The Millimeter and Submillimeter View of the Galactic Center

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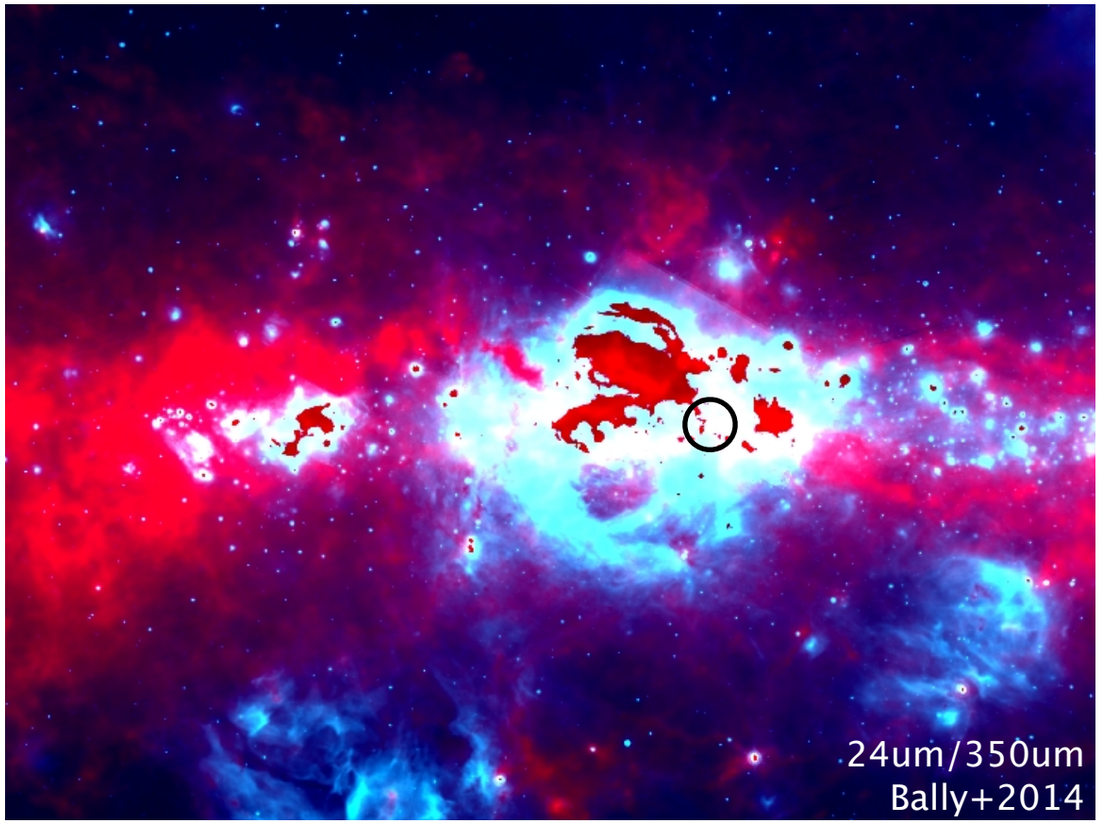
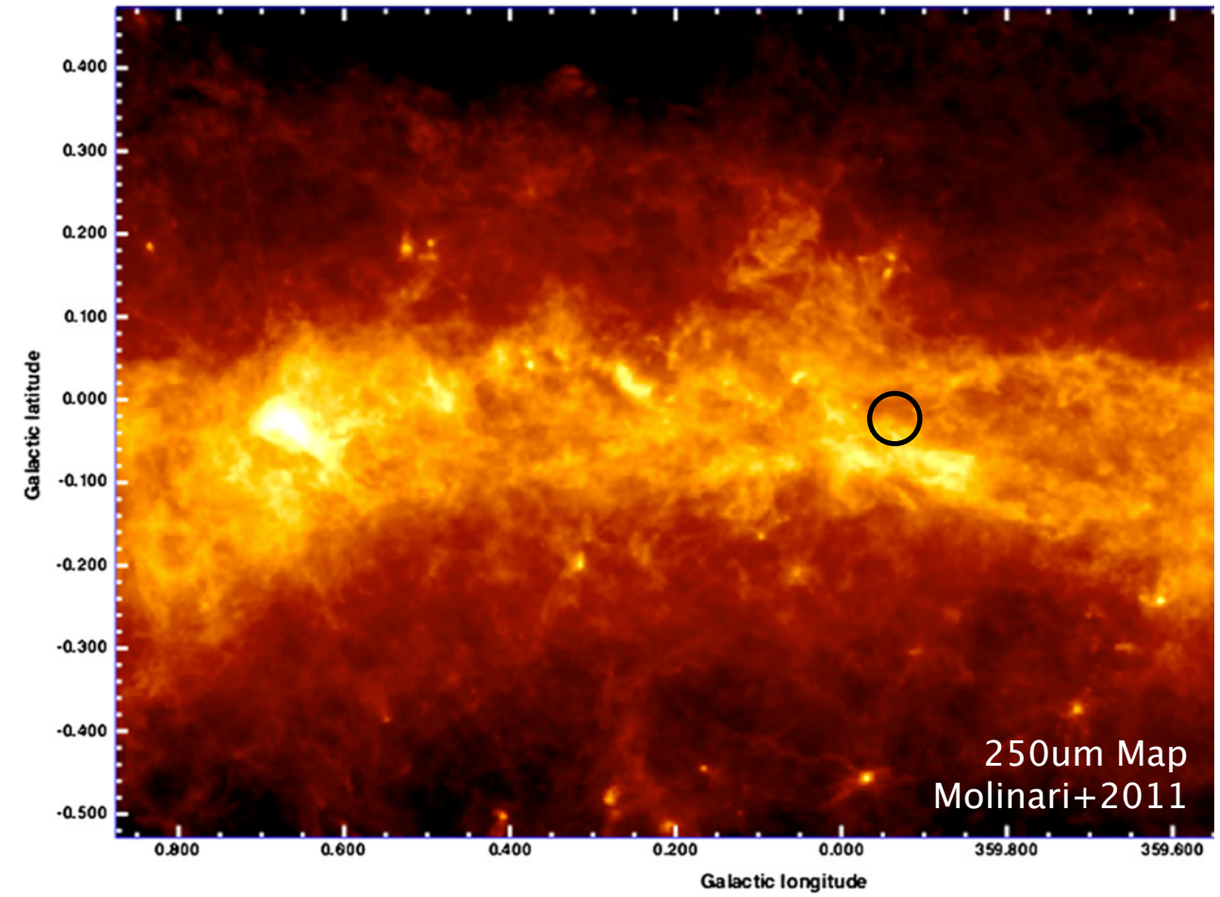
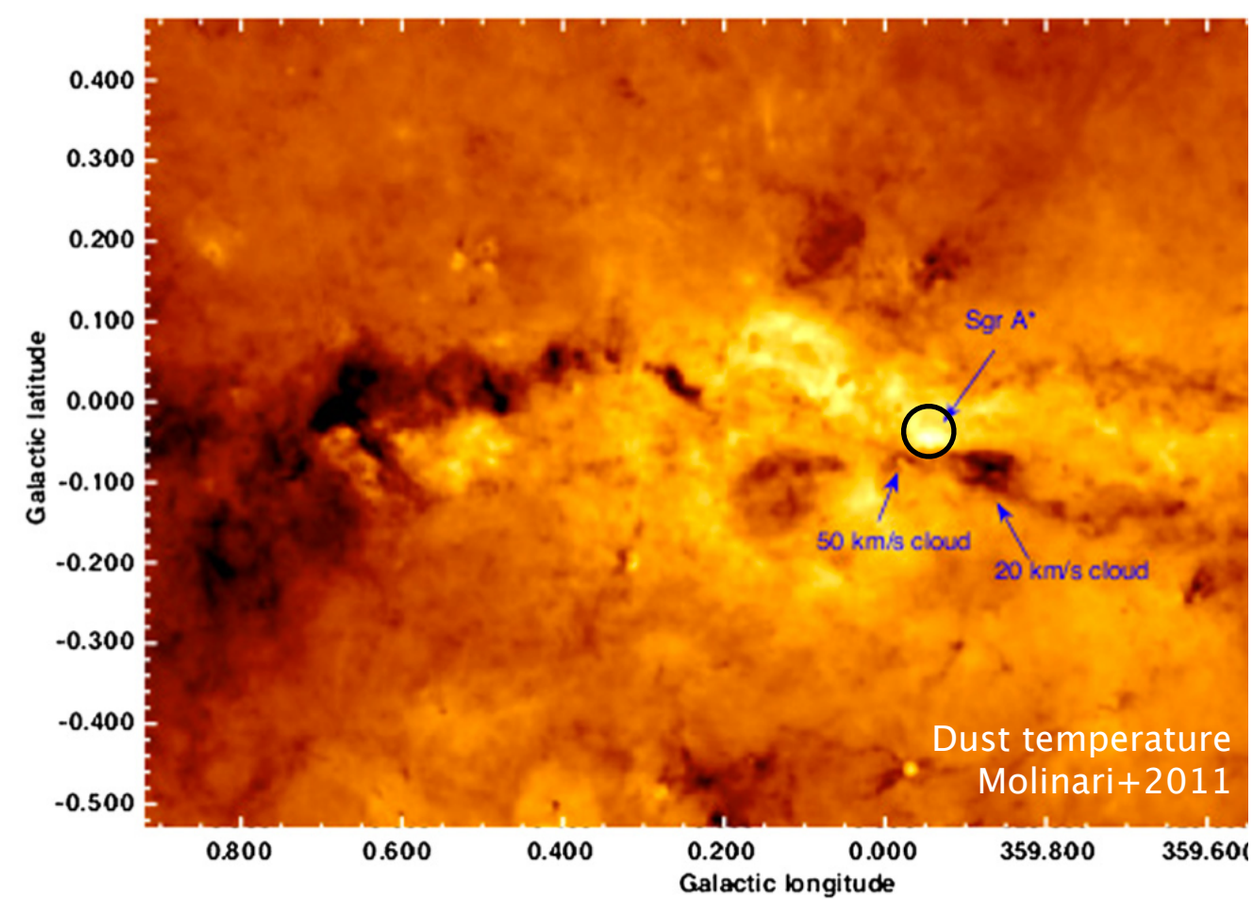
Jun-Hui Zhao
Diego Munoz
Mark Gurwell
Mark Morris
Fred Baganoff
Todd Hunter
EHT team
and more





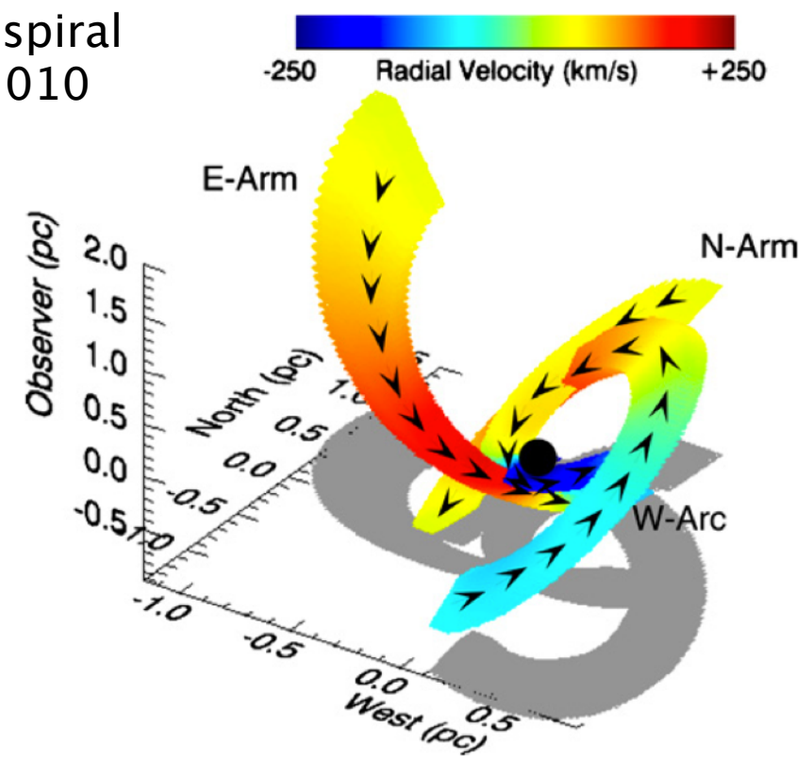
- A confused, confusing center
- Overlapping emission processes:
  - **Dust**, free-free, synchrotron, **molecules**
- A prime SMA target

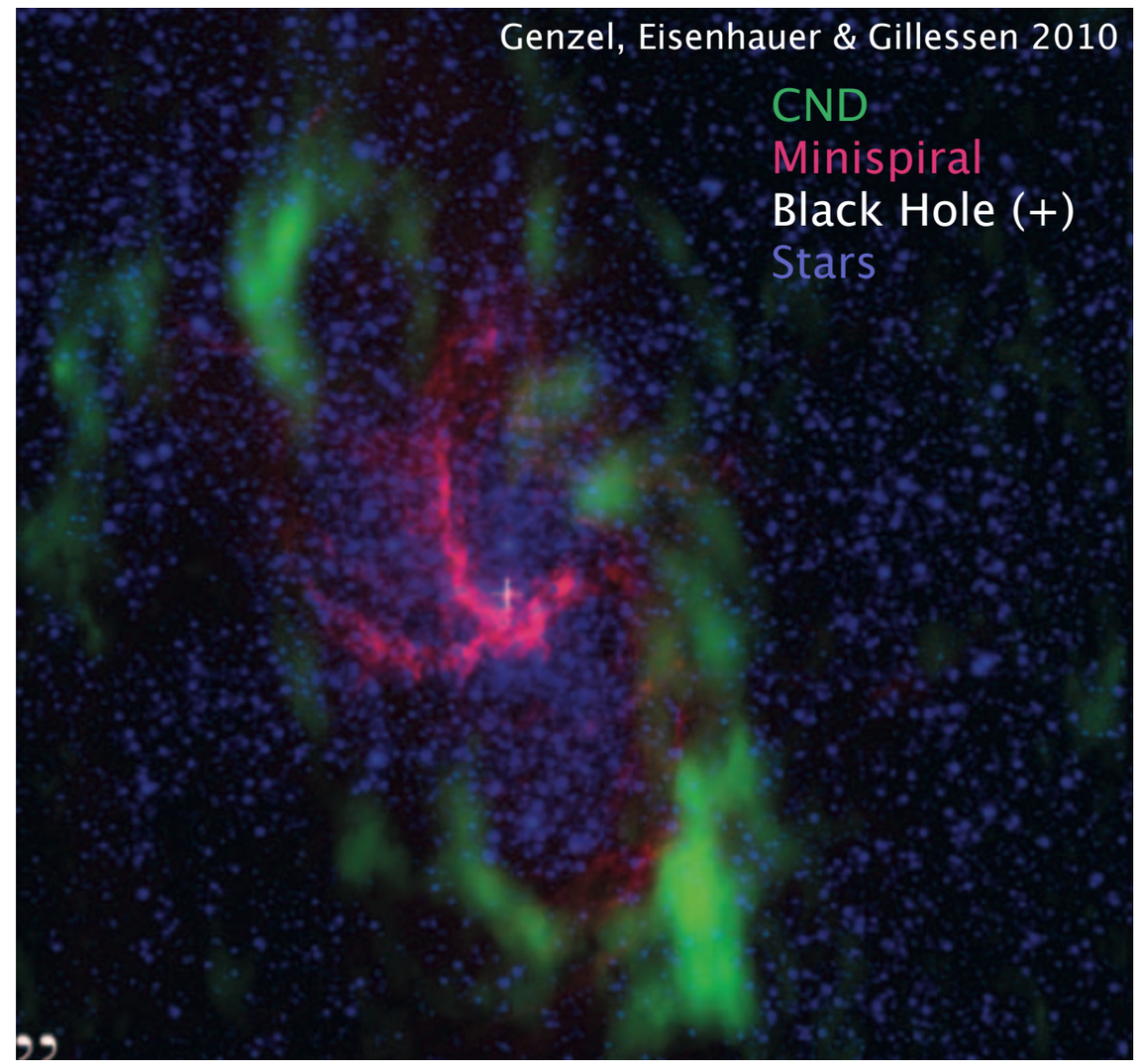


GC Overview

- Key Components:
  - Central black hole
  - Molecular gas at few pc distance ("Circumnuclear Disk" CND)
  - Ionized interior, prominent orbiting streamers ("Minispiral")

