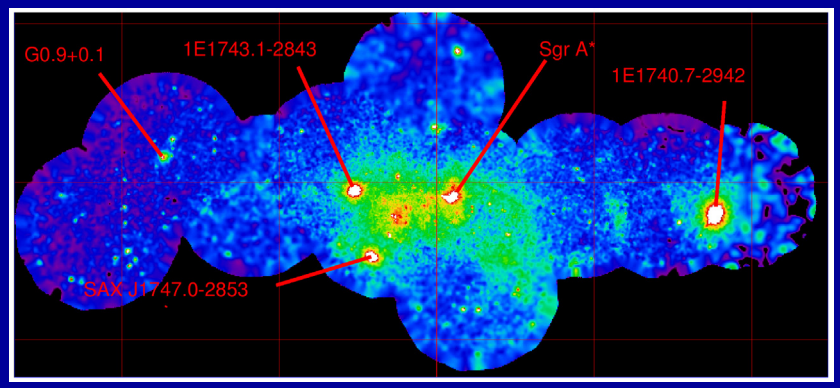
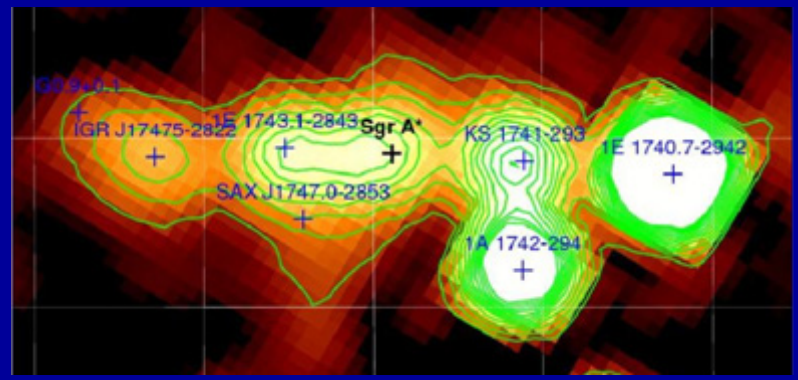
Activité de Haute Energie au Centre de la Galaxie

Andrea Goldwurm

AstroParticule et Cosmologie – Paris
Service d'Astrophysique / IRFU / CEA – Saclay
France





Original results based on data from

Space Observatories : **INTEGRAL, XMM-Newton**, HST/Nicmos

Ground Observatories : VLT, APEX, VLA, CSO, BIMA, ATCA

Work in collaboration with

R. Terrier, G. Trap, G. Ponti (SAp/CEA - Saclay, APC - Paris, F)
G. Bélanger (ESAC/ESA, Villafranca de Castillo, ES)
F. Melia (University of Arizona - Tucson, US)
F. Yusef-Zadeh (Northwestern University - Evanston, US)
R. Genzel, S. Giellessen, K. Dodds-Eden, P. Predehl (MPE – Garching, D)
D. Porquet, N. Grosso (OAS-Strasbourg, F)
R. Warwick , M. Sakano (Leicester University, UK)
M. Falanga (ISSI-Berne, CH) and many others

Publications:

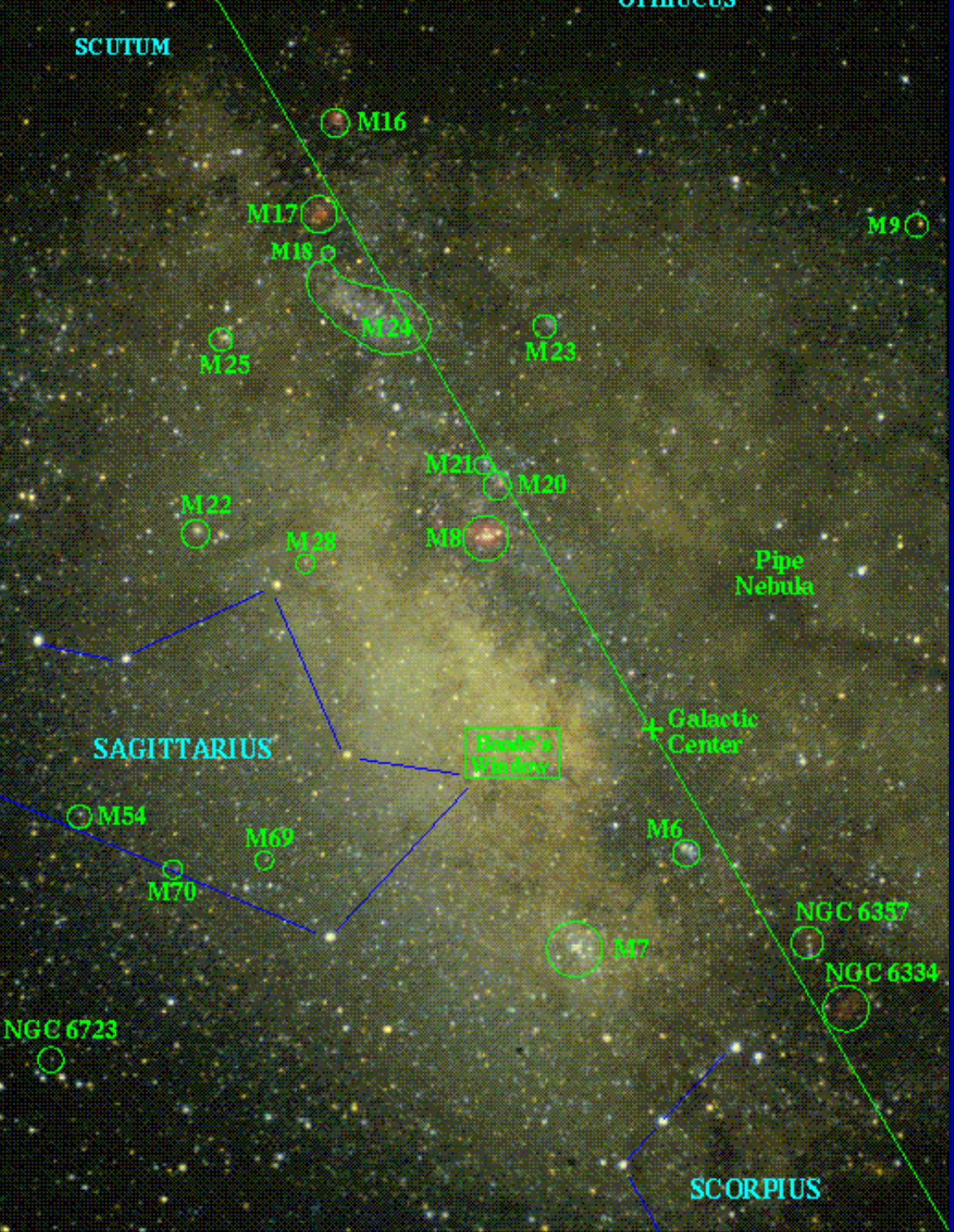
Bélanger etal 2004, 2005, 2006; Dodds-Eden etal 2009; Falanga etal 2007, 2008; Goldwurm etal 2003, 2004; Porquet etal 2003, 2005, 2008; Yusef-Zadeh etal 2006, 2009; Trap et al 2008, 2009, 2010 (in prep)

Outline

1. A Multi-λ overview of the GC region
2. The GC Super-Massive Black Hole : Sgr A*
3. X-ray view of GC region and Sgr A* flares
4. Search for soft gamma-rays with INTEGRAL
5. Multi-λ campaigns on Sgr A*
6. Sgr B IGR and TeV emission from the GC
7. New results : Suzaku, variability of SgrB & other MCs
8. Conclusions and Perspectives

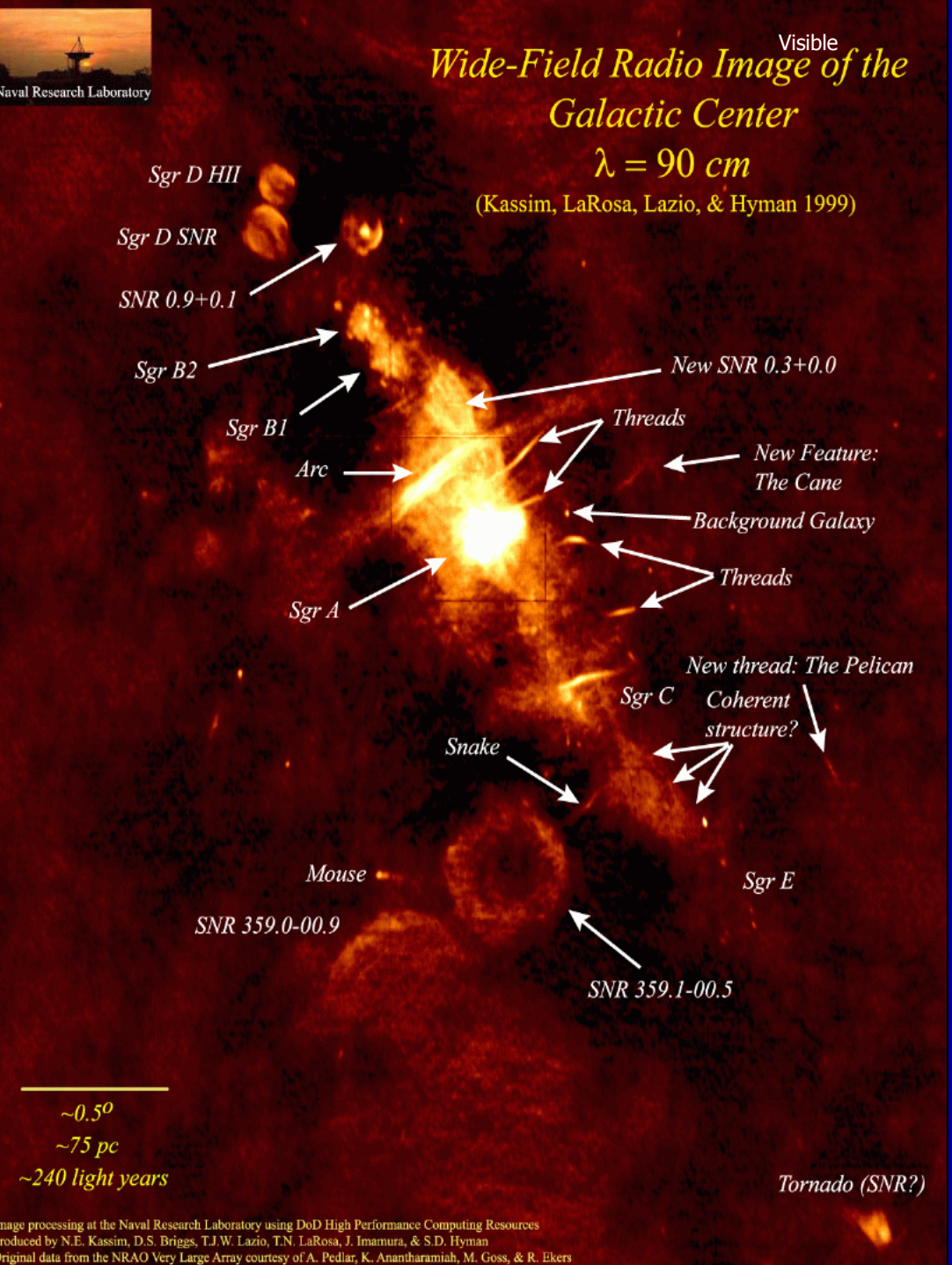
Reviews : from Mezger et al 96, Morris & Serabyn 96, Melia & Falcke 00

La Galaxie et le Centre Galactique



The Center of the Galaxy

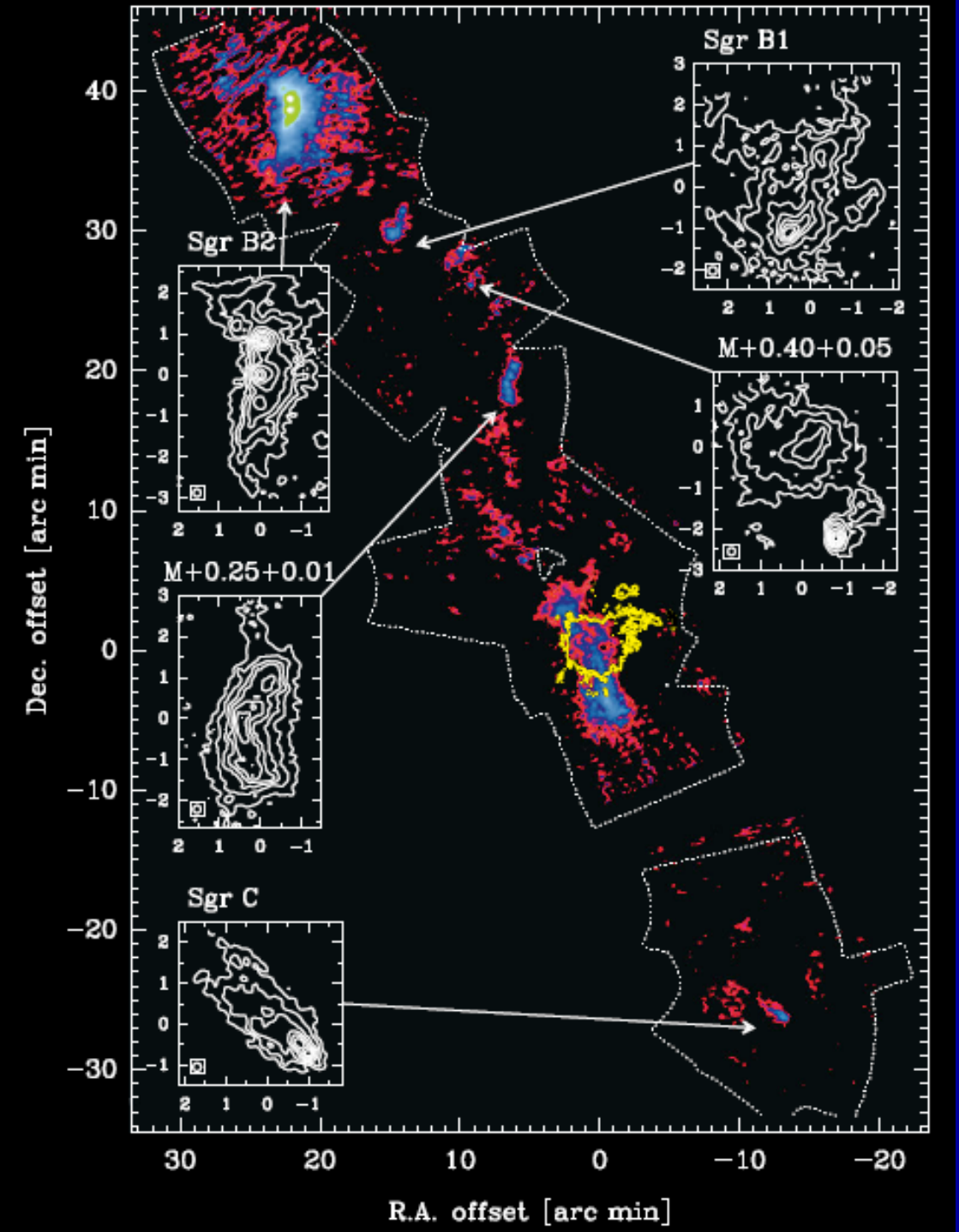
- **Since the ’30s: the dynamical and symmetry center** of our Galaxy is in Sagittarius
- The sky region is rich of globular and open clusters but obscured towards the center
- Distance ≈ 8 kpc (1" ~ 0.04 pc, 1’ ~ 2.4 pc, 1° ~ 150pc)
- Highly obscured (A_v = 31 mag) by dust of the galactic plane: not visible in opt. and UV, only Radio, IR and X/Gamma-rays
- Stellar cluster visible in NIR



The Galactic Center Region

(600 pc ≈ 4°)

- Giant Molecular Clouds (Sgr A, Sgr B, Sgr C, Sgr D, ..)
- Super Nova Remnants
- Non-thermal structures (radio Arc, NT Filaments)
- Thermal filaments (Bridge)
- H II regions (Pistol, Seiklo) and their ionizing hot star clusters (Quintuplet, Arches)
- Strong magnetic field (~1 mG), // gal. plane in GMC, ⊥ in inter-cloud medium
- Gas motions: large vel. fields radial inflow $\approx 10^{-2}\ M_{\odot}\ yr^{-1}$ and bipolar outflows

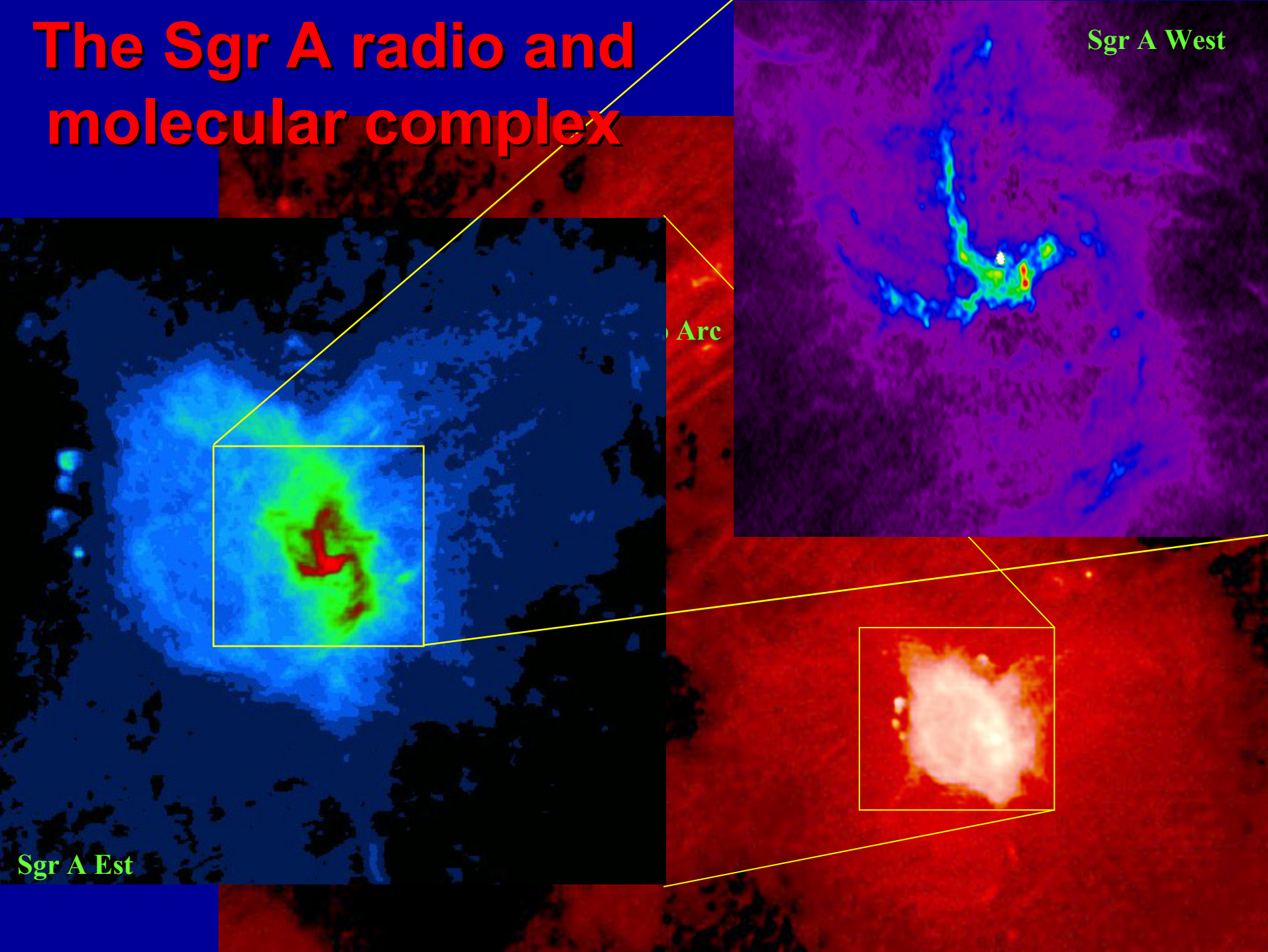


The CMZ

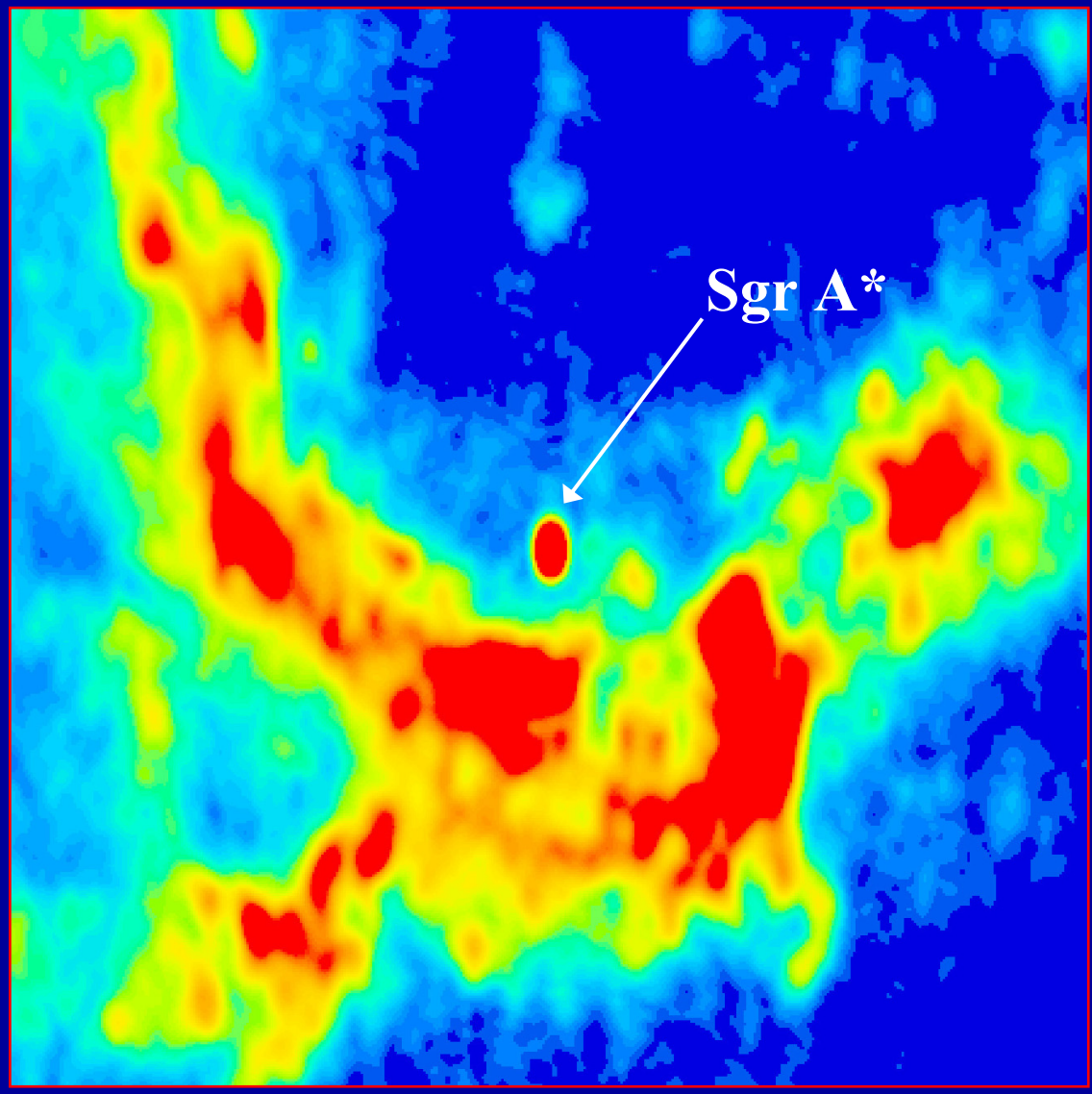
- It contains ≈ 10^8 $M_\odot$ ≈ 10% of all molecular gas of the G
- Observed in radio (mol. lines of CO, CS, SiO, H_2CN, HC_3N) and in sub-mm and FIR (dust)
- Dense (≈ 10^4 - 10^5 cm^{-3}) compact (50-70 pc), warm (T ≈ 30-60 K) clouds
- Star formation low 0.3-0.6 (instead of the GD 5.5) $M_\odot$ yr^{-1}
- Giant Molecular Clouds: Sgr B, Sgr A complex, Sgr C, G 01-01

CSO (800 μm): cold dust of GMC cores
IRAM/MRT (1300 μm)

