Cosmic Particle Populations at the Galactic Center with Molecular Cloud Sagittarius B2

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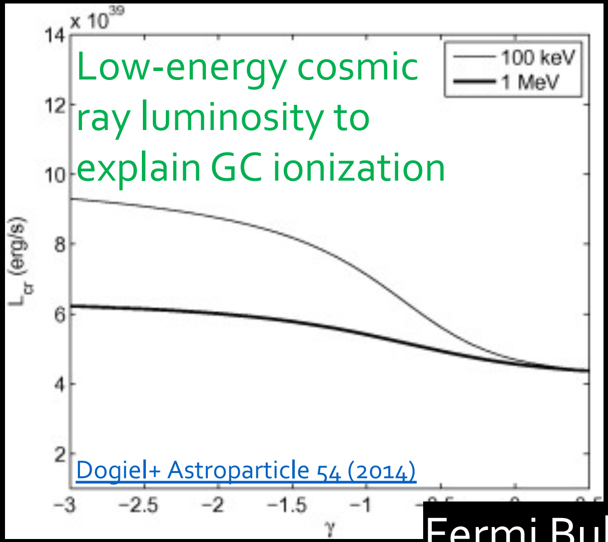
Cosmic Rays Abound at the Galactic Center!



Low-energy cosmic ray luminosity to explain GC ionization

Dogiel+ Astroparticle 54 (2014)

Radio filaments imply a population of GeV-scale electrons

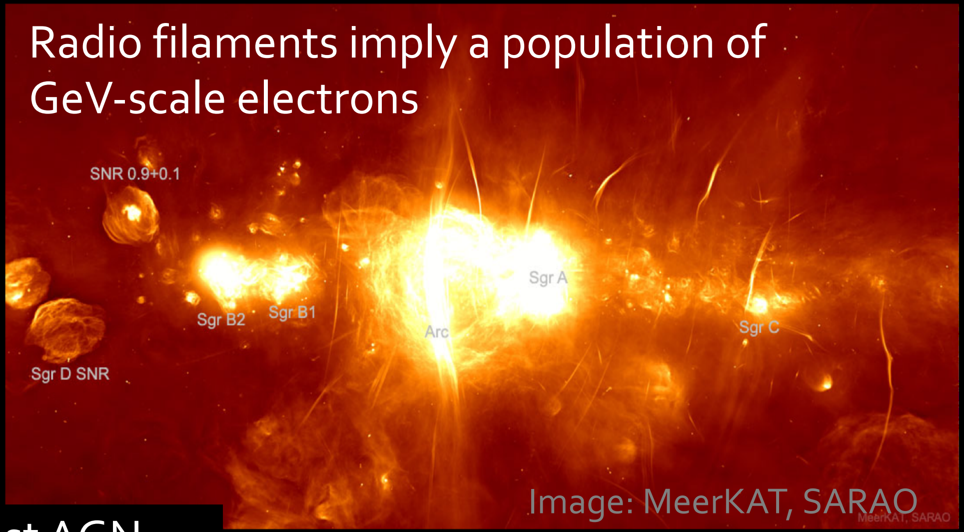


Image: MeerKAT, SARAO

Yusef-Zadeh+ ApJ 725 (2013)
Heywood+ Nature 537 (2019)

Fermi Bubbles may result from a past AGN phase of Sgr A*, and may be a Pevatron today

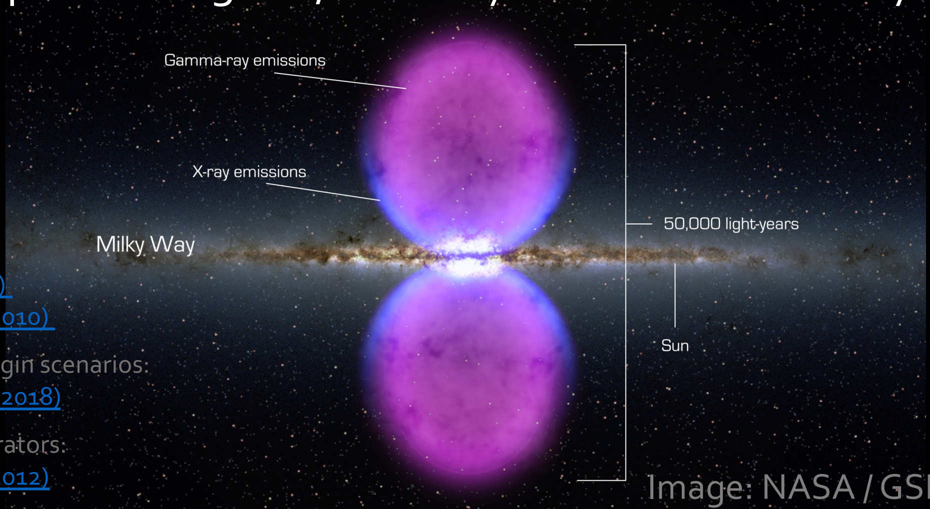


Image: NASA / GSFS

Fermi Bubbles:
Su+ ApJ 724 (2010)
Dobler+ ApJ 717 (2010)

