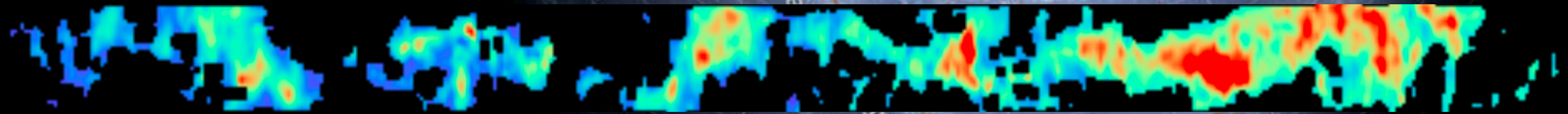


# A Kpc-Scale Molecular Wave in the Inner Galaxy



Veena V S

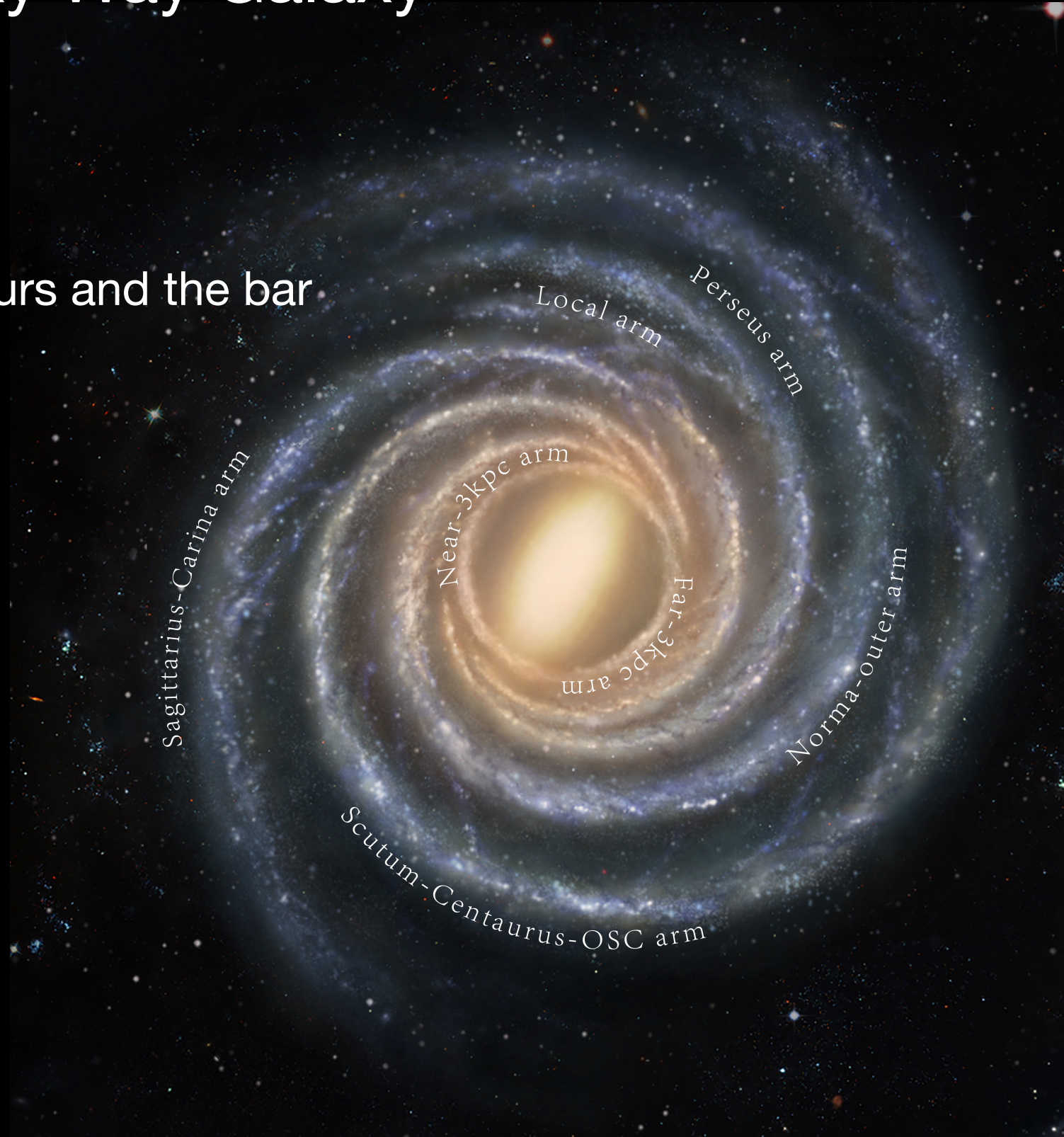
Humboldt Fellow  
University of Cologne

P. Schilke, A. Sanchez-Monge, M. C. Sormani, R. S. Klessen, F. Schuller, D. Colombo, T. Csengeri, M. Mattern, J. S. Urquhart



# The Milky Way Galaxy

- Barred spiral galaxy
- Four major arms, arm branches, spurs and the bar





# The Milky Way Galaxy

- Barred spiral galaxy
- Four major arms, arm branches, spurs and the bar

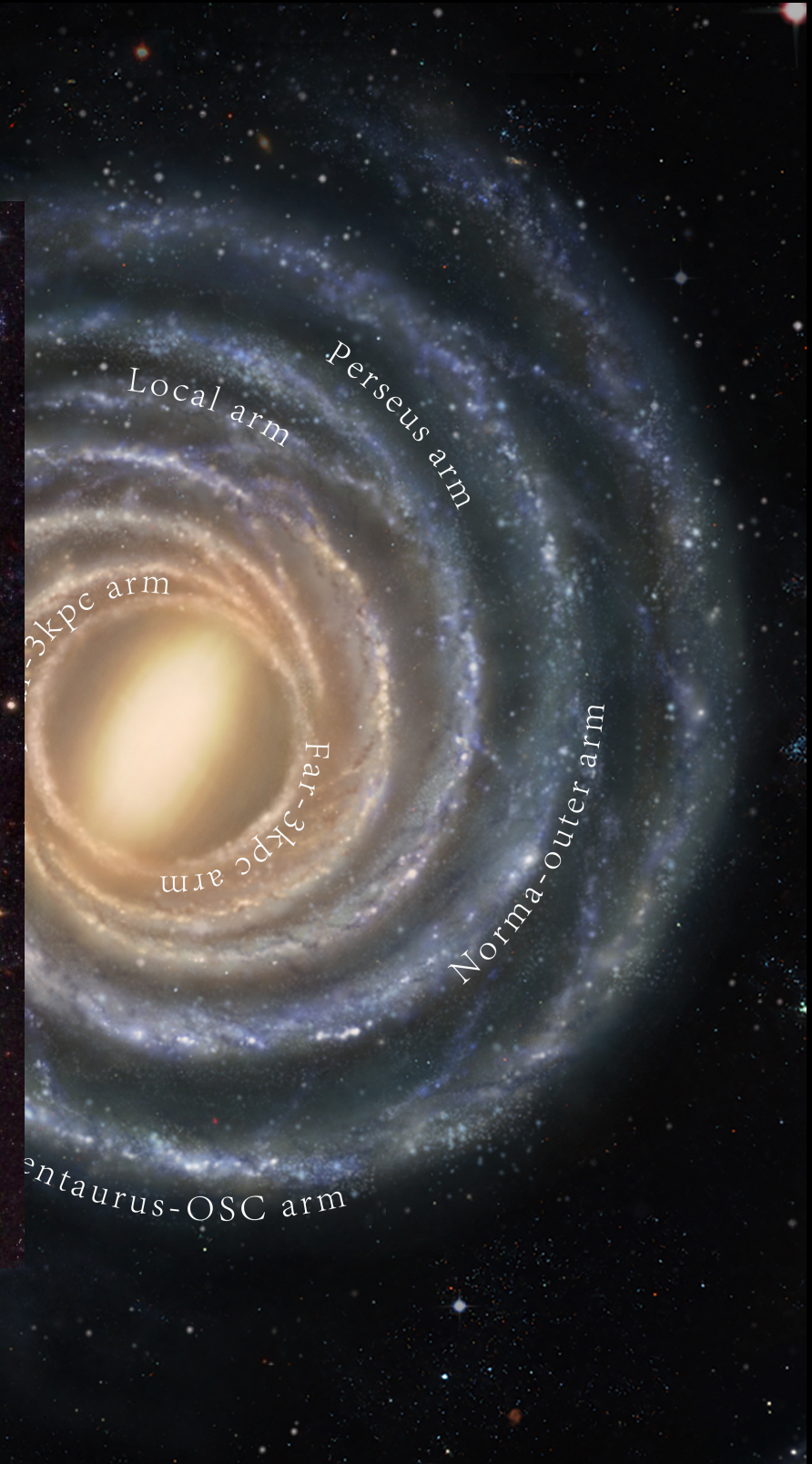
## Observation study - Challenging

- Solar system inside
- Superposition of features along line of sight



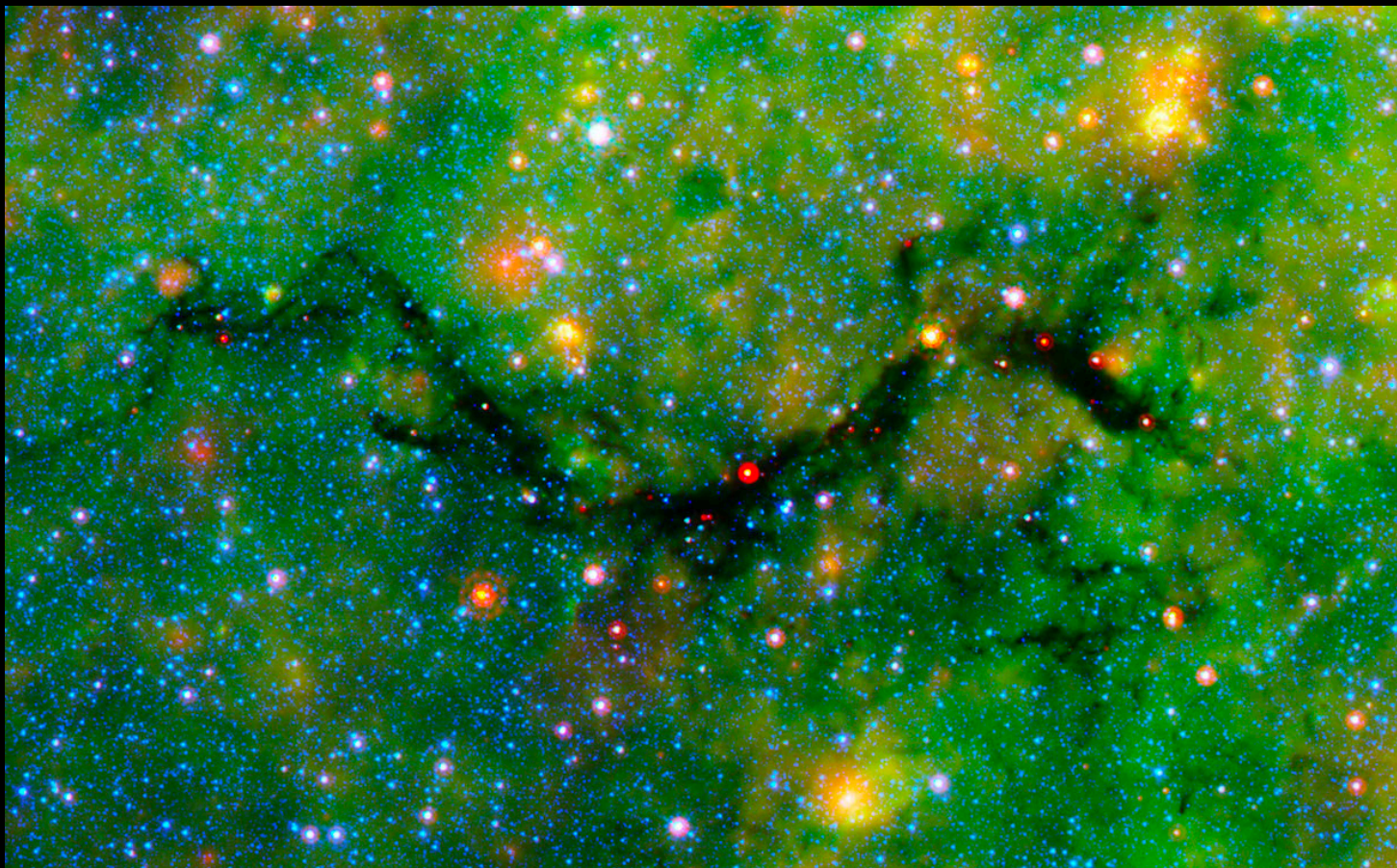


# The Milky Way Galaxy





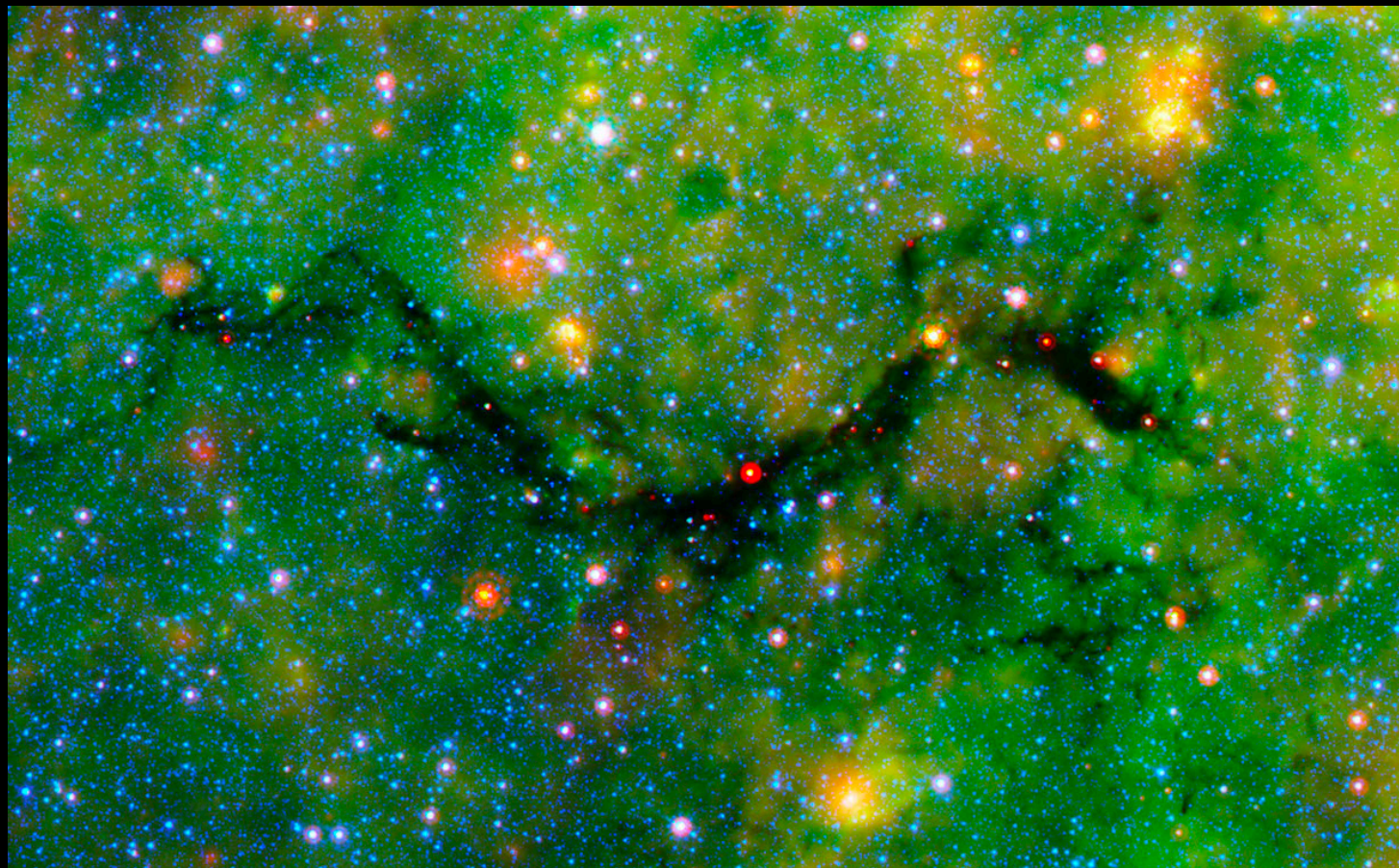
- High resolution infrared and millimetre surveys - large scale gas structures
- Infrared Dark Clouds (IRDCs)



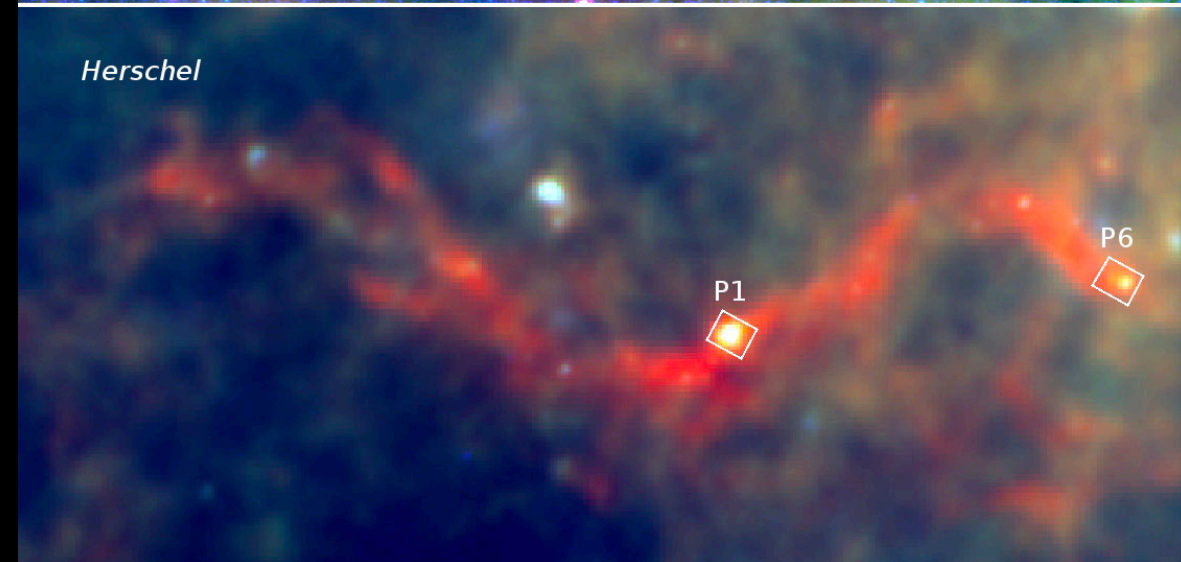
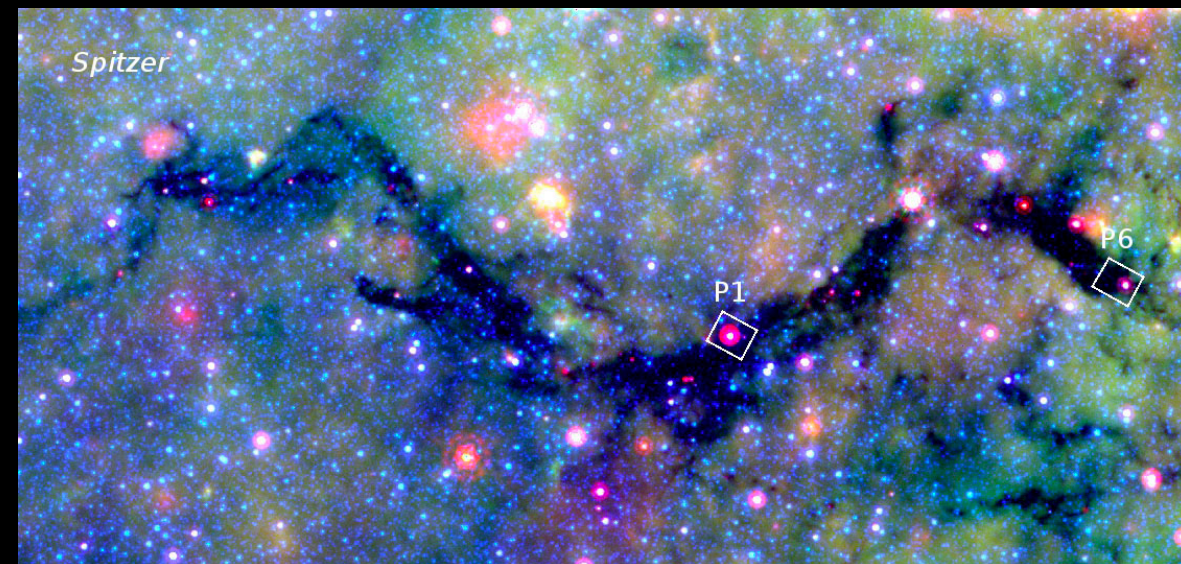
IRDC G11.11-0.12 (Snake cloud).  
NASA, JPL-Caltech / S. Carey (SSC / Caltech)



- High resolution infrared and millimetre surveys - large scale gas structures
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IRDC G11.11-0.12 (Snake cloud).  
NASA, JPL-Caltech / S. Carey (SSC / Caltech)



Spitzer/GLIMPSE/MIPS, Herschel/HiGal, Ke Wang (ESO)



# Giant Molecular Filaments

- IRDCs extending 100s of parsecs



Nessie filament (Jackson+2010)

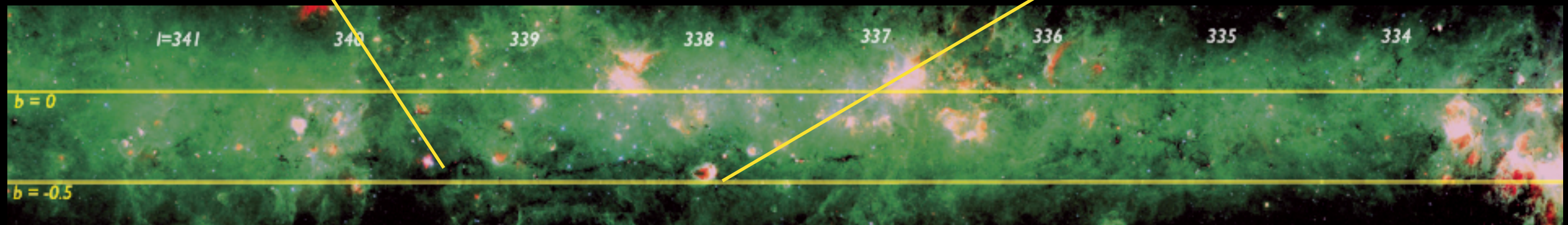


# Giant Molecular Filaments

- IRDCs extending 100s of parsecs



Nessie filament (Jackson+2010)



