X-ray properties of the Galactic center

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Galactic Center:
one of the most richest regions of the sky

* Distance ~ 8 kpc

* High column density along the line-of-sight: $N_H \sim 5\text{-}7 \times 10^{22}$ cm^{-3} ($A_v \sim 25\text{-}30$)

$\Rightarrow$ 'only' observable in radio, IR, X-rays ($\geq$ 1-2 keV) et γ-rays

<u>* Extended objects:</u>

SNR, molecular clouds, non-thermal, filaments, diffuse emission, …

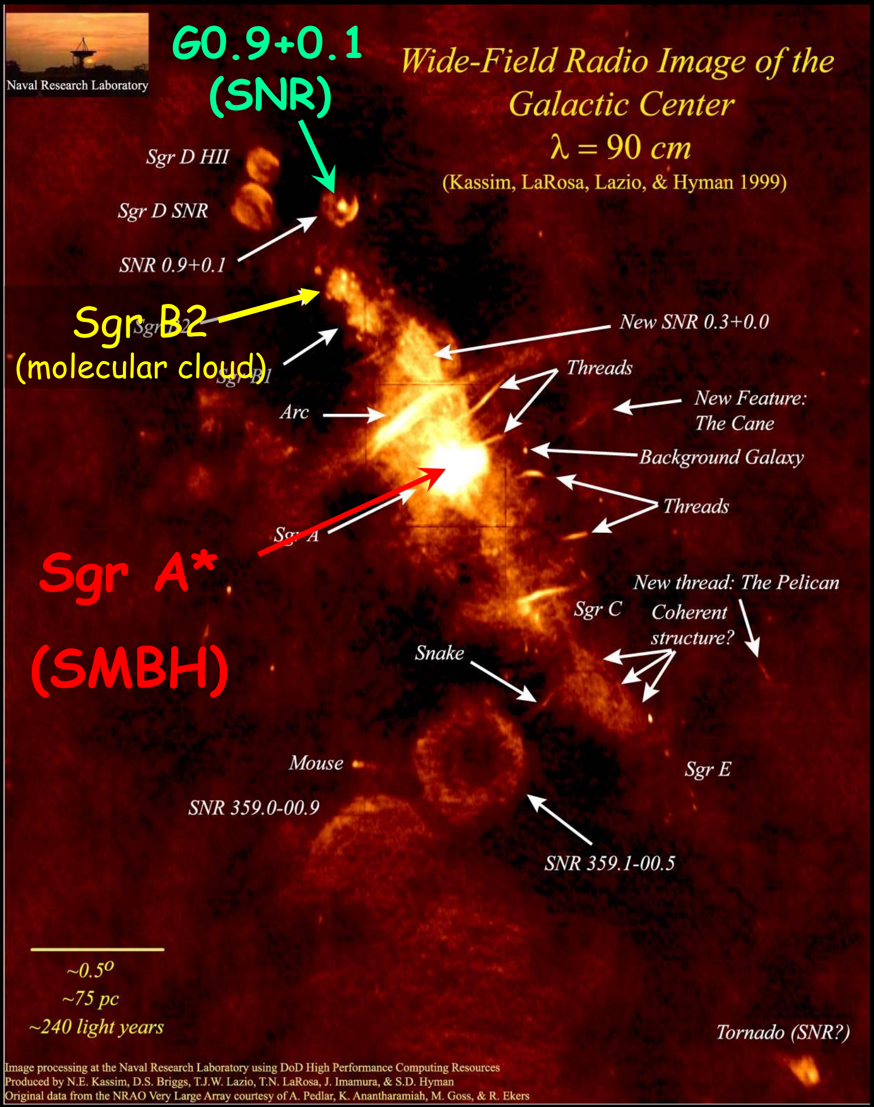
* <u>Stars</u>

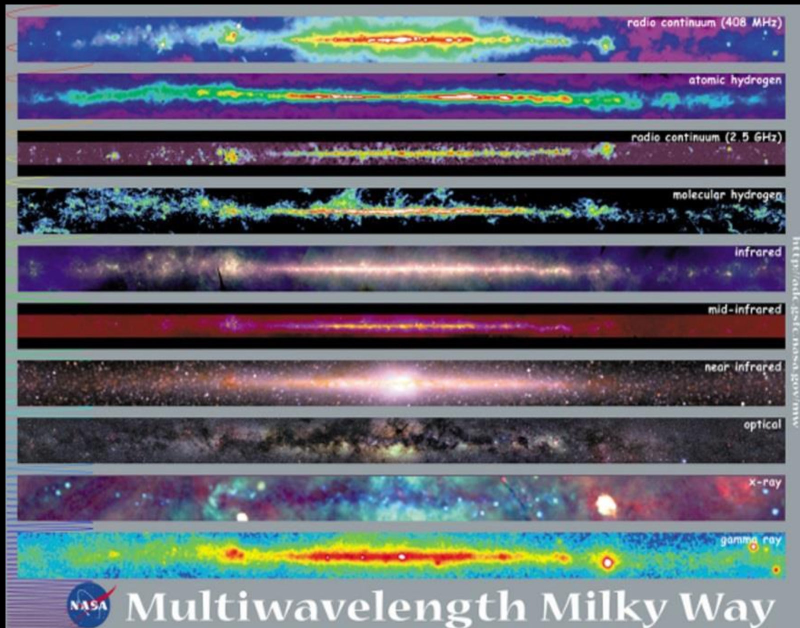
Old and young stars, the three most massive stellar clusters of the Milky Way (the Arches, The Quintuplet, Nuclear cluster)

* <u>Compact objects:</u>

X-ray binaries (neutron stars, black holes, white dwarfs), pulsars, magnetar(s), …

+ Supermassive BH: Sgr A*, ….





HST + Spitzer + Chandra

Credit: X-ray: NASA/CXC/UMass/D. Wang et al.; Optical: NASA/ESA/STScI/D.Wang et al.; IR: NASA/JPLCaltech/SSC/S.Stolovy

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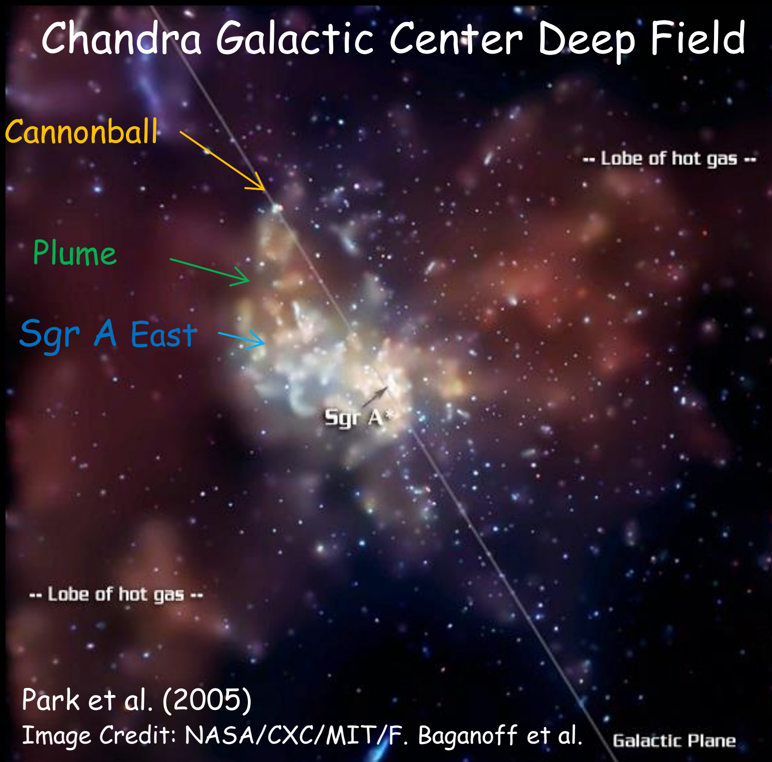
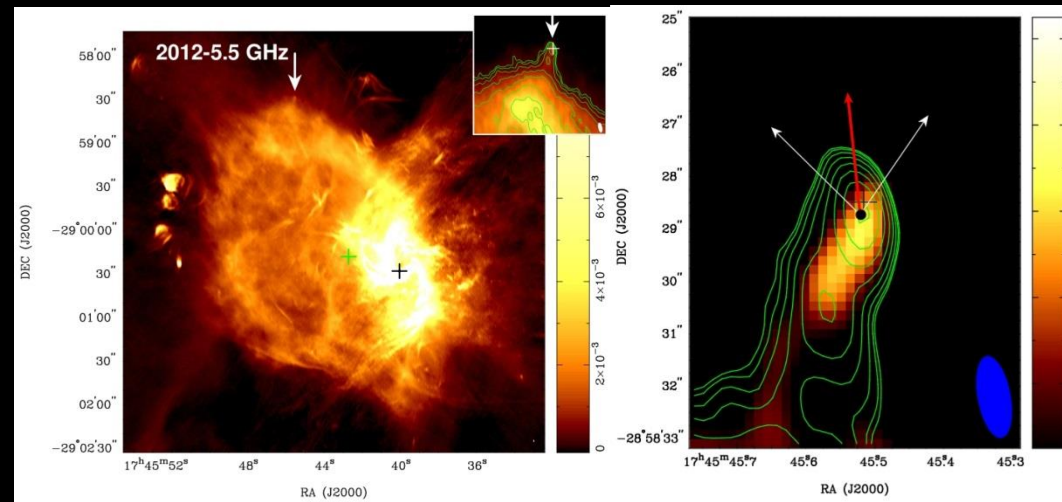
Sgr A East, the plume and the cannonball



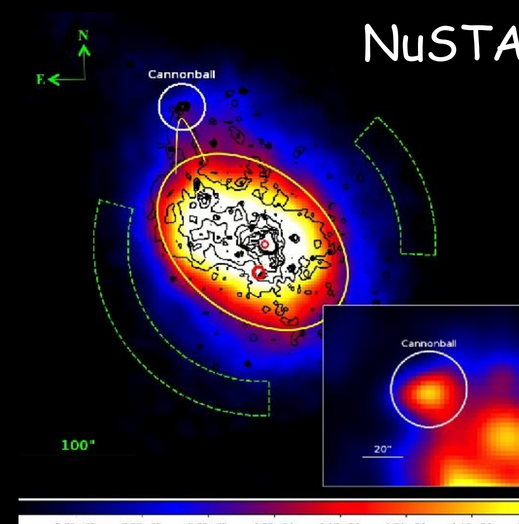
8.4′ x 8.4′ (19.5 x 19.5 pc; 63.6 x 63.6 l.y.)

The Cannonball (Park et al. 2005) is located at ~4.7 pc (~2′) from Sgr A East center and Sgr A* :



Zhao et al. (2013)

NuSTAR

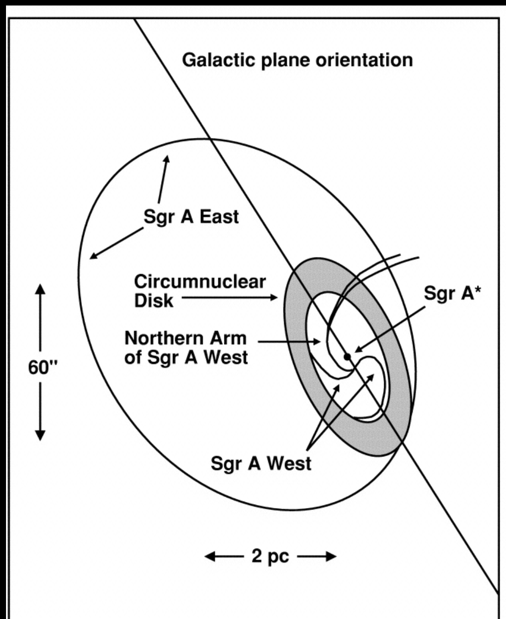


Nynka et al. (2013)

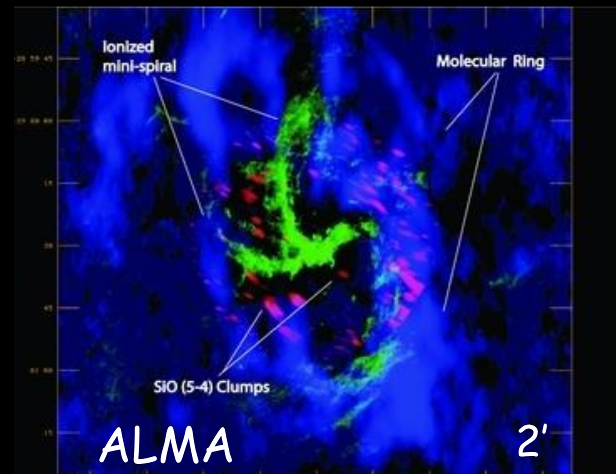
Radio and soft and hard X-ray counterparts:
$v \sim 500$ km/s, $L_R \sim 8 \times 10^{33}$ erg/s,
$\Gamma_X \sim 1.6$, $L_X \sim 1.3 \times 10^{34}$ erg/s
-> consistent with a PWN

If the origin coincides with the center of Sgr A East:
Age ~ 9000 years.

