Large scale filaments

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SEDIGISM Workshop, 15-17 Sep 2021

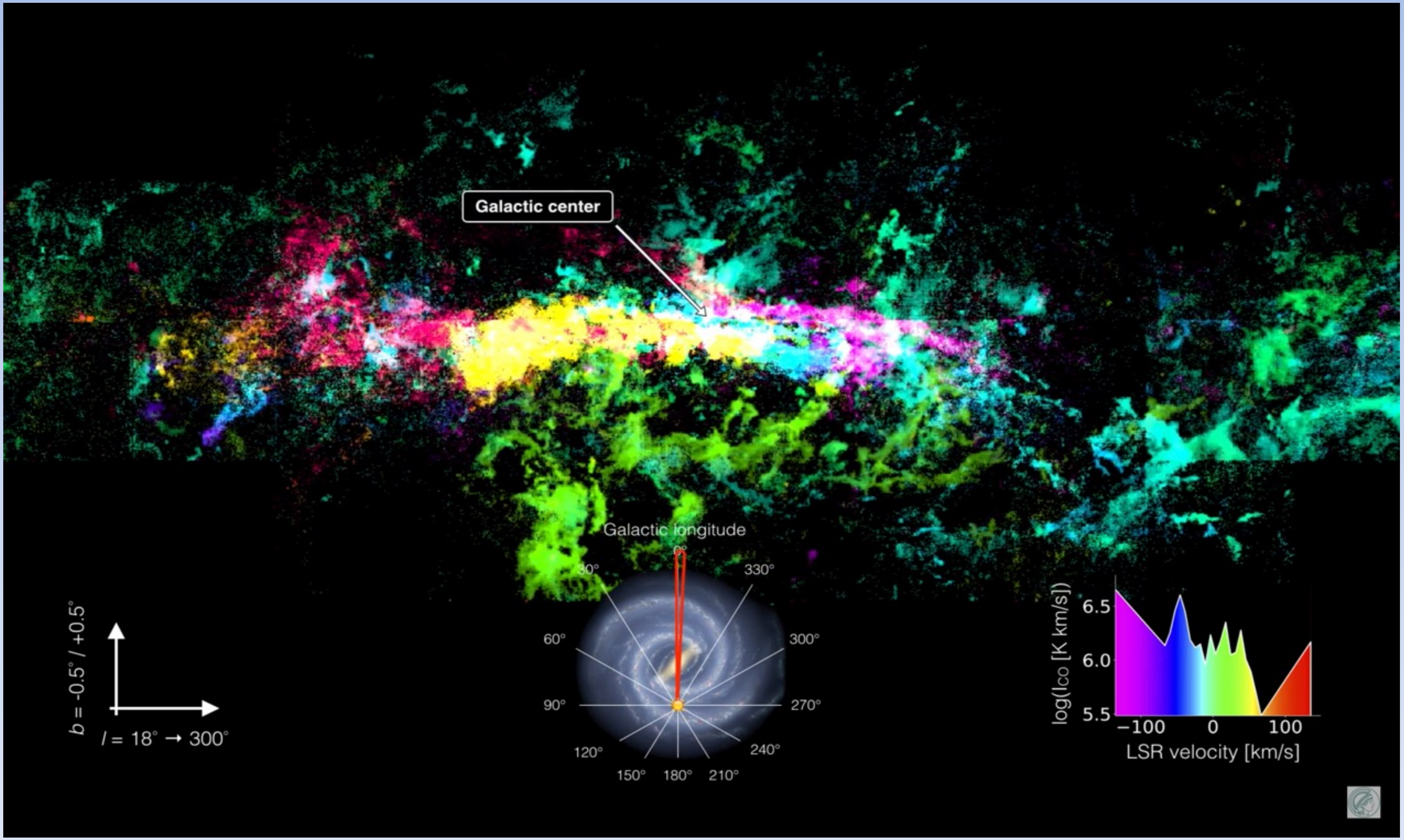
Outline

- Filaments small and large, old and new
- Building a filaments atlas for Milky Way
- A unified, filamentary view of ISM?
- Future developments with SEDIGISM

