An X-ray View of the GC

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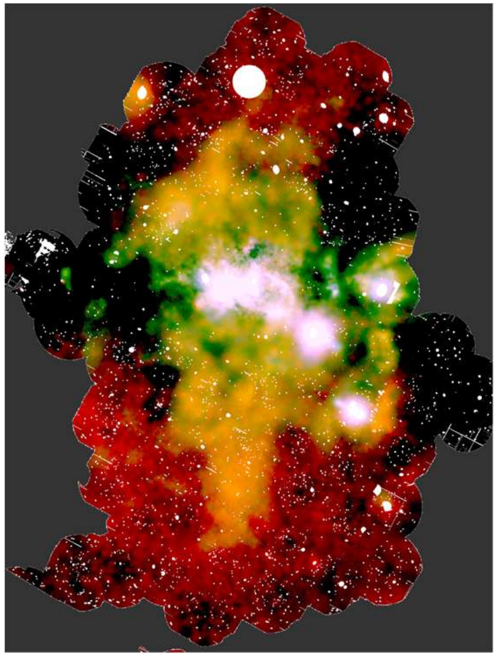
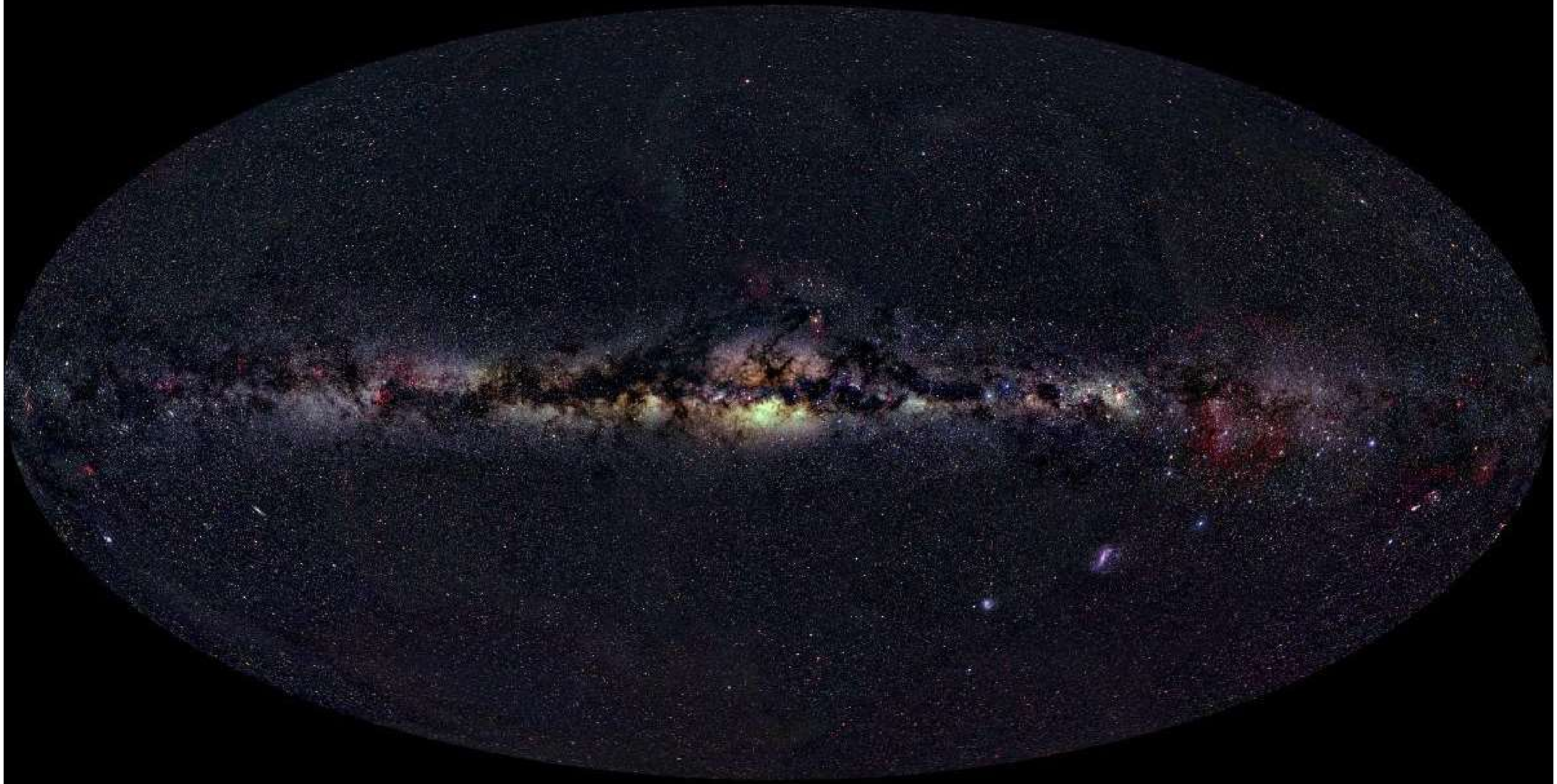


An X-Ray view of the Galactic Center

Topics:

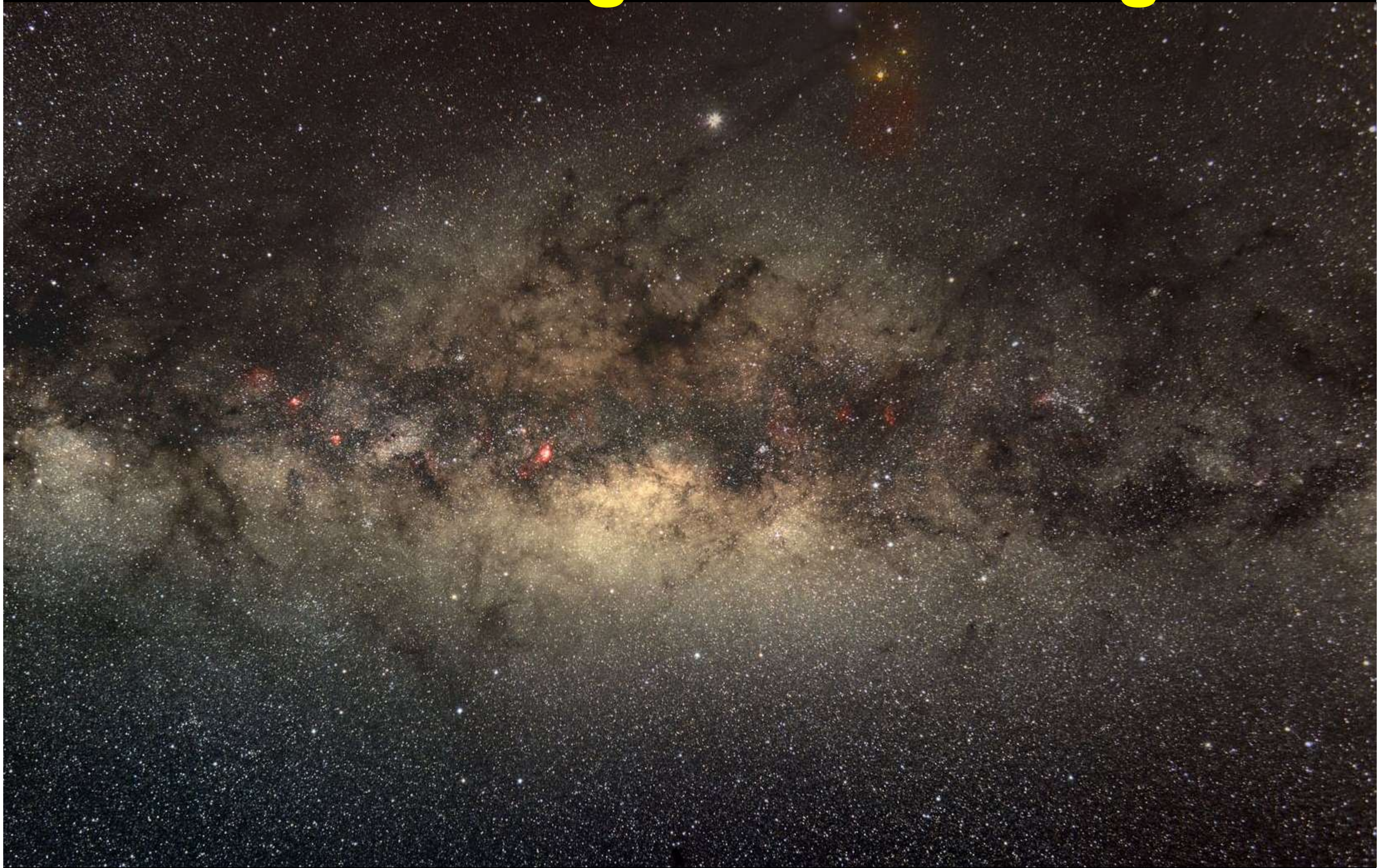
- Introduction to Galactic Center and CMZ
- Overview of the 2000-2012 XMM survey of CMZ
- **Sgr A* in X-rays: persistent and flaring emission**
- **Diffuse CMZ NT component: Echoes of Sgr A* (recent) past outbursts**
- Diffuse CMZ Thermal Hard component
- Point source population, cusp of (transients) XRBs
- **Soft X-rays from hot gaz, bubbles and chimneys: traces of more ancient Sgr A* AGN-like activity ?**
- Summary and perspectives

The Galaxy

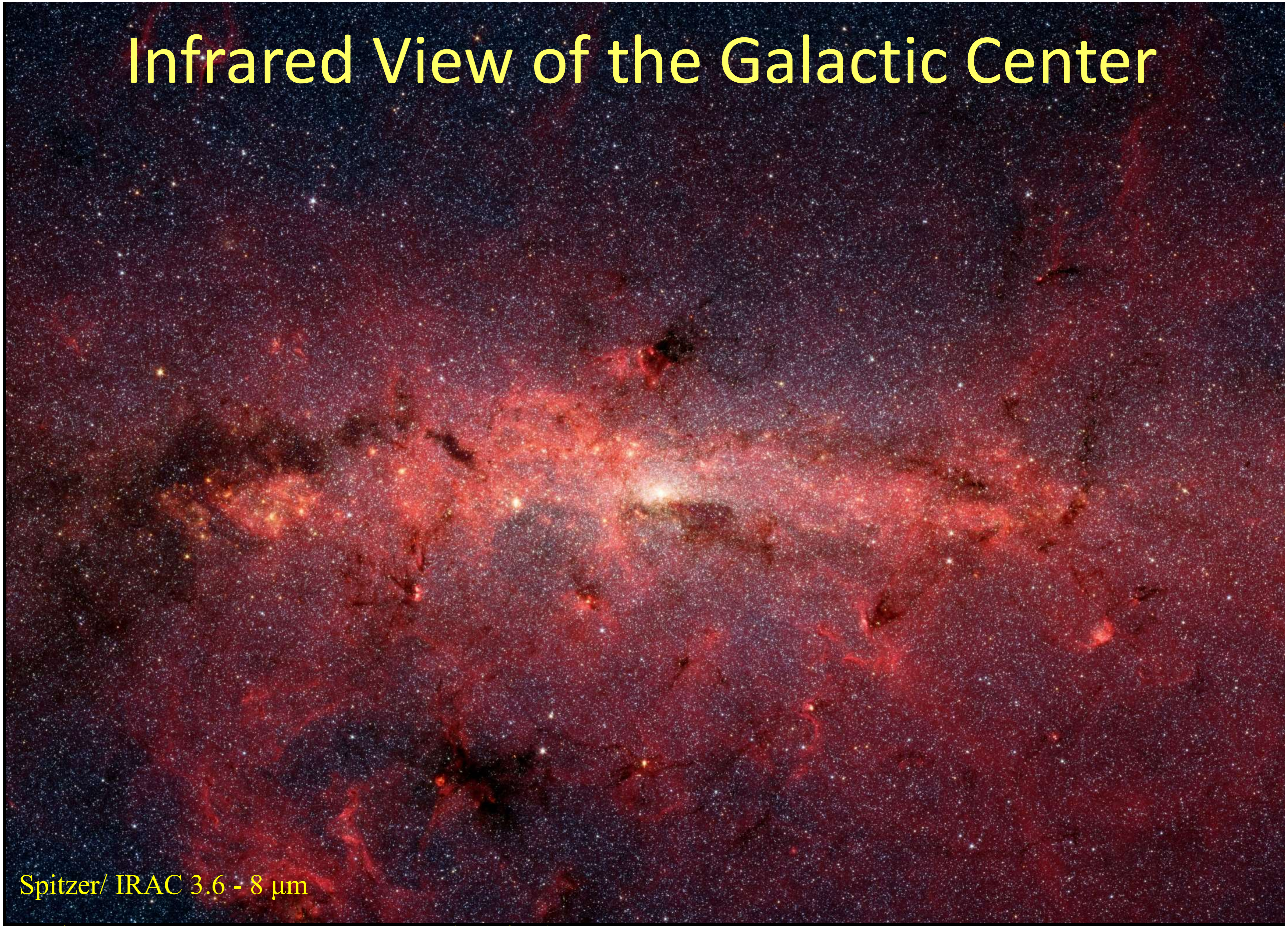


ESO

Galactic Bulge in Visible Light

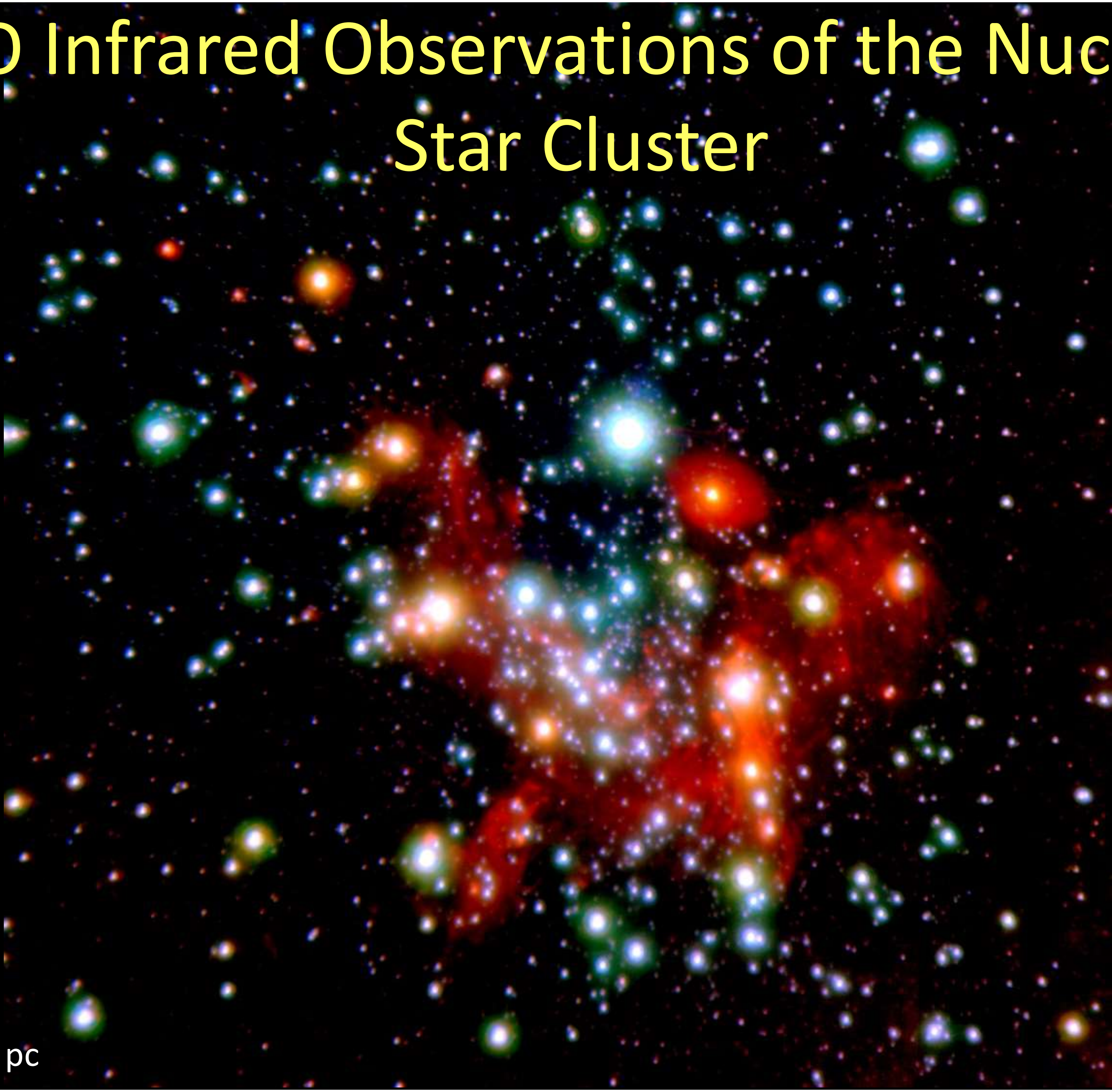


Infrared View of the Galactic Center



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

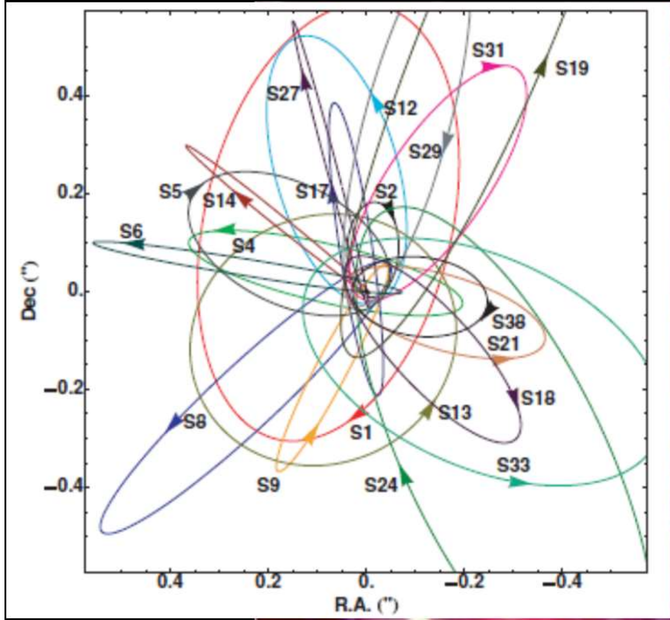
AO Infrared Observations of the Nuclear Star Cluster

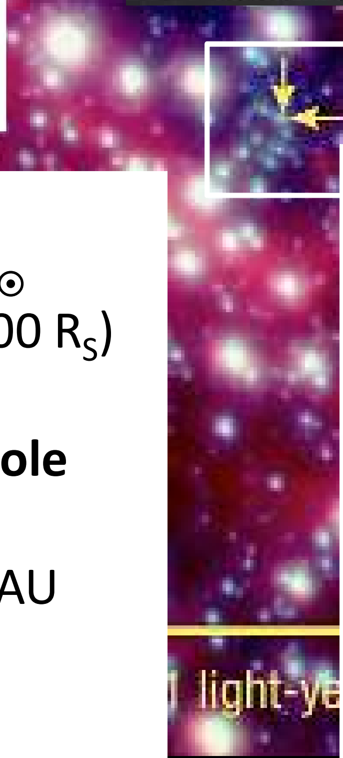


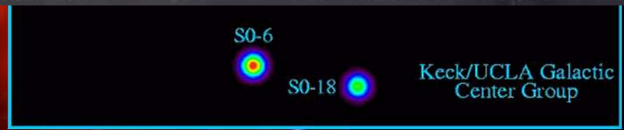
12″ = 0.5 pc

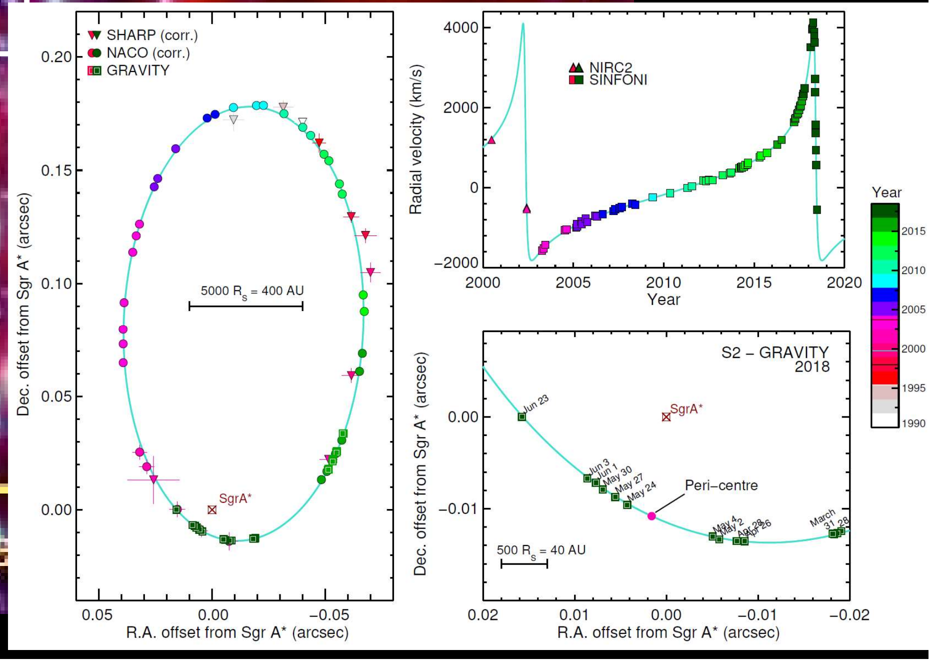
ESO

S-Cluster Star Orbits around a SMBH









At the GC distance of ~ 8 kpc
Enclosed Mass M_{enc}= 4 10^6 $M_\odot$
within a radius of 124 AU (1500 R_S)

=> A (Super) Massive Black Hole

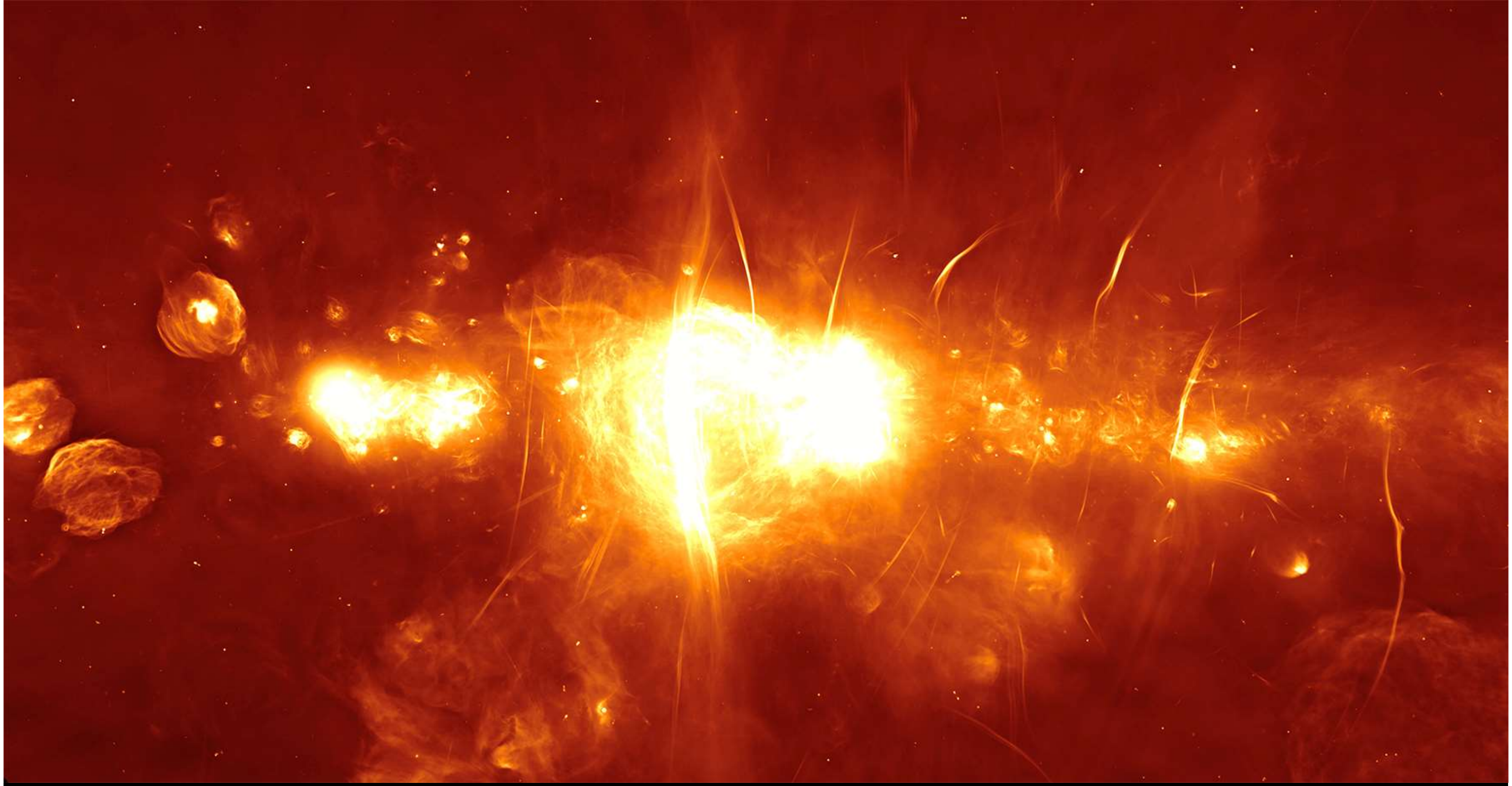
$M_\bullet$ = 4 10^6 $M_\odot$

R_S = 1.2 10^{12} cm = 0,08 AU

≅ 10 µas (at 8 kpc)

