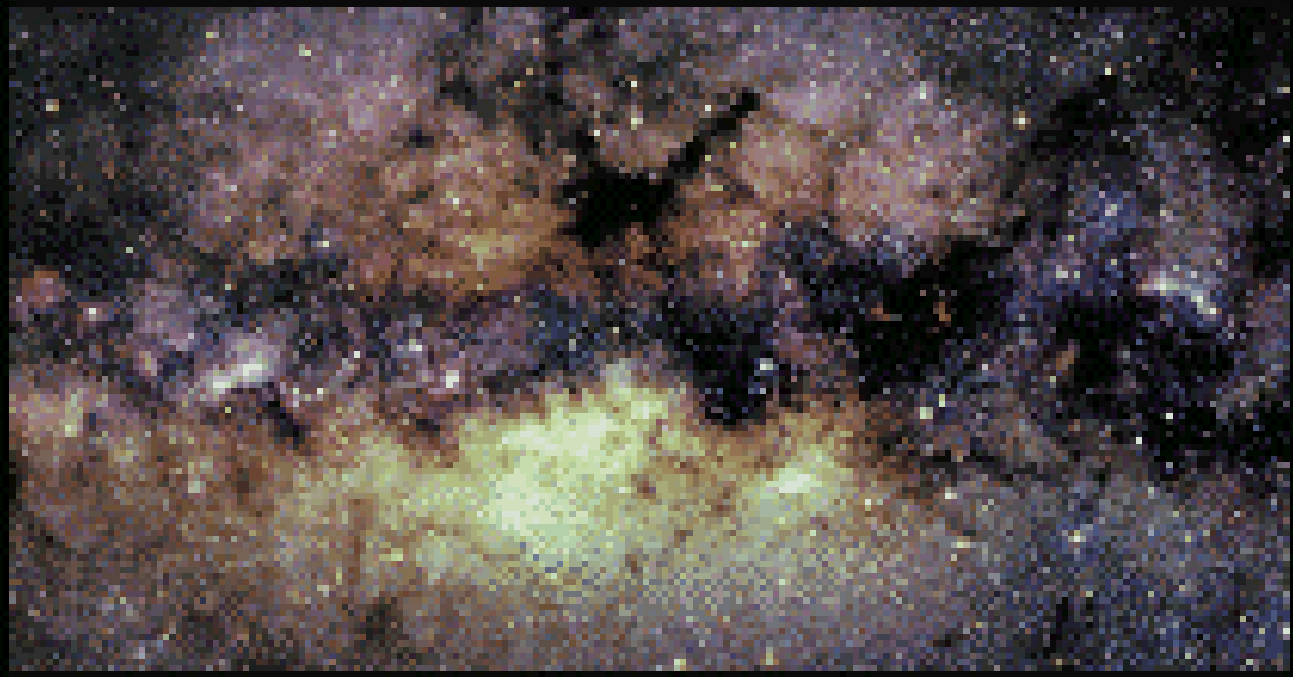
The Supermassive Black Hole at the Center of Our Galaxy – Sagittarius A*

Frederick K. Baganoff

MIT

Optical View of the Galactic Center

30 magnitudes of optical extinction => optical diminished by factor of a trillion!

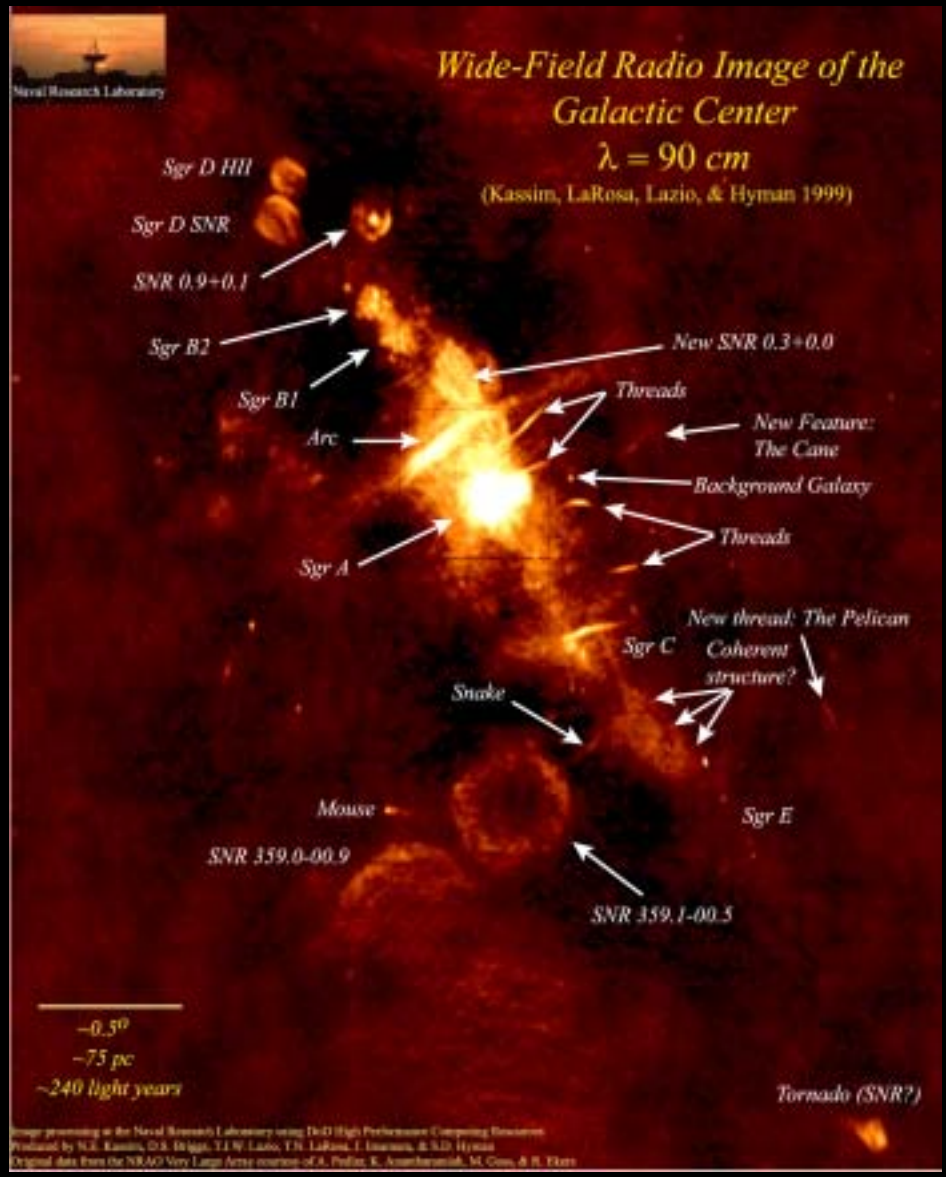


80 degrees. Courtesy of Dr. Axel Mellinger. Used with permission.

How Do We Study a Supermassive Black Hole That We Cannot “See”?

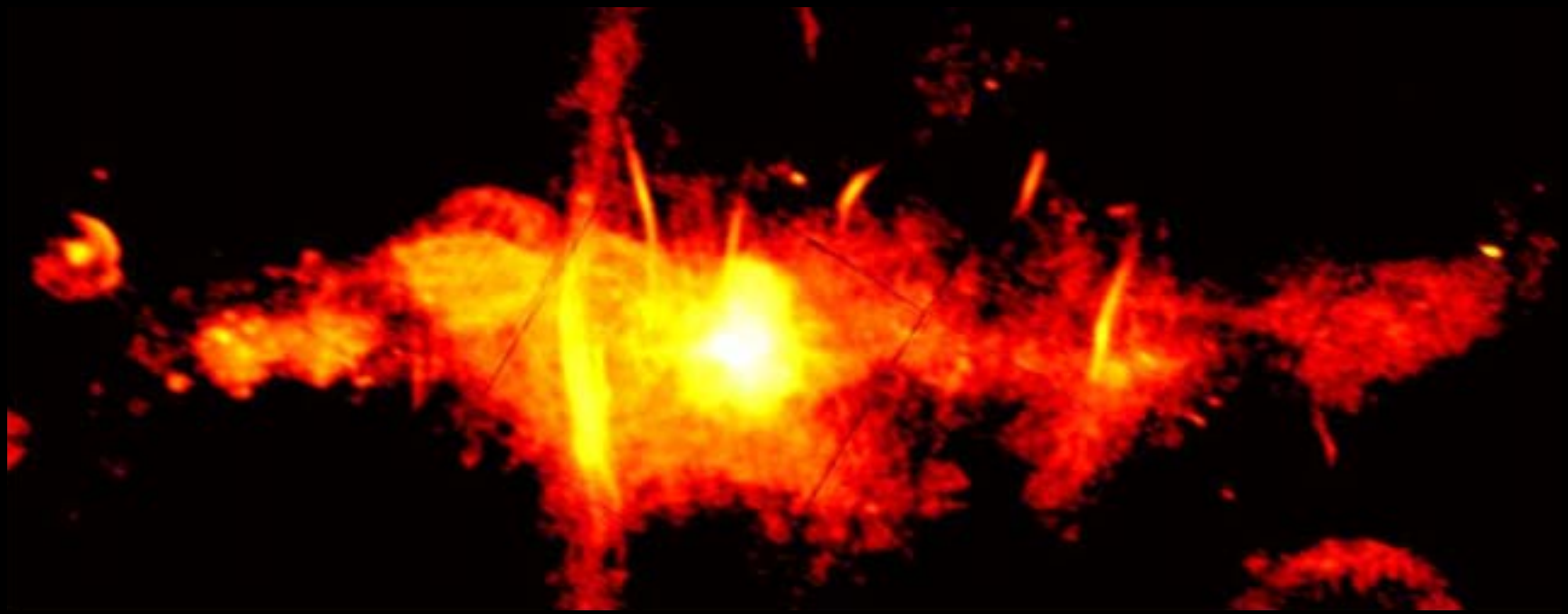
- Imaging or Photometry
- Spectroscopy
- Timing
- Multiwaveband

Annotated Radio View of the Galactic Center



Produced at the U.S. Naval Research Laboratory by Dr. N.E. Kassim and collaborators from data obtained with the National Radio Astronomy's Very Large Array Telescope, a facility of the National Science Foundation operated under cooperative agreement with Associated Universities, Inc. Basic research in radio astronomy at the Naval Research Laboratory is supported by the U.S. Office of Naval Research

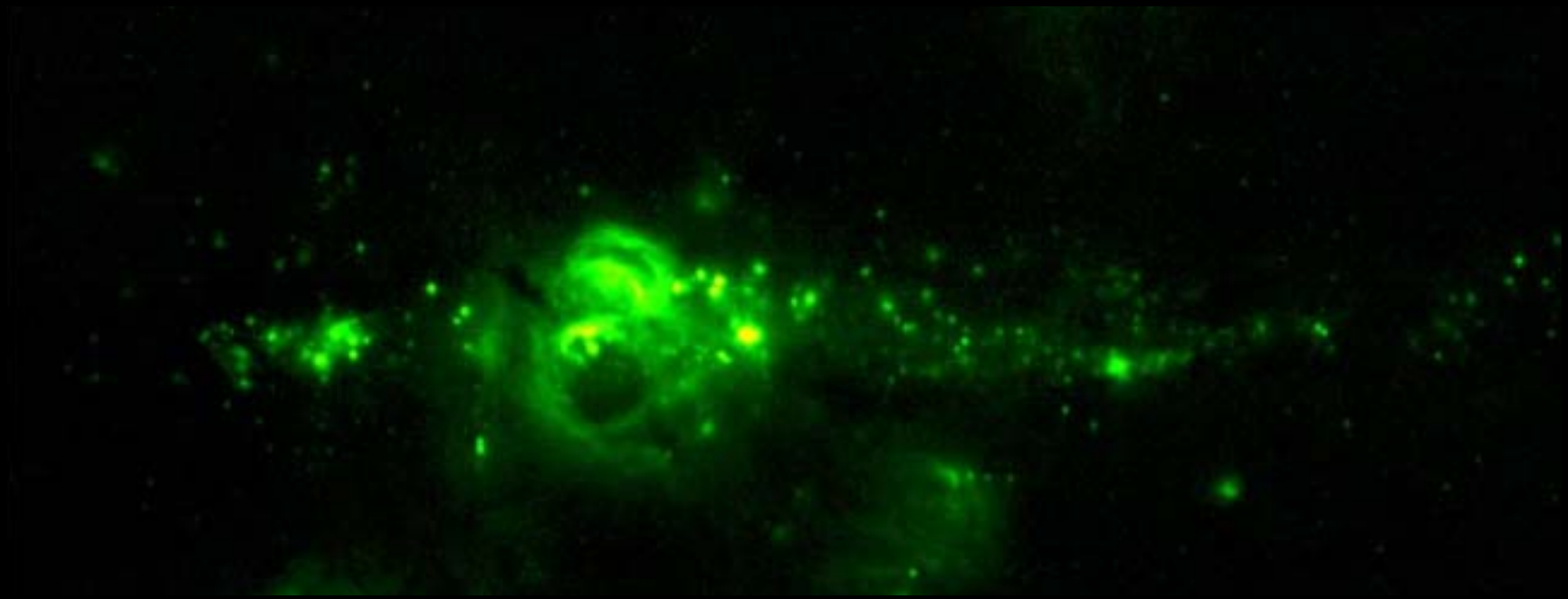
Radio View of the Galactic Center



2.8 x 0.8 degrees

Credit: VLA

Mid-Infrared View of the Galactic Center



2 x 0.8 degrees

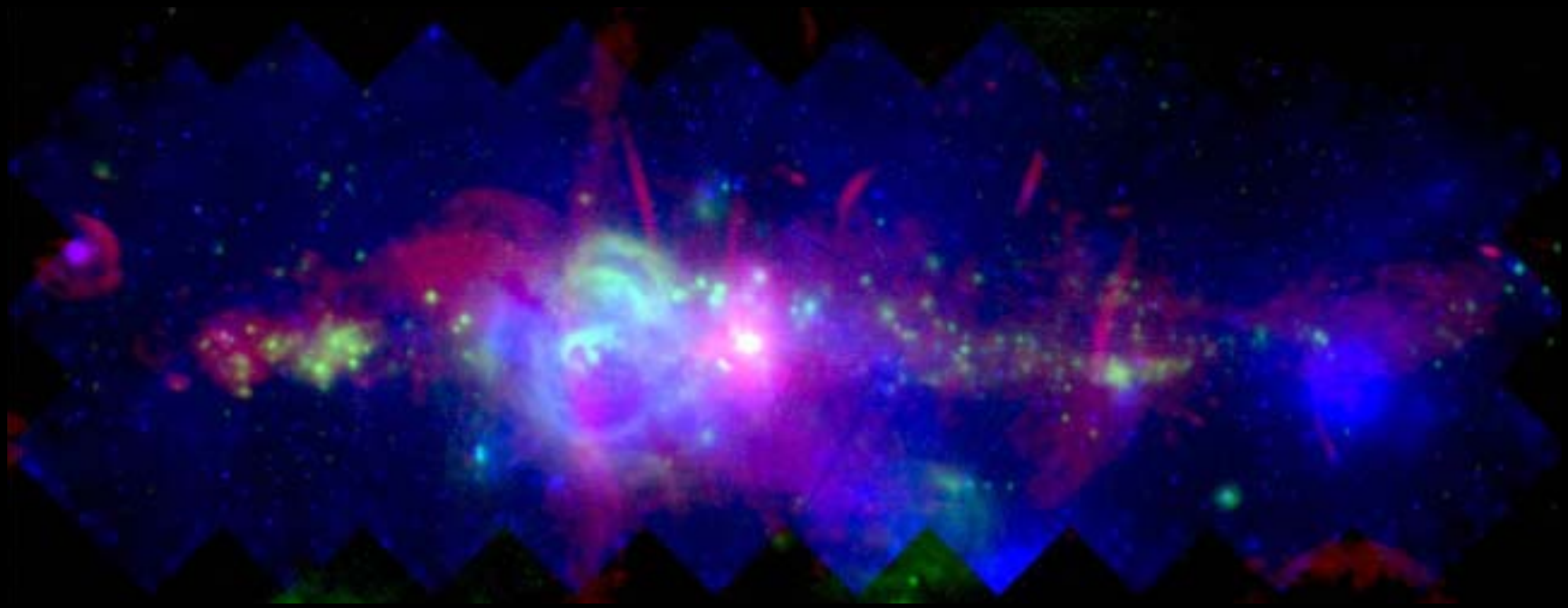
Credit: MSX

X-ray View of the Galactic Center

2 x 0.8 degrees

Credit: NASA/UMass/D. Wang et al.