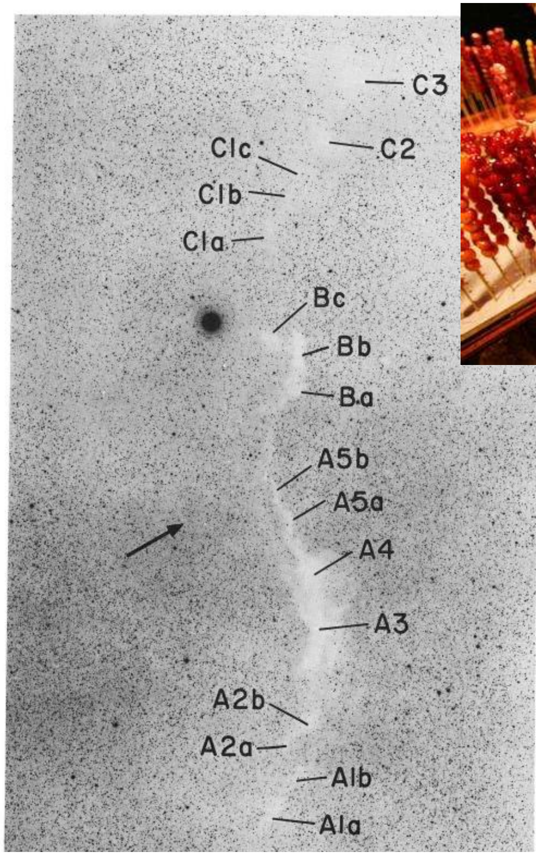
What is a filament?

SEDIGISM full data release (2020 Dec)

(“*Structure, Excitation and Dynamics of the Inner Galactic Interstellar Medium*”)



Filaments are known long time

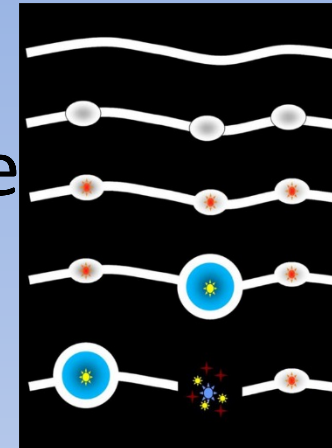


A CATALOG OF DARK GLOBULAR FILAMENTS

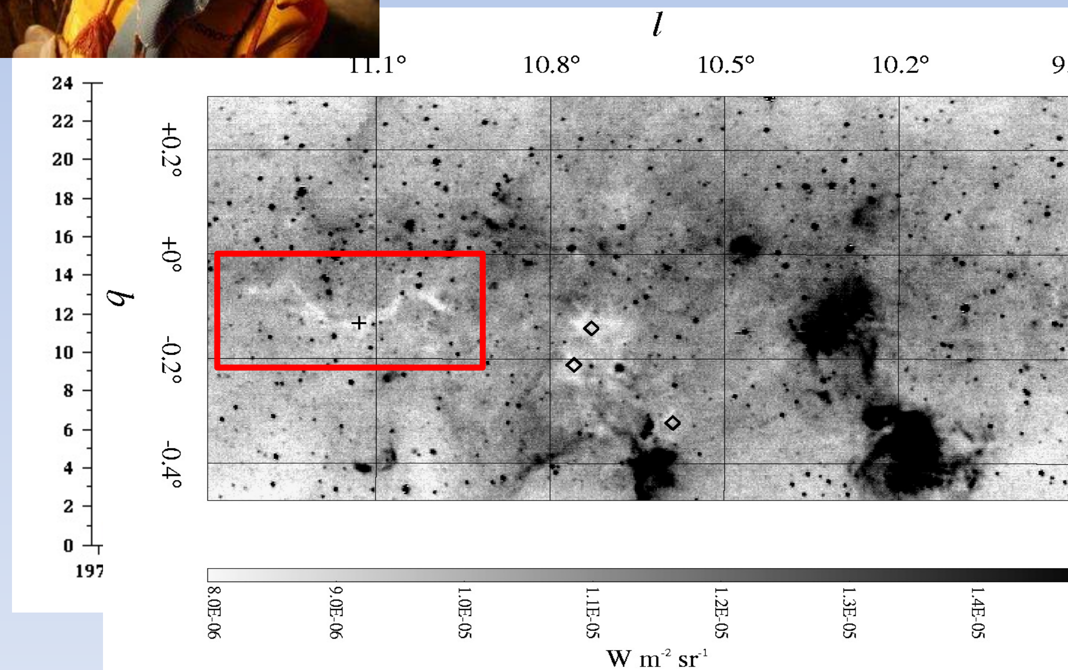
STEPHEN SCHNEIDER AND BRUCE G. ELMEGREEN
Harvard-Smithsonian Center for Astrophysics

