The Galactic center

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cnrs dépasser les frontières

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Observatoire astronomique de Strasbourg

SEVENTH FRAMEWORK PROGRAMME

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

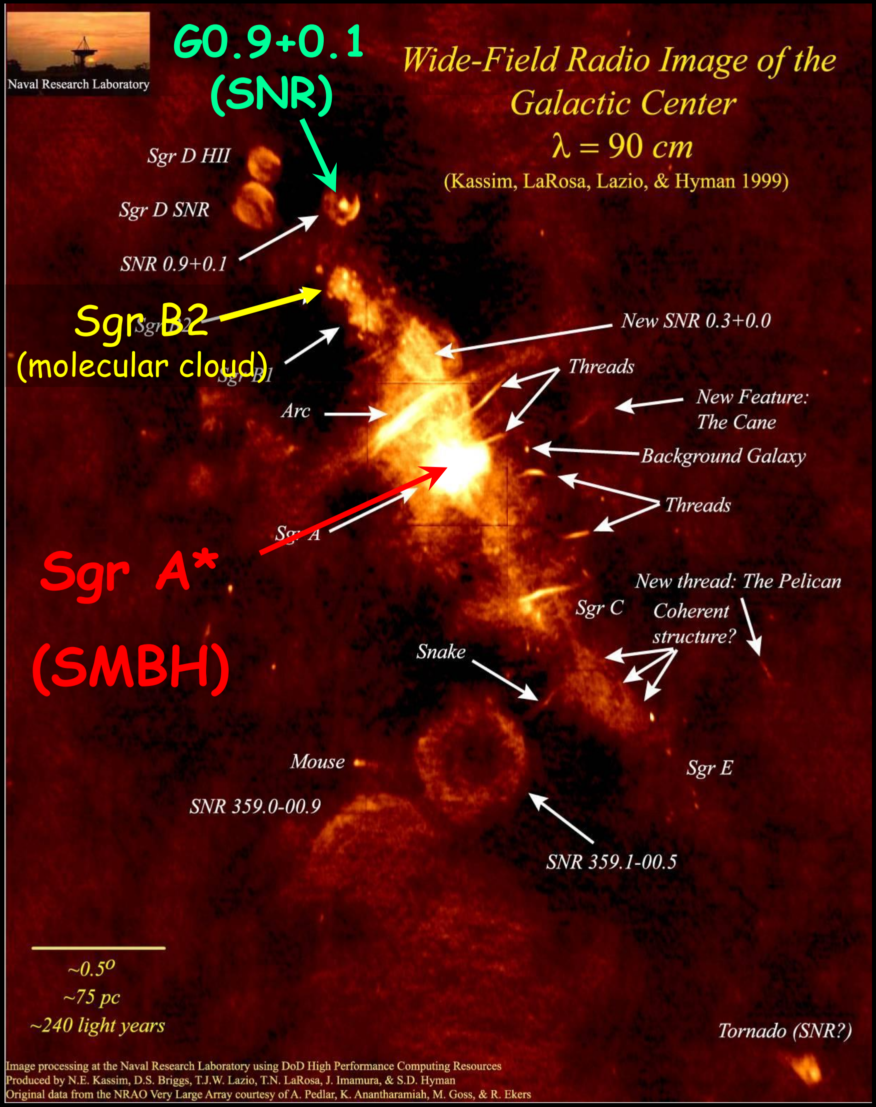
*   Distance ~ 8 kpc

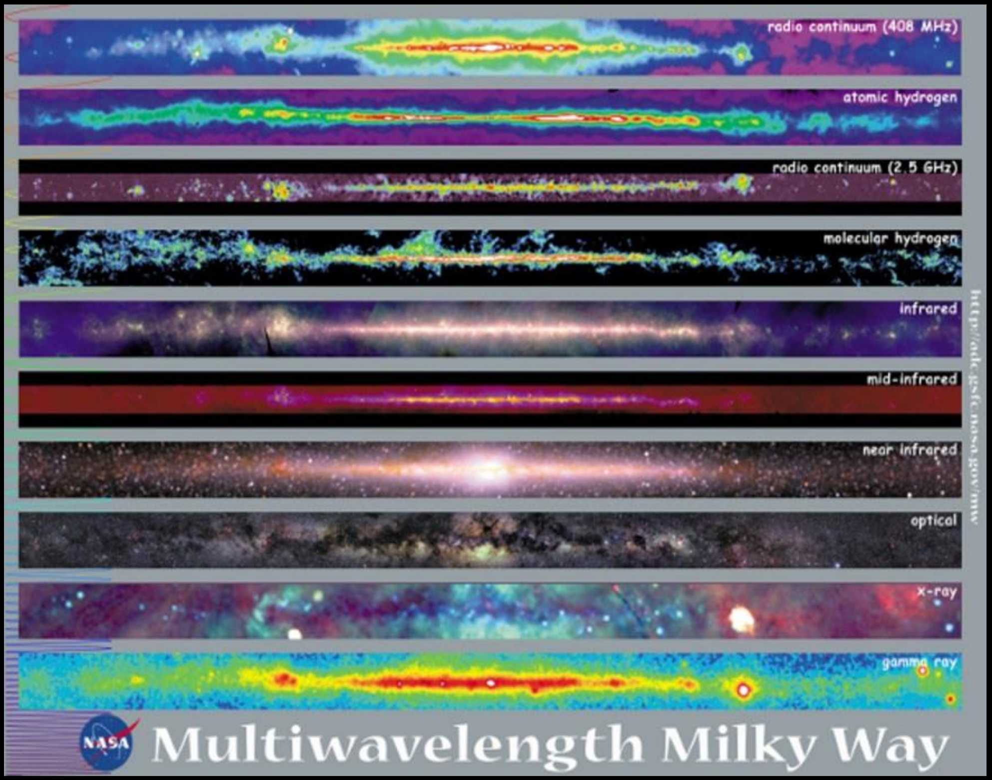
*   High column density along the line-of-sight: $N_H \sim 5\text{-}7 \times 10^{22}$ cm^{-3} ($A_v \sim 25\text{-}30$)
⇒ 'only' observable in radio, IR, X-rays (≥ 1-2 keV) et γ-rays

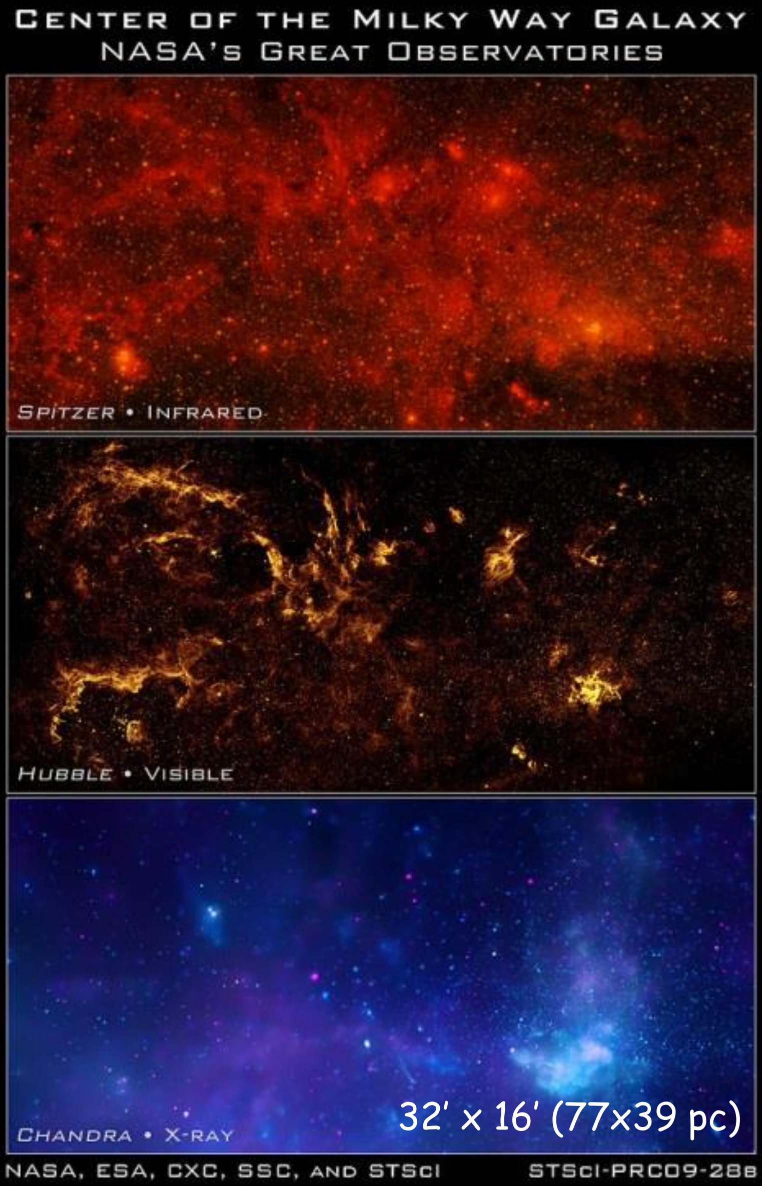
__ Extended objects:__
SNR, molecular clouds, non-thermal, filaments, diffuse emission, …

* Stars

* Compact objects:
X-ray binaries (neutron stars, black holes, white dwarfs),
SMBH: Sgr A*, ….







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

HST + Spitzer +Chandra

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

See Devaky Kunneriath's talk about the inner 400 pc region of the GC

Chandra Galactic Center Deep Field

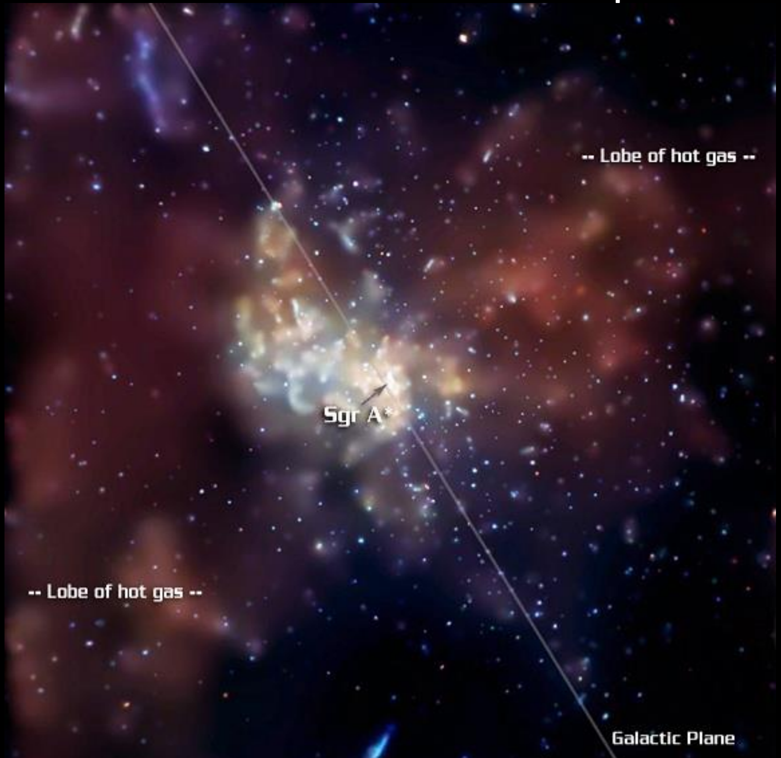
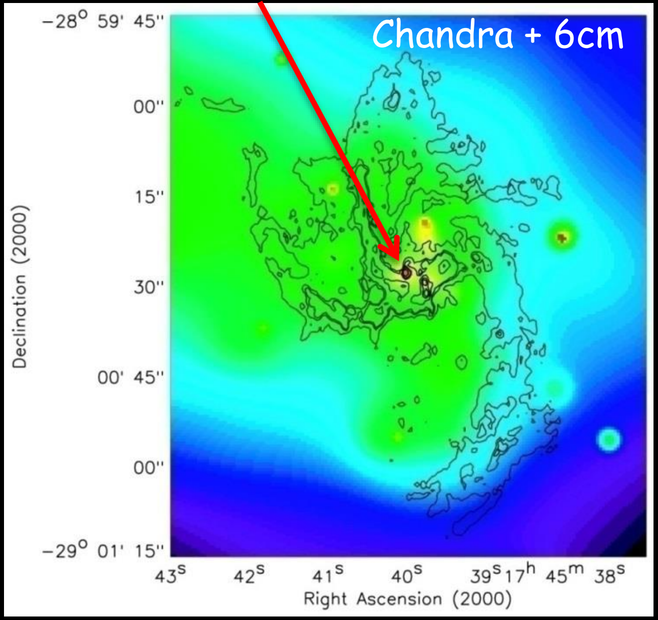


Image Credit: NASA/CXC/MIT/F. Baganoff et al.

