

# The X-ray Bubbles at the Galactic Center

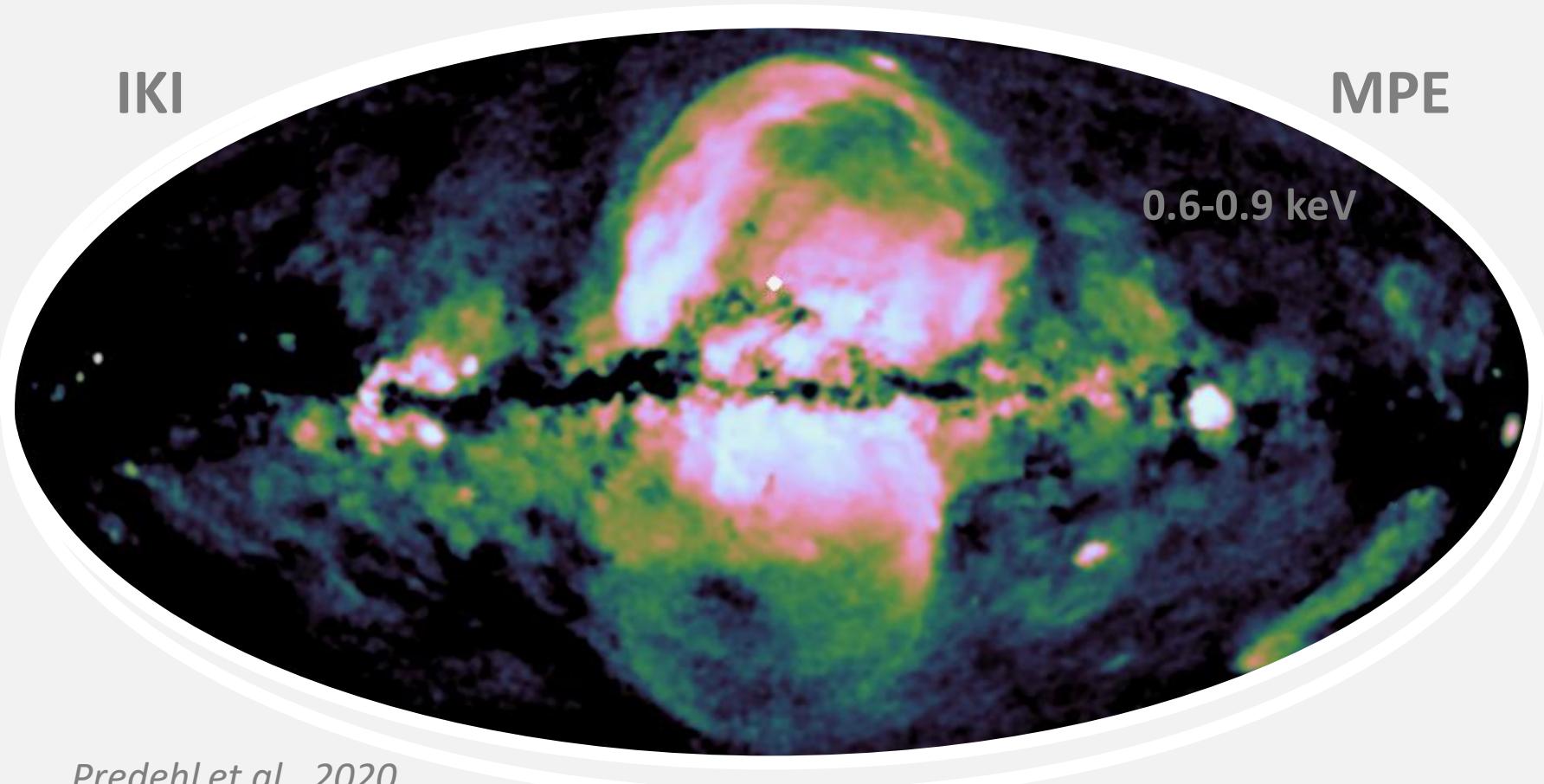
## Outflow from the Galaxy

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Praha, December 2023