Received 1978 December 14; accepted 1979 February 26

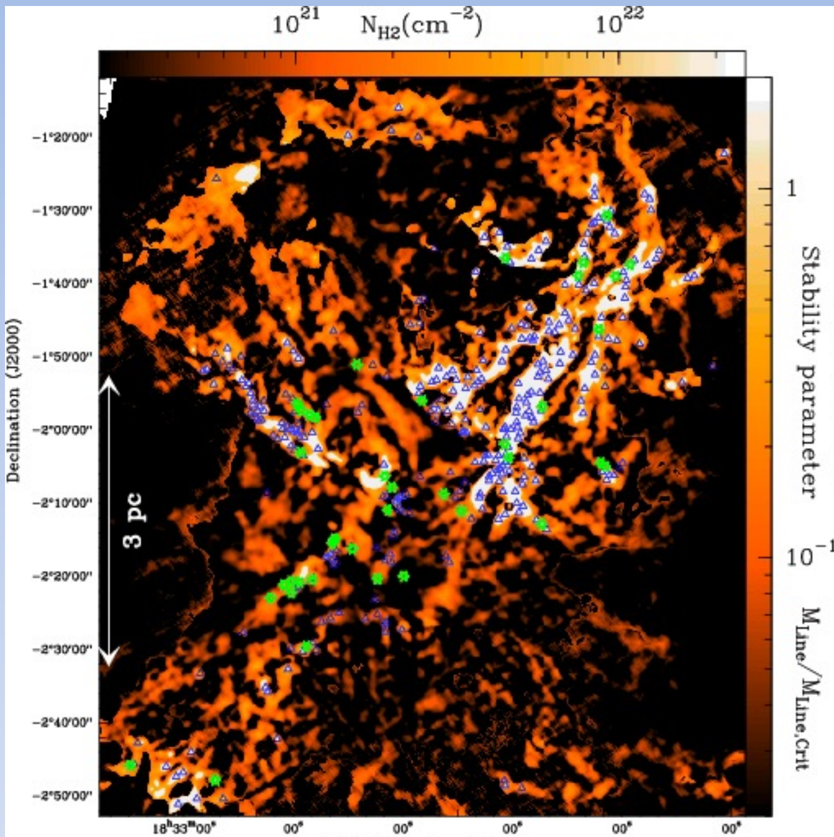
Optical dark clouds 1979



Cartoon by Jackson et al. 2010
based on Chandrasekhar & Fermi 1953

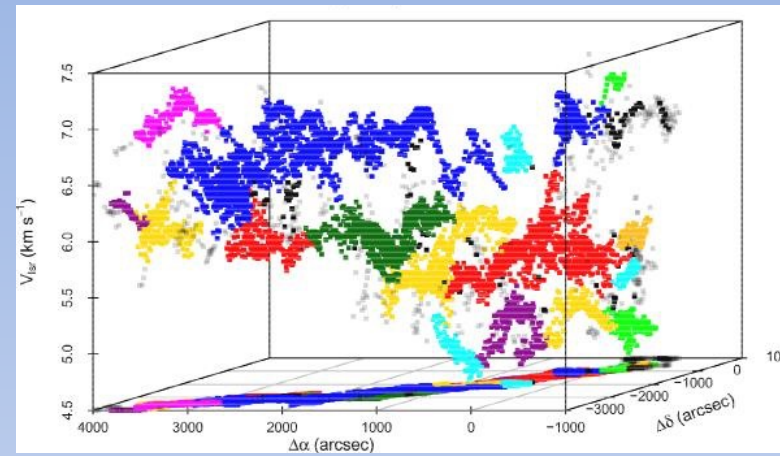


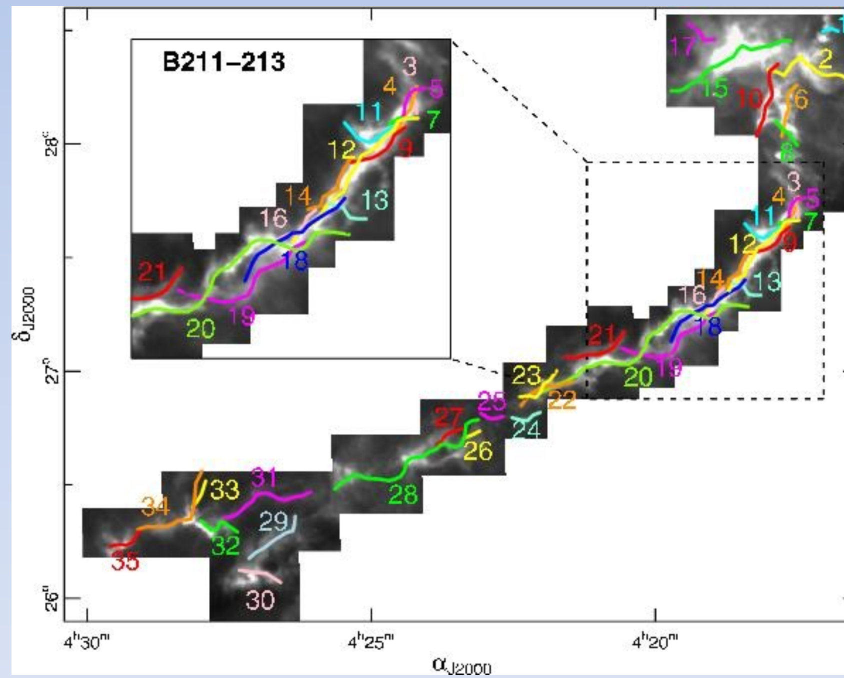
IR-dark clouds, Egan et al. 1998



Andre et al. 2010, Aquila

Cores on filaments





Hacar et al. 2013, Taurus

“Bundles of fibers” (thermal filaments)

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HERSCHEL'S HUNT FOR FILAMENTS IN THE MILKY WAY

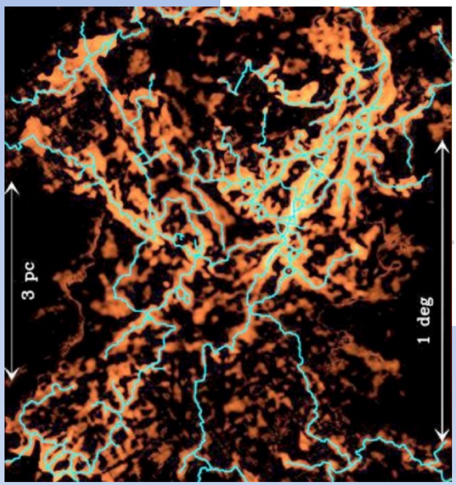