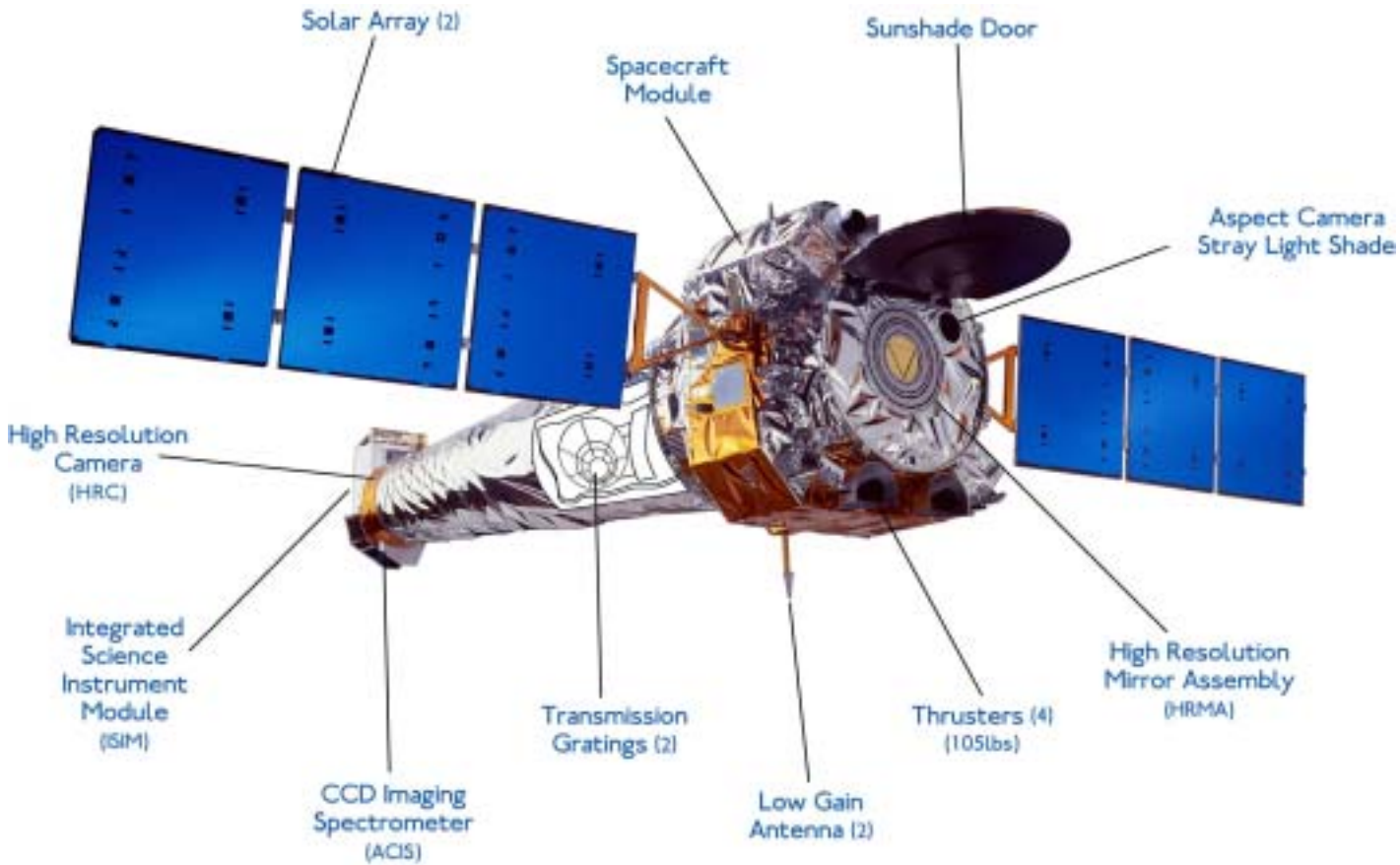
Radio/Mid-Infared/X-ray View of the Galactic Center



2 x 0.8 degrees

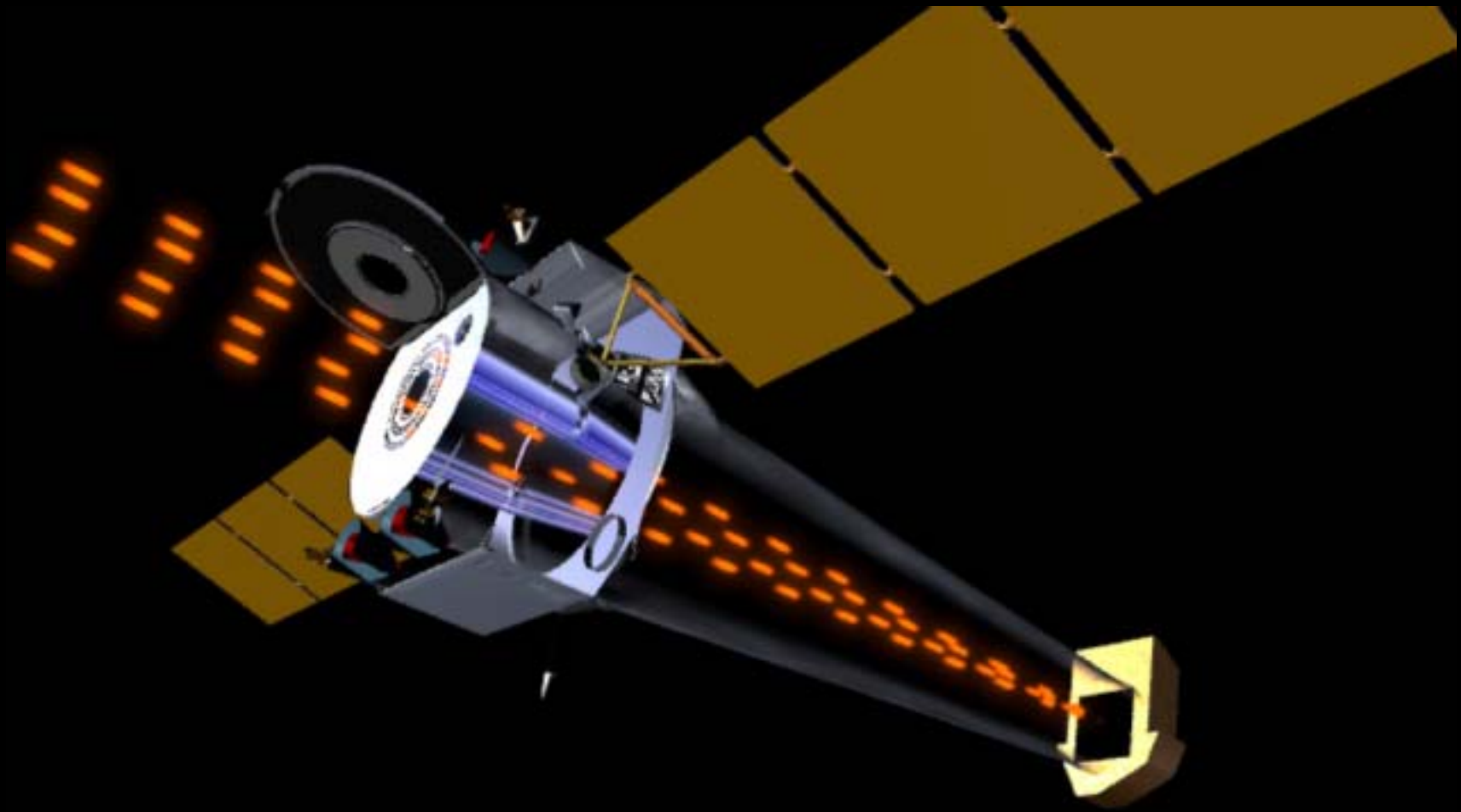
Credit: (X-ray) NASA/UMass/D. Wang et al., (Mid-IR) MSX, (Radio) VLA

Chandra X-ray Observatory



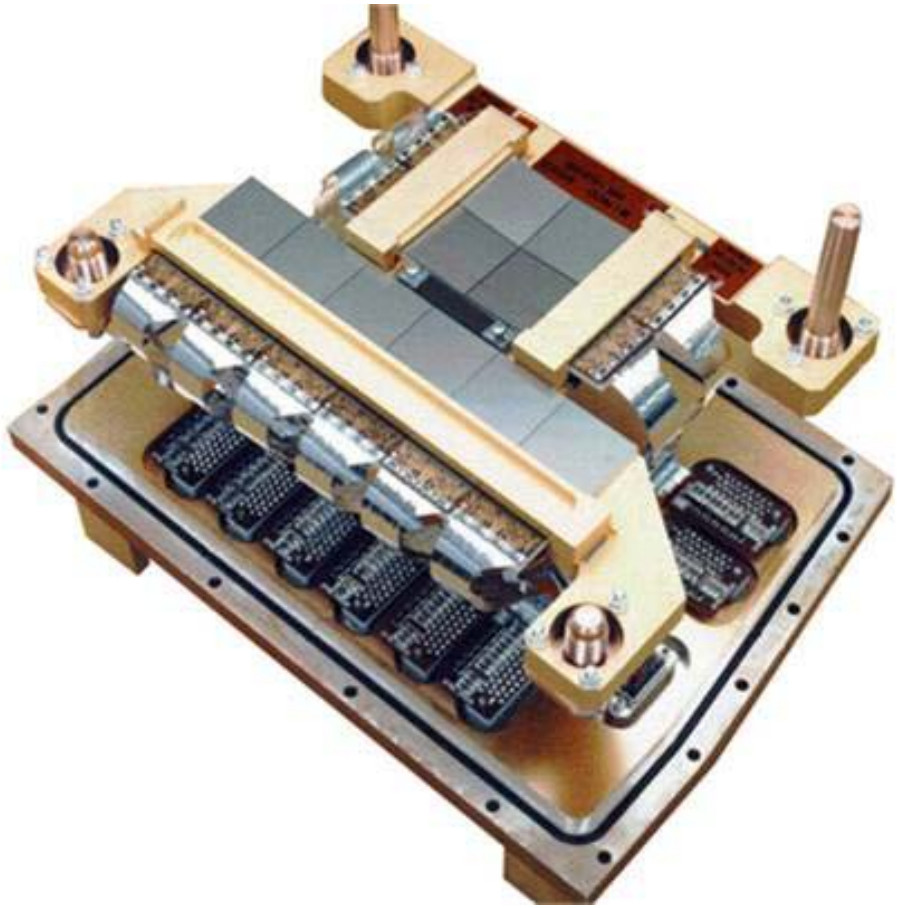
Credit: NASA/CXC/SAO

Light Path Through Chandra



Credit: NASA/CXC/SAO

Advanced CCD Imaging Spectrometer (ACIS)



Credit: NASA/CXC/SAO

Zooming into the Galactic Center in X-rays

2 x 0.8 degrees

Credit: NASA/CXC/SAO

Chandra Galactic Center Deep Field

8.4 x 8.4 arcmin

Credit: NASA/CXC/MIT/F.K. Baganoff et al.

Sagittarius A* – Milky Way's Central Black Hole

Courtesy of Max Planck Society for the Advancement of Science/R. Genzel et al. Used with permission.

Credit: NASA/CXC/MIT/F.K. Baganoff et al.

X-ray Point Sources

- 2287 sources have been resolved.
- 278 are of the foreground in the galactic center.
- About 40 are background AGN
- Sources have $L_X=10^{30}$-10^{33} erg s^{-1} (2-8 keV)

Muno et al. 2003, ApJ, 589, 225

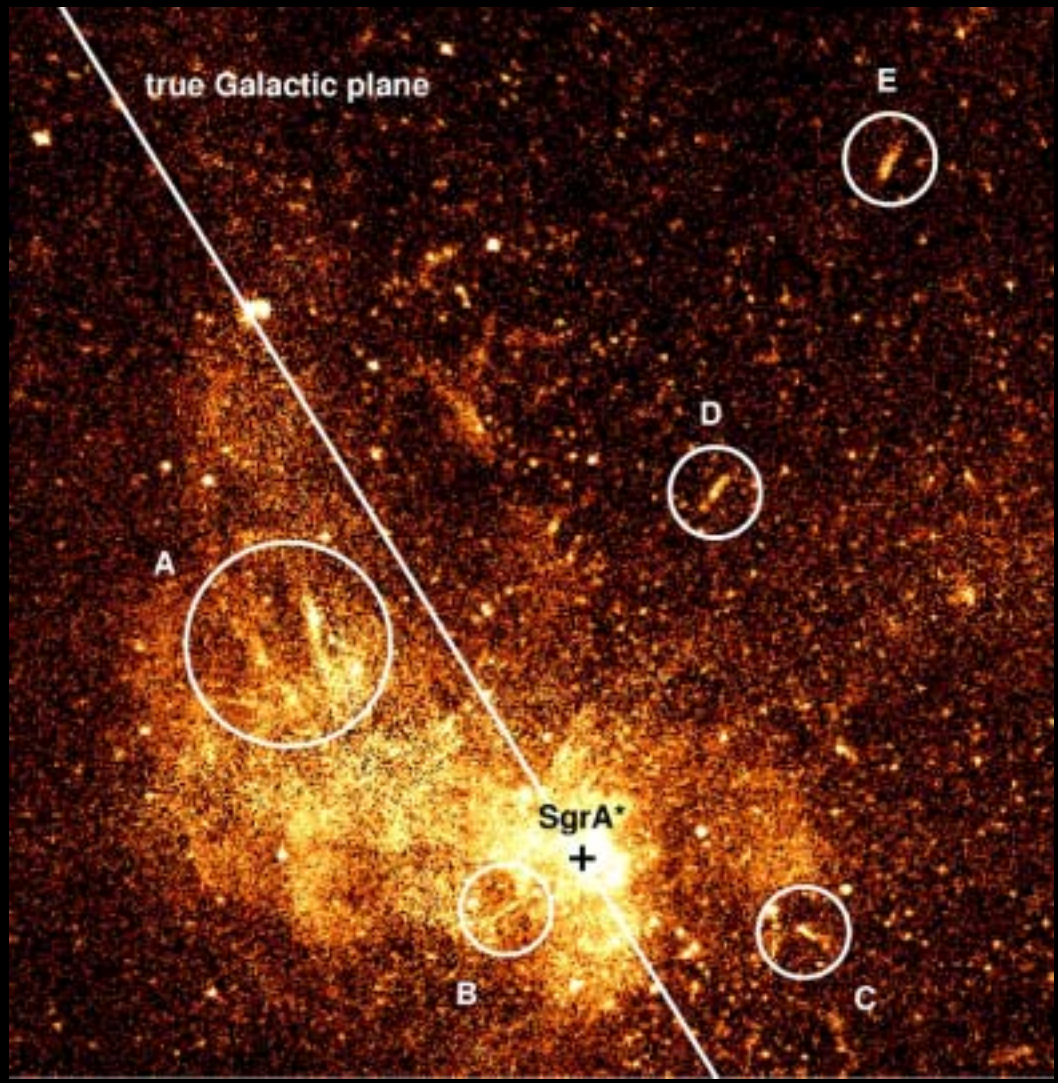
Credit: NASA/CXC/MIT/F.K. Baganoff et al.