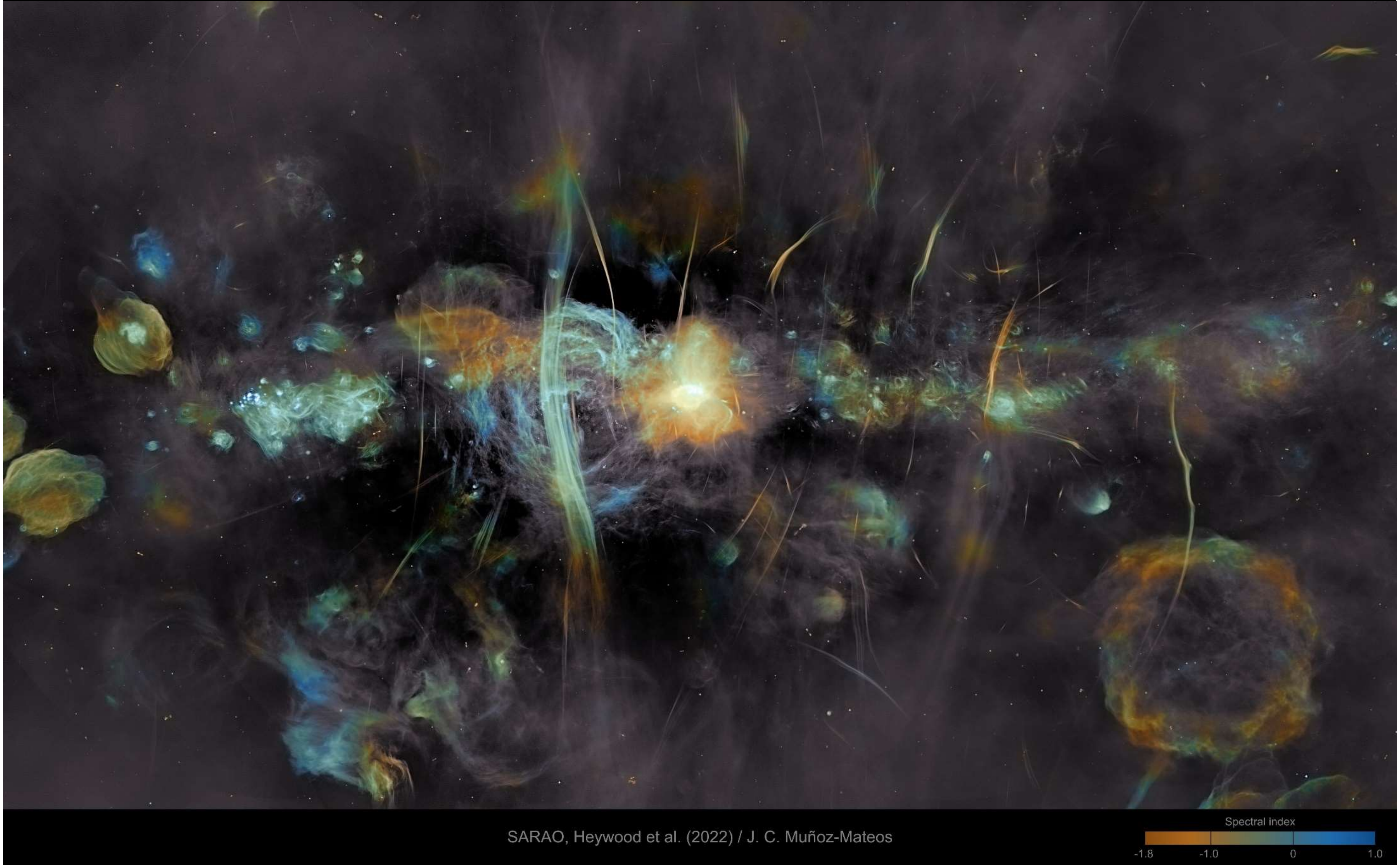
L_E = 5 10^{44} erg/s

Central Molecular Zone in Radio



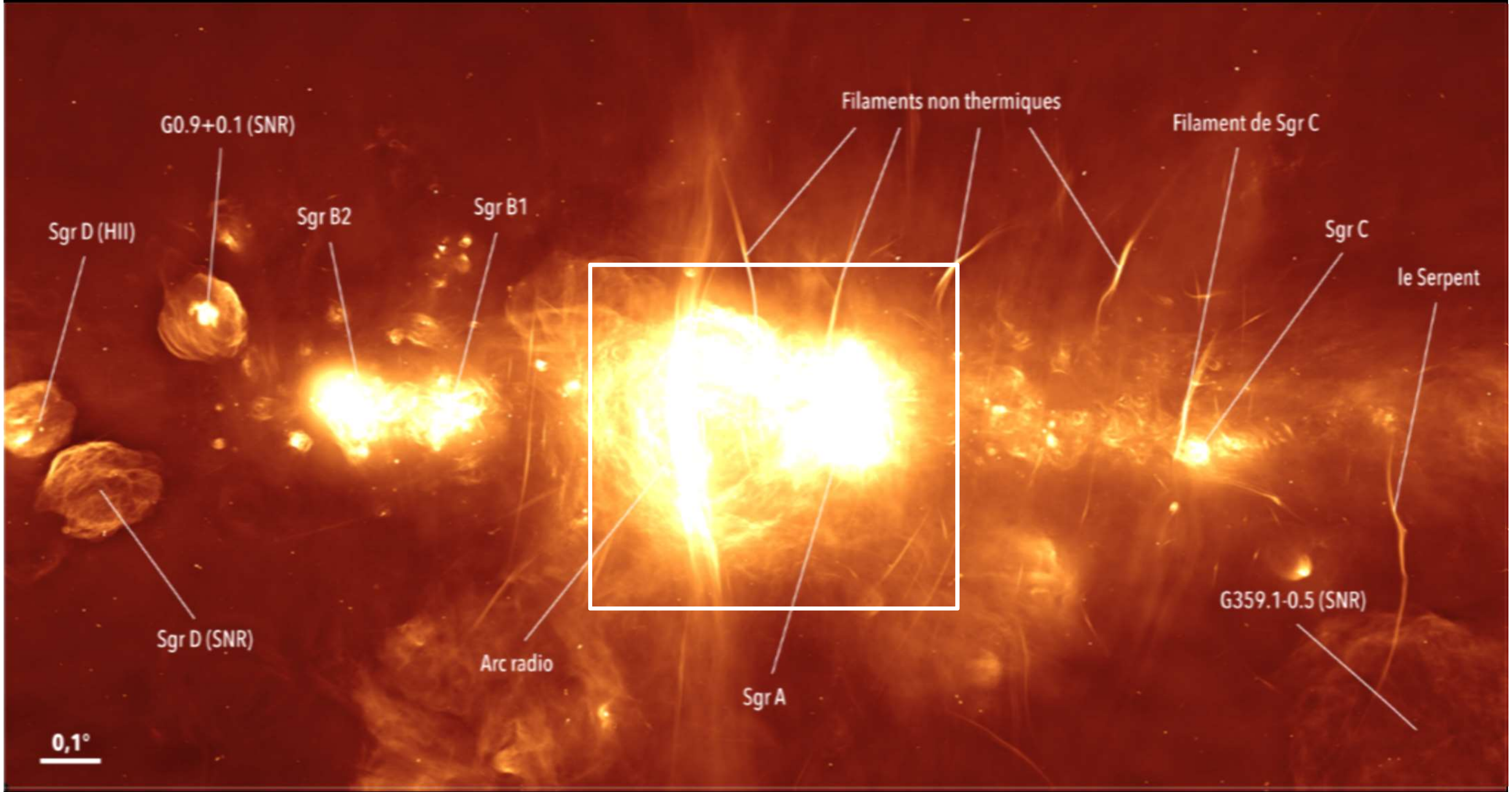
MERKAT

Central Molecular Zone in Radio

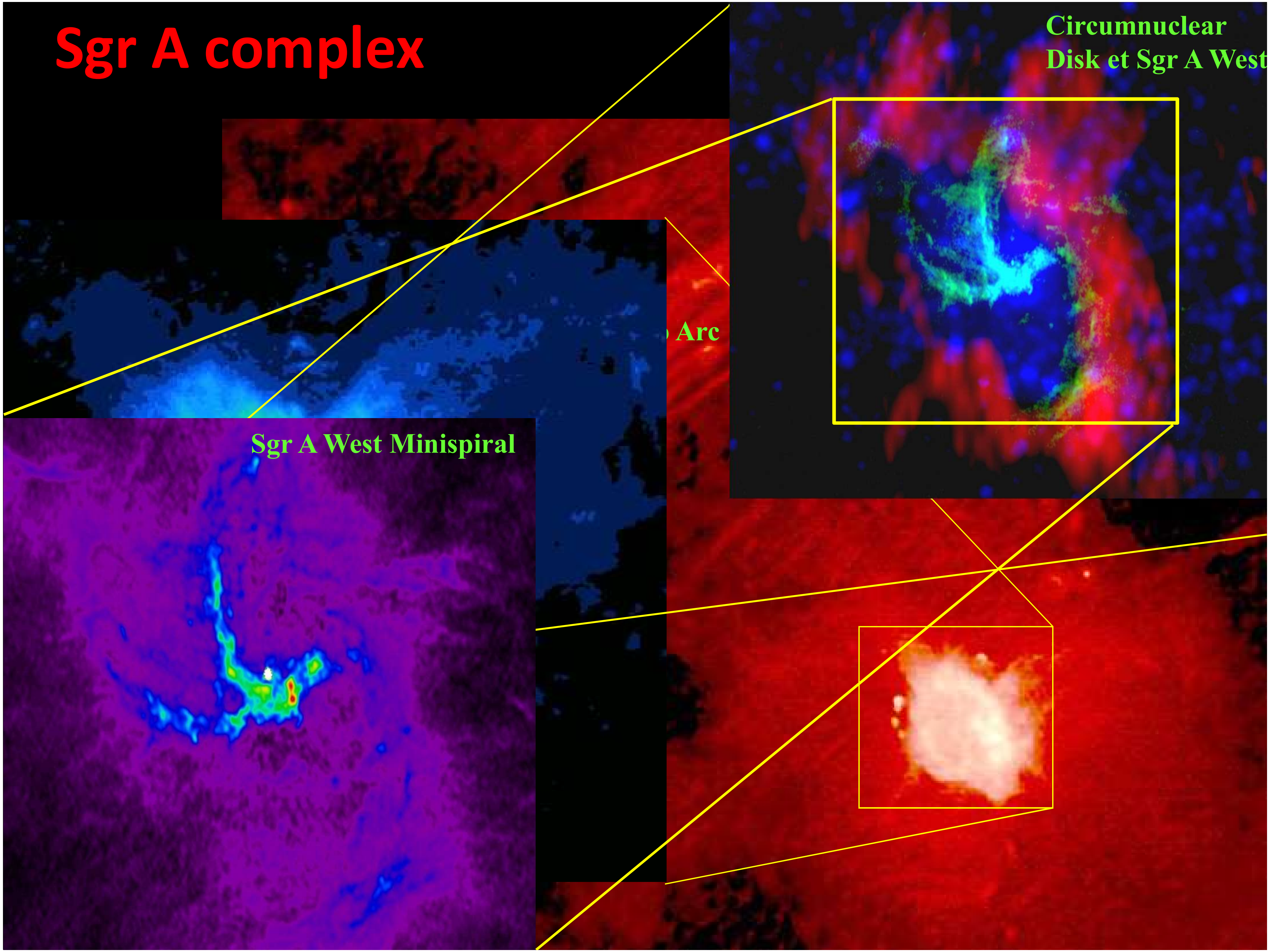


MERKAT

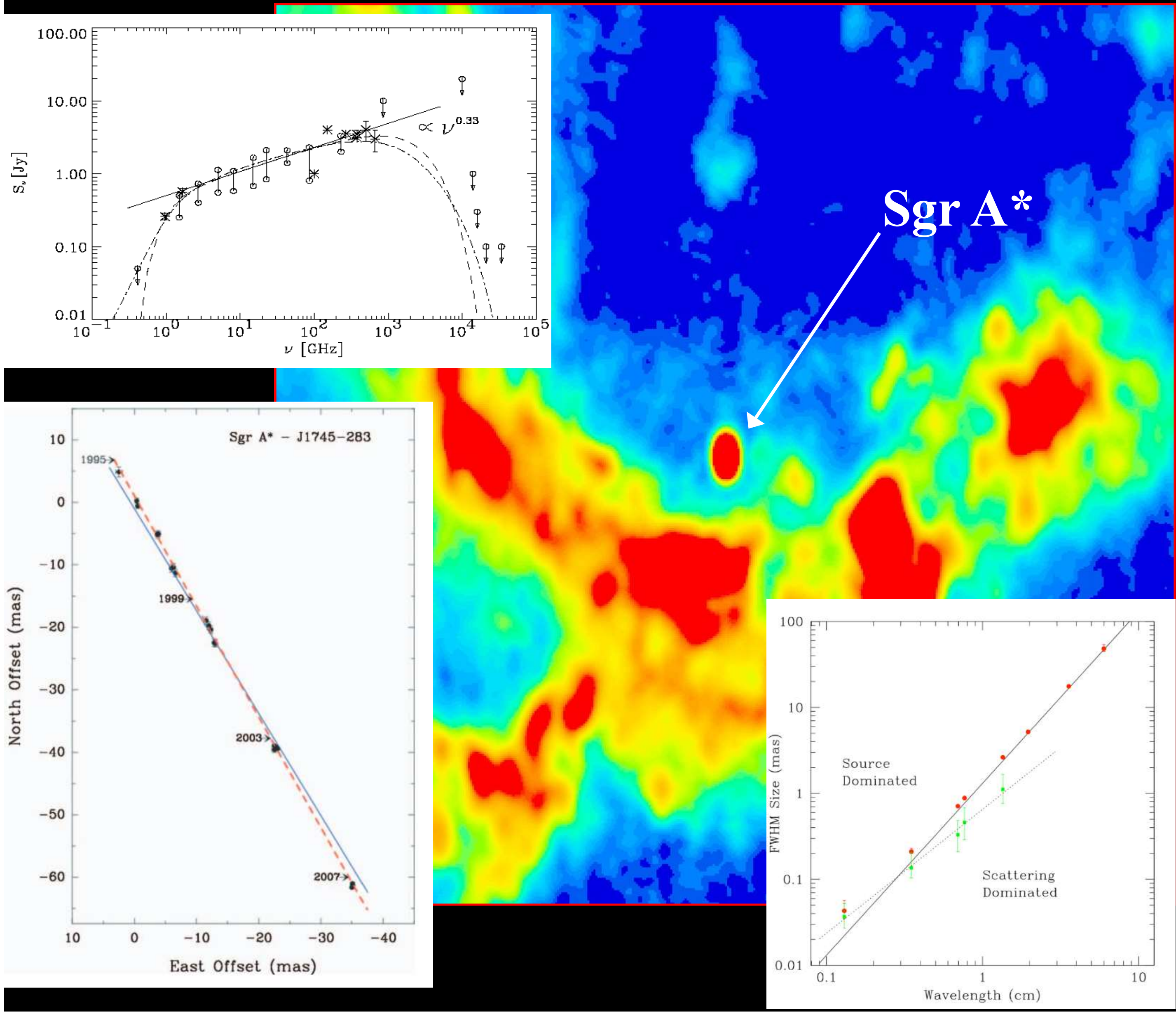
Central Molecular Zone in Radio



MEERKAT


Sgr A complex
Circumnuclear
Disk et Sgr A West
Arc
Sgr A West Minispiral

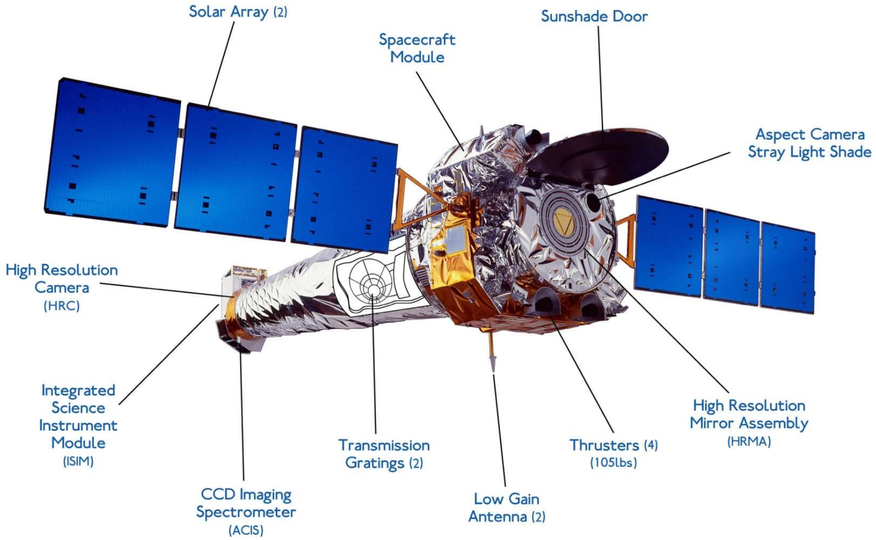
Sagittarius A* (discovered 1974)
electromagnetic counterpart of the Galaxy MBH



- Sgr A*: bright (1 Jy), variable, compact, synchrotron radio-s
- **Flat power-law spectrum** with high and low freq cut-offs, $L_R \approx 1.2\ 10^{36}$ erg s^{-1}, Sub-mm excess (> 100 GHz) linearly polar.
- **Size** ≈ 0.1 mas < 1 AU ≈ 15 R_S (M=3 $10^6\ M_\odot$)
- Low **proper motion** < 20km/s ⇒M>1000 $M_\odot$
- **Coincide** (< 10 mas) with star cluster dynamical center

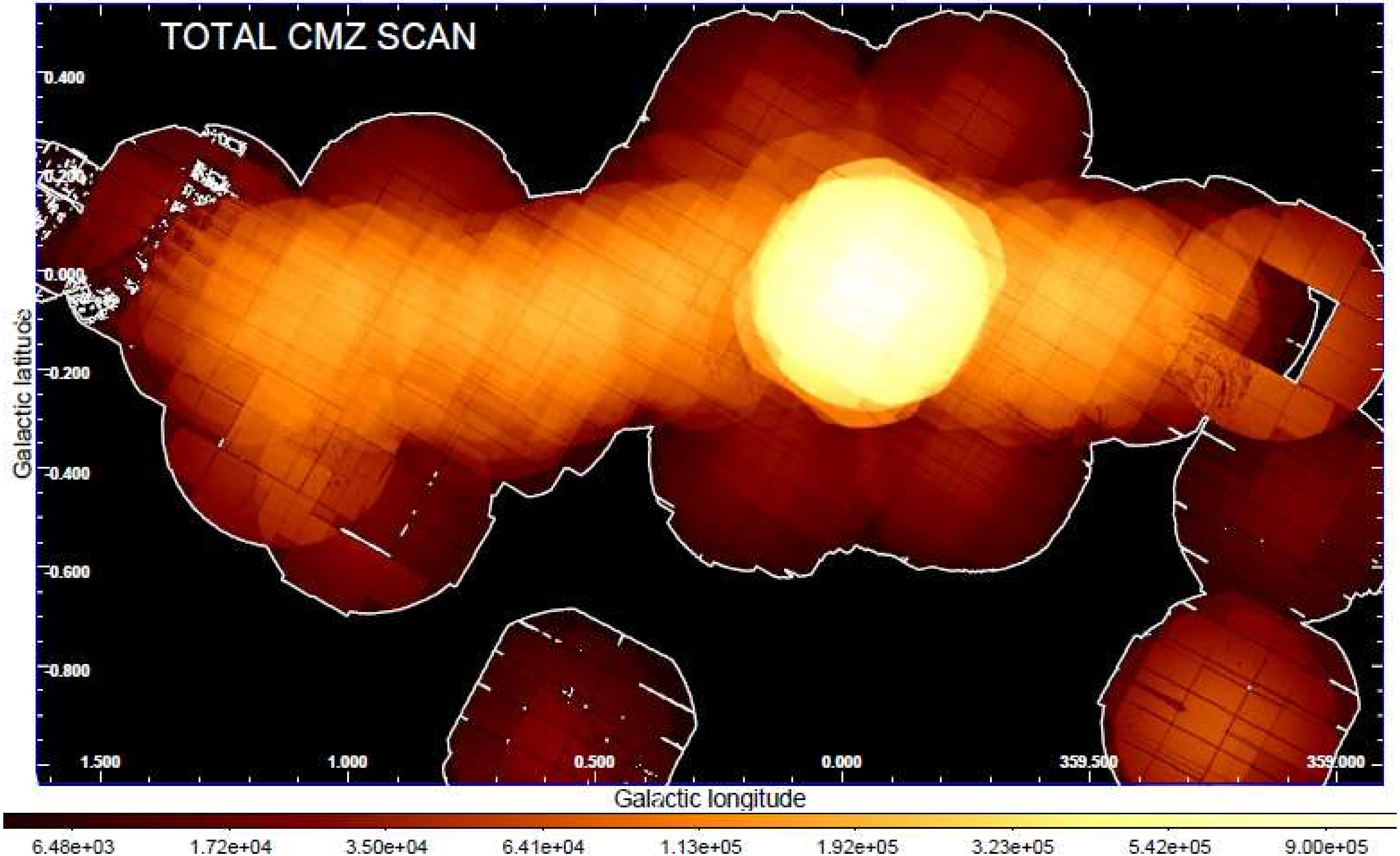
GC X-Ray Observations

Chandra (NASA) : 0.1 – 10 keV

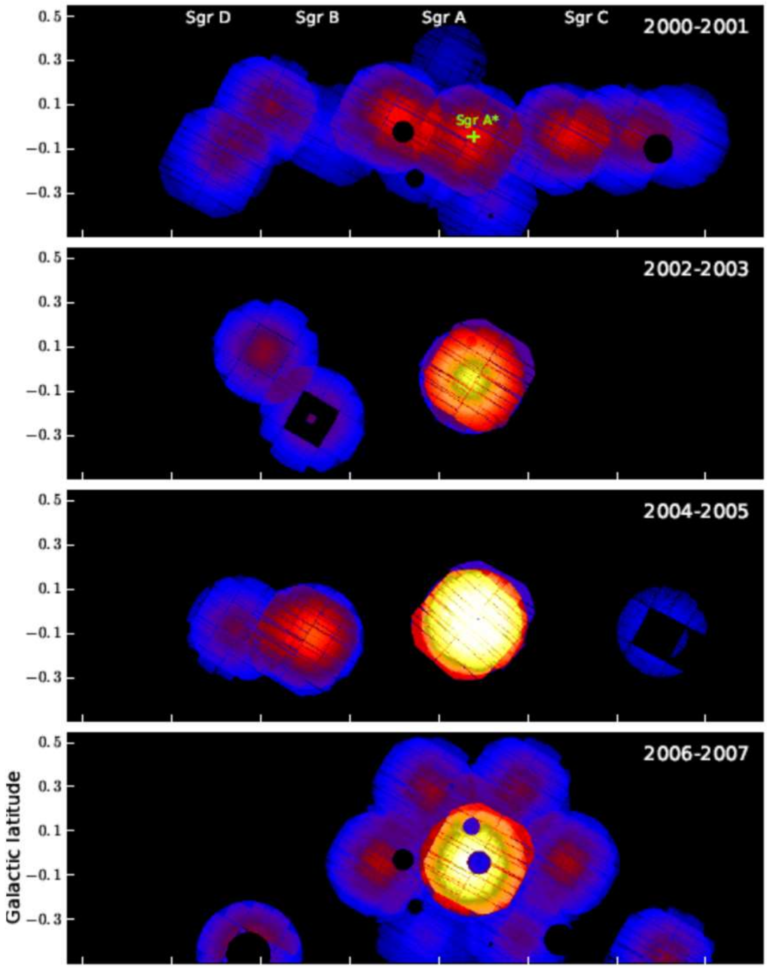


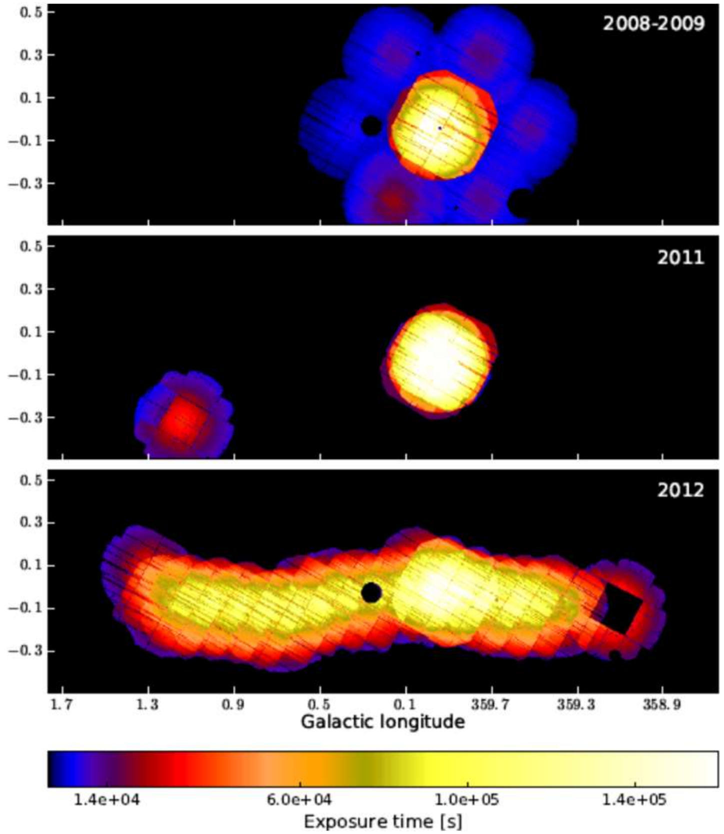
- X-ray Observatories used in the surveys of the Central Molecular Zone+ in 1999 – 2018
- Energy bands: 0.1 keV – 3 MeV
  Angular Res : 1” – 12’
- Also: Suzaku (1-10 keV), Nu-STAR (3-80 keV)

Total Exposure of GC 2000-2012 XMM Obs.



GC XMM-Newton Surveys





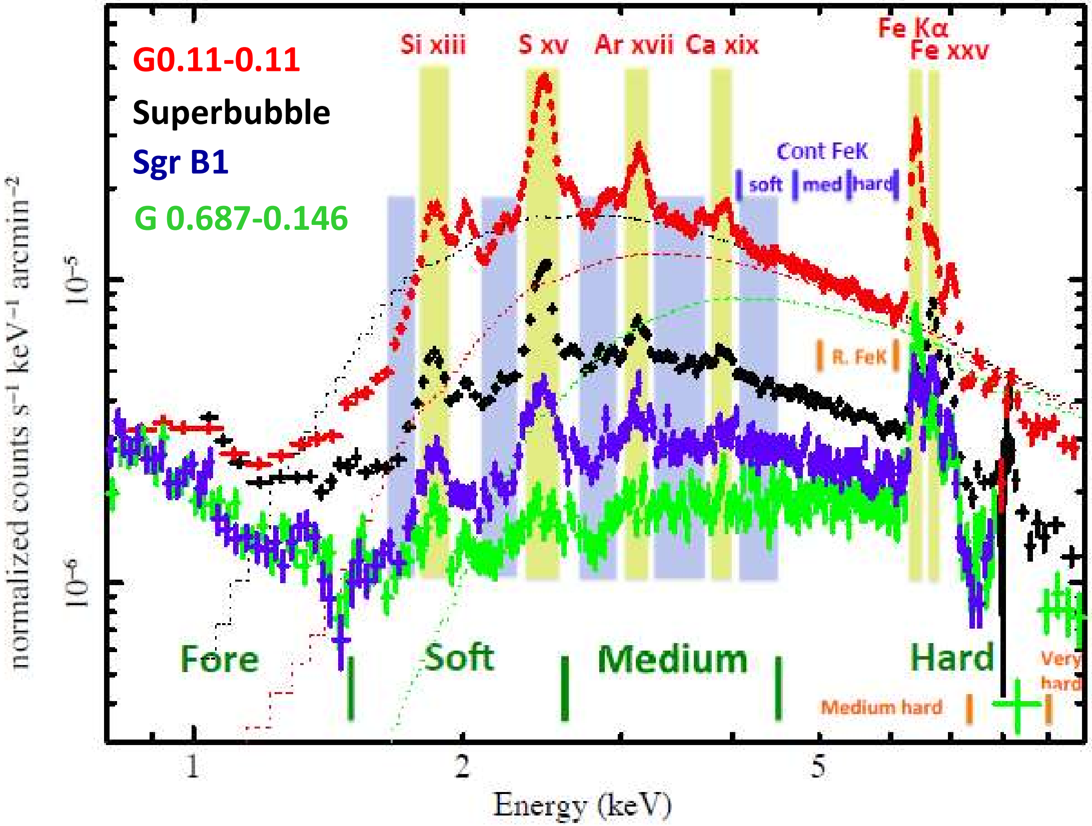
Exposure Map (s) in galactic coordinates from 2000-2012 XMM Observations of GC CMZ (3.2° x 1° = 461 pc x 144 pc) - point sources subtracted

XMM 2000-2012 data including 2 large programs of CMZ survey:

101 obs. with total exp. > 2 Ms

Terrier et al. 2018

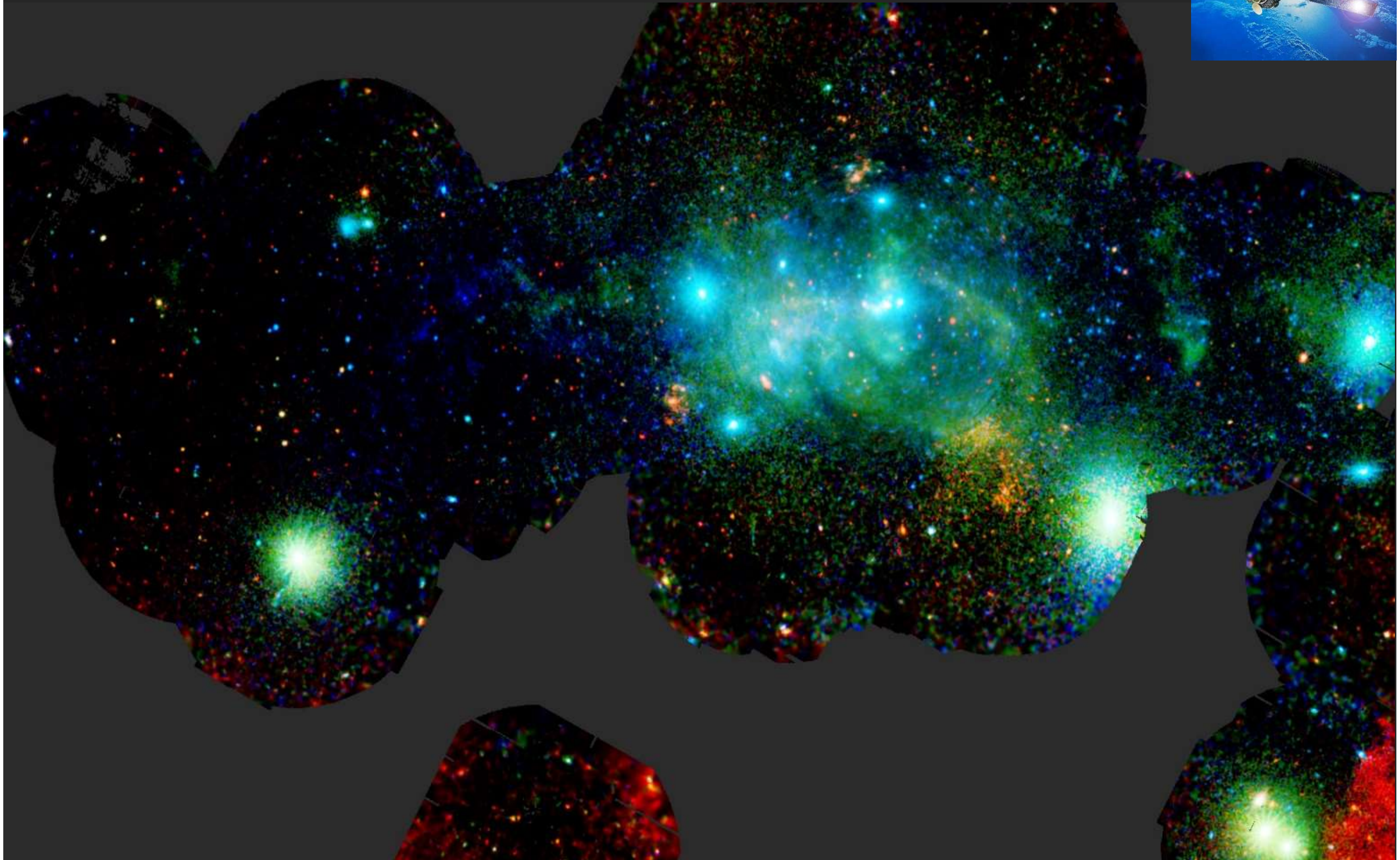
Energy Bands of GC CMZ XMM Maps



Standard continuum bands:				
Soft	Medium	Hard†		
0.5-2	2-4.5	4.5-12		
GC continuum bands:				
Fore	GC Soft	GC Medium	GC Hard†	
0.5-1.5	1.5-2.6	2.6-4.5	4.5-12	
Soft emission lines:				
Si XIII	S XV	Ar XVII	Ca XIX	
1.80-1.93	2.35-2.56	3.03-3.22	3.78-3.99	
Continuum subtraction soft emission lines:				
Red-Si	Si-S	S-Ar	Ar-Ca	Blue-Ca
1.65-1.77	2.1-2.3	2.7-2.97	3.27-3.73	4.07-4.5
Fe K lines:				
Fe Kα	Fe XXV			
6.3-6.5	6.62-6.8			
Continuum subtraction Fe K:				
CFeK	CsFeK soft	CmFeK medium	ChFeK hard	
5-6.1	4.0-4.7	4.7-5.4	5.4-6.1	