3D Minispiral
Zhao+2010

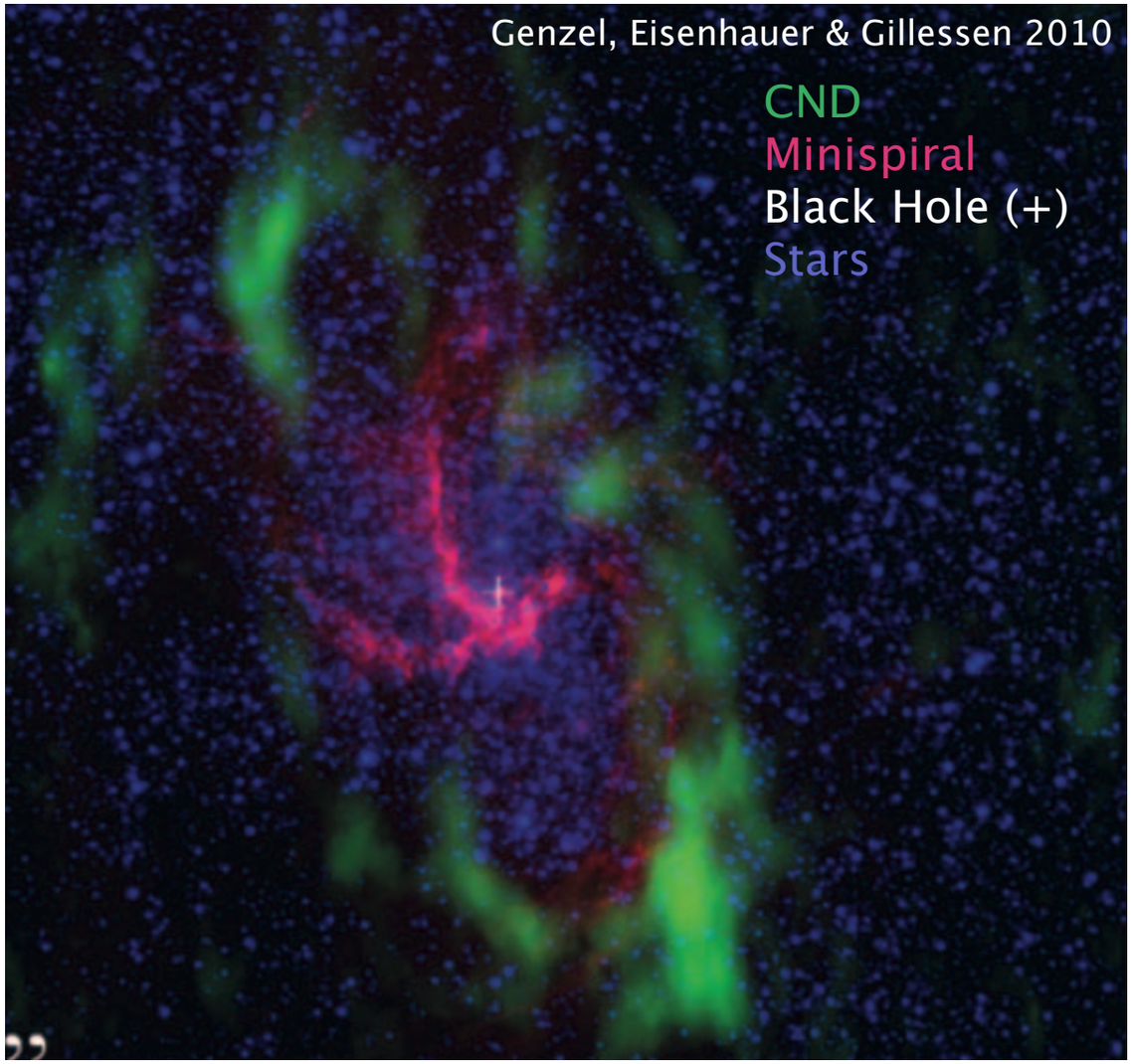




- Scales
  - 1 pc = 25"
  - 1" = 0.04 pc
  - Closest stellar approach: 5mas = 600r_s
  - Apparent BH size: 5r_s = 50 microarcsec

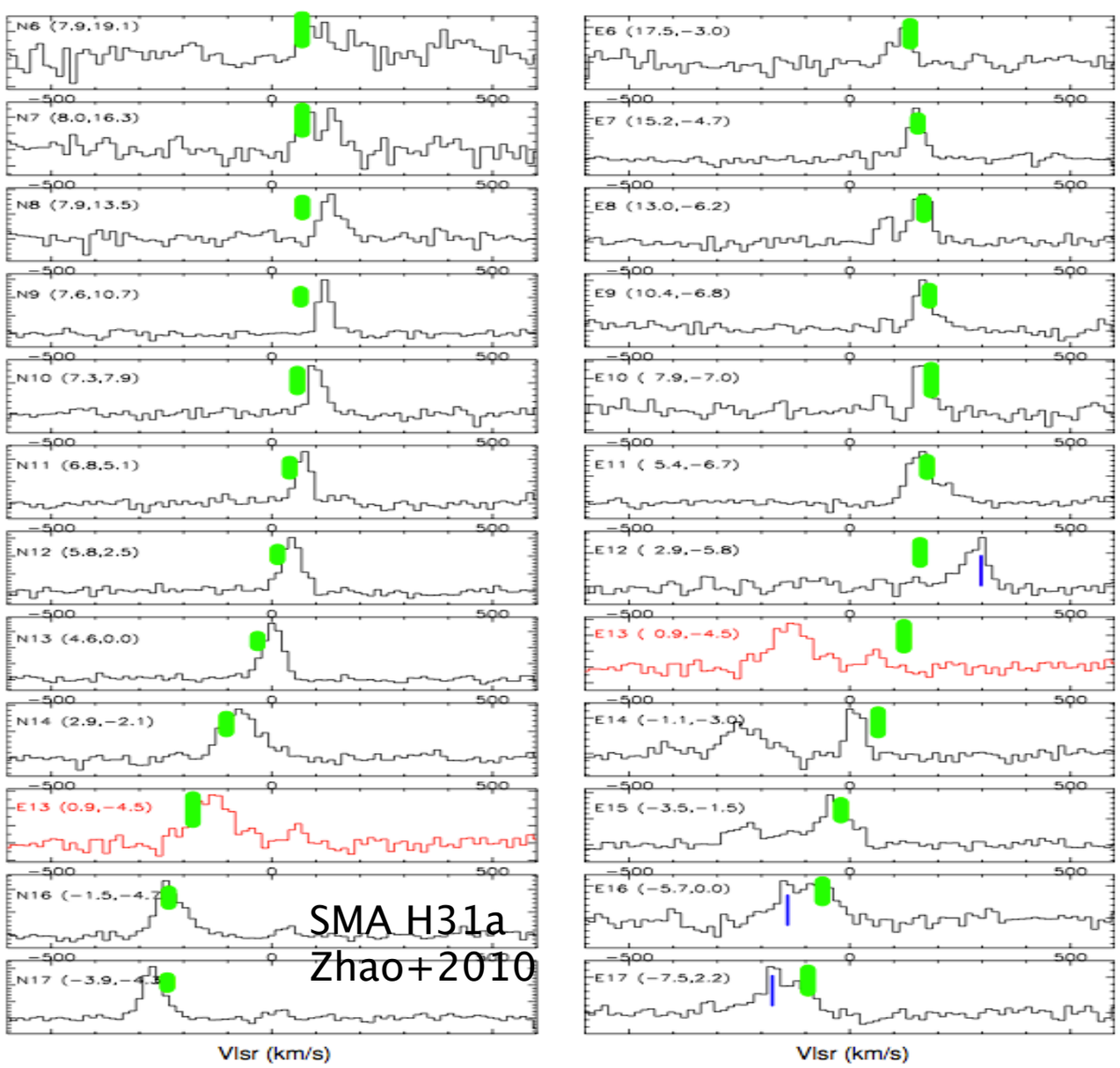
GC Overview

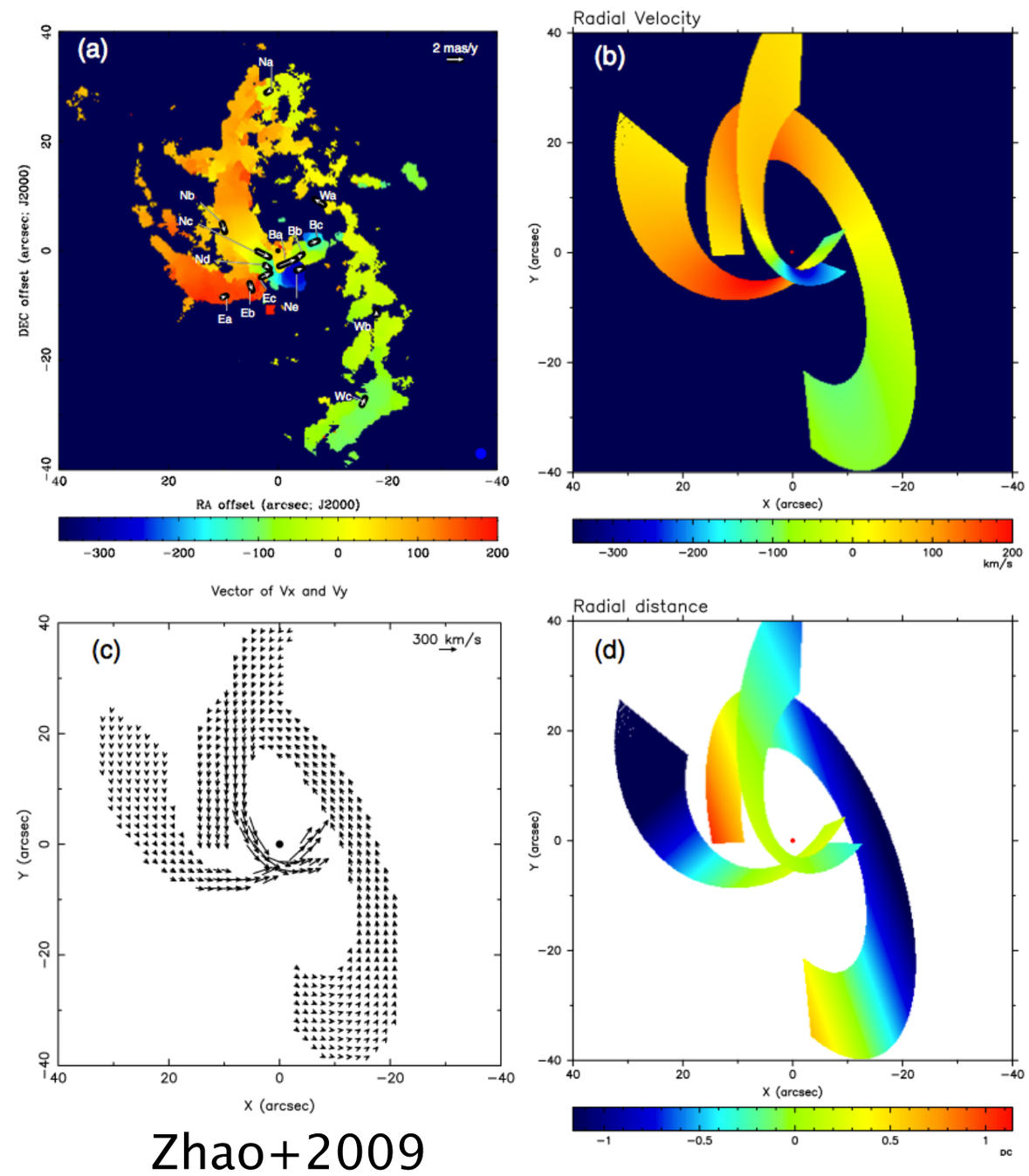
- Key Components:
  - Central black hole
  - Molecular gas at few pc distance ("Circumnuclear Disk" CND)
  - Ionized interior, prominent orbiting streamers ("Minispiral")
- A nuclear laboratory:
  - Stellar and nuclear feedback
  - Black hole accretion
  - Short-lived events



Feeding the Center

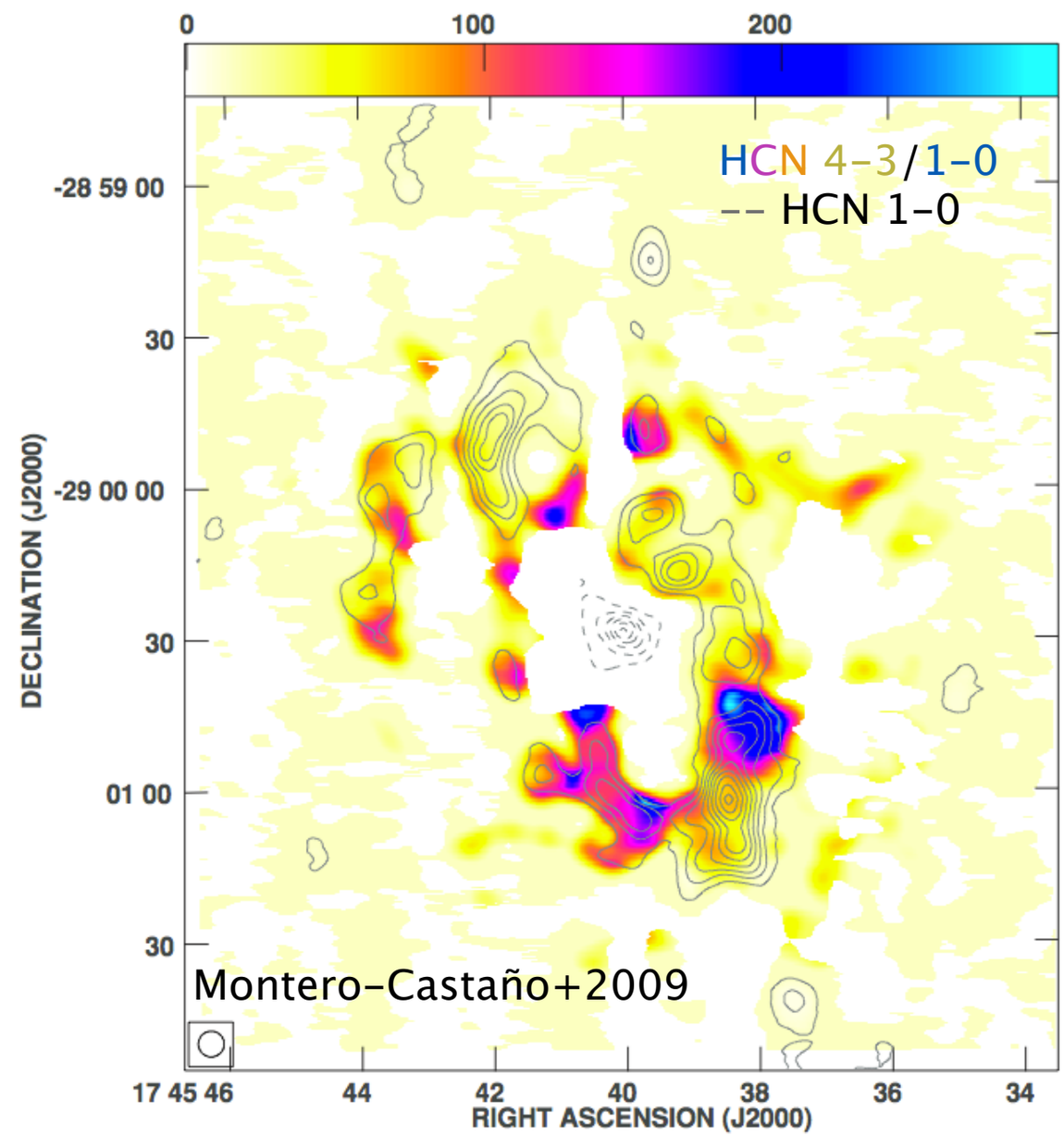
- Key questions: dynamical structure and persistence in central gas flows?
- Minispiral (Jun-Hui Zhao et al.)
  - 3D model from VLA proper motions
  - SMA: deviations from Keplerian motion





