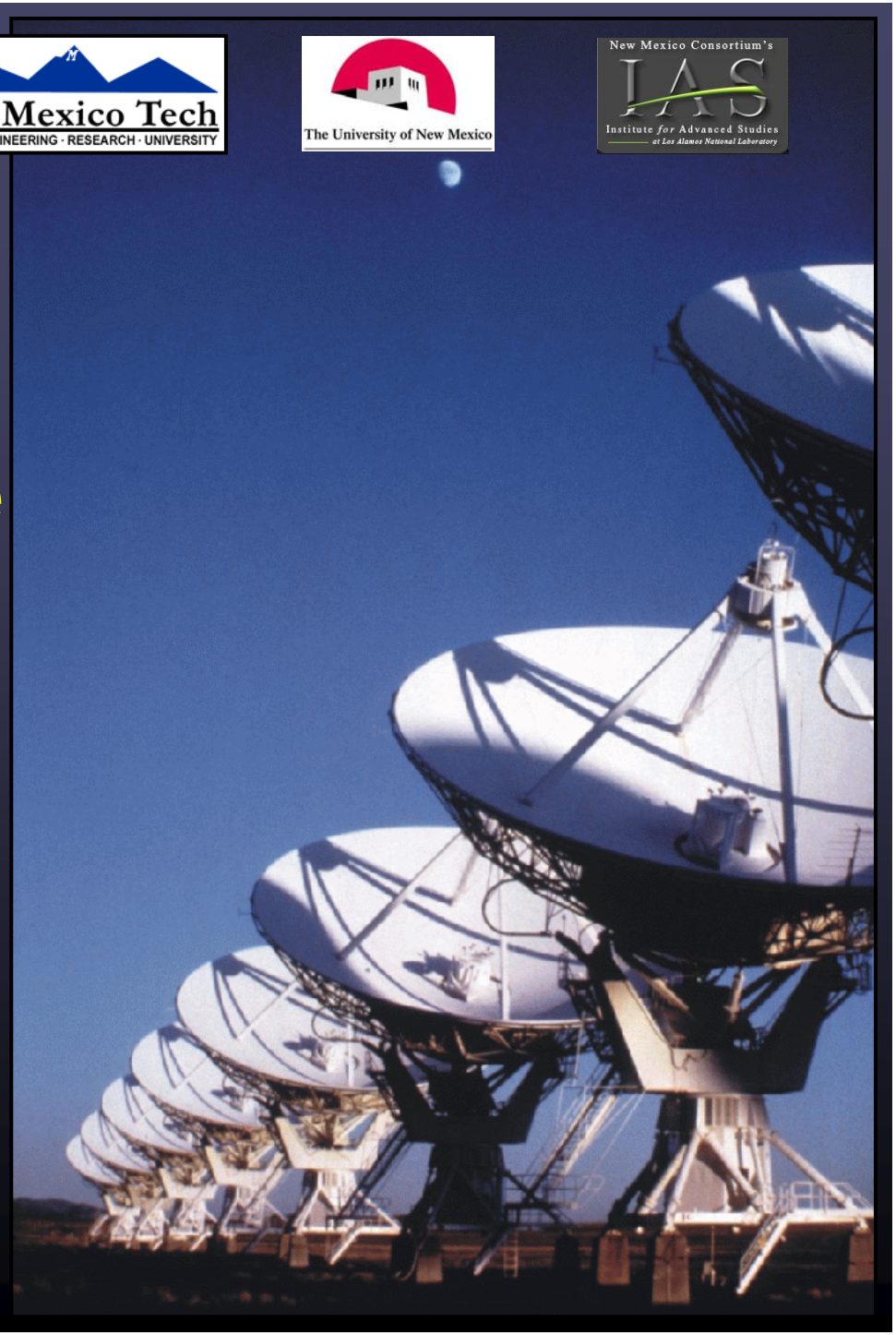


Galactic Radio Science

Cornelia C. Lang
University of Iowa

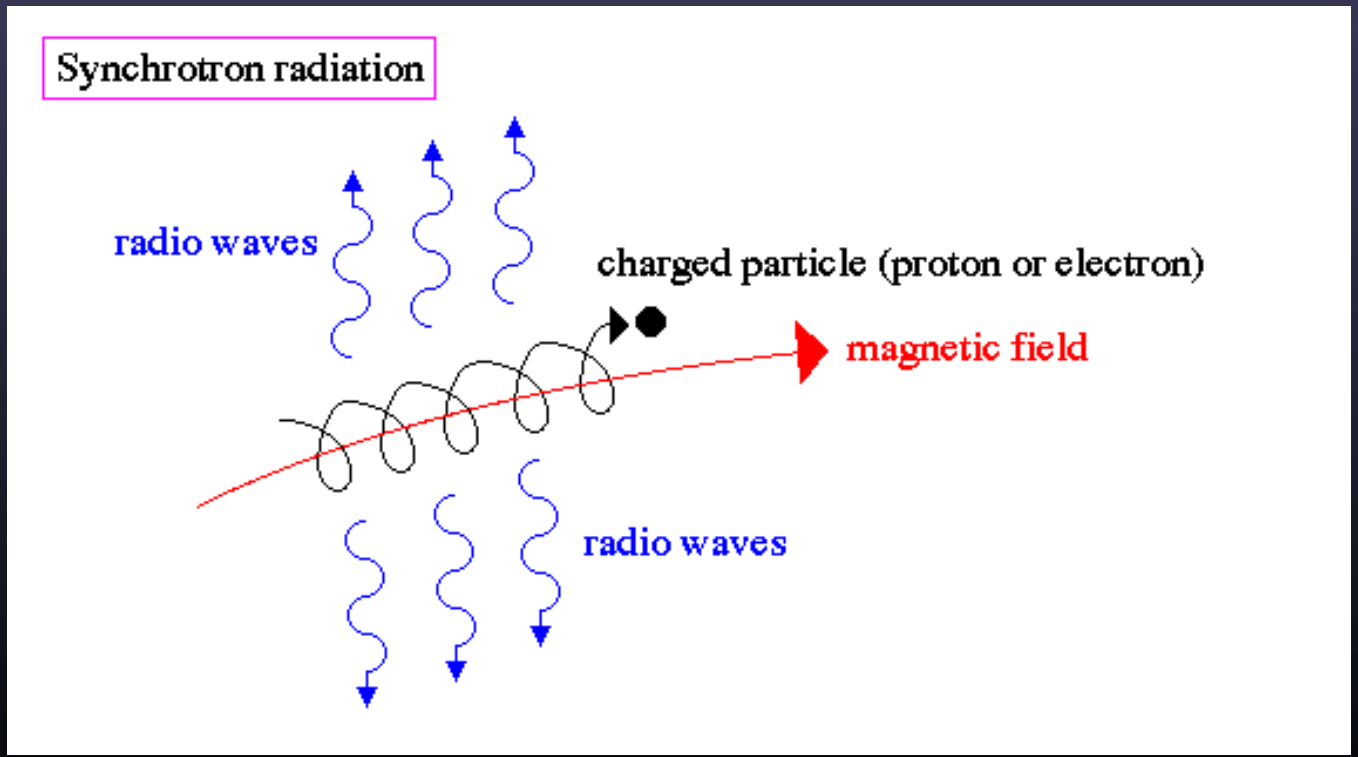
Eleventh Synthesis Imaging Workshop
Socorro, NM, June 10-17, 2008

Outline

- Radio Emission: what can we learn?
  - Thermal and non-thermal continuum emission
  - Spectral line radiation
  - The radio spectrum & interferometers
- A Radio Tour of the Milky Way
  - Star birth and death in the ISM
  - Stellar radio sources
  - Interstellar gas: ionized & atomic clouds
  - Exotic radio sources
- An Unusual Place: Galactic Center

Radio Emission Mechanisms

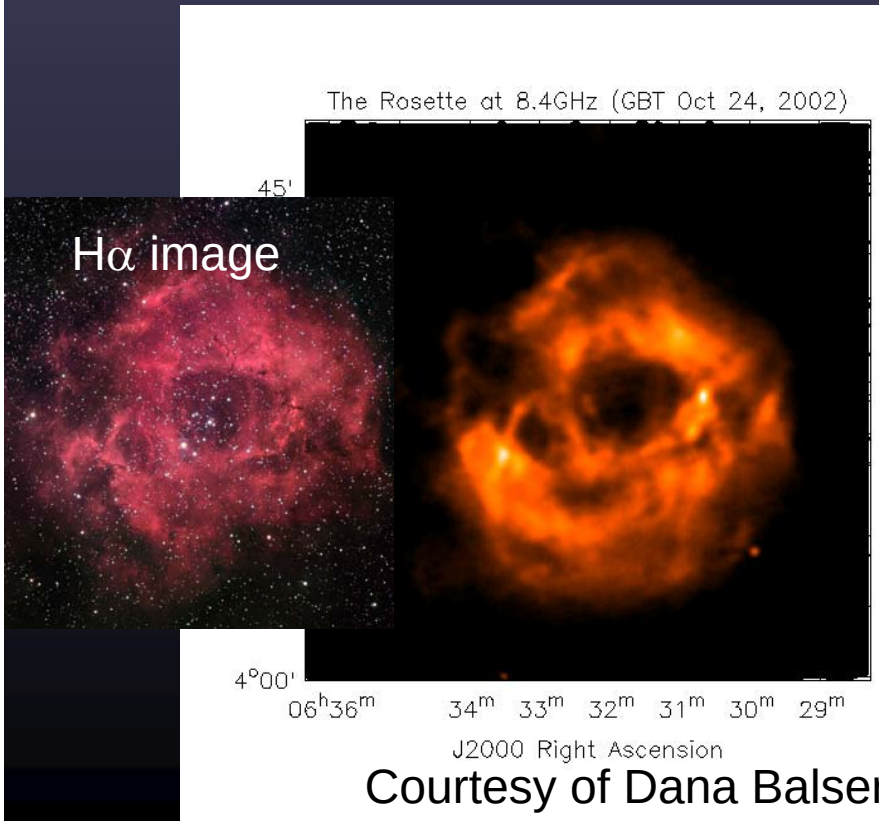
- Synchrotron radiation - continuum
  - Energetic charged particles accelerating along magnetic field lines (non-thermal)



- What can we learn?
  - particle energy
  - strength of magnetic field
  - polarization
  - orientation of magnetic field

Radio Emission Mechanisms

- Thermal emission - continuum
  - Blackbody radiation for objects with T~3-30 K
  - Brehmsstralung “free-free” radiation: charged particles interacting in a plasma at T; e^- accelerated by ion