The minispiral (Sgr A West) and the circumnuclear disk

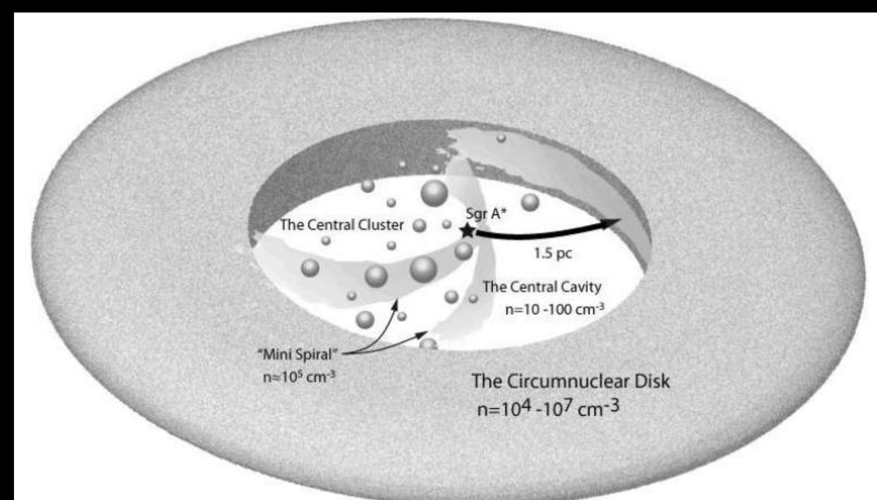


Baganoff et al. (2003)



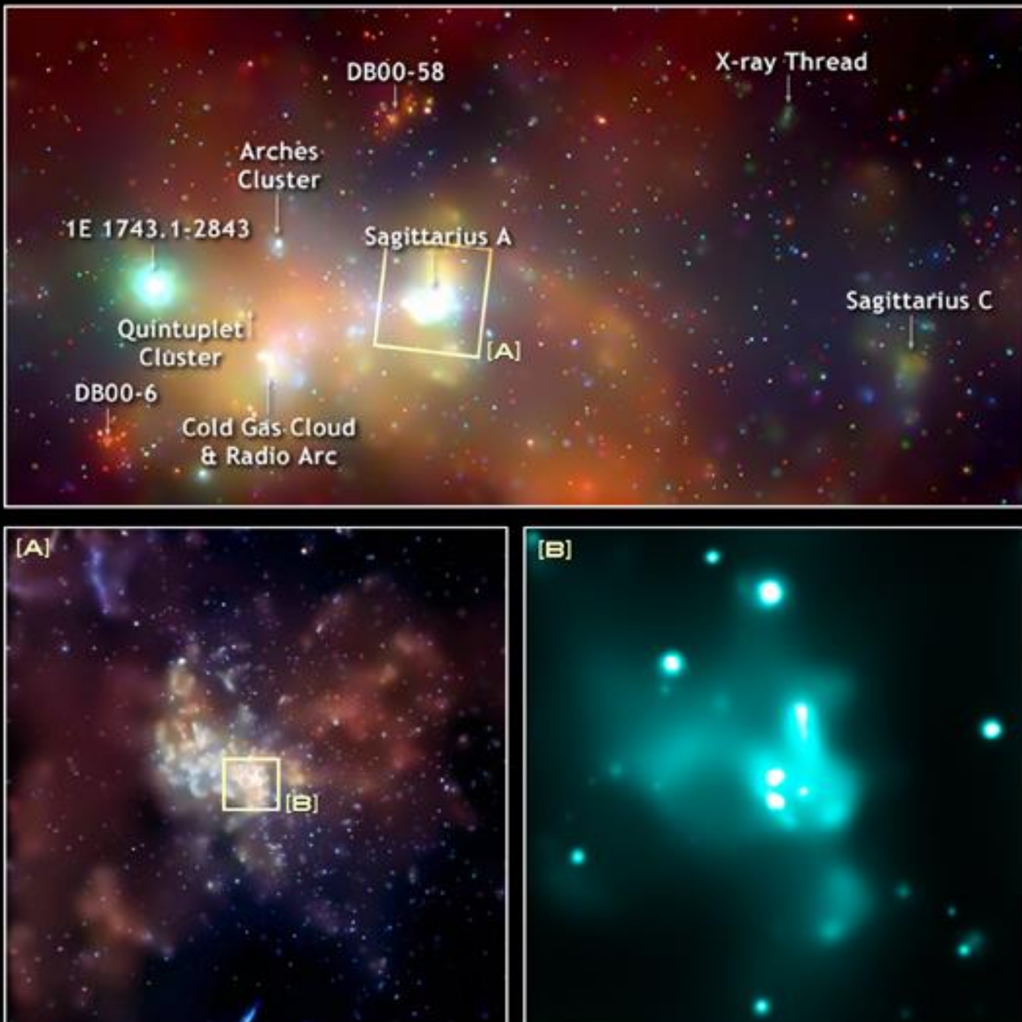
3.6 cm
HCN
SiO

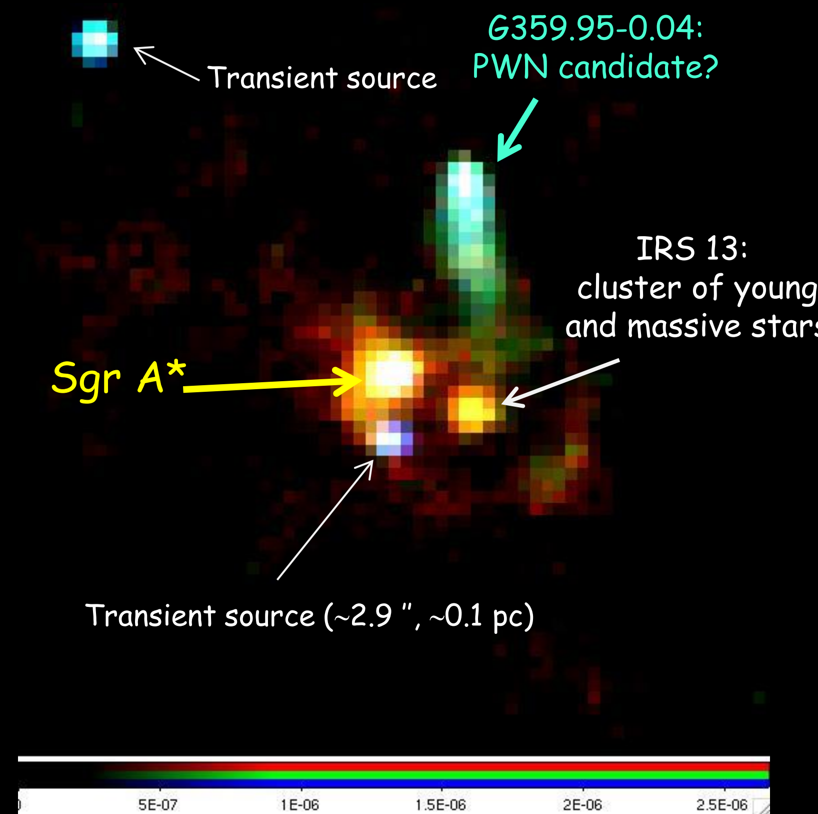
Yusef-Zadeh (2013)



Goto et al. (2013)

A zoom on Sgr A*



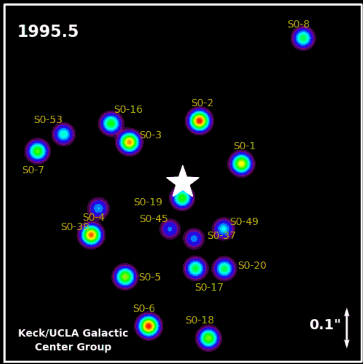


ACIS image (1Ms)
Image Credit:
NASA/CXC/MIT/Frederick K. Baganoff et al.

I. Current X-ray view of Sgr A*:

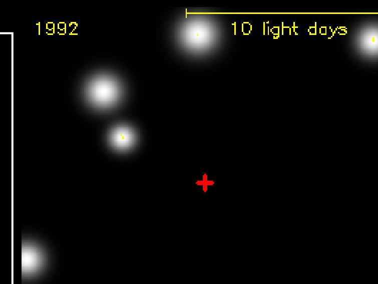
Quiescent and flaring states

Sgr A*: SMBH at the Galactic center



Keck/UCLA GC group

- Closest supermassive black : D ~ 8 kpc
- Stellar orbits ⇨ M_{BH} ~ 4.1 x 10^6 $M_\odot$
- Largest BH in projection (D~45-52 μarc)



Schödel, R. et al. 2002, Nature

- First detected as a non-thermal radio source with a proper motion of -0.4 ± 0.9 km/s
- Size @ 1.3mm (EHT) : 37 (+16,-10) μarc i.e., 0.3 A.U. or 4 R_S (here R_s= 1.2 x 10^{12} cm)
- Bolometric luminosity: L_{bol} ~ 10^{36} erg.s^{-1} ~ x 100 $L_\odot$!
  10^{-8}-10^{-9} * L_{Edd} (≡ 1.26 x 10^{38} M/$M_\odot$ ~ 4-5 x 10^{44} erg/s)

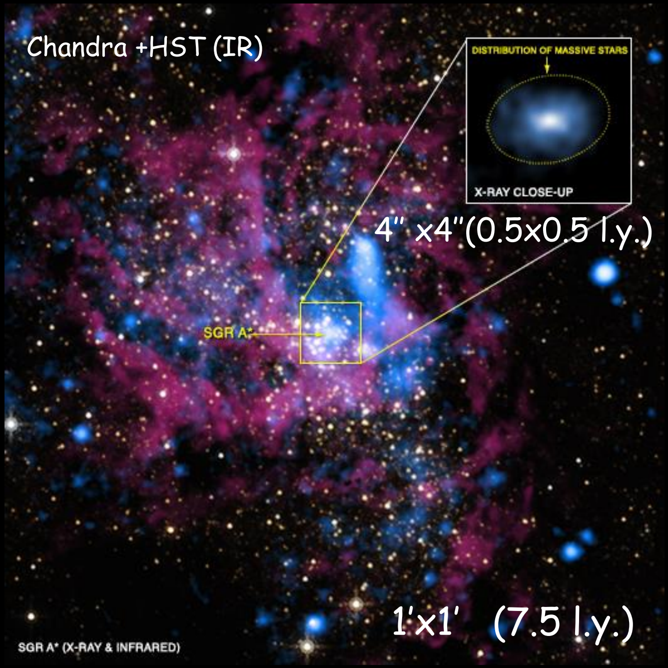
⇨ Various models for the quiescent emission have been proposed:

- ADAF: Advection-dominated accretion flow (Narayan, Yi, & Mahadevan 1996)
- RIAF: Radiatively inefficient accretion flow (Yuan 2003)
- ADIOS: Advection-dominated inflow outflow solution (Blandford & Begelman 1999)
- CDAF: Convection-dominated accretion flow (Nayaran et al. 2000, Quataert & Gruzinov 2000)
- Jet (e.g., Falcke & Markoff 2000) ,
- Jet/ADAF (Yuan, Markoff, & Falcke 2002)
- …