Classic - 81 pc, extended - 162 pc, optimistic 431 pc (Goodman+2014)

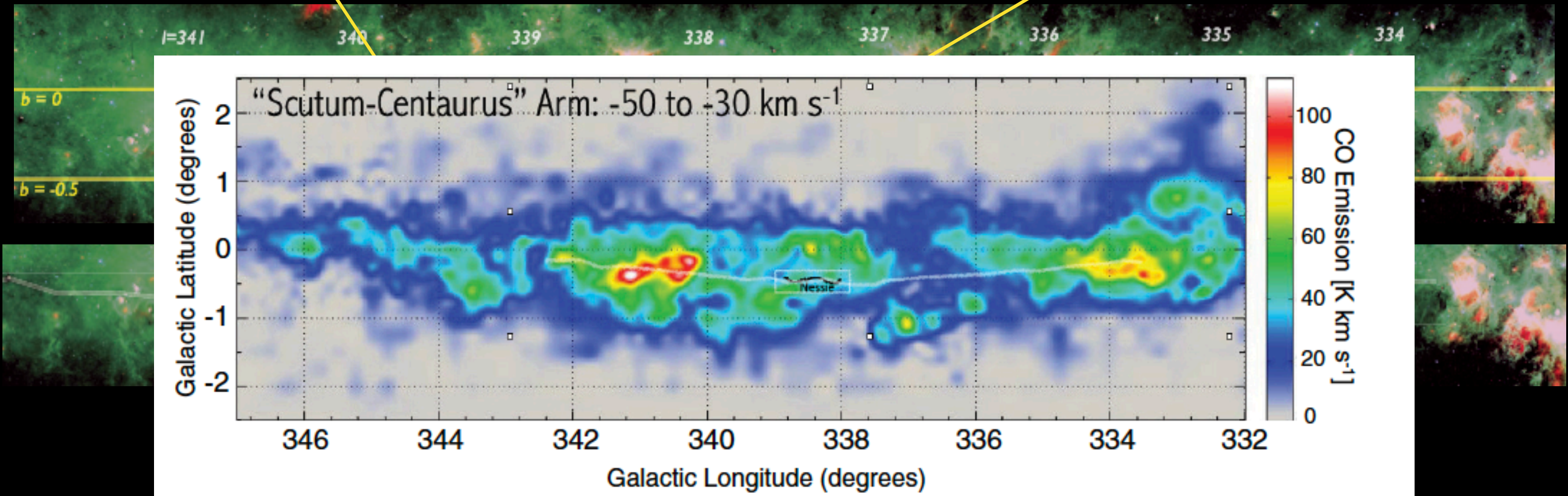


# Giant Molecular Filaments

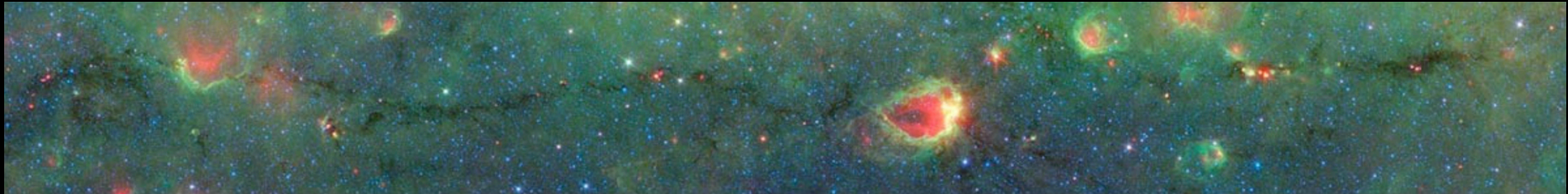
- IRDCs extending 100s of parsecs



Nessie filament (Jackson+2010)







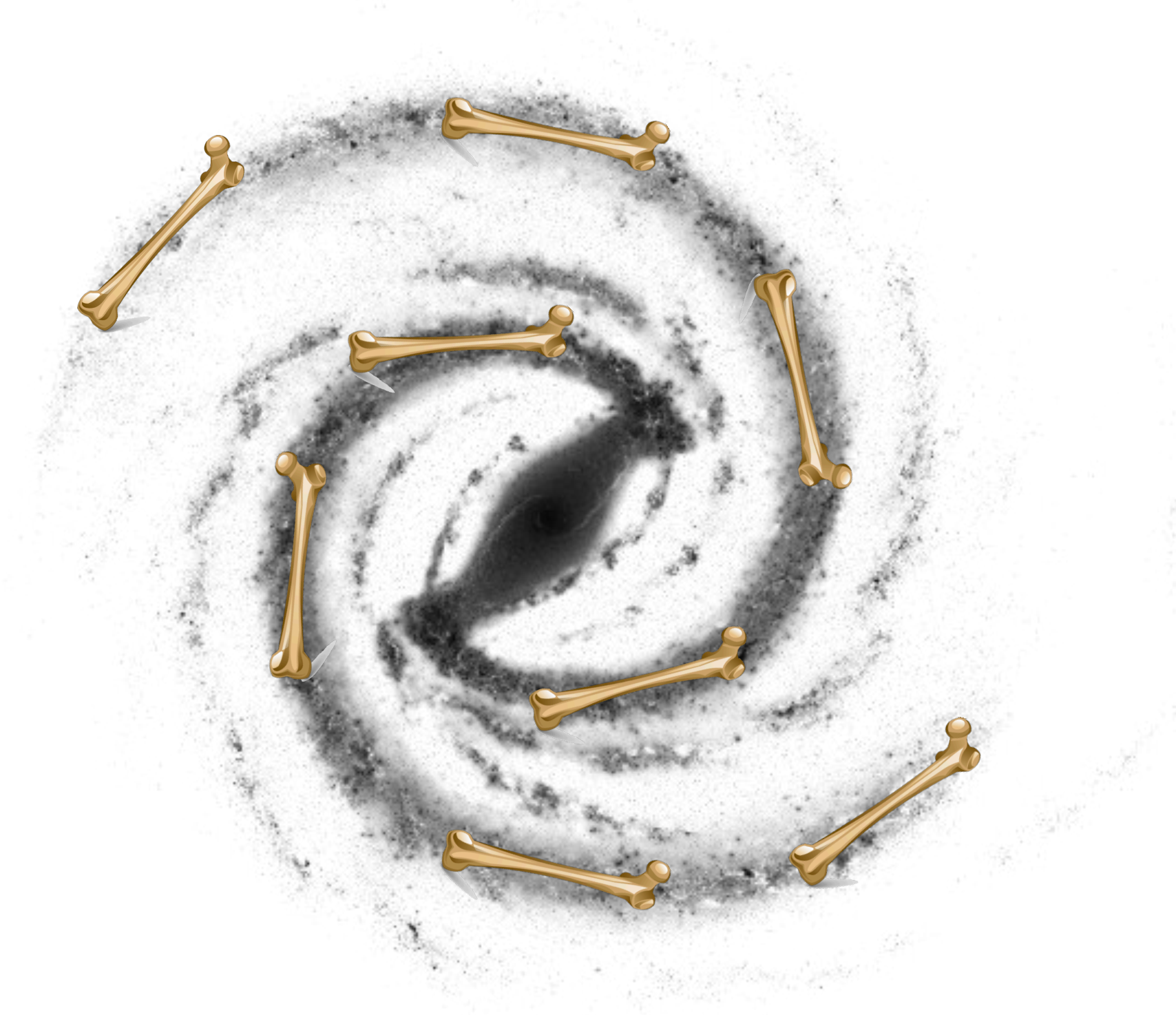
Credit:[https://uvamagazine.org/articles/galactic\\_bones](https://uvamagazine.org/articles/galactic_bones)

- Nessie-like filaments - spiral arm association, close to Galactic mid-plane (e.g. Zucker+2015)
- Dense spine of the Galaxy



# Bones

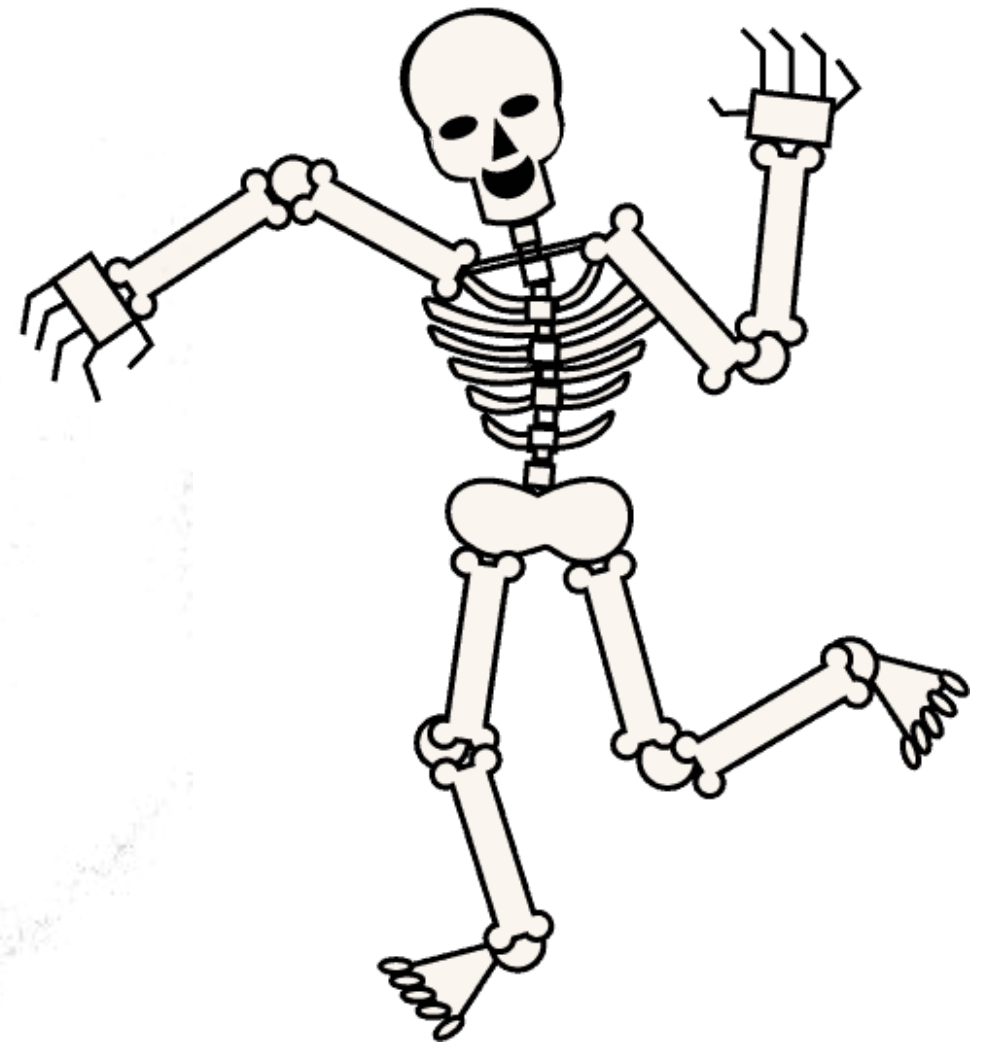
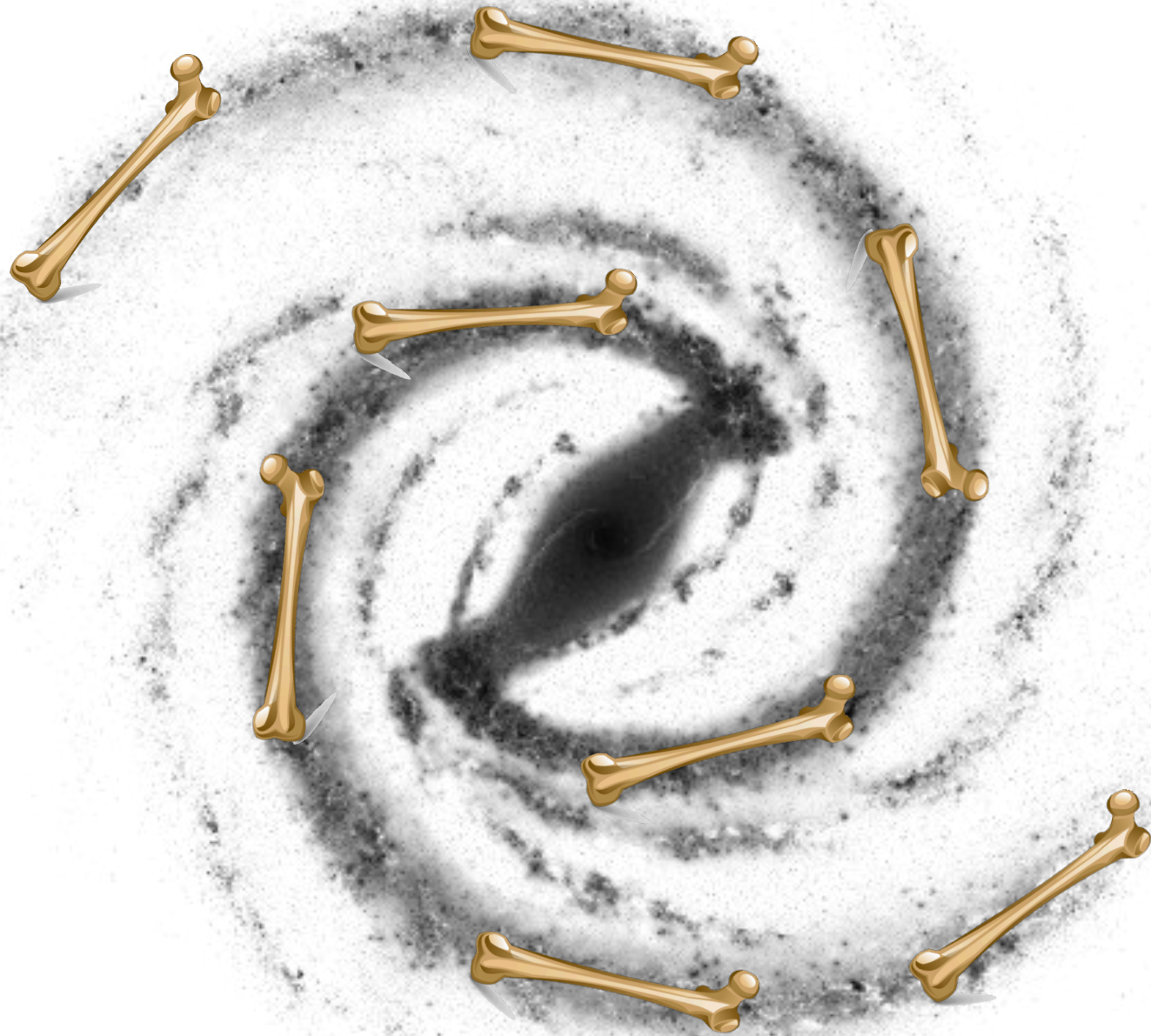
- High aspect ratio ( $>50$ )
- Within 10 km/s of spiral-arm
- Within 20 pc of mid-plane



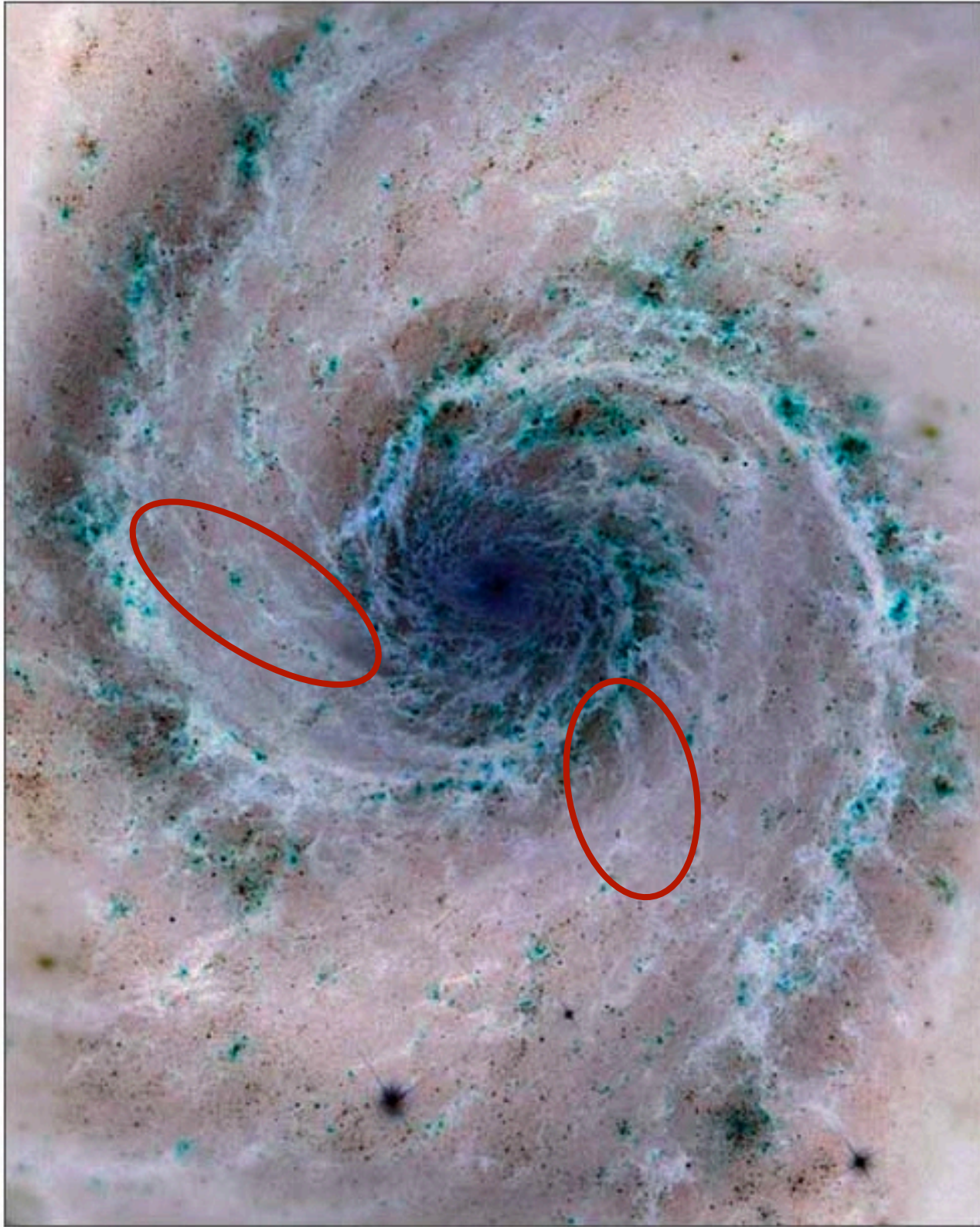


# Bones

- High aspect ratio ( $>50$ )
- Within 10 km/s of spiral-arm
- Within 20 pc of mid-plane
- Skeleton of the Milky Way (Zucker+2015)