Spatial Distribution

- Consistent with an isothermal sphere ($1/R^2$)
- Similar to spatial density of bright infrared stars in Nuclear Bulge
- Could provide important information about star formation history

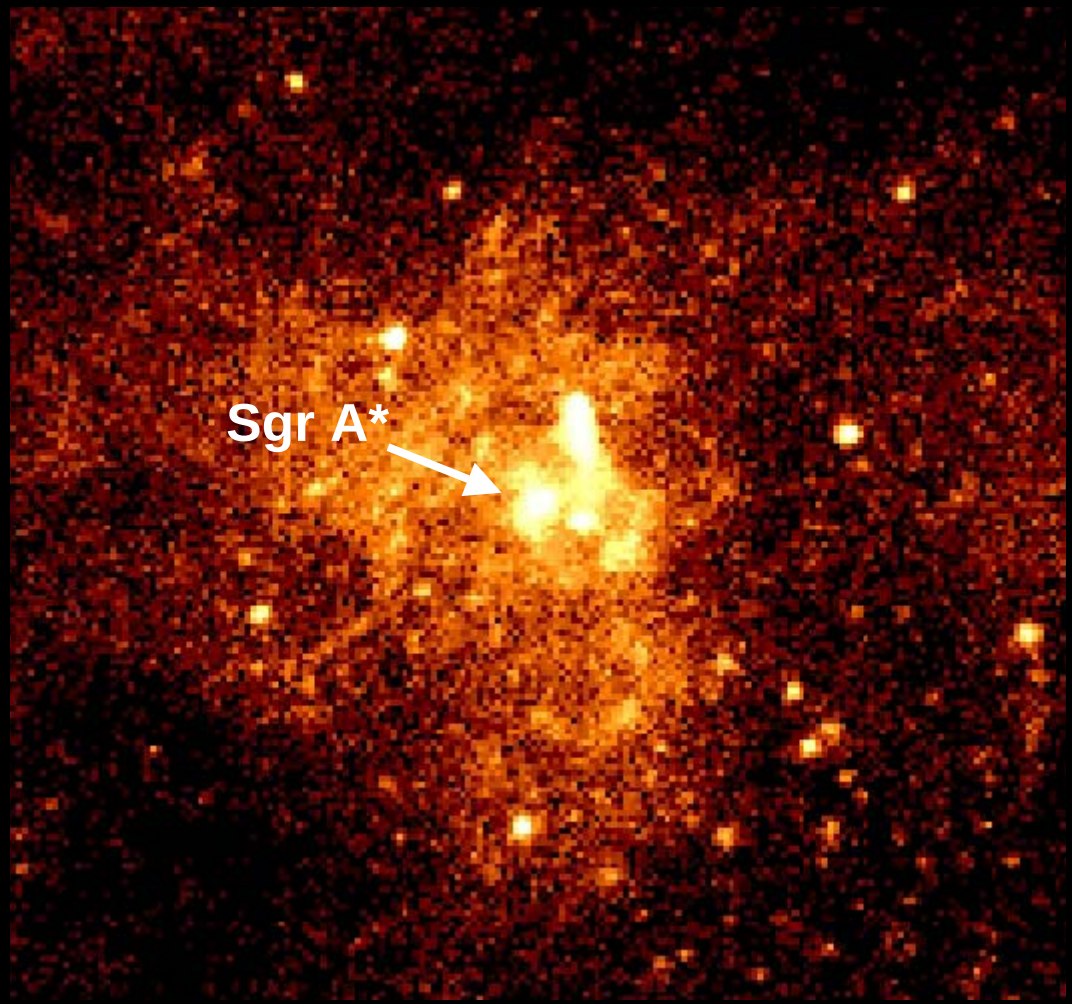
Muno et al. 2003, ApJ, 589, 234

X-ray Features in the Vicinity of the Sgr A Radio Complex



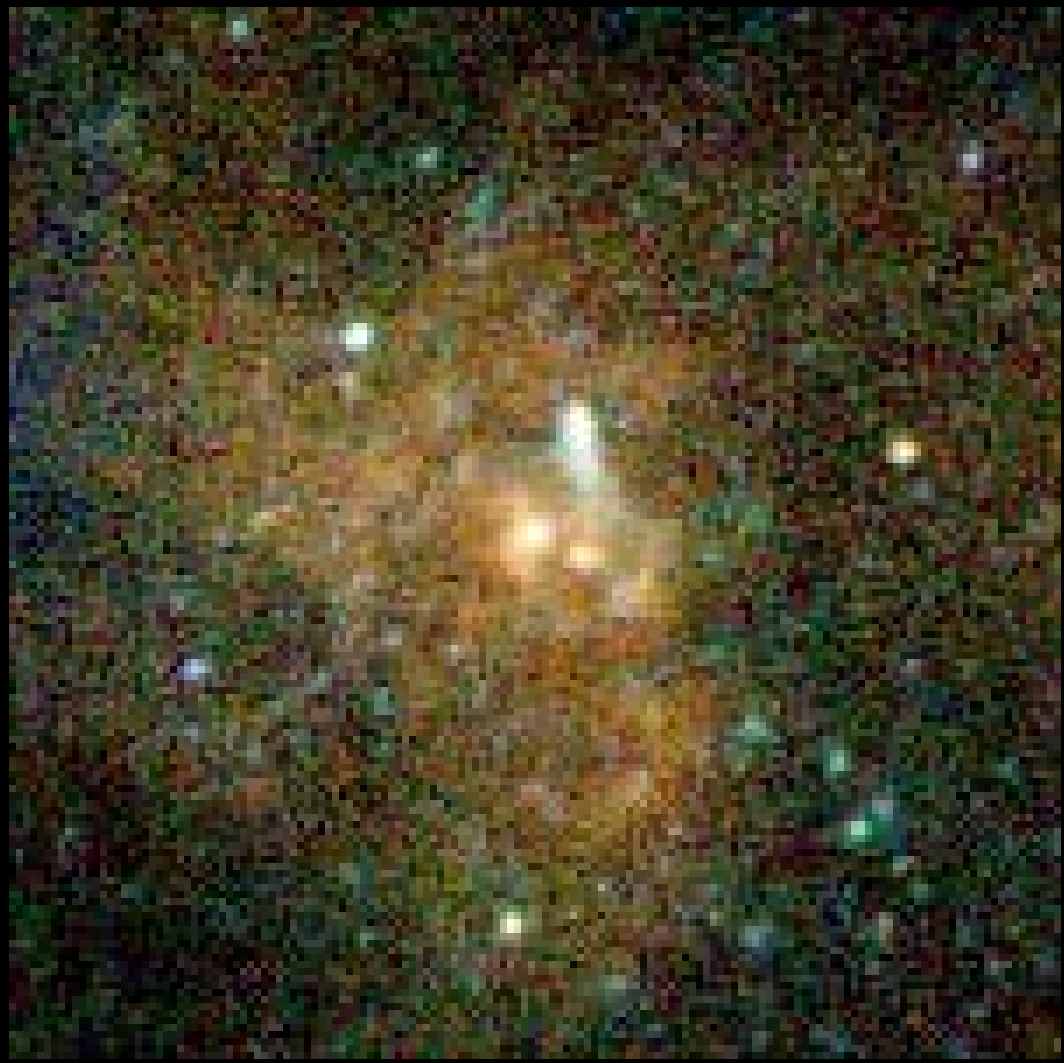
Credit: NASA/MIT/F.K. Baganoff et al.

X-ray View of Sgr A West and Sgr A*



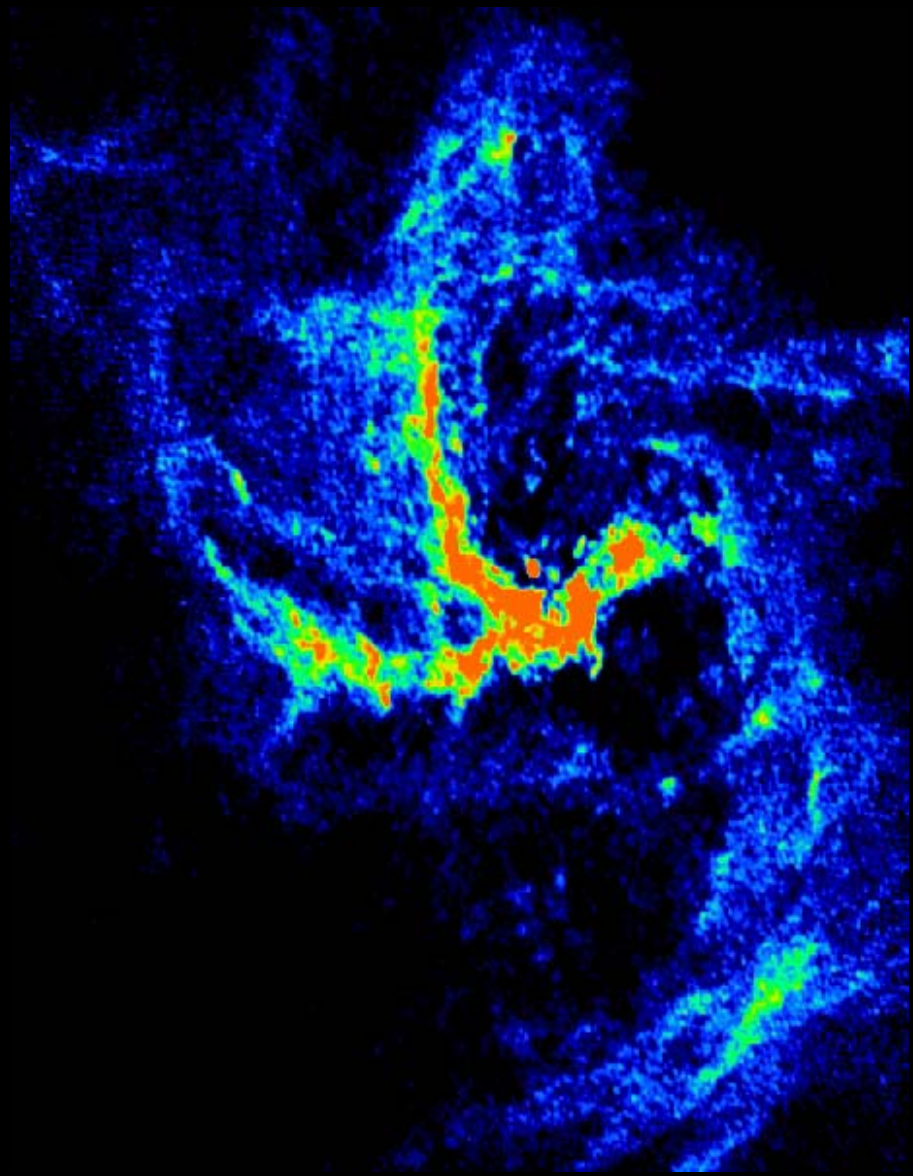
Courtesy of Max Planck Society for the Advancement of Science/R. Genzel et al. Used with permission.
Credit: NASA/MIT/F.K. Baganoff et al.

Three-color X-ray View of Sgr A West and Sgr A*



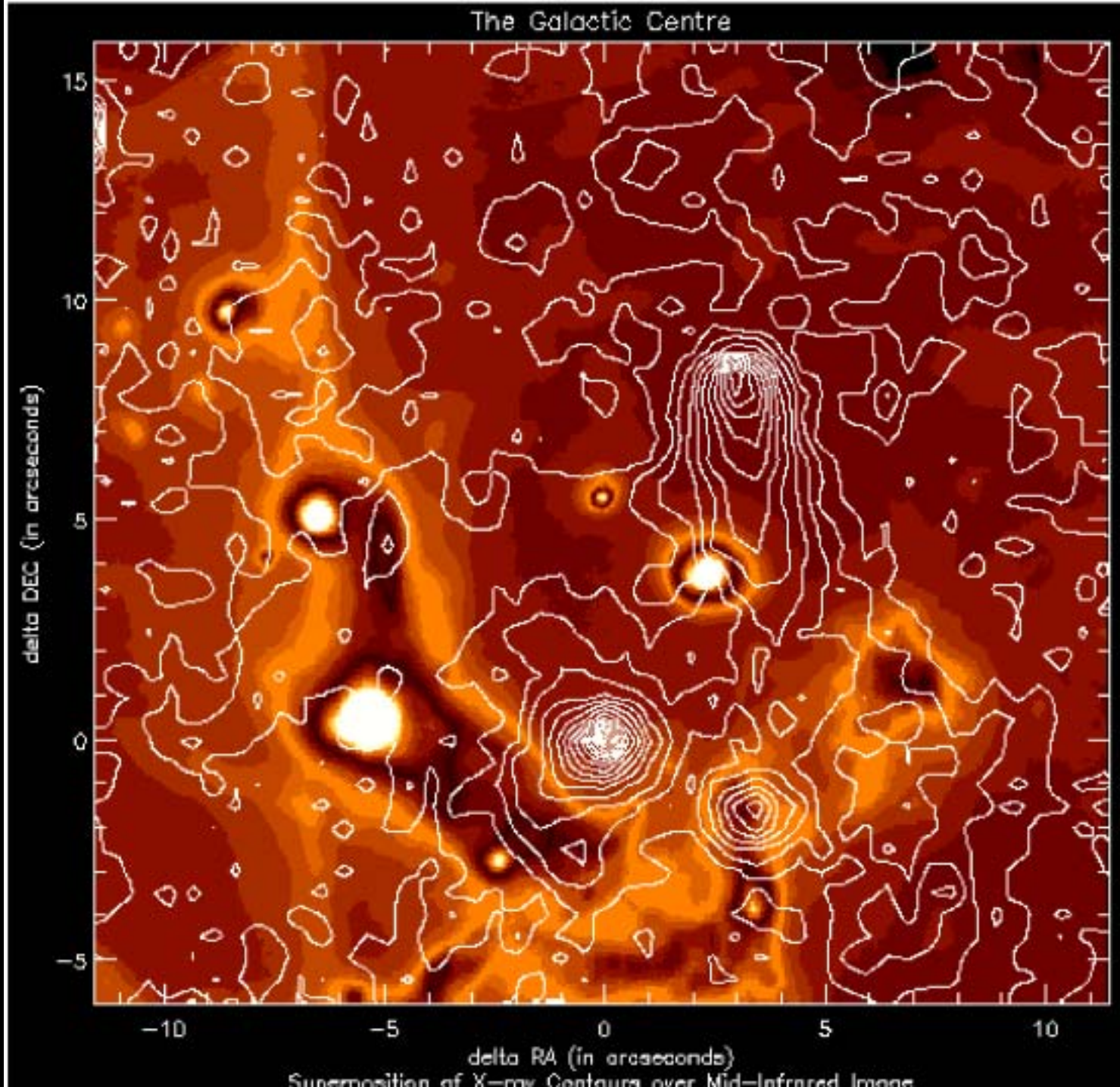
Credit: NASA/MIT/F.K. Baganoff et al.

Radio Image of the Sgr A West Minispiral



Credit: F. Yusef-Zadeh

Superposition of 2-8 keV x-ray contours on the mid-IR image.