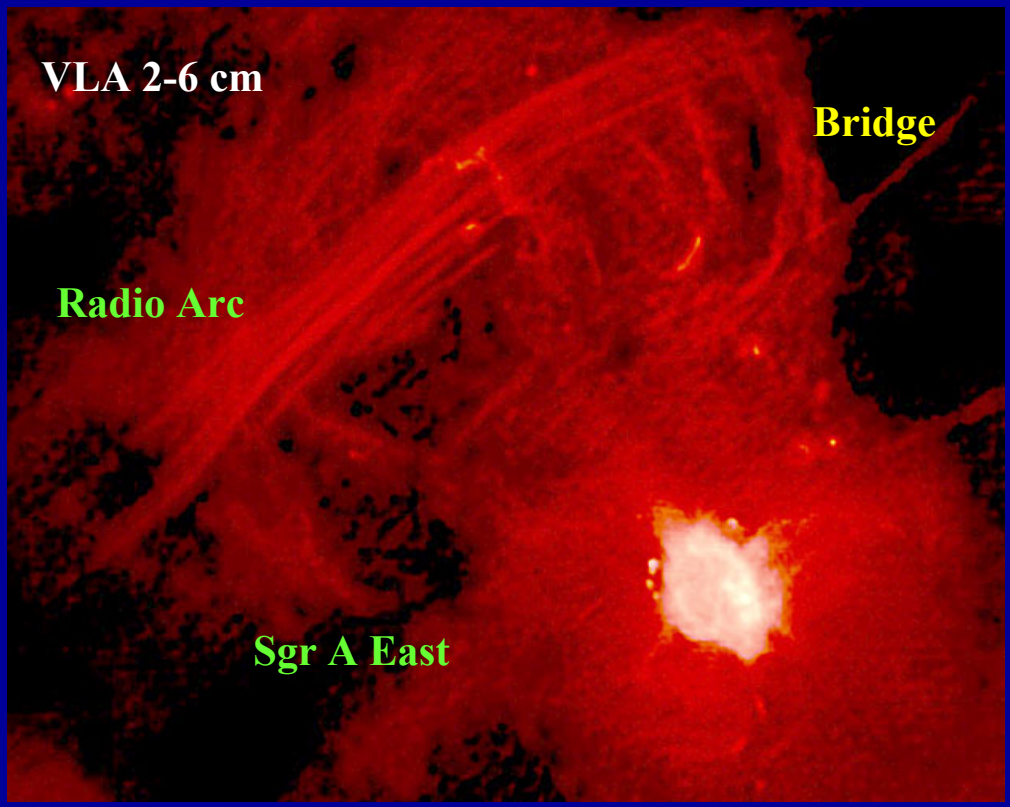
The Sgr A radio and molecular complex

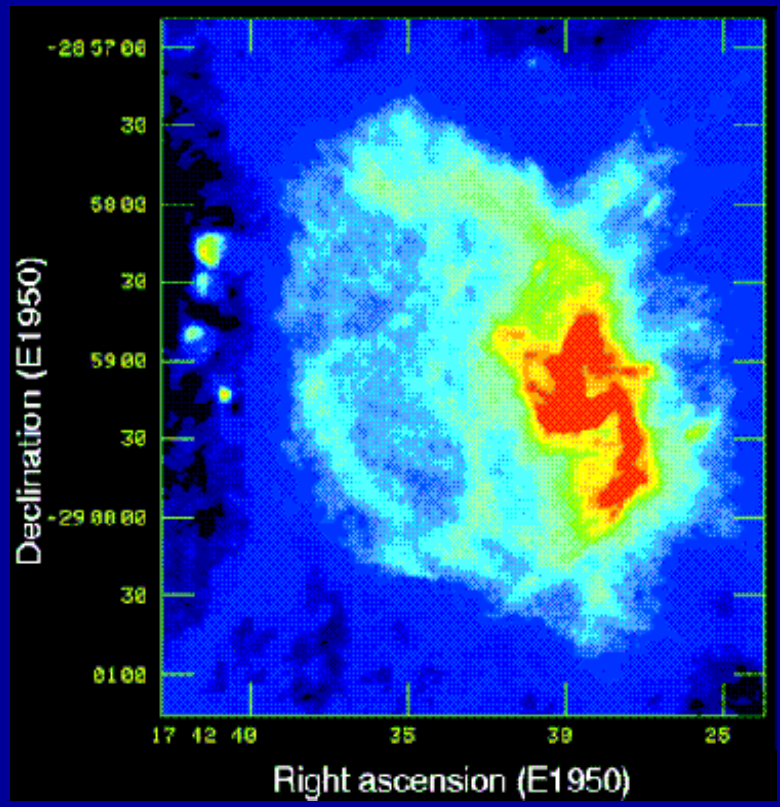


Sagittarius A* : le trou noir supermassif au centre de la Galaxie



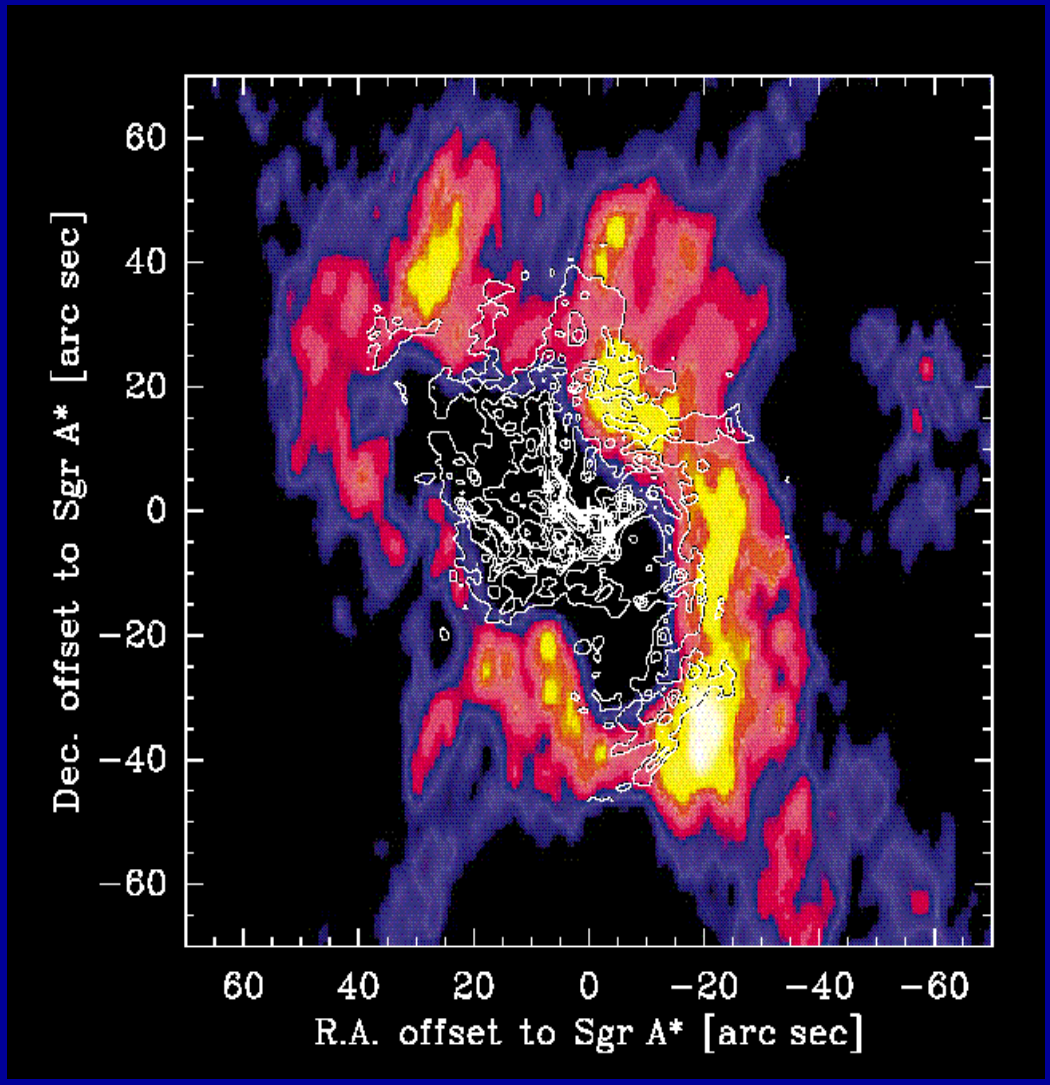
The Non-thermal Sgr A East





- The Non-thermal source Sgr A East is composed of a diffuse halo (8' ≈ 20 pc) and a shell structure (2' × 3' = 5 pc × 7 pc) centred at ≈ 50" = 2 pc from Sgr A*
- Power-Law Radio Spectrum with ($\alpha \approx -1.1$)
- Interacting with M-0.02-0.07 cloud (HII regions, OH masers) expansion within MC
- Initial uncertainties about energetic : E ≈ 4 10^{52} ergs (~40 SN !!), age ≈ 5 10^{4} yr
- Now: Standard mixed morphology SNR (radio shell and X-ray thermal emission)

The CircumNuclear Disk (CND)

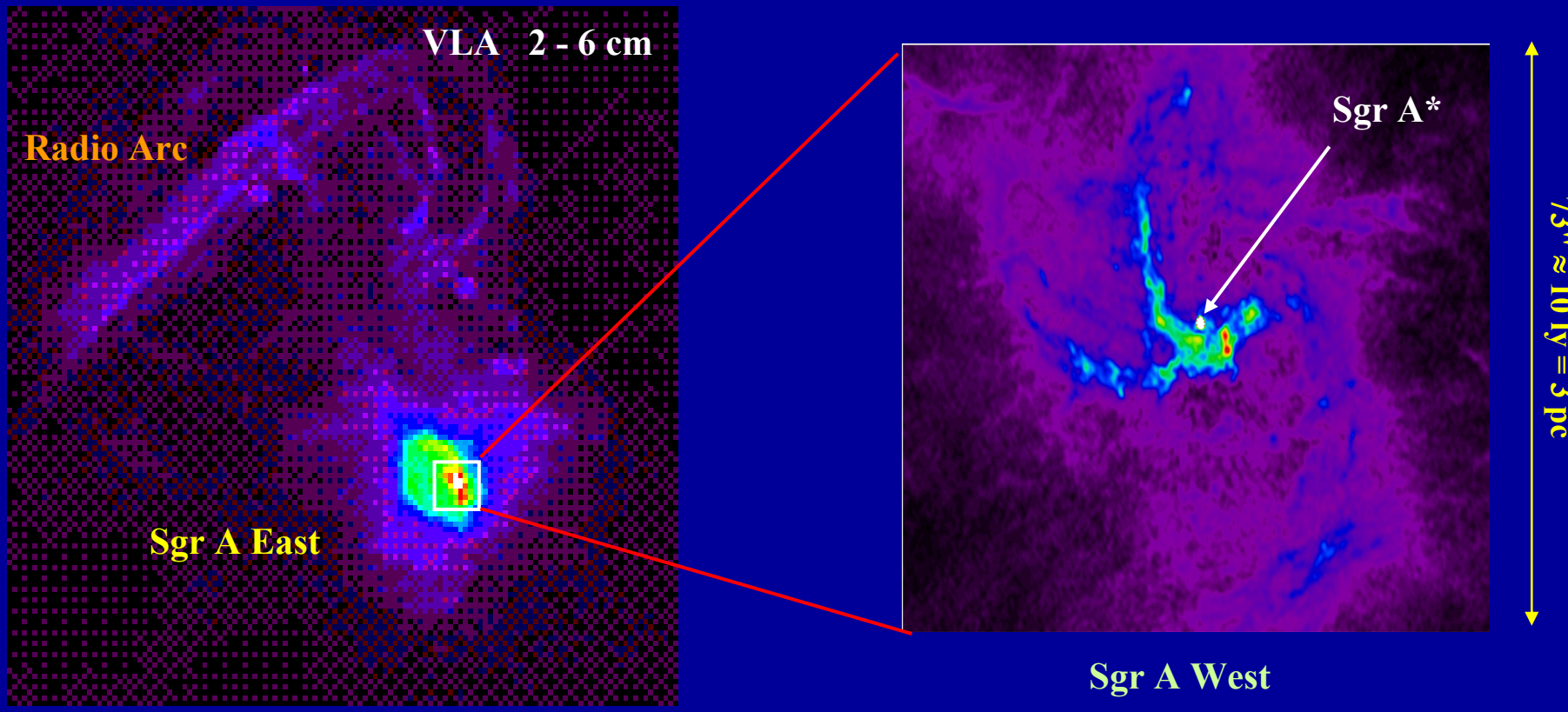


Internal edge of the CND seen in HCN line (88.6 GHz) with contours of Sgr A West

- A torus of clumsy dust & molecular gas rotating around **Sgr A West**
- Ring radius 1.7-7 pc (< 3') $V_{rot} \approx 110$ km s^{-1}, Total mass $\approx 10^4\ M_\odot$
- Fed by the M-0.13-0.08 GMC, at rate $\approx 10^{-2}\ M_\odot\ yr^{-1}$
- Bright in FIR and MIR due to reprocessing of central UV radiation by the heated warm (T ≈ 100 K) dust

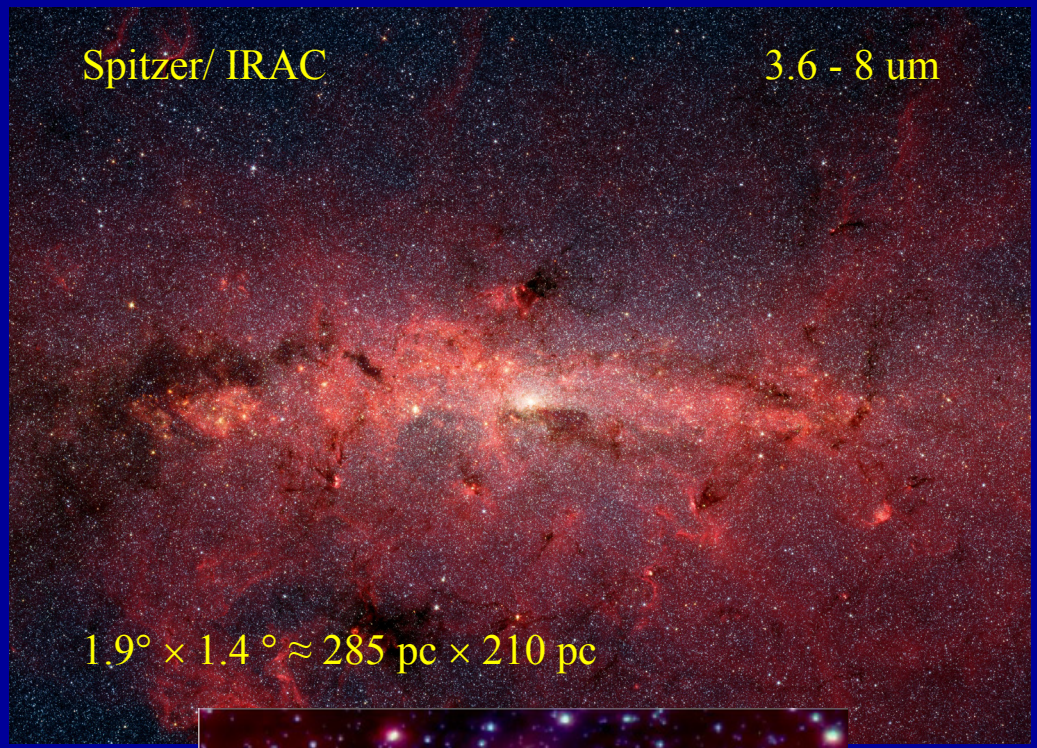
  => $L_{UV} \approx 2\ 10^7\ L_\odot$

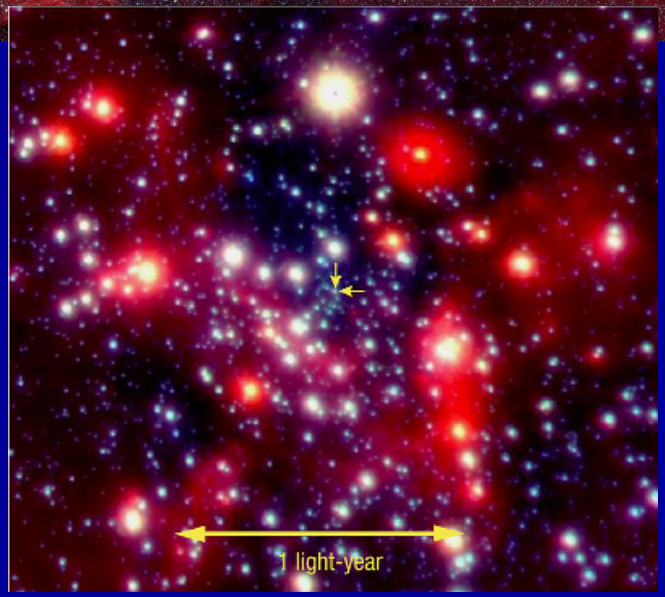
Sgr A* : a candidate GC SMBH



- Predicted in 1971 and Discovered in 1974: signature of a SMBH at GC
- Sgr A*: bright (~ 1 Jy), variable, compact, non-thermal radio source
- At < 10 mas from S-* cluster dynamical center. Proper motion < 15 km s^{-1}
- Radio (3 mm) size ≈ 0.15 mas < 1 AU (≈ 20 R_S for a BH of 3 10^6 $M_\odot$)

Stellar Content of the Central 300 pc





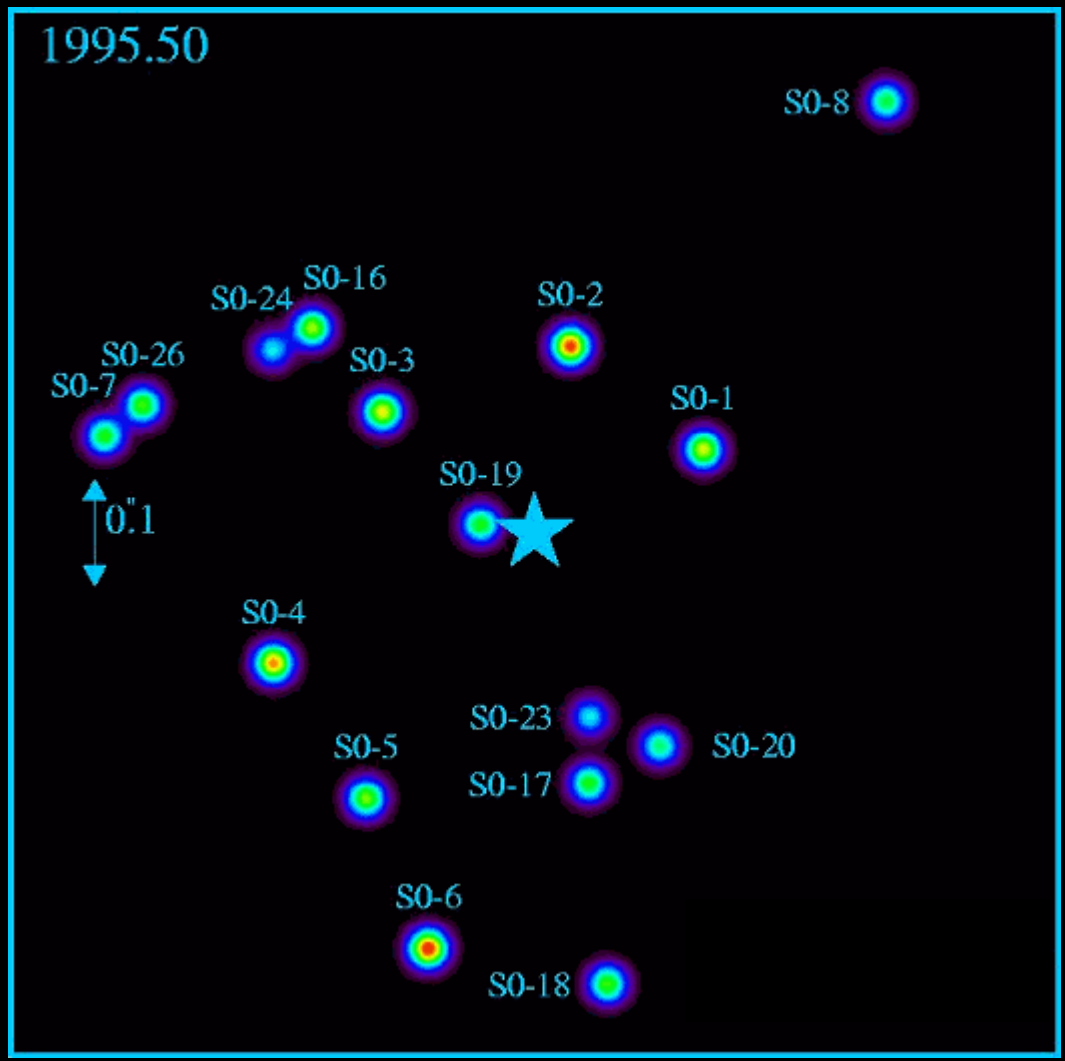
- NIR surface brightness ÷ $R^{-0.8}$ ⇒ stellar density ÷ $R^{-1.8}$ from R < 300 pc to $R_c \approx 0.1$. Within the core * density of $\approx 10^7\ M_\odot\ pc^{-3}$ and $M_c \approx 10^{5.5}\ M_\odot$
- This cluster of old stars dominates the dynamics for R > 1.5 pc
- No evidences of the expected cusp

- NIR images (R < 1 pc, K < 16) : 1000 stars, 200 spectra, 70 proper motions
- 24 blue, hot, massive, young stars (IRS 16 cluster) with HeI and HI emission lines provide total $L \approx 10^8\ L_\odot$ and powerful stellar winds

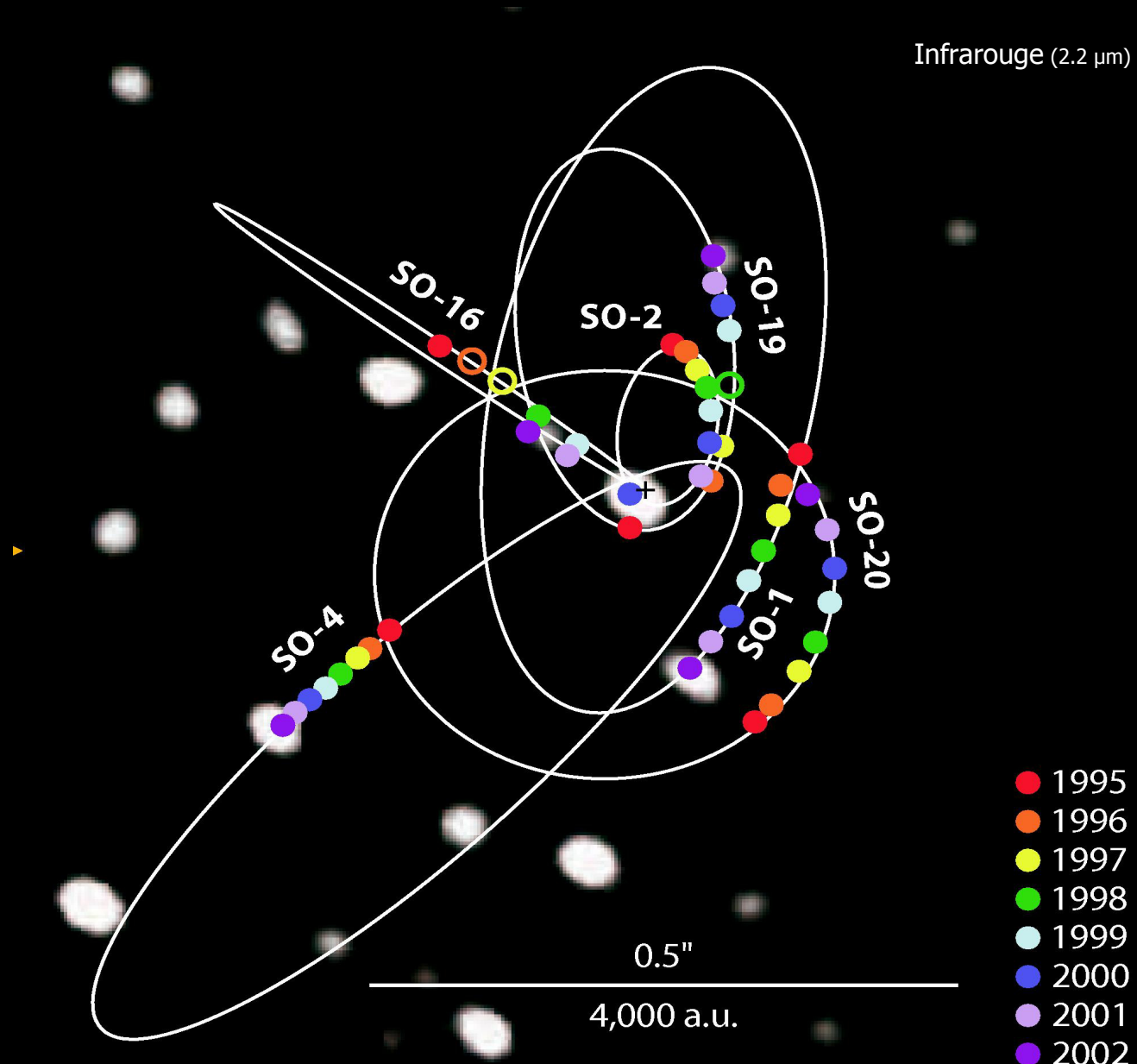
- Inner “Sgr A* star cluster”, (R< 0.1 pc), B stars

(Mezger et al 96, Ghez et al 98, Genzel et al 00)

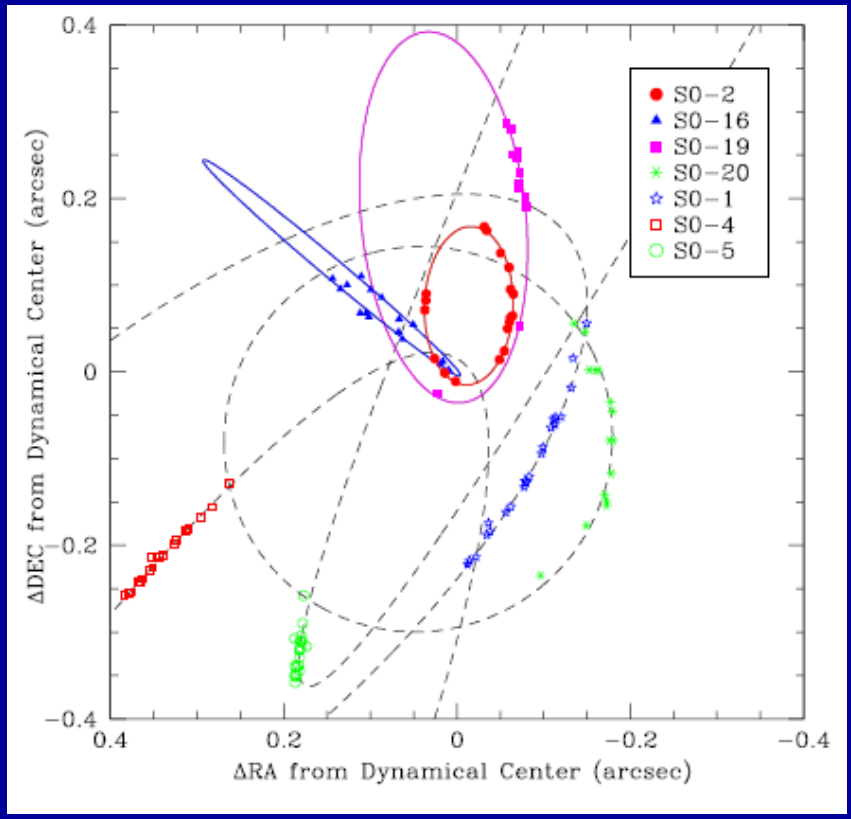
Orbites des étoiles du centre



Orbites des étoiles du centre



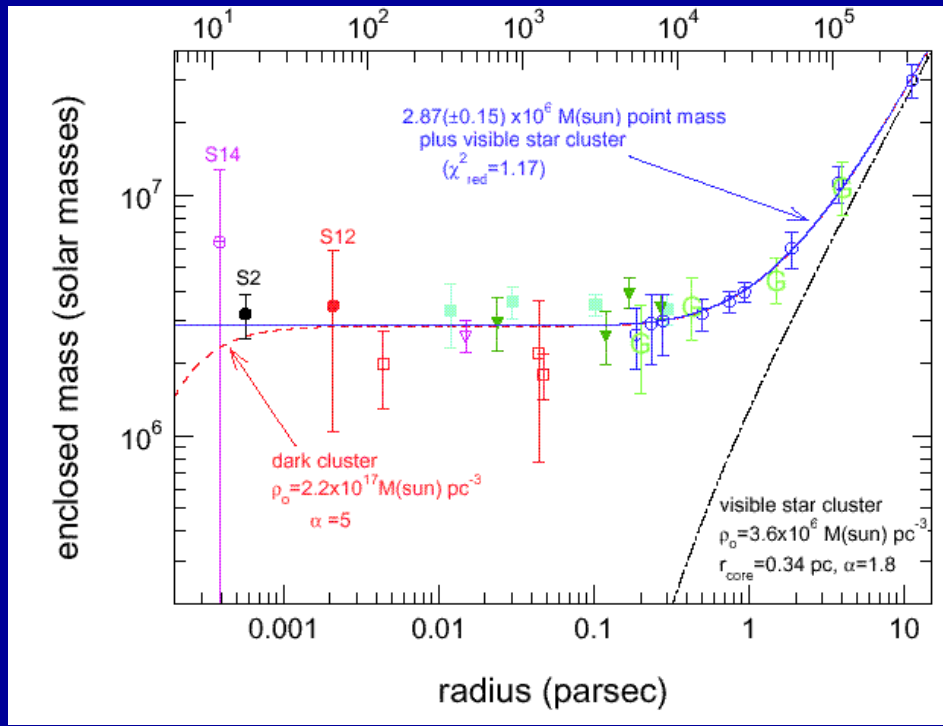
NIR Evidences of a SM-BH at the GC



NIR adaptive optics at VLT & Keck

- **Proper motions of the stars of the central cluster**
- **Orbital parameters of the closest star S2 to the GC:**