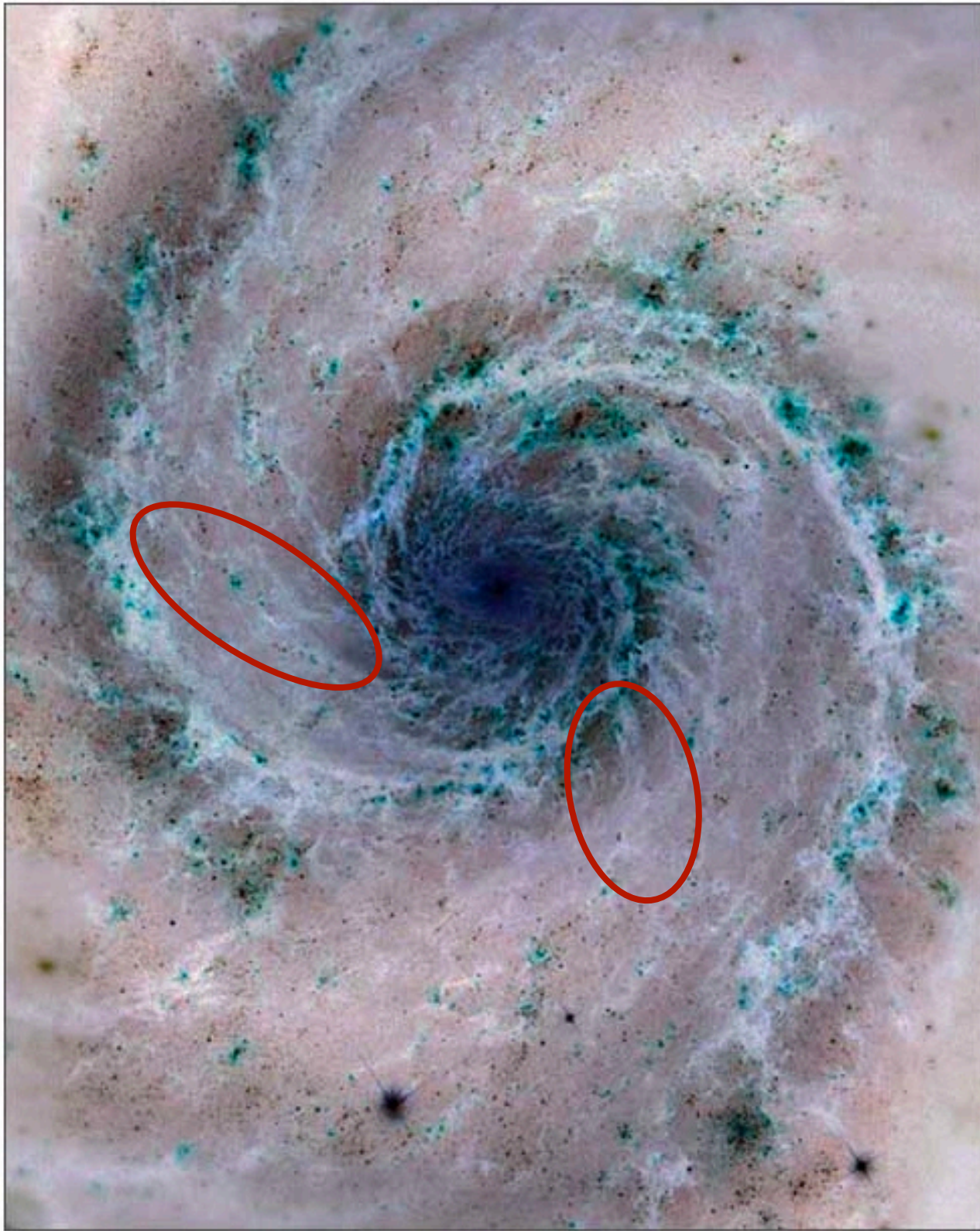




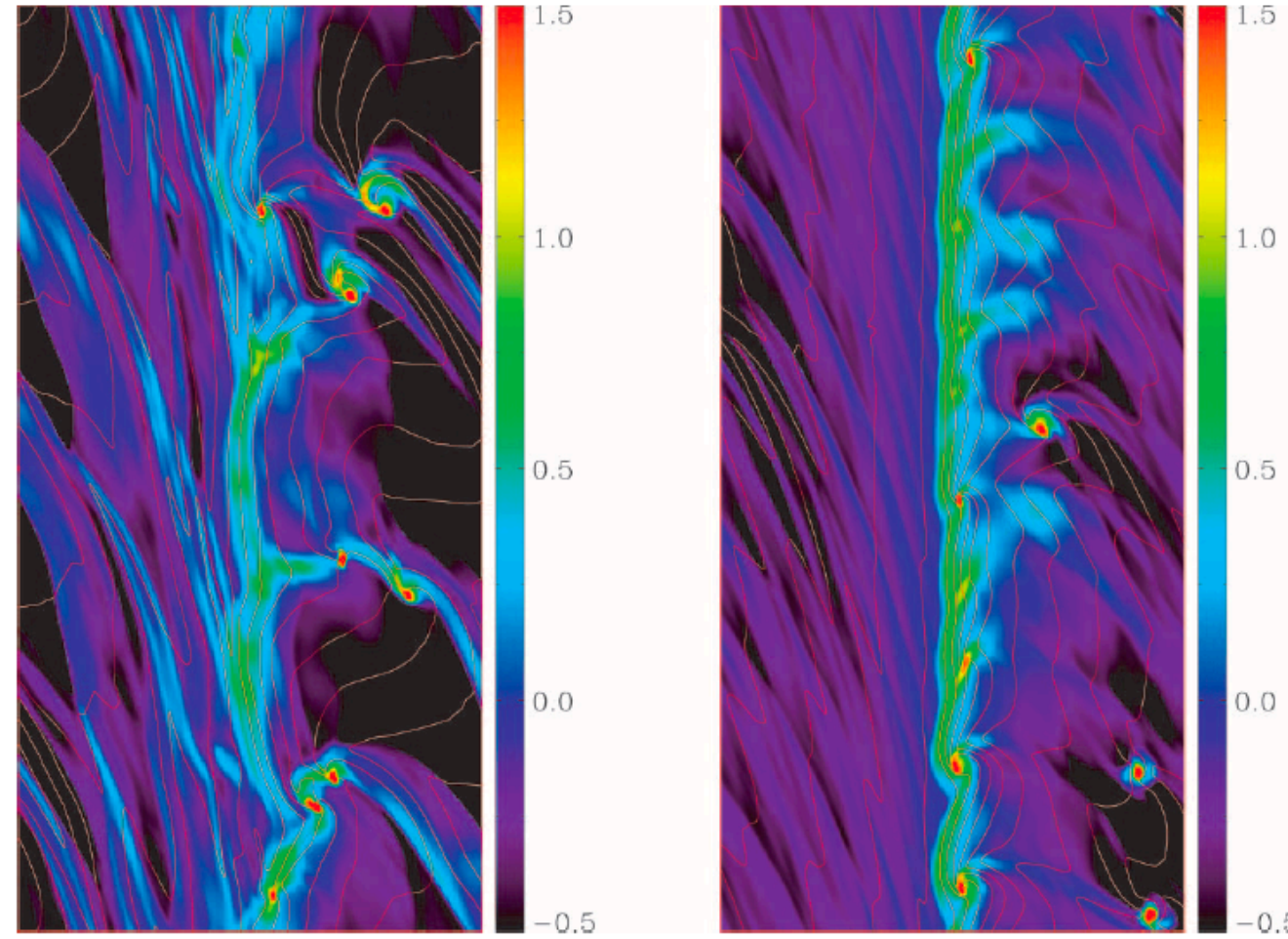


M51: Composite Hubble Image  
<https://ay201b.wordpress.com/>





M51: Composite Hubble Image  
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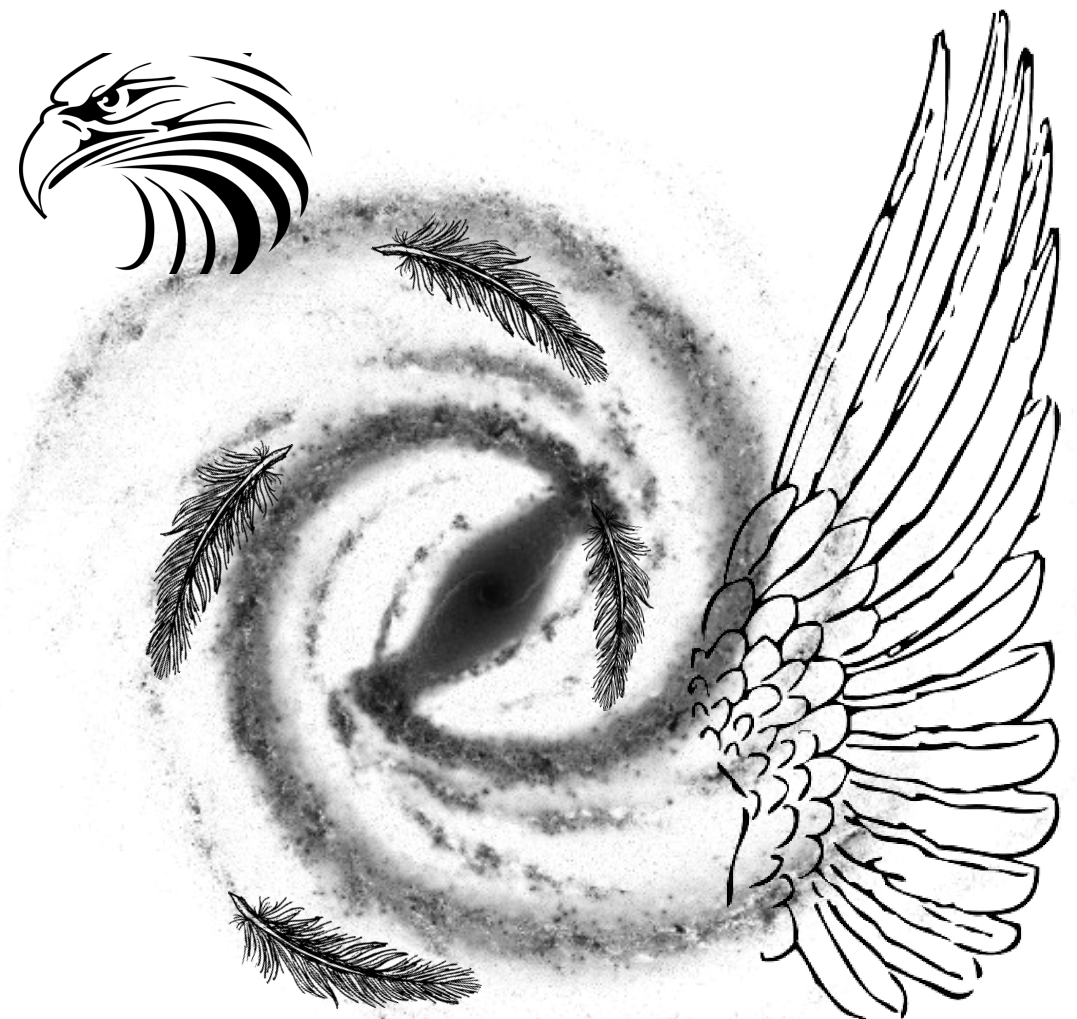
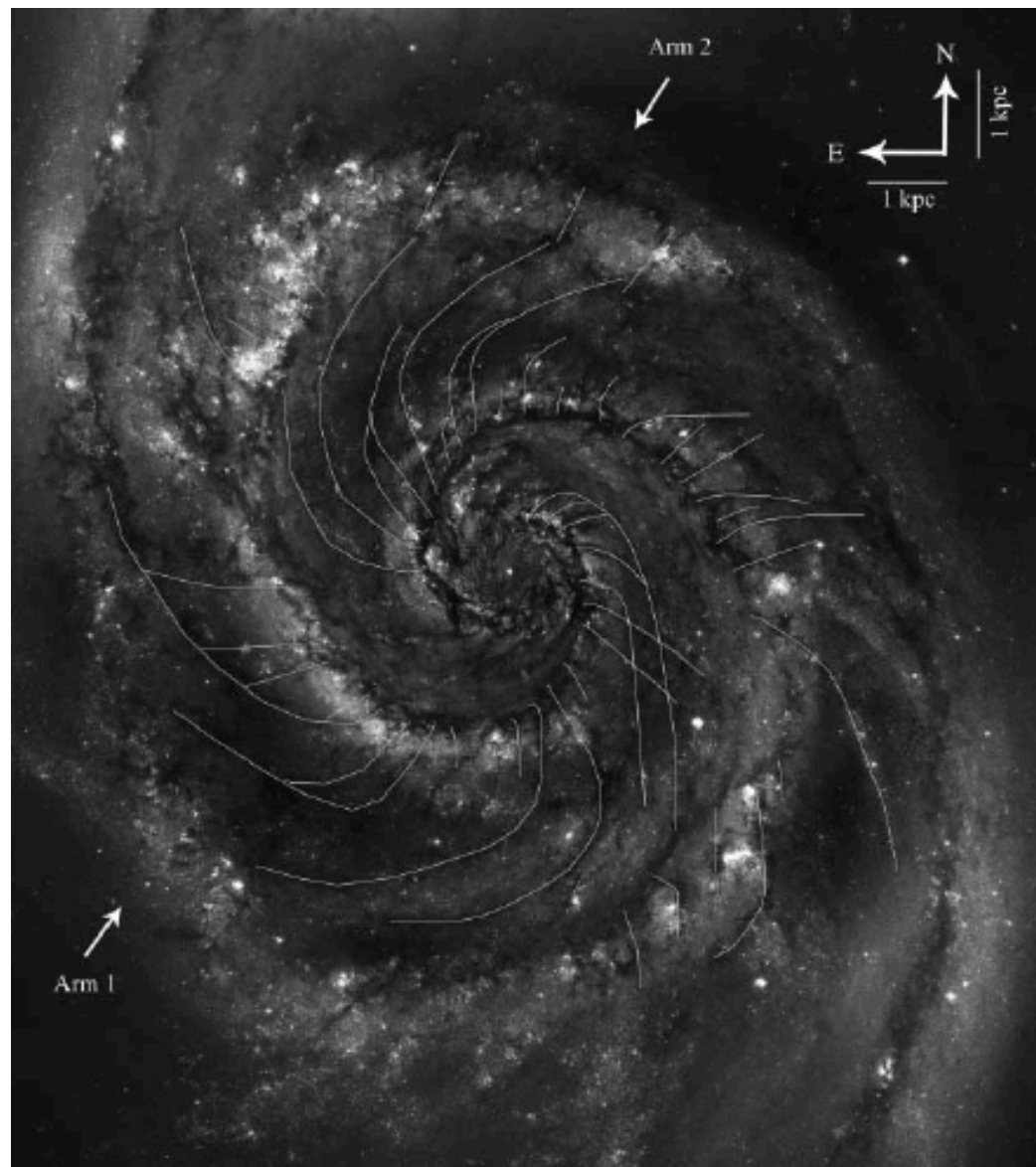


MHD simulation (Kim&Ostriker 2002)

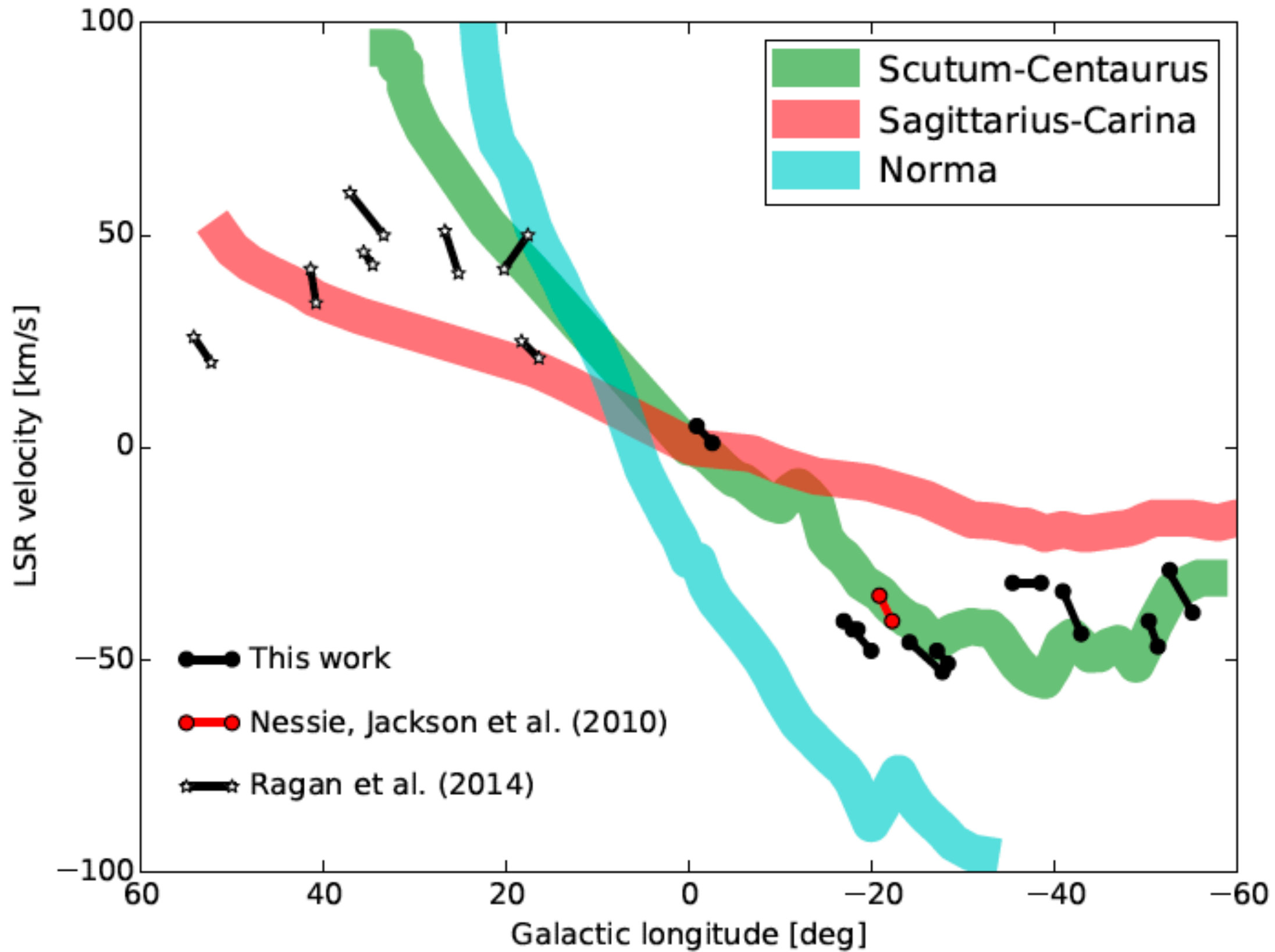


# Spurs/Feathers

- Narrow dust lanes - perpendicular to spiral arms
- Seen in external spiral galaxies

