Present and past high-energy activity of the Massive Black Hole at the Center of the Galaxy

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France

In memoriam of Giovanni (Nanni) Bignami

- Passed away on 25th May 2017
- Well known HE astrophysicist from Milan Beppo Occhialini Institut
- Participated to COS-B, XMM, promoted Integral, Agile and many others space and ground based observatories
- President of ASI, INAF, IRAP, COSPAR, member of ESA SSAC (Cosmic Vision)
- Promoted Astrophysics and space science in Italy & Europe
- My mentor and friend. Our community will miss his energy and dedication

Outline

Content:

- **The SuperMassive BH Sgr A* at the Galactic Center (GC)**
- **Recent results on the Sgr A* Flares**
- **Recent results on Sgr A* past activity from GC X-ray diffuse emission**
- **Conclusions and perspectives**

Collaborators:

R. Terrier, D. Chuard, S. Soldi (APC & CEA, Paris, F)

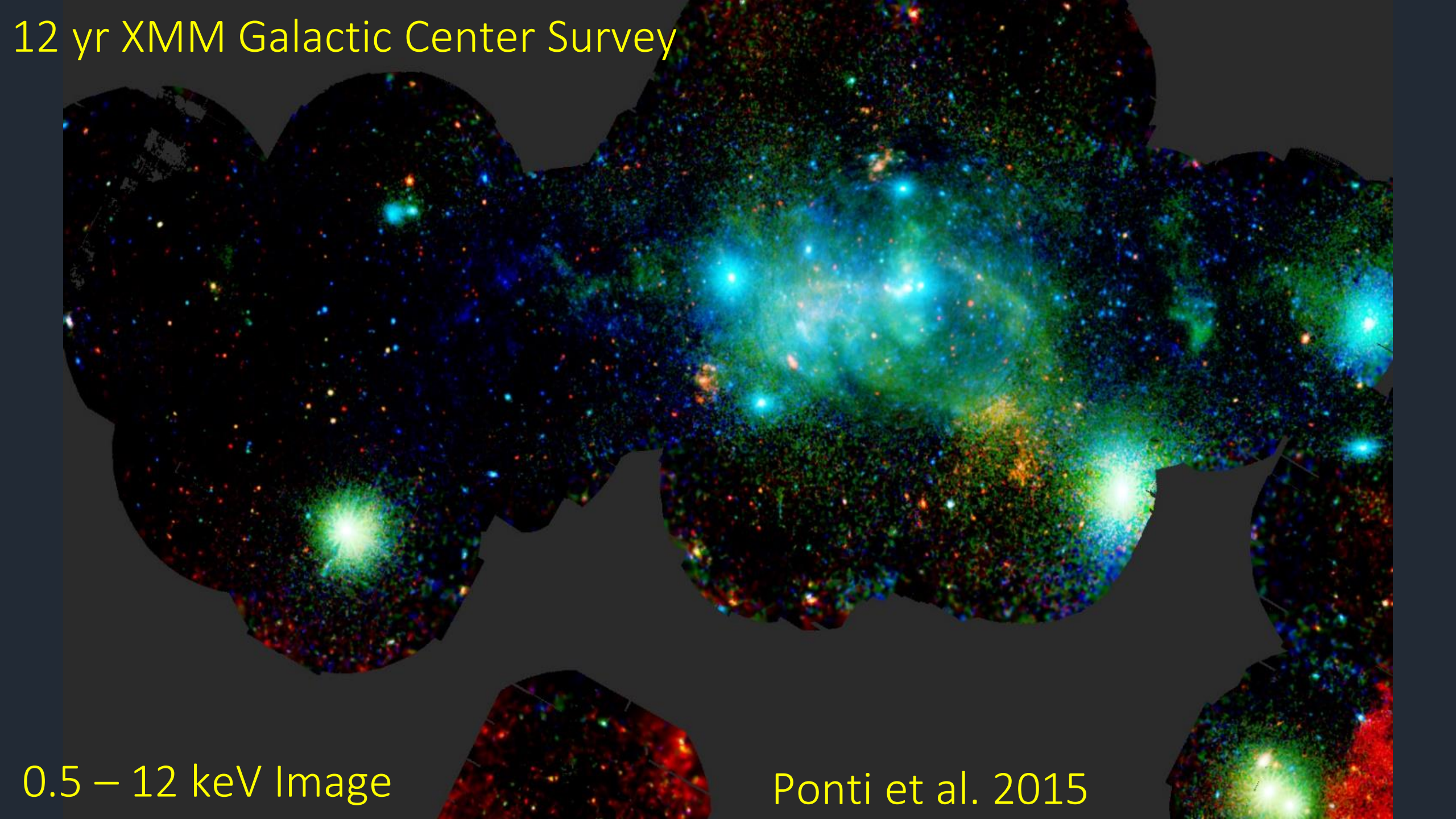
G. Ponti, S. Gillessen (MPE, Garching, D)

M. Morris (UCLA, US), M. Clavel (Berkeley, US)

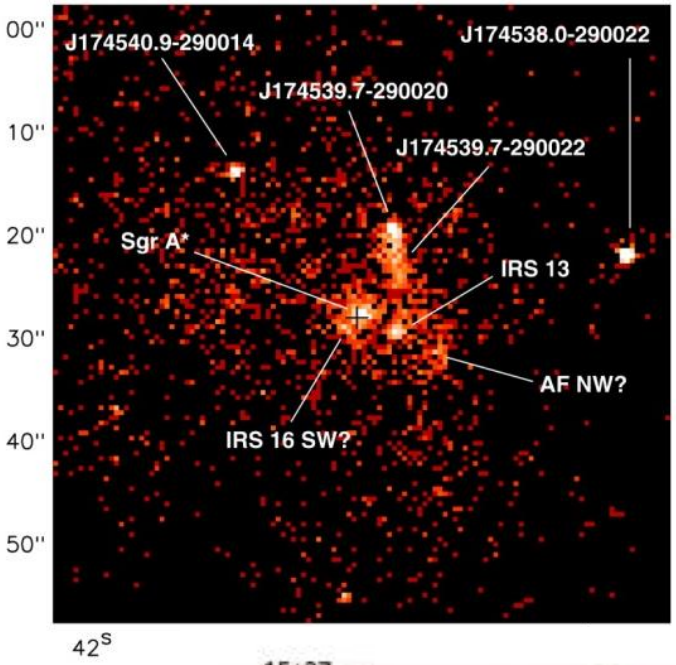
M. Chernyakova, M. Walls (DCU, Dublin, Ir)

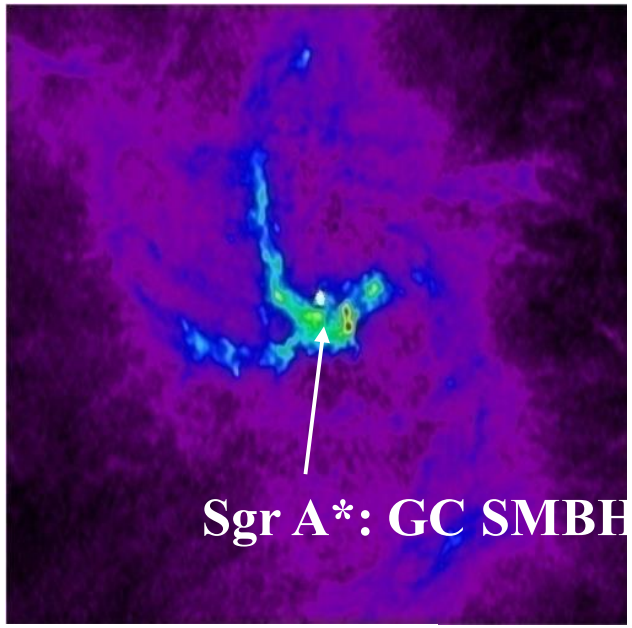
and others

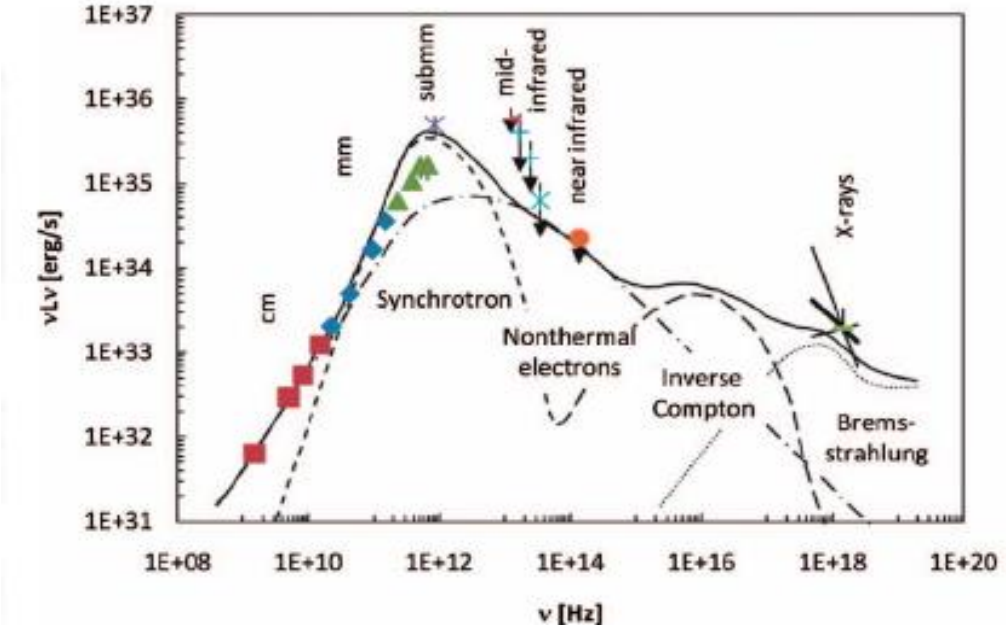
Data: INTEGRAL, **XMM-Newton (> 1.5 Ms GC surveys/obs.)**, Chandra, (VLT, NuSTAR)


12 yr XMM Galactic Center Survey
0.5 – 12 keV Image
Ponti et al. 2015

Sgr A* quiescent emission: a very low luminosity SMBH





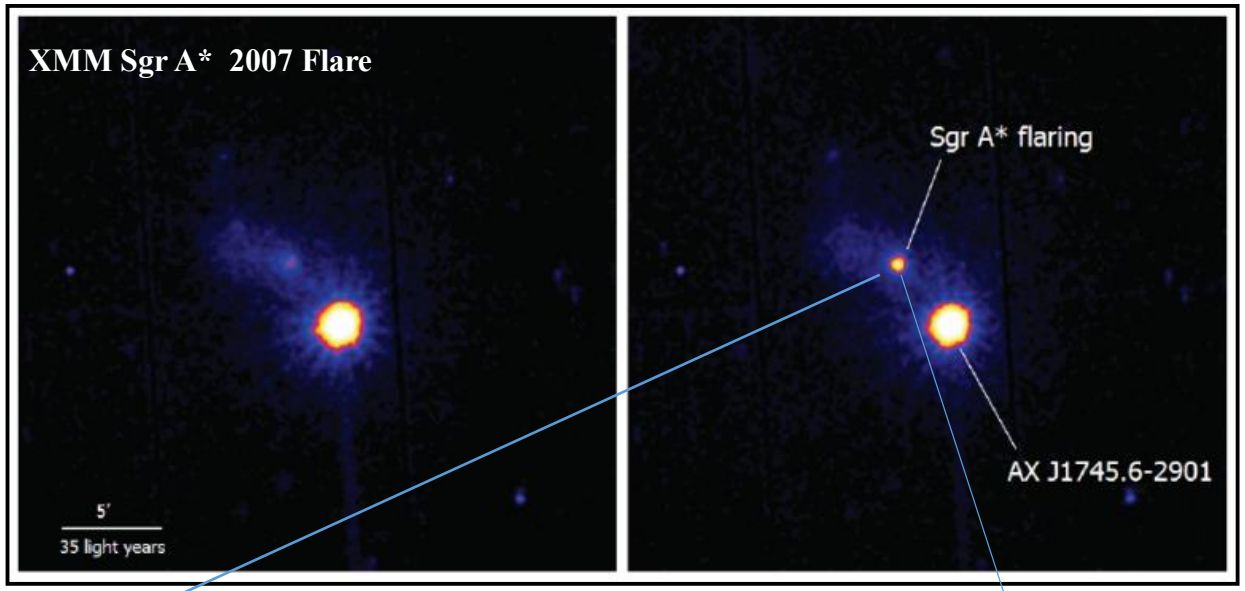


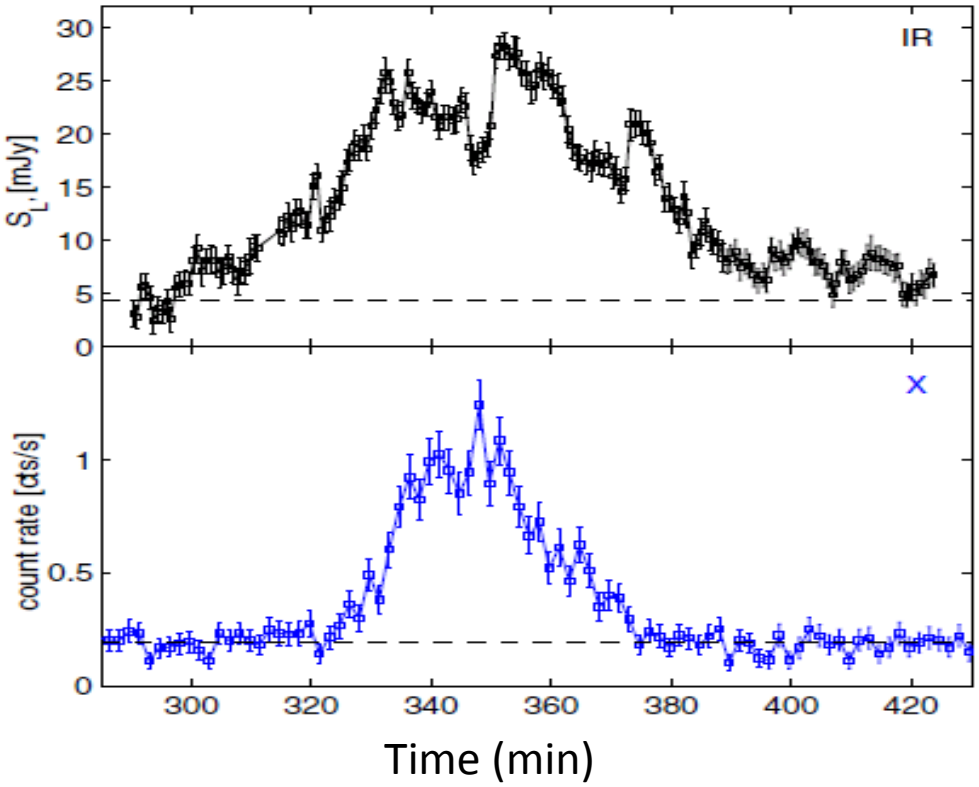
- Sgr A*: compact, variable, non-thermal radio source associated to 4 10^6 $M_\odot$ BH of the GC revealed by the proper motion of central cluster stars see in NIR
- R_S = 1.2 10^{12} cm ~ 0.1 AU; L_E = 7 10^{44} erg s^{-1}
- Visible in radio, sub-mm, IR (Flares only), X-rays (2 10^{33} erg/s) : total L ~ 10^{36} erg/s << L_E
- Very low mass accretion rate, sub-mm polarization => $\dot{M}$ ~ 10^{-8} $M_\odot$/yr << expected stellar winds $\dot{M}$ ~ 10^{-6} $M_\odot$/yr
- Sgr A* L << L of LLAGN (~ $10^{39\text{-}42}$ erg/s) !!