  P ≈ 15.2 yr, V ≈ 5000 km s^{-1}
- **Dynamical center in Sgr A***

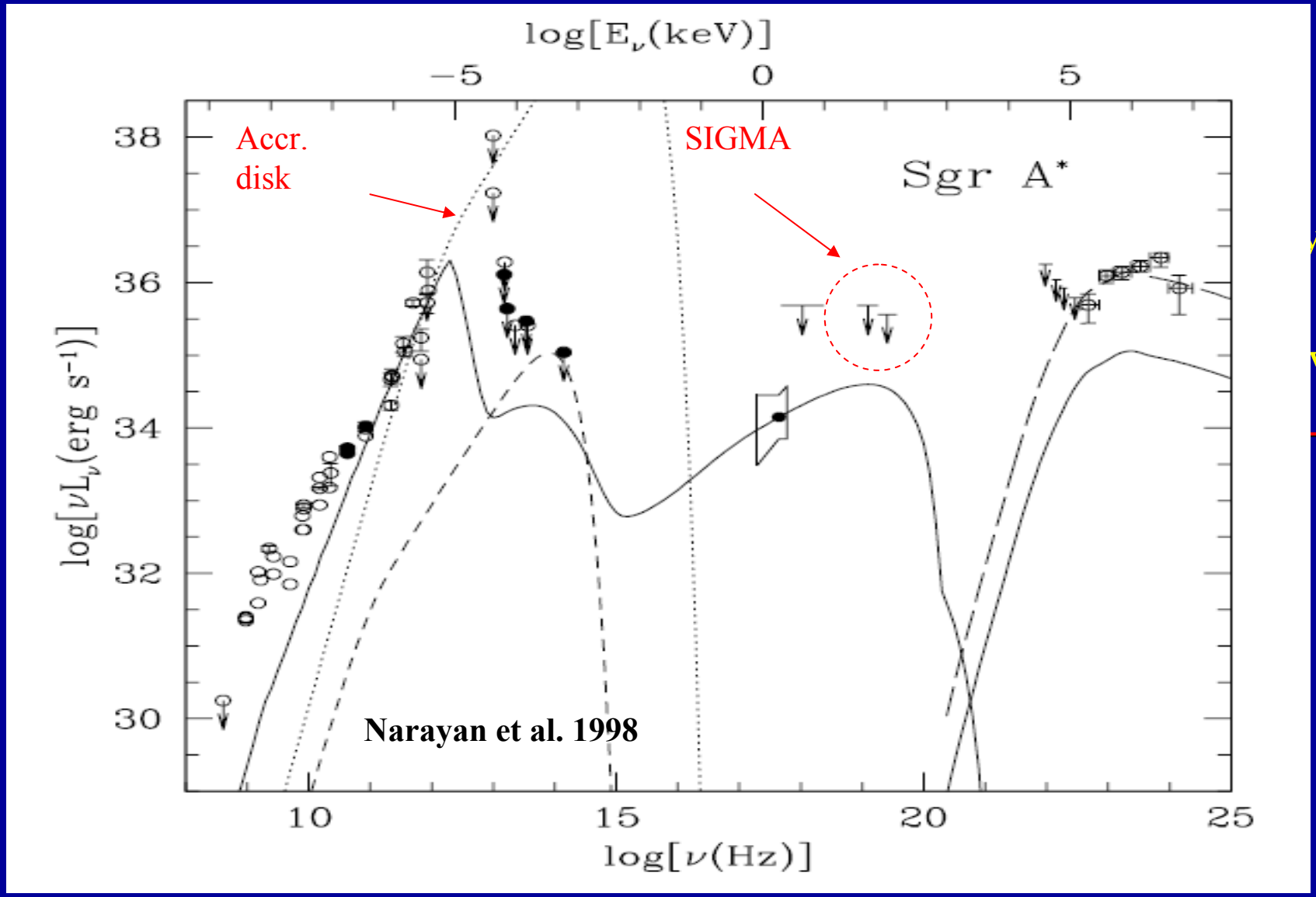


- **Enclosed Dark Mass ≈ 3-4 10^6 $M_\odot$ within 124 AU = 17 l. h. ≈ 2000 R_S**

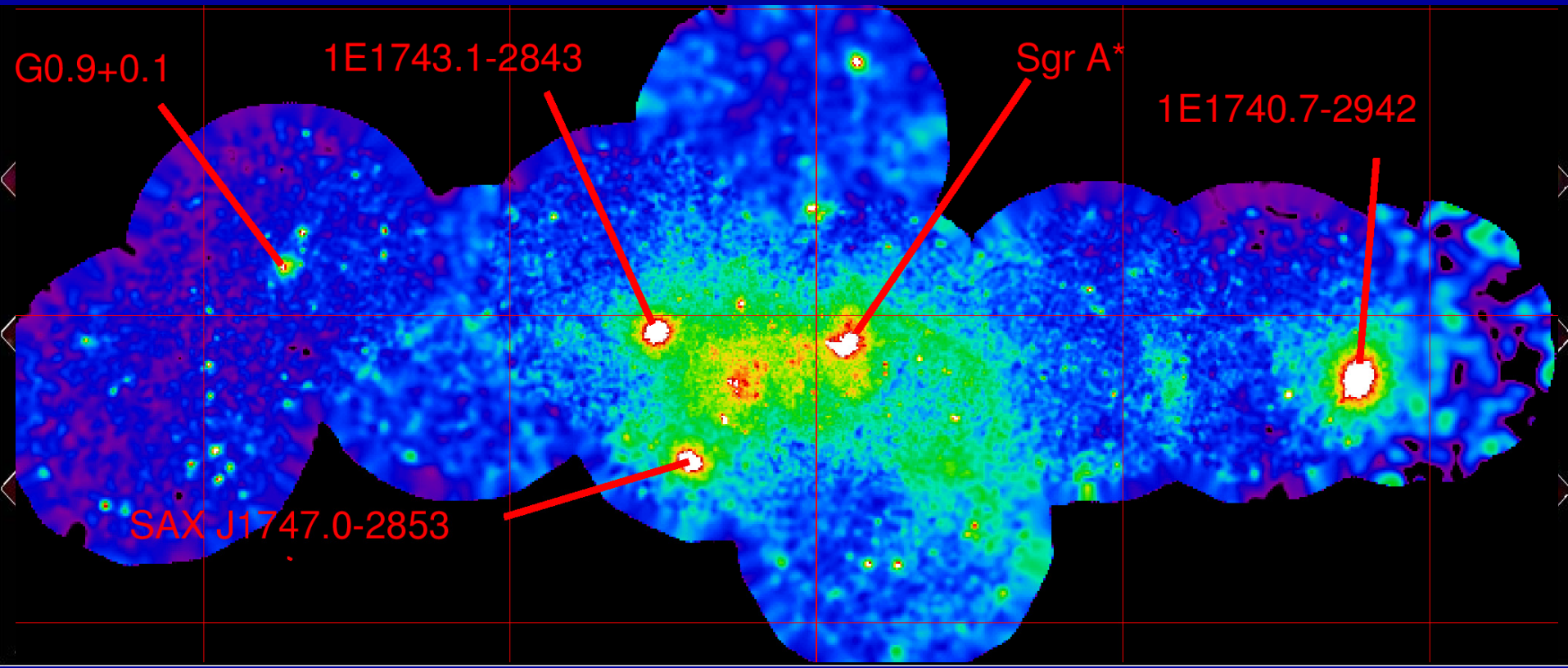
  ⇒ A SUPER MASSIVE BLACK HOLE

(Schoedel et al 03, Genzel et al '03,
Ghez et al '05, Eisenhauer et al. '05)

The problem of the extremely low luminosity of Sgr A*

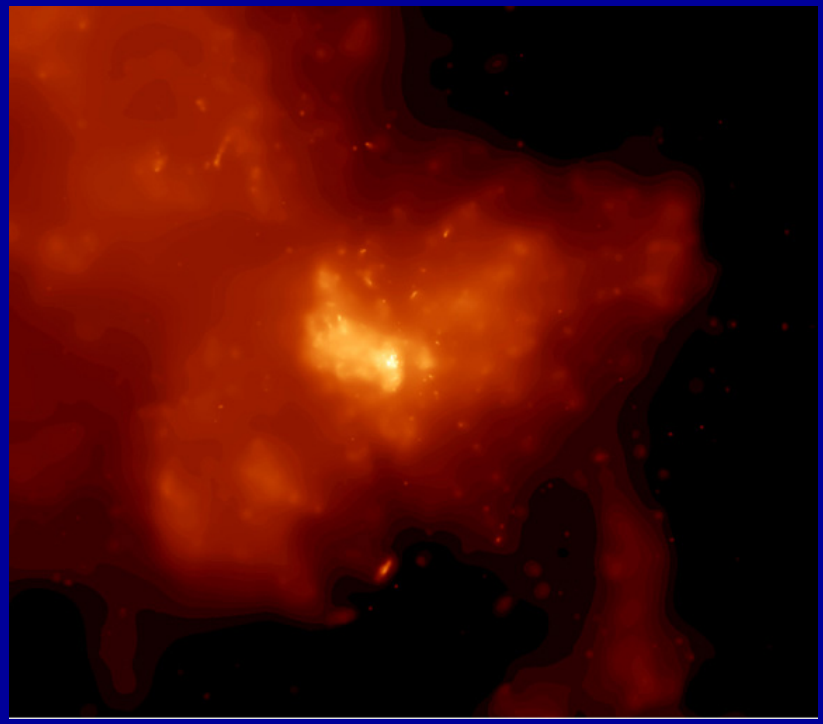


Chandra & XMM Surveys of the GC

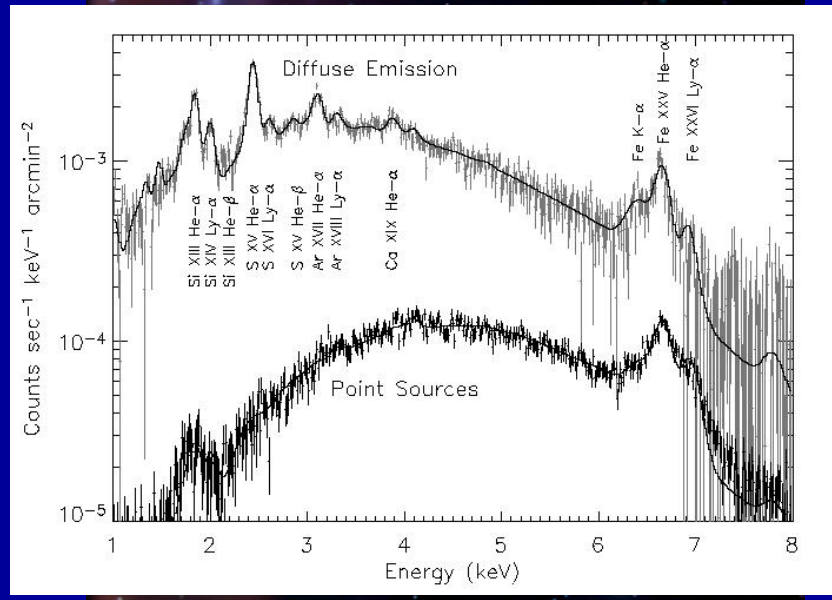


- Point sources: few bright (X-ray Binaries), several transients, many weak PS
- **Complex diffuse emission (continuum and lines) peaking towards Sgr A but with a structured 6.4 keV component associated to MCs**
- Shell SNR (**Sgr A East**), Plerion SNR (composite G09+01), star clusters (Arches), Non-Thermal-Filaments, …
- **Quiescent and flaring X-ray emission from Sgr A***

Diffuse components in the GC

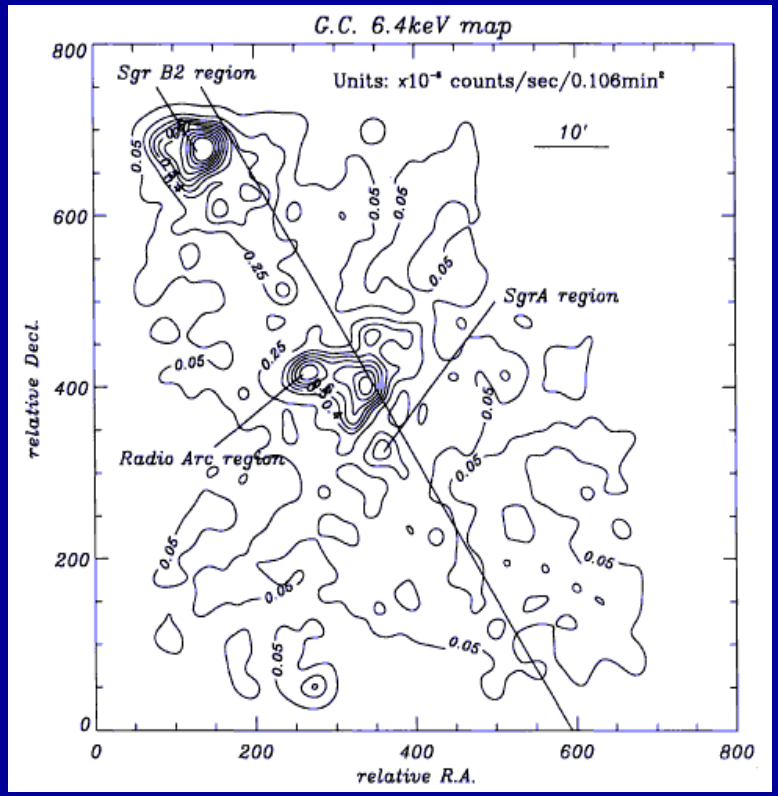


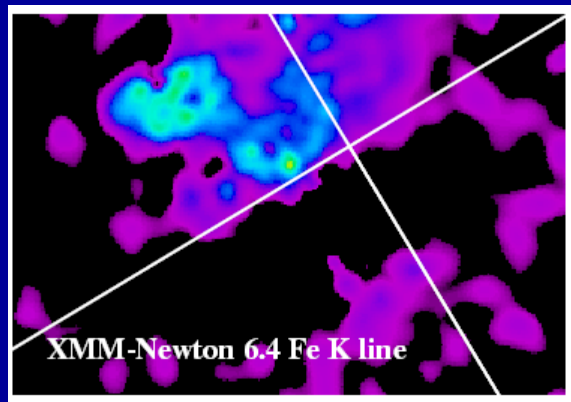
- Two component diffuse X-ray emission (lines from ionized elements Si, S, Ar, Ca, Fe): a soft (T~ 0.8 keV) (S line), a hard (T ~ 8 keV) (6.7-6.9 lines)
- Soft can be due to SN or WR/O winds
- Hard one (more uniform, ~ Gal. ridge) has a spectrum ~ weak point sources but they contribute only ~ 10%

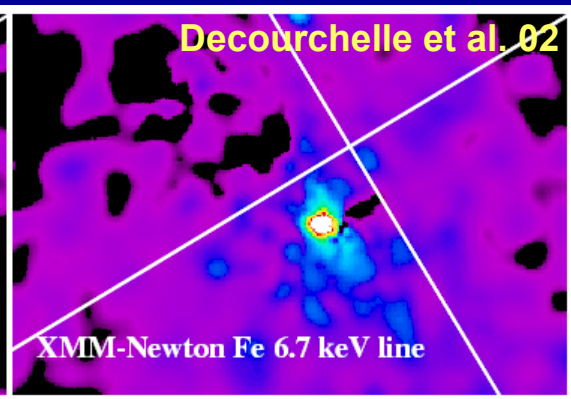


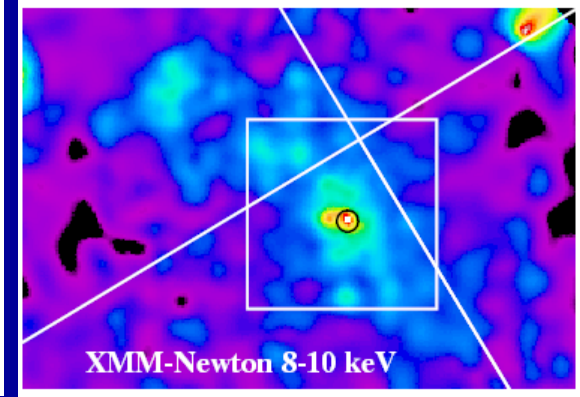
- Thermal emission from hot plasma (8 keV) in collisional equilibrium
- Too hot to be confined in the GC ➔ origin is still a mystery (Muno et al. 2004, Park et al. 2004)
- Point sources, He plasma or NT processes ? (Belmont et al. 2006, Valinia et al 2000, Dogiel et al)

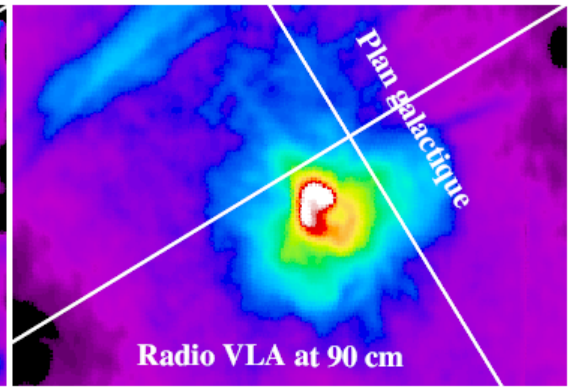
The Iron 6.4 keV Line from MCs





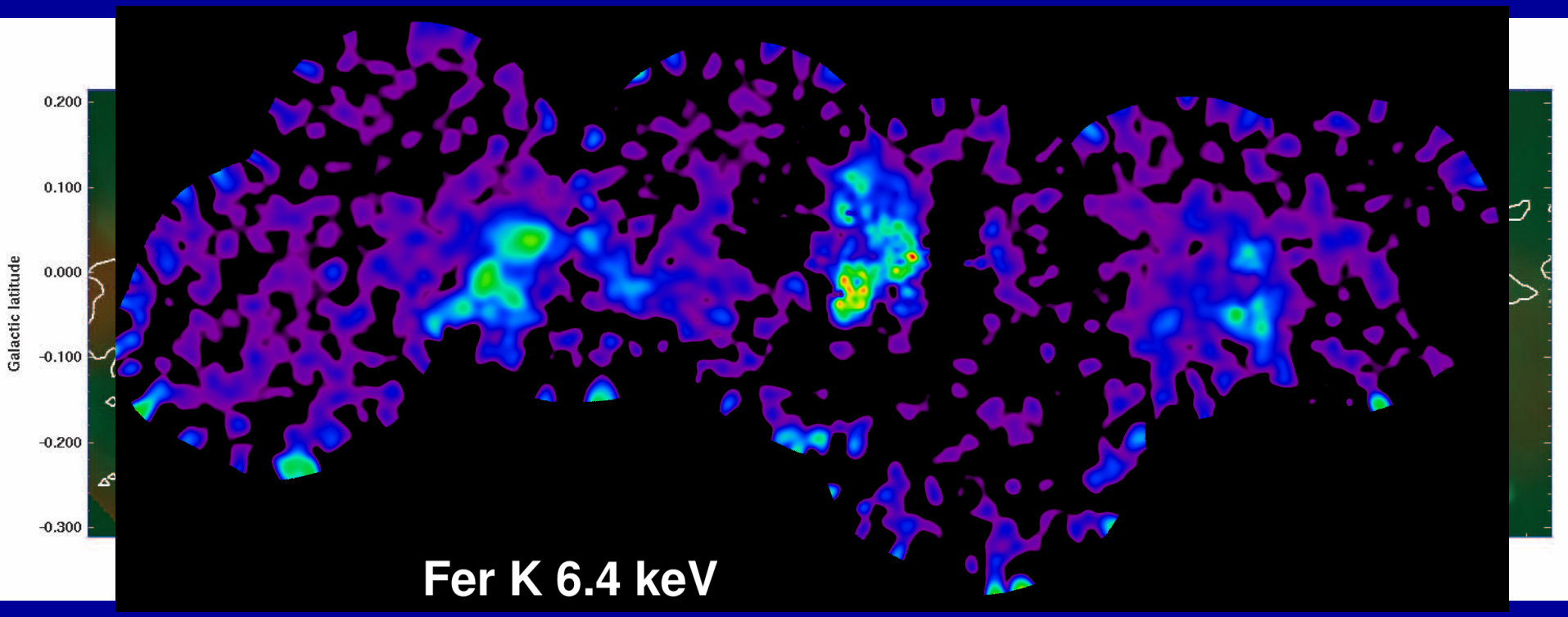






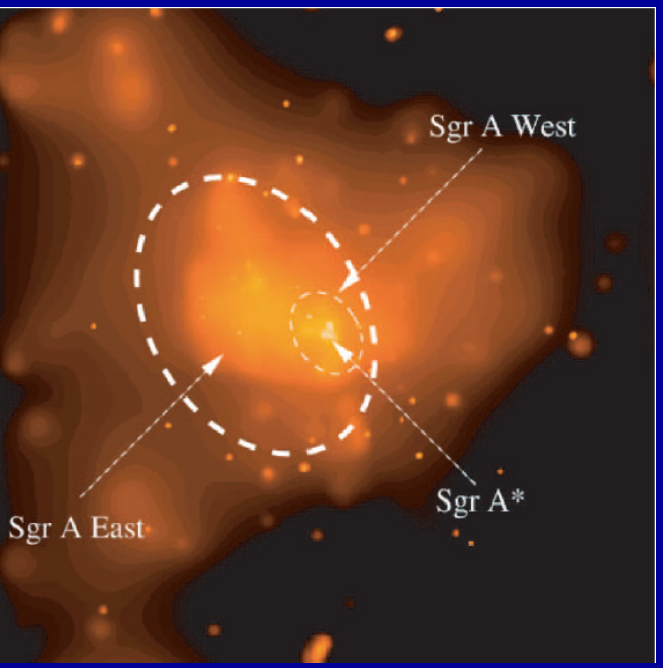
- Clumpy diffuse 6.4 keV line emission of neutral iron coincident with some GMC in particular Sgr B2. Very large EW: 1 - 2 keV.
- Fluorescence in the GMC Sgr B2 due to photo-ionisation by hard X-ray (>7.1 keV) emission from an external source
- For example a bright X-ray outburst (10^{39} erg/s) of Sgr A* occurred ~ 300 yr ago (Koyama et al 96, Murakami et al 01, Park et al 04)

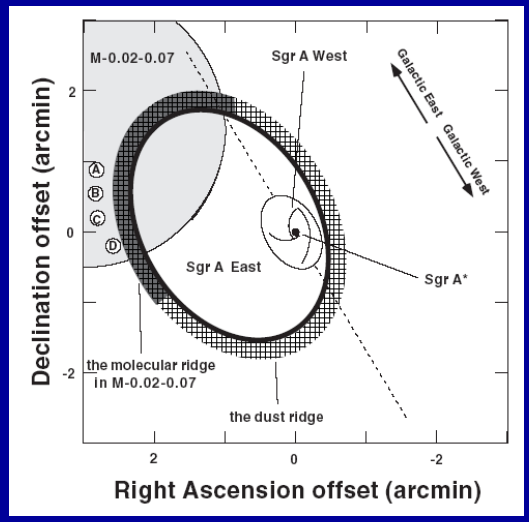
Distribution of the 6.4 keV

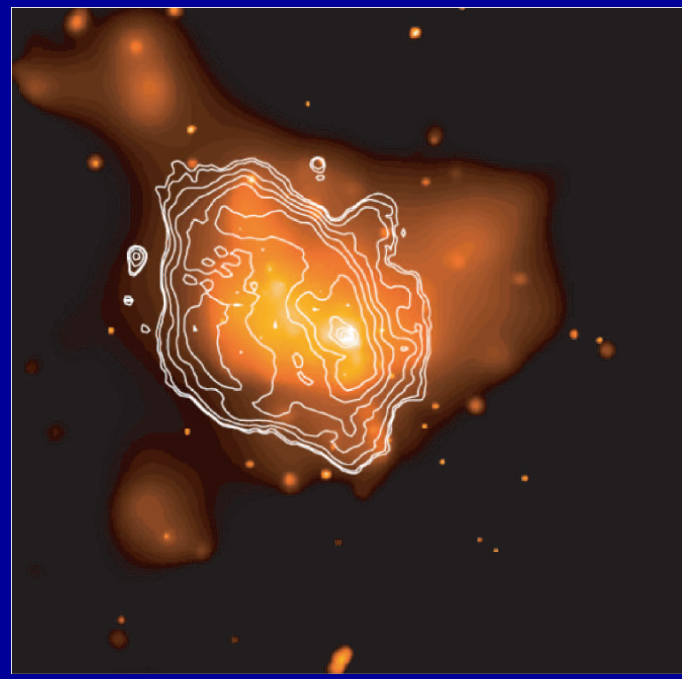


- Association of 6.4 keV also with N-T radio structures. Local acceleration of electrons.
- Low energy (< 0.1-1 MeV) CR elec. impacts on MC, ionize inner shell => 6.4 keV line + bremsstrahlung. High Z to have large EW. Can explain MC heating, MC ionization, relation with TeV diffuse emission (Valinia 00, Yusef-Zadeh etal 02 07)
- Energetic problem ? Too large Fe overabundance ?
- Other models: SN ejecta in ISM, LECRi or protons (Bykov 04, Dogiel etal 09)

Sgr A East in X-rays

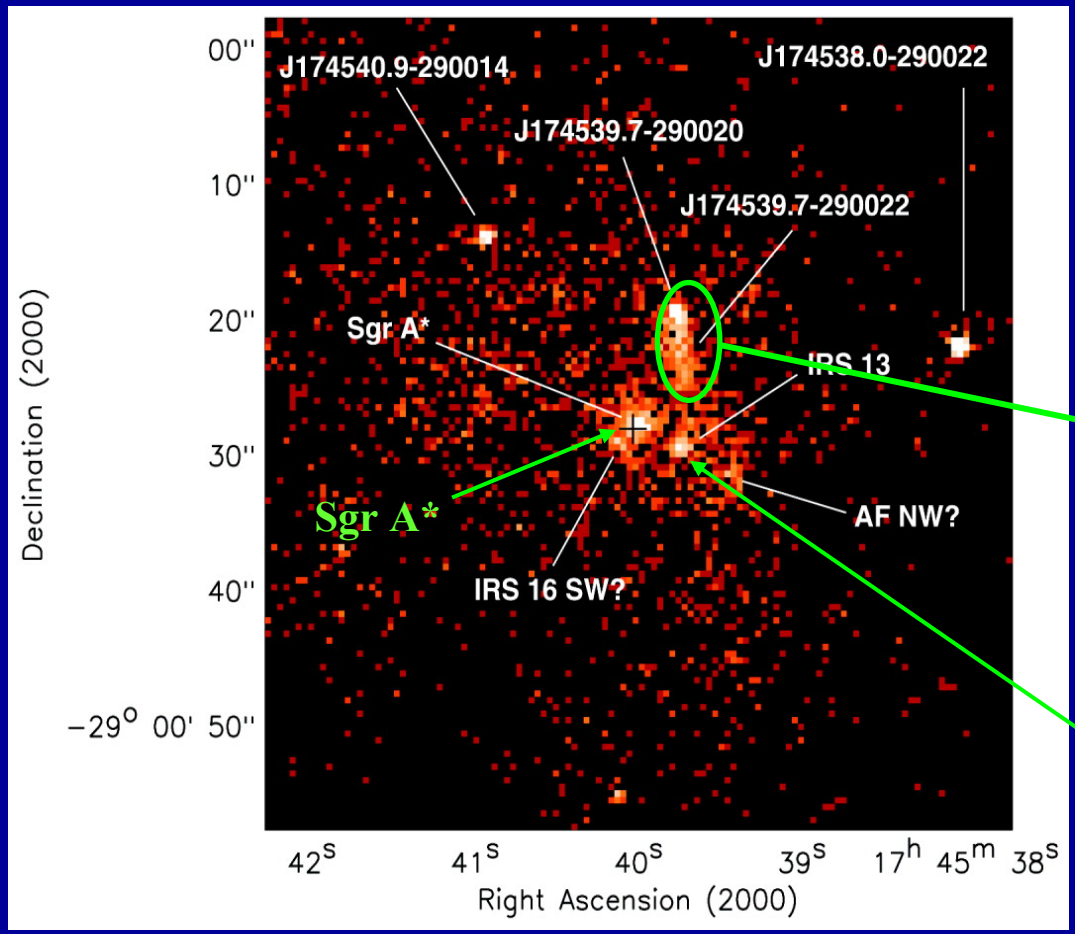


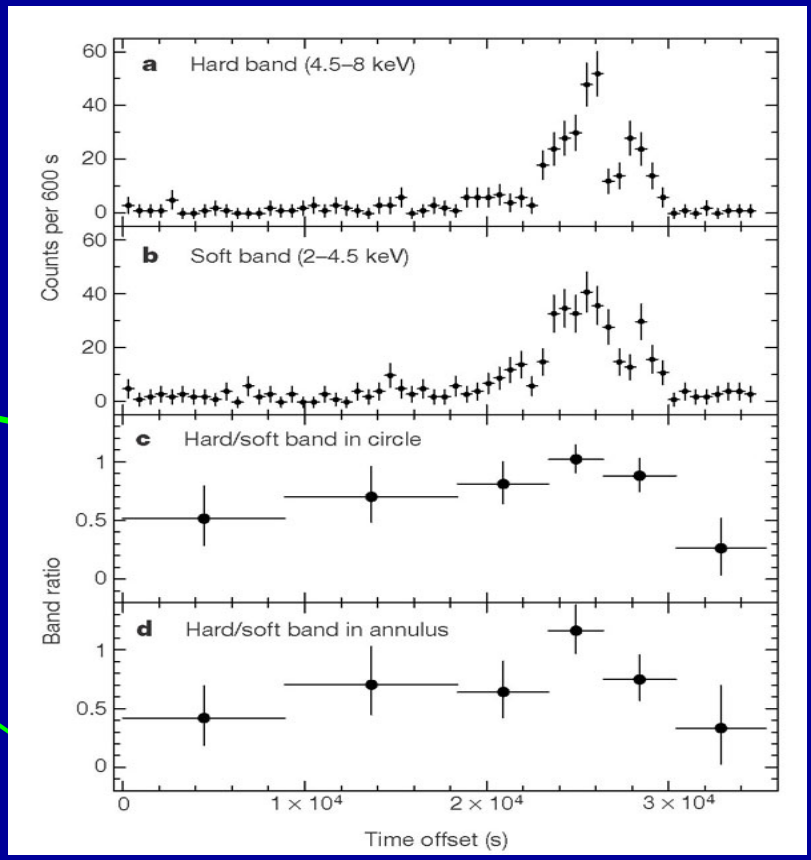




- Chandra and XMM-Newton observations clarified nature of Sgr A East
- X-ray emission in the core, thermal plasma with 2 T (~ 1 keV and 4 keV), high Z (~4) probably due to hot SN ejecta
- X-ray properties: 1 single SNR (type II or Ia < Mo), Ther. E ~ 10^{49} erg, t ~ 10^{4} yr (?)
- Mixed Morphology class of SNR (NT radio shell + Th X-ray core) but brighter and more compact: special GC environment (a dense 10^{3} cm^{-2} ionized gas halo)
- The Sgr A East shell swept the medium and activated the BH ~ few 100 yr ago (?) whose radiation produce 6.4 keV in Sgr B2 (Maeda et al. 2001, Sakano et al. 2004)

