A Legacy Study of Stellar Life Cycles in the Galactic Center

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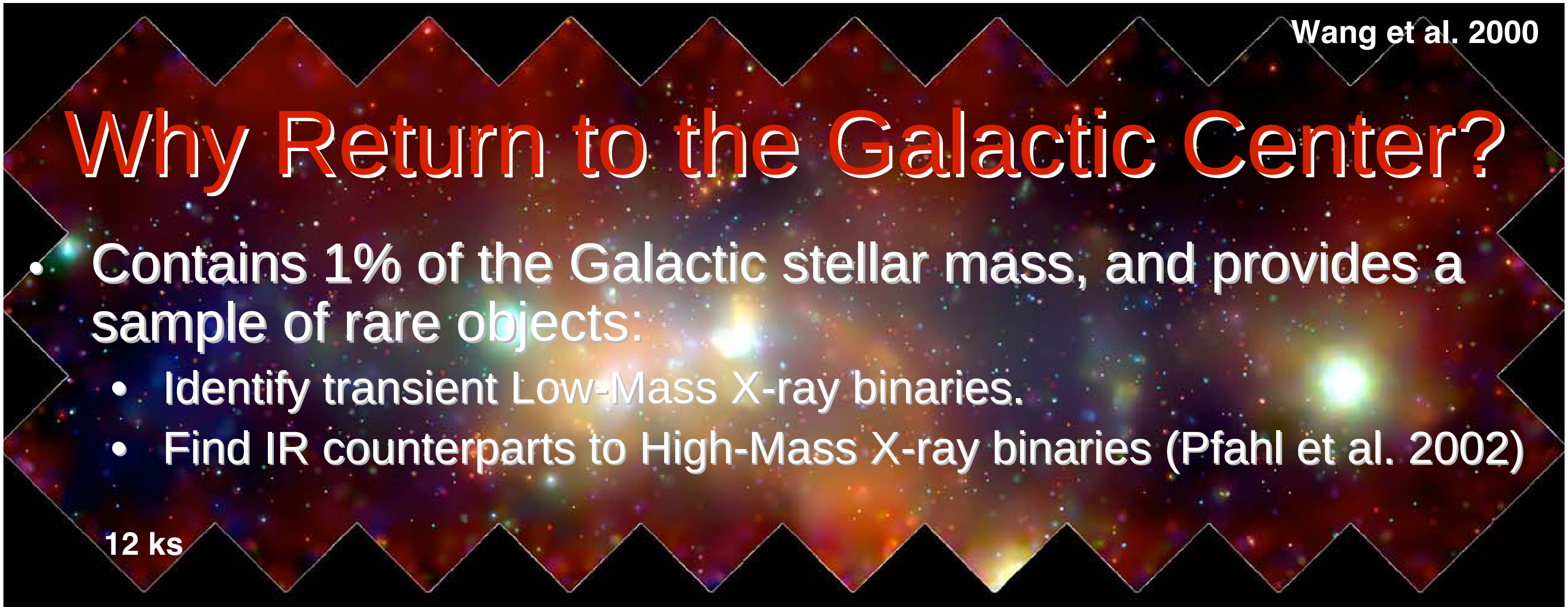
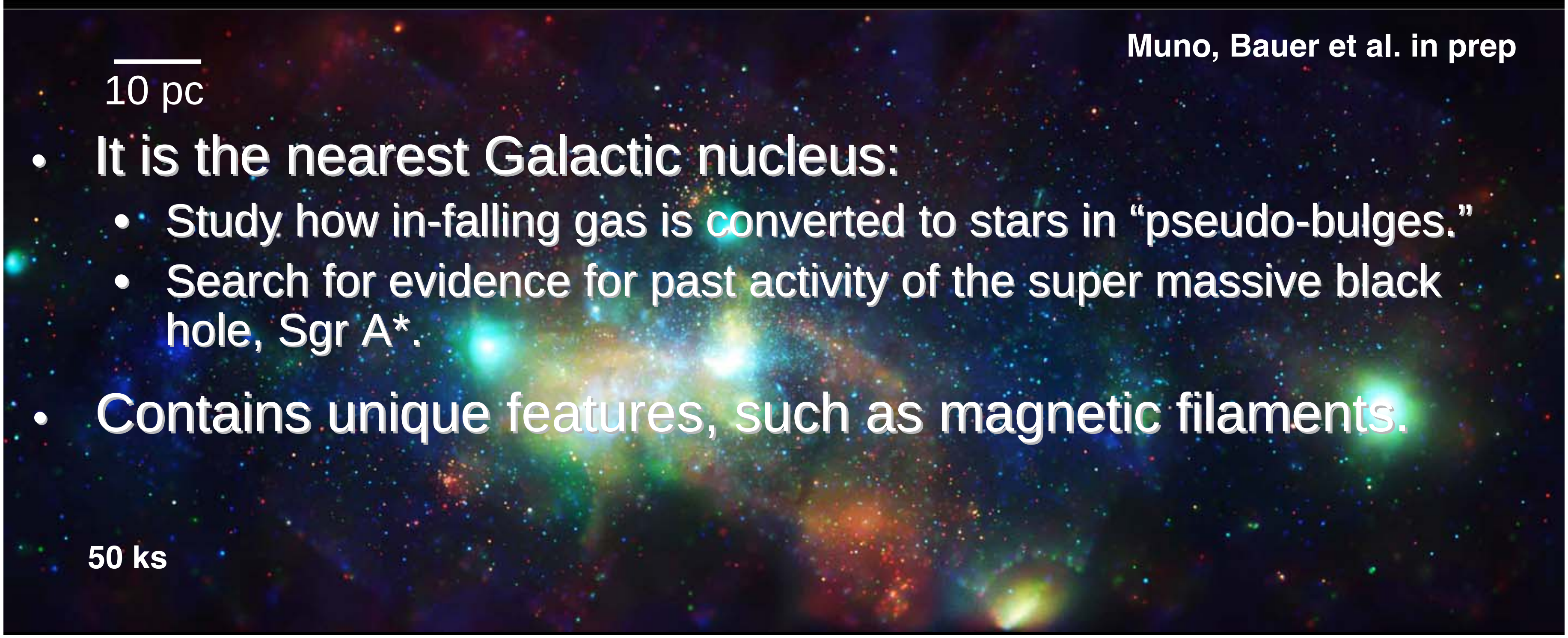
Why Return to the Galactic Center?

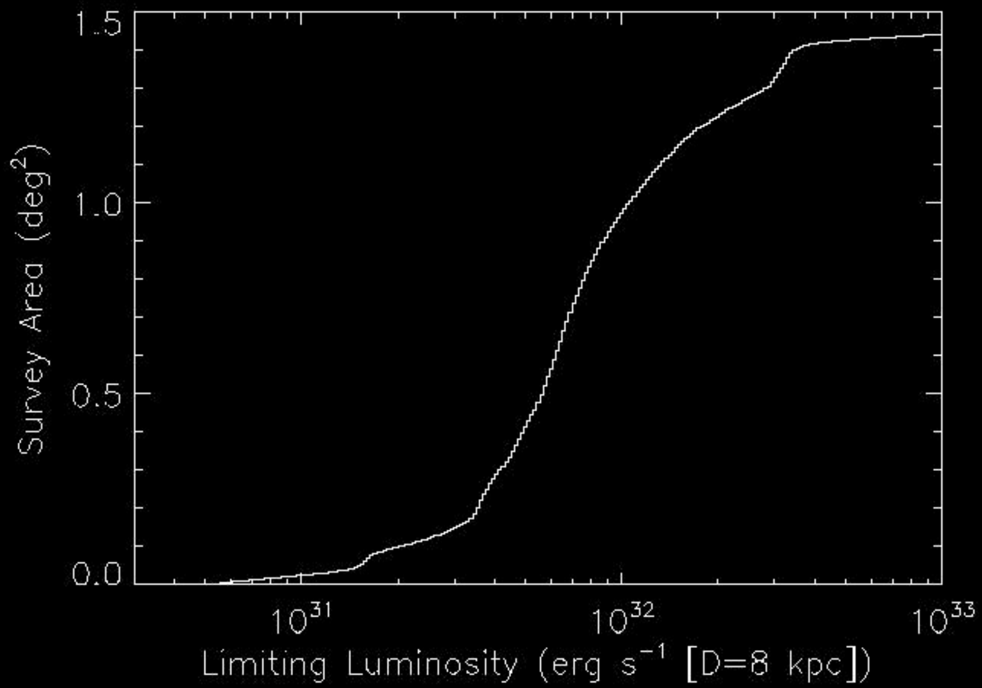
- Contains 1% of the Galactic stellar mass, and provides a sample of rare objects:
  - Identify transient Low-Mass X-ray binaries.
  - Find IR counterparts to High-Mass X-ray binaries (Pfahl et al. 2002)



- It is the nearest Galactic nucleus:
  - Study how in-falling gas is converted to stars in “pseudo-bulges.”
  - Search for evidence for past activity of the super massive black hole, Sgr A*.
- Contains unique features, such as magnetic filaments.

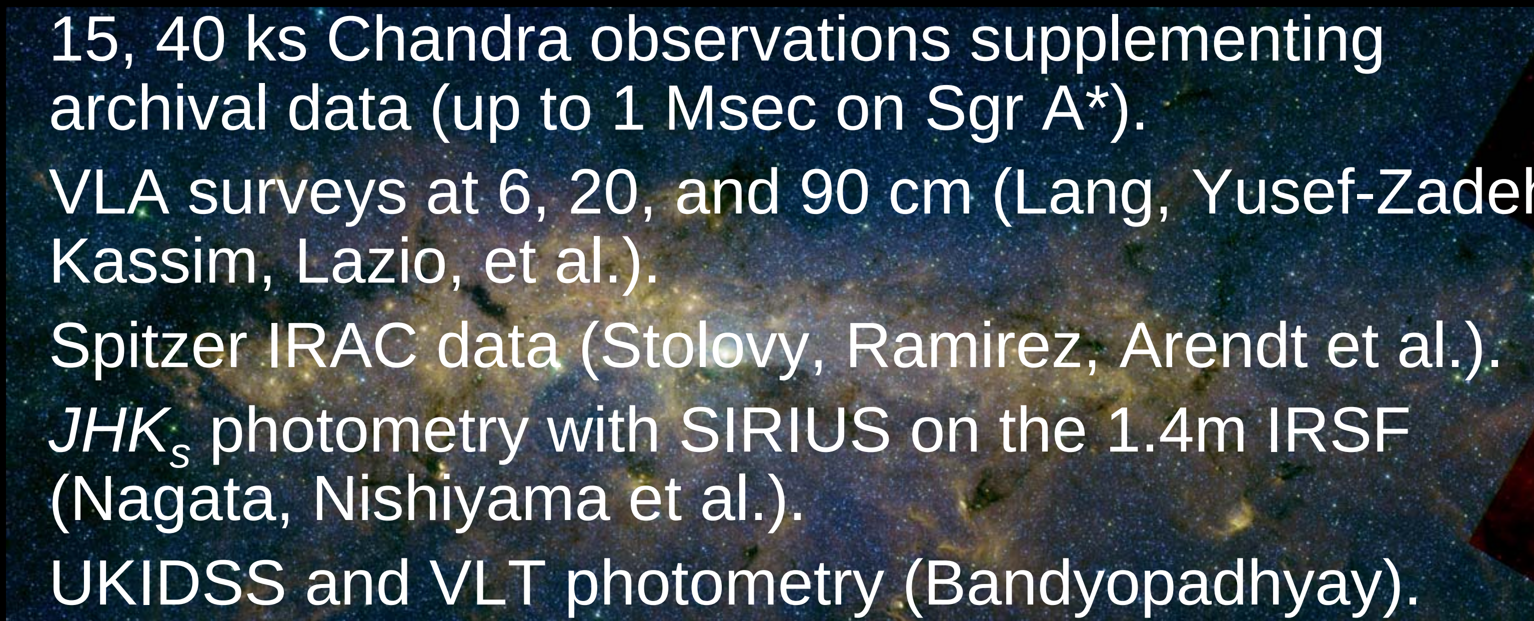


The Basic Statistics

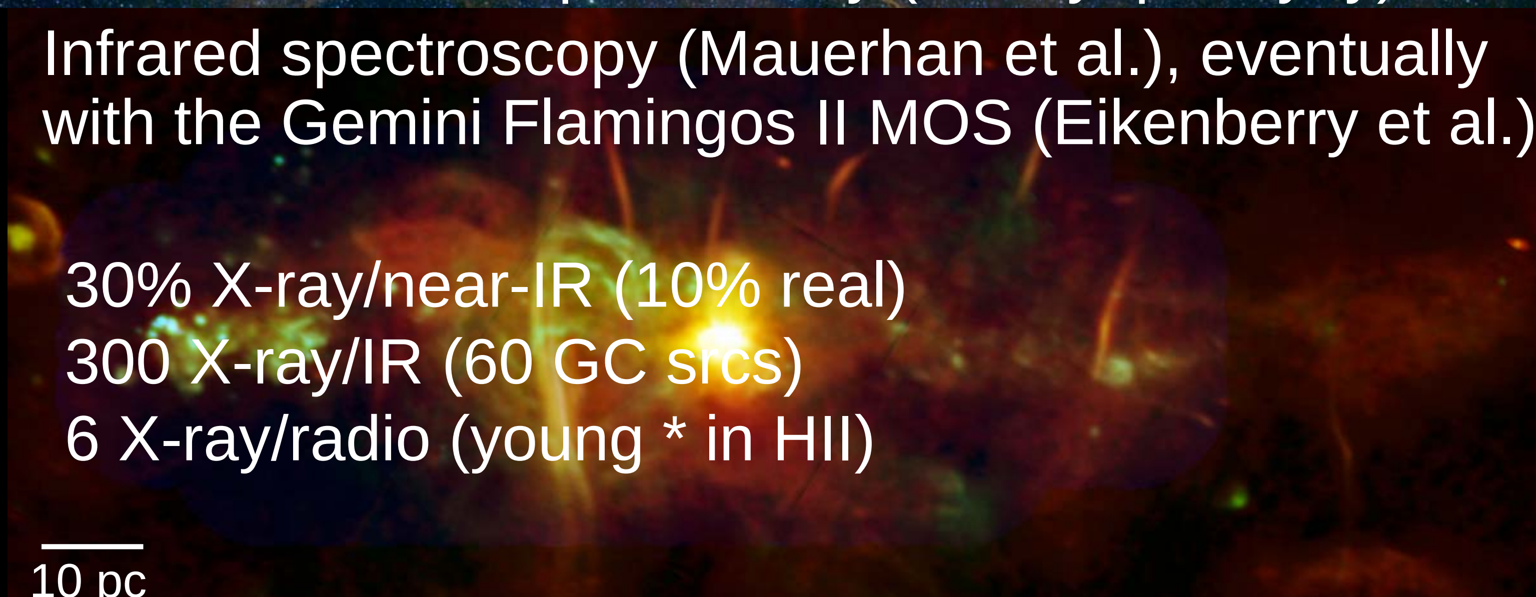


- We are sensitive to 10^{32} erg s^{-1} (90% conf) over 1 degree^2.
- We detect nearly 11,000 point sources.
- Typical positional uncertainties are 0.5-2”, depending on offset from aim point.