Ponti et al. 2015

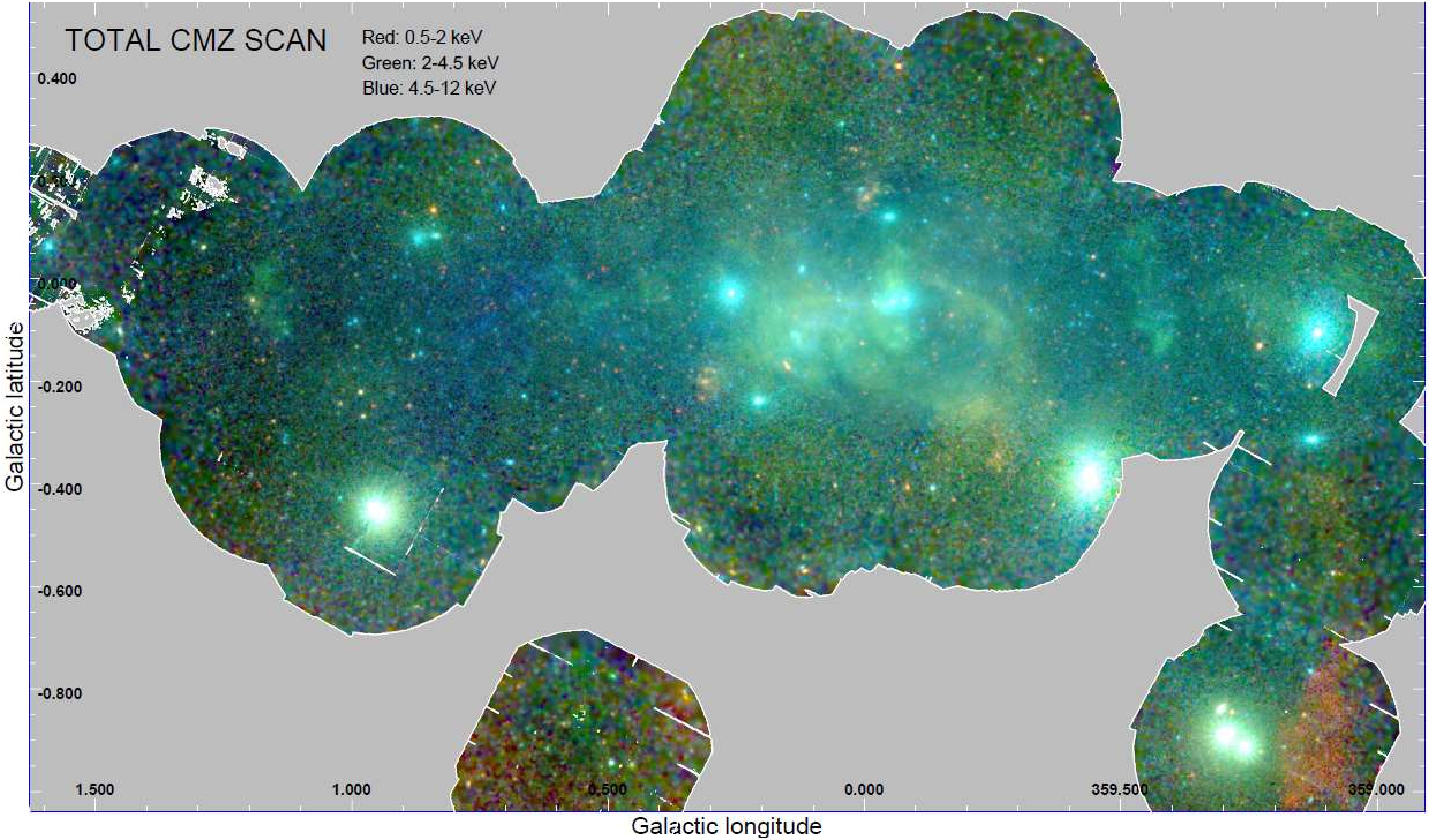
12 yr XMM Galactic Center Survey



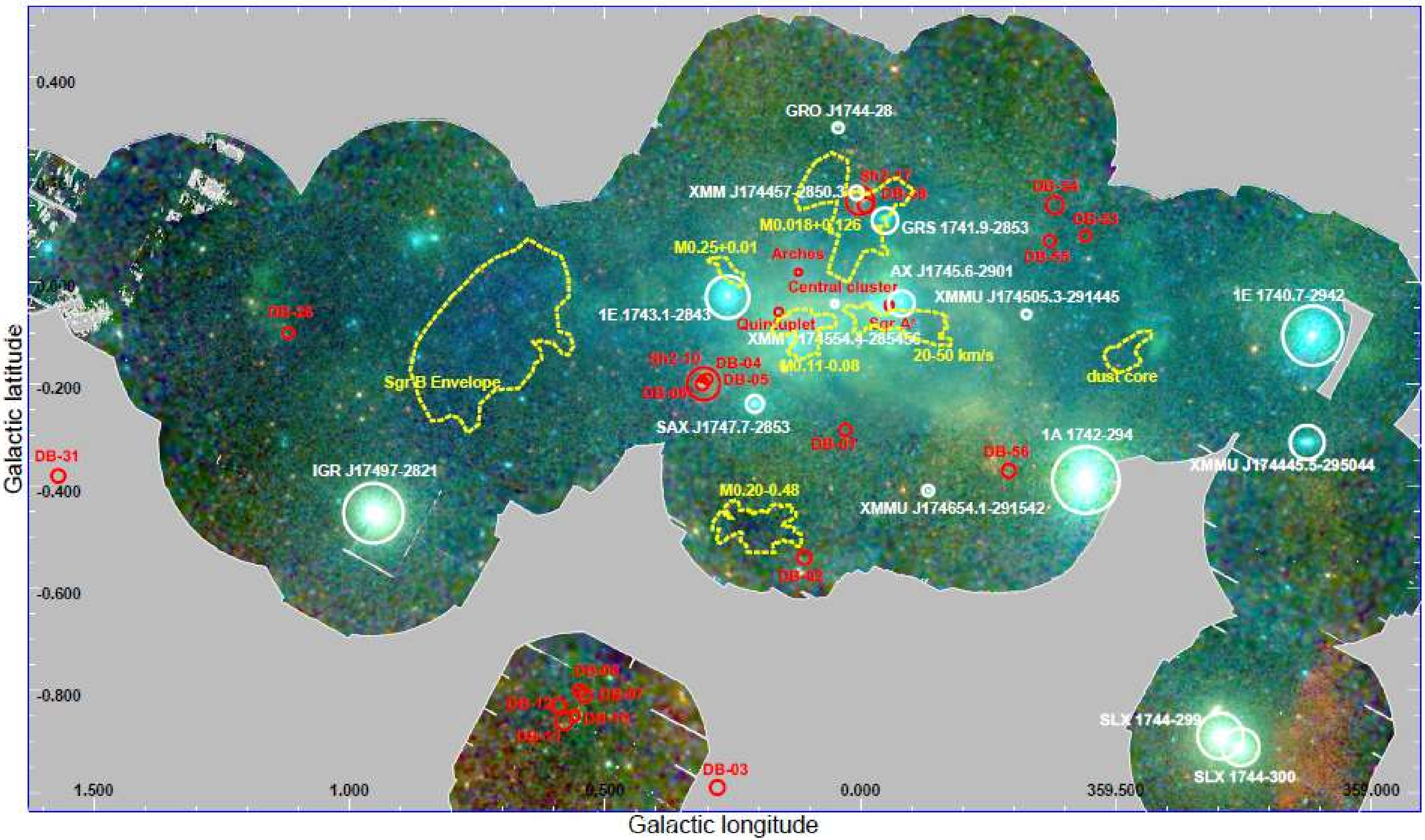
0.5 – 12 keV Image

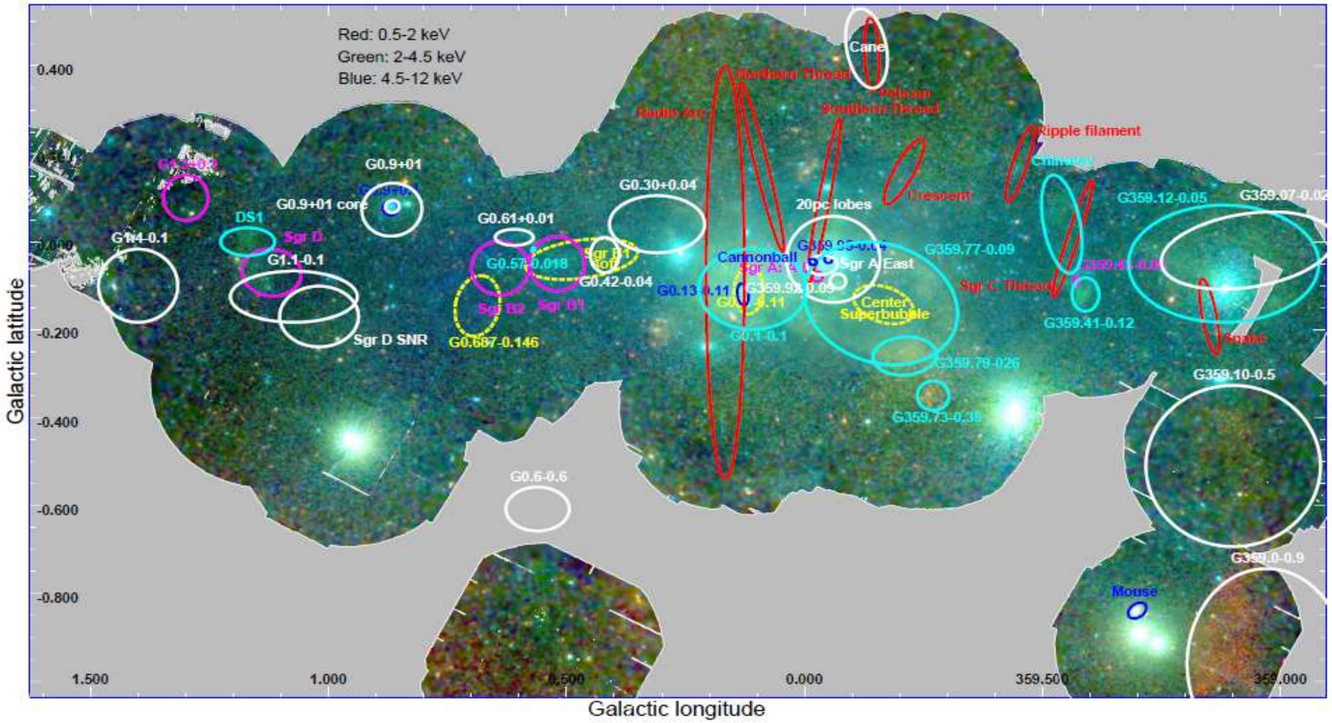
Ponti et al. 2015

XMM CMZ Survey



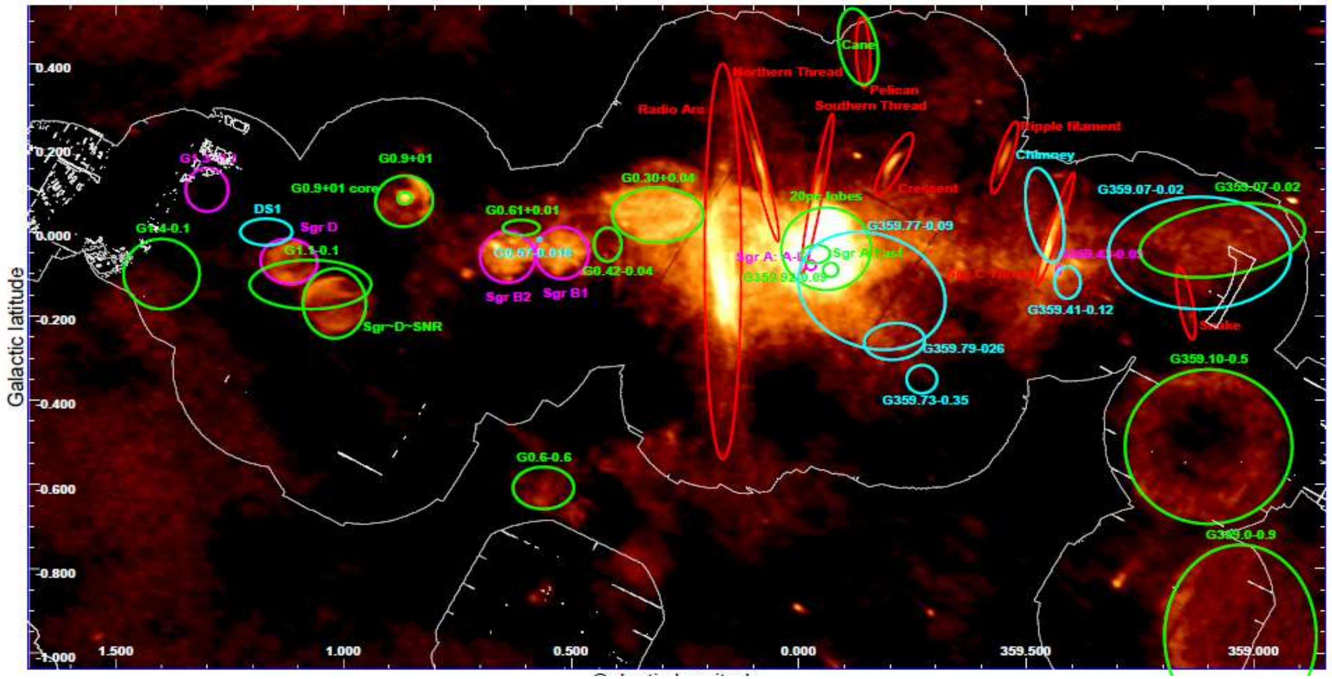
XMM CMZ Survey

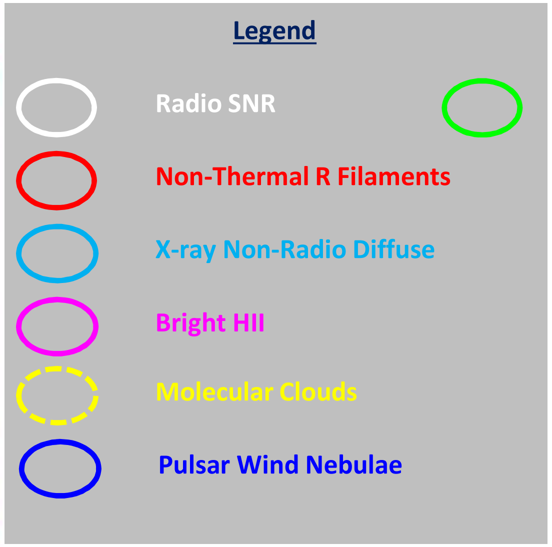


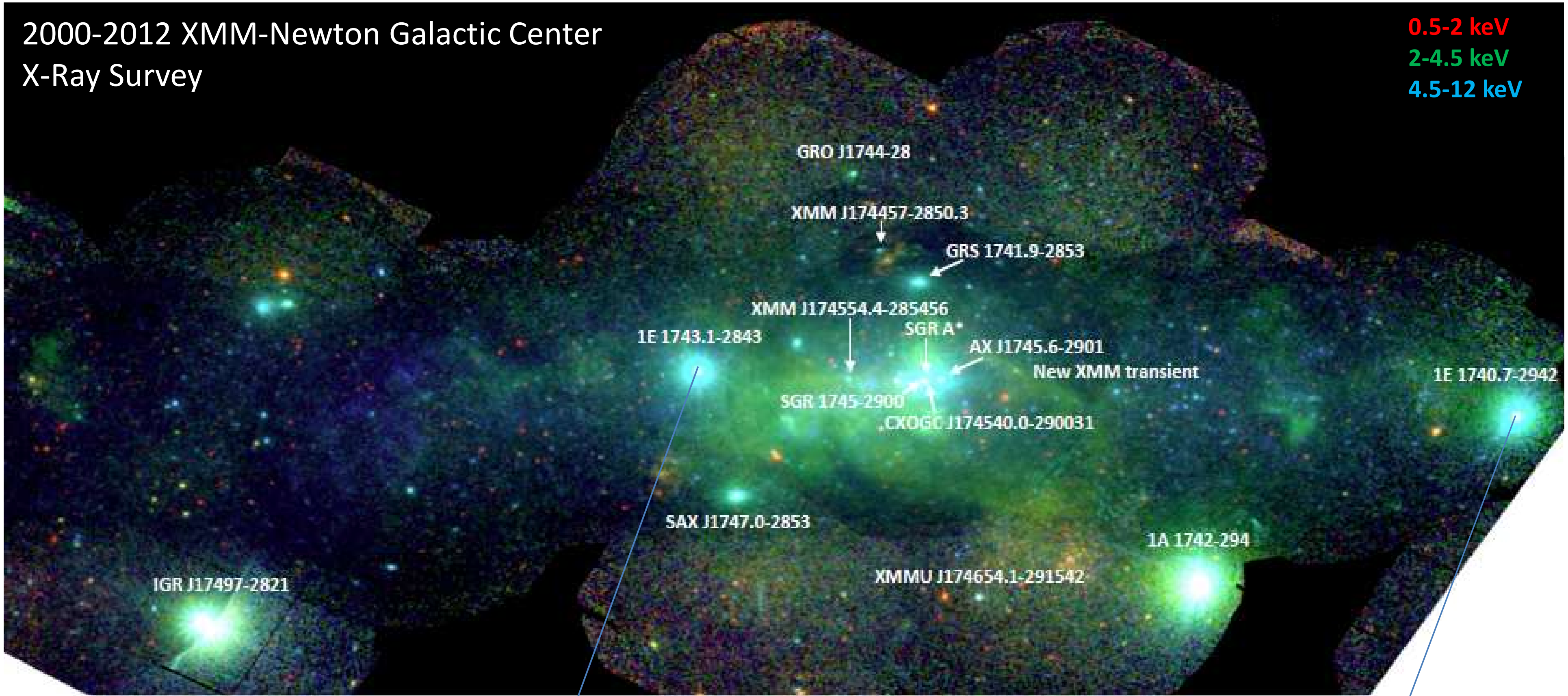


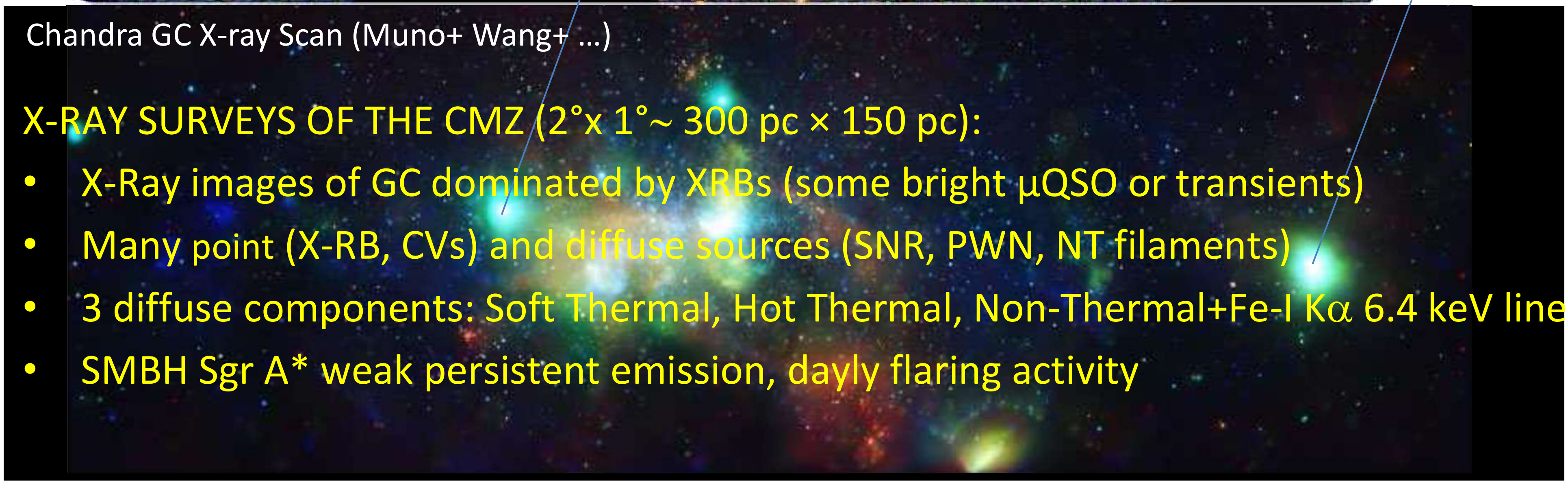
Central Molecular Zone XMM X-ray Survey and Catalog of Diffuse Sources

(Ponti et al. 2015)





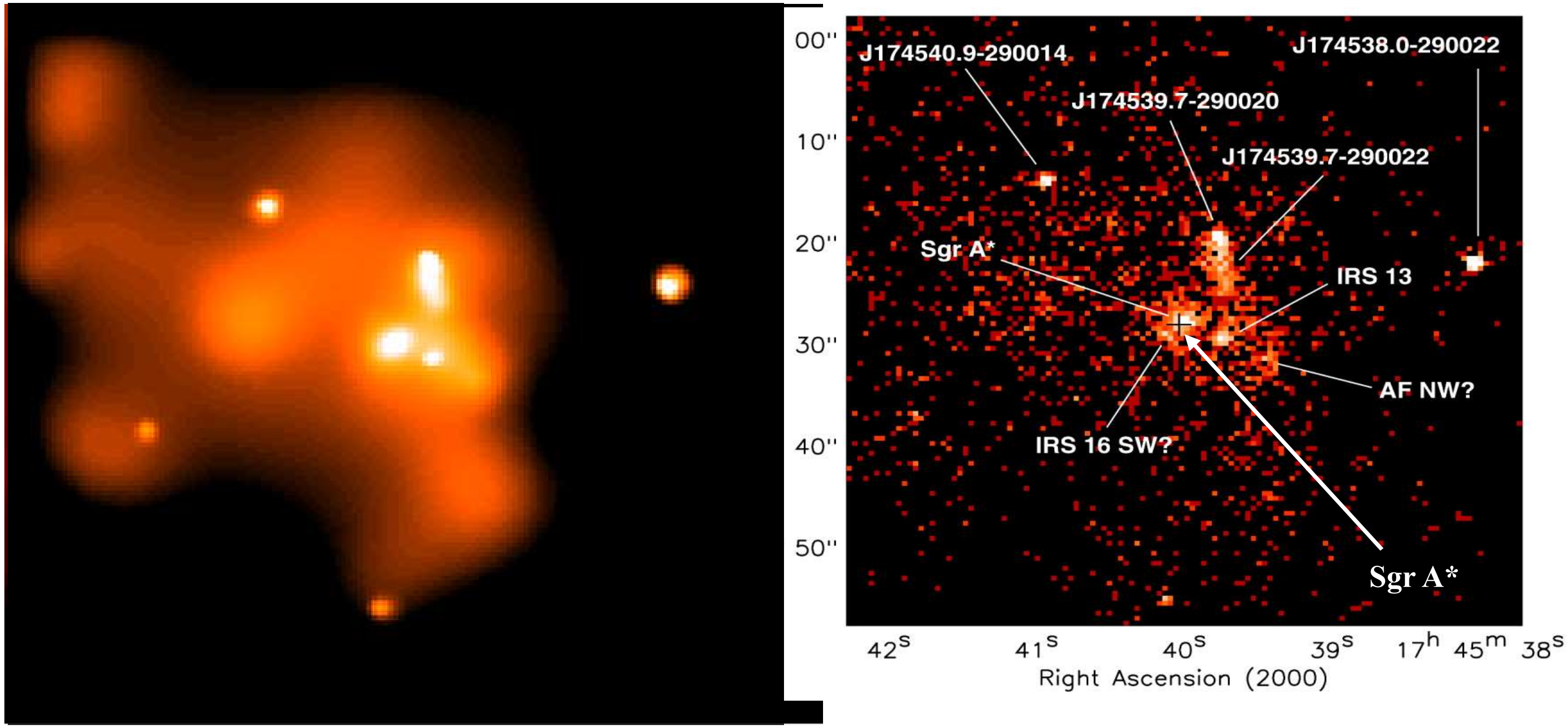




X-RAY SURVEYS OF THE CMZ (2°x 1°~ 300 pc × 150 pc):

- X-Ray images of GC dominated by XRBs (some bright µQSO or transients)
- Many point (X-RB, CVs) and diffuse sources (SNR, PWN, NT filaments)
- 3 diffuse components: Soft Thermal, Hot Thermal, Non-Thermal+Fe-I Kα 6.4 keV line
- SMBH Sgr A* weak persistent emission, dayly flaring activity

Chandra resolves the central pc in X-rays (2000)

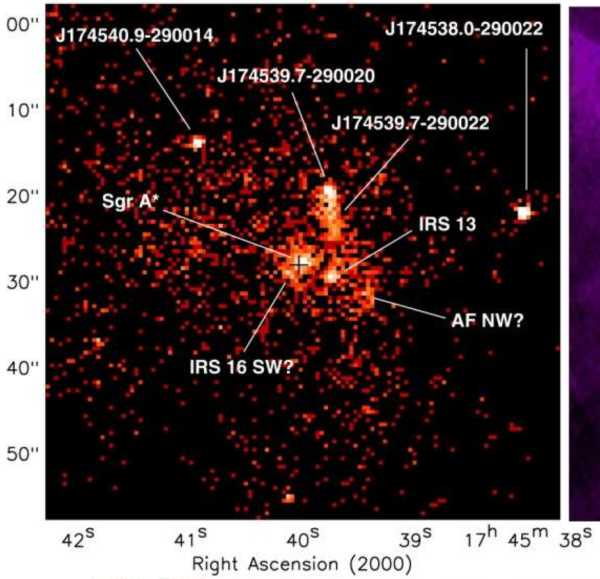


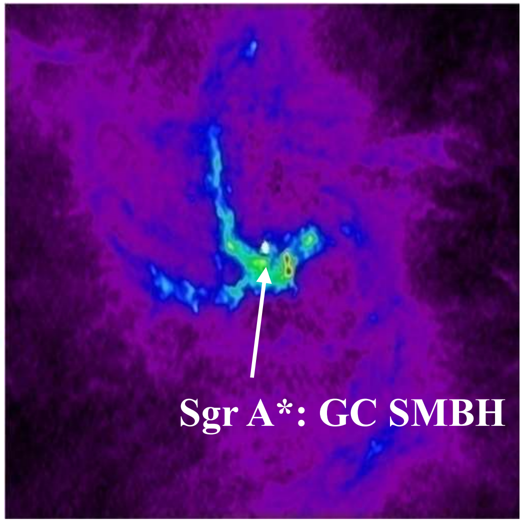
Diffuse Emission, several weak point sources, one compatible with Weak persistent emission of Sgr A*: L_X(2-10 keV) ≈ 2 10^{33} erg s^{-1}

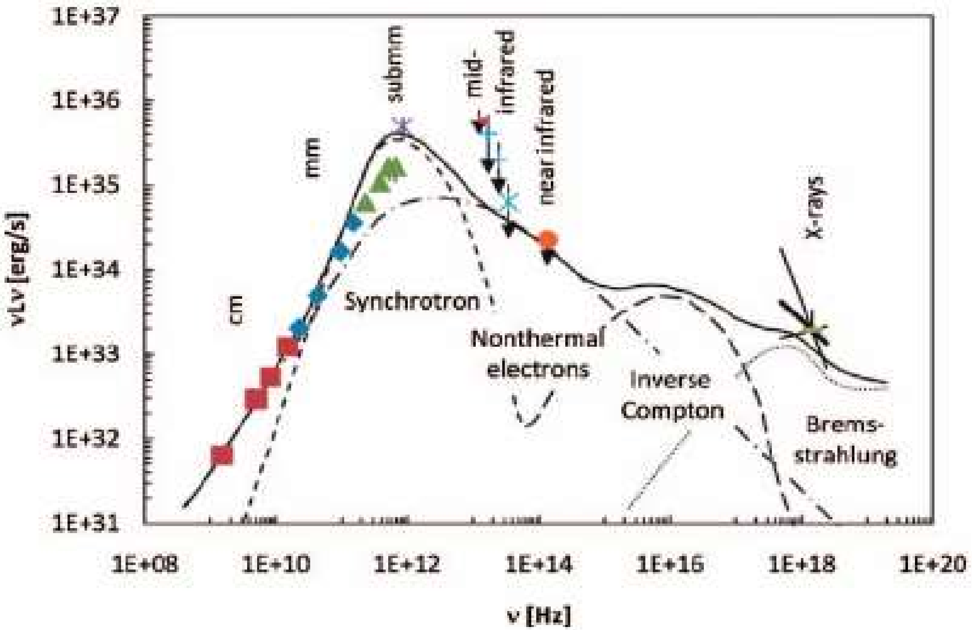
Soft power law spectrum (α ≈ - 2.7), partly extended (≈ 1″) , not variable

(Baganoff et al. 2003)

Chandra: Sgr A* X-ray persistent emission



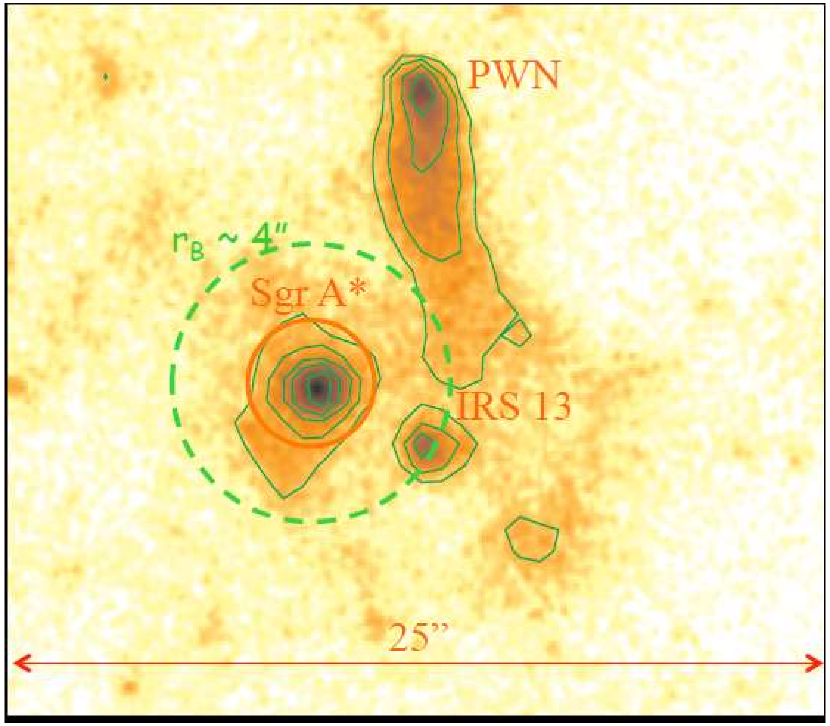




- Sgr A*: EM counterpart of the BH revealed in the GC by S-star cluster orbits measured in NIR
- SMBH M = 4 10^6 $M_\odot$, R_S = 1.2 10^{12} cm ~ 0.1 AU, L_E = 7 10^{44} erg/s
- **X-ray Chandra Detection: L_X=2 10^{33} erg/s), soft spectrum, extended (~1")**
- Sgr A* Total L ~ 10^{36} erg/s (radio) << L_E: Very low mass accretion rate
- Sub-mm polarization => $\dot{M}$~10^{-8} $M_\odot$/yr << stellar winds $\dot{M}$~$10^{-6/-5}$ $M_\odot$/yr
- Prototype of very low accretion BH: Sgr A* L << L of LLAGN (~ 10^{39-42} erg/s)
- Test bed for ADAF/RIAF models of BH accretion flow: at Bondi (R_B=10^5 R_S) n_e~ 10^2 cm^{-3}, T ~ 7 10^7 K°; at ~ 10 R_S n_e~ 10^{6-7} T ~ 10^{11} K°, B ~ 10-50 G

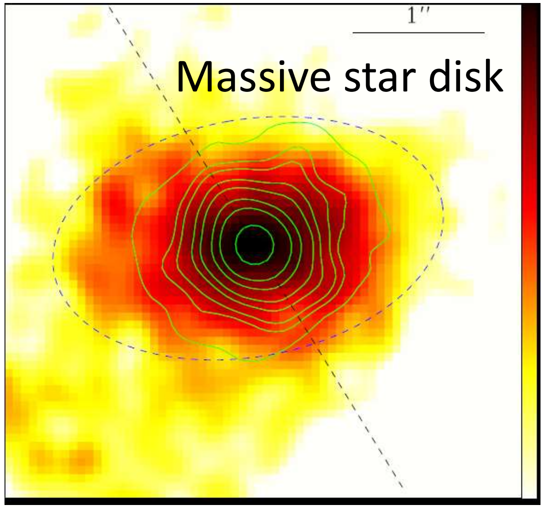
Baganoff+03, Quataert02, Genzel+10, Yuan&Narayan14, Wang+13

