

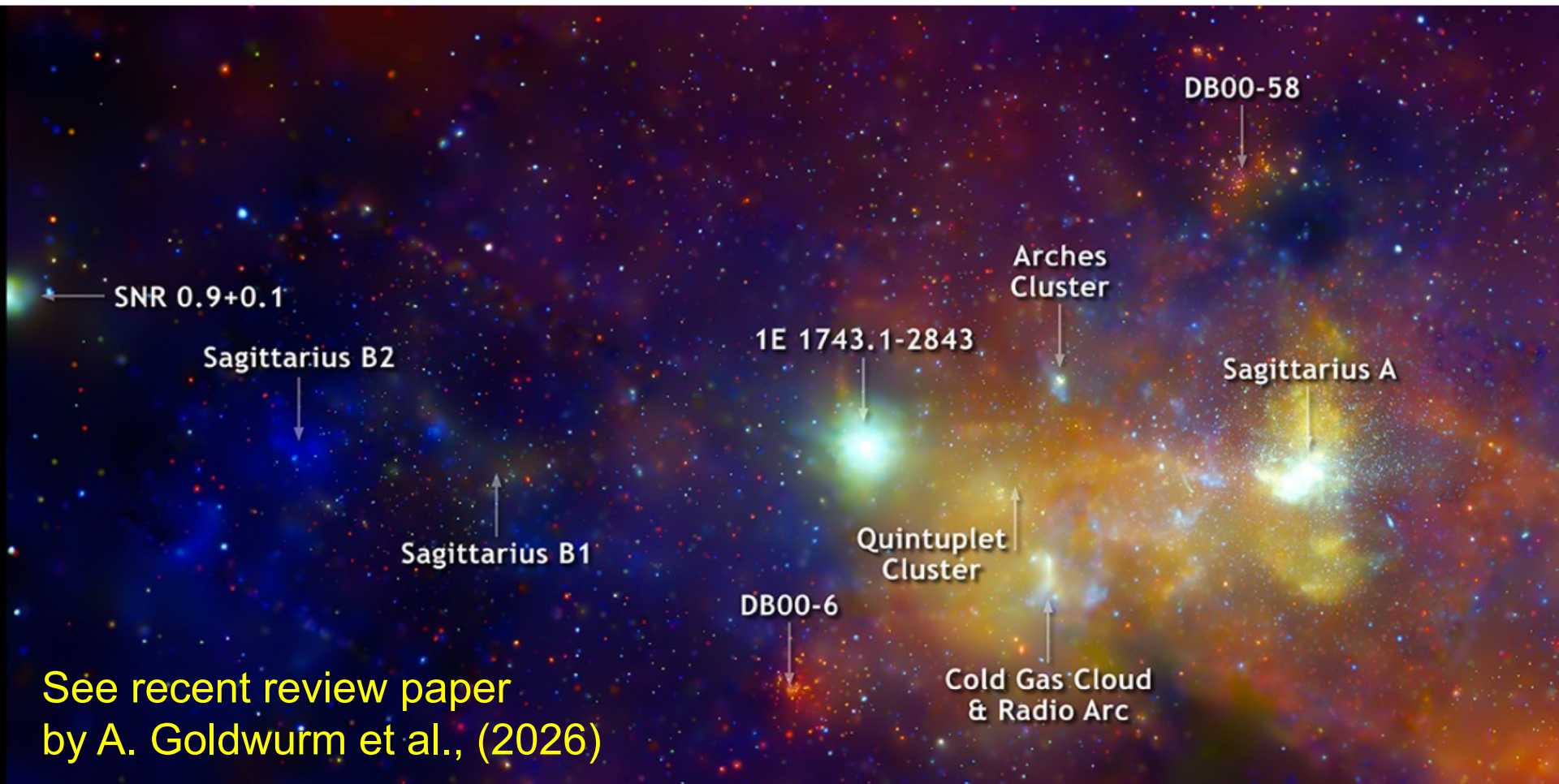
# X-ray emission from the Galactic Center

Roman Krivonos

Space Research Institute (IKI), Moscow, Russia

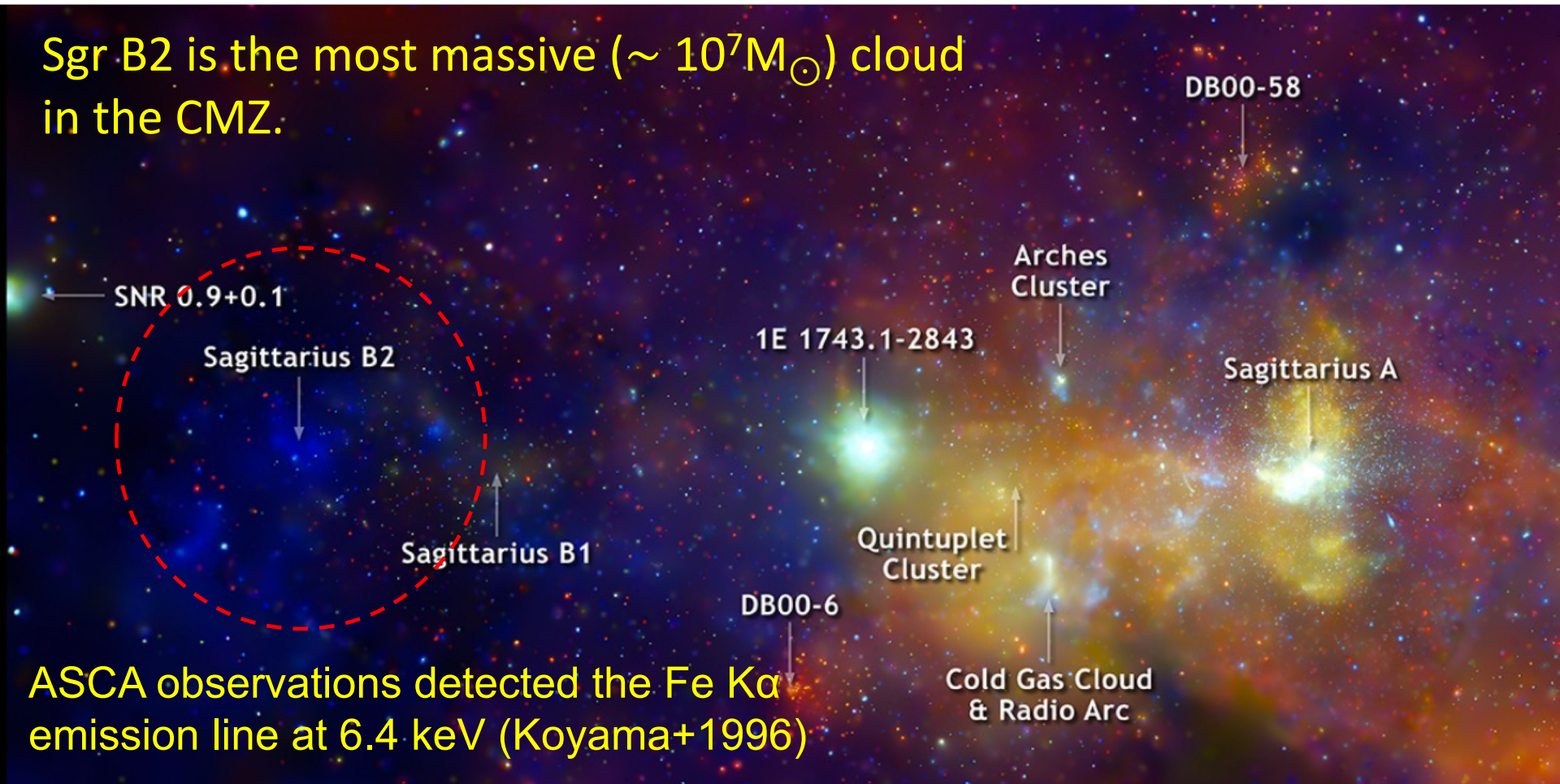
# Galactic Center in X-rays

---



# Sgr B2 molecular cloud

Sgr B2 is the most massive ( $\sim 10^7 M_{\odot}$ ) cloud in the CMZ.

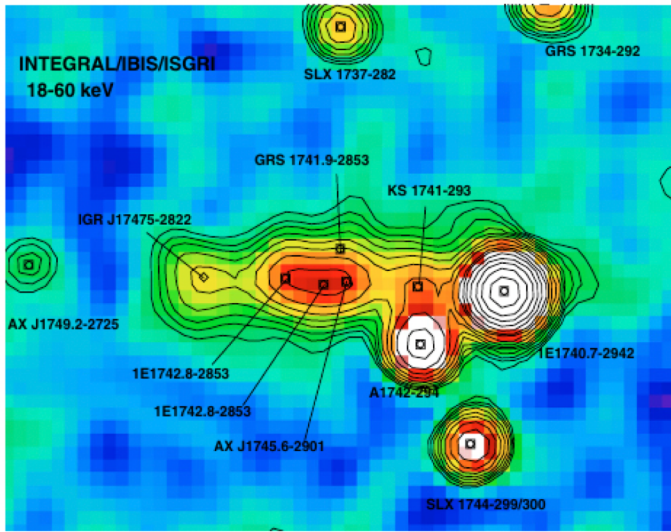


ASCA observations detected the Fe K $\alpha$  emission line at 6.4 keV (Koyama+1996)

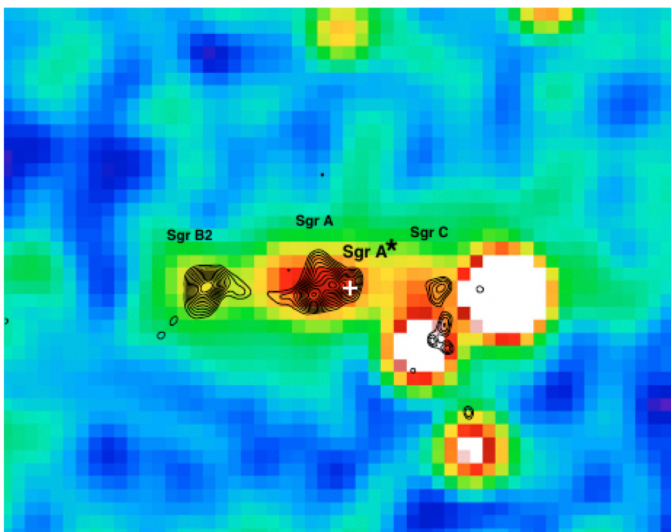
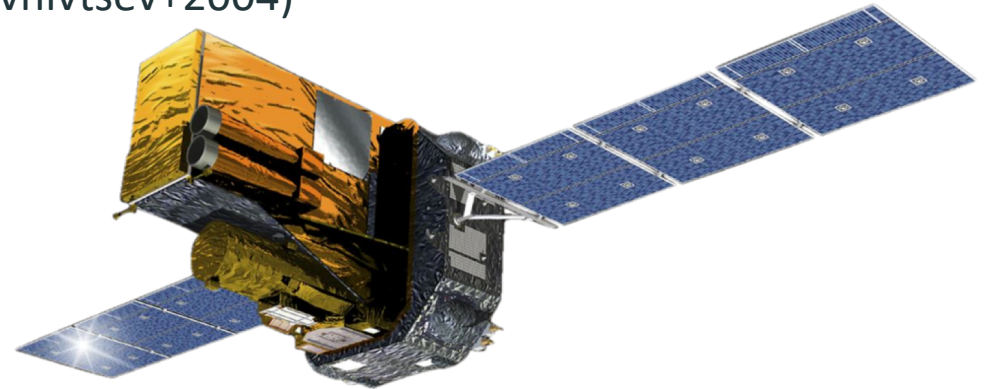
# Sgr B2 molecular cloud



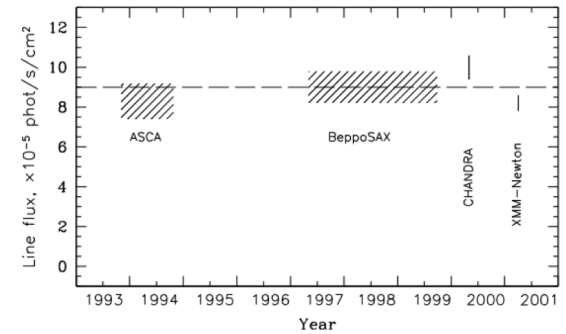
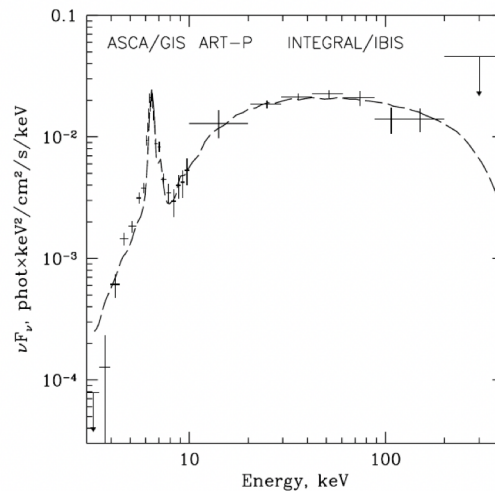
Revnivtsev 1974-2016



INTEGRAL observatory: hard X-ray source IGR J17475–2822 was associated with Sgr B2 (Revnivtsev+2004)



18–60 keV



Light curve 1993-2001

# Reflection scenario: Sgr A\* activity

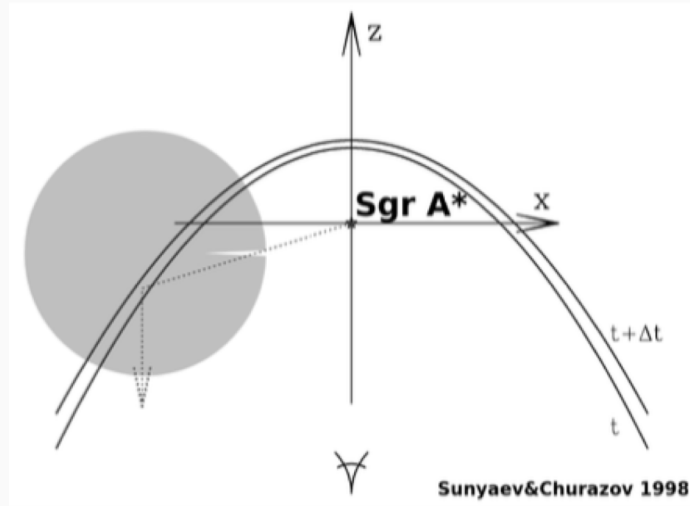
Sgr A\* is a supermassive black hole with a mass of  $4.3 \cdot 10^6 M_{\odot}$  situated in the Galactic Center (GC).

Now Sgr A\* is in a quiescent state with a luminosity of  $\sim 10^{33-34} \text{ erg s}^{-1}$ , which is ten orders of magnitude less than its Eddington limit. Was Sgr A\* active in the past?

Sunyaev+1993 predicted a possible X-ray activity of Sgr A\* in the recent past, which can be detected by the reflected emission of the CMZ.