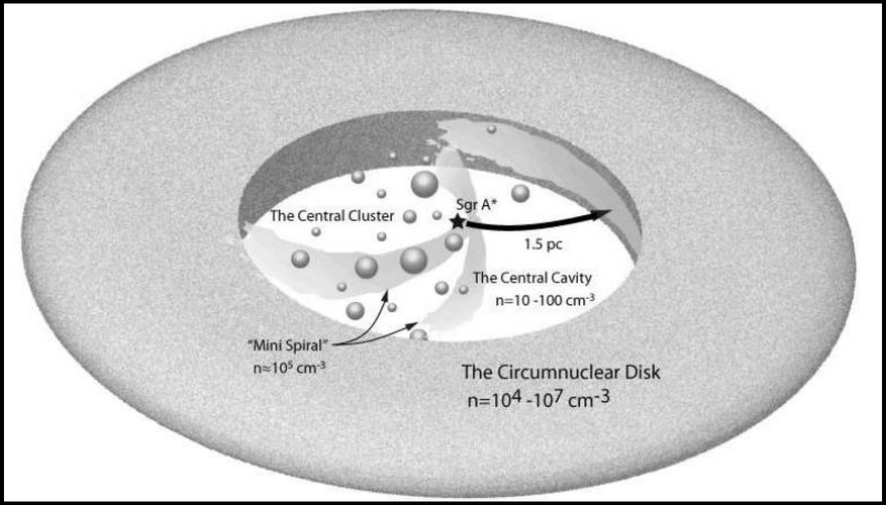
8.4′ x 8.4′ (19.5 x 19.5 pc; 63.6 x 63.6 l.y.)

Sgr A* + Sgr A West



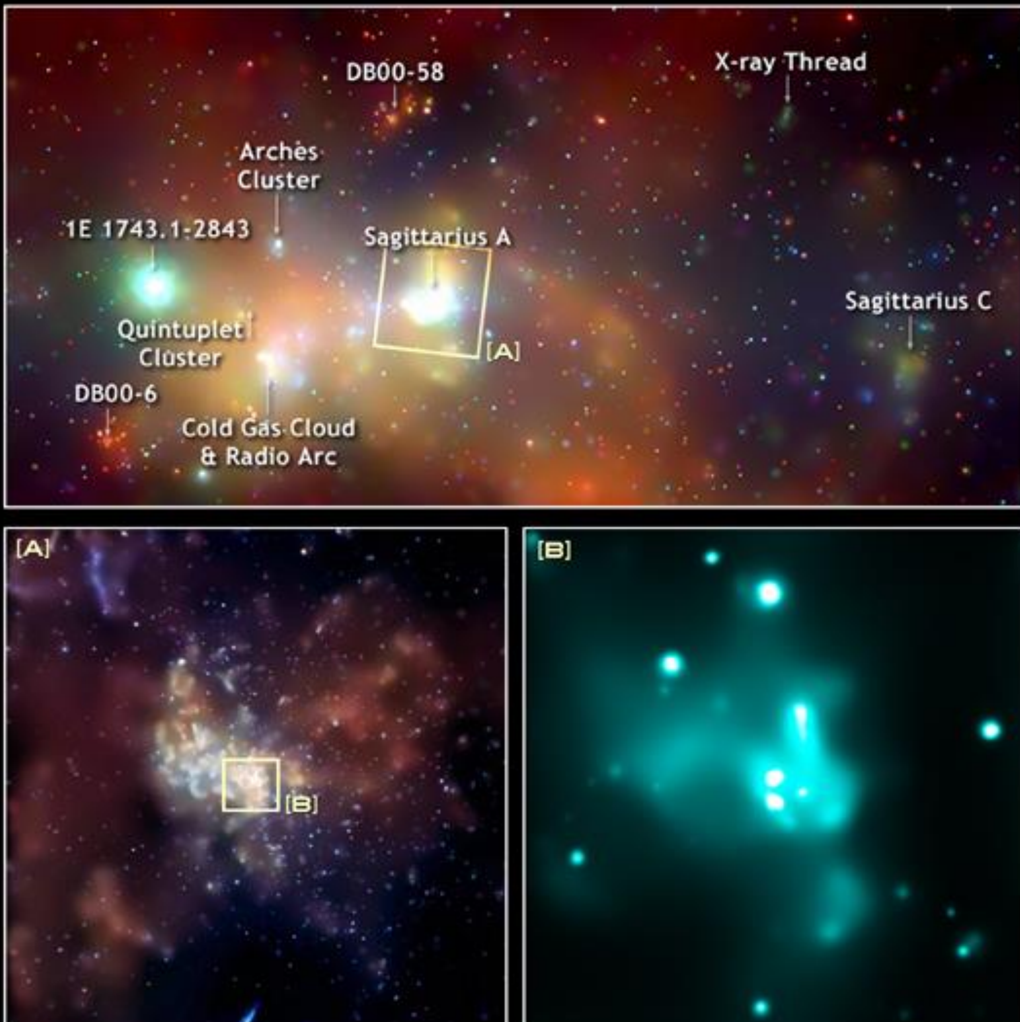
1.3′ x 1.5′
(3 x 3.5 pc; 9.8 x 11.4 l.y.)

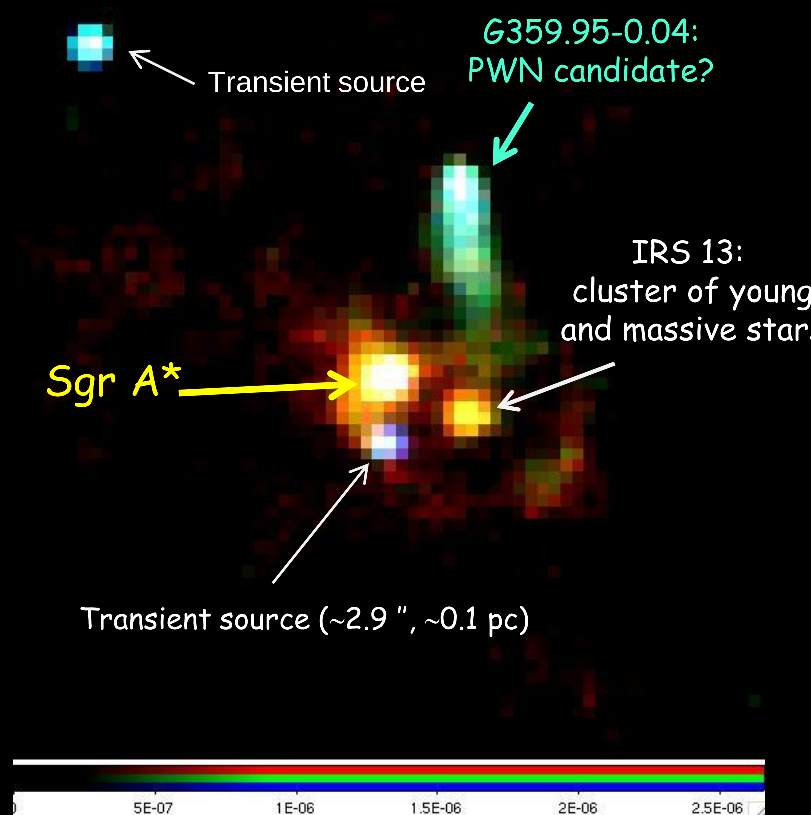
See Bozena Czerny's talk about accretion from the mini-spiral



Goto et al. (2013)

A zoom on Sgr A*

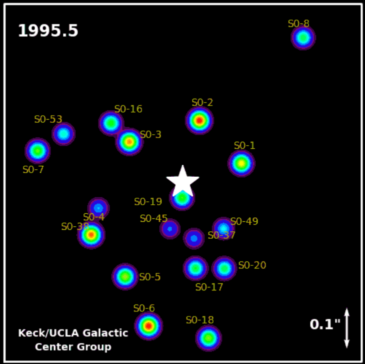




ACIS image (1Ms)
Image Credit:
NASA/CXC/MIT/Frederick K. Baganoff et al.

I. Current view of Sgr A*

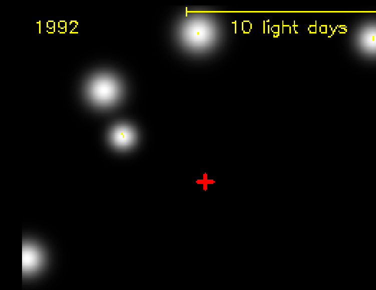
Sgr A*: SMBH at the Galactic center



Keck/UCLA GC group

- Closest supermassive black : D ~ 8 kpc
- Stellar orbits ⇨ $M_{BH} \sim 4 \times 10^6 M_\odot$
- Largest BH in projection

⇨ best place to test GR directly in a strong gravitational field.



Schödel, R. et al. 2002, Nature

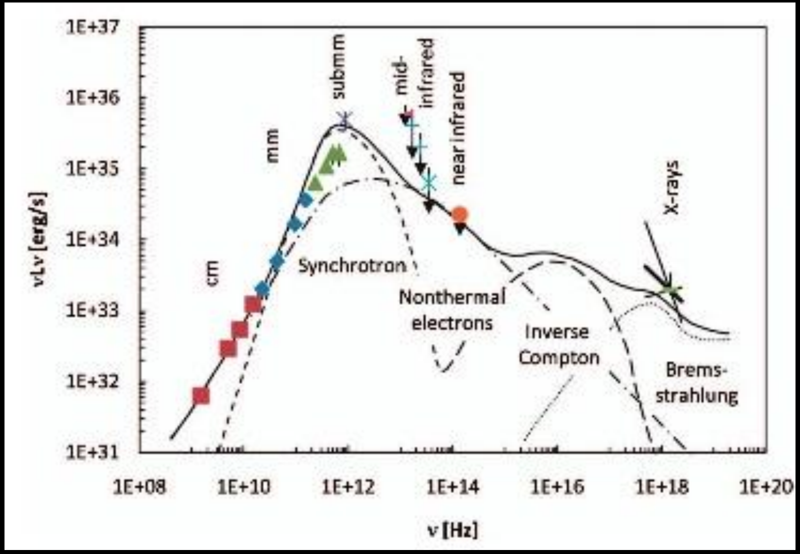
- First detected as a non-thermal radio source with a proper motion of -0.4 ± 0.9 km/s
- Size @ 1.3mm : 37 (+16,-10) μarc i.e., 0.3 A.U. or 4 R_S
- Bolometric luminosity: $L_{bol} \sim 10^{36}$ erg.s^{-1} ~ x 100 $L_\odot$!
  10^{-8}-10^{-9} * L_{Edd} ($\equiv 1.26 \times 10^{38} M/M_\odot \sim$ 4-5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

- A relatively low accretion rate at the Bondi radius (~4" = 4x10^5 R_s) : Mdot ~ 10^{-5-6} Mdot/yr
- Inefficient angular-momentum transport
- Outflows,
- Low radiation efficiency ($\eta \sim 10^{-6}$)

- Rotation measure (position angle of the linear polarization vector at ≠ wavelengths):

< 2x10^{-9} – 2x10^{-7} Mdot/yr (depending of the B configuration in the accretion flow)

Spectral energy distribution of Sgr A* (steady/quiescent state)



- Radio: predominantly optically thick synchrotron radiation from thermal electrons (kT~10-30 MeV) T_e ~ a few 10^{10}K , $n_e \sim 10^6$ cm^{-3}, and B~10-50 G

- X-rays: FWHM =1.4" (1" = 10^5 R_s = 0.04 pc) similar to the size of the Bondi accretion radius. Probable origin: thermal bremsstrahlung from the transition region between the ambient medium and the accretion flow.

Less clear whether there is a steady NIR counterpart. And no detection in MIR yet.

Models for the quiescent emission: ADAF, RIAF, CDAF, ADIOS, jet, jet/ADAF, ….

Sgr A* : a "quiescent" SMBH … but not inactive

- Bolometric luminosity: $L_{bol} \sim 10^{36}$ erg.s^{-1} ~ x 100 $L_{\odot}$! << AGN ($\geq 10^{42}$ erg s^{-1})
  10^{-8}-10^{-9} times weaker than the Eddington luminosity

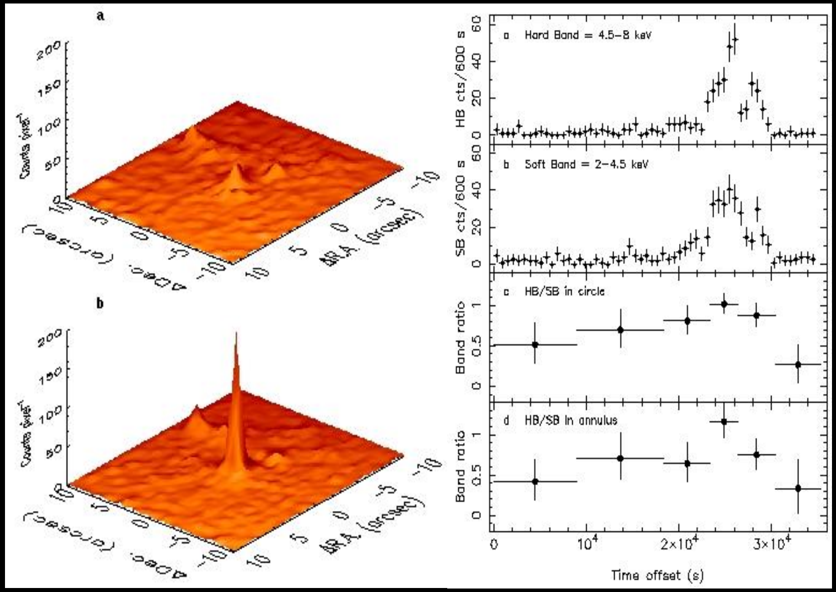
⇒ Extremely low radiative efficiency and low accretion rate.

