

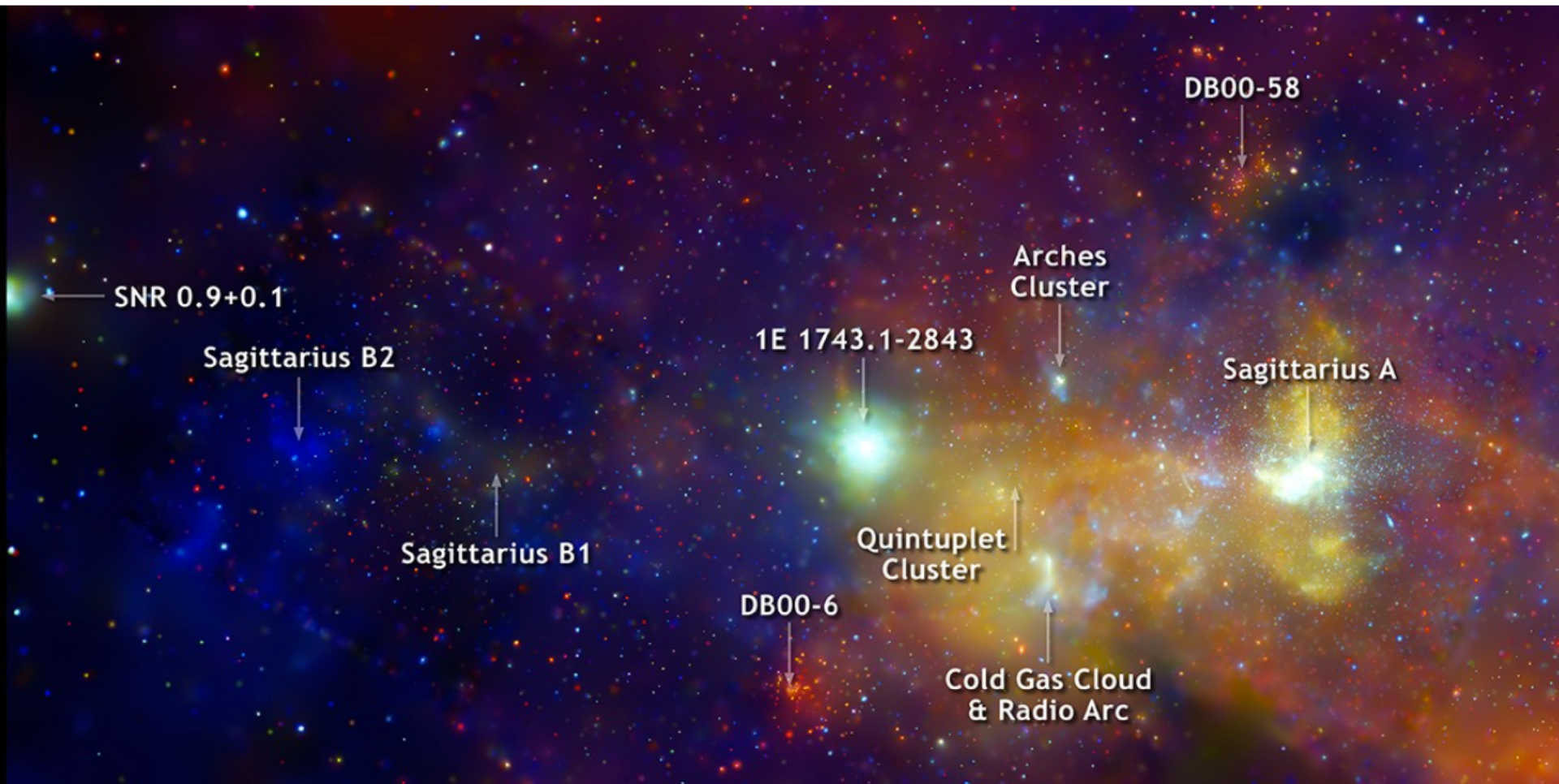
# X-ray emission from the Galactic Center

Roman Krivonos

Space Research Institute (IKI), Moscow, Russia

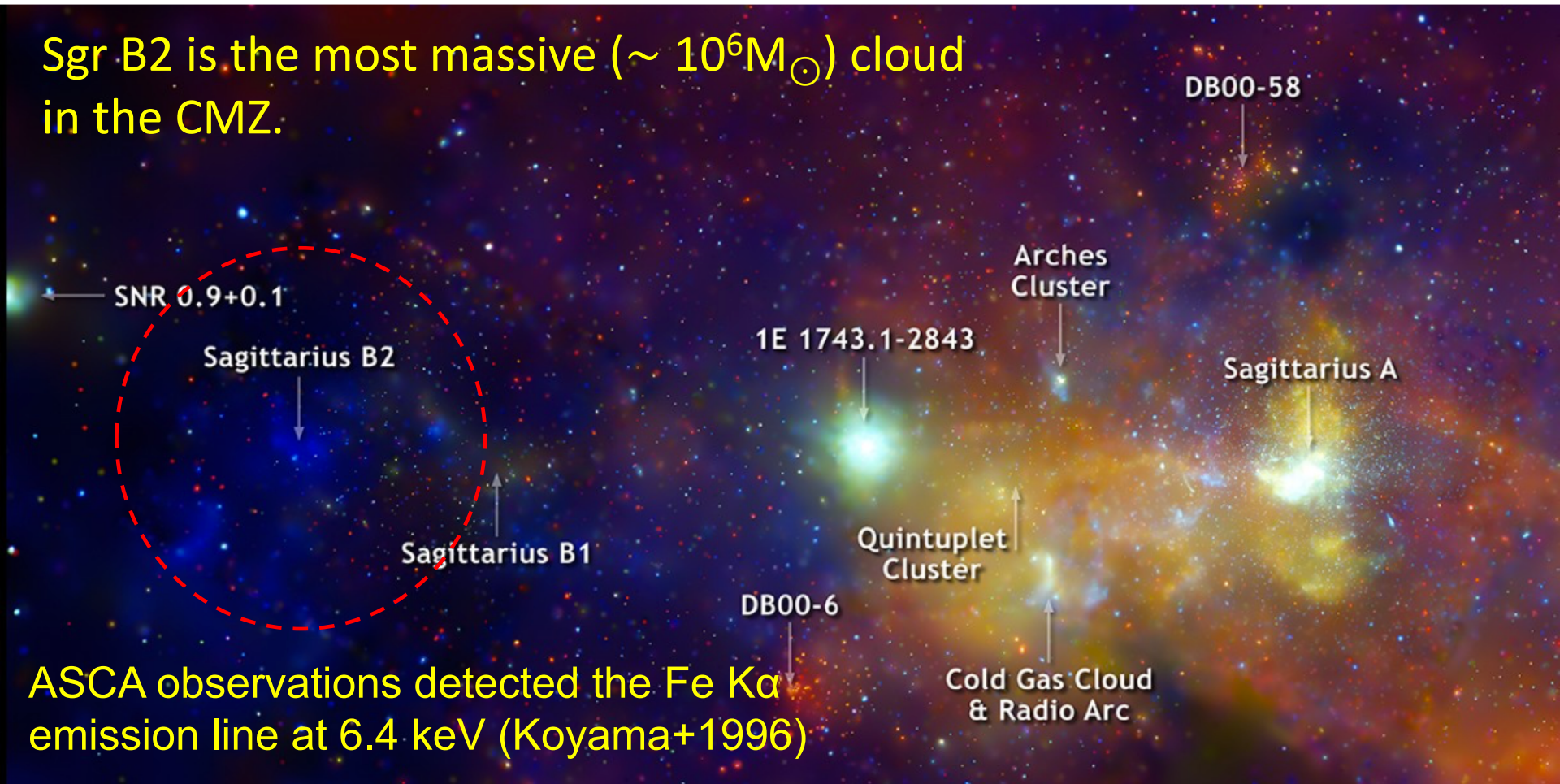
# Reflection in the GC (CMZ, Sgr B2, Arches cluster)

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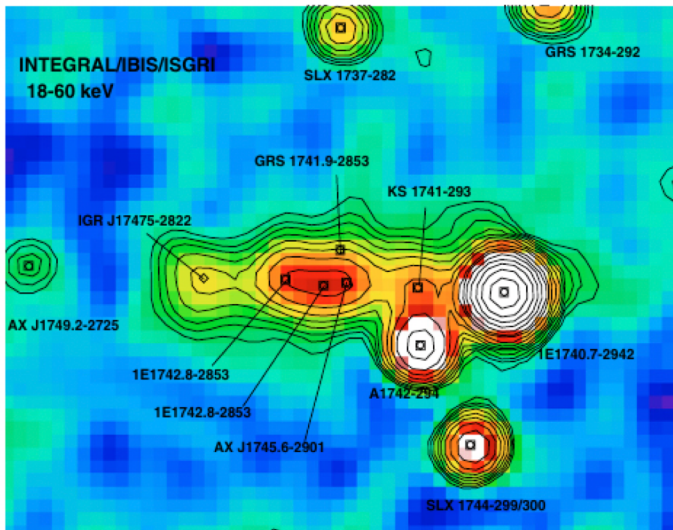
# Sgr B2 molecular cloud

Sgr B2 is the most massive ( $\sim 10^6 M_{\odot}$ ) cloud in the CMZ.