Radiatively Inefficent Accretion Flow in Sgr A*

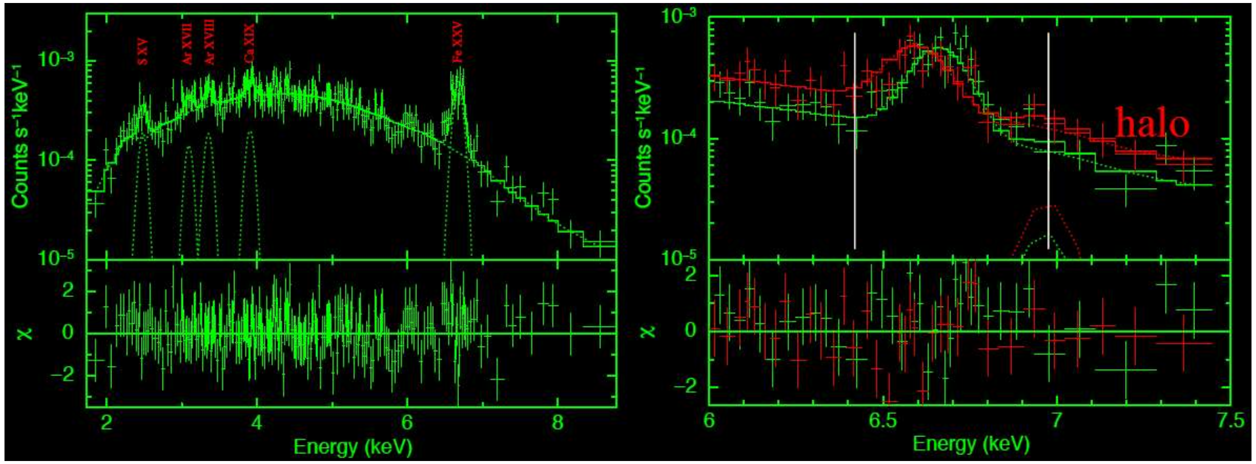


- Chandra 3 Ms XVP Obs. of Sgr A* persis. emiss. with ACIS-S /HEGT 0th ord.
- Detection lines from hot accretion flow
- Fe I Ka not detected =>no * coronal emiss.
- Low FeXXVI, E_{FeXXV} compared to halo, favor accretion flow with out-flows (RIAF) with s~1

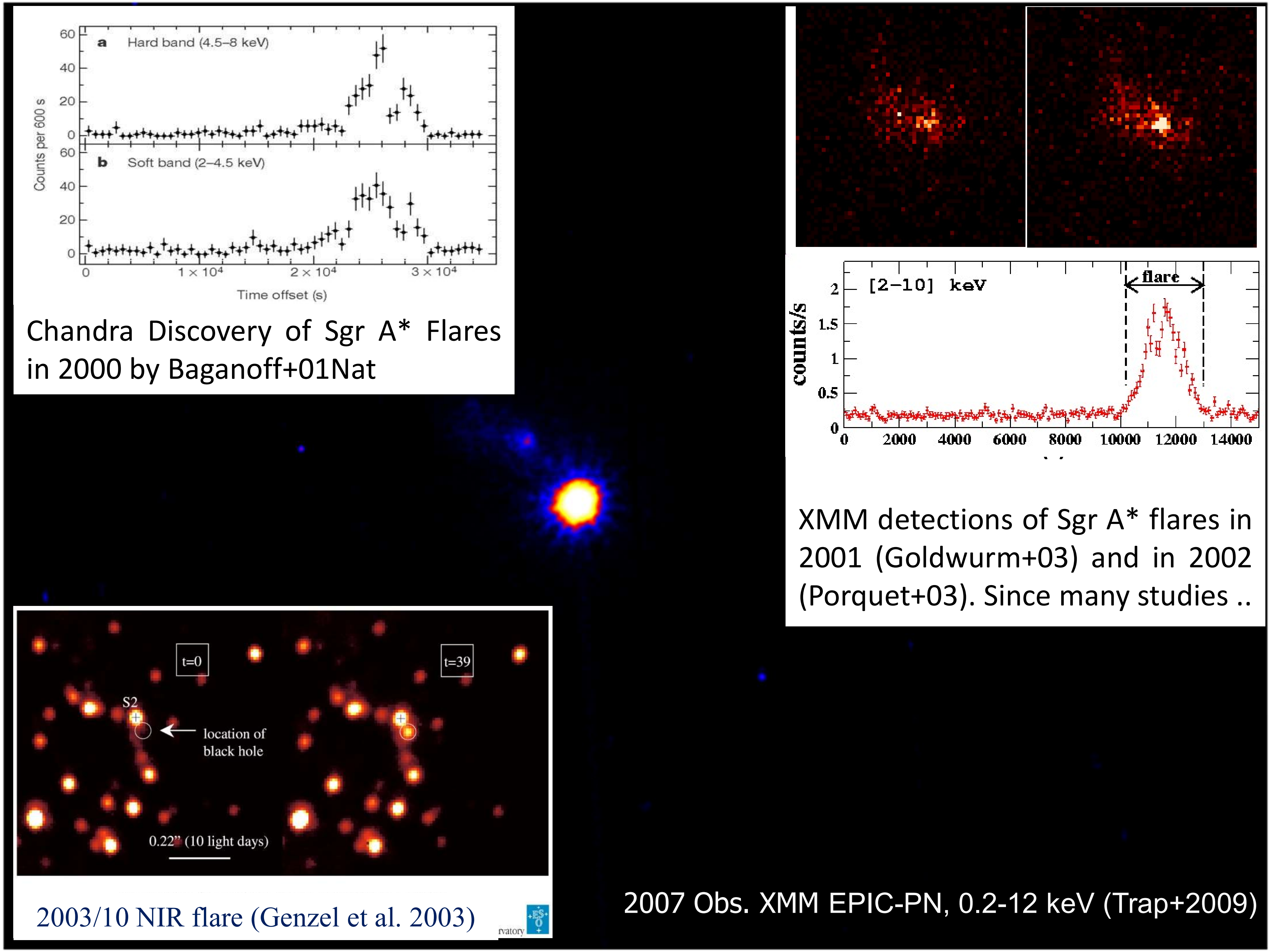
(Wang+13, Xu+06)



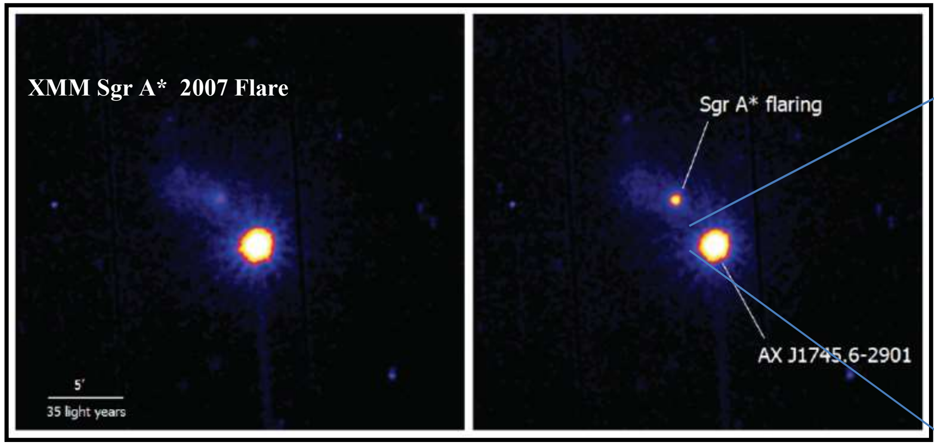
$$T = T_o(r_o/r)^\theta$$
$$n = n_o(r_o/r)^{3/2-s}$$
$$\dot{M} = \dot{M}_o(r/r_o)^s$$
$$dEM/d\log(T) \propto (T_o/T)^\gamma$$
$$(\text{where } \gamma = 2s/\theta)$$

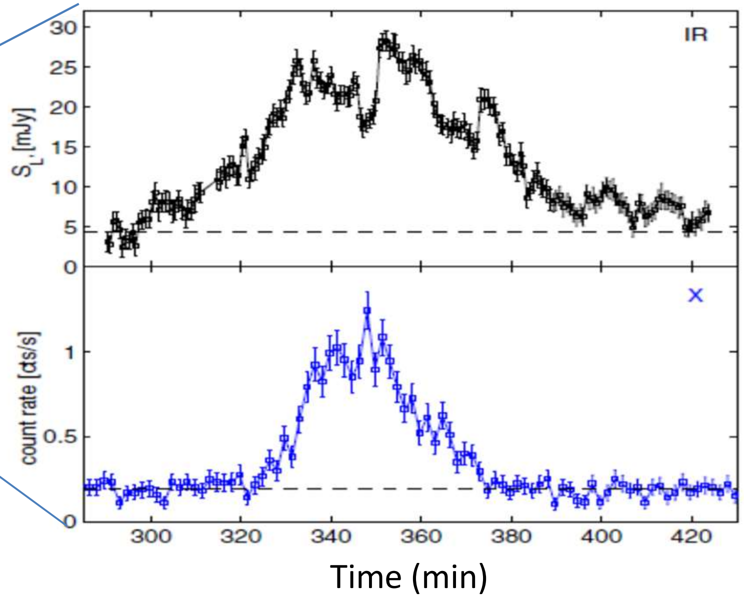


=> Low effective $\dot{M}$ compatible with ~ 10^{-8} $M_\odot$/yr << stellar winds $\dot{M}$ ~ 10^{-6} $M_\odot$/yr


a Hard band (4.5–8 keV)
b Soft band (2–4.5 keV)
Counts per 600 s
Time offset (s)
0
1 × 10⁴
2 × 10⁴
3 × 10⁴
Chandra Discovery of Sgr A* Flares in 2000 by Baganoff+01Nat
[2–10] keV
flare
counts/s
XMM detections of Sgr A* flares in 2001 (Goldwurm+03) and in 2002 (Porquet+03). Since many studies ..
t=0
t=39
S2
location of black hole
0.22" (10 light days)
2003/10 NIR flare (Genzel et al. 2003)
2007 Obs. XMM EPIC-PN, 0.2-12 keV (Trap+2009)

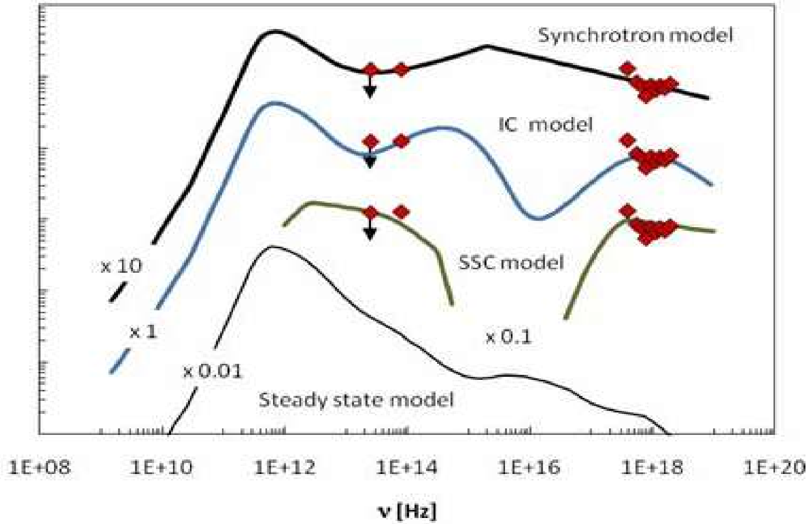
Sgr A* X – NIR Flares



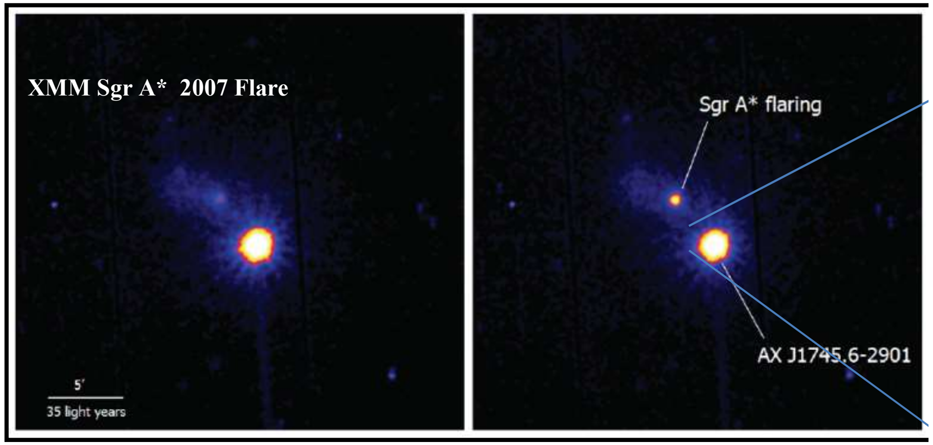


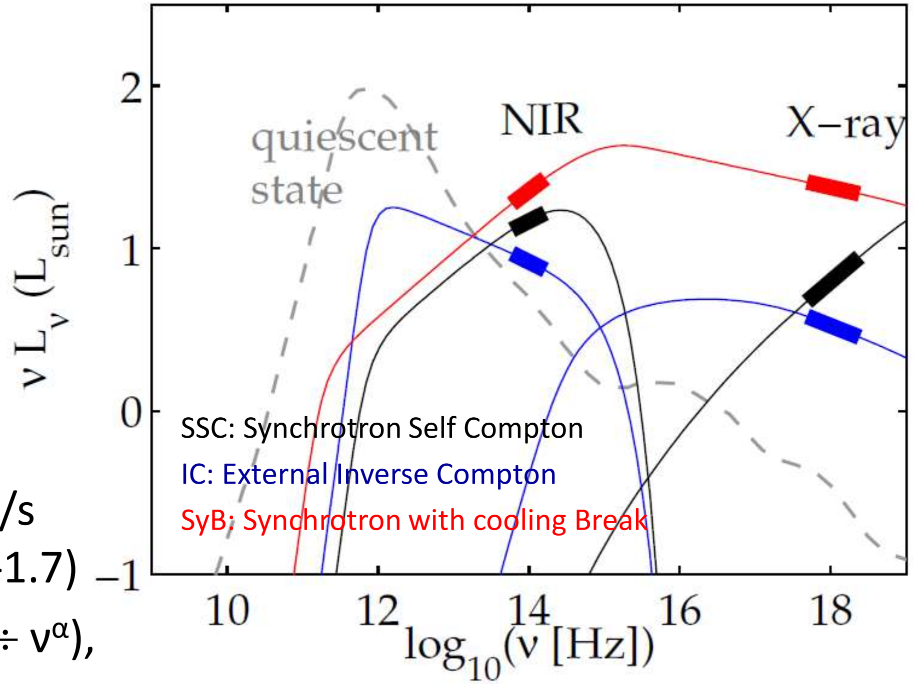
- X-ray Flares: peak L_X < 200 x Q.L.~ 4 10^{35}erg/s soft X-ray spectra: ph.i. ~ -2.2/-2.7 (α~-1.2/-1.7)
- NIR flares: Blue/hard spectra (α~-0.5, for $F_\nu \div \nu^\alpha$), linearly polar. => Opt. thin Synchrotron
- Frequency: X-rays ~ 1/d, NIR ~ 4/d
- Durations: 20 min – 3 hr (NIR usually longer)
- Variations <200 s => small emission region < 10 R_s
- **Constraints on mechanism from 2007 flare M-w obs: X-ray sp. + NIR flux + MIR upper limit favor Synch IR to X, but no simultaneous X-NIR spectra**

(Dodds-Eden+ 2009, Trap+ 2011)



Sgr A* X – NIR Flares





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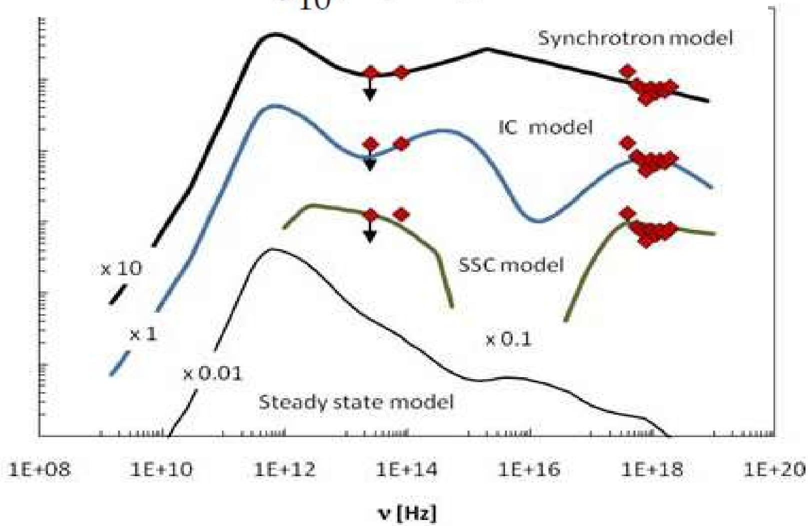
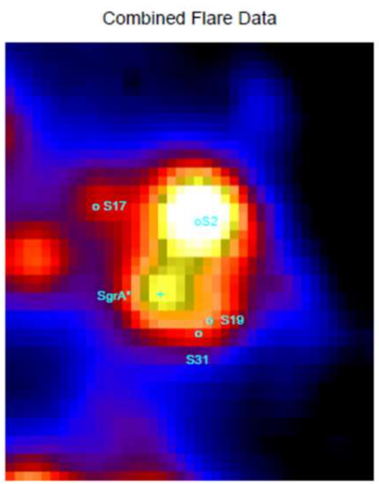
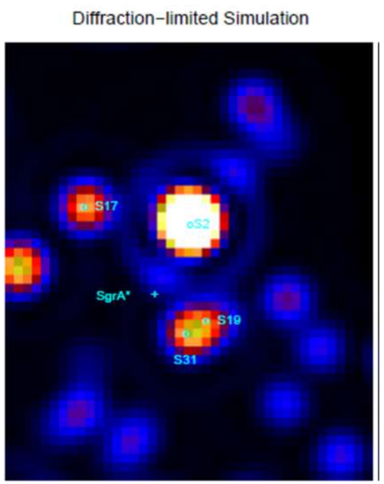
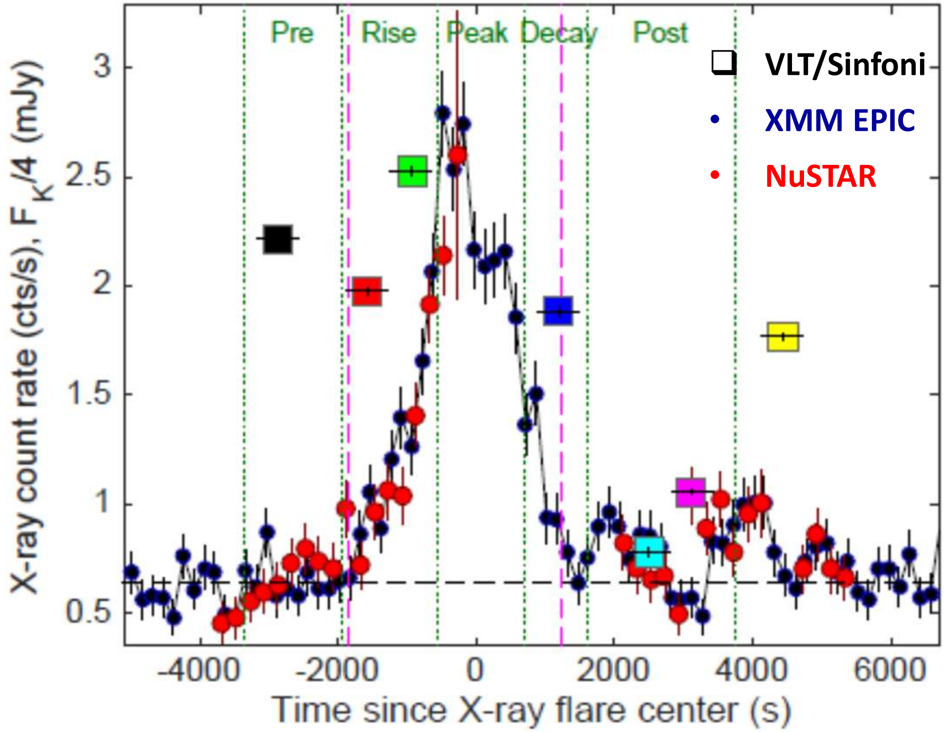


Multi-Wave Obs of bright 2014 Aug Sgr A* Flare



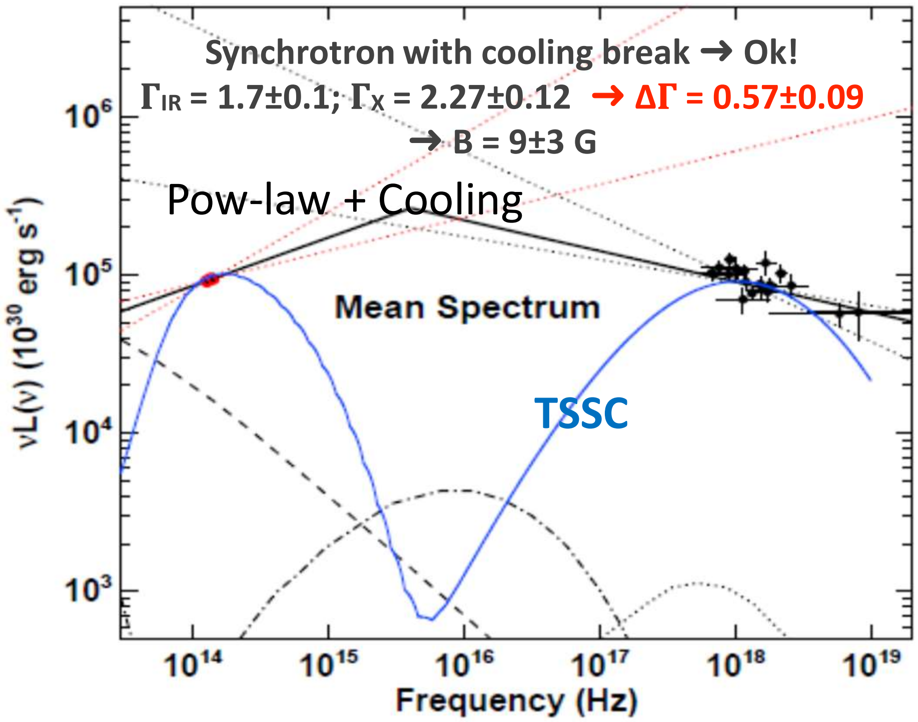




- 1st simultaneous measurement of spectra in X & NIR of Sgr A* very bright flare
- VLT/Sinfoni (2.03-2.39 µm) Image compared to a simulated image
- Light Curves in X and NIR show temporal behavior of the flare

(Ponti et al. 2017)

Fits of average Sgr A* 2014 Flare spectra



VB3 mean spectrum				
	Single PL	BPL	TSSC	PLCool
Γ_{NIR}	2.001 ± 0.005	1.7 ± 0.1		1.74 ± 0.08
Γ_X		2.27 ± 0.12		
$\Delta\Gamma$		0.57 ± 0.15		0.5
Log(B)		0.94 ± 0.16	4.0 ± 0.4	0.94 ± 0.16
Θ_e			9 ± 4	
Log(N_e)			39.5 ± 0.5	
Log(R_F)			-3.5 ± 0.5	
χ^2/dof	189.7/142	154.9/140	162.7/139	156.8/141

- Single PL not consistent, Broken PL much better ($\Delta\Gamma \sim 0.5$)
- Thermal SyncSelfComp fit ok but **unreasonable physical parameters**

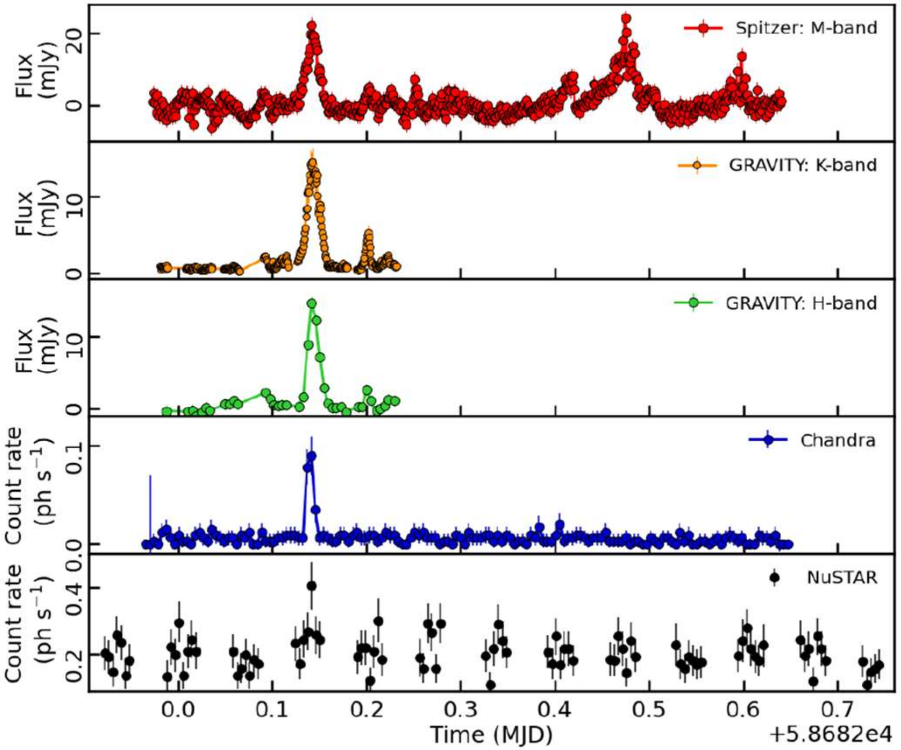
  ($B \sim 10^4$ G, $n_e \sim 10^{23}$ cm^{-3}, $R_F \sim 10^{-3}$ R_S)
- PL + radiative Cooling best-fit: Synchrotron mechanism with cooling break in V-UV

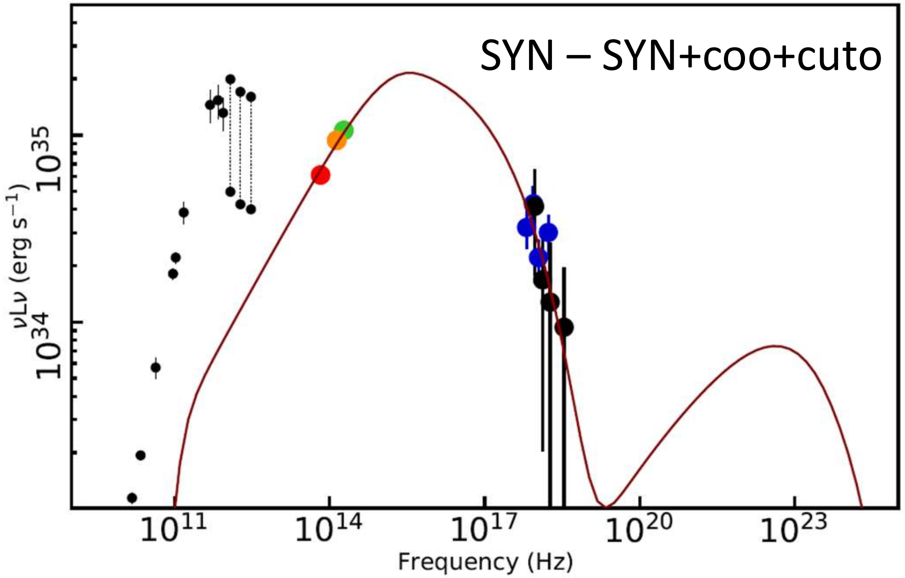
  ($B \sim 9$ G, $p \sim 2.5$, $\gamma_{max} > 10^6$)
- **Confirms results on 2007 NIR/X Flare based on MIR upper limit (Dodds-Eden et al. 2009): Synchrotron with cooling break and γ_{max} favored**
- However a constant γ_{max} (and E_{br}) not compatible with data evolution

Results on the very bright Sgr A* 2014 Flare

- Successful 2014 campaign on a Bright Flare (XMM – VLT/Sinfoni – NuSTAR): First ever simultaneous NIR/X-hardX spectral measure
- Confirm previous findings (2007 flare by Dodds+2009, Trap+2009)
  - Steep X-ray PL (no hard/soft flares). Same peak in IR & X but NIR different duration
  - Confirm Synchrotron Emission with cooling break and max energy for X-rays (exclude IC models)
- NIR spectral changes (steepening at low F), detection of X-ray evolution (slope, FWHM)
- Modelling the results using variable E_{br} and also a variable γ_{max} on long timescales (100 min–100 s) which implies "slow" acceleration process
- Slow acceleration (γ_{max} evolution) naturally explains different NIR/X Light Curves
- If t_{esc} constant => change in cooling break due to B decrease during flare peak and rise again at the end.
- Possibly Magnetically driven flare (e.g. reconnection).