- Two types of variability of Sgr A*:
  - Flares in the (present) X and NIR emission
  - Ancient outbursts traced by MC emission

Radiative inefficient accretion flow with outflow (see Baganoff+ 2003, Yuan&Narayan 2014, Wang+ 2013)

Sgr A* Flares

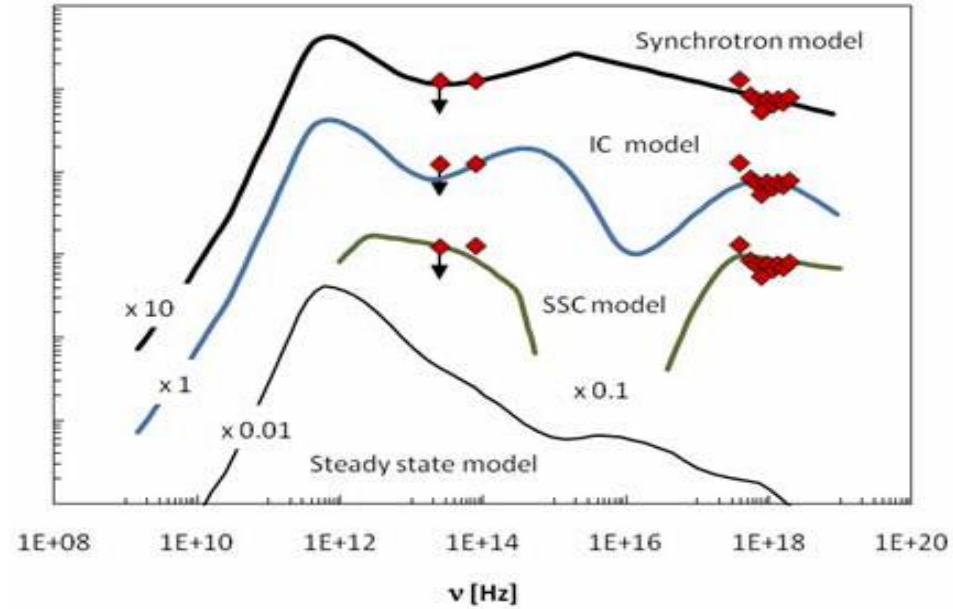




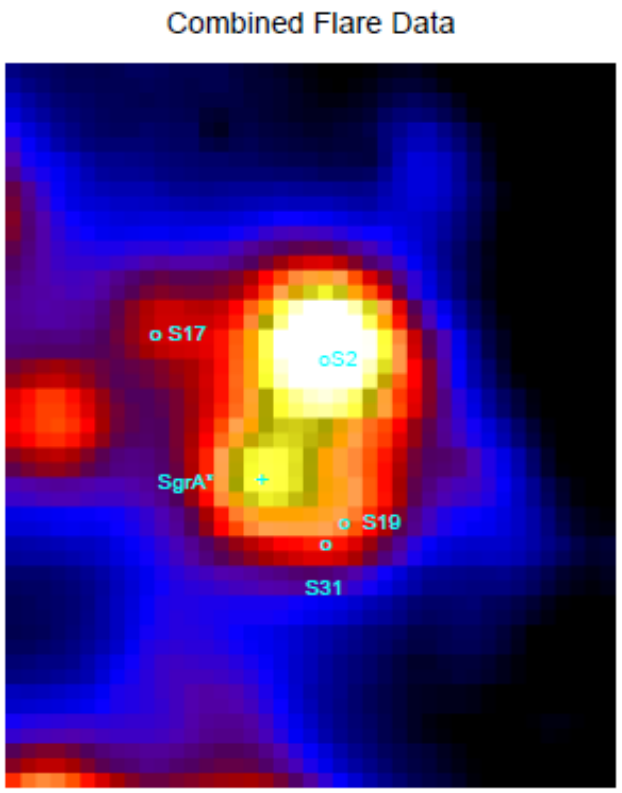
- NIR and X-ray Flares (L_X (at peak) ~ 200 x Q.L. = 4 10^{35} erg/s)
- Frequency: ~ 1/d, NIR: 4/d Durations: 20 min – 3 hr
- Variations ~200 s => small emis. region ~ 10 R_s near horizon
- NIR: Blue/hard spectra, linearly polarized => Synchrotron

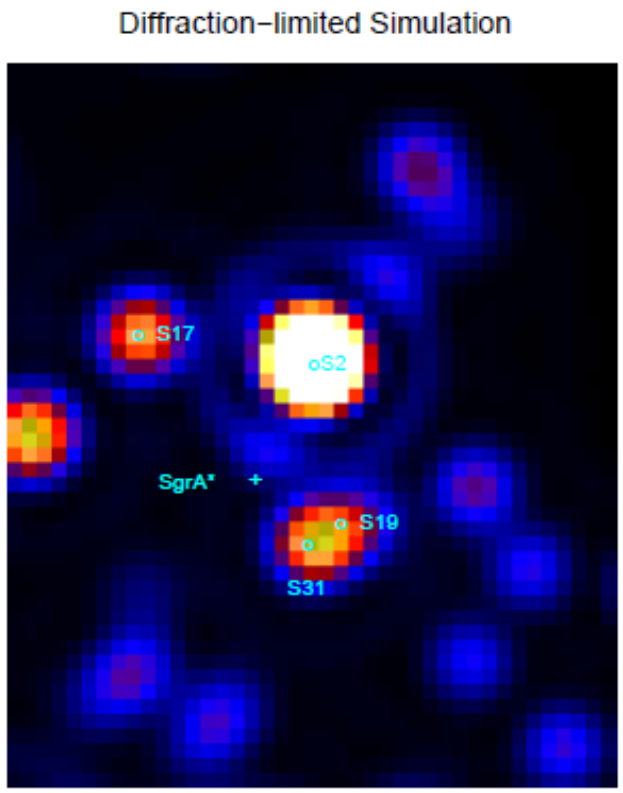
- Constraints on X-rays mechanism given by 2007 flare MIR upper limit but no simultaneous X- NIR spectra

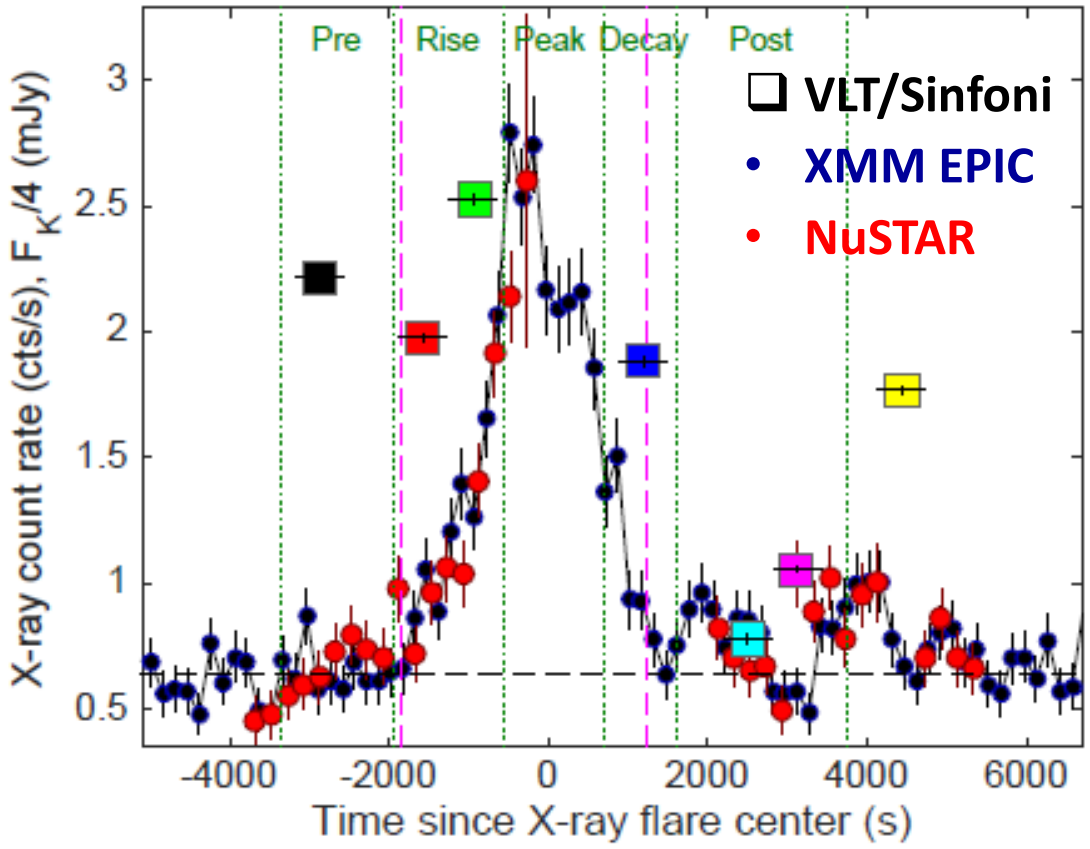
(Dodds-Eden et al. 2009, Trap et al. 2011)



MultiWave Obs of bright 2014 Aug Sgr A* Flare

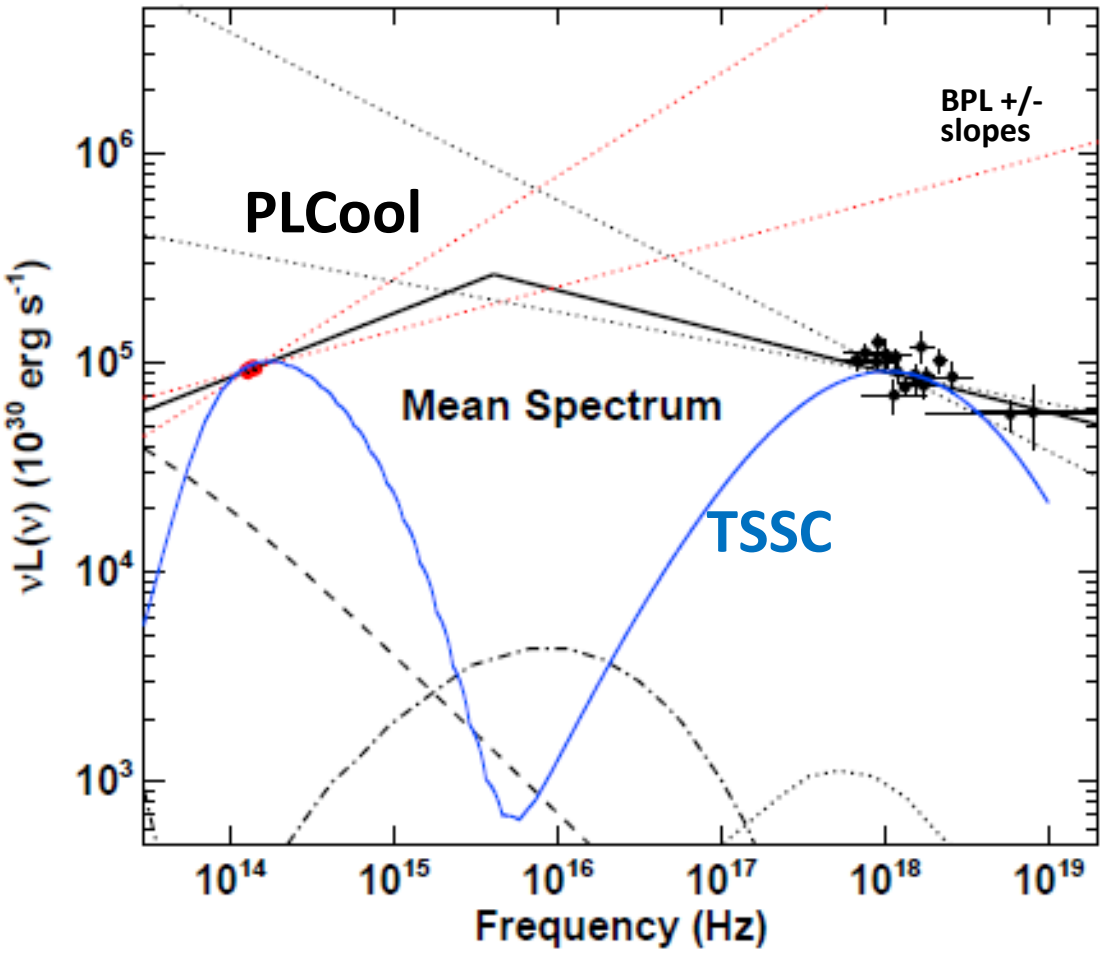






- First simultaneous measurement of spectra in X and NIR of a very bright flare from Sgr A*
- VLT/Sinfoni (2.03-2.39 µm) Image compared to a simulated image
- Light Curves in X and NIR show temporal behavior of the flare **(Ponti et al. 2017)**

SgrA* Aug 2014 Flare average SED fit



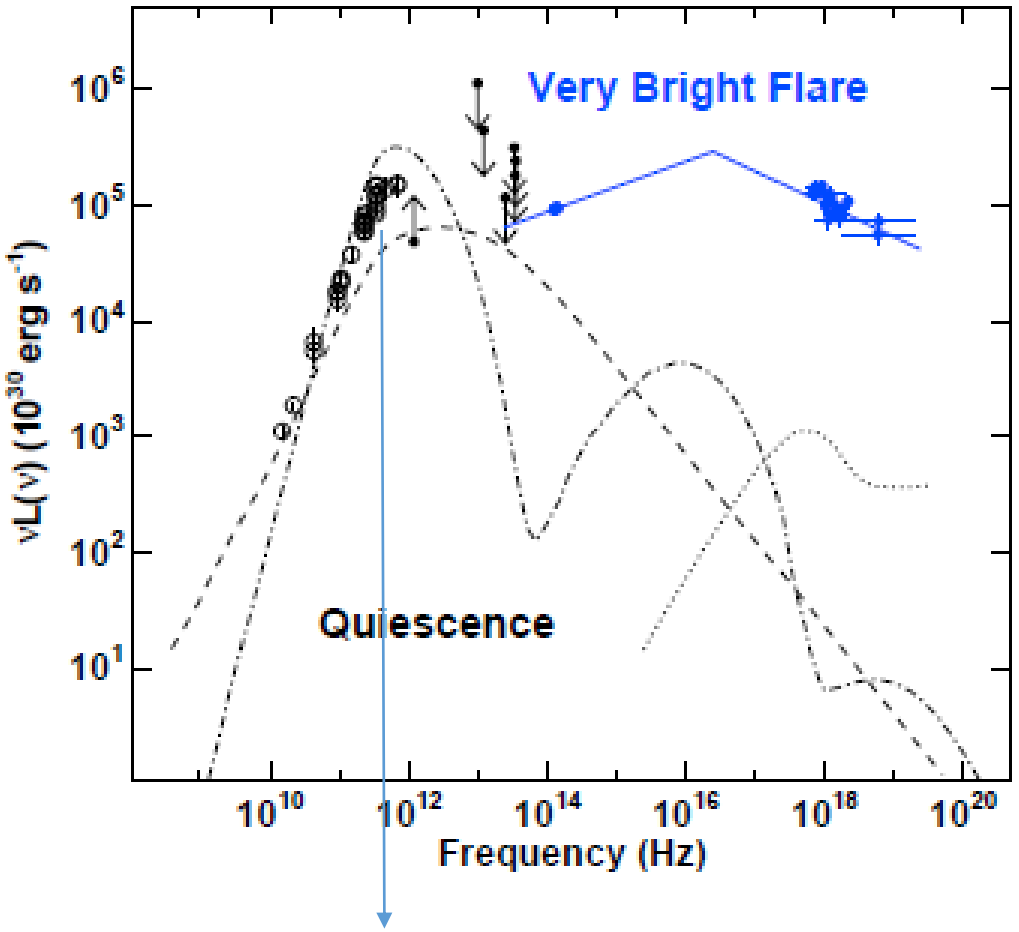
VB3 mean spectrum				
	Single PL	BPL	TSSC	PLCool
Γ_{NIR}	2.001 ± 0.005	1.7 ± 0.1		1.74 ± 0.08
Γ_X		2.27 ± 0.12		
$\Delta\Gamma$		0.57 ± 0.15		0.5
Log(B)		0.94 ± 0.16	4.0 ± 0.4	0.94 ± 0.16
Θ_e			9 ± 4	
Log(N_e)			39.5 ± 0.5	
Log(R_F)			-3.5 ± 0.5	
χ^2/dof	189.7/142	154.9/140	162.7/139	156.8/141

- 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

  ($B \sim 9$ G, $p \sim 2.5$, $\gamma_{max} > 10^6$)

SgrA* Flare SED compared to Quiescent Emission



Quiescent emission: thermal synch from RIAF

(R_{QE} ~ 10 R_S , B ~ 10-50 G, n_e ~ 10^6 cm^{-3}, γ_e ~ 10 , T_e ~ 10^{10} K)