Review of AGN origin scenarios:
Yang+ Galaxies 6 (2018)

Cosmic ray accelerators:
Cheng+ ApJ 746 (2012)

HESS observations imply a population of PeV protons

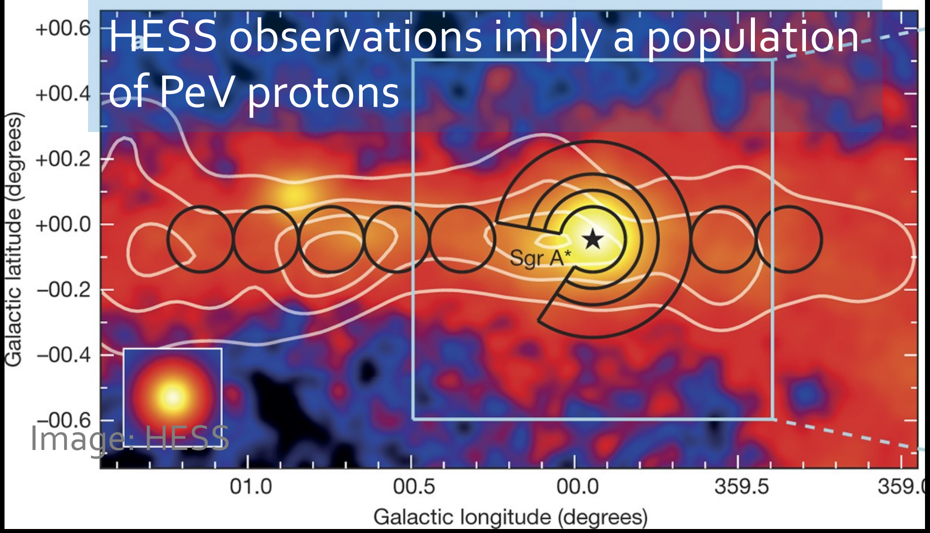
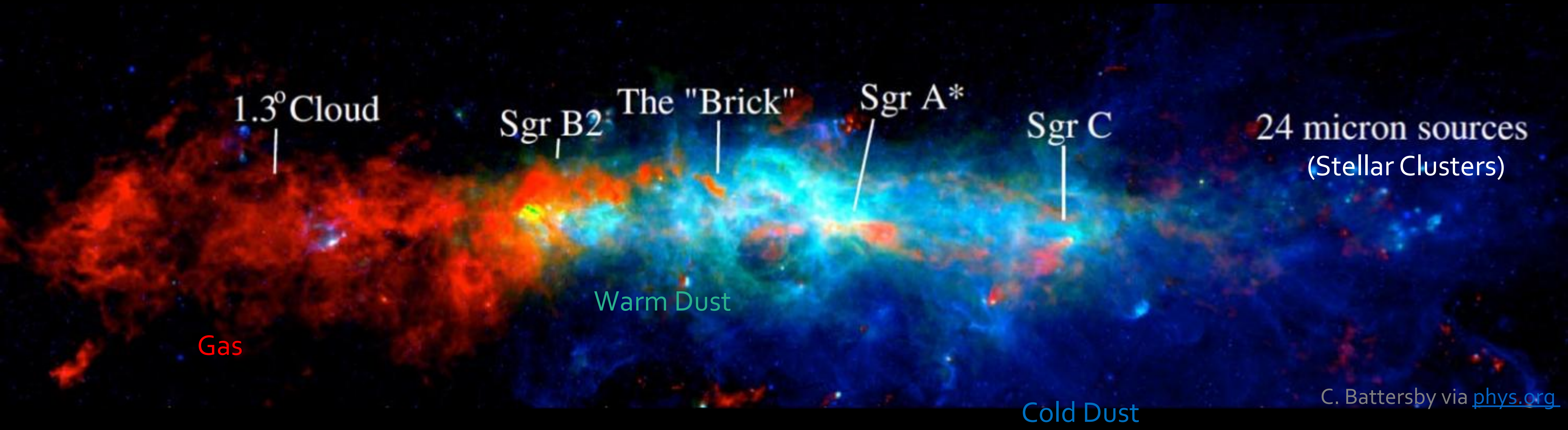


Image: HESS

Hess Collaboration, *Nature* **531**, 476–479 (2016)

