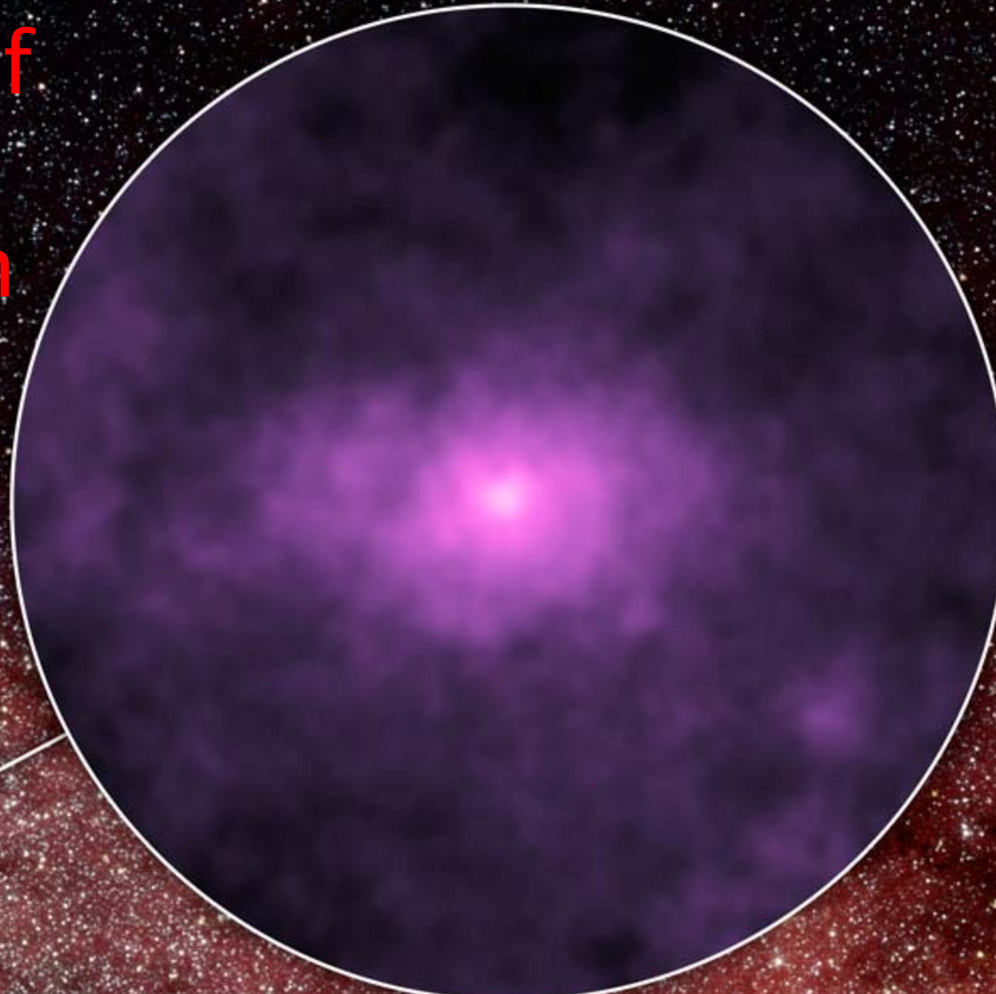
NuSTAR Discovery of Galactic Center Hard X-ray Emission

Kerstin Perez

Haverford College / MIT

/swexicana

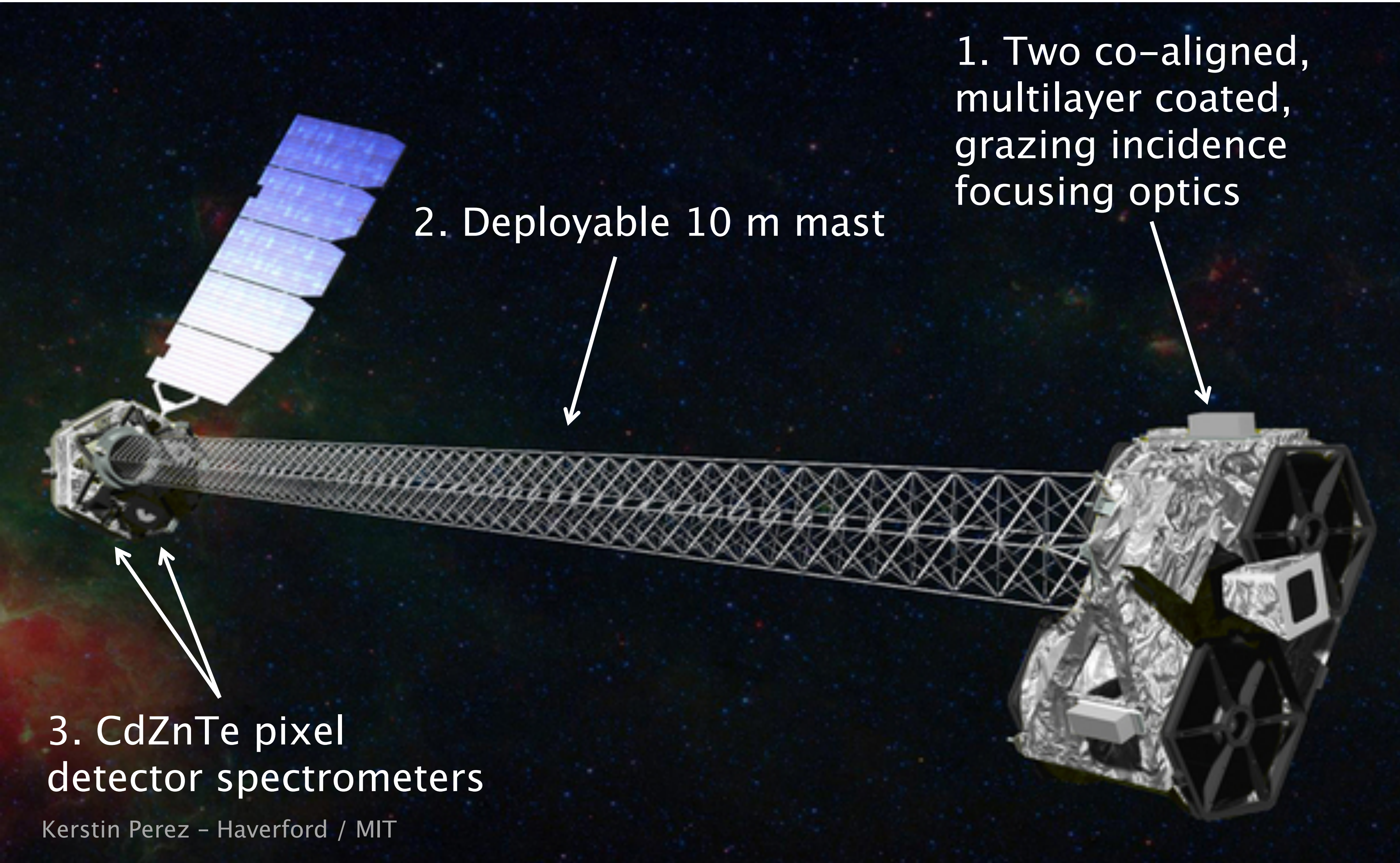
Texas Symposium 2015



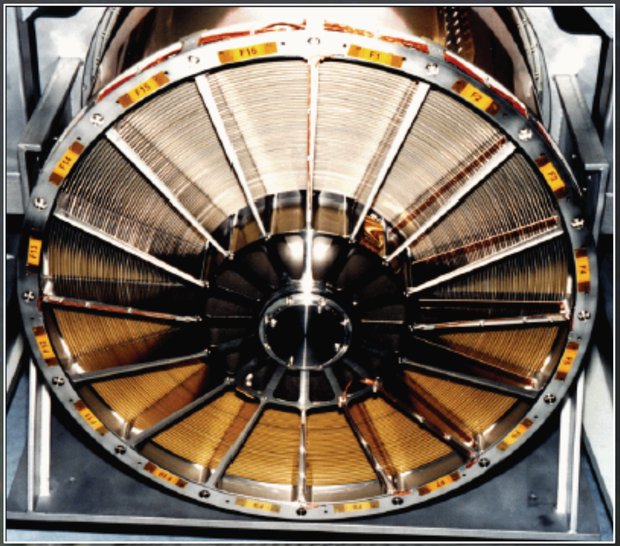
***Nature* 520, 646–649 (30 April 2015)**: Kerstin Perez, Charles J. Hailey, Franz E. Bauer, Kaya Mori, Frederick K. Baganoff, Nicolas M. Barriere, Steven E. Boggs, Finn E. Christensen, William W. Craig, Brian W. Grefenstette, Jonathan E. Grindlay, Fiona A. Harrison, Jaesub Hong, Roman Krivonos, Kristin Madsen, Melania Nynka, Daniel Stern, John Tomsick, Daniel R. Wik, Shuo Zhang, William W. Zhang, Andreas Zoglauer

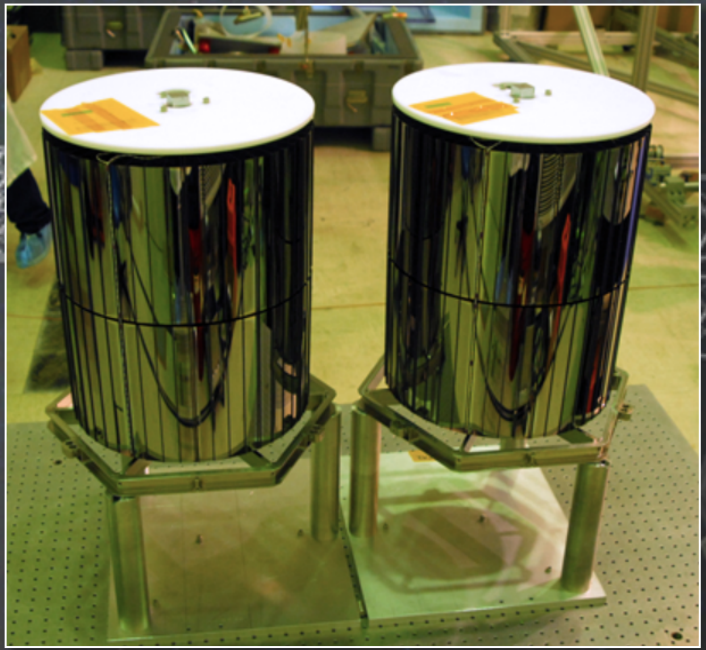
First *focusing* high-energy X-ray telescope in orbit

