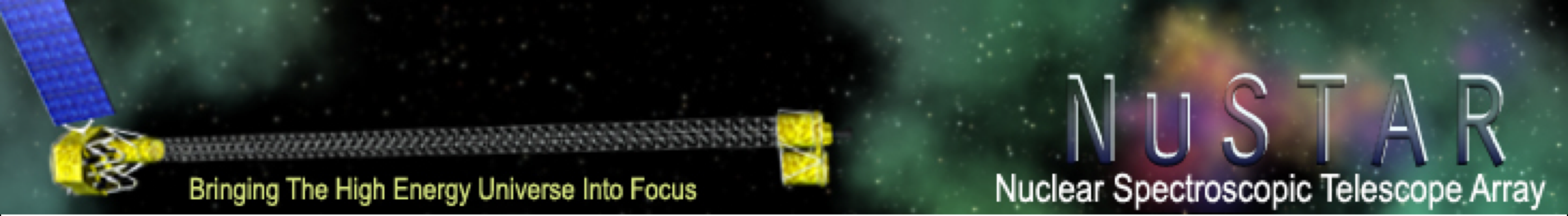


Observations of X-ray binary population in the Galactic Center

Roman Krivonos, Charles Hailey,
Kaya Mori, Franz Bauer, Michael Berkowitz, Jaesub Hong, Ben Hord, Shifra Mandel and Yve Schutt

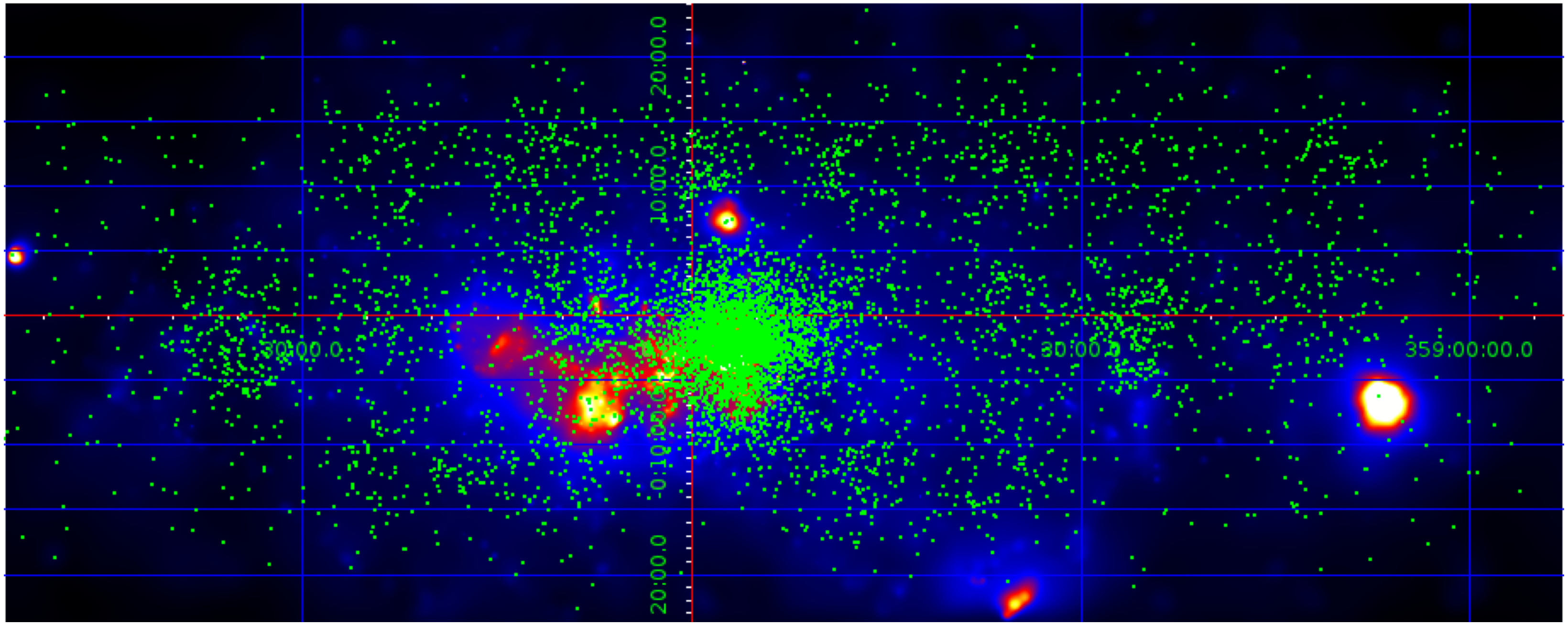
New horizons in GC astronomy and beyond workshop

October 22, 2019

Four fundamental questions about source populations in the Galactic Center

1) What are the source populations in the central ~ 1 pc of the Galactic Center?
2) What are the source populations comprising the diffuse central hard X-ray emission discovered by NuSTAR in the central 10 pc?
3) What are the source populations comprising the ~9000 point sources discovered by Chandra in the central few hundred pc ?
4) What is the Galactic ridge X-ray emission?

Chandra 2 x 0.8 deg GC map overlaid with 9,000 point sources (Wang+ 2002)



X-ray observations of the GC in the last two decades

- Quiescent X-ray sources
  - Chandra detection of > 9,000 X-ray point sources (Muno+ 09, Zhu+ 18)
  - NuSTAR observations (Hong+ 16)
  - XMM-Newton (Heard & Warwick 12)

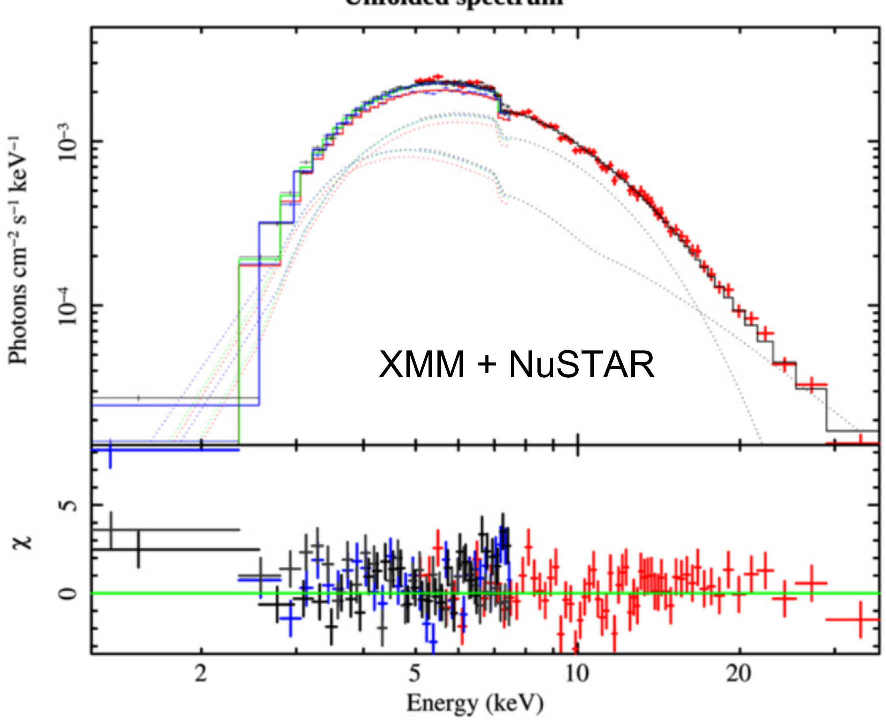
- X-ray transients
  - Swift/XRT monitoring of the central 50 pc region (Degenaar+ 12)
  - Chandra follow-ups for source localization + dust scattering halo (Corrales+ 17)
  - NuSTAR follow-ups for broad-band X-ray spectroscopy (Mori+ 13, Mori+ 19)

- Diffuse X-ray emission in the Galactic center, bulge and ridge
  - Central hard X-ray emission in r < 10 pc (Perez+ 15, Hailey+ 18)
  - Galactic ridge/bulge survey by RXTE, INTEGRAL, Suzaku and NuSTAR (Revnivtsev+ 06, Yuasa+ 12, Krivonos+ 07, Perez+ 19)

X-ray spectroscopy :
X-ray binary vs magnetic CV

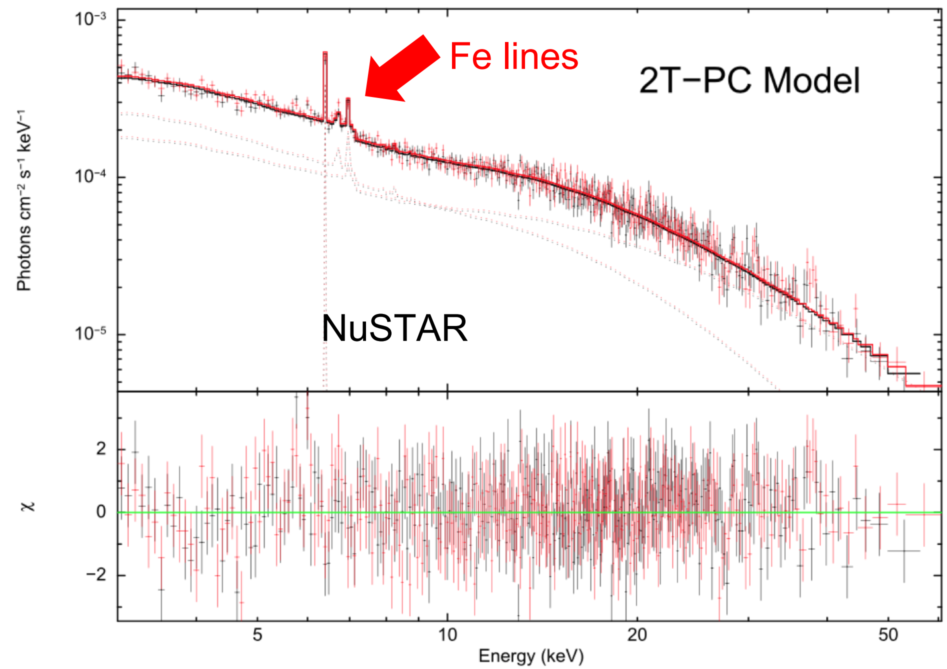
NS-LMXB 1E1743.1-2843
(Lotti+ 2016)

Non-thermal power-law spectrum

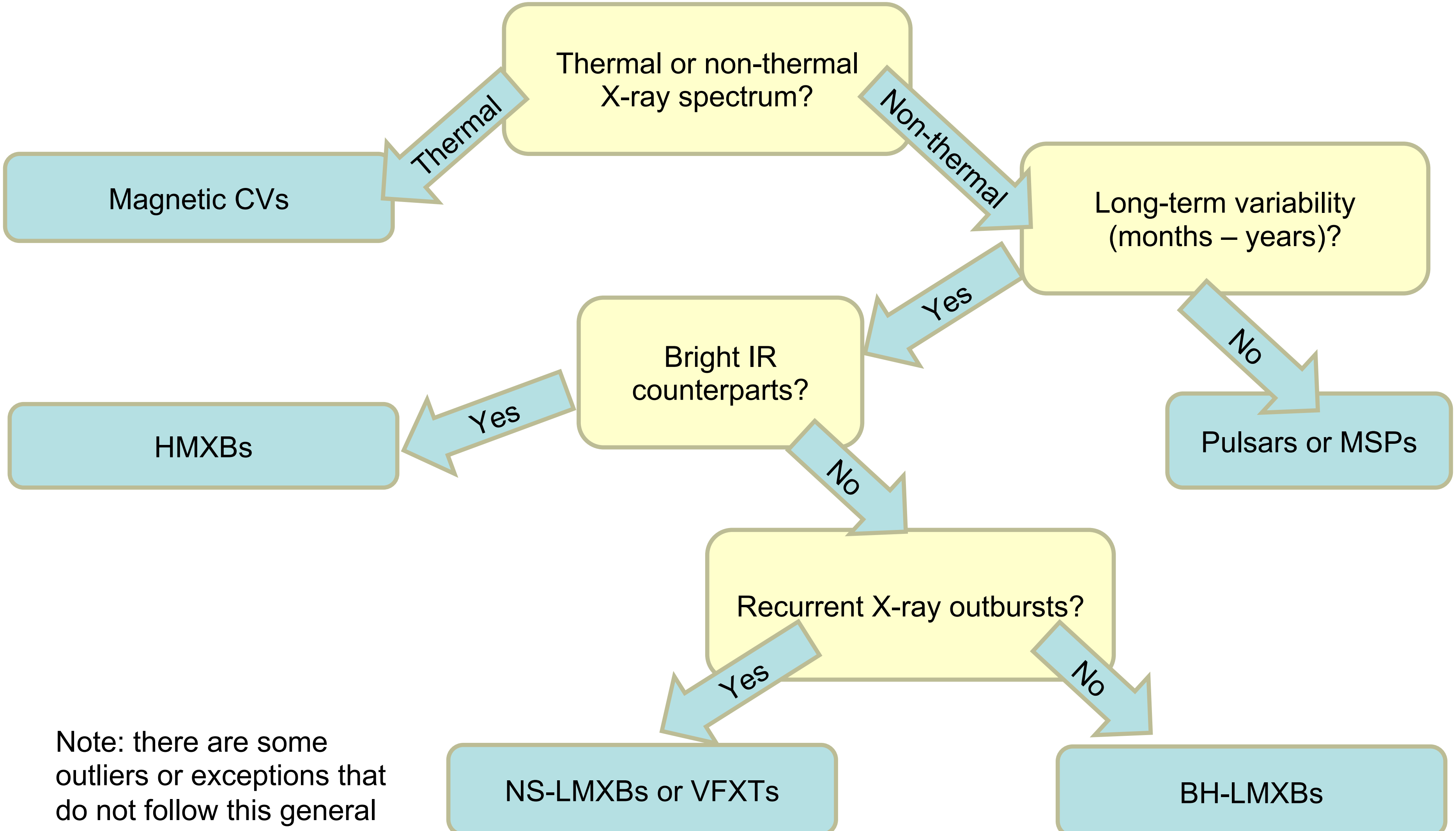


Magnetic CV IGR J17303-0601
(Hailey+ 2016)

Thermal spectrum with Fe lines



Identifying X-ray sources from their spectral and timing properties



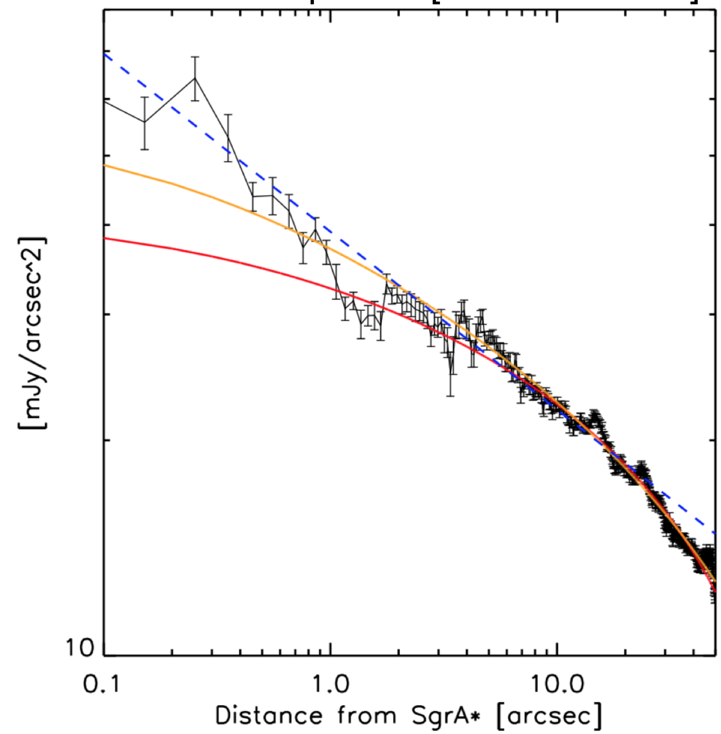
Note: there are some outliers or exceptions that do not follow this general source ID scheme.

The central 1 parsec region

Understanding the central parsec is interesting and important

- Galactic stellar dynamics: Where is the Galactic Center Bahcall-Wolf cusp in massive compact remnants?
- Gravitational waves: density/type of stellar remnants in the central parsec are important for predicting event rates
- Where are the pulsars, millisecond pulsars and magnetars?
- **Where are the black holes in the central parsec (~20,000 BHs (!))?** (Morris 93; Miralda-Escude & Gould 00, Generozov+ 17, Panamarev+ 19)

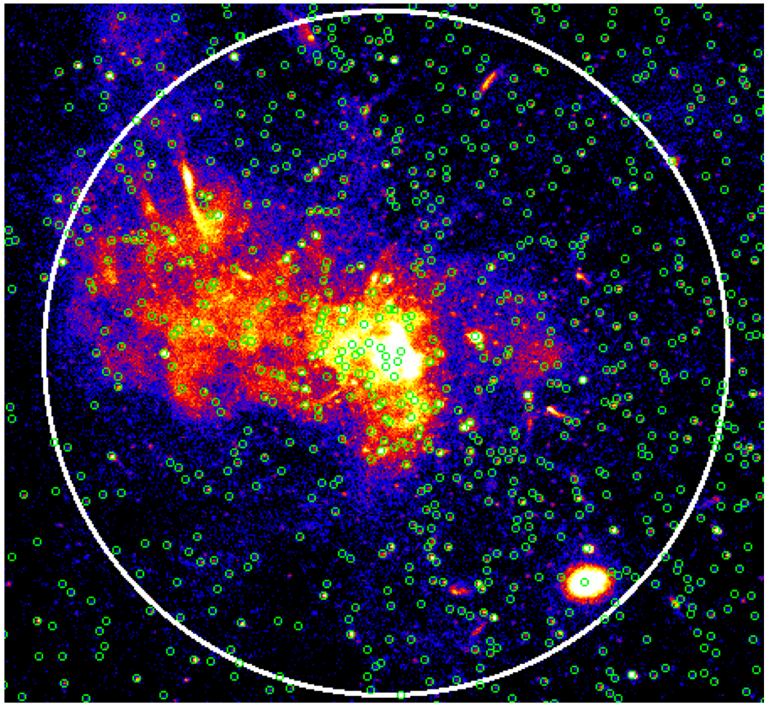
A cusp of IR sources (stars) in the central parsec [Schodel+ 2017]