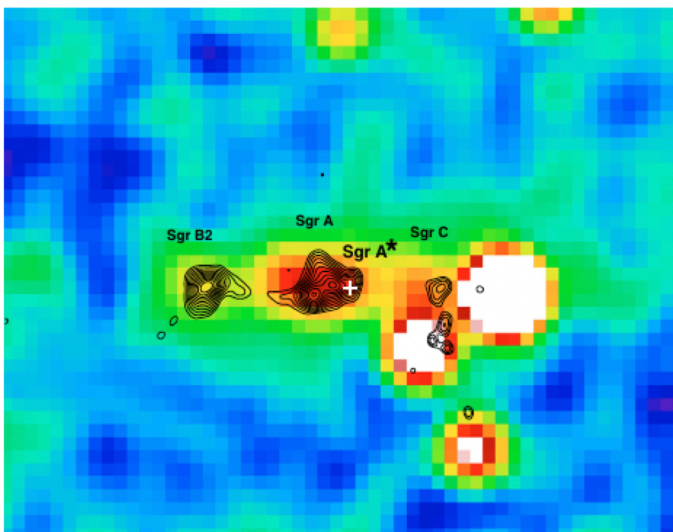
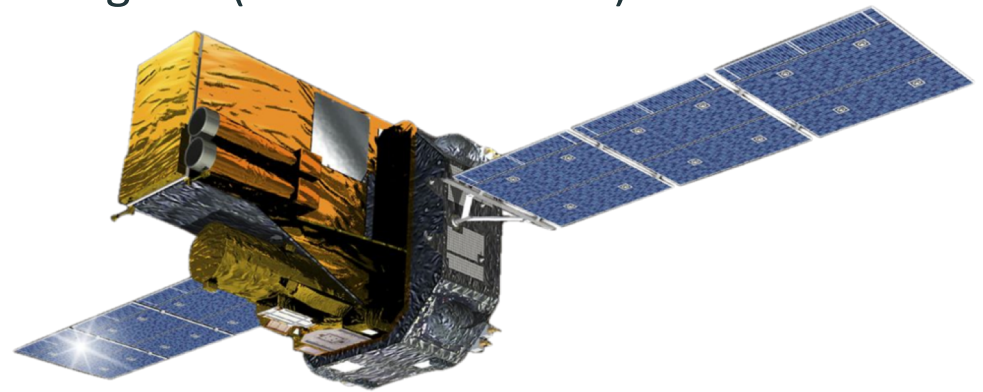


ASCA observations detected the Fe K $\alpha$  emission line at 6.4 keV (Koyama+1996)

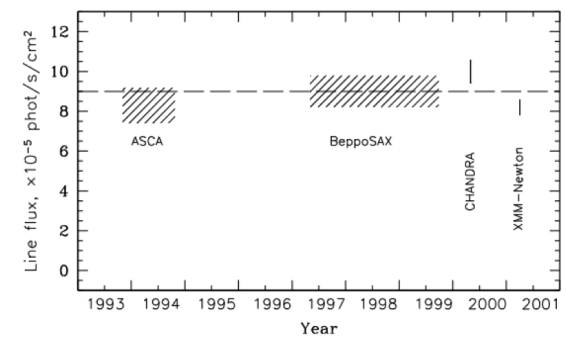
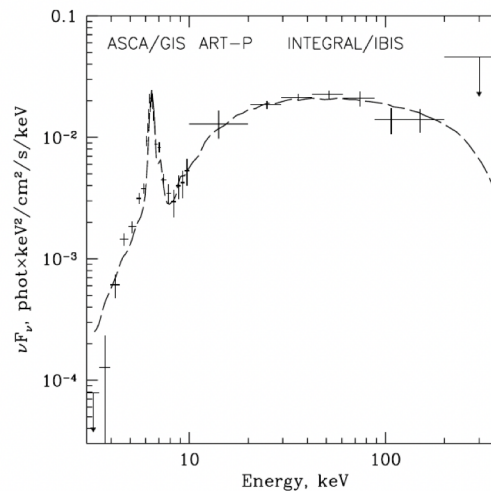
# Sgr B2 molecular cloud



**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

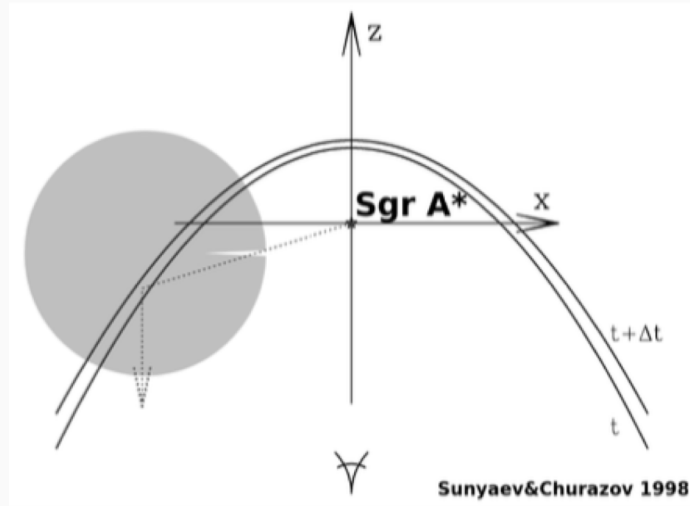
Sgr A\* is a supermassive black hole with a mass of  $4.3 \cdot 10^6 M_{\odot}$  situated in the Galactic Center (GC).

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*

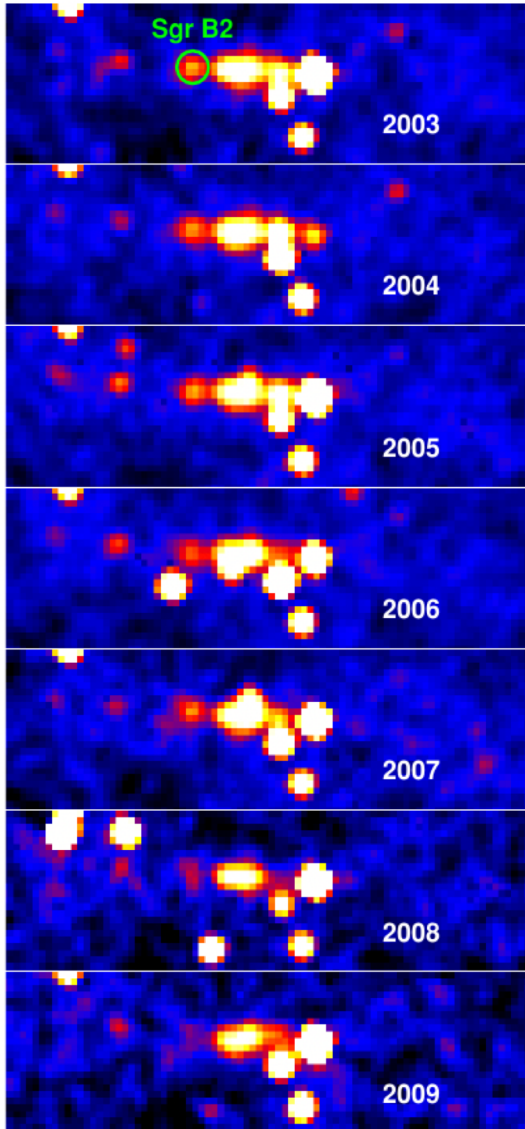
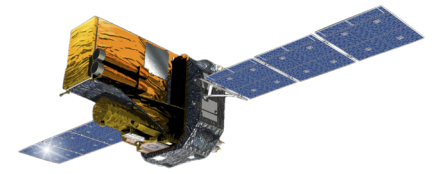
An alternative hypothesis of the X-ray emission generation is bombardment of a neutral matter by low-energy cosmic ray (LECR) particles.

### **Requirements:**

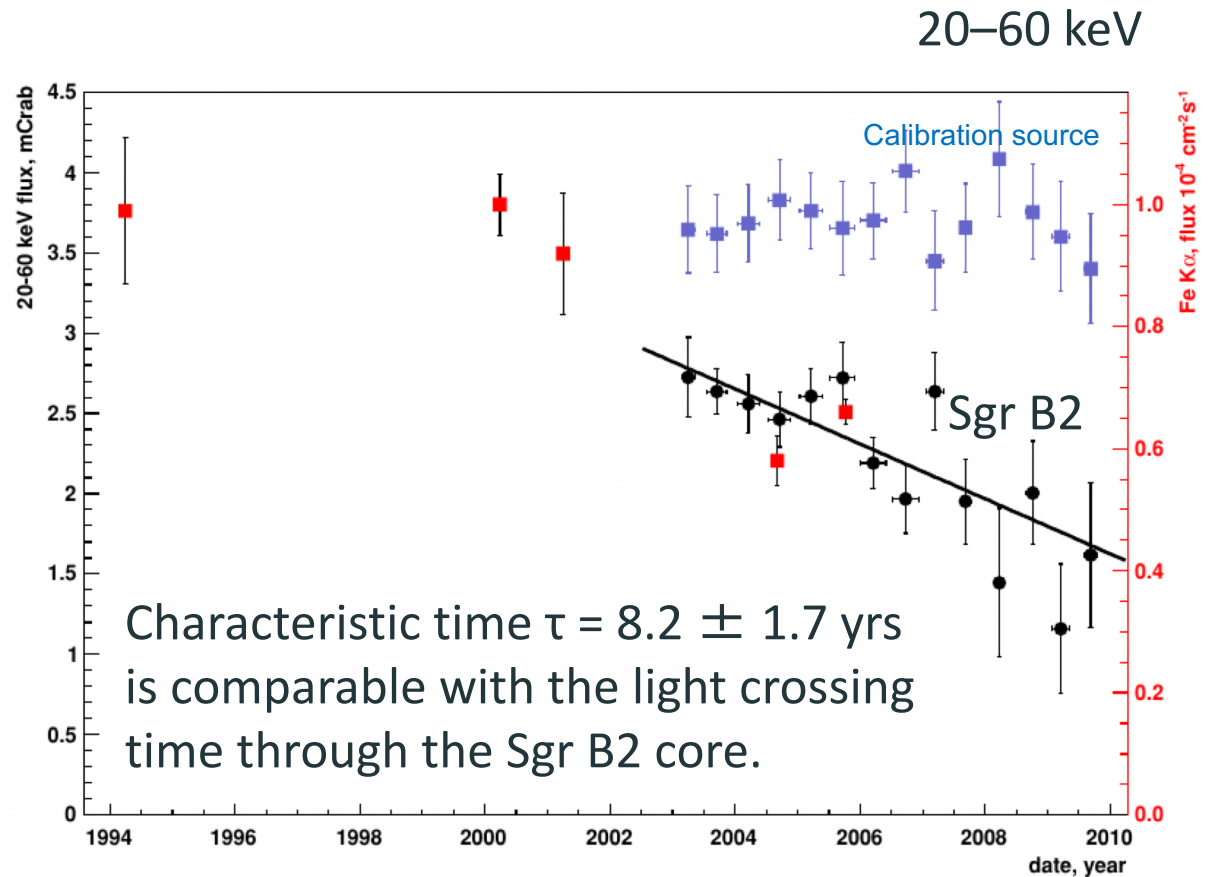
- presence of a LECR flow with a sufficient density and power
- Fe  $K_{\alpha}$  line with  $EW_{6.4 \text{ keV}} < 1 \text{ keV}$
- hard X-ray continuum
- absence of a multi-year time variability
- photon index of the continuum depends on the CR slope