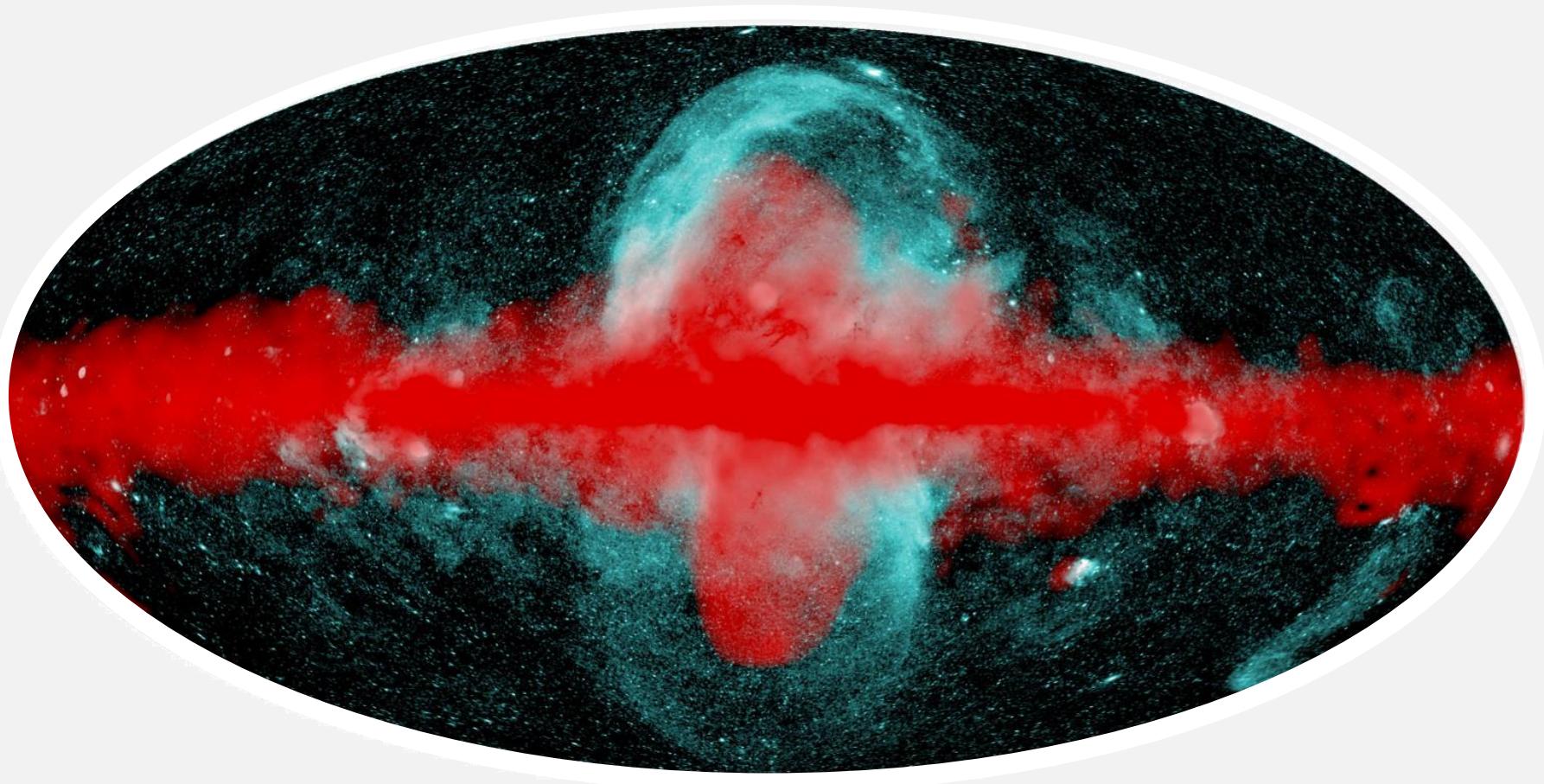
# „eROSITA Bubbles“



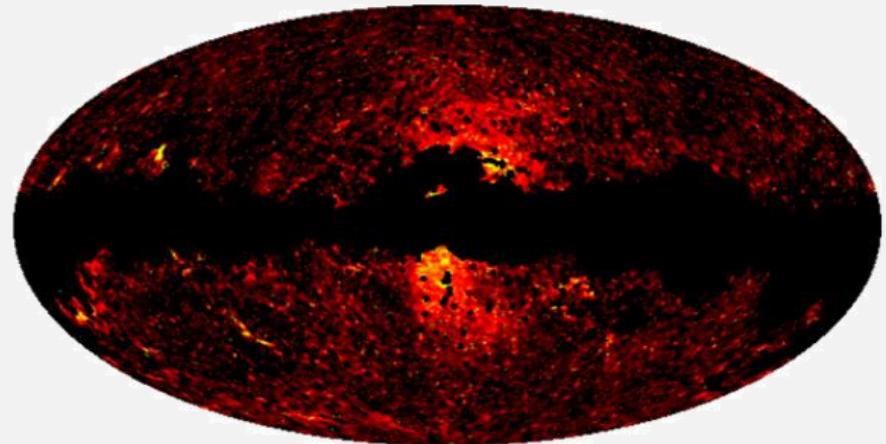
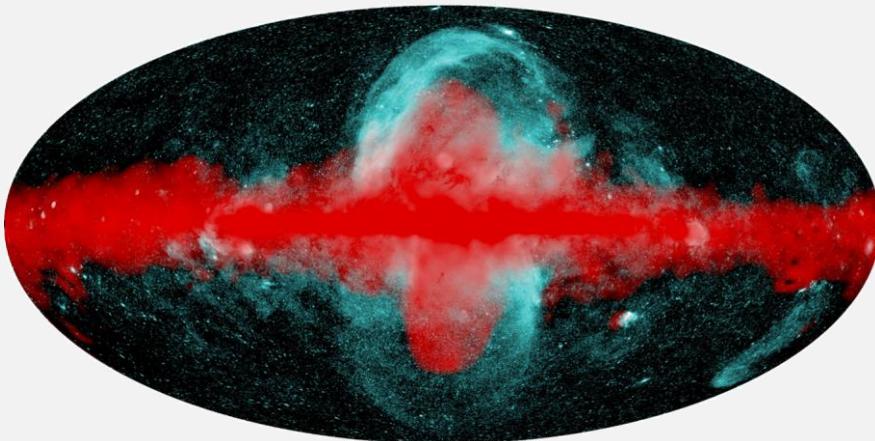
*Predehl et al., 2020*