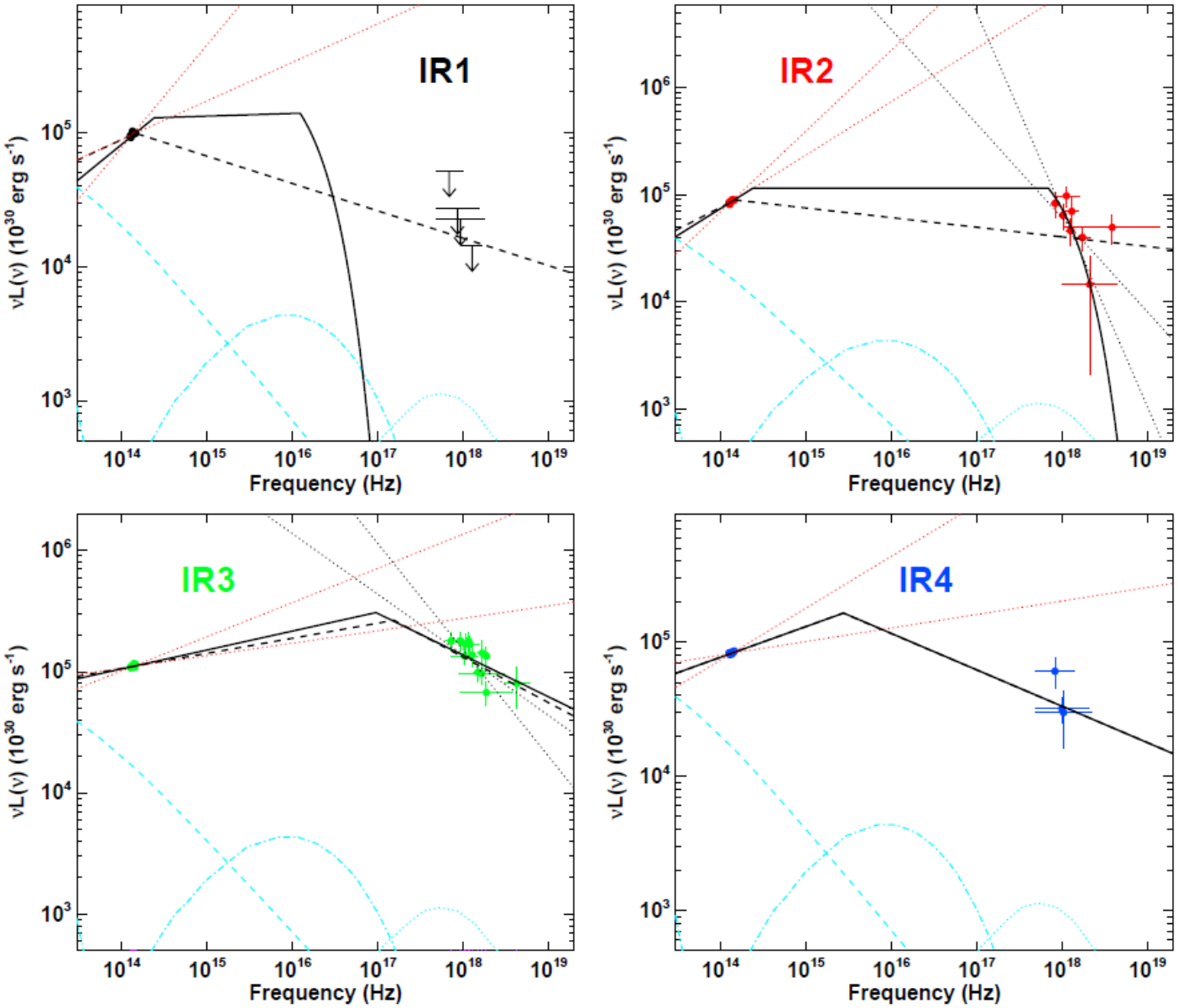
- Quiescent Sgr A* emission (sub-mm/X) by radiative inefficient accretion flow
- Flares are produced by suddenly accelerated e^- to $\gamma_{max} > 10^6$ with PL dist. in γ with index p
- Synchrotron in NIR that extends to X but with cooling break to account for 2 slopes
- Continuous acceleration => steady PL with break at ν_s => B field
- Compton process for X-rays no viable since gives unreasonable phys. parameters

Confirms result on 2007 Flare based on MIR upper limit (Dodds-Eden et al. 2009)

New important result:

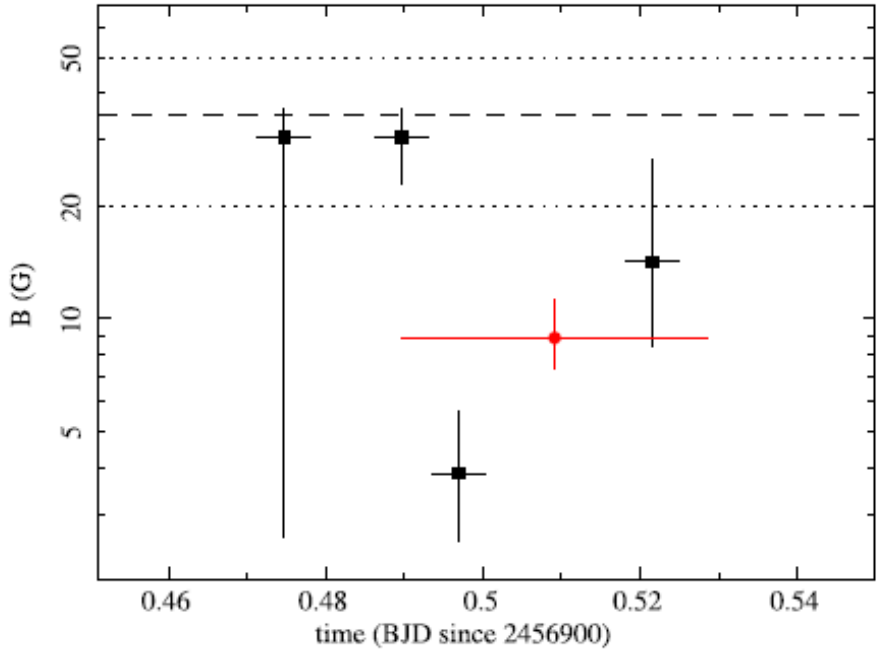
=> Evolution of Magnetic Field

Sgr A* 2014 Aug Flare SED at different phases



- NIR flare starts before & ends after X-Ray one
- NIR slope increases at low fluxes, X one steep at rise
- Can be due to variation of γ_{max}
- This implies variation of E_{br} and so of B (drop at peak)

  => **Flares powered by Magnetic Energy**



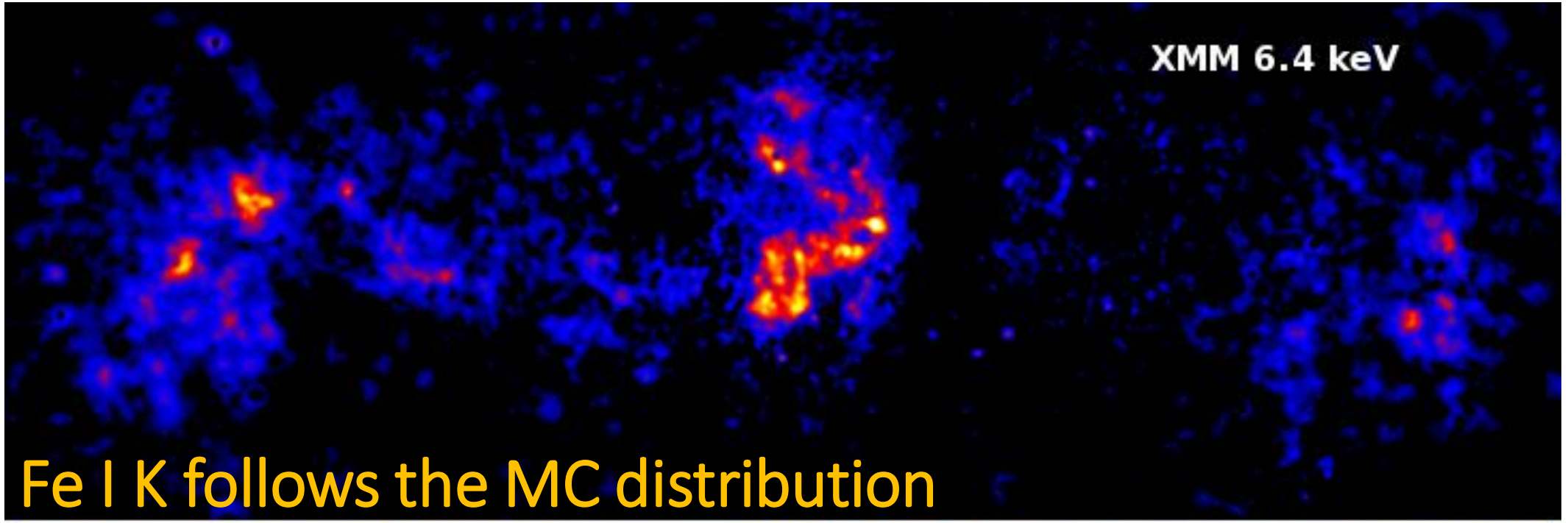
Traces of Sgr A* activity revealed by high energy emission from MC

- 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.

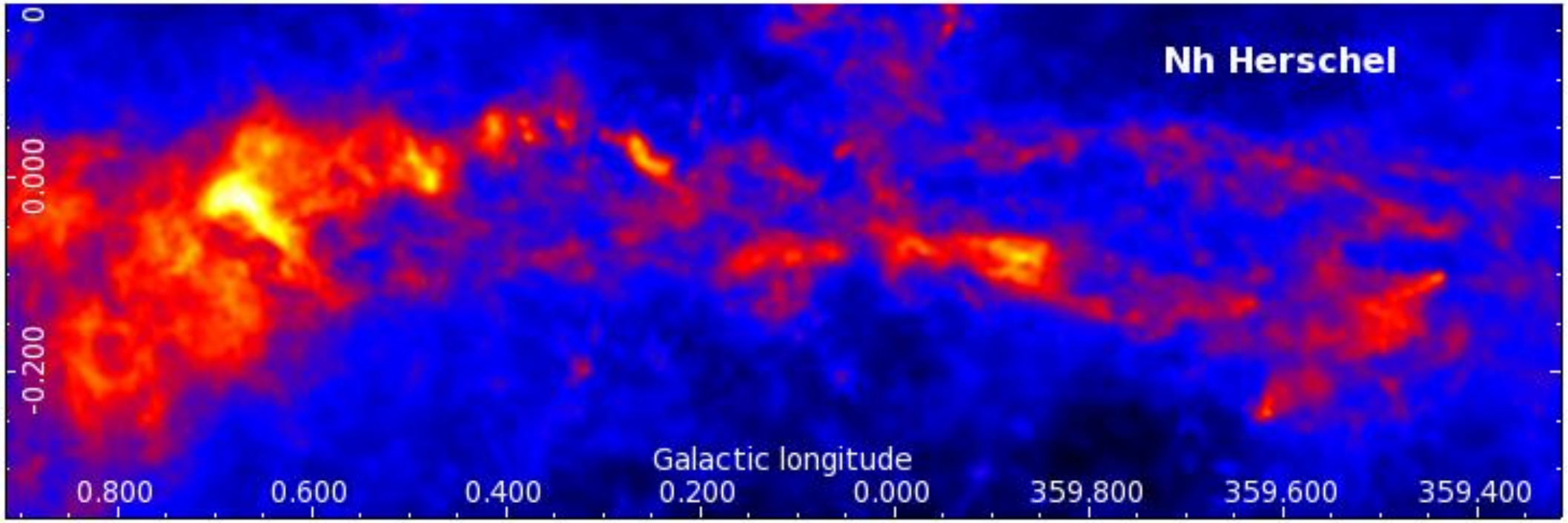
- **Traces of past intense activity in the GC region could be seen in the dense cold molecular clouds of the GC region that can act as mirrors reflecting the X-ray radiation that illuminates them.**

- **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, MC illuminated by same event lay on a parabola) => information on the past activity of illuminating source.**

- **Since discovery of diffuse 6.4 keV from GC MC by ASCA many works have presented obs. (Sgr B2 mainly, Chand, Suzaku, Integral, XMM) and theory of this process and pointed at the SMBH Sgr A* as illuminating source with peak Luminosity of 10^{39} erg/s in the past 100 – 300 yr (Koyama+ 1996, Sunyaev&Churazov 1998, Koyama+06,08 Inoui+07, Terrier 2010, ...).**