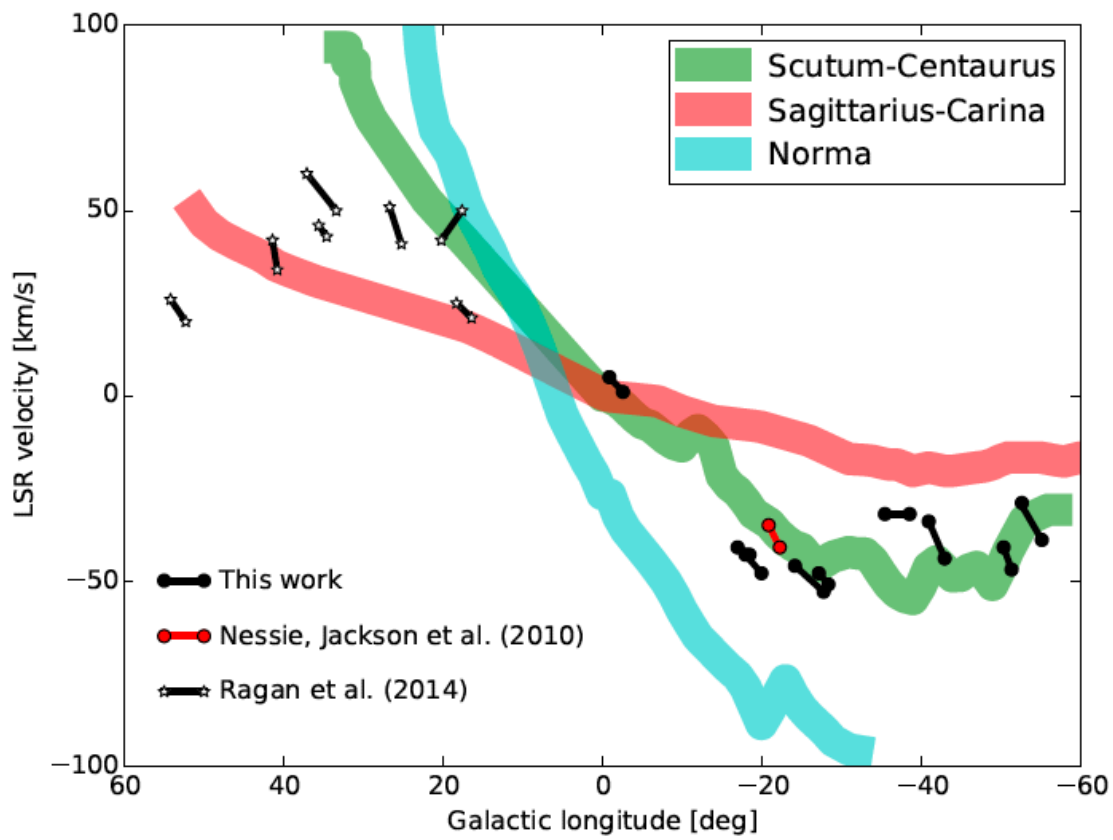




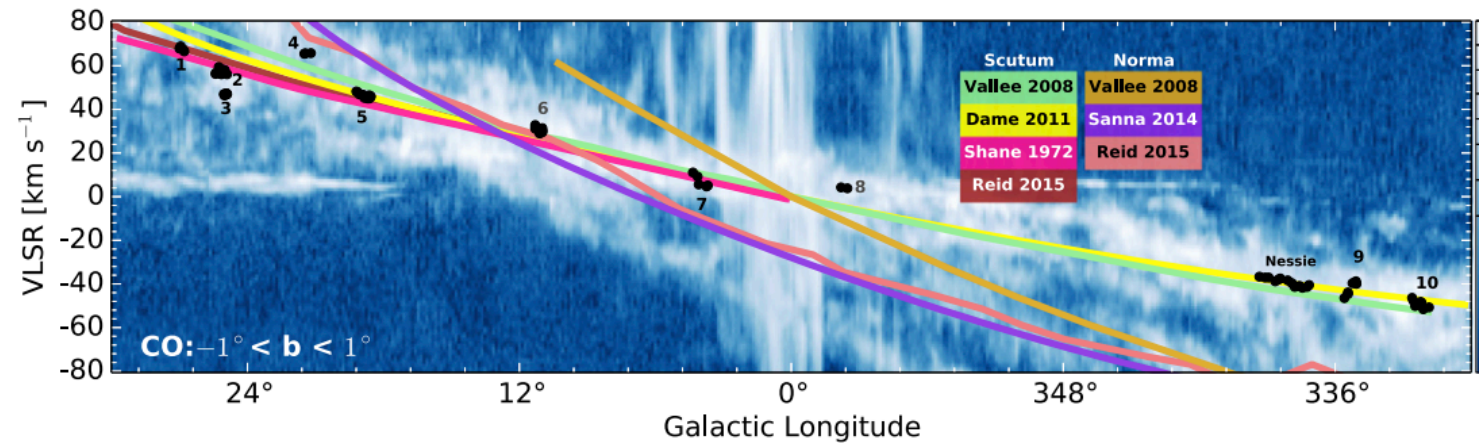


Abreu-Vicente+2016

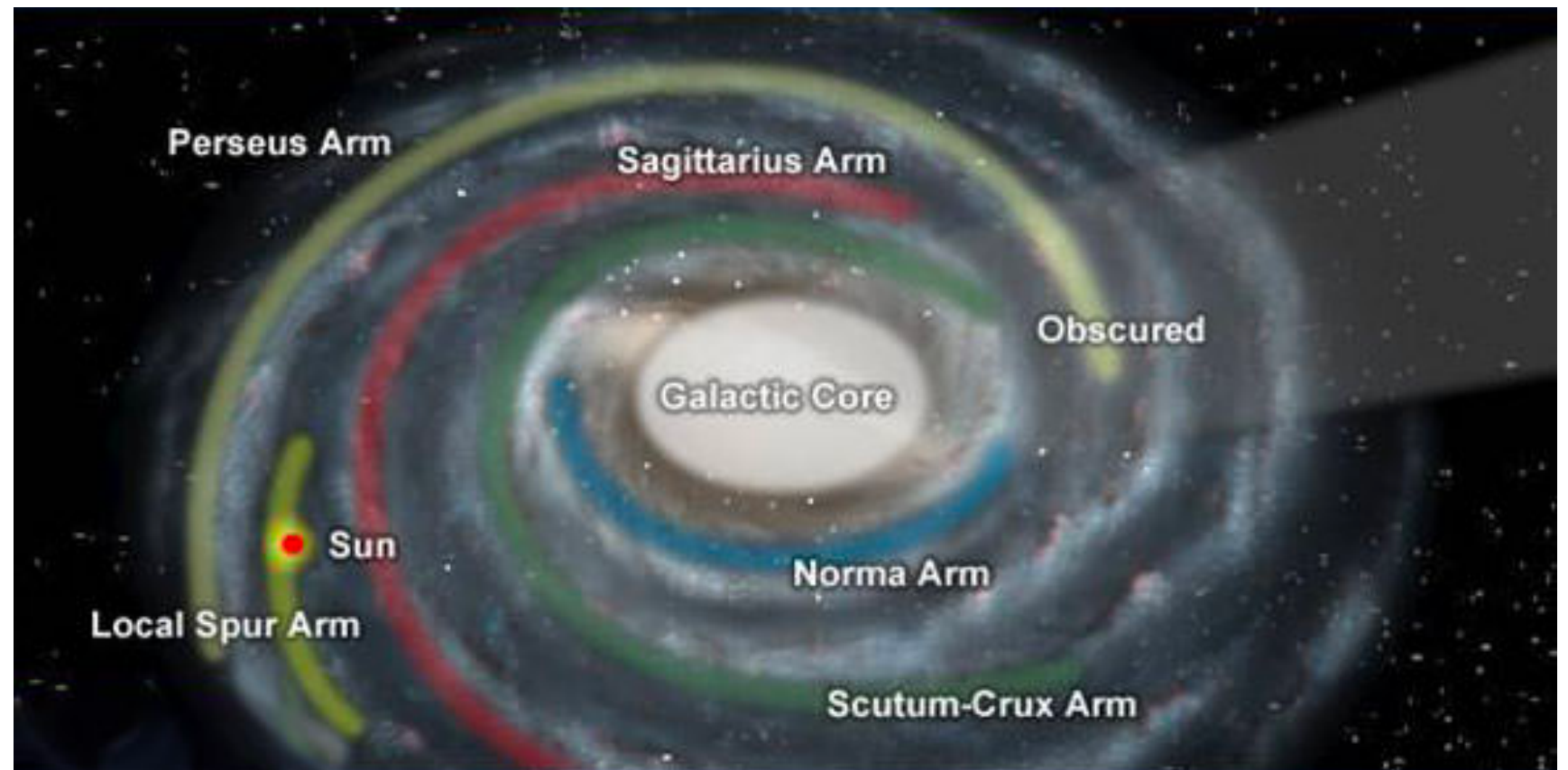




Abreu-Vicente+2016



Zucker+2015



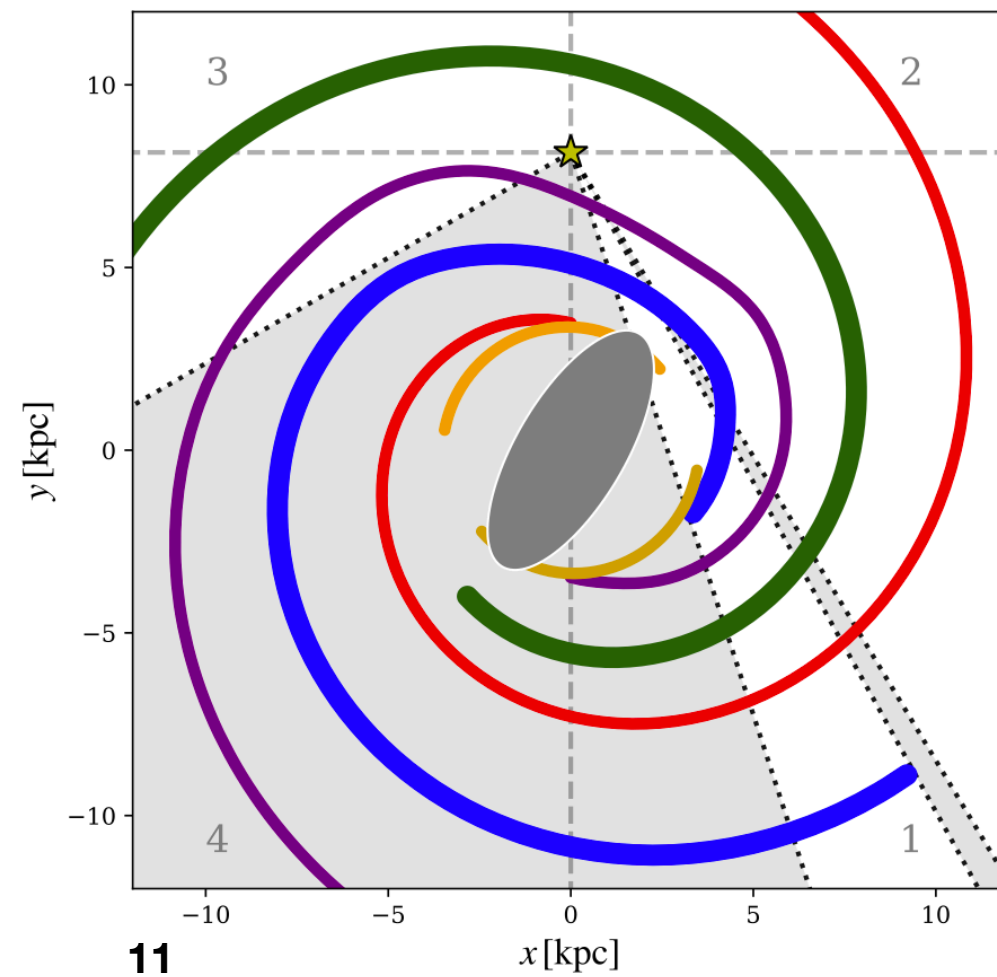
NASA /JPL



# Search for Bones/feathers in SEDIGISM CO survey

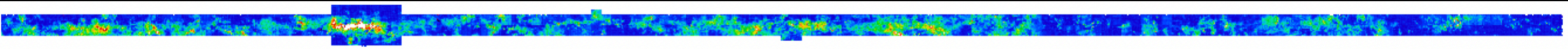


SEDIGISM





# Search for Bones/feathers in SEDIGISM CO survey



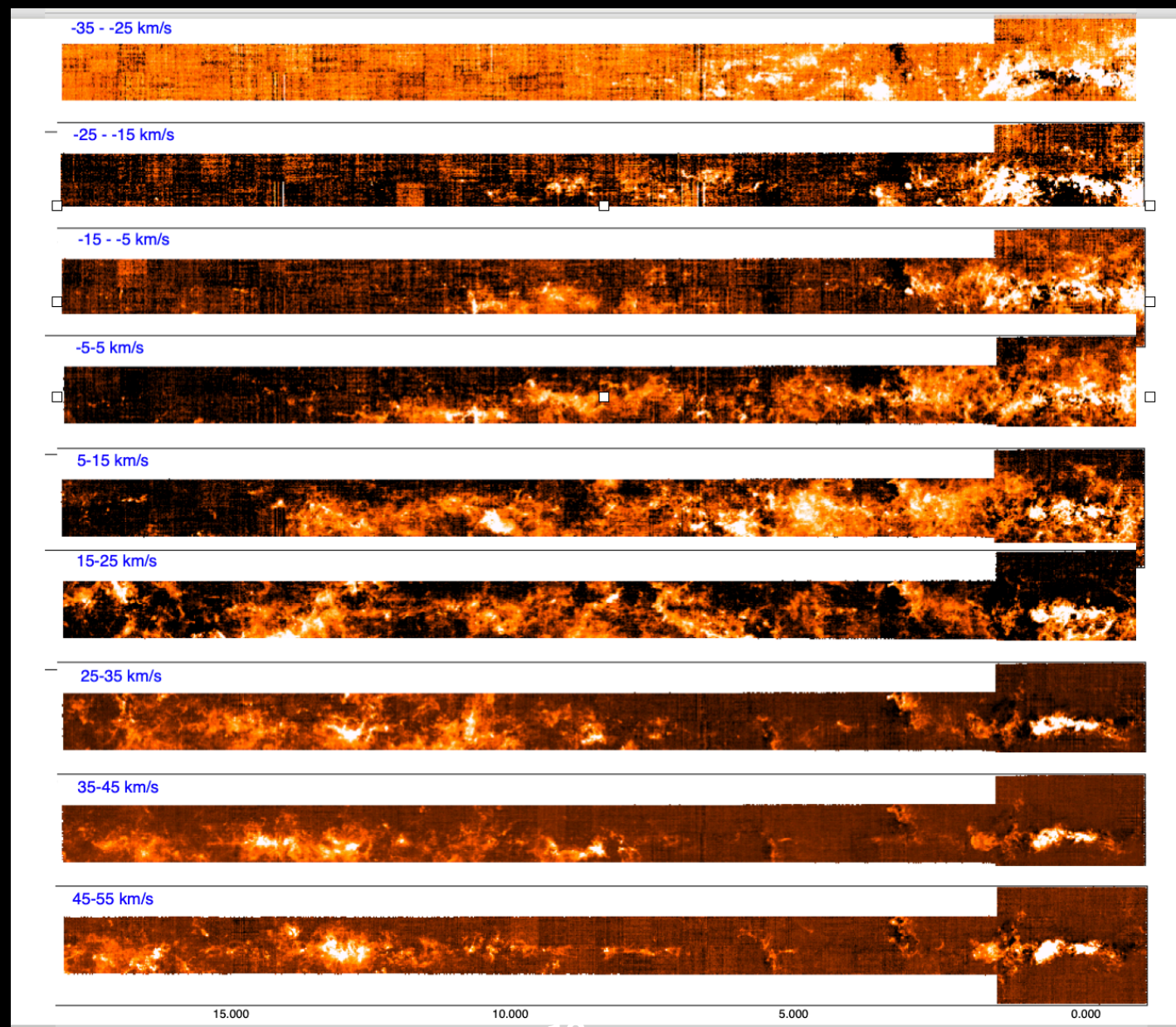
Integrated intensity map of the entire SEDIGISM field in the velocity range -200 km/s to 200 km/s (1' + 1.5 km/s resolution)



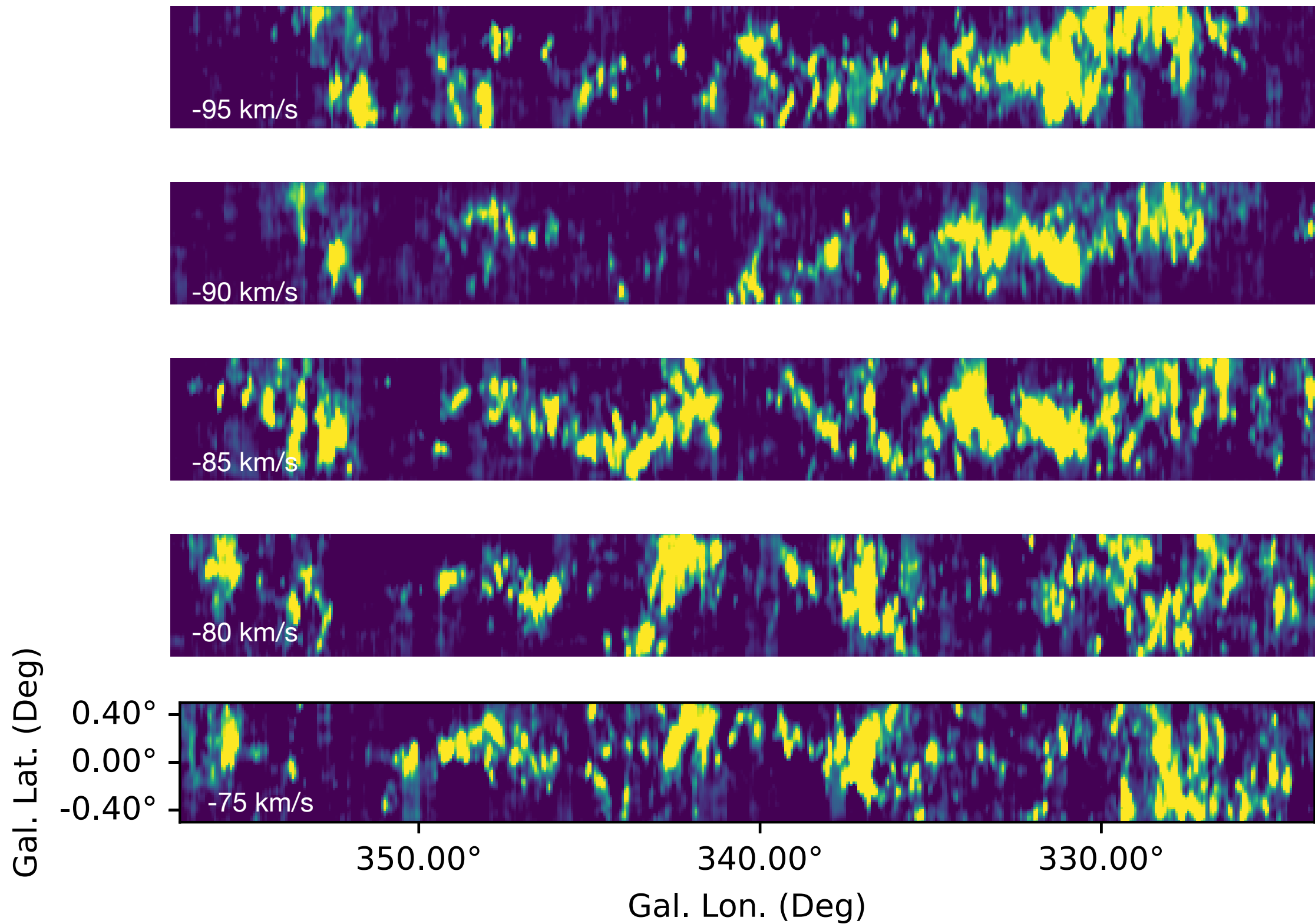
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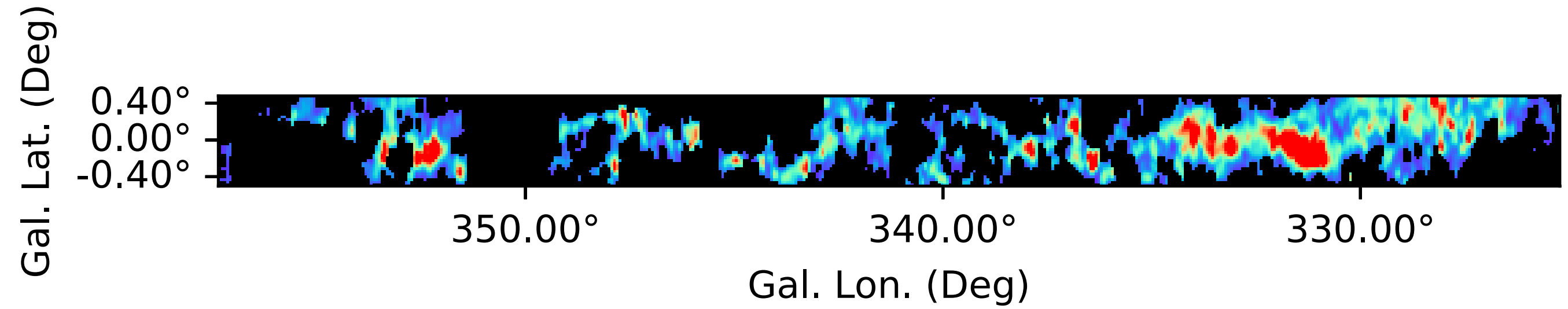
- Integrated intensity maps of  $^{13}\text{CO}$  - 10 km/s intervals
- Resultant maps - visual inspection to identify filamentary features





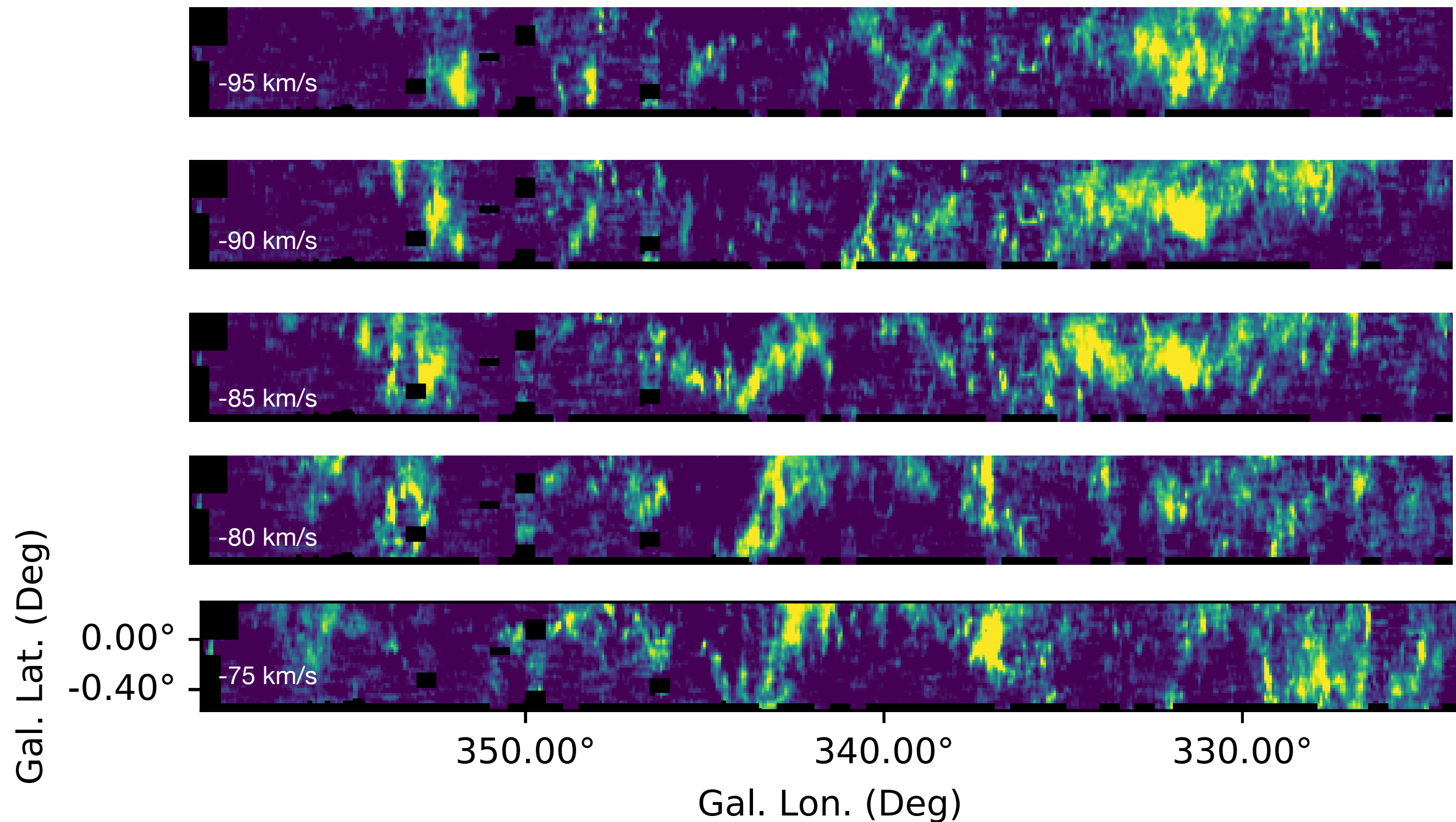




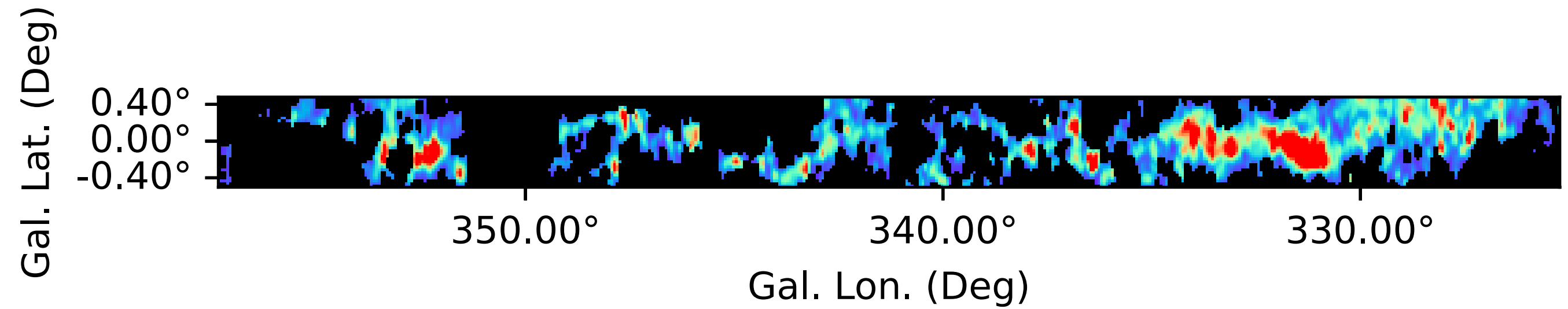


- $^{13}\text{CO}$  Integrated intensity map ( $325^\circ$ - $355^\circ$ ,  $-95$  km/s to  $-75$  km/s)
- Wave-like pattern

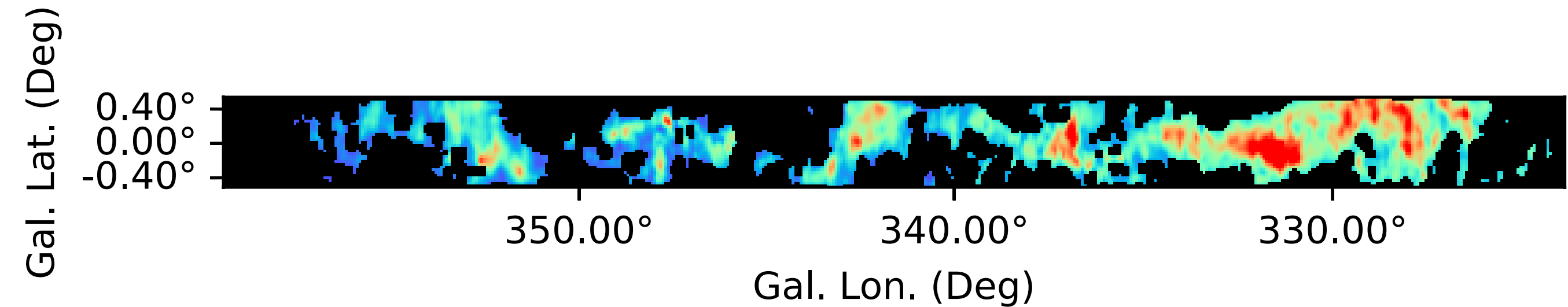






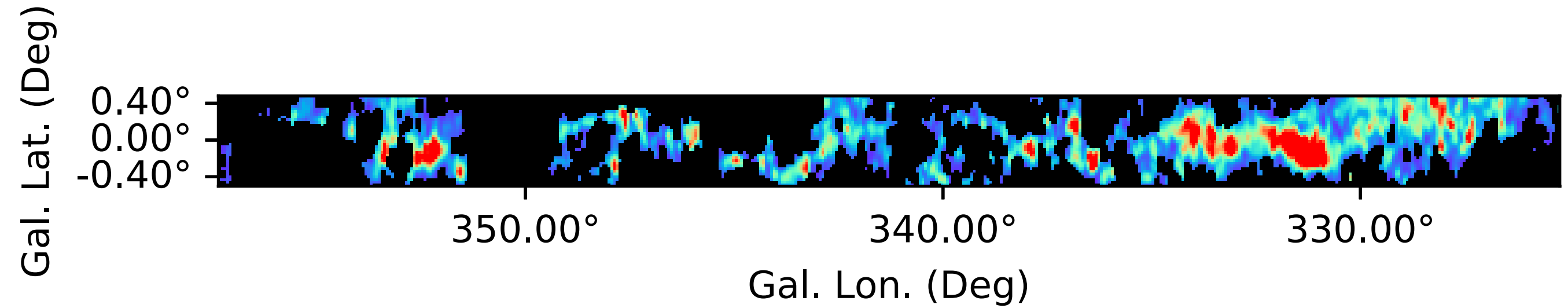


- <sup>13</sup>CO Integrated intensity map (325°-355°, -95 km/s to -75 km/s)
- Wave-like pattern