NuSTAR

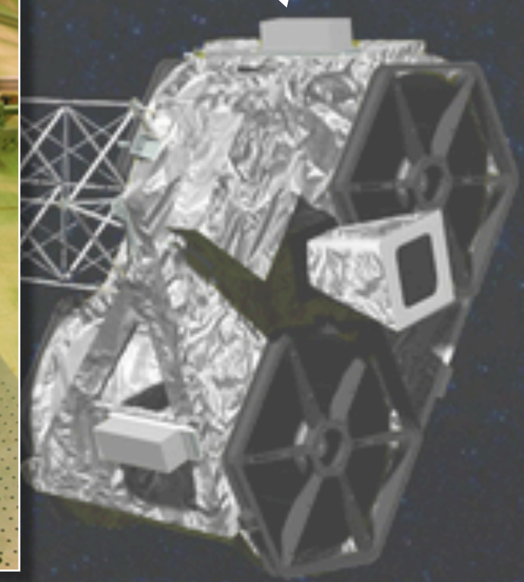


First *focusing* high-energy X-ray telescope in orbit

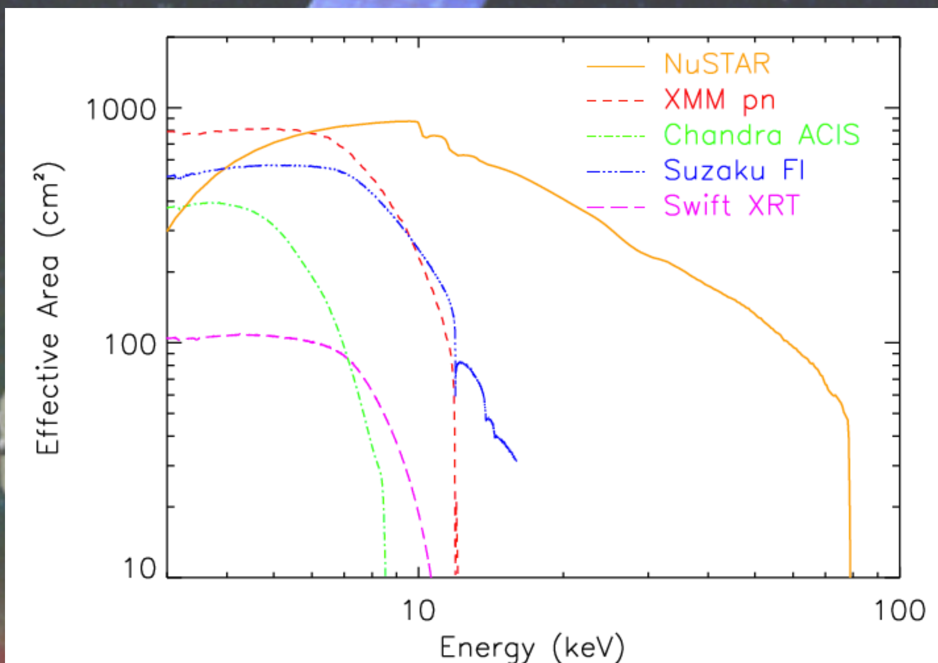




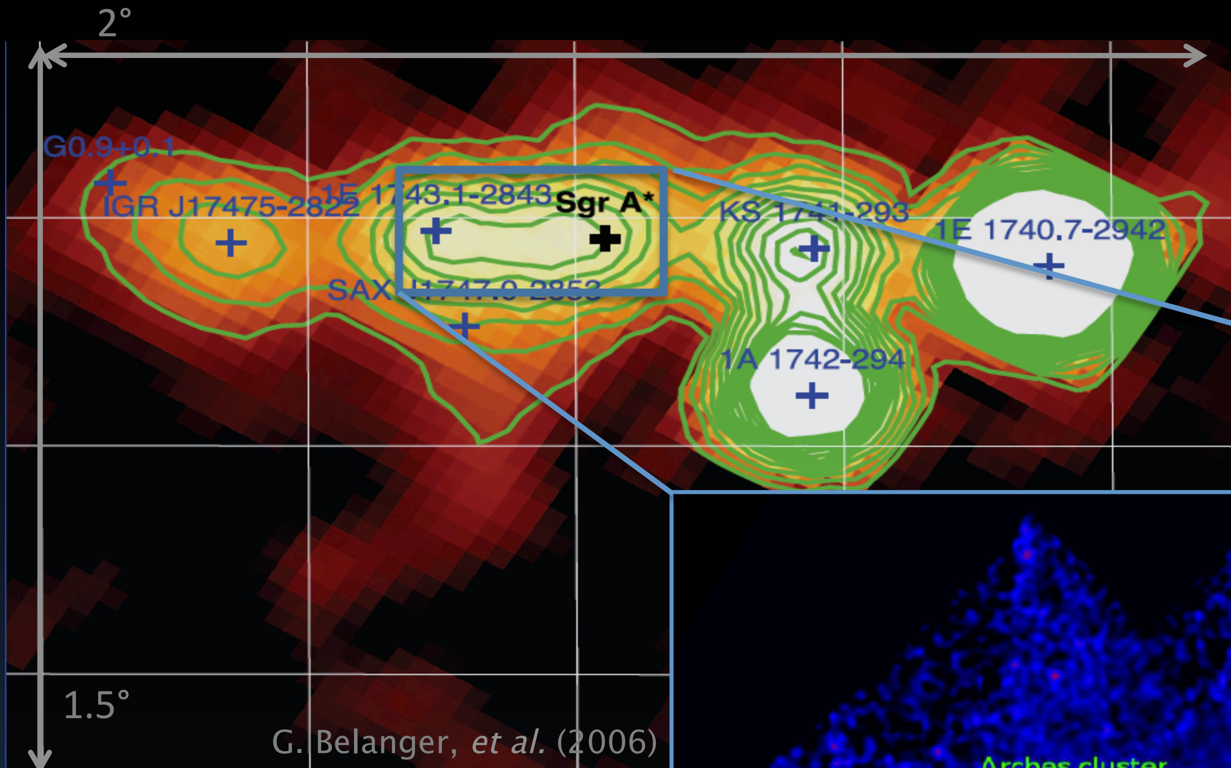
1. Two co-aligned, multilayer coated, grazing incidence focusing optics



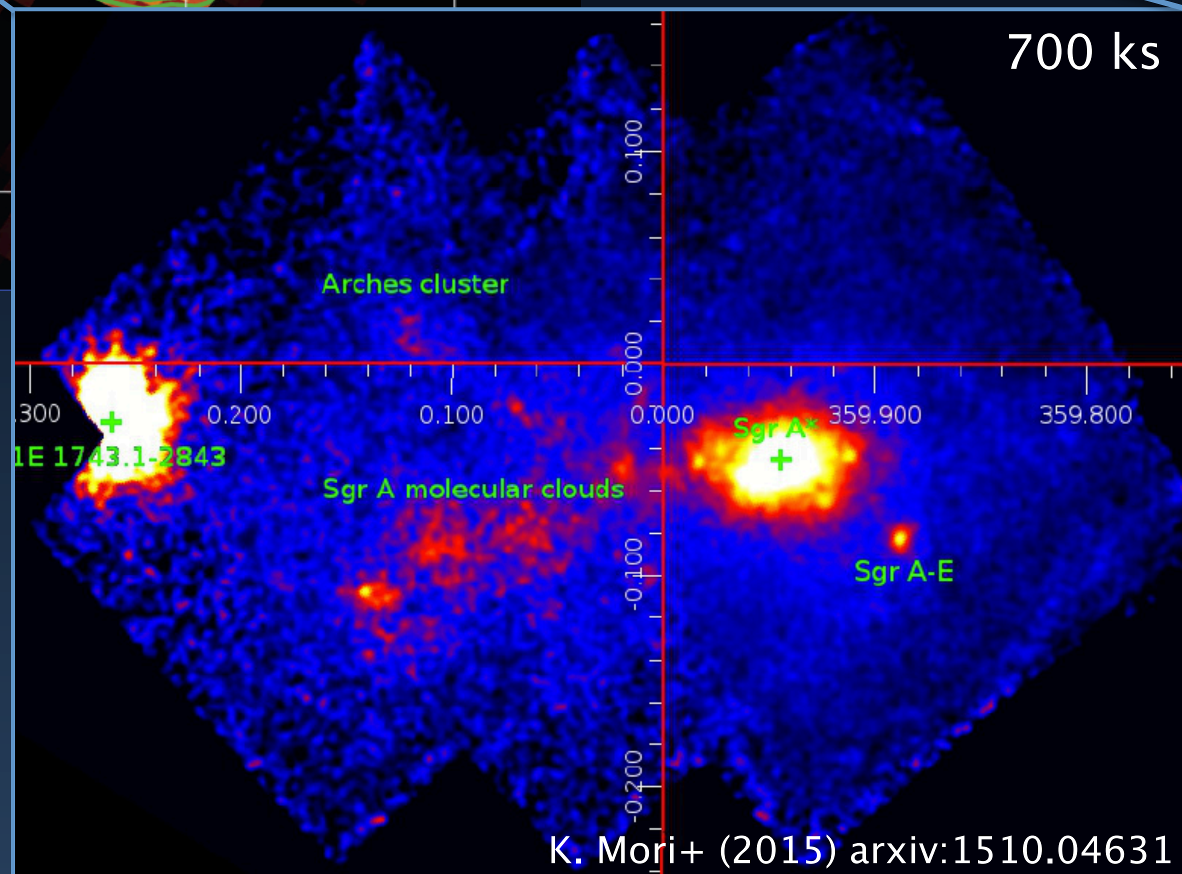
First *focusing* high-energy X-ray telescope in orbit



- **Energy Band:** 3–79 keV
- **Angular Resolution:**
  58" (HPD), 18" (PSF)
- **Field-of-view:** 12' x 12'
- **Energy resolution (FWHM):**
  0.4 keV at 6 keV,
  0.9 keV at 60 keV
- **Temporal resolution**: 0.1 ms
- **Maximum Flux Rate:** 10k ct/s
- **ToO response:** <24 hours

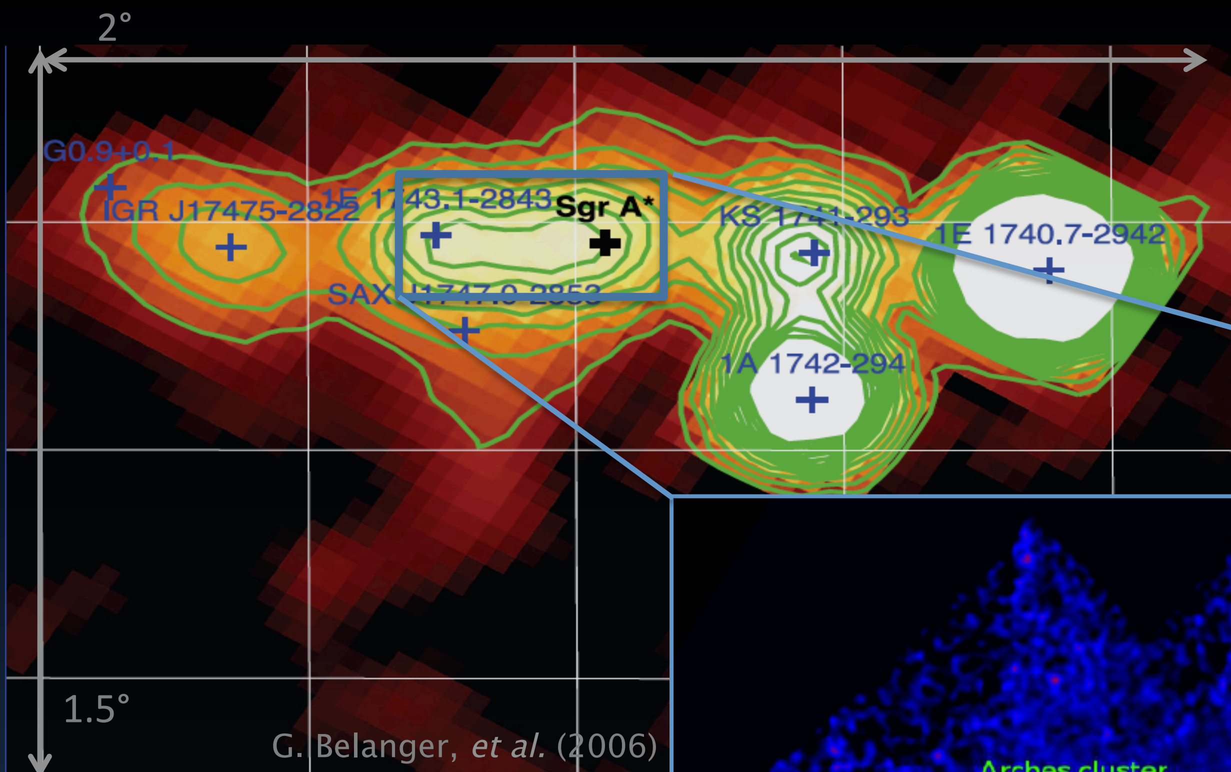


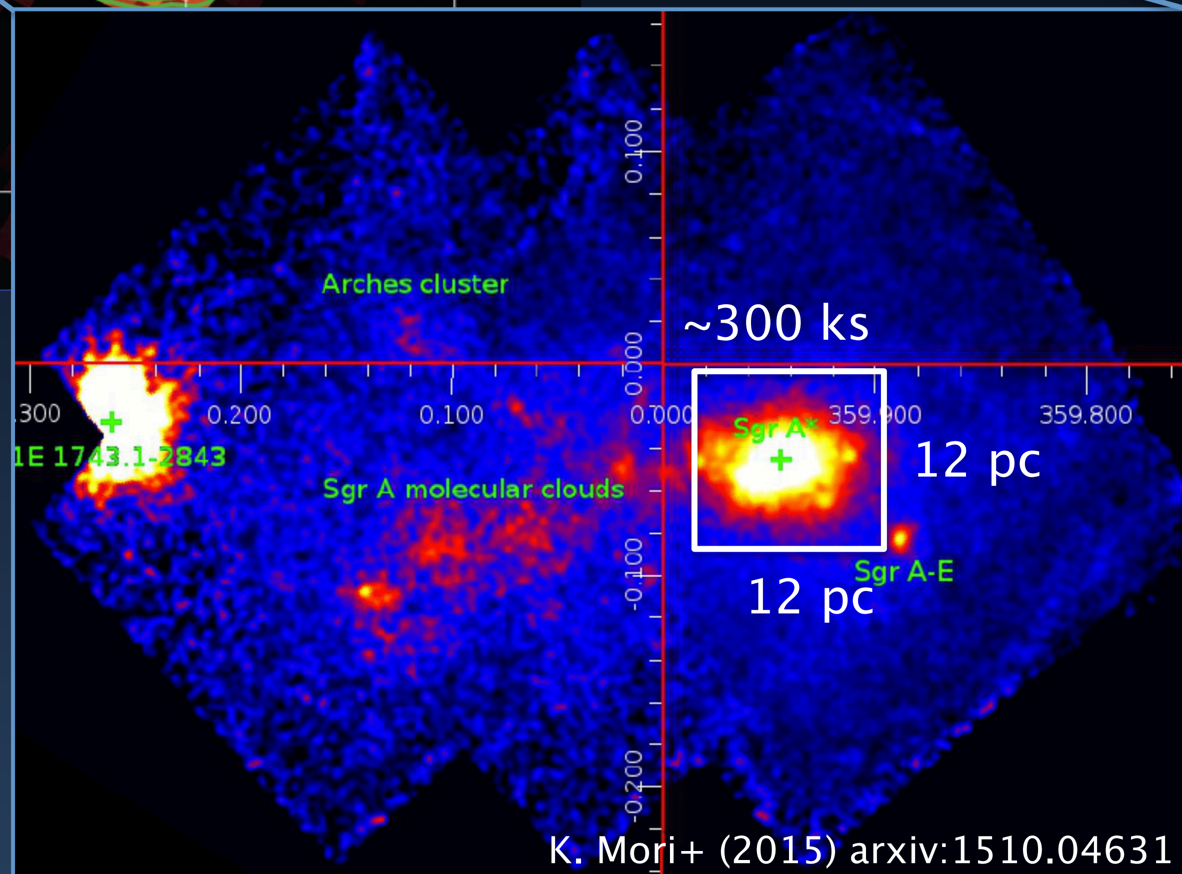
INTEGRAL
E = 20–40 keV



NuSTAR
E = 10–40 keV

- 58” (HPD), 18” (PSF)
- Nominal NuSTAR positional accuracy = 8” (90% C.L.)
- After astrometric correction, accuracy = ~1” in R.A. and ~1.2” in DEC

