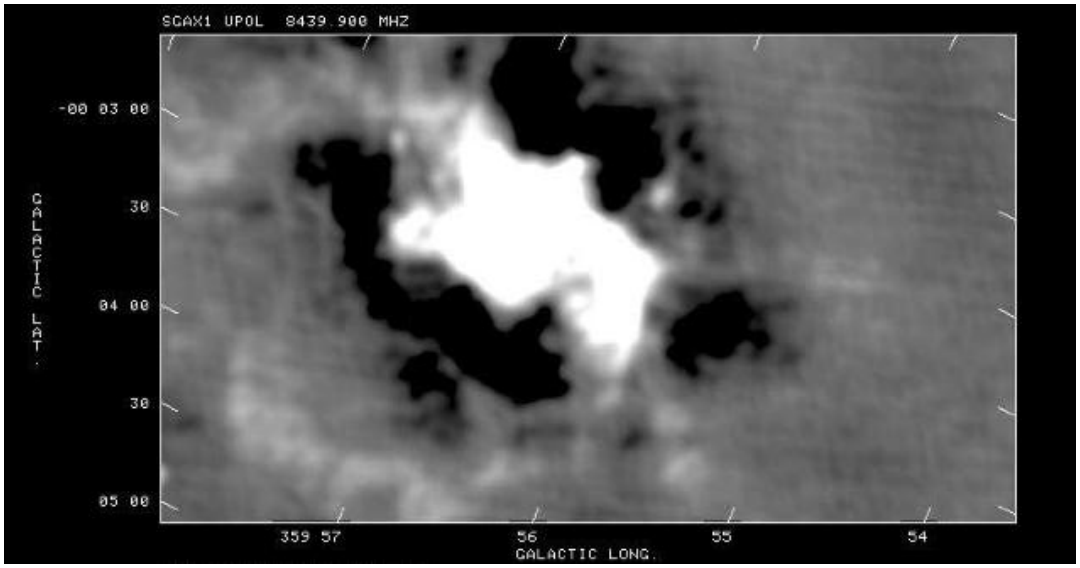
Radio Images



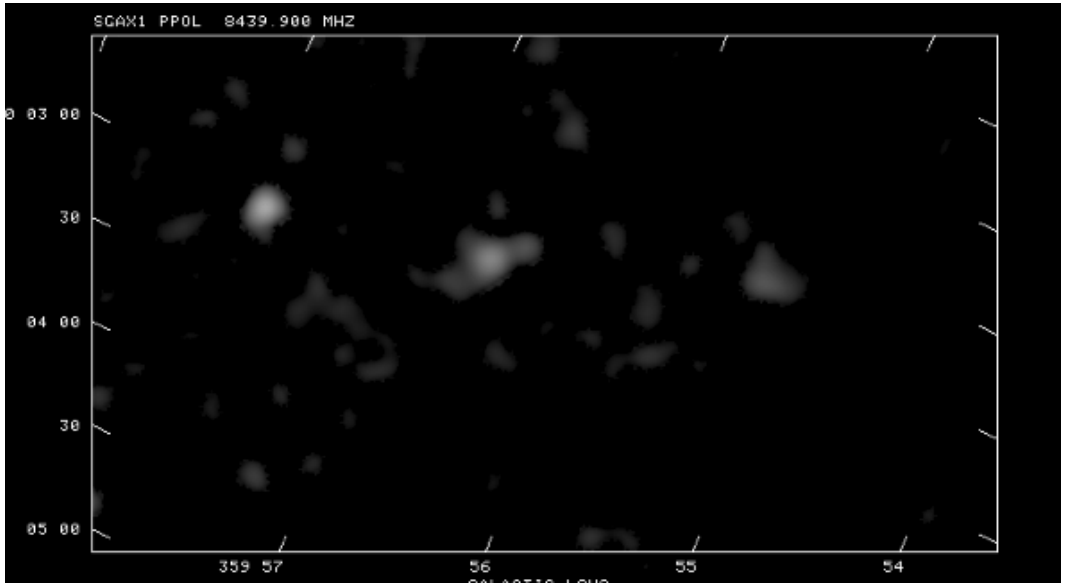


Linear Polarization

- Few to 20% polarization at 3.6cm
- Total intensity

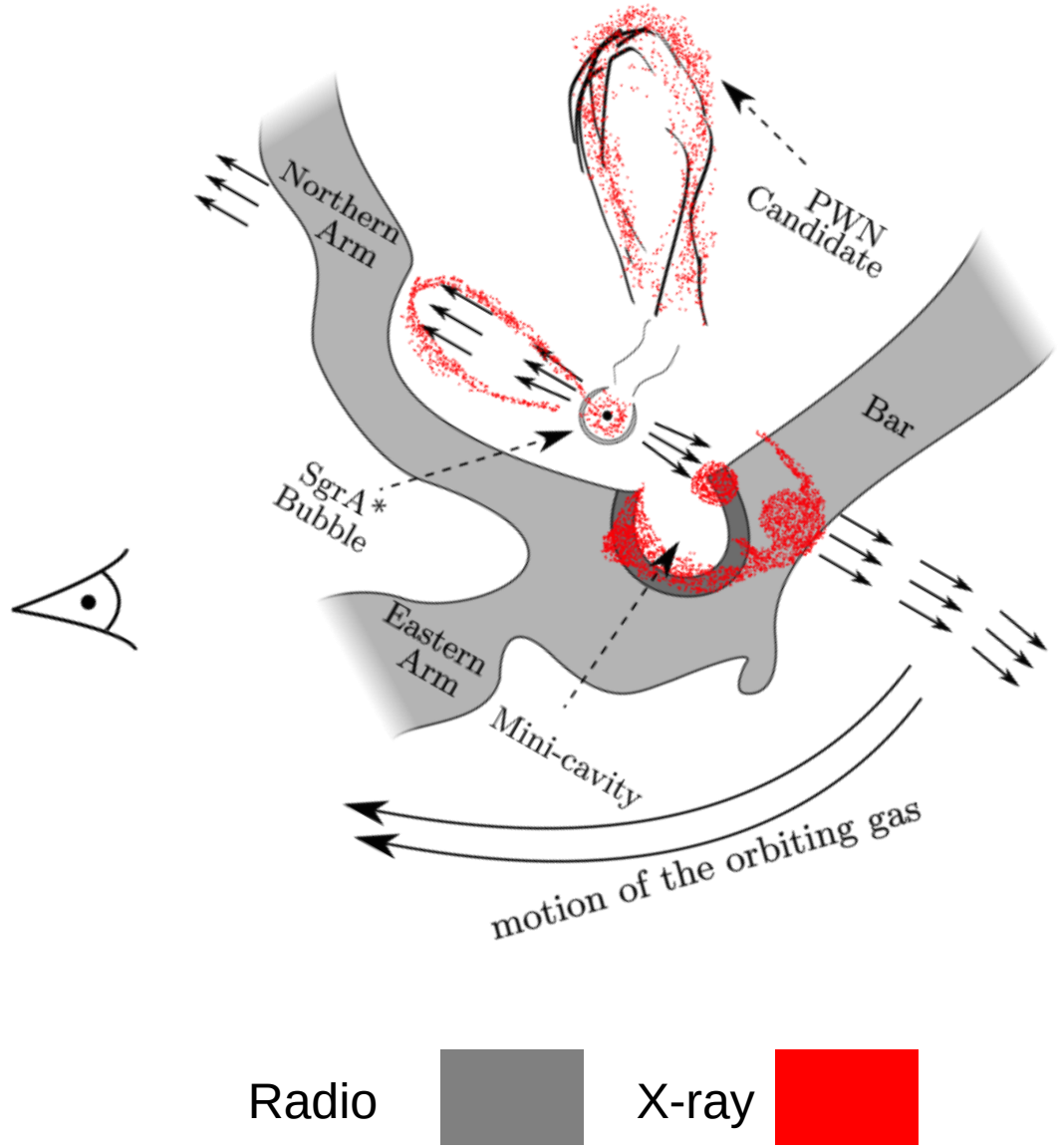


