

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

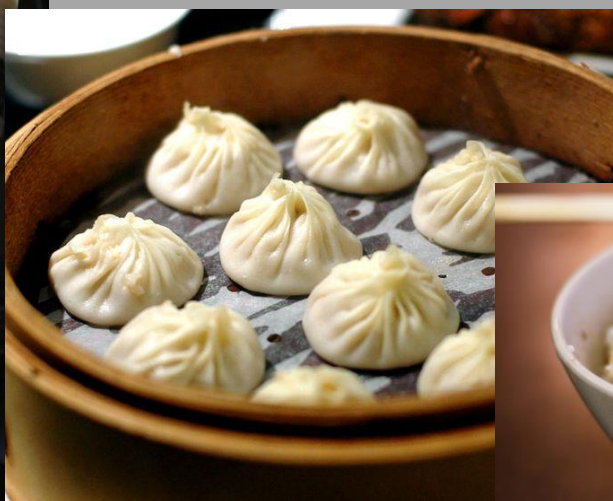


Pei-Ying Hsieh

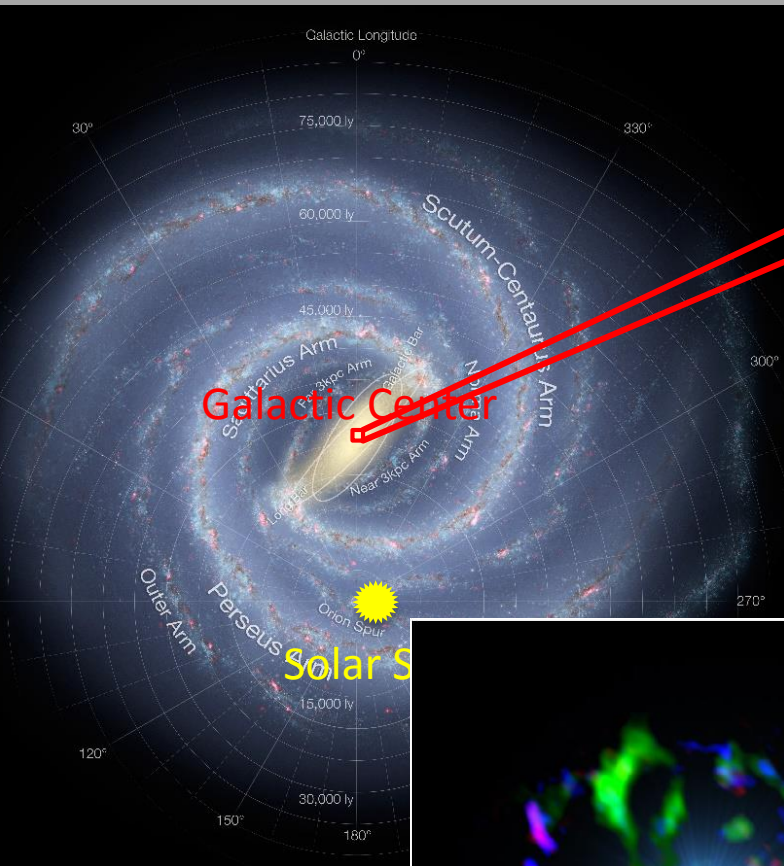
Postdoctoral Fellow (ASIAA)/ALMA Rregional Center Taiwan node

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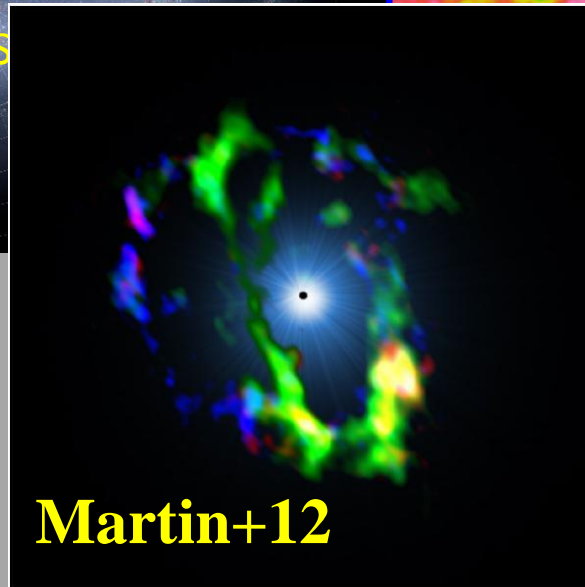
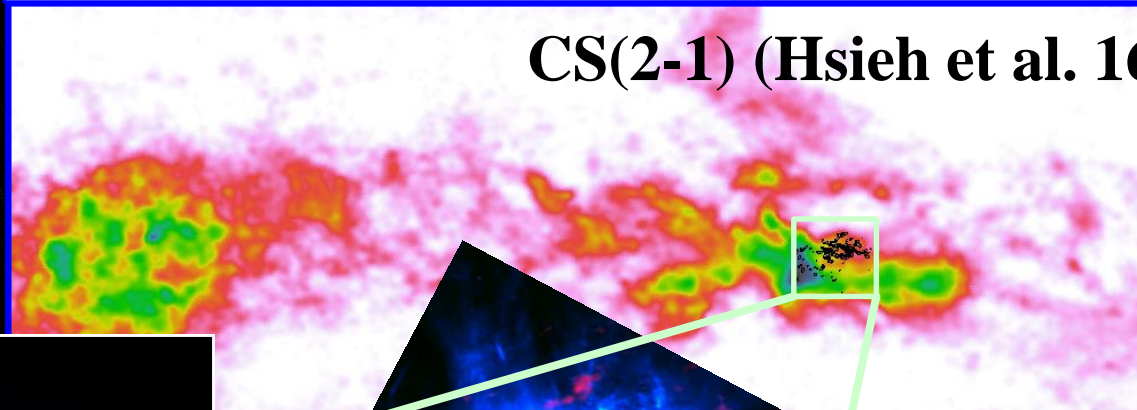
From black hole to environmental galaxy evolution across multiple wavelengths, Canberra, 2017 Aug



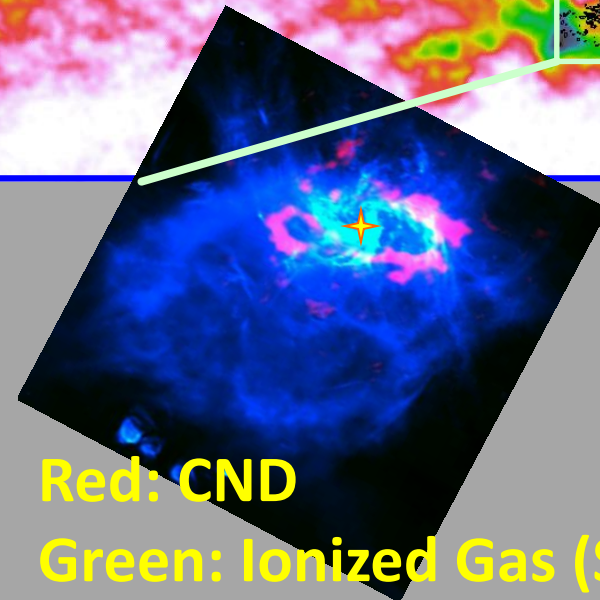
The Center of the Milky Way



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



Martin+12

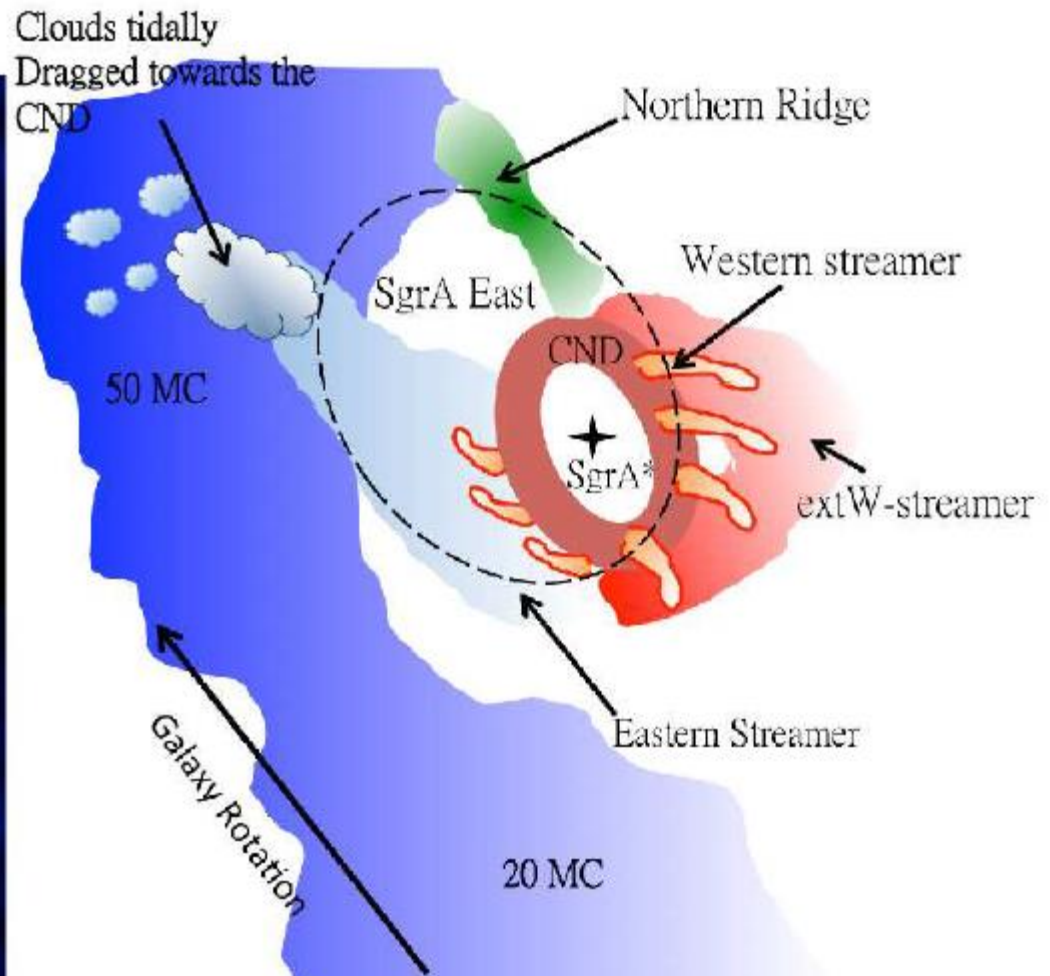
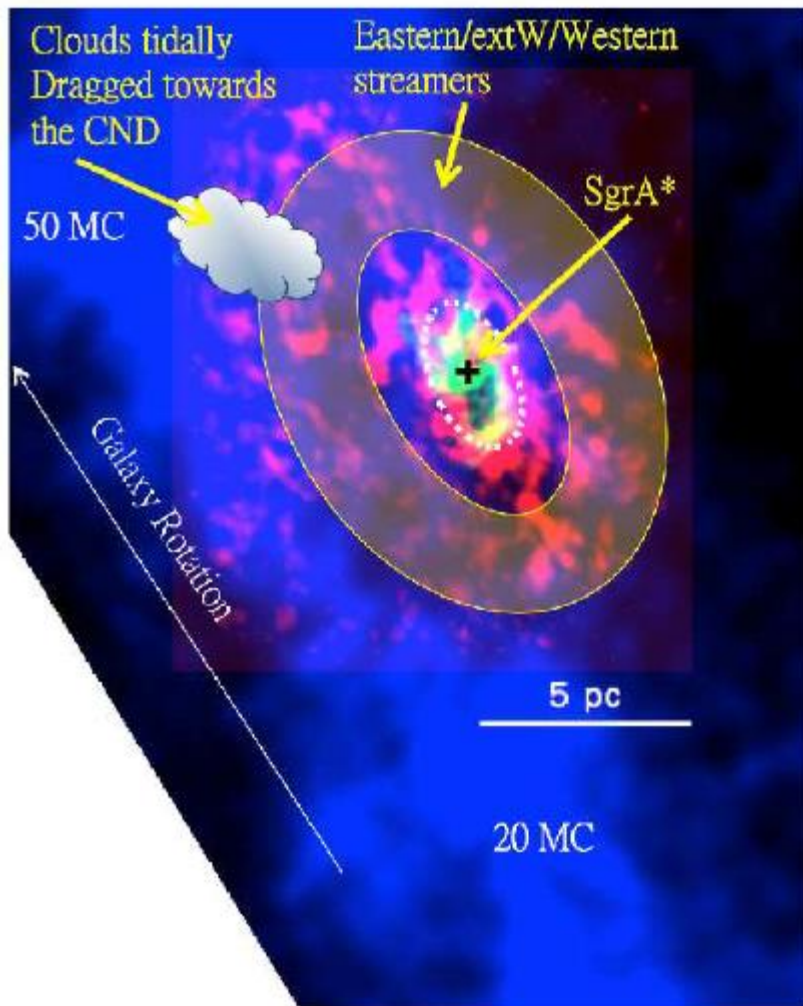


Red: CND

Green: Ionized Gas (Sgr West)

Blue: 20 cm continuum (SNR)