A Multi-Wavelength Survey

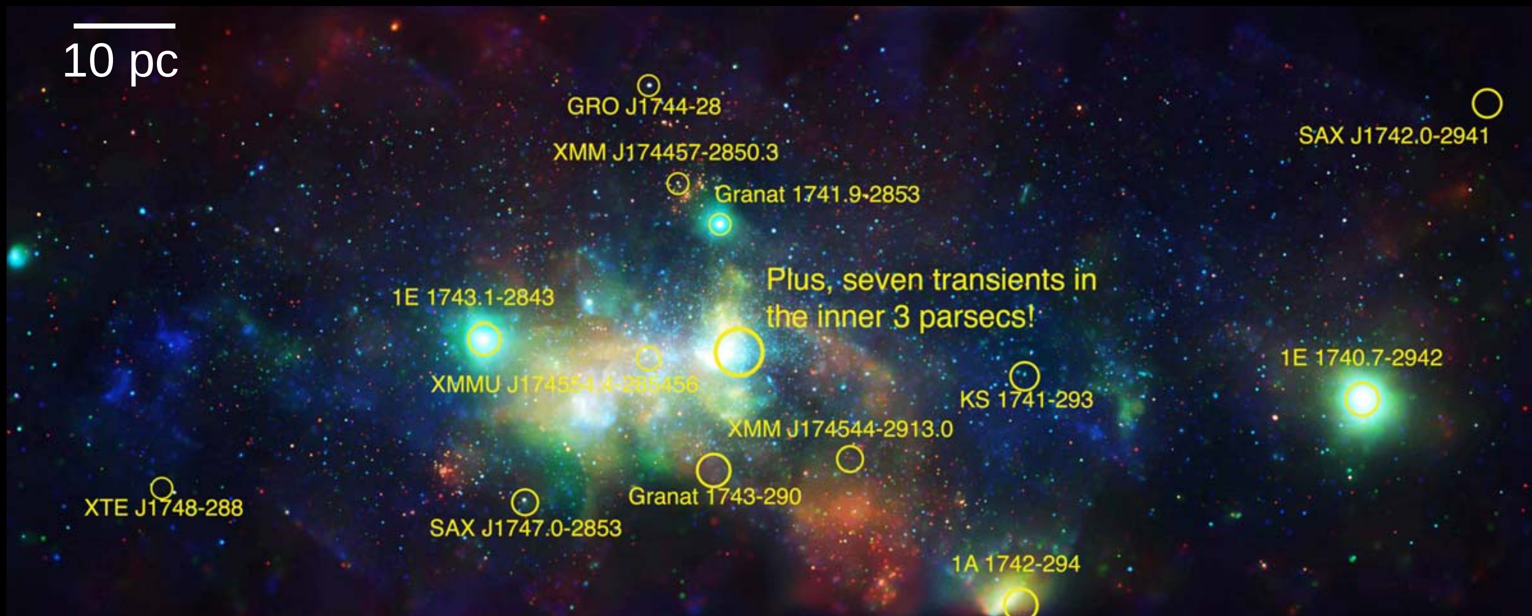


- 15, 40 ks Chandra observations supplementing archival data (up to 1 Msec on Sgr A*).
- VLA surveys at 6, 20, and 90 cm (Lang, Yusef-Zadeh, Kassim, Lazio, et al.).
- Spitzer IRAC data (Stolovy, Ramirez, Arendt et al.).
- *JHK$_s$* photometry with SIRIUS on the 1.4m IRSF (Nagata, Nishiyama et al.).
- UKIDSS and VLT photometry (Bandyopadhyay).
- Infrared spectroscopy (Mauerhan et al.), eventually with the Gemini Flamingos II MOS (Eikenberry et al.).



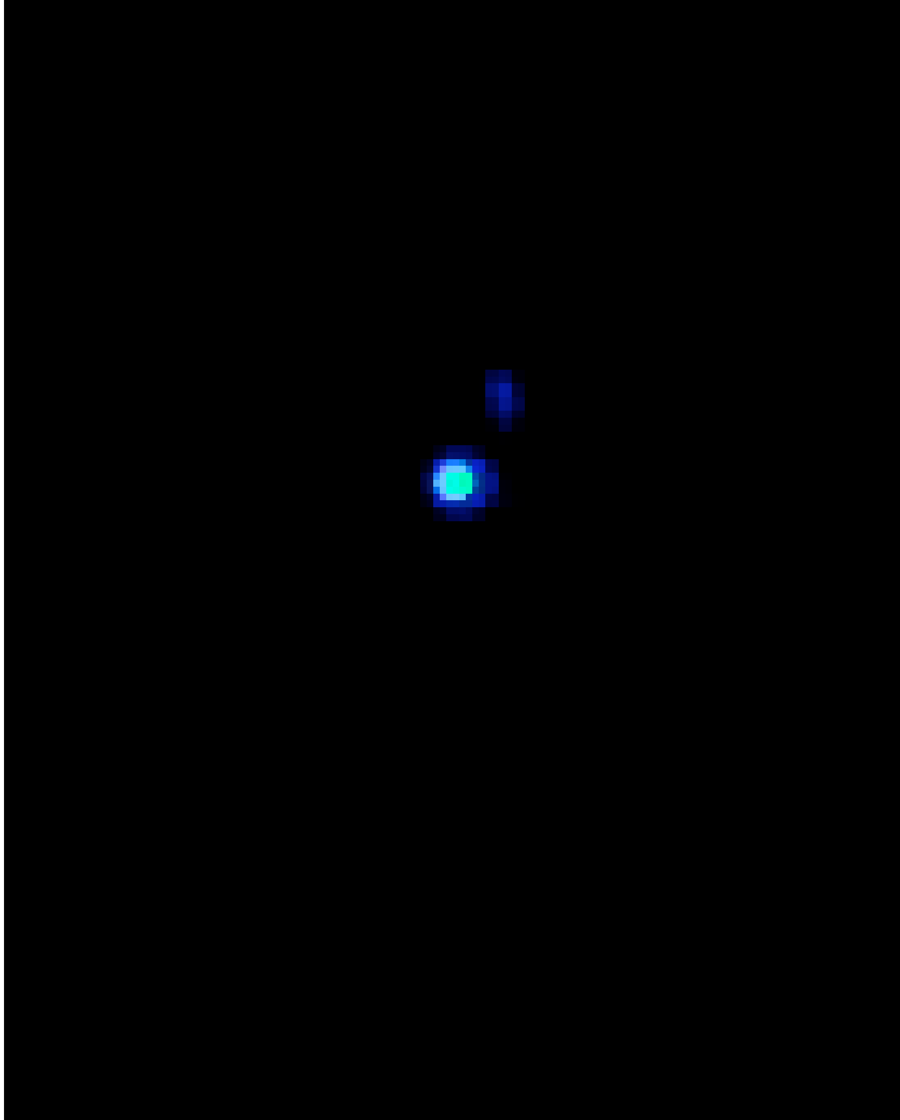
30% X-ray/near-IR (10% real)
300 X-ray/IR (60 GC srcs)
6 X-ray/radio (young * in HII)

X-ray Binaries in Outburst



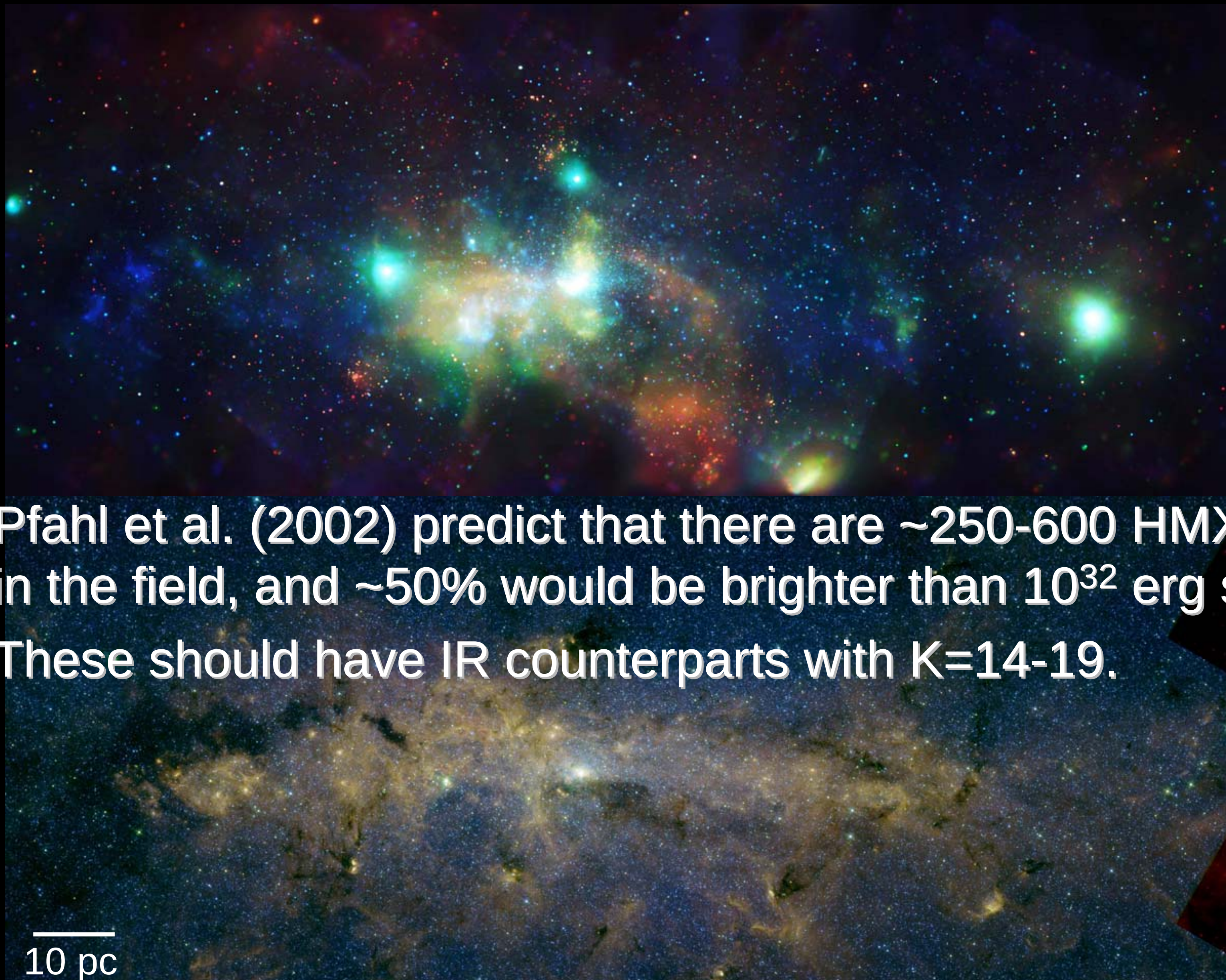
	Population Synthesis		Observed		Observed as transients	
	HMXB	LMXB	HMXB	LMXB	HMXB	LMXB
Galactic Center	~10	~10	~3	~17	~1	~16
Galaxy	~1000	~1000	114	185	63	103

X-ray Transients in the Central Parsec of the Galaxy



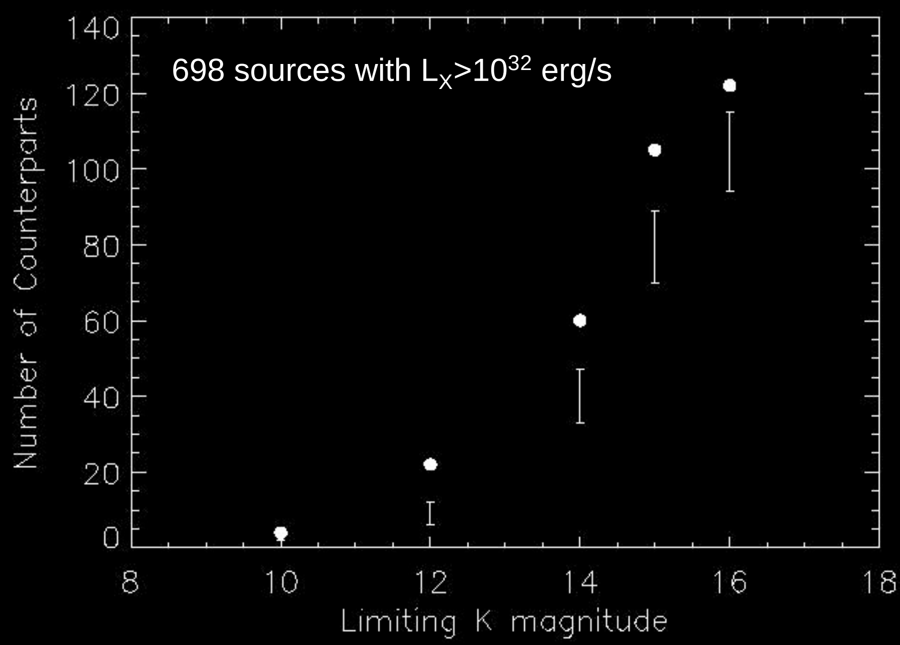
- 3 hr/frame (moving avg)
- 6 days 17 hr total
- Lowest color level 15σ above background
- Tail of PWN candidate has ~3 ct/pix, so Poisson statistics causes apparent variability
- 7 X-ray transients detected within central 3 pc in past 7 yr
- 4 of 7 detected within central pc => 20x overabundant per unit stellar mass (Muno et al. 2005)

High Mass X-ray Binaries



- Pfahl et al. (2002) predict that there are ~250-600 HMXBs in the field, and ~50% would be brighter than 10^{32} erg s^{-1}.
- These should have IR counterparts with K=14-19.

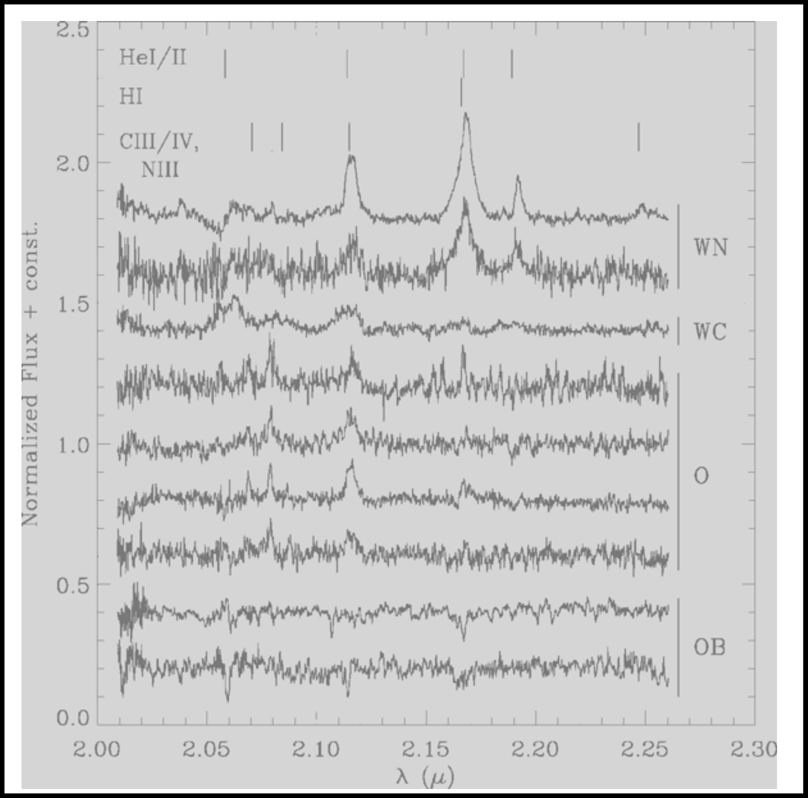
High Mass X-ray Binaries



- From our IR photometry, we find that ~3+/-2% of X-ray sources have counterparts with K<15. So, there are already ~20 candidate HMXBs with $L_X > 10^{32}$ erg/s in the field.
- UKIDSS will sample much more of the HMXB population (K<17).