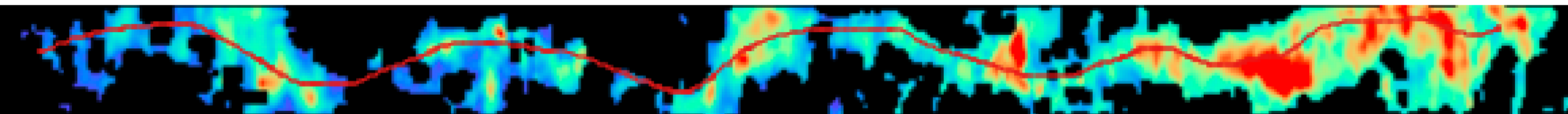


- <sup>12</sup>CO Integrated intensity map from ThruMMS survey (325°-355°, -95 km/s to -75 km/s)

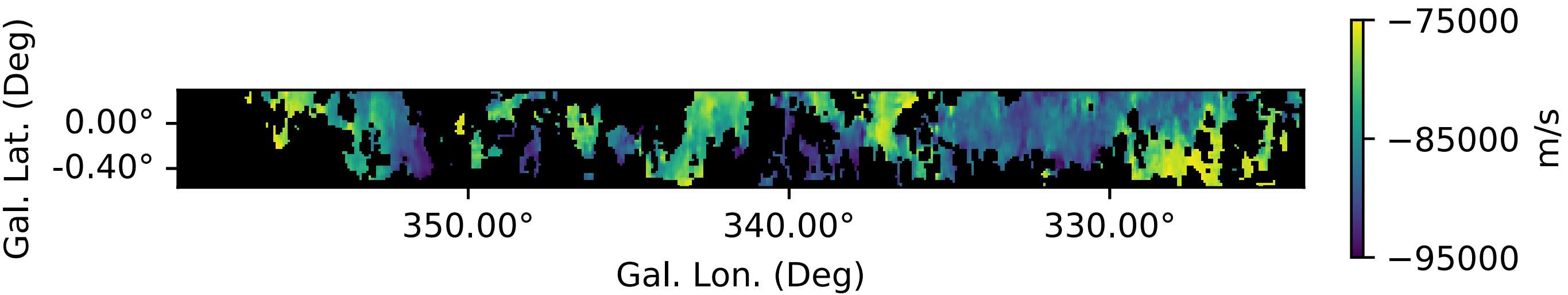




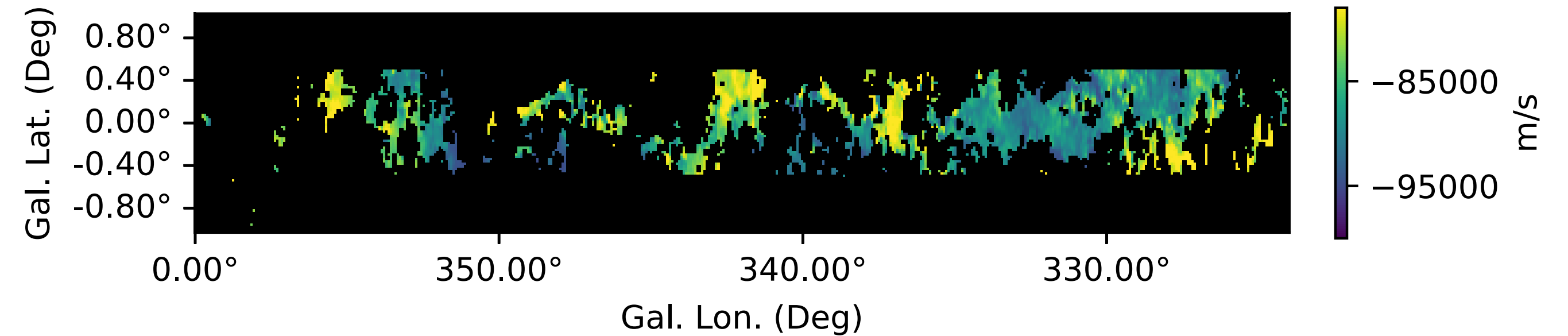
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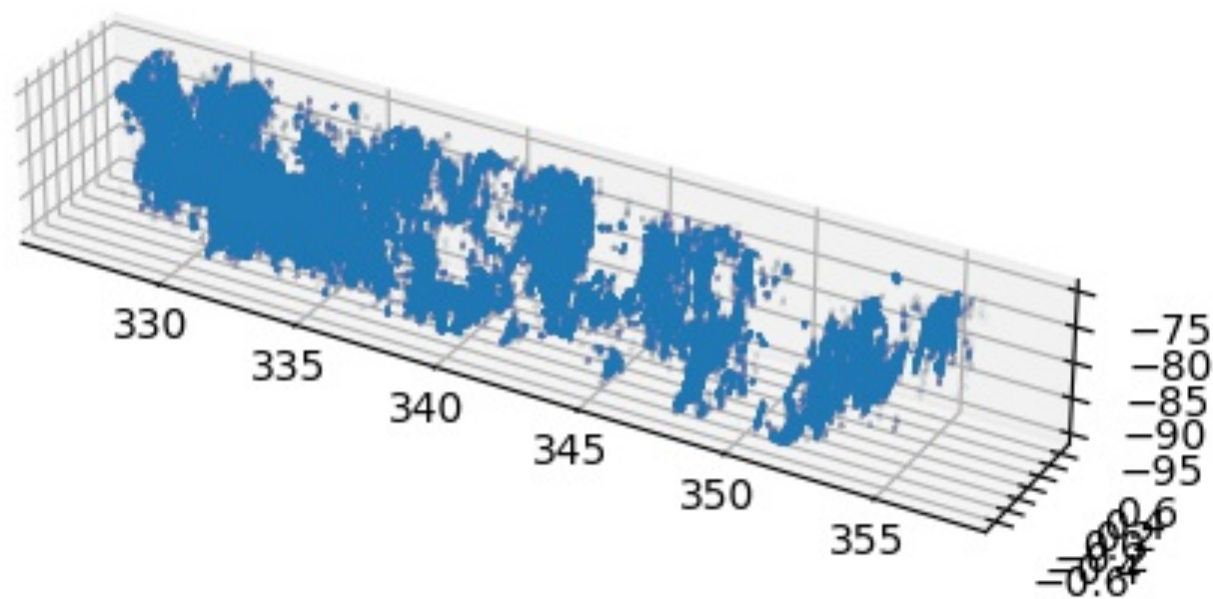
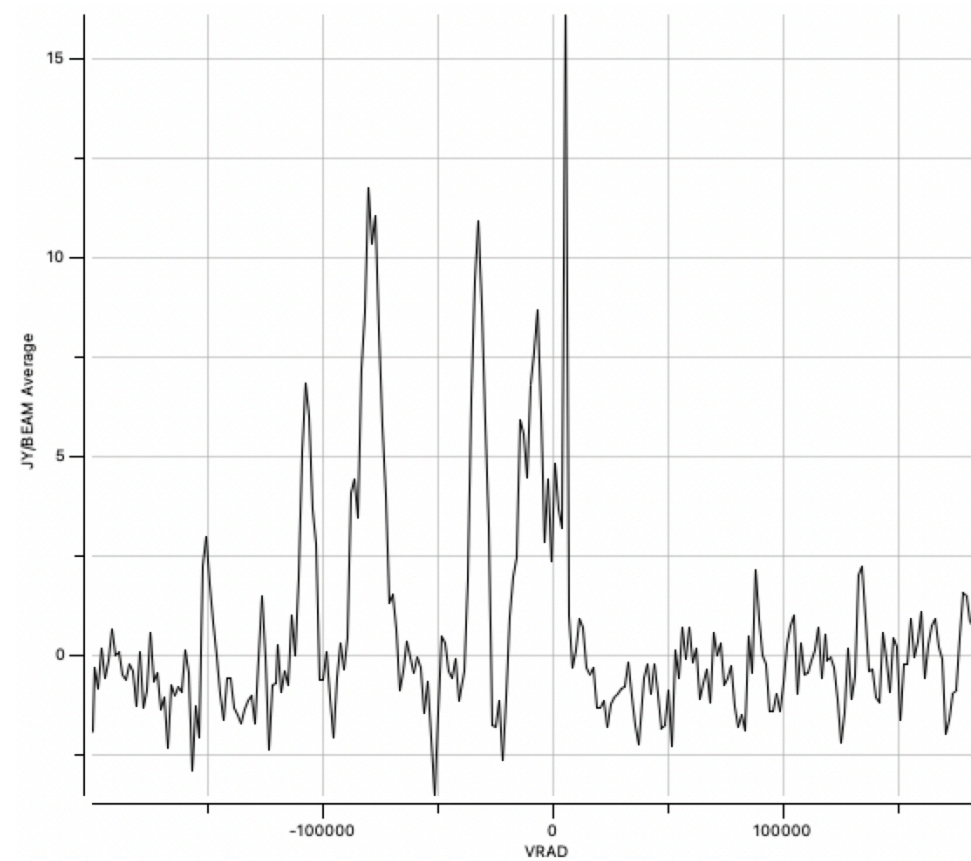
$^{12}\text{CO}$  moment 1 map



$^{13}\text{CO}$  moment 1 map



- Estimation of kinematic distance - velocity distribution of the filament
- Gausspy+ - automated multi-component spectral fit (Riener+2019)

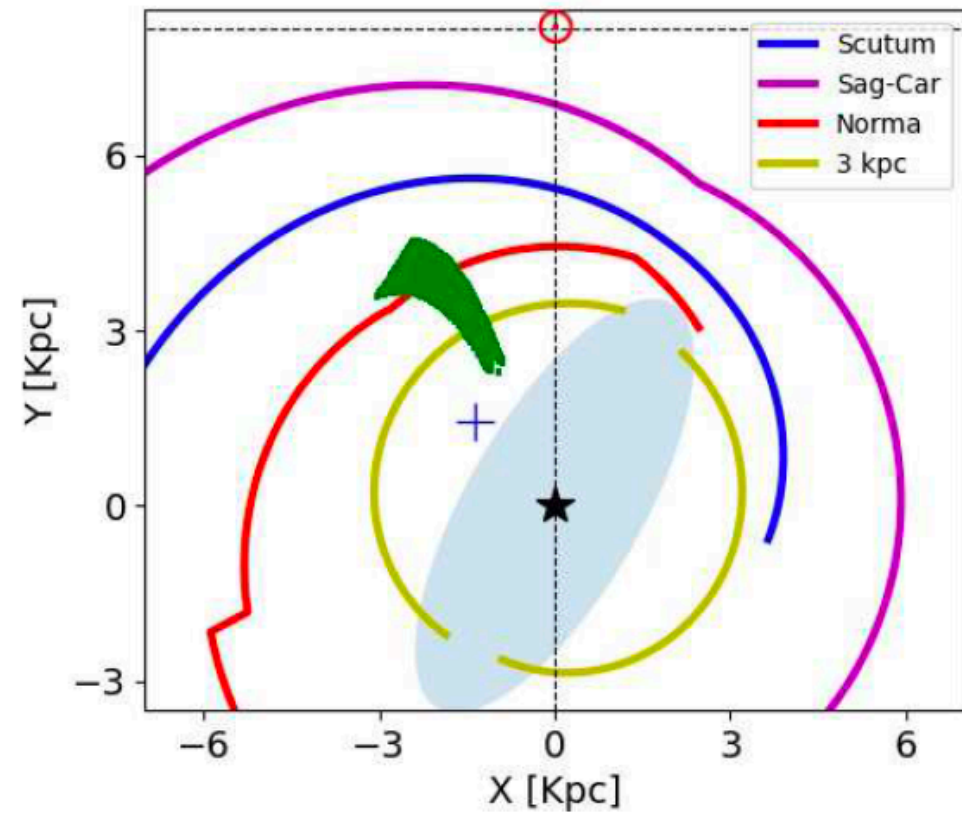
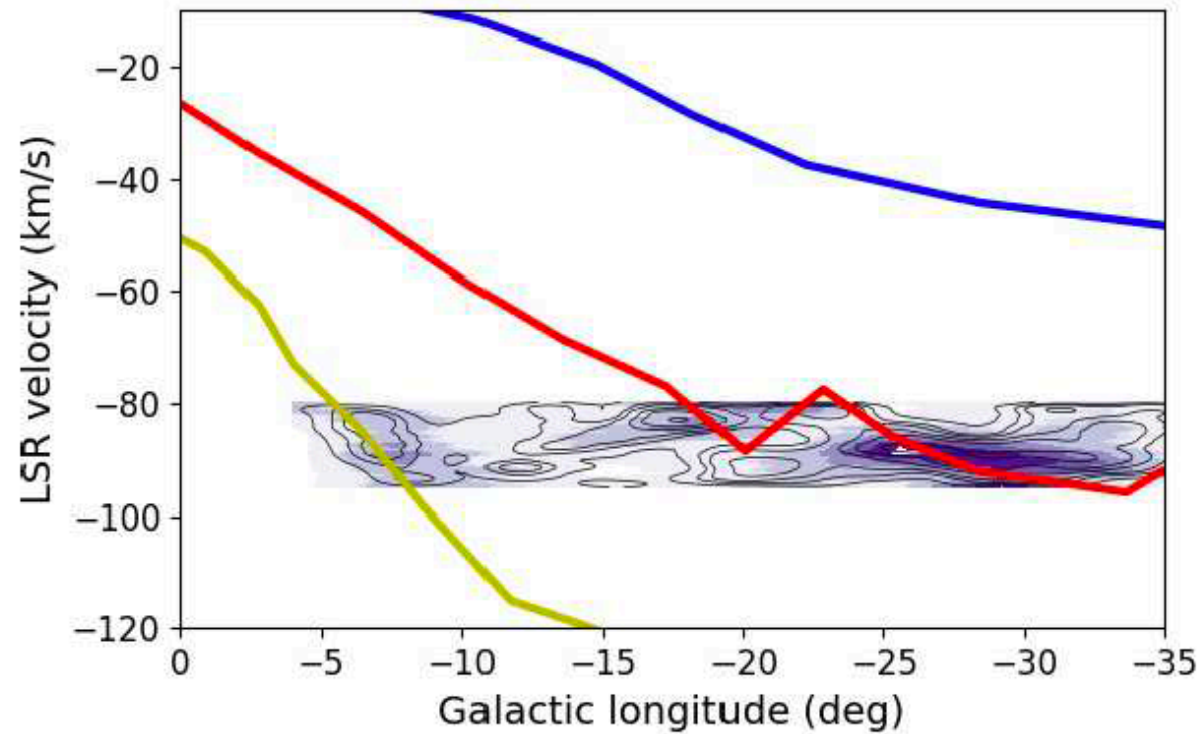


## Properties of the filament

- Near-kinematic distance - 4.5 kpc to 7 kpc
- Aspect ratio 60:1
- Length of the wavy feature - 2400 pc (assuming 4.5 kpc)
- H<sub>2</sub> column density :  $6.1 \times 10^{21} \text{ cm}^{-2}$  (average),  $2.1 \times 10^{23} \text{ cm}^{-2}$  (peak)
- Mass :  $8.7 \times 10^6$  Solar mass



# Orientation of the filament



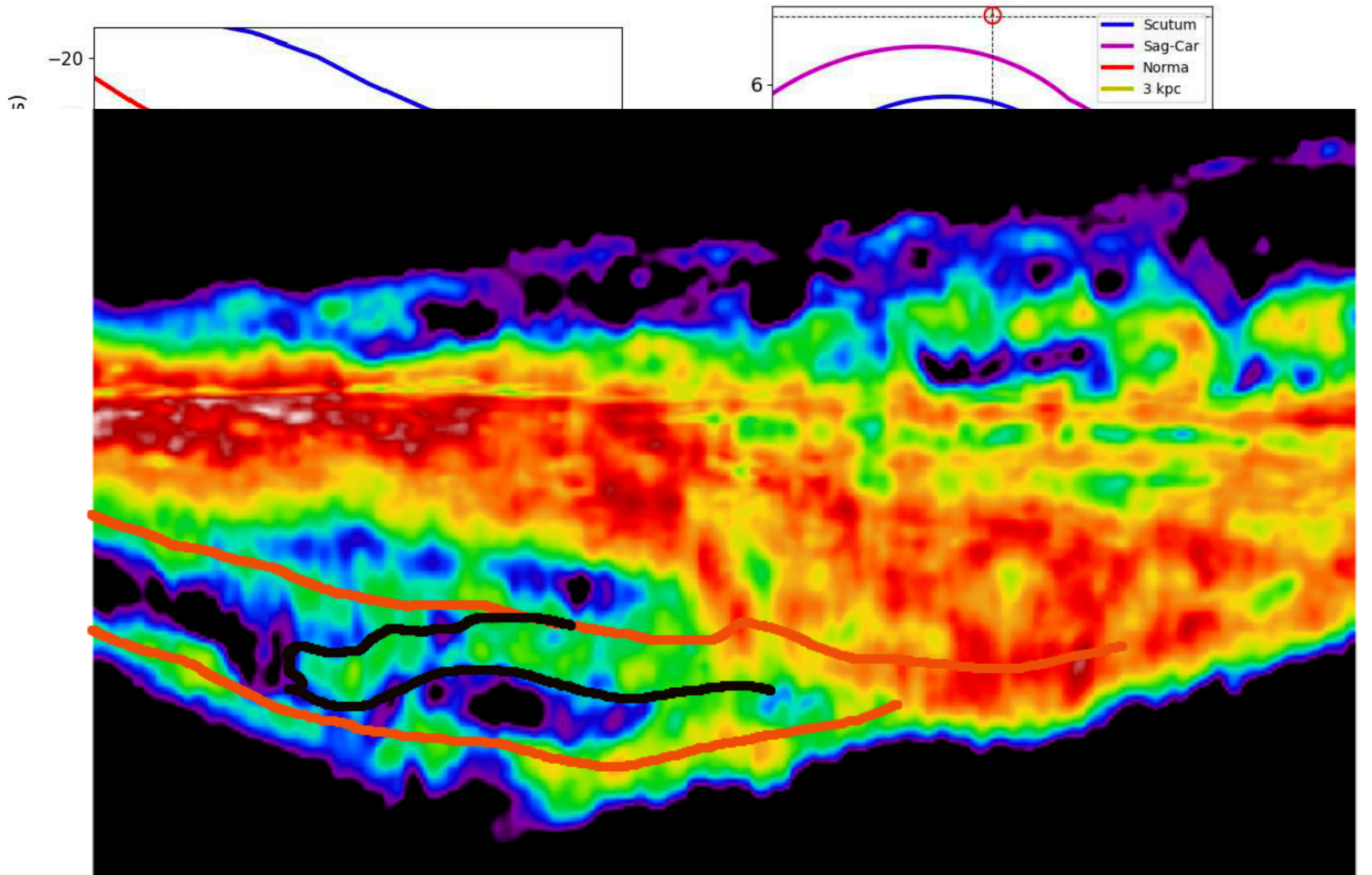
L-V plot of the wave (Contours) wrt to models of Reid+2019

- Velocity consistent with Norma arm at one end and 3-kpc arm at other end
- Orientation nearly perpendicular to spiral arms