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

# Sgr B2 molecular cloud

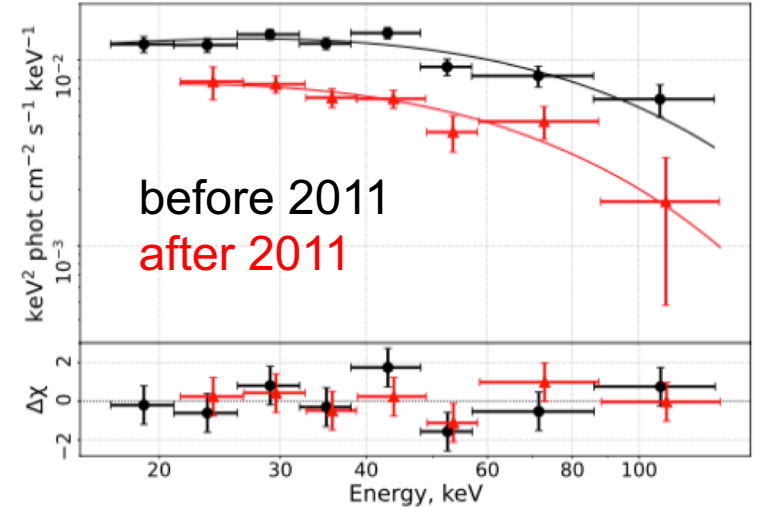
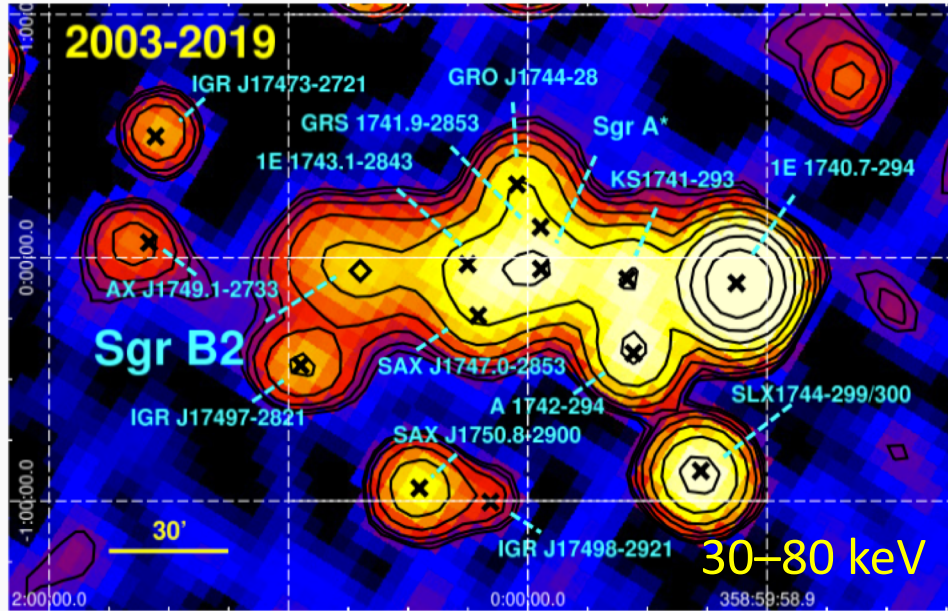
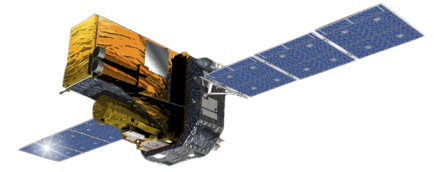


Sgr B2 light curve in the 20–60 keV energy band (black data) obtained from 2003 to 2010.



Terrier+ 2010

# Sgr B2 molecular cloud

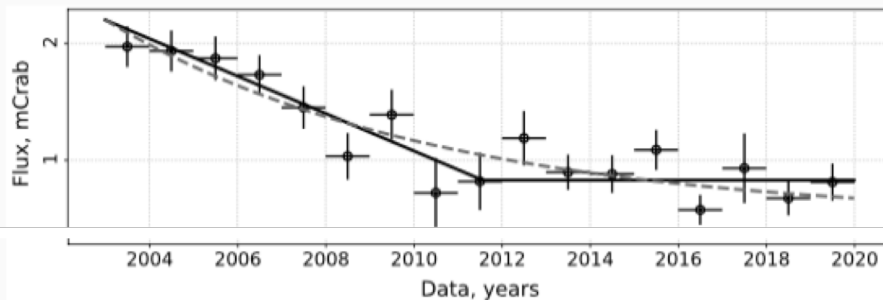


## Reflection scenario

- 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+2011) model.
- Estimated cosmic ray ionization rate too high compared to the GC



