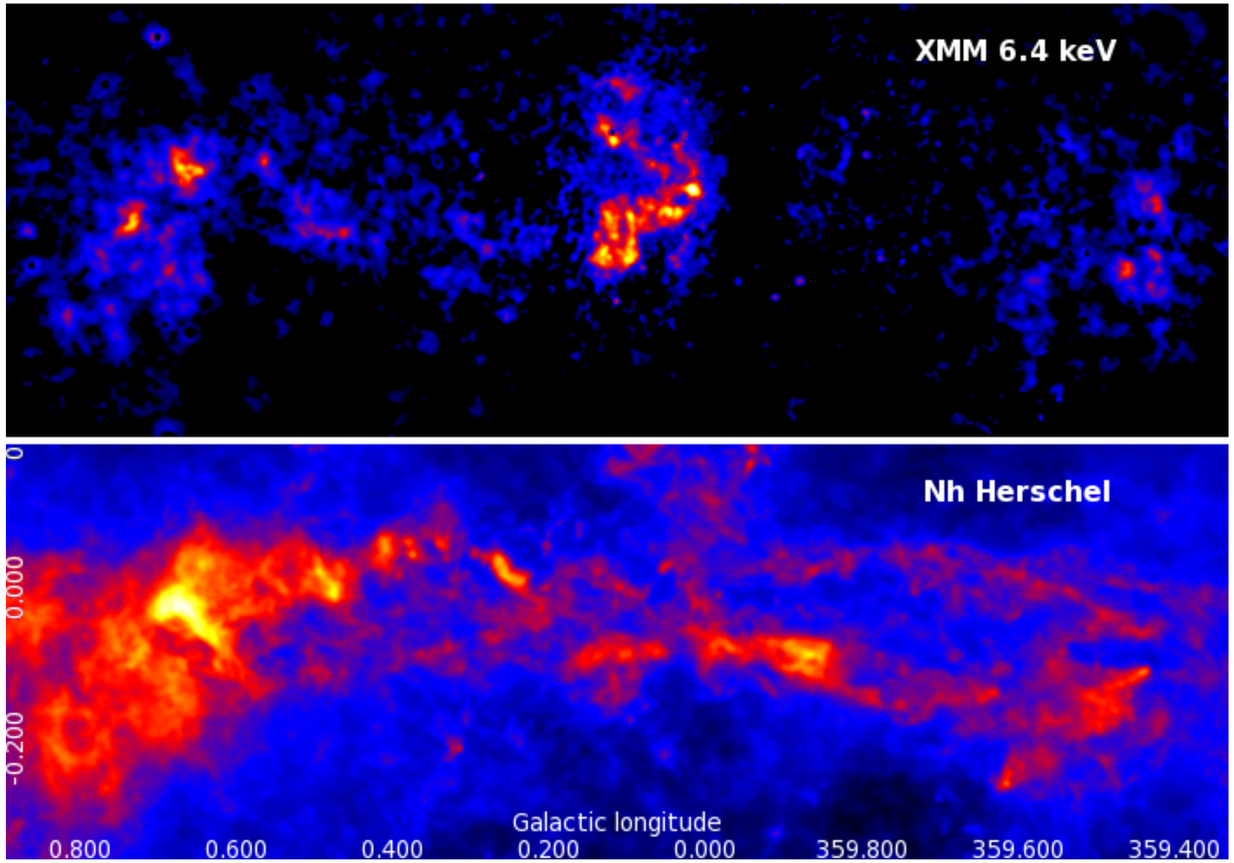
Past activity in the Galactic Centre



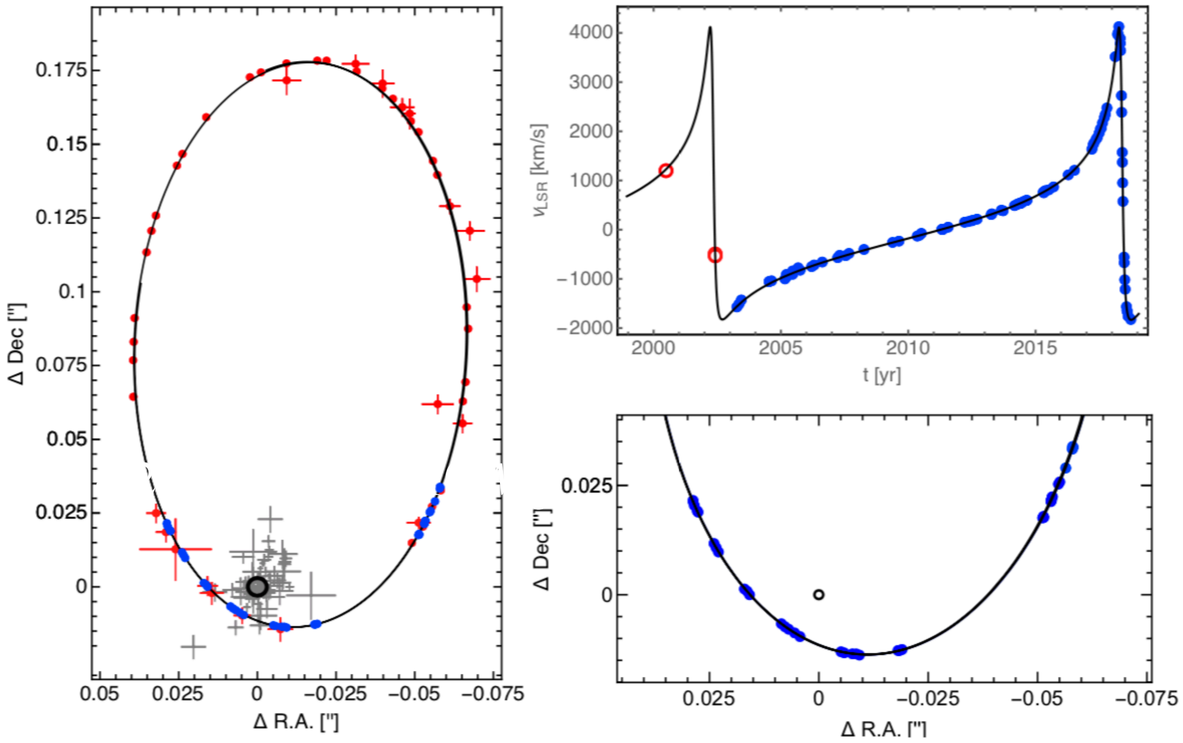
Variability of astrophysical sources across wavelengths: a tribute to Berrie

2025 November 18

R. Terrier
APC CNRS/Université Paris Cité

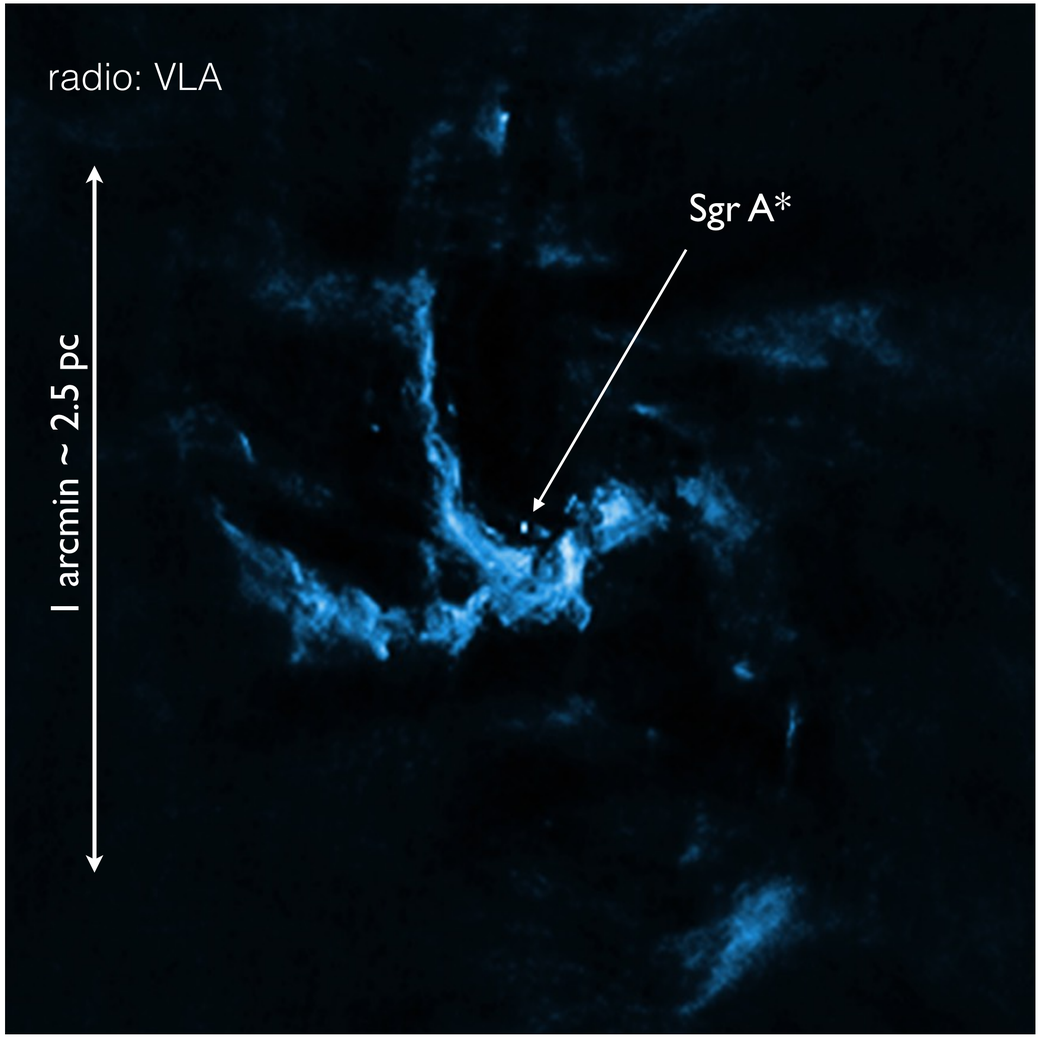
Sgr A*

the SMBH at the center of the MW



The GRAVITY Collaboration: R. Abuter et al. (2019)

$$M_{BH} = (4.297 \pm 0.013) \times 10^6 \ \mathrm{M}_\odot$$



Zooming out

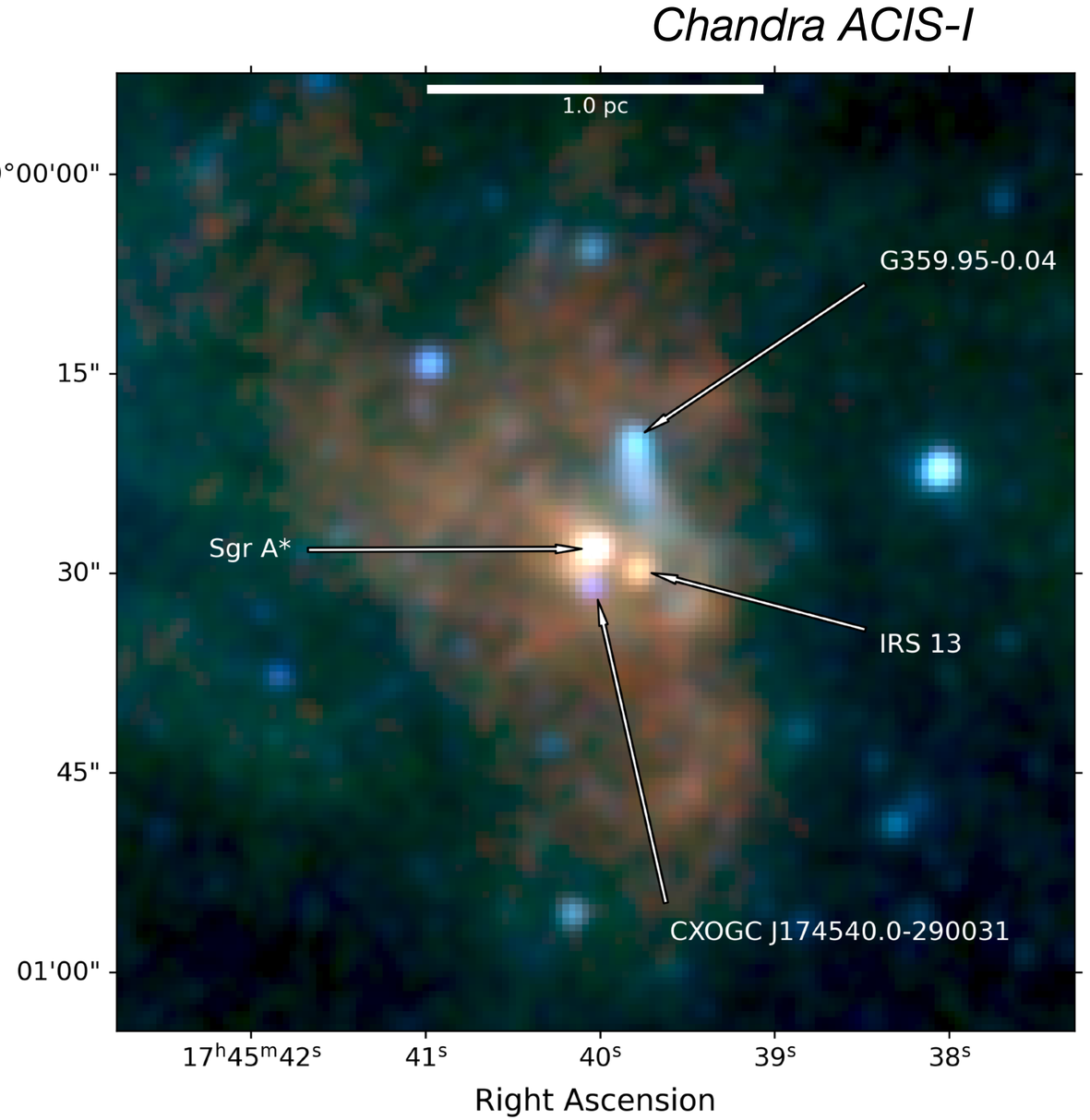
Inner cavity in Sgr A West

- Hot plasma fills inner 10-15”
  - kT = 1.3 keV and n ~ 26 cm-3

    Baganoff et al (2003)
  - powered by stellar winds from young nuclear cluster

    Rockefeller et al (2004), Cuadra et al (2008), Calderon et al (2020)
  - provides bulk of accreted material onto Sgr A*
    - typical rate $10^{-5} - 10^{-6}\ \mathrm{M}_{\odot}/\mathrm{yr}$

      Cuadra et al (2015)



Goldwurm et al (2025, submitted)

Zooming out

Sgr A* with Chandra

- Steady extended Chandra src (1.4” FWHM) with $L_X = (2-3) \times 10^{33}\,\mathrm{erg/s}$

  Baganoff et al (2003)