Sagittarius B2 in the Central Molecular Zone



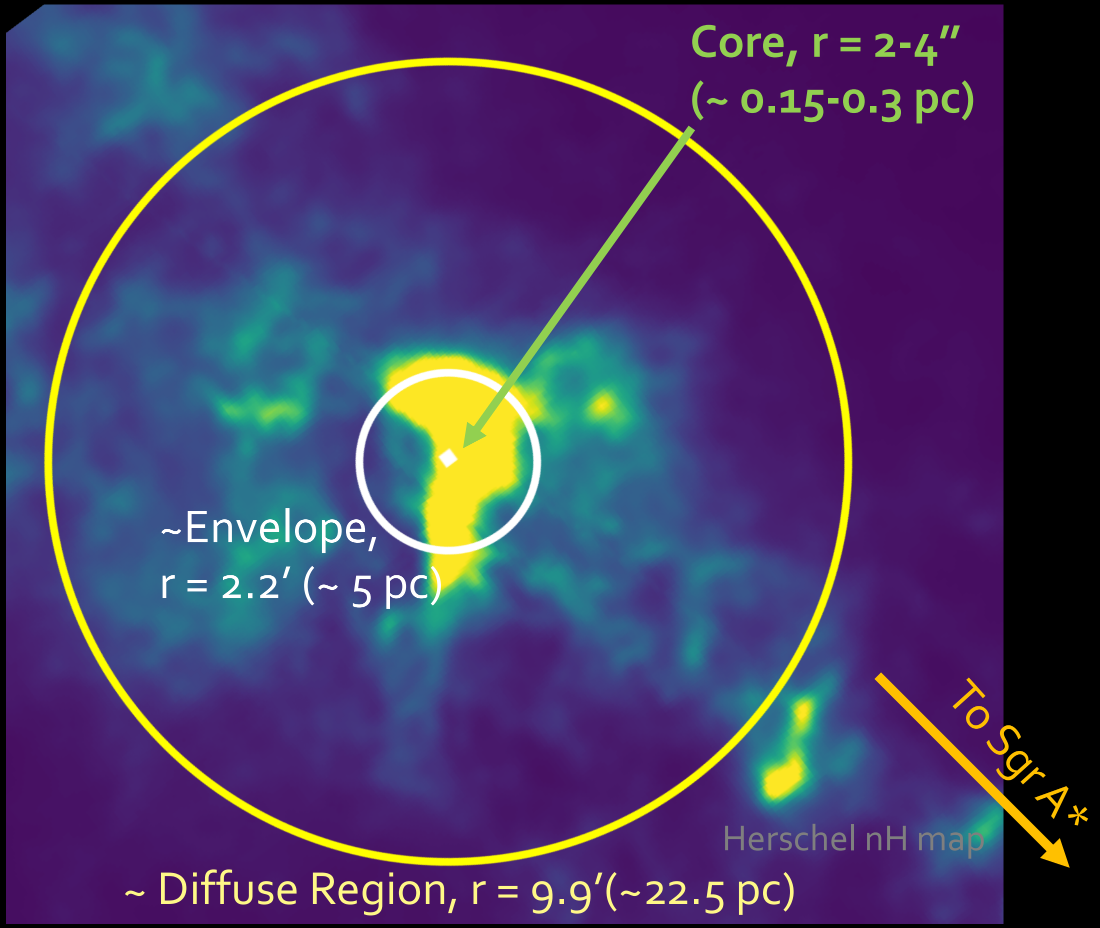
100 pc

CMZ review:
Morris & Serabyn, ARA&A 34 (1996)

X-ray reprocessing in the CMZ:
Terrier+ A&A 612 (2018)
Clavel+ A&A 558 (2013)
Sunyaev+ ApJ 407 (1993)

~80% of the dense gas in the Galaxy
Many clouds are X-ray-bright due to reprocessing past X-ray outbursts of Sgr A*
At ~ 6 million $M_{\odot}$, Sgr B2 is the densest and most massive cloud in the Central Molecular Zone!

Complex Gas Distribution in Sgr B2

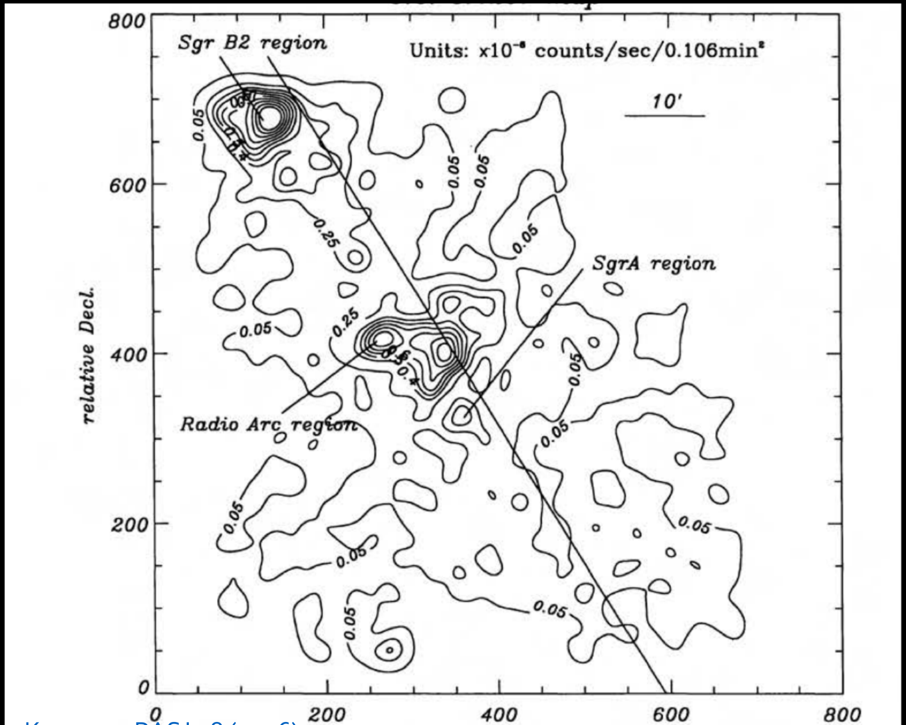


- The complex molecular gas structure includes several sub-dominant star-forming cores as well as substructures within the diffuse region
- Simplified gas model has a dense core, an intermediate envelope, and a diffuse region

