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PROBING GALACTIC CENTER COSMIC-RAYS IN THE X-RAY REGIME

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X-RAY CHANNELS TO PROBE COSMIC-RAYS

- Accelerated particles produce X-rays through *synchrotron radiation* and *bremsstrahlung*.

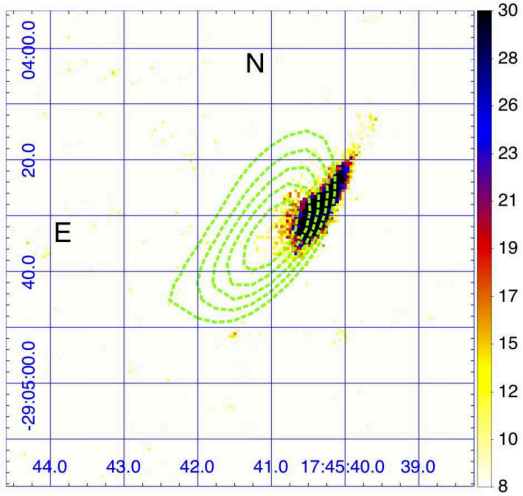
- **X-ray Synchrotron** → very high energy electrons at TeV

  GC: X-ray synchrotron emitting magnetic filaments

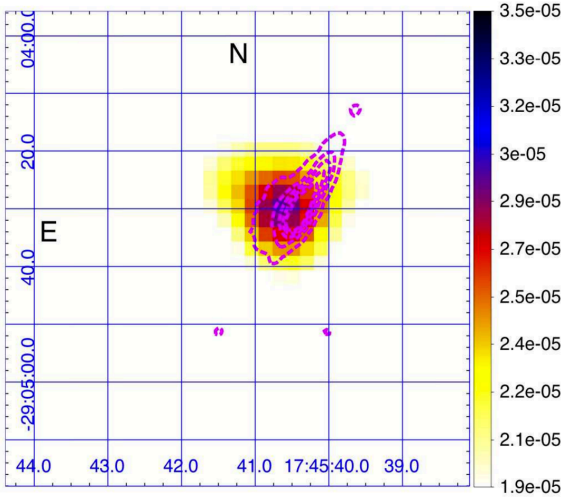
- X-ray Bremsstrahlung/collisional ionization → low energy particles at MeV-GeV

  GC: some X-ray bright molecular clouds

G359.89−0.08 (SGR A-E) BRIGHTEST X-RAY FILAMENT IN GC: A MAGNETIC FILAMENTARY STRUCTURE

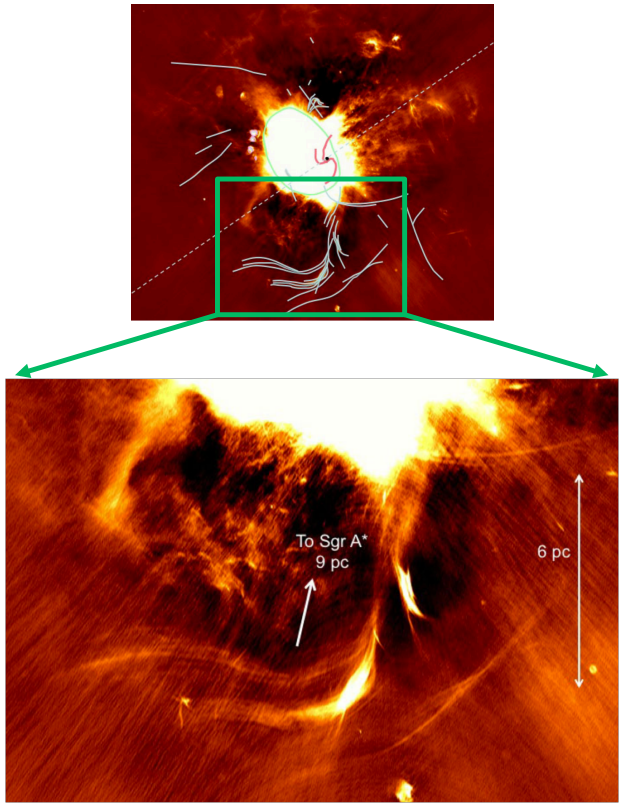


Chandra 2−10 keV image overlaid with VLA 20-cm continuum contours (green dashed) of Sgr A−E.



NuSTAR 10-50 keV image of Sgr A-E overlaid with Chandra 2-10 keV contours of Sgr A-E.

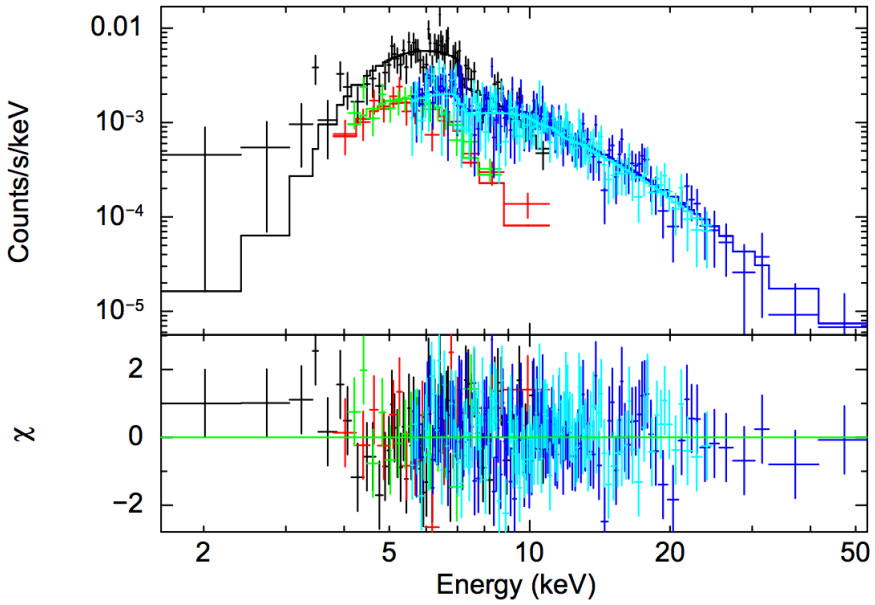
Zhang+ (2014)



JVLA 6-cm image of the Sgr A-E region.