Constant flux level after 2011

Kuznetsova+ 2021

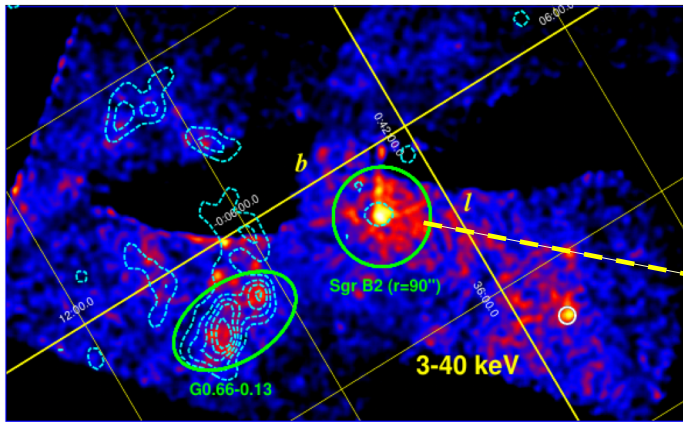


# Sgr B2 molecular cloud after 2011

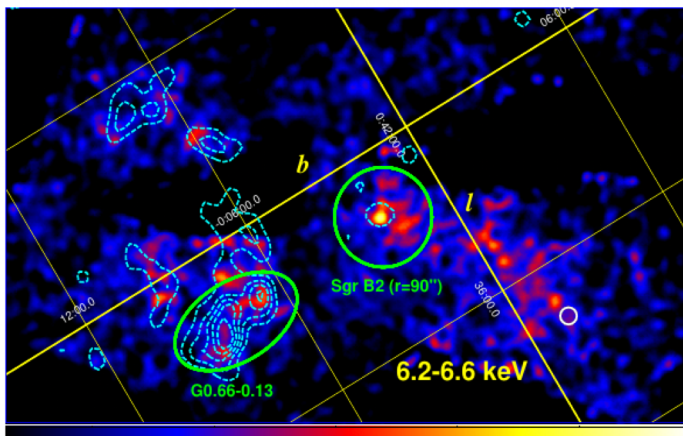


NuSTAR 2013

SRG/ART-XC May 2026

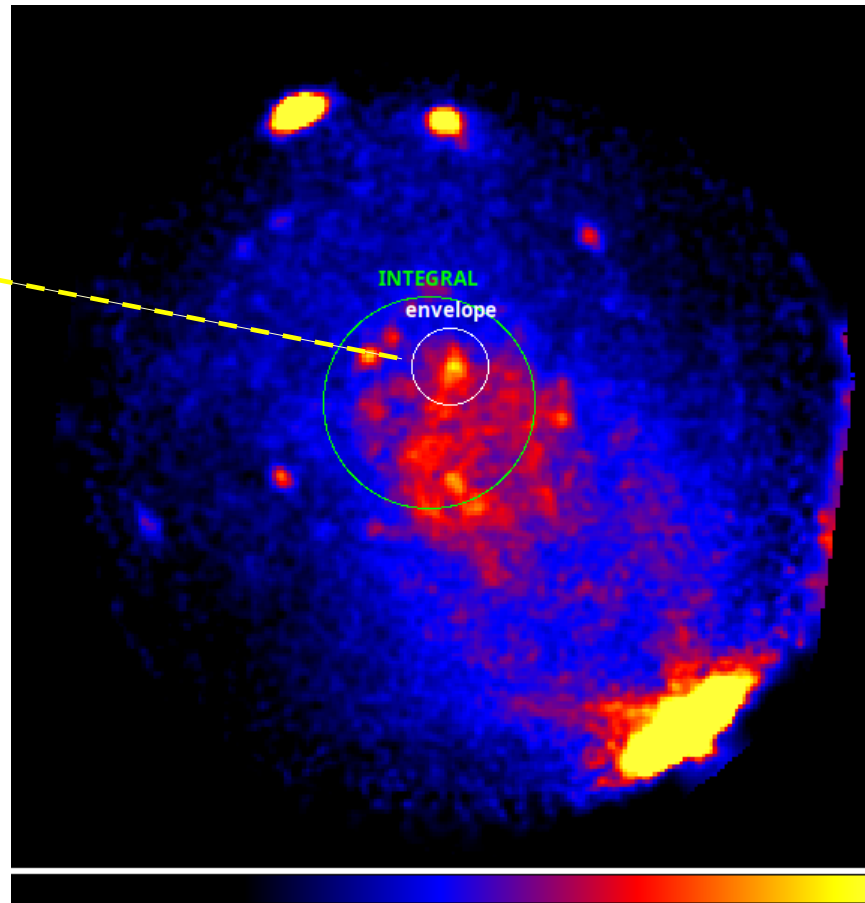


1E-05 1.2E-05 1.4E-05 1.6E-05 1.8E-05 2E-05 2.2E-05 2.4E-05 2.6E-05 2.8E-05



1E-06 1.5E-06 2E-06 2.5E-06 3E-06

Zhang+2015



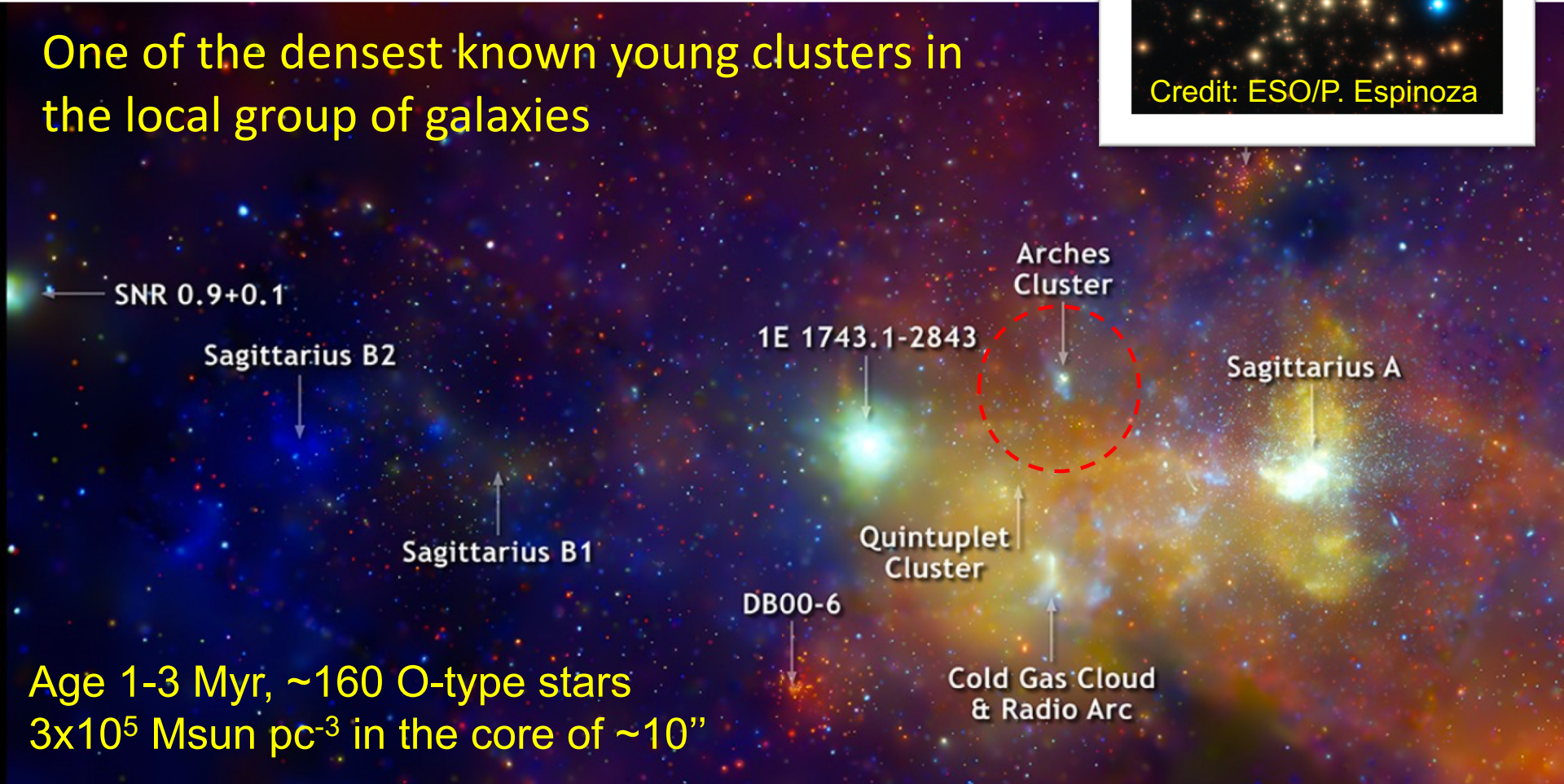
0.00011 0.00023 0.00035 0.00046 0.00058 0.00069 0.00081 0.00092 0.00104

E. Shtykovskaya (Kuznetsova) in prep.

# The Arches cluster



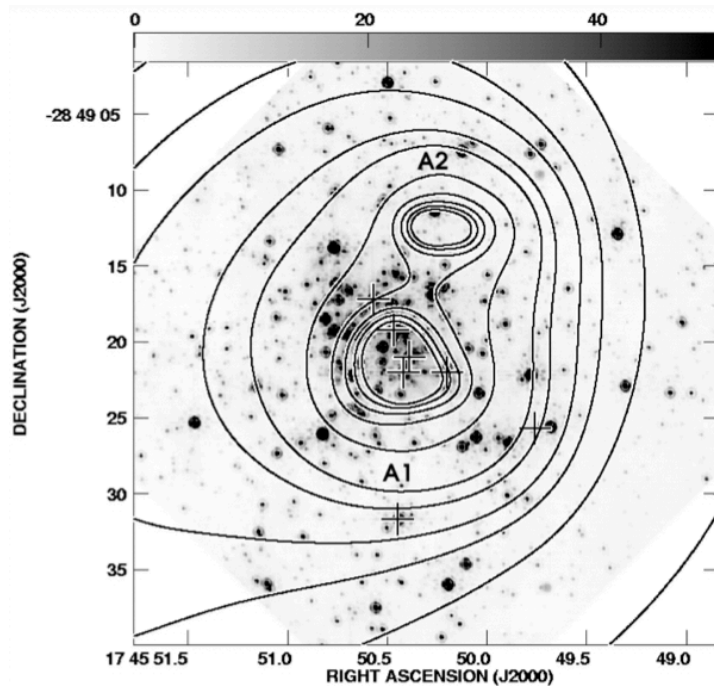
One of the densest known young clusters in the local group of galaxies



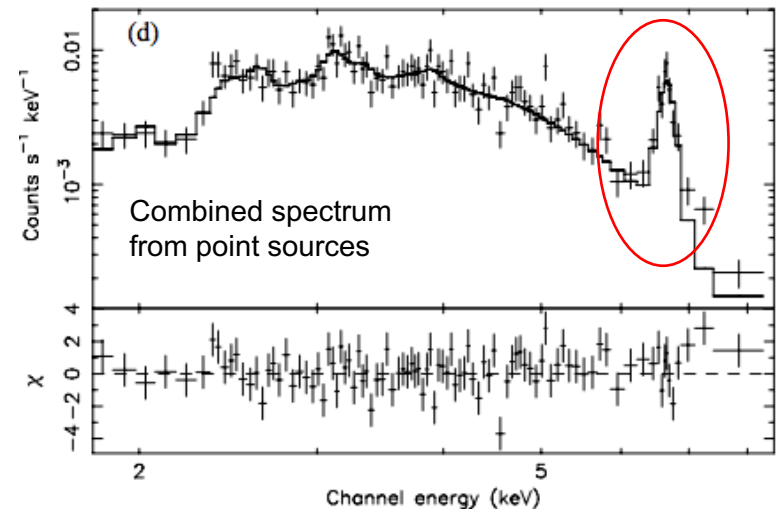
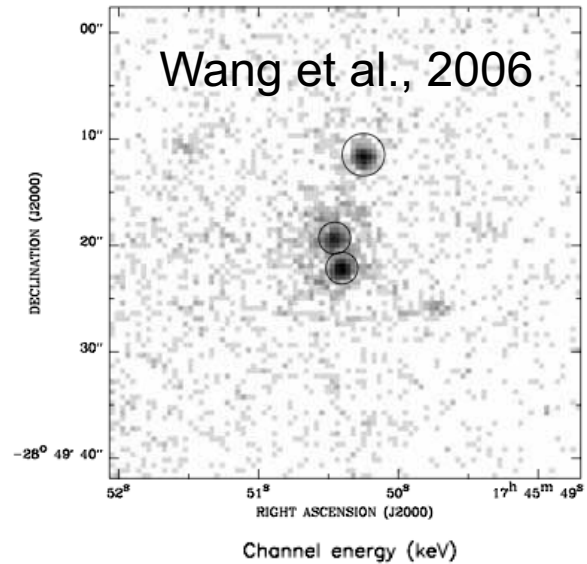
Age 1-3 Myr, ~160 O-type stars  
 $3 \times 10^5 \text{ Msun pc}^{-3}$  in the core of  $\sim 10''$

# X-ray emission from the Arches cluster

Thermal emission from the cluster: colliding winds from massive stars



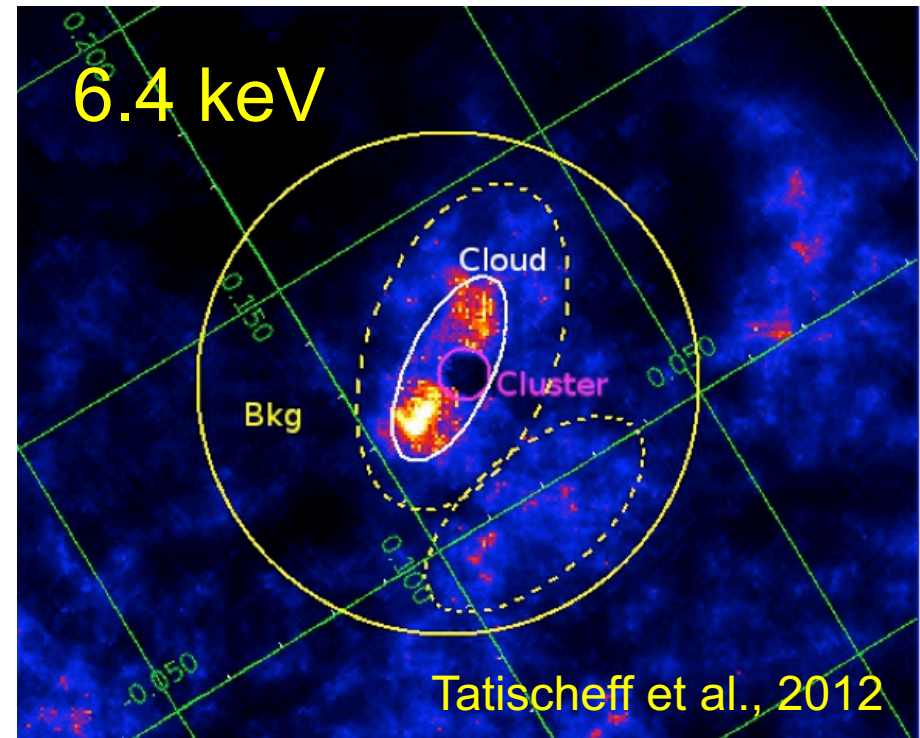
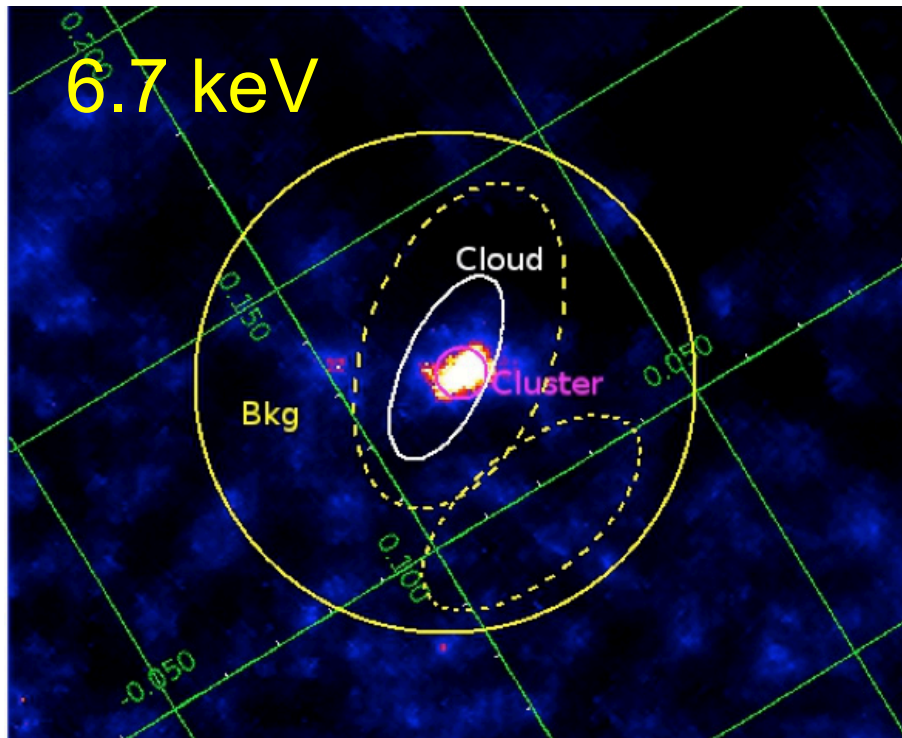
*Chandra* - Yusef-Zadeh et al. (2002)



Strong Fe K $\alpha$  6.7 keV line:

# *X-ray emission from the Arches cluster*

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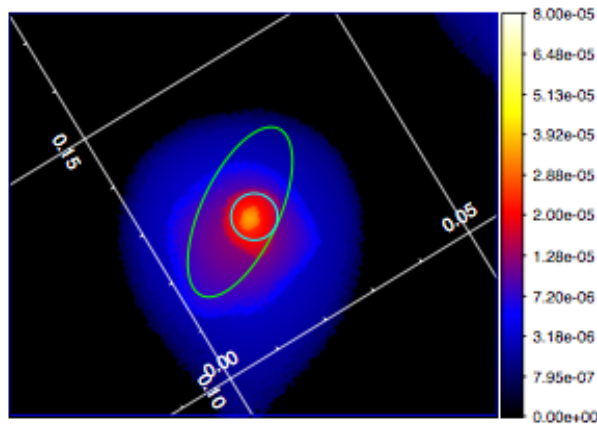


Origin of fluorescence?