## Observational features of the reflected emission:

- powerful fluorescent line Fe  $K_{\alpha}$  at 6.4 keV
- $EW_{6.4 \text{ keV}} \sim 1 \text{ keV}$
- hard X-ray continuum
- multi-year time variability



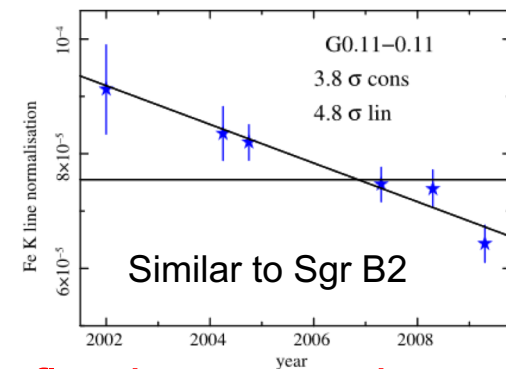
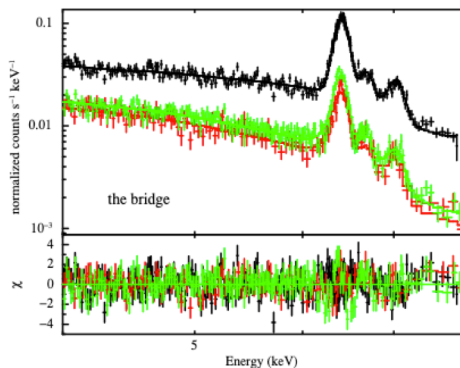
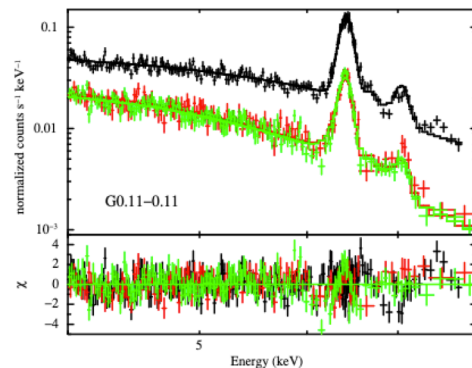
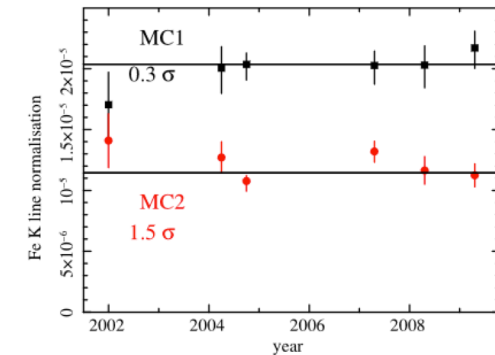
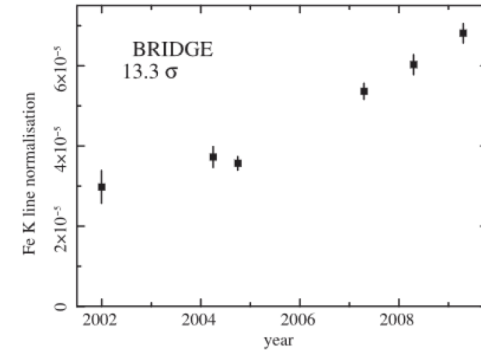
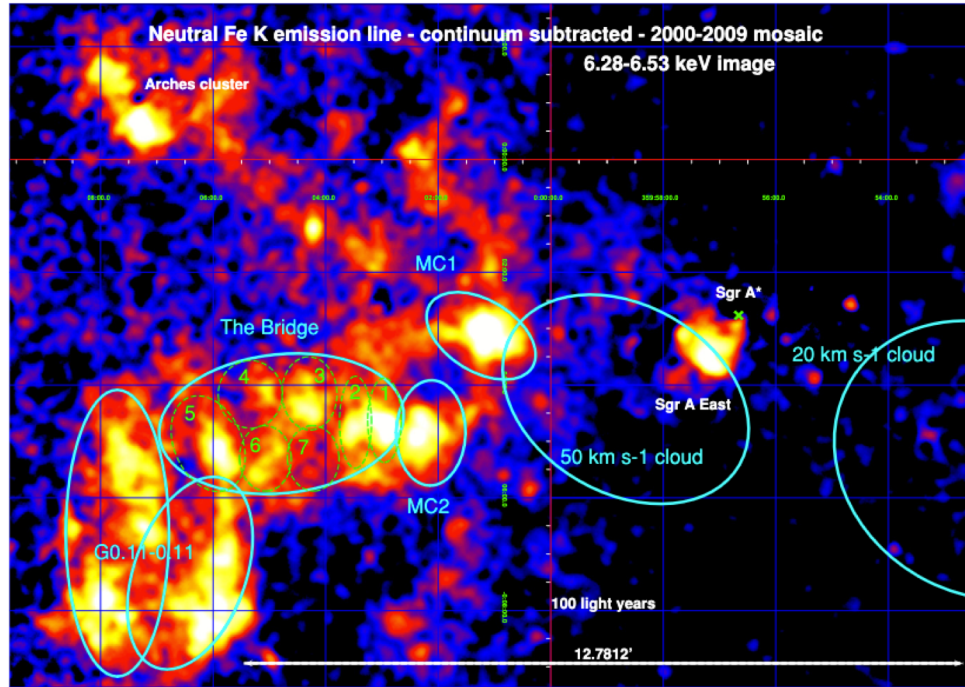
## *Cosmic ray scenario*

An alternative hypothesis of the X-ray emission generation is bombardment of a neutral matter by low-energy cosmic ray (LECR) particles.

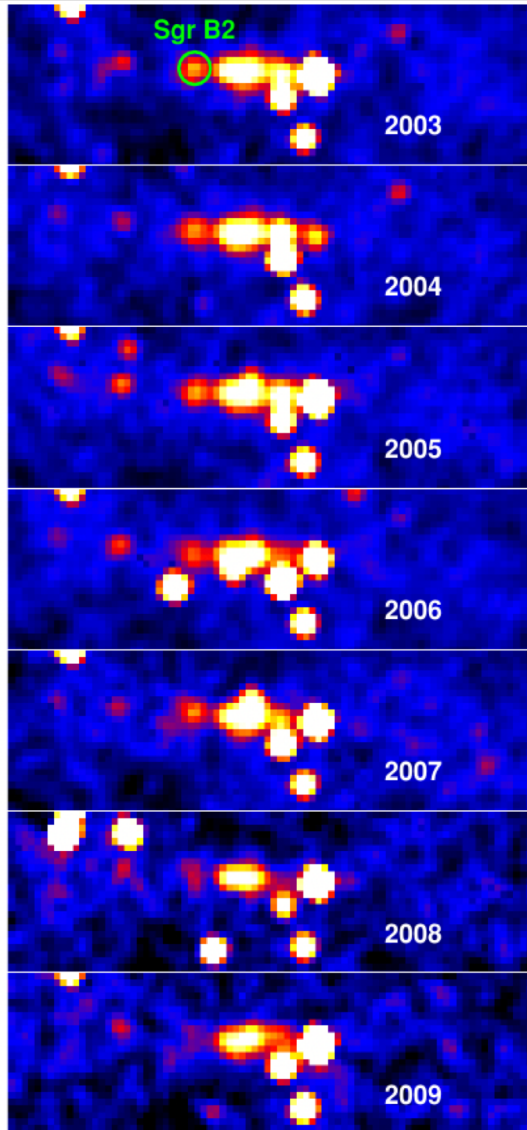
### **Requirements:**

- presence of a LECR flow with a sufficient density and power
- Fe  $K_{\alpha}$  line with  $EW_{6.4 \text{ keV}} < 1 \text{ keV}$
- hard X-ray continuum
- absence of a multi-year time variability
- photon index of the continuum depends on the CR slope

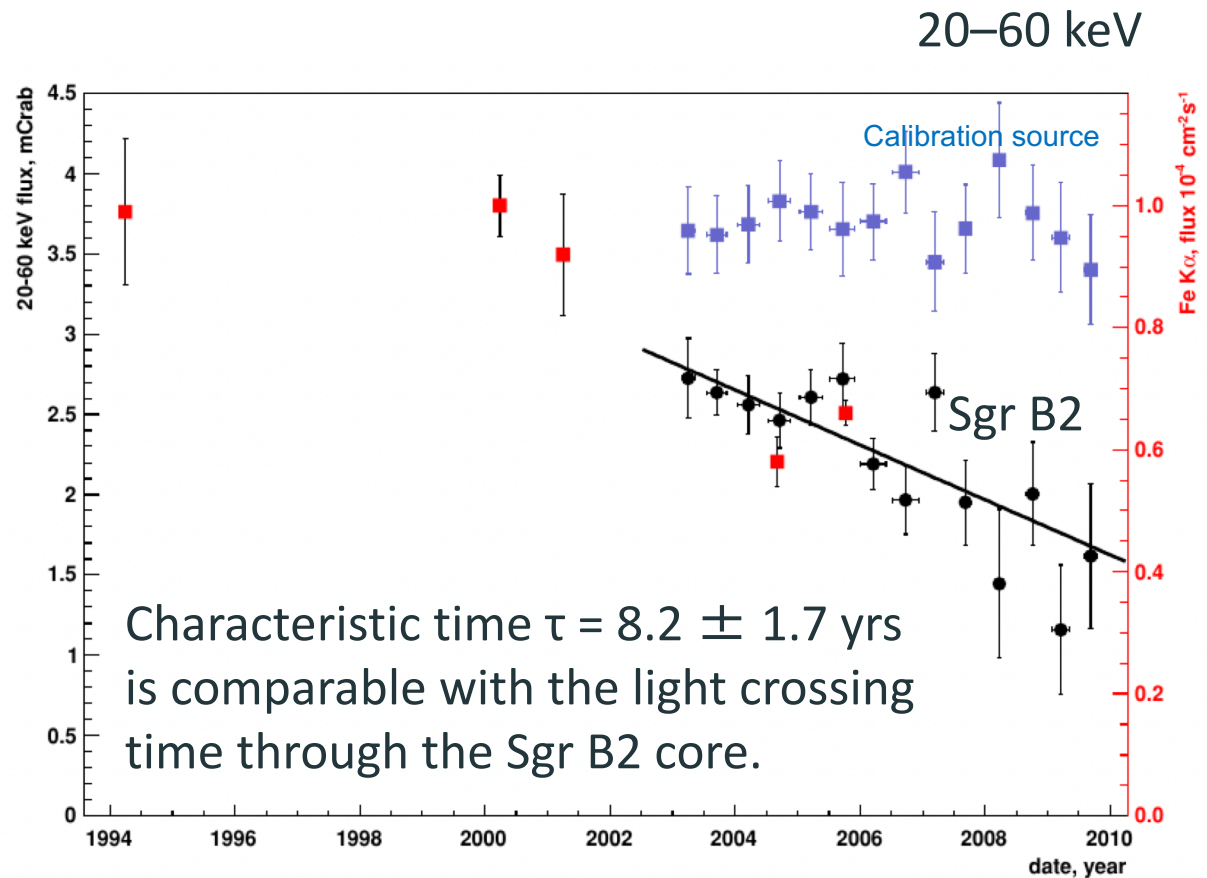
# Observed variability of the GC molecular clouds traces the propagation of the Sgr A\* flare front (Ponti+ 2010)



# Sgr B2 molecular cloud

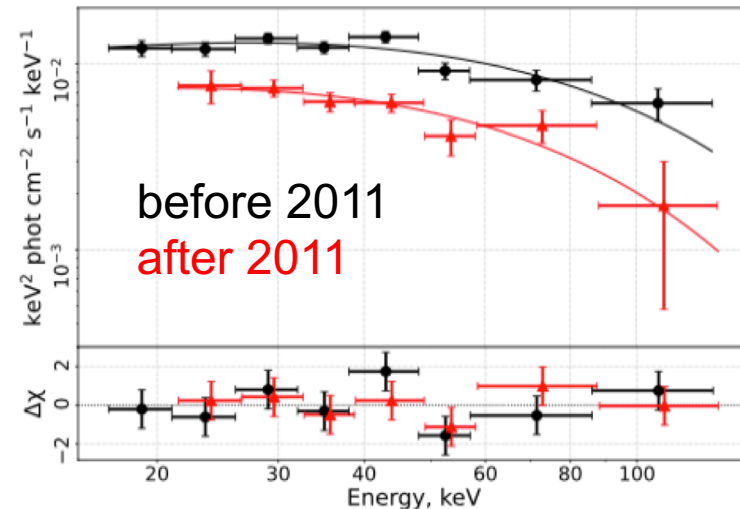
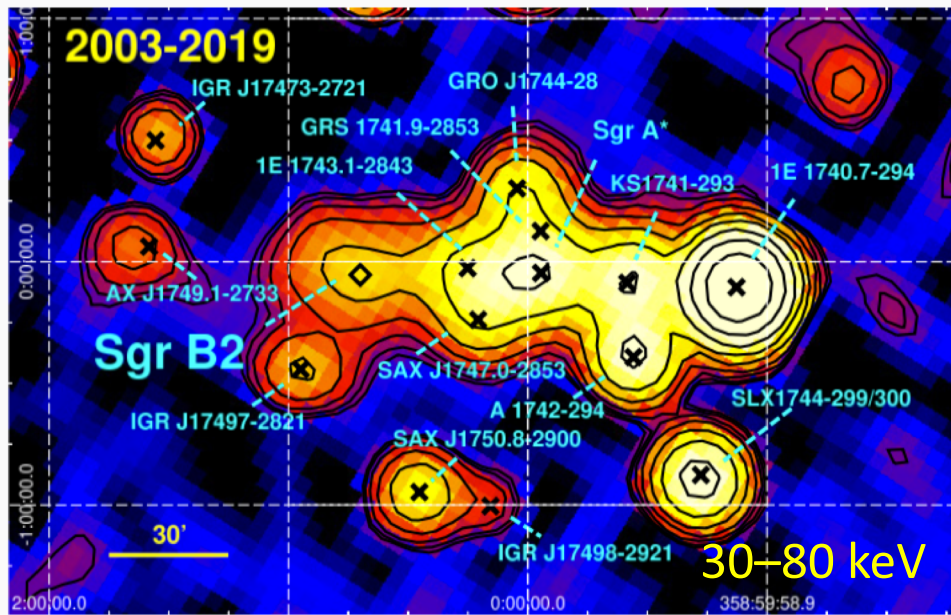
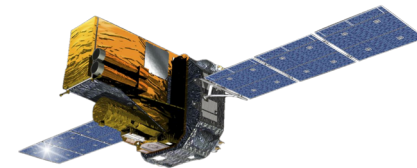


Sgr B2 light curve in the 20–60 keV energy band (black data) obtained from 2003 to 2010.