Sgr B2 molecular gas structure:
Etxaluze+ A&A 556 (2013)
Sato+ ApJ 535 (2000)
de Vicente+ A&A 320 (1997)
Lis & Goldsmith, ApJ 356 (1990)
Benson & Johnston ApJ 535 (1984)

nH data: Molinari+ ApJL 735 (2011)

Sgr B2 in Non-thermal X-rays



Koyama+ PASJ 48 (1996)

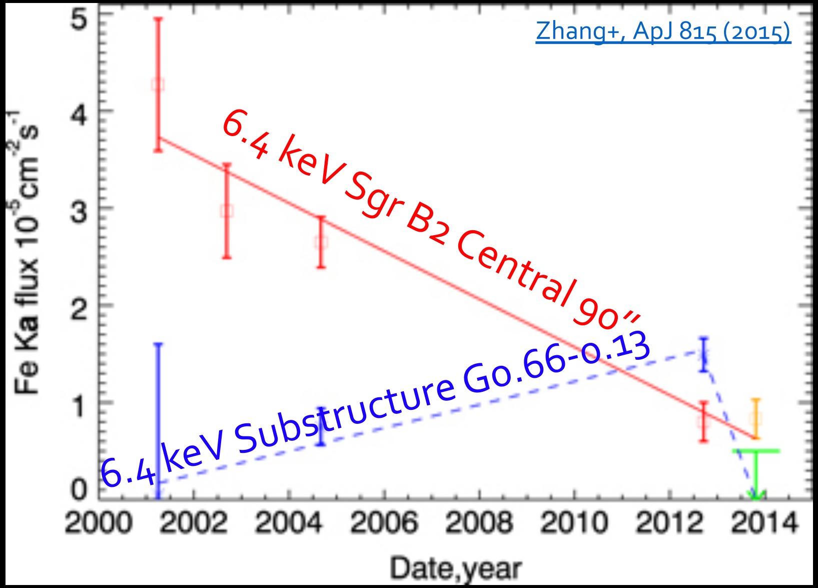
ASCA 6.4 keV map from 1996 shows Sgr B2 is bright in neutral Fe Kα emissions

- Non-thermal Fe Kα and hard X-ray continuum emission from Sgr B2 imply high-energy processes capable of ionizing neutral Fe and scattering up to 60 keV
- Possible origins include:
  - Reprocessing of hard X-rays from an external X-ray source, where the hard continuum originates in inverse Compton scattering
  - Low-energy (KE < 1 GeV) cosmic rays, where the hard continuum originates in Bremsstrahlung processes

See also:

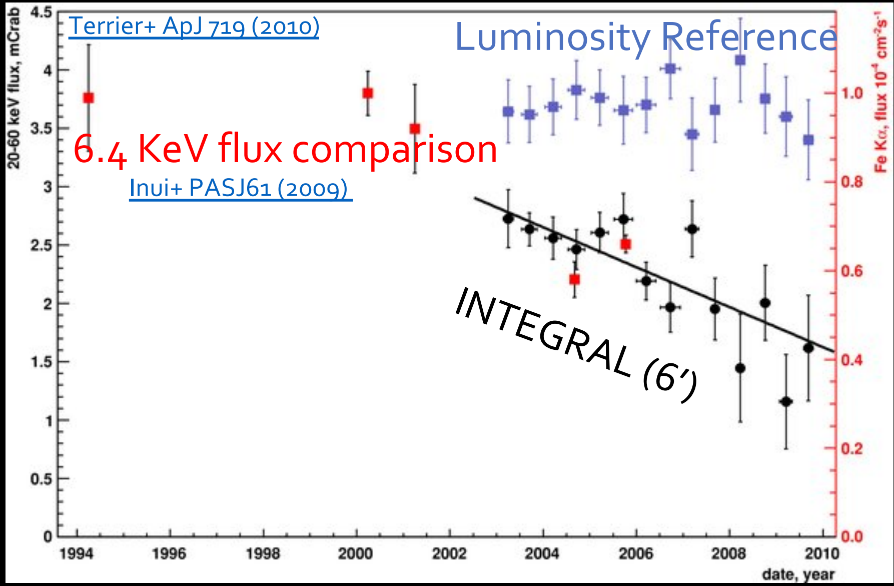
Koyama+ PASJ 48 (1996)
Revnivtsev+ A&A 425 (2004)
Terrier+ ApJ 719 (2010)
Nobukawa+ ApJL 883 (2011)
Zhang+, ApJ 815 (2015)
Murakami+, ApJ 558 (2001)
Koyama+ PASJ 59 (2007)
Inui+ PASJ61 (2009)
Terrier+ ApJ 719 (2010)
Terrier+ A&A 612 (2018)