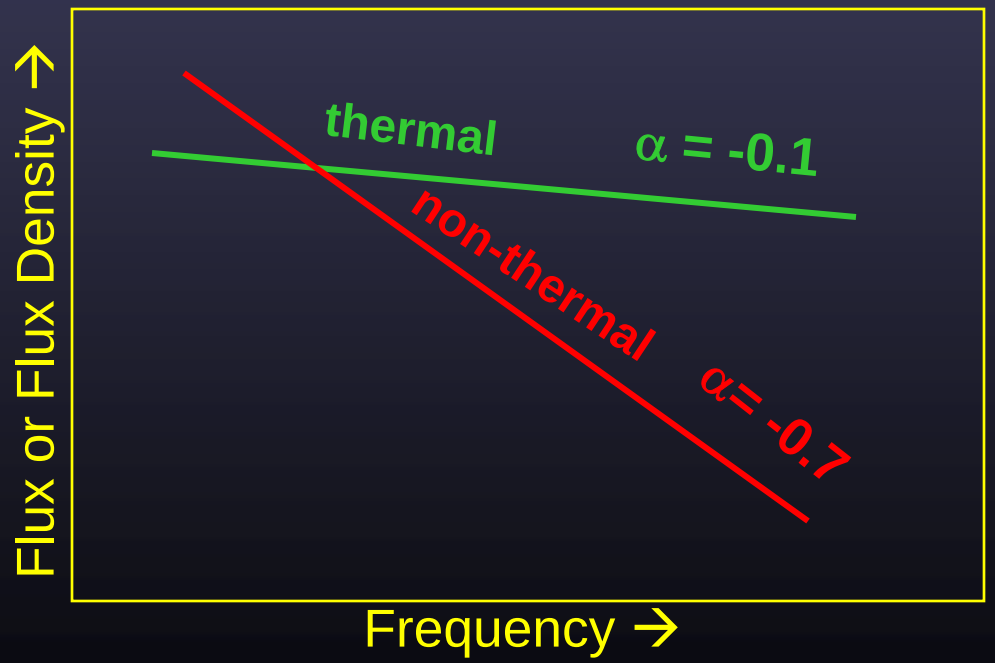
Courtesy of Dana Balser

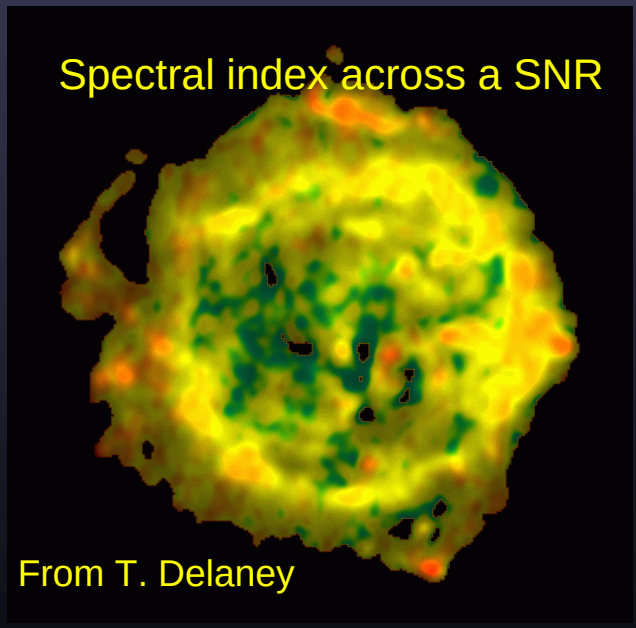
- What can we learn?

  - mass of ionized gas
  - optical depth
  - density of electrons in plasma
  - rate of ionizing photons

Radio Emission Mechanisms

- What we measure from radio continuum
  - Radio flux or flux density at different frequencies
  - Spectral index α, where $\Sigma_\nu \sim \nu^\alpha$

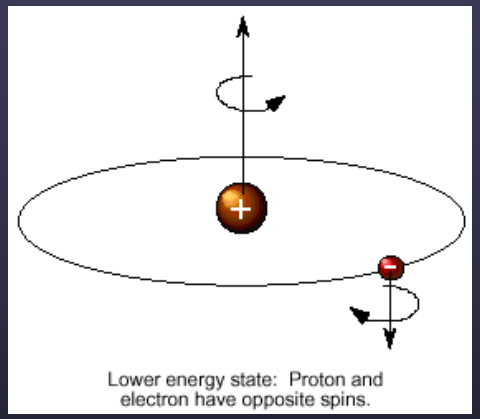




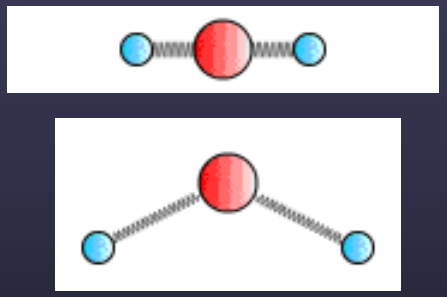
Radio Emission Mechanisms

- Spectral line emission

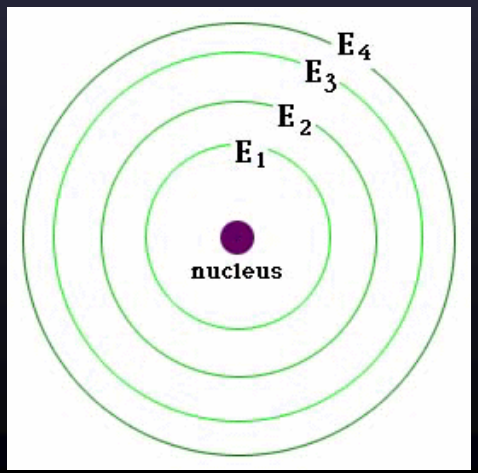
  - Discrete transitions in atoms and molecules



Atomic Hydrogen
"spin-flip" transition
21 cm



Molecular Lines
CO, CS, H_20, SiO, etc.!



Recombination Lines
outer transitions of H
H166α, H92α, H41α
(1.4, 8.3 GHz, 98 GHz)

- What can we learn?

  - gas physical conditions (n, T)
  - kinematics (Doppler Effect)

Also a wide variety of instruments!

ATA
CA, USA

VLA/EVLA
NM, USA

ATCA, Australia

Millimeter
> 15 GHz
< 10 mm

Low-Frequency
< 1.4 GHz
> 1 m

Centimeter
1.4 MHz - 15 GHz
20 cm – 1 cm

PdB,
France

GMRT, India

ALMA, Chile

LOWFAR, NL

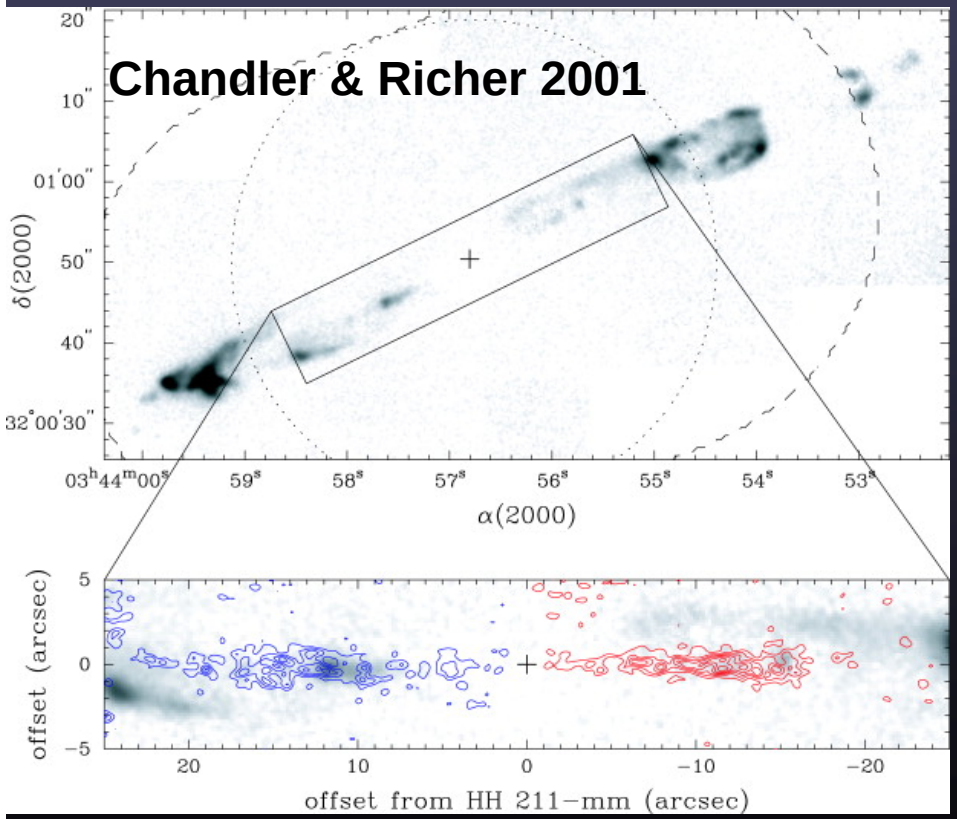
CARMA,
CA, USA

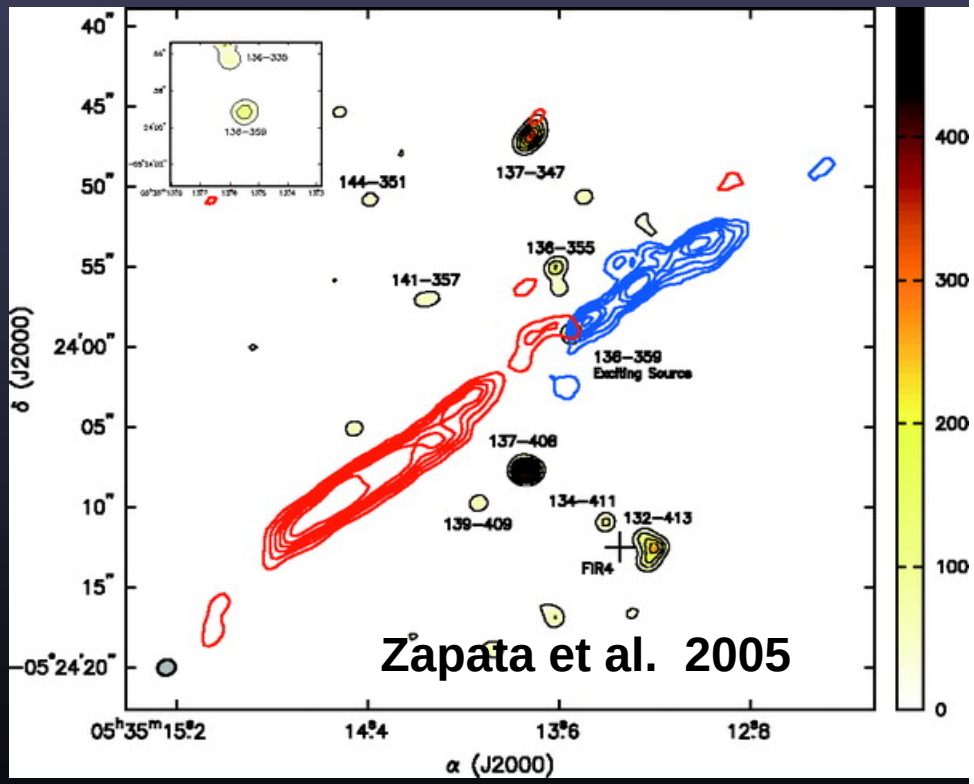
SMA, Hawaii, USA

LWA, NM, USA

Tour of the Galaxy: Interstellar

- Low Mass Star Formation
  - obscured regions of the Galaxy with high resolution
  - collimated outflows powered by protostar – 10000s AU