Dissecting X-ray-emitting Gas around the Center of our Galaxy

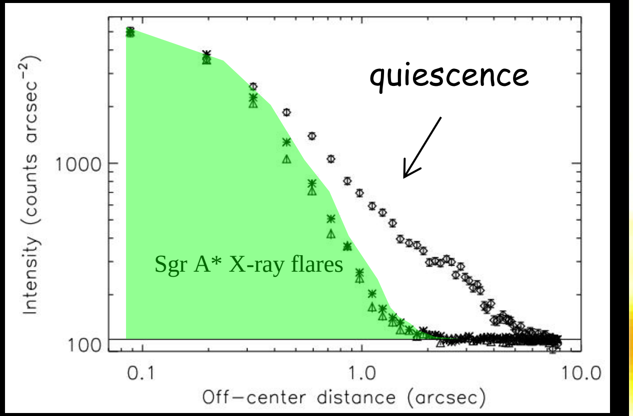
Wang et al. (2013)

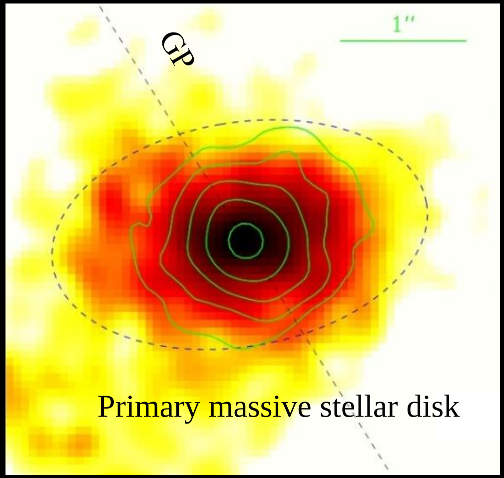
*Chandra X-ray Visionary Program of Sgr A** (Cycle 13; PI: F. Baganoff):
A 3 Ms exposure (≈ 35 days) with the High-Energy Transmission Gratings from Feb. to Nov. 2012.



ACIS-S (on-axis spatial resolution: FWHM ~0.4" i.e x2 ACIS-I)
HETG order 0

Radial 1.9 keV intensity profile



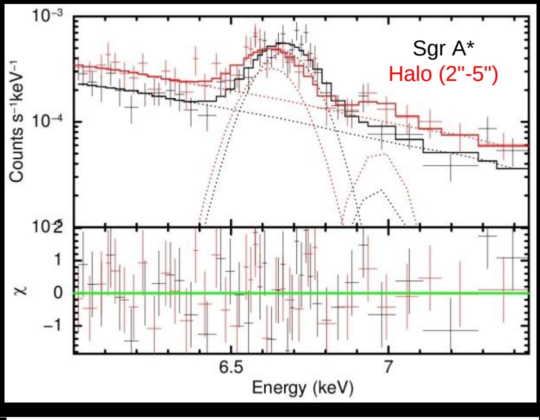


- Different from the Sgr A*'s flares distribution or from a point-like source.
- Relatively symmetric enhancement morphologically resembles to the so-called clockwise young massive stars.

Dissecting X-ray-emitting Gas around the Center of our Galaxy

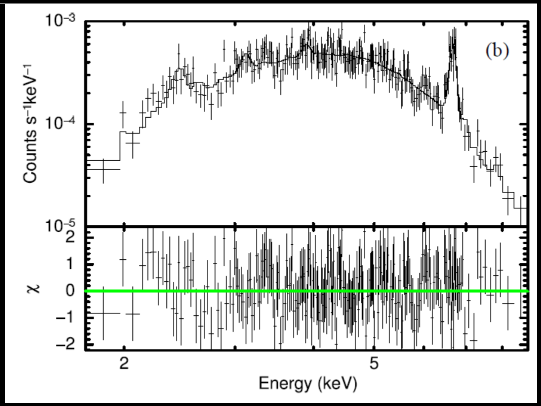
Wang et al. (2013)

→ Several lines of highly ionized ions:
He-like lines from S, Ca, Ar and Fe (K_α, K_β), and H-like line from Ar



No significant 6.4 keV line (EW<22eV) from neutral-low ionized Fe + no appreciable variations on time-scales of hours or days, as expected from the sporadic giant coronal flares of individual stars.

⇨ Quiescent X-rays: NOT from coronally active, low-mass main sequence-stars (where EW~50-100 eV are predicted).
BUT inflowing gas from winds produced by the shaped-disk of young massive stars.



No significant FeK H-like line at 6.97 keV (i.e. $kT_e \geq 9$ keV): EW < 42eV

Fit with a simple 1-T RIAF model:

→ A no-outflow solution ($M_{acc}=(M/M_o)^s$ = constant; i.e. $n \propto r^{-3/2+s}$ in which s=0) is rejected (Null hypothesis probability: 10^{-6})

Indeed a flat density profile with s~1 is found.

⇒ Outflow mass-loss rate nearly balances the inflow.
Only less than 1% of the initially accreted matter reaches the event horizon !

Chandra/HETG order 0 spectrum of Sgr A* in quiescence (1.5"-radius, i.e., $1.5\mathrm{x}10^5$ R_s)

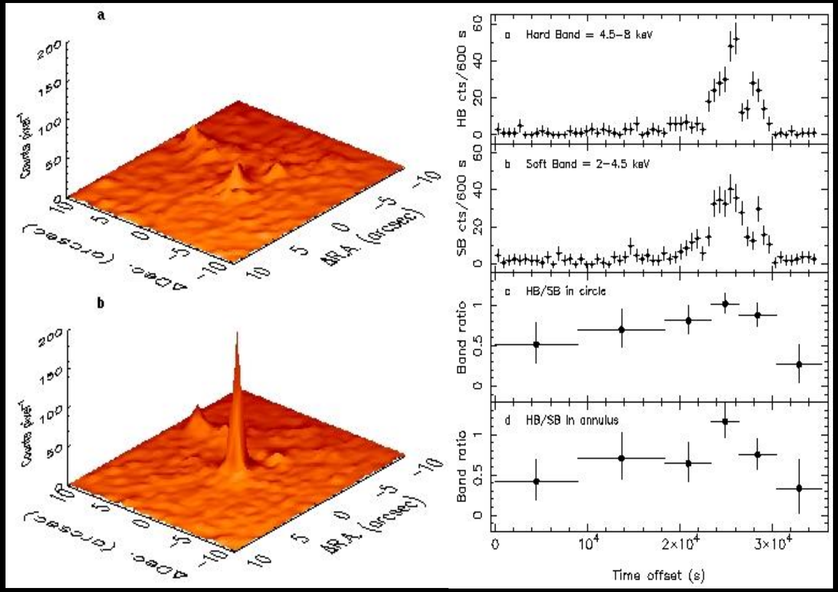
Sgr A* : A dormant supermassive black hole … but not inactive !

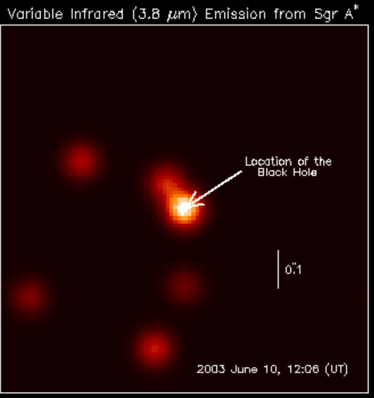
Flares first discovered in X-rays (Oct. 2000), then in IR in 2003.

⇨ Daily flares: ~ 1 every day in X-rays and up to several per day in NIR

⇨ New perspectives for the understanding of the processes at work in "quiescent" supermassive black holes.

Chandra (Baganoff et al. 2001)

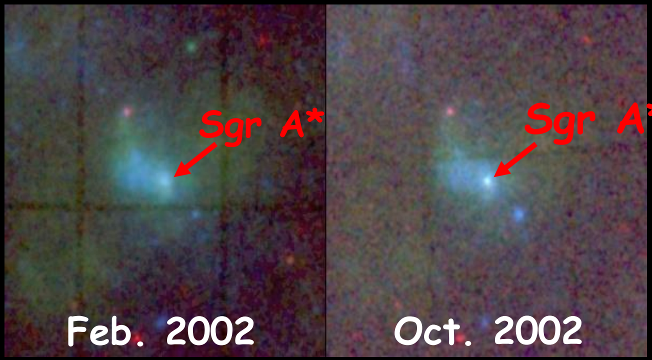


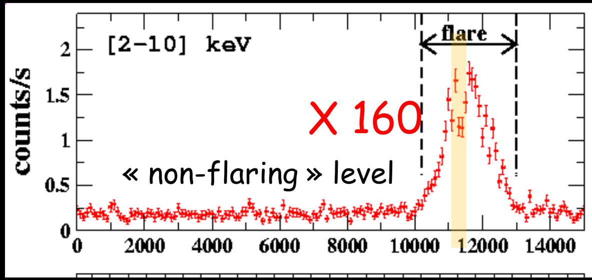


Keck II 10 m: adaptive optics L′ (3.8 μm)
Ghez et al. (2004)

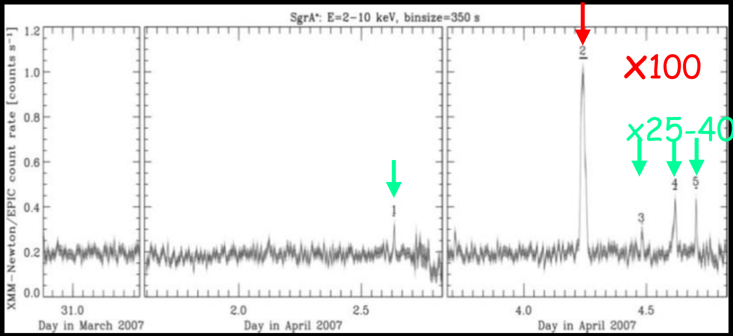
Most X-ray flares are weak (≲10) or moderate (≲40) BUT two (first) brightest X-ray flares from Sgr A* have been observed with XMM-Newton

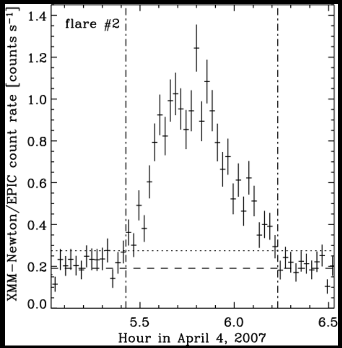
2002, Oct. 3: Porquet et al. (2003)



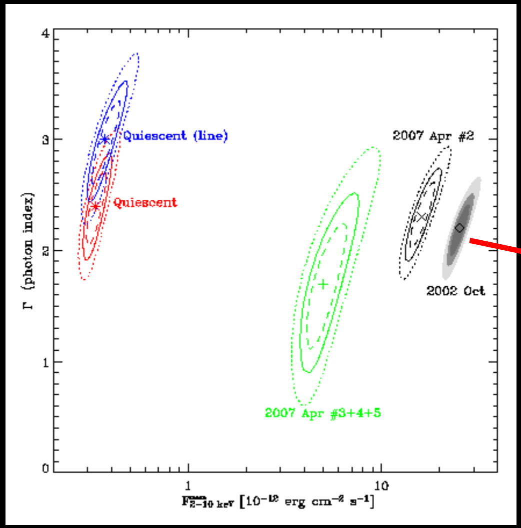


2007, April 4: Porquet et al. (2008)





XMM data PI : D. Porquet



- duration ~ 3000 s
- amplitude at the peak: ~ 160 and 100

(~ x 3.5 – 2.2 October 2000, Chandra)

$L_{2-10keV}$ (peak) = 3.6–2.2 x 10^{35} erg.s^{-1} ≈ L_{bol} (quiescent state)

- shortest time-scale: 200 s (3σ) → 7 R_s (R_s ~ 1 x 10^{12} cm): very small region !

- Bright to very bright X-ray flares have well constrained soft X-ray spectra Γ ~ 2.2-2.3 (±0.3)
Not constrained for weaker flares !