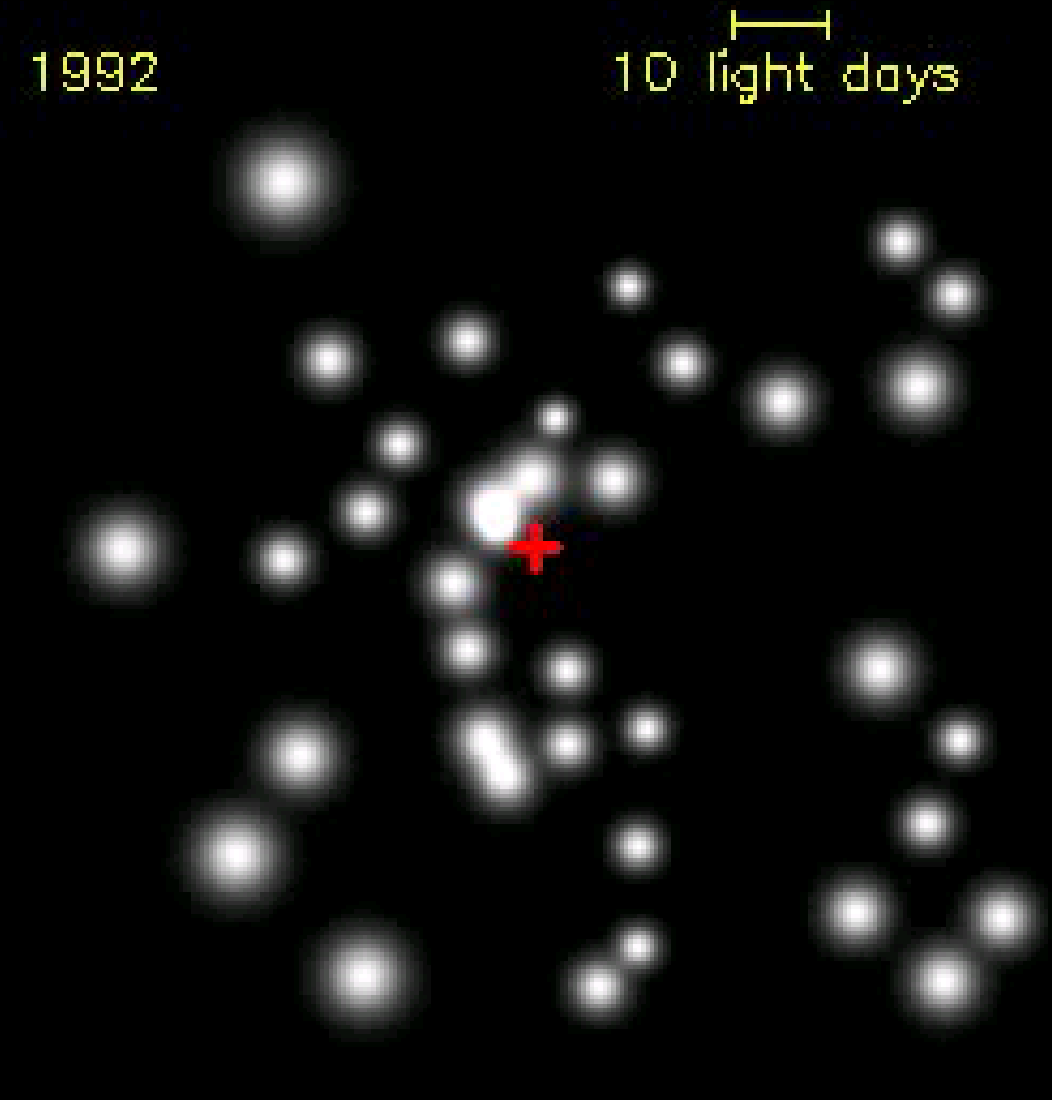


Credit:
(X-ray) NASA/ MIT/F.K. Baganoff et al., (mid-IR) UCLA/M. Morris et al.

Near-Infrared View of the Galactic Center

Credit: Courtesy of Peter Michaud, Gemini Observatory/NSF/U. Hawaii Adaptive Optics Group. Used with permission.

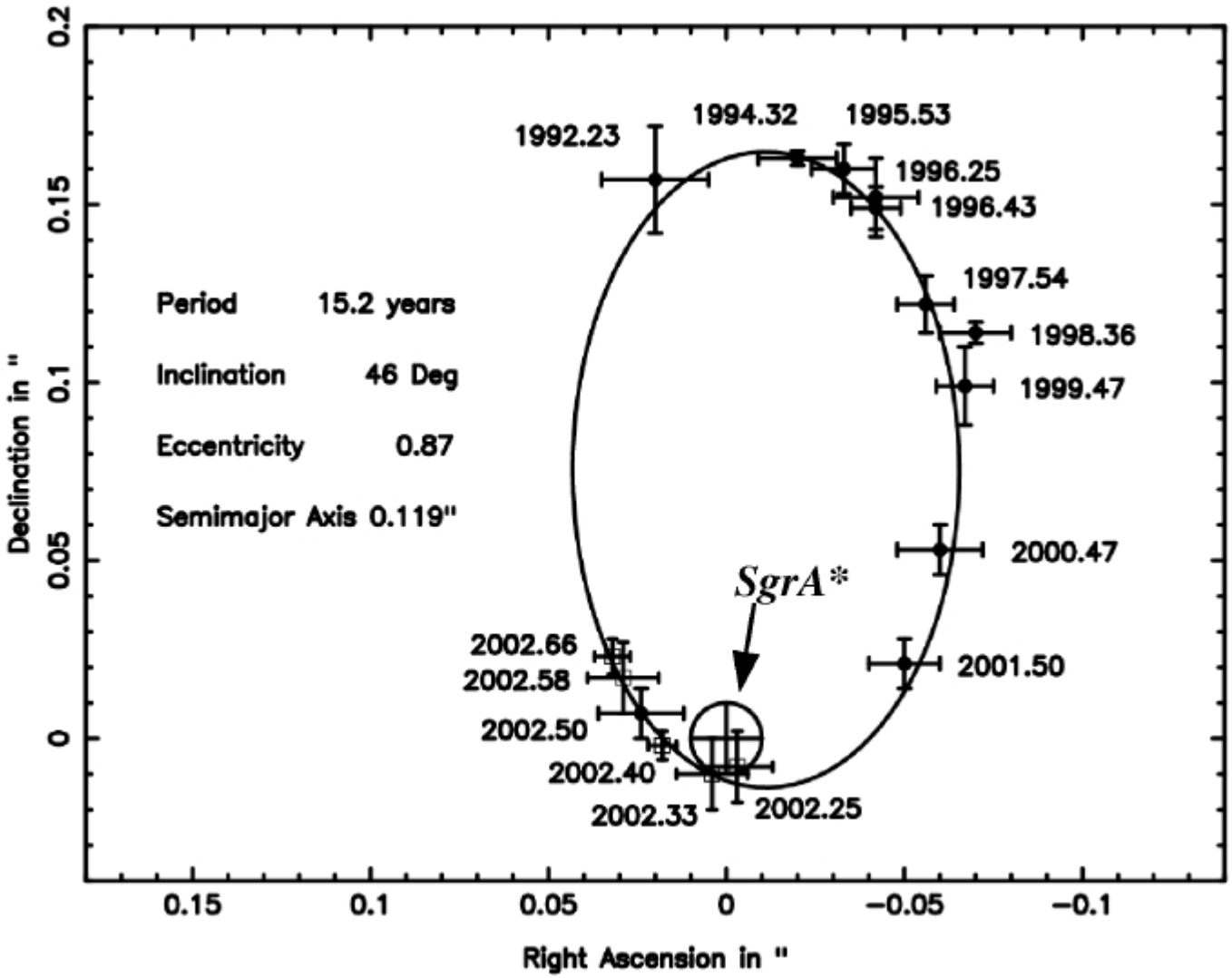
Proper Motions of Infrared Stars Around Sgr A*



Credit: Courtesy of Max Planck Society for the Advancement of Science/R. Genzel et al. Used with permission.