Terrier+ 2010

# Sgr B2 molecular cloud

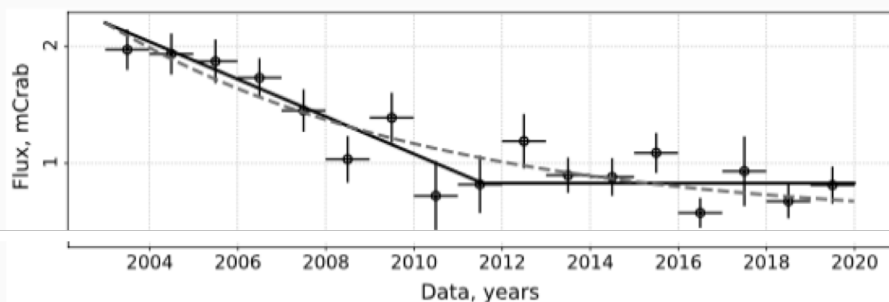


## Reflection scenario

- The decreasing trend of the Sgr B2 emission strongly supports the reflection scenario.
- After 2011 emission could be a result of long-lived multiple scatterings

## Cosmic rays scenario

- The low-energy cosmic ray ions (LECRp, Tatischeff+2012) model.
- Estimated cosmic ray ionization rate too high compared to the GC



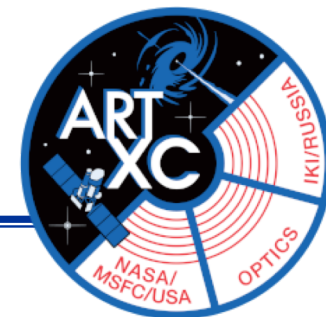
Constant flux level after 2011

Kuznetsova+ 2021



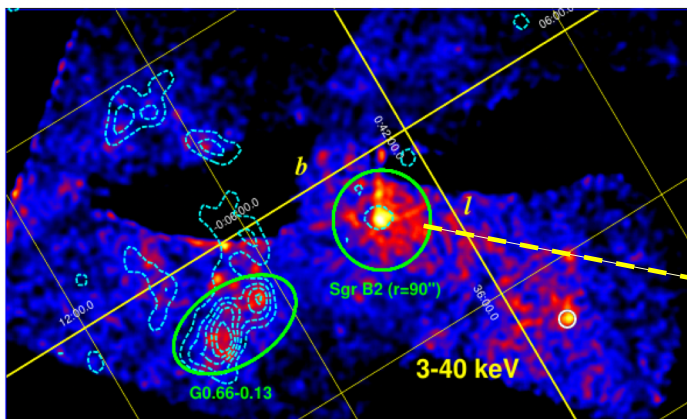


# Sgr B2 molecular cloud after 2011

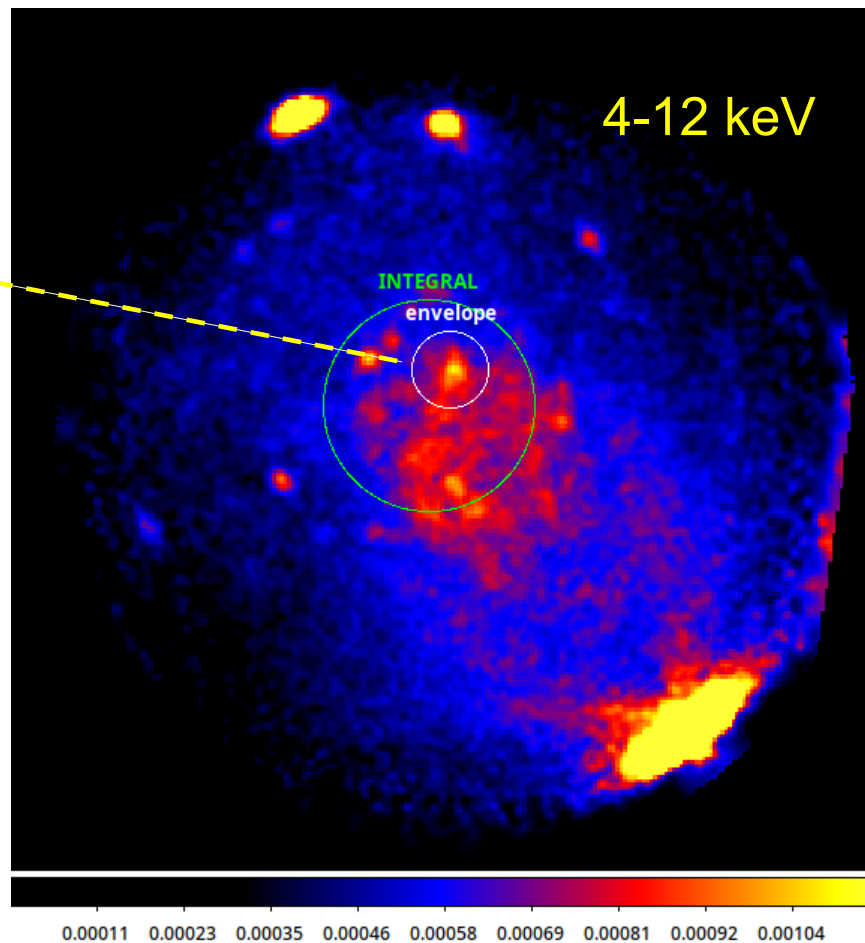


NuSTAR 2013

SRG/ART-XC May 2026



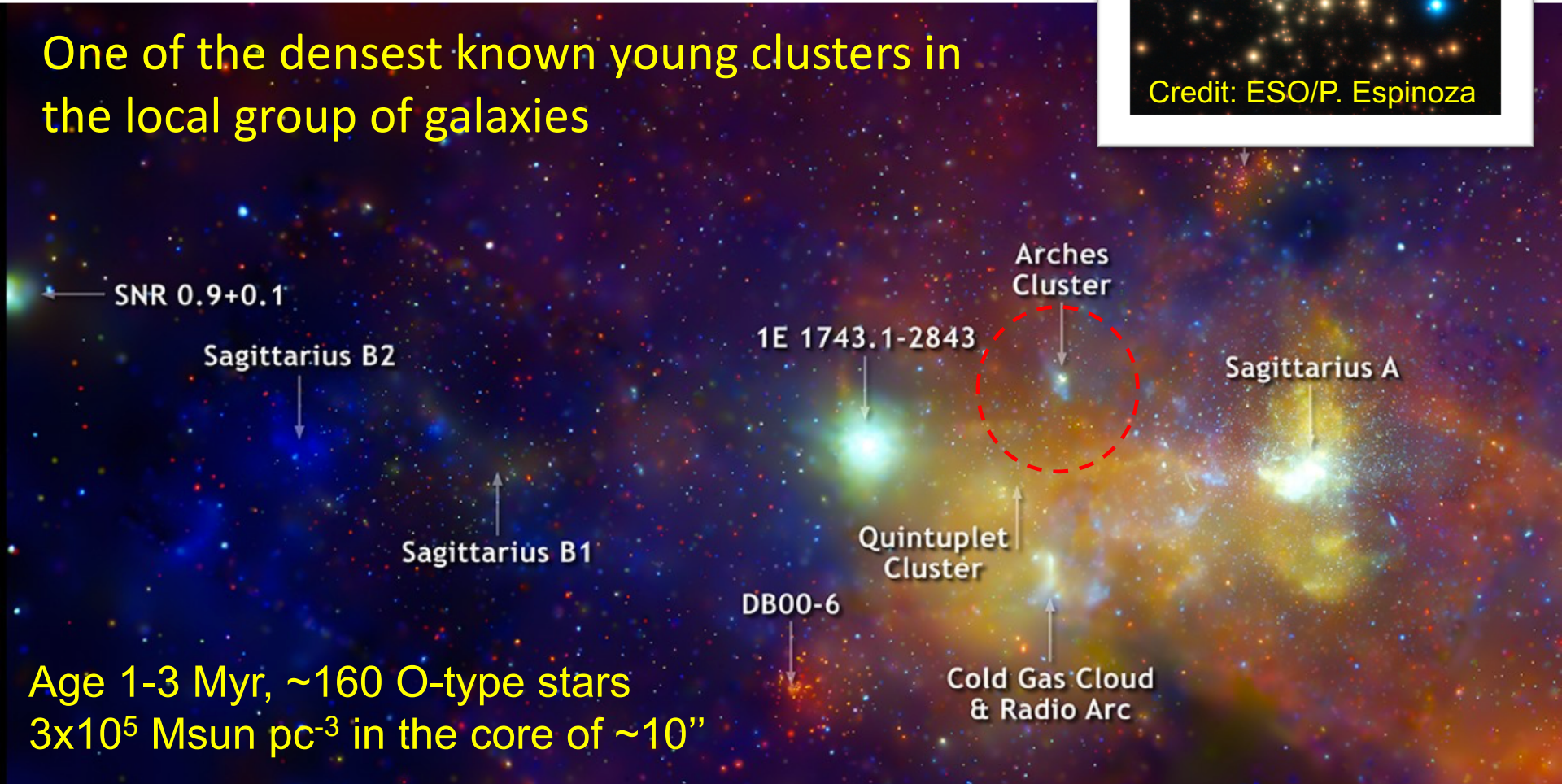
Zhang+2015



E. Shtykovskaya (Kuznetsova) in prep.

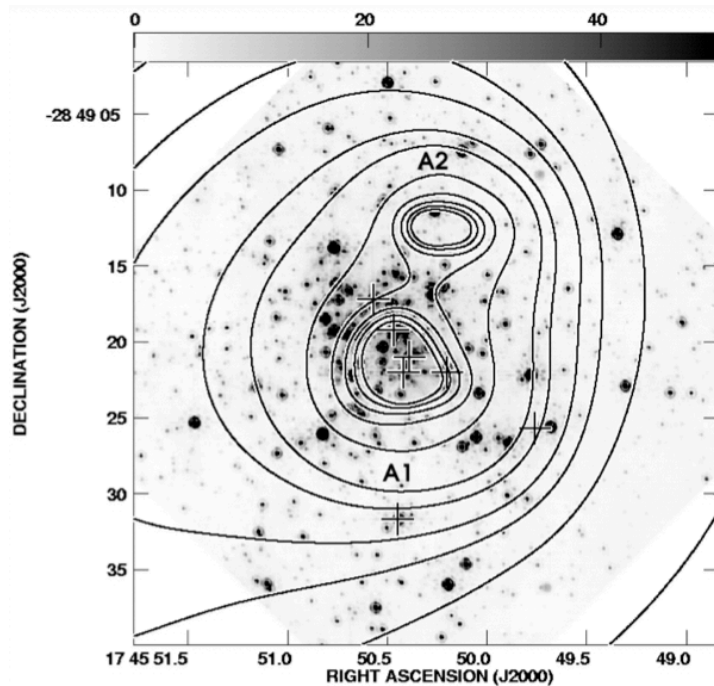
# The Arches cluster

One of the densest known young clusters in the local group of galaxies

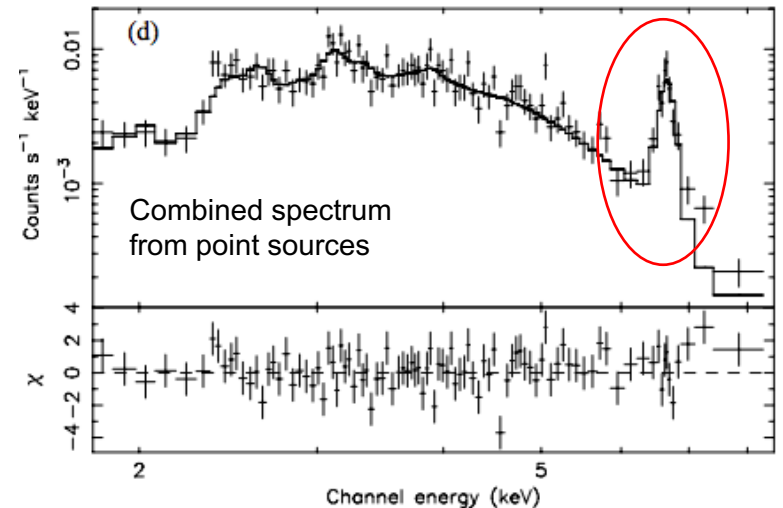
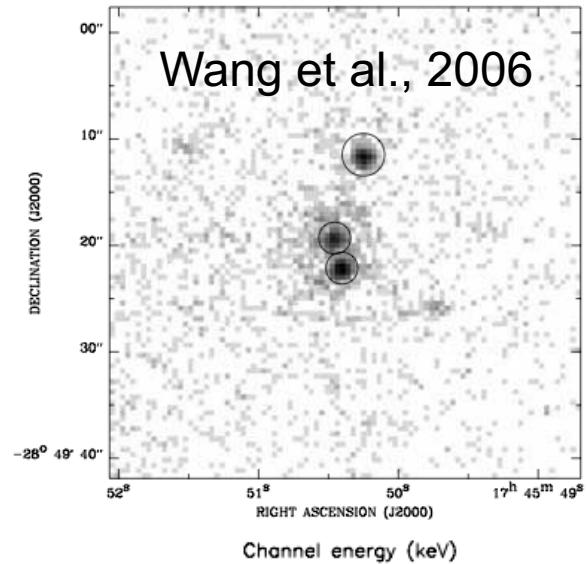


# X-ray emission from the Arches cluster

Thermal emission from the cluster: colliding winds from massive stars



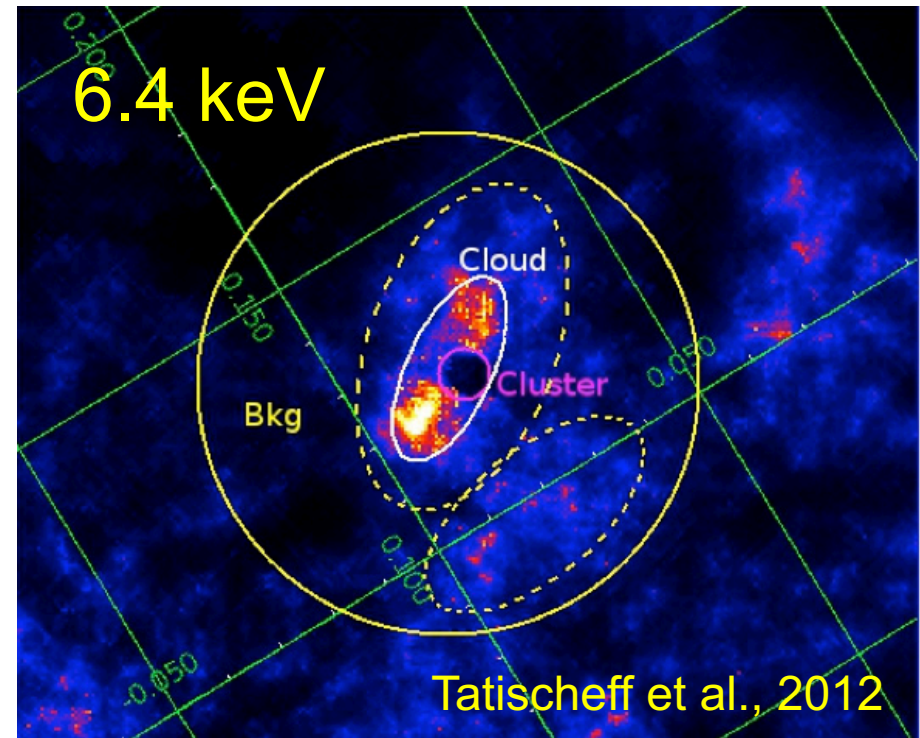
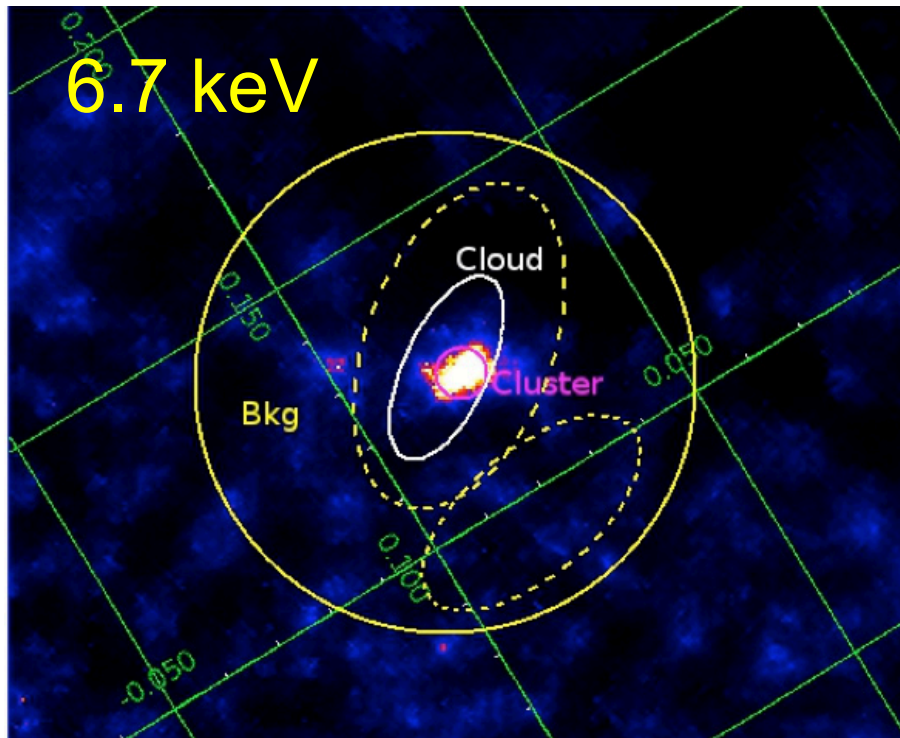
*Chandra* - Yusef-Zadeh et al. (2002)