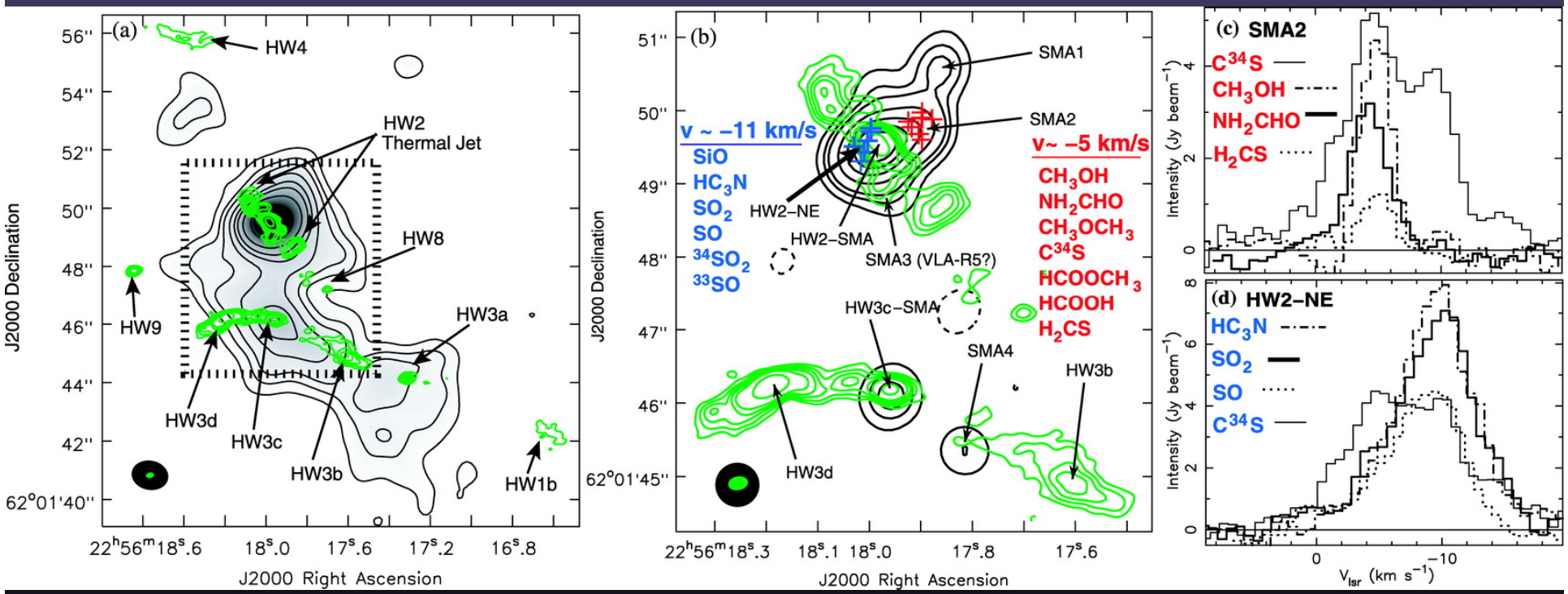


VLA 7mm spectral line (SiO) – 0.5”

SMA 1mm spectral line (CO 2-1) – 1”

Tour of the Galaxy: Interstellar

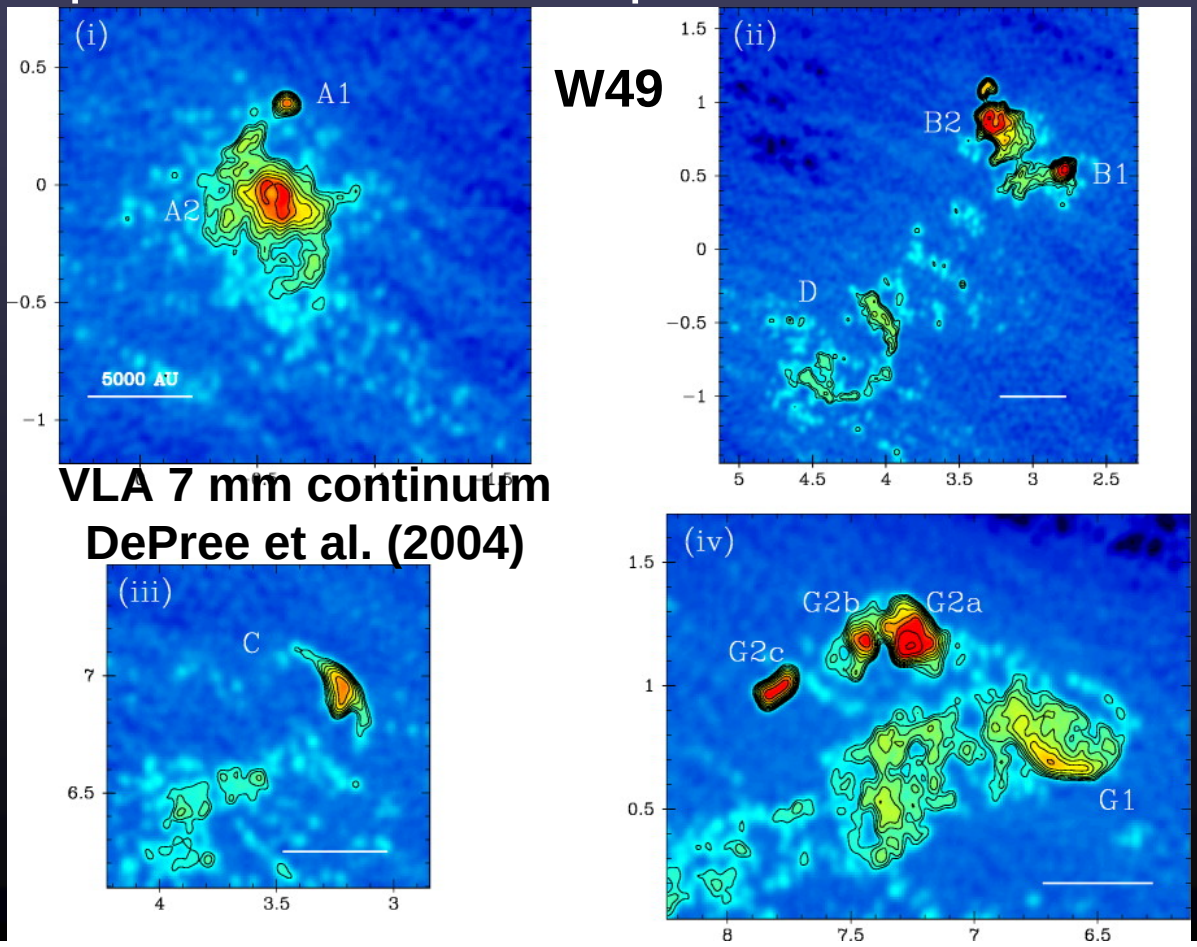
- Probing massive stars in formation
  - tend to be forming in clusters; confusion! go to high frequencies (sub-mm)
  - “hot molecular cores” (100-300K) around protostars; complex chemistry



Ceph A-East d=725 pc; black=SMA 875 μm; green=VLA 3 cm; lines=sub-mm species
Spatial resolutions of <1” (where 1”~0.004 pc or ~750 AU) from Brogan et al. (2007)

Tour of the Galaxy: Interstellar

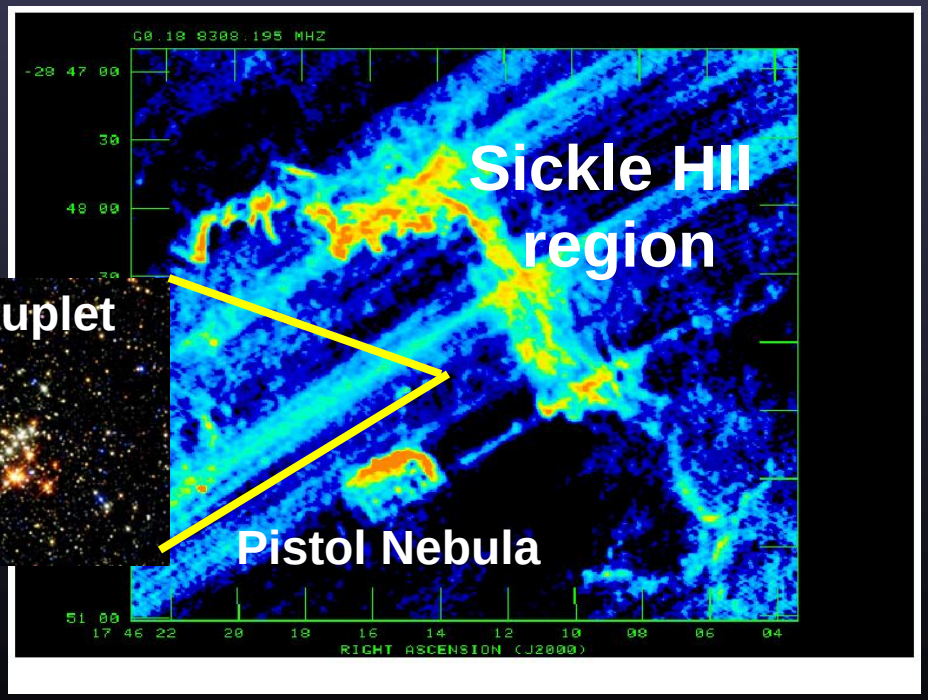
- High Mass Stars in HII Regions
  - high resolution shows objects forming of size ~1000s AU!
  - ultra-compact HIIs are < 0.1 pc with densities n > 10^4 cm^{-3}



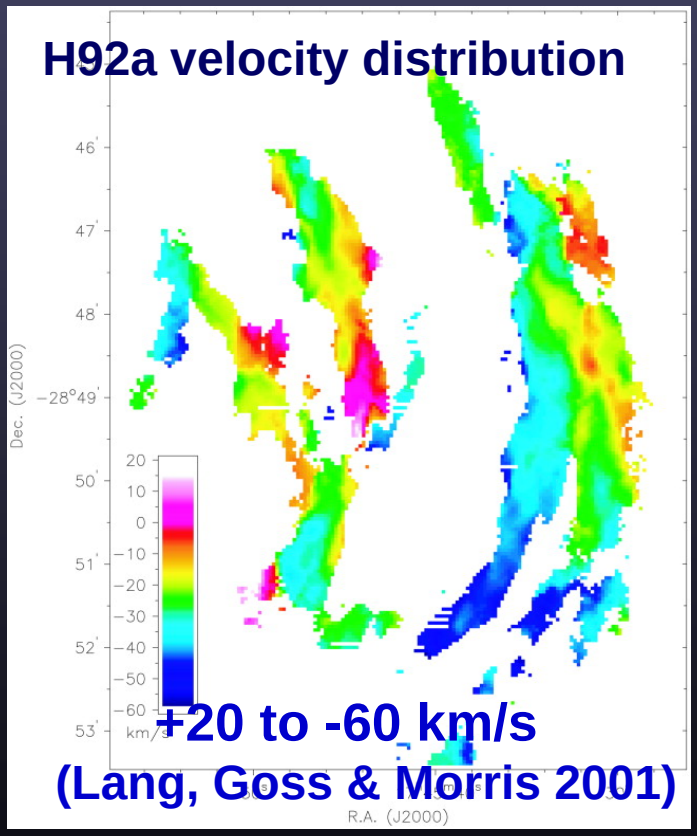
VLA 7 mm continuum
DePree et al. (2004)

