The Galactic Center and echoes of past activity from SgrA*

Overview on the Galactic Center and Sgr A*

(as key case of inefficient accretion)

- Nature of the high-energy emission from the Galactic Plane: point-like vs. extended emission. Presence of further extended structures (at different wavelengths)

- Twenty-year history of Sgr A* flares and current multi-band interpretation

- SgrA* quiescent X-ray emission

- Molecular clouds as “postcards” from past SgrA* activity? Shedding light with high-imaging *Chandra* observations

- Transient X-ray emission very close to SgrA*: the discovery of a flaring magnetar

- The deep view of the GC central degree as pictured by *XMM-Newton*, *NuSTAR*, and *Swift*

- Dynamical mass of SgrA* SMBH

- The line-map view of the Galactic Plane: thermal vs. non-thermal processes

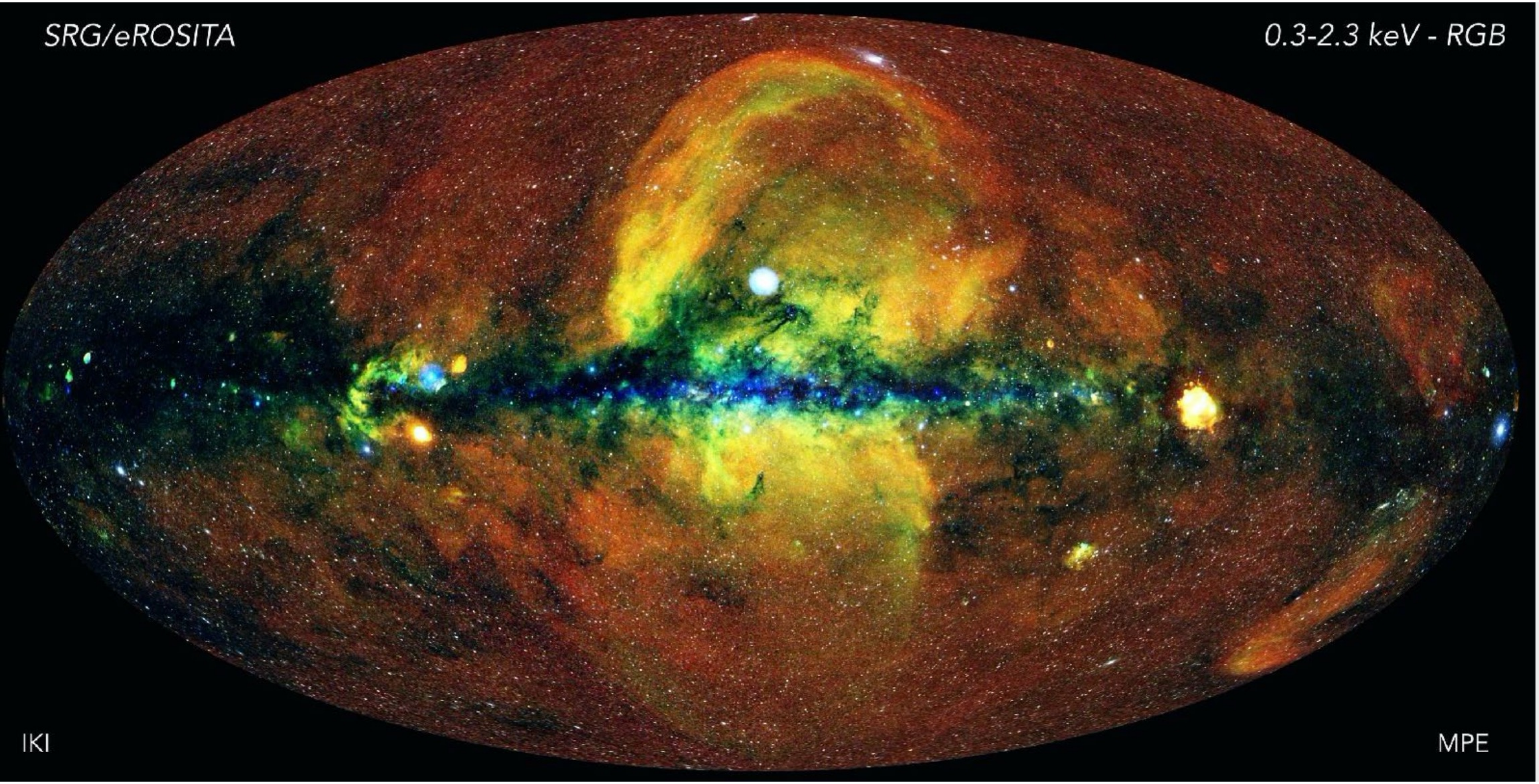
- The Fermi bubbles, *eROSITA* bubbles, X-ray chemneys, and jets

- The close passage of clouds to SgrA*: fuel for accretion and flares?

The Galactic plane represents a laboratory for investigating many emission processes (not necessarily all being accretion-related) → multiband perspective

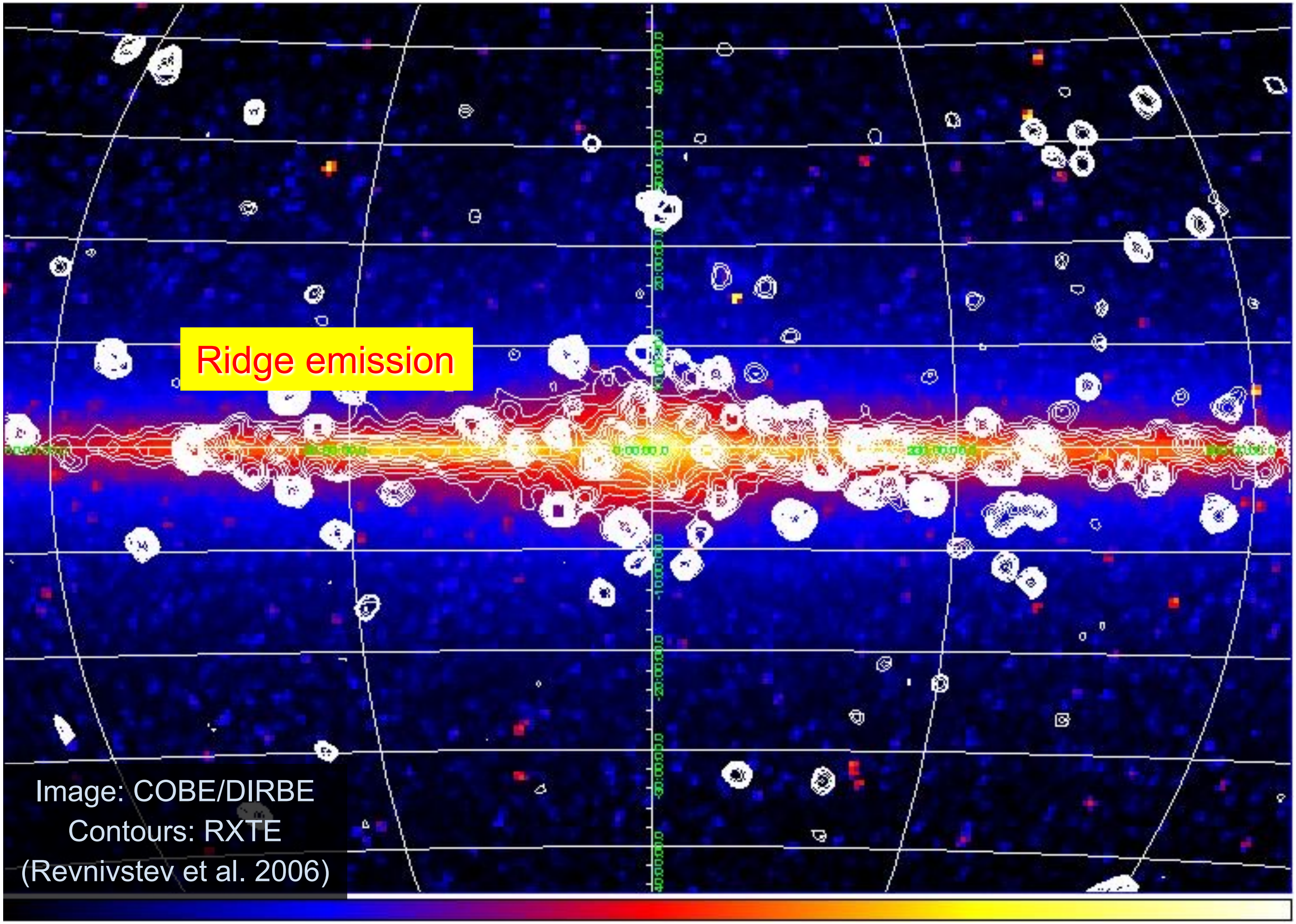
Why X-rays?

Their penetrating nature allows detection of source emission also in cases of strong extinction as in the Galactic Plane

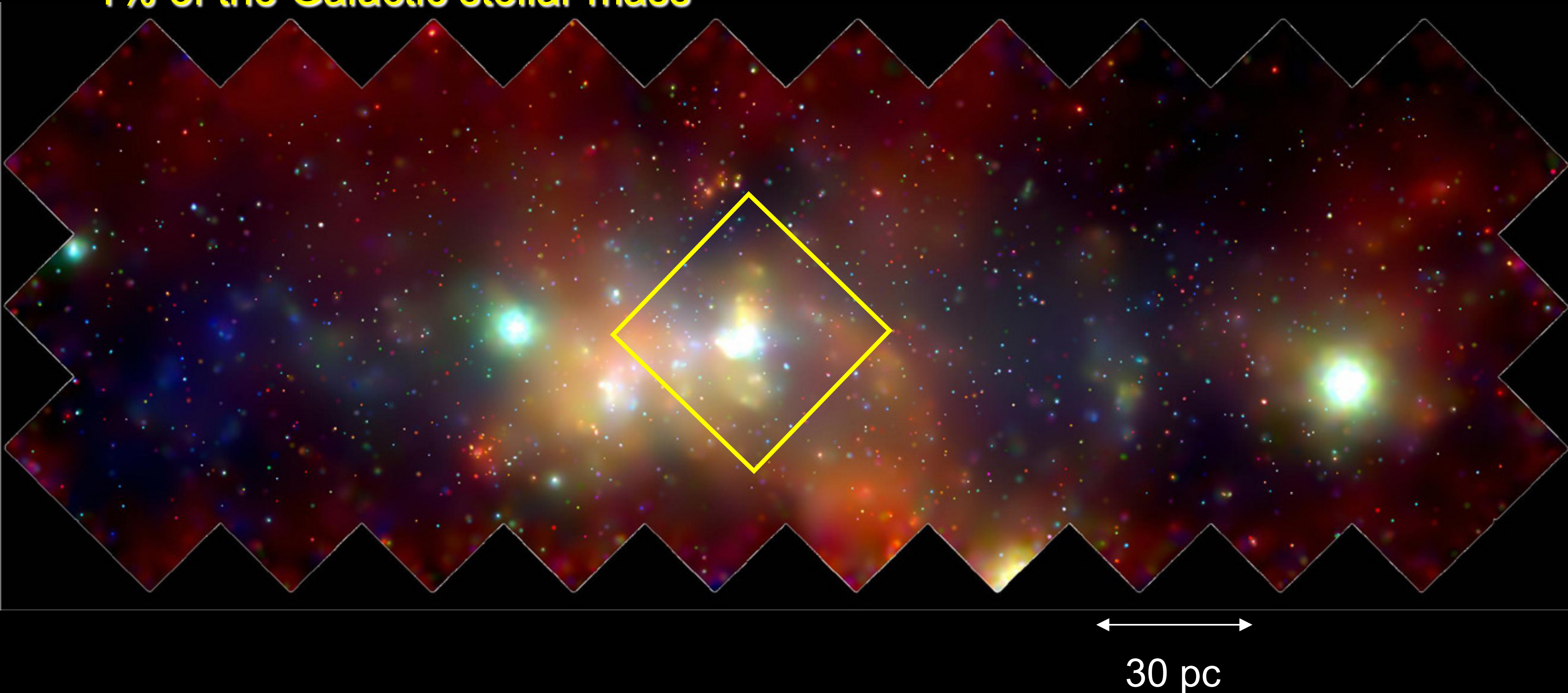


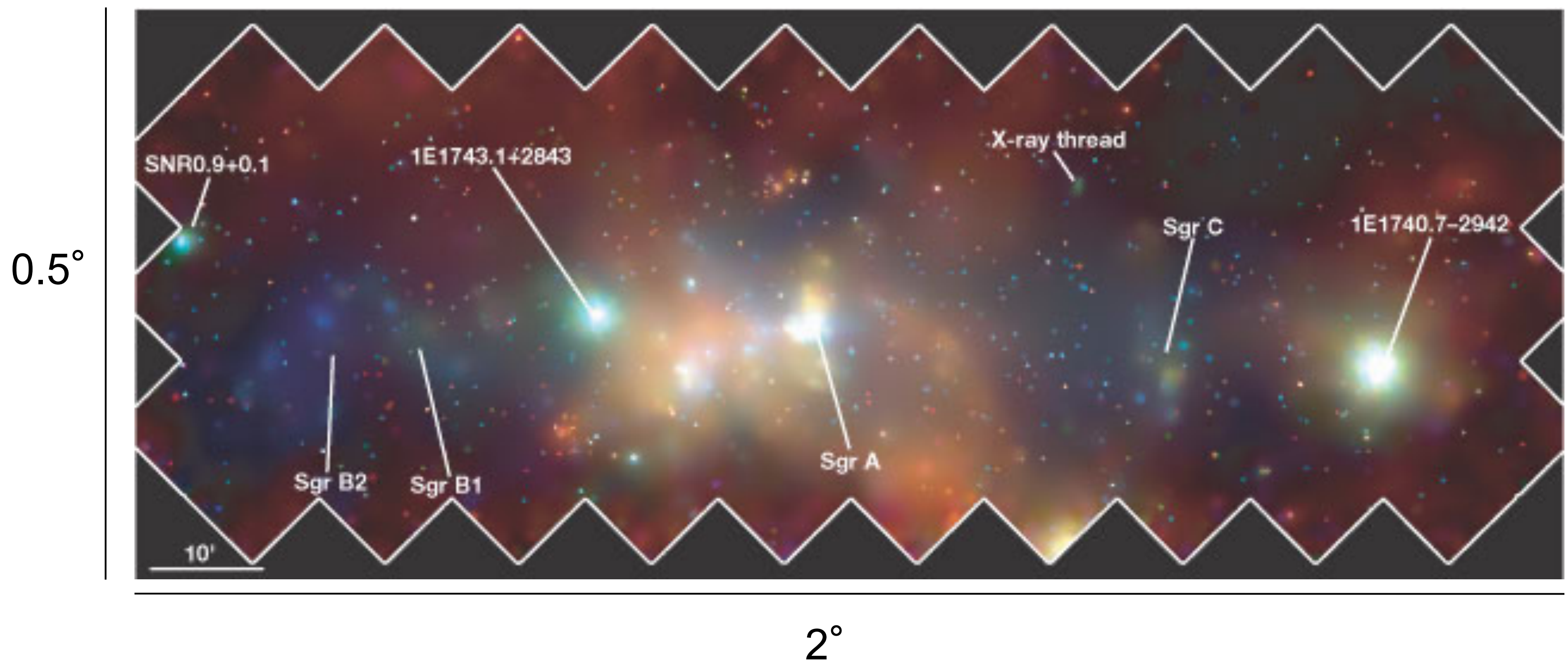
Predehl et al. (2020, Nature)

Galactic diffuse X-ray emission + pointlike contribution



Looking deeper and wide, the diffuse emission is there



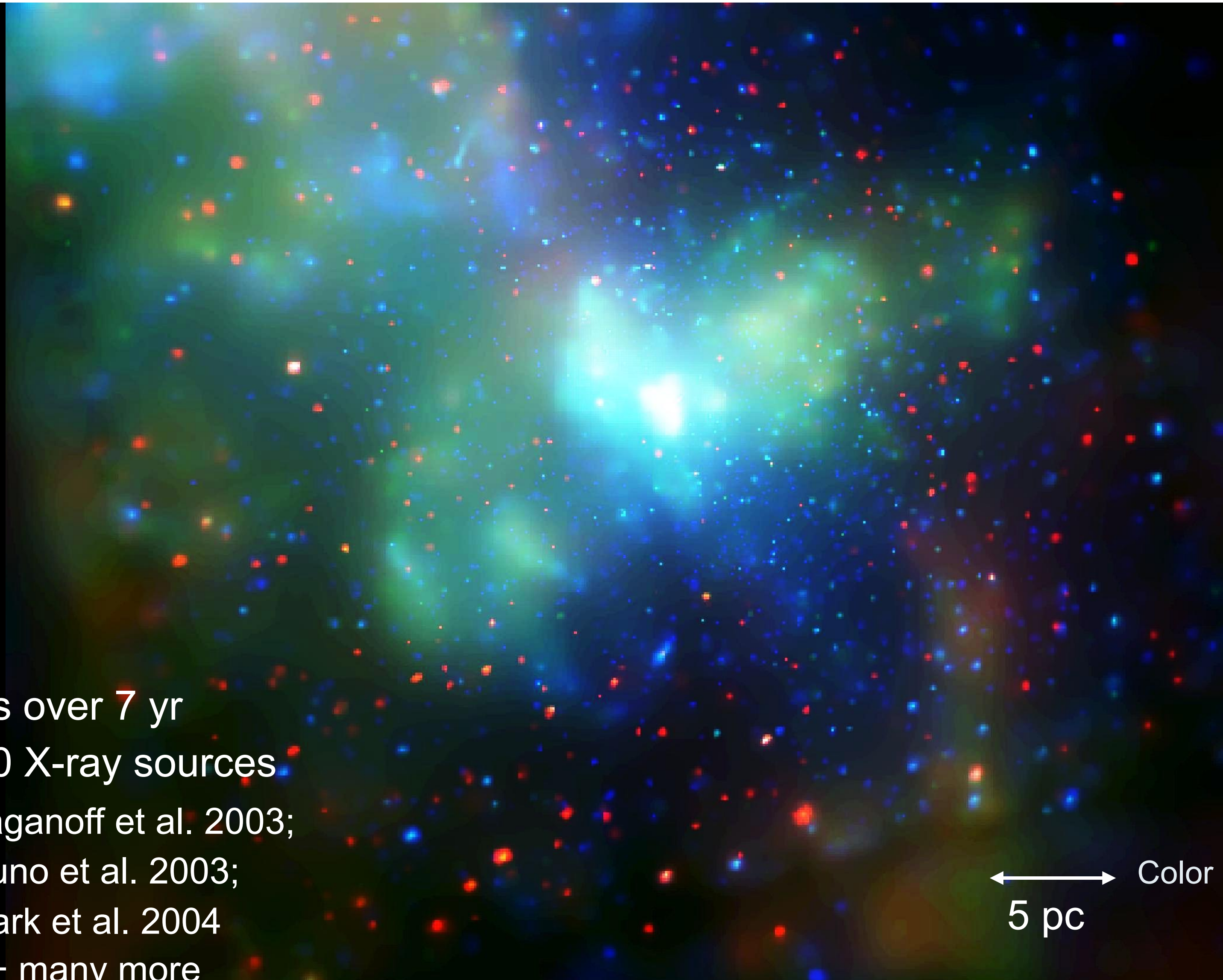


30 separate *Chandra* pointings (2001), ≈5000 X-ray sources

Resolution ≈0.5 arcsec on-axis, to 5-10 arcsec at large off-axis angles

Most of the detected sources at E>2 keV (because of Galactic interstellar absorption)

Looking even deeper in the central region, diffuse X-ray emission is still present



>1 Ms over 7 yr

≈4000 X-ray sources

Ref: Baganoff et al. 2003;
Muno et al. 2003;
Park et al. 2004
+ many more

Color (energy) code image

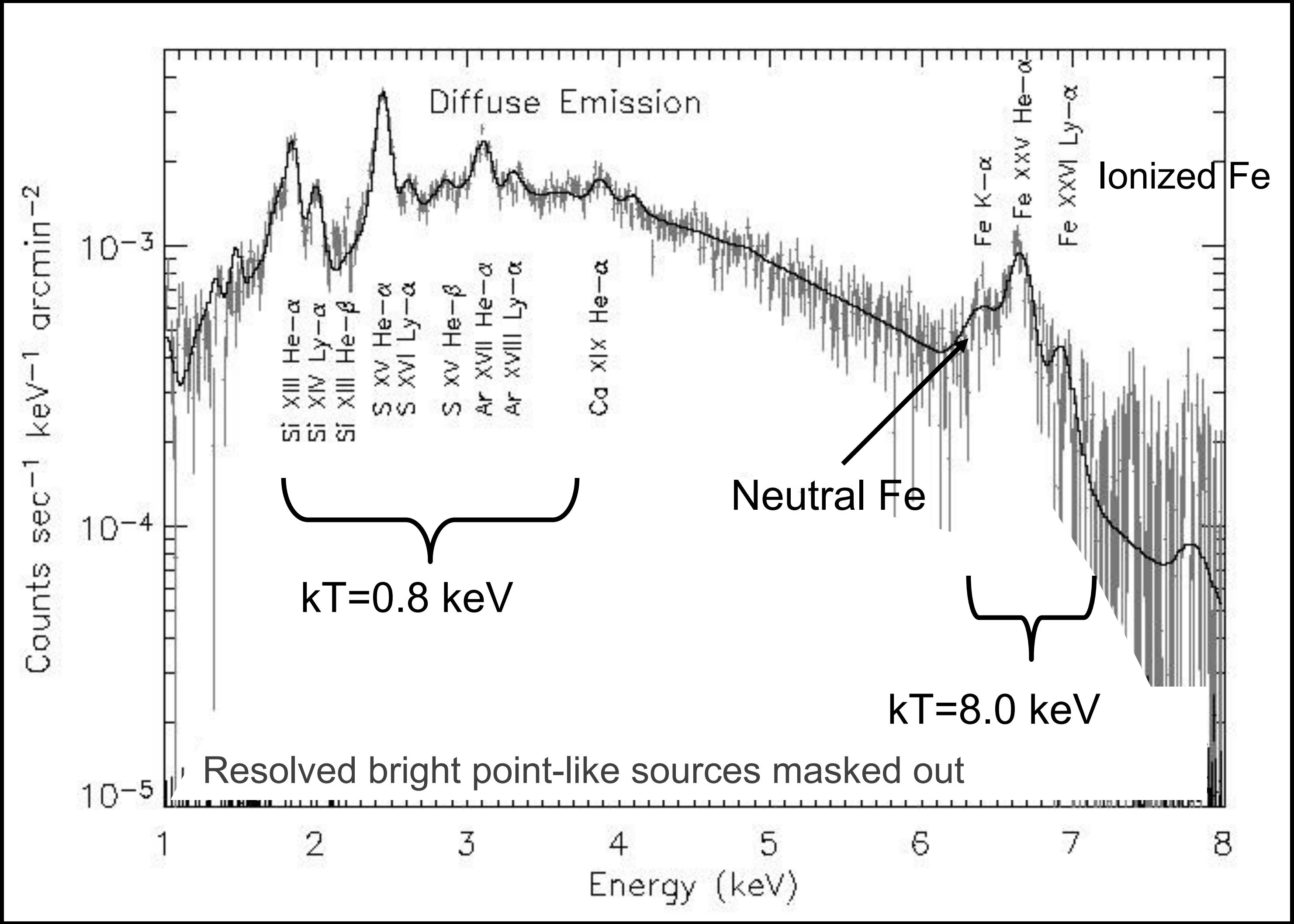
The Galactic plane (center) as a melting pot of multiple components

- A uniformly distributed soft emission ($kT \approx 0.8-1$ keV), likely associated to SN activity.
- A less uniform $kT \approx 7-8$ keV plasma (with ionized Fe emission at 6.7 keV) - hard to be confined - possibly associated with faint X-ray sources (at least in the inner GC center, where deep *Chandra* exposures are available).
- Clumpy 6.4 keV component, likely associated with molecular clouds and reflection of X-rays.

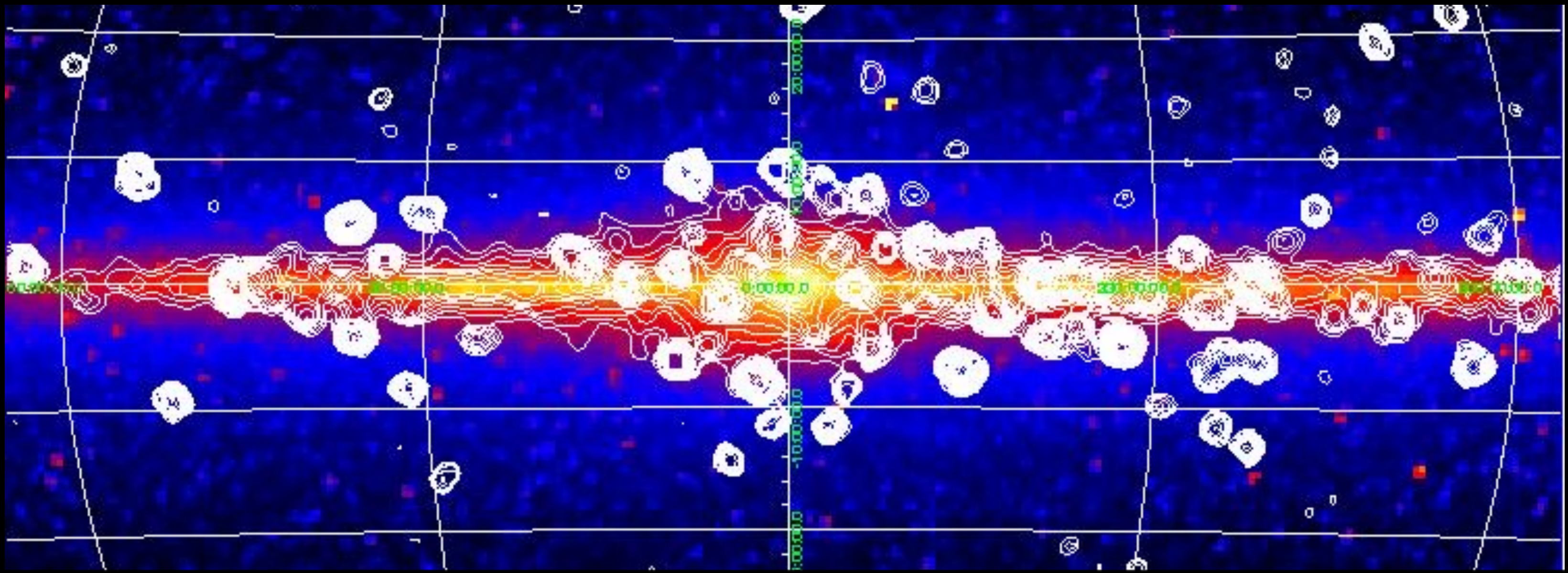
Sound speed of the $kT \approx 7-8$ keV plasma ≈1500 km/s vs. 900 km/s of the escape velocity from the Galactic potential ➔ a hot plasma would escape in ≈30,000 yr

➔Any hot plasma would have to be generated continuously, requiring a large (and partly unexplained) amount of energy (≈10^{40} erg/s)

Moderate-resolution spectrum of diffuse X-ray emission



Could the diffuse X-ray emission due to stellar sources?



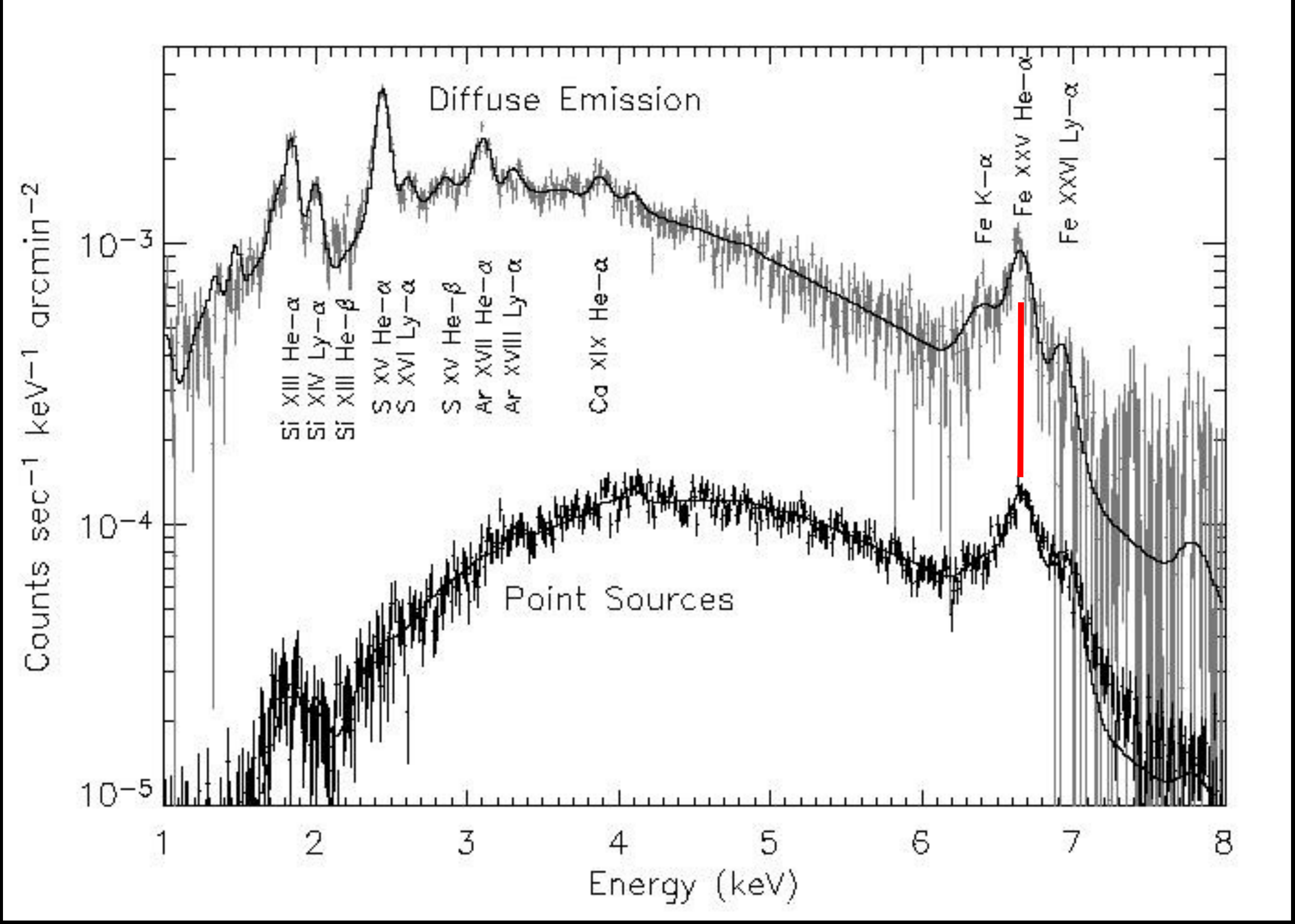
The diffuse X-rays trace the distribution of stars, not the ISM (Revnivtsev et al. 2006). Diffuse X-rays associated with the old population of the Galactic bulge

The density of stellar X-ray sources per unit of stellar mass in the Solar neighborhood is sufficient to explain the Ridge emission (Sazonov et al. 2006)

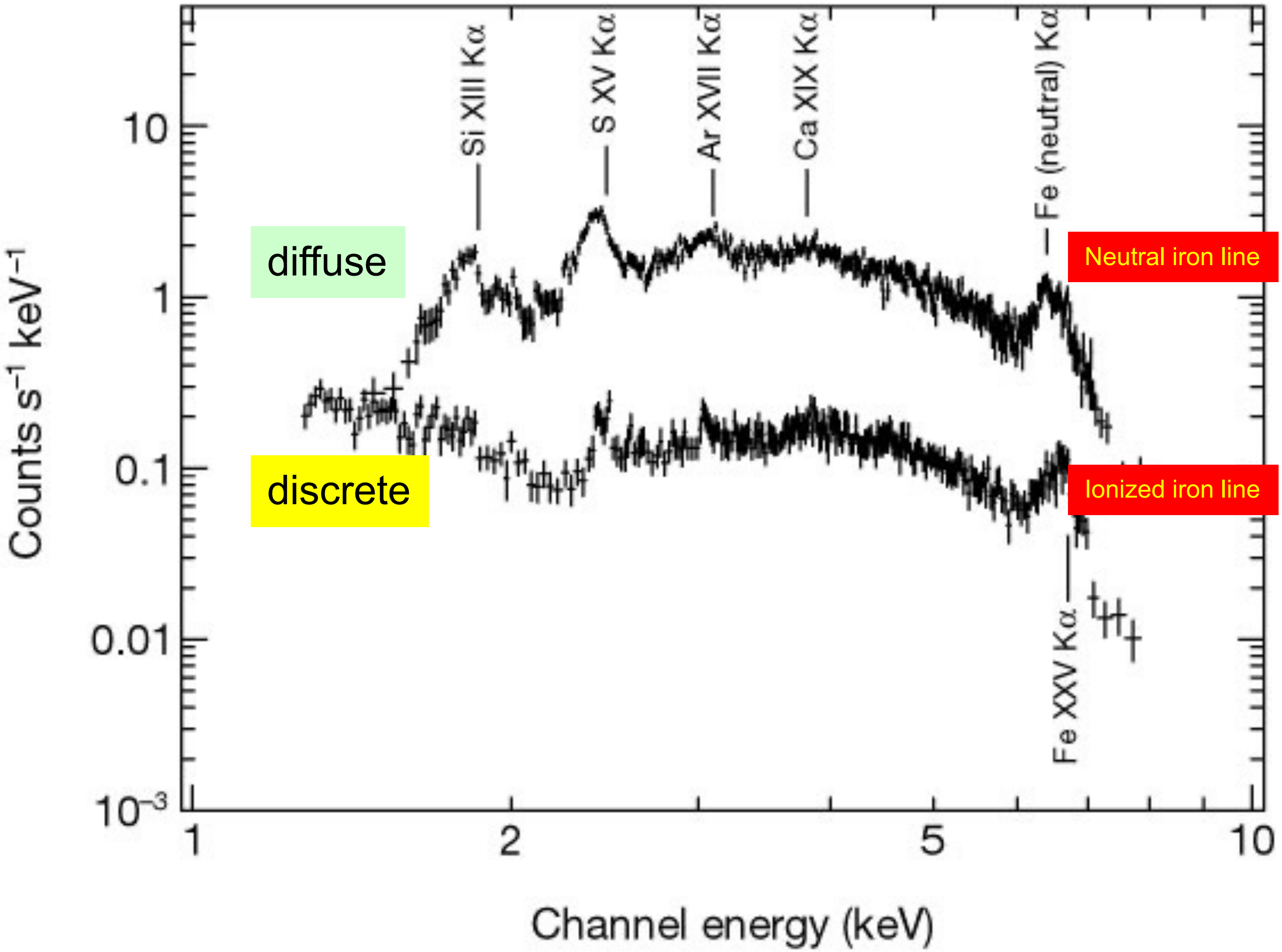
The local density of accreting white dwarfs scales as expected to the Galactic center, i.e., it is the same as in the local stellar neighborhood (Muno et al. 2006)

The spectra of diffuse and point-like emission

Ionized iron lines due to the contribution of point sources (better accounted for using modern high-resolution X-ray instruments



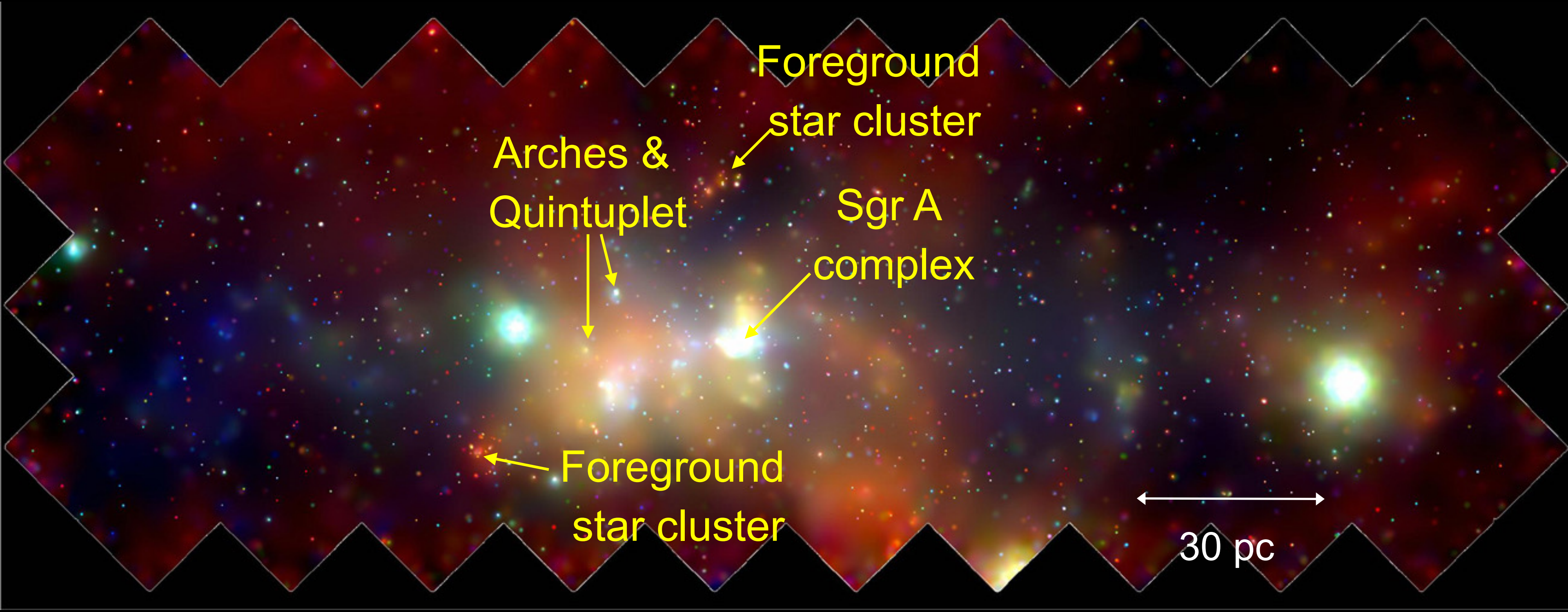
Muno et al. (2004)



Wang et al. (2002, Nature)

- **Originally**: diffuse+discrete were thought as a unique component with kT≈10^8 K because of the limited (poor) angular resolution
- **Now**: diffuse component=thin plasma with kT≈10^7 K, possibly related to SN (as in Sgr A East) + discrete sources (binaries) producing the 6.7 keV iron line (some still unresolved in the inner regions of the GC)

Likely, the smooth background is mostly stellar/compact. What about the patchy features?

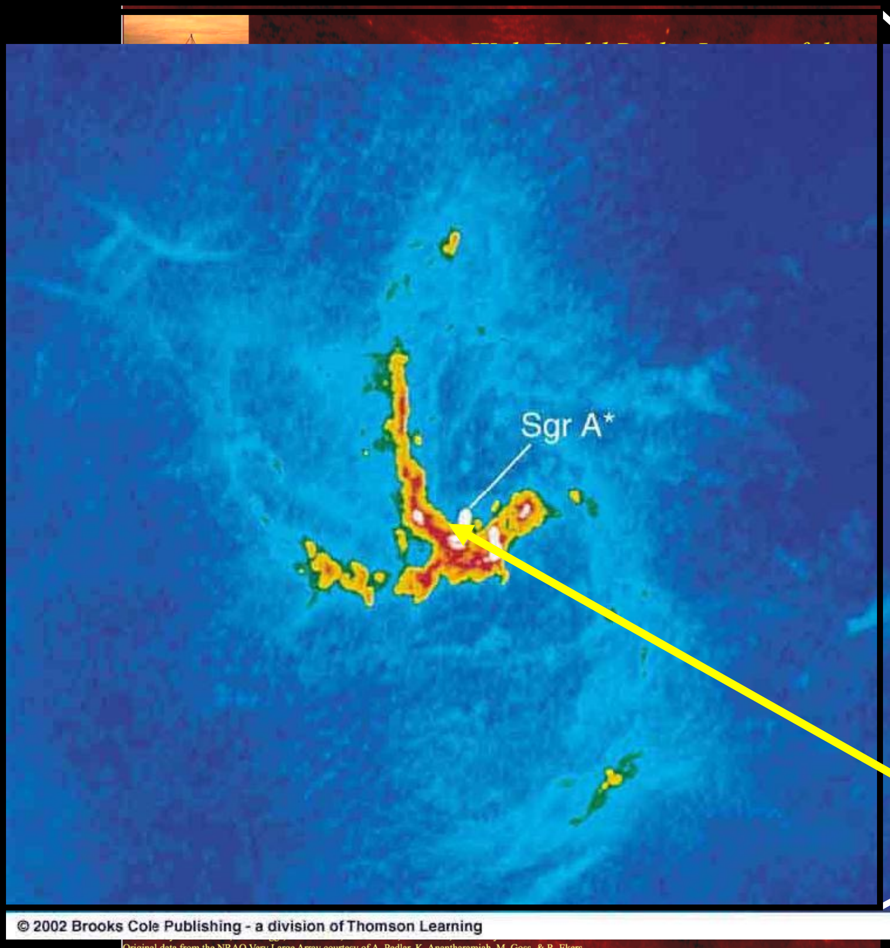


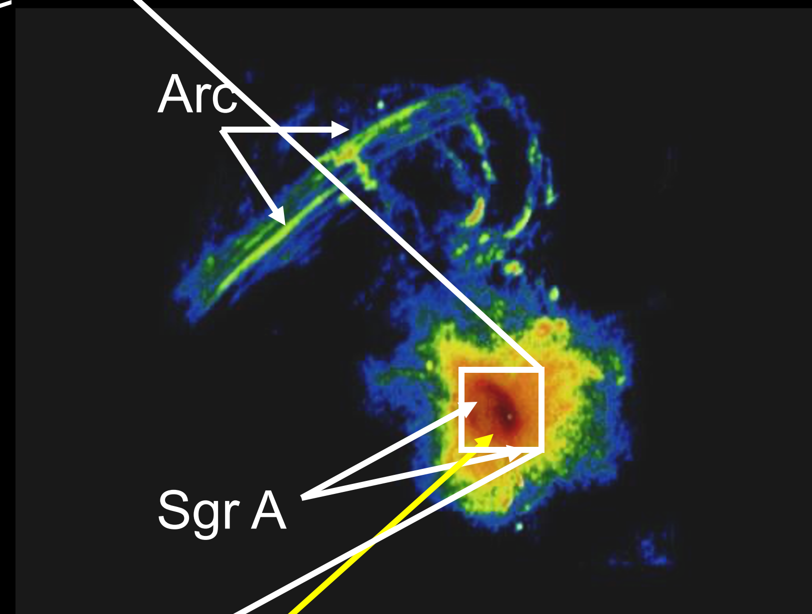
Some of the diffuse features trace the sites of recent star formation.

Winds, shocks, and SNRs are present ("violent" environment overall)

Arcs and filaments in radio

Many supernova remnants;
shells and filaments





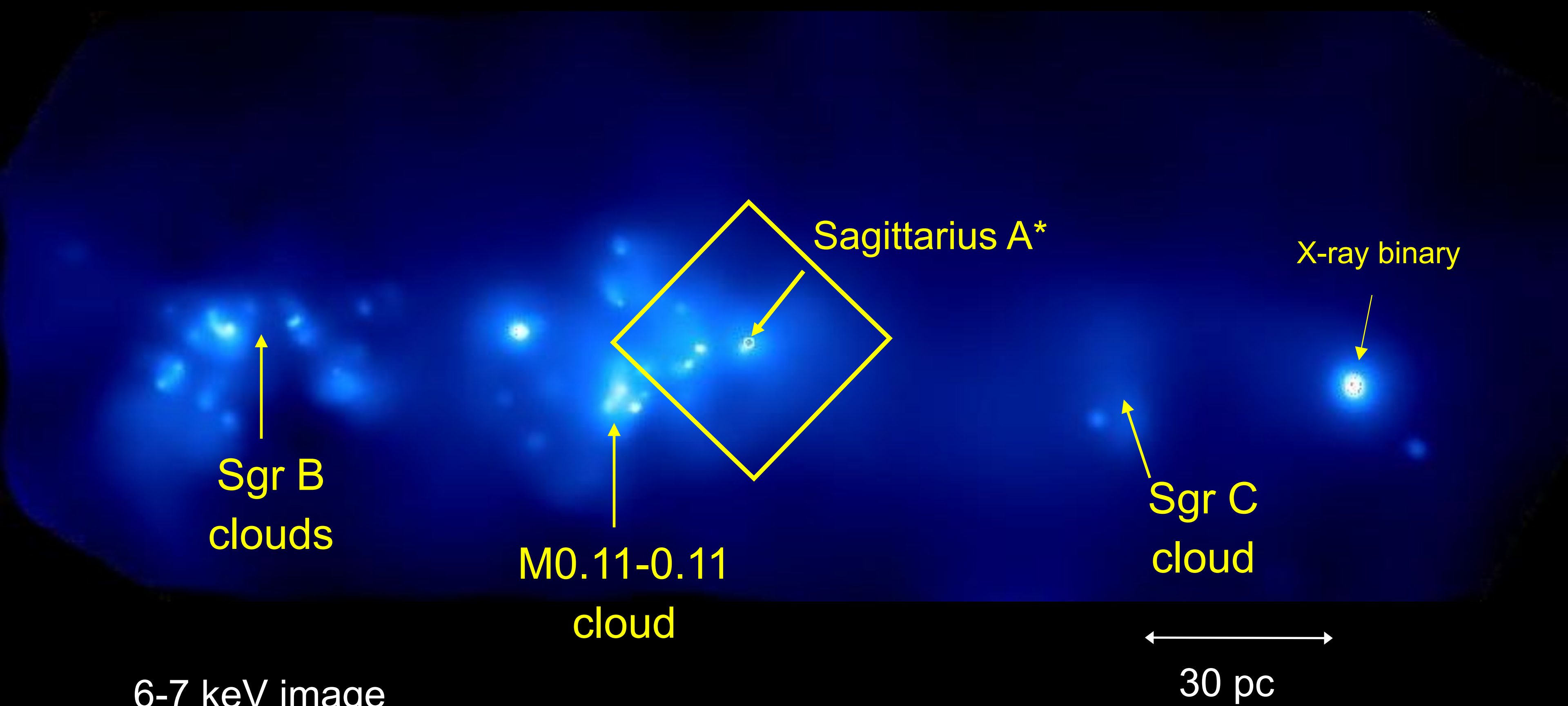
Arc

Sgr A

Sgr A*

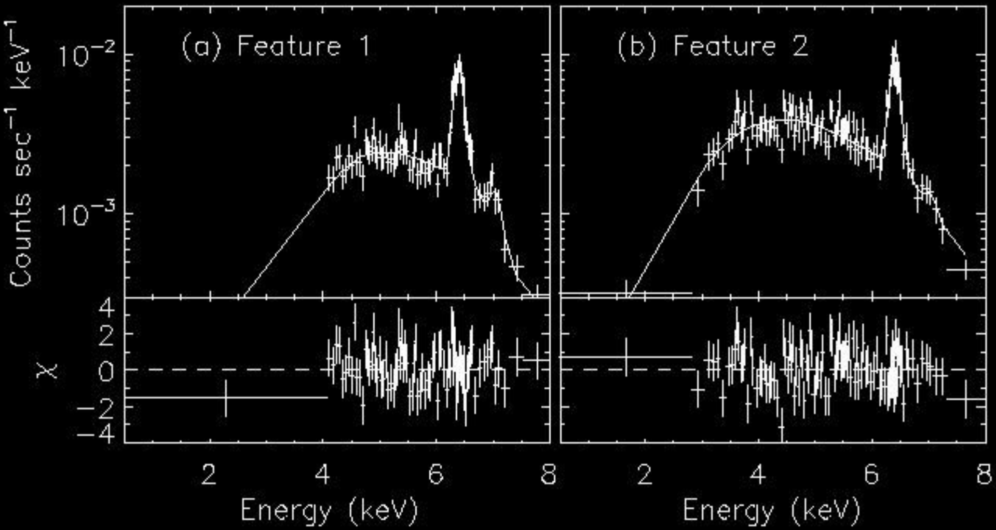
Magnetic reconnection is probably
at work in filaments (Wang+21)

Molecular clouds glowing in hard X-rays



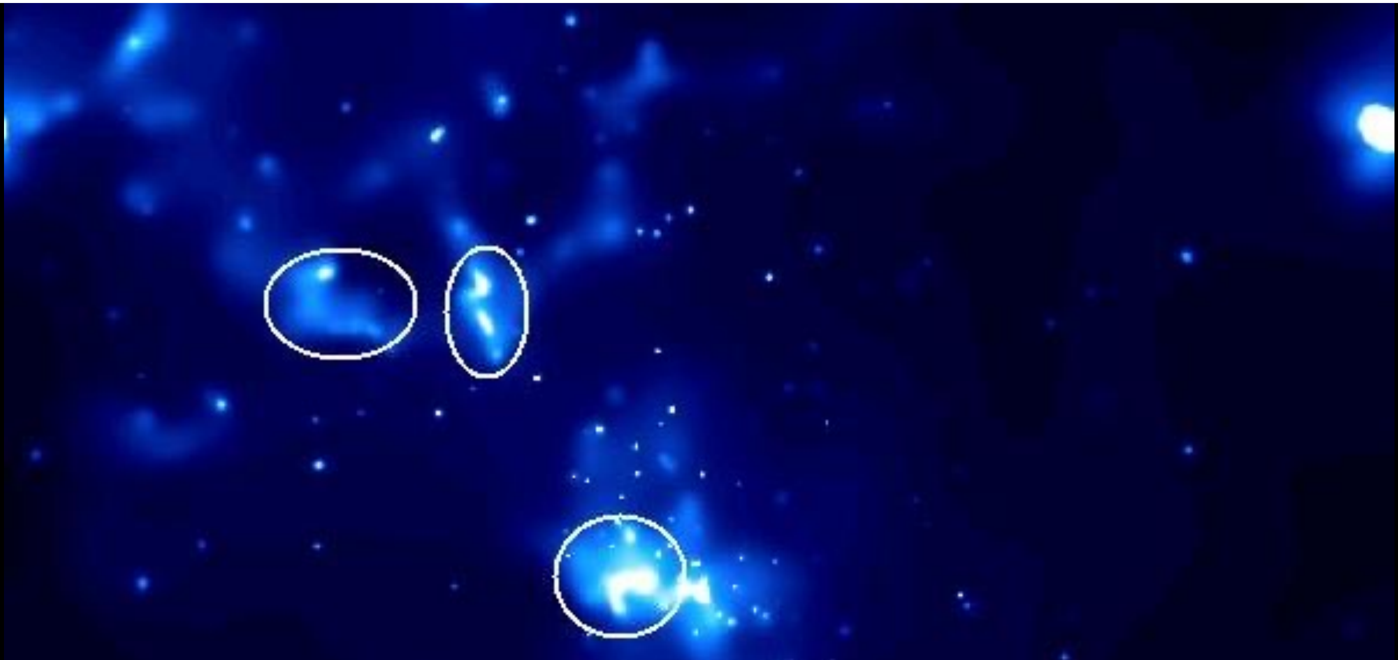
6-7 keV image

Iron fluorescence from molecular clouds



- Emission from molecular clouds exhibits strong Fe K-alpha lines with equivalent widths of 1 keV (Park et al 2000)
- Produced when neutral iron in molecular clouds with $N_H \sim 10^{23}$ cm^{-2} is bombarded either by photons (Koyama et al. 1996) or electrons (Valinia et al. 2000)

What is the origin of fluorescence in MC?