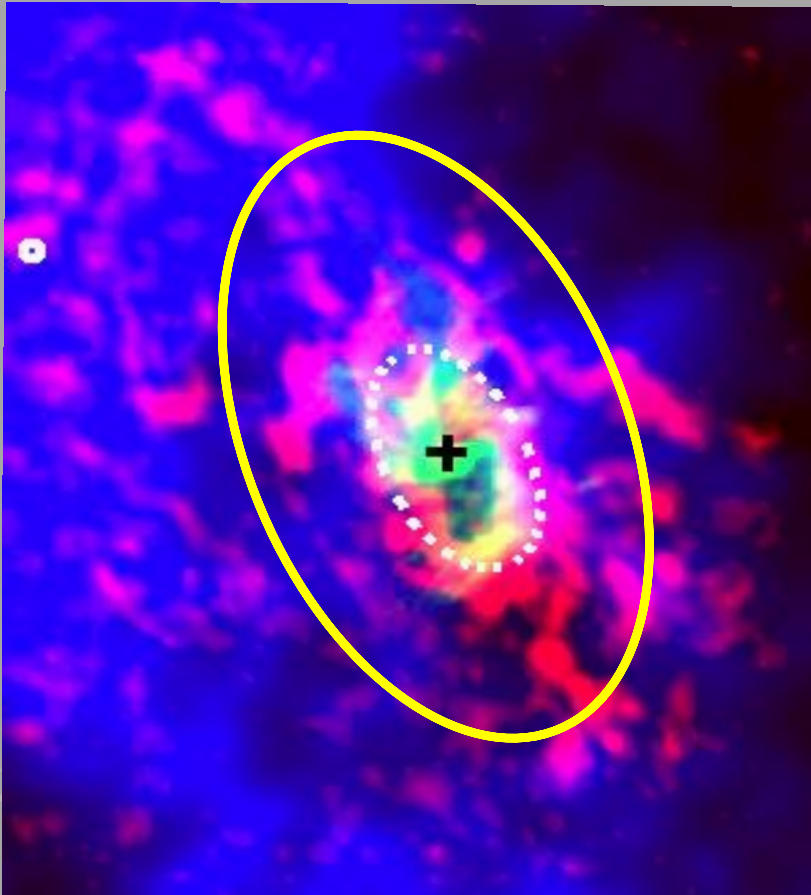
Gas Feeding System in the GC



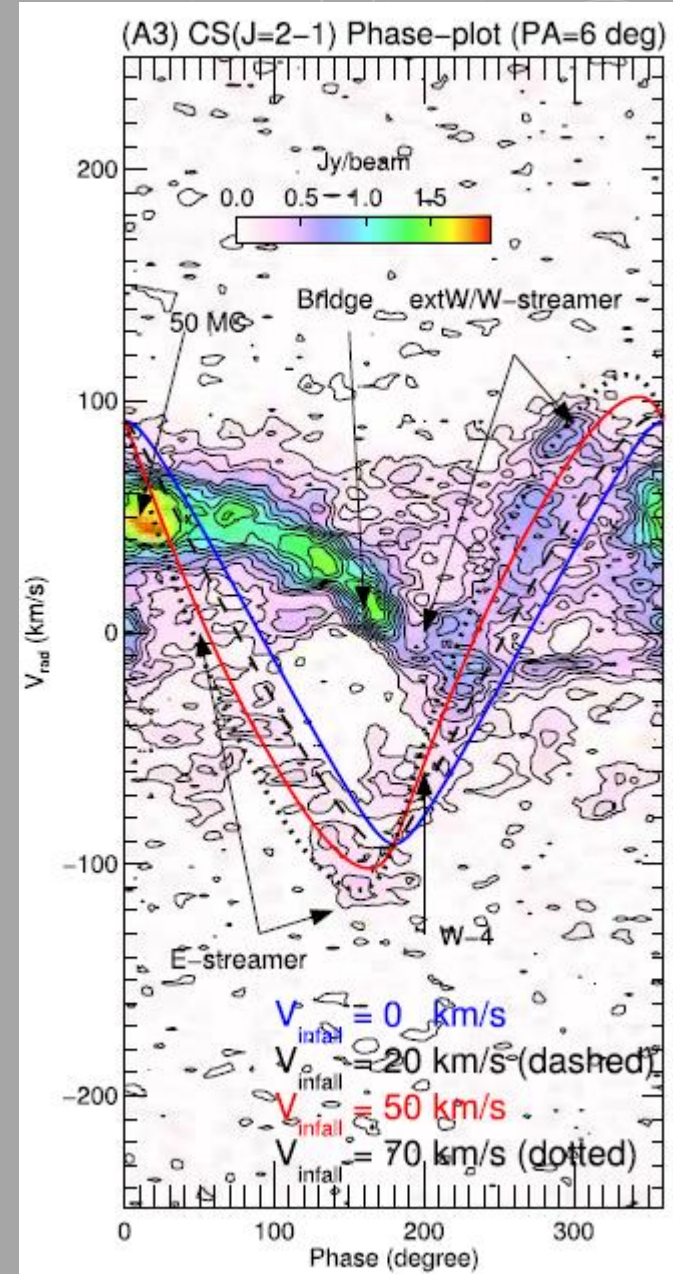
Hsieh+17a, ApJ in press

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

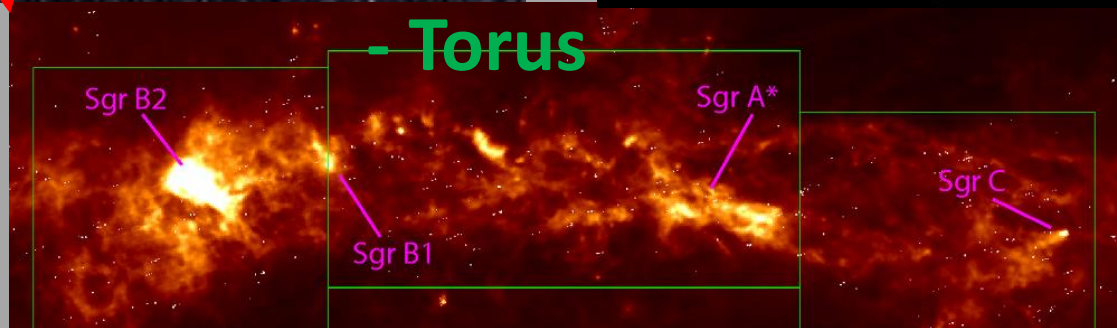
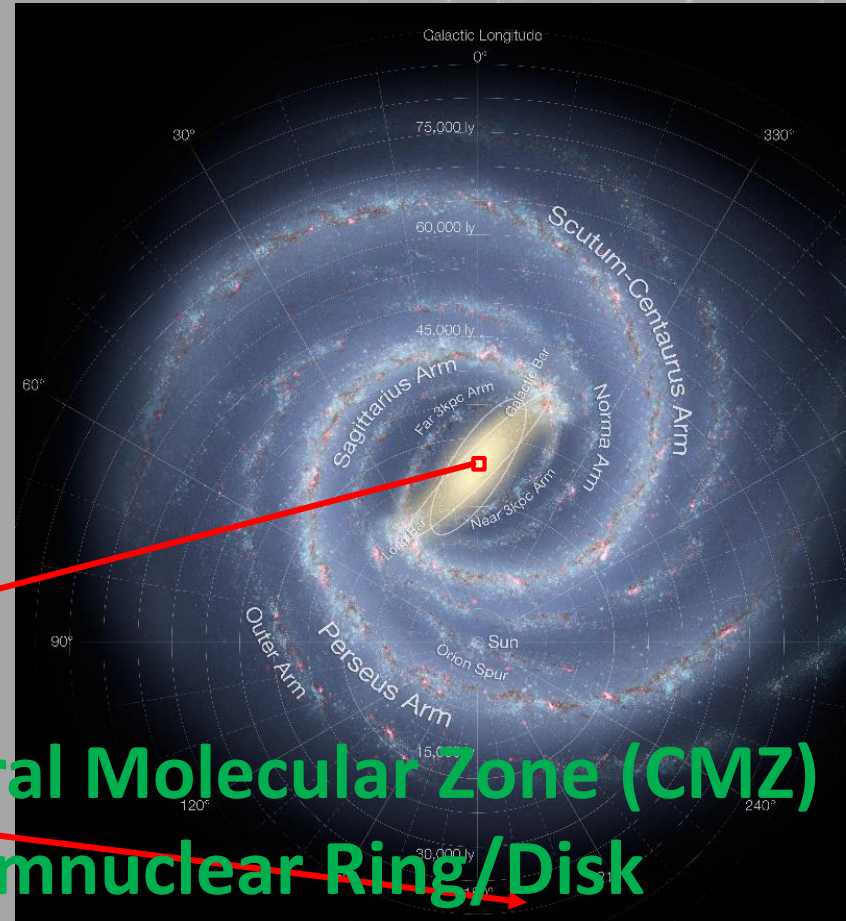
Big picture of galaxy evolution:

- **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

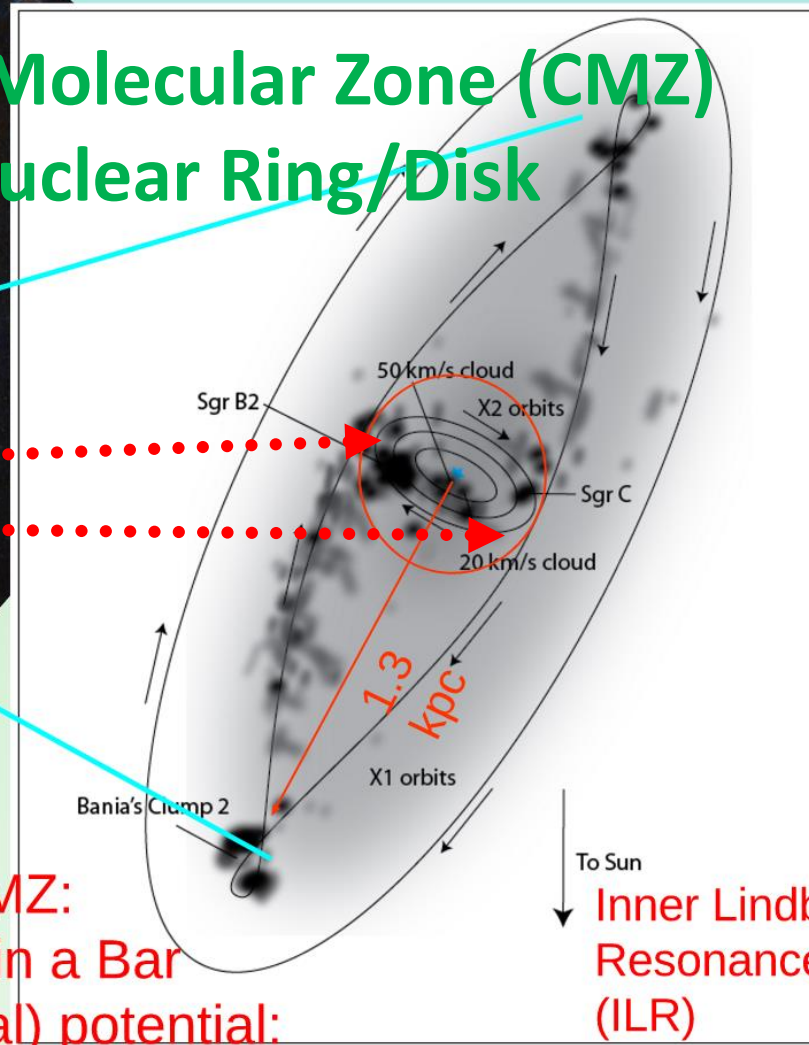
Gas inflow -> Central Molecular Zone (CMZ), SF, driven by bars and nuclear bars, fueling AGN/SF

