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

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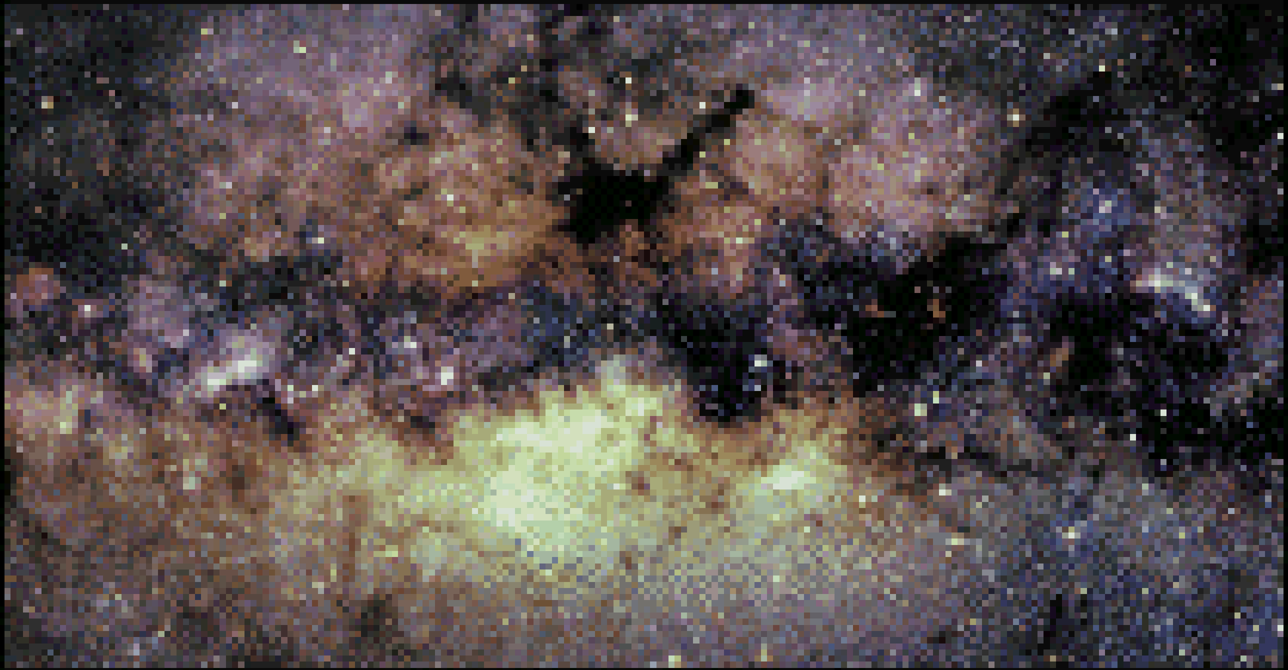
Optical View of the Galactic Center

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



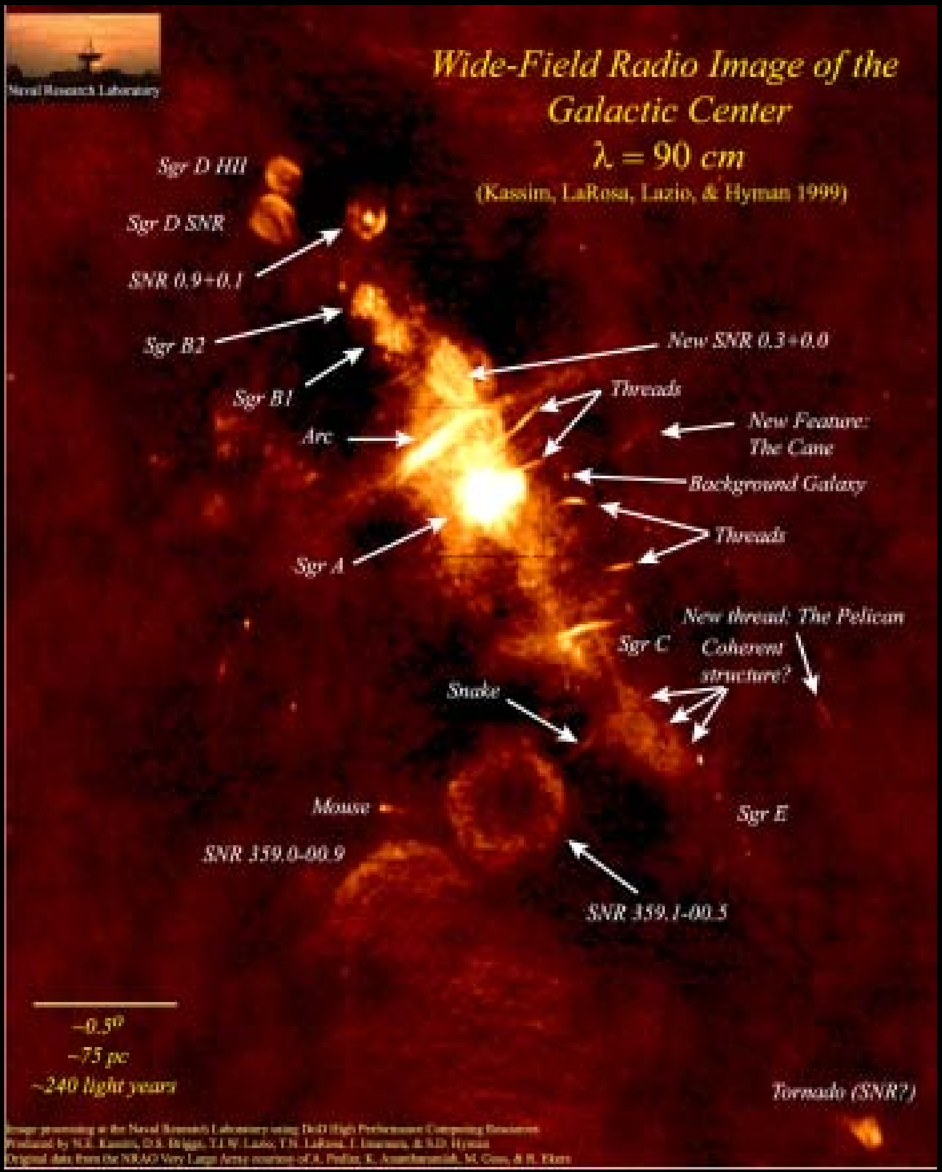
80 degrees

Credit: Axel Mellinger

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

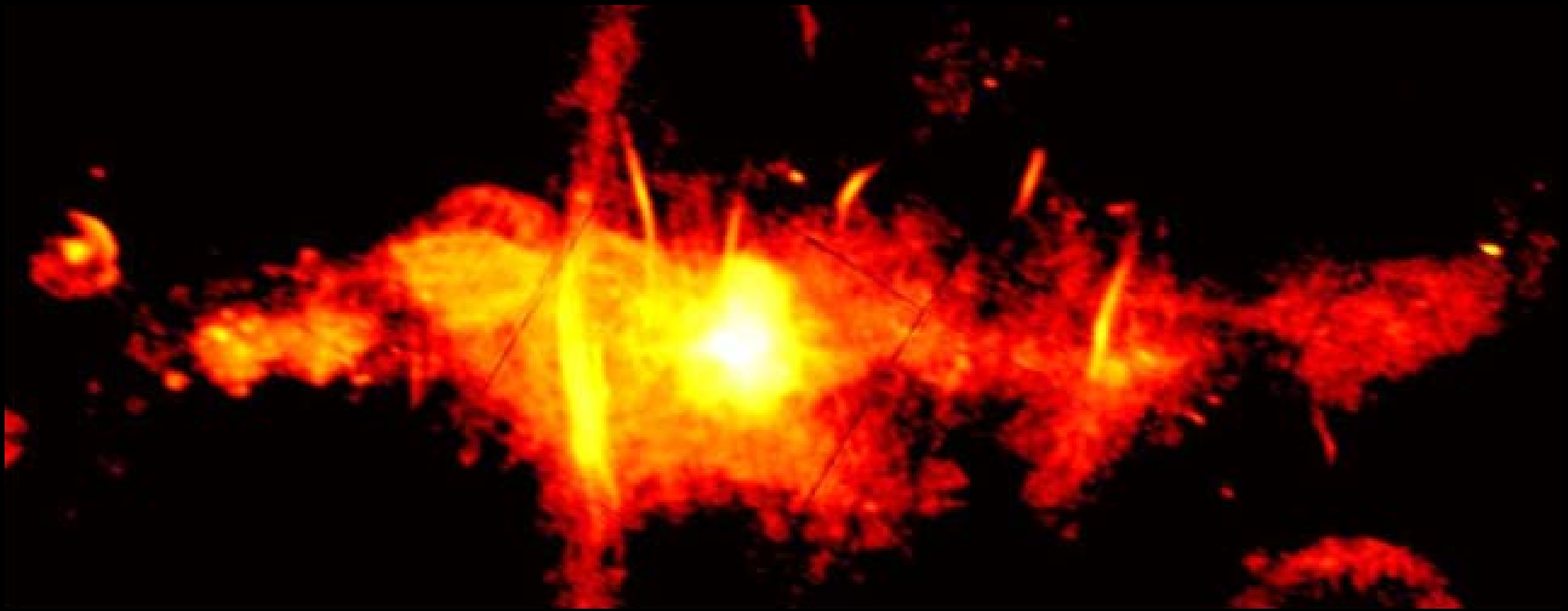
- Imaging or Photometry
- Spectroscopy
- Timing
- Multiwaveband

