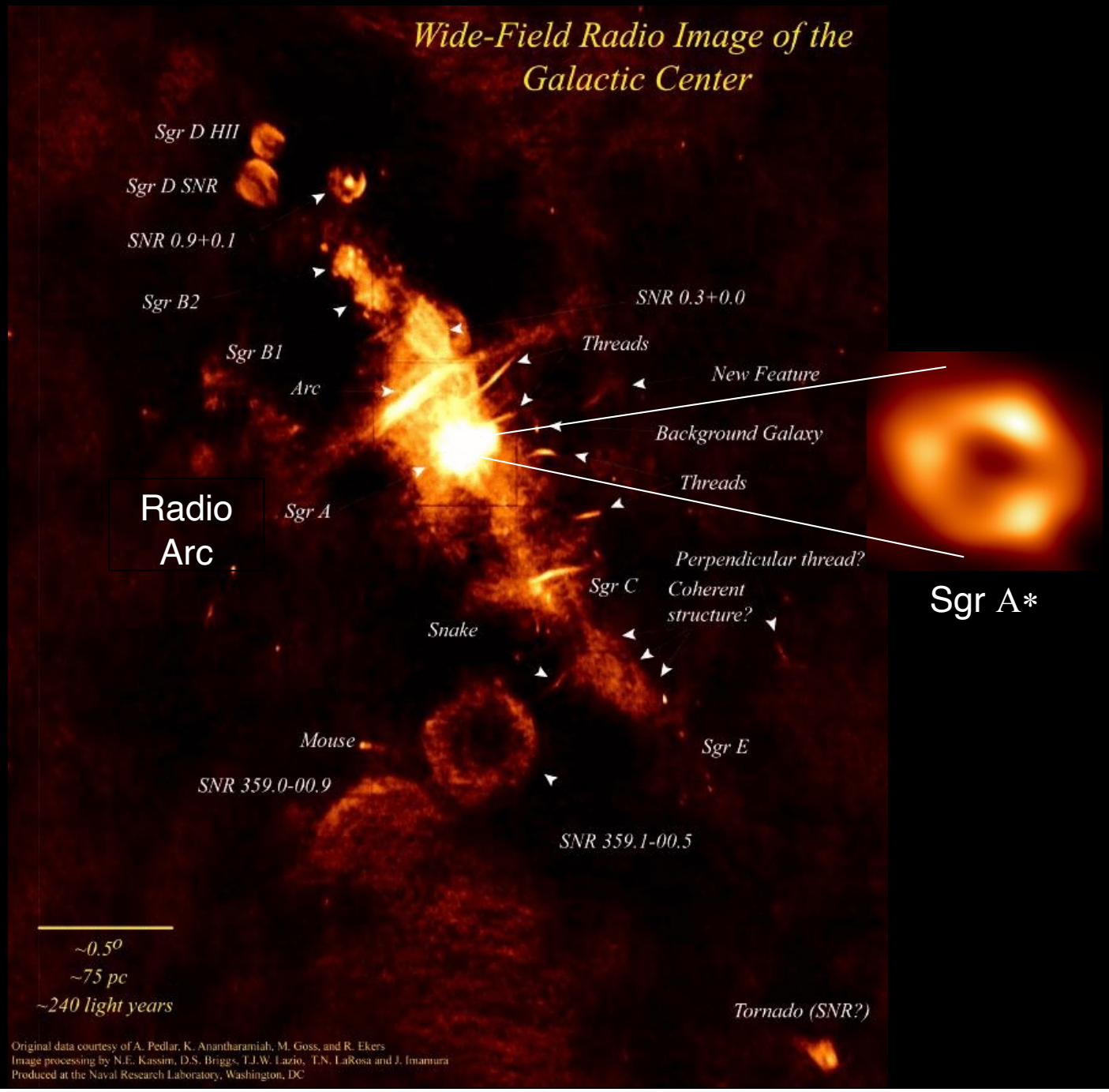

Wide-Field Radio Image of the Galactic Center
Sgr D HII
Sgr D SNR
SNR 0.9+0.1
Sgr B2
Sgr B1
Arc
SNR 0.3+0.0
Threads
New Feature
Background Galaxy
Threads
Sgr A
Radio Arc
Perpendicular thread?
Sgr C
Coherent structure?
Snake
Mouse
Sgr E
SNR 359.0-00.9
SNR 359.1-00.5
~0.5º
~75 pc
~240 light years
Tornado (SNR?)
Original data courtesy of A. Pedlar, K. Anantharamiah, M. Goss, and R. Ekers
Image processing by N.E. Kassim, D.S. Briggs, T.J.W. Lazio, T.N. LaRosa and J. Imamura
Produced at the Naval Research Laboratory, Washington, DC
Sgr A*

High Cosmic-ray Flux and an Abundance of Magnetized Filaments in the Galactic Center

F. Yusef-Zadeh
Northwestern University

Outline

- ❑ **Past**
- A bit of history
- VLA results

- ❑ **Present**
- **MeerKAT and RFI**
- **Statistical properties of the filaments**
  - Magnetic field
  - Spectral Index
  - Spacing

