

The Fossil Nuclear Outflow in the Central 30 pc of the Galactic Center

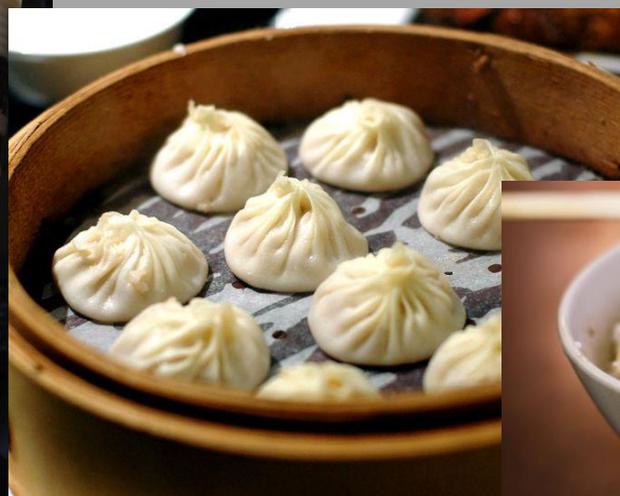


Pei-Ying Hsieh

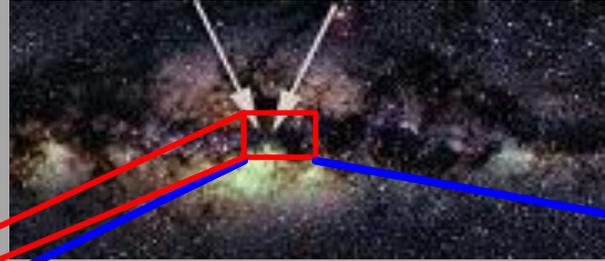
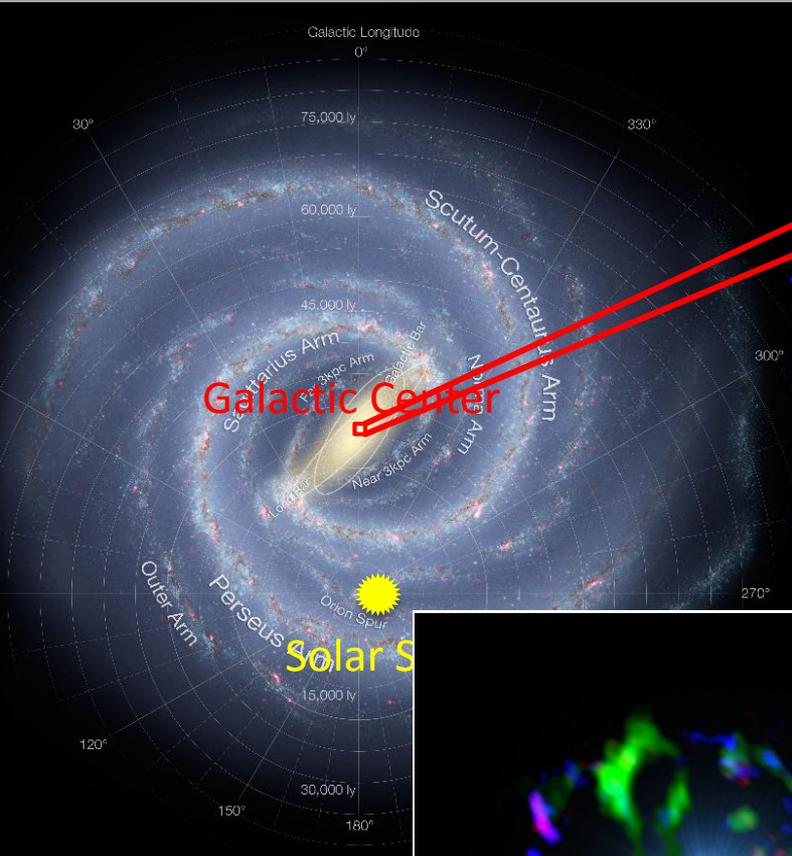
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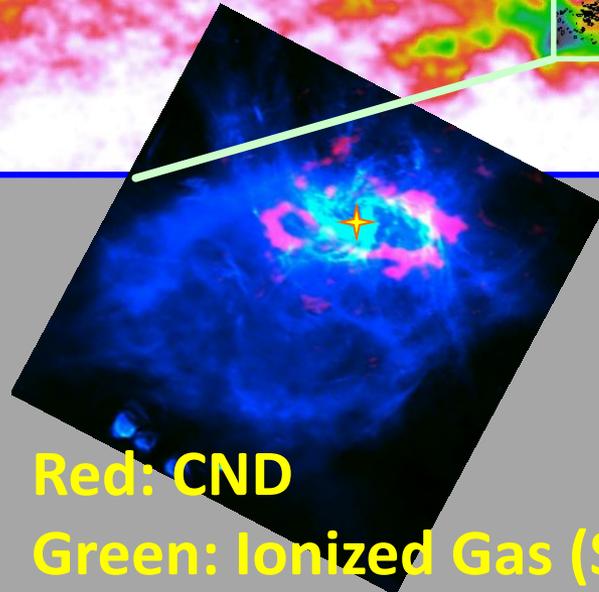
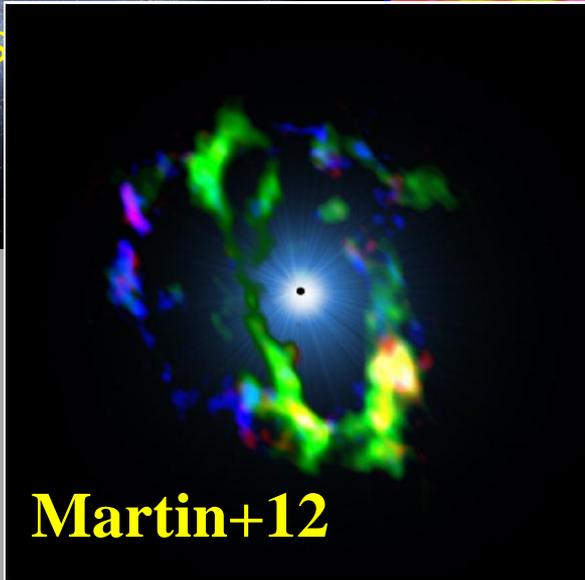
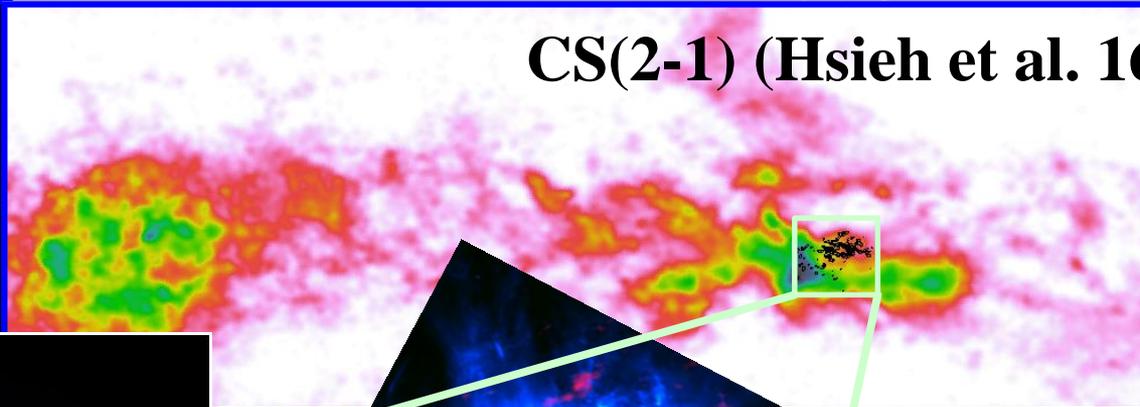
From black hole to environmental galaxy evolution across multiple
wavelengths, Canberra, 2017 Aug



The Center of the Milky Way

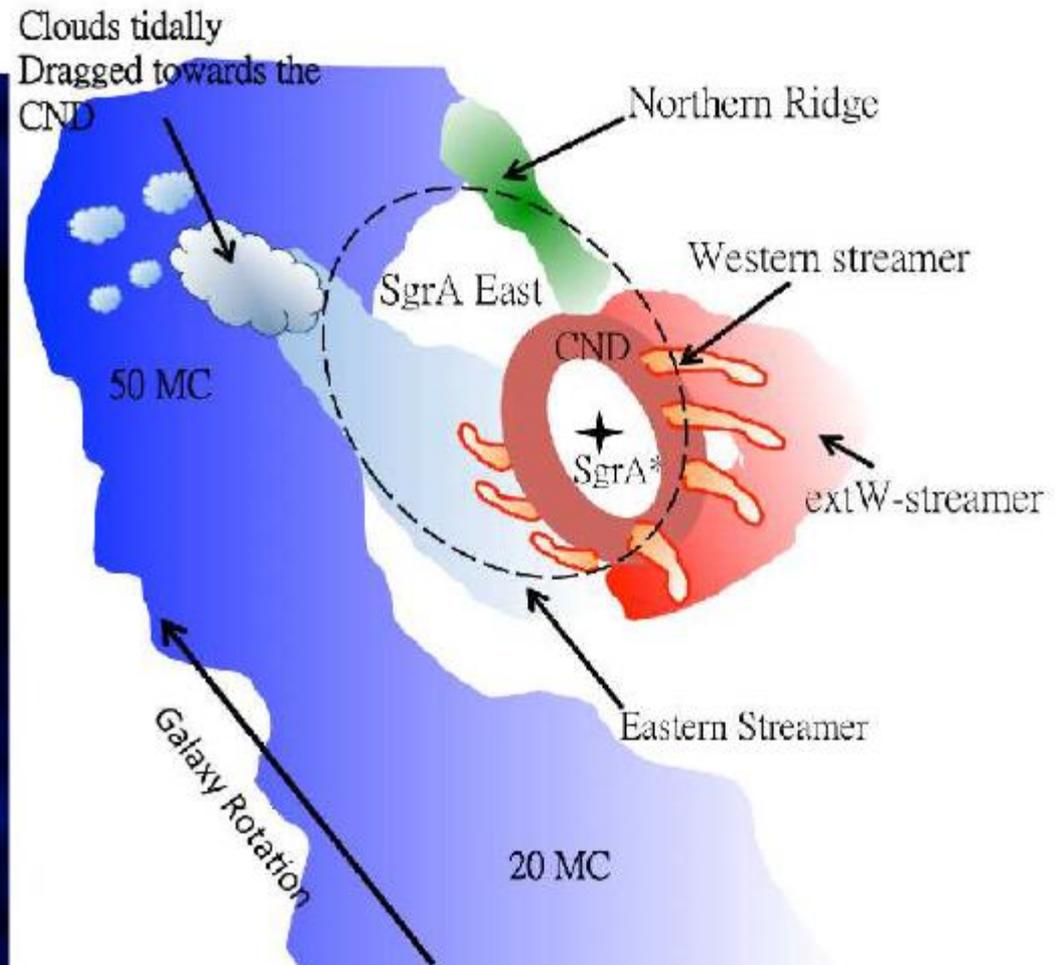
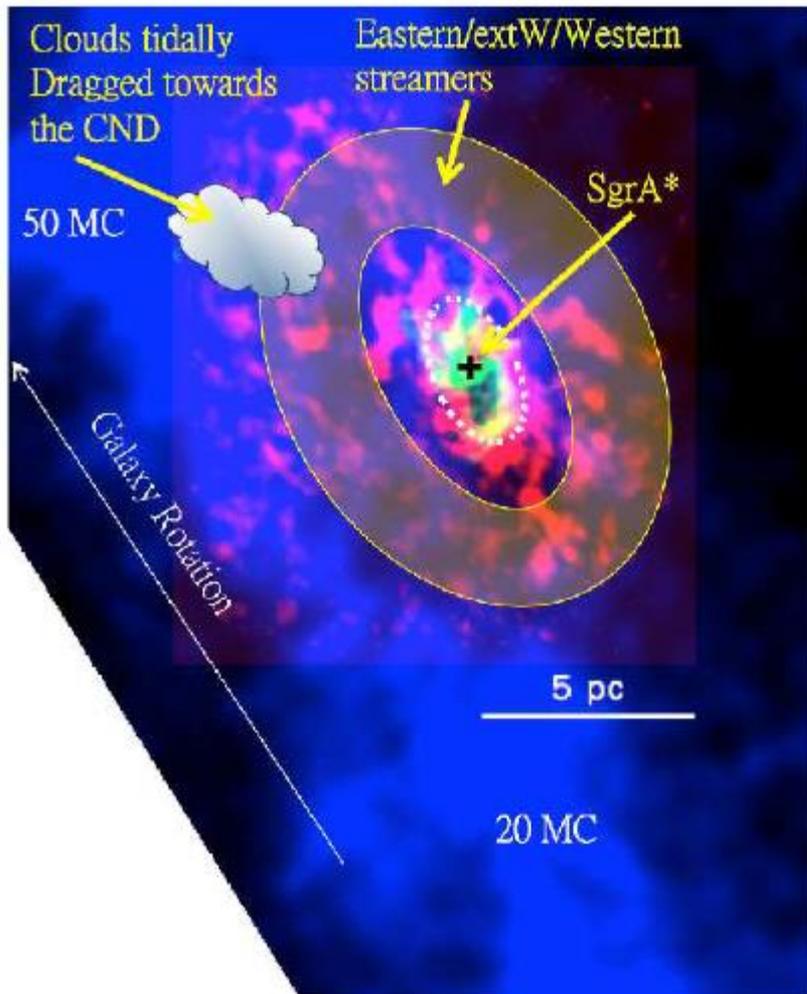


CS(2-1) (Hsieh et al. 10)



Red: CND
Green: Ionized Gas (Sgra West)
Blue: 20 cm continuum (SNR)