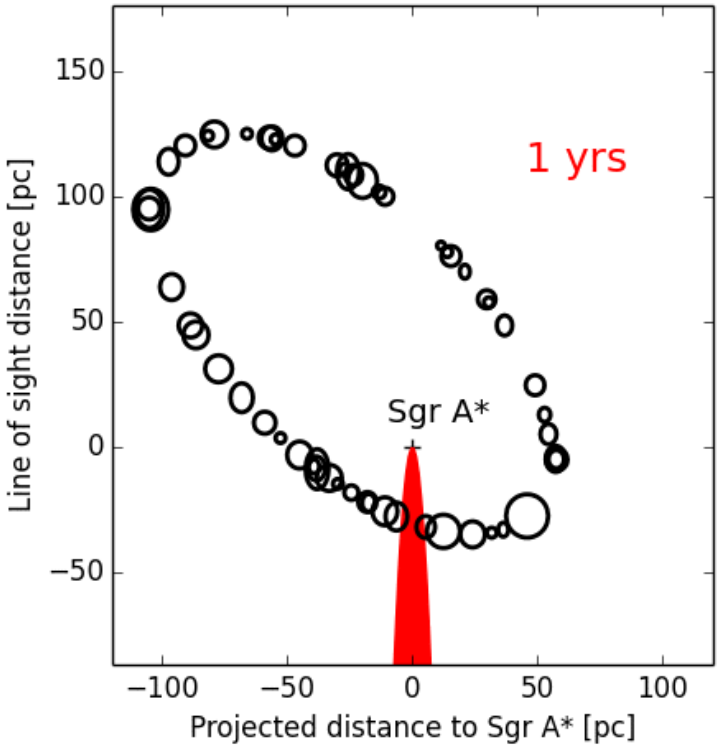


Fe I K follows the MC distribution

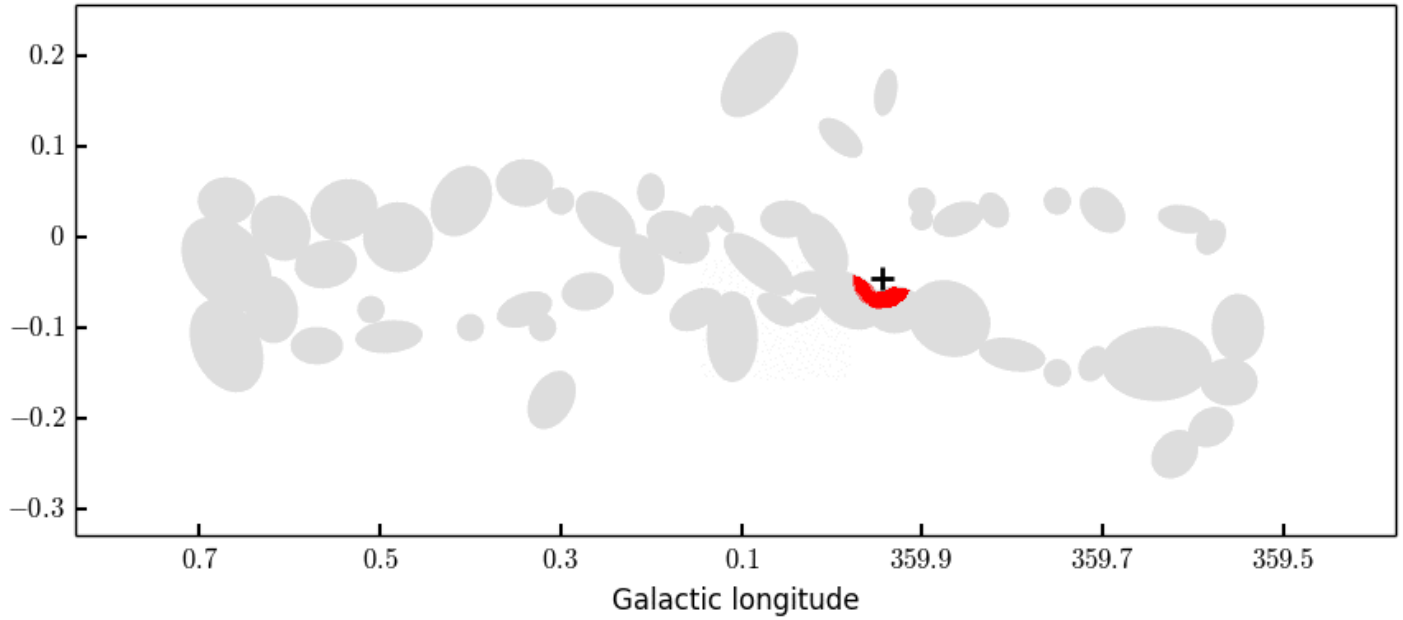


Propagation of an illuminating event from Sgr A* through a model of CMZ

Propagation seen from above the Galactic plane

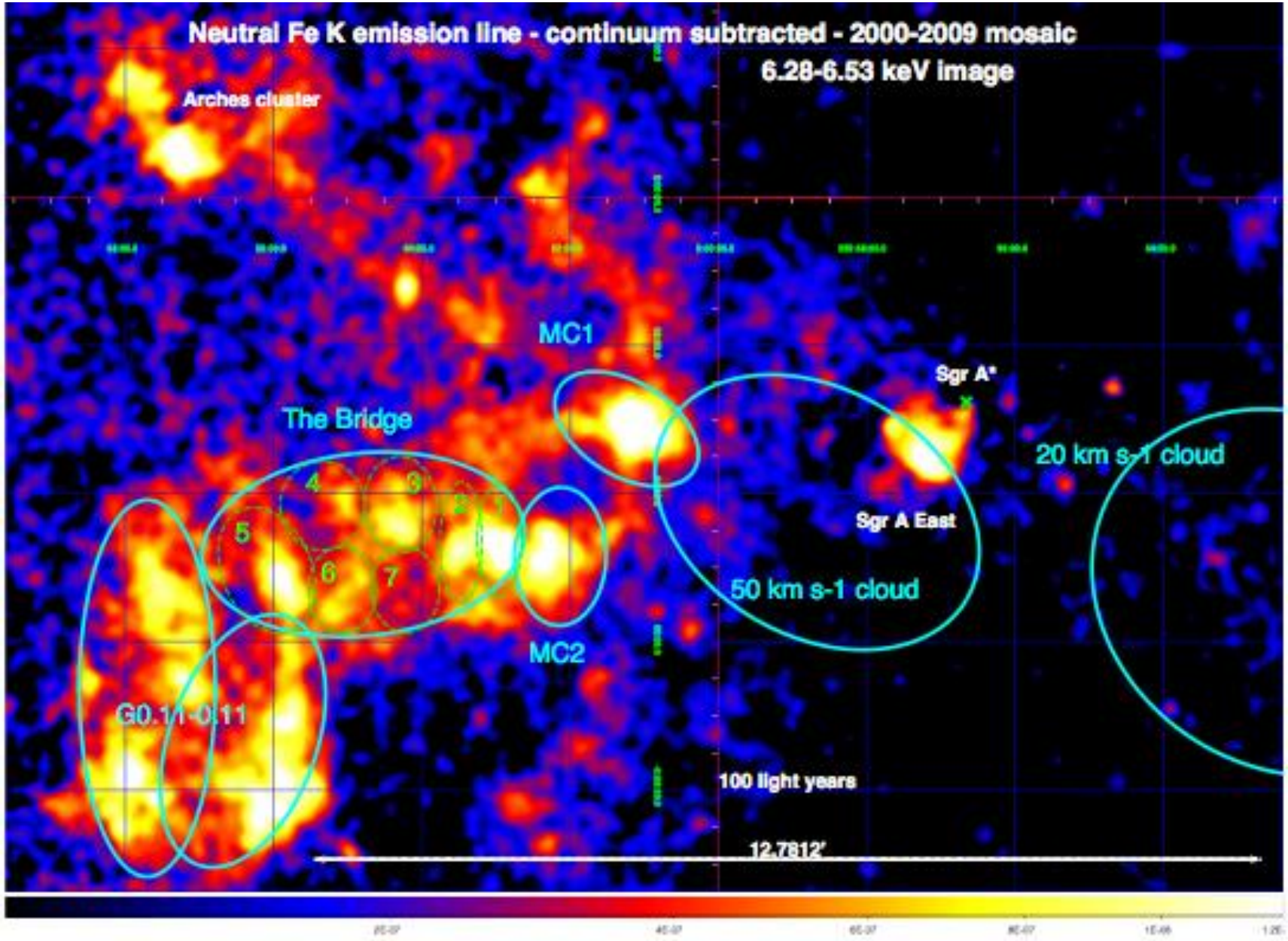


Reflected emission on the plan of the sky (as observed)

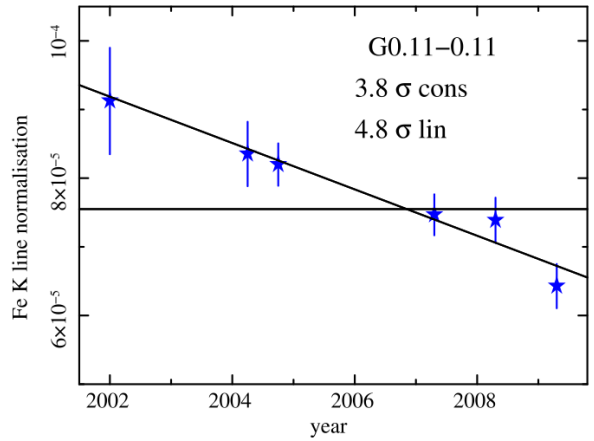


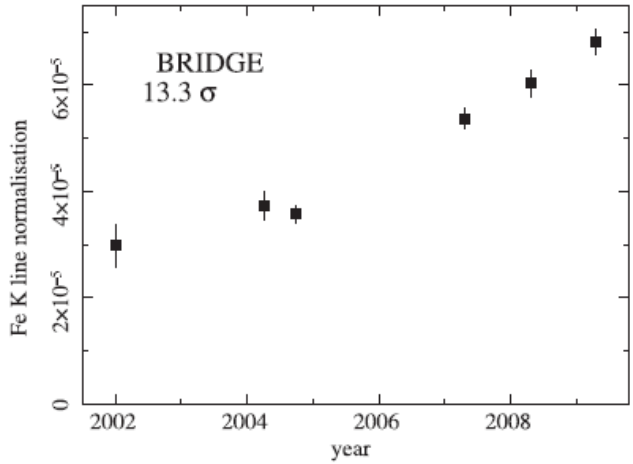
Courtesy of Maïca Clavel (PhD Thesis)

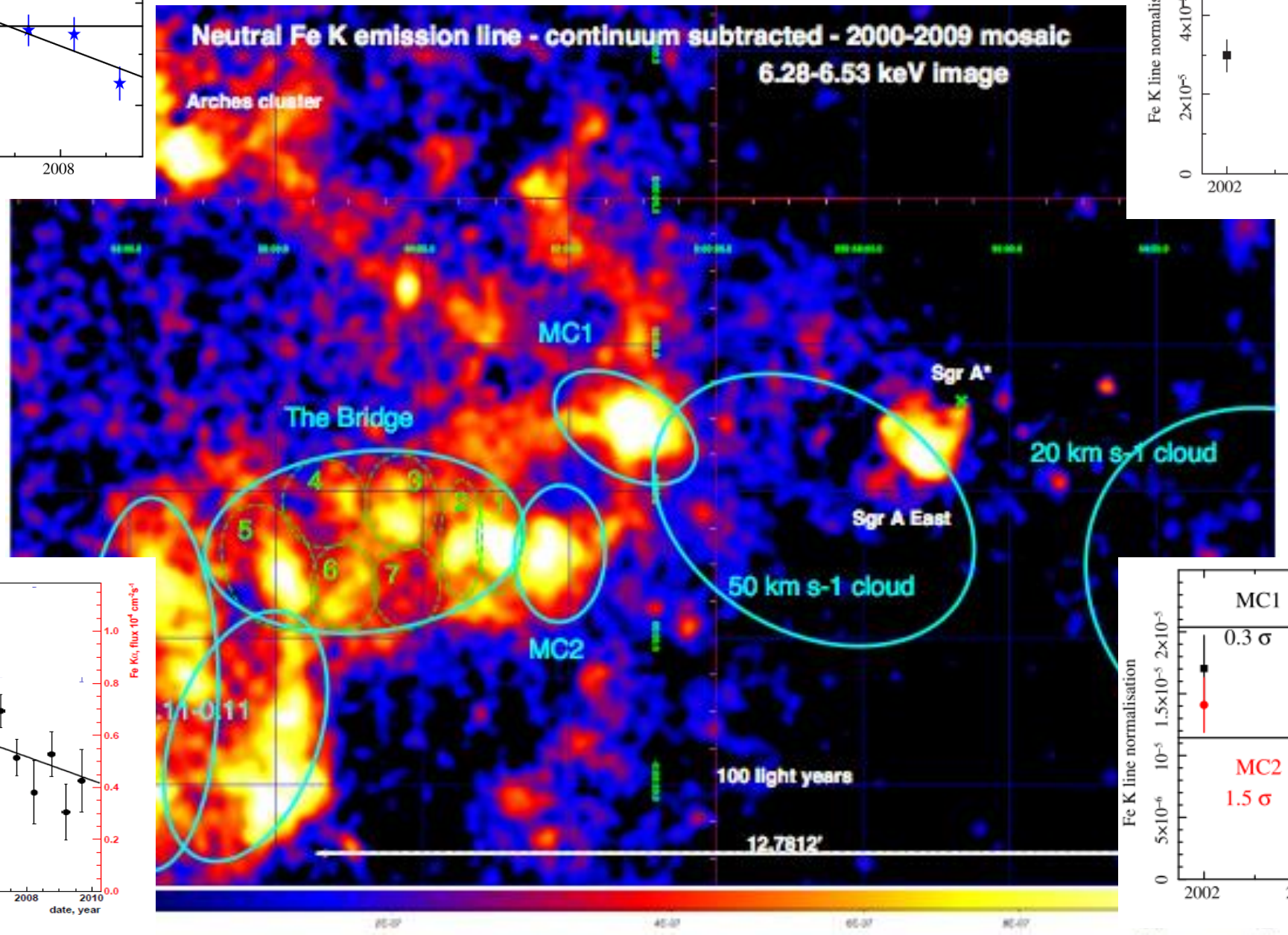
XMM-Newton results on Sgr A Complex in 2010

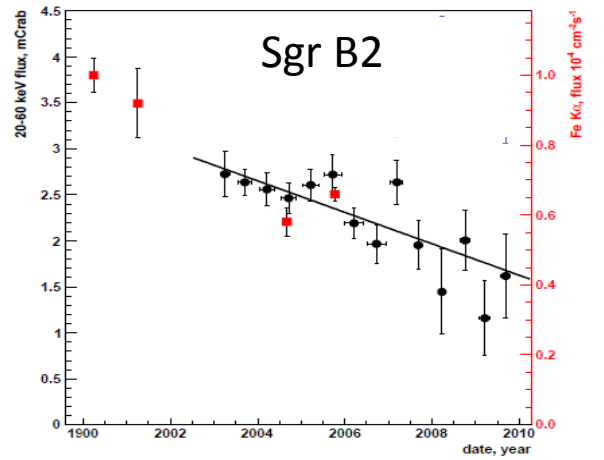


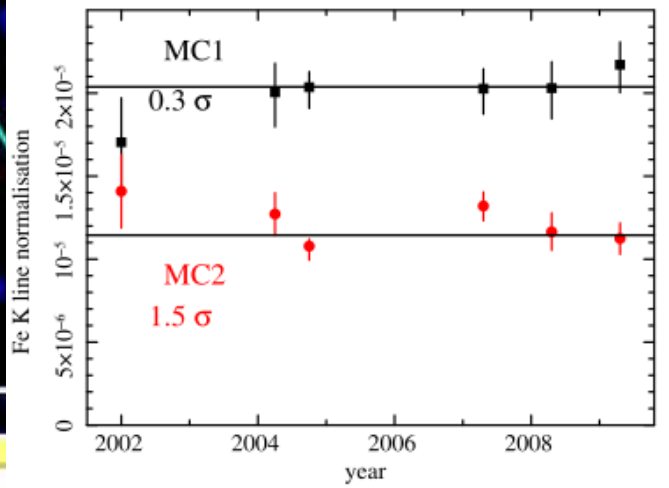
Ponti et al 2010


G0.11–0.11
3.8 σ cons
4.8 σ lin
Fe K line normalisation
year

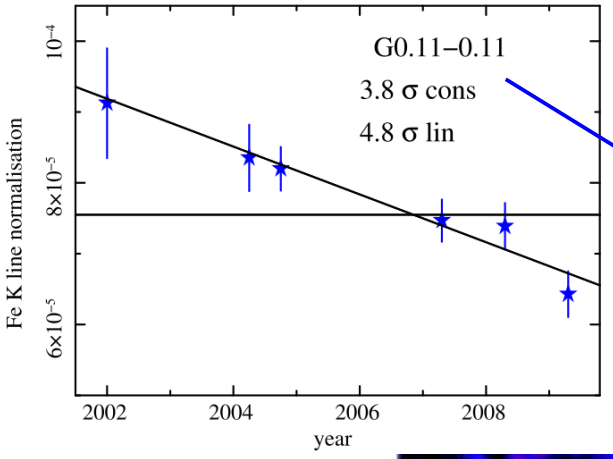

BRIDGE
13.3 σ
Fe K line normalisation
year

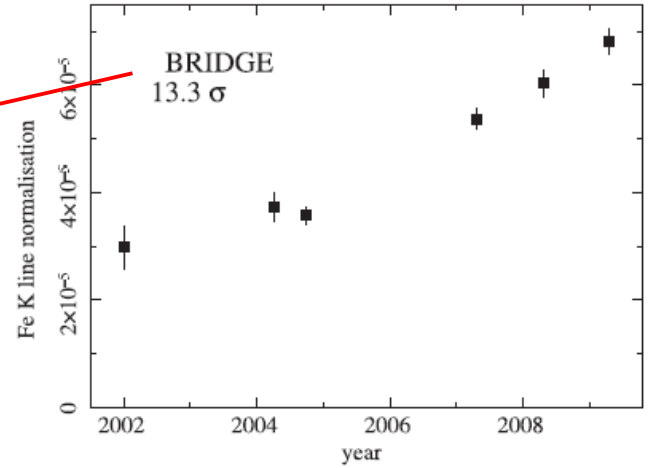

Neutral Fe K emission line - continuum subtracted - 2000-2009 mosaic
6.28-6.53 keV image
Arches cluster
MC1
The Bridge
Sgr A*
20 km s-1 cloud
Sgr A East
50 km s-1 cloud
MC2
100 light years
12.7812'