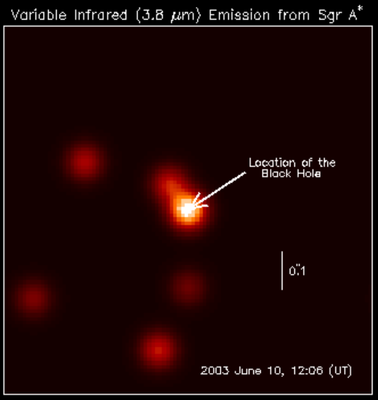
BUT not inactive: flares first discovered in X-rays (Oct. 2000), then in IR in 2003.

⇨ 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)

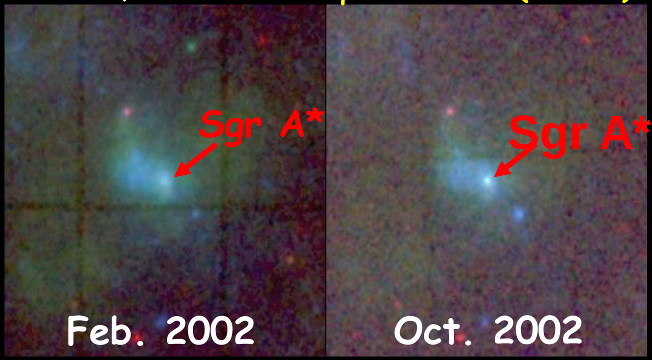




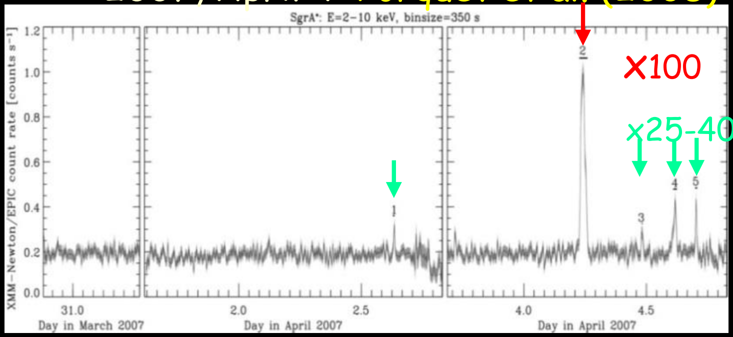
Keck II 10 m: adaptive optics L' (3.8 μm)
Ghez et al. (2004)

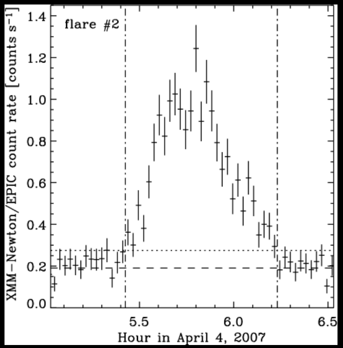
Most X-ray flares are weak (≲10) or moderate (≲40) BUT two (first) brightest X-ray flares from Sgr A* has been observed with XMM-Newton

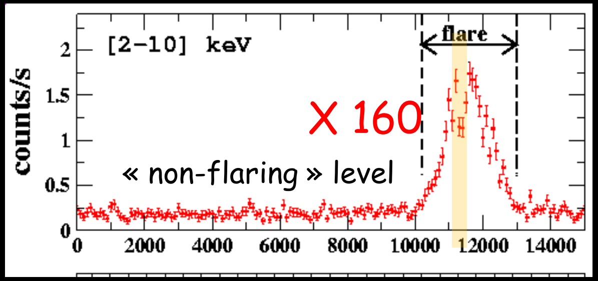
2002, Oct. 3: Porquet et al. (2003)



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





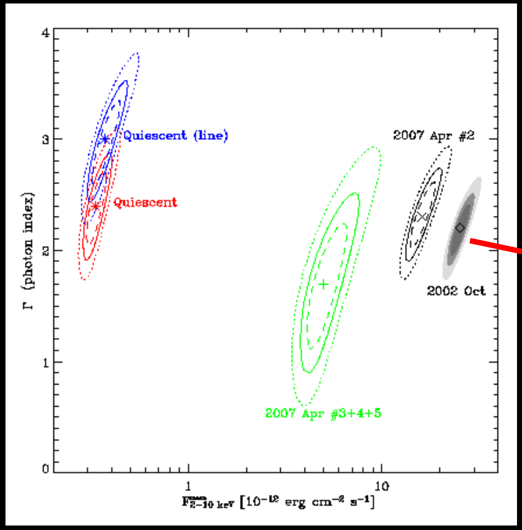


- duration ~ 3000 s
- amplitude at the peak: ~ 160 and 100

(~ x 3.5 – 2.2 October 2000, Chandra)

$L_{2\text{-}10keV}$ (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 !



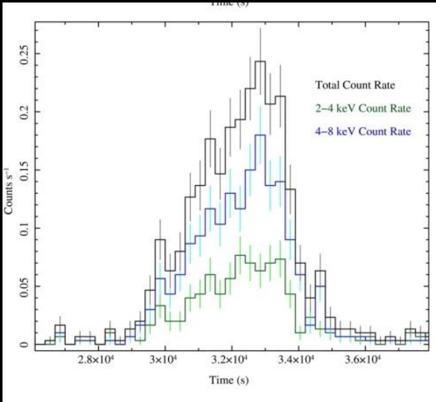
- Bright to very bright X-ray flares have well constrained soft X-ray spectra Γ ~ 2.2-2.3 (±0.3)
  Not constrained for weaker flares !

The most energetic Sgr A* flare observed by Chandra/HETG

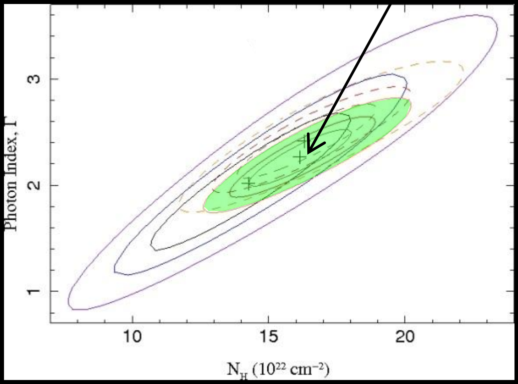
3 Msec (~35 days) of observations over the course of **Chandra/HETG** Cycle 13 (02/2012 – 10/2012) PI: F. Baganoff (MIT)

<u>Aim:</u> Observation and study of **Sgr A*, and its surrounding** inner few arcminutes
⇨ First high-resolution angular and high-resolution spectrum of Sgr A* during its quiescent state (ADAF/ RIAF, …) and its flaring state.

Nowak et al. (2012):
A very bright flare (x 160) has been observed for the first time with Chandra in Feb. 2012 ≡ Oct 2002 XMM-Newton flare but twice larger in time.

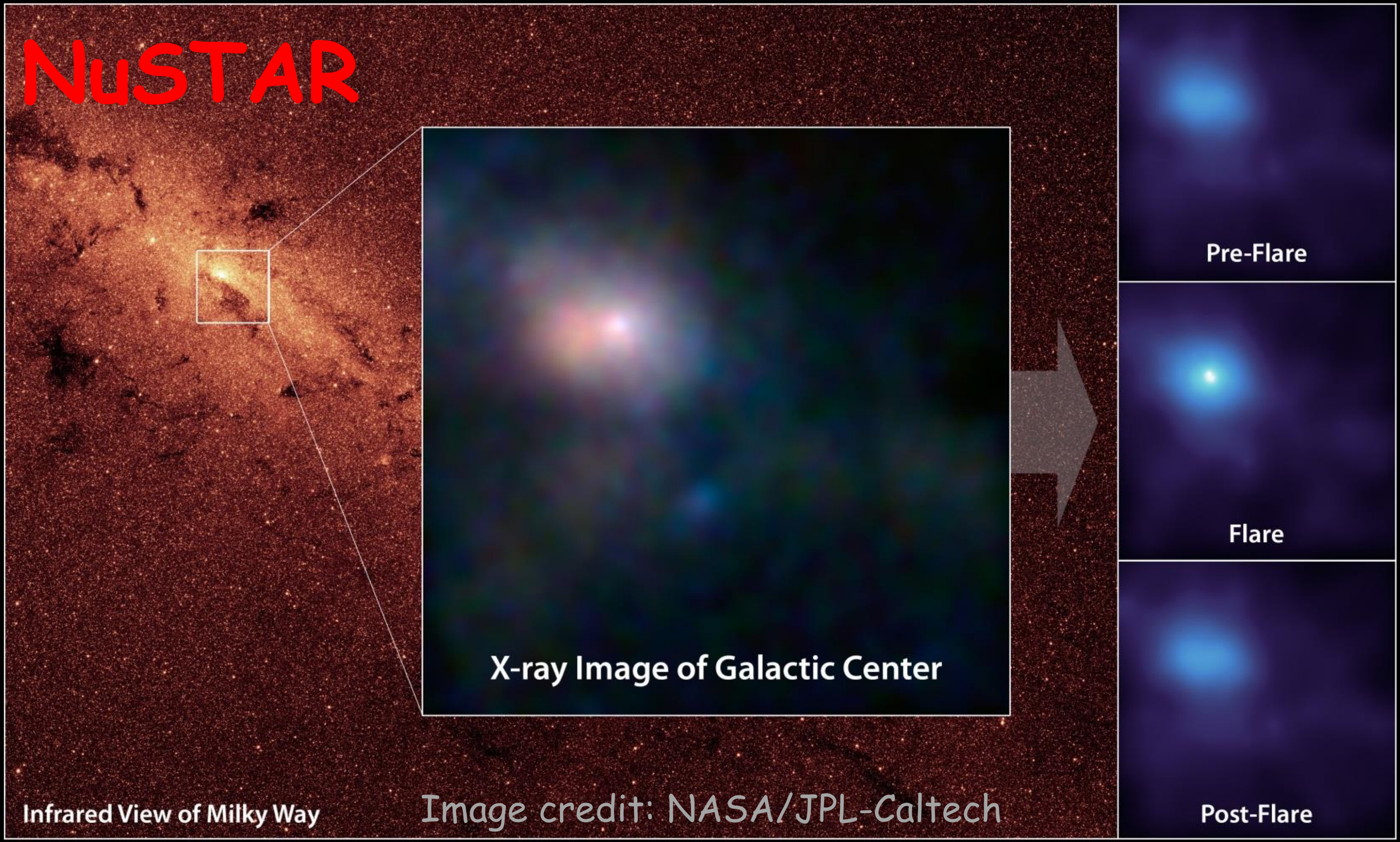


Chandra HETG XMM-Newton



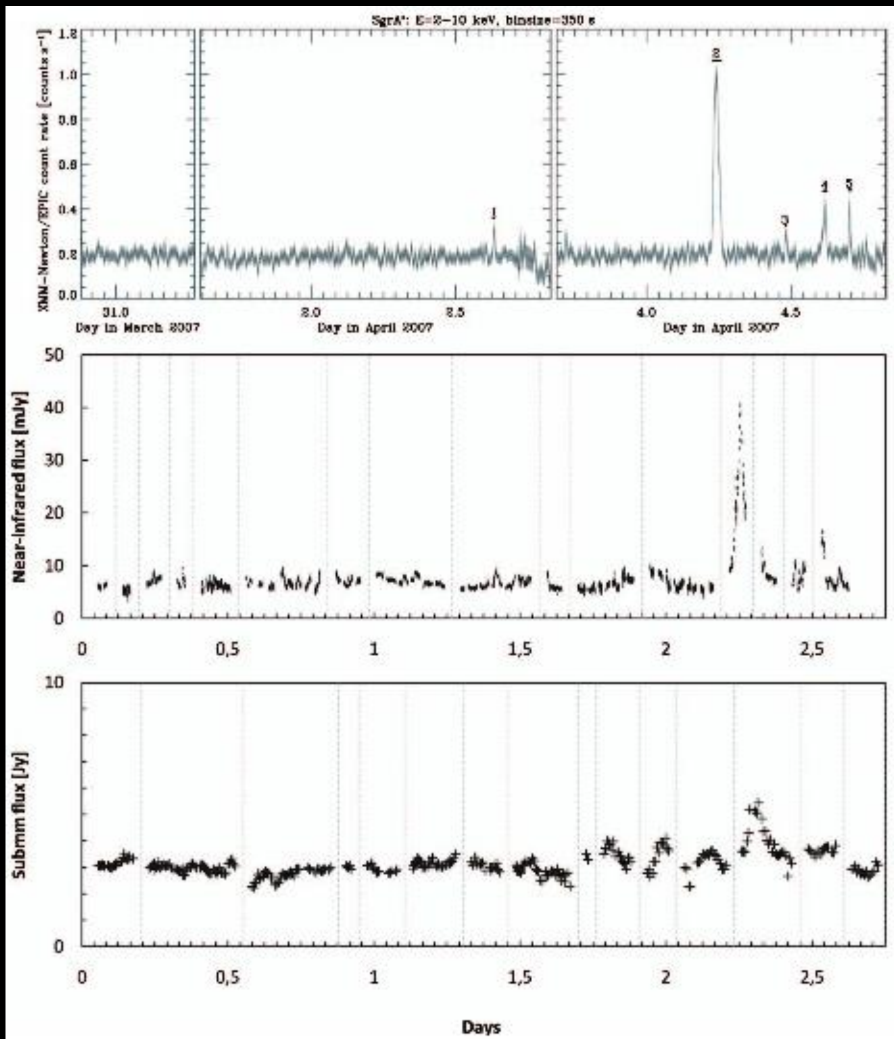
Nowak et al. (2012)