Extinction by 30 magnitude in optical
Better resolution



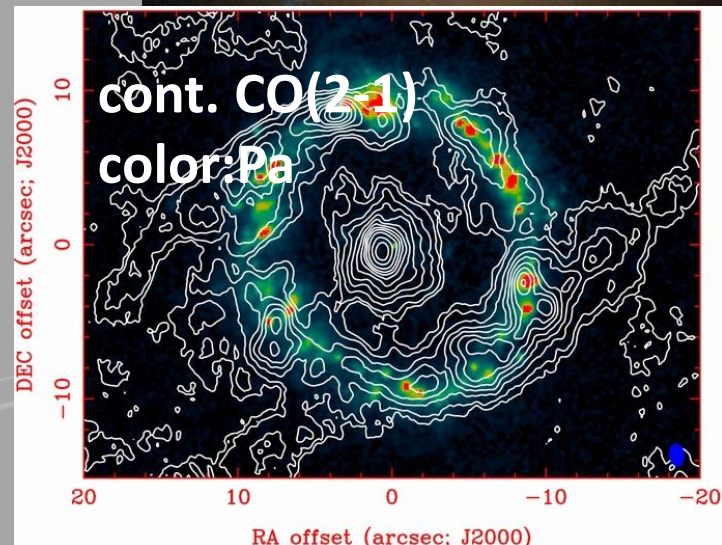
GC v.s. NGC 1097 extragalactic CMZ

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



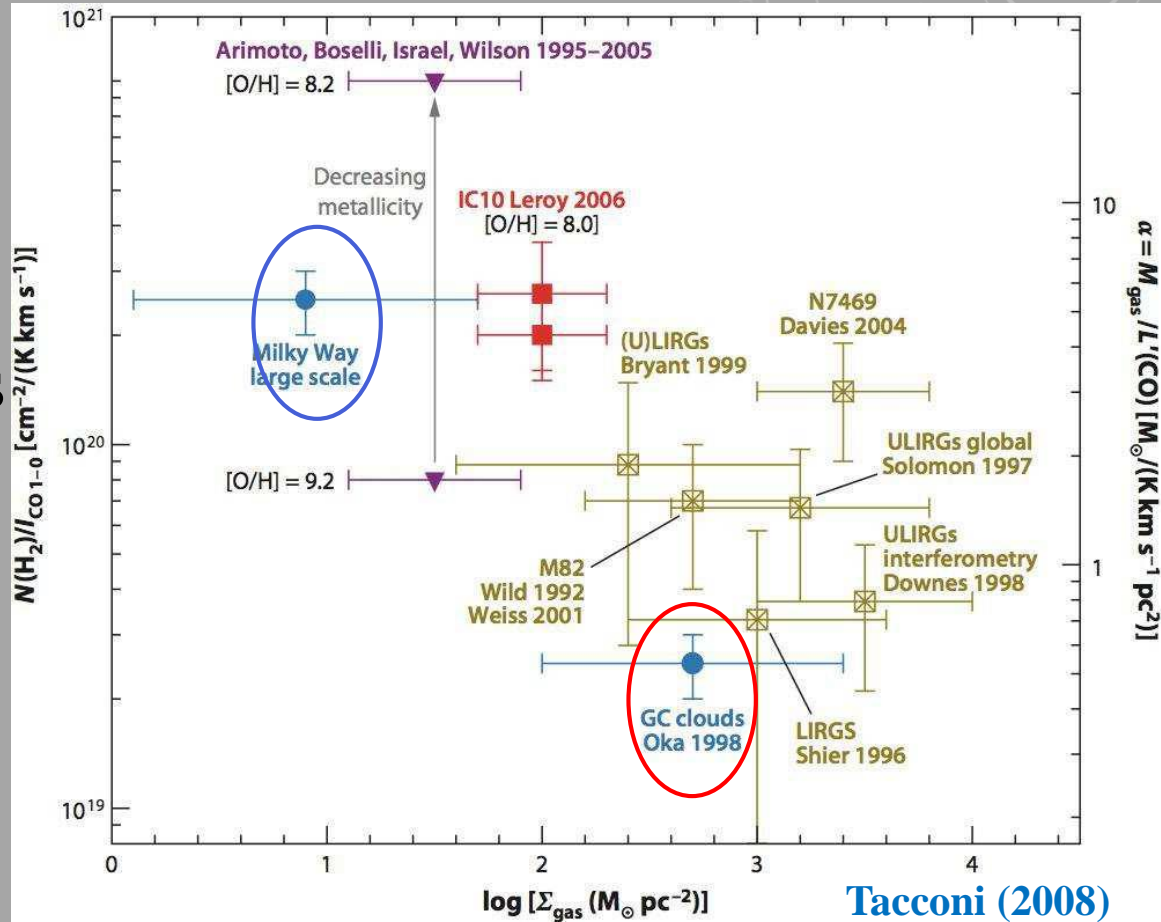
the CMZ:
orbits in a Bar
(tri-axial) potential:
1 vs. x2
Next: arm 1,2,3,4
R ~ 450 pc

Hsieh+08, 11, 12



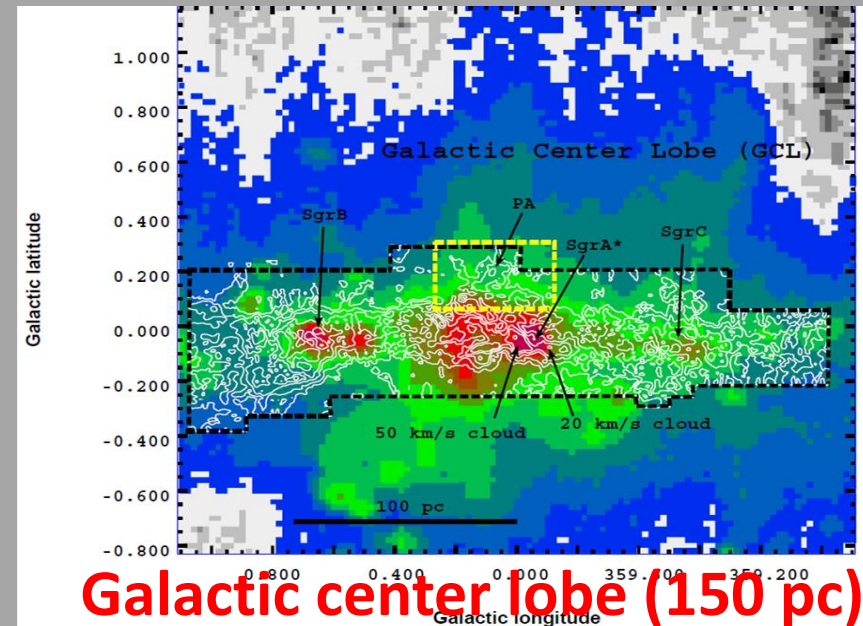
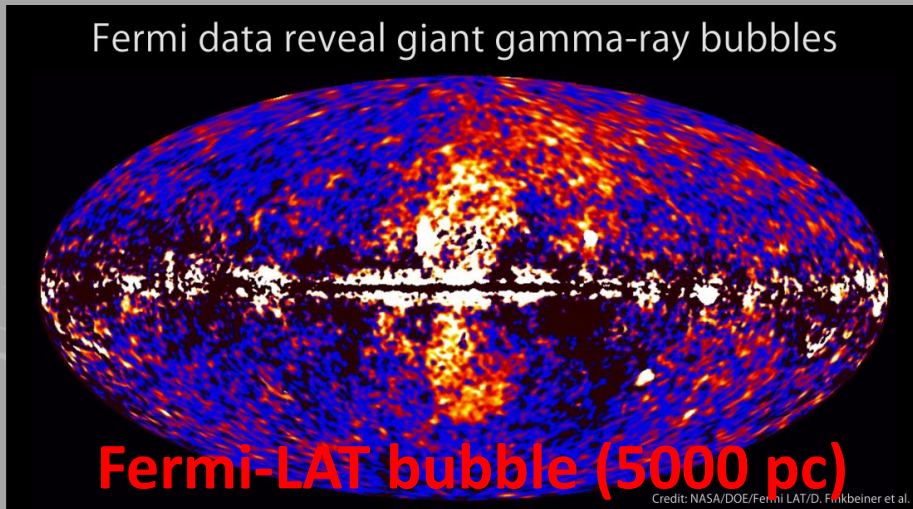
Hundred-pc Molecular Concentration - Central Molecular Zone

- 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 ($T > 80 \text{ K}$).

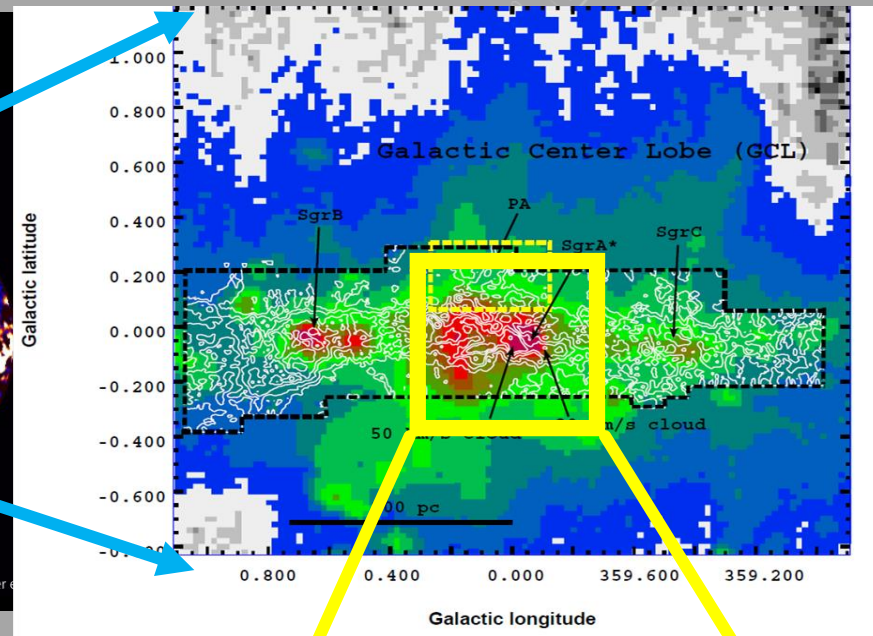
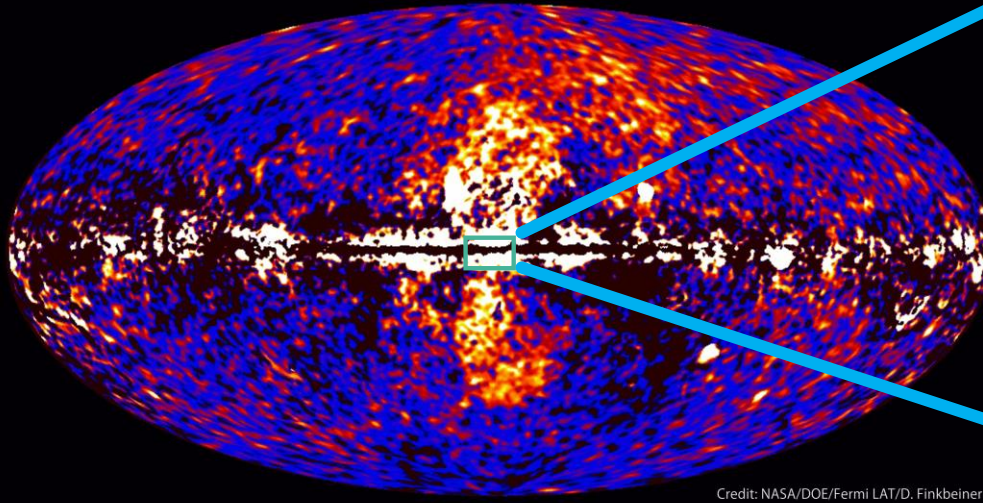


Quiet Nucleus: being quenched or periodic activity?

- 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



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

Bubbles from 5000 pc to 30 pc?