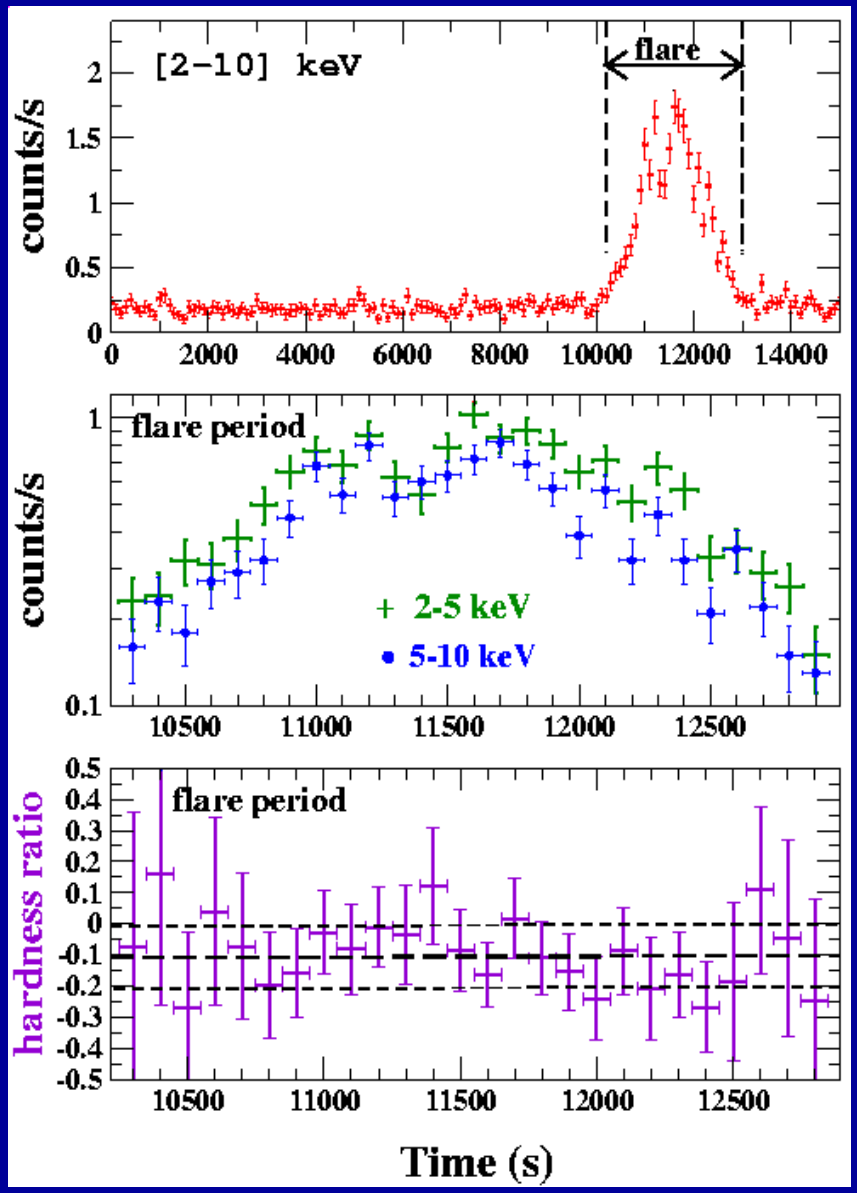
Chandra resolved the inner arcmin of the Galaxy

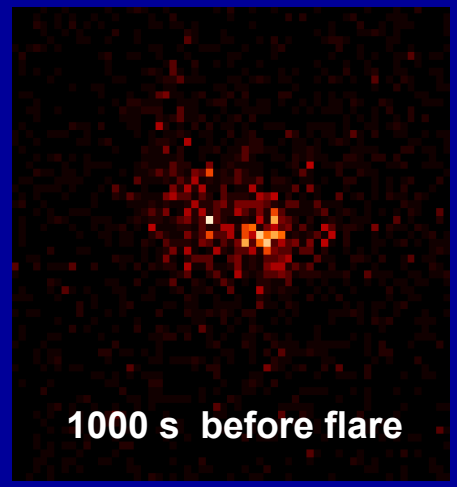


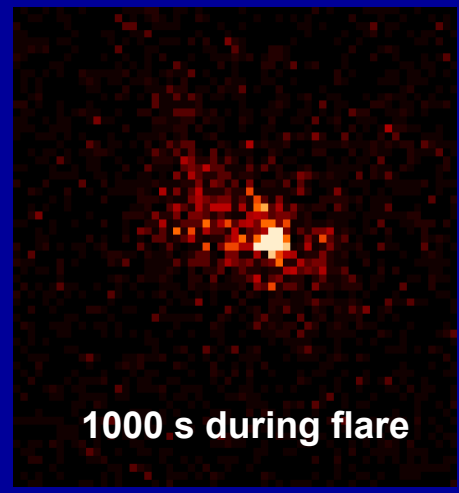


- Detection of Sgr A* flares (Baganoff etal 2001)

Sgr A* X-Ray Flares with XMM-N





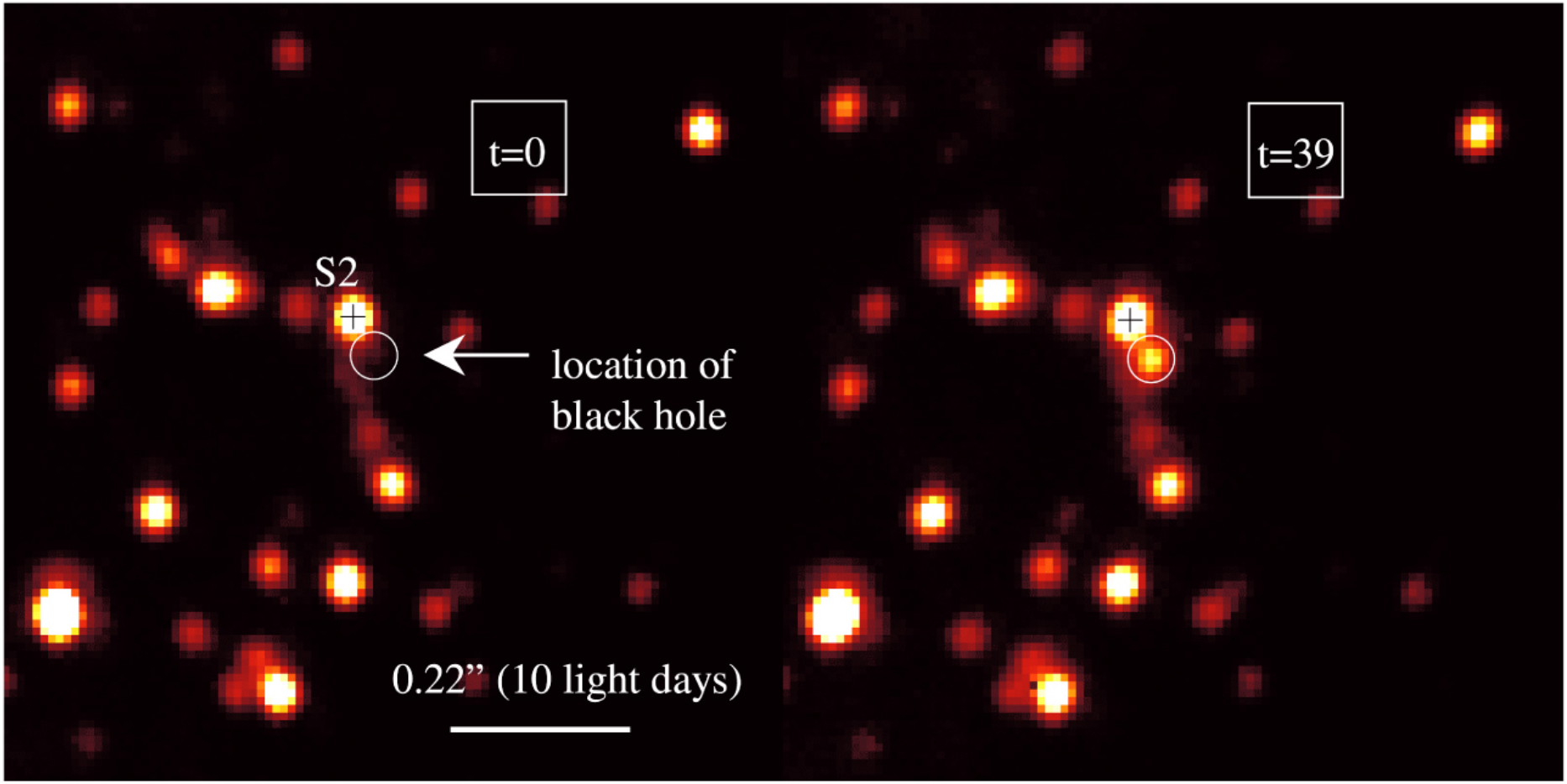


XMM-Newton detection in 2001 & 2002

- Peak L_X (2-10 keV) ≈ 3.6 10^{35} erg s^{-1}
- L increase ~ 180, duration ≈ 2.7 ks
- Hard and Soft spectra ($\alpha \approx 1.0 - 2.5$)
- No spectral variations, No Fe lines
- Changes on scales of 200 s
  => emitting region size of ≈ 10 R_S

(Goldwurm et al. 2003, Porquet et al. 2003)

The Sgr A* Near-IR Flares

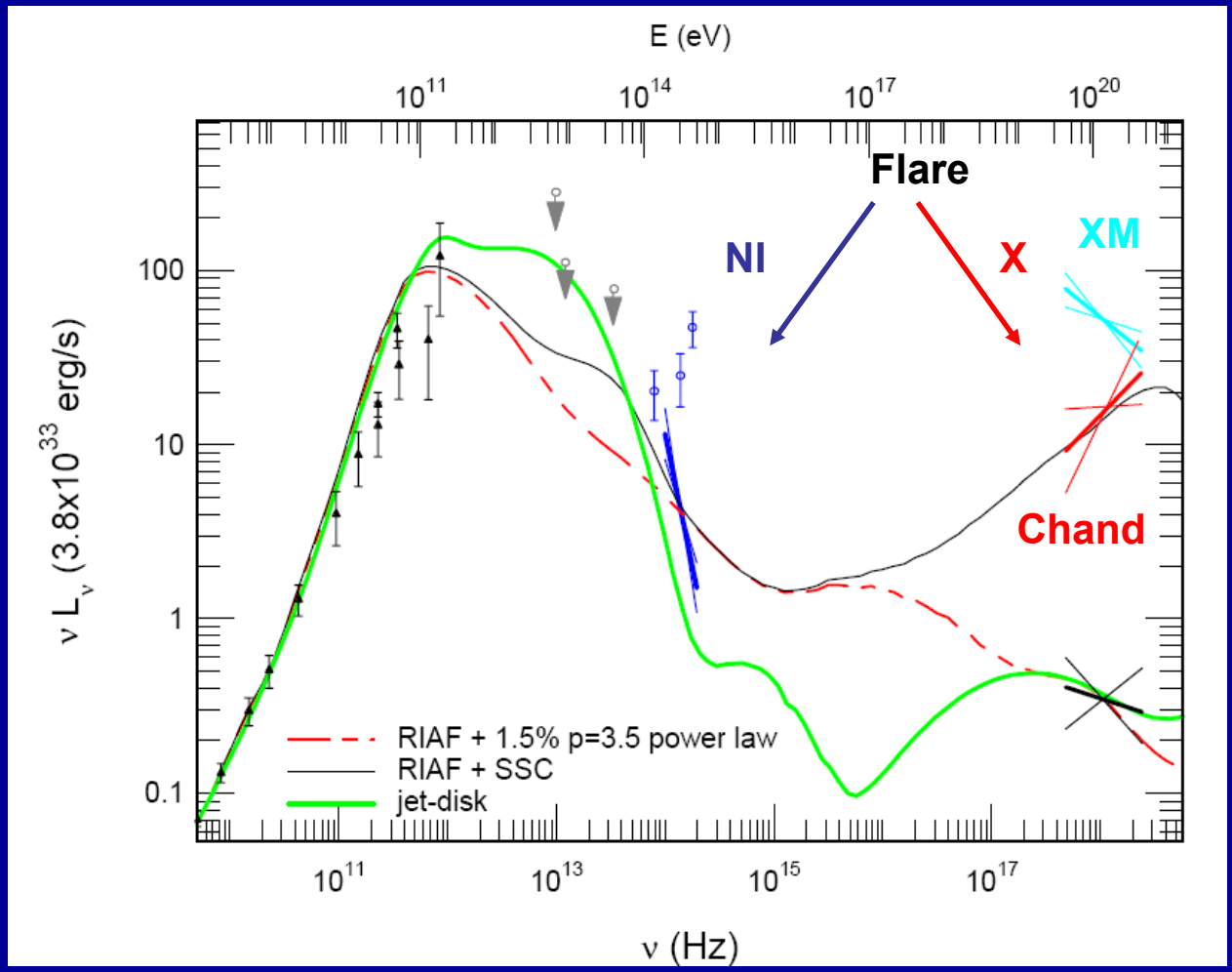


Near-IR Flare from Galactic Centre (VLT YEPUN + NACO)

ESO PR Photo 29a/03 (29 October 2003)

(Genzel et al. 2003)

Sgr A* Broad Band Spectrum (SED)



- NIR flares consistent with non-thermal radiation (synchrotron)
- X-rays either from SSC or synchrotron
- Several models:
  - RIAF + NT comp
  - Jet + Disk
  - Hot Keplerian disk
- Polarization implies very low accretion rate => convection/outflows (?)

(from Eisenhauer et al. 2005, Yuan et al. 2004, Markof et al. 2001, Liu et al. 2004)

Accretion or Jet Model for Sgr A* ?

- Simple ADAF models cannot explain the flares (possibly OK for quiescent emission but the linear polarization of sub-mm bump => convection or outflow)

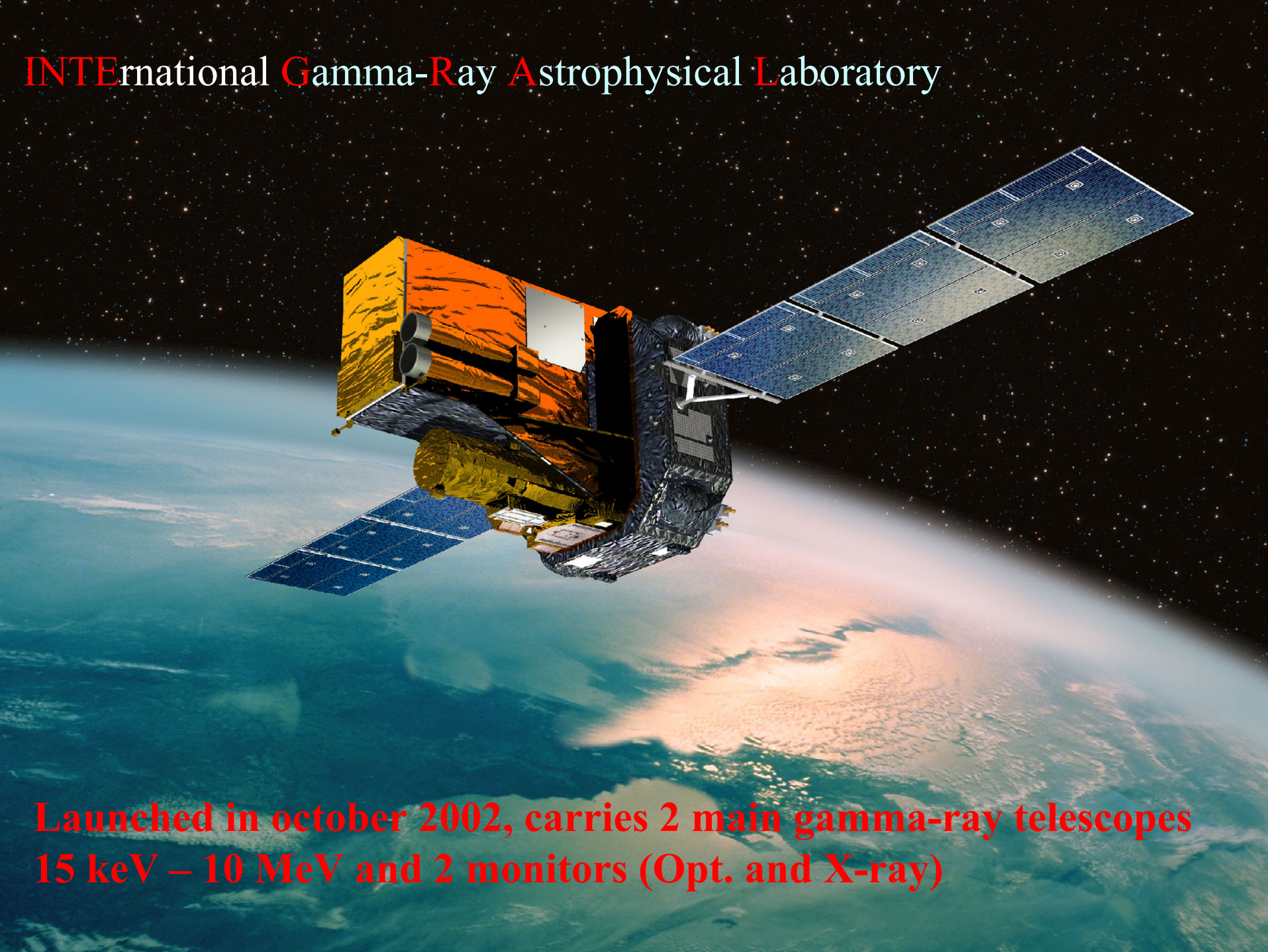
ROLE OF NON-THERMAL EMISSION

- Radiative Inefficient Accretion Model for Sgr A* (ADAF with convection : less effective $\dot{M}$) with non-thermal component close to the BH. Synchrotron flares produced by increase in the energy of NT el. and X-rays produced by synchrotron or SSC. (Yuan et al 2003, 2004)
- Jet Model possibly coupled to a ADAF disk where again the X-rays are either from SSC (acceleration) or from synchrotron (Markoff et al 2001, Yuan et al 2002)
- Keplerian hot relativistic disk (within 5-10 Rs) with NT particles. Flares may be due to acceleration powered by magnetic reconnections. (Liu et al 2002, 2004)

Crucial observational tests:

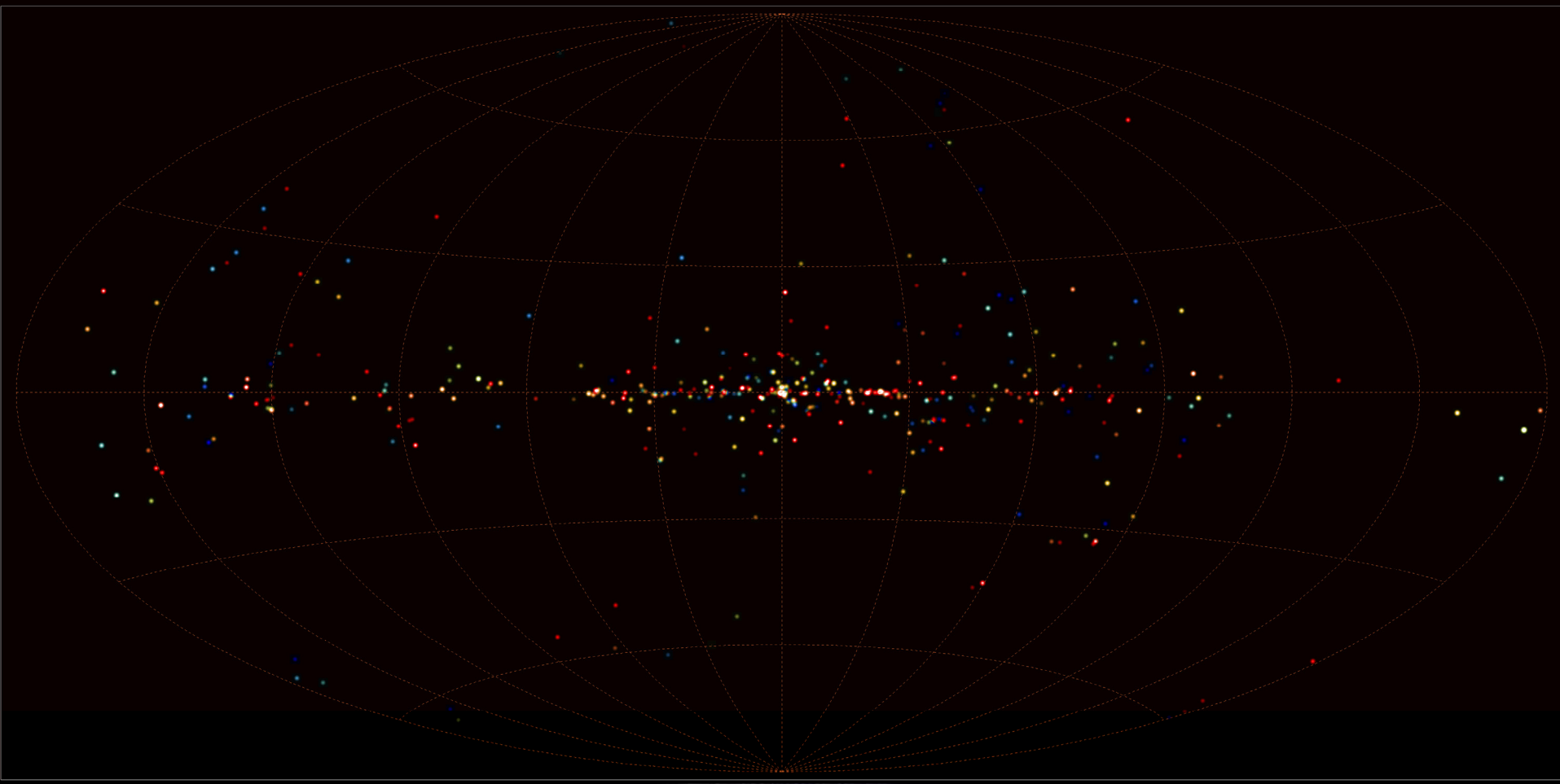
- Simultaneous obs. of radio-IR-X flares => MW campaigns
- Search for periodicity : Keplerian flow => NIR &/or X QPO?
- Study of the high energy tail (gammas) => INTEGRAL

INTErnational Gamma-Ray Astrophysical Laboratory

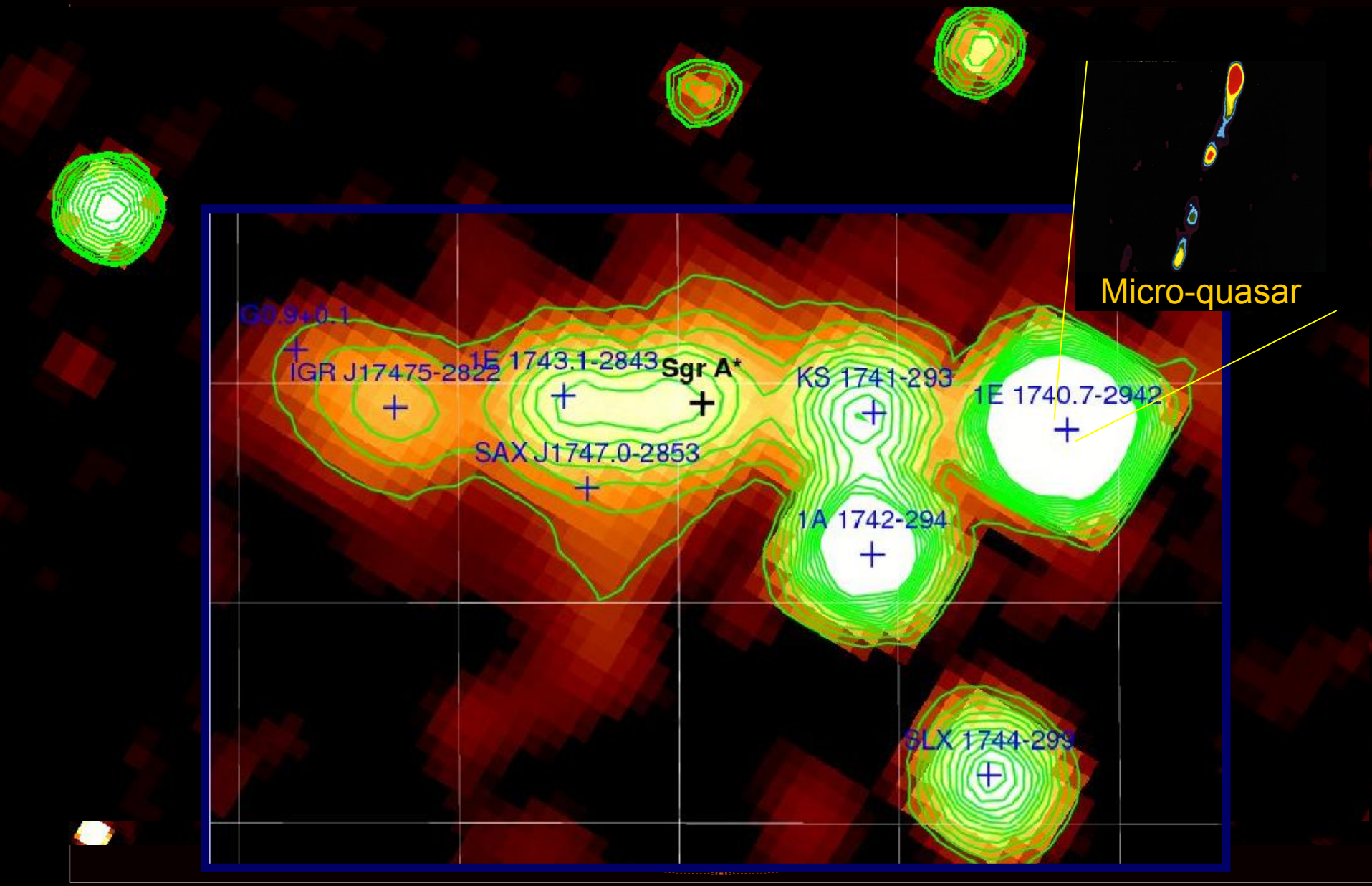


Launched in october 2002, carries 2 main gamma-ray telescopes 15 keV – 10 MeV and 2 monitors (Opt. and X-ray)