Tour of the Galaxy: Interstellar

- HII regions: ionization & kinematics
  - continuum→ Lyman photons = # stars
  - continuum → density, mass of ionized H
  - RRLs → kinematics, physical conditions



(Lang, Goss & Wood 1997)

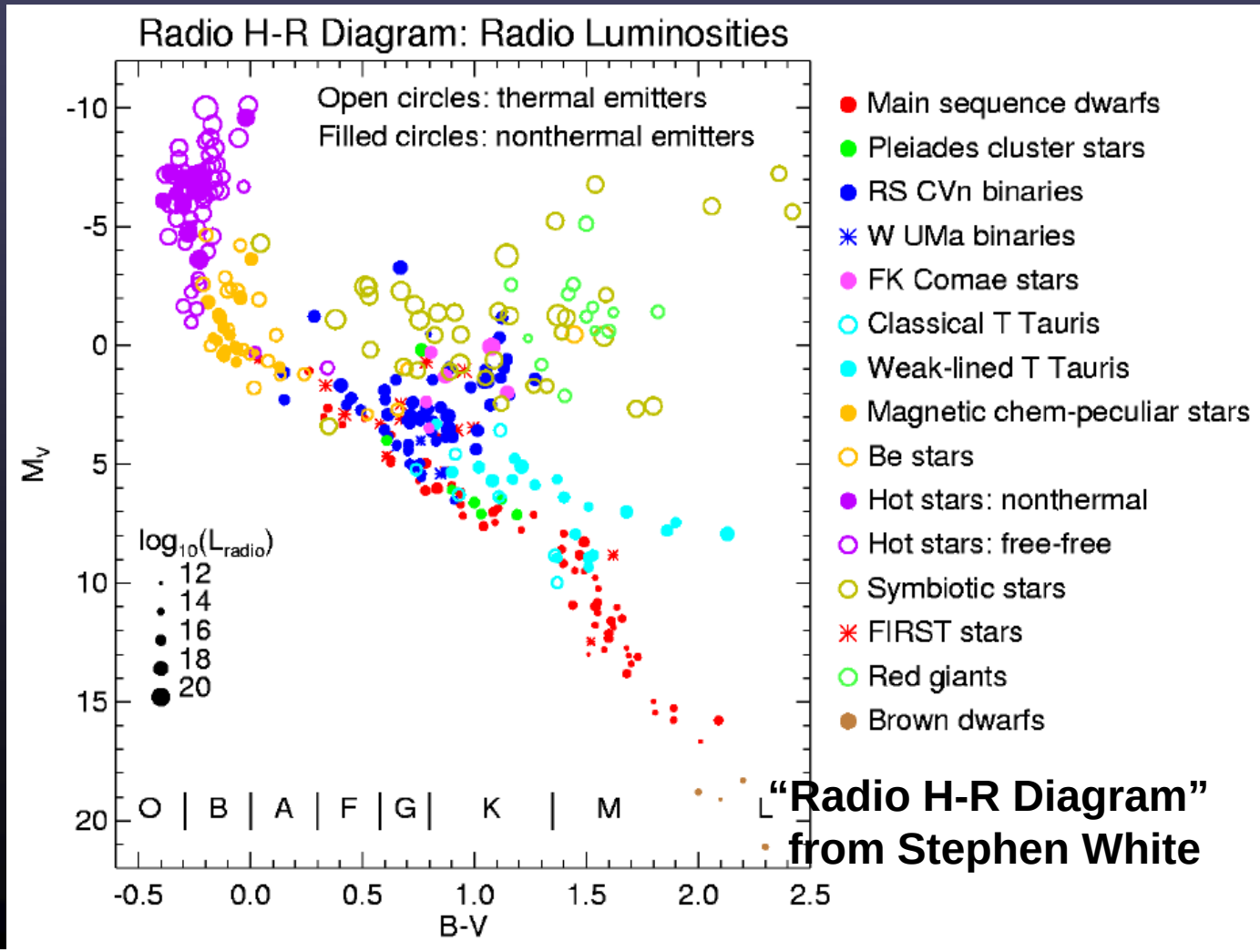


+20 to -60 km/s

(Lang, Goss & Morris 2001)

Tour of the Galaxy: Stellar Sources

- Stars: Middle Age and Evolving



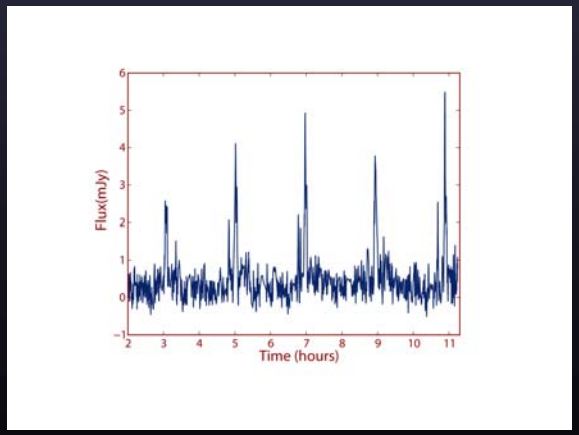
"Radio H-R Diagram" from Stephen White

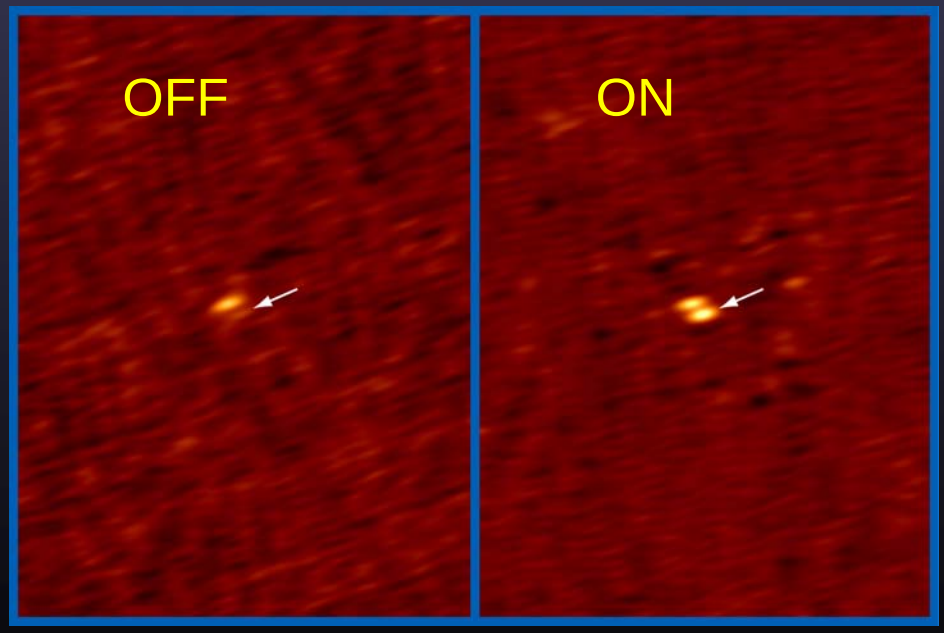
Tour of the Galaxy: Stellar Sources

- Stars: Very low mass and brown dwarfs

  - some M+L type dwarfs, brown dwarfs show quiescent and flaring non-thermal emission (Berger et al. 2001-7; Hallinan et al. (2006,2008)

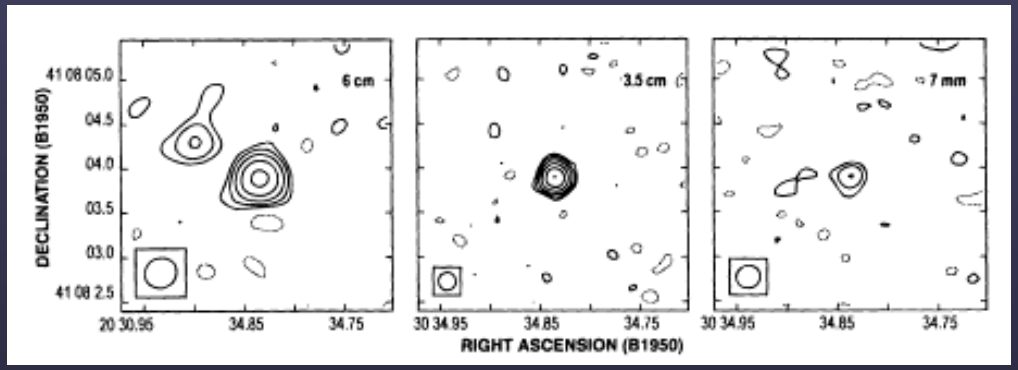
<-- magnetic activity at the poles: electrons interact with dwarf's magnetic field to produce radio waves that then are amplified by masers





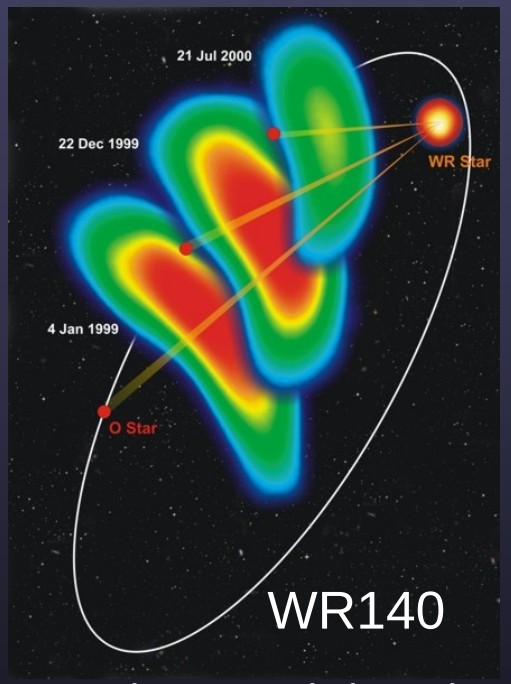
Tour of the Galaxy: Stellar Sources

- Stars: Middle Age and Evolving



CygOB2 #5– stellar wind emission
Contreras et al. (1996)

