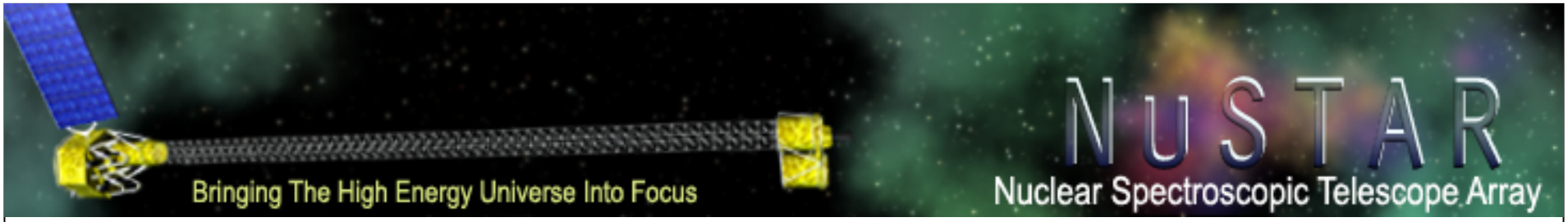

NuSTAR Observation of Galactic Center Molecular Clouds: Reconstructing Sgr A X-ray Outbursts*

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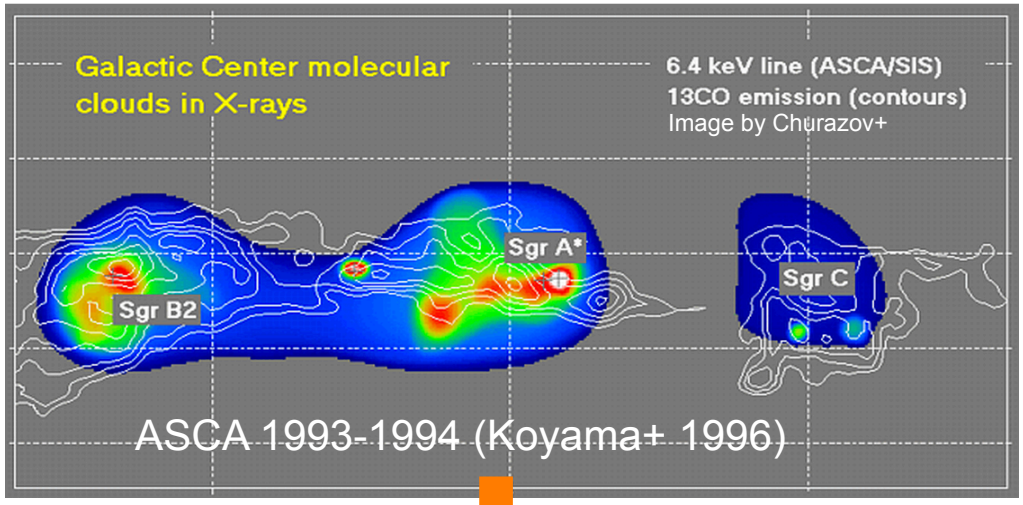
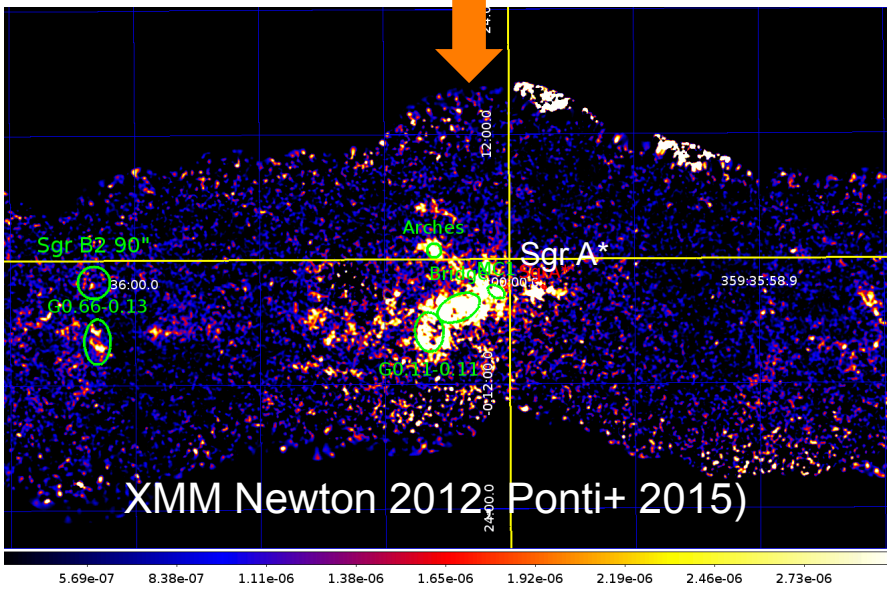
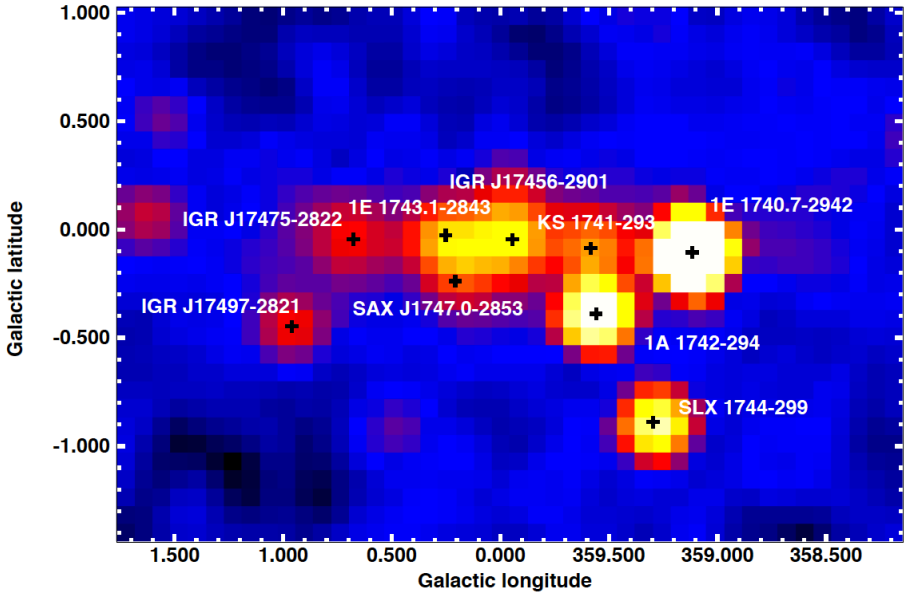
GC Molecular Clouds in X-rays: Fe Kα line + Continuum emission