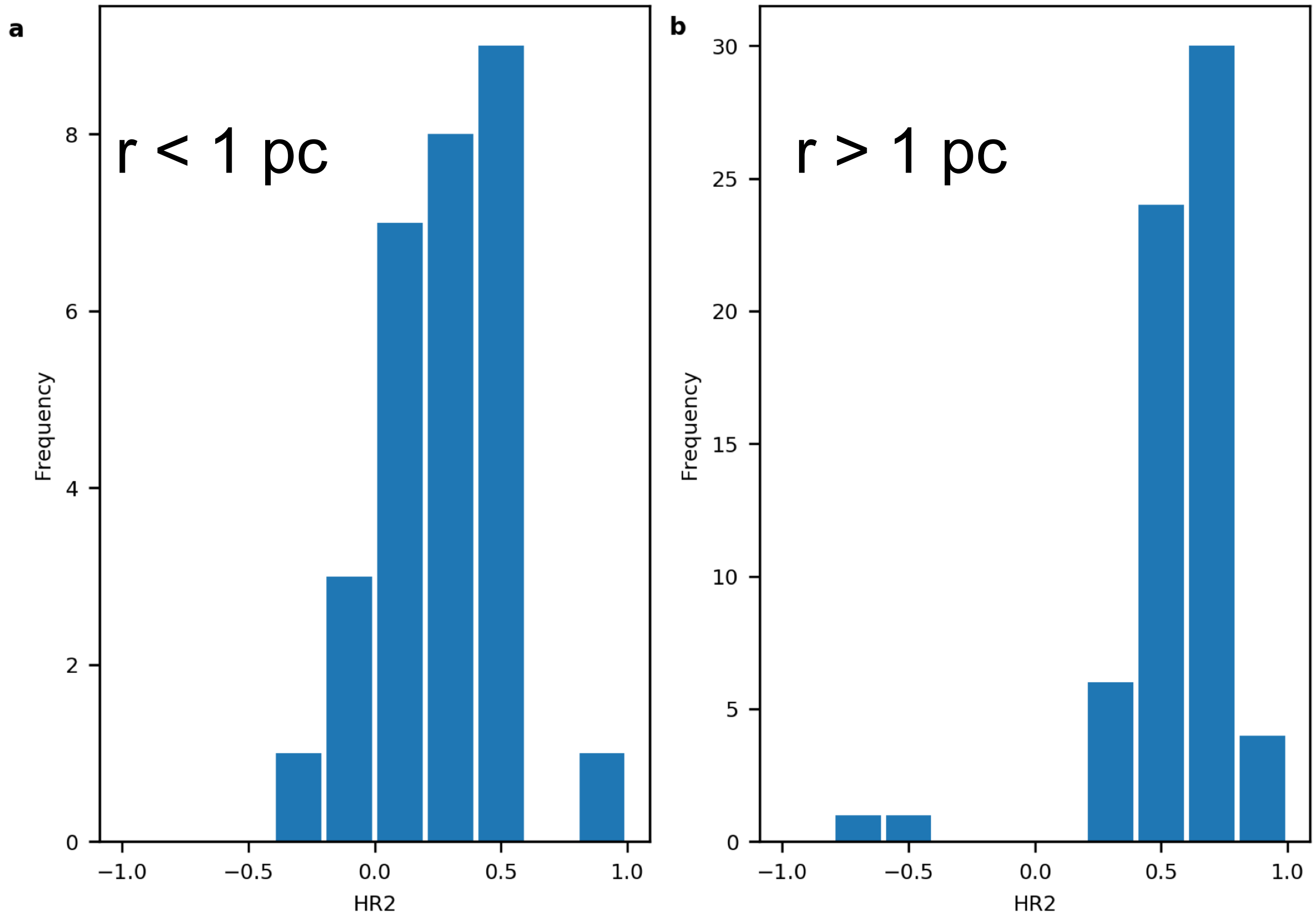
Chandra detected hundreds of point sources in the central 4 pc region

- 415 Chandra X-ray sources in r < 4 pc.
- Chandra is the only X-ray telescope capable of resolving point sources in this crowded region.
- Many Chandra observations pointed at Sgr A* with > 7 Msec exposure over the last two decades
- ~100 Chandra sources have enough photon counts (>~ 100) for decent hardness ratio or spectral fitting analysis.

Chandra image with all catalog sources (green) in the central r < 4 pc region (white circle)



Hardness ratio histogram for r < 1 pc and r > 1 pc show two distinct populations



For many of the Chandra sources, hardness ratios between 2-4 and 4-8 keV bands can be used to classify X-ray sources (Hailey+ 18.

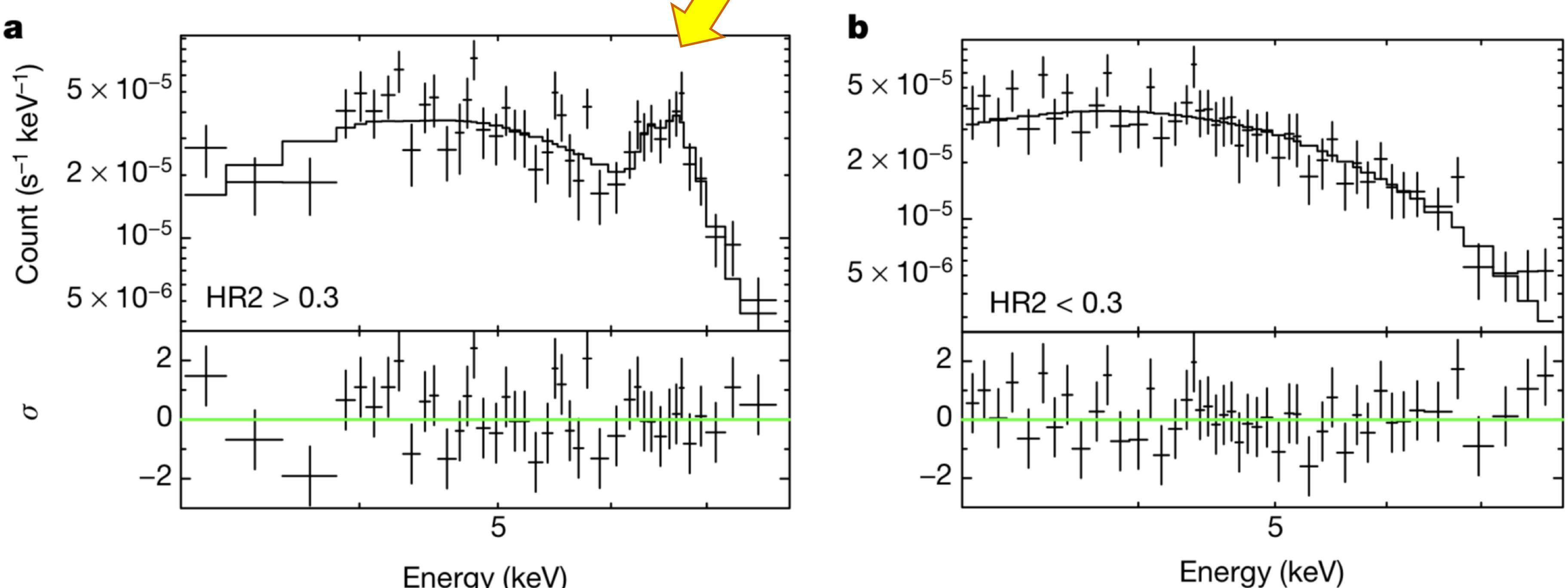
Stacked ACIS spectra are clearly distinct between hard and soft sources at r < 1 pc

We stacked Chandra spectra of the hard sources (HR2 > 0.3) and soft sources (HR2 < 0.3).

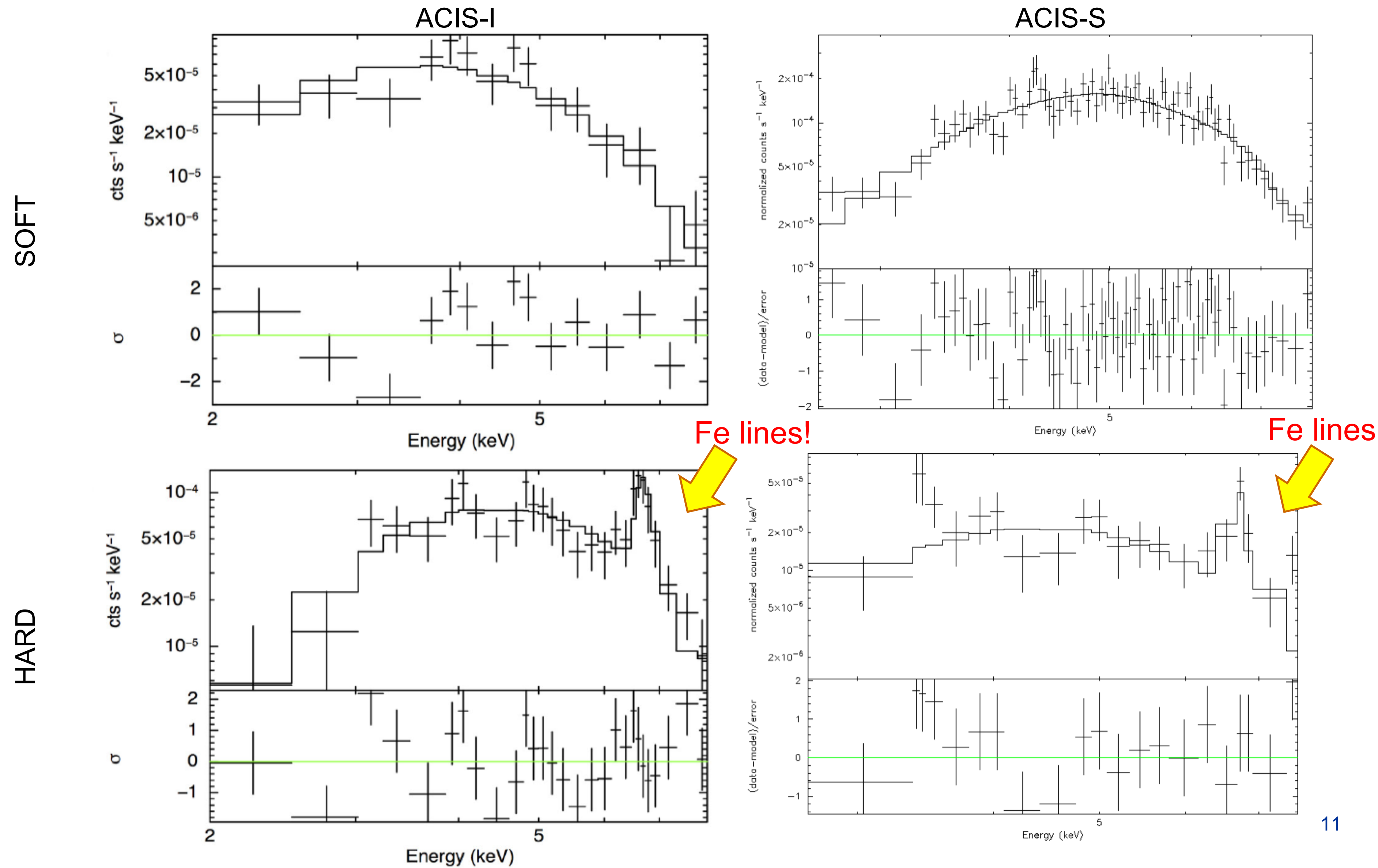
Thermal APEC model (kT = 7 keV)

Fe lines!

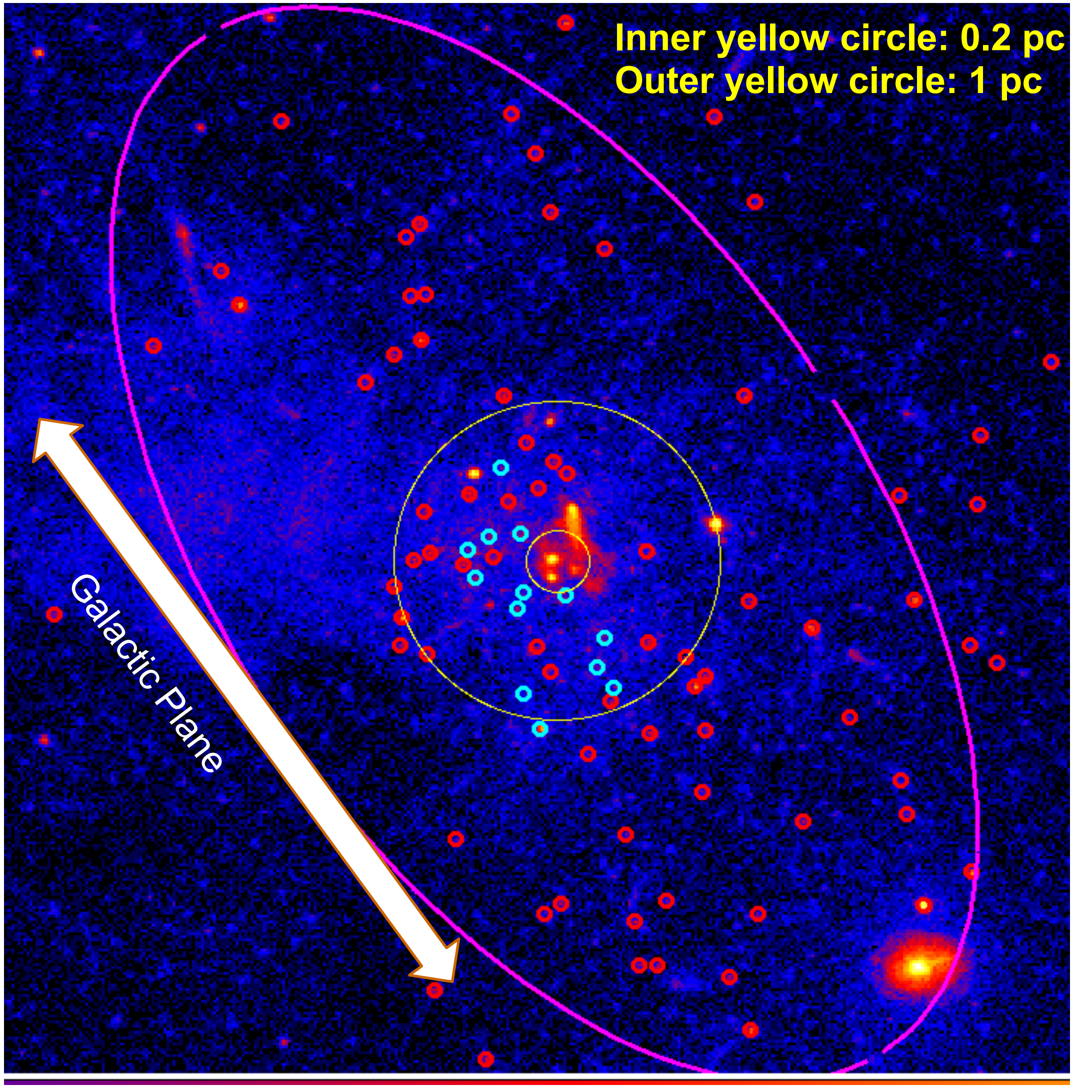
Power-law model (Γ = 1.7 +/- 0.3)



Individual sources with > 200 net counts show distinct spectral signatures



A clustering of 13 soft, non-thermal X-ray sources in the central 1 pc



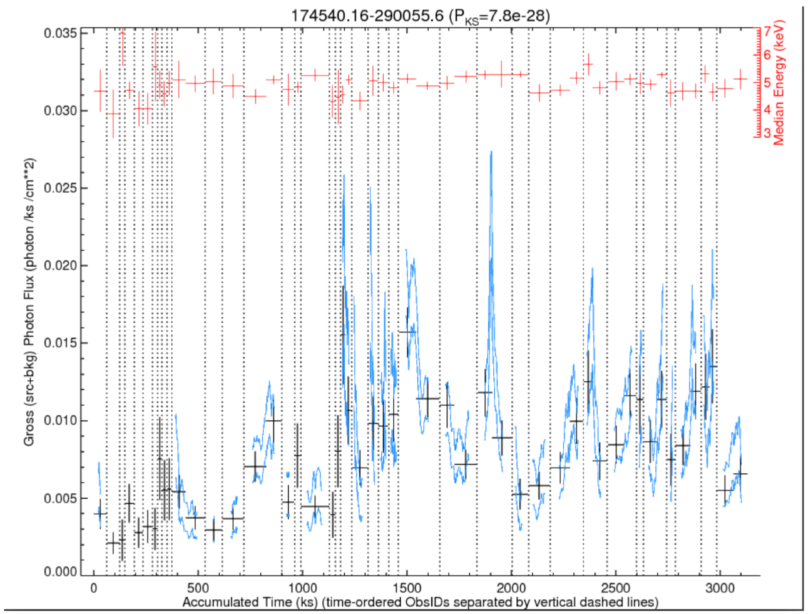
Chandra sources with > 100 net counts:

Cyan: Non-thermal (soft, HR2 < 0.3)

Red: thermal (hard, HR2 > 0.3) sources fill in the CHXE (purple ellipse).

10 out of the 13 soft, non-thermal sources are variable

- Long-term (months to years) X-ray variability detection
  - Bayesian block analysis
  - Kolmogorov-Smirnov test
  - Flux variability between ACIS-I and ACIS-S observations
- 3 steady sources may be milli-second pulsars.



Chandra X-ray lightcurve of one of the 13 non-thermal sources showing long-term variability.

X-ray transients in the Galactic Center

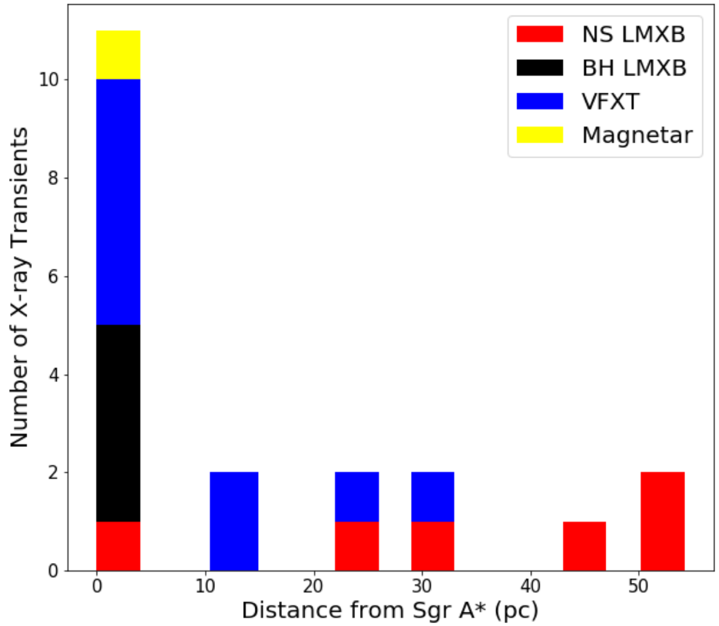
X-ray transients in the central 60 pc

- Swift/XRT monitoring of the GC region (r < 60 pc) provides the most complete data of X-ray outburst history down to 10^{34} erg/s (Degenaar+ 12).

- A half of the 20 X-ray transients are located within r < 3 pc.