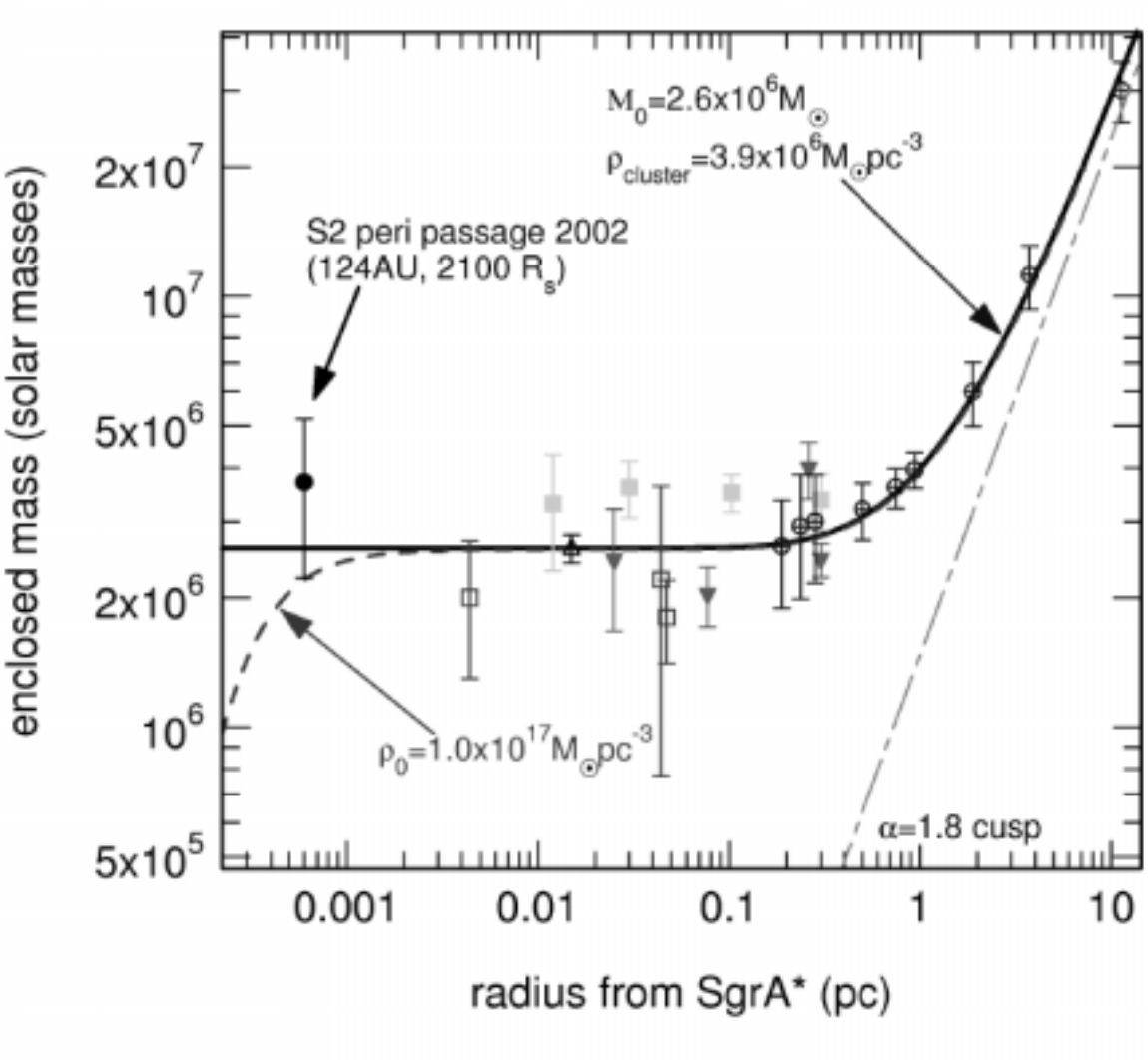
Star in a 15.2-year Orbit Around Sgr A*

Schoedel et al. 2002, Nature, 419, 694



Enclosed Mass vs. Radius Around Sgr A*

Schoedel et al. 2002, Nature, 419, 694

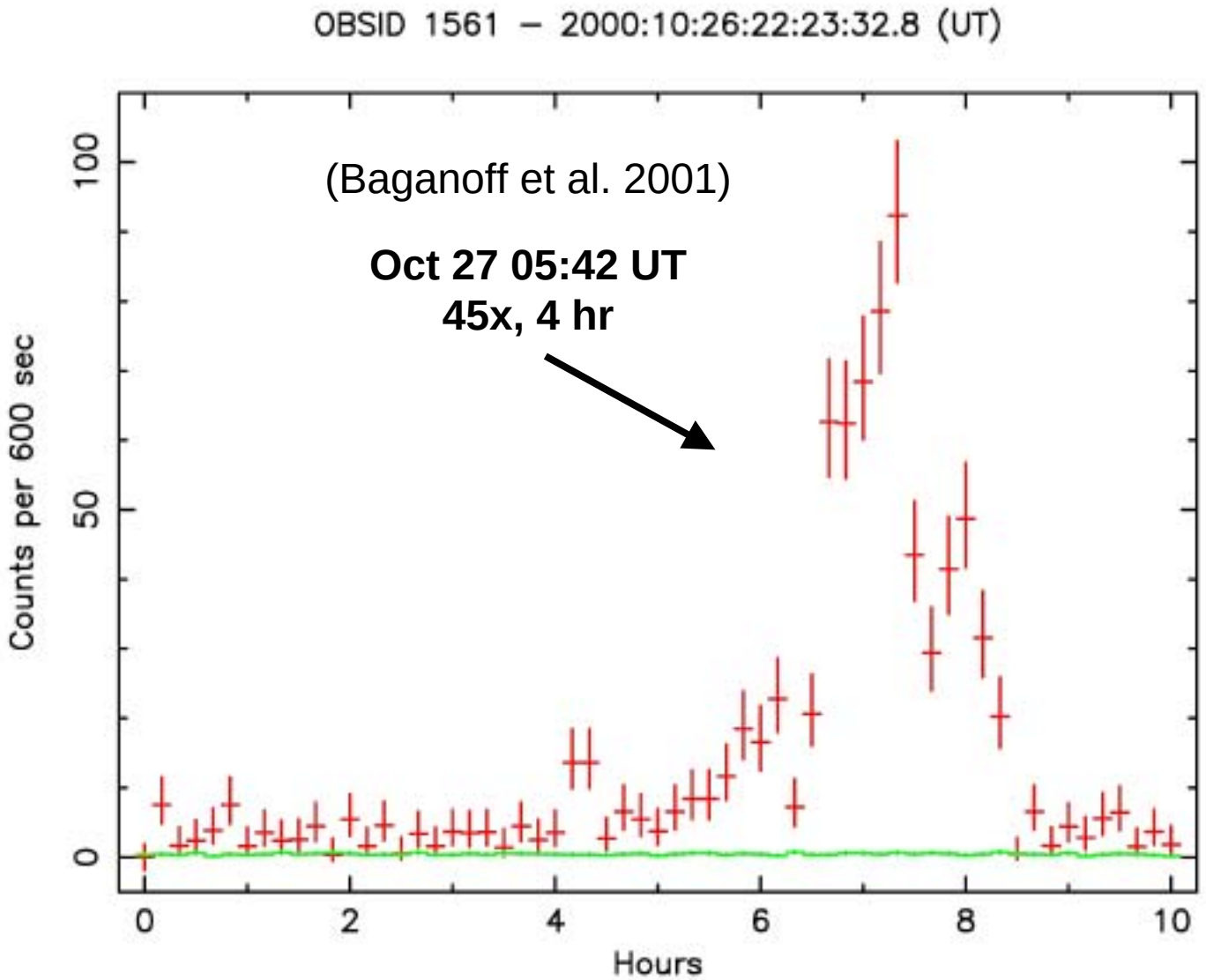


Mass Densities vs. Dark Object Masses in Nearby Galactic Nuclei

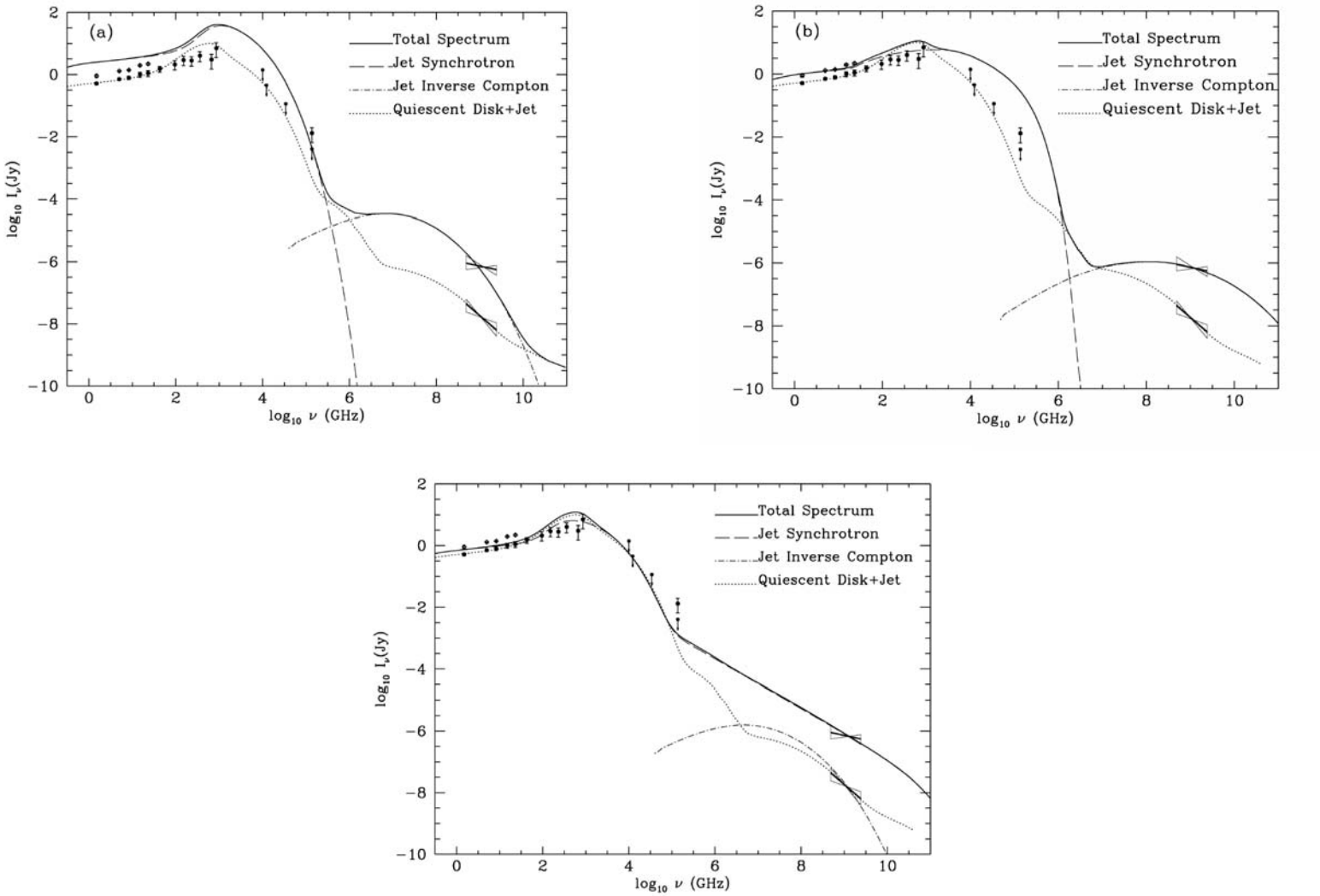
Maoz 1998, ApJ, 494, L181

- τ_{max} = maximum lifetime of a cluster of dark objects (e.g., brown dwarfs, stellar remnants, or elementary particles
- Current estimate for mass density in our Galactic center is 1×10^{17} Msun/pc^3
- Maximum lifetime for clusters of dark objects implausibly short only for Milky Way and NGC 42

2000 October 26-27



Jet Models - Markoff et al. 2001



MIT Physics 8.224 Seminar

Courtesy of Dr. Sera Markoff. Markoff et al. 2001, A&A, 379, L13
[Adapted from Markoff et al., Astronomy & Astrophysics, Vol. 379, pp L15-L16, Figs 1-2 (2001)]

Multiwavelength Monitoring of Sgr A* During Chandra Observations of Multiple X-ray Flares

F.K. Baganoff[1]

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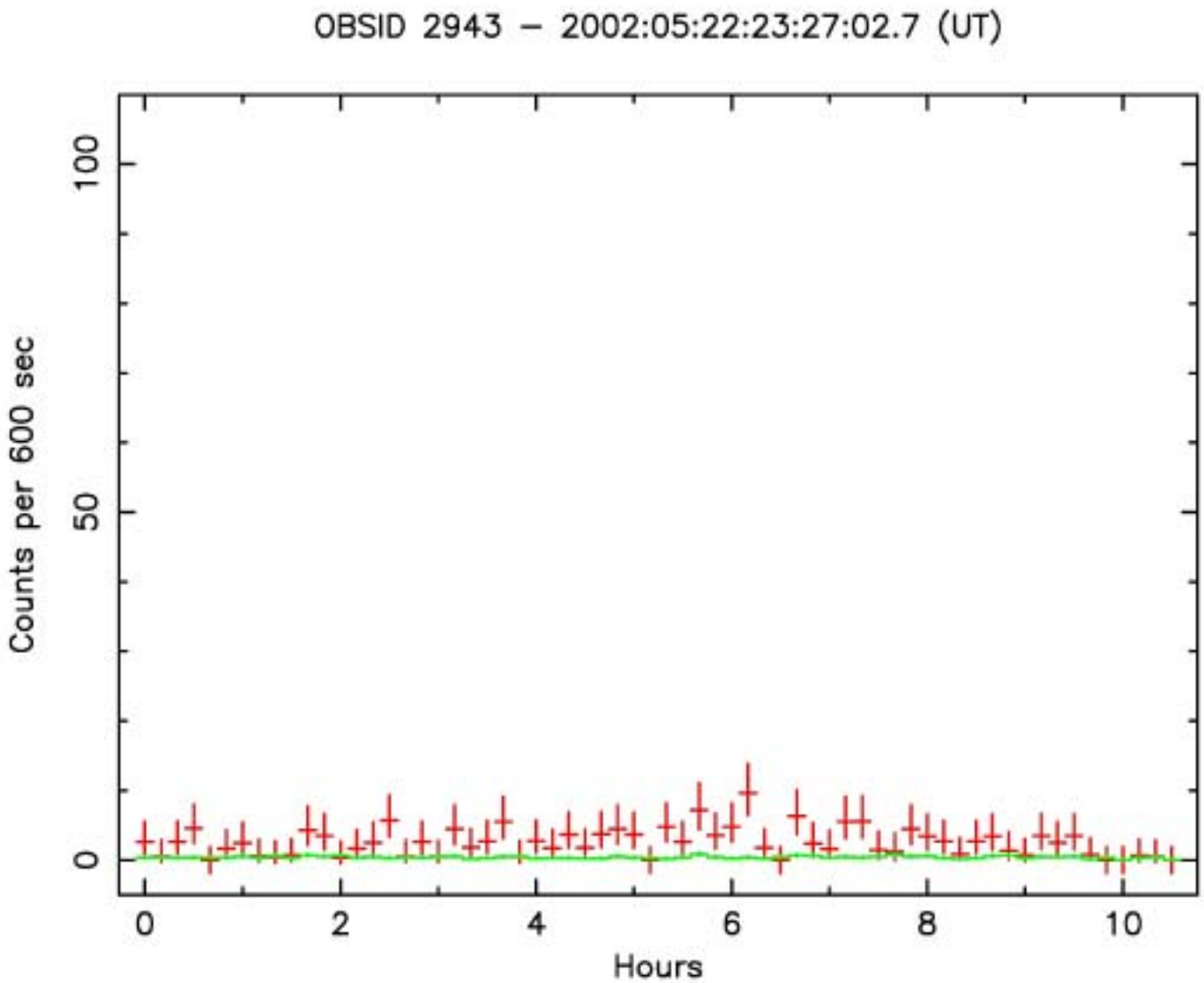
[1]MIT, [2]UCLA, [3]Penn State, [4]Steward Obs., [5]U. Cologne, [6]MPE, [7]CfA, [8]U. Groningen, [9]ISAS, [10]ATNF, [11]NRAO, [12]Caltech

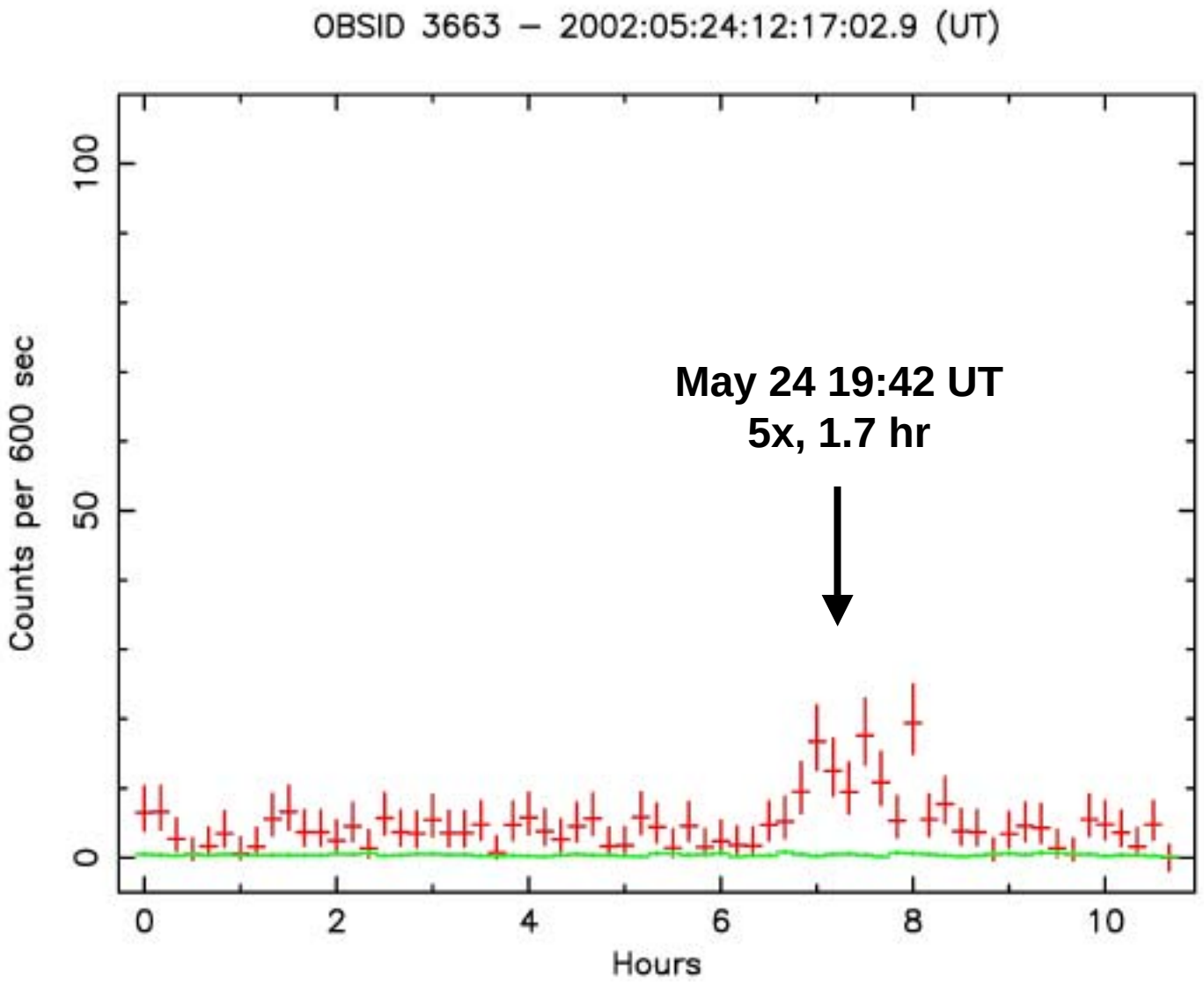
Observatories Participating in Sgr A* Monitoring Campaign

- Chandra (12–62 nm)
- Keck (2 & 10 μm)
- Very Large Telescope (2 & 3–5 μm)
- Magellan (10 μm)
- Submillimeter Array (1.3 mm)
- Caltech OVRO Millimeter Array (3 mm)
- Australia Telescope Compact Array (3 mm)
- Very Large Baseline Array (7 mm)
- Very Large Array (1.3 cm)