- GCMCs emit 6.4 keV line + continuum emission up to 100 keV.
- Previous studies focused on the 6.4 keV line emission.
- The continuum emission > 10 keV was not resolved by Integral.





X-ray Reflection Nebula (XRN) vs. Low Energy Cosmic Ray Electrons (LECRe) or protons (LECRp)?

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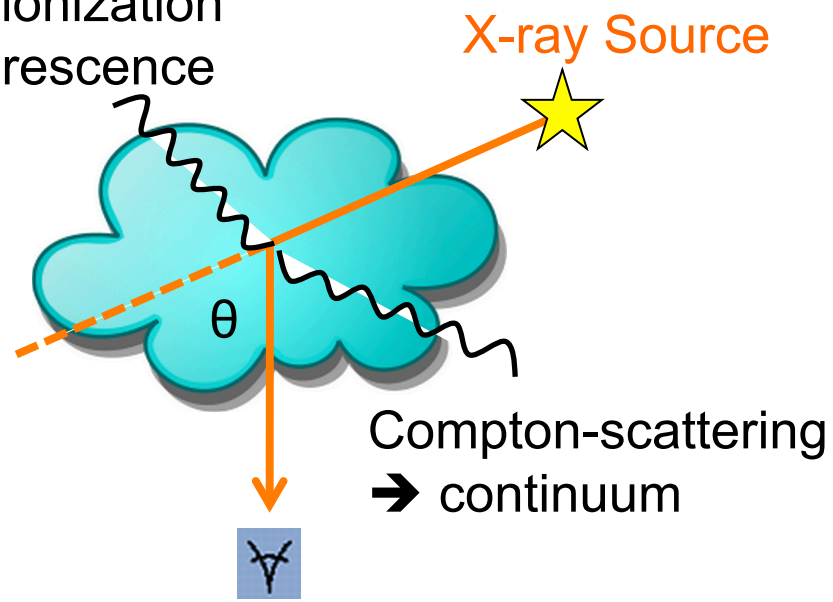
NuSTAR

