MIT KAVLI INSTITUTE

Diverse Origin of Galactic Center X-ray Filaments

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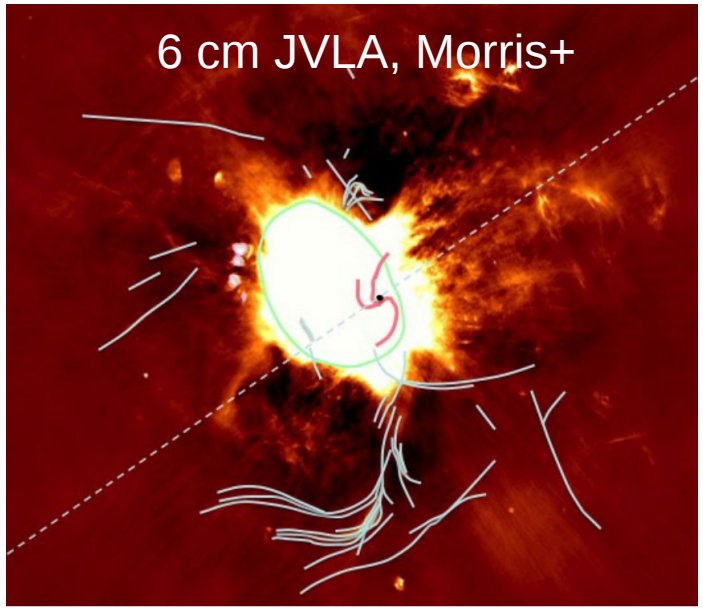
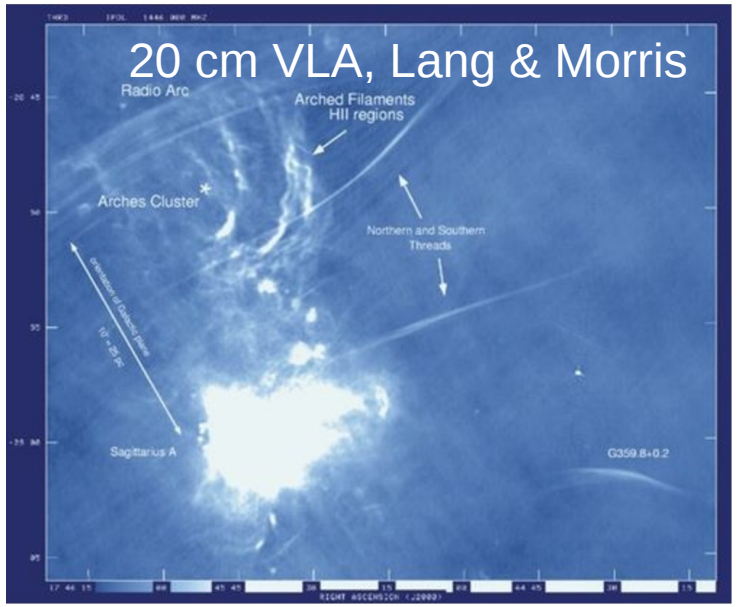
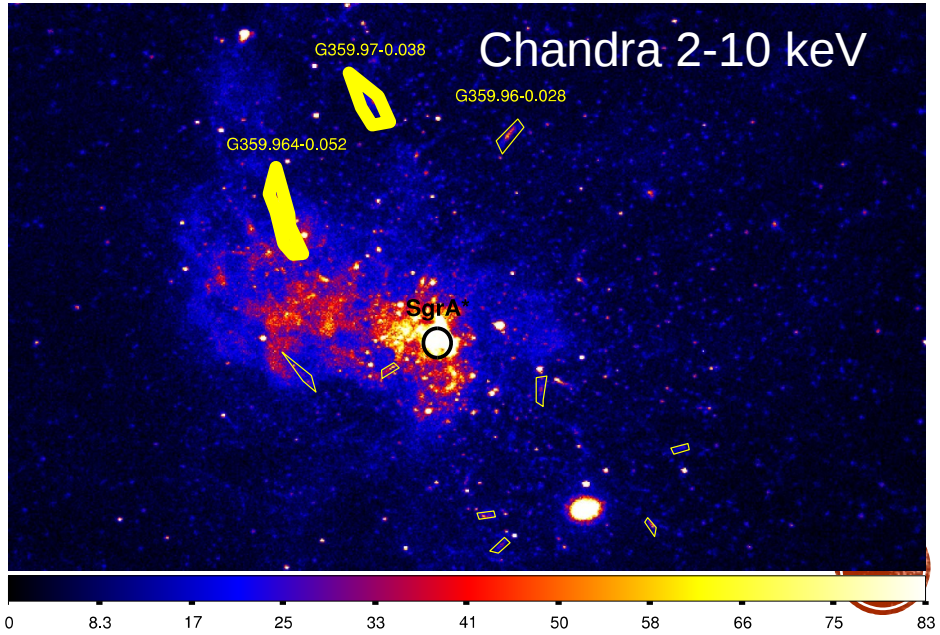
Galactic Center Non-thermal Filaments

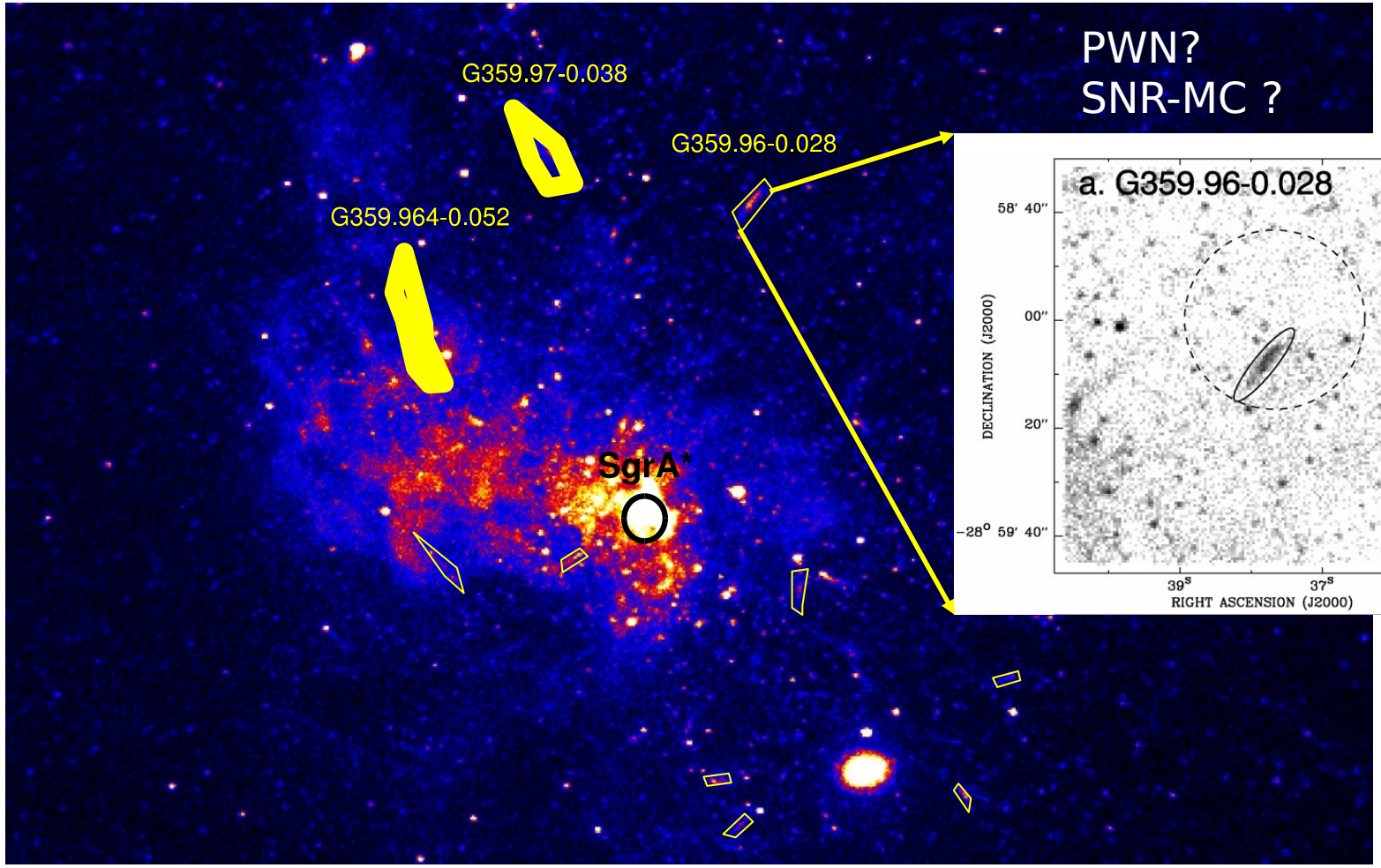
	Radio filaments	X-ray filaments
Number in 2° of GC	~80	~a dozen
length	Up to ~10s of pcs	A few pcs
Polarization	detected	---
Feeding source	GeV electrons	TeV electrons
Origin of CRs	Particle acceleration Dark matter annihilation	Particle acceleration

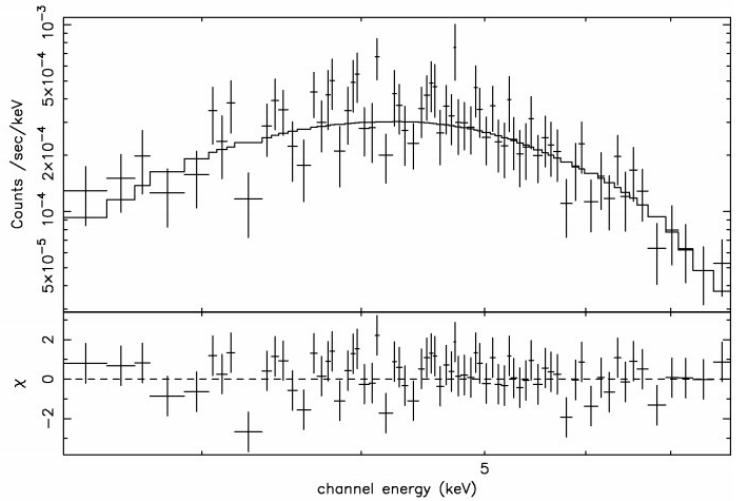






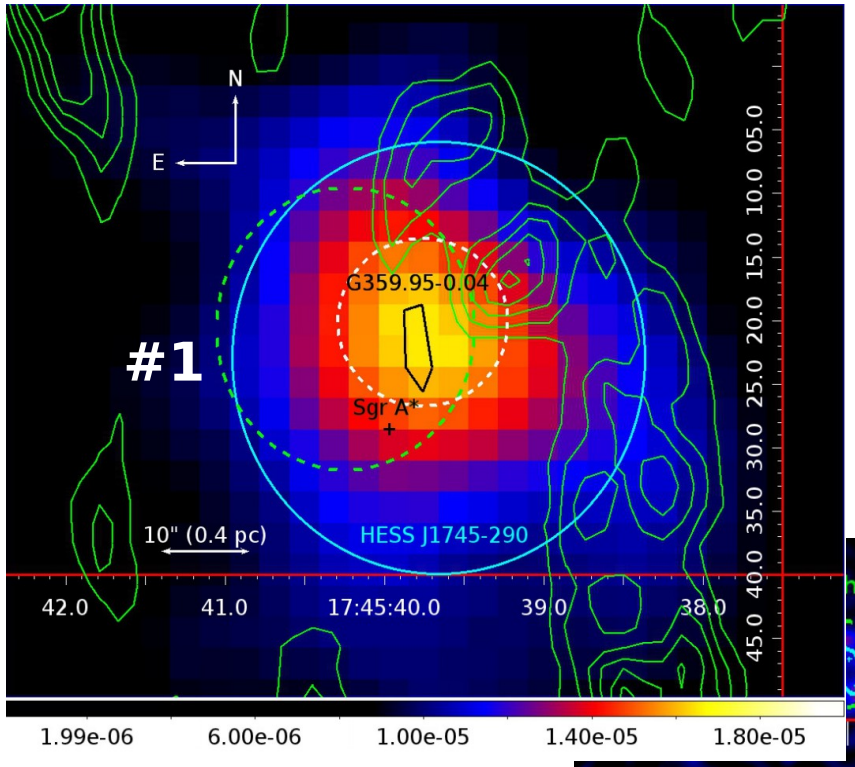
X-ray Filaments Detected within ~10 pc of Sgr A*