# NuSTAR: X-ray image 2012

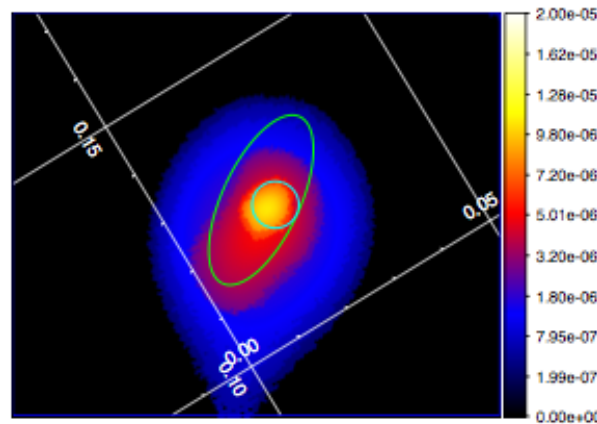
The Arches cluster is detected above 10 keV for the first time.

3-10 keV



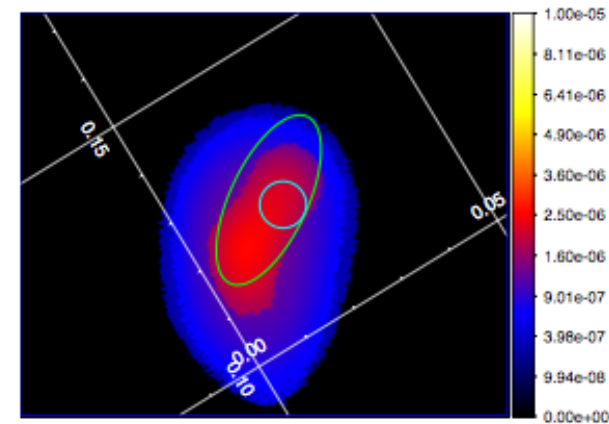
The core of the cluster and extended emission  
⇒ Thermal emission from the core dominates

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

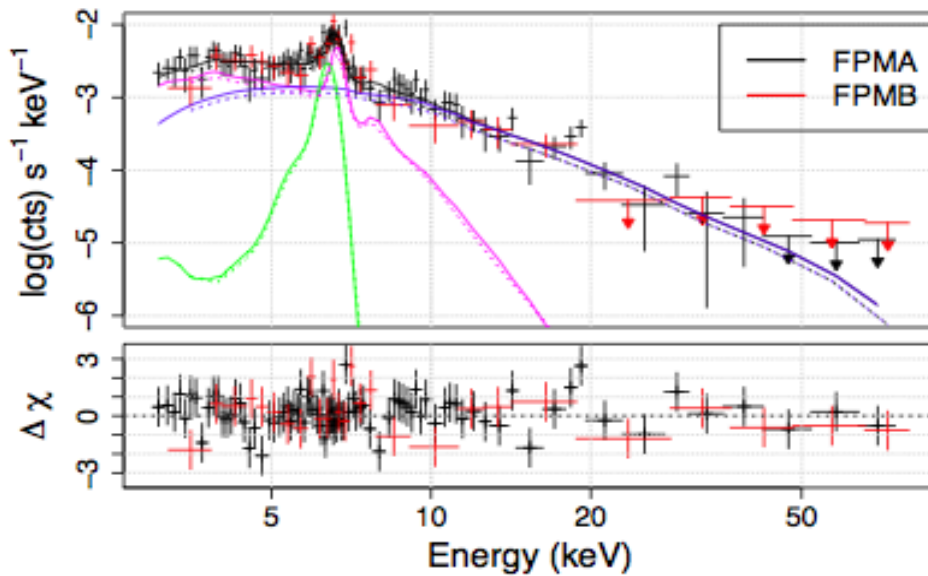
10-20 keV



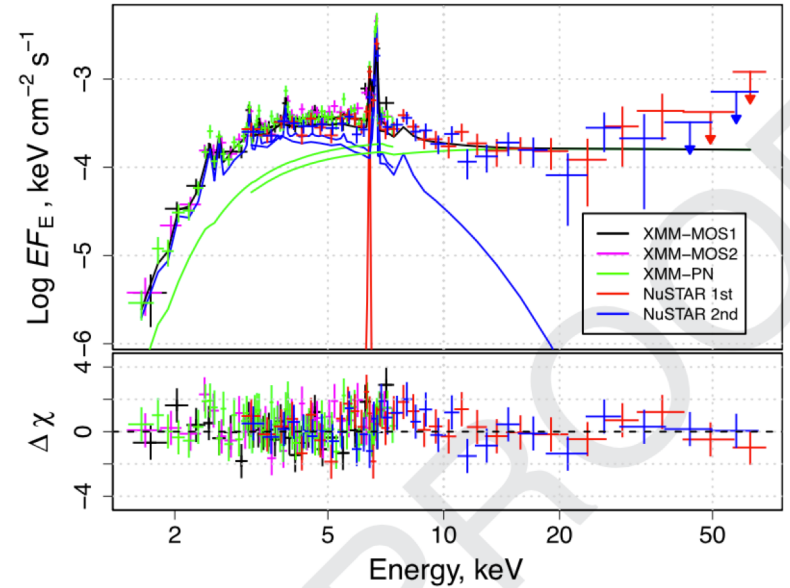
Non-thermal continuum  
⇒ No point sources in the core  
⇒ Continuum follows 6.4 keV line intensity