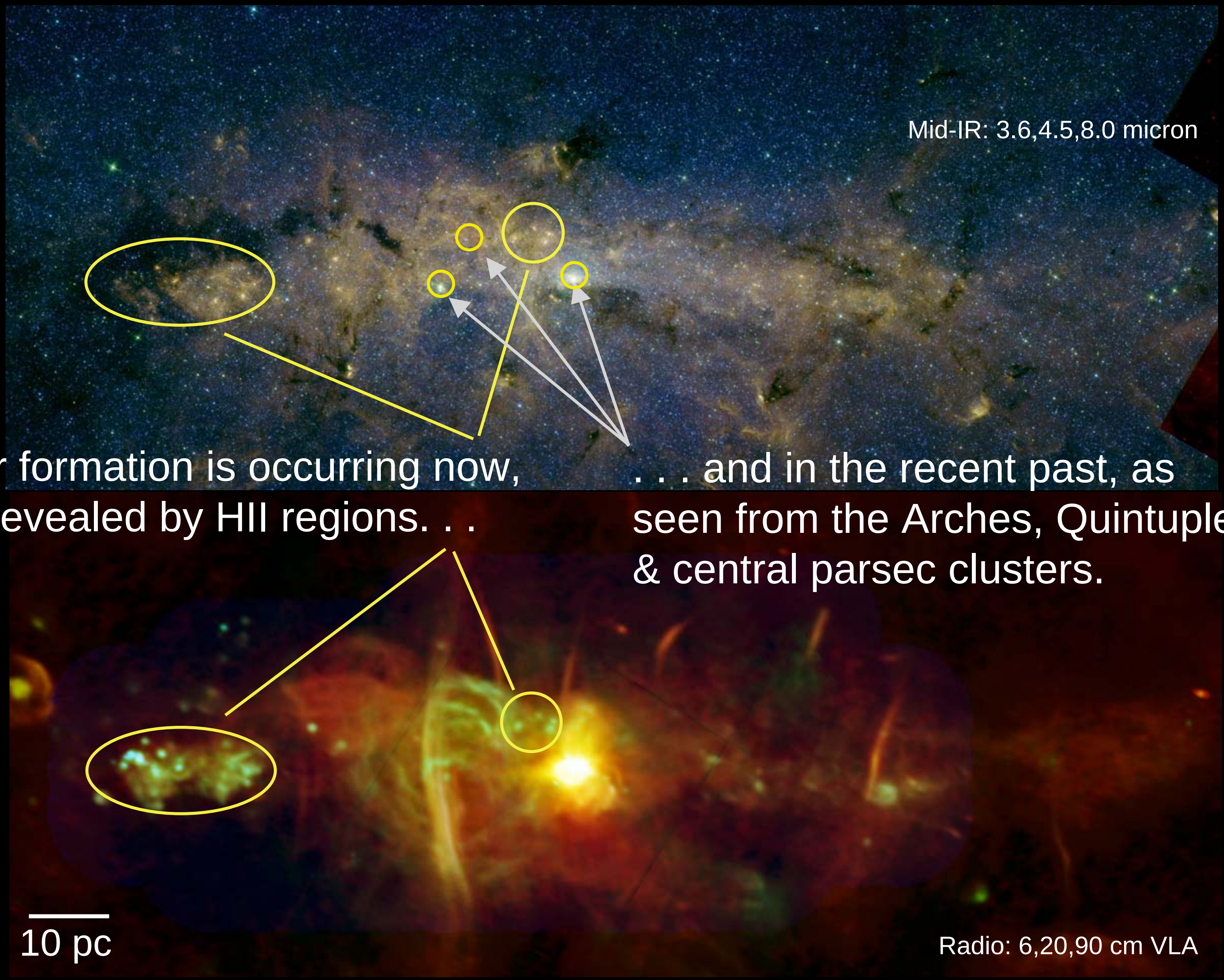
X-ray Selected Young Massive Stars

- So far, 16 of 49 stars we have obtained IR spectra of are Wolf-Rayet or O stars.
- Many show evidence that they are binaries.
- They are most likely colliding-wind binaries.



Mikles et al. (2006), Muno et al. (2006), Mauerhan et al. (2007, and in prep)

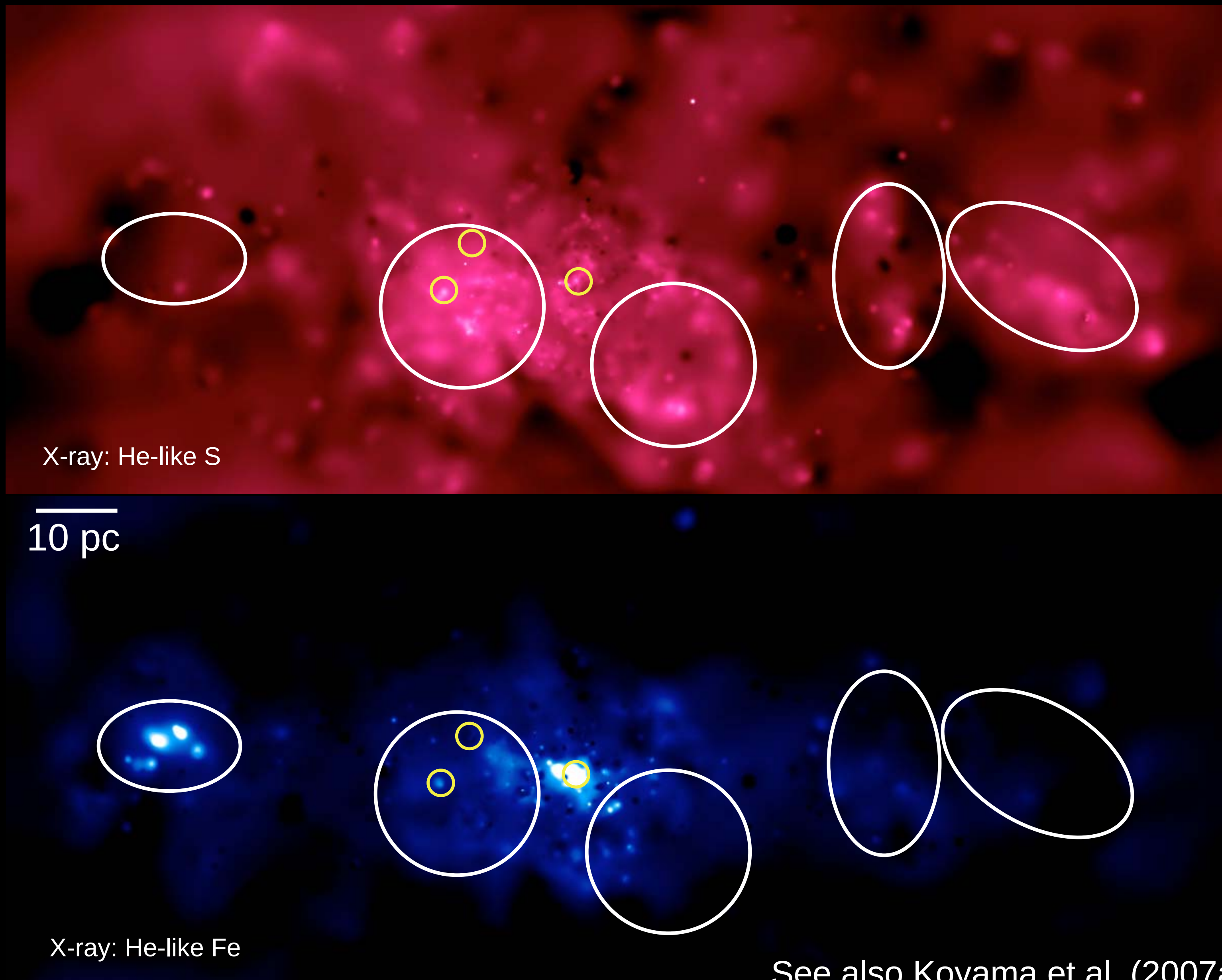
X-rays and Star Formation



X-rays and Star Formation

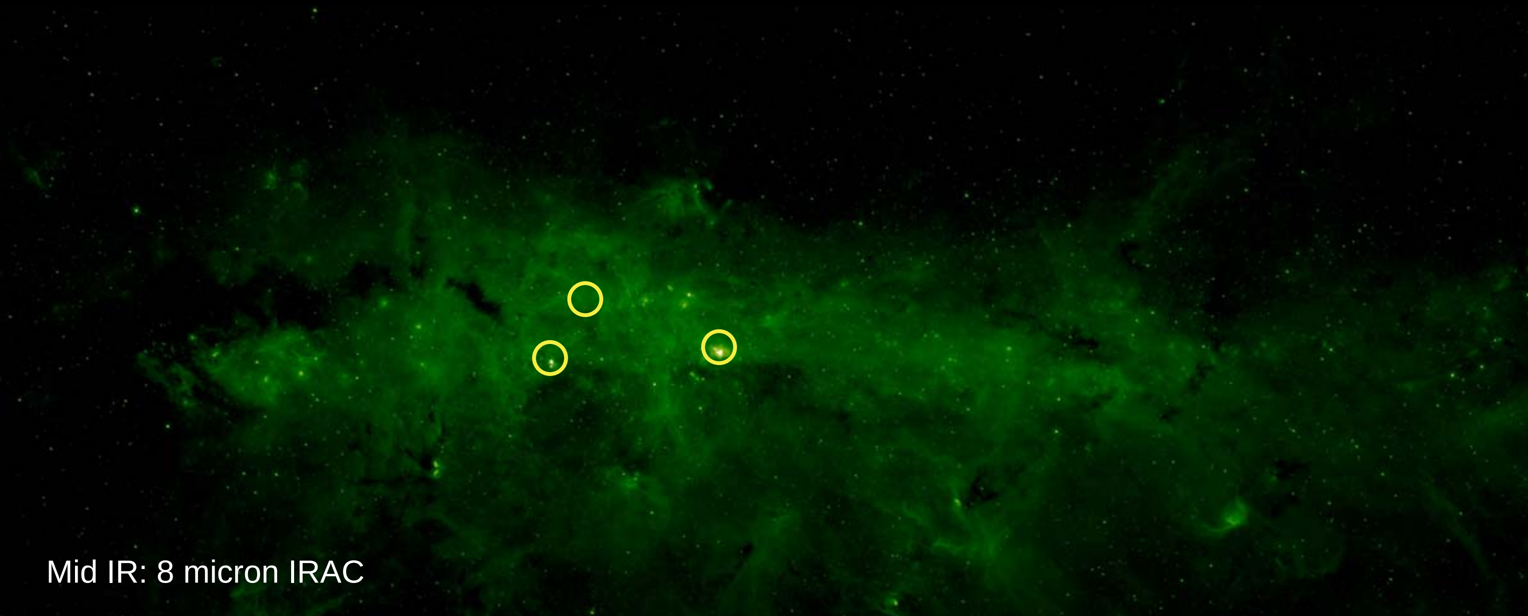
We have identified X-ray emission from the known young stellar population, and have a more widely-distributed population from earlier episodes of star formation.

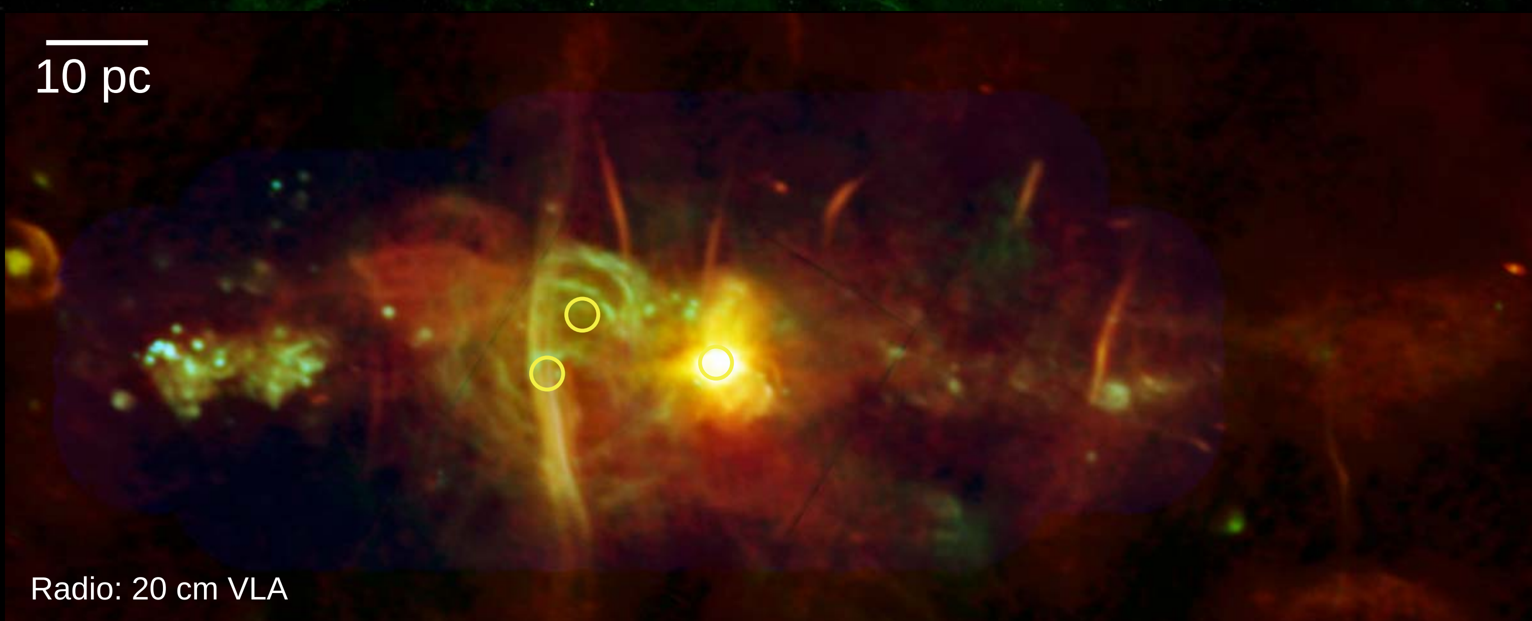
X-rays and Star Formation



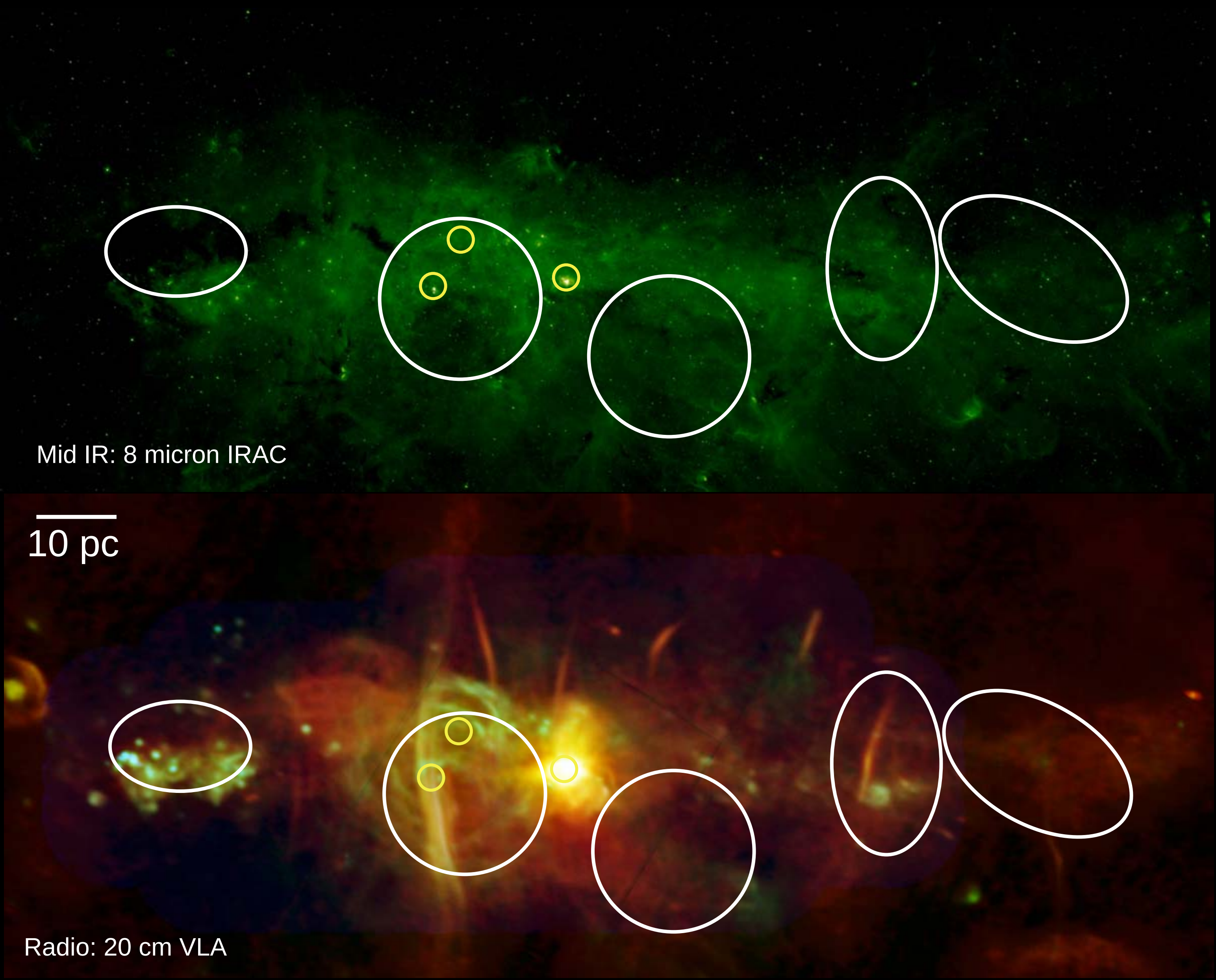
See also Koyama et al. (2007a,b)