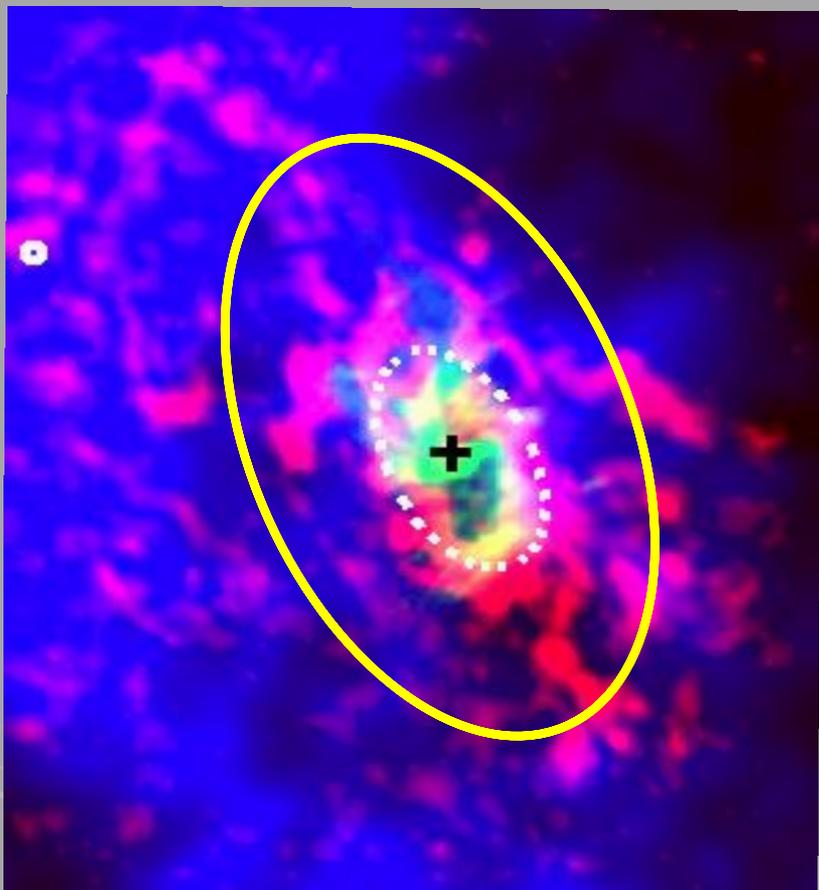
Gas Feeding System in the GC



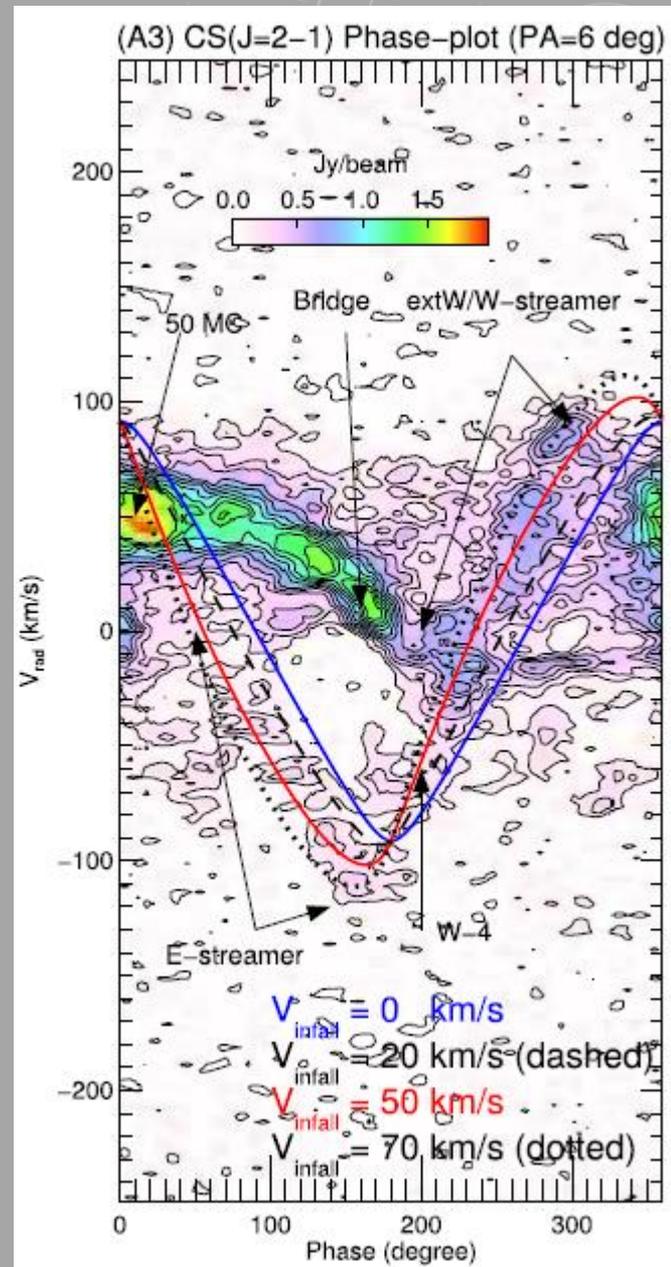
Hsieh+17a, ApJ in press

Phase plots of the accreting streamers

- Rotation plus inward motion.
- Magnetic field - gas dynamics (Hsieh+17b, in prep.)



Hsieh+17



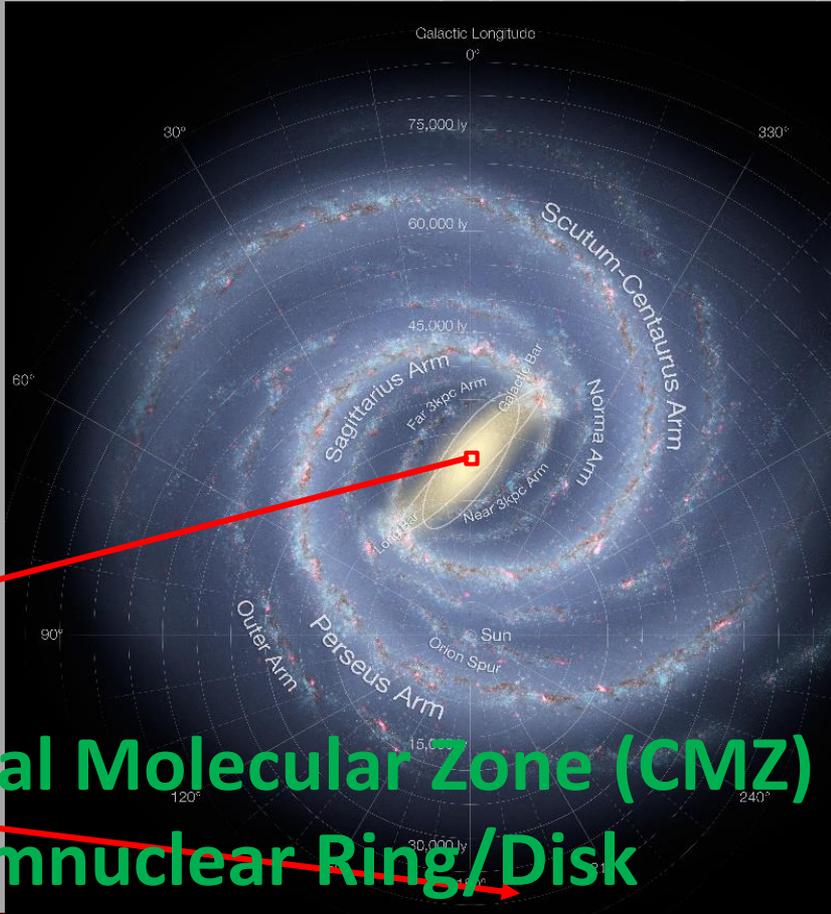
The Best Lab for Galactic Nuclei at sub-pc scale

Big picture of galaxy evolution:

- **Dynamics** - How does the gas approach SMBH from kpc to pc? How does the gas lose angular momentum? Last pc problem. (We don't know not even at 10 pc)
- **Material** - Which material is feeding SMBH? How many percent of the gas will be converted to star formation? How do we parameterize the competition of SF and BH fueling?
- The Galactic Center: $0.4 \text{ pc} = 10 \text{ arcsec}$
- galaxy at distance of 14 Mpc: $0.4 \text{ pc} = 0.006 \text{ arcsec}$
- 1700 times difference

Milky Way - Barred Galaxy

- Gas inflow -> Central Molecular Zone (CMZ), SF, driven by bars and nuclear bars, fueling AGN/SF
- Extinction by 30 magnitude in optical
- Better resolution

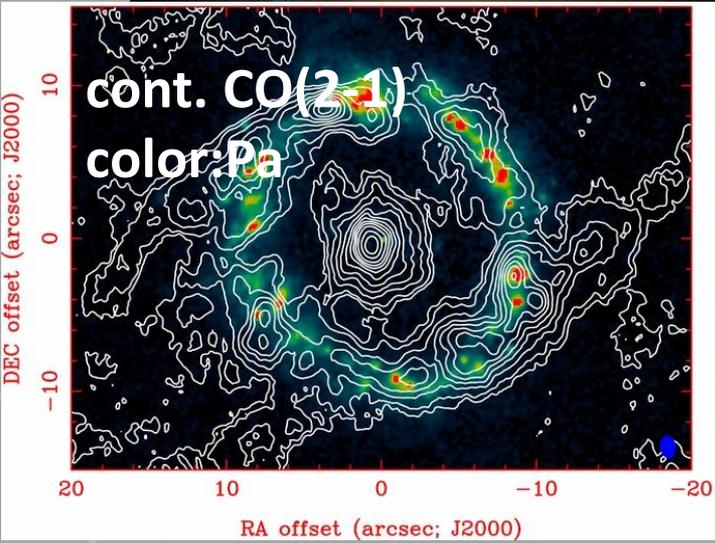
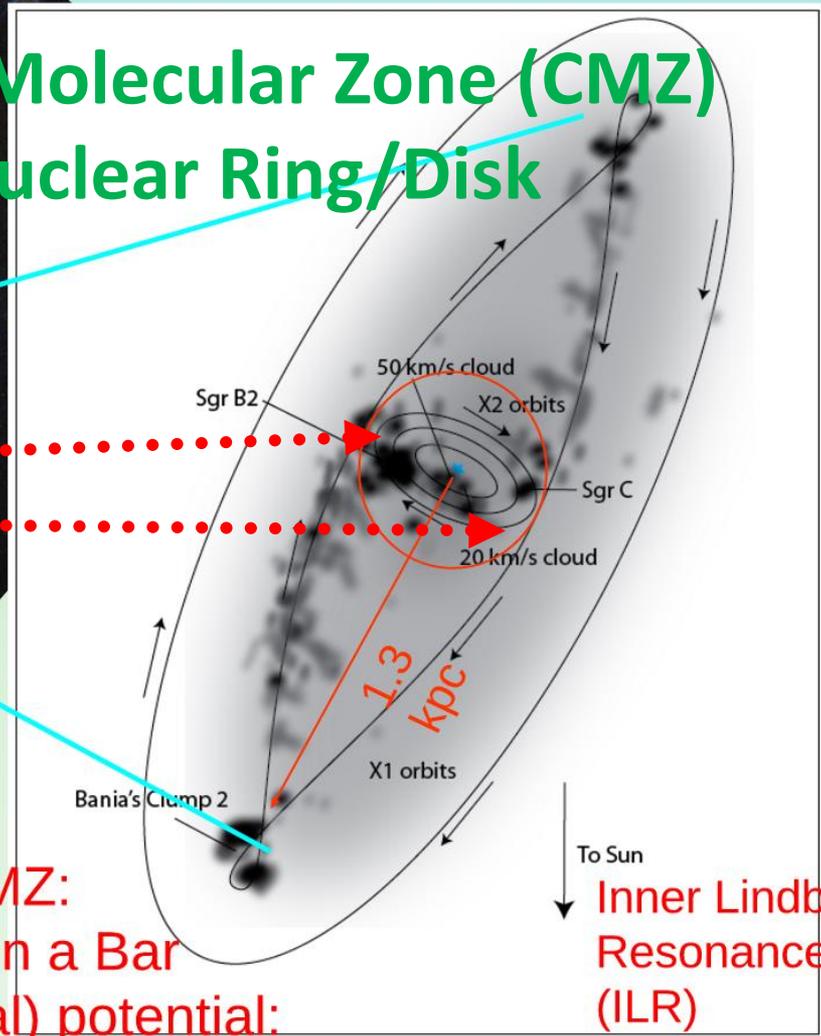