- Polarized Intensity

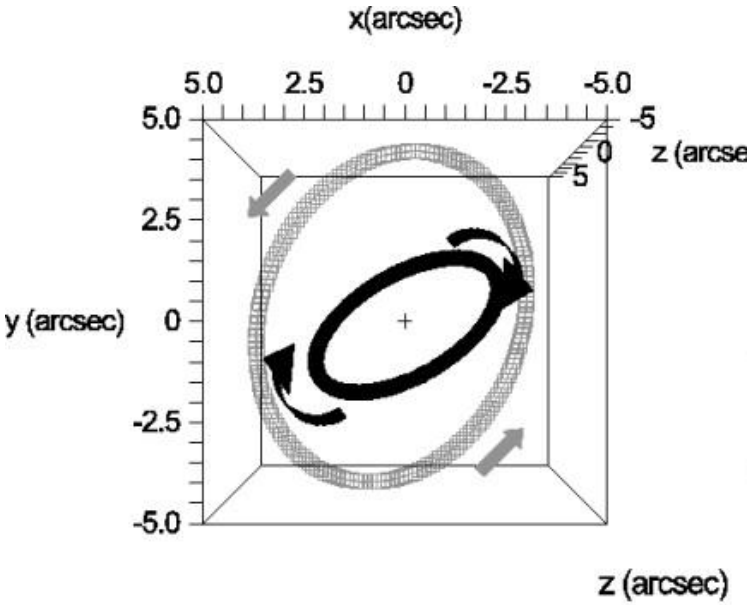


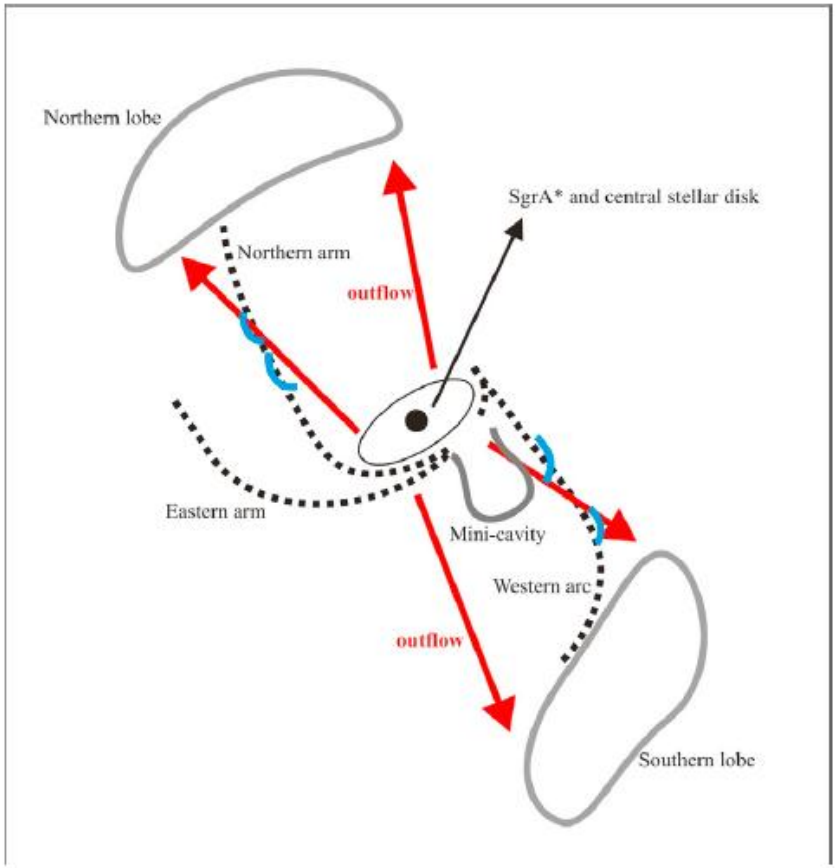
Relativistic or Sub-relativistic Jet Outflow?

- Highly collimated Jet
- Has to be fast not be bent by tidal effects
- Dynamically young (~100 years)
- Enough ram pressure to punch through $10^4 cm^{-3}$
- $L_{kinetic} \sim 10^{38}$ erg/s
- $L_{mini\text{-}cavity} \sim 10^{34}$ erg/s



Relativistic or Sub-relativistic Jet Outflow?