Annotated Radio View of the Galactic Center



Credit: Kassim, LaRosa, Lazio, & Hyman

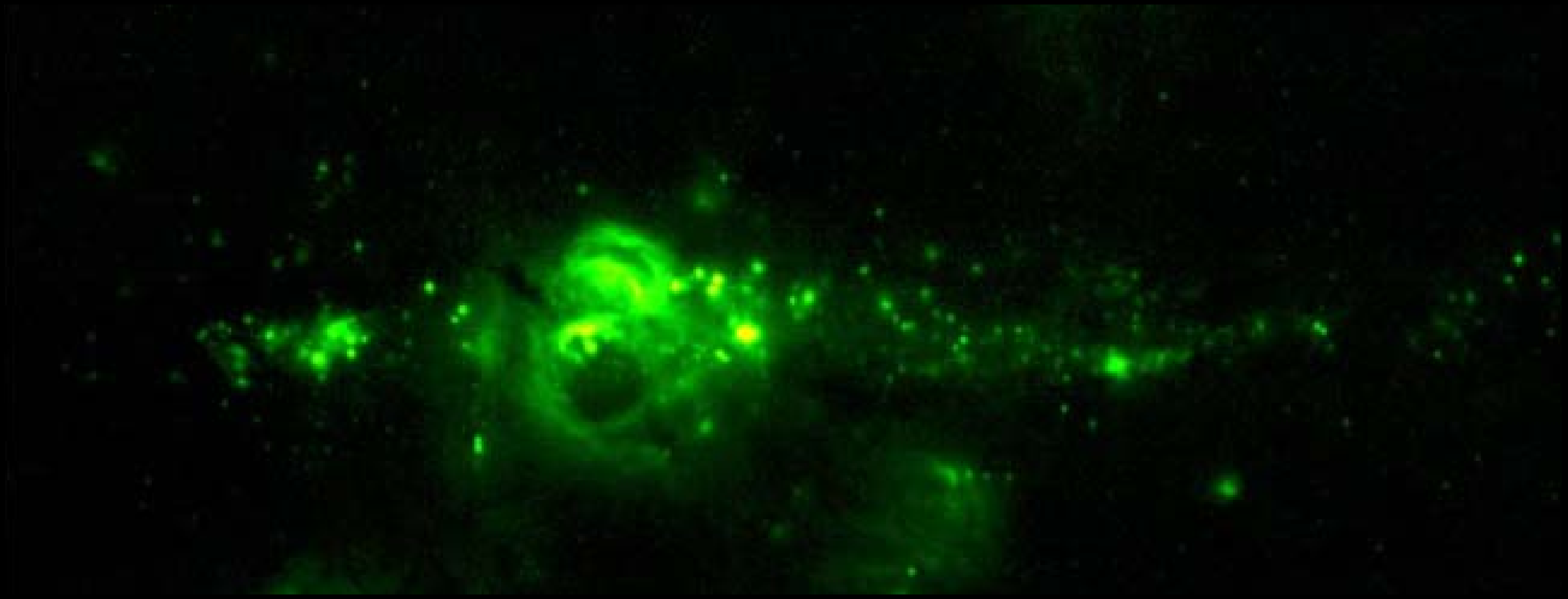
Radio View of the Galactic Center



2.8 x 0.8 degrees

Credit: VLA

Mid-Infrared View of the Galactic Center



2 x 0.8 degrees

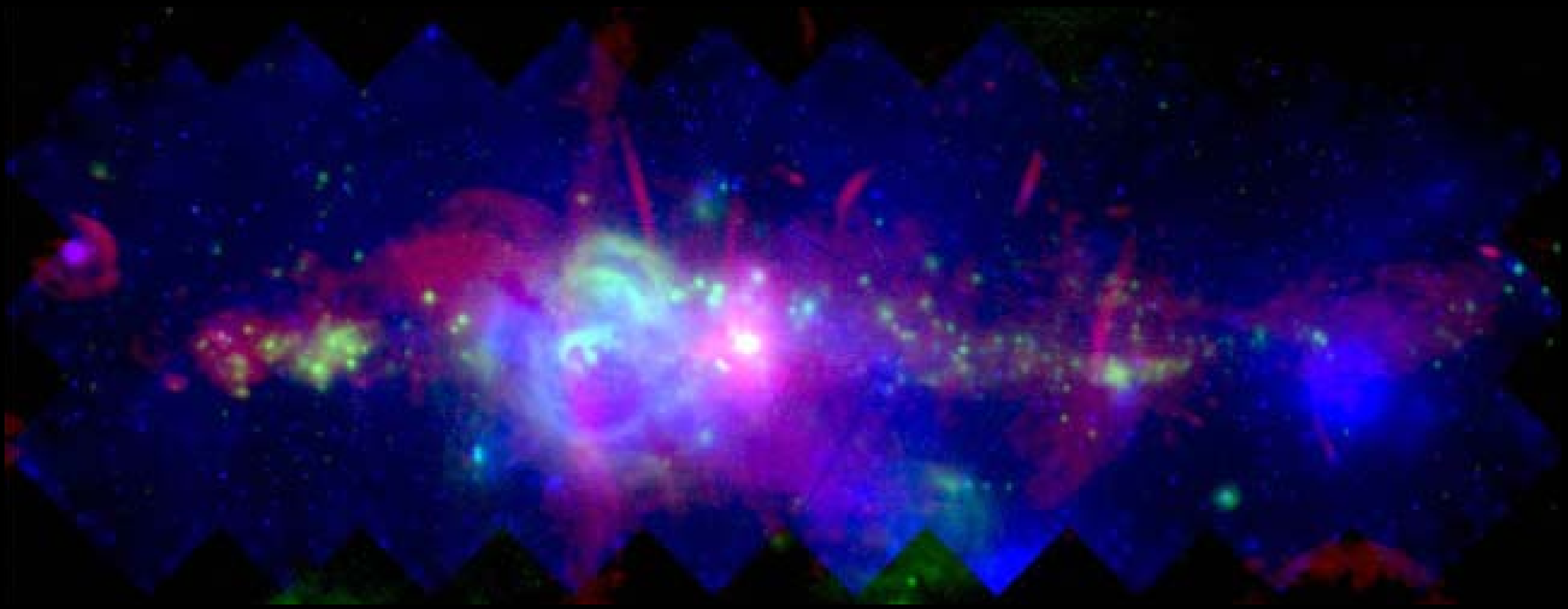
Credit: MSX

X-ray View of the Galactic Center

2 x 0.8 degrees

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

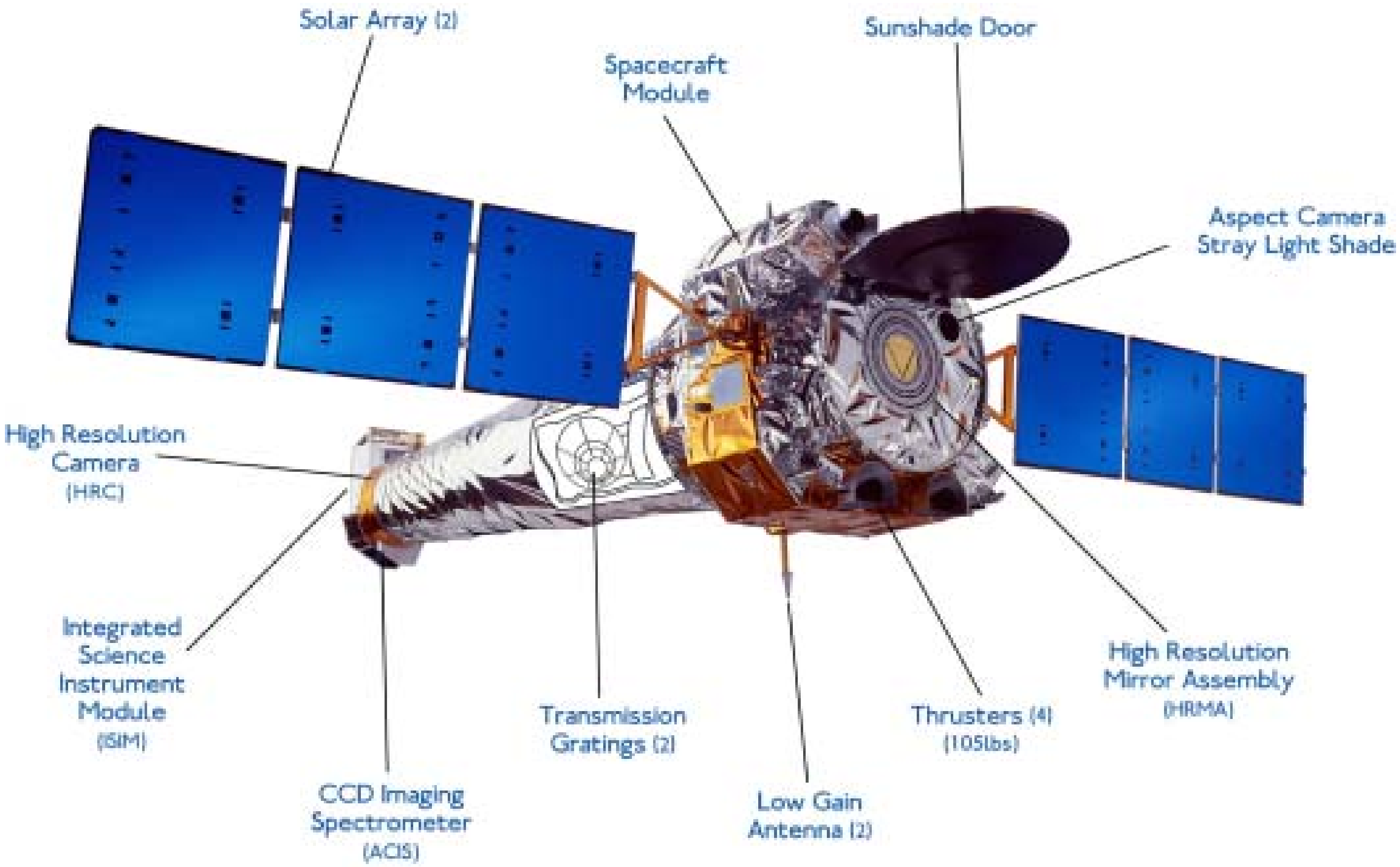
Radio/Mid-Infared/X-ray View of the Galactic Center



2 x 0.8 degrees

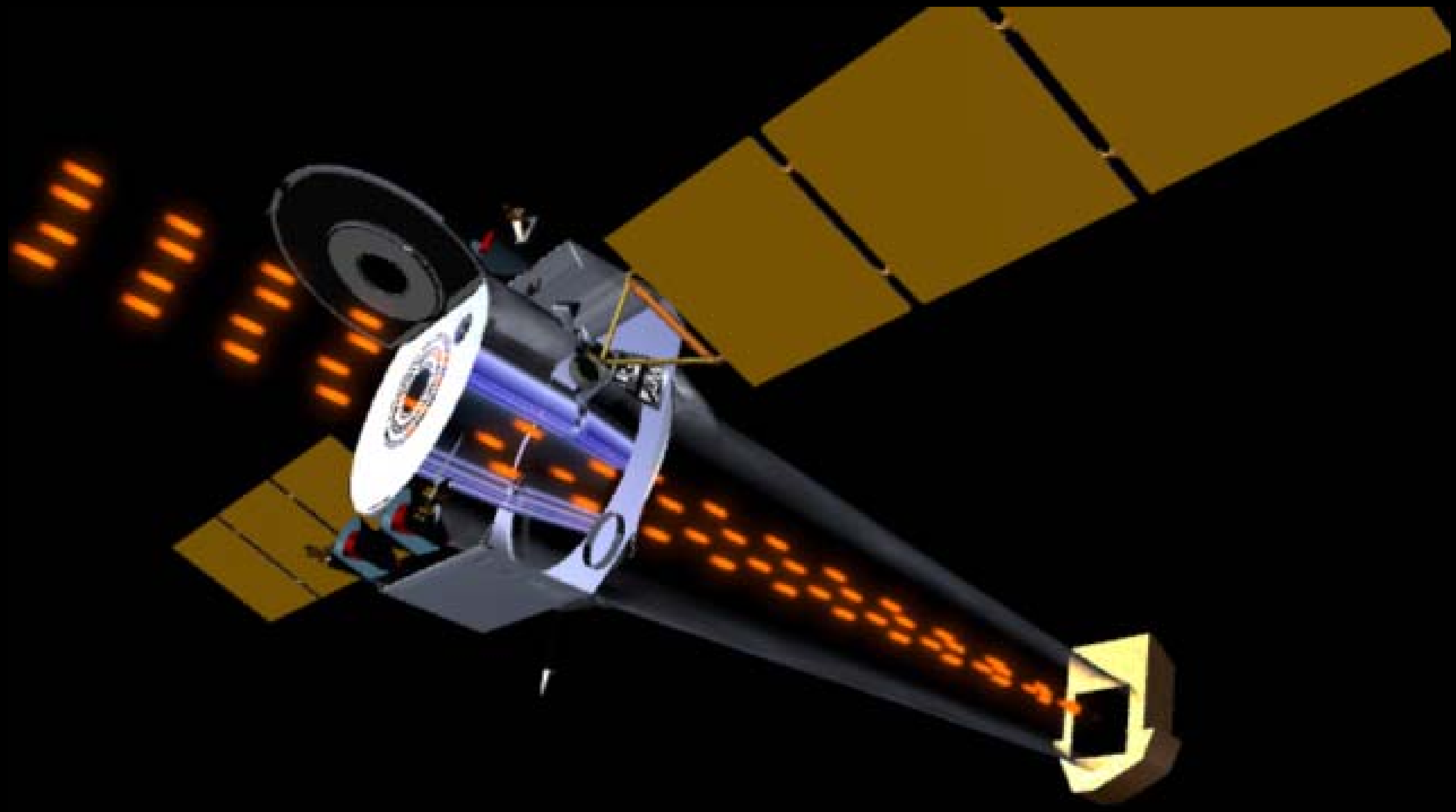
Credit: (X-ray) NASA/UMass/D. Wang et al., (Mid-IR) MSX, (Radio) VLA

Chandra X-ray Observatory



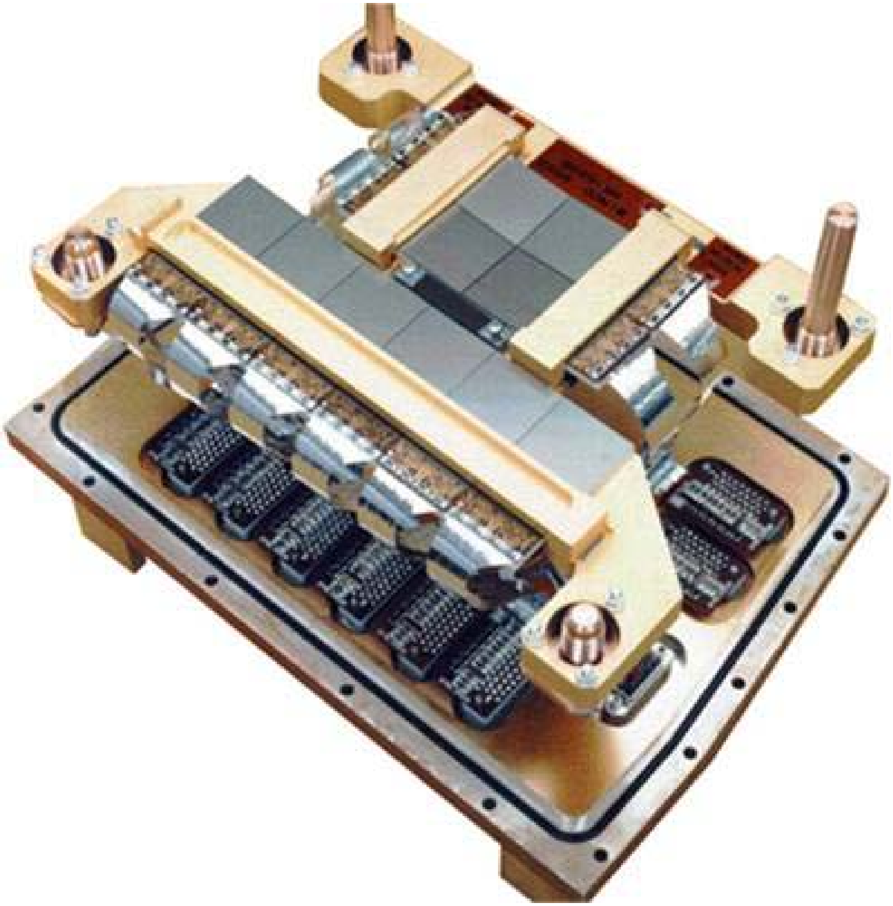
Credit: NASA/CXC/SAO

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

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

X-ray Point Sources

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

- 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)

