X-ray Properties of Sgr A* Flares

A Detailed X-ray View of the Central Parsecs

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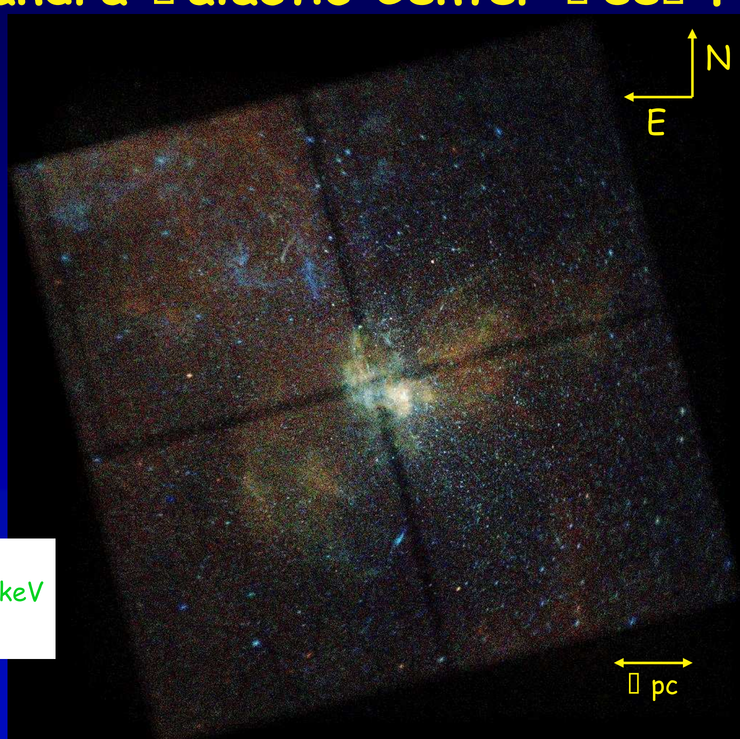
Gordon Garmire
Sangwook Park