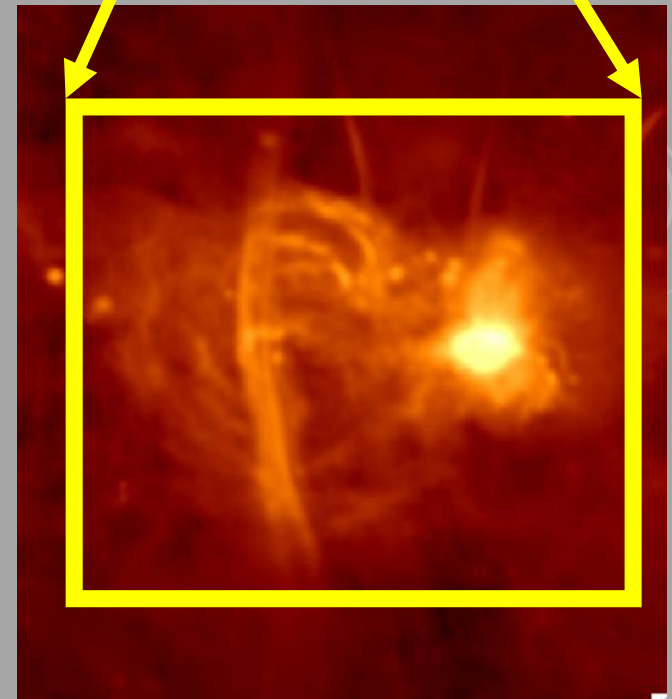
Sgr A East: 1 pc

GCB: 30 pc

Galactic center lobe: 150 pc

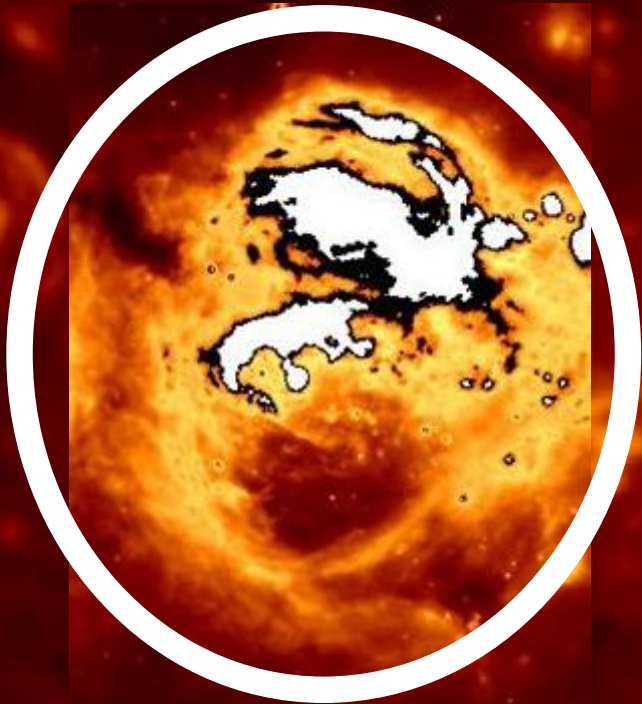
Fermi bubble: 5,000 pc

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

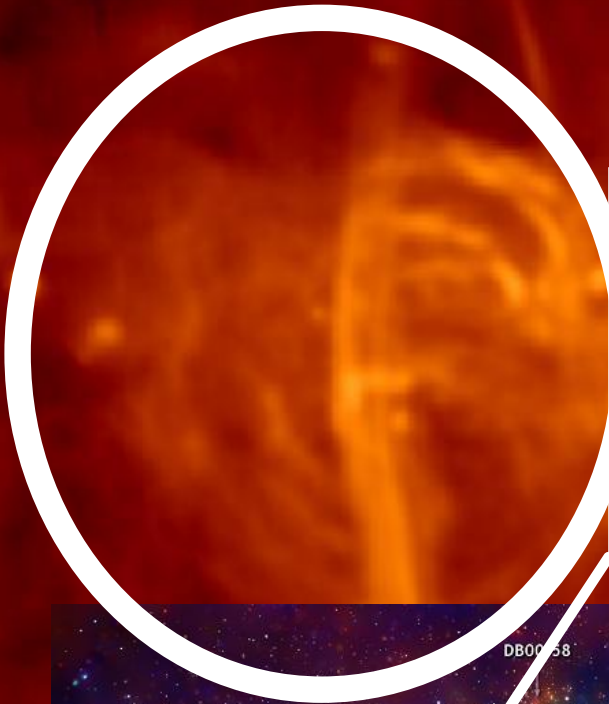


Central 30 -50 pc - Galactic Center Bubble, bipolar halo

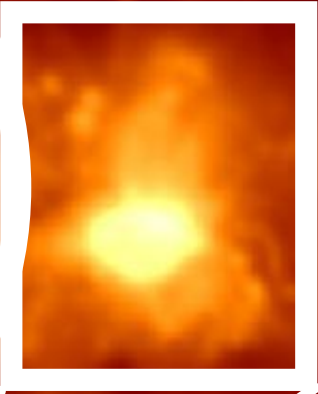
Spitzer 24 micron



Galactic center bubble



Bi-polar lobes
~ -30 pc



Yusef-Zadeh+04

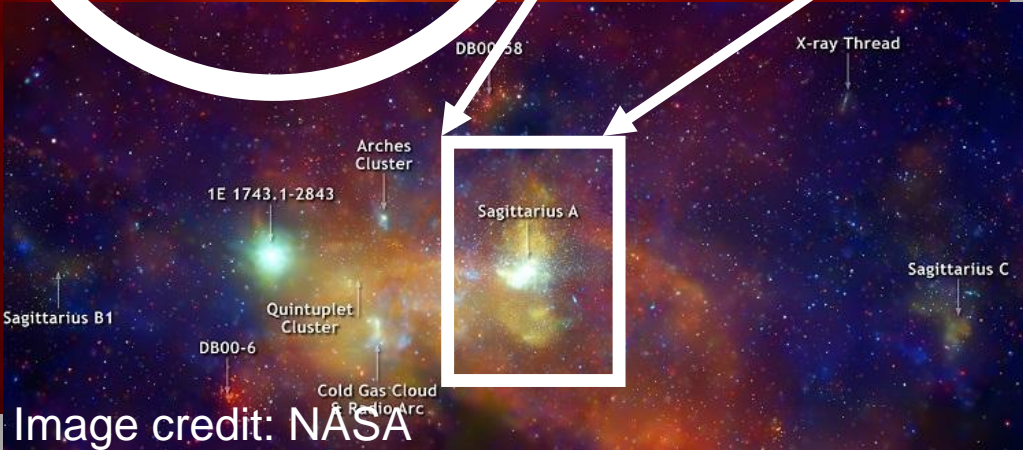


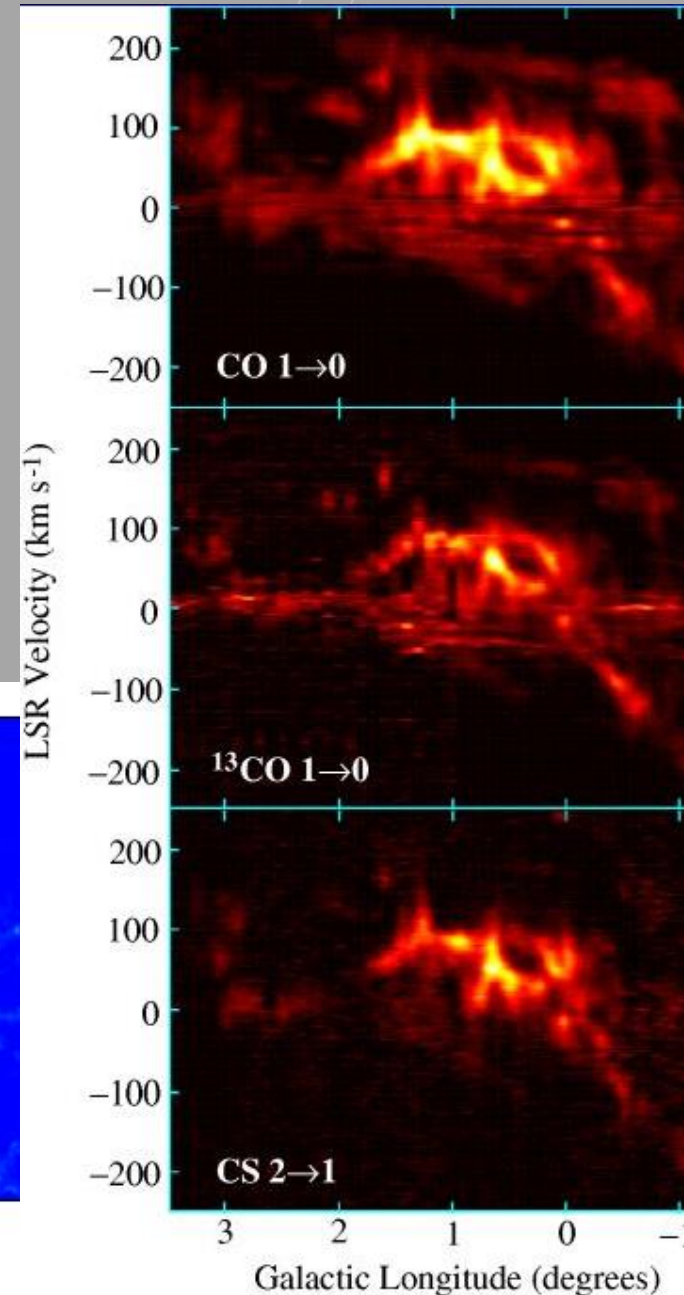
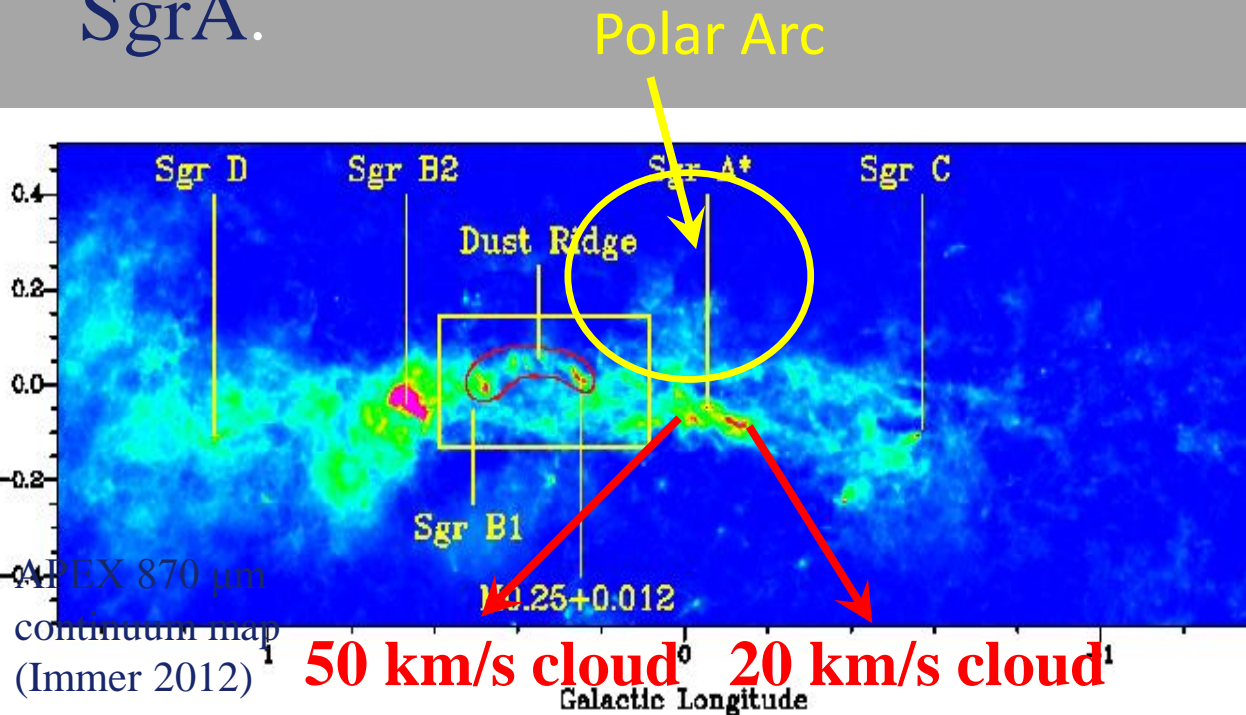
Image credit: NASA

How do we observe the Galactic Center?

- **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)

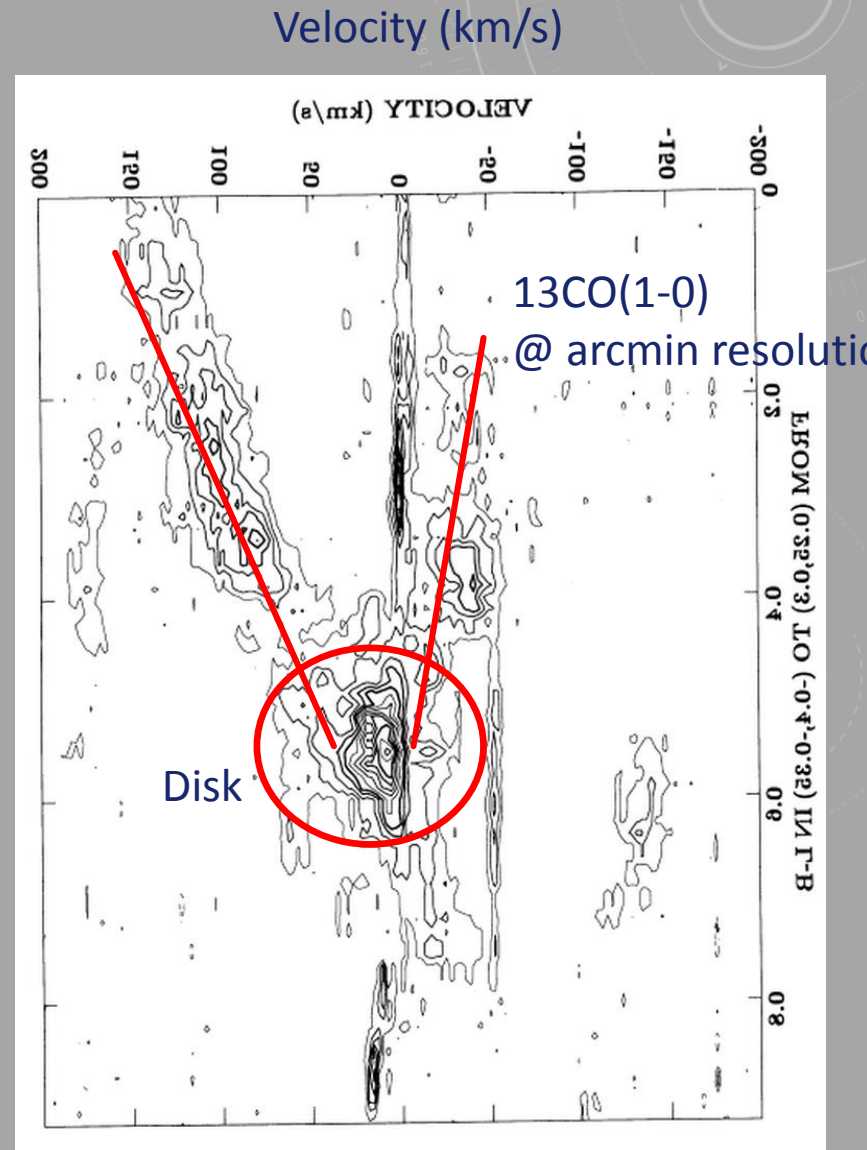
New Experiment: CMZ Probed by Carbon Sulphur (CS)