XRN

Photo-ionization
➔ fluorescence



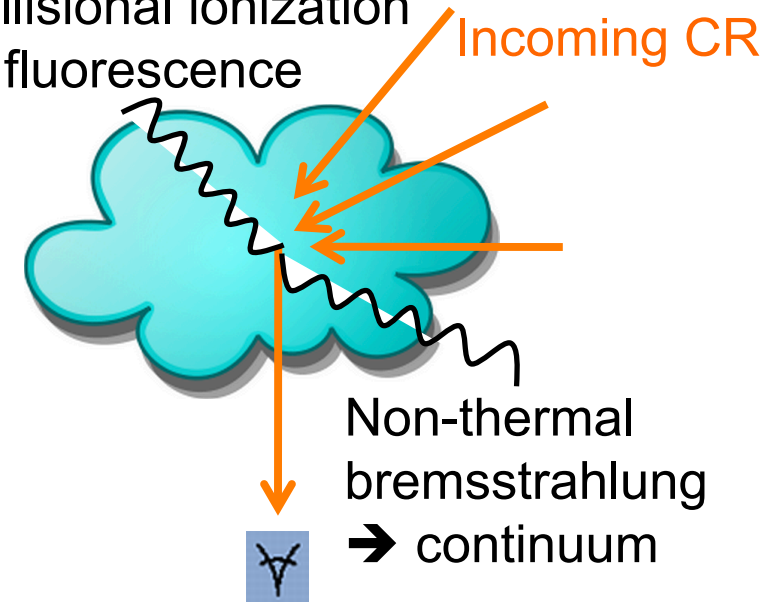
Reflecting a giant Sgr A* X-ray flare

Model Signature:

1) Variability on timescale of ~1-10 yrs
2) Fe Kα equivalent width ~ 1 keV
3) 7.1 keV Fe K absorption edge
4) Compton reflection hump

LECRe/LECRp

Collisional ionization
➔ fluorescence



Cosmic rays from

Model signature:

1) A power-law spectrum
2) Variability over electron cooling/ diffusion time (LECRe) or proton cooling time of >100 yrs (LECRp)

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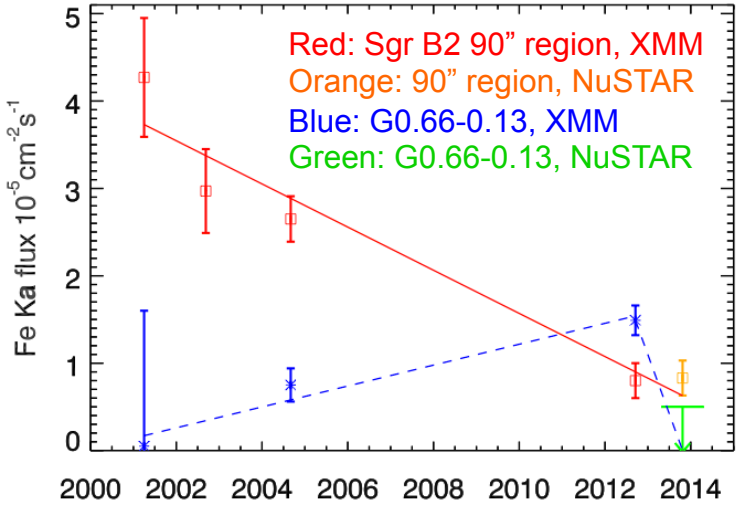
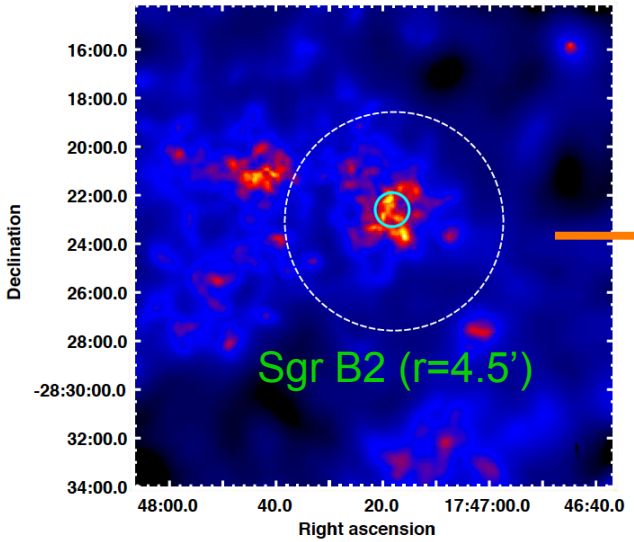
Sgr B2: Best Manifestation of XNR