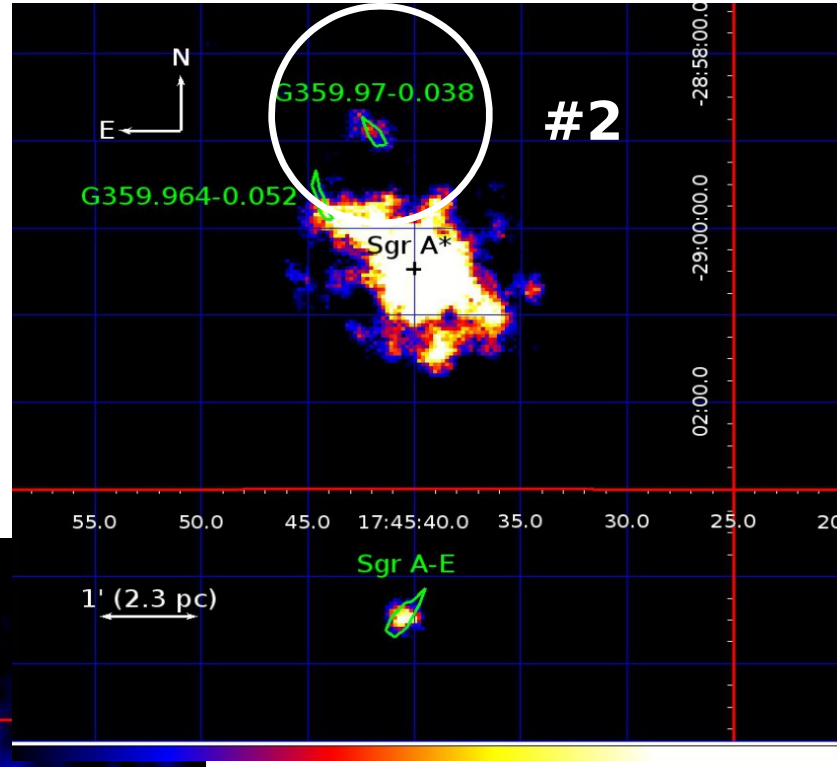


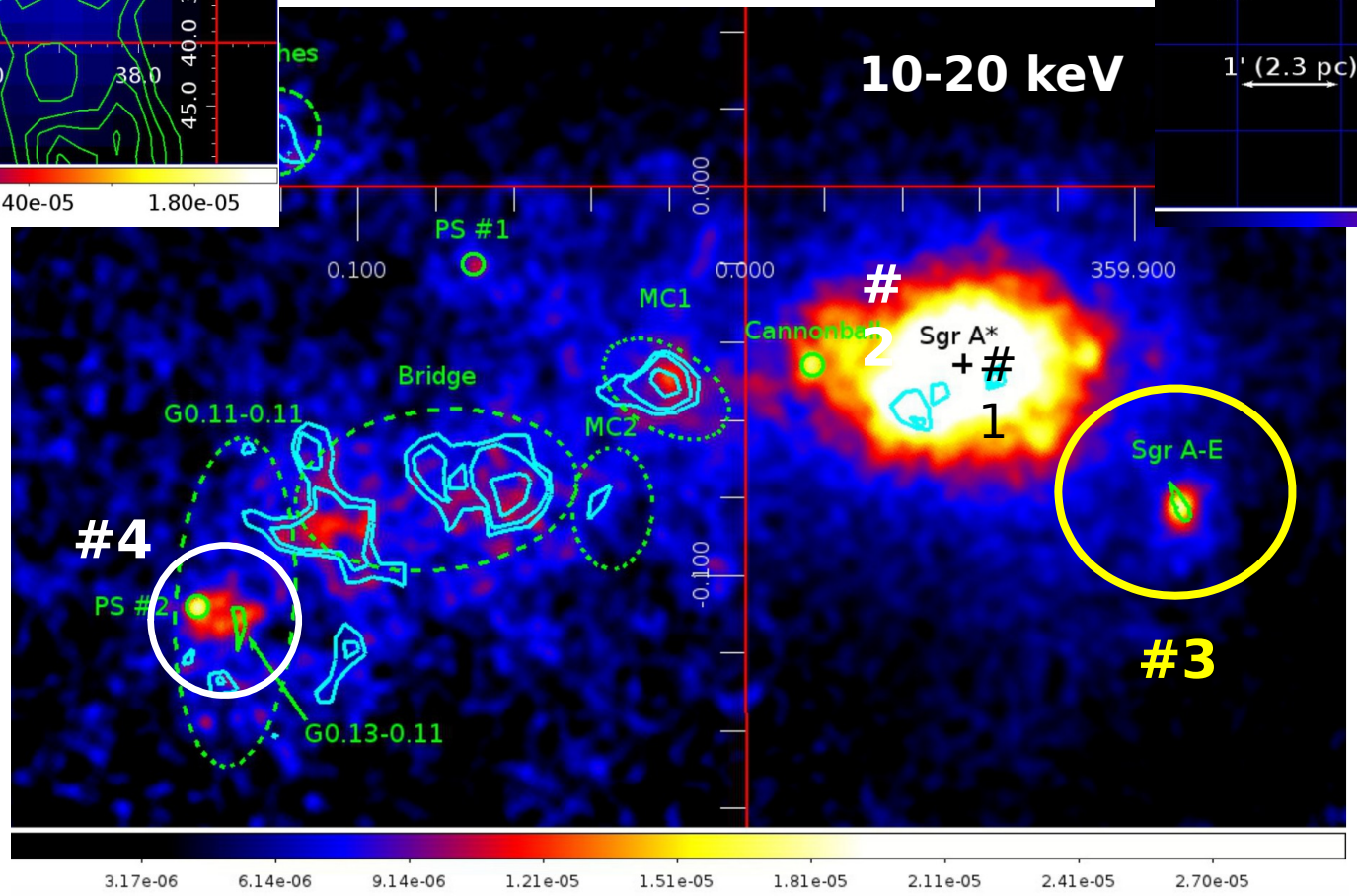


Johnson+ 2009
Based on ~2Ms Chandra observations
from 1999-2007

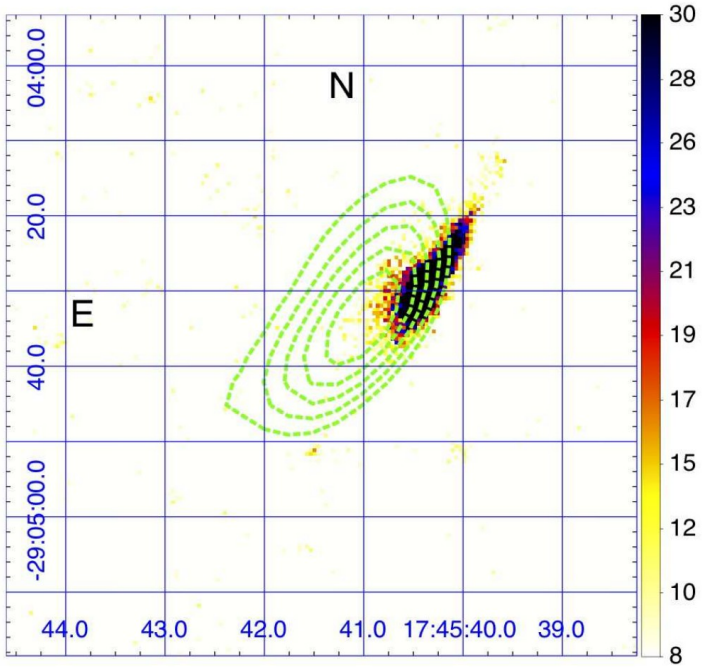
4 detected by by NuSTAR
Are they of
the same origin?