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



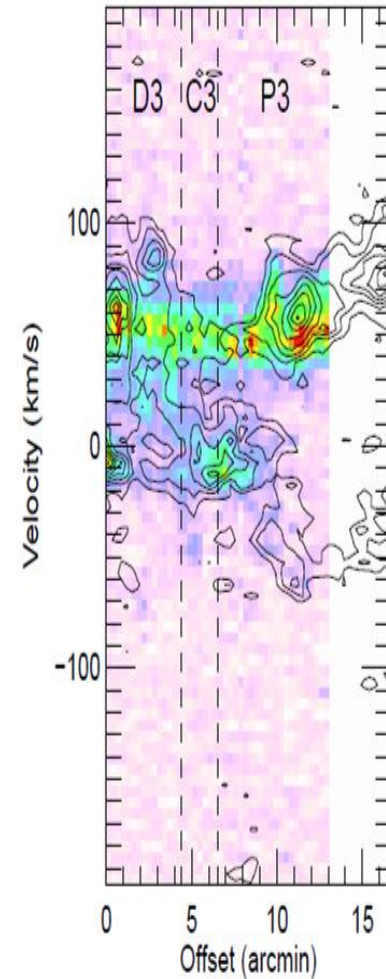
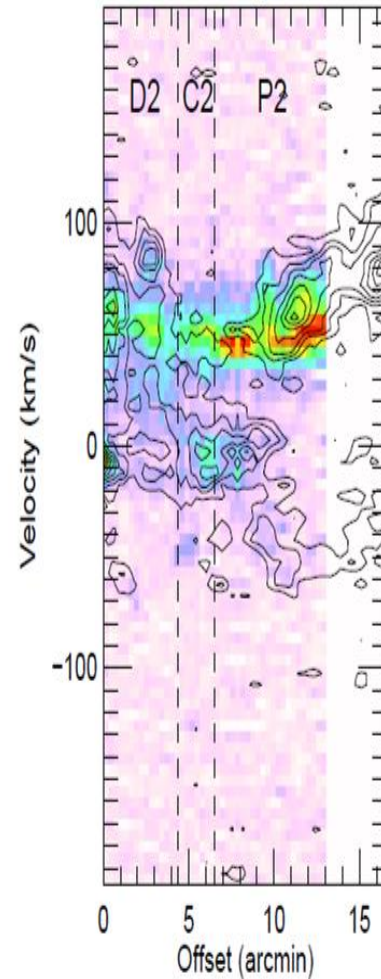
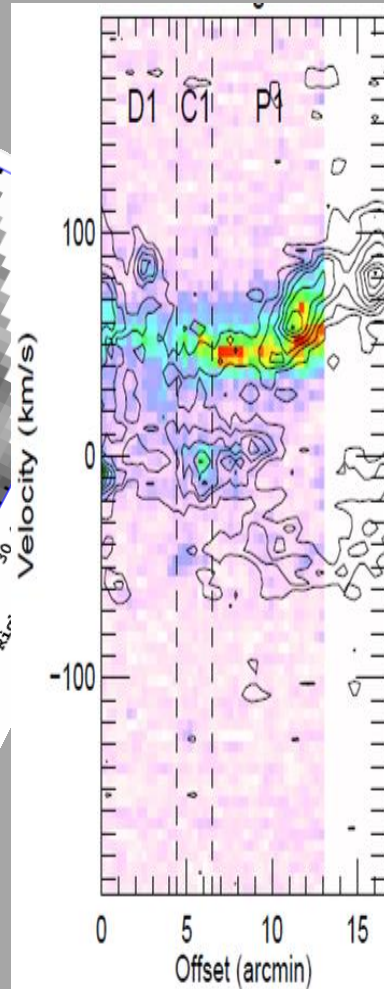
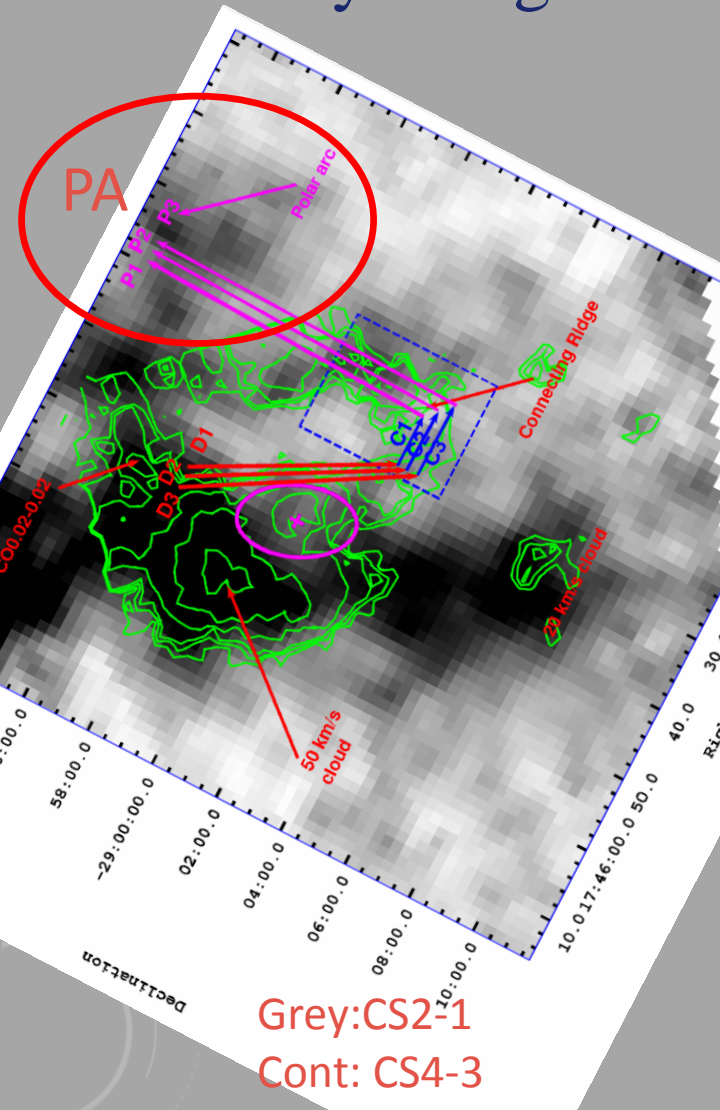
Is this Polar Arc related to SgrA*?

- Extended structure above SgrA region (^{13}CO ; 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



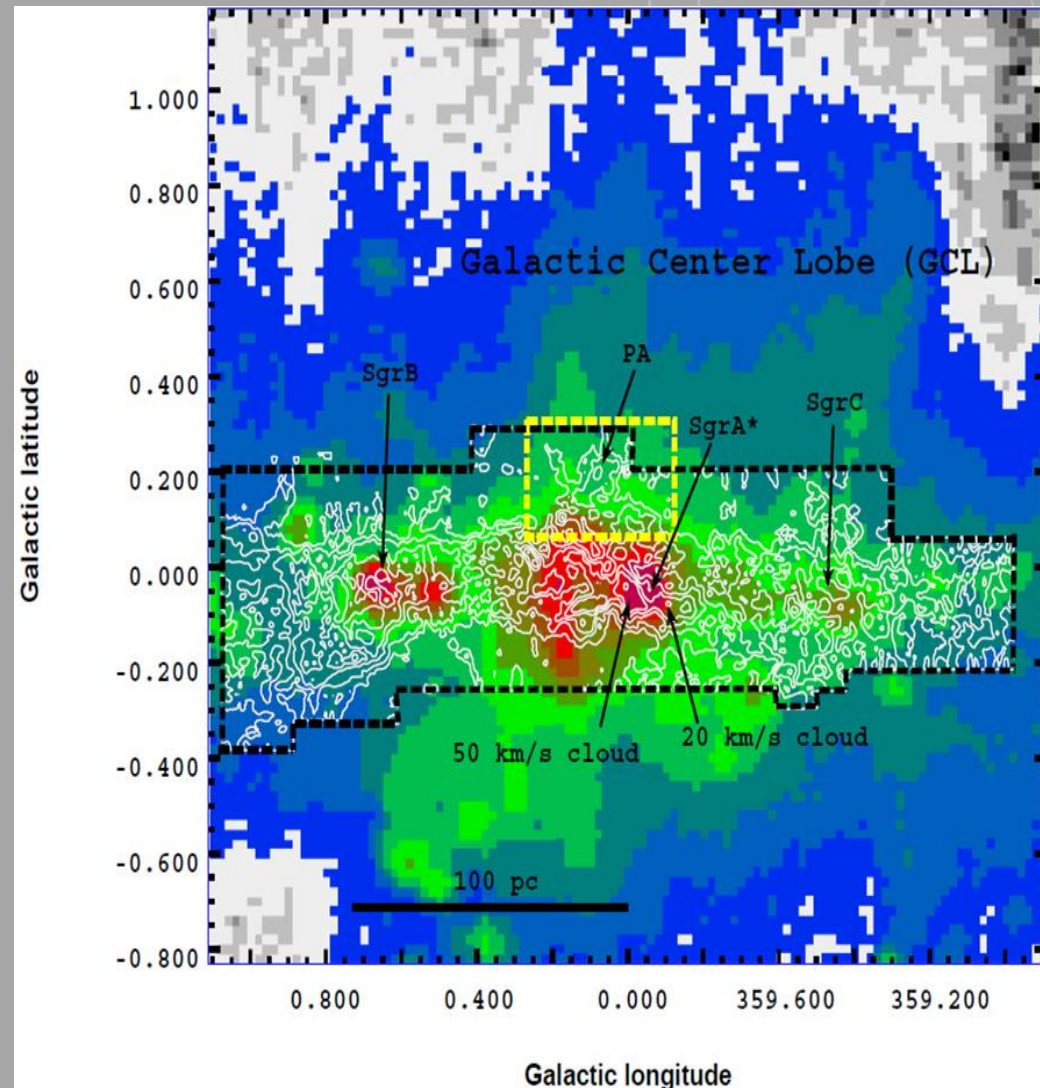
CSO High-J CS experiment: The Connecting Ridge

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



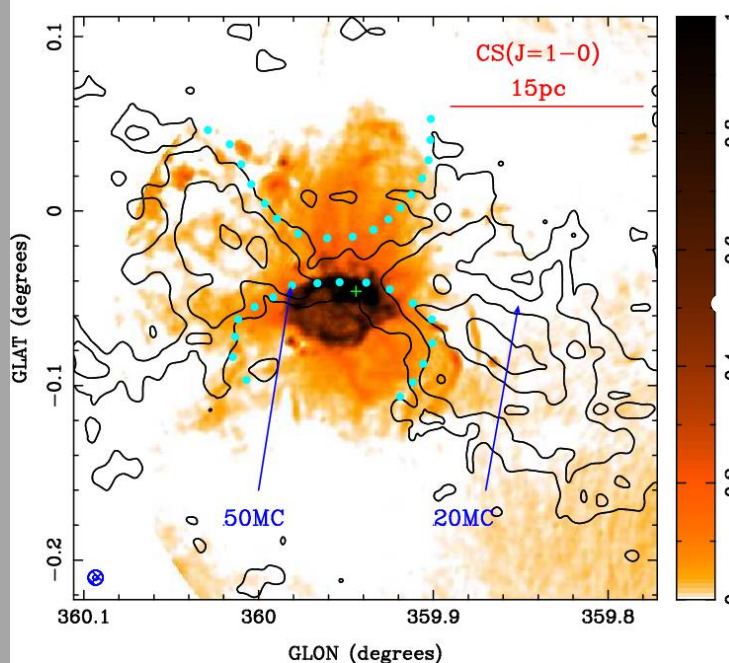
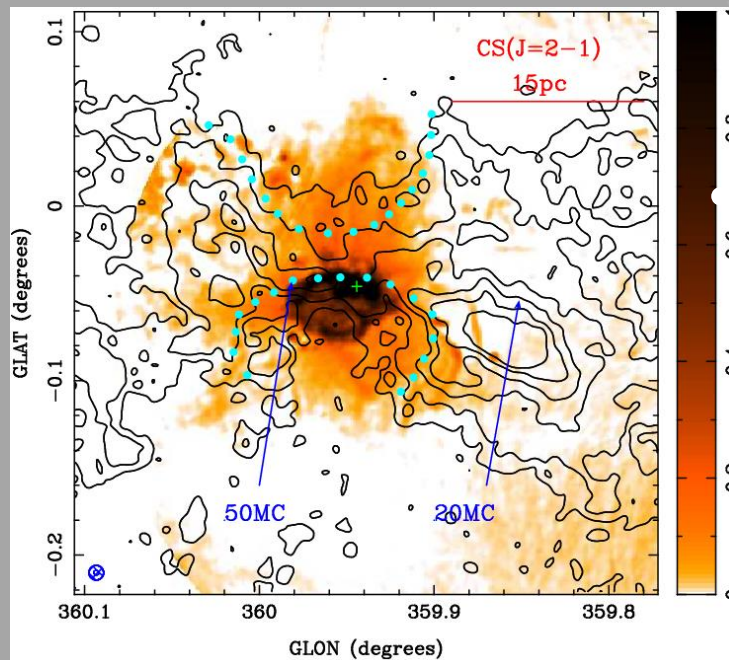
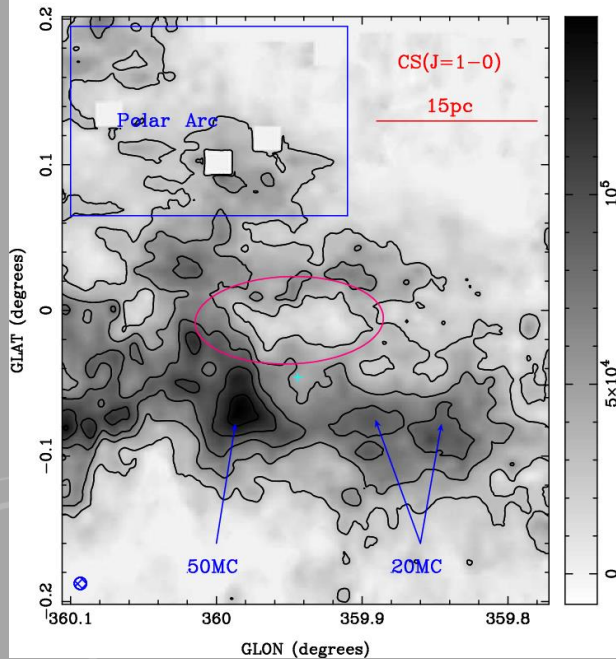
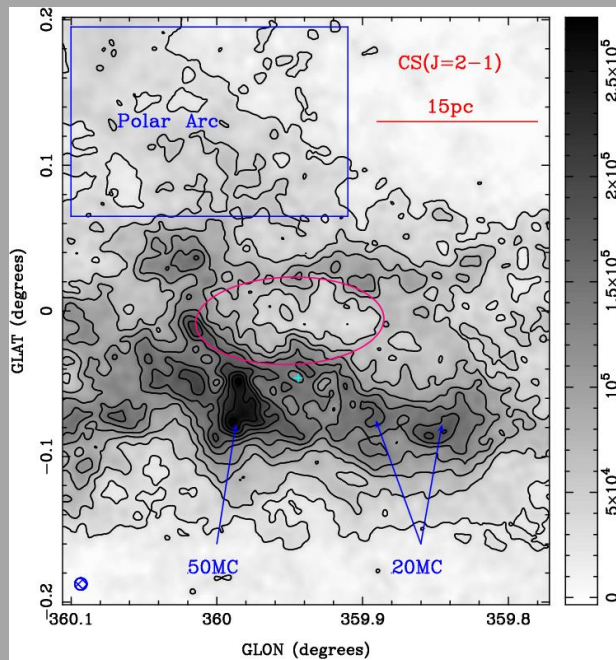
PA and the GCL: Launching point 6 M years ago