Strong Fe K $\alpha$  6.7 keV line:

# *X-ray emission from the Arches cluster*

**2000-2010**

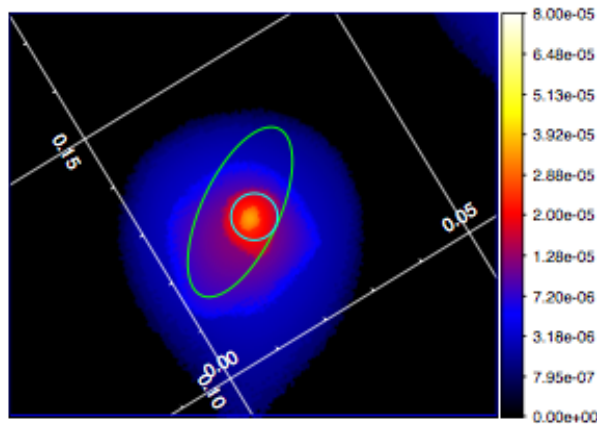


Origin of fluorescence?

# NuSTAR: X-ray image 2012

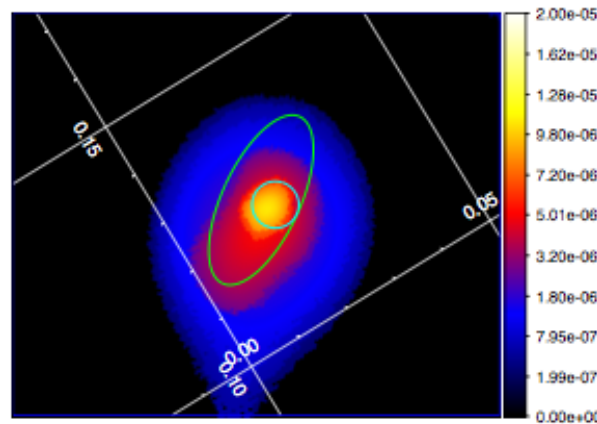
The Arches cluster is detected above 10 keV for the first time.

3-10 keV



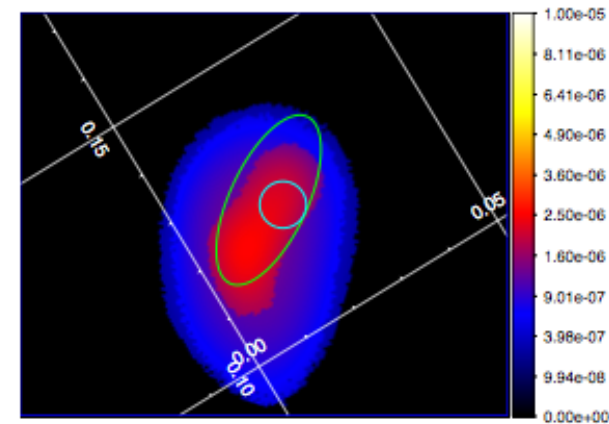
The core of the cluster and extended emission  
⇒ Thermal emission from the core dominates

6-7 keV



Blended 6.4 and 6.7 keV lines  
⇒ 6.7 keV line comes from the core  
⇒ 6.4 keV line confirms XMM results

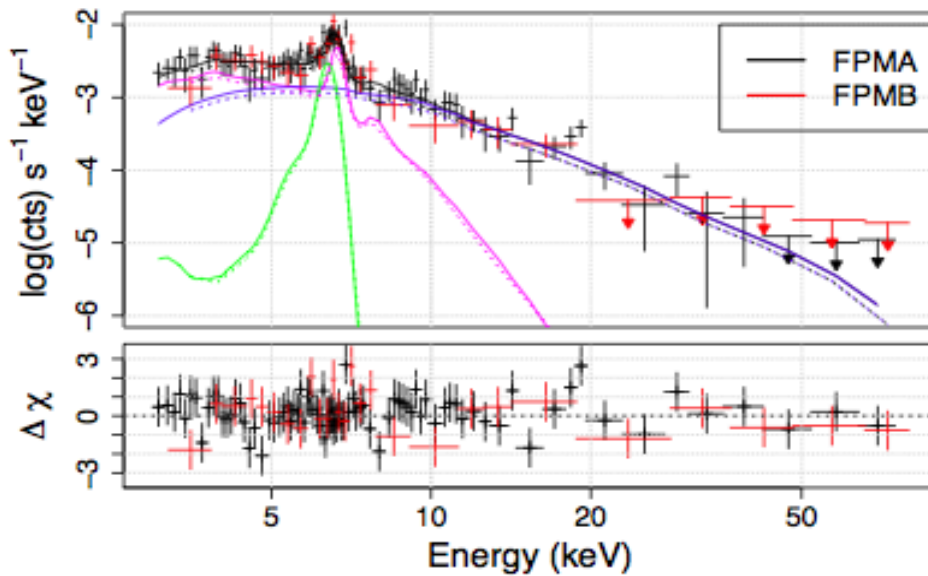
10-20 keV



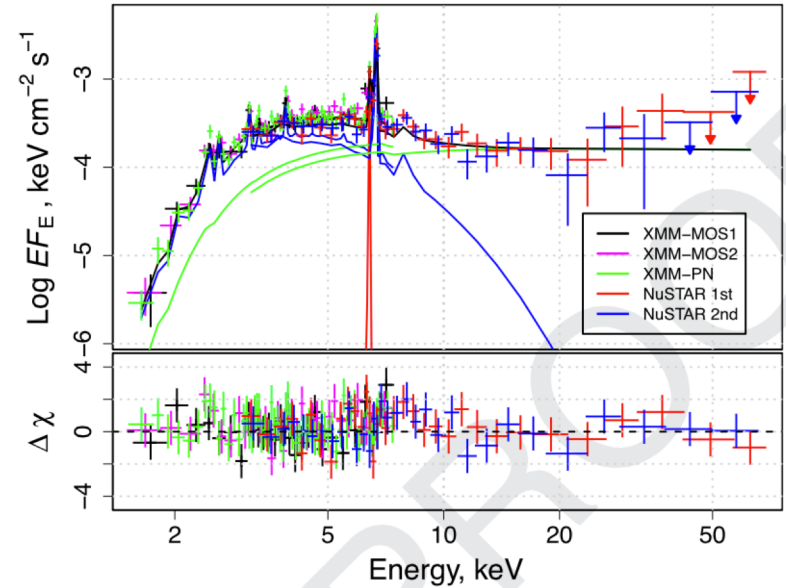
Non-thermal continuum  
⇒ No point sources in the core  
⇒ Continuum follows 6.4 keV line intensity

# XMM+NuSTAR: Spectral analysis

2012



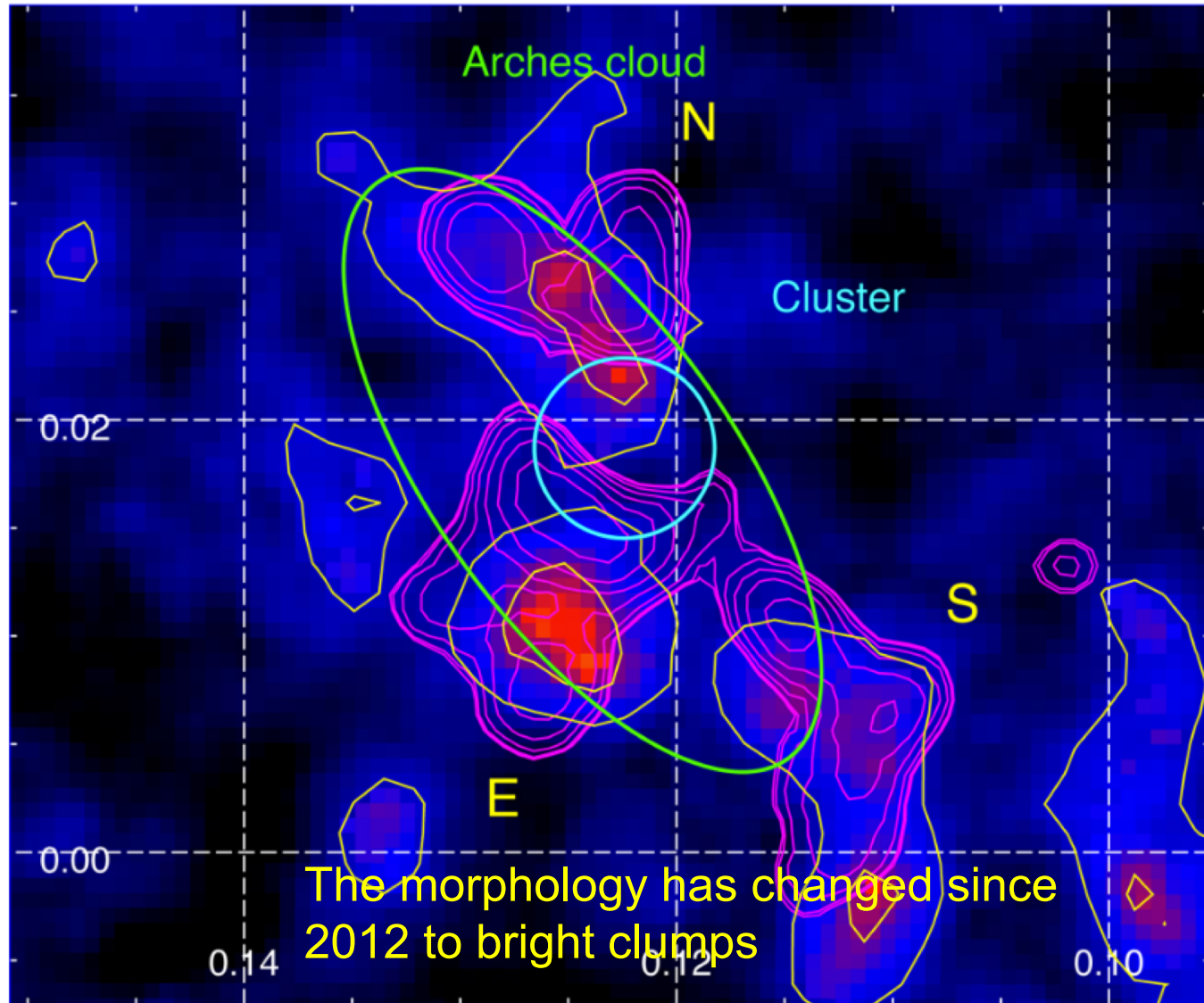
2015



APEC:  $kT \sim 2$  keV  
Power-law:  $\Gamma = 1.6-2$   
 $EW_{6.4 \text{ keV}} \sim 1.0$  keV

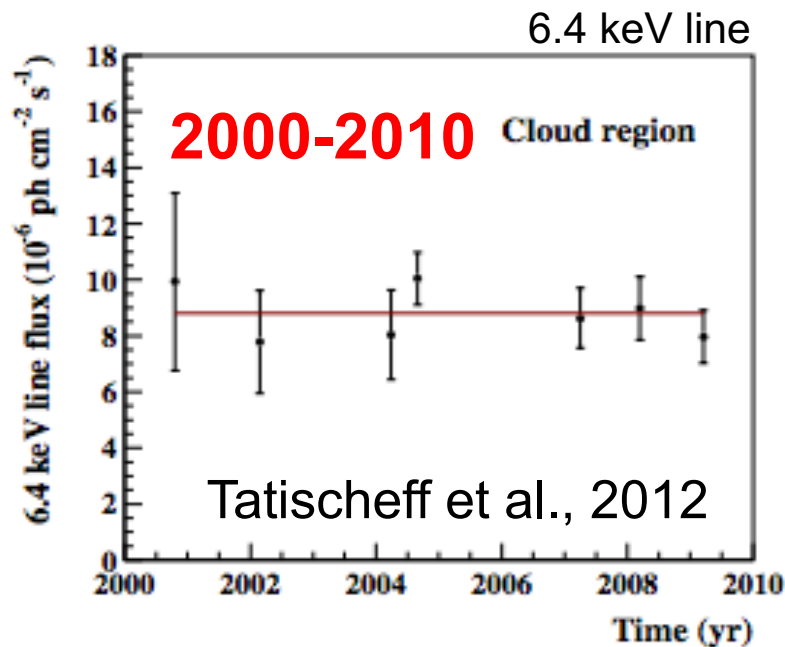
◆ Non-thermal continuum dominates above 10 keV