Morris+ (2014)

MAGNETIC FLUX TUBE: SUGGESTING ~100 TEV CR ELECTRONS EXISTING IN THE GC

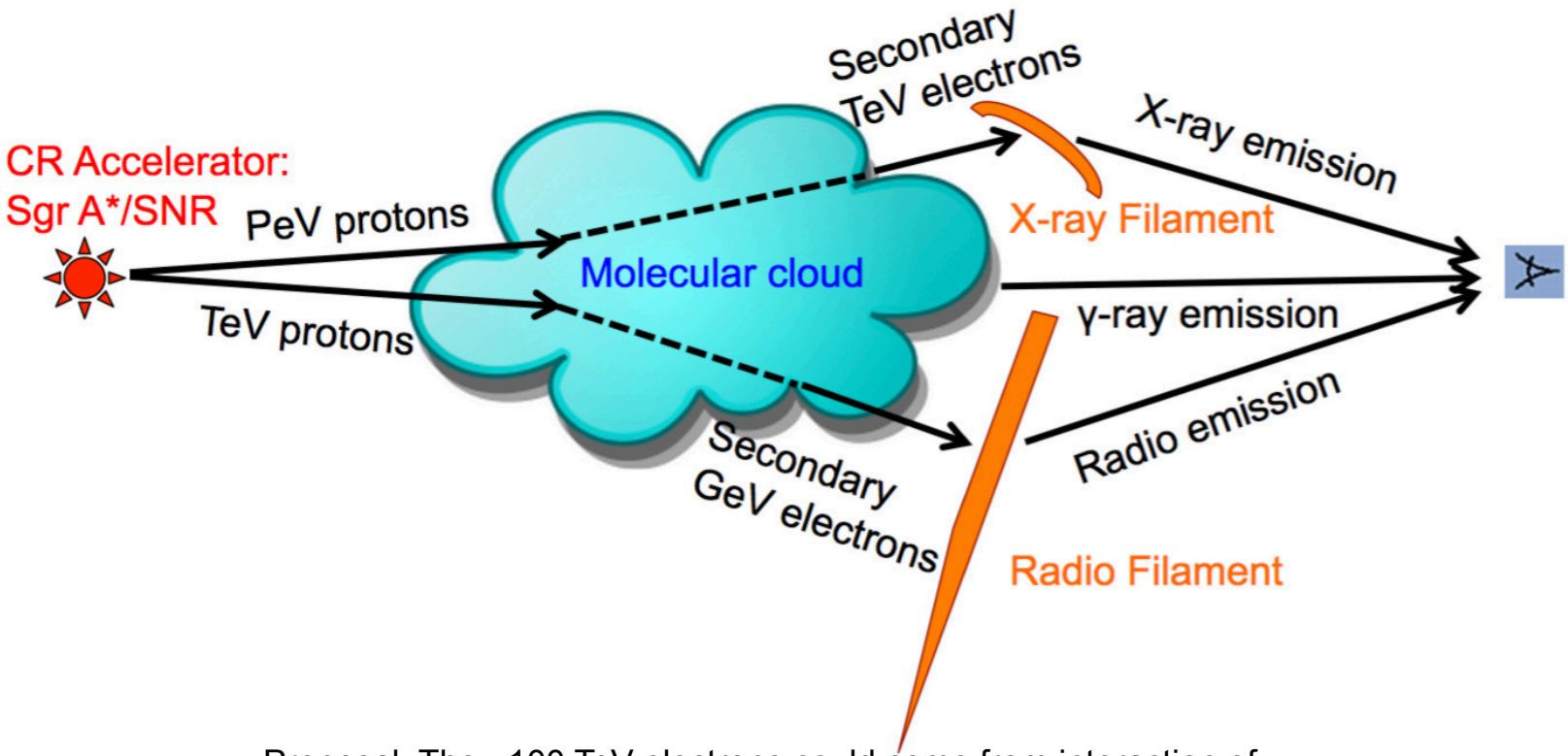


Power-law model of the *XMM* and *NuSTAR* data.

Parameter	Value
$N_{\rm H}$ (10^{23} cm^{-2})	7.2 ± 1.0
Γ	$2.28^{+0.17}_{-0.18}$
flux (erg/cm^2/s)	$(2.0 \pm 0.1) \times 10^{-12}$
χ^2_ν (DoF)	0.91 (298)

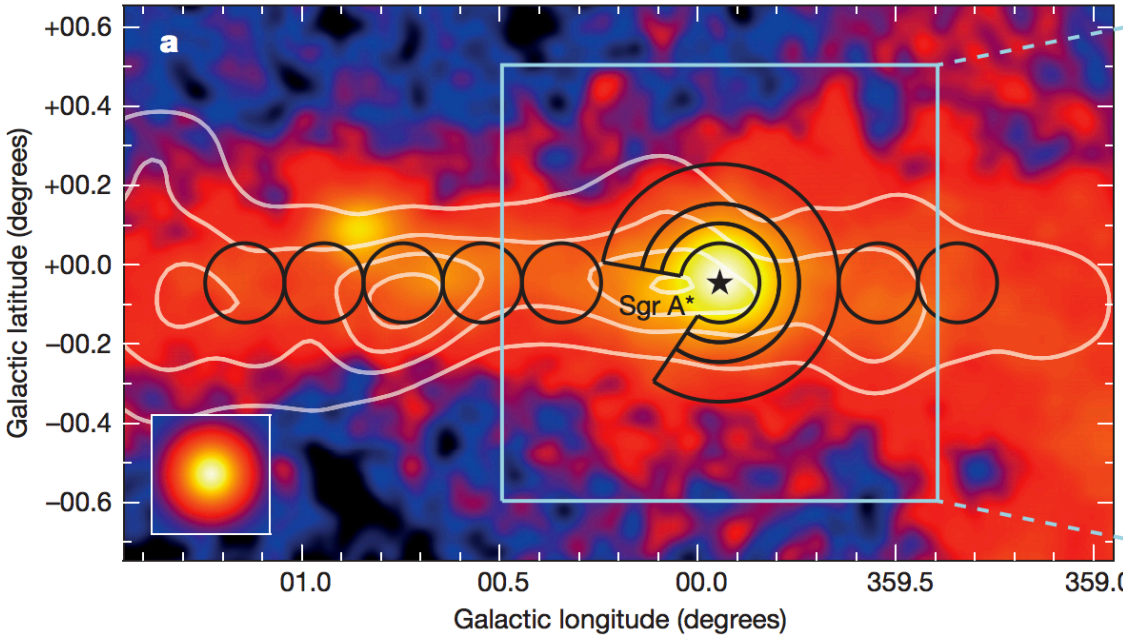
NuSTAR+XMM spectra of Sgr A-E. The synchrotron emission up to ~50 keV with B=100-300 μG requires 100-200 TeV CR electrons.
Origin??

