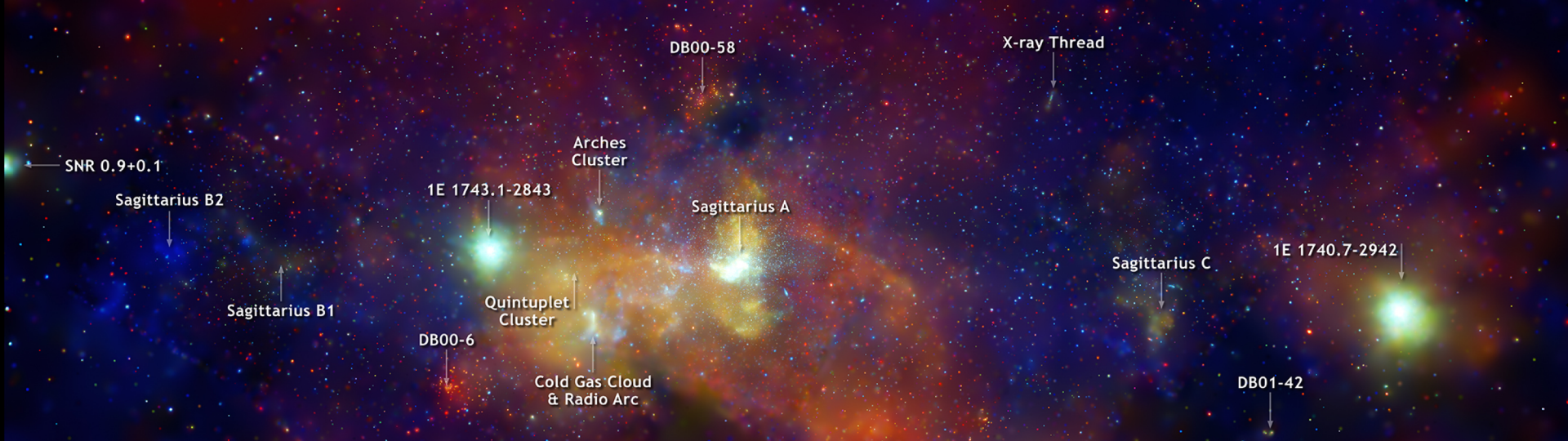


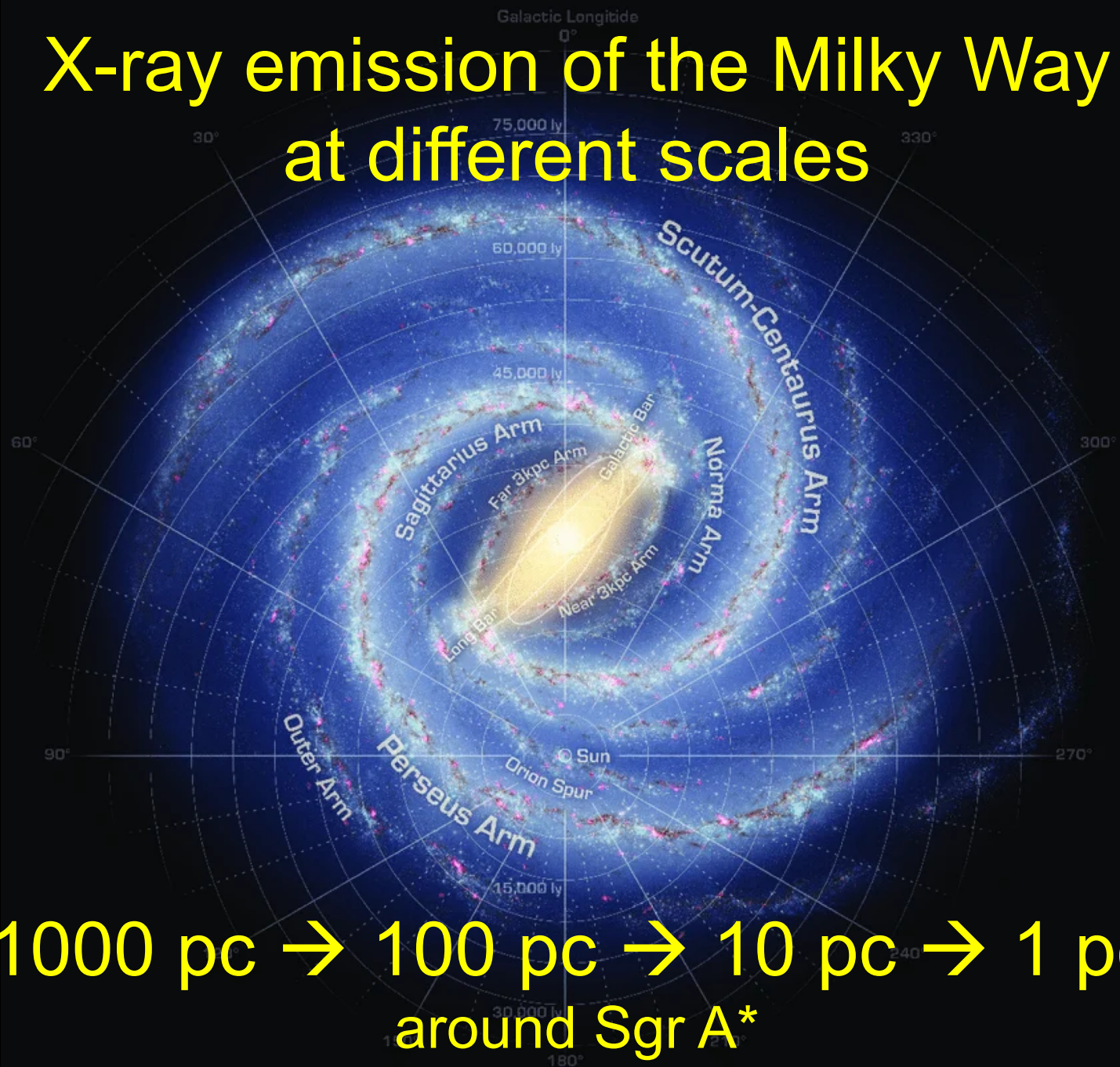


[From far to] The closest environment of the supermassive black hole Sagittarius A* in X-rays

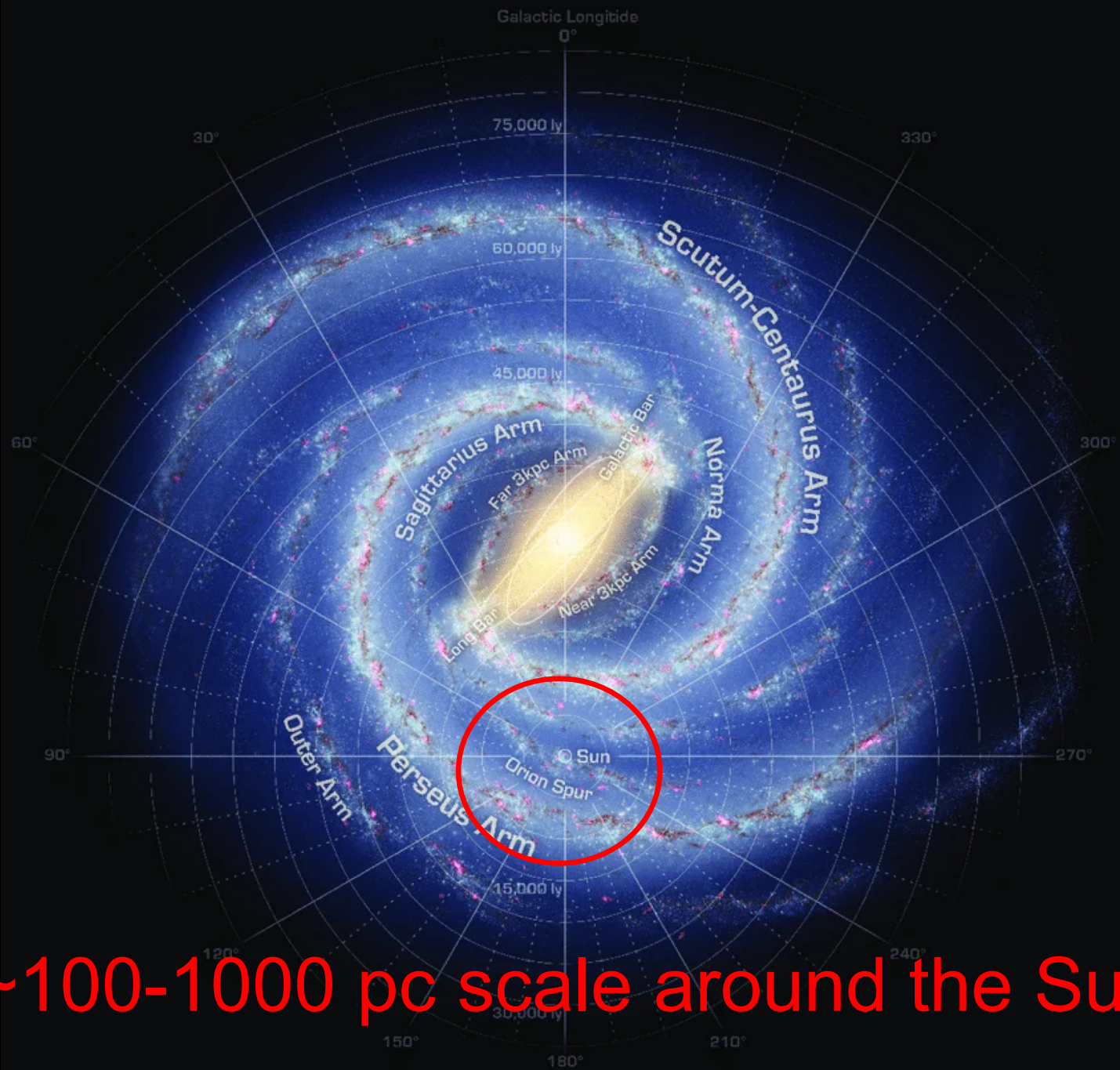
Roman Krivonos

Space Research Institute (IKI), Moscow, Russia

X-ray emission of the Milky Way at different scales



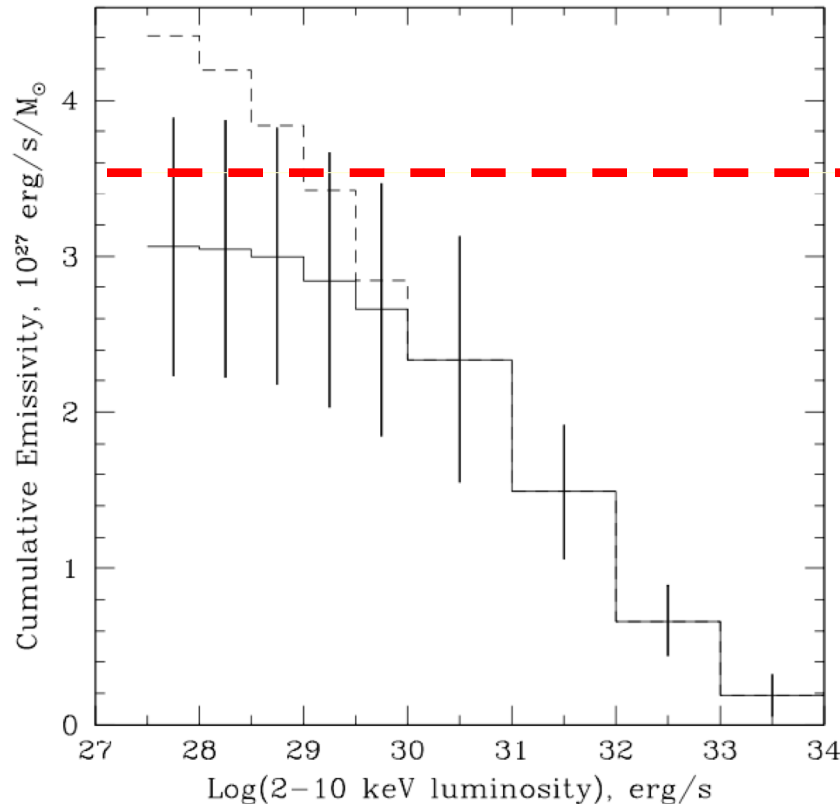
Part I
*~1000 pc scale around Sgr A**



~100-1000 pc scale around the Sun

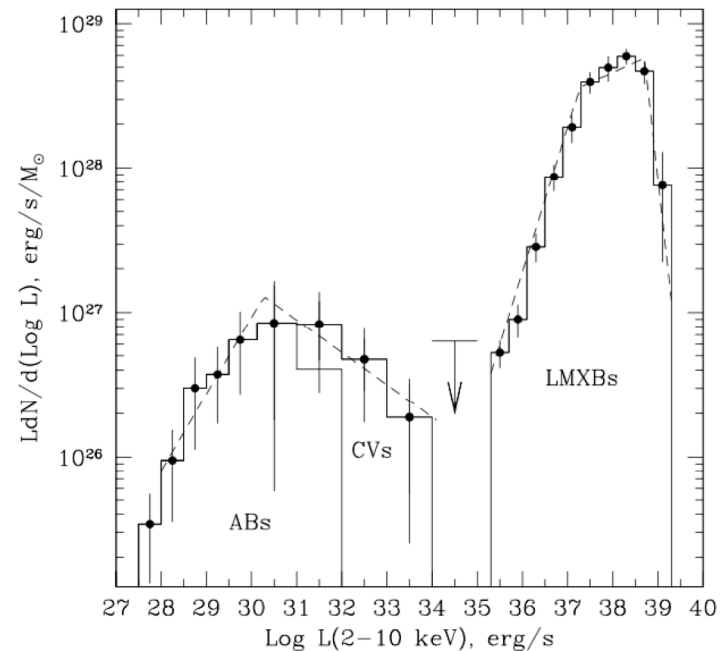
X-ray emitting stellar population ~100-1000 pc around the Sun