Decrease in X-ray Brightness since 2001



Fe Kα emissions from the core of Sgr B2 have decreased continuously since 2001

The hard (20-60 keV) X-ray flux from the Sgr B2 complex has also decreased



- The total non-thermal X-ray emissions from Sgr B2 have decreased since 2001
- Emissions over time suggest:
  - Peak emission was dominated by X-ray reprocessing from a past outburst of Sgr A*.
  - The past outburst is now moving past Sgr B2 molecular cloud
  - Any low-energy cosmic rays also contribute to the total non-thermal emissions
  - Now or in the future, low-energy cosmic rays may cause the bulk of the Sgr B2 X-ray emissions

This Work: New X-ray Observations from 2018

- Is the Fe Kα flux still decreasing, consistent with still being dominated by X-ray reprocessing
- Or, has the Fe Kα flux reached a constant level, consistent with arising from ionization by low-energy cosmic rays?

Instrument	Observation ID	Start Time (UTC)	Exposure (ks)
XMM-Newton	0112971501	2001-04-01T00:25:11	9.2
XMM-Newton	0203930101	2004-09-04T02:53:45	48.5
XMM-Newton	0694640601	2012-09-06T10:56:15	66.6
XMM-Newton	0802410101	2018-04-02T00:59:38	103.0
NuSTAR	40401001002	2018-04-10T12:01:09	149.2

NOTE—The exposure time reported for *XMM-Newton* observations is the *pn*-equivalent exposure.

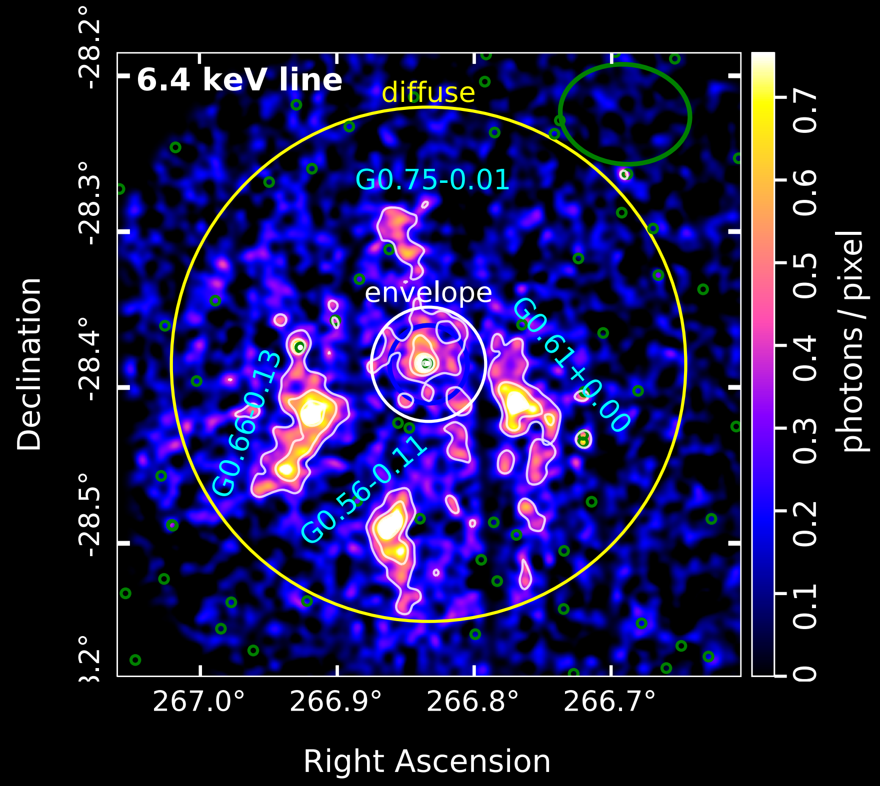
XMM-Newton: 2 MOS and 1 pn instruments, 0.15-15 keV, σ_E/E~ 2-5%, ~ 6" angular resolution

Turner+ A&A 365 (2001)
Strüder+ A&A 365 (2001)