- 6 NS-LMXBs confirmed through detection of type I X-ray bursts

- Very faint X-ray transients (VFXTs)
  - Peak luminosity Lx <~ 10^{36} erg/s
  - Recurrent X-ray outbursts every < 5 years

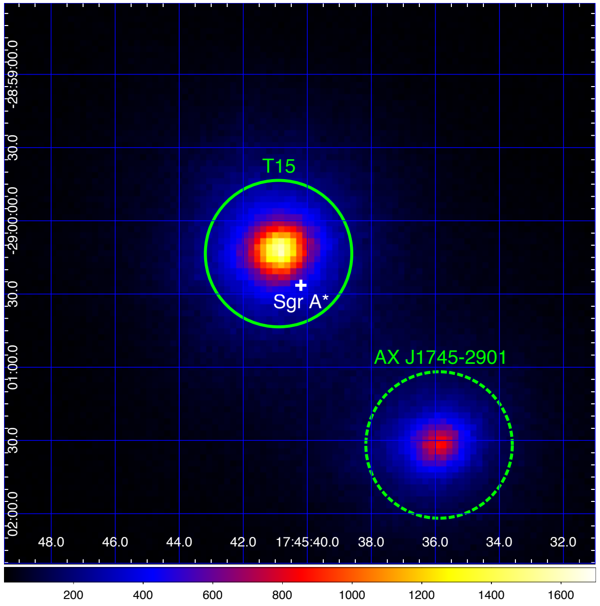


Note: VFXTs outside ~20 pc showed one X-ray outbursts possibly due to the poor sensitivity.

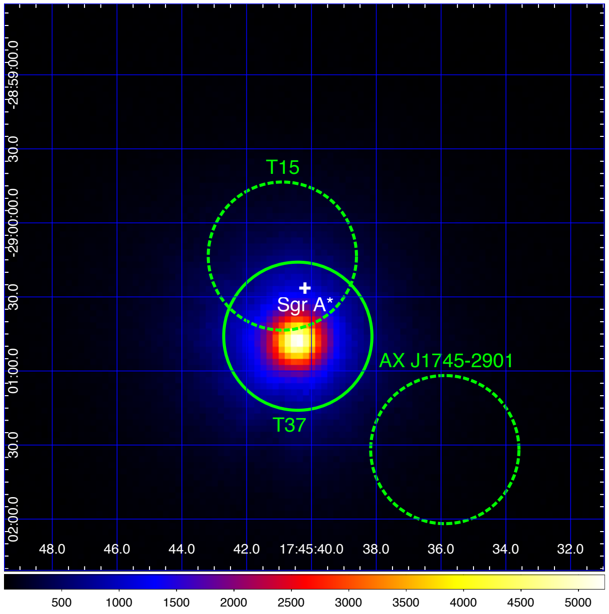
In 2016, Swift/XRT detected two new X-ray transients in the central parsec

- **Two new X-ray transients with Lx > 10^{37} erg/s**
  - No quiescent X-ray counterpart (quiescent Lx < 2×10^{31} erg/s)
  - No X-ray outbursts in the last > 13 years (during the Swift/XRT monitoring)

NuSTAR image of Swift J174540-290015

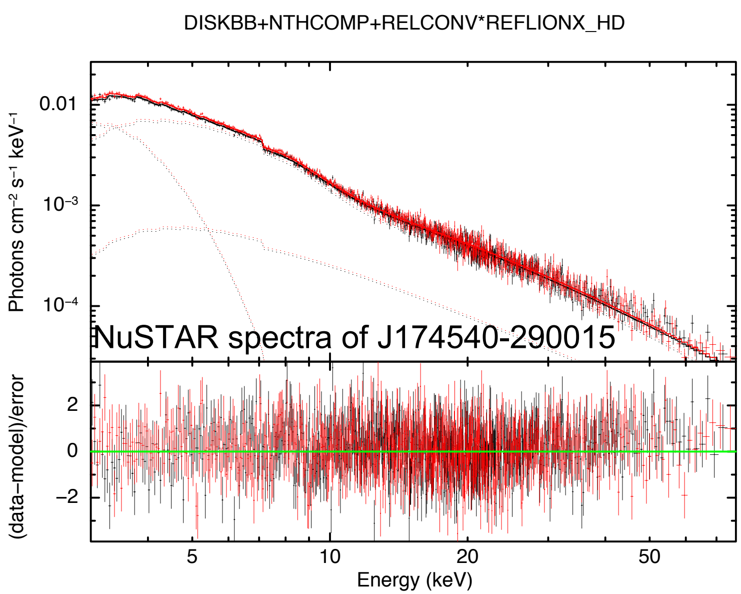


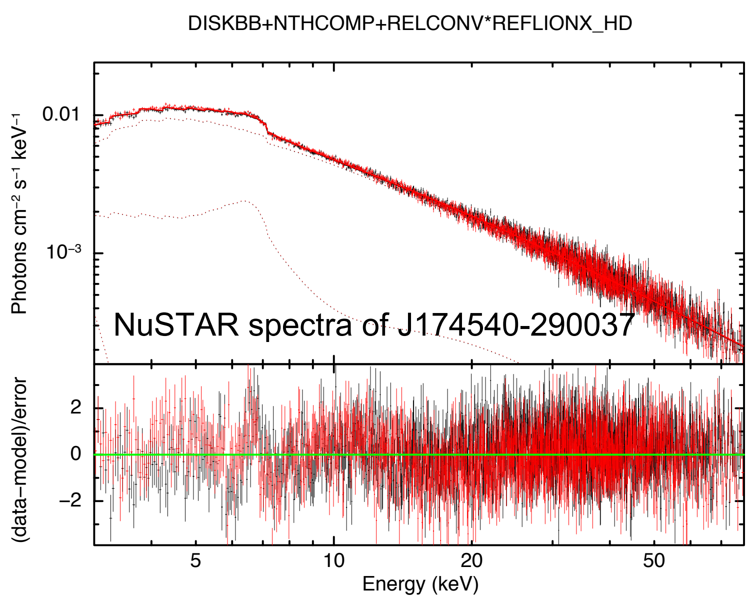
NuSTAR image of Swift J174540-290037



NuSTAR observations suggest 2016 transients are outbursting BH-LMXBs

- NuSTAR spectra show multiple components (Mori+ 19)
  - Thermal disk emission (diskbb)
  - X-ray continuum well described by thermal Comptonization models in hot corona
  - X-ray reflection from accretion disk showing relativistically broadened Fe atomic features.
- The first BH spin measurements from GC transients with NuSTAR:
  - **BH spin > 0.9 (nearly maximally spinning Kerr BH).**



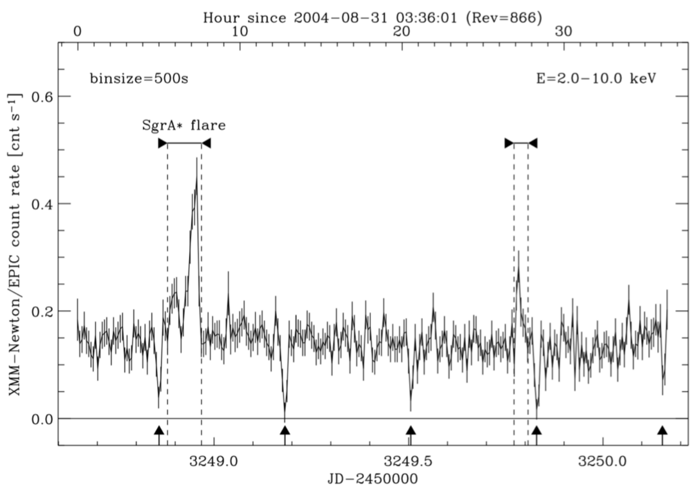


Swift/XRT monitoring exhibited distinct X-ray outburst history in the GC

- Swift/XRT GC monitoring offers the most complete historical data of X-ray outbursts (Carbone+Wijnands 19)
  - All sky monitoring with BAT and MAXI cannot detect faint X-ray transients.
- X-ray outburst recurrence time is a robust diagnostic to distinguish between different types of X-ray transients.
  - 6 NS-LMXBs (within 60 pc) and 5 VFXTs (within 10 pc) show < 5 year recurrence time on average.
  - 4 X-ray transients (including the 2016 Swift transients) have shown only one outburst in the past > 13 years -> **they are unlikely NS-LMXBs or VFXTs.**
- Note: most BH transients in our Galaxy also have > 50 year recurrence time (Corral-Santana+ 16), while NS transients have < 10 year recurrence time (except some outliers such as GX 334-4, Cen X-4).

13 non-thermal sources and 4 single X-ray outburst transients

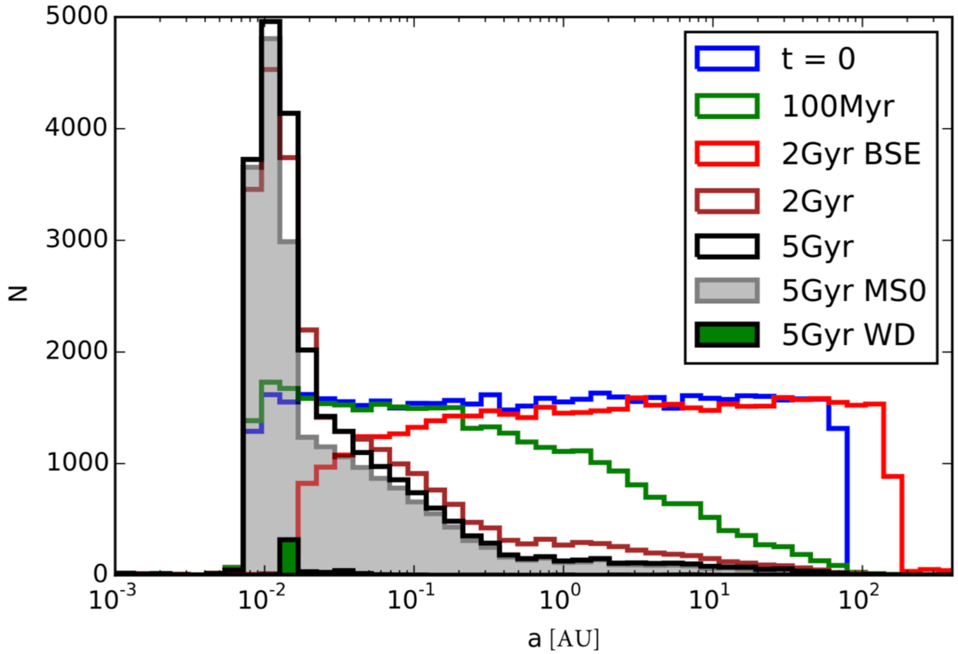
- Wu+ 10 and Lin+ 19 investigated the empirical relationship between orbital periods, X-ray peak luminosity and recurrence time of NS- and BH-LMXBs in the solar neighborhood.
- Lin+ 19 robustly found that BH-LMXBs with < 12 hour orbital periods have long (> 10 year) recurrence time.
- 13 non-thermal sources and 4 single X-ray outburst transients are likely BH-LMXBs with < 12 hour orbital periods.
- Indeed, Porquet+ 05 detected a 7.8 hour orbital period from one of these 4 transients!



XMM detection of 7.8 hour eclipses from CXO J174540-290031 (Porquet+ 05)

A population of tightly-bound X-ray binaries in the central parsec region

- N-body simulation of binary formation and evolution in the NSC showed tightly-bound binaries are largely populated in the central parsec region after surviving gravitational disruptions by Sgr A* BH and collisions with other stars (Panamarev+ 19).
- P(orbital) < 12 hours assuming 10 Msun BH, binary separation distance ~ 0.01 [AU] which is consistent with the simulation results.

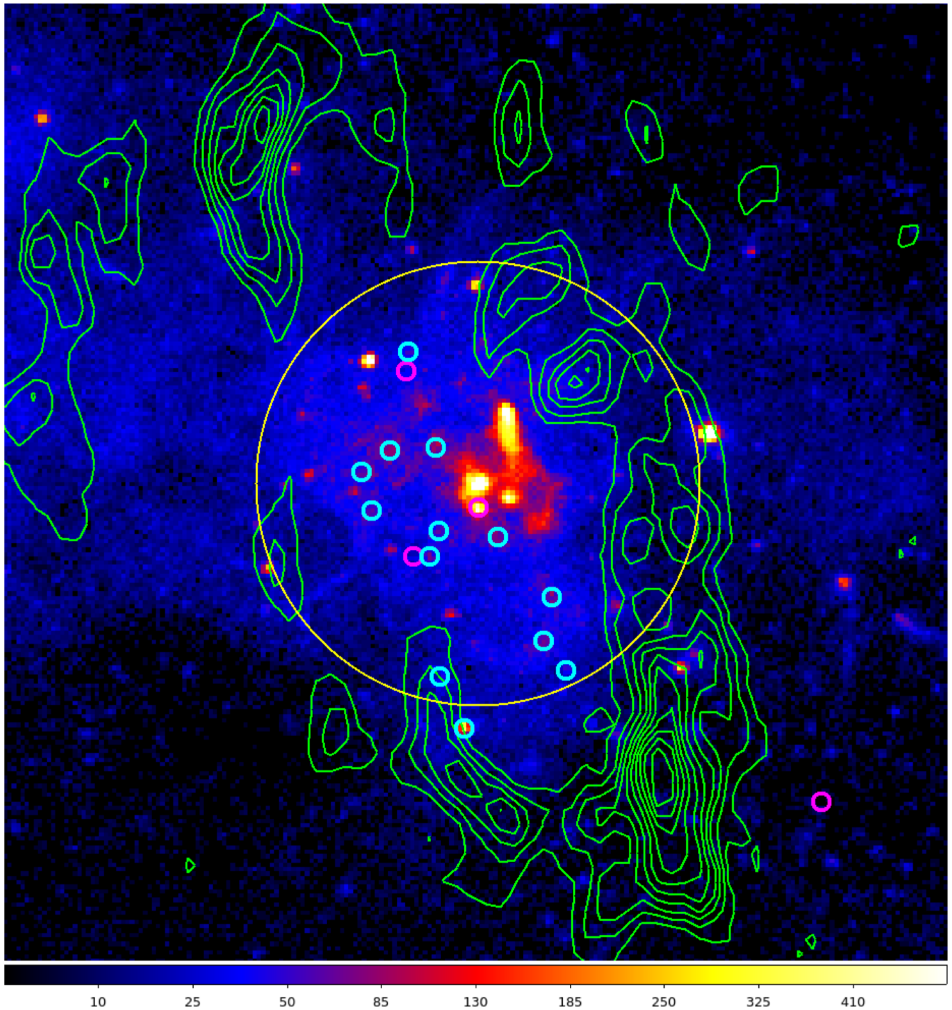


After 5 Gyrs, close binaries (< 0.01 AU separation) are largely populated in the NSC (Panamarev+ 19)

What are the VFXTs?

- VFXTs have smaller accretion rates as their outbursts are fainter.
  - NS-LMXBs with truncated accretion disk (Heike+ 15)
  - Ultra-compact X-ray binaries (UCXBs) with P(orbital) < 1 hour (Hameury & Lasota 16) and H-poor companion
- Some VFXTs in the solar neighborhood have been identified.
  - 7 NS-LMXBs (through type I X-ray burst detections)
  - 2 BH-LMXBs (from dynamical mass measurements) -> they have short (2.8 and 4.1 hour) orbital periods (Corral-Santana+ 13, Wagner+ 01).
- VFXTs in the GC
  - 5 VFXTs in r < 10 pc have short recurrence time (< 5 years). 4 VFXTs at r > 10 pc showed only one outburst but other (fainter) outbursts could have been missed by Swift/XRT due to the poor sensitivity away from Sgr A*.
  - Do VFXTs contain BH or NS or a mixture of them?
  - If they are confirmed as UCXBs, they support the population of tightly-bound X-ray binaries in the GC -> Need long X-ray observation follow-up of the next VFXTs (with XMM).

Spatial distribution of 17 BH-LMXBs is disk-like and aligned with the NSC.



Cyan circles: 13 quiescent BH-LMXBs

Magenta circles: 4 BH transients

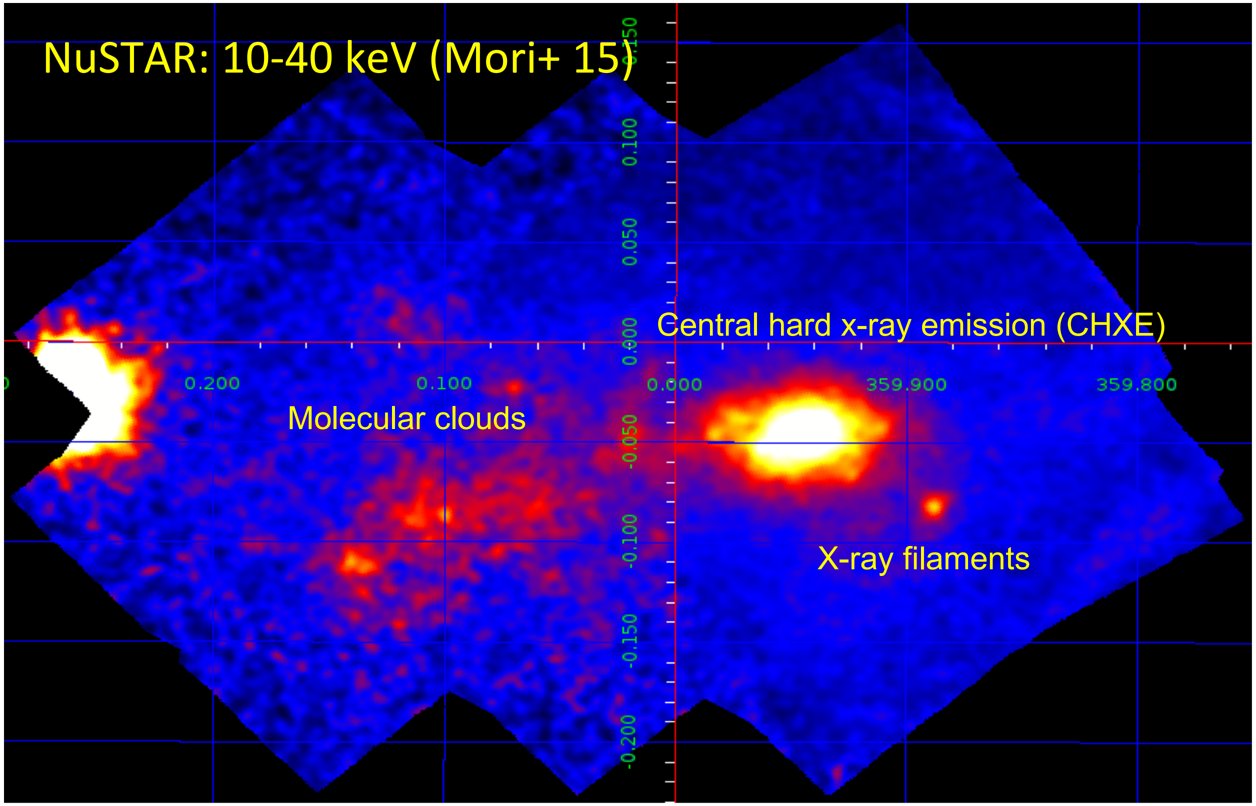
Yellow circle: r = 1 pc around Sgr A*

The spatial distribution of the 17 BH-LMXB is aligned with the NSC (with 95% CL) after taking into account the obscuration by CND (green contours) and bright diffuse X-ray sources [Mori+ in prep].

