X-Ray Surveys reveal the past activity of the Galactic Center Super-Massive Black Hole and of the nuclear region

Andrea Goldwurm
APC Paris, DAp/IRFU/CEA Saclay

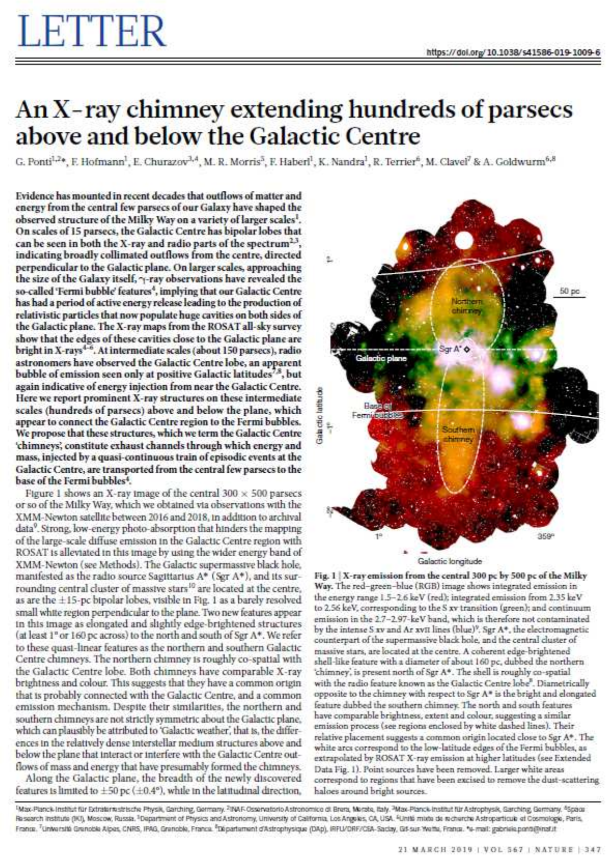
25e Congrès Général de la Société Française de Physique

Session parallèle: Les diverses facettes du centre galactique : des abords du trou noir à son environnement plus lointain

Outline

TOPICS:

- Introduction: Galactic Center SuperMassive Black Hole Sgr A*
- Search for past activity of Sgr A*
- Reflection from CMZ Clouds
- Hot gaz in the GC
- Gamma-ray Fermi Bubbles
- Summary



LETTER

https://doi.org/10.1038/s41586-019-1009-6

An X-ray chimney extending hundreds of parsecs above and below the Galactic Centre

G. Ponti[1,2]*, F. Hofmann[1], E. Churazov[3,4], M. R. Morris[5], F. Haberl[1], K. Nandra[1], R. Terrier[6], M. Clavel[7] & A. Goldwurm[6,8]

Evidence has mounted in recent decades that outflows of matter and energy from the central few parsecs of our Galaxy have shaped the observed structure of the Milky Way on a variety of larger scales[1]. On scales of 15 parsecs, the Galactic Centre has bipolar lobes that can be seen in both the X-ray and radio parts of the spectrum[2,3], indicating broadly collimated outflows from the centre, directed perpendicular to the Galactic plane. On larger scales, approaching the size of the Galaxy itself, γ-ray observations have revealed the so-called 'Fermi bubble' features[4], implying that our Galactic Centre has had a period of active energy release leading to the production of relativistic particles that now populate huge cavities on both sides of the Galactic plane. The X-ray maps from the ROSAT all-sky survey show that the edges of these cavities close to the Galactic plane are bright in X-rays[4–6]. At intermediate scales (about 150 parsecs), radio astronomers have observed the Galactic Centre lobe, an apparent bubble of emission seen only at positive Galactic latitudes[7,8], but again indicative of energy injection from near the Galactic Centre. Here we report prominent X-ray structures on these intermediate scales (hundreds of parsecs) above and below the plane, which appear to connect the Galactic Centre region to the Fermi bubbles. We propose that these structures, which we term the Galactic Centre 'chimneys', constitute exhaust channels through which energy and mass, injected by a quasi-continuous train of episodic events at the Galactic Centre, are transported from the central few parsecs to the base of the Fermi bubbles[4].

Figure 1 shows an X-ray image of the central 300 × 500 parsecs or so of the Milky Way, which we obtained via observations with the XMM-Newton satellite between 2016 and 2018, in addition to archival data[9]. Strong, low-energy photo-absorption that hinders the mapping of the large-scale diffuse emission in the Galactic Centre region with ROSAT is alleviated in this image by using the wider energy band of XMM-Newton (see Methods). The Galactic supermassive black hole, manifested as the radio source Sagittarius A* (Sgr A*), and its surrounding central cluster of massive stars[10] are located at the centre, as are the ±15-pc bipolar lobes, visible in Fig. 1 as a barely resolved small white region perpendicular to the plane. Two new features appear in this image as elongated and slightly edge-brightened structures (at least 1° or 160 pc across) to the north and south of Sgr A*. We refer to these quasi-linear features as the northern and southern Galactic Centre chimneys. The northern chimney is roughly co-spatial with the Galactic Centre lobe. Both chimneys have comparable X-ray brightness and colour. This suggests that they have a common origin that is probably connected with the Galactic Centre, and a common emission mechanism. Despite their similarities, the northern and southern chimneys are not strictly symmetric about the Galactic plane, which can plausibly be attributed to 'Galactic weather', that is, the differences in the relatively dense interstellar medium structures above and below the plane that interact or interfere with the Galactic Centre outflows of mass and energy that have presumably formed the chimneys.

Along the Galactic plane, the breadth of the newly discovered features is limited to ±50 pc (±0.4°), while in the latitudinal direction,

Fig. 1 | X-ray emission from the central 300 pc by 500 pc of the Milky Way. The red–green–blue (RGB) image shows integrated emission in the energy range 1.5–2.6 keV (red); integrated emission from 2.35 keV to 2.56 keV, corresponding to the S xv transition (green); and continuum emission in the 2.7–2.97-keV band, which is therefore not contaminated by the intense S xv and Ar xvii lines (blue)[9]. Sgr A*, the electromagnetic counterpart of the supermassive black hole, and the central cluster of massive stars, are located at the centre. A coherent edge-brightened shell-like feature with a diameter of about 160 pc, dubbed the northern 'chimney', is present north of Sgr A*. The shell is roughly co-spatial with the radio feature known as the Galactic Centre lobe[8]. Diametrically opposite to the chimney with respect to Sgr A* is the bright and elongated feature dubbed the southern chimney. The north and south features have comparable brightness, extent and colour, suggesting a similar emission process (see regions enclosed by white dashed lines). Their relative placement suggests a common origin located close to Sgr A*. The white arcs correspond to the low-latitude edges of the Fermi bubbles, as extrapolated by ROSAT X-ray emission at higher latitudes (see Extended Data Fig. 1). Point sources have been removed. Larger white areas correspond to regions that have been excised to remove the dust-scattering haloes around bright sources.

[1]Max-Planck-Institut für Extraterrestrische Physik, Garching, Germany. [2]INAF-Osservatorio Astronomico di Brera, Merate, Italy. [3]Max-Planck-Institut für Astrophysik, Garching, Germany. [4]Space Research Institute (IKI), Moscow, Russia. [5]Department of Physics and Astronomy, University of California, Los Angeles, CA, USA. [6]Unité mixte de recherche Astroparticule et Cosmologie, Paris, France. [7]Université Grenoble Alpes, CNRS, IPAG, Grenoble, France. [8]Département d'Astrophysique (DAp), IRFU/DRF/CEA-Saclay, Gif-sur-Yvette, France. *e-mail: gabriele.ponti@inaf.it

21 MARCH 2019 | VOL 567 | NATURE | 347

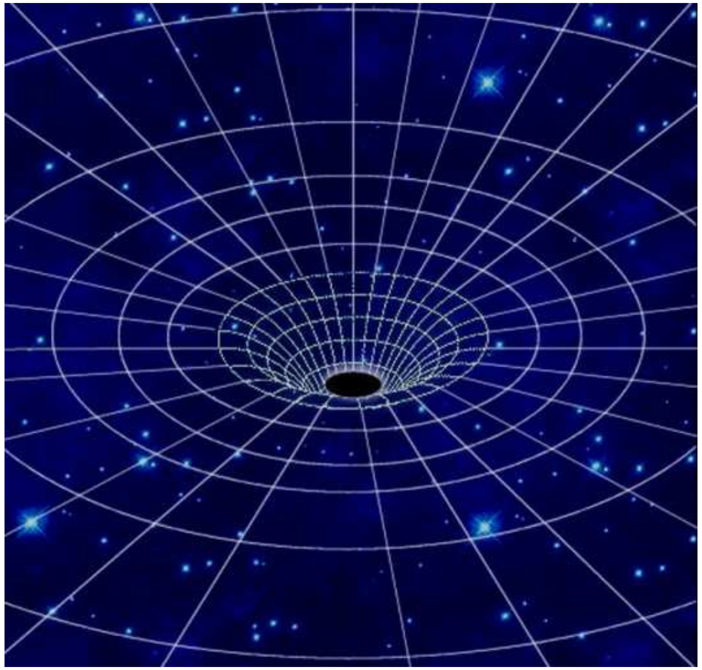
Collaborators:

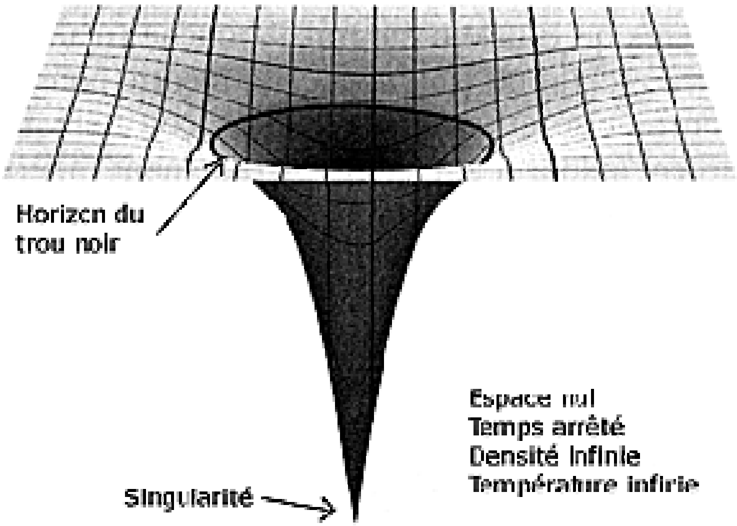
R. Terrier, D. Chuard (APC Paris, CEA Saclay)
M. Clavel (IPAG Grenoble)
G. Ponti (MPE Garching D, INAF Merate I)
M. Morris (UCLA, US)
M. Chernyakova, M. Walls (DCU, Dublin, Ir)
and others

Data (2000 – 2017):
INTEGRAL, **XMM-Newton (> 1.5 Ms GC surveys / obs.)**, Chandra

Recent publications: Terrier+ 2018, Chuard+ 2018, Ponti+ 2019 Nature

Black Holes



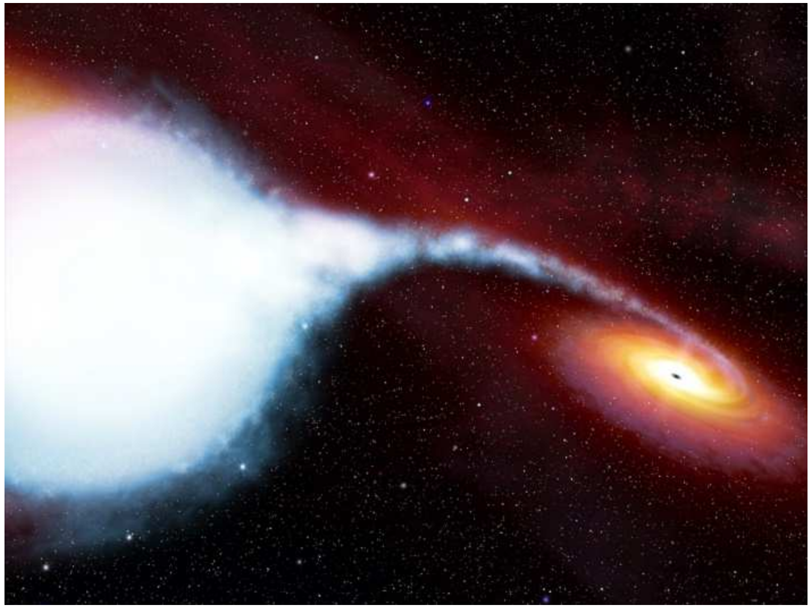


- BH are space time regions delimited by a event horizon
- When a given mass M is within a radius < its Schwarzschild radius ($M_\odot$ = Solar mass)

$$R \leq R_S = \frac{2\,G\,M}{c^2} \cong 3\,\frac{M}{M_\odot} \quad (km)$$

- Not even light can escape: BH are invisible
- Extreme distortion of space-time: probe for General Relativity in strong field
- Important Astrophysical objects but also for new physics at the frontier of Classical-Quantum theories (Quantum Gravity, String, ..)
- Two types of BH observed :
  - Stellar size (3 – 100 $M_\odot$)
  - SMBH in GN (10^6-10^{10} $M_\odot$)
- Historically studied through X-rays and now Multi-wave-messenger Astronomy (GW)