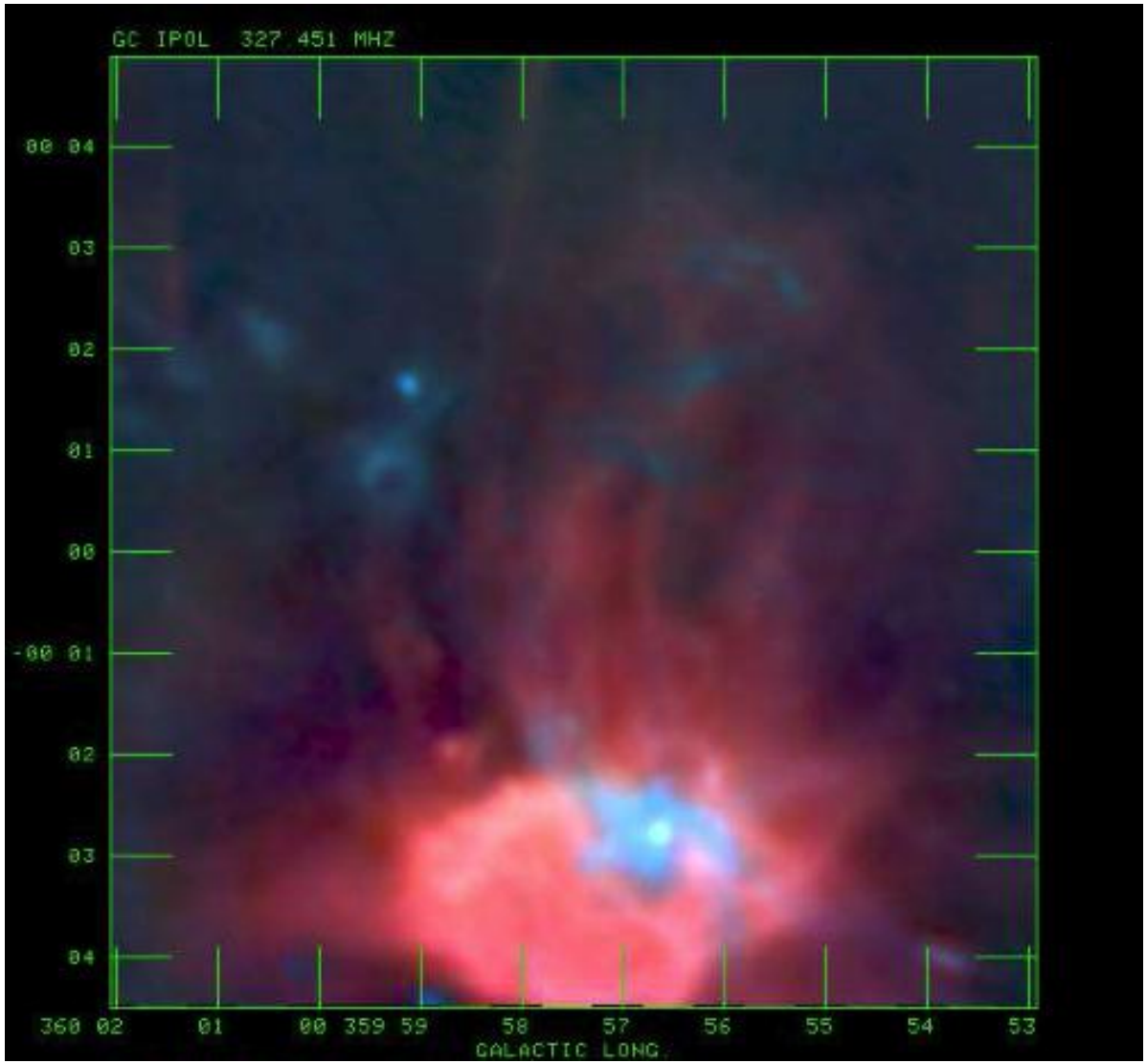




Large Scale Streamers

- Radio Continuum Image

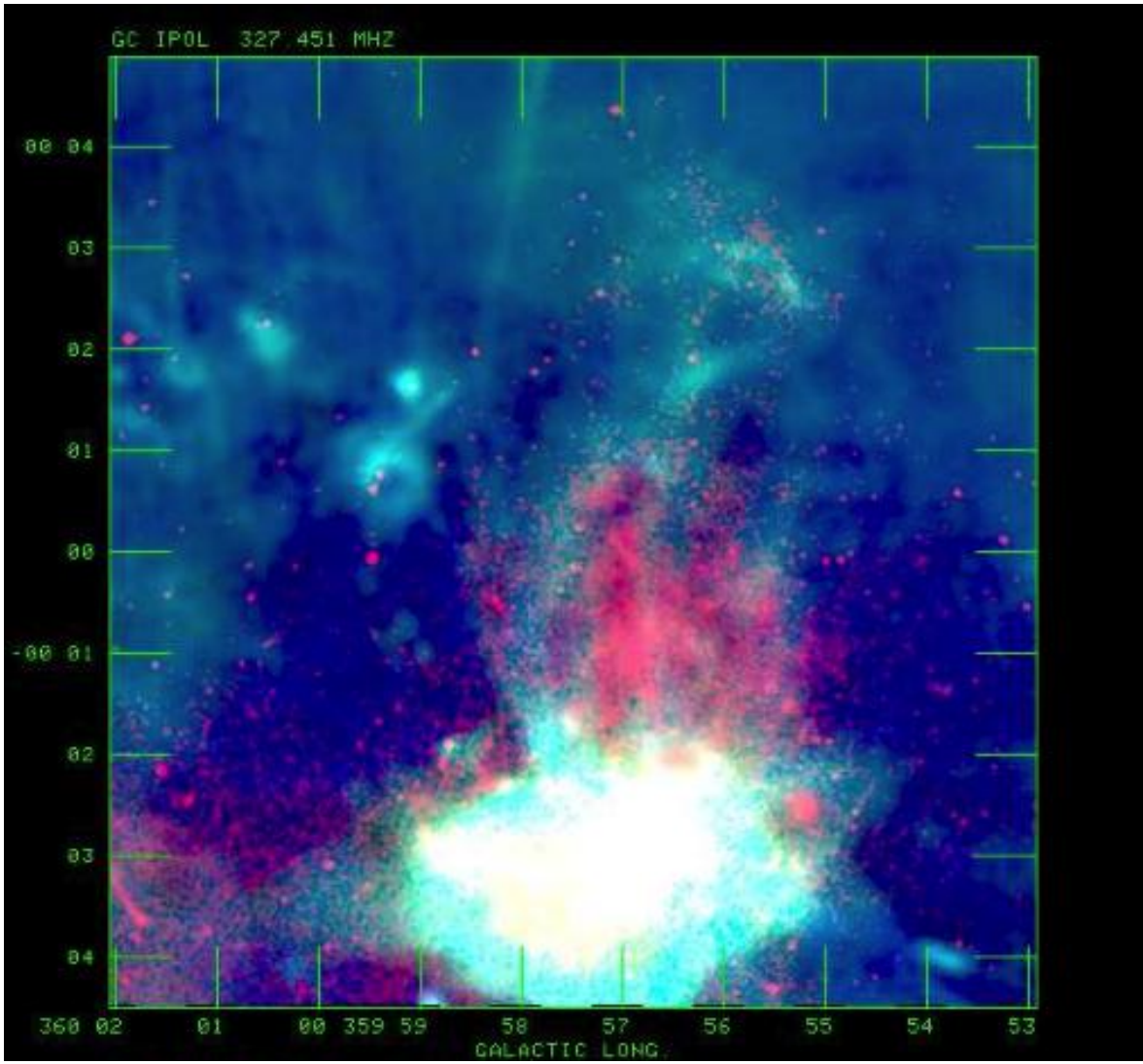