# Arches cloud morphology 2013-2015 (XMM)

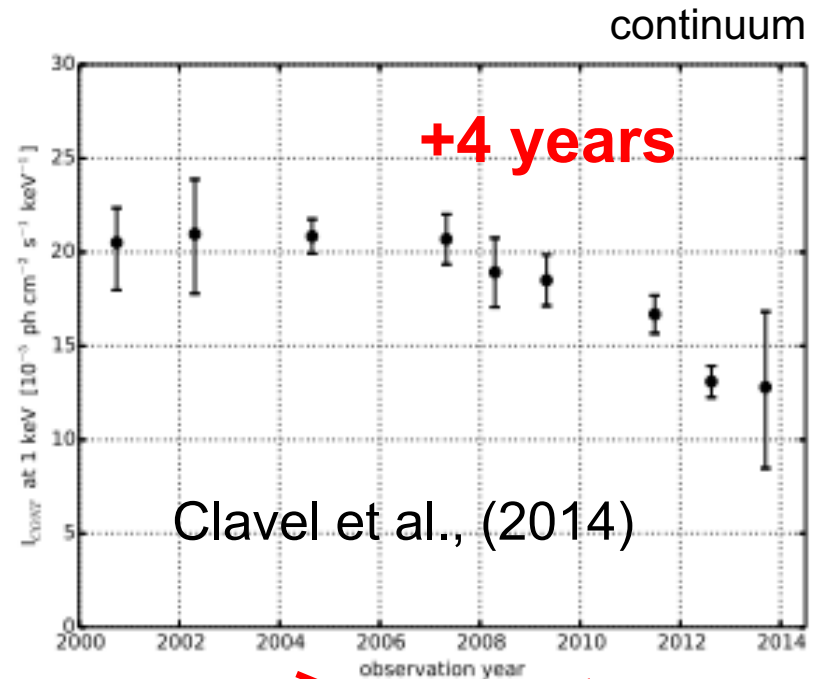


# Arches cloud (XMM)

- 30% flux drop in 6.4 keV line and continuum ( $>4\sigma$ )
  - EW is constant over time  $0.9 \pm 0.1$  keV
- a large fraction of the non-thermal emission is due to the X-ray reflection



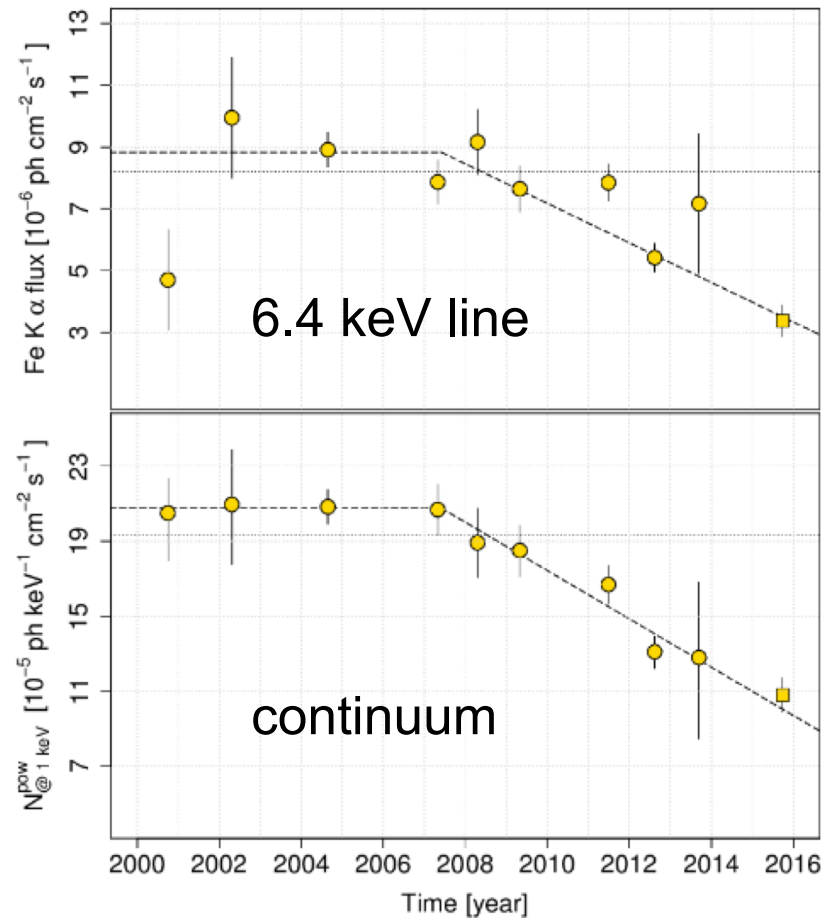
Cosmic Rays origin?!



~~Cosmic Rays origin?!~~

# Arches cloud after 2015

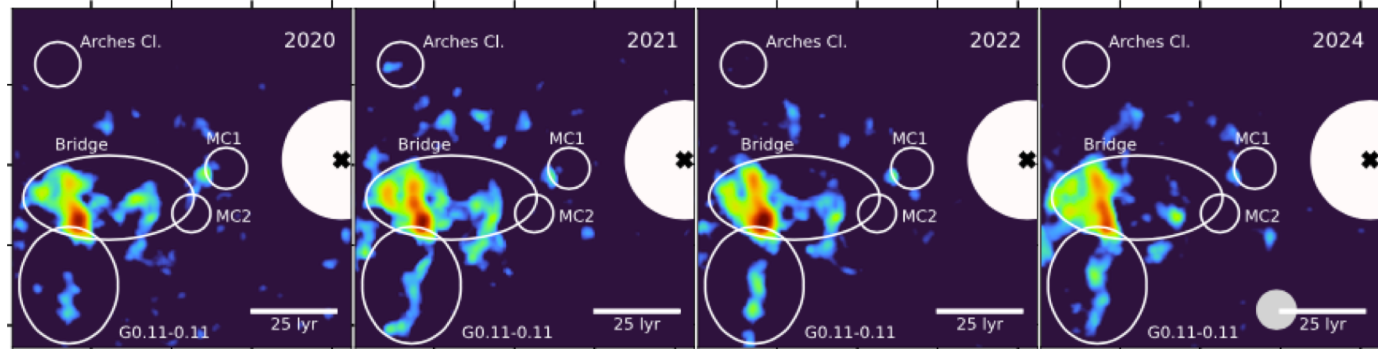
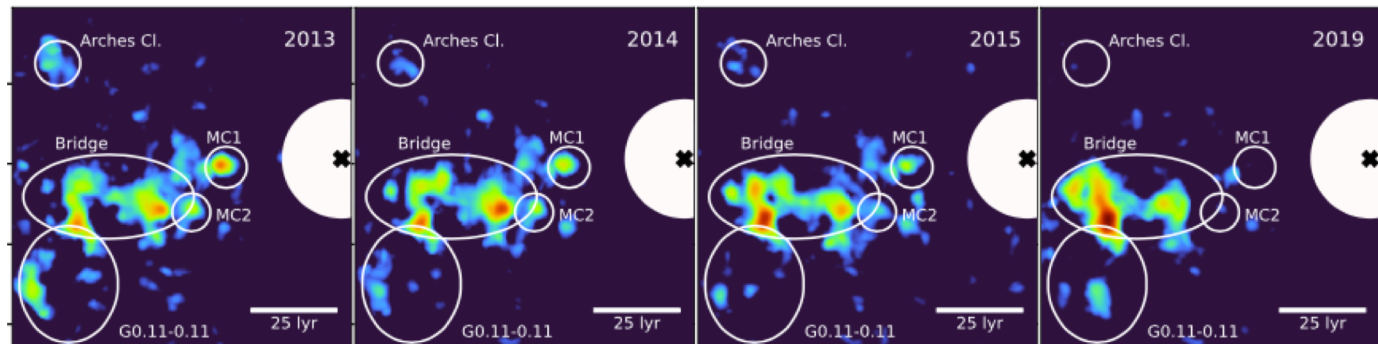
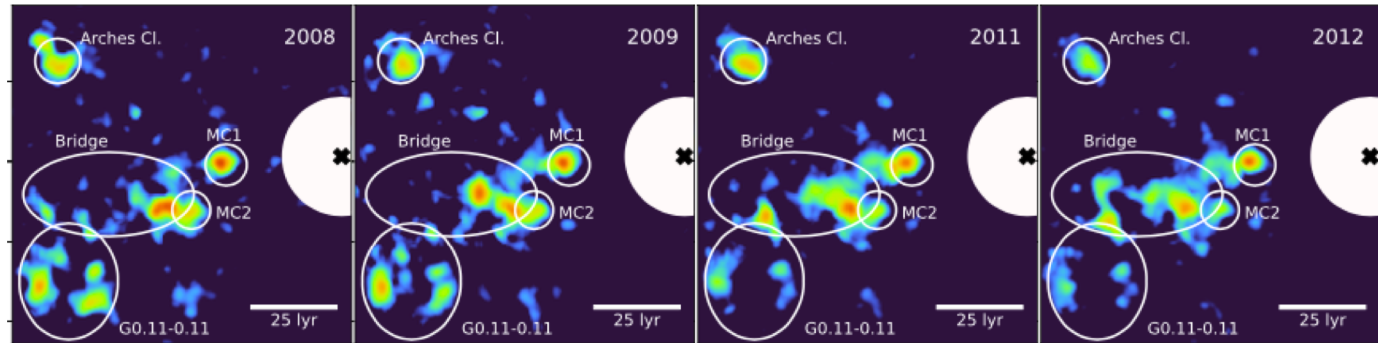
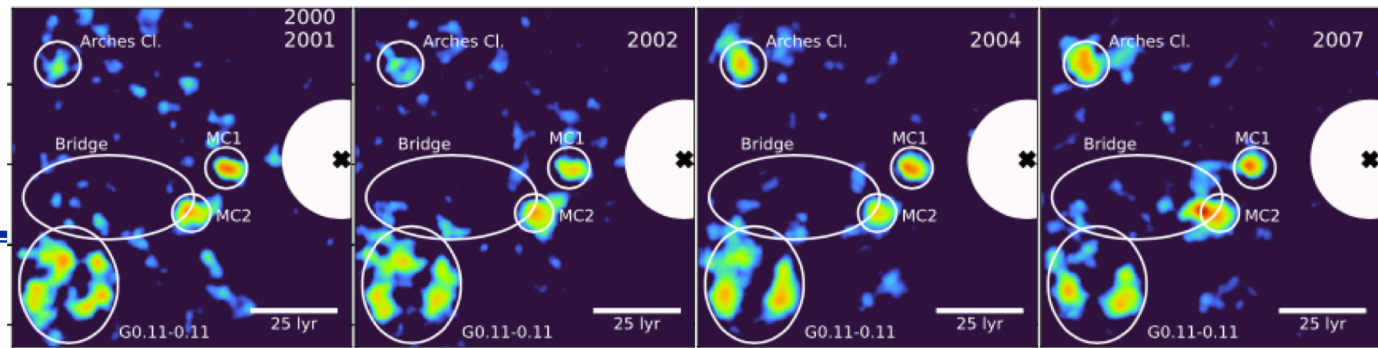
- non-thermal flux continues to decrease
- Time decay 8 yr for 6.4 keV line and continuum, similar to Sgr B2 cloud.
- EW shows drop in 2015 with a factor of 2



Krivosos+ 2016, Kuznetsova+ 2019

# 25 years of XMM observations of the Sgr A complex

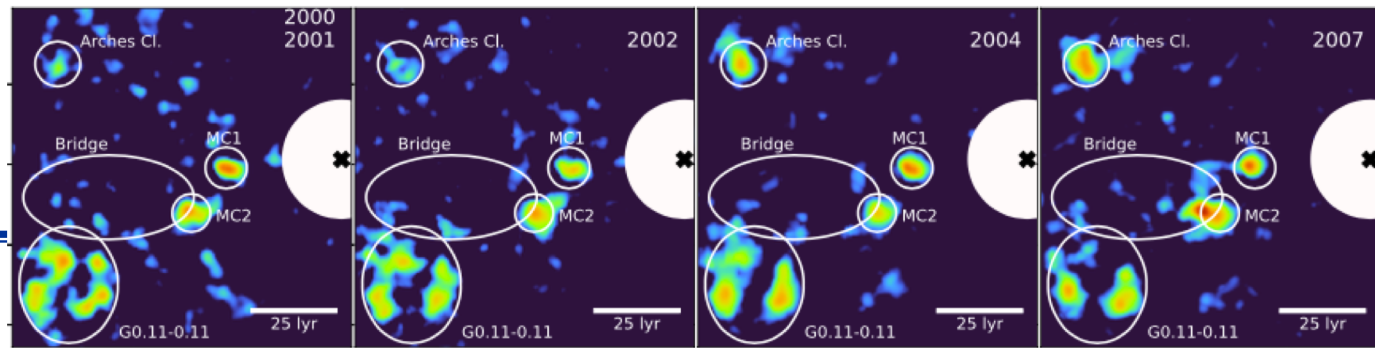
6.4 keV line



Stel+ 2025

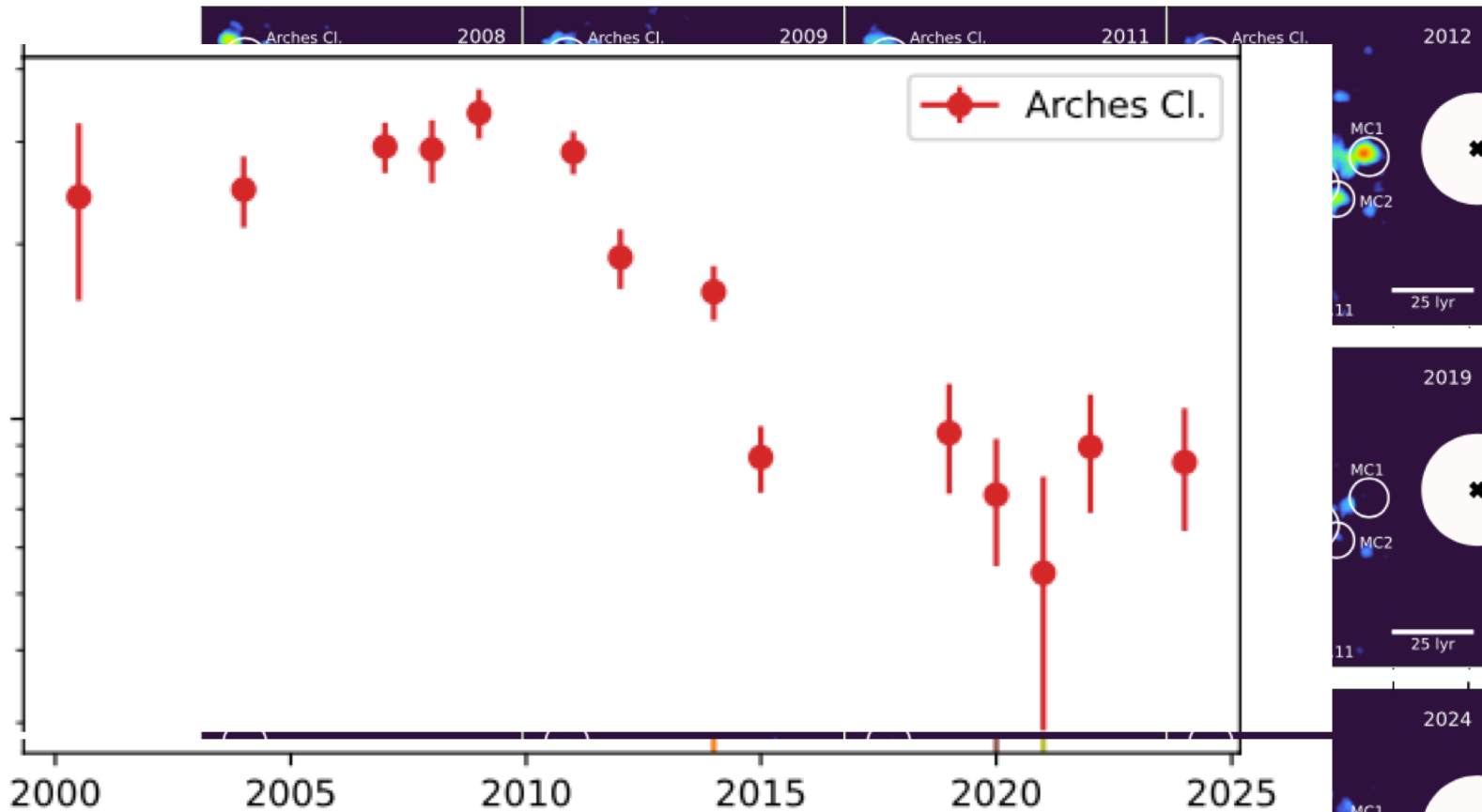
# 25 years of XMM observations of the Sgr A complex