ISAS
Yoshitomo Maeda

C□andra □alactic Center □ee□ Field



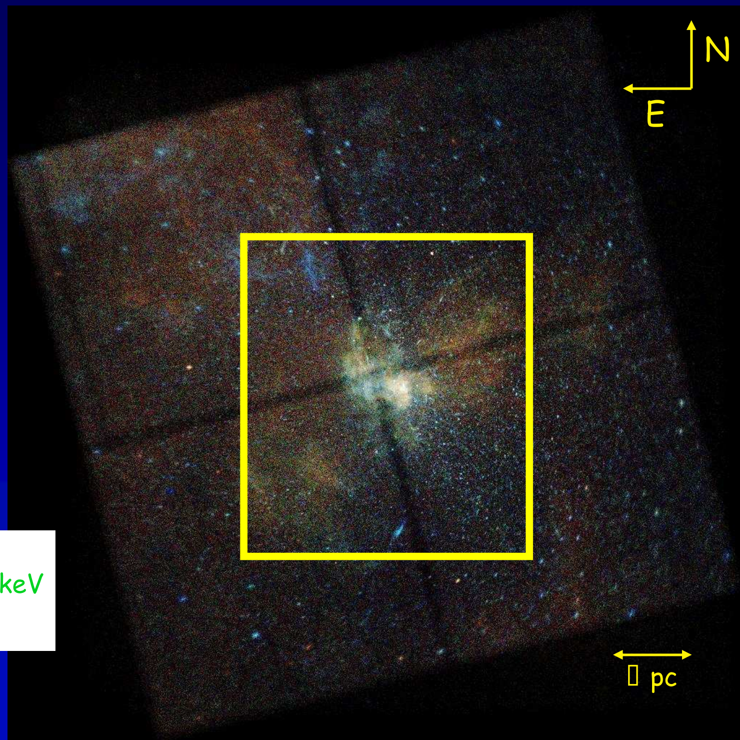
□□ x □□ arcmin

□□ x □□ pc

□□□ ks

Red□□-□□ keV
Green□□□-□□ keV
Blue□□□-□ keV

C□andra □alactic Center □ee□ Field



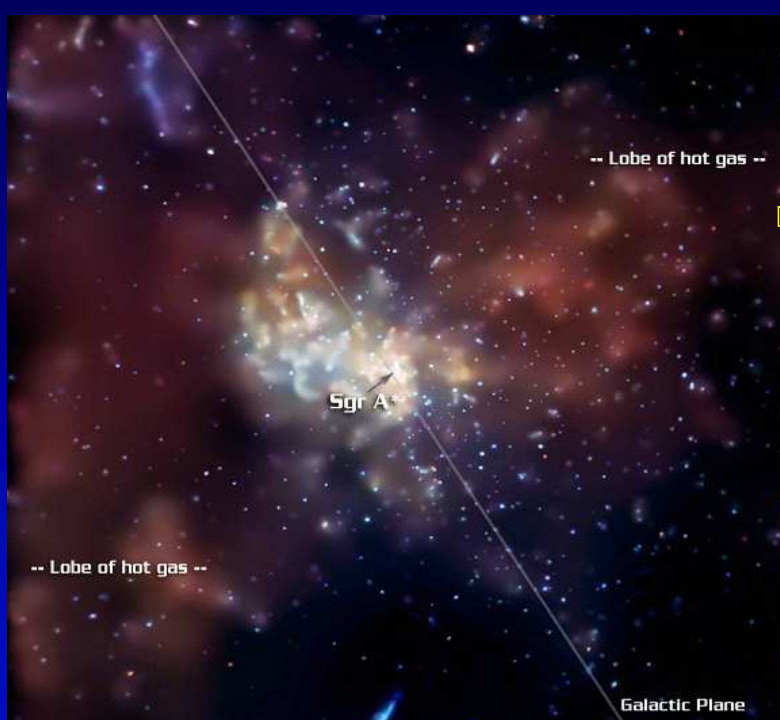
□□ x □□ arcmin

□□ x □□ pc

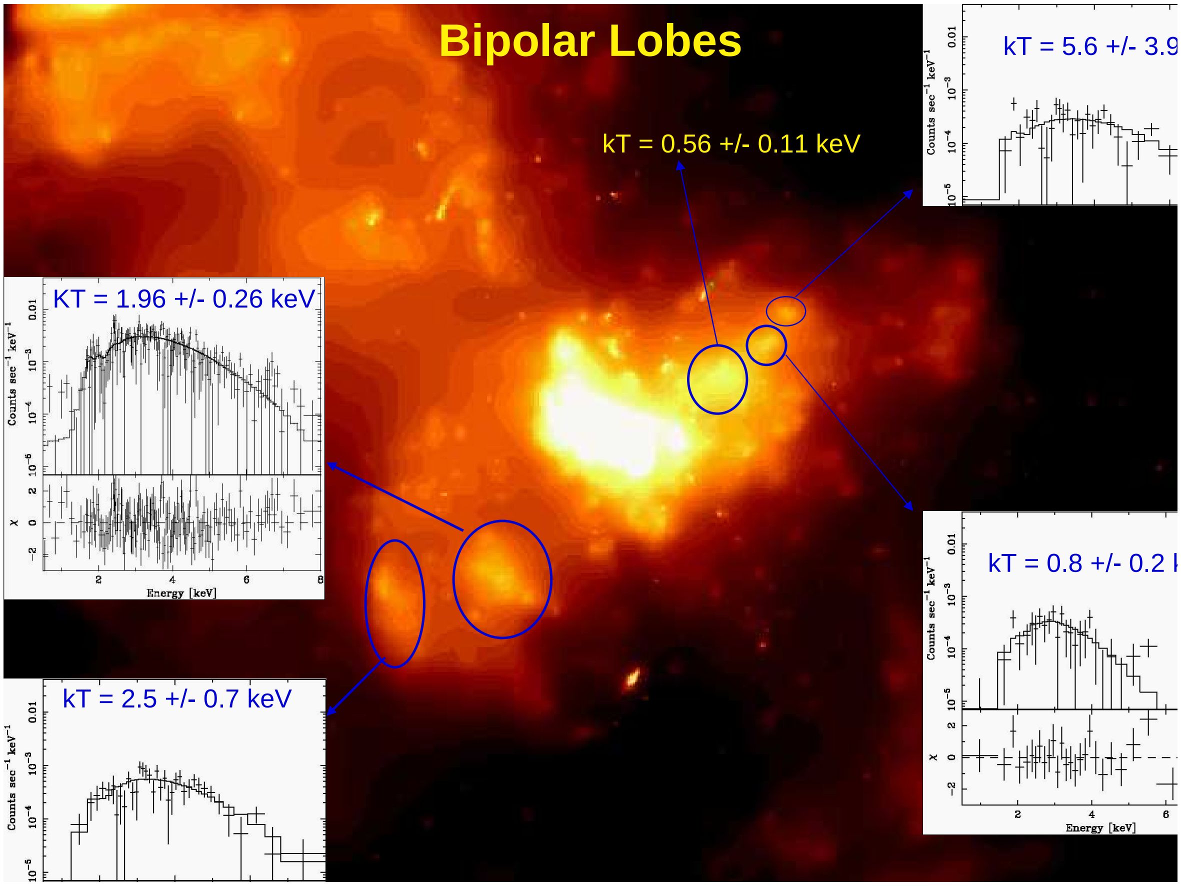
□□□ ks

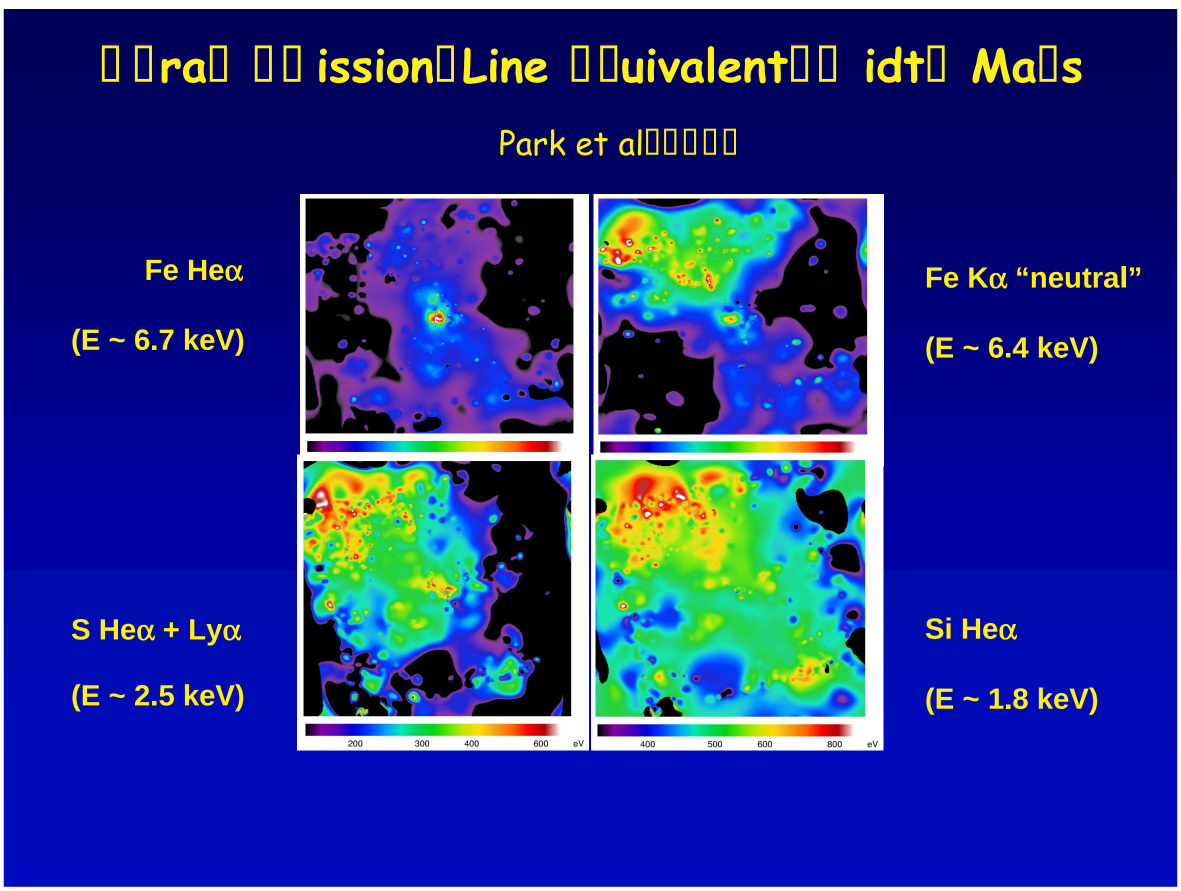
Red□□-□□ keV
Green□□□-□□ keV
Blue□□□-□ keV

C□andra □alactic Center □ee□ Field

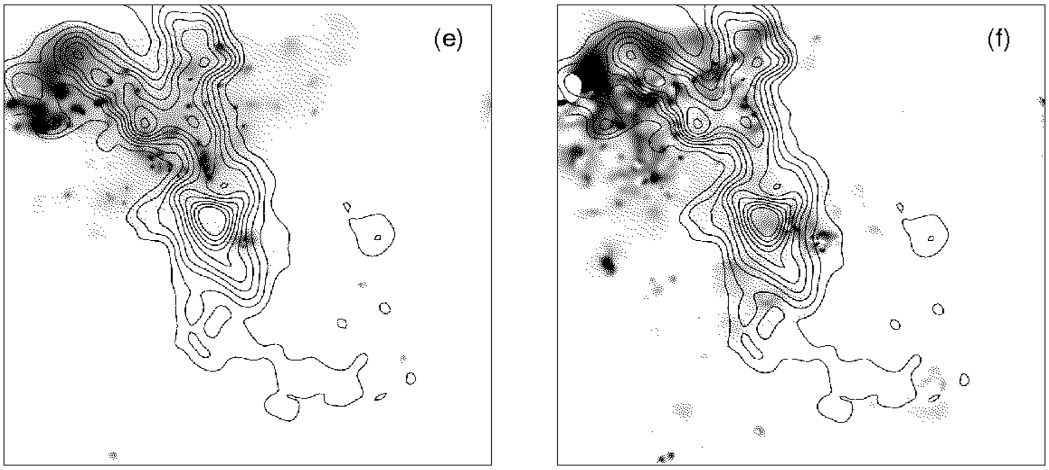


□□ x □□ arcmin


Bipolar Lobes
kT = 0.56 +/- 0.11 keV
kT = 5.6 +/- 3.9
KT = 1.96 +/- 0.26 keV
kT = 0.8 +/- 0.2
kT = 2.5 +/- 0.7 keV
Counts sec−1 keV−1
Energy [keV]
χ

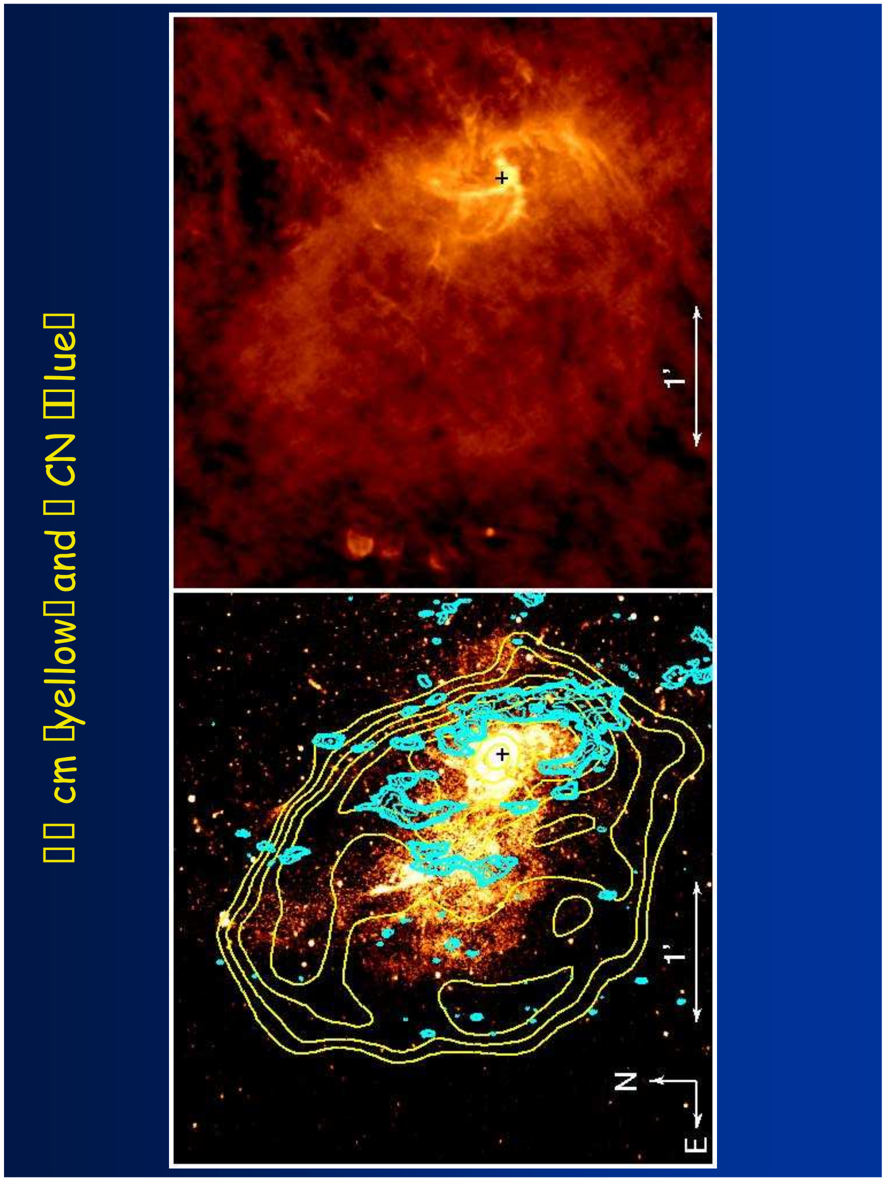

□ □ra□ □□ission□Line □□uivalent□□ idt□ Ma□s
Park et al□□□□□
Fe Heα
(E ~ 6.7 keV)
Fe Kα "neutral"
(E ~ 6.4 keV)
S Heα + Lyα
(E ~ 2.5 keV)
Si Heα
(E ~ 1.8 keV)
200
300
400
600
eV
400
500
600
800
eV