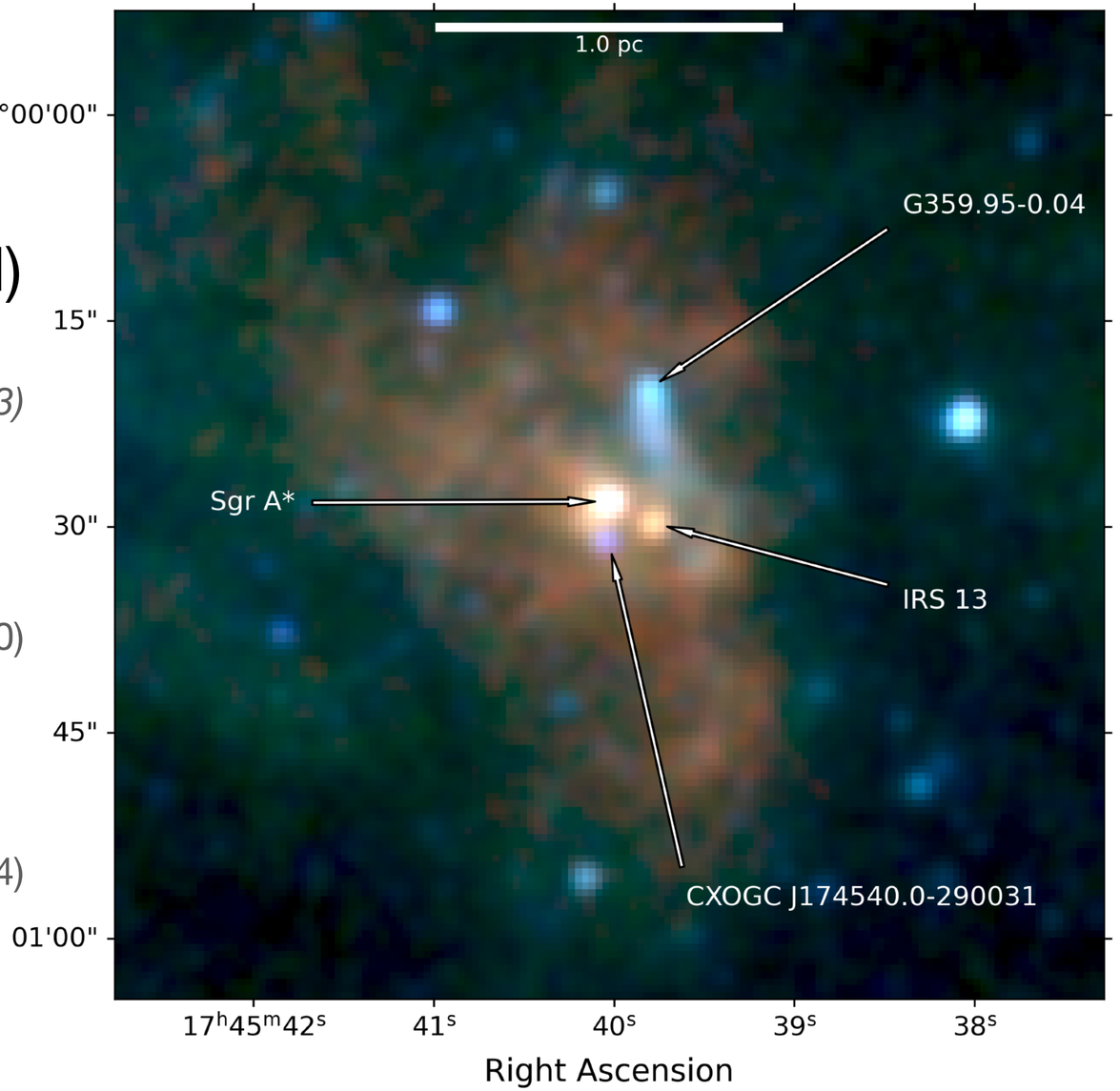
- Thin CIE plasma (with kT~3.5 keV) from captured gas at Bondi radius

  Wang et al (2013), Corrales et al (2020)

- Spectrum consistent with RIAF model with outflows

  Corrales et al (2020), Balakrishnan et al (2024)

Chandra ACIS-I



Goldwurm et al (2025, submitted)

Sgr A* : a dormant SMBH

Near-horizon accretion rate:

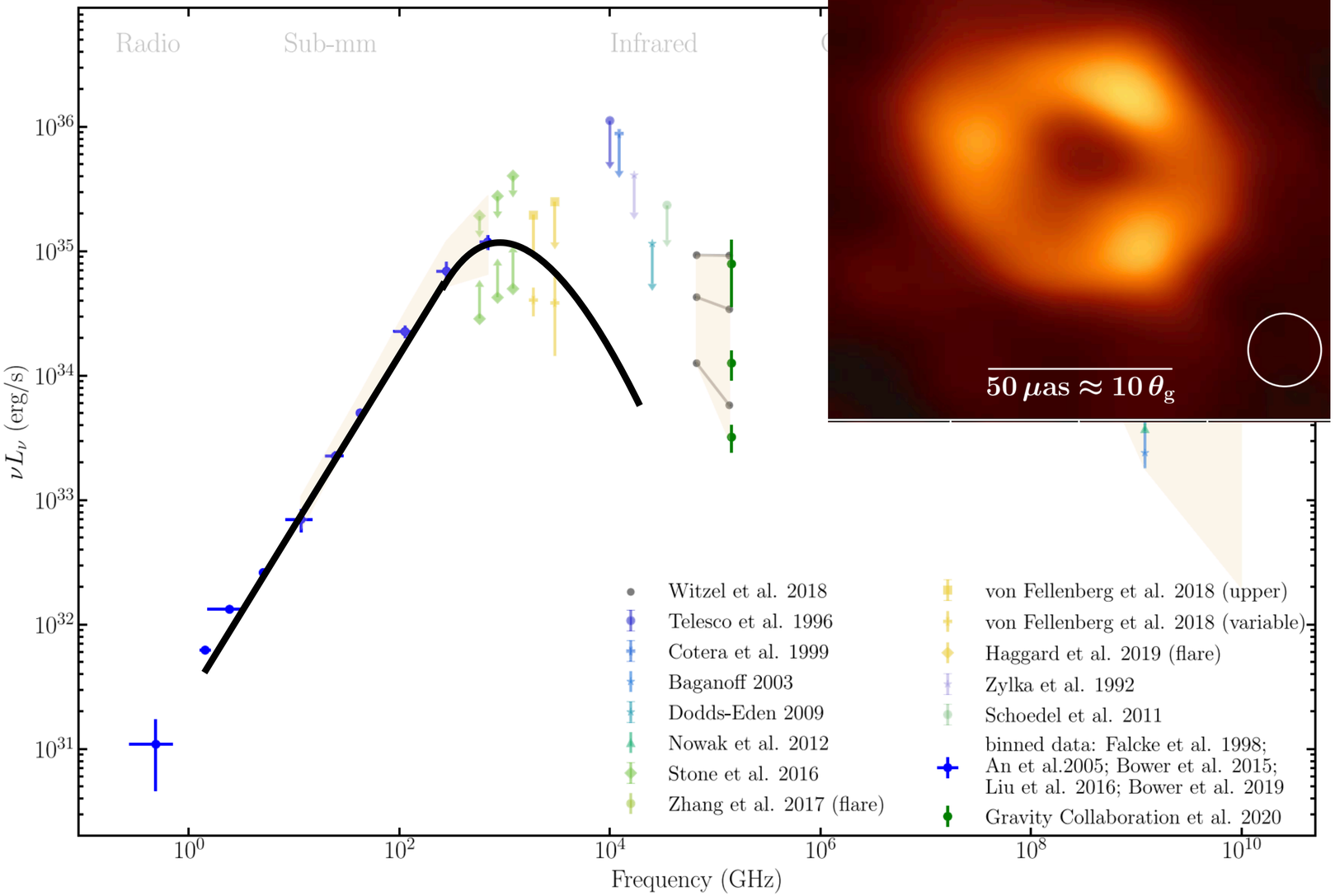
$$10^{-9} - 10^{-7}\ \mathrm{M}_\odot/\mathrm{yr}$$

Bower et al (2018), Marrone et al (2007)

$L_{submm} \sim 10^{35}$ erg/s

$L_{Edd} = 5 \times 10^{44}$ erg/s

for a $4 \times 10^6\ \mathrm{M}_\odot$ SMBH



from EHT collab. 2022

Sgr A* flares

In IR

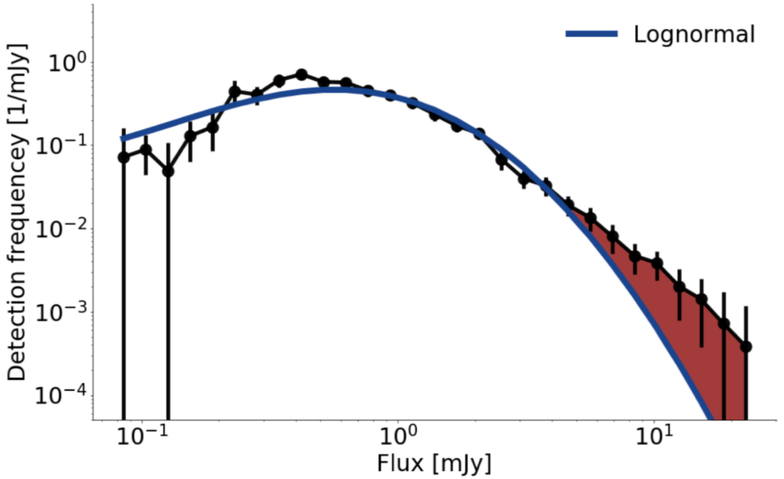
- About 3-4 flares a day
- Quiescent state characterised by log-normal variability with additional sporadic flaring state

Do et al (2019), Abuter et al (2020)

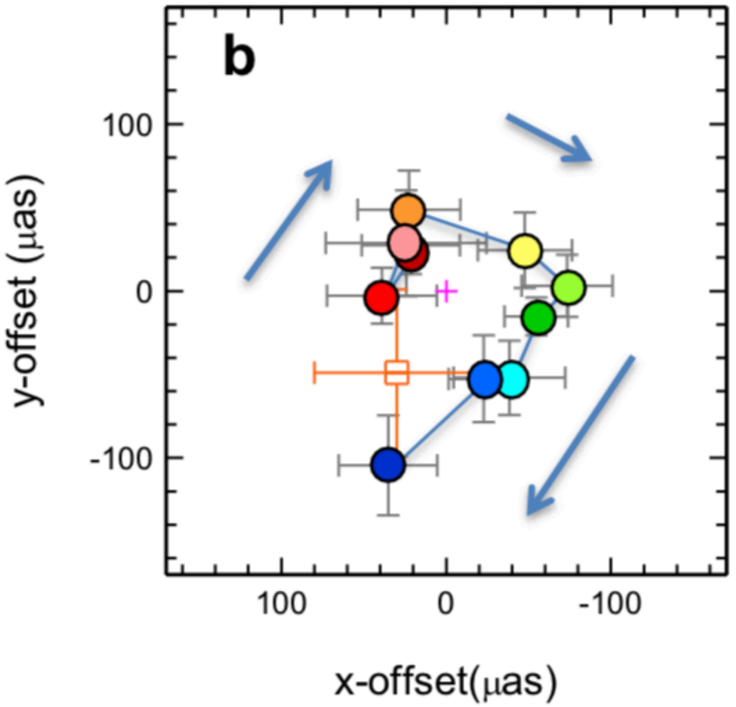
- Gravity observed 3 flares compatible with circular orbital motions over 150 μas at 0.3c

$$P = 33 - 65 \text{ min} \quad R = 6 - 10\ r_g \text{ or } 1.17 \pm 0.3 \text{ ISCO } (a = 0)$$

Abuter et al. (2018)



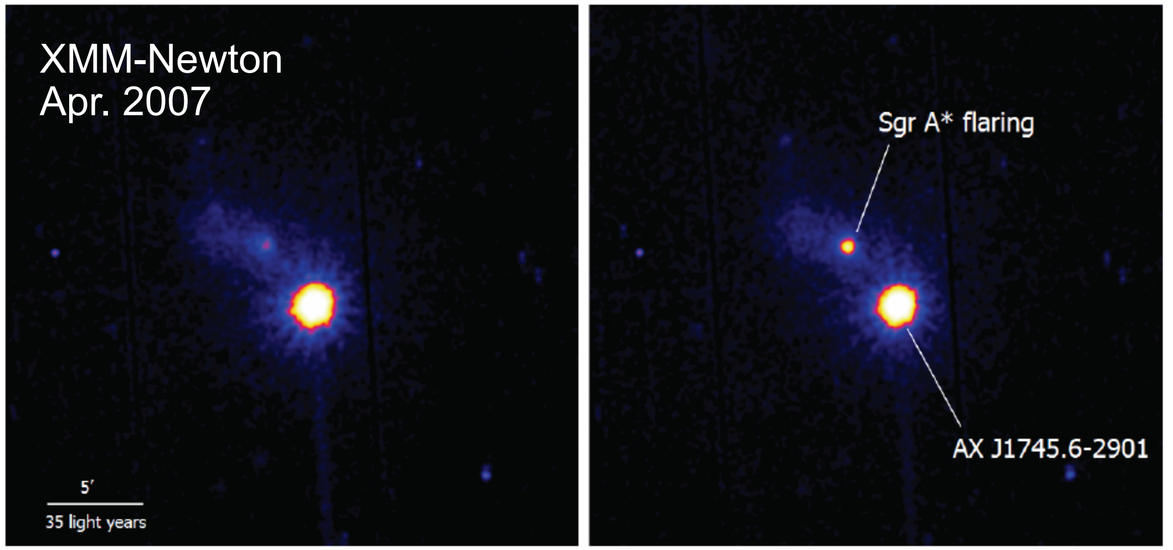
Abuter et al. (2020)



The GRAVITY Collaboration: Abuter et al. (2018)

Sgr A* flares

In X-rays



Trap et al (2010)

- Flare frequency: $1.1 \pm 0.2\,\mathrm{day}^{-1}$, luminosity distribution: $\frac{dN}{dL} \propto L^{-1.9}$

Neilsen et al (2013)

- Detection up to 40 keV with NuStar

Barrère et al (2014)

- Brightest flares detected at peak luminosity of $L_X \sim 10^{36}$ erg/s

Porquet et al (2008), Nowak et al (2012), Haggard et al (2019) etc.

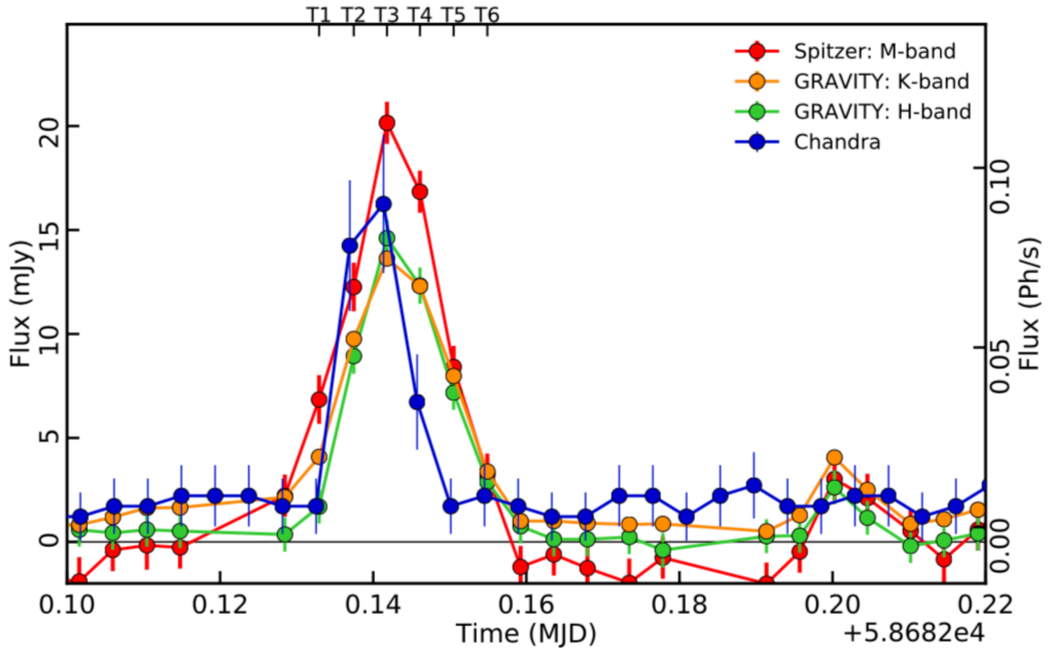
- Some evidence for a factor of 3 increase of brighter flare rate