6.4 keV line

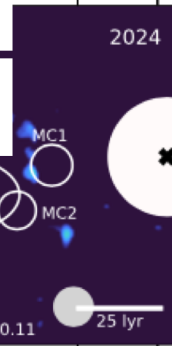
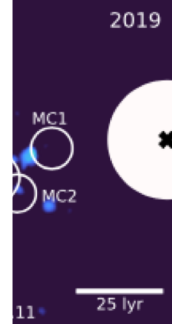
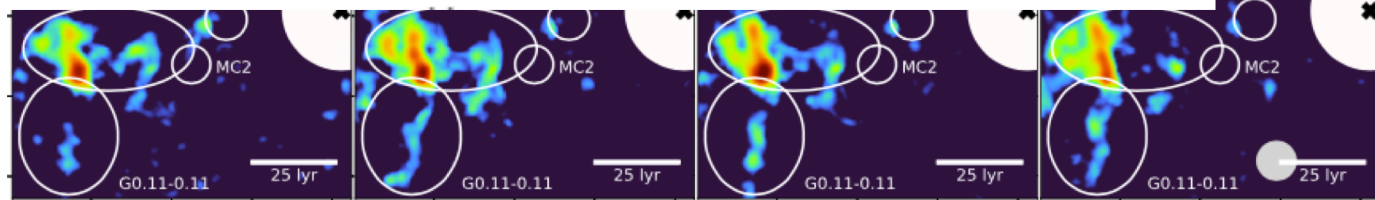


SR Fe  $K\alpha$  [cts s<sup>-1</sup> cm<sup>-2</sup> arcsec<sup>-2</sup>]

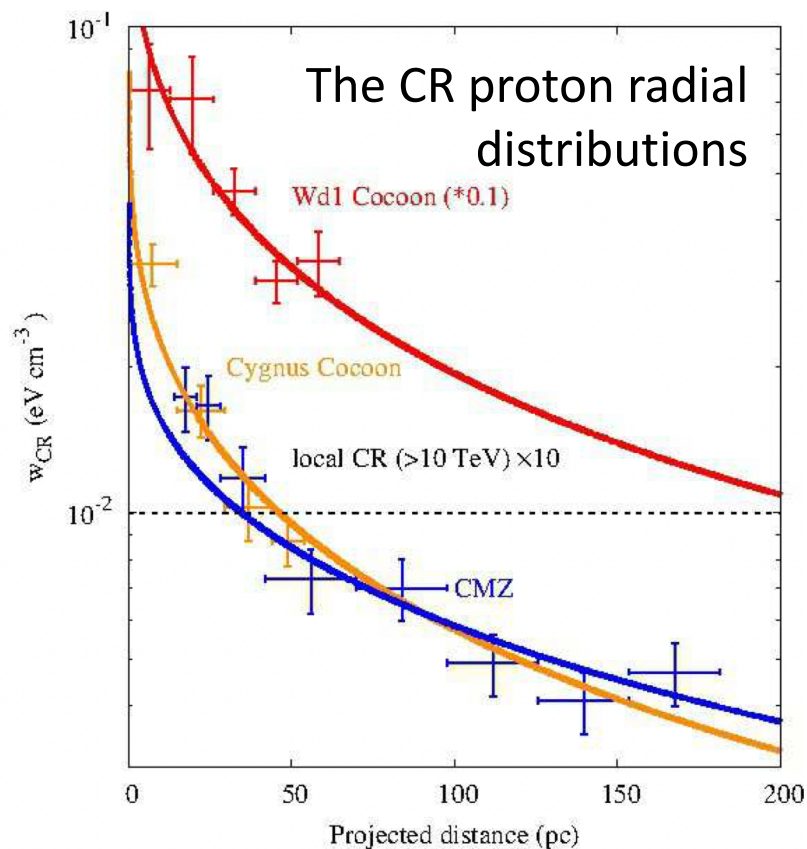
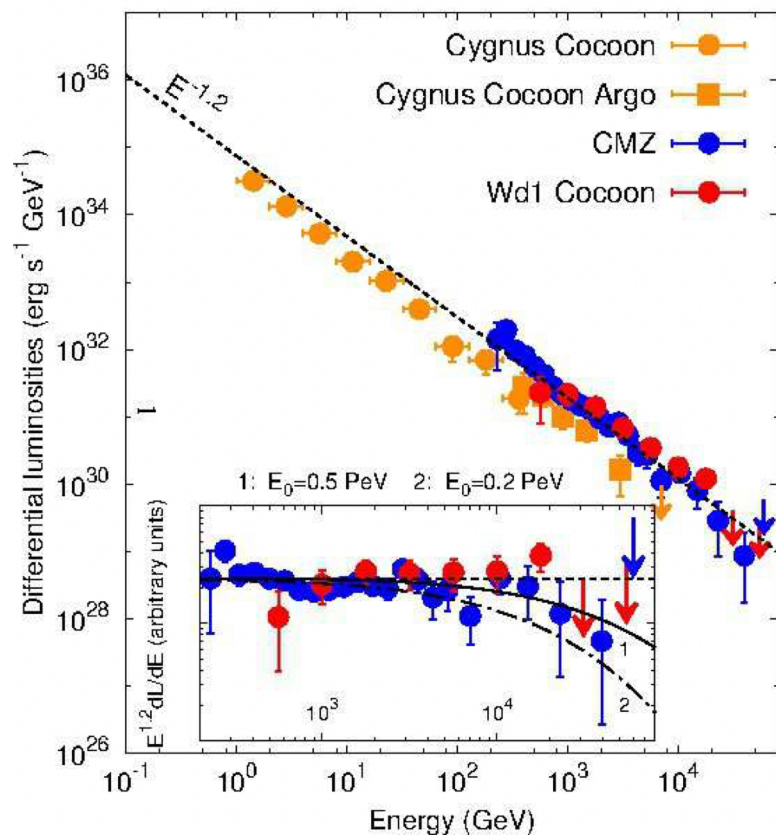
10<sup>-9</sup>



Stel+ 2025



# Detection of very high energy (VHE) $\gamma$ -rays from clusters of young massive stars (Aharonian+ 2019)

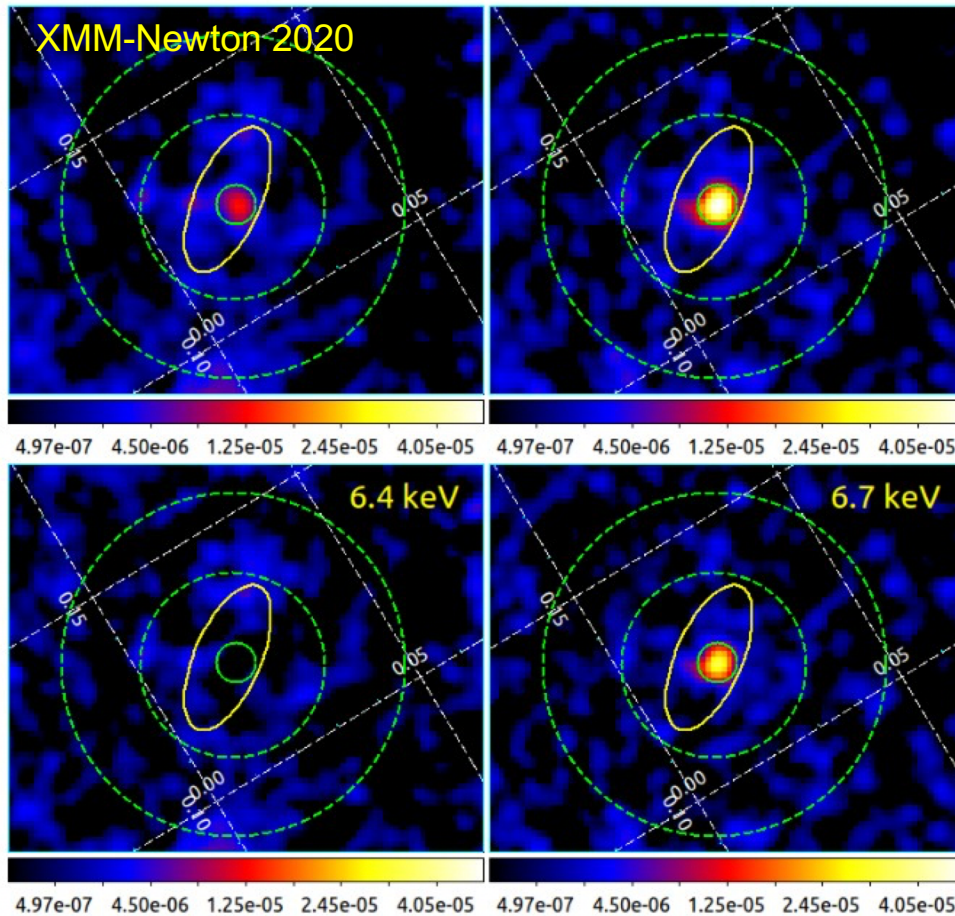


...“CRs responsible for the diffuse VHE  $\gamma$ -ray emission from the GC are accelerated by the ultracompact stellar clusters”

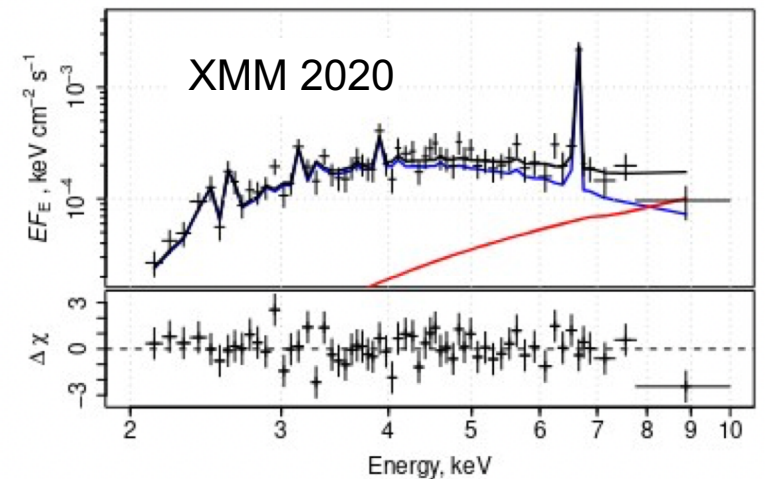
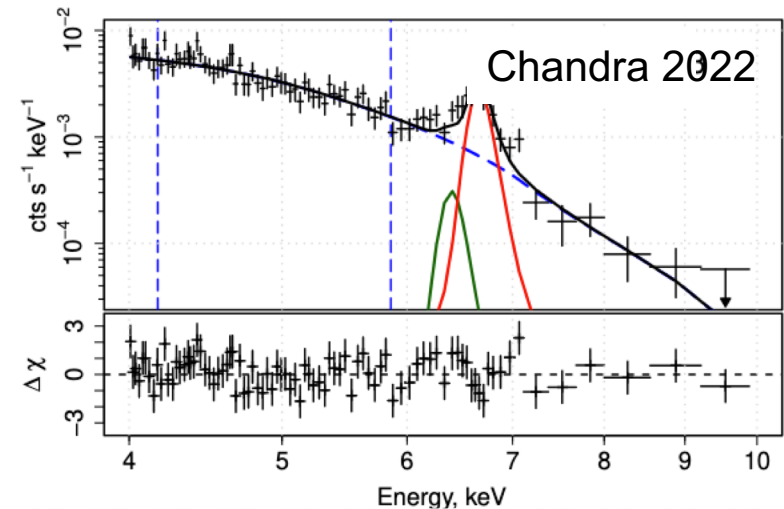
...“Arches, Quintuplet and Nuclear in GC, could be alternative sites for the CR acceleration”

# Arches cluster after 2015

Direct detection of the non-thermal X-ray emission from the Arches star cluster

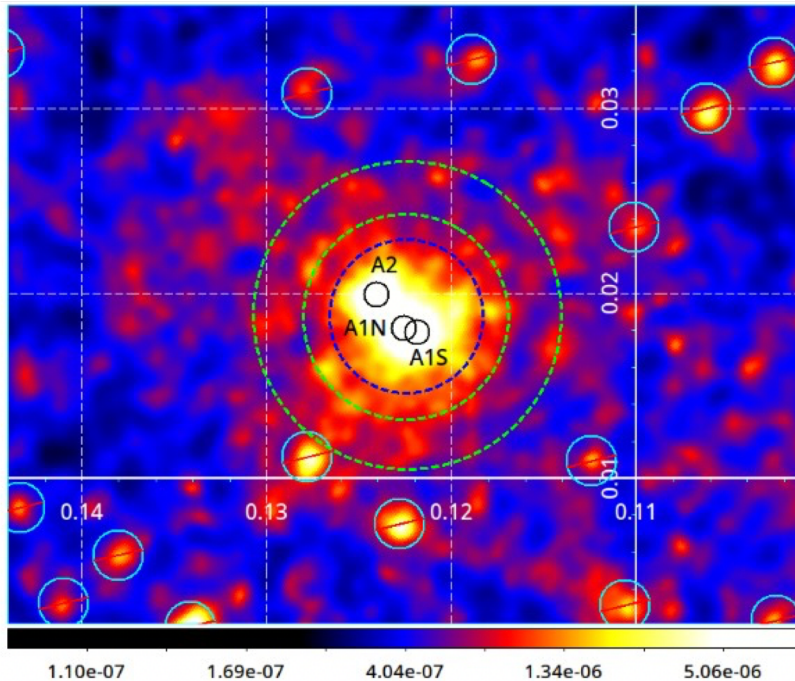


Krivonos+ 2025



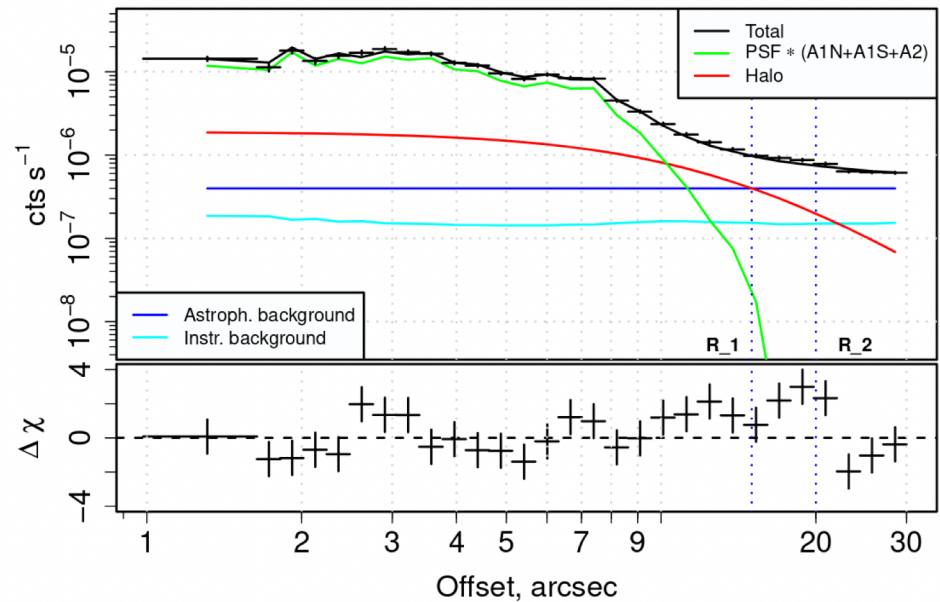
# Arches cluster after 2015

Chandra 2022



work is ongoing...