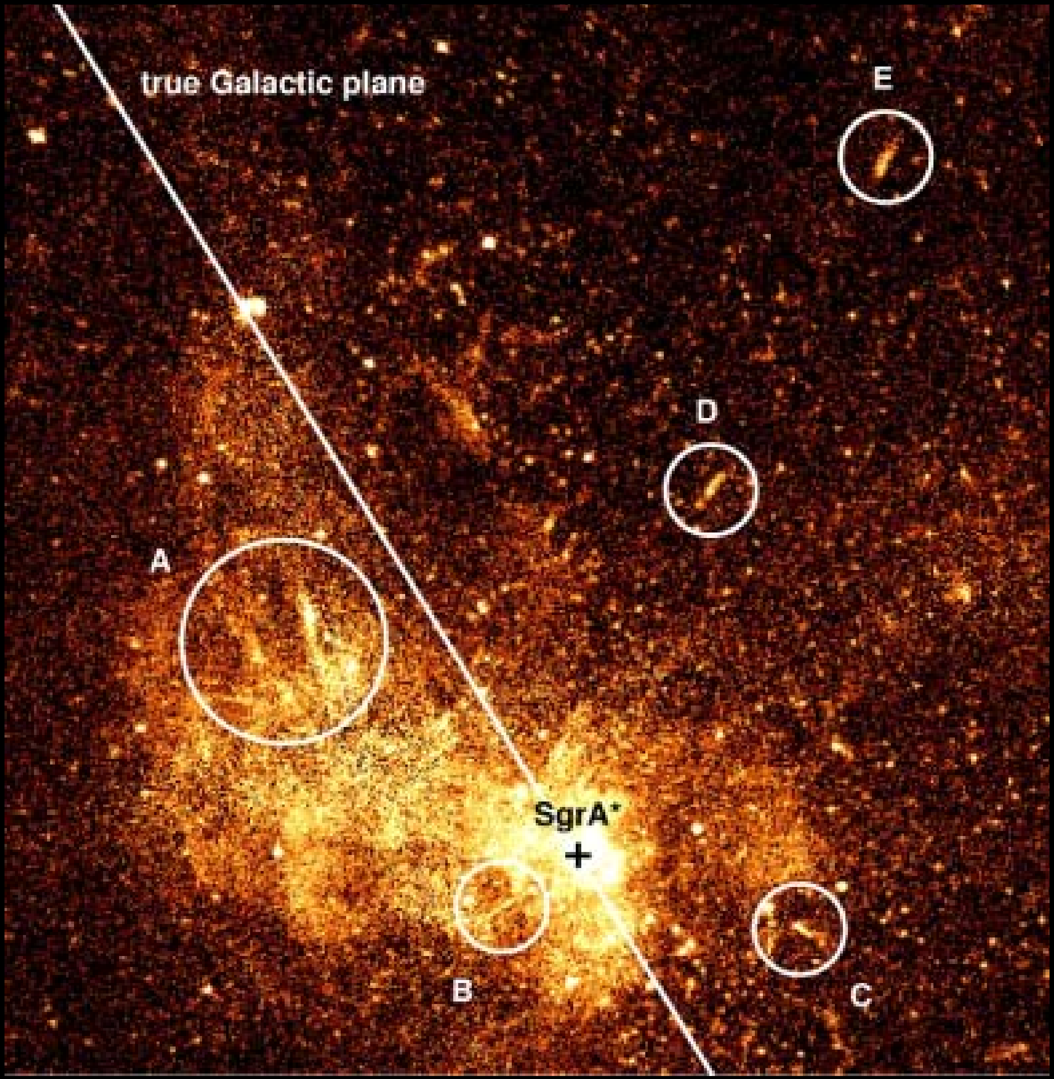
Muno et al. 2003, ApJ, 589, 225

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

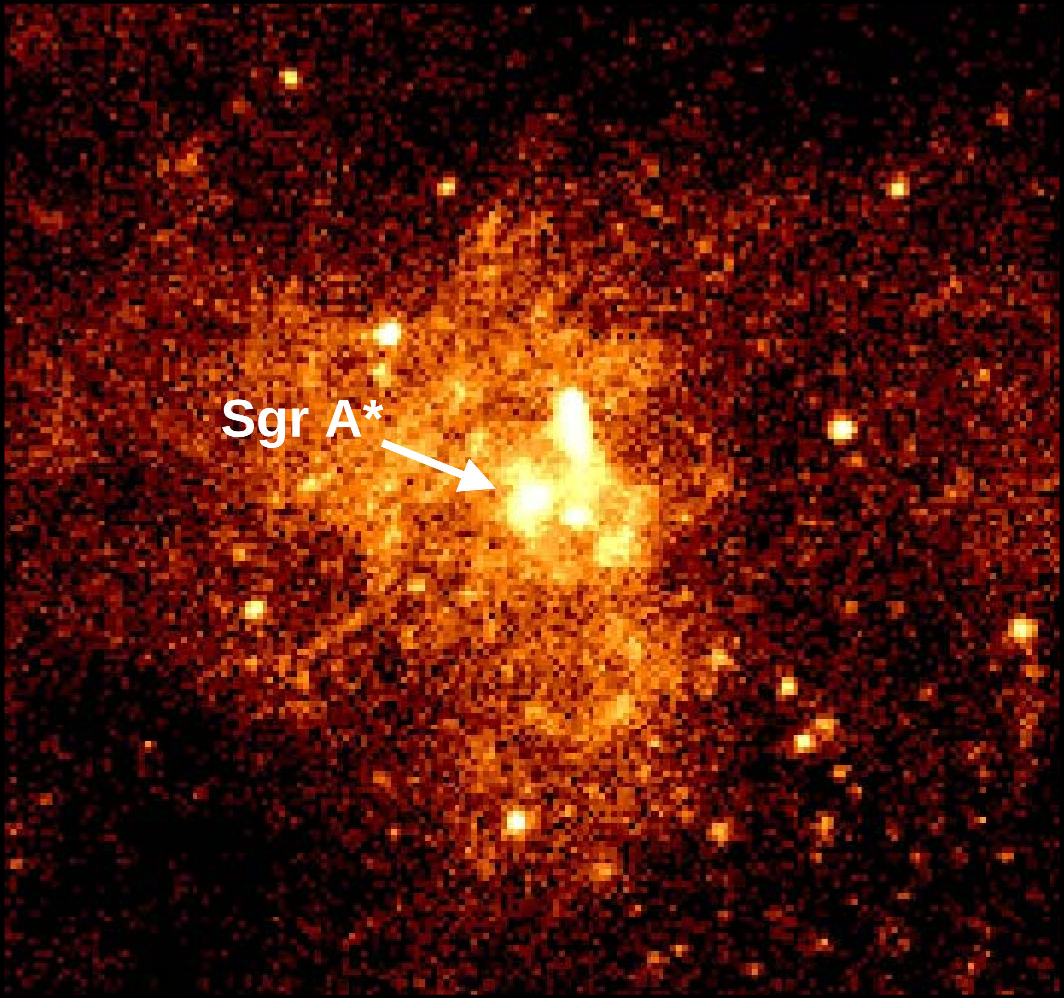
Muno et al. 2003, ApJ, 589, 234

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



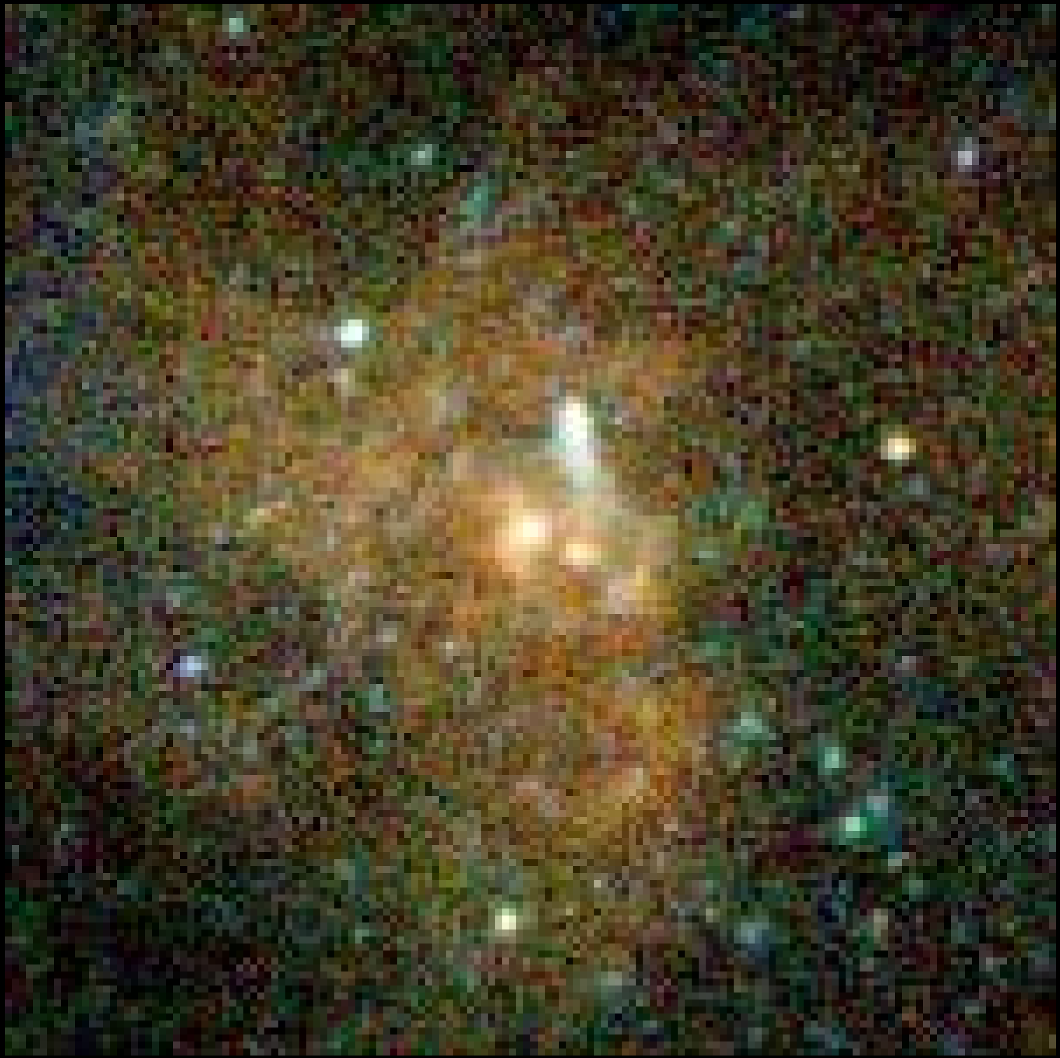
Credit: NASA/MIT/F.K. Baganoff et al.

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



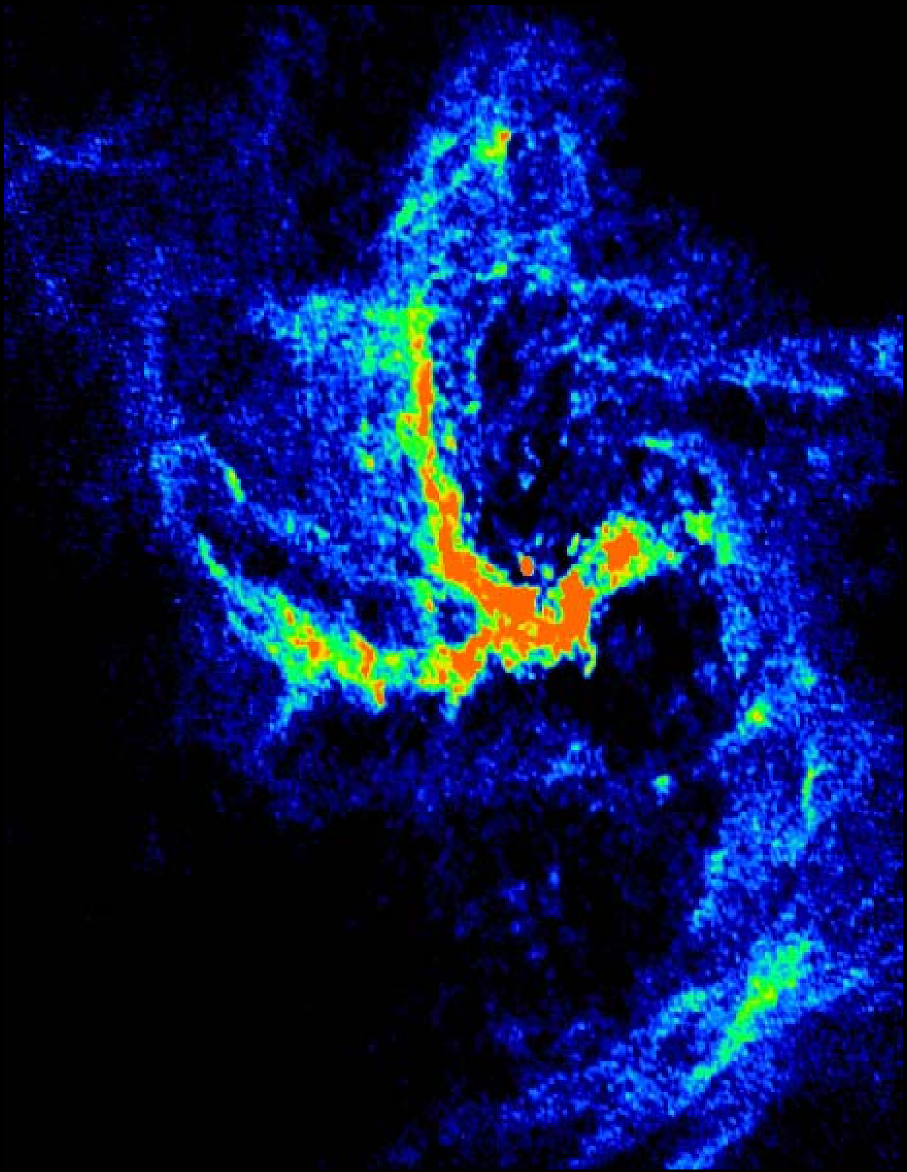
Credit: NASA/MIT/F.K. Baganoff et al.

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



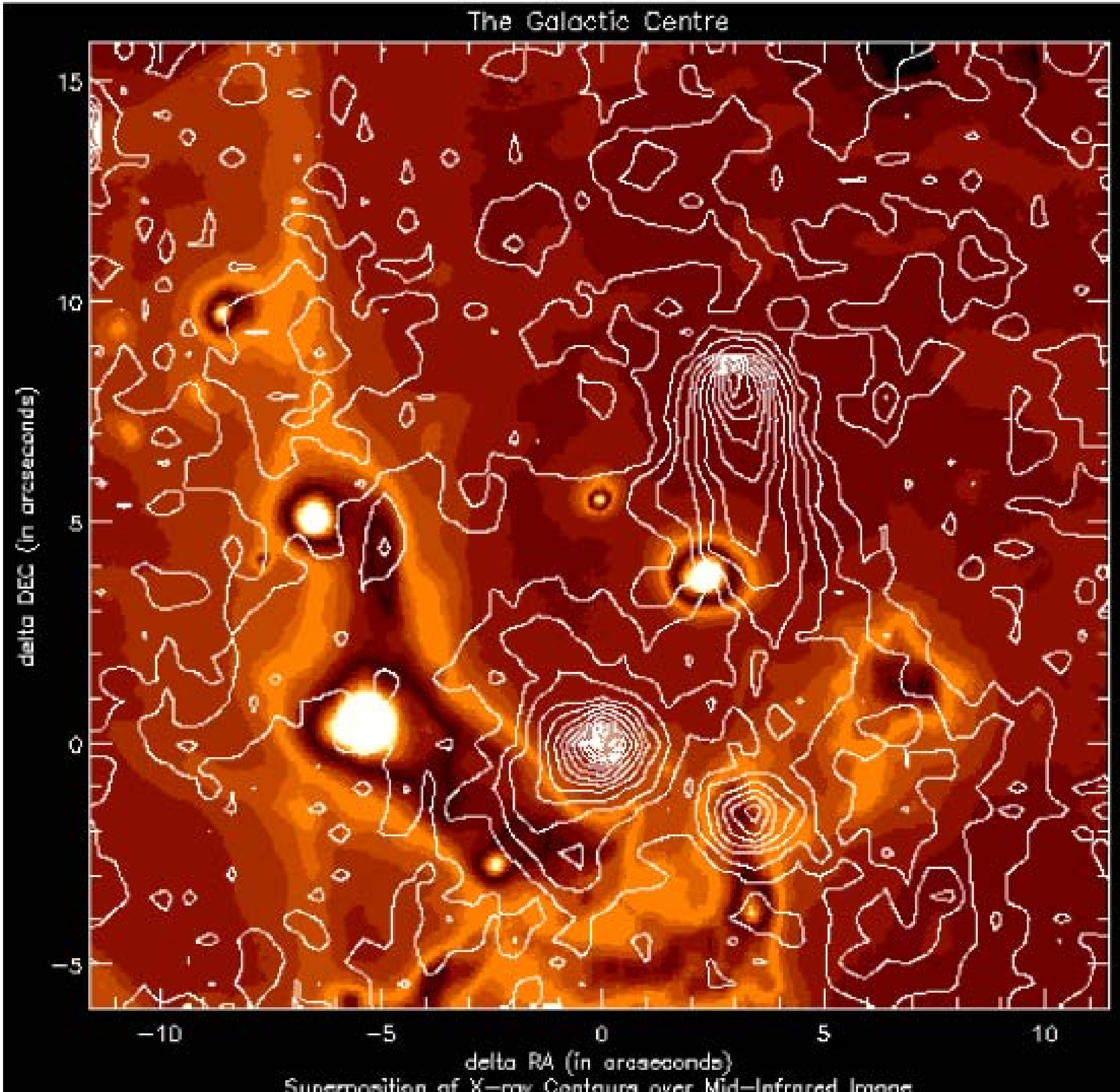
Credit: NASA/MIT/F.K. Baganoff et al.

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.