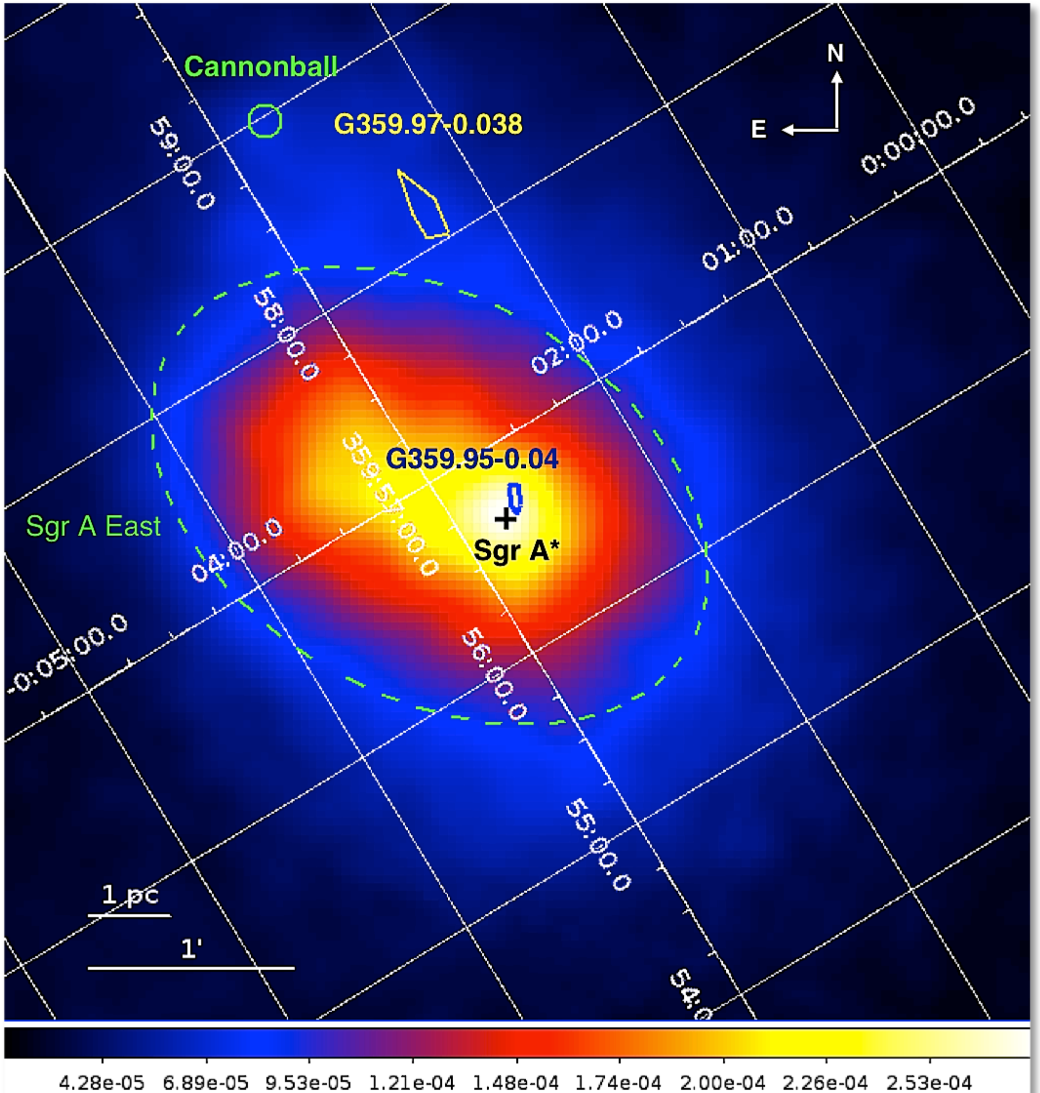




- **Will focus on NuSTAR detection of high-energy (20-40 keV) unresolved X-ray emission from the inner ~4 pc x 8 pc**
- Motivate a *distinct* population those indicated by previous studies of the Galactic Ridge X-ray Emission (GRXE)

Inner 12 pc x 12 pc at 3–10 keV

NuSTAR



- 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

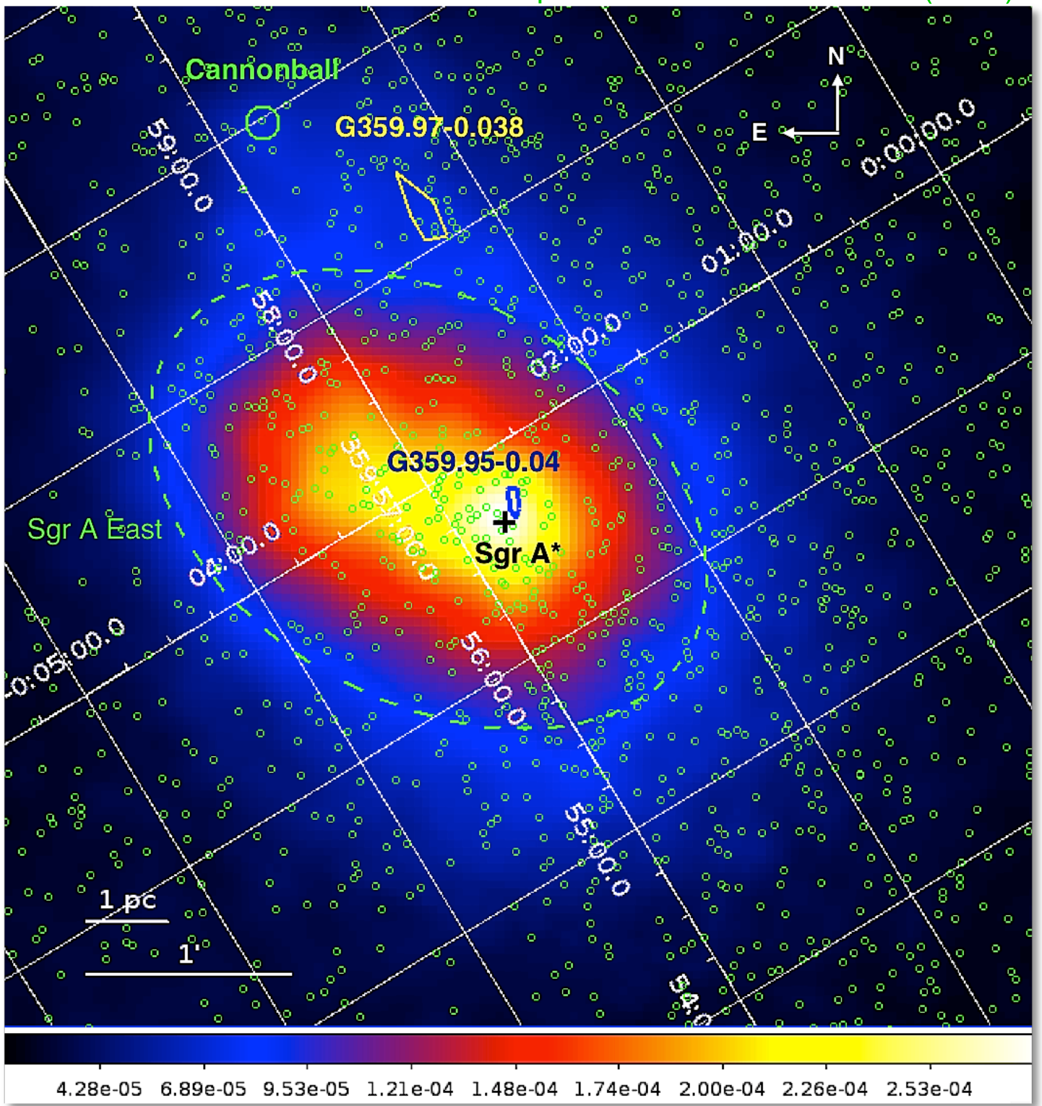
- To the north-east lies the extended emission of the Sgr A-East "plume" (bright blue), "cannonball" (*Nynka et al. 2013*), non-thermal filament G359.97-0.038 (*Nynka et al. 2014*)

- The entire region sits in a field of GRXE and unresolved point source emission (dark blue)

Inner 12 pc x 12 pc at **3–10 keV**

NuSTAR

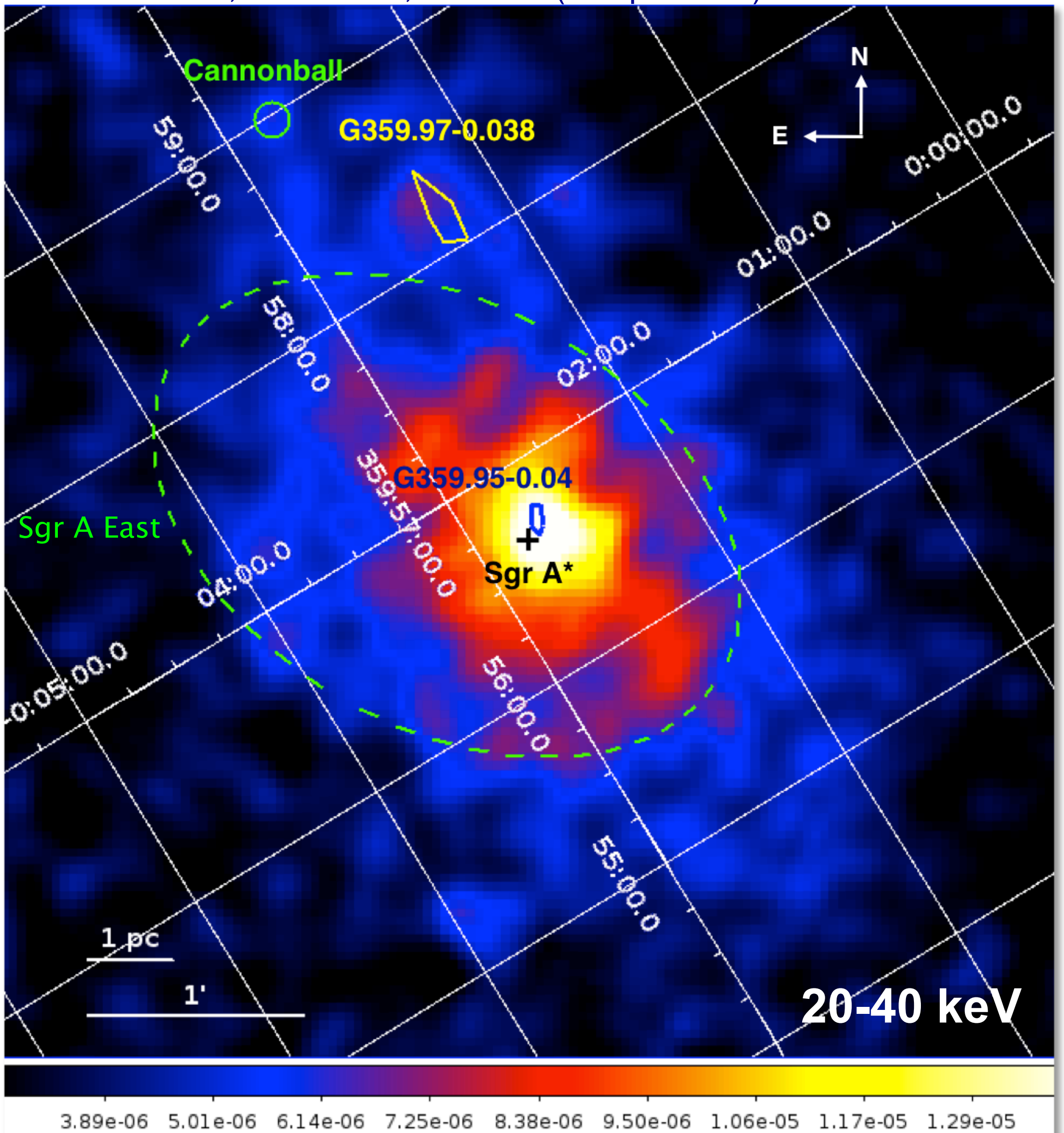
CHANDRA point sources - Muno *et al.* (2009)