Problems with the two hypotheses:

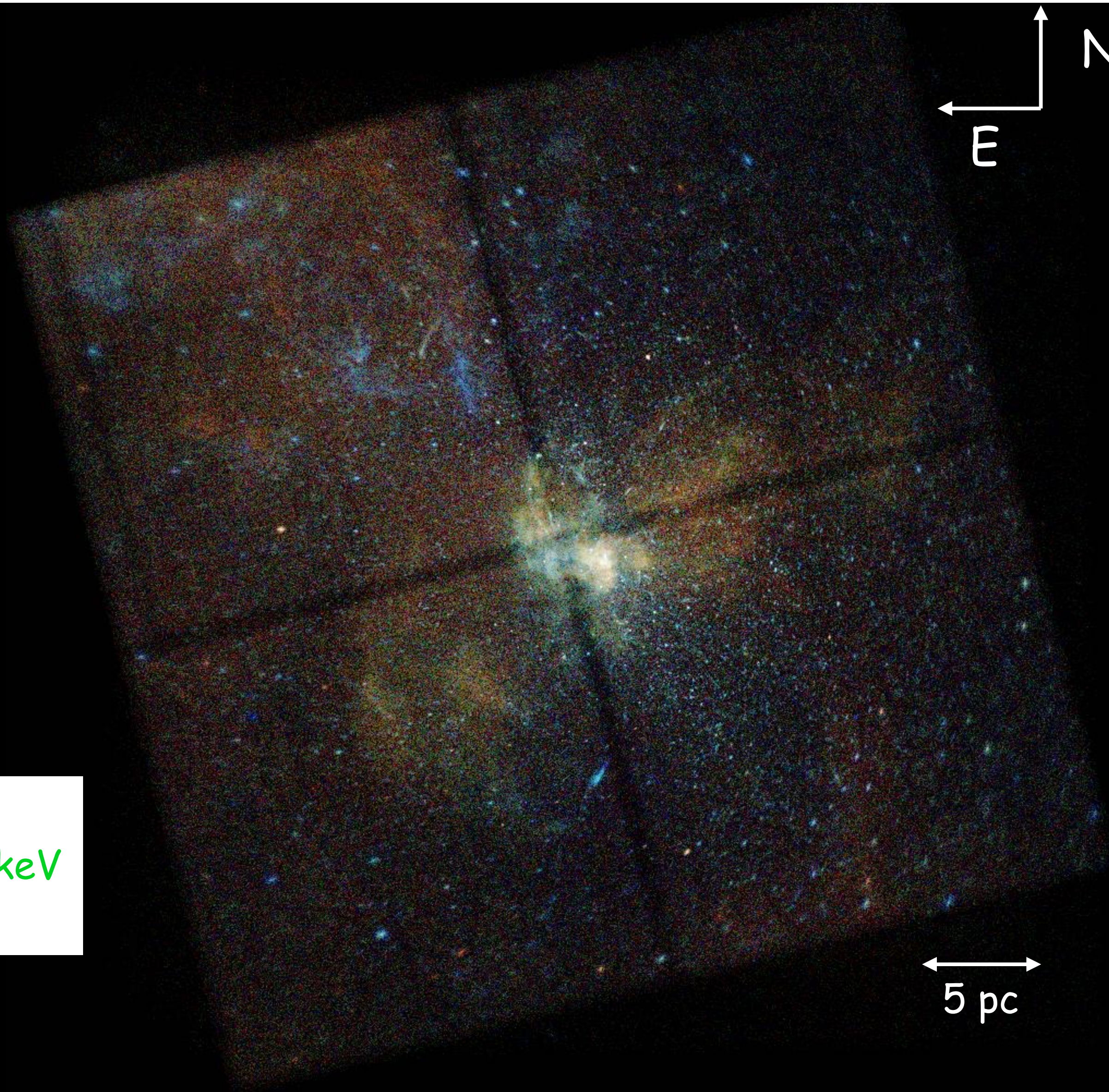
- ~30 keV Electrons
  - Only 0.005% of the energy would emerge as Fe emission, the remaining being lost in Coulomb collisions
- ~10 keV Photons
  - No X-ray source bright enough to illuminate the features is currently active in the Galactic center.

→ Transient X-ray source? Linked to Sgr A* activity…

The Galactic Center and Sgr A*

Sgr A* as the origin of X-ray photons for the glowing molecular clouds?

Chandra Galactic Center Deep Field



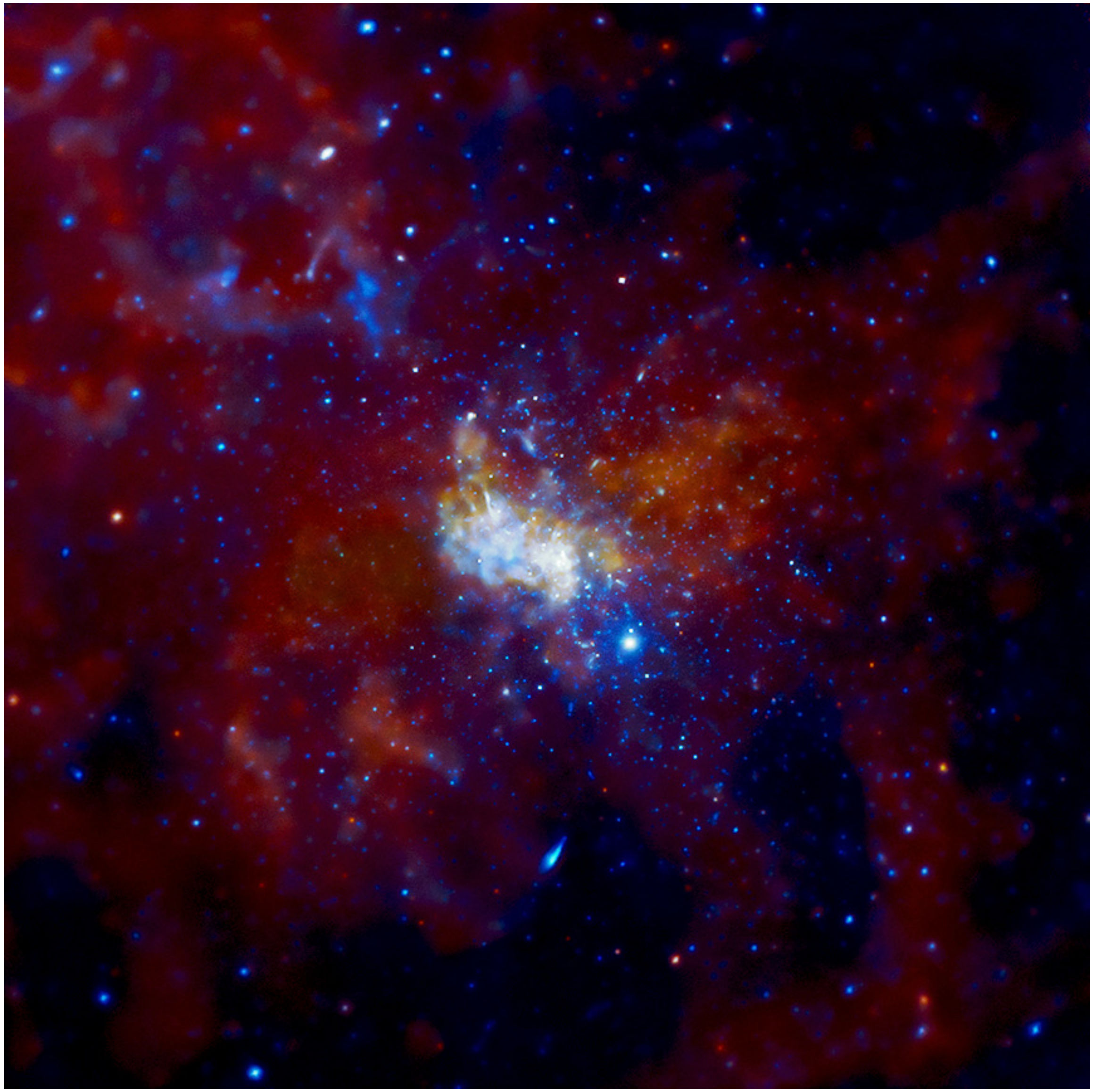
17 x 17 arcmin

40 x 40 pc

590 ks

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

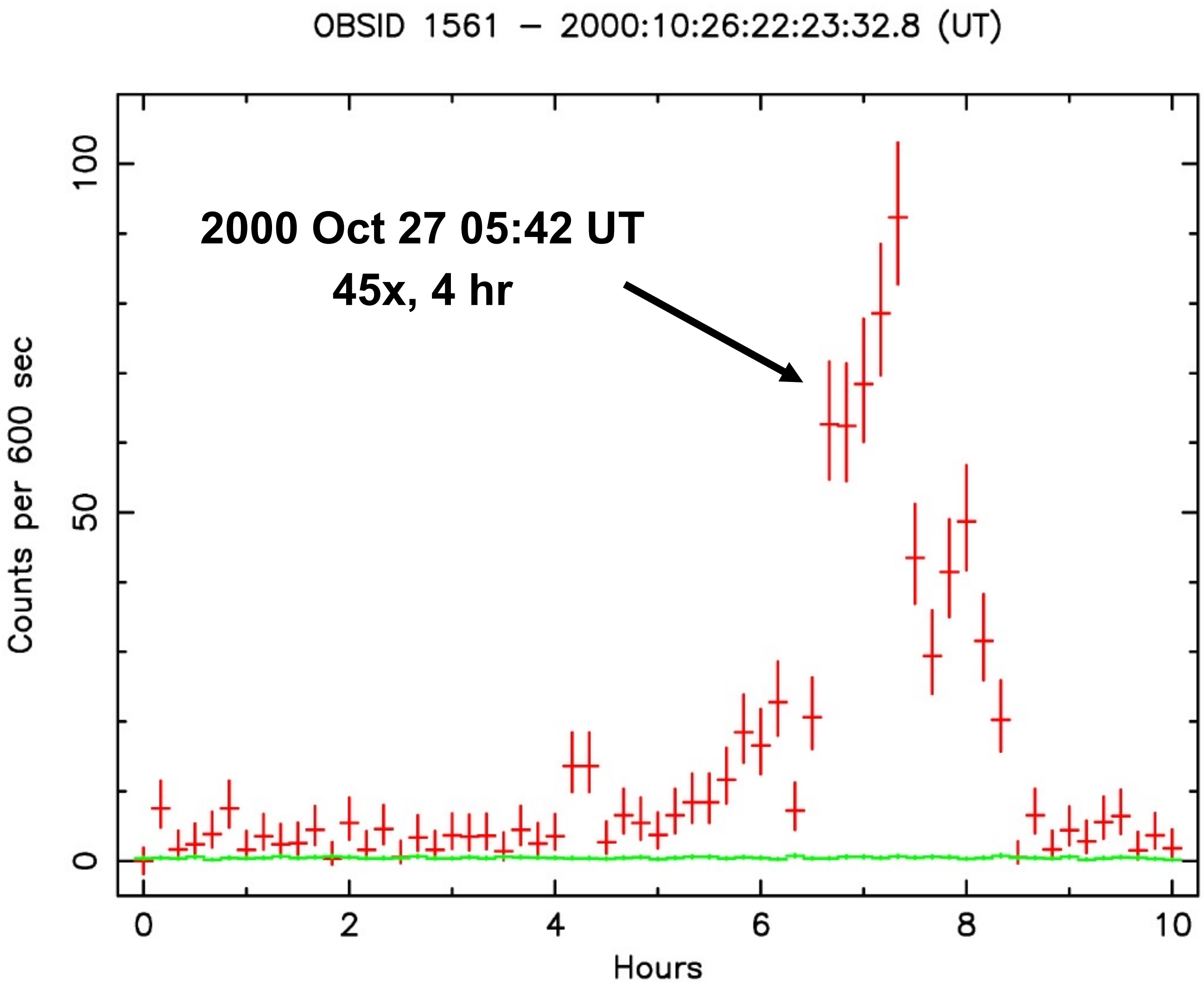
Chandra vs. XMM-*Newton*



Properties of Sgr A*

- Mass ~ $4.3 \times 10^6\ M_\odot$
- 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 × 10^{44} erg s^{-1}

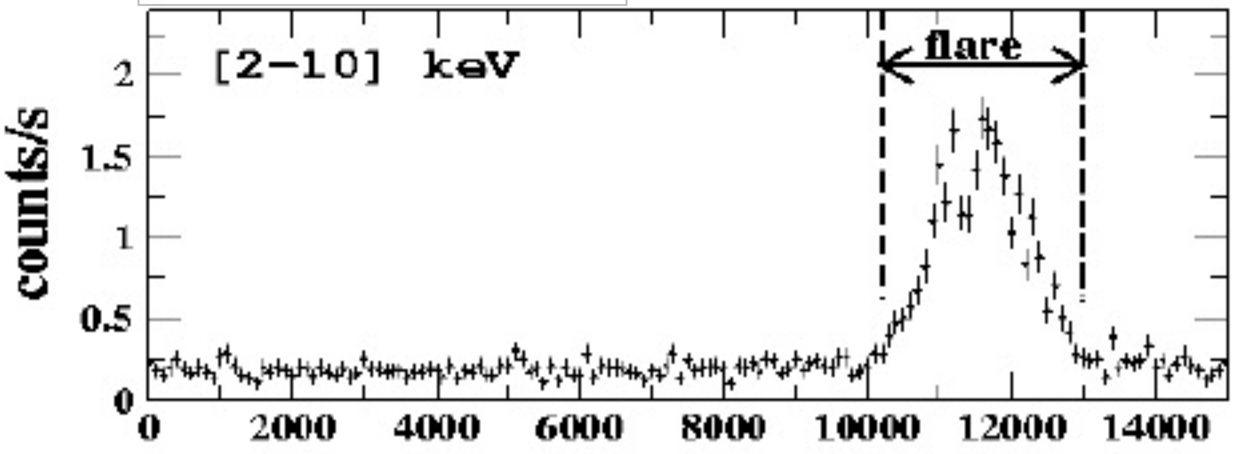
X-ray flaring of Sgr A*. I



Chandra detection of a powerful flare associated to Sgr A* (factor ≈50; Baganoff et al. 2001, Nature)

X-ray flaring of Sgr A*. II

$L_{2\text{-}10\ keV} \approx 4 \times 10^{35}$ erg/s



XMM-*Newton* detection of a powerful flare associated to Sgr A* (factor ≈160 × quiescence flux; Porquet et al. 2003)

Softening/hardening of the X-ray spectrum during the big flares represent a challenge for models (until the recent *Chandra*/HETG observation)

➔ *Sgr A* has few large flares but minor flares have a rate of ≈1 per day*

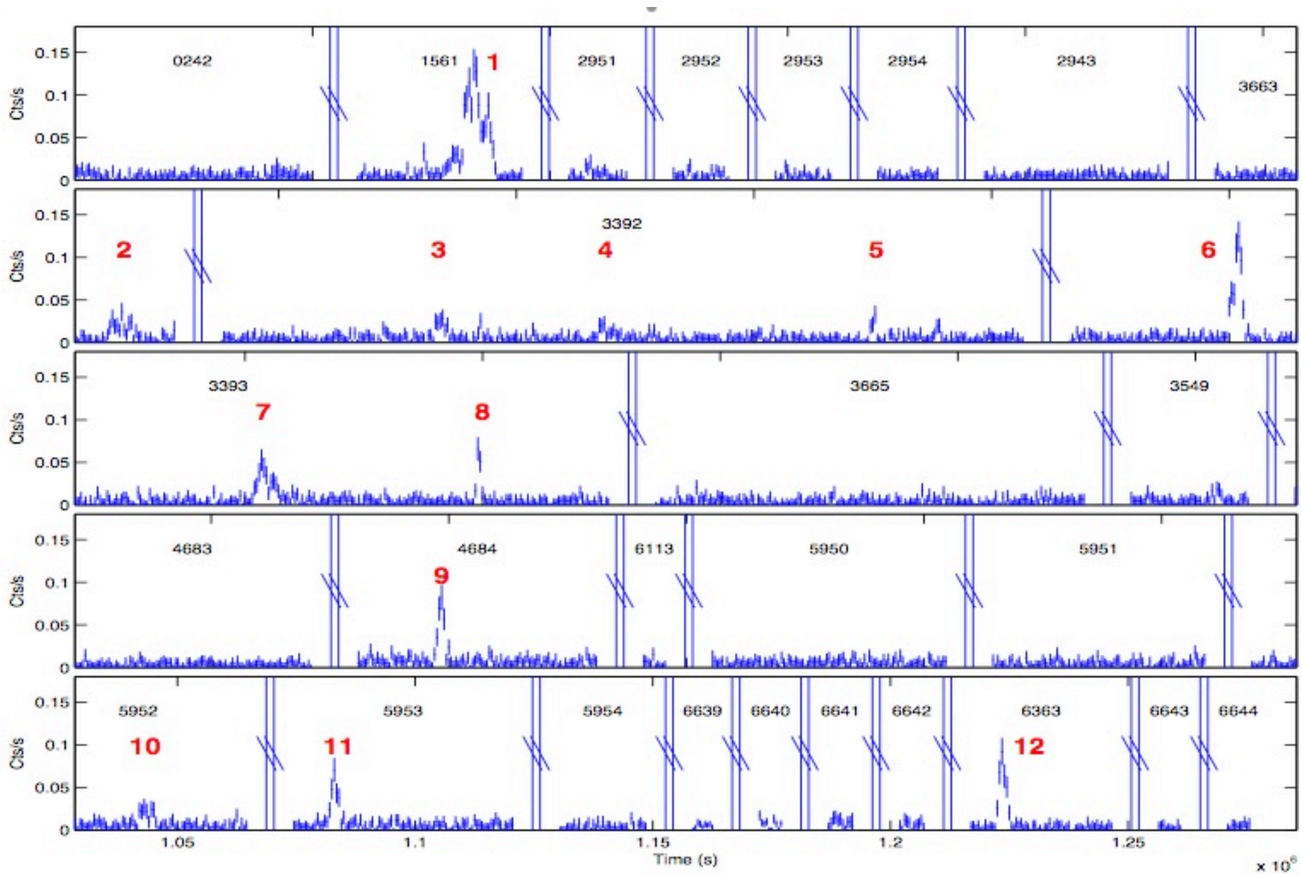
X-ray flaring of Sgr A*. III

Sgr A* low luminosity

$M_{SgrA^*}=4.3\times10^6\ M_{Sun}$

$L_{SgrA^*}\approx3\times10^{33} - 10^{35}$ erg s^{-1}
$L_{Edd} = 5.6\times10^{44}$ erg s^{-1}

$\boxed{\eta\sim10^{-9}}$



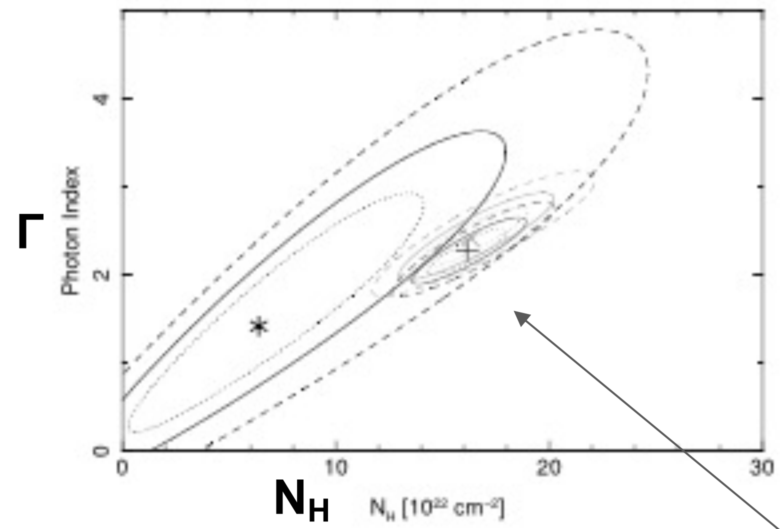
Chandra

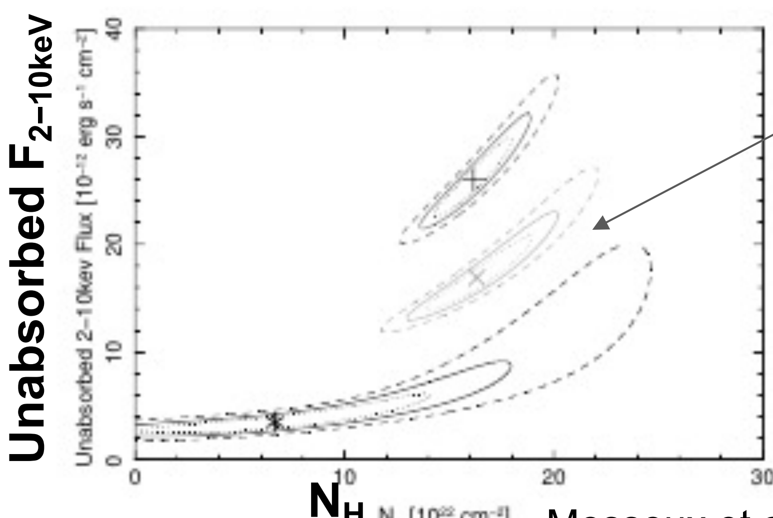
Credits:
M. Cappi

1.2 flares per 100ks from *Chandra*
3Ms monitoring (Nielsen+13)

How was the Sgr A* accretion rate in the past?
Are we witnessing a peculiar moment of Sgr A*?

X-ray flaring of Sgr A*. IV





X-ray spectrum in flare

- 2011, asterisk, black
- 2007, light grey, X point
- 2002, dark grey, cross point

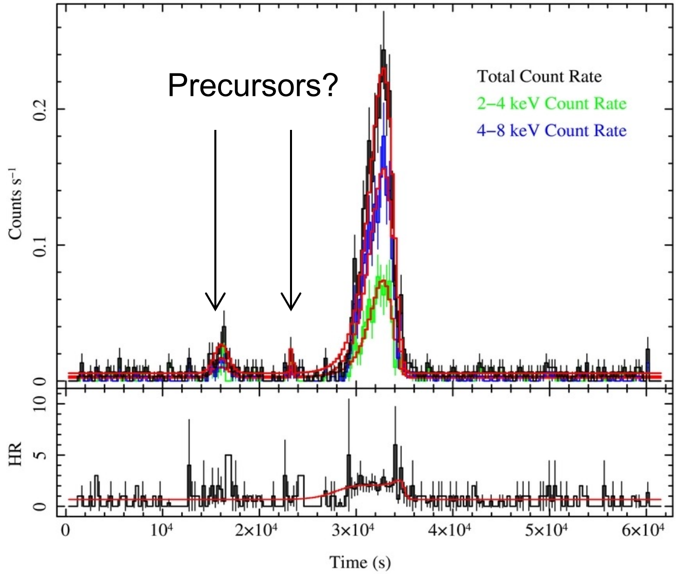
Moderately steep photon index and $N_H \approx 10^{23}$ cm^{-2}

68, 90 and 99% confidence contours (external/medium/internal): they show how the two plotted quantities vary during the three flares

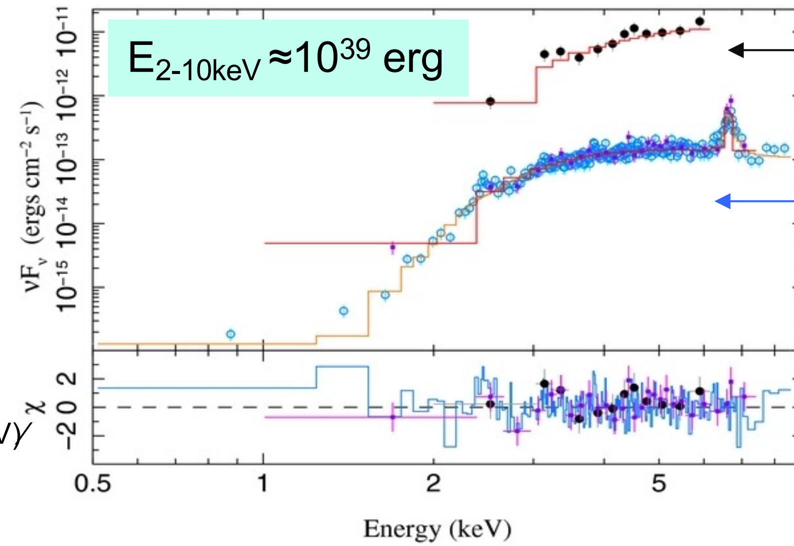
Mossoux et al. 2015
XMM flares of Sgr A*

X-ray flaring of Sgr A*. V

A recent event observed with *Chandra* HETG

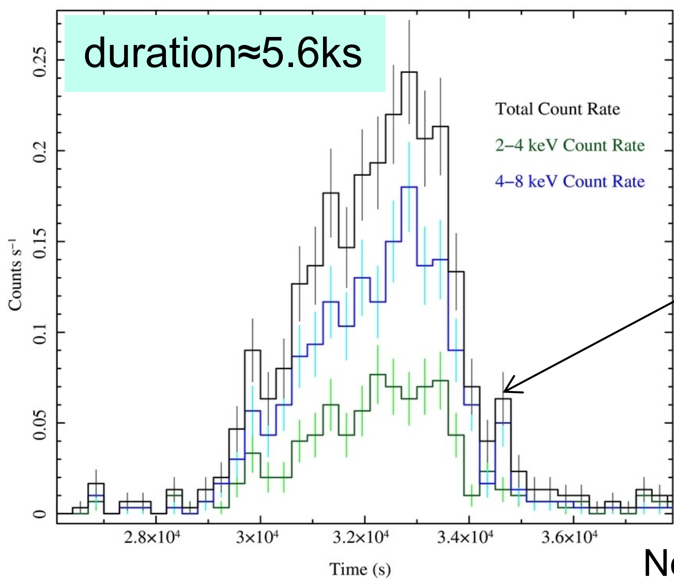


HR=(4−8keV)/(2−4keV)

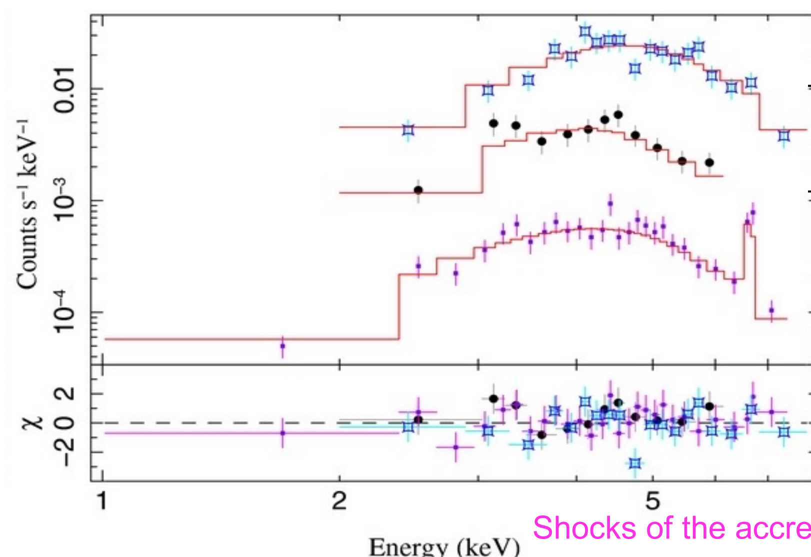


Flare emission

Quiescent emission (ACIS-I+HETG 0th order)



Asymmetric flare (sub-structures?), plus secondary flare



Flare emission

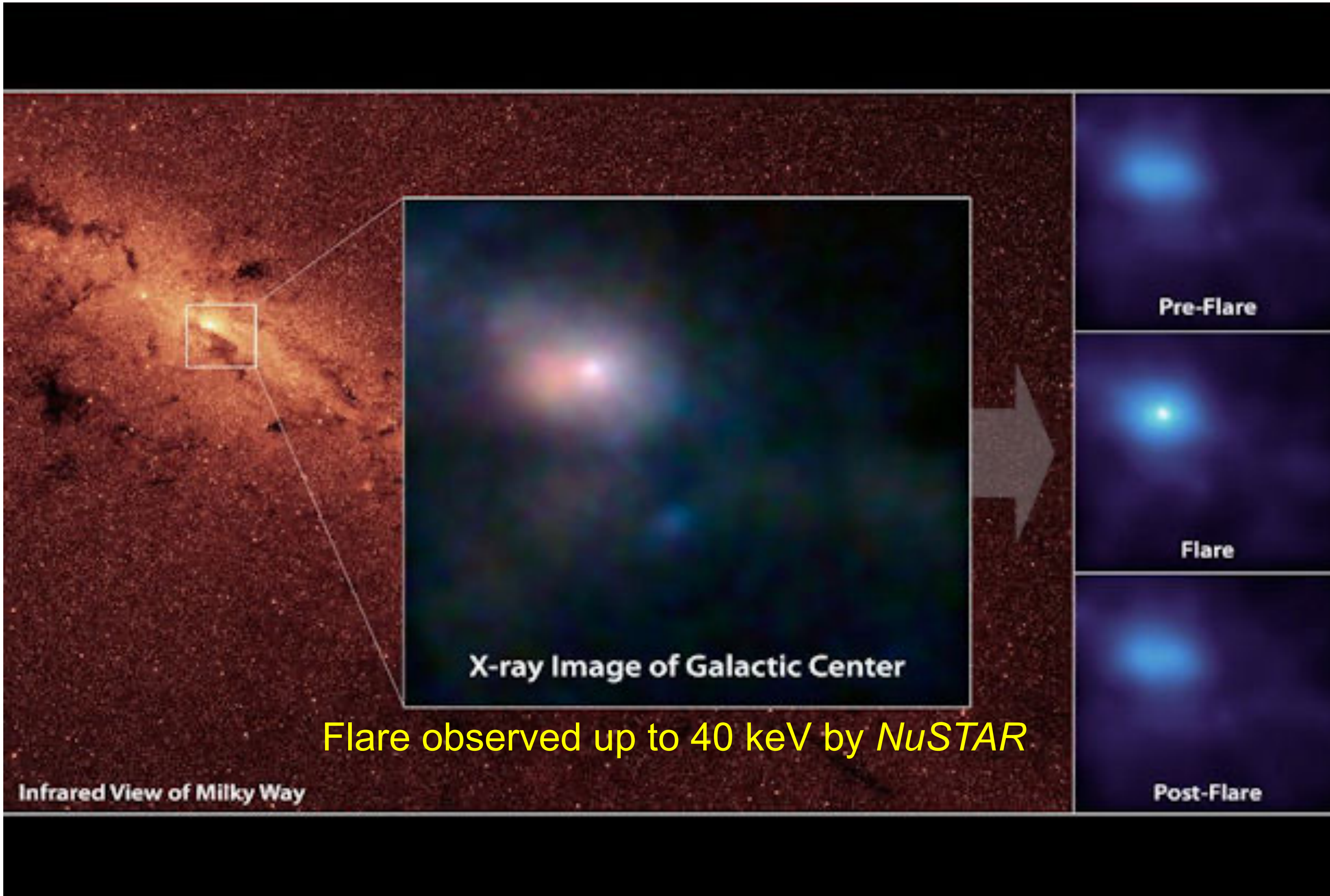
Quiescent emission (bremss)

Shocks of the accretion flow → thermalization at the Bondi radius → bremsstrahlung

Nowak et al. (2012), Feb. 2012 event

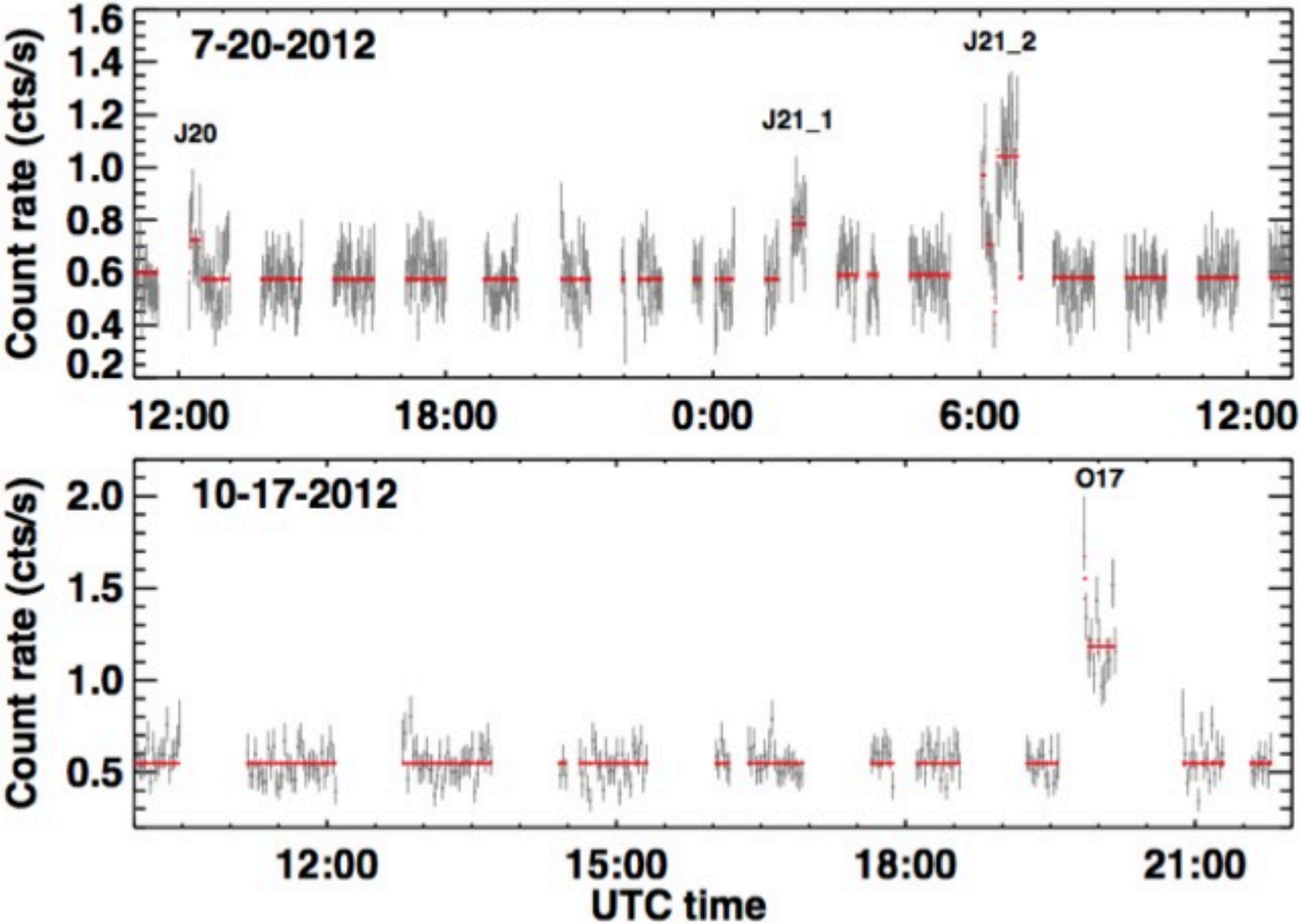
X-ray flaring of Sgr A*. VI

The *NuSTAR* view



X-ray flaring of Sgr A*. VII

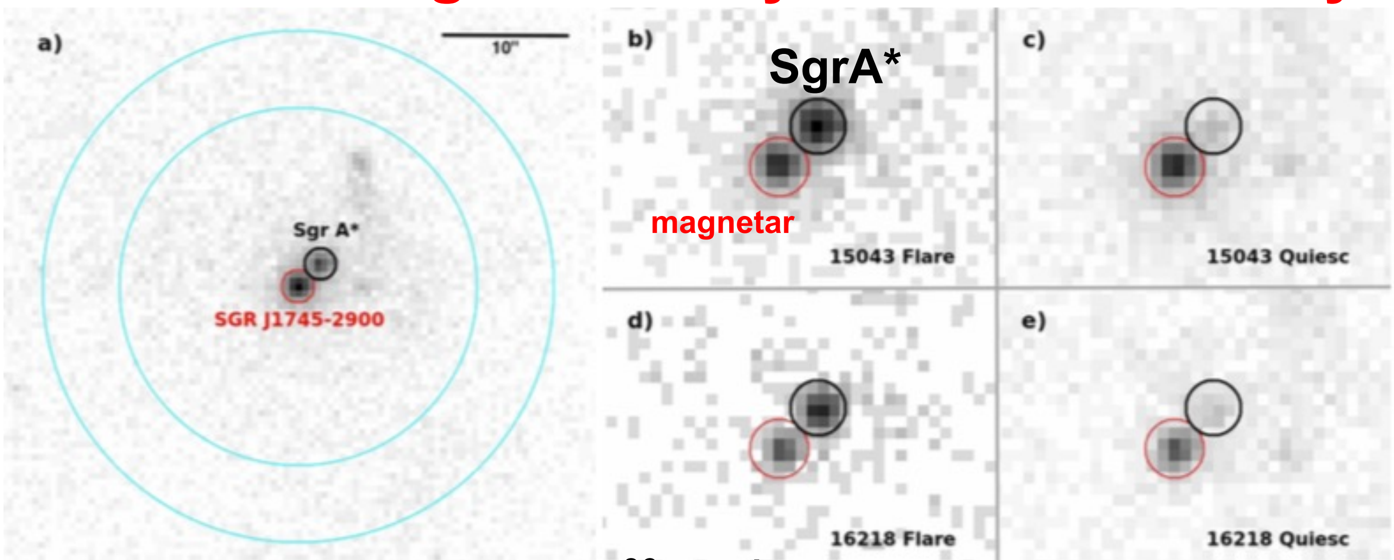
The *NuSTAR* view



Flaring within 10 R_S, Barriere+14

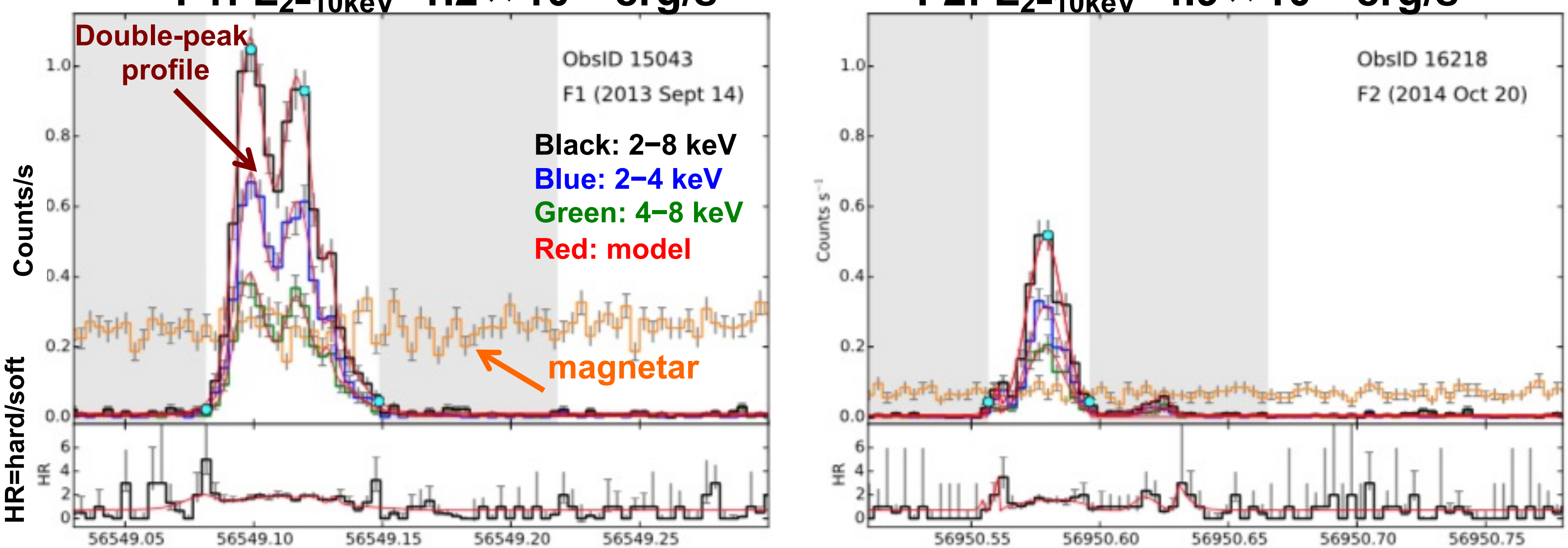
X-ray flaring of Sgr A*. VIII

The brightest X-ray flares detected by *Chandra*



Haggard et a. (2019)

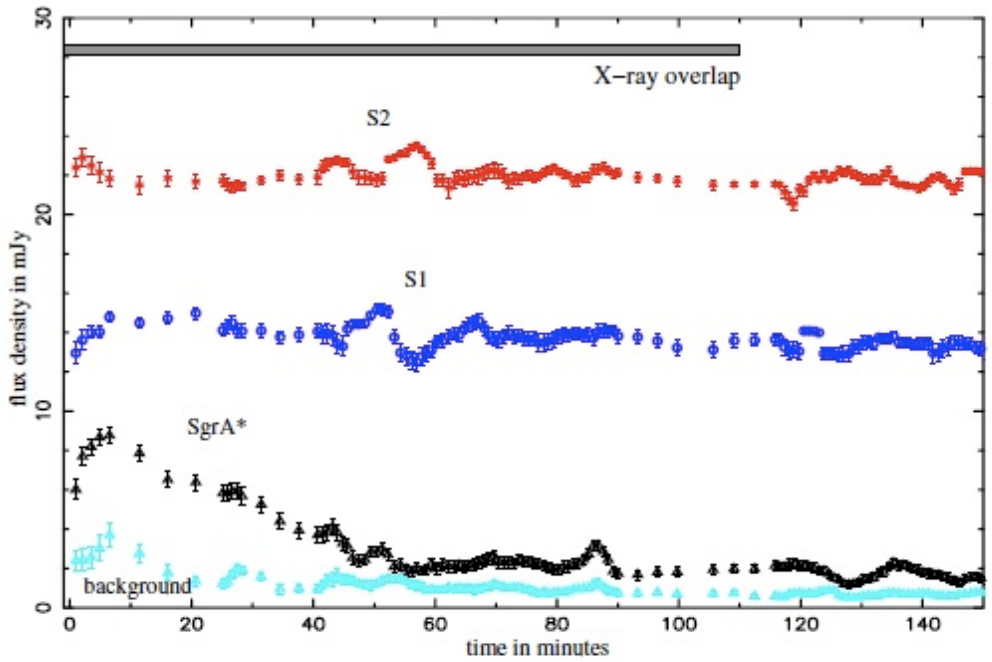
F1: $L_{2-10keV} \approx 1.2 \times 10^{36}$ erg/s **F2: $L_{2-10keV} \approx 4.9 \times 10^{35}$ erg/s**

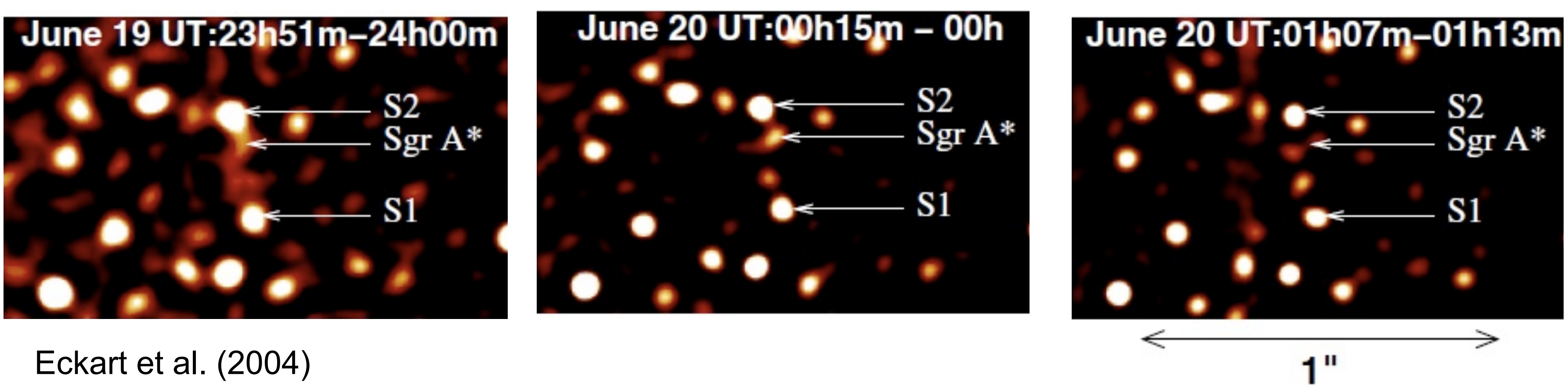


Duration=(5.7−3.4) ks

$E_{tot} \approx (3.3-0.7) \times 10^{39}$ erg

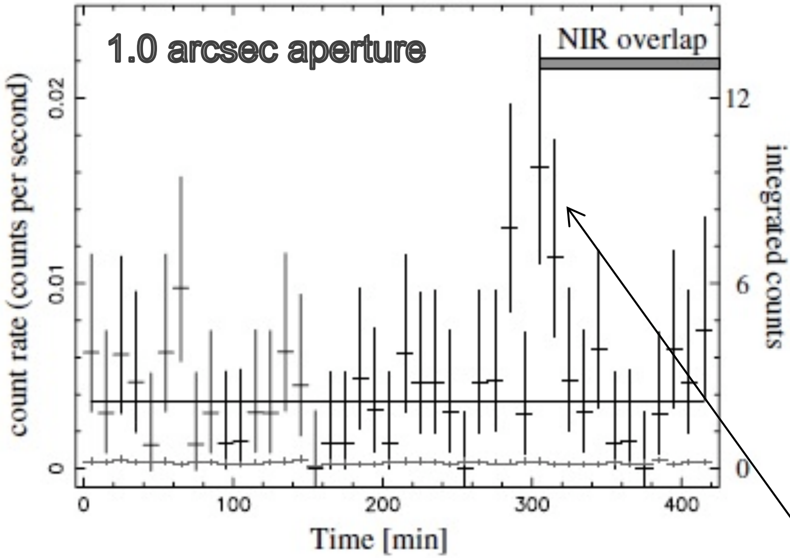
Simultaneous observations of X-ray/near-IR flare of Sgr A*. Early results. I





Eckart et al. (2004)

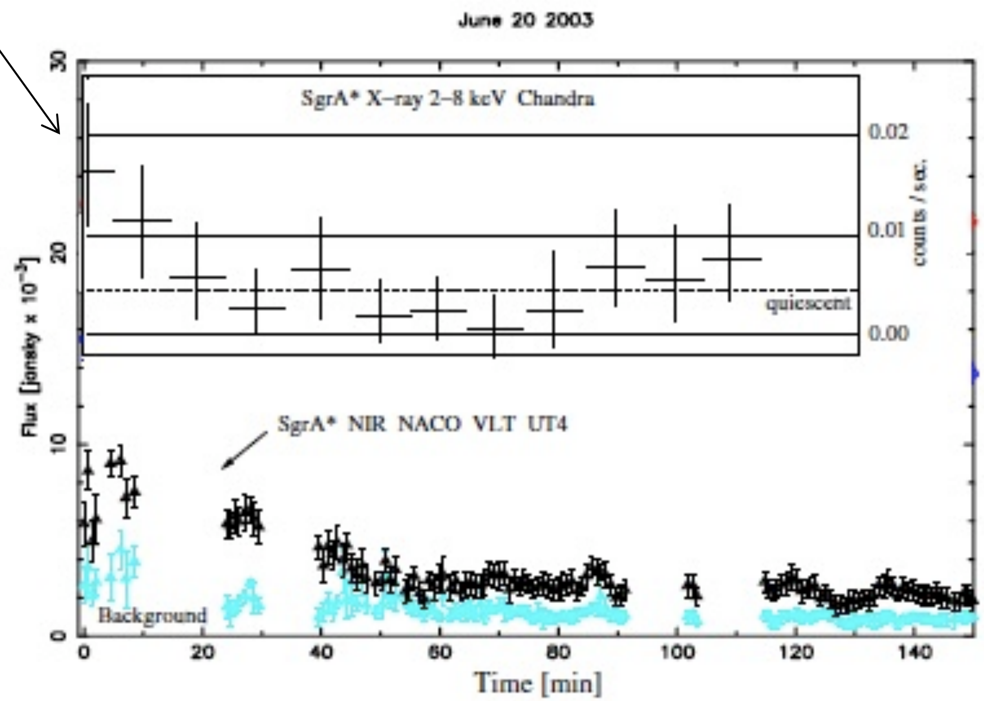
Simultaneous observations of X-ray/near-IR flare of Sgr A*. Early results. II



Delay time<15 min (near-IR, then X-rays)
Limited-amplitude X-ray flare!
Possible explanation: SSC of low-energy (mm/sub-mm) photons with electrons from a compact (≈ a few R_S) region

Chandra, bin interval=10 min
$L_X \approx 6 \times 10^{33}$ erg/s

Each X-ray flare has an IR flare
The opposite not necessarily true
Complex variability pattern



Simultaneous observations of X-ray/near-IR flare of Sgr A*. Recent results vs. models. I

Since Eckart et al. (2004), several reports on IR and X-ray flares: either simultaneous or X-ray leading the IR by <10 min

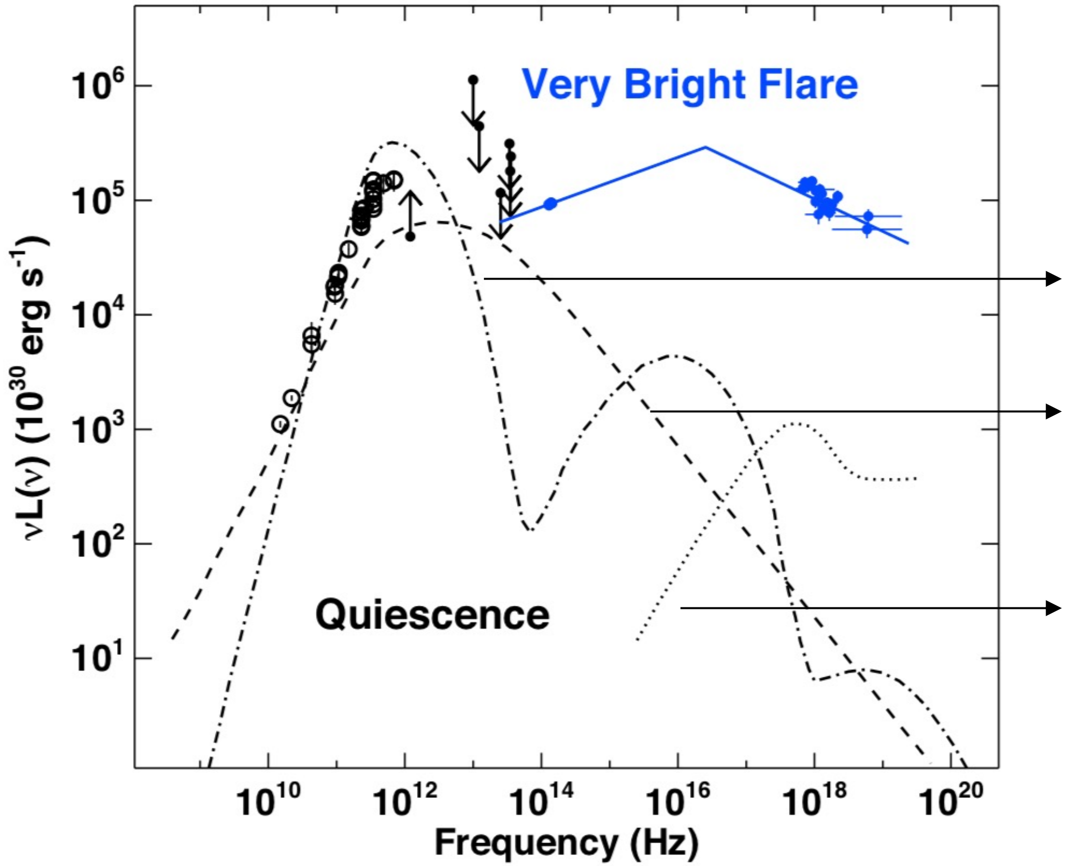
Possible mechanisms for IR flares: population of electrons undergoing continuous acceleration due to turbulent processes in the inner accretion flow

IR connected to X-rays through models of pure synchrotron (e.g., Ponti et al. 2017), SSC, and IC (all viable)

The synchrotron hypothesis supported by the spectral index of the flares (see also Dodds-Eden et al. 2009). Re-acceleration by magnetic reconnection is feasible

Observational problems: gaps in ground-based IR observations, typically shorter than (space-based) X-ray observations

Simultaneous observations of X-ray/near-IR flare of Sgr A*. Recent results vs. models. II



Thermal electrons with T_e~a few 10^{10} K and n_e~10^6 cm^{-3} embedded in B~10-50 G producing the submm (synchrotron) peak and possibly the IC emission, R~10 R_S