- Origin of the filaments
  - Interacting CR driven winds

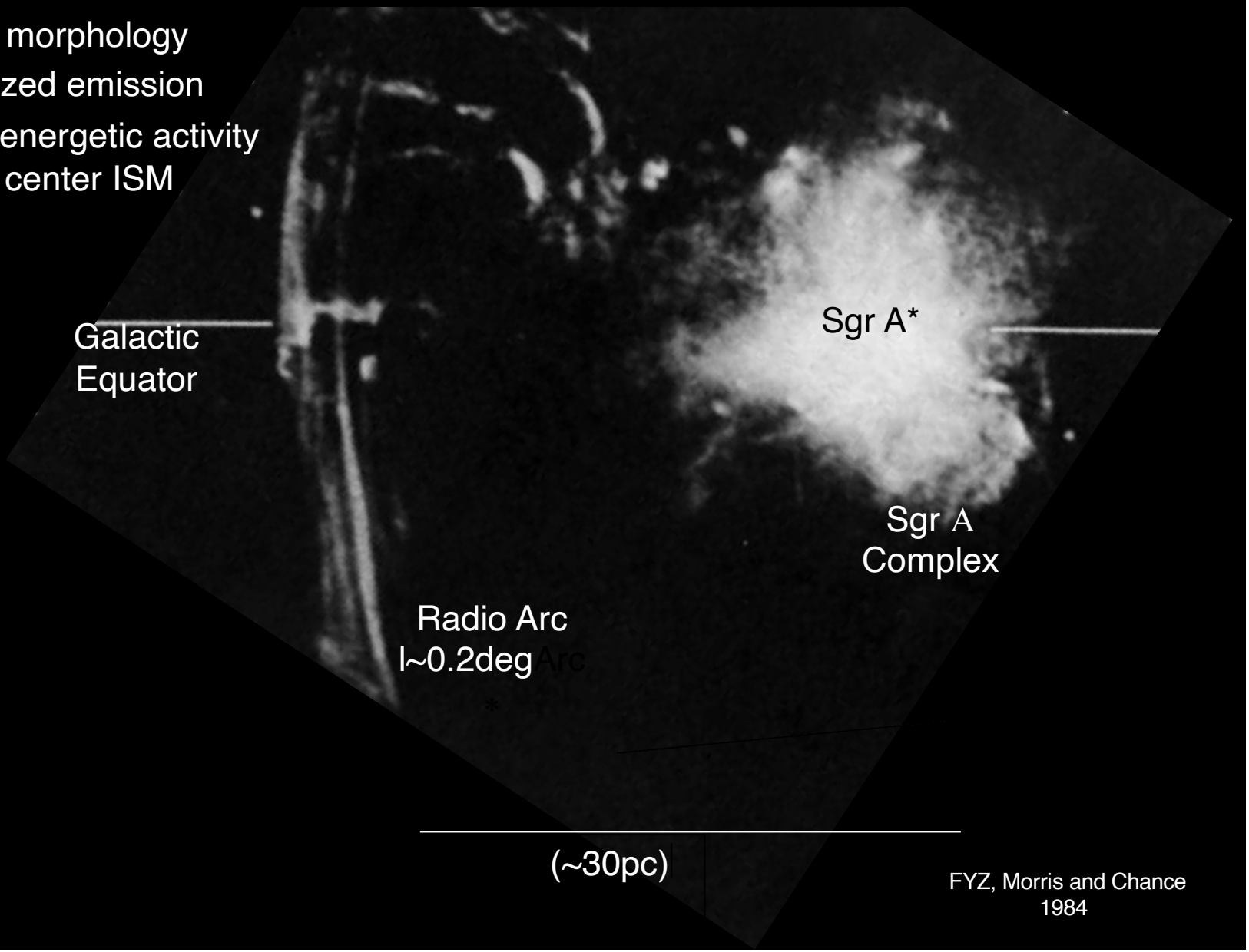
- Cultural aspects

Collaborators: R. Arendt, F. Camilo, W. Cotton, I. Heywood and M. Wardle

Discovery of Magnetized filaments

A signature of energetic activity

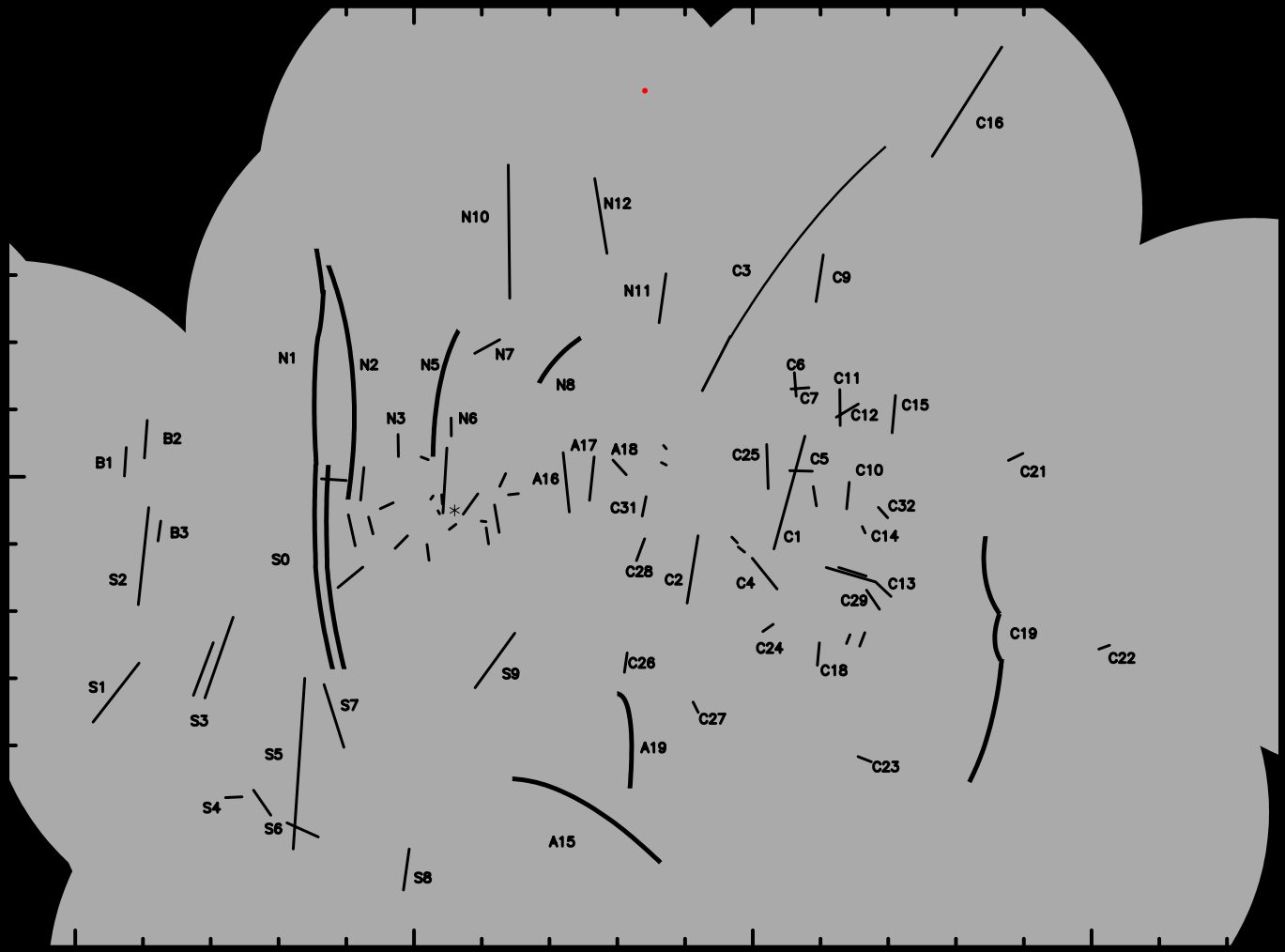
- Unusual linear morphology
- Linearly polarized emission
- A signature of energetic activity in the Galactic center ISM
- Mysterious



FYZ, Morris and Chance
1984

Numerous magnetized filaments

- Twenty years later
- Archival VLA data from dozens of 20cm observations
- 88 identified filaments
- Linear polarization with large RM



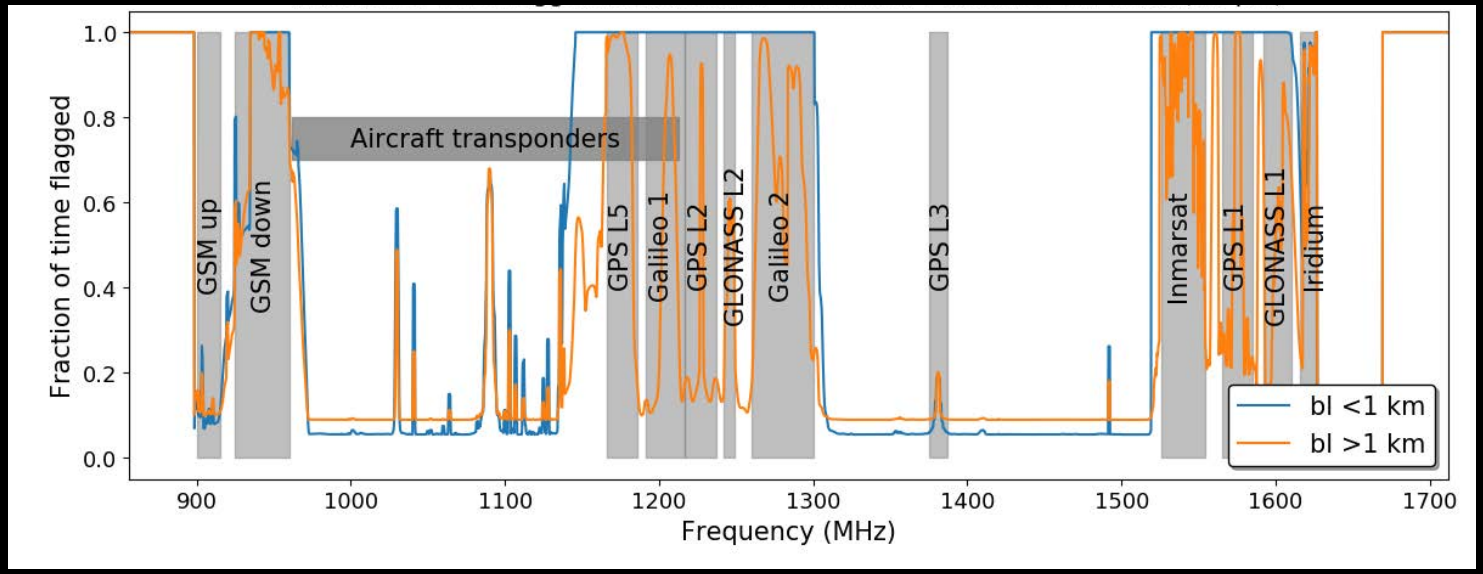
lactic Longitude

FYZ, Hewitt and Cotton 2004

MeerKAT Capabilities

- 64x13.5m dish, 26 pointings, 20x10h-track observations
- $\nu_{center} = 1{,}1284$ MHz, $910\ \text{MHz} < \nu < 1685\ \text{MHz}$
- 16 subbands to measure the spectral index α ($S_\nu = S_0\ \nu^{-\alpha}$)
- RFI free, 500 km away from Cape Town

L band RFI (MeerKAT)



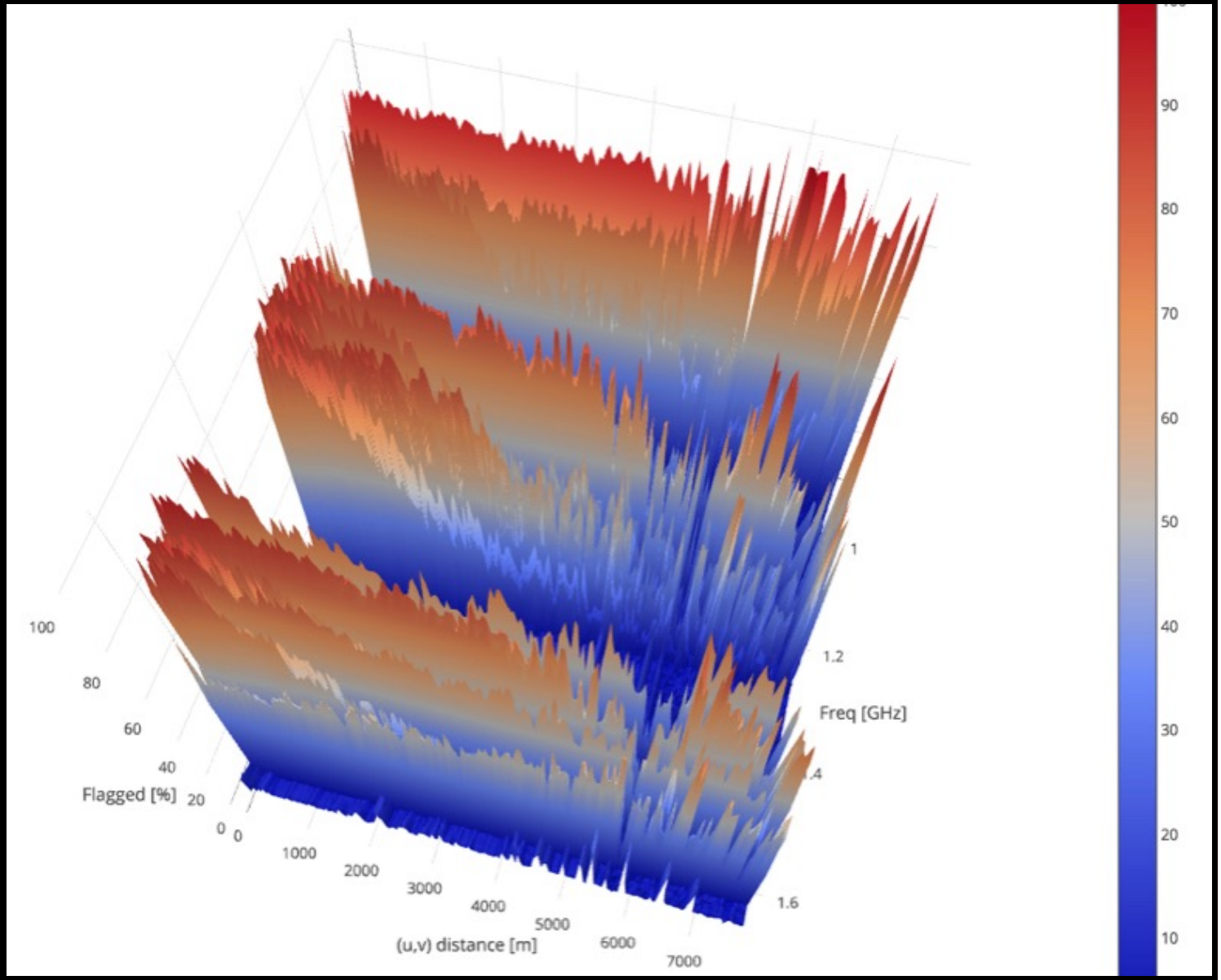
- Geolocation satellites are persistent
- interferers in several fixed bands, e.g.
- GPS
- GLONASS
- Galileo
- IRIDIUM
- 1565-1585, 1217-1237, 1375-1387, 1166-1186
- 1592-1610, 1242-1249
- 1191-1217, 1260-1300
- 1616-1626

- Aircraft transponders create multiple intermittent signals between 1000 and 1200