- 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)

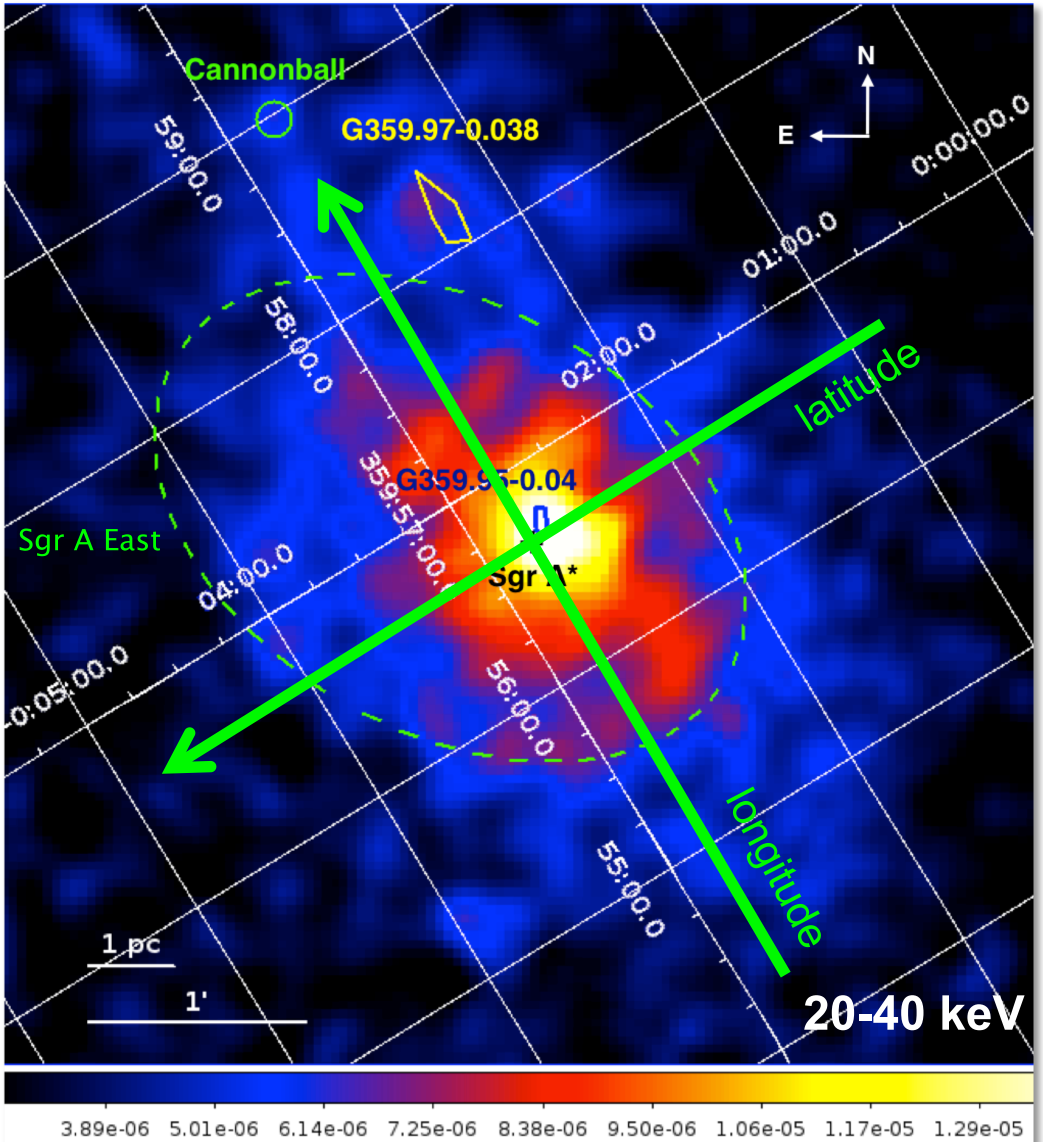
Inner 12 pc x 12 pc at **20–40 keV**

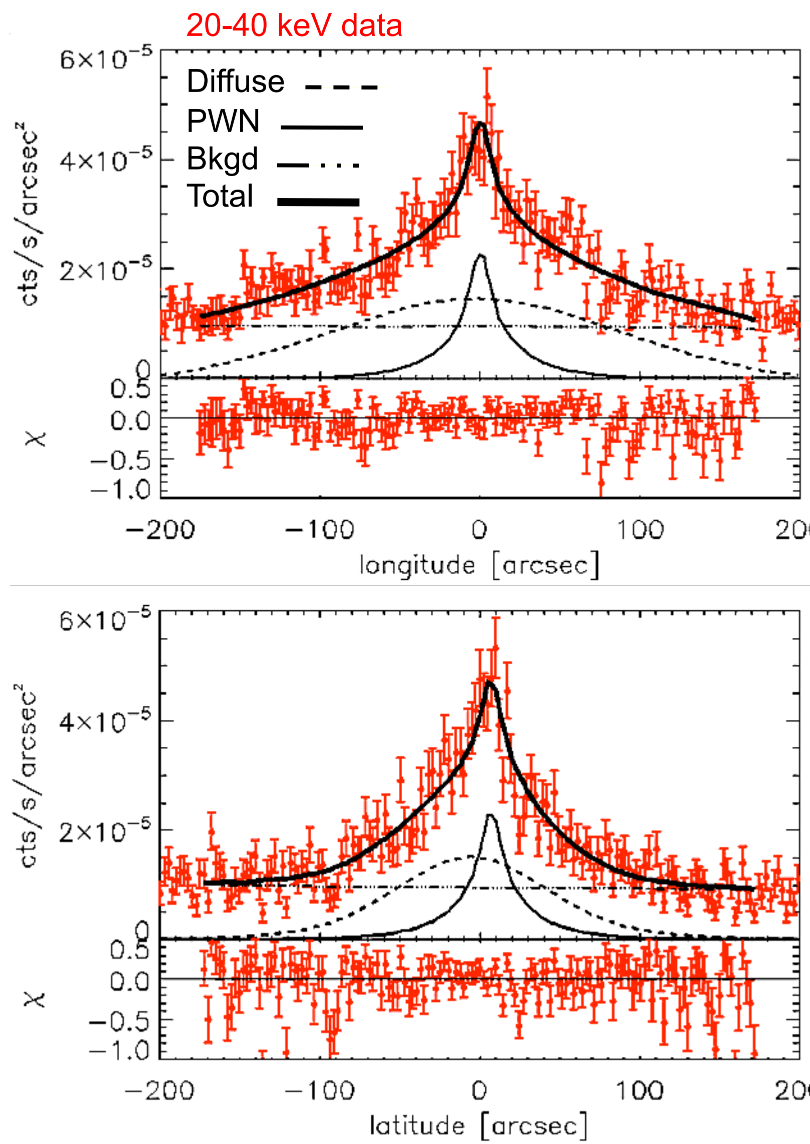
K. Perez et al., *Nature* **520**, 646–649 (30 April 2015)



- 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**

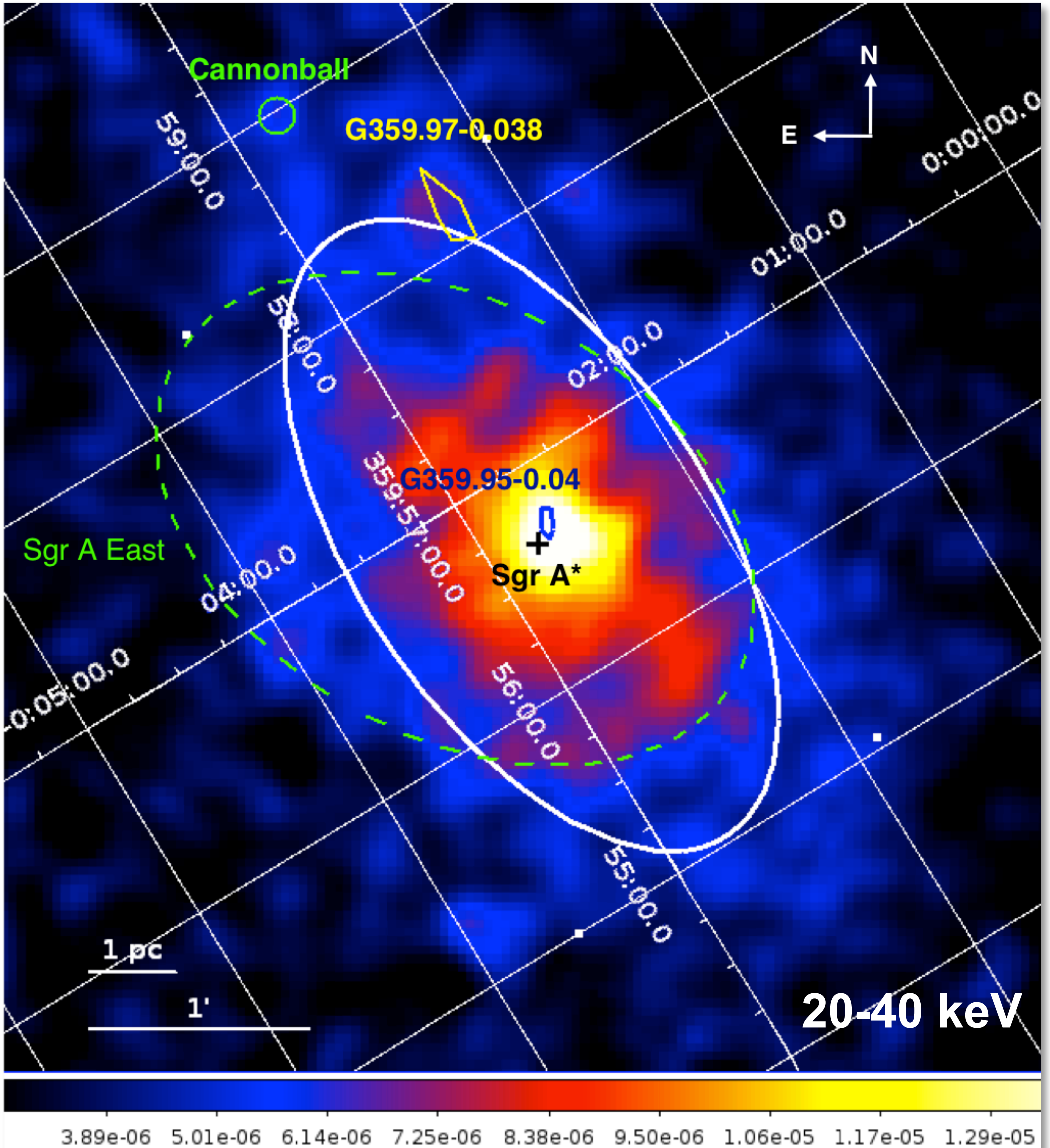
Diffuse emission has 8 pc x 4 pc spatial extent