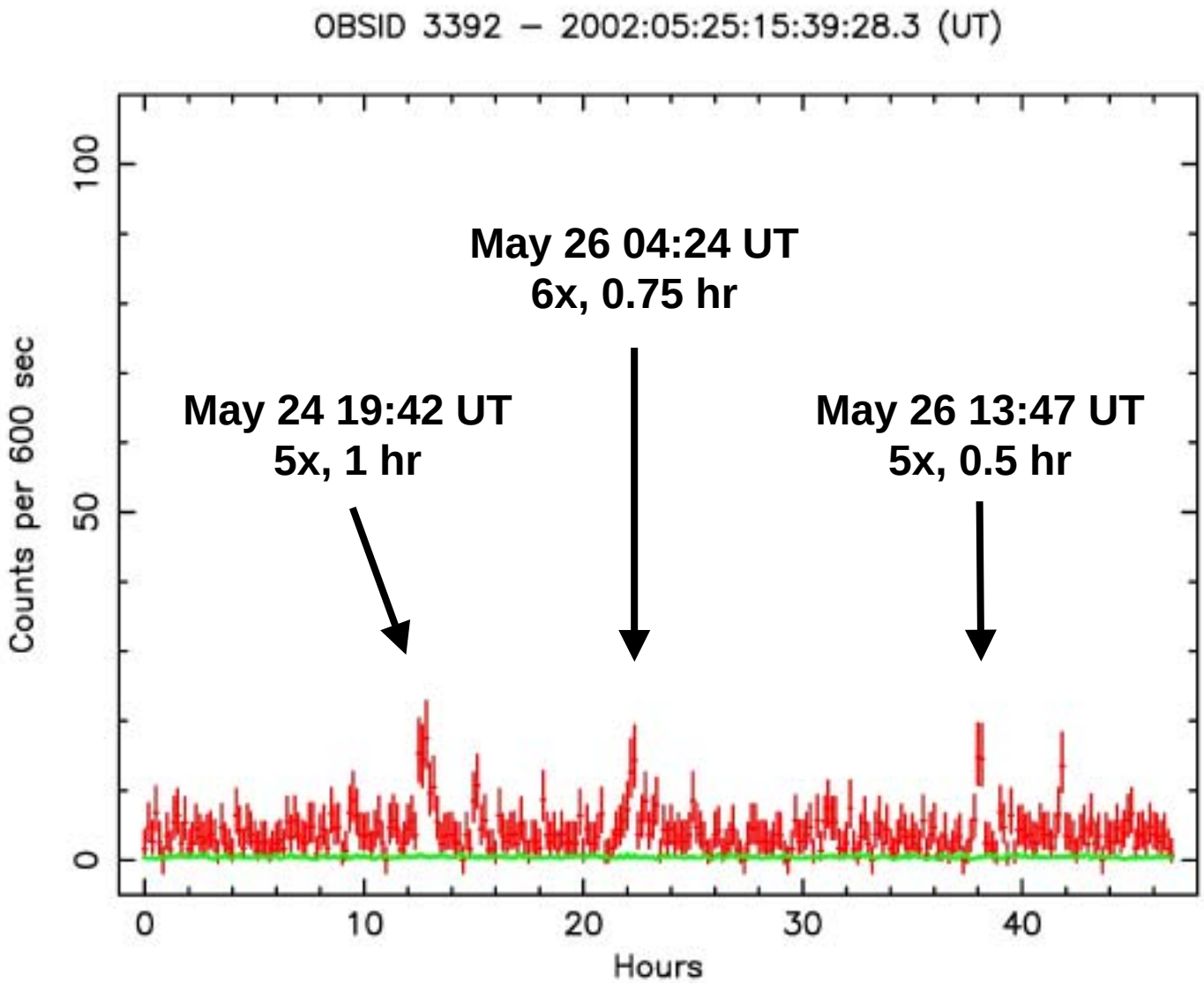
2002 May 22-23 – Orbit 1, Part 1



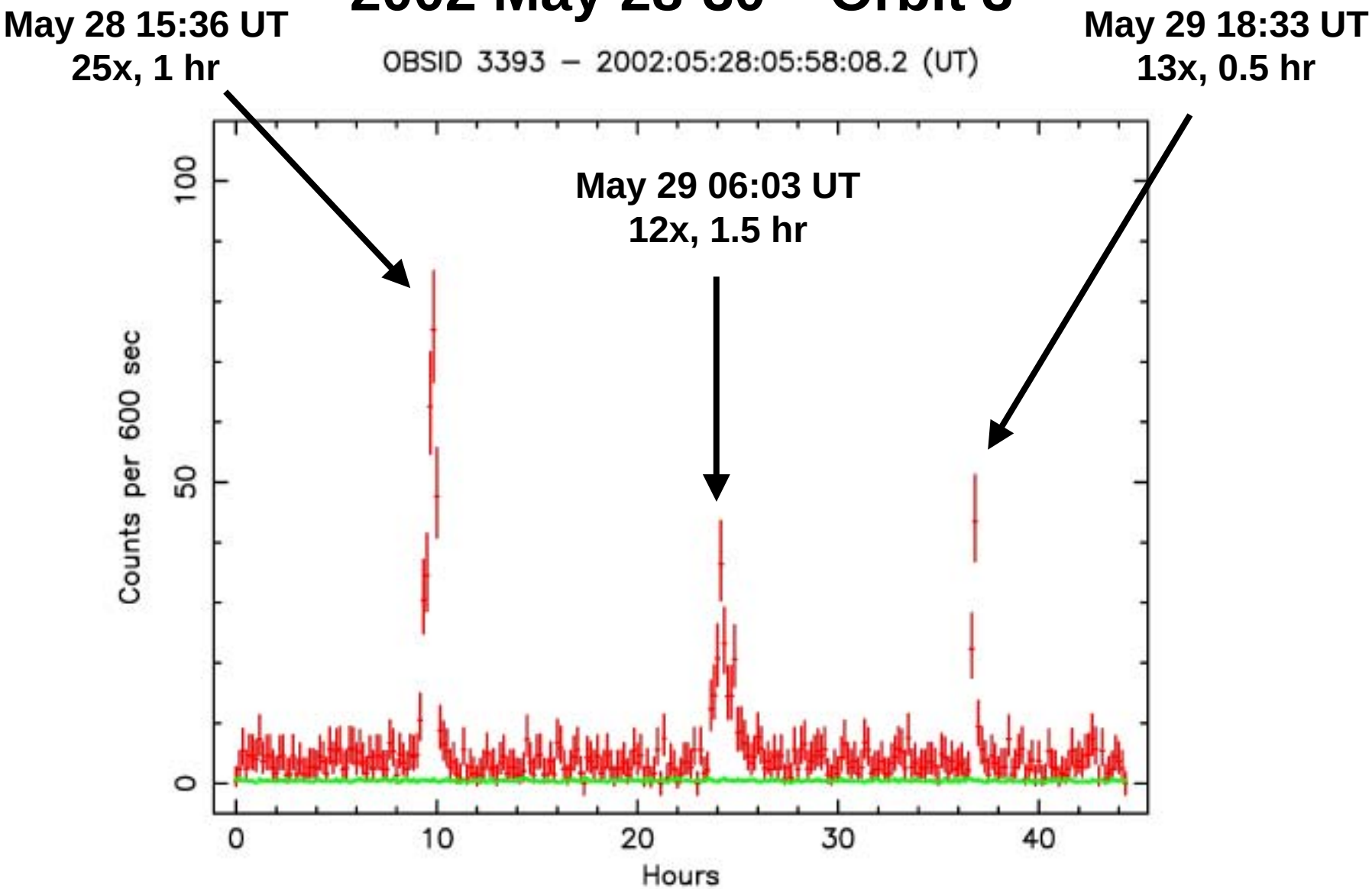
2002 May 24 – Orbit 1, Part 2



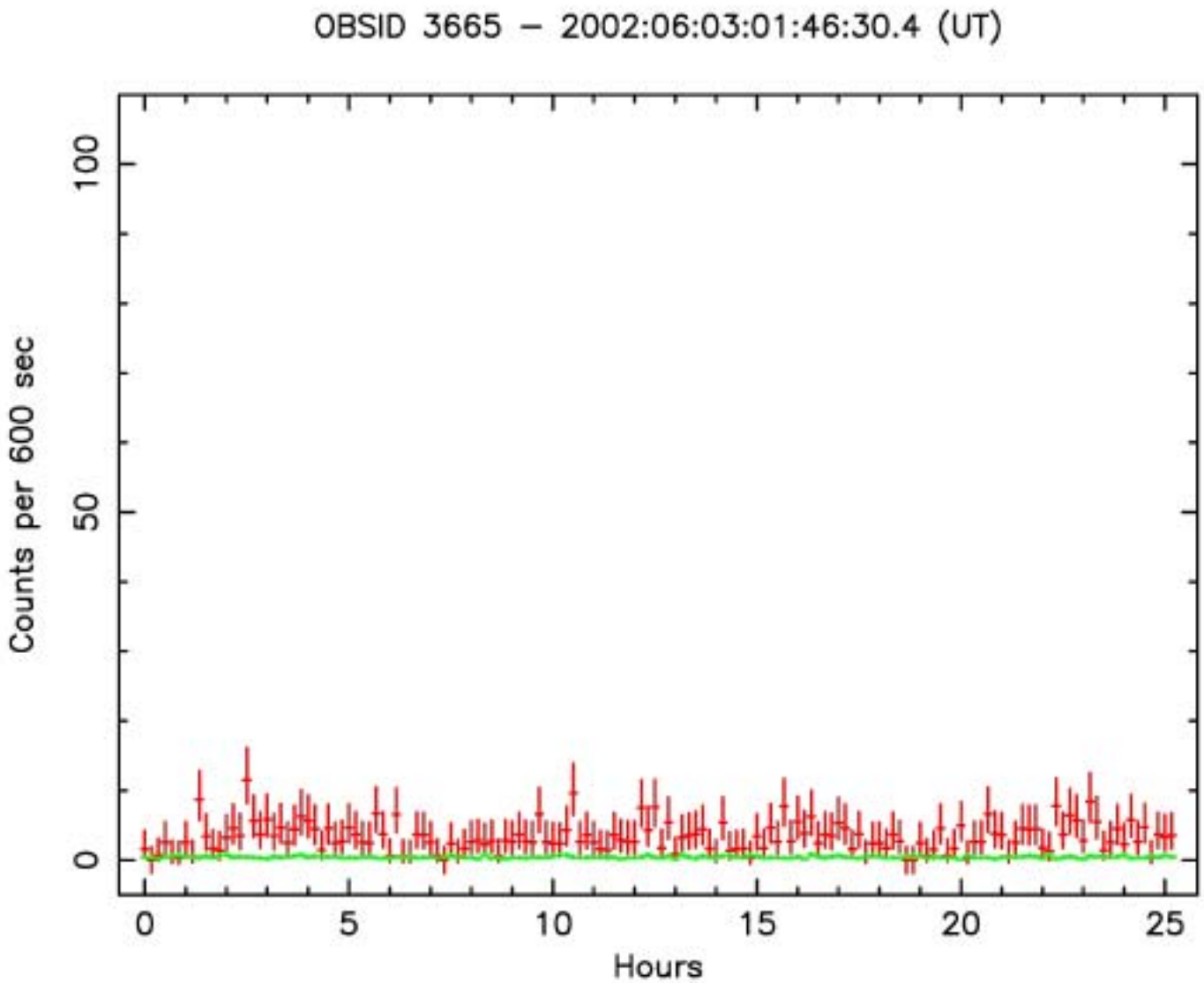
2002 May 25-27 – Orbit 2



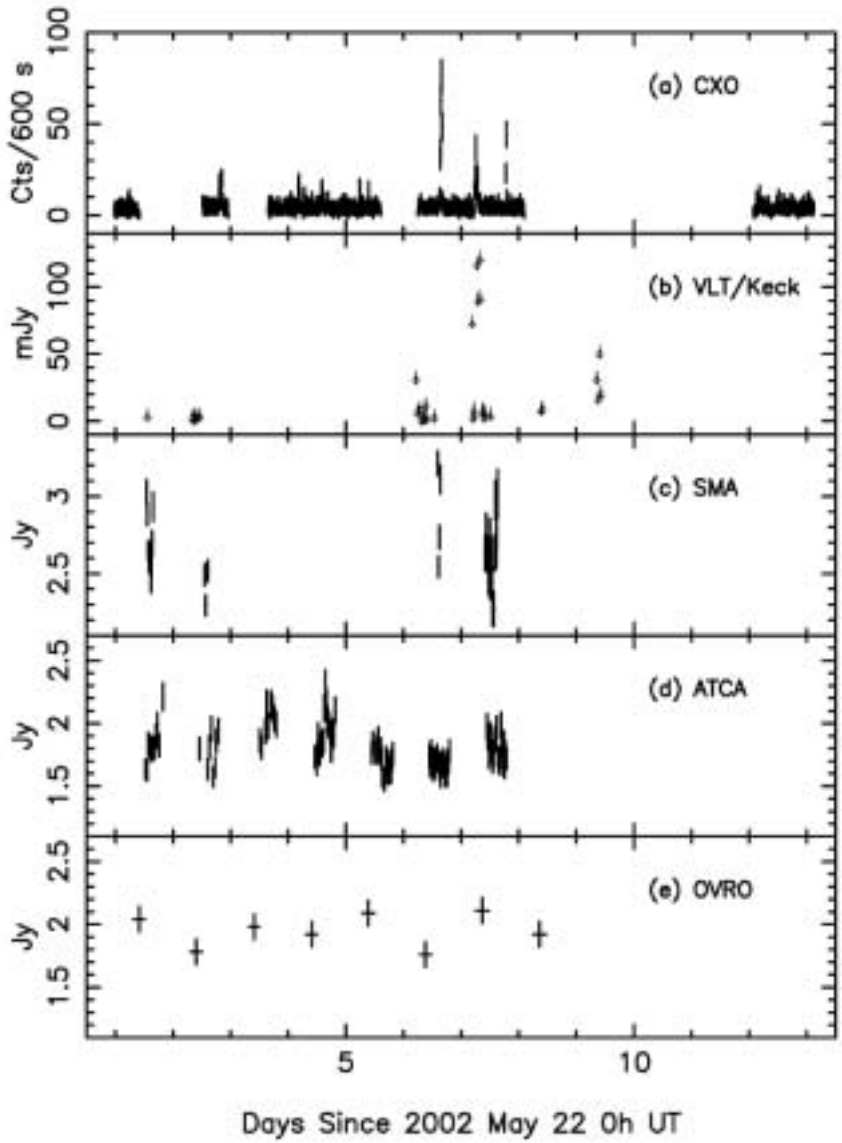
2002 May 28-30 – Orbit 3



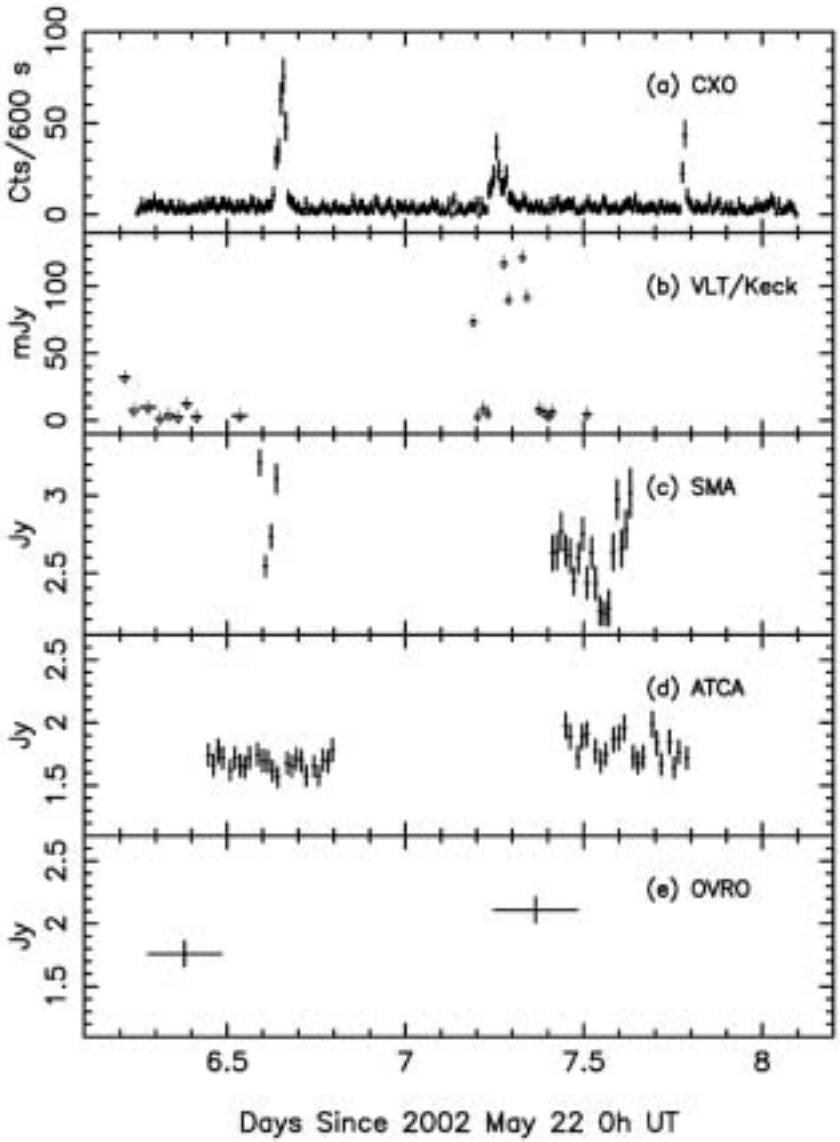
2002 June 3-4 – Orbit 5



Sgr A* Multiwavlength Monitoring Campaign

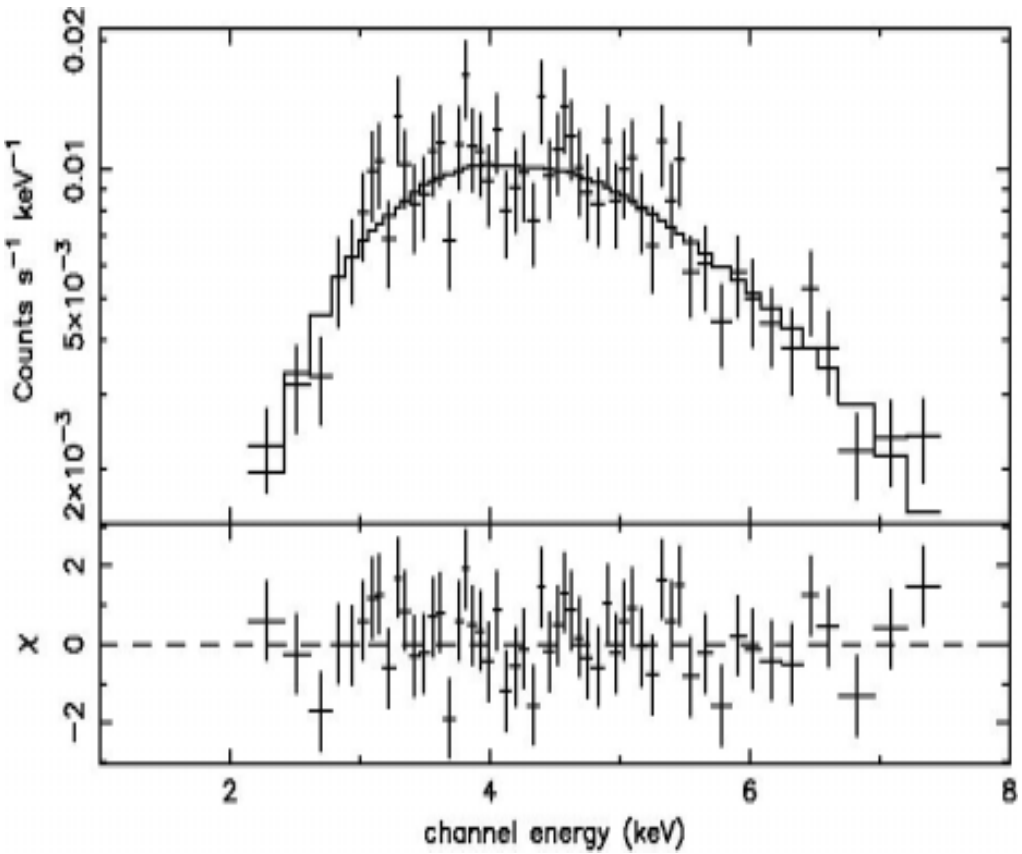


Three Large X-ray Flares from Sgr A*



Integrated X-ray Spectrum of Sgr A* During Flares

Model: Absorbed, Dust-Scattered Power Law

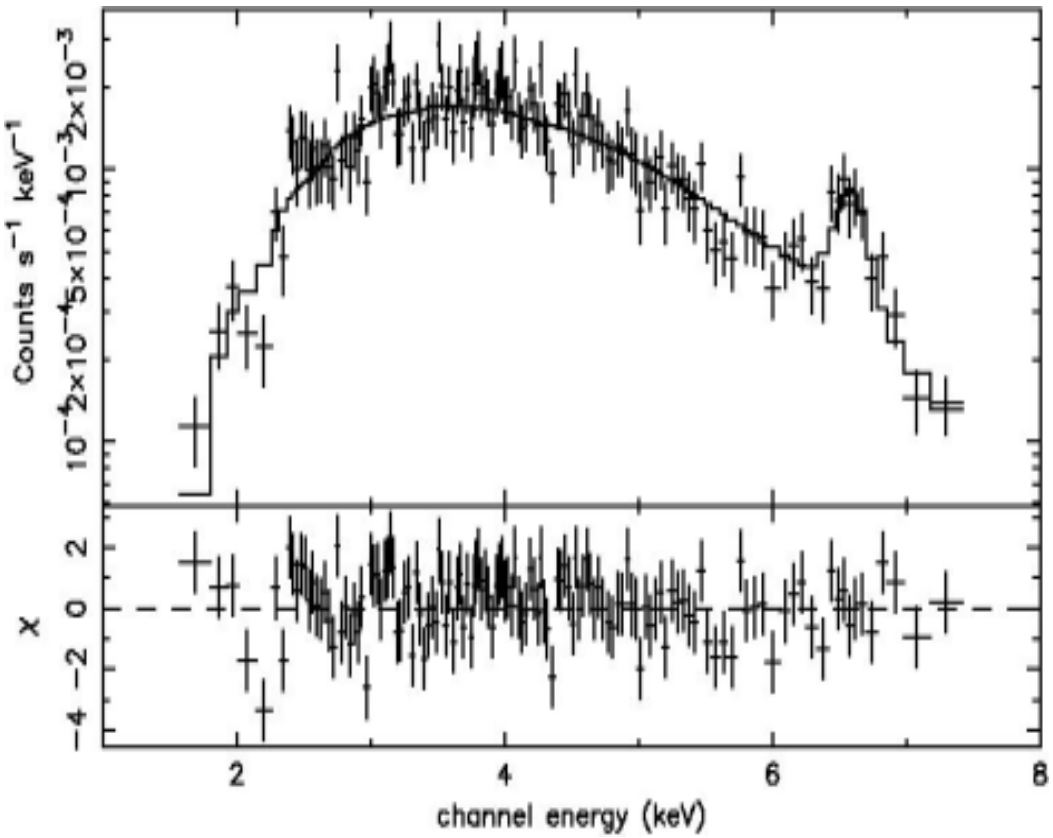


$N_H = 6.0 \times 10^{22}$ cm^{-2}
$\Gamma = 1.3$

$F_X = 1.6 \times 10^{-12}$ erg cm^{-2} s^{-1}
$L_X = 2.0 \times 10^{34}$ erg s^{-1}
D = 8 kpc

Integrated X-ray Spectrum of Sgr A* in Quiescence

Model: Absorbed, Dust-Scattered, Power Law Plus Line



$N_H = 5.9 \times 10^{22}$ cm^{-2}
$\Gamma = 2.4$

$E_{Fe} = 6.59$ (6.54-6.64) keV
Line is narrow and NIE

$F_X = 1.8 \times 10^{-13}$ erg cm^{-2} s^{-1}
$L_X = 1.4 \times 10^{33}$ erg s^{-1}
D = 8 kpc

$\langle L_F \rangle / \langle L_Q \rangle = 14.0$

X-ray Emission at Sgr A* is Extended

Baganoff et al. 2003, ApJ, 591, 901

- Intrinsic size of emission at Sgr A* is about 1.4 arcsec (FWHM)

- Consistent with Bondi accretion radius for a 3×10^6 solar-mass black hole

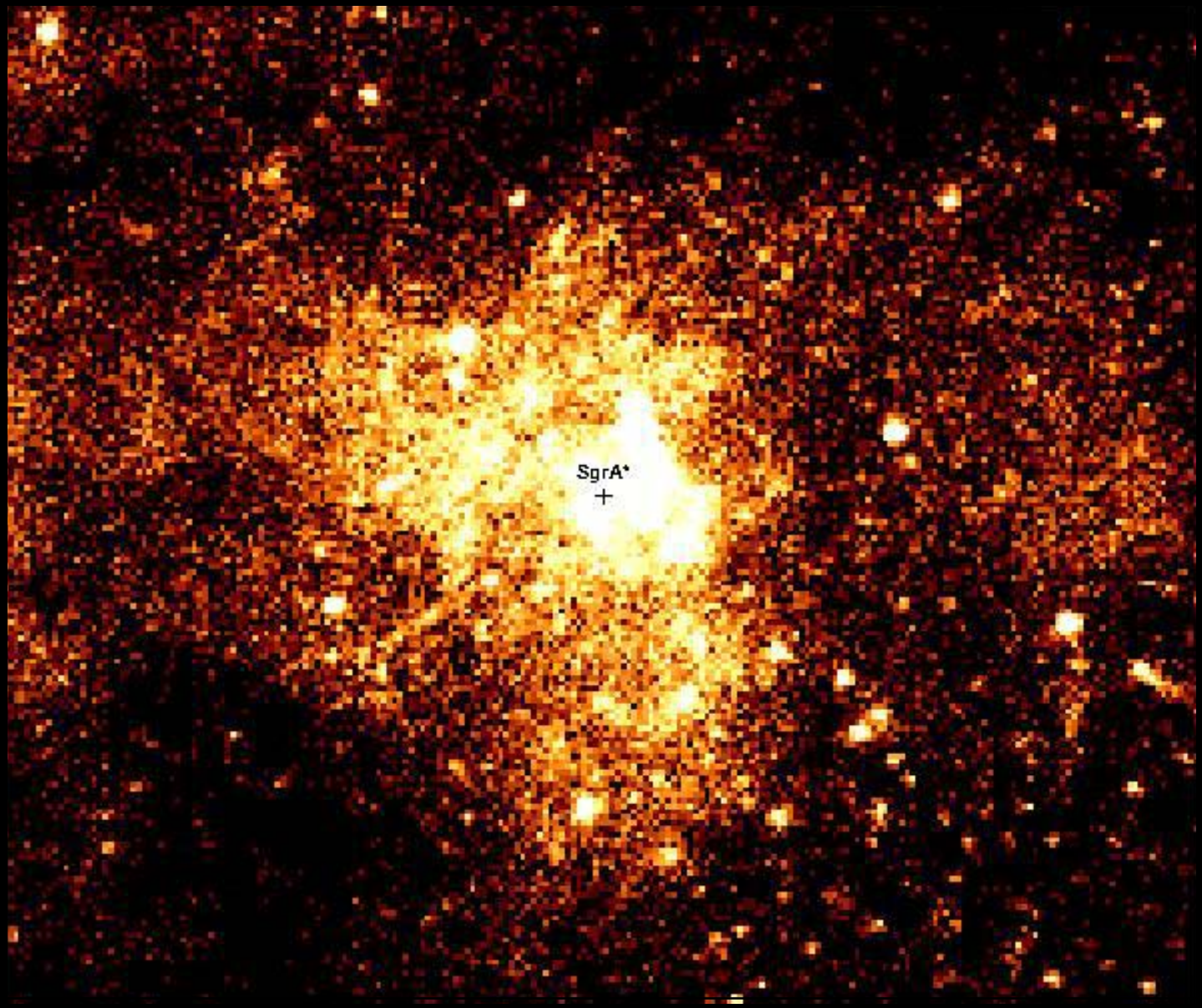