Recent Multi-w campaign on Sgr A* Flares



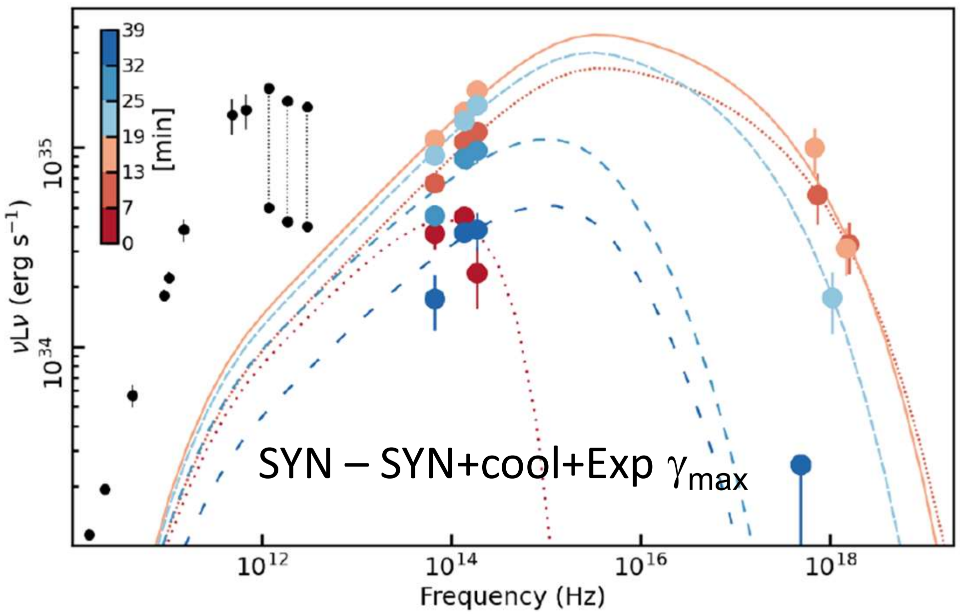


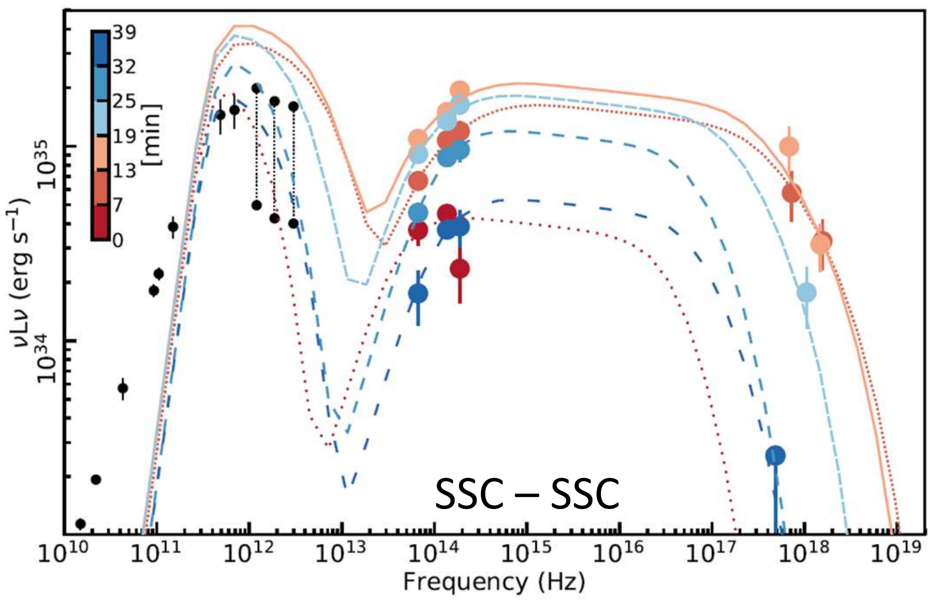
2019 - VLTI-Gravity Spitzer Chandra NuSTAR
Time-resolved spectral analysis of a Sgr A* bright NIR and moderate X-ray flare

- Confirm IR spectral variability correlated to flux
- Reject SYN (IR) – SSC (X) Model (and any Ext IC model)
- Fitted by SYN(IR)–SYN(X) + cooling + HE Exp. Cutoff: γ_{max} > 50000 R_{source}~ 1 R_S
- Compatible also with syn(submm) – SSC(IR) – SSC(X): γ_{max} =500, $n_e > 10^{10}$ cm^{-3}

Gravity coll 2021

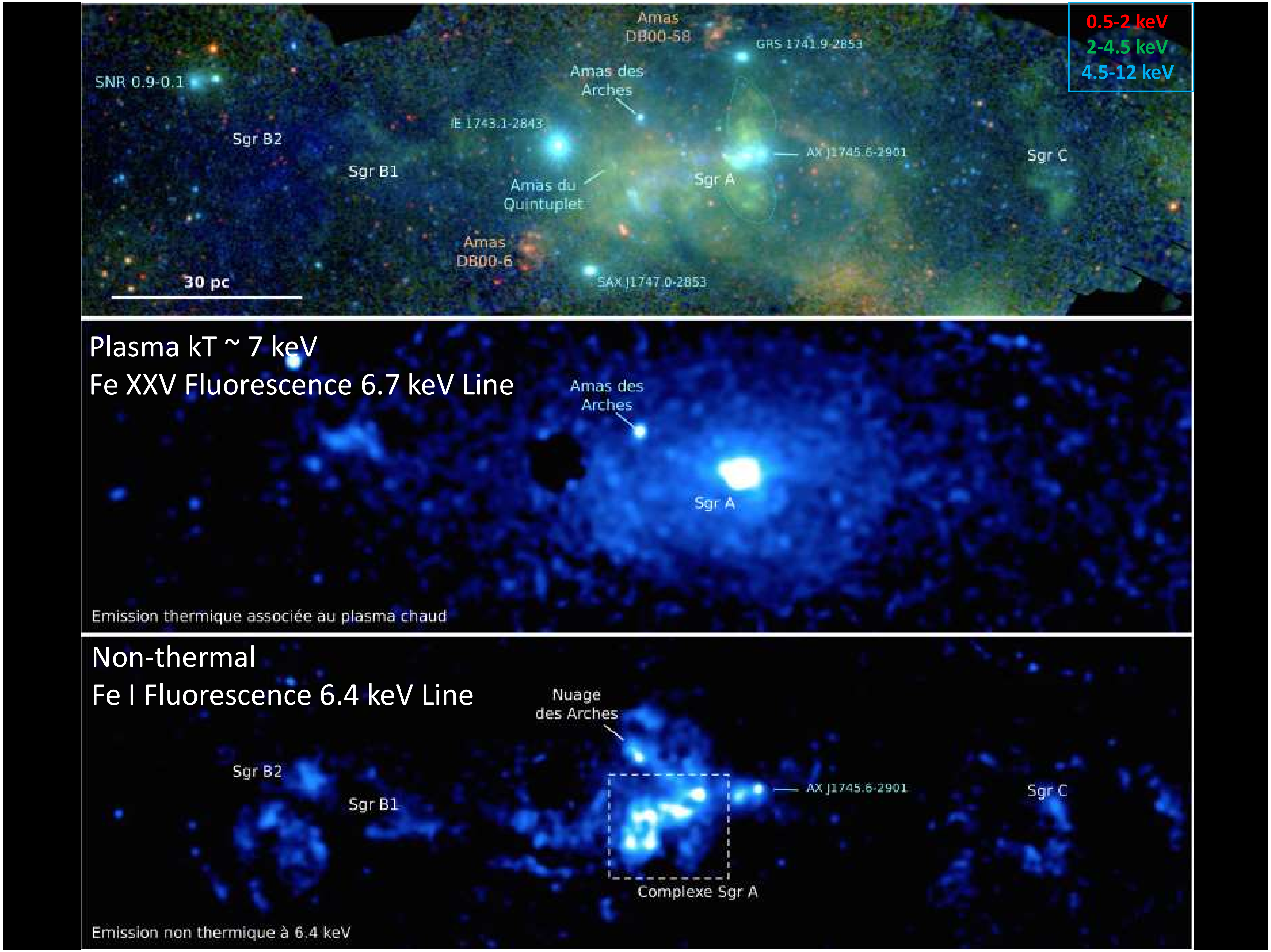
Recent Multi-w campaign on Sgr A* Flares - 2



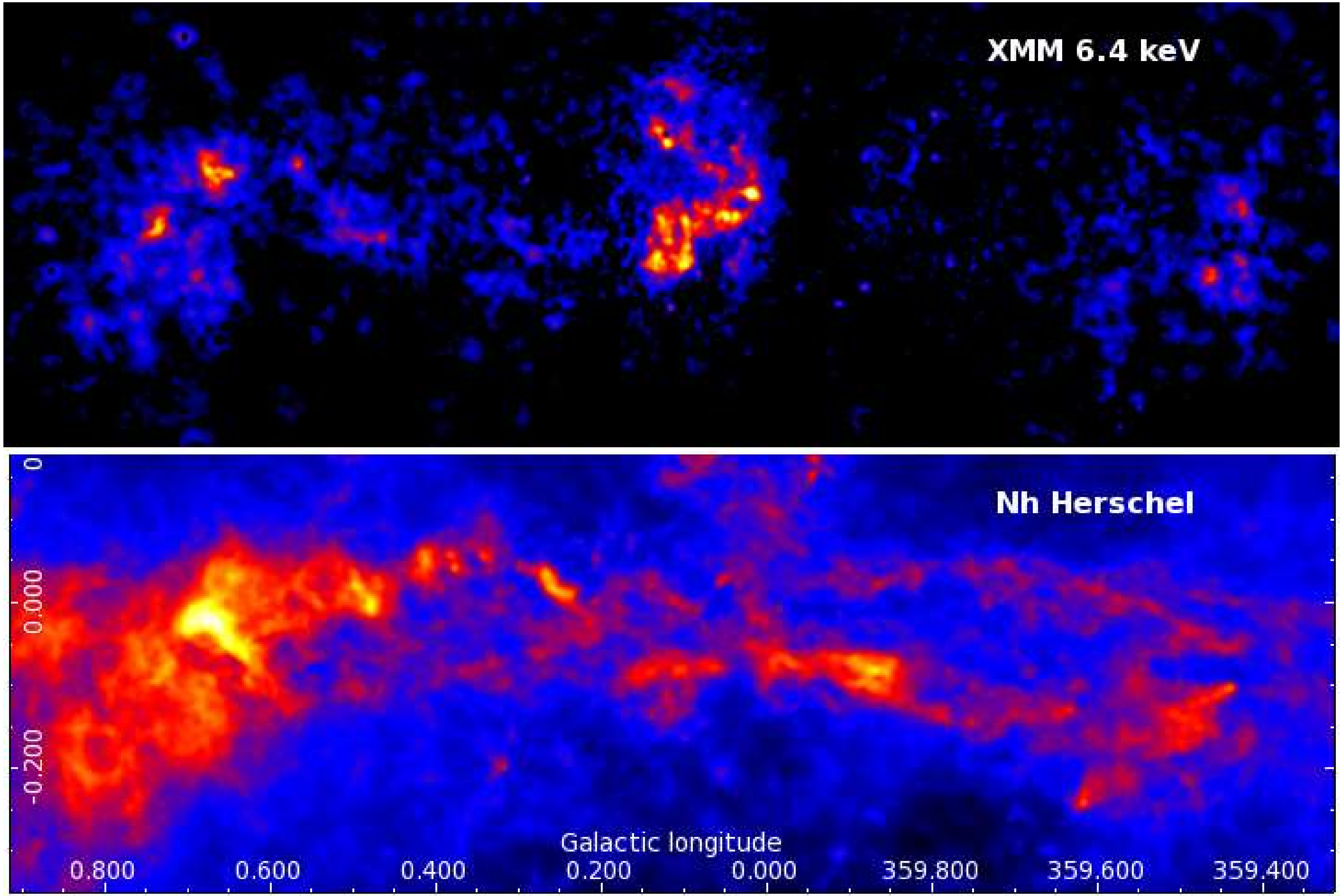


- The syn(submm) - SSC(IR) – SSC(X) Model also fits data with γ_{max} ~ 500 and reasonable magnetic field but requires very high density (n_e >> ambient n_e)
- It predicts correlated variability in the sub-mm range which could not be observed (planned SMA Obs not performed)
- It requires a variation of the particle density that is inconsistent with the average mass-flow rate inferred from polarization measurements and can therefore only be realized in an extraordinary accretion event.
- In both models temporal evolution is regulated through γ_{max} implying that sustained particle acceleration is required to explain at least part of evolution

Gravity coll 2021, see also Witzel+ 2021


0.5-2 keV
2-4.5 keV
4.5-12 keV
Amas DB00-58
GRS 1741.9-2853
SNR 0.9-0.1
Amas des Arches
1E 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

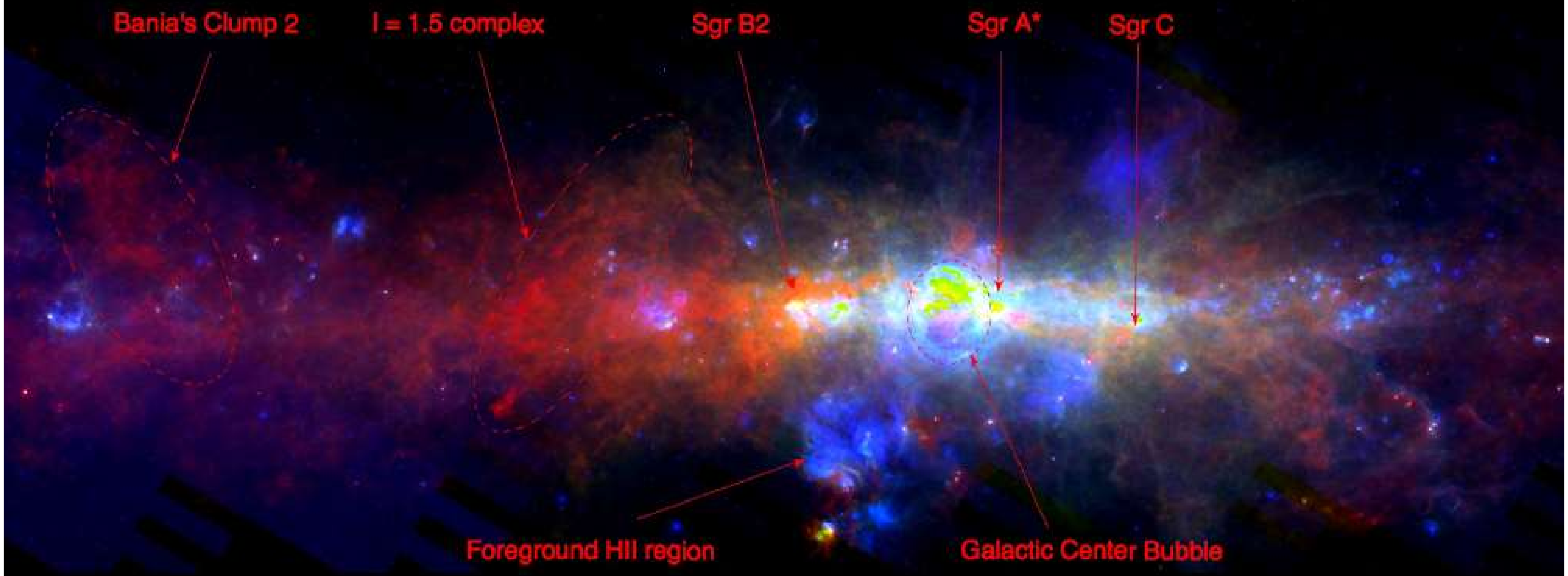


Central Molecular Zone

24 μm, 70 μm, 350 μm

Herschel Hi-Gal

Bally, Molinari +



- Radio (mol. lines of CO, CS, SiO, H_2CN, HC_3N), sub-mm and FIR (dust)
- Central 450 pc x 50 pc contains ≈ 10^8 $M_\odot$ molecular gas ≈ 10% of all Galaxy m.g. content
- Dense (≈ 10^4 - 10^5 cm^{-3}), compact (50-70 pc), cool (T ≈ 30-60 K°) clouds
- Star formation 0.3 - 0.6 $M_\odot$ yr^{-1} (low when compared to Galactic Disk ~ 5.5)
- Giant Molecular Clouds: Sgr B, Sgr A complex, Sgr C, G 01-01, Sgr D, Sgr E

Traces of Sgr A* activity from MC H-E emission

- The SMBH Sgr A* seats at the center of the so called Central Molecular Zone (CMZ) the complex region of the inner 400 pc of the galaxy, dominated by most massive and dense molecular clouds of the MW. Sgr B2, Sgr A, Sgr C, G01-01 and other MCs emit molecular radio lines and FIR from associated dust.

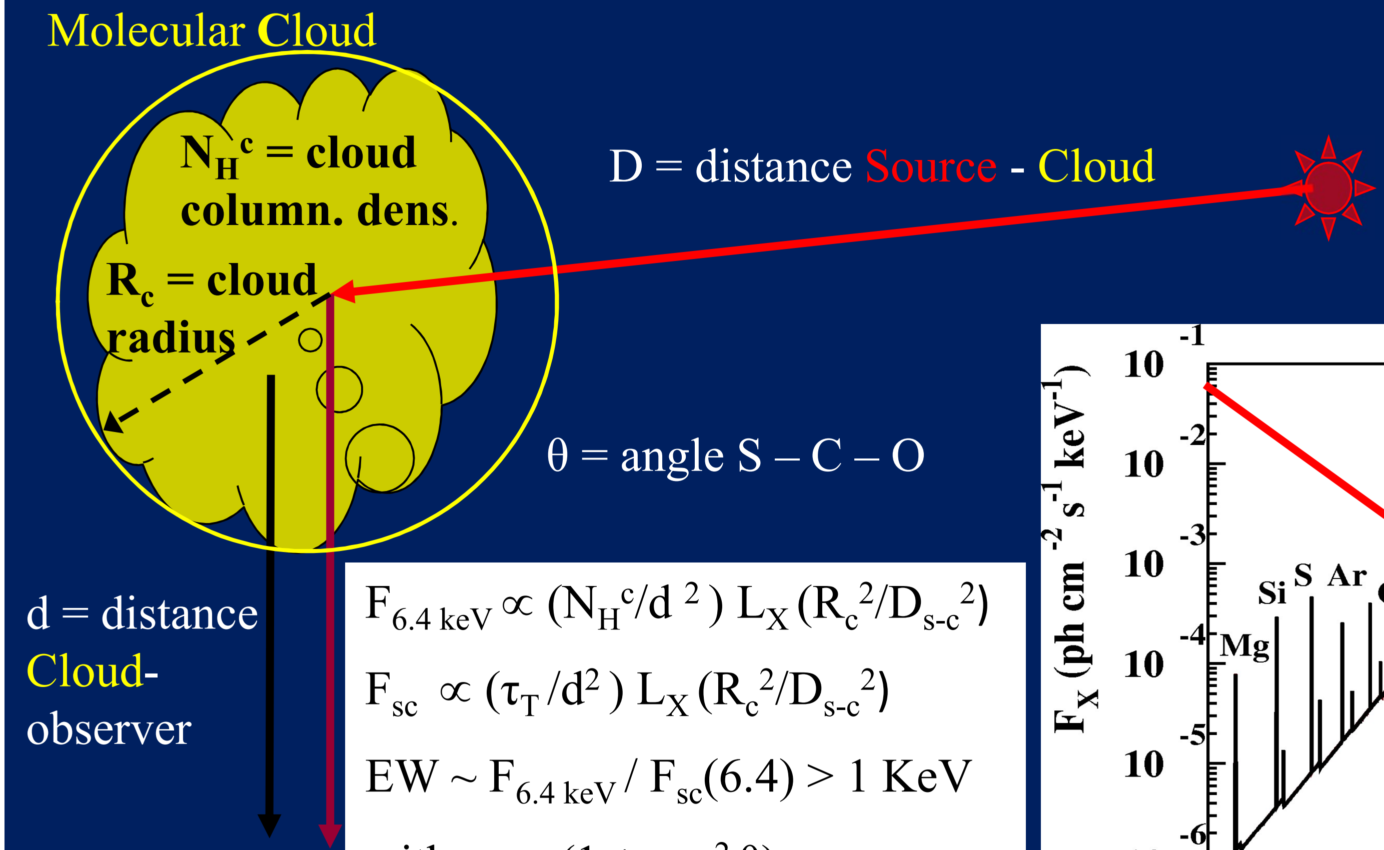
- **Traces of past intense activity in the GC region could be seen in the dense cold molecular clouds of the GC region that can act as mirrors reflecting the X-ray radiation that illuminates them.**

- **This reflected radiation will reach us with a delay with respect to the primary. This light echo carries specific spectral (6.4 keV line + compton hump) & timing features (delay depending on MC distance, MCs illuminated by same event lay on a parabola) => past activity of illuminating source.**

- **Since discovery of diffuse 6.4 keV from SgrB2 MC by ASCA ('94) many works presented obs. (Chandra, Suzaku, XMM, Integral) and theory of this process proposing Sgr A* as illuminating source with peak Luminosity of 10^{39} erg/s in the past 300 yr (Koyama+ 96, Sunyaev&Churazov 98, Koyama+ 06 …)**

- **Detection of variability excluded the alternative LECR scenario (Inoui+07, Terrier+10, Ponti+10, Clavel+13 ….)**

Fluorescent Iron line and reflected continuum from X-ray irradiation



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

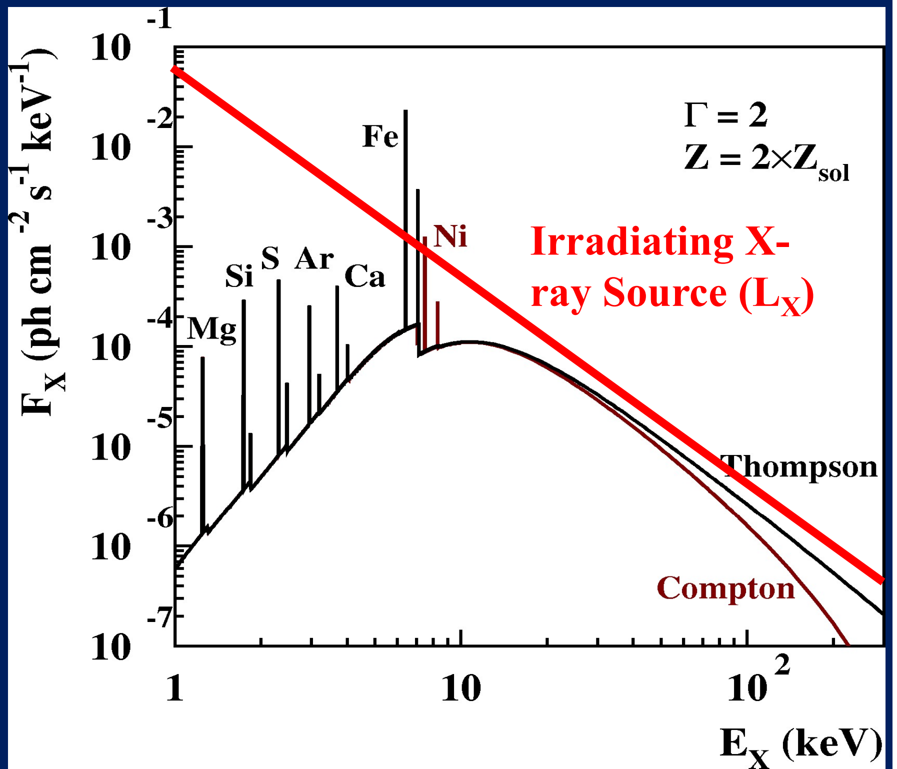
$F_{sc} \propto (\tau_T/d^2)\, L_X\, (R_c^{\,2}/D_{s\text{-}c}^{\,2})$

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

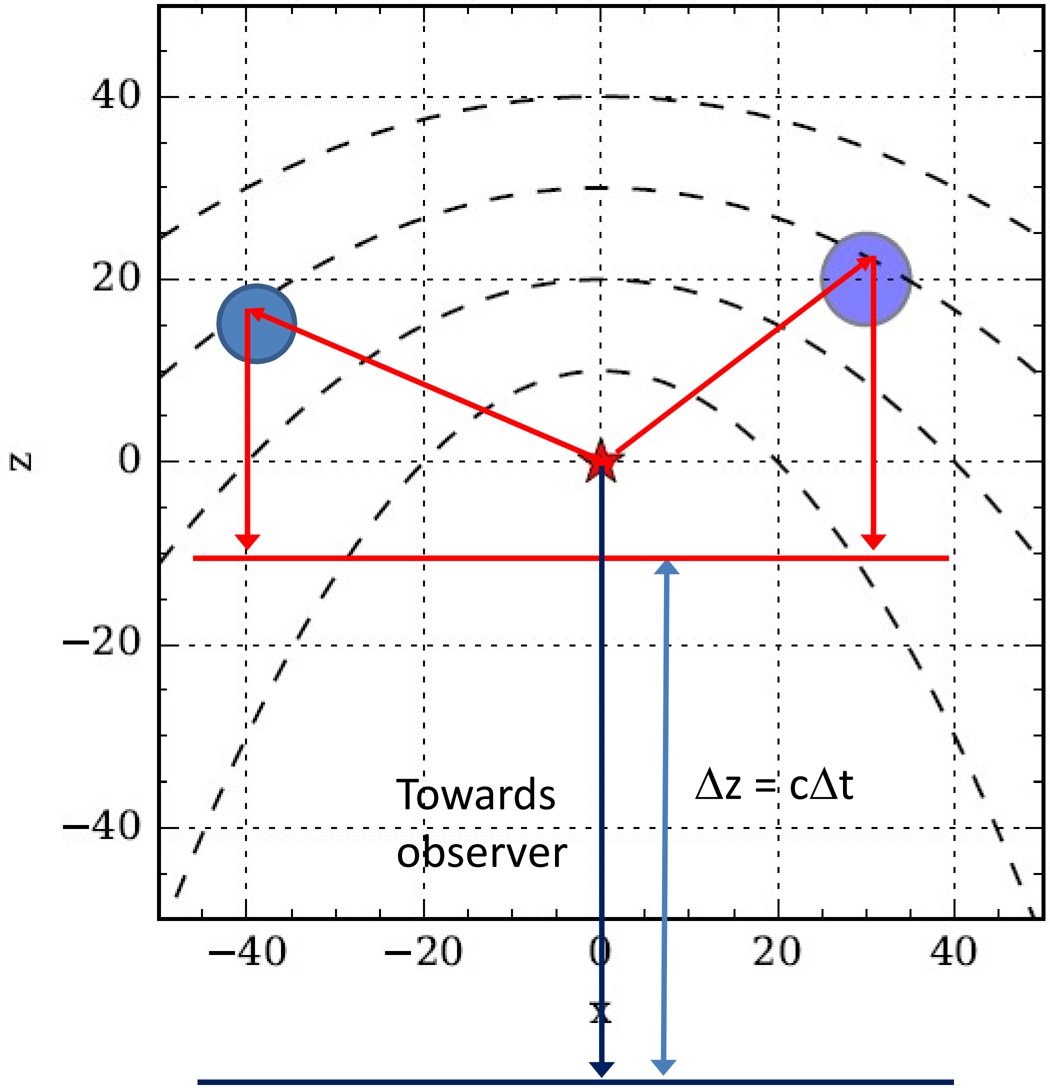
with $\tau_T \propto (1 + \cos^2\theta)$

Fluorescence Iron line at 6.4 keV

Scattered X-rays



Geometry of Light-Echoes



Primary emission

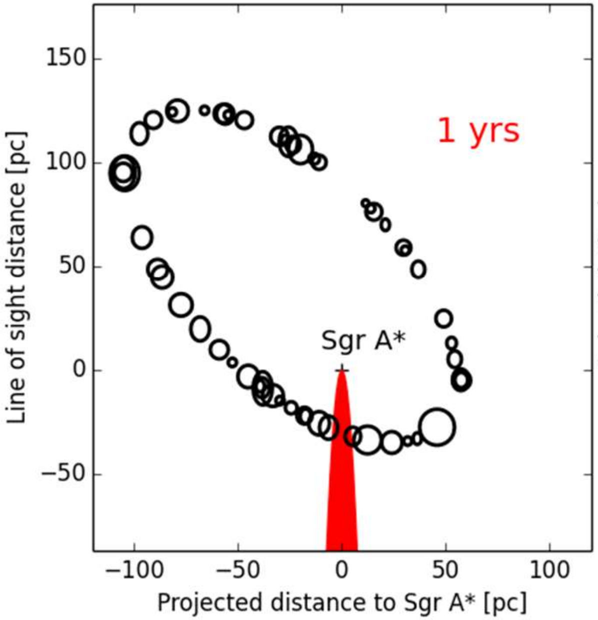
Reflected light

Points of equal time delay Δt seen by an observer at infinity lie on an parabolic surface with focus on the illuminating source

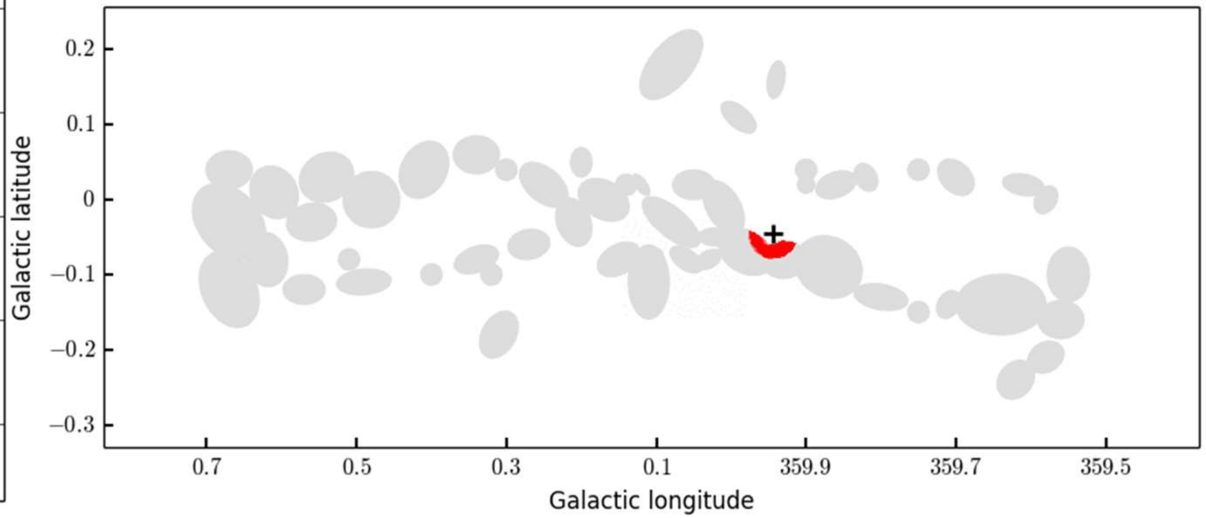
$$z(x) = \frac{1}{2}\left(\frac{-x^2}{c\Delta t} + c\Delta t\right)$$

Sgr A* Light-Echo Propagation in CMZ

Propagation seen from above
the Galactic plane



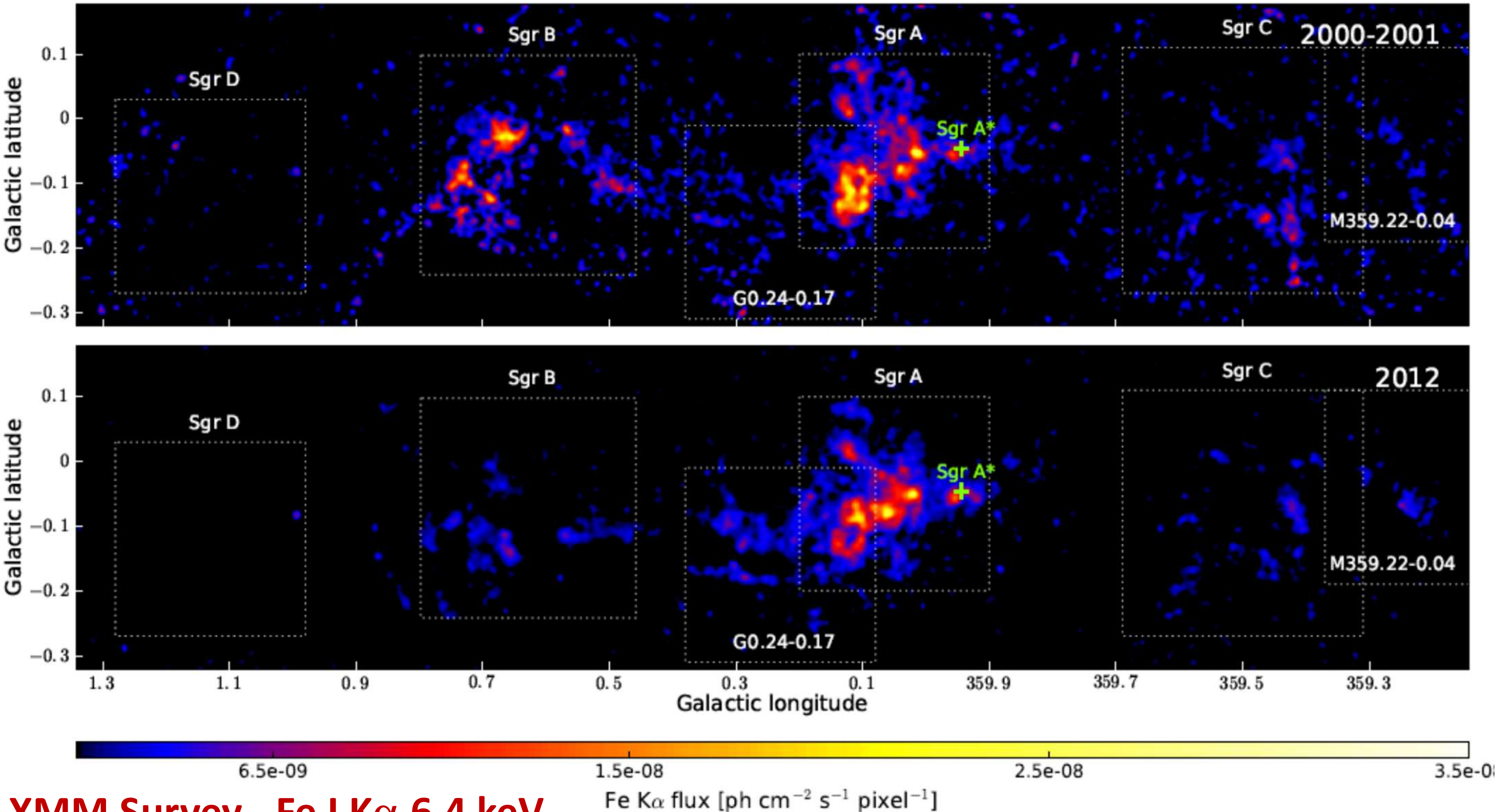
Reflected emission on the plan of the sky (as observed)