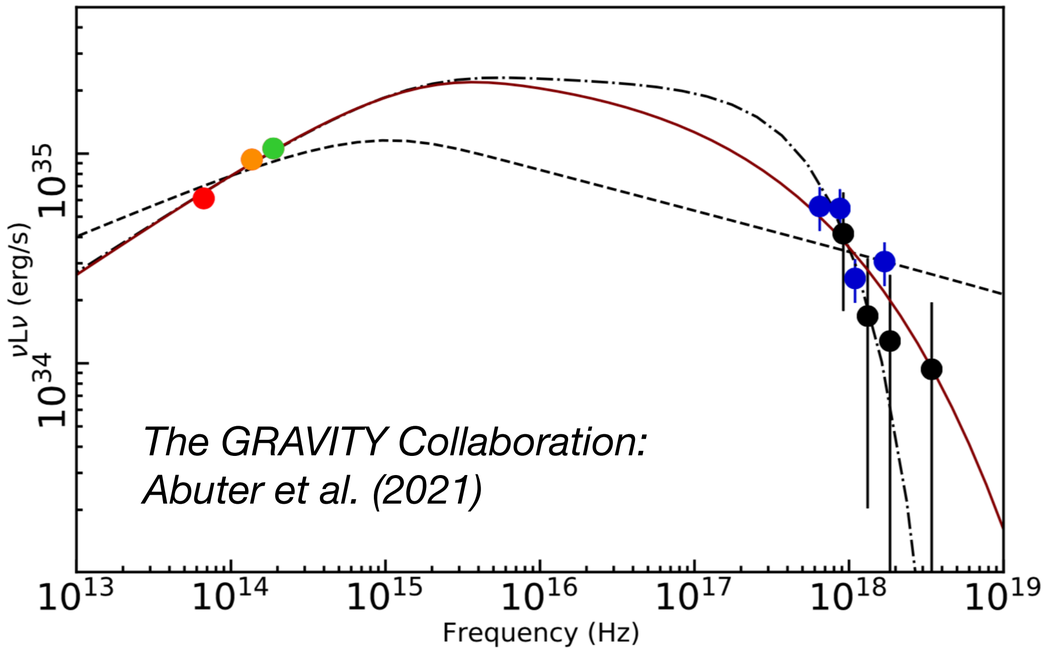
Ponti et al (2015), Mossoux et Grosso (2017), Bouffard et al (2019), Mossoux et al (2020)

Sgr A* flares

Radiative models

- IR emission polarized implies synchrotron emission from non-thermal electrons
- X-rays radiative mechanism still debated
  - SSC (synchrotron self-Compton)
  - synchrotron spectrum with cooling break

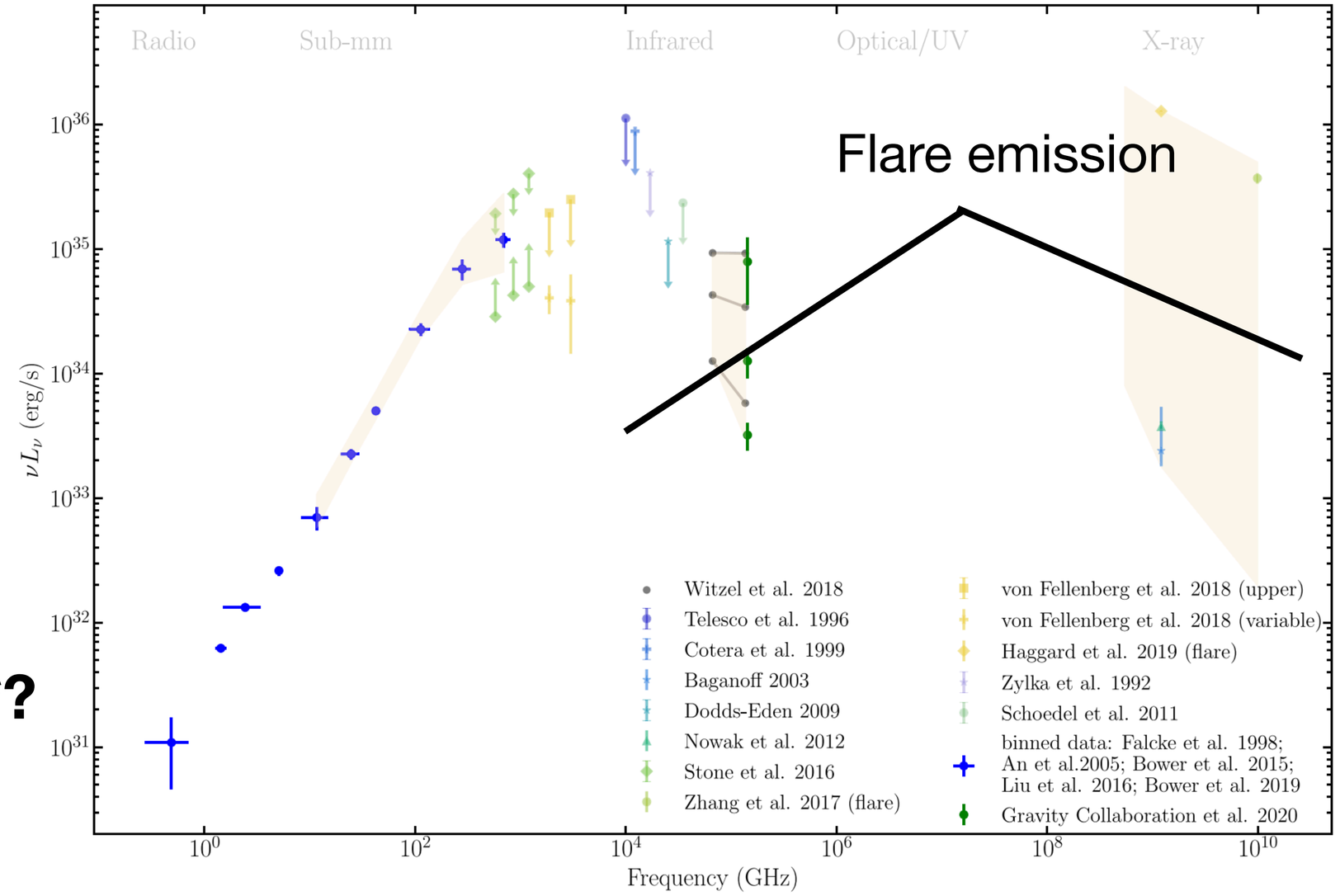




Sgr A* : a dormant SMBH

How long has Sgr A* spent at current low activity level?

Are there traces of past activity of Sgr A*?



Non thermal X-ray for GC molecular clouds

Cosmic-rays or illumination?

- Hard X-rays and Fe-Kα line emission observed from clouds throughout the inner 100 pc

  Sunyaev et al (1993), Koyama et al (1996), Revnivtsev (2004)

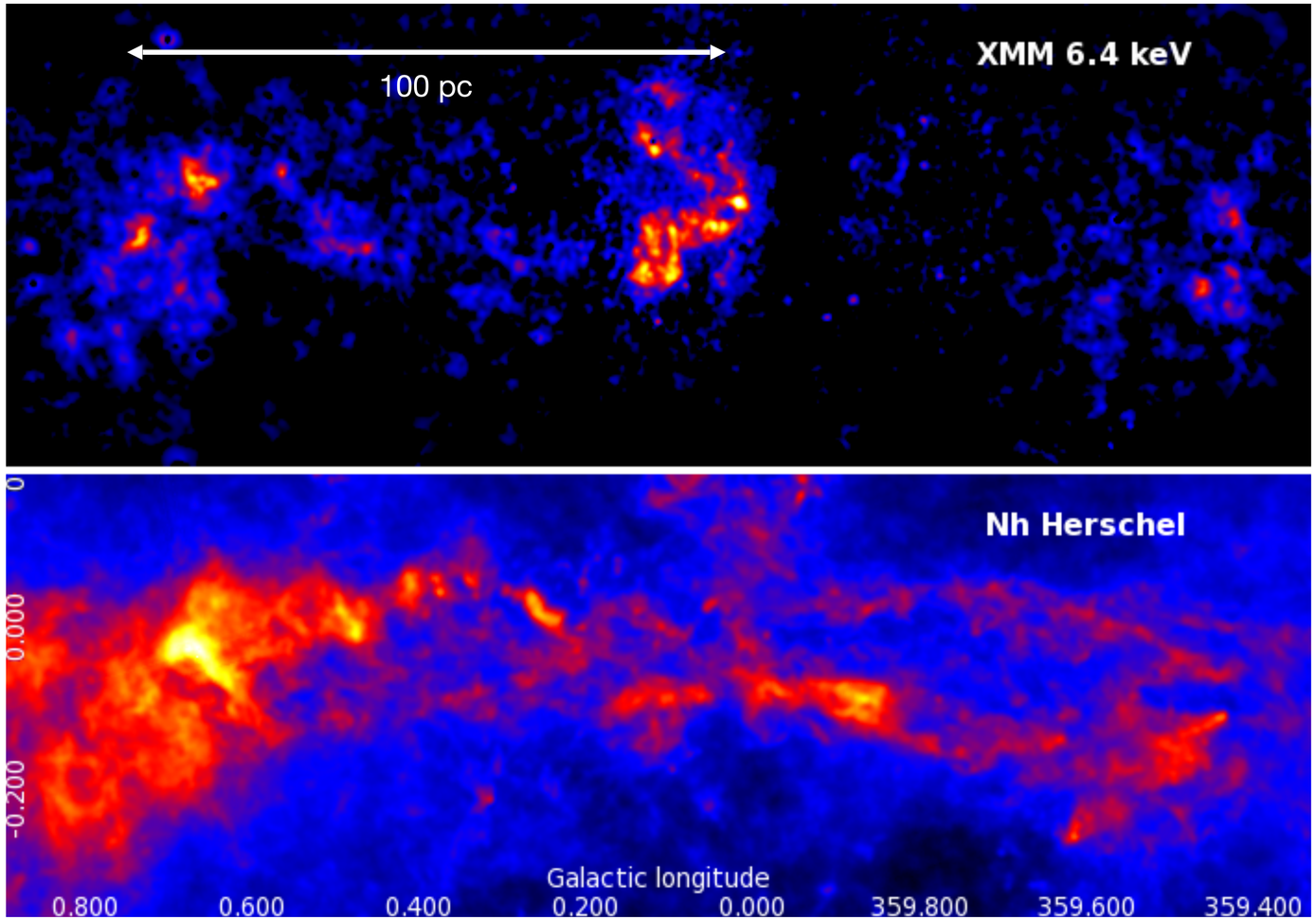
  - Low-energy cosmic-ray bombardement?

    Valinia et al (2000), Tatischeff et al (2012)

  - Fluorescence induced by past illumination from bright source?

    Koyama et al (1996), Sunyaev & Churazov (1998)

- $L_X \sim 10^{39} \left(\frac{\mathrm{T_{illum}}}{10\ \mathrm{yrs}}\right) \left(\frac{\mathrm{d}}{100\ \mathrm{pc}}\right) \mathrm{erg/s}$

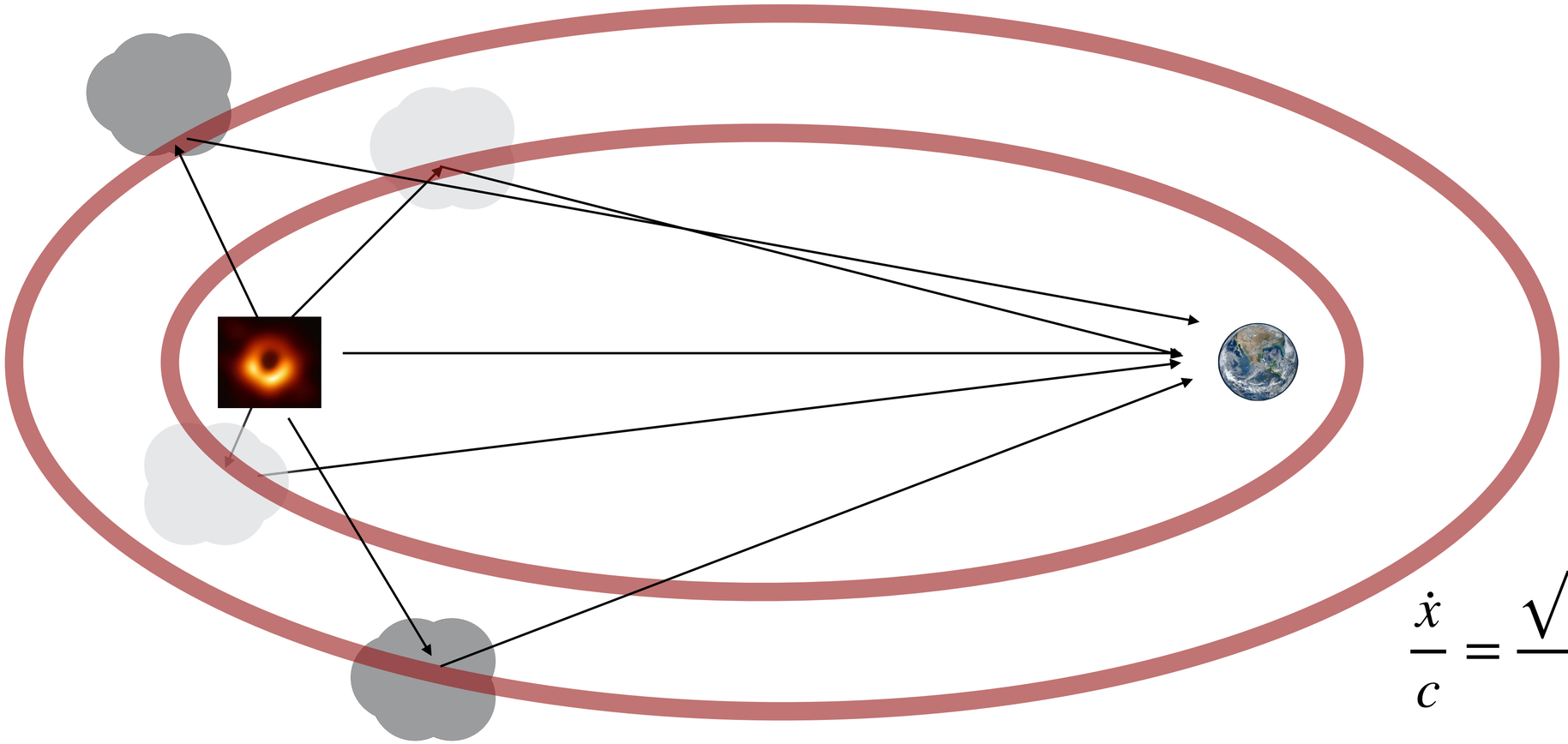


Light echoes

Principle

J.C. Kapteyn: Sur le mouvement de la nébuleuse voisine de l'étoile temporaire de Persée (1902)

P. Couderc: Les auréoles lumineuses des novae (1939)

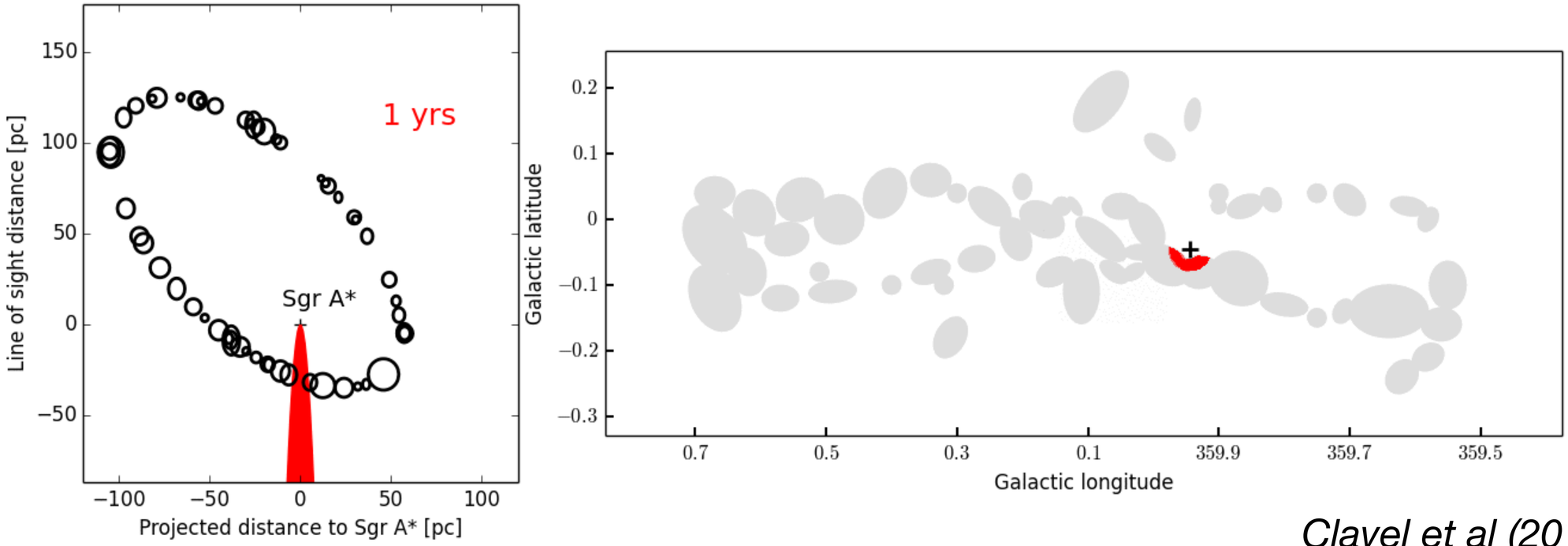


$$\frac{\dot{x}}{c} = \frac{\sqrt{x^2 + z^2}}{||x||} \geq 1$$

Apparent superluminal motion!