- Central Molecular Zone (CMZ)
- Circumnuclear Ring/Disk
- Torus



GC v.s. NGC 1097 extragalactic CMZ

- Central Molecular Zone (CMZ)
- Circumnuclear Ring/Disk
- Torus



the CMZ:
 orbits in a Bar
 (tri-axial) potential:
 1 vs. x2

Next: arm 1,2,3,4

R ~ 450 pc

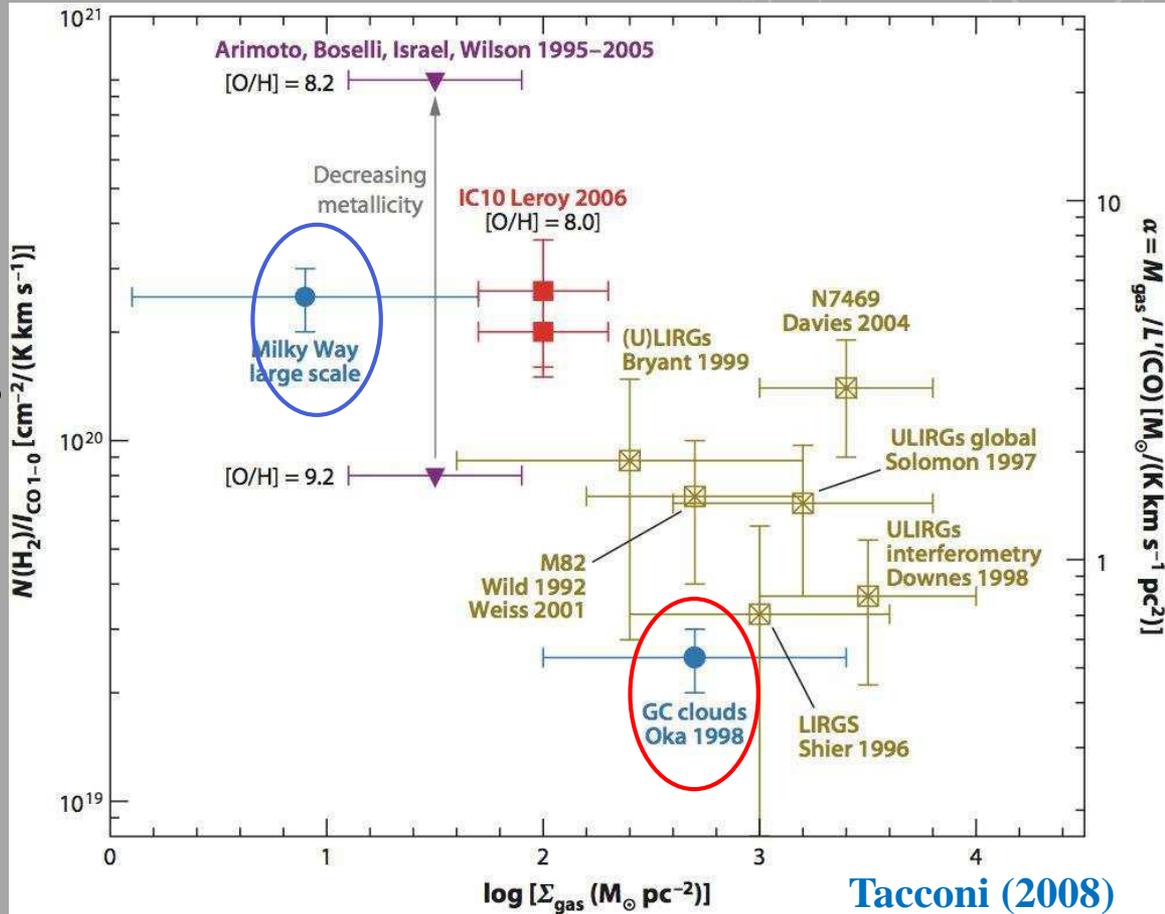
Hundred-pc Molecular Concentration - Central Molecular Zone

The CMZ has similar surface gas density and conversion factor to that of (U)LIRGs.

The physical properties of the GC is different from the disk gas.

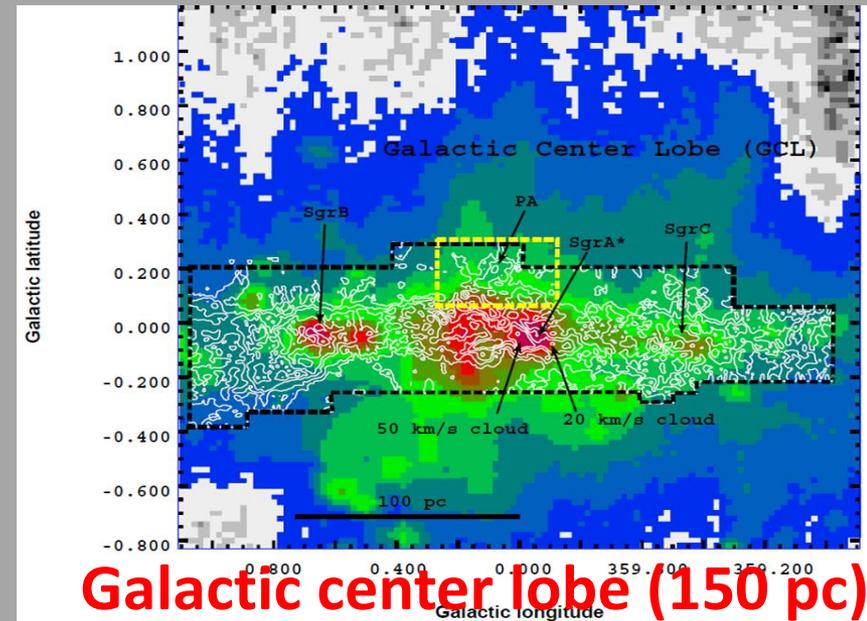
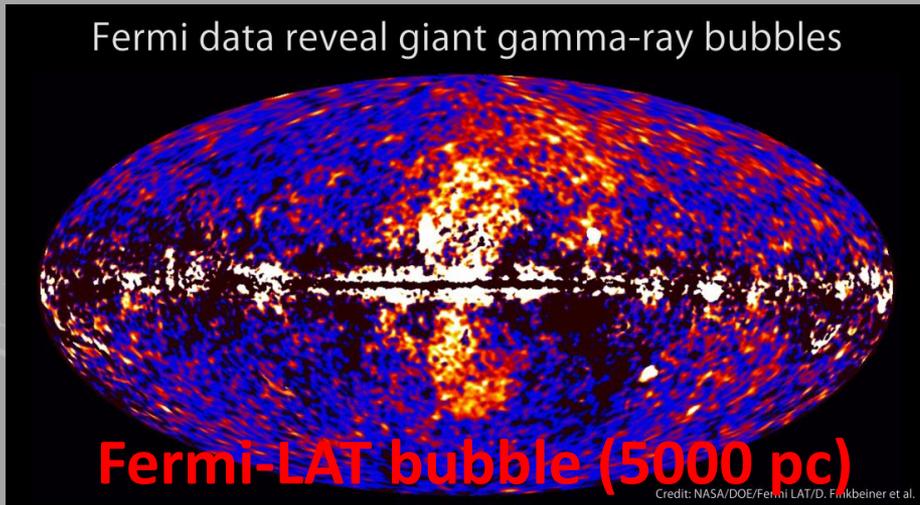
The GC accounts for ~10% of Milky Way's molecular gas content.

Dense ($n > 10^5 \text{ cm}^{-3}$), warm ($T > 80\text{K}$).

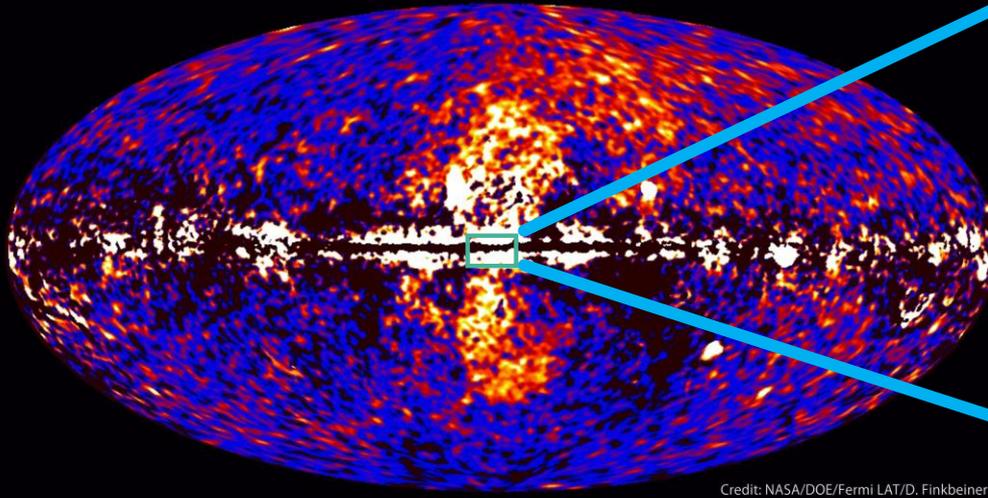


Quiet Nucleus: being quenched or periodic activity?

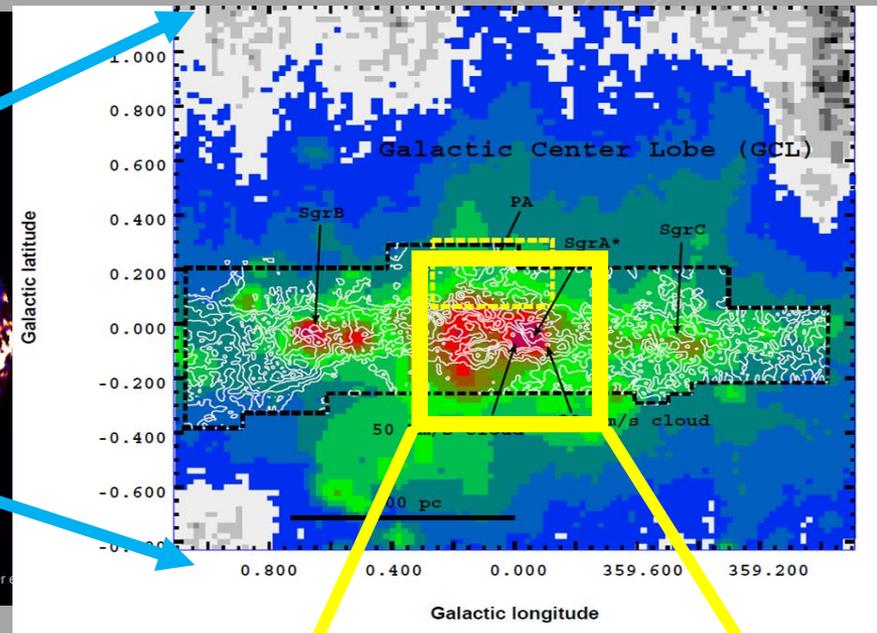
- The SgrA* is dim (10^{-9} times the Eddington luminosity) (e.g. Genzel+10).
- The SFR is 10 times lower than expected from the high molecular surface density (e.g., Longmore+13)
- Hints of recent activities, GCL (Sofue-Honda, Bland-Hawthorn+03), X-ray echo (Koyama+96), Fermi bubble confined by the CMZ (Su+12), Magellanic Stream (Bland-Hawthorn+13), etc.
- Quenching process



Fermi data reveal giant gamma-ray bubbles



Credit: NASA/DOE/Fermi LAT/D. Finkbeiner et al.



- Brightest super-bubble in Galaxy at 24 μm
- Arches, Pistol clusters, Sgr A East SNR

Bubbles from 5000 pc to 30 pc?

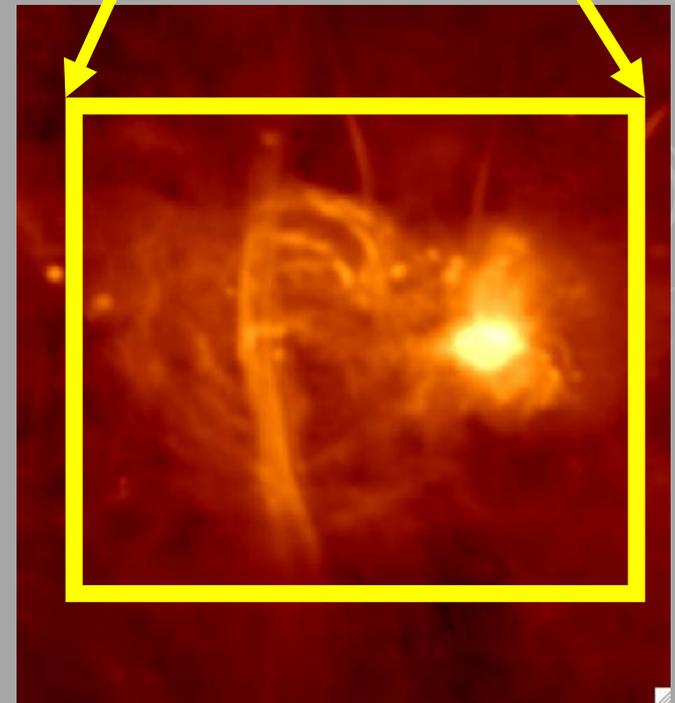
Sgr A East: 1 pc

GCB: 30 pc

Galactic center lobe: 150 pc

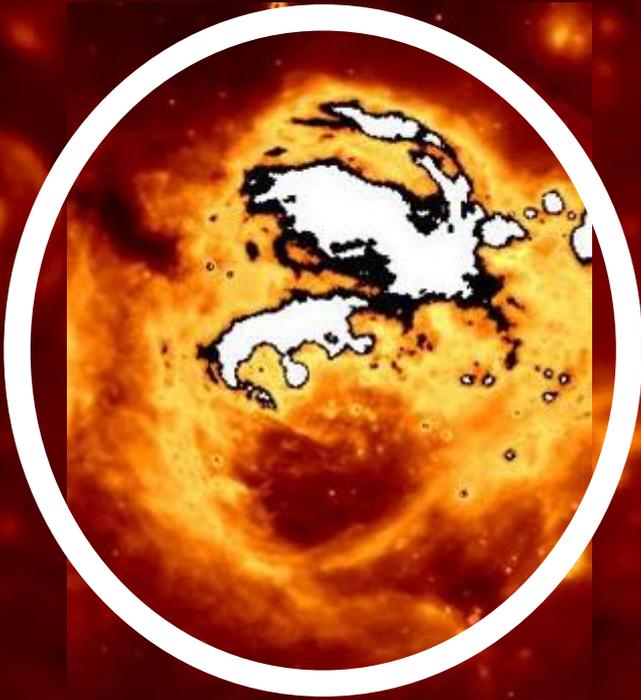
Fermi bubble: 5,000 pc

A weak 'nuclear wind' ? / Star formation or SMBH ?