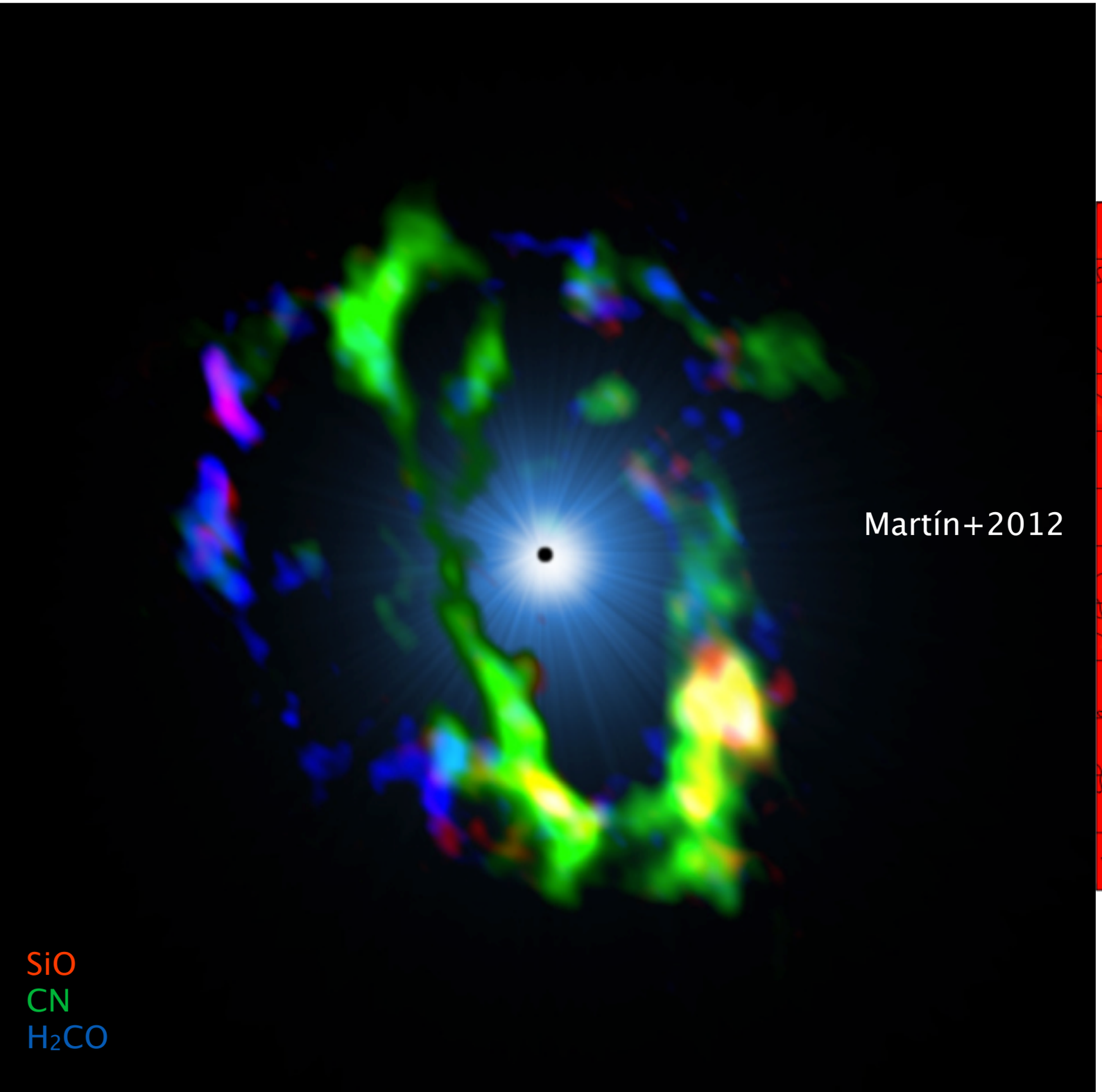
Feeding the Center

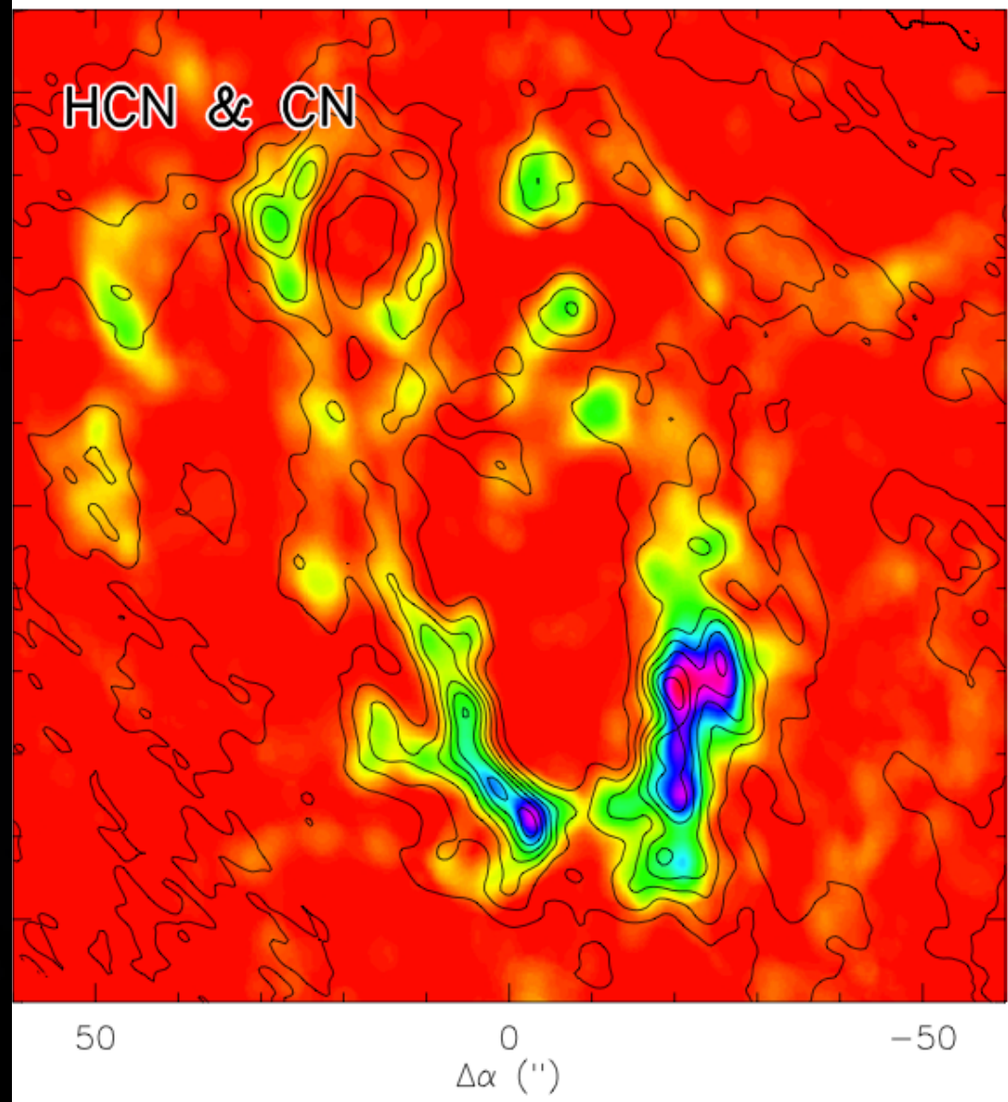
- Key questions: dynamical structure and persistence in central gas flows?
- CND (PTP Ho and students, predocs, postdocs)
  - Variations in physical conditions around the "ring"
  - Possibly stable clumps
  - (No star formation, however)
- See next talk



Nuclear Chemistry

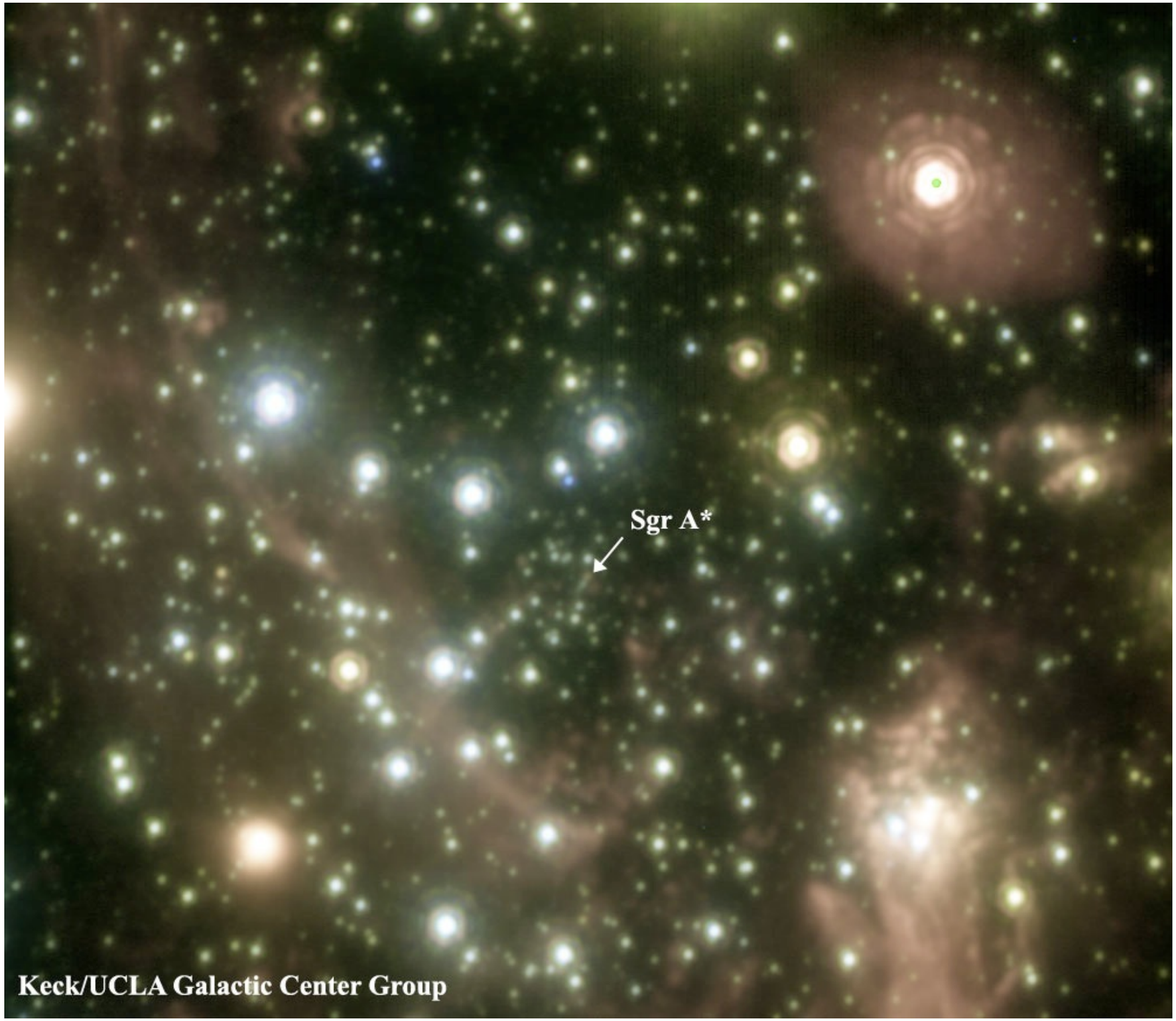
- Formation/interactions of CND with surroundings further explored through multiple tracers





Sagittarius A*

- Faint, variable heart of the Milky Way galaxy



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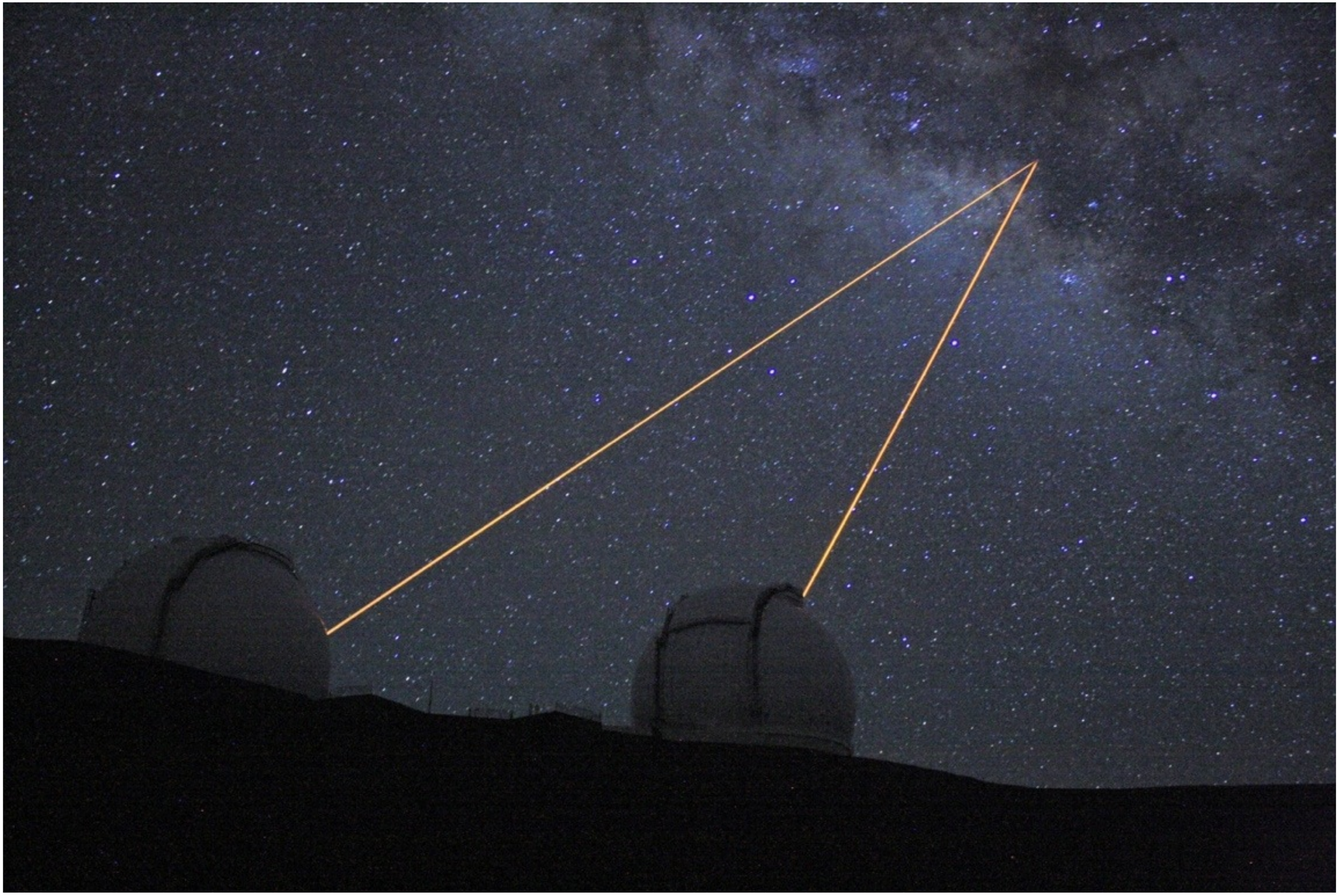
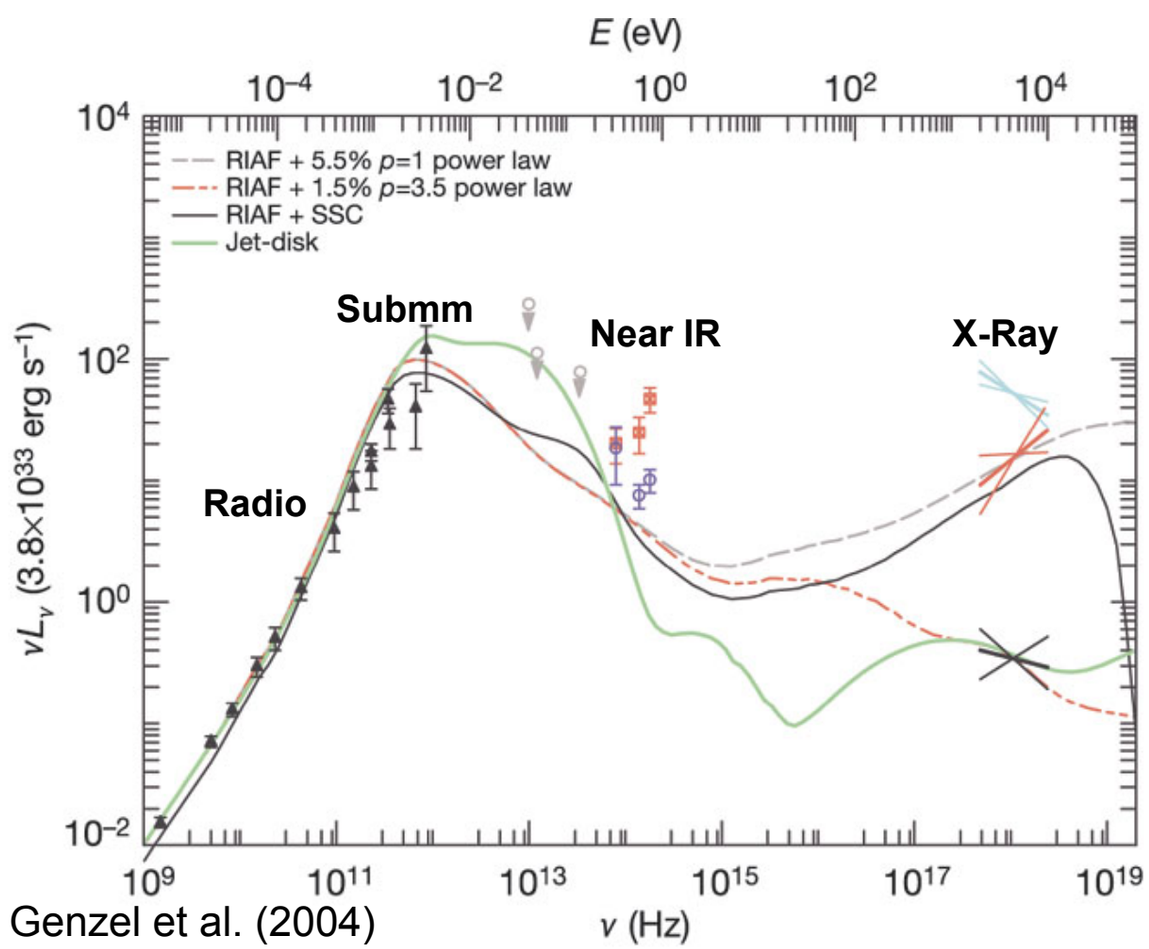
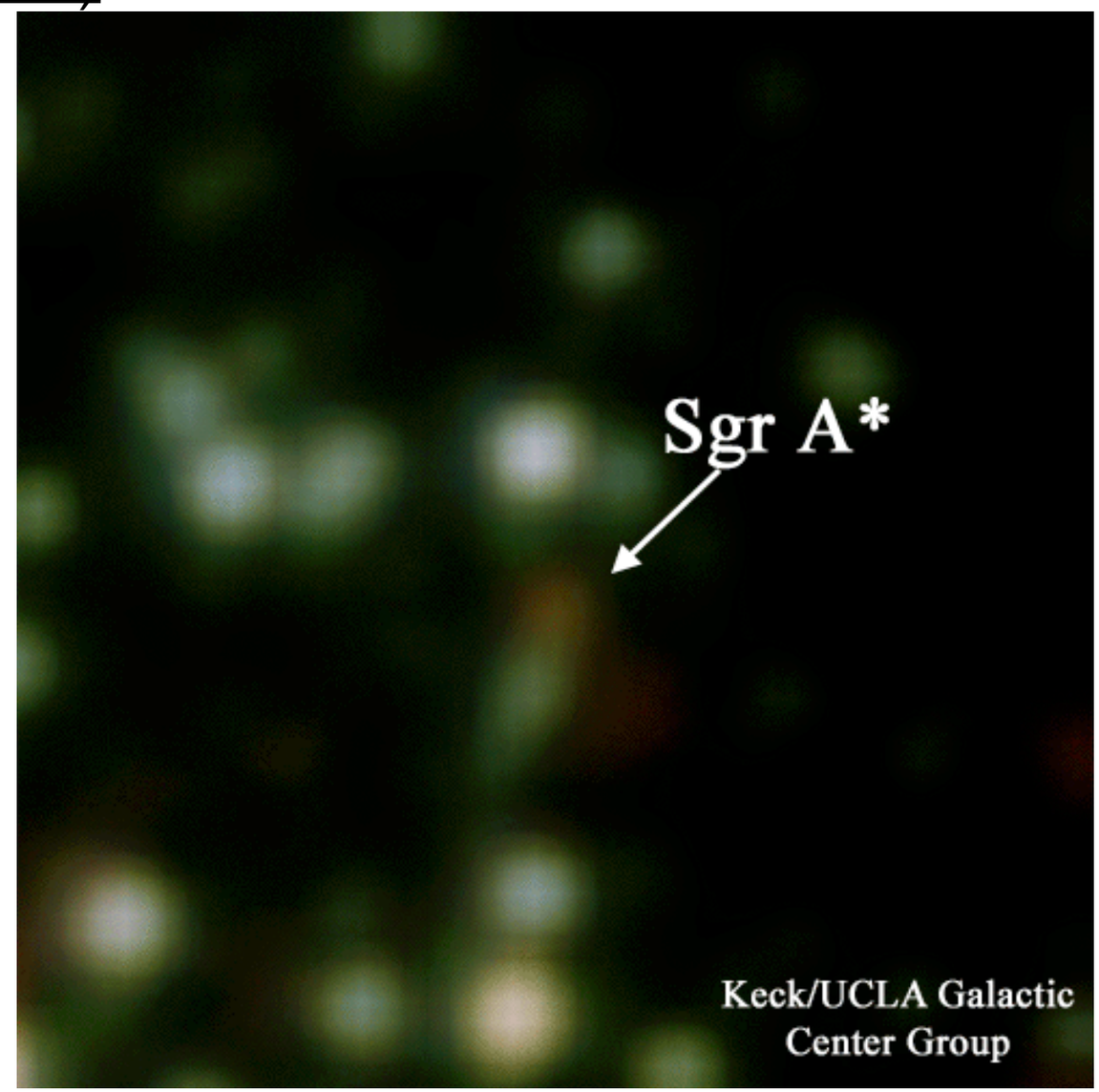