A Chandra/HETGS Census of X-ray Variability From Sgr A* During 2012

Neilsen et al. (2013)

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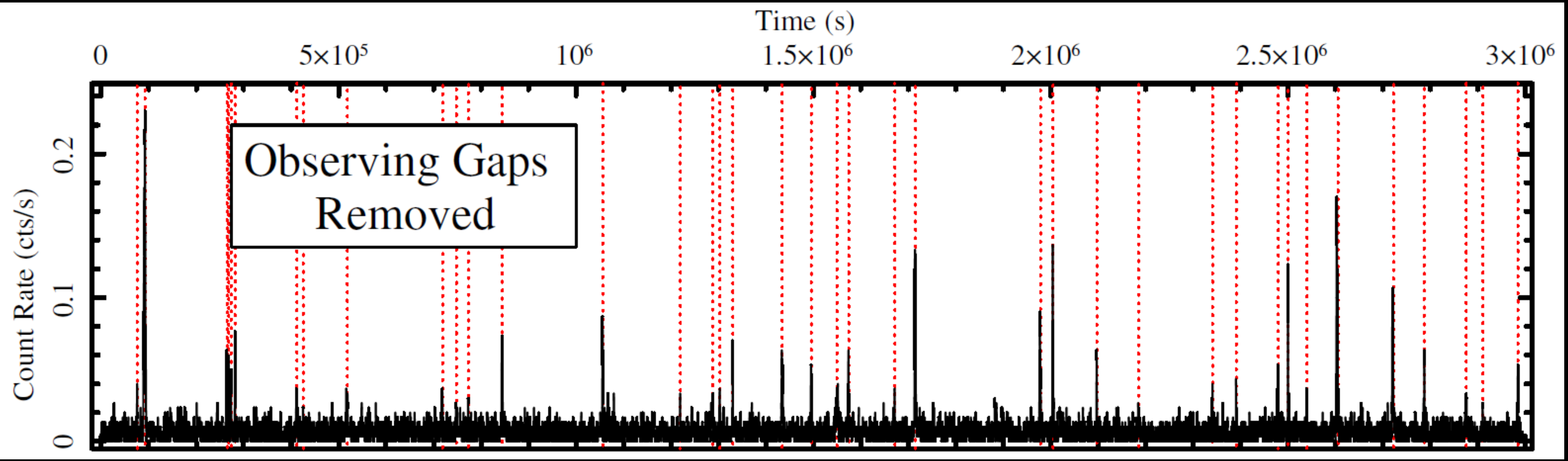

HETG 0 order (i.e., undispersed) + 1rst order photons light curve (2-8 keV) from 1.25"-radius and 2.5"-wide rectangular regions.

39 X-ray flares detected from Sgr A* in 21/38 observations !

- Spanning a factor of 20 in average luminosity
- Frequency: ~1.1 flare per day (~3.5%)
- Duration: a few 100s - ~ a few ks

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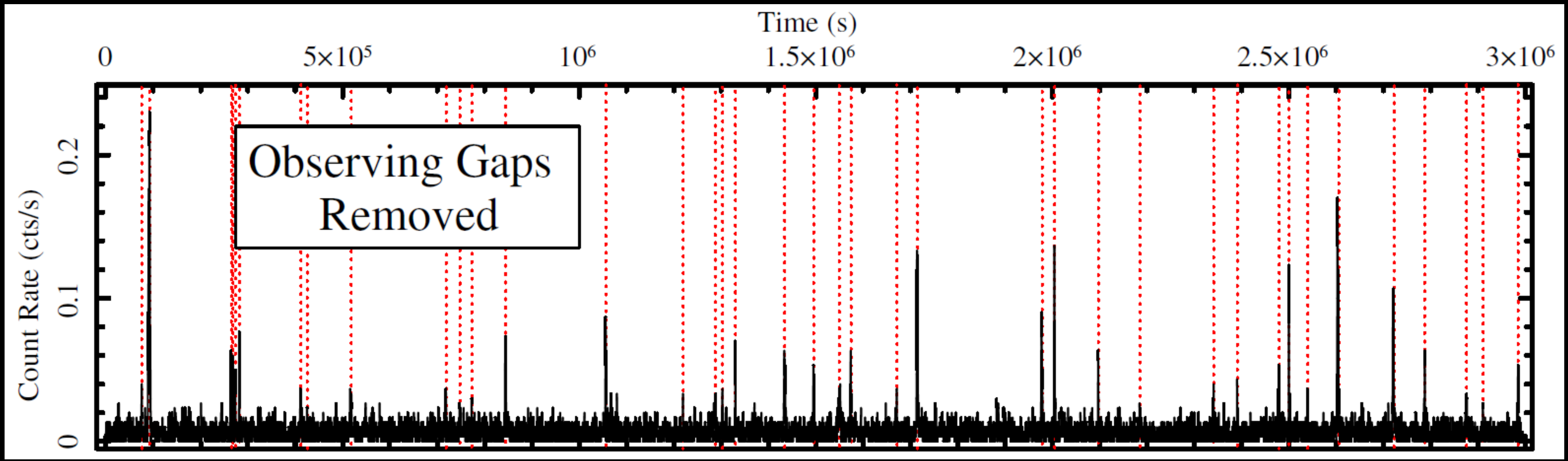

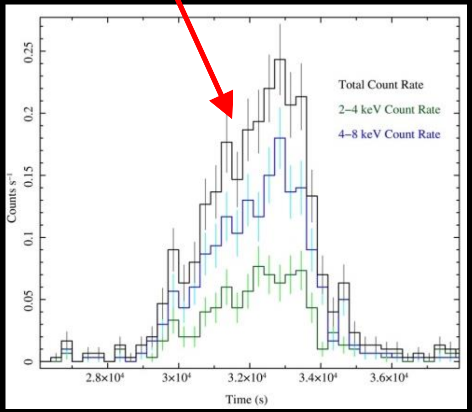

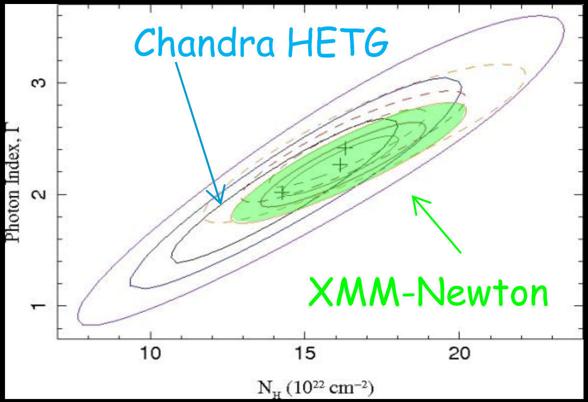

The most energetic X-ray flare x160 (Nowak et al. 2012).

≡ Oct 2002 XMM-Newton flare (x160) but twice larger in time.

⇨ Consistent with the "soft" spectral shapes found for the 2 brightest XMM-Newton X-ray flares (Porquet et al. 2003, 2008).

A Chandra/HETGS Census of X-ray Variability From Sgr A* During 2012

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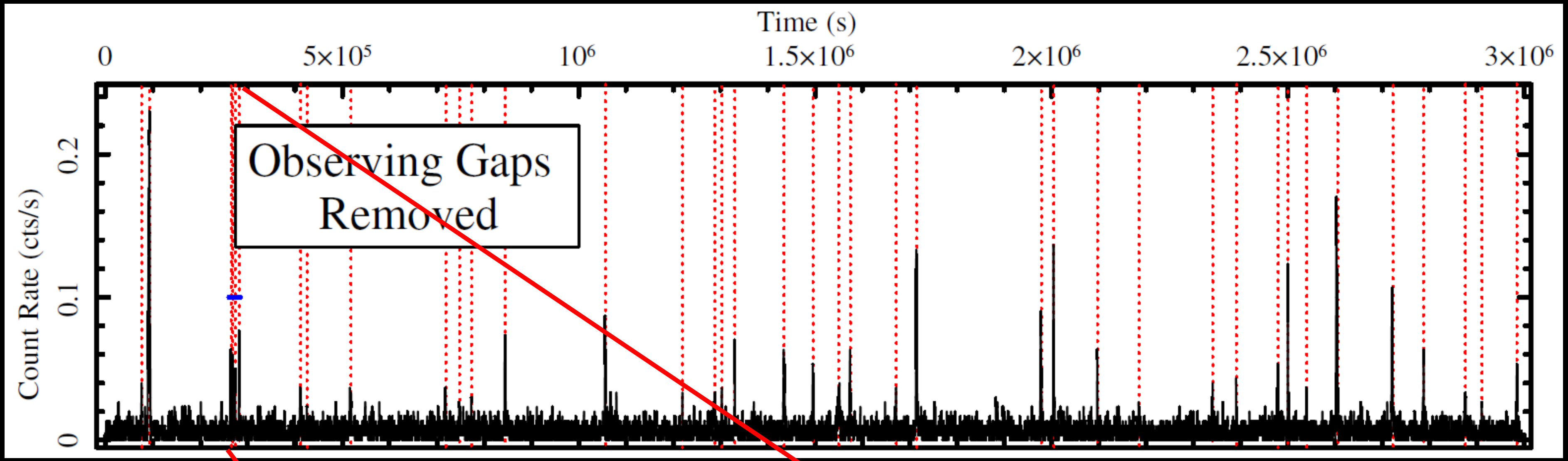

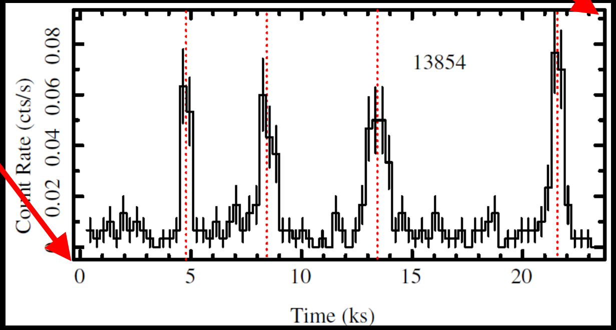

Four moderately bright X-ray flares within 5 h.

A Chandra/HETGS Census of X-ray Variability From Sgr A* During 2012

Neilsen et al. (2013)

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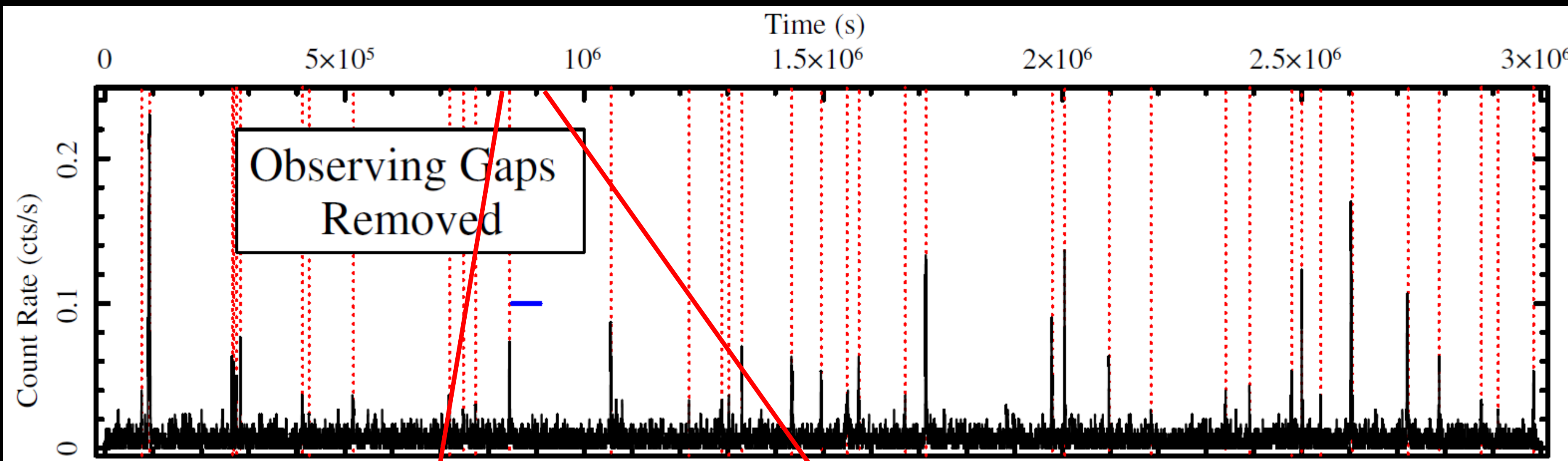
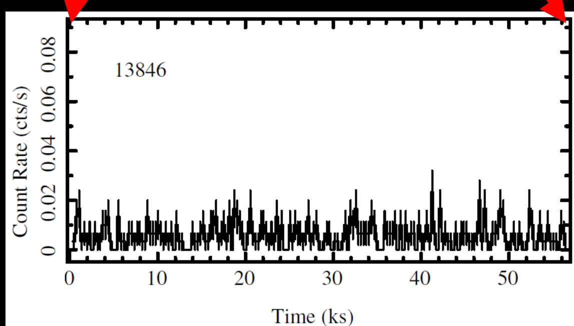
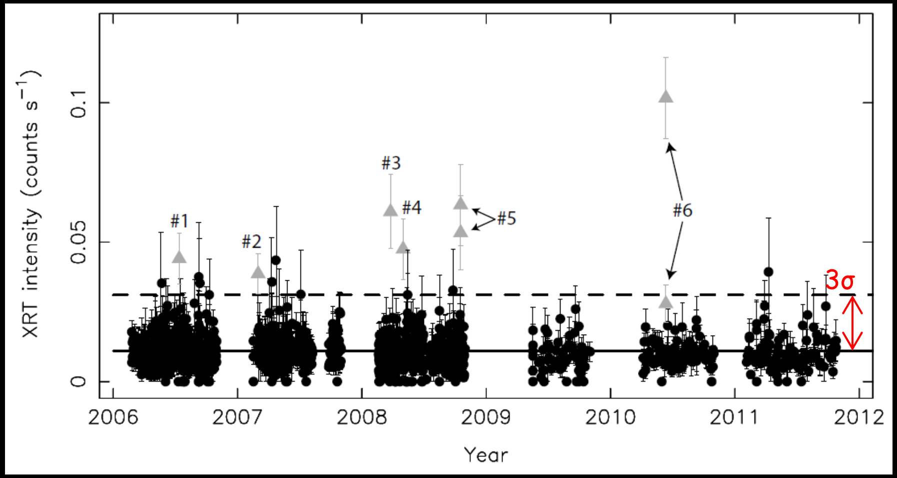