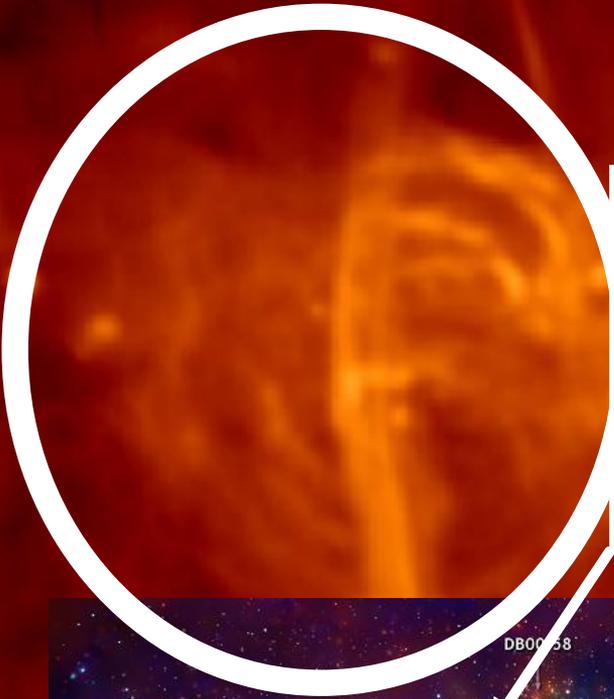


Central 30 -50 pc - Galactic Center Bubble, bipolar halo

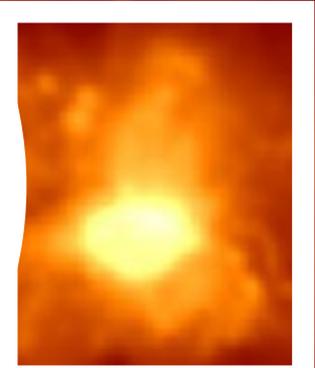
Spitzer 24 micron



Galactic center bubble



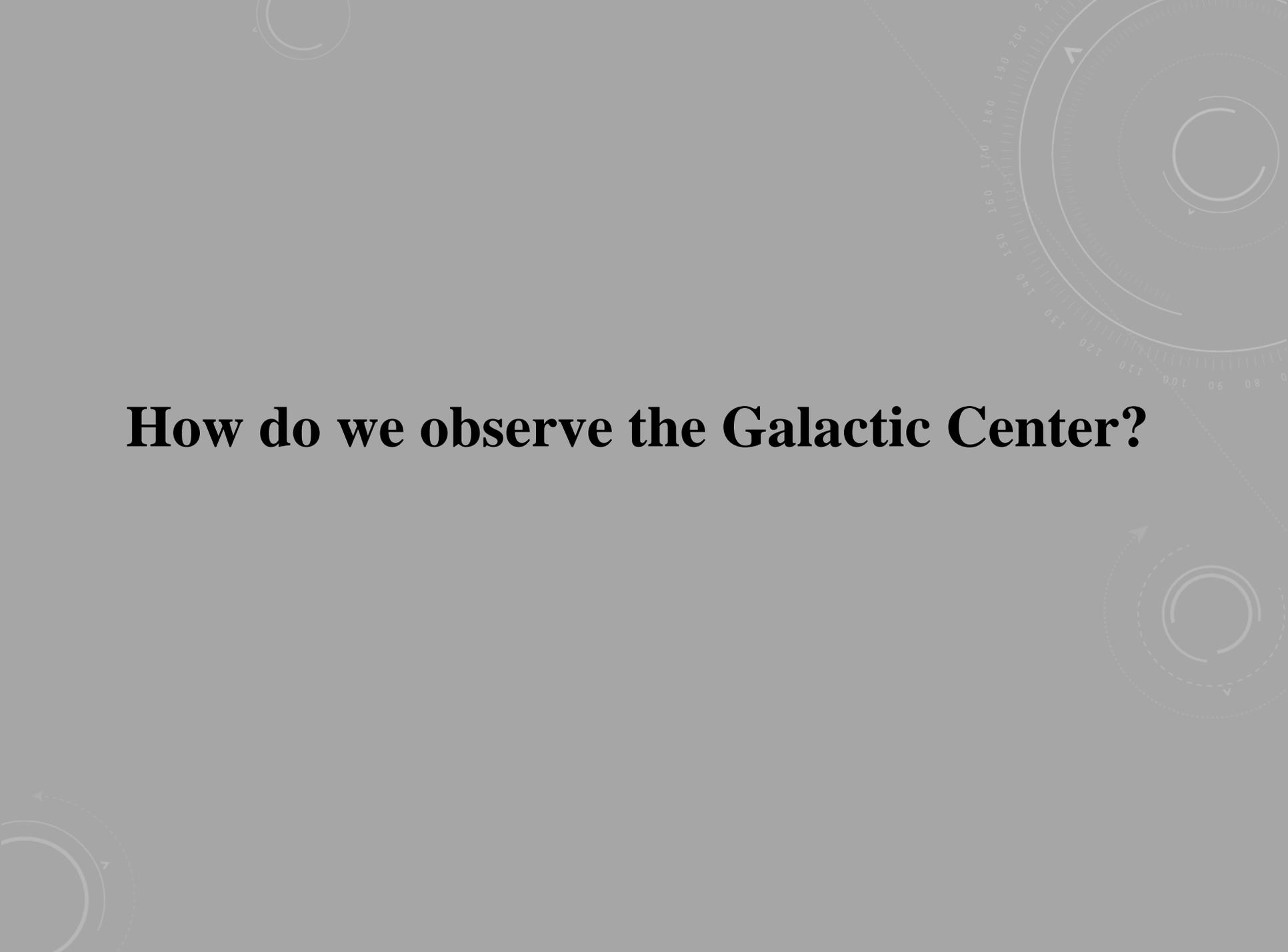
Bi-polar lobes
~ -30 pc



Yusef-Zadeh+04

Image credit: NASA

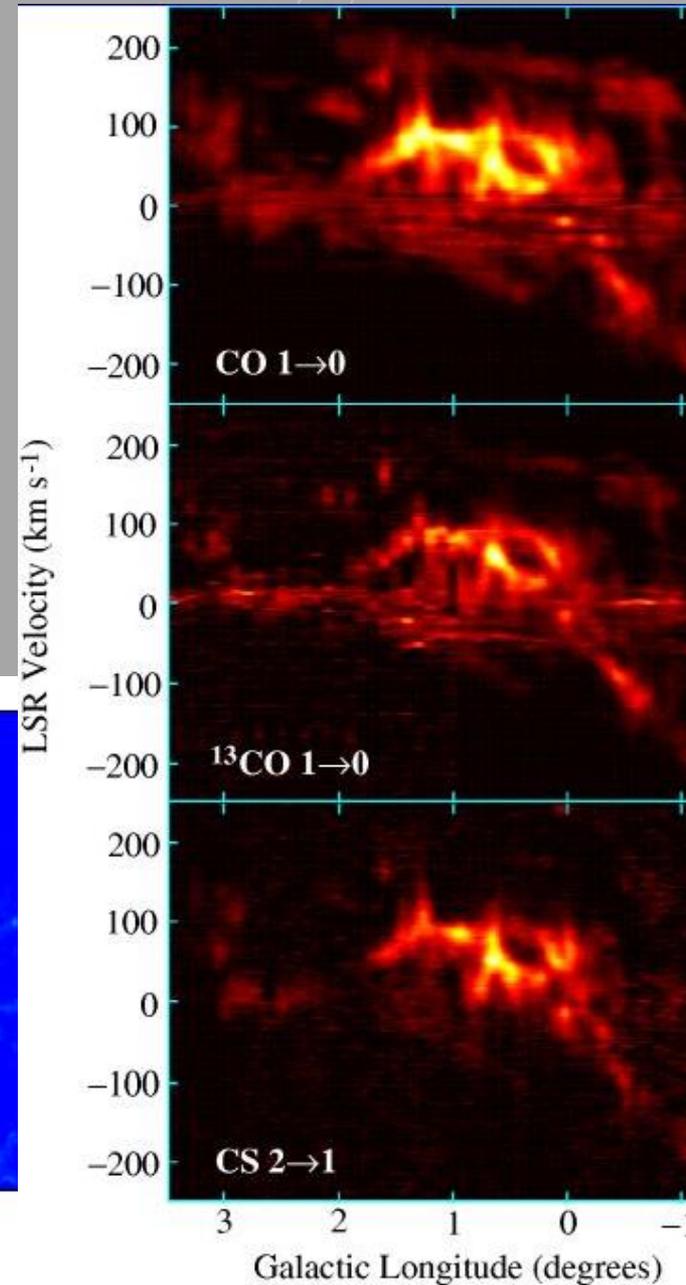
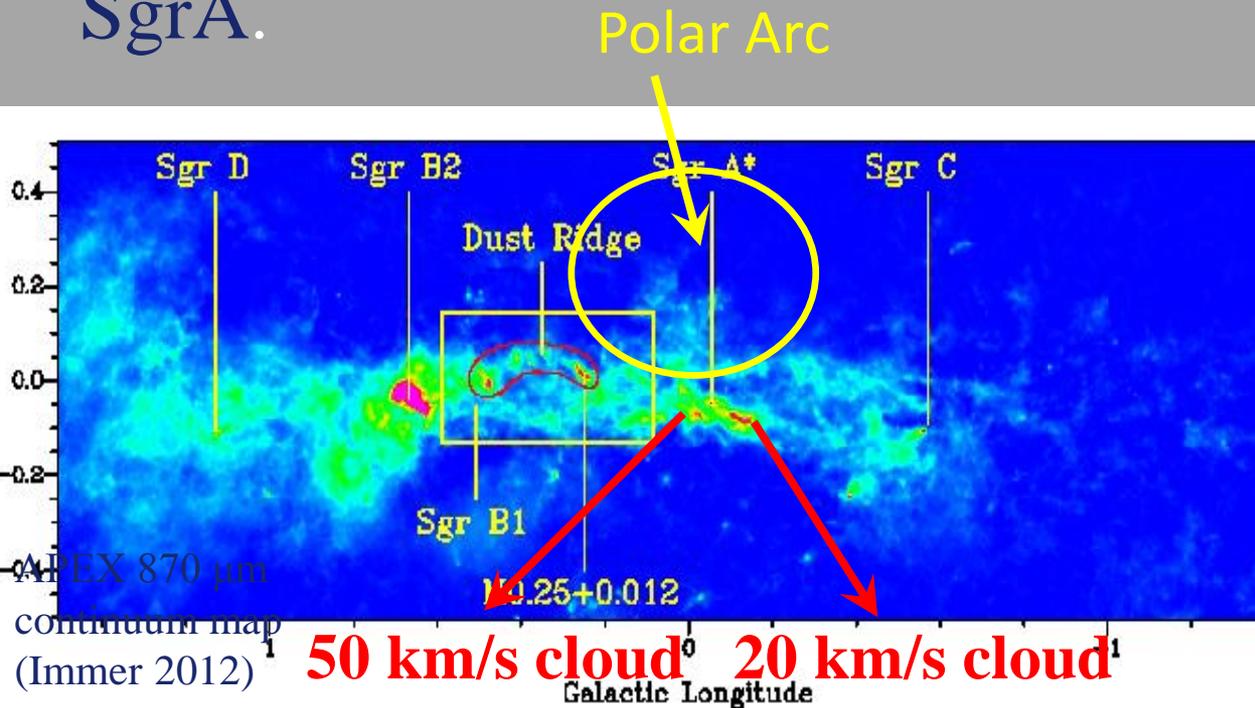
How do we observe the Galactic Center?

The background features several faint, light-gray circular elements. In the top right, there is a large circular scale with numerical markings from 0 to 210 in increments of 10, and a dashed line with an arrow pointing clockwise. Below it is another circular diagram with concentric circles and arrows. In the bottom left, there is a partial circular diagram with an arrow pointing clockwise. The overall aesthetic is technical and scientific.

- **Single dish mapping (NRO 45m, CSO, JCMT)**
 - NRO 45m CS(2-1): Dense Nuclear Spirals in the Galactic Central Molecular Zone (PI: Hsieh, Pei-Ying)
 - CSO CS(5-4), CS(4-3): The inflow and outflow in the Galactic center (PI: Hsieh, Pei-Ying)
 - JCMT CS(7-6), SiO(5-4): (PI: Hsieh, Pei-Ying)
- **Interferometer: SMA, ALMA**
 - ALMA CS multiple transitions at band 3-7: 2017.1.00040.S (PI: Hsieh, Pei-Ying, rank A)
 - ALMA HC3N multiple transitions at band 3: 2016.1.00247.S (PI: Hsieh, Pei-Ying, rank B)
 - ALMA band 7, band 9 imaging: From cycle 0 to cycle 4 (PI: Ho, Paul, rank A)
 - SMA HCN(4-3), HCO+(4-3): From 2011 to 2013 (PI: Ho, Paul, rank A)

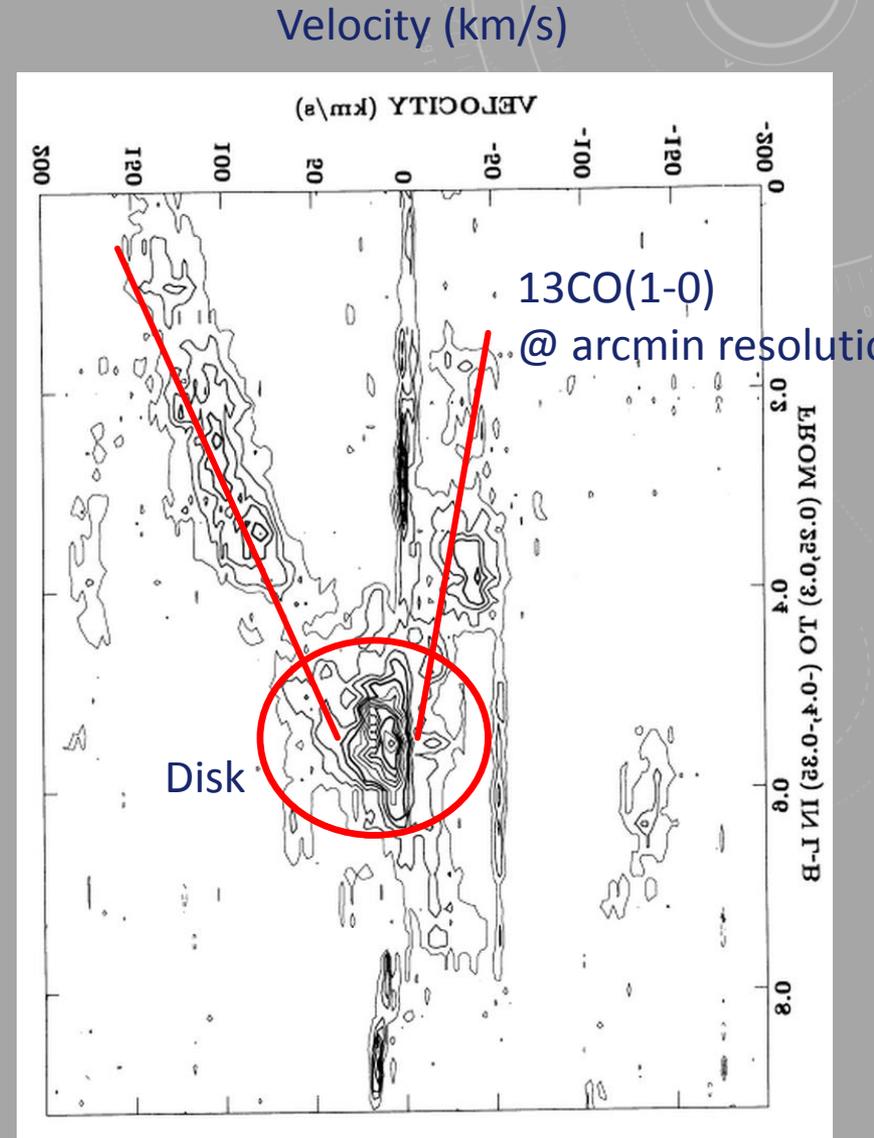
New Experiment: CMZ Probed by Carbon Sulphur (CS)

- CS(2-1): high-excitation tracer to eliminate the foreground emission (better than CO and HCN).
- The **Polar Arc (PA)** located above SgrA.