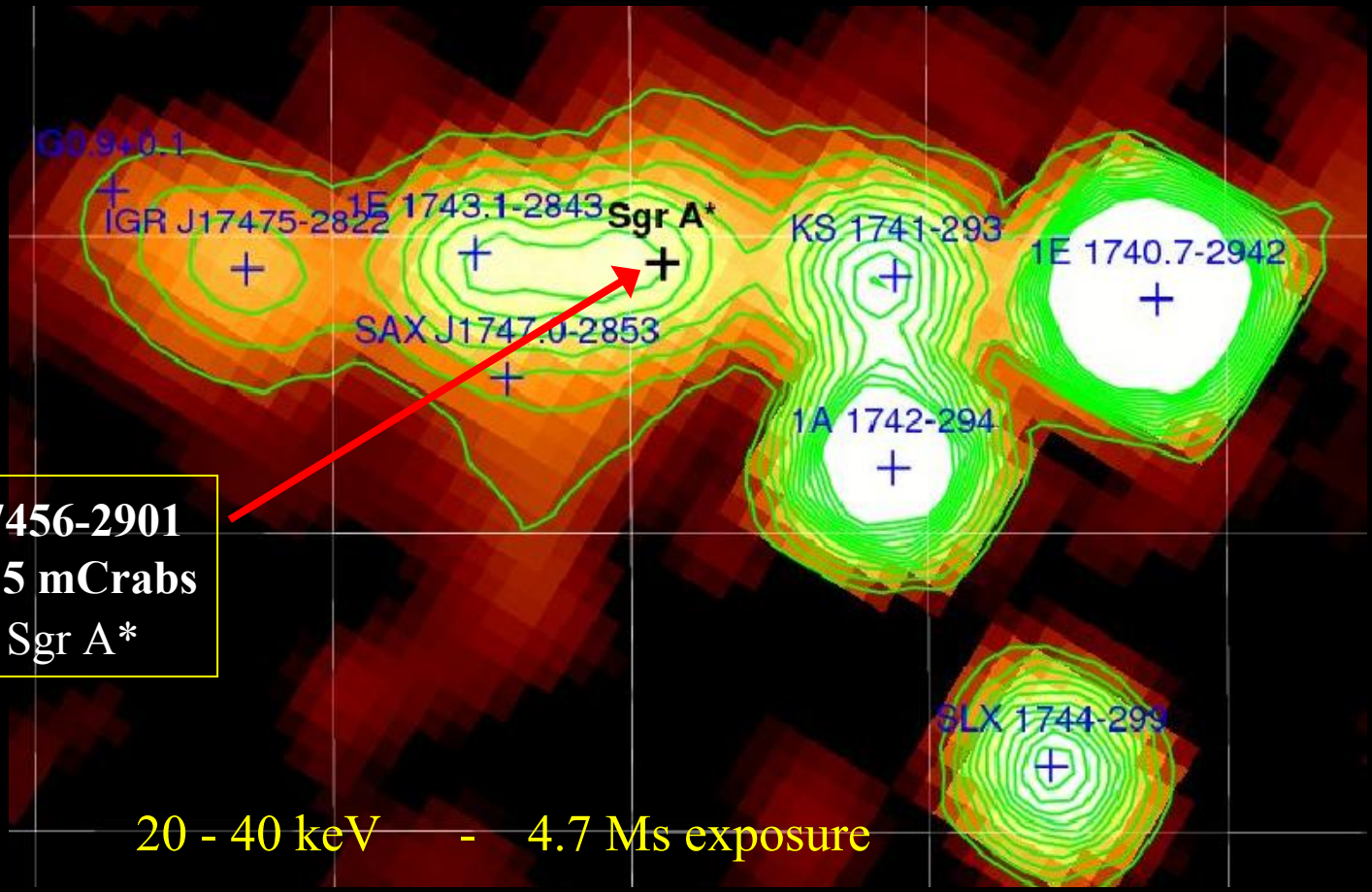
Cartographie 20- 40 keV de la Galaxie avec INTEGRAL / IBIS / ISGRI



CARTES INTEGRAL 20-40 keV

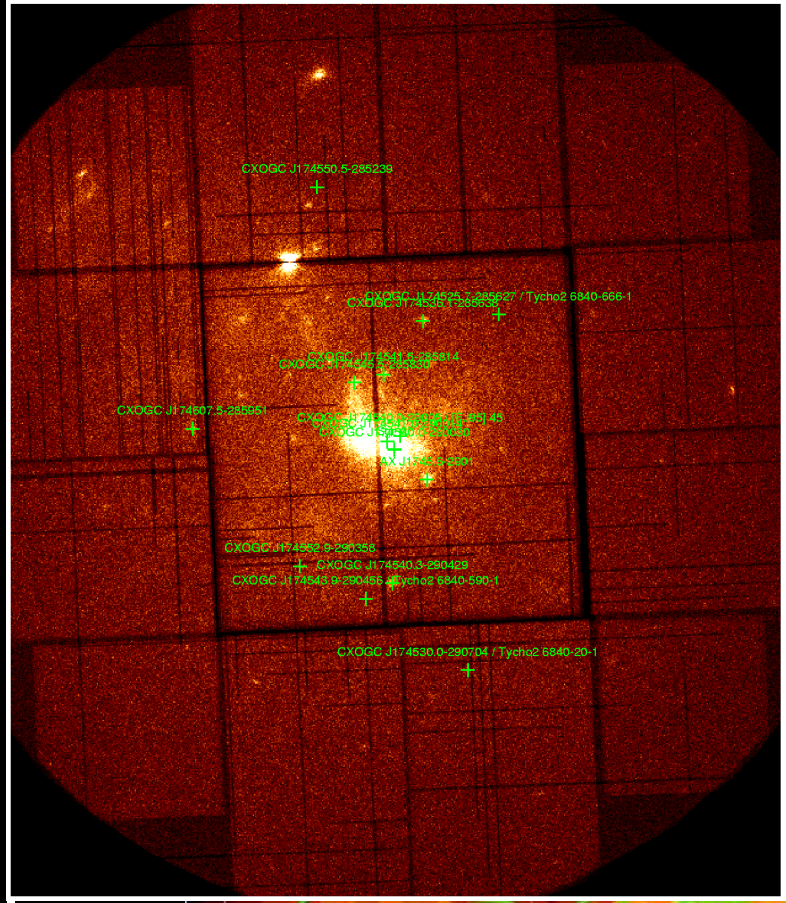


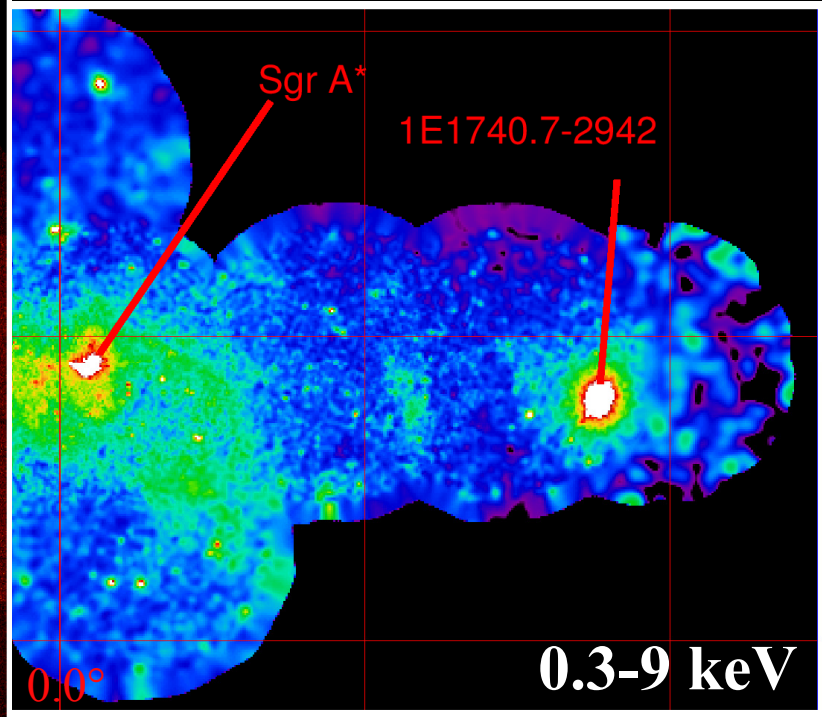
IBIS / ISGRI IMAGES of the GC

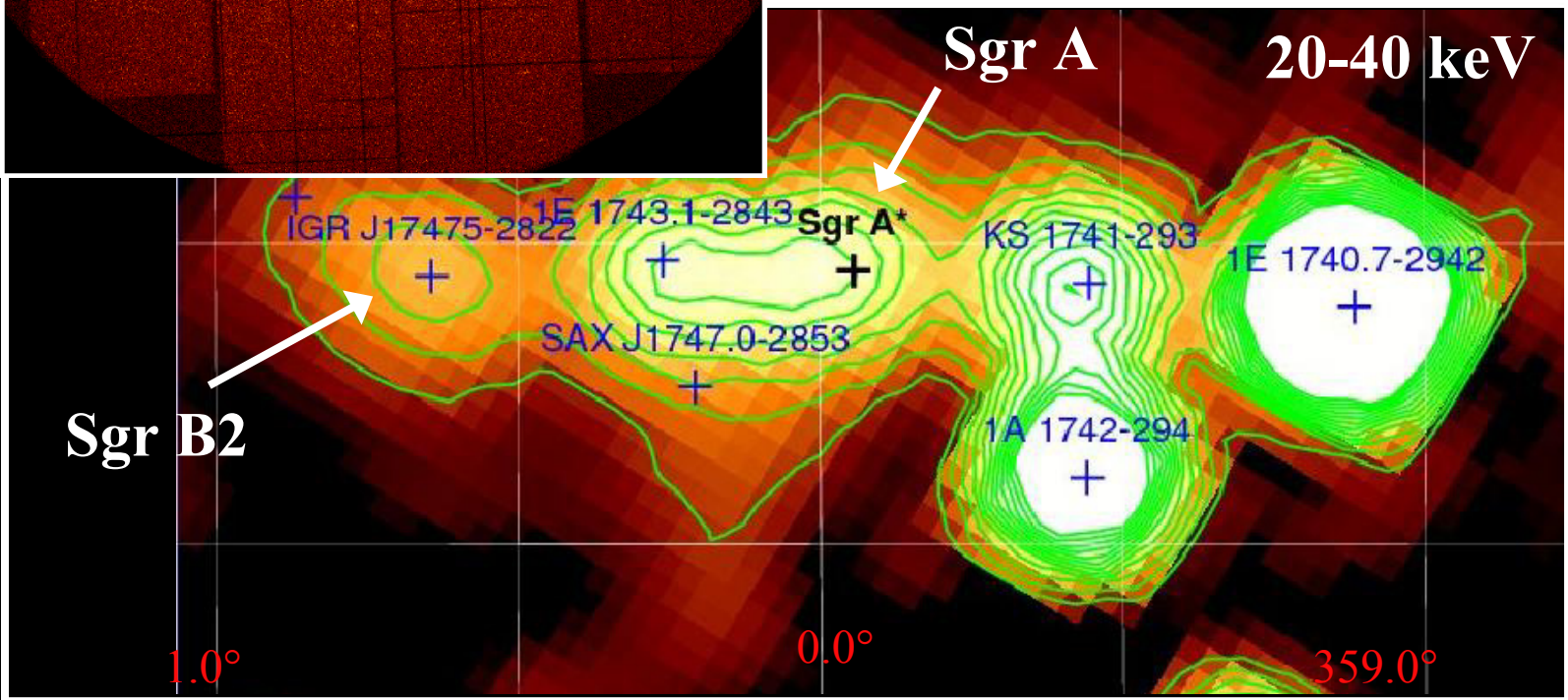


IGR J 17456-2901
~ 45 σ ~ 5 mCrabs
~ 1' from Sgr A*

Combined IBIS/SGRI images (20-40 keV) of the central ~ 2° × 1.5° of the Galaxy from 2174 pointing obs. in 2003-2004 (eff. Exp. ~ 4.7 Ms): contours 9.5 to 75 σ



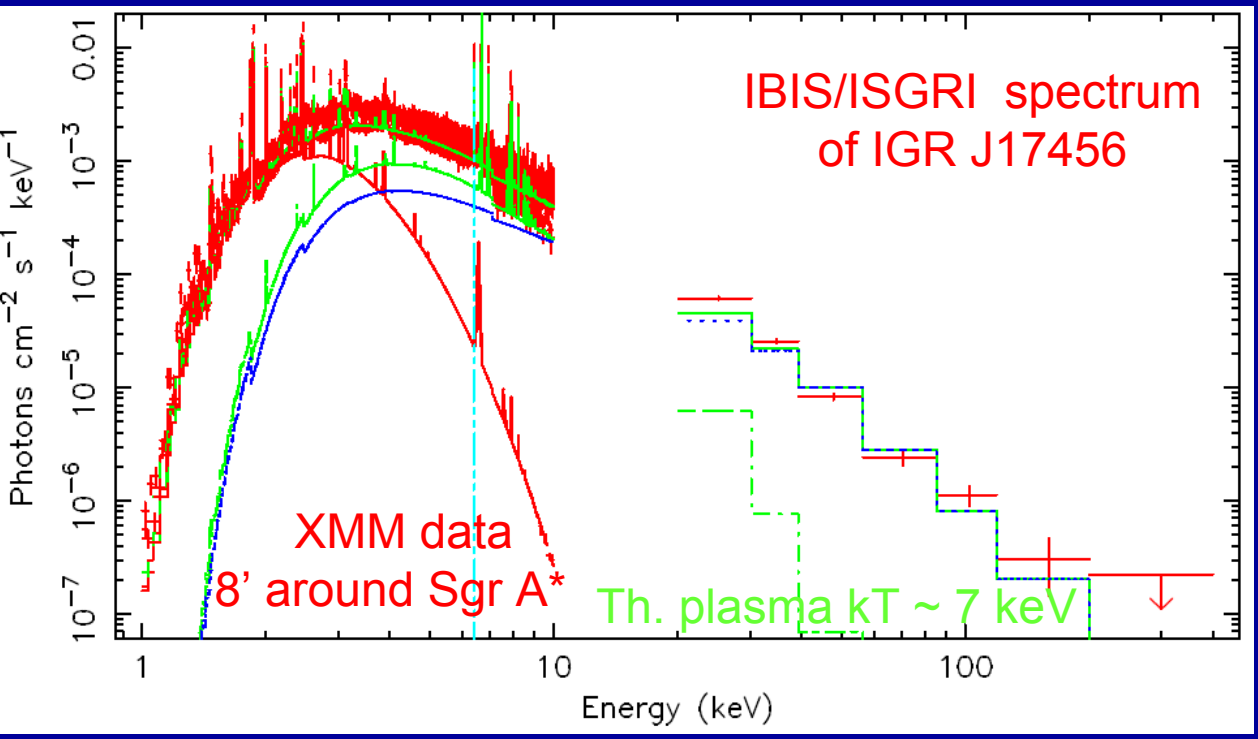




(Decourchelle et al. 2003)

(Belanger et al. 2006)

IBIS/IGRI Spectrum of the IGR (Sgr A) source



INTEGRAL/IBIS/ISGRI Spectrum of IGR J17456
Simple Power-Law : α = 3.04 +/- 0.98
L(20-120 keV) = 4.76 +/- 0.24 10^{35} erg s–1

No XMM P-S counterpart but IBIS-PSF-integrated XMM spectrum match well the IGR one

The IBIS/ISGRI spectrum cannot be explained by extrapolation of the hot thermal plasma model

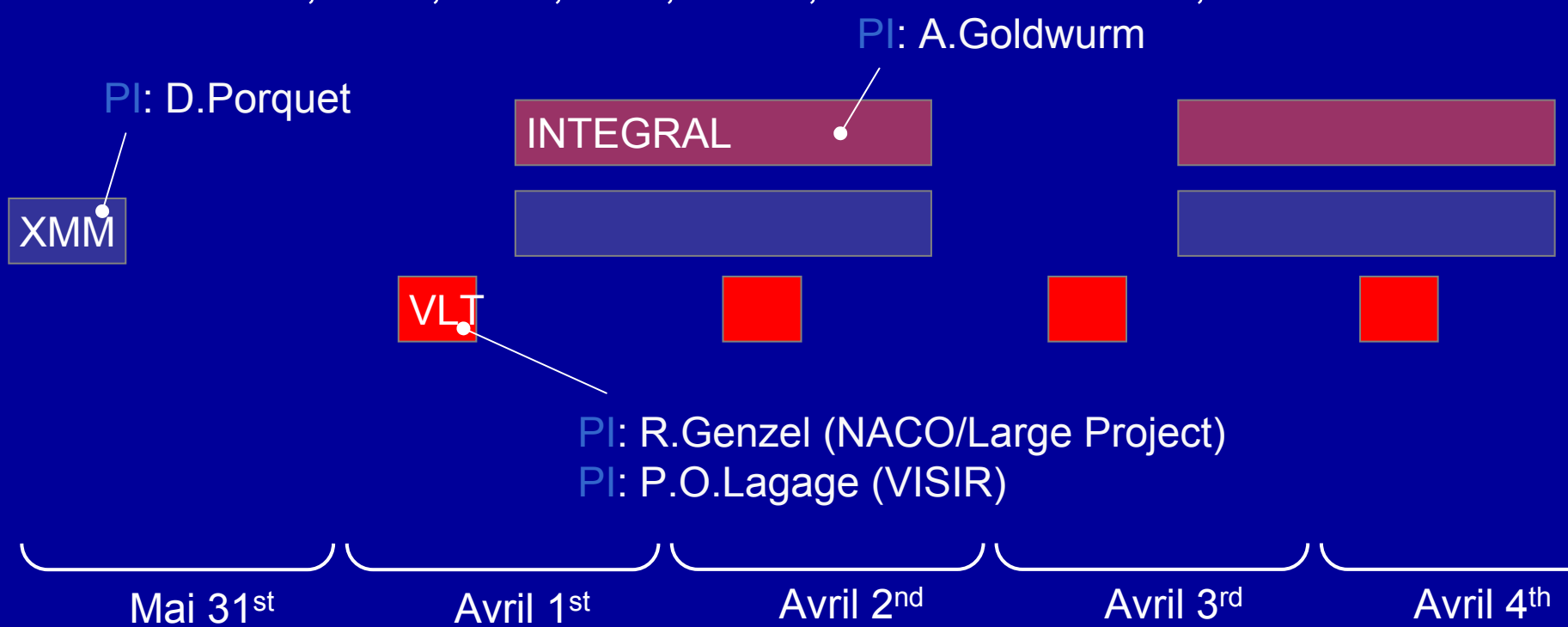
IBIS & XMM-Newton (8' around Sgr A*) :

2 - T thermal model + cutoff power-law :
α ~ 1.1 , $E_{Cut\ off}$ ~ 24 keV

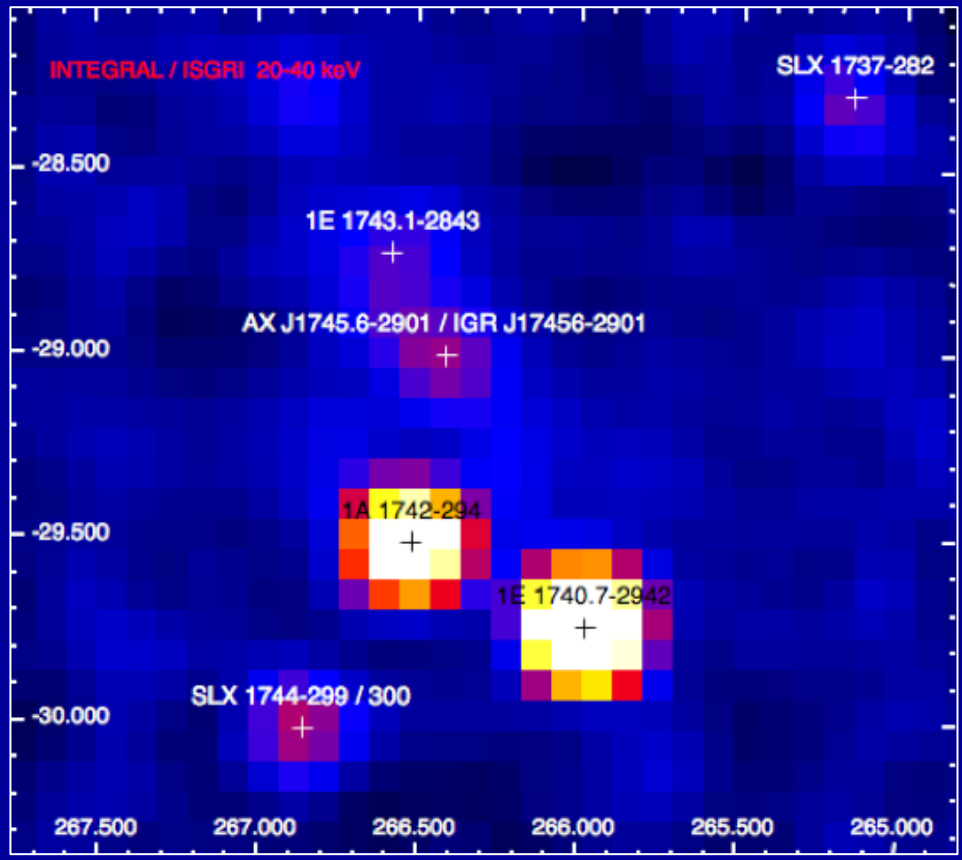
Broken P-L:
α ~ 1.5 , E_B ~ 27 keV,
α ~ 3.2