90(R), 20(G) and 6B) cm



Large Scale Streamers

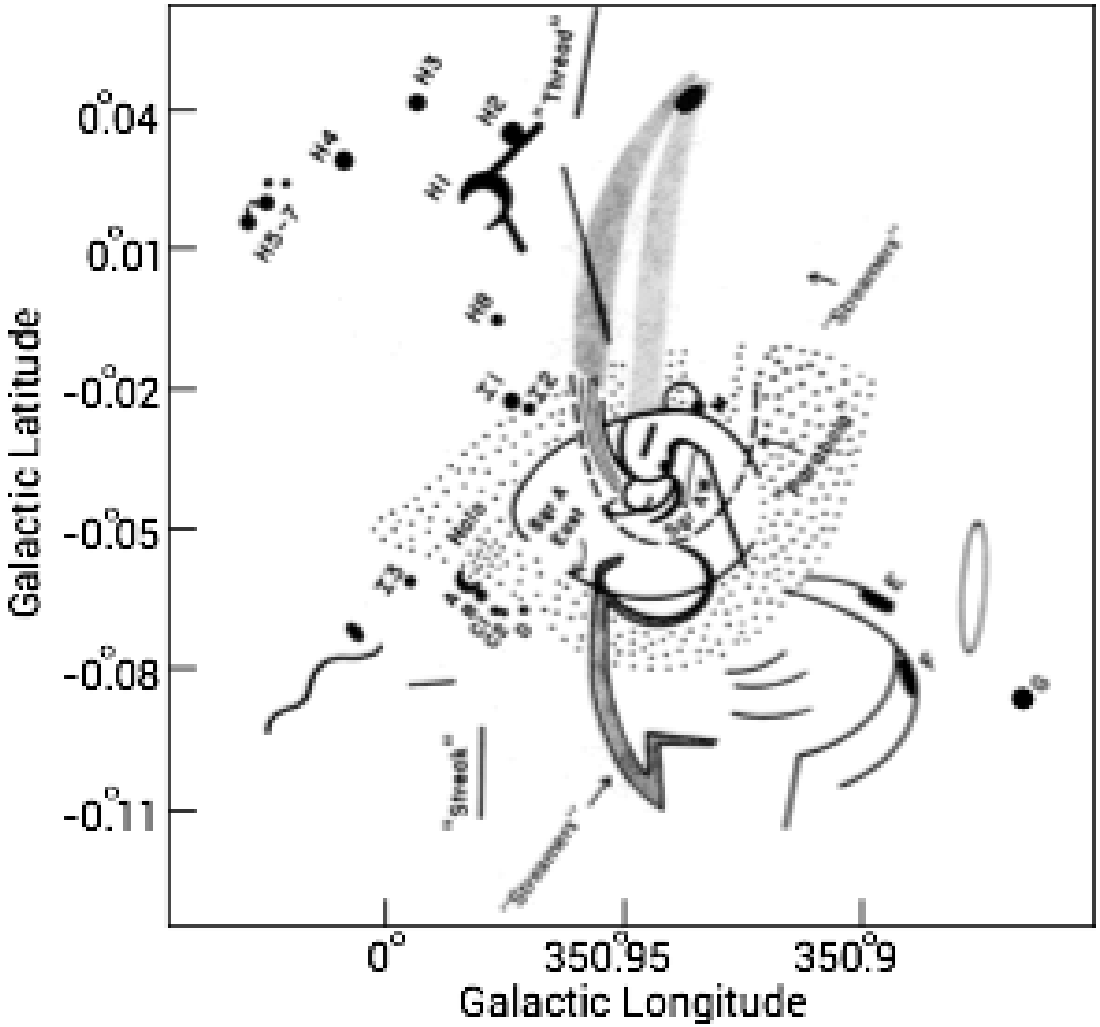
- 6cm Continuum image (B)
- X-rays 1.4-4 keV (R)