*Sunyaev, Becker, Brunner, Burenin, Bykov, Cherepashuk, Chugai, Churazov, Doroshenko, Eismont, Freyberg, Gilfanov, Haberl, Khabibullin, Krivonos, Maitra, Medvedev, Merloni, Nandra, Nazarov, Pavlinsky, Ponti, Sanders, Sasaki, Sazonov, Strong, Wilms*

# Fermi Bubbles



# Multiwavelength Features



1. X-ray maps (0.6-0.9 keV) show shells surrounding Fermi Bubbles
2.  $\gamma$ -ray maps ( $> 1\text{GeV}$ ) show Fermi Bubbles
3. 24-60 GHz maps show synchroton emission in volume of FB

Observation:

Hard  $\gamma$ -ray spectrum  $>1 \text{ GeV}$

Similar Morphology with MW Haze

Theories:

Most likely IC of CRe produced at GC  
But: short period, high accretion rate

# Outflows from Galaxies



$SFR \sim 10 M_{\odot} \text{ yr}^{-1}$

$M_{bh} \sim \text{---}$

$v_{rot} \sim 80 \text{ km s}^{-1}$

$SFR \sim 10 M_{\odot} \text{ yr}^{-1}$

$M_{bh} \sim 2 \times 10^6 M_{\odot}$

$v_{rot} \sim 200 \text{ km s}^{-1}$

$SFR \sim \text{---}$

$M_{bh} \sim 2 \times 10^9 M_{\odot}$

$v_{rot} \sim 2000 \text{ km s}^{-1}$

MW

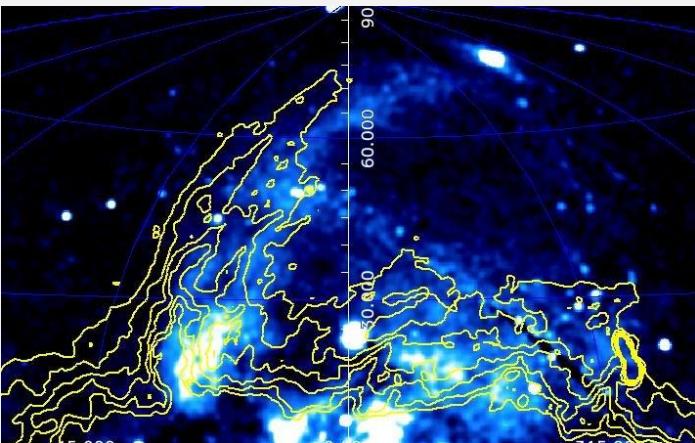
$SFR \sim 0.1 M_{\odot} \text{ yr}^{-1}$