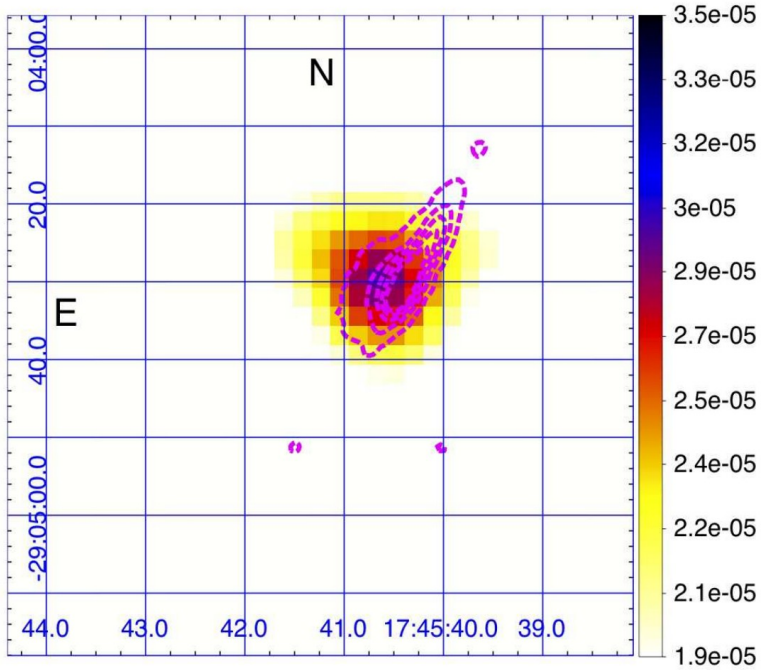




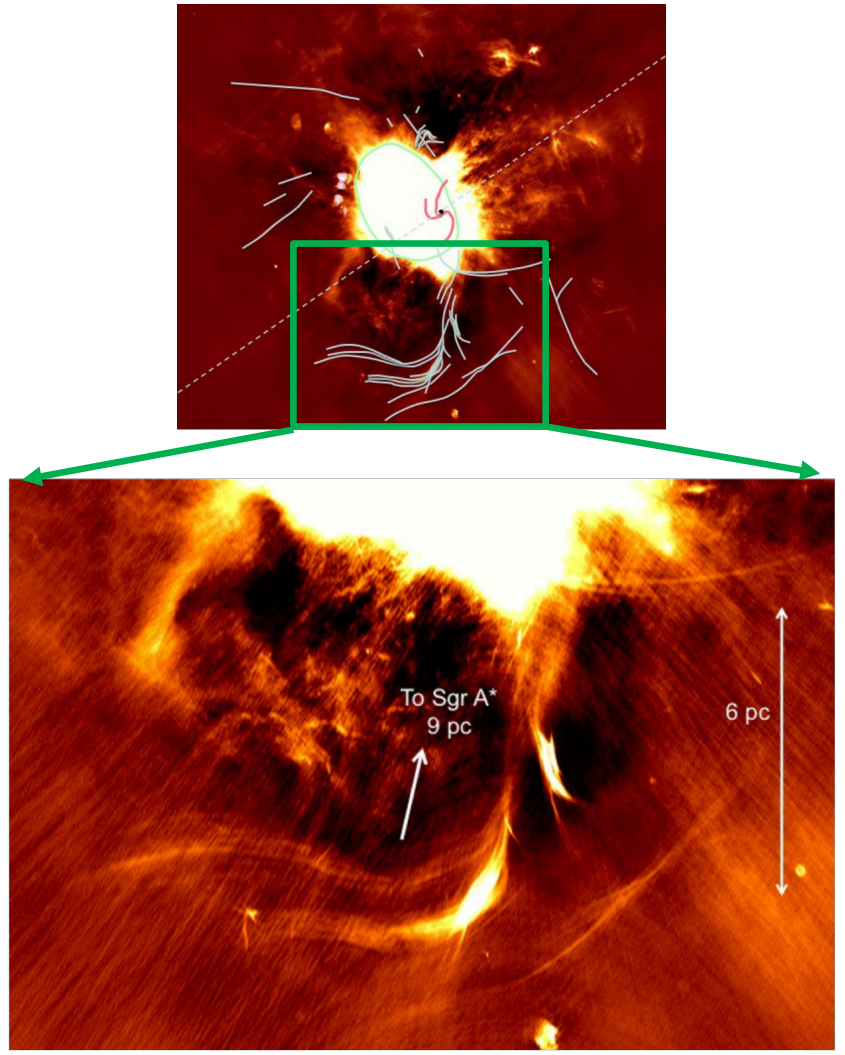
Brightest X-ray filament (Sgr A-E): A Magnetic Filamentary Structure 100 TeV Electrons in the GC



Chandra 2−10 keV with VLA 20-cm continuum contours.



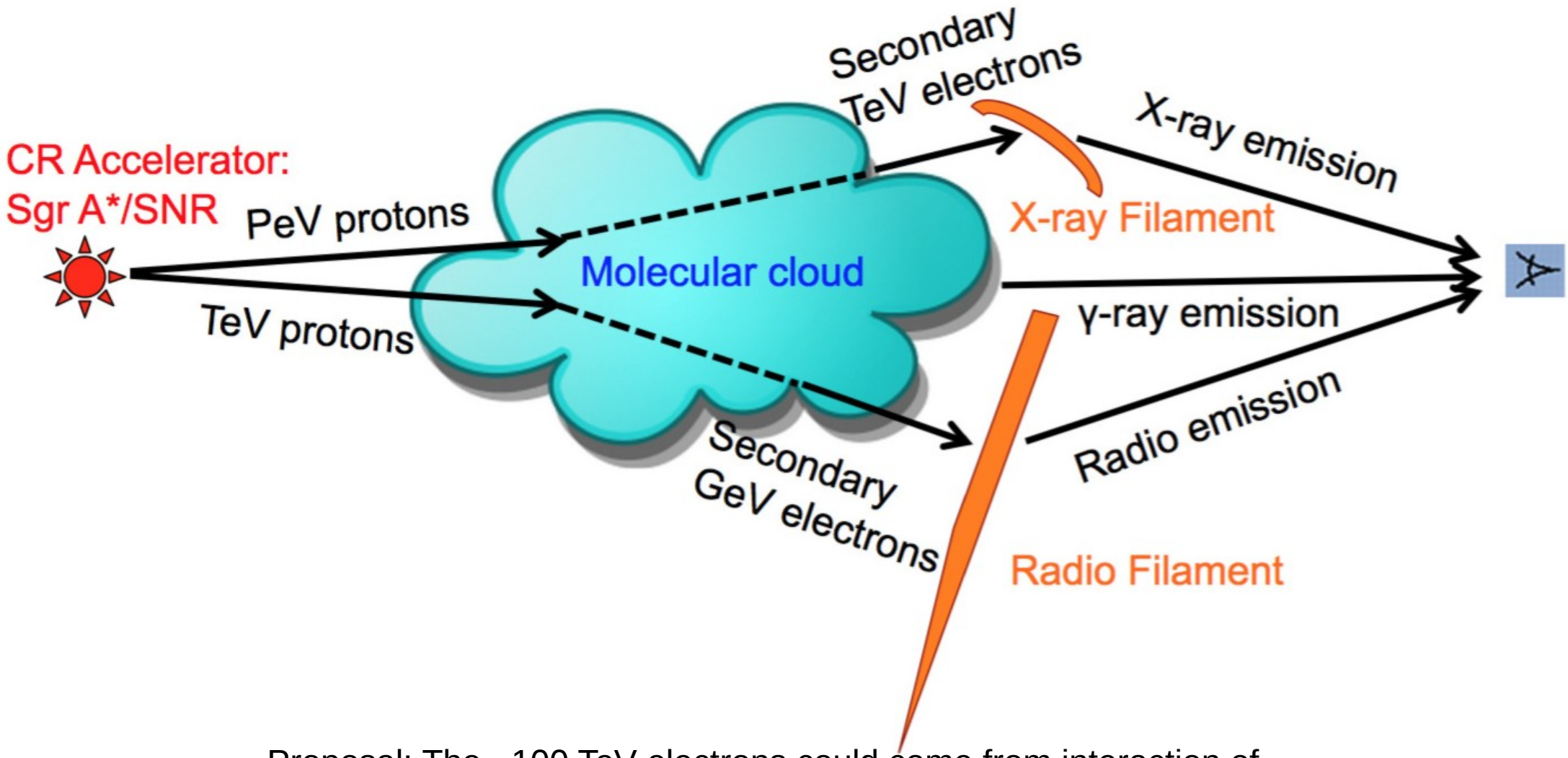
NuSTAR 10-50 keV with Chandra 2-10 keV contours (Zhang+ 2014).



JVLA 6-cm (Morris+ 2014)

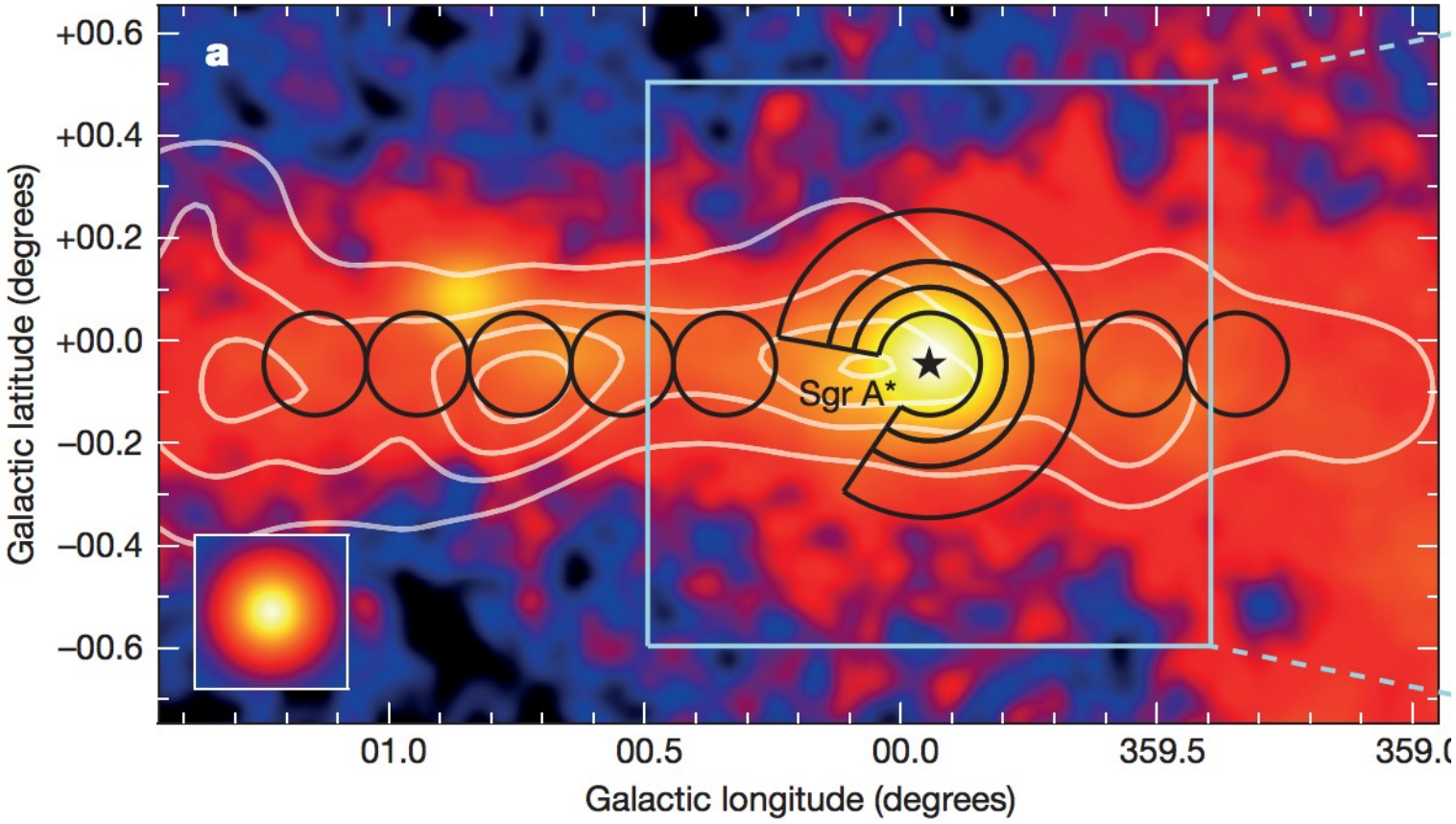
Featureless Power-law with Γ=2.3+/-0.2. Synchrotron up to 50 keV with B=100-300 μG requires 100-200 TeV CR electrons. Origin??
Particle Accelerator: BH, SNR, PWN?