- Active binaries (ABs) and Cataclysmic Variables (CVs)



$$L / M = (3.5 \pm 1.5) \times 10^{27} \text{ erg s}^{-1} M_{\odot}^{-1}$$

Galactic X-ray Luminosity Function

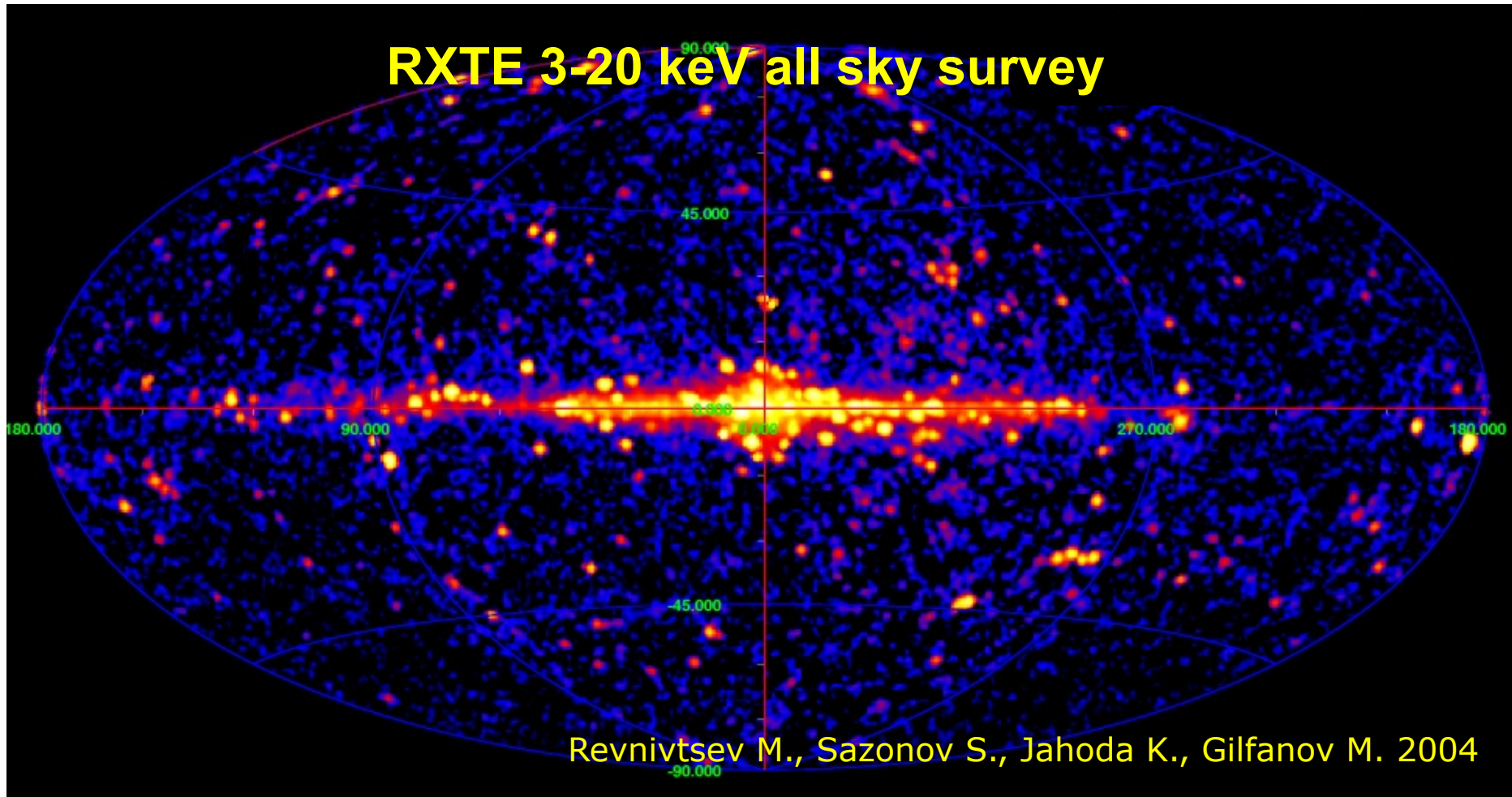


Cumulative emissivity of ABs and CVs as a function of luminosity

Sazonov et al., 2006

High energy view of the Milky Way

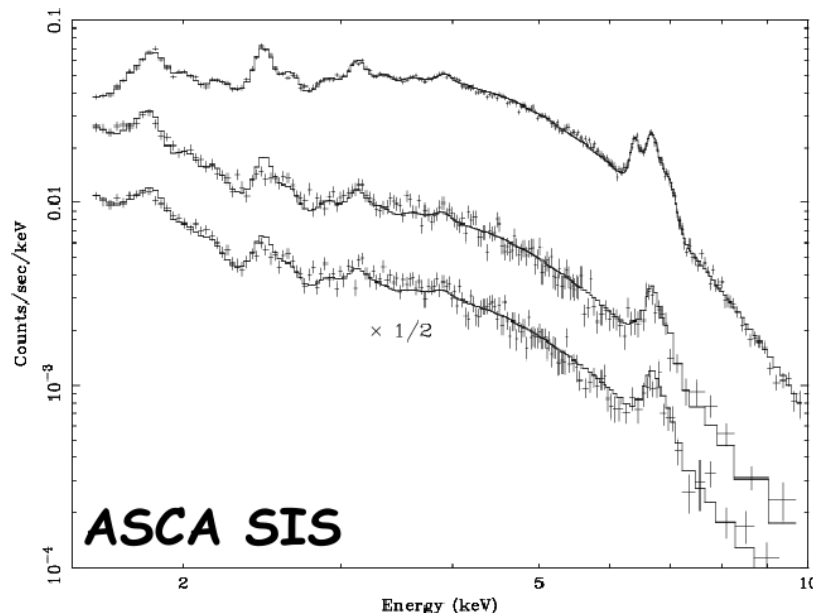
RXTE 3-20 keV all sky survey



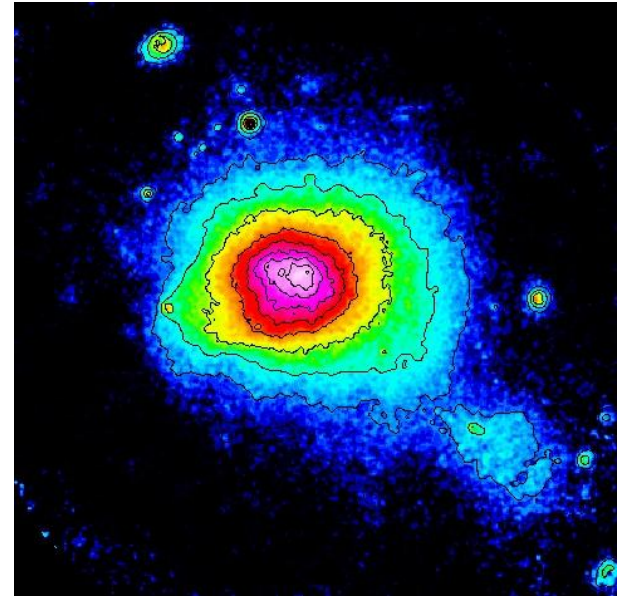
Galactic Ridge X-ray Emission (GRXE) origin explanations

1) Emission of optically thin plasma

To explain spectrum
necessary to have very
hot (7-10 keV) gas



Coma cluster



2) Superposition of point sources ?

COBE/DIRBE ($3.5\ \mu\text{m}$)

RXTE (3-20 keV)

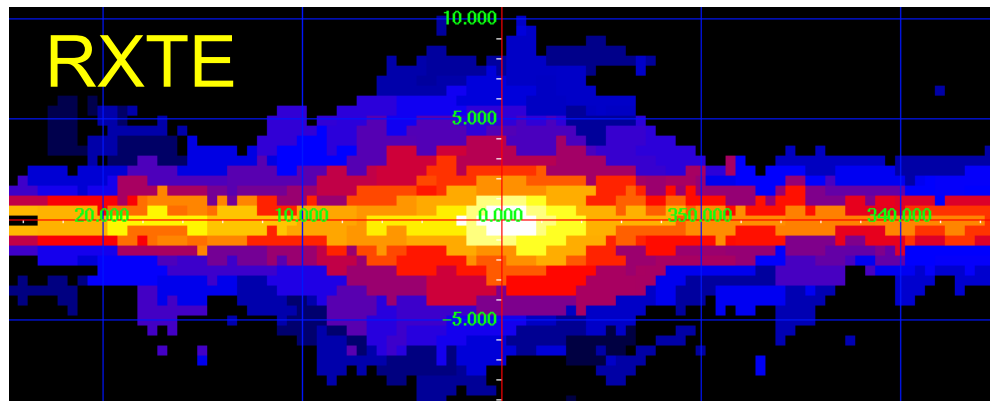


M. Revnivtsev
1974-2016

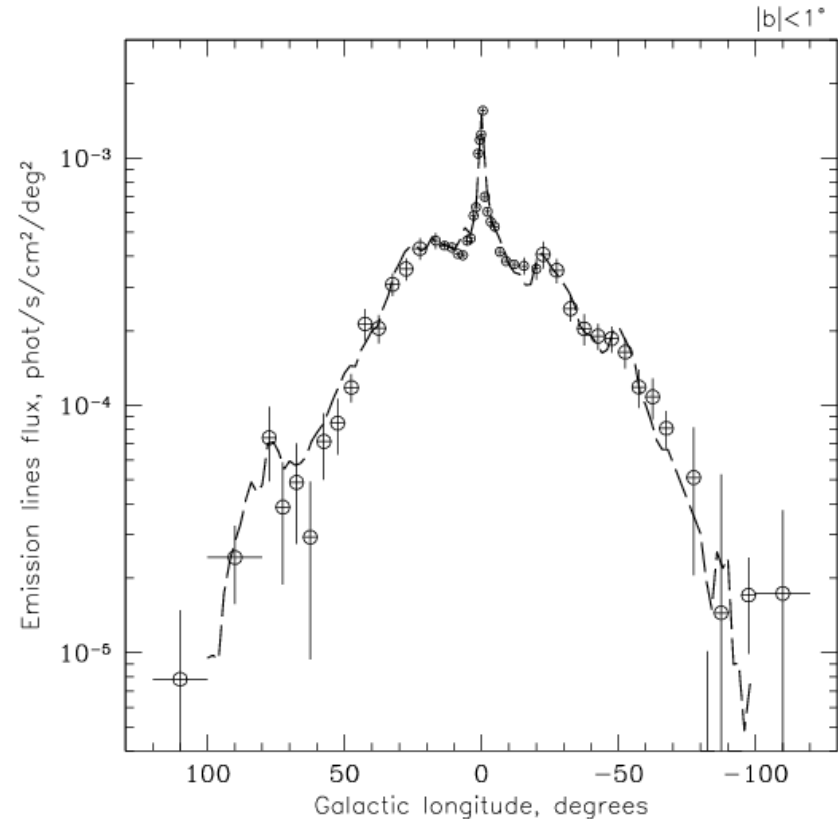
- GRXE follows near-infrared emission revealing stellar origin
- GRXE is formed by a large population of low-luminosity sources
- Type of these sources is known (accreting WDs)
- GRXE properties are uniform across Galaxy
- Unit-stellar-mass emissivity is in good agreement with that measured in Solar neighbourhood

GRXE is traced by 6.7 keV iron line emission

GRXE 6.7 keV map



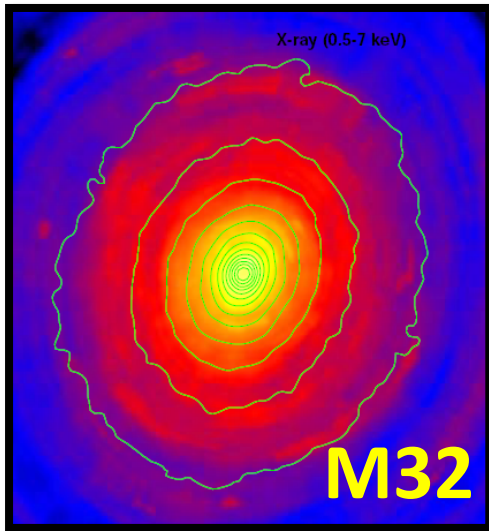
Revnivtsev et al., (2006)



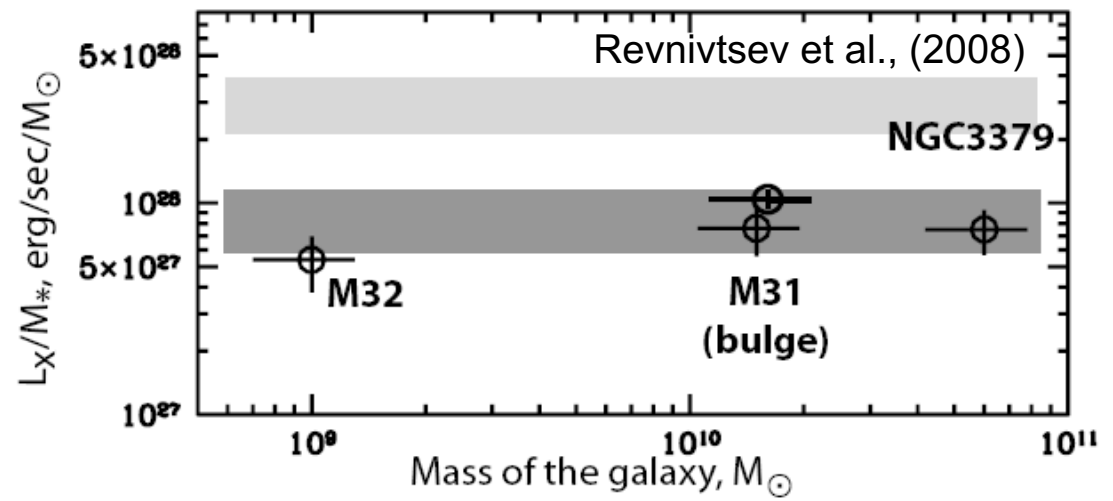
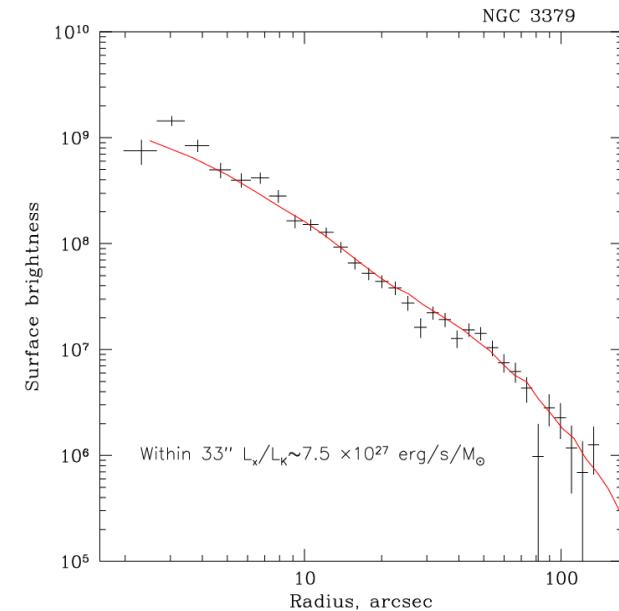
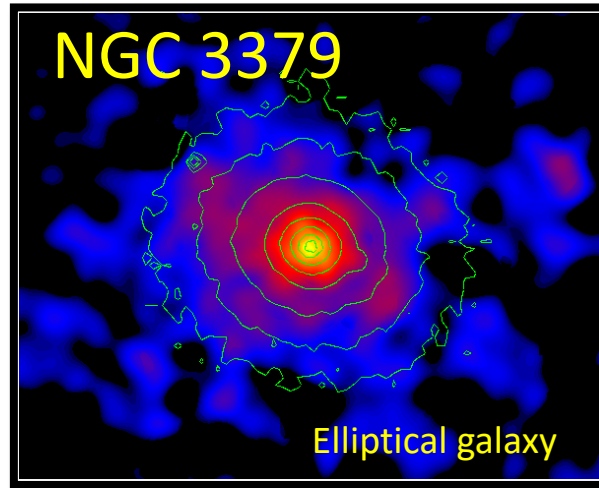
Galactic longitude profile

$$L_{2-10 \text{ keV/M}} = (3.5 \pm 0.5) \times 10^{27} \text{ erg/s/Msun}$$

The same phenomena in other galaxies



Revnivtsev et al., (2007)



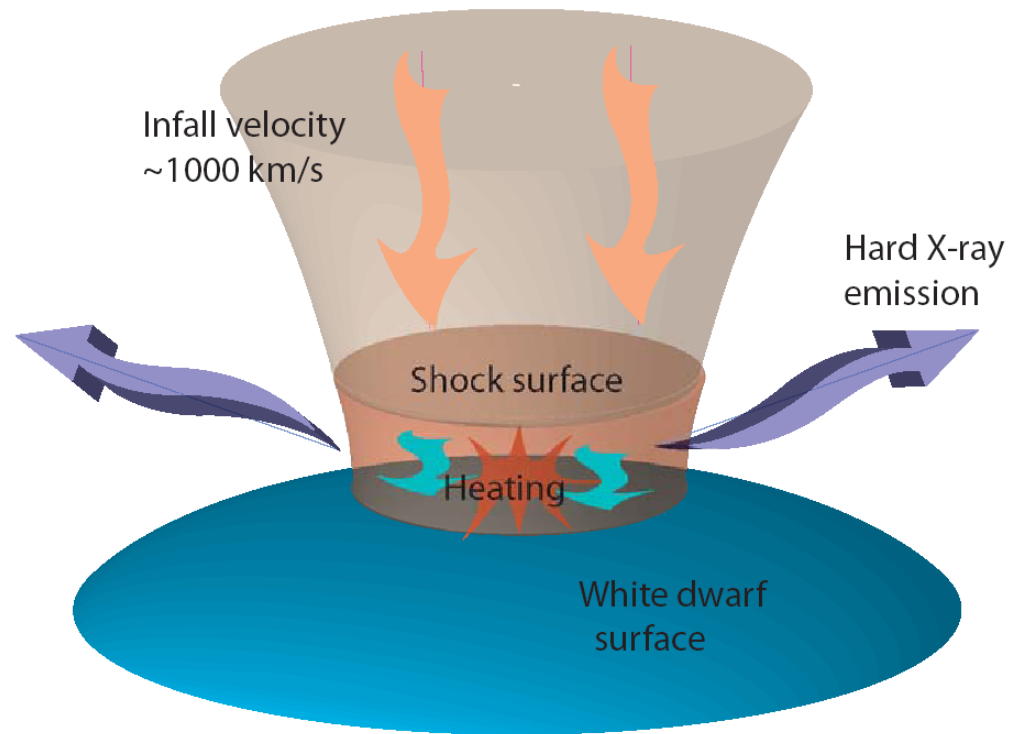
RXTE main results

- * GRXE follows near-infrared emission revealing stellar origin
- * Unit-stellar-mass emissivity is in good agreement with that measured in Solar neighbourhood