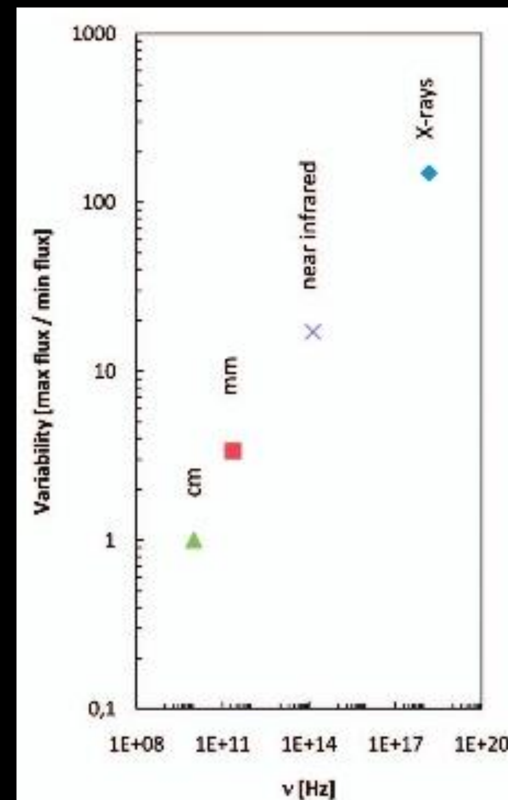
⇨ Consistent with the "soft" spectral shapes found for the 2 brightest XMM-Newton X-ray flares (Porquet et al. 2003, 2008)



See Dominic Walton's talk about NuSTAR (Thursday)

Multi-wavelength overview of SgrA* flares

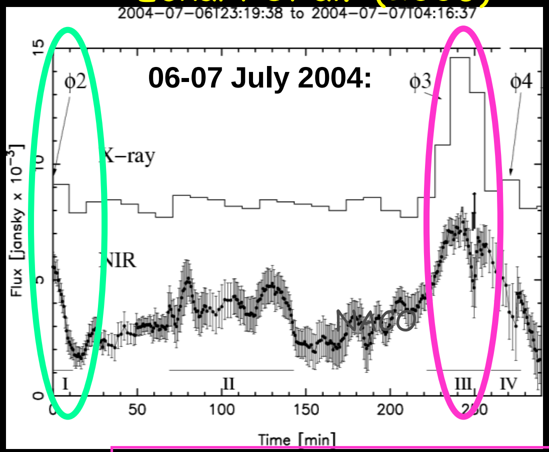




NIR/X-ray Flares

Chandra/VLT

Eckart et al. (2006)

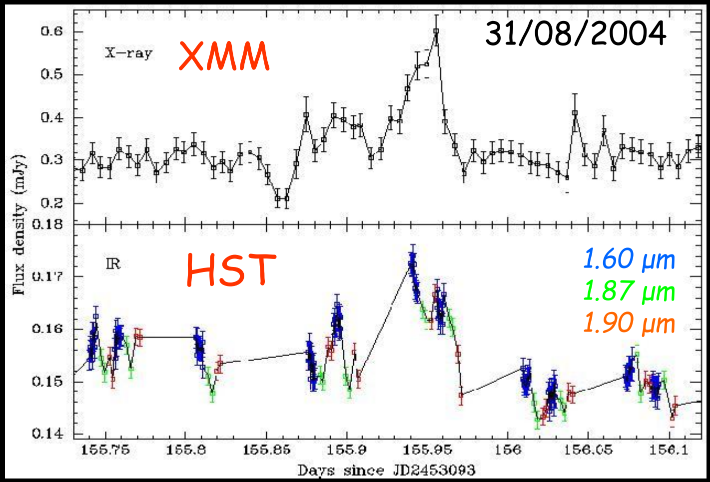


$\alpha_{X/NIR}$ (φ2)= 1.35±0.2

L_x (φ3)~ 33 x 10^{33} erg s^{-1}, ampl.~15,
Δt ~ 42 min
F (NIR) = 6 ± 1.5 mJy
$\alpha_{X/NIR}$ (φ3)= 1.12±0.05 ($S_\nu \propto \nu^{-\alpha}$)
Time lag ≤ 10 mn

XMM-Newton/HST

Yusef-Zadeh et al. (2006)



3 bright NIR flares detected with HST:

* amplitudes: 10-20% increase;
* durations: 20 min to 2.5 hours;
* flaring activity: ~30-40% of the observing time.

One simultaneous X-ray/NIR flare observed: similar morphology, similar duration with no apparent delay.

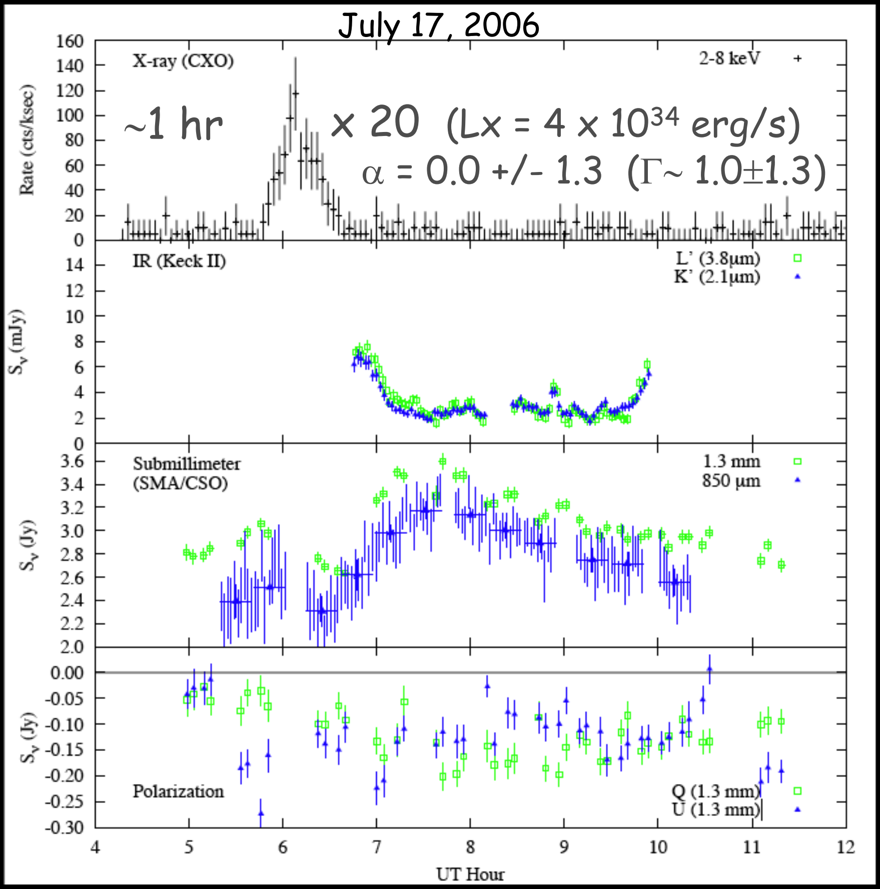
→ Believe to come from the same region close to the event horizon.

⇨ When simultaneous X-ray and NIR observations:
All X-ray flares have NIR counterpart **BUT** not all NIR flares have (detected) X-ray counterpart

See also Eckart et al. 2004, 2008, Yusef-Zadef et al. 2007, Hornstein et al. 2007, Marrone et al. 2007, …

First observations of a flare detected at X-ray, NIR and sub-mm

Marrone et al. (2008)



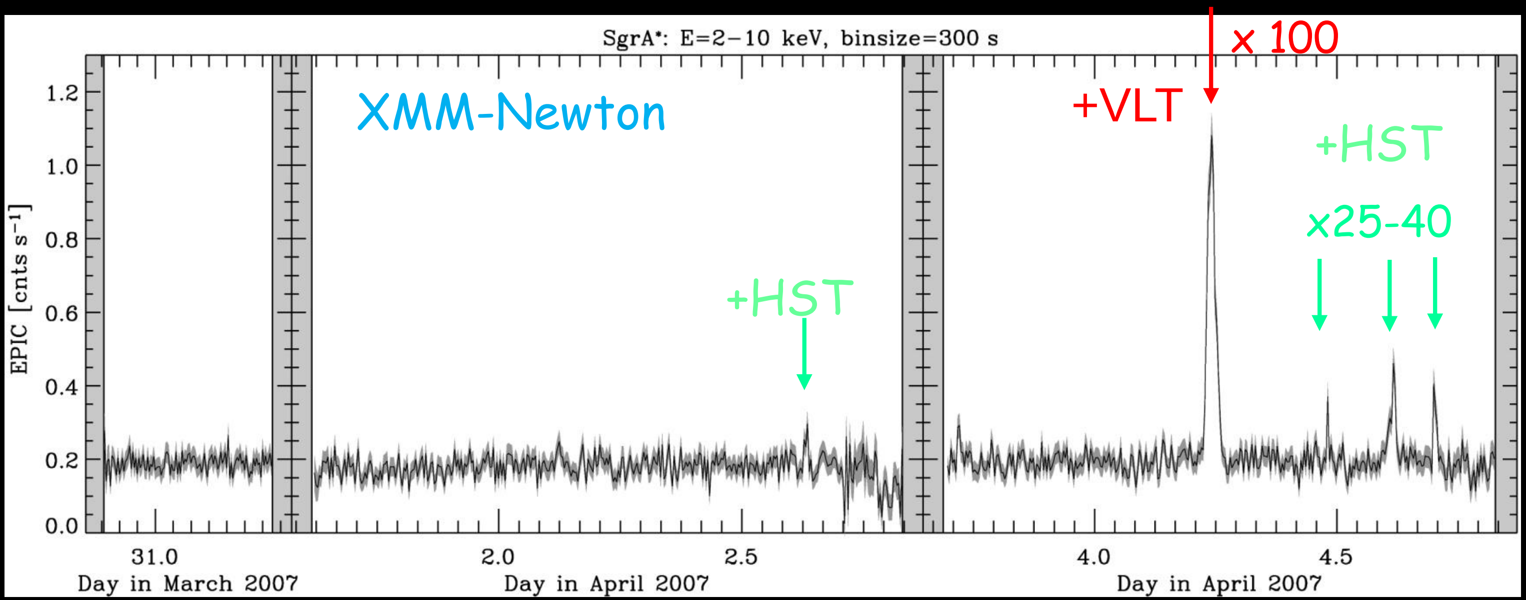
* L_{peak} (2-8keV) ~ 40 x 10^{33} erg/s
  Amplitude ~ x 20

* NIR data begins 36 min after X-ray peak

* Sub-mm flare occurs nearly 100 min after the X-ray peak.

X-ray hiccups from SgrA* on April 4th 2007

Porquet et al. (2008)



4 flares detected within 12 hours with different amplitudes !