Adapted from Baganoff et al., CHANDRA X-RAY SPECTROSCOPIC IMAGING OF SAGITTARIUS A* AND THE CENTRAL PARSEC OF THE GALAXY. Astrophysical Journal, Vol. 591, p. 901, Fig. 6 (2003). Used with permission.

Summary

- Chandra observed Sgr A* for 139 hr over a two-week period in late May to early June 2002
- **3 X-ray flares with amplitudes >10x detected in a 28-hr period!**
- 4 X-ray flares with amplitudes ~5x detected in addition
- **“Factor-of-10” flares occur about once every other day, on average**
- Typical flare duration is about 1 hr (0.5-4 hr)
- **Frequent, large-amplitude, short-duration flaring** behavior of Sgr A* is **unique** among supermassive black holes!
- Probably selection effect: **flares too faint to detect in other galaxies**
- Behavior **inconsistent** with X-ray binaries and **not seen** from any of the other **>2,300** X-ray point sources in the field
- **Strong evidence** that X-ray flaring source **is** the Milky Way’s central, supermassive black hole!

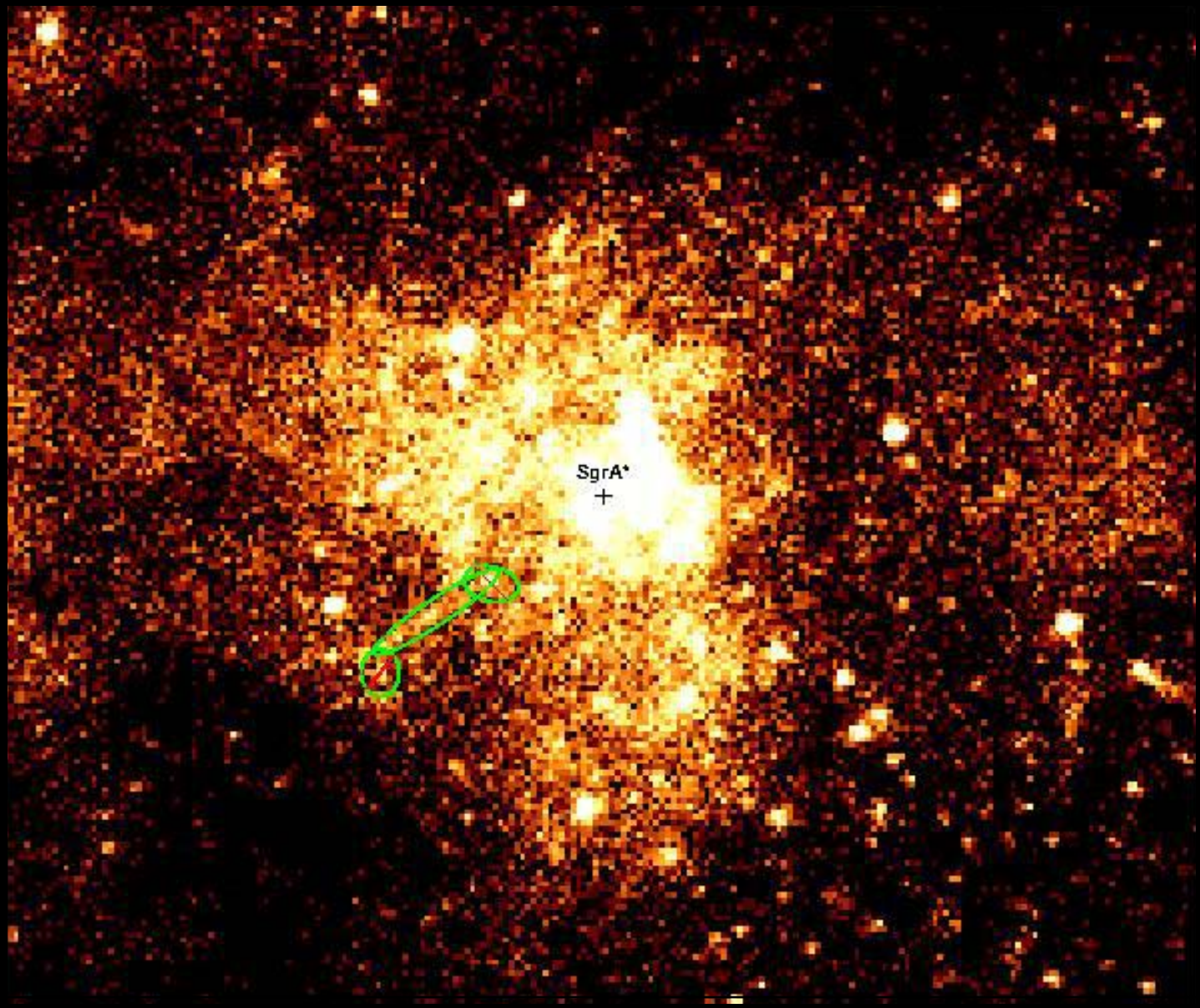
Summary (continued)

- **No factor-of-2 or larger flares seen at longer wavelengths**
- Some evidence for variations at tens of percent level in millimeter band on timescales of hours to days seen – **upper limit currently about 50%**
- Efforts to improved calibration of millimeter data underway



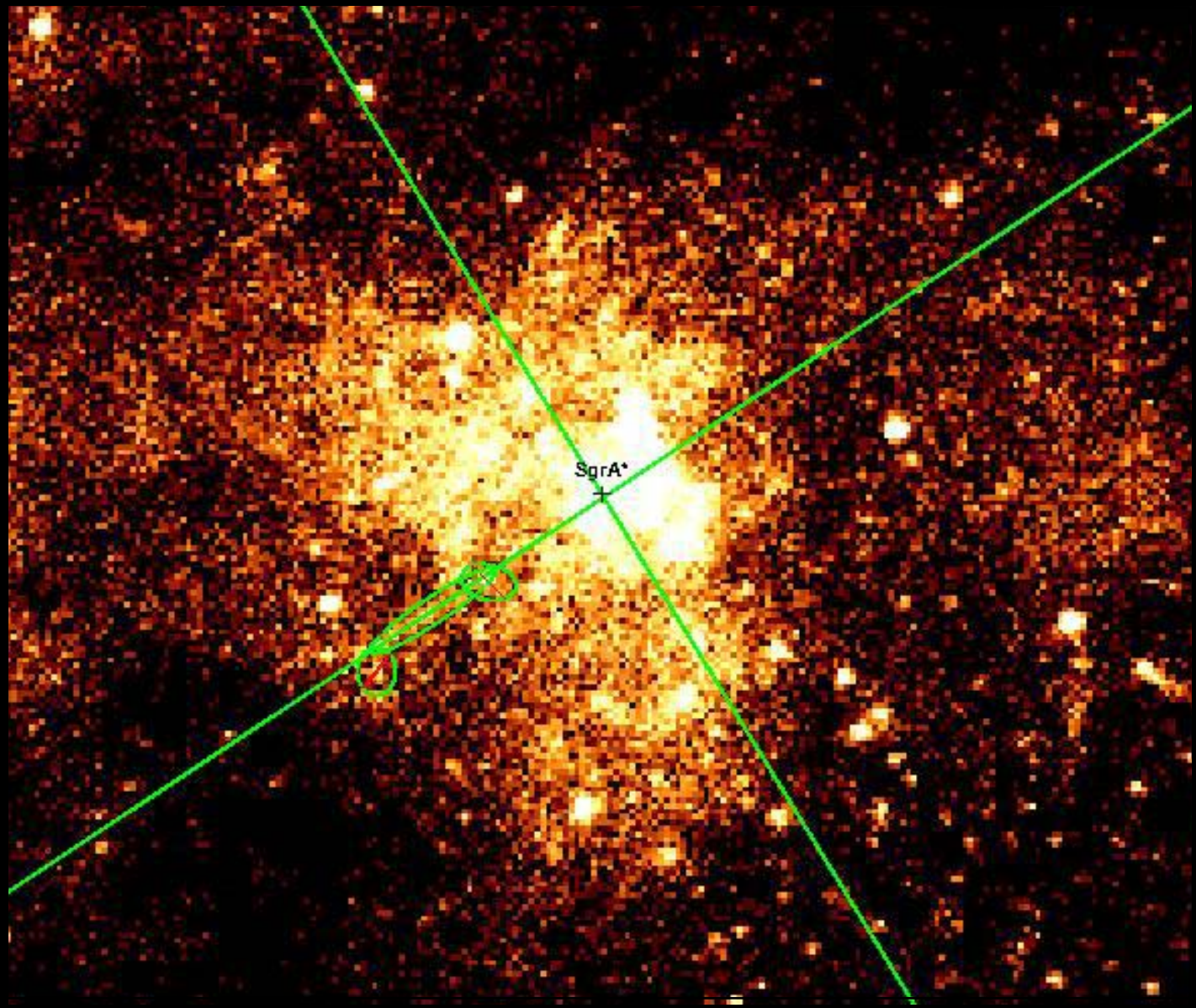
Courtesy of Max Planck Society for the Advancement of Science/R. Genzel et al. Used with permission.