Observations without detected X-ray flares.

X-ray flares viewed by Swift and NuSTAR

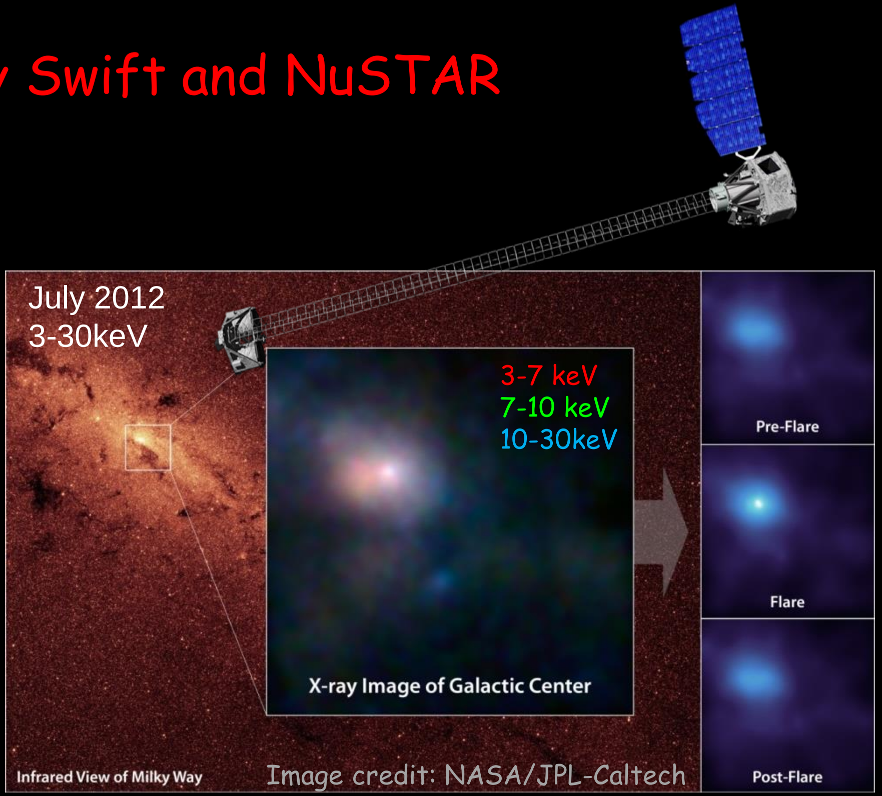
6 years of monitoring with Swift



Degenaar et al. (2013)

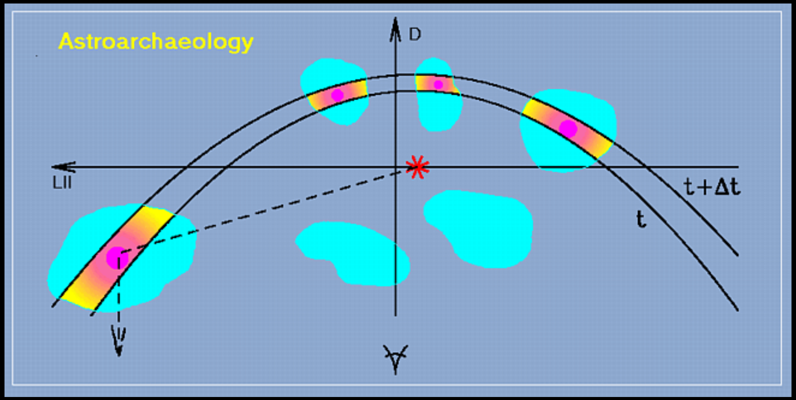
- Co-added spectra of flare #1-5: photon index Γ= 2.0 ± 0.6.
- Spectra of flare #6: Γ= 3.0 ± 0.8.

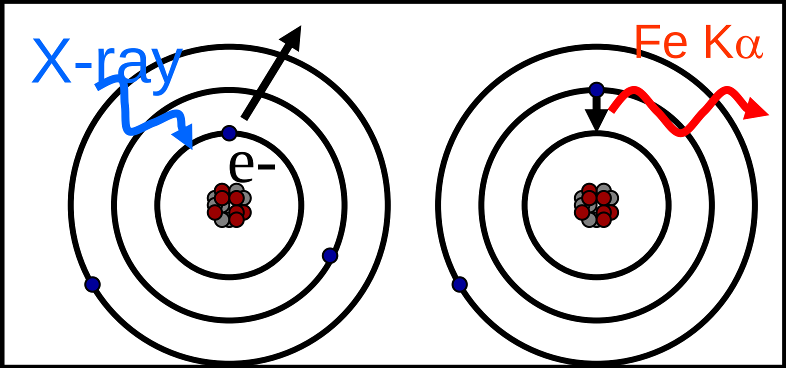
⇒ Soft X-ray spectra.

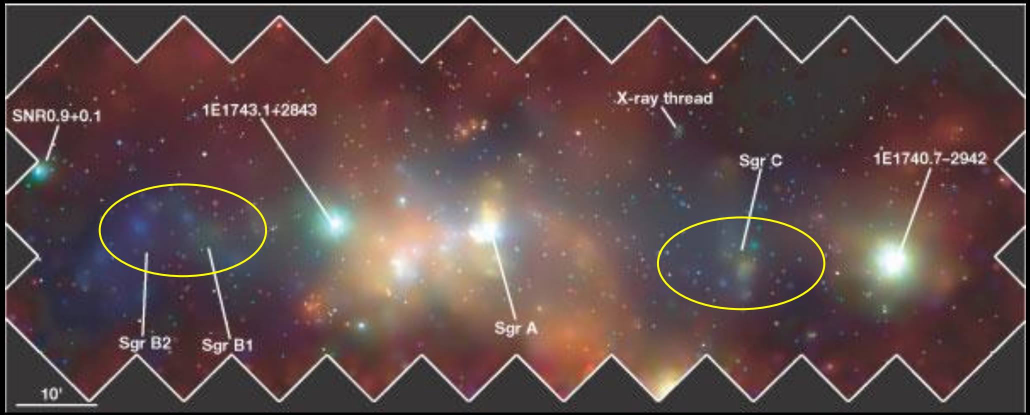


First focused image of Sgr A* in the 10-30 keV energy band.

II. X-ray archaeology:
X-ray echo(s) from a past activity of Sgr A* ?

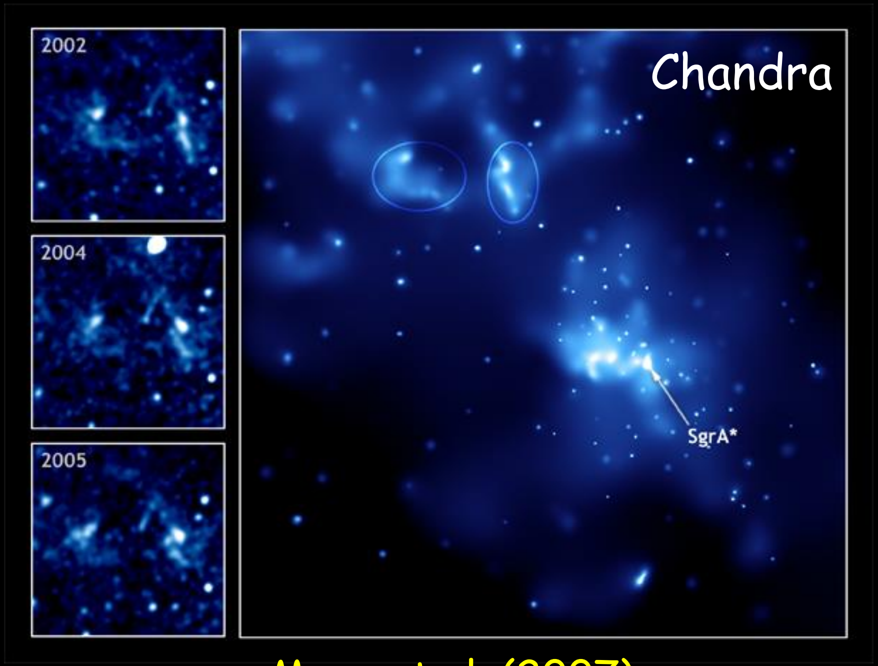




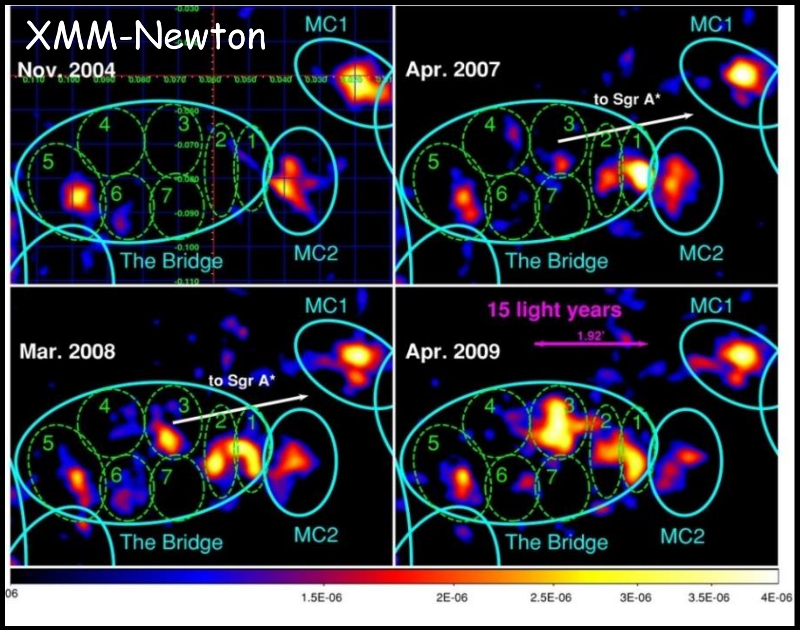


Sunyaev et al. 1993, Koyama et al. 1996, Murakami et al. 2001, Inoue et al. 2009, Nakajima et al. 2009, …

Molecular clouds close to Sgr A*: ~ 15 pc



Muno et al. (2007)



Ponti et al. (2010)

Variations of the 4-8keV continuum

⇨ 2-3 year long outburst of a point source (either Sgr A* or an X-ray binary) with a luminosity of at least 10^{37} ergs s^{-1}.