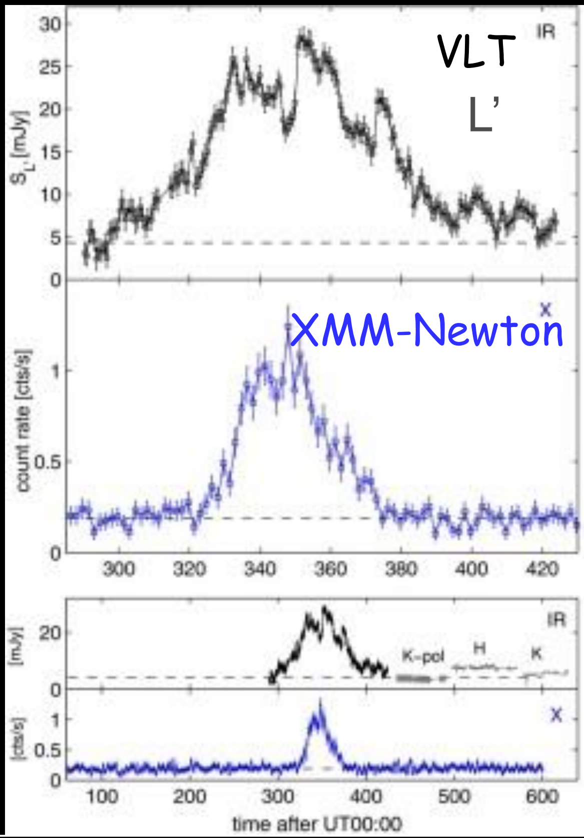
Detection of the second brightest X-ray flare from SgrA* : ~x 100

followed by 3 moderate X-ray flares: ~ x 25-40

Simultaneous multi-wavelength observation campaign: from radio to X-rays

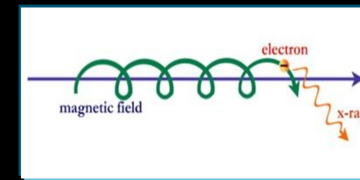
Brightest IR/X-ray flare (April 4th 2007)

(Porquet et al. 2008; Dodds-Eden et al. 2008)

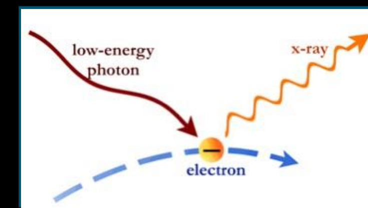


__Possible emission mechanisms for the X-ray flares :__

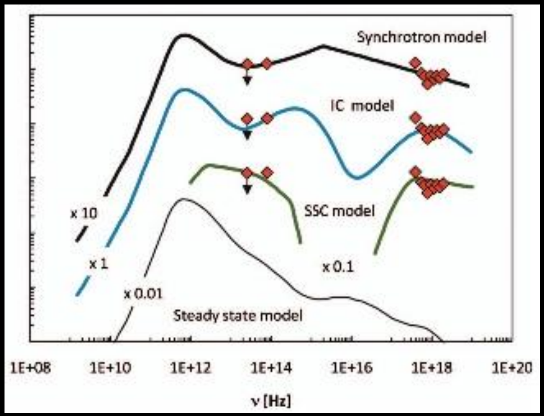
Synchrotron scenario:
-> X-rays (as for NIR)



Synchrotron self-Compton (SSC):
NIR photons are up-scattered by the same e^- responsible for the NIR synchrotron radiation.



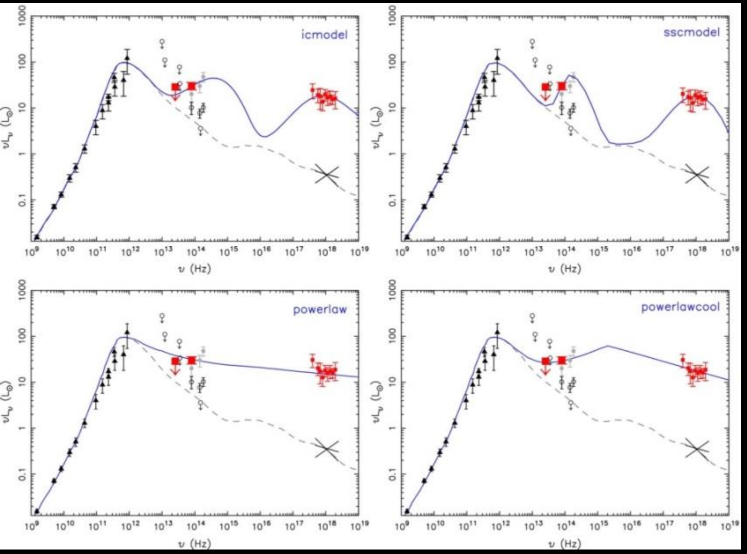
Inverse Compton Scattering:
Sub-mm photons (quiescent) are up-scattered by the NIR e^- (synchrotron)



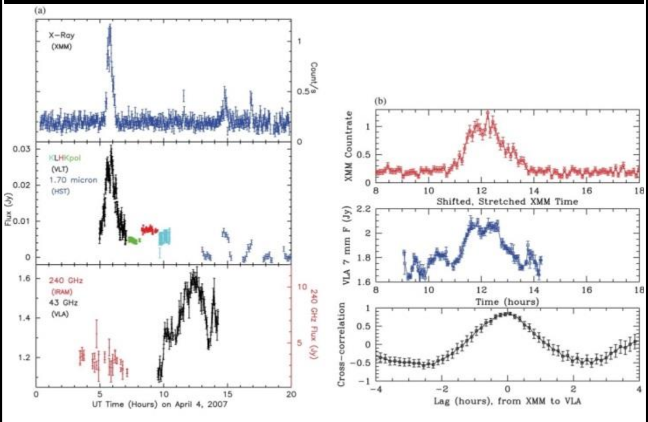
__Observational constraints:__

$\nu L_\nu \propto \nu^{-\beta}$ with $\beta_{NIR} > 0$ and $\beta_X = -0.3$
NIR/X : simultaneous with 3 min
Durations: $FWHM_{IR}$=66 min $FWHM_X$=28 min
IR shortest time-scale = 1.2 Rs in size
Upper limit in MIR.

Dodds-Eden et al. (2009)



Yusef-Zadeh et al. (2009)



⇨Adiabatic cooling in an expanding emission region ?

Hypothesis:

NIR: synchrotron emission

1) Sub-mm IC and SSC:

Thermal distribution of transiently heated/accelerated electrons: γ typical energy of the electron distribution kT_e/mc^2

2) Synchrotron with a cooling break:

Power law energy distribution of accelerated electron $N(\gamma) \propto \gamma^{(3-p)/2}$ (below cooling break) $\propto \gamma^{(2-p)/2}$

Sub-mm IC: $\gamma \leq 1000$, B ≥25 G, and R (sub-mm seed photons) < 0.1 Rs << R (VLBI)

SSC: $\gamma \leq 100$, B ≥2400 G, and R (seed IR photons) < 0.002 Rs $\rightarrow n_e > 10^{10}$ cm^{-3} >> x ~1000 n_e and B in the inner accretion flow (Yuan et al. 2003)

Synchrotron with a cooling break:

B~ 6 G and p~2.4

⇨ Most viable scenario for the X-ray emission: synchrotron from an electron distribution with a cooling break.

However other and/or more sophisticated scenarios has been proposed for SSC (e.g., Sabha et al. 2010) and IC (e.g., Yusef-Zadeh et al. 2012) that could explain these NIR/X-ray flare properties.

- The emission mechanism(s) of the daily (present) X-ray flares not yet settled: SSC, IC, or synchrotron ?

- Associated mechanism(s) ?

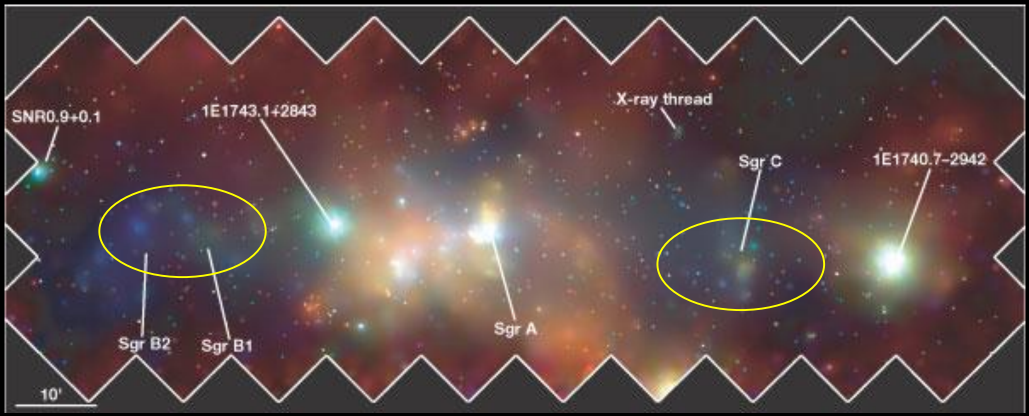
Increase of the accretion rate, accretion instability,
Turbulent shocks
Tidal disruption (asteroids)
magnetic reconnection, hot spots,
Tilted black hole accretion disc
Jet acceleration
Blob of relativistic plasma,
....

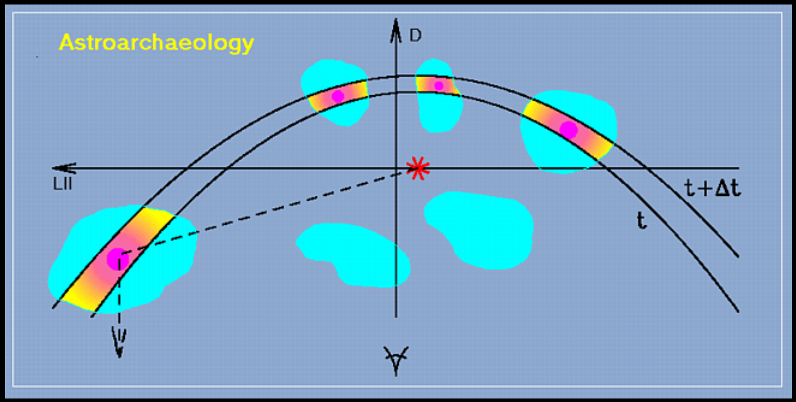
(e.g., Liu et al. 2002, 2004; Yuan et al. 2003, Eckart et al. 2004, 2006, Yusef-Zadeh et al. 2006, Marrone et al. 2007, Dodds-Eden et al. 2009, 2010; Markoff et al. 2001, Sabha et al. 2010, Zamaninasab et al. 2010, Kunneriath et al. 2010, Zubovas et al. 2012, Dexter & Fragile 2013, …)

Simultaneous multi-wavelength constraints are required, e.g.:
Intensity, durations, timing, spectral and polarization properties, …

See Grisha Karssen's talk about "Modelling the flares of Sgr A*"

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

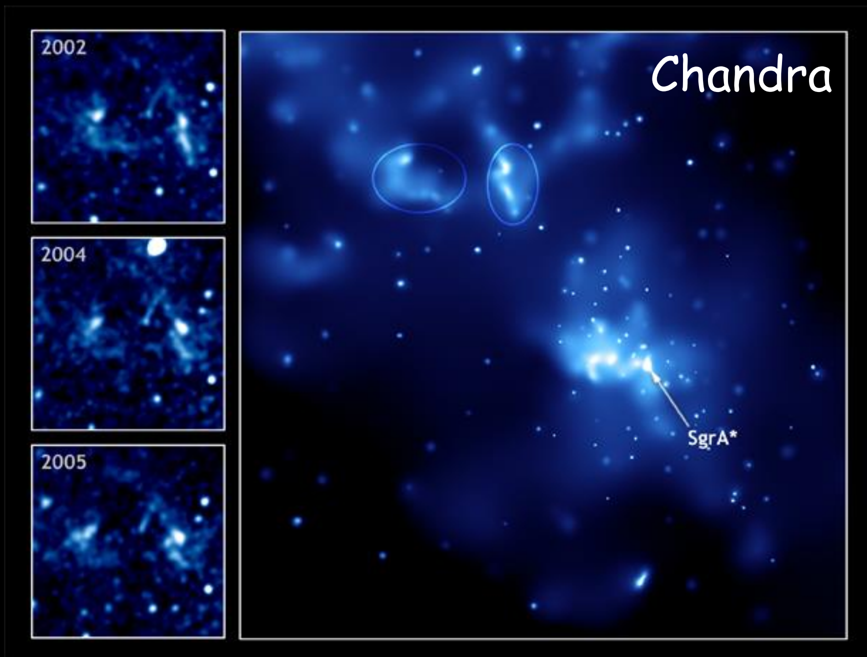




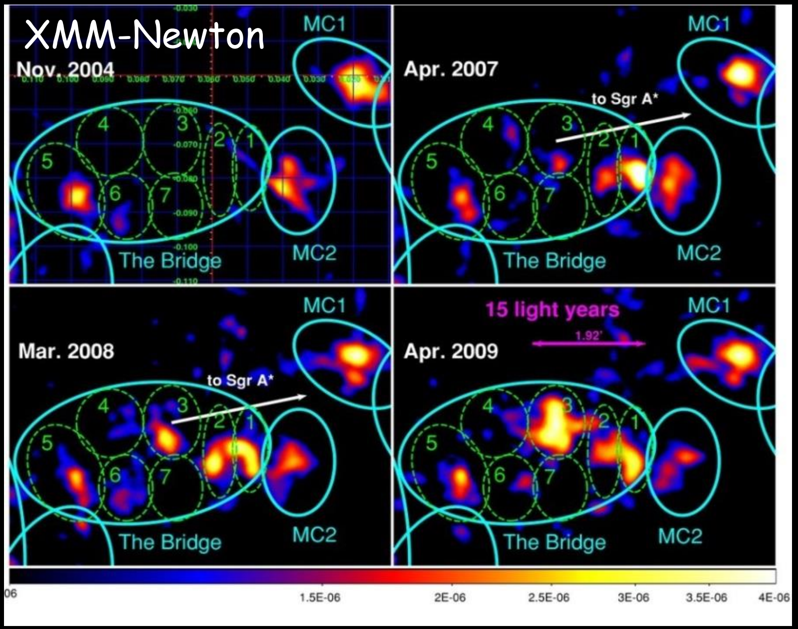
Sunyaev et al. 1993, Koyama et al. 1996, Murakami et al. 2001

Molecular clouds close to Sgr A*: ~ 15 pc

Sunyaev et al. 1993, Koyama et al. 1996, Murakami et al. 2001



Muno et al. (2007)



Ponti et al. (2010)

⇨ 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}.