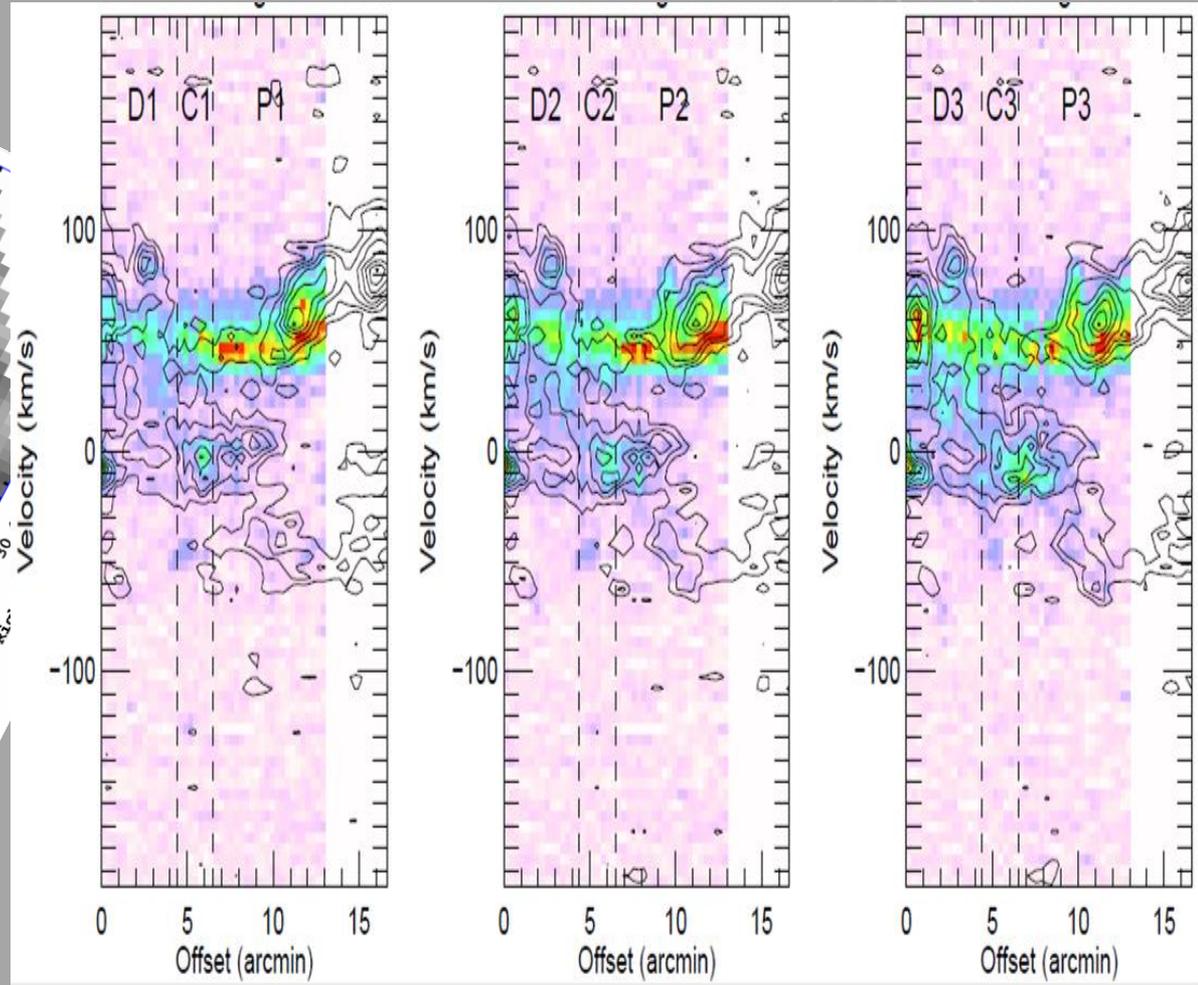
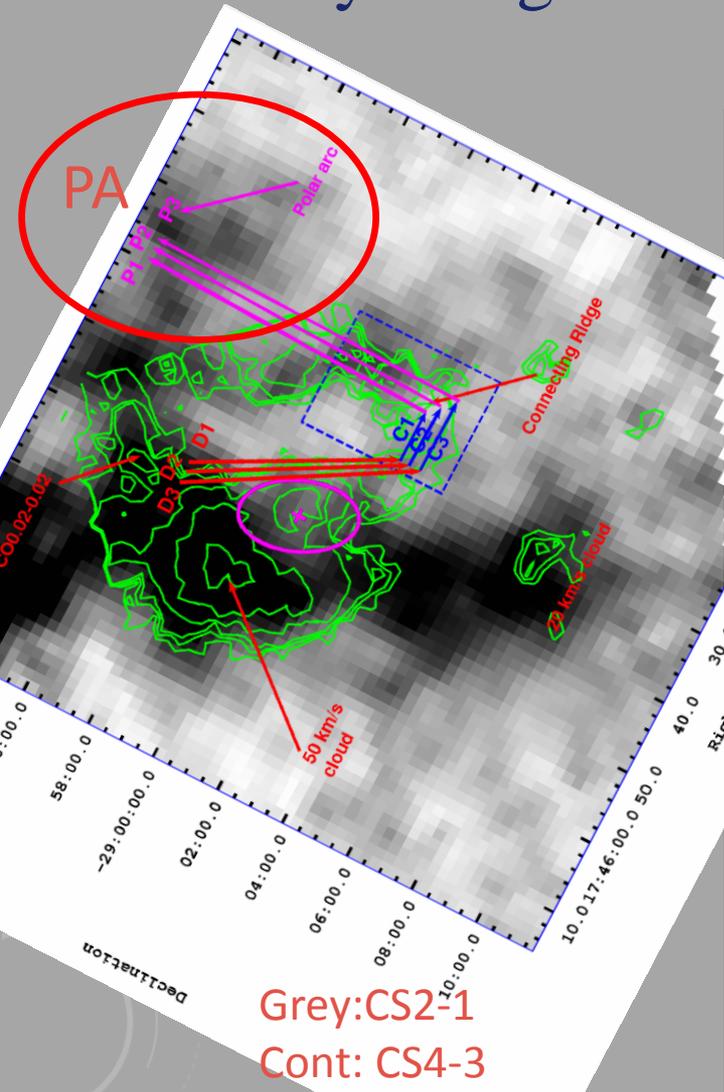
Is this Polar Arc related to SgrA*?

- Extended structure above SgrA region (13CO; Bally 88)
- Acceleration?
- Originated to SgrA region? – High resolution
- NRO 45m CMZ: CS(2-1), 20'' (0.76 pc)
- CSO 10m: 30-40'' CS(5-4), CS(4-3), SgrA region



CSO High-J CS experiment: The Connecting Ridge

- Turn over: Smooth connection of the PA and disk in velocity and geometry (Hsieh+15)

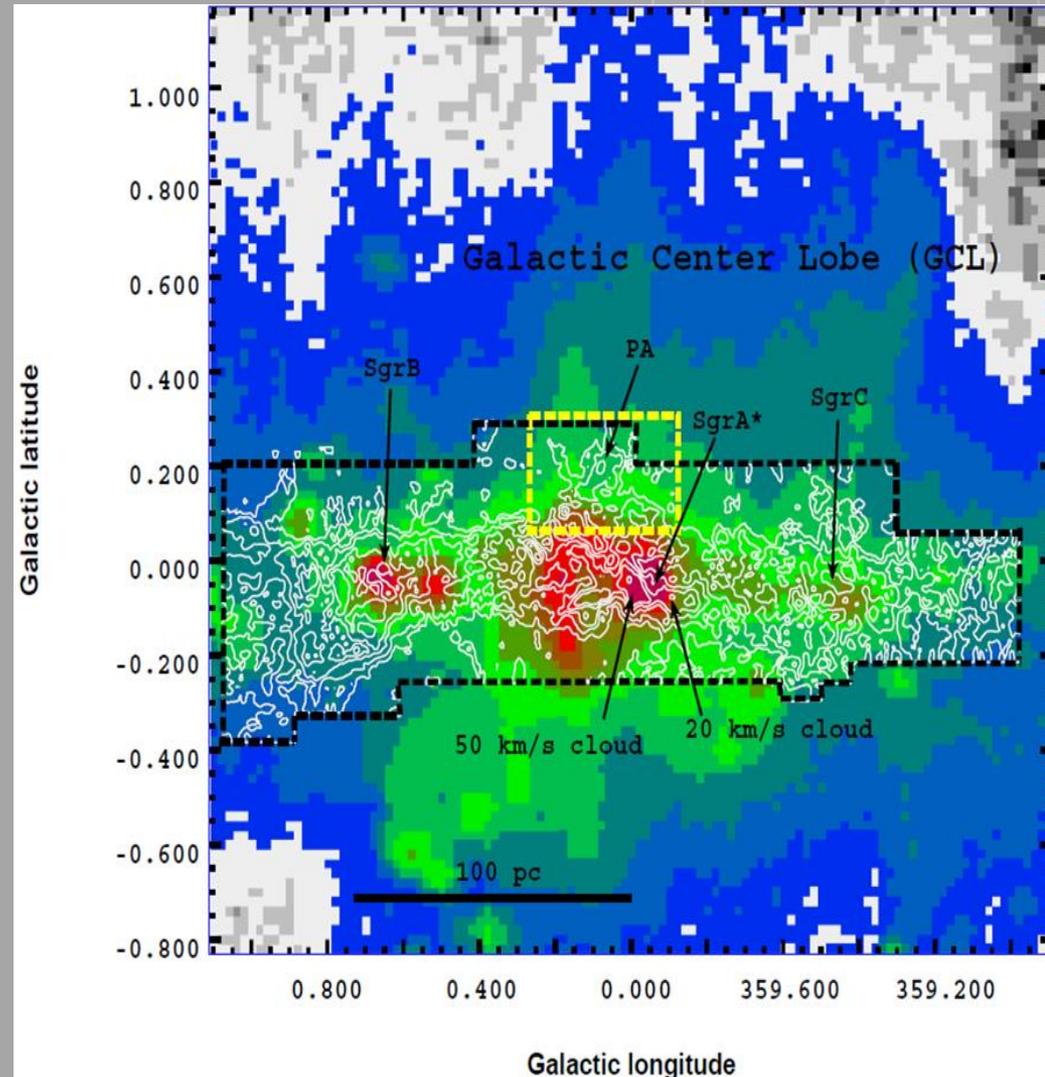


PA and the GCL: Launching point 6 M years ago

- The PA is the eastern protrusion of the GCL in consistent time scale (Bland-Hawthorn+03).