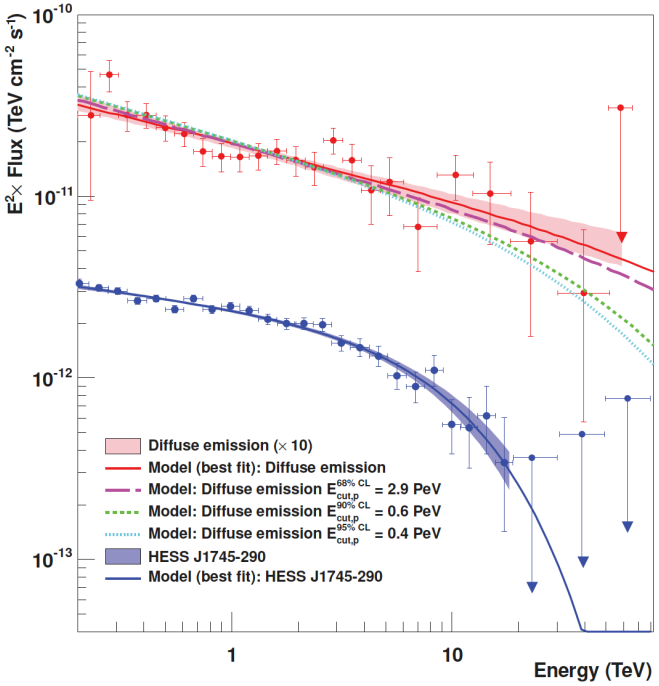
A HYPOTHESIS OF THE ORIGIN OF TEV ELECTRONS



Proposal: The ~100 TeV electrons could come from interaction of PeV protons and the giant molecular clouds (Zhang+ 2014).

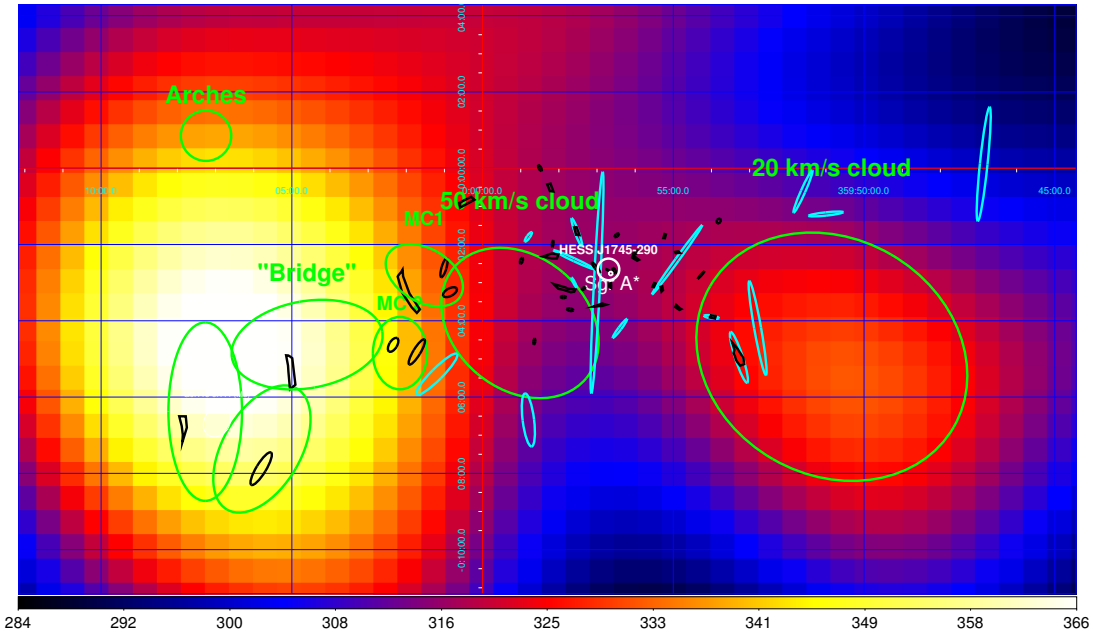
SUPPORTED BY THE MOST RECENT HESS GC NATURE PAPER: THERE COULD BE A PEVATRON THE GC!





HESS collaboration (2016) Nature

OUTLOOK: PROBING GC COSMIC-RAYS WITH MAGNETIC FILAMENTARY STRUCTURES



H.E.S.S. residual map with the GC point source HESS 1745-290 subtracted, overlaid with molecular cloud regions (green), X-ray filaments (black) and radio filaments (cyan).

- Search for more similar X-ray bright magnetic structures close to molecular clouds.
- Build PeV CR proton-cloud interaction model, predicting secondary electron spectrum and compare with that required by the magnetic filaments.
- X-ray polarization measurements may reveal the magnetic field configuration.