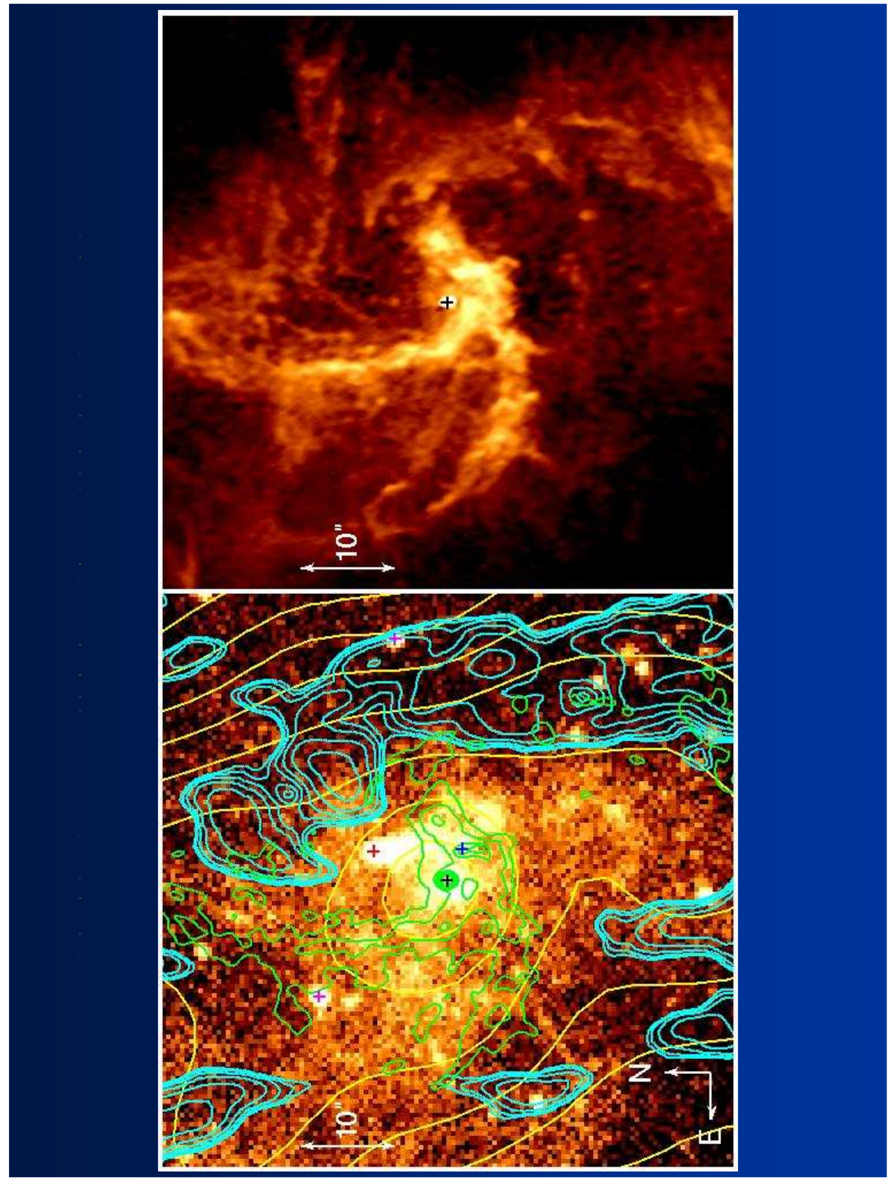
□□ I□ages of Lo□□Ioni□ation Fe and S □ver□lotted □it□ CS Contours

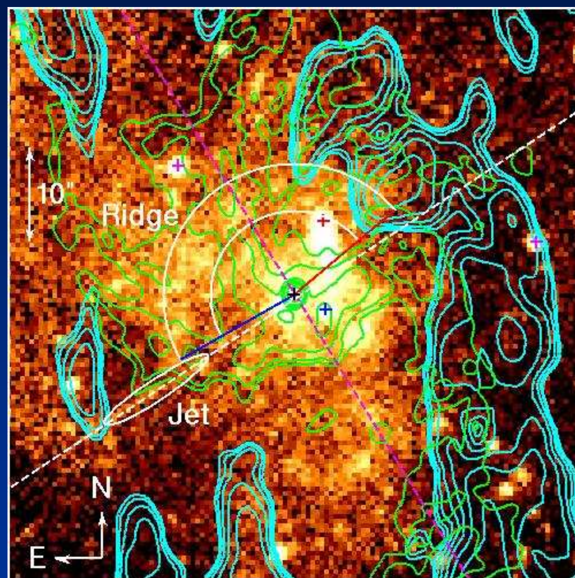


Galactic Center Bipolar Lobes

- □o□e material is distri□uted differently than □hot□ □□□□ keV□ and fluorescent □neutral□ □□□□□ keV□ Fe
- Emission grows in intensity and size perpendicular to Galactic plane toward lower energies
- □$_e$ □ □ x □□□$^{□}$ □
- n_e □ □ cm$^{-□}$
- Separate lumps may indicate separate episodes of acti□ity spaced □y □□□□–□□□□□ yr
- □imescale for outer portions to flow from Sgr A*□ □□□$^{□}$ yr □□$_{out}$□□□□□ km s$^{-□}$□
- Mass per □lo□ □ □ M_{sun}
- □imescale of episodic acti□ity argues in fa□or of an outflow from Sgr A* rather than star formation in central pc

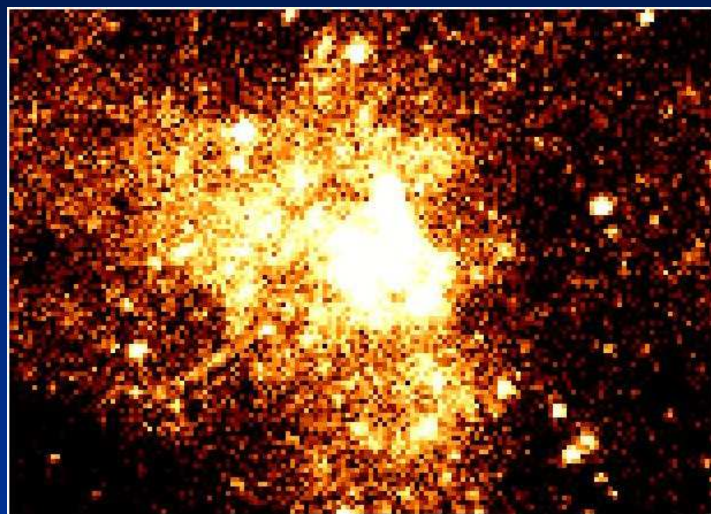

cm yellow and CN lue
1'
1'
N
E


10"
10
N
E



725 ks exposure using ACIS subpixel analysis

X-ray View of the Central Parsec of the Milky Way

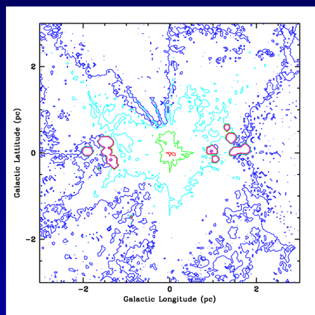


725 ks exposure using ACIS subpixel analysis

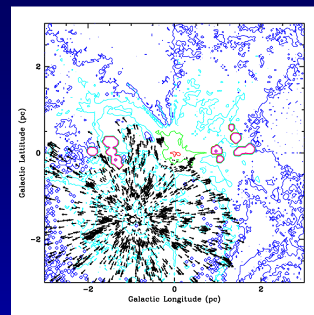
Three-color X-ray View of Sgr A East and Sgr A*