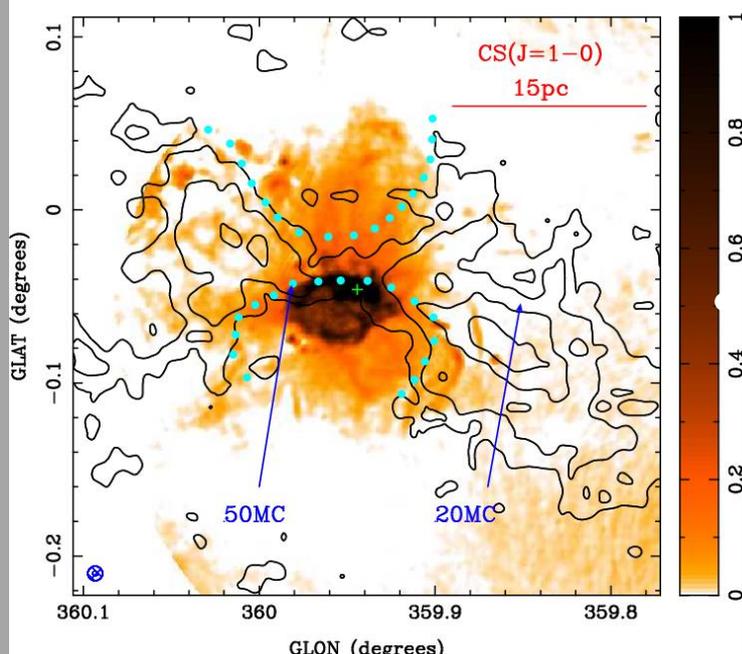
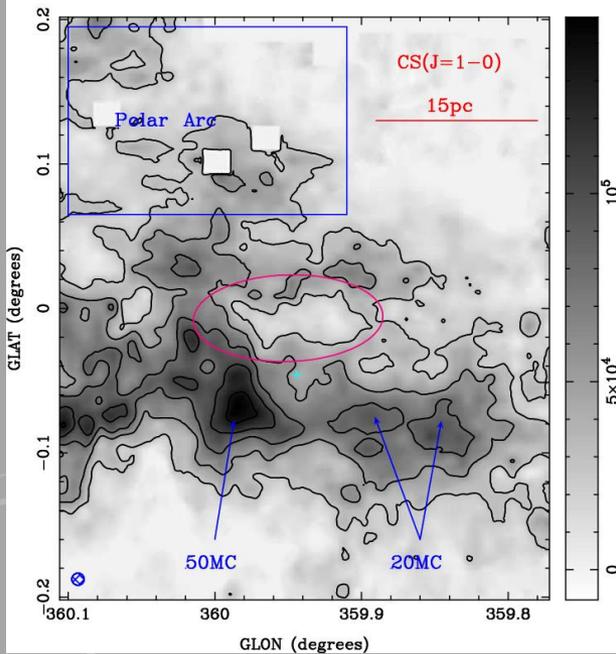
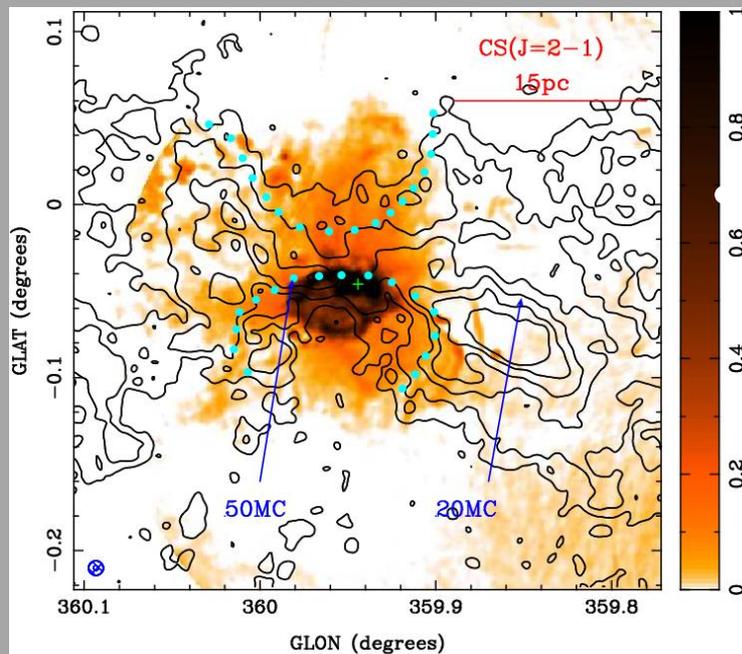
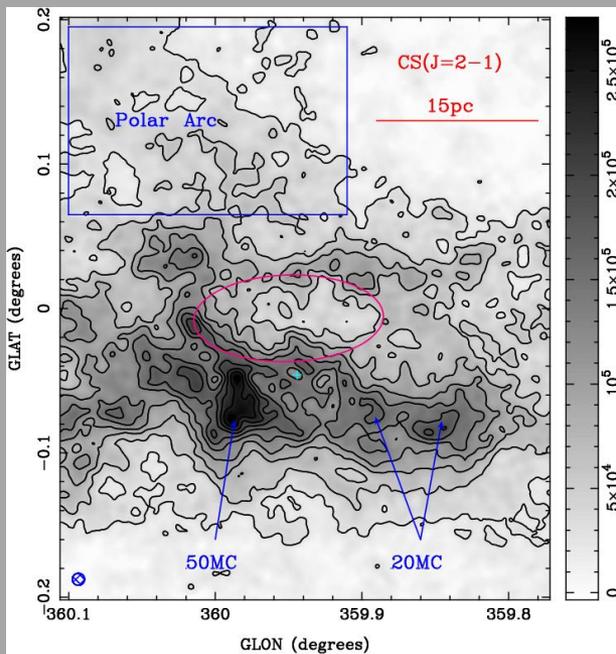
- The PA is lifted from the disk. **The orbit is altered.**

- Linewidth ~ 74 km/s, $T_{\text{ex}} \sim 20$ K, CS abundance $\sim 10^{-8}$
- $M_{\text{H}_2} = 1.5 \times 10^5 M_{\odot}$
- 20% to convert the supernova explosions into the ISM, ~ 8 supernova explosions.
- For the eastern protrusion of the GCL.



Hsieh+15

Integrated over ± 198 km/s Integrated over ± 10 km/s

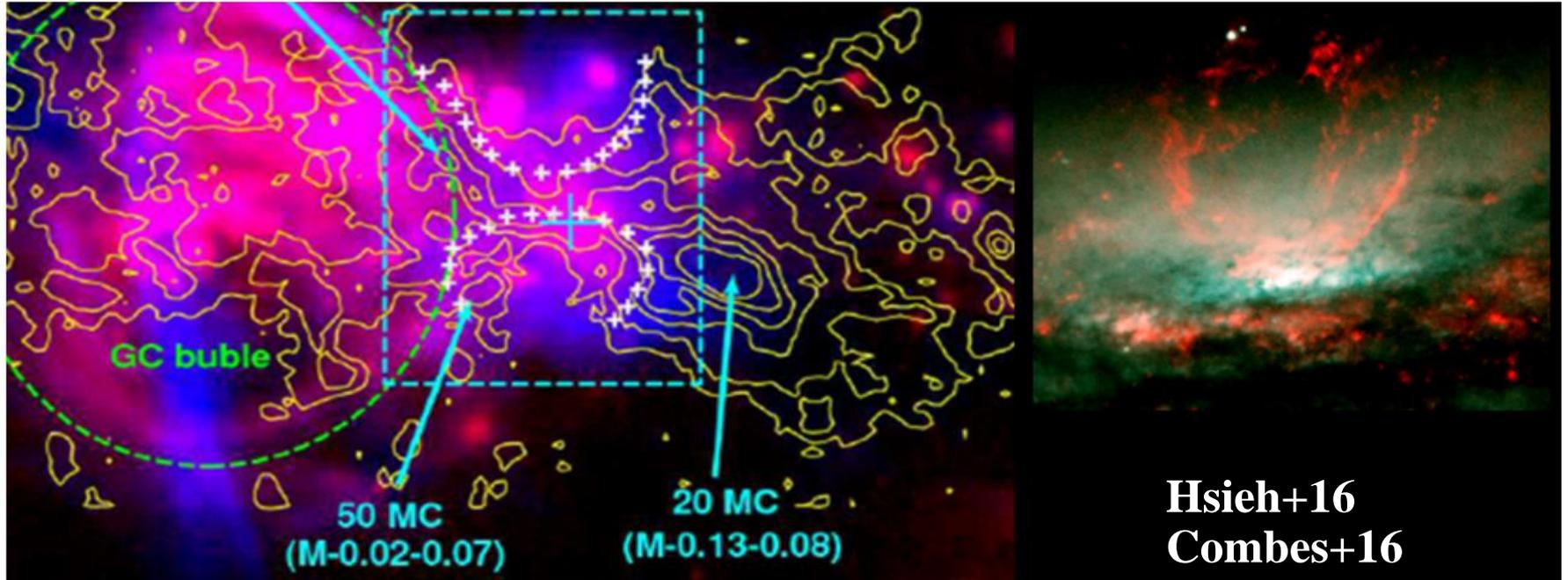


Low velocity
CS emission
surrounding the
20 cm radio
bipolar halo.
(Hsieh+16,
Tsuboi+99)

Hourglass-
shaped feature

Low velocity outflow?

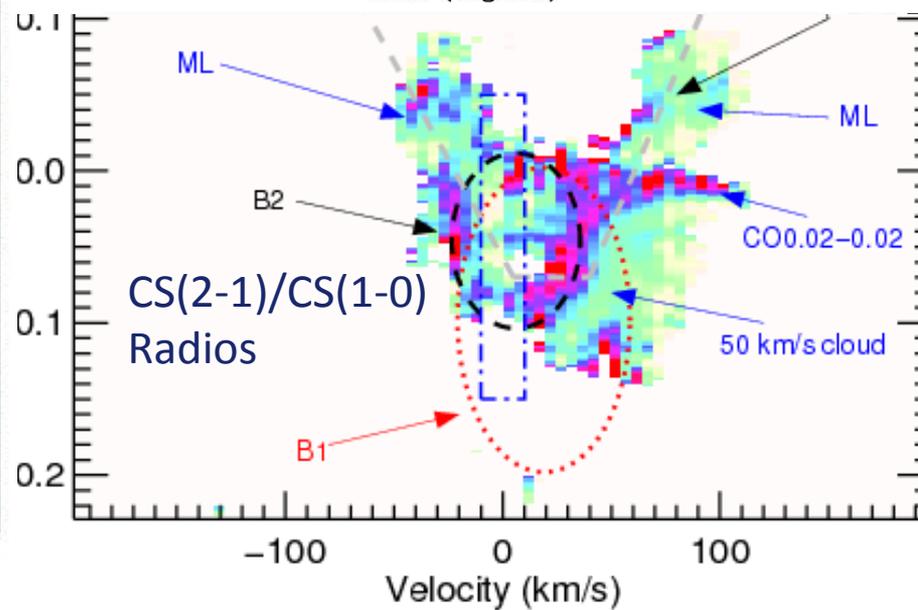
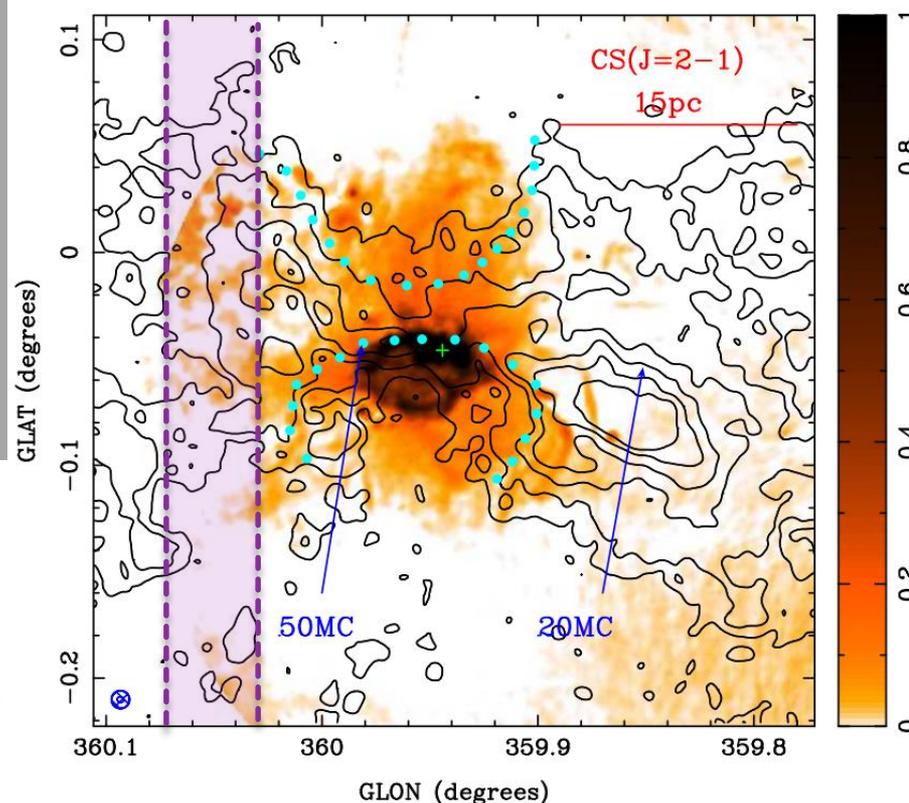
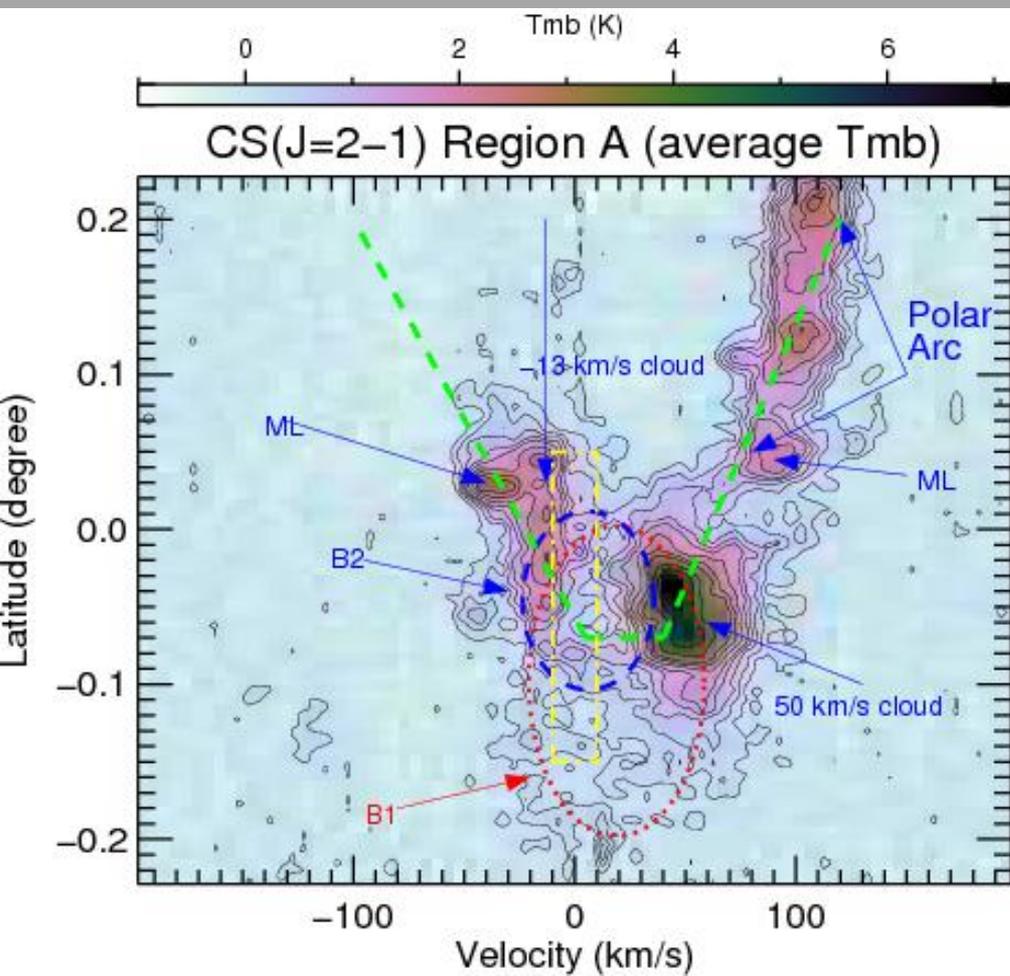
IAU-S322 Galactic Center compared with extragalactic nuclei



- Galactic Center bubble (infrared)
- Extragalactic outflow, but is in GMC scale
- 30-pc nuclear outflow - associated with SgrA*?