28 May 2015

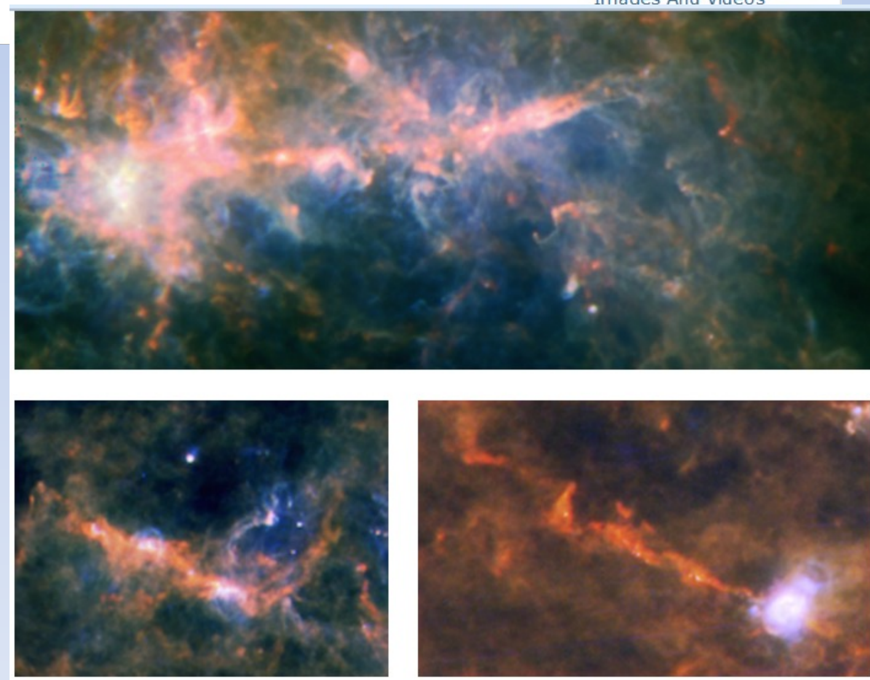
Observations with ESA's Herschel space observatory have revealed that our Galaxy is threaded with filamentary structures on every length scale. From nearby clouds hosting tangles of filaments a few light-years long to gigantic structures stretching hundreds of light-years across the Milky Way's spiral arms, they appear to be truly ubiquitous. The Herschel data have rekindled the interest of astronomers in studying filaments, emphasising the crucial role of these structures in the process of star formation.