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

M. Clavel (PhD Thesis, 2014)

Variability of the 6.4 keV line in the CMZ

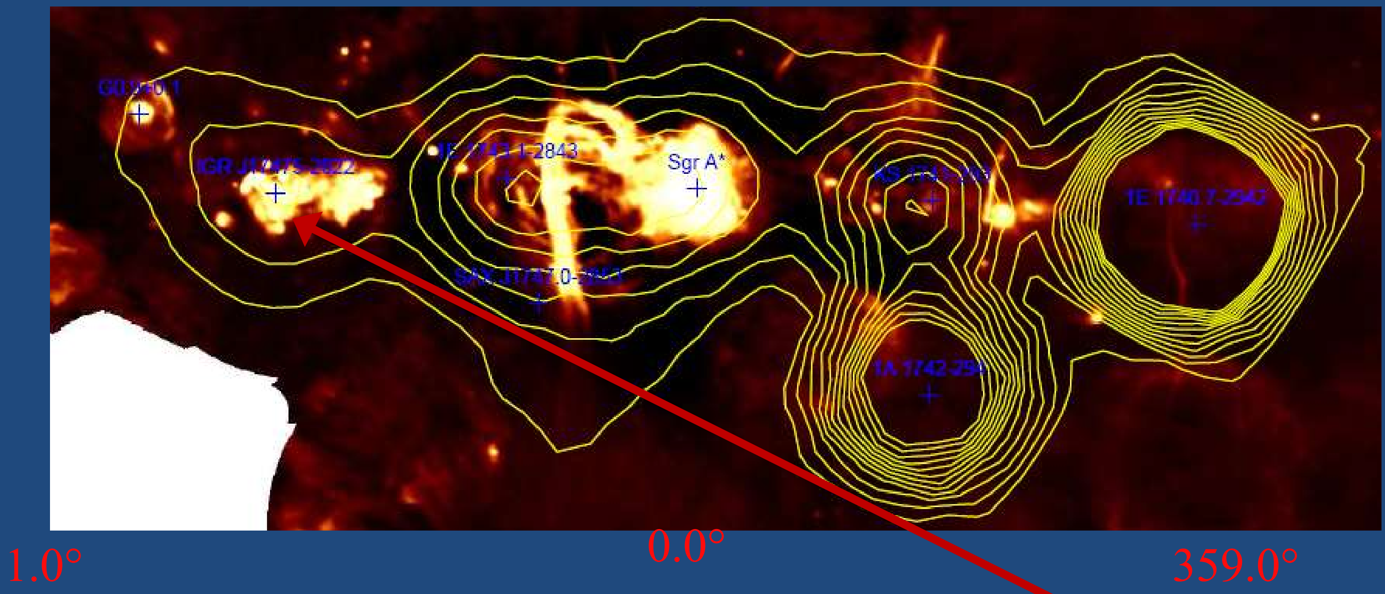


XMM Survey - Fe I Kα 6.4 keV

(Terrier et al. 2018)

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

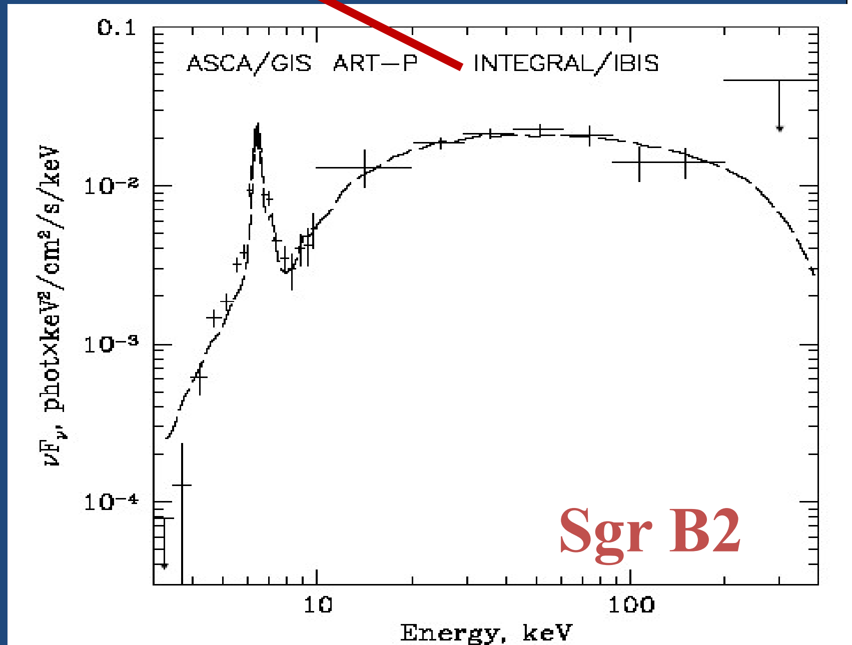
(Belanger et al. 2006)

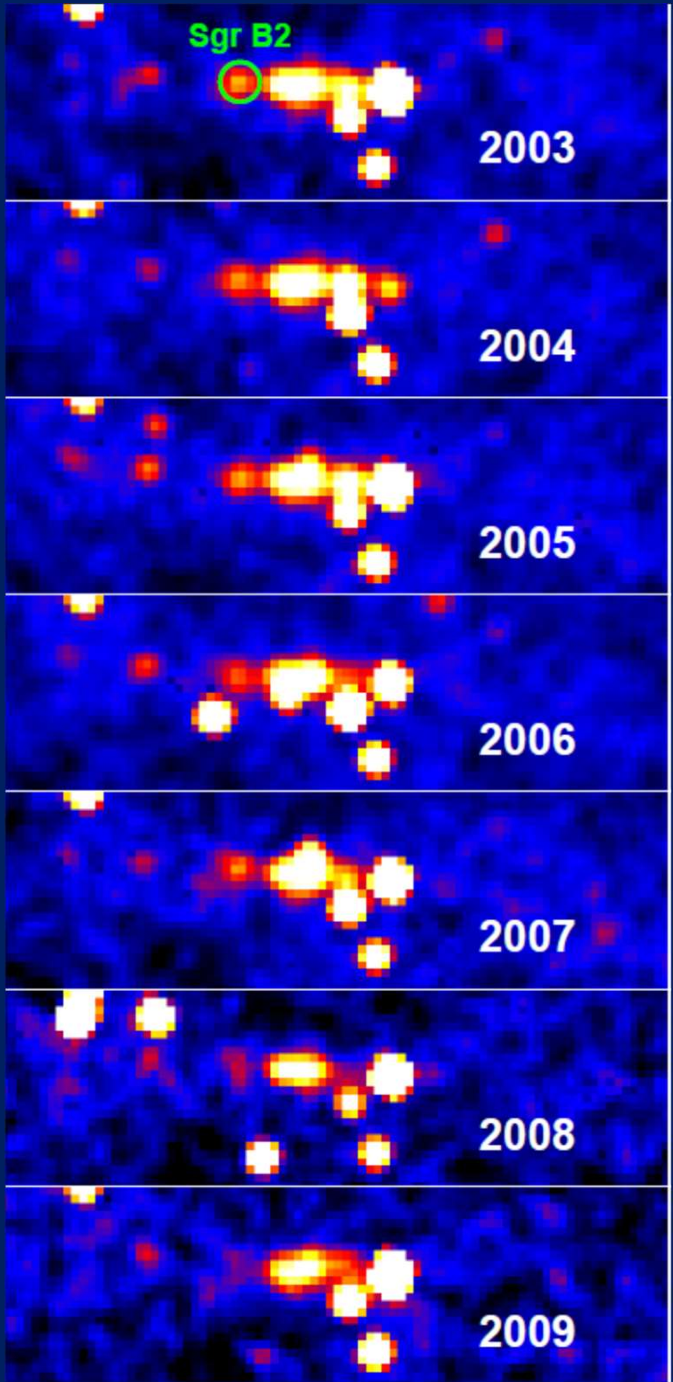


- INTEGRAL (20-200 keV) Sgr B2 spectrum compared to ASCA & ART-P data at low energy
- Broadband spectrum: Fe I fluorescence + Compton scattering of a 10^{39} erg/s luminosity outburst of Sgr A* ~300 yr back lasted > 10 yr

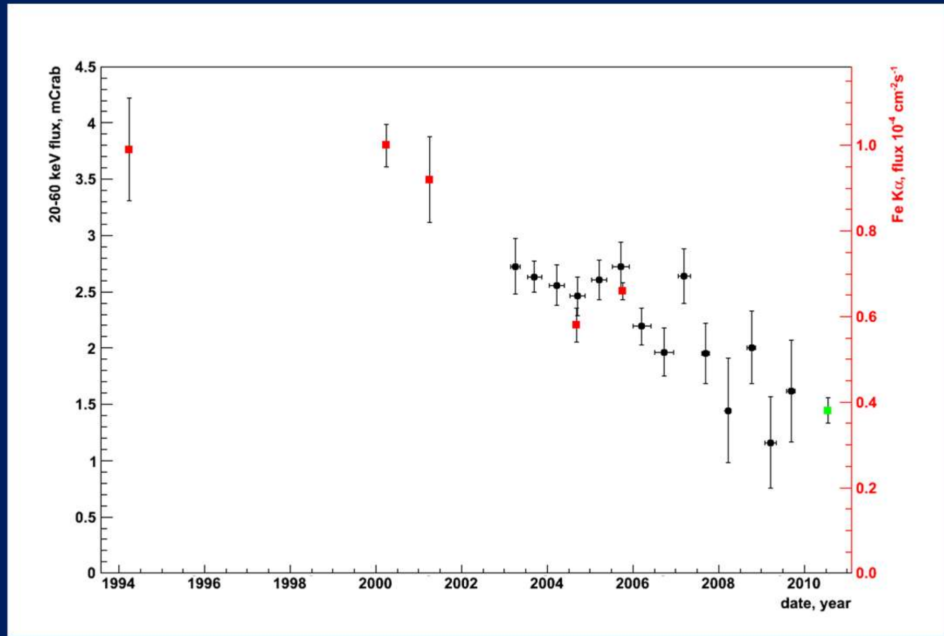
  (Revnivtsev et al 2004)

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



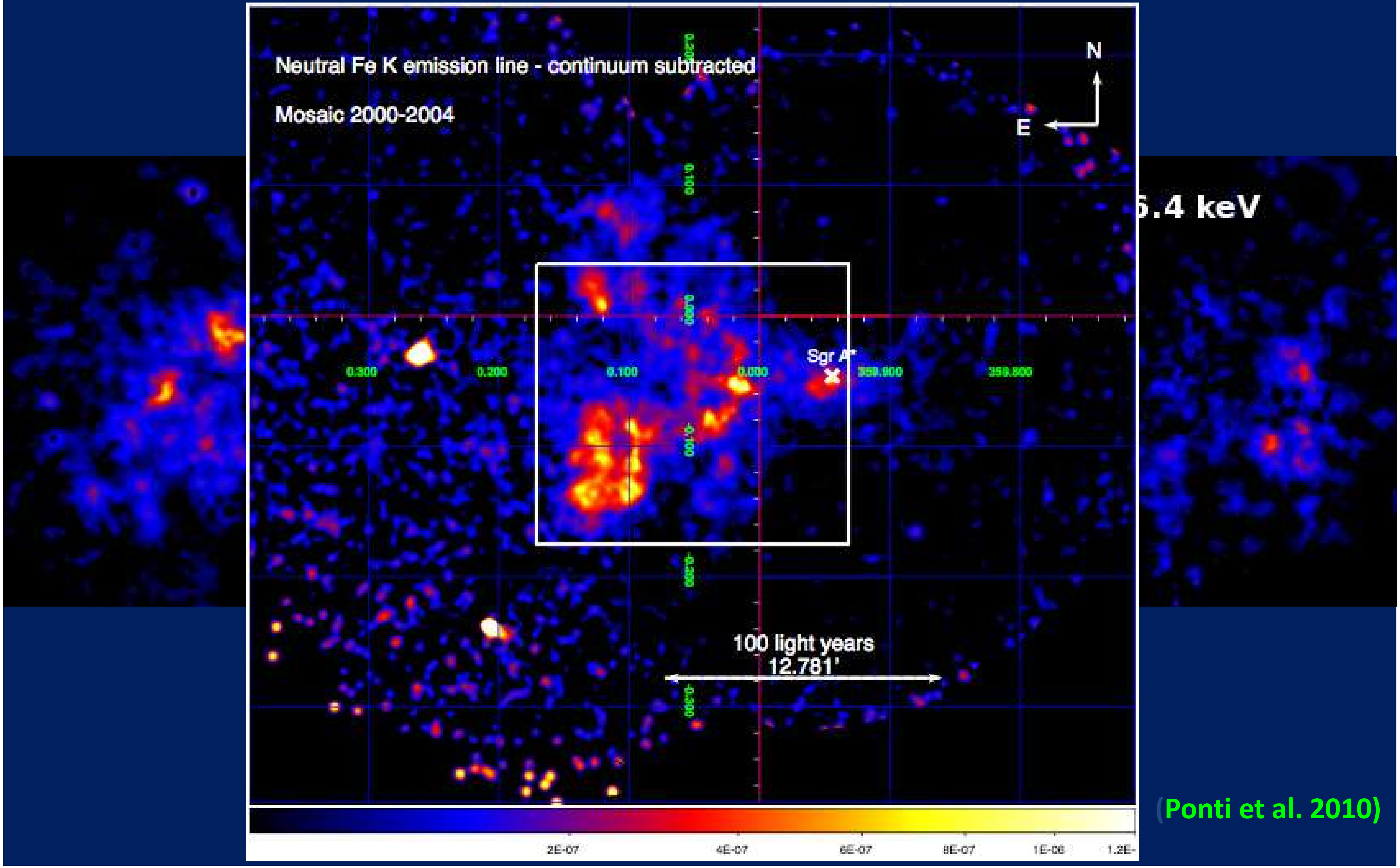


INTEGRAL GC survey: Discovery of gamma-ray variability of Sgr B2



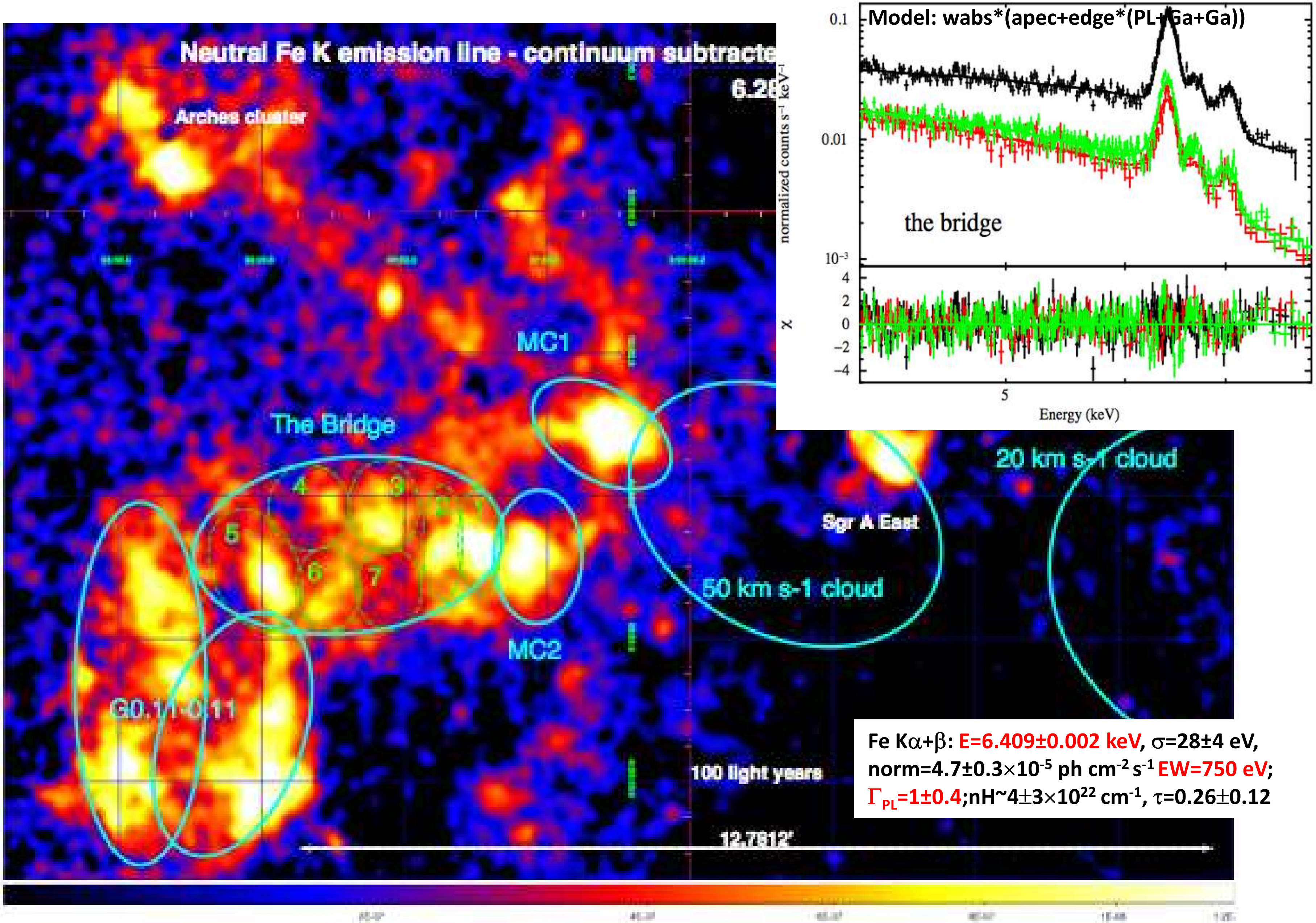
- Decrease of Sgr B2 20 - 60 keV flux over 7 ys (cloud core size ~ 8 ly)
- Variation up to 40 %, compatible with the 6.4 keV decrease observed by Suzaku (compared to XMM)
- Consistent with hypothesis of reflection of hard X-ray emission: end of outburst => decrease
- Not with particle interpretation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

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



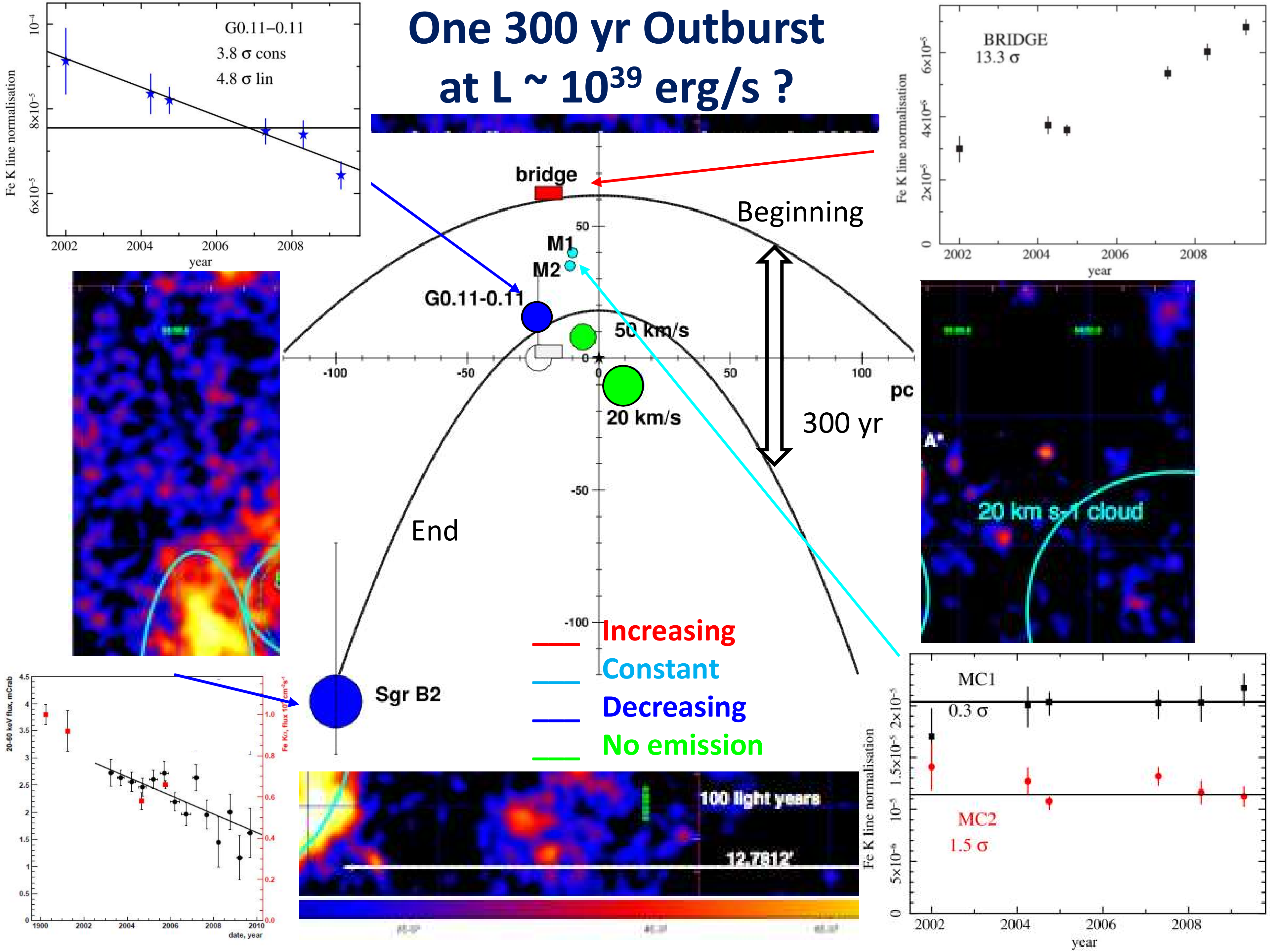
(Ponti et al. 2010)

XMM Surveys of Molecular Complex near Sgr A

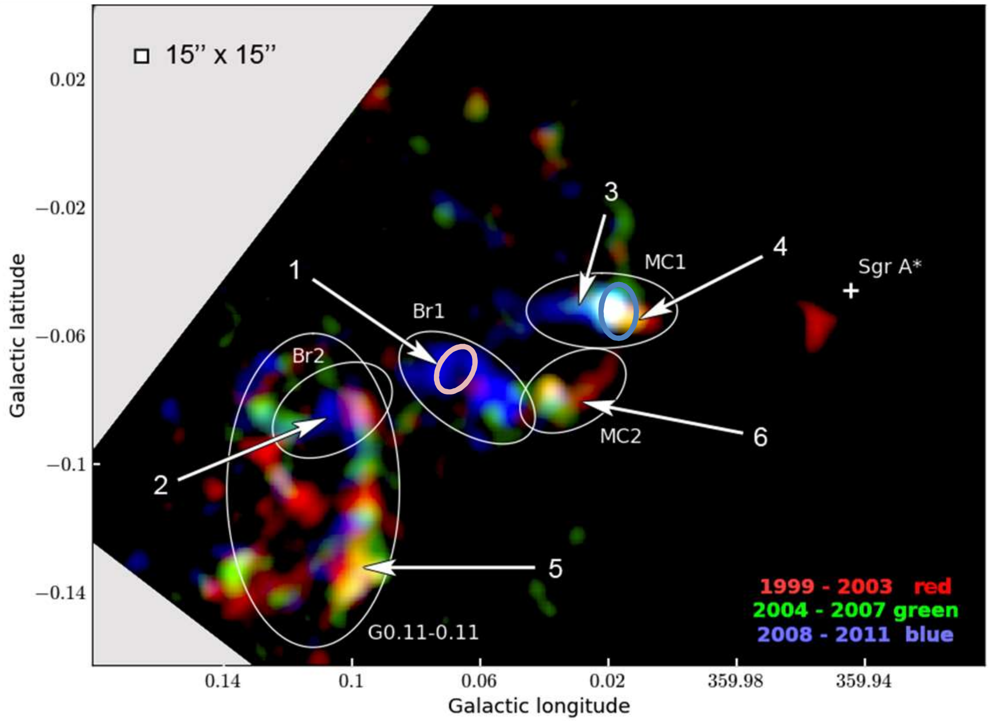


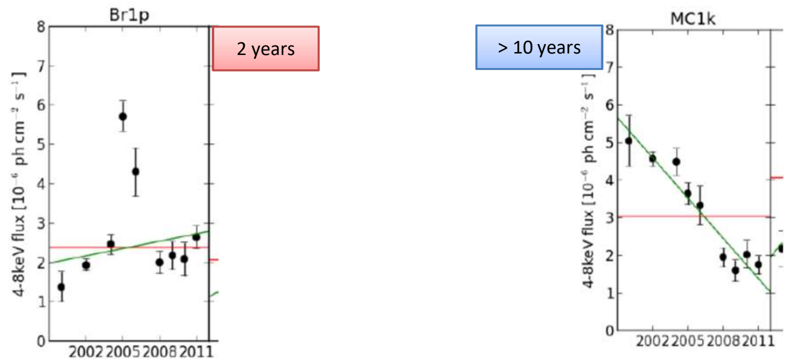
Fe Kα+β: E=6.409±0.002 keV, σ=28±4 eV, norm=4.7±0.3×10^{-5} ph cm^{-2} s^{-1} EW=750 eV; Γ_{PL}=1±0.4;nH~4±3×10^{22} cm^{-1}, τ=0.26±0.12

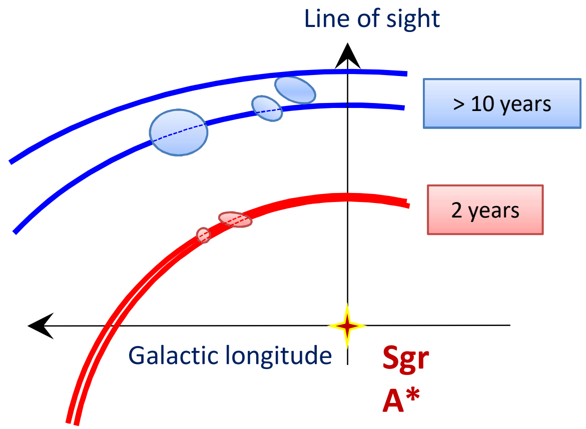
One 300 yr Outburst at L ~ 10^{39} erg/s ?



Chandra CMZ Obs.: multiple Echo events





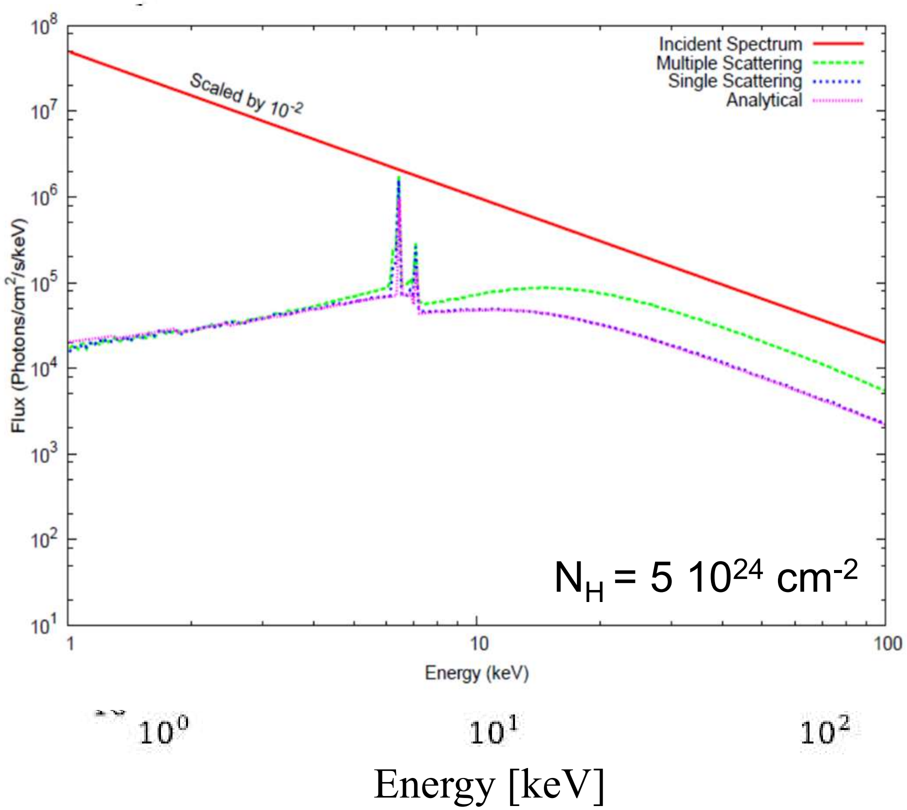


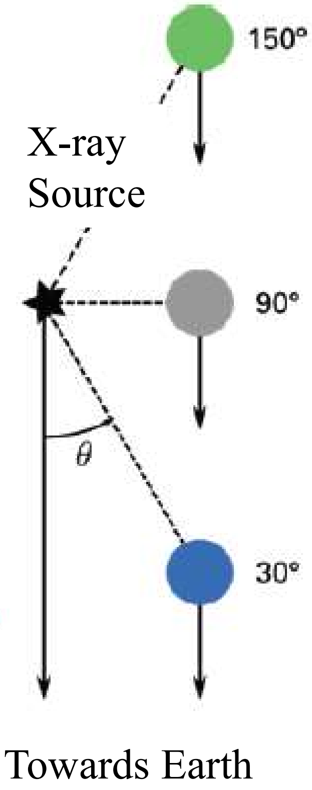
NOT A SINGLE 300 YR LONG OUTBURST !!