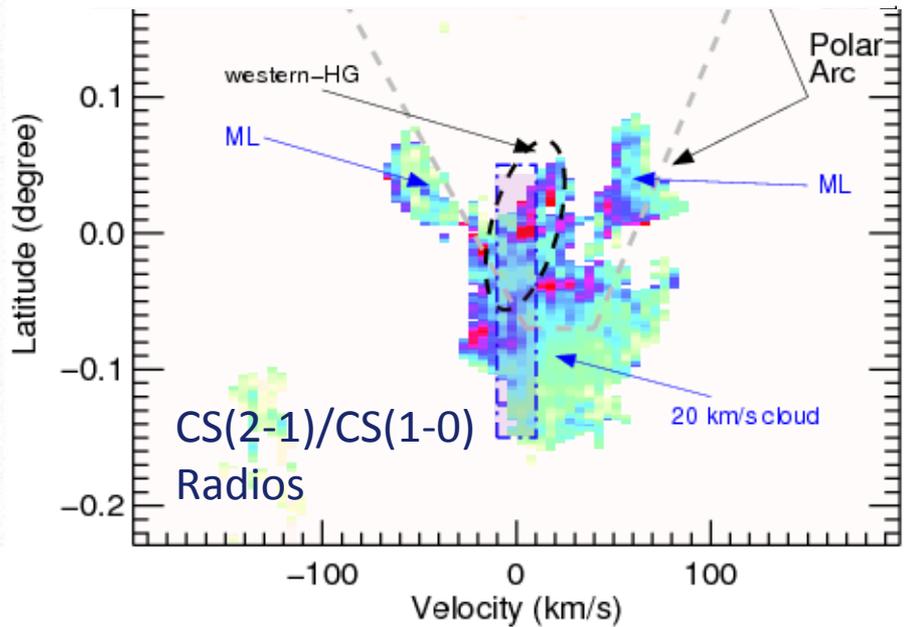
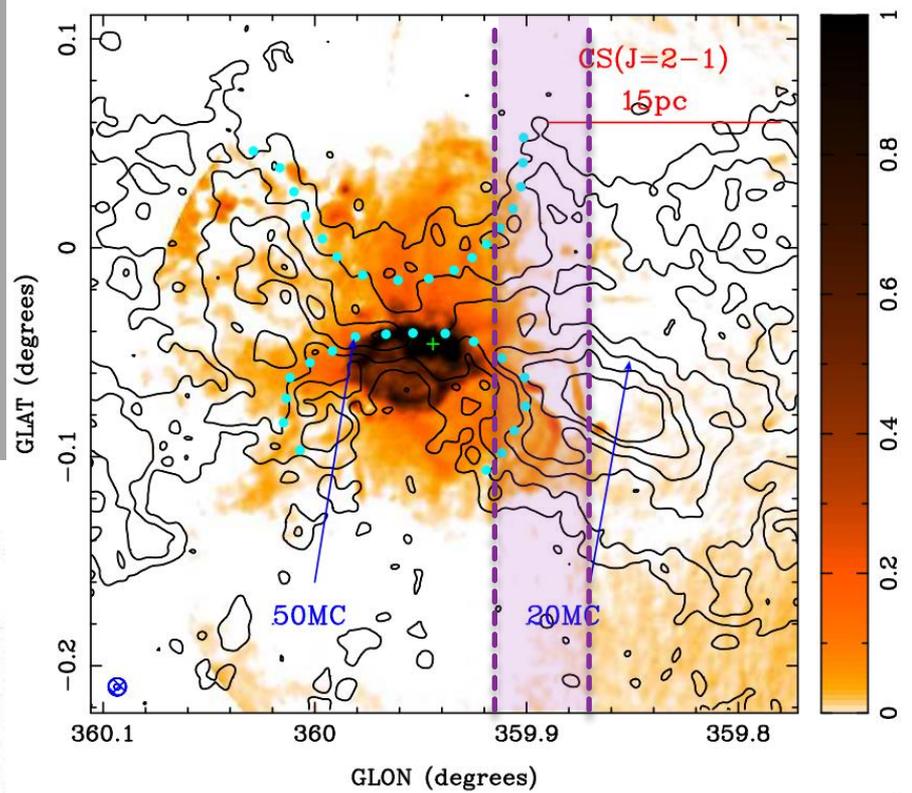
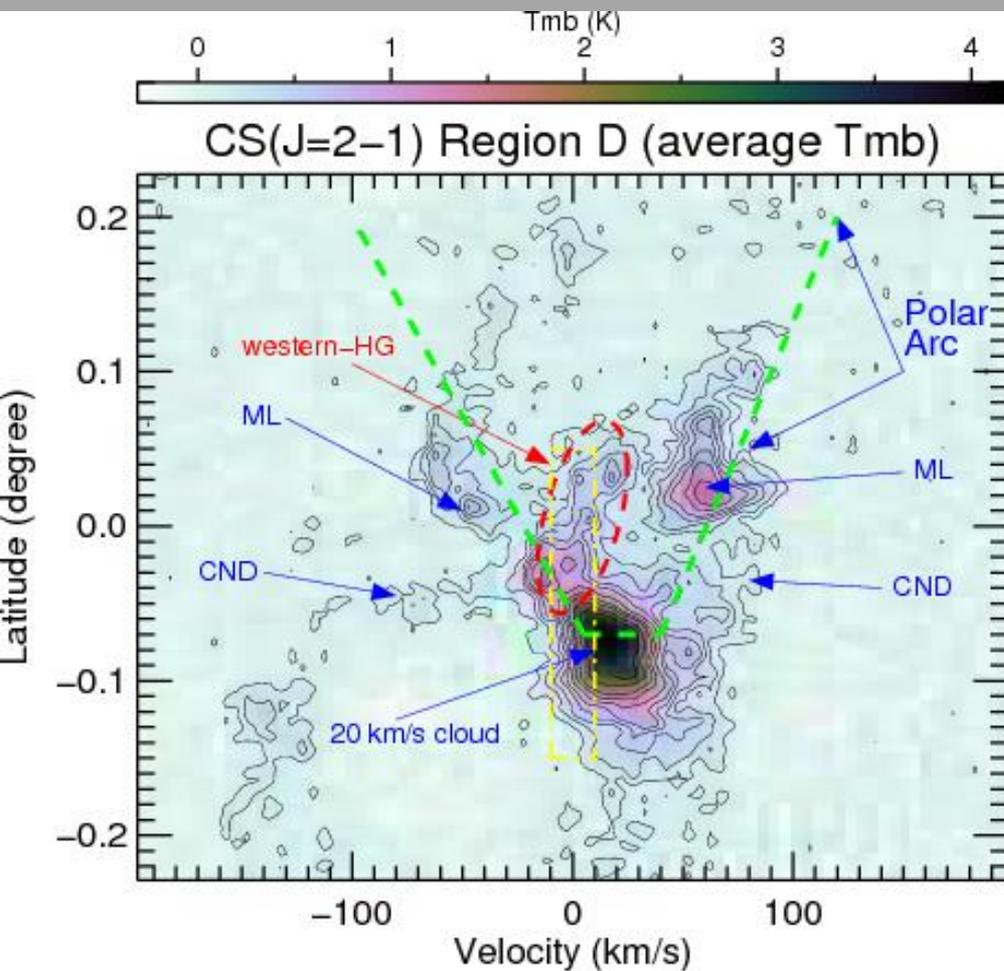
Eastern-HG feature

- Bubbles: B1 and B2, swept gas from the 50 MC to 7 pc from SgrA*.
- $T_{\text{dyn}} \sim 3 \times 10^5$ years
- High CS(2-1)/CS(1-0) ratios



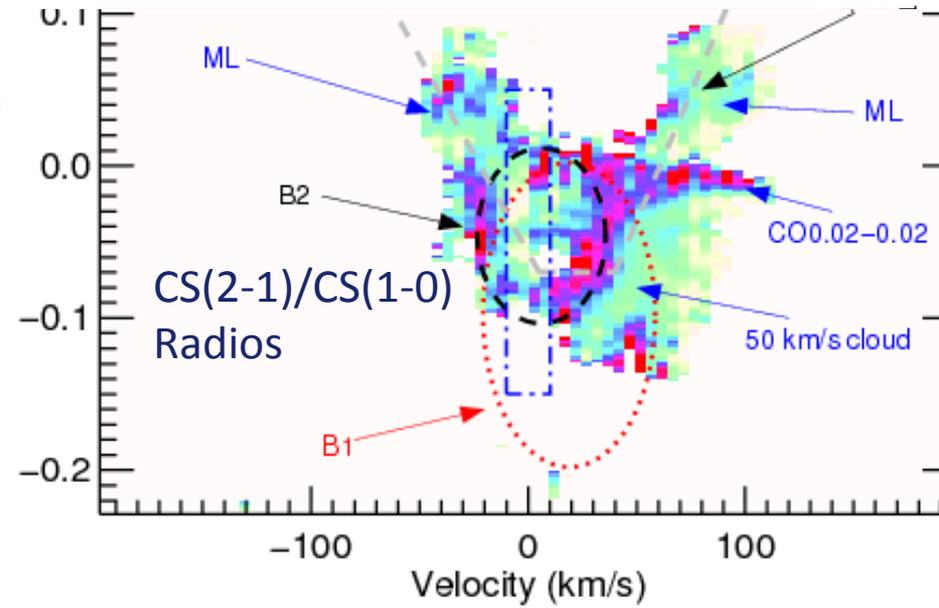
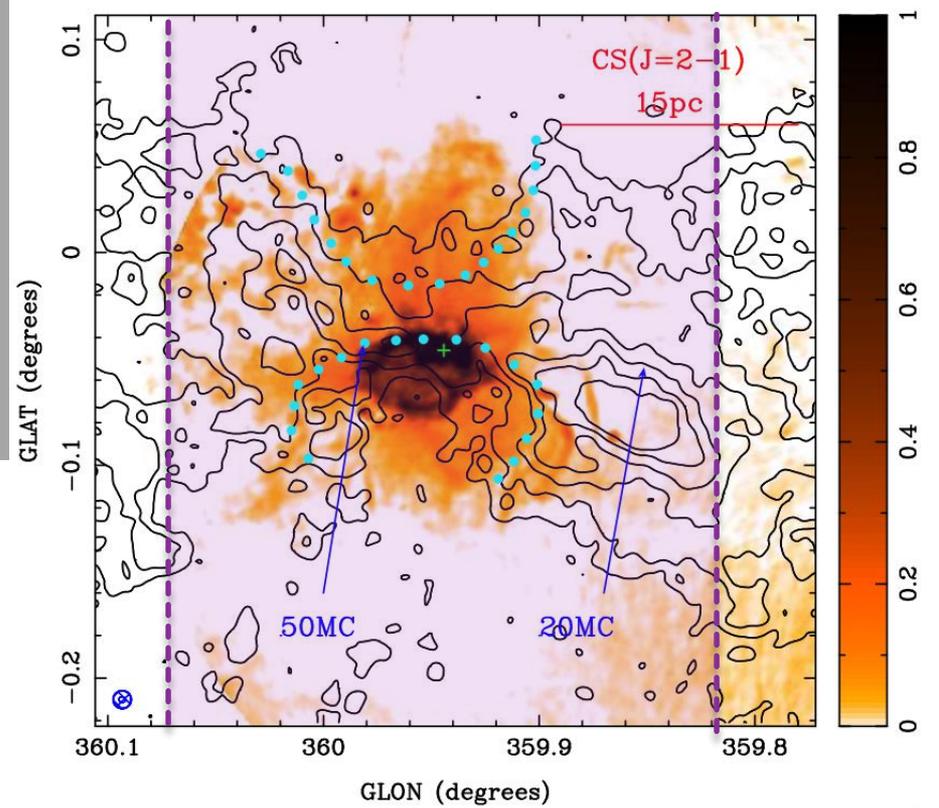
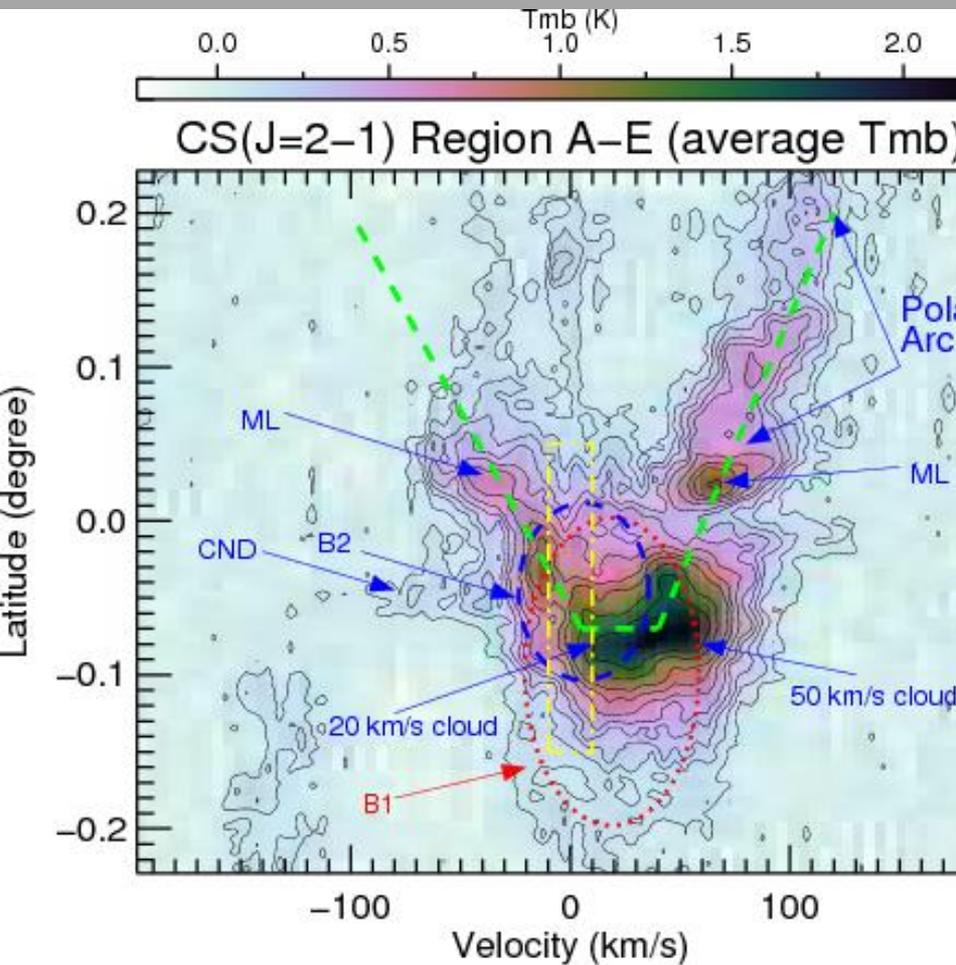
Western-HG feature