- Lx ~ 10^{36} ergs/s



II. NGC 4258: Mega Maser Disk

- Application: Engulfing Cloud
- Keplerian dominated regime
- $M_{disk} < 1\text{-}15\%\ M_{bh}$
- Thin disk: h/r <2% (NGC 4258)



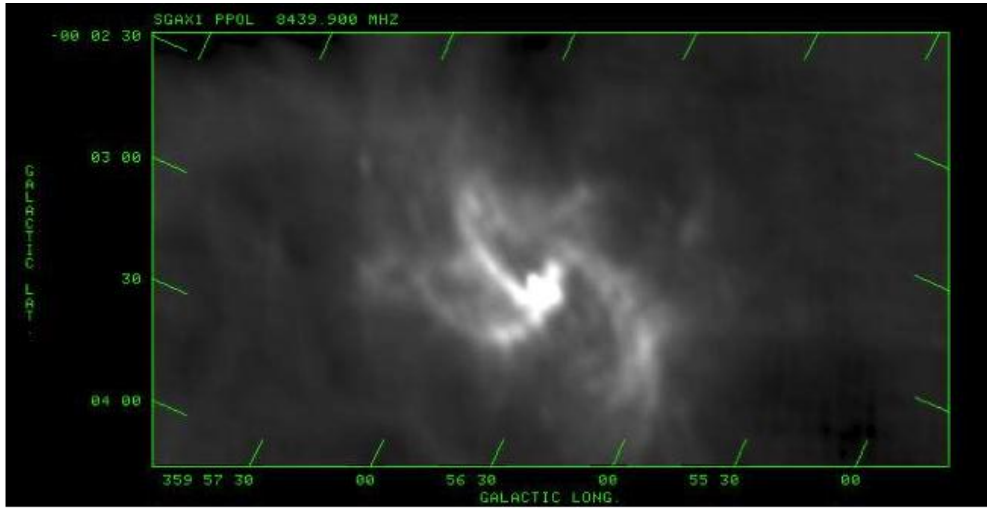
- **Conclusions**

1. **Preliminary Measurements: Outflow from Sgr A***
   - ❑ Accretion disk
   - ❑ Orientation of clockwise stellar disk
   - ❑ Interaction with the mini-cavity
   - ❑ Support the jet mode

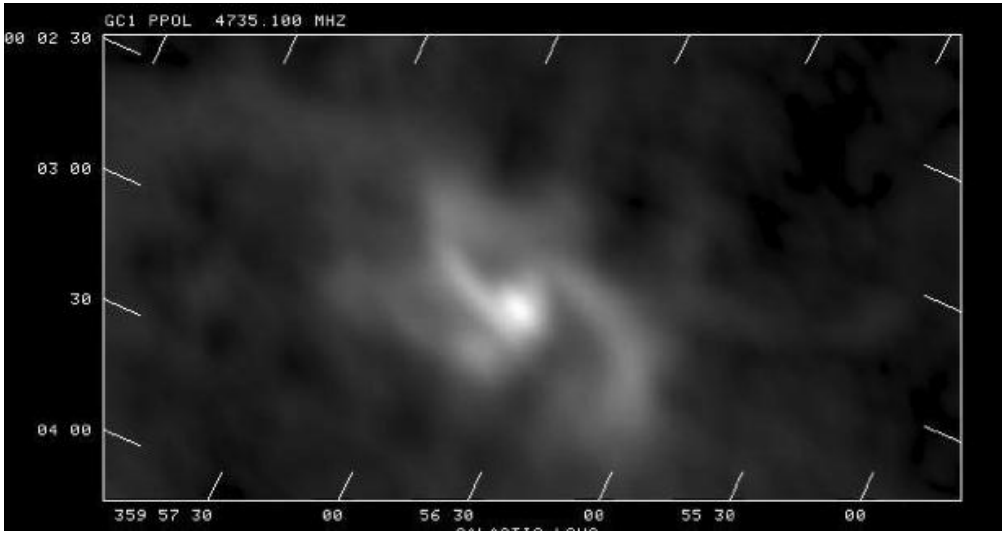
2. **Streamers: Thermal X-rays and Nothermal radio Emission**
   - ❑ Mixture: Hot, warmd and cold phases
   - ❑ Collimation by the 2pc molecular ring