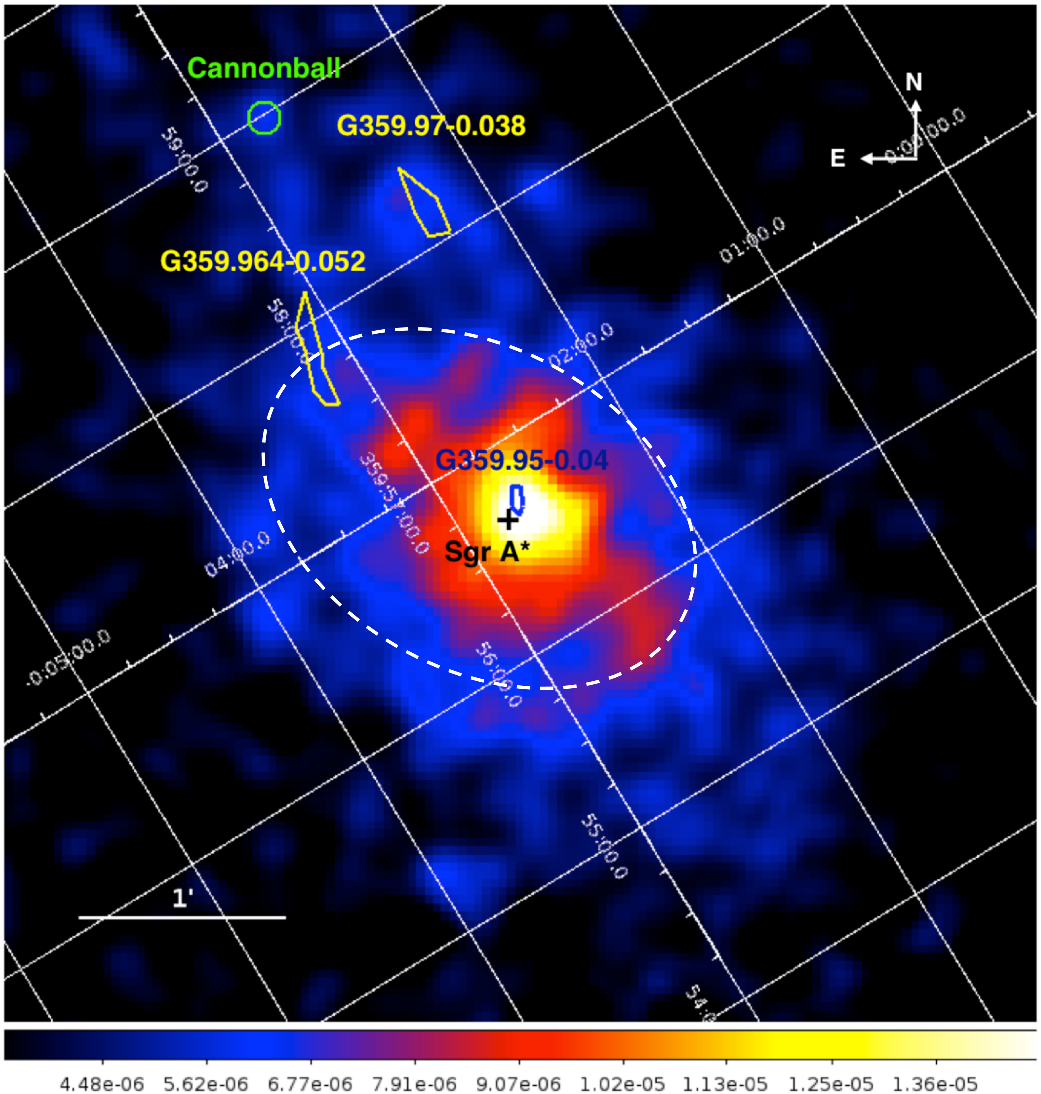
The central 10 parsec region:

NuSTAR resolved diffuse X-ray features in the central 10 pc above 10 keV.

- NuSTAR detected distinct diffuse hard X-ray sources
  1) Non-thermal X-ray filaments
  2) Molecular clouds
  3) Central hard X-ray emission (CHXE) around Sgr A*



NuSTAR discovery of hard X-ray diffuse emission within r < 10 pc

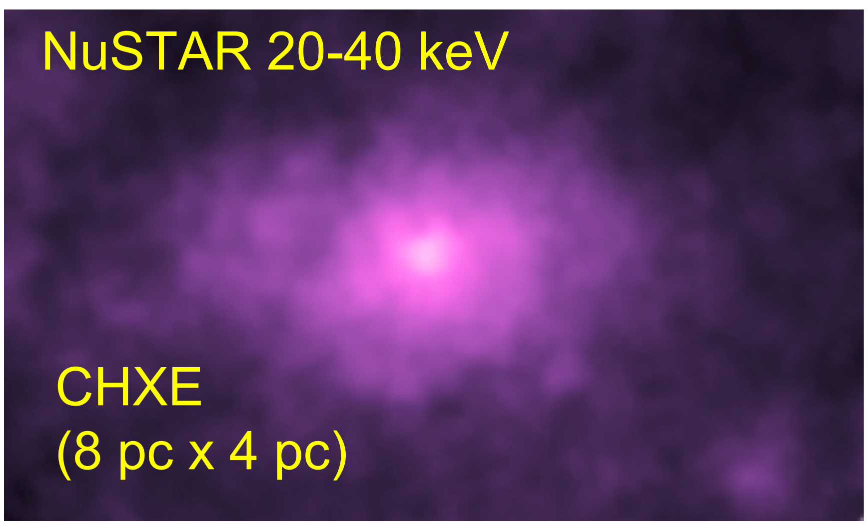


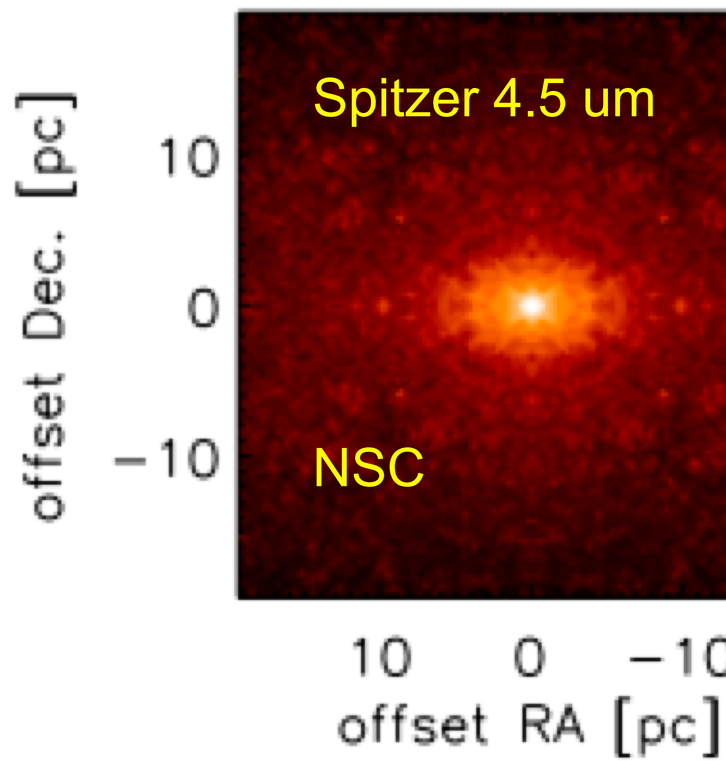
There is a pervasive, diffuse >20 keV X-ray emission from the Galactic Center (Perez+ 15)

- Thermal emission from Sgr A East (kT ~ 1-5 keV) is no longer present
- Only non-thermal filament, Cannonball, and bright central emission remain

CHXE and Nuclear Star Cluster (NSC) have similar spatial distributions.

- The NSC distribution is elliptical and elongated along the Galactic Plane in Spitzer/IPAC 4.5 um image (Schodel+ 2014).
  - Scale length: 4-8 pc (CHXE) vs 4 pc (NSC)
  - Eccentricity: 0.5 (CHXE) vs 0.7 (NSC)
- **The similar morphology to NSC suggests a stellar origin.**

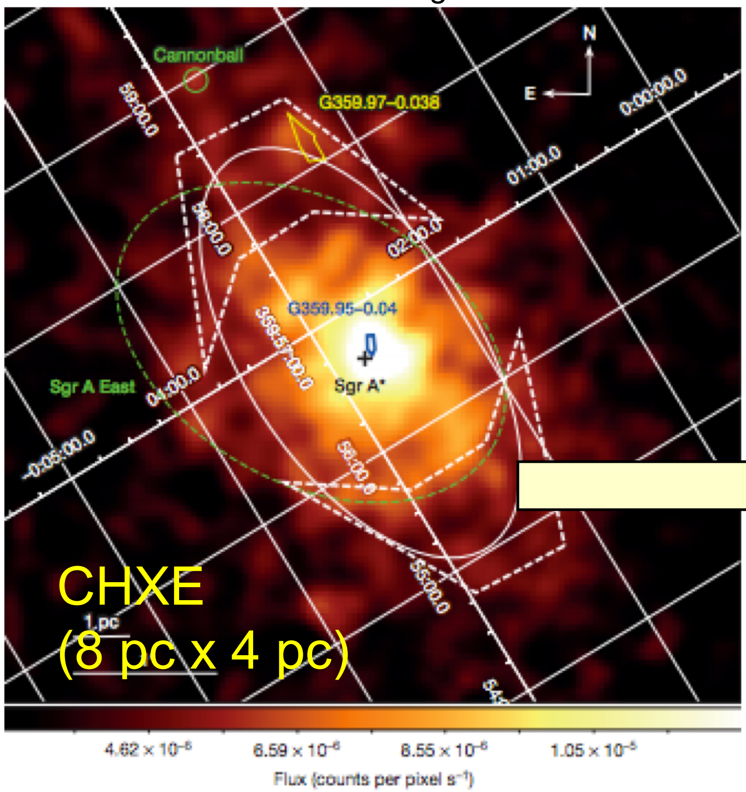




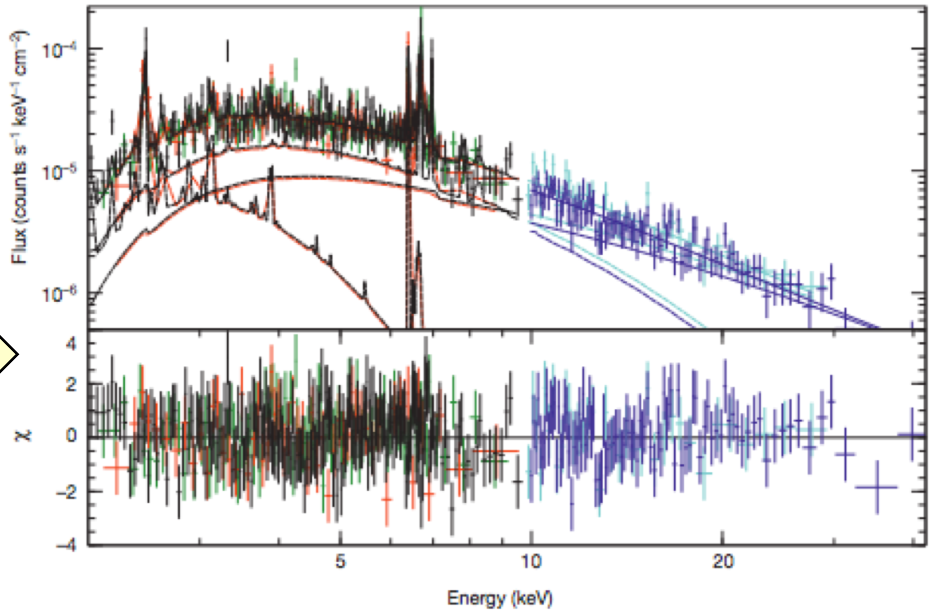
NuSTAR spectrum of the CHXE fits to a thermal model indicating IP origin.

- Broad-band X-ray spectra fit to an optically-thin thermal plasma model (APEC) with kT ~ 35 keV and Fe lines.
- CHXE is NOT a population of BH- or NS-LMXBs.

20-40 keV NuSTAR image of the GC

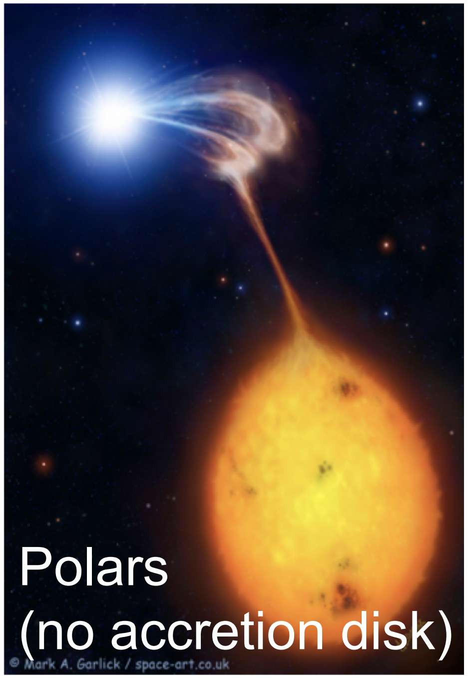


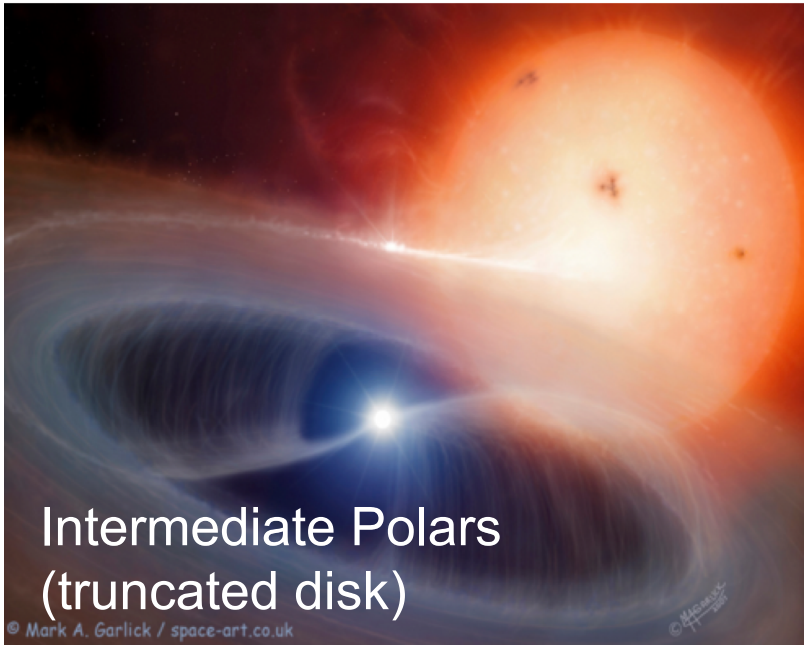
2-40 keV XMM + NuSTAR spectra of the CHXE fit by 3-temperature model with kT = 1, 8 and 35 keV



kT ~ 35 keV suggests CHXE is composed of intermediate polars

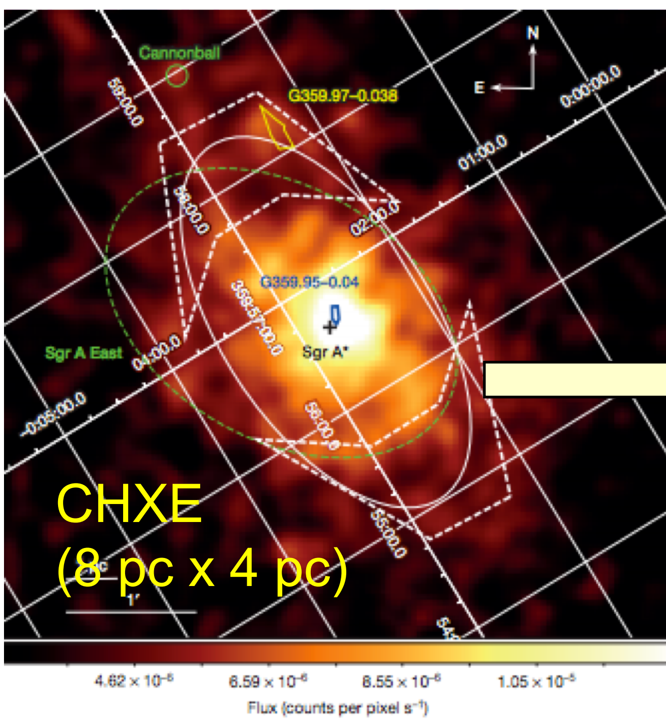
- Non-magnetic CVs (~ 80% of CVs) are faint (Lx < 10^{31} erg/s) and most of them are below the Chandra or NuSTAR detection threshold.
- Magnetic CVs (~20% of CVs) have two types.
  - Polars (B > 10 MG): **kT ~ 5-10 keV**
  - Intermediate Polars (B < 10 MG): **kT ~ 20-40 keV**
- **IPs are harder and brighter than non-magnetic CVs and Polars.**



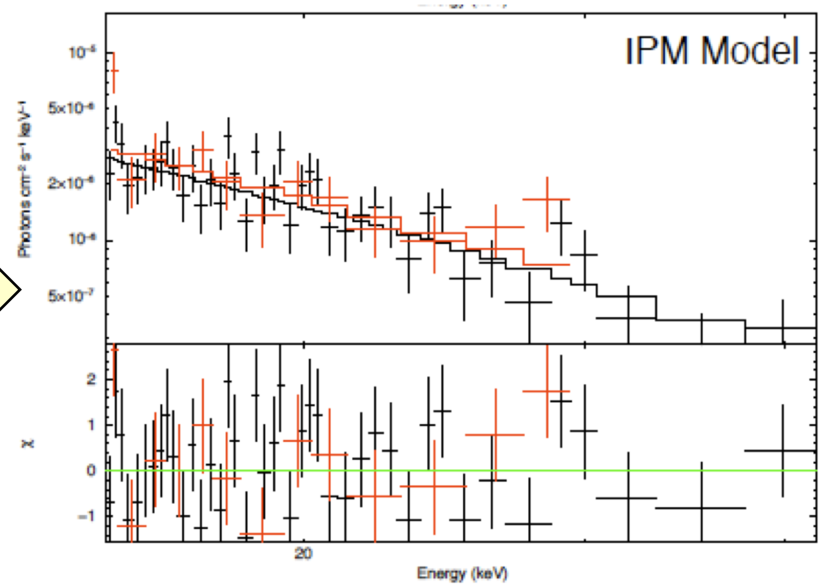


CHXE is an unresolved IP population with white dwarf mass M_{WD} ~ 0.9 M_S

- kT ~ 8 keV for the Chandra GC sources suggests mean M_{WD} ~ 0.5 Ms.
- **NuSTAR spectrum of the CHXE fits to IP model with M_{WD} = 0.9 M_S.**
- The NuSTAR-measured WD mass is consistent with M_{WD} = 0.8-0.9 M_S of local CVs (SDSS, Bernardini 2012+) and local IPs (Zorotovic+ 2012).