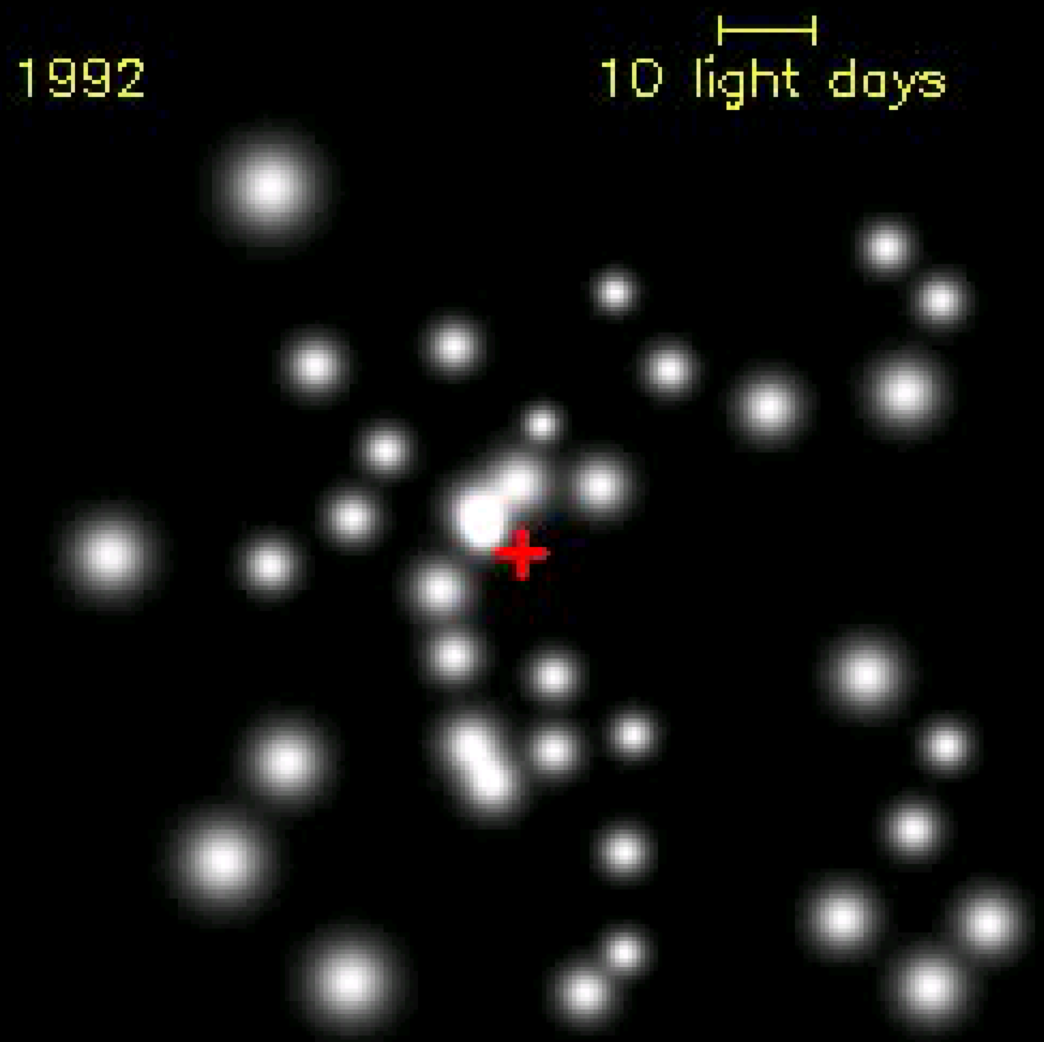


Credit:
(X-ray) NASA/MIT/F.K. Baganoff et al., (mid-IR) UCLA/M. Morris et al.

Near-Infrared View of the Galactic Center

Credit: Gemini Observatory/NSF/U. Hawaii Adaptive Optics Group

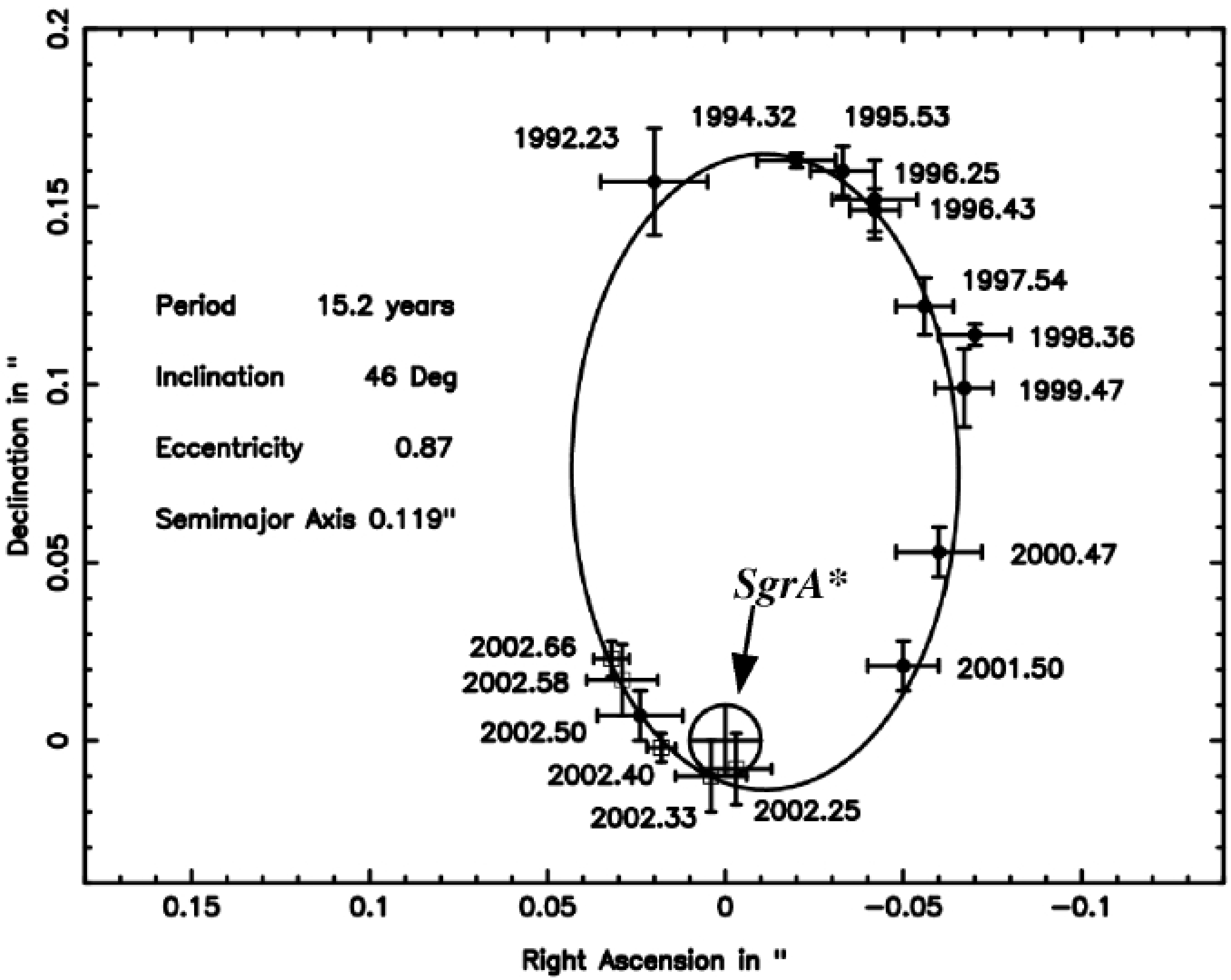
Proper Motions of Infrared Stars Around Sgr A*



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

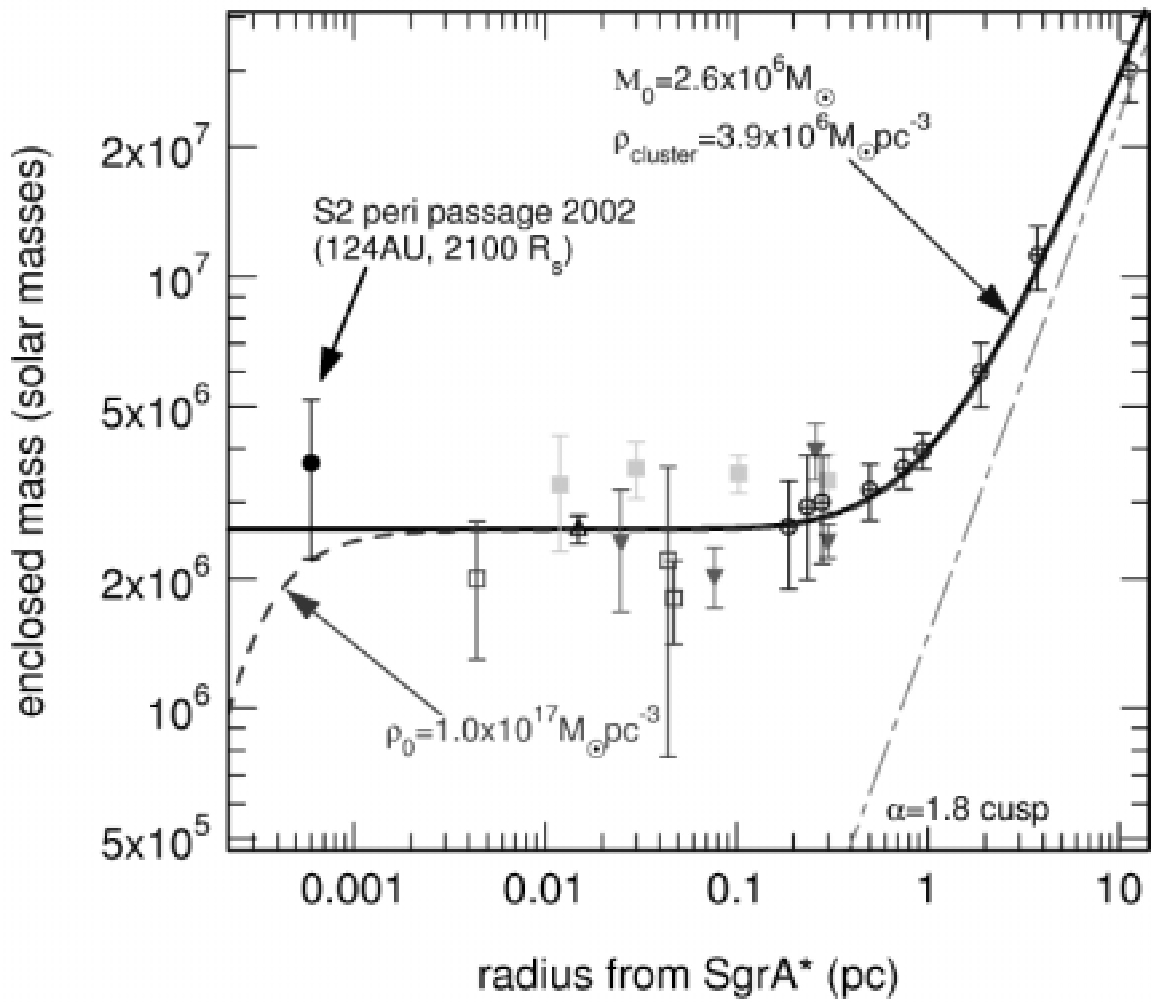
Star in a 15.2-year Orbit Around Sgr A*

Schoedel et al. 2002, Nature, 419, 694



Enclosed Mass vs. Radius Around Sgr A*

Schoedel et al. 2002, Nature, 419, 694

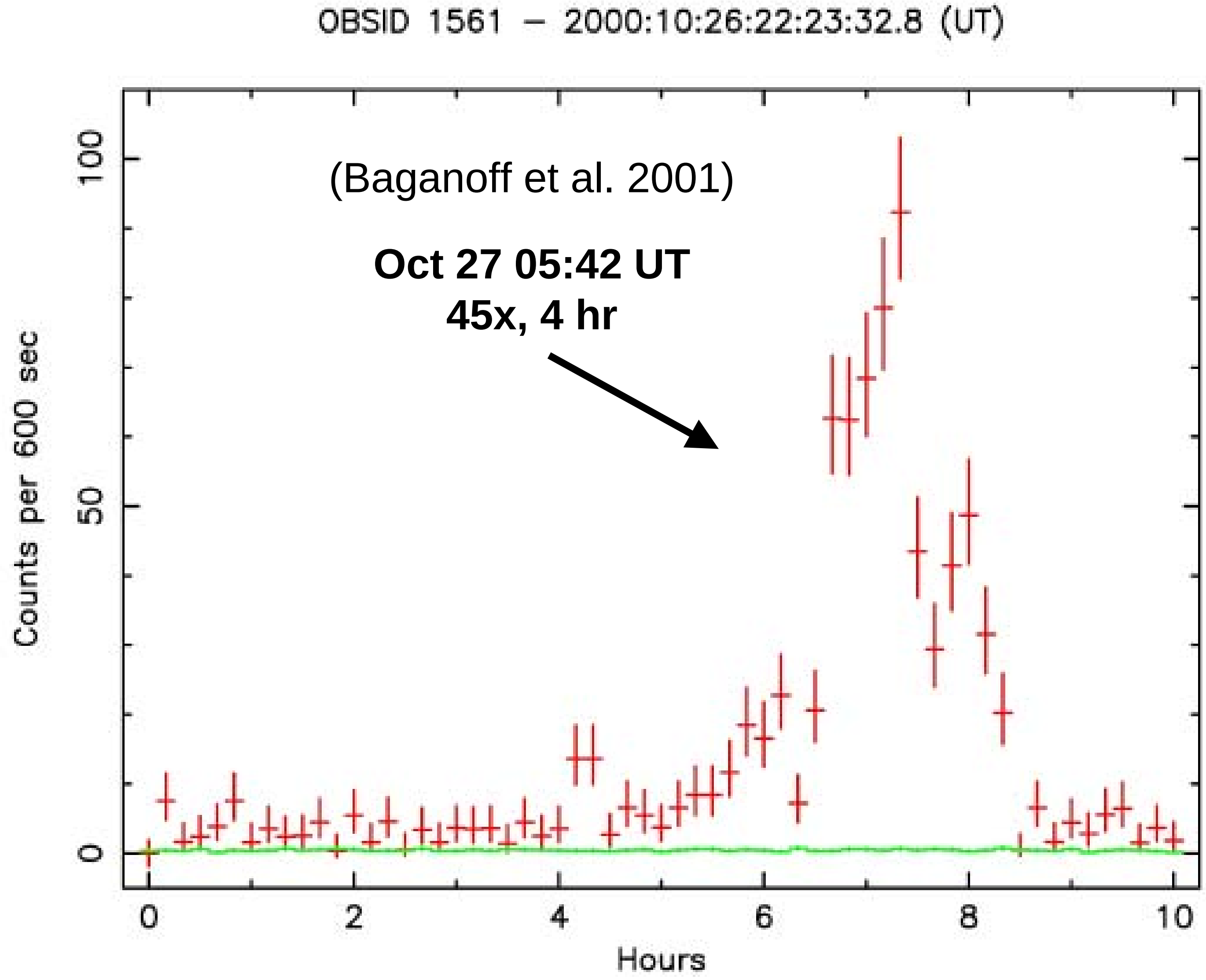


Mass Densities vs. Dark Object Masses in Nearby Galactic Nuclei

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 4258

2000 October 26-27



Jet Models

Markoff et al. 2001, A&A, 379, L13

ADAF Model – Narayan 2002

R. Narayan, in *Lighthouses of the Universe*, p. 414

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

F.K. Baganoff[1]