X-rays and Star Formation

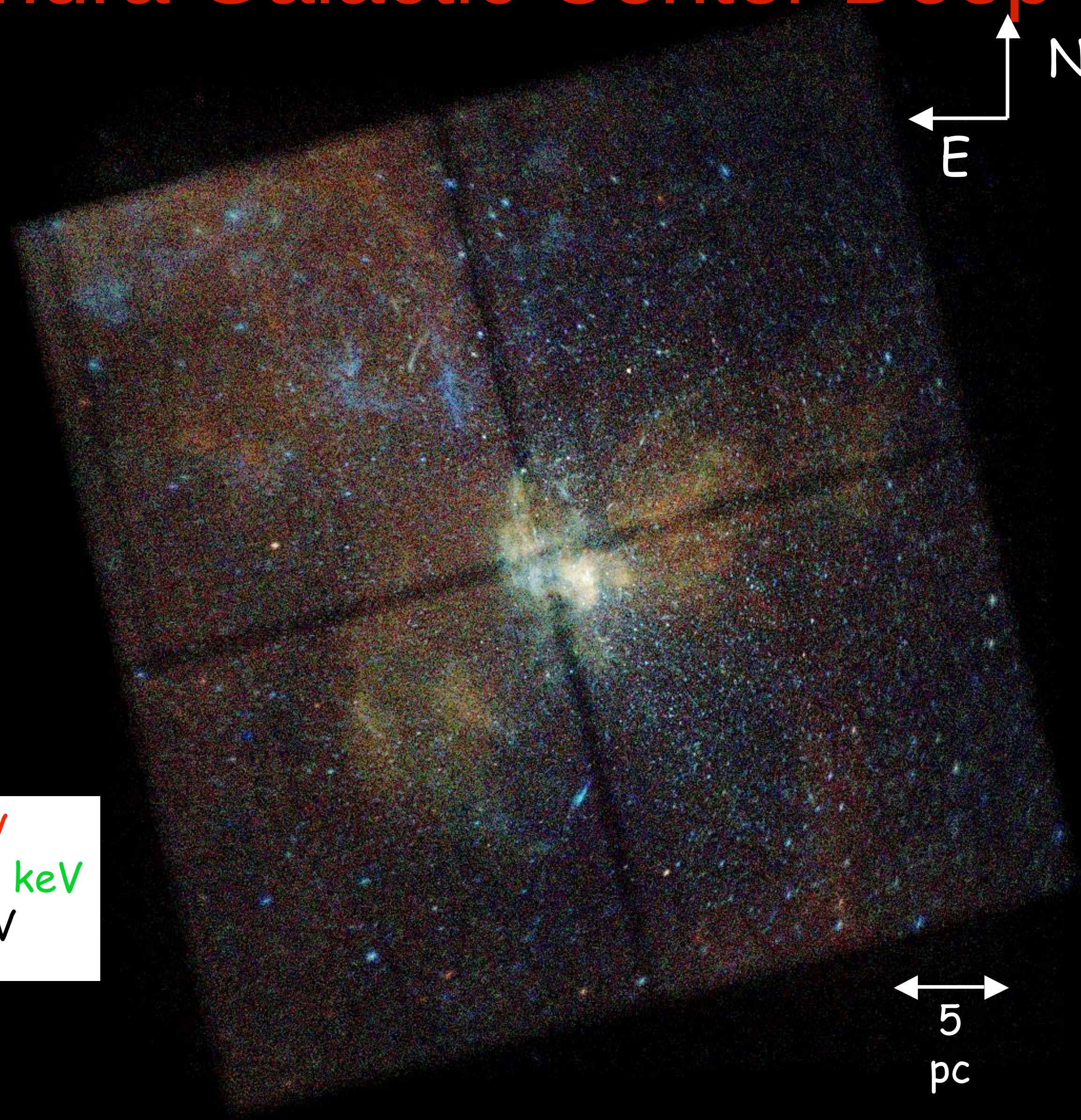




X-rays and Star Formation



Chandra Galactic Center Deep Field



17 x 17 arcmin

40 x 40 pc

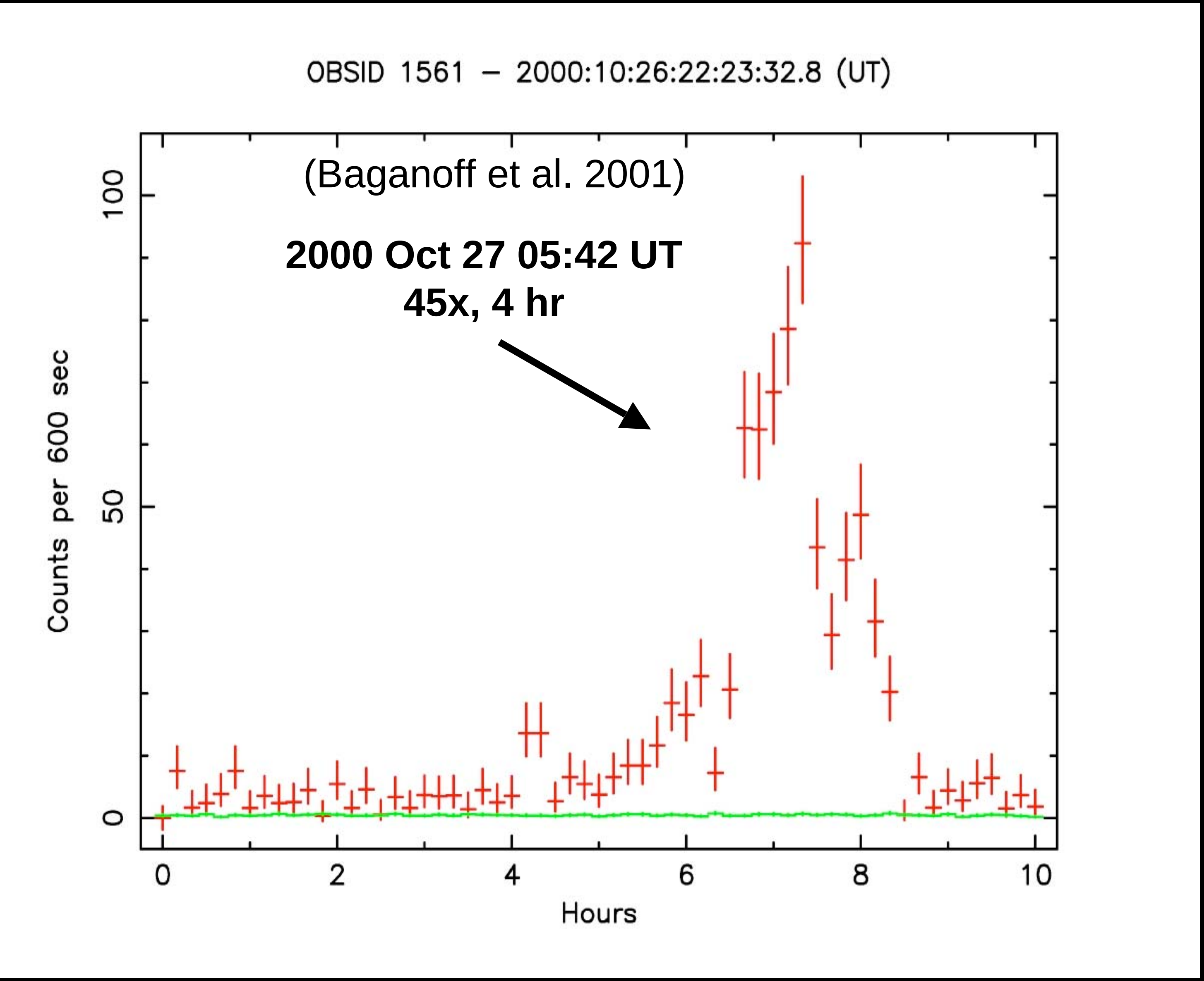
590 ks

Red: 2-3.7 keV
Green: 3.7-4.5 keV
Blue: 4.5-8 keV

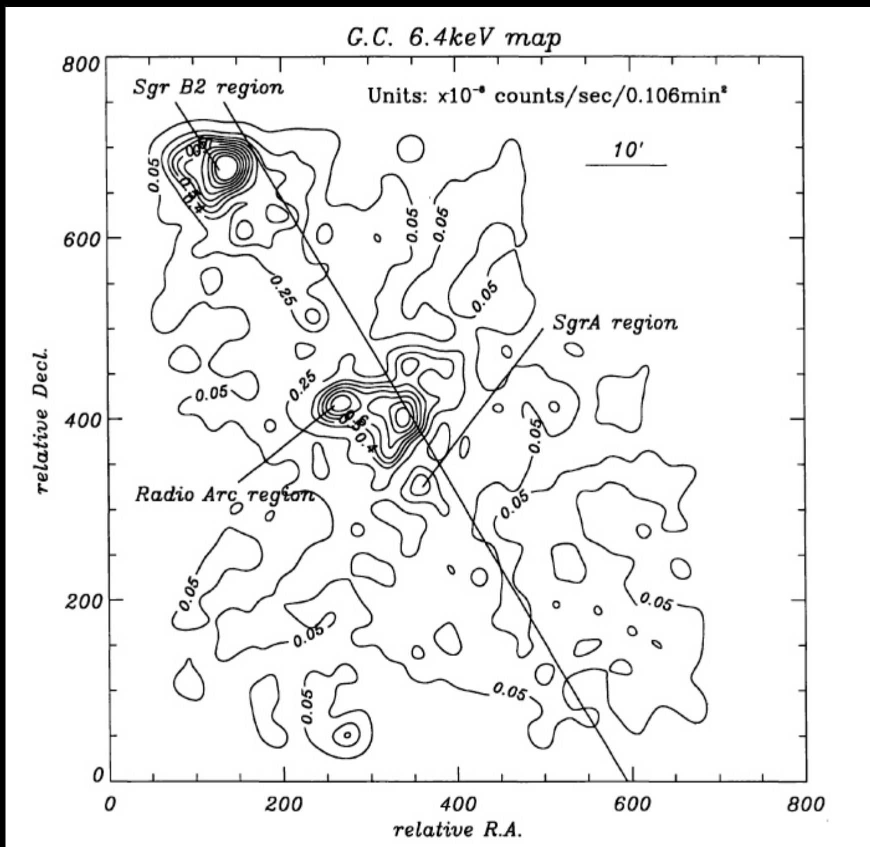
Properties of Sgr A*

- Mass ~ 3.7×10^6 Msun
- Distance ~ 8 kpc
- Quiescent X-ray luminosity ~ 2×10^{33} erg s^{-1} (2-10 keV)
- Daily X-ray flares <~ 10^{35} erg s^{-1}
- Eddington luminosity ~ few x 10^{44} erg s^{-1}

Chandra Discovery of X-ray Flaring from Sgr A*

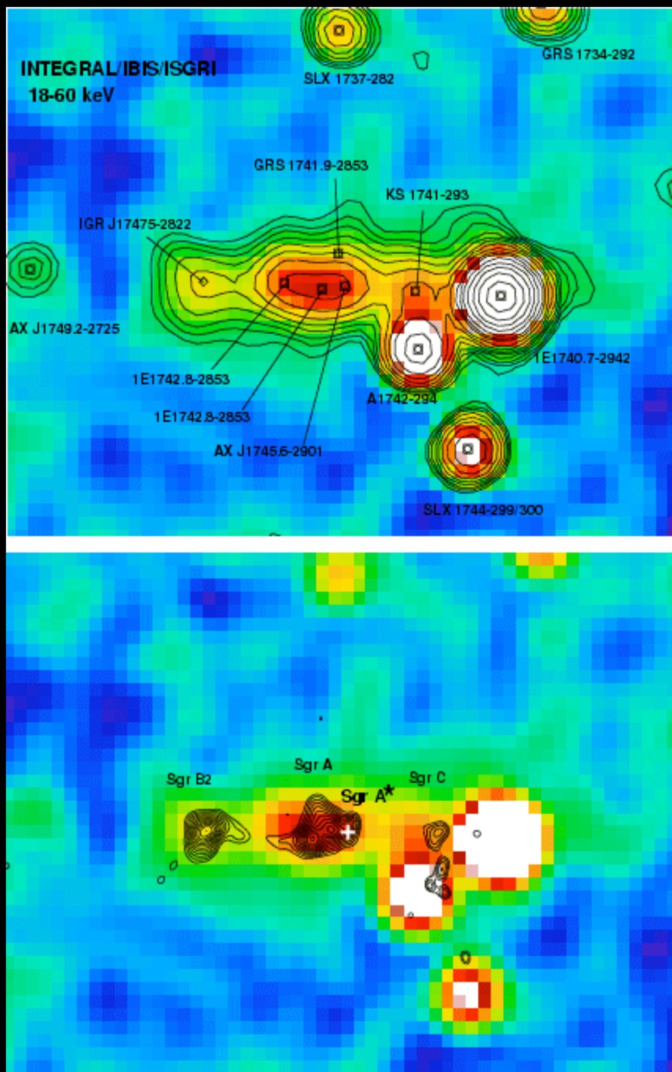


ASCA Discovery of Fe Fluorescence in the Galactic Center

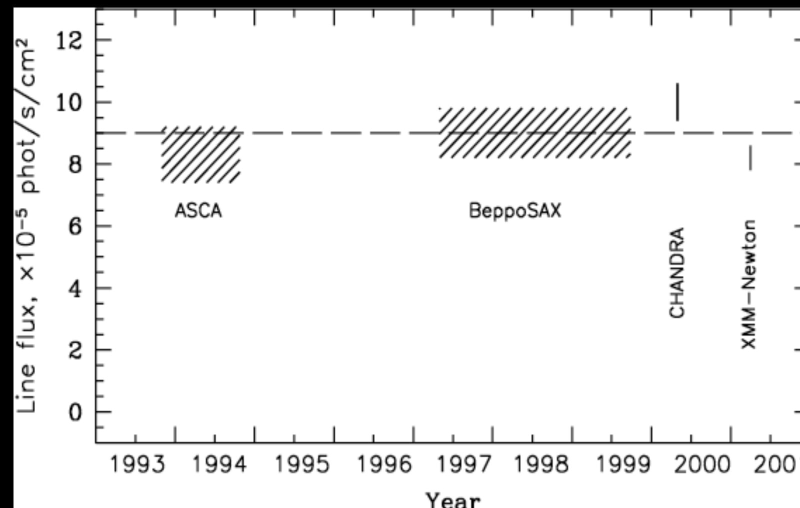


- ASCA is first X-ray satellite launched with CCD cameras
- Discovers Fe Ka fluorescence line (6.3-6.5 keV) in Sgr B2 molecular cloud (Koyama et al. 1996)
- Equivalent width ~1 keV
- Sgr A* upper-limit ~10^{36} erg s^{-1} (2-10 keV)
- Time-averaged luminosity required to produce the line, ~10^{38} erg s^{-1}, is much brighter than any nearby X-ray binaries
- Size of cloud ~7 pc => light-crossing time ~23 yr
- Koyama et al. suggest irradiator might have been Sgr A*, if it was at least 100x brighter ~300 years ago

INTEGRAL View of Sgr B2

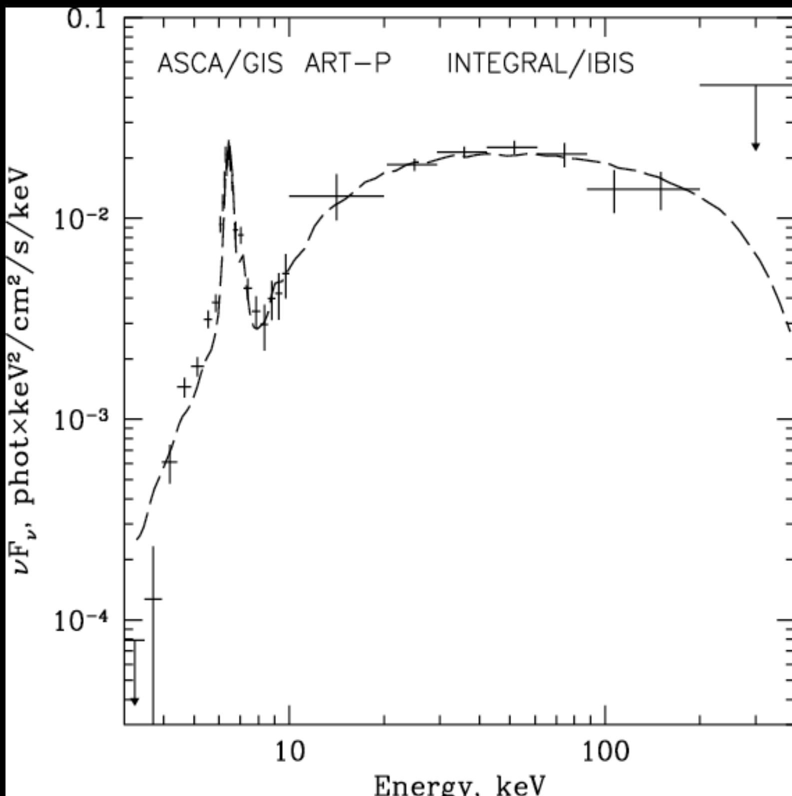


IBIS (18-60 keV)