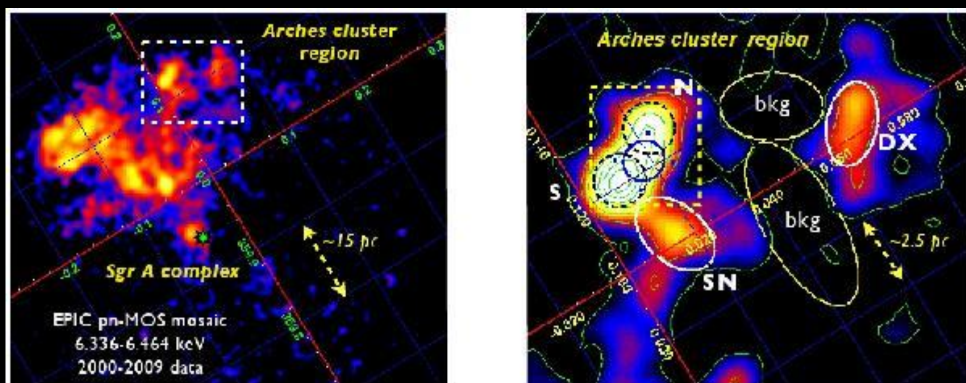
If Sgr A* then outburst occured 60 years ago (14 pc in projection)

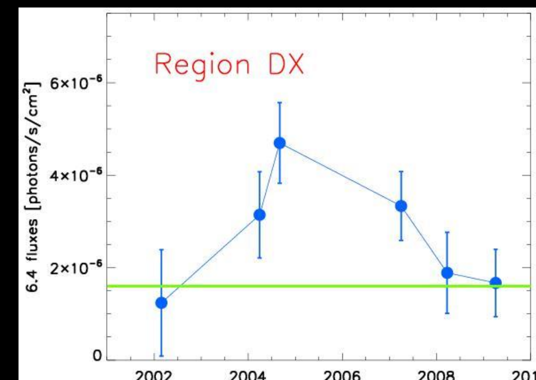
⇨ A single flare from Sgr A* (~ 1.5 × 10^{39} erg s^{-1}) fading about 100 years ago.

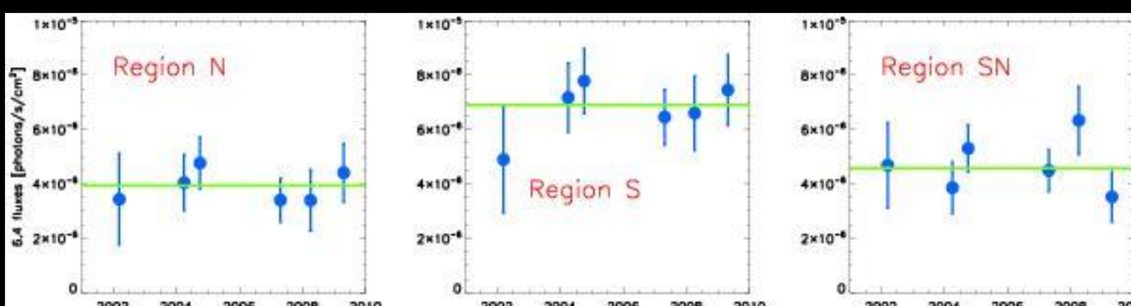
Molecular clouds close to Sgr A*: ~ 15 pc

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

Example of the Arches cluster (Capelli et al. 2011a, 2011b) as a likely location of particle acceleration.







EW (6.4 keV) ~ 1keV

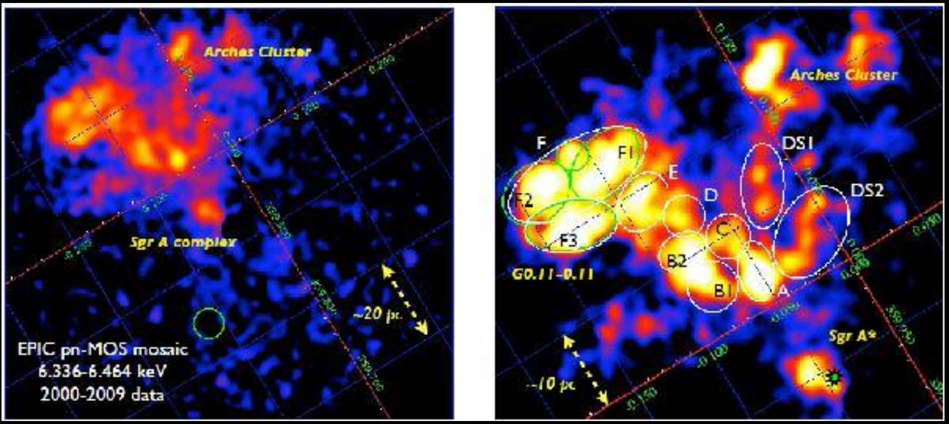
Fastest variability yet reported for the GC region: t ~ 2-3 years ⇨ most likely the result of its X-ray illumination by a nearby transient X-ray source.

+ 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.

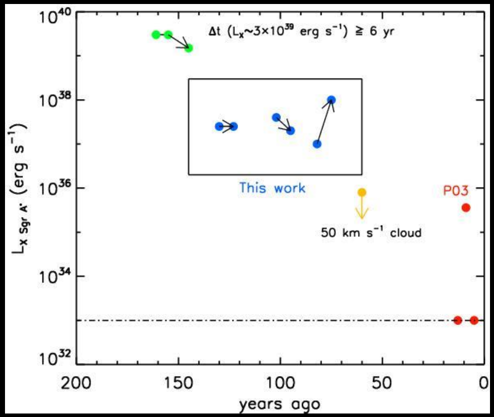
Dogiel et al. (2013): This FeK emission "can result from the bombardment of molecular gas by energetic ions, but probably not by accelerated electrons."

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

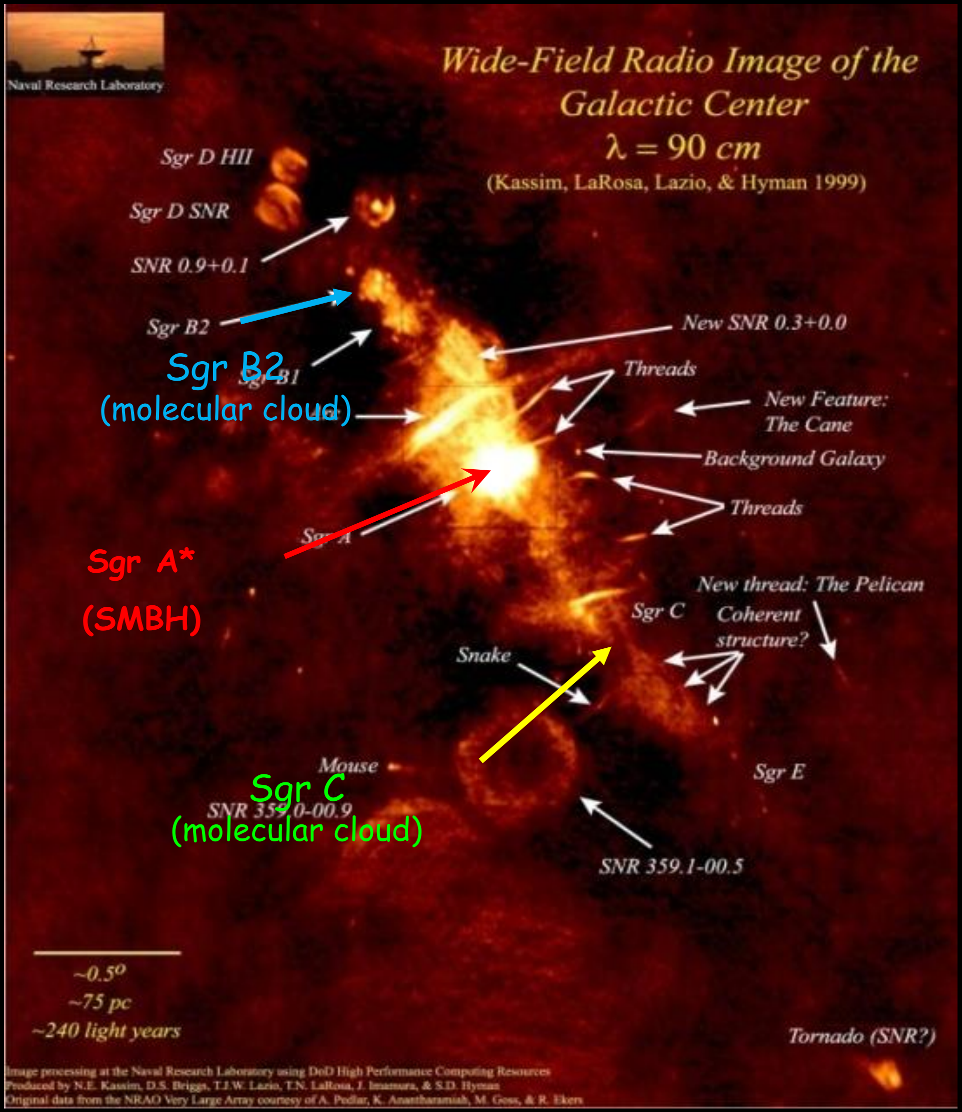
XMM-Newton



Capelli et al. (2012)



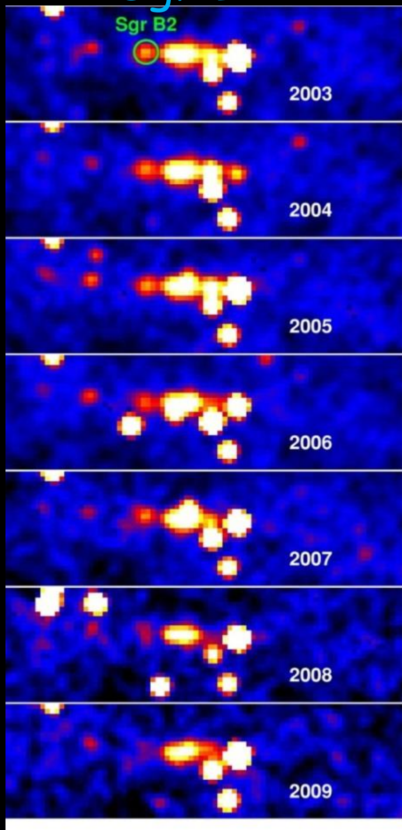
⇨ A long-term downwards trend punctuated by occasional counter-trend brightening episodes of at least 5 years duration.