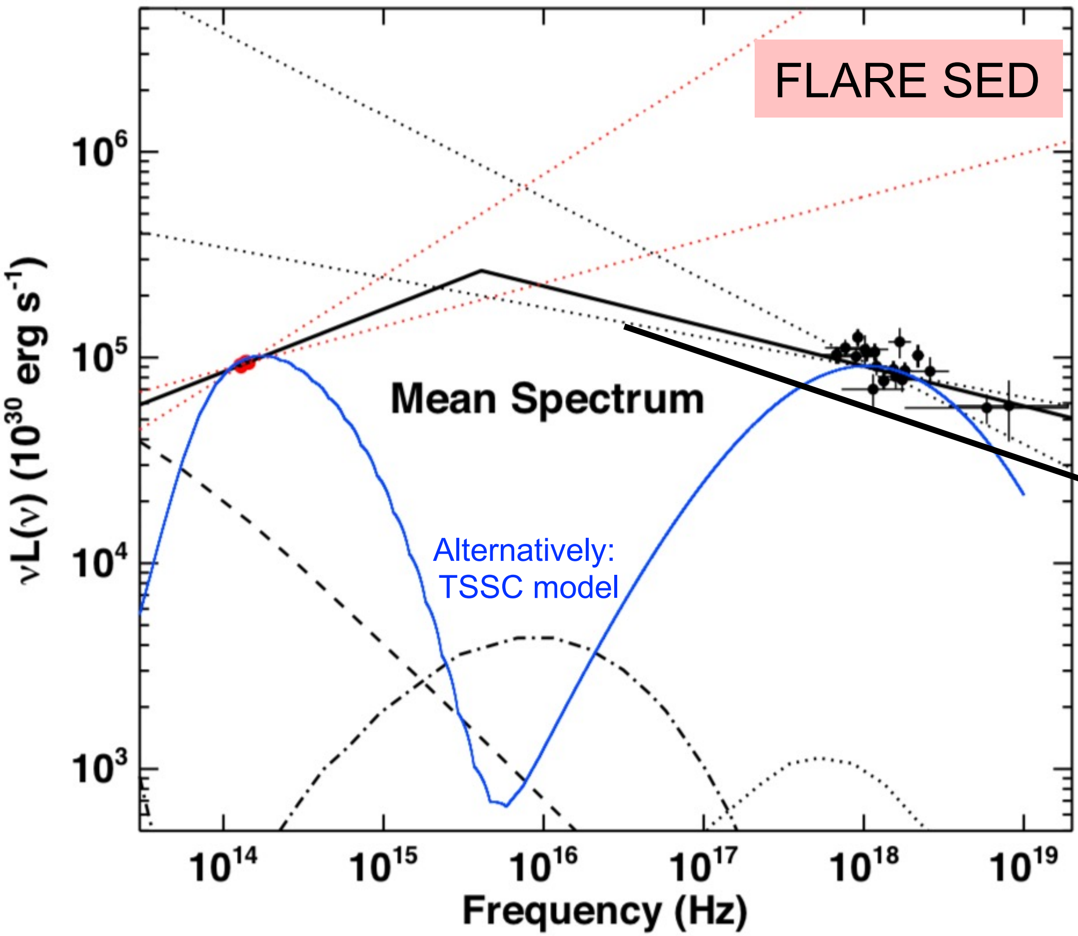
Contribution from a non-thermal tail in the electron population (traced mostly at low frequencies)

Bremsstrahlung emission from hot plasma (stellar wind) at Bondi radius (~10^5 R_S, 1-arcsec region)

Ponti et al. (2017)

The quiescent SgrA* activity has no significant impact on the circum-galactic medium

Simultaneous observations of X-ray/near-IR flare of Sgr A*. Recent results vs. models. III



XMM-*Newton* + *NuSTAR* constraints in X-rays (black points) vs. *SINFONI* in near-IR (red points, polarized emission, synchrotron)

Dotted lines: uncertainties in the determination of the spectral slopes in the two observed bands

(Black solid model)

Best-fitting synchrotron model with cooling break that imposes $\Gamma_X = \Gamma_{NIR} + 0.5$

The cooling break may evolve due to an evolution in the magnetic field (Ponti et al. 2017)

Ponti et al. (2017)

Synchrotron emission with cooling break

$$N(E)dE = E^{-p}dE$$

Powerlaw distribution of electrons (p=particle index)

$$\alpha = \frac{p-1}{2}$$

Spectral index of the synchrotron emission ($S_\nu \propto \nu^{-\alpha}$)

$$\nu\ L_\nu \propto \nu\ \nu^{-\alpha} = \nu^{(2-p+1)/2} = \nu^{\frac{3-p}{2}}$$

Dodds-Eden et al. (2009) – see also Ponti et al. (2017)

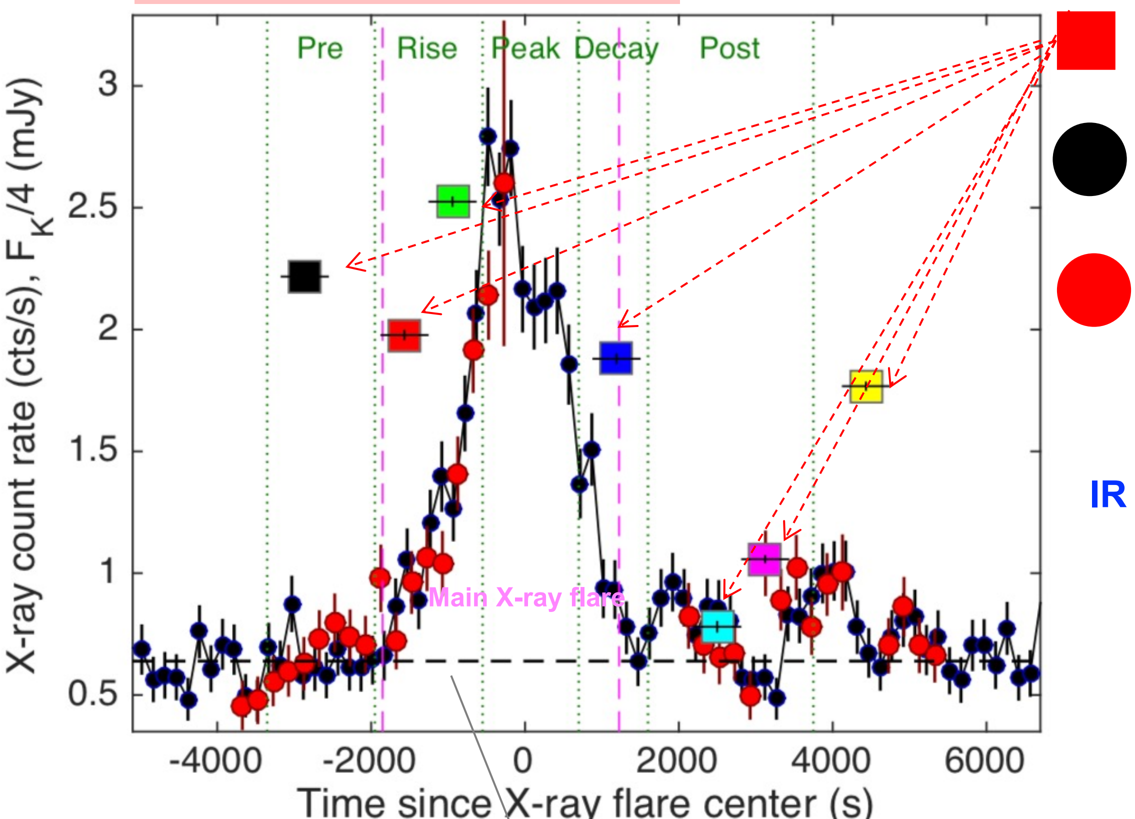
Synchrotron emission may exhibit breaks due to cooling processes → **synchrotron emission with cooling break model** to fit SgrA* flare emission

- The electrons responsible for the emission above the cooling break (due to synchrotron losses) lose energy due to synchrotron cooling faster than they can typically escape
- If the source of acceleration in the plasma occurs continuously (i.e, there is a continuous injection of electrons from the heating/acceleration process), a steady-state solution exists where the spectrum has a spectral index $\beta=(3-p)/2$ below the cooling-break frequency and $\beta=(2-p)/2$ above

Example: $p=3.6$ → $\beta=-0.3$ at low E → $\alpha=(p-1)/2)=1.3$ → $\Gamma=1+\alpha=2.3$

Simultaneous observations of X-ray/near-IR flare of Sgr A*. Recent results vs. models. IV

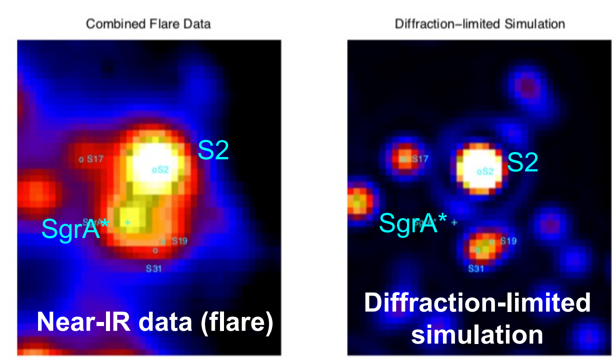
Flare lightcurves → delays



Ponti et al. (2017)

non-flare (quiescent) X-ray level

IR flare, then X-ray flare (~1 ks delay)



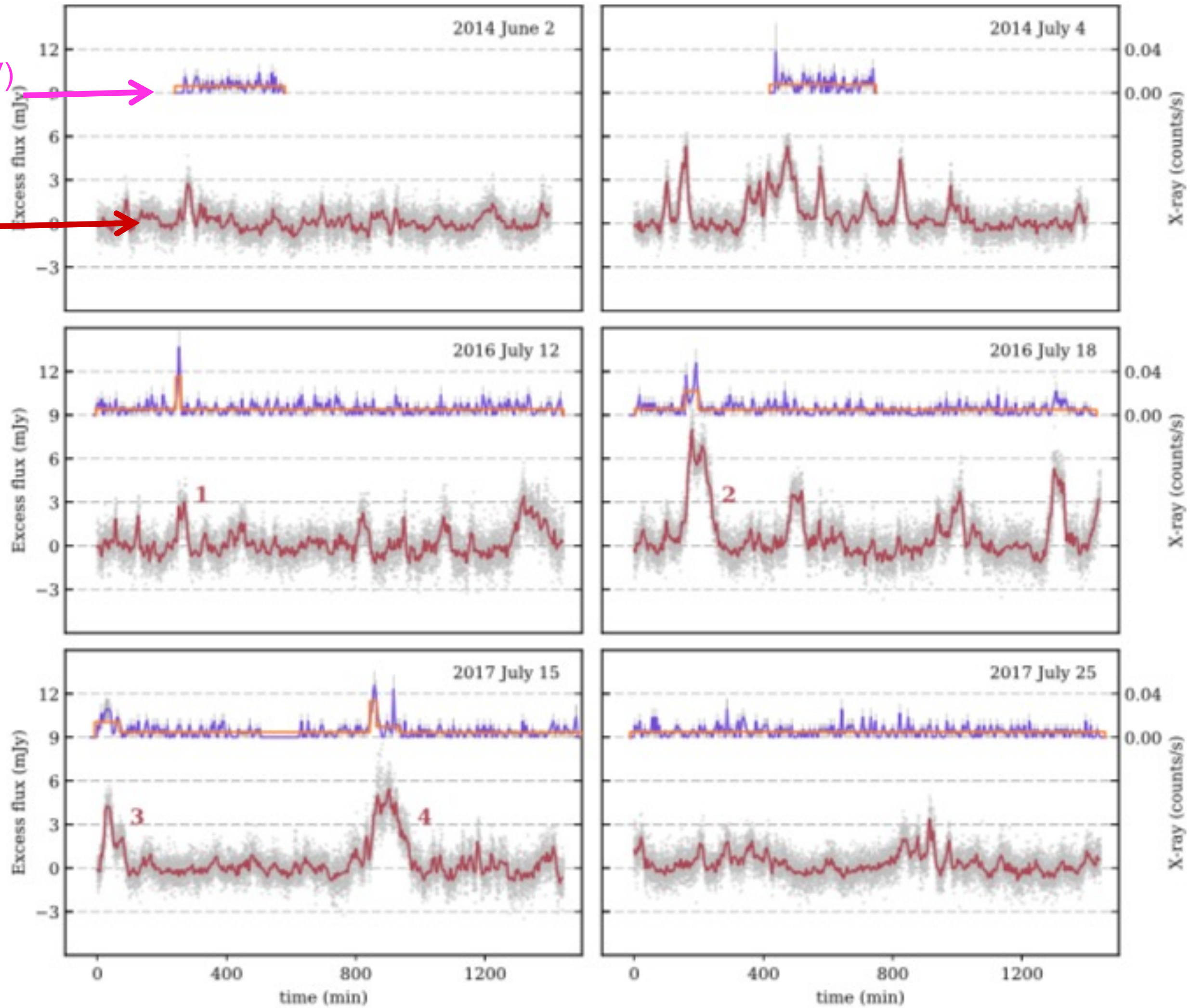
Simultaneous observations of X-ray/near-IR flare of Sgr A*. Recent results vs. models. V

Chandra (2-8 keV)
(300-s bin)

Spitzer (4.5μm)
(3.5-min bin)

Four X-ray flares ≈4 × quiescence

Boyce et al. (2019)



Main results

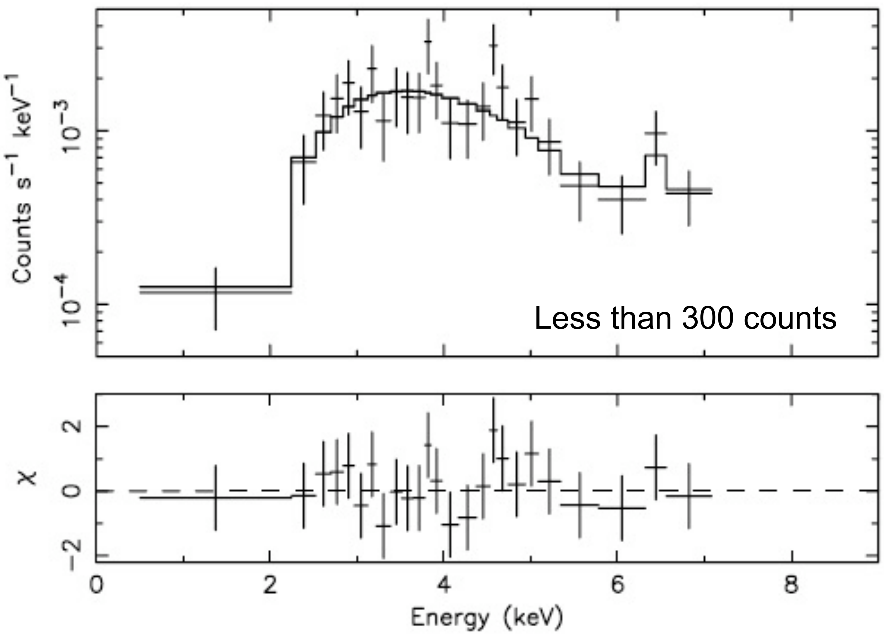
(1) X-ray flares have an IR flare, not necessarily the opposite

(2) X-ray flares of low intensity may be hidden in the diffuse thermal emission around SgrA*

(3) X-ray flares may lead the IR by ≈10−20 min (but 99.7% conf. interval still consistent with no zero time-lag)

Agreement with models describing both IR and X-ray flares as **synchrotron emission** originating from particle acceleration events involving magnetic reconnection and shocks in the accretion flow; still consistent with SSC processes

X-ray spectrum of Sgr A* in quiescent state

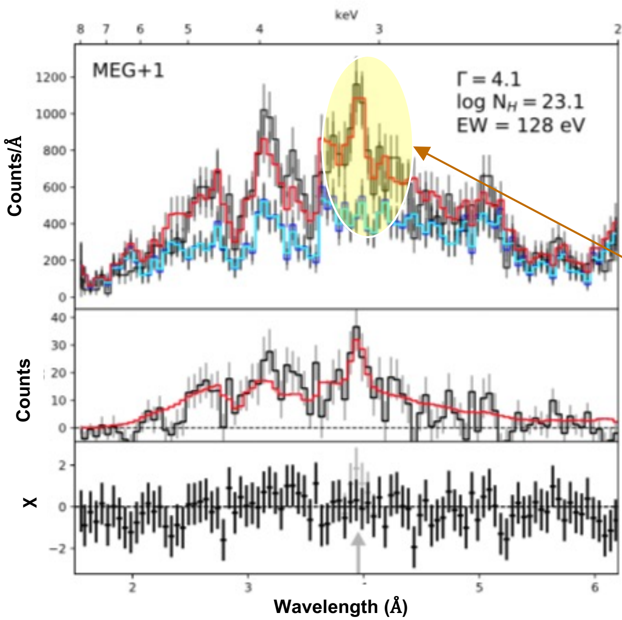


Bremsstrahlung (kT≈2 keV) emission emitted near the Bondi radius + iron line as best-fitting model

Obscuration of ≈10^{23} cm^{-2}

Almost no counts below 2 keV (A_V≈30 mag)

Baganoff et al. 2003



Corrales et al. 2020

Counts=black

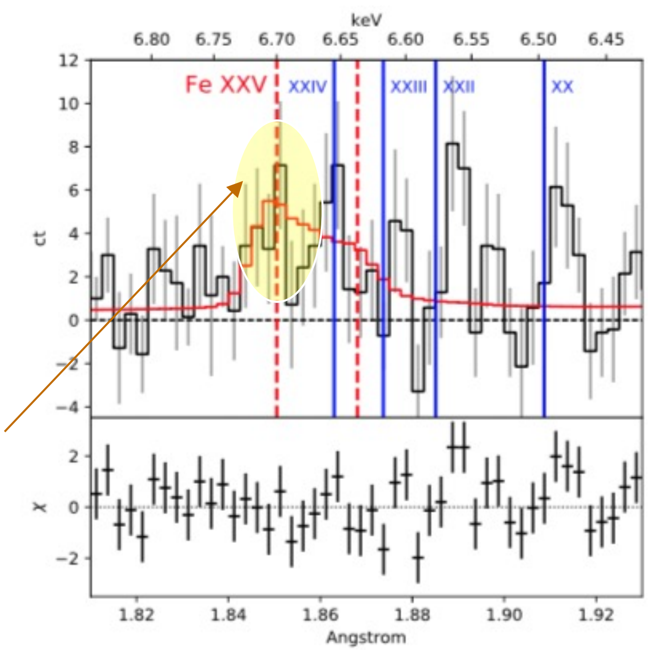
Raw backg=dark blue

Backg fit with a spline: light blue

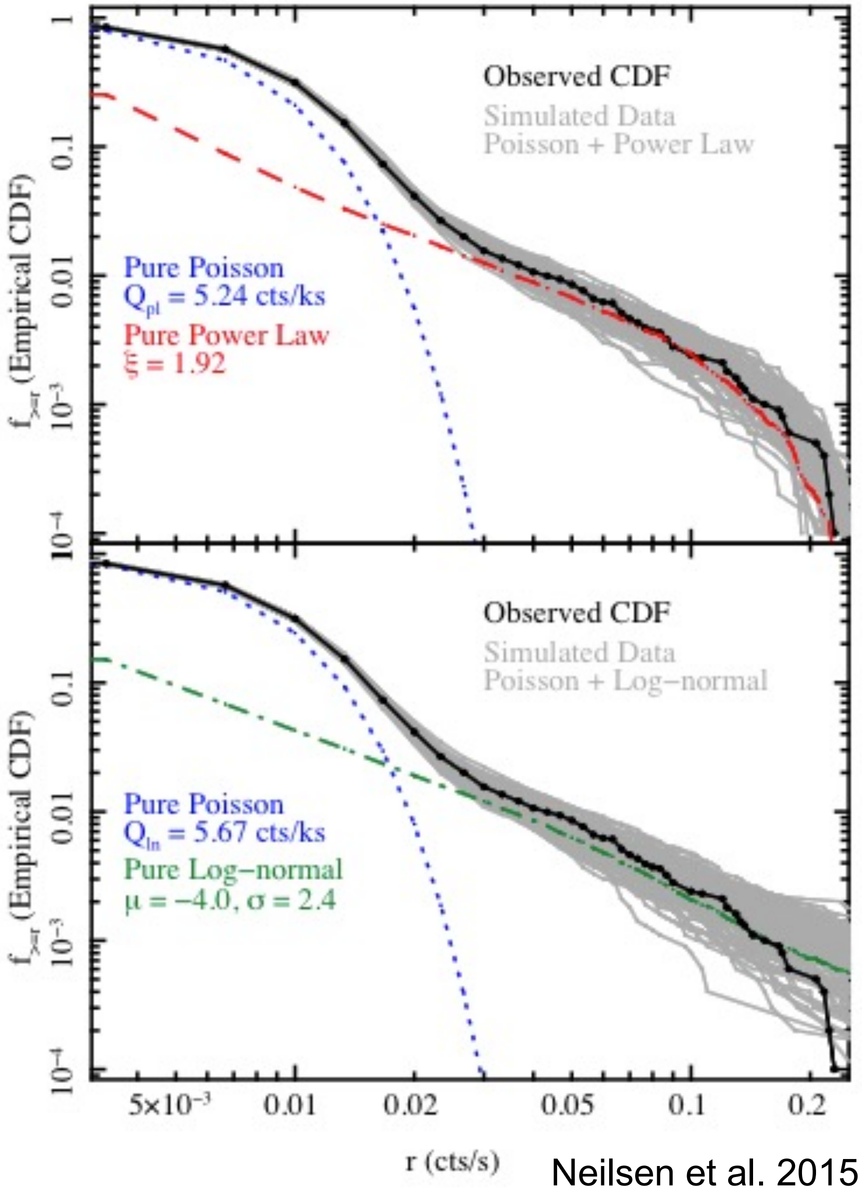
Back+model: red

3Ms *Chandra*/HETG program

3.1 keV Argon line + 6.7 keV FeXXV line consistent with **RIAF** (inefficient-disc) model



Quiescent + flare emission in Sgr A*



Neilsen et al. 2015

Chandra count rate distribution function since 2013 (fraction of time bins with a count rate larger or equal a given rate)

Emission from SgrA* as the sum of a **quiescent** and a **flare** emission (modelled in two different ways in the two panels)

Simulations (**grey**) drawn randomly from the joint probability distributions of the two events

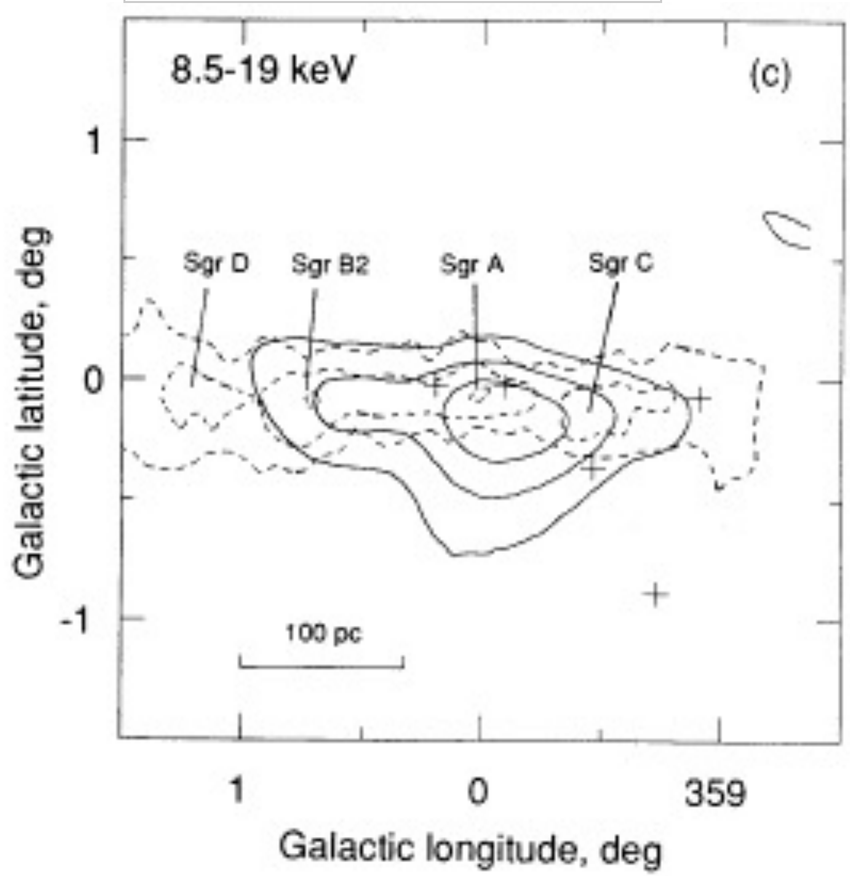
“Postcards” from the past: how the molecular clouds reflect the past activity of SgrA*

[mostly derived from Ponti et al. 2010]

Open problems: what is the origin of the hard X-ray emission from molecular clouds (MC)

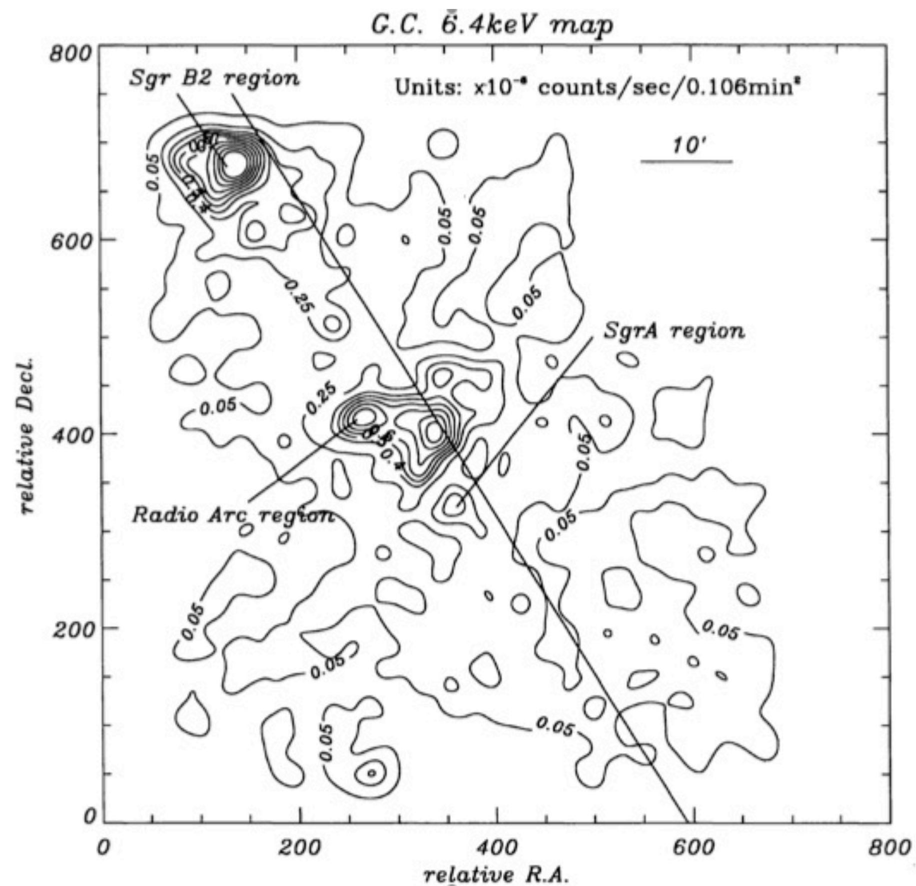
Former studies limited by spatial resolution

GRANAT: Hard X-ray/MC



Sunyaev et al. 1993

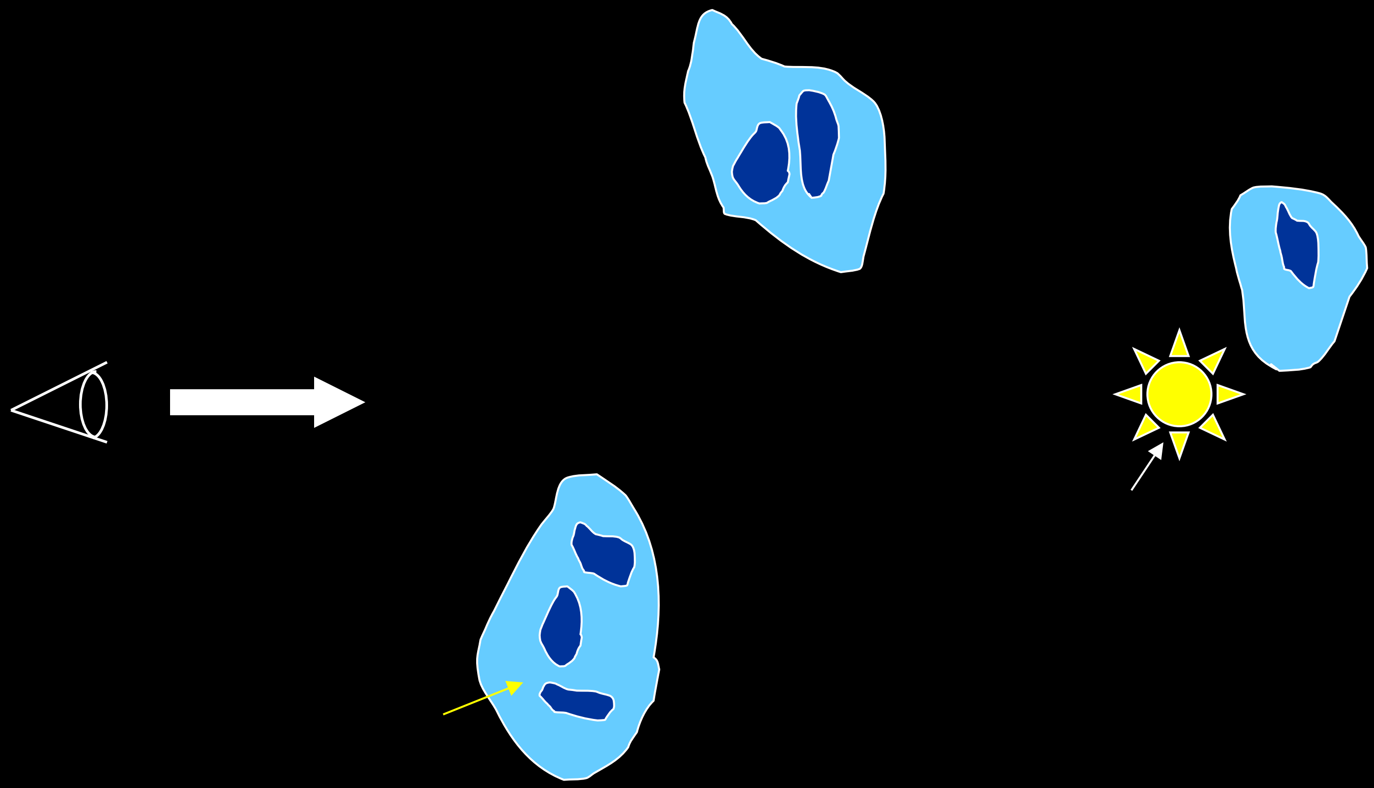
ASCA: Fe Kα from some MC



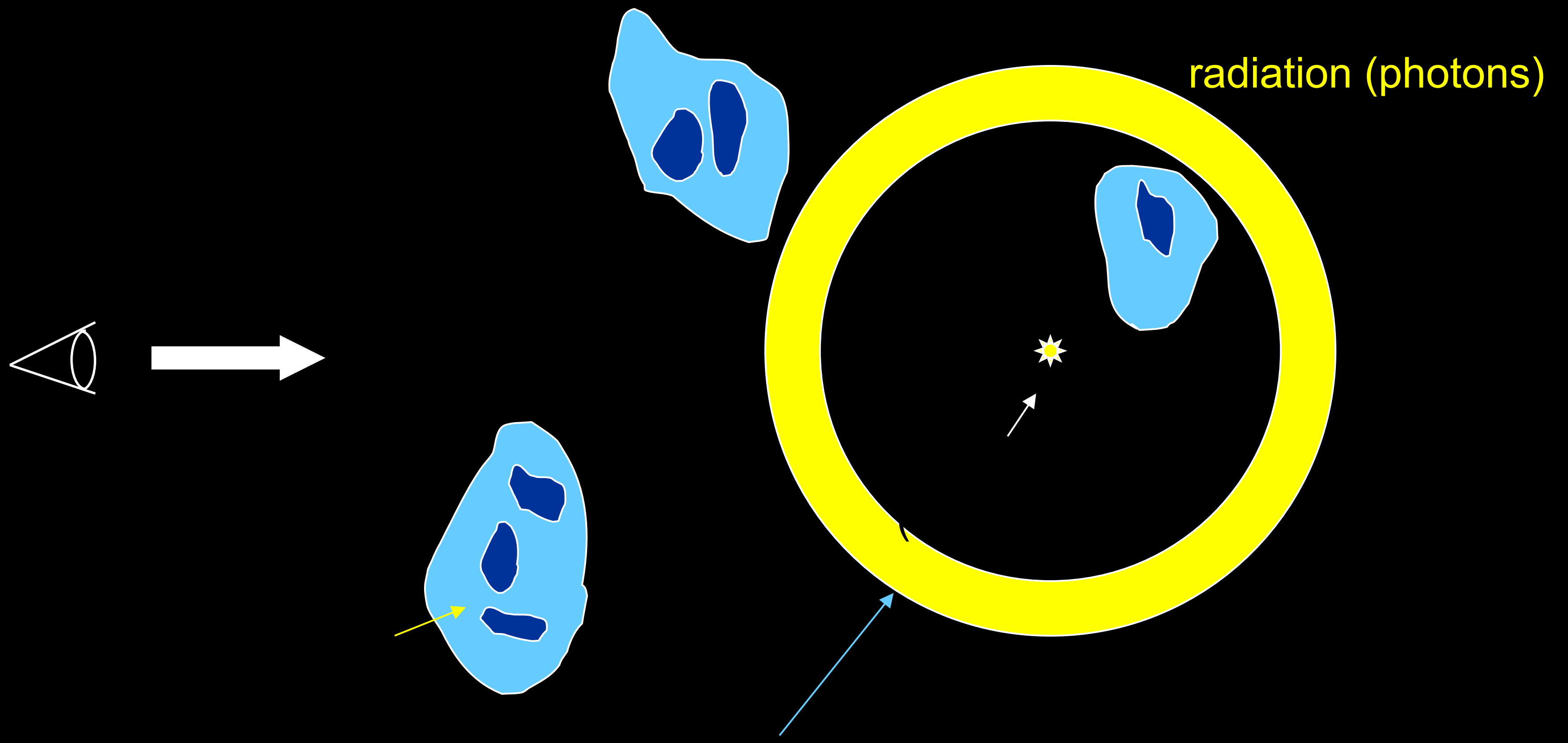
Koyama et al. 1996

The idea: molecular clouds as mirrors of past activity (**X**-ray **R**eflection **N**ebula − XRN − model)

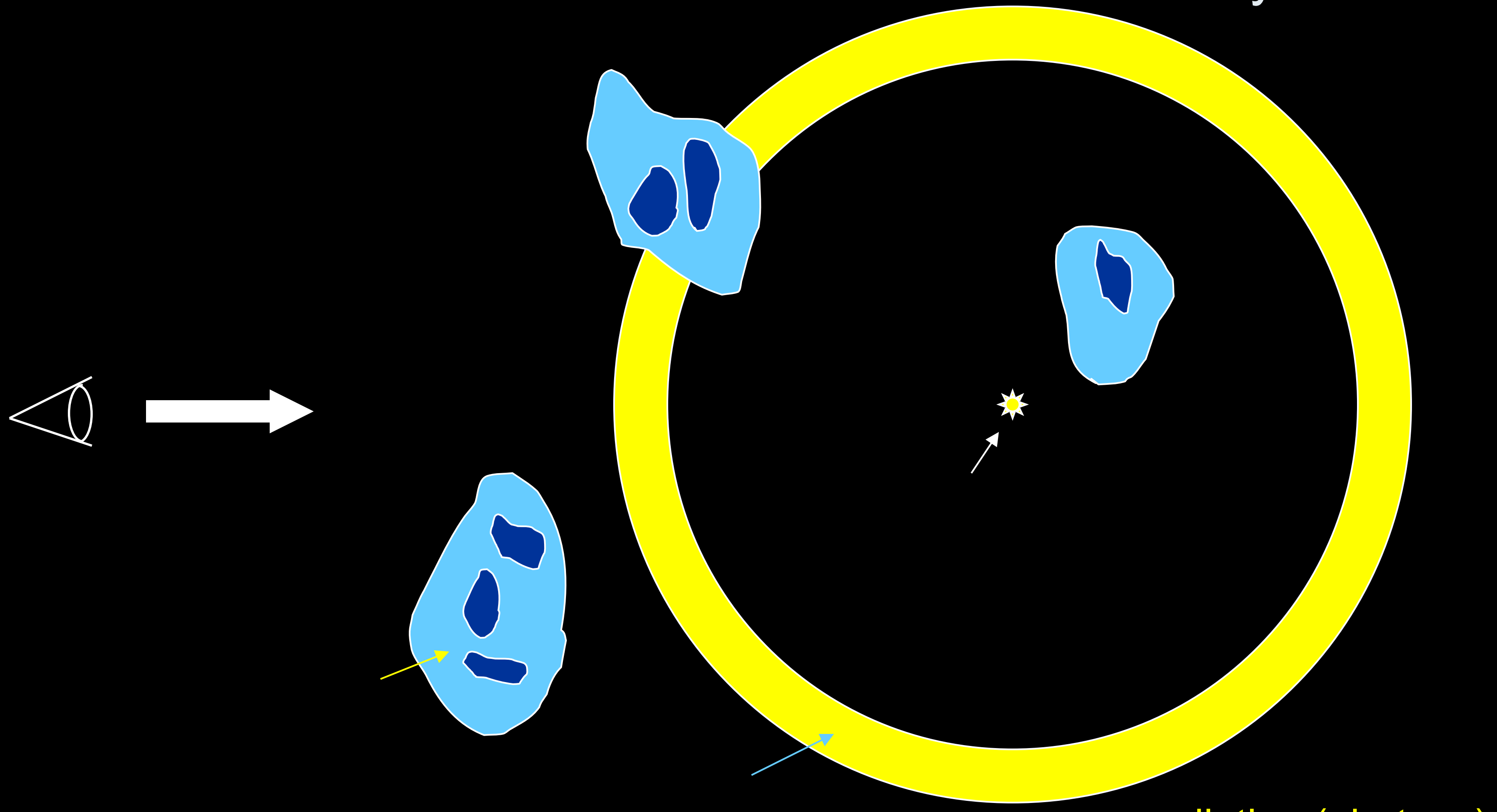
Reflected Emission from the Past Outburst of an X-ray Source



Reflected Emission from the Past Outburst of an X-ray Source



Reflected Emission from the Past Outburst of an X-ray Source



The idea: molecular clouds as mirrors of past activity (**X**-ray **R**eflection **N**ebula − XRN − model)

Sgr A* sits on the centre of the Central Molecular Zone (CMZ)

10^7-10^8 $M_\odot$ of MC in the central 300 pc (in total, 10% of the neutral gas mass of the Galaxy)

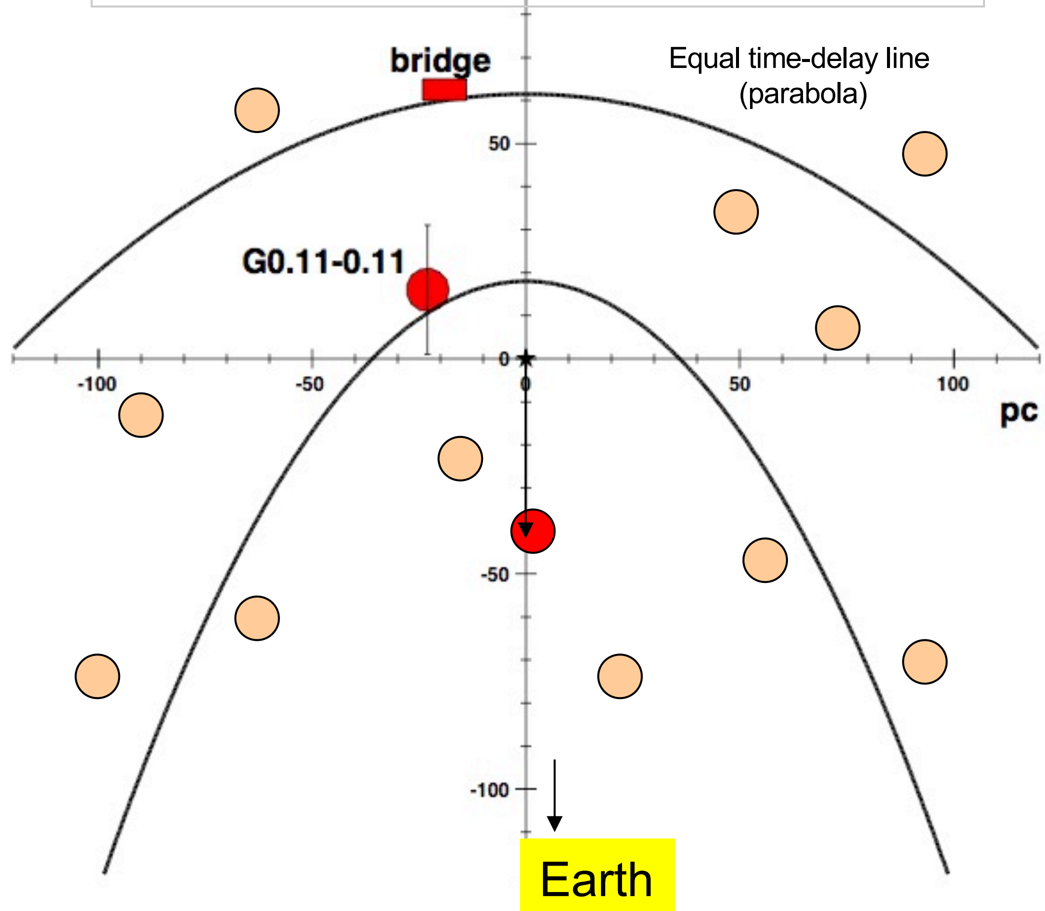
⇒ MC are mirrors of the GC past activity

$$I_{\mathrm{FeK}} \propto \frac{n_H \times r^2 \times L_{SgrA*}}{d^2}$$

Light fronts appear to us as parabola

⇒ Tool to study history of GC emission

Face-on view of the Galactic Plane as seen from the direction of the North Galaxy Pole



Sunyaev et al. 1993; 1998

$$\Omega = r^2 / 4d^2 = \frac{4\pi D^2 \times F_{6.4}}{\tau \times L_{\mathrm{X}} \times 10^7 \times Z} =$$

$$= 5.17 \times 10^{-4} \left(\frac{F_{6.4}}{10^{-4}} \right) \left(\frac{0.1}{\tau} \right) \left(\frac{Z_{\mathrm{sun}}}{Z} \right)$$

“adapted” from Sunyaev & Churazov (1998)

$$F_{6.4} = I_{\mathrm{FeK}} \propto \frac{r^2 n_H L_{\mathrm{X}} Z}{d^2}$$

Ω=solid angle of the cloud from the location of the primary source (Sgr A*)

r=radius of the cloud

d=distance of the cloud from Sgr A*

D=distance to the observer (≈8 kpc)

$F_{6.4}$=iron Kα line flux (in photons/cm^2/s)

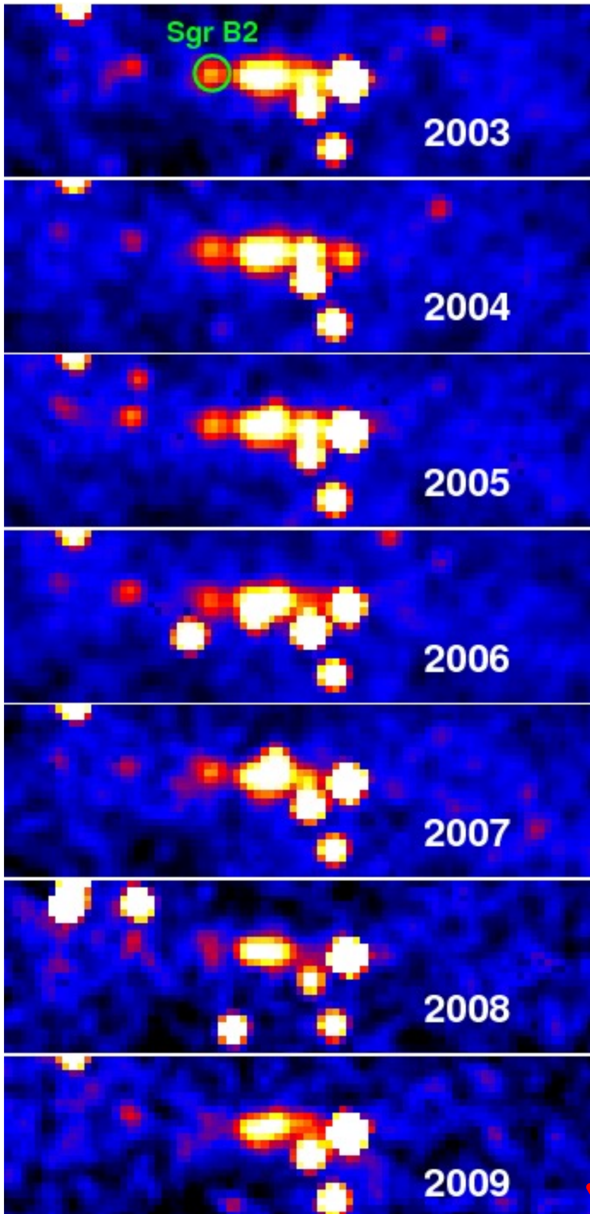
τ=optical depth of the cloud

L_X=X-ray luminosity of the SgrA* flare

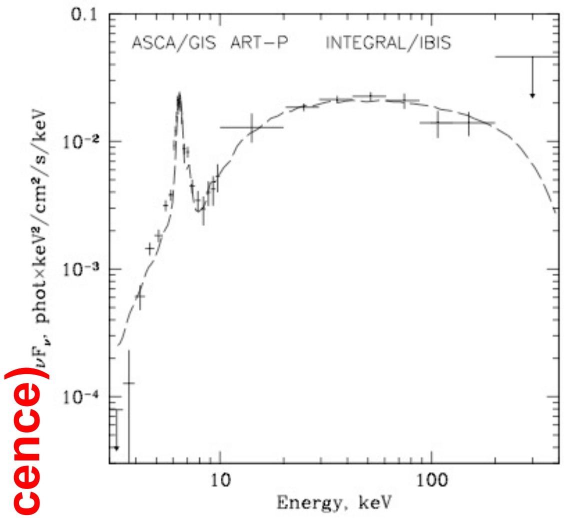
Z=iron abundance

n_H=column density of the cloud, related to its optical depth τ

The high-energy (INTEGRAL) view of Sgr B2



Decaying Sgr B2 flux (fluorescence)

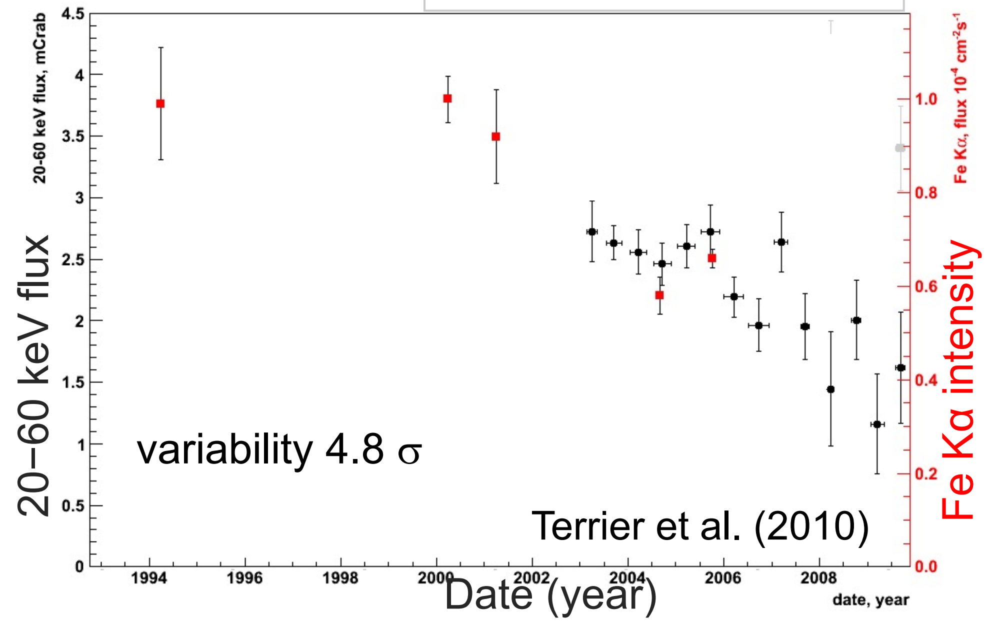


INTEGRAL: MC - reflection

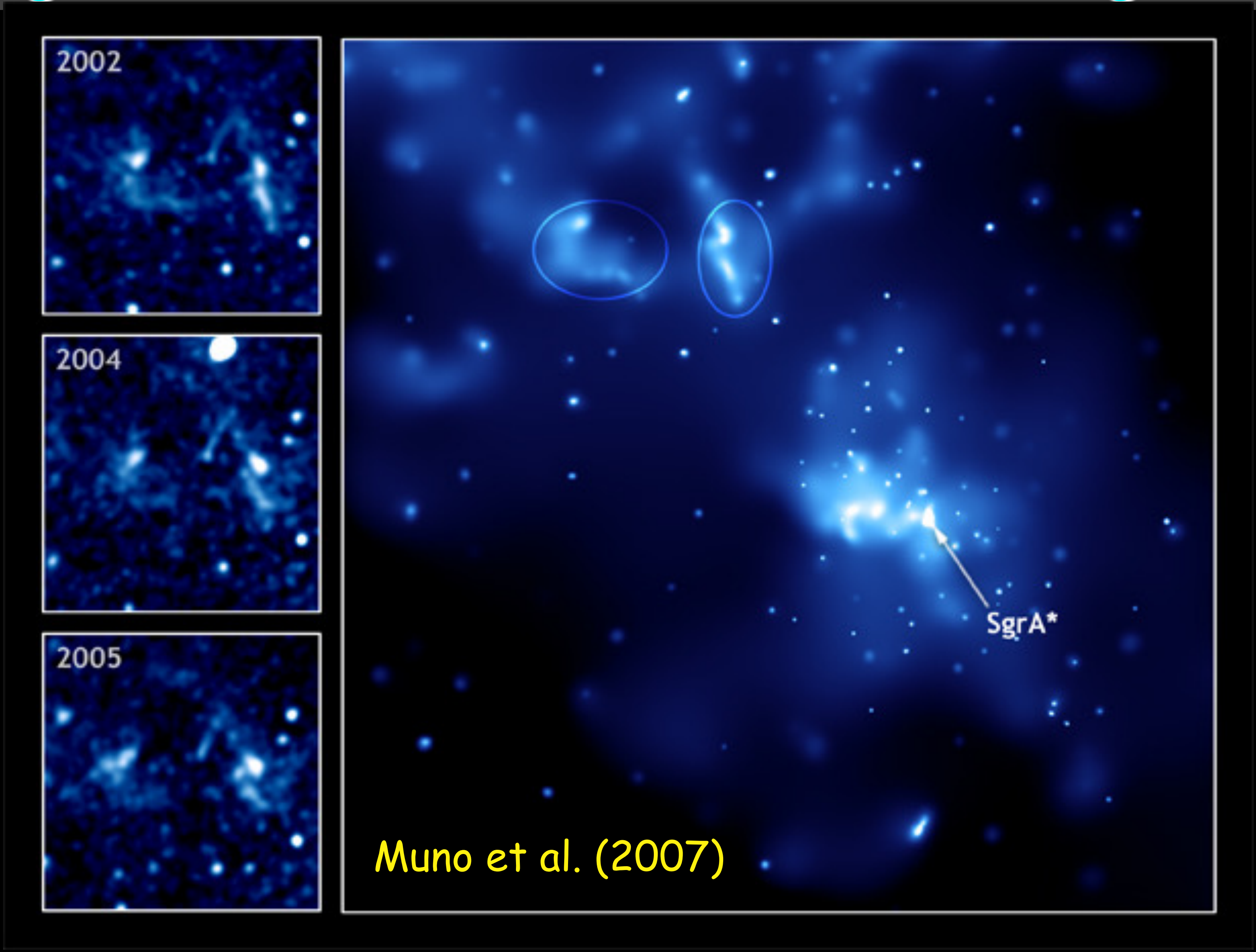
Large (>30%) level of linear polarization expected in X-rays

Revnivtsev et al. 2004 – see also Kuznetsova et al. (2021) for >2011 obs.