$M_{bh} \sim 4 \times 10^6 M_{\odot}$

$v_{rot} \sim 220 \text{ km s}^{-1}$

*Sarkar, 2023*

# Energetics



*shock compression*

$$T_s \sim 3 \times 10^6 \text{ K}$$

$$\mathcal{M} \sim 1.4$$

$$T_{\text{CGM}} \sim 2 \times 10^6 \text{ K}$$

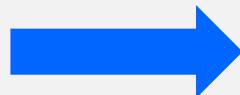
$$V_s \sim 320 \text{ km s}^{-1}$$

$$\text{EM} \sim 0.05 \text{ pc cm}^{-6}$$

$$D \sim 12 \text{kpc } (\times 2)$$

$$d_{\text{em}} \sim 4 \text{kpc}$$

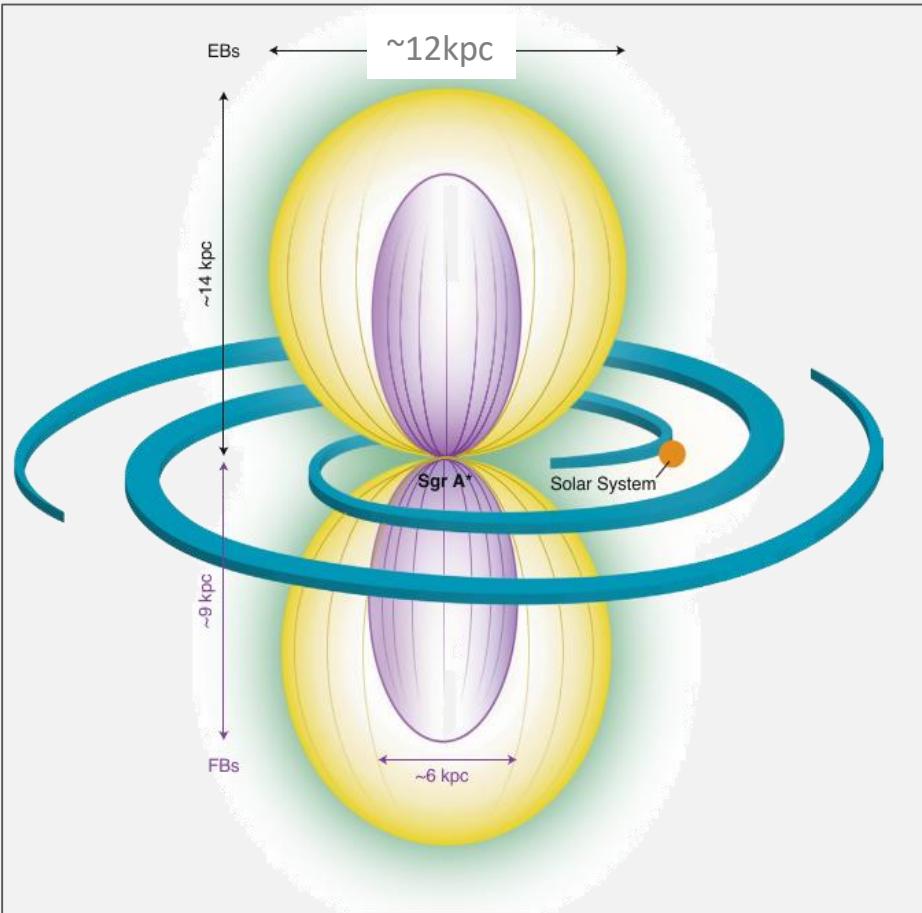
$$\tau_{\text{dyn}} \sim 20 \text{ Myr}$$



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

$$P_{\text{dyn}} = E_{\text{th}} / \tau_{\text{dyn}} \sim 10^{41} \text{ erg s}^{-1}$$

# Bubble Schematics



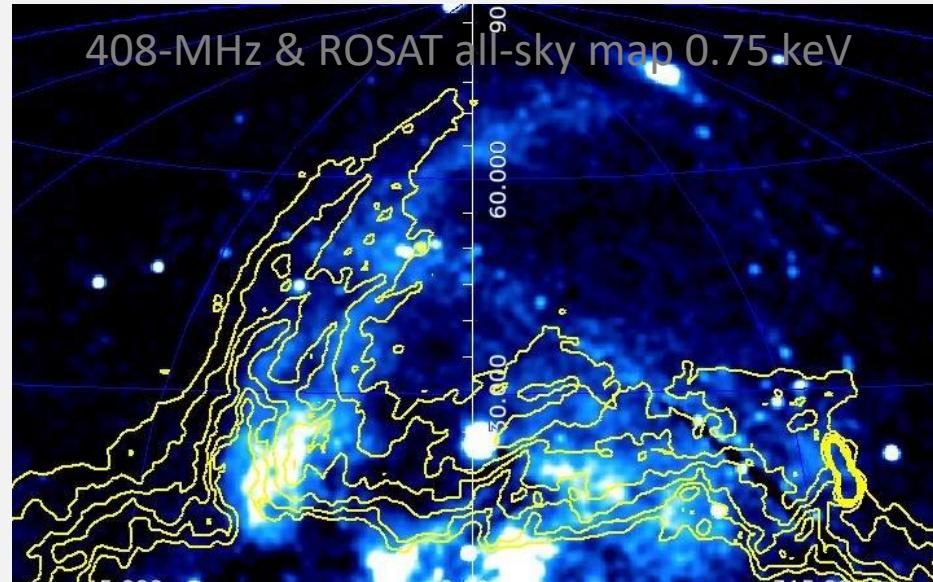
## Some numbers:

distance (GC)	~8 kpc
brightness	$6 \times 10^{38} \text{ ergs}^{-1}$
kT	0.3 keV
t <sub>cool</sub>	$1.9 \times 10^8 \text{ yr}$
v <sub>exp</sub>	$\sim 300 \text{ kms}^{-1}$
age	15-20 Myr
E <sub>th</sub>	$1.3 \times 10^{56} \text{ erg}$