12-Jan-2016 15:16 UT

Shortcut URL
http://sci.esa.int
/jump.cfm?oid=55942

Images And Videos





Some of the most prominent filaments detected in the Milky Way: G49 (top), G47 (bottom left) and G64 (bottom right). *Credit: ESA/Herschel/PACS/SPIRE/Ke Wang et al. 2015*

Largest, coldest, densest filaments in our Galaxy

Wang et al. 2015MNRAS.450.4043W

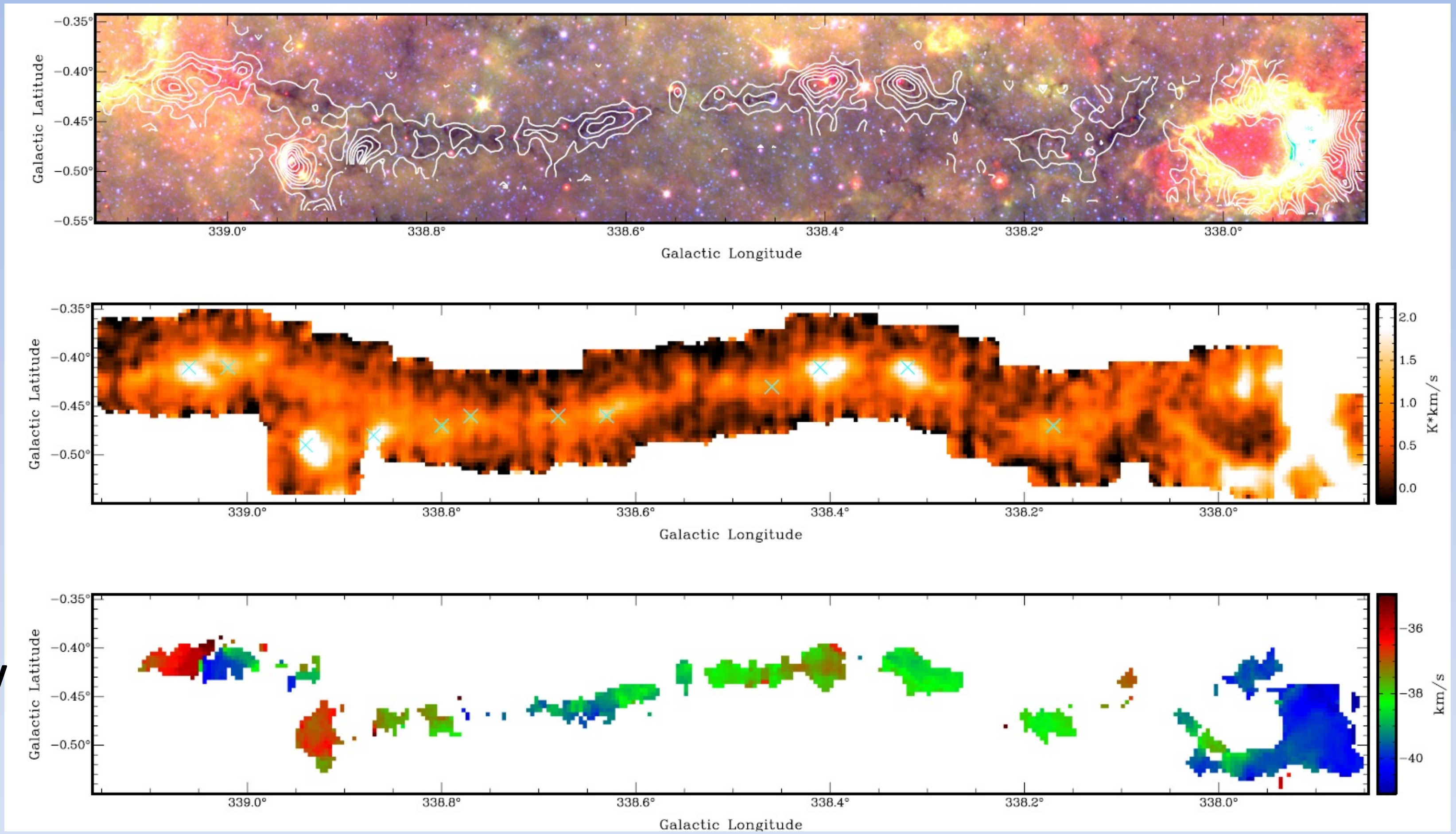
ESA feature article

An extreme IR-dark cloud “Nessie”