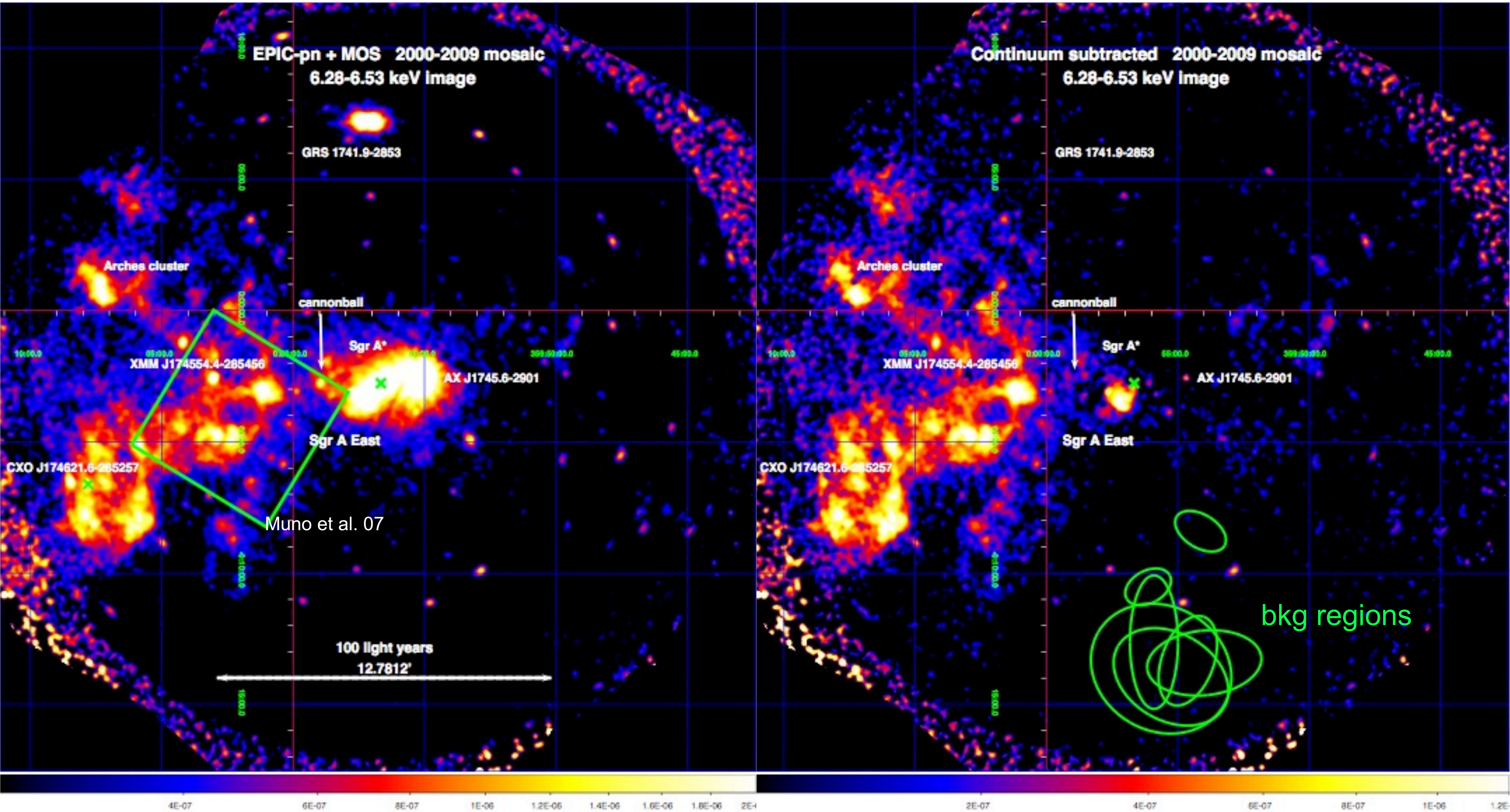
Decay time ~8.2±1.2 yr
~core light crossing time



Light Echoes from a Past Outburst of Sgr A*?



The XMM-*Newton* monitoring of Sgr A



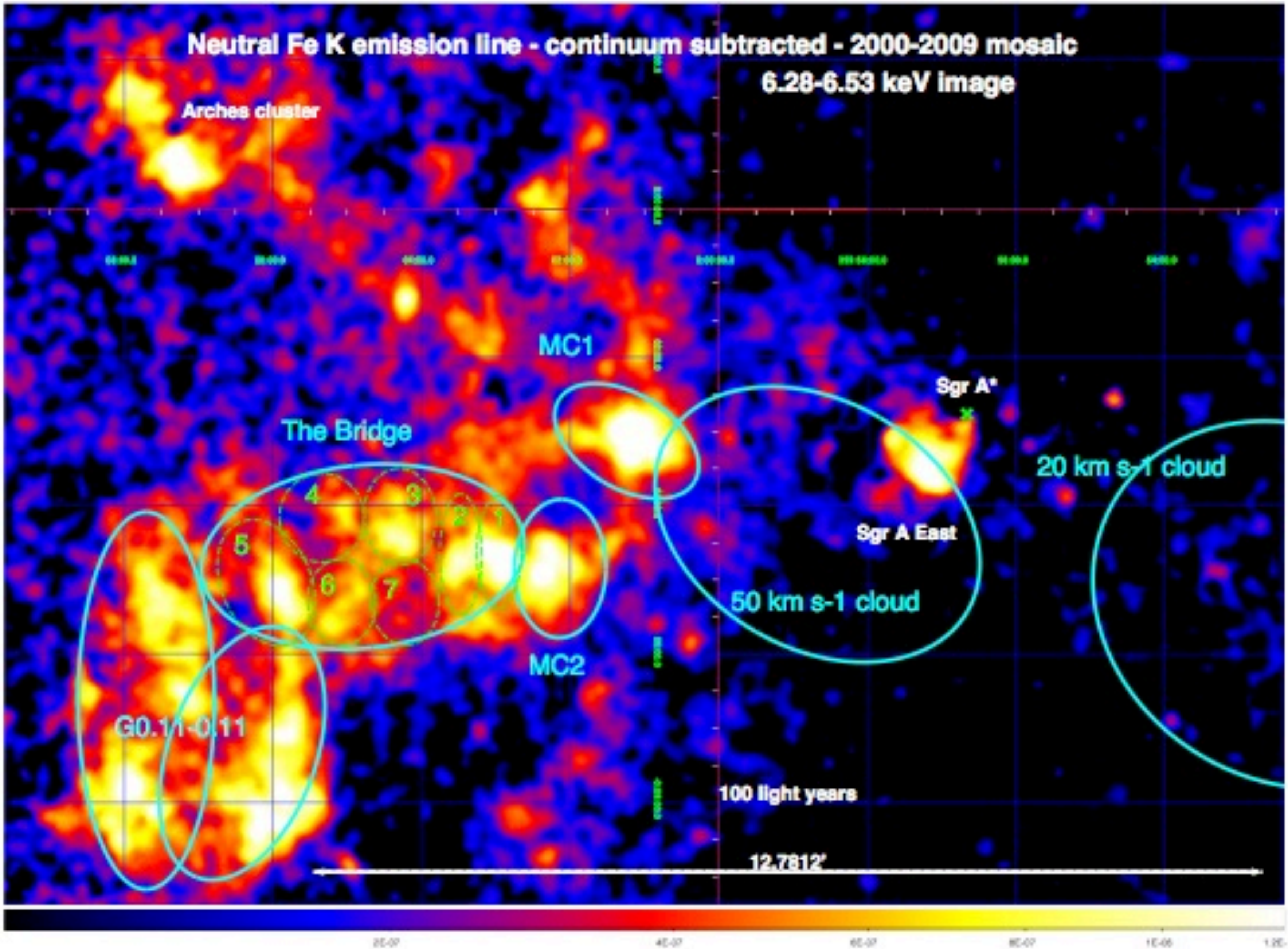
6.4 keV map

2000−2009 mosaic

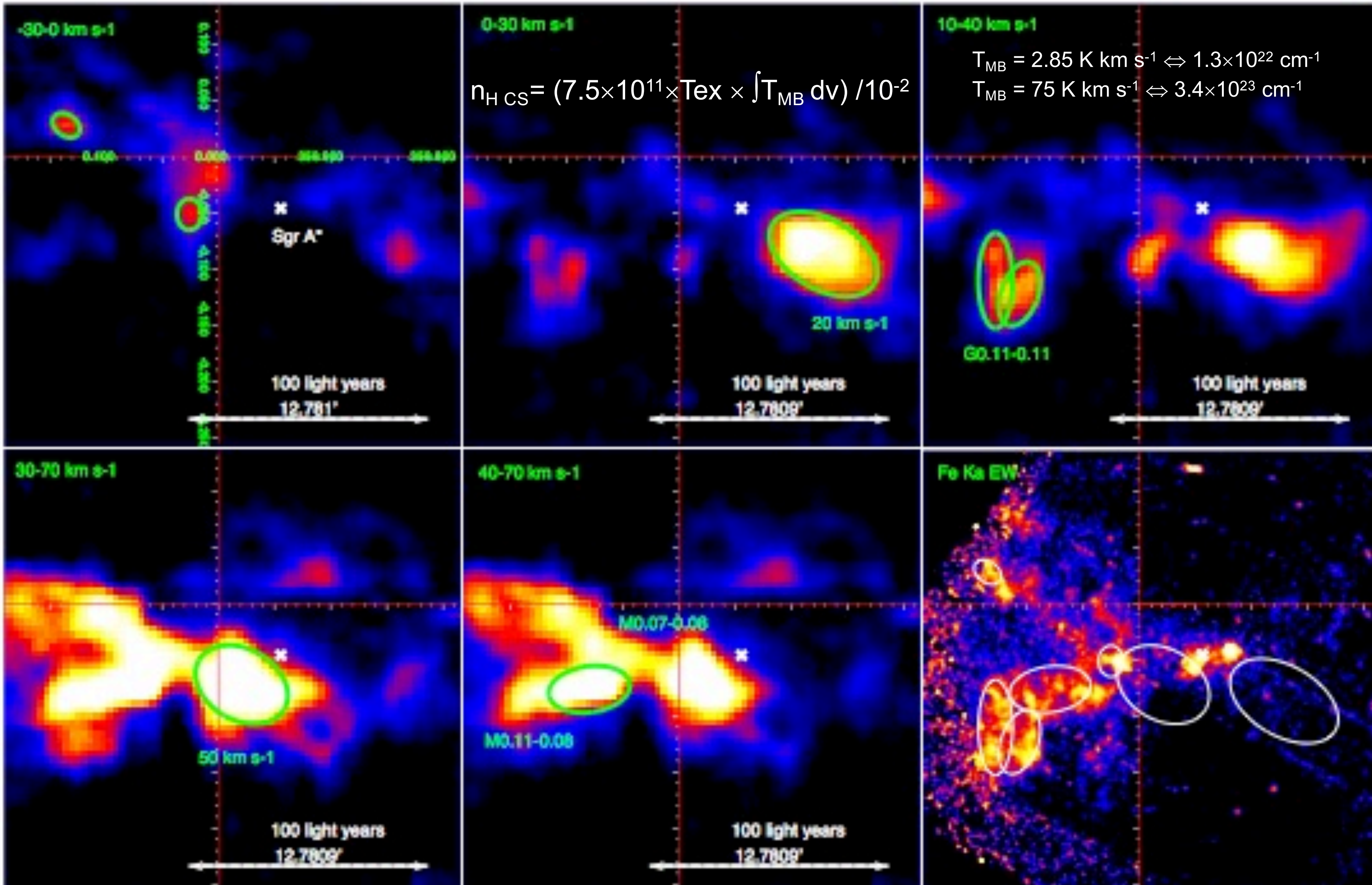
6.4 keV map − continuum

The X-ray continuum has ben removed from the iron map

Zoom into the inner regions



Molecular (CS) emission in the GC to locate MC



Past activity of Sgr A*: Sgr B2 and G0.11-0.11

Sgr B2

N_H= 8×10^{23} cm^{-2}

D_{proj}= 100 pc but 130 pc in front of Sgr A* (Reid et al. 2009)

Radius = 7 pc

$norm_{FeK}$= 1.7×10^{-4} ph cm^{-2} s^{-1}

$L_{2\text{-}10\ keV\ SgrA*}$ ~ 1.4×10^{39} erg s^{-1} (Revnivtsev et al. 2004)

t = 100 yr ago

G0.11-0.11

N_H=2×10^{22} cm^{-2} (Amo-Baladron et al. 2009)

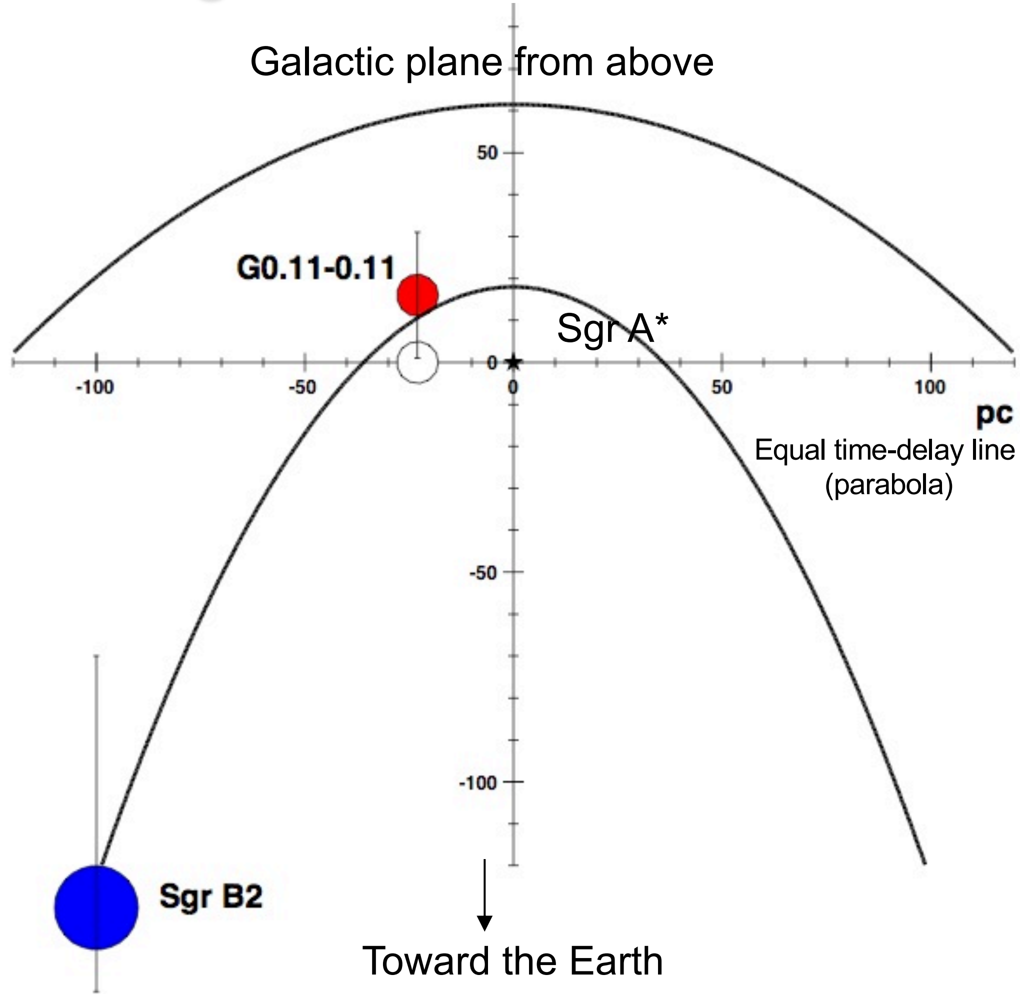
D_{proj}=25 pc

Radius=3.7 pc

$norm_{FeK}$=0.9×10^{-4} ph cm^{-2} s^{-1}

L_{SgrA*} > 10^{39} erg s^{-1}

t > 75 years ago



Assuming a flare$_{Sgr\ A*}$ = 1.4×10^{39} erg/s, lasting ≥10 yr and terminated ≈100 yr ago

$$L_{SgrA*} \propto \frac{d^2 \times I_{FeK}}{r^2 \times n_H}$$

Past activity of Sgr A*: the Bridge

Bridge

$N_H = 9 \times 10^{22}$ cm^{-2}

$D_{proj} = 15$ pc

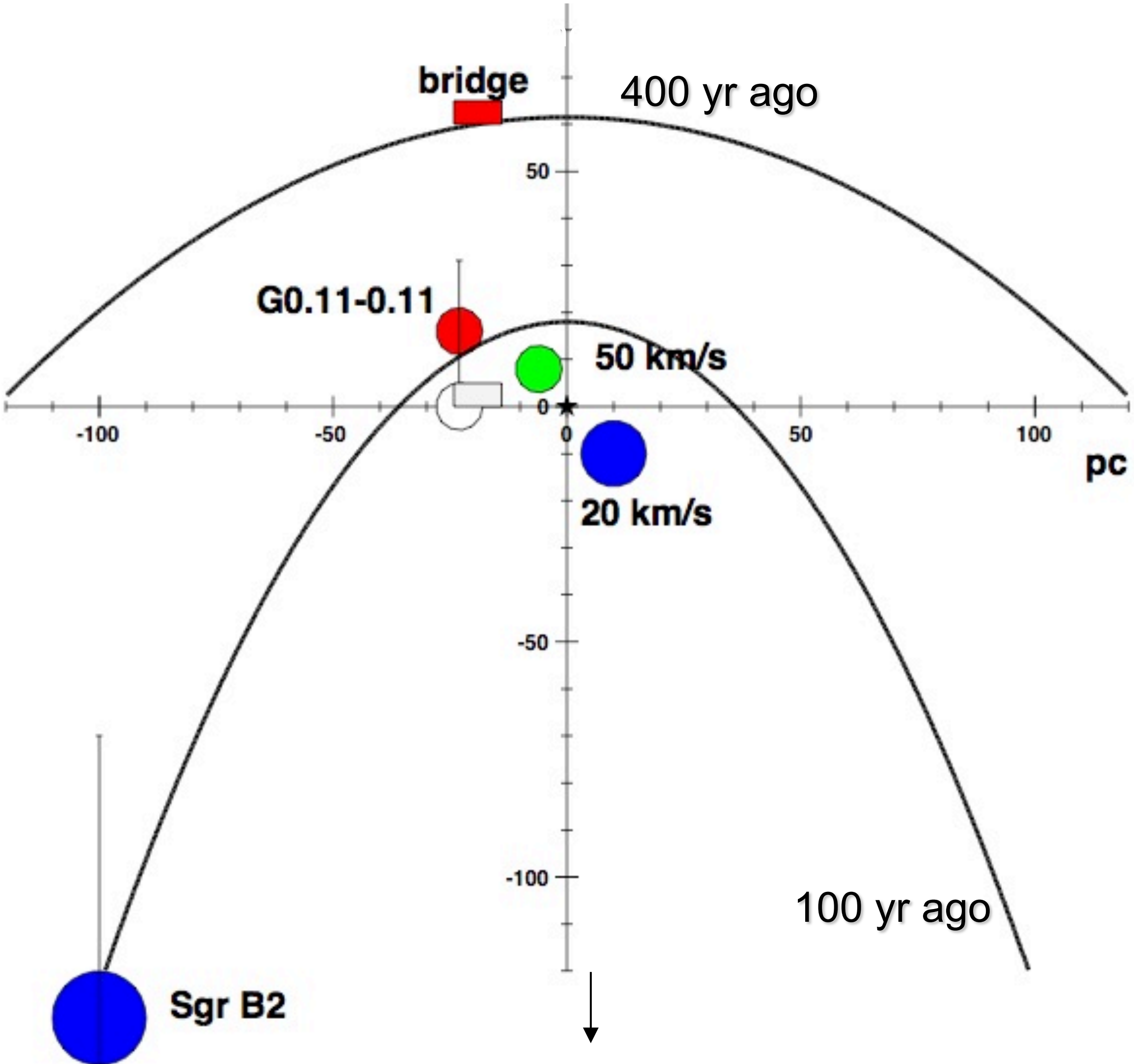
Radius=1.1 pc

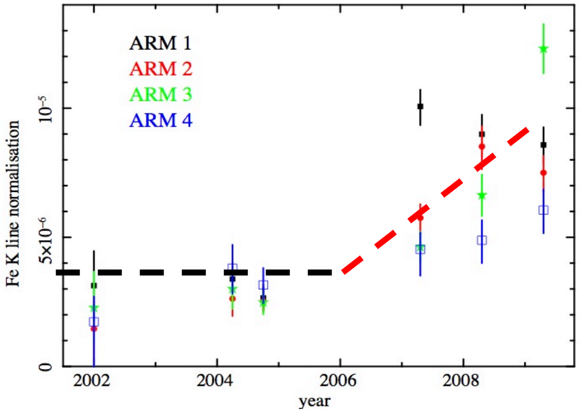
$norm_{FeK} = 1.1 \times 10^{-5}$ ph cm^{-2} s^{-1}

Assuming $L \sim 1.4 \times 10^{39}$ erg s^{-1}

→ 60 pc

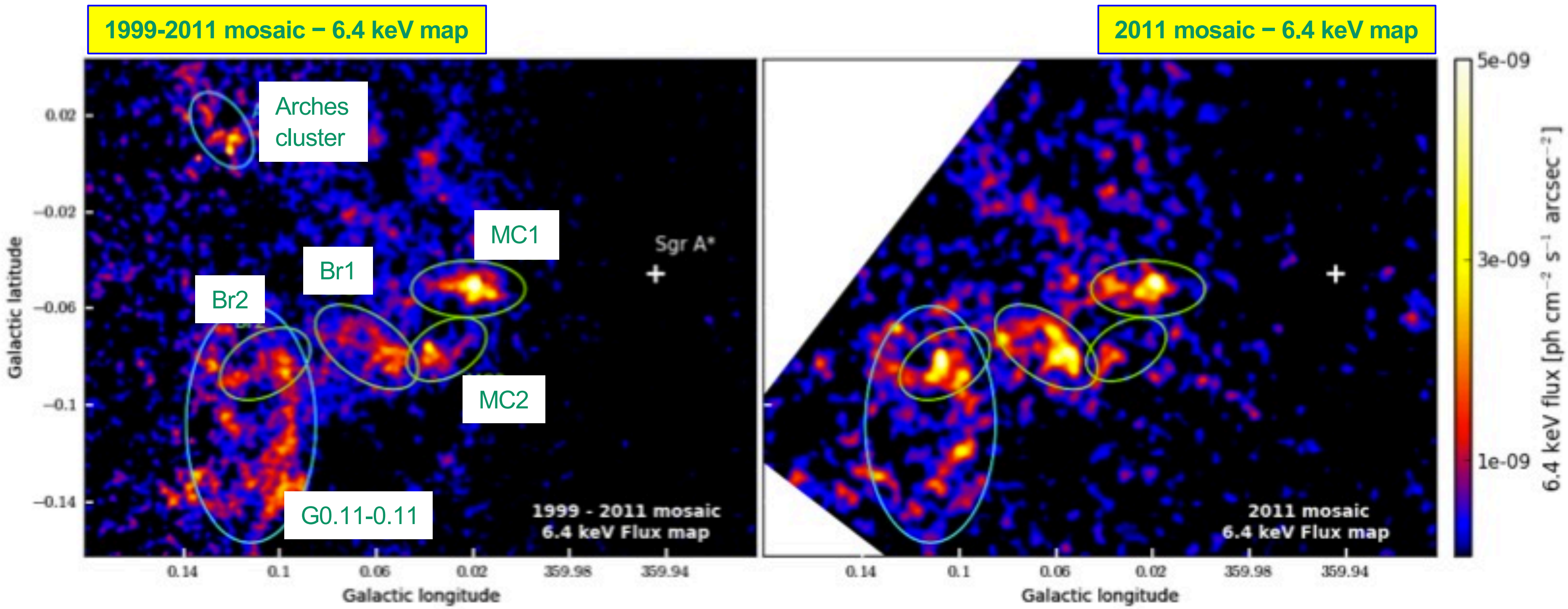
➔ Sgr A* activity 400 yr





Increasing Fe 6.4 keV emission in the Bridge ➔ the light front from SgrA* was emitted 400 yr ago

Sgr A complex: the *Chandra* view. I



Clavel et al. 2013

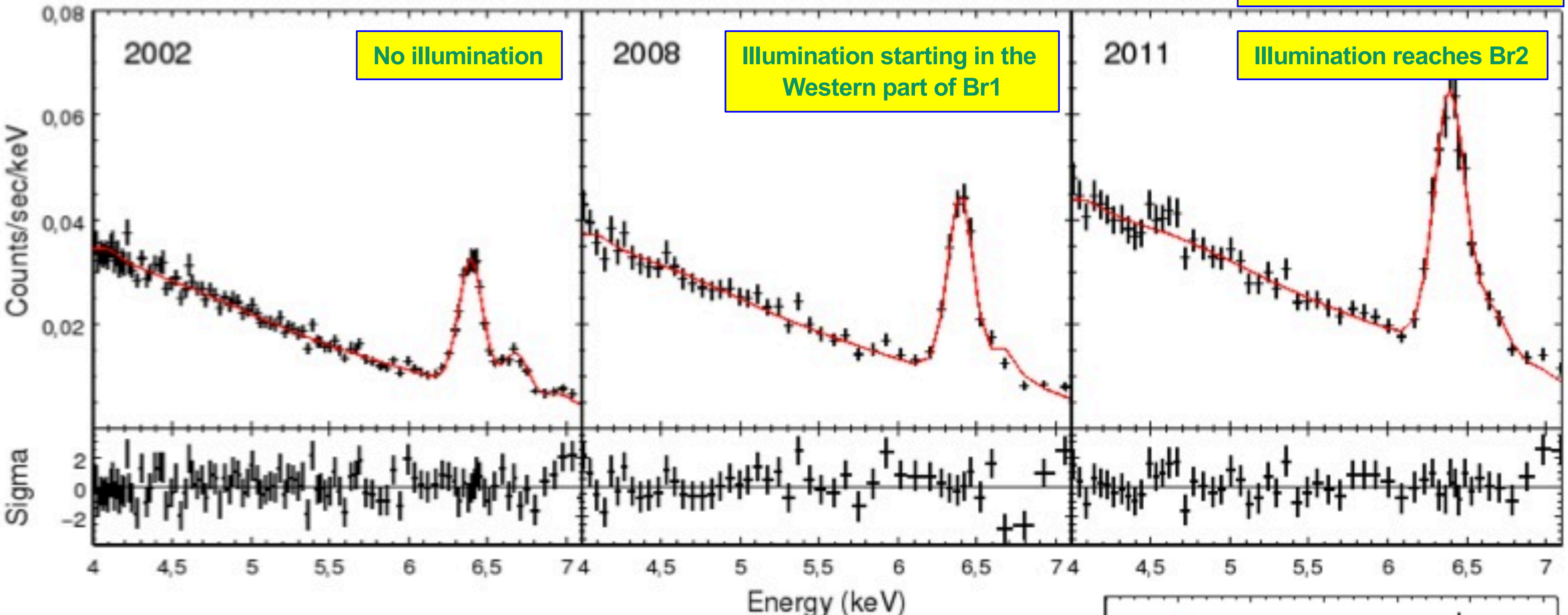
Strongly variable Fe Kα emission line from molecular clouds, suggesting reflection

Propagation of the “illumination” along the Bridge

Here MC2 flux decreasing at the 6.8σ level

Sgr A complex: the *Chandra* view. II

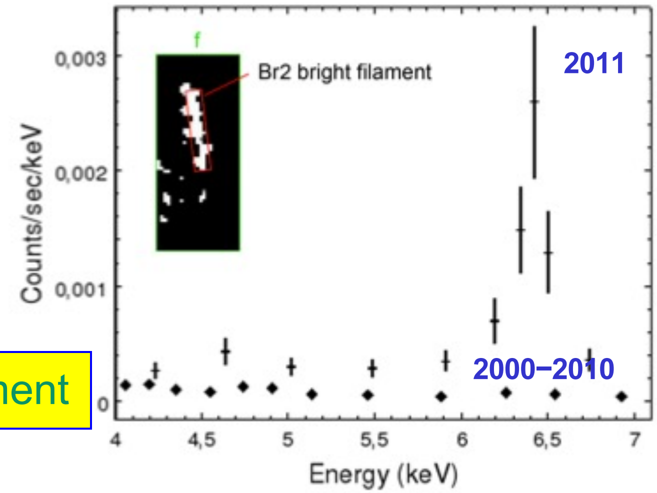
Bridge spectra



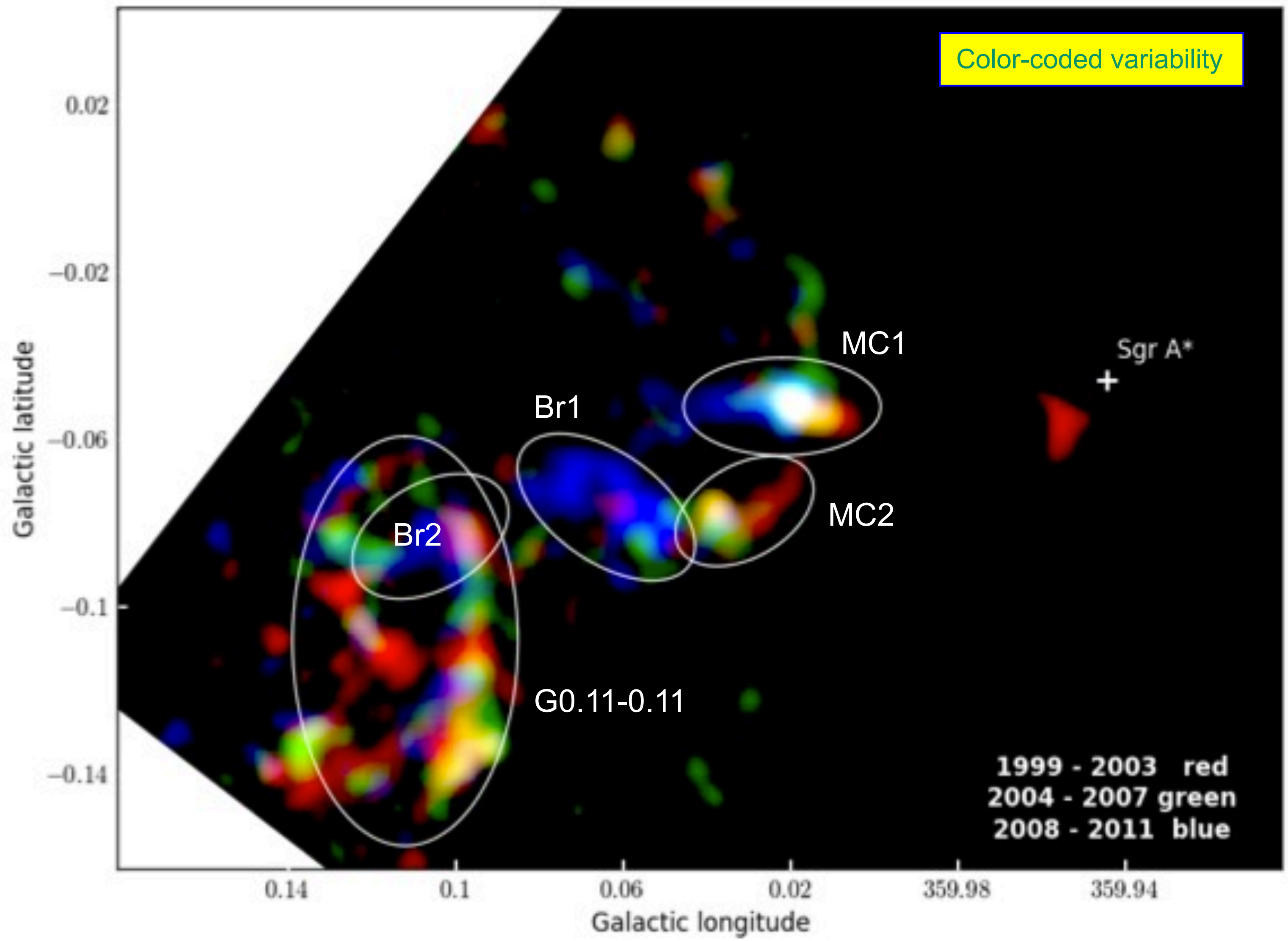
Fe Kα increases with time (Clavel et al. 2013)

Br1 and Br2 are likely illuminated by a single strong event lasting less than 3 yrs

Br2 filament



Sgr A complex: the *Chandra* view. III



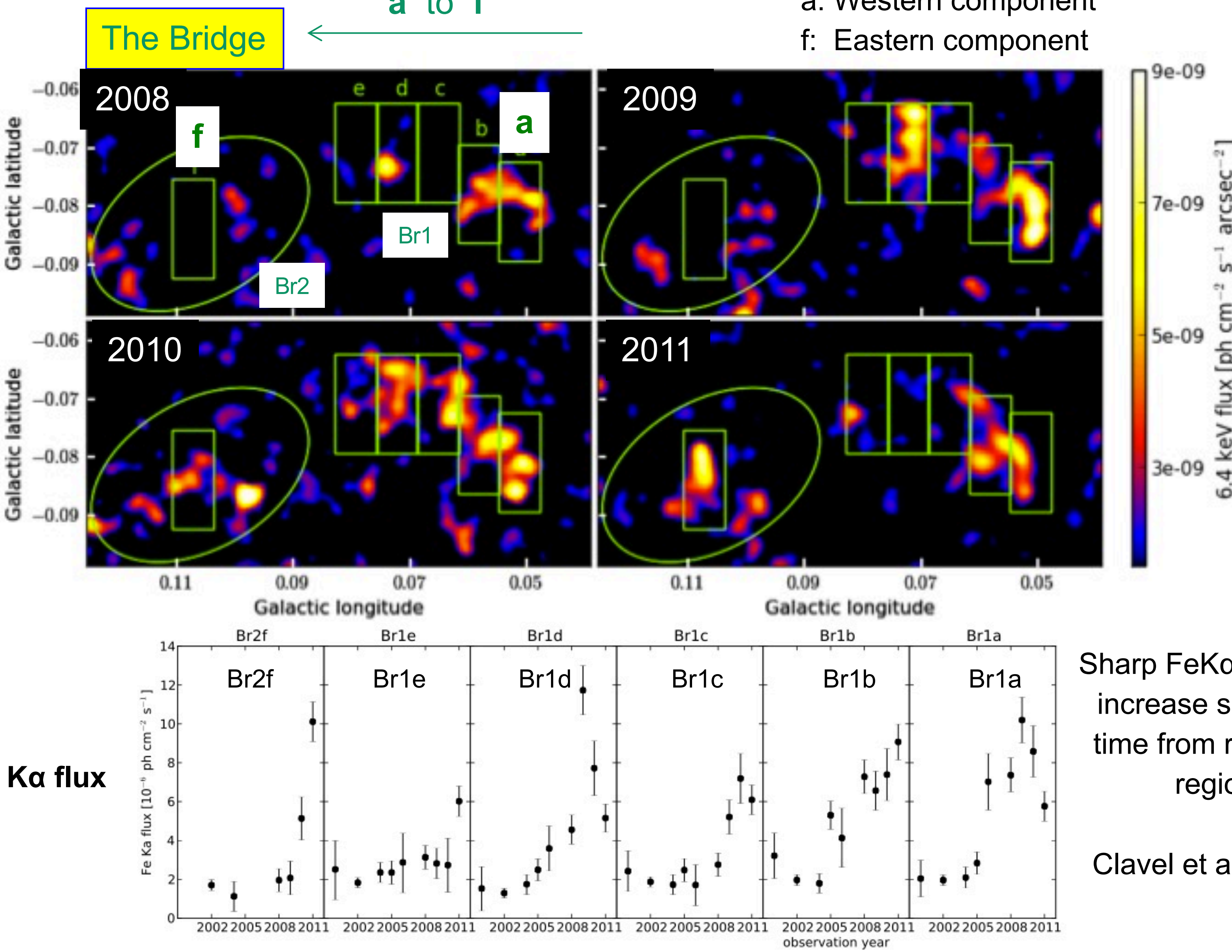
MC1 and MC2: variability from West to East, then late illumination of Br1 and Br2
More complex variability pattern for G0.11-0.11 (Clavel et al. 2013)

Sgr A complex: the *Chandra* view. IV – The 6.4 keV line

a to f

a: Western component

f: Eastern component



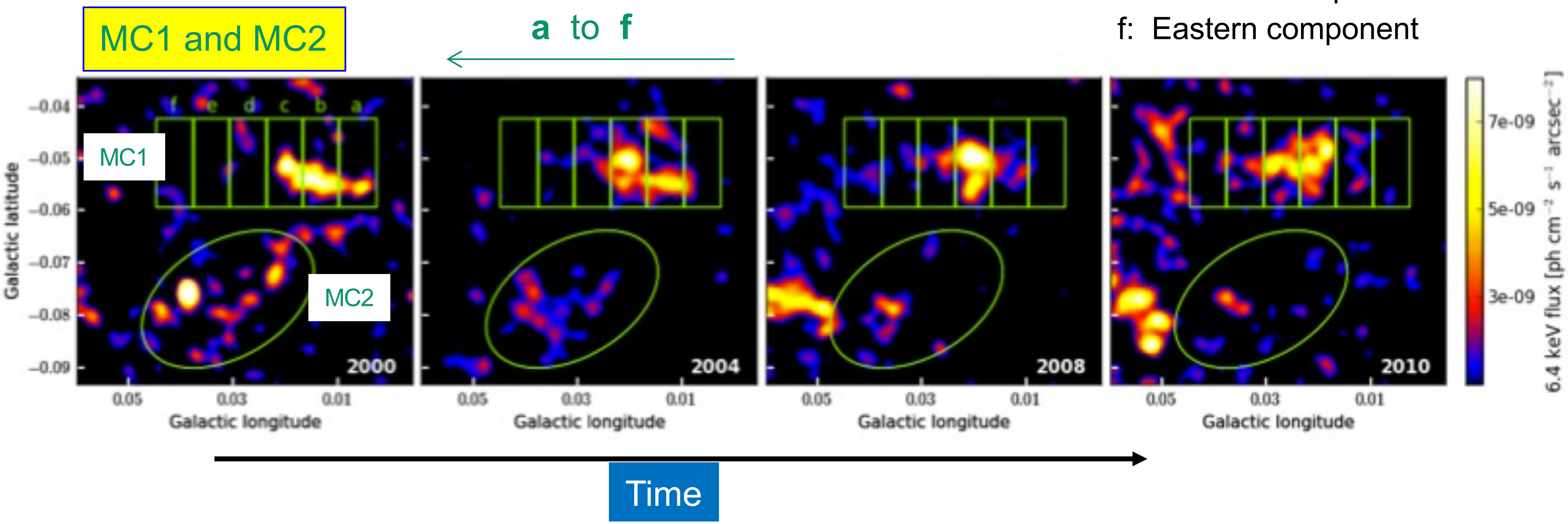
Fe Kα flux

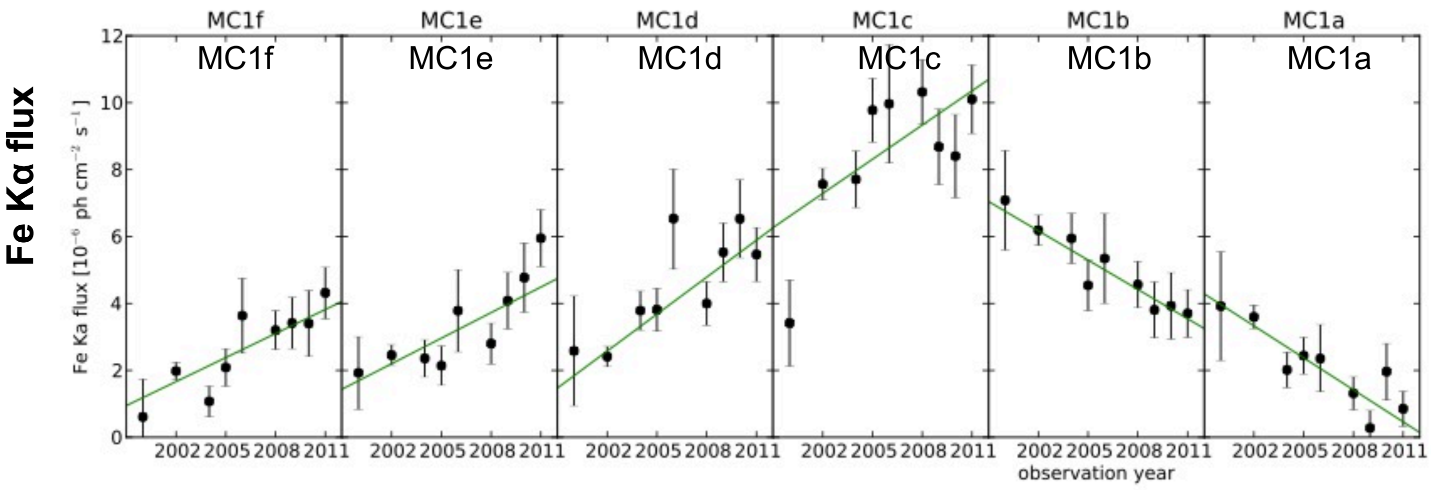
Sharp FeKα intensity increase shifted in time from region to region

Clavel et al. (2013)

Sgr A complex: the *Chandra* view. V – The 6.4 keV line

a: Western component
f: Eastern component

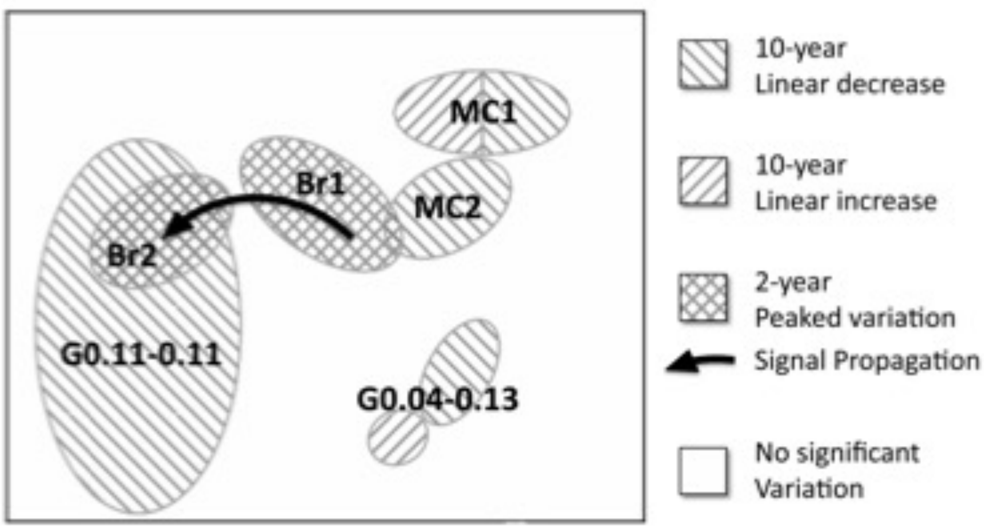




Sharp FeKα intensity except for MC1a and MC1b

Clavel et al. (2013)

Sgr A complex: the *Chandra* view. VI



Cloud \ Scale / Energy / Section	few arcmin Fe Kα 3	26″ x 61″ Fe Kα 4	15″ x 15″ 4-8 keV 5
Br1 & Br2	Increasing		
MC1	Constant		
MC2	Decreasing	---	
G0.11-0.11	---	---	
G0.04-0.13	---	---	

Clavel et al. (2013)

Increasing flux in Br1 and Br2 (factor ≈10 in ≤2 yrs)
Much slower linear time variations in both MC1 and MC2 clouds over 10 yrs

➔ Two distinct events of similar intensity

Spatially resolved variability analysis to possibly investigate the behaviour of past SgrA* activity

Alternative solutions to X-ray reflection nebula (XRN) model: **cosmic rays**

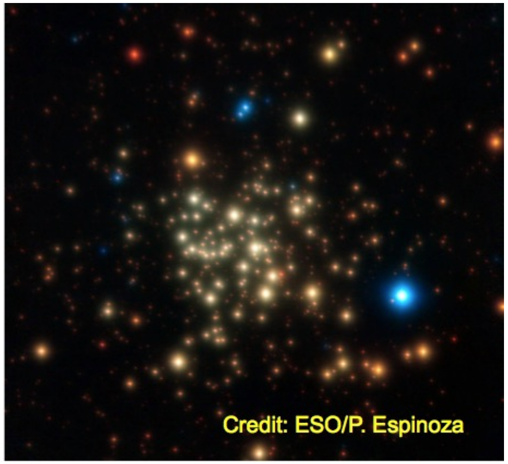
(e.g., Valinia et al. 2000; Yusef-Zadeh et al. 2002, 2007; Capelli et al. 2011)

But keep in mind that

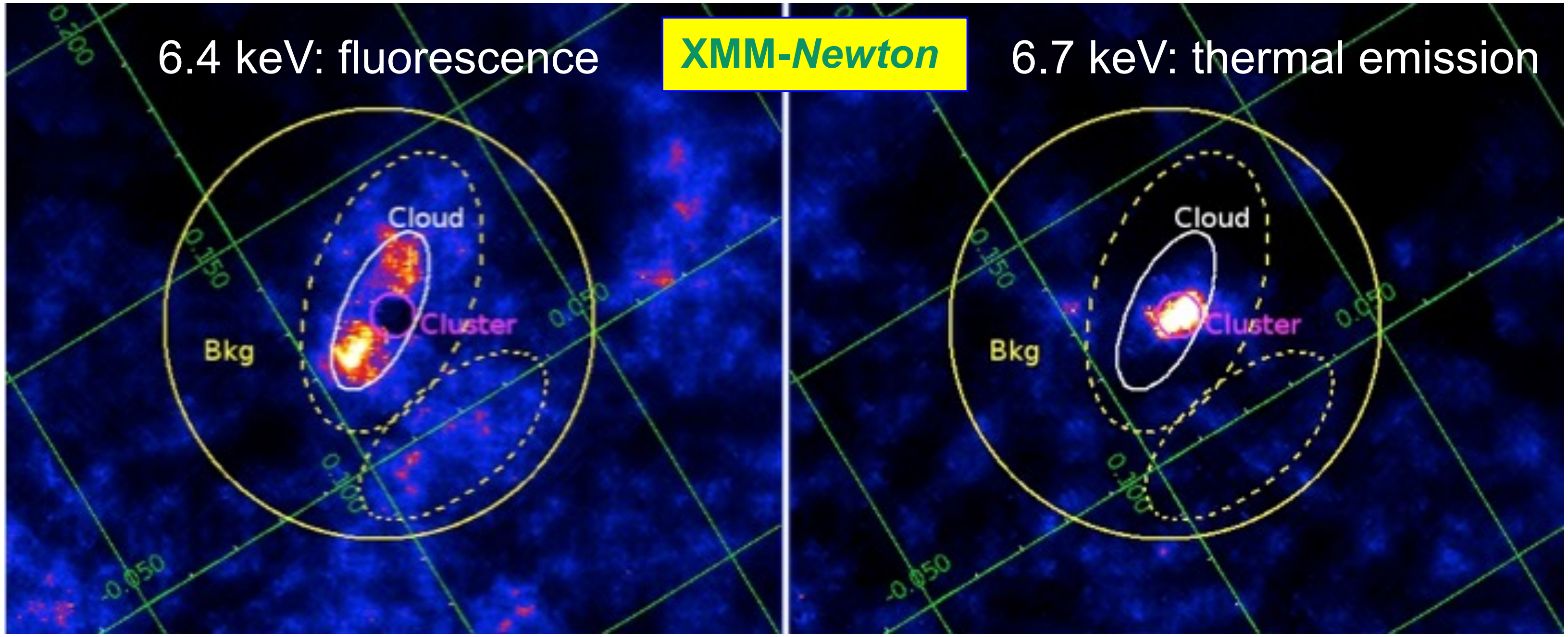
- X-ray variability time scales of small clumps
- “Decaying” behavior of the X-ray spectrum
- High apparent velocity of ~3c from the Bridge

all strongly suggest an external illuminating source and seem to rule out models based on internal sources and/or cosmic rays

The Arches cluster – I

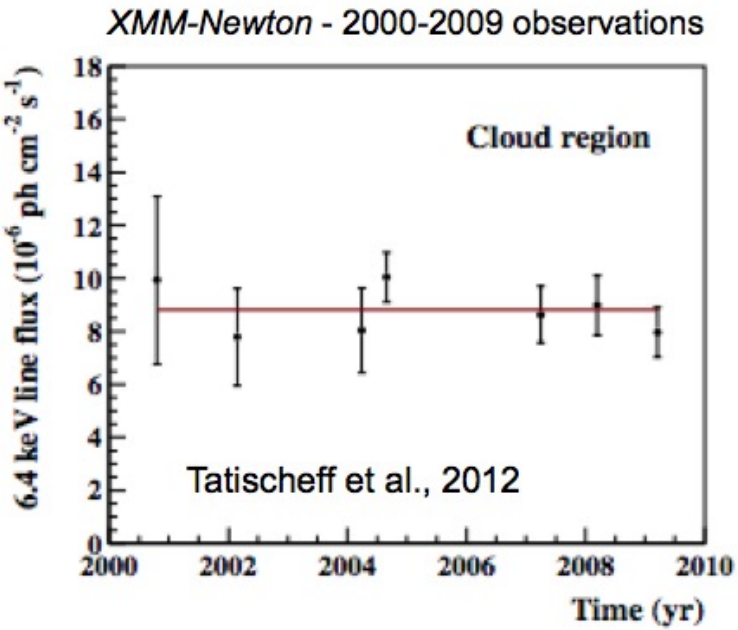


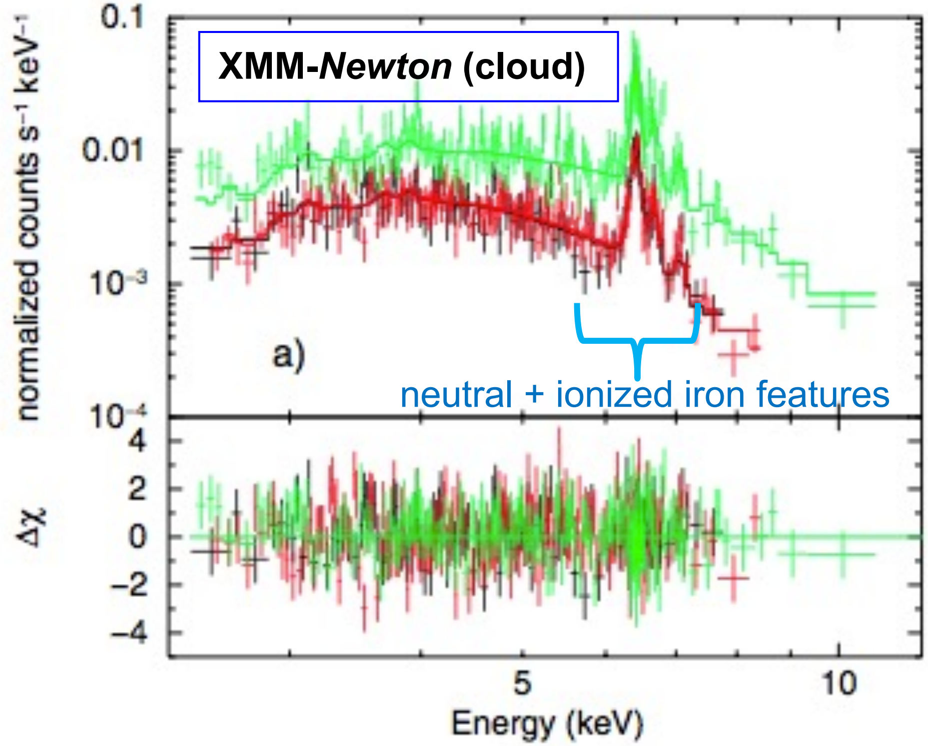
Massive star cluster 11 arcmin from Sgr A*
Age≈1−3 Myr, ≈160 O-type stars, ≈3×10^5 $M_\odot$ in the core (10”)
One of the densest young-star regions



Tatischeff et al. (2012)

The Arches cluster – II

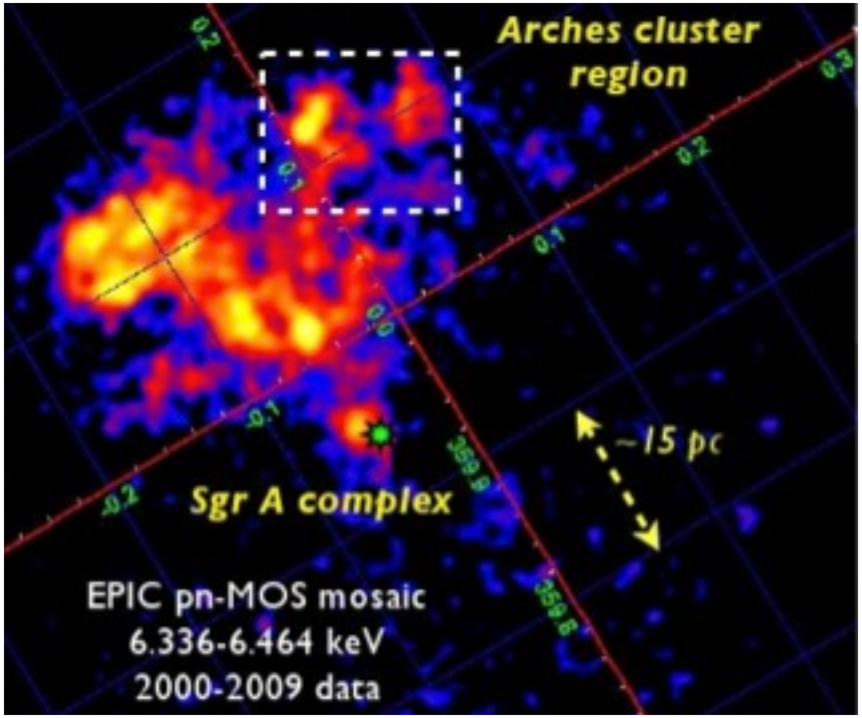


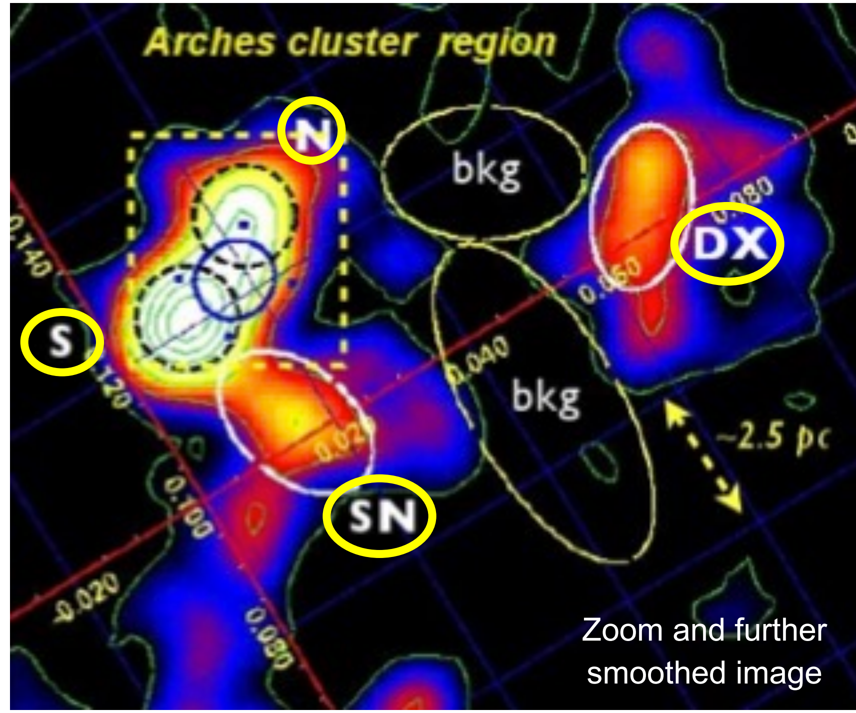


- Constant X-ray flux for the Fe Kα emission line at 6.4 keV (EW≈1.2 keV), in contrast to other MCs
- Presence of both neutral and ionized (due to the stellar emission) iron lines

➔ Neutral line consistent with being produced by low-energy hadronic cosmic rays LECRs (i.e., bombardment of molecular clouds by energetic ions), accelerated in the bow shock resulting from the cluster's proper motion against the MC. The ambient medium has a metallicity of about 1.7 times solar (Tatischeff et al. 2012)

The Arches cluster – III. Analysis of sub-regions



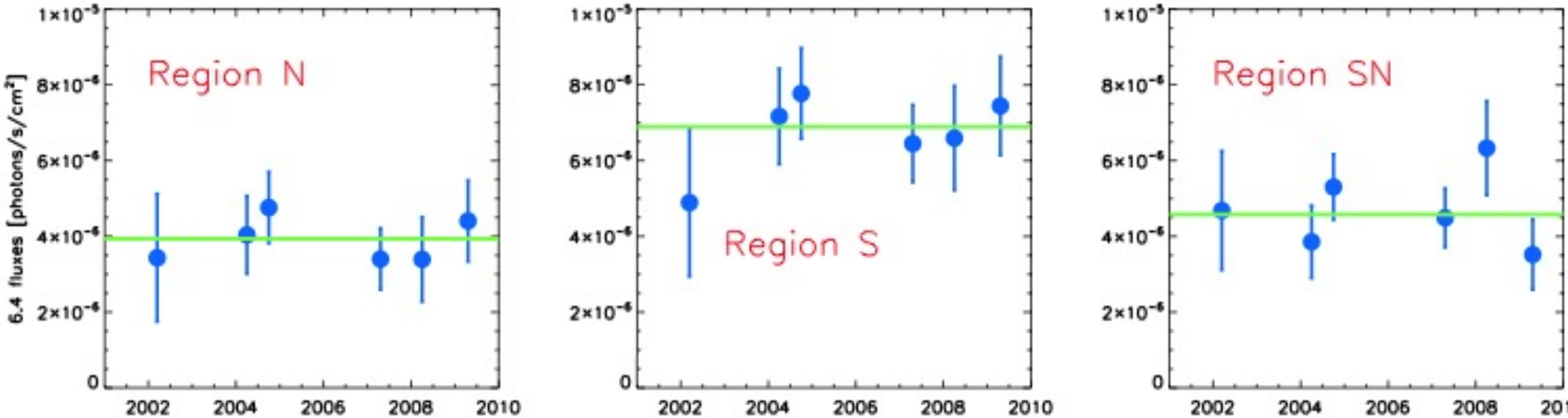


Capelli et al. 2011

Map at 6.4 keV (fluorescence Kα line) consisting of bright spots (size<2 pc), high-energy photons needed to produce fluorescence:

- Photoionization (X-ray reflection nebula, XRN, model)?
- Flare from a nearby X-ray source?
- Bombardment by high-energy particles?