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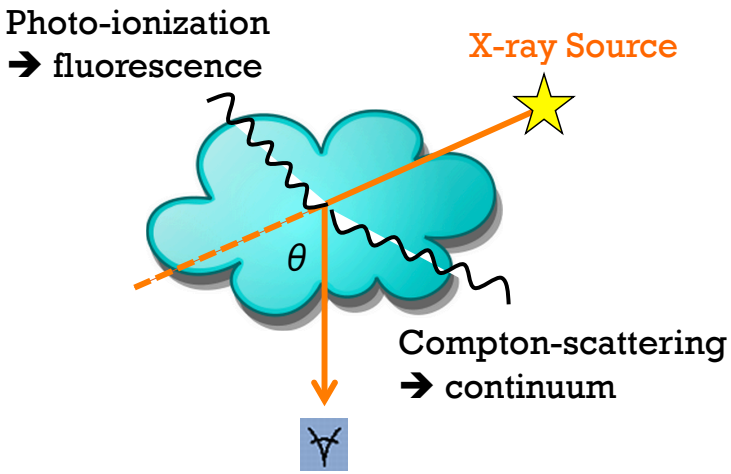
X-RAY REFLECTION VS. LOW ENERGY COSMIC RAY PROTON (LECRP)

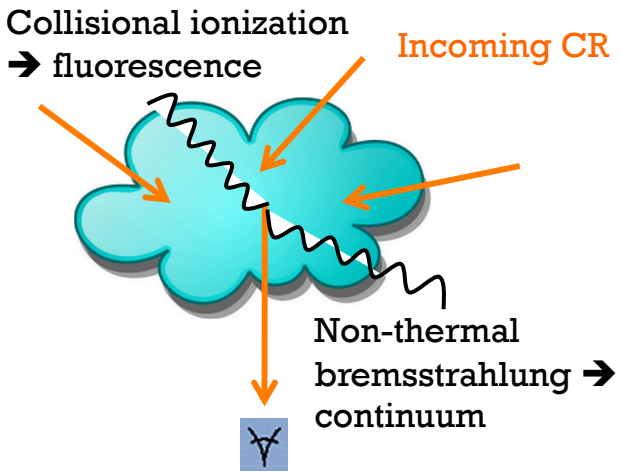
X-ray Reflection



Reflecting a Sgr A* X-ray outburst ~100 yrs ago

Variability on timescale of ~1-10 yrs

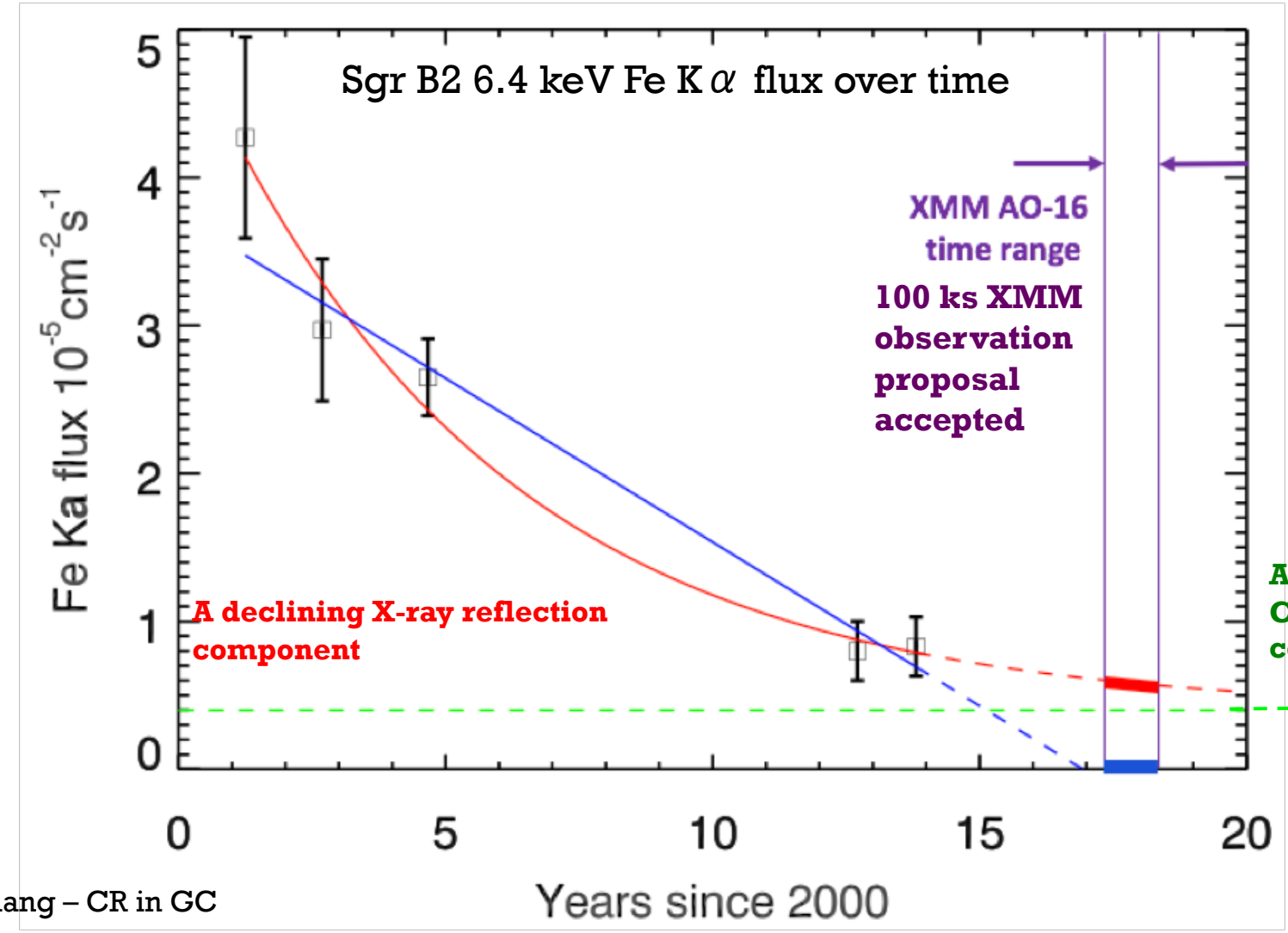
Cosmic-ray Proton/Electron



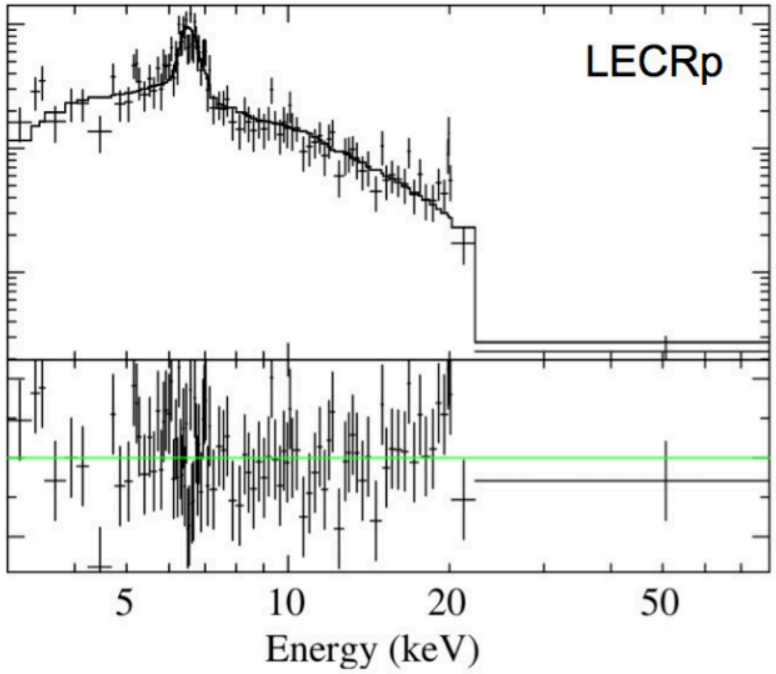
Cosmic-ray bombardment into clouds

Variability (proton cooling time) of >100 yrs

X-ray polarimetry can distinguish between the two scenarios.
For X-ray reflection: degree of polarization can measure θ ➔ constrain cloud distance


Sgr B2 6.4 keV Fe Kα flux over time