Accretion / Ejection in Black Holes

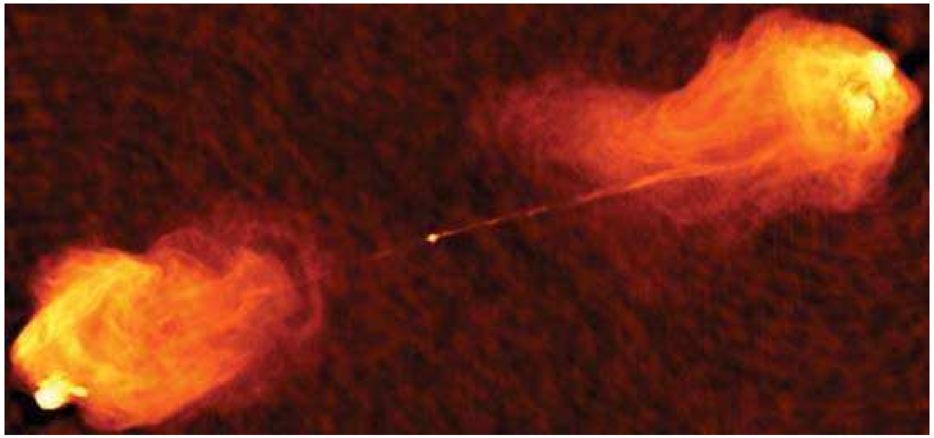


Huge radiative luminosities and powerful particles ejections

Maximal (Eddington) Luminosity

$L_E = 1.26\ 10^{38} \left(\frac{M}{M_\odot}\right)$ erg/s

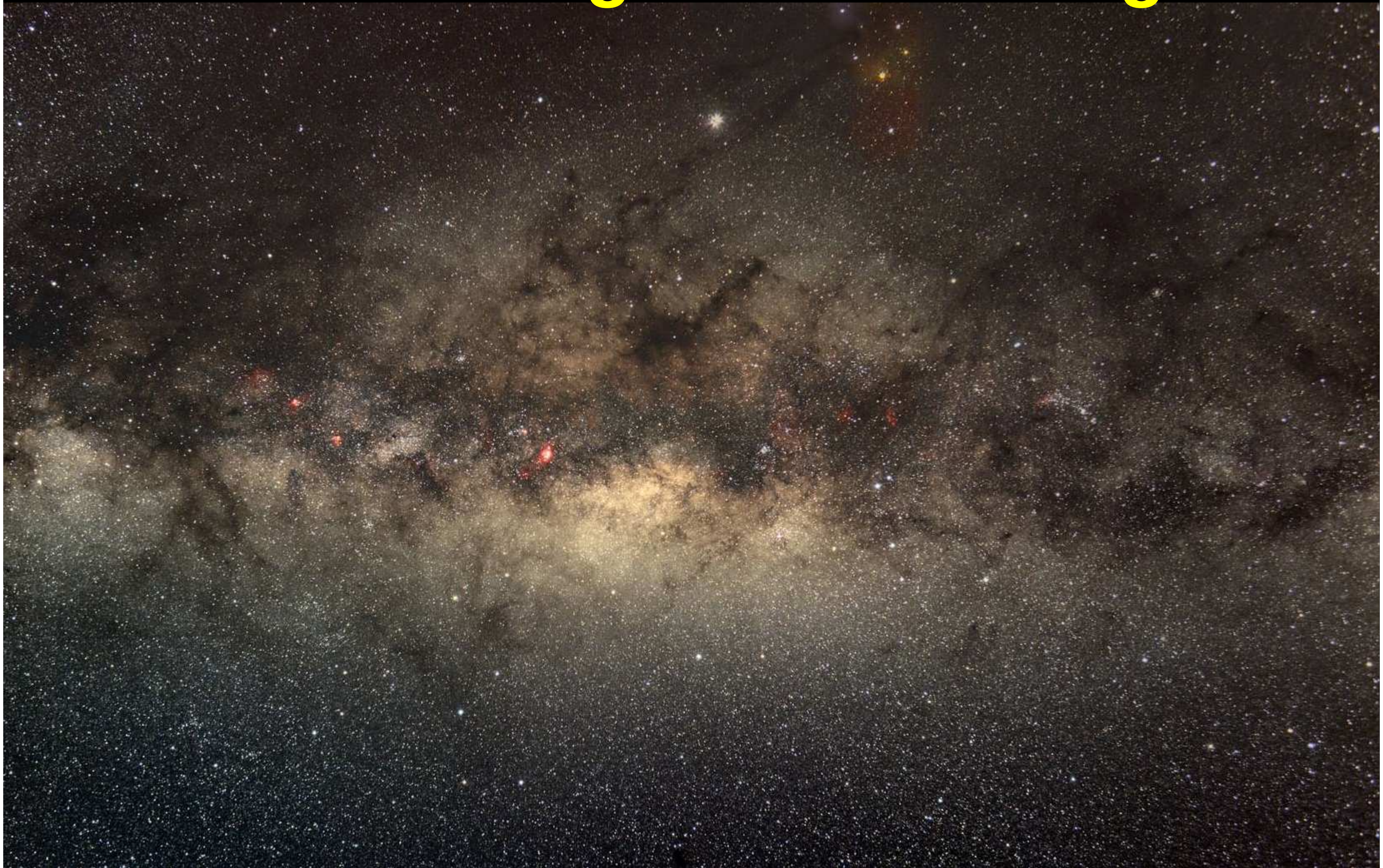
Mainly in (UV) X and gamma rays



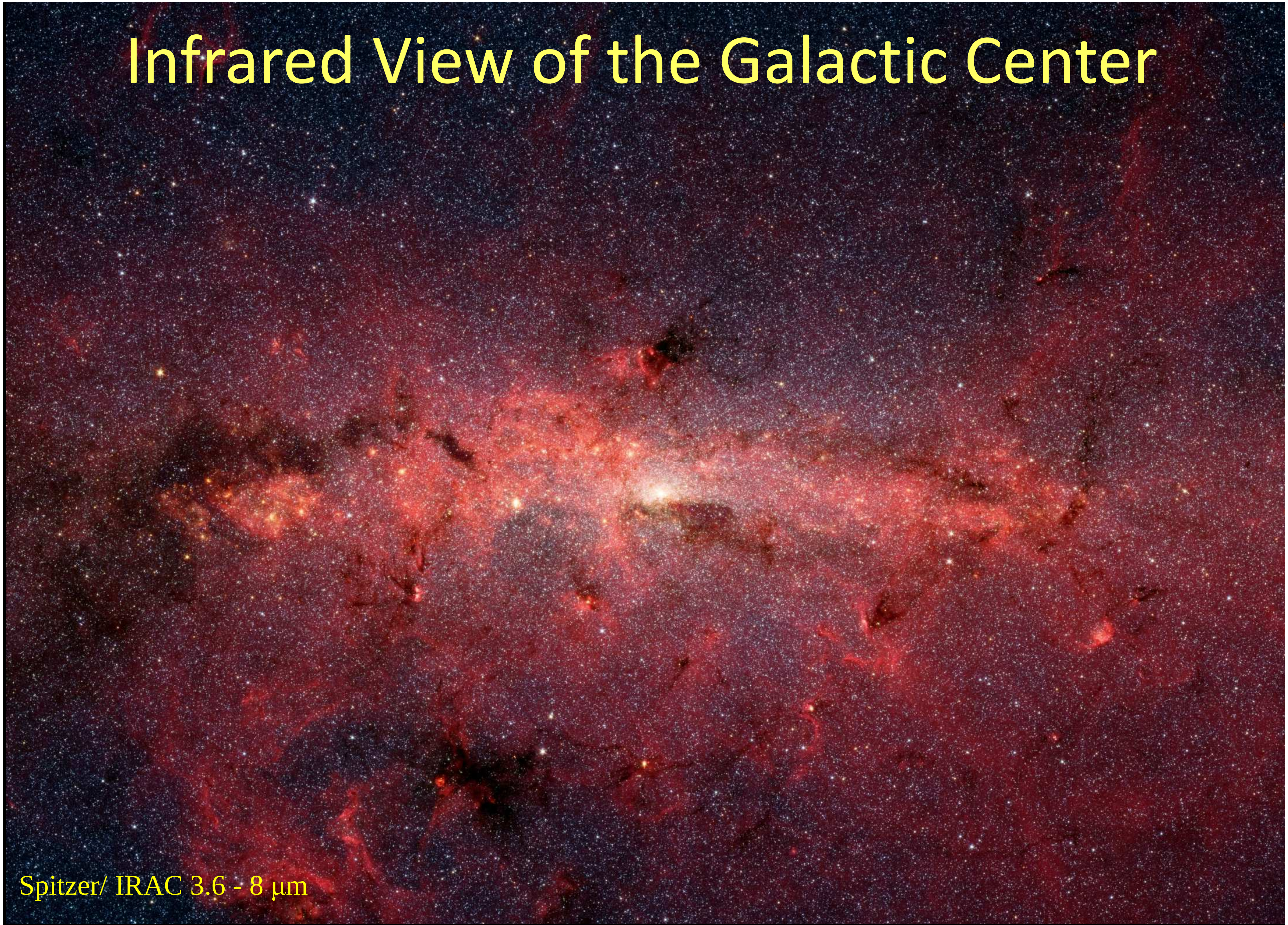
The Galaxy

ESO

Galactic Bulge in Visible Light

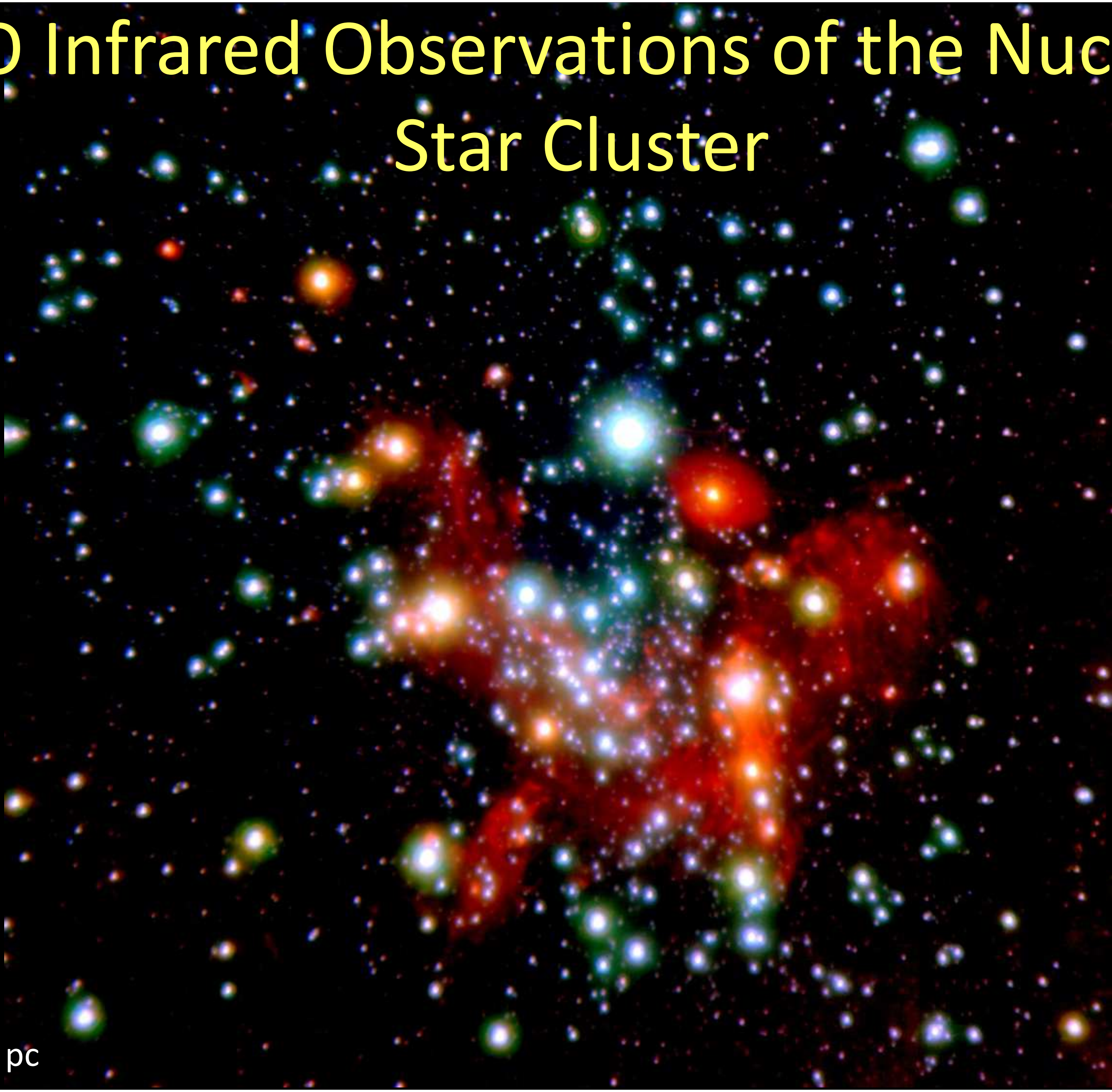


Infrared View of the Galactic Center



Scale: 1.9° × 1.4 ° ≈ 274 pc × 202 pc (8 kpc)

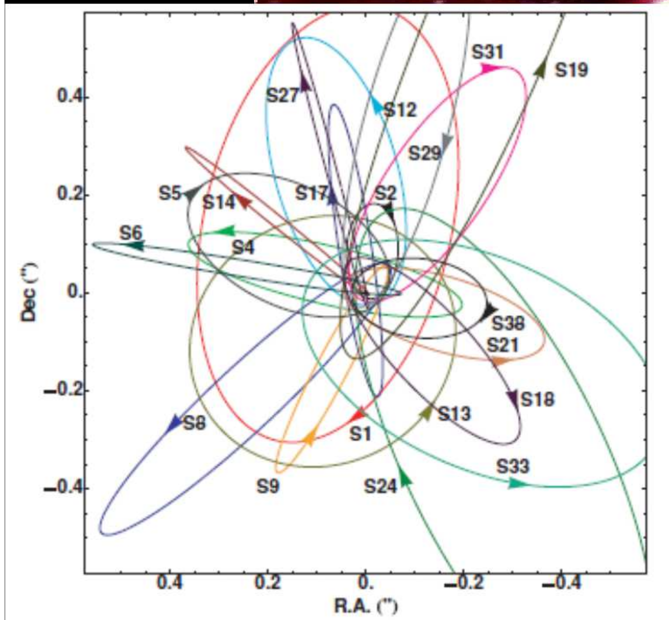
AO Infrared Observations of the Nuclear Star Cluster

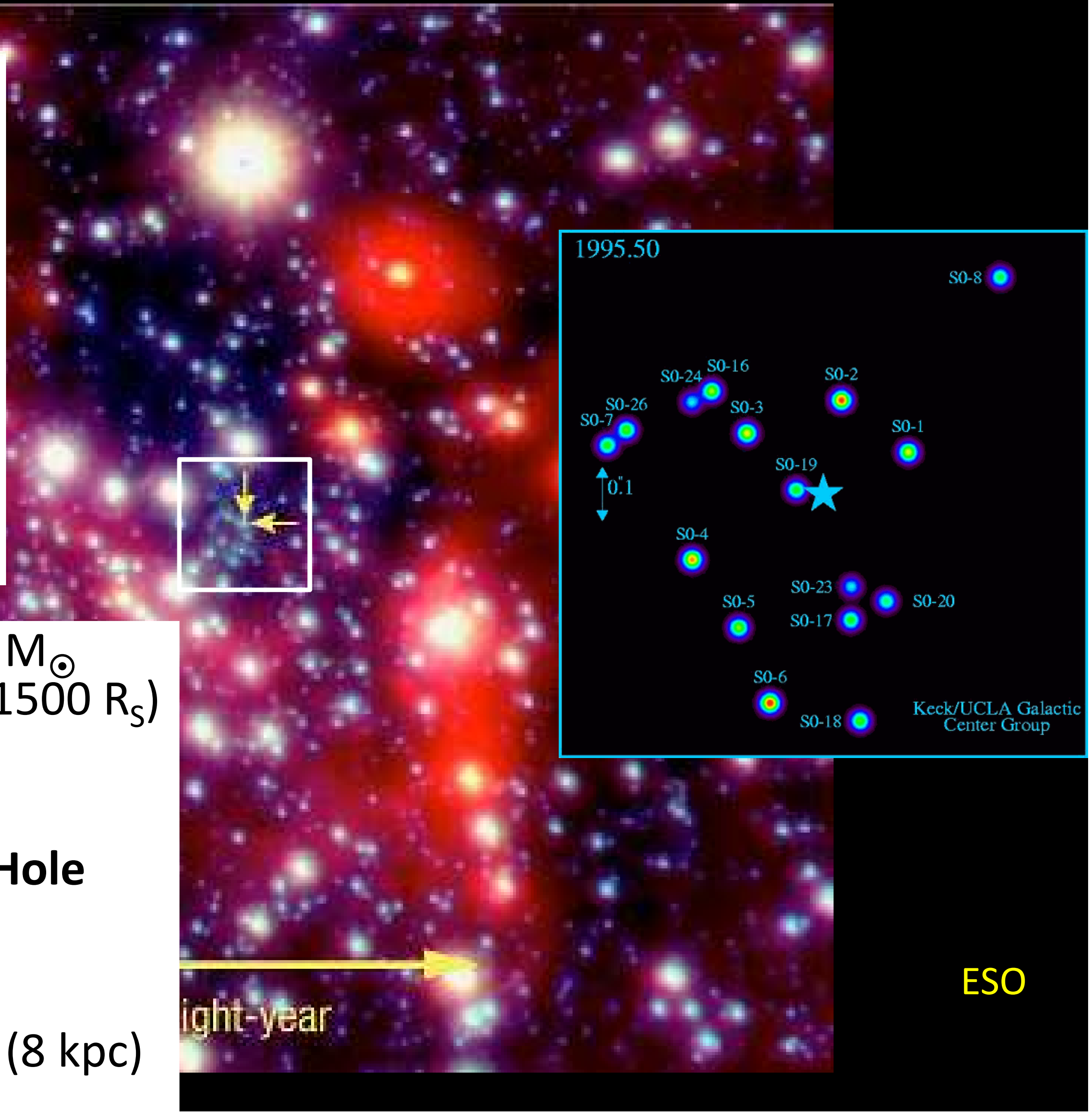


12″ = 0.5 pc

ESO

S-Cluster Star Orbits around a SMBH





Enclosed Mass M_{enc}= 4 10^6 $M_\odot$
within a radius of 124 AU (1500 R_S)

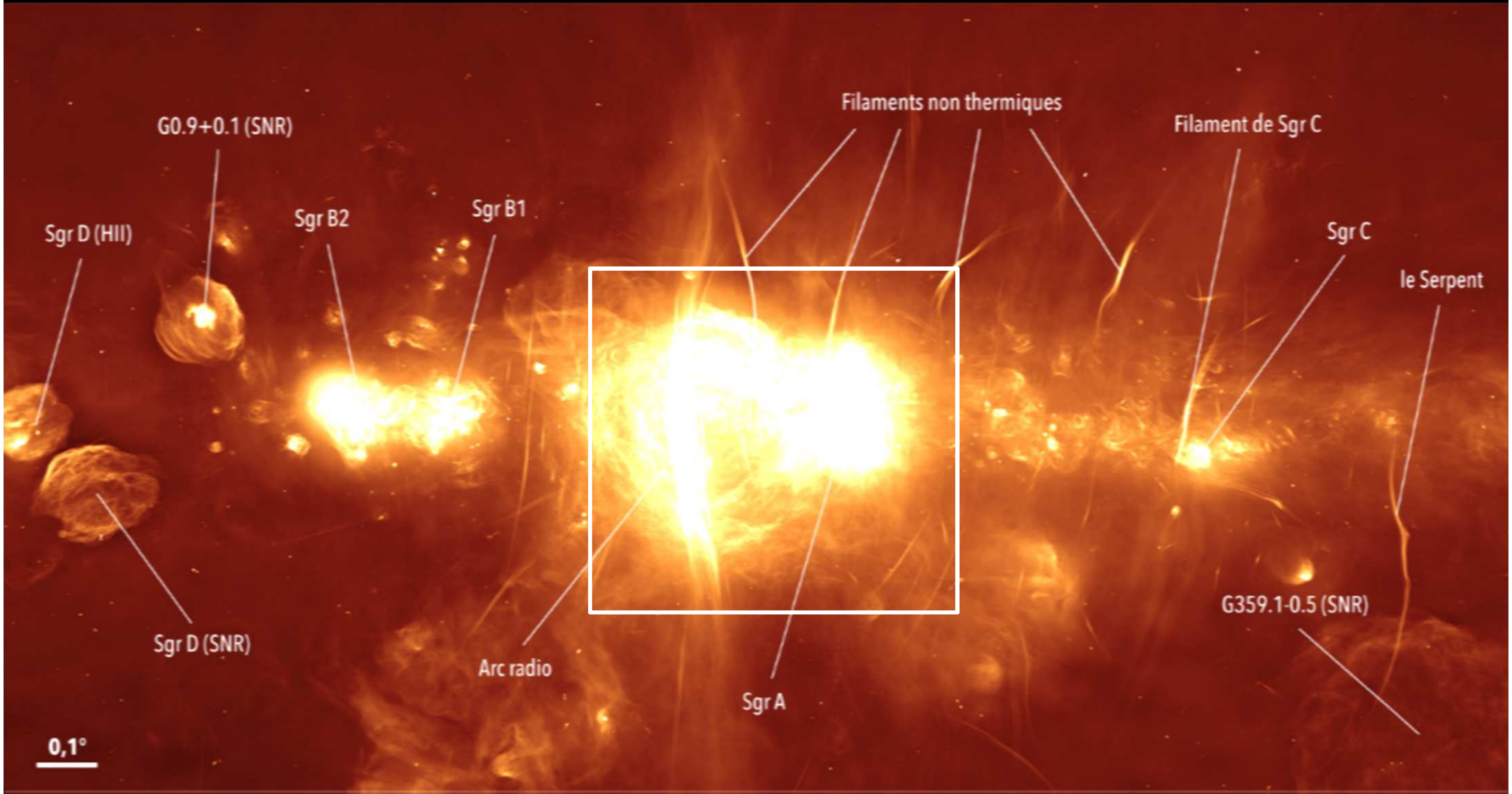
=> A Super Massive Black Hole

$M_\bullet$ = 4 10^6 $M_\odot$

R_S = 1.2 10^{12} cm

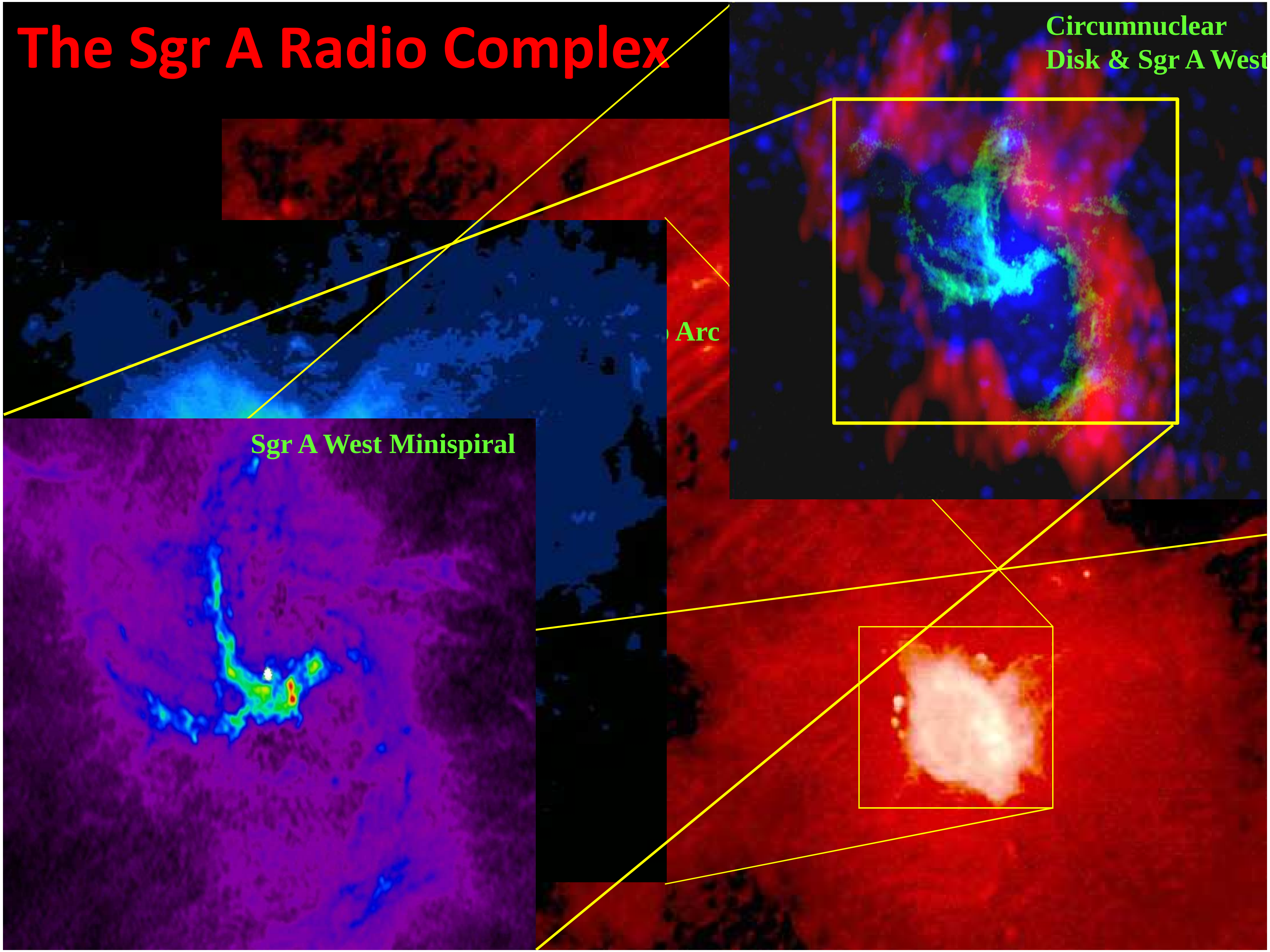
= 0,08 AU = 10 µas (8 kpc)