- Mobile communication GSM

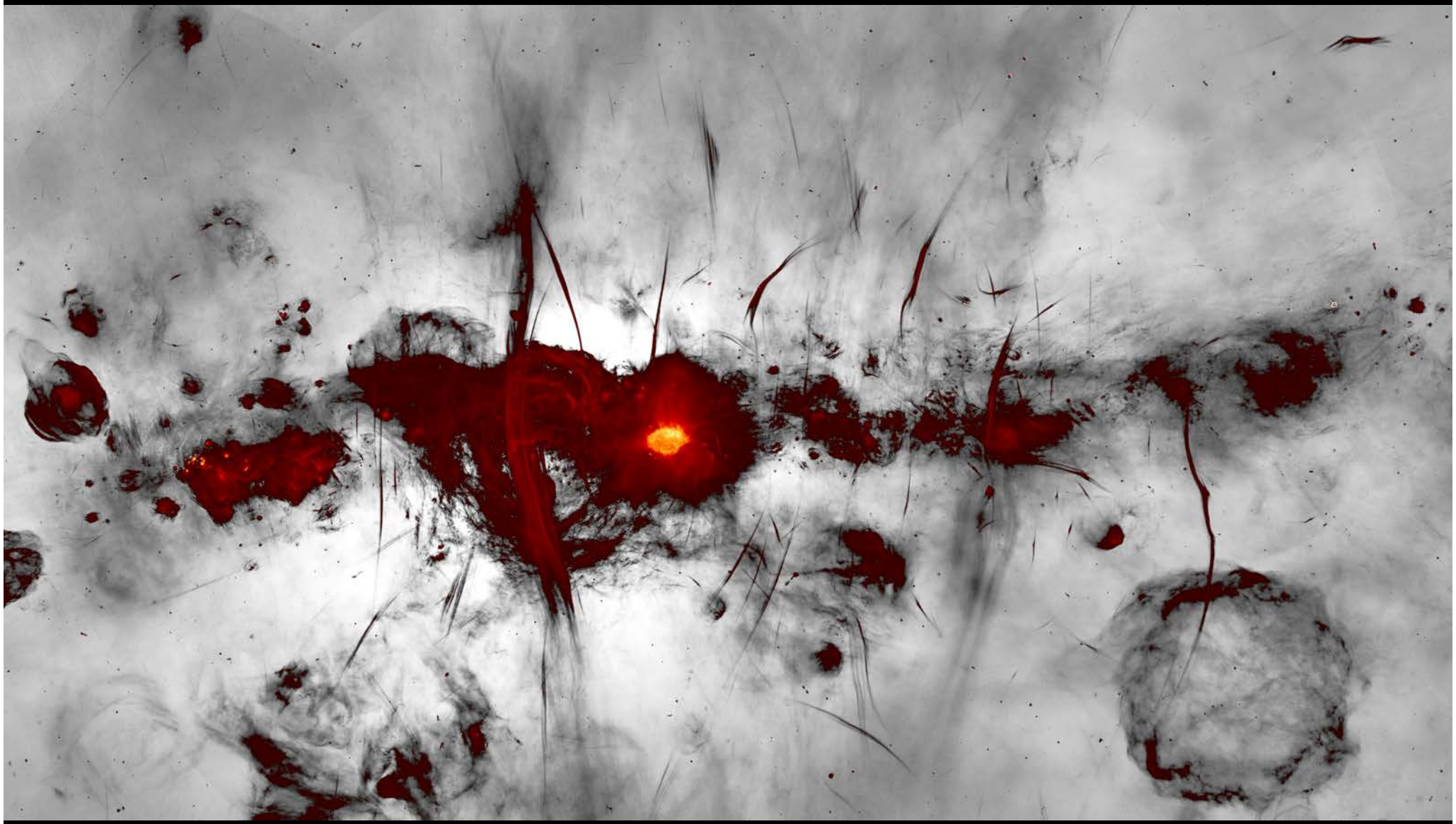
L band RFI (MeerKAT)

- 50% data flagged but long baseline data can be recovered because of lack of correlation

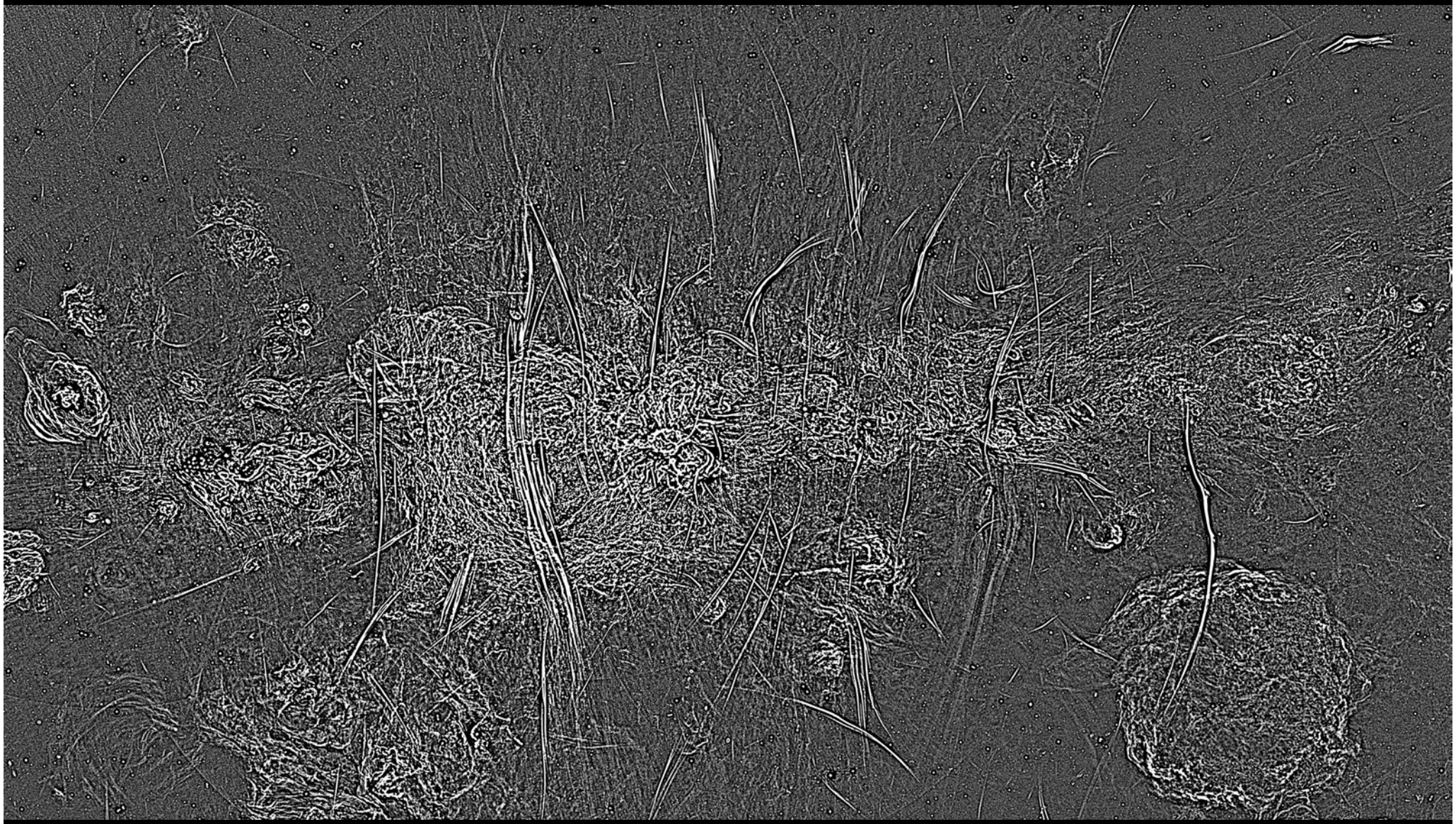


Heywood et al. (2019, 2022)

Image 20 cm, unfiltered and filtered (MeerKAT)

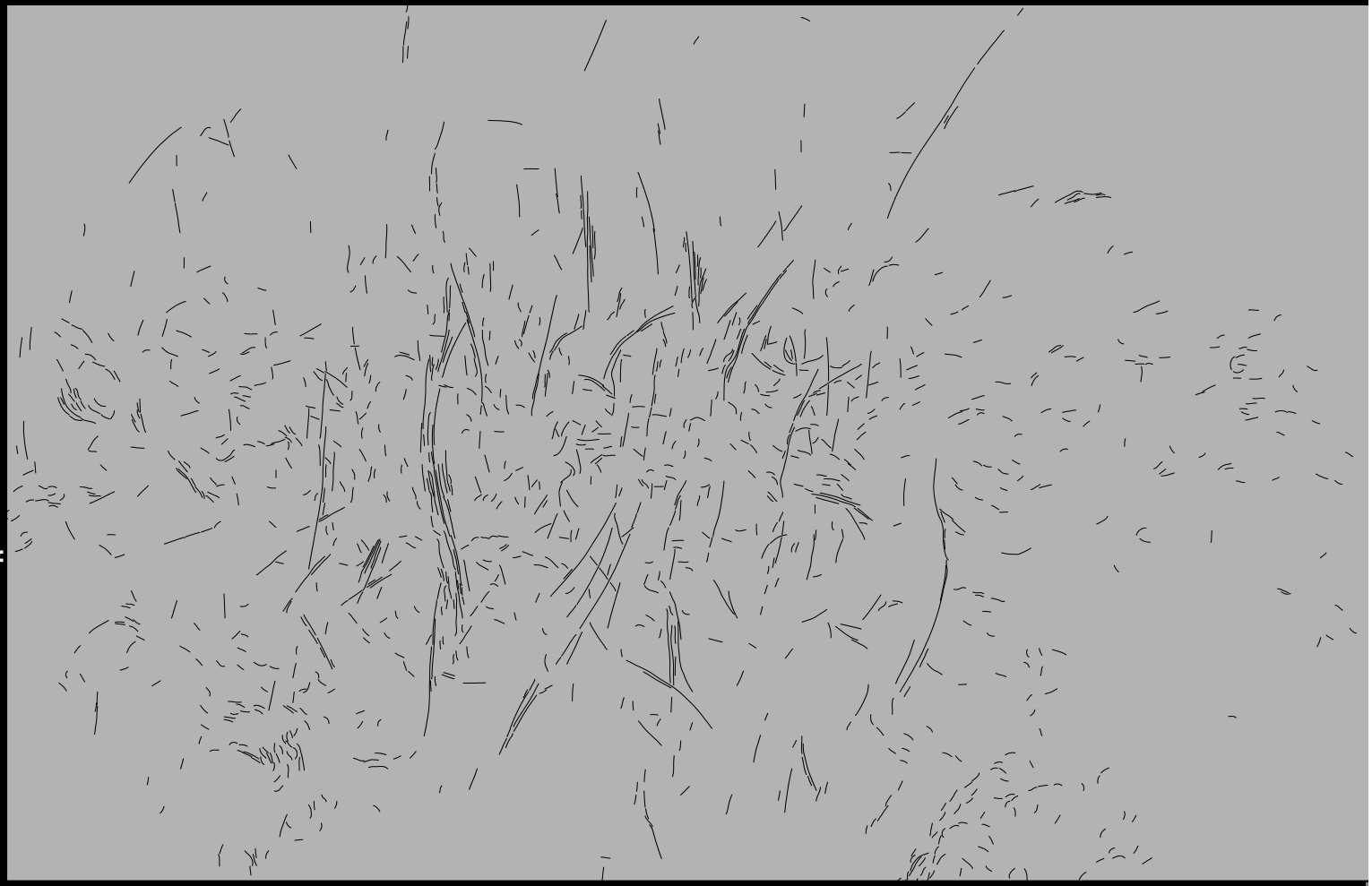


Structural details of filaments (Filtered Image)