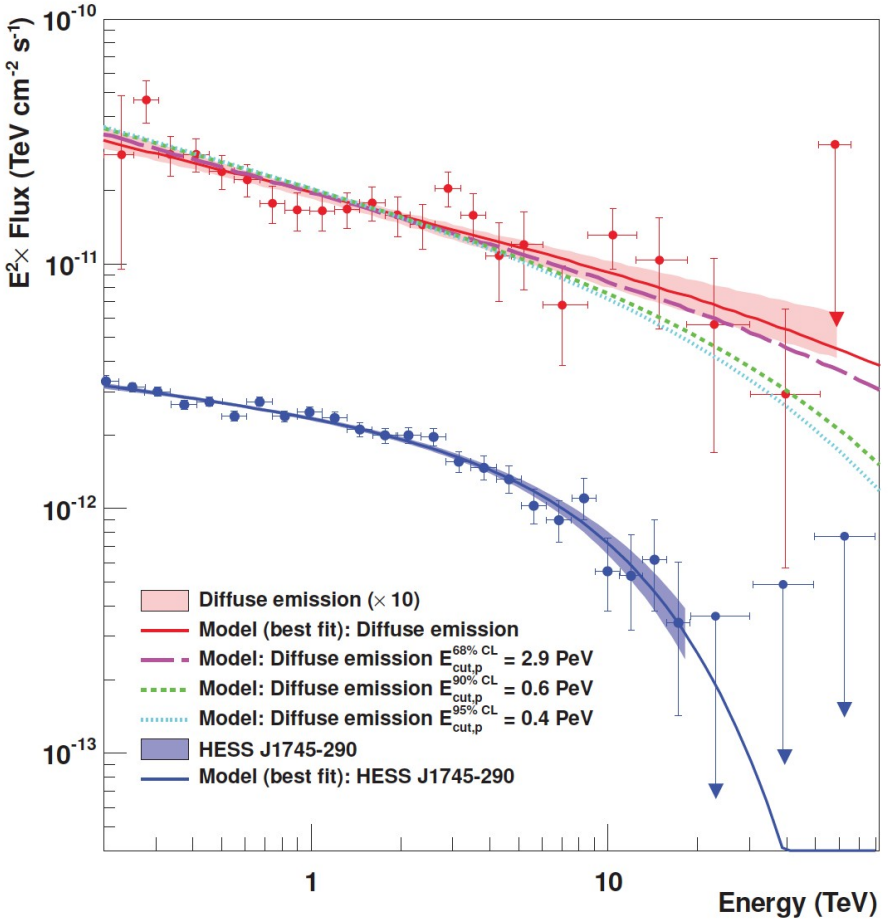
A Hypothesis of the Origin of TeV Electrons



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

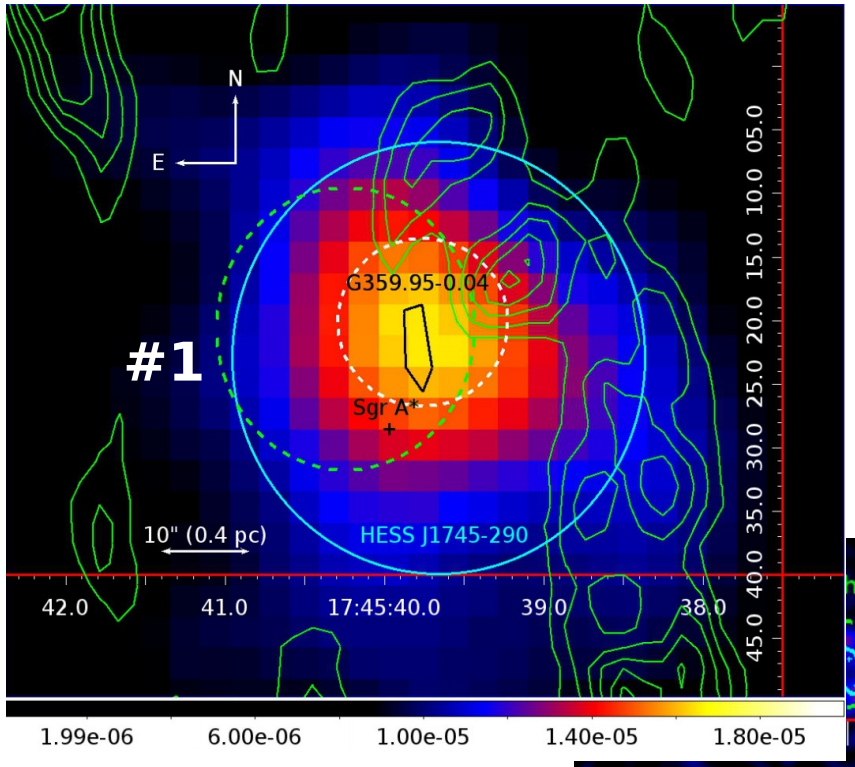
Supported by recent HESS GC Nature paper: There could be a PeVatron the GC!