# XMM+NuSTAR: Spectral analysis

2012



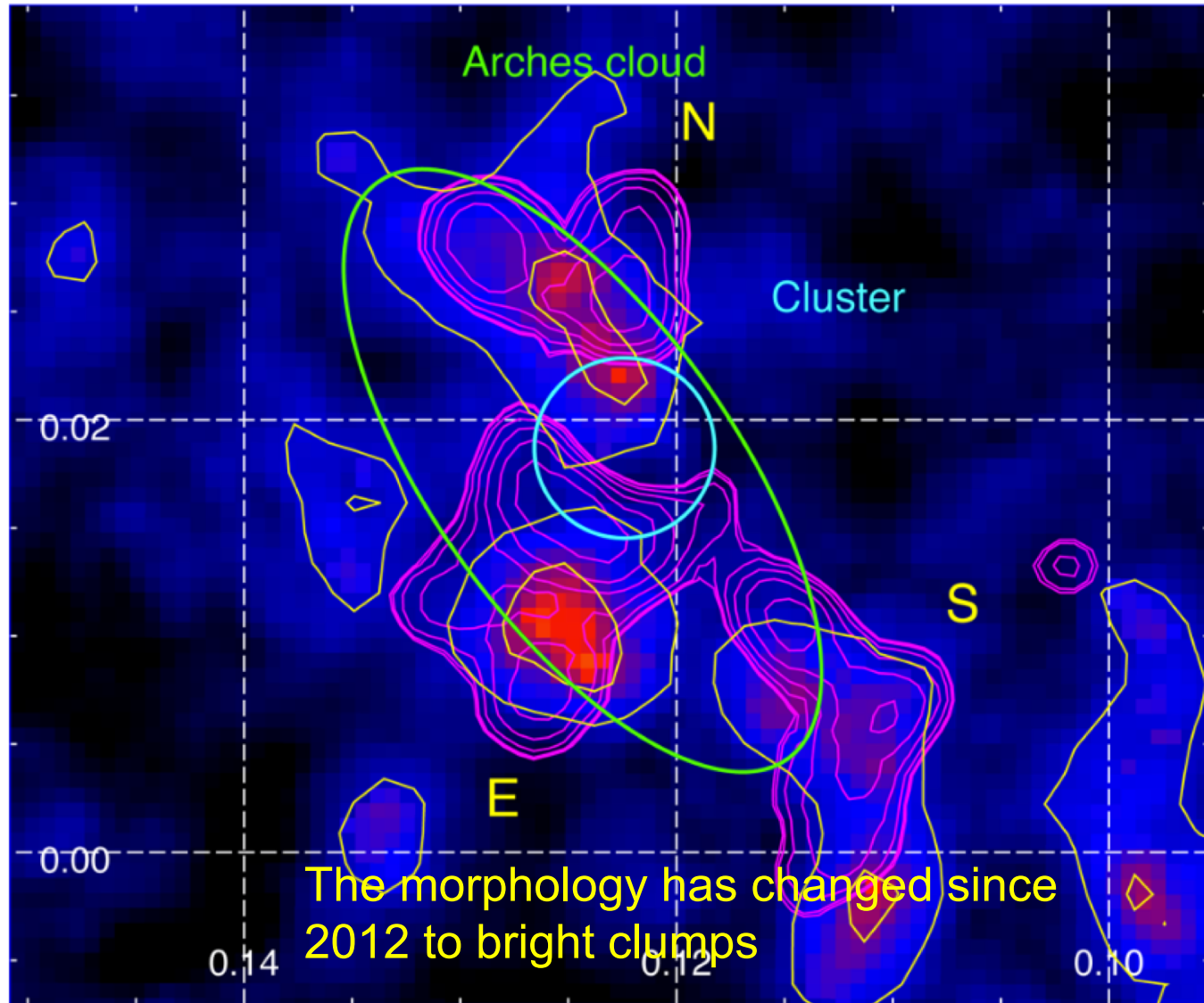
2015



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

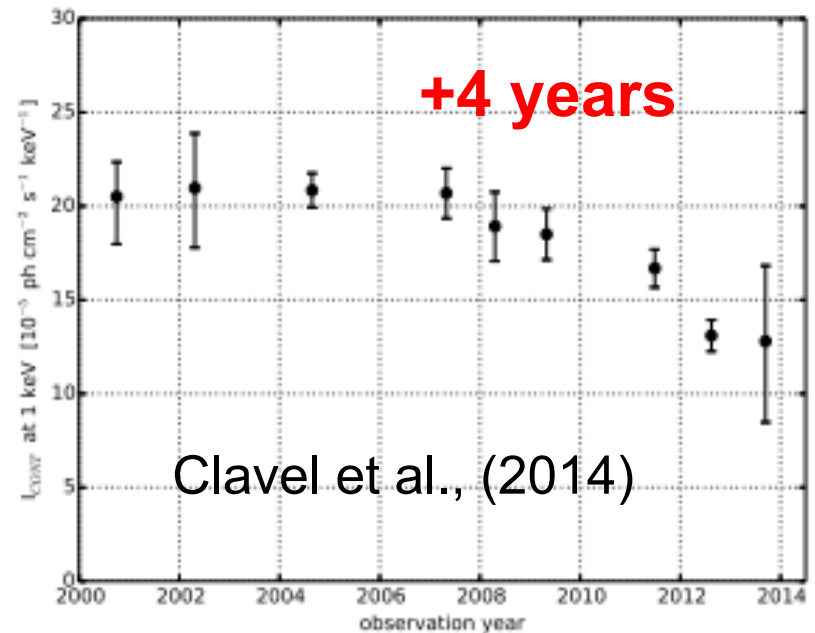
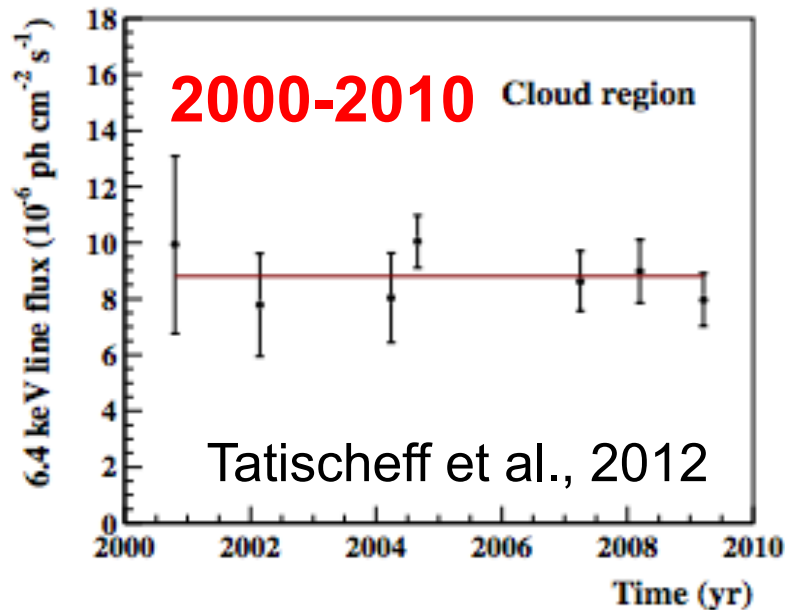
◆ Non-thermal continuum dominates above 10 keV

# Arches cloud morphology 2013-2015 (XMM)



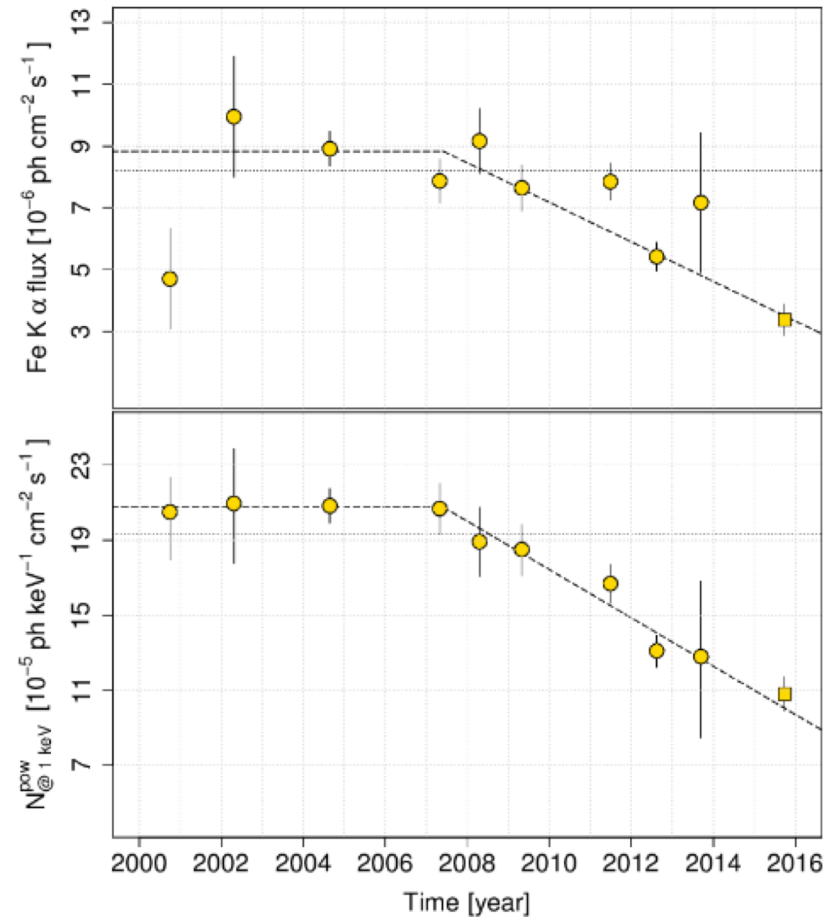
# Arches cloud (XMM)