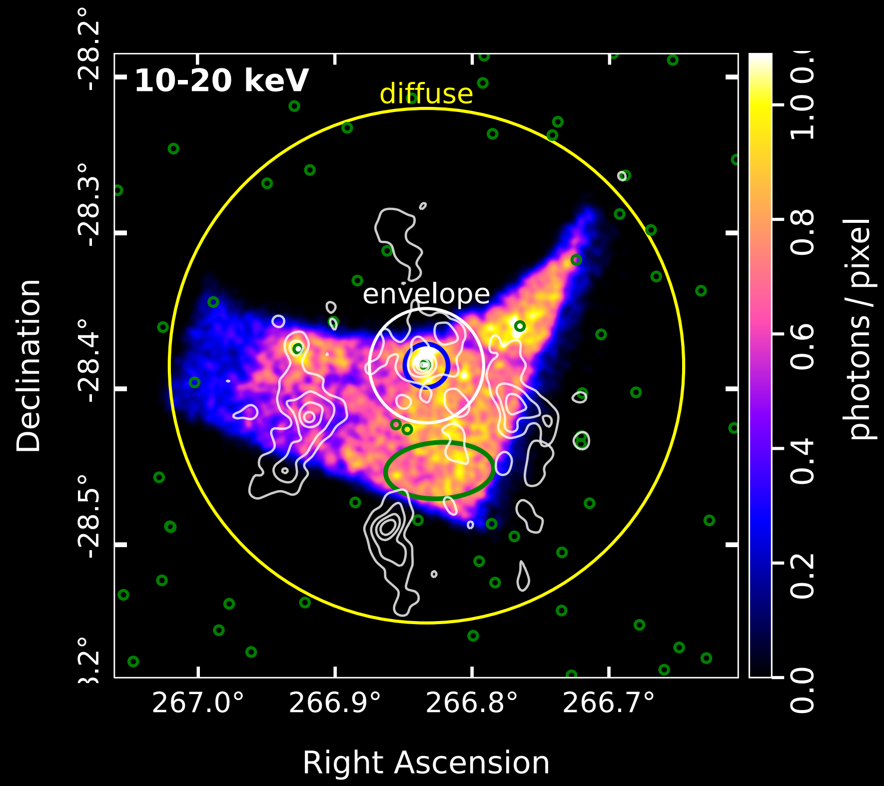
NuSTAR: two focal plane modules (FPMA & FPMB) , 3-79 keV, σ_E~ 400 eV, ~18" angular resolution

Harrison+ ApJ 770 (2013)

Sgr B2 X-ray Morphology in 2018



XMM-Newton pn

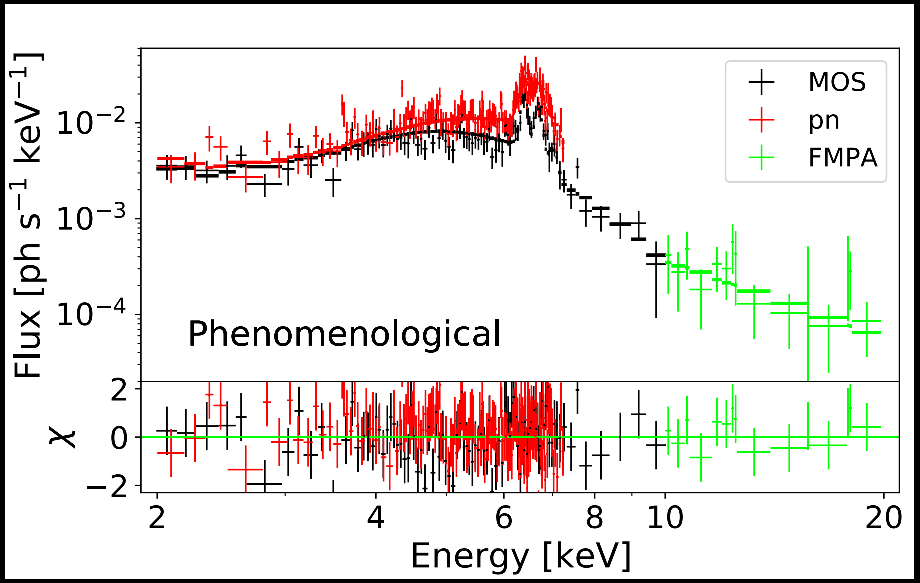


NuSTAR FPMA

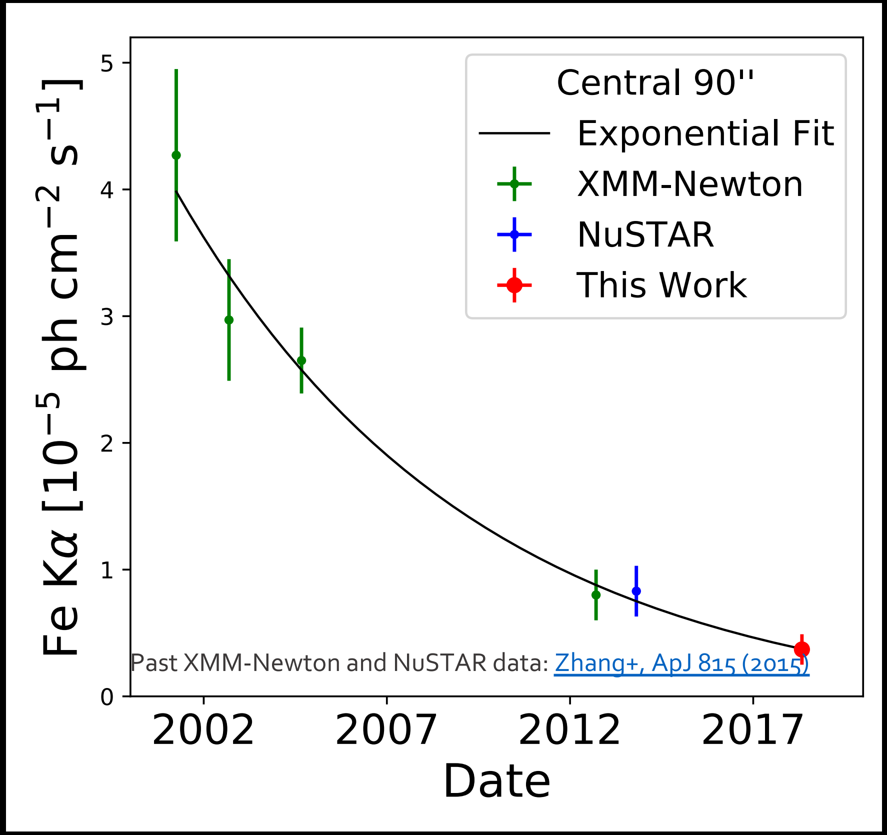
Hard X-ray point sources from the Chandra catalog: [Muno+ ApJS 181 (2009)]