If Sgr A* then outburst occured 60 years ago (14 pc in projection)

Variation at 6.4keV (fluorescence line from neutral iron)

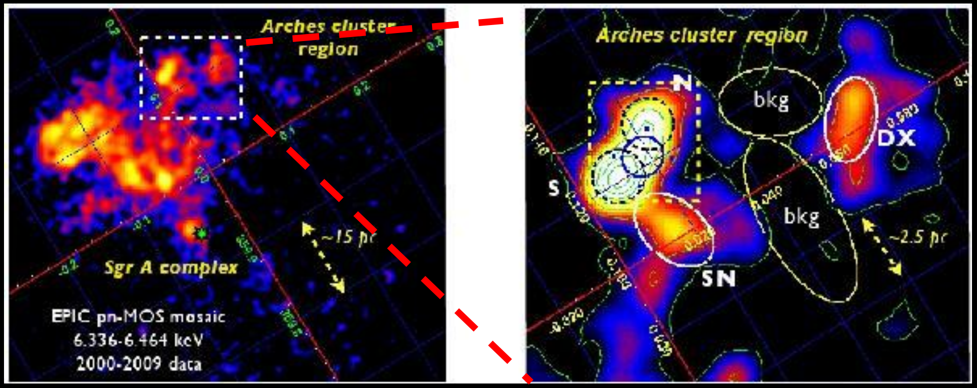
⇨ A <u>single</u> flare from Sgr A*

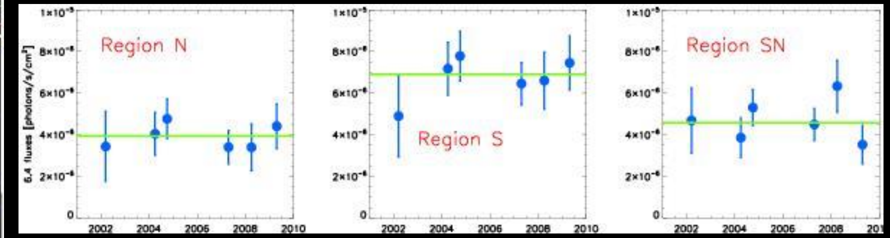
(~ 1.5 × 10^{39} erg s^{-1}) fading about 100 years ago.

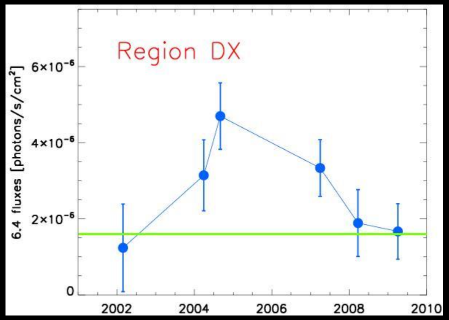
Contributions of cosmic-rays and/or other X-ray transient sources

Example of the Arches cluster (densest cluster of young and massive stars in the MW) as a likely location of particle acceleration.

XMM-Newton (Capelli et al. 2011a, 2011b)





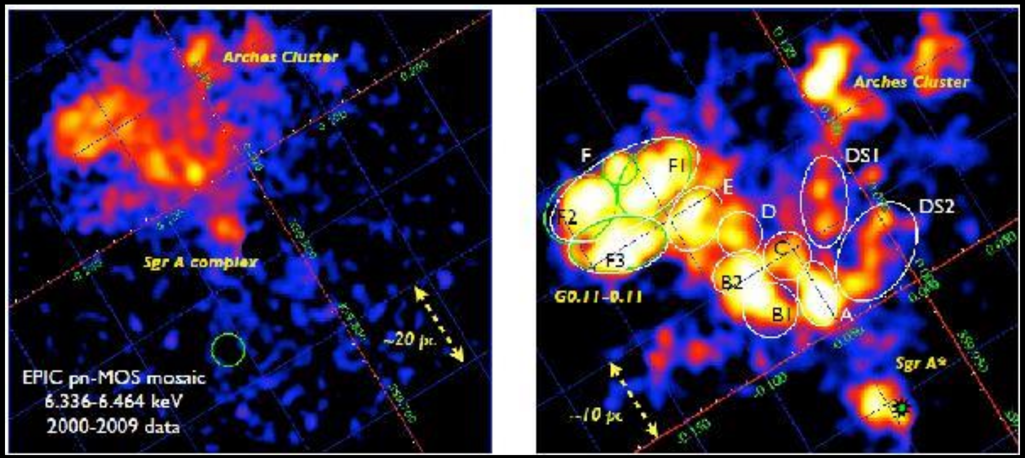


Fastest variability yet reported for the GC region: t~2-3 years ⇨ most likely the result of its X-ray illumination by a nearby transient X-ray source.

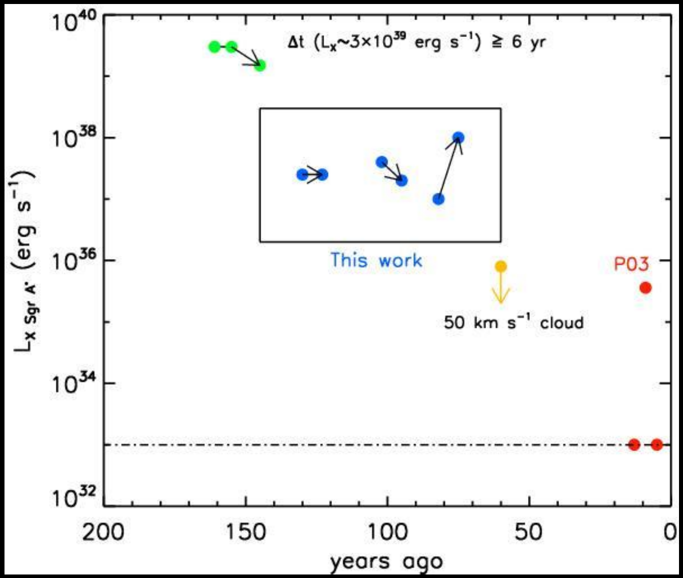
+ the non-zero underlying level of the FeK line flux, suggests the possibility that both the reflection and CR bombardment processes may be working in tandem.

The Sgr A* over the past 150 years

XMM-Newton

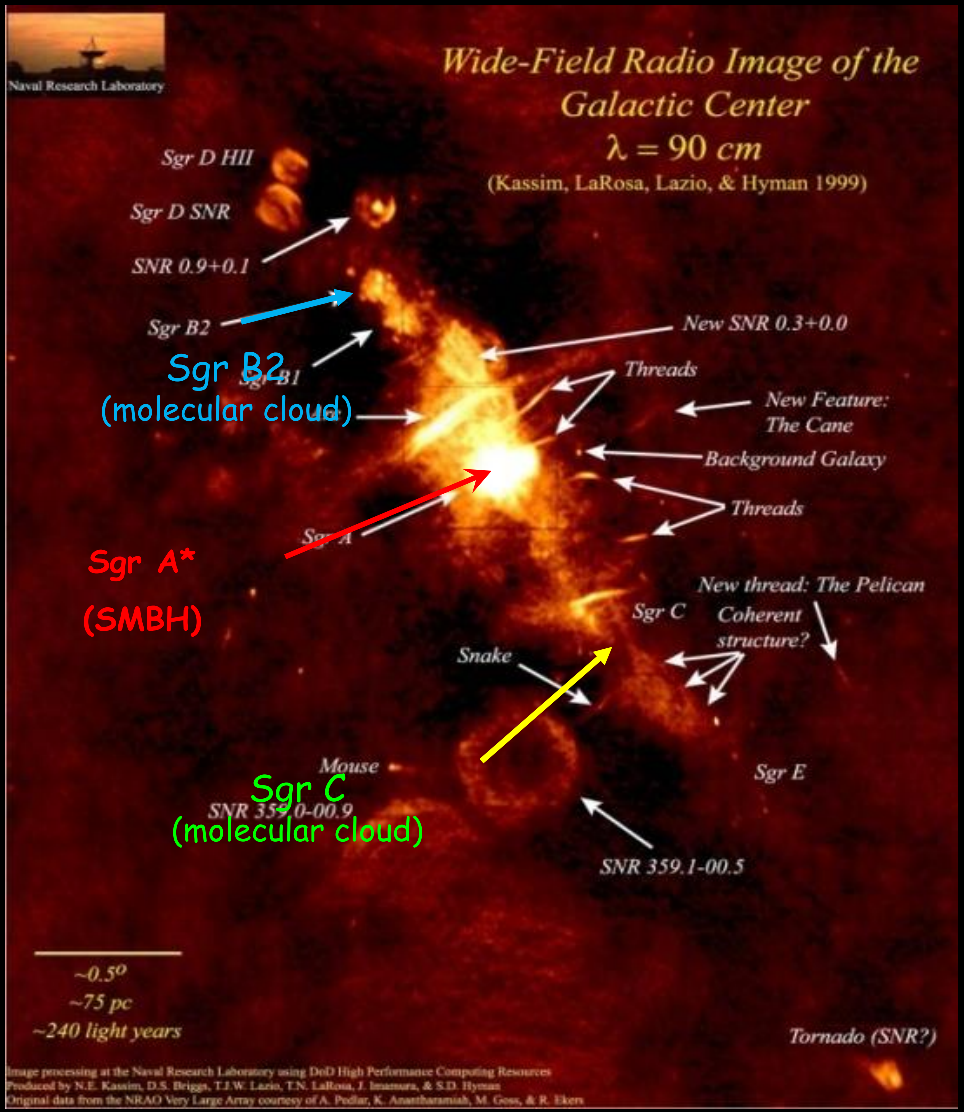


Capelli et al. (2012)



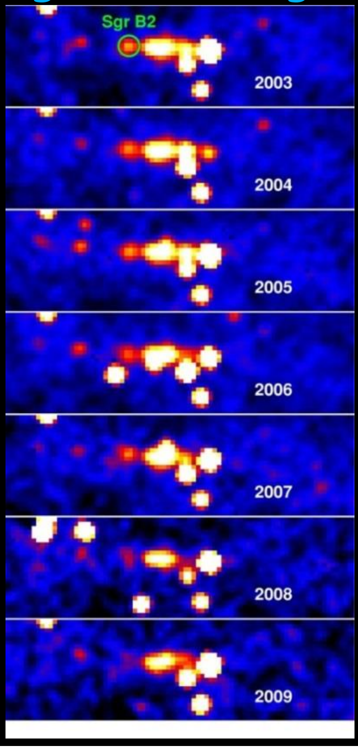
⇨ <u>A long-term downwards trend punctuated by occasional counter-trend brightening episodes of at least 5 years duration.</u>

Let's come farther from Sgr A*: then farther in past



Molecular clouds farther from Sgr A* (~100s years ago)

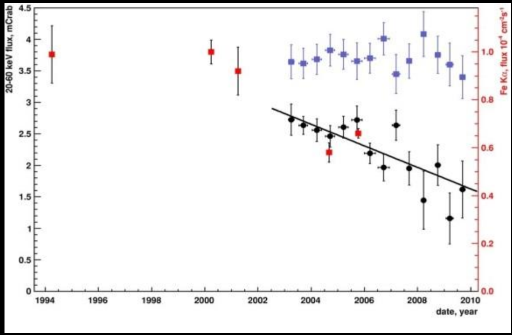
Sgr B2 (Integral)



decay time : 8.2 ± 1.7 yr

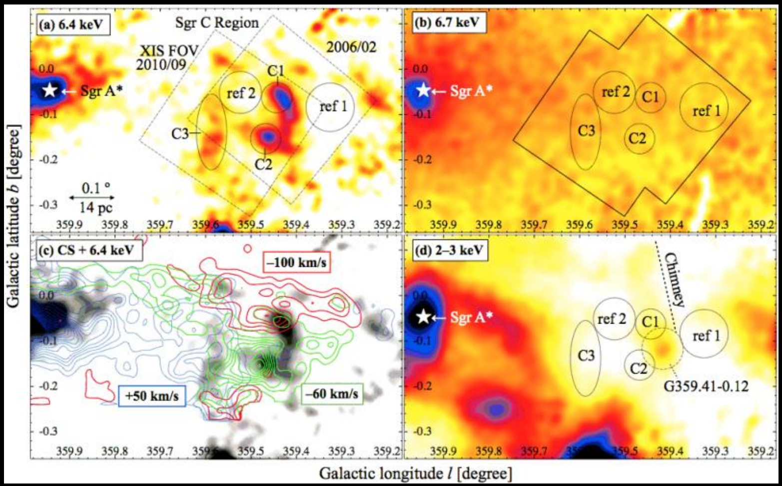
⇨ period of intense activity of Sgr A* ($L \sim 1.5\text{-}5 \times 10^{39}$ erg s^{-1}) ended between 75 and 155 years ago.