Chandra Survey 1999–2011: 6.4 keV Iron K line rapid variability from Sgr A molecular clouds. **MC1 MC2 not constant**, **Br1 rapid event** => **exclude 300 yr long flare,** rather 2 bright events (10^{39} erg/s), 1 short (< 2 yr) + 1 longer (~ 10 yr) from Sgr A* in 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)

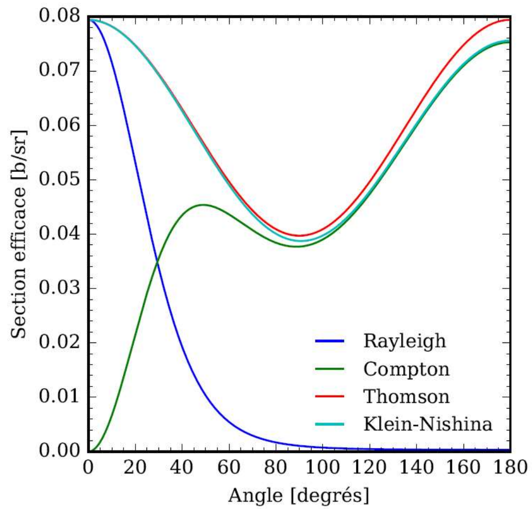
Monte Carlo Modeling of Reflection Spectrum





The Model

- (Total) Illumination (parallel beam) of spherical isolated cloud of diameter D
  - Uniform, Non-Uniform (Gauss, Exp) density
  - Solar composition
- By an external X-ray source
  - Power Law spectrum 1-300 keV, Ph. Index α=2



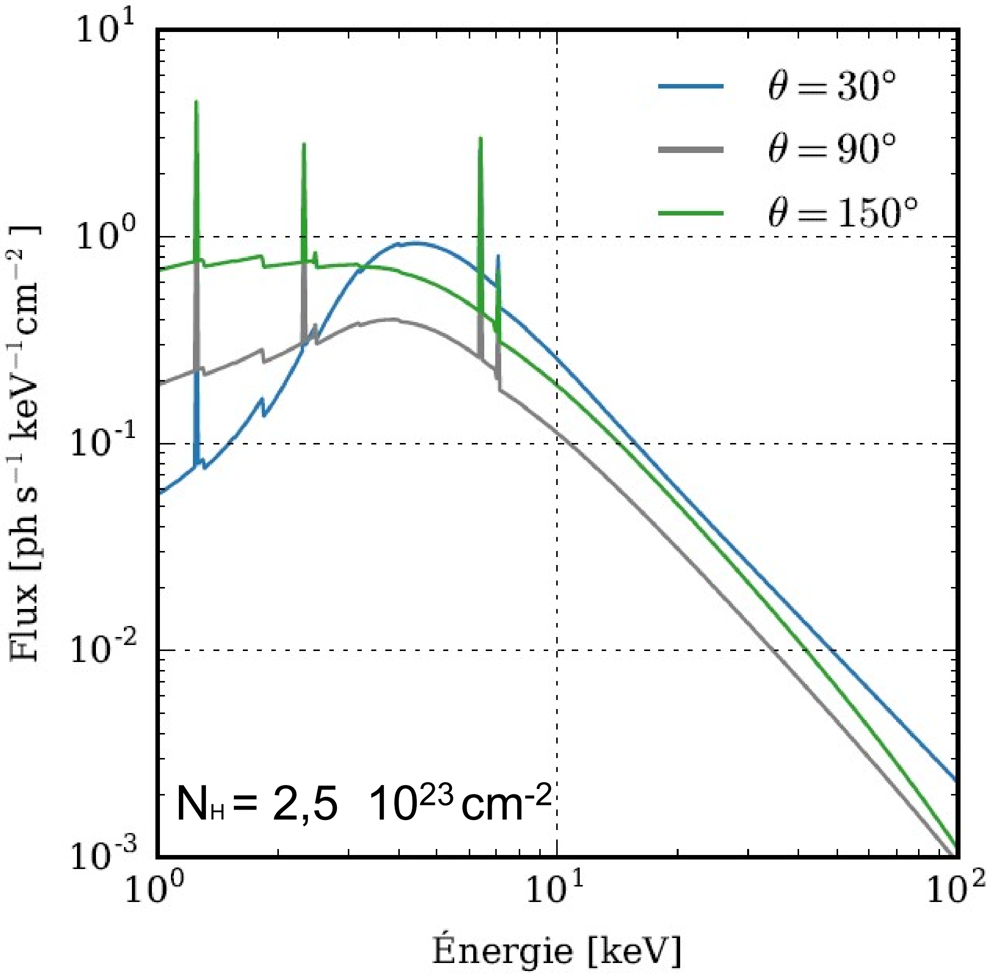
Physical effects (xraylib):

- Absorption and Fluorescence (Fe)
- Multiple Scattering (Compton)
- Bound-electrons (Rayleigh)

=> **Strong dependence on scattering angle**

Walls et al. 2016
Chuard PhD 2018

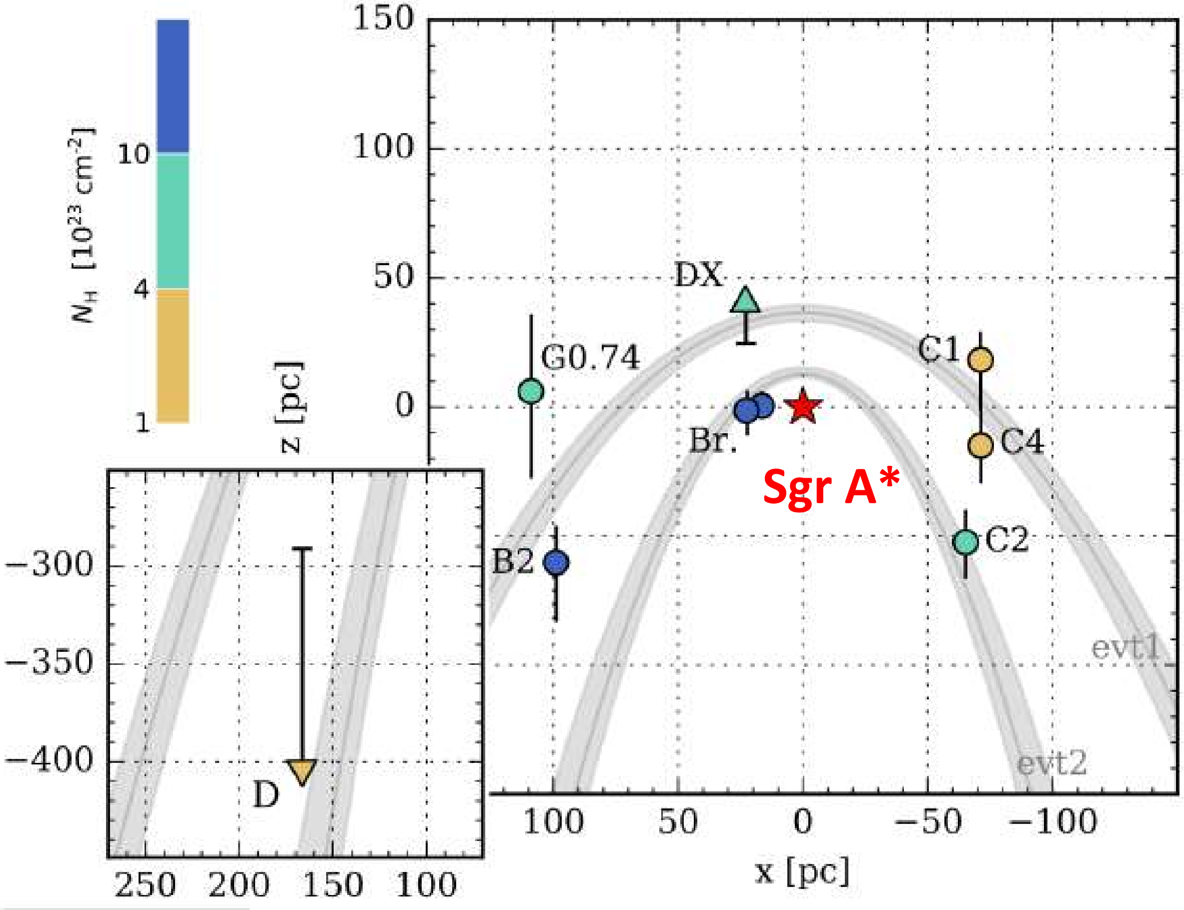
Reflection Spectrum as a function of scattering angle



- 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



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

Delays of 2 events derived from several MCs data fit :

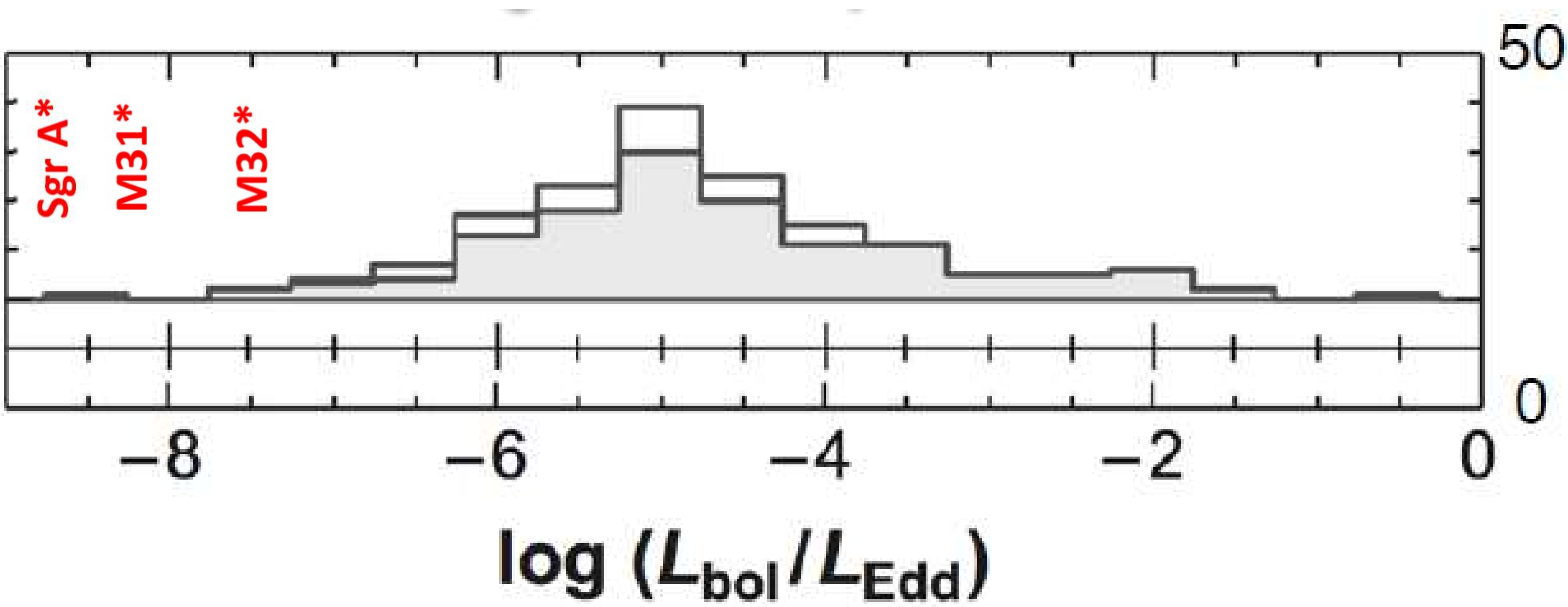
Δt1 = 84 +16/-9 yr
Short Event (1-2 yr)

Δt2 = 238 +19/-20 yr
Long Event (~ 20 yr)

=> Estimation-of / constraint-on the line of sight location of the reflecting MC

Chuard PhD Nov 2018,
Chuard et al. 2019/20 conf. Proc.
Chuard+ in prep. .....

Sgr A* and the Low-Luminosity AGN

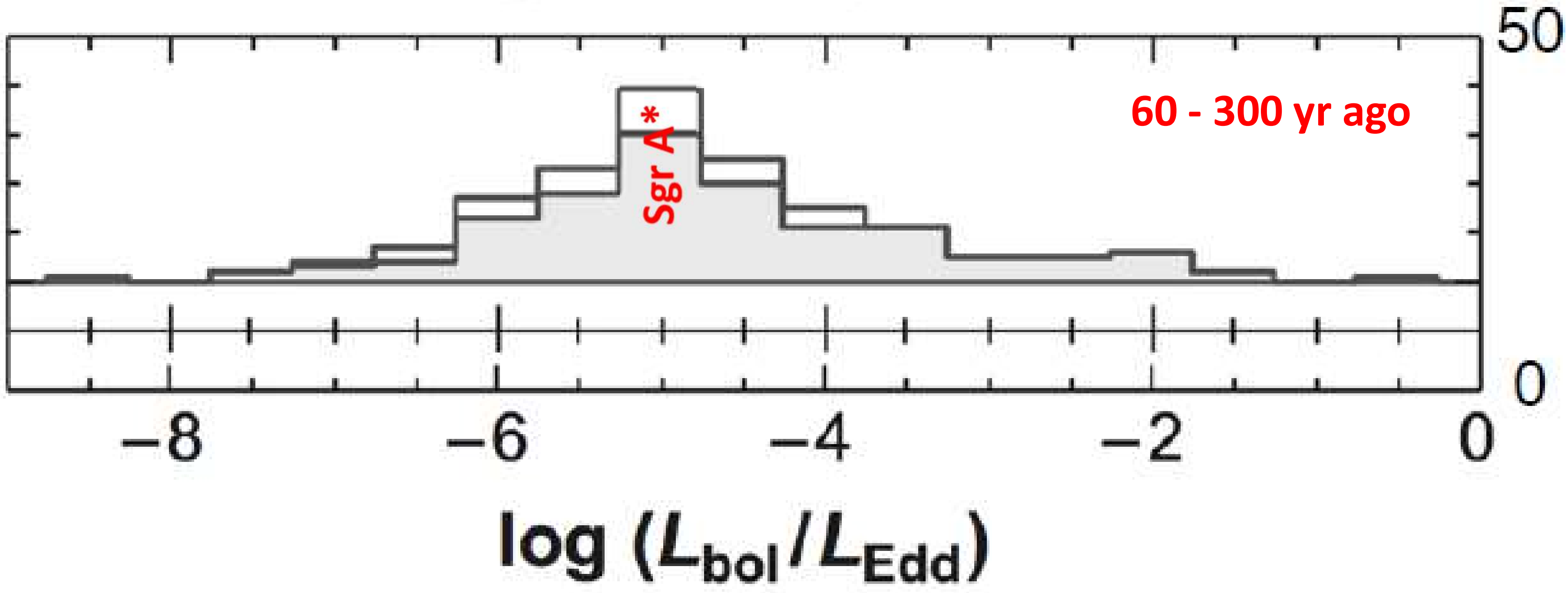


Ho 2008

43% of brightest Galaxies

(Chuard PhD Nov 2018)

Sgr A* and the Low-Luminosity AGN

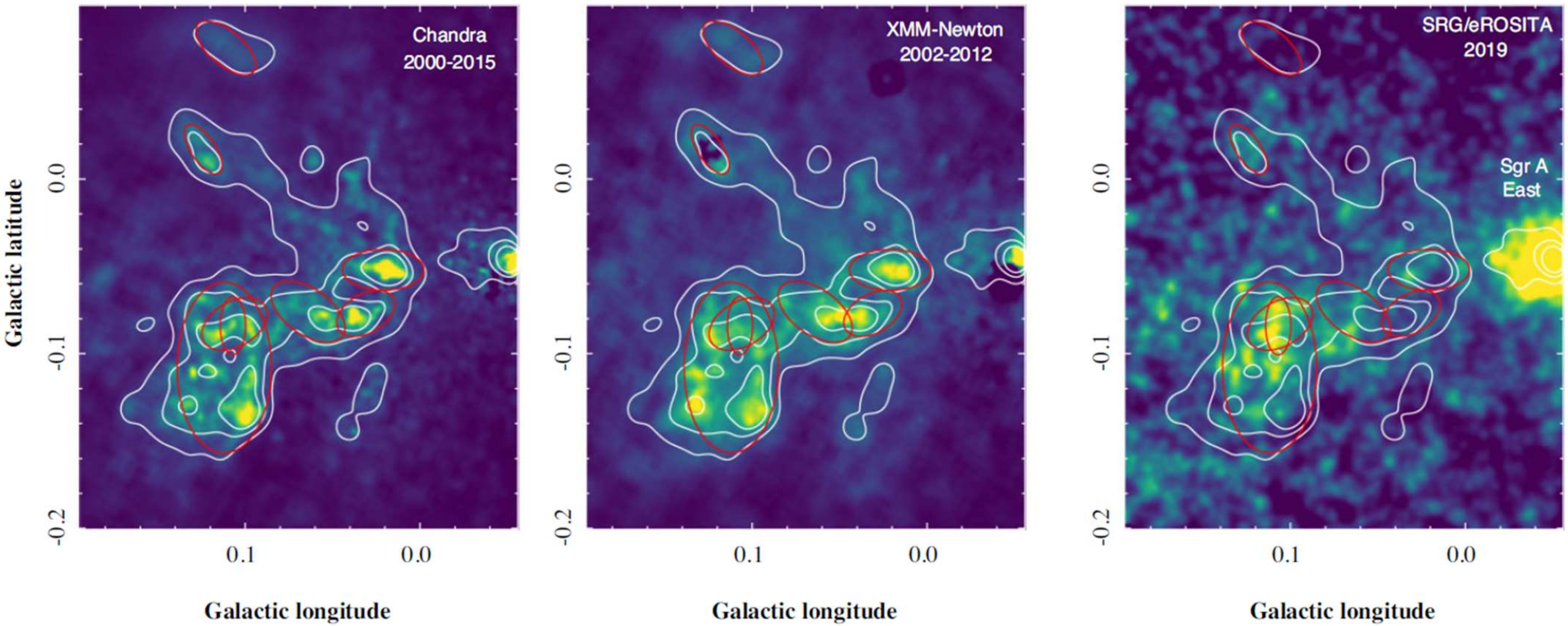


Ho 2008

43% of brightest Galaxies

(Chuard PhD Nov 2018)

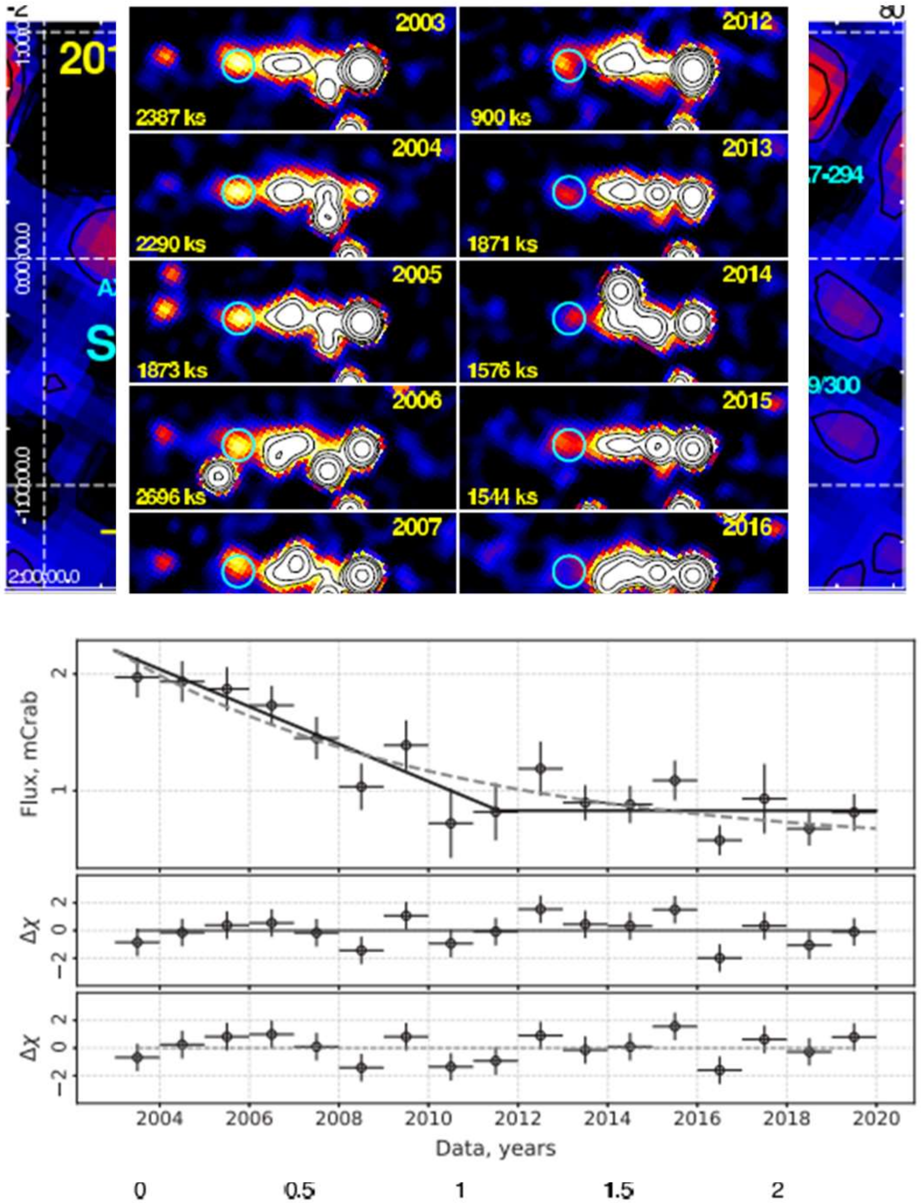
Recent SRG/eROSITA results on Sgr A* echos



- Sgr A complex still bright at ~ 4 10^{-13} erg/s/cm²/arcmin²
- Morphological changes clearly visible when compared to earlier *Chandra* XMM
- Upper limits for other molecular complexes
- Some MC clumps dominated by multiply scattered radiation
- No new MC brightening up

Khabibullin+22

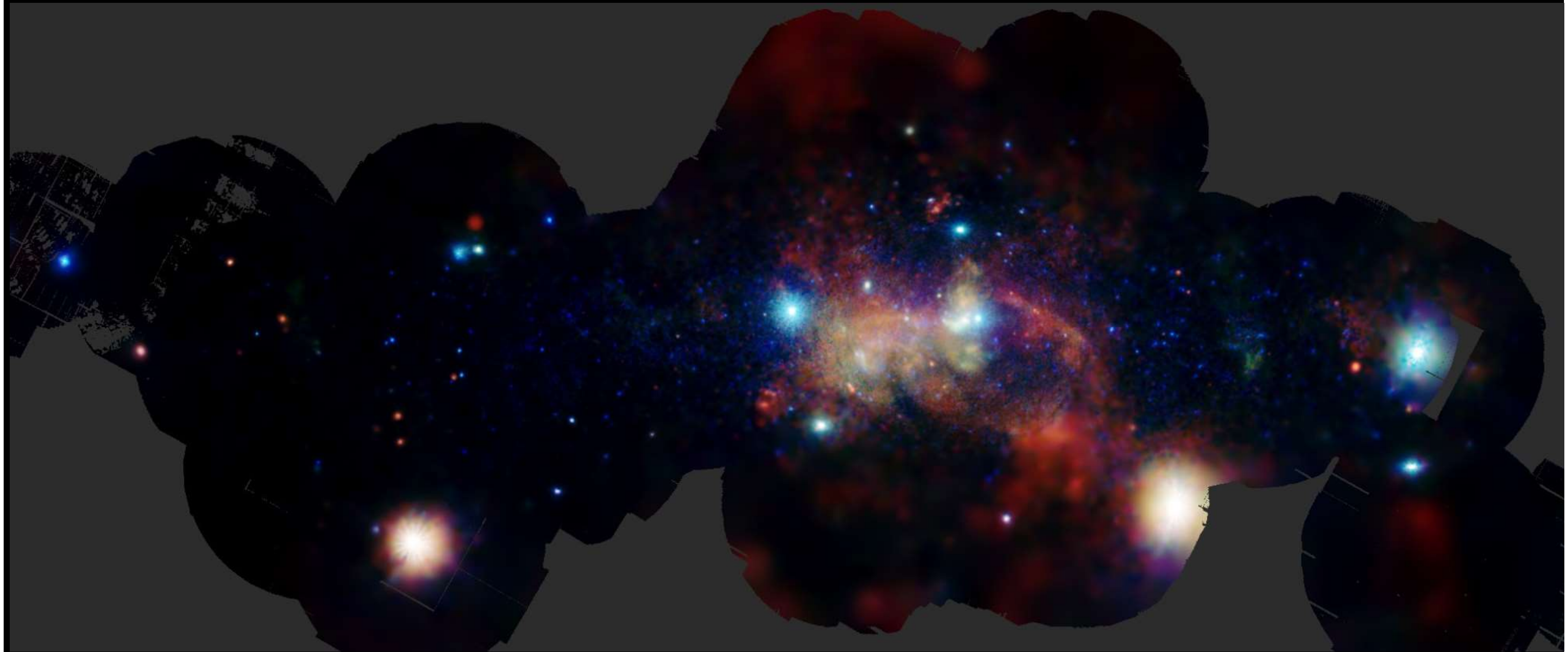
Recent Integral Results on X-ray echoes in CMZ



- Sgr B2 decrease slope flattened in 2011
- Residual em. compatible with reflection: multiple scattering ?
- Or … LECRp (s~2.7 > DSA) => higher ionization rate than measured
- Unres. P-S seen by Nu*: < 50% contribution

Kuznetsova+22

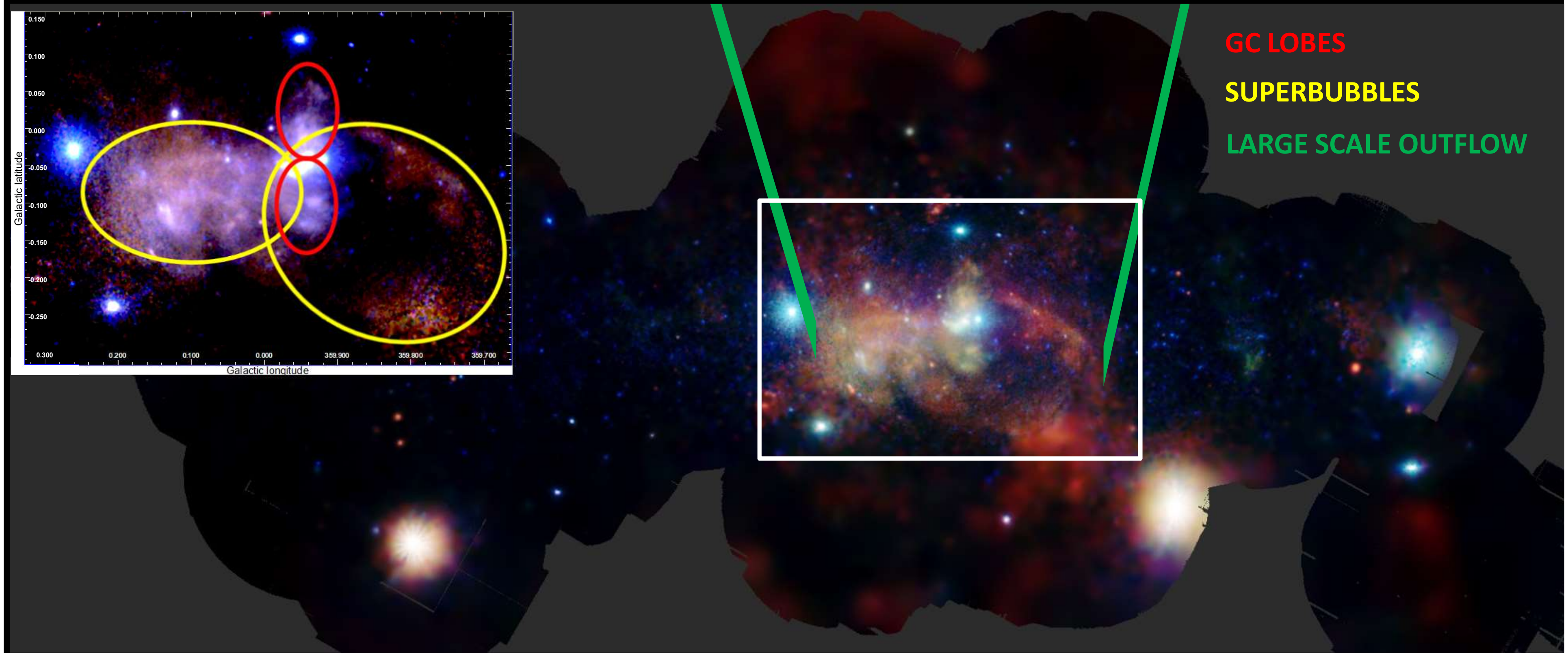
CMZ Soft X-ray Line Emission as mapped by XMM-Newton