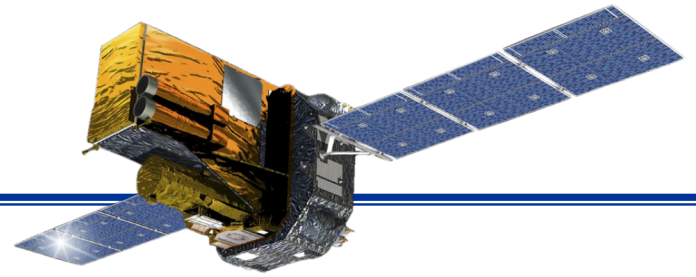
Prediction:

- * Energy cut-off in GRXE spectrum depends on the mass of typical WD

=> The observed spectral shape can be translated to the WD mass

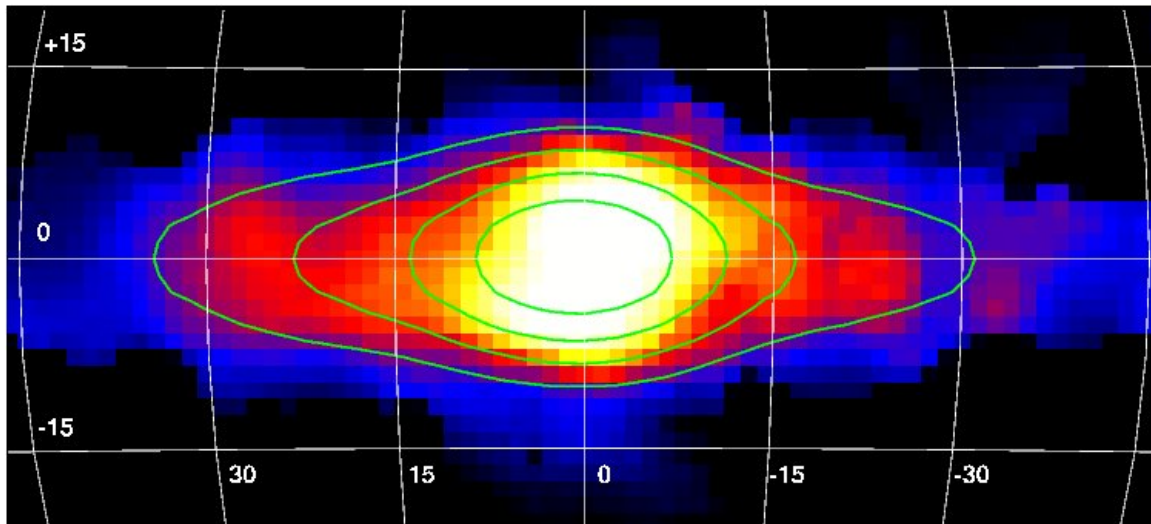


GRXE study with INTEGRAL

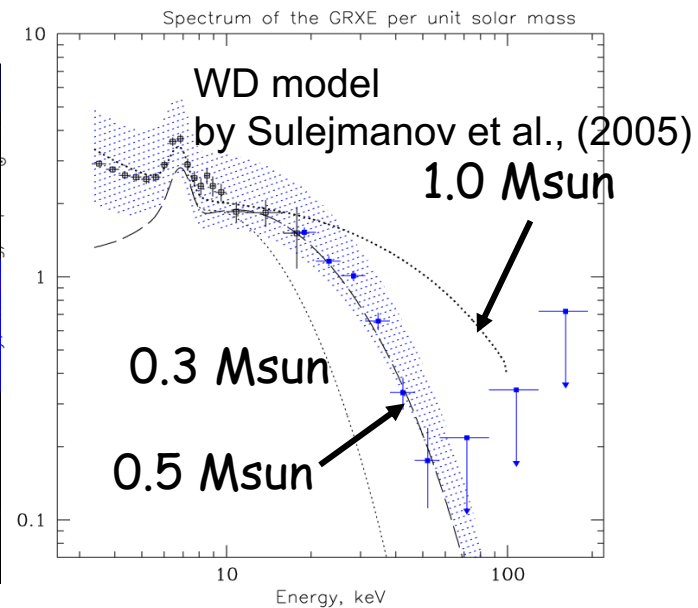


17-60 keV

Krivonos et al., 2007

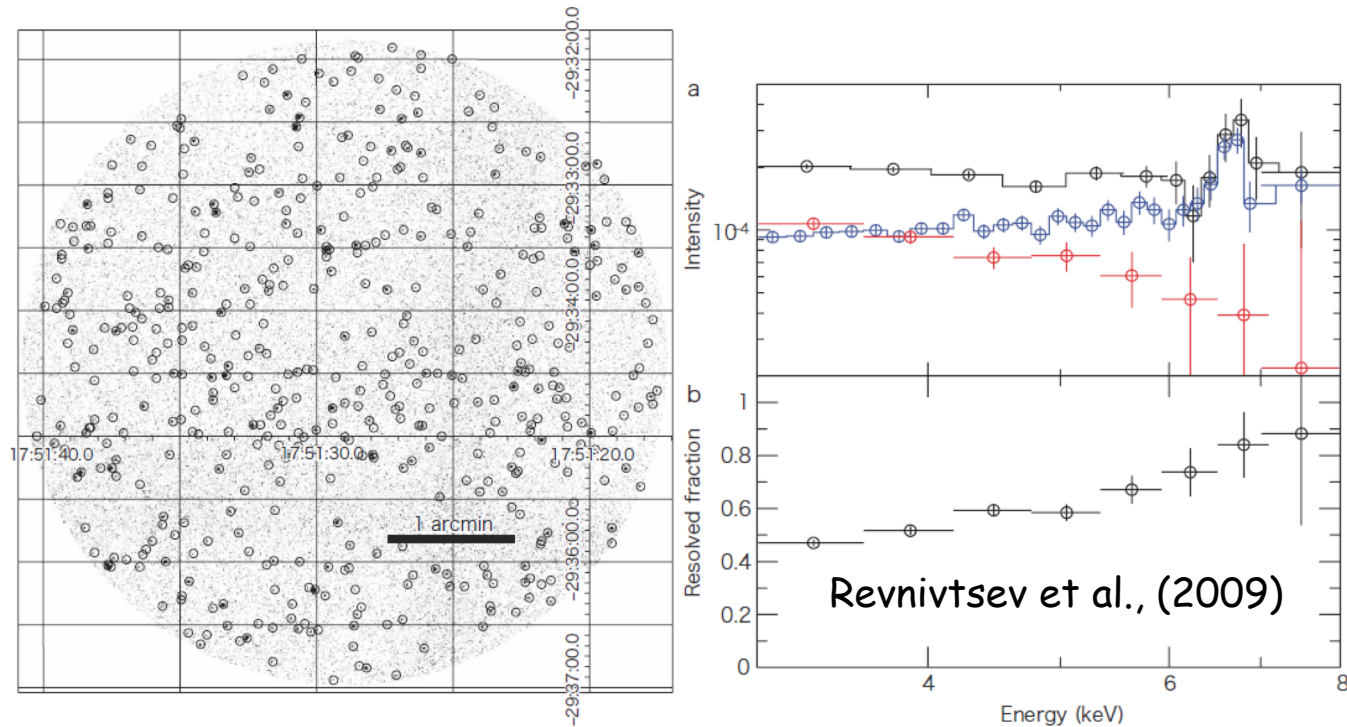


GRXE Spectrum



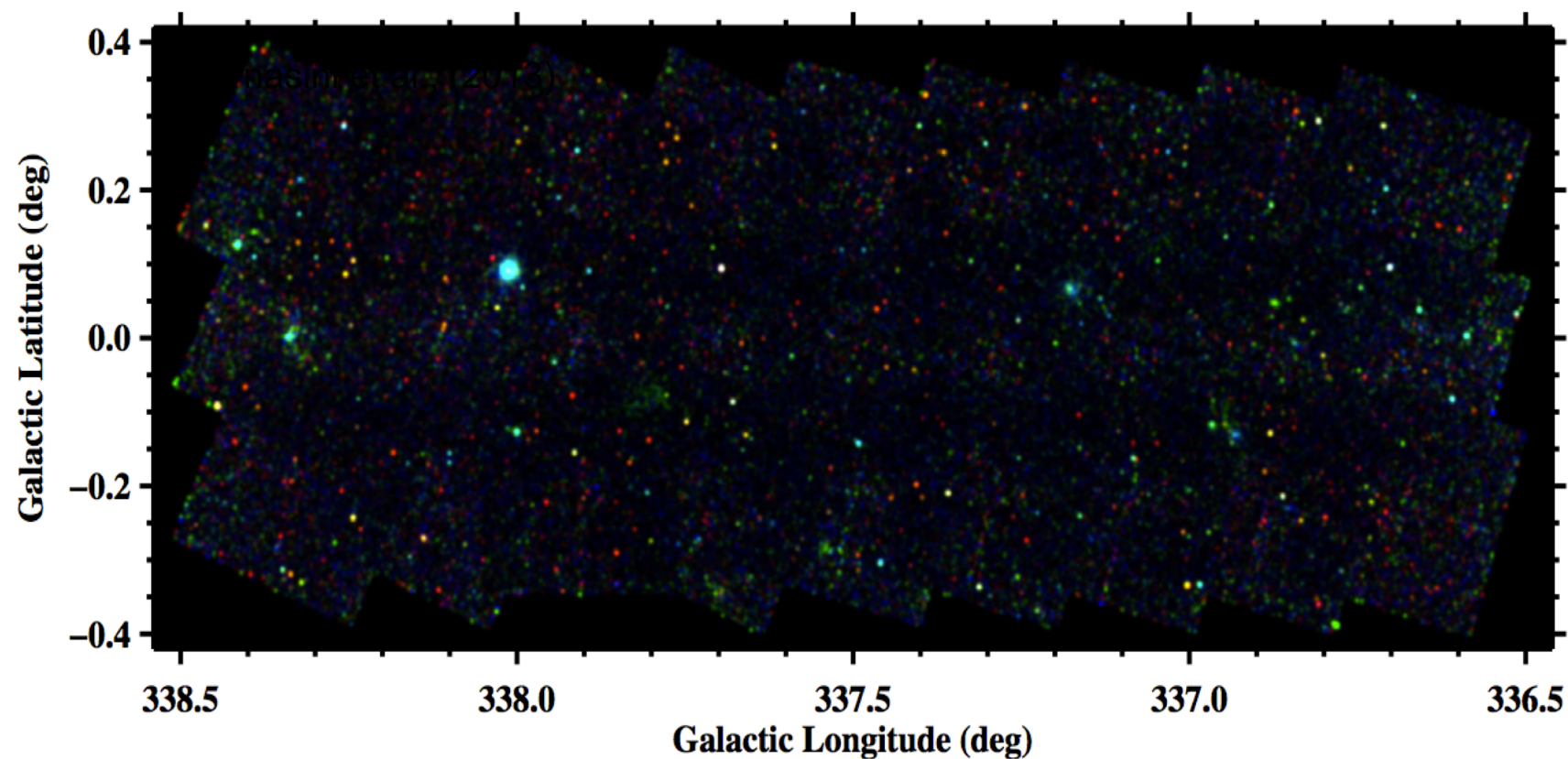
- High energy cutoff found ~ 50 keV
- accreting WD mass ~ 0.5 Msun

Chandra ultradeep field in GC (1Ms)