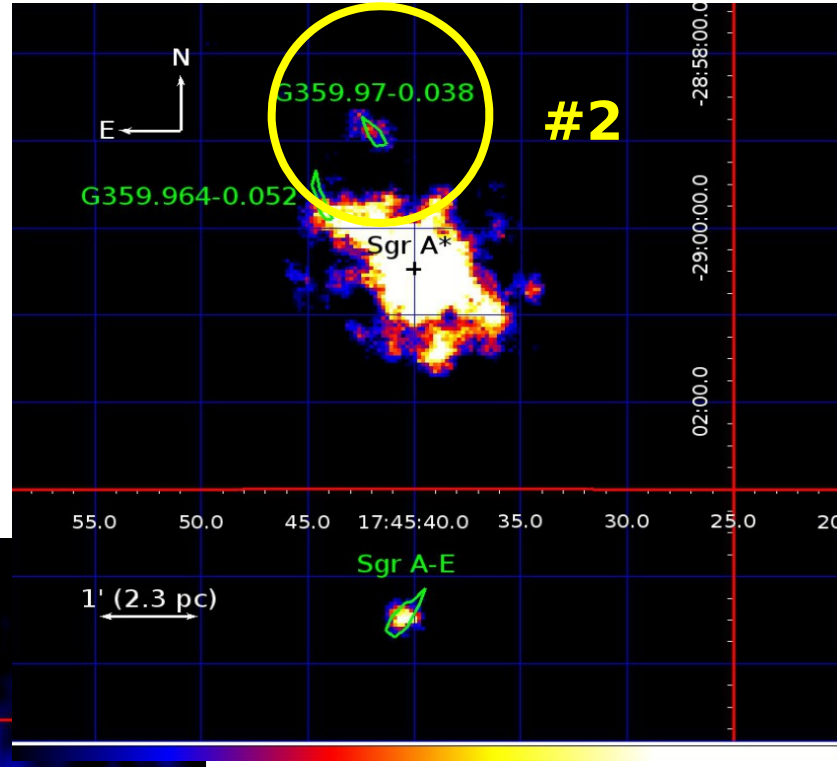


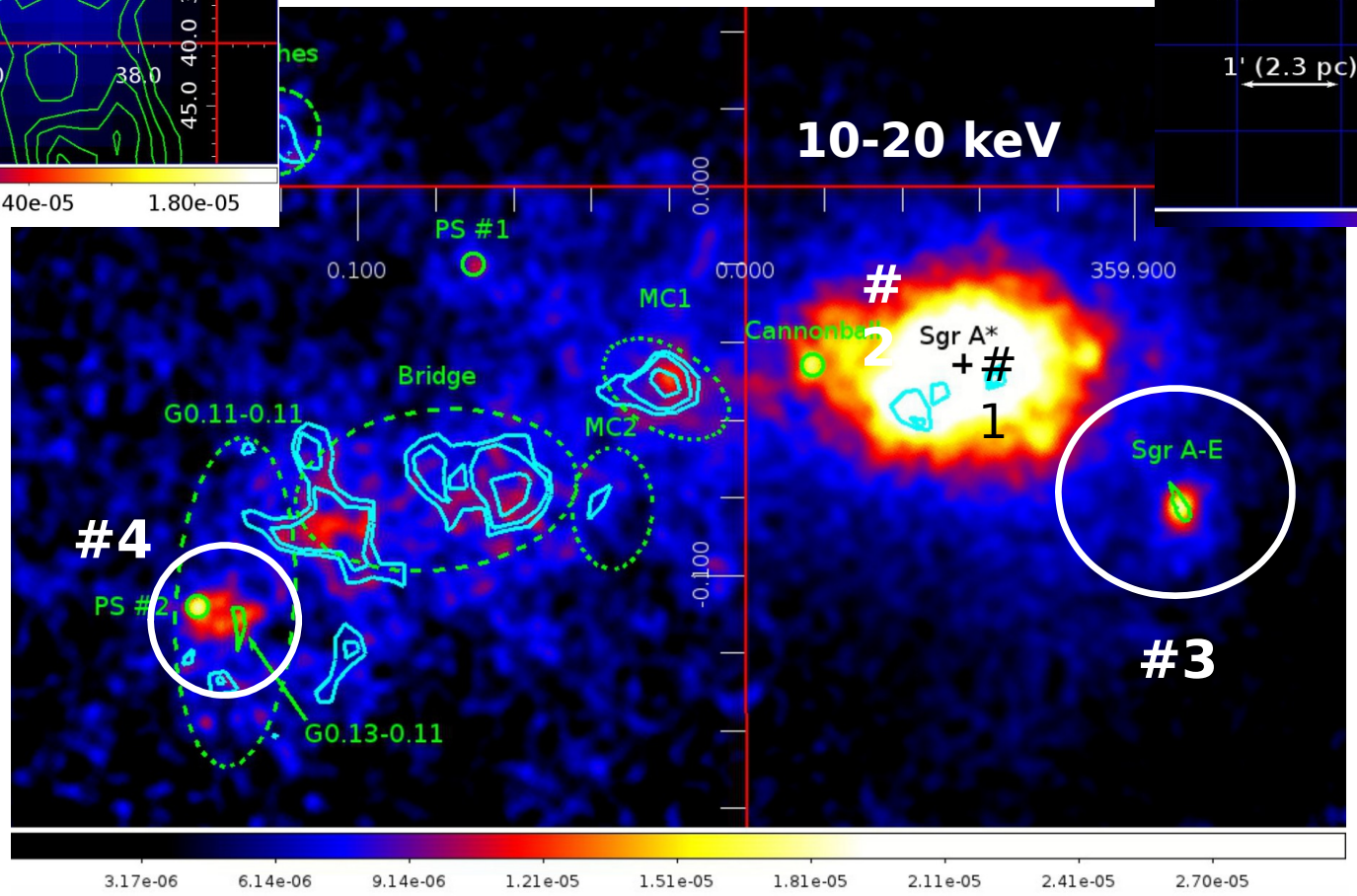


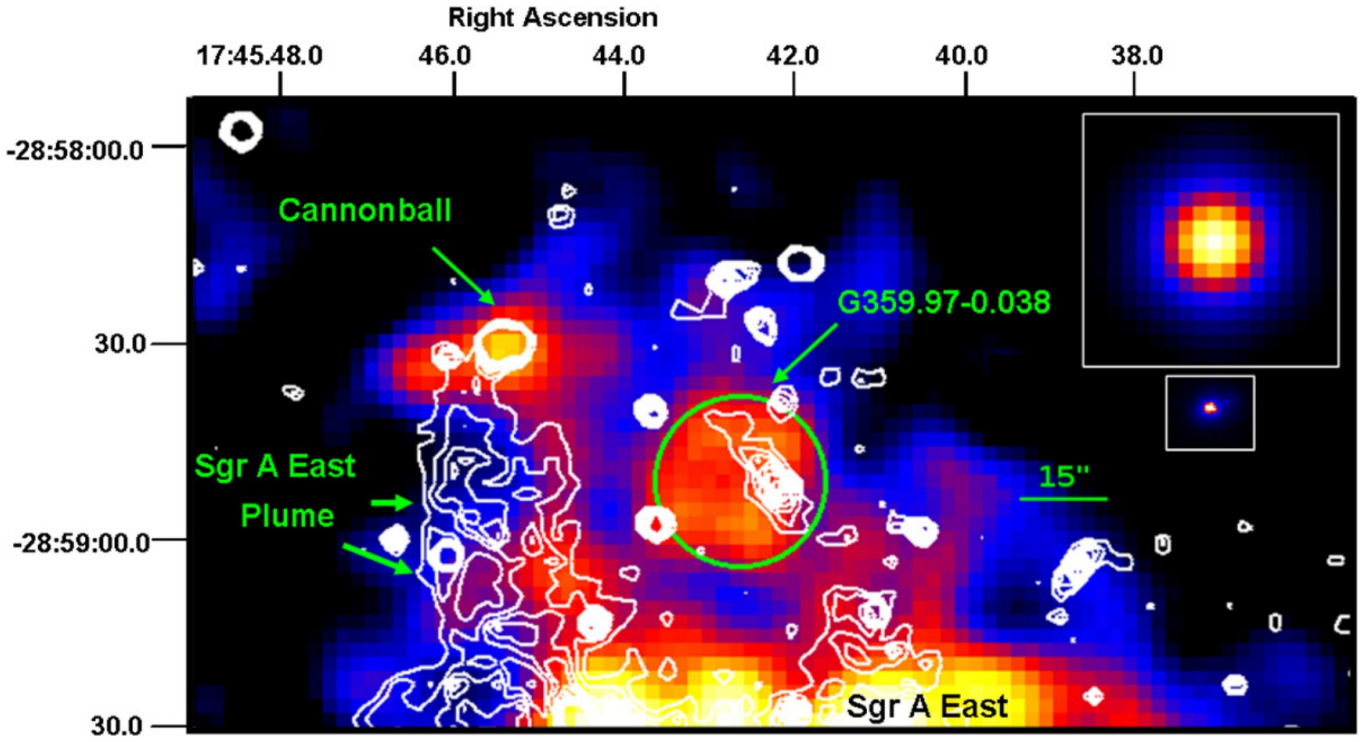
HESS collaboration (2016) Nature

4 detected above 10 keV
Are they of
the same origin?

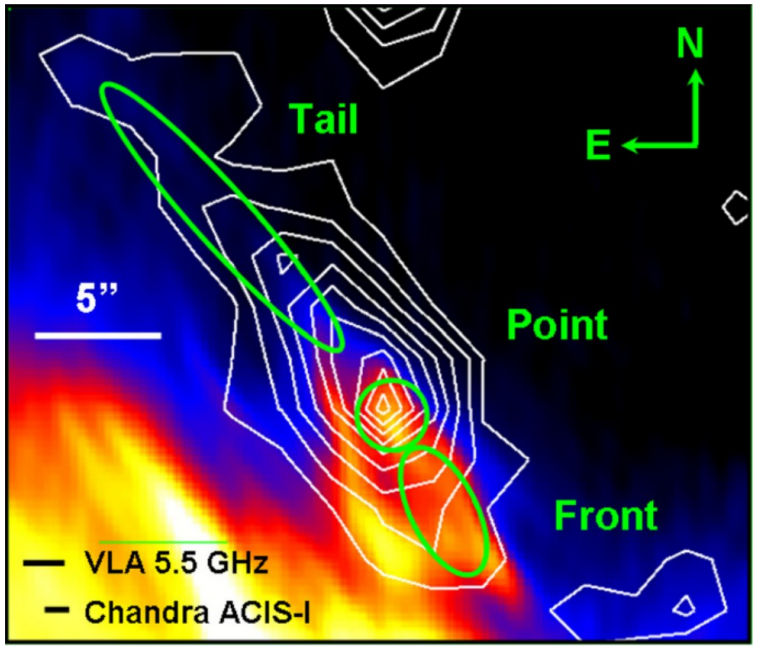








NuSTAR 10–40 keV mosaicked and exposure map corrected image overlaid with Chandra 2-8 keV contours.



5.5 GHz VLA image centered on G359.97- 0.038. overlaid with Chandra contours.

Nynka, Hailey, Zhang et al. (2015)

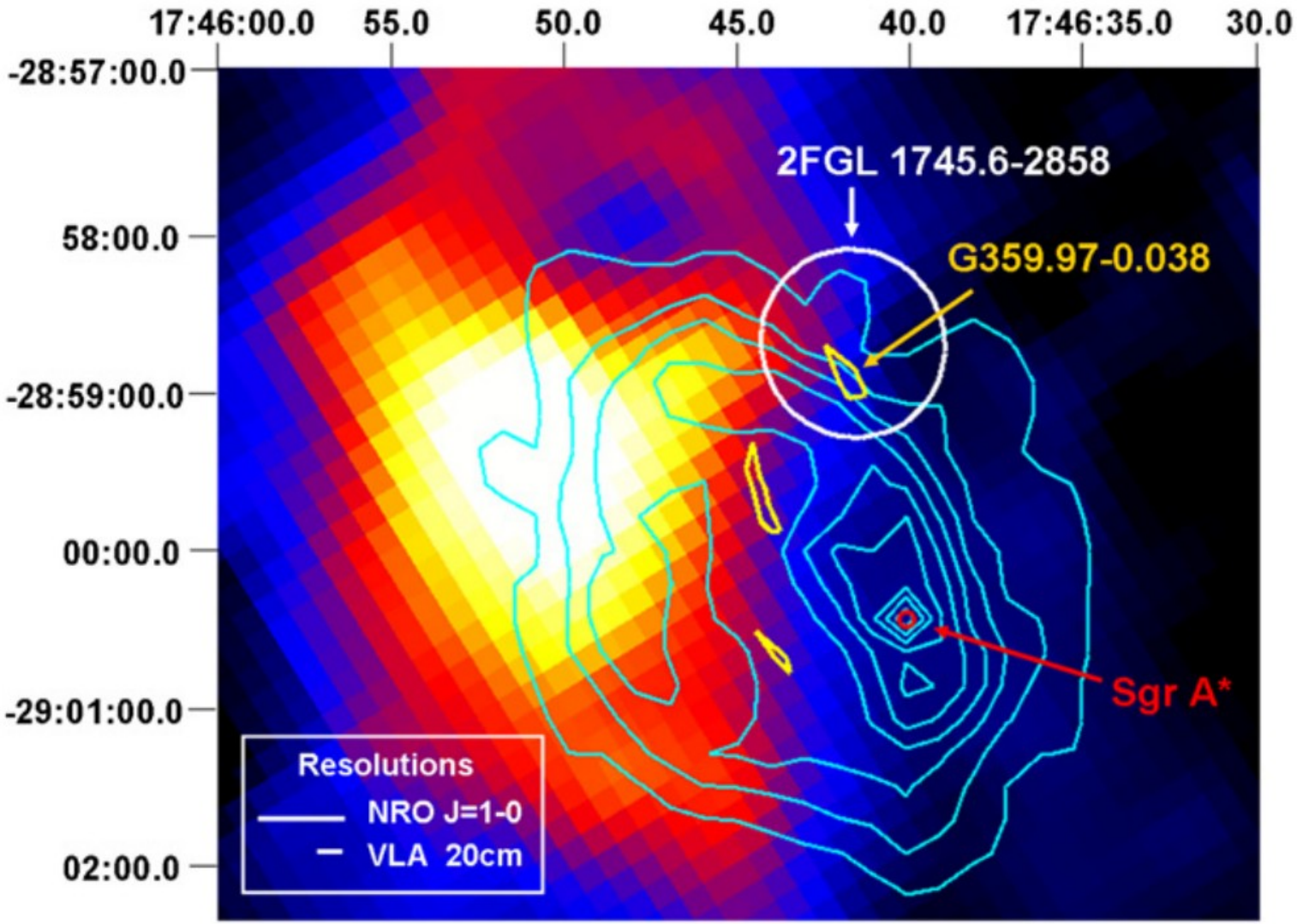
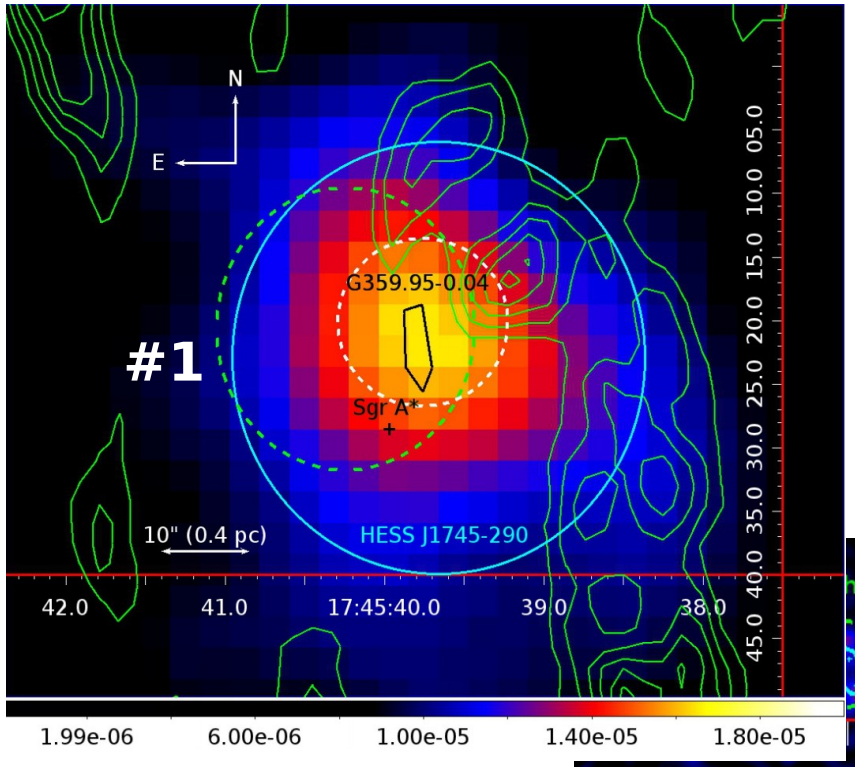
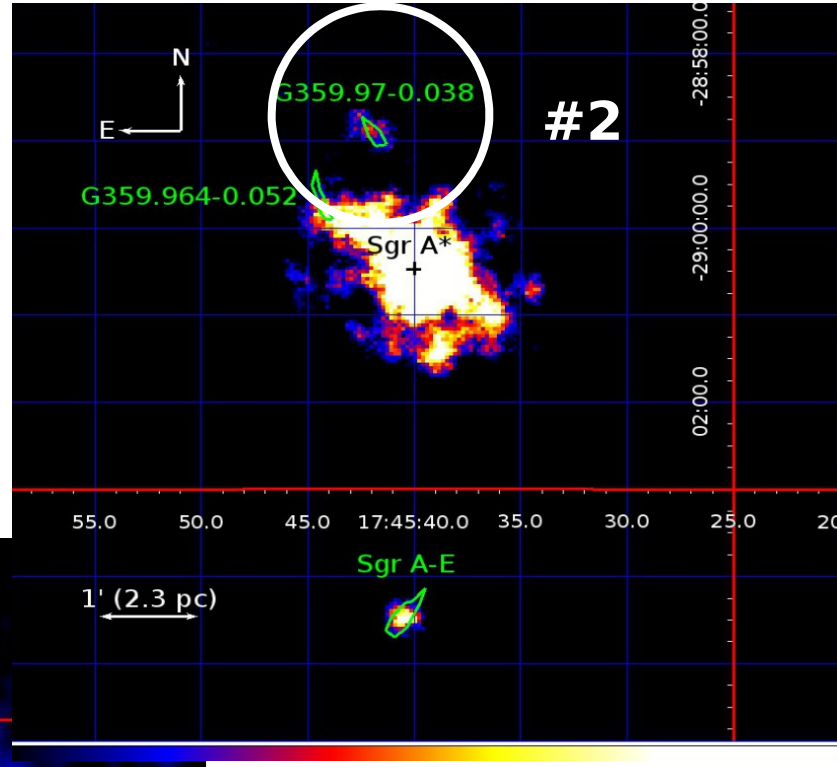
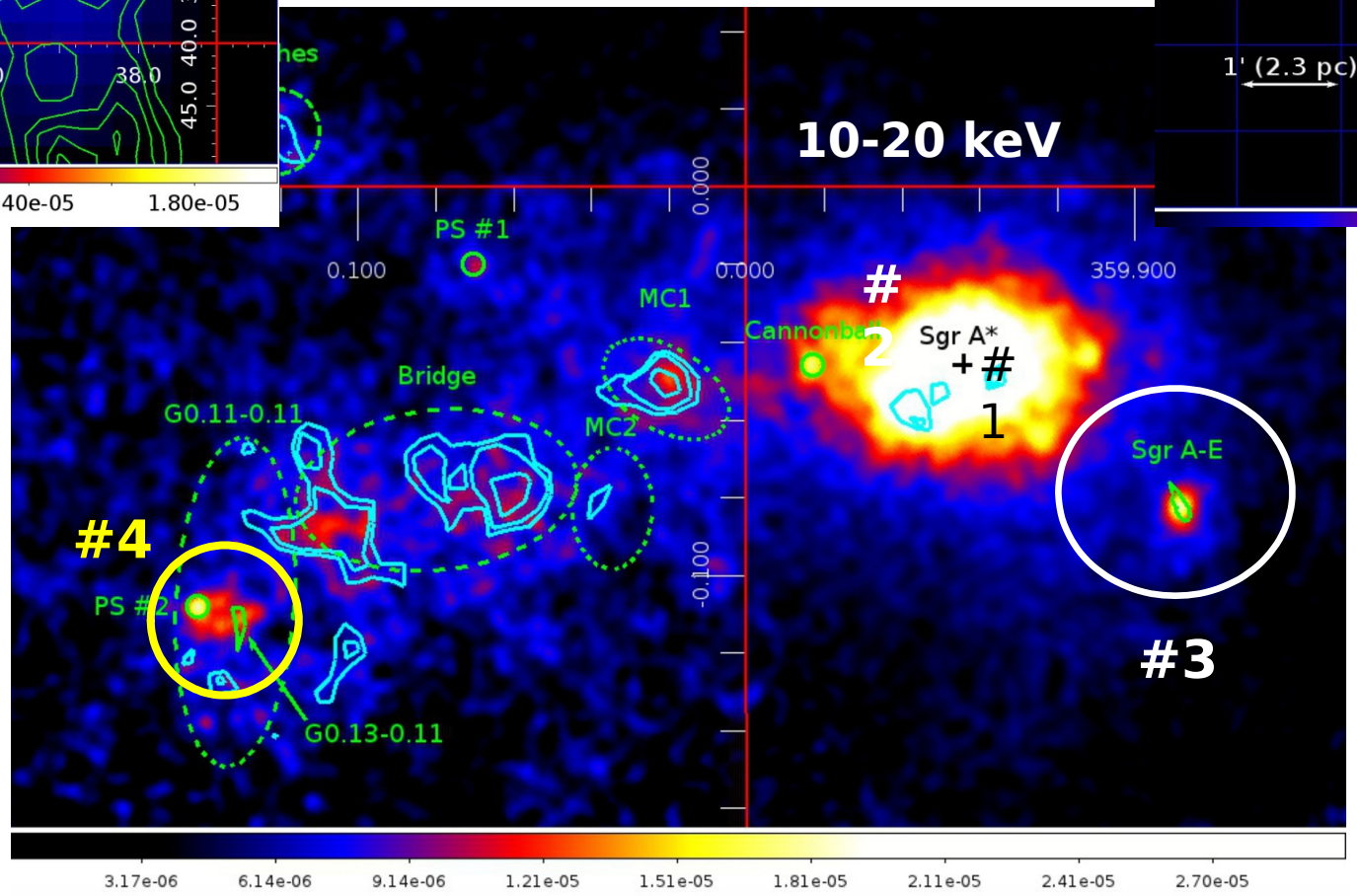