# Open Questions

- Distance: NPS near or far
- Timing: ,Explosive' or periodic event
- Origin: AGN activity of Sgr A\* or Starbursts

# North Polar Spur



*Haslam et al., 1974; Kataoka et al., 2018*

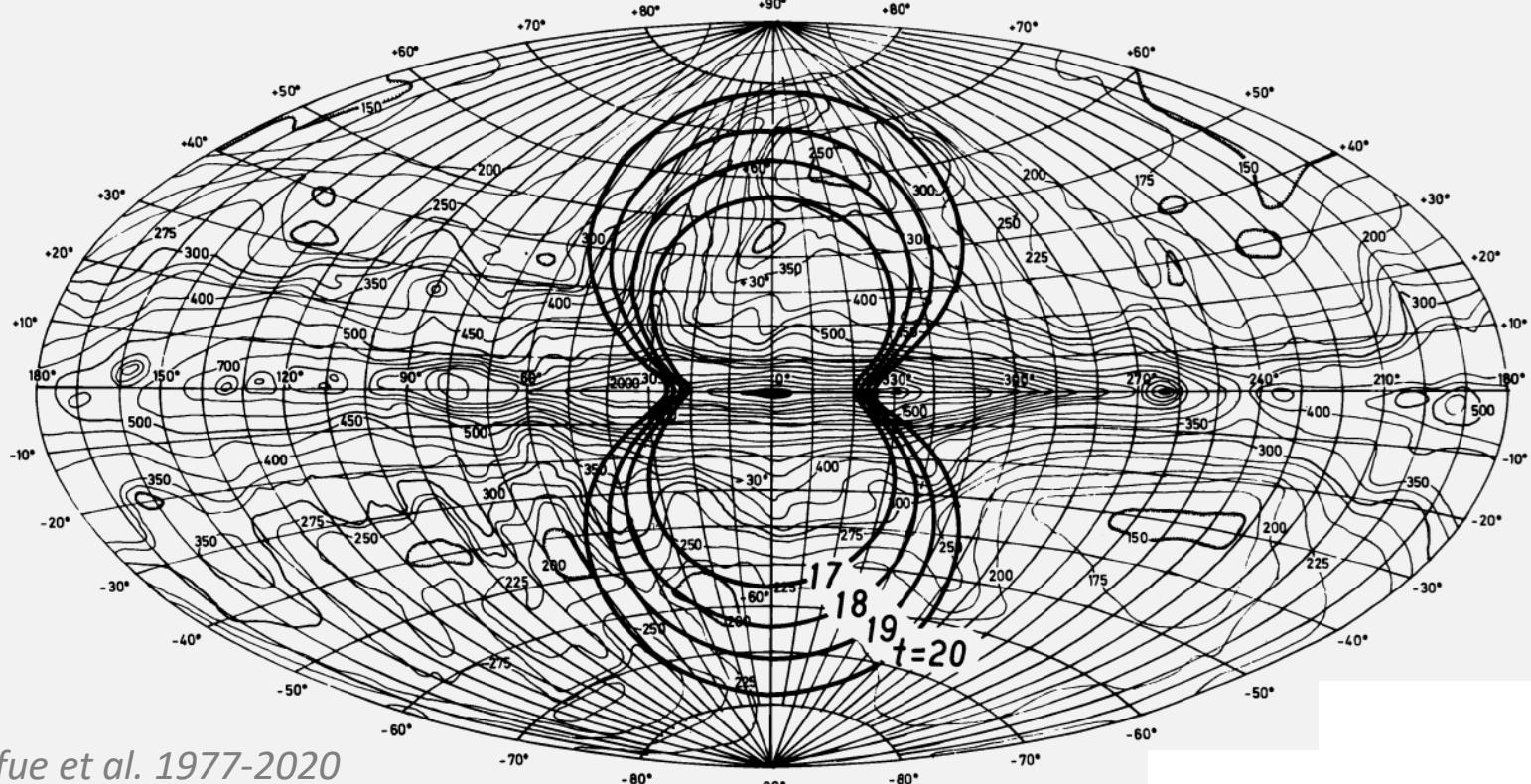
Radio (Hanbury Brown et al., 1960):