At least 80% of GRXE is explained by point X-ray sources

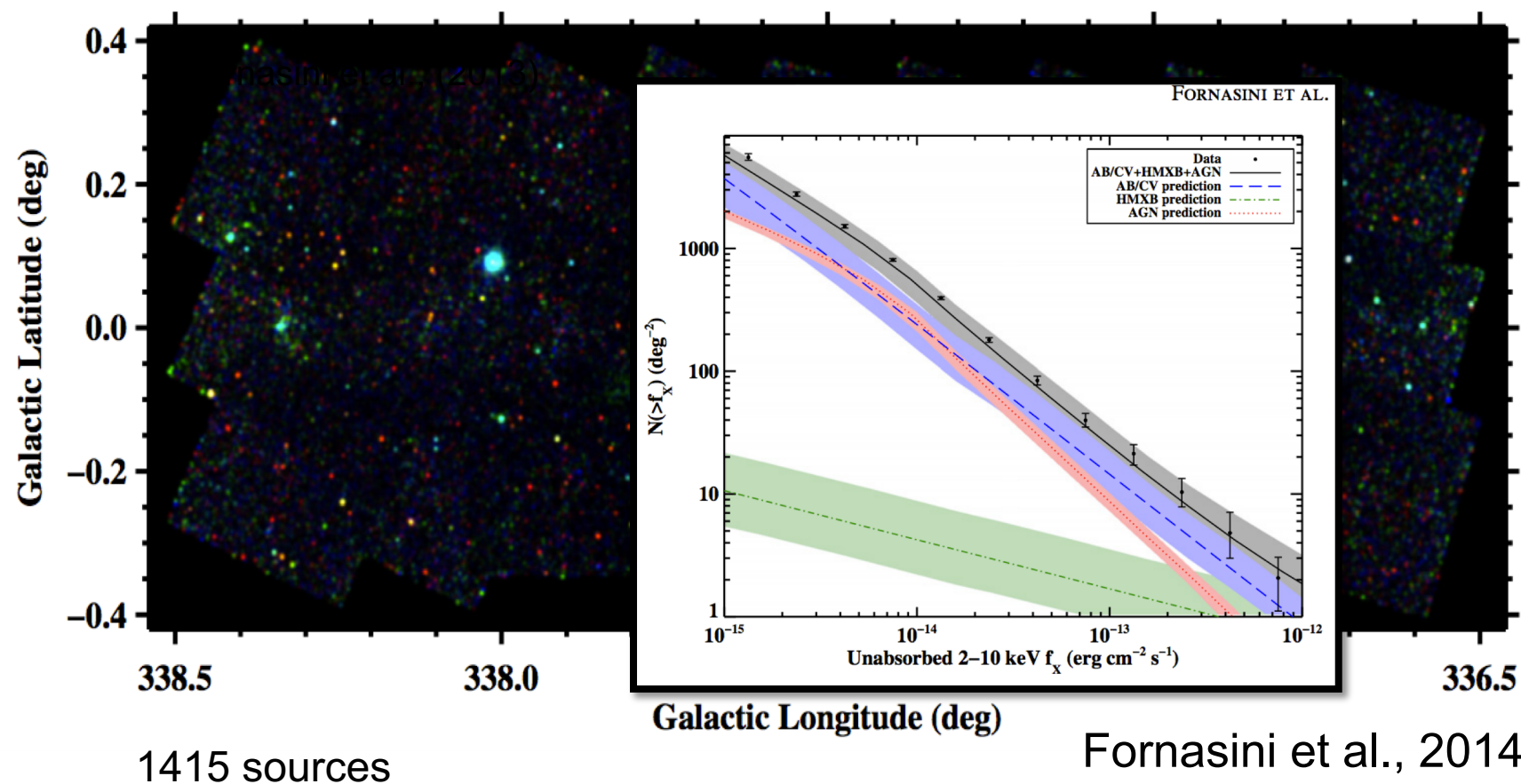
Chandra deep field in Norma Spiral Arm



1415 sources

Fornasini et al., 2014

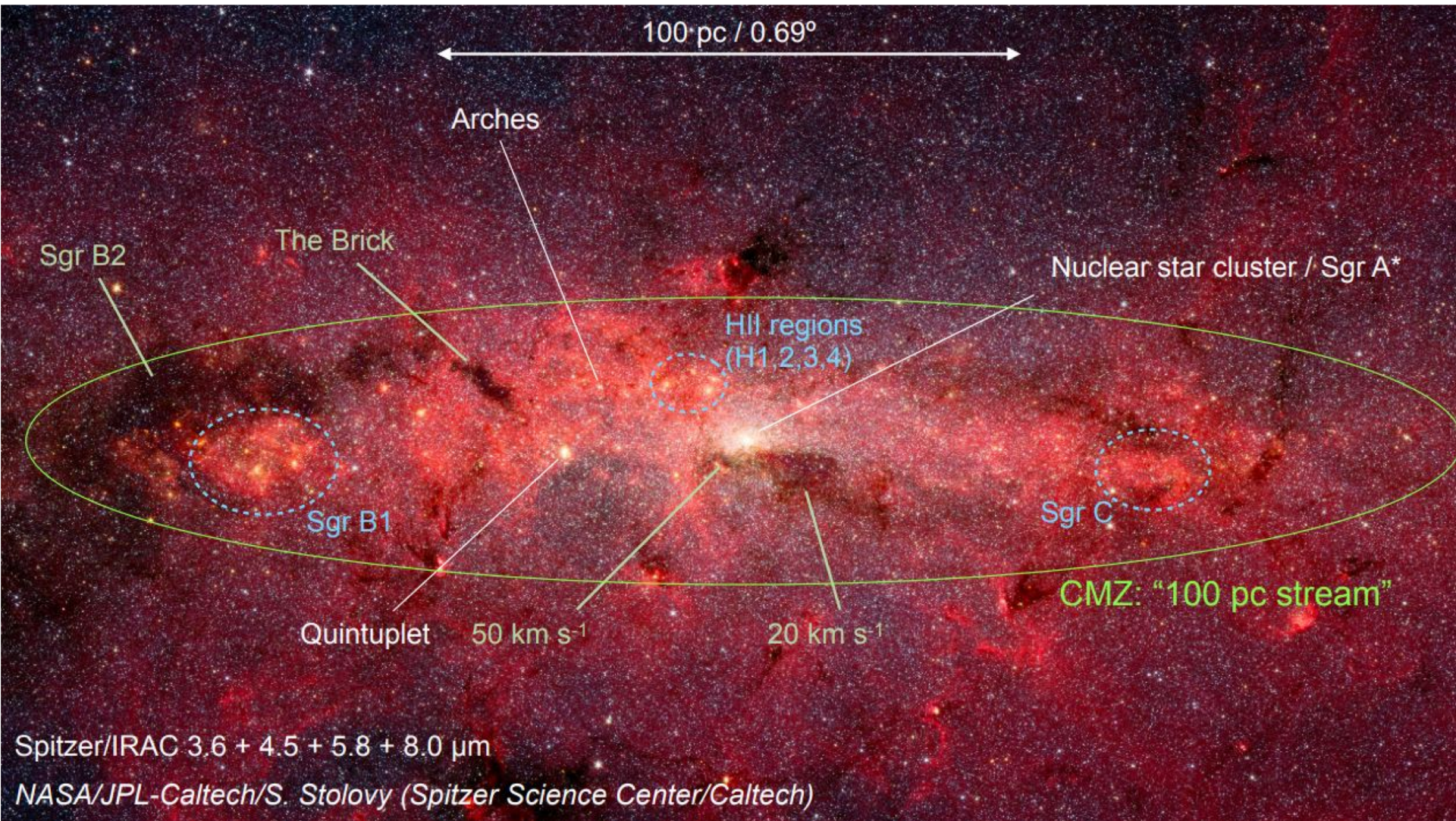
Chandra deep field in Norma Spiral Arm



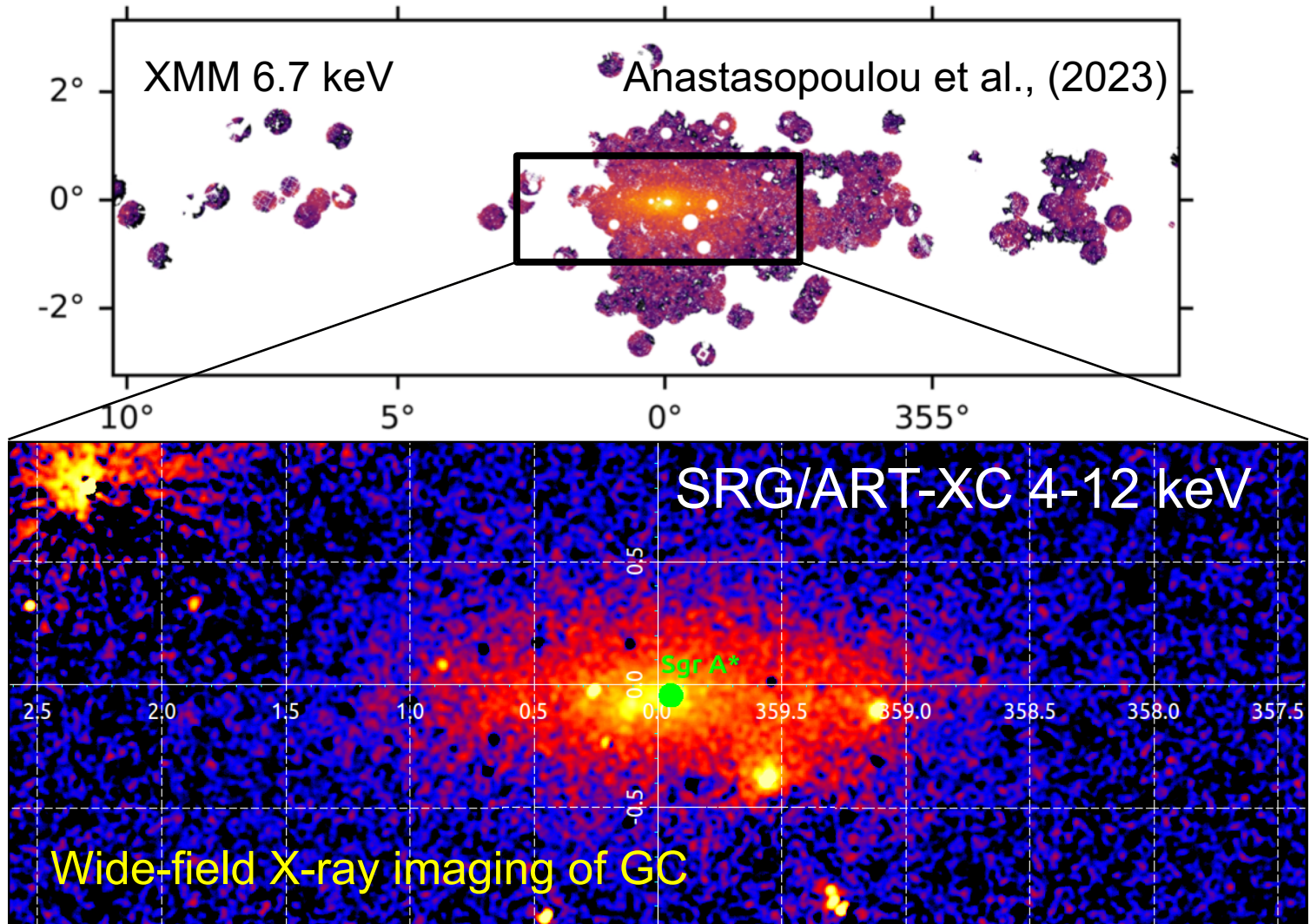
Based on Galactic stellar mass models and L/M measured in solar neighborhood

Part II
*~100 pc scale around Sgr A**

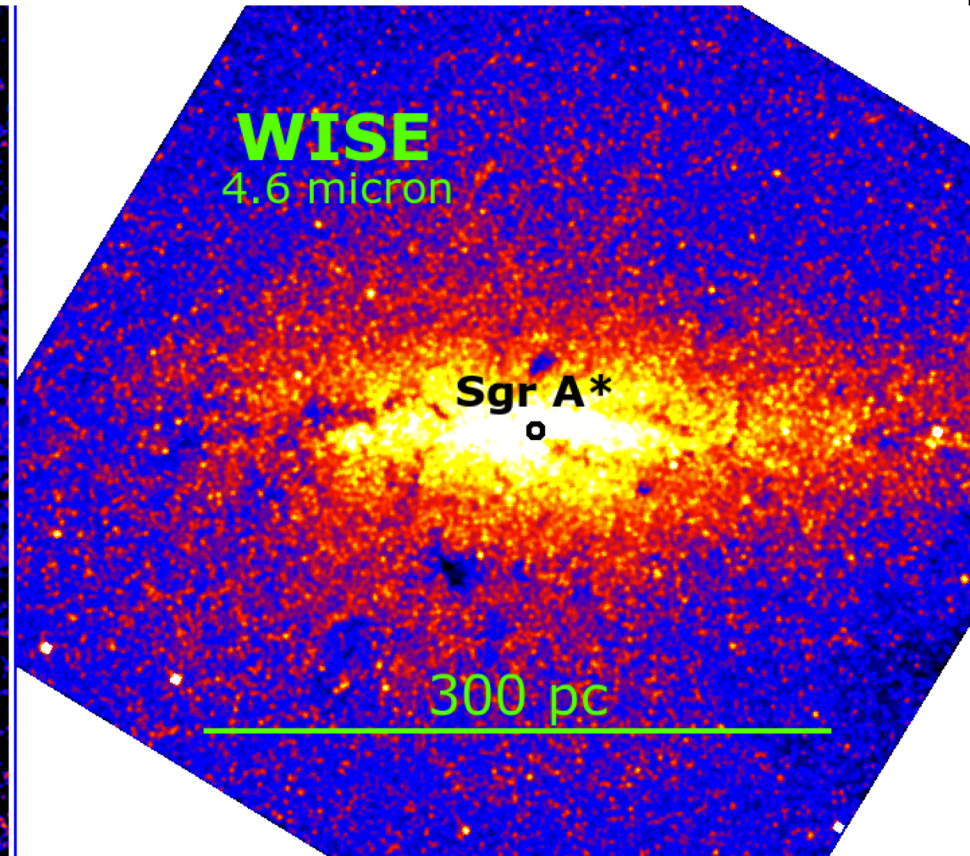
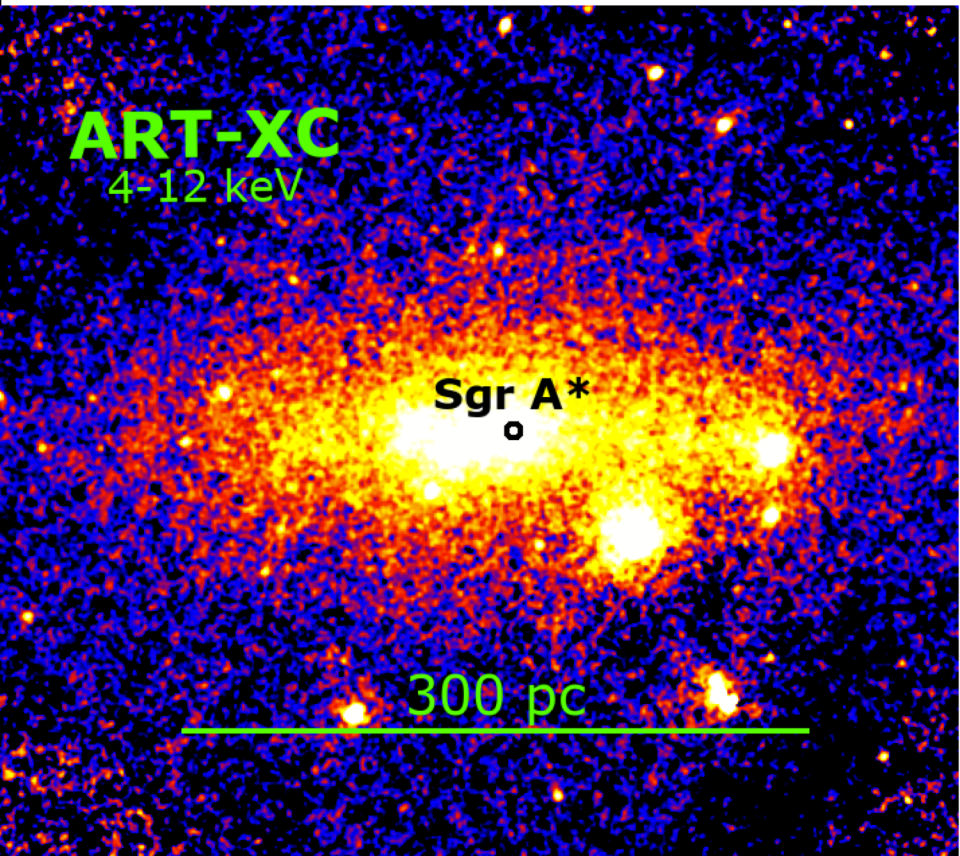
Densely-packed environment of Galactic Center



~100 pc scale around Sgr A*



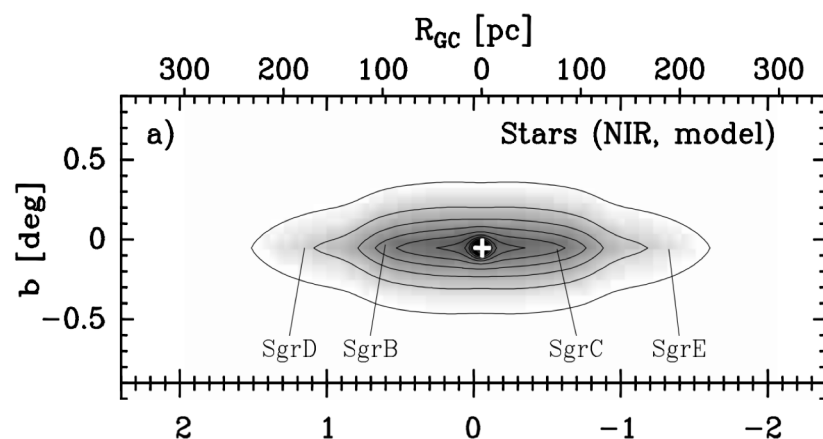
The Nuclear Stellar Disc of the Milky Way



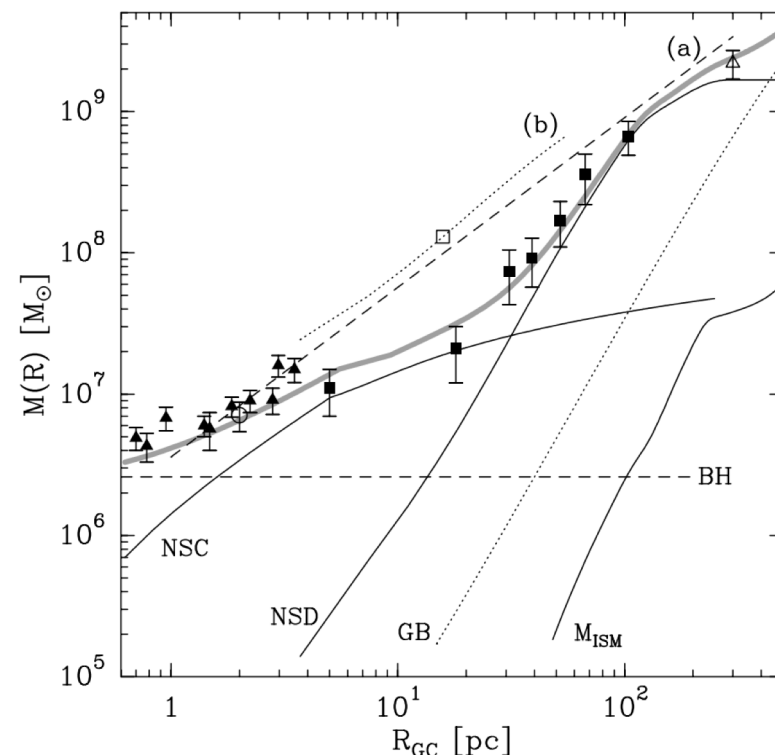
Nezabudkin et al., (2025)

Nuclear Stellar Disk (NSD)

- The structure was first described by Launhardt et al. (2002)
- The mass of the NSD was estimated at $1.4 \times 10^9 M_{\odot}$.
- The NSD radius was approximately 230 pc.