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

SP Siulation of Sgr A ast ecta Interacting it Stellar ind of Central Pc Cluster

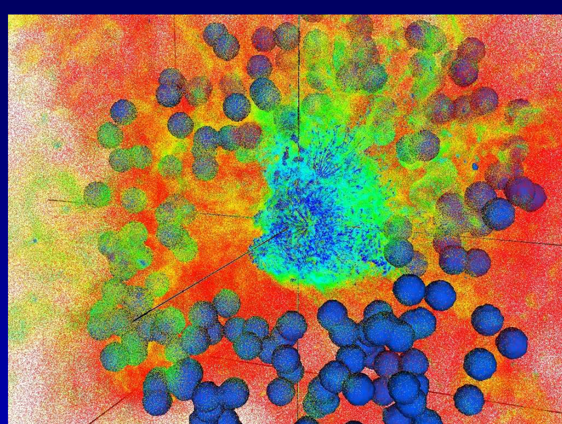


Simulation y
Gariel Rockefeller Chris Fryer
AN
with
Frederick Baganoff M
and
Fulio Melia Arizona



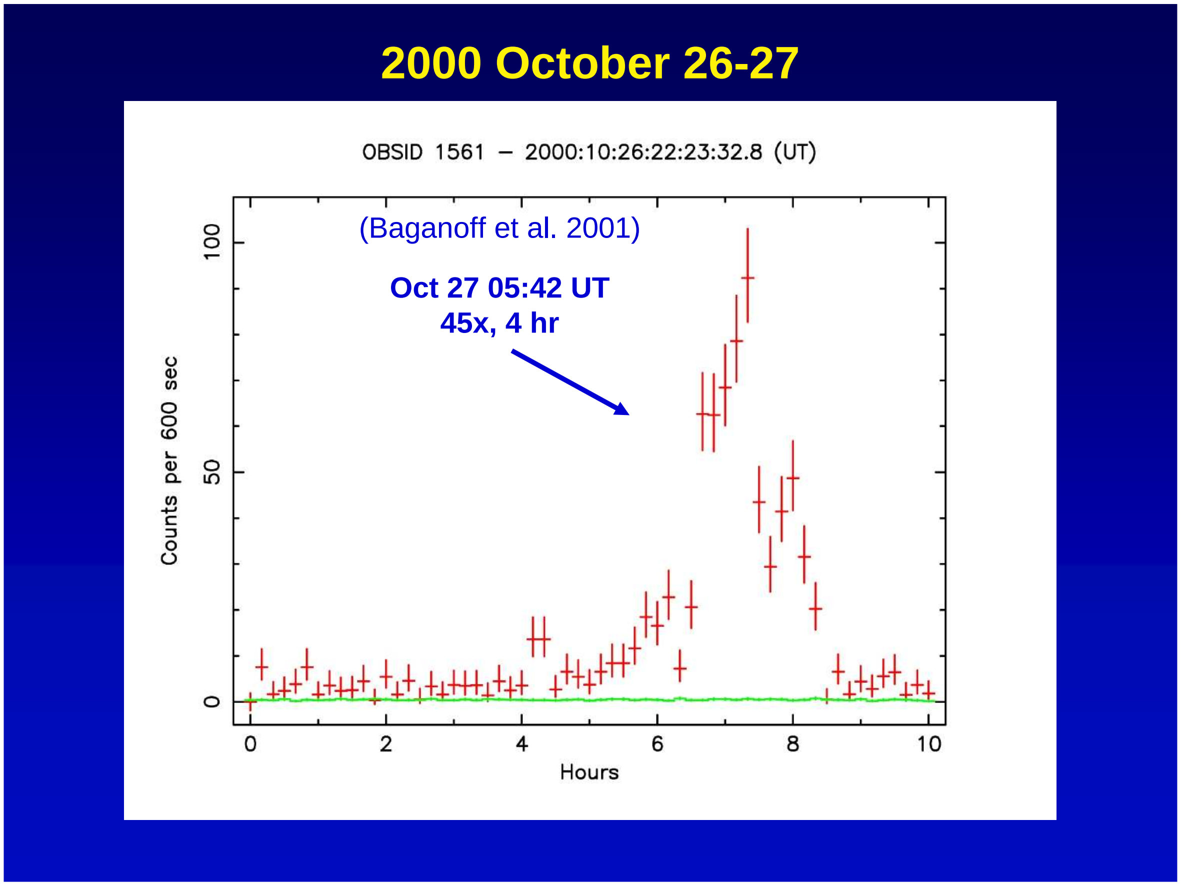
- Density contours in slice perpendicular to Sin simulationoth Sgr A* and center of Sgr A East SNR lie in this plane
- Small red dot in lower left uadrant of left plot is the expanding SN
- Greenalue contours are stellar wind density of Central Pc Cluster
- Magentared contours along Galactic plane are cross-sections of los in toy CND
- Right plot shows the same plane around the time SN shock reaches Sgr A* yr after the explosion
- SP elocity ectors show how gas flows through low-density regions around the central parsec and doesnt penetrate within the cloud of wind material eected y the stars there

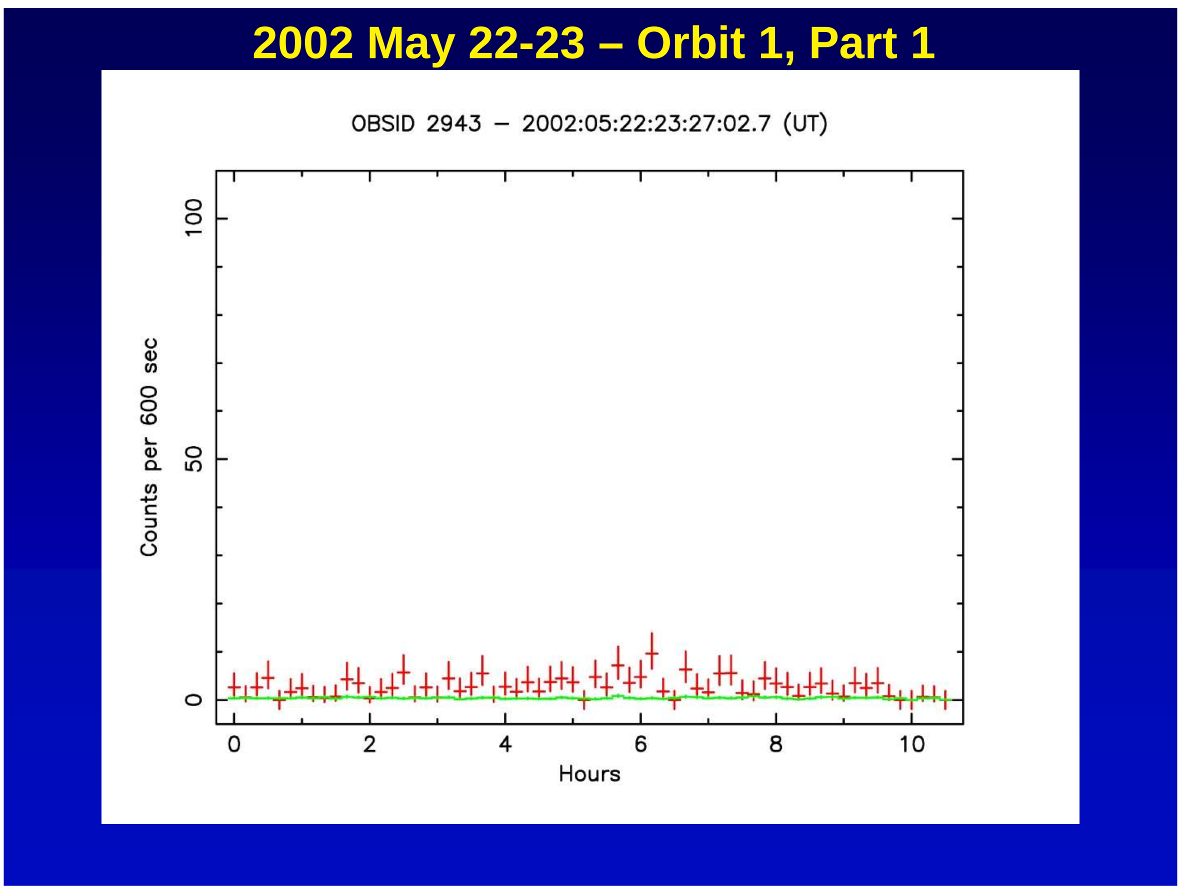
SP Siulation of Sgr A ast ecta Interacting it Stellar ind of Central Pc Cluster