Fe Ka flux 10^{-5}cm^{-2}s^{-1}
Years since 2000
XMM AO-16 time range
100 ks XMM observation proposal accepted
A declining X-ray reflection component
A constant CR proton component
0
1
2
3
4
5
0
5
10
15
20

2013 SGR B2 DATA FIT WITH CR PROTON MODEL



2013 NuSTAR Sgr B2 data fitted with Cosmic-ray proton Model devel0ped by Tatischeff (2011).

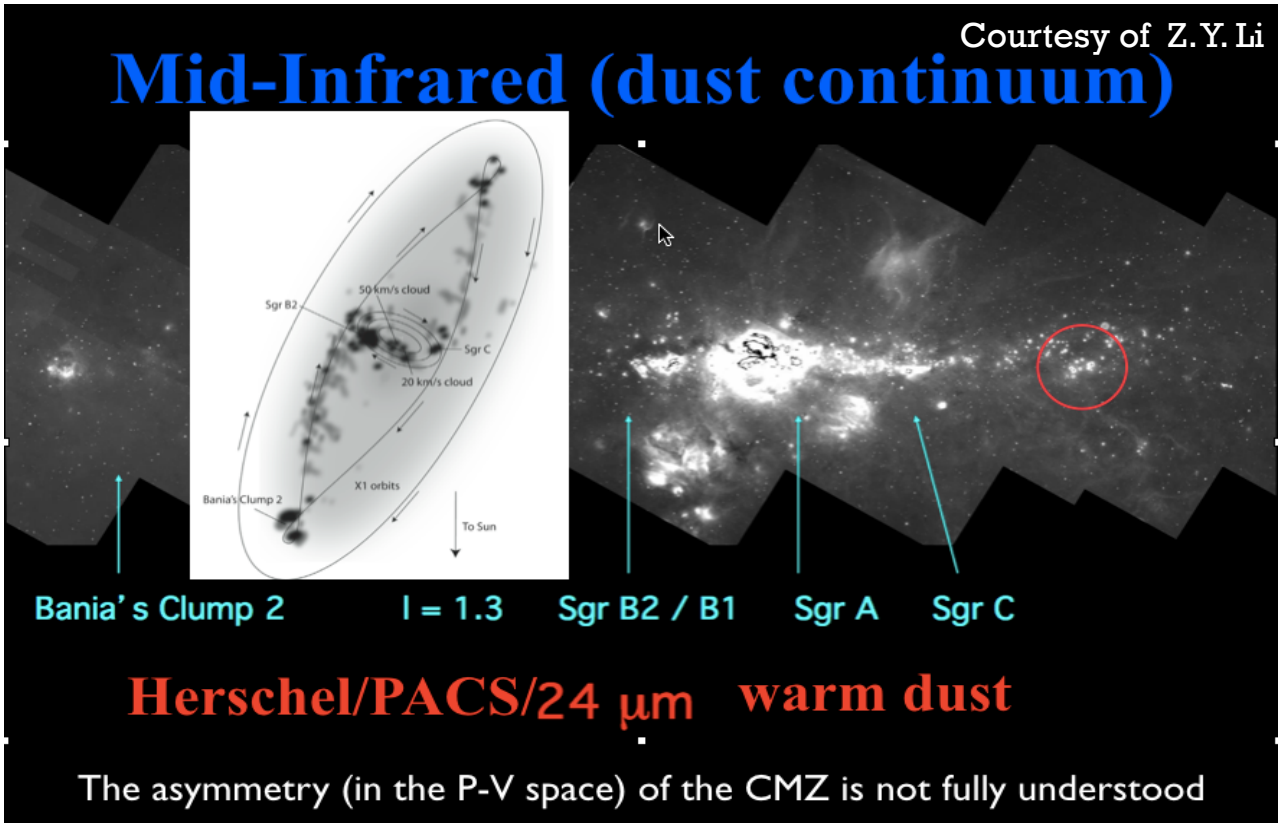
- 2013 NuSTAR Sgr B2 data fit with self-consistent CR proton model → Not ruled out!
- CR proton (10 MeV – 1GeV) spectral index

  s=1.9 (+0.8, -0.7)
- Required proton power: $E_p=(0.4\text{-}2.3)\times10^{39}$ erg s^{-1}
- Ionization rate: $\xi=(6\text{-}10)\times10^{-15}\,H^{-1}\,s^{-1}$