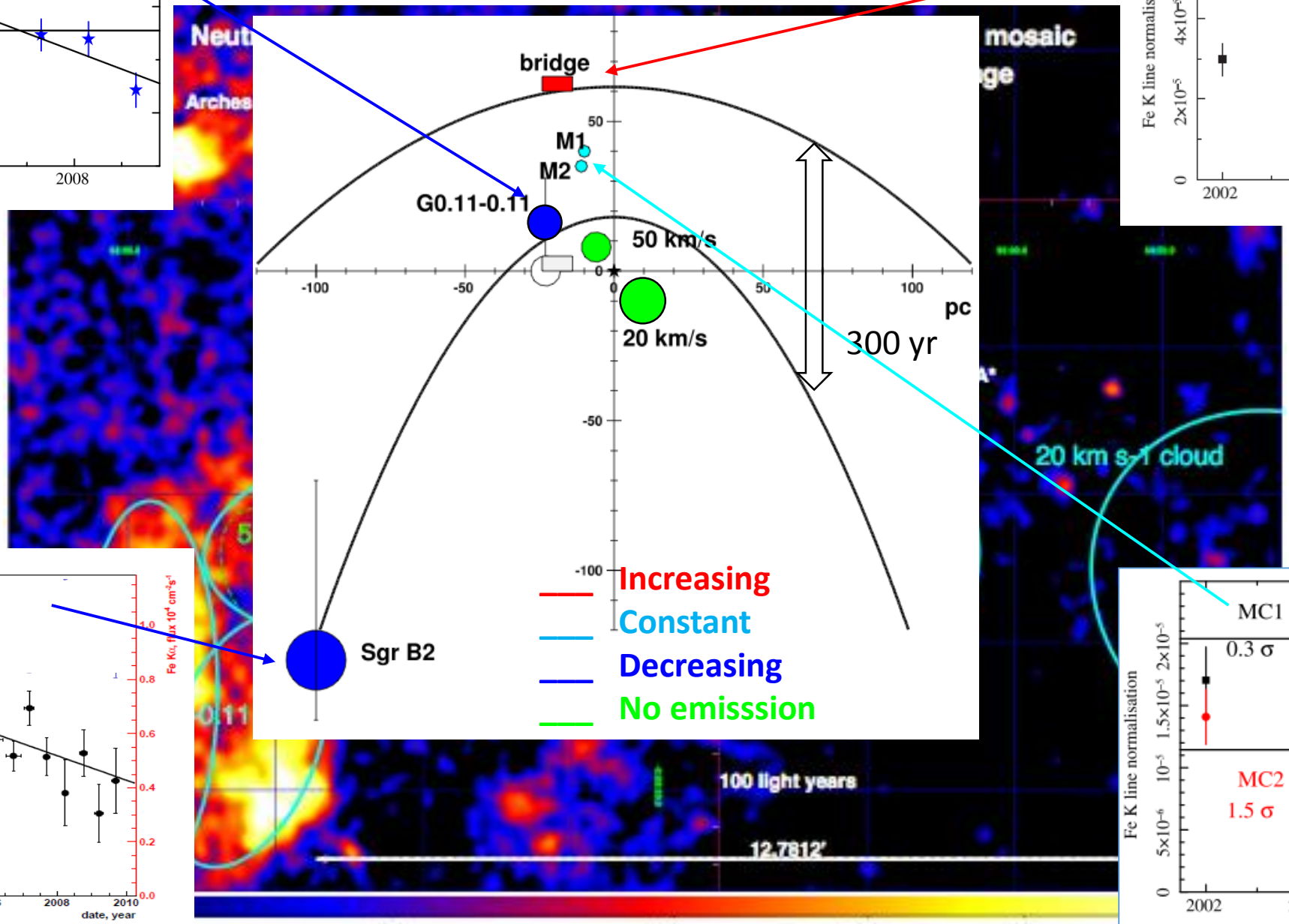

Sgr B2
20-60 keV flux, mCrab
Fe Kα, flux 10⁴ cm⁻²s⁻¹
date, year

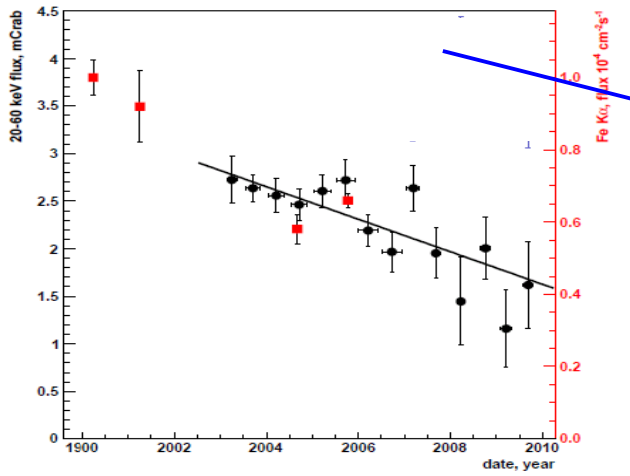

MC1
0.3 σ
MC2
1.5 σ
Fe K line normalisation
year

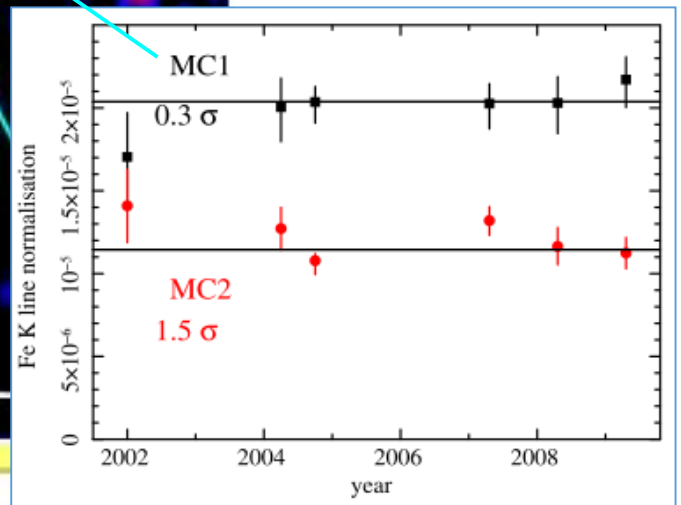
One 300 yr Outburst





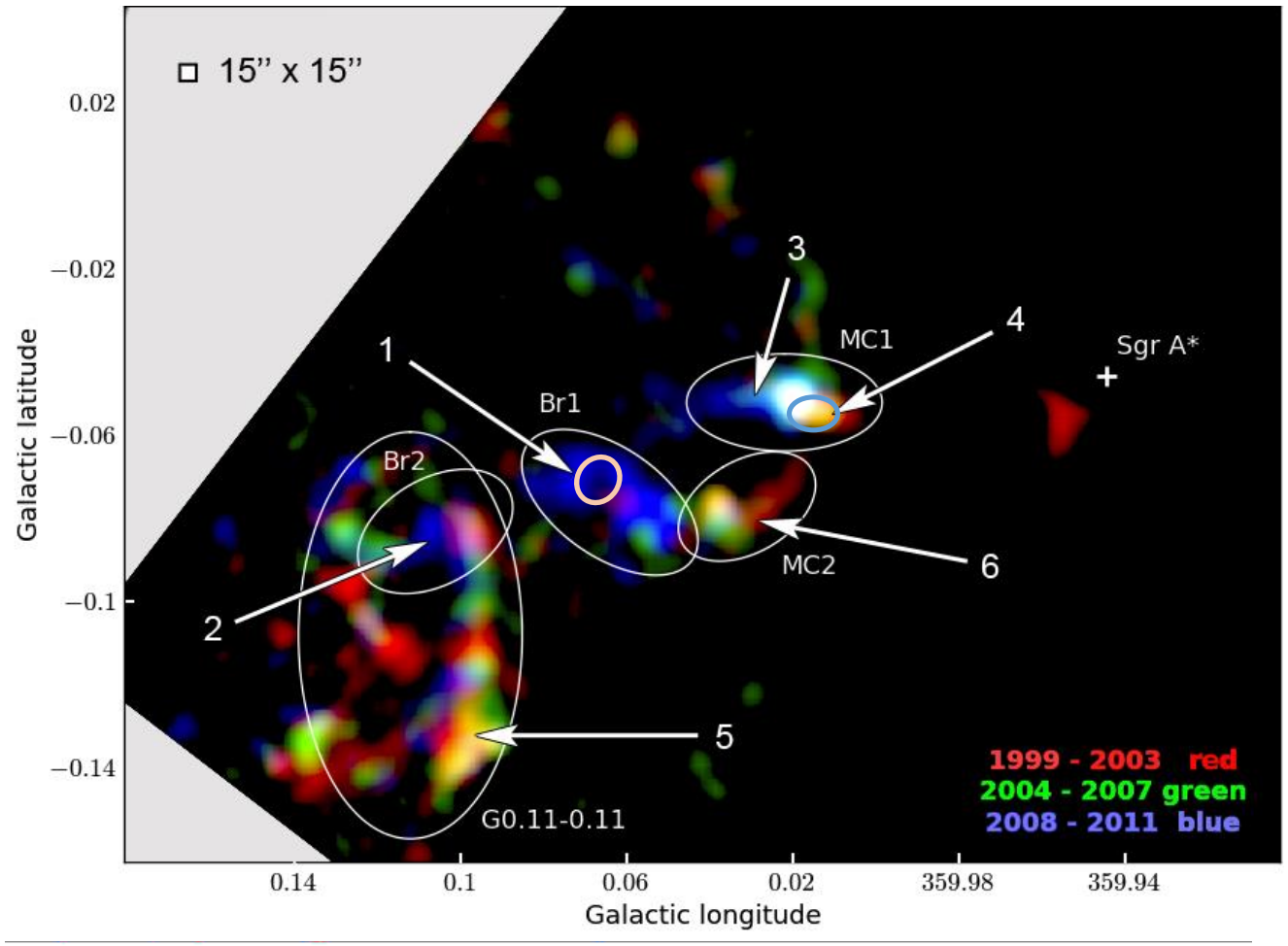


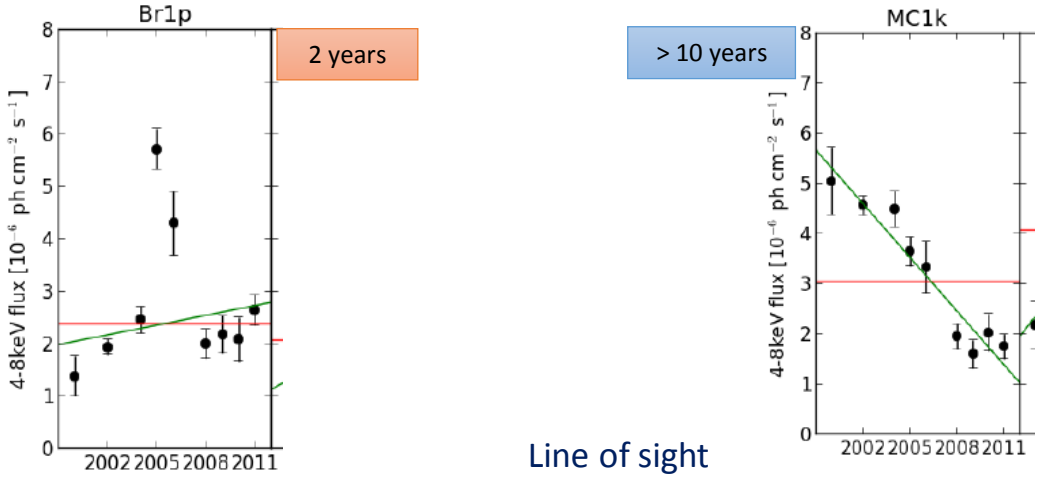


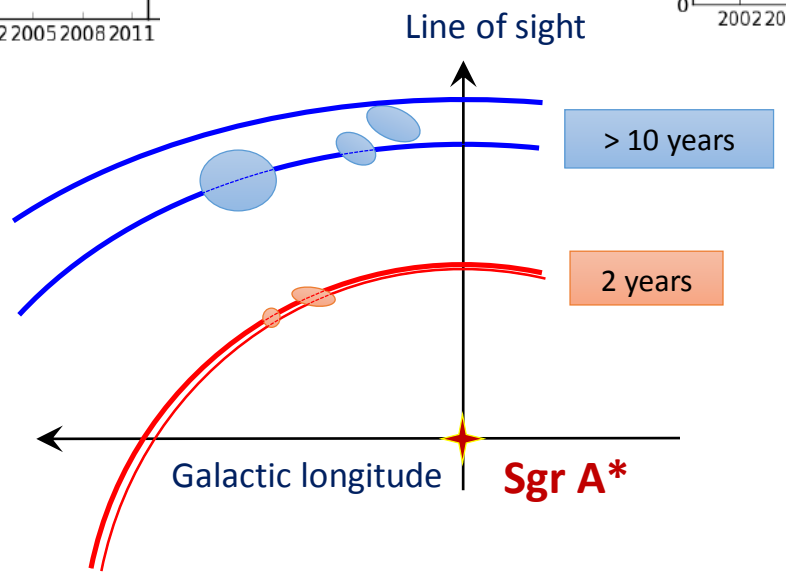


Ponti et al 2010
Terrier et al. 2010

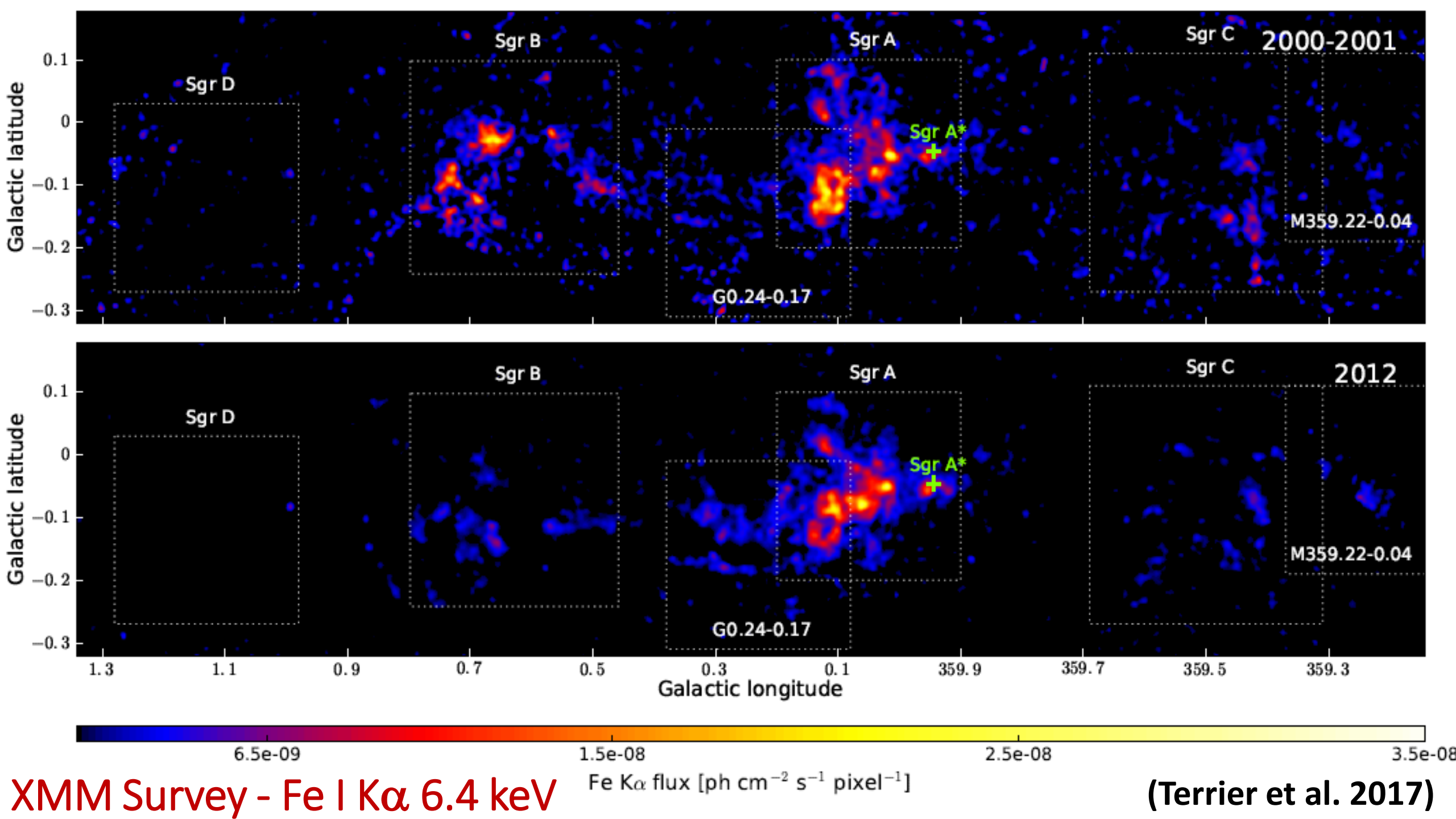
Chandra in 2013: multiple events







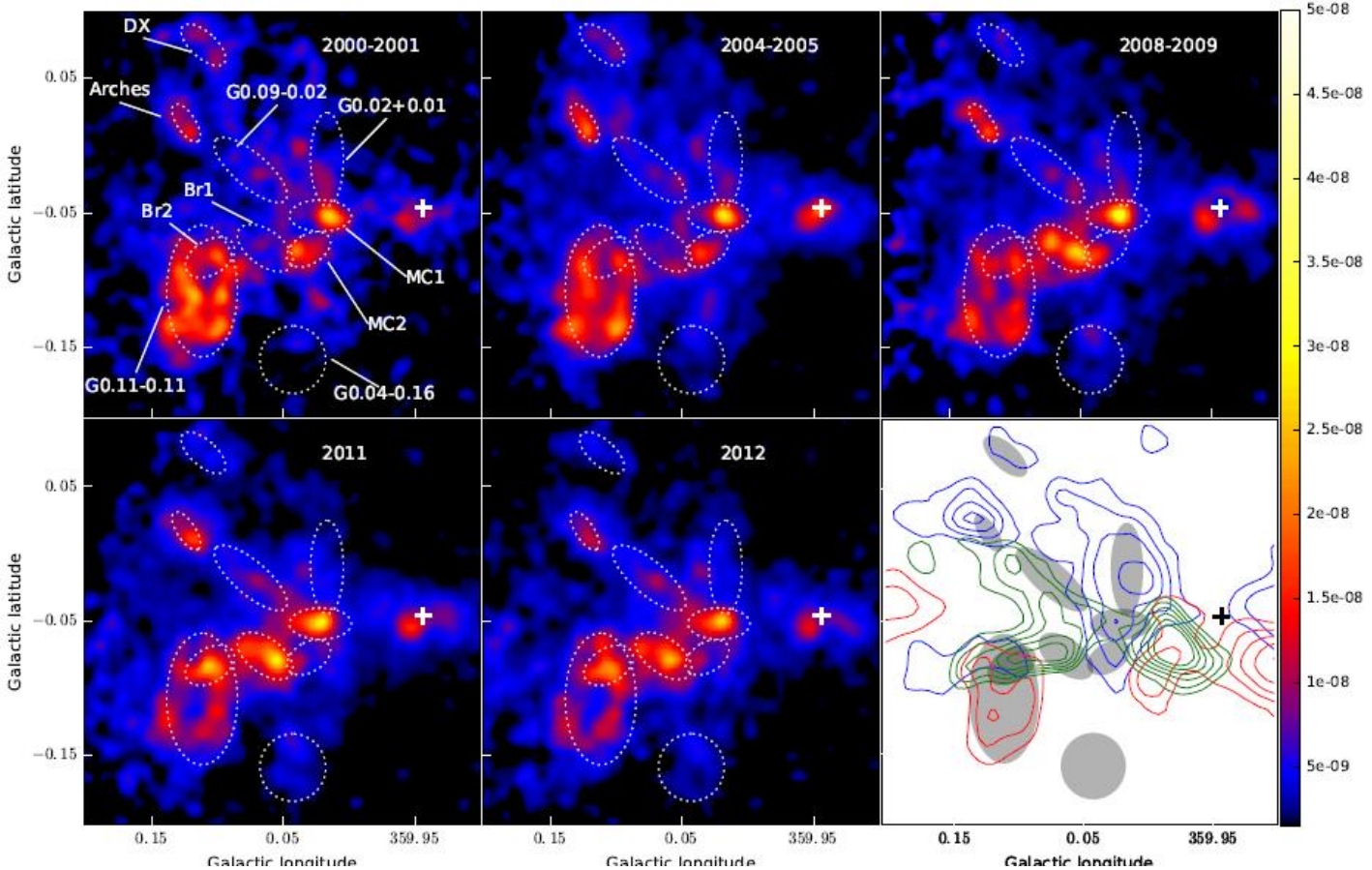
Chandra Survey 1999–2011: movie of 6.4 keV Iron K line variability from Sgr A molecular cloud clump structures. The data can be interpreted with the reflection