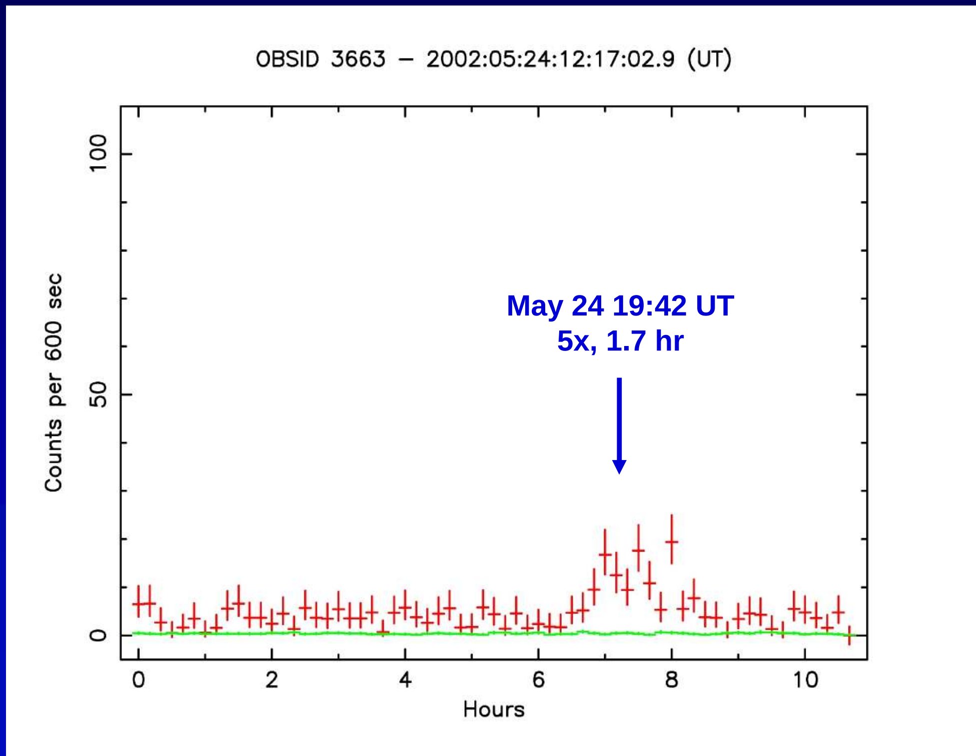


 pc x pc x pc

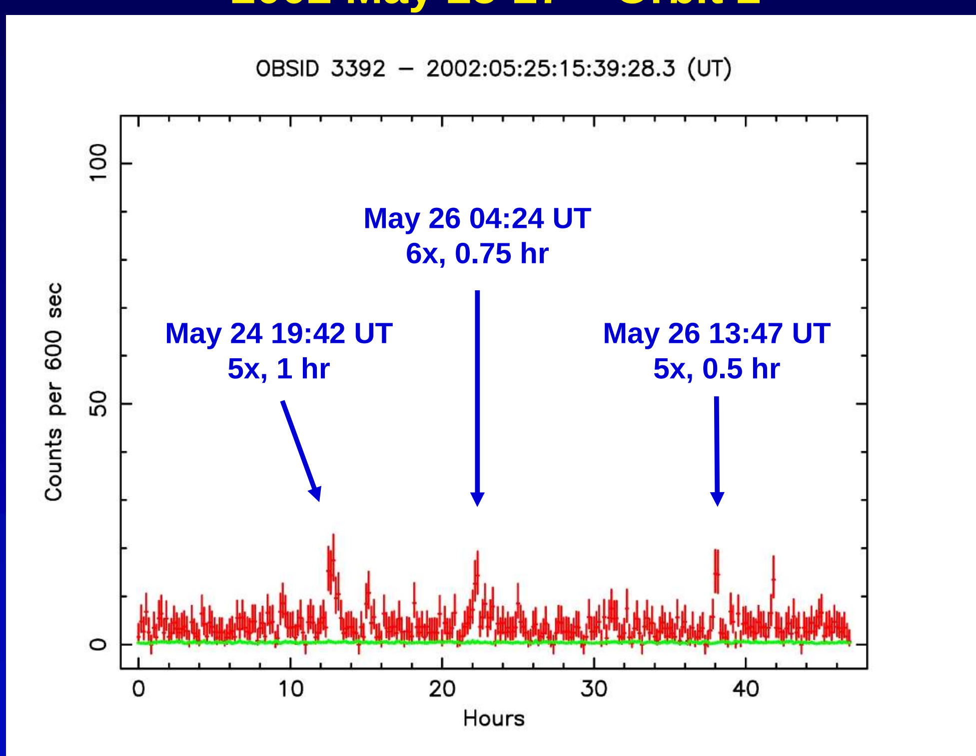
- Image of SPH particles and density isosurfaces showing 3D structure and interface between incoming shock and outgoing winds in the central parsec.
- "Vertical" axis is z axis (along LOS); +z is toward us.
- Site of SN explosion is near left edge of image, in the z=0 plane.
- The x-y axes are galactic axes; galactic latitude increases toward "back" of image, and the left-right axis is the Galactic equator.
- The colors represent density on a logarithmic scale; blue indicates the highest density. The isosurface value was chosen to emphasize the densest regions: the central fraction of a parsec and our toy CND blobs.


2000 October 26-27
OBSID 1561 – 2000:10:26:22:23:32.8 (UT)
(Baganoff et al. 2001)
Oct 27 05:42 UT
45x, 4 hr
Counts per 600 sec
Hours
0
50
100
0
2
4
6
8
10