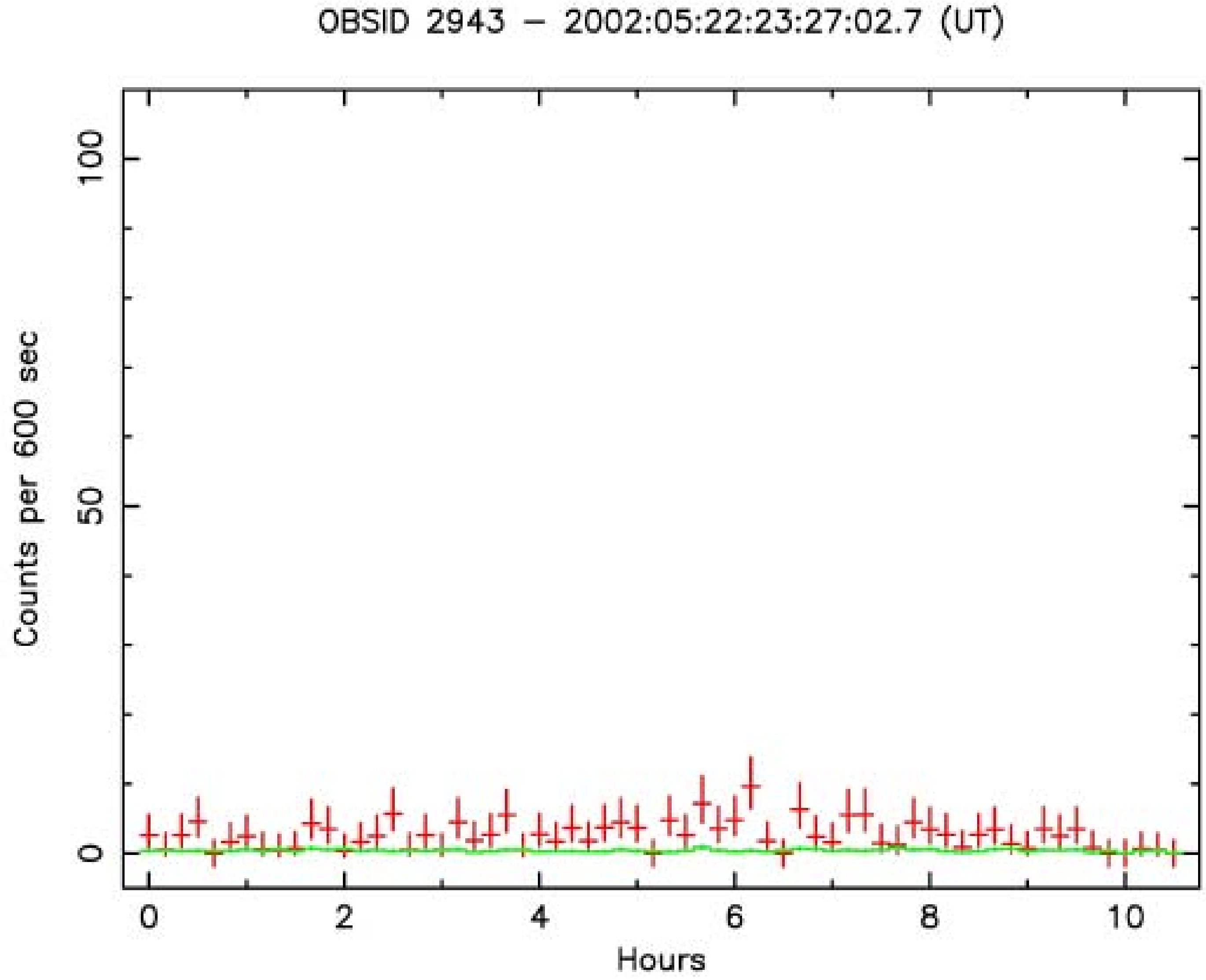
M.W. Bautz[1], G.R. Ricker[1], M. Morris[2], E.E. Becklin[2], A.M. Ghez[2], S.D. Hornstein[2], A.M. Tanner[2], W.N. Brandt[3], G. Chartas[3], E.D. Feigelson[3], G.P. Garmire[3], A.S. Cotera[4], P.M. Hinz[4], W.F. Hoffmann[4], M.R. Meyer[4], A. Eckart[5], R. Genzel[6], J.-H. Zhao[7], R.M. Herrnstein[7], J.L. Hora[7], J.-P. Macquart[8], Y. Maeda[9], R.J. Sault[10], G.B. Taylor[11], F. Walter[12]

[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

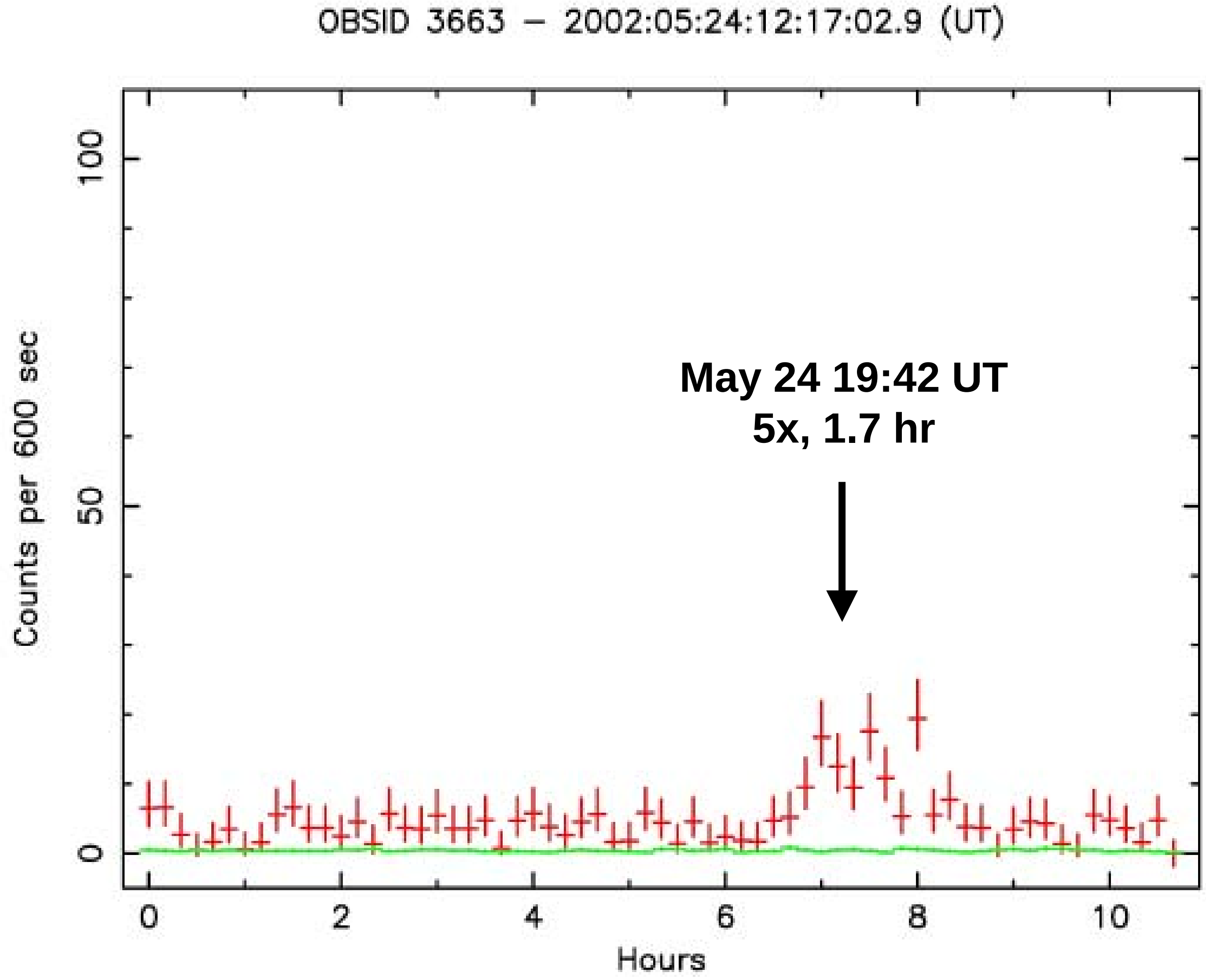
Observatories Participating in Sgr A* Monitoring Campaign

- 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)