Image of CS J = 1–0 emission obtained (NRO 45 m telescope)
location of the 50 km s−1 cloud (M-02-0.07).
Cyan contour: Sgr A East (from a 20 cm VLA map)
Yellow regions: G359.97-0.038 + two other Chandra X-ray filaments

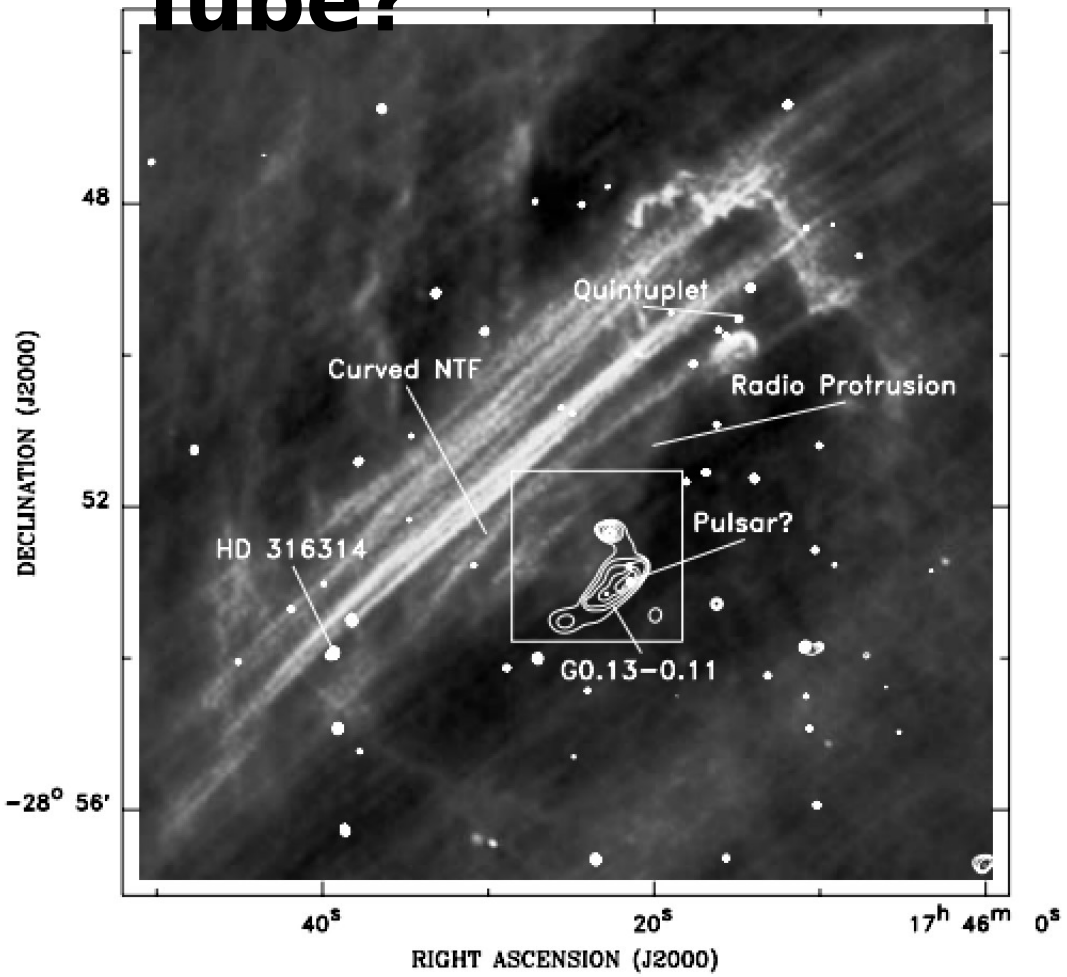
4 detected above 10 keV
Are they of
the same origin?



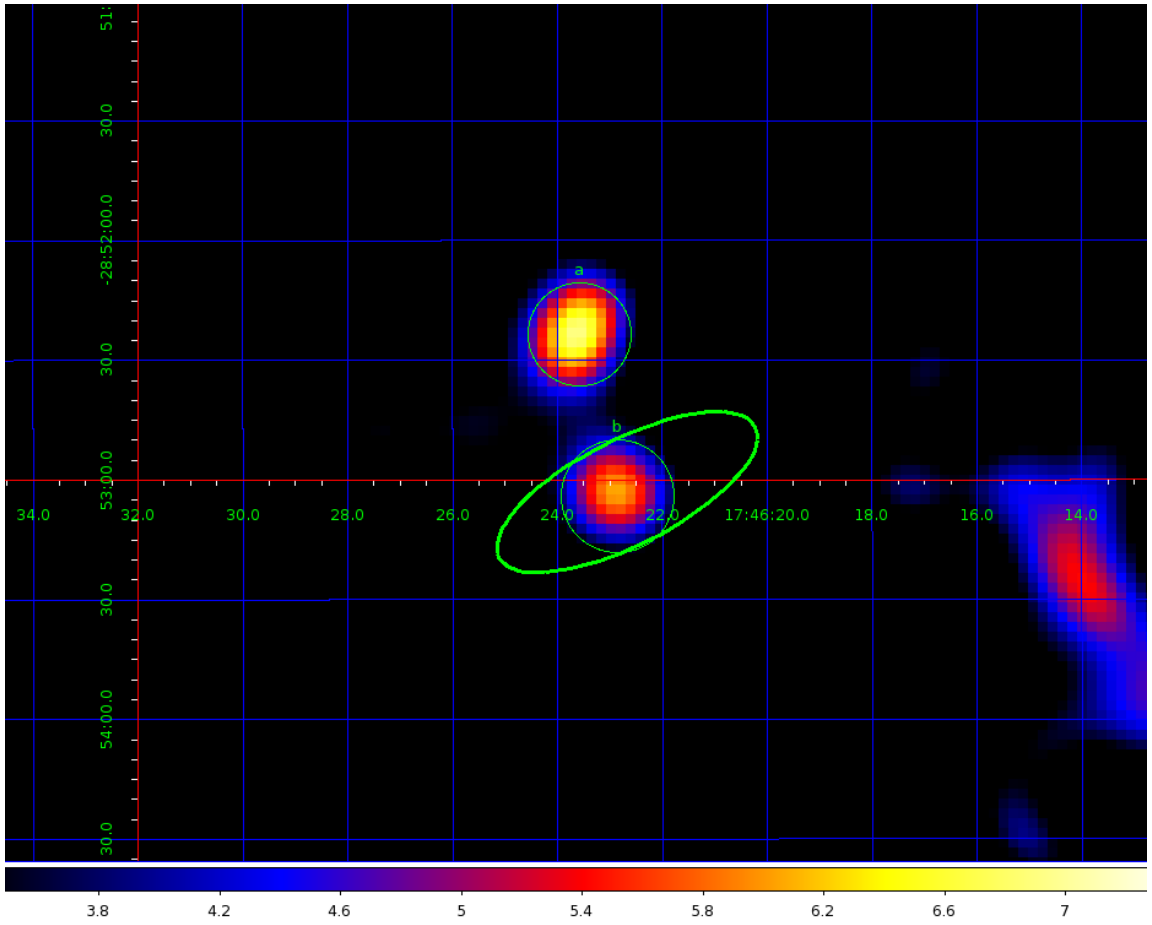




#4 (0.13-0.11): PWN or Magnetic Flux Tube?