Population of magnetized filaments

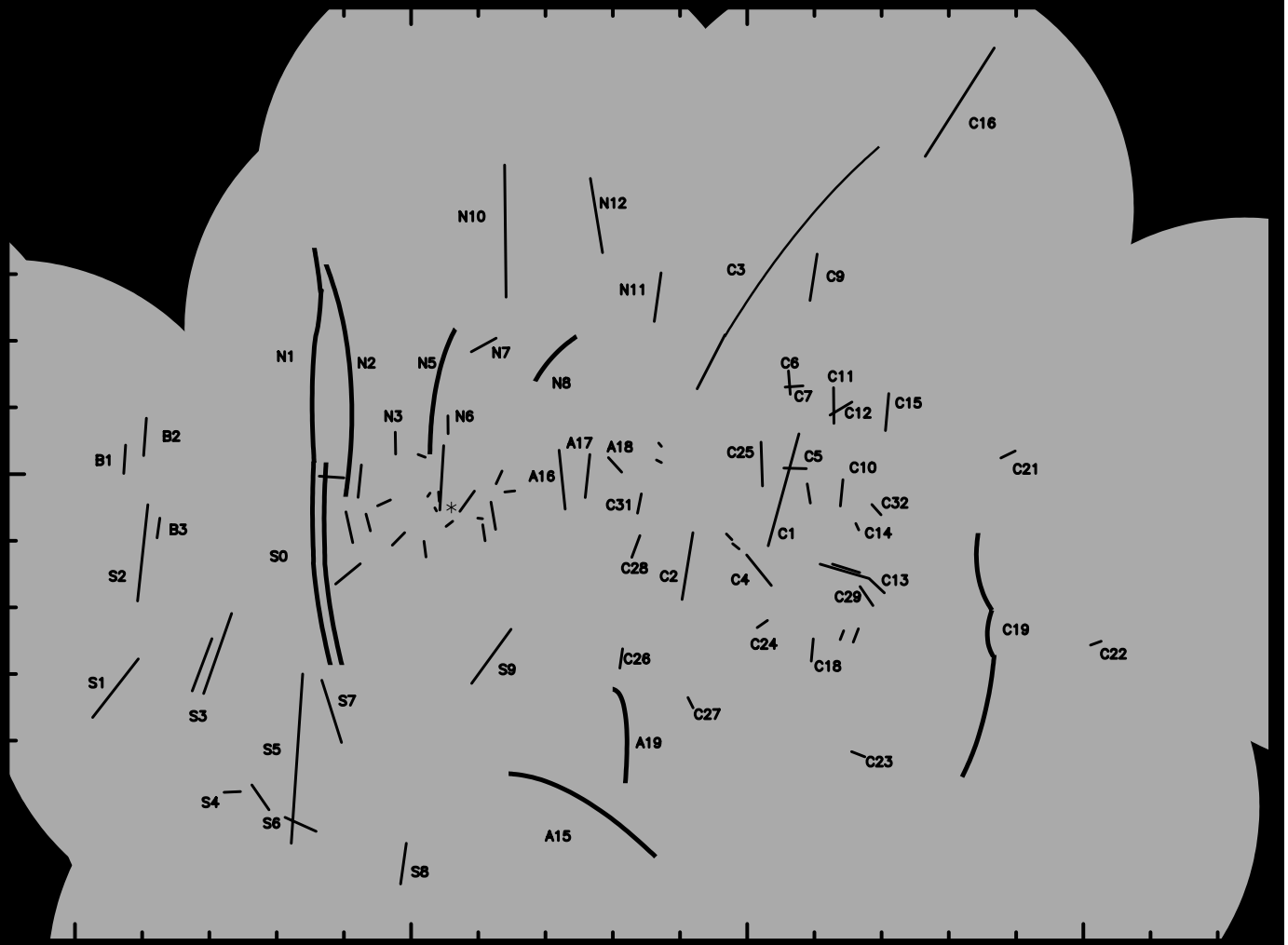
- 18 years later
- MeerKAT data
- ~1000 identified filaments
- The emission tracks CR electrons
- High concentration of CR sources
- GeV cosmic ray electrons
- $P_{cr} \sim 10^3$ eV cm^{-3}



Fyz, Arendt, Wardle, Heywood, Cotton and Camilo (2022)

Numerous magnetized filaments (VLA)

- 18 years later
- MeerKAT data
- ~1000 identified filaments
- The emission tracks CR electrons
- High concentration of CR sources
- GeV cosmic ray electrons
- $P_{cr} \sim 10^3$ eV cm^{-3}

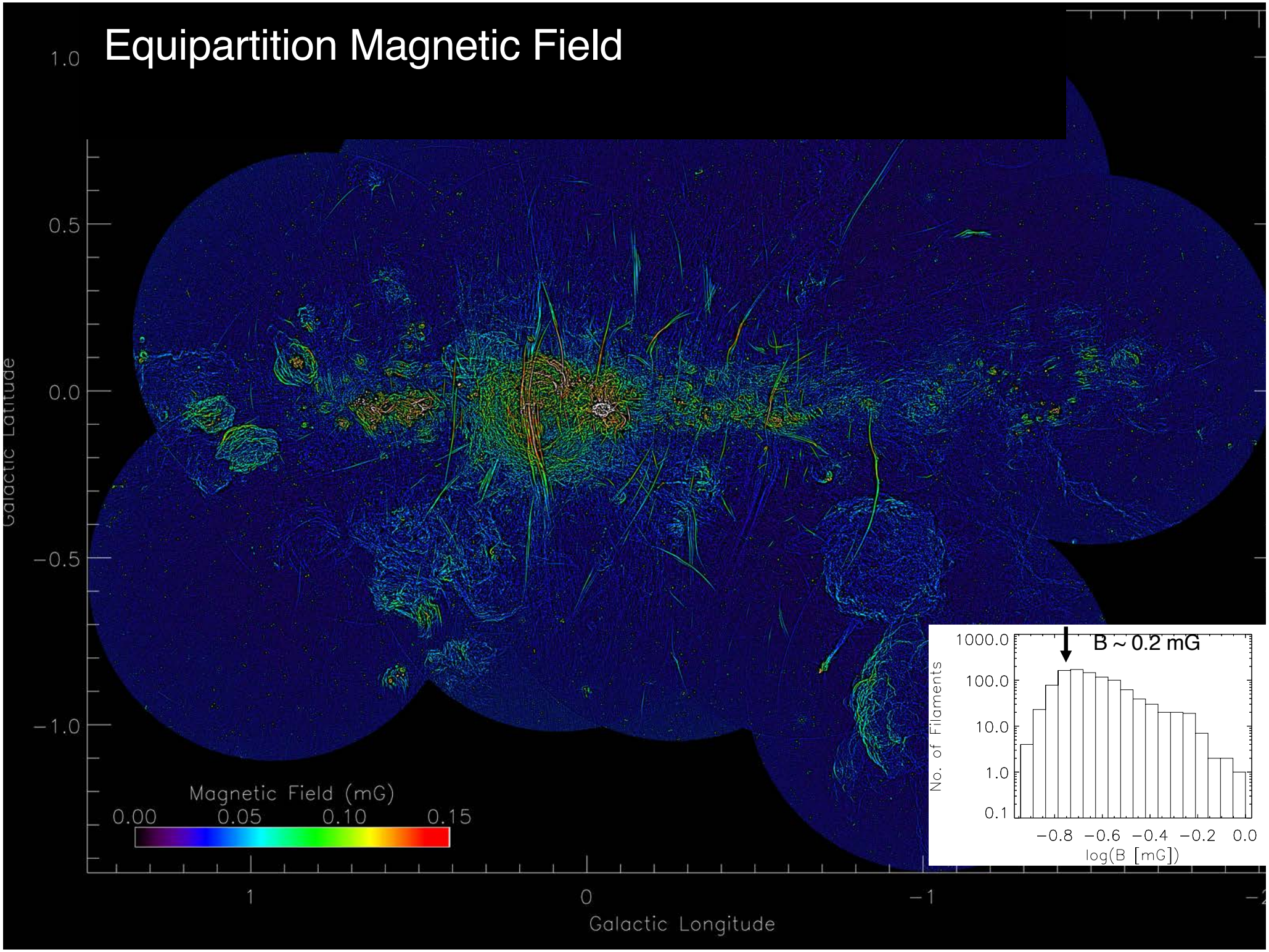


lactic Longitude

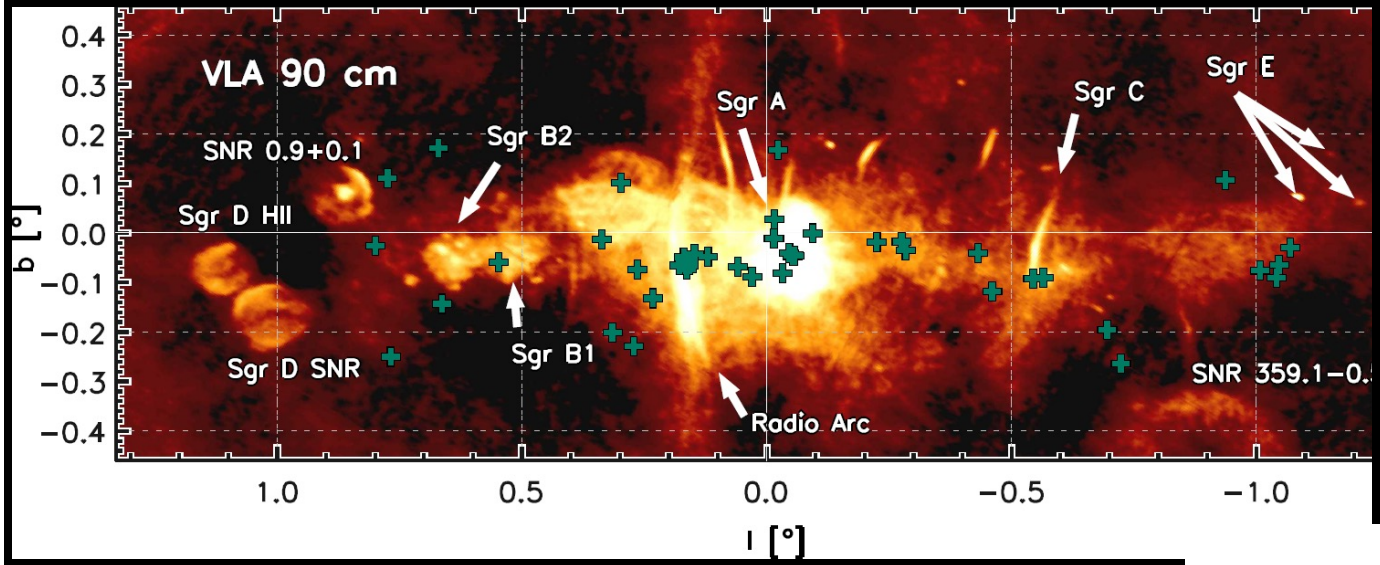
Population of magnetized filaments

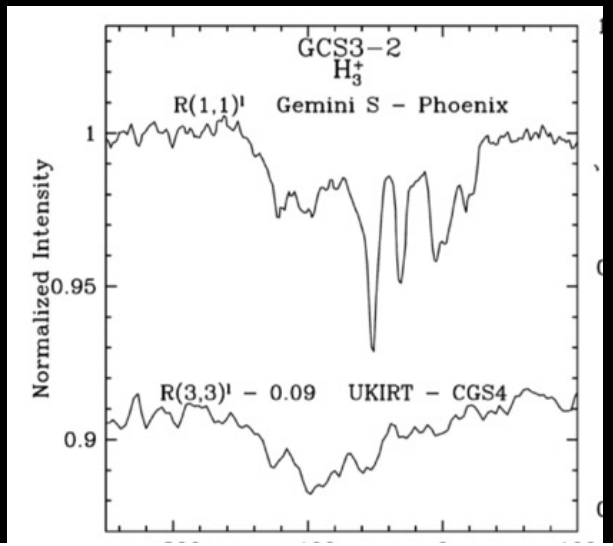
- Statistical Study of a population
  - Magnetic field along the filaments
  - Spectral index of the filaments
  - Filament Spacing
  - Filament splitting