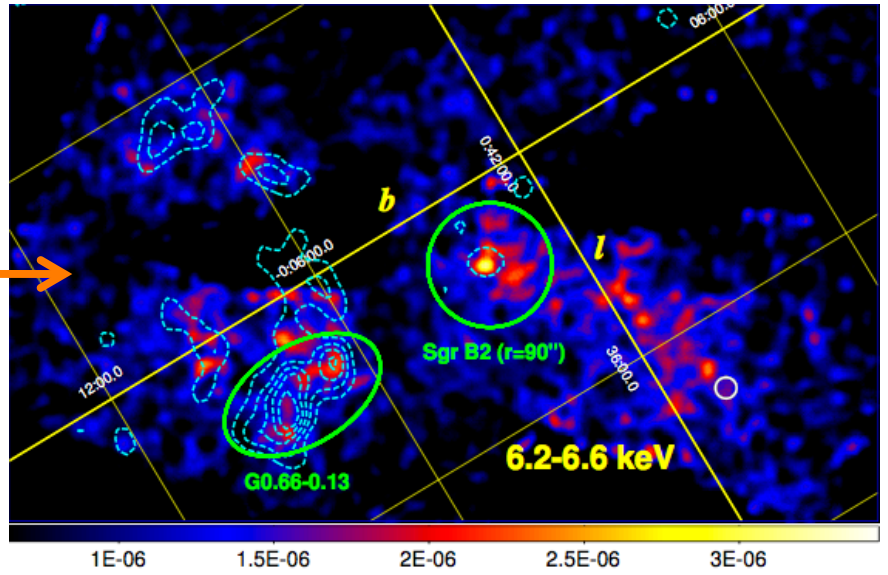


- Sgr B2 is the densest and most massive GMC in CMZ.
  - -- The Fe Kα emission is fading since ~2001.
  - -- Still decreasing or has reached background level?
  - -- G0.66-0.13 is a newly emerging cloud feature with maximum flux observed in 2012, and quickly diminished in 2013.

← Sgr B2 Fe Kα emission variability (Zhang+ 2015)



XMM Fe Kα map of Sgr B2 in Sep. 2004 (Terrier+ 2010)



NuSTAR Fe Kα map of Sgr B2 in Oct. 2013 (Zhang+ 2015)

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First time to resolve Sgr B2 on sub-arcmin scales > 10 keV by NuSTAR

- Two prominent features detected:

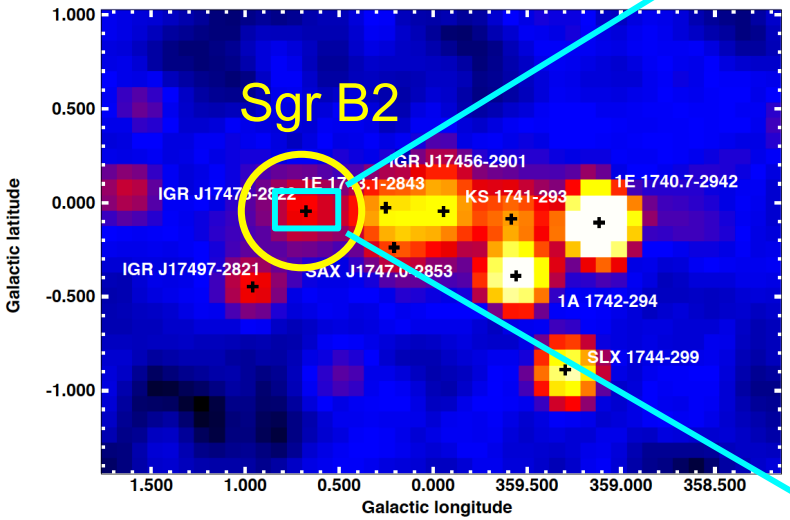
G0.66-0.13 + central 90” radius region of Sgr B2