VLA 6-cm overlaid with Chandra 2-6 keV contours (Wang+ 2002)



NuSTAR deconvolved image

Zhang+ in prep.

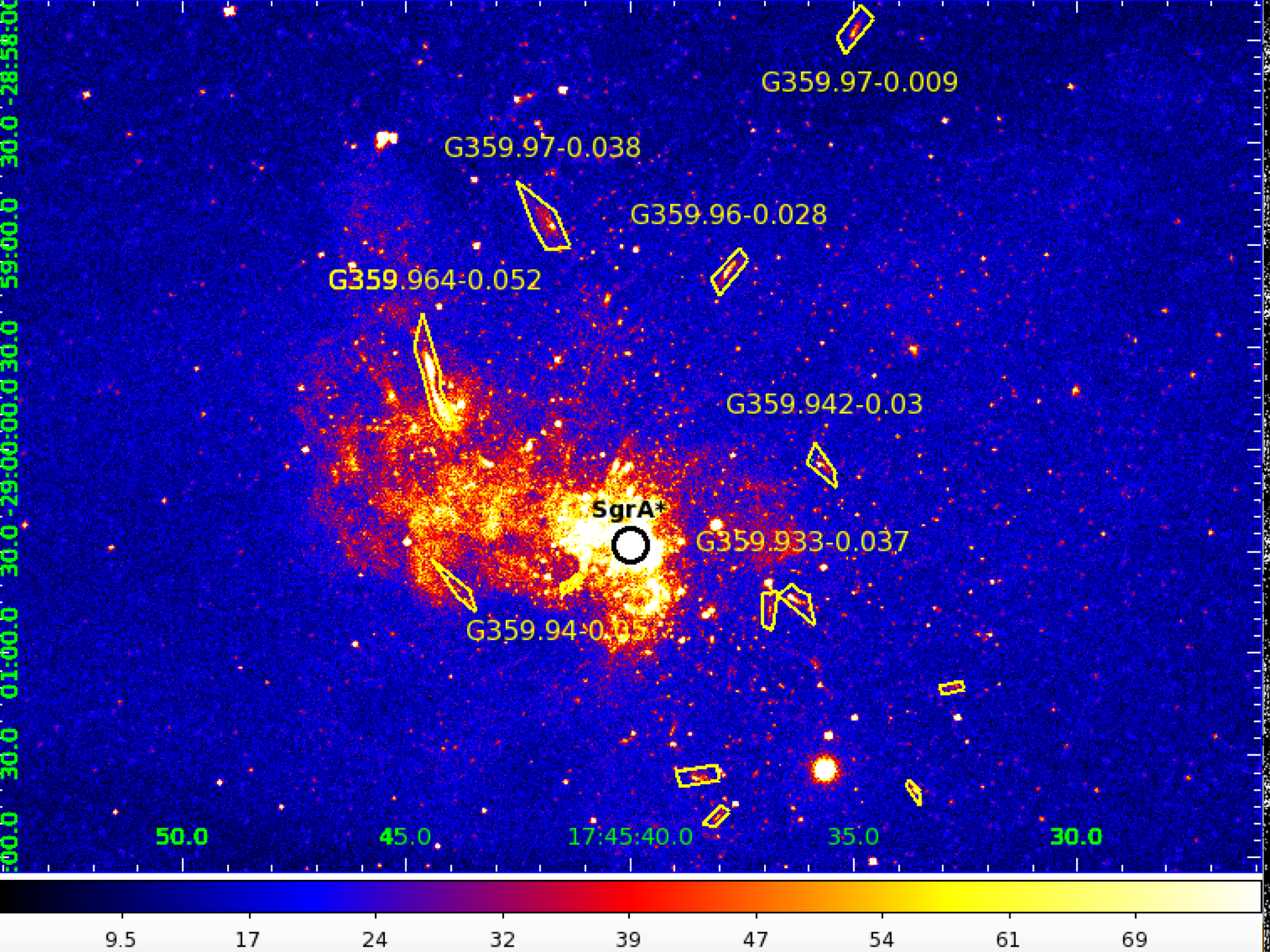
Three Scenarios for Non-thermal X-ray Filaments

- **PWN (e.g. #1, G359.95-0.04) Are # of PWN as expected in GC?**
  - Morphology: Point-like source + tail
  - Spectroscopy: Spectral hardening towards the point source
  - Signature: Timing: Pulsation detection **- Lynx**

- **Magnetic flux tube (e.g. #3, Sgr A-E) Probing GC particle accelerator**
  - Morphology: sub filaments; attached to Molecular clouds
  - Spectroscopy: Feature-less power-law spectrum
  - Signature: sub-filaments along B filed lines **– X-ray polarization**

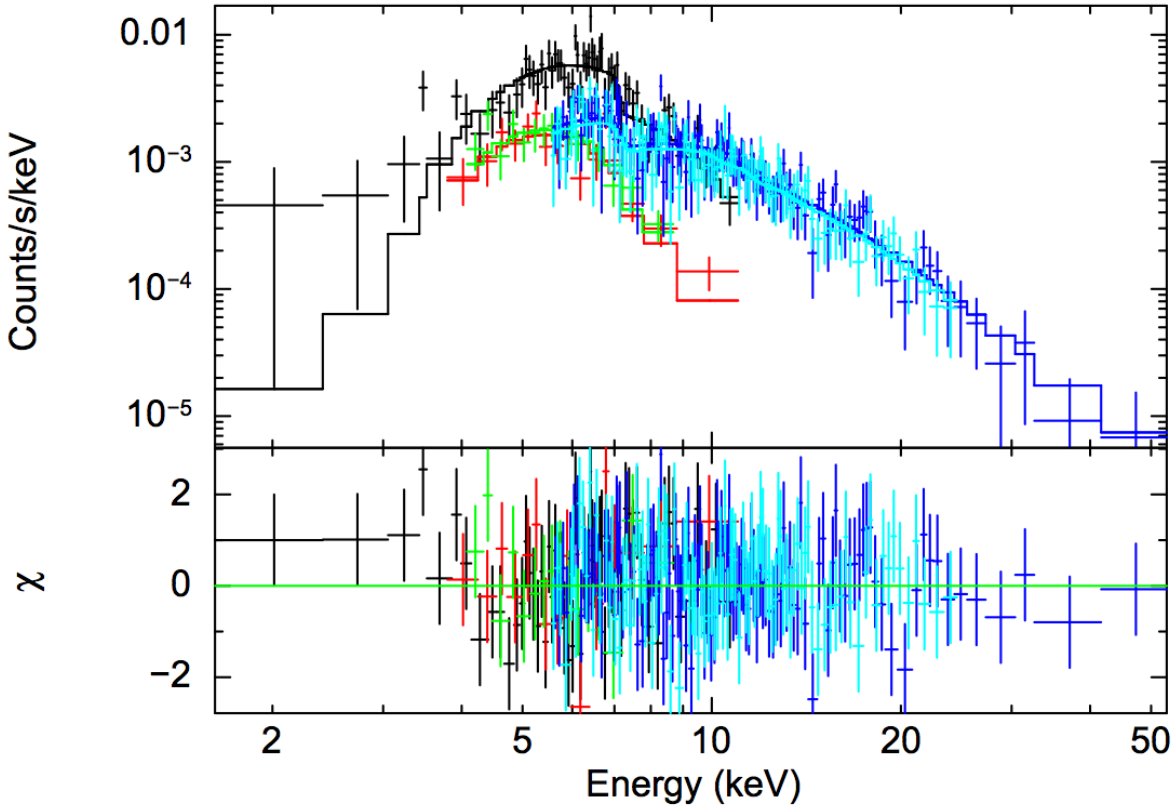
- **SNR-cloud (e.g. #2 G359.97-0.038) Understanding SNR particle acceleration**
  - Morphology: along SNR shells
  - Spectroscopy: Hard power-law spectrum, spectral evolution along minor axis
  - Signature: Shock-cloud signatures like OH masers

- **#4 (G0.13-0.11): ?**


G359.97-0.009
G359.97-0.038
G359.96-0.028
G359.964-0.052
G359.942-0.03
SgrA*
G359.933-0.037
G359.94-0.05
50.0
45.0
17:45:40.0
35.0
30.0
-28:58:0
30.0
59:00.0
30.0
29:00:00.0
30.0
01:00.0
30.0
:00.0
9.5
17
24
32
39
47
54
61
69