Light echoes in the CMZ

propagation and apparent superluminal motion



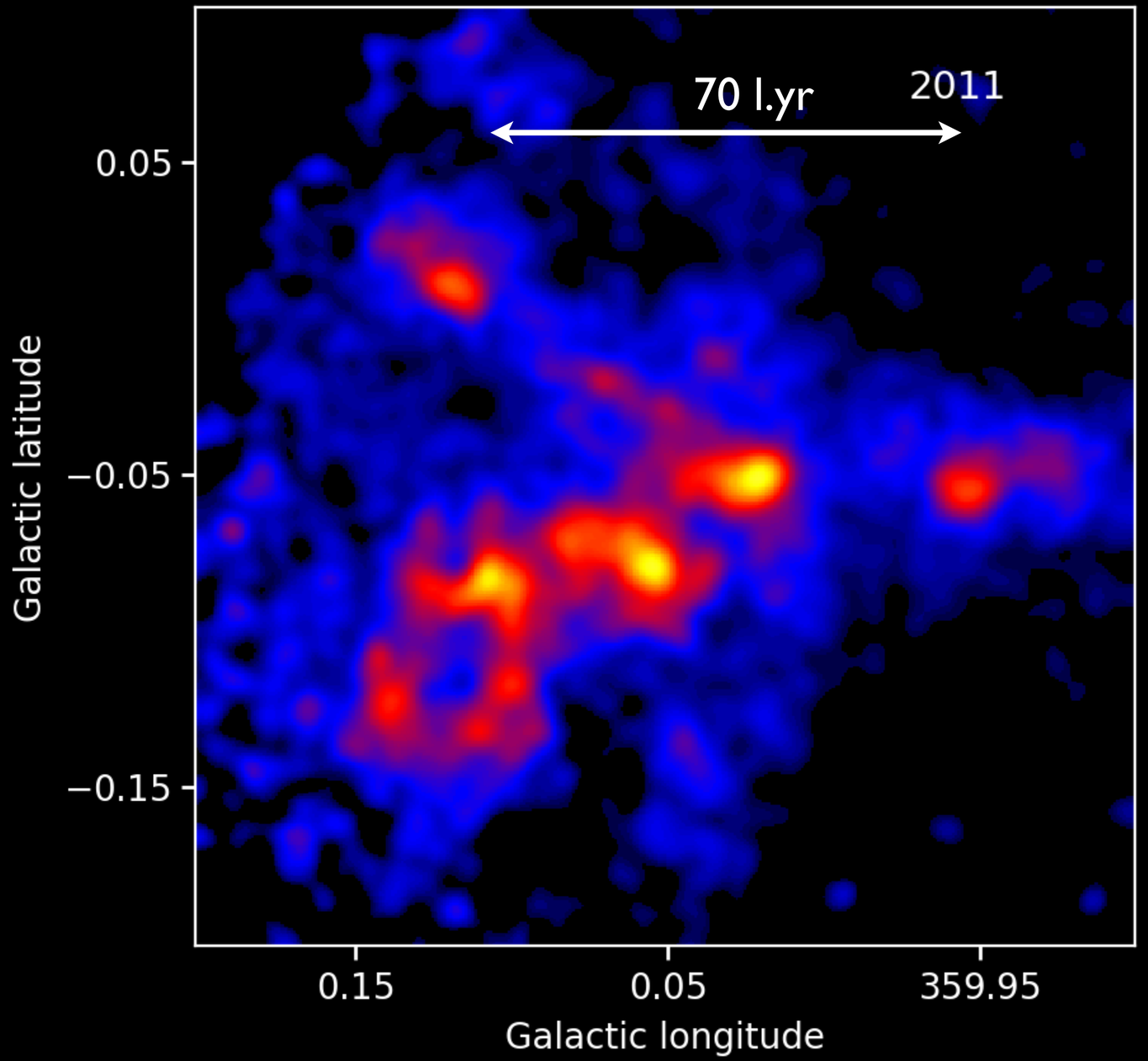
Clavel et al (2014)

$$\frac{\dot{x}}{c} = \frac{\sqrt{x^2 + z^2}}{||x||} \geq 1$$

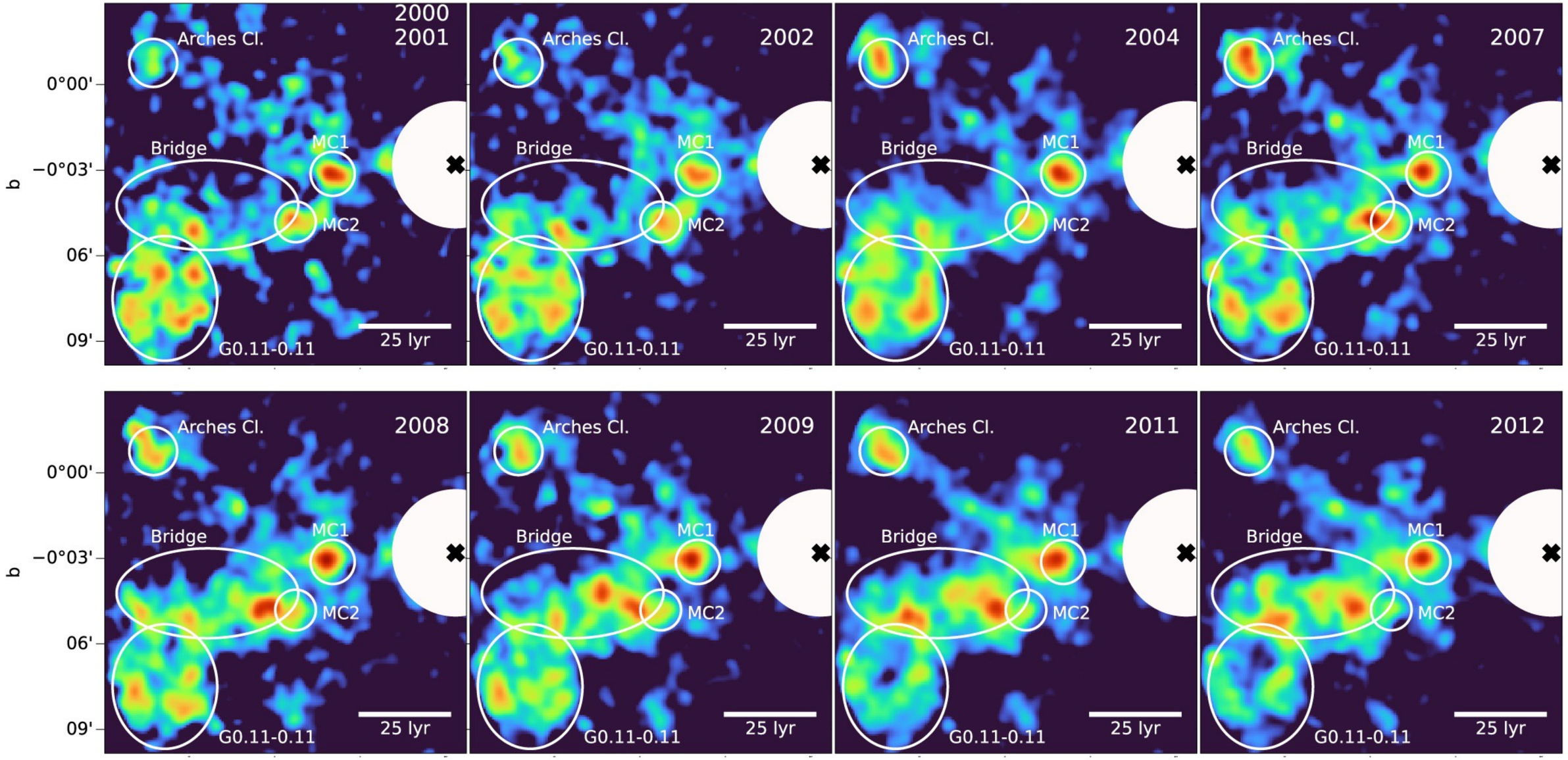
Apparent superluminal motion

P. Couderc (1939)

XMM-Newton
6.4 keV

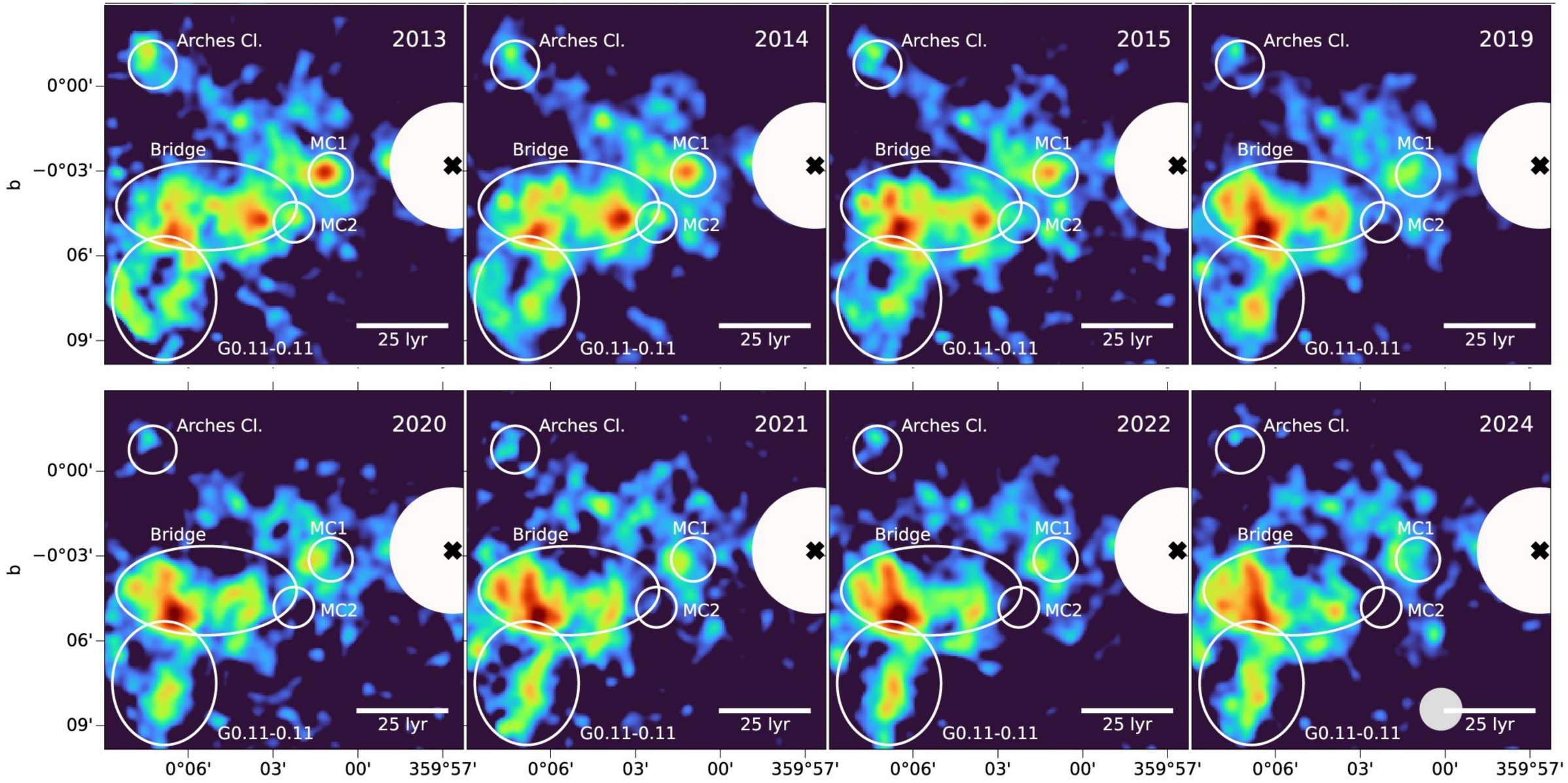


Ponti et al (2010)



XMM-Newton
6.4 keV

Stel et al (2025)



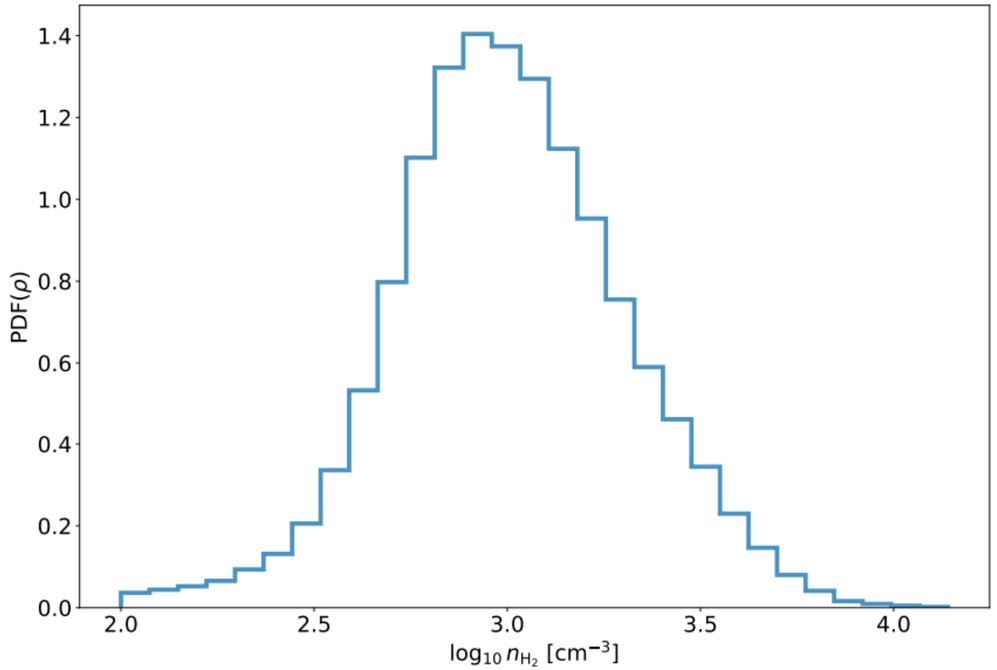
XMM-Newton
6.4 keV

Stel et al (2025)