- Binary system with two O7I stars
- Mass loss ~ 4-5 x 10^{-5} M_o $year^{-1}$

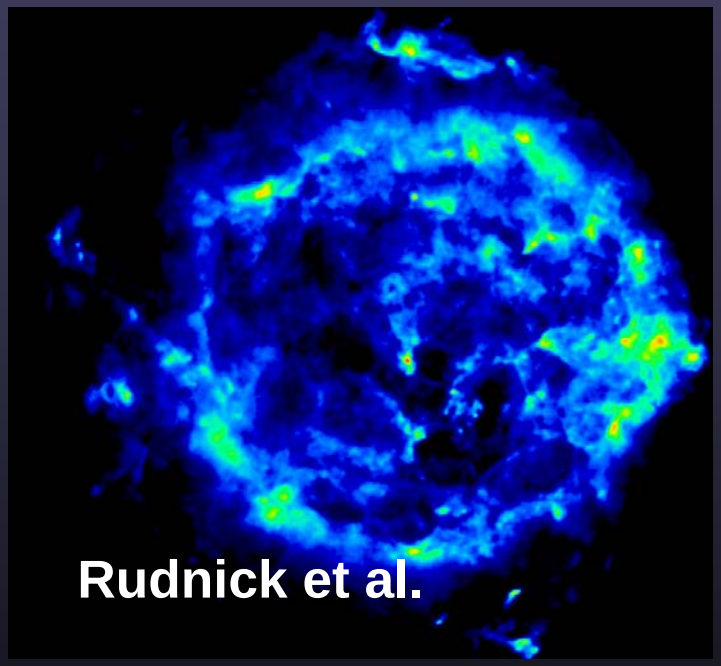


Dougherty et al. (2005)

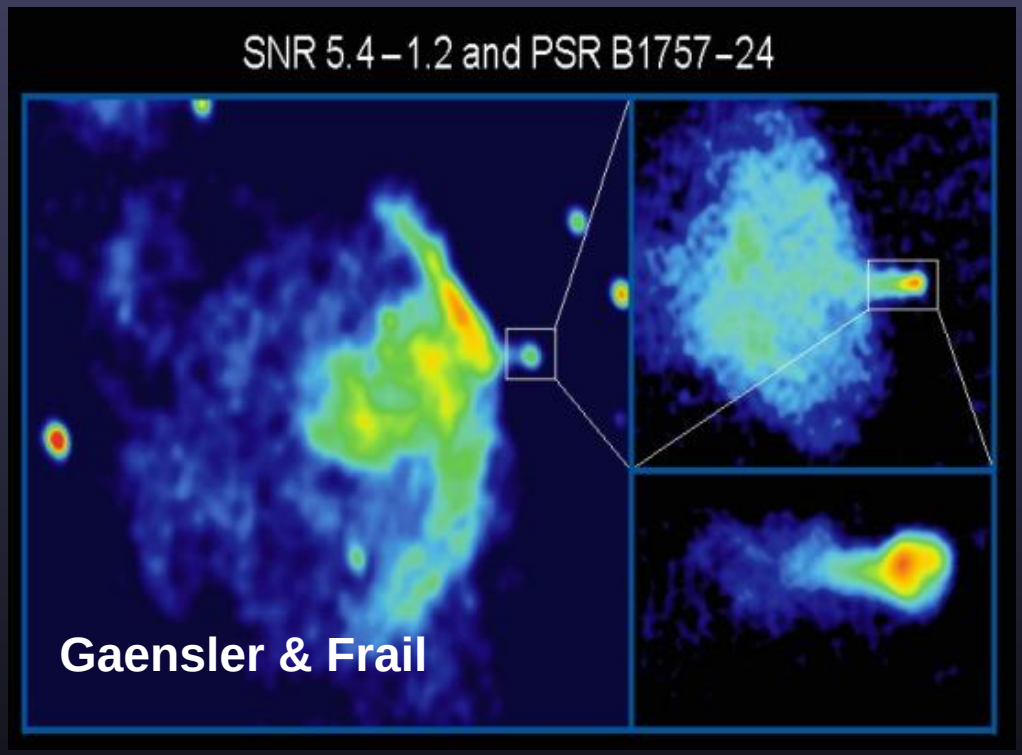
- WR star and O-star binary
- Nonthermal, varying emission traces wind-wind collision

Tour of the Galaxy: Interstellar

- Supernova Remnants



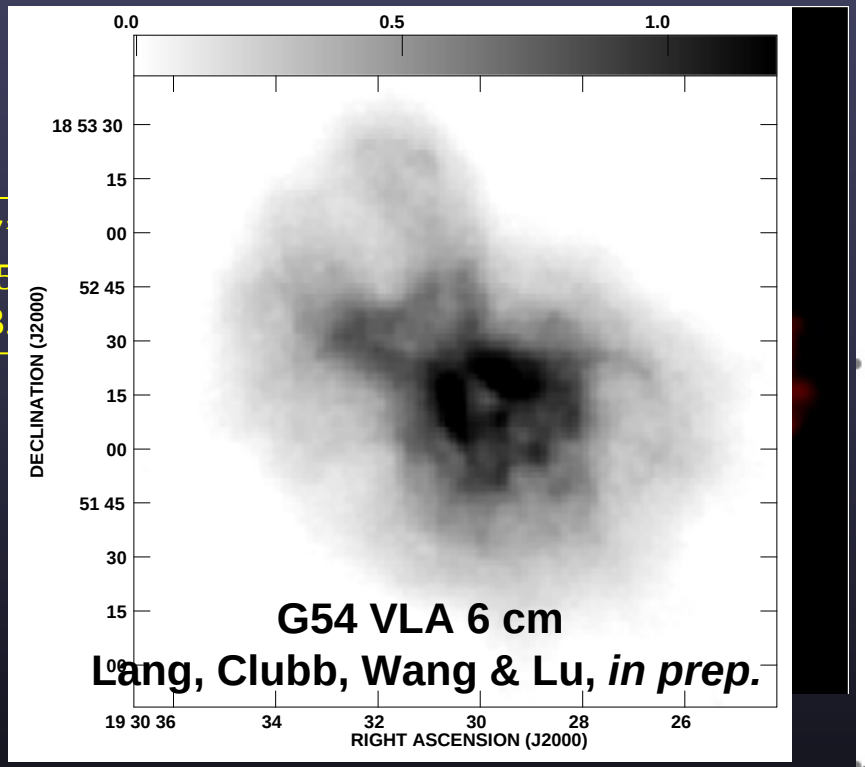
Cassiopeia A SNR
VLA 6 cm image
d = 3 kpc Cassiopeia