BACK-UP SLIDES

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



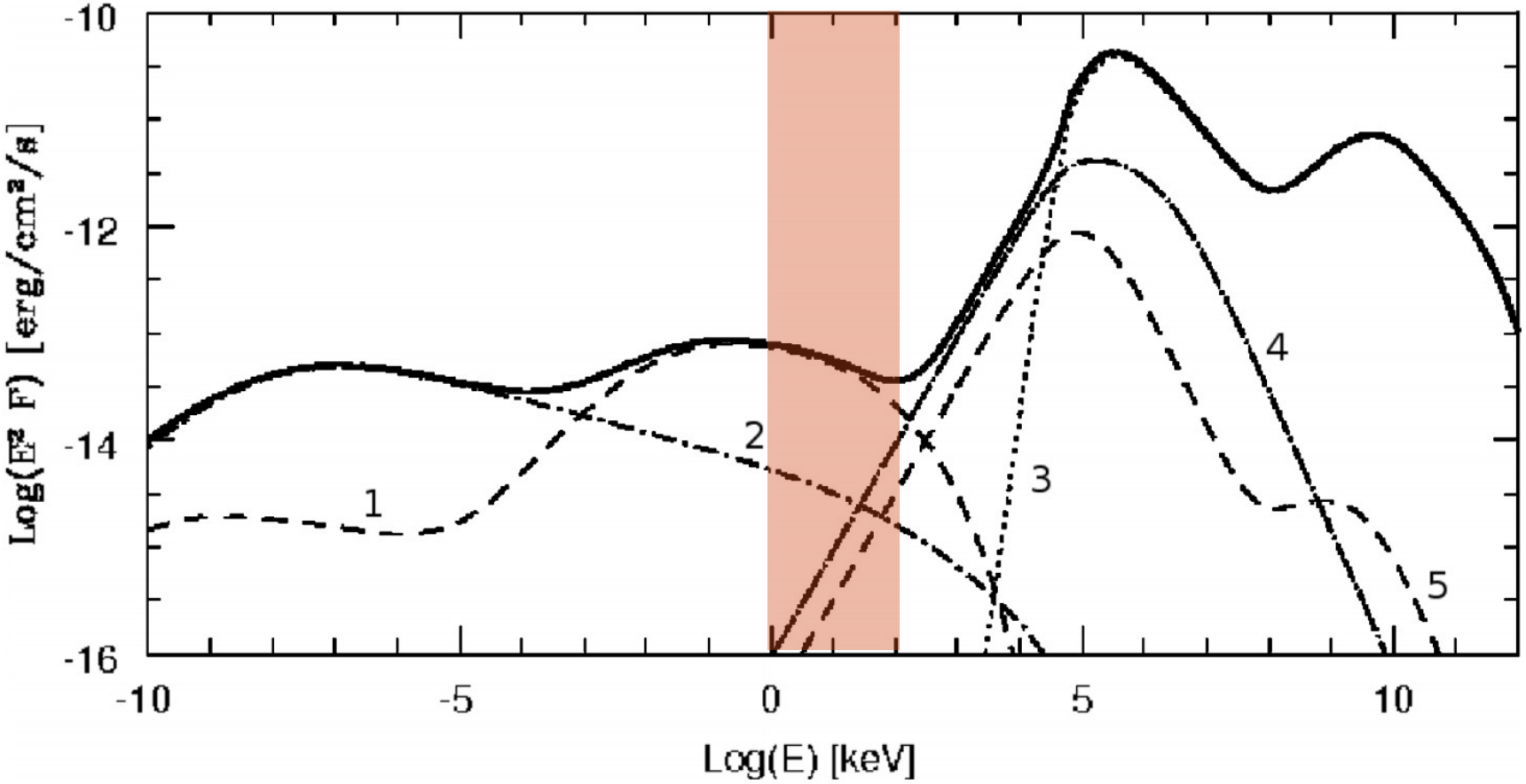
Feature-less power-law spectrum up to 50 keV; Spectral indices of consistent with synchrotron emission from radio to X-rays.

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)

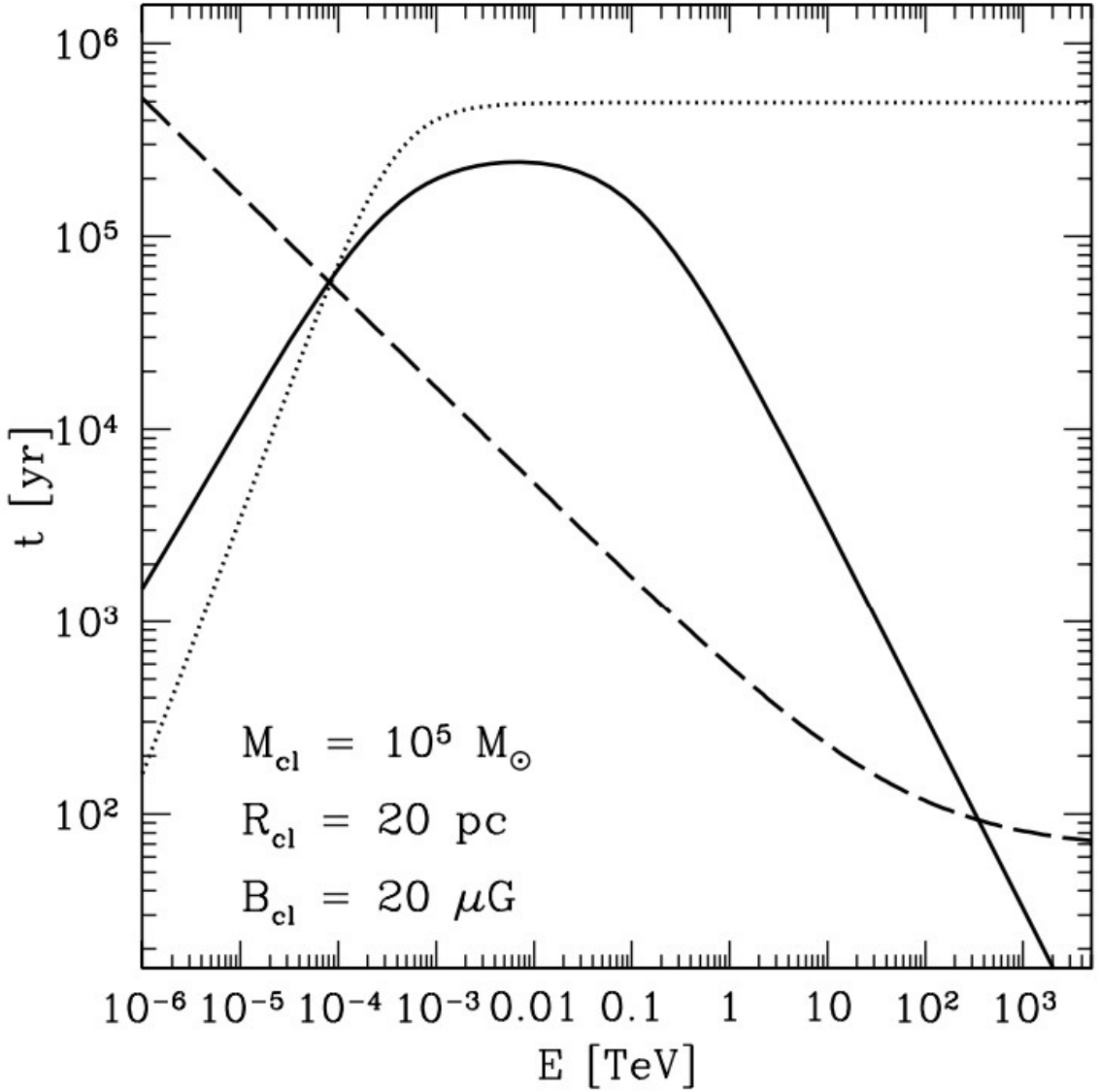
NuSTAR+XMM spectra of Sgr A-E. The synchrotron emission up to ~50 keV with B=100-300 μG requires 100-200 TeV CR electrons.
Origin??
Particle acceleration:
Accelerator: BH, SNR, PWN?

SED MODEL FOR COSMIC-RAY PROTON AND INTERACTION



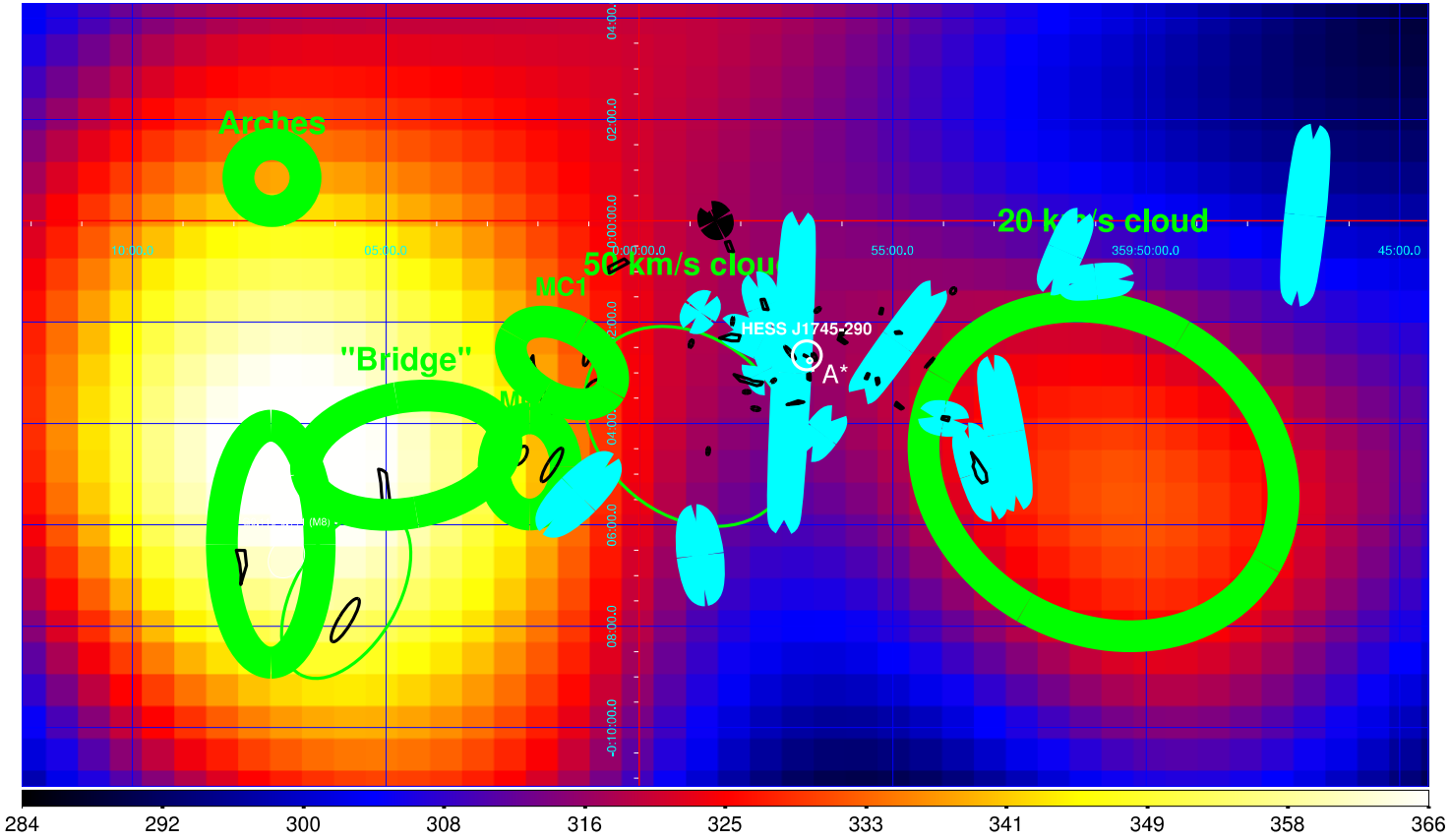
Dotted line: pi-0 decay (curve 3)
Dot-dashed line: synchrotron (2) and bremsstrahlung (4) from bkg CR electrons
Dashed line: synchrotron (1) and bremsstrahlung (5) from secondary electrons

Gabici+ (2009), Tang+ (2011)



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

PROBING GC COSMIC-RAYS AND MAGNETIC FILED TURBULENCE 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)

- **Identify** more magnetic magnetic structures.
- **Build** PeV CR proton-cloud interaction model, predicting secondary electron spectrum and compare with that required by the magnetic filaments.
- **Measure** magnetic field structures within the filament with future X-ray polarimeters (IXPE, XIPE, eXTP, etc.)