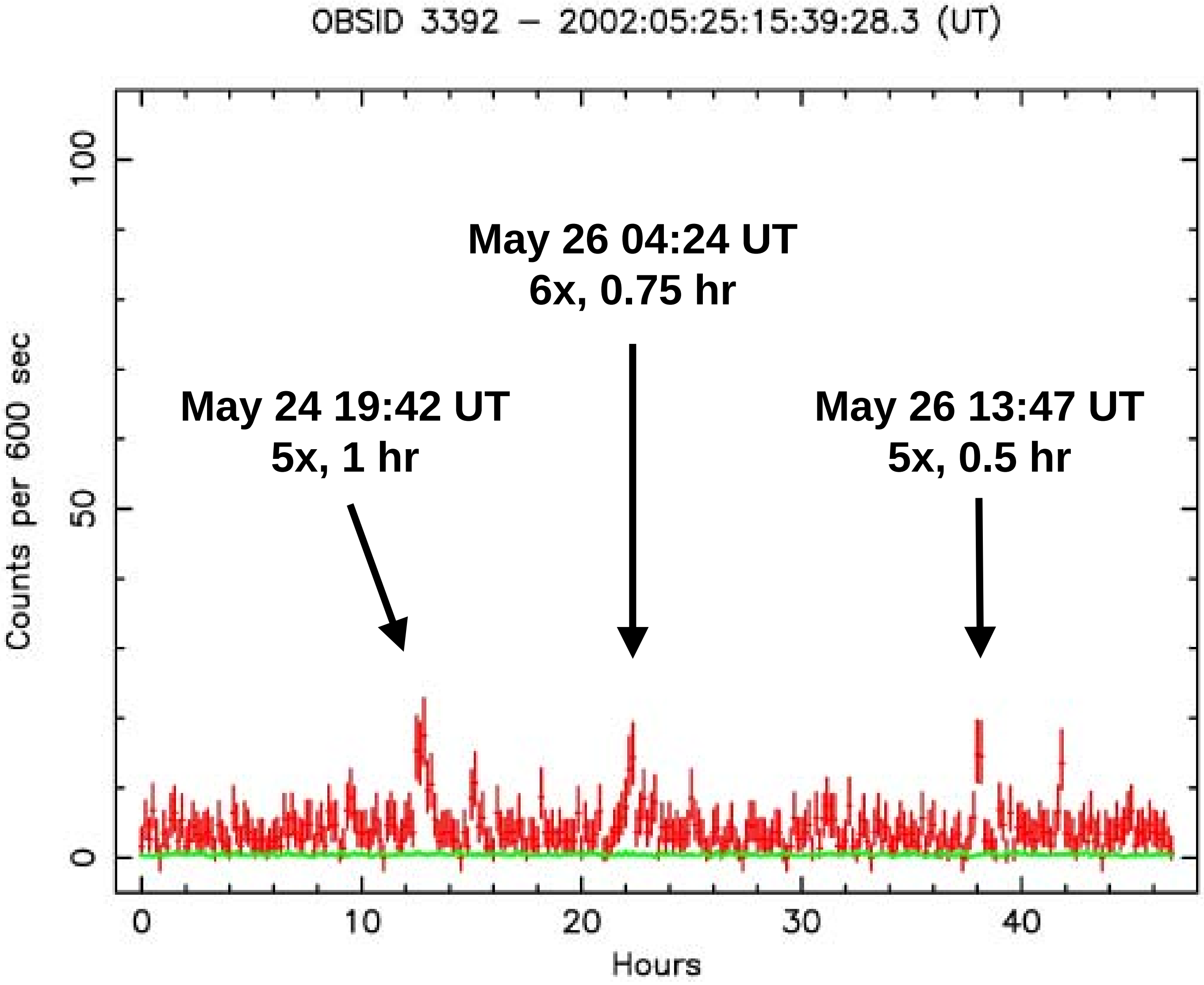
2002 May 22-23 – Orbit 1, Part 1



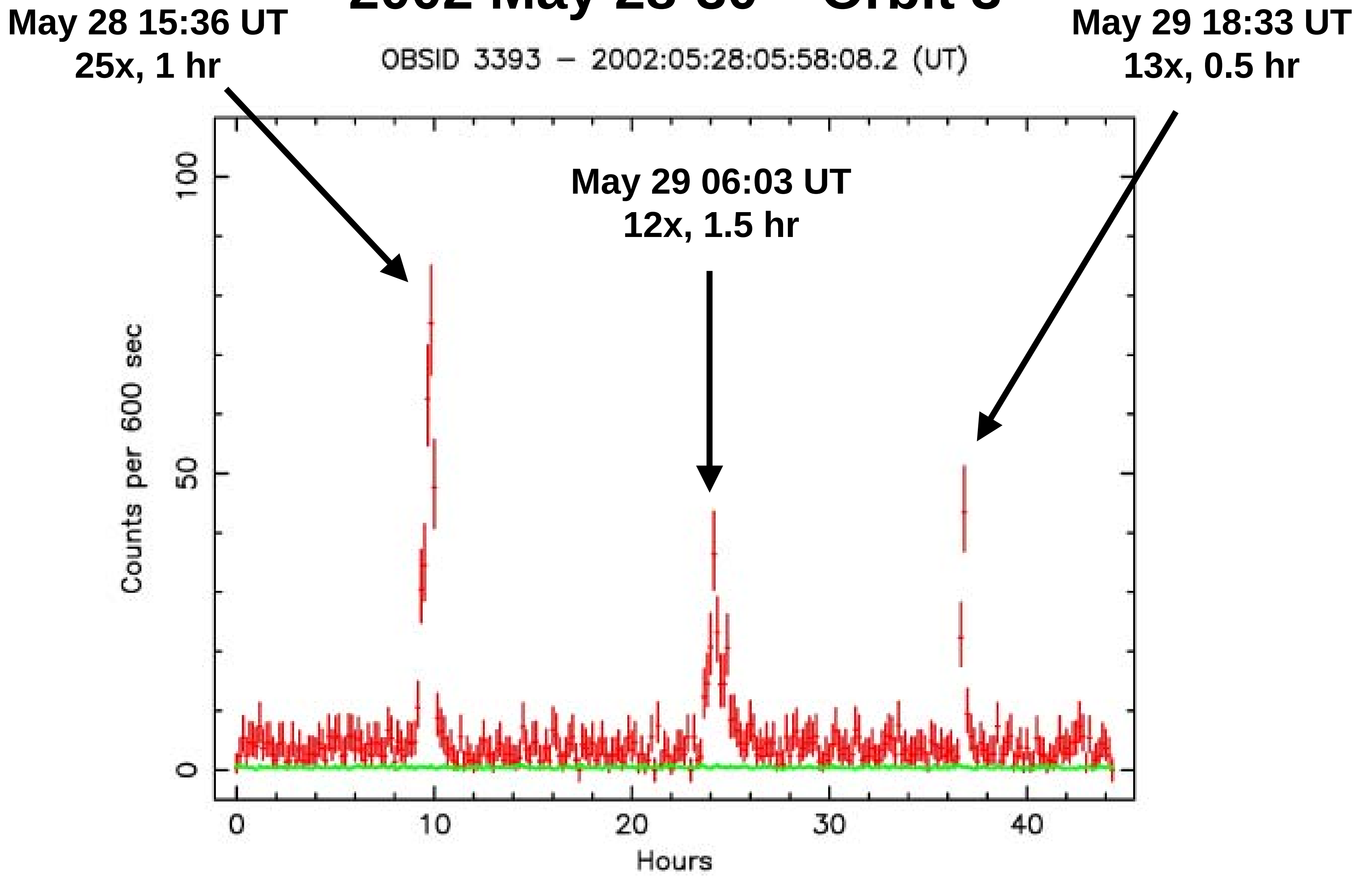
2002 May 24 – Orbit 1, Part 2



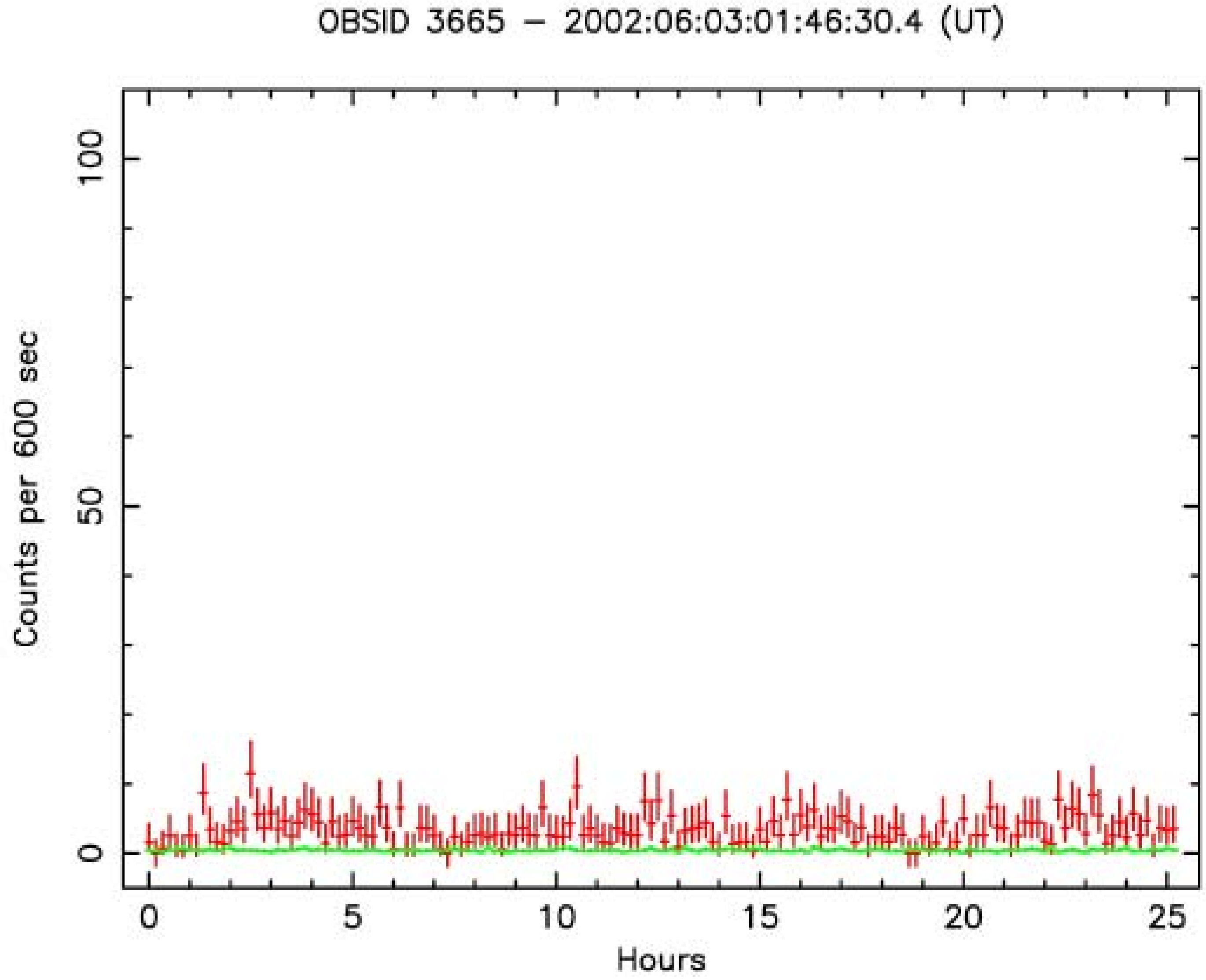
2002 May 25-27 – Orbit 2



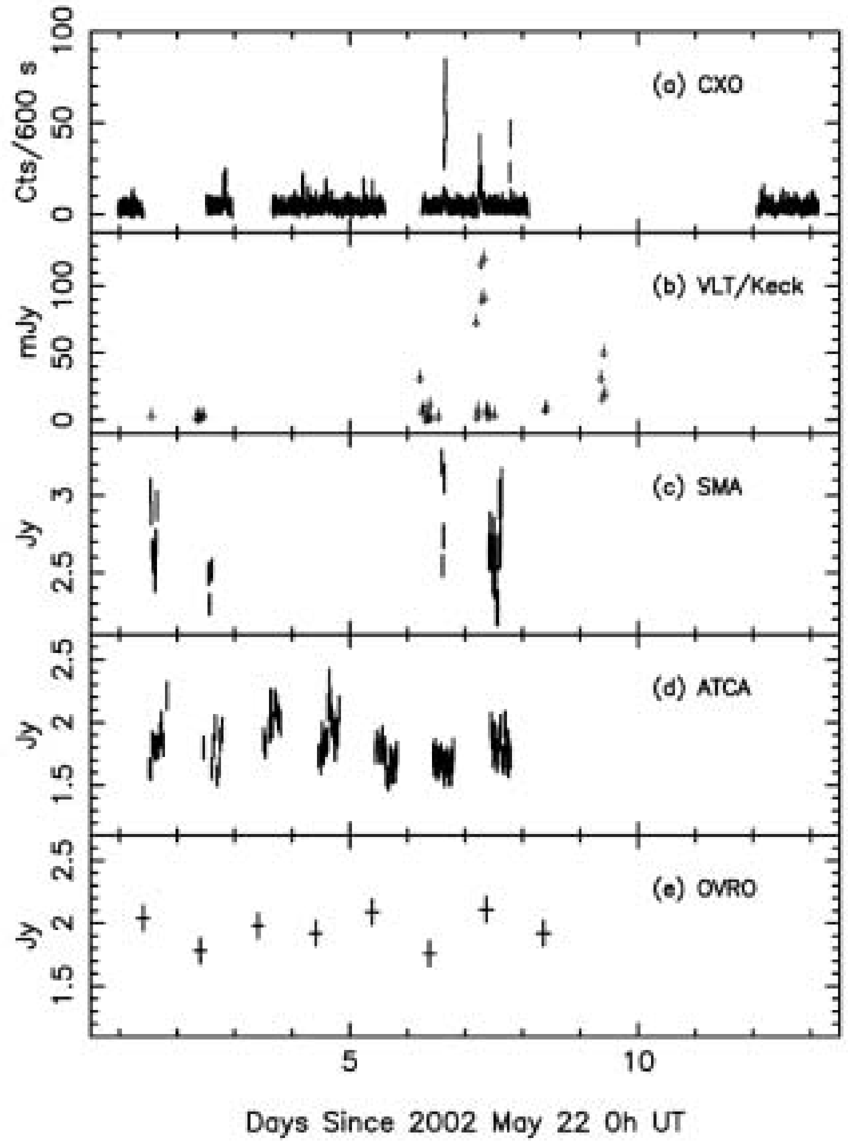
2002 May 28-30 – Orbit 3



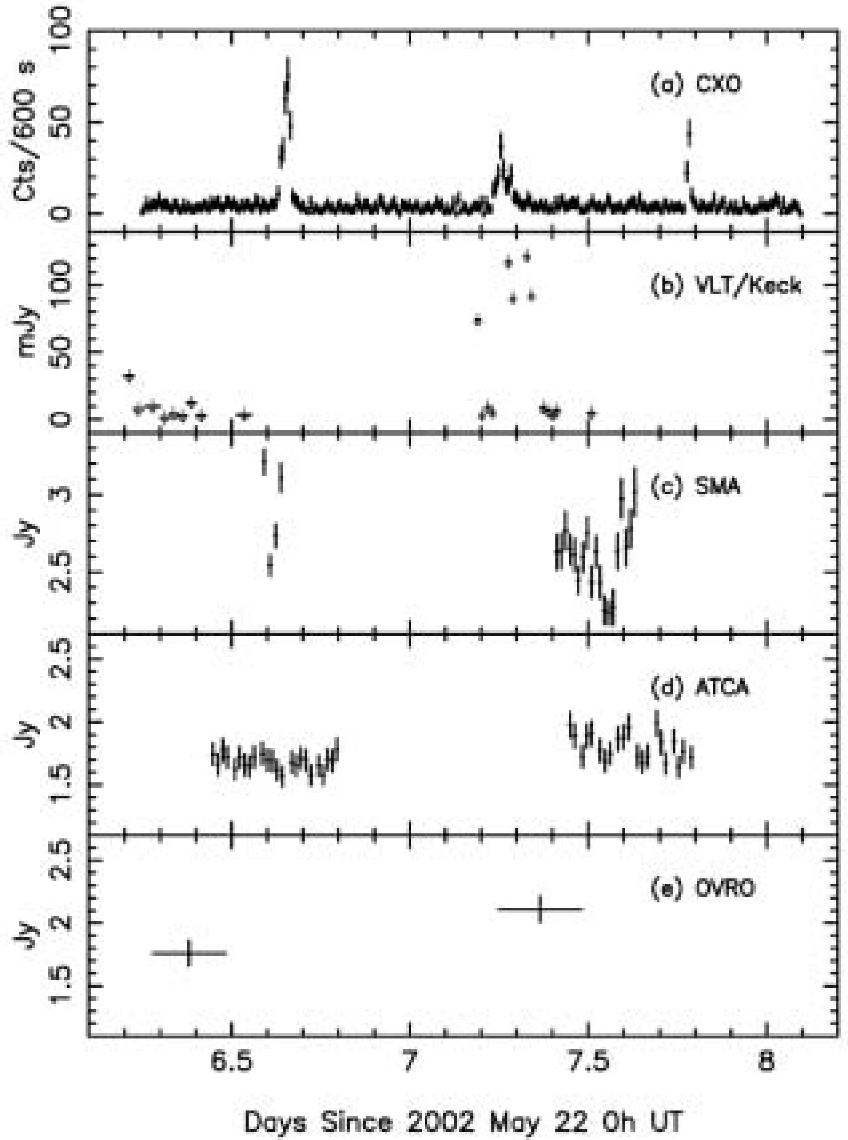
2002 June 3-4 – Orbit 5



Sgr A* Multiwavlength Monitoring Campaign



Three Large X-ray Flares from Sgr A*

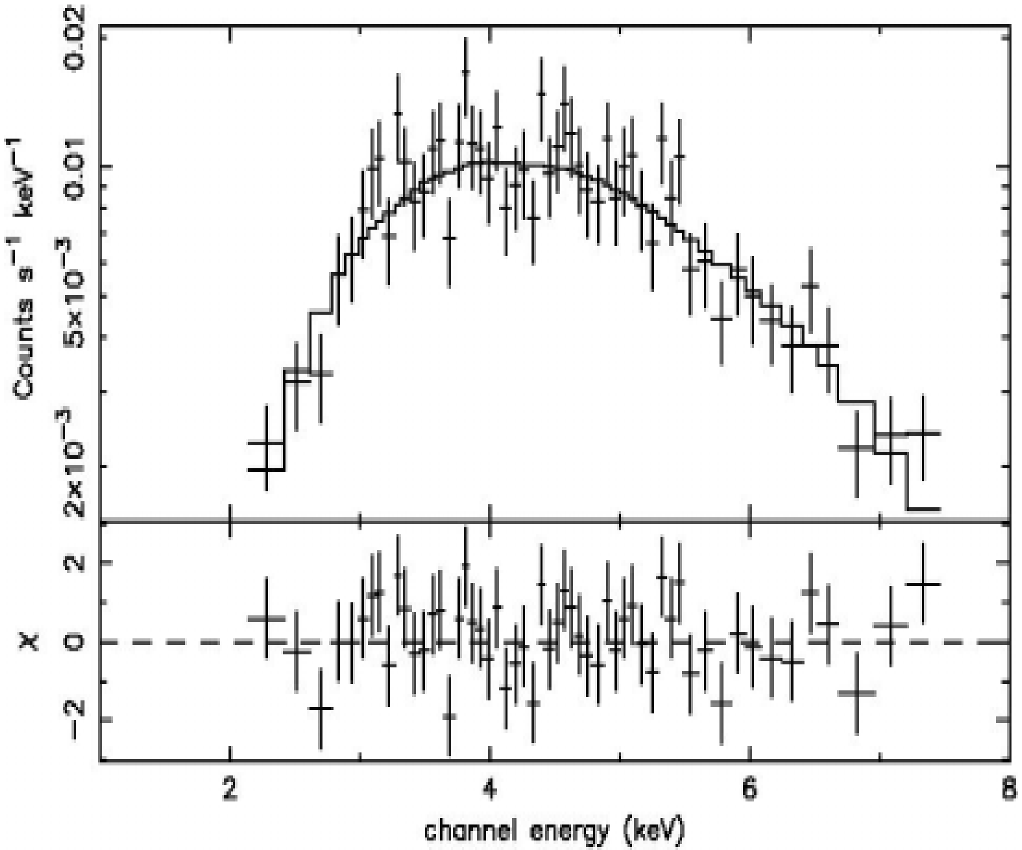


Animation of Sagittarius A* Flaring

Credit: NASA/SAO/CXC/D. Berry

Integrated X-ray Spectrum of Sgr A* During Flares

Model: Absorbed, Dust-Scattered Power Law

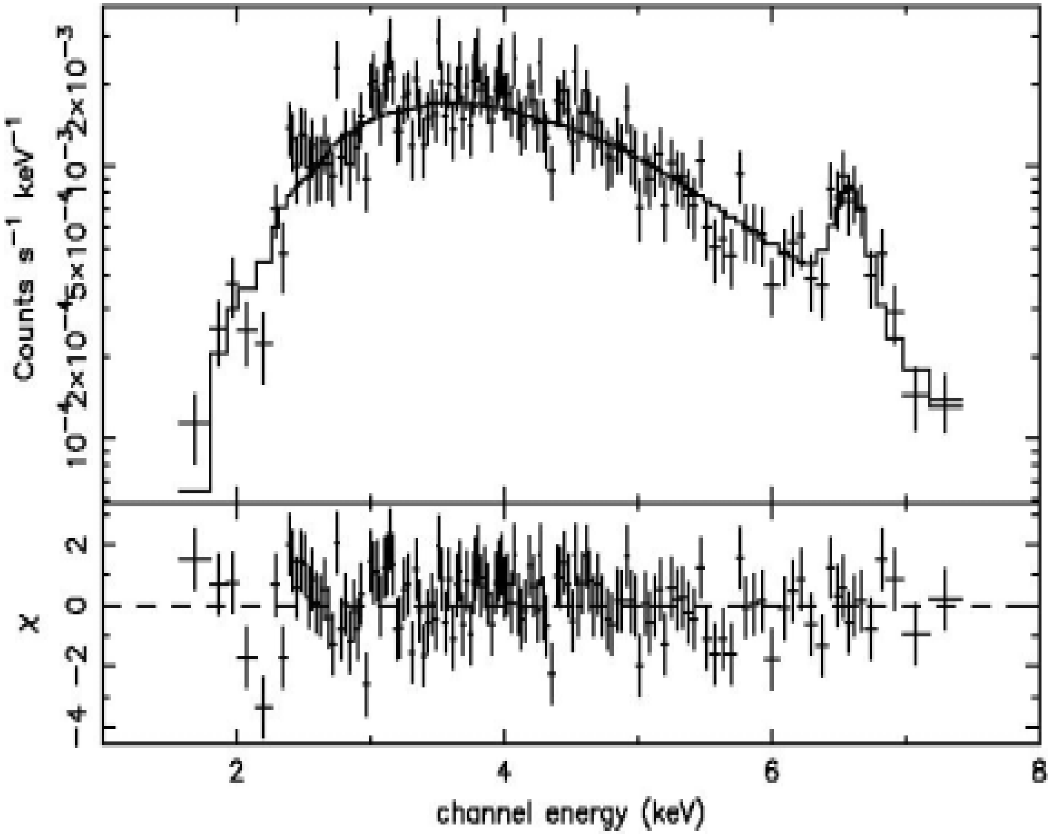


N_H = 6.0 x 10^{22} cm^{-2}
Γ = 1.3

F_X = 1.6 x 10^{-12} erg cm^{-2} s^{-1}
L_X = 2.0 x 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 x 10^{22} cm^{-2}
Γ = 2.4

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

F_X = 1.8 x 10^{-13} erg cm^{-2} s^{-1}