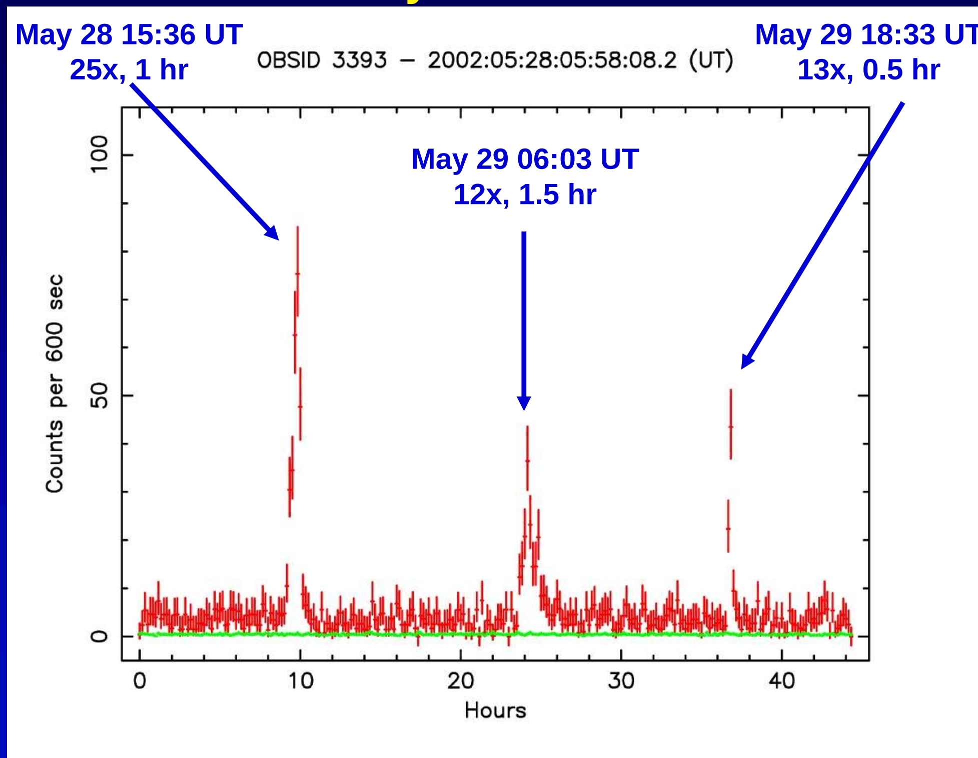

2002 May 22-23 – Orbit 1, Part 1
OBSID 2943 – 2002:05:22:23:27:02.7 (UT)
Counts per 600 sec
Hours
0
50
100
0
2
4
6
8
10



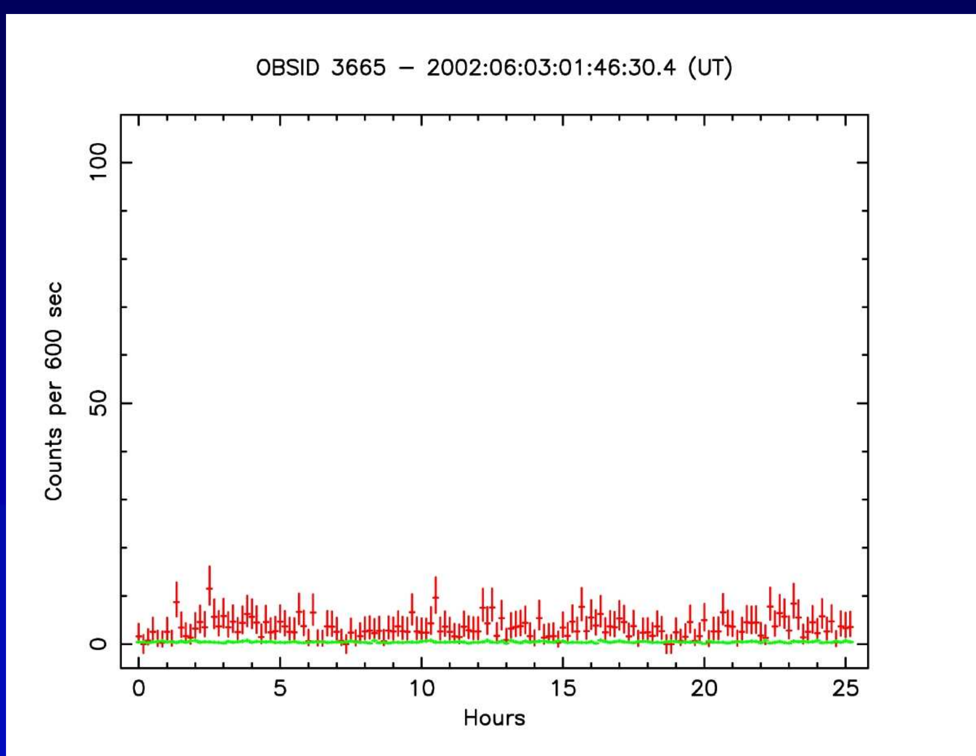
2002 May 25-27 – Orbit 2



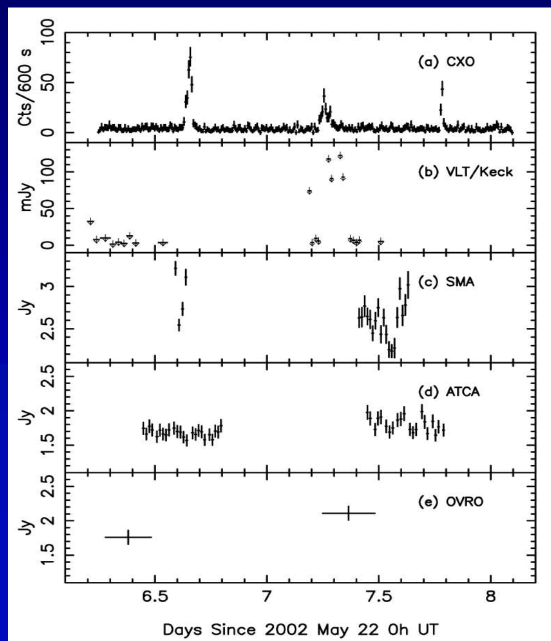
2002 May 28-30 – Orbit 3



2002 June 3-4 – Orbit 5

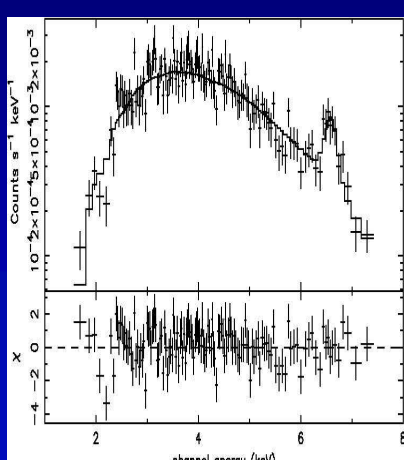


Sgr A* Millimeter Emission Steady During Large X-ray Flares



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 (2.3-2.6)

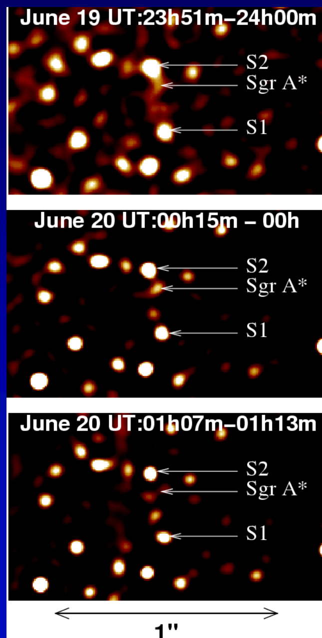
E_{Fe} = 6.59 (6.54-6.64) keV
Line is narrow and NIE

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

Sgr A Flare une   LTA K and

Eckart et al. (2004)



V Collaorators

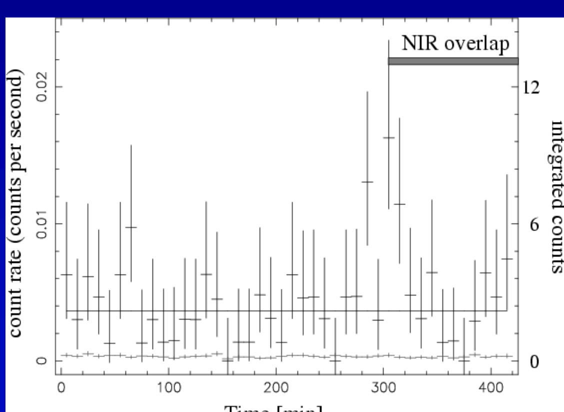
AEckartRSchoedel
RGenzel tt
CStraumeier Viehmann

Sgr A Flare une   Candra ke

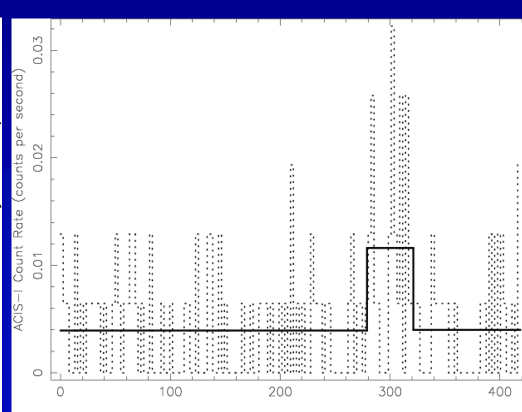
Eckart et al. (2004)

- Excess amplitude factor of ~2x
- Duration ~40-60 min
- 99.92% confidence using Bayesian blocks algorithm (Scargle 1998)

Raw X-ray ight Cure

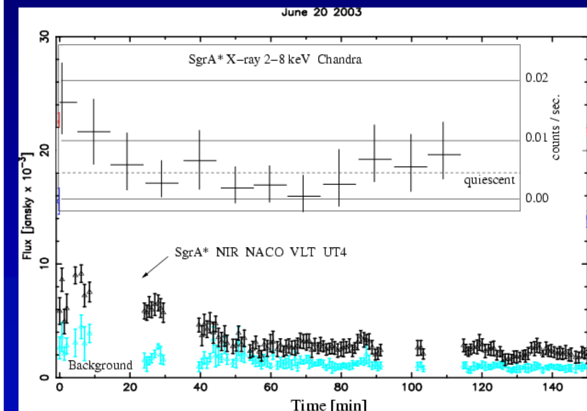


Bayesian Blocks Representation



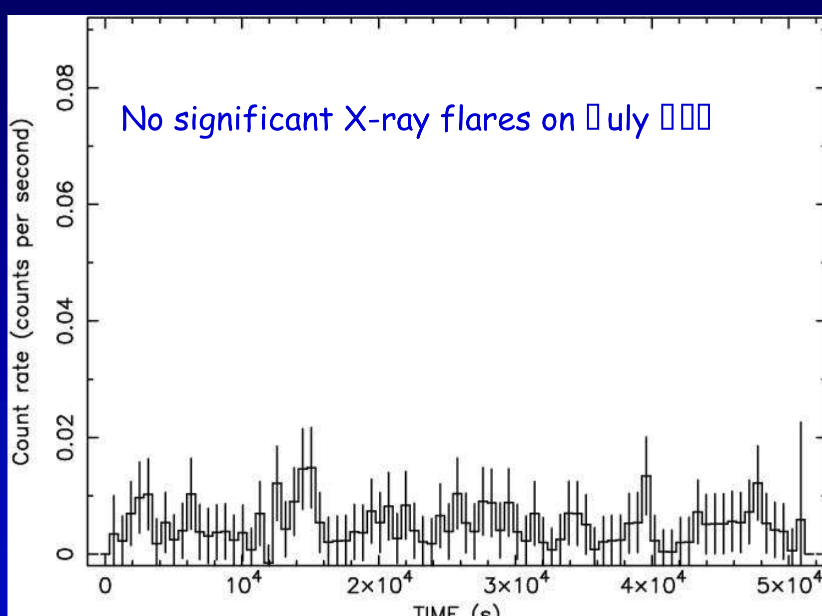
Sgr A□ □□□□□ □une □□□□ □ □I□□□ □ra□ Flare

Eckart et al. (2004)