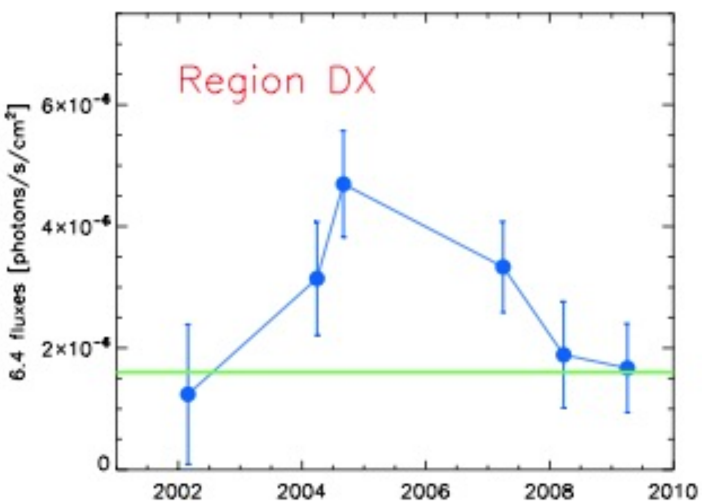
The Arches cluster – IV. Analysis of sub-regions



Separation knots <7 pc from AC

Capelli et al. 2011

Fastest variability ever for a MC



Variable X-ray emission only from DX region

✓ *Constant fluorescence emission in 3 out of 4 bright knots* ➔ Origin within the AC region (photons or particles)

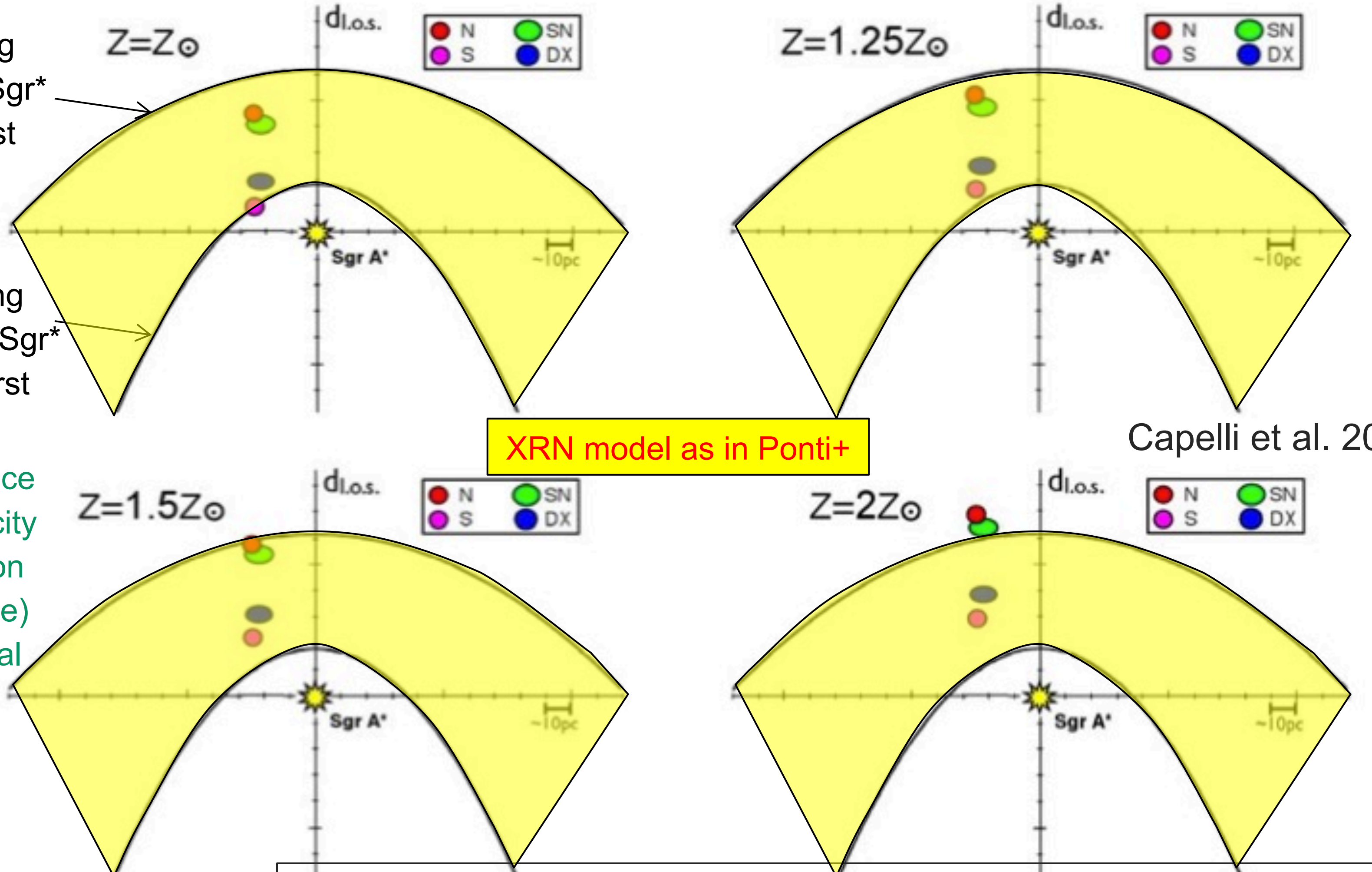
✓ Photons: X-ray luminosity of AC not enough, not even considering its X-ray emission during X-ray flaring activity – likely from stellar winds interactions in one or more binary systems – being three orders of magnitude below requirements → importance of VARIABILITY TIMESCALES + ENERGETICS

✓ Sgr A* past flaring activity (XRN model)? Variability in the DX region too fast

The Arches cluster – V. Analysis of sub-regions

Leading edge of Sgr* outburst

Trailing edge of Sgr* outburst



XRN model as in Ponti+

Capelli et al. 2011

Dependence on metallicity (hence iron abundance) and optical depth

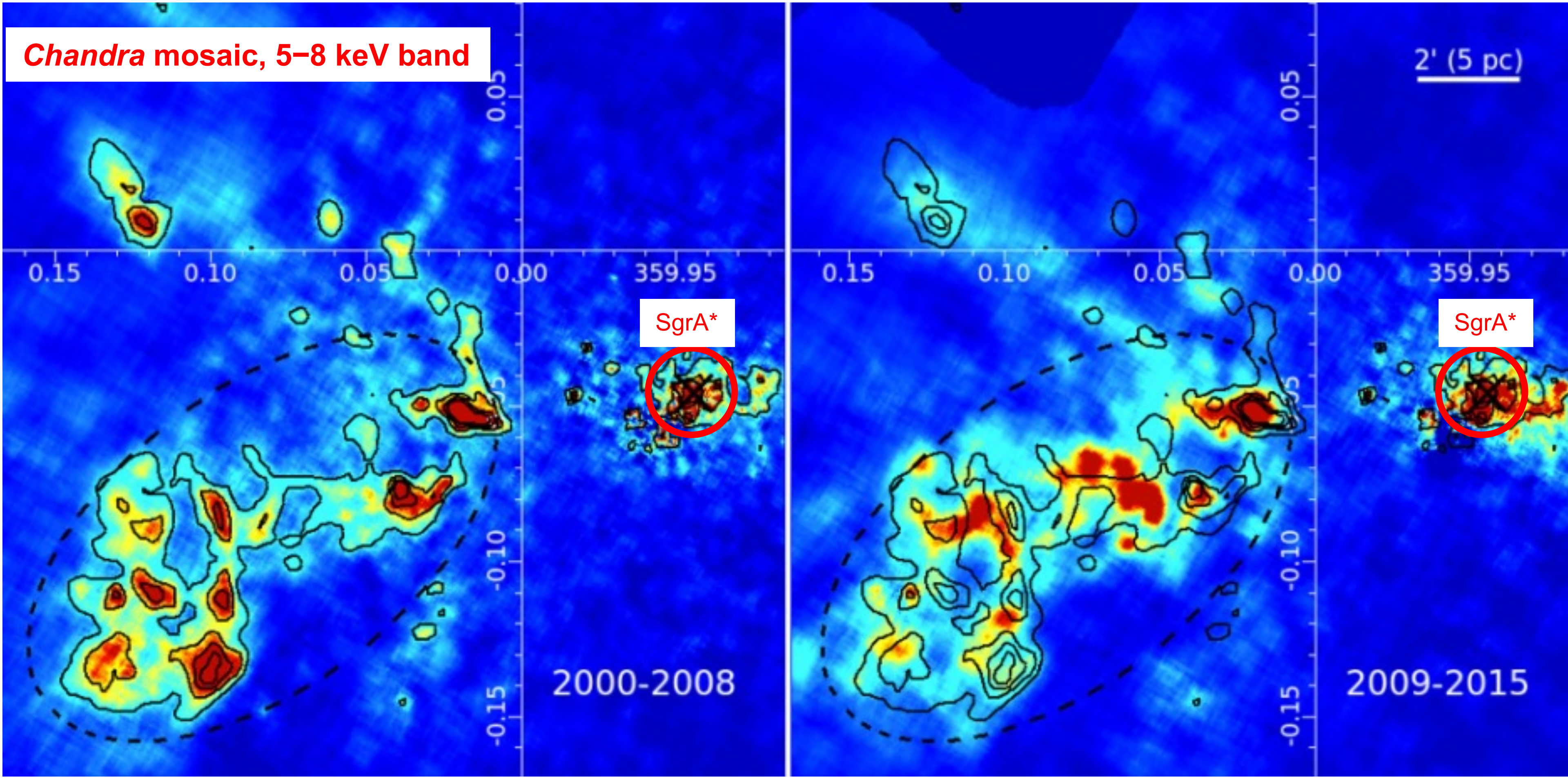
DX: hard X-ray spectrum: Γ≈0.8−1.1 vs. 1.3−1.4 expected from CR e⁻ bombardment

Fast X-ray variability hardly compatible with any model

I. SgrA* flare should have reached **DX** region (**blue**), decay not explained
II. CR particle bombardment: requires particle energy densities likely too high (a few ten−hundred eV/cm^3 vs. ≈0.2 eV/cm^3 in the Galactic Ridge)
III. Emission from a binary ➔ $L_X \approx 10^{37}$ erg/s over 8-yr interval (too long)

Considerations about outbursts

The duration of the outburst. I

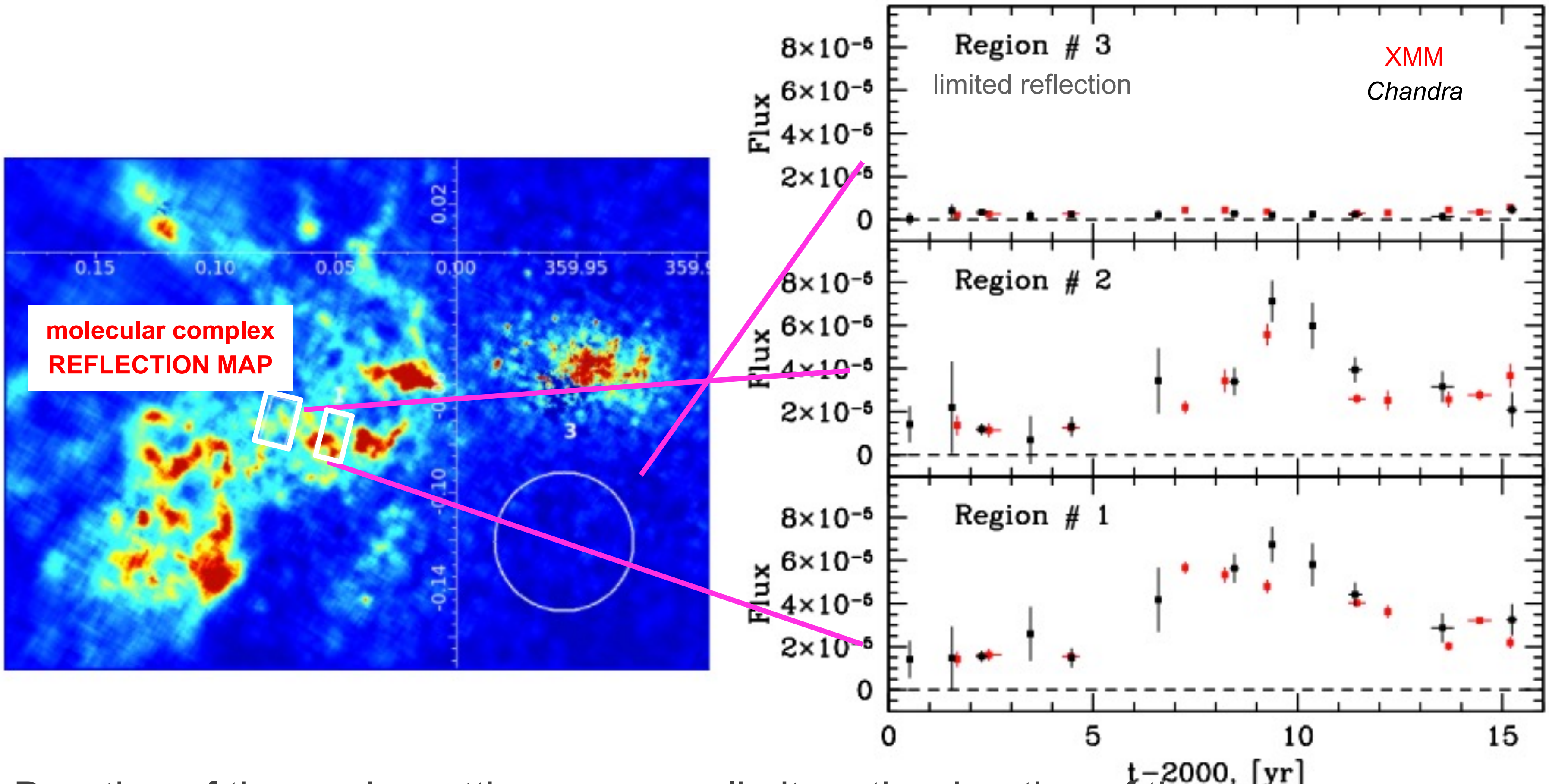


Churazov+17

Decomposition of X-ray emission into thermal and reflection components

Monte Carlo simulations of a spherical homogeneous cloud illuminated by a parallel beam of X-ray radiation

The duration of the outburst. II



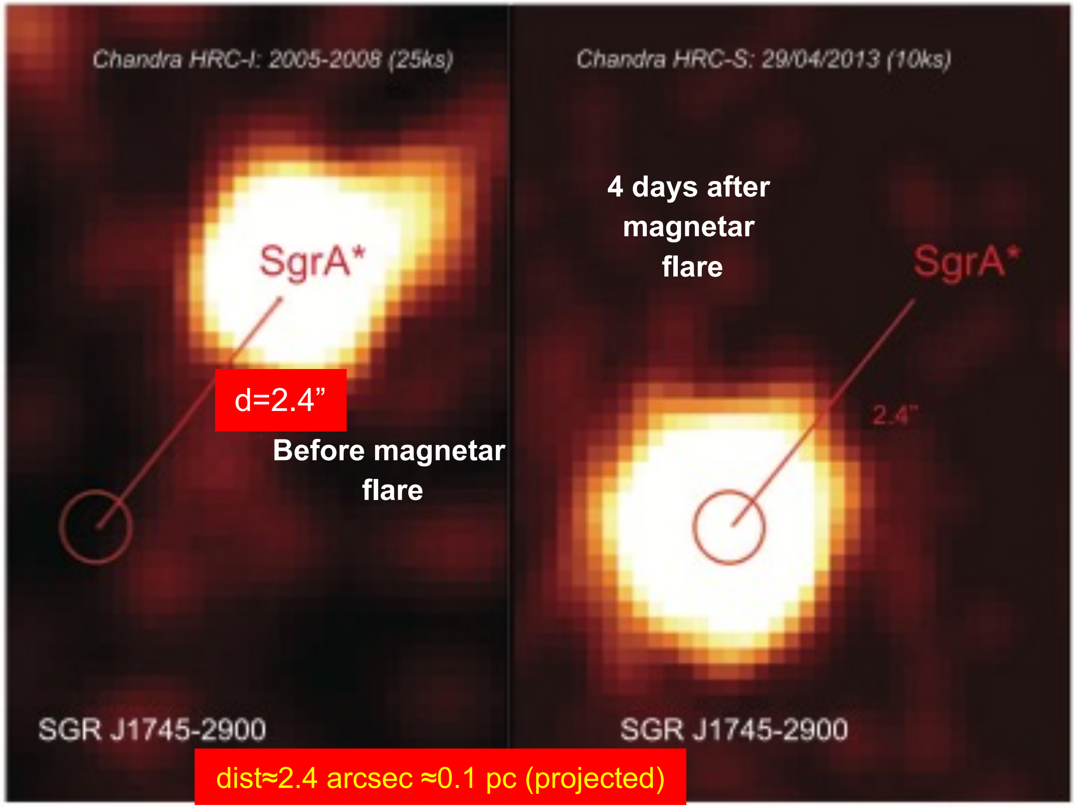
Duration of the peaks setting an upper limit on the duration of the outburst. Peaks broadened by the finite spatial scale of the cloud

Churazov+17

Support to a few-year duration of the outburst by Clavel+13: tidal disruption event? Capture of a planet?

So, we may need transient sources.
Are there any of these (besides SgrA*)?

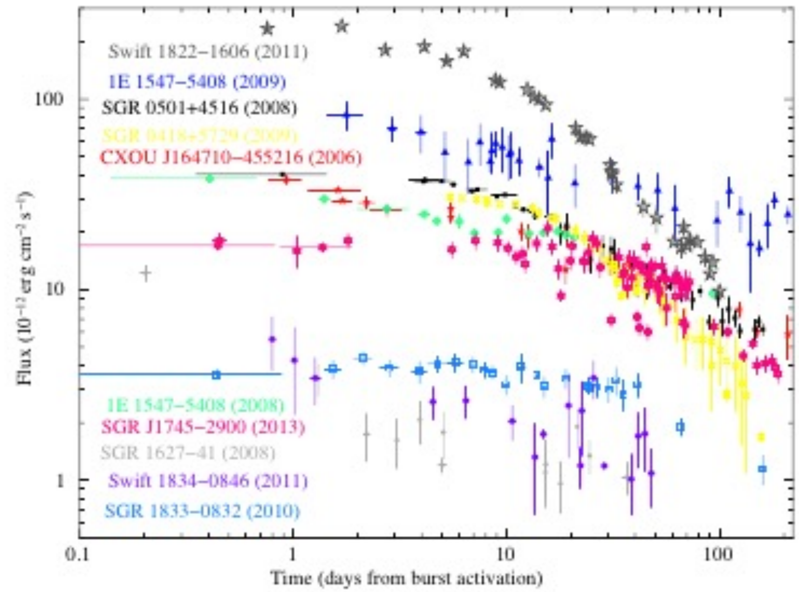
A possible source of transient X-ray emission: SGR J1745-2900. I



Rea et al. (2013)

X-ray spectrum (magenta) compared to other magnetar outbursts

BB with kT≈0.9 keV and R_{BB}≈1.4 km constant; L[1−10 keV]≈10^{35} erg/s



Coti Zelati et al. (2015)

Magnetars are expected to exhibit *flaring activity* at various levels: giant flares (≈10^{46-47} erg emitted in several minutes), intermediate flares (≈10^{42-45} erg emitted in few minutes) and short X-ray bursts (≈10^{38-40} erg in less than a second) plus persistent X-ray emission

τ_c≈P/(2Pdot)≈9000 yr is indicative of recent star-formation activity in the Galactic disk

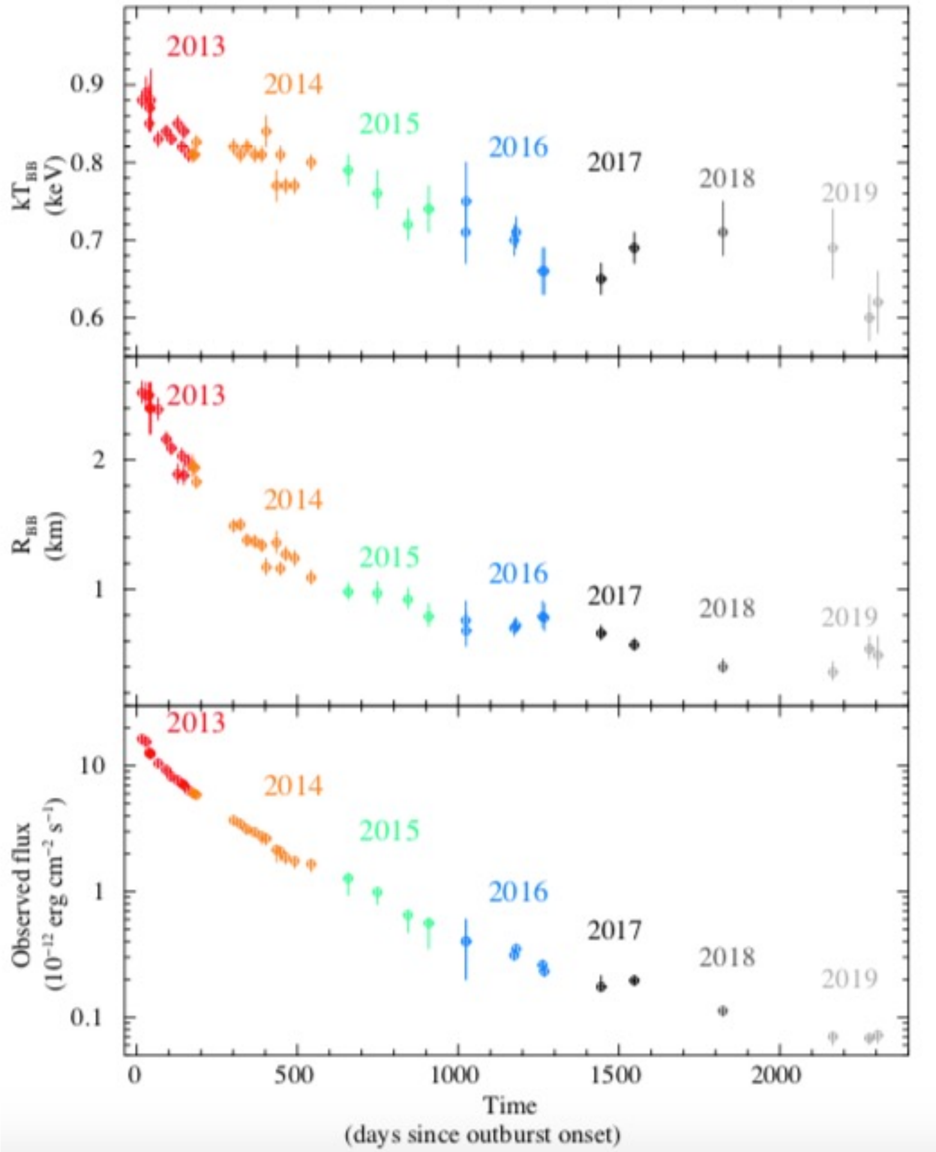
A possible source of transient X-ray emission:

SGR J1745-2900. II – Temporal evolution of the BB over 6 years

Surface temperature

Blackbody radius

0.3-10 keV flux

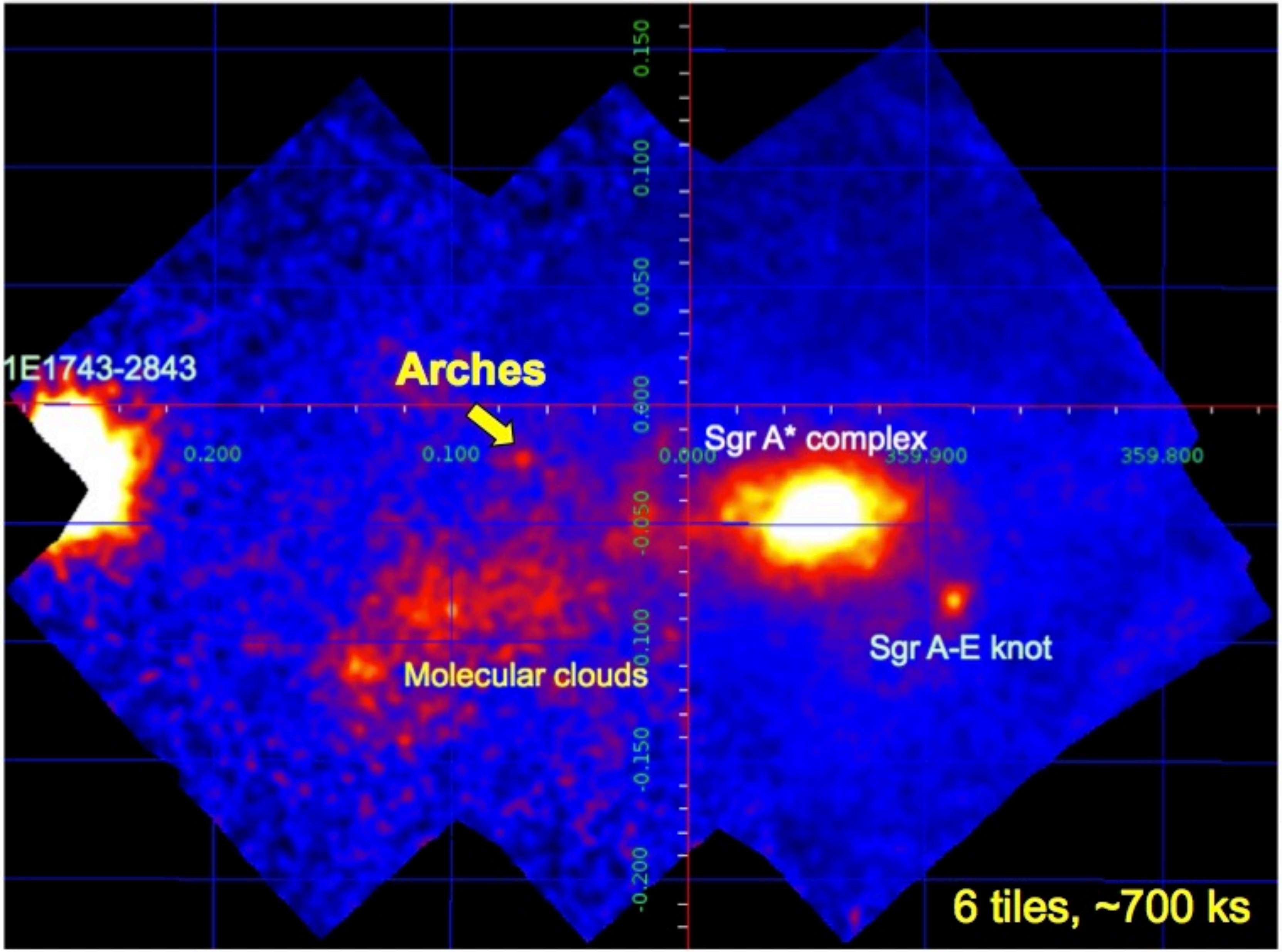


kT: from ~0.9 keV to ~0.6 keV in 6 years

Rea et al. (2020)

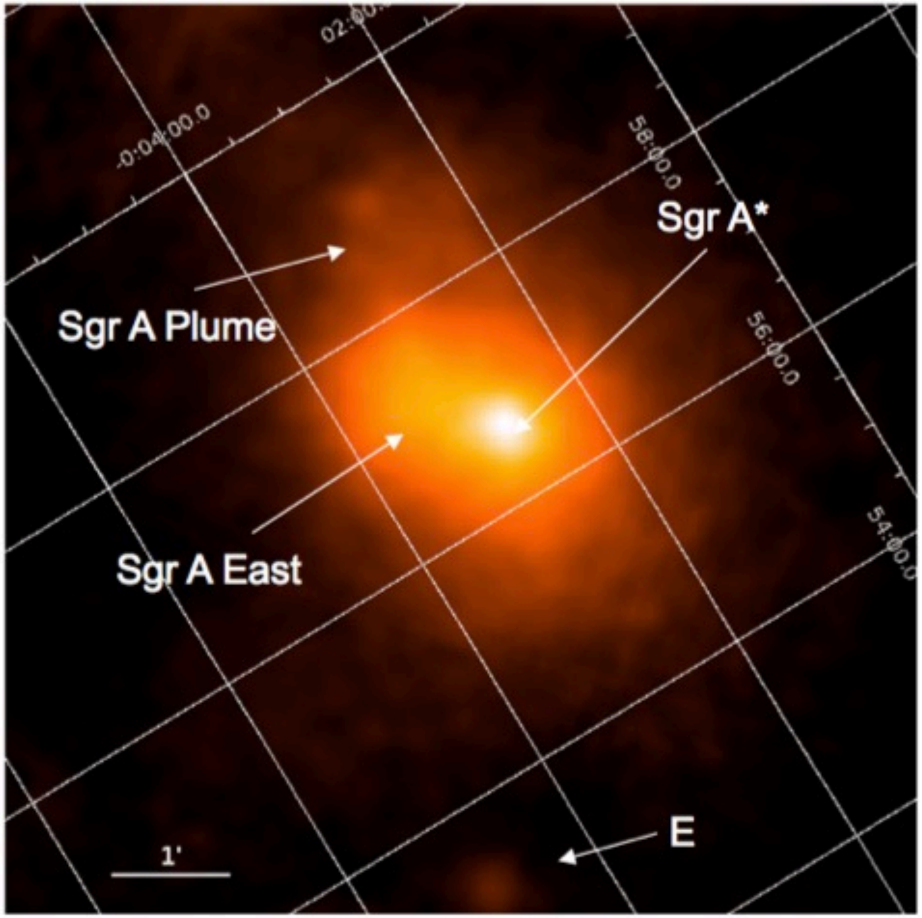
The *NuSTAR* view of the Galactic Center

The 10–40 keV *NuSTAR* mini survey

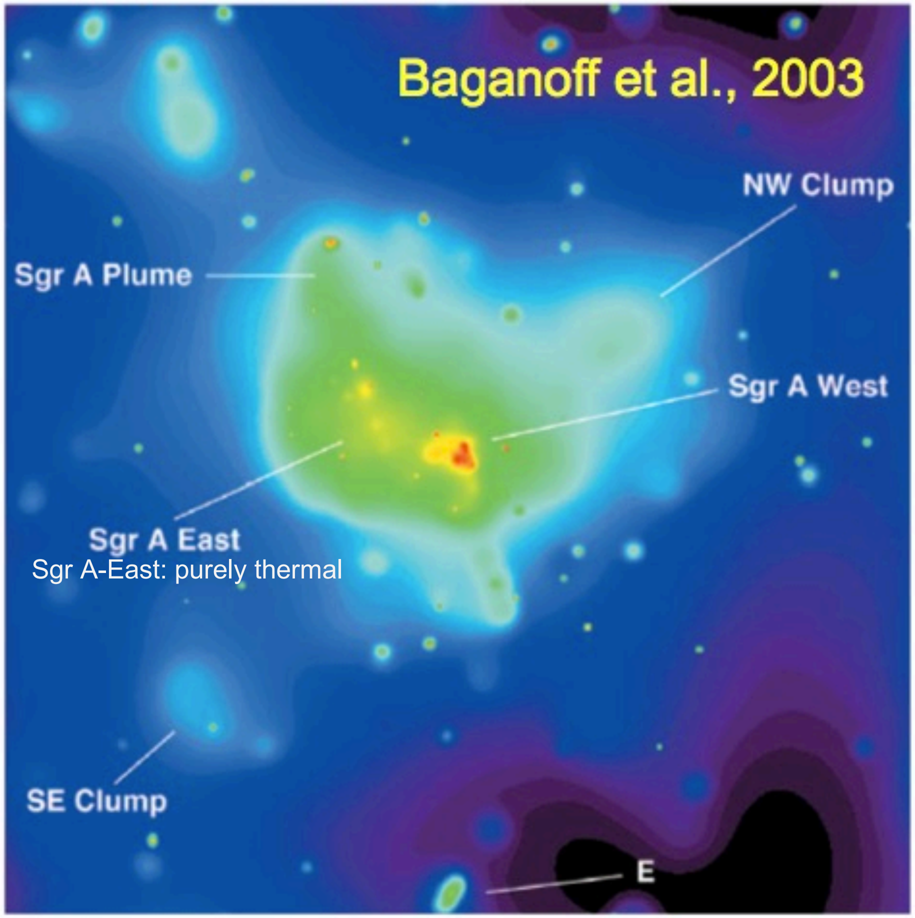


Similarities with *Chandra*

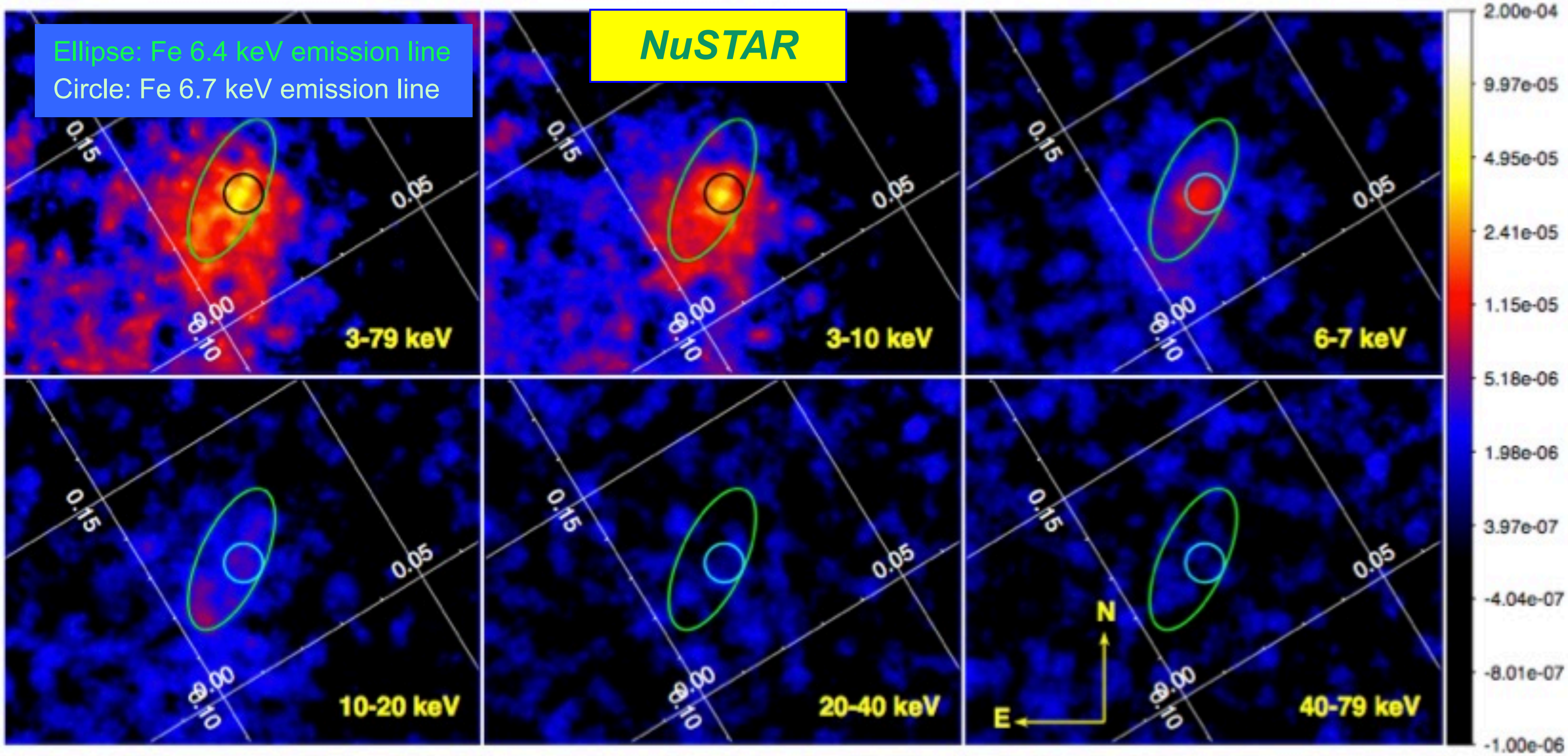
NuSTAR 3-79 keV



Chandra 2-10 keV



The Arches cluster seen by *NuSTAR*



- Core component + extended halo emission in the 3−10 keV band
- Extended emission in the 10−20 keV energy range well beyond the Arches cluster with a spatial morphology consistent with the Fe Kα emission-line emission observed with XMM-*Newton* → reflection

Arches cluster itself is unlikely to be the source of the cloud fluorescence emission

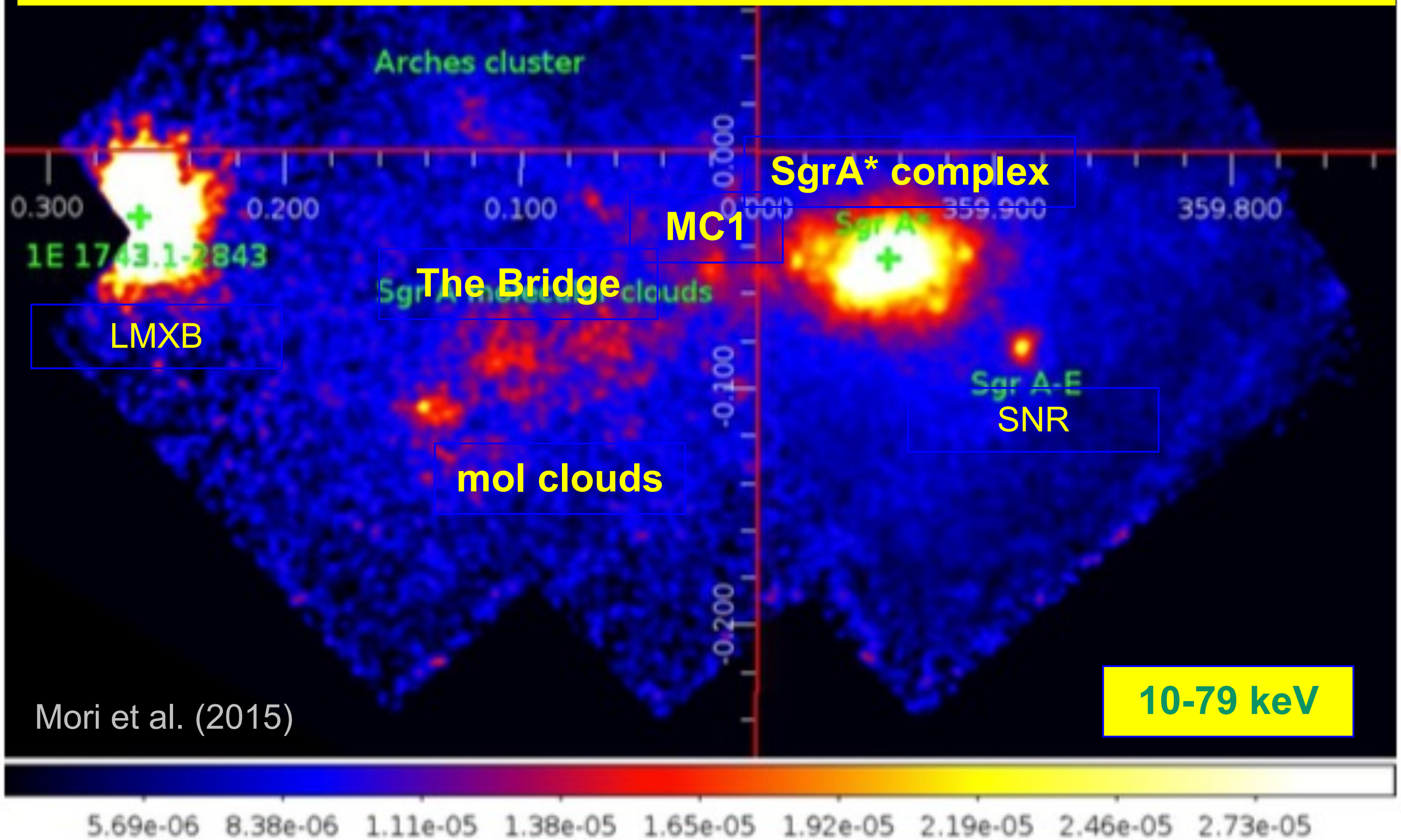
→ Overall emission consistent with a thermal component mostly due to multiple collisions between strong winds of massive stars and a non-thermal one (powerlaw) due to LECRs.