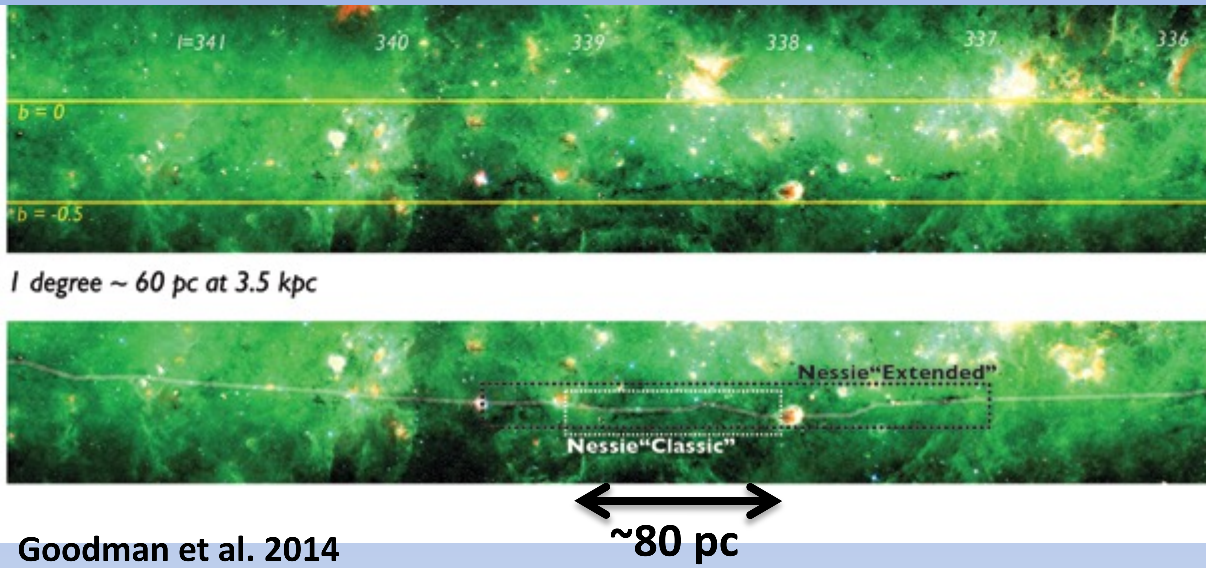
IR

HNC

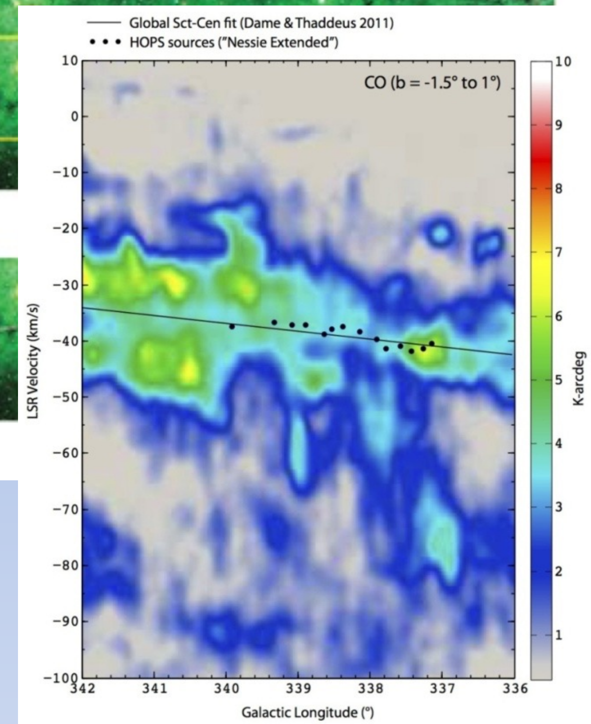
Velocity



Jackson et al. 2010