- Irregularity in the local spiral structure
- Nearby Supernova Remnant
- Large-scale effect in the galactic corona

X-ray (Bunner et al., 1972):

- ‘Shell’ somewhat smaller than radio
- Distance  $\sim 100\text{pc}$  given absorption, starlight polarization

# Bipolar Hypershell Origin in Galactic Center



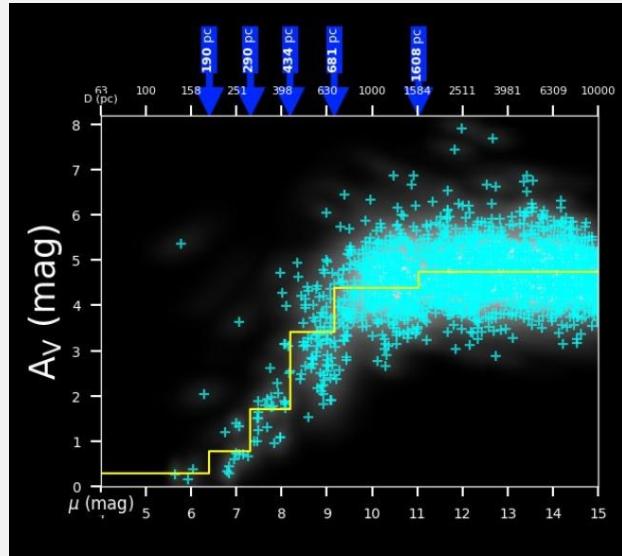
Sofue et al. 1977-2020

- MHD wave model, NPS & 3kpc arm
- But no southern counterpart
- Center of NPS not in GC

# NPS near or far?

Near:	Supernova Remnant? But...	(Hanbury-Brown et al., 1960)
Near:	Supernova Remnant	(Berkhuijsen et al., 1971)
Far:	Bipolar Hypershell explosion at GC	(Sofue 1977)
Near:	Stellar Winds from Sco-Cen Ass. - LHB	(Aschenbach & Egger, 1995)
Near:	NPS local, unrelated to Galactic Halo	(Miller et al., 2007)
Far:	Emission Measure	(Akita et al., 2018)
Far:	Emission Measure	(LaRocca, 2020)
Near:	X-ray absorption- Visual Extinction	(Das et al., 2020)
Far:	Bubbles	(Kataoka 2021)

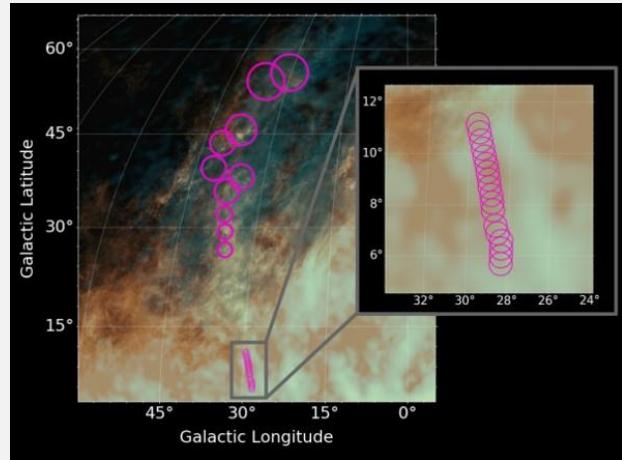
# NPS at near distance



X-ray absorption / visual extinction:  
70-135 pc, <700 pc at southern terminus  
NPS a uncorrelated feature?

X-ray absorption:  $N_{\text{H}}/A_{\text{V}} = 1.79 - 2.08 \times 10^{21} \text{ mag}^{-1}$

*Predehl et al., 1995; Valencic & Smith, 2015; Zhu et al., 2017*



But:  $N_{\text{H}}$  (HI) is not  $N_{\text{H}}$ (X-ray)!  
Local dust destruction by SNR

For most recent dust maps see:

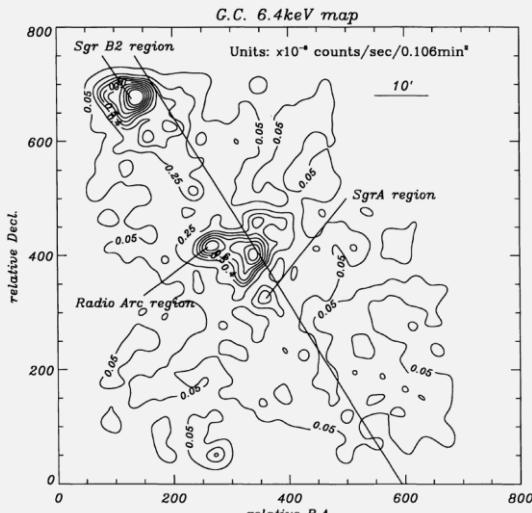
*Lallement et al., 2022* and visit  
<https://explore-platform.eu/sda/g-tomo>