Model surface brightness map



Radial profile of cumulative mass

X-Ray Emission of the NSD

NSD X-ray flux model (2D)



NSD X-ray luminosity model (3D)



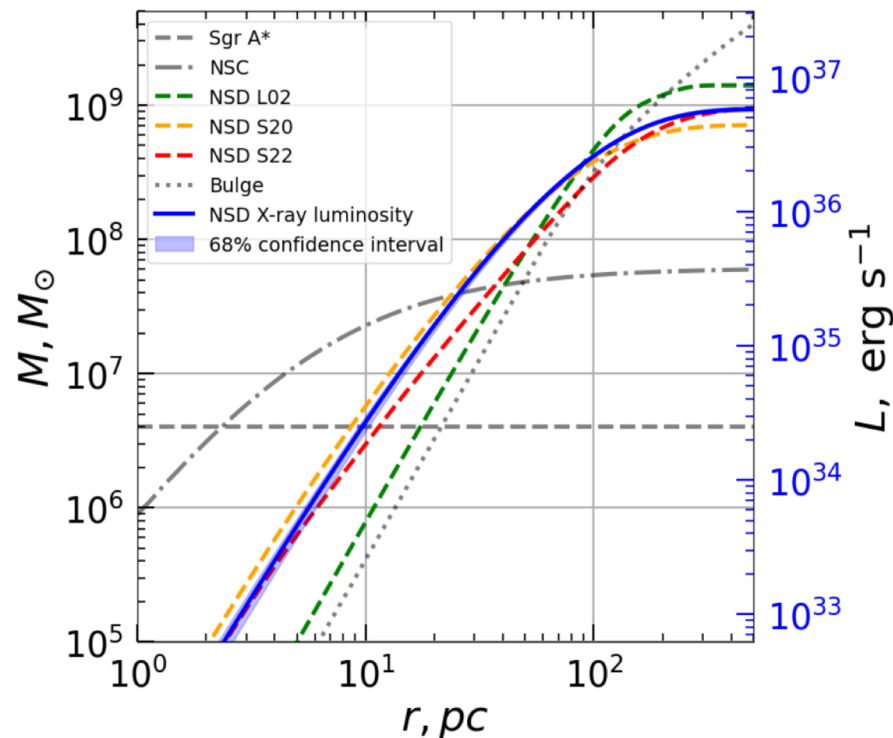
$$\text{NSD: } \langle L/M \rangle = (5.58^{+0.54}_{-0.65}) \times 10^{27} \text{ erg s}^{-1} M_{\odot}^{-1}$$

$$\text{Ridge: } \langle L/M \rangle = (1.69^{+0.15}_{-0.08}) \times 10^{27} \text{ erg s}^{-1} M_{\odot}^{-1}$$

Depends on the Galactic bar and disk models

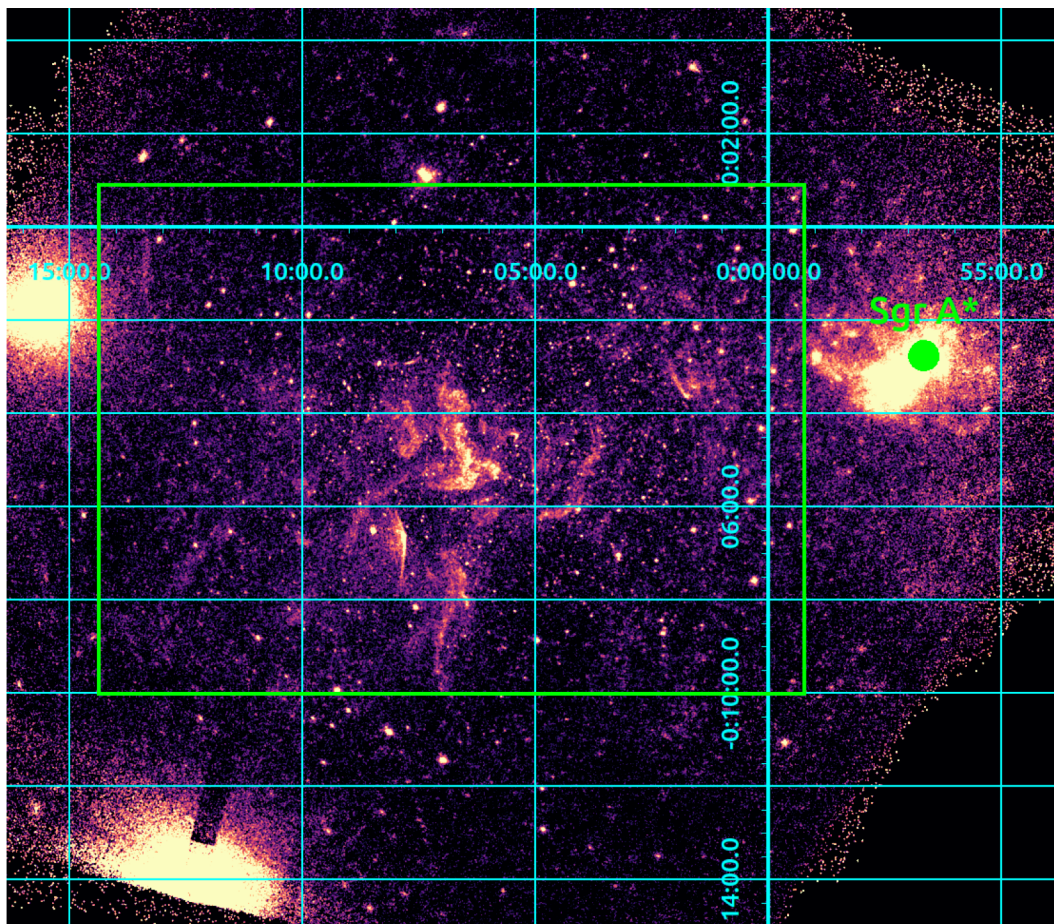
Resulting ratio is $\sim 2\text{--}3$ depending on the model

Total 6.7 keV line flux per unit mass in the NSD region is $\sim 1.3\text{--}1.5$ times higher than in the bar/disk
(Anastasopoulou et al., 2023)



Nezabudkin et al. (2025)

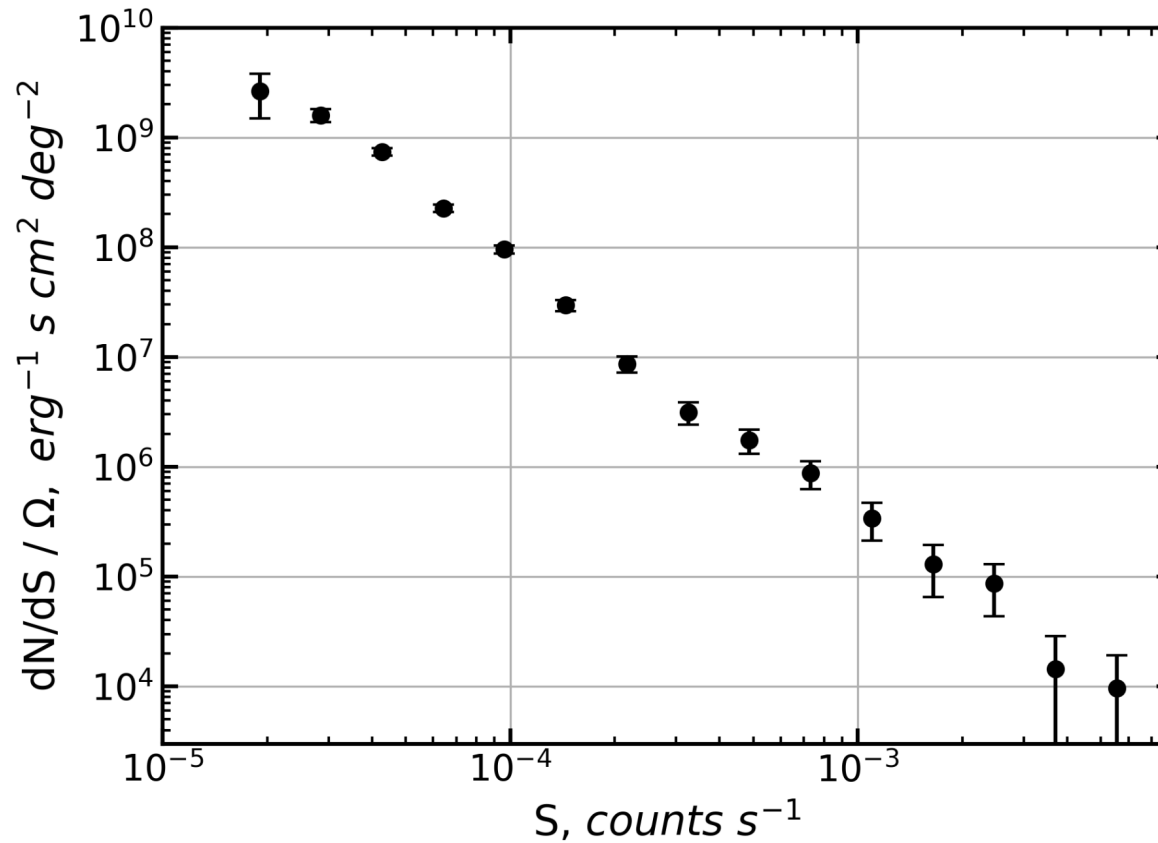
Deep Chandra Observations



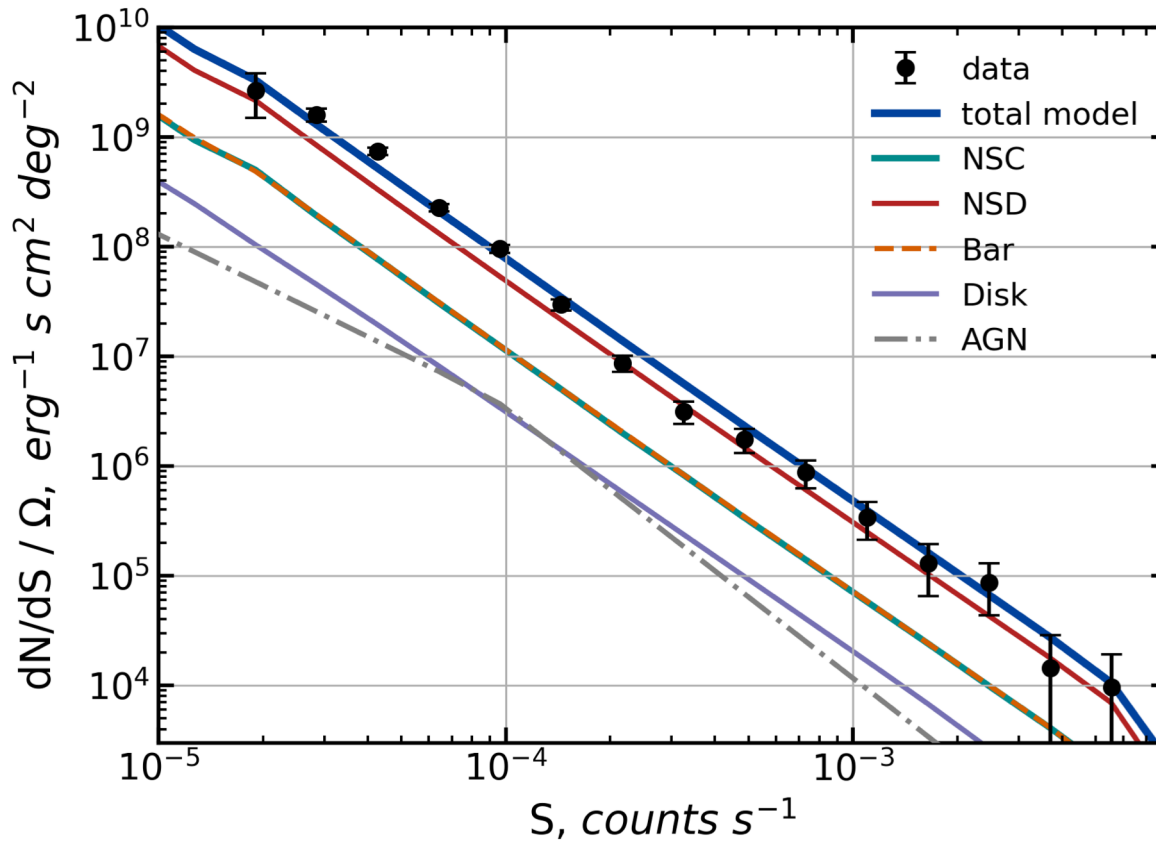
- *Target: CMZ region with molecular clouds*
- *Dataset: Chandra deep field*
- *Energy range: 4-8 keV*
- *Peak exposure: 800 ks*

**Total 1725 sources
(165 arcmin²)**

dN/dS Distribution of Sources in CMZ (NSD region)