Equipartition Magnetic Field

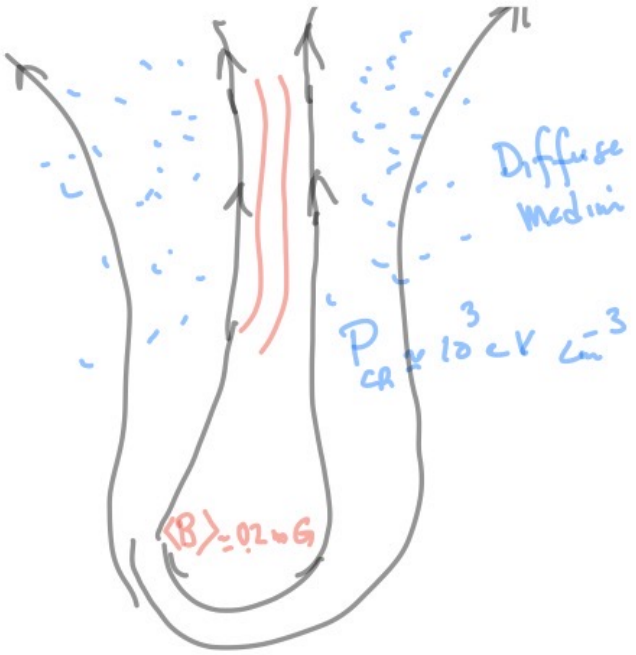


Diffuse Medium: High CR ionization rate from H_3^+





- Simple chemistry and straightforward analysis
- $\zeta \sim 2 \times 10^{-14}$ s^{-1} (Galactic center)
- 2-3 orders of magnitude higher than ζ elsewhere
- Low energy cosmic ray electrons produce H_3^+

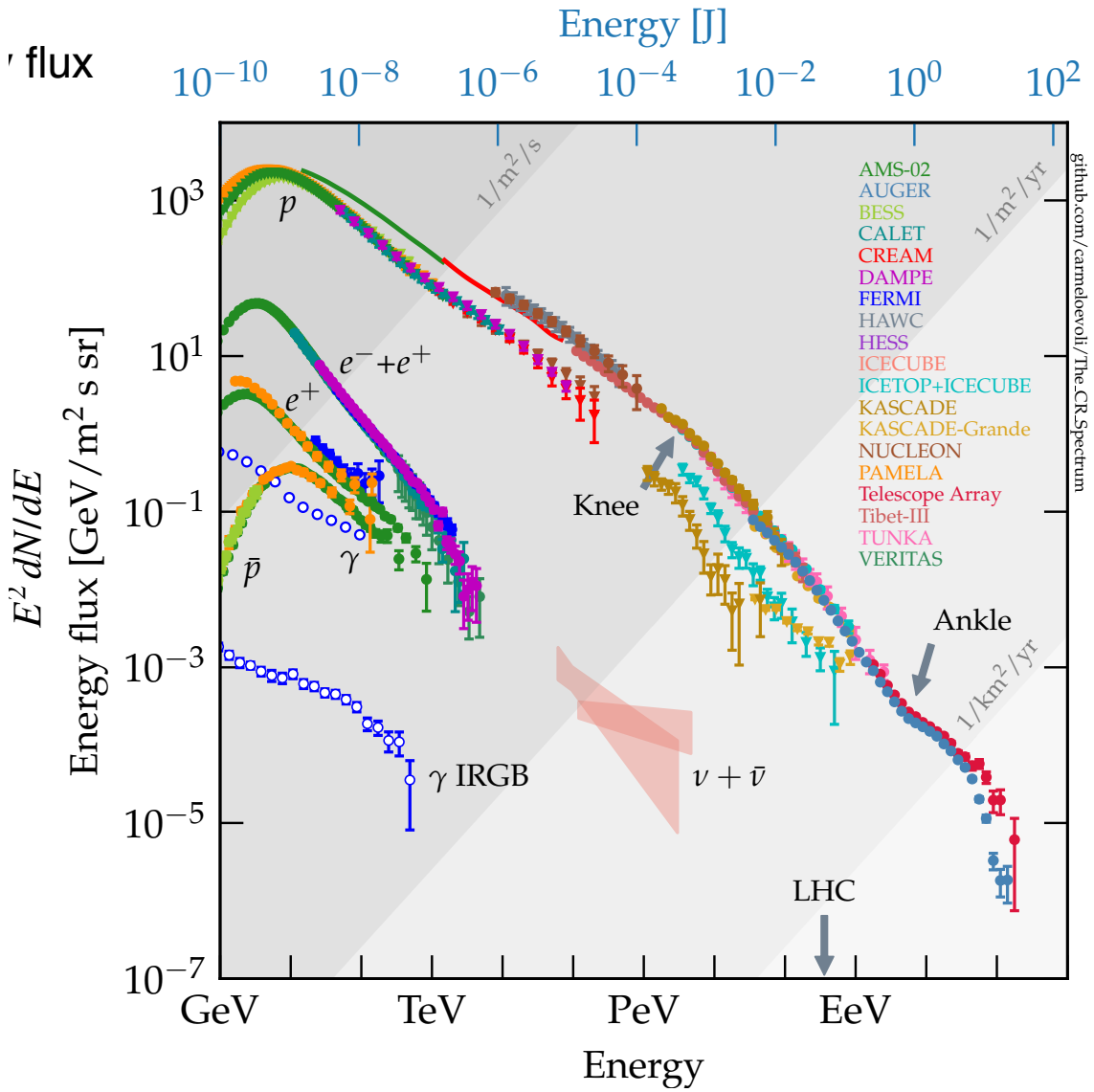


Local Neighborhood ISM

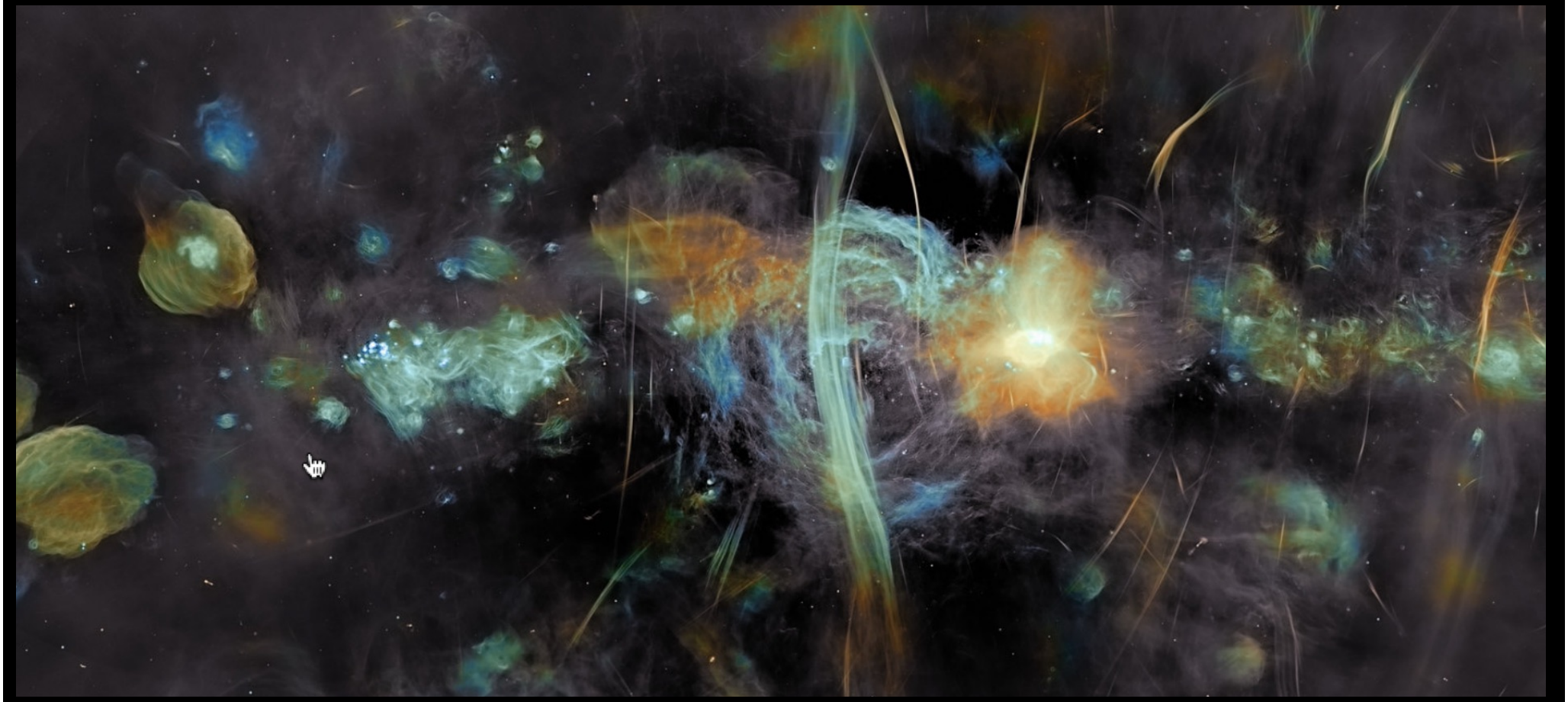
The local cosmic ray flux

Energy density ~1.5 eV cm^{-3}

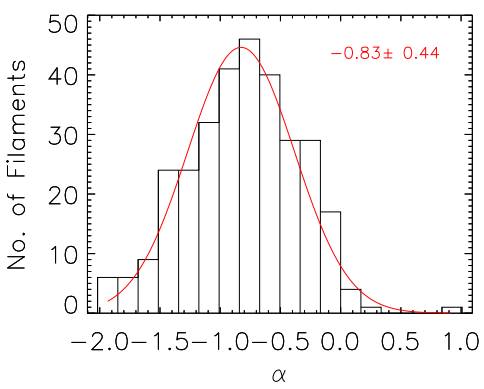
Energy Index p~2.7 where
N(E) = N(0) E^{-p}