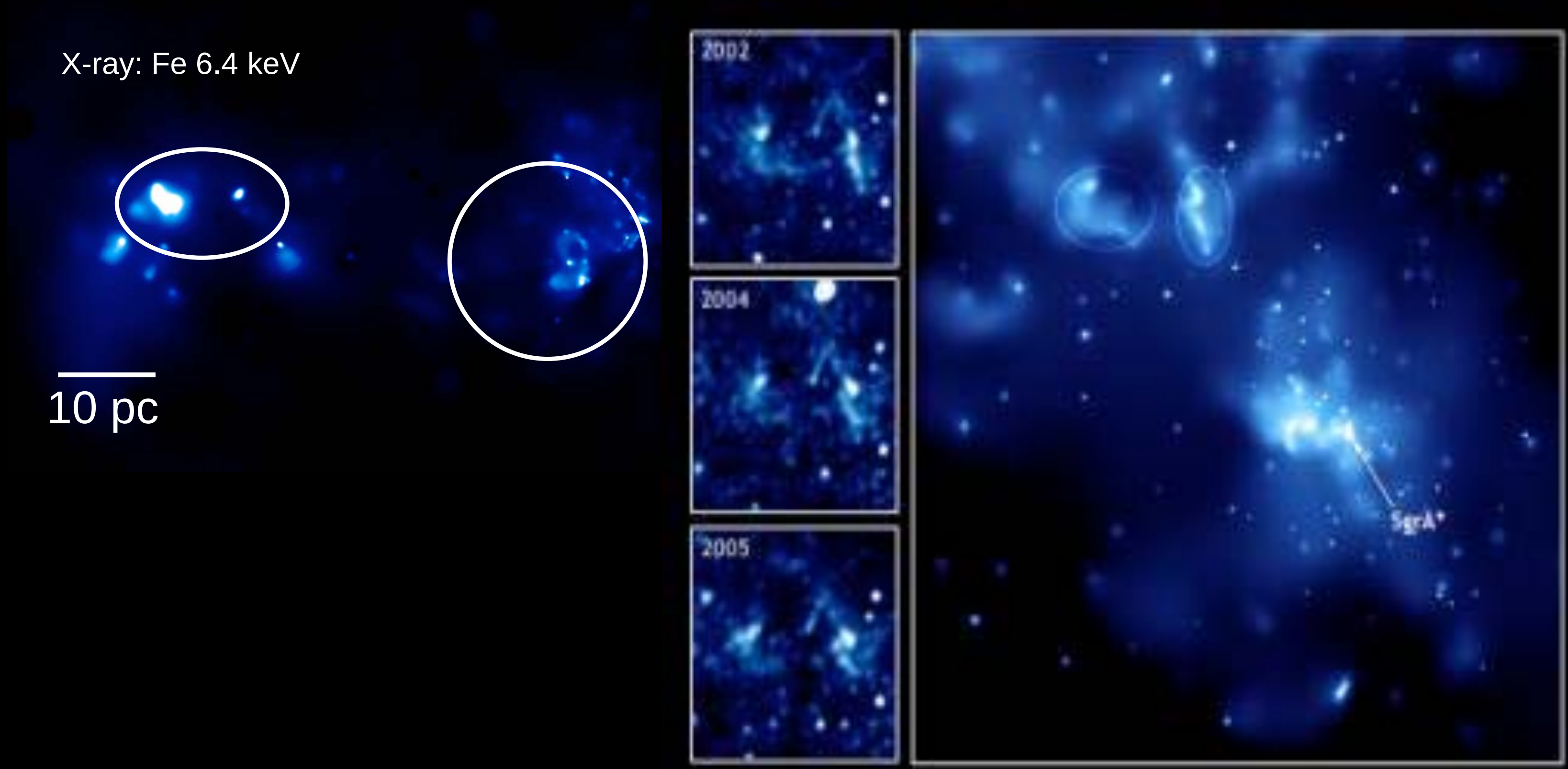
- INTEGRAL detects hard X-ray emission from Sgr B2 (Revnivtsev et al. 2004)
- First detection of a molecular cloud above 20 keV
- Composite light curve from ASCA, BeppoSAX, Chandra, and XMM shows constant 6.4 keV line flux from 1993-2000
- BeppoSAX catalog of bright X-ray sources near GC have 2-10 keV Lx ~ 1-4x10^{36} erg s^{-1} and are generally stable

Composite X-ray Spectrum of Sgr B2



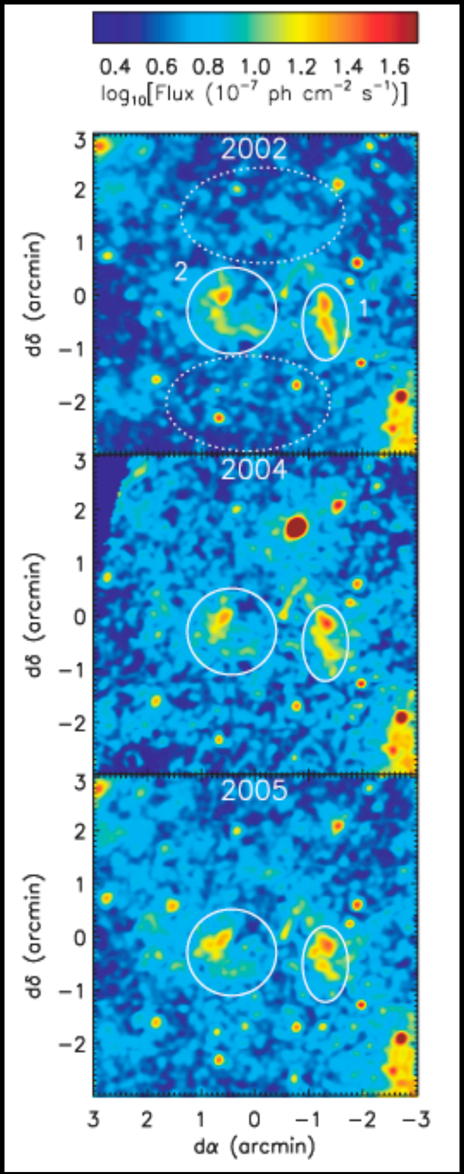
- Best-fit X-ray reflection model to ASCA, GRANAT, and INTEGRAL spectrum of Sgr B2
- Continuum photon index is 1.8 +/- 0.2 (typical AGN or XRB spectrum)
- IBIS hard bandpass eliminates possibility of a hidden local irradiator in or behind Sgr B2
- Cosmic ray excitation requires ~10^{40} erg s^{-1} ~ L_{bol} ~ L_{IR} (produced by hot stars)
- Revnivtsev et al. suggest Sgr A* was a low luminosity AGN Lx ~ $1.5x10^{39}$ erg s^{-1} (2-200 keV) about 300-400 yr ago

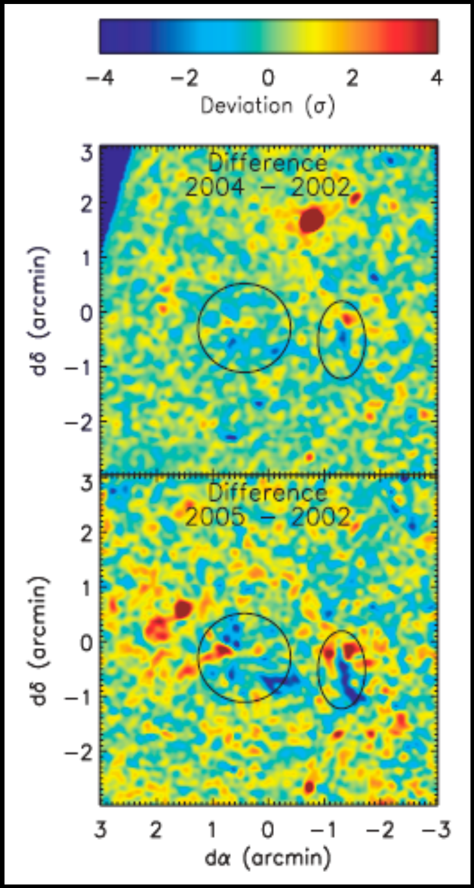
Reflections of Sgr A*'s Past as an AGN



Murakami et al. (2001); Park et al. (2004);
Muno et al. (2007); Koyama et al. (2007)

Morphological Variability of Fe Fluorescence Features





Muno et al. (2007)

- Features are ~1′ (2 pc) long and ~0.3′ (0.7 pc) long
- Intensity and morphology of fluorescent Fe lines change on timescales of 2-3 yr
- Rapid variability precludes origin by keV electrons (v ~ 0.6c) interacting with molecular gas (Valinia et al. 2000, Yusef-Zadeh et al. 2002)
- Argues against motion of Fe-rich SN ejecta (Bykov 2002)
- Pc scales require X-ray irradiator >~10^{38} erg/s with 2-3 yr duration

X-ray Spectra of Fluorescence Features

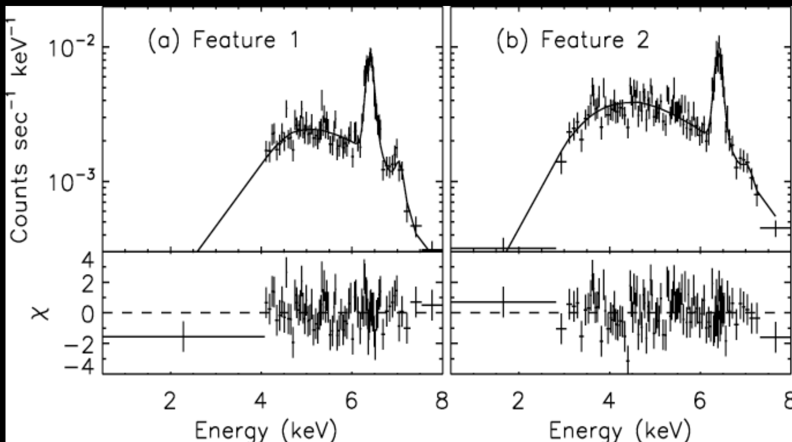


TABLE 1

SPECTRA OF THE IRON FLUORESCENCE FEATURES

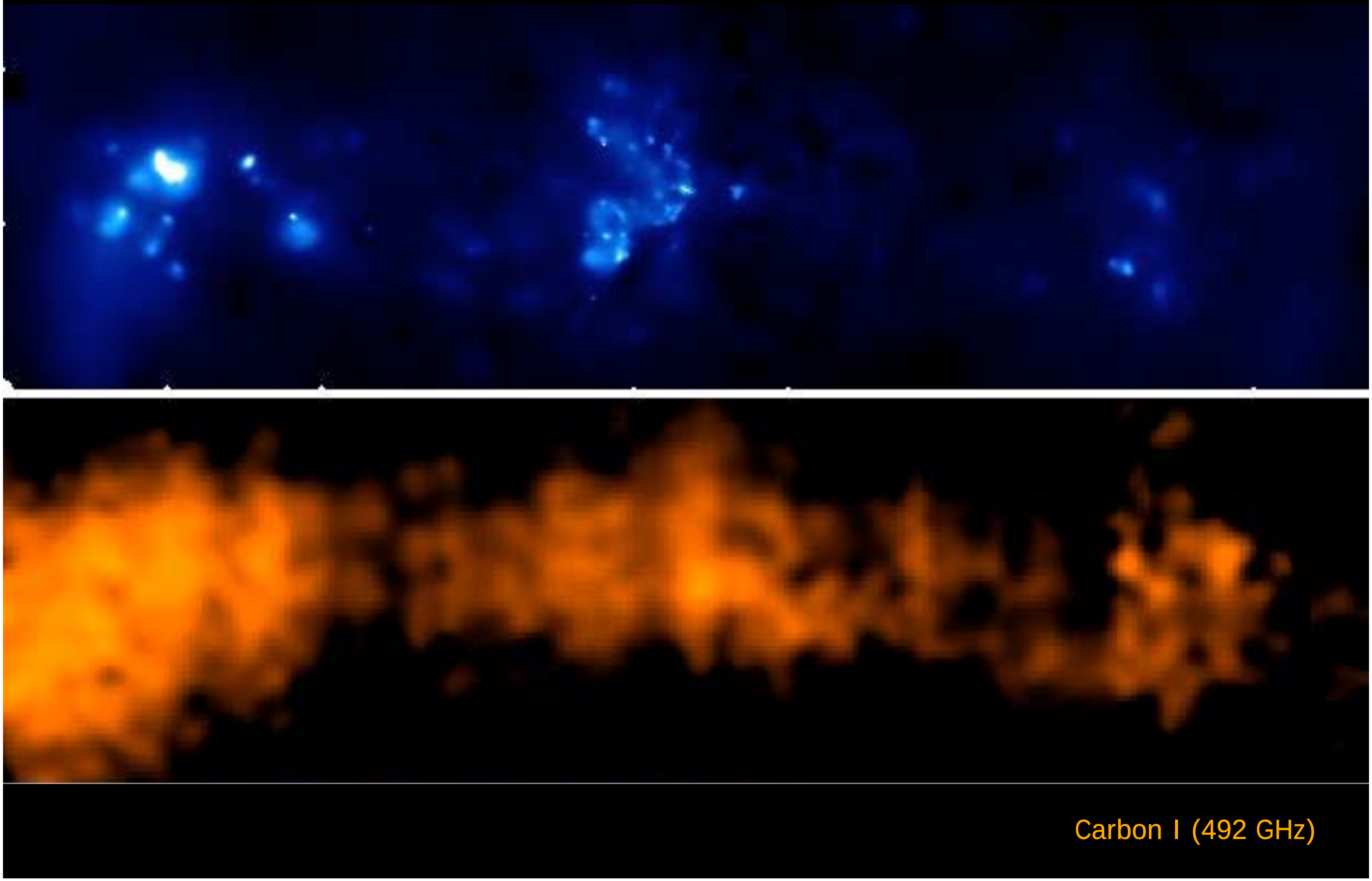
	Feature 1		Feature 2	
Parameter	2002	2004–2005	2002	2004–2005
$N_{H, ISM}$	11^{+2}_{-1}	11^{a}	11^{a}	11^{a}
$N_{H, cloud}$	25^{+4}_{-2}	23^{+4}_{-2}	29^{+20}_{-6}	64^{+26}_{-18}
f_{cloud}	1.0^{b}	1.0^{b}	$0.61^{+0.10}_{-0.05}$	$0.76^{+0.08}_{-0.05}$
Γ	$1.84^{+0.03}_{-0.13}$	1.84^{a}	1.84^{a}	1.84^{a}
N_{Γ}	6^{+2}_{-2}	5^{+4}_{-2}	6^{+1}_{-2}	8^{+6}_{-2}
$F_{K\alpha}$	18^{+2}_{-1}	16^{+1}_{-1}	19^{+3}_{-2}	18^{+8}_{-4}
$F_{K\beta}$	$2.1^{+0.6}_{-0.6}$	$1.9^{+0.9}_{-0.9}$	$1.5^{+0.8}_{-0.8}$	$1.9^{+1.7}_{-1.8}$
$EW_{K\alpha}$	1000^{+240}_{-90}	1010^{+190}_{-90}	930^{+160}_{-160}	690^{+220}_{-220}
$EW_{K\beta}$	140^{+70}_{-20}	150^{+60}_{-70}	90^{+40}_{-45}	90^{+100}_{-80}
F_X	$4.0^{+0.2}_{-0.2}$	$3.7^{+0.2}_{-0.2}$	$5.7^{+0.3}_{-0.3}$	$4.2^{+0.3}_{-0.3}$
F'_X	$5.2^{+0.2}_{-0.3}$	$4.8^{+0.2}_{-0.3}$	$7.7^{+0.5}_{-0.4}$	$5.5^{+0.3}_{-0.5}$

- Assumed identical ISM absorption and continuum shape for both features at all epochs
- Best-fit photon index is 1.8 +/- 0.13, consistent with continuum of Sgr B2 irradiator
- Supports recent claim made for Sgr B2 by Revnivtsev et al. (2004)
- Continued deep monitoring may reveal direction of propagation