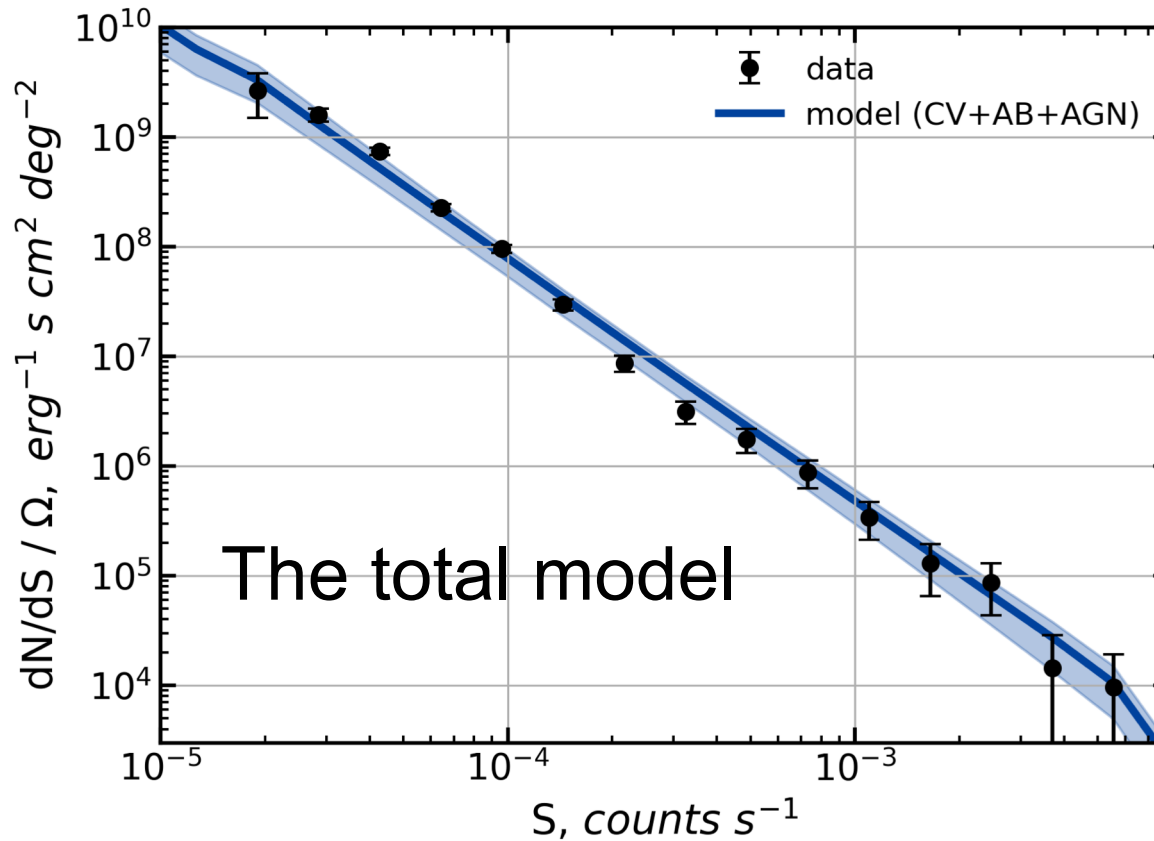
LogN-LogS modelling



NSC – 14.5%
NSD – 62.5%
Bulge/Bar – 14.7%
Disk – 4.0%
AGN – 4.3%

**Based on Galactic stellar mass models and L/M
measured in solar neighborhood**

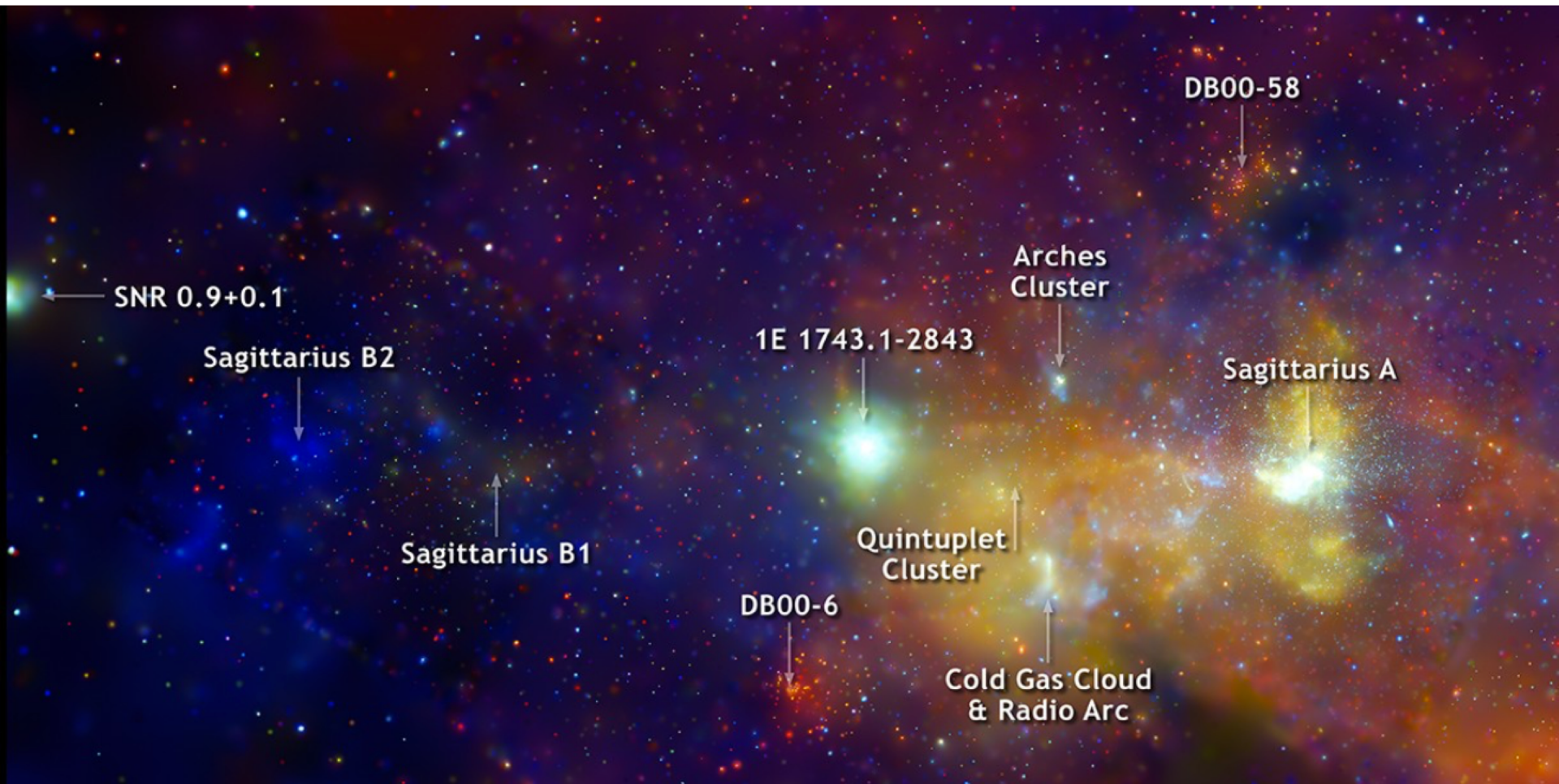
LogN-LogS modelling



**Based on Galactic stellar mass models and L/M
measured in solar neighborhood**

Part III
*~10 pc scale around Sgr A**

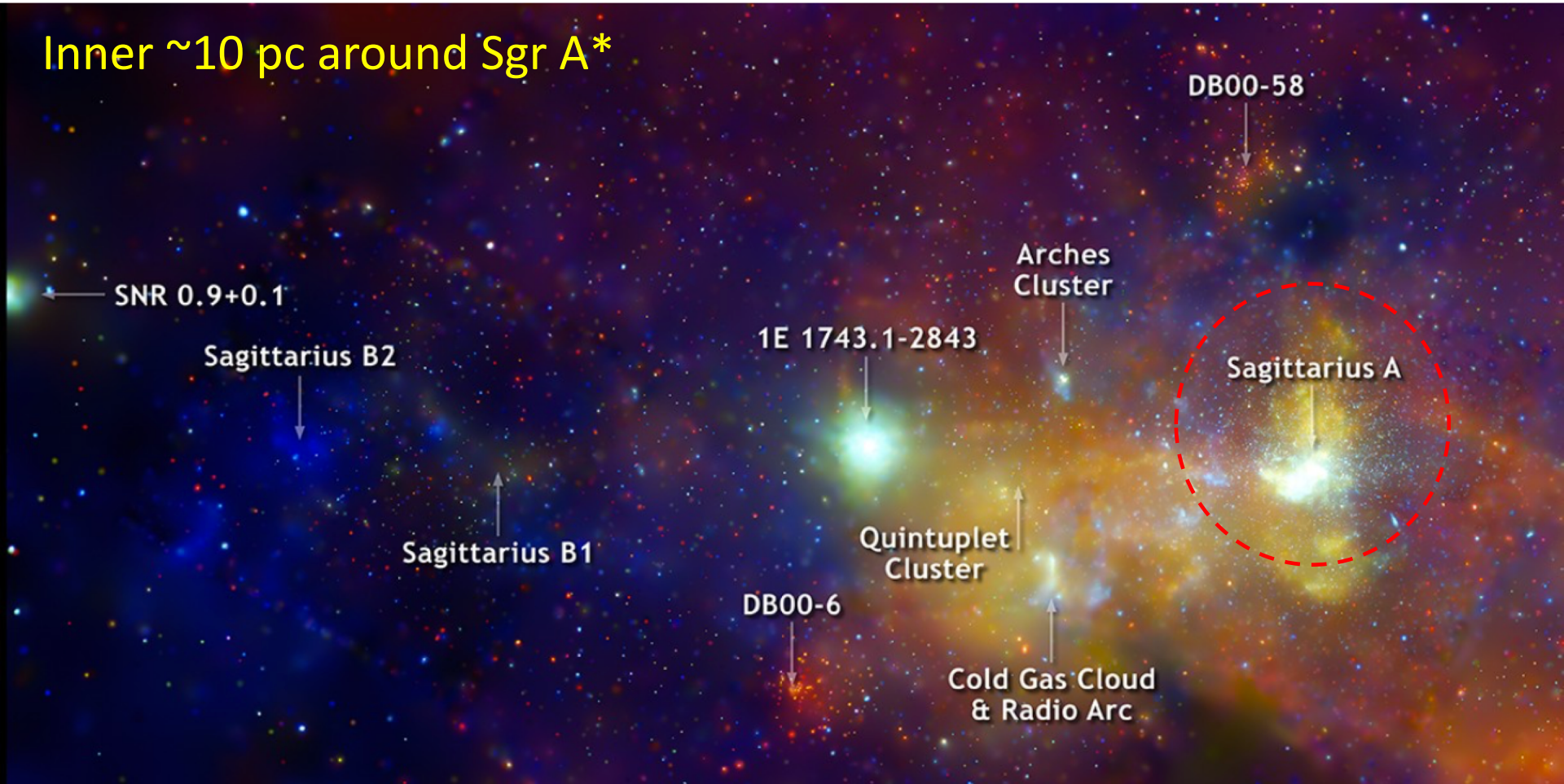
Galactic Center in X-rays



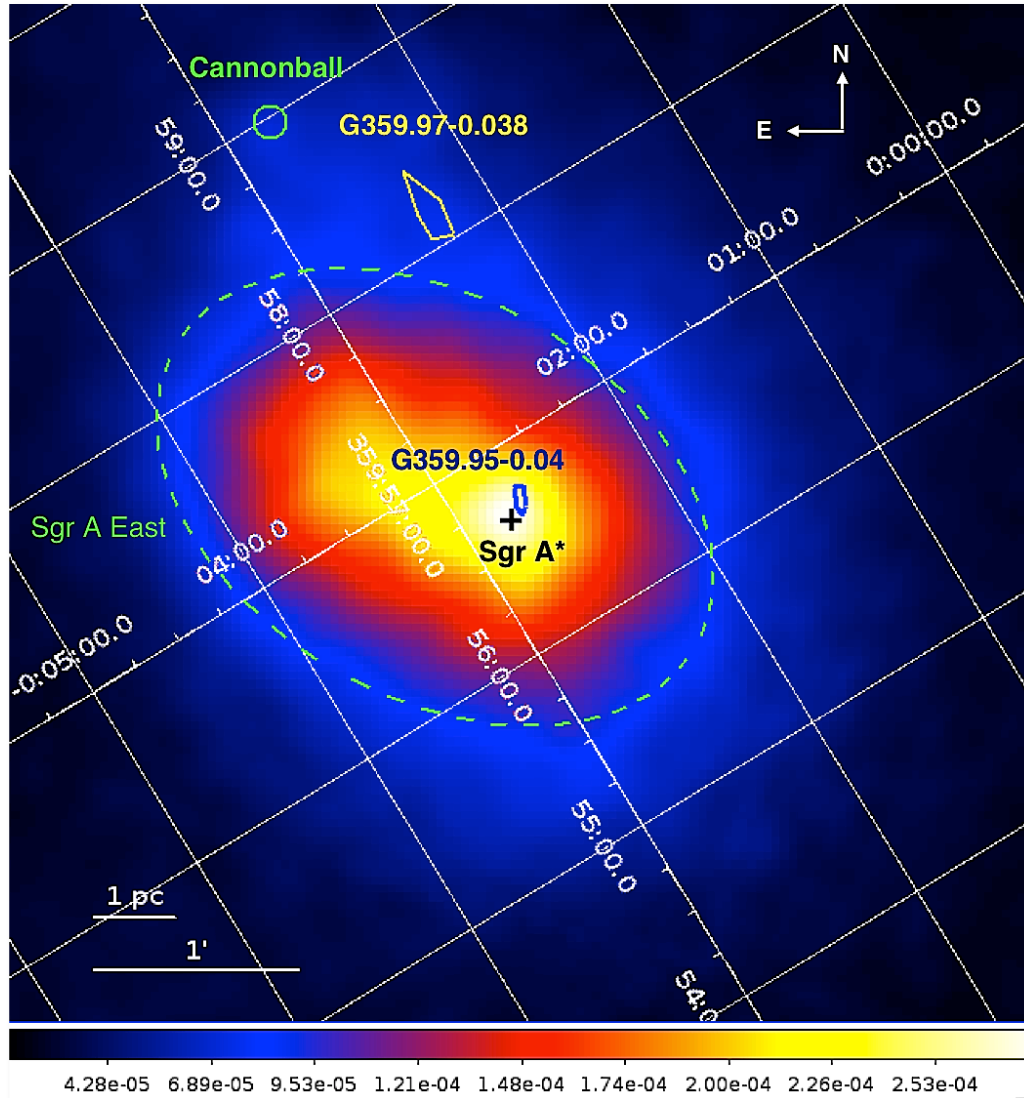
Central Hard X-ray diffuse emission



Inner ~ 10 pc around Sgr A*



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



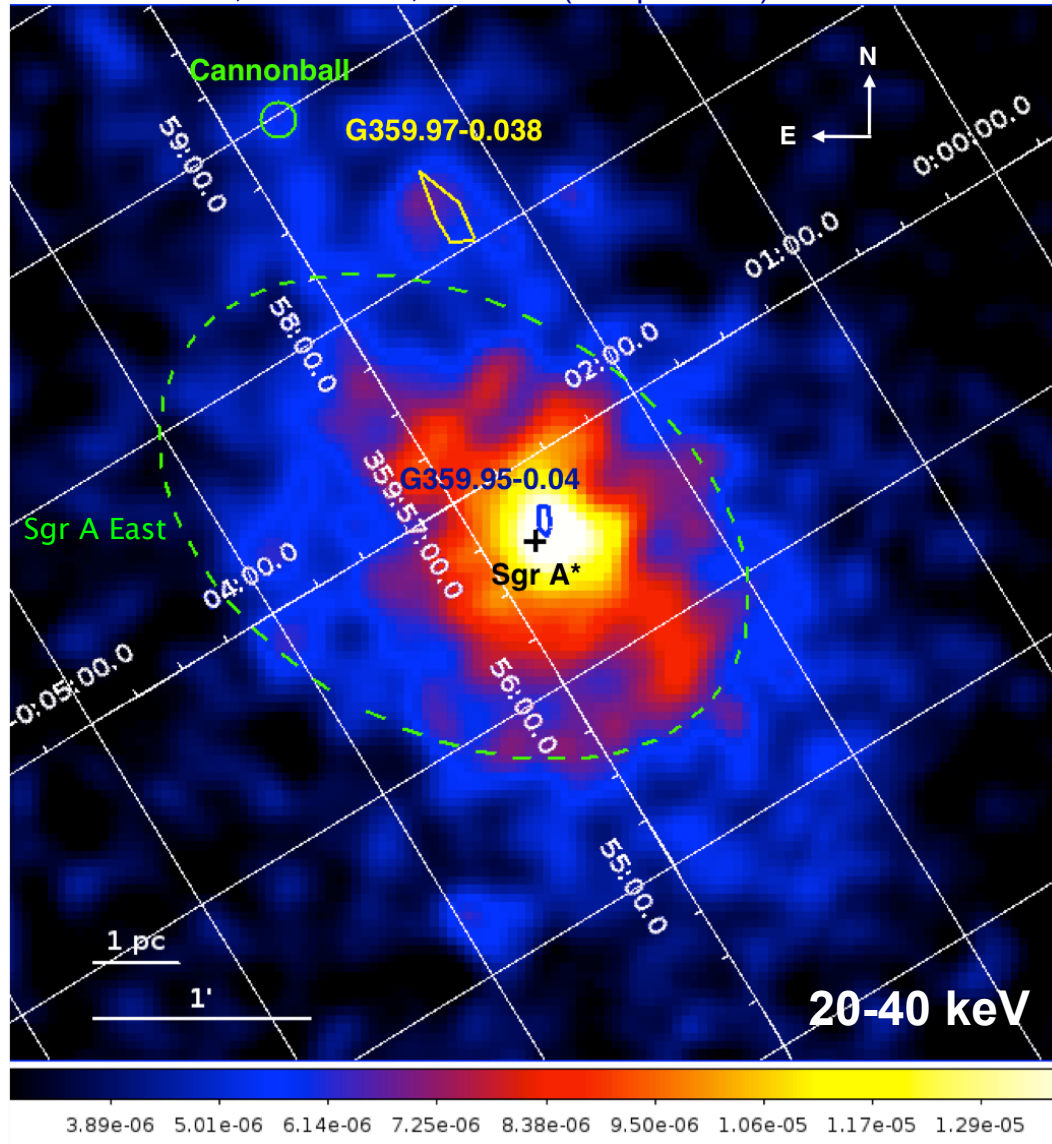
Credit: Kerstin Perez

- 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

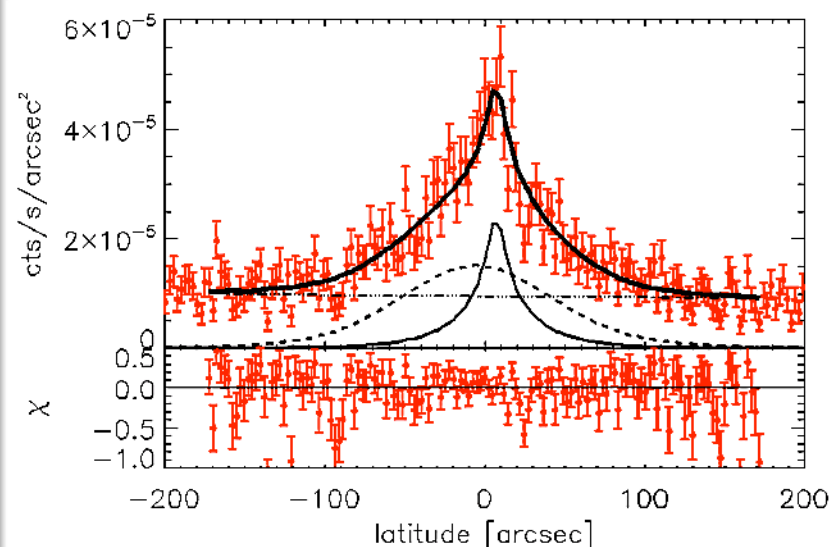
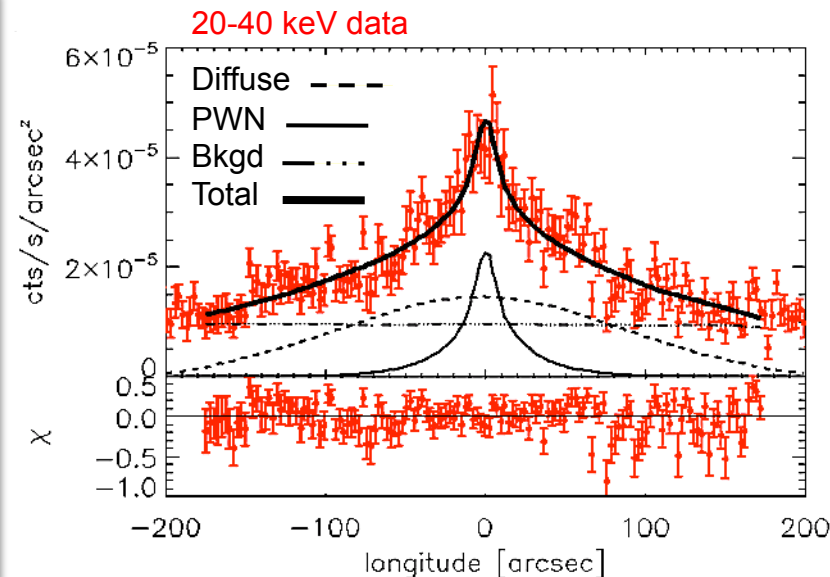
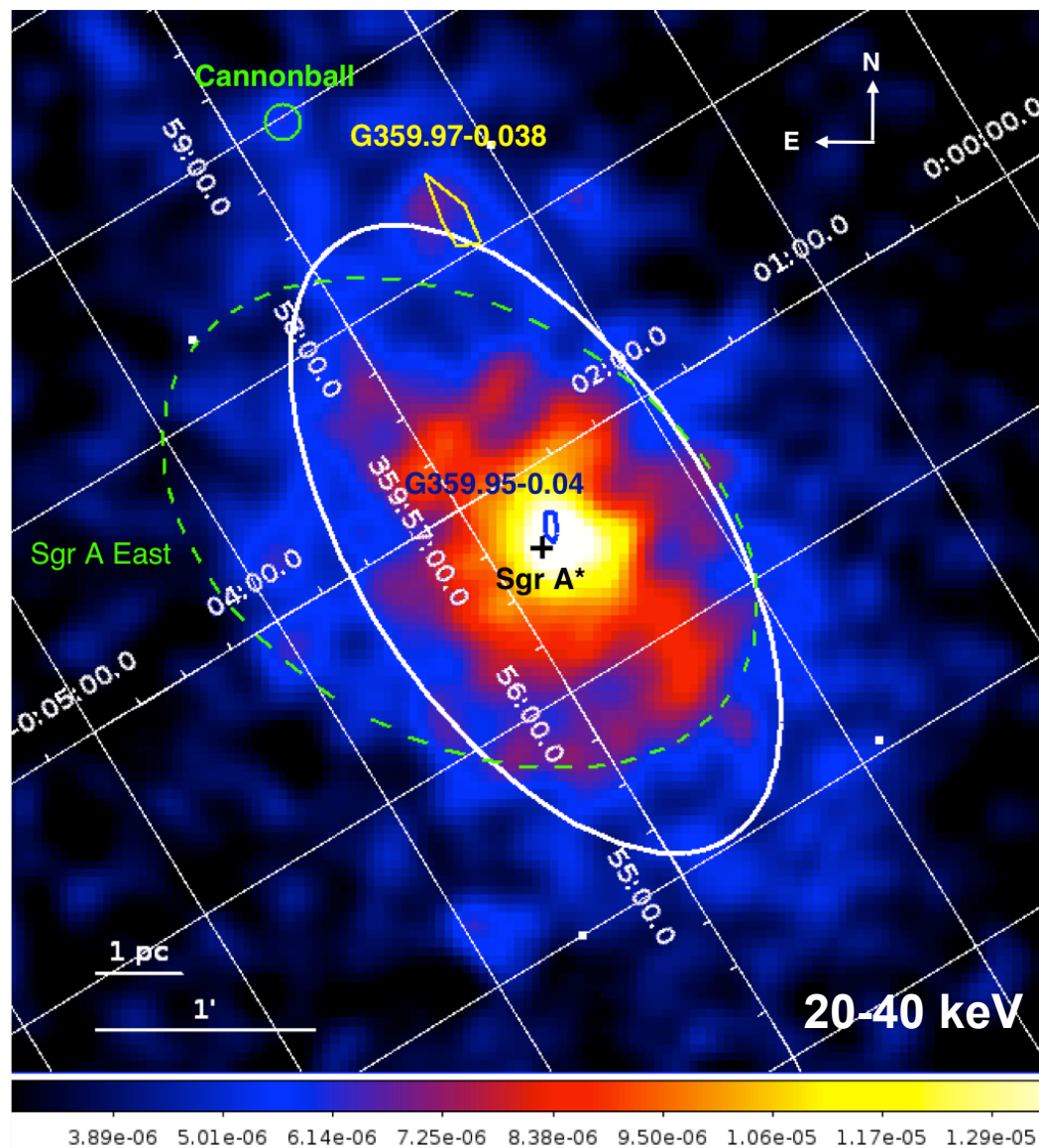


K. Perez et al., *Nature* **520**, 646–649 (30 April 2015)

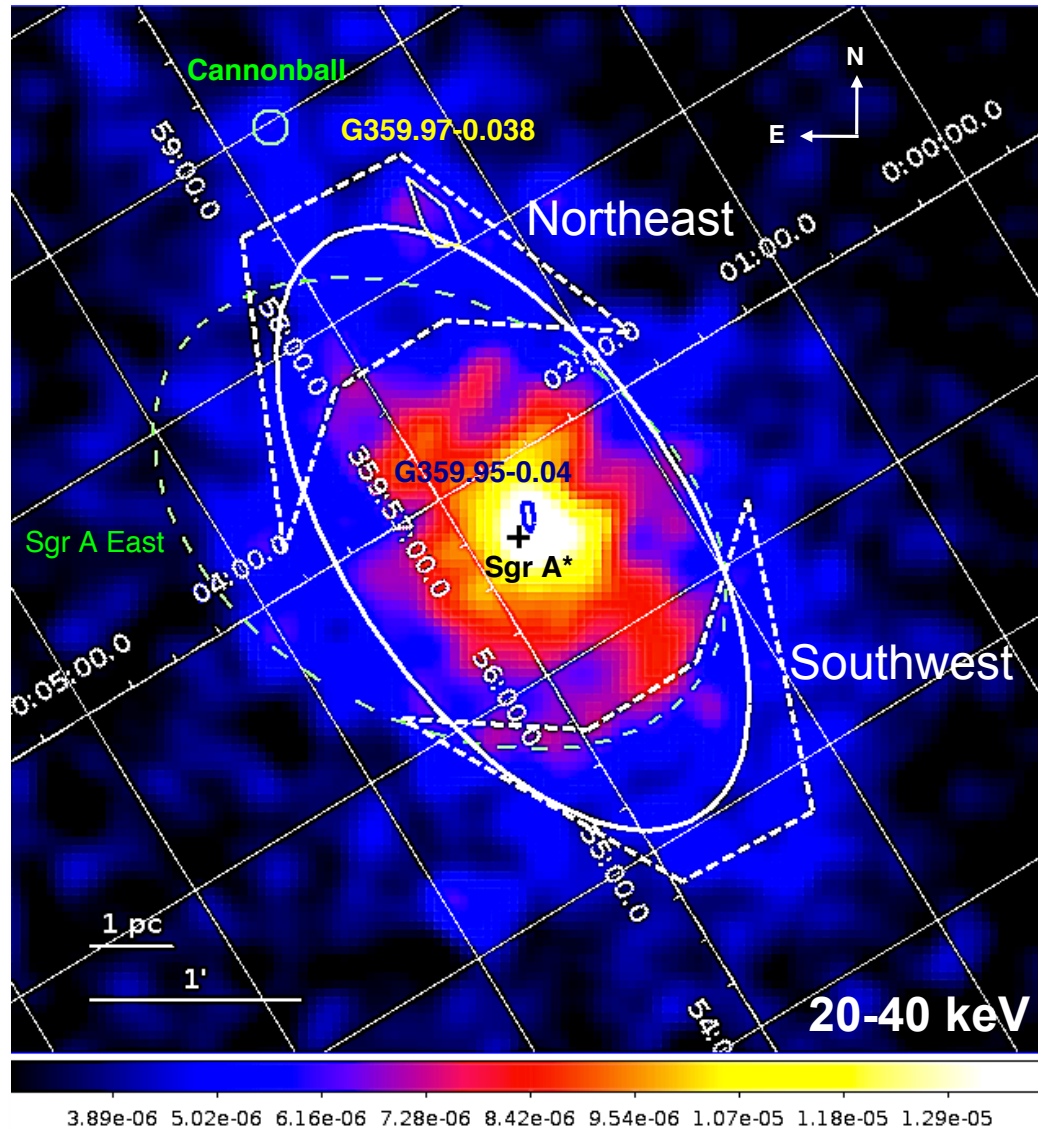


- Bright emission from pulsar wind nebula remains
- In addition, there is an **unresolved >20 keV X-ray emission extending along the Galactic plane from the Galactic Center**