- 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



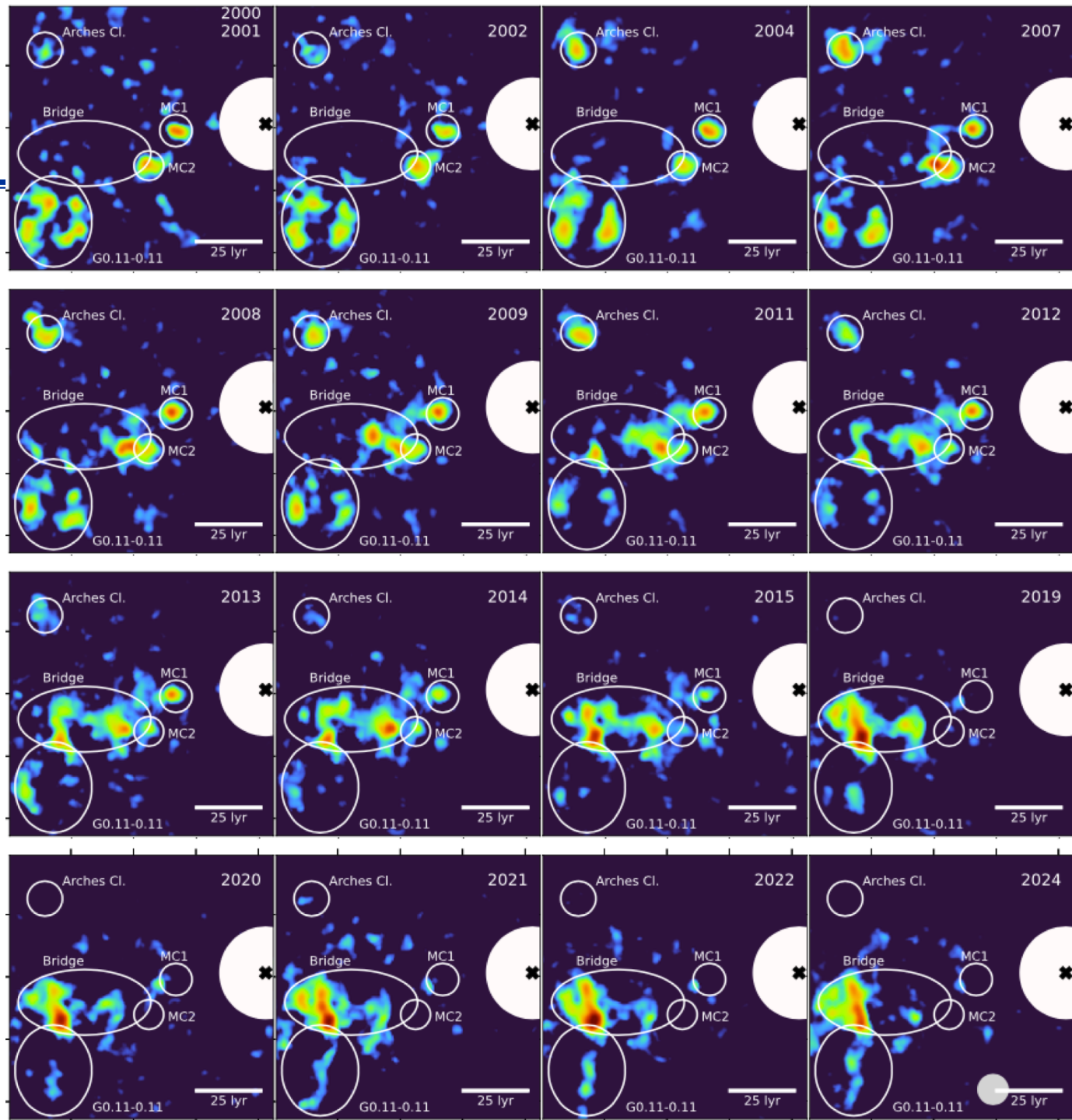
# Arches cloud after 2015

- 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



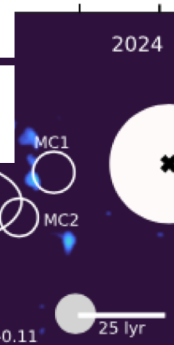
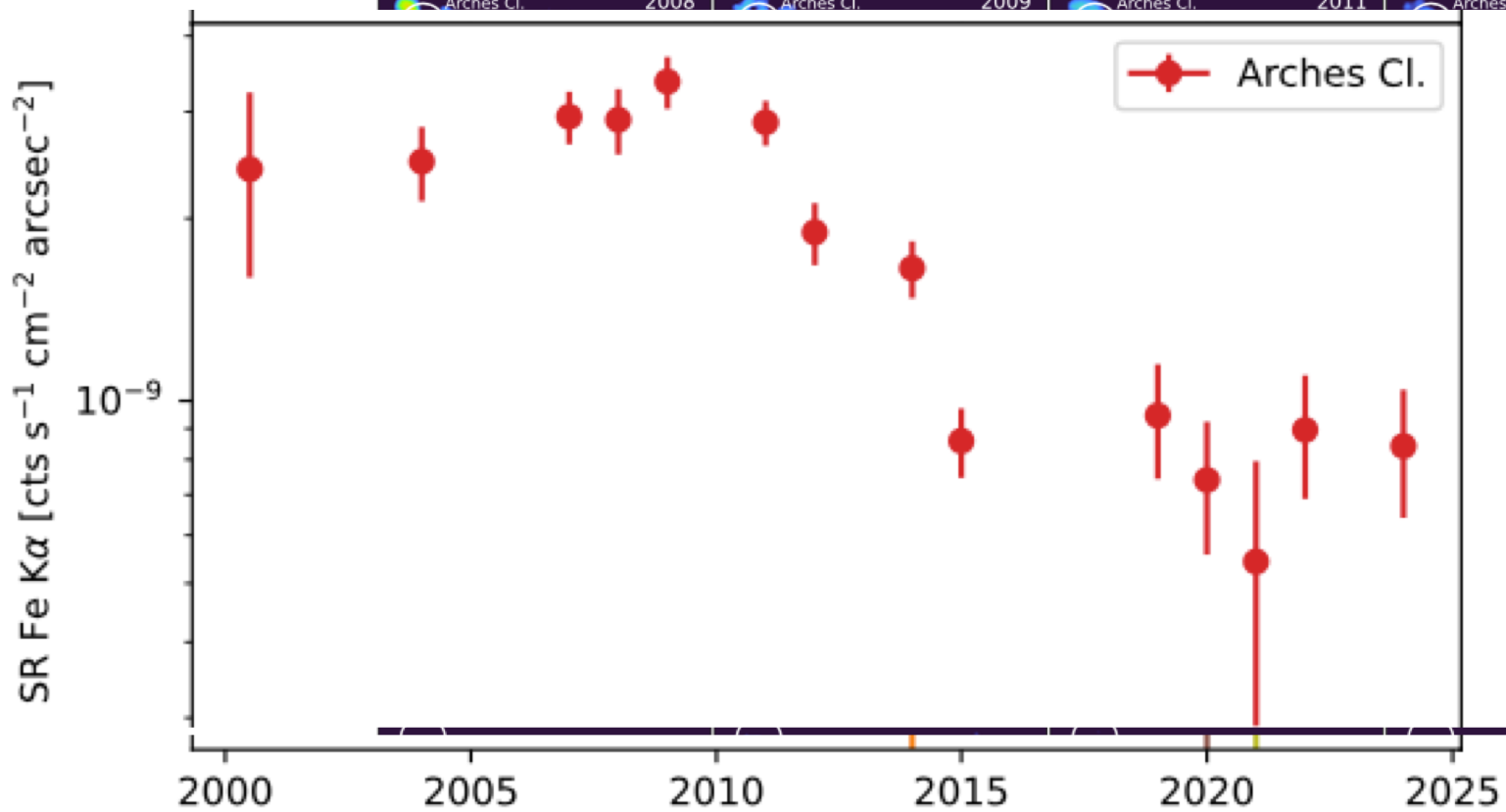
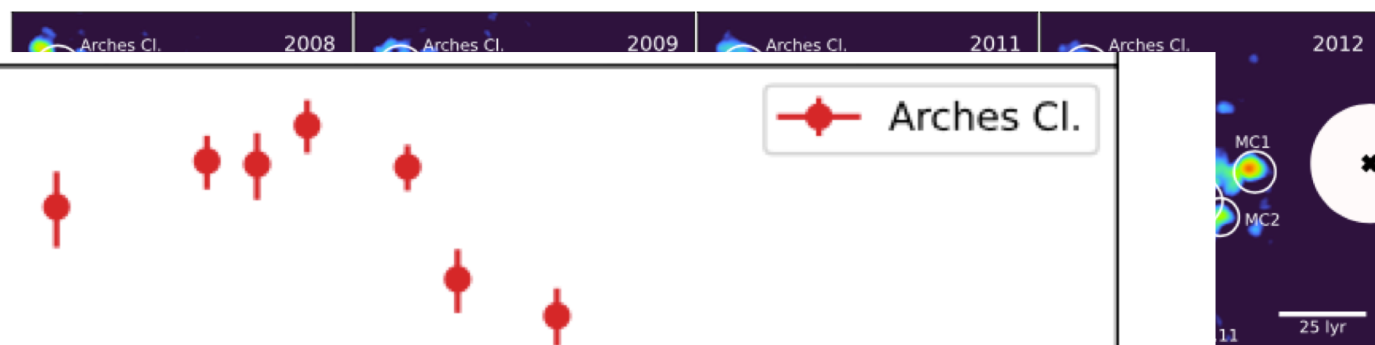
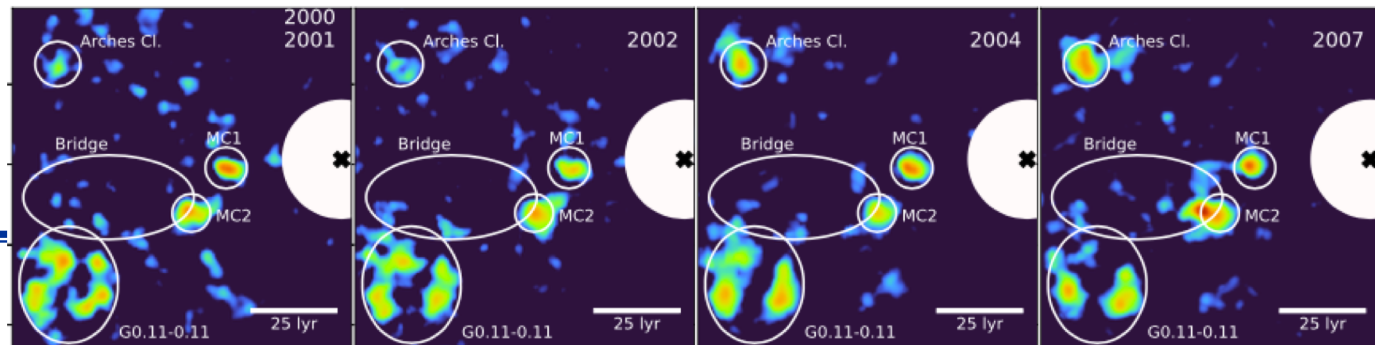
Krivosos+ 2016, Kuznetsova+ 2019

# 25 years of XMM observations of the Sgr A complex

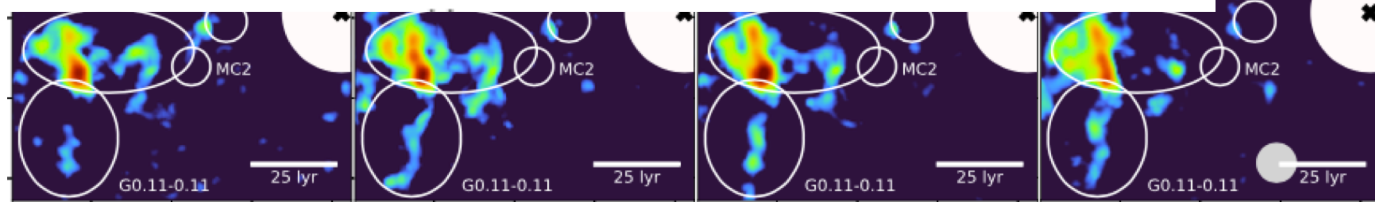


Stel+ 2025

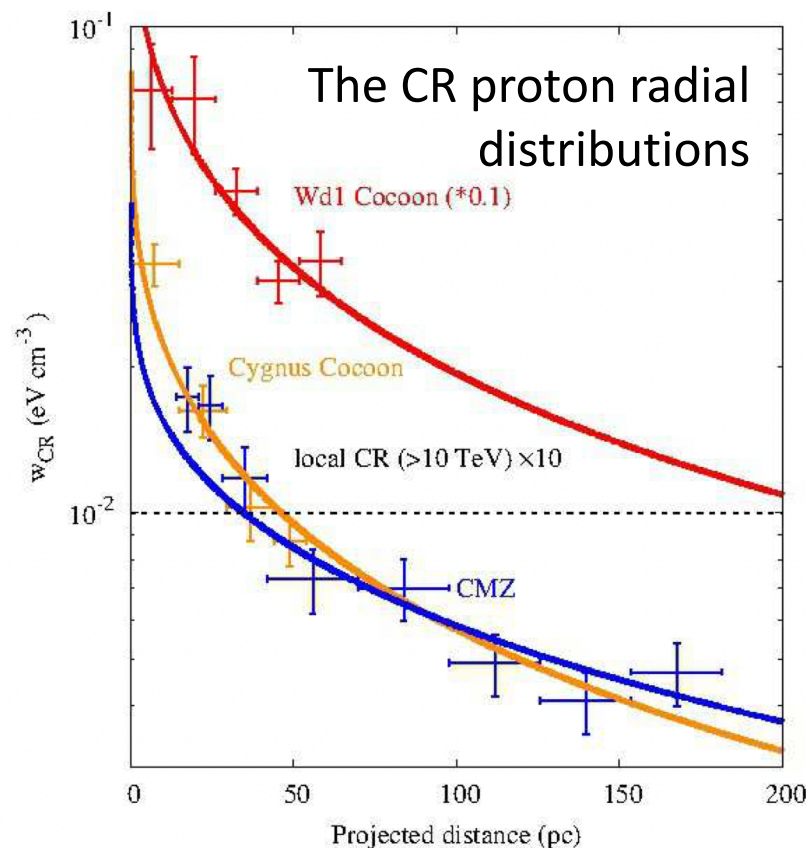
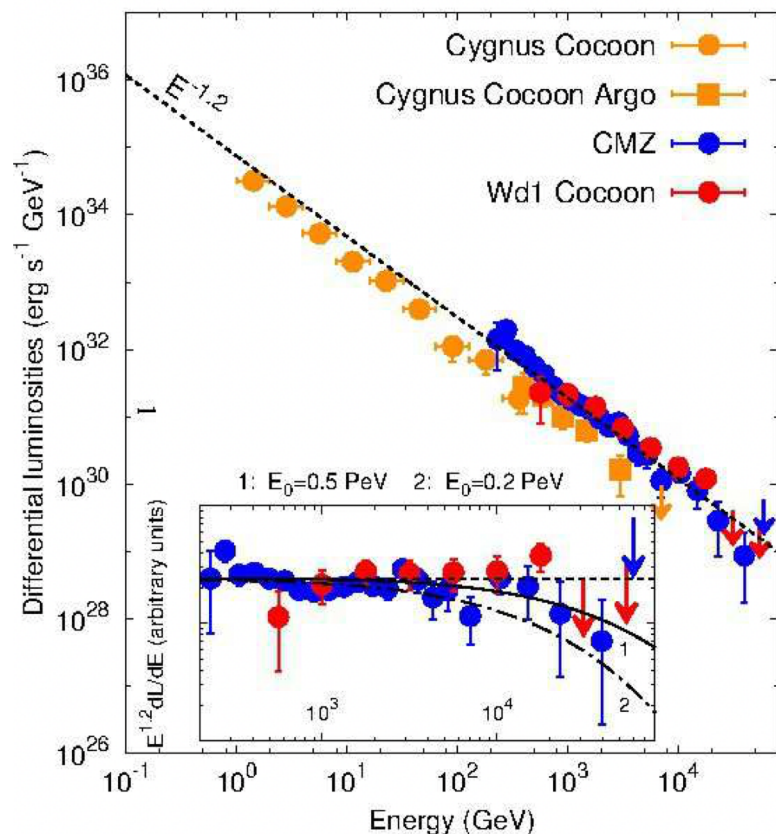
# 25 years of XMM observations of the Sgr A complex