**Norma**  
**Norma-3kpc inter-arm**  
**3 kpc**

# Orientation of the filament

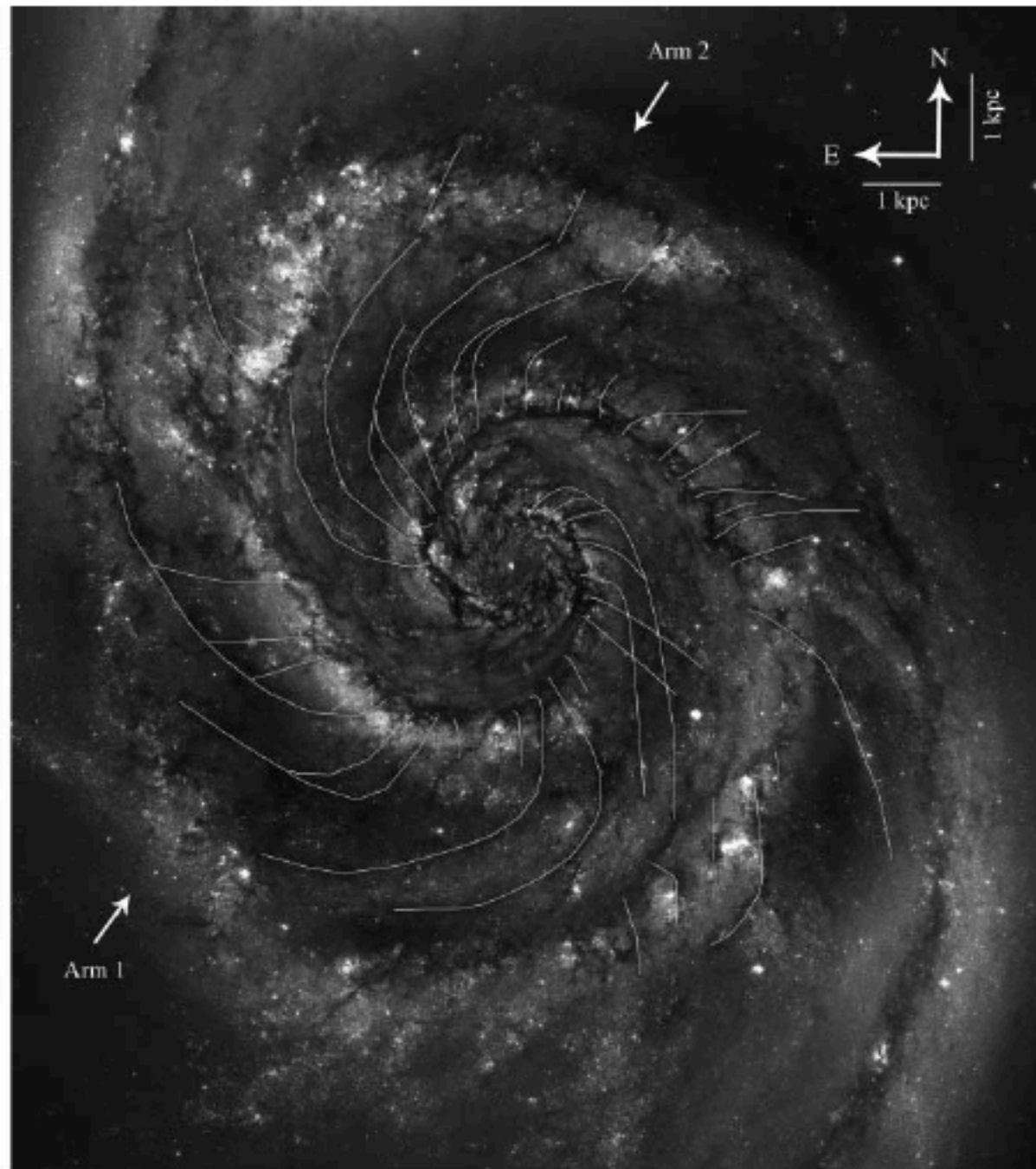
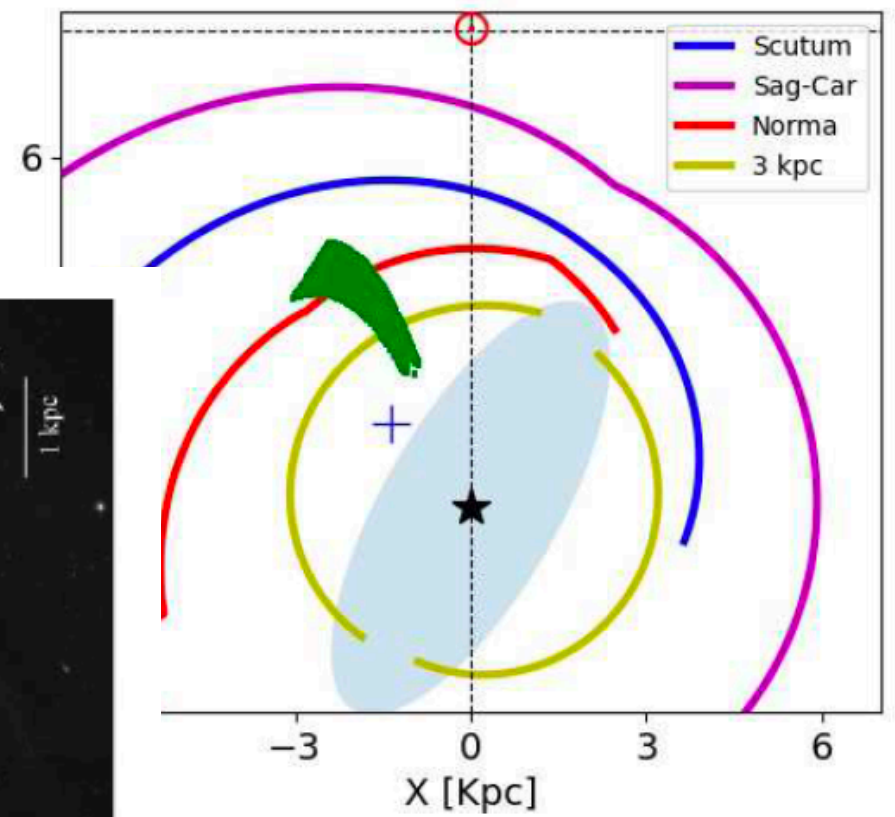
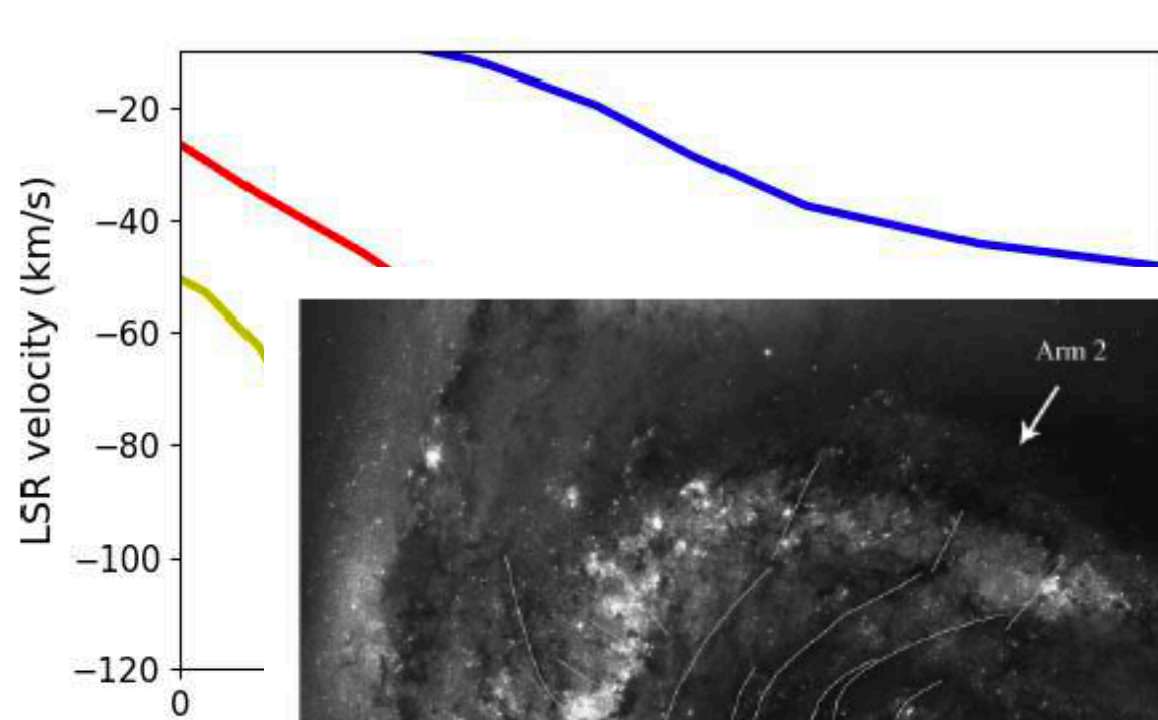


L-V plot (GASS HI survey)

Norma-3kpc inter-arm  
3 kpc



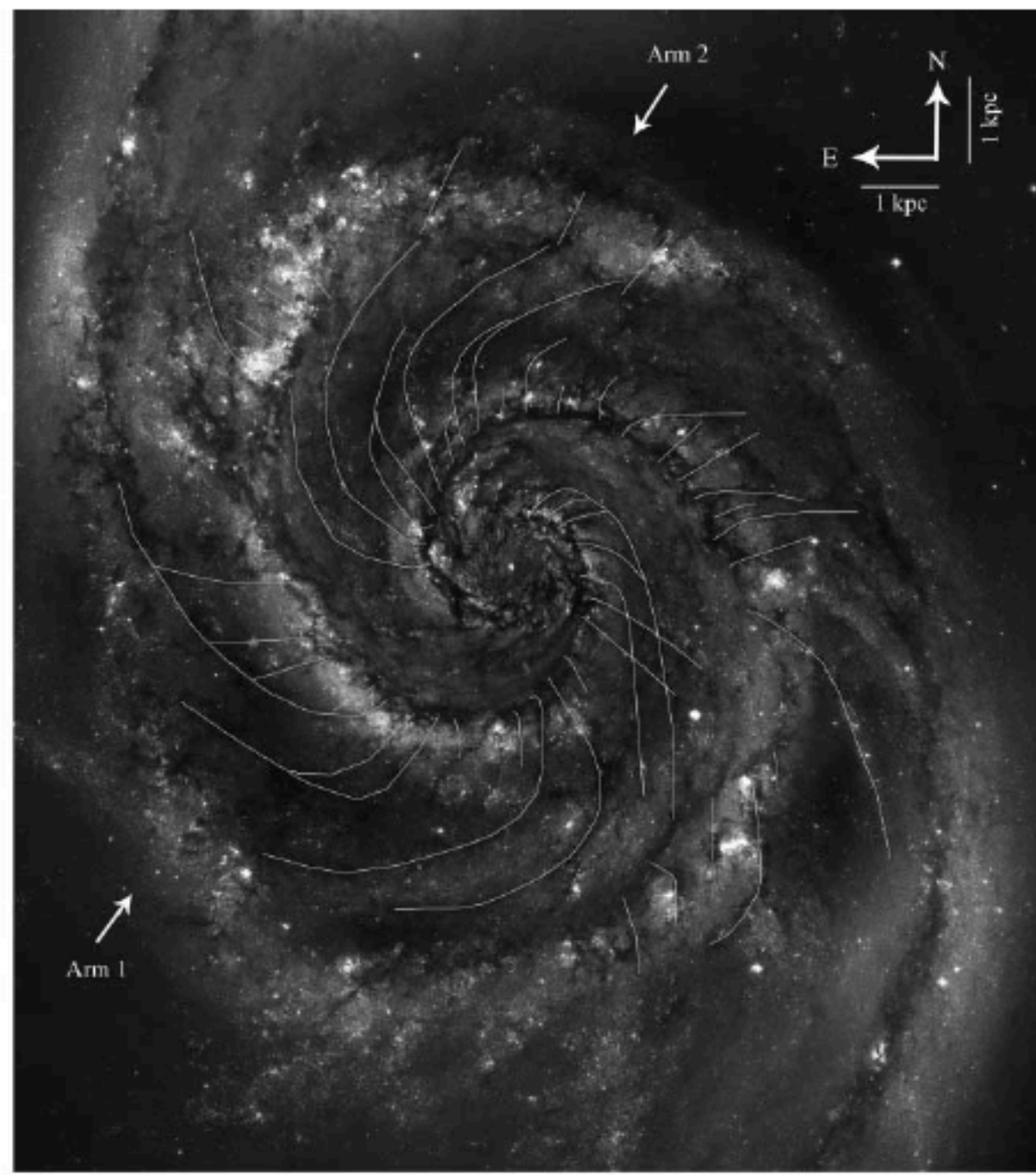
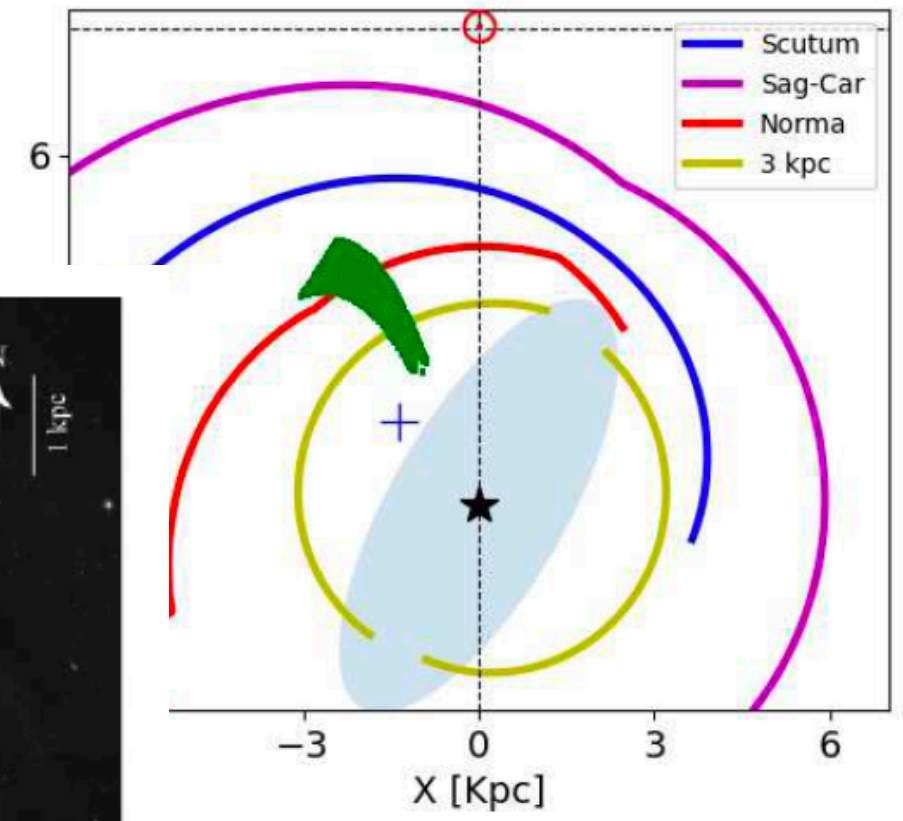
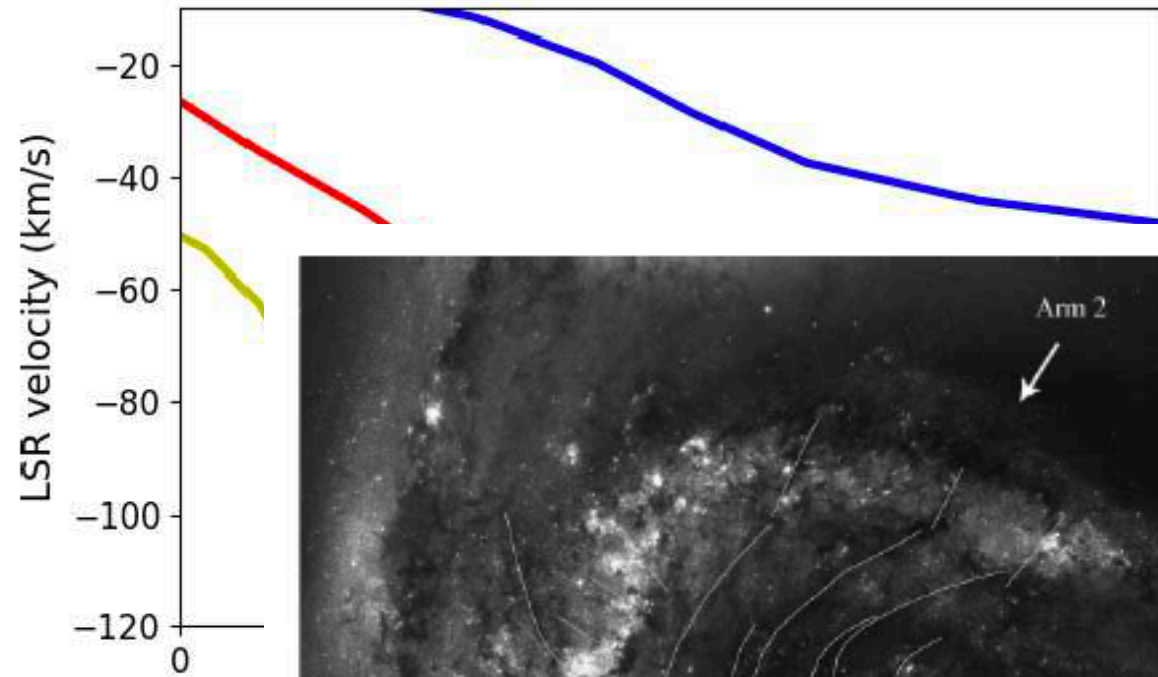
# Orientation of the filament



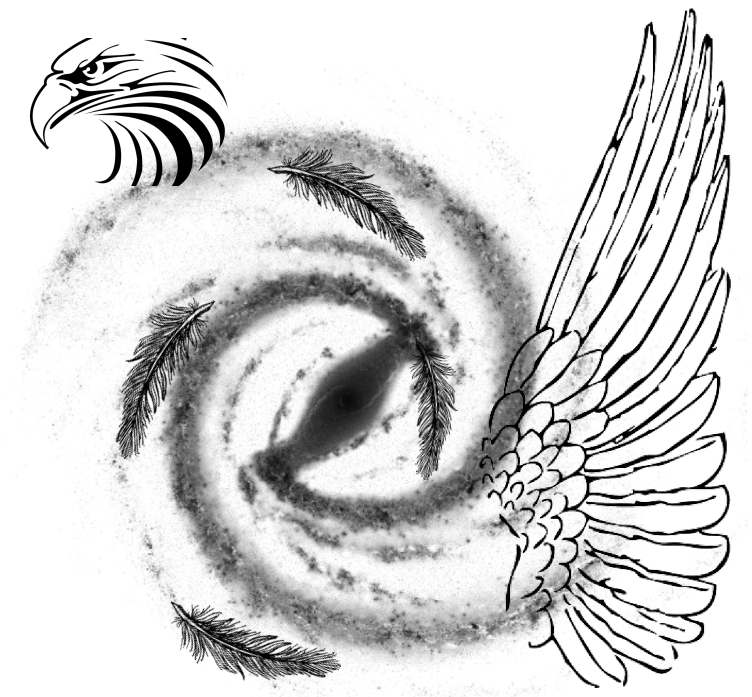
and 3-kpc arm at other end

- Velc
- Oriē

# Orientation of the filament



and 3-kpc arm at other end



- Velc
- Oriē

NGC5194; La Vigne+2006



## Possible feather/spur?

- Shearing due to density overgrowth in arms (gravity+magnetic field)
- Gas clouds exiting spiral arms - stretching due to differential rotation (Smith+2014, Duarte-Cabral&Dobbs 2017)
- Wiggle instability - Vorticity at a distorted shock front (Kim+2014; Sormani+2017)
- Supernova feedback -short lived spurs (~30 Myr) - B field parallel to length (TIGRESS; Kim+2020)

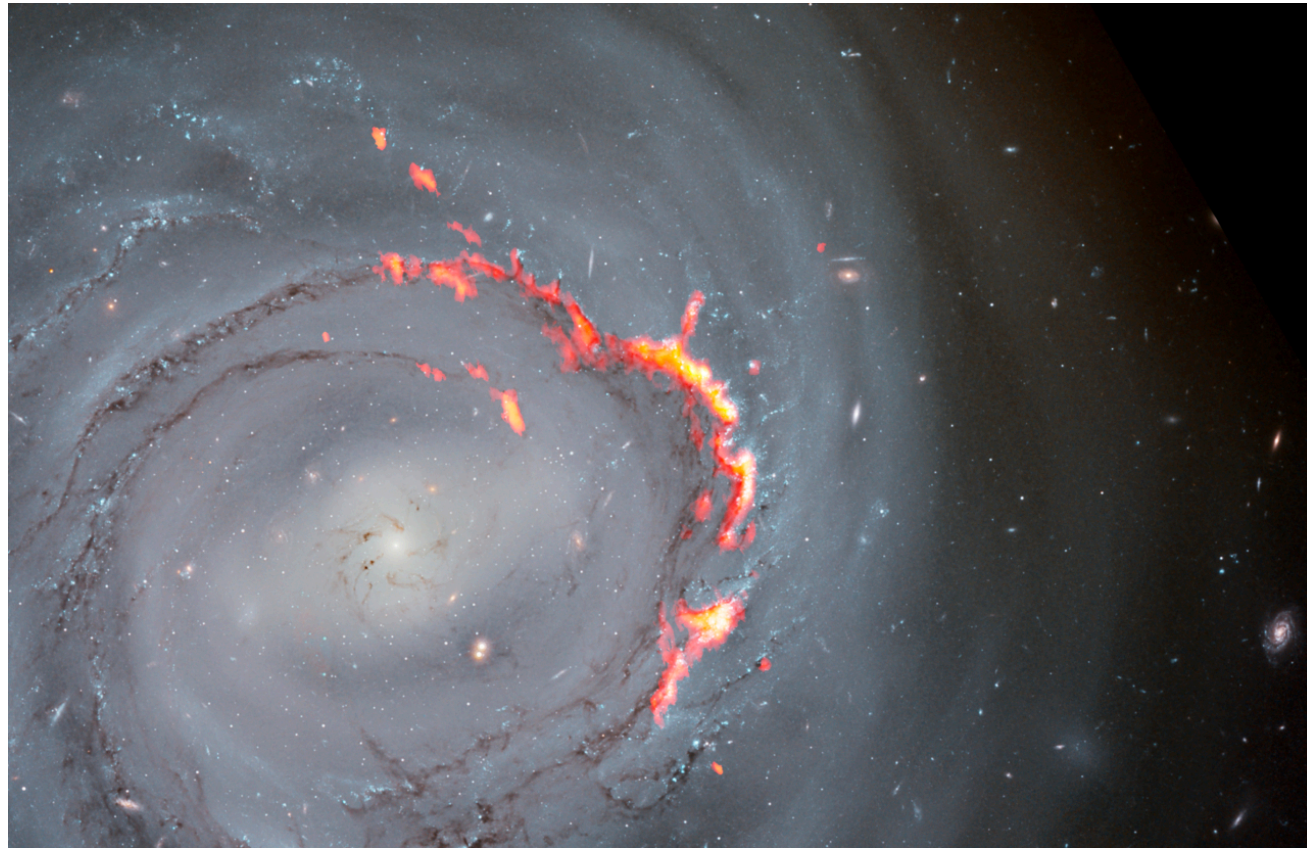


NGC 4921 barred spiral galaxy (Cramer+2021)

Credit: ALMA (ESO/NAOJ/NRAO)/S. Dagnello (NRAO), NASA/ESA/Hubble/  
K. Cook (LLNL), L. Shatz

- Kpc-scale (1-3 kpc) CO clouds blue shifted up to 50 km/s wrt rotation curve
- Gas re-accretion in RAM pressure stripped galaxy