Diffuse emission has 8 pc x 4 pc spatial extent



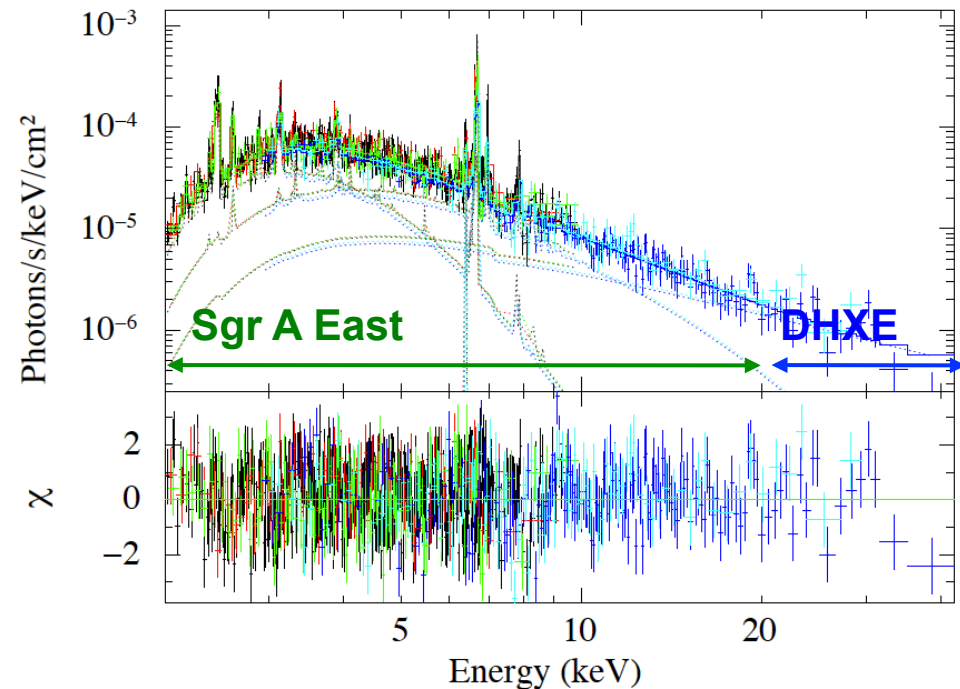
Spectra examined from regions away from central pulsar nebula



Credit: Kerstin Perez

- 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

“Northeast” region shows same high-energy spectrum



- Below 20 keV, dominated by:

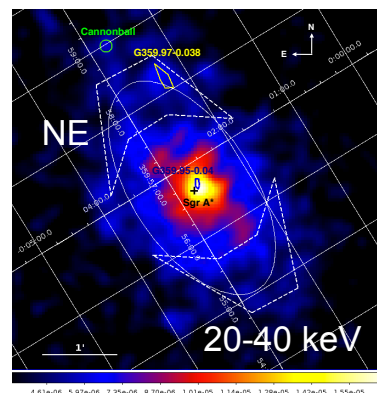
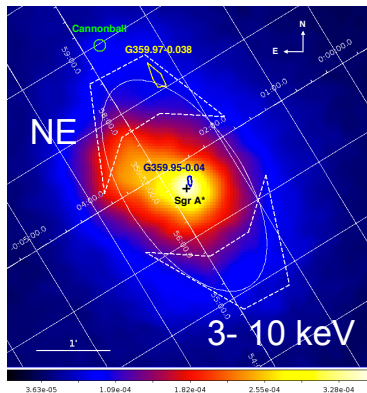
$$\left. \begin{aligned} kT_1 &= 1.1^{+0.1}_{-0.2} \text{ keV} \\ kT_2 &= 5.1^{+0.9}_{-0.7} \text{ keV} \\ Z &= 2.3^{+0.9}_{-0.4} \end{aligned} \right\} \text{The SNR Sgr A East}$$

- 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)
- $L(20-40 \text{ keV}) \approx 2.4 \times 10^{34}$ ergs/s within the $8 \text{ pc} \times 4 \text{ pc}$ FWHM

- Anomalously **massive Intermediate Polars** (IPs) with $\langle M_{\text{WD}} \rangle \approx 0.9 M_{\odot}$
- 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 (~ 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

The baryon mass estimate of central 10 pc

The hard X-ray (17-60 keV) emissivity of the Galactic Ridge emission is $(0.9-1.2) \times 10^{27}$ erg/s/Msun (Krivonos et al., 2007, astro-ph/0605420)