Sagittarius A*

- Faint, variable heart of the Milky Way galaxy
- Just becoming optically thin at λ1.3mm (and shorter)
- Just emerging from interstellar scattering at λ1.3mm (and shorter)
- Polarized at λ1.3mm (and shorter)
- <u>SMA observes at λ1.3mm (and shorter)</u>



Genzel et al. (2004)



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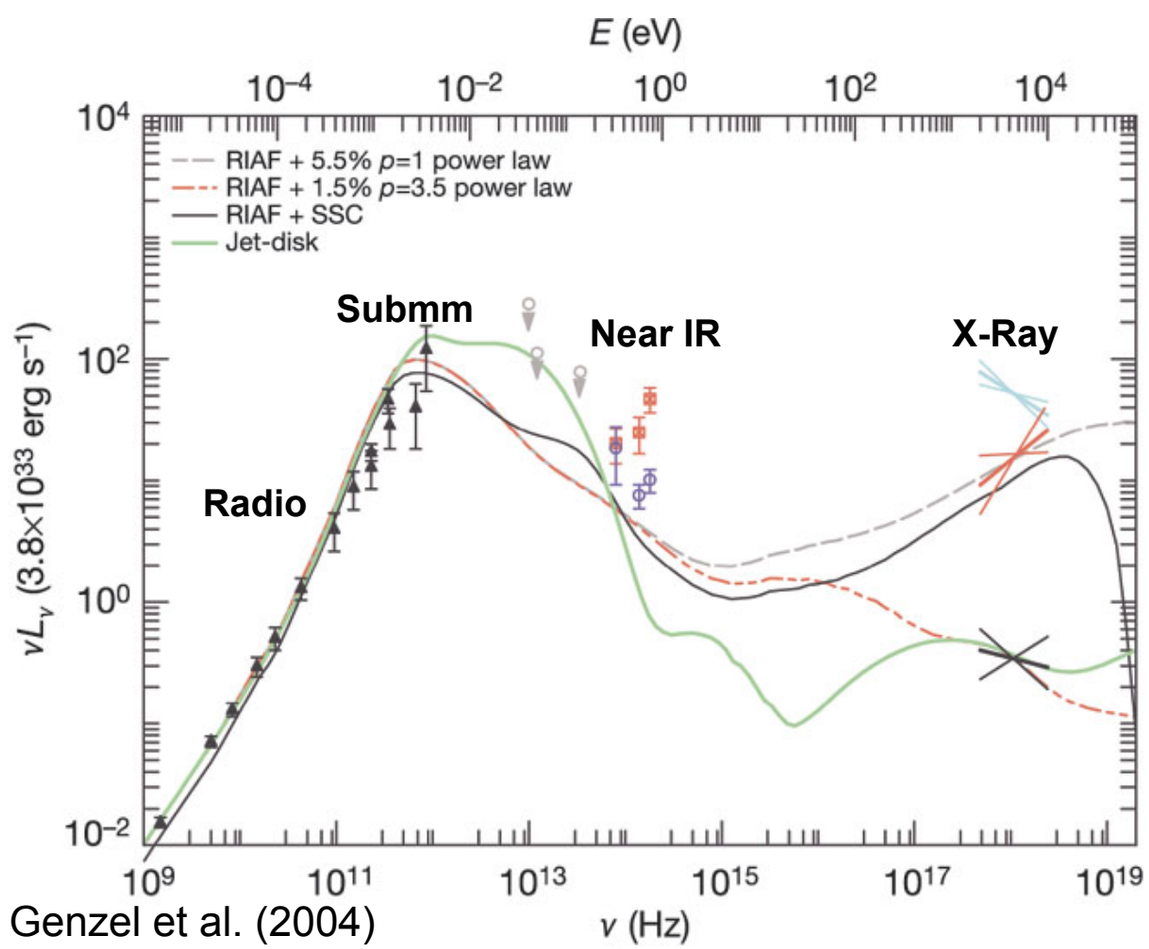

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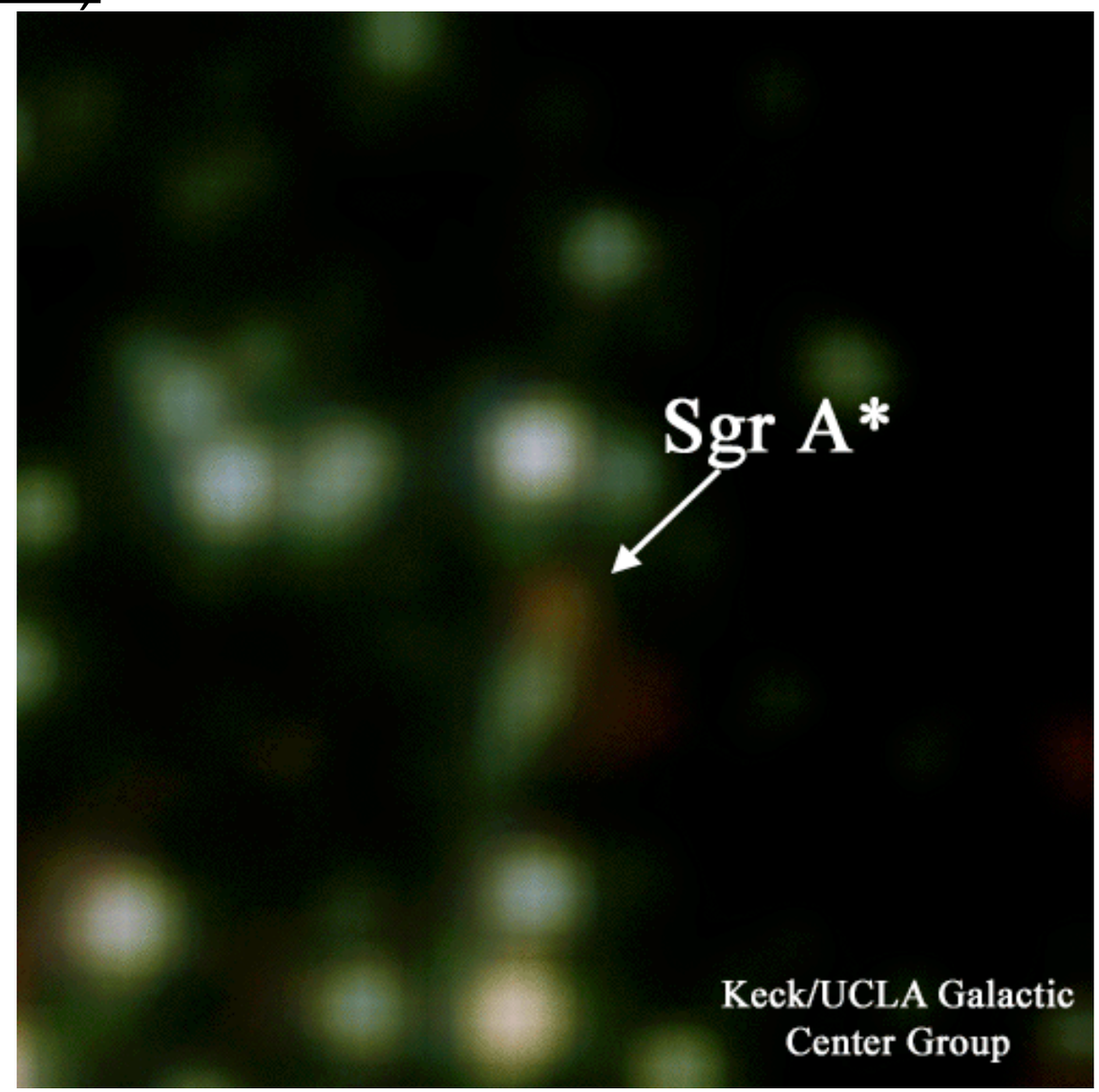
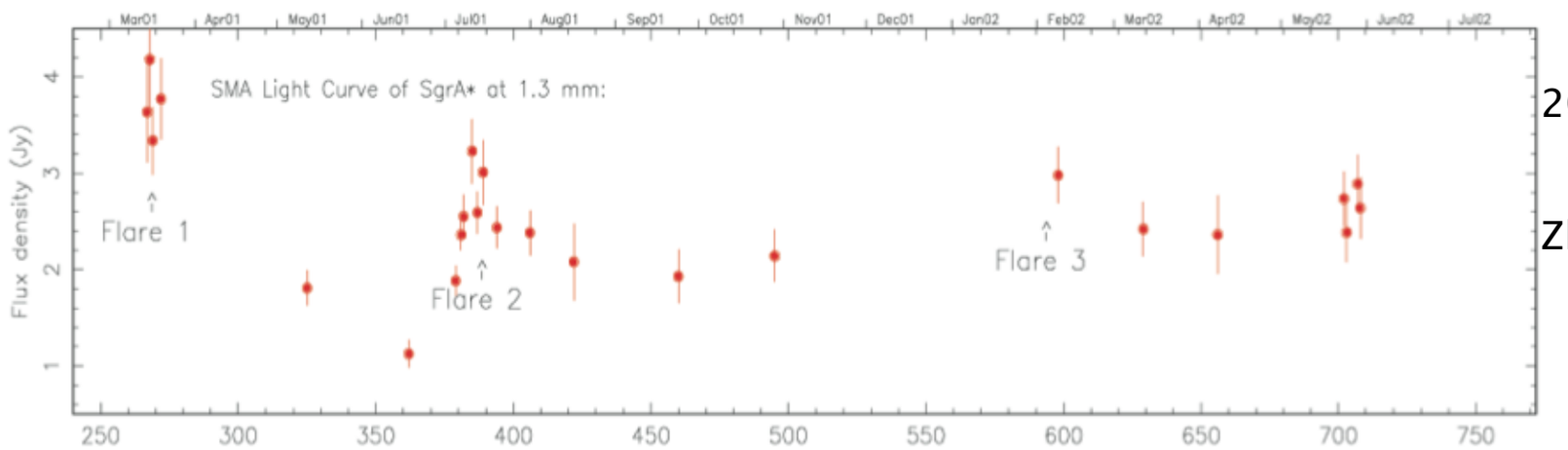
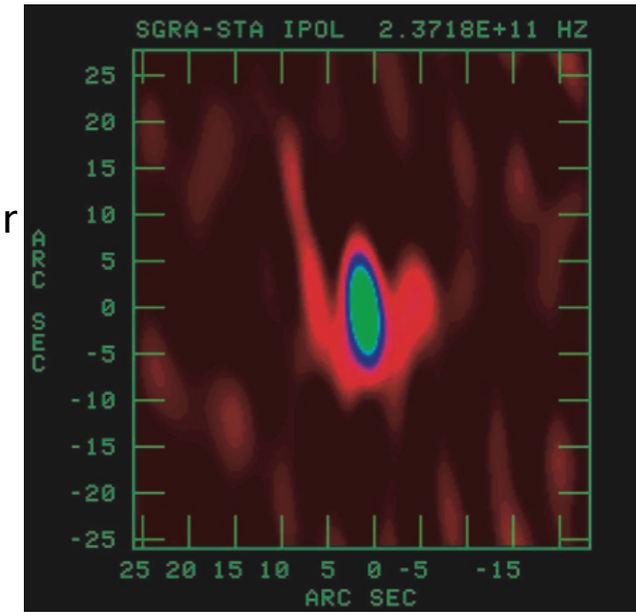


Variability of Sgr A*

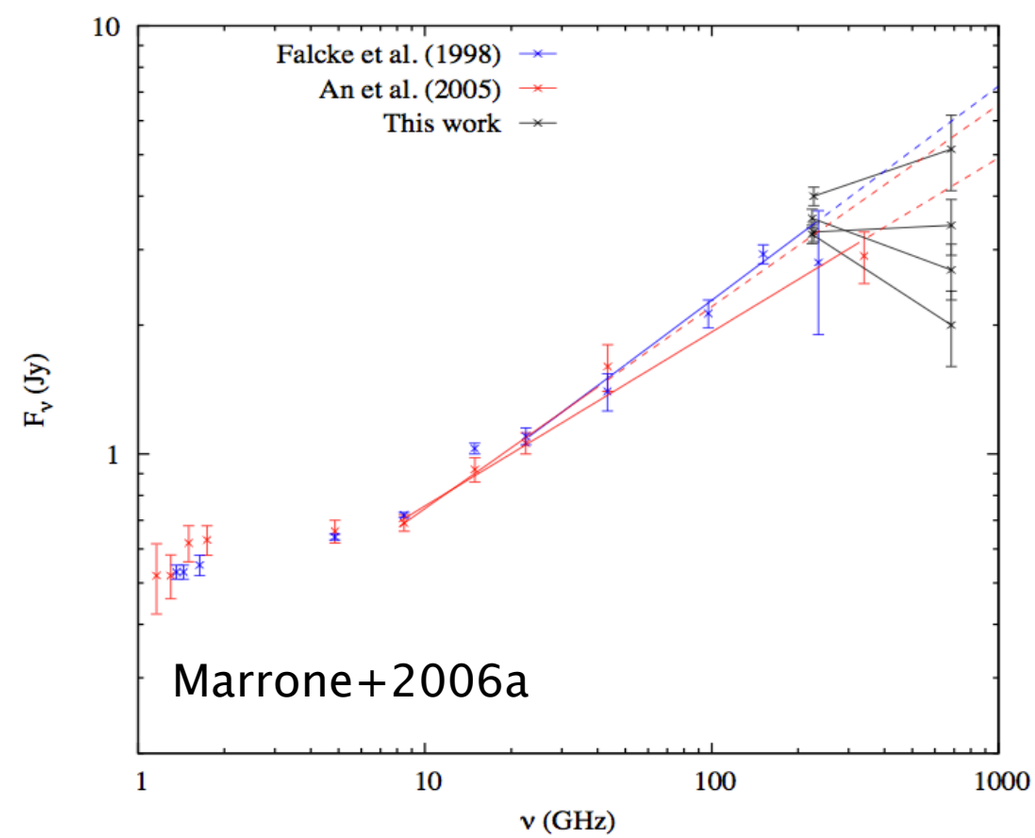
- Probe of accretion changes, possible orbiting features
- Zhao+2003: secure 1.3mm variability, no ISCO periodicities (27min or less)