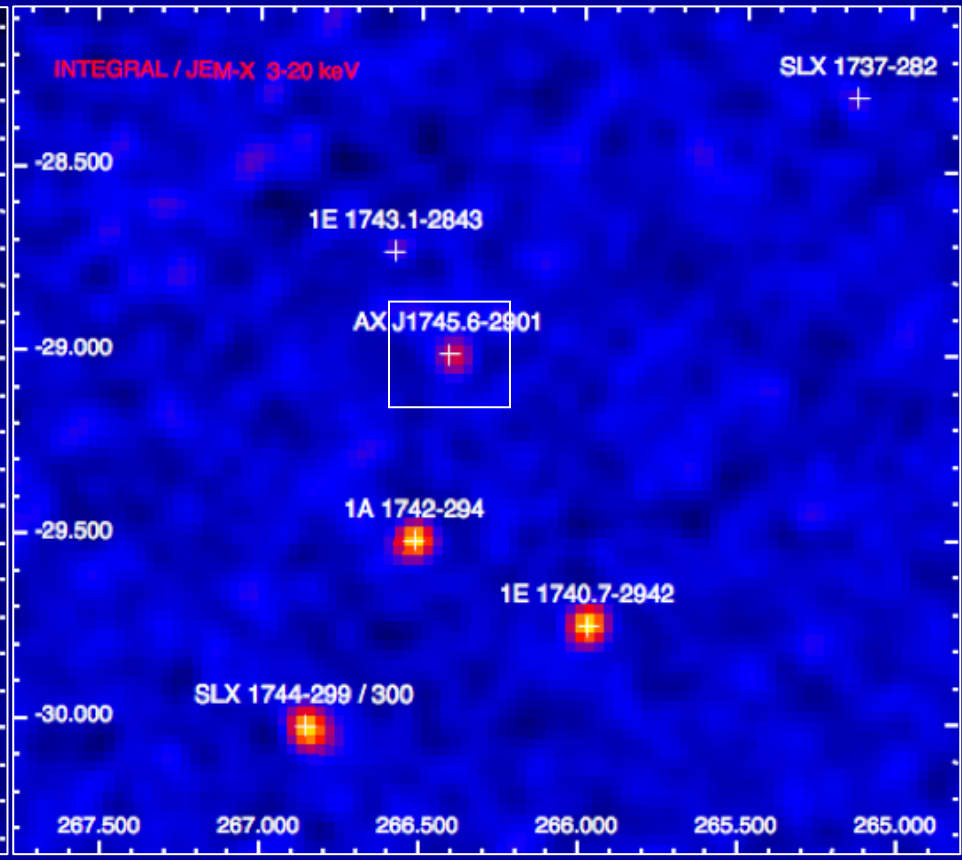
April 2007 Campaign on Sgr A*

Observatories: CARMA, CSO, GMRT, HST/NICMOS, INTEGRAL, IRAM,
NRO, SMA, SMT, VLA, VLBA, VLT/NACO/VISIR, XMM



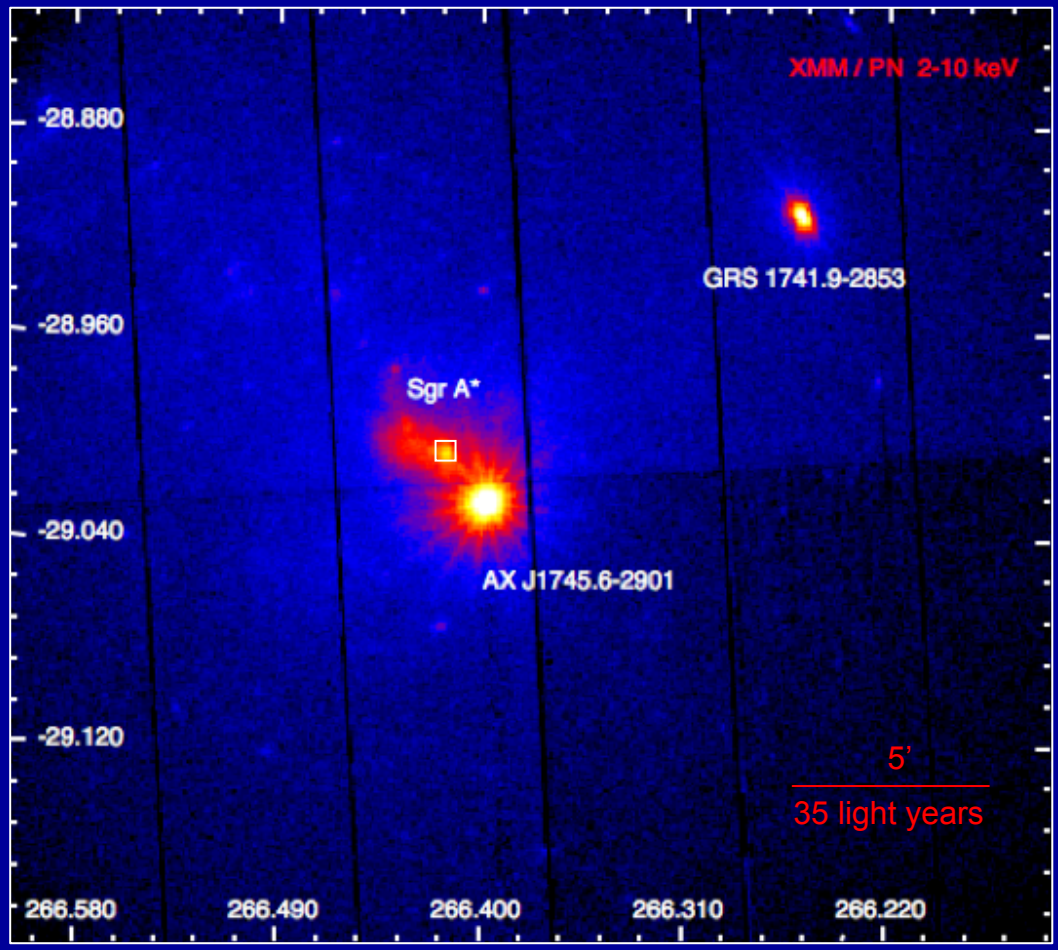
INTEGRAL IBISS/JEM-X





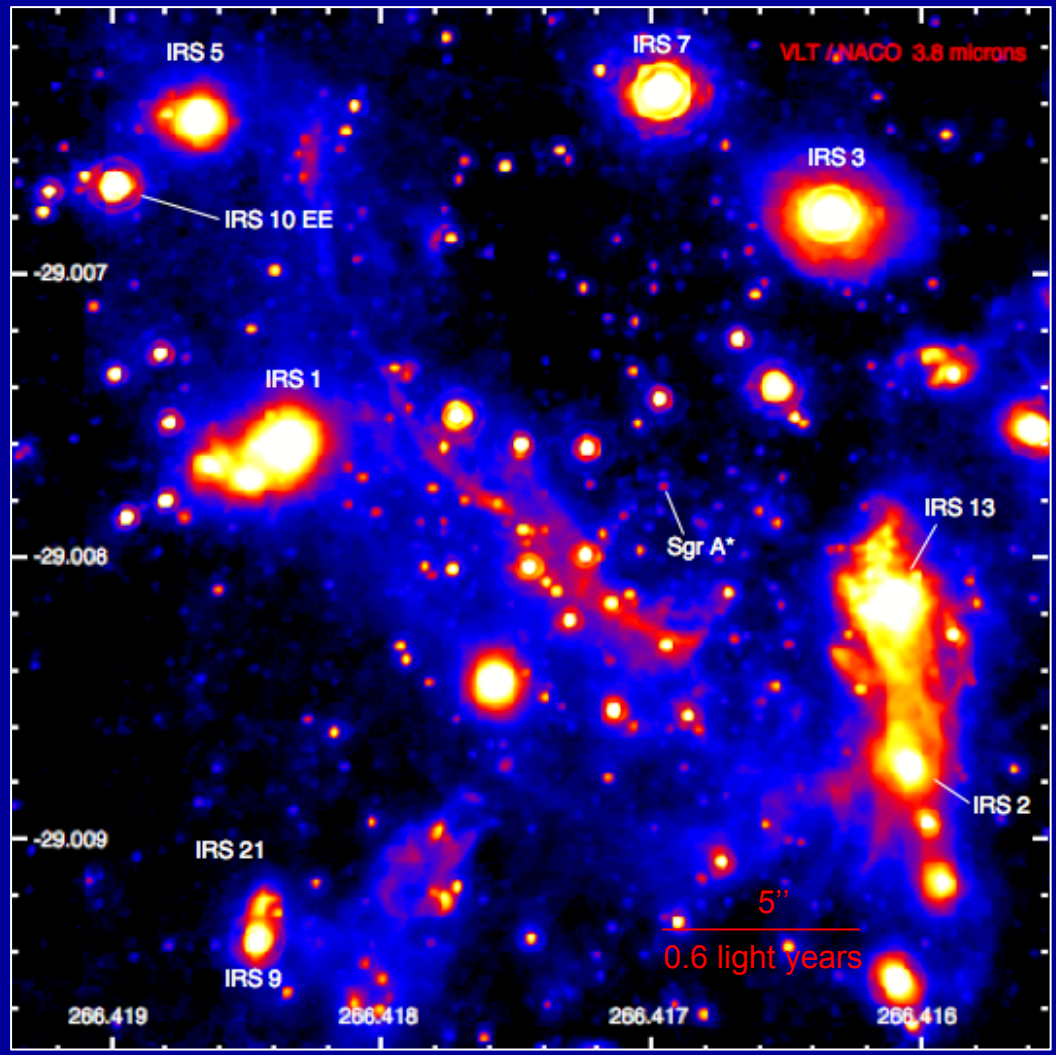
(Trap et al. 2009)

XMM-Newton EPIC PN



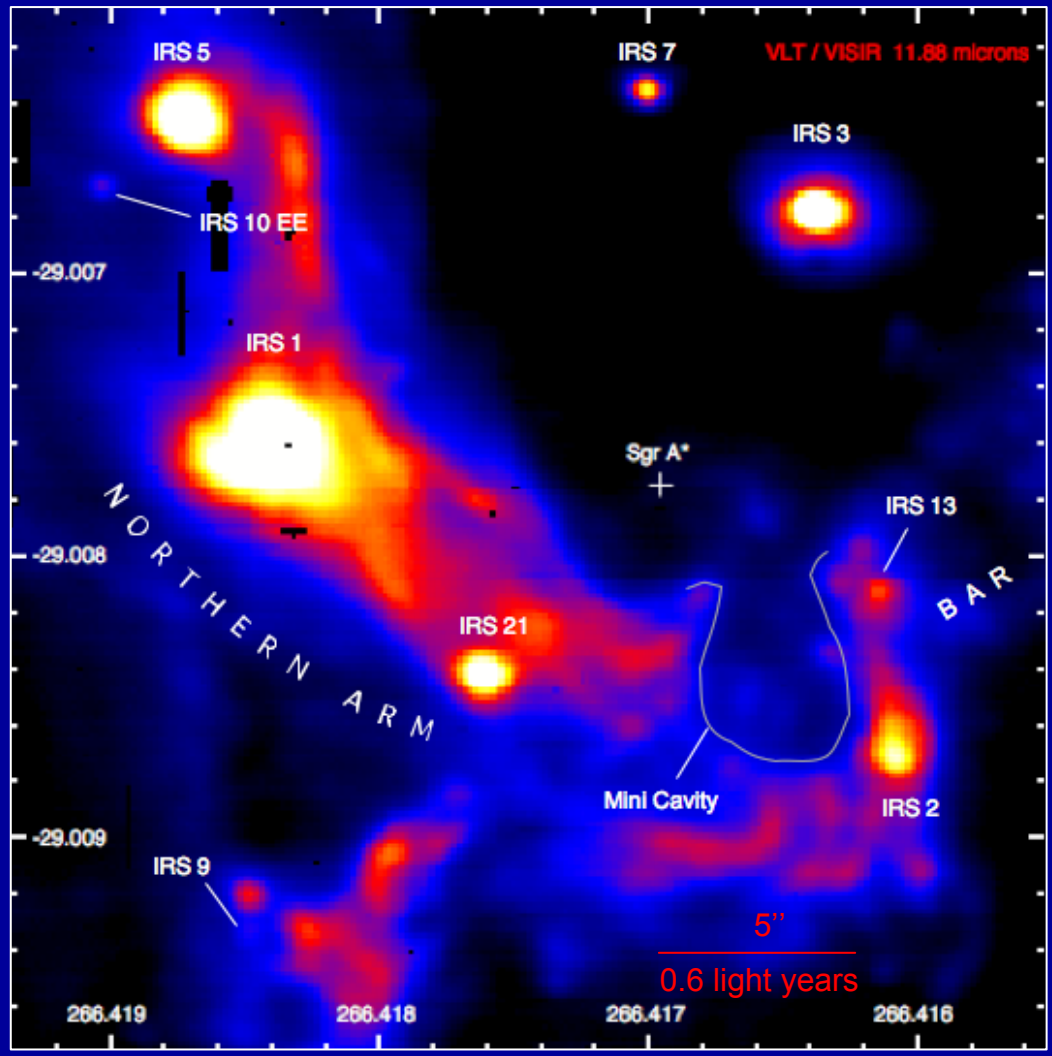
(Porquet et al. 2008)

NIR VLT / NACO



(Dodds-Eden et al. 2009)

MIR VLT / Visir

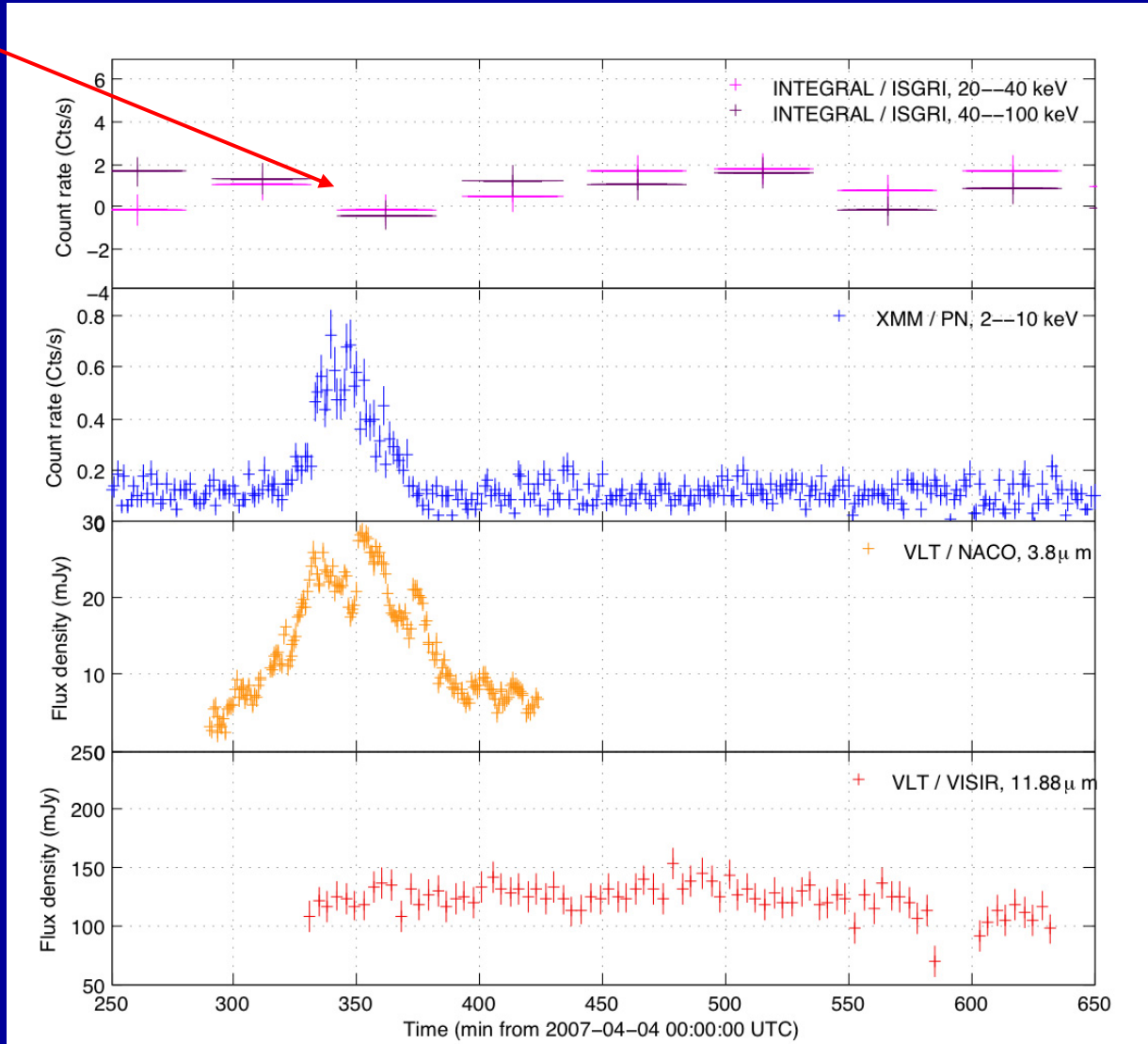


(Trap et al. 2009)


XMM / EPIC / PN, 0.2-12 keV

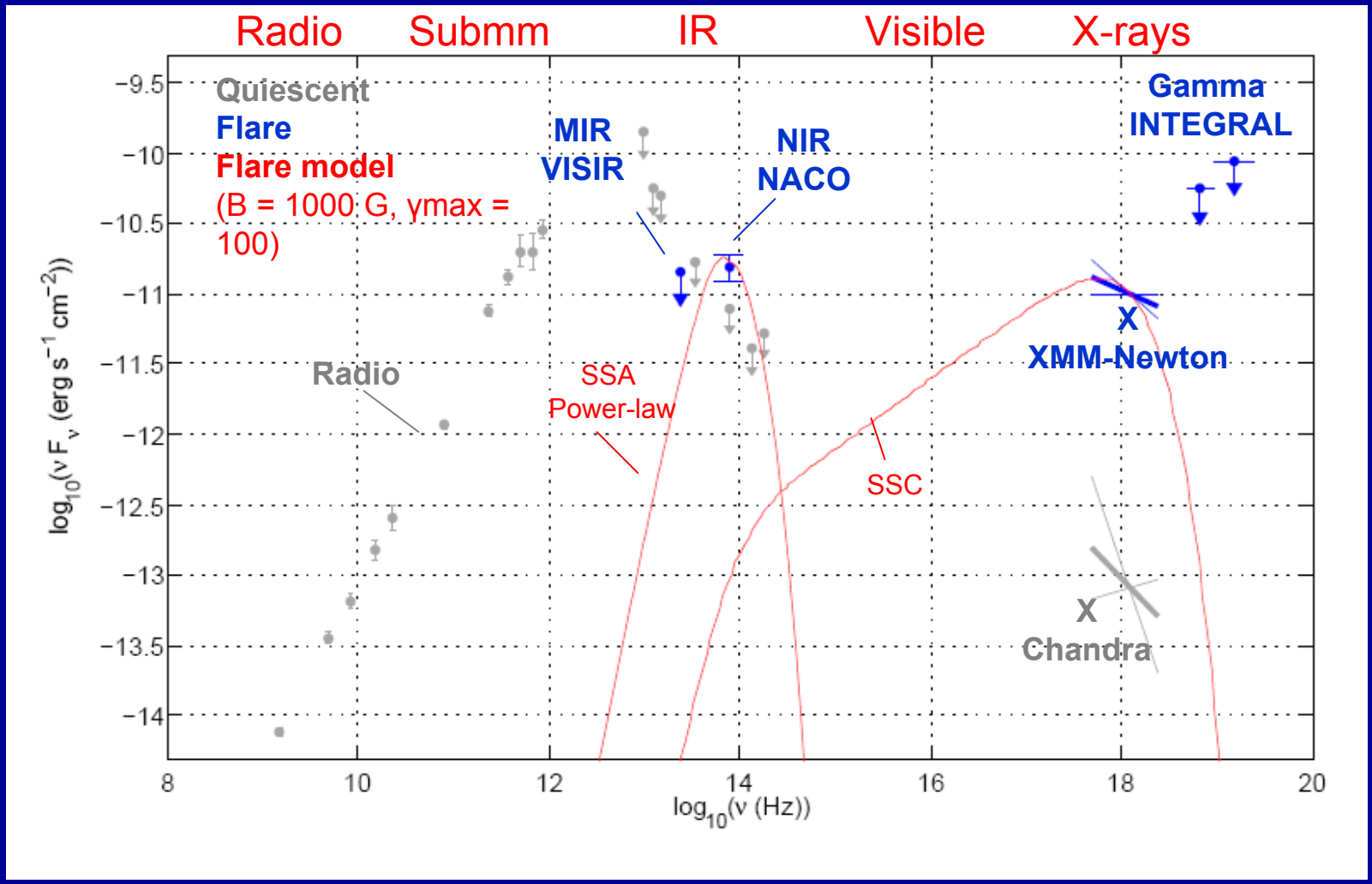
Sgr A* Flare Light Curves of the April 2007 event

No variability of IGR J17456-2901 during the bright SgrA* flare of April 2007

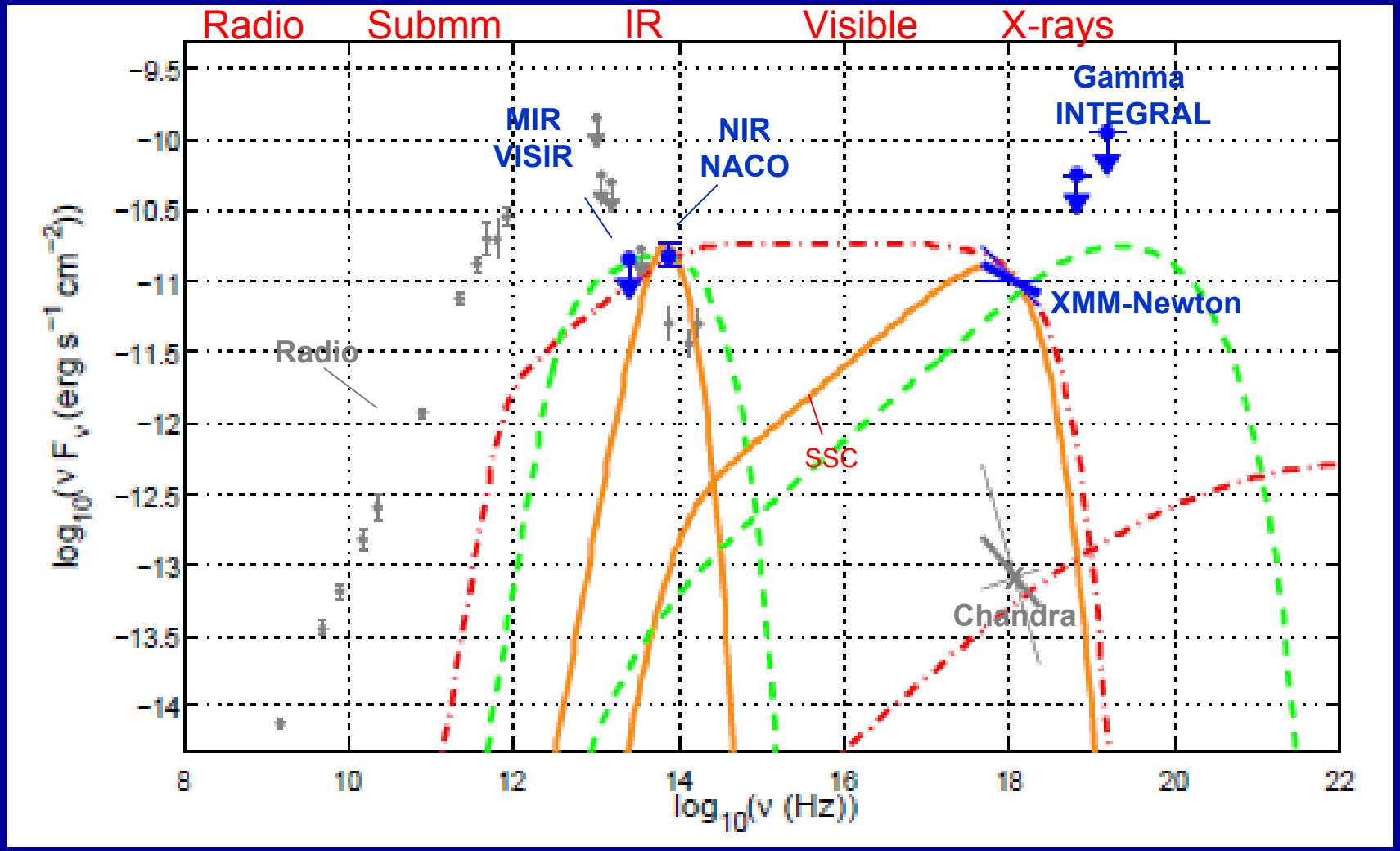


(Trap et al. 2009)

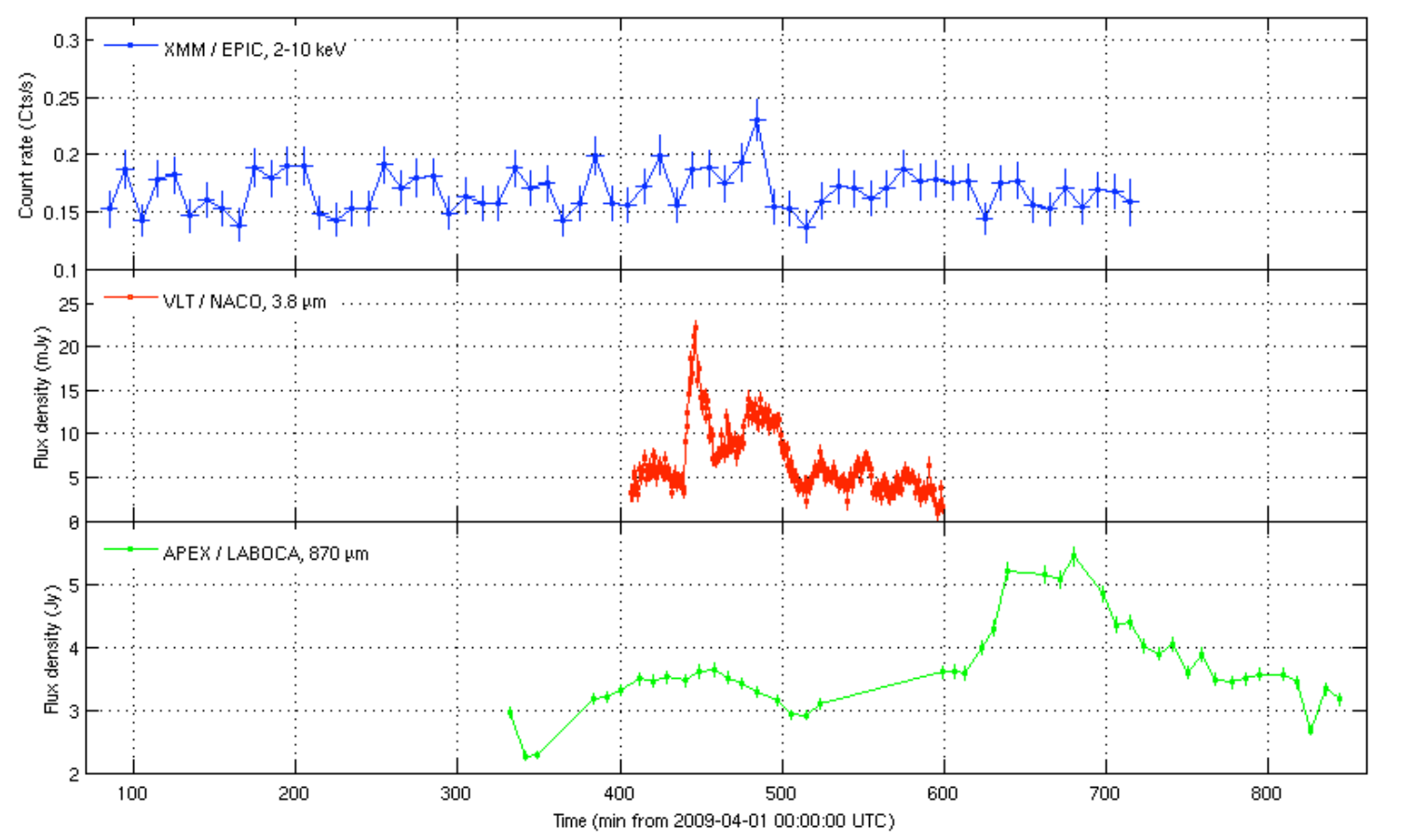
Sgr A* April 2007 flare SED



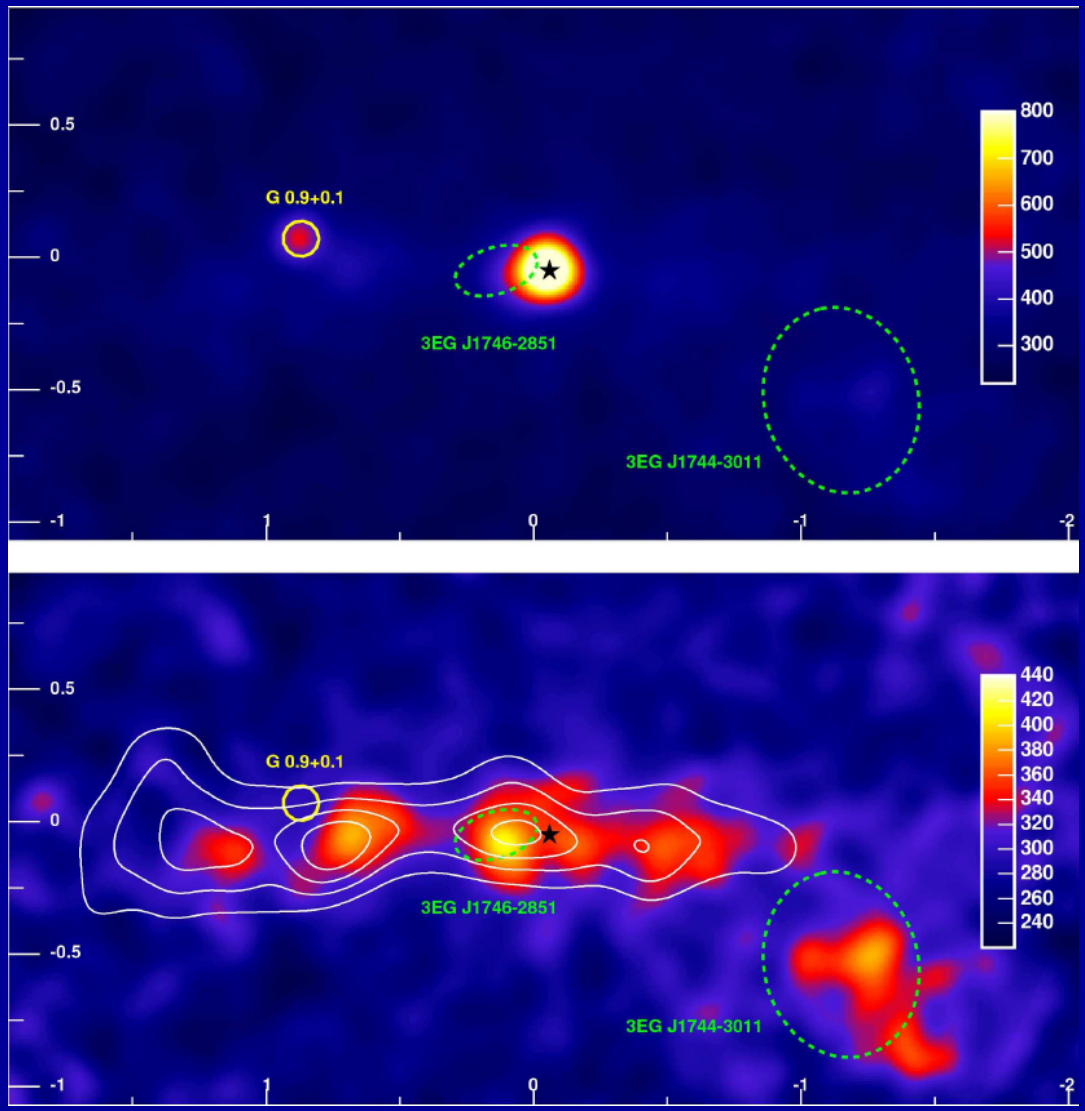
Sgr A* April 2007 flare SED



Sgr A* April 2009 flare: delay in sub-mm => expansion ?