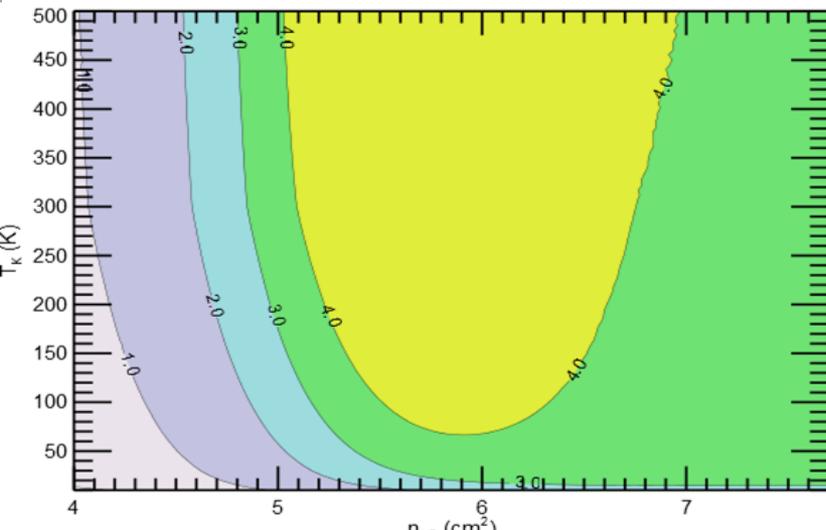
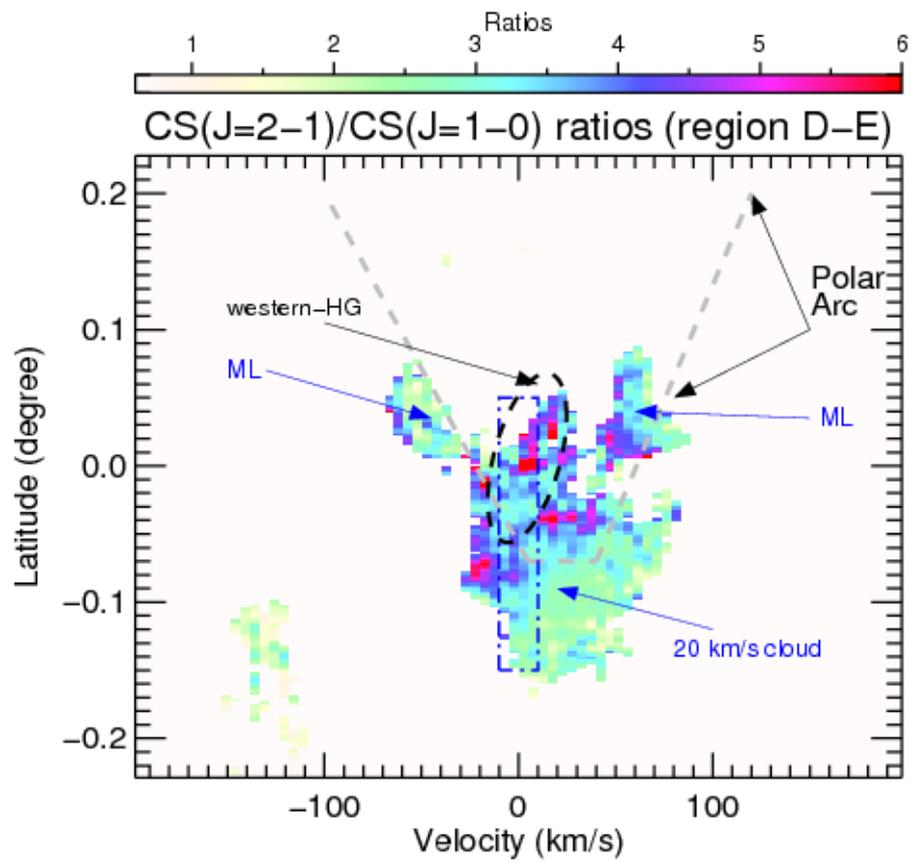
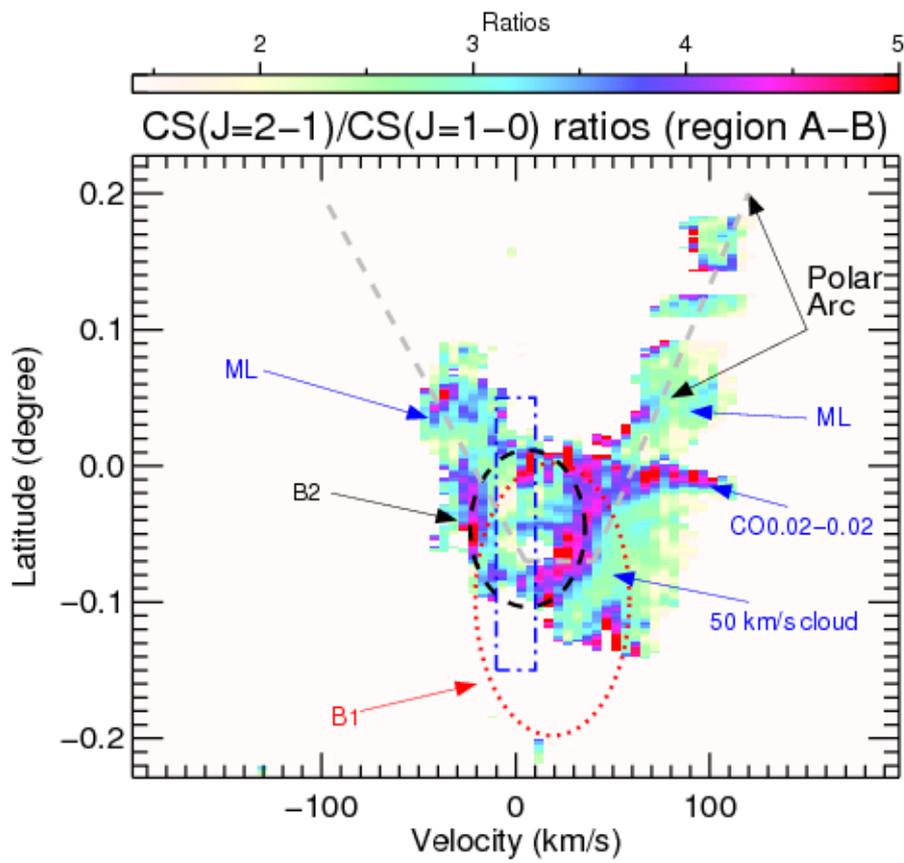
Entrained from the 20 MC



Latitude-Vel Diagrams

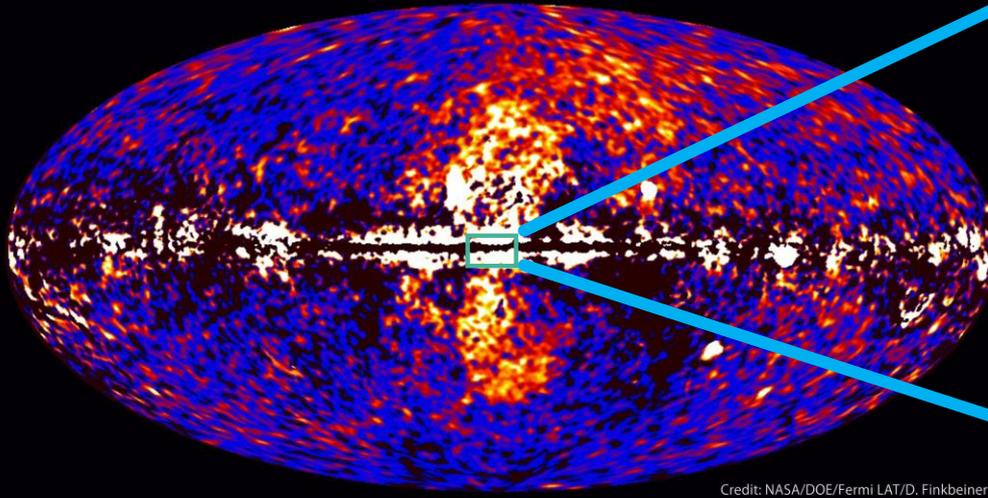
- The PA: outflow feature
- Bubbles
- Disk



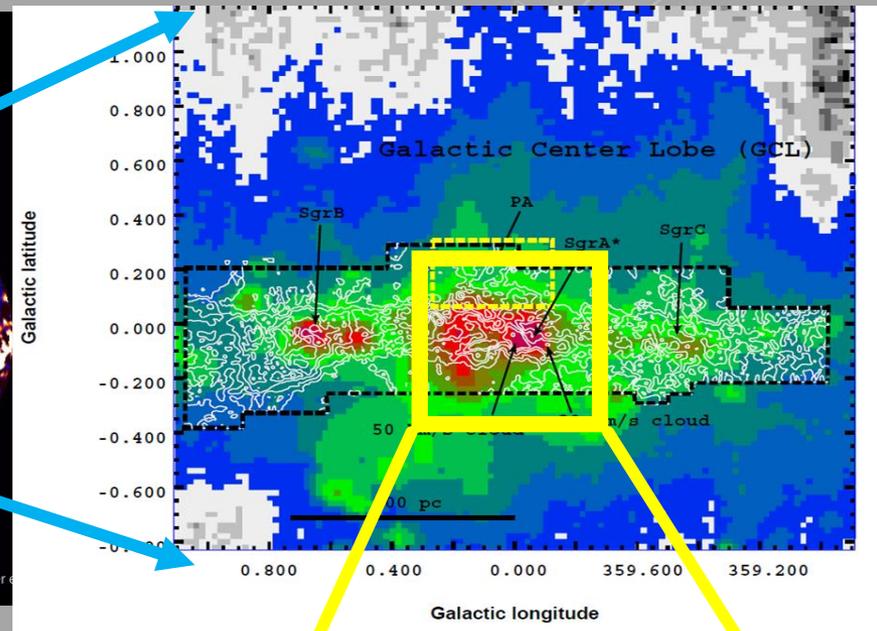


High temperature and density gas ($T > 70$ K, $n_{H_2}: 10^{(5-7)} cm^{-3}$) associated with the nuclear outflow

Fermi data reveal giant gamma-ray bubbles



Credit: NASA/DOE/Fermi LAT/D. Finkbeiner et al.

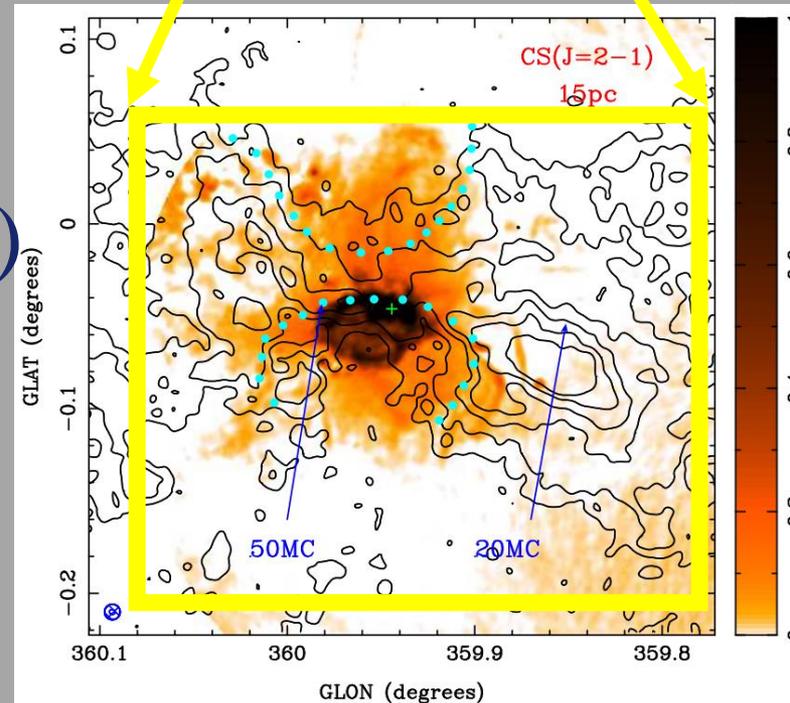


Cascading structures:

1 kpc bubble (>100 -10 Myr)

300 pc bubble (~ 7 Myr)

30 pc bubble (~ 0.5 -5 Myr)



Fossil features and the big picture

- Back to the inflow problem, will the outflow destruct inflow gas (orbit)? High-T suppresses SF? Tidal forces?
- Scales of the CMZs in external galaxies – Sizes, masses, structures, magnetic fields, dynamics.