  Comparable to the uniform GC CR ionization rate
- Still some contribution from reflection component
- X-ray polarization can pin down the contribution from both scenarios.
- Strong Fe Kα line from clouds: Good targets for eXTP/SFA with good spectral resolution and low background!

Zhang+ (2015)

OUTLOOK: MONITOR LARGE-SCALE MOLECULAR CLOUDS TO TEST COSMIC-RAY PROTON/ELECTRON SCENARIO



CONCLUSION

- TeV electron/ PeV protons
  - Can be probed via X-ray synchrotron emitting magnetic filaments
  - X-ray polarization → magnetic field configuration

- MeV-GeV protons/electrons
  - Can be probed via X-ray molecular clouds
  - X-ray polarization → can distinguish between X-ray reflection and CR bombardment

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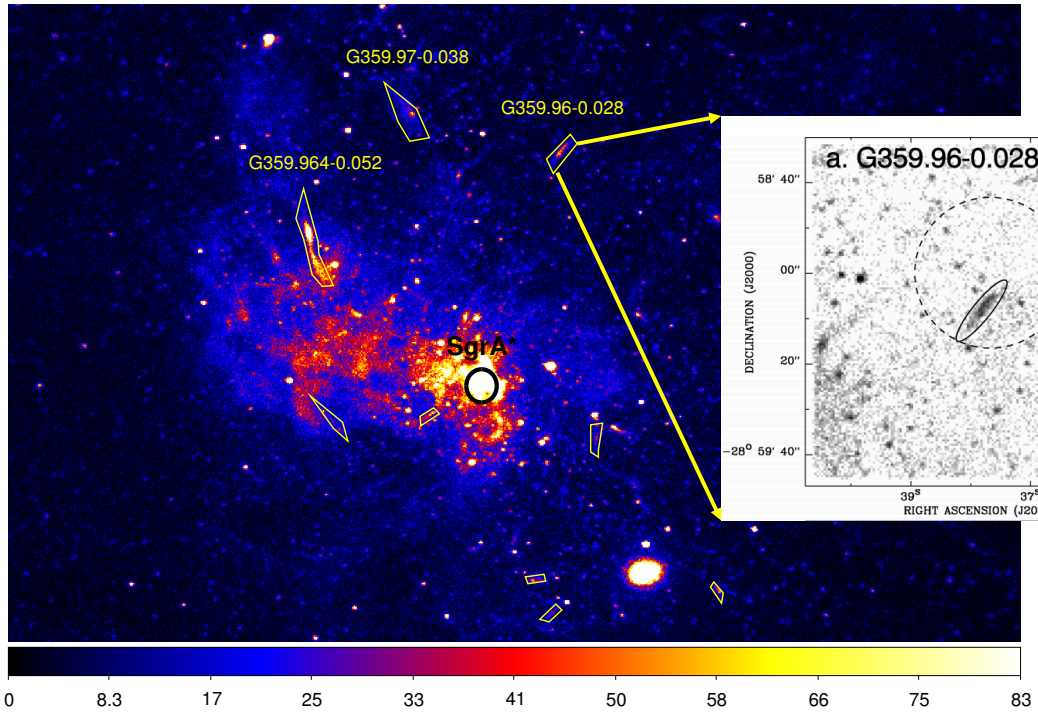
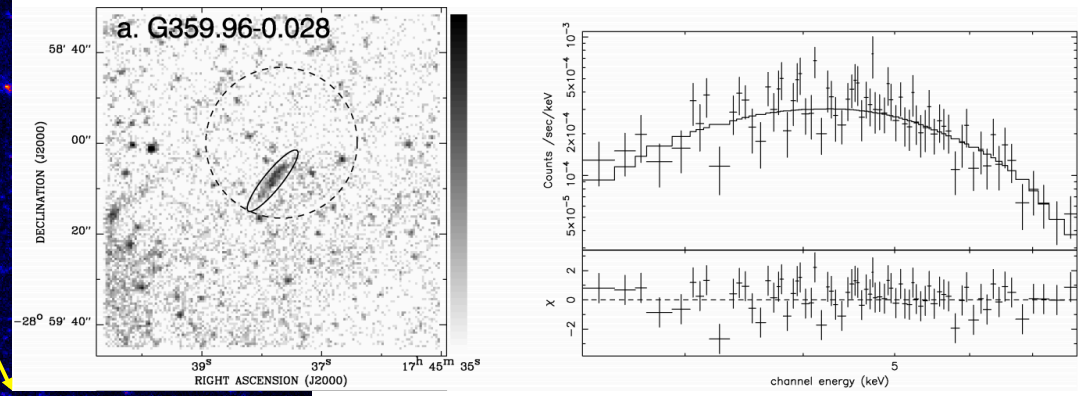
BACK-UP SLIDES