Credit: NASA/MIT/F.K. Baganoff et al.



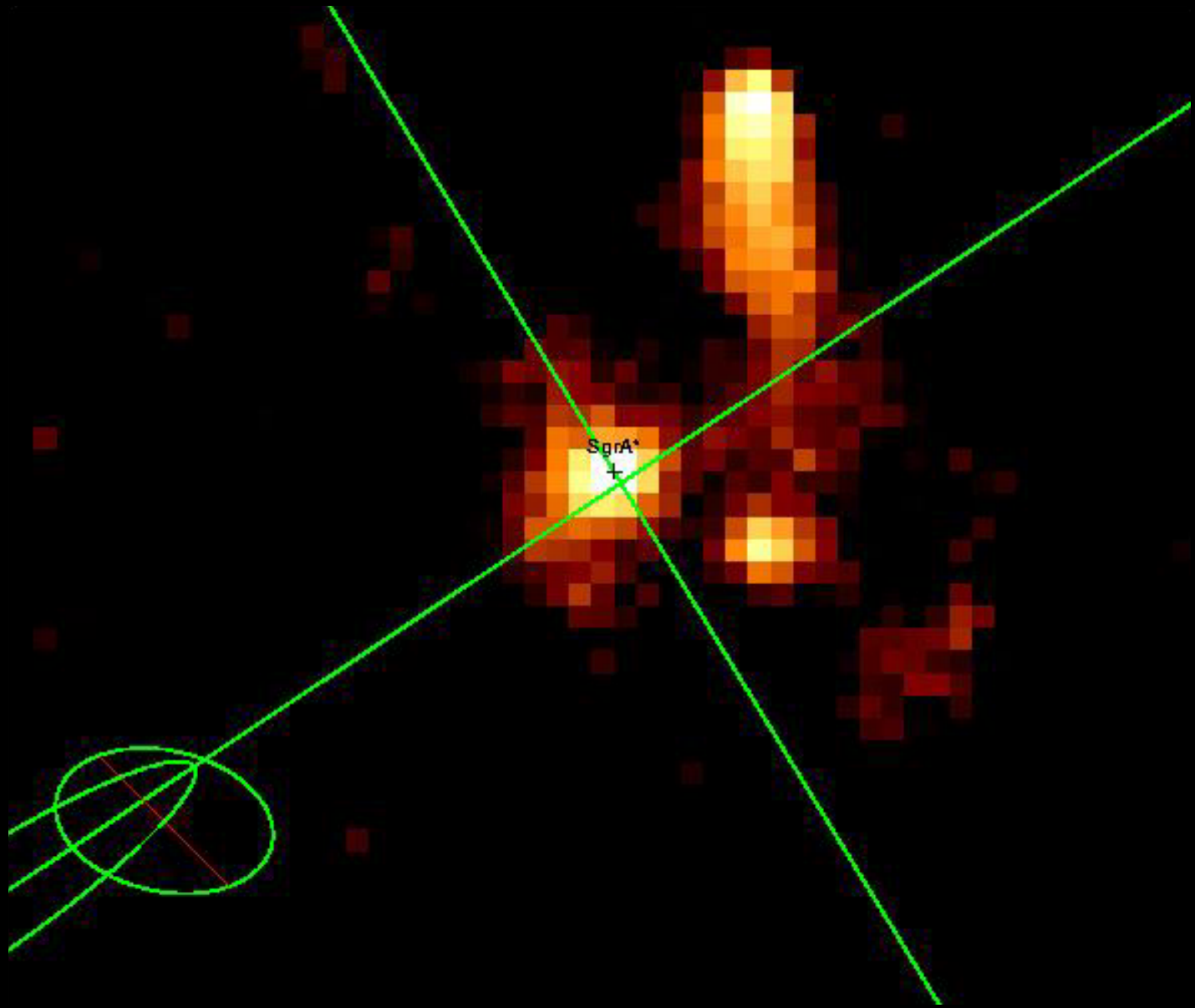
Courtesy of Max Planck Society for the Advancement of Science/R. Genzel et al. Used with permission.

Credit: NASA/MIT/F.K. Baganoff et al.

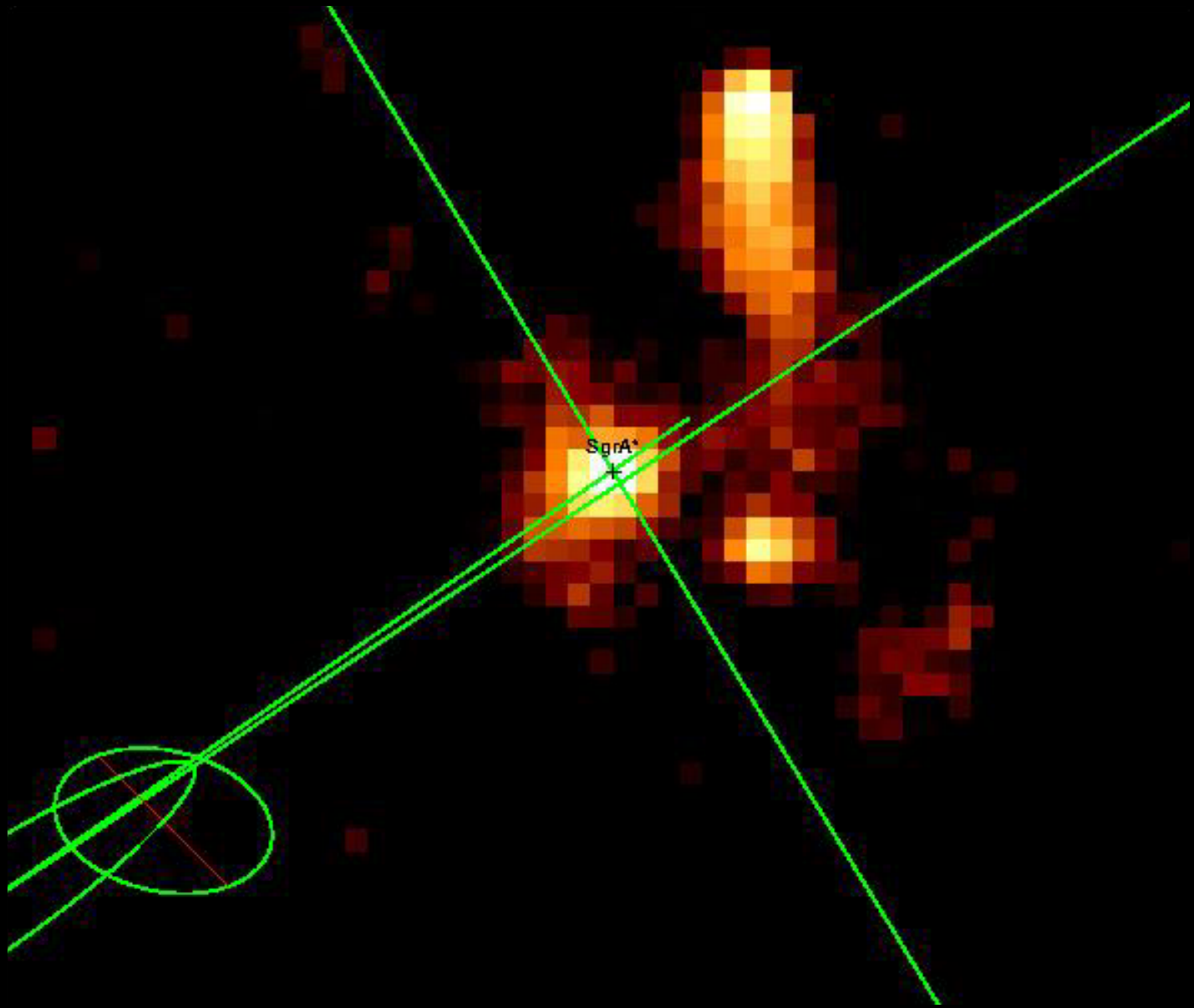


Courtesy of Max Planck Society for the Advancement of Science/R. Genzel et al. Used with permission.

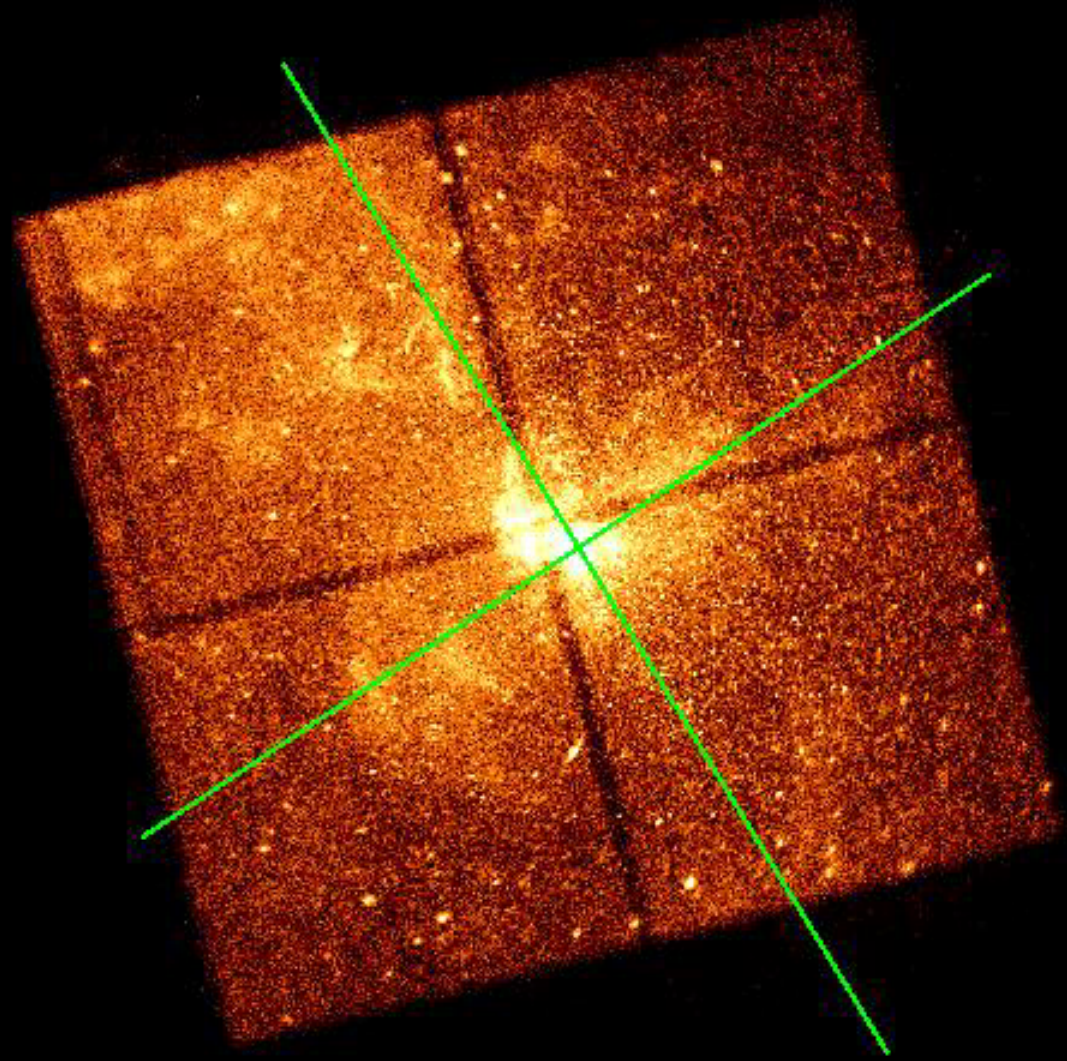
Credit: NASA/MIT/F.K. Baganoff et al.



Credit: NASA/MIT/F.K. Baganoff et al.

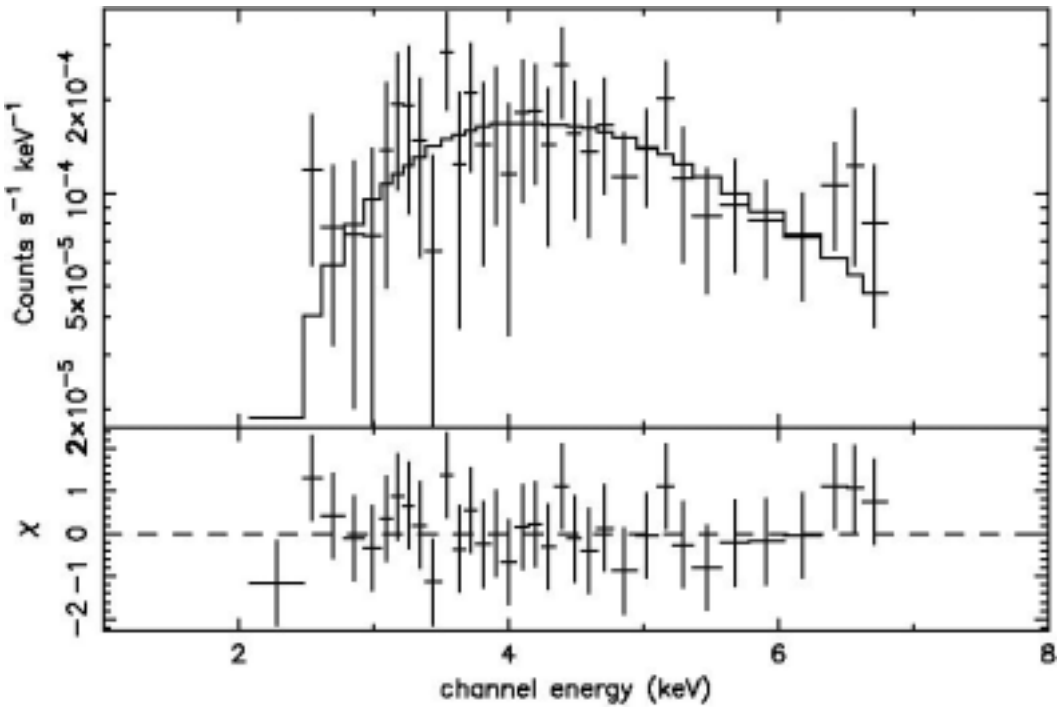


Credit: NASA/MIT/F.K. Baganoff et al.



Credit: NASA/MIT/F.K. Baganoff et al.

Spectrum of Possible Jet-like Feature Near Sgr A*



Gamma = 1.8

$N_H = 8.0 \times 10^{22}$ cm^{-2}

Summary – X-ray Jet

- Discovery of an apparent X-ray jet from the Milky Way's central black hole
- Never before seen in any other waveband!
- Jet is 1 light-year long and located 1.5 light-years from the black hole
- Jet aligned with large-scale bipolar X-ray lobes
- Lobes may be due to past ejections or outflows from the supermassive black hole
- Strongly suggests we are seeing "fingerprints" of activity over the past few thousand years
- X-ray flares tell us about the current activity