Central Molecular Zone in Radio

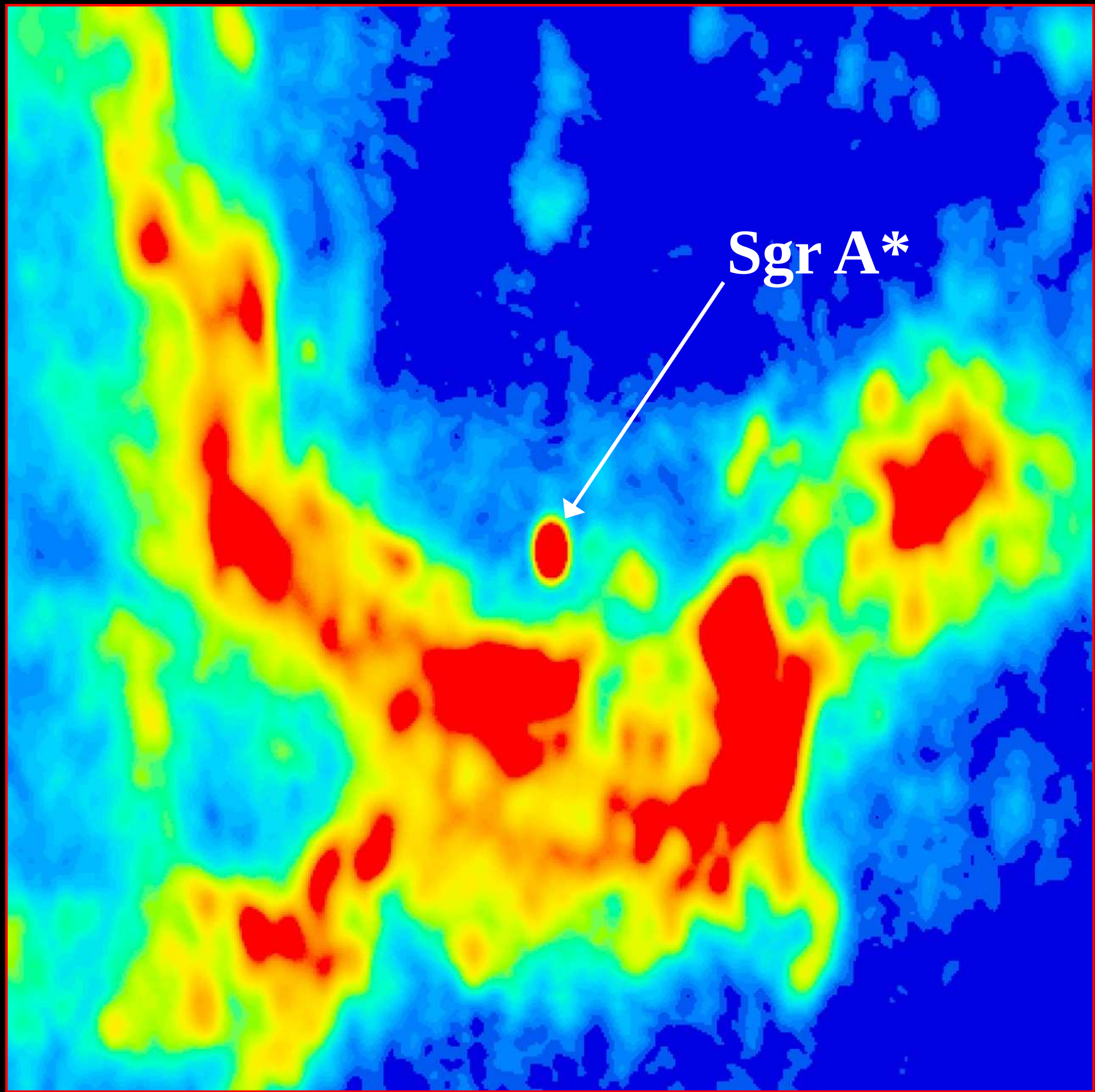


MEERKAT

The Sgr A Radio Complex

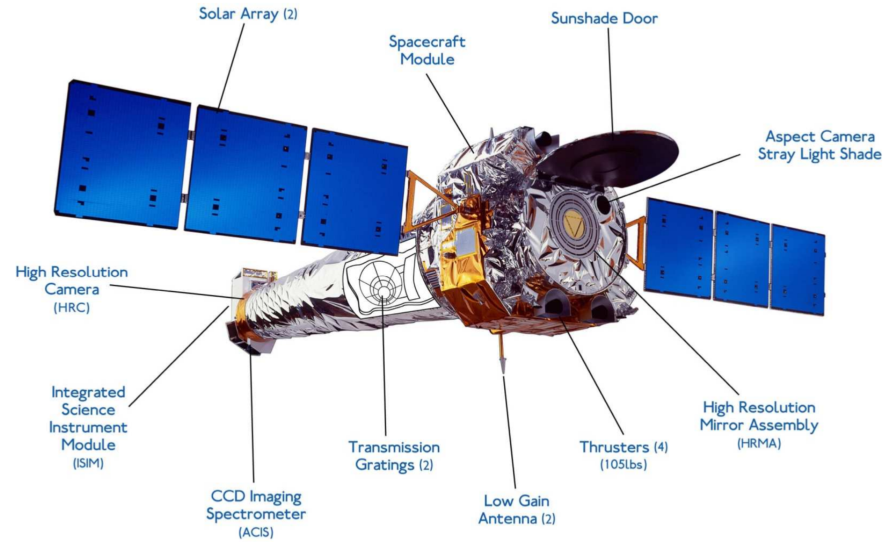


Sagittarius A*: electromagnetic counterpart of the SMBH of the Galaxy



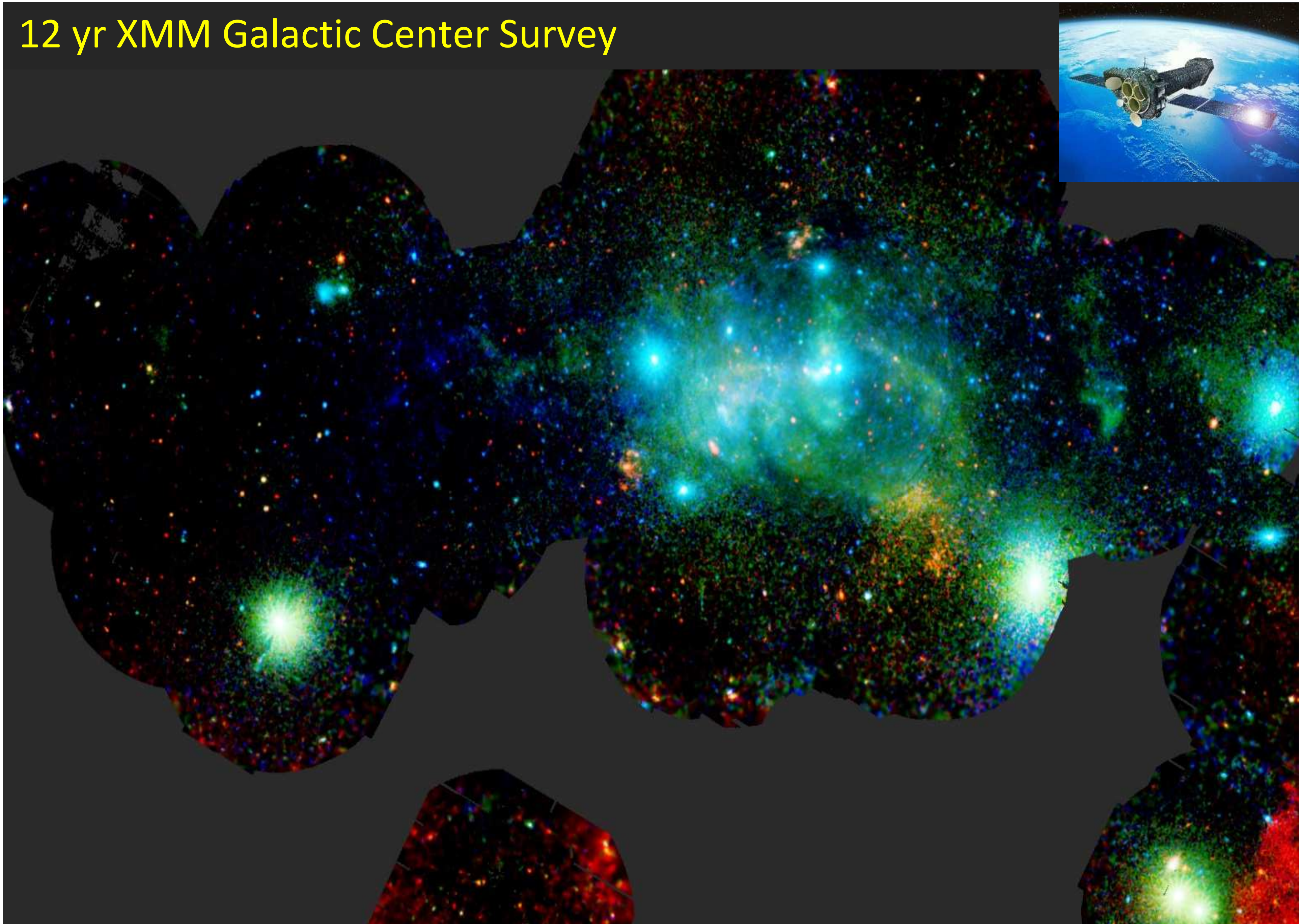
X-Ray Obs.: 1 keV - 1000 keV

Chandra (NASA) : 0.1 – 10 keV



- X-ray Observatories used in the surveys of the Central Molecular Zone from 2000 – 2017
- Energy bands: 0. keV – 3 MeV Angular Res :1” – 12’
- Other: Suzaku (1-10 keV) and Nu-STAR (3-80 keV)

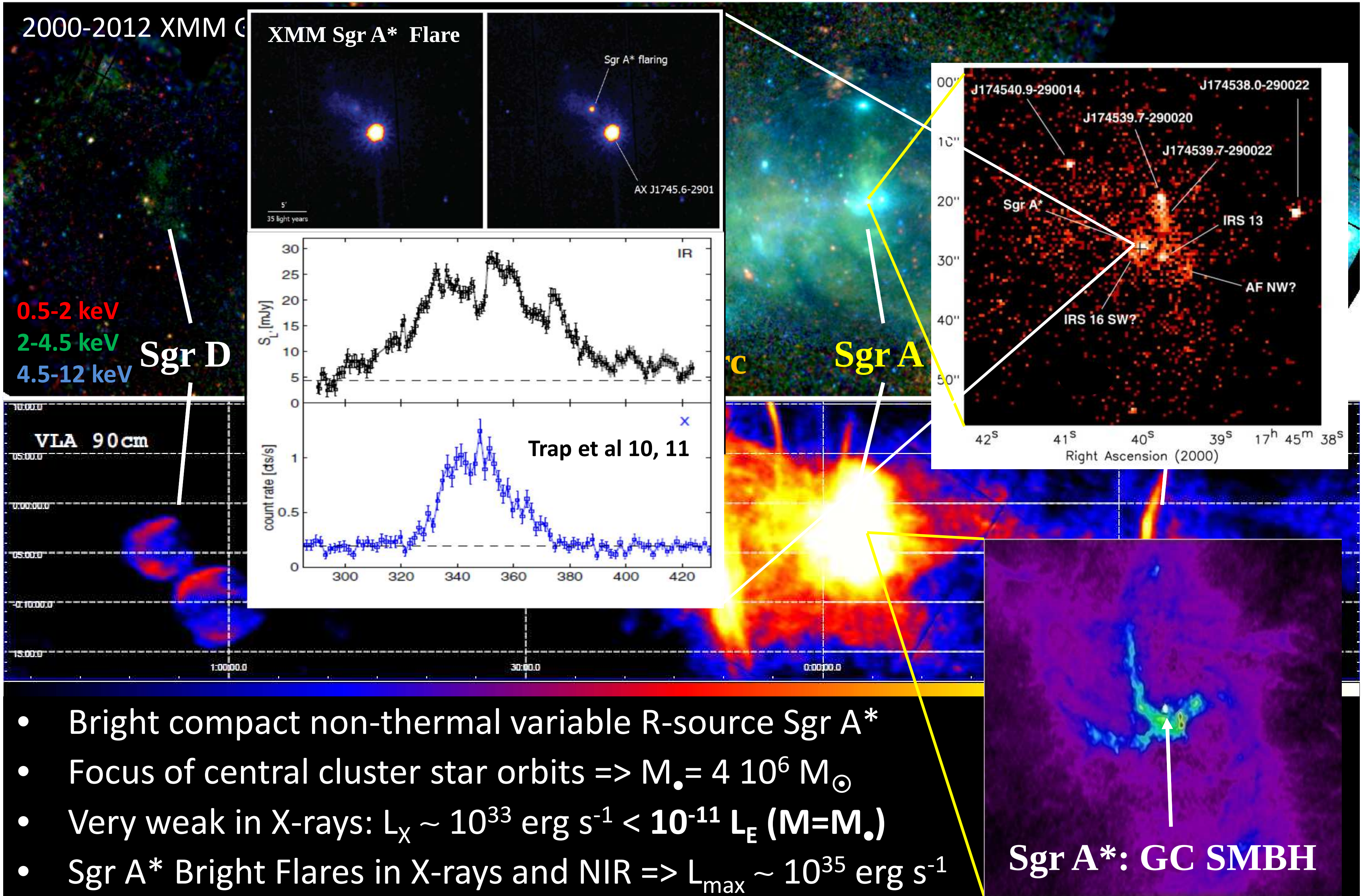
12 yr XMM Galactic Center Survey



0.5 – 12 keV Image

Ponti et al. 2015

Sgr A*: GC SuperMassive Black Hole



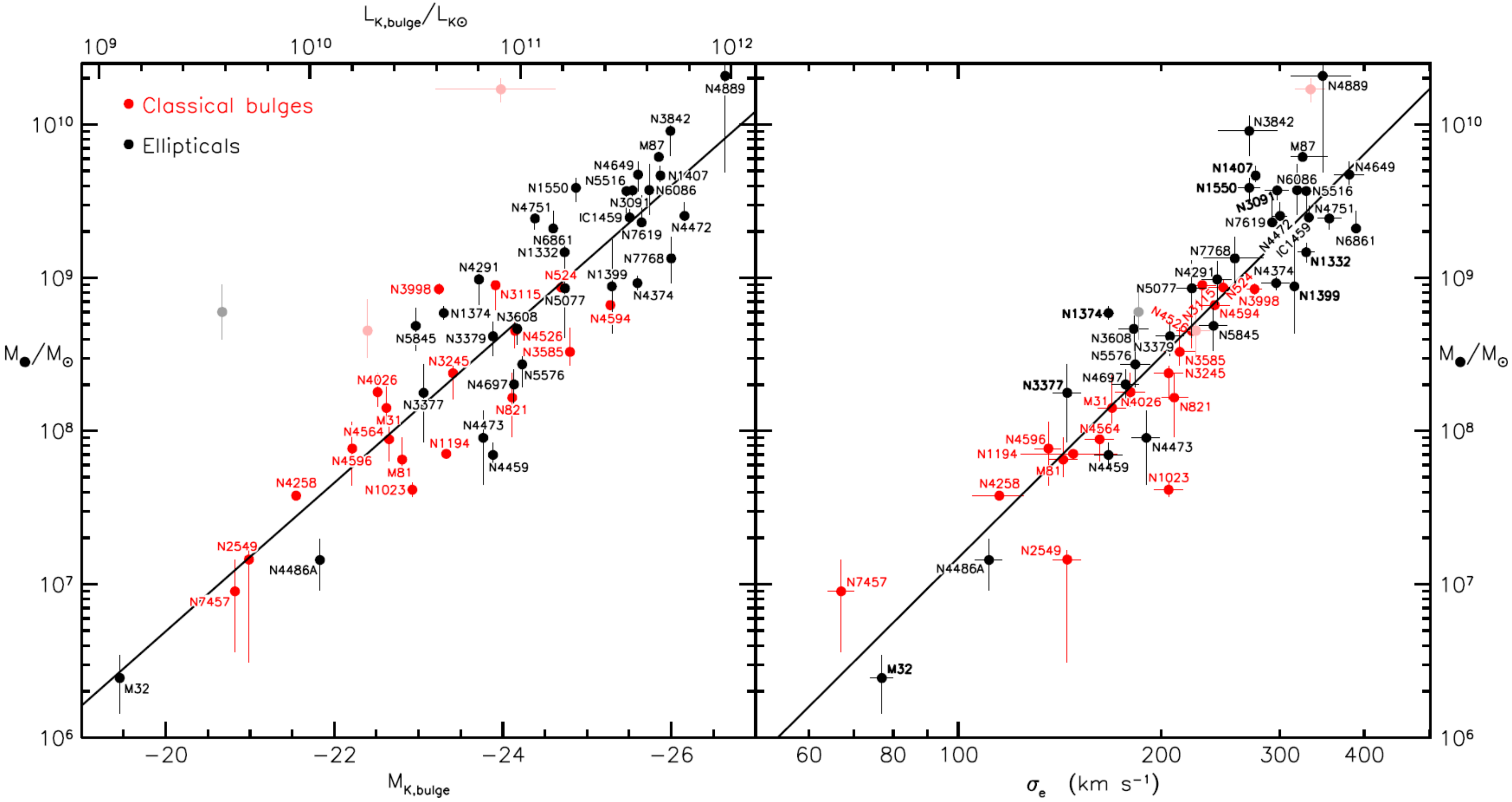
- Bright compact non-thermal variable R-source Sgr A*
- Focus of central cluster star orbits => $M_\bullet = 4\ 10^6\ M_\odot$
- Very weak in X-rays: $L_X \sim 10^{33}$ erg s^{-1} < **10^{-11} L_E ($M=M_\bullet$)**
- Sgr A* Bright Flares in X-rays and NIR => $L_{max} \sim 10^{35}$ erg s^{-1}

Open questions

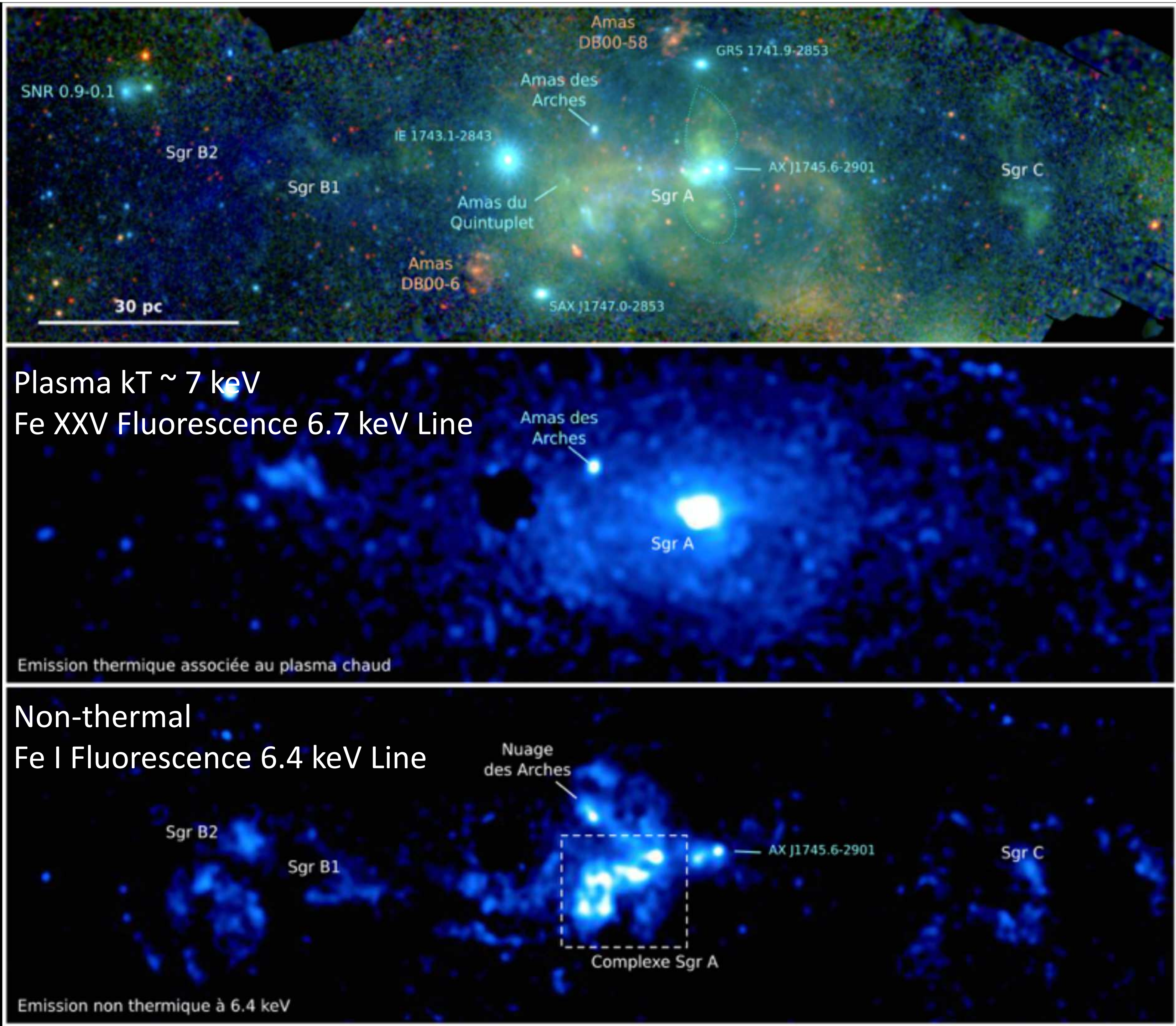
Sgr A* Super-Massive BH at the GC

- Very quite today: was it active before ? Did it have an AGN-like phase ? When how why ?
- Activity linked to mass accretion (galactic environment
- The SMBH and Galaxy (bulge) relations indicates co-evolution: feedback of BH to Gal ?
- Which power SMBH has injected in Galaxy ?
- Are there traces of large past activity from GC ?