DOZENS OF SMALL NON-THERMAL X-RAY FILAMENTS DETECTED WITHIN 1X0.5 DEGREE° REGION OF SGR A*

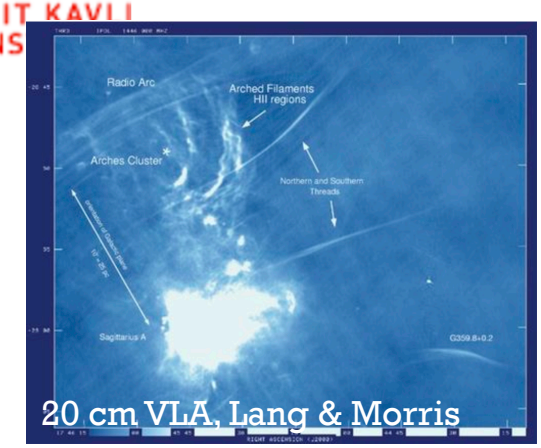


~2 Ms Chandra observation of the GC
Muno+ (2007)



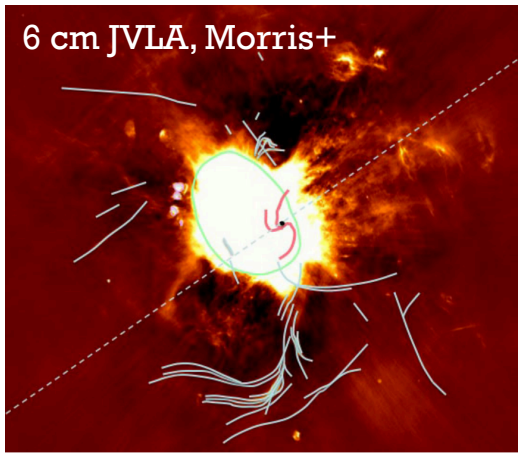
Johnson+ 2009
Based on ~2Ms Chandra observations from 1999-2007

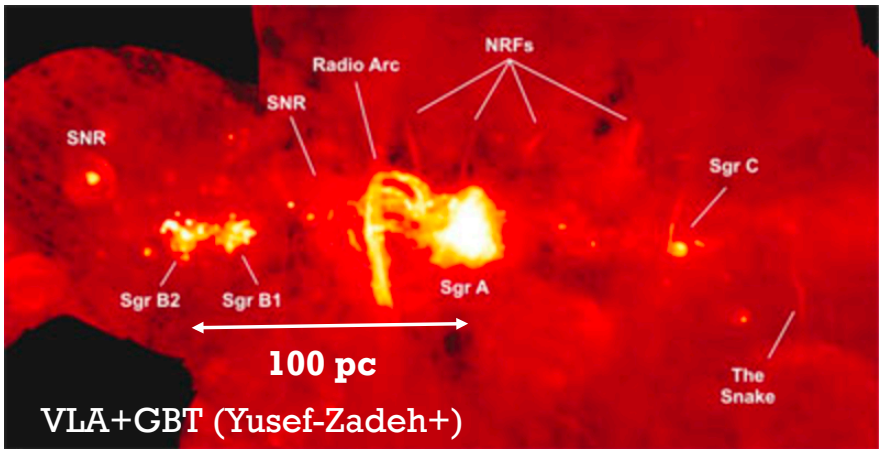
NON-THERMAL FILAMENTS DISCOVERED IN RADIO



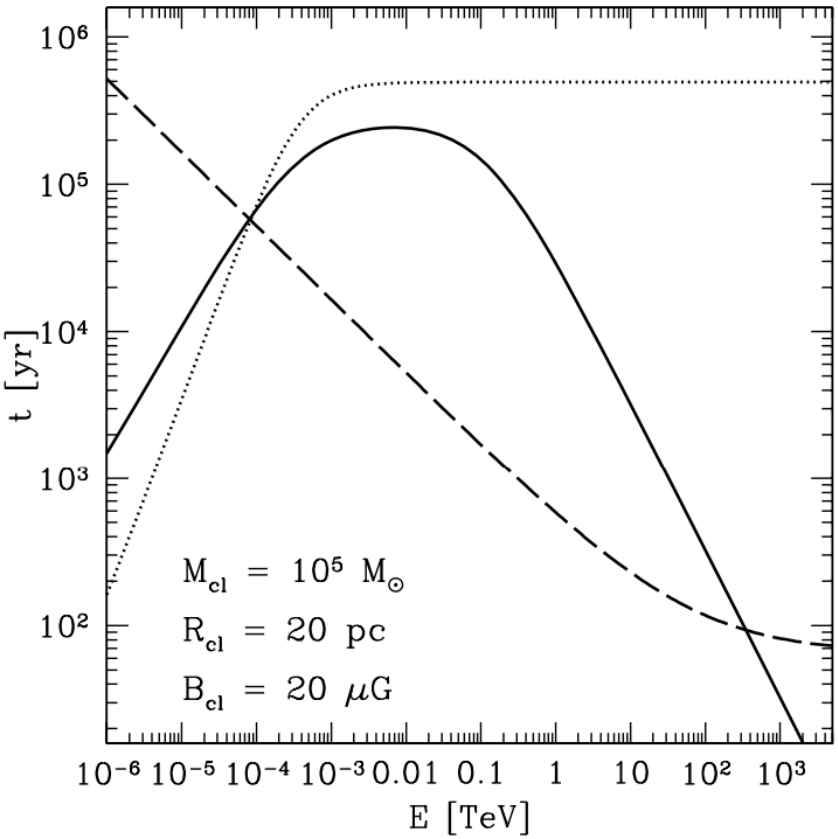
20 cm VLA, Lang & Morris

- ~80 radio filaments within 2° of GC
- As large as ~1 pc thick, ~10s of pc long
- Tracing magnetic field line + Polarization detection → Synchrotron emission → requires GeV electrons
- Origin of GeV CR e^-: particle acceleration mechanism (Clouds, winds, BH magnetic activity, Young stellar clusters, etc.) vs. dark matter annihilation