L_X = 1.4 x 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

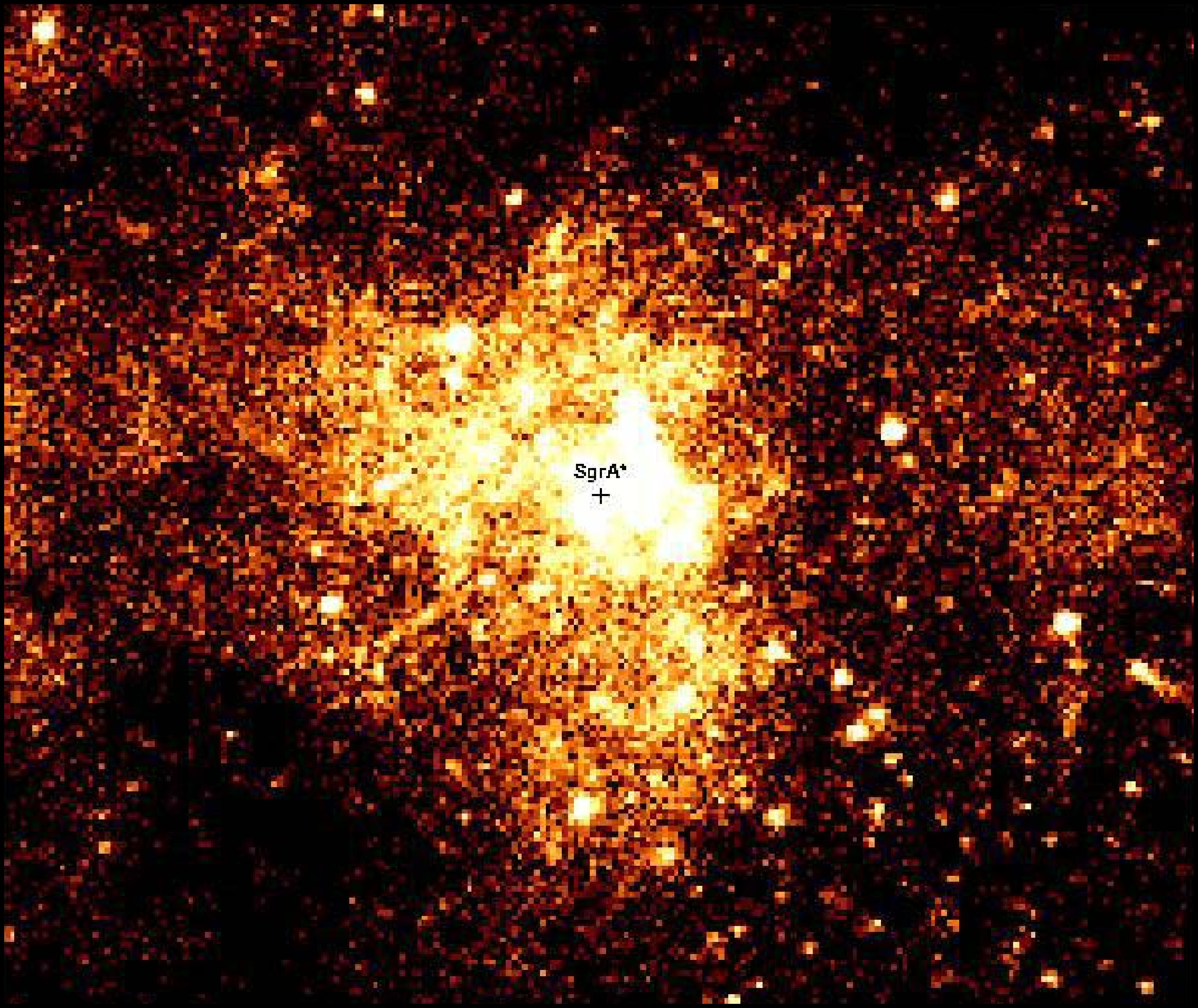
- Intrinsic size of emission at Sgr A* is about 1.4 arcsec (FWHM)
- Consistent with Bondi accretion radius for a 3×10^6 solar-mass black hole

Summary

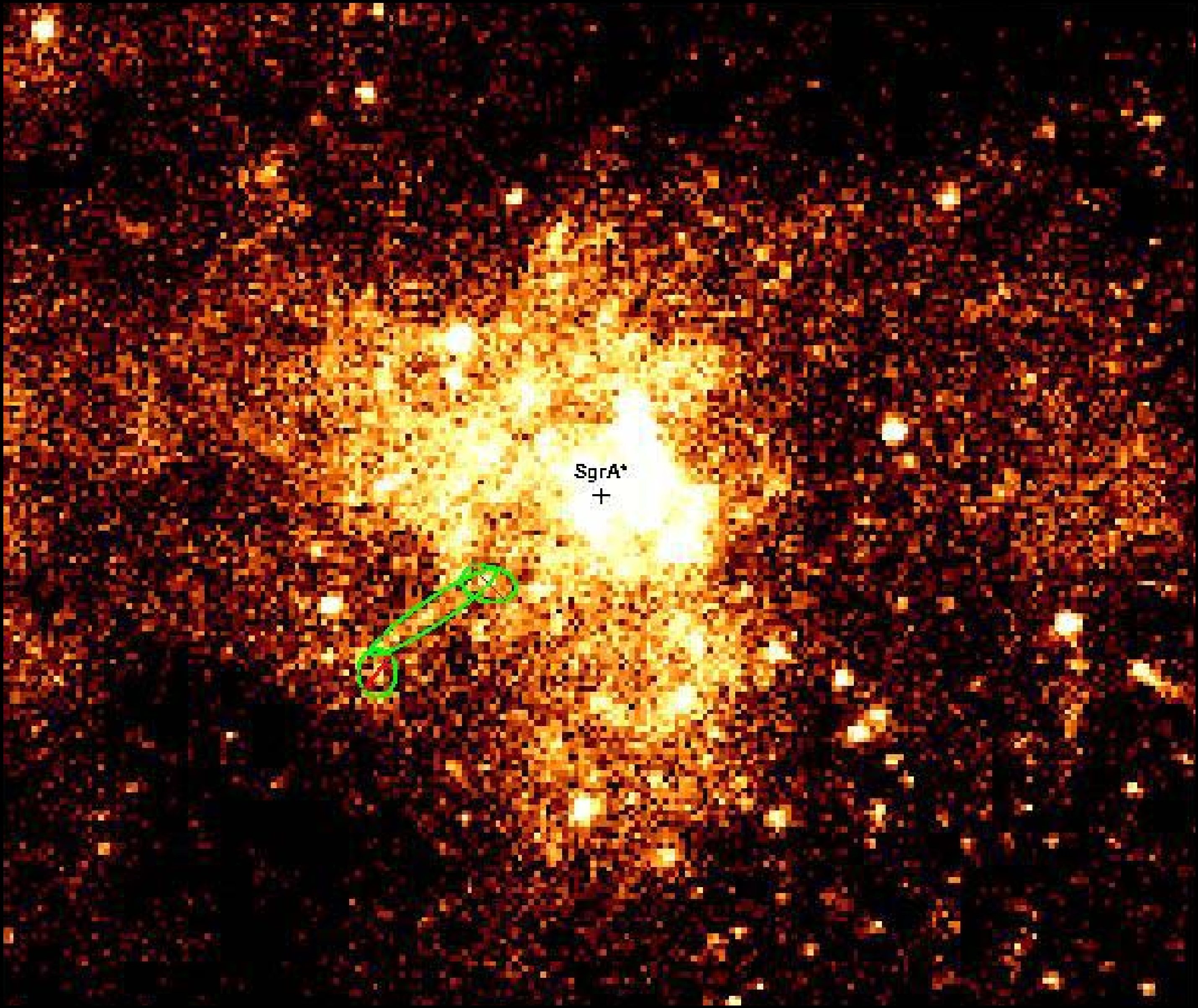
- Chandra observed Sgr A* for 139 hr over a two-week period in late May to early June 2002
- **3 X-ray flares with amplitudes >10x detected in a 28-hr period!**
- 4 X-ray flares with amplitudes ~5x detected in addition
- **“Factor-of-10” flares occur about once every other day, on average**
- Typical 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)

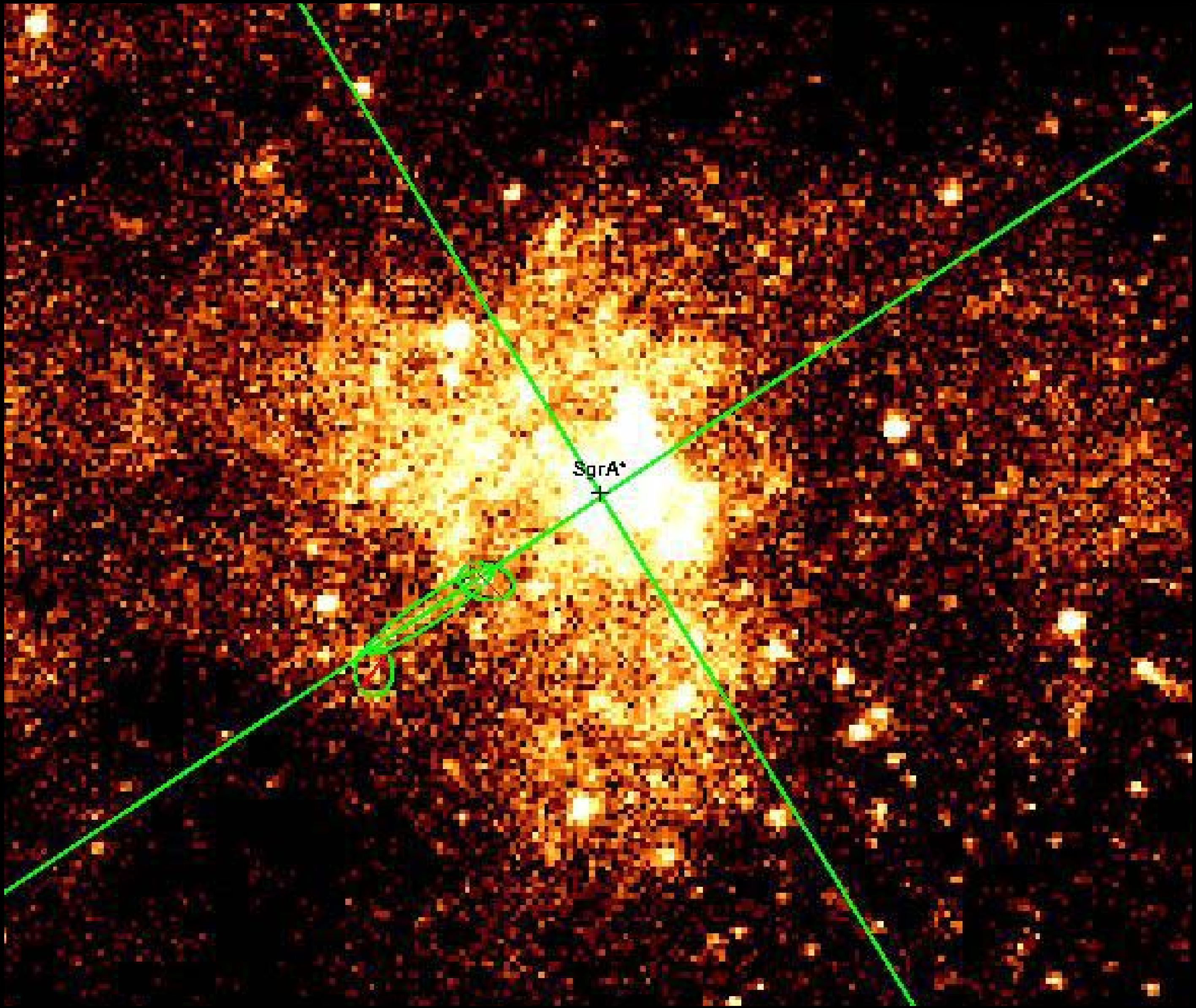
- **No factor-of-2 or larger flares seen at longer wavelengths**
- Some evidence for variations at tens of percent level in millimeter band on timescales of hours to days seen – **upper limit currently about 50%**
- Efforts to improved calibration of millimeter data underway