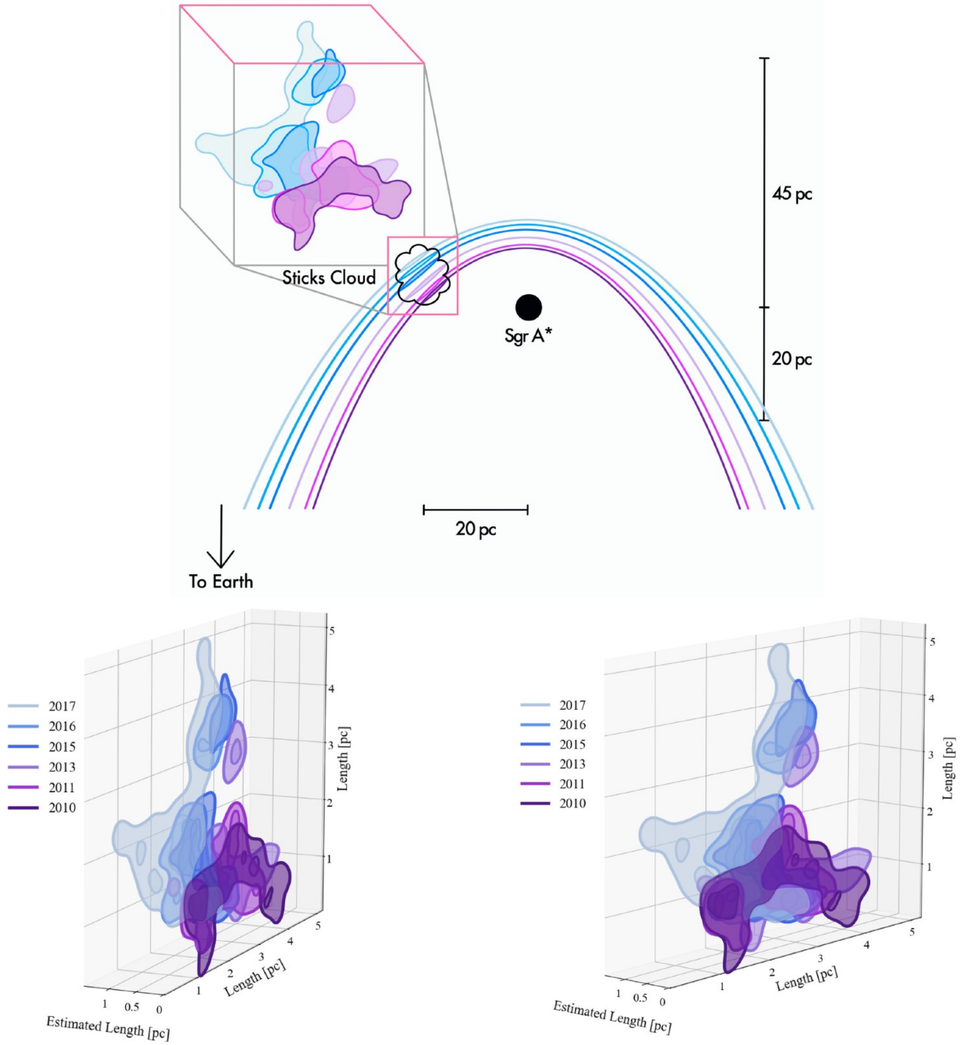
Tomography of the GC ISM

Scanning gas with the X-ray light front

PDF(ρ) in Sgr A molecular complex



Stel et al (2025)



Brunker et al (2025)

Constraining GC past activity

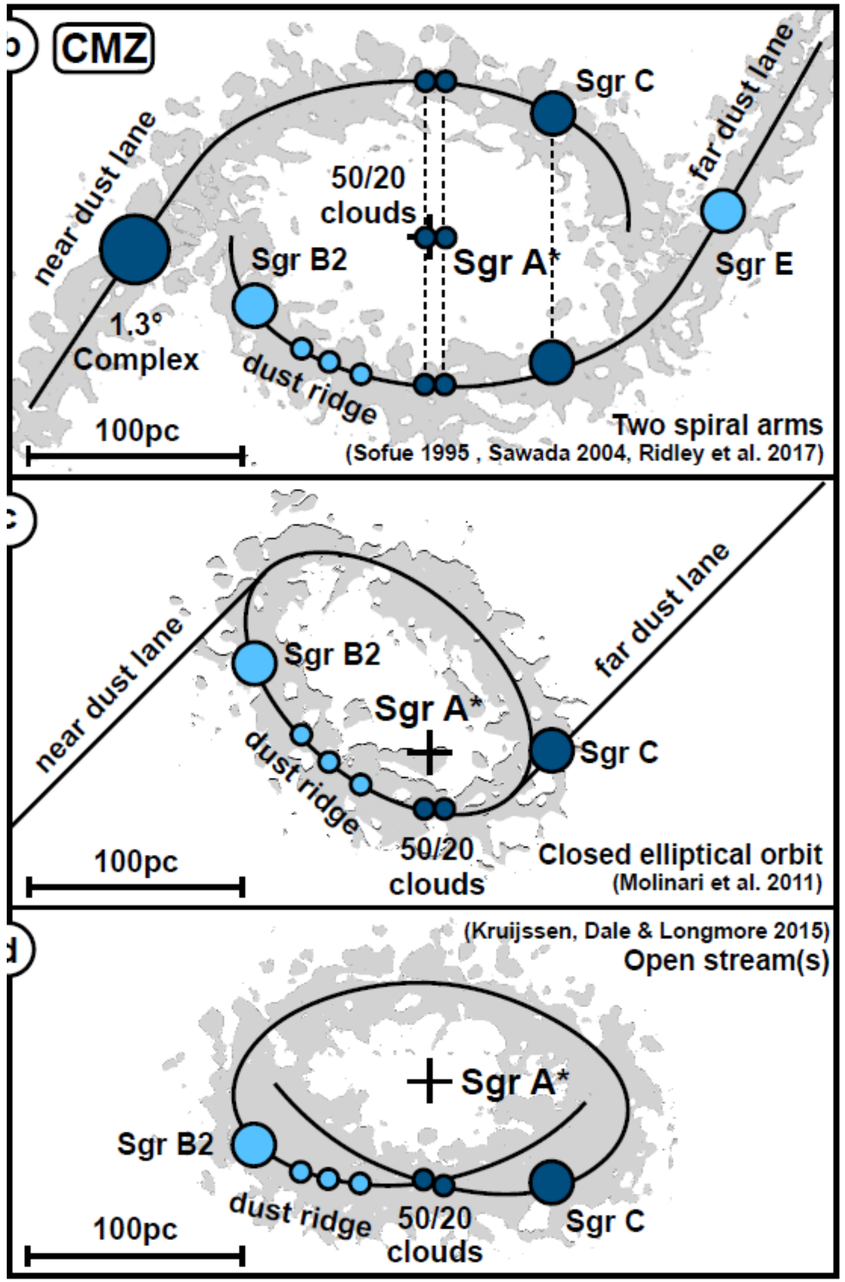
How long? How many events? When? Origin?

- Time delay given by (poorly known) cloud position along Line of Sight (LoS)
- Use X-rays to constrain the GC clouds (LoS) position
- Observables:
  - Timescales of reflected emission

    Clavel et al (2013), Churazov et al (2017)
  - Spectra

    Ryu et al (2009), Capelli et al (2012), Walls et al (2016), Chuard et al (2018) …
  - Polarization of X-ray emission

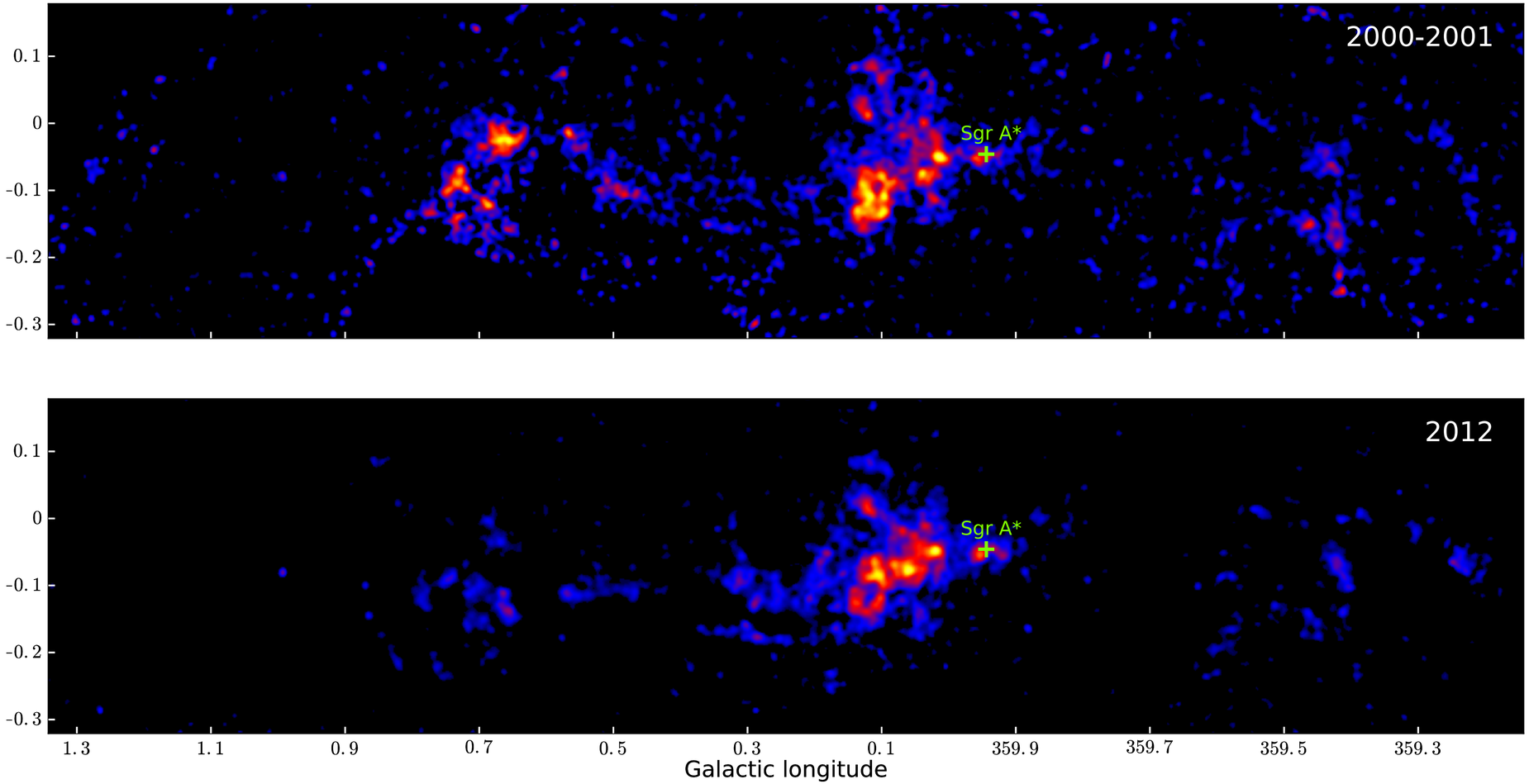
    Marin et al (2023), Khabibulin et al (2025)



Henshaw et al (2023)

Duration of illumination?

CMZ is illuminated by short duration event(s)



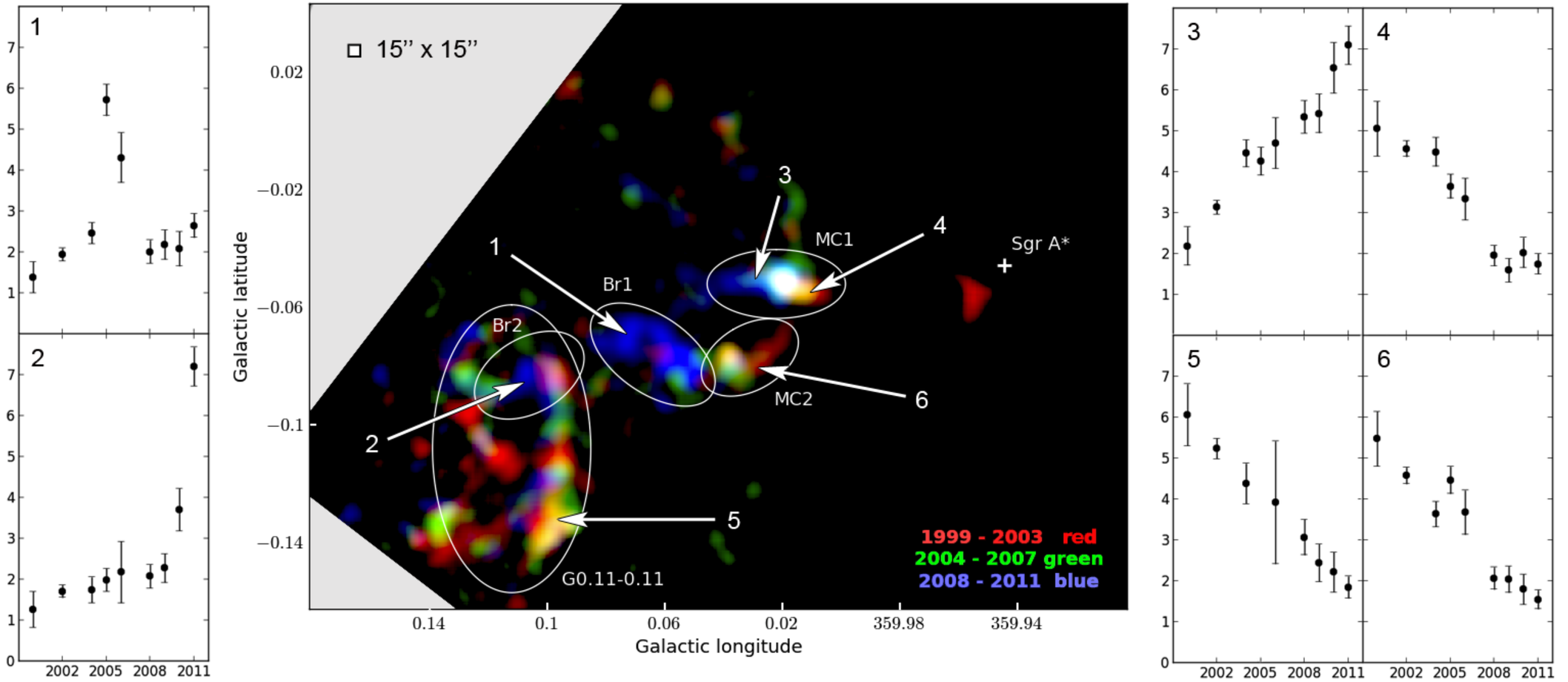
XMM-Newton
6.4 keV

Variations in CMZ over 10 years period: consistent with short illuminations *Terrier et al (2018)*

How many echoes in the CMZ?

2 distinct events

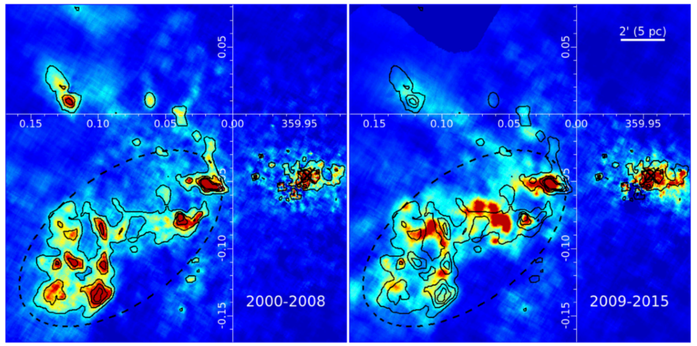
Measuring variability timescales in 15” regions with *Chandra*



2 distinct time scales : ~1 yr, ~10 yrs : 2 distinct events?