Spatial analysis

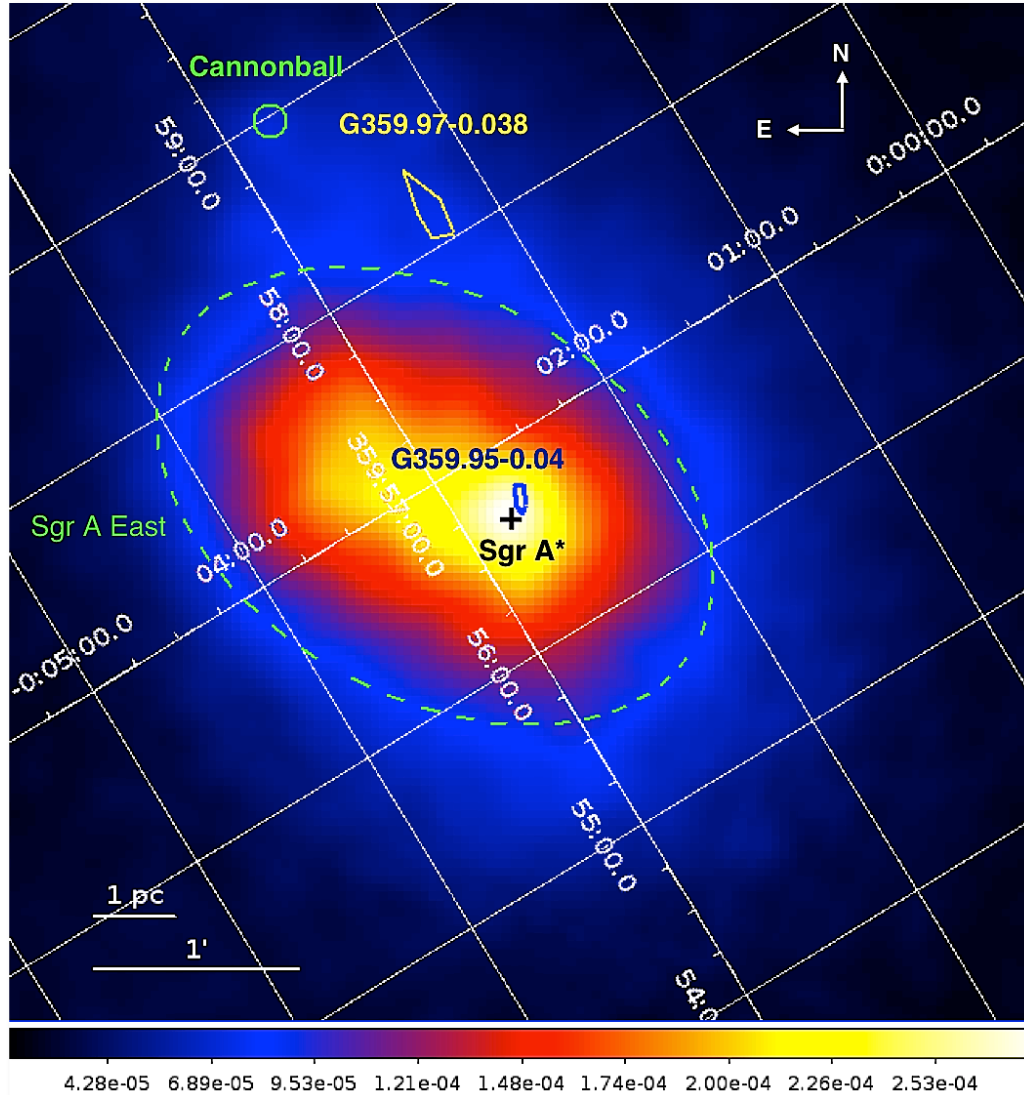


**Spatial halo is detected!**

Krivonos et al., in prep



# Inner 12 pc x 12 pc at 3–10 keV NuSTAR



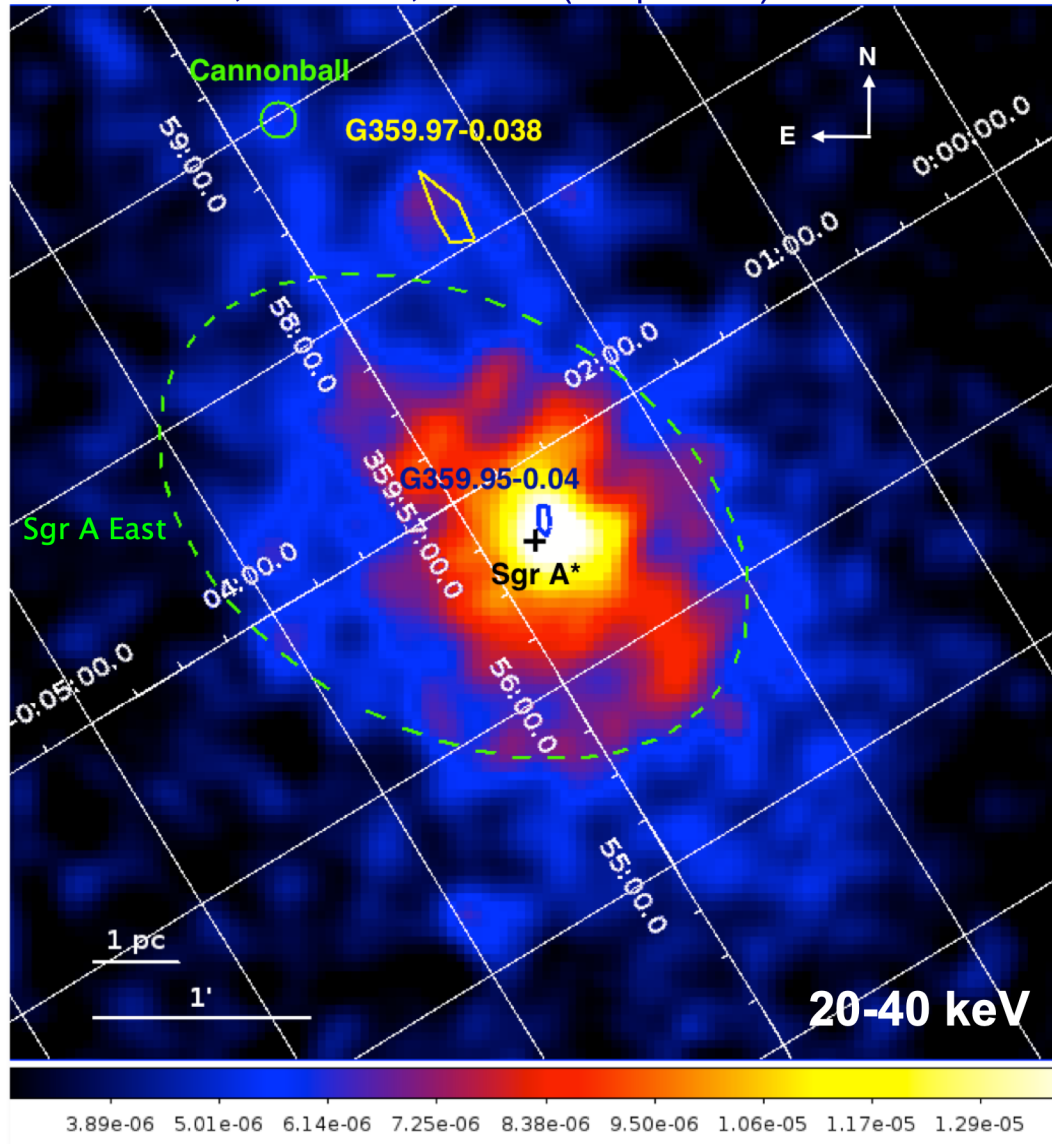
Credit: Kerstin Perez

- The brightest emission (white) comes from the hot plasma surrounding Sgr A\* (flaring removed) and the pulsar wind nebula G359.95-0.04
- The surrounding emission (red and yellow) fills the shell of supernova remnant Sgr A East
- To the north-east lies the extended emission of the Sgr A-East “plume” (bright blue), “cannonball” (Nynka et al. 2013), non-thermal filament G359.97-0.038 (Nynka et al. 2014)
- The entire region sits in a field of GRXE and unresolved point source emission (dark blue)

# Inner 12 pc x 12 pc at 20–40 keV

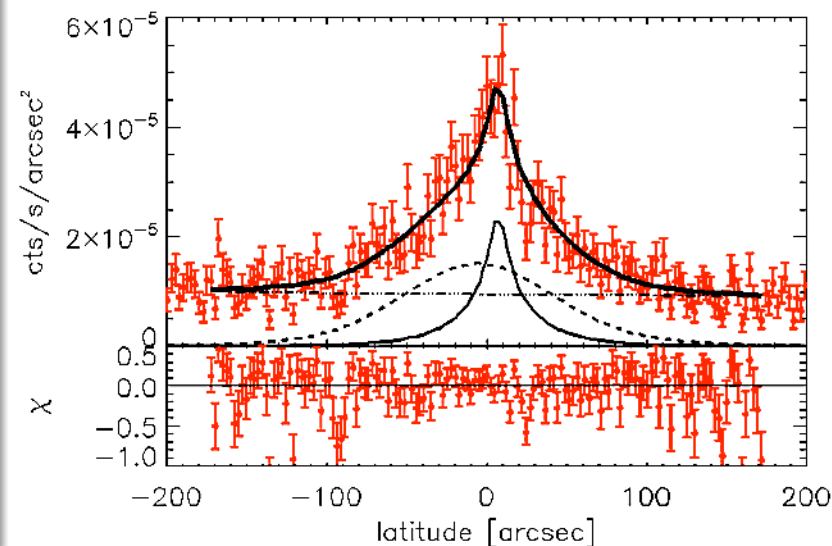
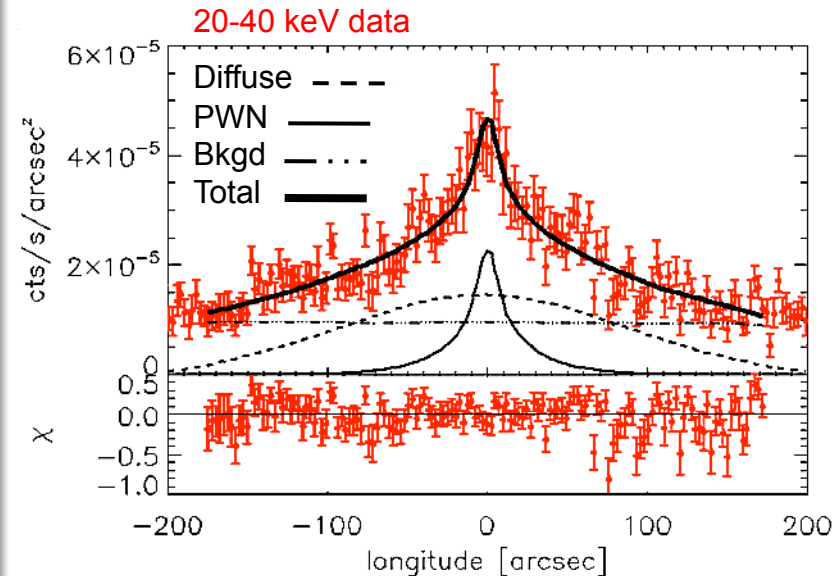
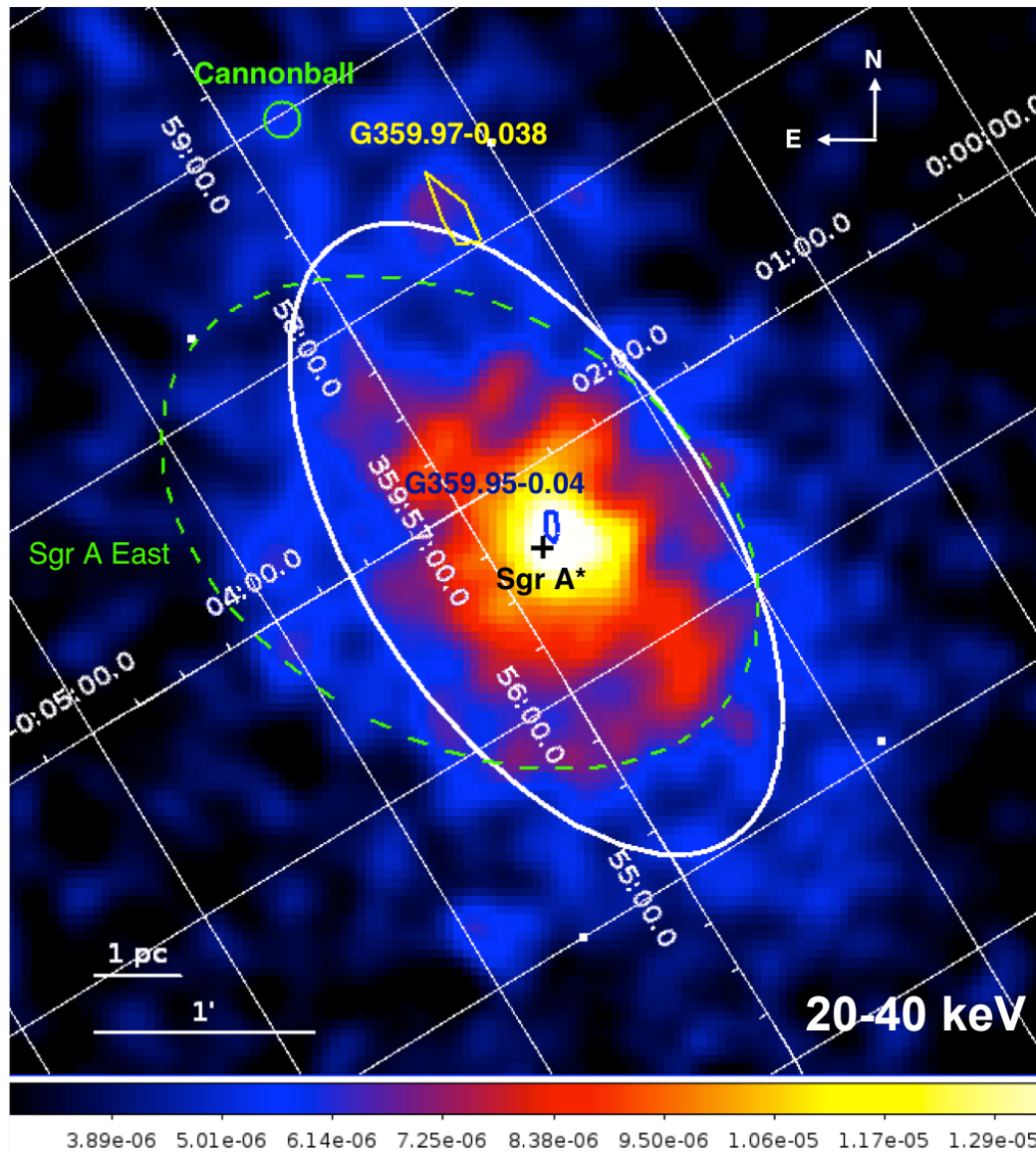