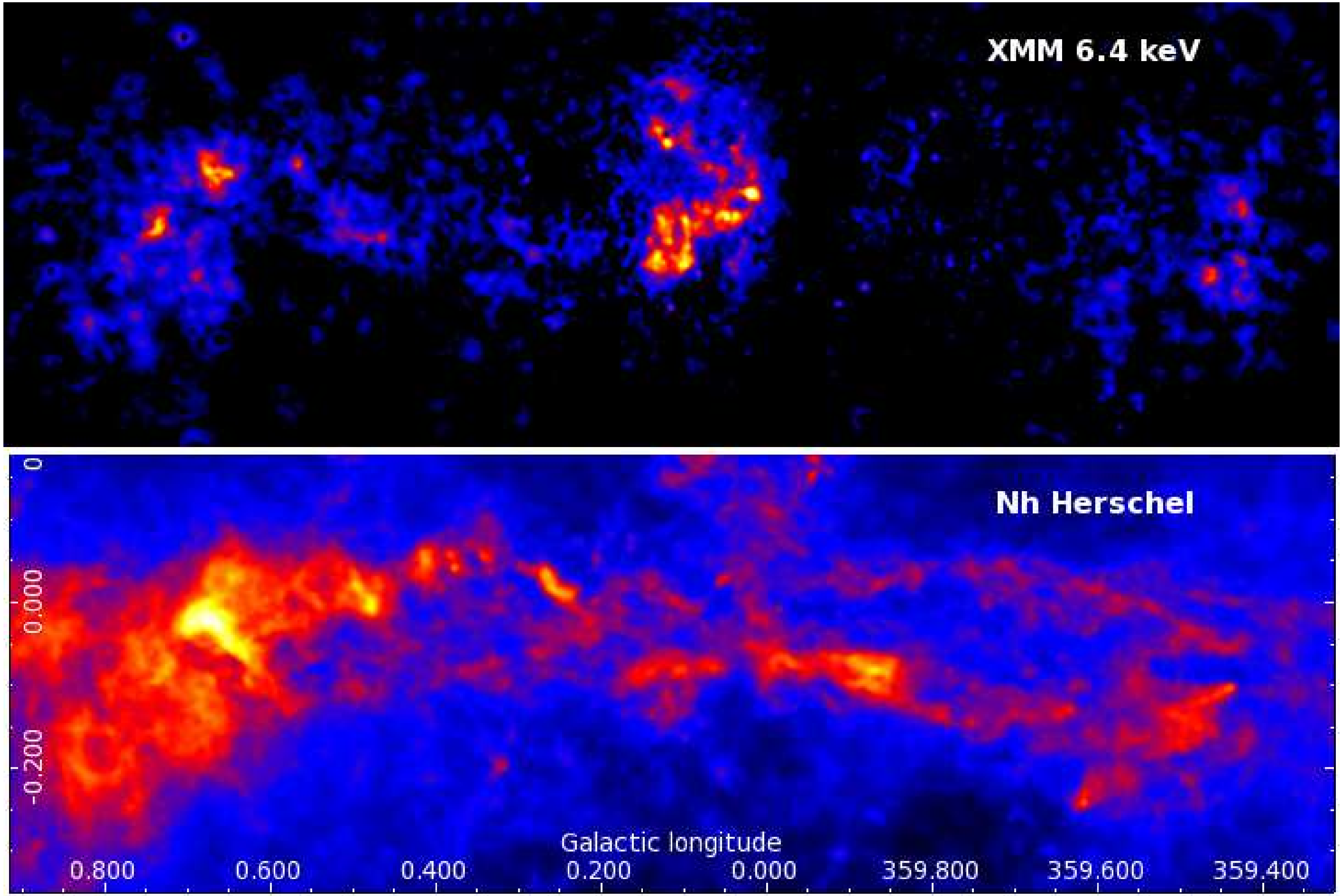
Co-evolution of SMBH and Host-G



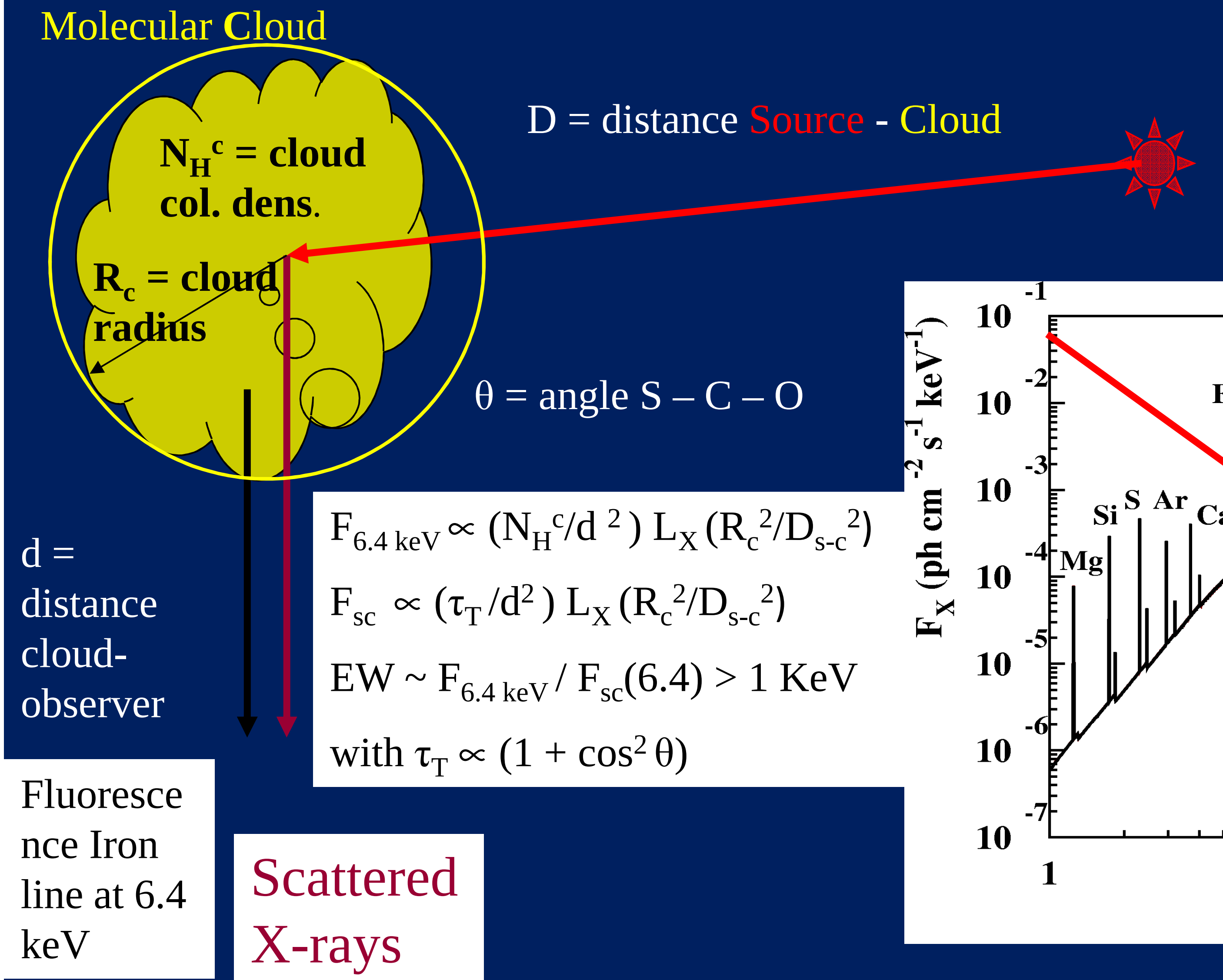
Kormendy & Lo 2013


Amas
DB00-58
GRS 1741.9-2853
SNR 0.9-0.1
Amas des
Arches
IE 1743.1-2843
Sgr B2
Sgr B1
AX J1745.6-2901
Sgr C
Amas du
Quintuplet
Sgr A
Amas
DB00-6
30 pc
SAX J1747.0-2853
Plasma kT ~ 7 keV
Fe XXV Fluorescence 6.7 keV Line
Amas des
Arches
Sgr A
Emission thermique associée au plasma chaud
Non-thermal
Fe I Fluorescence 6.4 keV Line
Nuage
des Arches
Sgr B2
Sgr B1
AX J1745.6-2901
Sgr C
Complexe Sgr A
Emission non thermique à 6.4 keV

Neutral Fe fluorescence line – Molecular Clouds



Fluorescent Iron line and reflected continuum from X-ray irradiation

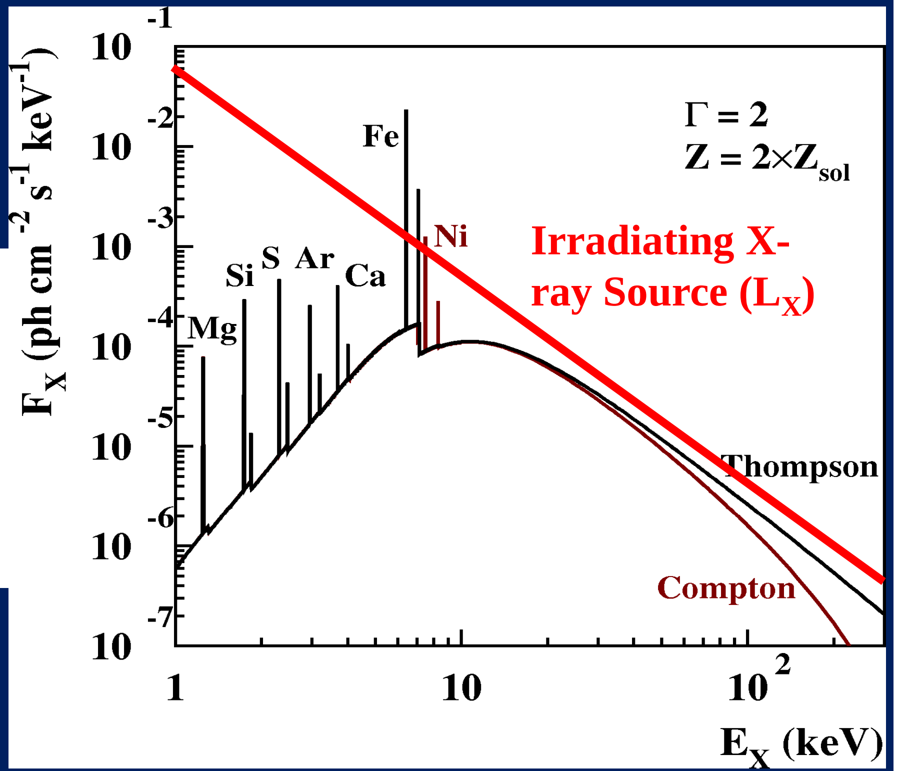


$F_{6.4\ keV} \propto (N_H{}^c/d^{\,2})\, L_X\, (R_c{}^2/D_{s\text{-}c}{}^2)$

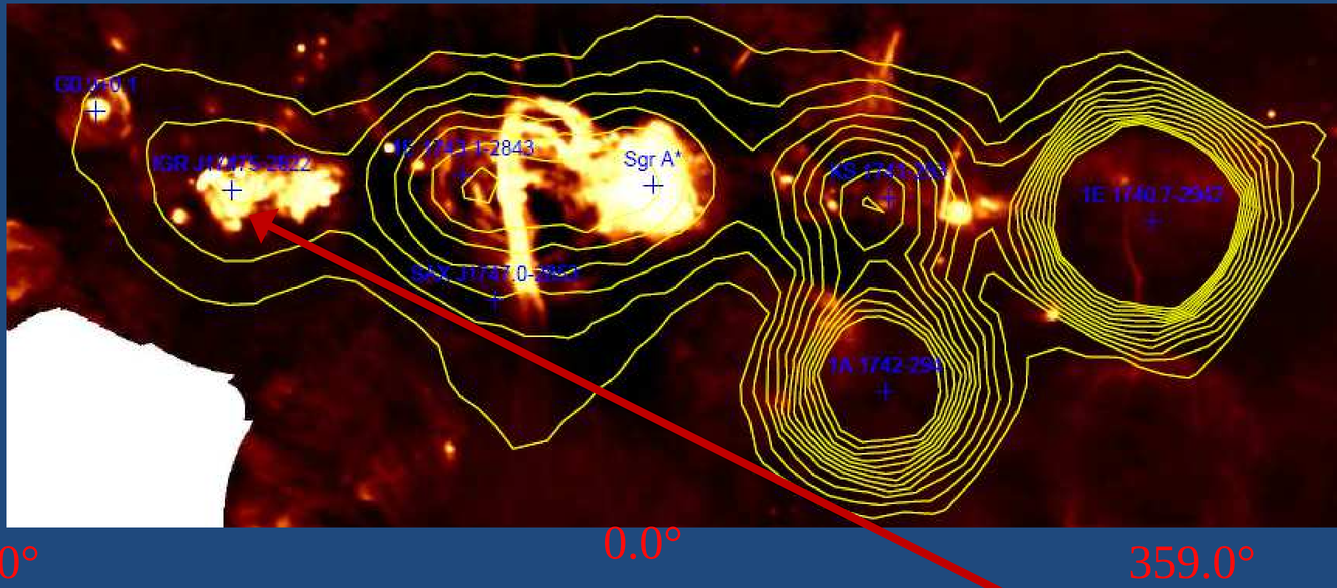
$F_{sc} \propto (\tau_T/d^2)\, L_X\, (R_c{}^2/D_{s\text{-}c}{}^2)$

$EW \sim F_{6.4\ keV} / F_{sc}(6.4) > 1$ KeV

with $\tau_T \propto (1 + \cos^2\theta)$



VLA (20cm) and INTEGRAL (20-30 keV, contours)

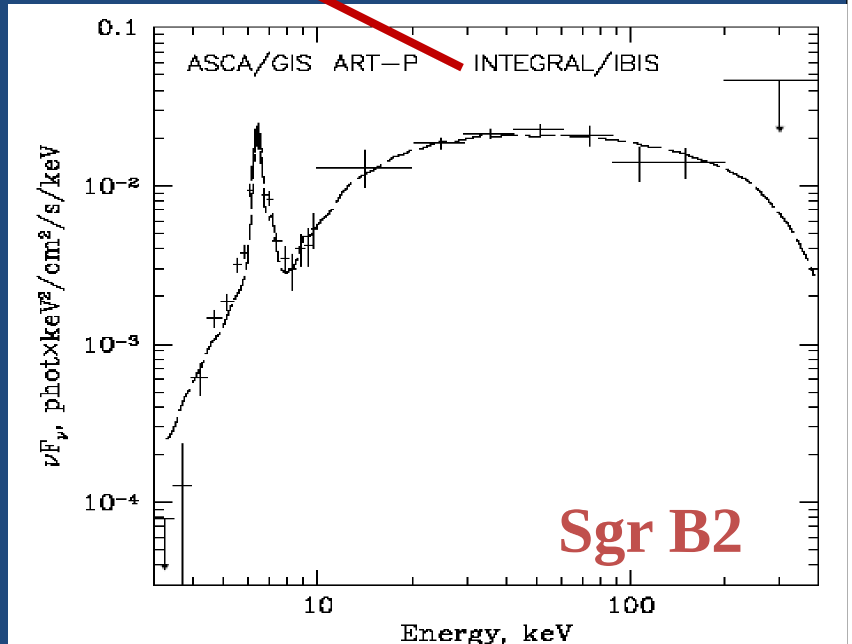


(Belanger et al. 2006)

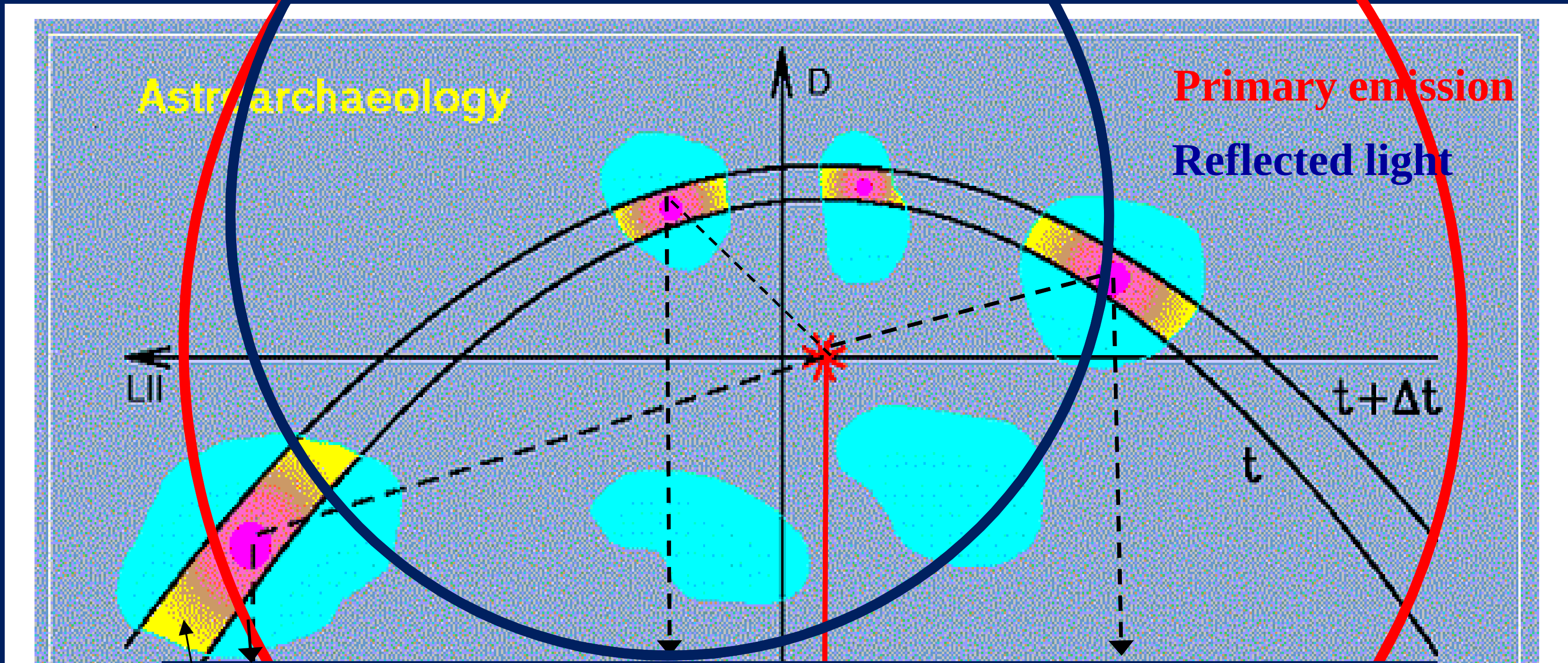
- INTEGRAL (20-200 keV) Sgr B2 spectrum compared to ASCA & ART-P data at low energy
- Broadband spectrum: Fe I fluorescence + Compton scattering of a 10^{39} erg/s luminosity outburst of Sgr A* ~300 yr back lasted > 10 yr

  (Revnivtsev et al 2004)

- **However hypothesis of particle induced non-thermal emission not completely excluded**



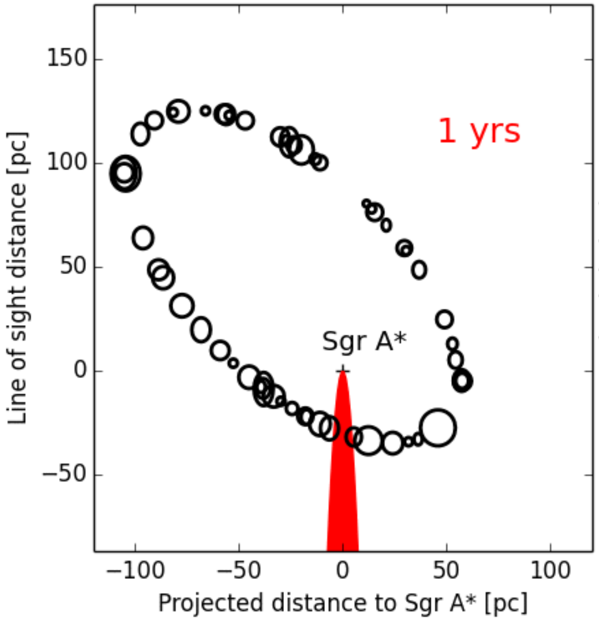
Time delay of the reflection component and parabola of equal time-delay points