of 2 bright events (10^{39} erg/s), one short (< 2 yr) and one longer (~ 10 yr) produced by Sgr A* in the past few 100 yrs **(Clavel et al. 2013)**



XMM Survey - Fe I Kα 6.4 keV

(Terrier et al. 2017)

Sgr A Complex



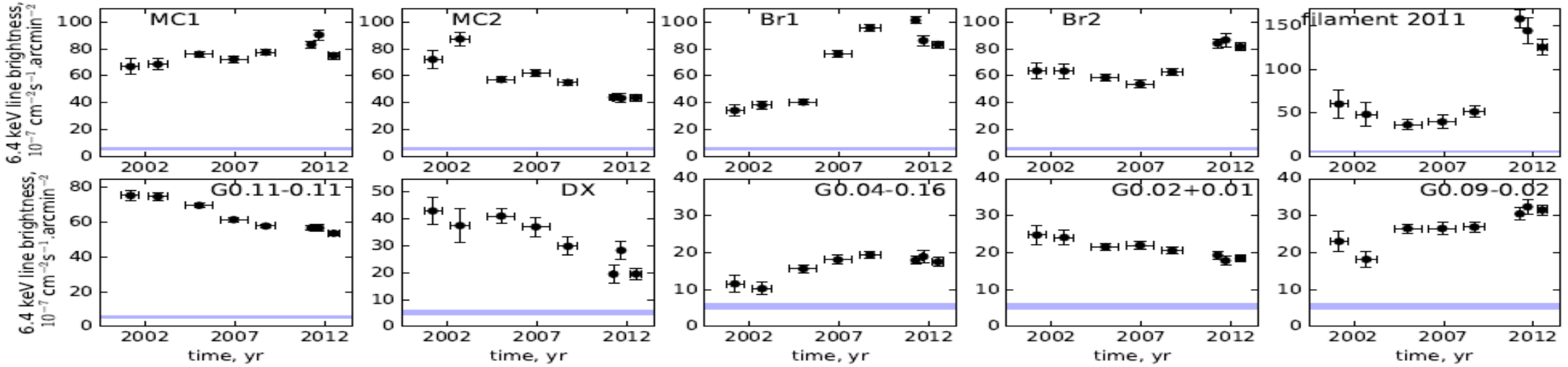
- Confirm two type of variability in this region, fast and slow
- Rapid variations from clouds with V_R in 40-70 km/s range: Br1, Br2, 2011 filament
- Trend as predicted by Clavel+2013

CS Mol line contours

-20 – 10 km/s

10 – 40 km/s

40 – 70 km/s

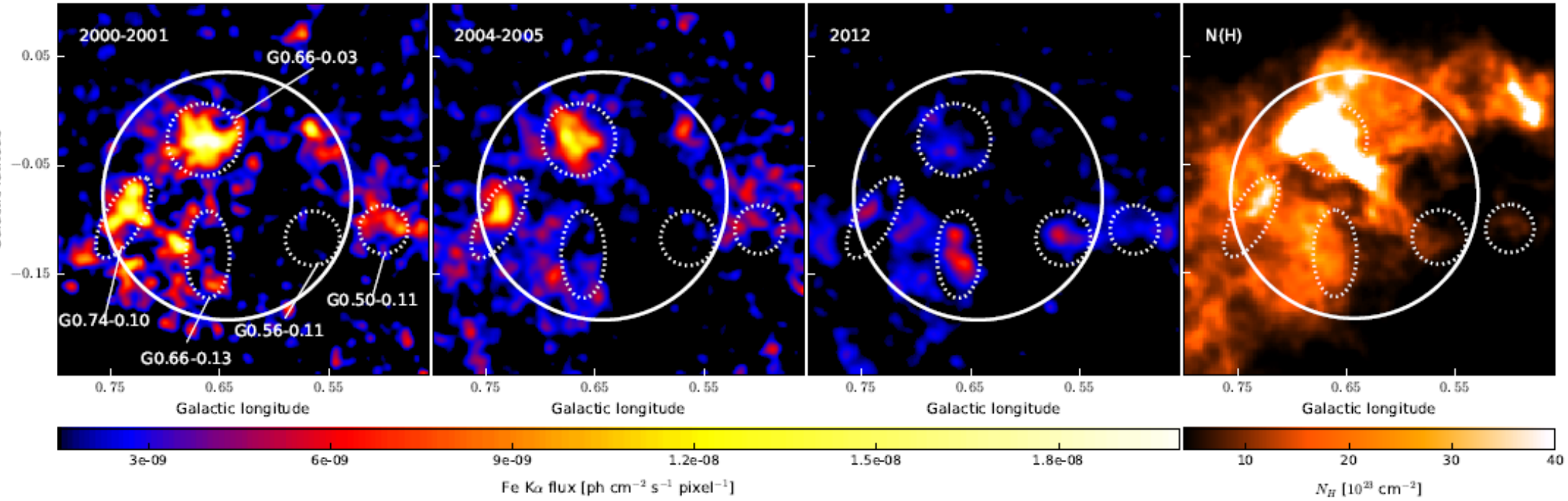


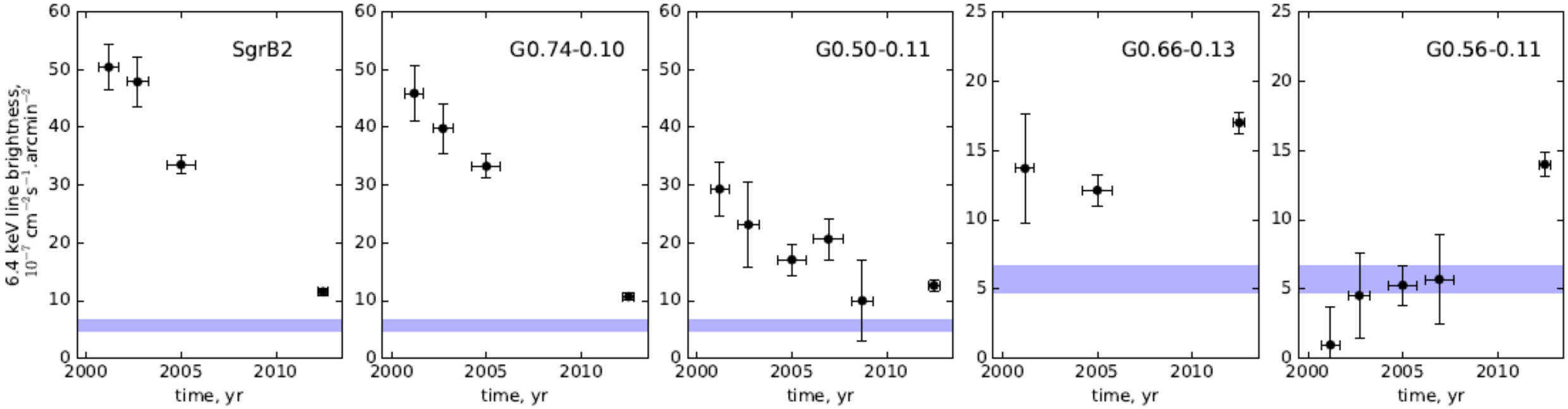
Sgr B2

Confirmed decaying trend for the cores

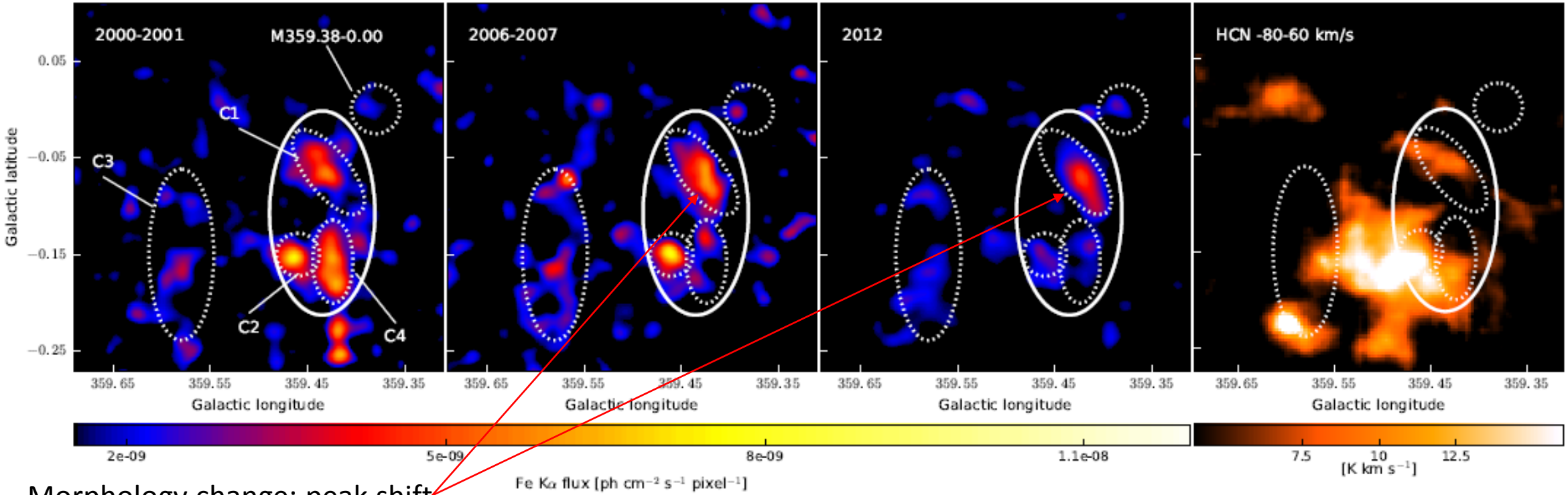
(See also Zhang+ 2015)