NuSTAR CHXE spectra fit in 15-40 keV band yielding M_{WD} = 0.9 M_{solar}. (Suleimanov 2005)

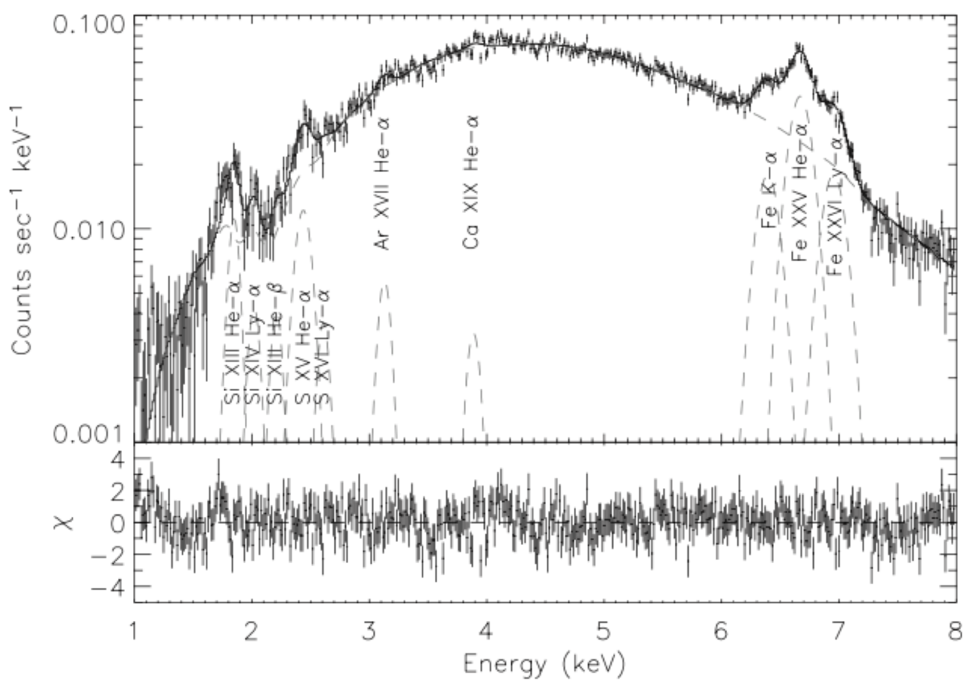


The central ~100 parsec region

A majority of the 9,000 Chandra sources have thermal X-ray spectra

- Chandra detected ~9,000 point sources in the 2-8 keV band above ~10^{31} erg/s detection limit (Muno+ 09).
- Most Chandra sources have **thermal** spectra with apparent kT ~ 8 keV.
- NuSTAR can measure the **true** plasma temperatures beyond kT ~ 8 keV.

Stacked Chandra spectra of the Chandra X-ray sources in the GC (Muno+ 2005)



Two optically-thin thermal plasma models with kT ~ 1 and 8 keV.
Emission lines are clearly visible.

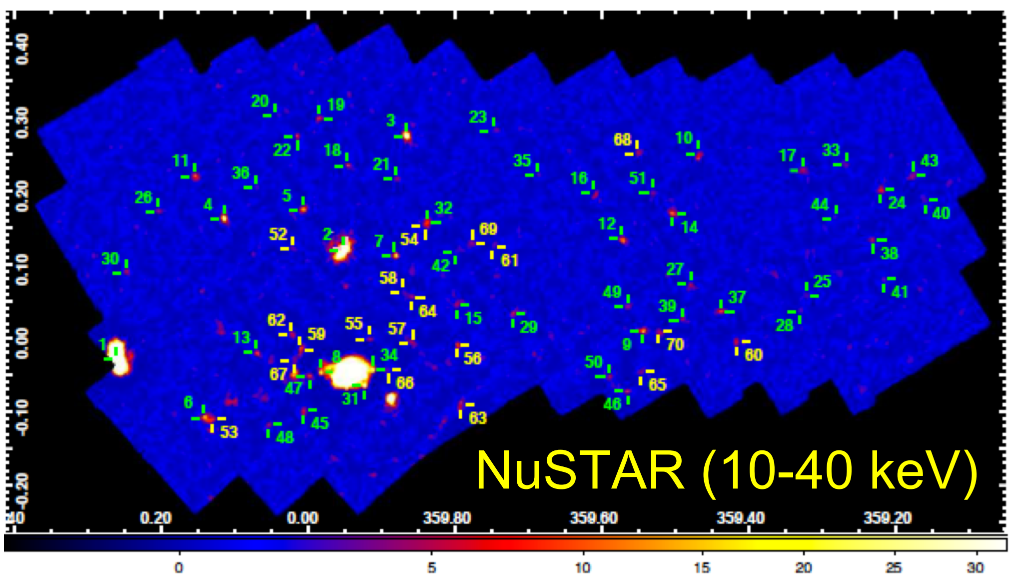
kT > 8 keV?

kT ~ 8 keV?

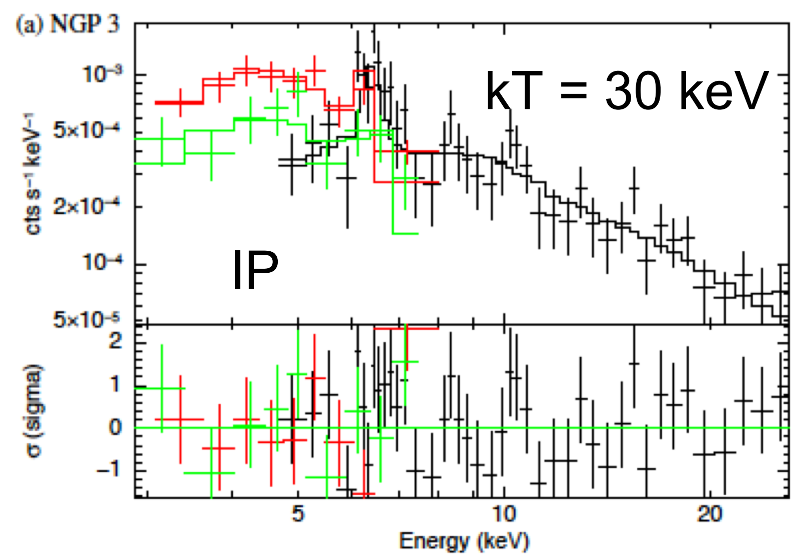
NuSTAR detected 77 point sources above 10 keV; most of them are IPs

- 10-40 keV detection limit : Lx > 8×10^{32} erg/s (at 8 kpc), so all the NuSTAR-detected sources are very bright.
- Hardness ratios of the NuSTAR sources (= $(C_H - C_L)/(C_H + C_L)$) suggest **kT ~ 20-40 keV => Intermediate Polars.**

NuSTAR 10-40 keV image (Hong+ 16)



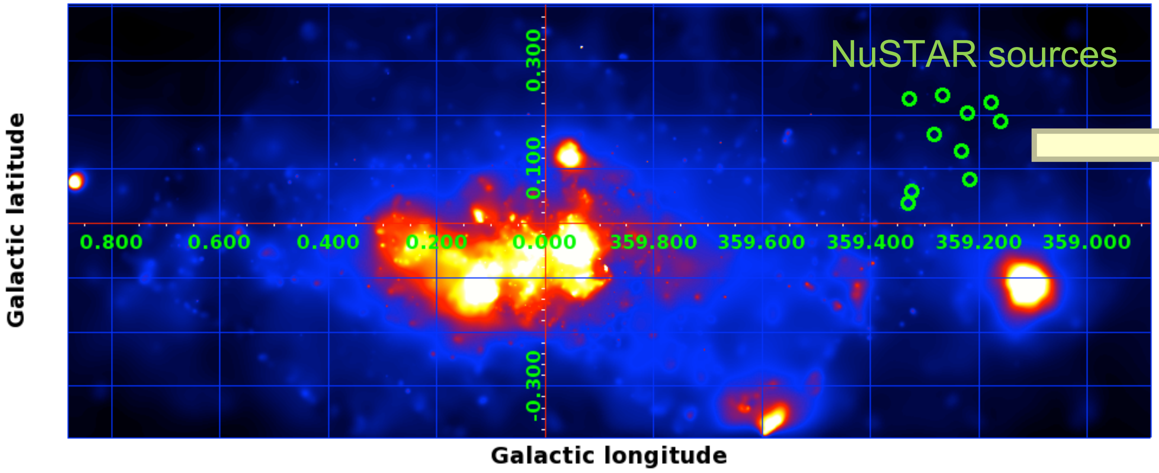
X-ray spectra of NuSTAR source #3

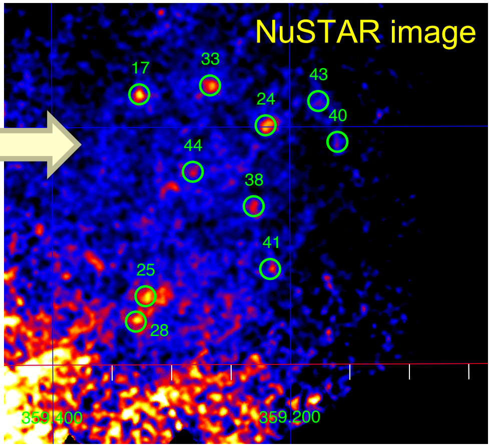


Runaway neutron stars?

- Some of the NuSTAR sources show a hint of non-thermal X-ray spectra.
- If the lack of Fe emission lines should be confirmed by XMM etc., these sources are NS-LMXBs or pulsars.
- Runaway neutron stars ejected from the central parsec region via natal kick (Bortolas+ 17)?

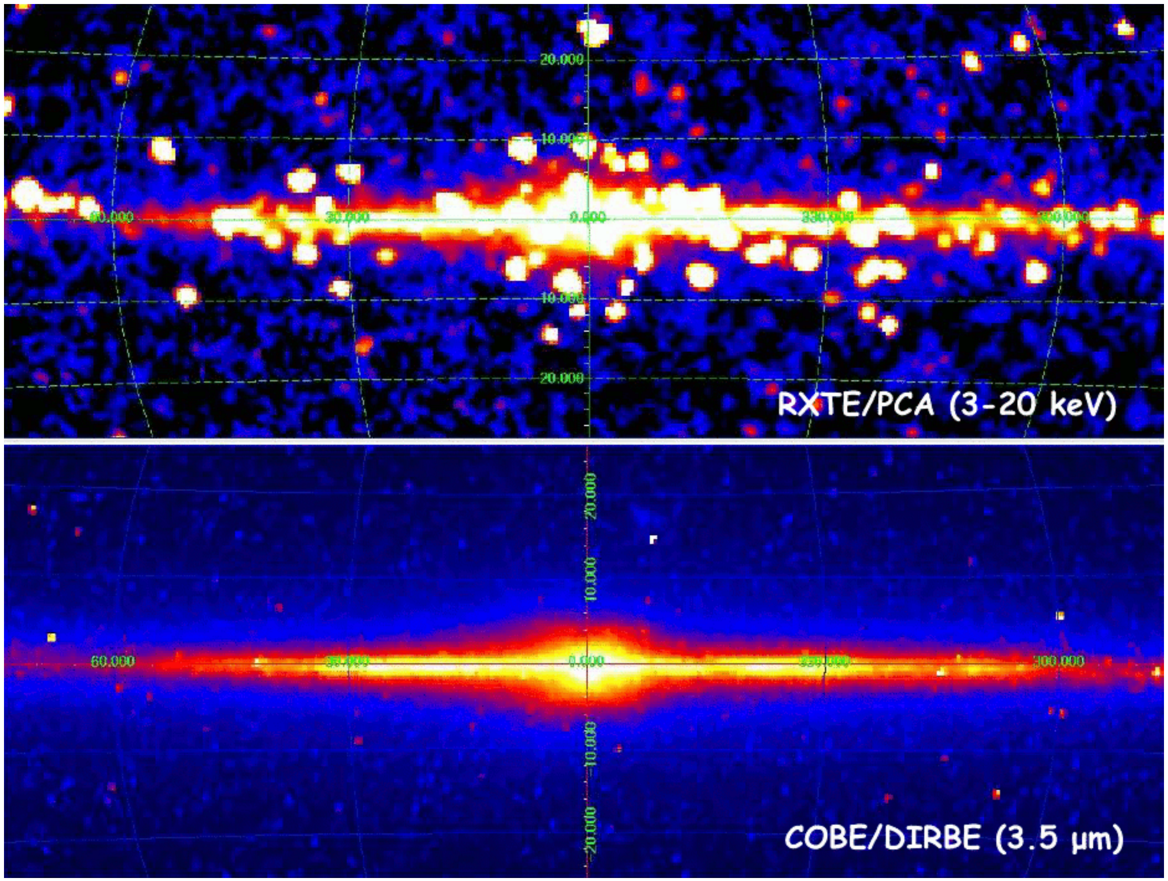
Chandra image of the central 2 x 0.8 deg region





Galactic ridge/bulge X-ray emission

Galactic ridge/bulge X-ray emission

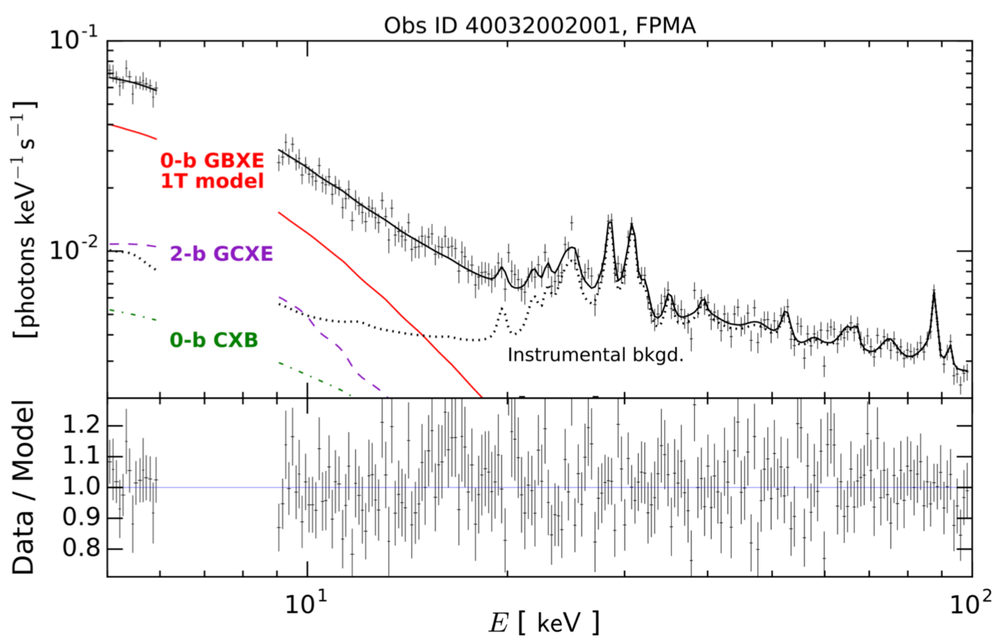


Mike Revnivtsev
1974-2016

"GRXE is not truly diffuse, it follows stellar mass"

Galactic ridge/bulge X-ray emission

- INTEGRAL, Suzaku and NuSTAR surveyed the Galactic ridge/bulge region with broad-band X-ray spectroscopy (Krivonos+ 05, Yuasa+ 12, Perez+ 19)
- The Galactic ridge/bulge X-ray emission shows kT ~ 8 - 15 keV

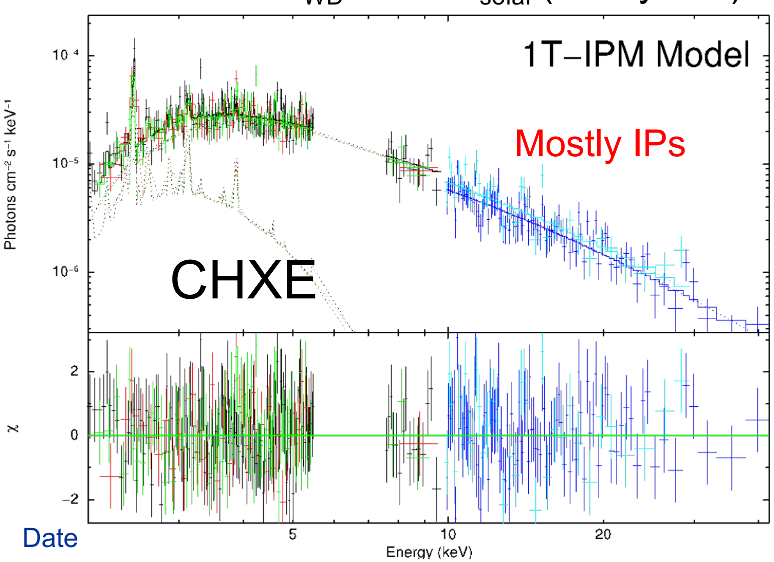


NuSTAR spectra of the inner bulge region, 1-3 deg away from Sgr A* (Perez+ 19)

Distinct CV populations between the Galactic center and ridge/bulge?

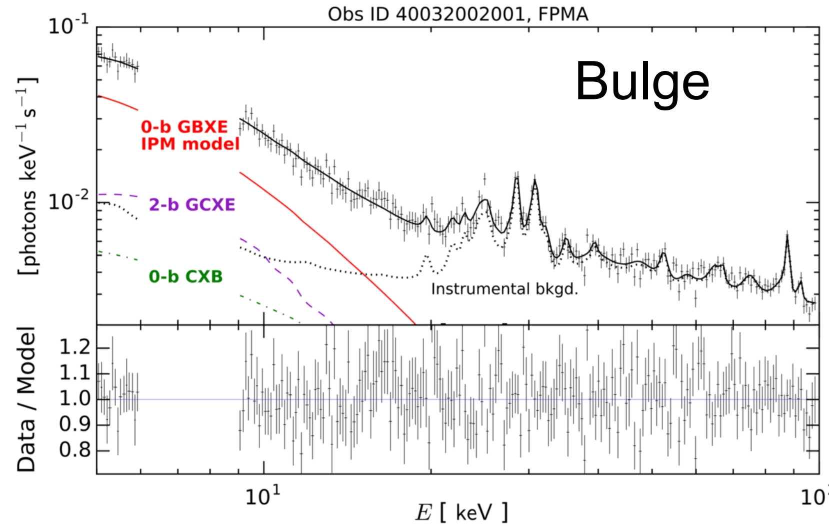
- The Galactic ridge/bulge X-ray emission (kT ~ 8 - 15 keV) is softer than CHXE in the central 10 pc (kT ~ 35 keV).
- Fitting the same IP spectral model yields different white dwarf masses of 0.9 Ms (CHXE) and 0.5 Ms (Bulge).
- The ridge and bulge may be populated largely by dwarf novae (Xu+ 2016) or polars -> CV population transition from r < 10 pc to r > 200 pc?