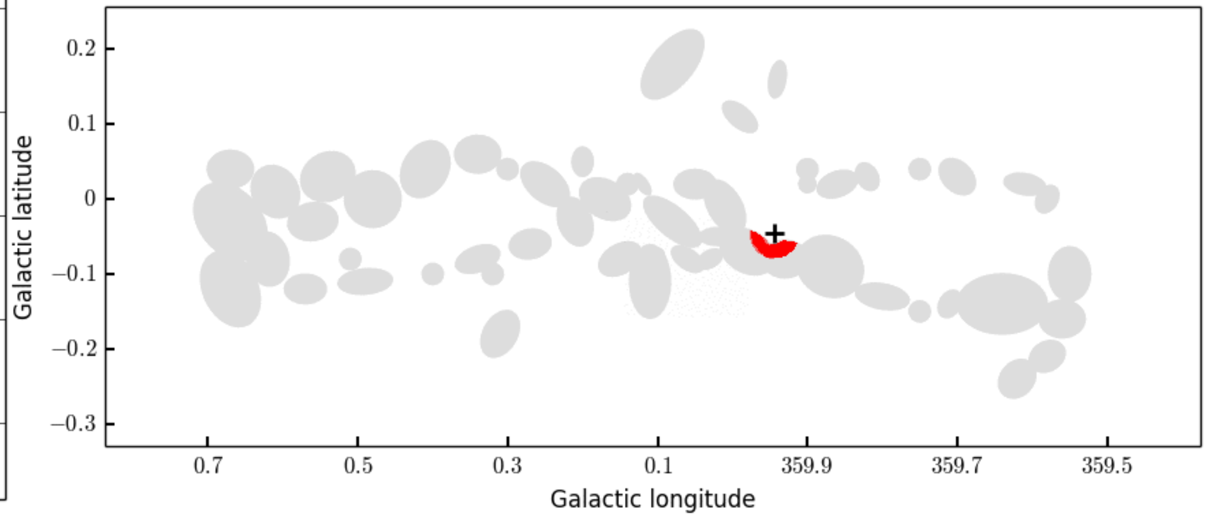
- Points of equal time delay seen by an observer at infinity lie on an parabolic surface with focus on the illuminating source
- Light echoes easily produce variability in the reflected emission, even apparent superluminal motion (Sunyaev Churazov 98, Crampton Sunyaev 02)
- First variability of 6.4 keV line from Sgr B2 observed w/t different instruments (ASCA, Chandra, XMM, Suzaku) (Koyama+ 06 07 08, Inui+ 07)

Sgr A* Light-Echo Propagation in CMZ

Propagation seen from above the Galactic plane



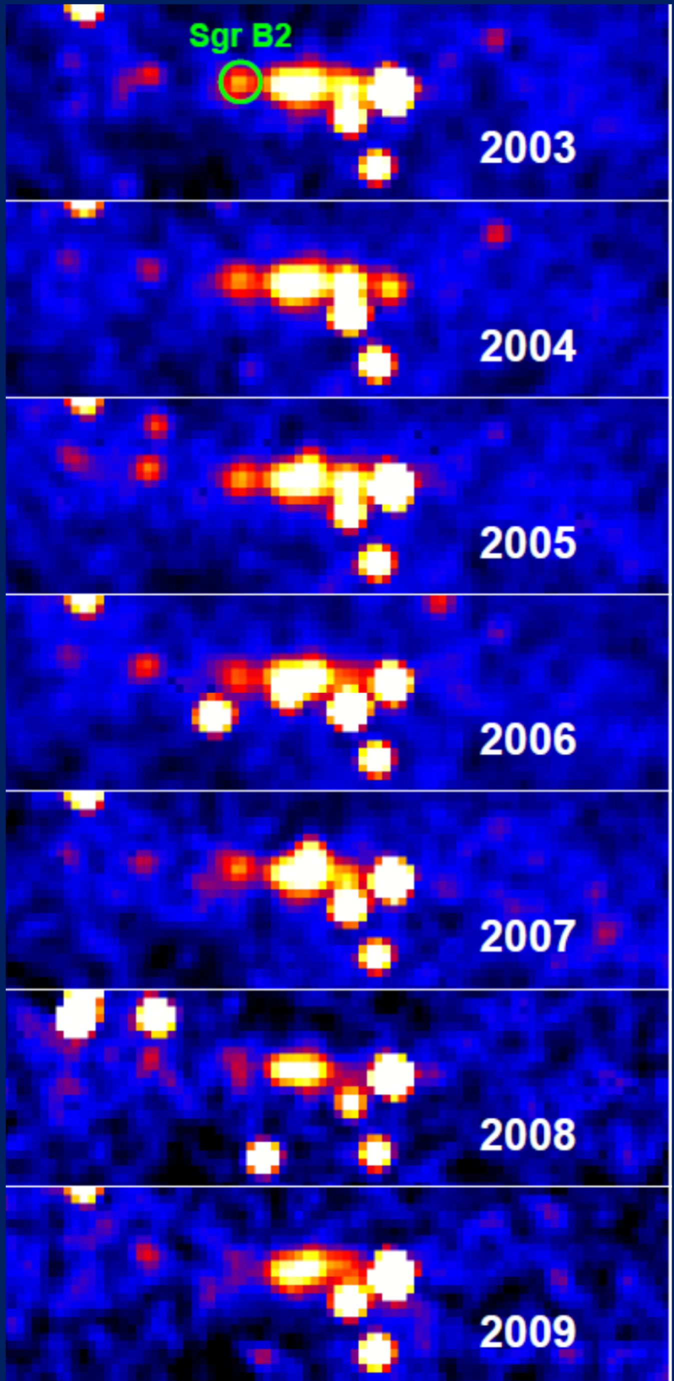
Reflected emission on the plan of the sky (as observed)



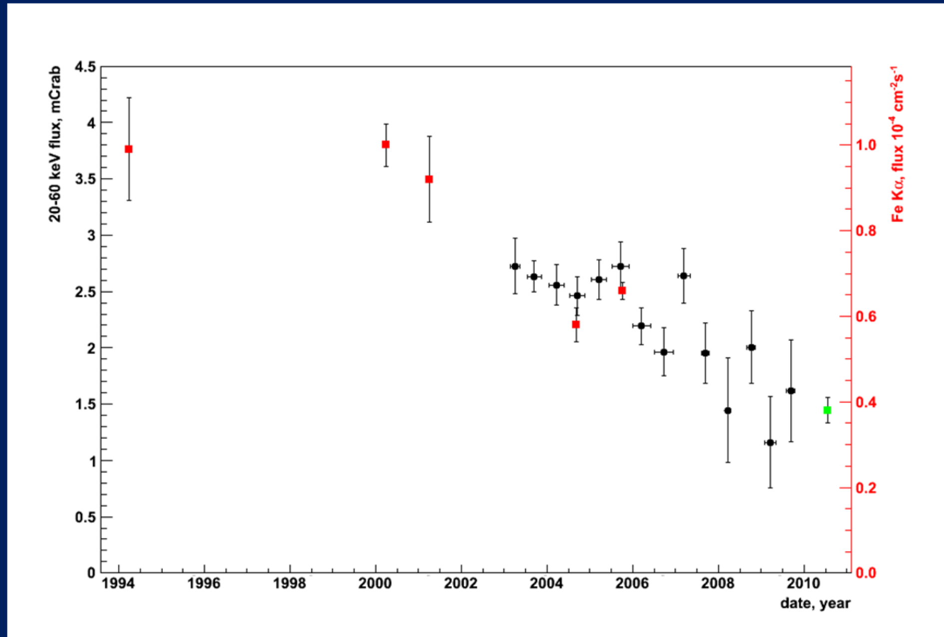
Simulation of reflection from a putative distribution of molecular clouds in the CMZ of a short (1 yr) X-ray outburst from Sgr A* at different delays (< 1000 yr)

Complicated pattern of morphological changes related to the matter distribution

Courtesy of Maïca Clavel (PhD Thesis, 2014)

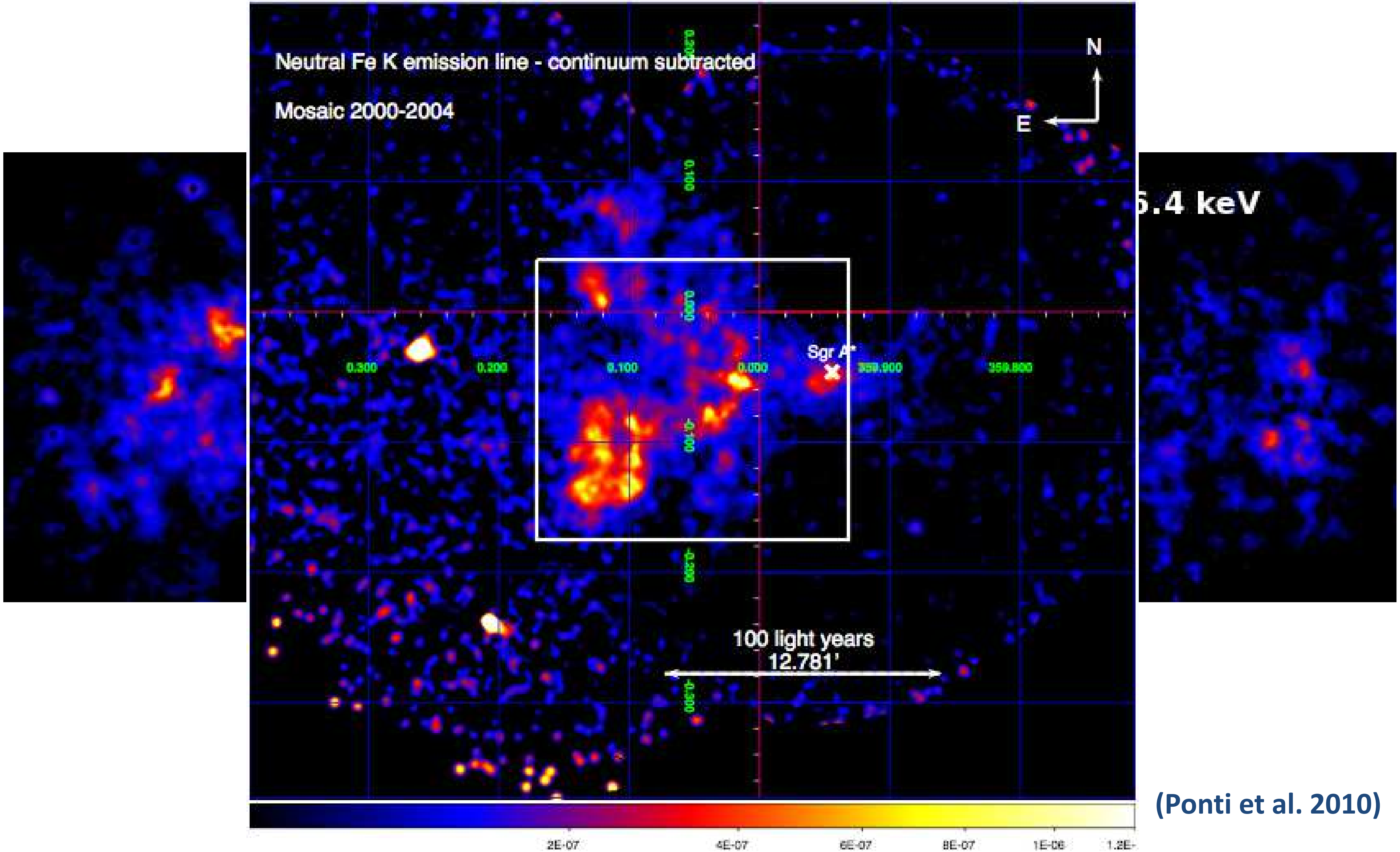


INTEGRAL GC survey: Discovery of gamma-ray variability of Sgr B2



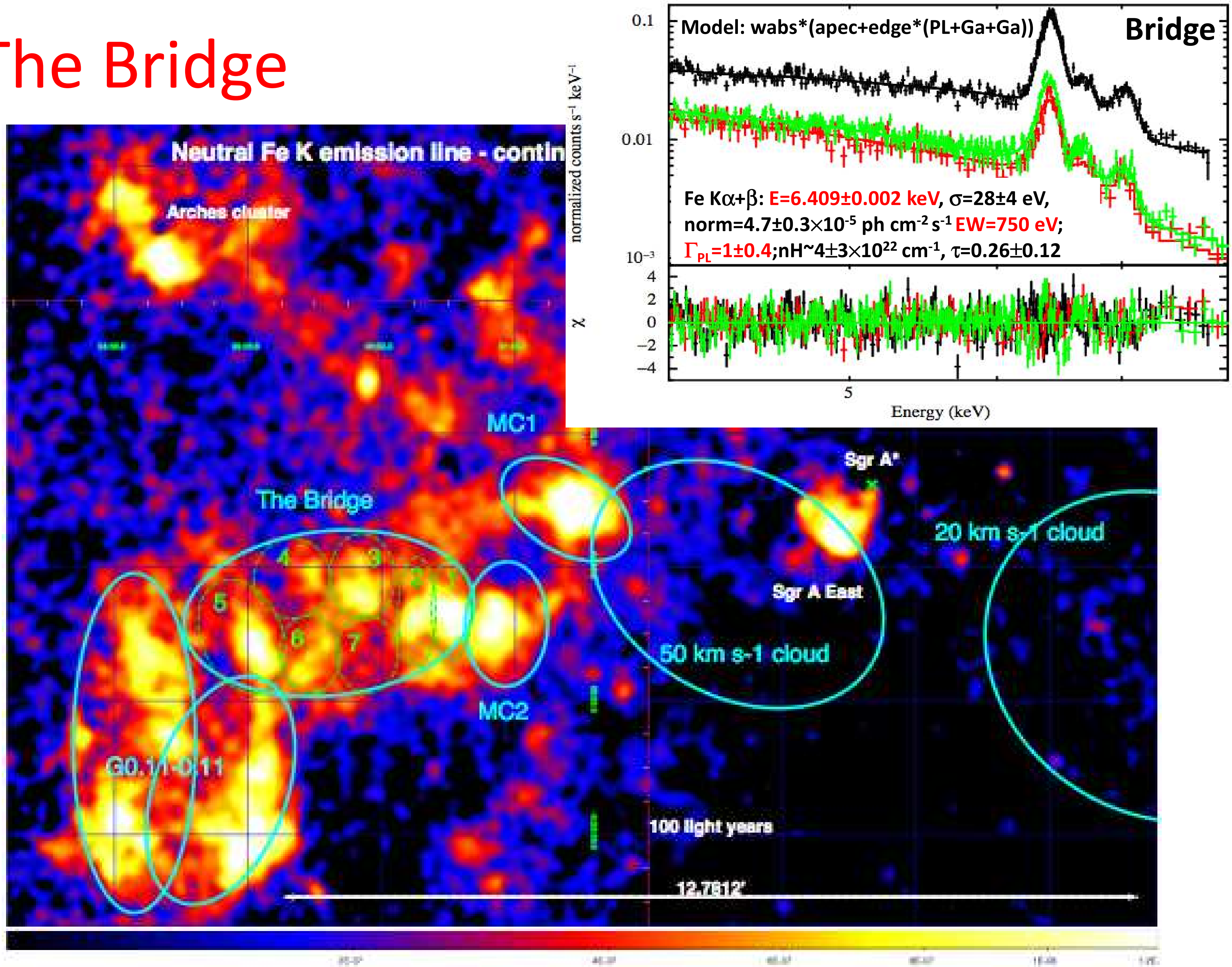
- Decrease of Sgr B2 20 - 60 keV flux over 7 ys (cloud core size ~ 8 ly)
- Variation up to 40 %, compatible with the 6.4 keV decrease observed by Suzaku (compared to XMM)
- Consistent with hypothesis of reflection of hard X-ray emission: end of outburst => decrease
- Not with particle interpretation (Terrier et al. 2010)

XMM monitoring of 6.4 keV line from MC around Sgr A*: discovery of superluminal motion

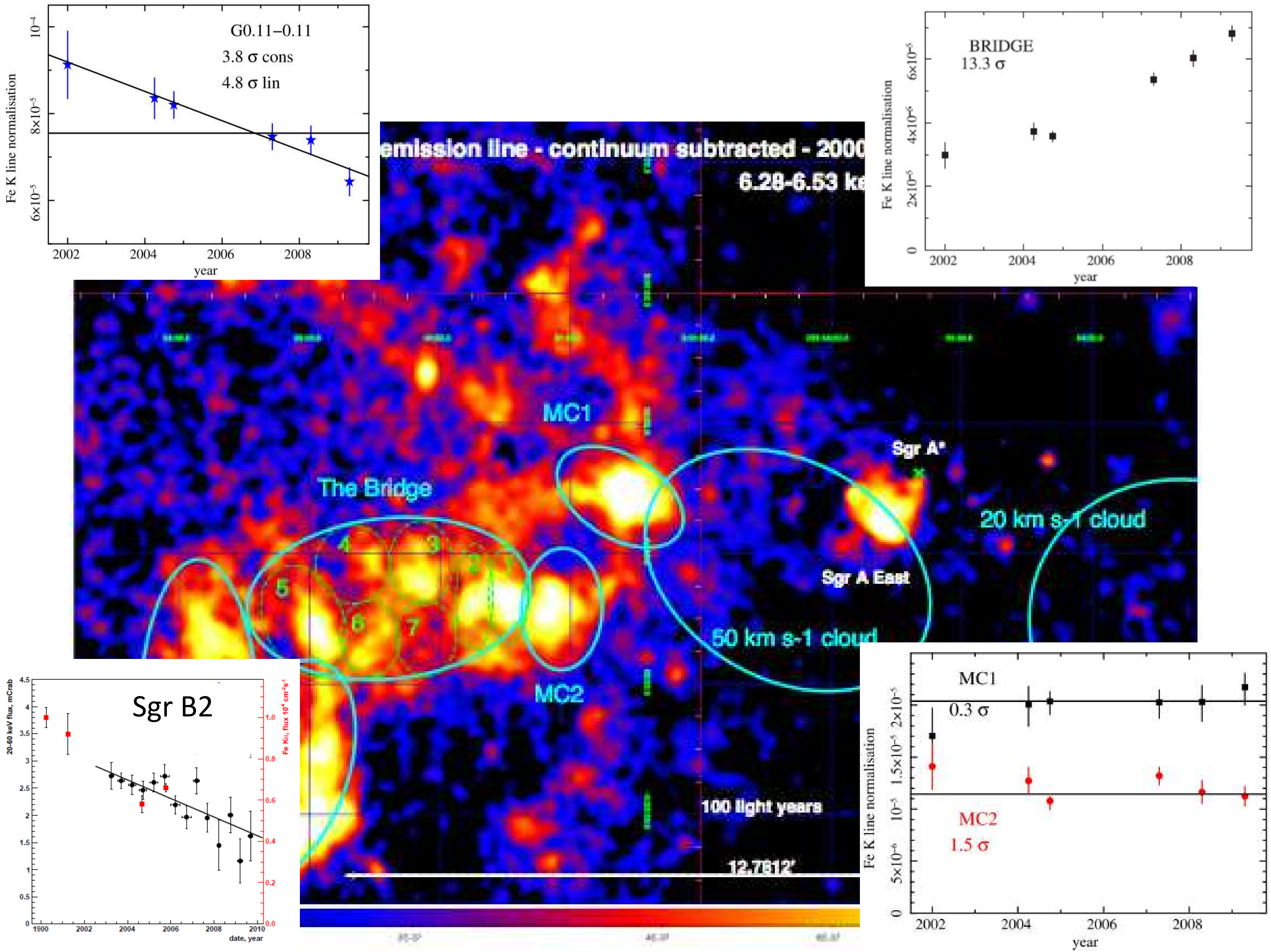


(Ponti et al. 2010)