Clavel et al (2013)

Dating past flares

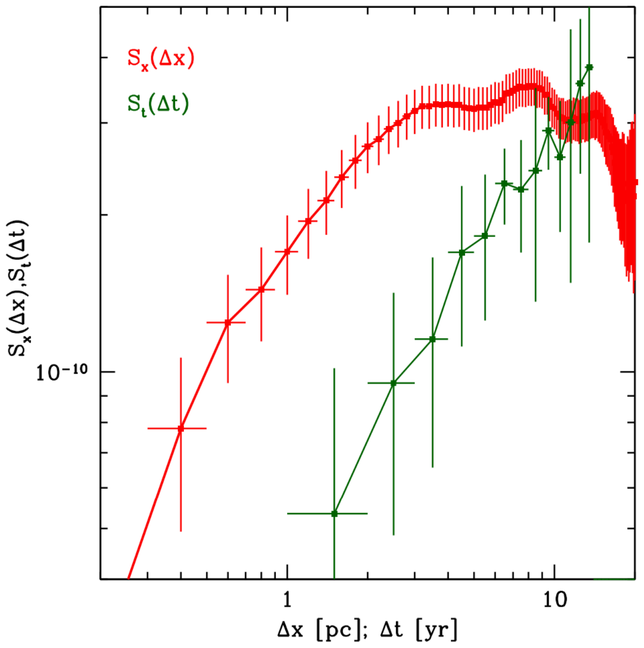


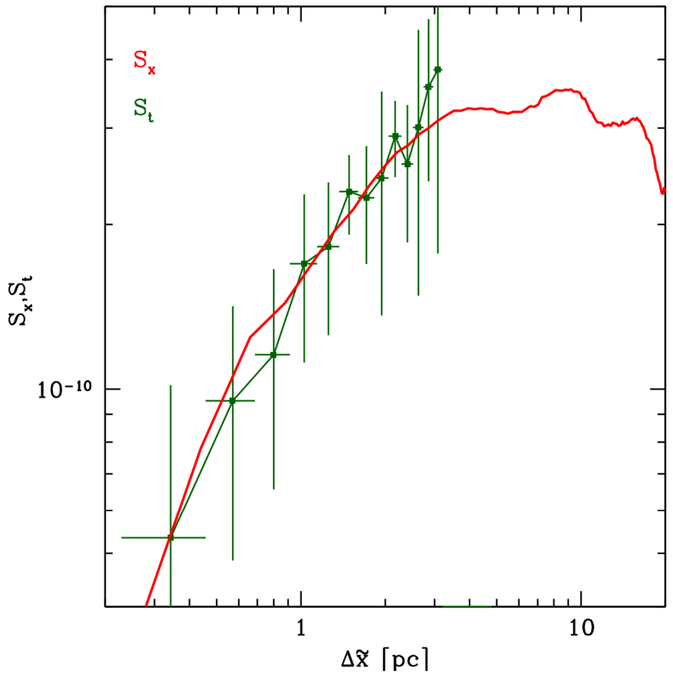
- Using spatial and temporal structure functions of emission in Sgr A molecular complex

$$S_s(\Delta\vec{x}) = \left\langle \left[I(\vec{x},t) - I(\vec{x}+\Delta\vec{x},t) \right]^2 \right\rangle,$$

$$S_t(\Delta t) = \left\langle \left[I(\vec{x},t) - I(\vec{x},t+\Delta t) \right]^2 \right\rangle,$$

- Evolution of light front connects the two
  - $\Delta t = 110\,\mathrm{yr}$





Churazov et al (2017)

Churazov et al (2017)

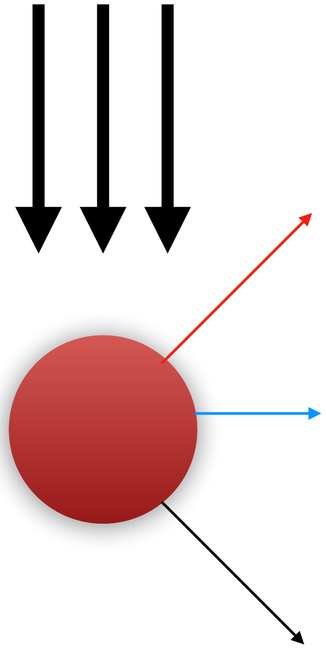
Constraining the geometry with the reflected spectrum

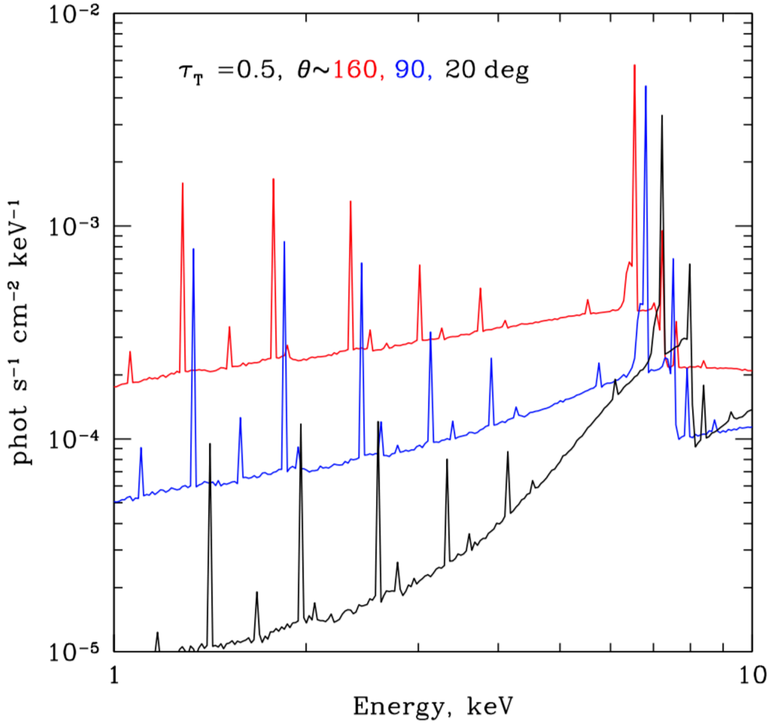
- Several attempts using Fe line EW, absorption on soft plasma emission

  e.g. Ryu et al (2009), Capelli et al (2012) etc

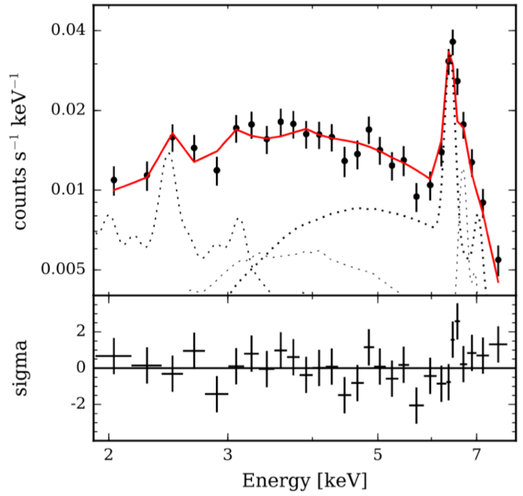
- Build MC models of reflected emission by spherical cloud

  Revnivtsev et al (2004), Walls et al (2016), Chuard et al (2018)





Churazov et al (2017)



Sgr B2 spectrum consistent with location 48 ±16 pc in front of Sgr A*

Walls et al (2016), D. Chuard et al (2018)

Dating two flares

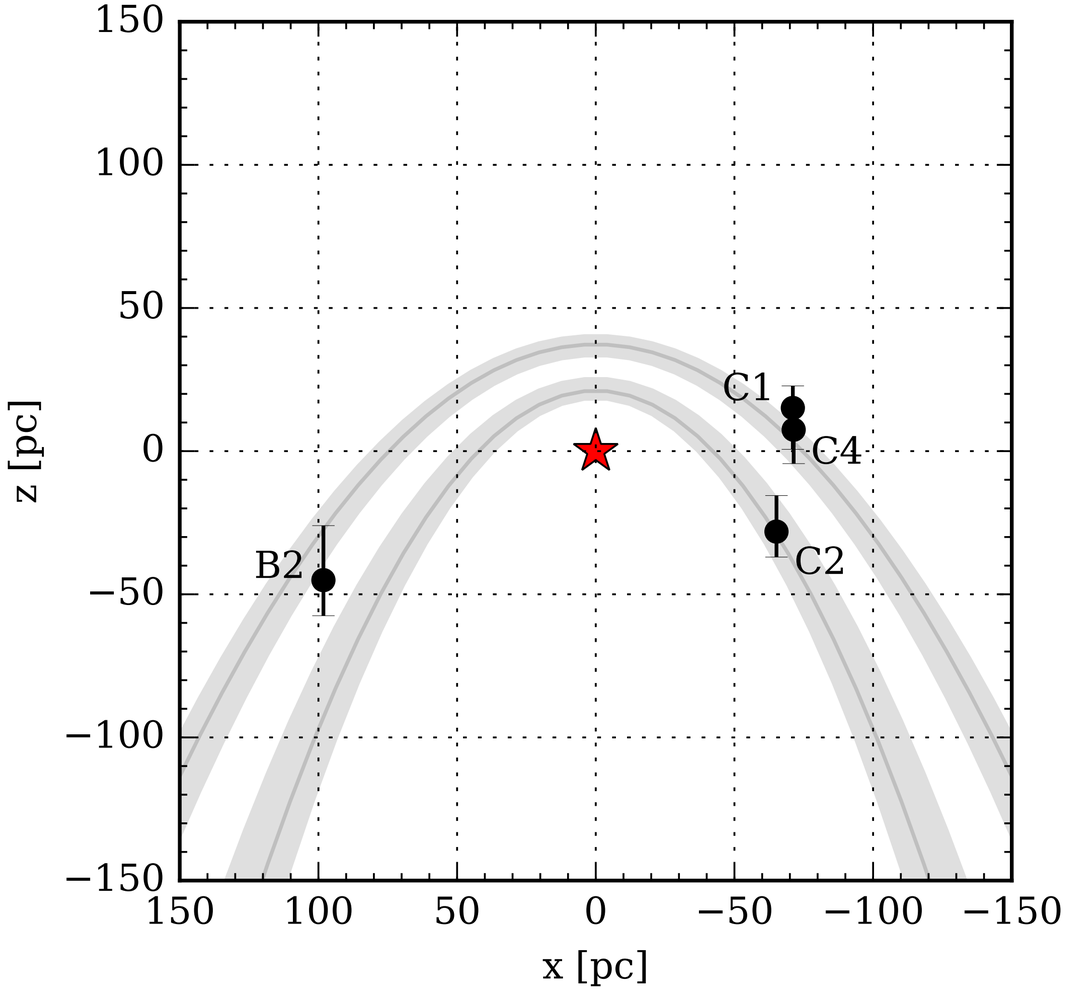
- Spectroscopy of clouds in Sgr C and Sgr B2

  Chuard et al (2018)

  - Hint (~2.5σ) for 2 distinct echoes
  - $\Delta t_2 = 243^{+20}_{-25}\,\mathrm{yr}$
  - $\Delta t_1 = 138^{+27}_{-17}\,\mathrm{yr}$
- Inclusion of additional clouds increases significance for two flares

  Chuard et al (2021)

Region	Angle (°)	N_H ($10^{23}\mathrm{cm}^{-2}$)	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



Chuard et al (2018)

X-ray polarimetry

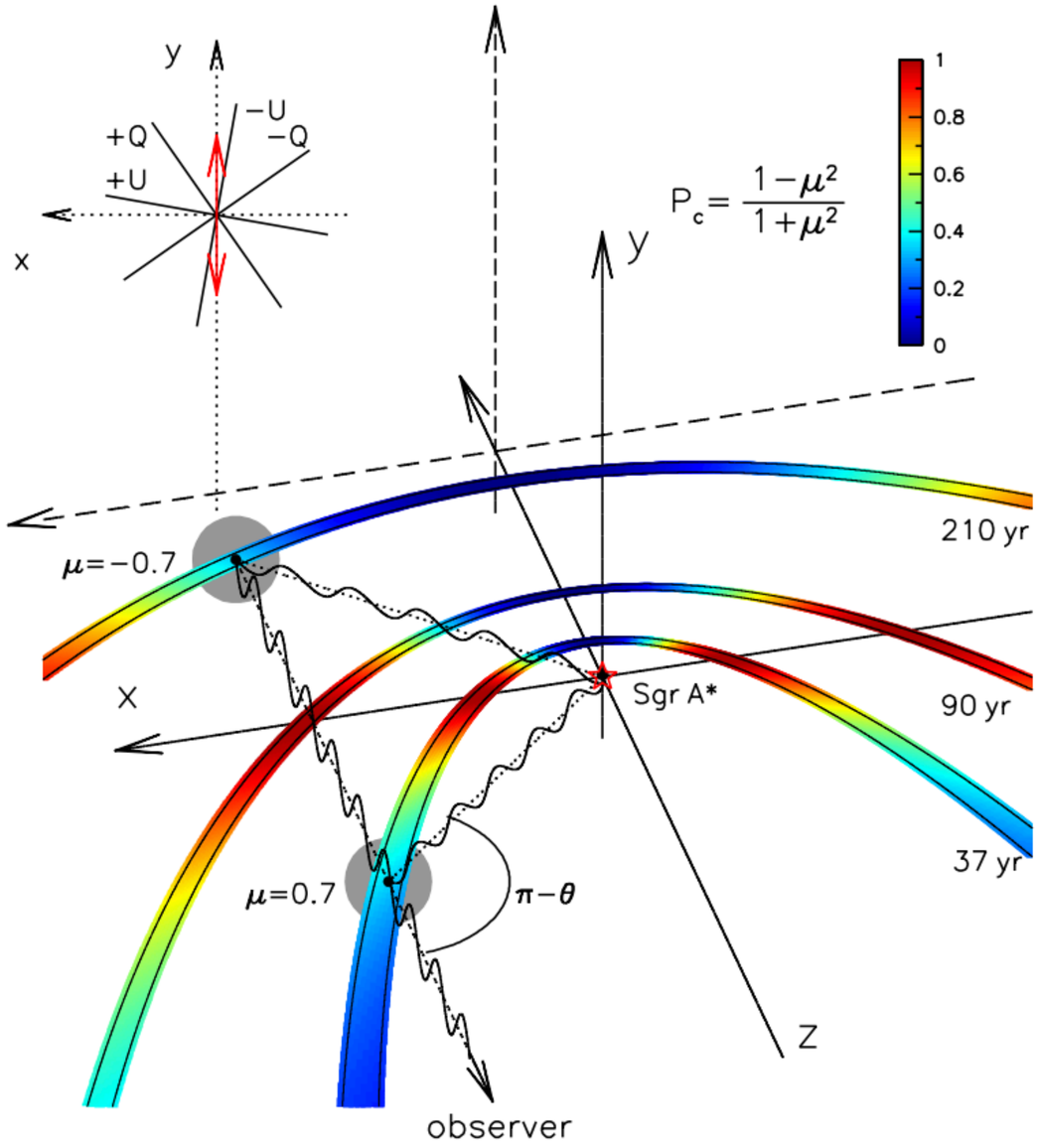
Localizing scattering clouds

- Un-polarized X-ray emission reflected by clouds becomes polarized
- Degree of polarization depends on the cosine of scattering angle

$$P = \frac{1-\mu^2}{1+\mu^2}$$

- Polarization angle orthogonal to direction of illumination

Churazov et al (2002), Marin et al (2014) etc

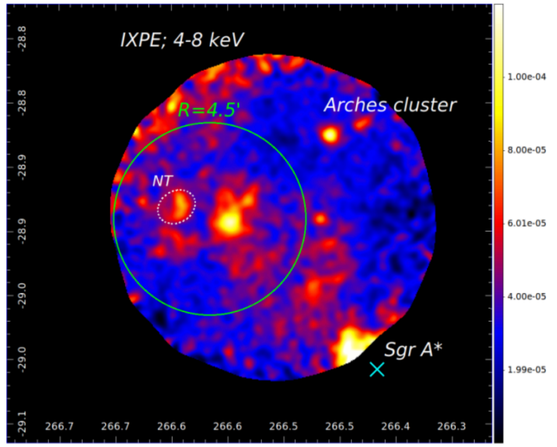


from Khabibulin et al (2025)