- 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

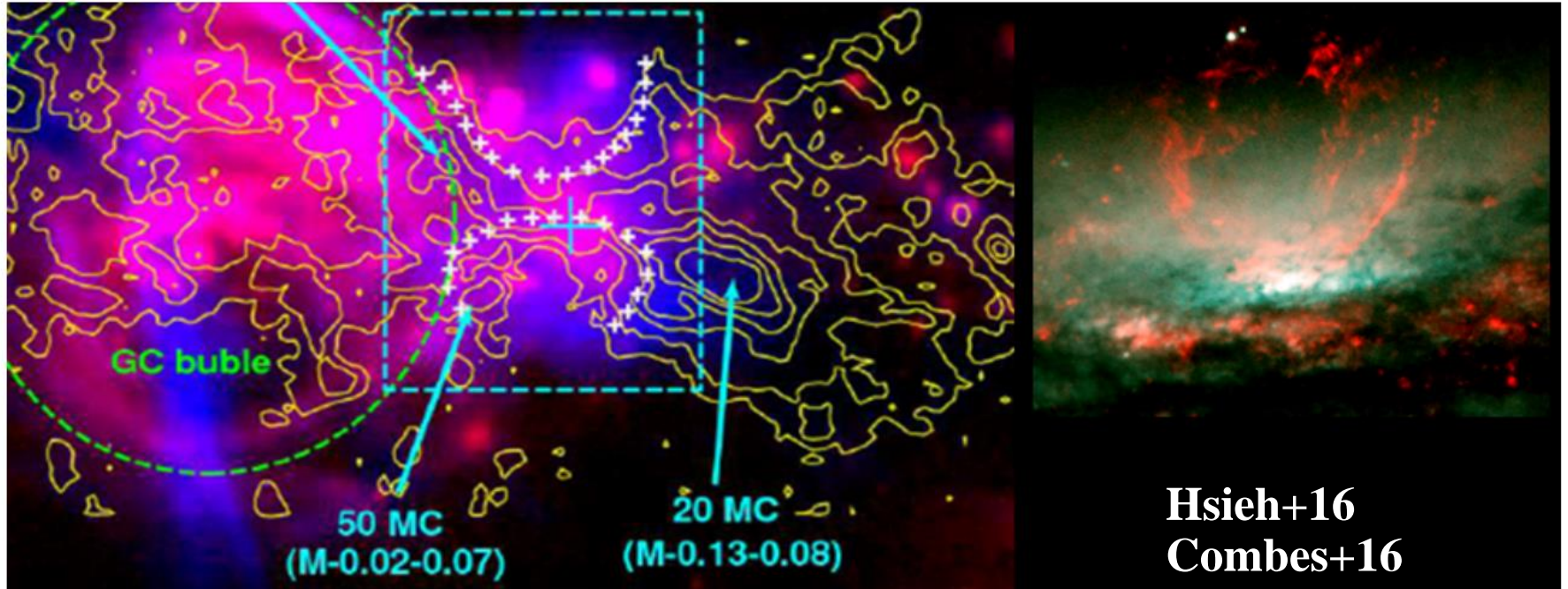


Low velocity
CS emission
surrounding the
20 cm radio
bipolar halo.
(Hsieh+16,
Tsuboi+99)

Hourglass-
shaped feature

Low velocity outflow?

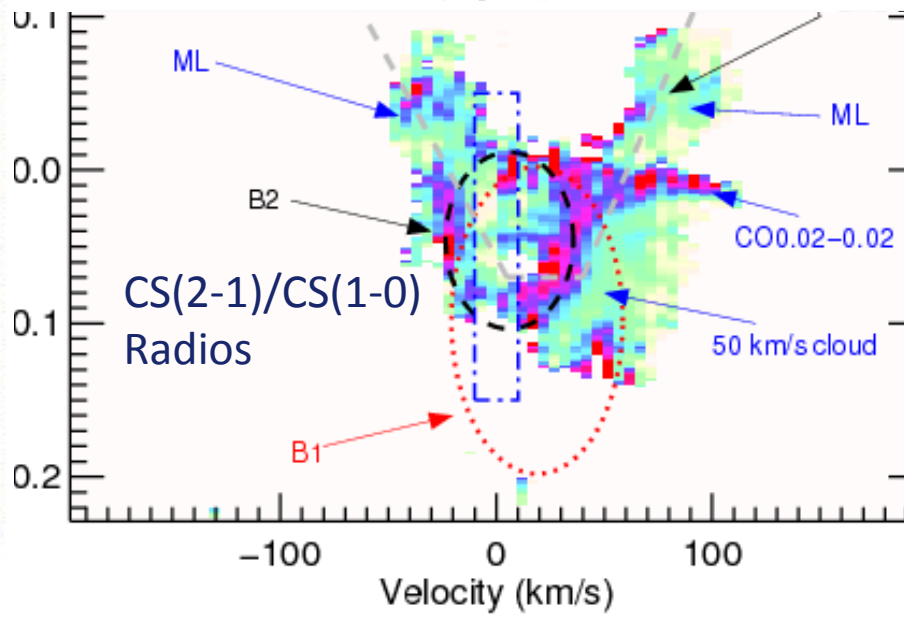
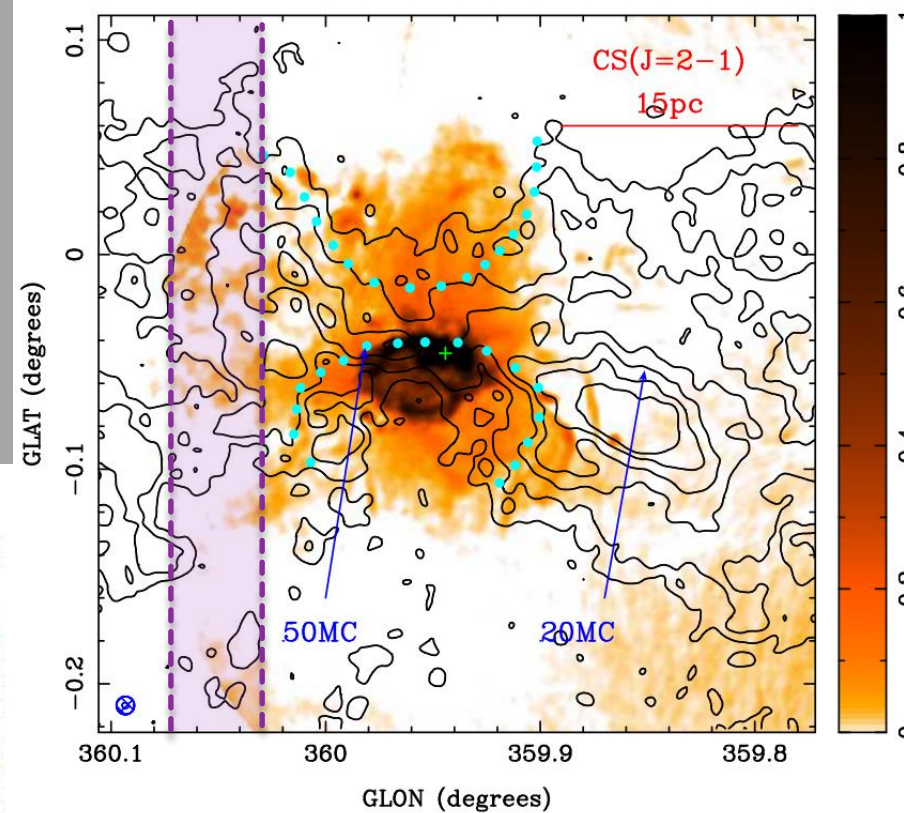
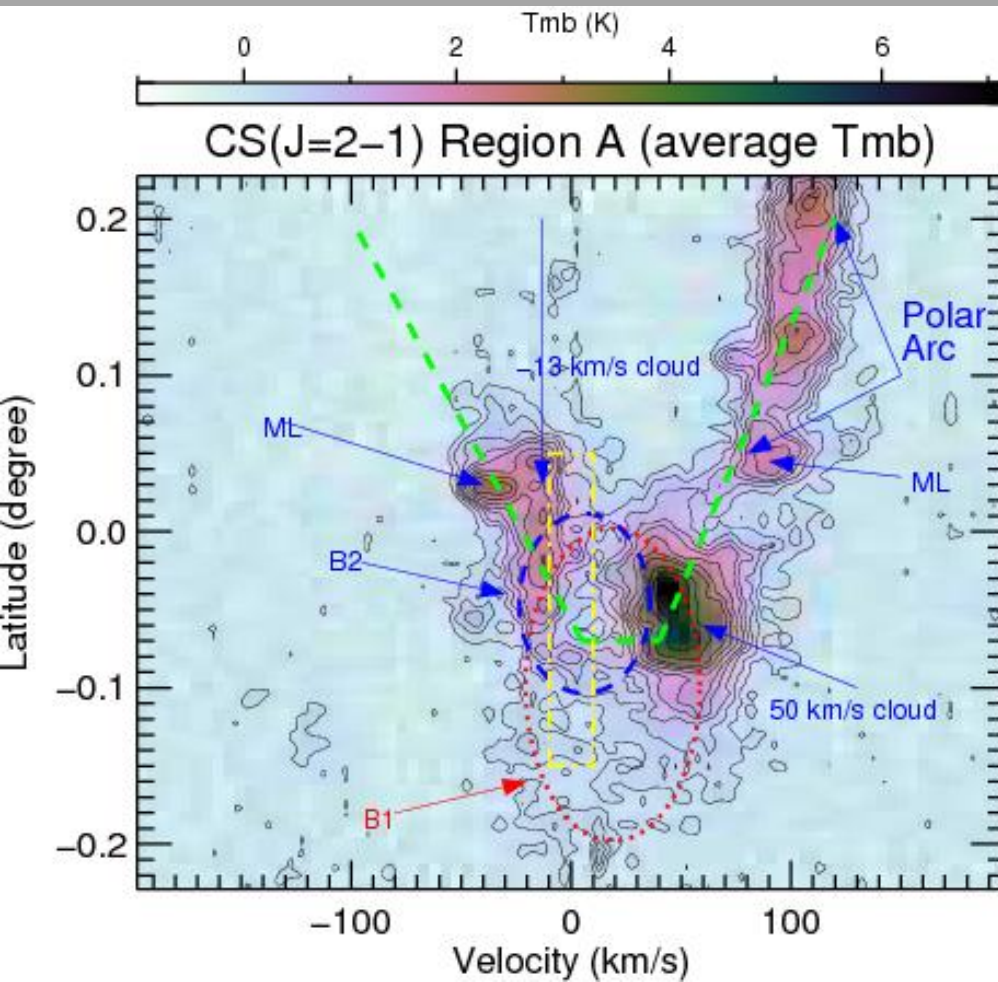
IAU-S322 Galactic Center compared with extragalactic nuclei