*Das et al., 2020*

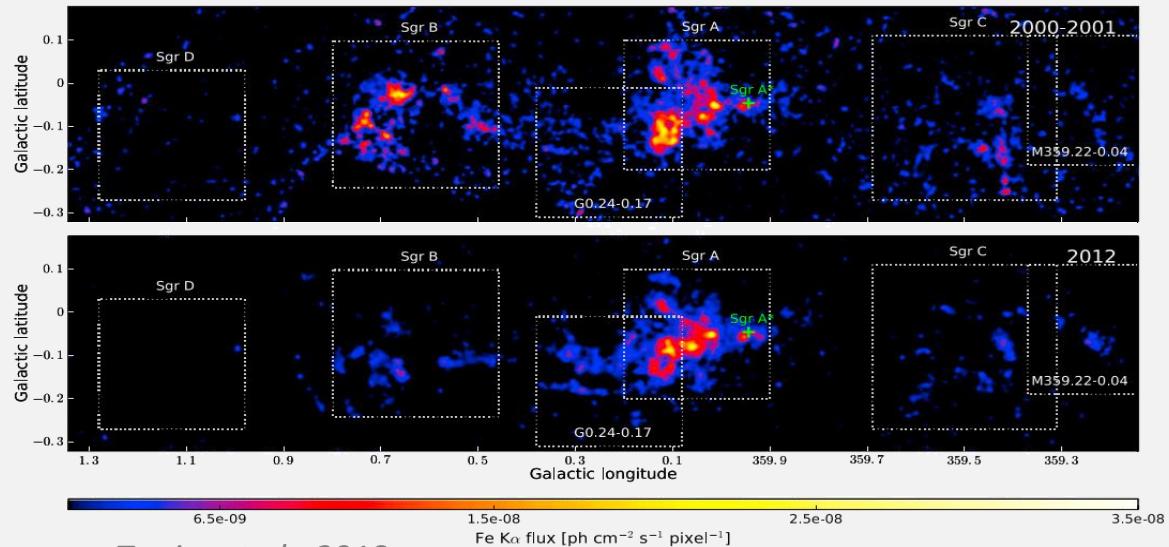
# Sgr A\* Activity

- Sgr A\* is quiet  $\sim 10^{33}$  erg/s (X-ray)
  - Frequent Flares (1/d)  $\sim 10^{34-35}$  erg/s  
(e.g., Porquet et al., 2003; Haggard et al., 2019)
  - $\sim 10^2$  years ago (‘Fe-K $\alpha$  Echo’)  $\sim 10^{39}$  erg/s  
(Sunyaev et al., 1993; Koyama et al., 1996; Clavel et al., 2013; Terrier et al., 2018; Marin et al. 2023)
  - $\sim 10^{6-7}$  years ago  $\sim 10^{??}$  erg/s

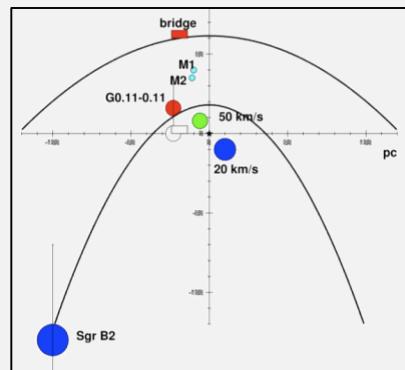
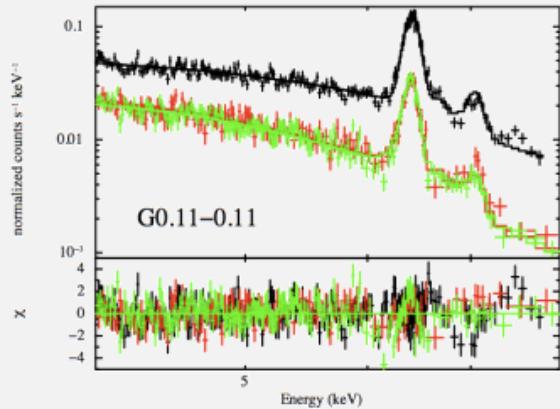
# Galactic Center Molecular Clouds & Fe K $\alpha$ Fluorescence