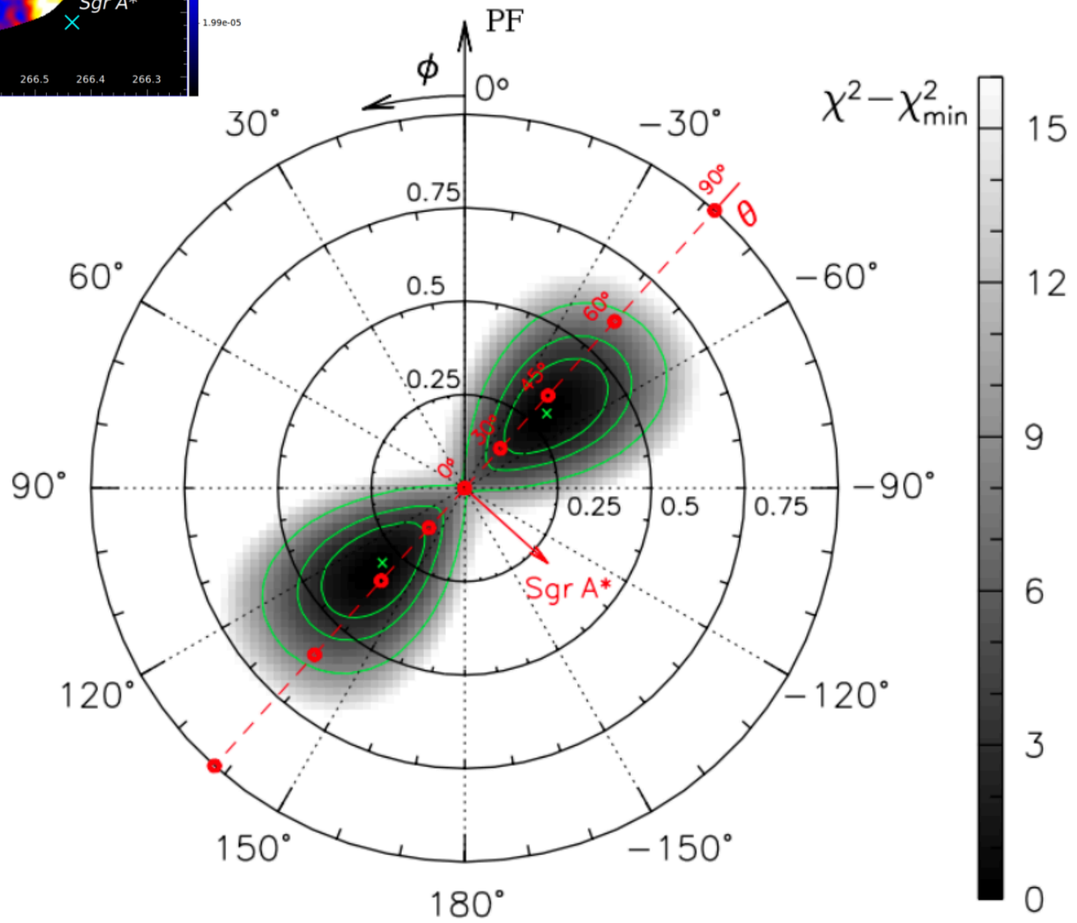
X-ray polarimetry

illumination from Sgr A*

- IXPE detected polarisation of non-thermal continuum towards Sgr A molecular complex
- polarization degree: $(31 \pm 11)\,\%$
- polarization angle: $-48^\circ \pm 11^\circ$
- Consistent with reflection of non-polarised emission from Sgr A*
  - $\Delta t = 205^{+50}_{-30}\,\mathrm{yr}$



IXPE

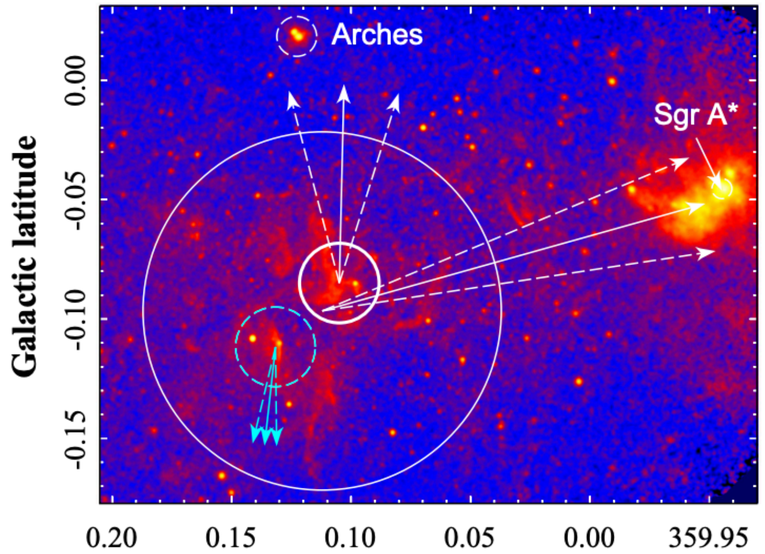


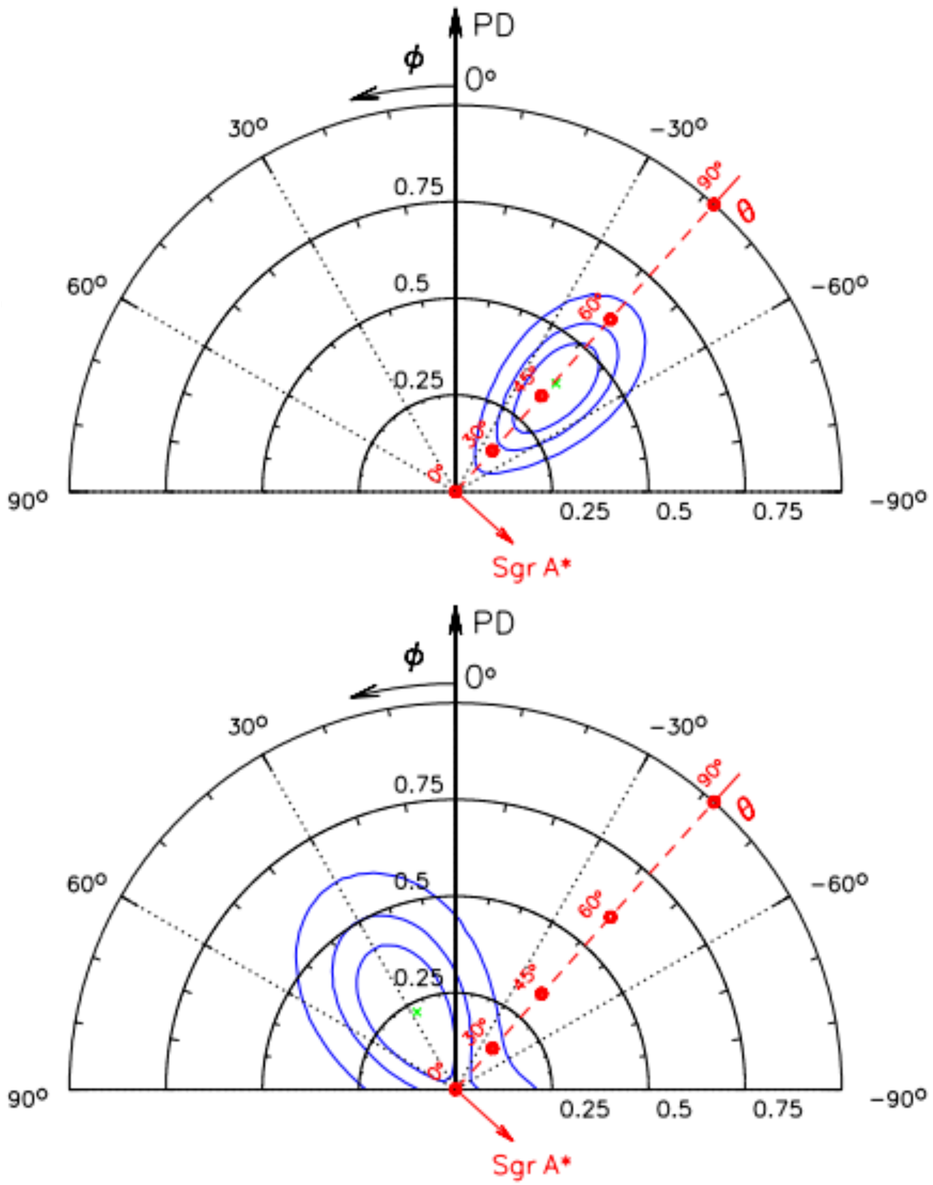
Marin et al (2023)

X-ray polarimetry

2 distinct illuminations?

- Spatially resolved polarimetry yields evidence for different illuminations
  - A second source towards the Arches cluster?
  - Polarized emission from Sgr A*?





Khabibulin et al (2025)

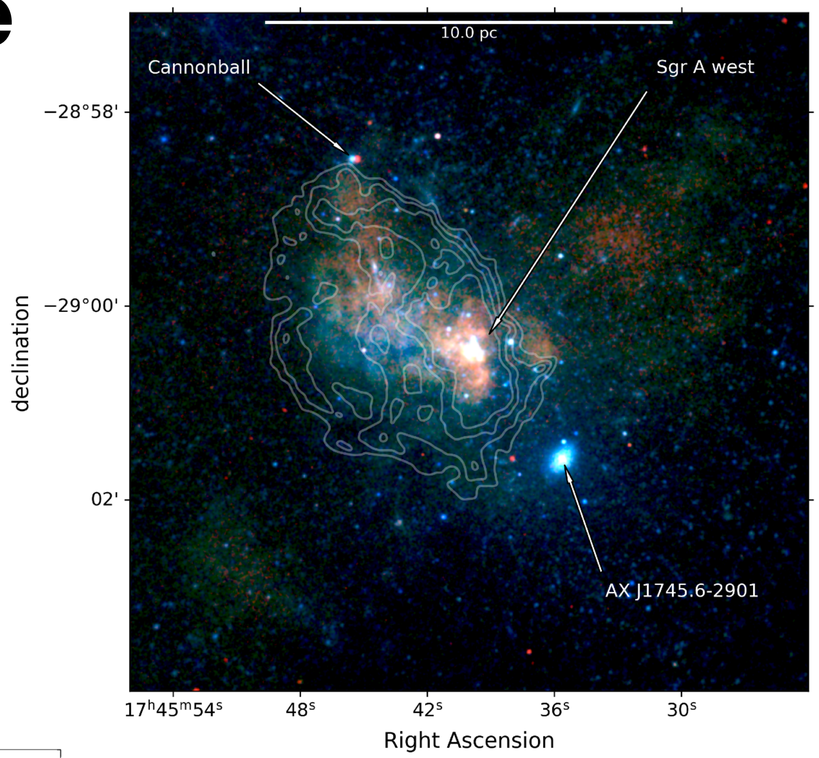
Other signatures of century-old flare

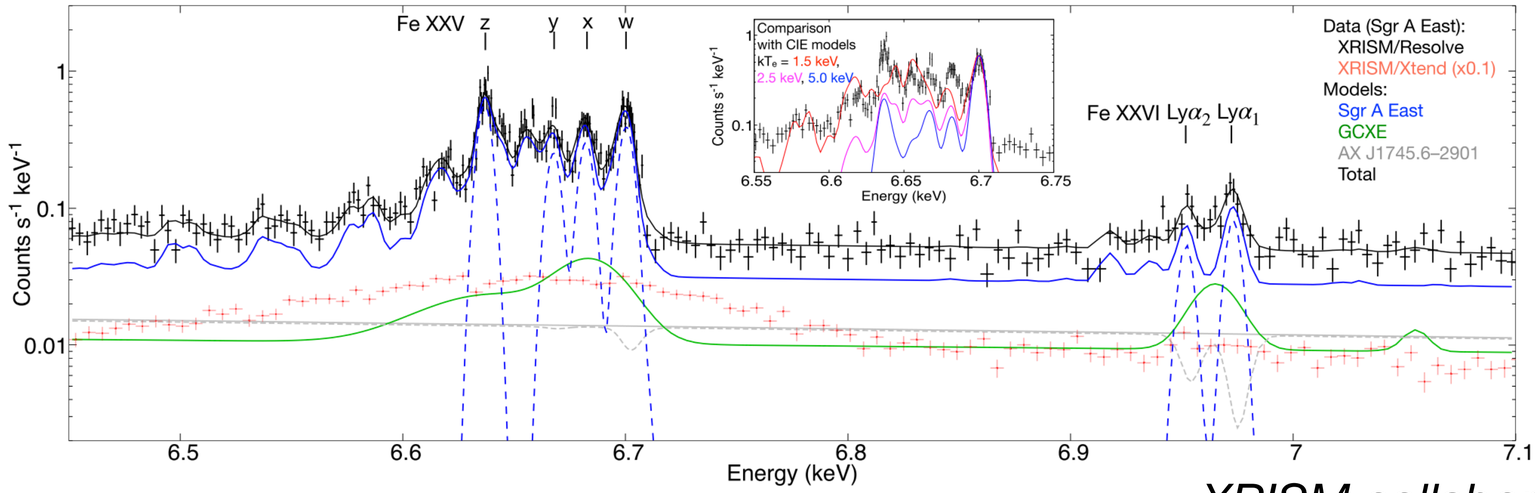
High resolution spectroscopy of Sgr A East

- High resolution spectroscopy of Sgr A East SNR reveals out of equilibrium plasma
- Possible cause of excess ionisation is illumination by intense X-ray source in the last 1000 yrs.

Ono et al (2019), XRISM collaboration (2025)

Chandra ACIS-I - MeerKAT contours





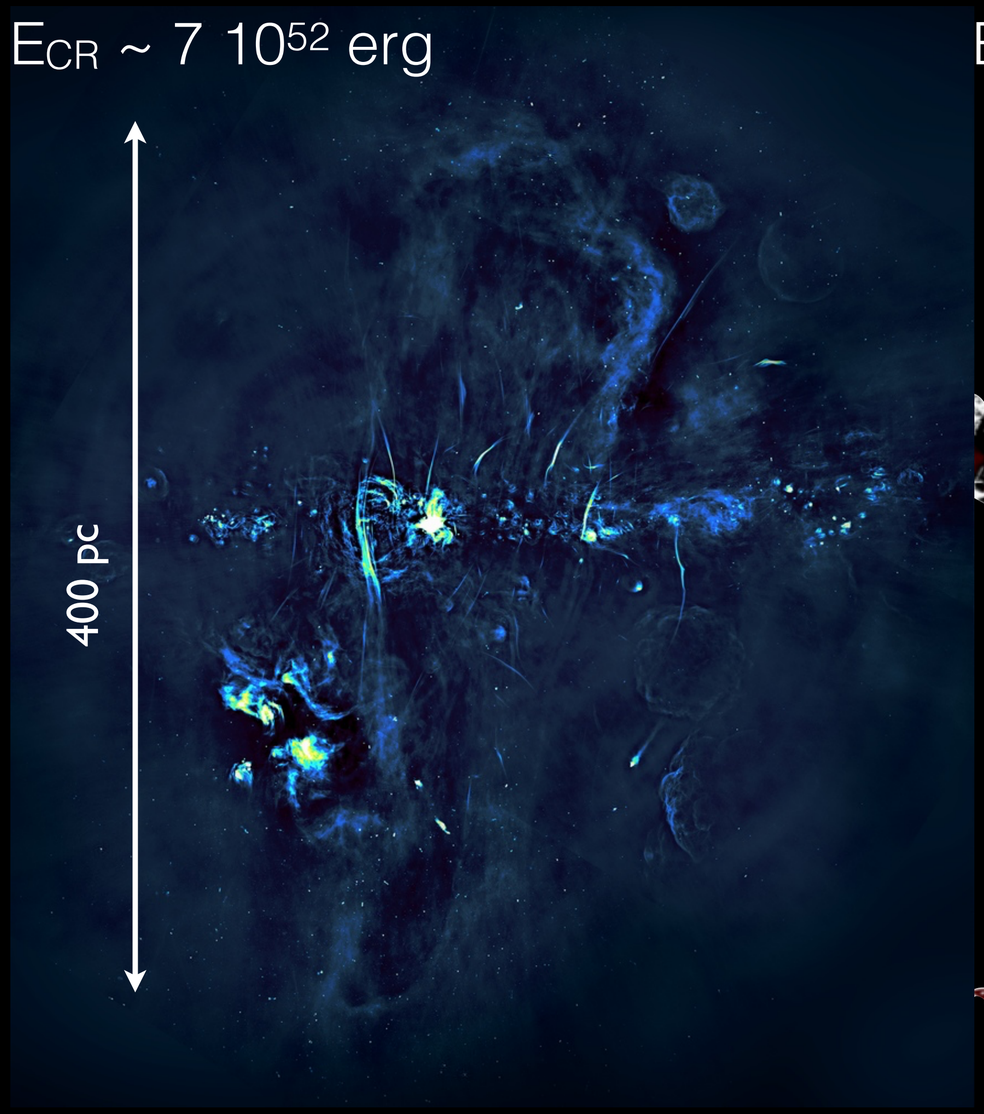
XRISM collaboration (2025)