IP model with M_{WD} ~ 0.9 M_{solar} (Hailey+ 16)

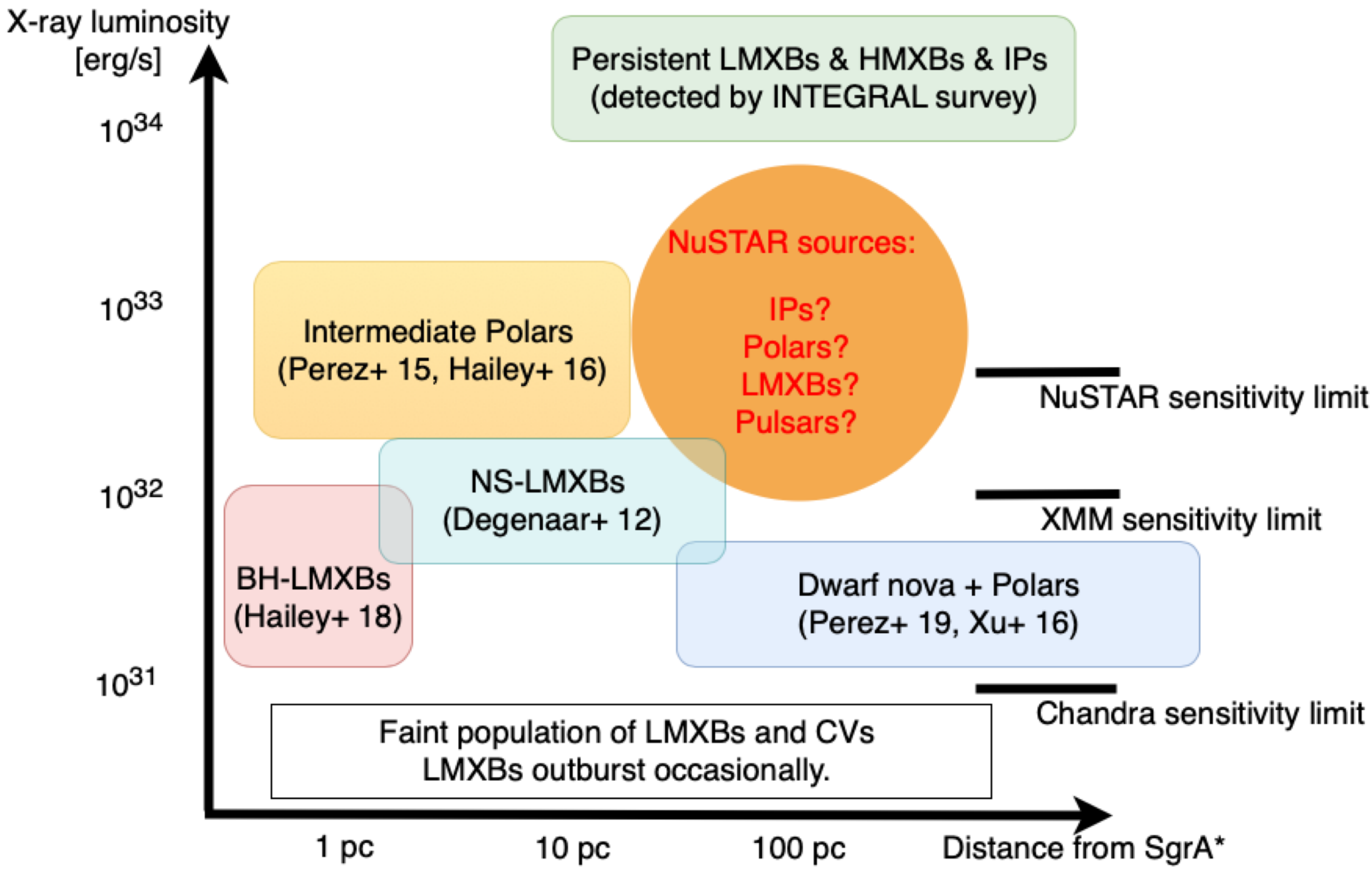


Different source populatio

IP model with M_{WD} ~ 0.5 M_{solar} (Perez+ 19)



What do we know about X-ray source populations in the GC?



Summary

- Deep X-ray survey and frequent monitoring of the GC in the last two decades detected thousands of quiescent X-ray sources and two dozen X-ray transients.
- Their X-ray spectral and timing properties revealed distinct X-ray source populations in the GC.
  - A cusp of 13 non-thermal X-ray sources in the central parsec region indicates a population of 300-1,000 BH-LMXBs.
  - 6 NS-LMXBs have been detected at r < 60 pc, but there could be many more undetected NS-LMXBs with soft thermal emission.
  - A majority of ~9,000 Chandra sources are magnetic CVs.
  - A majority of 77 NuSTAR sources are likely intermediate polars, but some of them may be runaway neutron stars.
  - One transient magnetar (Mori+ 13).
- These results may have implications for:
  - X-ray binary formation near the supermassive BH at Sgr A*
  - Gravitational wave event rates in other galactic nuclei
  - Dark matter vs MSP interpretation of the GeV excess
  - Population of radio pulsars and magnetars in the GC

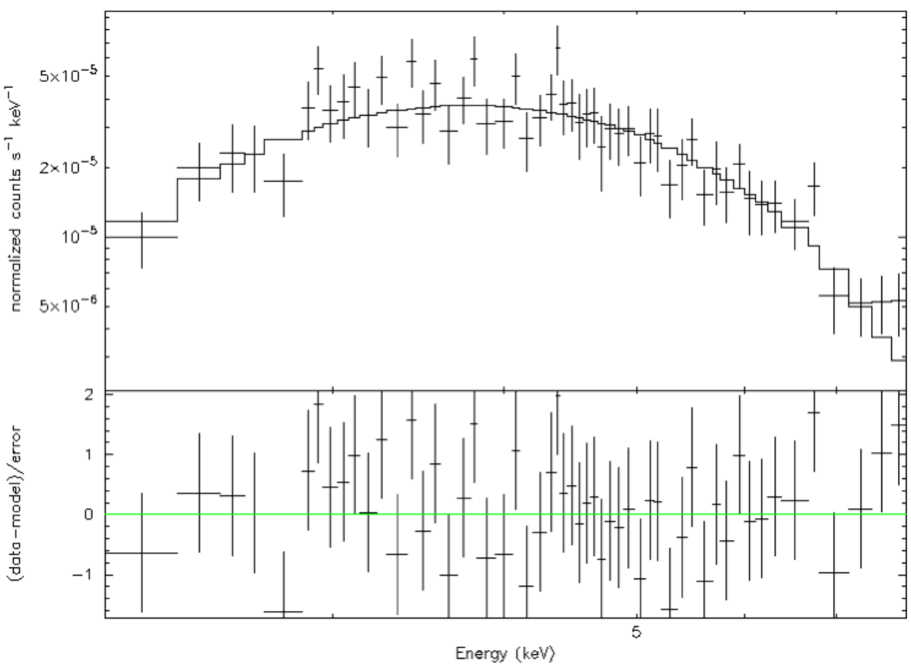
BACK-UP SLIDES

A primer on identifying X-ray point sources

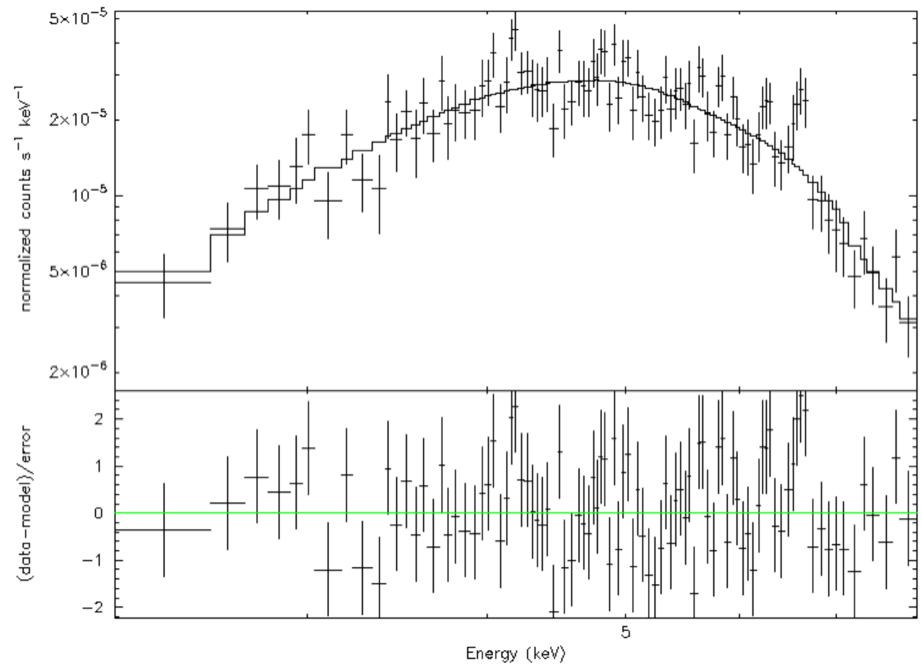
	Lx [erg/s]	X-ray spectrum; other emission	Variability
BH-LMXB	<~ 10^{32}	Power-law (Γ ~ 1.5-2.5); radio emission in hard state	Rarely outburst (recurrence ~ 100-1000 yrs (?))
BH-HMXB	<~ 10^{32}	Power law (Γ ~ 1.5 – 2.5); bright optical, K <~ 13 mag	
NS-LMXB	<~ 10^{32}	Power-law (Γ ~ 1-2)	~3-10 yr outburst recurrence
NS-HMXB	>~ 10^{33}	Power-law (Γ ~ 0) with 10-20 keV cutoff	
MSPs	<~ 10^{31}	BB (kT < 1 keV) + Power-law (Γ ~ 1-1.5)	No long-term variability
mCV (Intermediate polars)	~10^{32}-10^{34}	Thermal (kT ~20-40 keV), with Fe lines	A factor of few variability
mCV (Polars)	~10^{31}-10^{32}	Thermal (kT ~ 5-10 keV) with Fe lines	A factor of few variability?

Soft X-ray sources: stacked ACIS-I and ACIS-S spectra comparison

ACIS-I



ACIS-S



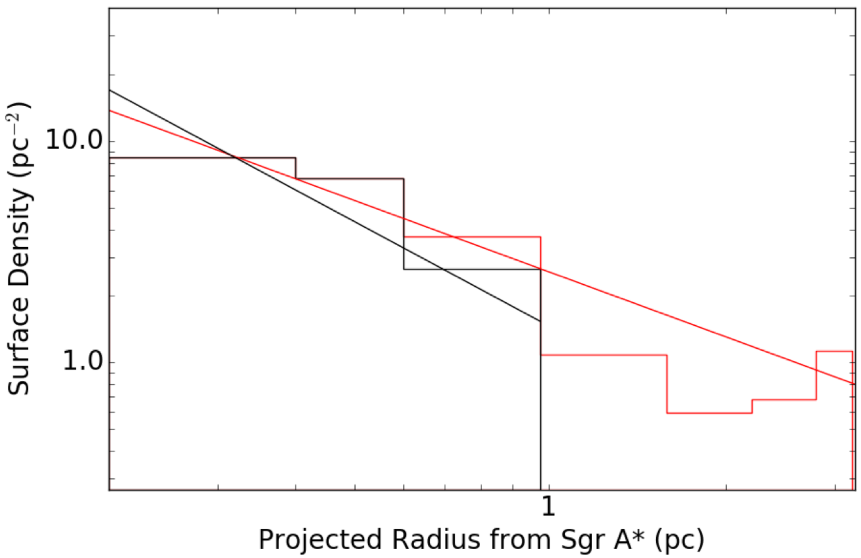
- ACIS-S stacked soft spectra fit well to absorbed powerlaw model (Γ = 1.4 ± 0.2, χ_ν^2 = 1.1 (94 dof))
- Spectra were also fit to absorbed APEC model, but we obtain an unphysically low abundance of 0.1

Three BH transients at <~ 1 pc implies ~30-300 BH binaries, consistent with quiescent source analysis

- The new transients in 2016 bring the total number of BH-LMXB candidates in the central 1 pc to 3.
- # of observed transients in T_{obs} years = N_{total}* ($T_{obs}/T_{recurrence}$)
- How many total BH-LMXBs? In ~ 10+ yrs of continuous Swift monitoring, there are ~ 3 BH-LMXB candidates.
- The total number of BH-LMXBs (in quiescence) is ~ 30-300 depending on recurrence time of ~ 100 or 1000 yrs respectively.

Surface density of BH-LMXBs shows clear evidence of a cusp

- **The density profile shows a cusp with $n(r) \sim r^{-\gamma}$ where $\gamma = 2.4$ +/- 0.3**
- This is consistent with theoretical expectations ($\gamma = 1.3 - 2.3$).
  - Infalling globular clusters (Morris 1993; Miralda-Escude & Gould 2000)
  - BHs are formed from massive stars in disk around Sgr A*, followed by tidal capture on old stellar population. Our result is consistent with numerical simulation (Generozov+ 2018)
- **Hundreds of BH binaries implies lots of isolated BHs, ~10^4 for binary formation rates comparable to globular clusters**

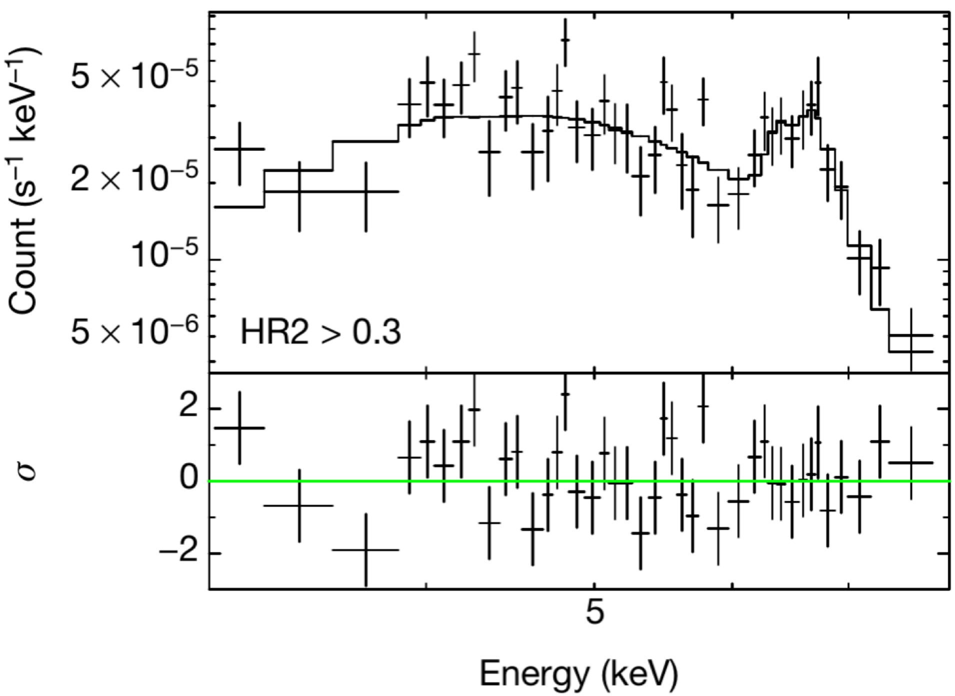


Surface density of the BH-LMXBs

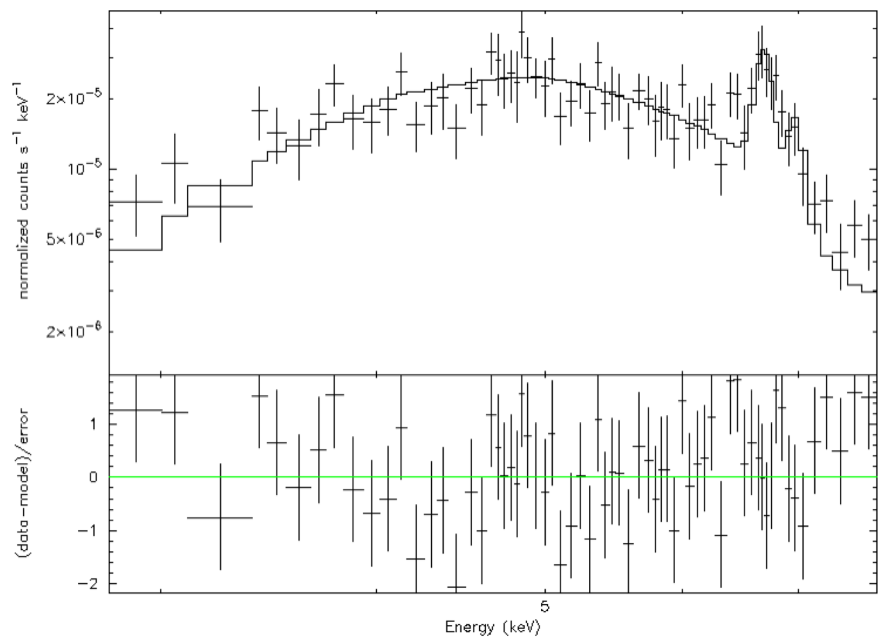
black: sources with > 100 net cts
red: > sources with 50 net cts

Hard X-ray sources: stacked spectra

ACIS-I



ACIS-S



- ACIS-S stacked hard spectra fit well to absorbed APEC model
  - kT = 7.8 ± 1.0, χ_ν^2 = 0.95 (67 dof))
- Compare to ACIS-I stacked hard spectral fit
  - kT = 6.3 ± 1.7, χ_ν^2 = 1.25 (36 dof))

The majority of the 13 soft, non-thermal sources are not MSPs

- **10 out of the 13 soft sources show months to year scale variability.**
  - Quiescent BH-LMXBs are known to be variable, but data is sparse on whether they can also be steady on year time scales.
  - MSPs are steady over these time scales.

- We cannot rule out the MSP scenario for < ~ 31% of the sources.

- Other source types are ruled out.
  - Non-magnetic CV: too soft, too faint and have Fe-line complex
  - Coronal flaring stars and active binaries (e.g, RS CVn): too faint (Sazanov+ 2012)
  - BH-HMXBs: No K < 13 mag stars associated with Chandra sources in the central parsec (Mauerhan+ 2009, Laycock+ 2005).

If a significant fraction of the soft sources are NS binaries, where are the outbursts?