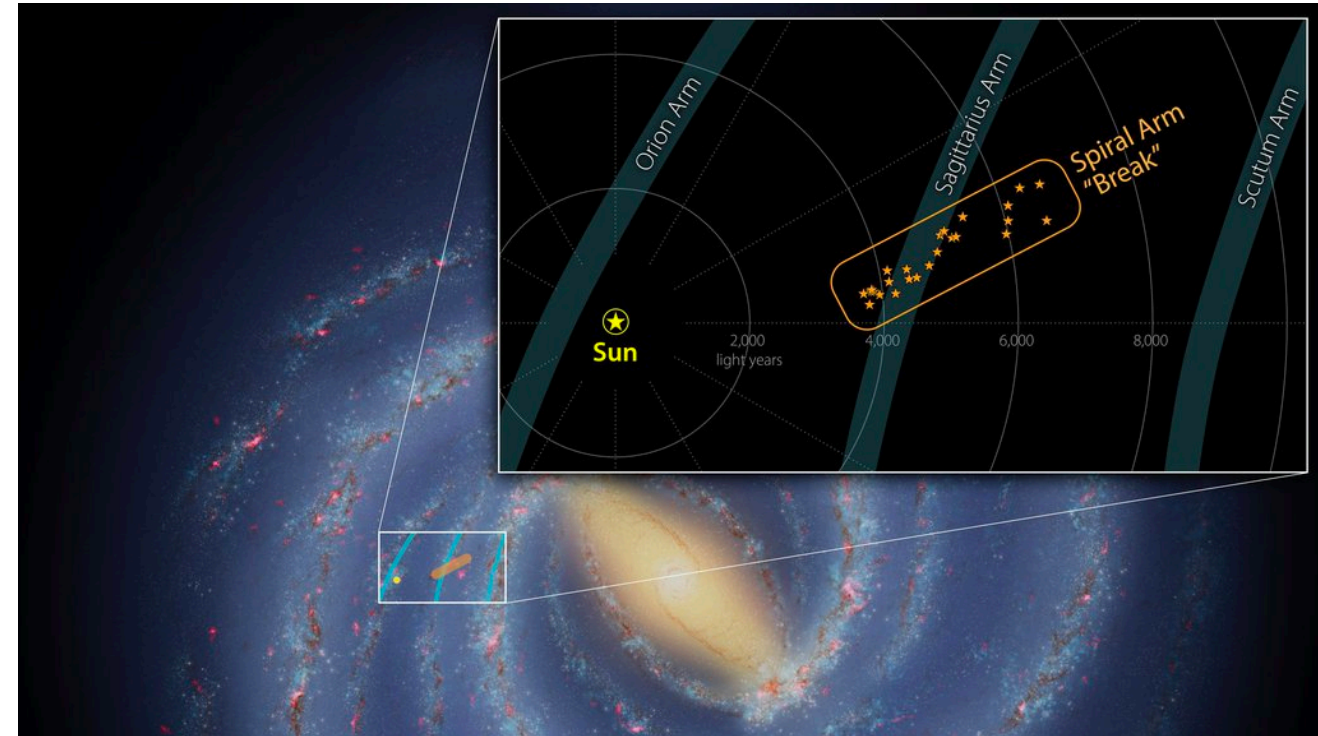




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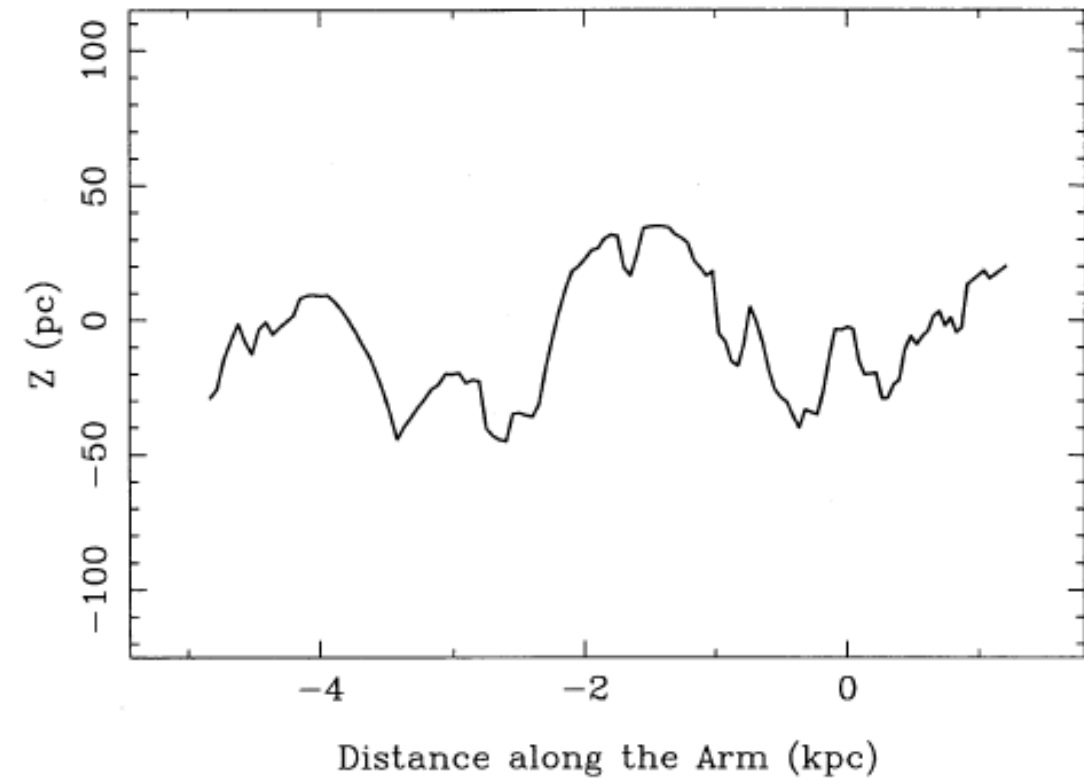
- Kpc-scale (1-3 kpc) CO clouds blue shifted up to 50 km/s wrt rotation curve
- Gas re-accretion in RAM pressure stripped galaxy



Credits: NASA/JPL-Caltech

- 1 kpc linear structure containing 25 SF regions with high (7:1) aspect ratio
- Sagittarius sub-arm/spur/isolated structure (Kuhn+2021)

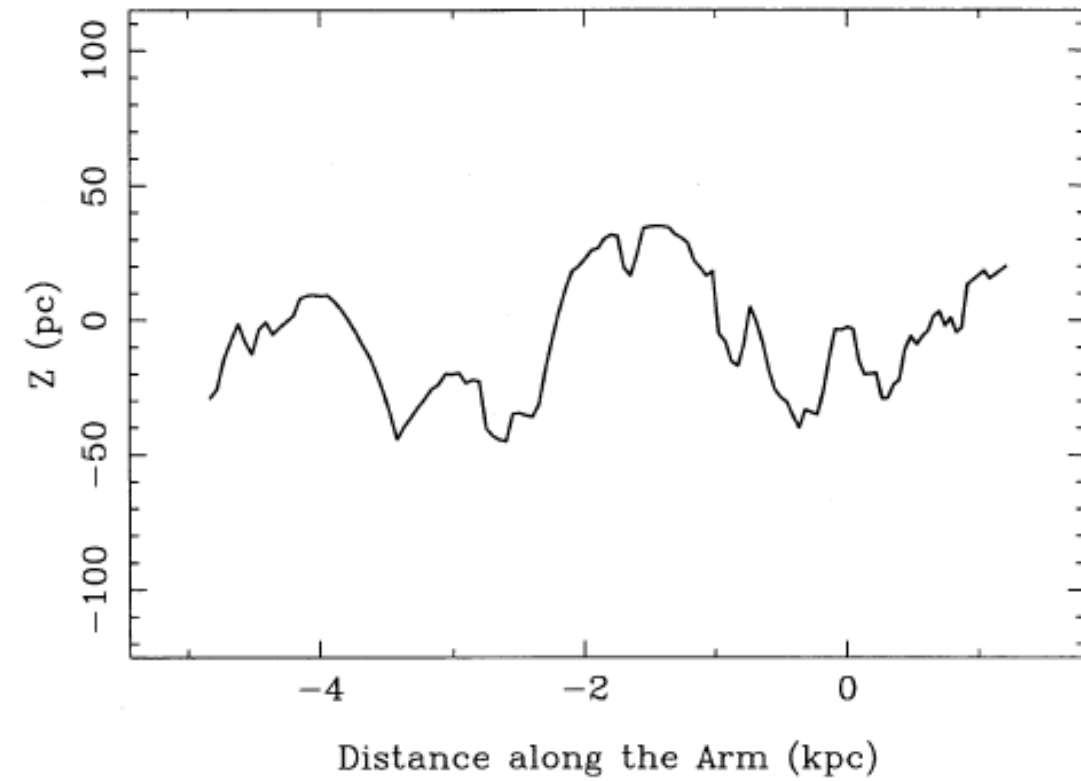
# Wave-like morphology



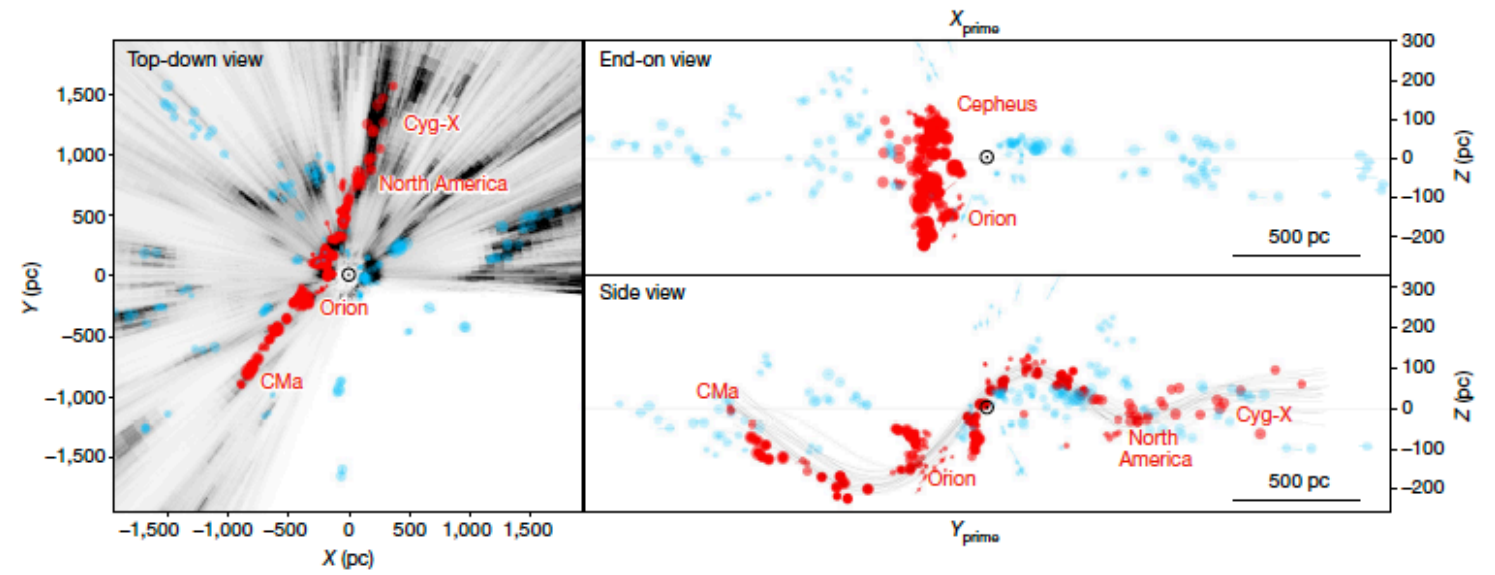
Open clusters in Sag-Car arm; Alfaro+1992



# Wave-like morphology

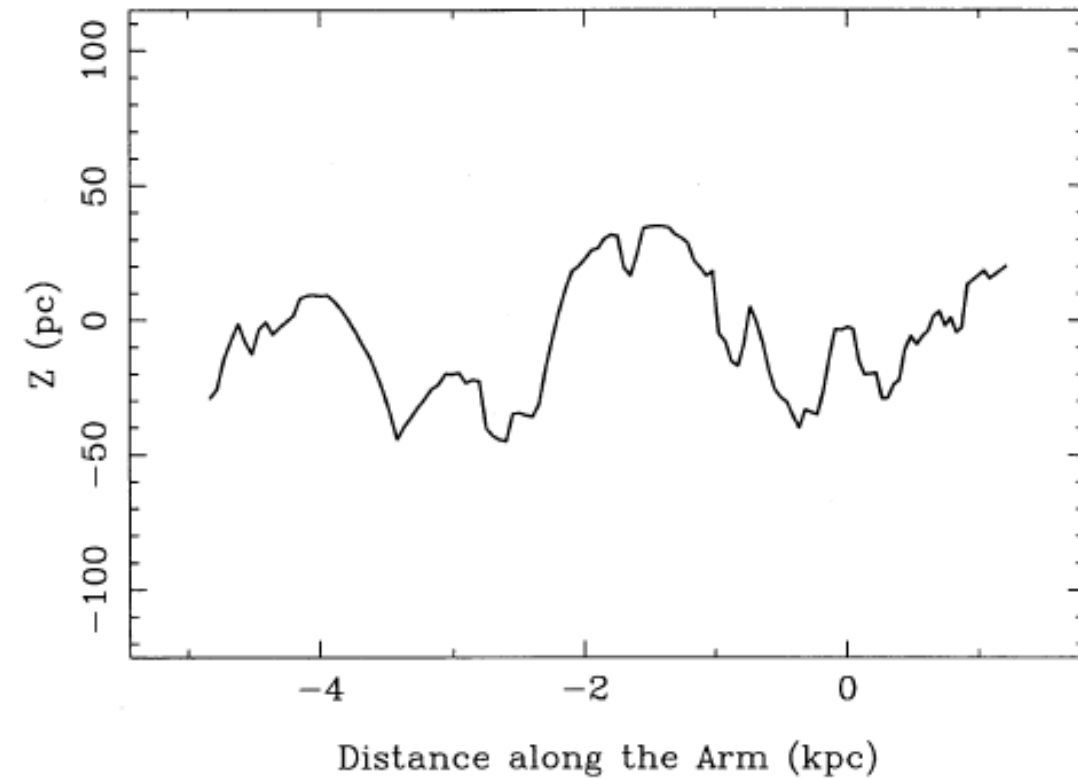


Open clusters in Sag-Car arm; Alfaro+1992

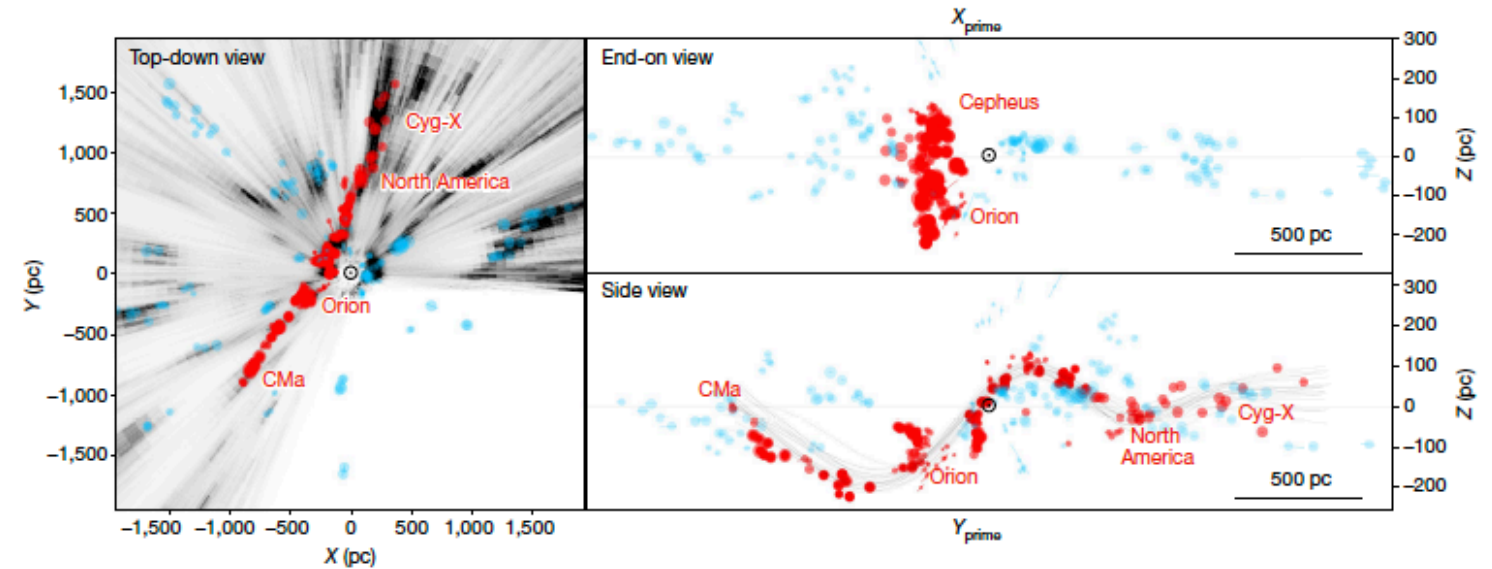


Radcliffe wave; Alves+2020

# Wave-like morphology



Open clusters in Sag-Car arm; Alfaro+1992

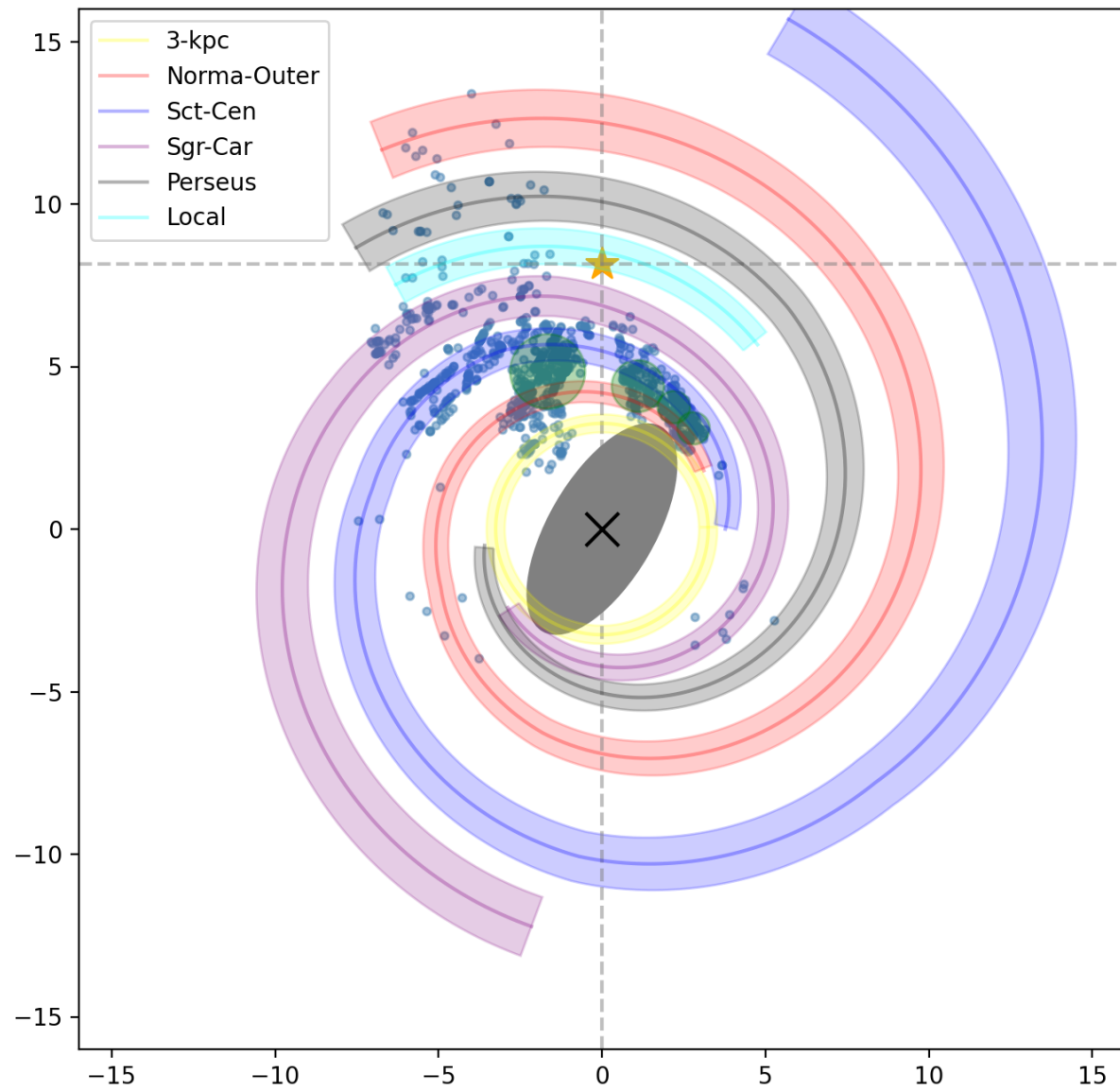


Radcliffe wave; Alves+2020

- 3D density waves (Alfaro+1992)
- Gravitational settling and cooling of gas (Alves+2020)
- Interaction of satellite galaxy with Milky Way (Binney&Schönrich 2018)
- Galactic bar-spiral arm coupling (Monari+2016)

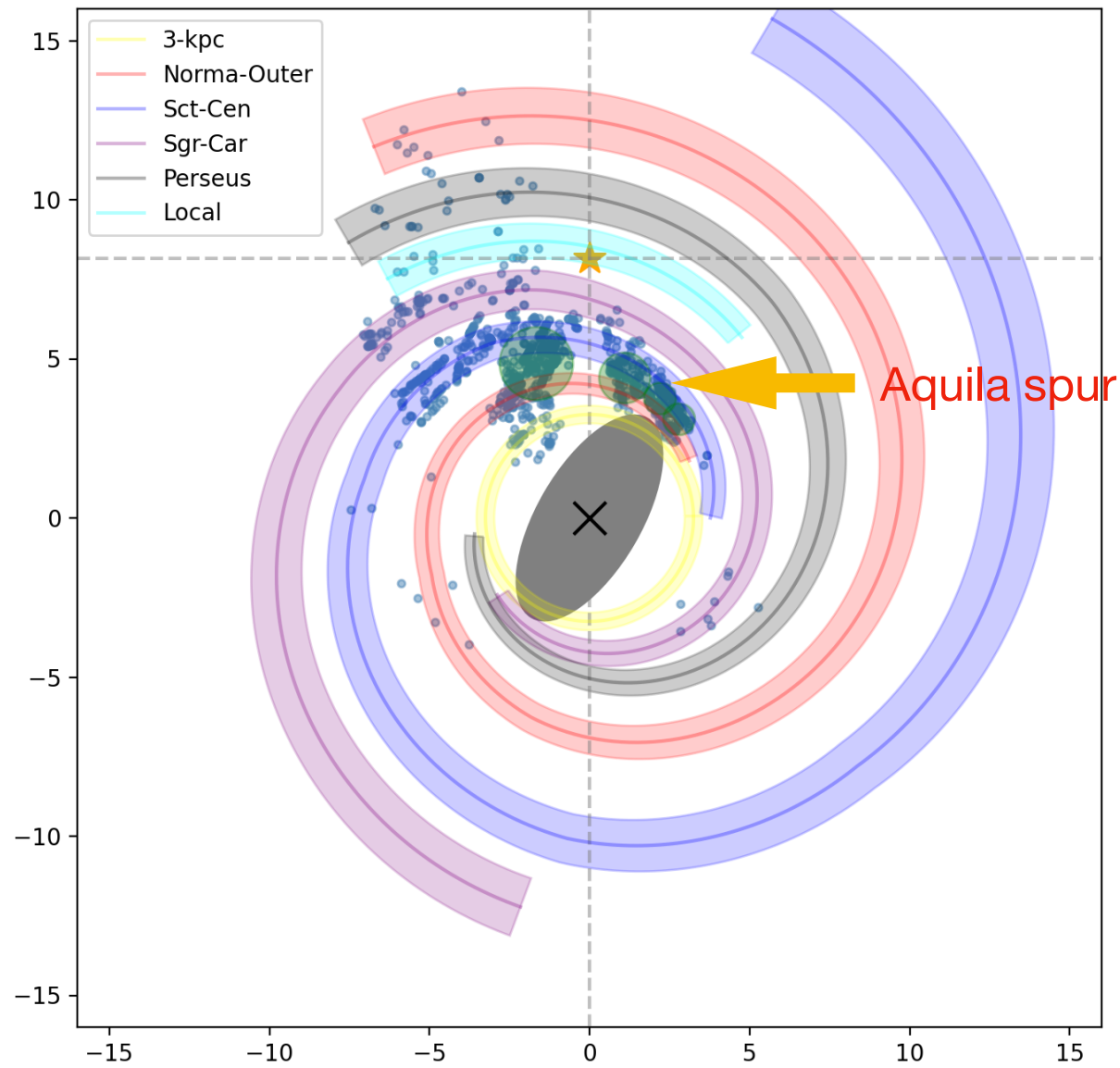


# Comparison with ALMAGAL data



Overlay of ALMAGAL Sources on spiral arm models of Reid+2019 (Image credit: Kahmin Goh)