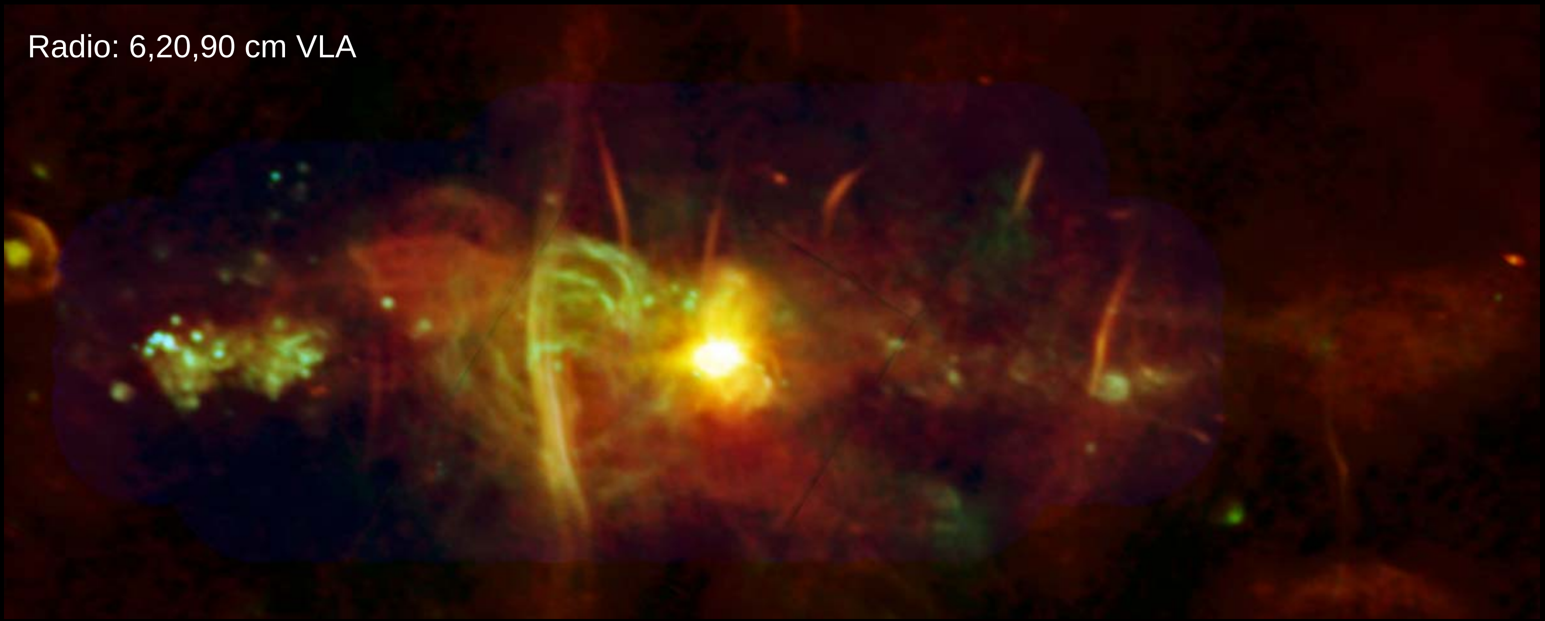
Arguments Against Local X-ray Irradiators

- Unusual for an XRB to be in outburst for so long (Chen et al. 1997).
- Microquasars and some pulsars might have required luminosity and hard spectrum in high state
- Fluorescent line seen in Sgr B2, Sgr C, and central parsecs of Galaxy, so would need multiple microquasars, such as GRS 1915+10, but none of them would currently be bright.
- Need sources that are bright for years and then shut off completely for years.
- Circinus X-1 dims for only 5 of its 16-day period; it never really shuts off.
- No X-ray satellite has seen these hypothetical microquasars turn on or off.
- Irradiation by a single source, Sgr A*, provides simpler explanation.

Reflections of Sgr A*'s Past as an AGN

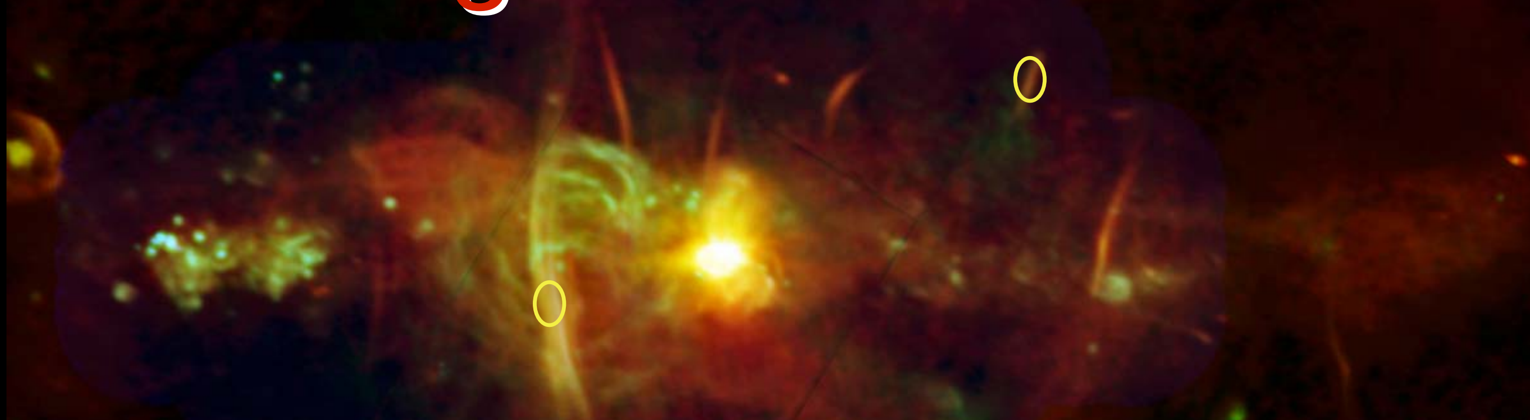


Magnetic Filaments

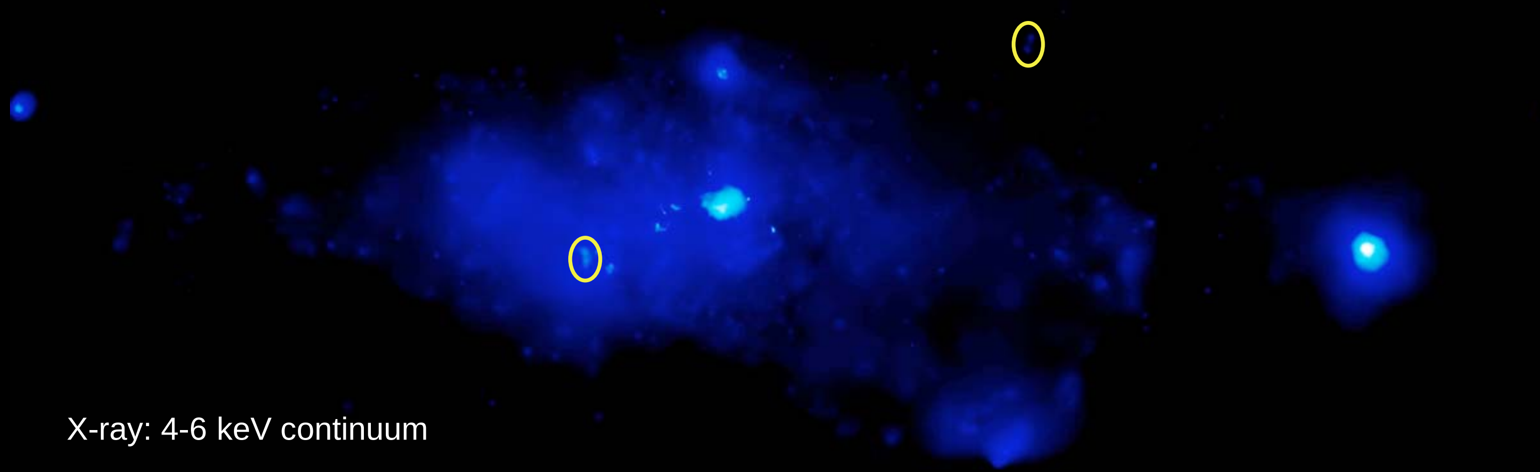


- Radio images of the Galactic center show numerous "filaments", powered by synchrotron emission from relativistic electrons spiraling along mGauss magnetic fields (Yusef-Zadeh & Morris 1987).
- The origins of these electrons and magnetic fields is a matter of debate:
  - Are the fields pervasive through the Galactic center (Morris & Serabyn 1996)?
  - Are the fields and particles both enhanced locally, by young stars or supernova (LaRosa et al. 2005; Yusef-Zadeh et al. 2005)?

Magnetic Filaments

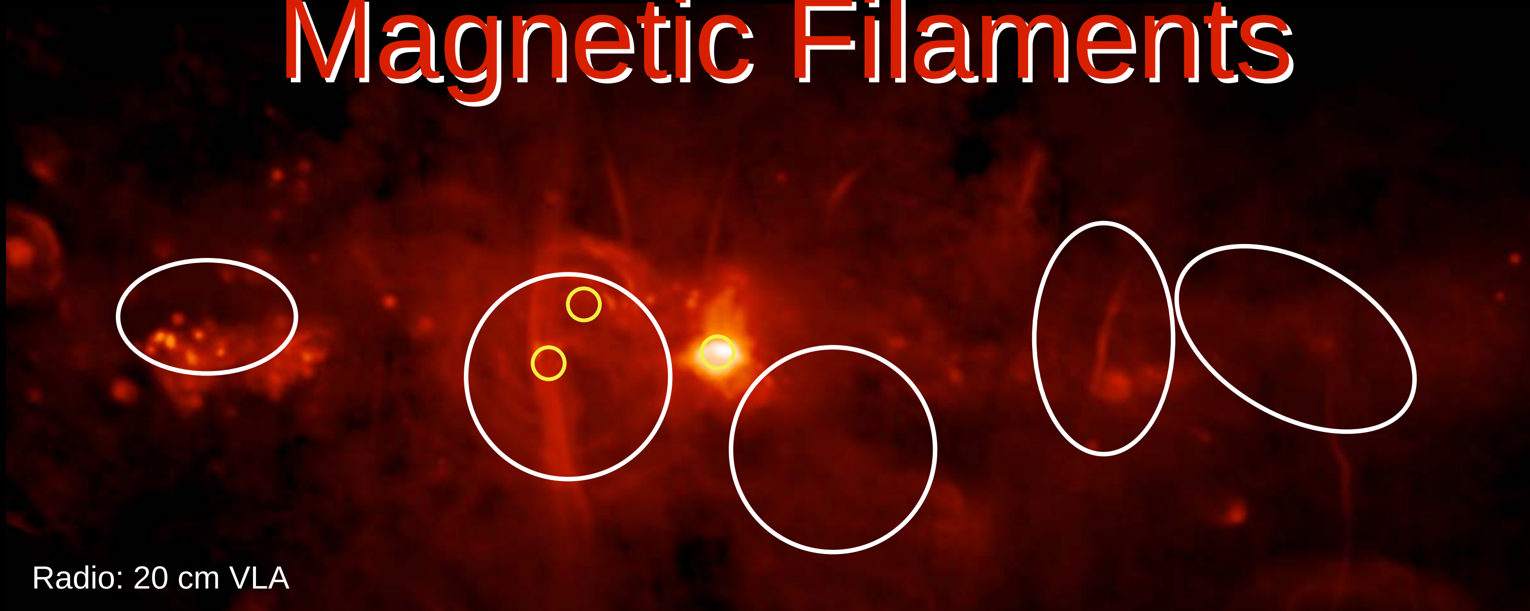


- There are X-rays from a few filaments (e.g., Lu et al. 2003), but
  - The X-rays don’t extend the length of the radio filament.
  - Most equally-bright filaments show no X-rays.

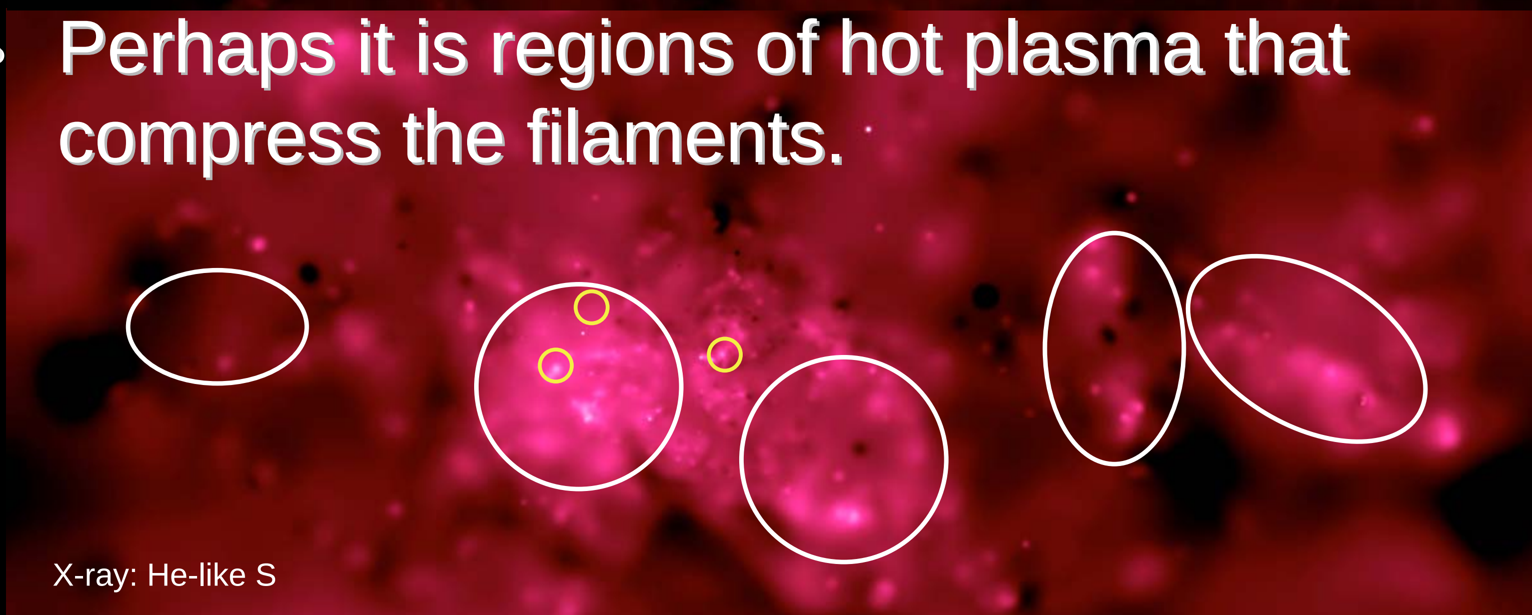


X-ray: 4-6 keV continuum

Magnetic Filaments



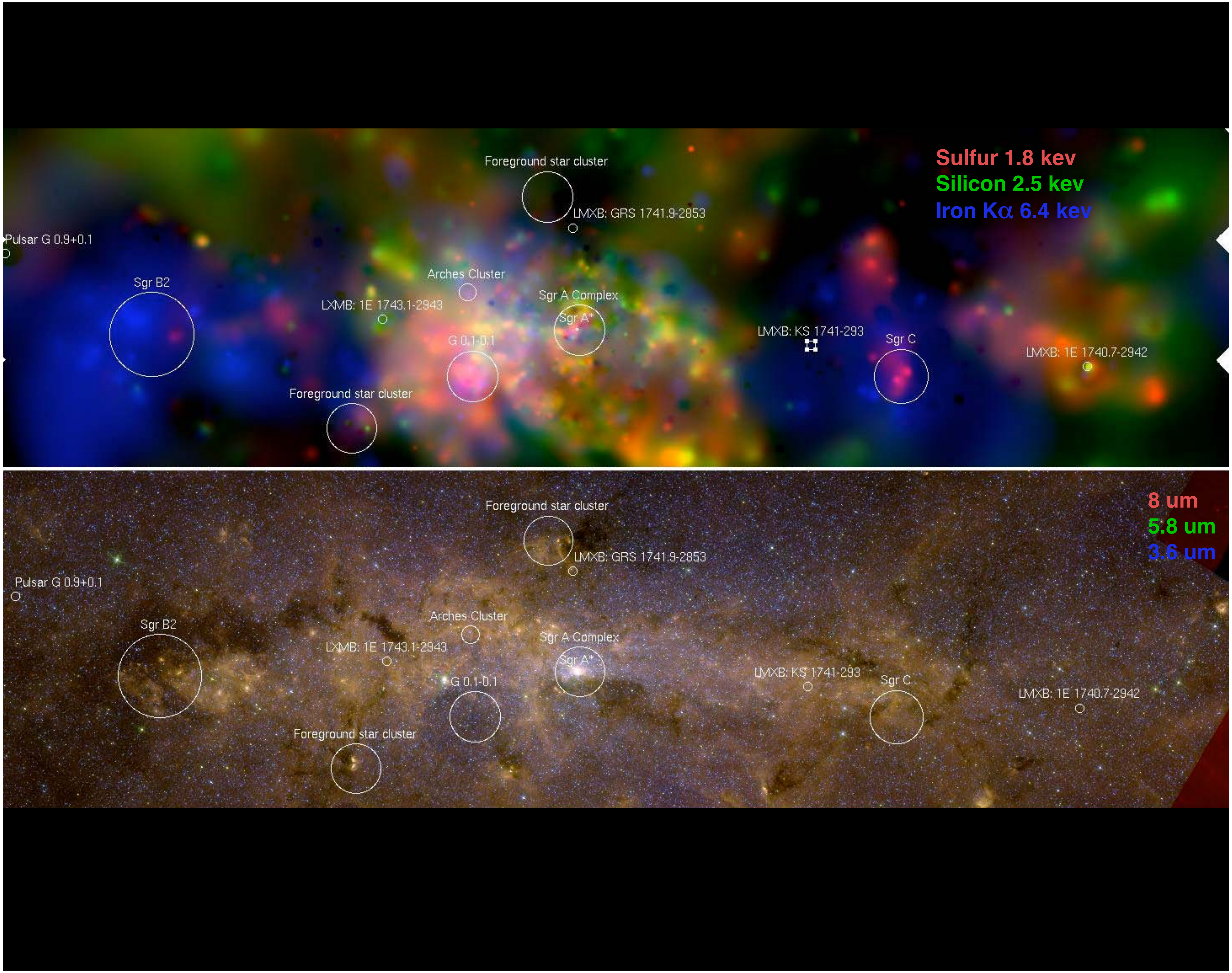
- Perhaps it is regions of hot plasma that compress the filaments.