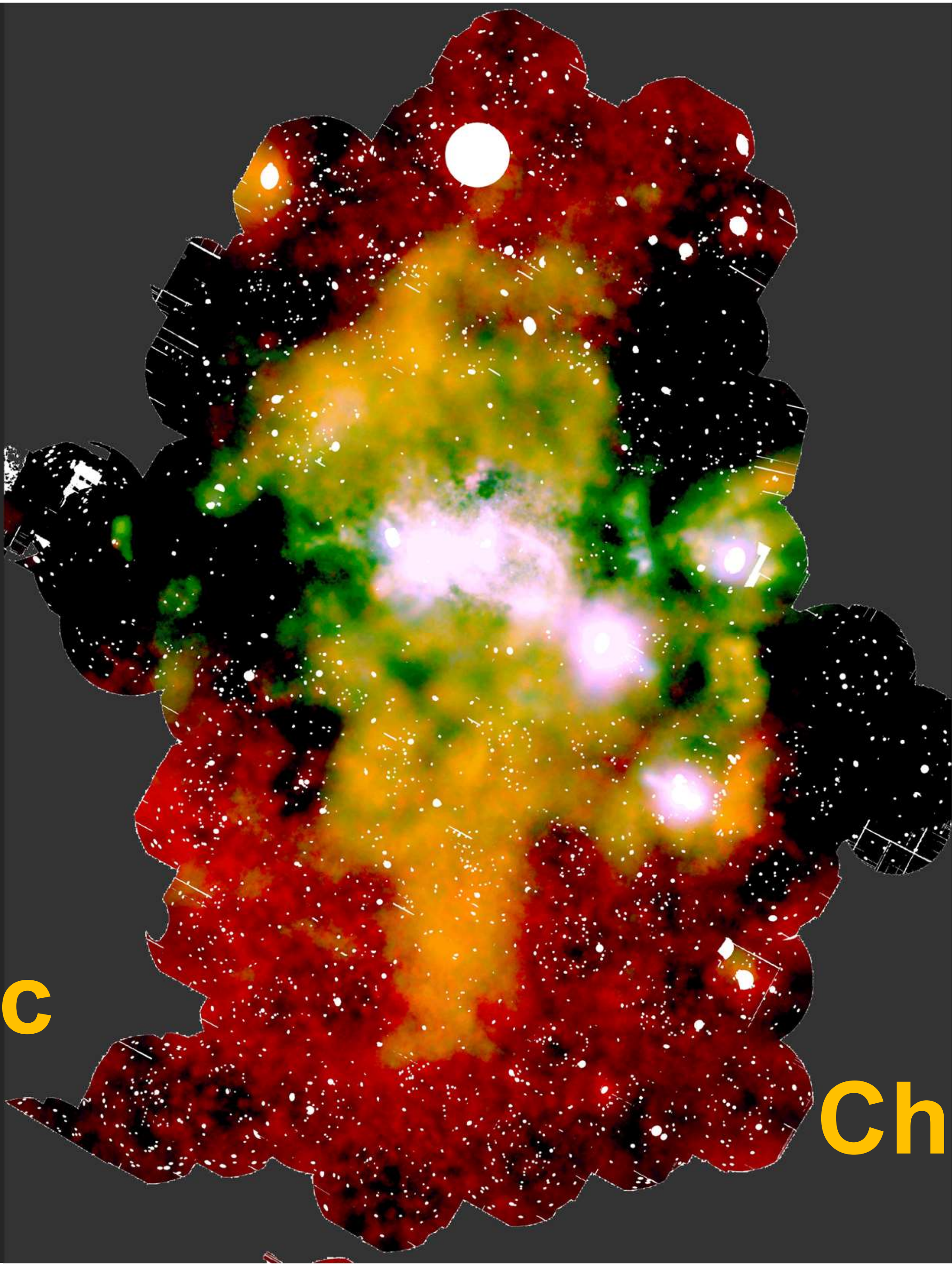
Red: Si xiii
Green: S xv
Blue: Ar xvii

Ponti+ 2015

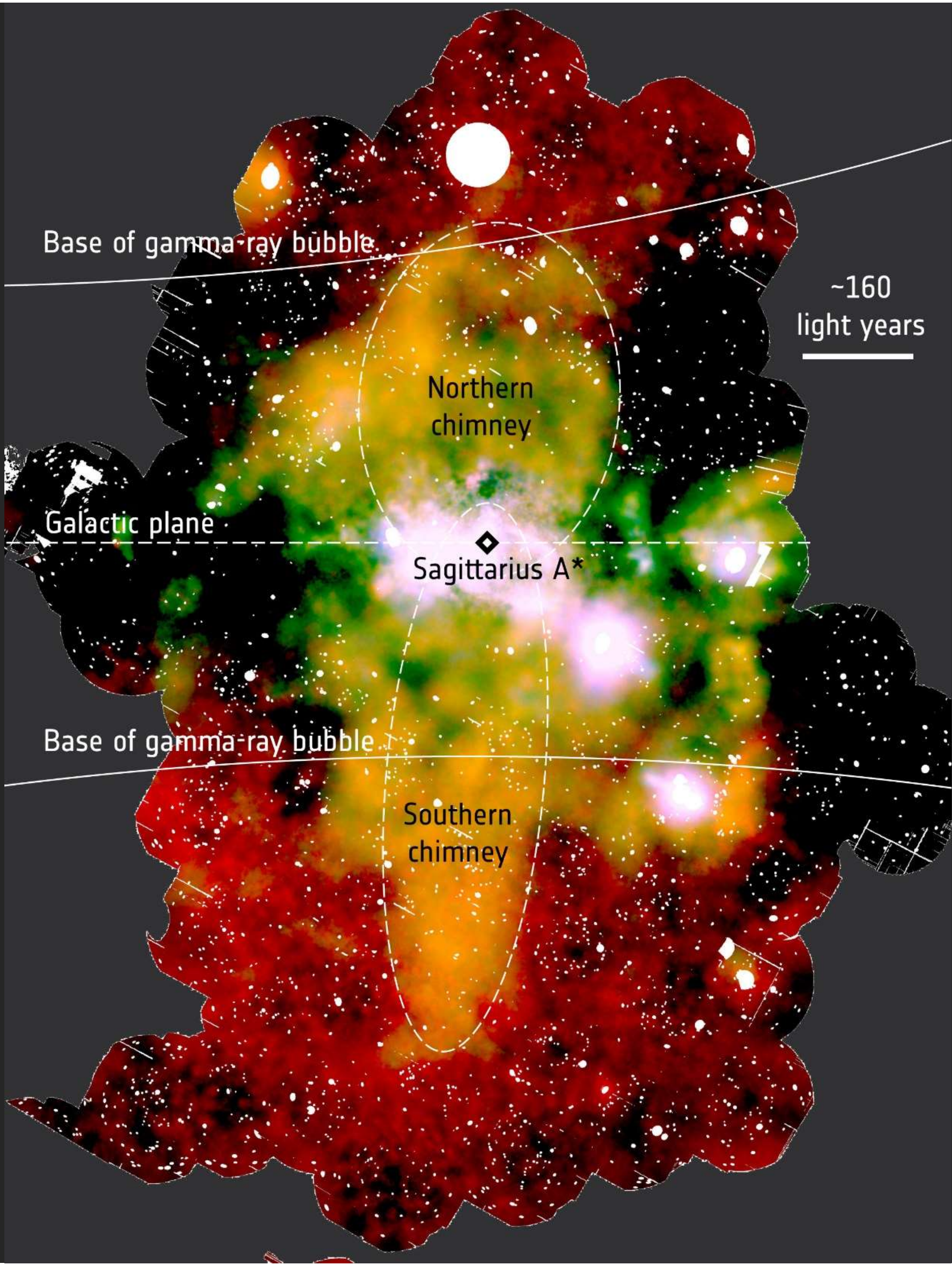
CMZ Soft X-ray Line Emission: the structures



Galactic X-Ray



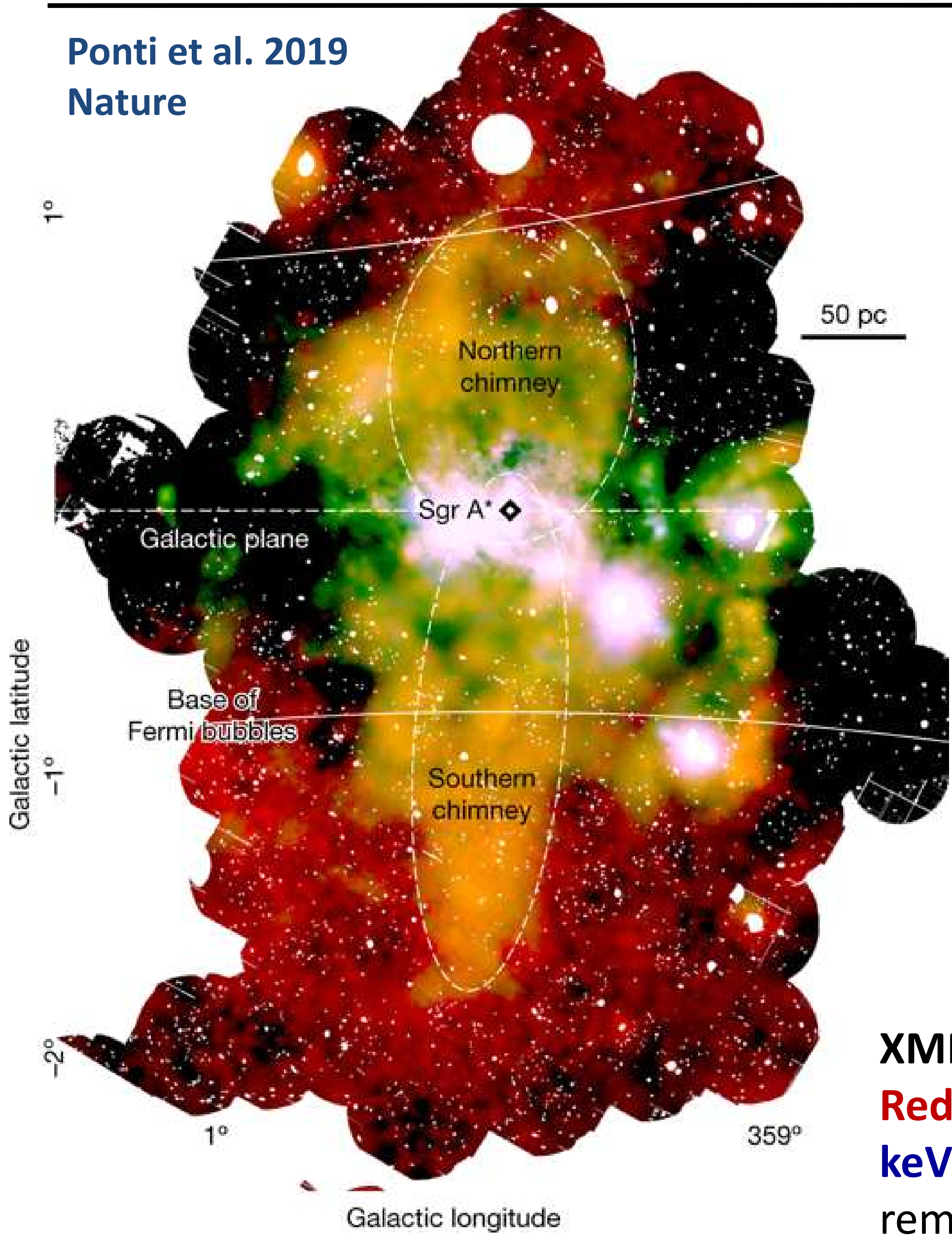
Center Chimneys



Ponti+ 2019 Nature

Discovery of Galactic Center X-ray Chimneys of Hot Gas

Ponti et al. 2019
Nature



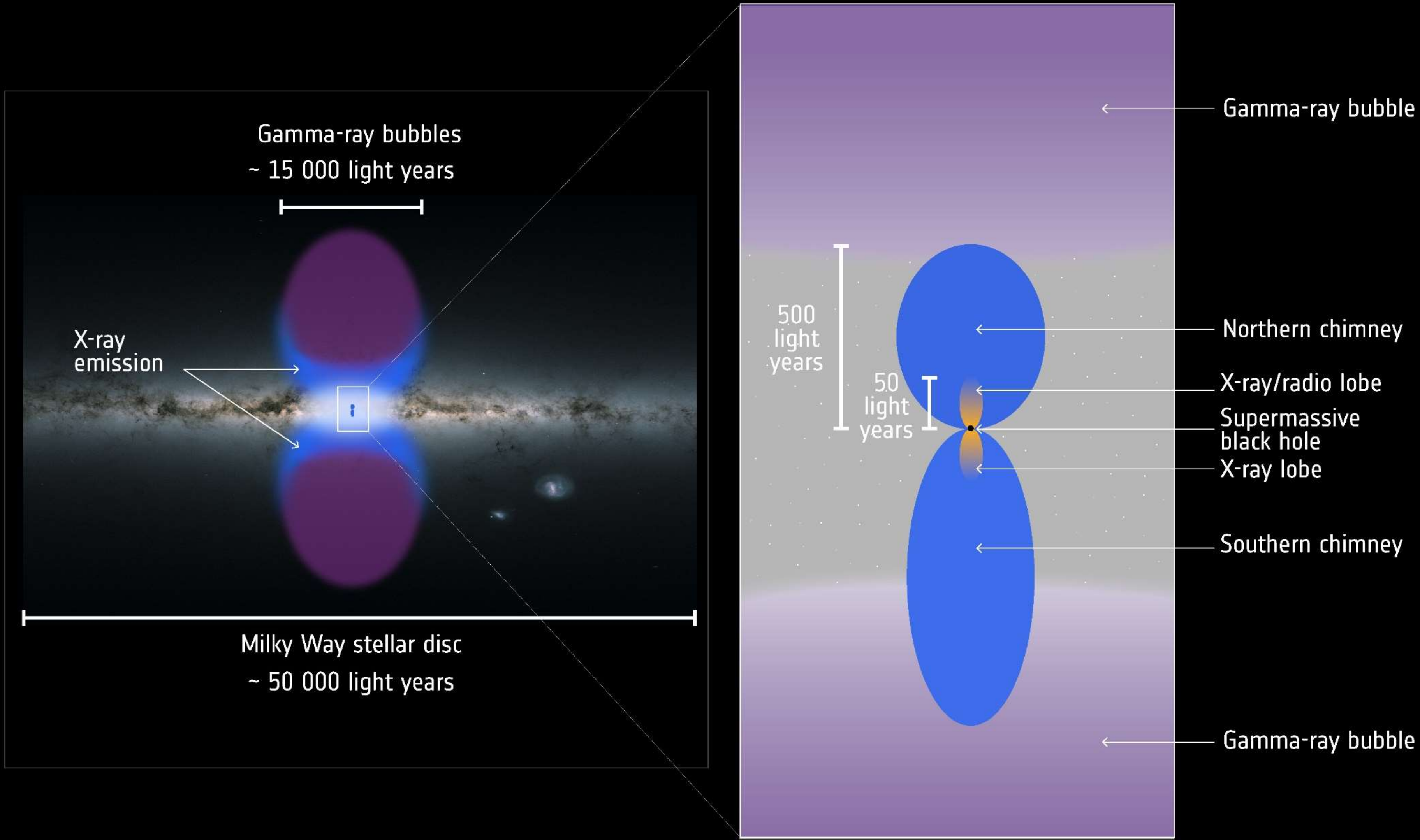
From XMM GCL Survey + Archival data:

- Detection of 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: diff in 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
  Energy: $E_{th\text{-}Chi}$ ≈ 4 10^{52} erg

- Connect GC to Fermi Bubbles Bases

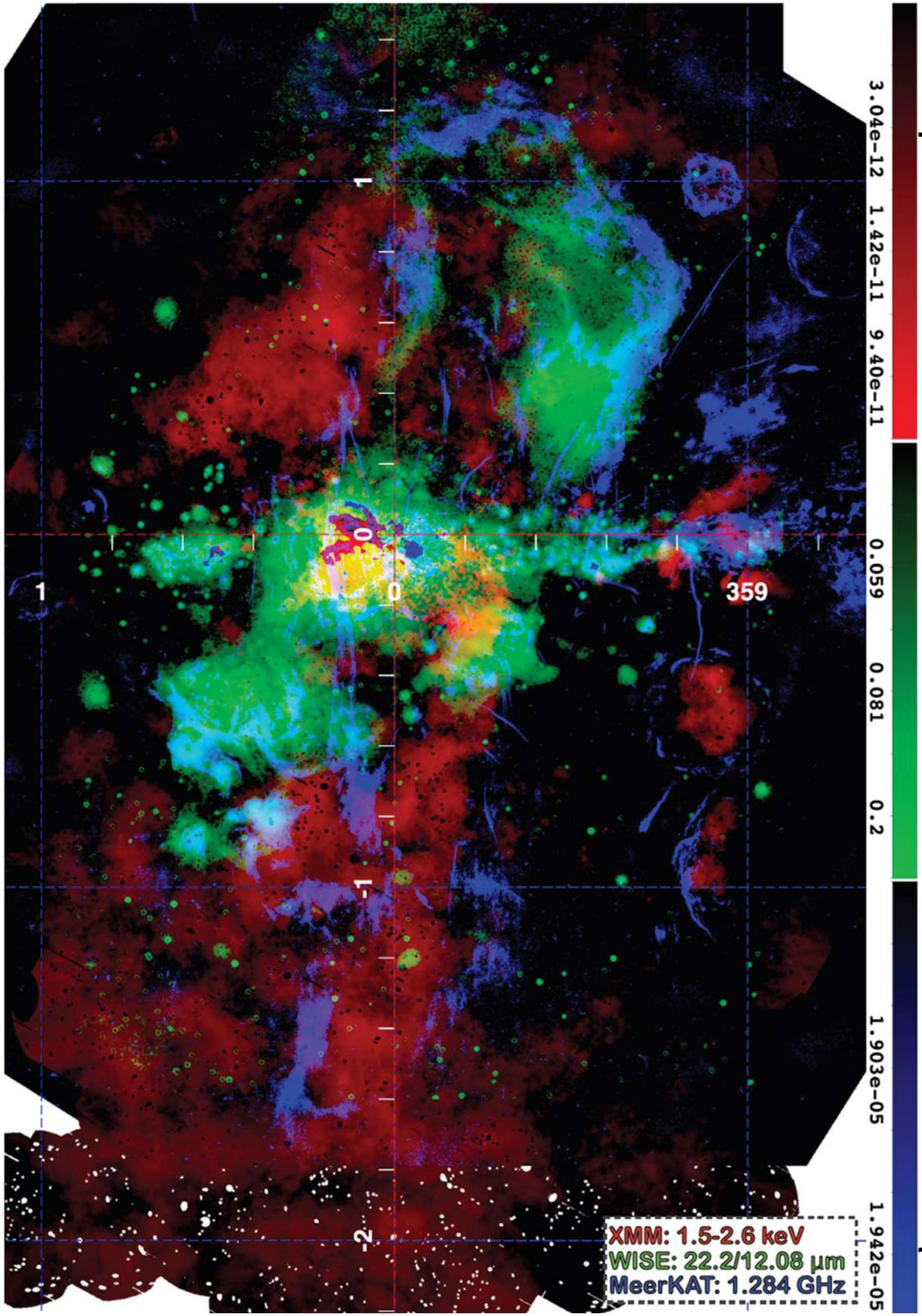
XMM-Newton Soft X-ray GC 300 pc x 500 pc image: **Red 1.5-2.6 Green 2.35-256 SXV line Blue 2.7-2.97 keV (continuum, no SXV ArXVII)**. Point Sources+dsh removed. Sgr A*, Base Fermi-B (Extrapolated Rosat)

The Galactic Center Chimneys



Credit: ESA – XMM-Newton

Ponti et al. 2019 Nature



R-IR-X GC Chimneys

Multiphase nature of Chimneys (P+21):

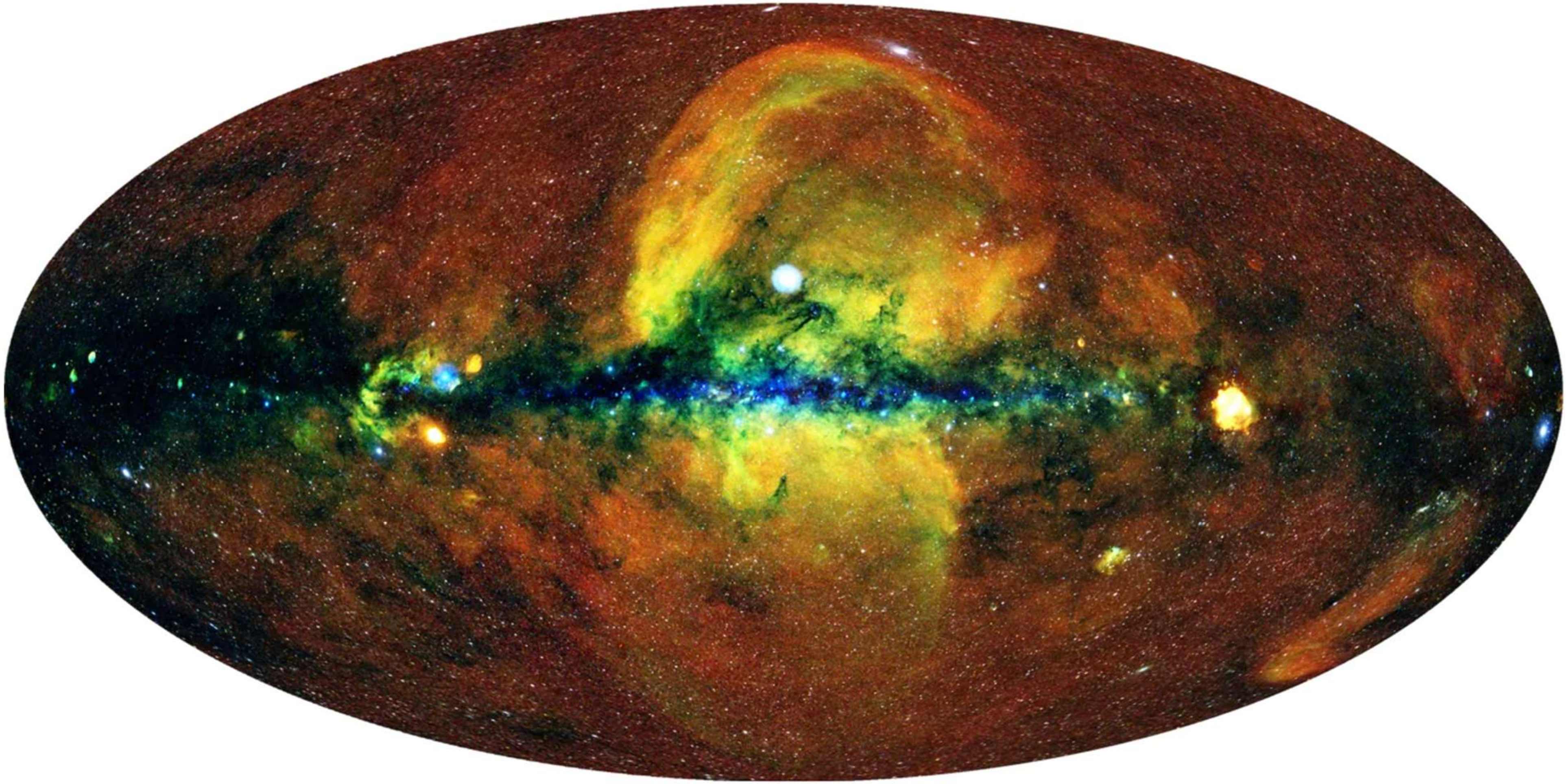
- MeerKAT (Radio) WISE (FIR) XMM(X)
- Correlated/interacting components: Hot plasma in X-r, warm dust in IR shocks + non-thermal filaments in R
- Byproduct of the same phenomenon that drives them all ?
- 200-pc Chimneys represent the channel connecting the quasi-continuous, but intermittent activity at the GC with (/ powering ?) the base of the Fermi bubbles
- “The prominent radio edges are signposts of the most powerful and recent outflow from the central parsecs, which has created the radio shell partially filled with X-ray emitting plasma and swaths of warm dust at the boundary.”

X-rays: Nakishima+2013 Ponti+2019

R: Heywood+2019

M-w: Ponti+2021 Wang2021

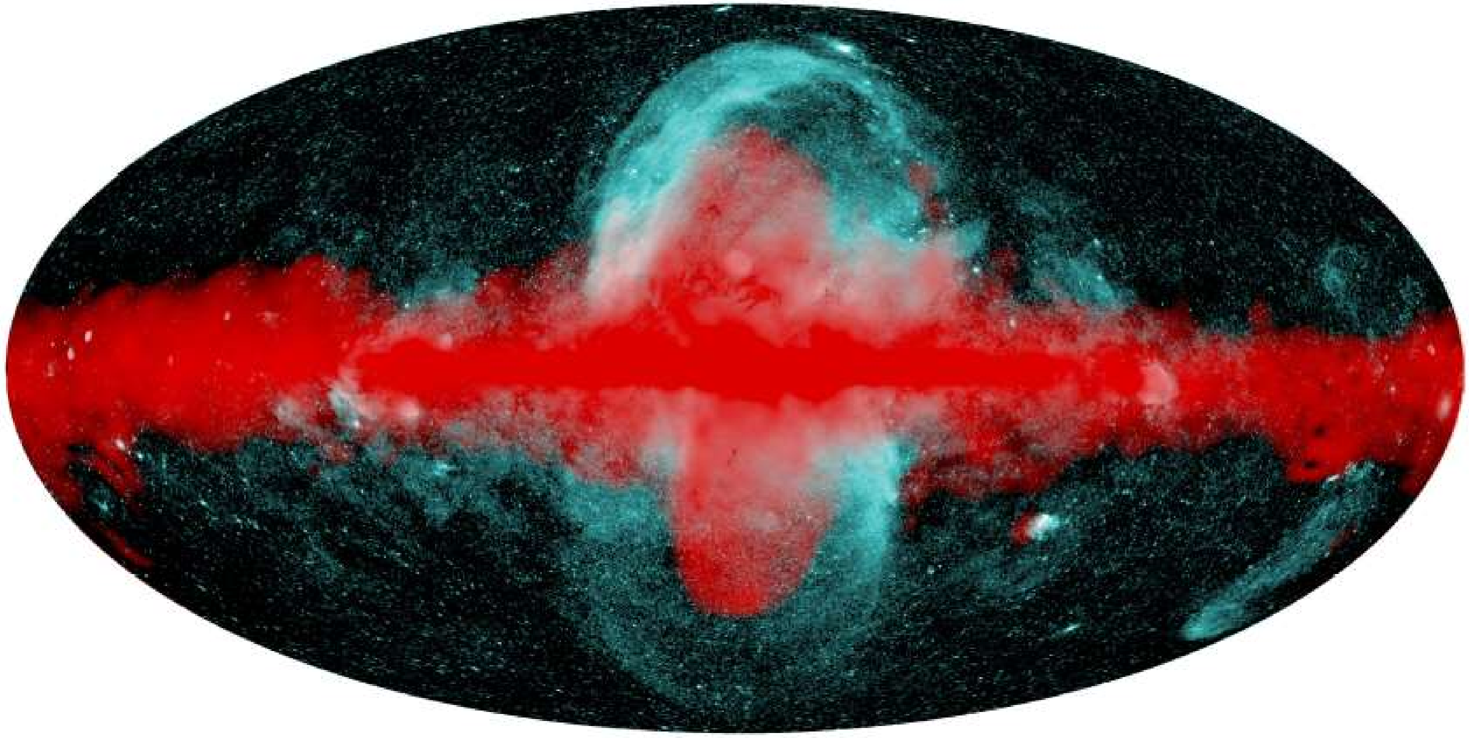
SRG-eROSITA all-Sky Map



red for 0.3–0.6 keV
green for 0.6–1.0 keV
blue for 1.0–2.3 keV

Predehl, Sunyaev et al 2020 Nat

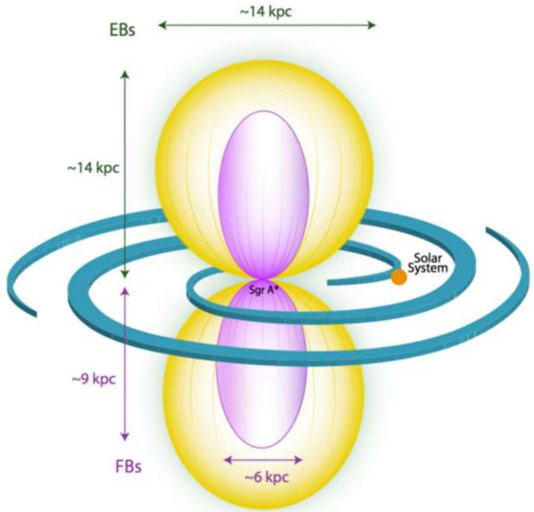
Discovery of eROSITA Bubbles



Estimated EB Energy ~ 10^{56} ergs = x 10 FB Energy

Inflated by $L \sim 10^{41}$ erg/s for 10 Myr or by 1-2 Myr Seyf-like activity at $L \sim 10^{43}$ erg/s of Sgr A*

Comparison eROSITA – FERMI: Red: gamma-rays Fermi bubbles
Cyan: 0.6-1 keV eROSITA bubbles



Geometry of eROSITA (EBs; yellow) and Fermi bubbles (FBs purple) with respect to Galaxy & Solar System: much larger =>
E at the limit of what provided by the last MW star burst episode
=> GC SMBH AGN-type activity ?

Summary of X-Ray Obs. of Galactic Center

- **Galactic Center region observed regularly in the last 20 yr with Chandra, XMM, Integral, Suzaku, NuSTAR, Swift, SRG …**
- **Sgr A* detected and studied: persistent from inefficient accret. flow (+outflow), variable em. from NT flares seen also in M/NIR**
- **CMZ Diffuse NT emission: echoes of SgrA* recent past (100-1000 yr) outbursts (~ 10^6 x Quiescent X-ray emission)**
- **Soft Diffuse emission from hot (1 keV) gaz in Chimneys: more ancient GC activity (SMBH AGN-like ? / Star Formation burst ?)**
- Large variety of HE sources & phenomena: XRB, PSR/Magn, SNR, PWN, Source populations of AB, (magn.)CVs .. + XRB inner cusp
- Diffuse thermal hard (6 keV) emission: unresolved sources like G. Ridge or real diffuse component ? … still controversial
- Link with HE (GeV, TeV) sources => GC CR content, acceleration diffusion interaction
- **GC Feedback to entire galaxy powering Fermi/eROS Bubbles**

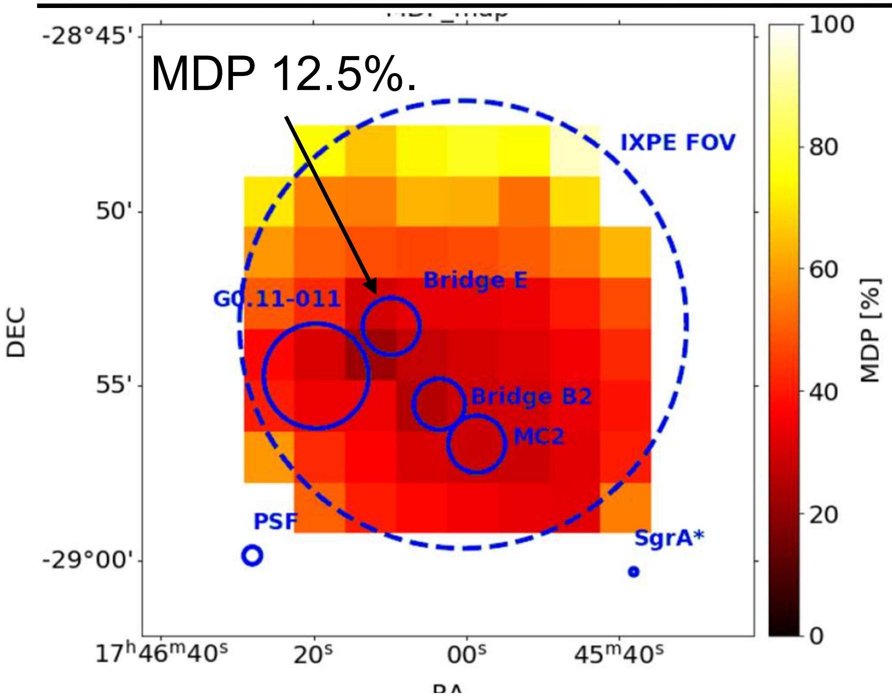
Perspectives of H-E Obs. of Galactic Center

- Chandra, XMM-Newton, Swift, Nu-STAR, INTEGRAL, Fermi, Hess still in operation …

- SRG/eRosita (2019 - …) – German/Russia (Obs. stopped now !)
- XIPE (launched 12/2021) – NASA+: im-polarimetry in 1-10 keV

- XRISM (2023 ?) JAXA/NASA+: fine X-ray im-spectroscopy
- CTA (2025-….) – Europe+: ground TeV γ-Ray Obs.
- ATHENA (2034) – ESA L2+: super-fine X-ray im-spectroscopy

X-Ray polarization measurements of GC echoes



Cloud	Energy (keV)	MDP [a] (%)	$P_{model,diluted}$ [b] (%)	$P_{other,diluted}$ [c] (%)	$\lvert d_{los}\rvert^{MDP}$ [d] (pc)
MC2	4–8	17.9	3	1–11	≥21 [*]
Bridge B2	4–8	17.9	4	19–25	≥27
G0.11-0.11	4-8	12.5	17	29–30	≥50
Bridge E	4–8	13.5	5	24–39	≥45

Cloud	Energy (keV)	P_{obs} [a] (%)	D [b] (%)	$P_{dmapcorr}$ [c] (%)	$P_{subcorr}$ [d] (%)	$\lvert d_{los}\rvert^{dmapcorr}$ [e] (pc)
MC2	4–8	≤17.9	11 ± 9	≤53	≤30	≥9
Bridge B2	4–8	≤17.9	25 ± 6	≤45	≤34	≥13
G0.11-0.11	4–8	15 ± 6	30 ± 3	49 ± 20	53 ± 13	19±7
Bridge E	4–8	≤13.5	39 ± 4	≤31	≤20	≥26

- Compton scattered rad. is linearly polarized up to 100% for 90° scattering angle. Direction to external illuminating source is perpendicular to pol. direction
- Echoes Polarization Measurement can provide incidence angle => MC line of sight position (some degeneracy)
- Issues: contamination, weakness of fading GC MCs, incident rad. polariz.
- XIPE could detect 4-8 keV Pol (only) in G011-011 of Sgr A complex with 2 Ms obs. (for assumed MC locations)
- Methods to increase sensitivity allow measure G011-011 pol => LoS location within 4 -7 pc (for assumed condit.)
- VERY CHALLENGING experiment

Churazov+02 17a 17b Marin+ 14 15

Kabibullin+20

XIPE sim.: DiGesu+20 **Ferrazzoli+21**

An X-Ray view of the Galactic Center

Thanks