- Substructures of 90” region:

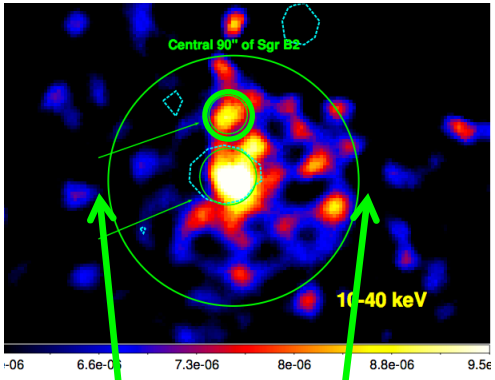
Compact cores Sgr B2(M) and Sgr B2(N) +diffuse emission

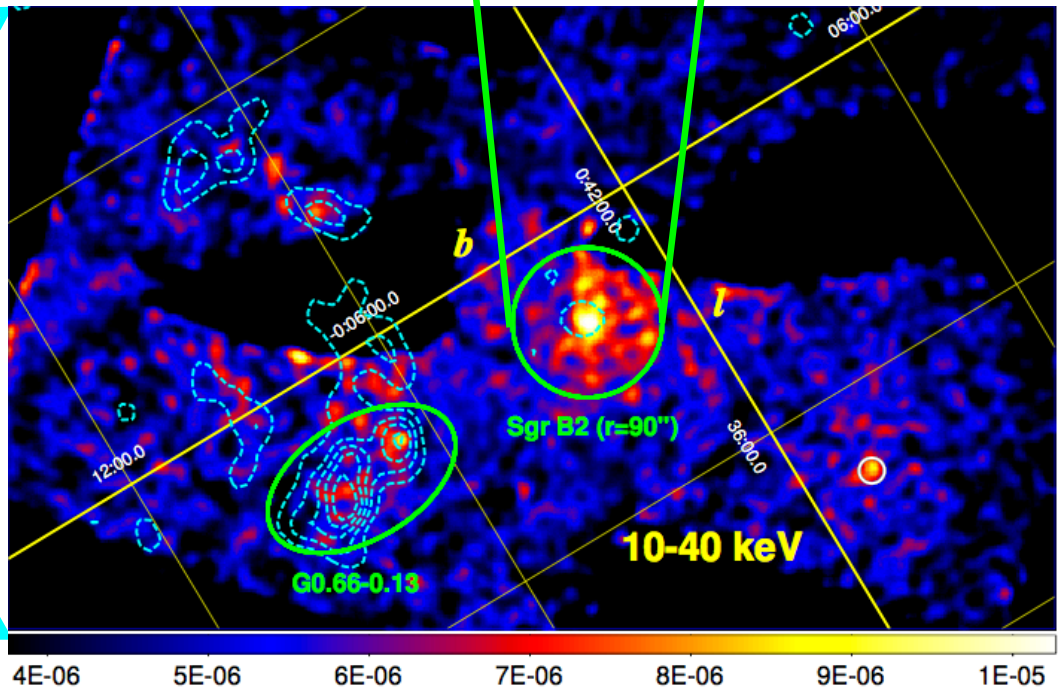
- G0.66-0.13:

Newly emerged cloud feature with a maximum L_x obtained in 2012



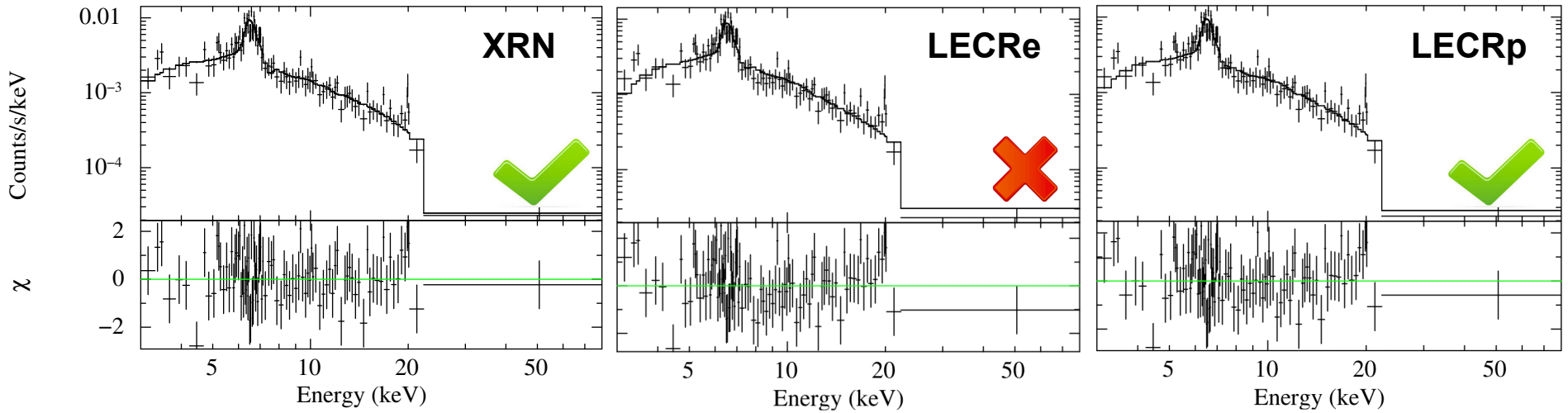
INTEGRAL/IBIS 20-40 keV image of GC (Terrier+ 2010)





NuSTAR 10-40 keV image of the Sgr B2 region (Zhang+ 2015)

Sgr B2 3-79 keV Spectroscopy



The 3-79 keV spectrum of the Sgr B2 90" region fitted with three models (Zhang+ 2015)

XRN scenario

Sgr A* Outburst spectrum:

Γ=2.2±0.4

Required luminosity:

$L_{3\text{-}79keV}$~$5\times10^{38}(d/100pc)^2$ erg s^{-1}

Favored if X-ray emission keeps decreasing.

LECRe scenario

Requires

1) Z_{Fe}~4 solar

➔ Unphysically high

2) E_{min} of e^- <100 keV

➔Unable to penetrate cloud

Excluded to be a major contributor to the remaining level of Sgr B2 X-ray emission

Zhang+ 2015

LECRp scenario

CRp spectrum:

s=1.9±0.7

Required power:

dW/dt~1×10^{39} erg s^{-1}

Favored if X-ray emission has reached constant background level.