Summary

- Current level of luminosity of Sgr A* is very low $L_{bol} \sim 10^{-9} L_{Edd}$
- Central Molecular Zone is currently illuminated by short and luminous event of at least $L_X \sim 10^{39}$ erg/s
  - Time variability, spectroscopy, polarimetry constraints show that
    - Sgr A* underwent at least one bright outburst in the last 250 yrs
    - Phenomenon causing the outburst is unknown (accretion of cold clump, tidal disruption of a planet, etc)
- Additional evidences of intense activity in the last Myrs…

Bi-polar chimneys

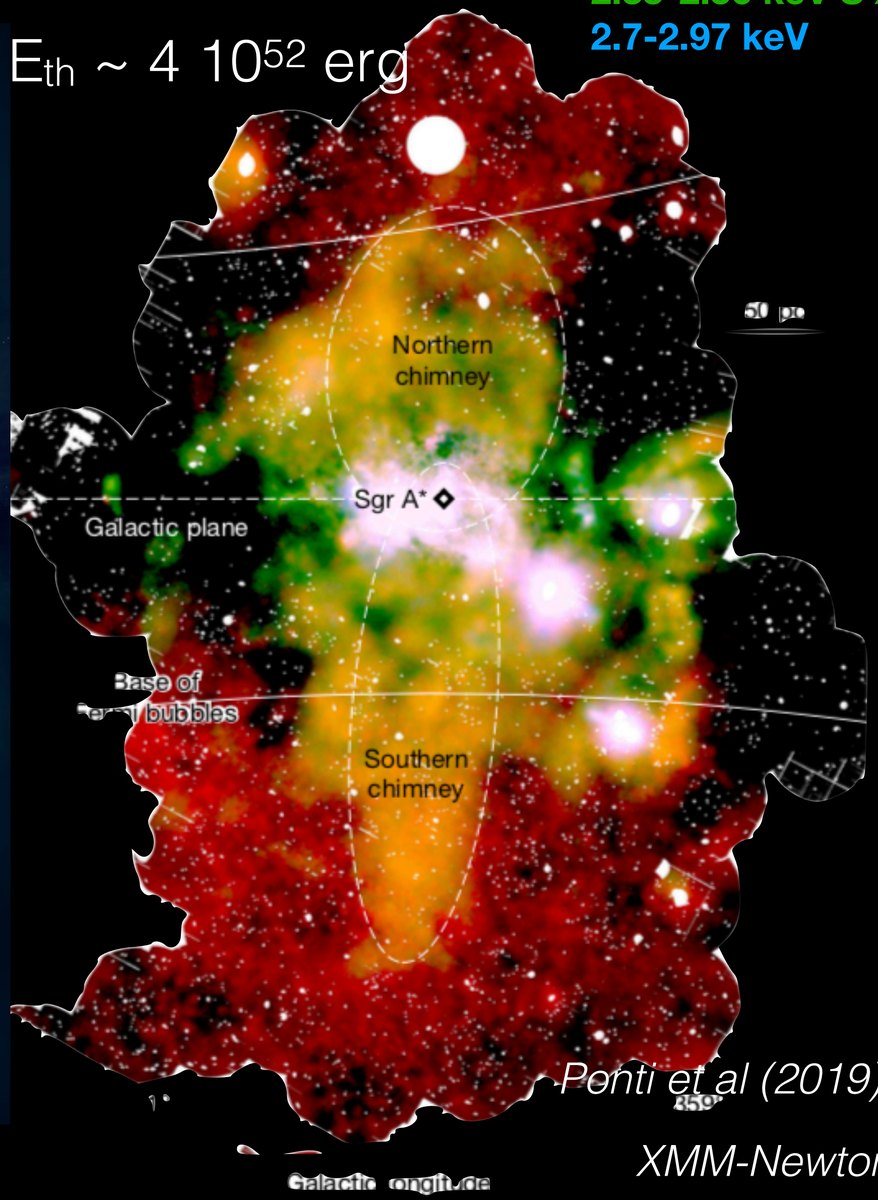
E_{CR} ~ 7 10^{52} erg



MeerKAT *Heywood et al (2019)*

E_{th} ~ 4 10^{52} erg

1.5-2.6 keV
2.35-2.56 keV S XV
2.7-2.97 keV



Ponti et al (2019)

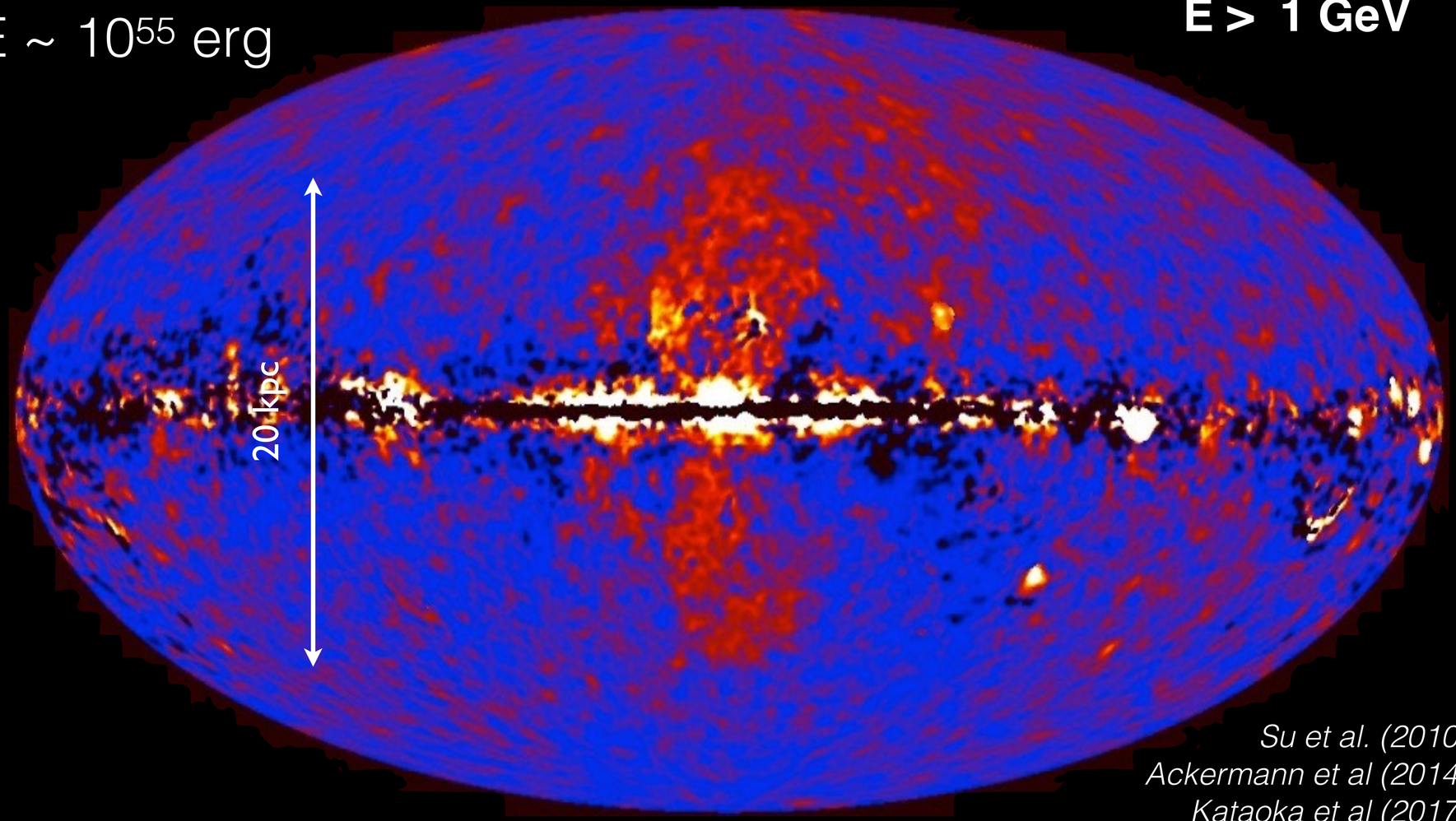
XMM-Newton

Fermi bubbles

$L_\gamma \sim 10^{37}$ erg/s

$E \sim 10^{55}$ erg

Fermi-LAT
E > 1 GeV



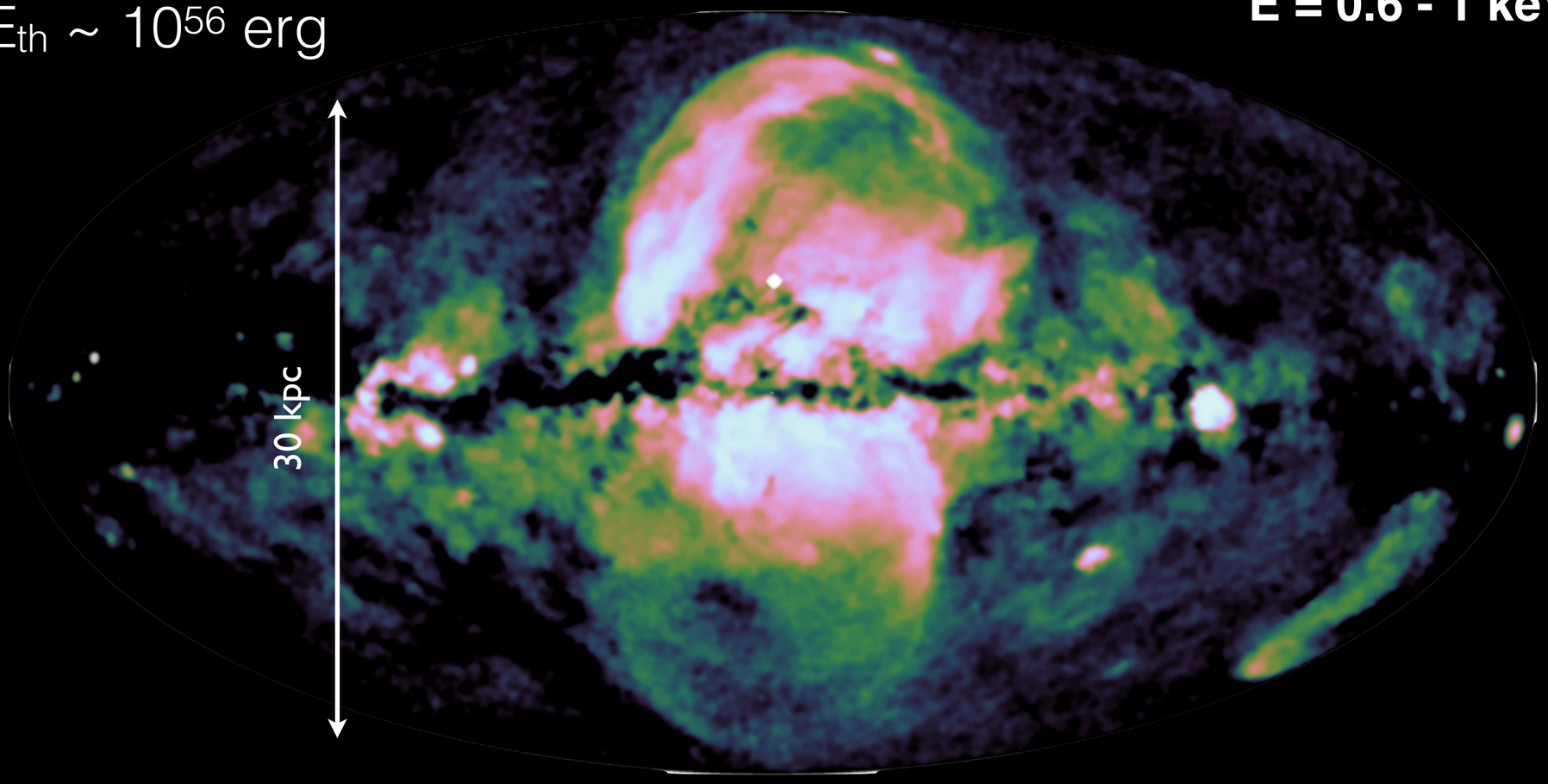
Su et al. (2010)
Ackermann et al (2014)
Kataoka et al (2017)

e-ROSITA bubbles

$L_X \sim 10^{39}$ erg/s

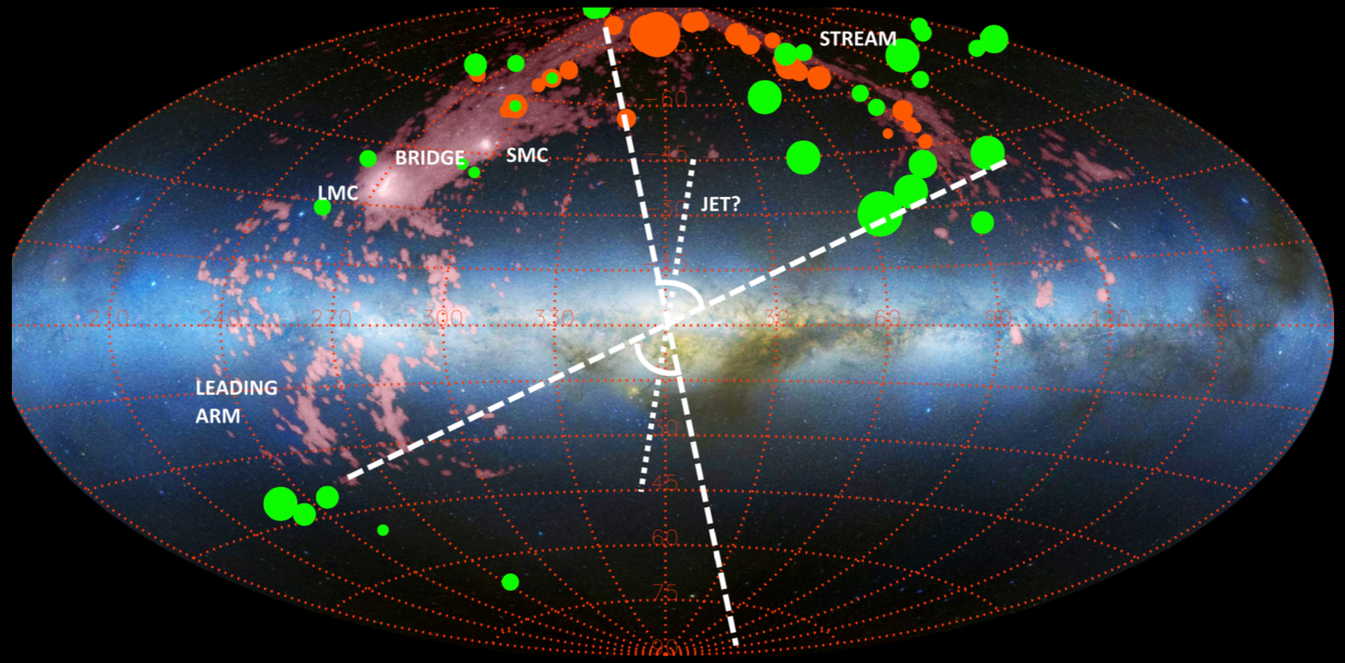
$E_{th} \sim 10^{56}$ erg

e-ROSITA
E = 0.6 - 1 keV



Predehl et al. (2020)

Ionization in the Magellanic stream



- Observation of a large level of ionisation in part of the Magellanic stream
- MW stellar UV radiation is too weak to explain measurements
- Consistent with scenario where Sgr A* was close to Eddington few Myr ago

Bland-Hawthorn et al (2013), Bland-Hawthorn et al. (2019), Fox et al. (2020)