Two new increasing regions

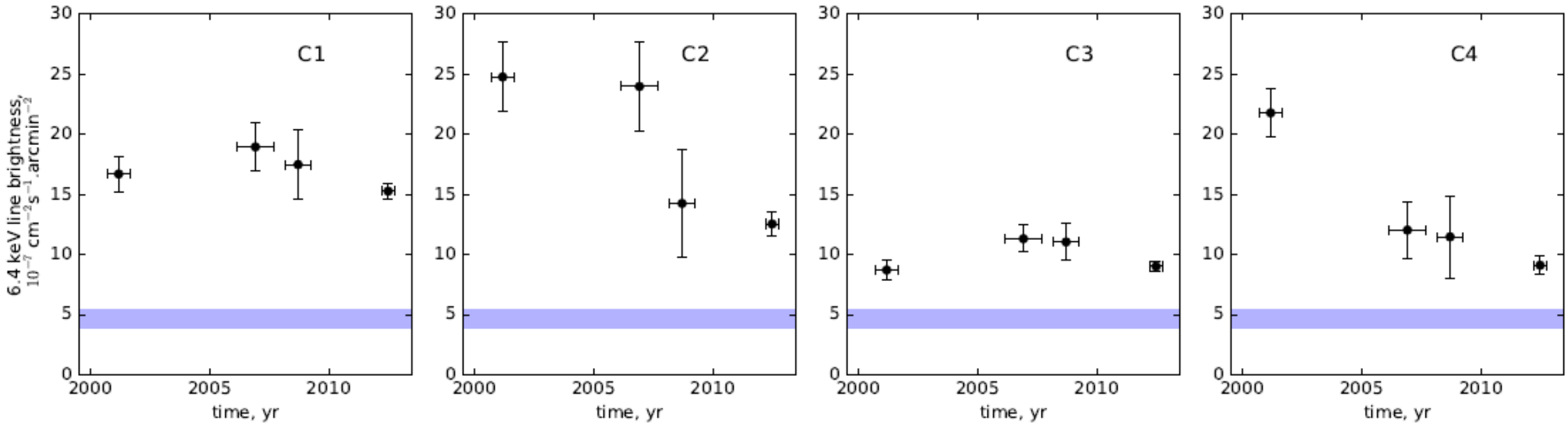




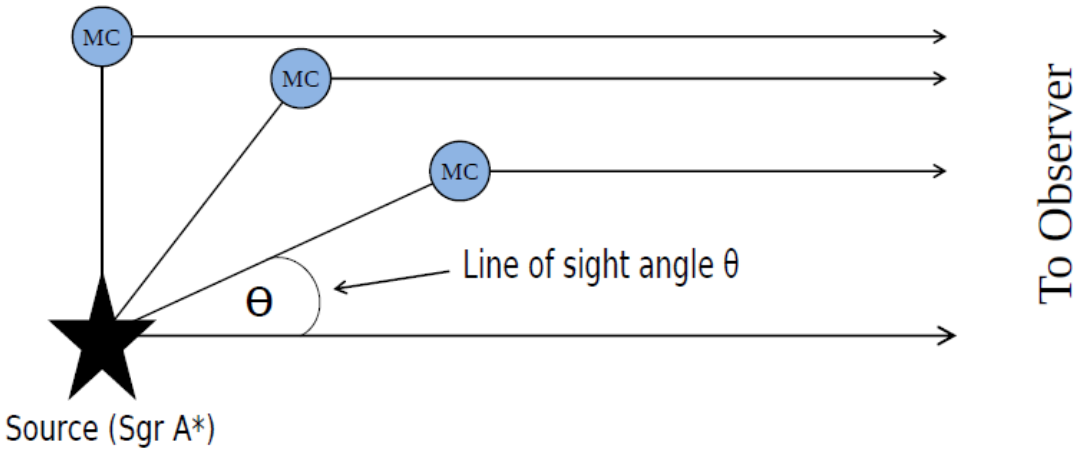
Sgr C Complex



Morphology change: peak shift

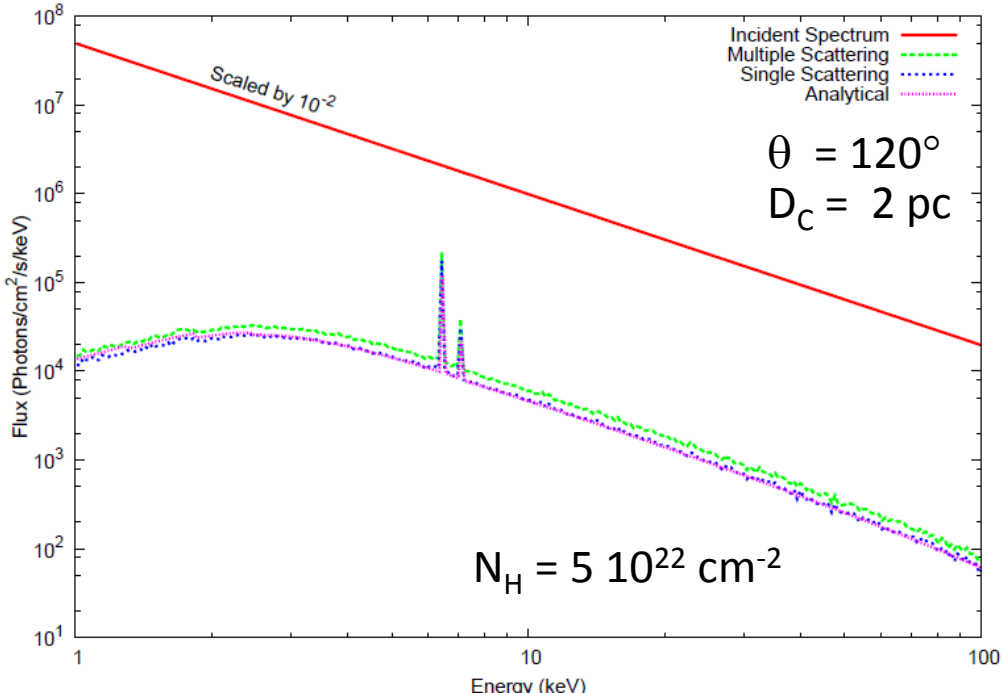


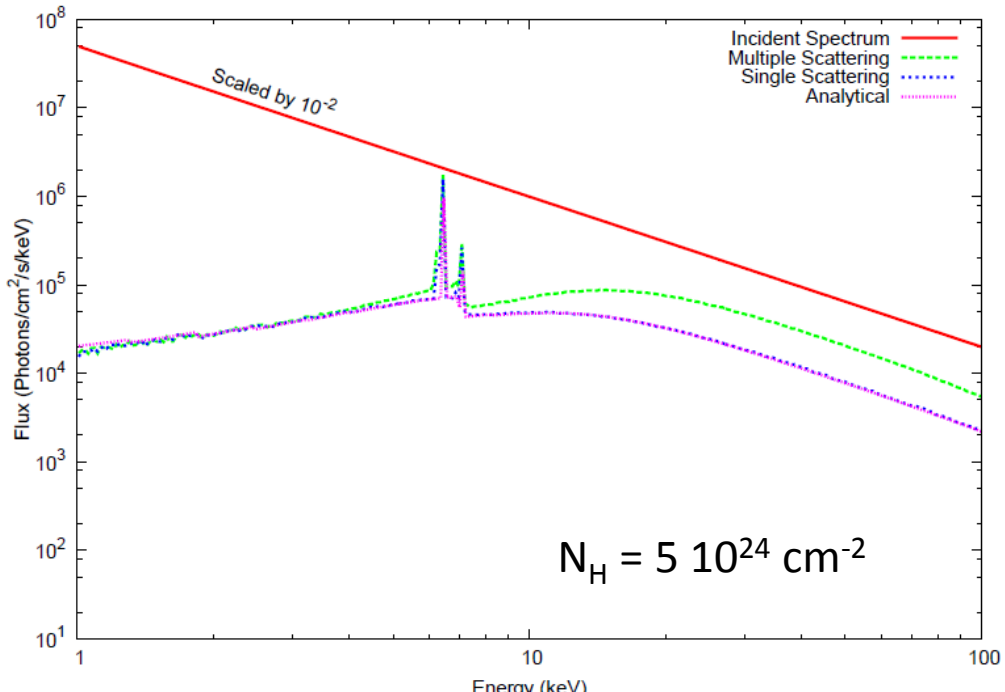
Monte Carlo Modeling of Reflection Spectrum