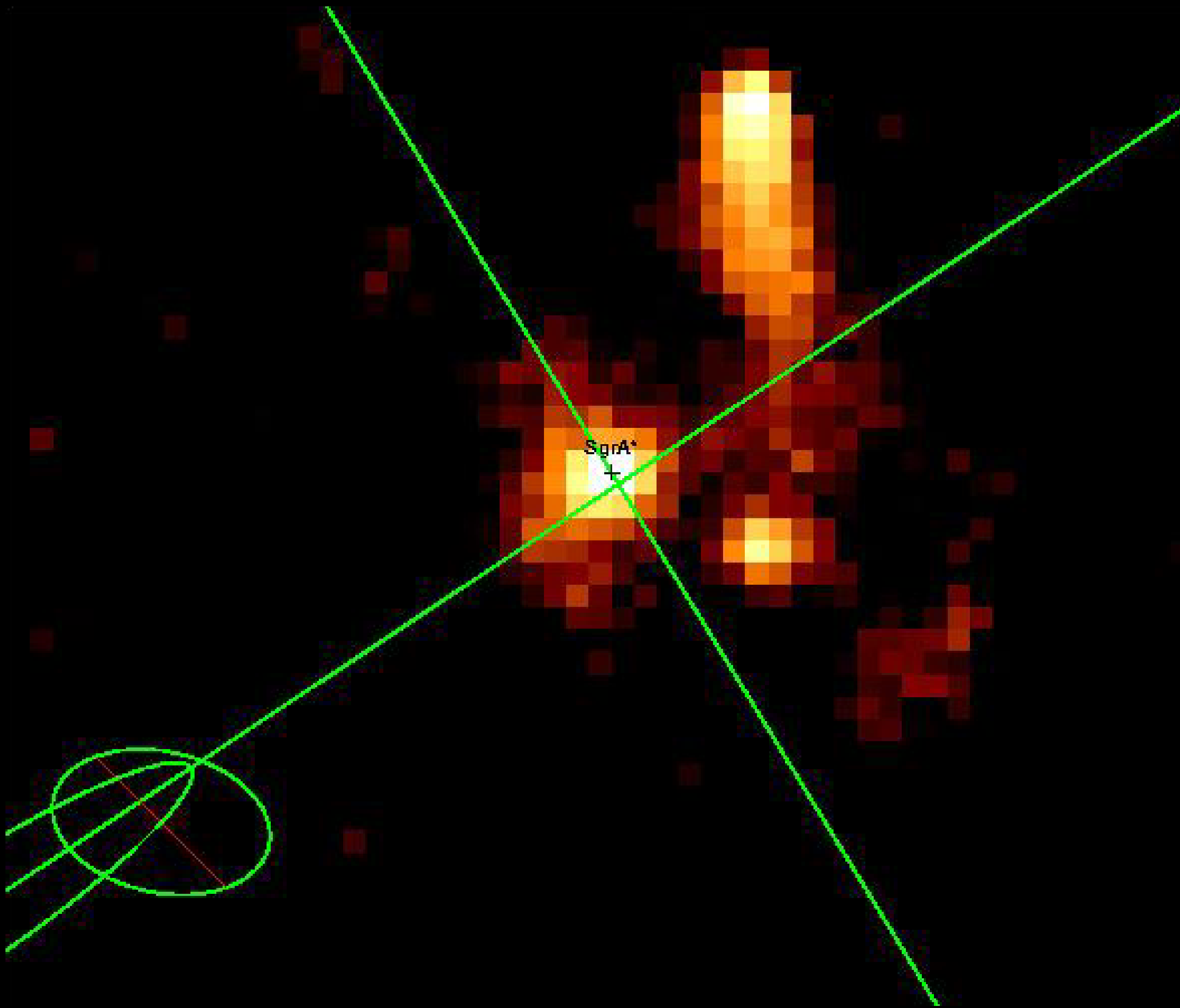
Credit: NASA/MIT/F.K. Baganoff et al.



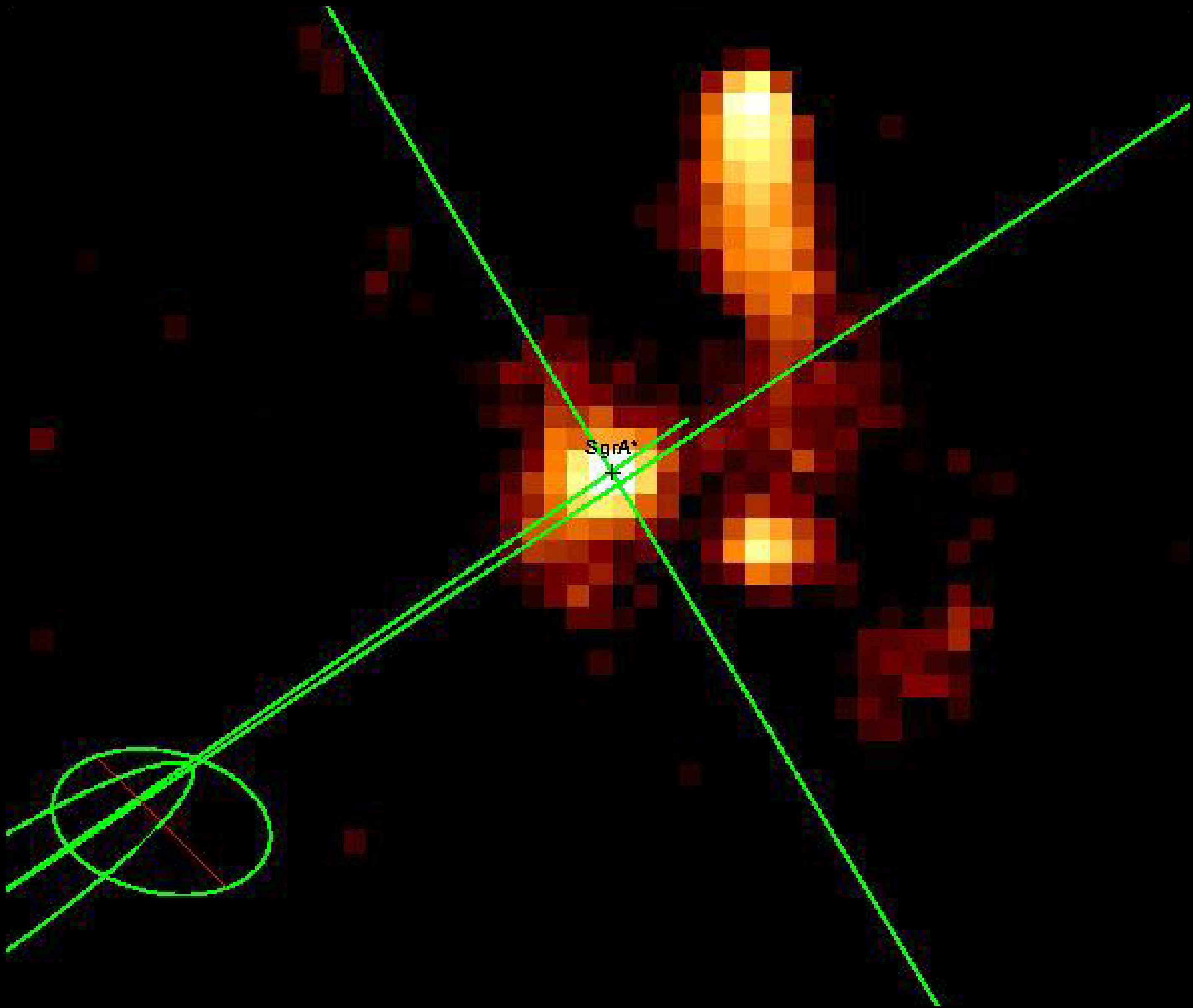
Credit: NASA/MIT/F.K. Baganoff et al.



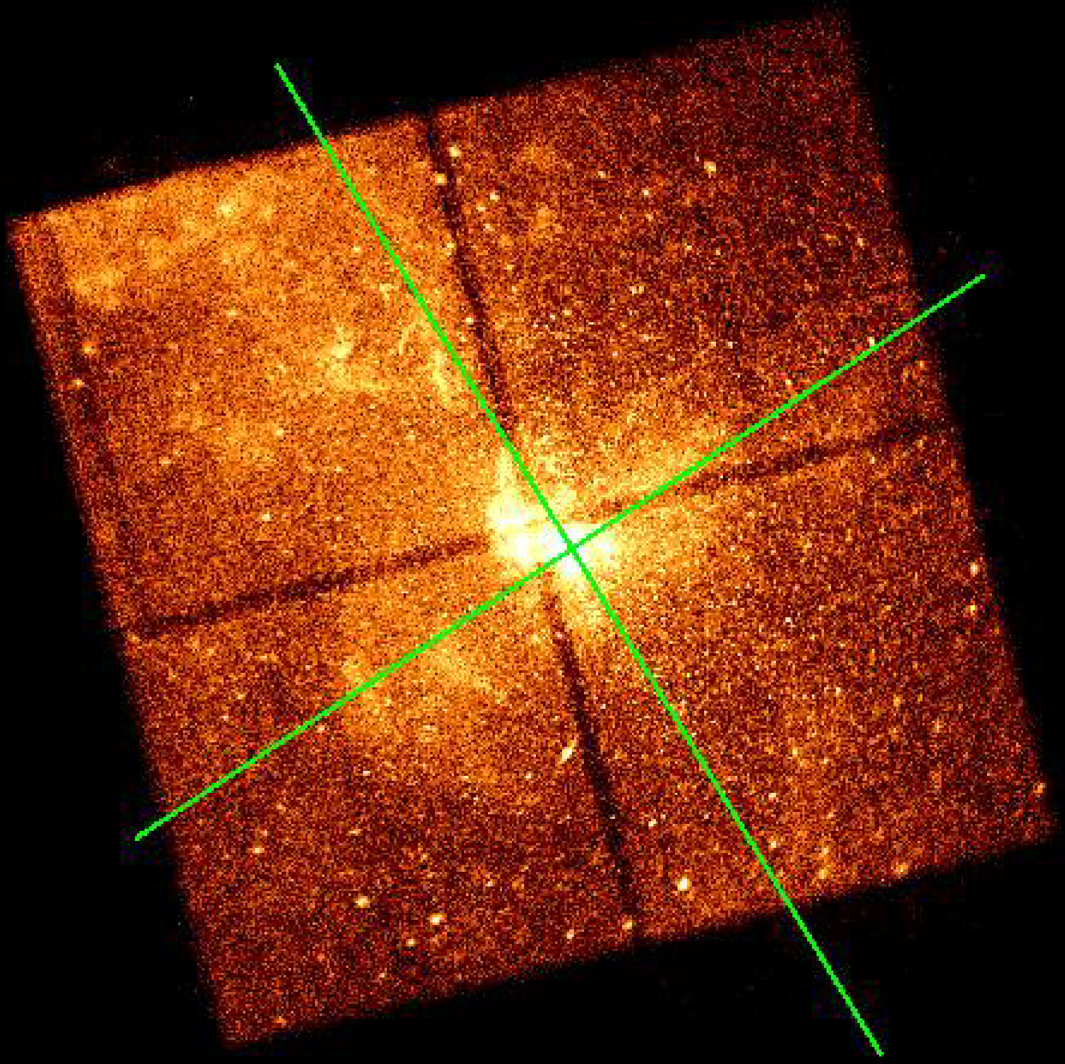
Credit: NASA/MIT/F.K. Baganoff et al.



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

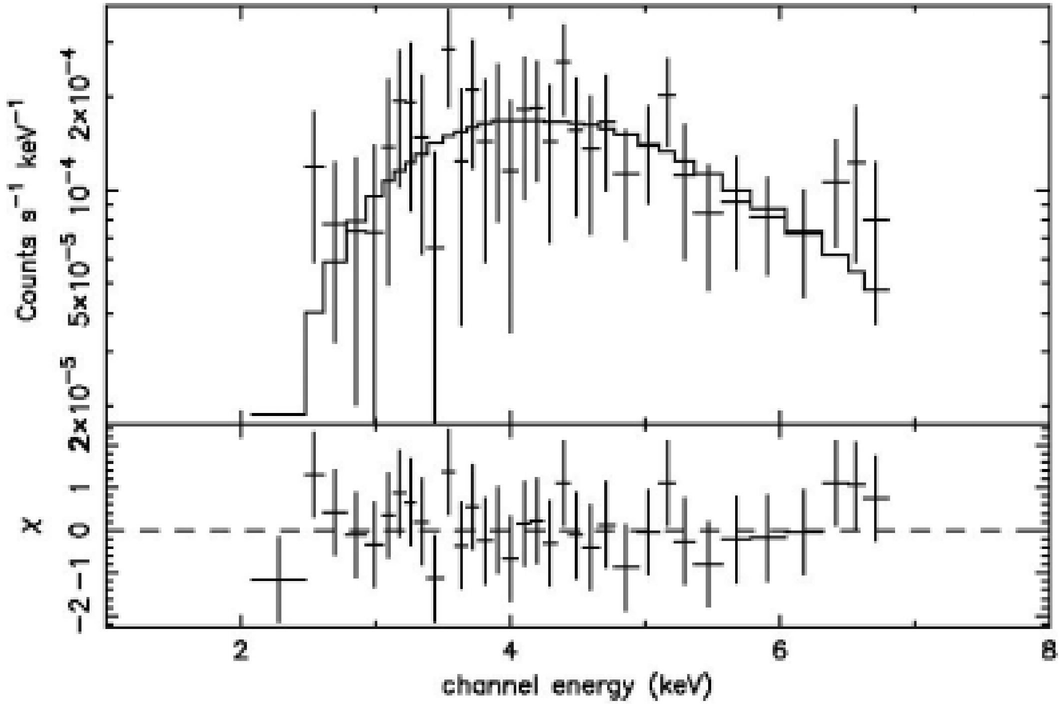


Credit: NASA/MIT/F.K. Baganoff et al.



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