Linear Polarization

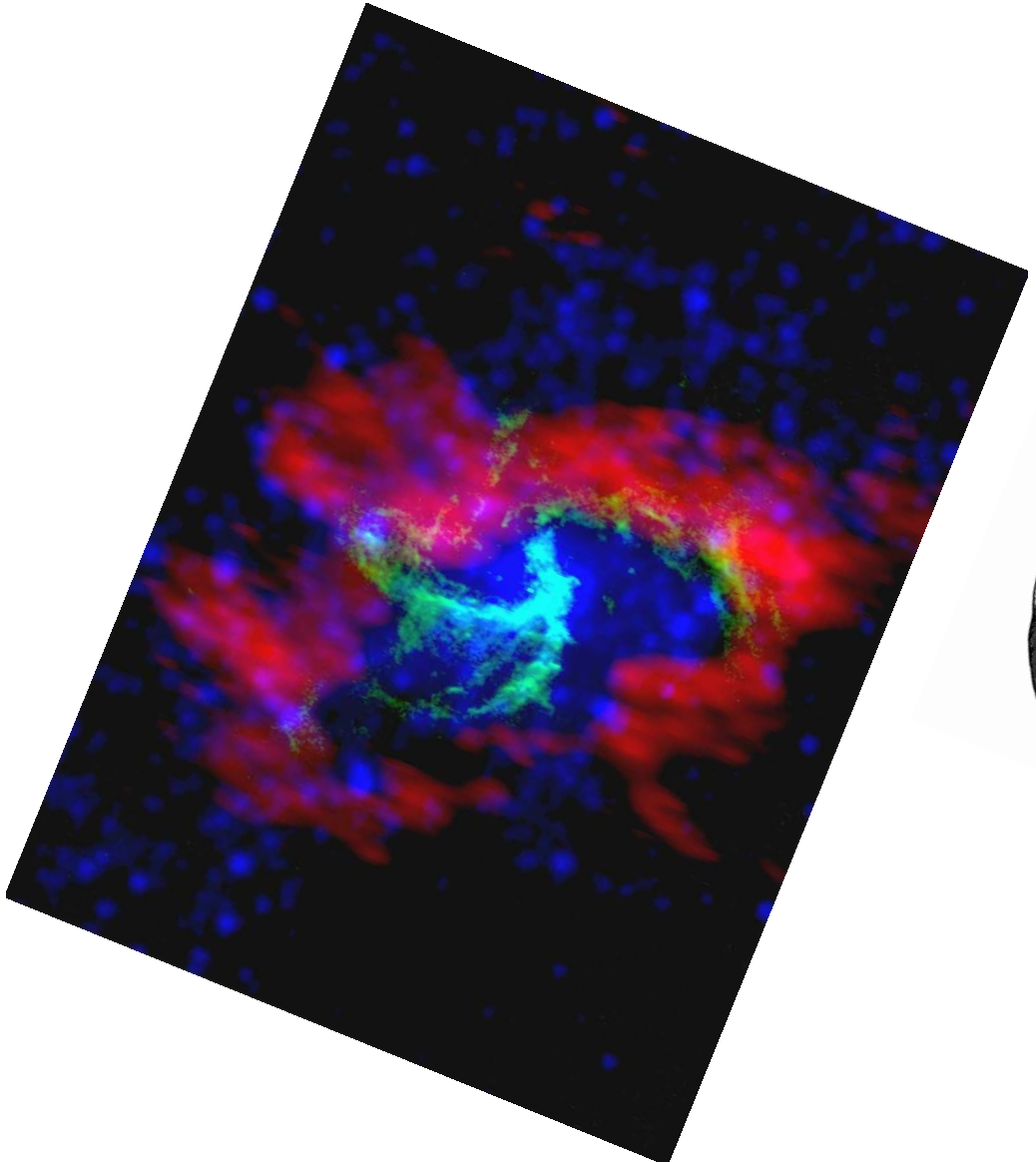
- Few % polarization at 6cm
- Total intensity image