Naval Research Laboratory
Wide-Field Radio Image of the Galactic Center
λ = 90 cm
(Kassim, LaRosa, Lazio, & Hyman 1999)
Sgr D HII
Sgr D SNR
SNR 0.9+0.1
Sgr B2
Sgr B2
(molecular cloud)
New SNR 0.3+0.0
Threads
New Feature: The Cane
Background Galaxy
Threads
Sgr A*
(SMBH)
New thread: The Pelican
Sgr C
Coherent structure?
Snake
Mouse
Sgr C
(molecular cloud)
Sgr E
SNR 359.1-00.5
~0.5°
~75 pc
~240 light years
Tornado (SNR?)
Image processing at the Naval Research Laboratory using DoD High Performance Computing Resources
Produced by N.E. Kassim, D.S. Briggs, T.J.W. Lazio, T.N. LaRosa, J. Imamura, & S.D. Hyman
Original data from the NRAO Very Large Array courtesy of A. Pedlar, K. Anantharamiah, M. Goss, & R. Ekers

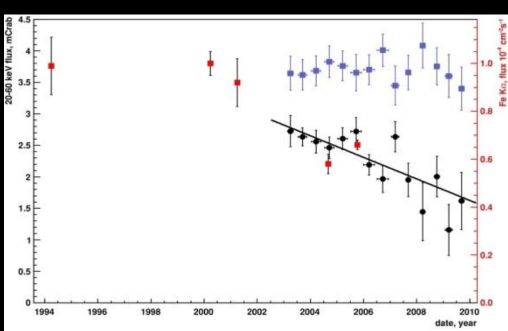
Molecular clouds farther from Sgr A* (~100s years ago)

Sgr B2



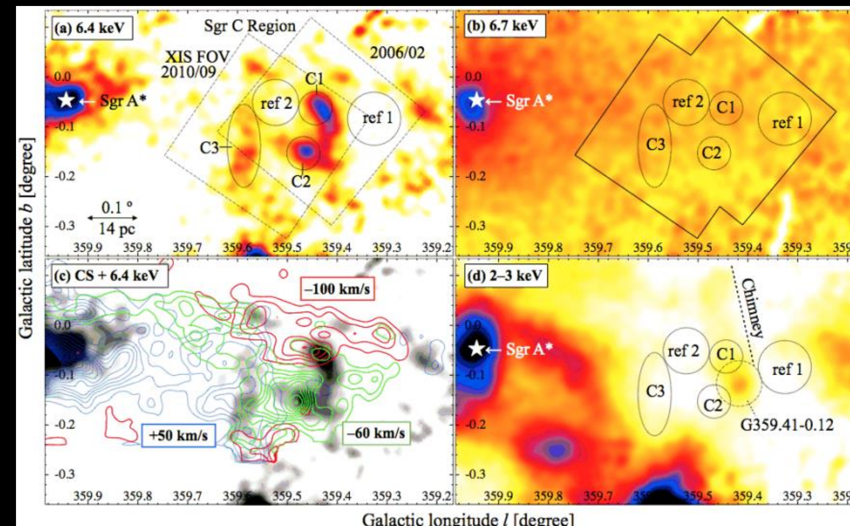
decay time : 8.2 ± 1.7 yr

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



Terrier et al. (2010)

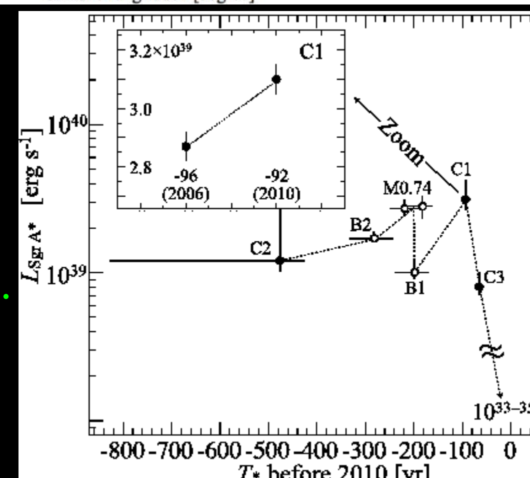
Sgr C



Sgr A* continuously active with sporadic flux variabilities of L_X (1-3) × 10^{39} erg s^{-1} in the past 50 to 500 years.

+ 2 short-term flares of 5-10 years.

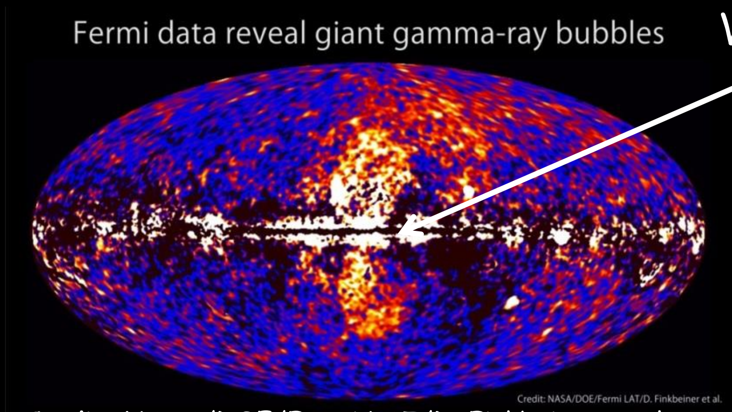
⇨ multiple flares superposed on a long-term high state.



Ryu et al. (2013)

The Fermi Bubbles

1-10 GeV



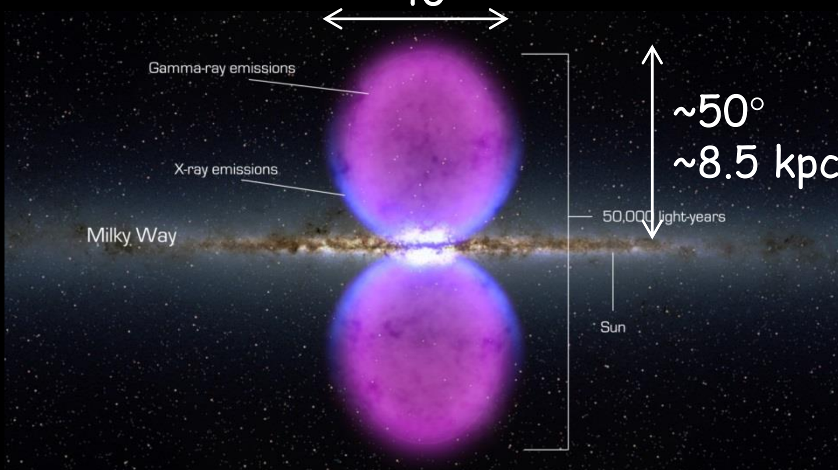
Credit: NASA/DOE/Fermi LAT/D. Finkbeiner et al.

Well centered on longitude zero (close to latitude zero)

<u>Origin</u> :

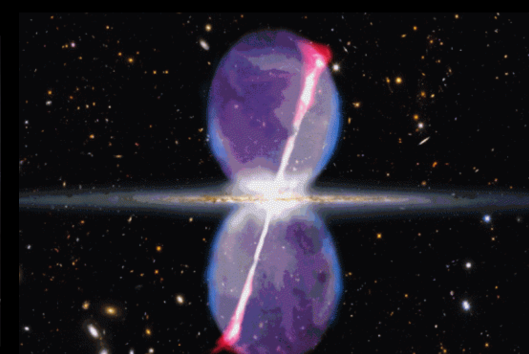
- Past AGN jet activity (~1-3 Myr lasted for ~0.1-0.5 Myr with and accreted matter mass ~100 –10000 $M_{\odot}$) ?
- Wind bubble: nuclear starburst in the GC in the last 10 Myr ?
- Dark matter annihilations ?

~40°



Credit: NASA's Goddard Space Flight Center

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



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

Finkbeiner, Su et al.

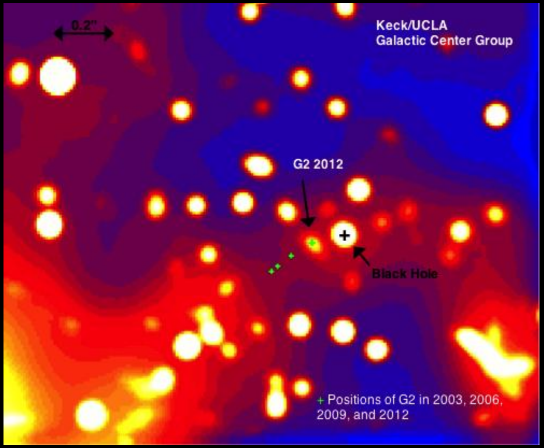
III. Back to the Future :

A renew of Sgr A* activity ?

The incoming G2 « cloud »

A gas cloud on its ways into SgrA*

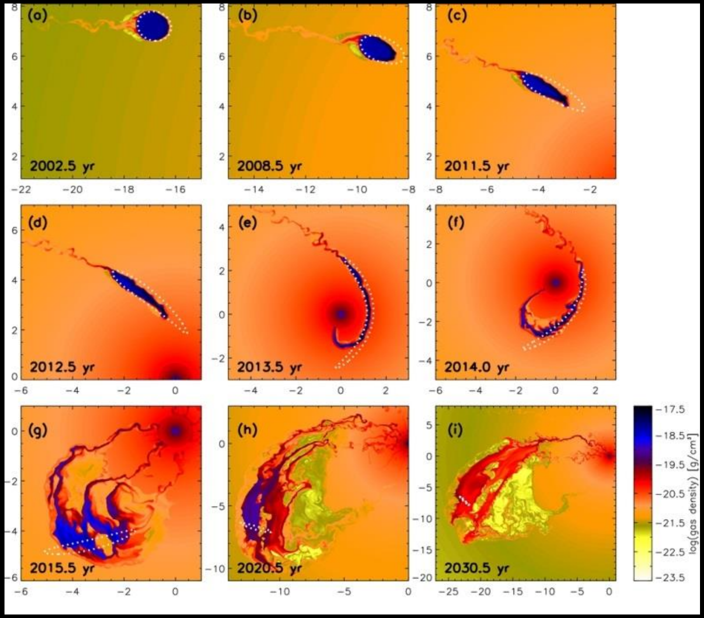
Gillessen et al. (2011)



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

M_{cloud} ~3 M_{Earth}, T_{dust}~ 550 K, T_{gas} ~ 10^4 K, L~5 L_{sun}

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



Schartmann et al. (2012)

Gillessen et el. (2013):

- Ionized gas in the head is now stretched over more than 15,000 Rs 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

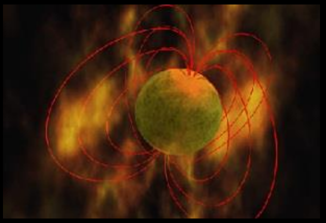
An unprecedented amount of satellites and ground-based telescopes are monitoring the Galactic center to follow the course and impact of the G2 "cloud' on Sgr A* activity

⇨

- On April 24^{th} : Increase in the X-ray flux from the vicinity of Sgr A* by an order of magnitude above its quiescent level (Degenaar et al. 2013)

The enhanced emission persisted much longer than typical Sgr A* flare events, which only last tens of minutes to hours !

The awaited outburst from Sgr A* ?



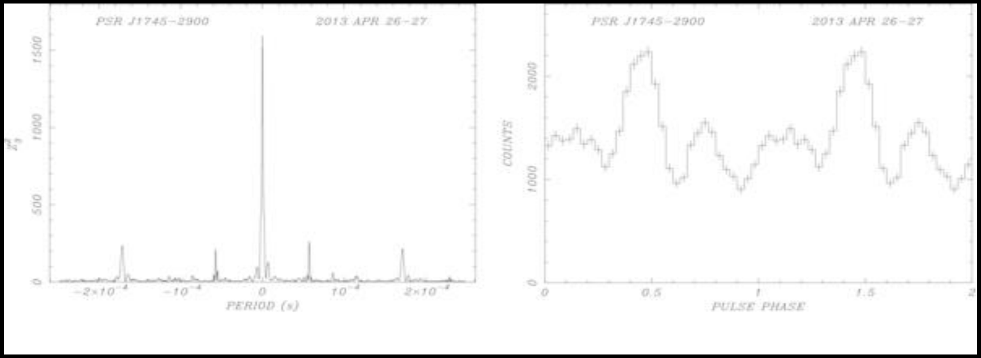
- On April 25, during a scheduled observation of Sgr A*, the *Swift/BAT* triggered on a short (~30 ms), hard X-ray burst at a position consistent with Sgr A* ⇨ characteristics of this burst were consistent with Soft Gamma Repeater (SGR) bursts (Kennea et al. 2013a)

- On April 29 (Chandra): located at only ~3" (i.e. ~ 0.1pc) from SgrA* (Rea et al. 2013)

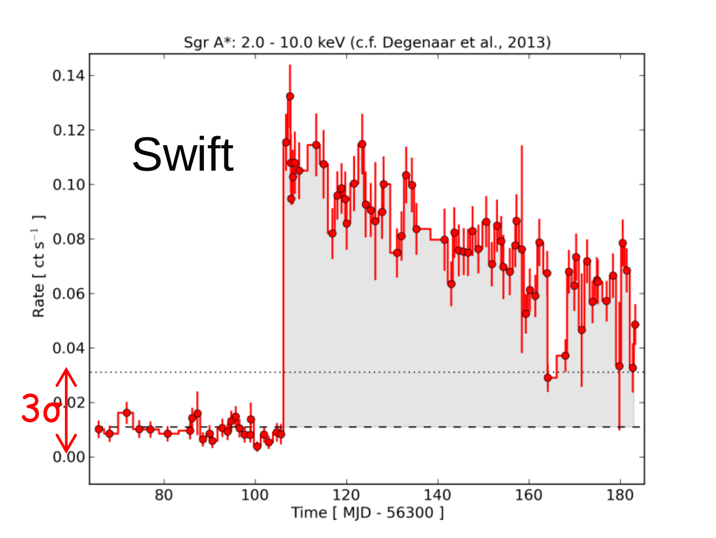
SGRs are members of a very small group of sources (26 known to date), which are suggested to be magnetars (slowly rotating neutron stars with extreme surface dipole magnetic fields of $>10^{14}$ G)

A *NuSTAR* follow-up observation on April 26 found a ~3.76 s periodicity well within the range of magnetar periods (2–12 s)
+ Spin down rate implies B= 1.6 x 10^{14} G.