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

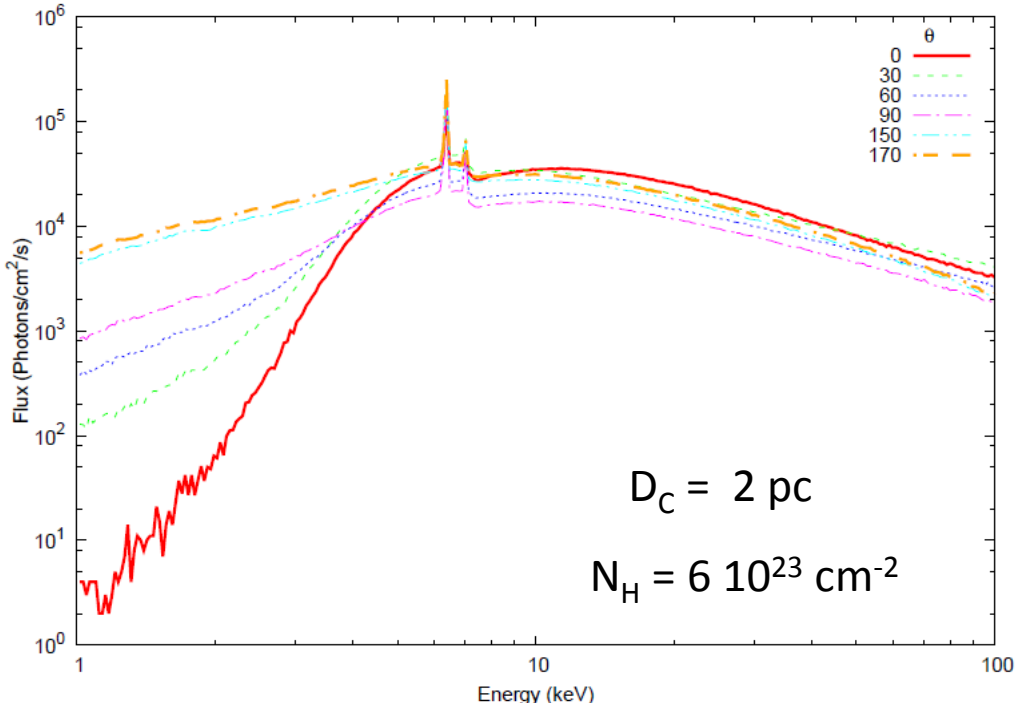
Walls et al. 2016



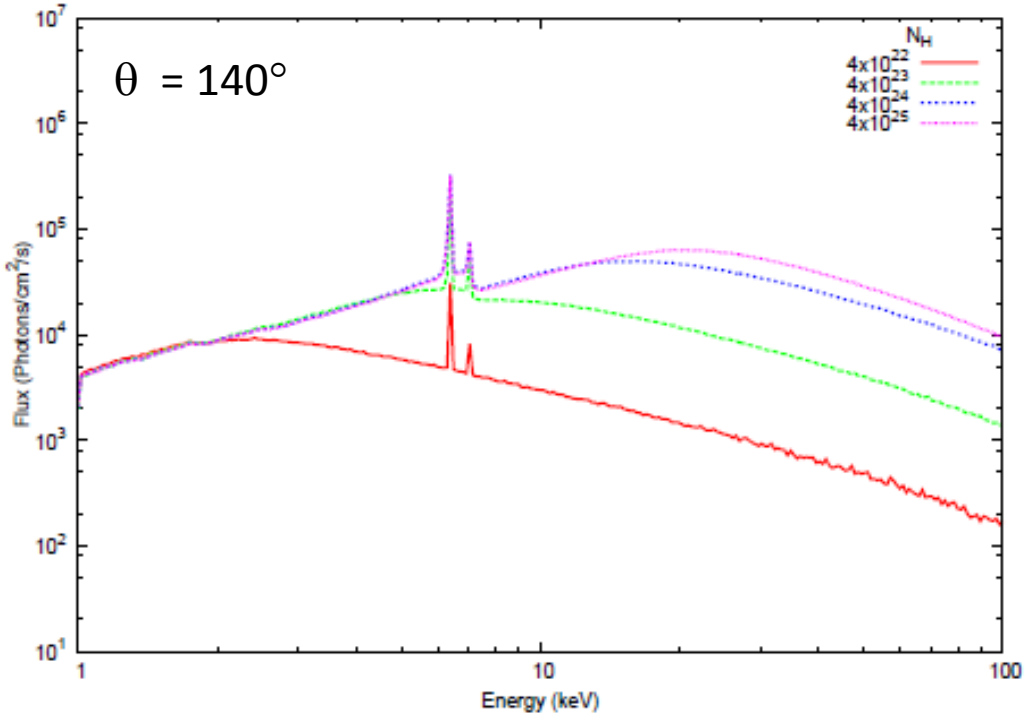


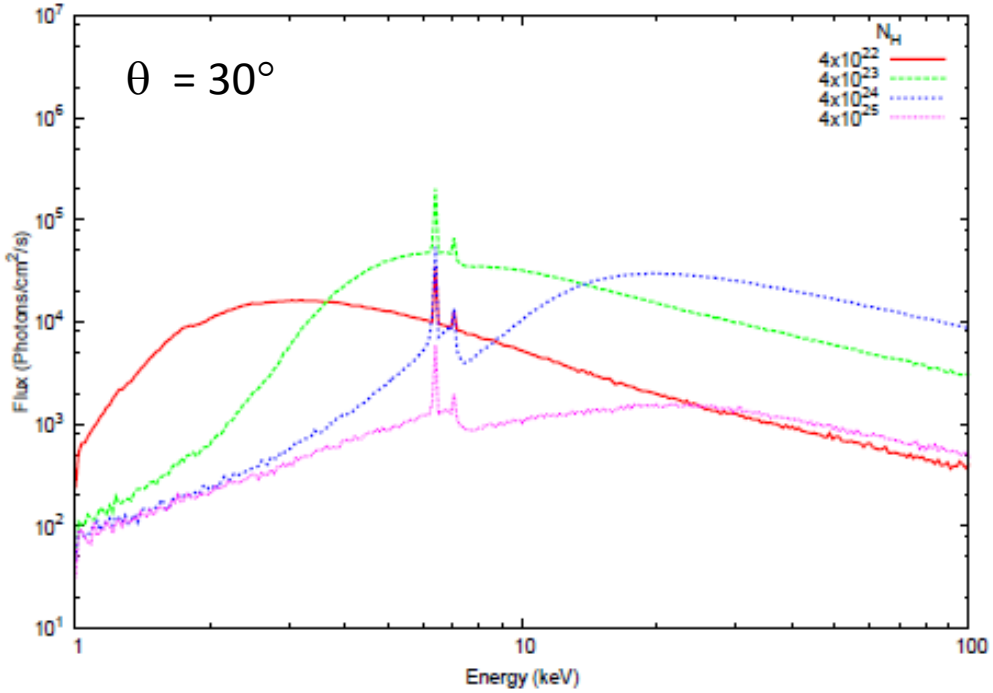
Dependence of Reflection Spectrum

- Scattering angle θ
- Column Density
- Both

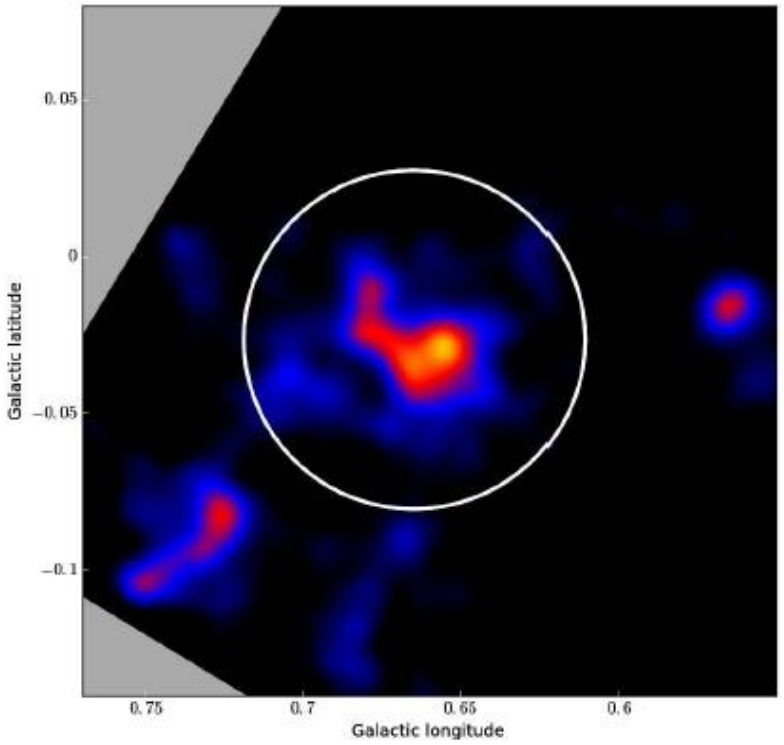


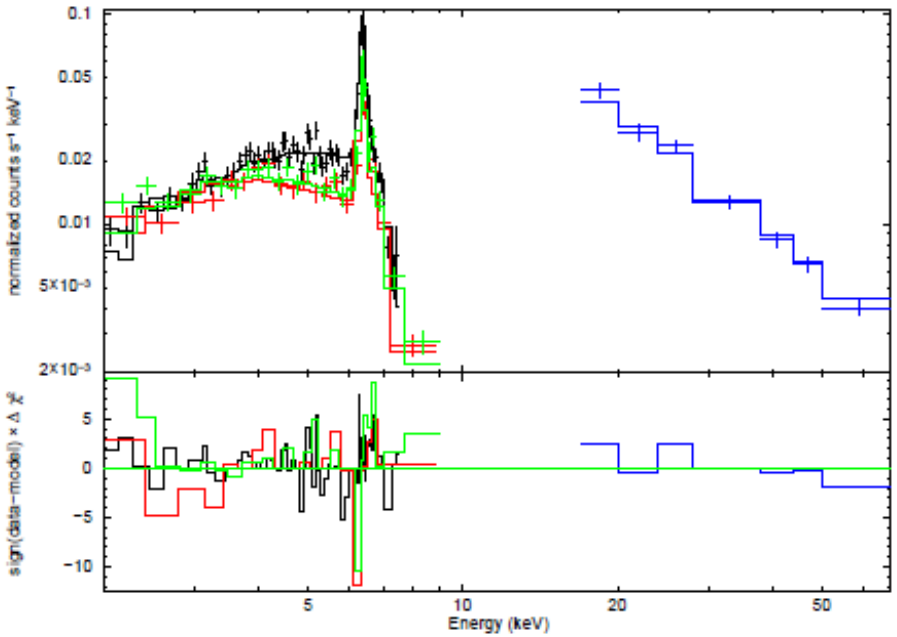
Walls et al. 2016





Fitting Model to Sgr B Data

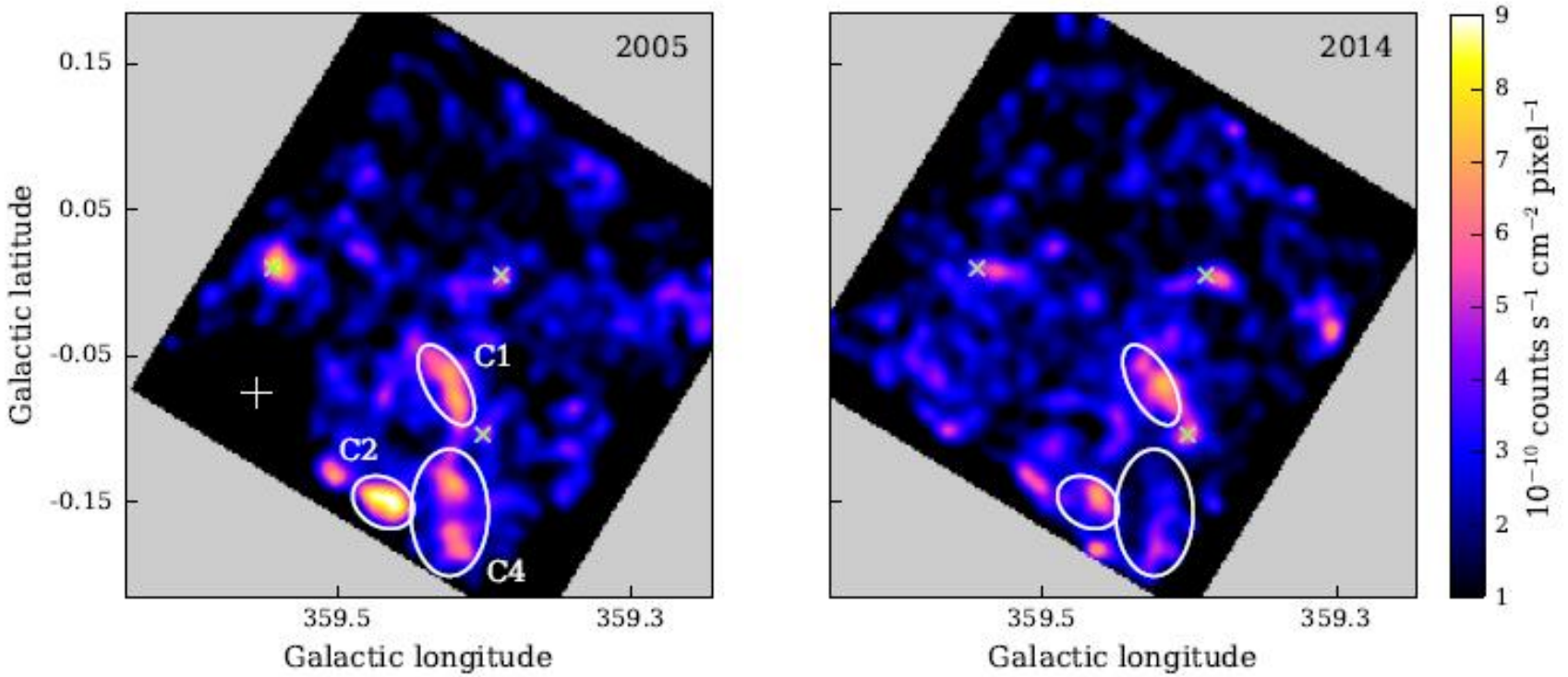


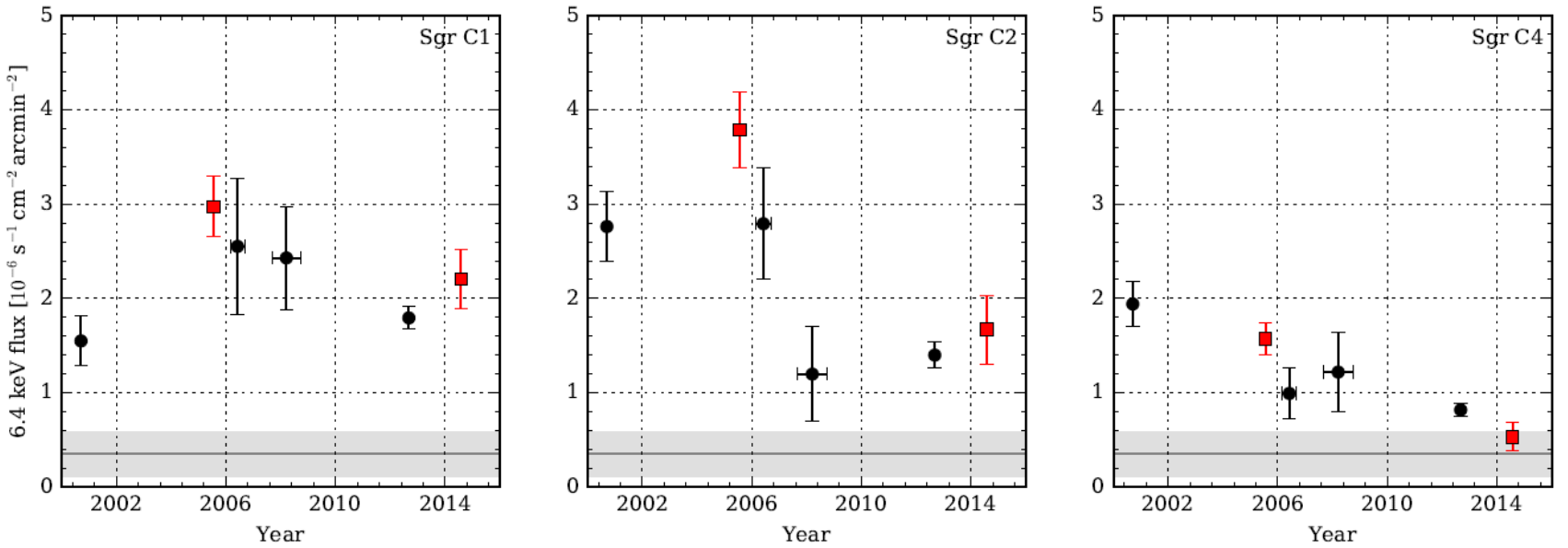


- MC model of reflected emission fitted to XMM, Chandra and Integral data of Sgr B2 (2010) along with 2 APEC for the 2 thermal components
- Uniform and Gaussian Cloud gaz distribution
- Fixed param: abundance, APEC kT (1 & 6.5 keV)
- Result: Sgr B2 is located at 48 pc in front of Sgr A* for const. distr. (at 0 pc for Gauss, but assuption of full illumination breaks down)
- Derived Luminosity ~ 10^{39} erg/s

Density Profile	θ $(10^{24} cm^{-2})$	N_H	Γ $(10^{22} cm^{-2})$	wabs N_H (keV)	kT 1 & 2	$\chi^2(dof)$
Constant	64^{+8}_{-7}	$2.13^{+0.28}_{-0.35}$	$2.16^{+0.12}_{-0.16}$	$6.31^{+0.9}_{-0.89}$	1 & 6.5	731 (618)
Gaussian	89^{+10}_{-11}	$2.5^{+0.43}_{-0.66}$	$1.83^{+0.06}_{-0.11}$	$6.79^{+0.78}_{-0.84}$	1 & 6.5	820 (618)

Sgr C Chandra Obs.

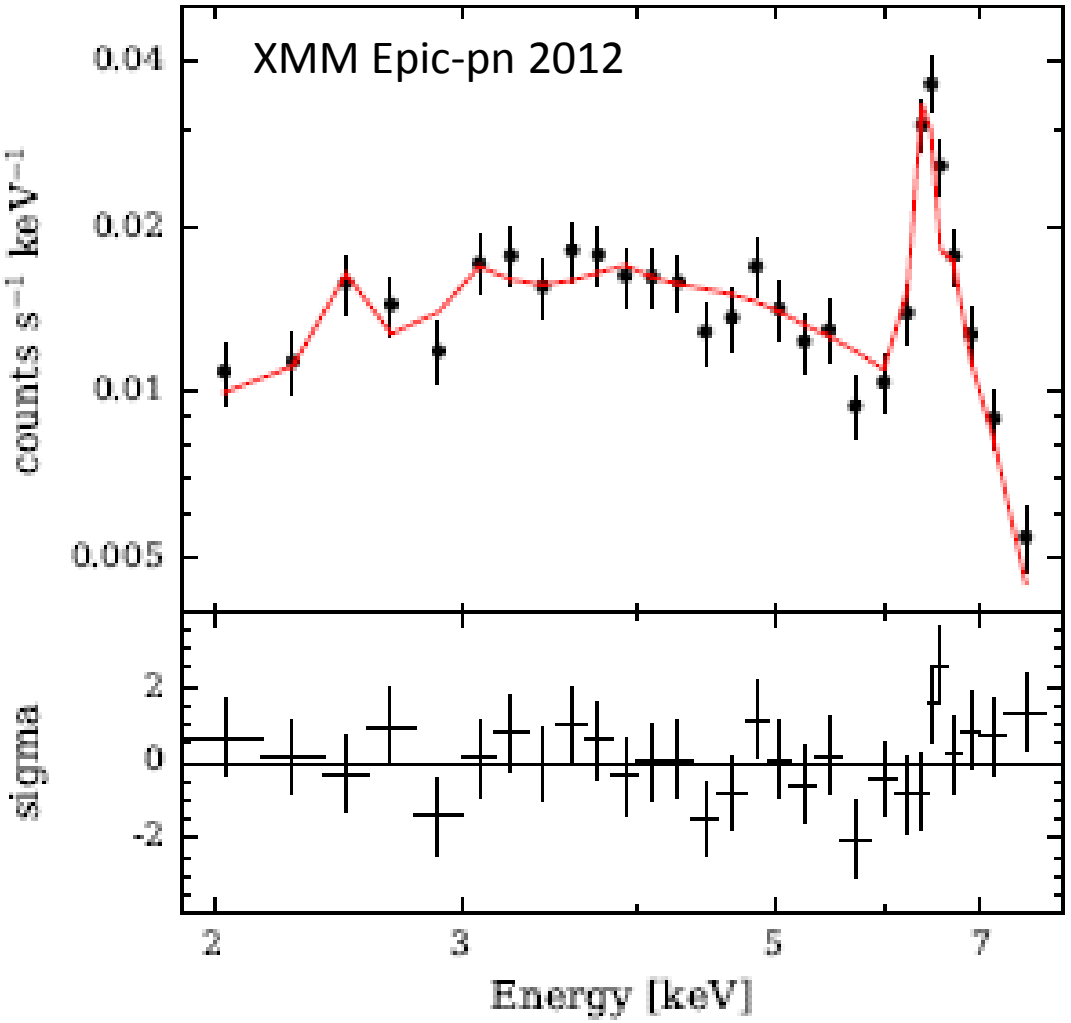




- Analysis of Sgr C Chandra Obs (200 ks 2005 & 2014)
- Fe 6.4 K line images
- Line flux light curves of 3 main molecular structures (C1, C2, C4) computed from spectra
- 200 ks XMM data points shown (15 yrs span)
- Variability with 2 time-scales: a rapid one for C2 (< 3 yr) and a longer (>10 yr) for C4 and (possibly) for C2

(Chuard et al. 2017 subm.)

Sgr C Reflection component: spectral analysis

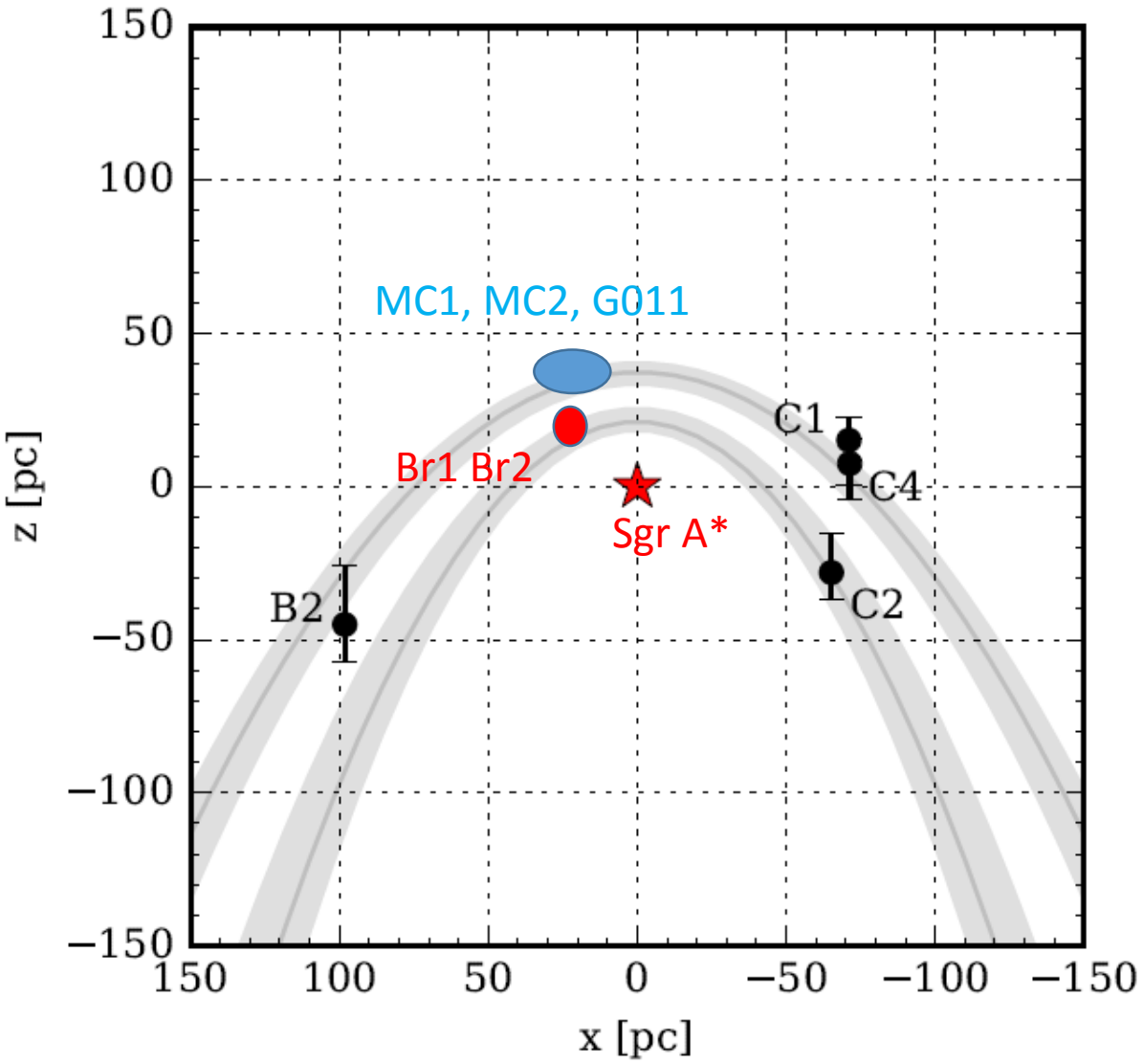


- Spectral analysis: fit data with model APEC(1keV) + APEC(6.5) + Ref(param), absorbed by ISM NH
- Reflection Sp. by MC model allows to derive the scattering angle of C1, C2, C4
- From these the position of the cloud and therefore time delay of the outburst can be derived

(Chuard et al. 2017)

Region	Angle (°)	N_H (10^{23}cm^{-2})	χ^2/d.o.f.
Sgr C1	$102.0^{+5.8}_{-11.5}$	$2.18^{+0.20}_{-0.37}$	423.6/372
Sgr C2	$66.7^{+9.9}_{-6.3}$	$7.0^{+1.2}_{-1.2}$	234.0/206
Sgr C4	$96.0^{+6.2}_{-9.5}$	$1.63^{+0.12}_{-0.13}$	436.2/420

Sgr C Reflection emission: derived parameters



- C1 and C4 position are behind the Sgr A* plane, C2 in front
- The long event illuminating C1 C4 is emitted 243 +20/-25 yr ago and is compatible with the one illuminating Sgr B2
- C2 experiences a short flare emitted 138 +27/-17 yr ago
- These results compatible with previous findings (Terrier+17)
- Not with Riu+2011 because they neglected scattering angle effect

Predictions:

- If MC1, MC2 G011 see C1C4 event => their should be at z = +37 +36 +34 pc
- If Br1, Br2 see the C2 event => they should be at z = +18 +15 pc

Conclusions

- We carried out **the first fully simultaneous spectral obs. in X and in NIR** of a very bright Sgr A* flare: **Synchrotron with cooling break**
- Evidence of spectral evolution (γ_{max}, cooling break) indicates a drop of magnetic field at the peak => **Magnetically driven particle acceleration**
- The CMZ XMM survey results on reflected emission indicate all main MC structures vary so no century long outpburst, rather variations show **at least 2 events with different time scales propagate in CMZ**
- Using Monte Carlo spectral modelling on Chandra data of Sgr C allowed us **to locate the clumps and to date the two events**
- Further work is in progress to establish X-ray emission of Sgr A* in the last millenium and search for other traces of the SMBH past activity

Present and past high-energy activity of SMBH at the Center of the Galaxy

Thanks