2002 SMA:
3–4 telescopes
1/6 of correlator
Zhao+2003

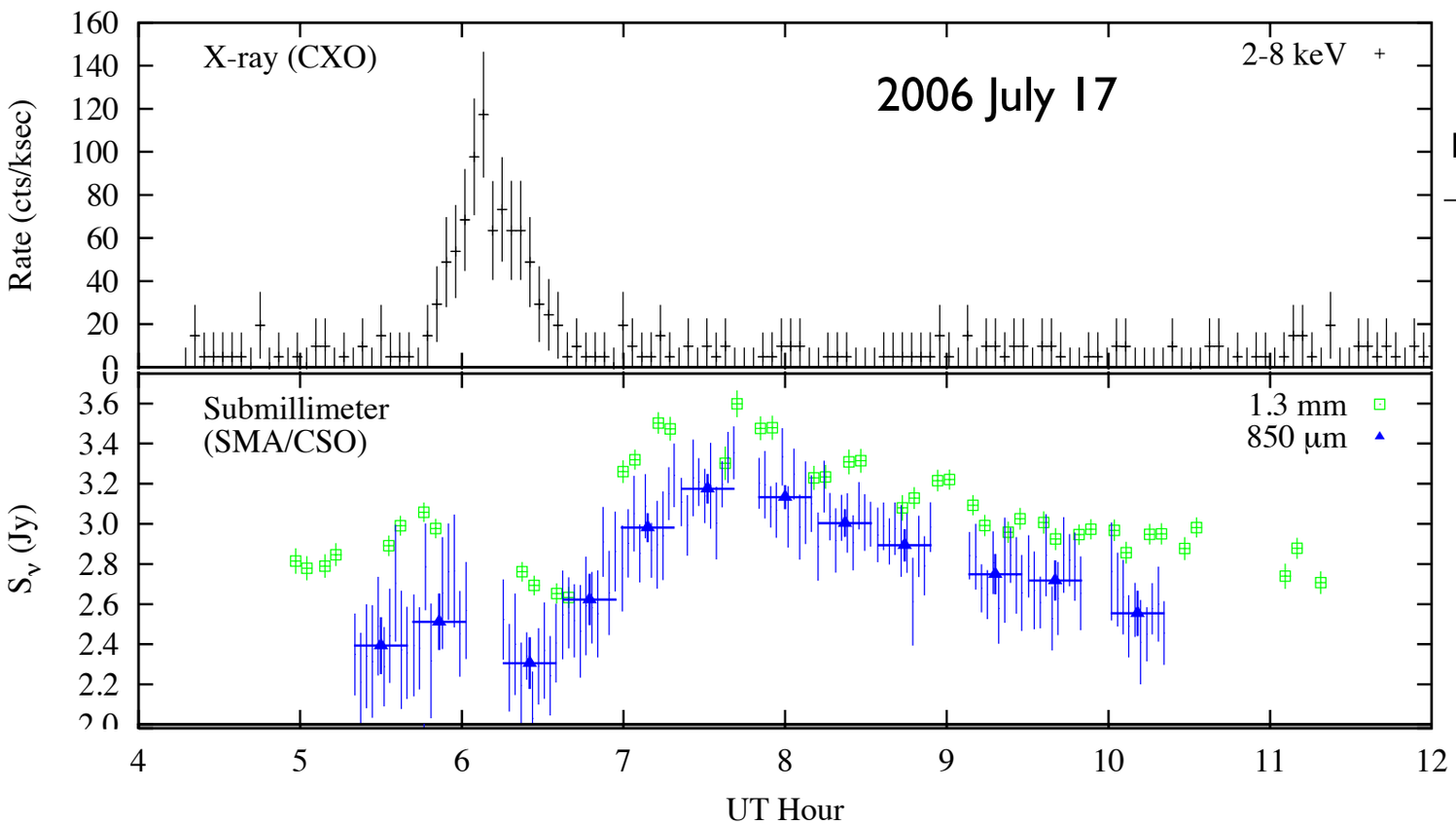


- SMA 230/690: Sgr A* becomes optically thin between these frequencies. Spectral index varies during flaring

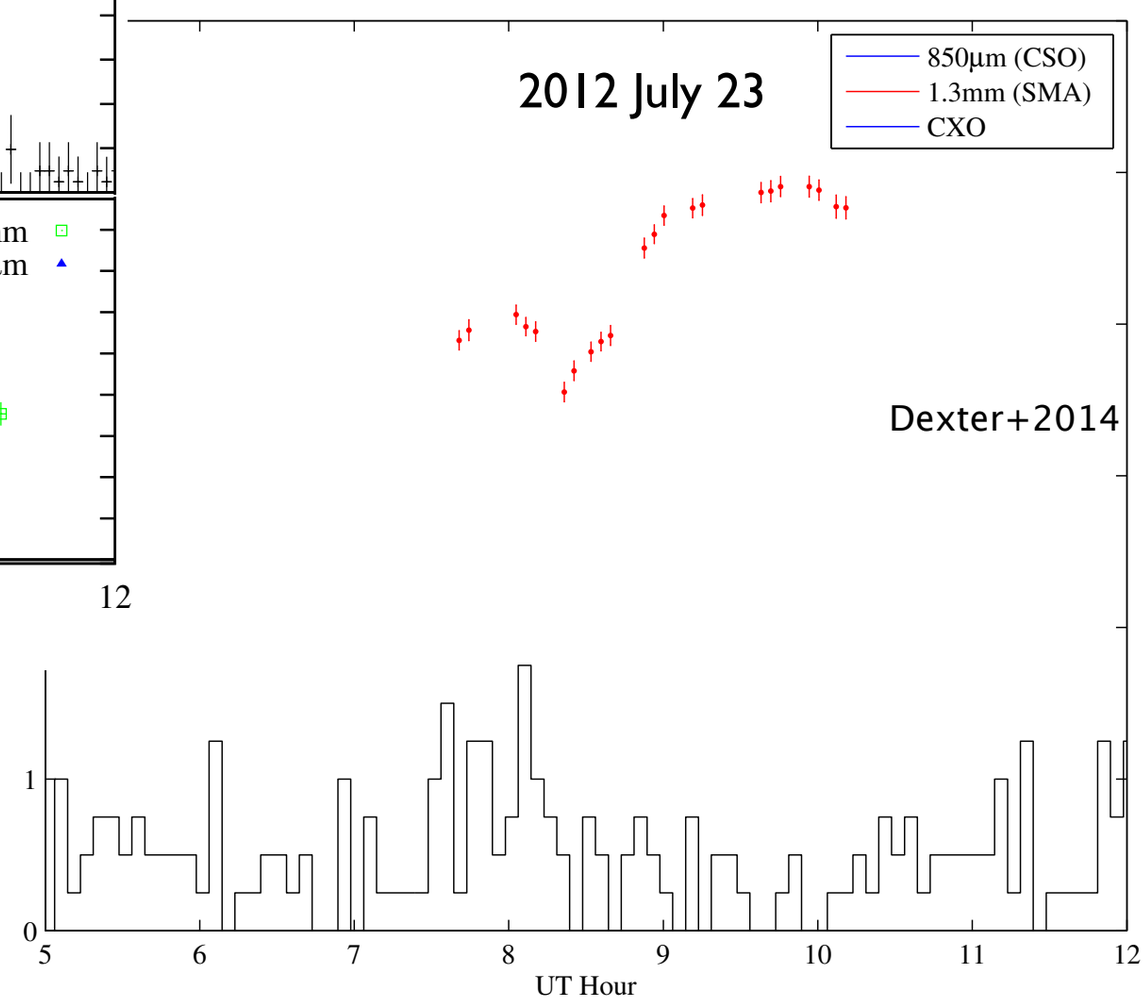


Variability of Sgr A*

- What is the origin of the flares?
  - Submm lags behind IR and X-ray
  - Somehow energy of flares is hidden in submm despite low opacity
    - Different populations of radiating electrons in IR and submm?



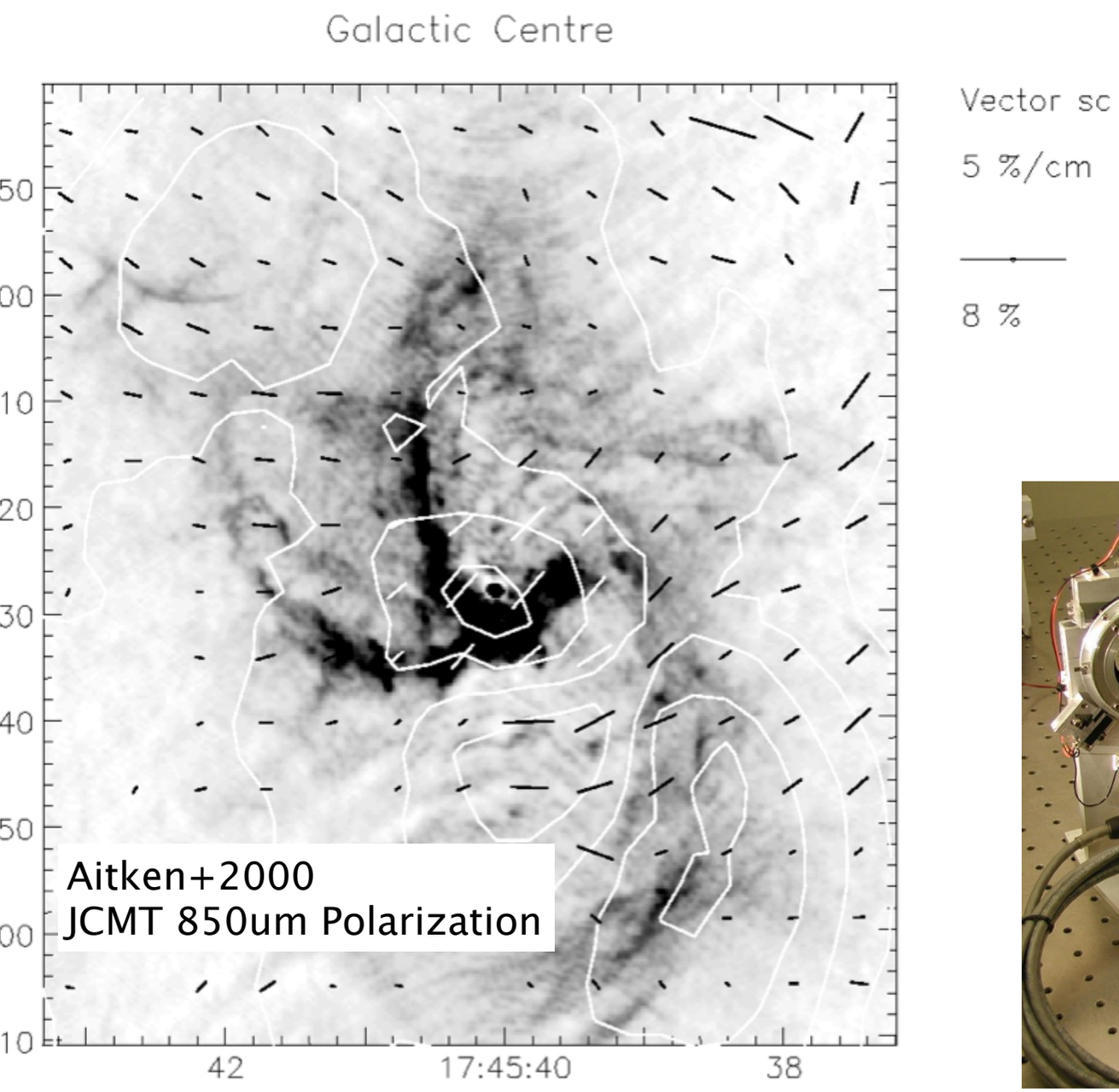
Marrone+2008



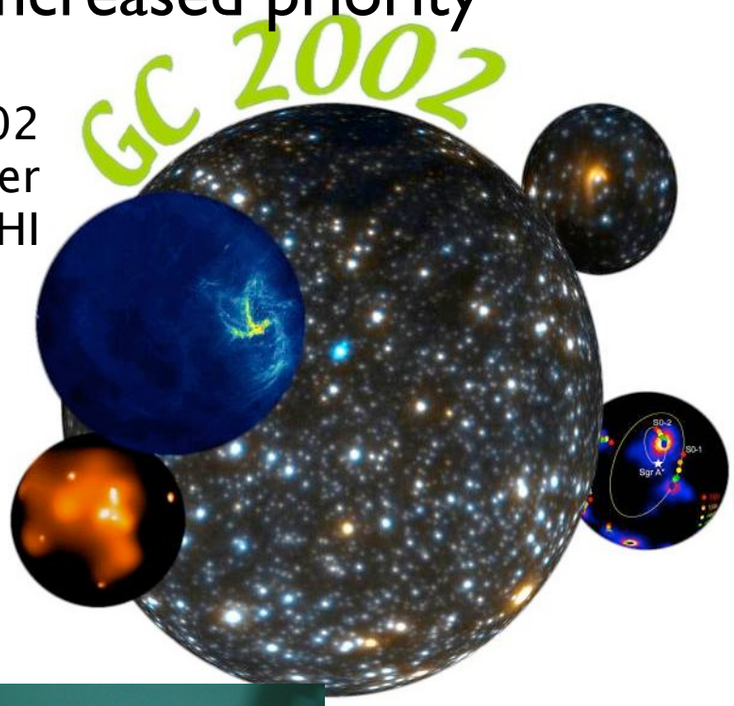
Dexter+2014

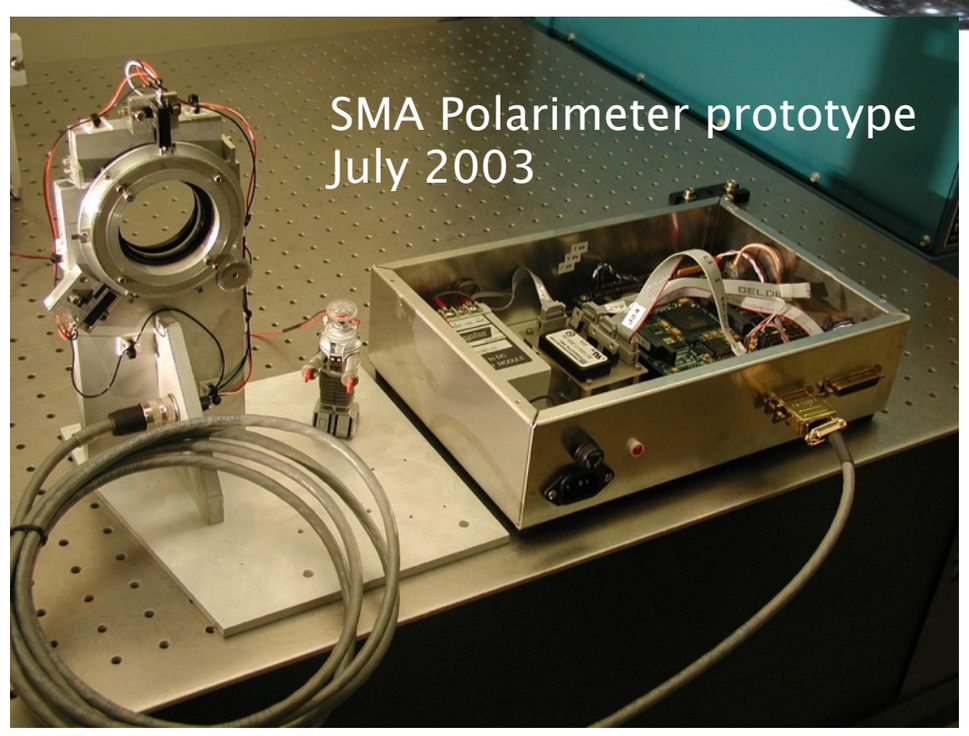
Polarization of Sgr A*

- Submm linear polarization discovered in 1999 (Aitken+2000)
  - Highly confused in JCMT beam
- BIMA polarimetry + GC2002 conference in Kona increased priority of SMA polarimeter