In-band Spectral Index α

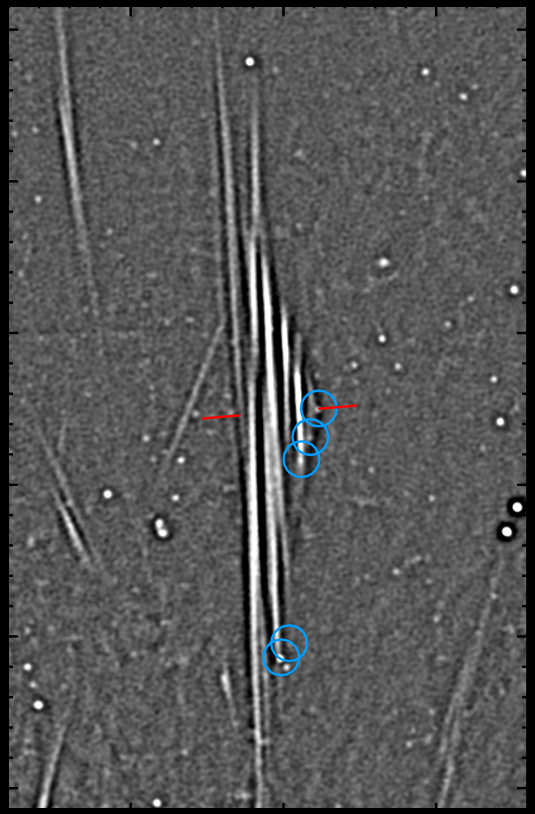


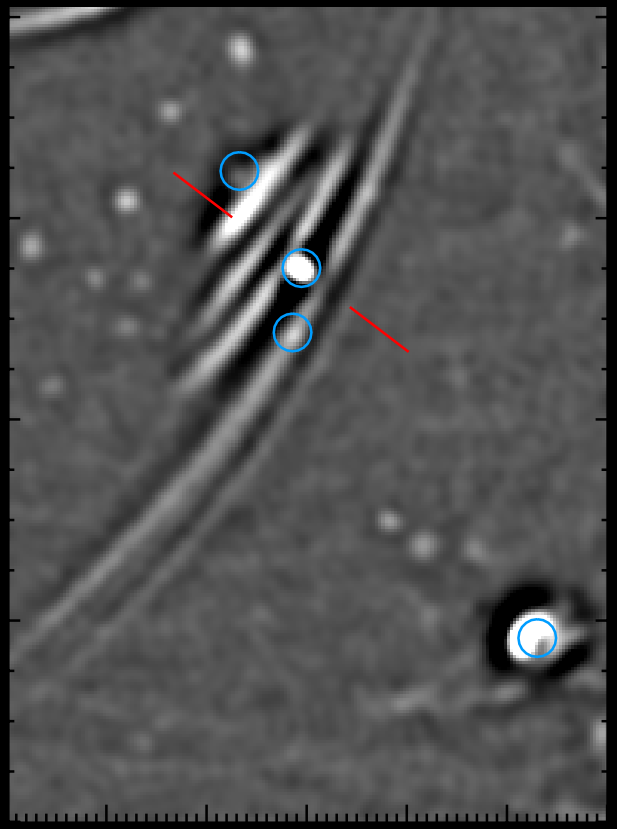
- 16 subbands to measure the spectral index α ($S_\nu = S_0\ \nu^{-\alpha}$)
  - **The origin of filaments remain mysterious**

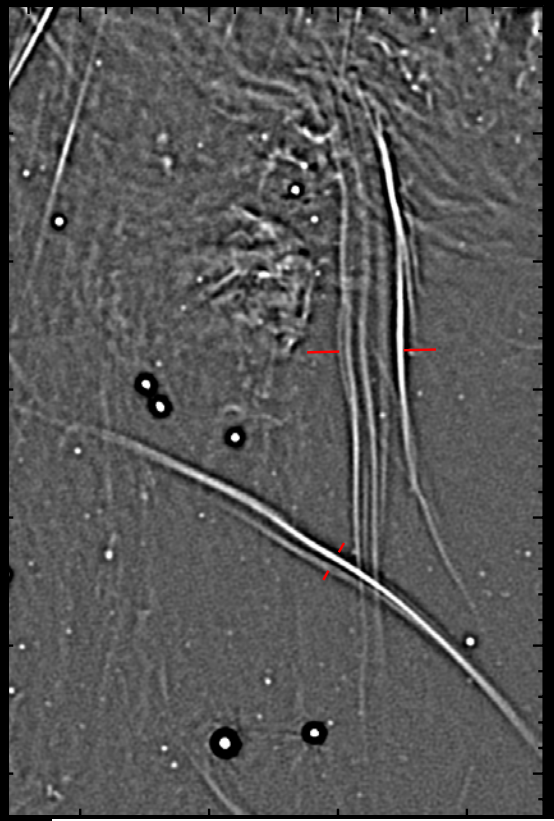


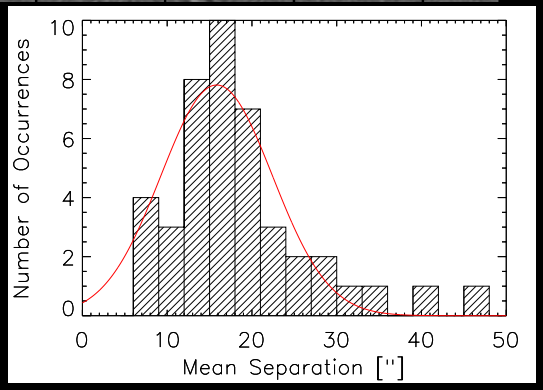
Filament Spacing

Cometary tail behind obstacles





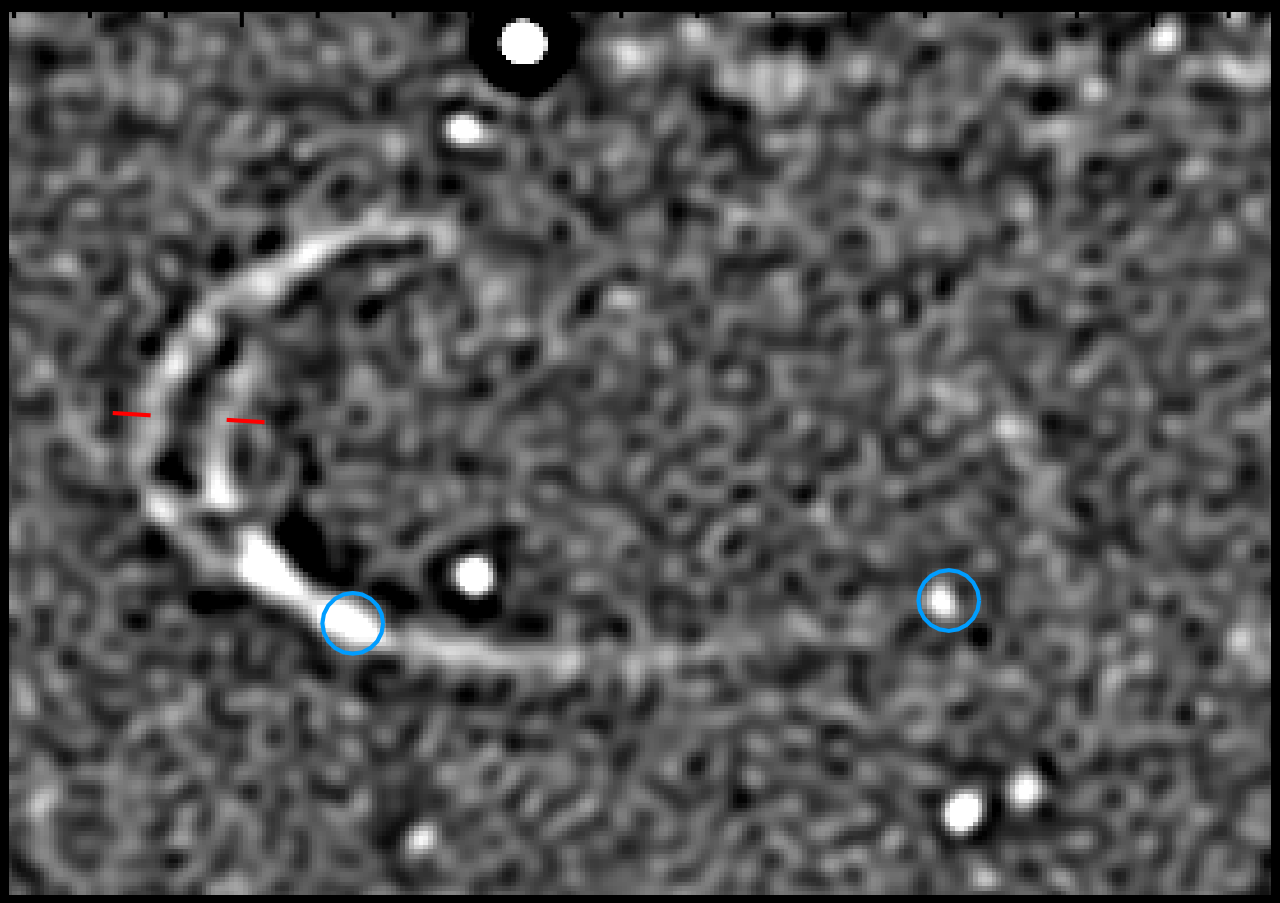


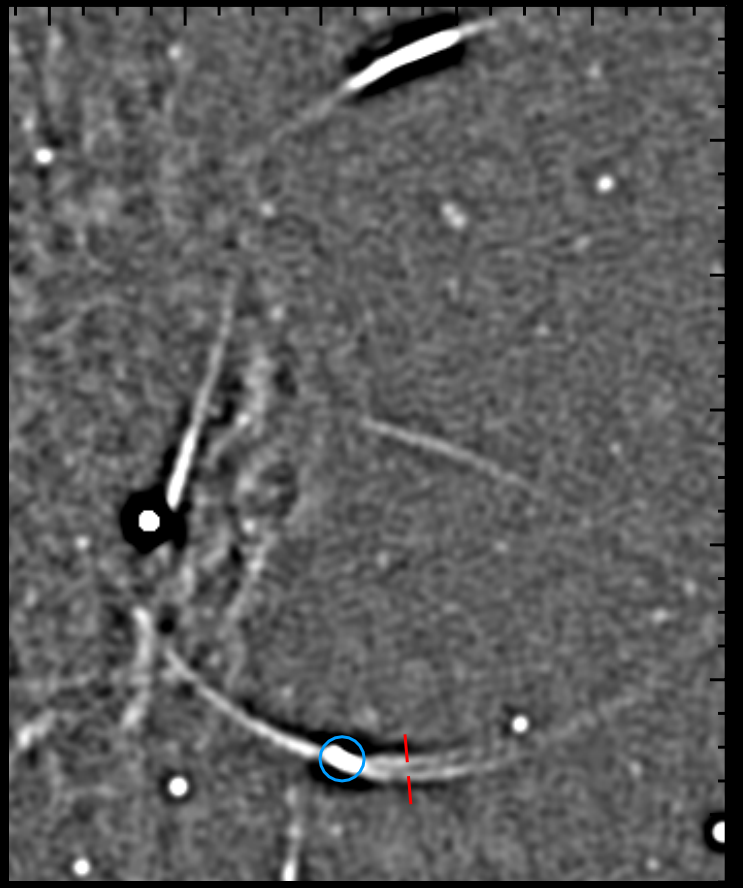


- Nuclear wind and stellar wind interactions
- Magnetic field amplification due to compression

Filament Splitting

Streaming vs diffusion?