+ See also observations with Suzaku



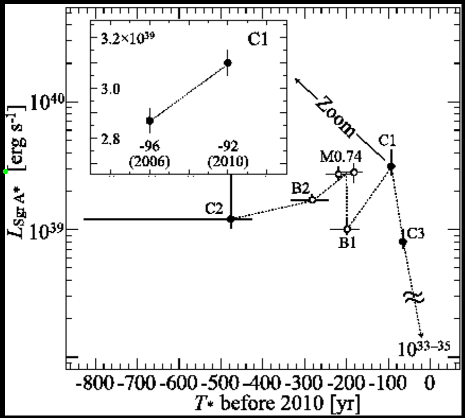
Terrier et al. (2010)

Sgr C (Suzaku)



Sgr A* continuously active with sporadic flux variabilities of $L_X = 1\text{-}3 \times 10^{39}$ erg/s in the past 50-500 yrs.
+ 2 short-term flares of 5-10 years.

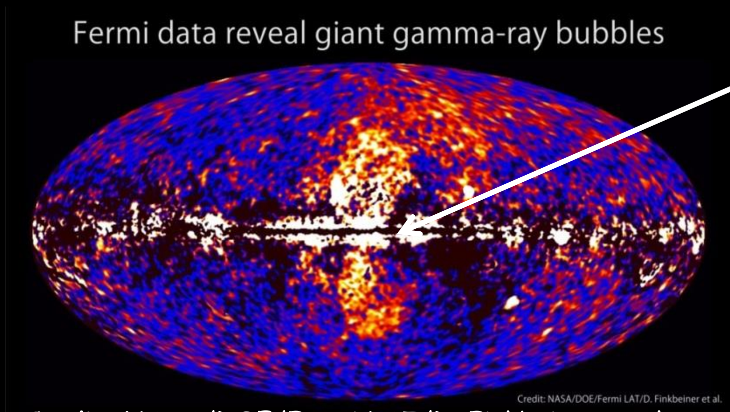
⇨ <u>multiple flares superposed on a long-term high state.</u>



Ryu et al. (2013)

The Fermi Bubbles

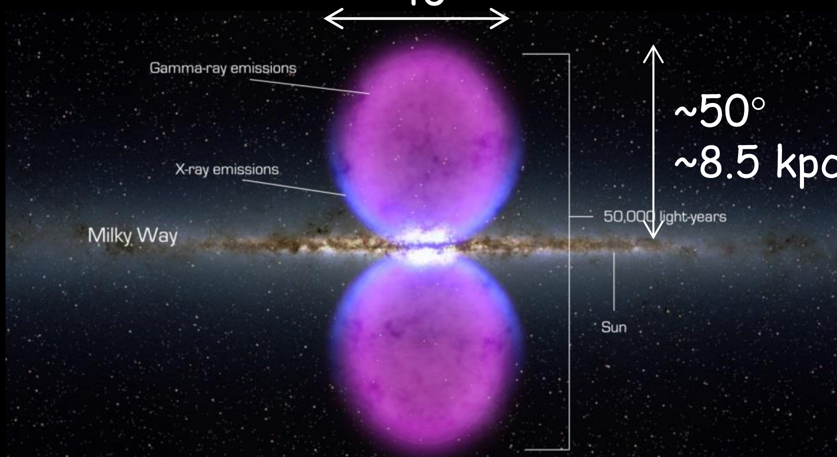
1-10 GeV



Credit: NASA/DOE/Fermi LAT/D. Finkbeiner et al.

Su , Slatyer, Kinkbeiner (2010)

~40°

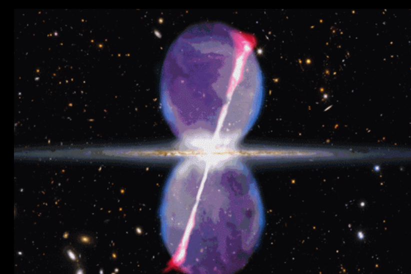


Credit: NASA's Goddard Space Flight Center

Well centered on longitude zero (close to latitude zero)
2×10^{37} erg/s, uniform intensity, and sharp edges

<u>Possible Origins</u> :

- ✓ Past AGN jet activity (~1-3 Myr lasted for ~0.1-0.5 Myr with M_{acc} ~100 –10000 $M_{\odot}$) ?



Gamma ray "bubbles" and a tilted jet are seen erupting from the center of the Milky Way in this artist's conception.
Credit: David A. Aguilar/CfA

- ✓ Wind bubble: nuclear starburst in the GC in the last 10 Myr ?

M82, Credit: NASA, ESA, and the Hubble Heritage Team (STScI/AURA)

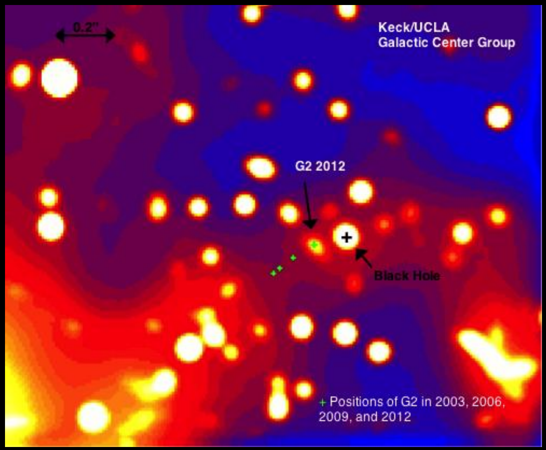
- ✓ Dark matter annihilations ?

III. Back to the Future :

A renew of Sgr A* activity ?

The incoming G2 « cloud » or DSO

A gas cloud on its ways into SgrA*: G2/DSO

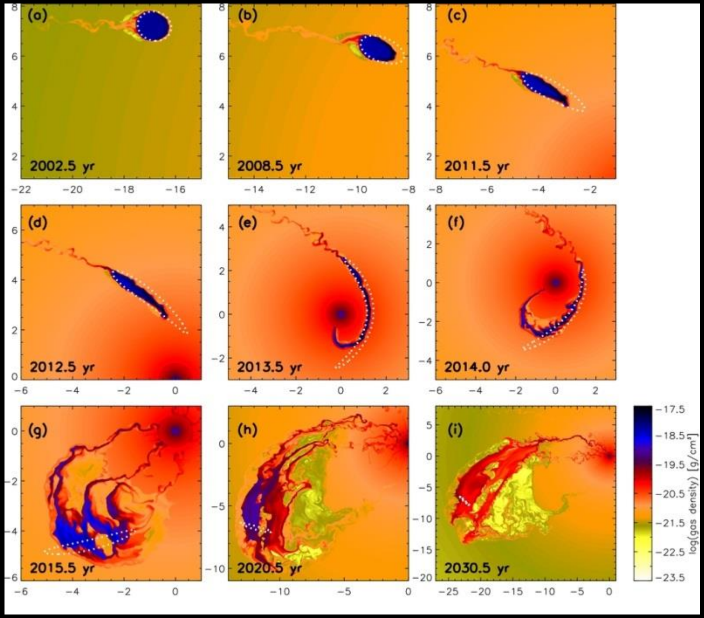


Gillessen et al. (2011)

G2: dusty ionized cloud with v = 1700 km/s, e=0.966 coplanar with the clockwise stellar disk.

M_{cloud} ~3 M_{earth} (~10^{28} g), T_{dust}~ 550 K, T_{gas} ~ 10^4 K, L~5 $L_\odot$

Should rich its pericenter in late 2013 or early 2014 (Extended event ~1 year) at only ~2200 R_s (~2 mas) << R_{bondi} (~4")



Schartmann et al. (2012)

Gillessen et el. (2013):

- Ionized gas in the head is now stretched over more than 15,000 R_s around the pericenter of the orbit, at ≈ 2000 R_S ≈ 20 light hours from the BH.
- The first parts of G2 have already passed pericenter

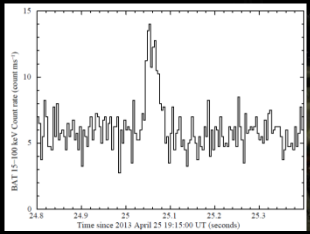
An unprecedented amount of satellites and ground-based telescopes are monitoring the Galactic center to follow the course and impact of the DSO/G2 source on Sgr A* activity.

The Awakening of a Supermassive Black Hole ?

- 2013 April 24 : *Swift/XRT* detects a large X-ray flare from Sgr A* (Degenaar et al. 2013).

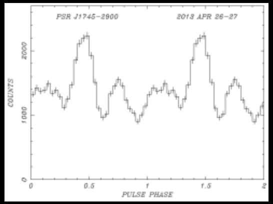
But, the enhanced X-ray emission persisted much longer than typical hour flare from SgrA*...

- 2013 April 25: *Swift/BAT* triggered on a short (~30 ms), hard X-ray burst at a position consistent with Sgr A*
  ⇨ Soft Gamma Repeater (SGR) bursts (Kennea et al. 2013).
  SGR: very small group of sources (26 known to date), which are suggested to be magnetars (slowly rotating neutron stars with extreme surface dipole magnetic fields of >10^{14} G).

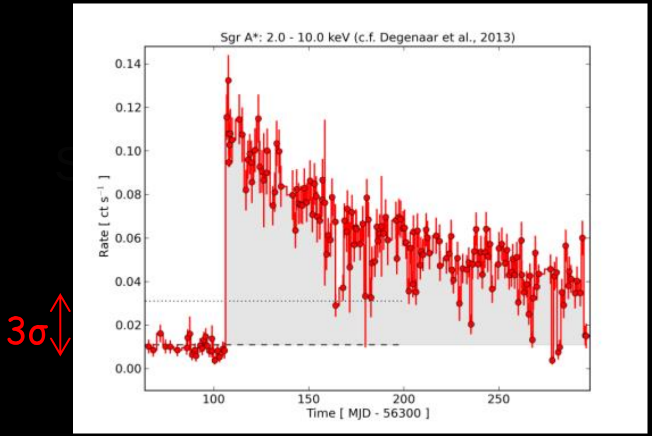


- 2013 April 26: *NuSTAR* detects a 3.76 second pulsar (Mori et al. 2013).

This period has been confirmed in radio:
⇨ fourth magnetar detected in radio wavelengths (Eatough et al. 2013).
+ Spin down rate implies B= 1.6 x 10^{14} G.