- Assume all VFXTs are NS binaries, and the non-recurring ones at r >> 1 pc are not seen to recur due to intrinsic effects (it is much more likely their non-recurrence is an observing efficiency effect)

- Then if the 13 soft sources at r < 1 pc are NS binaries, the number of bursts N_b expected in ~ 10 years of constant monitoring is N_b >~ N_s*f*T_{obs}/T_{recur}

- T_{recur} ~ 4 years; T_{obs} ~ 10 years; N_s = 13; f = fraction of NS binaries that recur = (6 NSB + 0.5*10 VFXT)/16 = 11/16

- **N_b >~ 22 bursts; observed number of bursts in r < 1 pc = 0**

Neutron Star Binaries in Globular Clusters: Outburst Recurrence is Unknown

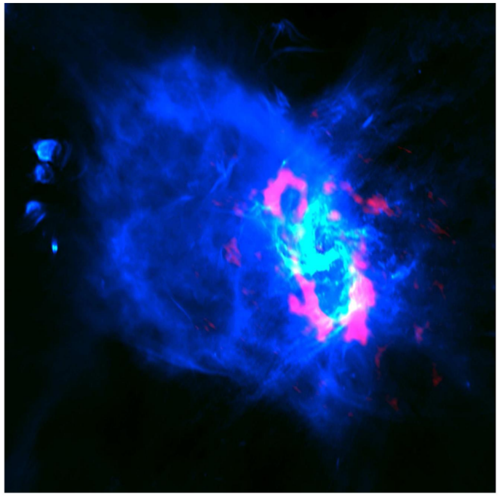
- Few neutron stars in globular clusters have been detected in repeated outburst, probably due to poor efficiency (large observation gaps)
- Swift BAT, MAXI, and INTEGRAL all-sky monitors do not cover the entire sky at all times and have a high luminosity detection threshold, so they could easily miss faint or short-duration outbursts
- Outbursts in globular clusters that have densely-packed unresolved point sources are less likely to be detected as flares by sky monitors
- Outburst recurrence for known neutron stars is erratic => difficult to calculate probability of outburst for period <10-20 yrs
- **All known neutron star transients <u>in the Galactic Center region</u> are repeat bursters**

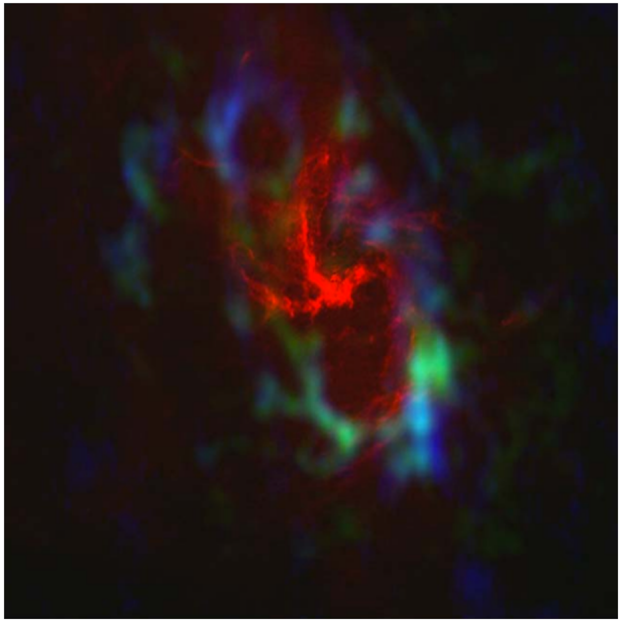
It is difficult to reconcile the soft sources with a NS binary origin

- Since L_x for the 13 soft sources and the VFXT/NSB are comparable, the disk instability model would predict comparable recurrence times unless the mass of the two populations is different
- Generozov, Metzger, Stone and Ostriker (2018) predict NSB/BHB ~ 1, but with wiggle room for NSB factor of 2-3 times lower
- If the 2 new Swift transients are BHB, then NSB(transient)/BHB(transient) = 1 at r < 1 pc
- But if ~1/2 of the soft sources are NSB, why aren't they repeating – dynamical suppression of accretion in NSB in the GC?

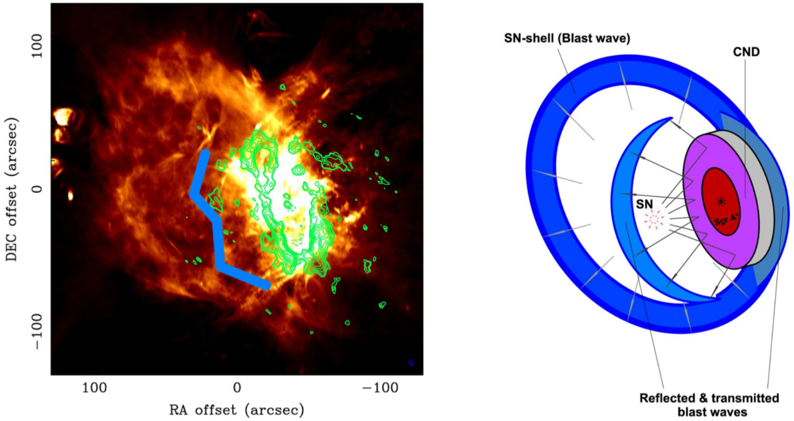
Understanding Sgr A Complex

- Constituents
  - Sgr A* - Supermassive Black Hole
  - Circumnuclear Disk (CND)
  - Sgr A West - “Mini-Spiral”
  - Sgr A East - Supernova Remnant





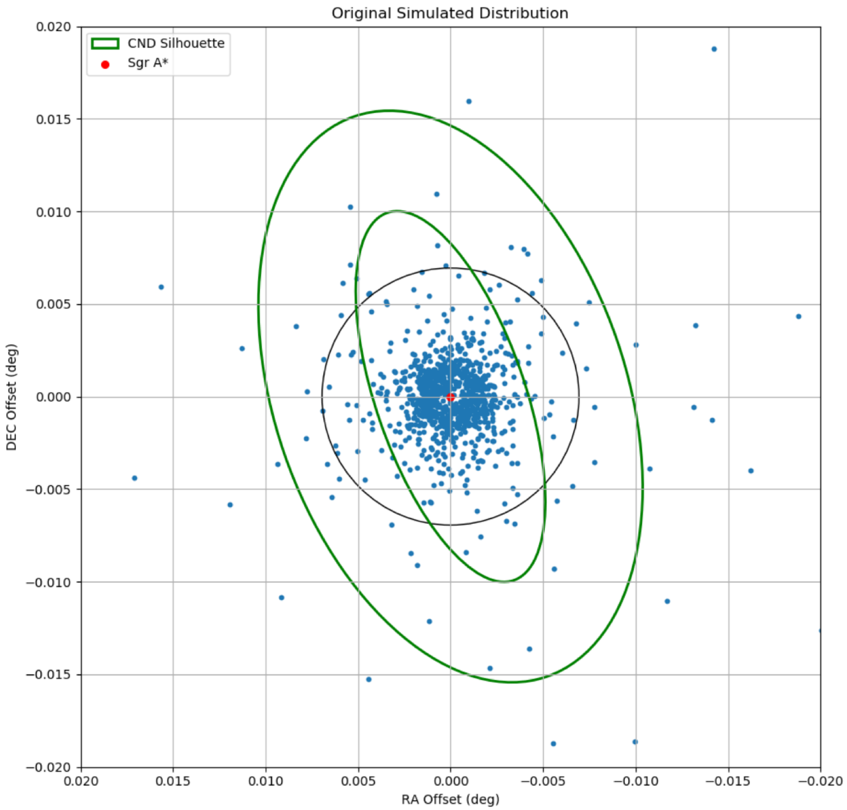
CND and Sgr A West (Genzel et al 2010)

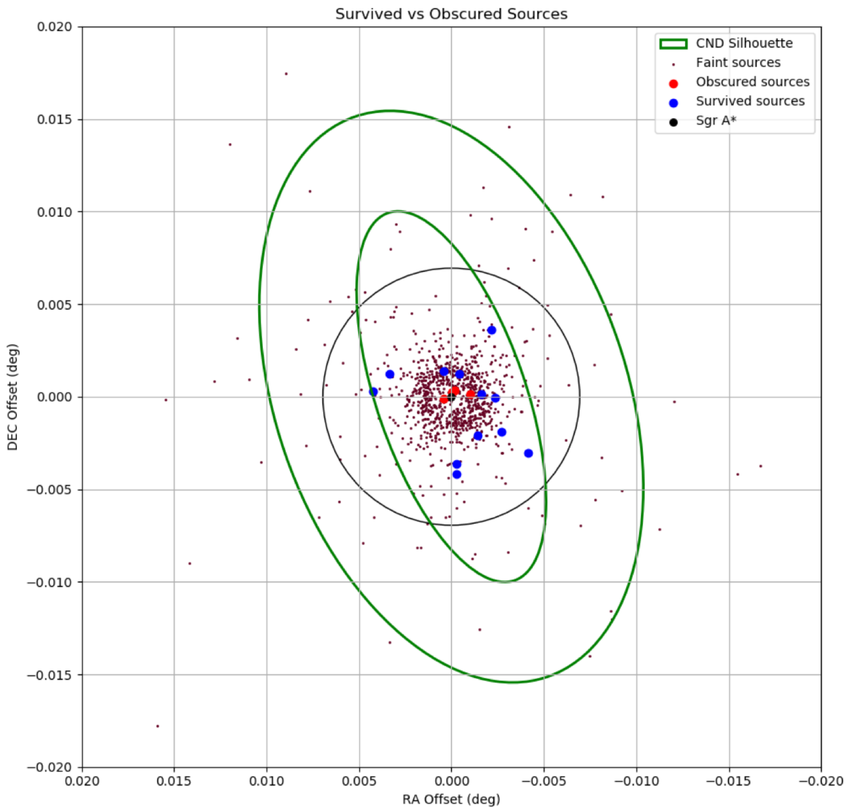


Orientation of Sgr A Complex (Zhao et al 2016)

Monte Carlo simulation to account for observational bias

- Throw out sources from distribution using 3 filters:
  - Observational flux threshold
  - Bright, diffuse emission (e.g. Sgr A*, PWN)
  - Absorption from CND





Black hole binary physics

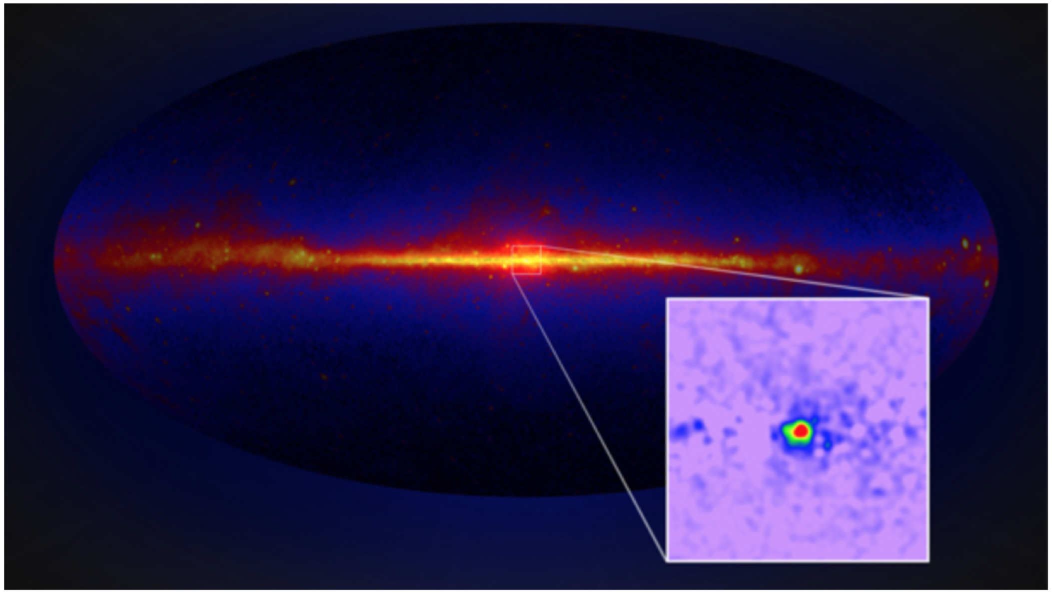
- Hopman (2009): 3-body exchange to form BHB was overestimated by Muno et al. (2005).
- Dominant source of BHB in GC is tidal capture
- Previous estimates of isolated BH in GC based on BH in globular cluster infall (which also provides old stellar population)
- More recent calculation of Generozov et al. (2017) assume BH are formed from massive stars in disk around Sgr A*, followed by tidal capture on old stellar population
- Hundreds of BH binaries implies lots of isolated BH, $\sim 10^4$ for binary formation rates comparable to globular clusters

Neutron Star Binaries in Globular Clusters: NuSTAR

- Few NS-LMXBs in globular clusters have been detected in repeated outburst; different behavior/environment than GC, or poor efficiency?
  - Literature review shows large gaps between observations
- Difficulties detecting outbursts in globular clusters with Swift BAT, MAXI, and Integral all-sky monitors:
  - Each covers only about 1/3 of the sky at any given time
  - Occasionally eclipsed by Earth, blocking view of the stars
  - High Luminosity threshold (~10^35 erg/s) for detection
  - Would not detect fainter outbursts, may miss short-duration outbursts even if bright
  - Sources densely packed & unresolved in most globular clusters => outbursts not detected as flares if integrated luminosity of entire cluster doesn't change significantly
- Known NS-LMXBs in globular clusters:
  - Some (repeat) bursts detected during planned pointing observations through sheer good luck (Terzan 5 and NGC 6440); some bursts detected by all-sky monitors
  - 3-5 NS qLMXBs in 47 Tuc are weakly persistent/non-transient, but low M-dot and large gaps in observations ('05-'14); may have missed outbursts
- Outburst recurrence for known NS-LMXBs is erratic => difficult to calculate probability of outburst for period <10-20 yrs

≲ 1/3 of the soft sources in the central parsec can be millisecond pulsars

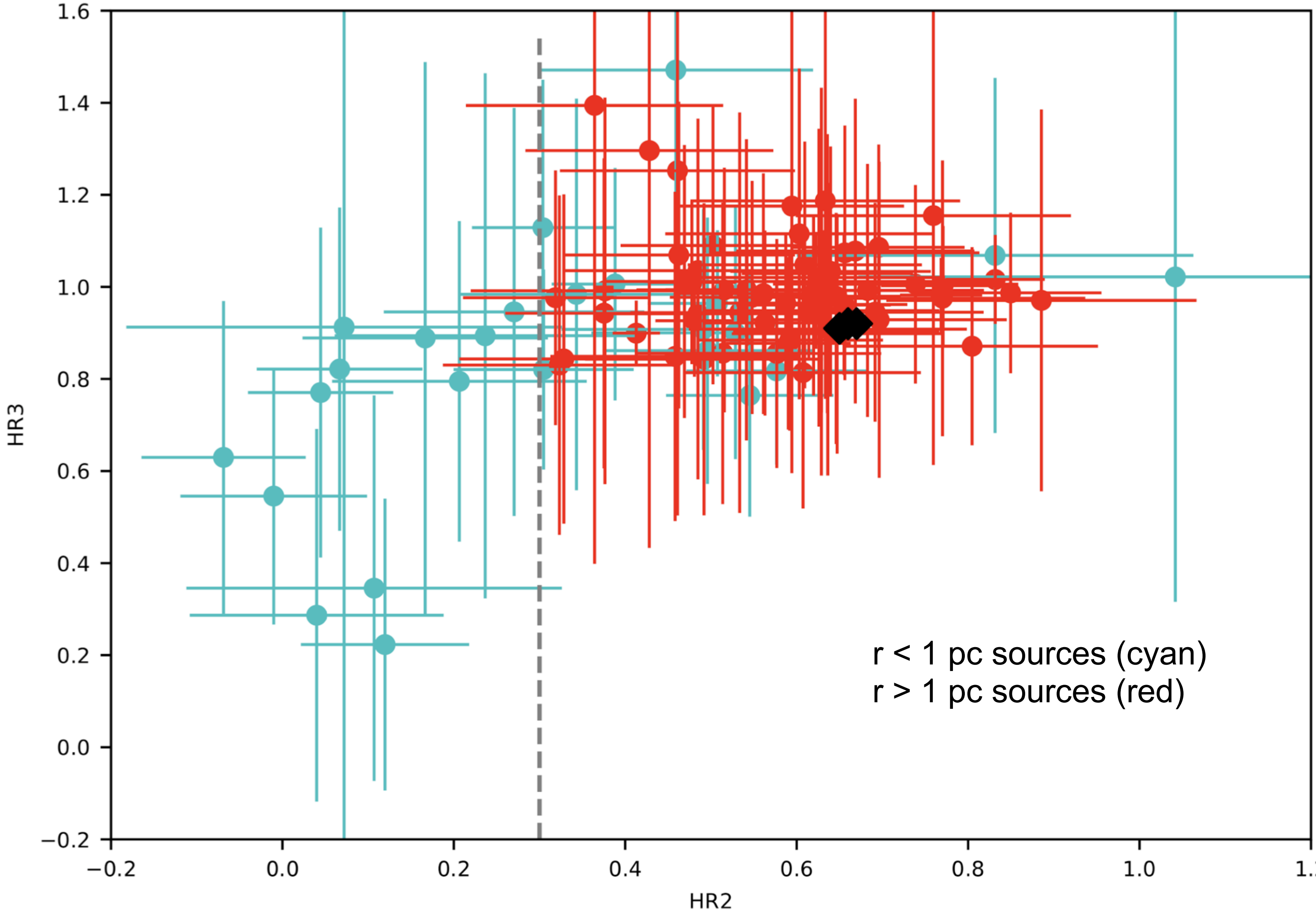
- ≲ 6 of the 12 soft sources with no time variability can be MSPs.
- Use Lx vs spin-down power (Edot) correlation of a large sample of MSPs; a fraction of MSPs above the Chandra detection limit ~ 3%.
- This implies <~ 6/0.03 ~ 200 MSPs in the central parsec.
- Implications for MSP population in the Galactic bulge and the GeV gamma-ray excess?