Conclusions

- Appear to have found all active transients in the field
- Looks like GC may be a LMXB factory
- We have ~20 potential quiescent HMXBs candidates, and will have many more in near future
- Find large number of wind-driven massive star binaries associated with active star formation regions
- X-ray line maps provide new views of star formation and allow us to piece together some dynamics
- Sgr A*'s reflections associated with diffuse clouds
- No constraints on the magnetic filaments as yet!

THE END


Sulfur 1.8 kev
Silicon 2.5 kev
Iron Kα 6.4 kev
Foreground star cluster
LMXB: GRS 1741.9-2853
Pulsar G 0.9+0.1
Sgr B2
Arches Cluster
LXMB: 1E 1743.1-2943
Sgr A Complex
Sgr A*
G 0.1-0.1
LMXB: KS 1741-293
Sgr C
LMXB: 1E 1740.7-2942
Foreground star cluster
8 um
5.8 um
3.6 um
Foreground star cluster
LMXB: GRS 1741.9-2853
Pulsar G 0.9+0.1
Sgr B2
Arches Cluster
LXMB: 1E 1743.1-2943
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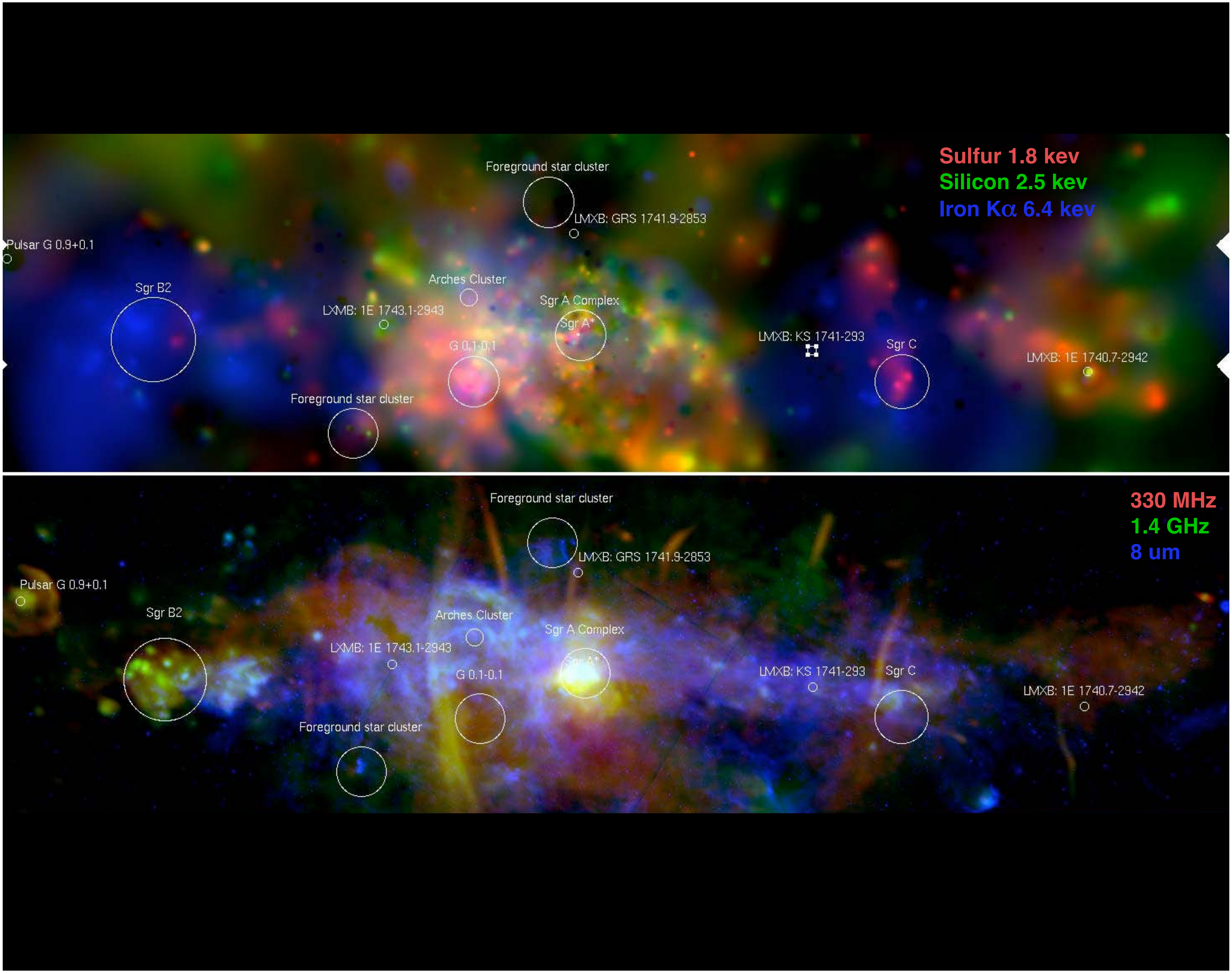
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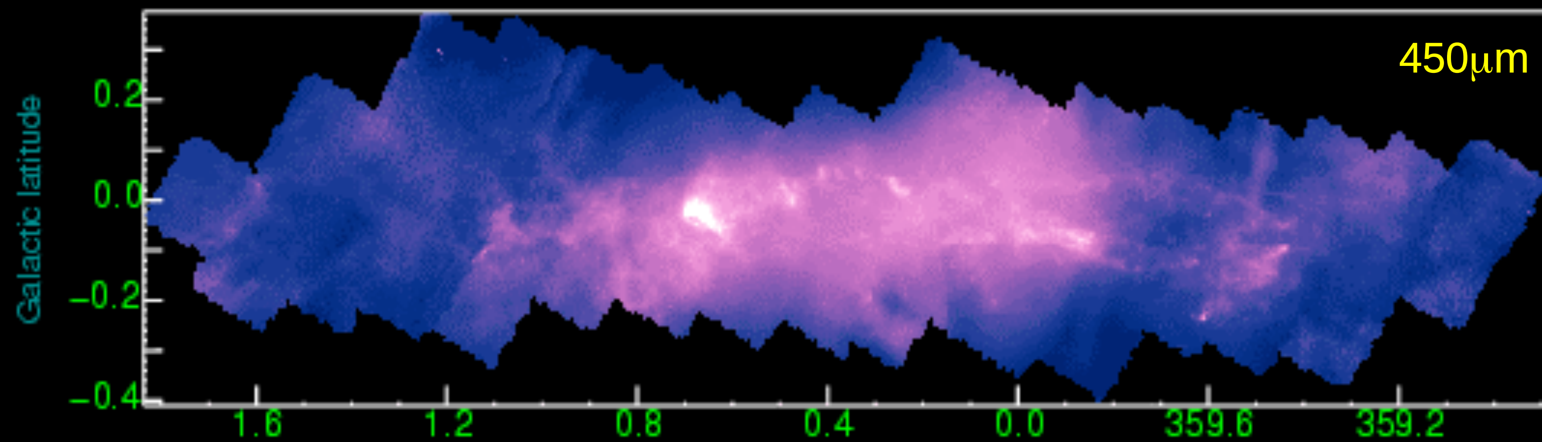
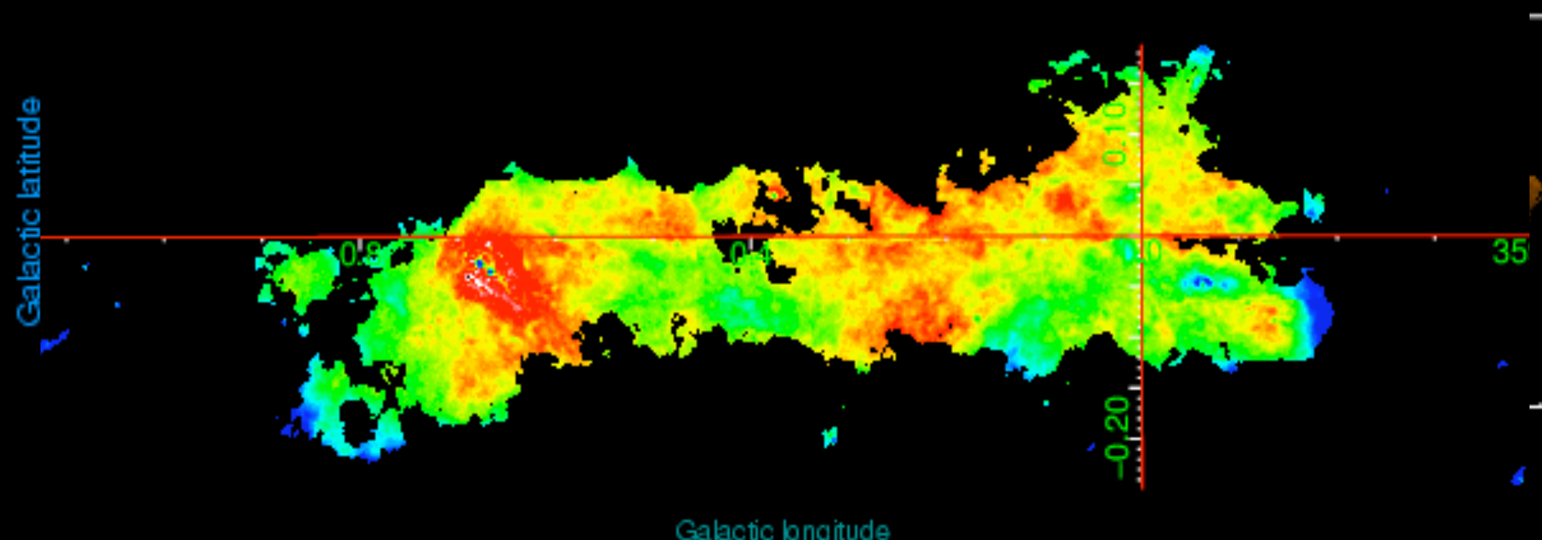
LMXB: KS 1741-293
Sgr C
LMXB: 1E 1740.7-2942
Foreground star cluster
330 MHz
1.4 GHz
8 um

Dual-colour imaging:
Investigate the variation of dust properties on large scales



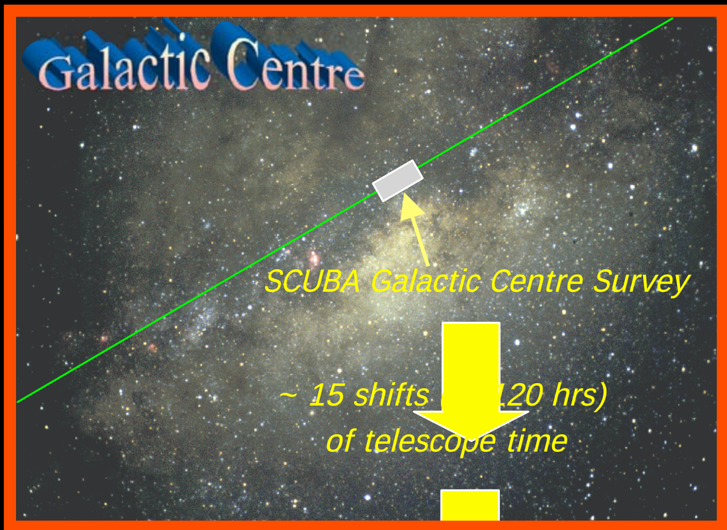
SCUBA F-O-V

SCUBA-2 F-O-V



SCUBA Survey of the Galactic Centre (Pierce-Price et al. 2000)

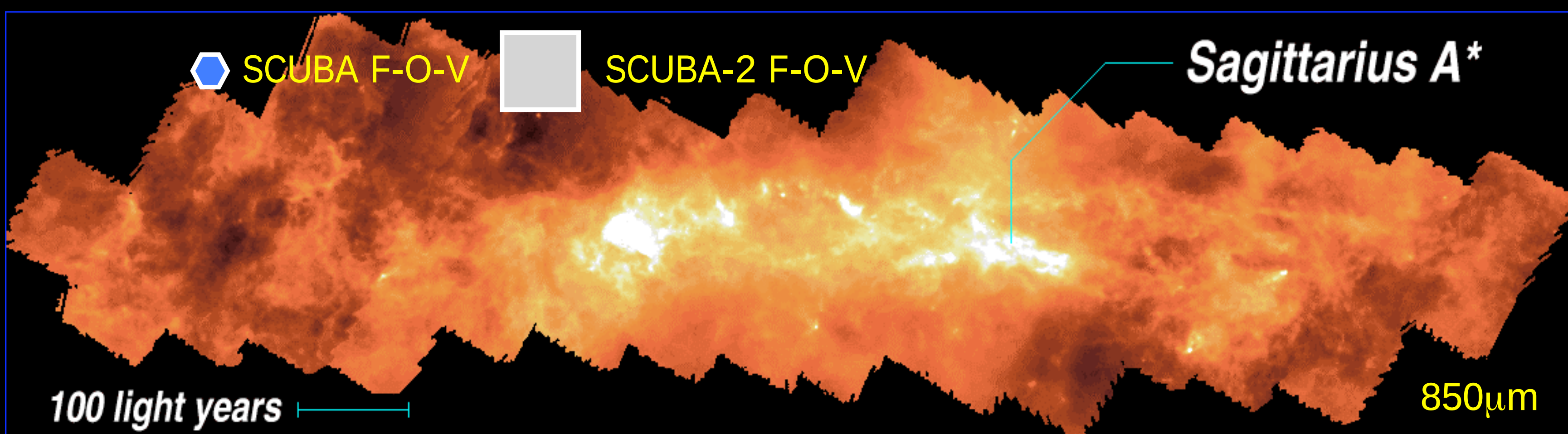
Maximum mapping speed: Unbiased surveys of the Galaxy



Our global picture of Galactic star formation is based on the study of only a few molecular clouds (e.g. Orion or Galactic Centre).

SCUBA-2 will allow a complete census of giant molecular clouds, star-forming regions, protostars and pre-stellar cores.

SCUBA-2 field in same integration time -
The first submillimetre Galactic PLANE Survey?