X-ray photo-ionization and CR-induced emission models can reproduce data equally well (Krivonos+14)

The latest news from *NuSTAR:*

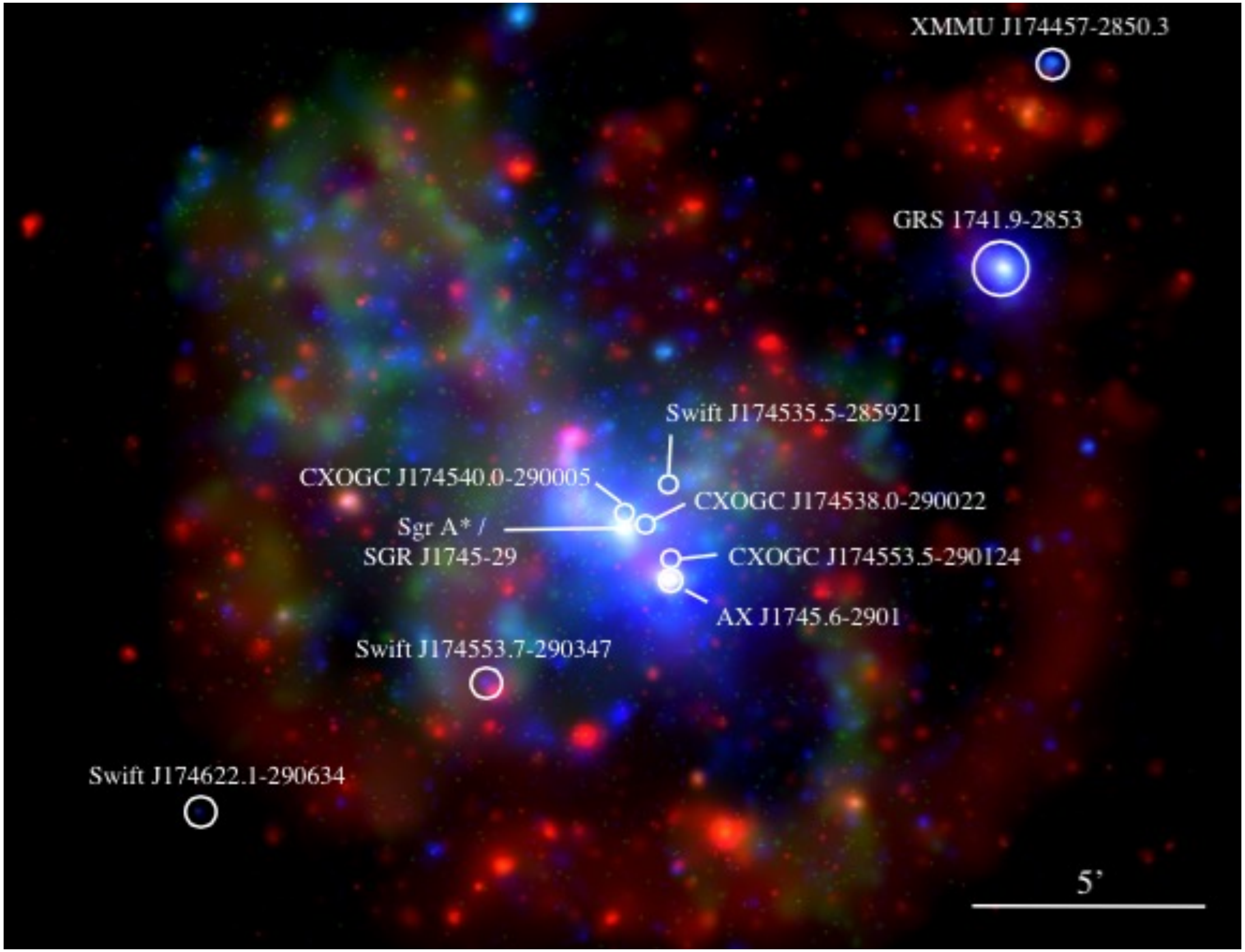
Viewing the GC in the hard X-rays

- Detection of hard X-ray emission centered on Sgr A*: population of massive magnetic CVs (largely intermediate polars)?
- Detection of non-thermal X-ray filaments: PWNe? SNR-cloud interactions?
- Hard (>10 keV) X-ray emission from MC1 and the Bridge



The *Swift*/XRT view of the Galactic Center

The Swift view (2006−2014) of the Galactic Center. I

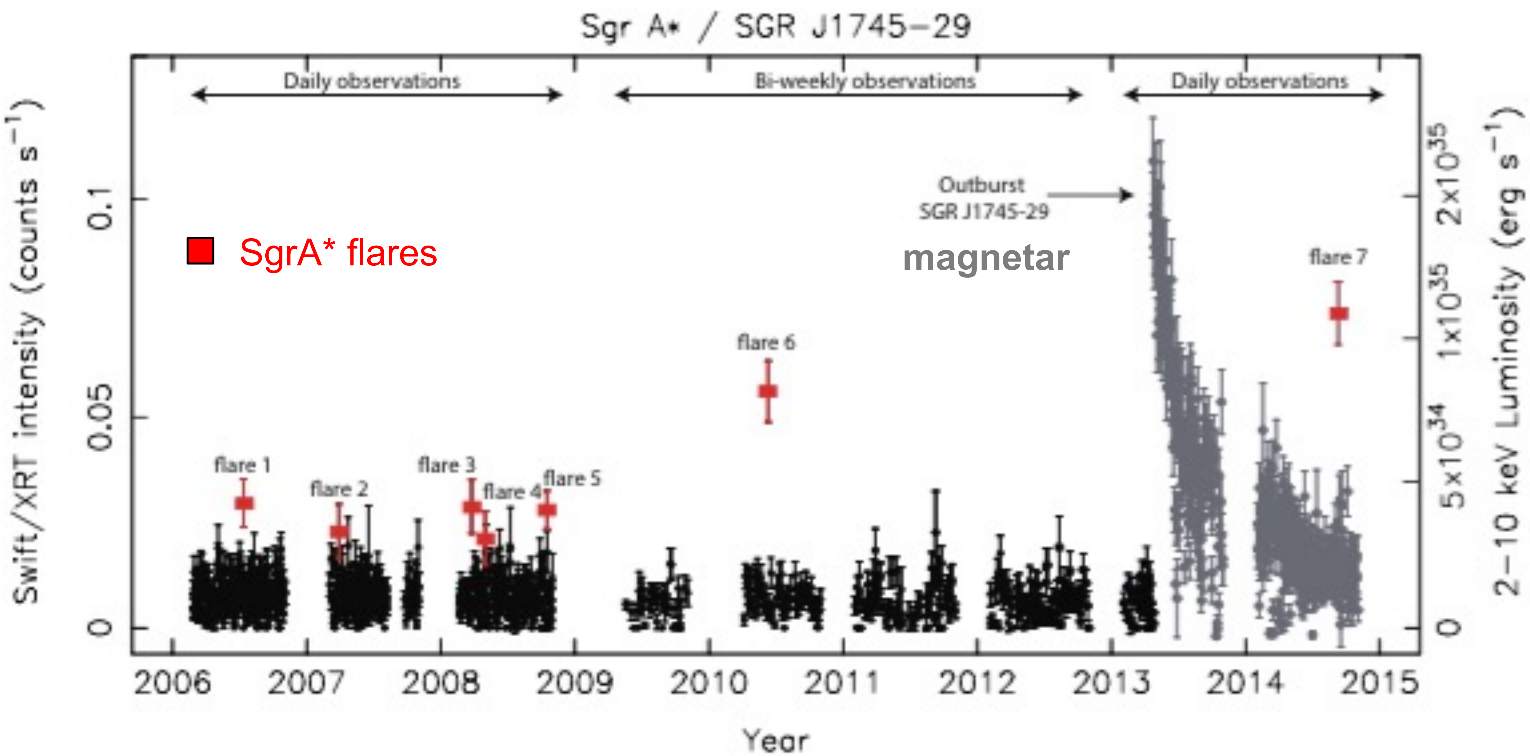


1.3Ms *Swift*/XRT data

SgrA* + magnetar + 9 transients X-ray binaries (up to ≈10^{37} erg/s)

Degenaar et al. 2015

The *Swift* view (2006–2014) of the Galactic Center. II

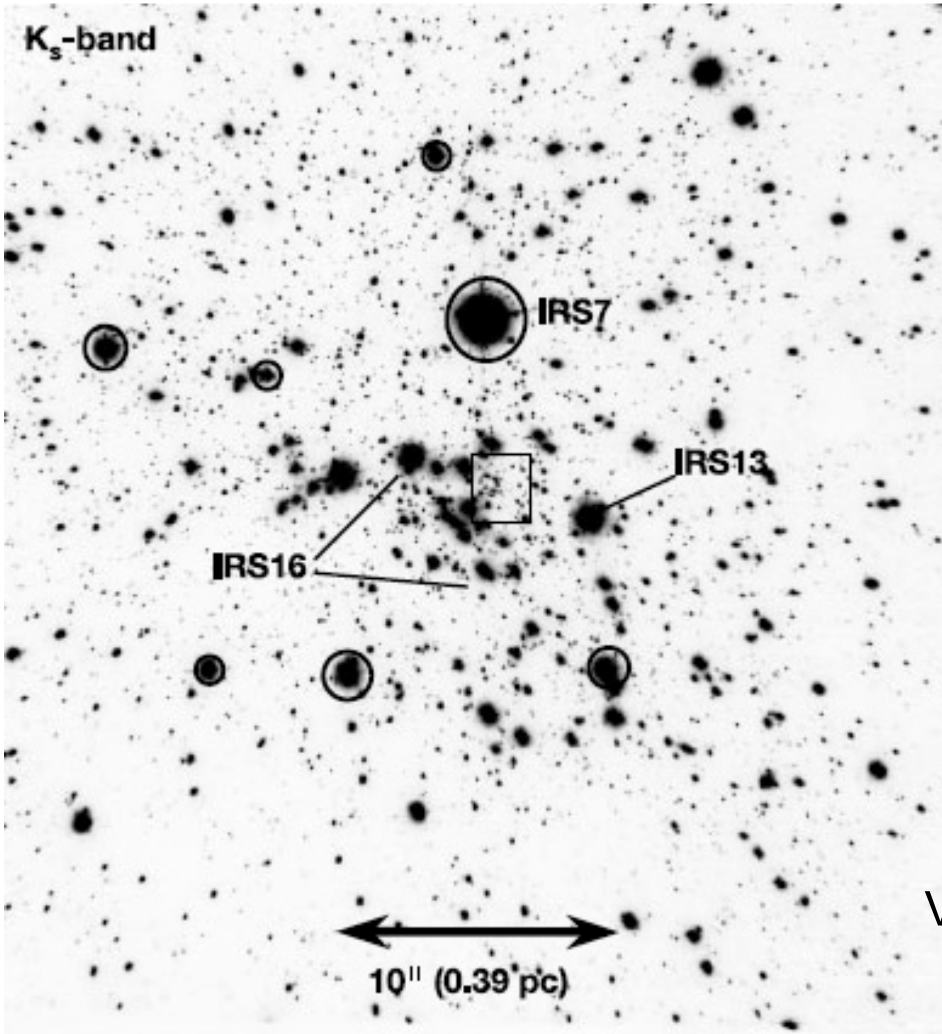


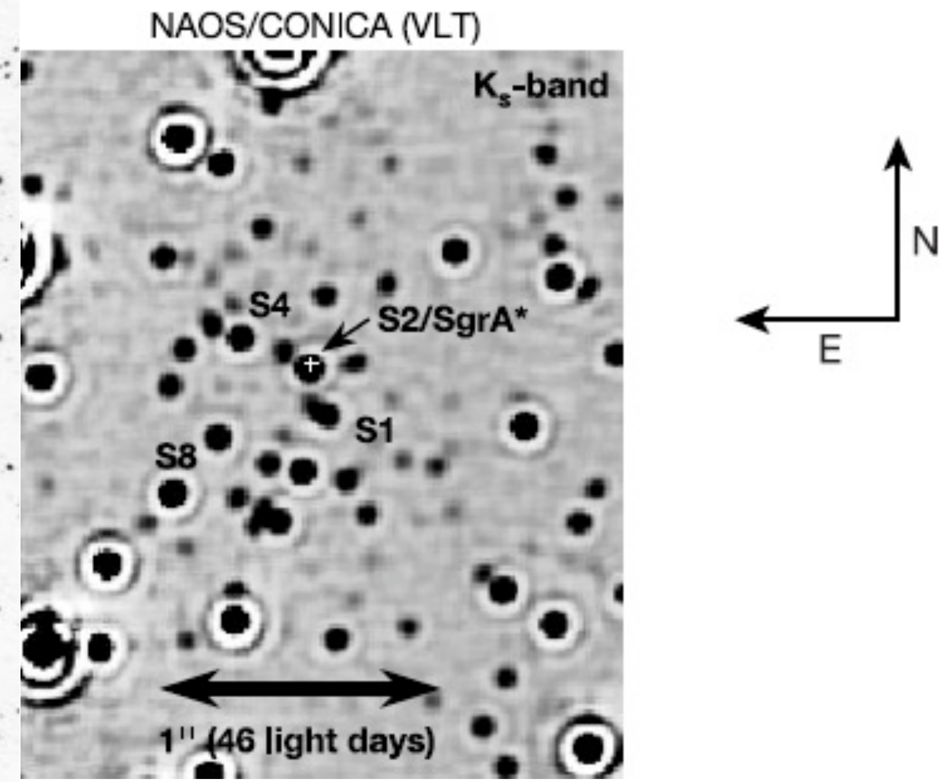
Degenaar et al. 2015

The scheduling of *Swift*/XRT observations have allowed the tracing of bursts from SgrA*, hence their demography and statistics → constraints on models (once combined with *Chandra* and XMM-*Newton* results), low-intensity vs. high-intensity burst activity in the GC

SgrA*: the right place for dynamical studies

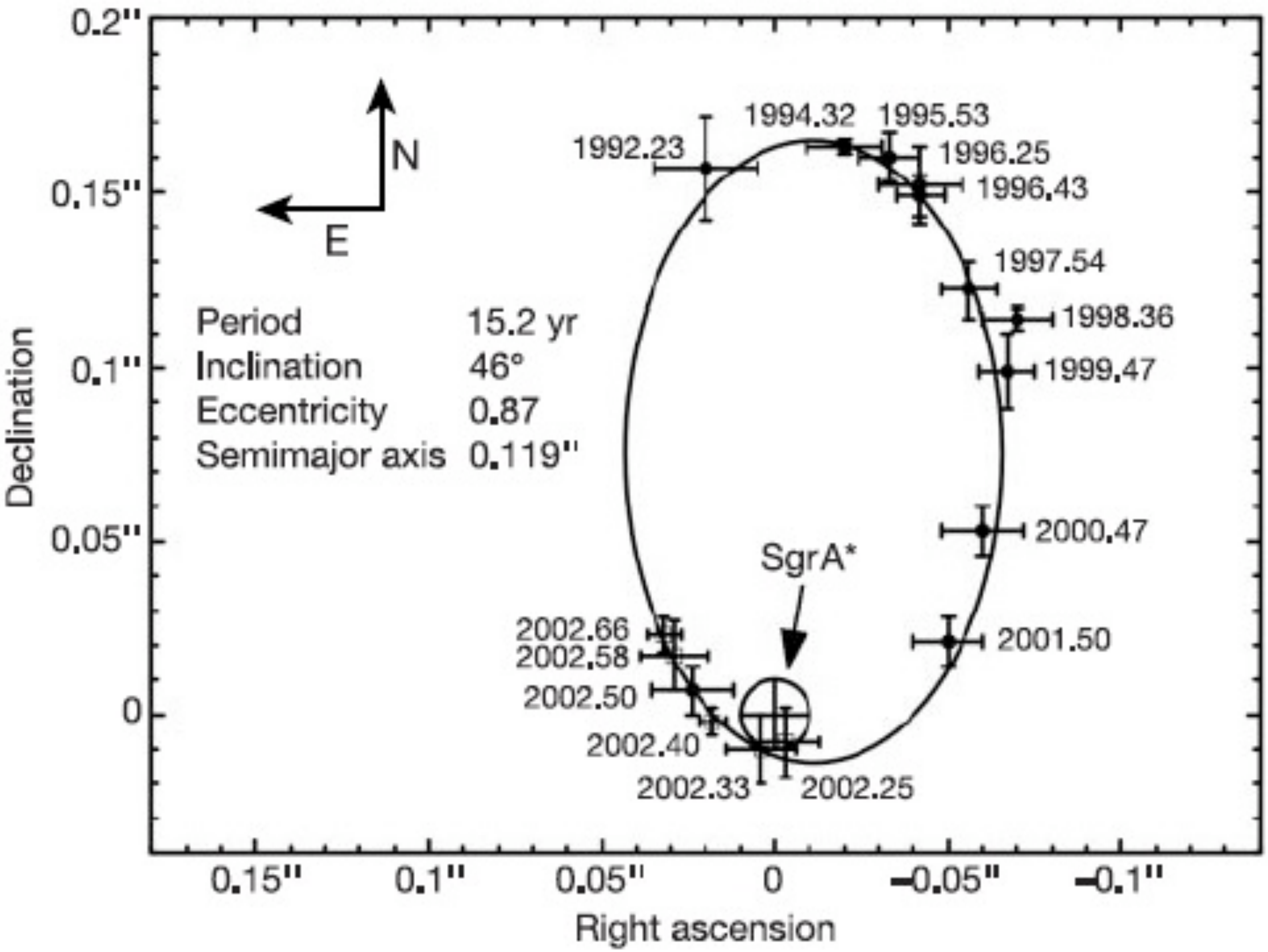
Dynamics of the Galactic Center
from high-resolution near-IR imaging

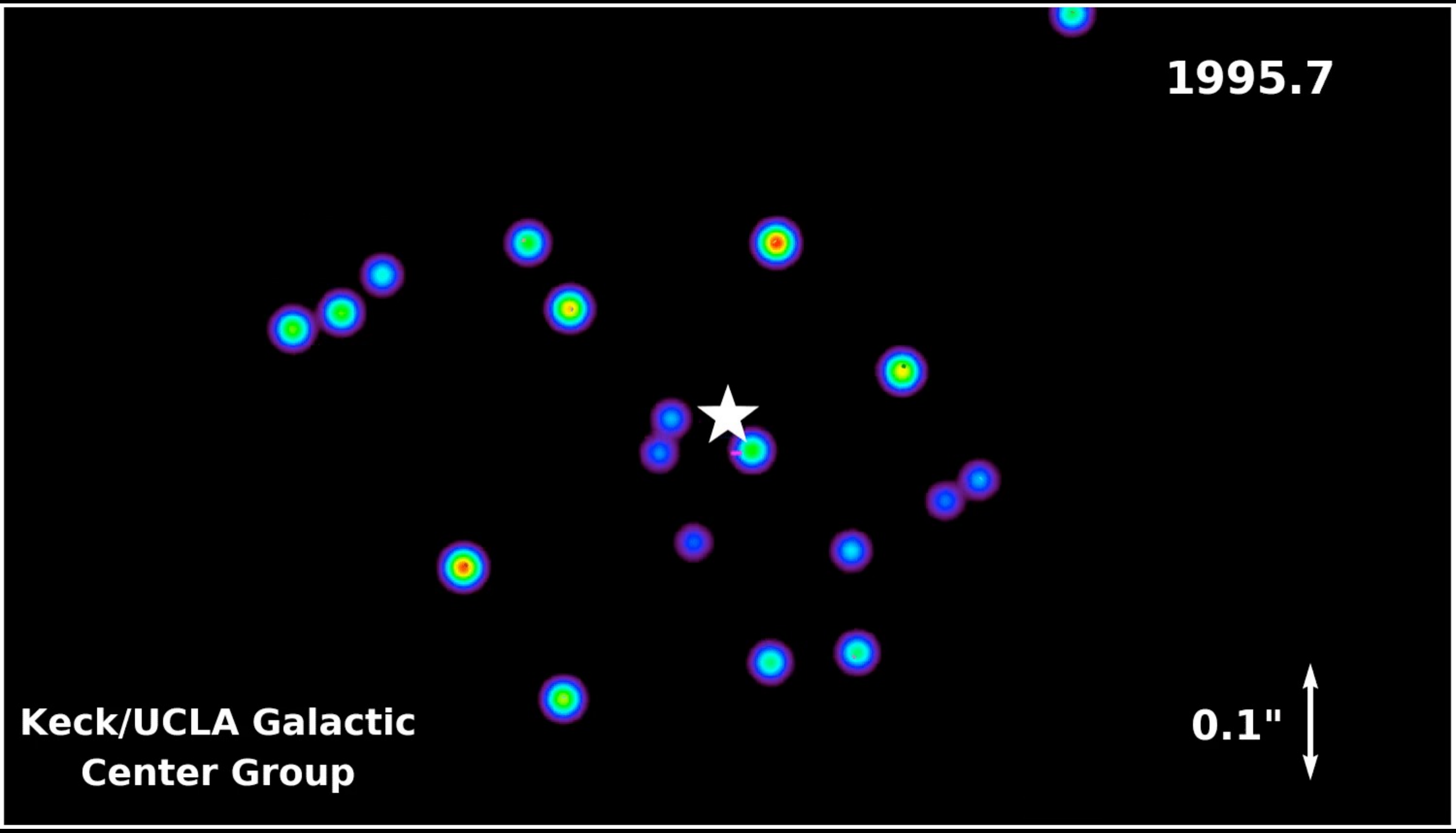




VLT NACO (near-IR) observations
(Schodel et al. 2002)

Orbit of S2 (star) around SgrA*

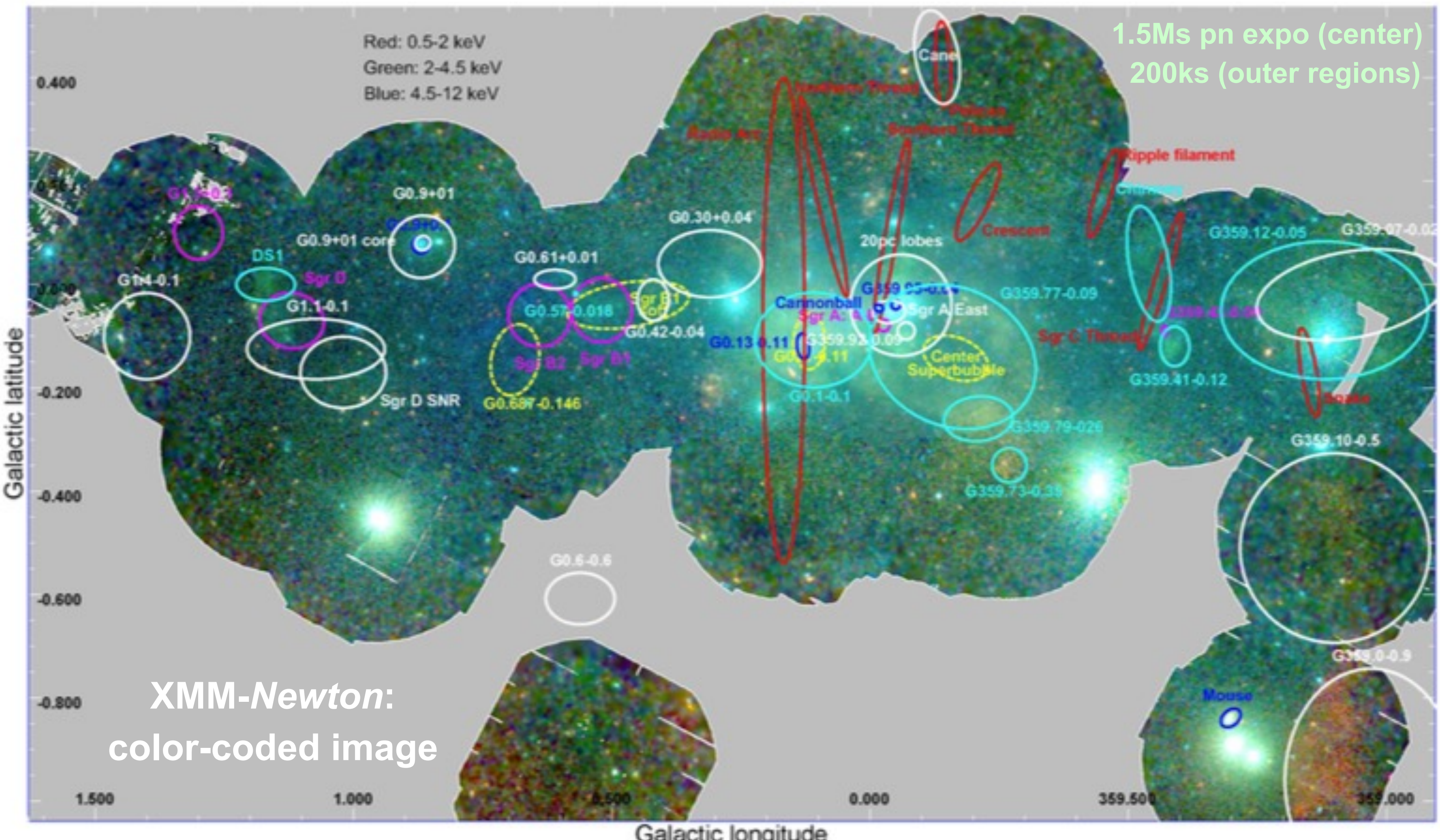



1995.7
0.1"
Keck/UCLA Galactic
Center Group

The line-map view of the Galactic Center:
from X-ray to near-/far-IR and radio emission.
Thermal vs. non-thermal processes

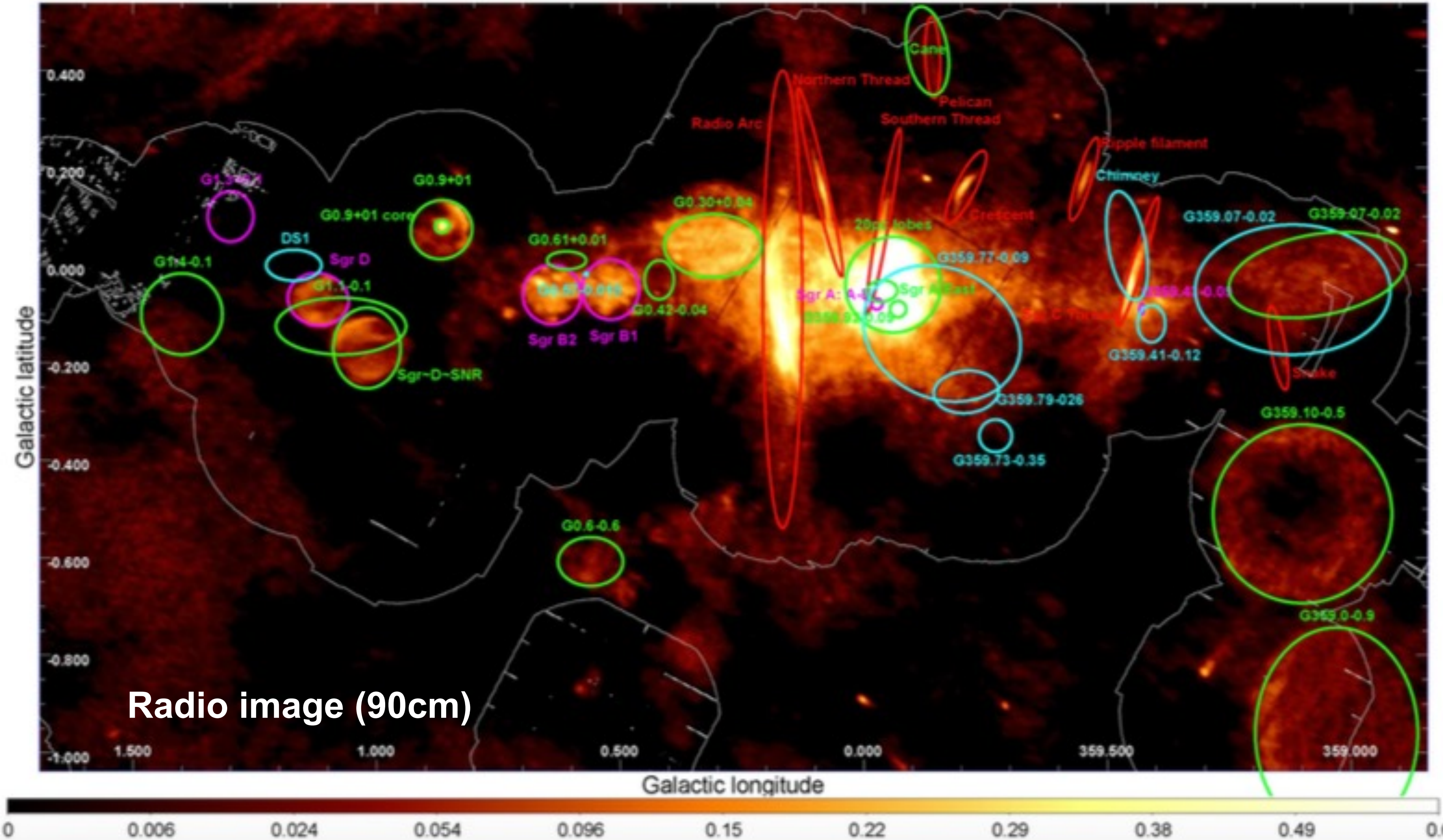
The deepest and largest XMM-*Newton* view of the central degree of the Milky Way

(Ponti et al. 2015)



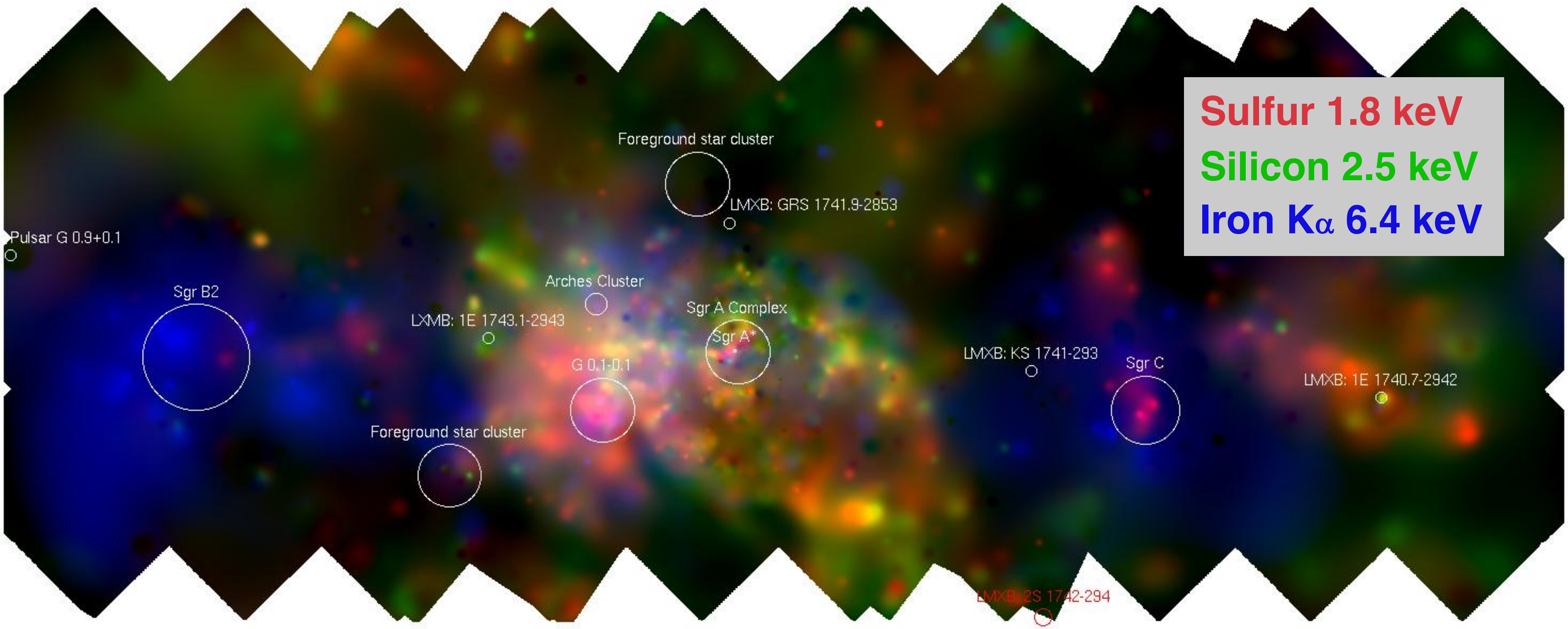
Still missing X-ray-radio associations

SN rate≈(3.5−15) $\times 10^{-4}$ yr^{-1} ➔ SFR≈(0.035−0.15) $M_\odot$ yr^{-1} over the past several × 1000 yr



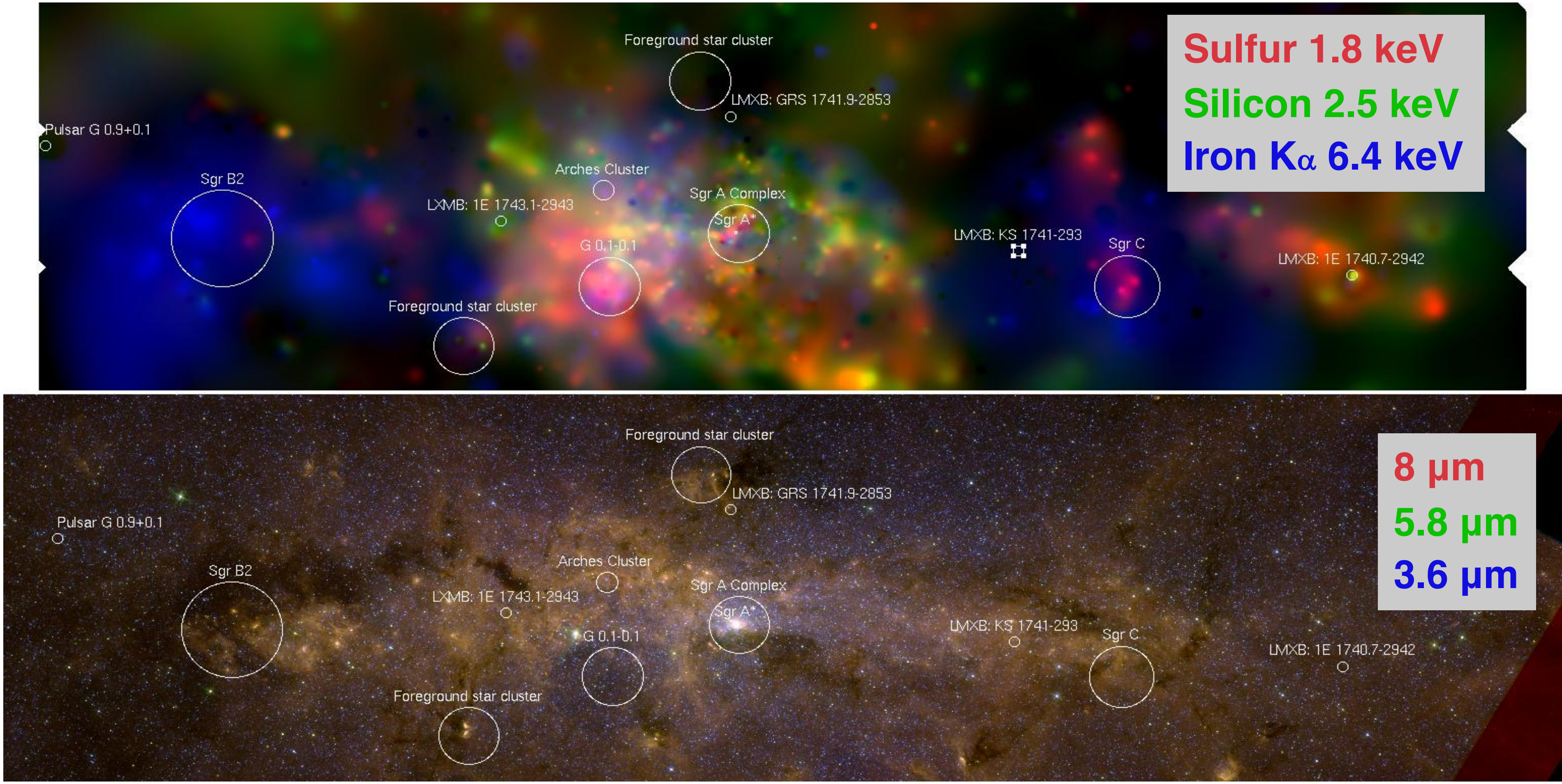
Line-map exposures of the Galactic plane

Line EW MAPS pinpoint diffuse emission mechanism

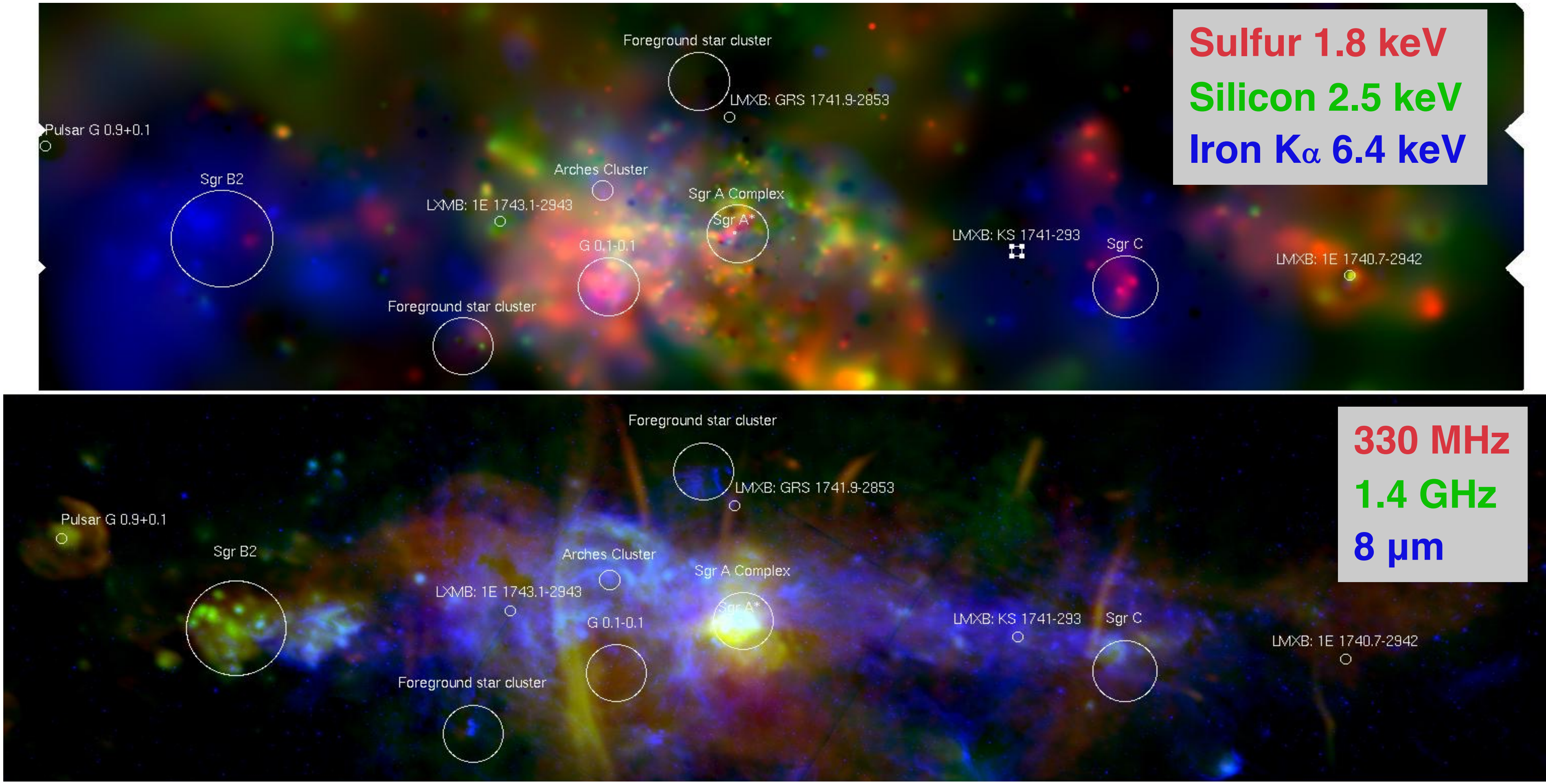


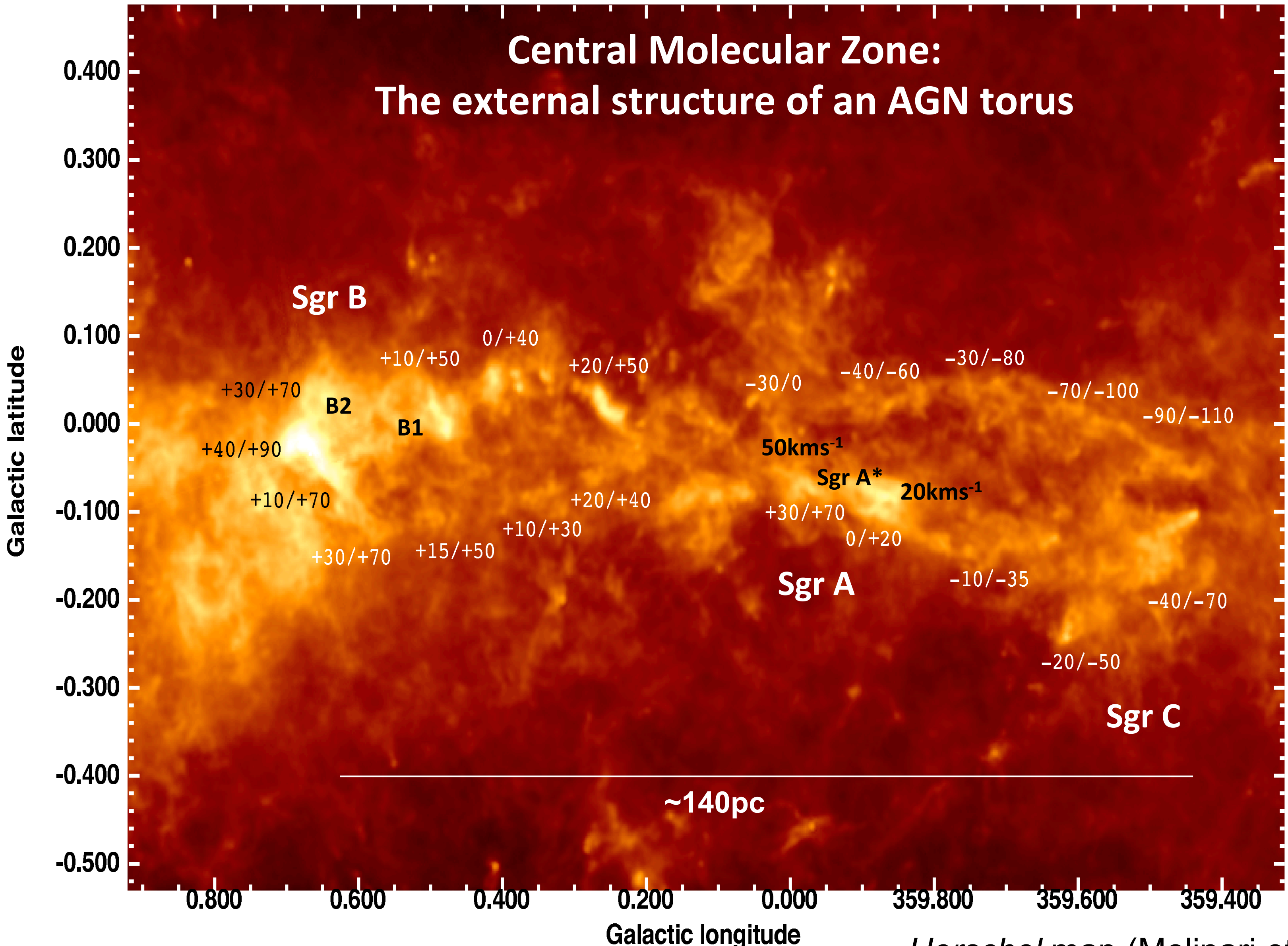
S/Si trace hot thermal gas associated with *active star formation*

Fe Kα traces *cold reflection* and is likely associated to past higher activity of Sgr A*

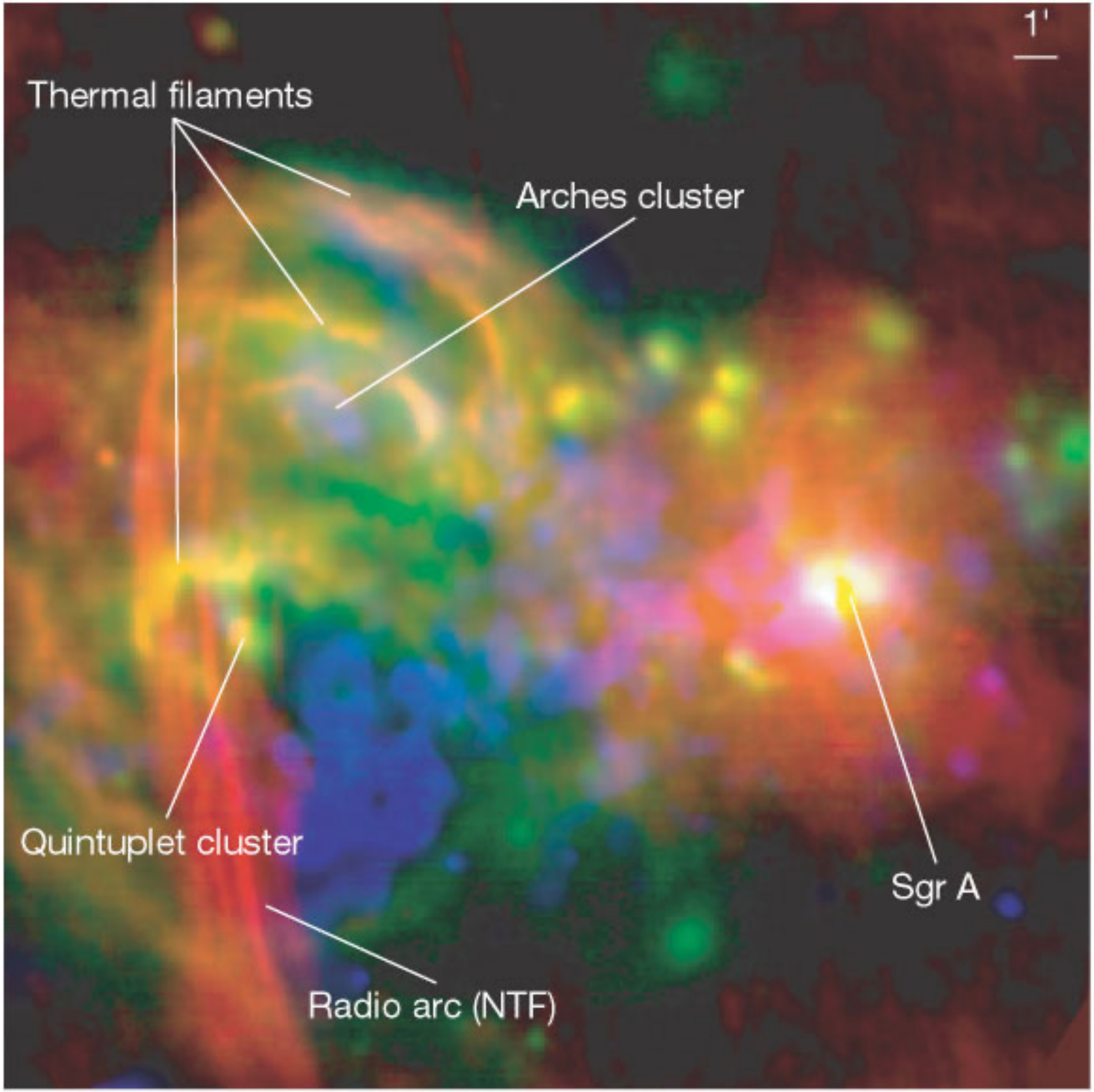


Sulfur 1.8 keV
Silicon 2.5 keV
Iron Kα 6.4 keV
Foreground star cluster
LMXB: GRS 1741.9-2853
Pulsar G 0.9+0.1
Sgr B2
Arches Cluster
LXMB: 1E 1743.1-2943
Sgr A Complex
Sgr A*
G 0.1-0.1
LMXB: KS 1741-293
Sgr C
LMXB: 1E 1740.7-2942
Foreground star cluster
8 μm
5.8 μm
3.6 μm


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
Arches Cluster
Sgr B2
Sgr A Complex
LXMB: 1E 1743.1-2943
Sgr A*
LMXB: KS 1741-293
Sgr C
G 0.1-0.1
LMXB: 1E 1740.7-2942
Foreground star cluster
330 MHz
1.4 GHz
8 μm
Foreground star cluster
LMXB: GRS 1741.9-2853
Pulsar G 0.9+0.1
Sgr B2
Arches Cluster
Sgr A Complex
LXMB: 1E 1743.1-2943
Sgr A*
LMXB: KS 1741-293
Sgr C
G 0.1-0.1
LMXB: 1E 1740.7-2942
Foreground star cluster



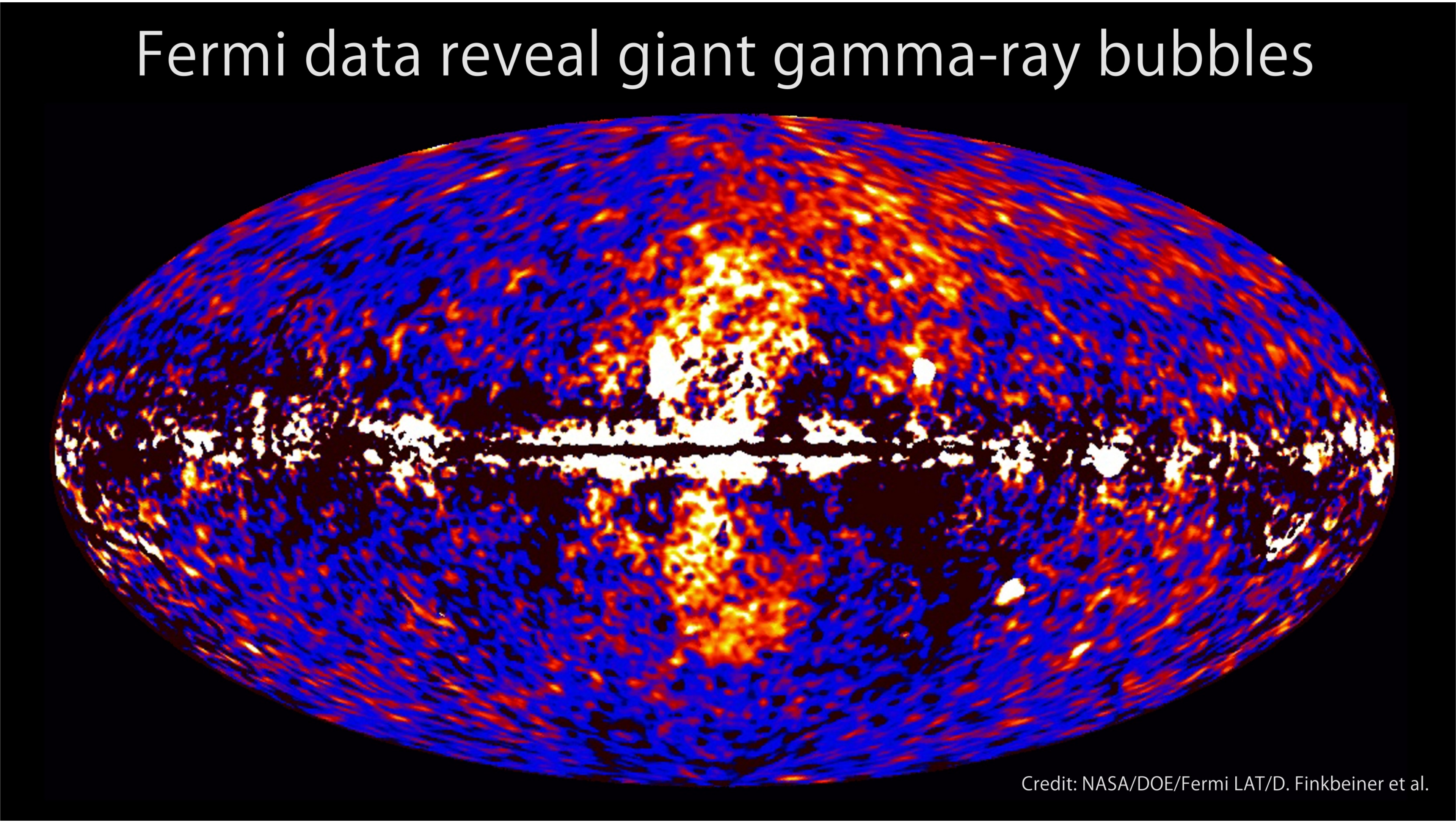
Herschel map (Molinari et al. 2011)



Radio: 20 cm
Mid-IR: 25μm
X-ray: 6.4 keV

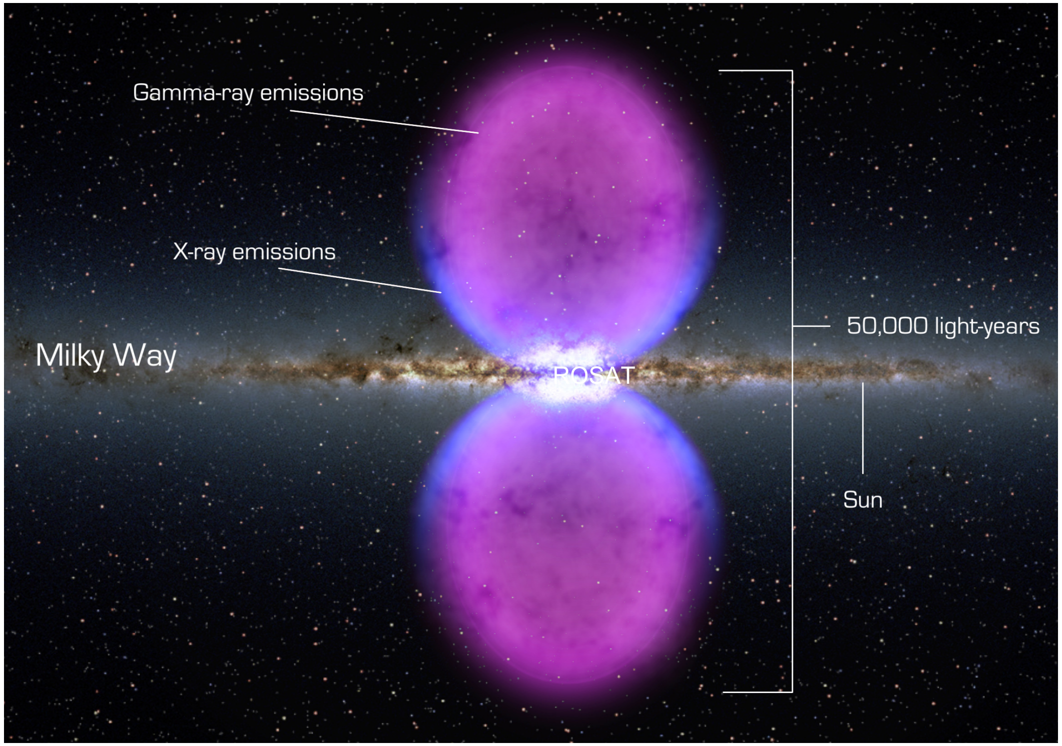
The *Fermi* bubbles

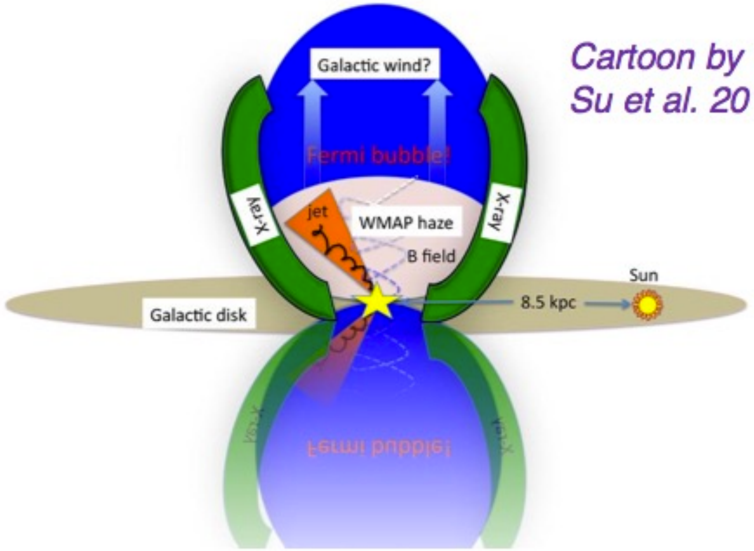
A recent discovery by *Fermi* – The Fermi Bubbles



GeV region

Bubble extension





Cartoon by Su et al. 2010

Mechanism: likely, IC emission from CR electrons on the CMB photons + other radiation fields

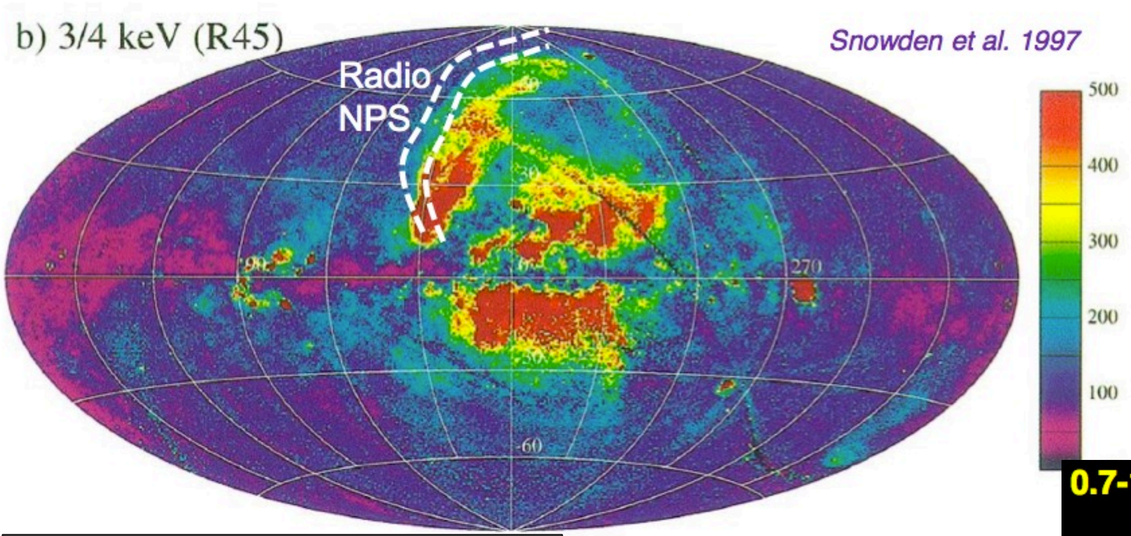
≈10kpc above and below the Galactic plane
L≈4×10^{37} erg/s (≈10^{55} erg in total)

Possible explanation:

Sharp edges → transient event cause by a huge energy injection in the GC in the last 1−10 Myr: *BH accretion event* (but needed 10^{55} erg a few 10^{6} yr ago)? *Nuclear starburst*? (Finkbeiner et al. 2010, …)