Stel+ 2025



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

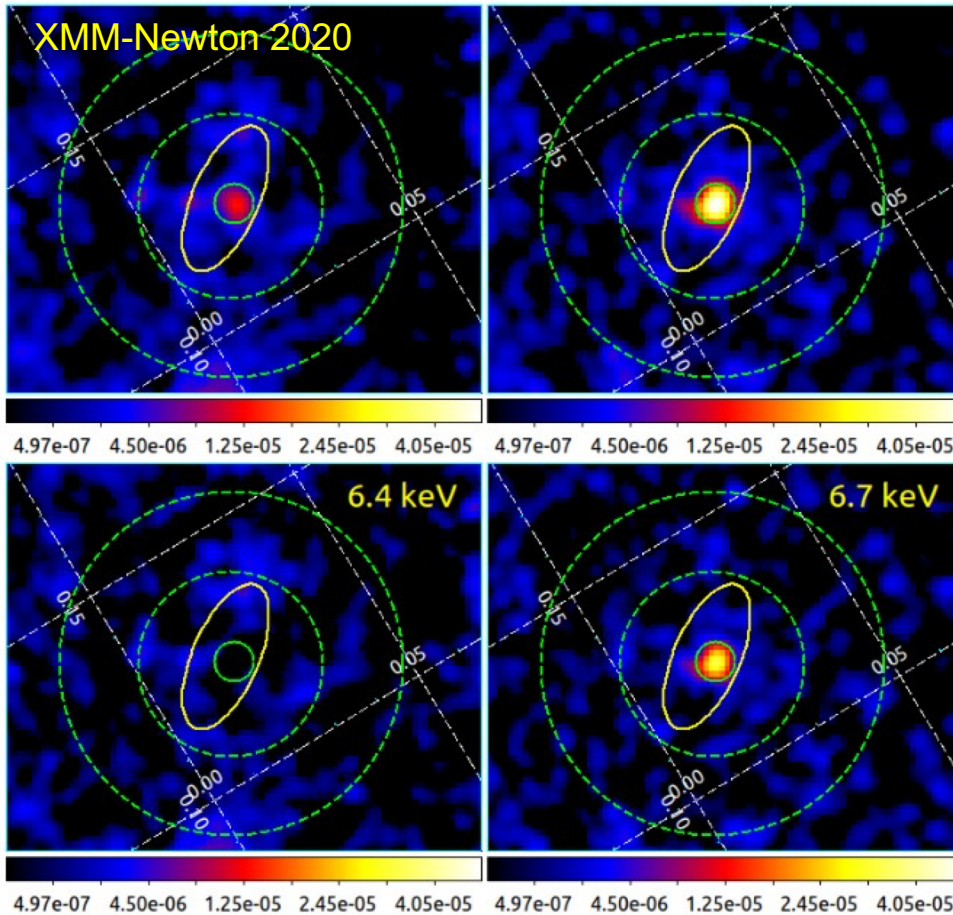


...“CRs responsible for the diffuse VHE  $\gamma$ -ray emission from the GC are accelerated by the ultracompact stellar clusters”

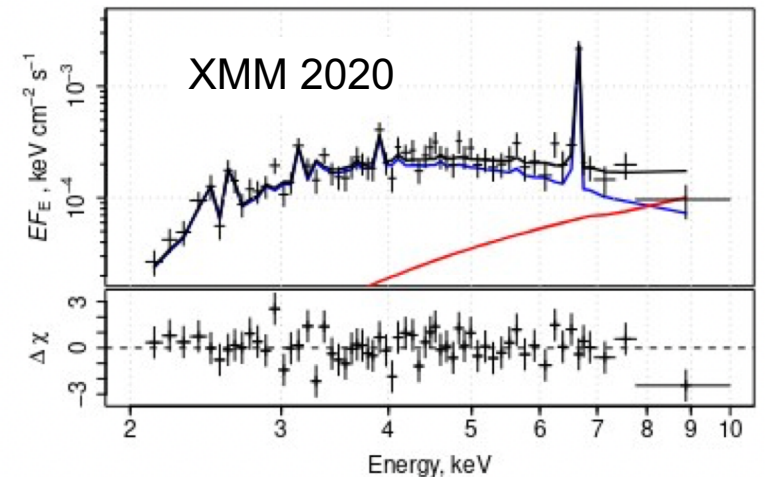
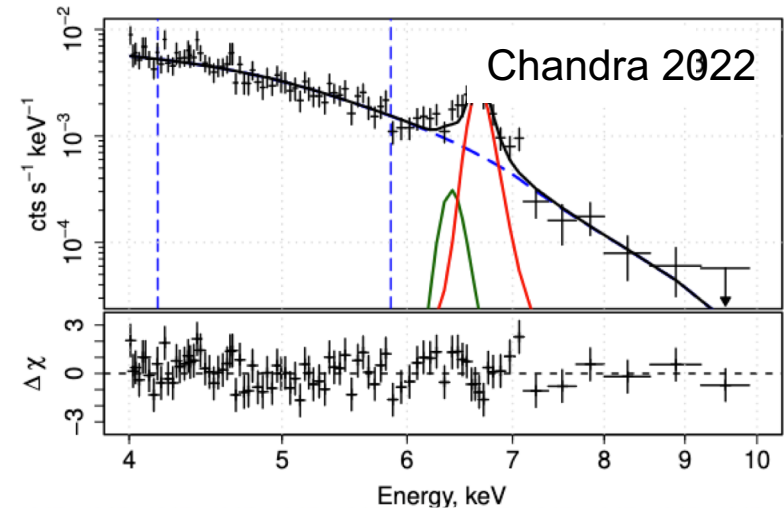
...“Arches, Quintuplet and Nuclear in GC, could be alternative sites for the CR acceleration”

# Arches cluster after 2015

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

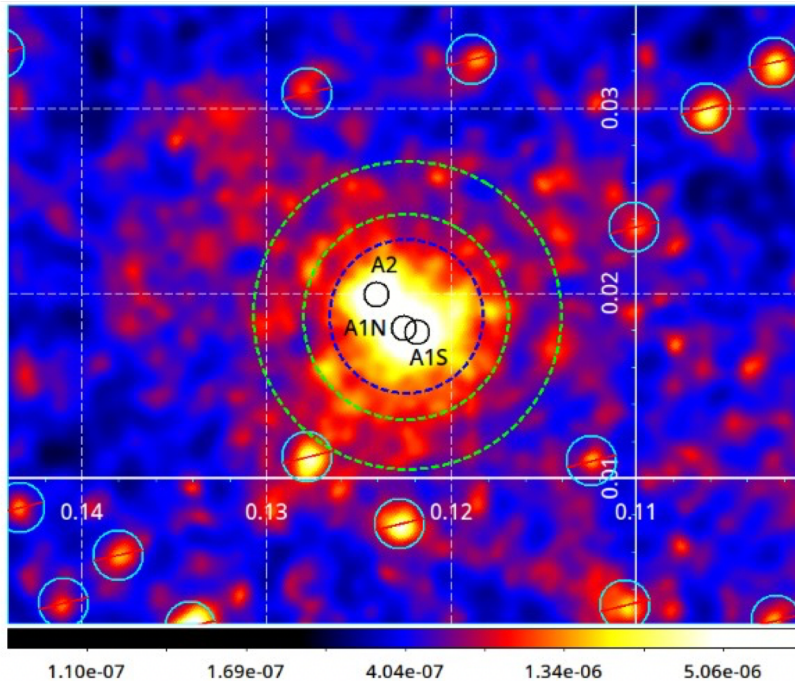


Krivonos+ 2025

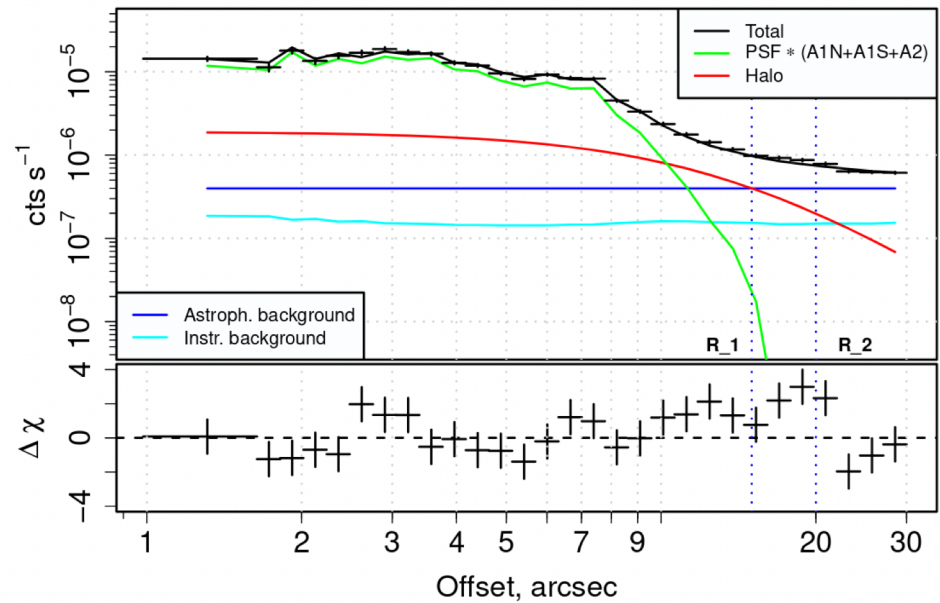


# Arches cluster after 2015

Chandra 2022



Spatial analysis



**Spatial halo is detected!**

Krivonos et al., in prep

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*Спасибо за внимание !!!*

*Thanks for your attention !!!*

*Շնորհակալութիւն ուշադրութիւն  
համար !!!*

- 
- The massive stellar cluster RMC 136 in LMC observed with *SRG/eROSITA* by Sasaki et al. (2022)