(Mori et al. 2013)



This period has been confirmed in radio:
⇨ fourth magnetar detected in radio wavelengths (Eatough et al. 2013).

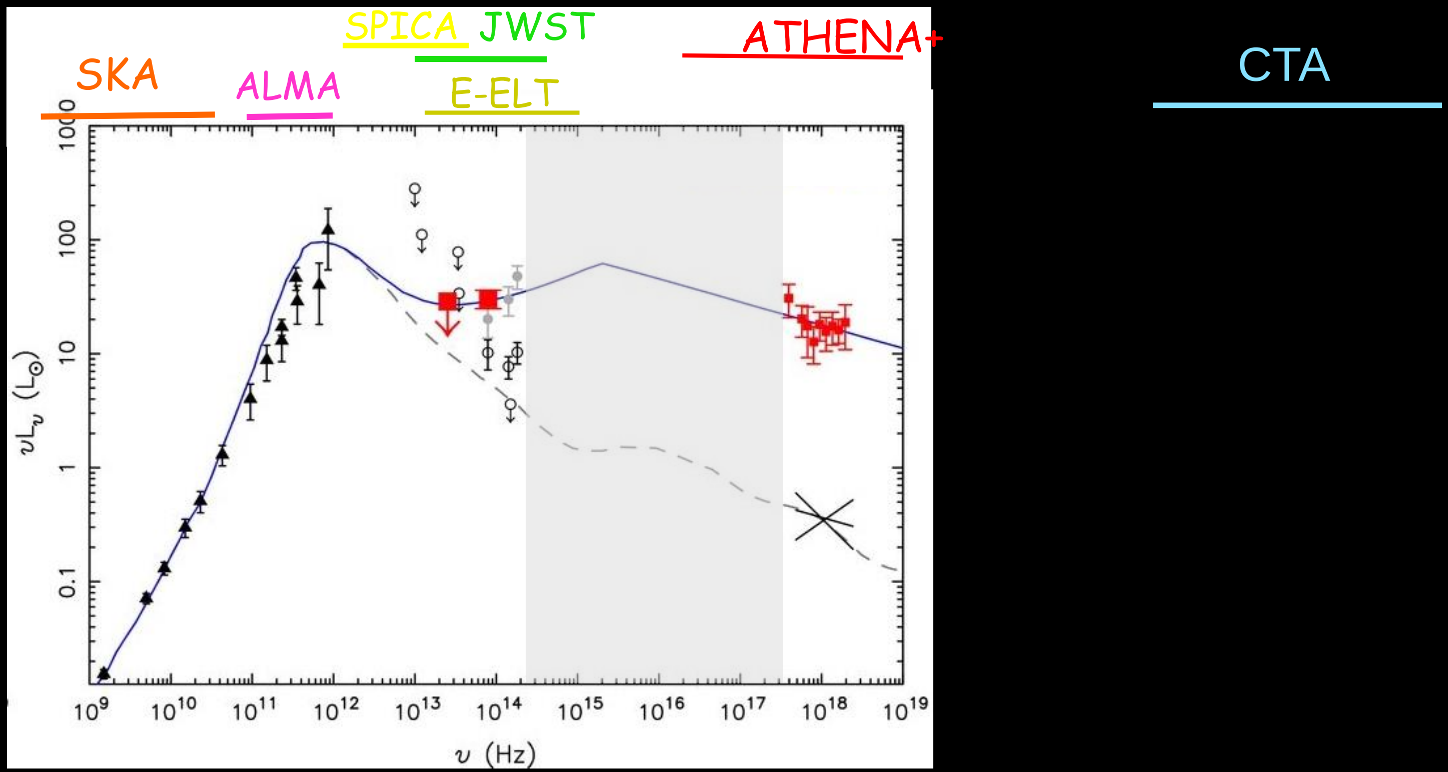


Degenaar et al. (2013)

Note: The dip at day 163/164 is an instrumental/analysis artifact (M. Reynolds - 130625).

IV. Observational perspectives …
Just to cite a few toys !

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



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

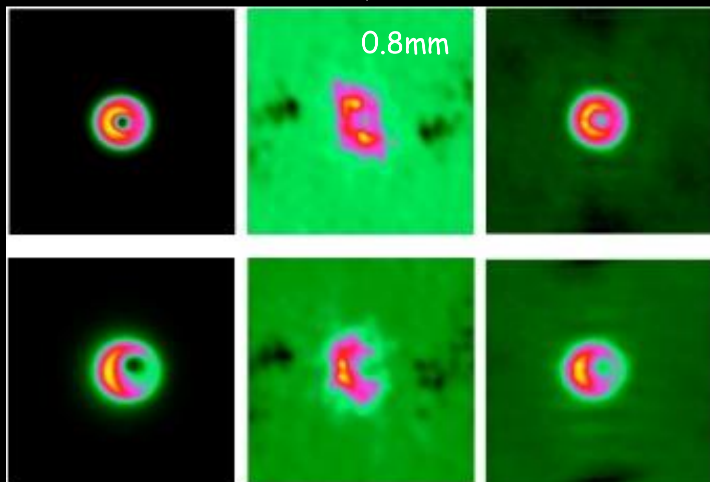
VLBI/EHT

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

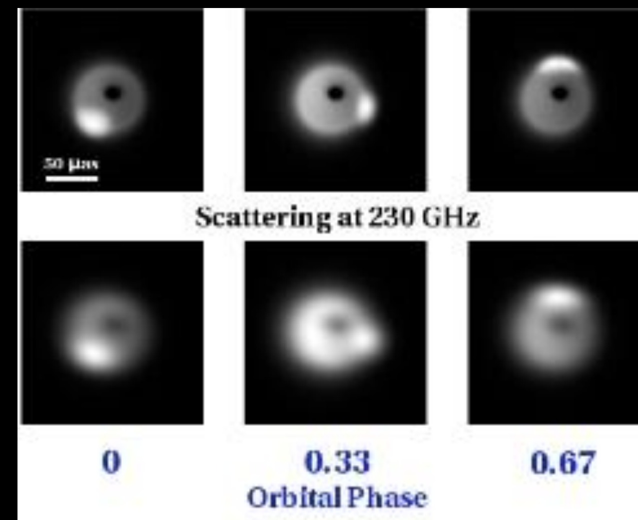
a=0 θ=60



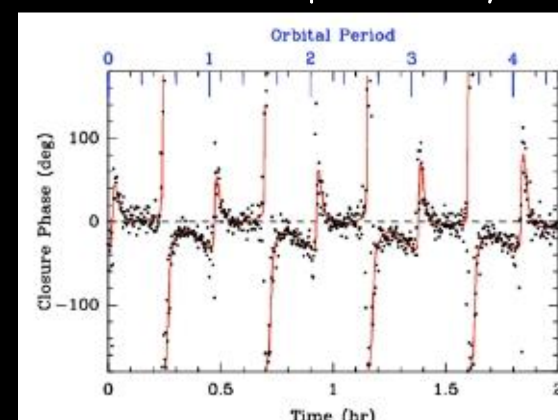
Courtesy: C. Gammie & A. Broderick

Signature of a hot spot orbiting around SgrA*

a=0 θ=60

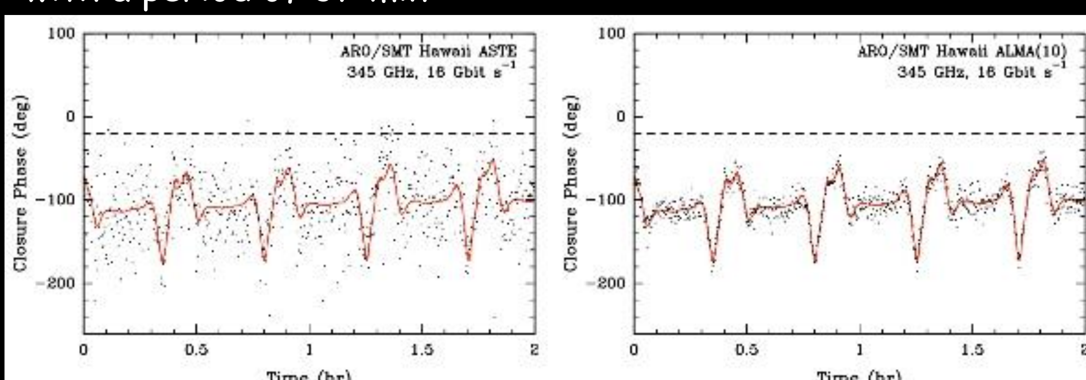


1.3mm VLBI closure phases every 10s



ARO/SMT-Hawai-CARMA

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

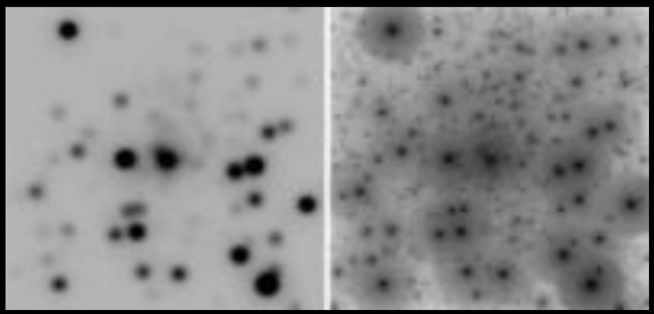


Periodicity ⇨ spin

Doeleman at al. (2009)

E-ELT (40-m class telescope)

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



(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:

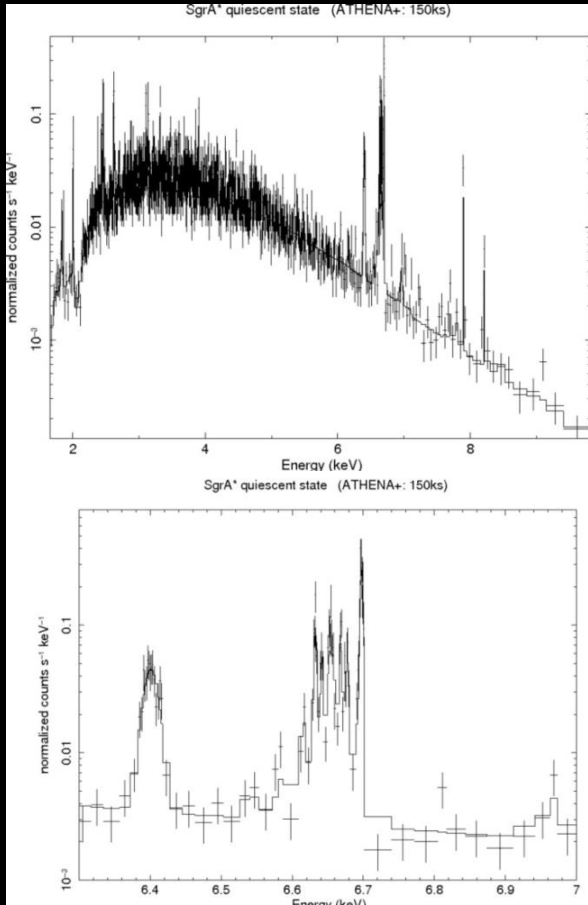
- Extremely accurate measurements of the positions of the stars (50-100 mas)
- Radial velocity measurements with ~1 km/s precision

⇨ Test the predicted relativistic signals of BH spin and the gravitational redshift caused by the BH, and even detection of GW effects.

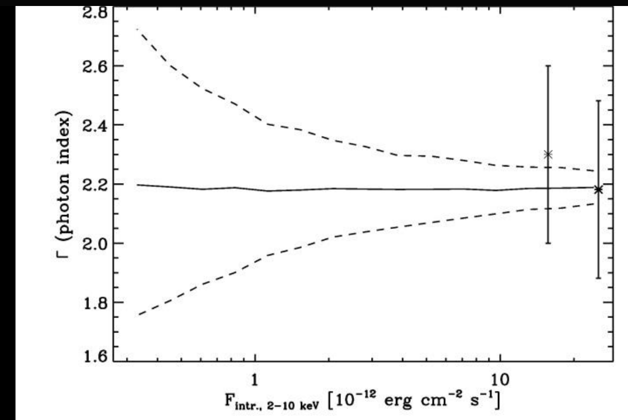
⇨ DM distribution around the BH (predicted by cold DM cosmologies).

⇨ The distance to the GC and mass of SgrA* will be measured to < 0.1%
(⇨ Size and shape of the Galactic halo, and the Galaxy's local rotation speed)

ATHENA +



(D. Porquet; N. Grosso)



(D. Porquet; N. Grosso)

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

⇨ X-ray plasma diagnostic to disentangle the ionization process during the quiescent state : CIE, NIE, …

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

TO BE
CONTINUED....