Spectral Analysis: Central 90" (Core + Envelope)

Used a phenomenological model to fit and extract Fe Kα and continuum flux components



Spectra are also consistent with simulated spectral models of both low-energy cosmic ray ionization and X-ray reflection

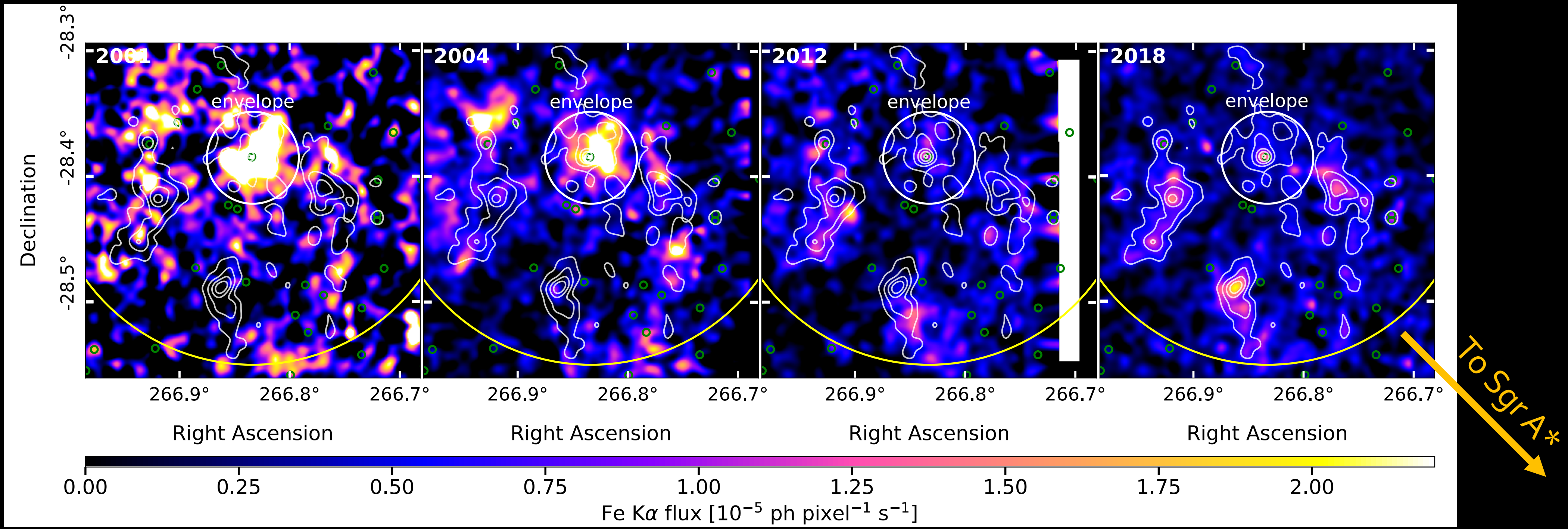


- The Fe Kα emission has continued to decrease since 2012 / 2013
- Light curve is consistent with a pure exponential decrease or with an offset of the 2018 flux level
- With the lowest flux yet observed, we can set best upper limits on low-energy cosmic ray populations in Sgr B2

Physical spectral models:
Tatischeff+ A&A 546 (2012)
Yaqoob, MNRAS 423 (2012)
Walls+, MNRAS 463 (2016)
Churazov+ MNRAS 468 (2017)

➢ Details of the models and fitting procedures are in a publication in preparation!