HESS Results on the GC TeV source

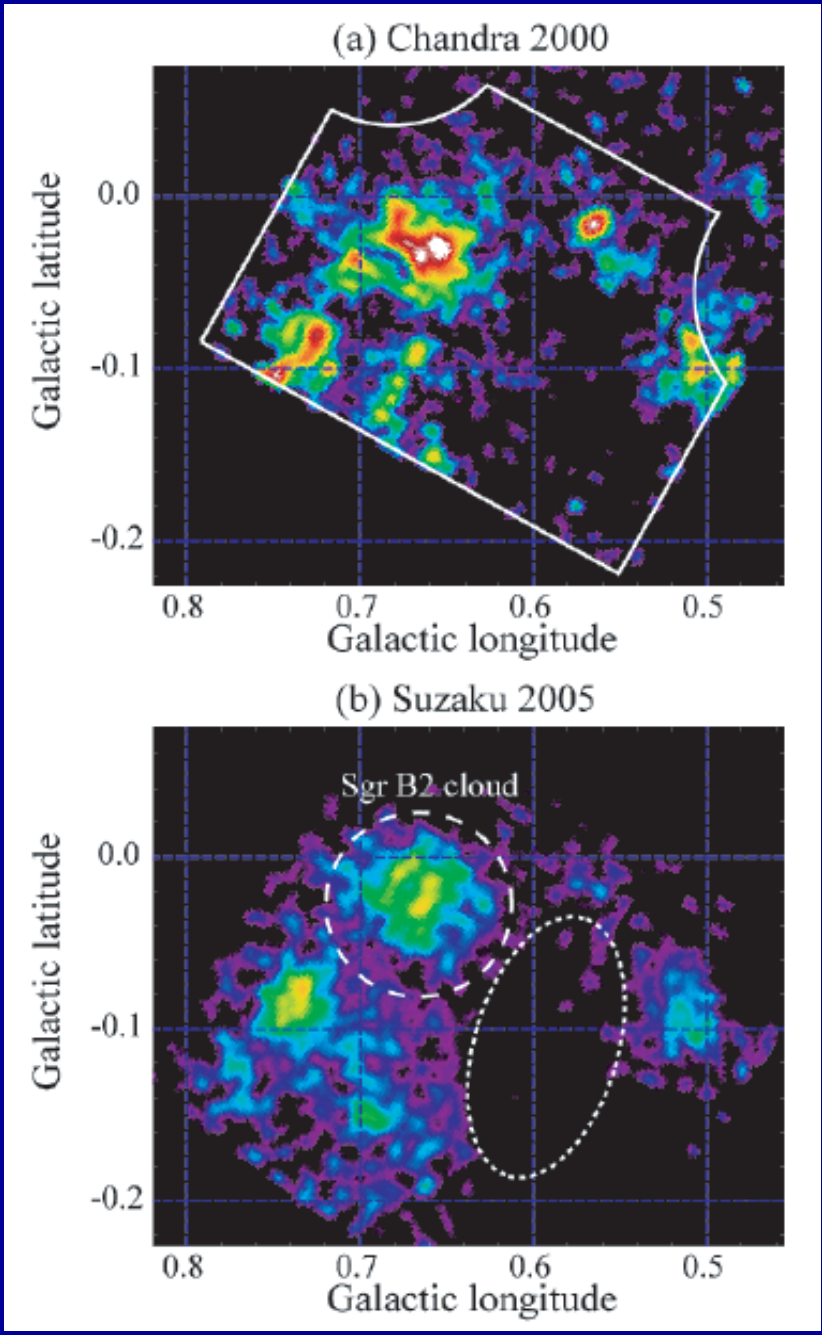


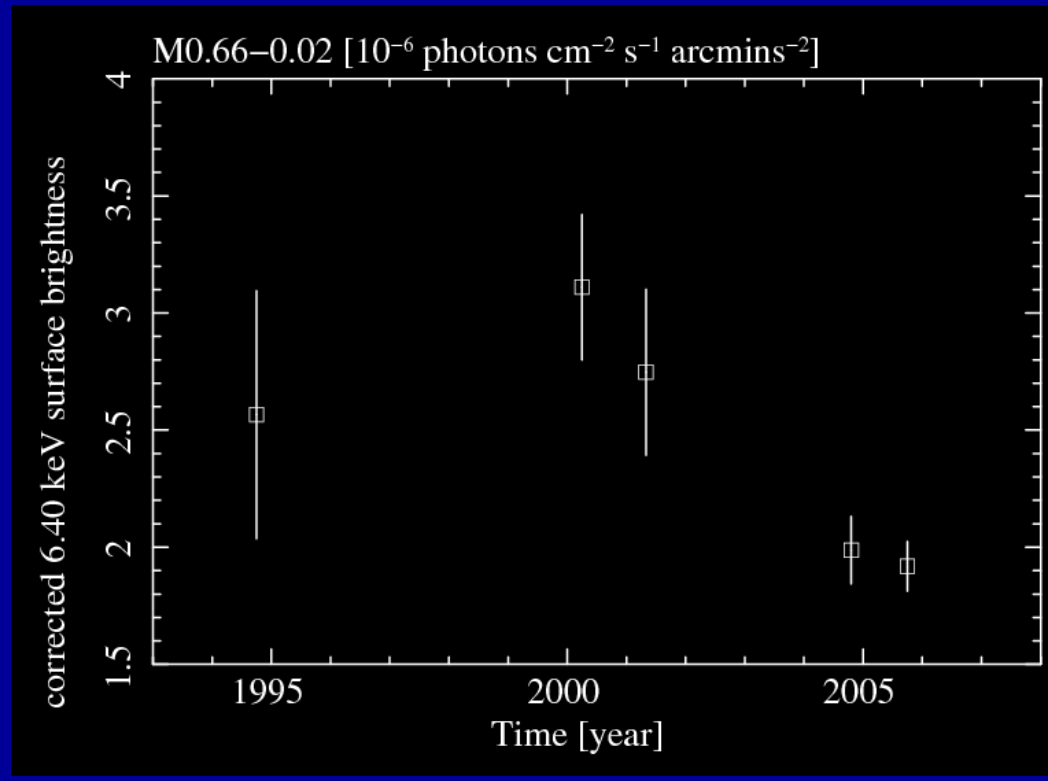
- A TeV source at the Sgr A* position (< 6" from it)
- Non-variable, P-L spectrum with photon index ~ 2.2
- Too hard (4 TeV) to be explained by annihilation of DM particles like neutralinos (=> particle mass ~ 12 TeV)

- Particle acceleration by Sgr A*, by Chandra PWN or by IRS16 SW (Sgr A East excluded !!)

- TeV Diffuse emission from MC => hadrons accelerator at the GC !

(Aharonian et al. 2004, 2006)

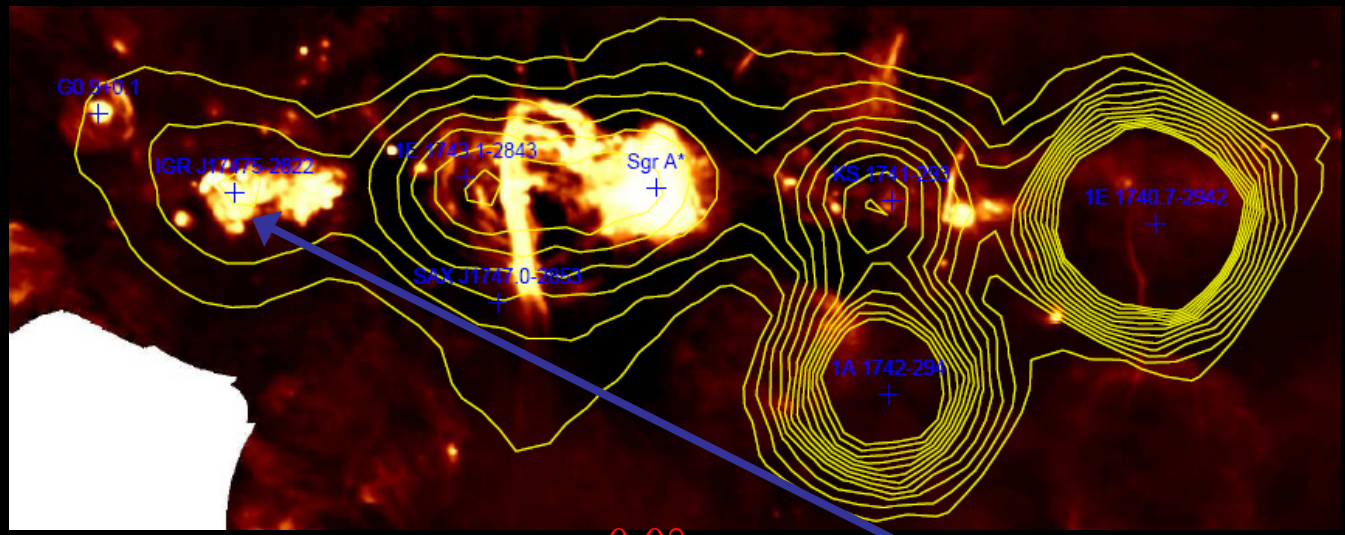




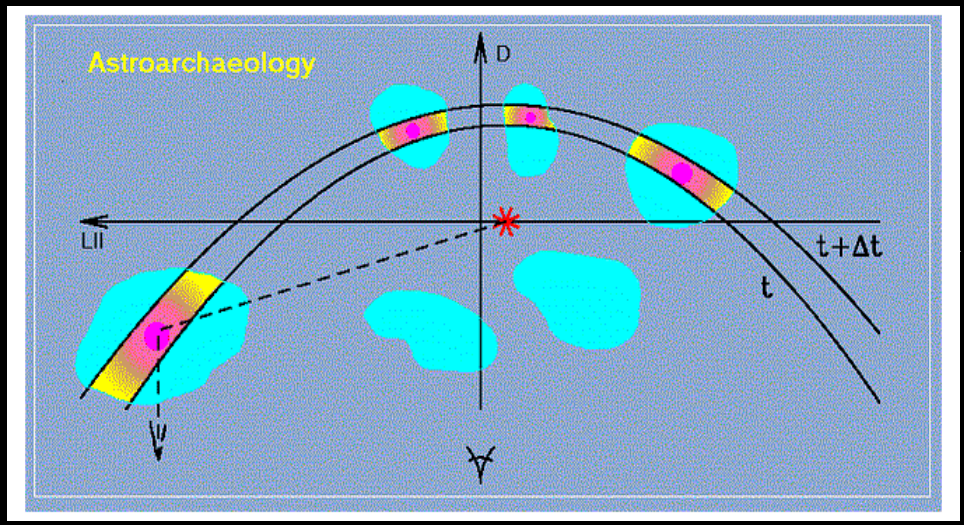
- Detection of 6.4 keV line variability in Sgr B2 from Chandra, XMM, and Suzaku measurements between 2000 - 2005
- Confirmation of previously (Muno et al 2004) reported variability Fe line features with Chandra

(Koyama etal 06 07 08, Inoui etal 07, Yuasa etal 08)

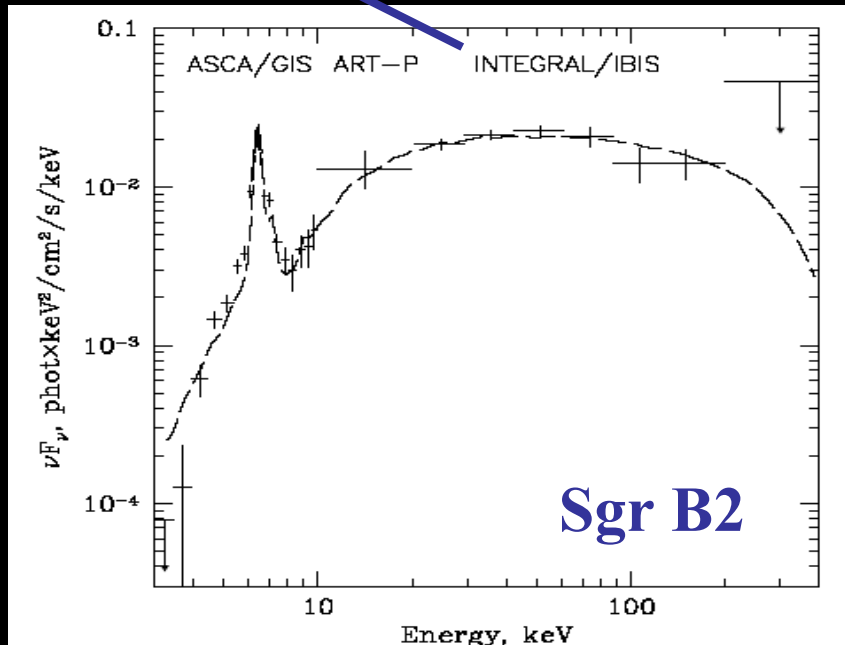
VLA (20cm, col) & INTEGRAL (20-30 keV, contours)

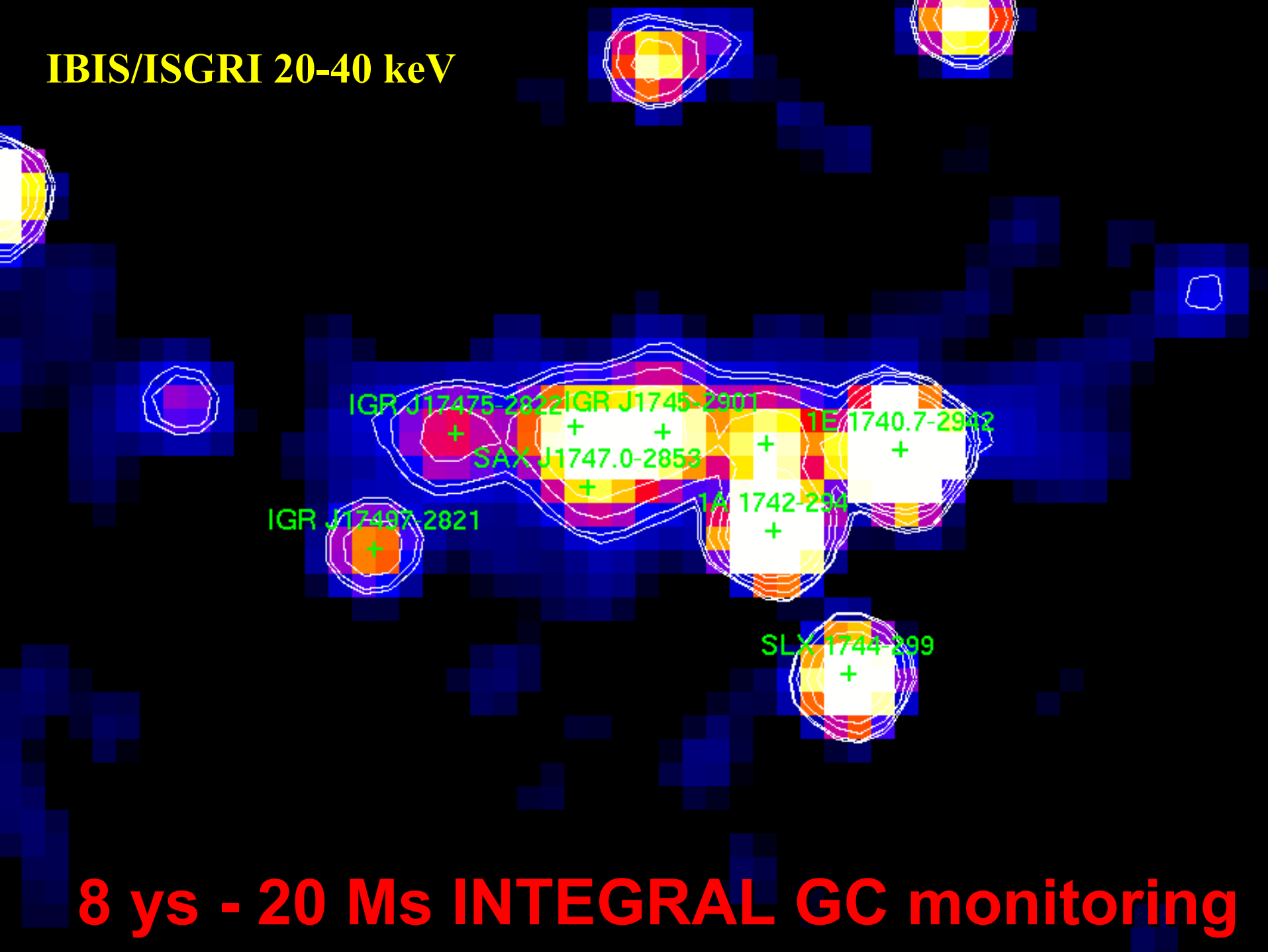


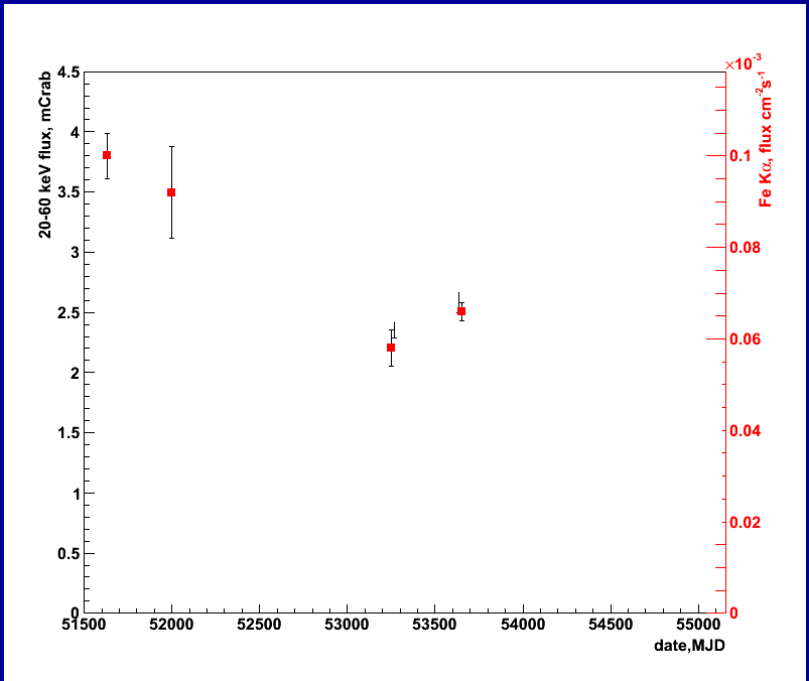
(Belanger et al. 2006)



(Revnivtsev et al 2004)



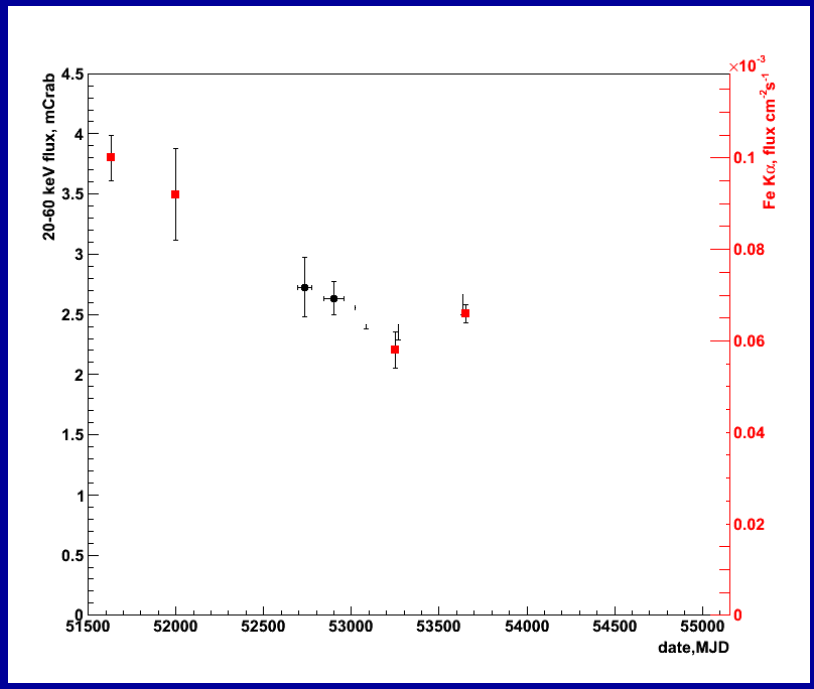

IBIS/ISGRI 20-40 keV
IGR J17475-2822
IGR J1745-2901
1E 1740.7-2942
SAX J1747.0-2853
1A 1742-294
IGR J17497-2821
SLX 1744-299
8 ys - 20 Ms INTEGRAL GC monitoring

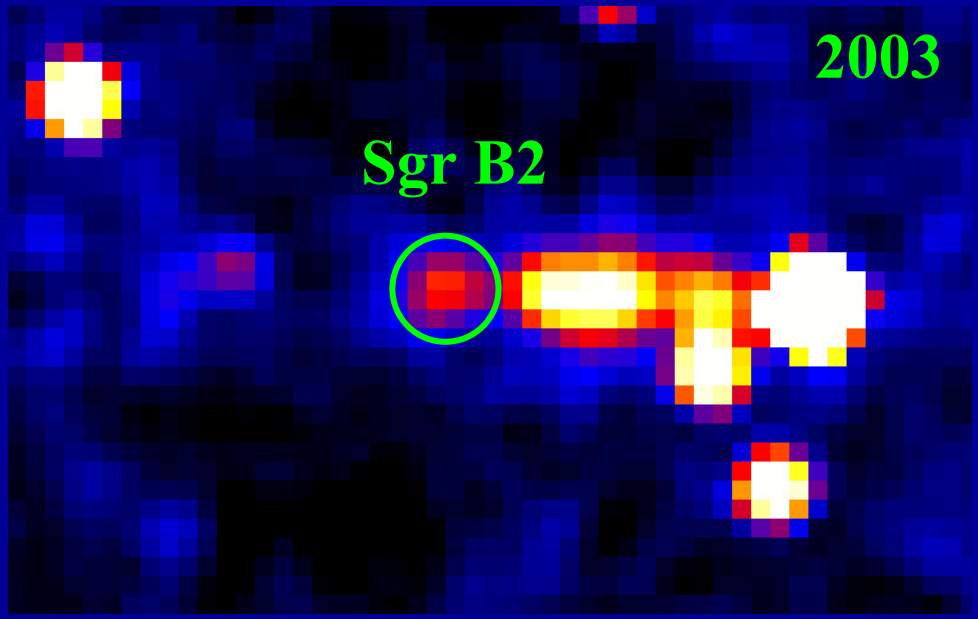


INTEGRAL Monitoring of Sgr B

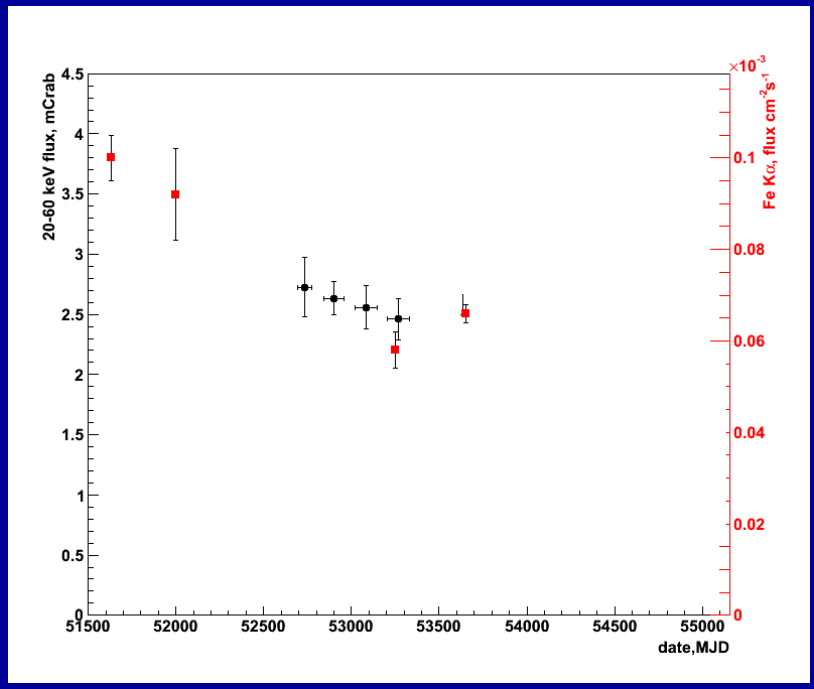
- Detection of significant decrease of Sgr B2 Integral source over 7 ys
- Variation up to 40 %, compatible with the reported 6.4 keV decrease
- Time of variation ~ cloud core size (8 ly)
- Consistent with hypothesis of reflection of hard X-ray emission: we witness the end of the outburst
- Sign of a past activity of Sgr A*: outburst of 1039 erg/s that ended ~ 100 yrs ago (new location of Sgr B2) (Terrier et al. 2008, 2010submit)