SCUBA Survey of the Galactic Centre (Pierce-Price et al. 2000, ApJ 545, L121)

Outline

- Properties of the Galactic supermassive black hole: Sagittarius A*
- Fe Ka fluorescence in the molecular cloud Sgr B2
  - ASCA
  - INTEGRAL
- Chandra detection of variable Fe fluorescence features within 6' (14 pc projected) of Sgr A*
- Thomson scattering constraints on the luminosity of Sgr A* in the past 10^4 to 10^5 yr

X-ray Emission-Line Equivalent-Width Maps

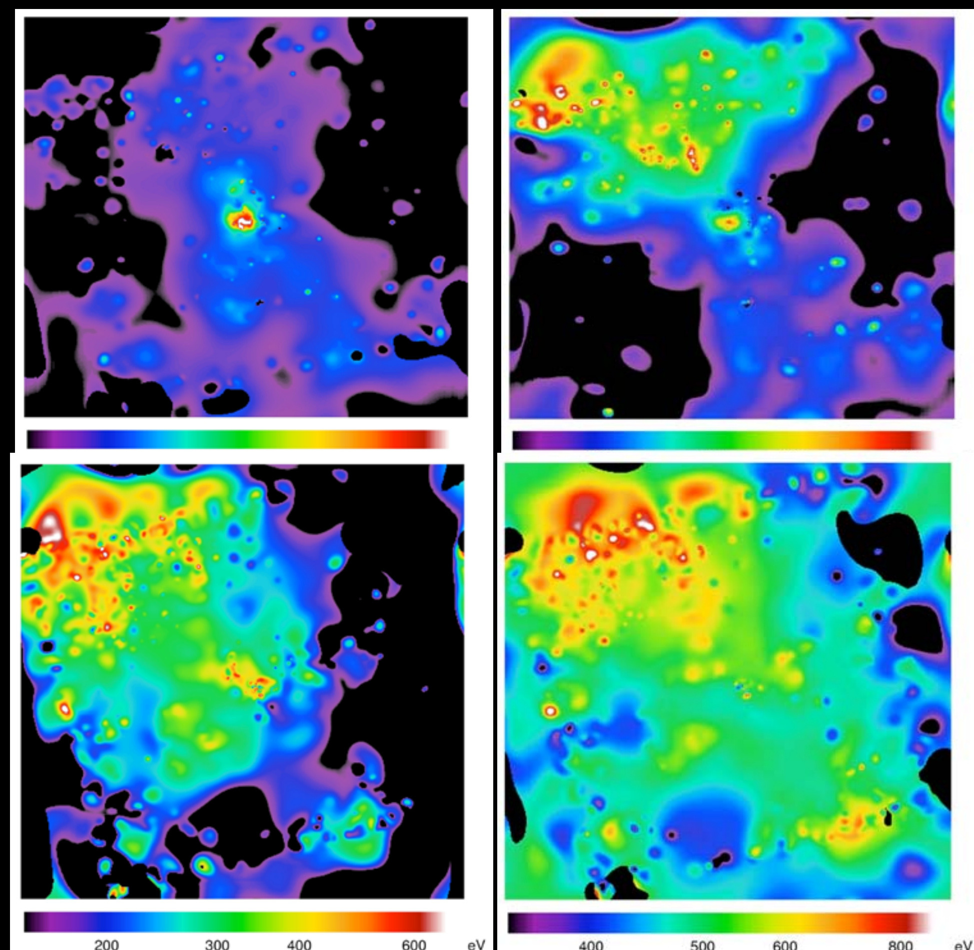
Park et al. 2004

Fe Heα

(E ~ 6.7 keV)

Fe Kα “neutral”

(E ~ 6.4 keV)



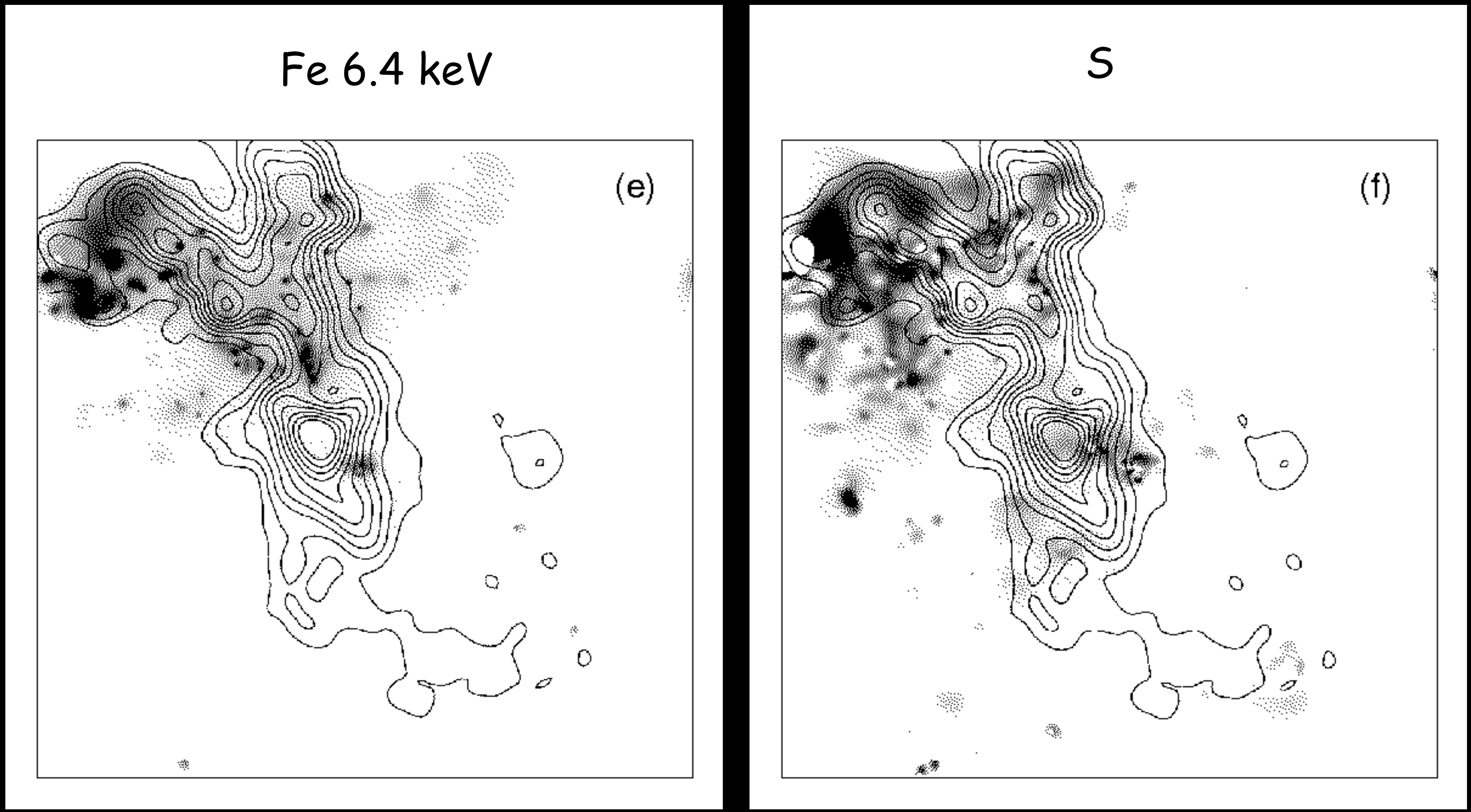
S Heα + Lyα

(E ~ 2.5 keV)

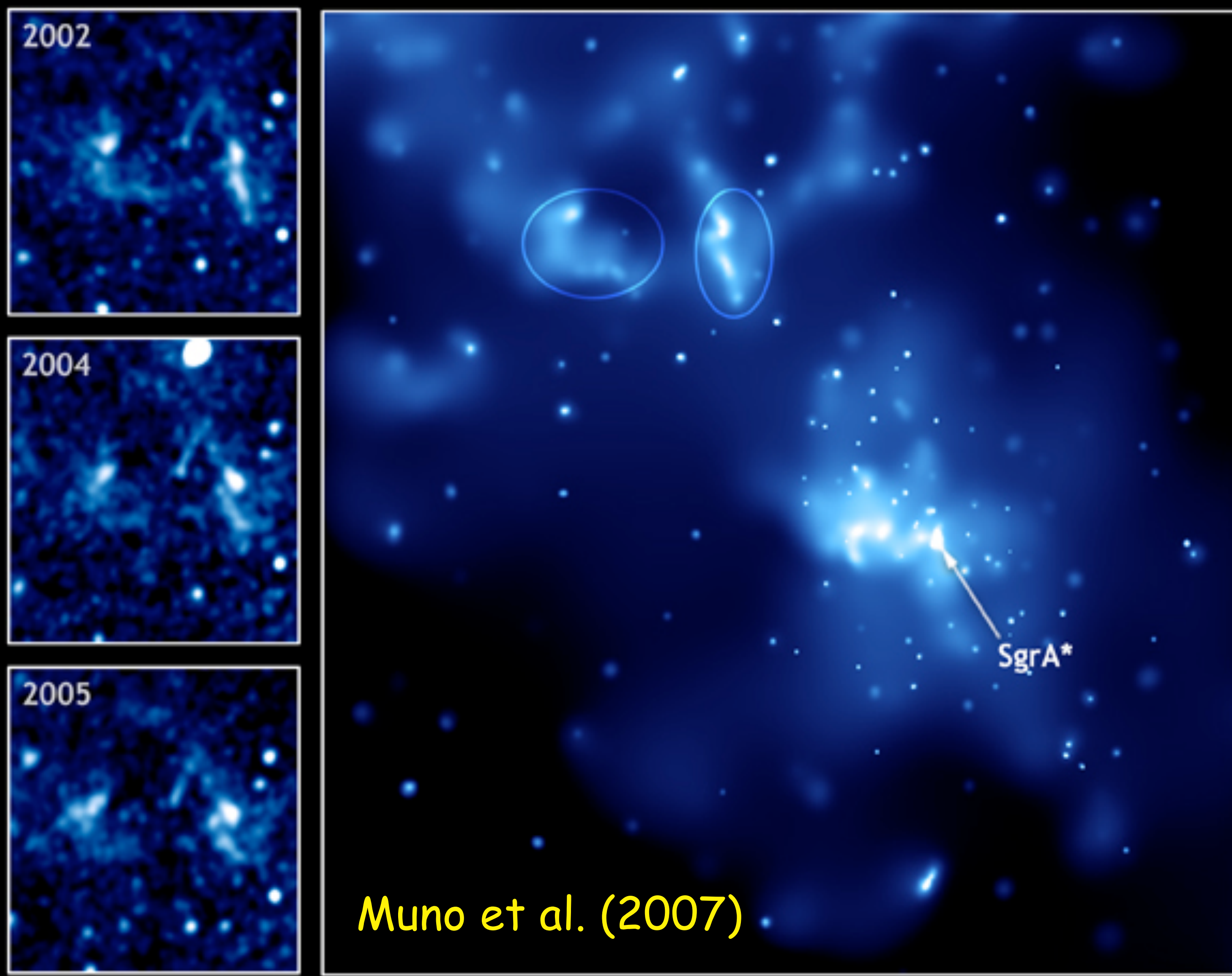
Si Heα

(E ~ 1.8 keV)

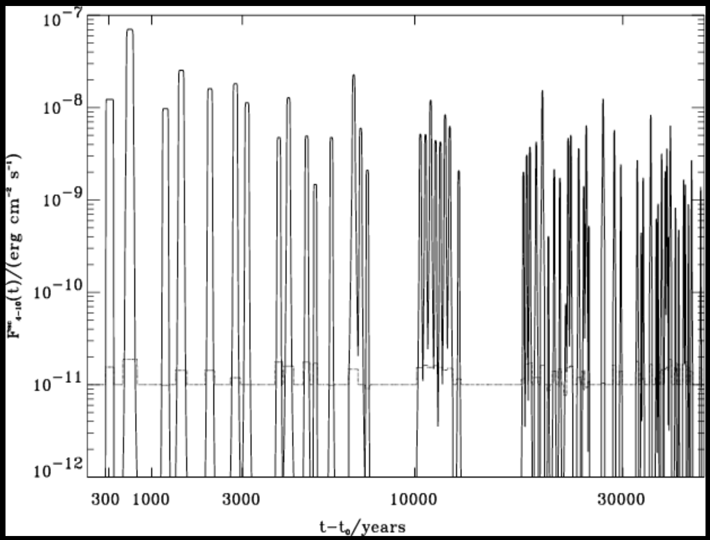
and S Overplotted with CS Contours

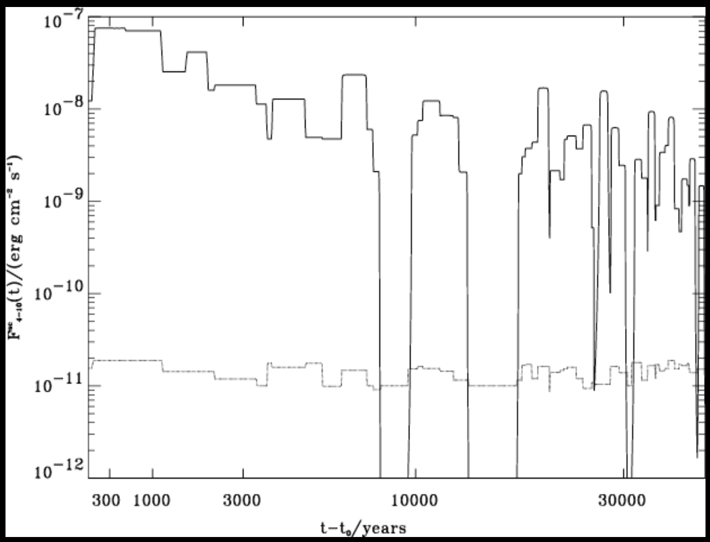


Light Echoes from a Past Outburst of Sgr A*?



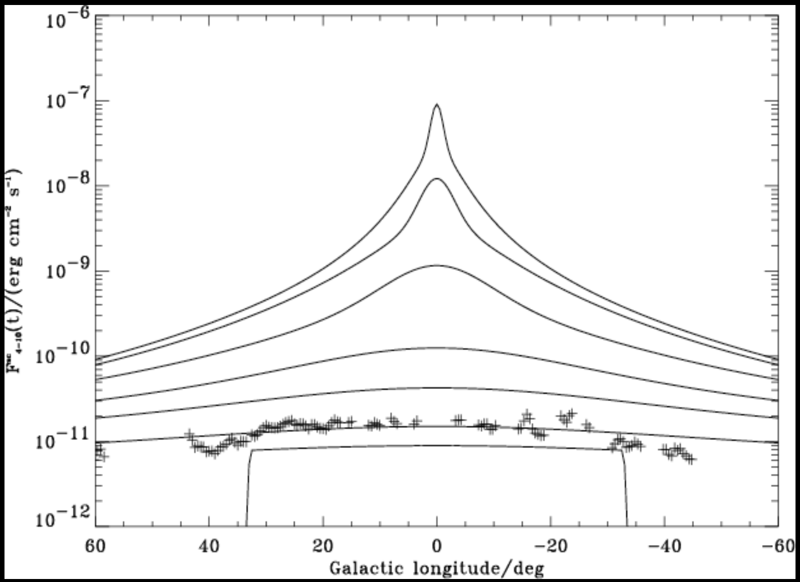
Luminosity Constraints from Thompson Scattering off Molecular Clouds





- Cramphorn & Sunyaev (2002) used ASCA observations of known molecular clouds to constrain the X-ray luminosity of Sgr A* in the past
- At times during last 4×10^4 yr, Lx < 8×10^{40} erg s^{-1}
- At other times during last 4×10^4 yr, Lx < 10^{41} - 10^{42} erg s^{-1}
- CO data insensitive to enhanced activity 8,000 and 14,000 yr ago for a few 10^3 yr
- During last 4×10^4 yr, Lx < 10^{42} erg s^{-1} for flares with durations > 3,000 yr since they fill the gaps

Luminosity Constraints from Thomson Scattering Off H I in the Disk



- Typical H I cloud mass <~ 10^4 Msun with ~ 300 lt-yr separation
- During last 8×10^4 yr, Lx < few 10^{42} erg s^{-1} (1% L_{Edd}) for durations > 1000 yr
- During last 10^5 yr, Lx < few 10^{44} erg s^{-1} (L_{Edd}) for durations > 1000 yr

Not So Long Ago, in a Galaxy Not So Far Away…

- Sgr A* currently has a quiescent X-ray luminosity of ~2×10^{33} erg s^{-1} or ~10^{-10} L_{edd}
- Flares daily by 10-100x for <~ few hrs
- Fluorescent Fe features in the central 6' suggest Sgr A* may have been >~ 10^{38} erg s^{-1} for at least 2-3 yr about 60 yr ago, before the first X-ray satellites were launched; *however an X-ray binary origin is still possible; proper motion key test!*
- Sgr B2 fluorescence indicates Sgr A* may have been as luminous as a few 10^{39} erg s^{-1} for at least 20-30 yr about 300-400 yr ago
- Constraints from Thomson scattering off of molecular clouds and neutral hydrogen indicate that Sgr A* has been less than 1% L_{edd} during the past 10^4 yr and less than L_{Edd} for the past 10^5 yr for outbursts lasting 1000 yr or more