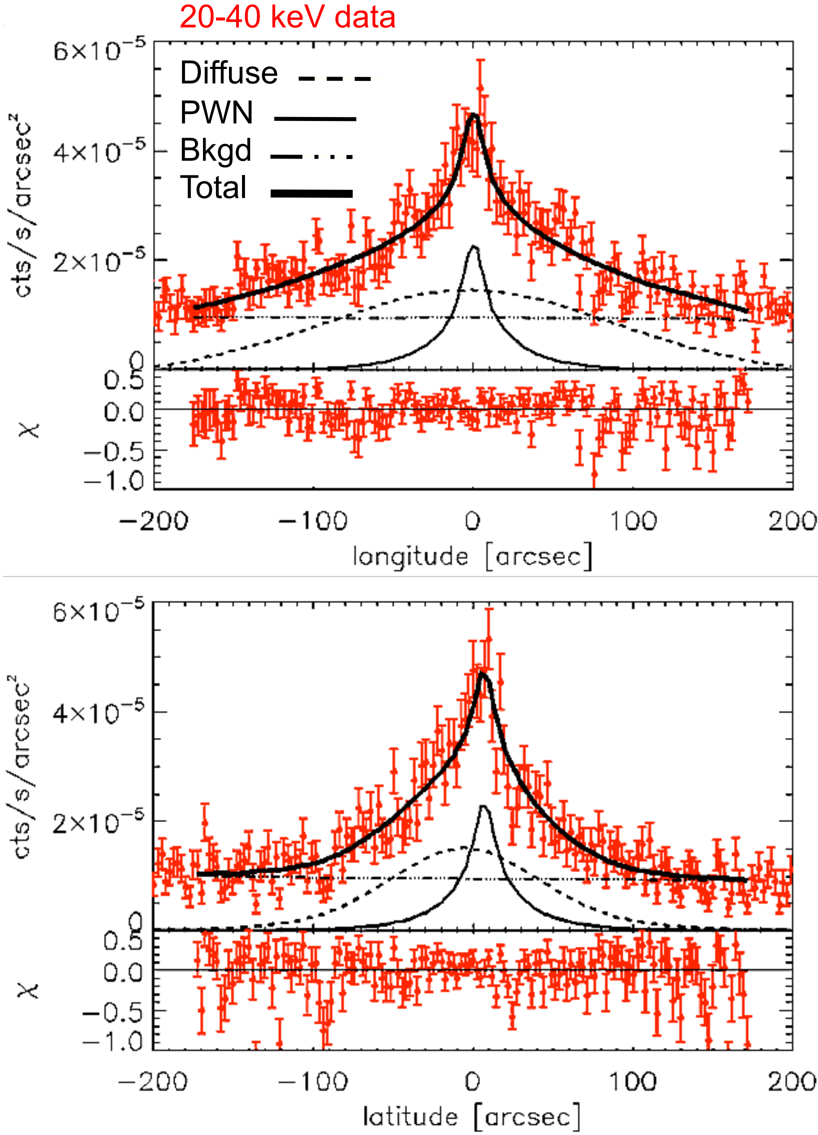




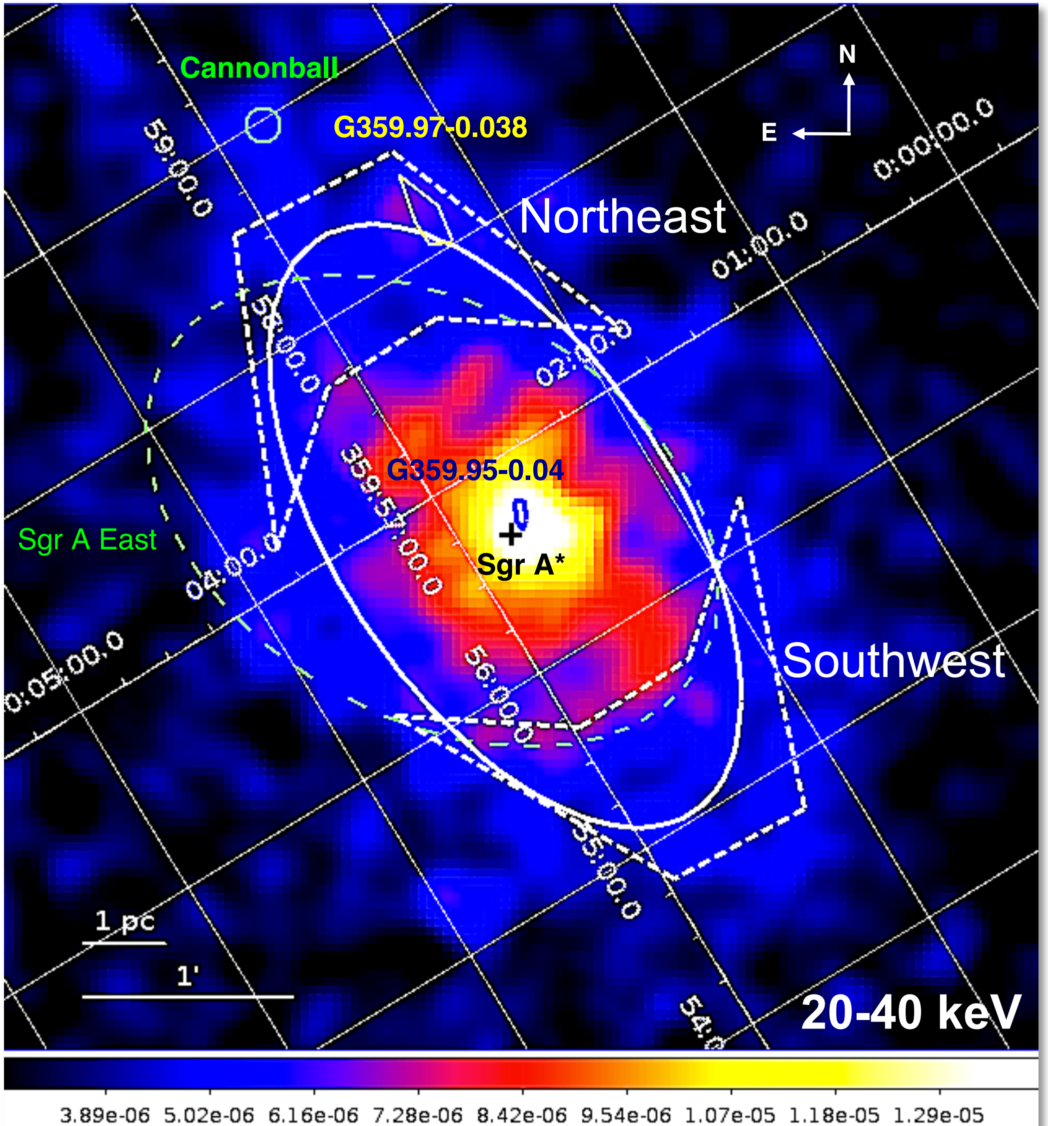
Diffuse emission has 8 pc x 4 pc spatial extent

NuSTAR



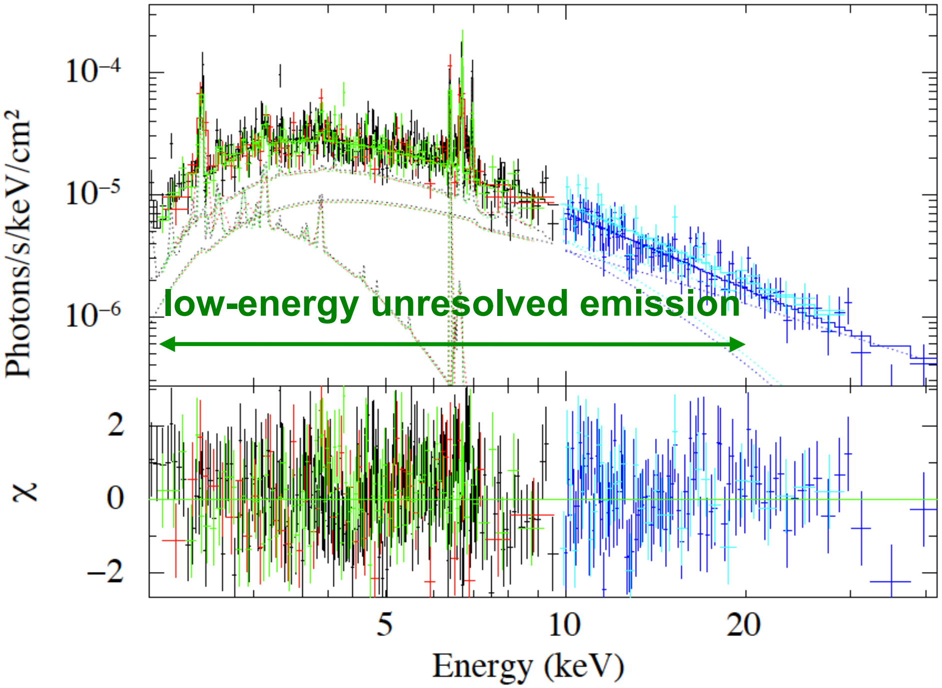


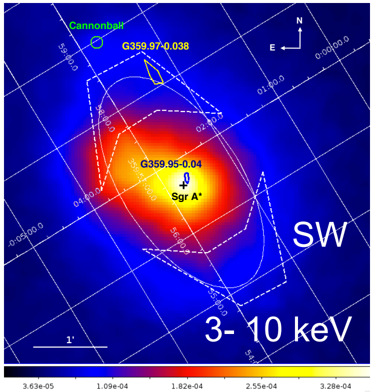
Spectra examined from regions away from central pulsar nebula

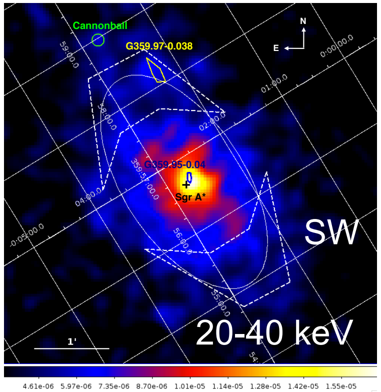


- Spectra taken from >75% encircled energy radius away from the central pulsar wind nebula
- Different dominant emission sources at low energy: "Northeast" region has significant overlap with Sgr A East, "Southwest" region only underlying point sources
- Combined with XMM-Newton data from same time periods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

Spectrum of “Southwest” region







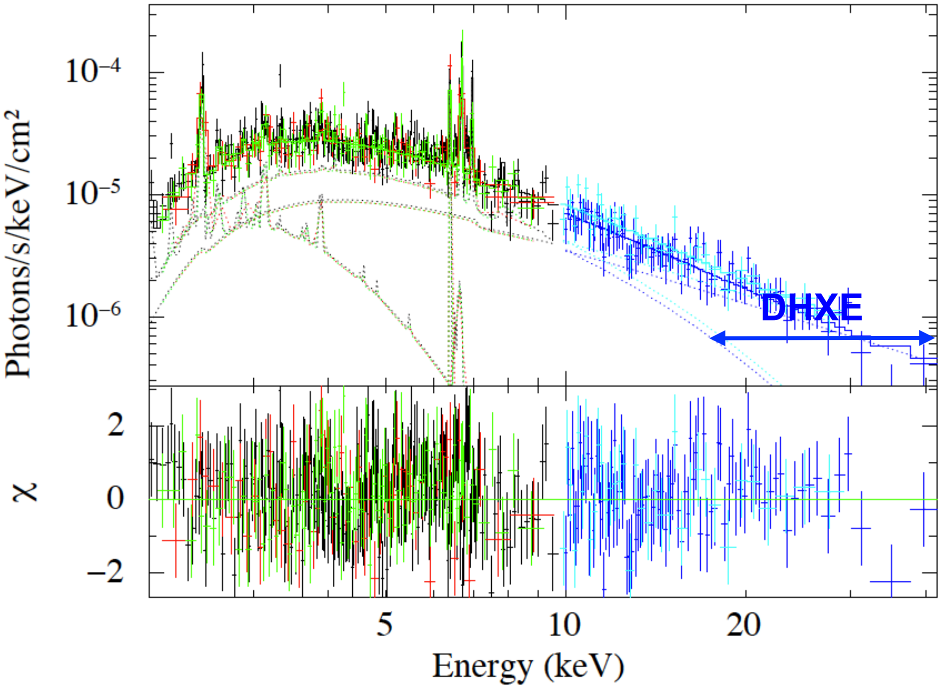
- **Below 20 keV** dominated by:

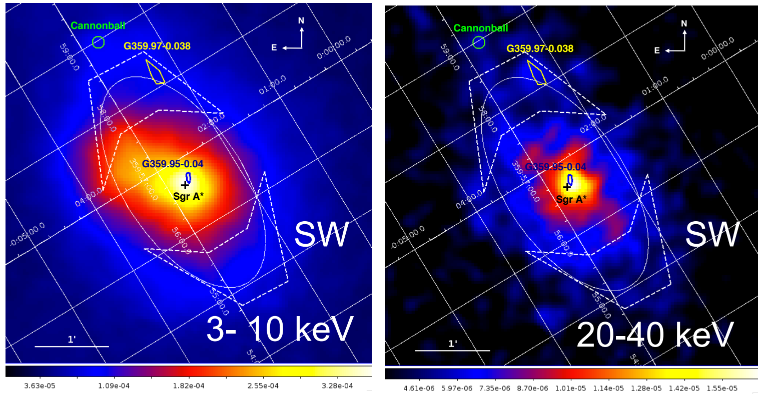
$kT_1 = 1.0^{+0.3}_{-0.4}$ keV
$Z_1 = 5.0$
— **Coronally active stars, SNR heated plasma…**

$kT_2 = 7.5^{+1.6}_{-1.3}$ keV
$Z_2 = 1.7$
— **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)*