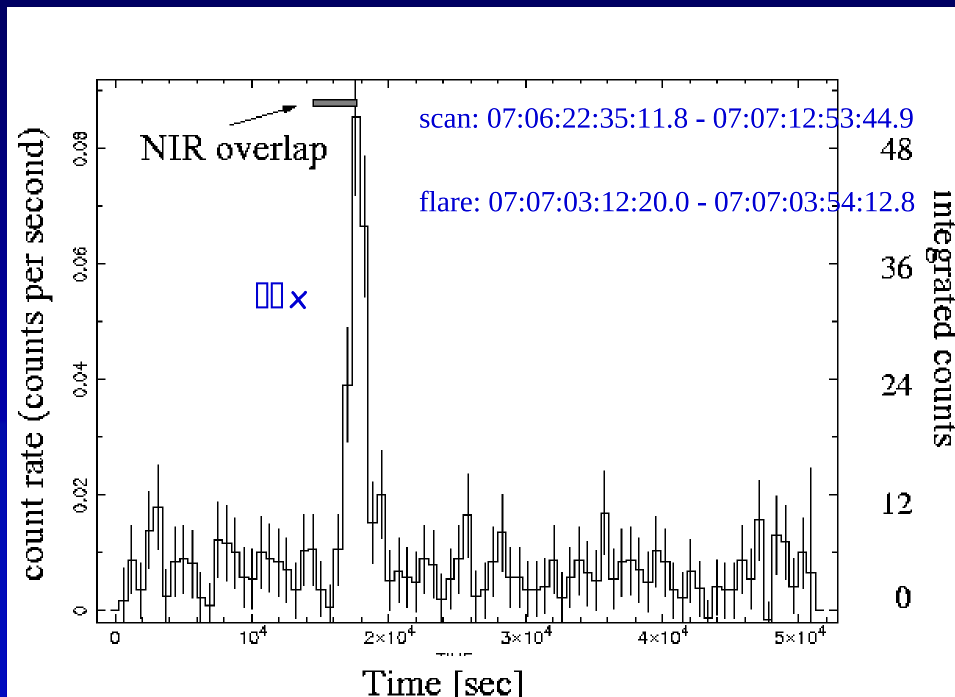


- □First detection of *simultaneous* X-ray and N□R flaring
- □□n this case at least□X-ray and N□R photons appear to come from *same* electron population
- □□$_{x}$ □ □x□□□□ erg s-□
- □□$_{nir}$ □ □x□□□□ erg s-□
- □Spectral index □ □□□
- □X-rays coincident within □□□ mas
- □N□R coincident within □□ mas
- □X-ray flares *are* from Sgr A*□

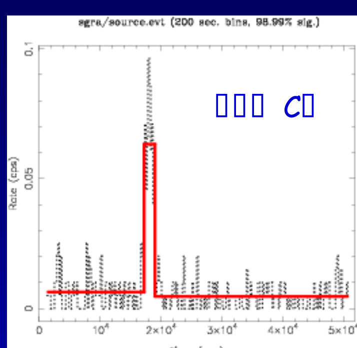
□□□□ □ul□ Sgr A□ Ca□ □aign

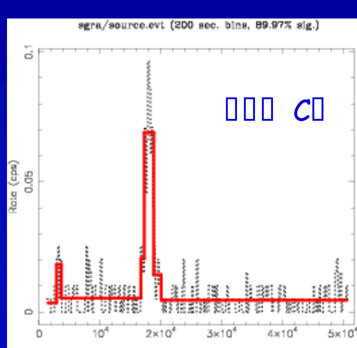


July 2004: Detection of a Strong X-ray flare



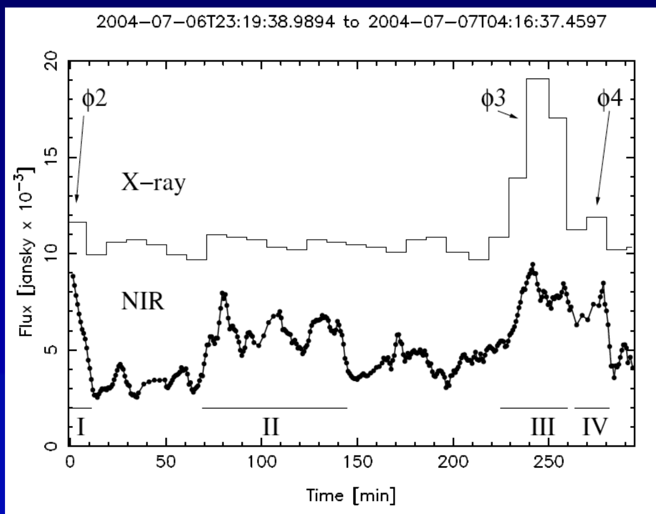
Ba□esian Blocks Anal□sis of □ul□ □□□ □□ra□ Lig□tcurve





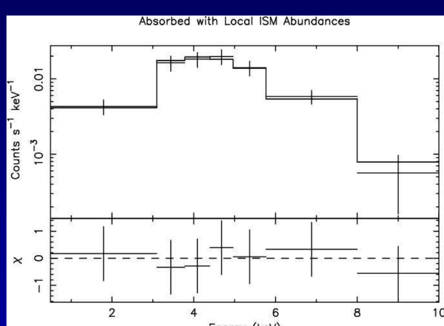
- Bayesian □locks algorithm of Scargle □□□□□□ models the lightcur□e as piecewise constant segments or □locks□
- For a discussion of the algorithm□see Eckart et al□ □□□□□□
- □ nly the large flare □□□ ks into the o□ser□ation is significant at the □□□ C□□
- At □□□ C□□a possi□le second e□ent is found □y the algorithm near the □eginning of the o□ser□ation□

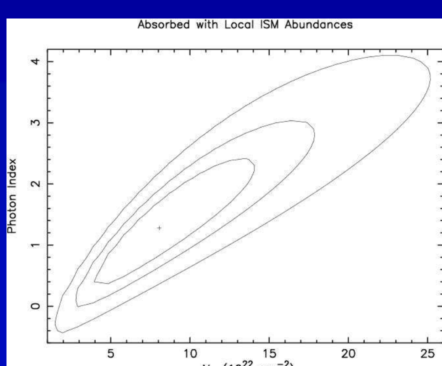
Comarison of ra and I Ligtcurves



- At least four separate NR flares were detected at -and y the V with NA SC NCA on uly
- NR flare is correlated with the strong X-ray flare
- NR flare is associated with the possile X-ray eent at the eginning of the oserationsut the ratio of X-ray to NR amplitudes is clearly different
- Additional strong NR flares and V hae no detected X-ray counterparts