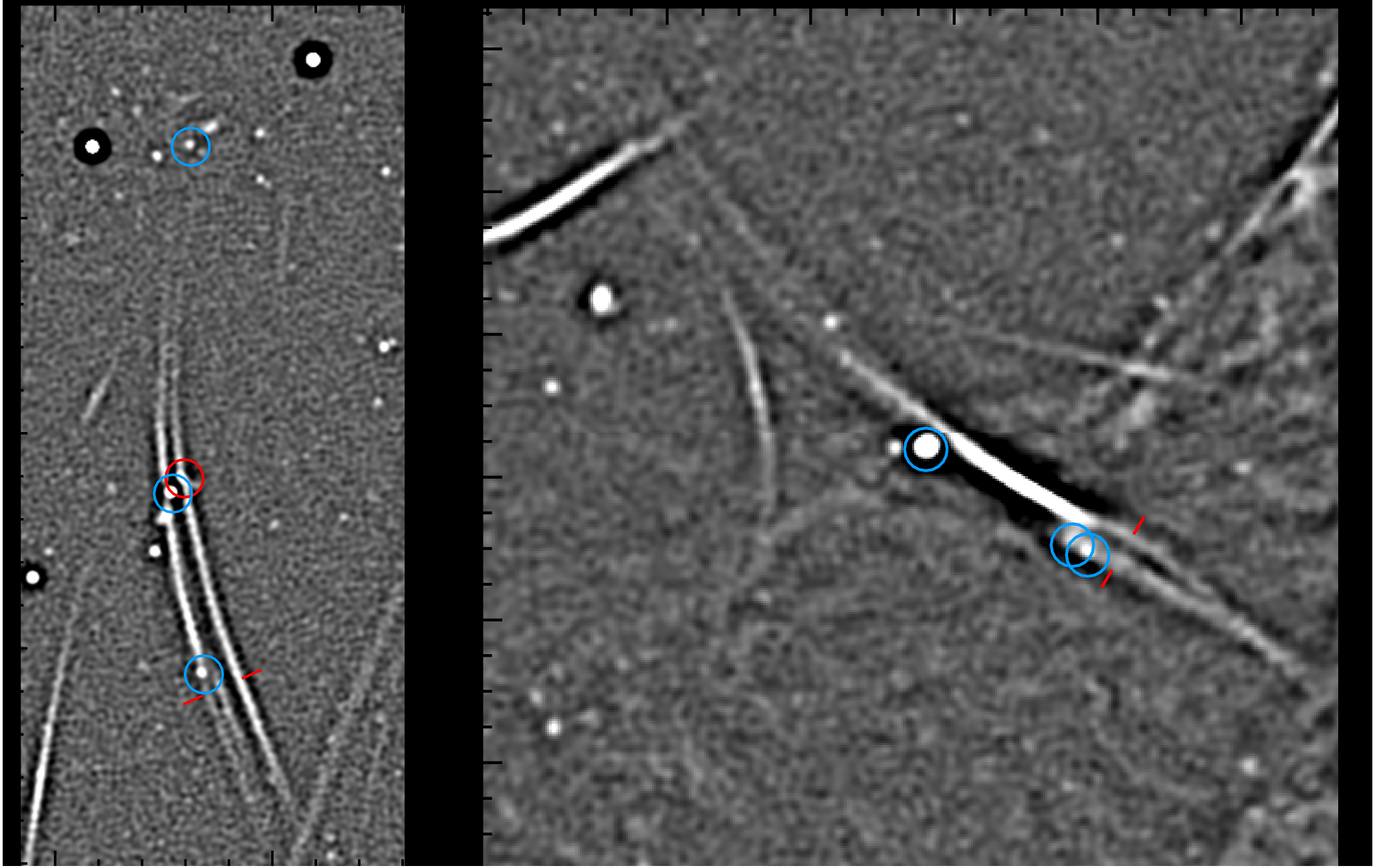




- Nuclear wind and stellar wind interactions
- Magnetic field amplification due to compression

Filament Splitting

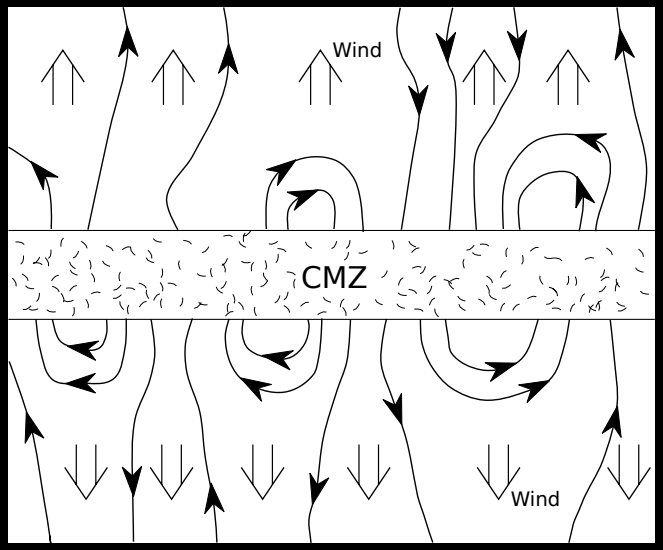
Streaming vs diffusion?

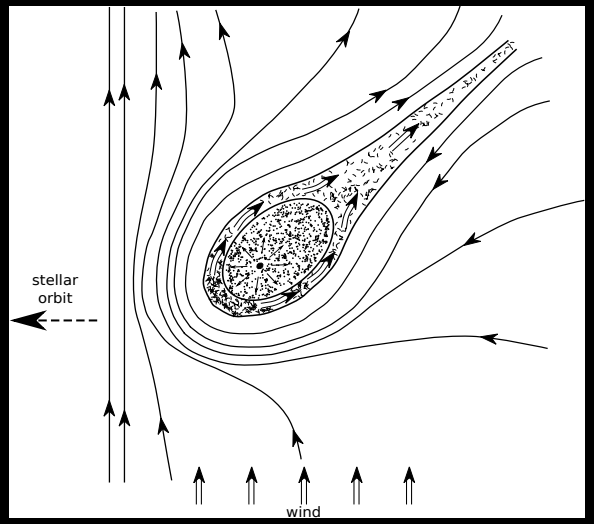


- Origin of the filaments
- Cosmic-ray driven wind

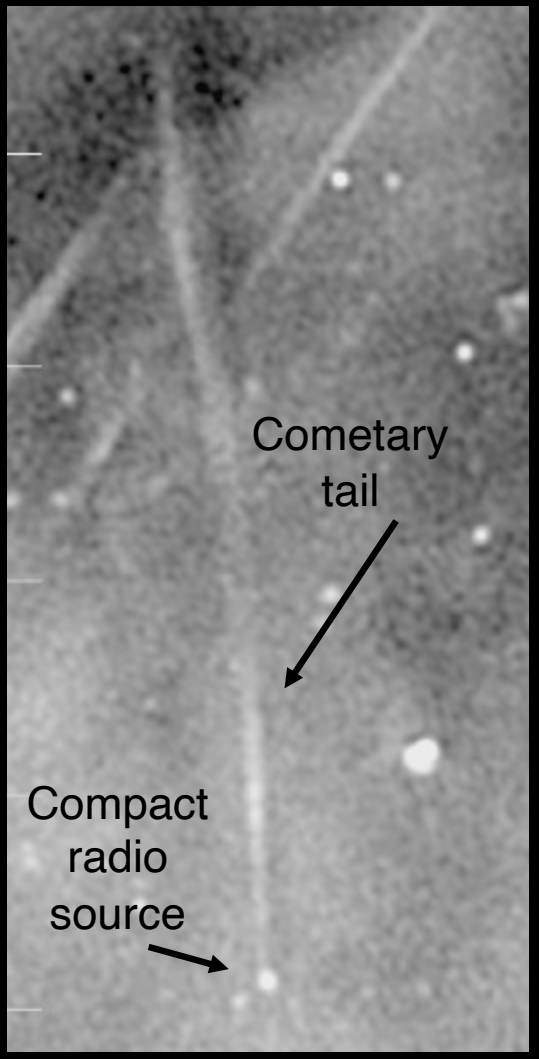
Cometary Model

Cometary tail behind obstacles





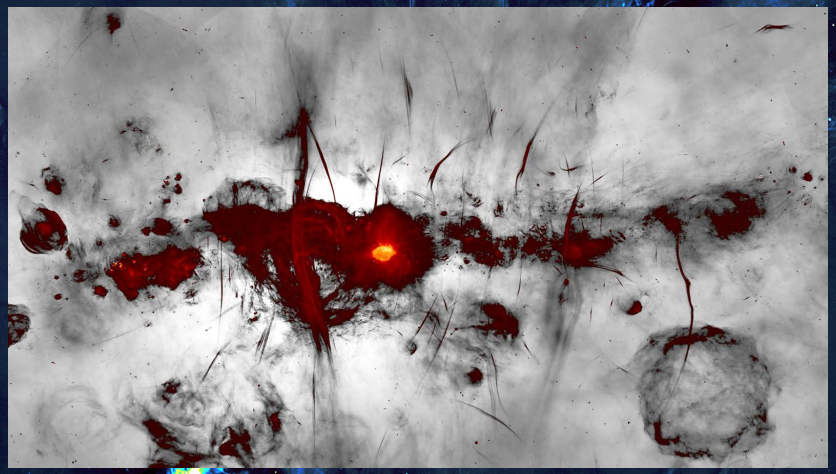
- CR-driven wind
  - Lift the material
  - Heat the gas to high latitudes
  - Magnetic field geometry
- The wind wraps magnetic field around a moving obstacle
- Magnetic field and cr electron density amplification due to compression



- Future observations

MeerKAT Radio Bubble

- 430 pc bubble perpendicular to the Galactic plane
- Relic of past acivity
- The bubble is inflated by the wind