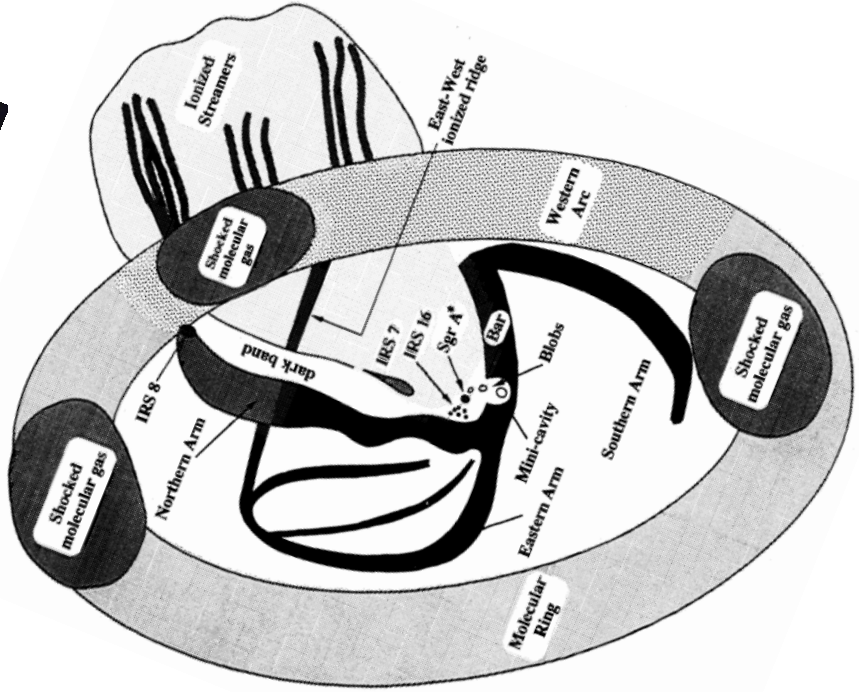


- Polarized Intensity image



Large Scale Streamers



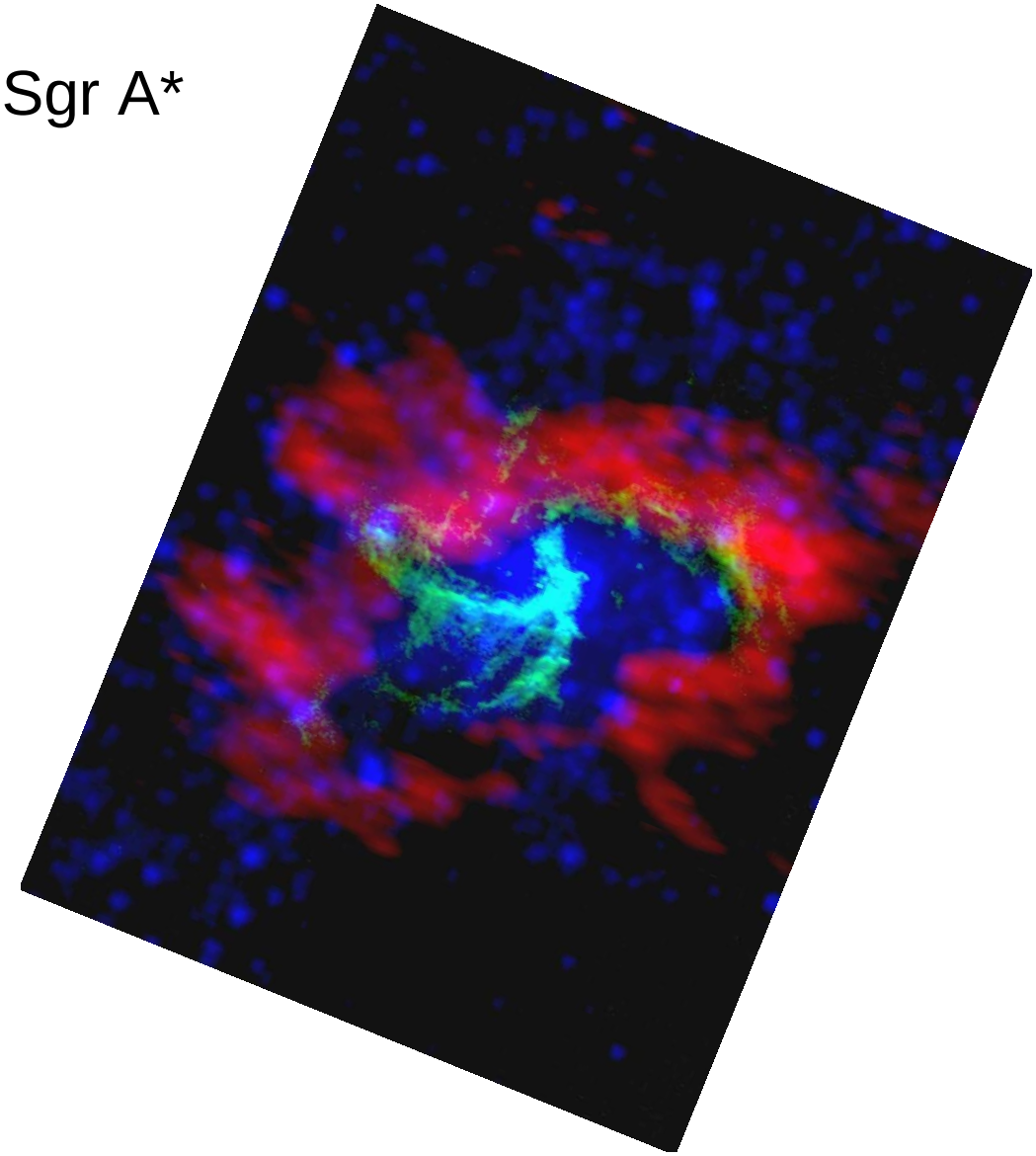


III. Molecular Ring Orbiting Sgr A*

- Kinematics: rotation with v~110 km/s
- Velocity dispersion ~27 km/s; Disturbed motion
- 26 dense cores
- size ~ 0.25 pc

- Tidal Stability?
  - Virialized mass
  - Optically thick HCN(1-0) line
  - Optically thin HCN(1-0) line

- Mass ~ 5.5, 7.9, 0.6 x10^5 M_{solar}
- density ~ 3.8, 5, 0.1 x10^7 cm^{-3}



1.3cm Free-free emission

HCN (1-0) emission