The Bridge

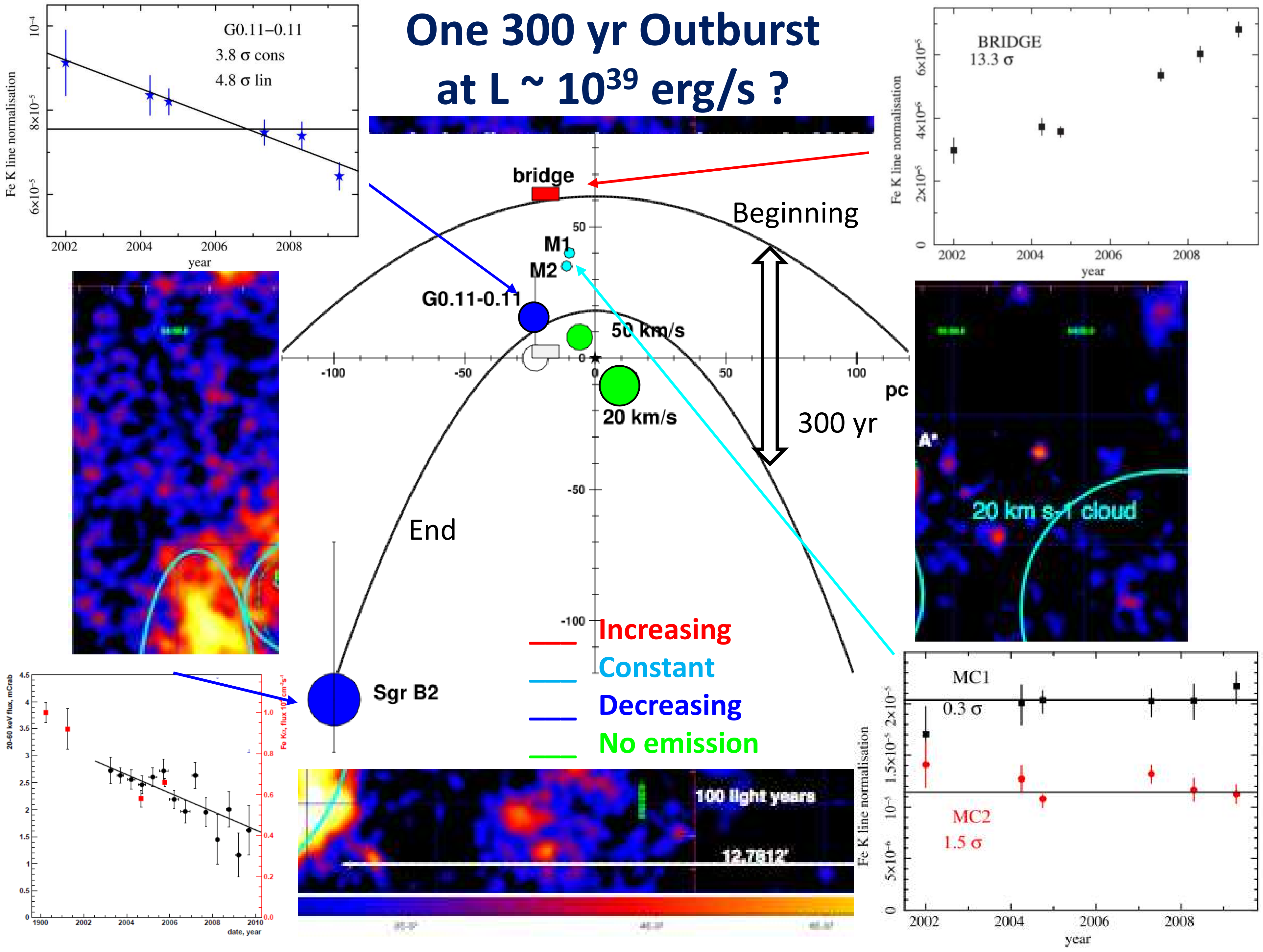


Model: wabs*(apec+edge*(PL+Ga+Ga))
Bridge
Fe Kα+β: E=6.409±0.002 keV, σ=28±4 eV,
norm=4.7±0.3×10^{-5} ph cm^{-2} s^{-1} EW=750 eV;
Γ_{PL}=1±0.4;nH~4±3×10^{22} cm^{-1}, τ=0.26±0.12
normalized counts s^{-1} keV^{-1}
0.1
0.01
10^{-3}
χ
4
2
0
−2
−4
5
Energy (keV)
Neutral Fe K emission line - contin
Arches cluster
MC1
The Bridge
MC2
Sgr A*
Sgr A East
20 km s-1 cloud
50 km s-1 cloud
G0.11-0.11
100 light years
12.7812'

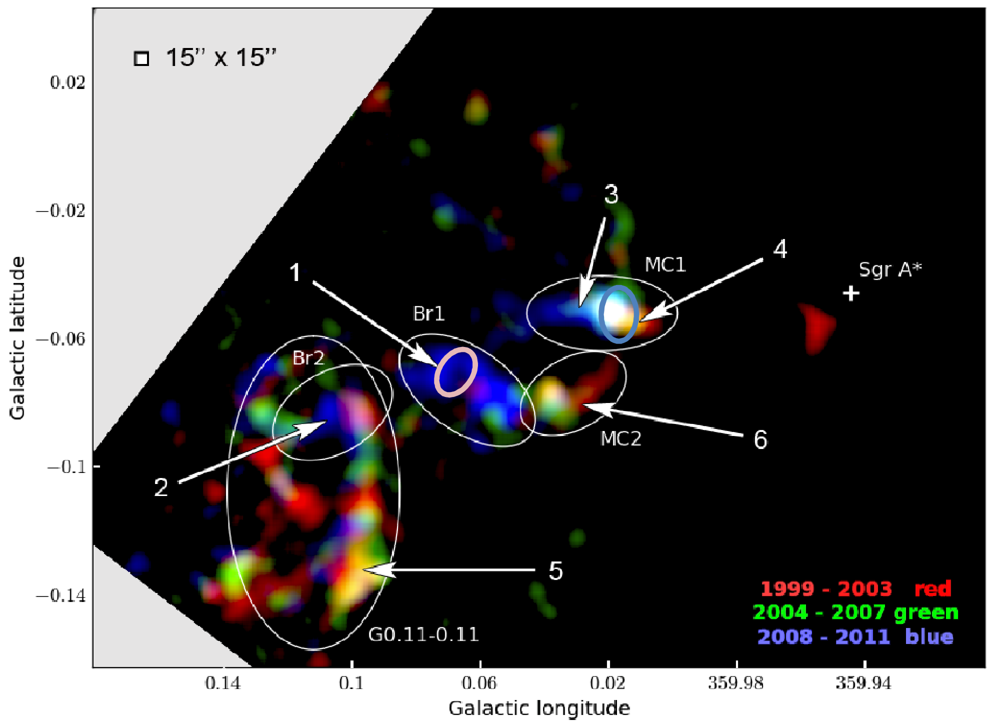


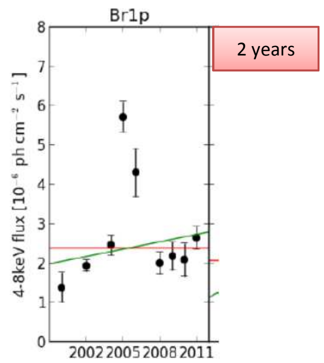
G0.11−0.11
3.8 σ cons
4.8 σ lin
Fe K line normalisation
year
BRIDGE
13.3 σ
emission line - continuum subtracted - 2000
6.28-6.53 ke
MC1
The Bridge
Sgr A*
20 km s-1 cloud
Sgr A East
50 km s-1 cloud
MC2
100 light years
12.7812'
Sgr B2
20-60 keV flux, mCrab
Fe Kα, flux 10⁻⁴ cm⁻²s⁻¹
date, year
MC1
0.3 σ
MC2
1.5 σ

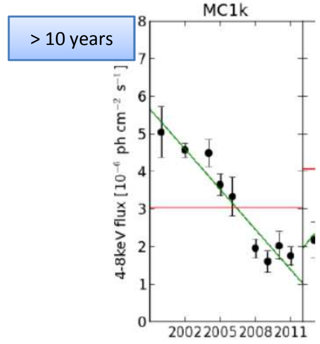
One 300 yr Outburst at L ~ 10^{39} erg/s ?

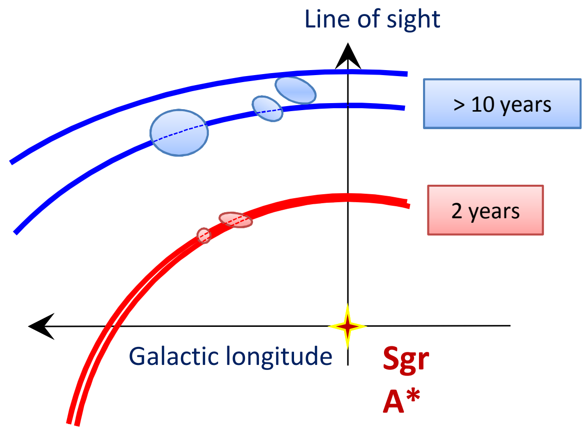


Chandra CMZ Obs.: multiple Echo events







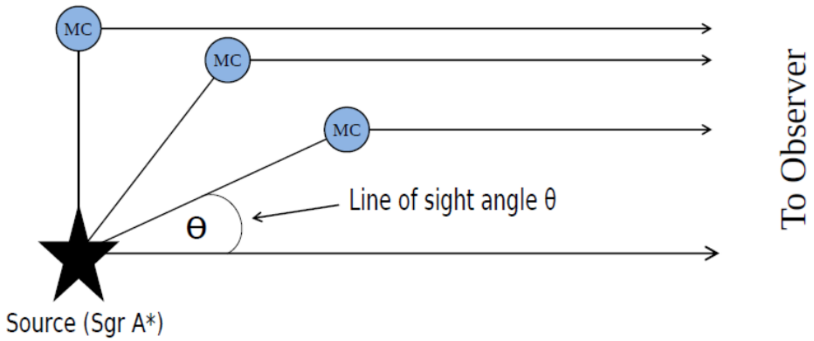


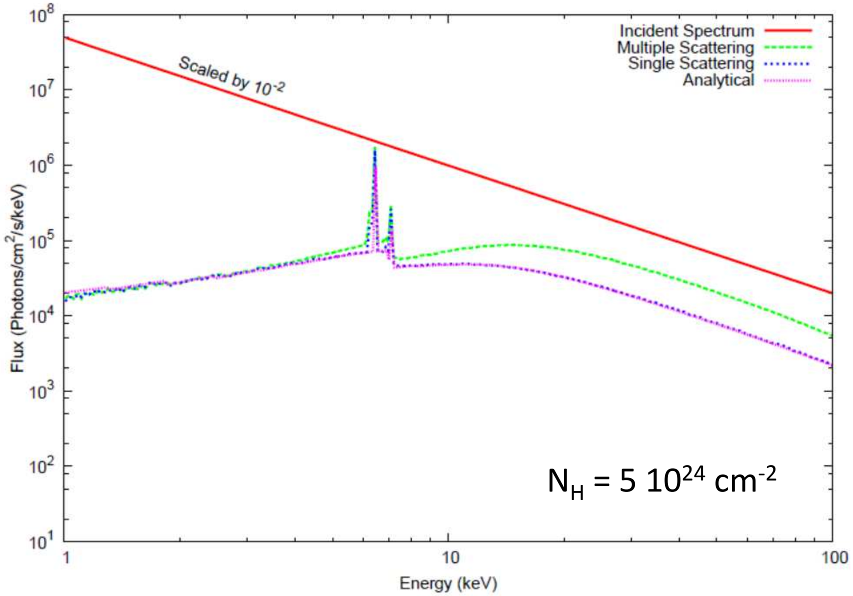
NOT A SINGLE 300 YR OUTBURST !!

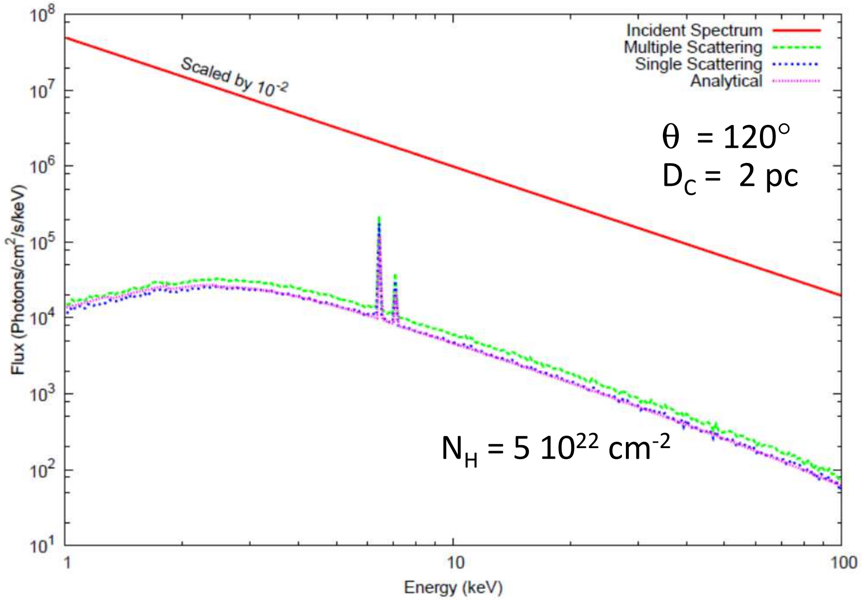
Chandra Survey 1999–2011: 6.4 keV Iron K line rapid variability from Sgr A molecular cloud. **MC1 MC2 not constant**, **Br1 rapid event** => reflection of 2 bright events (10^{39} erg/s), 1 short (< 2 yr) and 1 longer (~ 10 yr) produced by Sgr A* in the past few 100 yrs. **Not possible to determine the delays because unknown location of clouds. Need for spectral modelling.**

(Clavel et al. 2013, Clavel PhD 2014)

Monte Carlo Modeling of Reflection Spectrum



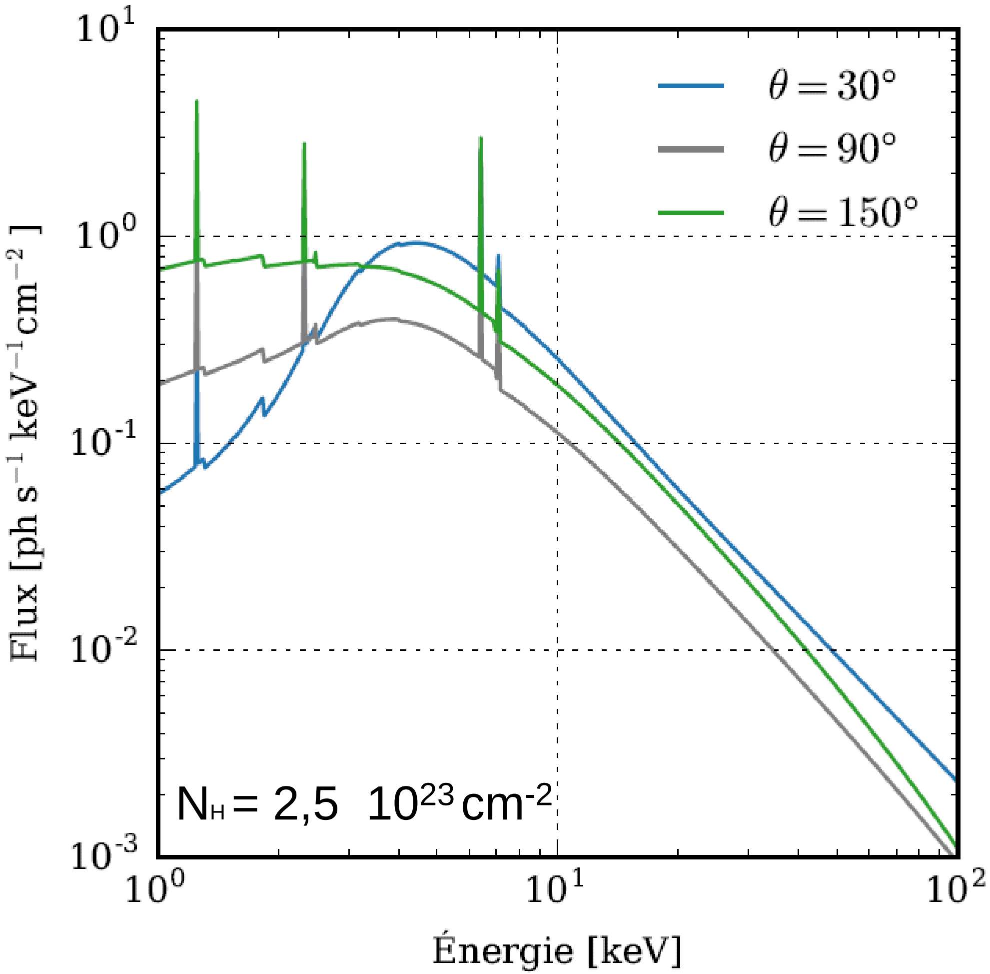




- Illumination (parallel beam) by external source, Power Law spectrum 1-300 keV and Ph. Index α
- Spherical cloud diameter D
  - Uniform, Variable (Gaussian, Expo) Density
  - Solar composition
- Effects:
  - Absorption and Fluorescence (Fe)
  - Multiple Scattering
  - Bound-electrons

Walls et al. 2016
Chuard PhD 2018

Reflection Spectrum as a function of scattering angle

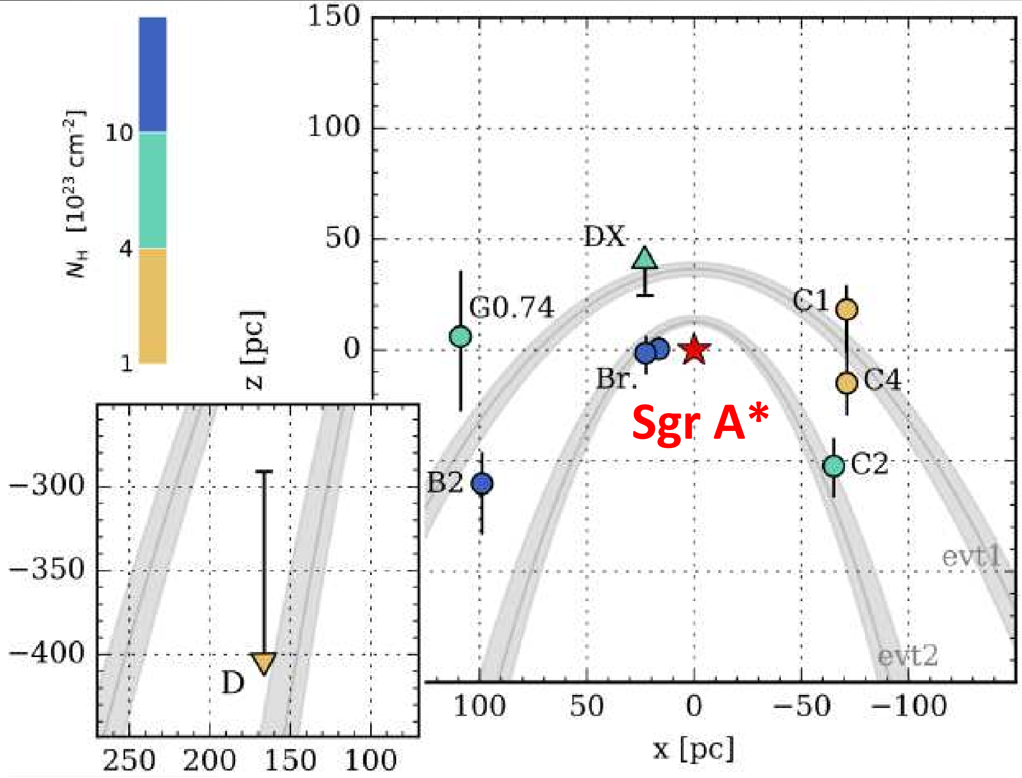


- Strong dependence of low energy spectum on Scattering angle θ
- Determination of θ allows the location of the reflecting clump line-of-sight position
- Applied first to Sgr B (XXM + Chandra + INTEGRAL) (Walls+ 2016)
- Then to Sgr C (Chuard+ 2018)
- Improved code of simulation and simultaneous fit of several MC clumps (XMM) data confirm with increased accuracy the previous estimations.

D. Chuard, PhD 2018

Fitting Reflection spectra of several MCs

Région	x (pc)	z (pc)
DX	22,9	> 25
Filament 2011	22,3	$-1,1^{+7,5}_{-10,0}$
Sgr B2	98,9	$-60,4^{+14,2}_{-23,0}$
G0.74−0.11	108,9	$5,5^{+30,5}_{-33,3}$
Sgr C1	−71,1	$18,3^{+10,9}_{-19,6}$
Sgr C2	−65,2	$-52,4^{+12,7}_{-14,3}$
Sgr C4	−71,4	$-14,7^{+33,4}_{-14,9}$
Sgr D	166,2	< -291



The two-events ($L_X \sim 10^{39}$ erg/s) model is significant at 5 sigma c. l.