Role of G0.66-0.13

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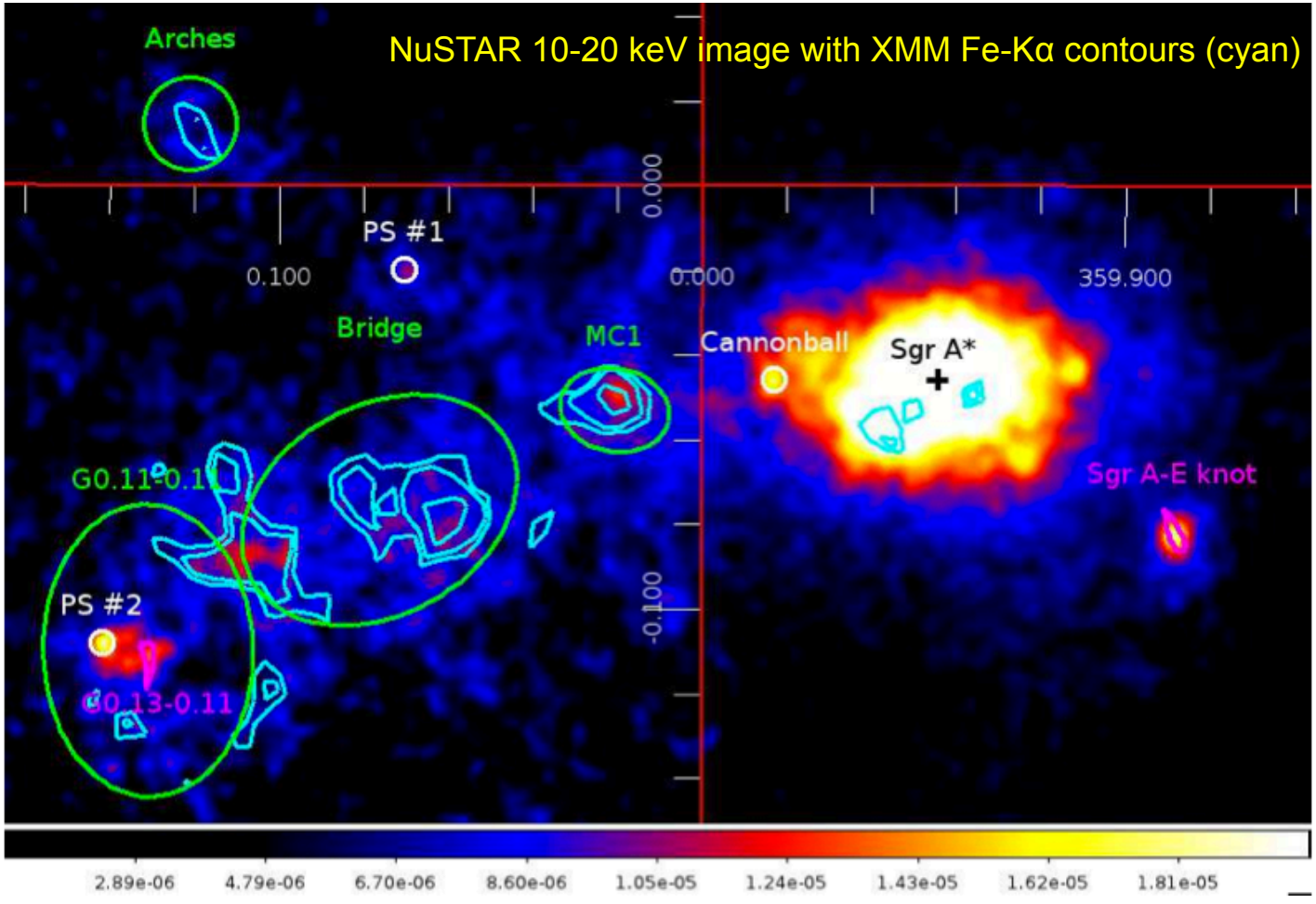
Hard X-ray emission correlates with 6.4 keV Fe Kα line in Sgr A clouds

- NuSTAR detected hard X-ray emission, associated with Fe K fluorescence line, from molecular clouds in the Sgr A region.



Mori+ 2015

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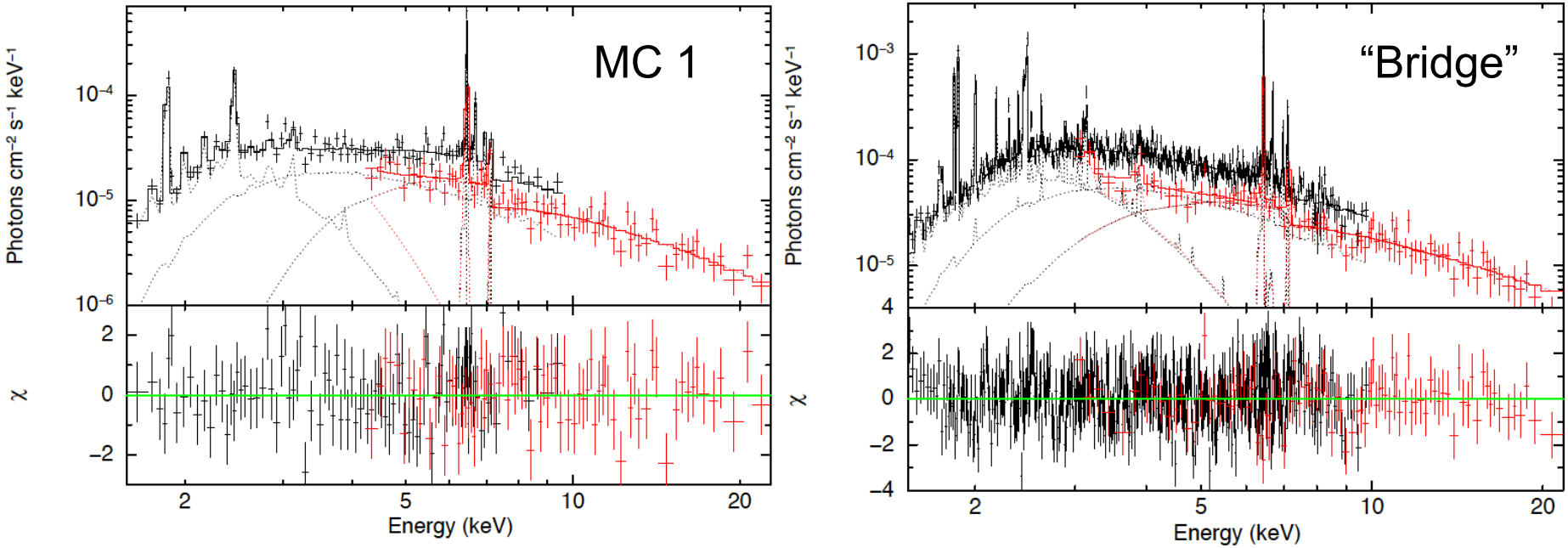
MC1 and Bridge spectra fit to the X-ray reflection model well