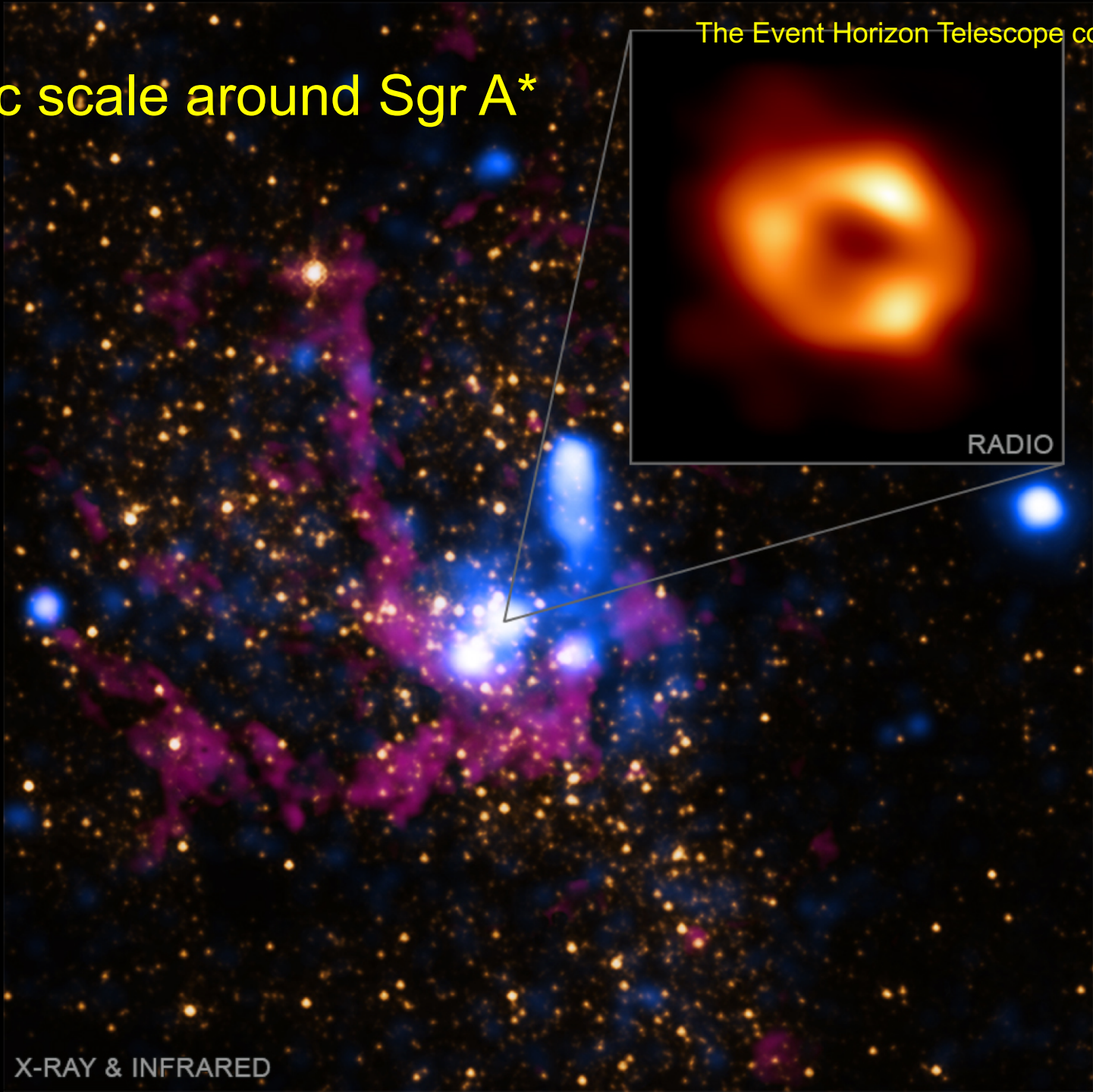
Taking DHXE luminosity of 2.4×10^{34} erg/s and assuming *the same* emissivity in the vicinity of Sgr A*, we obtain:

$(2.0-2.6) \times 10^7$ Msun — the baryon mass of the X-ray emission of the central 10 pc

This estimate is in a general agreement with the total mass of the Nuclear Stellar Cluster (NSC), **$\sim 1.3 \times 10^7$ Msun** provided by NIR observations (Frits et al., 2013, arXiv:1311.5258).

Part IV
*~1 pc scale around Sgr A**

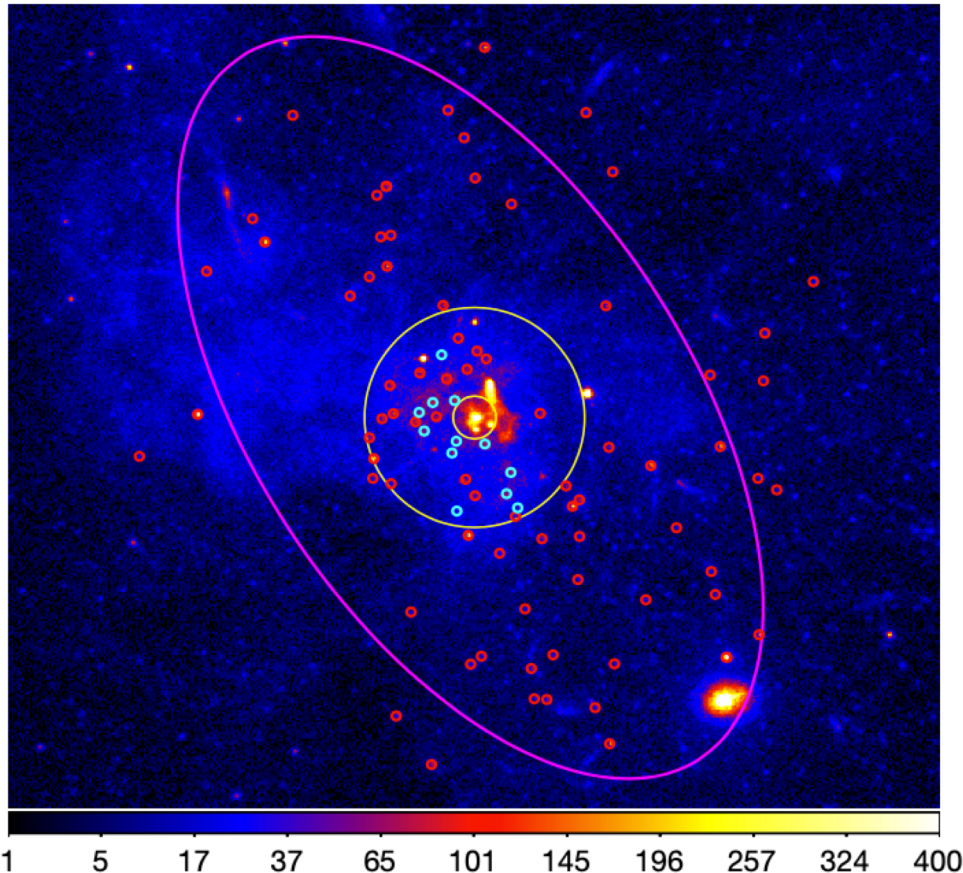
~1 pc scale around Sgr A*



*The close vicinity of Sgr A**

A density cusp of quiescent X-ray binaries in the central parsec of the Galaxy

Charles J. Hailey¹, Kaya Mori¹, Franz E. Bauer^{2,3,4}, Michael E. Berkowitz¹, Jaesub Hong⁵ & Benjamin J. Hord¹



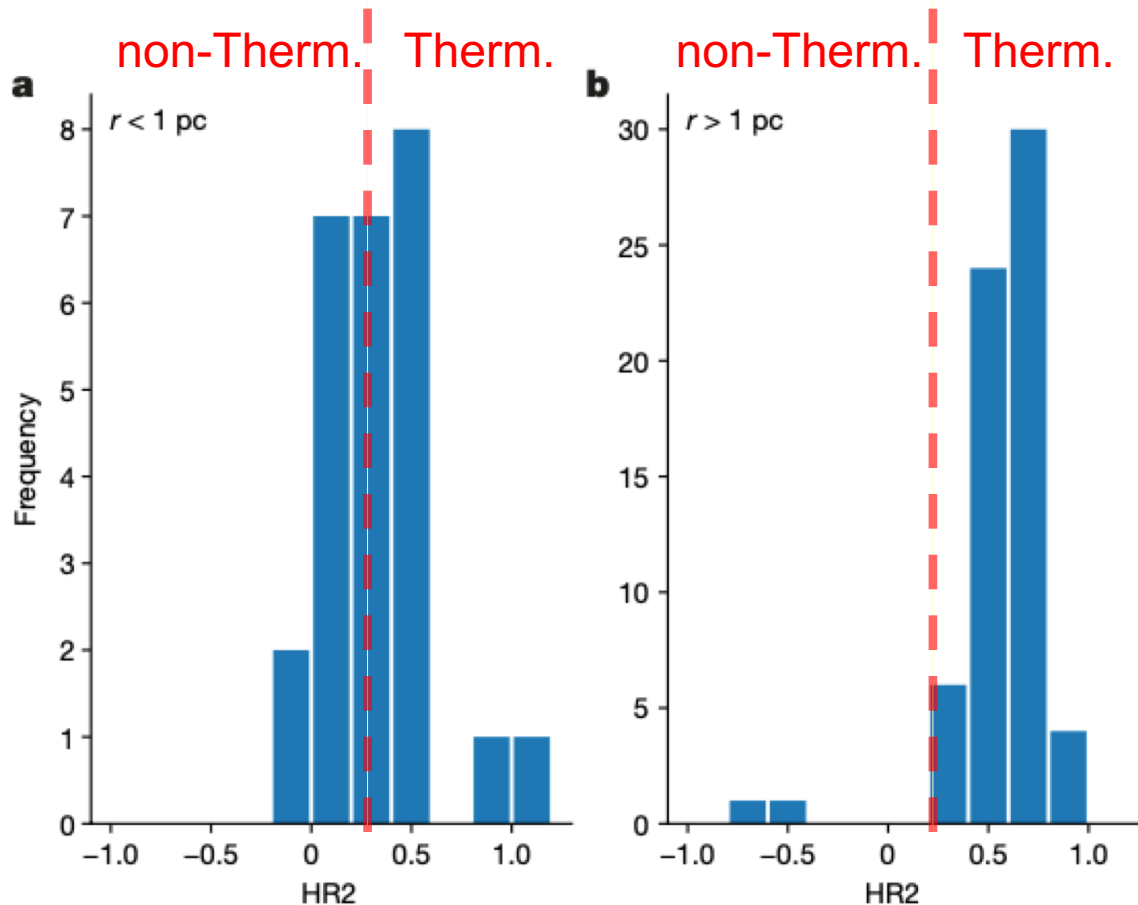
92 X-ray sources with net counts > 100 selected for analysis (26 within 1 pc)

Hardness ratio is used to separate thermal and non-thermal sources

*The close vicinity of Sgr A**

A density cusp of quiescent X-ray binaries in the central parsec of the Galaxy

Charles J. Hailey¹, Kaya Mori¹, Franz E. Bauer^{2,3,4}, Michael E. Berkowitz¹, Jaesub Hong⁵ & Benjamin J. Hord¹

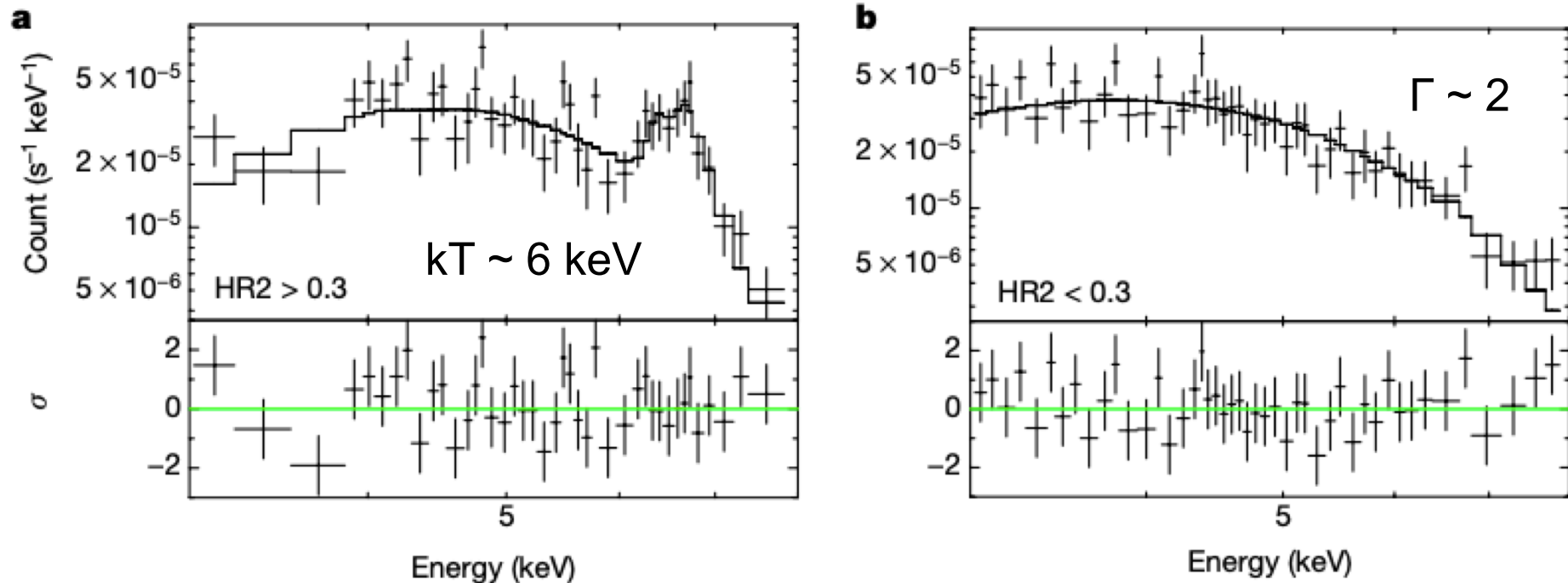


Thermal HR > 0.3
Non-thermal HR < 0.3

*The close vicinity of Sgr A**

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The stacked spectra of the $HR < 0.3$ and $HR > 0.3$ sources in the inner parsec

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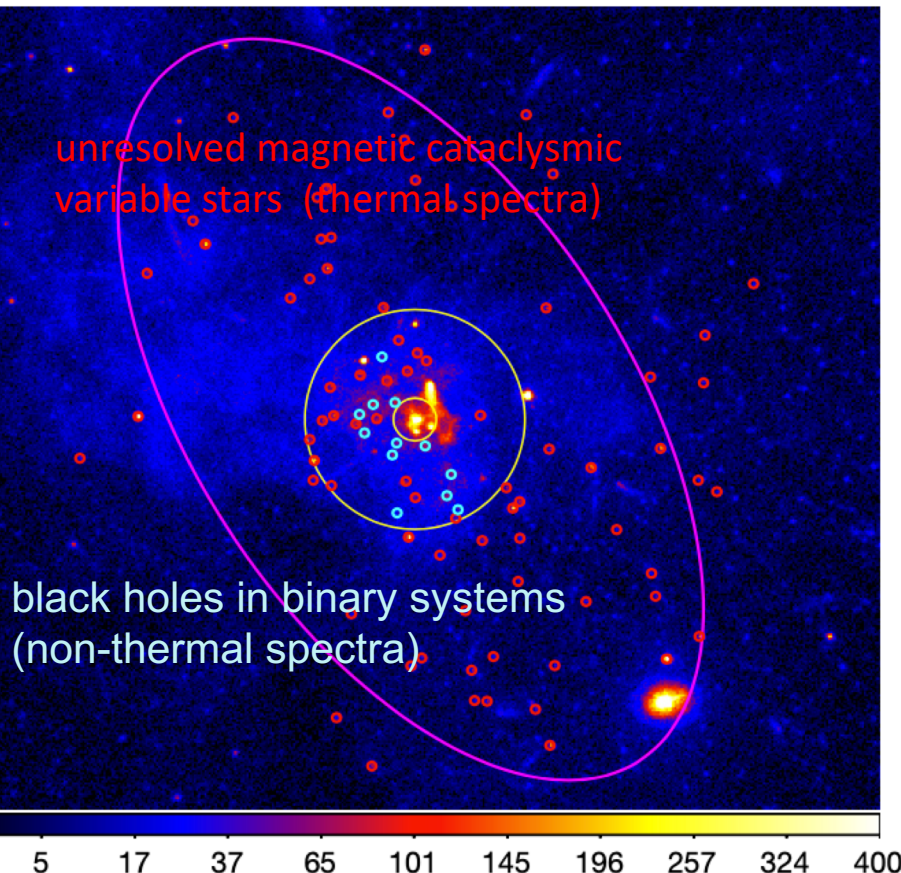
The newly identified $HR < 0.3$ population is prominent only inside the central parsec.

Hypothesis: quiescent black-hole low-mass X-ray binaries (qBH-LMXBs)

rotation-powered millisecond pulsars (rMSPs) cannot be excluded

LogN-LogS estimation gives 600–1,000 qBH-LMXBs within 1 pc

Expected 10,000 isolated black holes



Conclusions

- The X-ray output (L/M) of the stellar population of Milky Way is very uniform at different scales:
 - around the Sun
 - 1000 pc (GRXE)
 - 100 pc (NSD)
 - 10 pc (NSC)
- Deep Chandra observations of the inner parsec reveal $\sim 1,000$ black holes in binary systems which implies 10,000 isolated black holes around Sgr A*