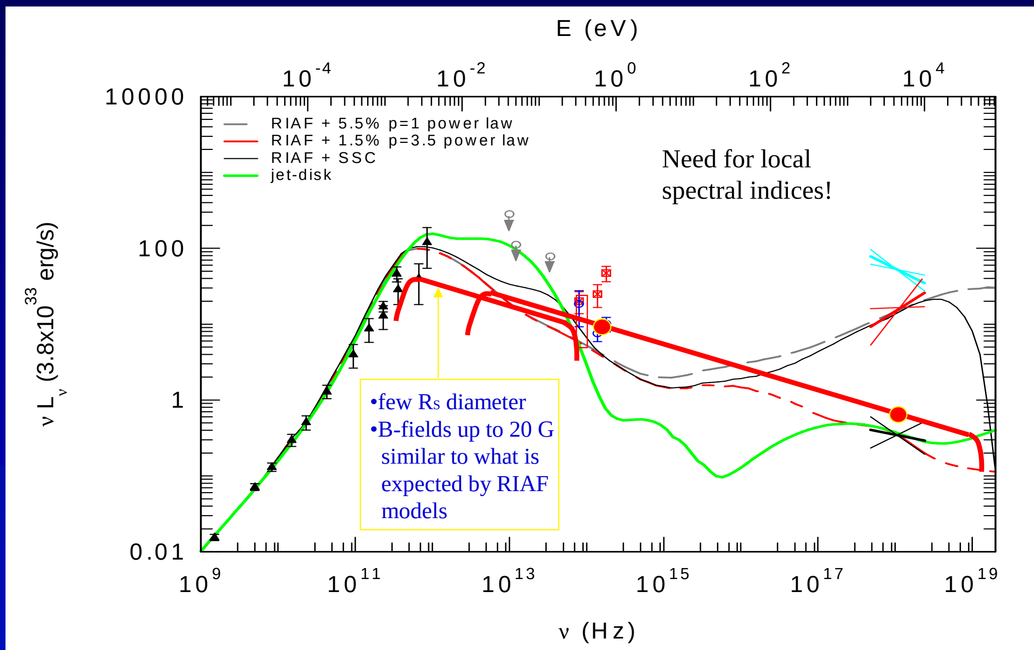
ra Sectru of ul Flare





- ModelAsored power law with dust scattering
- N x cm-
- Γ   C

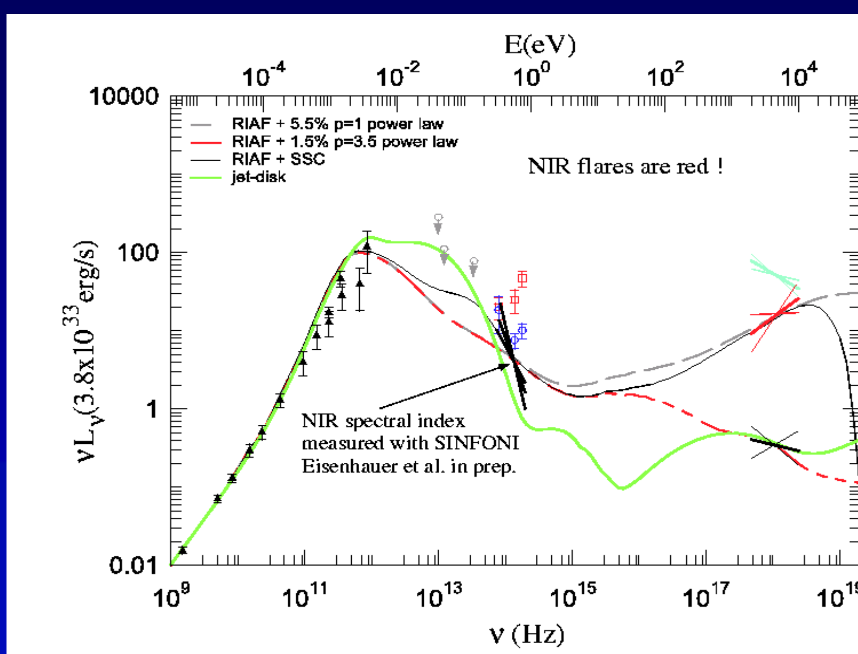
First Si□ultaneous □ eak Flare and Models



Radio: Zhao, Falcke, Bower, Aitken, et al. 1999-2003
X-ray: Baganoff et al. 2001, 2003, Goldwurm et al. 2003, Porquet et al. 2003,
NIR: Genzel et al. 2003, Ghez et al. 2003
models: Markoff, Falcke, Liu, Melia, Narayan, Quataert, Yuan et al. 1999-2001
SSC model after Marscher (1983) and Gould (1979)

Data and model
Eckart, Baganoff, Morris et al. 2004

Sgr A* NIR Flares are Red

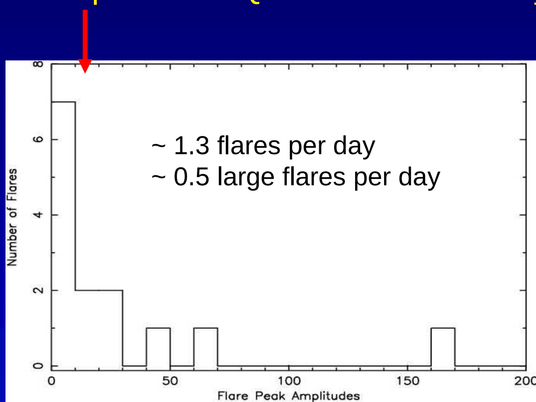


Implies that at least some X-ray flares must be SSC

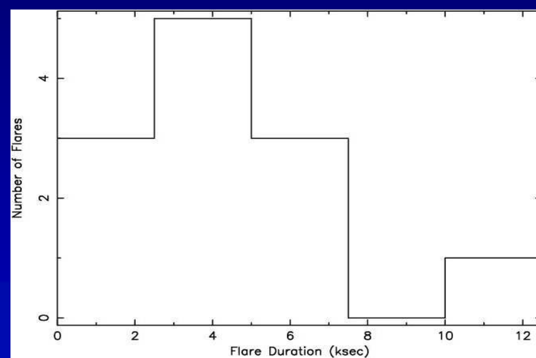
Distributions of Flare Properties

Baganoff et al 2001, 2003; Goldwurm et al. 2003; Porquet et al. 2003; Eckart et al. 2004

Amplitudes x Quiescent Luminosity



Durations in ksec



Chandra: 11 flares in 675 ks
XMM-Newton: 2 flares in ~100 ks

Duty Cycle: 7.1 % (Chandra)

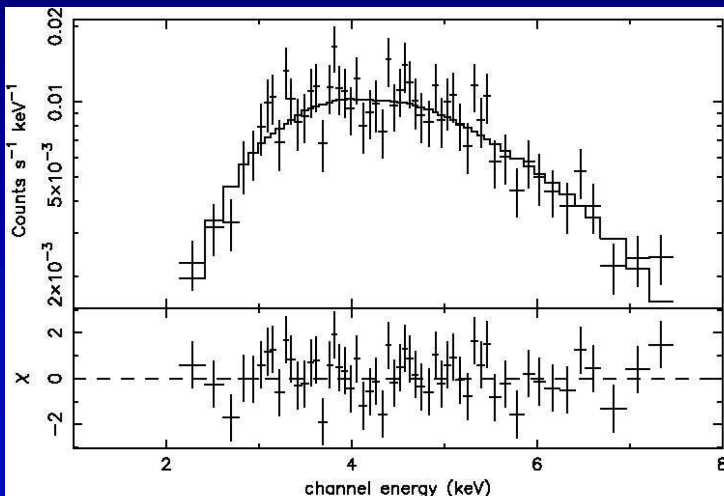
Sgr A* Flares and X-ray Transients in the Central Parsec of the Galaxy

QuickTime™ and a YUV420 codec decompressor are needed to see this picture.

- □ hr□frame □moving avg□
- □ days □□ hr total
- Lowest color level □□σ above background
- Tail of PWN candidate has □□ ct□pix□so Poisson statistics causes apparent variability
- □ X-ray transients detected within central □□ pc in past □ yr
- □ of □ detected within central pc □□ □□x overabundant per unit stellar mass □Muno et al□ □□□□□

Integrated X-ray Spectrum of Sgr A* During Flares

Model: Absorbed, Dust-Scattered Power Law

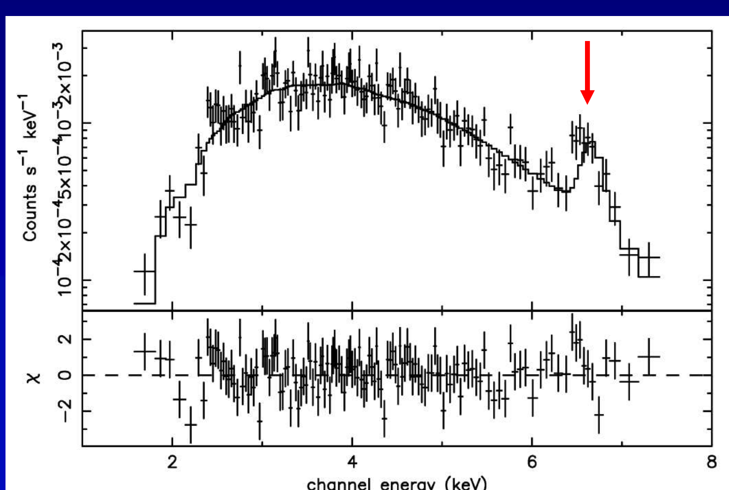


$N_H = 6.0 \times 10^{22}$ cm^{-2}
$\Gamma = 1.3$ (0.9-1.8)

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

Integrated Quiescent X-ray Spectrum of Sgr A*

Model: Absorbed, Dust-Scattered, MEKAL



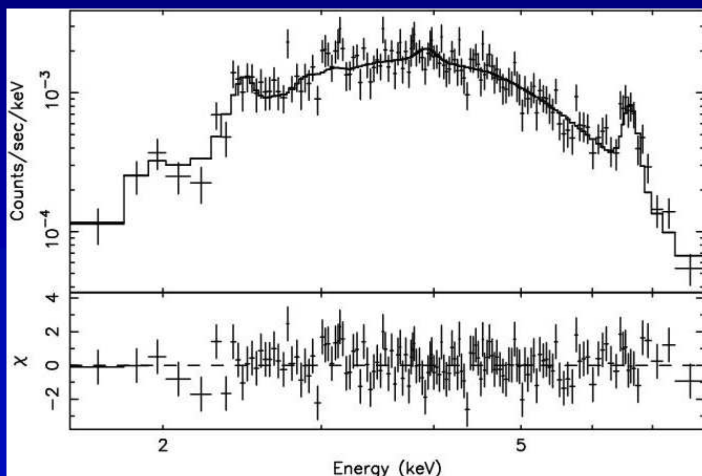
Bad fit to Fe line

Line energy too high

Abundances of light elements forced to zero

Integrated Quiescent X-ray Spectrum of Sgr A*

Model A sor ed ust Scattered I Plas a



N_H = 5.9 x 10^{22} cm^{-2}
kT = 4-5 keV

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