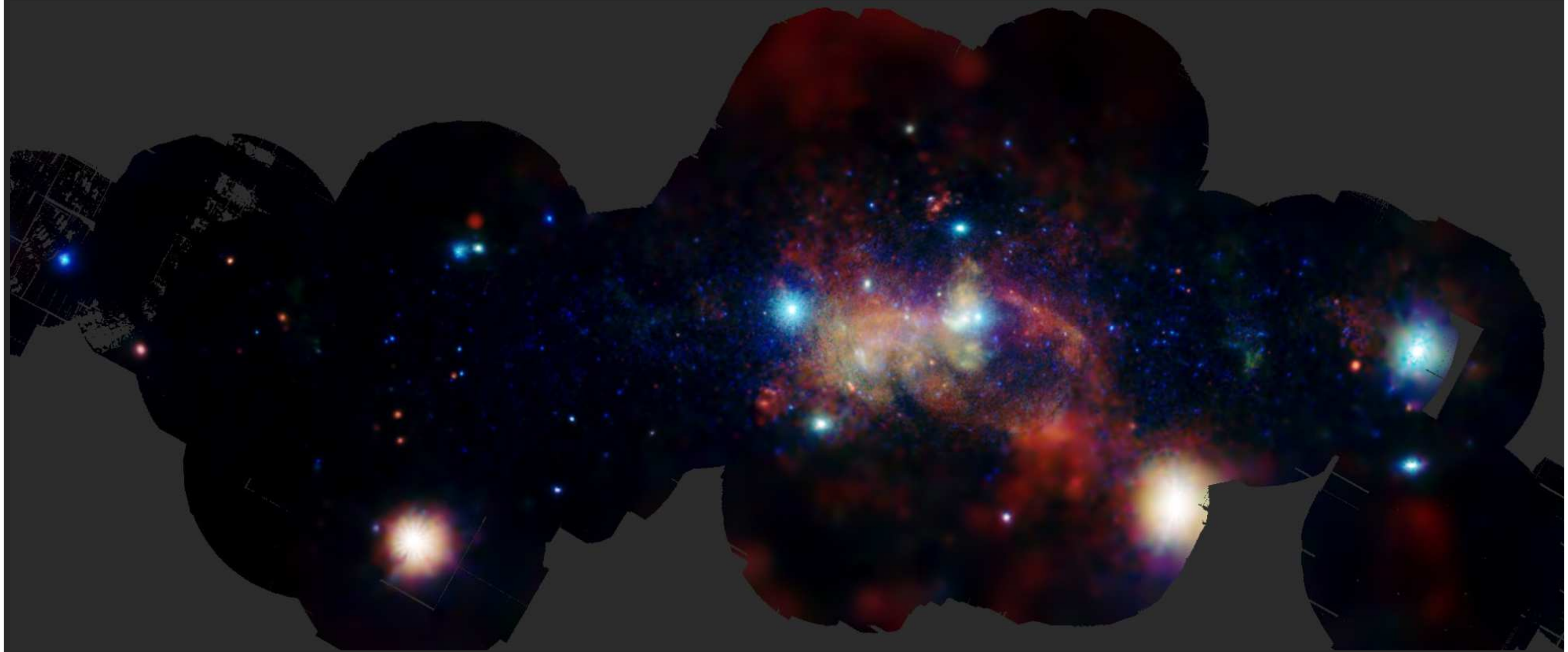
Delays of 2 events derived from all MCs data fit :

Δt1 = 84 +16/-9 yr Short Event

Δt2 = 238 +19/-20 yr Long Event

(Chuard PhD Nov 2018,
Chuard et al. 2019 in prep.)

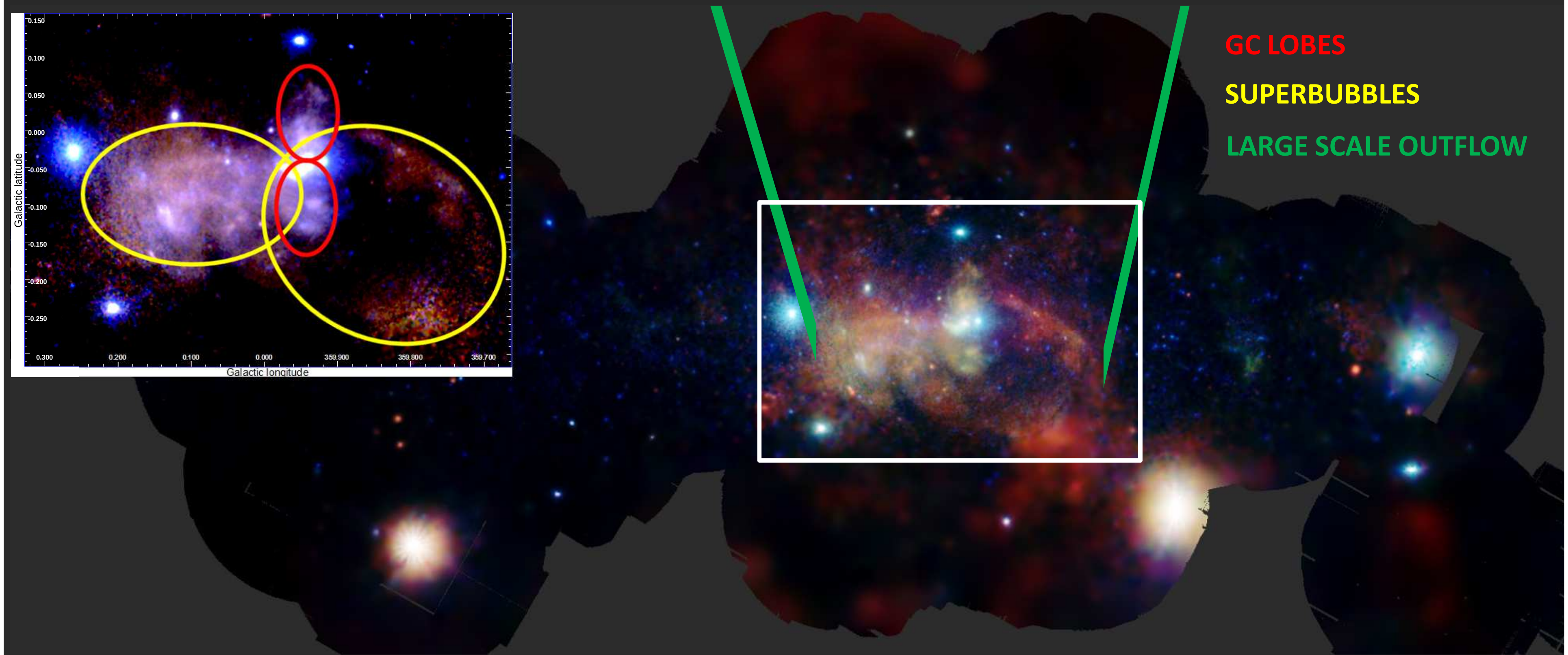
CMZ Soft X-ray Line Emission as mapped by XMM-Newton



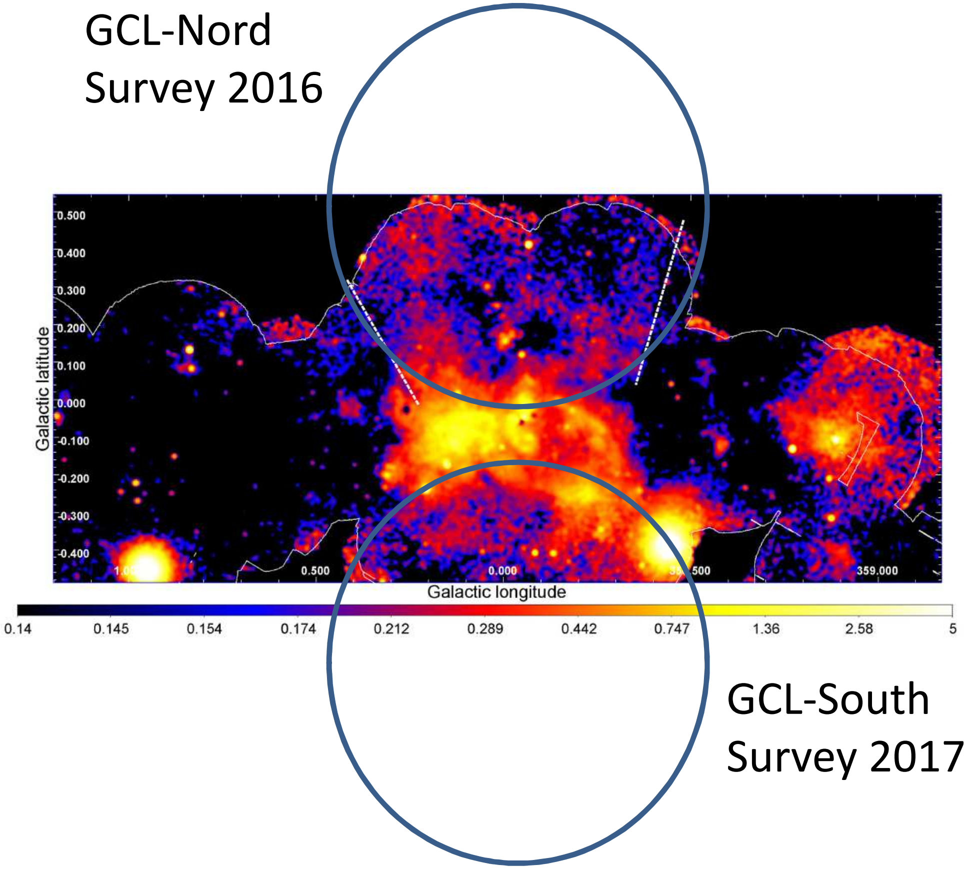
Red: Si xiii
Green: S xv
Blue: Ar xvii

Ponti+ 2015

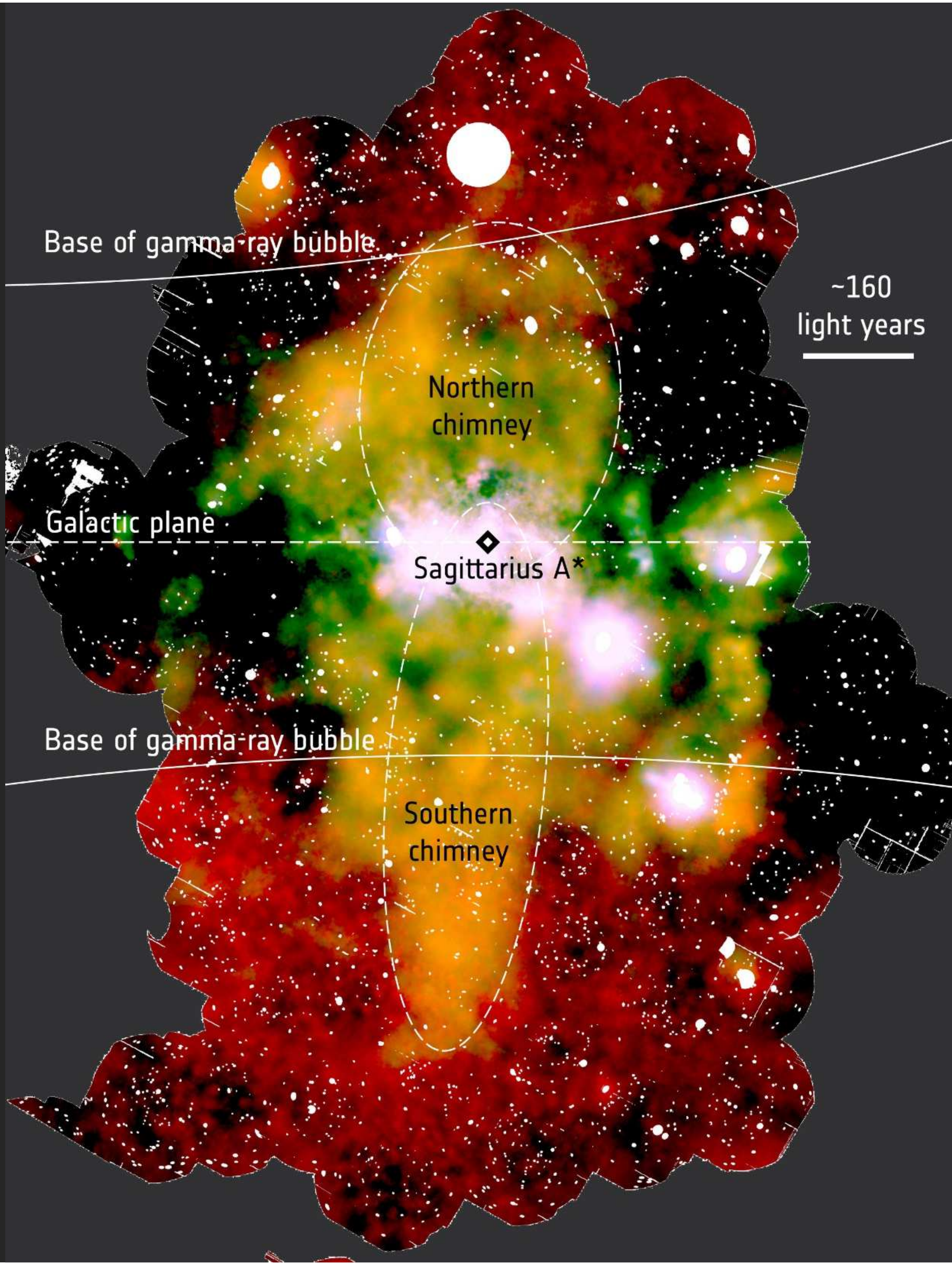
CMZ Soft X-ray Line Emission: the structures



XMM Survey of Galactic Center polar regions



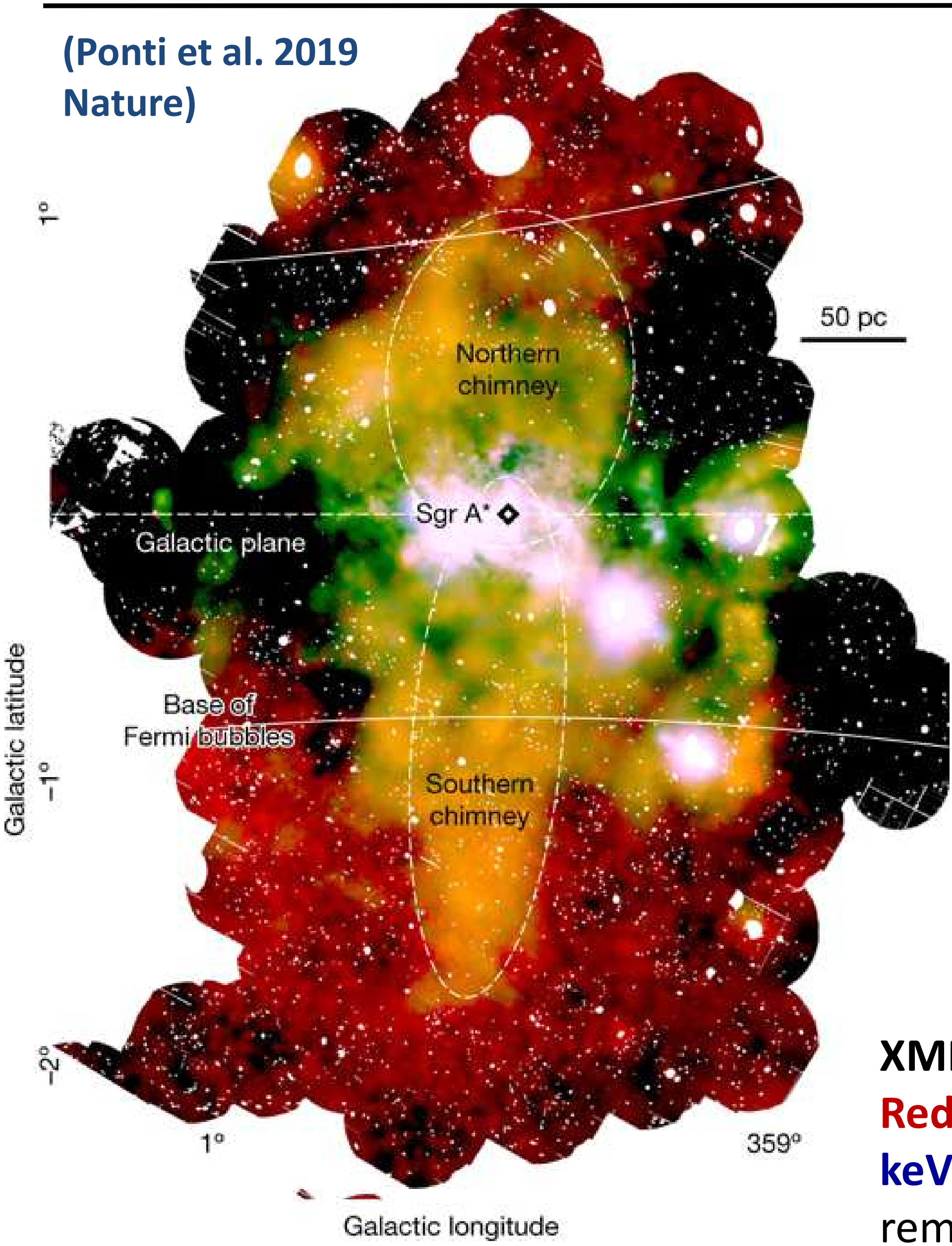
- 2000-2012: Large GC X-ray surveys (b ≈ +/- 0.5°)
- Large project to explore GCL-N Approved and performed in 2016 -2017
- Total of 46 XMM obs (25 ks) => 1.15 Ms ≈ 320 hr expo
- Images reveal structures of thermal gas extending towards Gal poles



Ponti+ 2019 Nature

Discovery of Galactic Center X-ray Chimneys of Hot Gas

(Ponti et al. 2019 Nature)

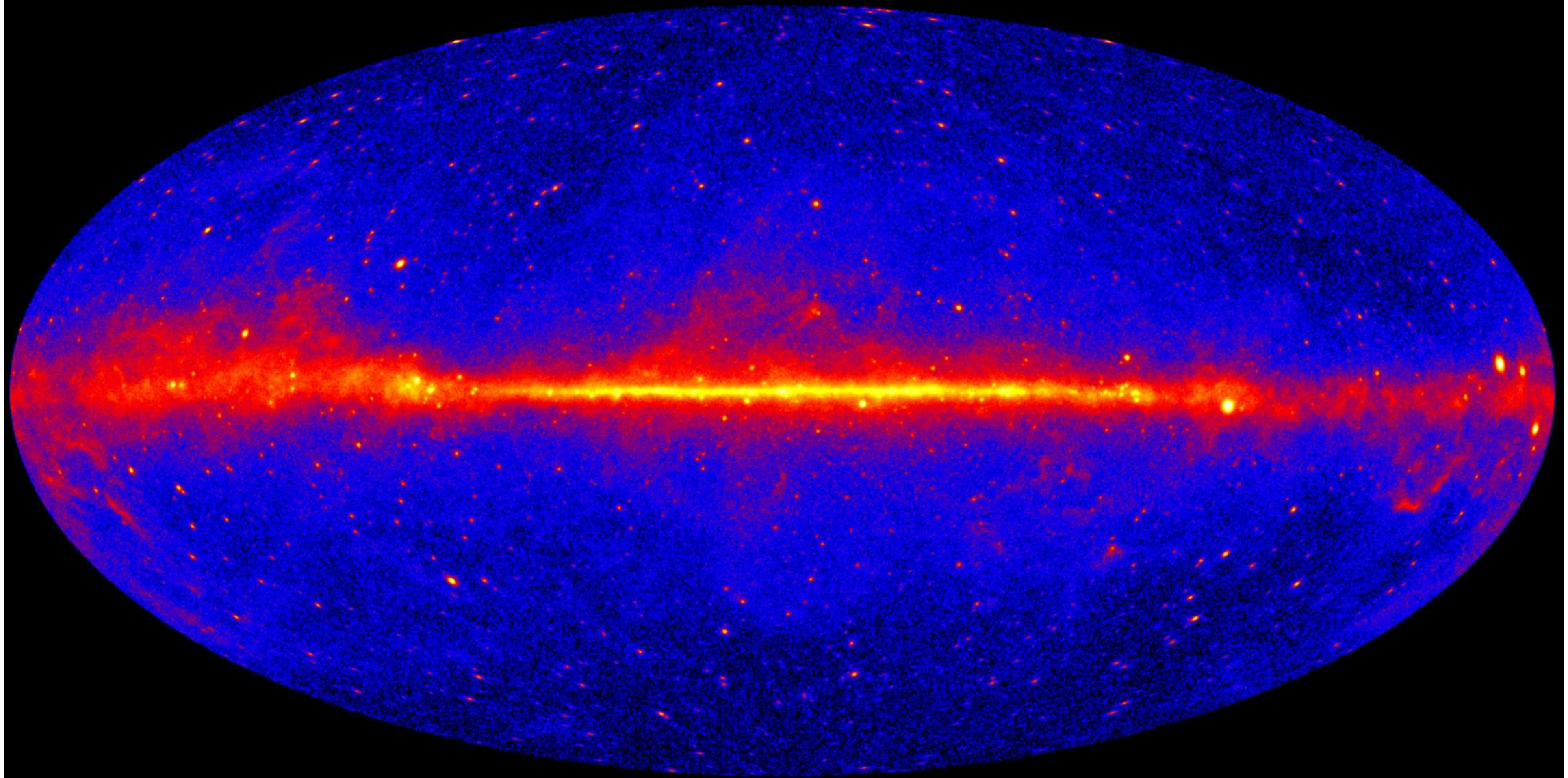


From XMM GCL Survey + Archival data we detected and characterized

- 2 long (1°≈ 160 pc) thermal (T ≈ 7 10^6 K°) structures extending N & S of GC (d=8 kpc), width: ±0.4° ≈ 50 pc
- Similar parameters and origin N / S
- N-Ch co-spatial with R/IR GCLN
- N-S Differences: galactic weather (ISM density)
- Origin within 50 pc from Sgr A*
- 15pc-lobes (L≈8 10^{38} erg/s, t_s≈3 10^4 yr) nested but not clearly related
- Total power: **$L_{X\text{-}Chi}$ ≈ 4 × 10^{39} erg/s** Time scale: **t_s ≈ 3 10^5 yr**
- **Reach the Fermi Bubbles Bases !!**