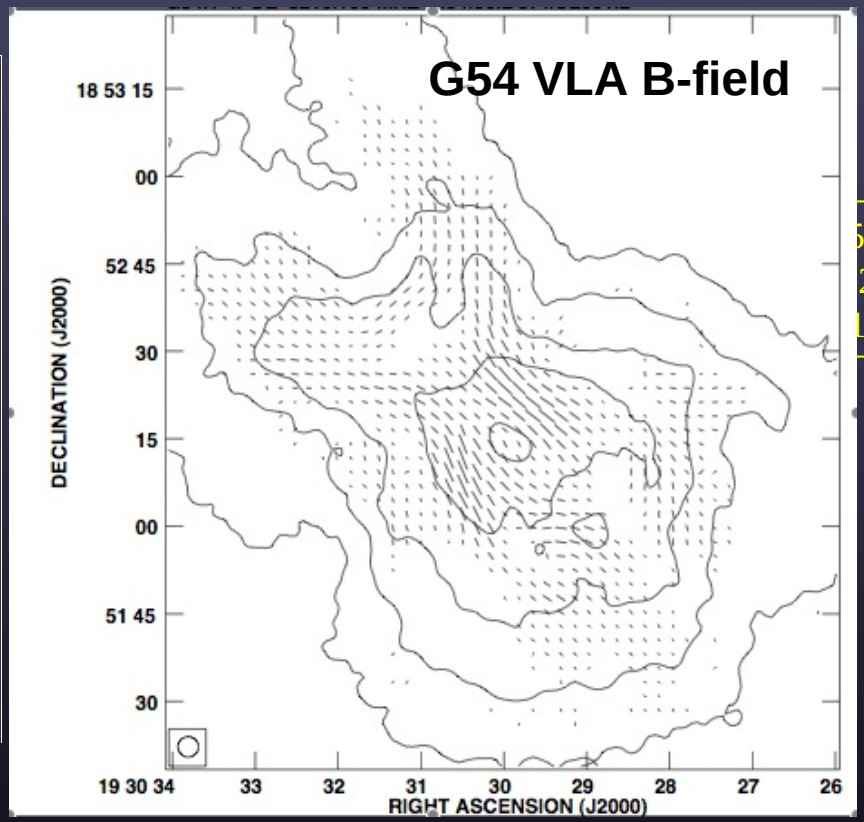


G5.4-1.2 and PSR B1757-24
d = 5 kpc Sagittarius
PSR moving 1,000 miles/sec

Tour of the Galaxy: Interstellar

- Star Death: Pulsar Wind Nebulae



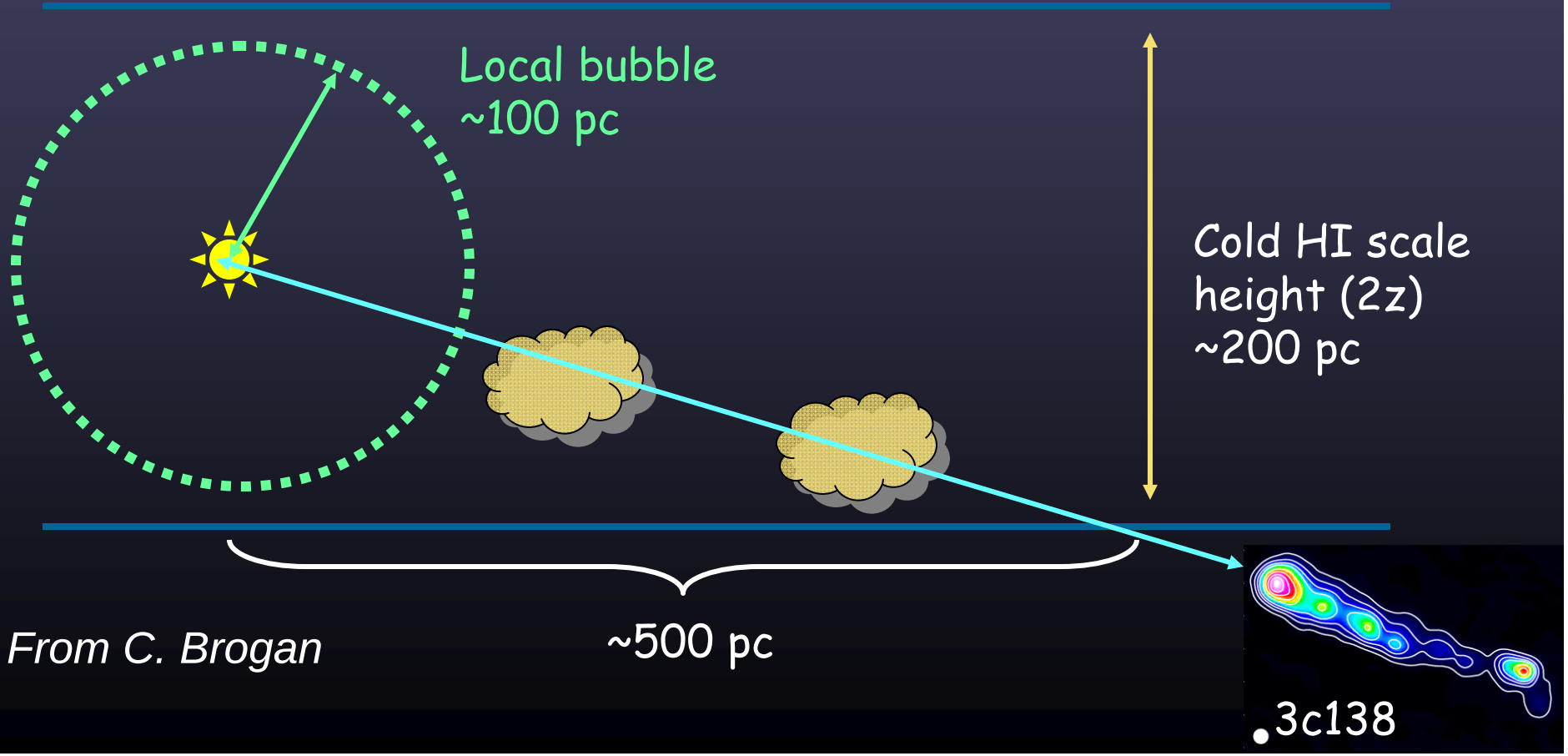


→ radio studies: particle energies, polarization, magnetic field orientation
→ VLA/VLBA pulsar proper motion can be combined with spin-axis orientation (X-ray)
→ Pulsar timing and discovery done with single dish radio telescopes – Parkes, GBT

Tour of the Galaxy: Interstellar

- HI absorption against bright sources

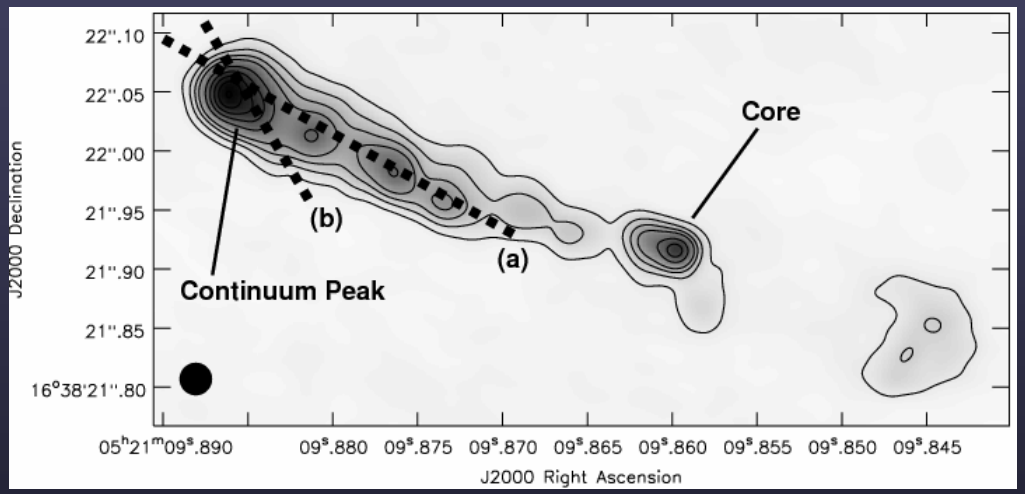
  - Interferometer resolves out Galactic HI emission features, allows the study of small-scale features

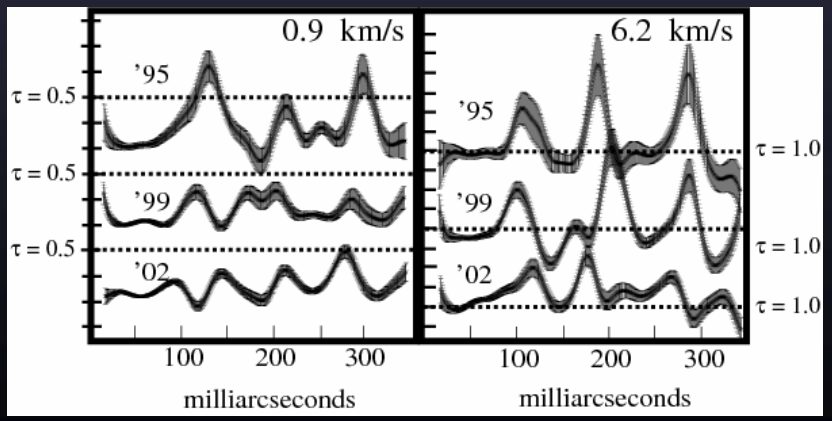


From C. Brogan

Tour of the Galaxy: Interstellar

- HI absorption toward 3c138





VLBA: '95, '99, 2002

Resolution: 20 mas = 10AU at 500 pc

Changes in τ indicate changes in density of Galactic atomic gas

Sizescale of features **~ 25 AU!**

Brogan et al. (2005)

Tour of the Galaxy: Exotic

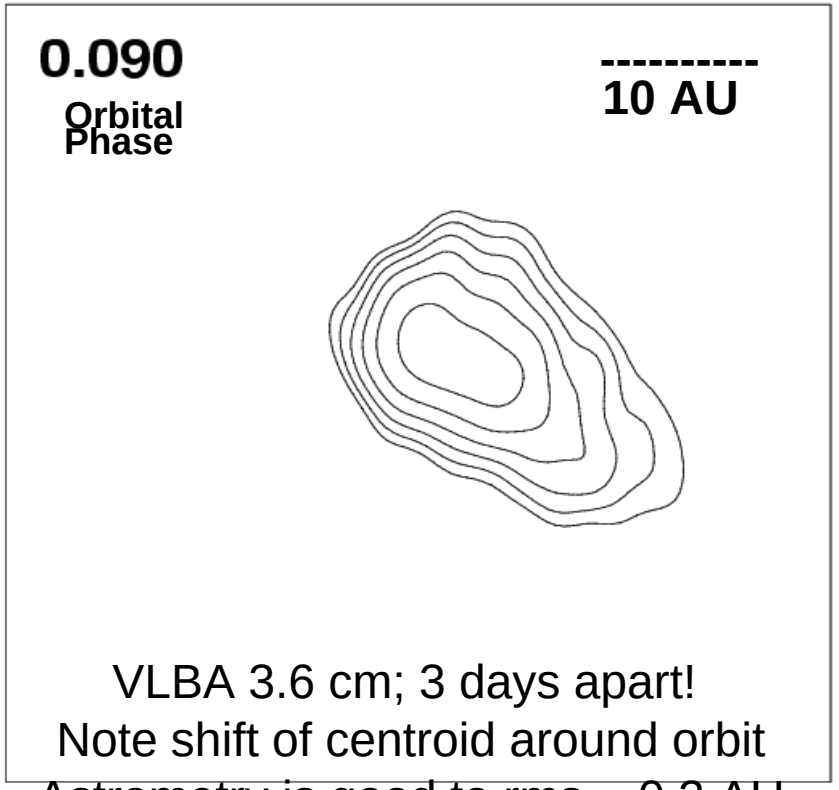
- LS I+61 303 : A pulsar comet around a hot star?

- well known radio, X-, γ–ray, source

- high mass X-ray binary with
12 solar mass Be star and NS

- radio emission models:
(a) accretion-powered jet or
(b) rotation powered pulsar

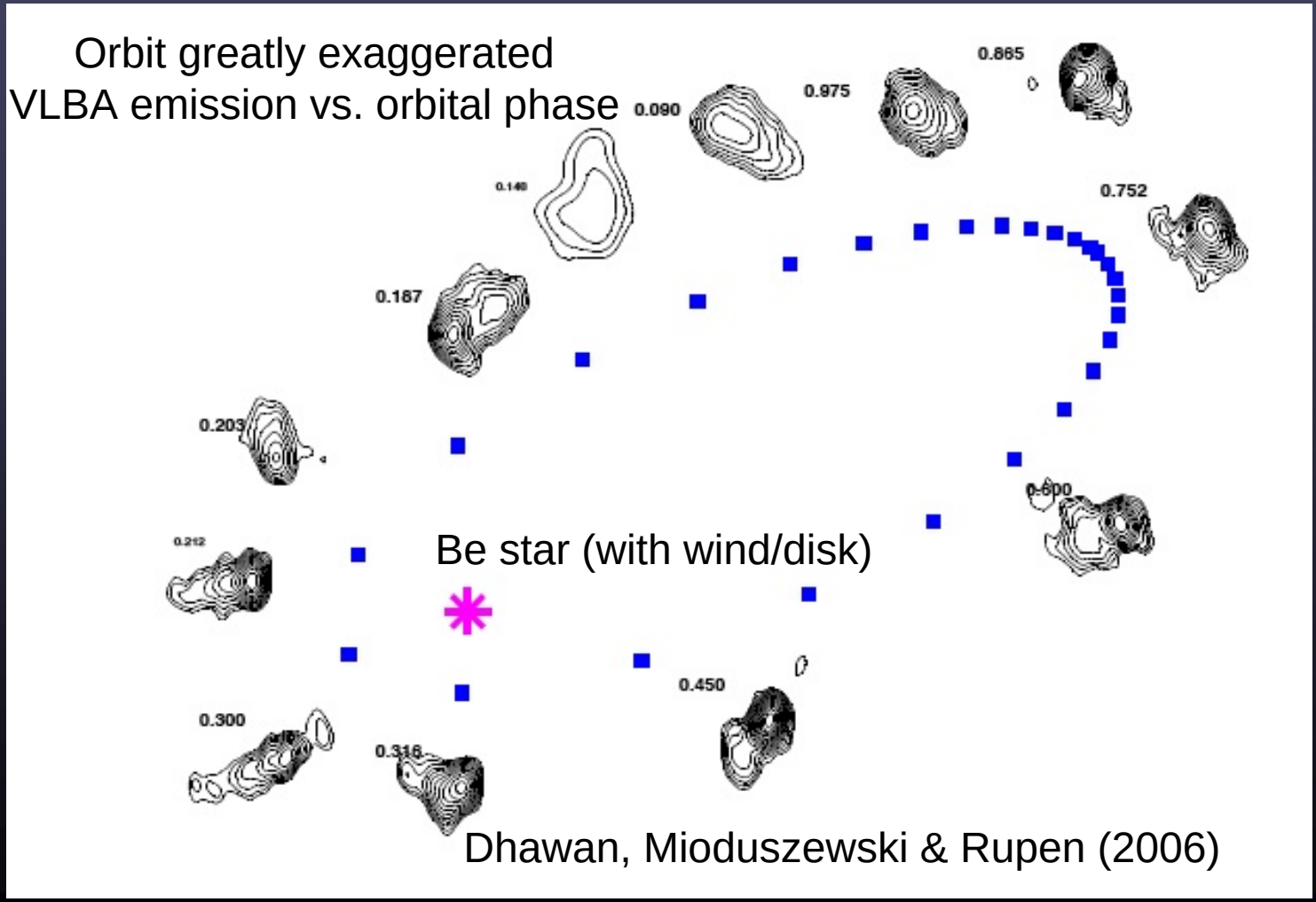
-VLBA data support pulsar model in which particles are shock-accelerated in their interaction with the Be star wind/disk environment