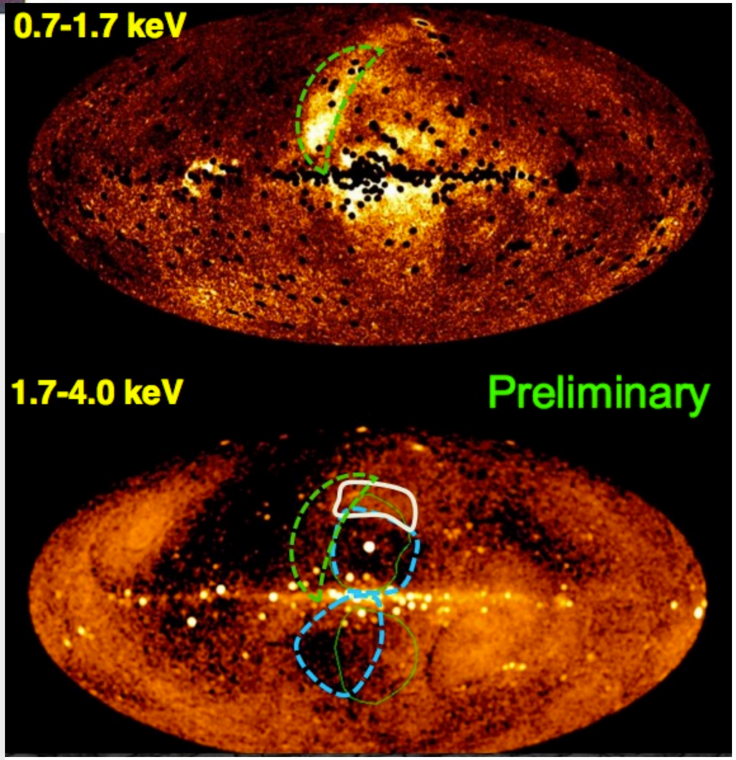
Cosmic-ray electrons may be responsible for the radio emission (synchrotron) and the γ-ray emission detected by *Fermi* (inverse Compton) − rapid e^{-} transportation or *in-situ* acceleration

ROSAT, MAXI and *eROSITA* "pictures"

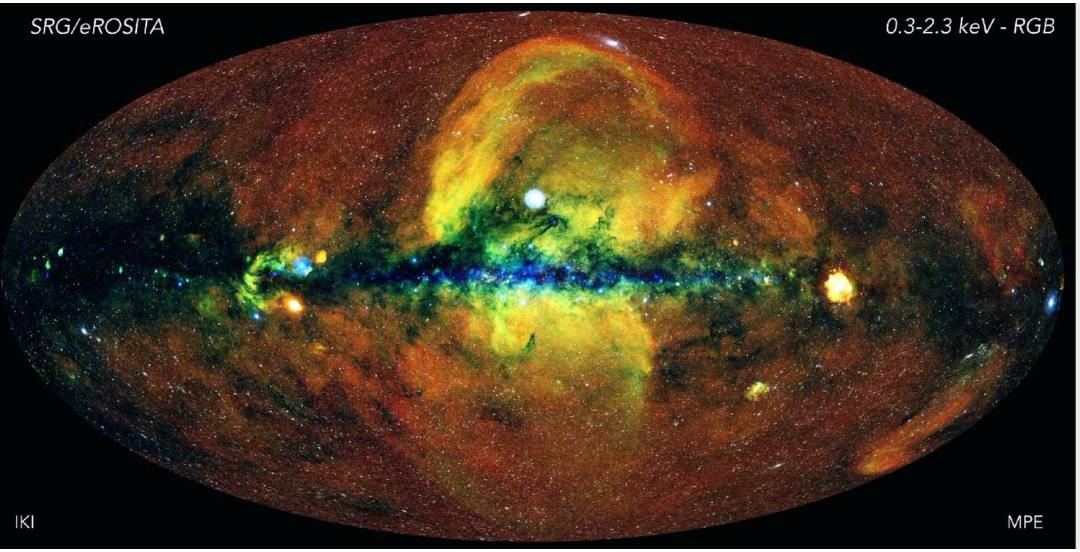


ROSAT soft X-ray map

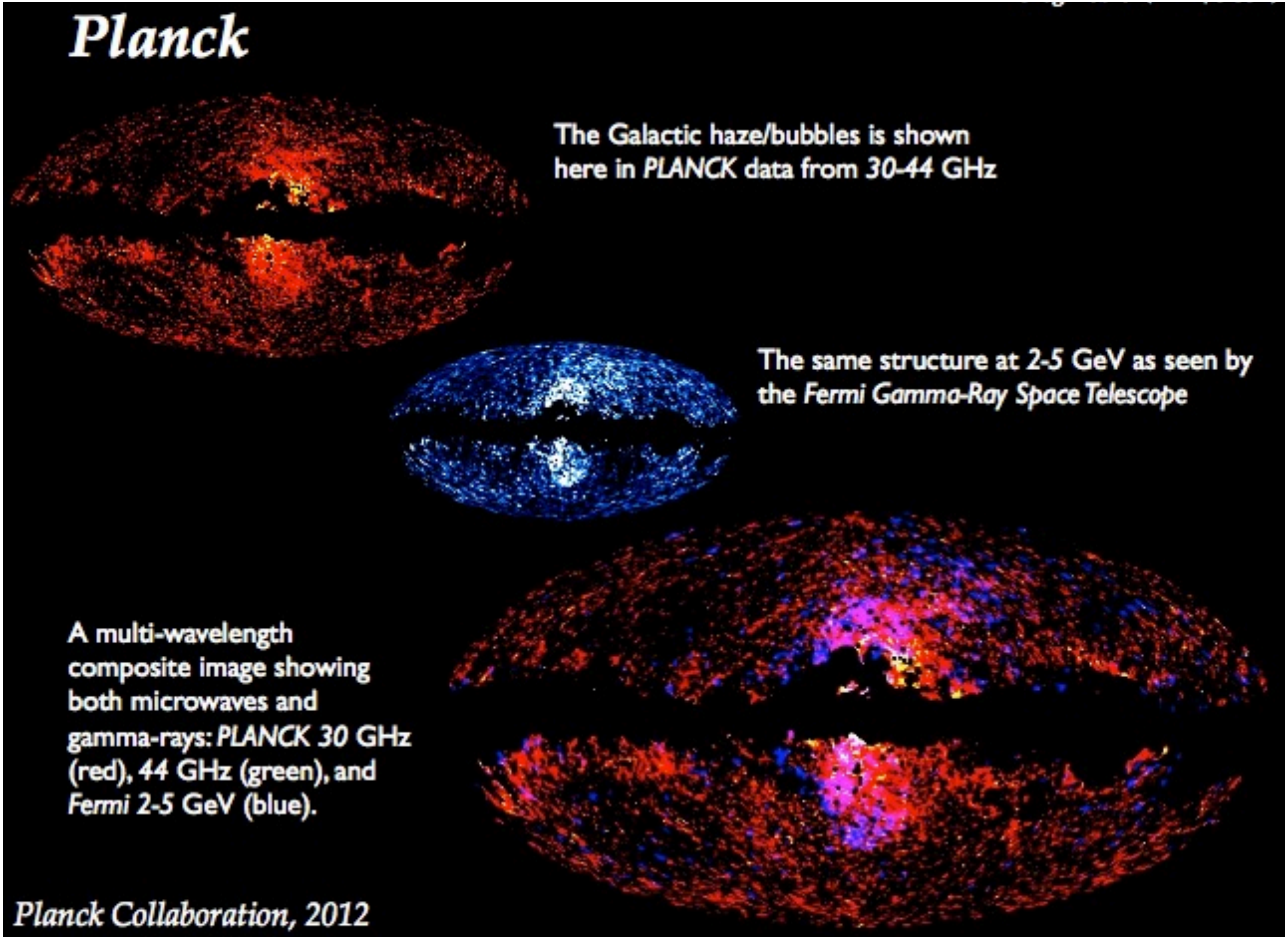
Kimura+, *MAXI* results



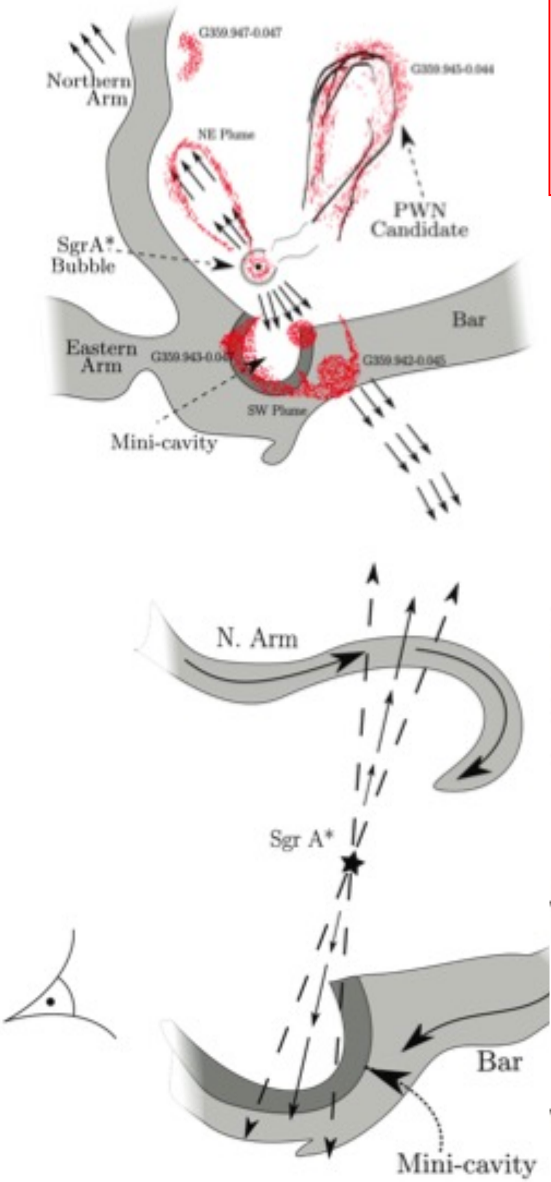
eROSITA soft X-ray map



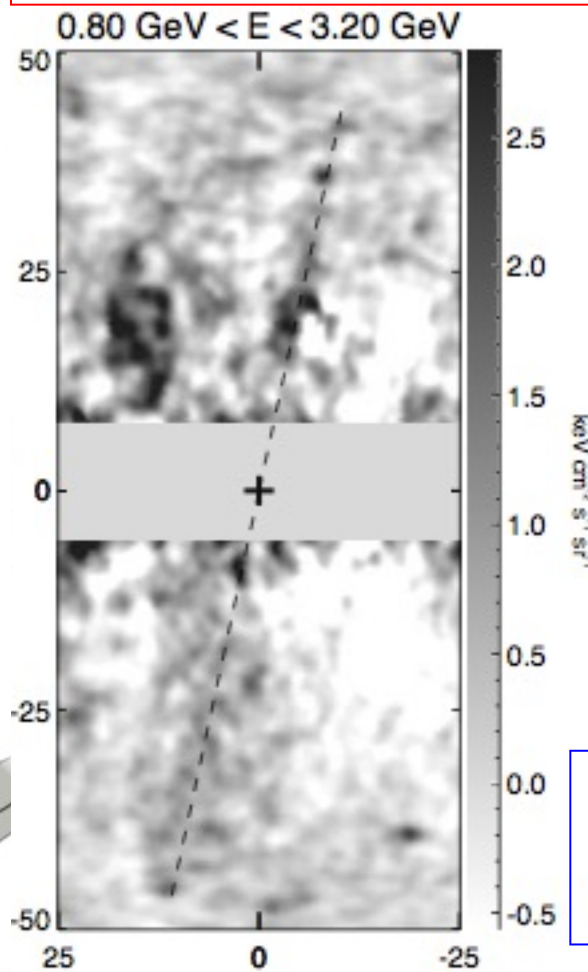
The *Planck* haze



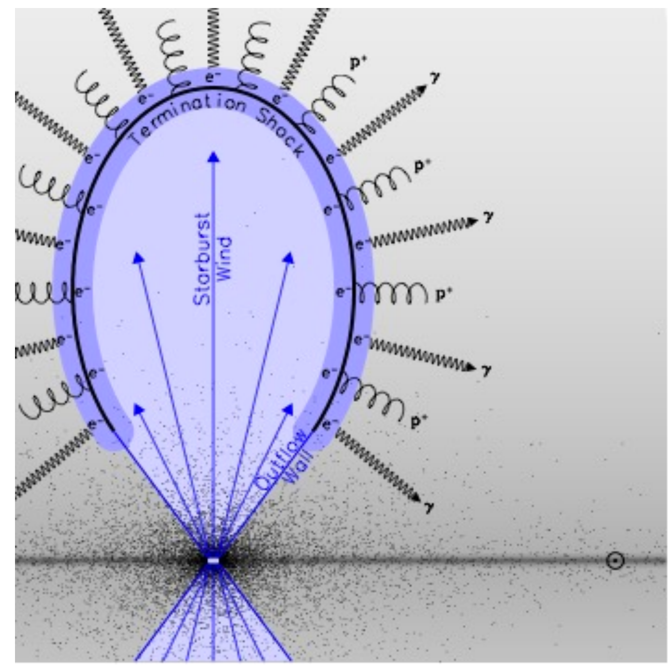
The *Fermi* Bubbles: AGN vs. starburst activity



AGN bubble? Tentative evidence for a γ-ray jet (8kpc), 15° from the Galaxy rotational axis? (Su & Finkbeiner12) – not confirmed



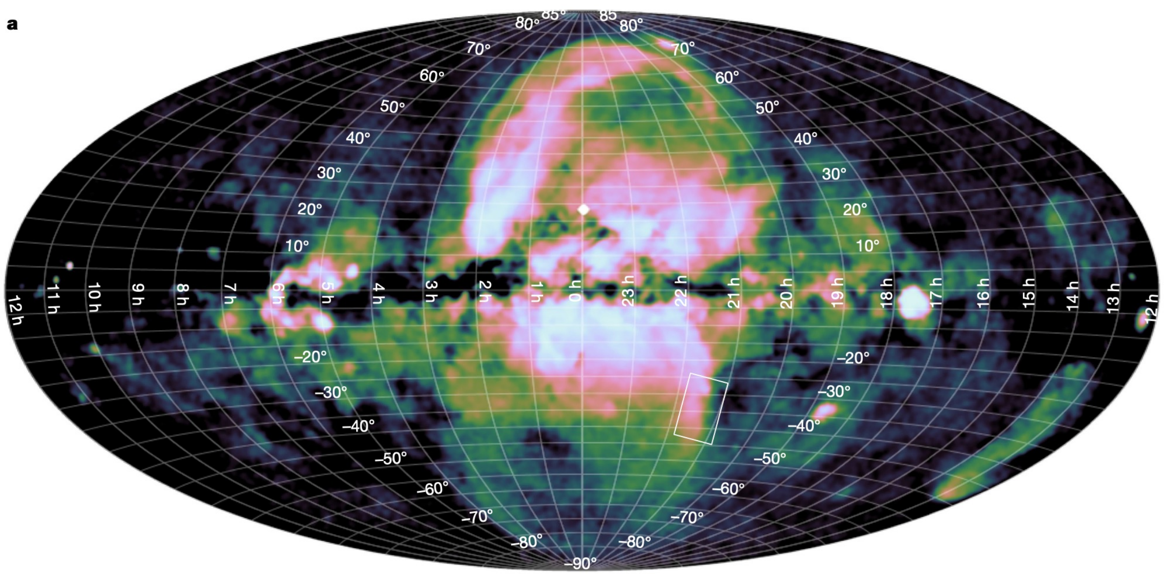
$L_{[1-100GeV]}$ (jet)≈10^{35} erg/s



Starburst-driven wind (as observed in local galaxies/Seyferts)? – Lacki13
What causes the confinement?

The *eROSITA* view

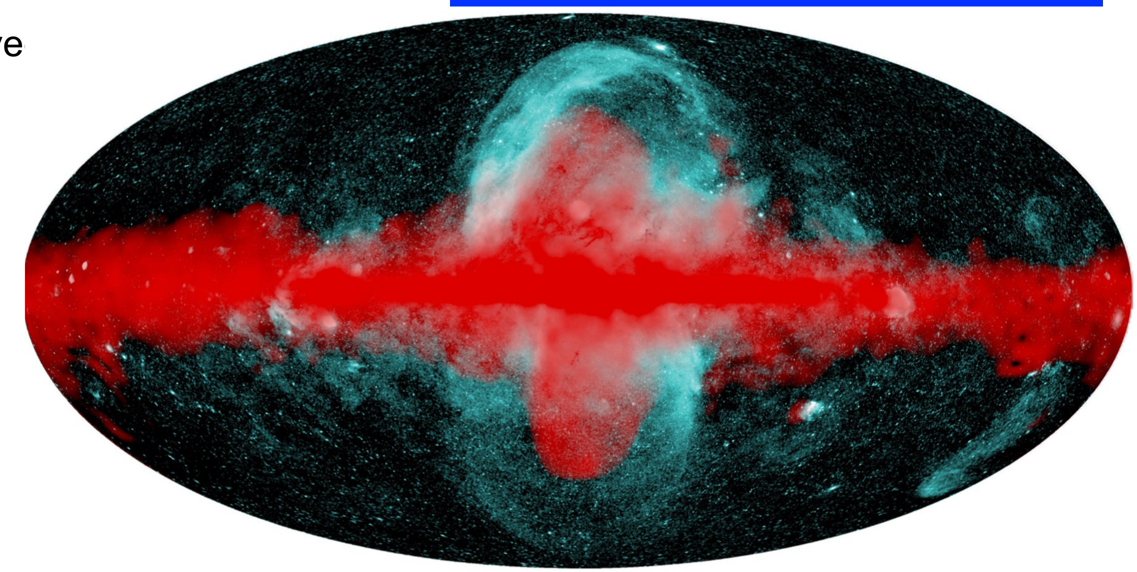
Predehl et al. (2020, Nature)



eROSITA: 0.6−1 keV, point sources remove

- To inflate the *eROSITA* bubbles, an average luminosity of ~10^{41} erg/s is needed during the past tens of millions years
- Their energetics is at the boundary for SNe explosions associated with the past star-formation activity of the MW
- They could be inflated by a 1-2 Myr of Seyfert-like (~10^{43} erg/s) activity by SgrA*. The long cooling time of the hot plasma is consistent with this picture.

eROSITA bubbles vs. *Fermi* bubbles



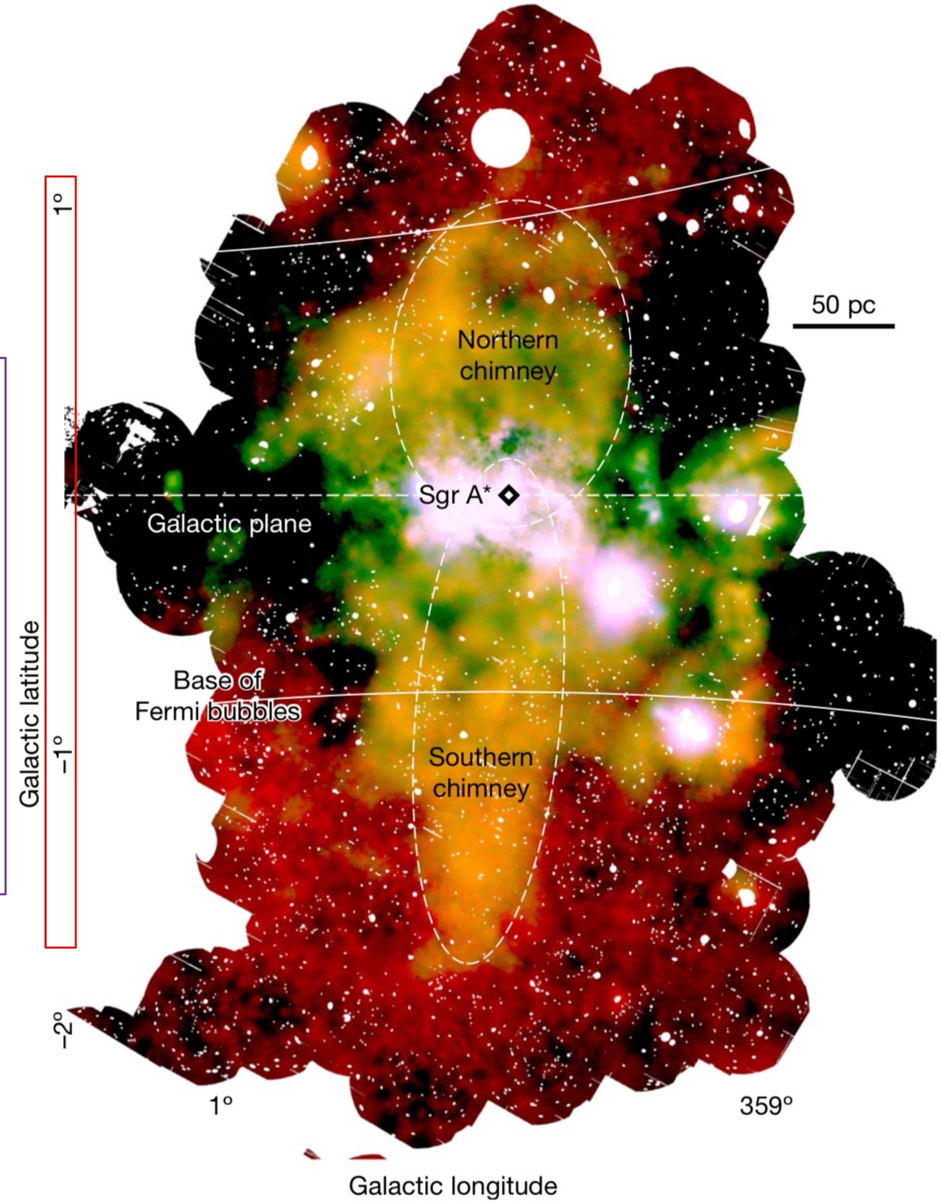
- *Are the Fermi bubbles driving the expansion of the eROSITA bubbles?*
- *Are the two extended structures associated with the same (gradual/instantaneous) energy release in the nuclear region of the MW?*

The Fermi bubbles are not the only extended structures. The X-ray chimneys above and below the GC. I

300 × 500pc
Red: 1.5−2.6 keV
Green: 2.35−2.56 keV (S_{XV})
Blue=2.7−2.97 keV (continuum emission)

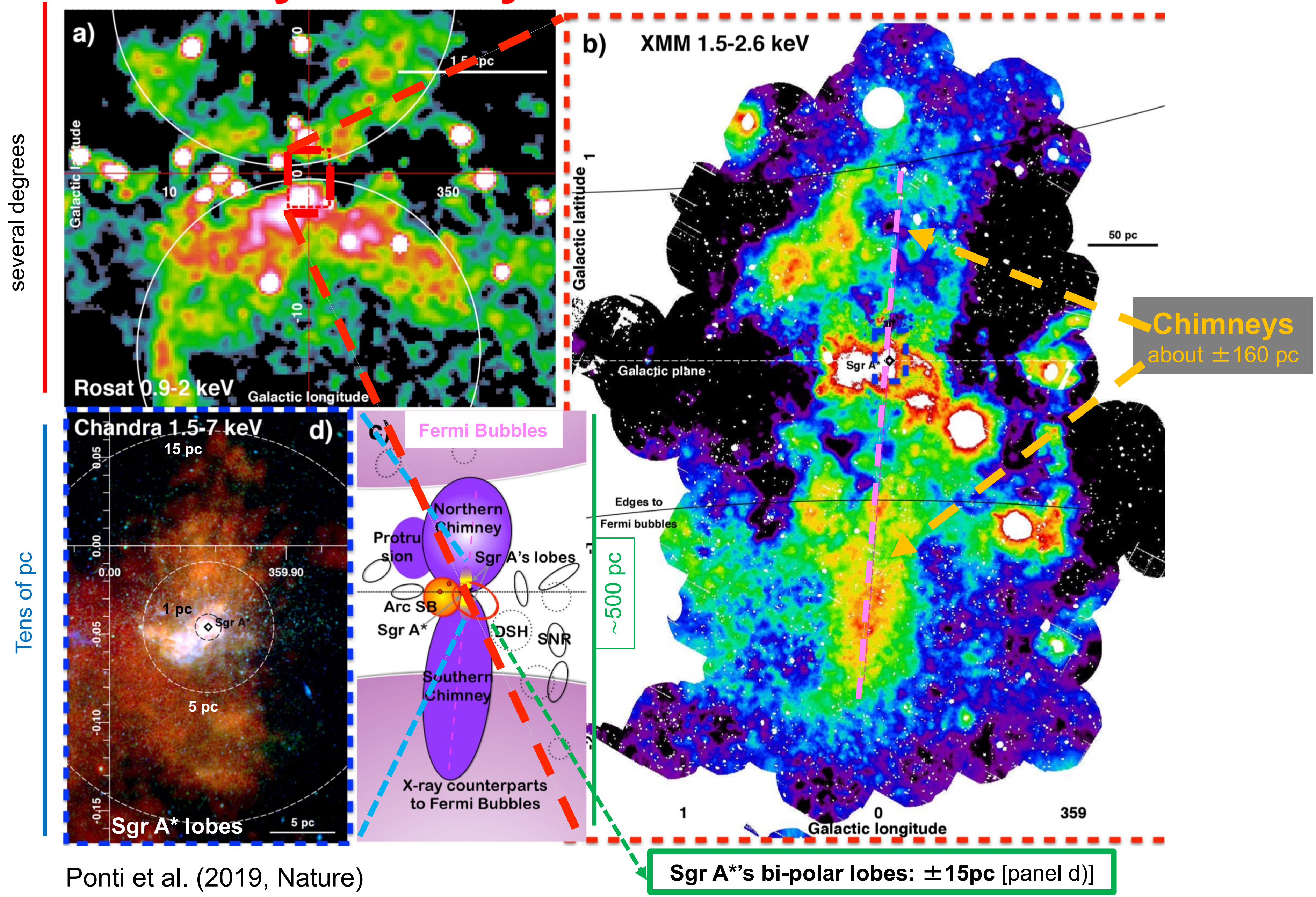
On a much more (and innermost) scale

- About ±160 pc (±1 deg) N-S extension, ±50 pc (±0.4 deg) along the Galactic plane
- Comparable brightness and color of the two extended emissions → common origin most likely
- Two structures not strictly symmetric wrt. the Galactic plane



Ponti et al. (2019, Nature)

The X-ray chimneys above and below the GC. II



Ponti et al. (2019, Nature)

The X-ray chimneys above and below the GC. III

- E_{th} (**±15pc lobes**, thermal energy)~6 × 10^{50} erg + t_S (sound crossing-time of the lobes) ~3 × 10^4 yr → **L_{15pc}~8 × 10^{38} erg/s** → **modest requirement** in terms of time-average **energetics** (TDE – tidal disruption events - and SN feasible, besides SgrA* activity)
- Higher energetics in case of very low filling factor for the X-ray emitting gas

- E_{th} (**chimneys, 160pc**, thermal energy)~4 × 10^{53} erg + t_S (sound crossing-time of the chimneys) ~3 × 10^5 yr → **L_{160pc}~4 × 10^{39} erg/s** → TDE and SN still viable options.
- The kT~0.7 keV gas may be close to hydrostatic equilibrium (feels the Galactic grav. potential)

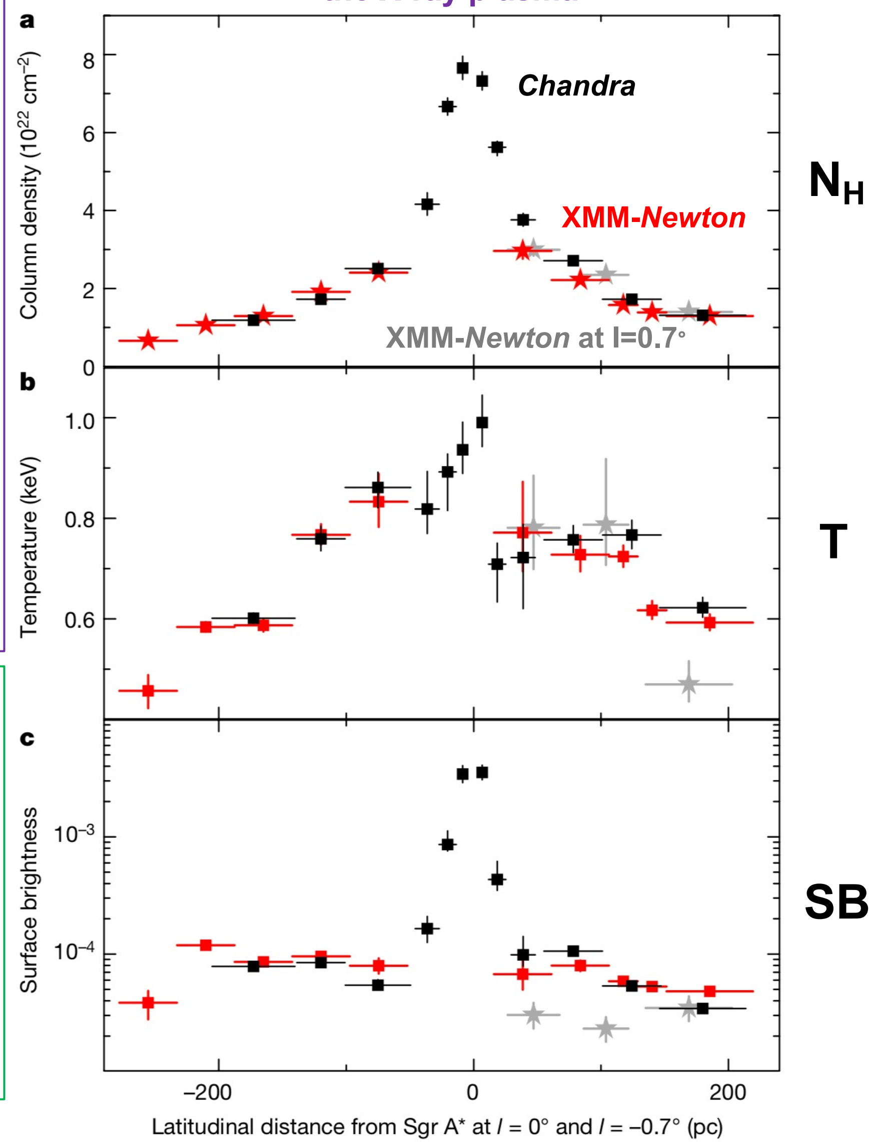
→ The chimneys could represent the channel excavated by powerful outflows associated with a series of past episodic events connecting the GC with the halo

- Long cooling times (~2 × 10^7 yr) expected
- Edge-brightened morphology consistent with interation of the gas with the denser ISM
- Confinement by ISM or magnetic field

→ SF-powered mechanism most likely

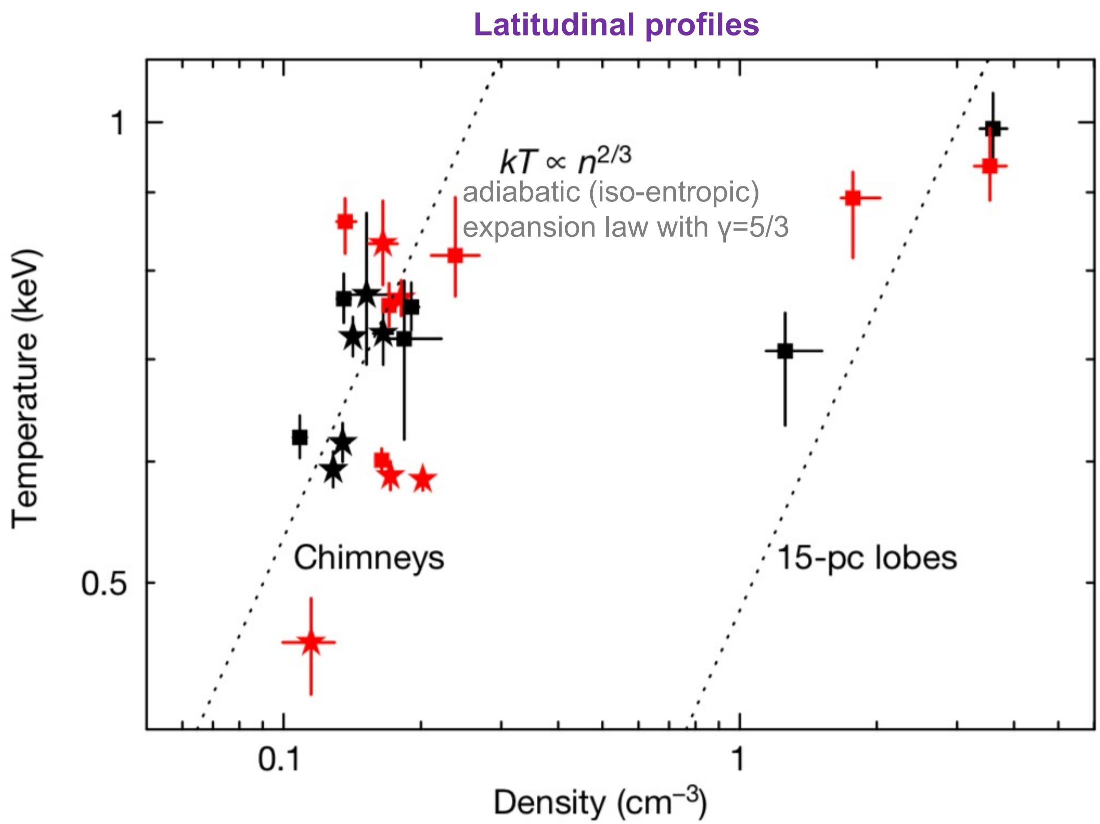
(from the presence of stars of the CMZ at the base of the chimneys)

Latitudinal variations of the physical parameters of the X-ray plasma



Ponti et al. (2019, Nature)

The X-ray chimneys above and below the GC. IV



Ponti et al. (2019, Nature)

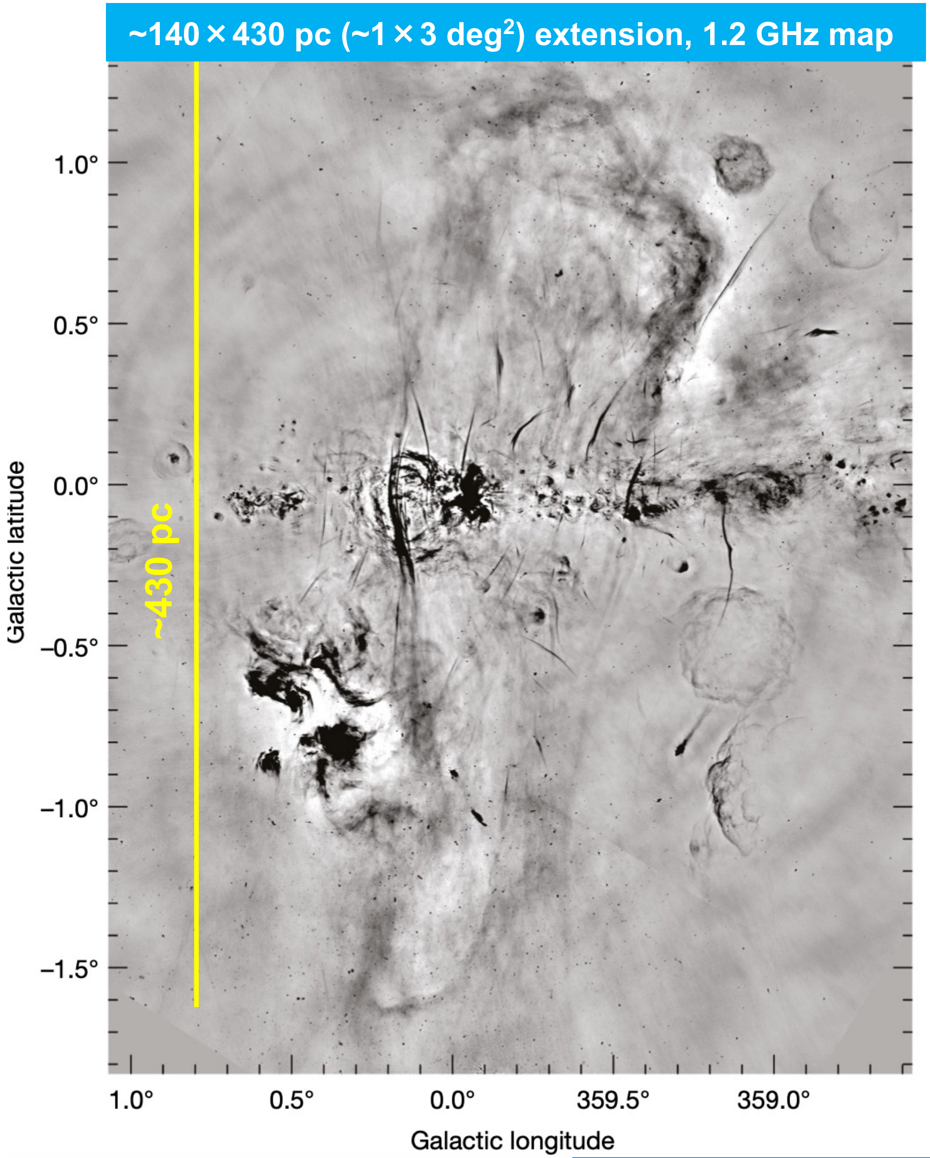
Chimneys are not simple adiabatic continuation of the outflow of the ±15pc lobes

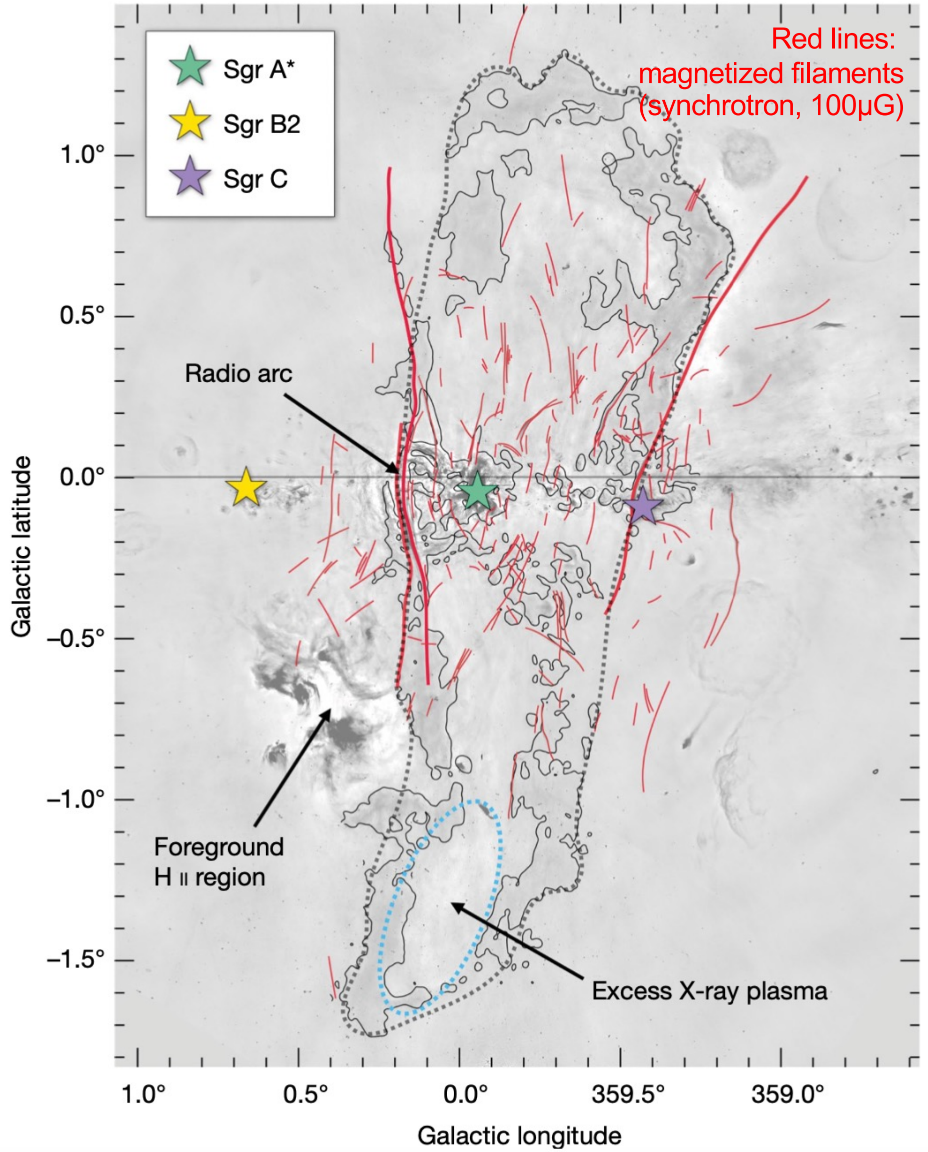
- inner lobes as the most recent episode of energy injection into the chimneys?
- *chimneys as the way to transport energy from the GC to the Fermi Bubbles?*

Power(Fermi Bubbles)~10^{40}–10^{44} erg/s >> P(chimneys) - likely a lower limit: only a fraction of energy can be deposited into the X-ray emitting gas

- data consistent with a *SN-powered wind with limited role from SgrA** (but further support to this hypothesis is needed)

The radio view of extended emission





Heywood et al. (2019, Nature)
MeerKAT radio data (6'' res.)

Edge-brightened and bounded structure, largely overlapping with X-ray chimneys
Synchrotron, age~a few million yrs, E~7 × 10^{52} erg for the progenitor
Cosmic ray (CR) and gas pressures required to drive outflows along the magnetic field lines
Relativistic CR particles is likely powering the synchrotron emission of the bubbles

Recap of extended emission (below/above the plane) in our Galaxy

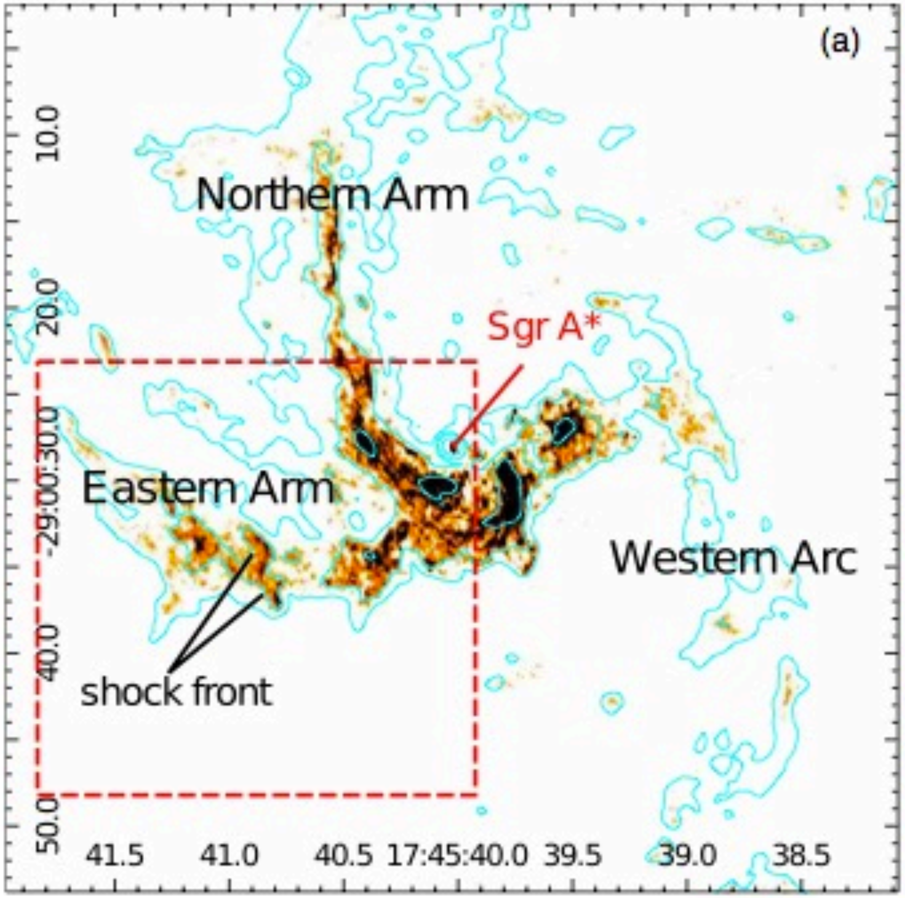
- The mechanism for the progenitor event is still unknown (likely something happening close to SgrA*)
- Not necessarily the same event is responsible for all the reported emissions (different energetics, similar spatial distributions in some cases)
- The radio bubbles can be one example of a series of *intermittent events*, possibly combined with weakier and steadier outflows → cumulative influence of these events being possibly responsible for the observed extended radio, X-ray and ɣ-ray structure connecting the Galactic Center region with the regions at high latitude

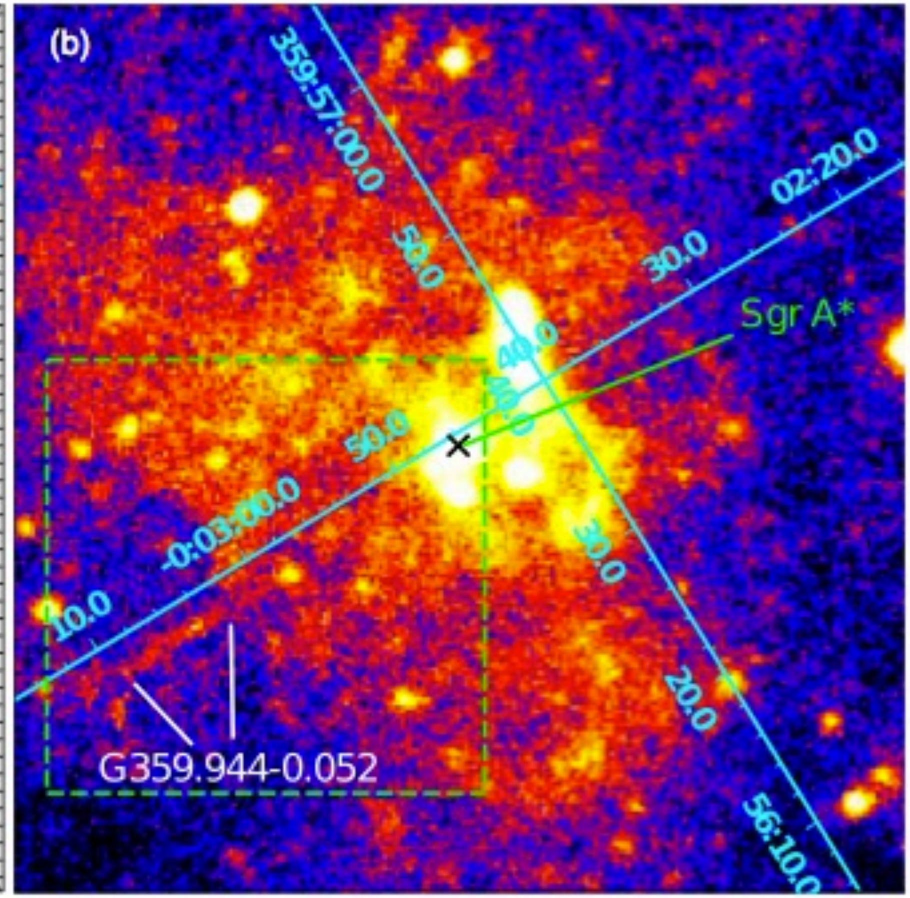
Are jets, or jet-like structures, at some scale unusual in the GC region?

The pc-scale jet. I

VLA 1.3cm map with 3.6cm intensity contours

Chandra 2−8 keV image





2 × 2pc map

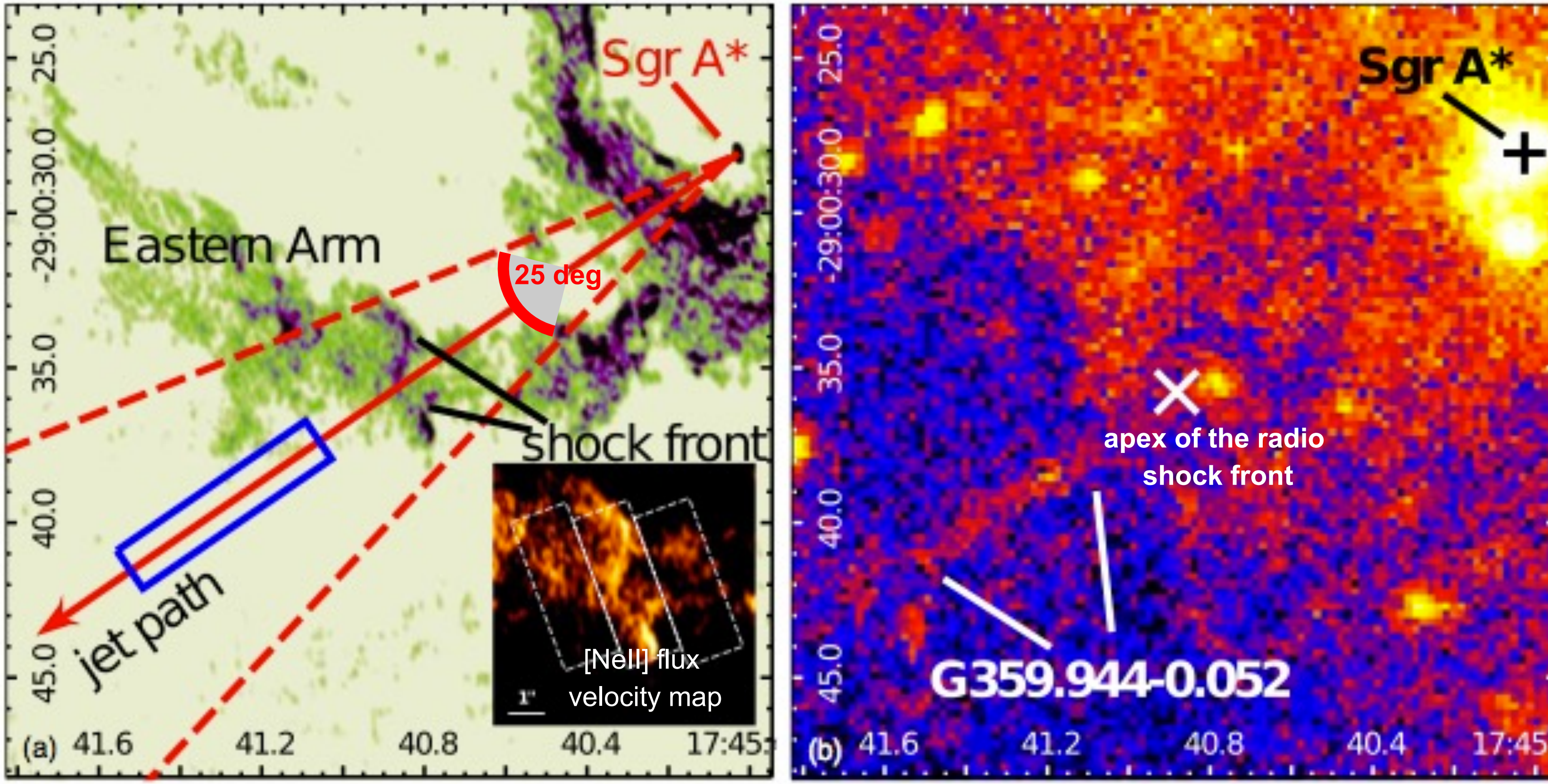
1999−2011 map (1.46 Ms)

Li & Morris (2012)

One shock front in the radio and X-ray emission: any possible link?