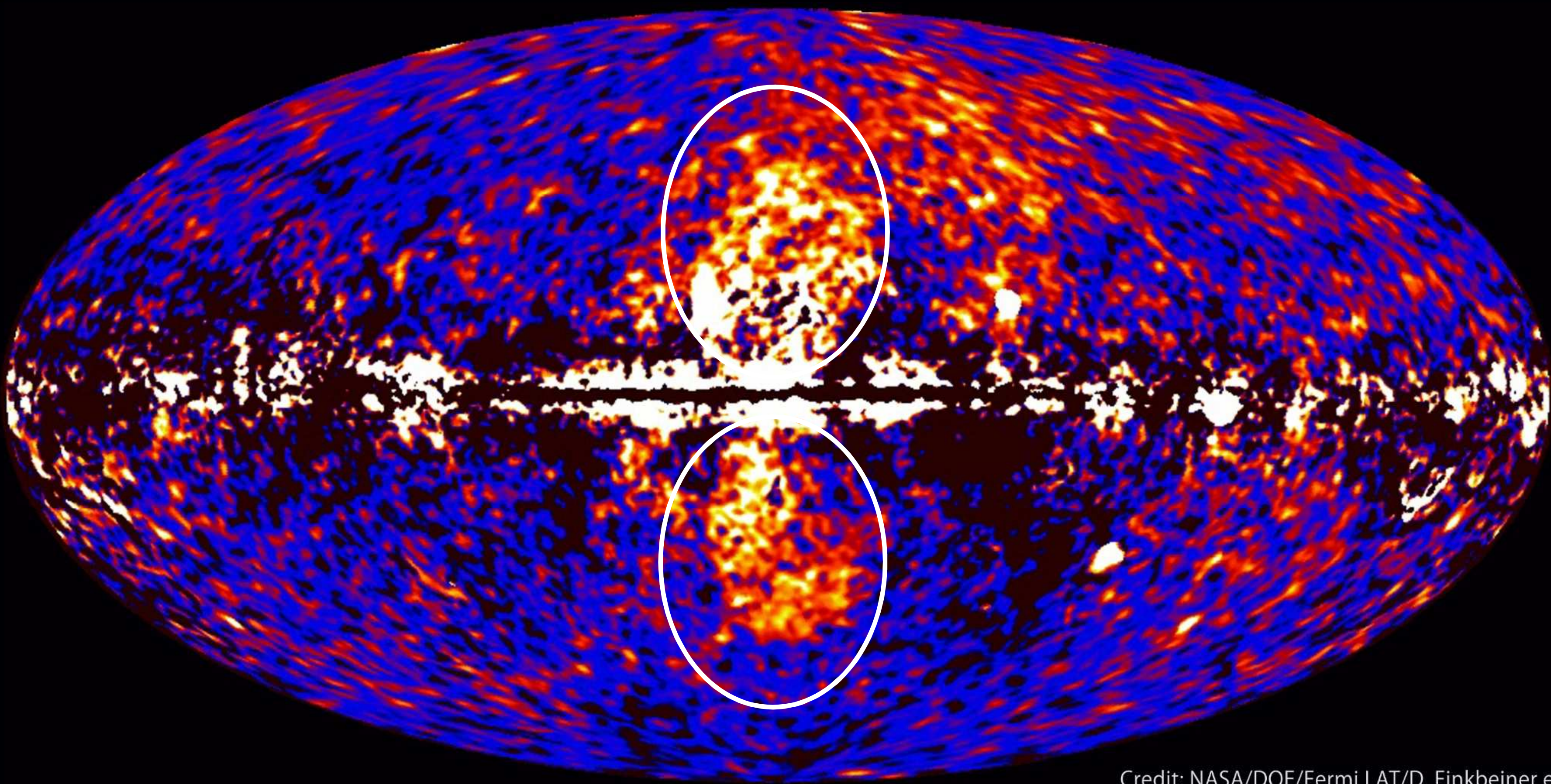
XMM-Newton Soft X-ray GC 300 pc x 500 pc image: **Red 1.5-2.6 Green 2.35-256 SXV line Blue 2.7-2.97 keV (continuum, no SXV ArXVII)**. Point Sources+dsh removed. Sgr A*, Base Fermi-B (Extrapolated Rosat)

FERMI All-Sky Image > 1 GeV – Six years

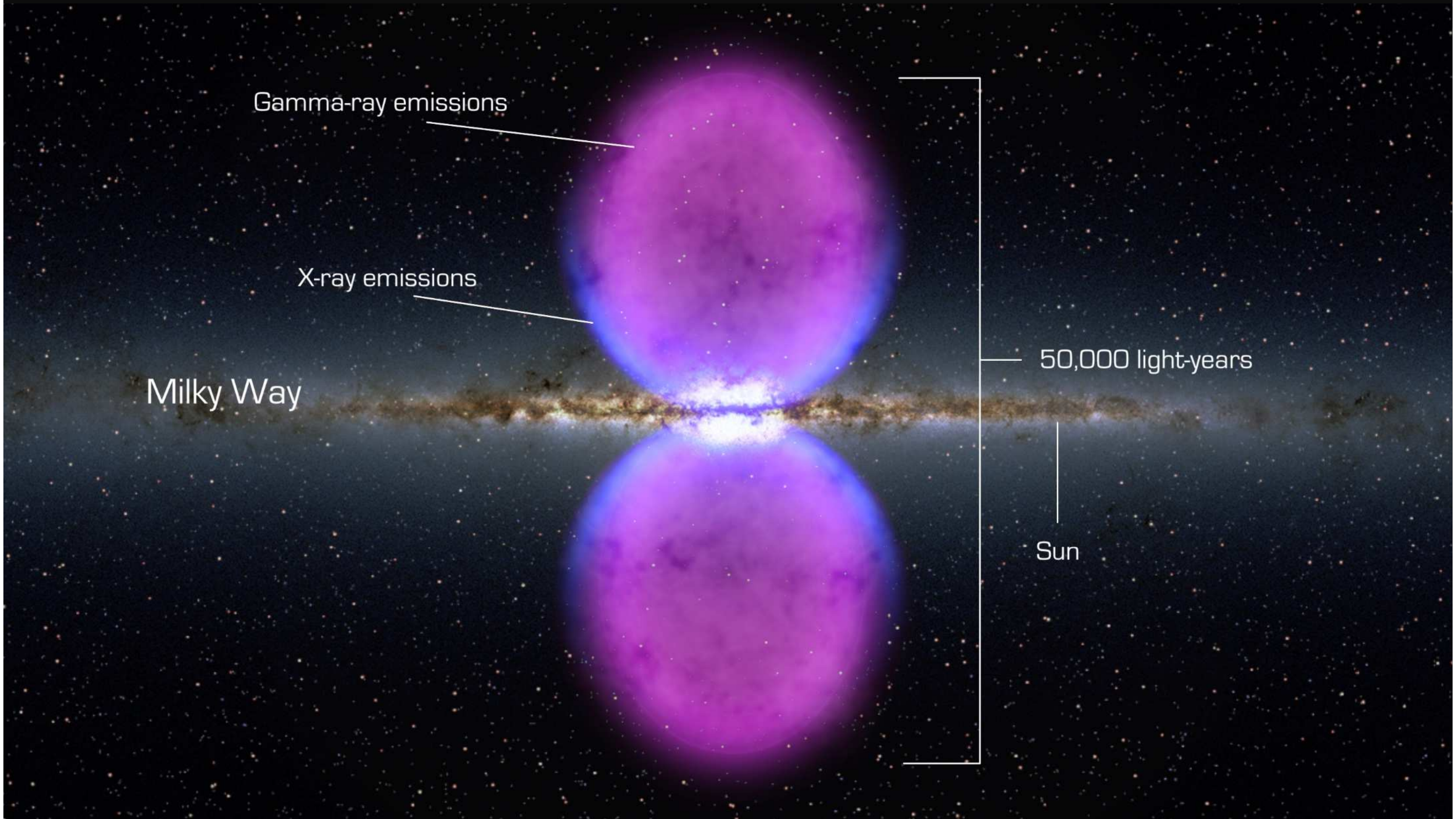


NASA

Fermi data reveal giant gamma-ray bubbles

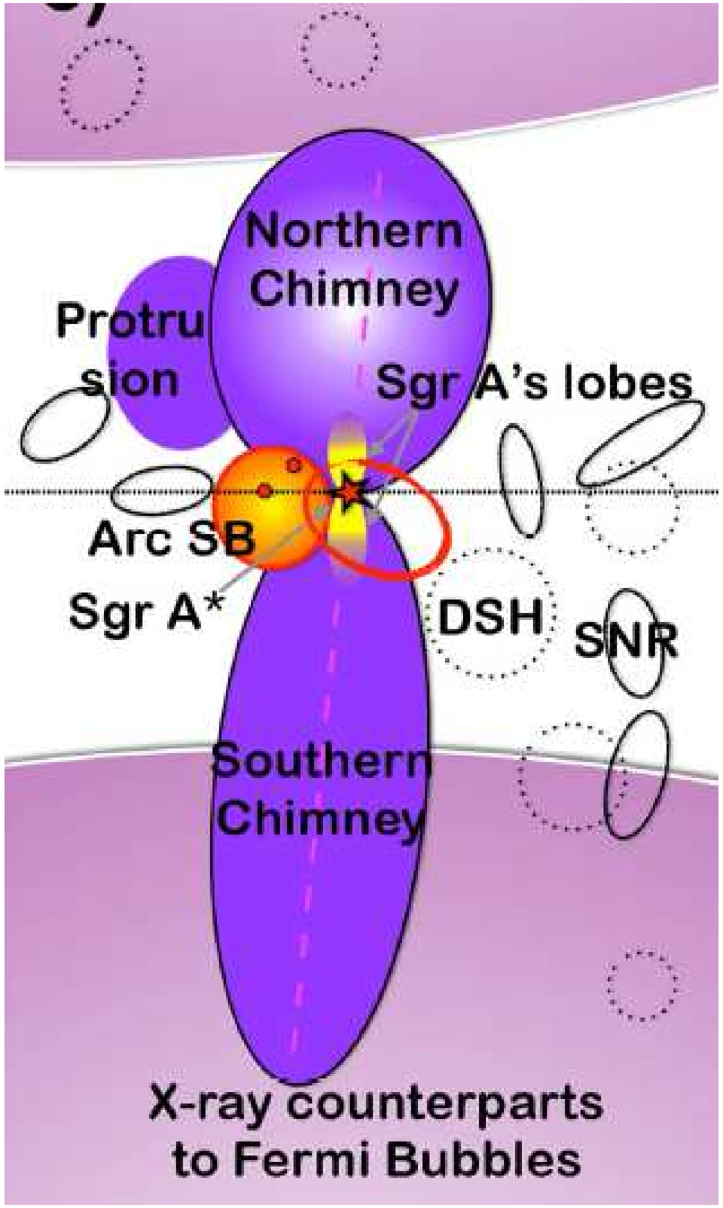


Credit: NASA/DOE/Fermi LAT/D. Finkbeiner et al.


Gamma-ray emissions
X-ray emissions
Milky Way
50,000 light-years
Sun

NASA

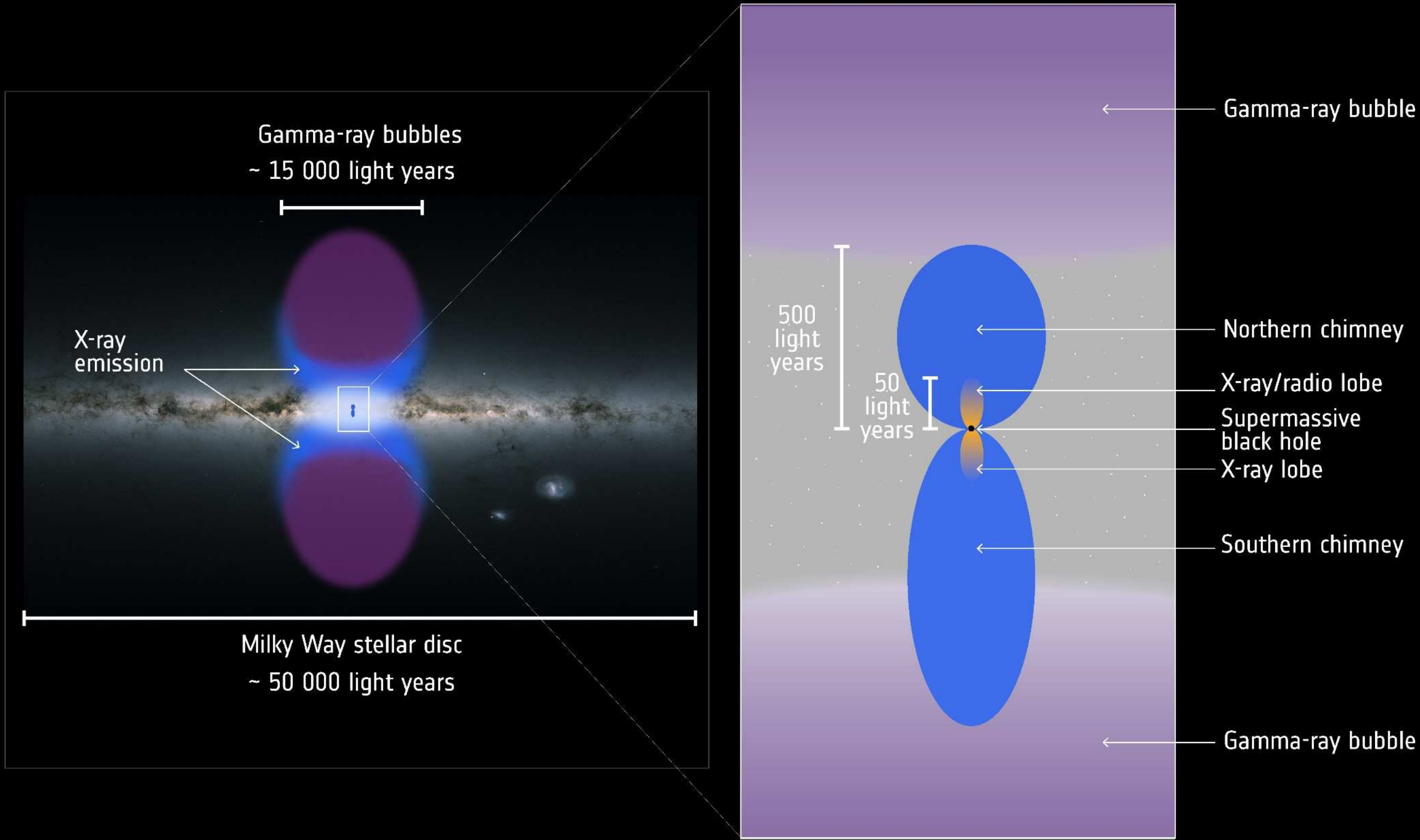
The Galactic Center Chimneys



- Scheme of Chimneys and other X-ray structures of the GC region
- The Chimneys link the GC region to the Fermi Bubbles
- No clear connection to the bipolar lobes (not excluded either)
- Originated in the nuclear region (like the lobes) or over more extended region (50 pc in long.)

- Origin:
  - Large Star Formation Episodes
  - AGN-like activity of the Super-Massive Black Hole

The Galactic Center Chimneys



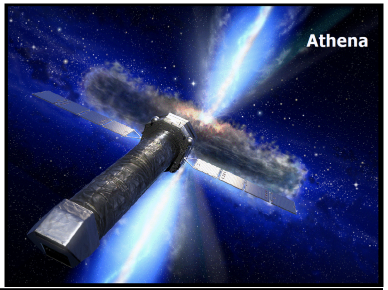
Credit: ESA – XMM-Newton

Summary

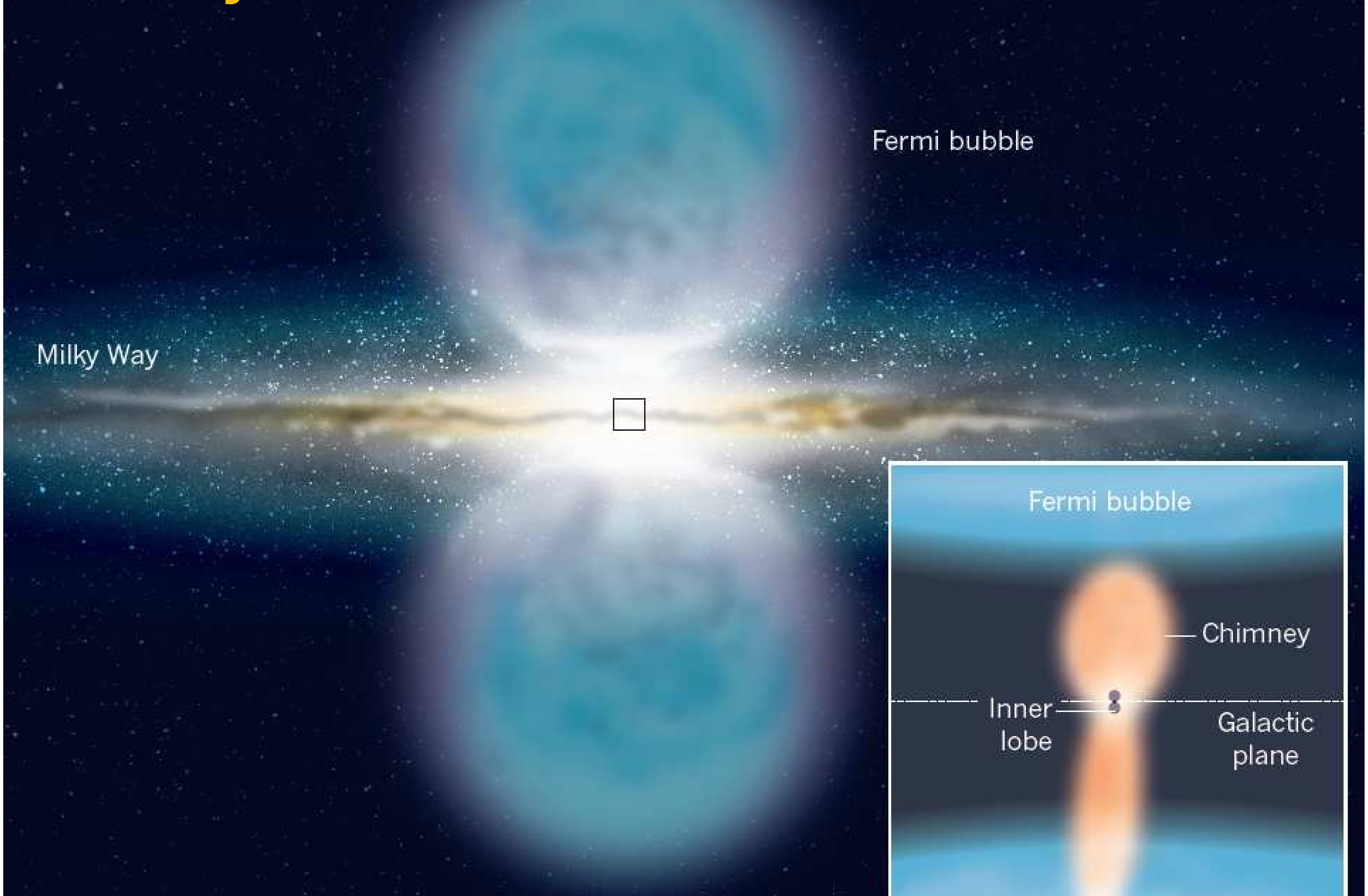
- **Variable Neutral Iron fluorescence line and X-ray continuum from molecular clouds (MC) in the Galactic Center (GC) are due to reflection of past X-ray outbursts (> 10^6 increase in Luminosity) from supermassive Black Hole Sgr A***
- The emission of all main MC varies => **no single century long outburst**
- **At least 2 events of different time scales (2 yr, 10 yr) propagate in CMZ (as proposed by Clavel+ 2013)**
- Monte Carlo spectral modelling on XMM/Chandra data of several MC allowed us **to locate the clumps and to determine the time of the 2 events**
- Work is in progress to establish X-ray emission of Sgr A* in the last millennium

- **Discovery of 150-pc Chimneys of hot gas North and South of the GC**
- **Connect the GC region to the Fermi Bubbles: channel of energy injection**
- Power 10^{39} erg/s , t $\approx 10^5$ yr => modest, compatible with the lower estimations of Fermi Bubbles power
- Origin: Star formation episodes or SMBH active phase ?

- Future observations: XMM, Chandra, Nu-STAR, …
- Future observatories : eROSITA, XRISM, XIPE, Athena …



Thank you Merci



Chernyakova 2019 March, Nature, N&V