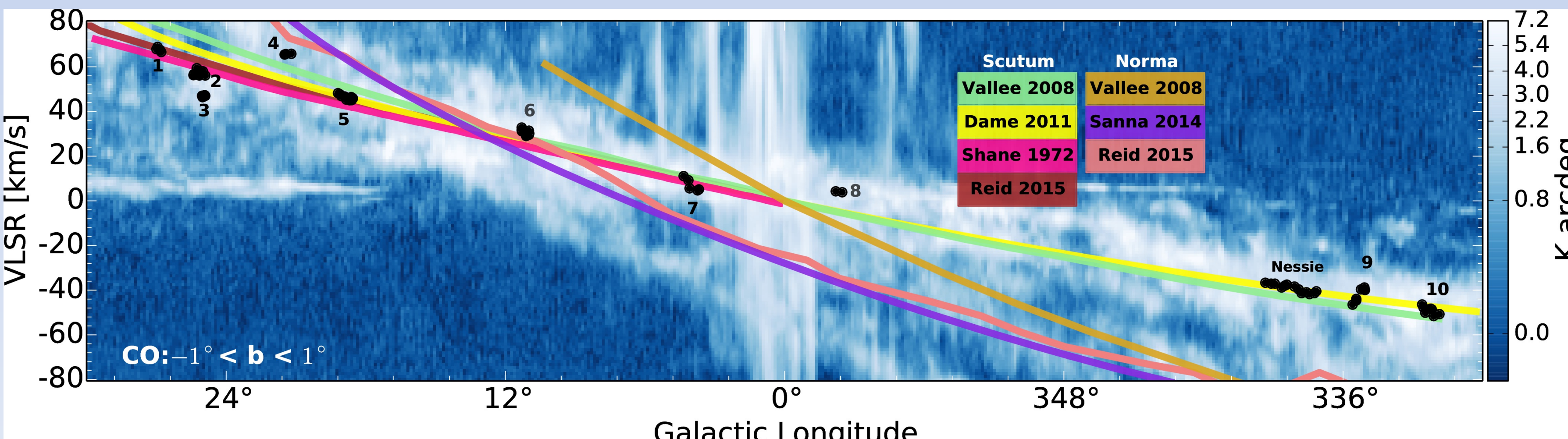
Goodman et al. 2014



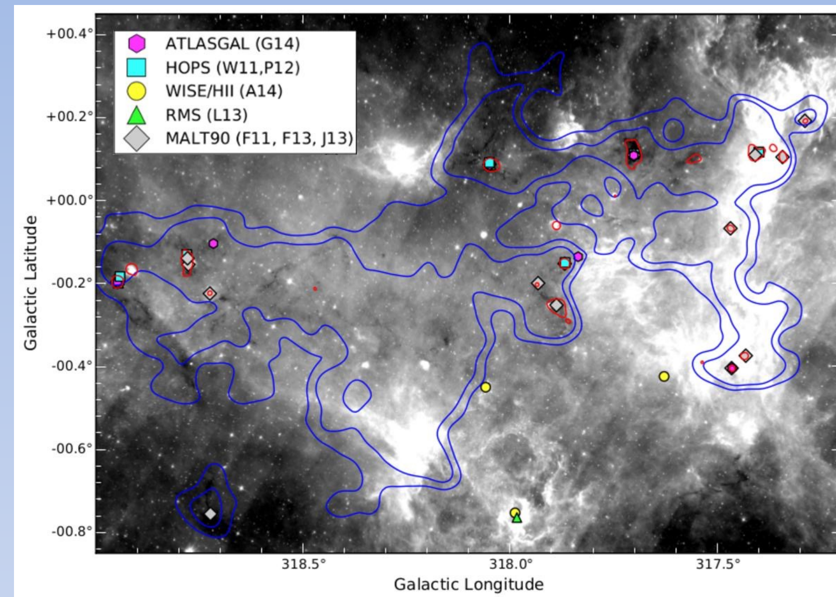
"Nessie" as first identified "bone" of MW