Nov 2002
Galactic Center
Workshop, Kona, HI

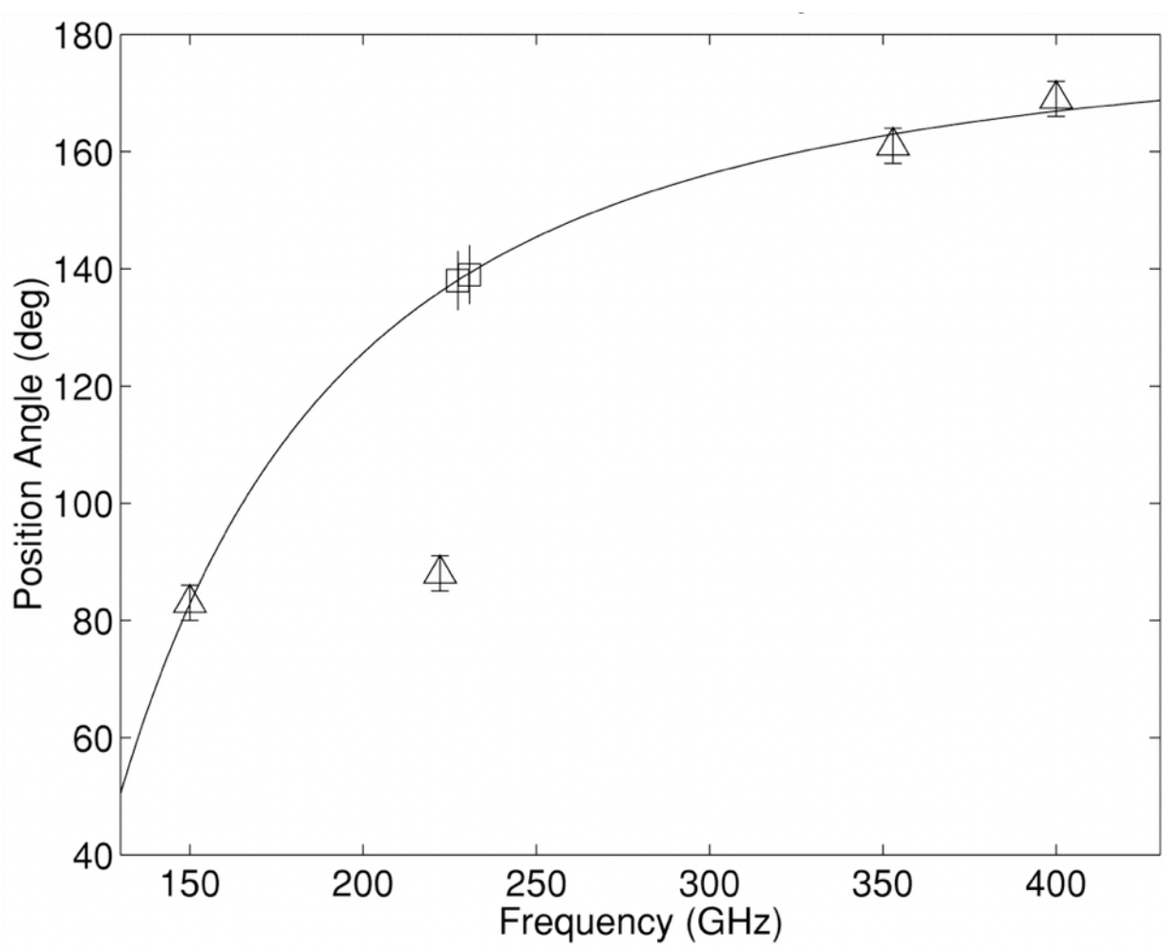


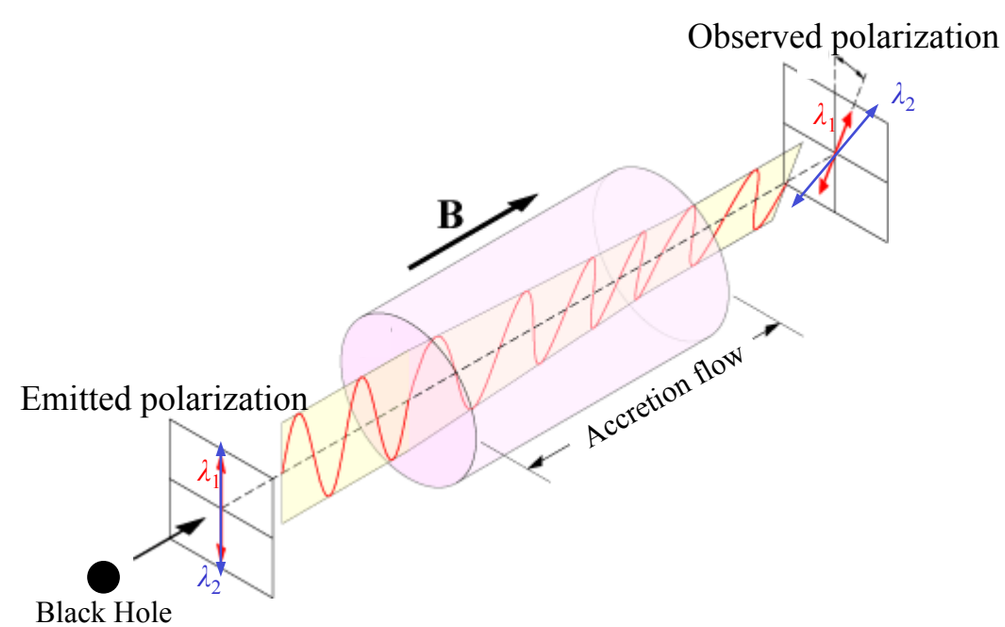


Polarization of Sgr A*

- BIMA 230 GHz polarimetry indicated possible Faraday rotation (Bower+2003)
- Faraday rotation provides unique access to accretion flow profile
  - Density profile in radiatively inefficient accretion flows subject to considerable debate

$$\chi(\lambda) = \chi_0 + \lambda^2 RM \qquad RM \propto \int n_e(r) B(r) \cdot dr$$





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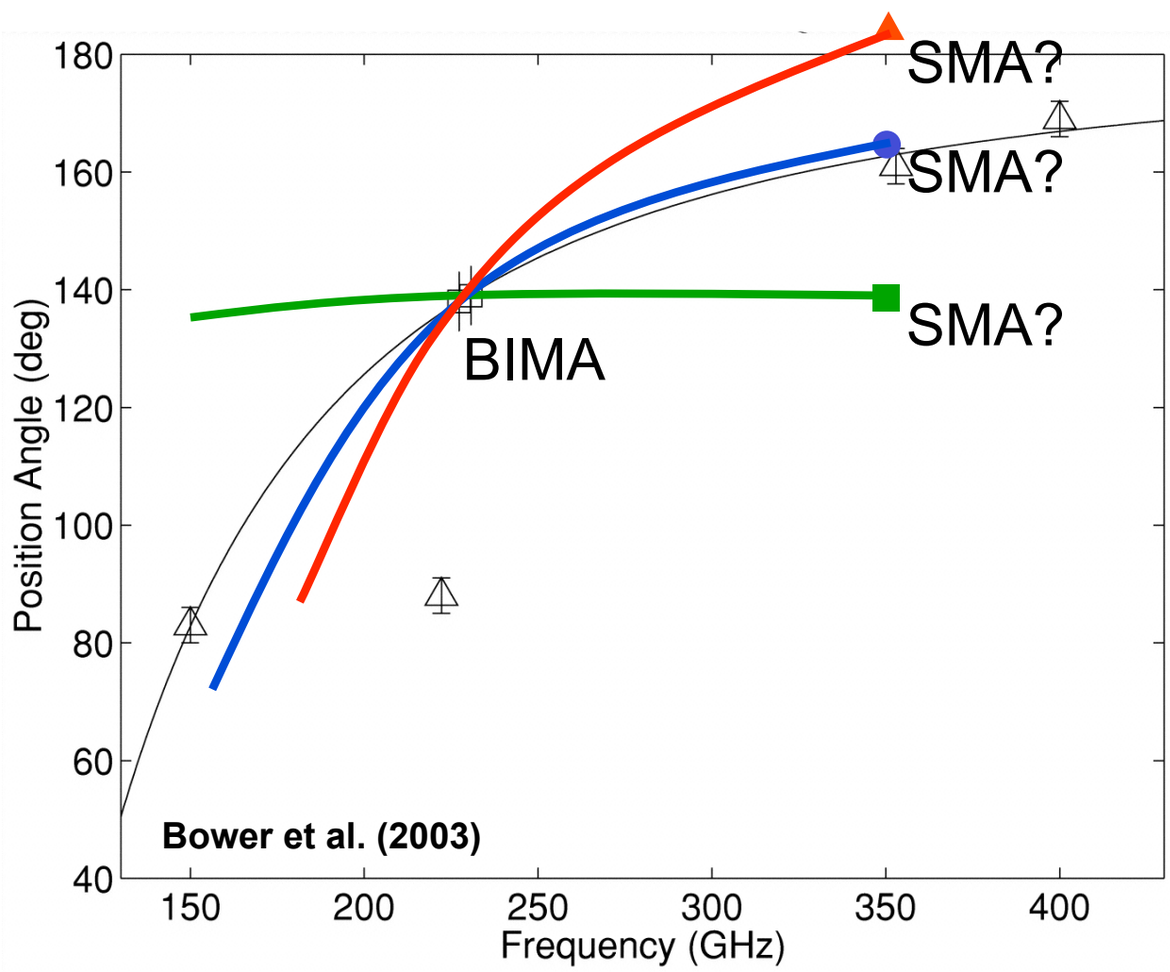
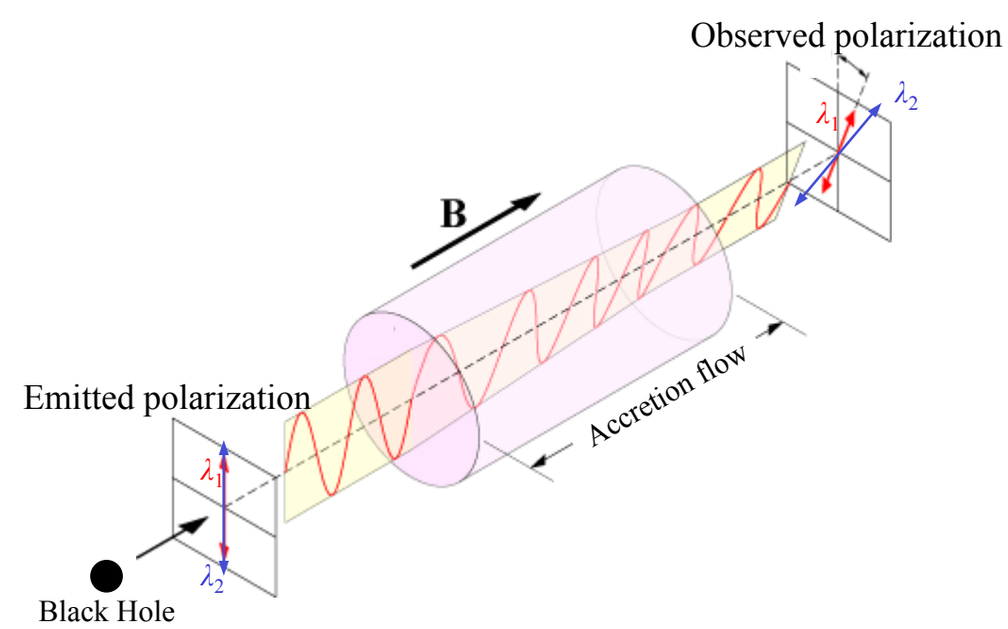


- Simple experiment:

  Use SMA to measure polarization at 345 GHz, compare to 230 GHz, and make clean inference of RM



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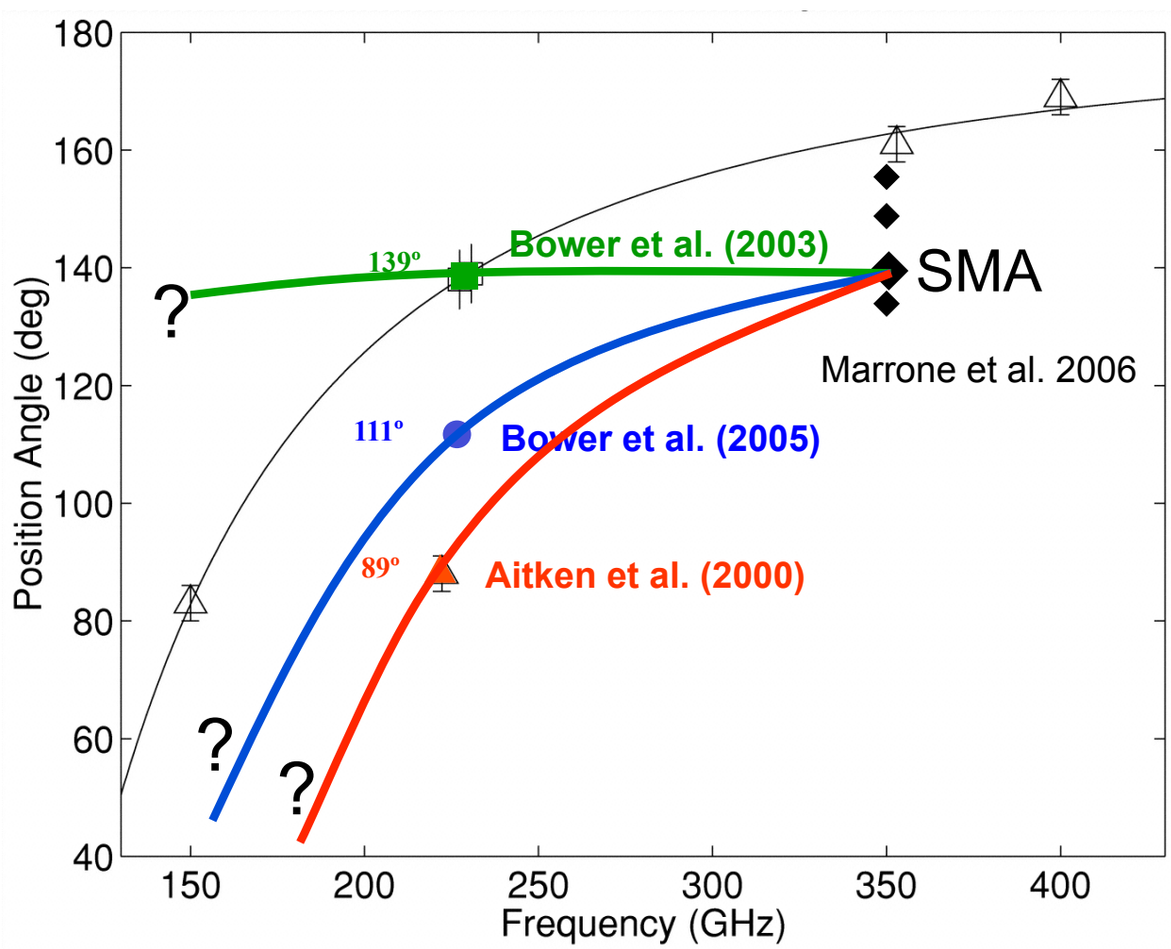


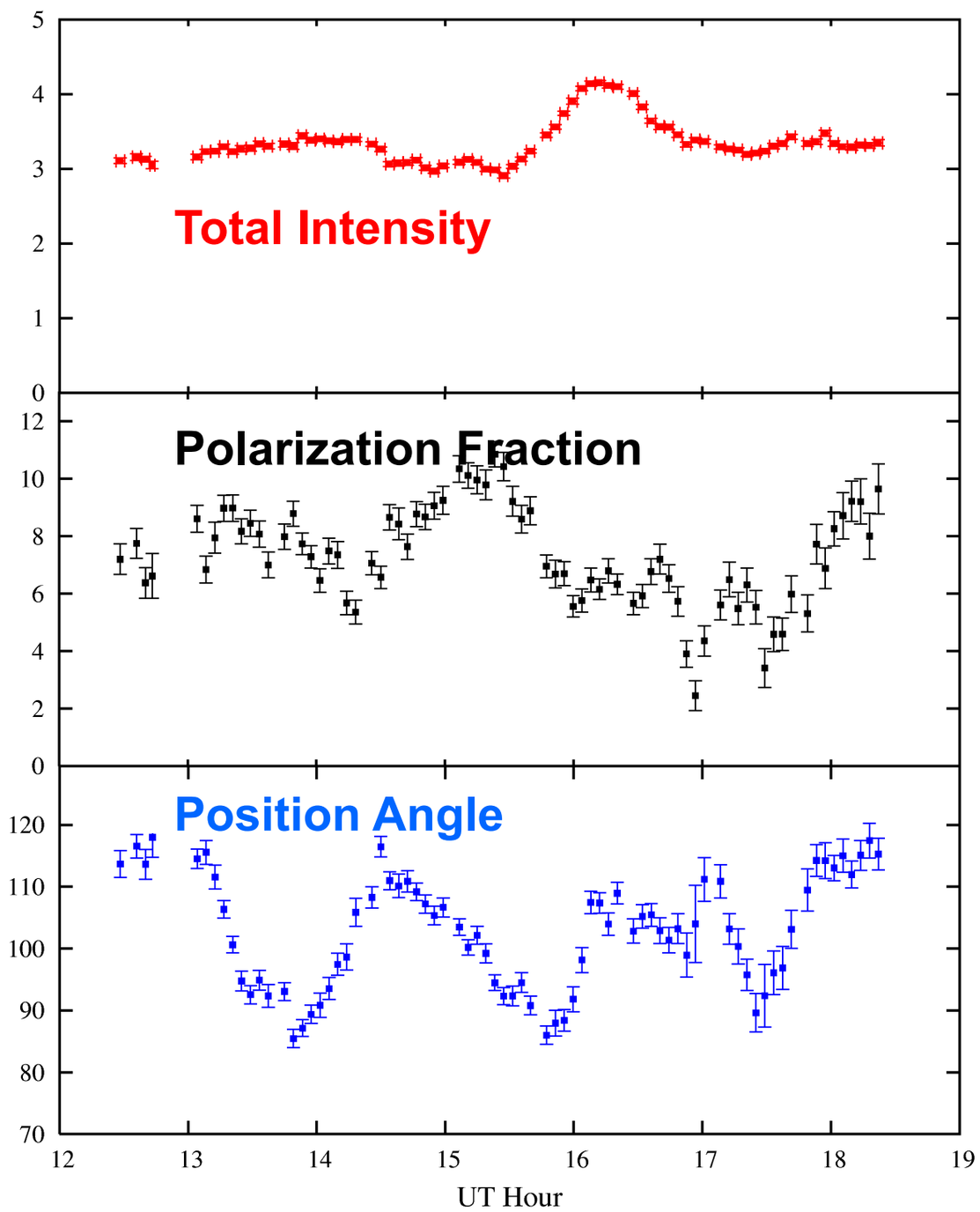
- Simple experiment:

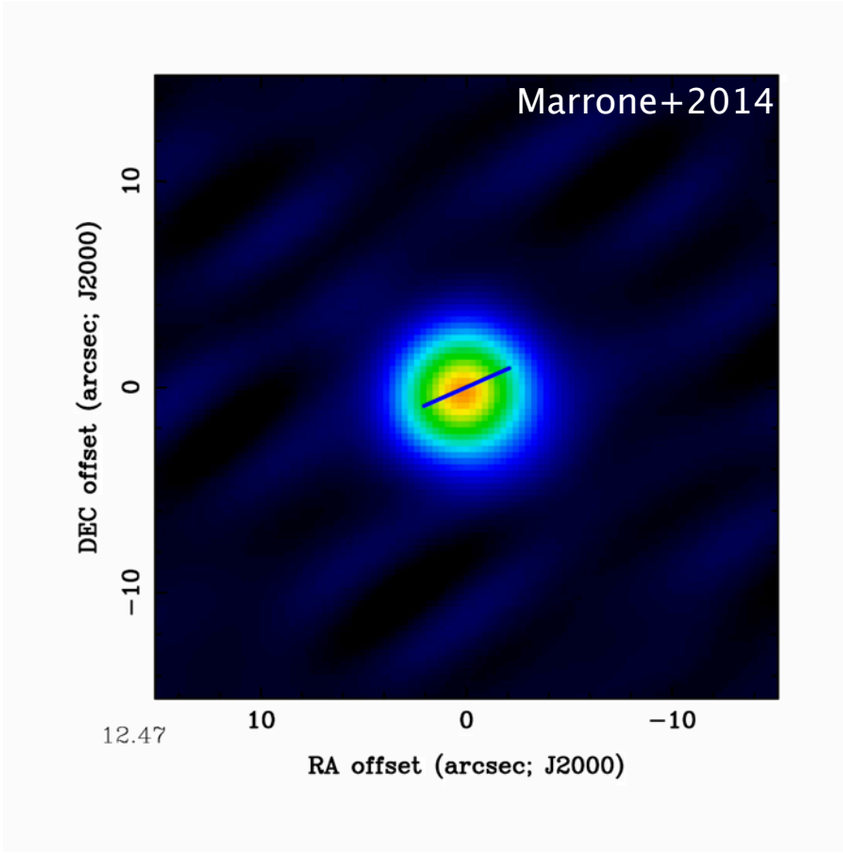
  Use SMA to measure polarization at 345 GHz, compare to 230 GHz, and make clean inference of RM

  Didn't work out so simply

Variability of Sgr A*

- Polarization of Sgr A* is (highly) variable





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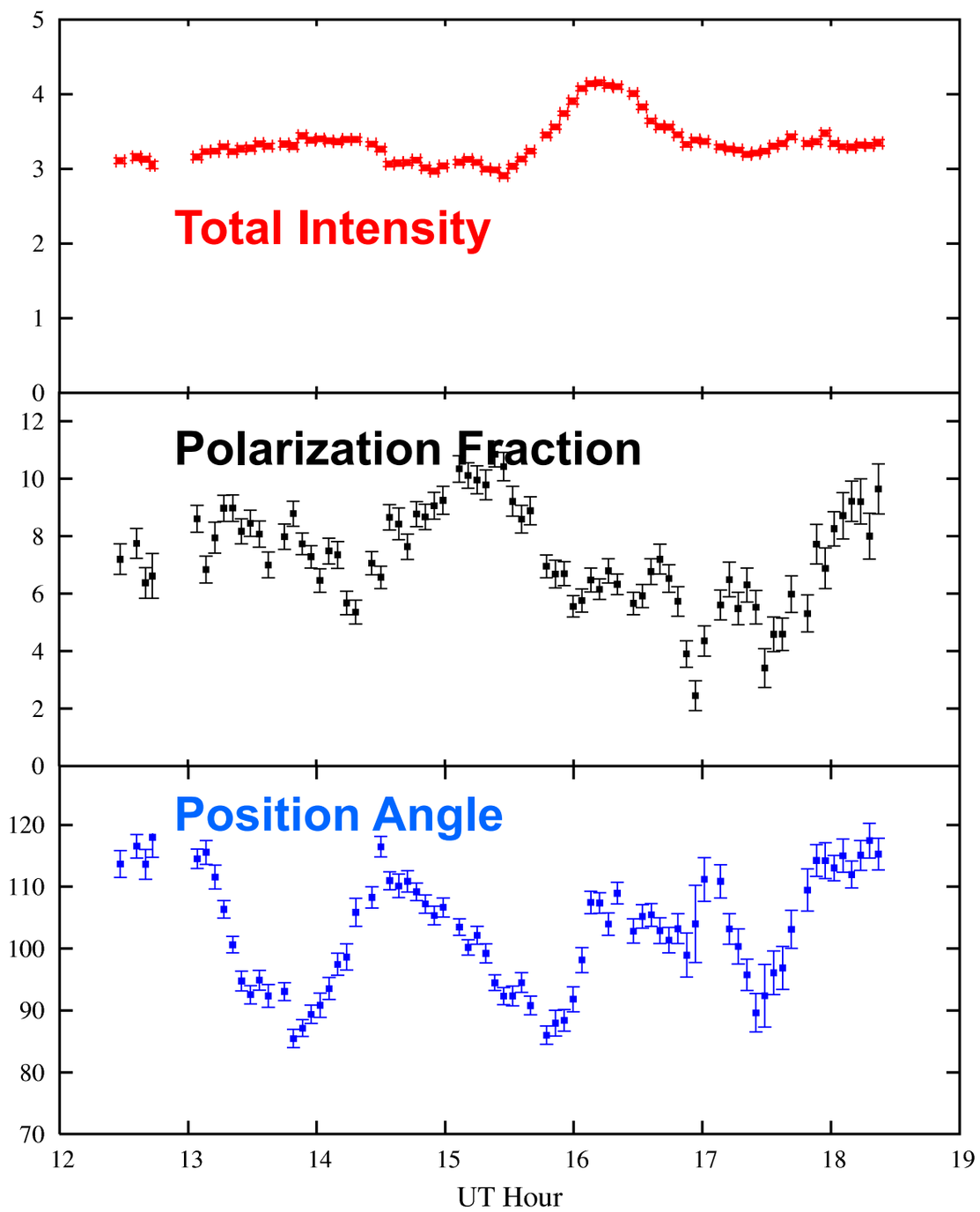
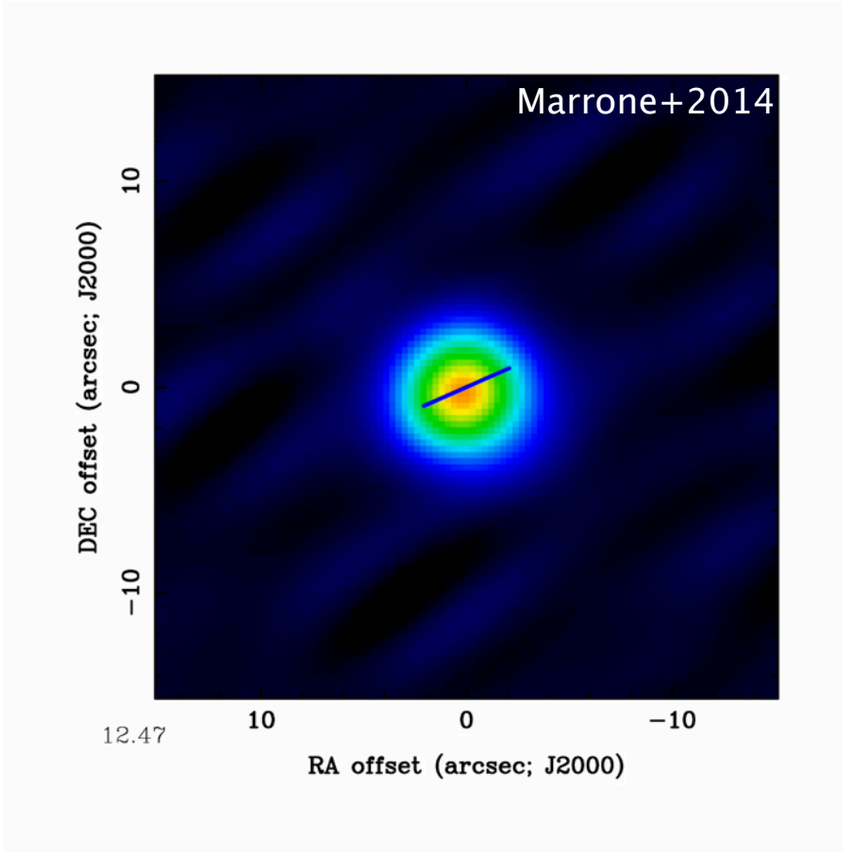
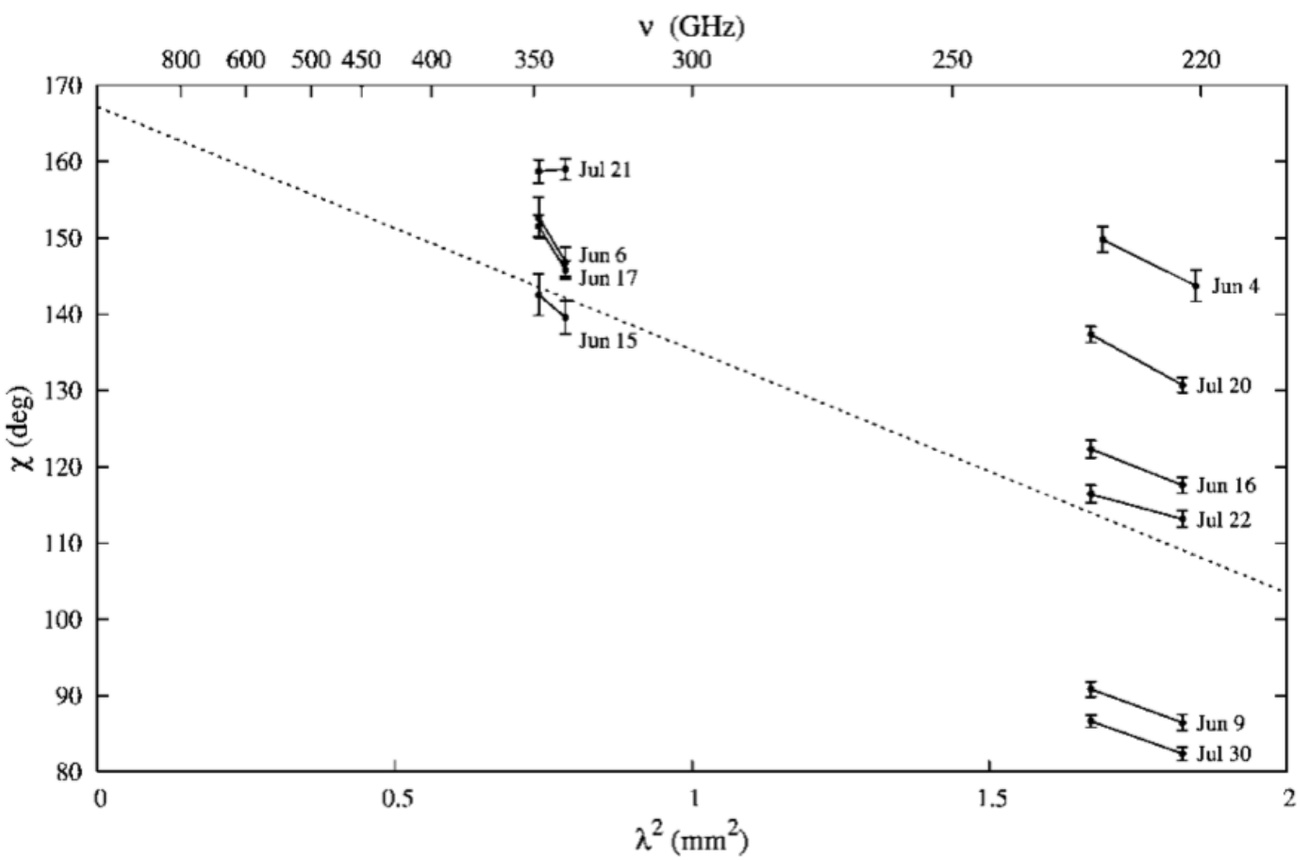


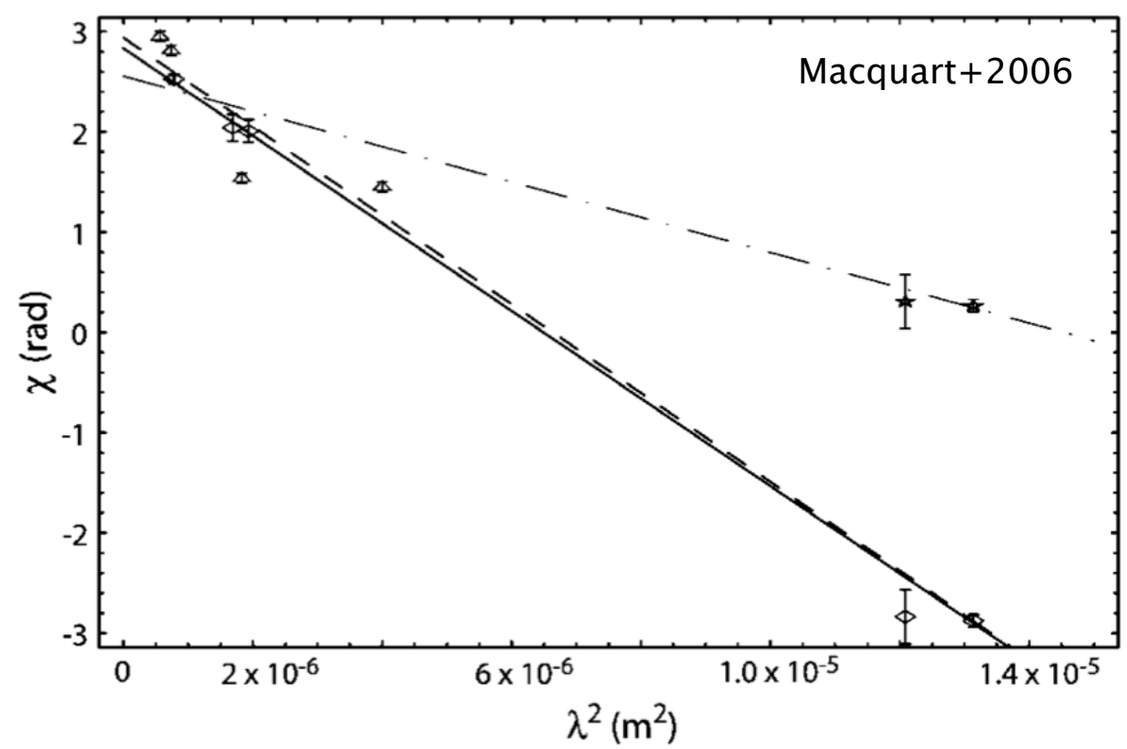


Invariability of Sgr A*

- Ultimately, RM measured (Marrone+2007)
  - Consistent with what you find by averaging over all time (Macquart+2006)
- Parameterized accretion profile allows us to translate to $\dot{M}$
  - $\dot{M} \sim 10^{-7}$–10^{-9} $M_\odot$/yr