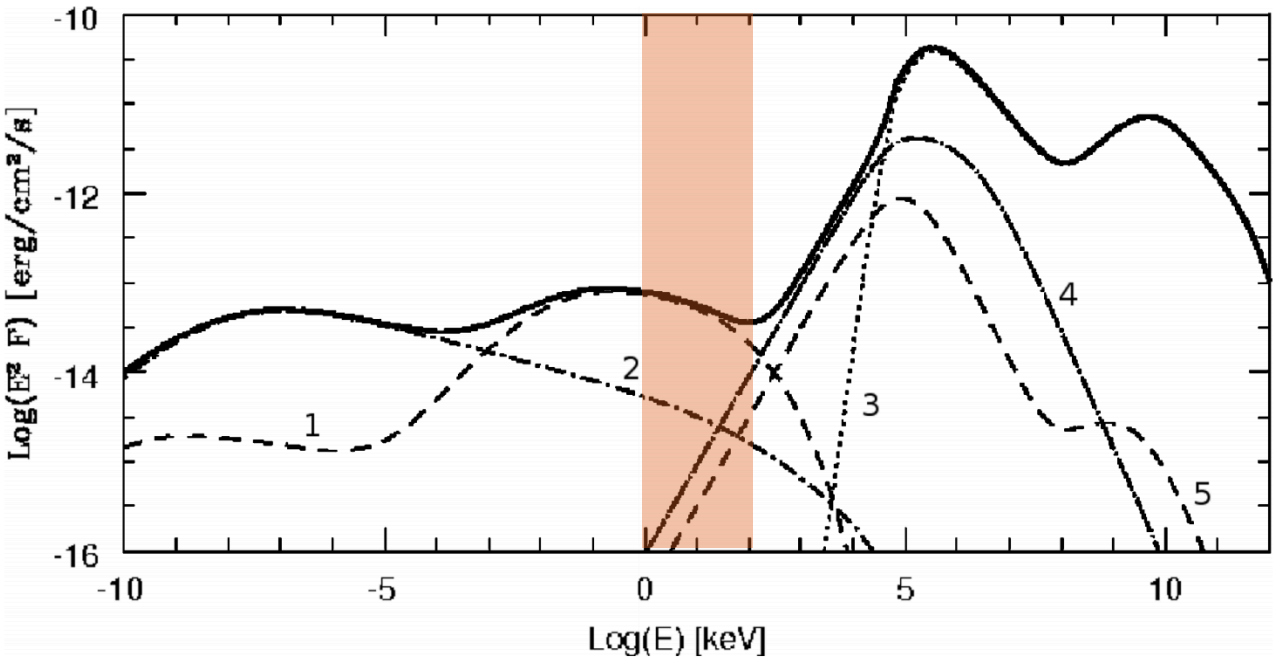


VLA+GBT (Yusef-Zadeh+)



Dashed: CR propagation time
Dotted: energy loss time for CR protons
Solid: energy loss time for CR electrons
Gabici+ (2009)

SED MODEL FOR COSMIC-RAY PROTON AND CLOUD INTERACTION



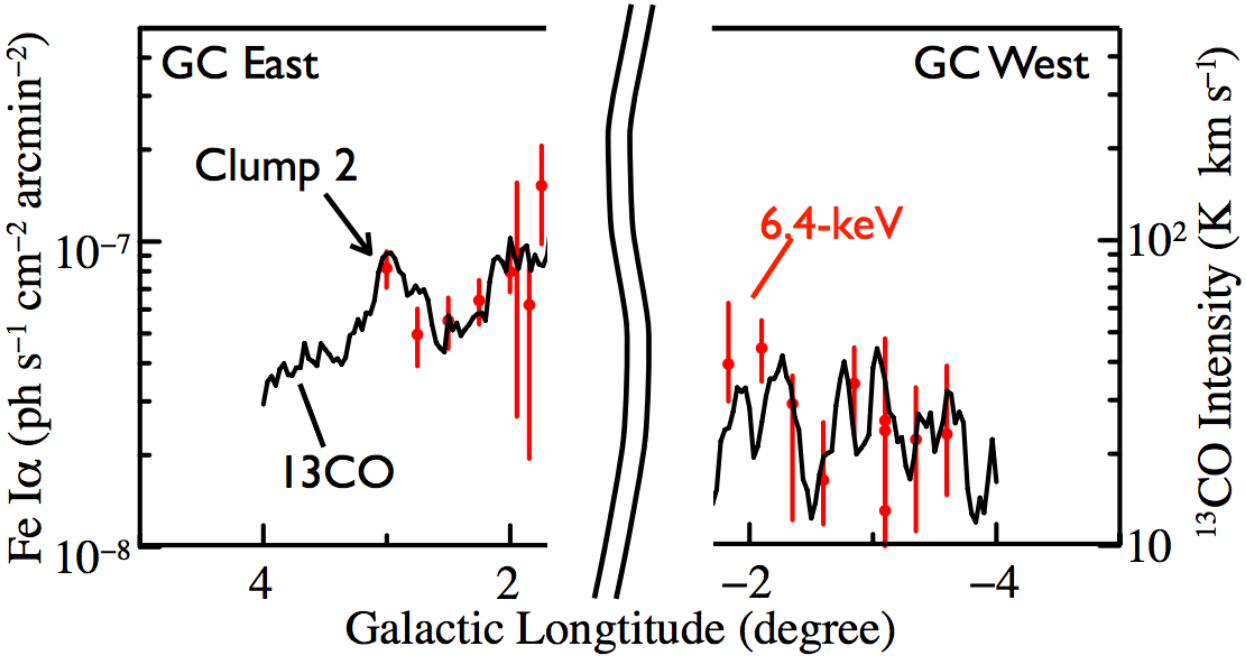
Dotted line: pi-0 decay (curve 3)

Dot-dashed line: synchrotron (2) and bremsstrahlung (4) from bkg CR electrons

Dashed line: synchrotron (1) and bremsstrahlung (5) from secondary electrons

Gabici+ (2009), Tang+ (2011)

FE K INTENSITY ∝ MOLECULE DENSITY IN LARGE SCALE: CR PROTON OR ELECTRON??



Tsuru+ (2014)