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

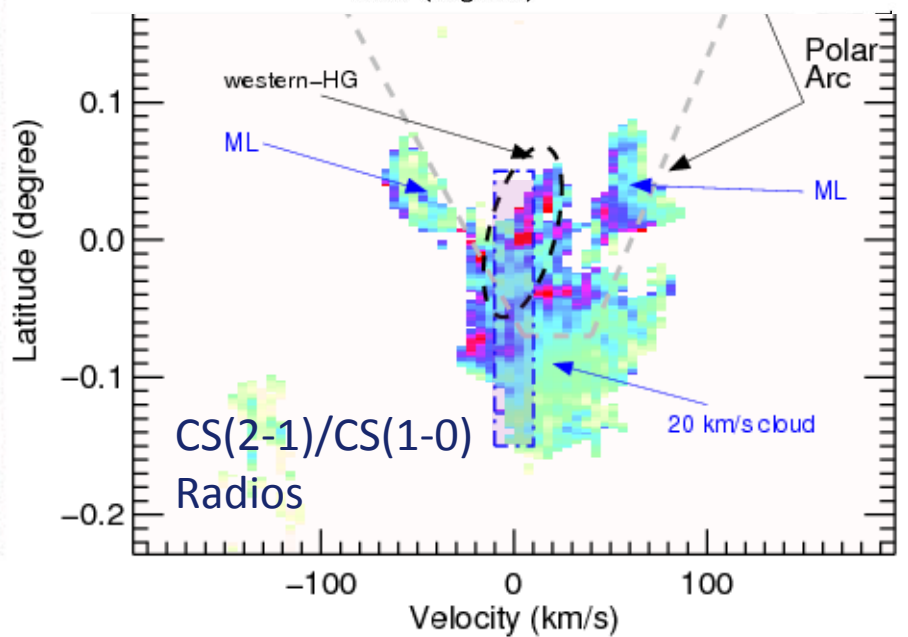
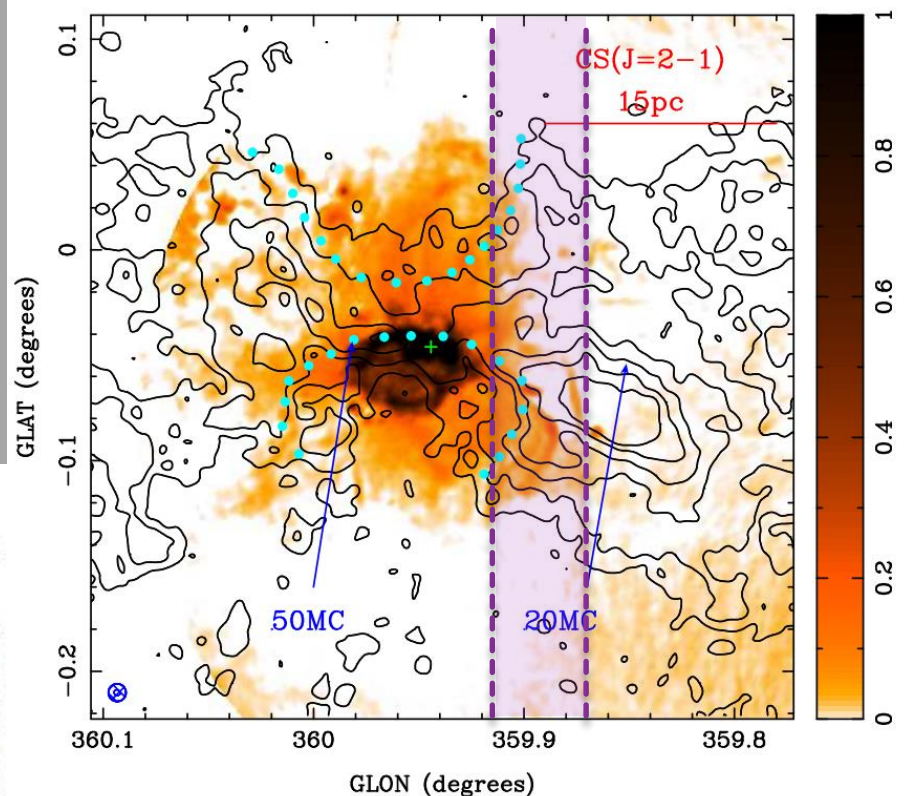
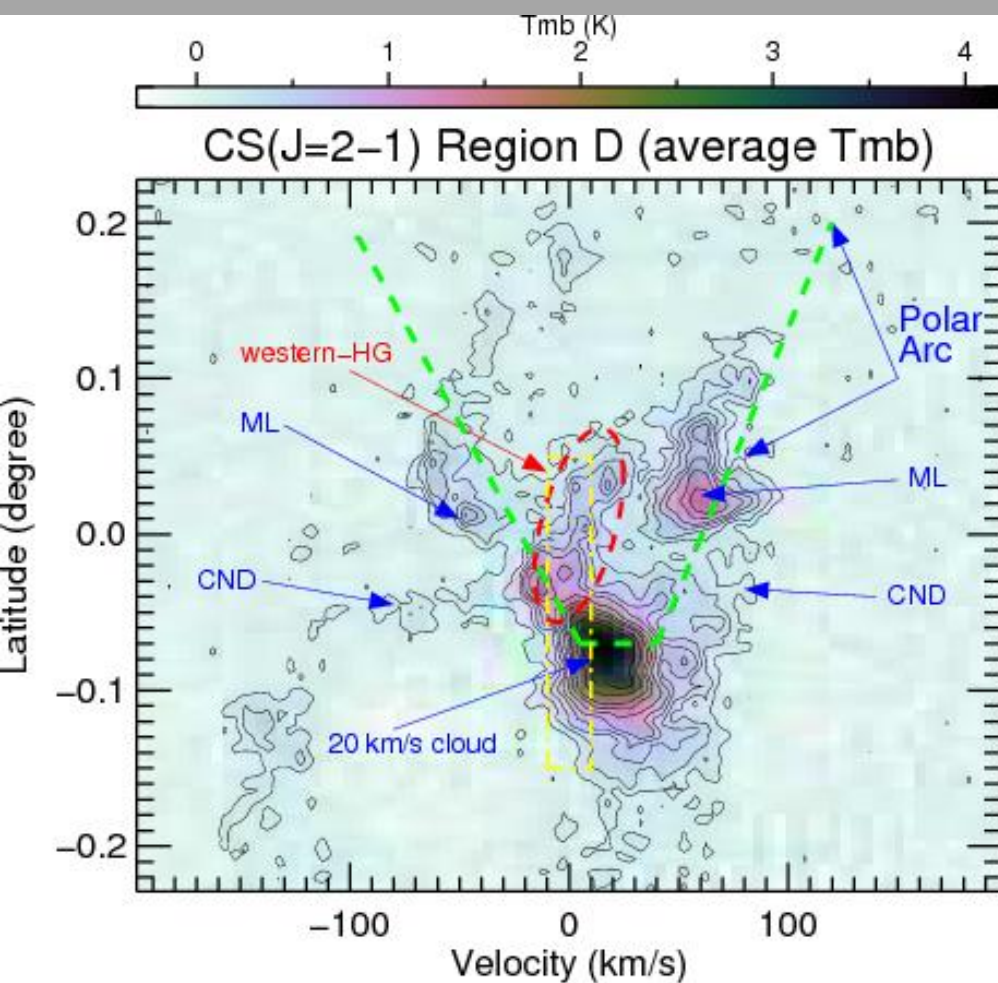
Eastern-HG feature

- 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



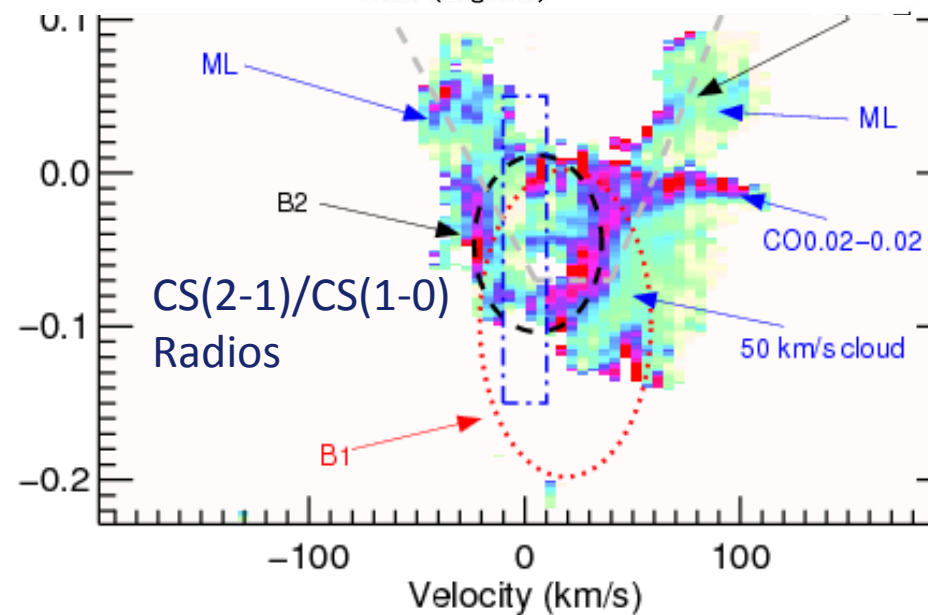
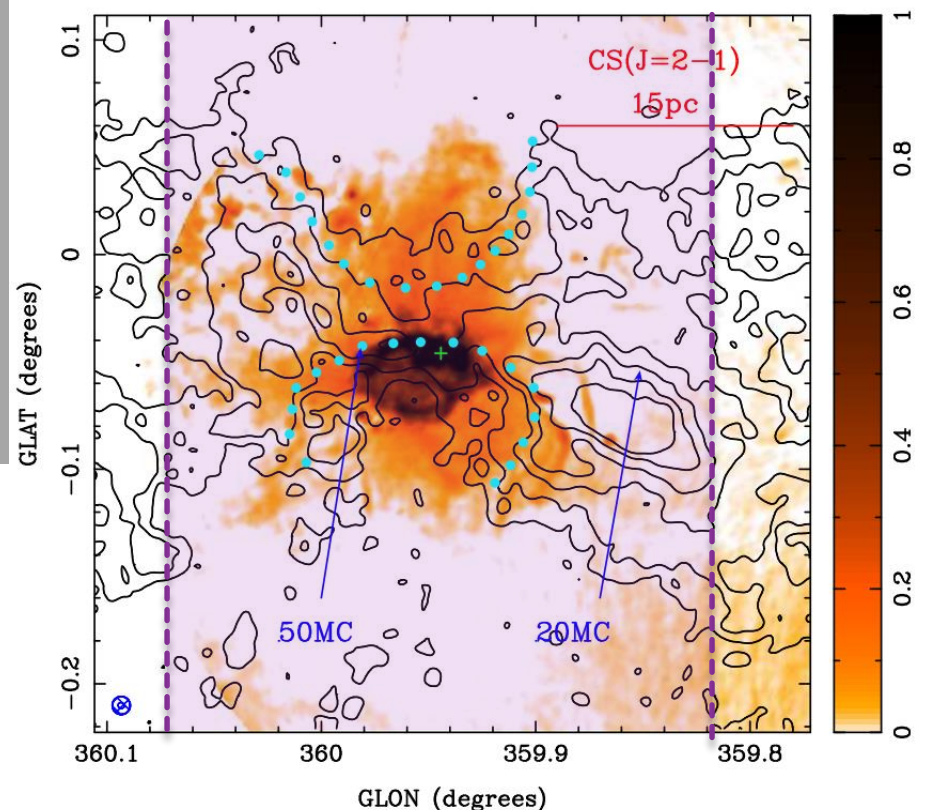
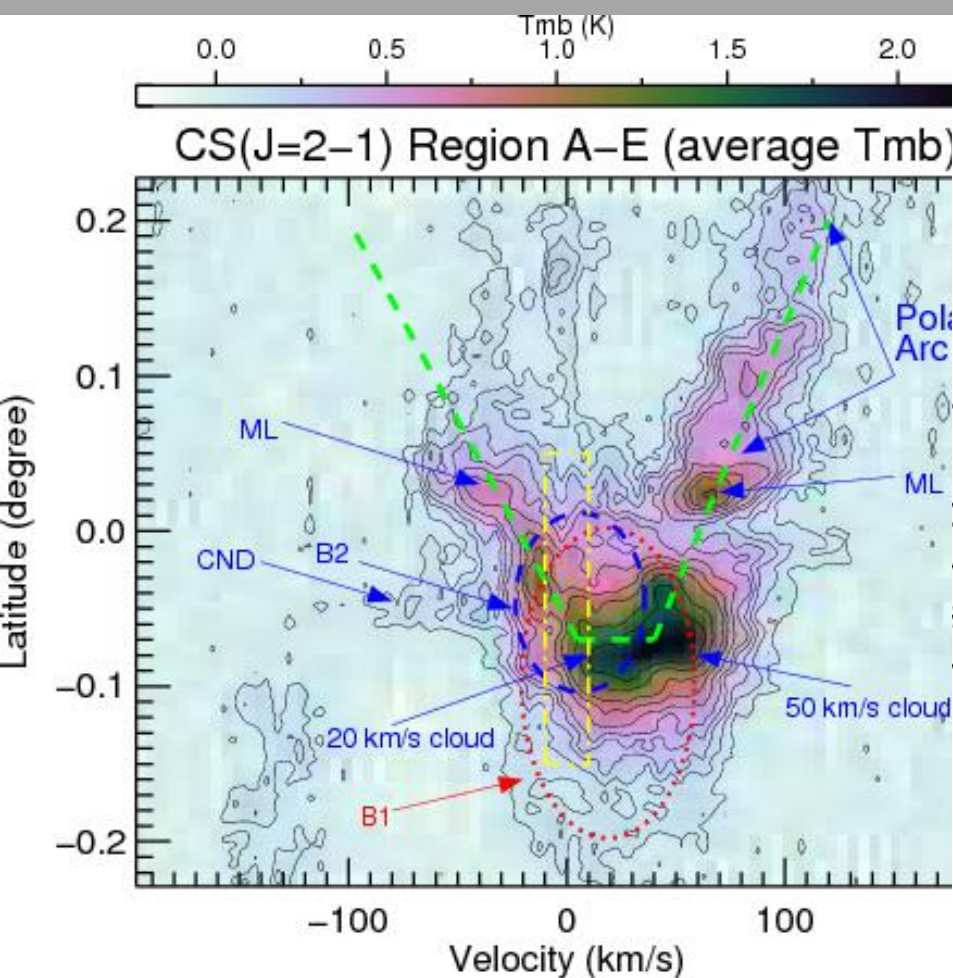
Western-HG feature