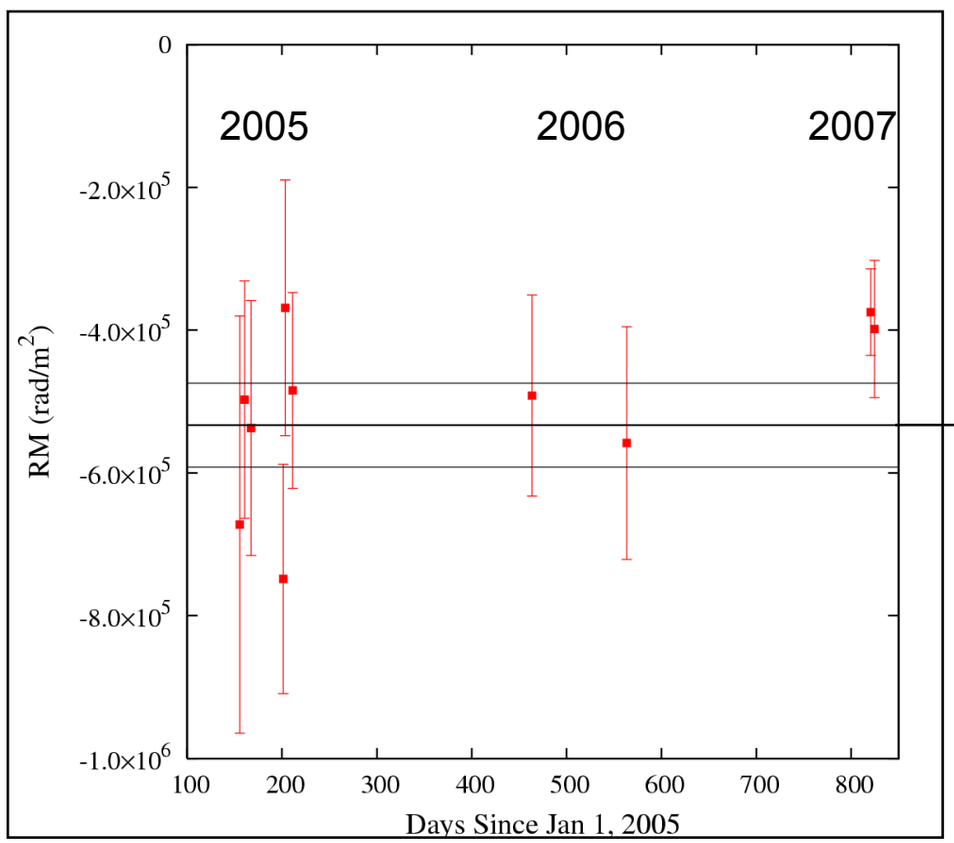


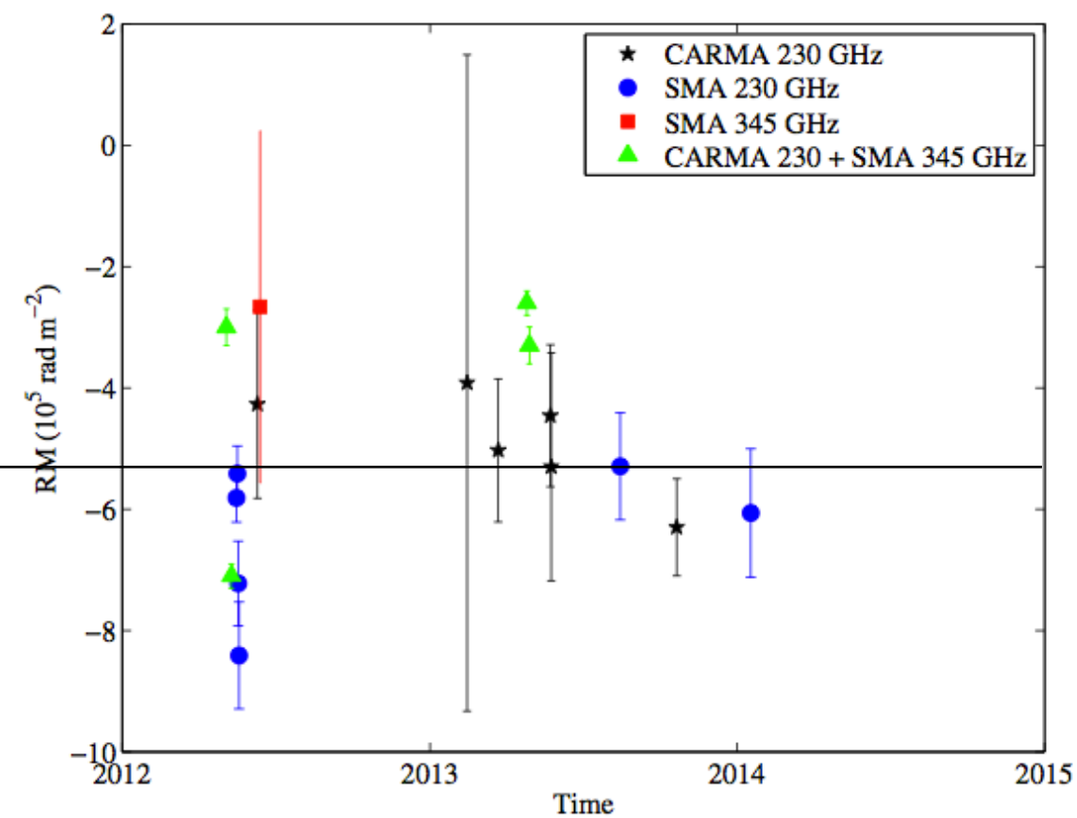
Marrone et. al (2007)



Invariability of Sgr A*

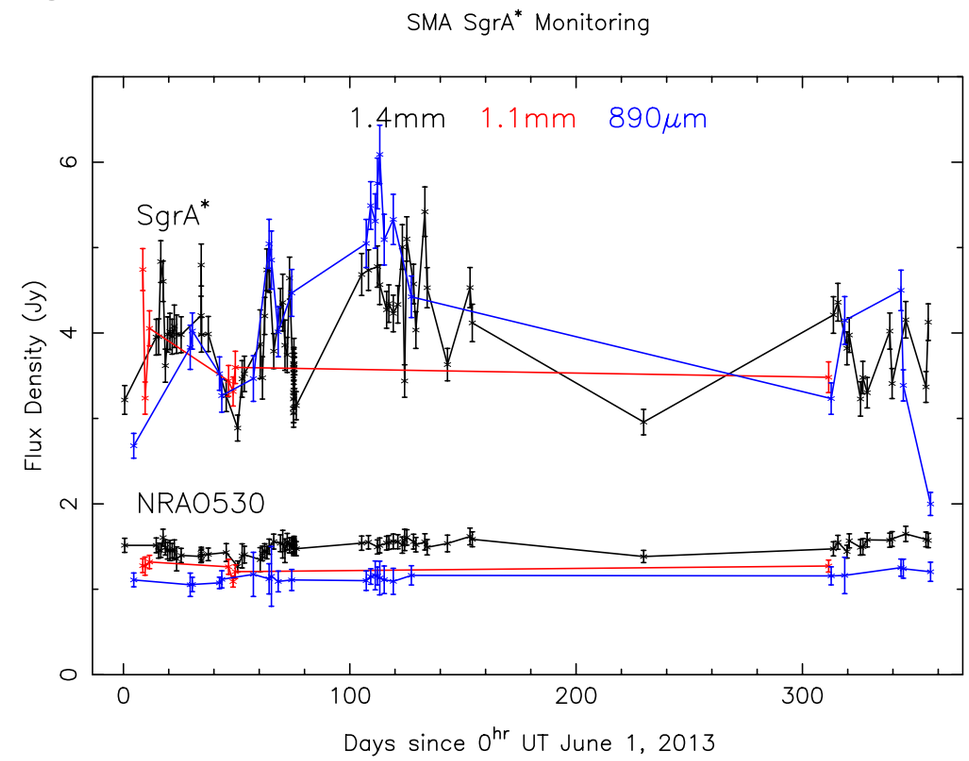
- If it originates in a turbulent accretion flow, RM surprisingly stable!
  - No reversals of RM since at least 1999
  - Possible variation at 50% level, though not with best data



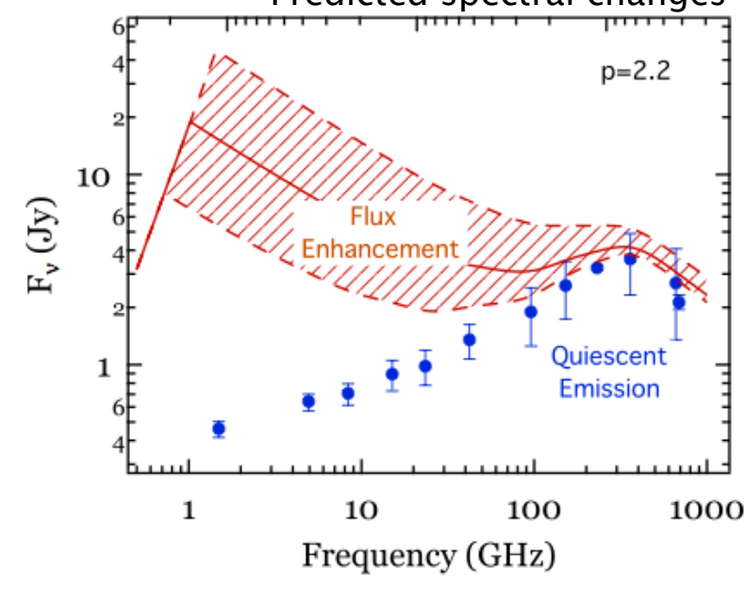


Invariability of Sgr A*: G2

- Most frustrating because incoming cloud "G2" should be changing $\dot{M}$
  - RM ought to be good tool for studying this
- Flux monitoring similarly underwhelming
  - Excursions similar to past monitoring
  - See Moran poster (G3)



Narayan+2012
Predicted spectral changes



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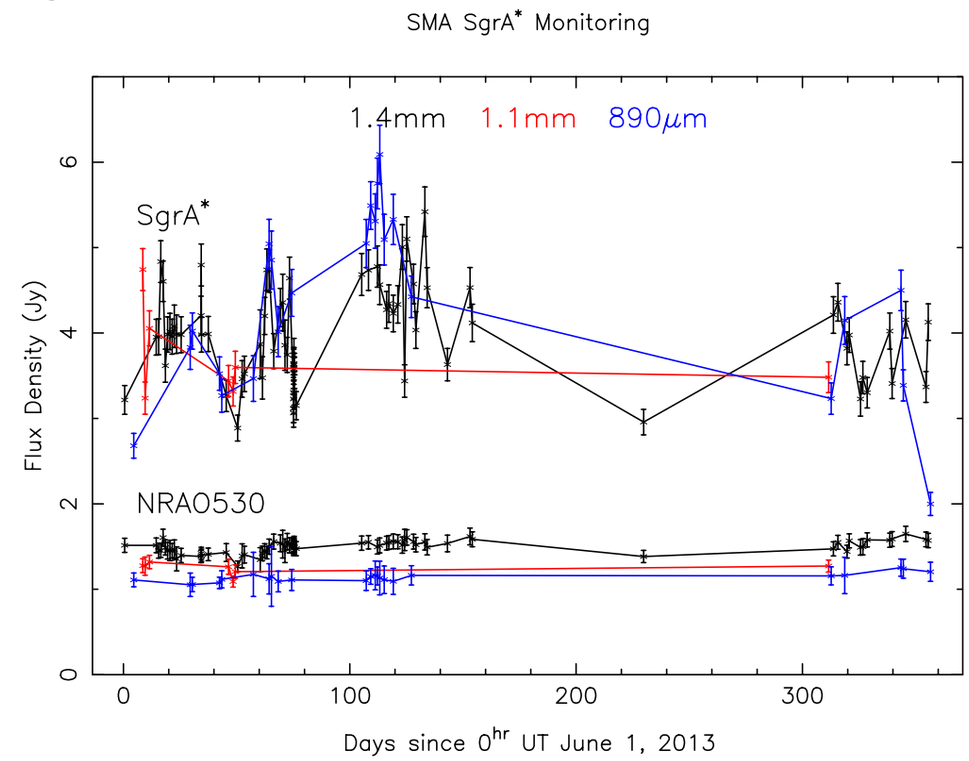

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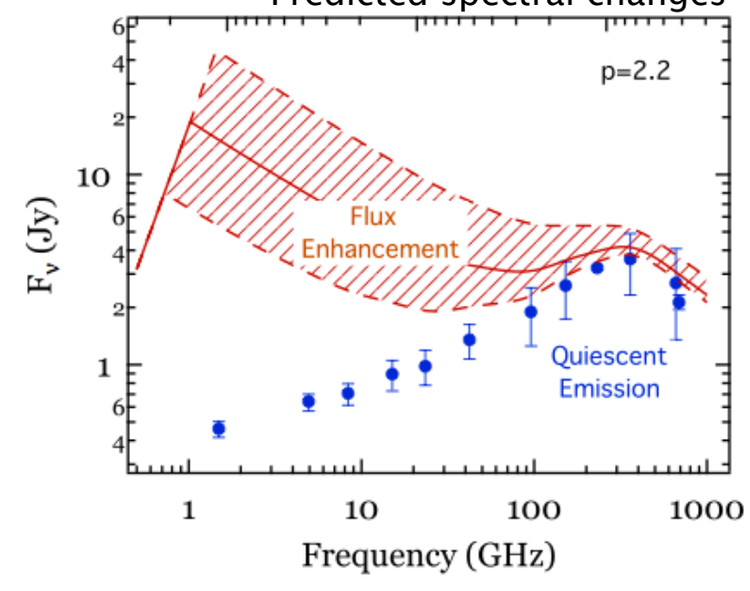
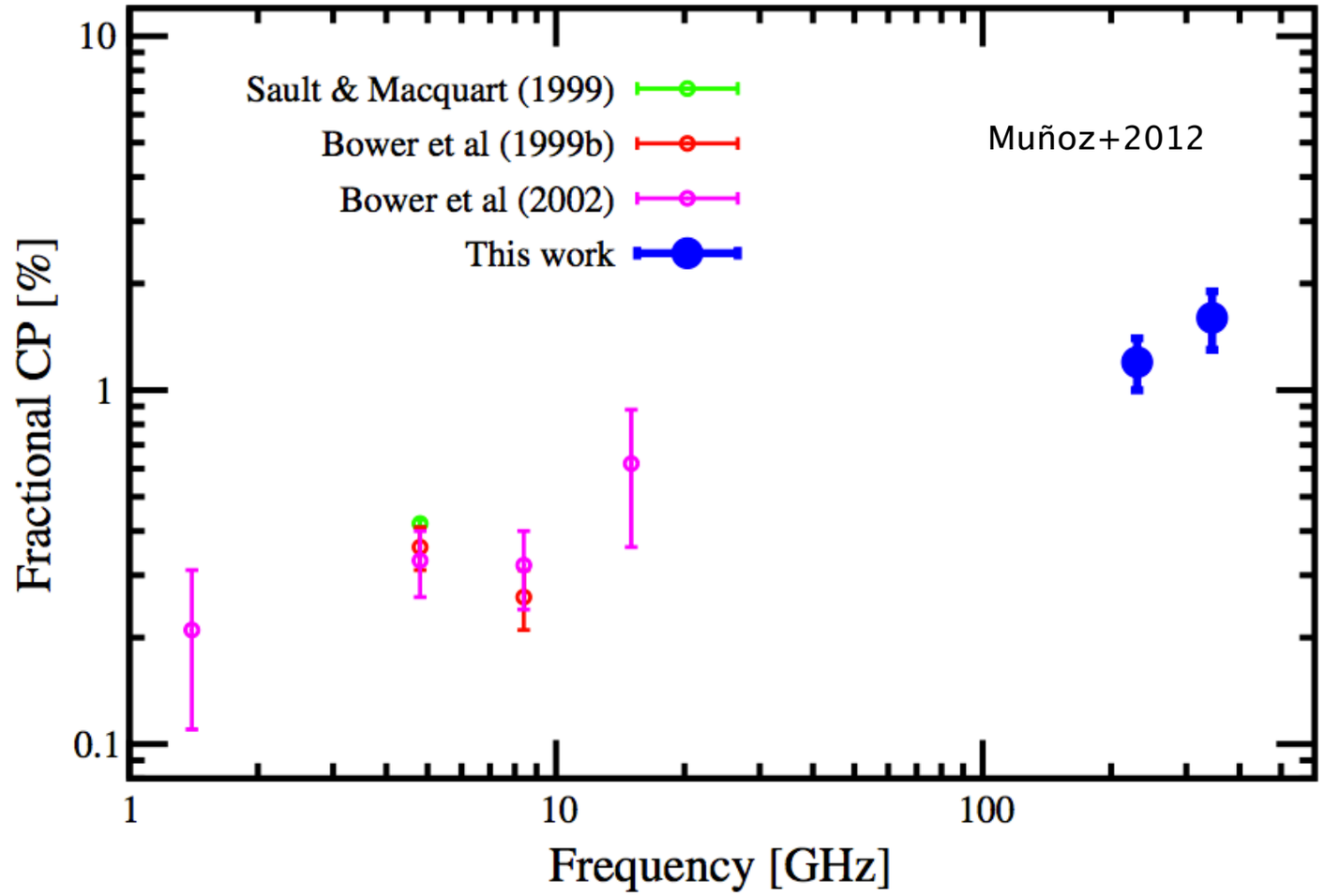


Invariability of Sgr A*

- Sgr A* has unique submm circular polarization
- Increasing CP with increasing frequency
  - Consistent with single power law ($nu^{0.35}$)
  - Persistent for ~10 years (SMA)
  - Lower-frequency: CP sign persistent for 35 years (Bower+2002)

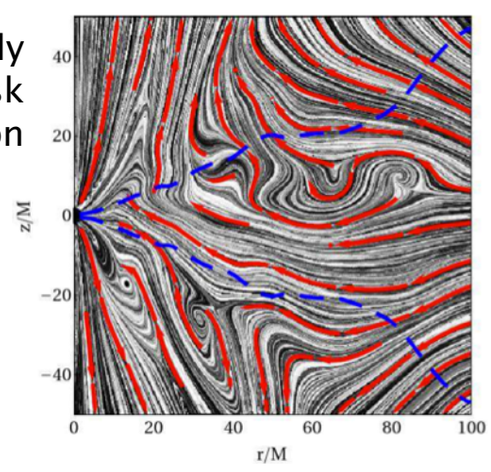


Invariability of Sgr A*

- What are we seeing?
  - Faraday rotation (B along line of sight) stable for >10y
  - CP stable for >30y
    also B-dependent (Faraday conversion LP→CP, or cyclotron)
- Possibilities:
  - Strong B field suppressing disorder - maintains RM
    - Magnetically Arrested Disc?

R. Narayan, A. Sądowski, R. F. Penna, A. K. Kulkarni

Magnetically Arrested Disk Simulation



LETTER

doi:10.1038/nature13399

Dynamically important magnetic fields near accreting supermassive black holes

M. Zamaninasab[1], E. Clausen-Brown[1], T. Savolainen[1] & A. Tchekhovskoy[2,3]

Nature, yesterday

  - Cool electrons at small radius - RM and cyclotron (CP) contributions?
    - Possible evidence would be RM differences between frequencies
  - Faraday conversion also possible
    - Possible if Faraday rotation at same radius where LP emitted

Structure of Sgr A*?

- Resolved imaging of Sgr A* and its magnetic structure is coming!
  - Poster I-1: Michael Johnson
  - EHT Talk: Doeleman tomorrow