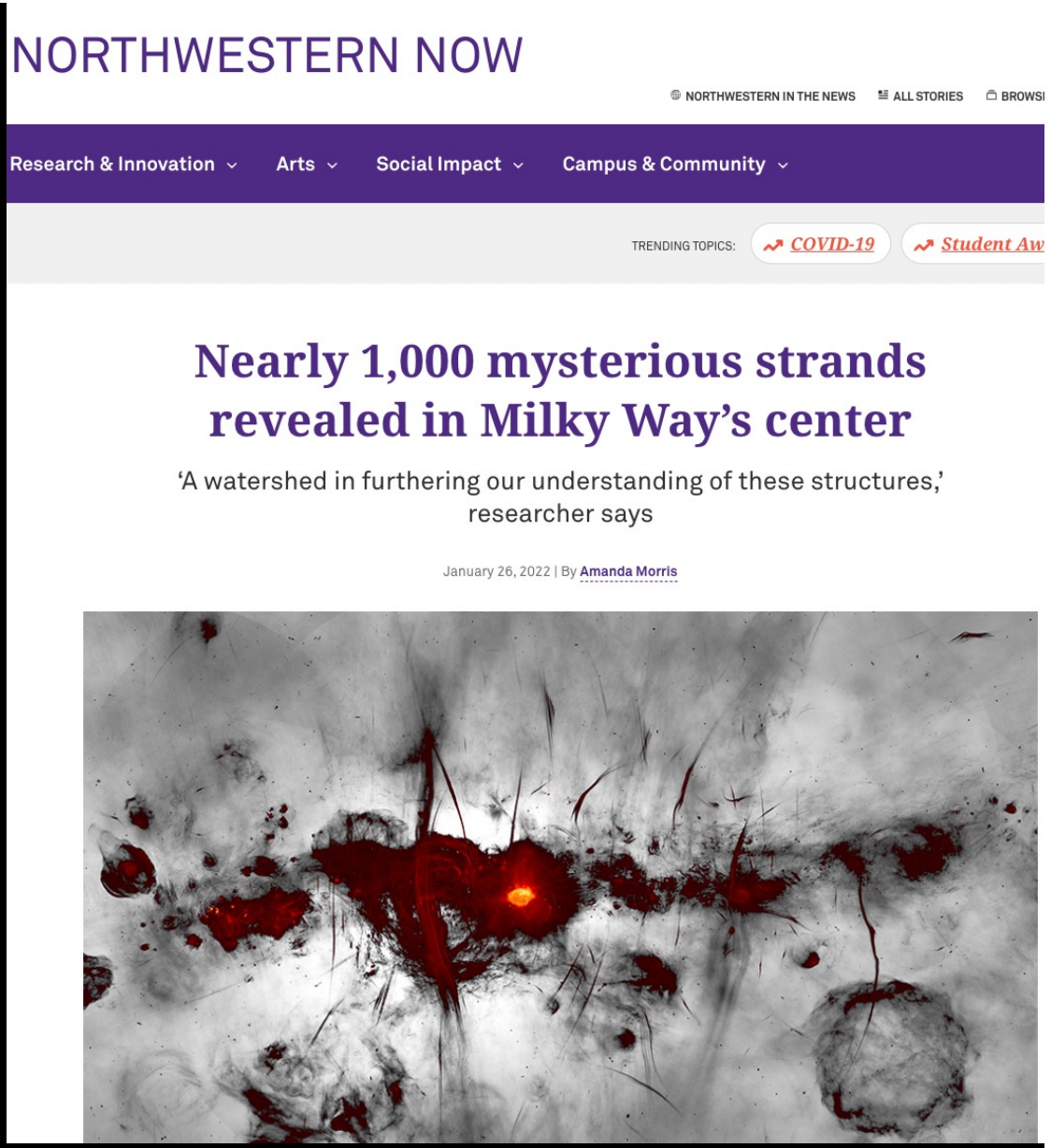
Cultural Connection

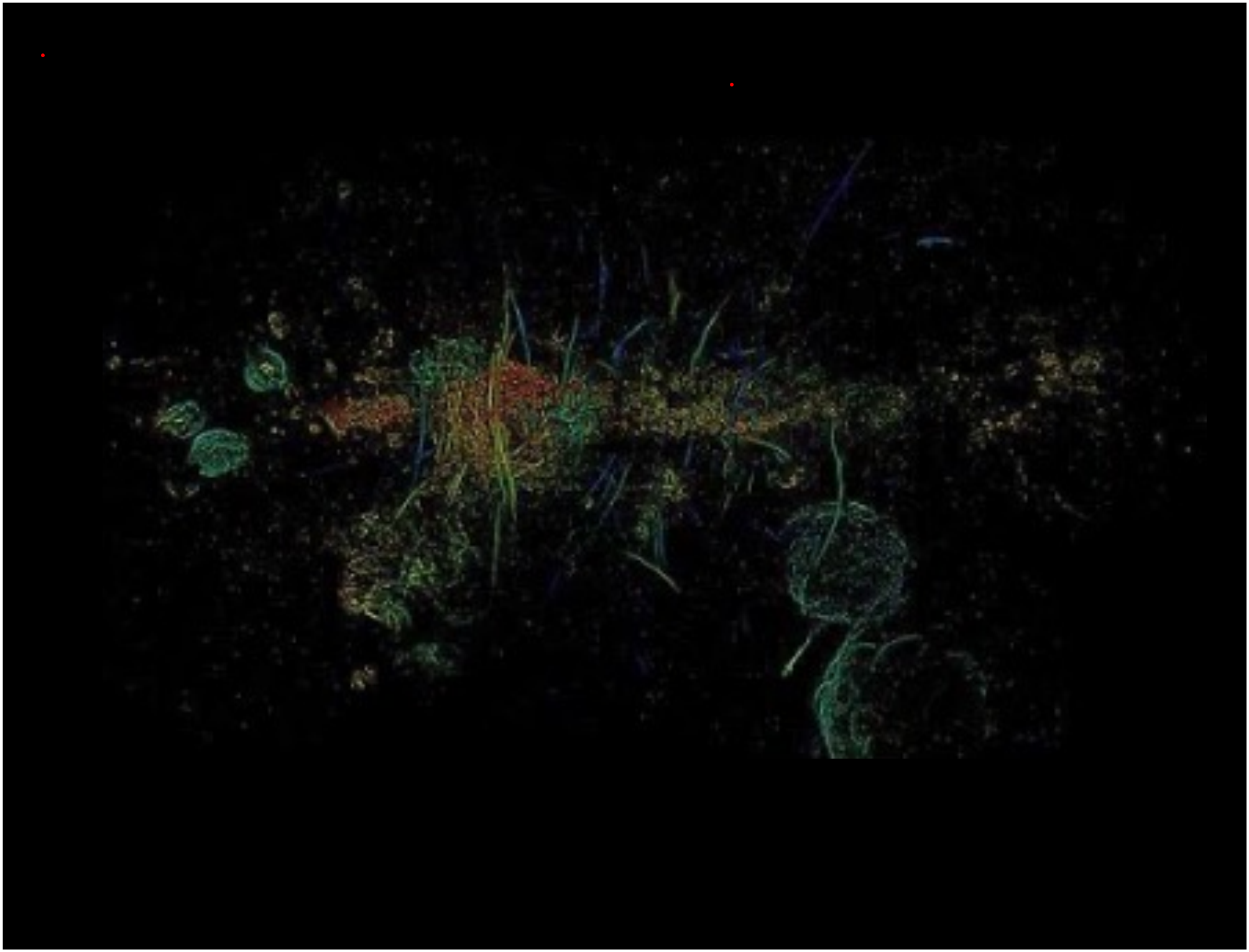
- Radio filaments and non-scientists

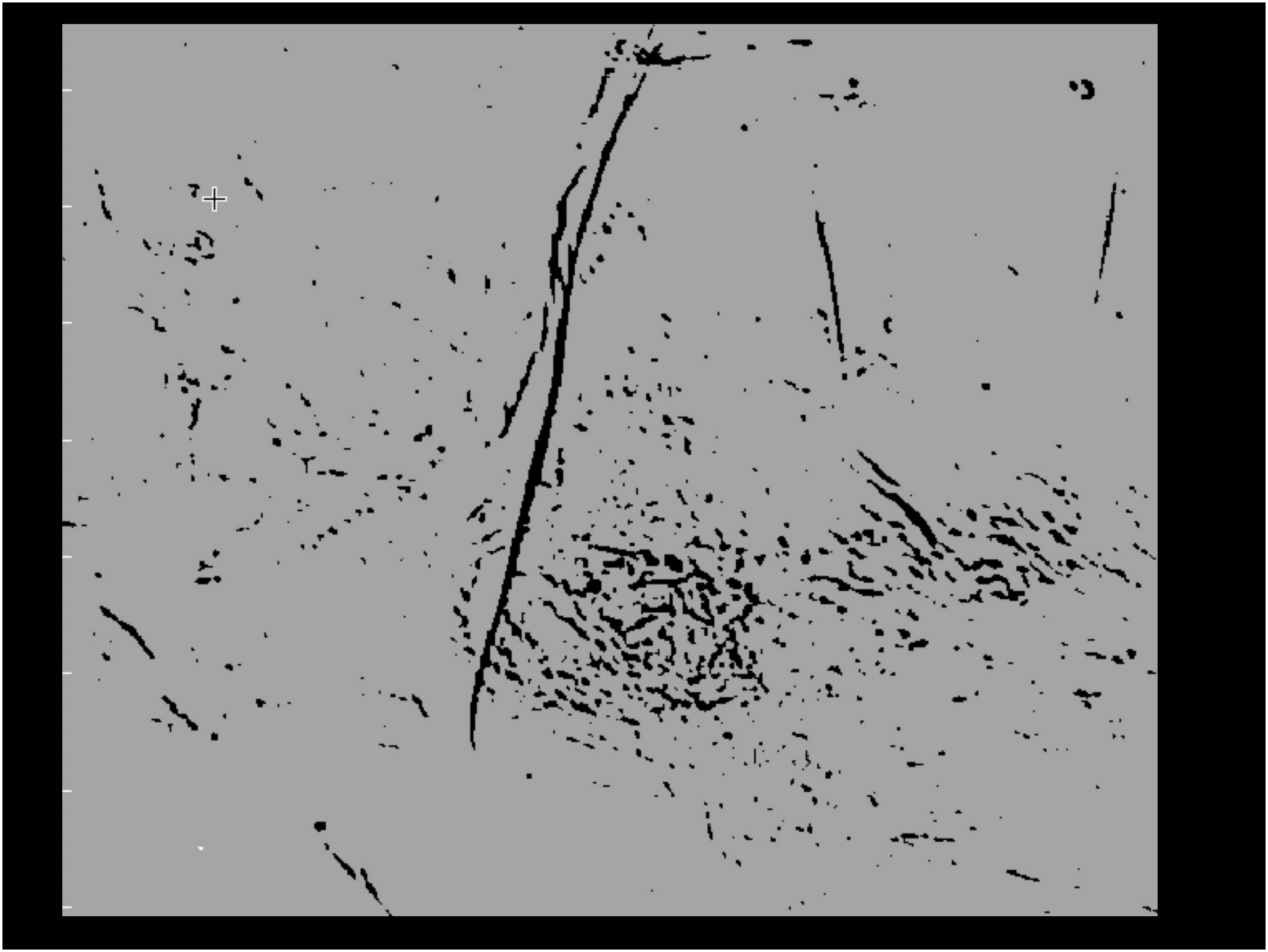
- Press release
- Music composition
- Artsy visuals

Press Release

- Reached ~7 million (NU only)
- Top story in 2022 at NU (except covid)
- Coverage still continues (not a 24h news cycle)







- **Summary**
- **Multiple lines of evidence for high cosmic ray pressure**
- **High cosmic-ray pressure drives a wind**
- **Magnetized filaments**
  - **Created by winds interacting with an obstacle**
  - **Filamentation: synchrotron cooling instability**
- **Future**
  - **High resolution to test the cometary model**
  - **Observe at other wavelengths**