Spectrum of "Southwest" region





- Below 20 keV dominated by:

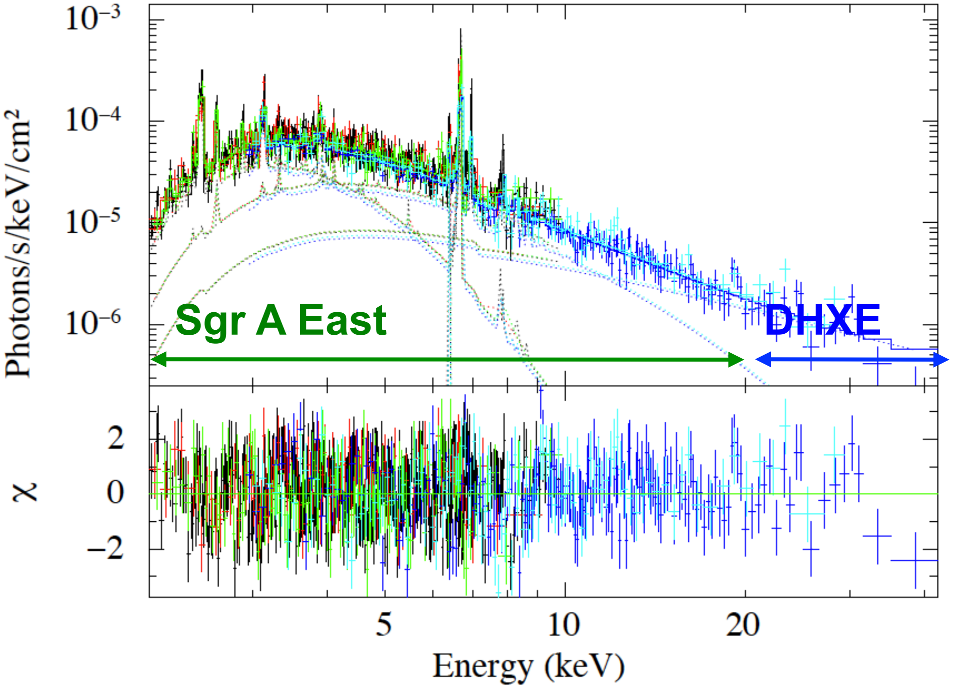
$kT_1 = 1.0^{+0.3}_{-0.4}$ keV
$Z_1 = 5.0$
} **Coronally active stars, SNR heated plasma…**

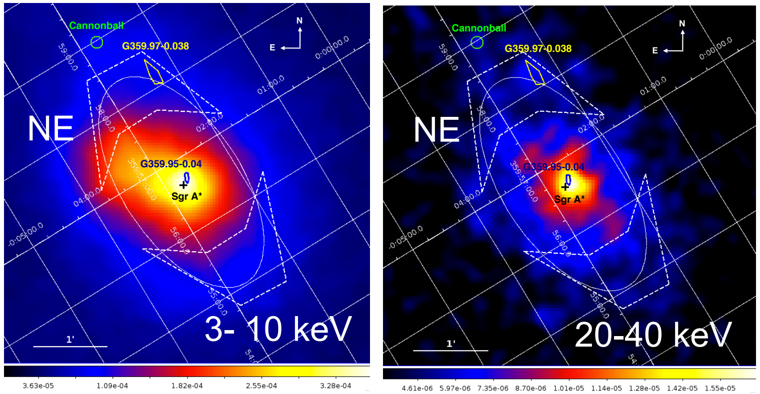
$kT_2 = 7.5^{+1.6}_{-1.3}$ keV
$Z_2 = 1.7$
} **Magnetic Cataclysmic Variables (Polars and Intermediate Polars**

- 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:**
  $N(E) = E^{-\Gamma}$ with $\Gamma = 1.5^{+0.3}_{-0.2}$
  OR
  Thermal bremsstrahlung with kT ~ 60 keV (> 35 keV)

“Northeast” region shows same high-energy spectrum





- Below 20 keV, dominated by:

  $kT_1 = 1.1^{+0.1}_{-0.2}$ keV
  $kT_2 = 5.1^{+0.9}_{-0.7}$ keV
  $Z = 2.3^{+0.9}_{-0.4}$

  } **The SNR Sgr A East**

- **Above 20 keV dominated by:**

  $N(E) = E^{-\Gamma}$ with $\Gamma = 1.6^{+0.3}_{-0.4}$
  OR
  Thermal bremsstrahlung with kT ~ 60 keV (> 36 keV)

Origins of Diffuse Hard X-ray Emission (DHXE)

NuSTAR

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) $\approx 2.4\times10^{34}$ ergs/s within the 8 pc $\times$ 4 pc FWHM
- ***radio observations and transient limits from SWIFT monitoring***

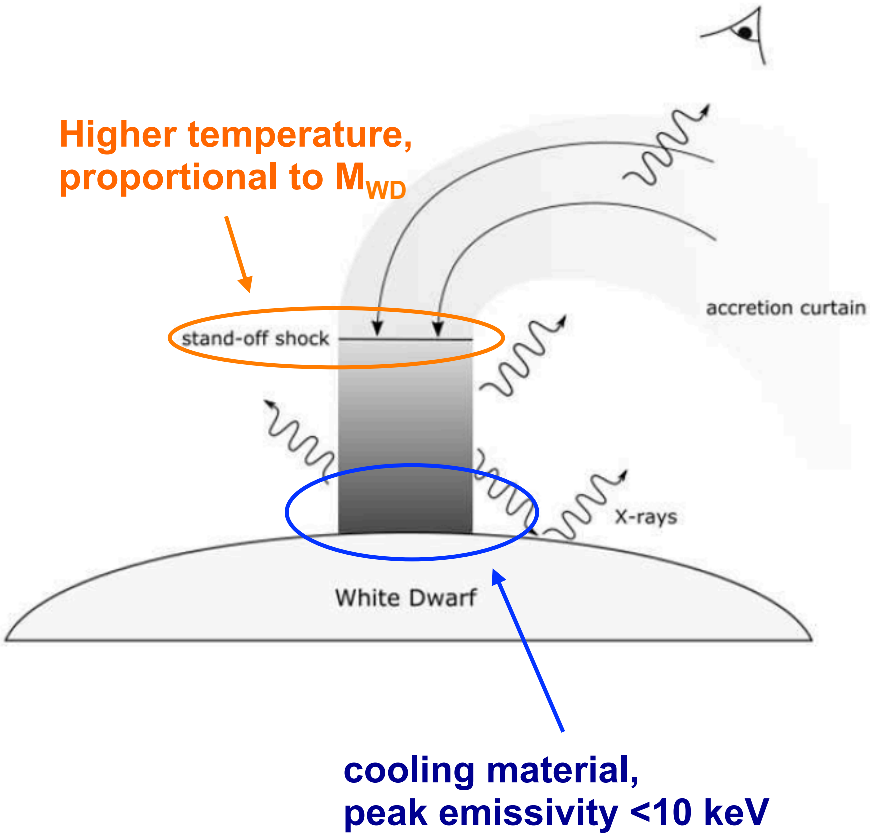
- Anomalously **massive Intermediate Polars** (IPs) with $\langle M_{WD} \rangle \approx 0.9 M_{\odot}$
- Quiescent **black hole low-mass X-ray binaries** (qBH-LMXB)
  - Previously undiscovered large population (~600–1200)
  - Must have very faint or long-recurrence outburst
- **Millisecond pulsars** 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

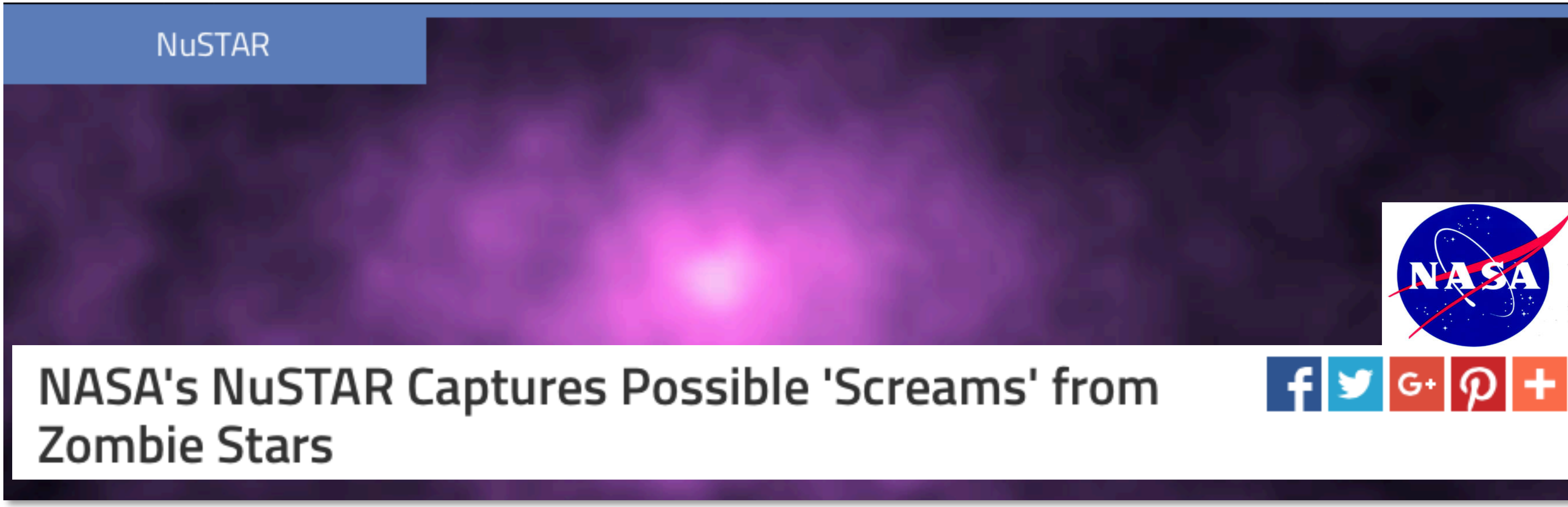
A coherent origin for Galactic Center Intermediate Polar populations?

NuSTAR

C. Hailey, K. Mori, K. Perez et al. (2015, submitted to ApJ)

- Analyzed two isolated IPs: TV Columbae and IGR J17303-0601
- Compared masses derived using different IP spectral models
- **NuSTAR Galactic Center hard X-ray spectrum**
  and **Chandra/XMM-Newton 2-10 keV observations of inner 50 pc**
  and **hard X-ray observed nearby IPs**
  are all **consistent with population of IPs with $\langle M_{WD} \rangle \approx 0.88 M_{O}$**
- These results contrast with the Galactic ridge, where hard X-ray observations by INTEGRAL and Suzaku suggest a population of IPs with $\langle M_{WD} \rangle \approx 0.6 M_{O}$





NuSTAR has provided the first view of the Galactic Center at > 10 keV with sub-arcminute angular resolution

- There is a diffuse hard X-ray emission with 8 pc x 4 pc spatial extent (FWHM), either non-thermal with $\Gamma \approx 1.6$ or thermal with $kT \approx 60$ keV (>35 keV)

- Stellar origin has implications for accretion physics, dynamical formation, and evolution of exotic binaries near the central supermassive black hole
  - If intermediate polars, not clear why heavier here than in the Galactic ridge

- A cosmic-ray origin, has implications for models of particle outflow from Sgr A*, as well as radiation and magnetic field distributions.

- Follow-up observations with NuSTAR planned for early 2016!

BACKUP

20–40 keV Spatial Model

NuSTAR

Supplementary Table 1: Parameters of the best-fit 2-D Gaussian models of the central source and the extended emission. The errors quoted are 3σ confidence levels. All parameters refer to source models before convolution with the NuSTAR PSF.

Parameter	Point source	Extended
R.A. (Center, J2000)	$266.4150^{\circ}{}^{+4.5''}_{-3.8''}$	$266.4172^{\circ}{}^{+6.6''}_{-6.2''}$
DEC (Center, J2000)	$-29.007245^{\circ}{}^{+3.4''}_{-4.1''}$	$-29.00716^{\circ}{}^{+8.1''}_{-7.1''}$
FWHM [arcseconds]	$1.8^{+2.3}_{-0.7}$	$195.8^{+21.9}_{-16.8}$
Amplitude [10^{-3} cts s^{-1}]	$5.2^{+7.1}_{-3.5}$	$0.0064^{+0.0012}_{-0.0017}$
Ellipticity	–	0.52
θ^{a} [degree]	–	57

[a] The angle θ is defined with respect to the positive northern axis.

Spectral Model

Supplementary Table 2: Spectral model of the two extended emission regions in the energy range 2-40 keV, obtained from joint fit of XMM (2-10 keV) and NuSTAR (10-40 keV) data, with the high-energy emission modeled as a power-law. All quoted errors are at 90% C.L.