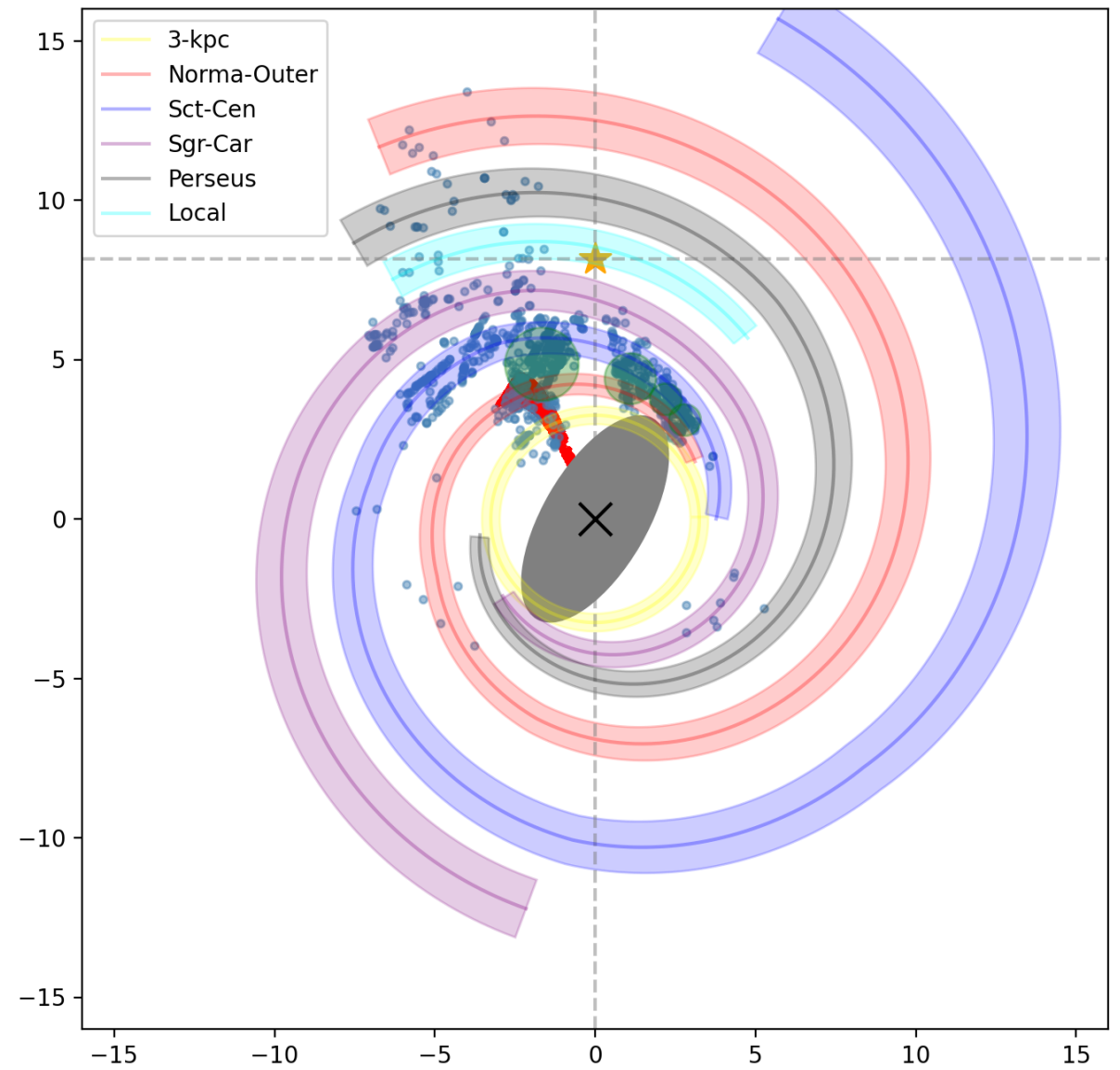
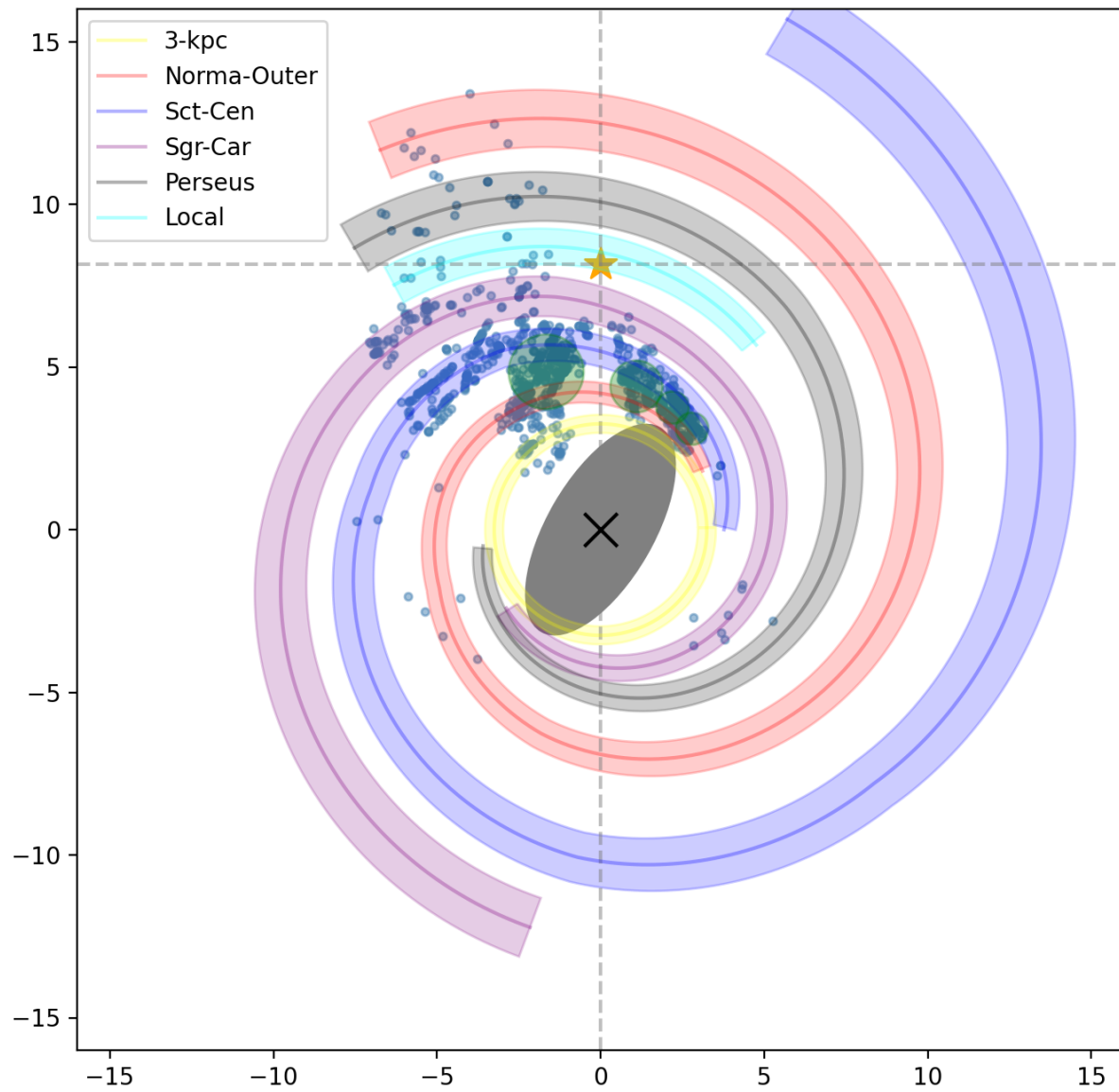
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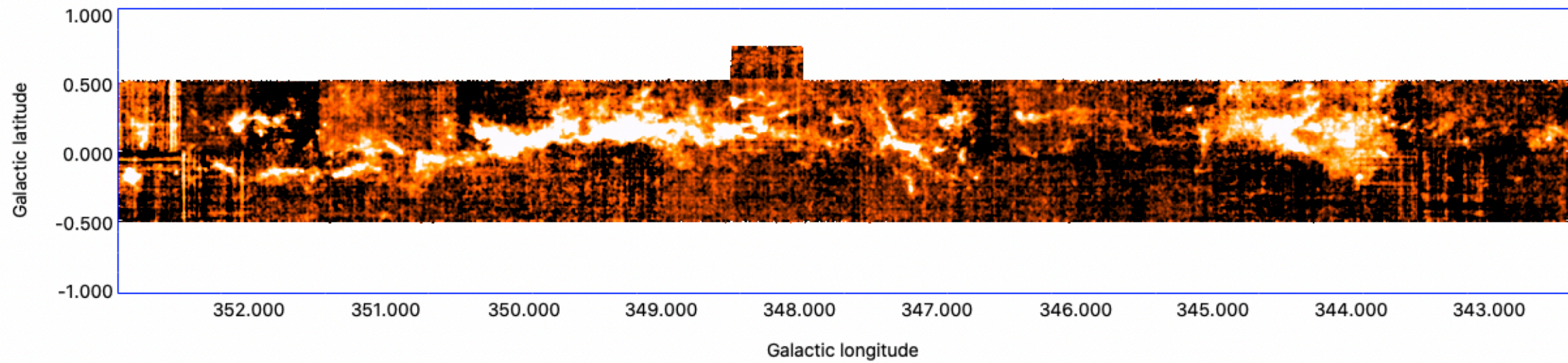


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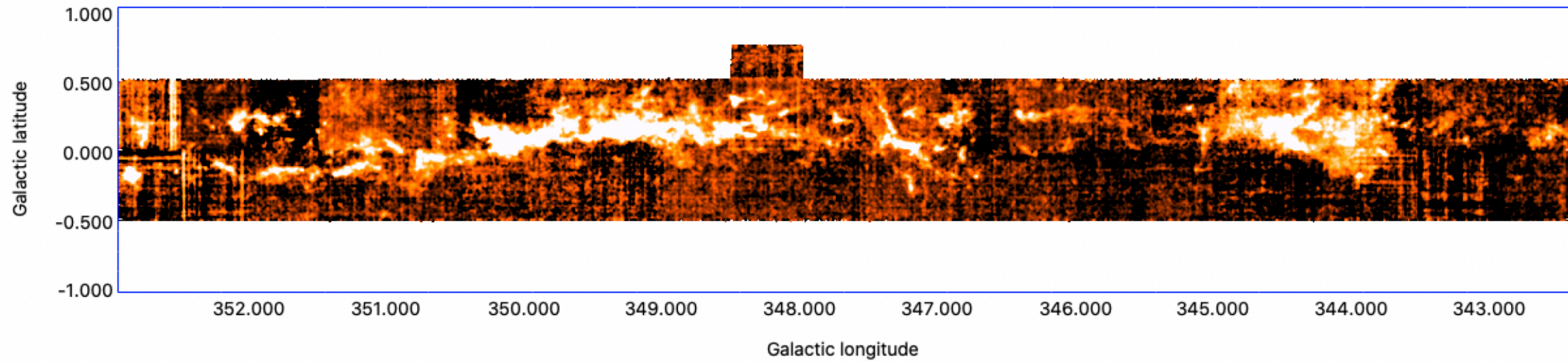
# More filaments/spurs near GC ?



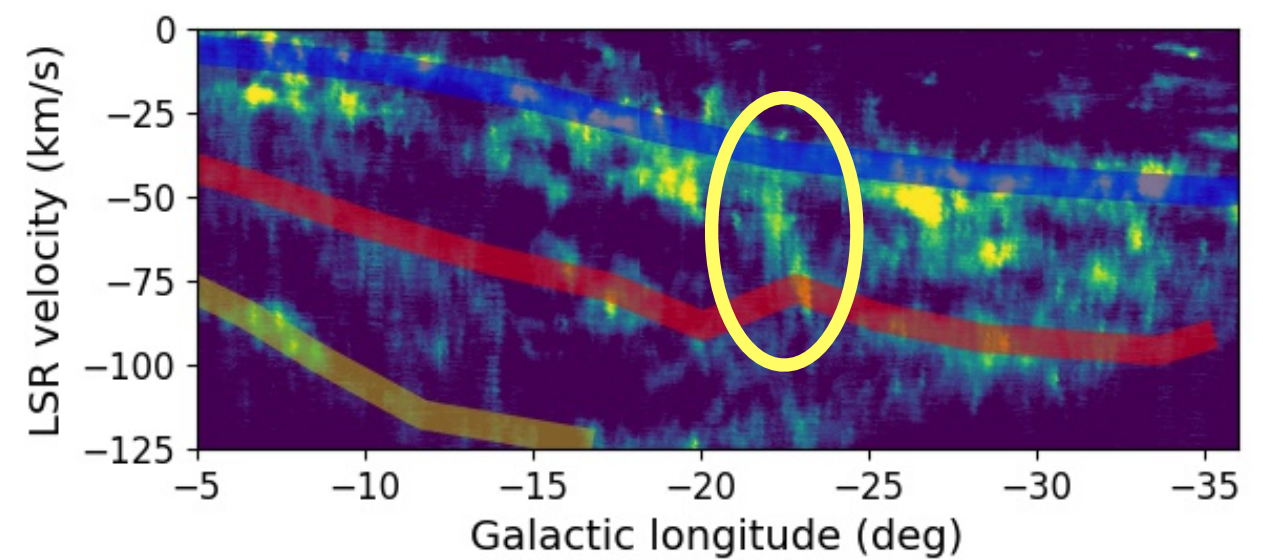
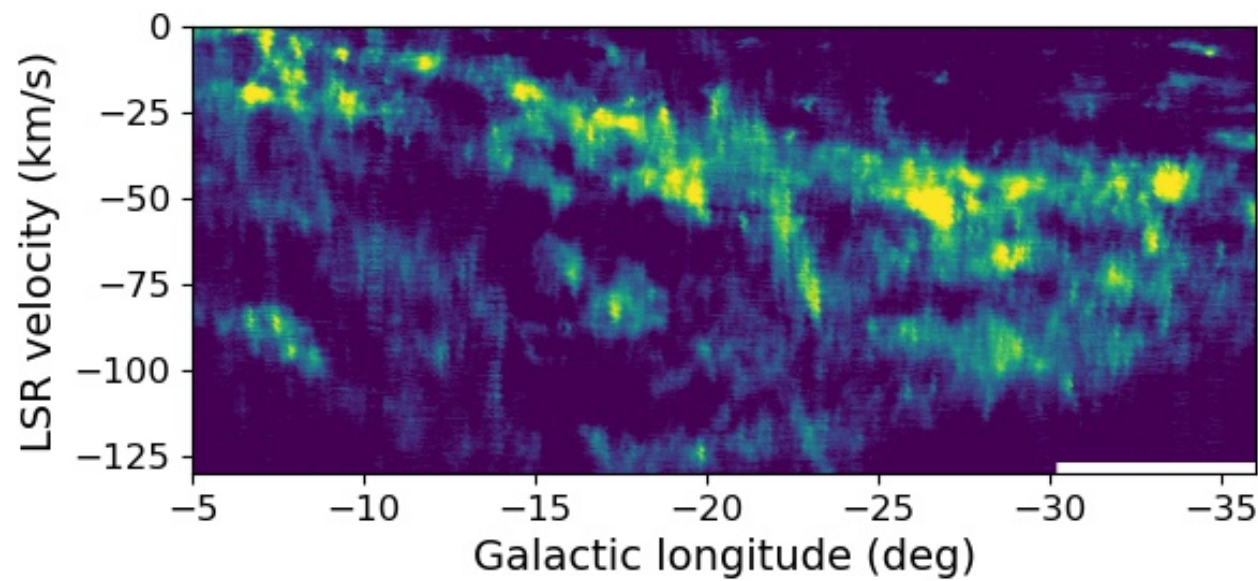
~800 pc Norma arm filament



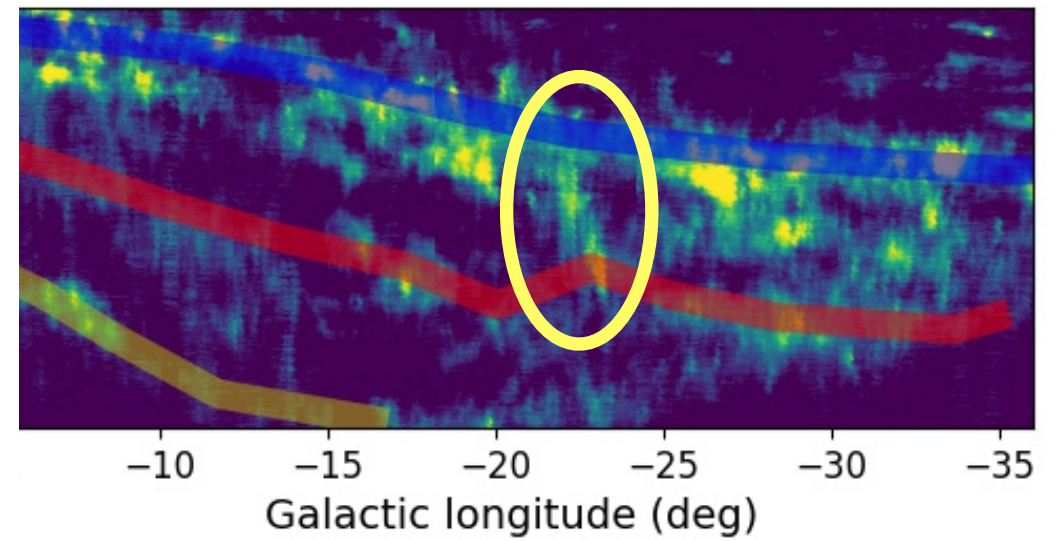
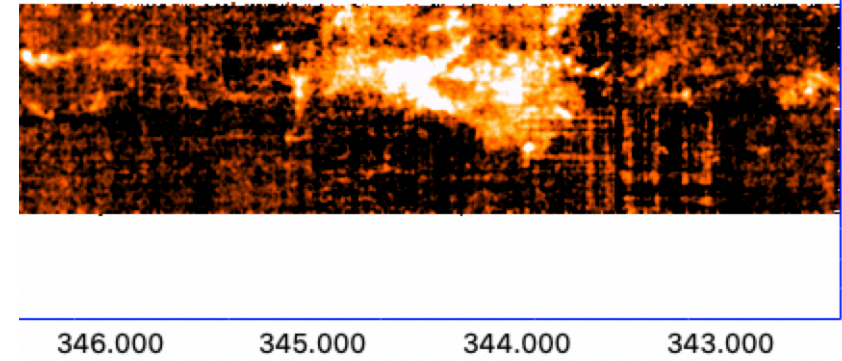
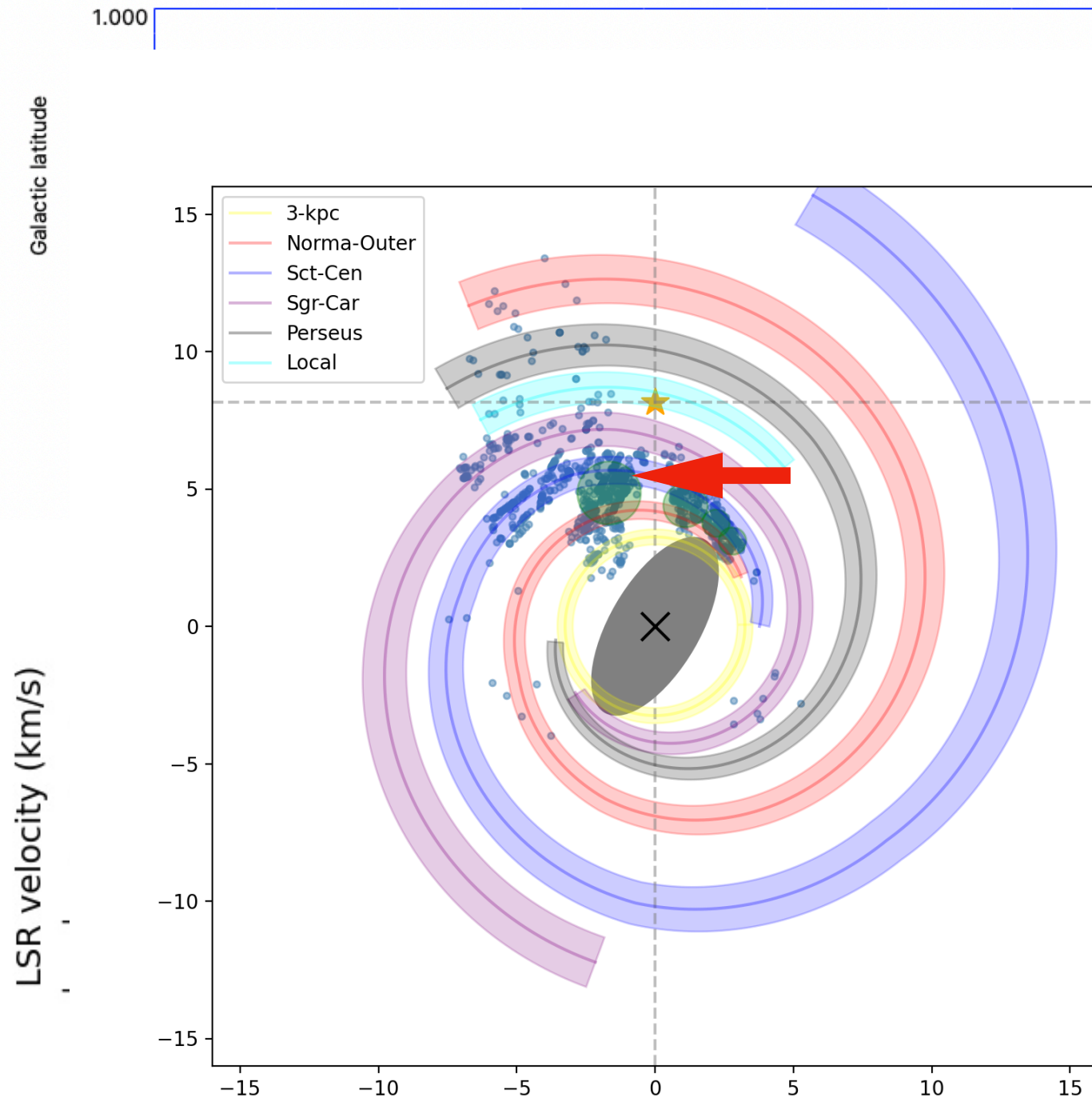
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~800 pc Norma arm filament



# More filaments/spurs near GC ?





# Summary

- GMFs - redefined view on the large scale structure of Galaxy
- First velocity coherent filamentary cloud with wave-like structure
- Orientation favouring wave being a Galactic feather or arm sub-branch
- One of the most unusual and intriguing structures identified in the Galaxy



ApJL (under revision)

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ApJL (under revision)

*Thank you*