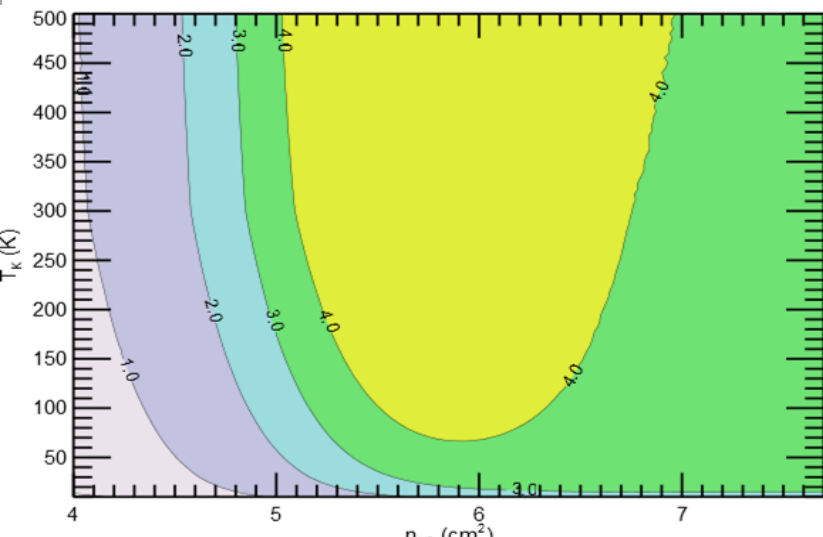
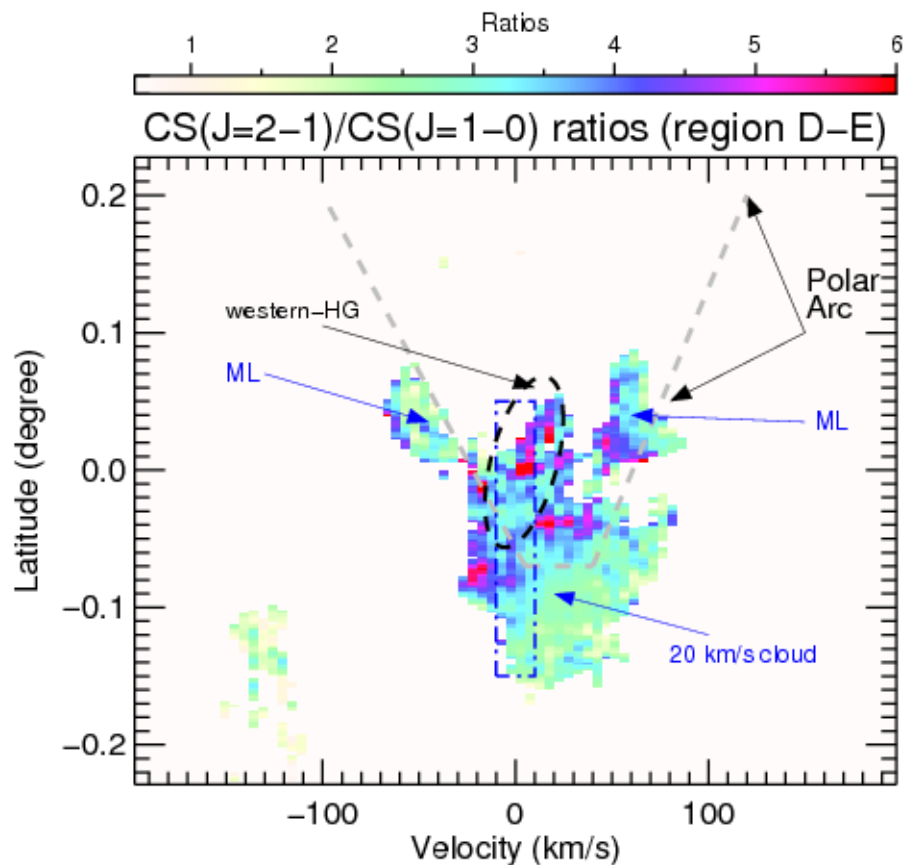
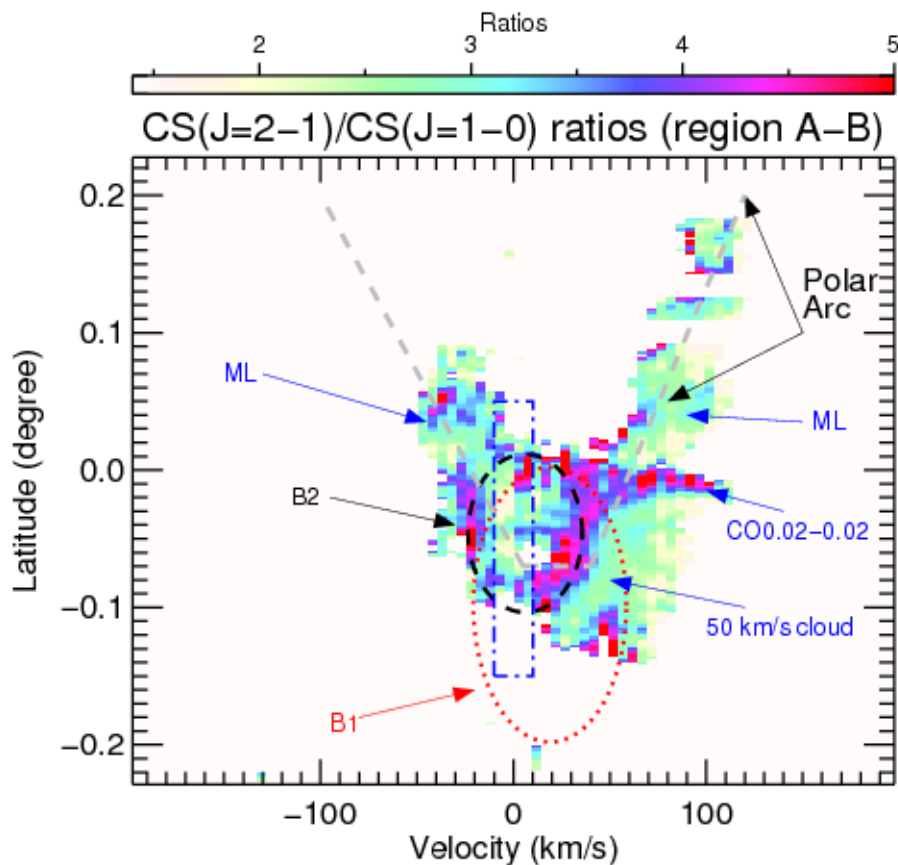
Entrained from the 20 MC



Latitude-Vel Diagrams

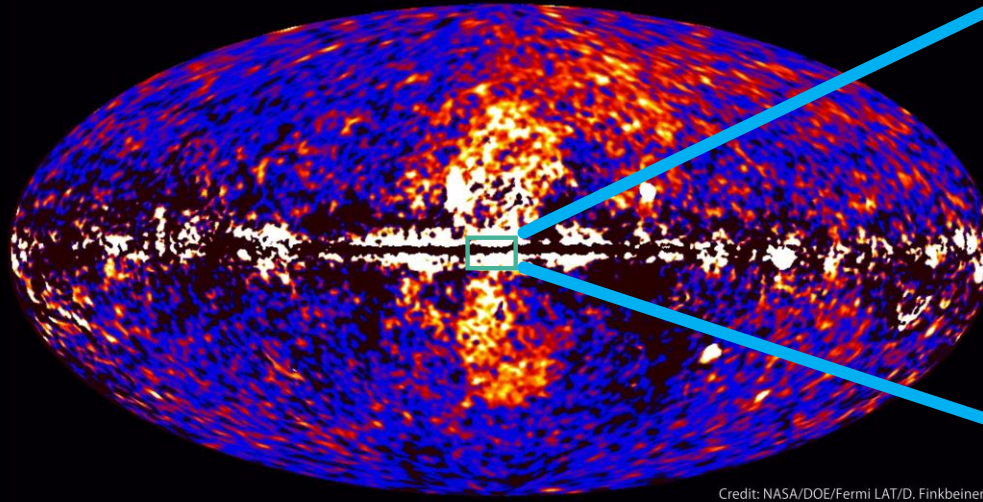
- The PA: outflow feature
- Bubbles
- Disk



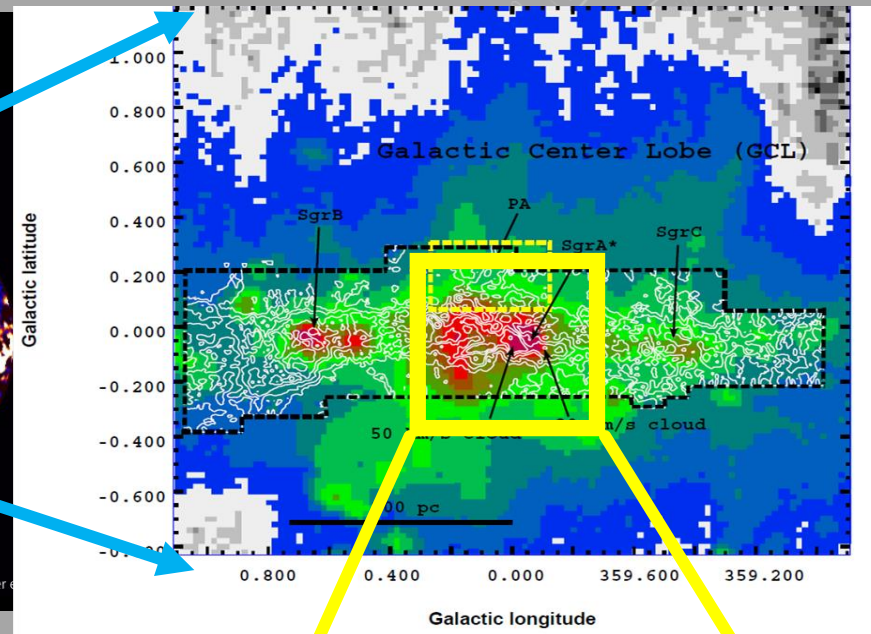


High temperature and density gas ($T > 70$ K, n_{H_2} : $10^{(5-7)} cm^{-3}$) associated with the nuclear outflow

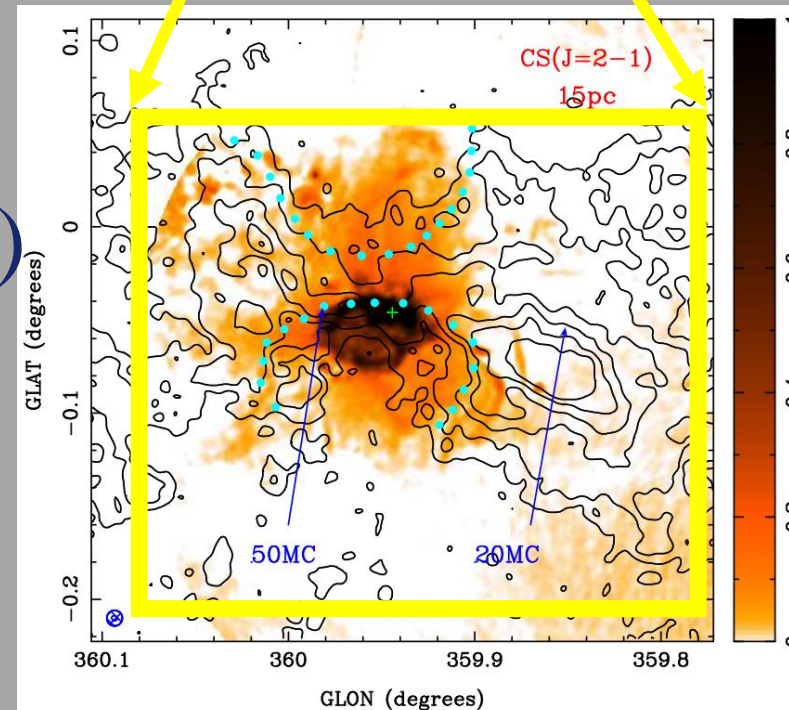
Fermi data reveal giant gamma-ray bubbles



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.