Parameter	Southwest	Northeast
PN norm.[a]	$1.1^{+0.1}_{-0.1}$	$1.1^{+0.1}_{-0.1}$
MOS1 and MOS2 norm.	$1.0^{+0.1}_{-0.1}$	$1.1^{+0.1}_{-0.1}$
NuSTAR FPMA norm. (fixed)	1.0	1.0
NuSTAR FPMB norm.	$1.2^{+0.1}_{-0.1}$	$1.1^{+0.1}_{-0.1}$
N_H [10^{22} cm^{-2}]	$14.1^{+1.5}_{-1.3}$	$16.4^{+1.2}_{-0.8}$
Γ	$1.5^{+0.3}_{-0.2}$	$1.6^{+0.3}_{-0.4}$
N_Γ [10^{-4} photons cm^{-2} s^{-1} keV^{-1}]	$1.3^{+1.6}_{-0.7}$	$1.6^{+2.4}_{-1.1}$
kT_1 [keV]	$1.0^{+0.3}_{-0.4}$	$1.1^{+0.1}_{-0.2}$
N_{kT_1} [10^{-4} photons cm^{-2} s^{-1} keV^{-1}]	$10.8^{+103}_{-5.0}$	$89.9^{+56.1}_{-28.7}$
$Z_1[Z_\odot]$[b]	$5.0^{+--}_{-3.6}$	$2.3^{+0.9}_{-0.4}$
kT_2 [keV]	$7.5^{+1.6}_{-1.3}$	$5.1^{+0.9}_{-0.7}$
N_{kT_2} [10^{-4} photons cm^{-2} s^{-1} keV^{-1}]	$9.2^{+1.7}_{-1.6}$	$17.5^{+6.7}_{-5.9}$
$Z_2[Z_\odot]$[c]	1.7	$2.3^{+0.9}_{-0.4}$
Fe K-α eq. width [eV]	128^{+40}_{-31}	47^{+84}_{-16}
χ^2/d.o.f.	1.00 (503.4/503)	1.05 (807.1/770)
F_X(20-40 keV) [10^{-13} ergs cm^{-2} s^{-1}][d]	7.6	8.0

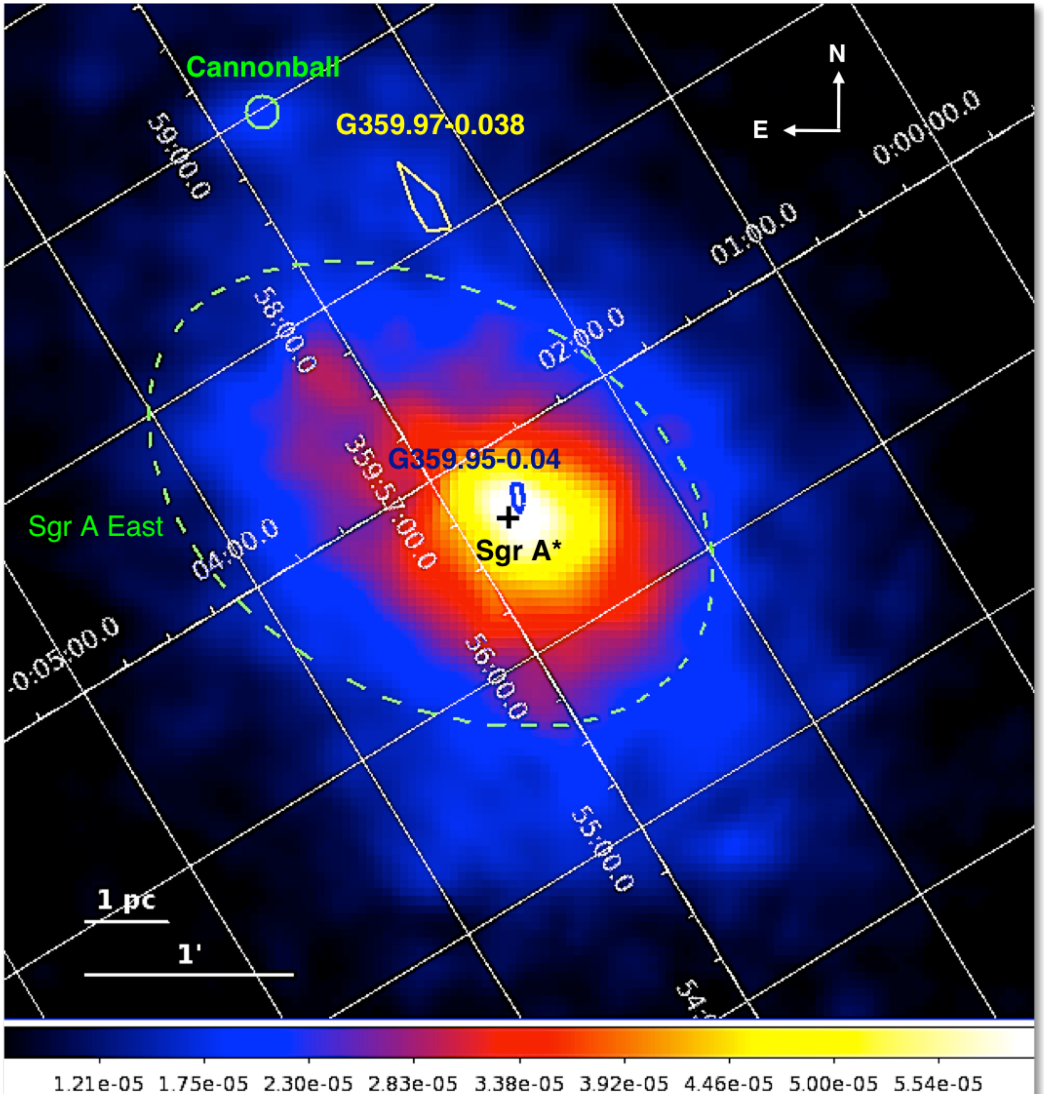
[a] Relative normalizations between different instruments, defined with respect to NuSTAR FPMA.
[b] Abundance relative to solar. These are best-fit values. In the southwest, Z_2 was then fixed during error calculations, as described in the text.
[c] Abundances are independent (linked) for the two temperature components in the southwest (northeast).
[d] Observed Flux.

Supplementary Table 3: Spectral model of the two extended emission regions in the energy range 2-40 keV, obtained from joint fit of XMM (2-10 keV) and NuSTAR (10-40 keV) data, with the high-energy emission modeled as a thermal bremsstrahlung. All quoted errors are at 90% C.L.

Parameter	Southwest	Northeast
PN norm.[a]	$1.1^{+0.1}_{-0.1}$	$1.2^{+0.1}_{-0.1}$
MOS1 and MOS2 norm.	$1.1^{+0.1}_{-0.1}$	$1.2^{+0.1}_{-0.1}$
NuSTAR FPMA norm. (fixed)	1.0	1.0
NuSTAR FPMB norm.	$1.2^{+0.1}_{-0.1}$	$1.2^{+0.1}_{-0.1}$
N_H [10^{22} cm^{-2}]	$13.4^{+1.6}_{-1.3}$	$16.4^{+1.2}_{-0.8}$
kT_{bremss} [keV]	58^{+127}_{-23}	66^{+203}_{-30}
N_{bremss} [10^{-4} photons cm^{-2} s^{-1} keV^{-1}]	$1.8^{+0.4}_{-0.4}$	$1.9^{+0.4}_{-0.3}$
kT_1 [keV]	$1.0^{+0.3}_{-0.3}$	$1.1^{+0.1}_{-0.2}$
N_{kT_1} [10^{-4} photons cm^{-2} s^{-1} keV^{-1}]	$9.5^{+30}_{-2.0}$	$93.2^{+55.0}_{-22.2}$
$Z_1[Z_\odot]$[b]	$5.0^{+--}_{-3.2}$	$2.2^{+0.4}_{-0.3}$
kT_2 [keV]	$7.2^{+1.4}_{-1.3}$	$5.0^{+0.9}_{-0.7}$
N_{kT_2} [10^{-4} photons cm^{-2} s^{-1} keV^{-1}]	$8.8^{+2.0}_{-1.8}$	$18.0^{+6.1}_{-4.8}$
$Z_2[Z_\odot]$[c]	1.6	$2.2^{+0.4}_{-0.3}$
Fe K-α eq. width [eV]	123^{+90}_{-46}	46^{+12}_{-13}
χ^2/d.o.f.	1.00 (501.6/503)	1.05 (807.1/770)
F_X(20-40 keV) [10^{-13} ergs cm^{-2} s^{-1}][d]	7.3	8.0

[a] Relative normalizations between different instruments, defined with respect to NuSTAR FPMA.
[b] Abundance relative to solar. These are best-fit values. In the southwest, Z_2 was then fixed during error calculations, as described in the text.
[c] Abundances are independent (linked) for the two temperature components in the southwest (northeast).
[d] Observed Flux.

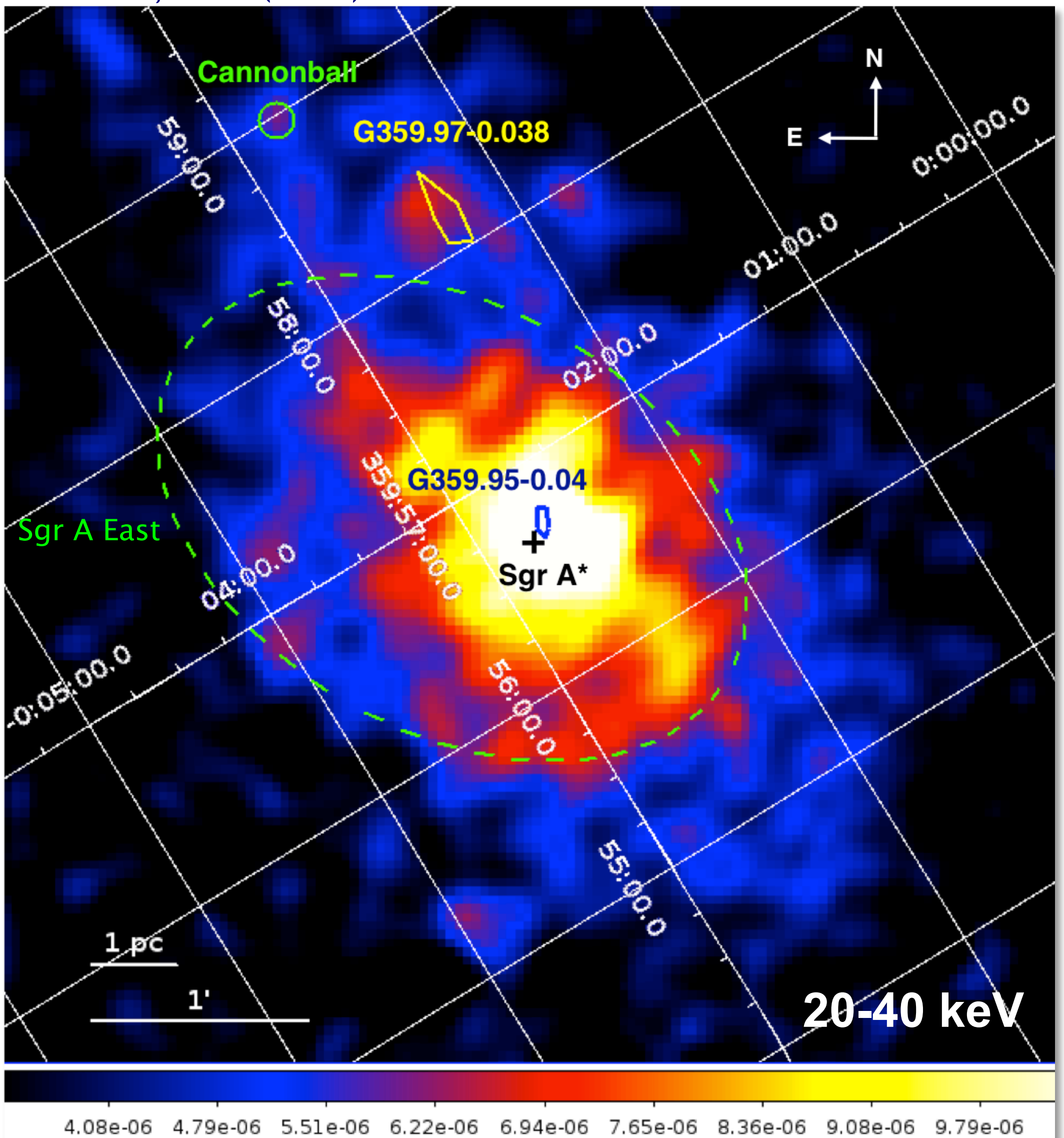
Inner 12 pc x 12 pc at **10–20 keV**



- Emission from near Sgr A* and G359.95-0.04 still dominates
- Dimmer, but persistent emission inside the Sgr A-East shell
- The "Cannonball" neutron star (Nynka et al. 2013) and the non-thermal filament G359.97-0.038 (Nynka et al. 2014)