- Molecular cloud MC1 and the Bridge spectra are well fitted with the XRN model. The measured intrinsic nH ~ 10^{23} cm^{-2} indicates these clouds are optically thin
  - → No Compton hump observed.
  - → Primary source spectrum shape is nearly unchanged.
- [note: the superluminal propagation of Fe K emission observed by XMM rules out LECR and internal source scenario (Ponti 2010)].



1.5-20 keV XMM-Newton and NuSTAR spectra of MC1 and the "bridge" fitted with the XRN model (Mori+ 2015)

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Multiple Sgr A flaring stages in the past a few hundred years?*

- MC1, the Bridge and Sgr B2 spectra require consistent source photon indices but different Sgr A* flare luminosities.

Parameters	MC1	Bridge	Sgr B2
Projected distance from Sgr A* [pc]	~ 12	~20	~ 100
Column density N_H [10^{23} cm^{-2}]	2.3±1.1	1.5±0.8	10±4
Source photon index	2.1±0.3	1.8±0.1	2.2±0.4
$L_{2\text{-}20keV}$ [erg s^{-1}]	(1.1±0.5)×10^{38}	(0.9±0.2)×10^{38}	(3.5±1.5)×10^{38}

- XMM+Chandra observations of Sgr A clouds and their Fe K line emission indicate multiple Sgr A* flares (Capelli 2012, Clavel 2013, 2014)
- NuSTAR monitoring of Sgr A clouds with broadband X-ray spectroscopy will be useful to further constrain Sgr A* outburst stages.

	When?	PL index	Lx [$ergs^{-1}$]
Bright Sgr A* flares	3 yrs ago	Γ~2	~5x10^{35}
Sgr A clouds	~100 yrs ago	Γ=1.8-2.4	~1×10^{38}
Sgr B2	~150 yrs ago	Γ~2.2	~4×10^{38}

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Summary

Observation of the GC molecular clouds reveals past giant X-ray outbursts from Sgr A* and can reconstruct the Sgr A* outburst history.

- Hard X-ray emission (>10 keV) from Sgr B2 is resolved by NuSTAR in 2013,
- The 2013 Sgr B2 X-ray emission is best explained by XRN if the flux is still decreasing, or by LECRp if it has reached the constant background level.
- G0.66-0.13 could be a clump located in the Sgr B2 envelope and reflected the same Sgr A* X-ray outburst.
- Molecular clouds in the Sgr A region are also detected and resolved >10 keV by NuSTAR. Their spectra require a less luminous and more recent Sgr A* outburst.
- Future observations of GCMCs can reveal their hard X-ray emission evolution and help constrain past Sgr A* X-ray outbursts.
- Thanks to the NuSTAR Galactic Survey team and collaborators!
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NuSTAR