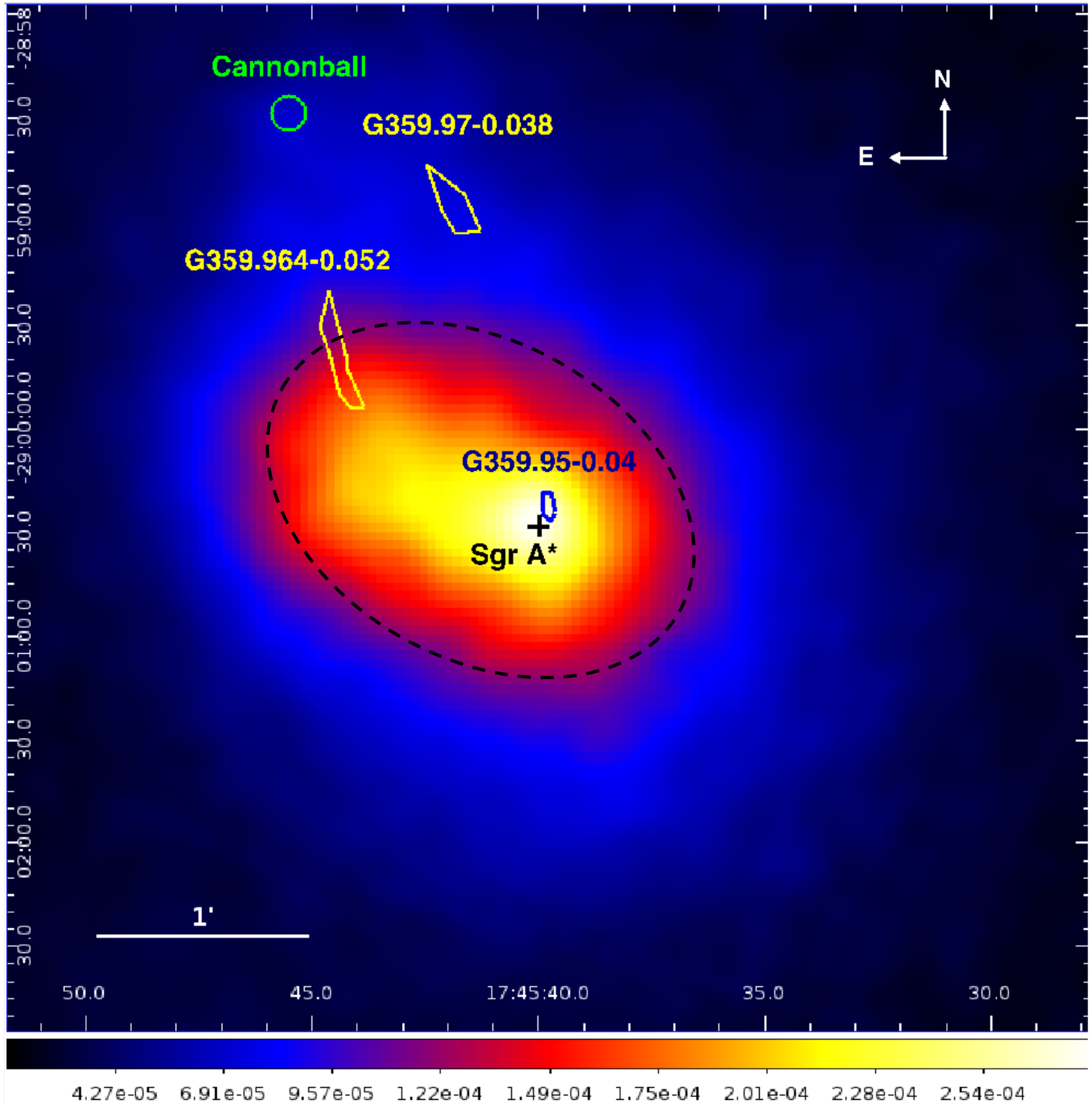
GeV gamma-ray excess in the Galactic Center: MSPs or Dark matter?

The total Fermi-LAT gamma-ray excess map with an inset showing the apparent GeV excess surrounding the Galactic Center. (Credit: NASA/T. Linden, U.Chicago) + Learn More

Dust scattering cannot turn hard HR2 > 0.3 sources into HR2 < 0.3 soft sources unless there is low column density, as indicated by HR3 < 0.6

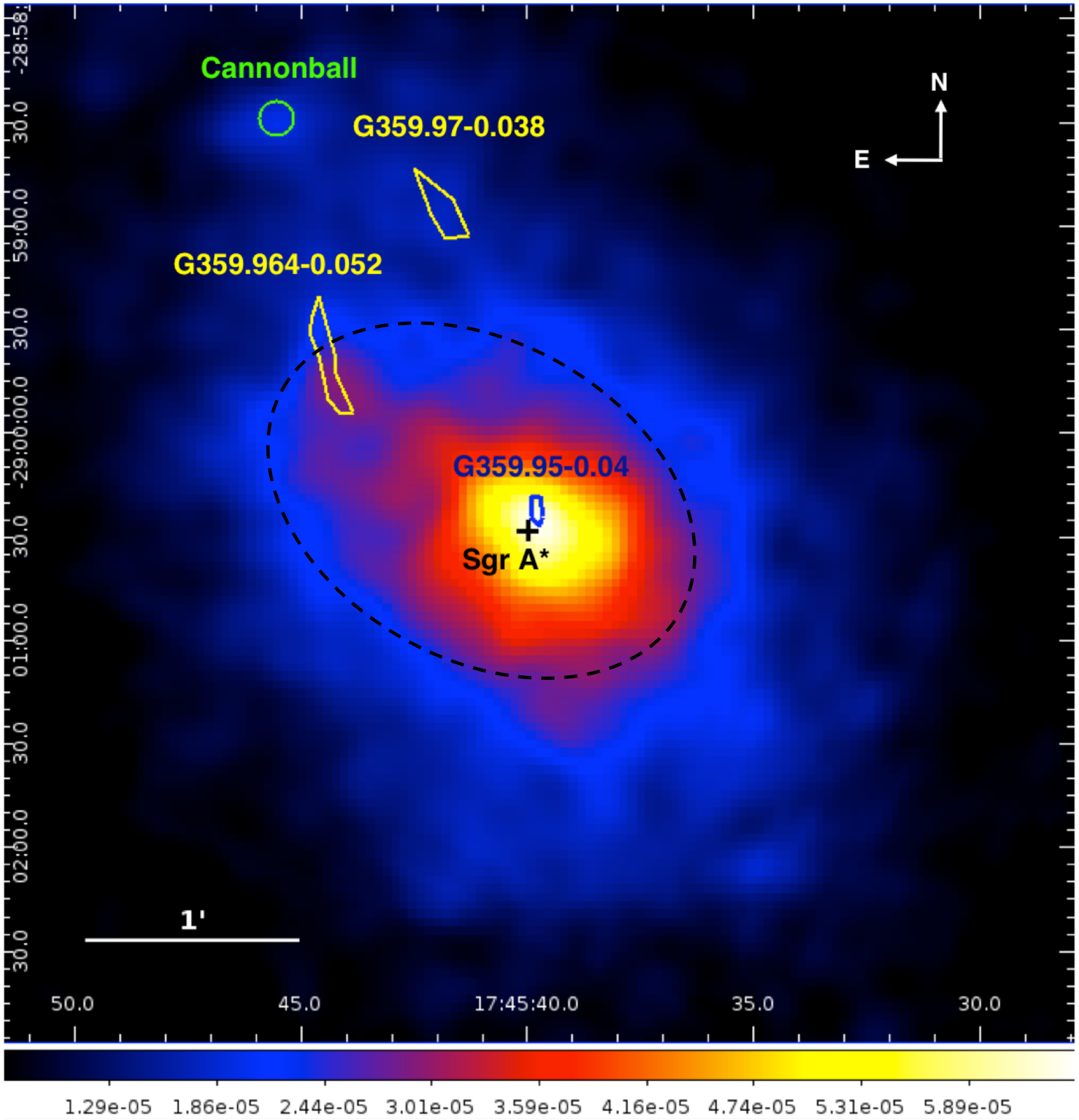


NuSTAR 3-10 keV image



- The brightest emission (white) comes from the hot plasma surrounding Sgr A* and the PWN 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)
- The entire region sits in a field of diffuse and unresolved point source emission (dark blue)

NuSTAR 10-20 keV image



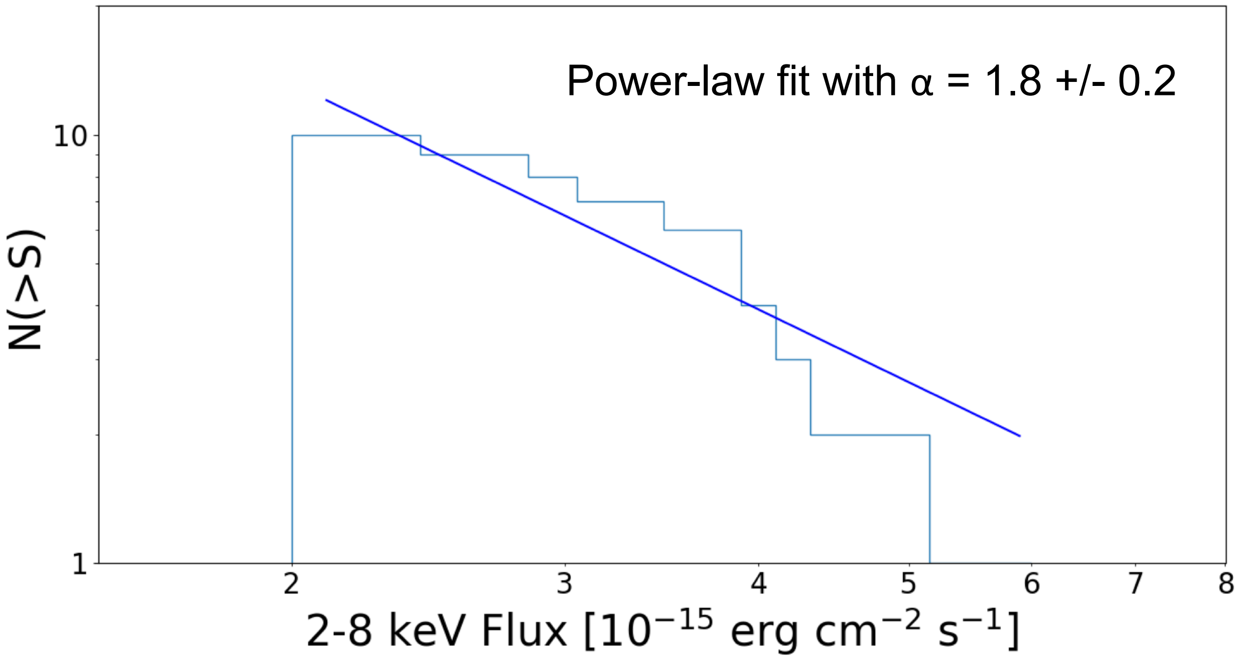
- Emission from near Sgr A* and G359.95-0.04 still dominates

- Dimmer, but persistent emission inside the Sgr A-East shell

- The "Cannonball" neutron star (Nynka 2013) and the non-thermal filaments G359.954-0.052 and G359.97-0.038 (Nynka . 2014)

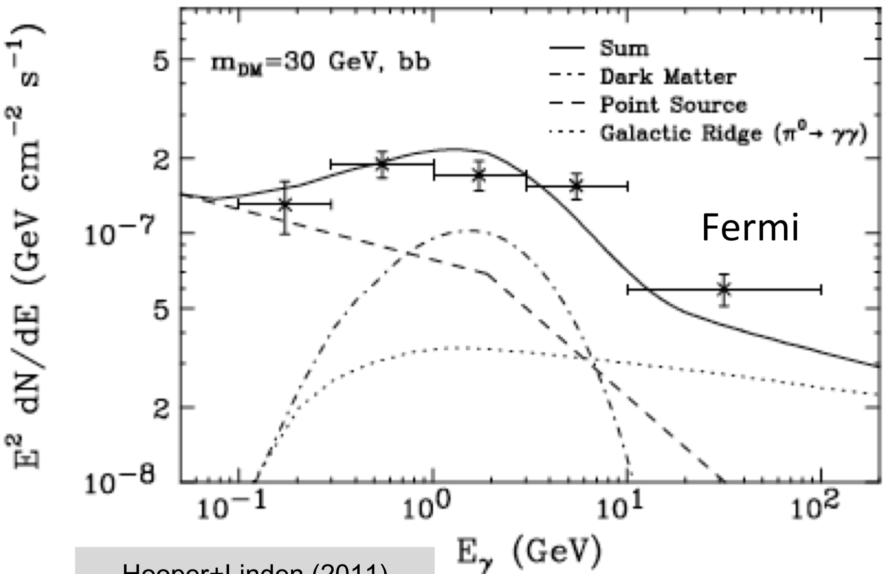
logN-logS of the soft sources inside 1 pc yields <~500-1000 BH-LMXBs

- There may be more fainter BH-LMXBs below our threshold (C > 100).
- Our logN-logS distribution is consistent with that of local, dynamically identified BH-LMXB (α = 1.4 +- 0.1, Padilla+ 2014).
- Extrapolating logN-logLx to the minimum Lx (~10^{30} erg/s) of local BH-LMXBs => **<~500-1000 BH-LMXBs in the central parsec**



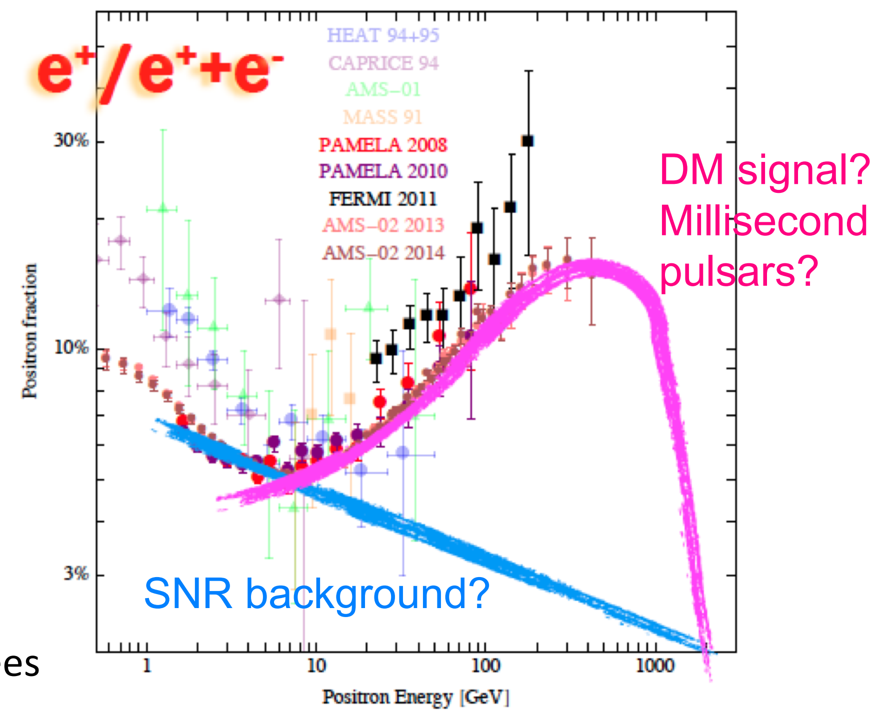
Millisecond pulsars are at the center of the dark matter controversy

γ-rays from the Galactic Center



Hooper+Linden (2011)

M. Cirelli (TAUP 2015)

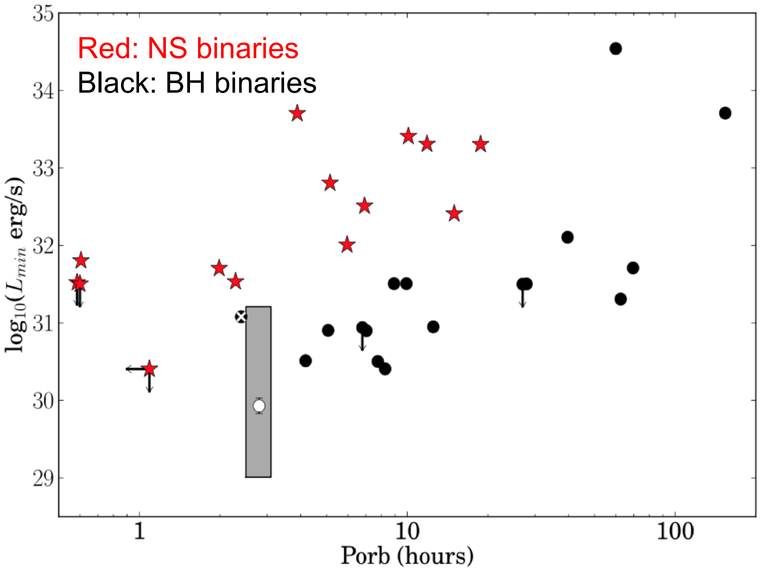


Spectrum of gamma-rays in central tens of degrees of Galaxy consistent with dark matter…but also millisecond pulsars…But are there enough of them?

A rationale for long recurrence times may be found in the disk instability model plus luminosity-period correlation

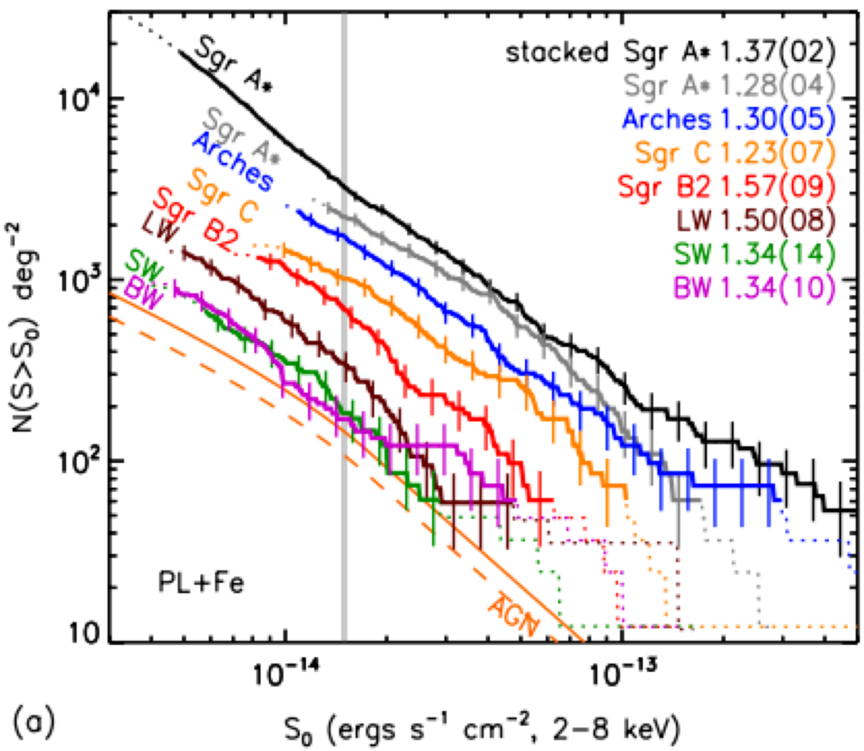
- Low X-ray luminosity correlates with long outburst recurrence time in disk instability model (Coriat+ 2012)
- The qBH-LMXBs we observe are all low luminosity
- But why do these qBH-LMXBs have low X-ray luminosities?
- The short orbital period (and thus small orbital radii) correlates with the hardening (decreased orbital radius) of binaries near the SMBH (hard binaries get harder, and soft binaries get softer – and evaporate)

Padilla+ 2014



Background AGNs are negligible

- We can use the measured logN-logS curves for AGNs and estimate number of AGNS in a given region above the flux threshold (~ 10^{31} erg/s).
- <u>0.03 AGN (F > 1e-14) or 0.1 AGN (F > 3e-15) is expected within a r=25” circle.</u>



Hong et al. 2012