Koyama et al., 1996



Terrier et al., 2018



Alternative/Additional Explanation  
Interaction of particles with MCs

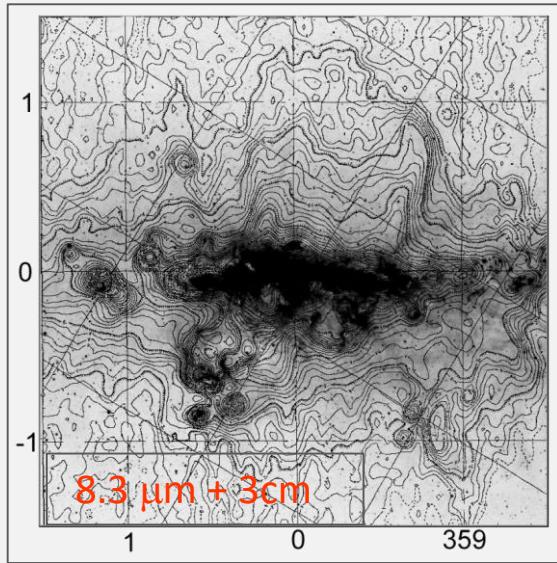
CRe

(Yusef-Zadeh et al., 2007; Valinia et al., 2000)

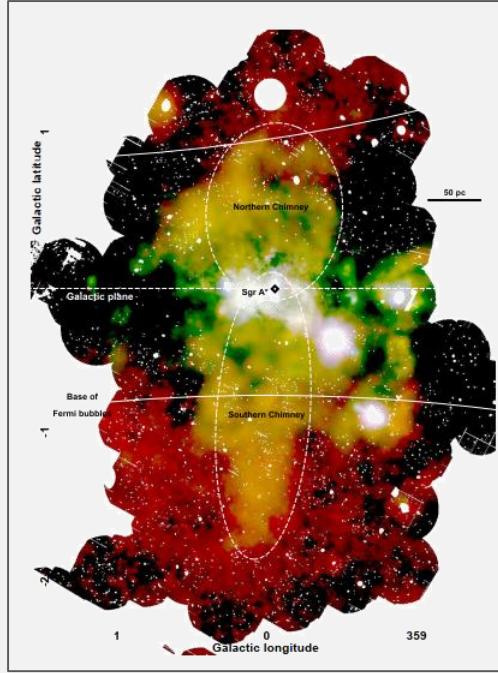
CRp

(Dogiel et al., 2009; Predehl et al., 2003)

# Outflows from GC



Bland-Hawthorn & Cohen, 2003



‘Channeled Outflows’  
Recurrent Nuclear Starbursts  
  
Mass Ejection 150pc 1Myr  
Hyp.shells  $10^{55}$  ergs, 15 Myrs

‘Chimneys’ & GCL  
*Ponti et al., 2019/21*

Cold Gas Outflow  
*Teodoro et al., 2020*

Models:

AGN-Jet

0.1 edd.  $\sim 10^{44}$  erg/s

2.6Myr ago, 0.1Myr durat.

*Yang et al., 2022*

Accretion or SF Wind/Jet

$O_{VIII}/O_{VII}$ ,  $10^{40.5-41}$  erg/s

100Myr duration, still active

*Sarkar et al., 2022*

AGN or SF still open ?

# Unanswered Questions

1. Temperature of the NPS/eROSITA bubbles.
  - 0.3 keV (collisional eq), 0.2 keV (non-Solar abundance), 0.7 keV (non-eq ionization)
  - Should be solidified once expansion velocity is constrained. XRISM/Athena/LEM?
2. Could the unified FERMI/eROSITA bubbles be wrong?
  - Two different events?
3. Star formation rate at the central melecular zone.
  - $0.09 \text{ Msun/yr}$  (last few Myr),  $0.2\text{-}0.8 \text{ Msun/yr}$  (last 30 Myr)
4. How long did the  $\sim 3$  Myr old AGN burst last? Was it long enough to partially power the FERMI Bubbles?
  - $dt > 4 \text{ kyr}$  (ionization time)

# Bubbles in other Galaxies?

According to TNG Simulations 2/3 of MW galaxies may have bubbles

Pillepich et al., 2022



# Summary

- With eROSITA we have found the southern counterpart to the northern structure.
- The total energy of the bubbles is of the order  $10^{56}$  erg.
- In combination with ‘outflows’ observed at other wavelengths and smaller scales it is extremely likely that the eROSITA Bubbles have their origin in the Galactic Center.
- Everything together suggests an active period of the GC (since) some million years ago.
- We have not found bubbles in other spiral galaxies. Contrast?

# eROSITA 1. All-Sky Survey

SRG/eROSITA

0.3-2.3 keV - RGB



Thank you very much  
for your attention

IKI

MPE

*Credit: Jeremy Sanders, Hermann Brunner and the eSASS team (MPE)  
Eugene Churazov, Marat Gilfanov (on behalf of IKI)*