Inner 12 pc x 12 pc at **20–40 keV**

K. Perez, *et al.* (2014)

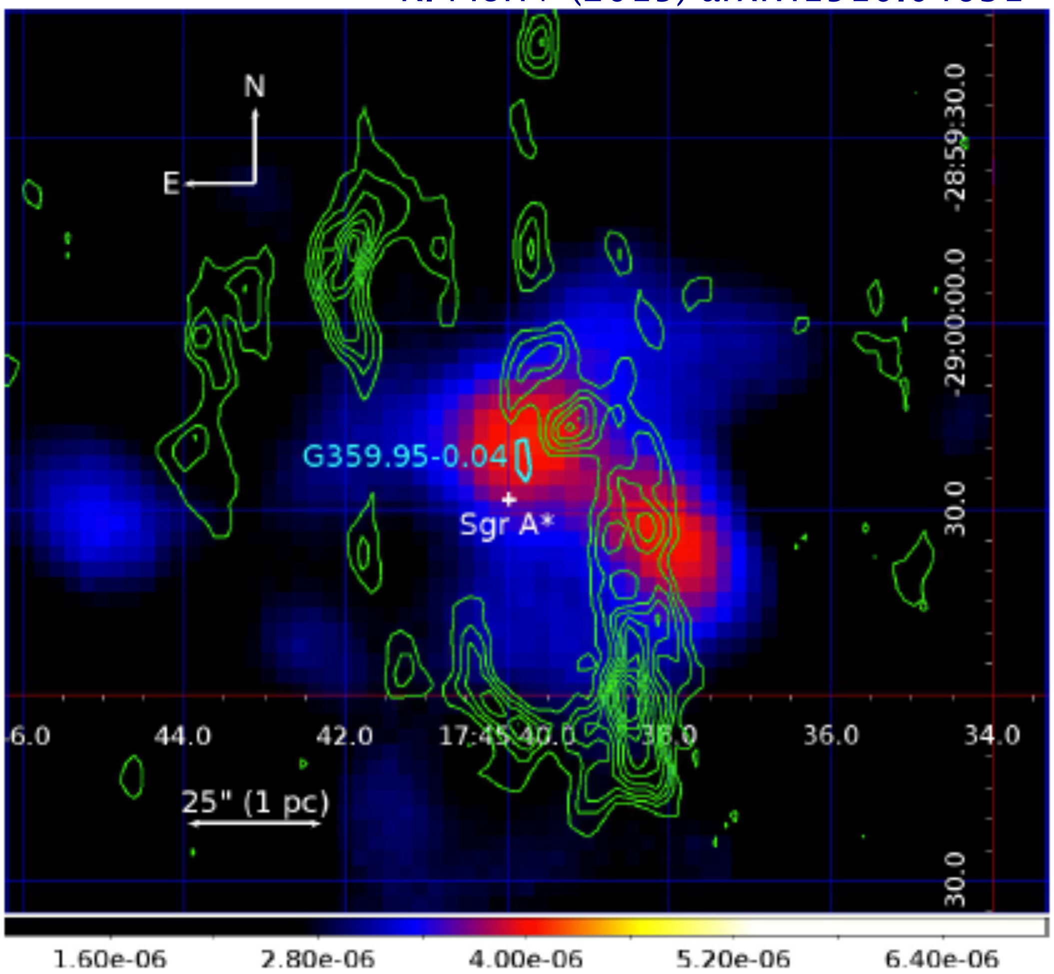


- Bright emission from pulsar wind nebula/Sgr A* region remains

- In addition, there is **a diffuse >20 keV X-ray emission extending along the Galactic plane from the Galactic Center**

The Galactic Center at >40 keV

K. Mori+ (2015) arxiv:1510.04631



- **One strong source dominates**, consistent with both the Chandra Pulsar Wind Nebula G359.95-0.04 and the HESS TeV source J1745-290

- The INTEGRAL >20 keV source IGR J17456-2901 is a combination of 1E1743; molecular clouds; Cannonball; non-thermal filaments; GC diffuse hard X-ray background

- only at >10x better angular resolution can this really be deduced

- Many of these objects have different spectral indices and widely disparate fluxes

The Inner Galactic Center

K. Mori+ (2015) arxiv:1510.04631

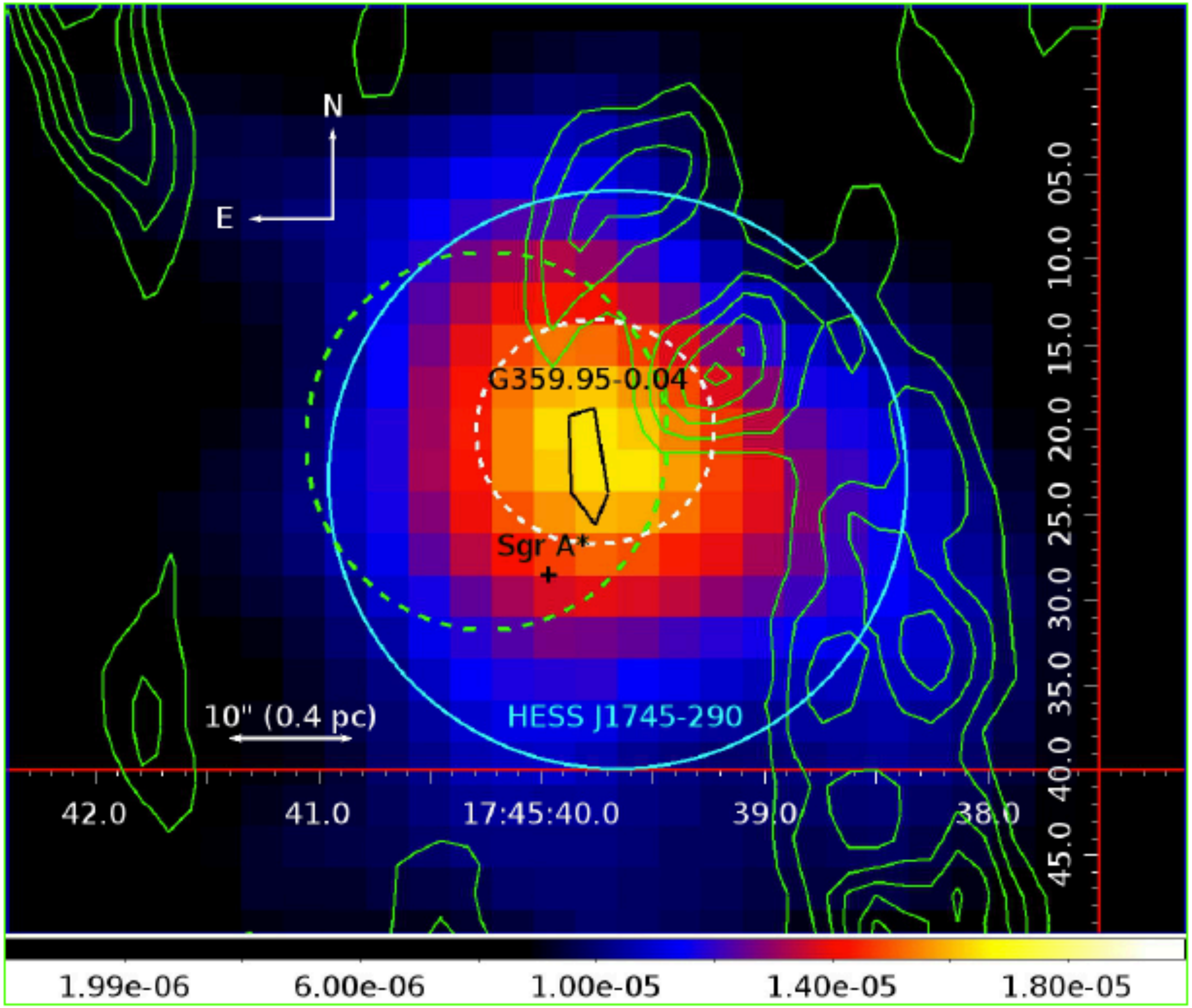


Figure 6. *NuSTAR* 20-40 keV image zoomed in the central 3′ region overlaid with Sgr A* (black cross), the centroid of the TeV source HESS J1745−290 (cyan circle), PWN candidate G359.95−0.04 (black polygon) and circumnuclear disk (green contours). The centroid of the CHXE and point source detected in the 20-40 keV band are indicated by green and white dashed circles with the 90% c.l. circles including both statistical and systematic errors, respectively.

Hot Intermediate Polars ?

NuSTAR

Scenario 1: Intermediate Polars (IPs) with kT > 35 keV

- much hotter than the kT ≈ 8 keV in the inner arcminutes (Muno 2004; Heard and Warwick 2012) or kT ≈15 keV observed in the inner Galactic bulge (Yuasa 2012)

- Swift, INTEGRAL, Suzaku, and XMM-Newton measurements of individual IPs show an average temperature of kT ≈ 20 keV, but exhibit a range in temperature from kT ≈ 10 keV to kT ≈ 90 keV

- Assume L_{min}(2-10 keV) ≈ $10^{30} – 10^{31}$ erg/s
  L_{max}(2-10 keV) ≈ 10^{33} erg/s
  $\alpha \approx 1.0\text{-}1.5$
  → **800 – 8000 IPs in 8 pc × 4 pc**
  → **6-60 IPs pc^{-3}**

- Observed spectrum implies white dwarf mass **$\langle M_{WD} \rangle > 0.9$ M**

Are there enough massive B-stars to support IP popultion?

NuSTAR

- Convert M_{wd} to initial stellar mass M (Zhao et.al. 2012)
- Use Kroupa initial mass function as measured in GC $\xi(M) \sim M^{-\alpha}$; α = 2.15 (Bartko et.al. 2010) (can add <~ 10% admixture of “top-heavy” IMF for central pc)
- Enough massive (>~ 6 M_o) B-stars in central <~ 10 pc to provide L_x
- These massive IP are NOT seen in the Galactic Ridge,
- Massive (isolated) WD are extremely rare (~1%; Kepler 2007, SDSS)
- May (just) be consistent with number/L_x of cooler (less massive) polars/IP in Galactic Center

Black hole low-mass X-ray binaries ?

NuSTAR

Scenario 2: Quiescent black hole low-mass X-ray binaries (qBH-LMXB)

• Knowledge of the luminosity of qBH-LMXBs is limited to ~12 known systems

• For L_{min}(2-10 keV) ≈ 2-4 × 10^{31} erg/s → 600-1200 qBH-LMXBs

• In the last decade, X-ray monitoring surveys uncovered virtually all transient systems within the inner 50 pc of the Galaxy with

  - recurrence times of < 5-10 years
  - outburst durations longer than a few days
  - outburst L(2-10 keV) > 10^{34} erg/s

→Typical qBH-LMXB with T_r ~ 50-100 years could make up at most 10% of DHXE

• Long T_r, long outburst BH-LMXB such as GRS 1915+105 also cannot dominate

• Fainter, non-transient BH-LMXB have been proposed (Menou 1999)(Casares 2014): the transition radius between the advection dominated accretion flow and the normal thin accretion disk is at large enough radius that the outer disk is always cool

Millisecond pulsars?

NuSTAR

Scenario 3: millisecond pulsars; old rotation-powered neutron stars spun up in period to ~ 10 msec

• typical photon index of 1-2 in the hard X-ray band

• For L_{min}(2-10 keV) ≈ 10^30-10^33 erg/s; black body emission ~ 0.1-0.3 keV too soft to be observed at Galactic Center

• spin down powers range from ~4x10^32 – 2x10^36 erg/s and with L(2-10 keV) ~ 10^-4 * spin down power >> L(2-10 keV) ~ 6x10^30 erg/s

•Require ~ 3000 MSP to explain entire emission

•~ 96% of these MSP would be below Chandra detection limit and the remaining < 4% are a very small fraction of the resolved Chandra sources in the hard X-ray observed regions

Alternate populations

NuSTAR

Although explanations in terms of hot IPs, qBH-LMXBs, or MSPs present challenges, other possible populations have been ruled out as majority contributors to the DHXE.

- **Neutron star LMXBs** have typical T_r ~ 5-10 years, would have been detected by Swift monitoring
- **Magnetars** with consistent spectra (soft gamma repeaters) have typical T_r ~ 10 years
- A large enough population of **non-thermal filaments** is not supported by Chandra or radio mapping of the Galactic center
- Low surface brightness **PWN** would require at least x10 higher PWN birth rate
- **Dark matter** does not reproduce spatial extent