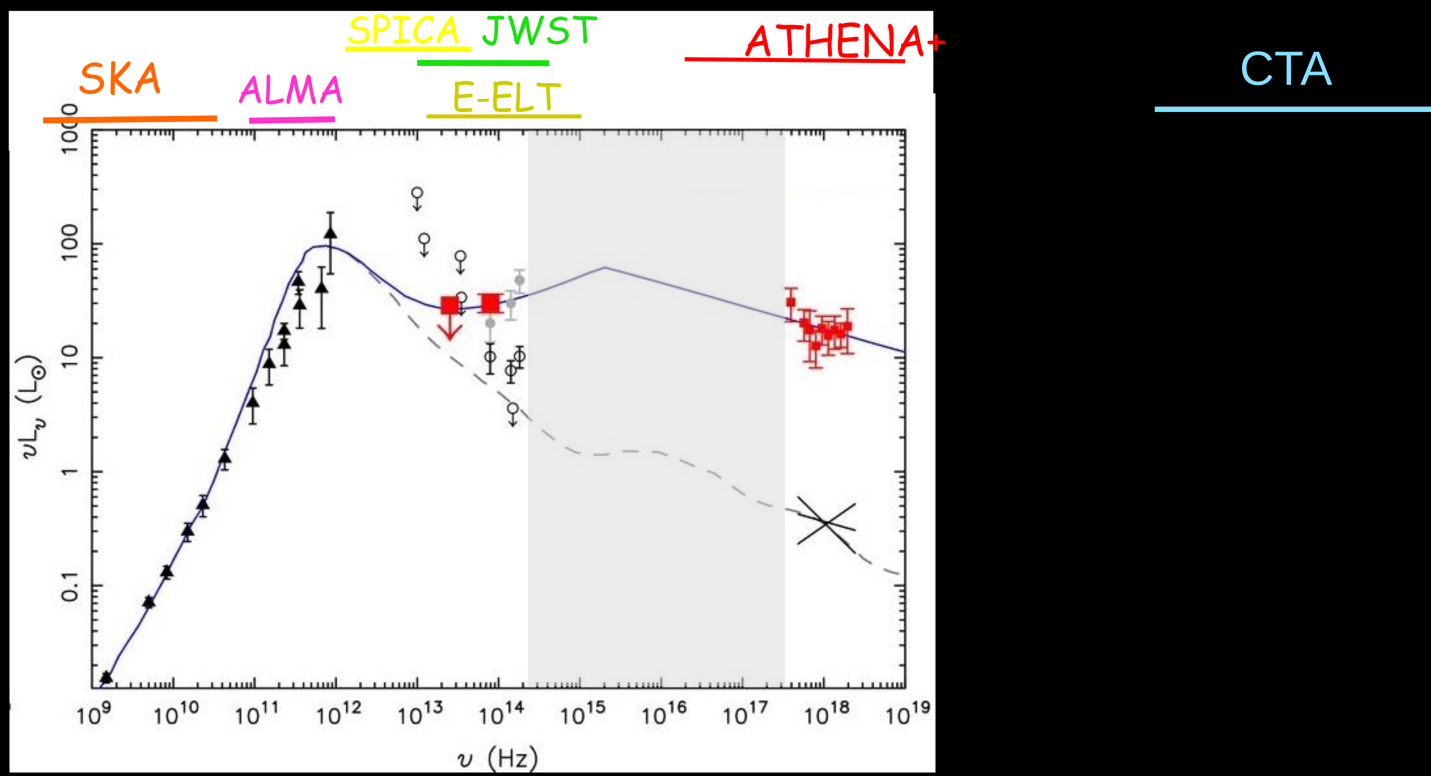
- 2013 April 29: *Chandra/HRC-S* imaged it at only ~3" (~ 0.1 pc) from SgrA* (Rea et al. 2013)



Degenaar et al. (2013)

IV. X-ray and other observational perspectives …
Just to cite a few toys to probe the Galactic center !

Multi-wavelength synergies of planned and proposed facilities,
e.g. SKA, VLBI/EHT, ALMA, SPICA, JWST,
E-ELT, GRAVITY, ATHENA+, CTA, …



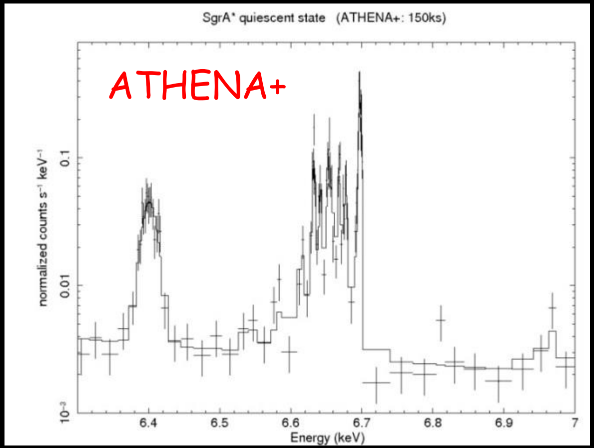
(Adapted from figure in Dodds-Eden et al. 2009)

X-ray satellites to probe the Galactic center

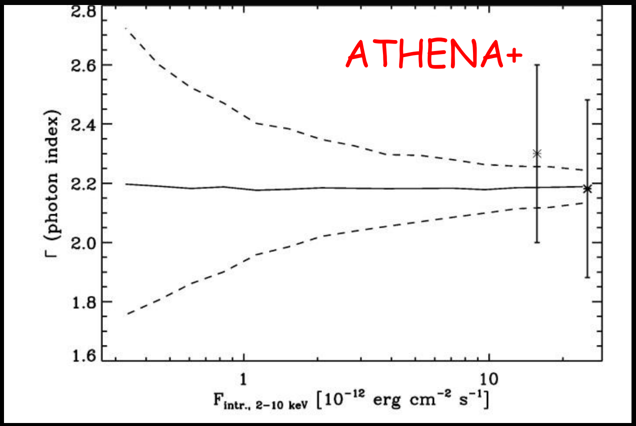
Current: Chandra, XMM-Newton, Suzaku, Swift and NuSTAR

Soon: Astro-H (Fall 2015): first bolometer in X-rays:
Fine X-ray spectroscopy above 5keV : plasma diagnostics !

Future: LOFT (XRB, AGN) and ATHENA+ (proposed ESA L2 mission for 2028)



(D. Porquet; N. Grosso)



(D. Porquet; N. Grosso)

⇨ X-ray plasma diagnostics to disentangle the ionization process during the Sgr A* quiescent state and in other regions of the galactic center : CIE, PIE, NIE, …

Such as those based on He-like ions (c.f. Porquet et al. 2010 for a review)

Stringent constraints on the spectral slopes for both moderate and bright X-ray flares + time-spectroscopy during flares

+ A third complementary X-ray tool:
X-ray polarimetry

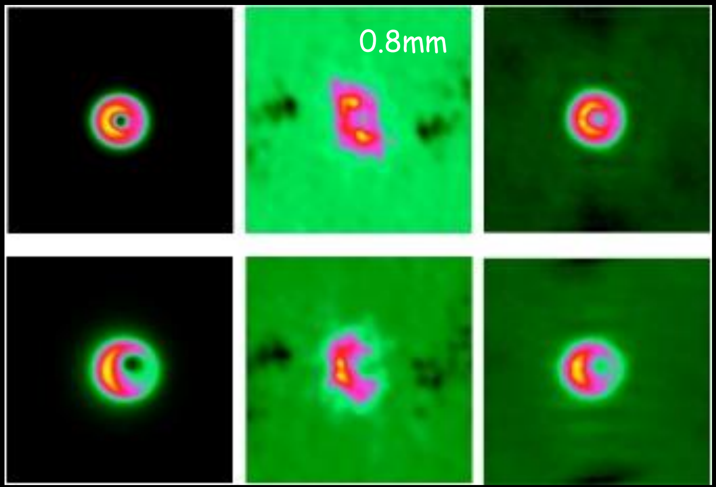
VLBI/EHT (Sgr A*)

Discrimination between geometry (circular Gaussian, annulus, …), direct test for the 'shadow', and spin determination, etc.

GRMHD simulations | 7-station array | 13-station array

a=0.5 θ=85

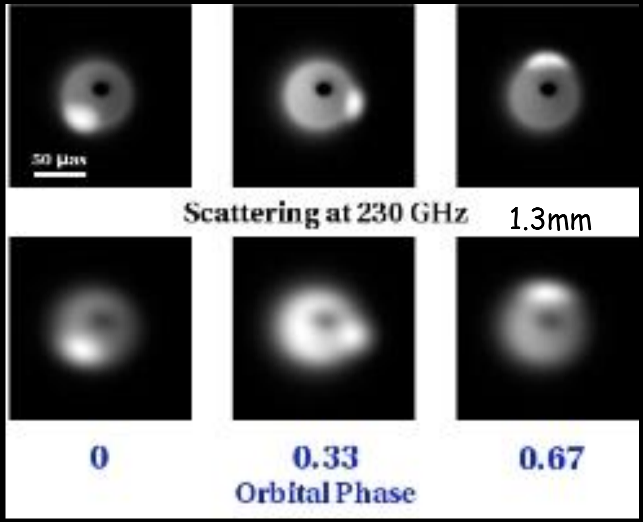
a=0 θ=60



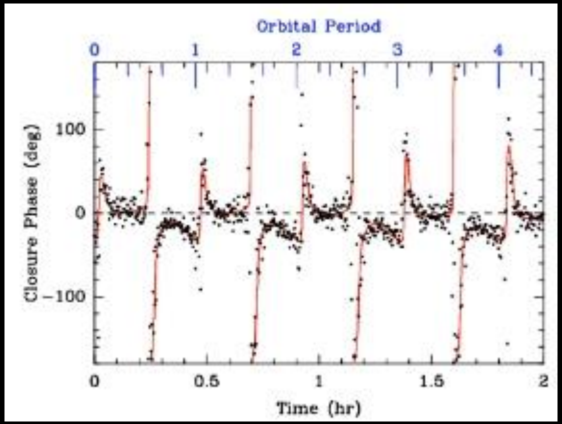
Courtesy: C. Gammie & A. Broderick

Signature of an orbiting hot spot

a=0 θ=60

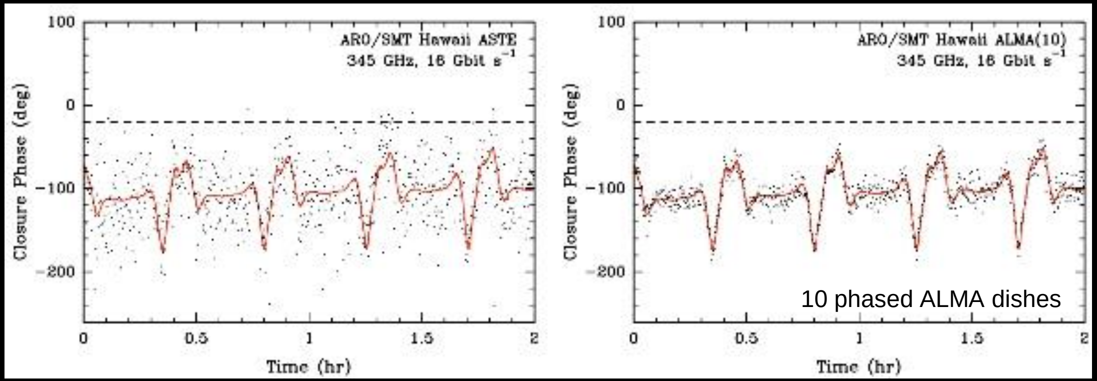


1.3mm VLBI closure phases every 10s



ARO/SMT-Hawai-CARMA

Signature of a hot spot orbiting around a BH a=0.9, R=3R_s with a period of 37 min



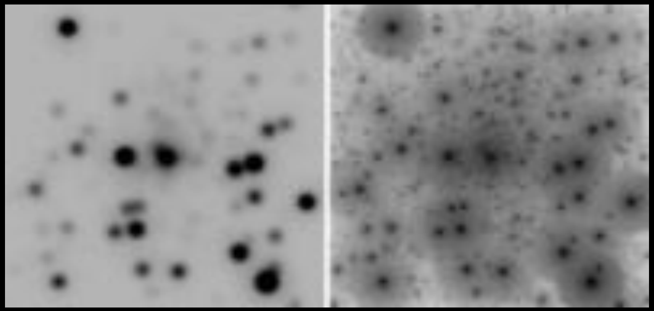
Periodicity ⇨ spin

Doeleman at al. (2009)

E-ELT (40-m class telescope; 2022)

Current studies are confusion-limited in both the spatial and spectral dimension

8–10 m telescopes E-ELT/MICADO



(Trippe et al. 2010; Paumard et al. 2010)

Central 1 × 1 arcsec^2 (8000 × 8000 a.u.) of the nuclear star cluster of the Milky Way at 2.2 μm.

Study of stars as close as 100 R_s (8.2 a.u.) where v_{orb} ~ 1/10 *c*
(i.e. 10 time closer than achieved with the current 10-m telescopes) thanks to:

- Extremely accurate measurements of the positions of the stars (10 mas instead of 50 mas currently)
- Radial velocity measurements with ~1 km/s precision

⇨ Measuring the mass distribution (including dark matter) around the central black hole.

⇨ The distance to the GC and mass of SgrA* will be measured to < 0.1%

TO BE CONTINUED....