Time Variability of the Fe Kα Emissions



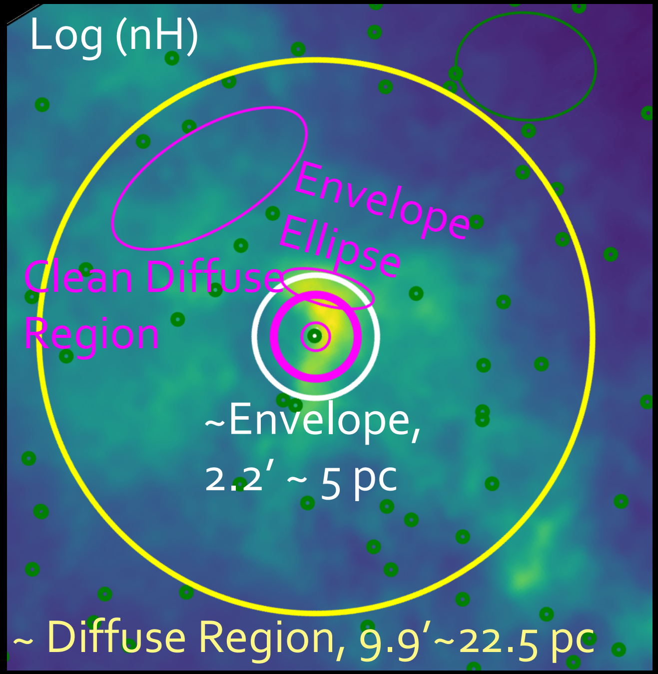
Hard X-ray point sources from the Chandra catalog: Muno+ ApJS 181 (2009)

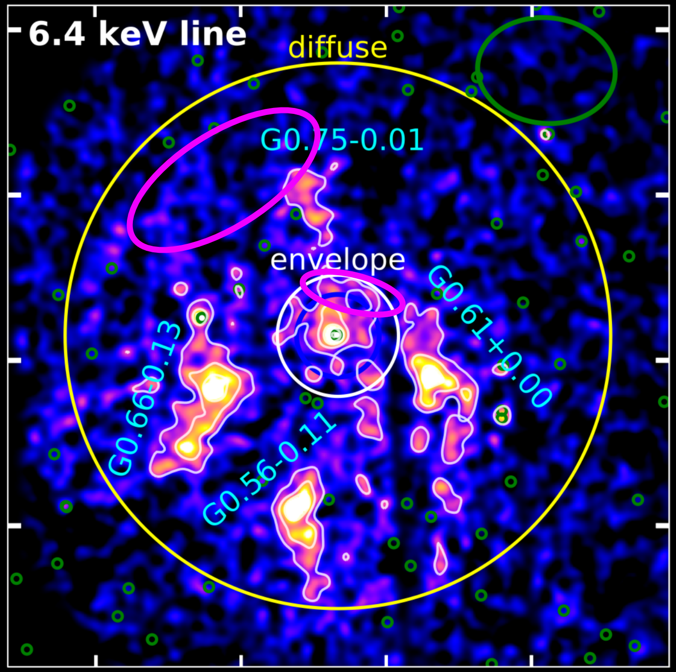
- Contour lines from the 2018 Fe Kα map are overlaid on exposure-corrected XMM-Newton observations over time
- The overall flux, and the flux from the core, have continued to decrease over time
- New regions continue to brighten in Fe Kα emissions

Previous image-based analysis with data through 2012: Terrier+ A&A 612 (2018)

Best Limits on < 1 GeV Cosmic Rays in Sgr B2

- Ambient cosmic ray transport into dense molecular clouds is model dependent and the subject of much theoretical work





Cloud Region	Fe Kα flux $10^{-6}\,\mathrm{ph\,cm^{-2}\,s^{-1}}$	Fe Kα surface brightness $10^{-7}\,\mathrm{ph\,cm^{-2}\,s^{-1}\,amin^{-2}}$
Diffuse*	6.9 ± 1.9	3.2 ± 0.9
Env. (ellipse)†	2.1 ± 0.5	6.5 ± 1.4
Env. (0.5′ – 2.2′)†	12.7 ± 1.2	8.8 ± 0.8

Lowest flux yet observed (2018) means best upper limits on cosmic rays!

We extracted spectra from regions compatible with the diffuse and envelope cloud regions in both the observed and model gas distribution, while also avoiding bright spots and point sources

- Our results are comparable to the Fe Kα flux expected in the model from Dogiel et al (2015) based on the proton population needed to explain relative ionization rates in and out of the cloud

Hard X-ray point sources from the Chandra catalog: Muno+ ApJS 181 (2009)

Dogiel+ ApJ 809 (2015)
Morlino & Gabici MNRAS 451 (2015)

Summary

- Cosmic rays abound at the Galactic Center!
- Sgr B2, the largest and densest molecular cloud in the Central Molecular Zone, has been a known source of non-thermal (neutral Fe Kα and hard continuum) X-rays for decades
- The non-thermal X-ray flux has decreased since 2001, with the time-variable flux attributed to reprocessing of a past Sgr A* flare
- The flux observed in 2018 is consistent with arising primarily from either X-ray reprocessing of cosmic rays ionization, but brightening and dimming of cloud substructures complicates the cosmic ray picture
- We set upper limits on low-energy cosmic ray populations within Sgr B
  - limits are comparable with the 6.4 keV line intensity expected if ambient low-energy cosmic ray protons are the source of the excess H_2 ionization the CMZ

Acknowledgments

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- ❖This project used a dedicated observation by NuSTAR, a project funded by NASA, managed by Jet Propulsion Laboratory, and led by California Institute of Technology
- ❖Data was obtained through the High Energy Astrophysics Science Archive Research Center Online Service, maintained by NASA/Goddard Space Flight Center
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