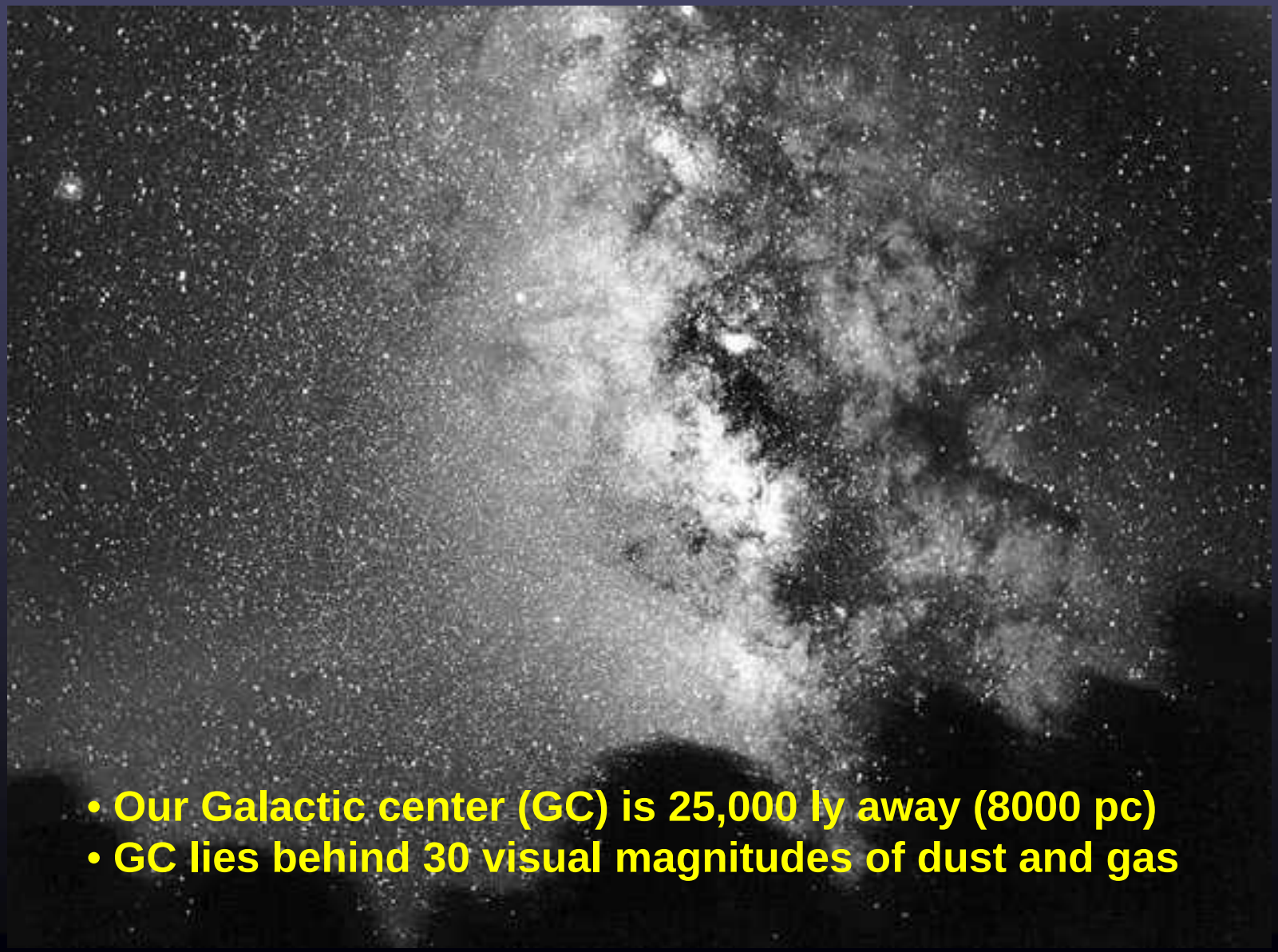
VLBA 3.6 cm; 3 days apart!
Note shift of centroid around orbit
Astrometry is good to rms = 0.2 AU
(Dhawan, Mioduszewski & Rupen 2006)

Tour of the Galaxy: Exotic

- LS I+61 303 : A pulsar comet around a hot star?

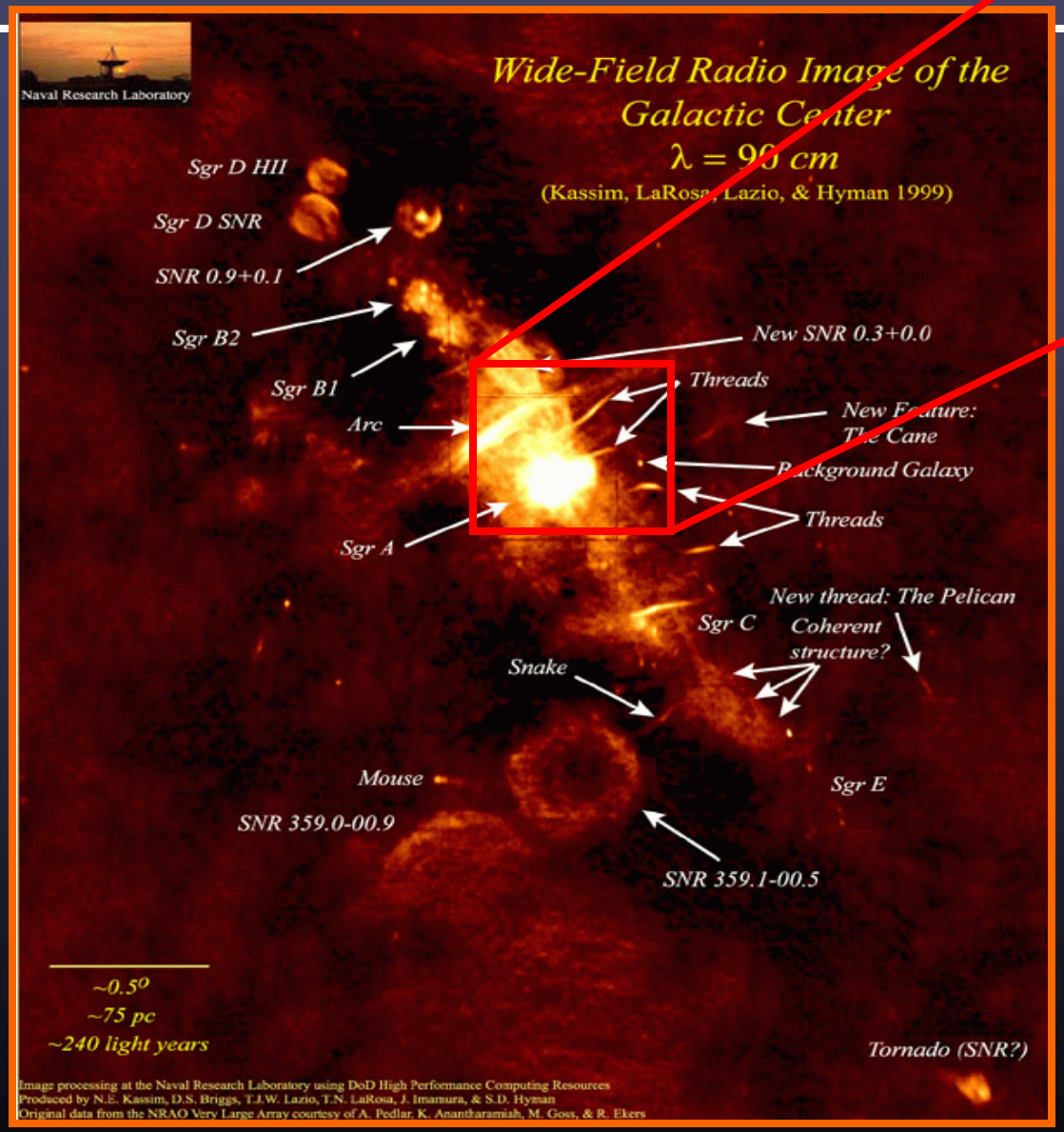


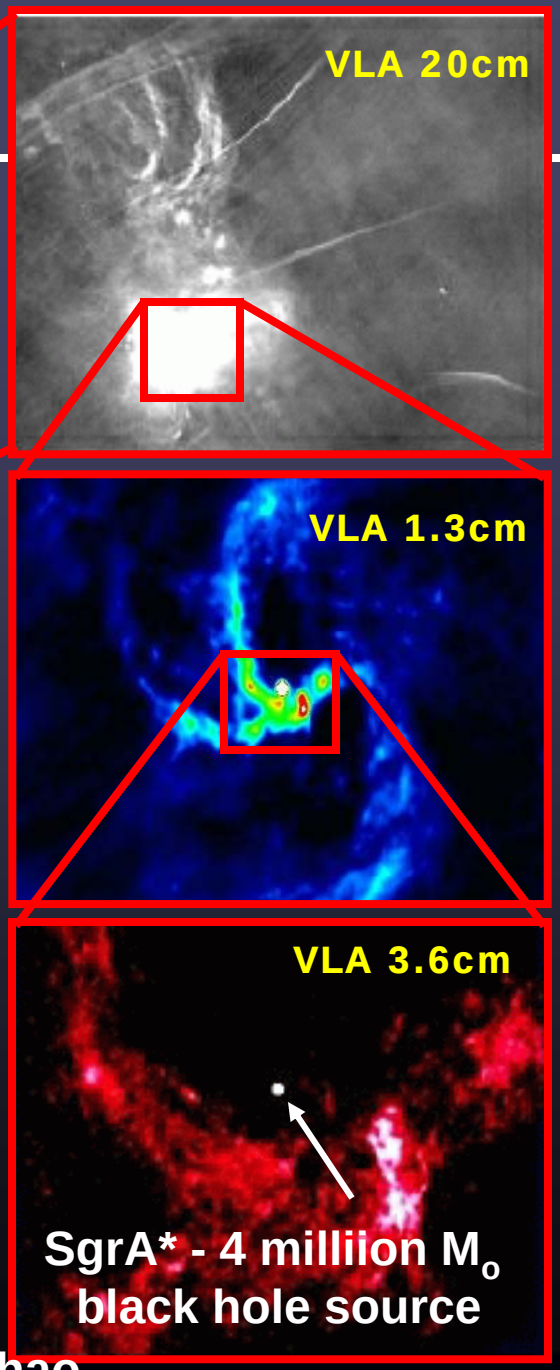
Tour of the Galaxy: The Galactic Center



- Our Galactic center (GC) is 25,000 ly away (8000 pc)
- GC lies behind 30 visual magnitudes of dust and gas