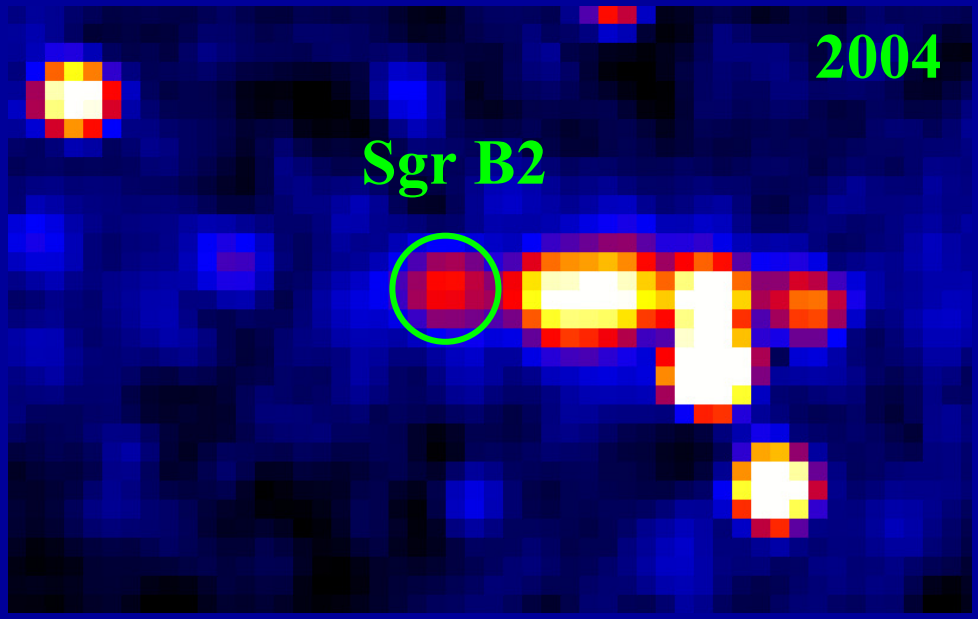
INTEGRAL
Monitoring of Sgr B



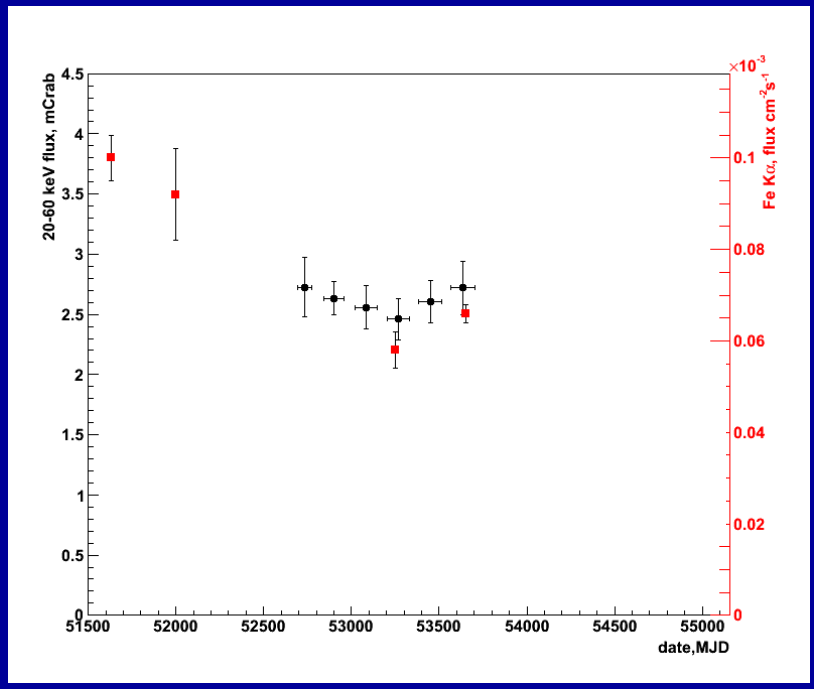


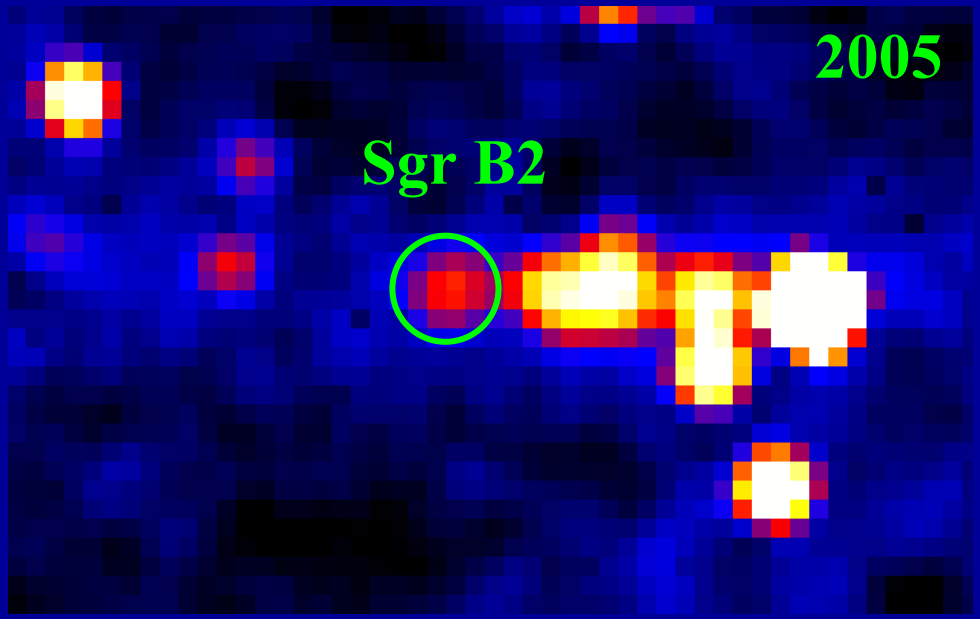
INTEGRAL
Monitoring of Sgr B



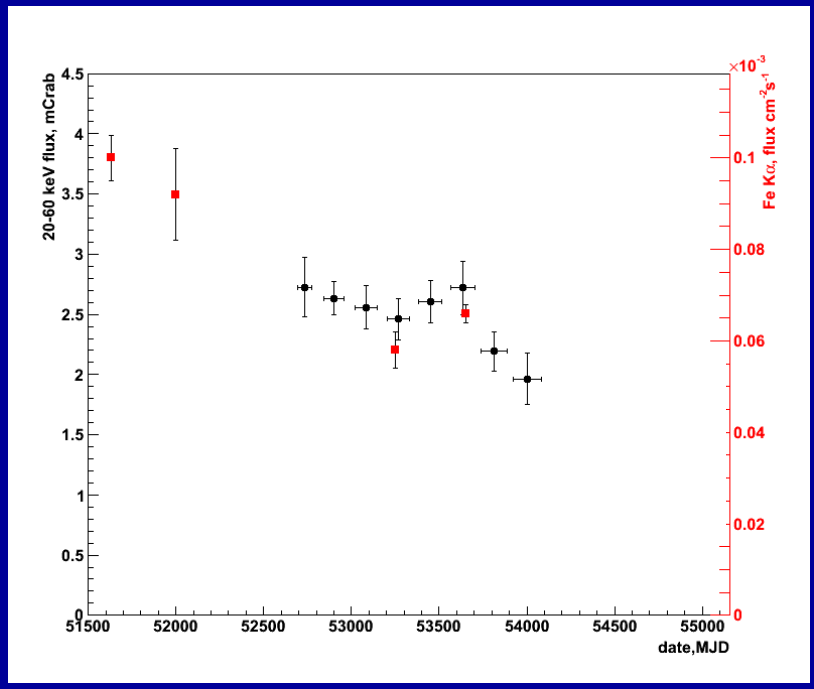


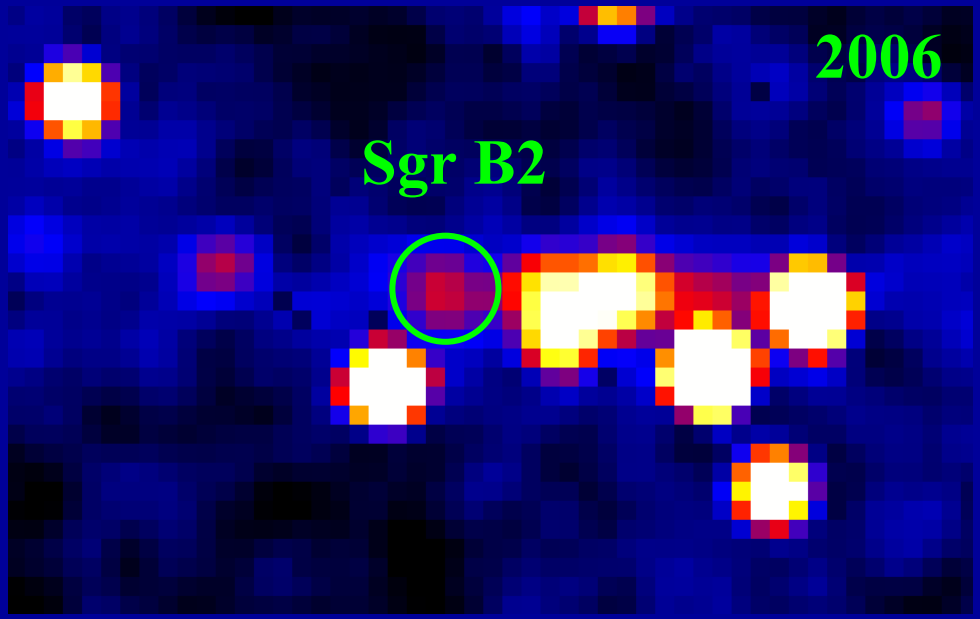
INTEGRAL
Monitoring of Sgr B



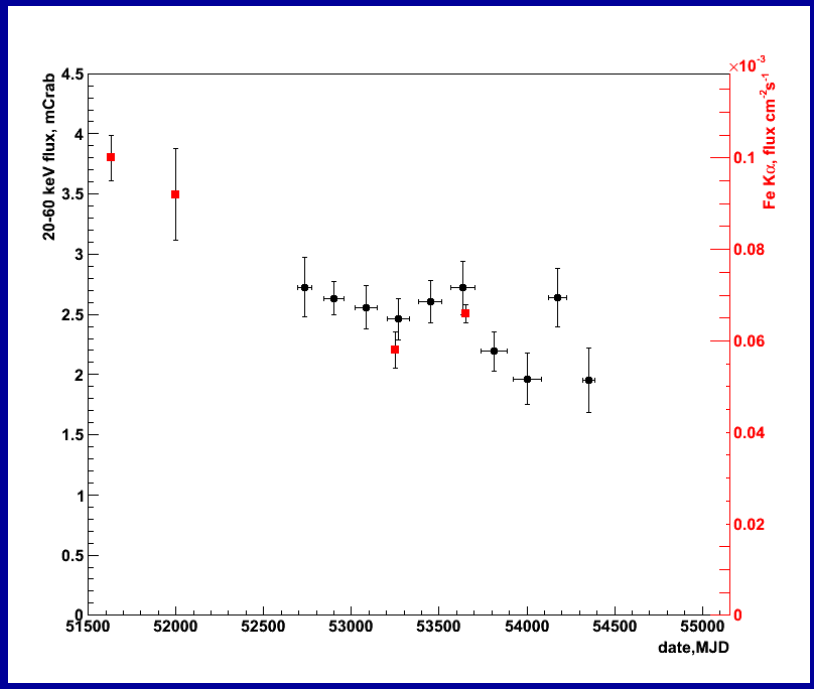


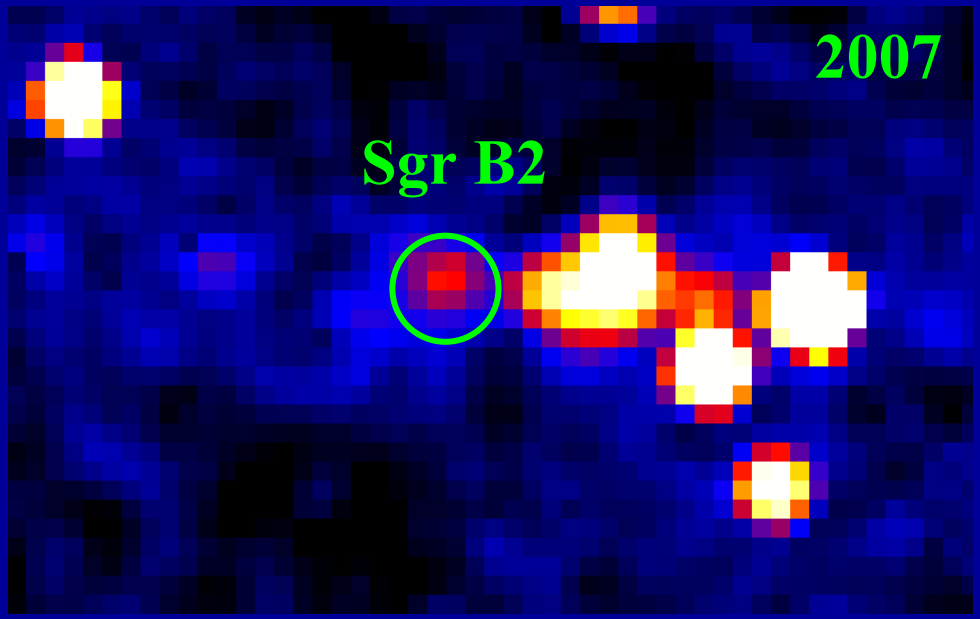
INTEGRAL
Monitoring of Sgr B



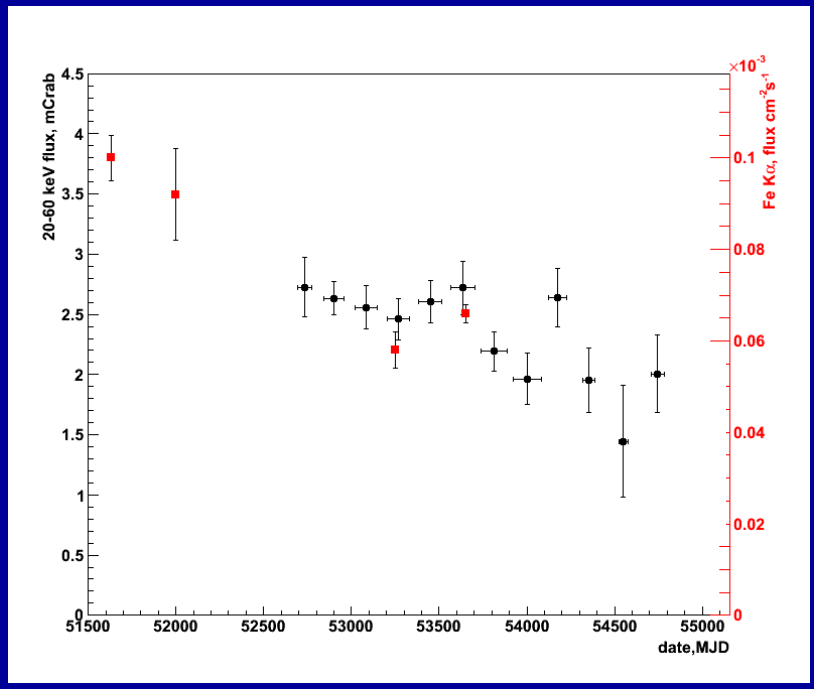


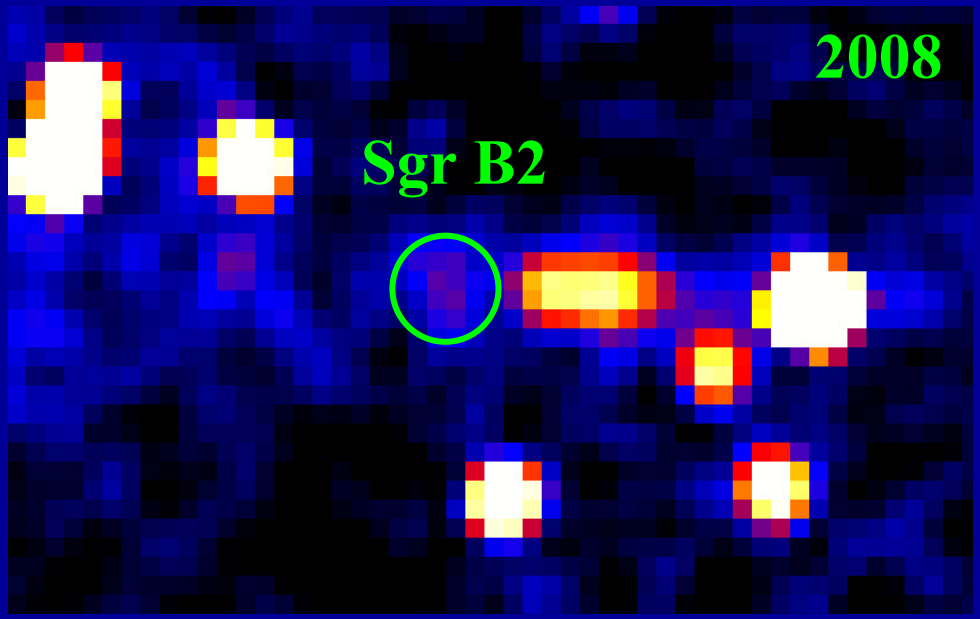
INTEGRAL
Monitoring of Sgr B



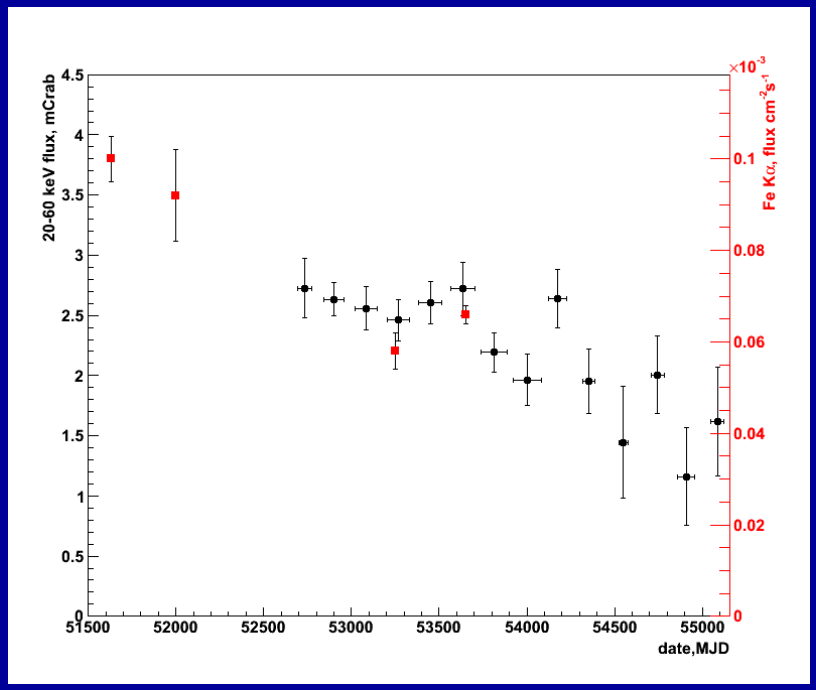


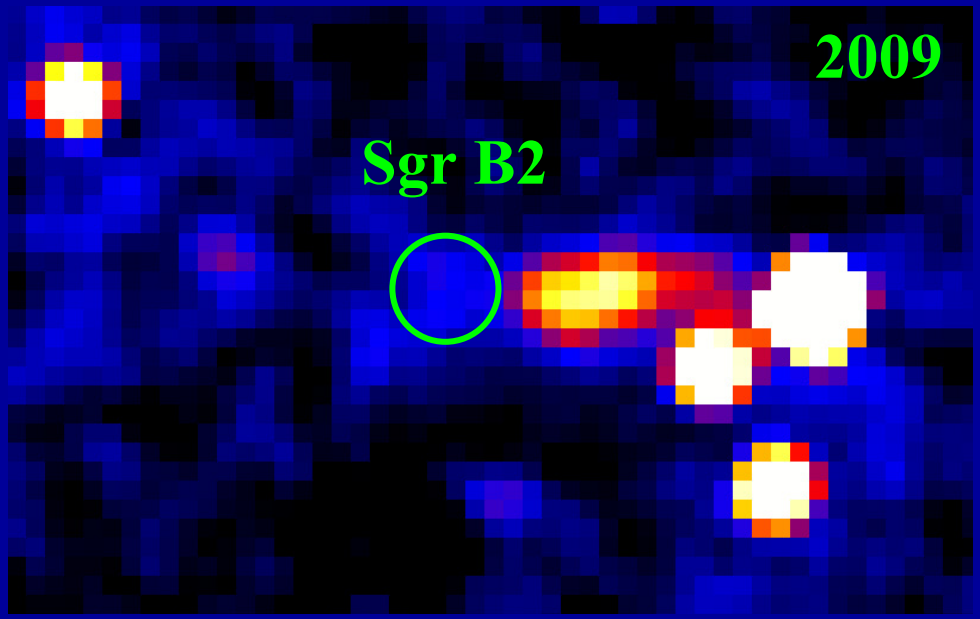
INTEGRAL
Monitoring of Sgr B





INTEGRAL Monitoring of Sgr B

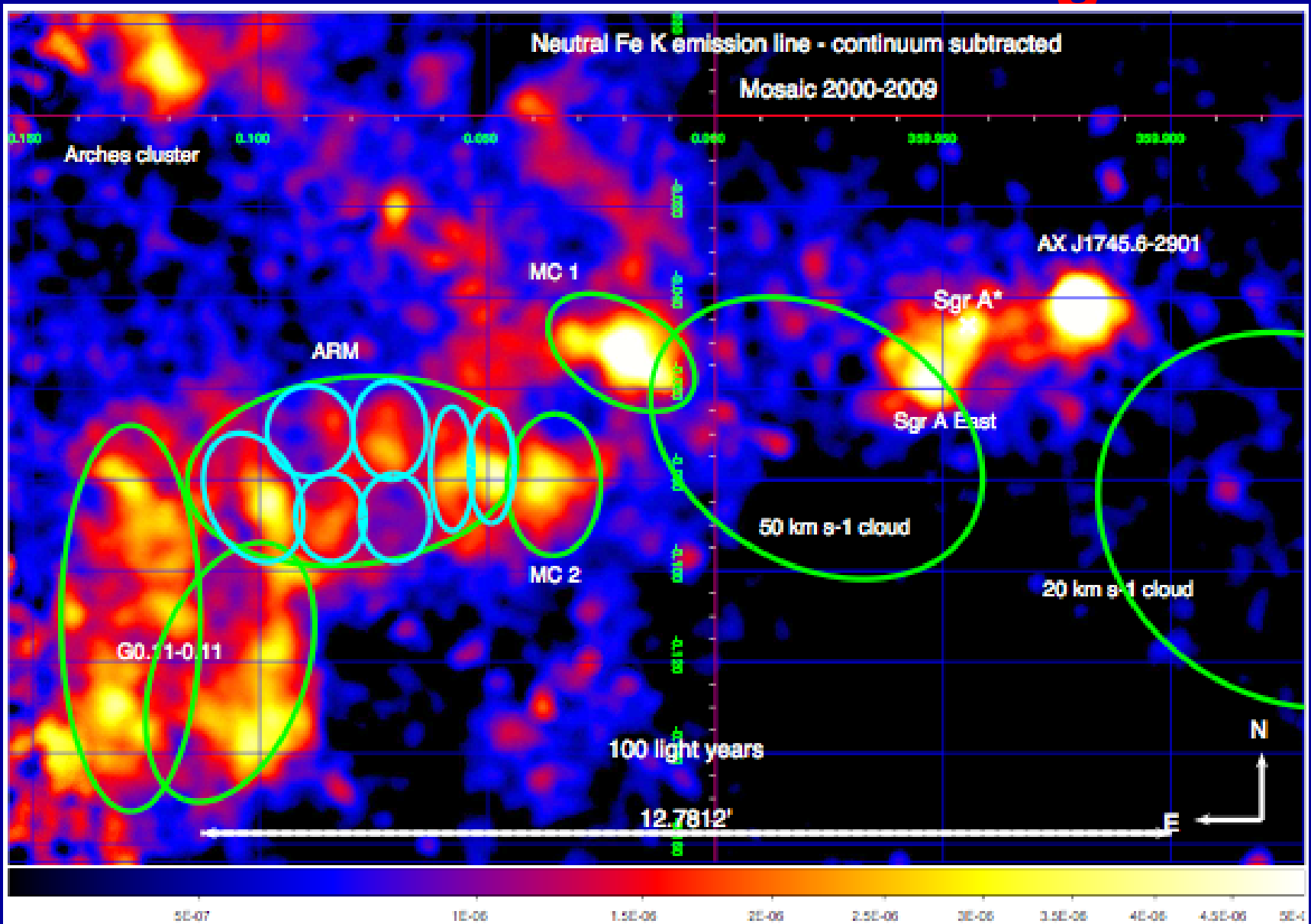




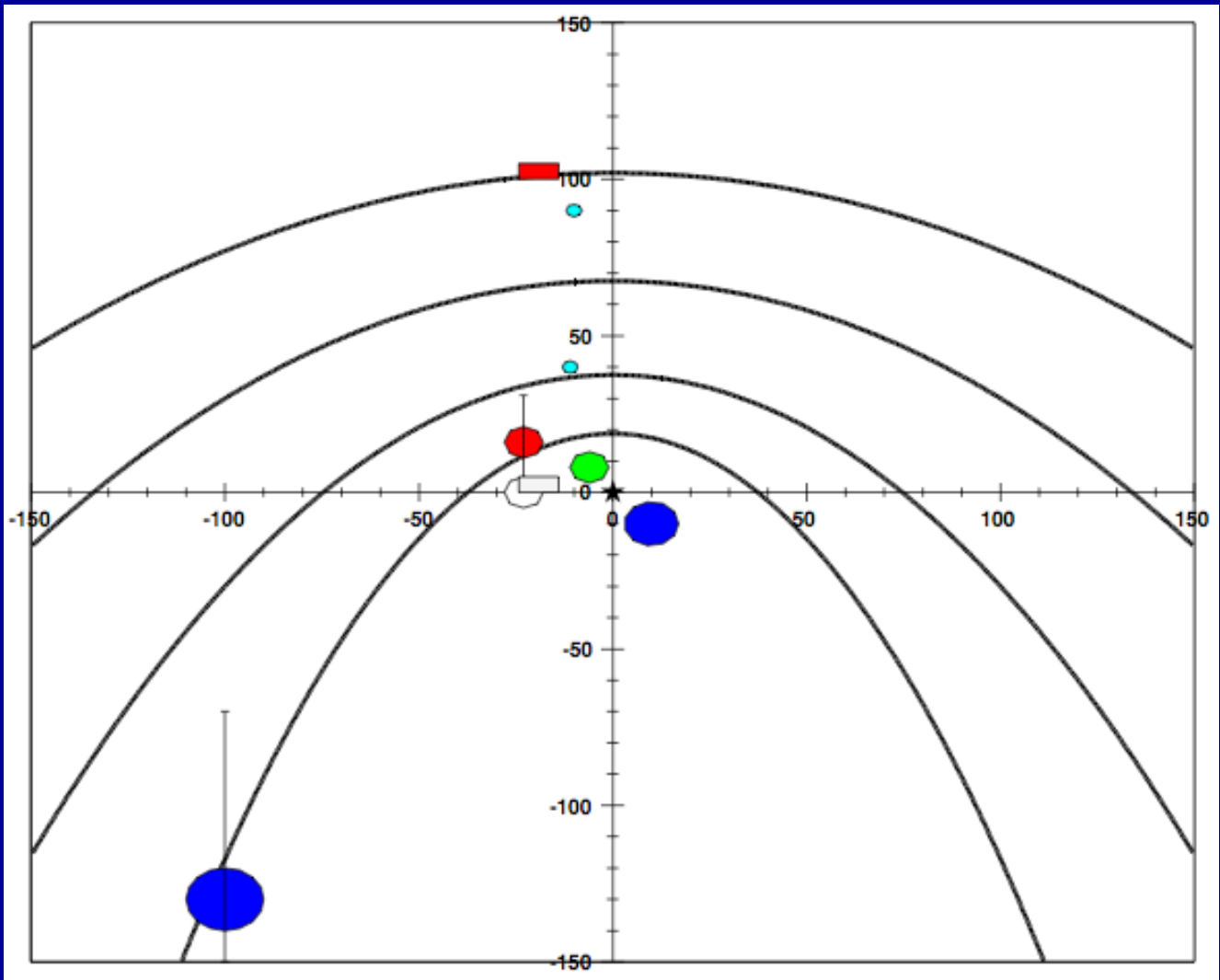
- Detection of significant decrease of Sgr B2 Integral source over 7 yr
- Variation up to 40 %, compatible with the reported 6.4 keV decrease
- Time of variation ~ cloud core size
- Consistent with hypothesis of reflection of hard X-ray emission: we witness the end of an outburst
- Sign of a past activity of Sgr A*: outburst of 10^{39} erg/s that ended ~ 100 yrs ago (new location of Sgr B2)

(Terrier et al. 2008, 2010submit)

XMM monitoring of the 6.4 keV line emission of MC around Sgr A*



Discovery of a superluminal echo: of a past outburst of Sgr A* ?



(Ponti et al. 2010 in prep.)

Open Questions on High-Energy Phenomena in the GC

- Physical processes and radiation mechanisms in Sgr A* (why under-luminous, accretion or jet, Sync/SSC/IC)
- Origin of the hot diffuse X-ray em. (plasma vs sum of PS)
- Origin of 6.4 keV diffuse line emission (XRN from Sgr A* event , LECR interaction)
- Nature of the central NT emission (CVs ?)
- Nature of the TeV central source (Sgr A*, PWN, relation with GMC emission)
- Origin of TeV diffuse emission
- The GeV component ?

HE Missions Perspectives

- Results from Fermi on the GC emission will be soon available …. lot of expectation, even if probably strongly diffuse-emission model dependent.
- XMM and Integral extended till 2012 by ESA few weeks back.
- Simbol-X (hard X-ray focusing mission) cancelled but Nu-star (2012) and especially ASTRO H (2014) are in schedule
- HESS 2 shall start next year to provide results in the range 10-100 GeV => overlap with Fermi !!
- CTA (new generation of Atmospheric Cherenkov TeV observatory) in the 2014 horizon

Merci