The pc-scale jet. II

VLA 1.3cm map	*Chandra* 2−8 keV image

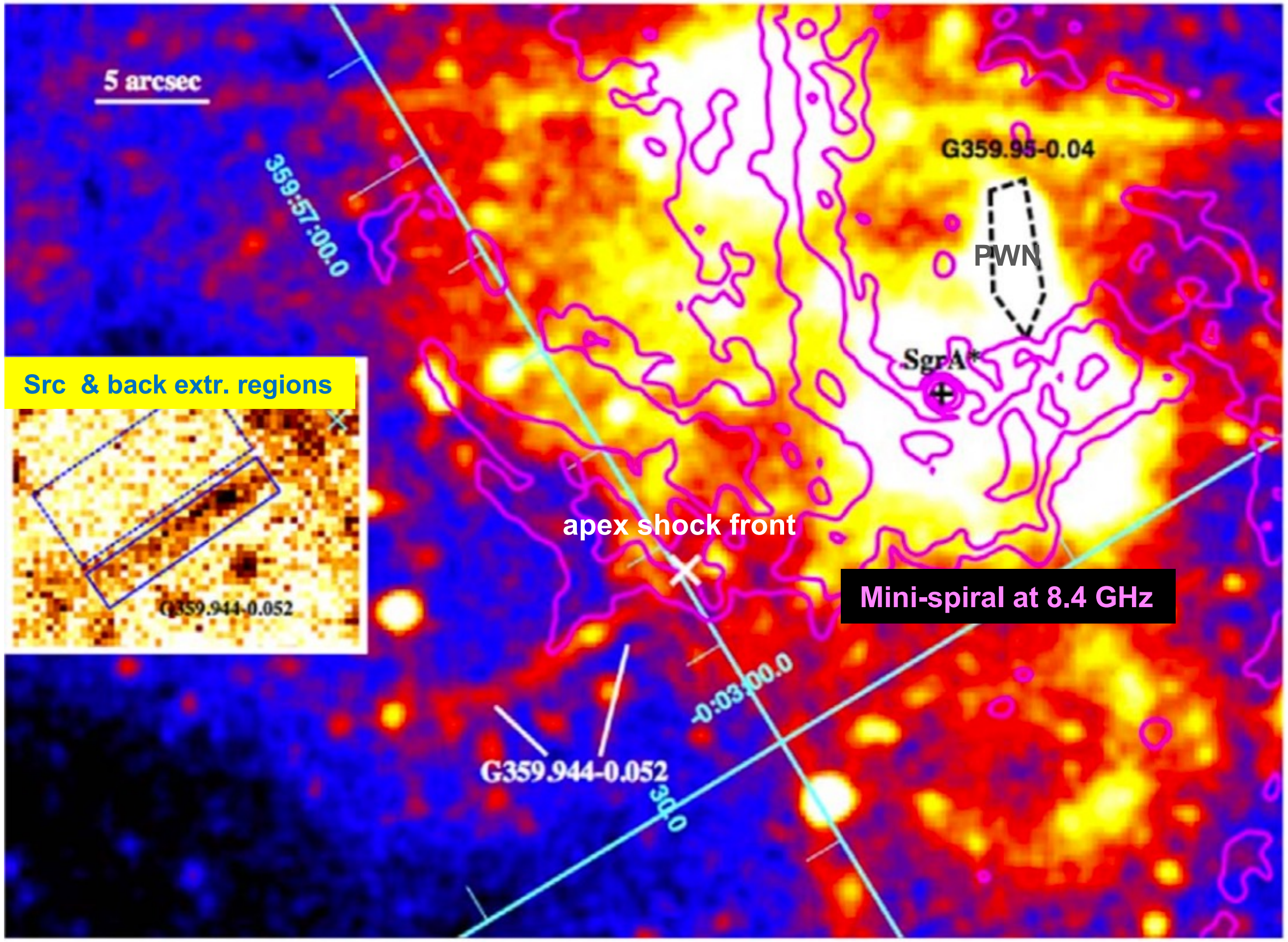


Li & Morris (2012)

Shock front due to the pc-scale, one-sided jet, hence X-rays from the post-shock region downstream along the jet path. X-ray emission is almost constant over 10 yrs. Absorbed power-law emission L(2−10keV)≈2×10^{32} erg/s, i.e., non-thermal (synchrotron?) emission as in extragalactic jets

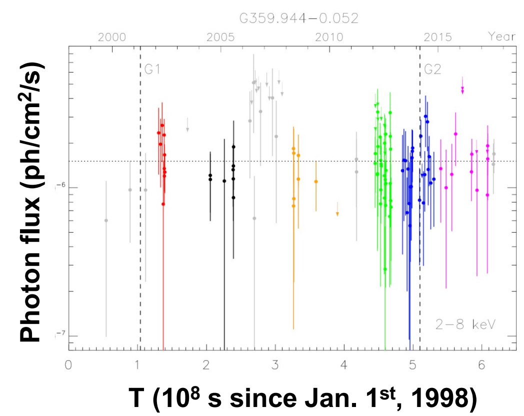
The pc-scale jet. III

New *Chandra* 2−8 keV image



Zhu et al. (2019)

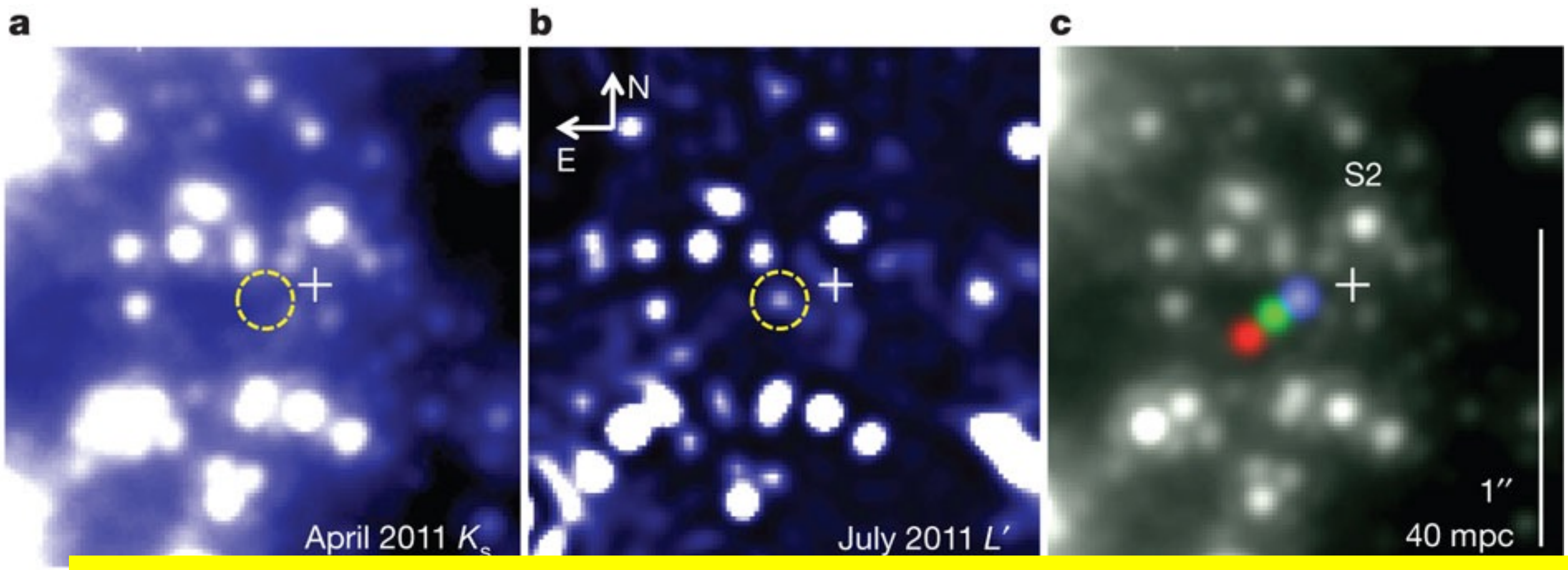
- No flux/spectral variations after the passage of G2
- Synchrotron cooling from shock-induced relativistic electrons, cooling along the jet (t_{cool}~1 yr)
- Length(jet)~7.5"~0.3pc (before being dominated by bkg emission)
- *Stable jet over ~20 yrs*



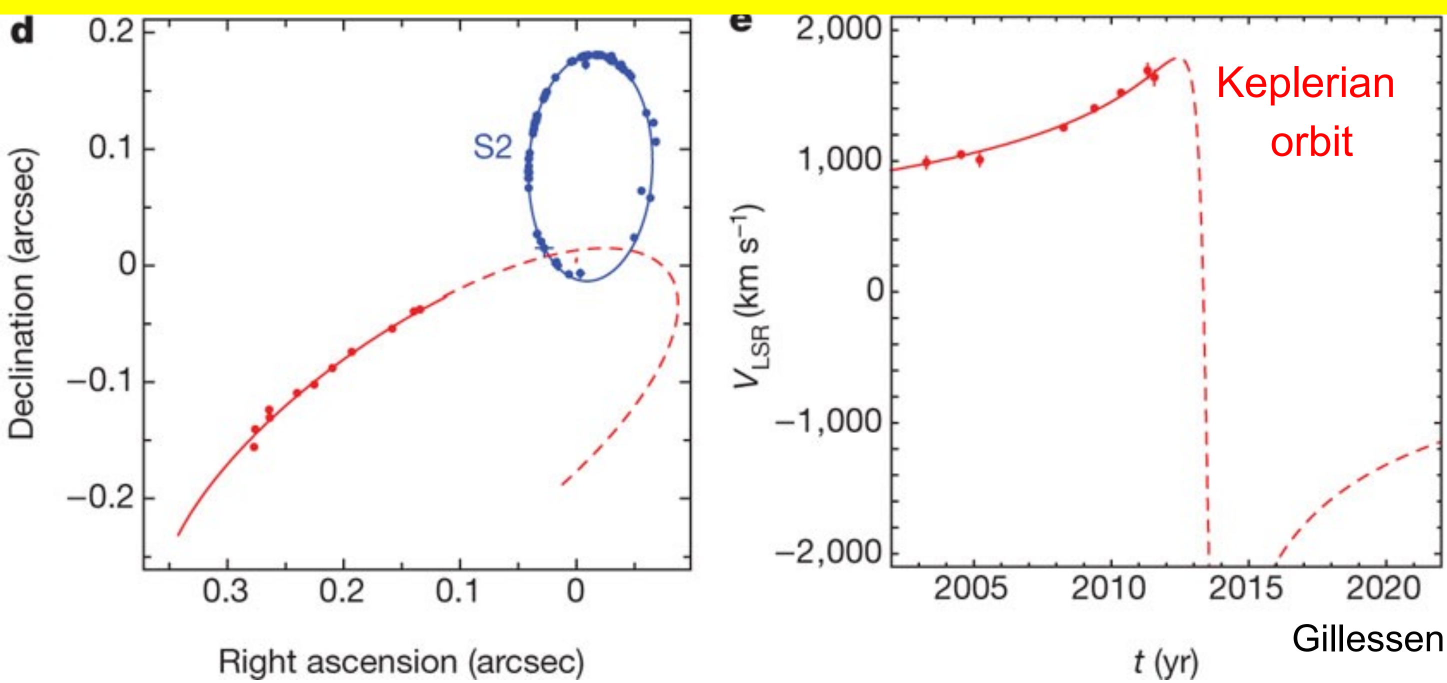
Following a gas cloud in its passage close to SgrA*.
Any effect on SgrA* activity and flaring rate?

‘Live’ accretion event

The cloud: detection and orbit

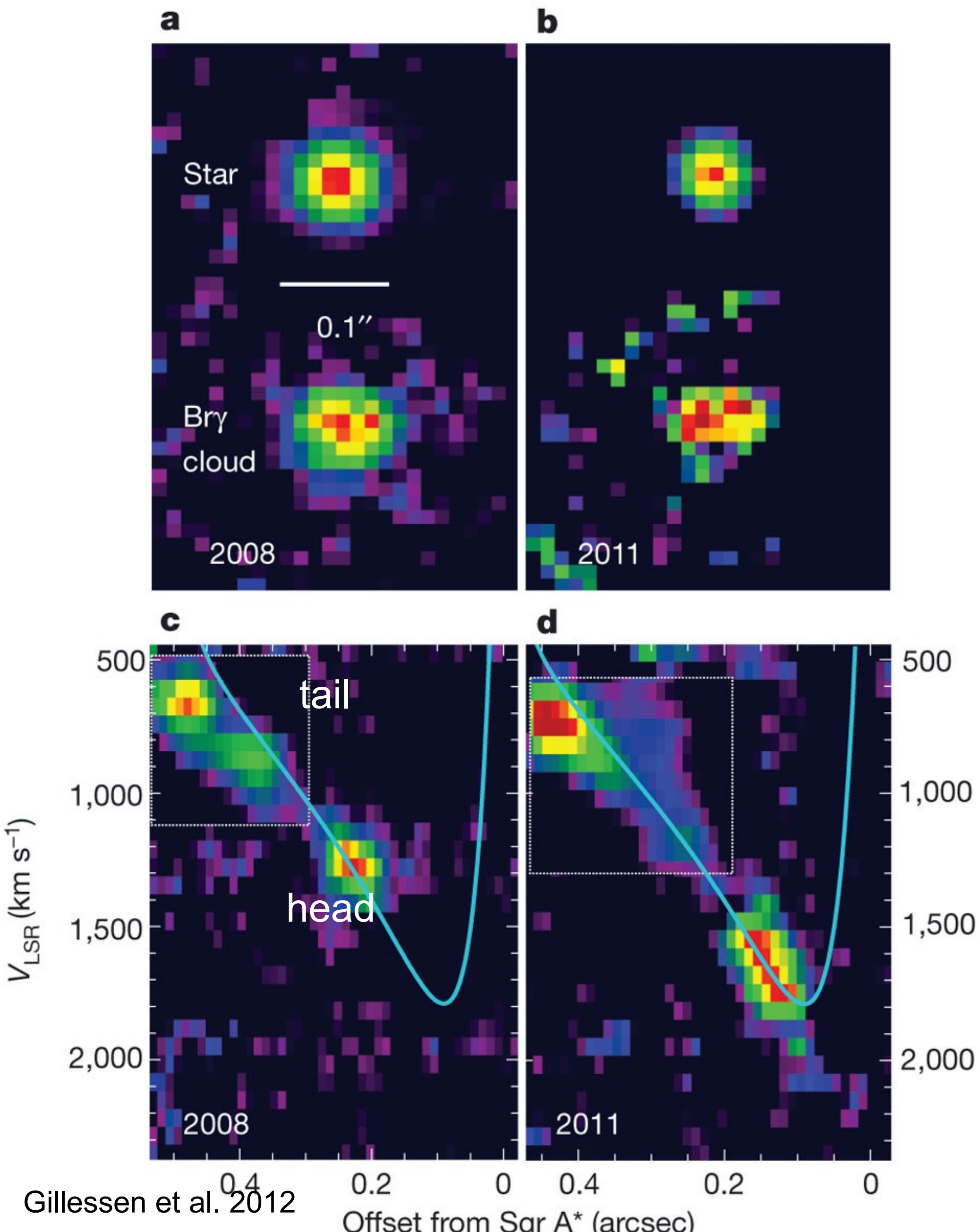


Detection in the L' band, non in K_S → not a star, dusty ionized cloud in motion



Gillessen+12, Nature

The velocity shear in the gas cloud



Gillessen et al. 2012

Gas cloud properties

- Gas cloud (**$M \approx 3 M_{Earth}$**) photo-ionized by the radiation field from nearby massive stars
- Highly elliptical (e=0.94) orbit
- Disruption already begun since 2008
- Velocity≈1700 km/s (in acceleration)
- $T \approx 550$ K; $L \approx 5\ L_{\odot}$; $n_e = (0.1-2) \times 10^5$ cm^{-3}

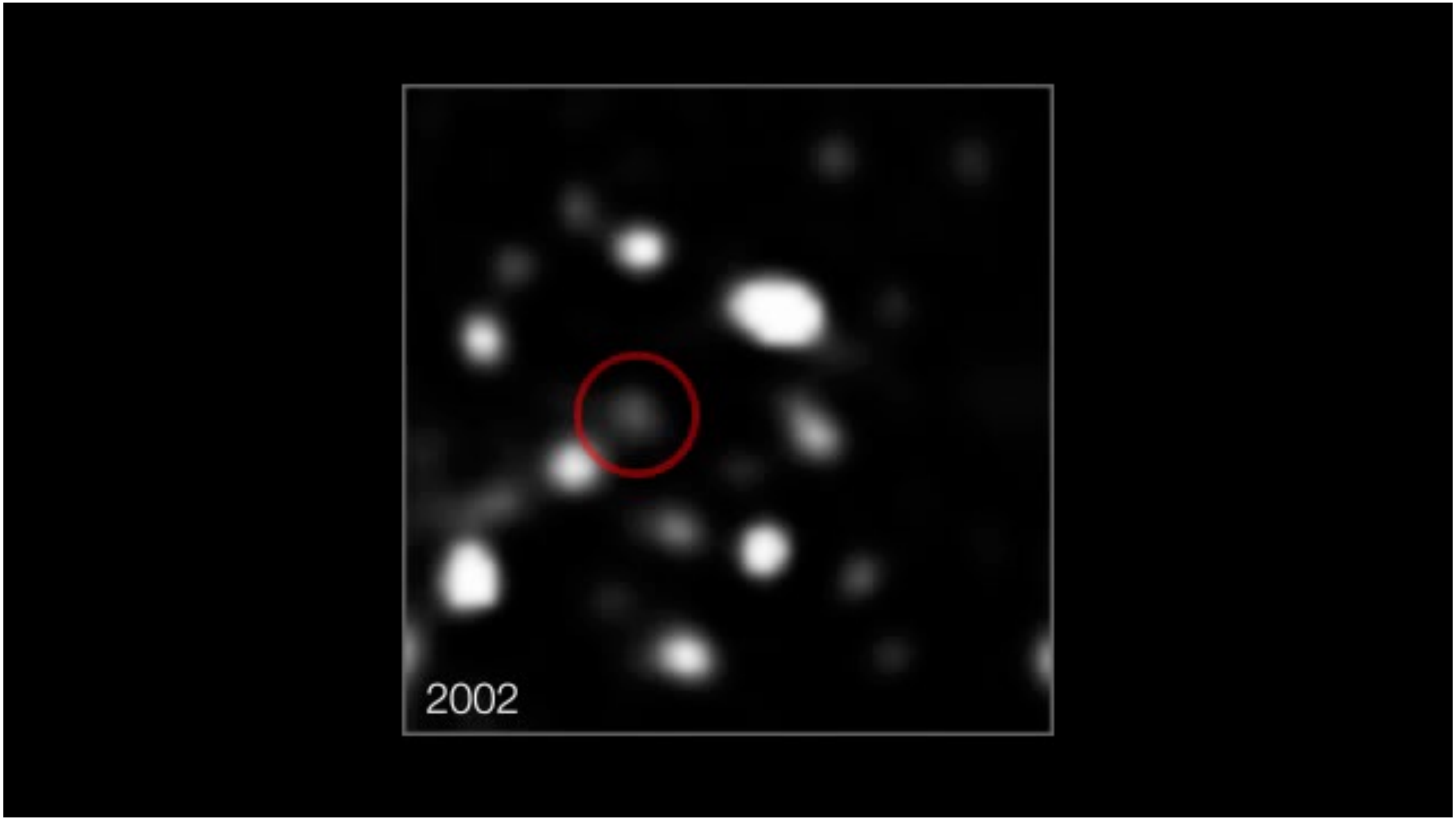
Predictions

- Shock with hot gas in the inner region ➔ T≈(6-10) × 10^6 K ➔ X-rays (*$L_{2-8keV} \approx 10^{34}$ erg/s vs. quiescent≈10^{33} erg/s*)
- Radiated energy <1% of the total E_{kin} of the cloud ($E \approx 10^{45.4}$ erg)
- Cloud can eventually feed the BH in out Galaxy (with a radiative efficiency of ≈1−10%)

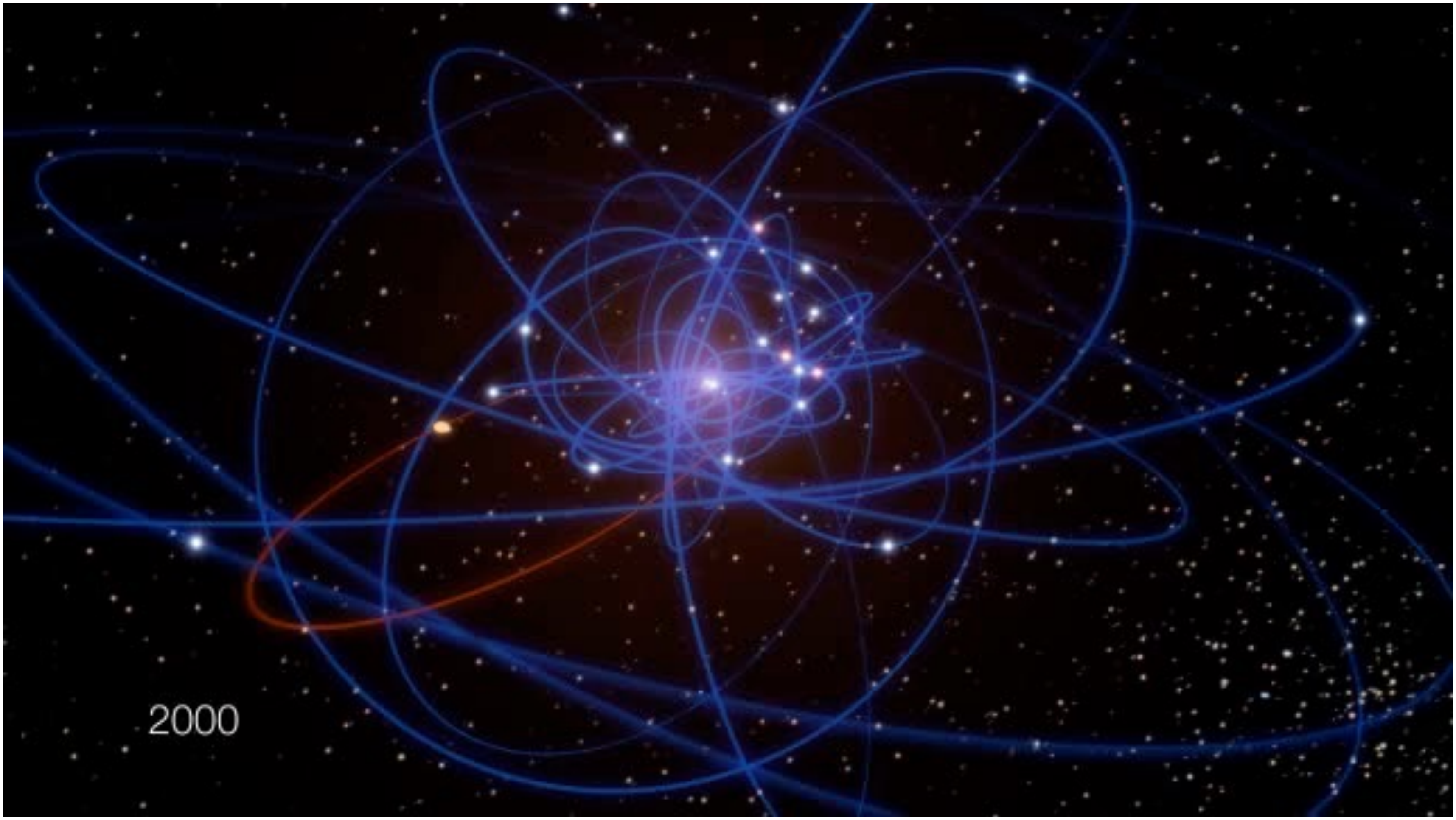
Nature

Colliding winds in the stellar disk (binaries) may create low angular momentum gas falling in the potential well of SgrA*

The cloud: observations with VLT



Modeling the cloud orbit and behaviour



Possibility of long-lasting mechanism to feed the BH in SgrA*
Closest approach predicted for 2013, then spring 2014 … then Atel update…

G2 closest approach to SgrA*

Outside
GCN
IAUCs

Other
ATel on Twitter and Facebook
ATELstream
ATel Community Site
MacOS: Dashboard Widget

The Astronomer's Telegram

Present Time: 6 May 2014; 16:25 UT

[Previous | Next]

Detection of Galactic Center Source G2 at 3.8 micron during Periapse Passage Around the Central Black Hole

ATel #6110; *A. M. Ghez (UCLA), G. Witzel (UCLA), B. Sitarski (UCLA), L. Meyer (UCLA), S. Yelda (UCLA), A. Boehle (UCLA), E. E. Becklin (UCLA), R. Campbell (WMKO), G. Canalizo (UCR), T. Do (Toronto), J. R. Lu (UH), K. Matthews (Caltech), M. R. Morris (UCLA), A. Stockton (UH)*
on 2 May 2014; 16:11 UT
Credential Certification: Andrea Ghez (ghez@astro.ucla.edu)

Subjects: Infra-Red, AGN, Black Hole, Transient

We report new observations of Galactic Center sources G2 & SgrA* from the W. M. Keck Observatory. Both sources are of great interest and vary temporally; G2 is the putative gas cloud now passing through periapse in its orbit around the black hole at the center of the Milky Way Galaxy and SgrA* is the emission associated with the central black hole. Our observations were obtained on 2014 March 19 & 20 (UT) with the Keck II laser guide star adaptive optics (LGSAO) system and the facility near-infrared camera (NIRC2) through the K'[2.1 μm] and L'[3.8 μm] broadband filters. At this time, G2 was expected to have been at closest approach with a separation from SgrA* of only ~20 mas and, therefore, to be spatially unresolved from SgrA* in our L' observations, which have an angular resolution of ~90 mas. Nevertheless, the two can be disentangled spectrally. In the L'-band, both Sgr A* and G2 contribute to the total flux; however, Sgr A*'s L' flux is estimated and removed based on (1) the K'-flux, where G2 does not contribute significantly, and (2) the well measured and constant K'-L' color of Sgr A*. Each night, roughly 20 interleaved measurements were made at each wavelength (exposure time of 28 and 30 sec at K' and L', respectively), with a duty cycle time of 134 sec for the two wavelengths. Our preliminary estimate of G2's 3.8 μm de-reddened flux density is 1.7 ± 0.2 mJy (or equivalently an observed magnitude of 14.1 ± 0.2 in the L'-band), which is consistent with measurements from earlier years (2002-2013). During these observations, SgrA* was quite faint (3.8 μm de-reddened flux density of 1.5 ± 0.2 mJy, which is 1/30 of the maximum observed at near-infrared wavelengths), allowing G2's flux density to be robustly measured. We conclude that G2, which is currently experiencing its closest approach, is still intact, in contrast to predictions for a simple gas cloud hypothesis and therefore most likely hosts a central star. Keck LGSAO observations of G2 will continue in the coming months to monitor how this unusual object evolves as it emerges from periapse passage.

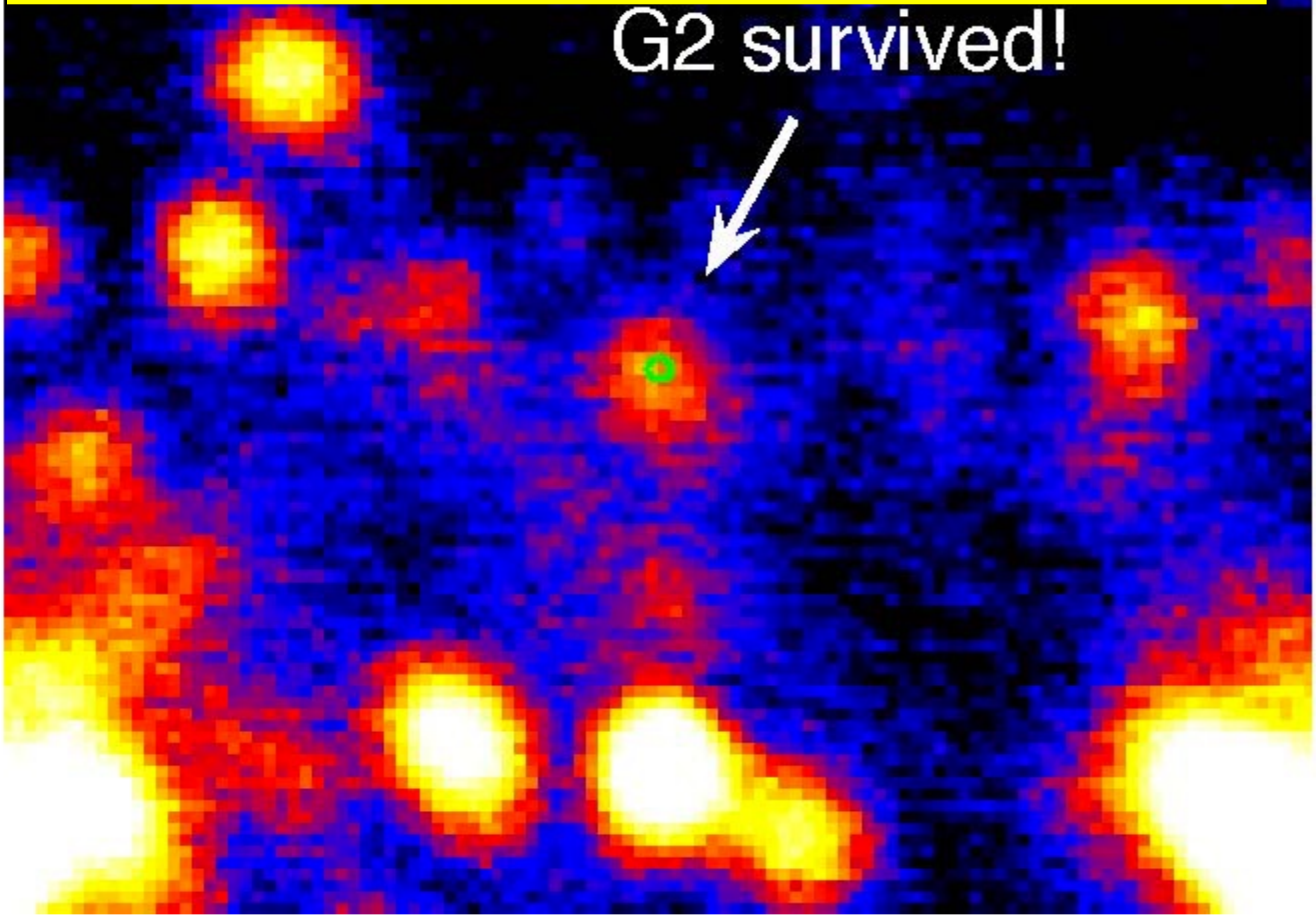
UCLA Galactic Center Group

March 2014: the closest approach of G2 to SgrA* observed with *Keck* adaptive optics

SgrA* has L'(3.8μm) de-reddened flux density of 1.5 ± 0.2 mJy, while G2 has L'=1.7 ± 0.2 mJy (mag=14.1 ± 0.2), which is consistent with measurements from earlier years (2002−2013), i.e., **G2 is still intact**

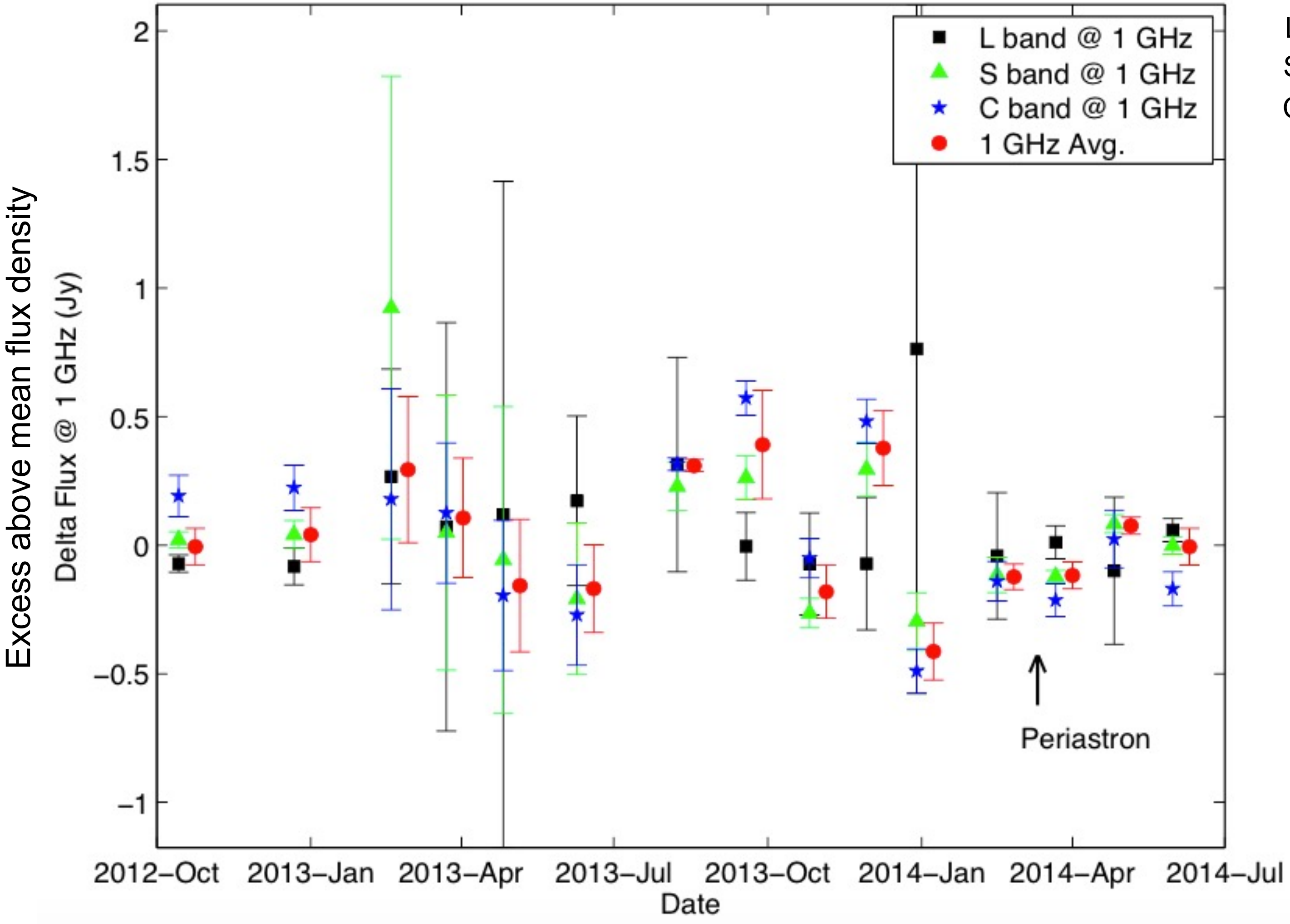
Presence of a central star?

- Originally, a pair of binary stars? (Ghez+14)
- Formed out of the debris stream produced by the removal of mass from the outer envelope of a nearby star? (Guillochon+14)



Keck
near-IR obs.
(late 2014)

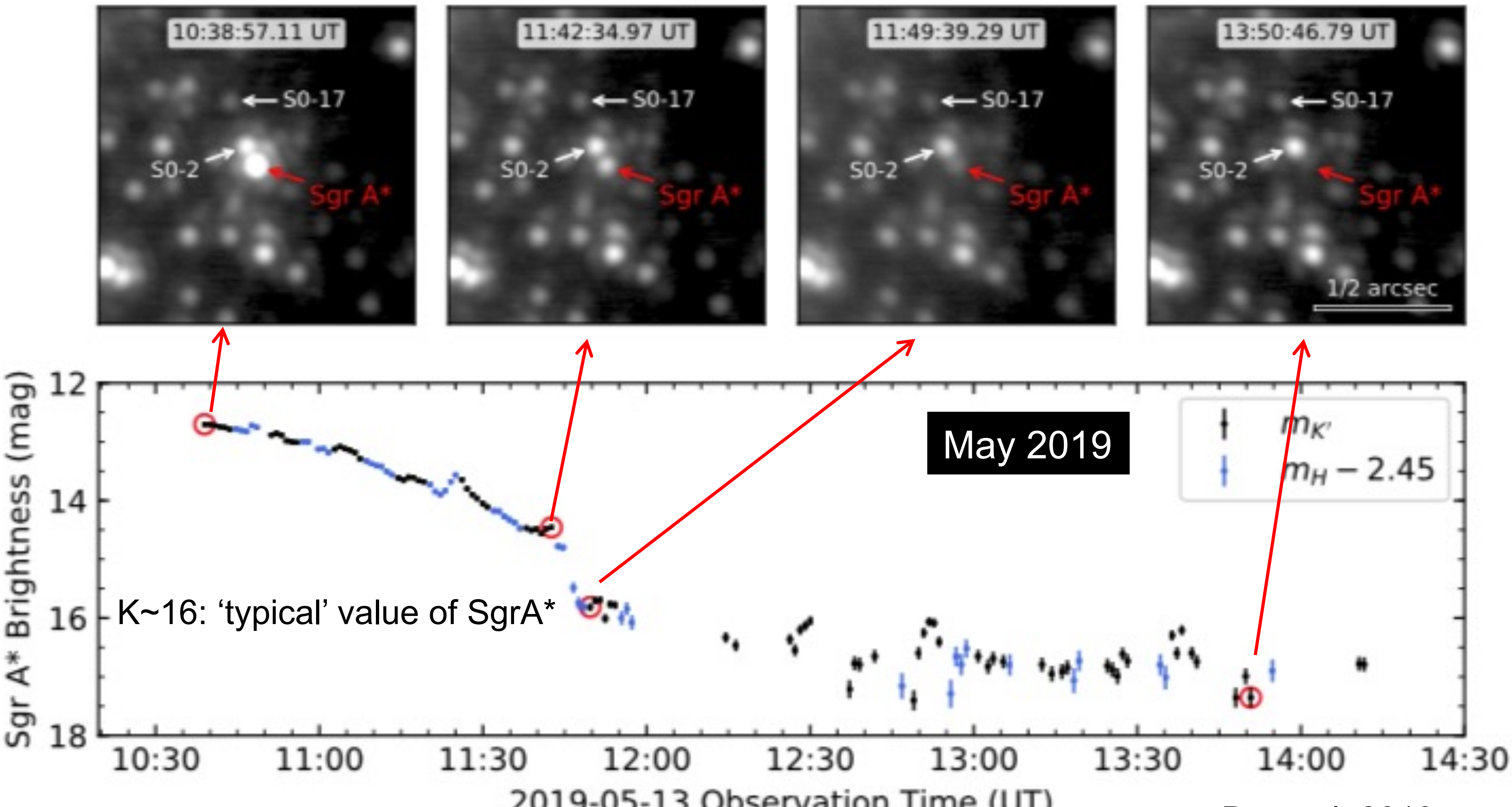
G2 cloud: no significant variation in the radio



L=1.5 GHz
S=3.1 GHz
C=5.4 GHz

Bower et al. 2015

SgrA* unprecedented variability in the near-IR



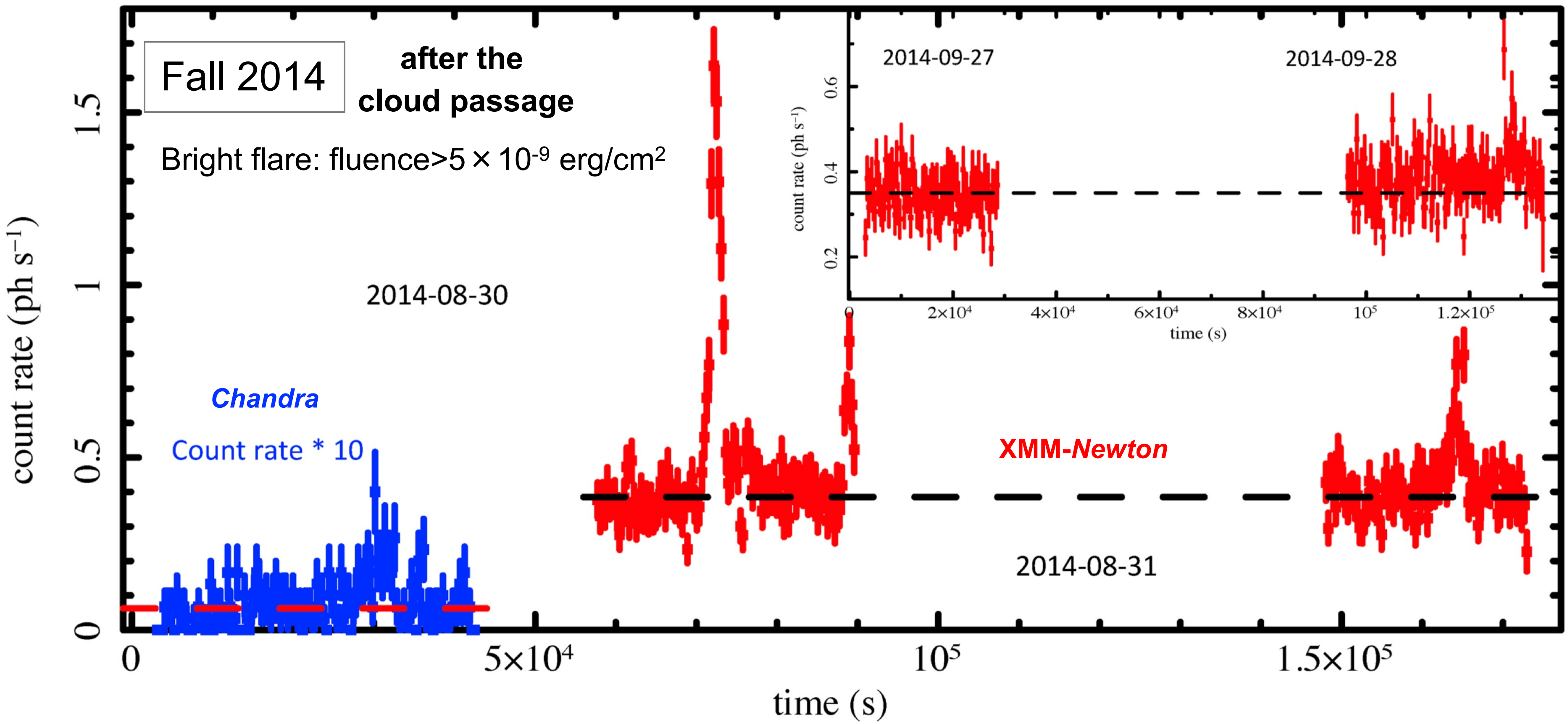
Do et al. 2019

Not only G2 can be responsible for the variability of SgrA*…

Possible explanations for SgrA* variability: (a) closest S0-2 passage to SgrA* in 2018

(b) delayed enhancement due to G2 passage in 2014

Evidence for a recent increase in the bright flaring rate. I

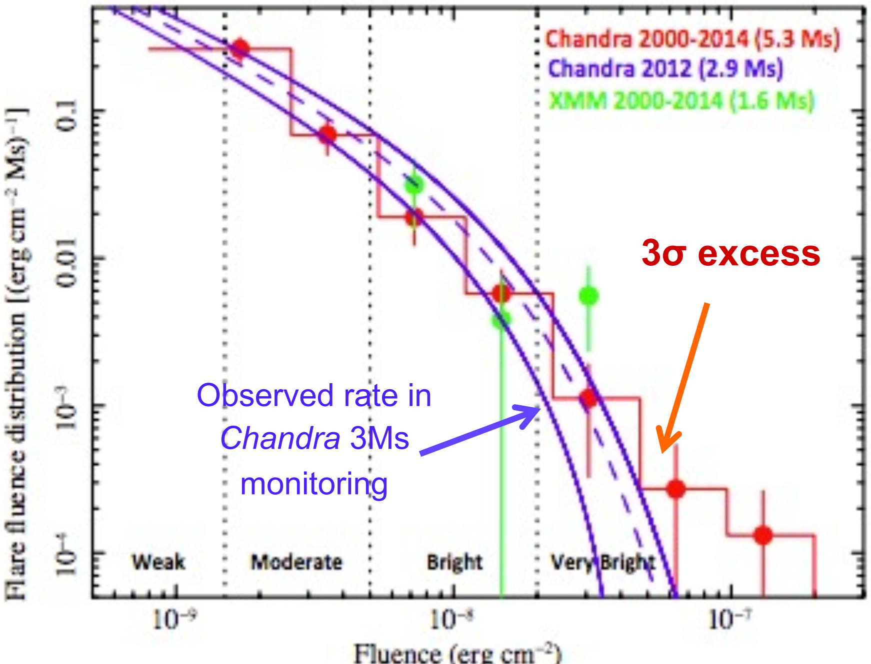


Ponti et al. (2015)

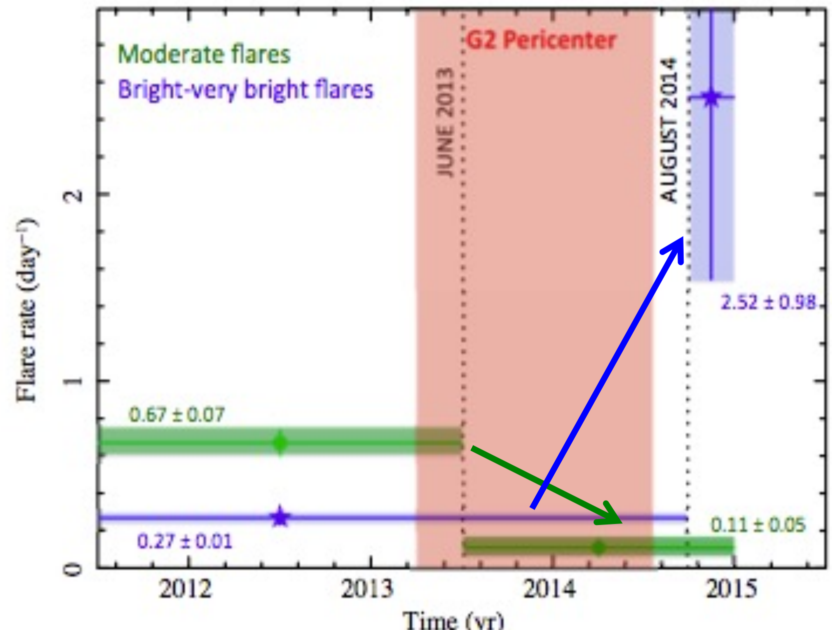
Four bright flares in ≈130 ks XMM-*Newton* obs. vs. <bright flaring rate> from *Chandra* 3Ms monitoring of ≈0.3 per 100ks (0.4 such bright expected in 130ks) ✚ 1 observed *Chandra* ➔ **5 bright flares observed in 200ks vs. 0.6 expected** (not a stochastic fluctuation at the 3σ level) ✚ 1 from *Swift* ➔ **6** in total in 272ks (3.8σ significance level above constant rate)

Evidence for a recent increase in the bright flaring rate. II

Flare fluence distribution



3.5 past years flaring rate



Ponti et al. (2015)

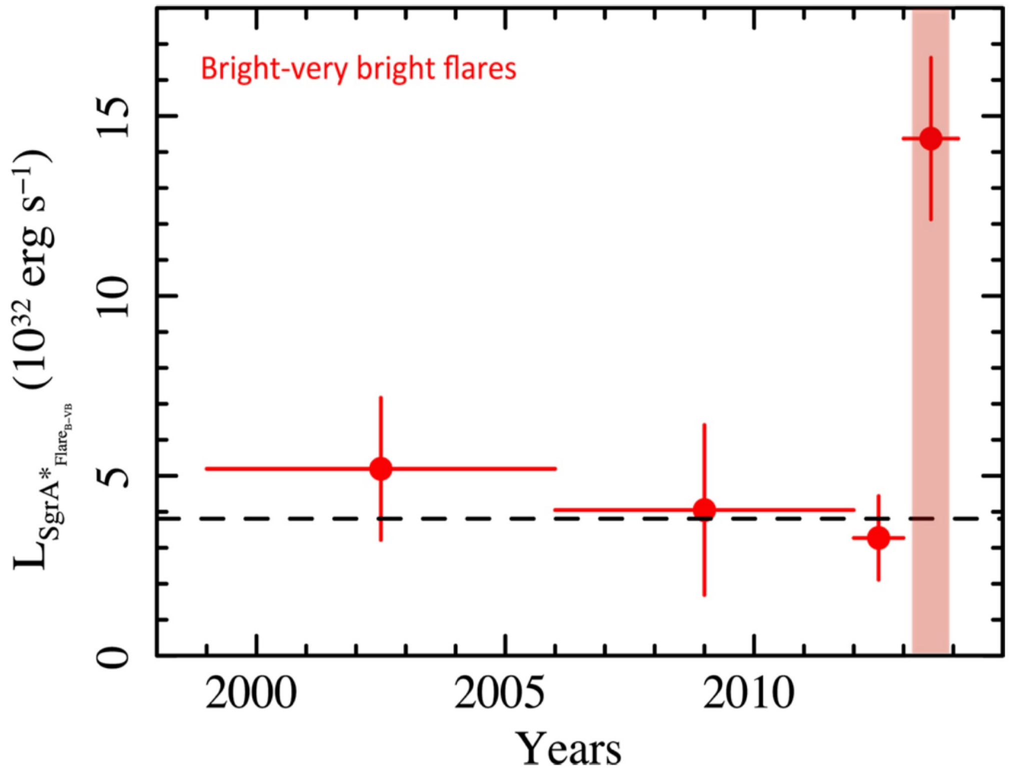
Green: moderate flares (*Chandra* only)

Blue: bright/very-bright flares (XMM+*Chandra*)

Apparent increase in the bright/very-bright flaring activity after the G2 pericenter passage (and decrease of moderate flares)

- ❑ Real? Similar to what is observed in quiescent BHs and related to the inner accretion flow
  Outer envelope of G2 captured by SgrA*? Increase of accretion rate? Shocks?
- ❑ Related to the increase of X-ray monitoring? (i.e., observational bias)

SgrA* luminosity in the bright flares



large increase
in recent years

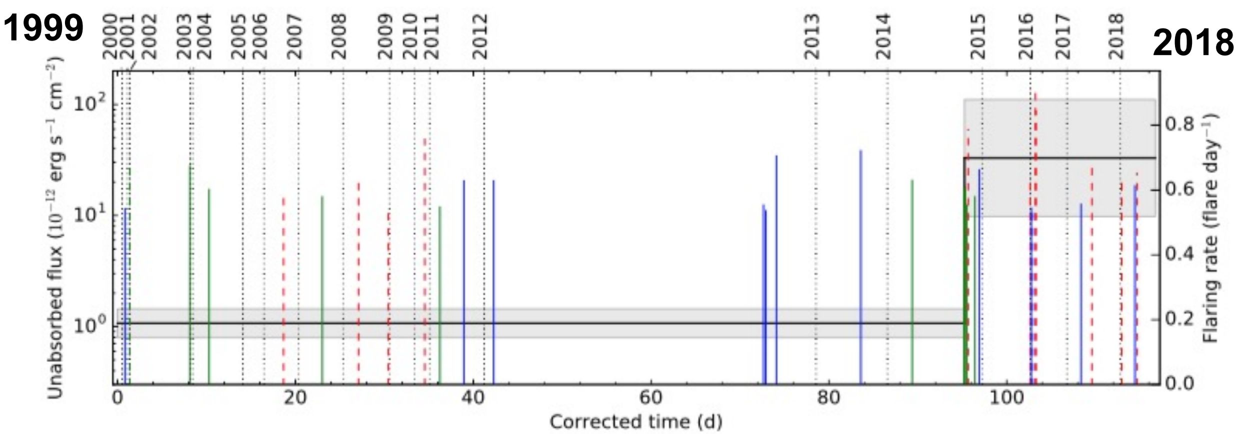
The increase in Sgr A* X-ray luminosity during bright flares in 2014 campaing is significant at the ≈3.7σ level

$$\boxed{L_X \propto \dot{M}}$$

Moscibrodzka et al. (2012)

Evidence for a recent increase in the bright flaring rate. III
[inclusion of 2016-2018 data: *Chandra*, XMM-*Newton*, *Swift*]

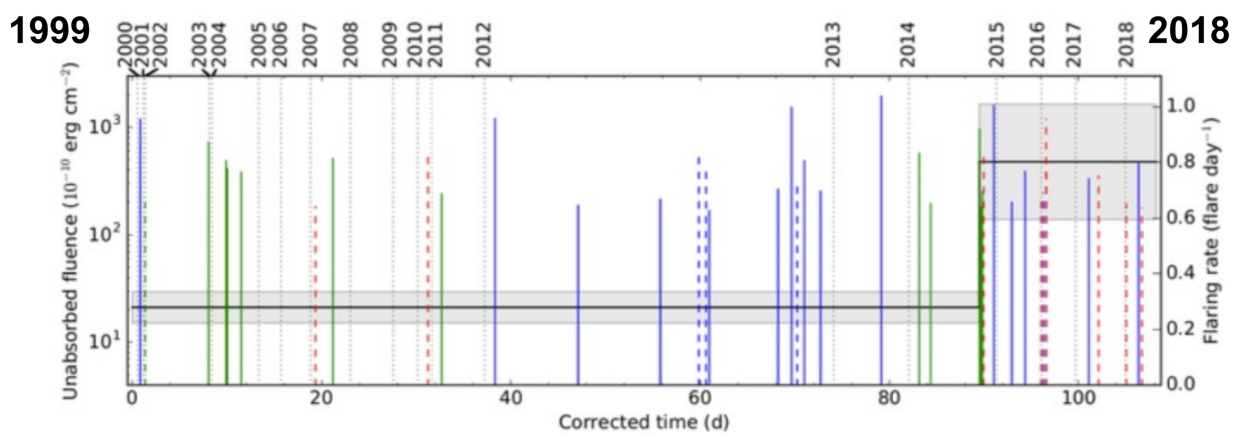
- Increase by a factor ~3 in the flaring rate of the most luminous and energetic flares (flux>1.1×10^{-11} erg/cm^2/s; fluence>1.68×10^{-8} erg/cm^2) since Aug 30, 2014
- Constant flaring rate (2.4$\pm$0.2 flare per day) for the fainter (more common) ones



Flare flux (erg/cm^2/s) distribution

Blue line: *Chandra*
Green line: XMM-*Newton*
Red line: *Swift*

Flare fluence (erg/cm^2) distribution



Mossoux et al. (2020)