Center of our Galaxy

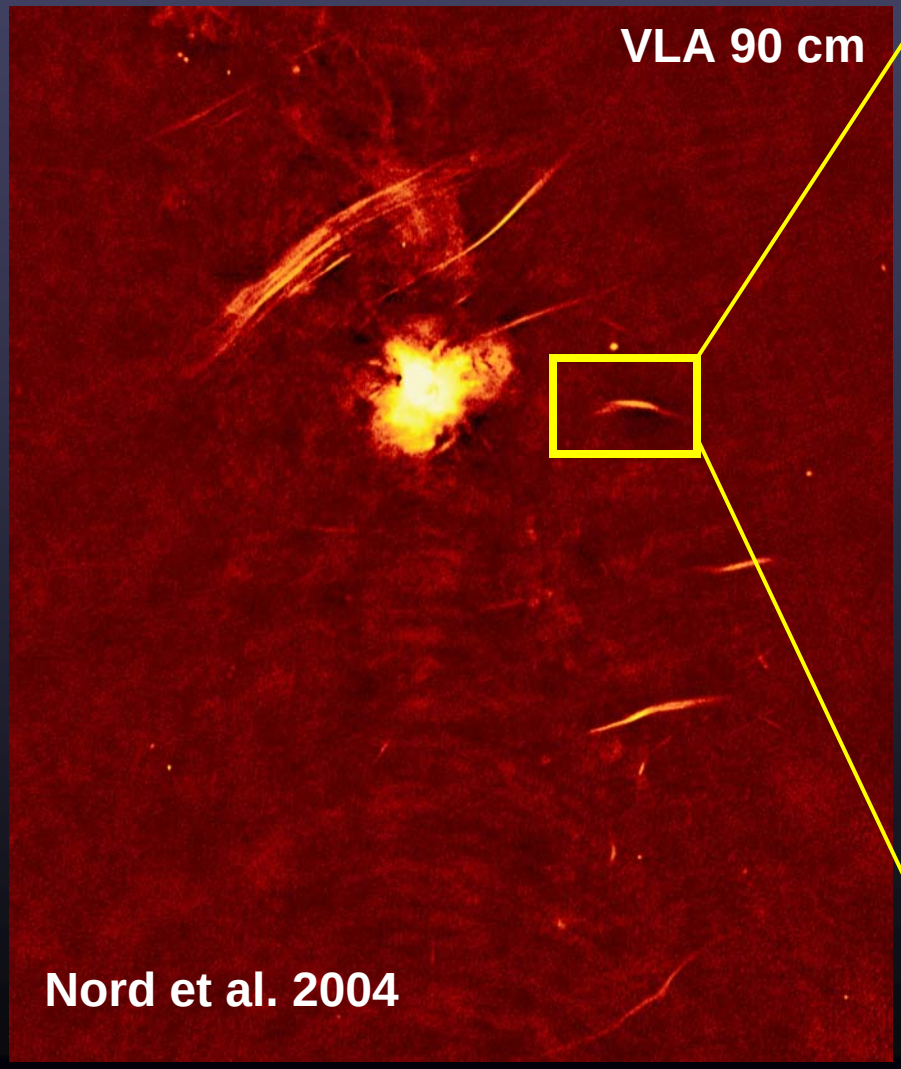


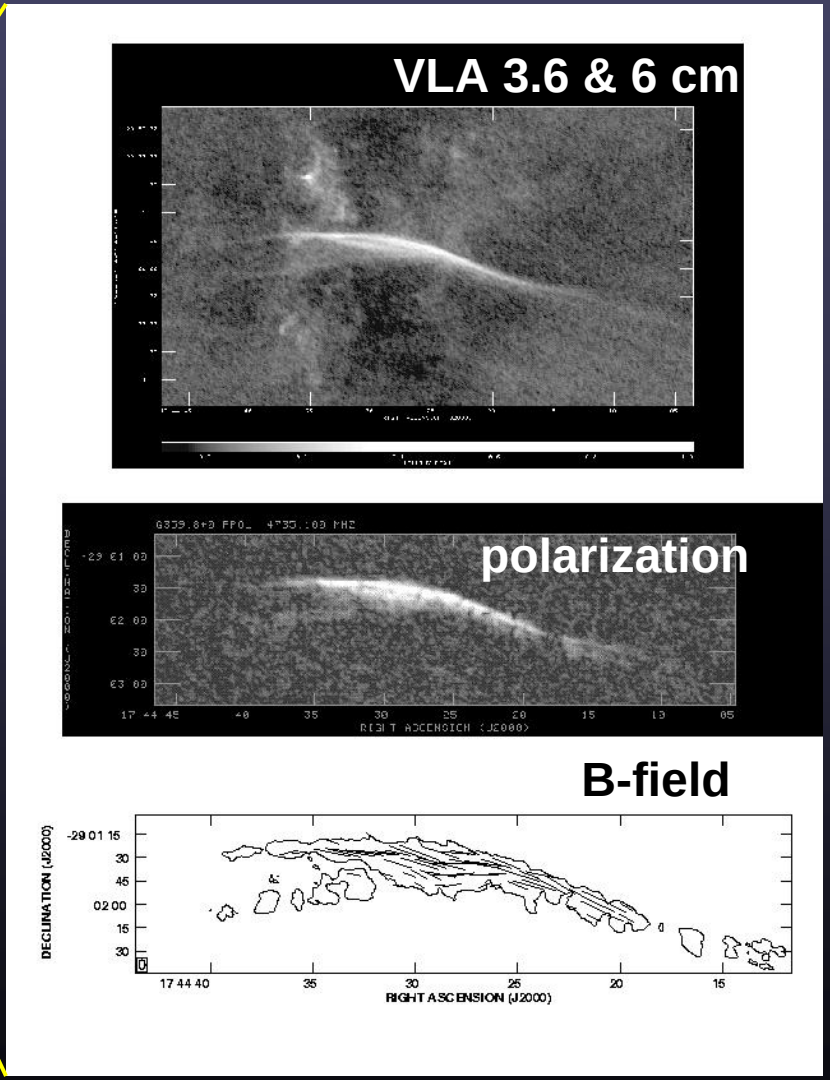


Credits: Lang, Morris, Roberts, Yusef-Zadeh, Goss, Zhao

Tour of the Galaxy: The Galactic Center

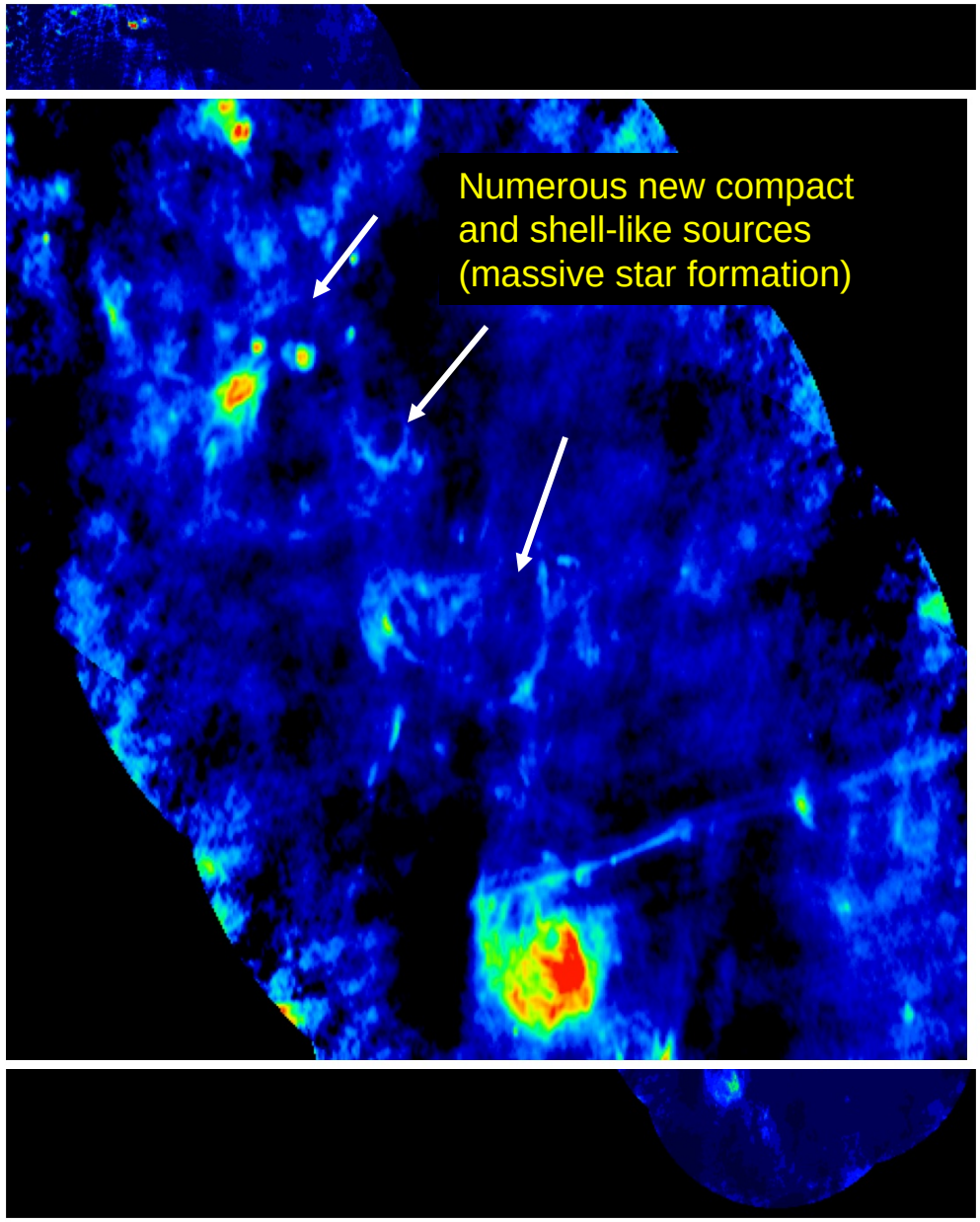
- Magnetic Field: Pervasive vs. Local?





Lang & Anantharamaiah, *in prep.*

Tour of the Galaxy: The Galactic Center



Galactic Center Survey

D and C array - 4.9 GHz
Full polarization
~1 hour per pointing

First high-resolution VLA polarimetric study on large scales!

Preliminary results
<--------- C-array
(Lang, Drout, Lazio and Golap, in prep.)

Summary

- Radio Interferometry: a powerful tool
  - Physical insight into many different processes
  - Spatial scales comparable or better than at other wavelengths: multi-wavelength approach

- A great time for students & interferometry!
  - Amazing science opportunities with new tools