K. Perez et al., *Nature* **520**, 646–649 (30 April 2015)

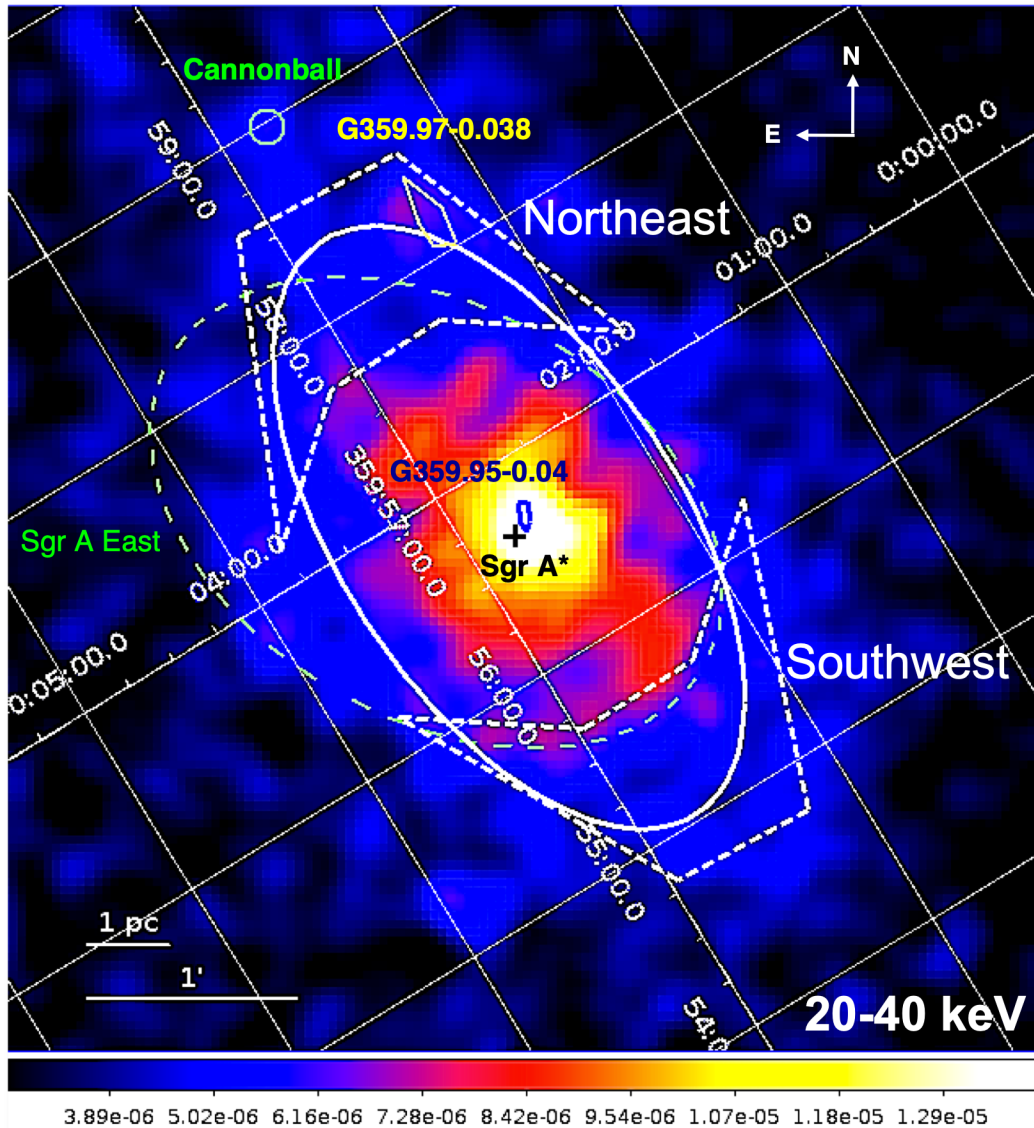


- Bright emission from pulsar wind nebula remains
- In addition, there is an **unresolved >20 keV X-ray emission extending along the Galactic plane from the Galactic Center**

# Diffuse emission has 8 pc x 4 pc spatial extent



# Spectra examined from regions away from central pulsar nebula



- Spectra taken from >75% encircled energy radius away from the central pulsar wind nebula
- Different dominant emission sources at low energy: “Northeast” region has significant overlap with Sgr A East, “Southwest” region only underlying point sources
- Combined with XMM-Newton data from same time periods at 2-10 keV

# Spectrum of “Southwest” region



- Below 20 keV dominated by:

$$kT_1 = 1.0^{+0.3}_{-0.4} \text{ keV}$$

$$Z_1 = 5.0$$

$$kT_2 = 7.5^{+1.6}_{-1.3} \text{ keV}$$

$$Z_2 = 1.7$$

Coronally active stars, SNR heated plasma...

Magnetic Cataclysmic Variables (Polars and Intermediate Polars)

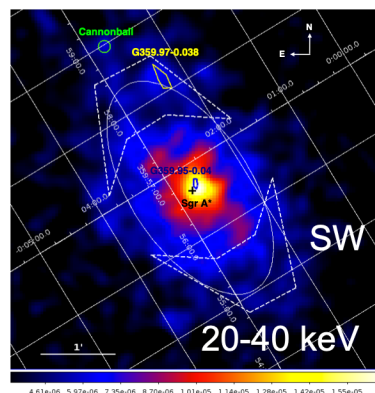
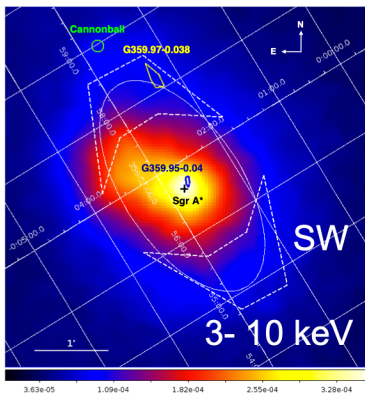
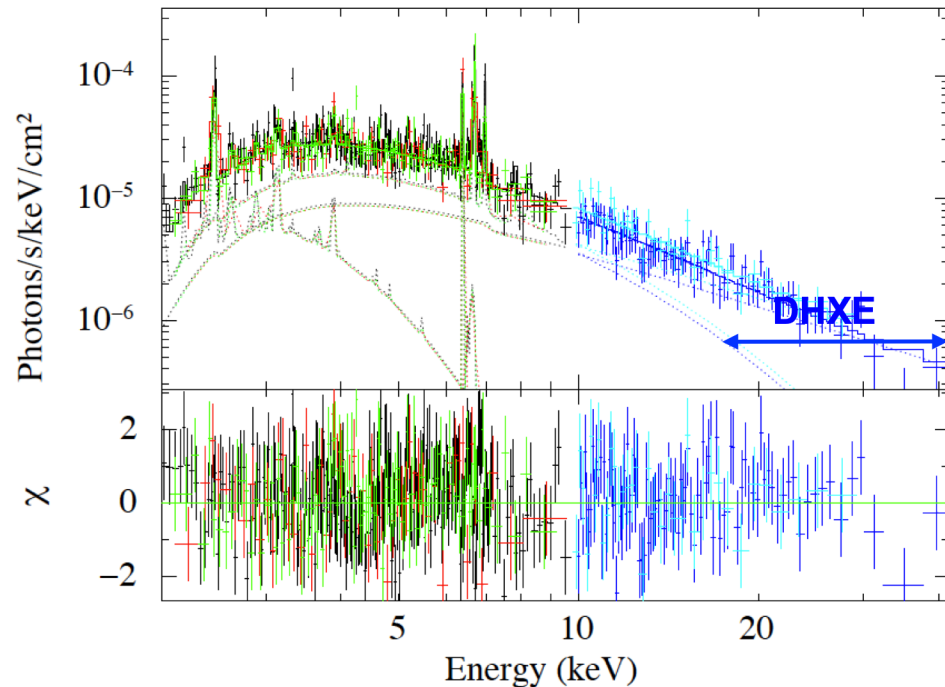
- 2-10 keV luminosity-to-mass ratio of low-energy thermal component consistent with that measured by XMM-Newton (*Heard and Warwick 2012; Launhardt 2002*)

- Above 20 keV dominated by:

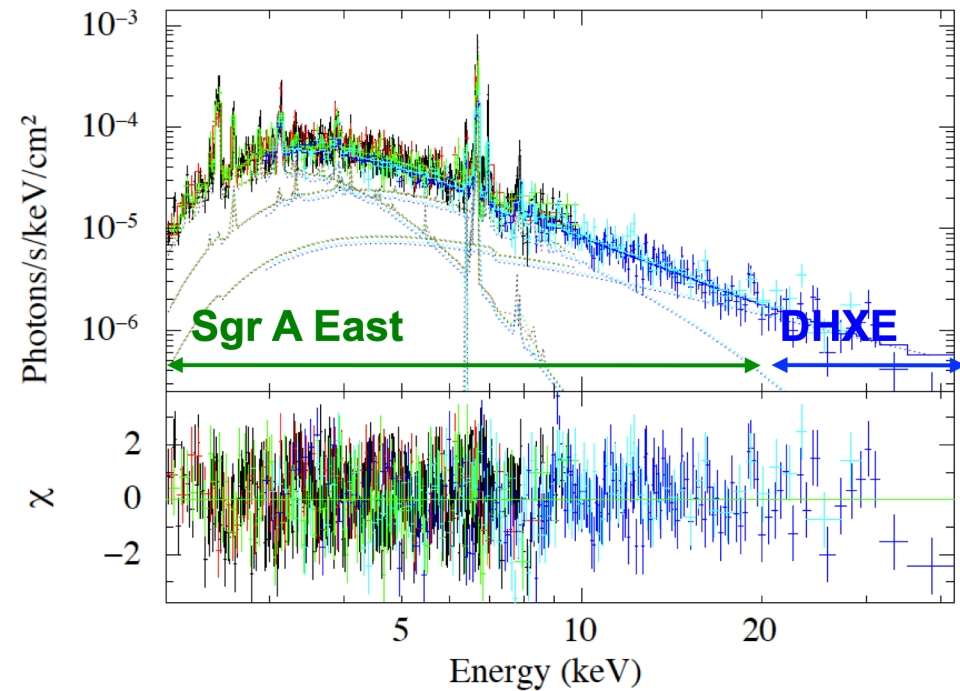
$$N(E) = E^{-\Gamma} \text{ with } \Gamma = 1.5^{+0.3}_{-0.2}$$

OR

Thermal bremsstrahlung with  $kT \sim 60 \text{ keV} (> 35 \text{ keV})$



# “Northeast” region shows same high-energy spectrum



- Below 20 keV, dominated by:

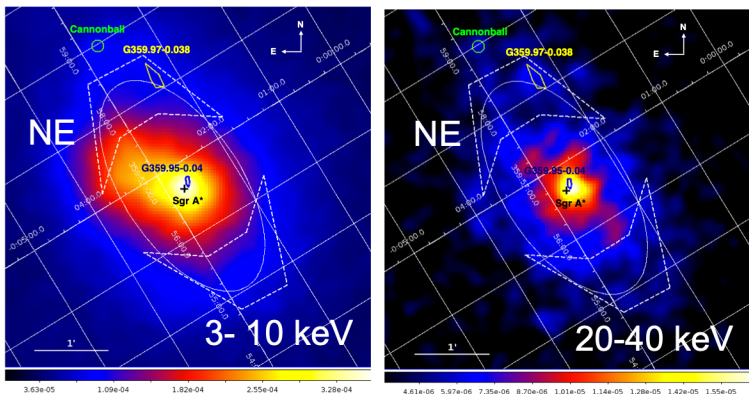
$$\left. \begin{aligned} kT_1 &= 1.1^{+0.1}_{-0.2} \text{ keV} \\ kT_2 &= 5.1^{+0.9}_{-0.7} \text{ keV} \\ Z &= 2.3^{+0.9}_{-0.4} \end{aligned} \right\} \text{The SNR Sgr A East}$$

- Above 20 keV dominated by:

$$N(E) = E^{-\Gamma} \text{ with } \Gamma = 1.6^{+0.3}_{-0.4}$$

OR

Thermal bremsstrahlung with  $kT \sim 60 \text{ keV} (> 36 \text{ keV})$



# Origins of Diffuse Hard X-ray Emission (DHXE)



Any possible explanation of the DHXE must account for:

- symmetric along the Galactic plane around Sgr A\*
  - non-thermal with  $\Gamma \approx 1.6$  or thermal with  $kT \approx 60$  keV ( $>36$  keV)
  - $L(20-40$  keV)  $\approx 2.4 \times 10^{34}$  ergs/s within the  $8$  pc  $\times$   $4$  pc FWHM
- 
- Anomalously **massive Intermediate Polars** (IPs) with  $\langle M_{WD} \rangle \approx 0.9 M_{\odot}$
  - Quiescent **black hole low-mass X-ray binaries** (qBH-LMXB)
    - Previously undiscovered large population ( $\sim 600-1200$ )
    - Must have very faint or long-recurrence outburst
  - **Millisecond pulsars** with non-thermal high-energy spectrum
    - Previously undiscovered large population ( $\sim 3000$ )
  - Bremsstrahlung and inverse Compton emission from **Sgr A\* particle outflows** interacting with dense molecular material (Dogiel et al. 2015)
    - No correlation with radio or radiation density models

# Galactic Center in X-rays

Remaining non-thermal emission:  
multiple scatterings  
or/and CRs?

“Naked” stellar  
cluster, search for  
CR acceleration

Hard X-ray  
diffuse emission

SNR  $0.9 \pm 0.1$

Sagittarius B2

Sagittarius B1

1E 1743.1-2843

Arches  
Cluster

DB00-58

Sagittarius A

Quintuplet  
Cluster

DB00-6

Cold Gas Cloud  
& Radio Arc

---

*Спасибо за внимание !!!*

*Thanks for your attention !!!*

*Շնորհակալութիւն ուշադրութիւն  
համար !!!*