Zucker et al. 2015

Bones of Milky Way



Hunting for large filaments

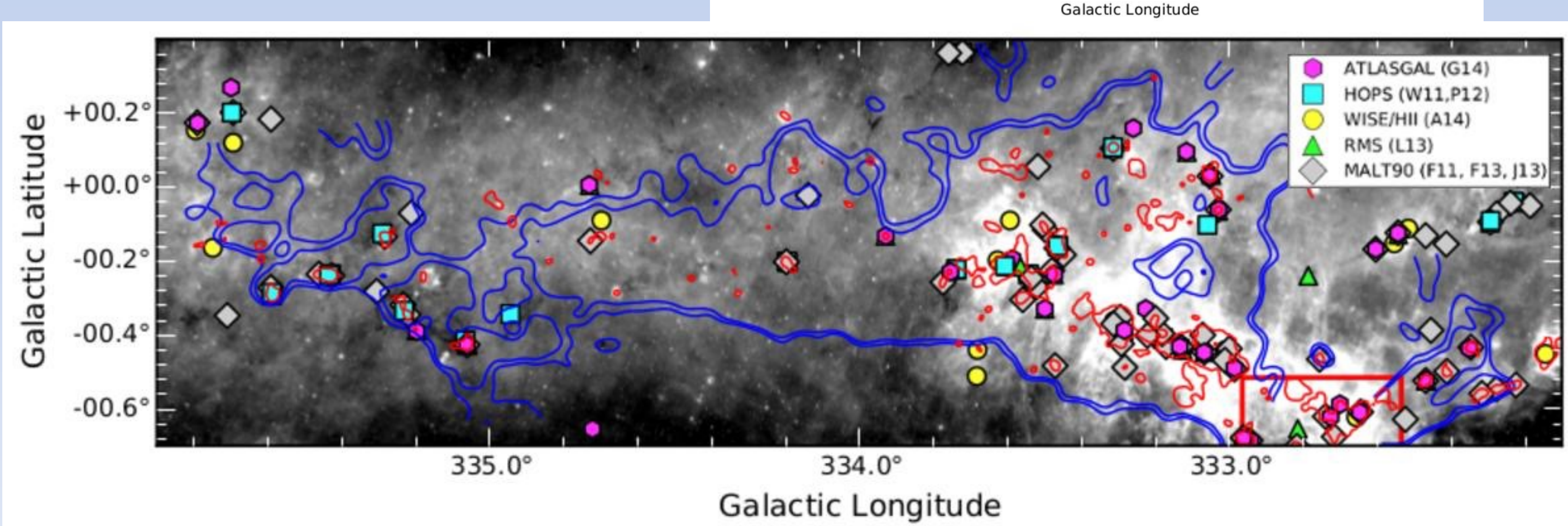


Ragan et al. 2014

Abreu-Vicente et al. 2016

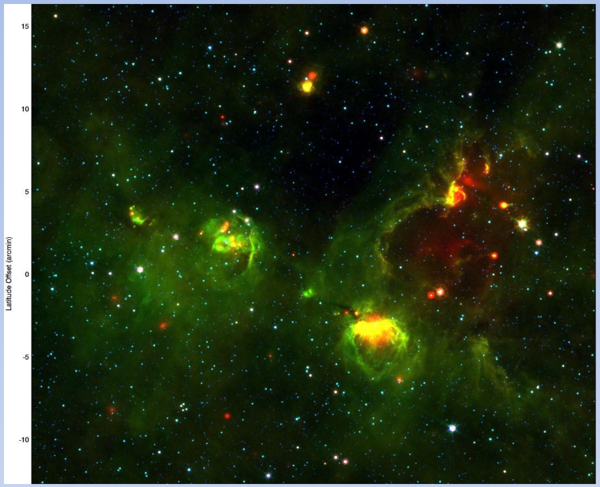
"Giant Molecular Filaments"

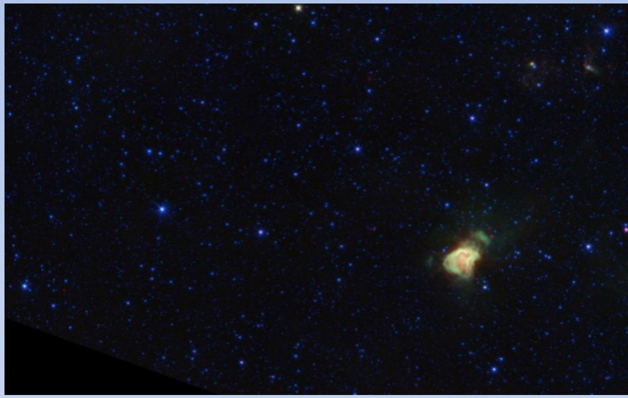
Mostly located inter-arm.

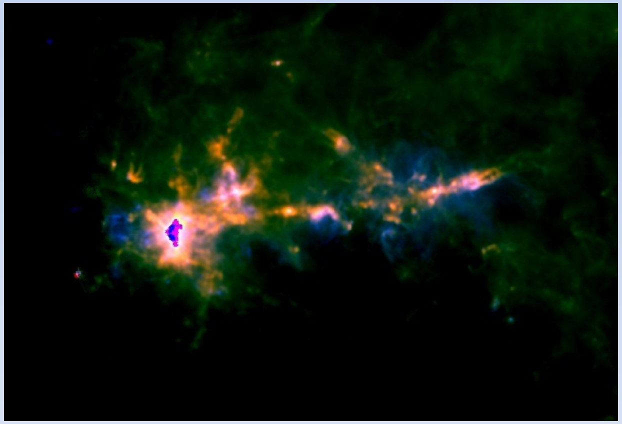


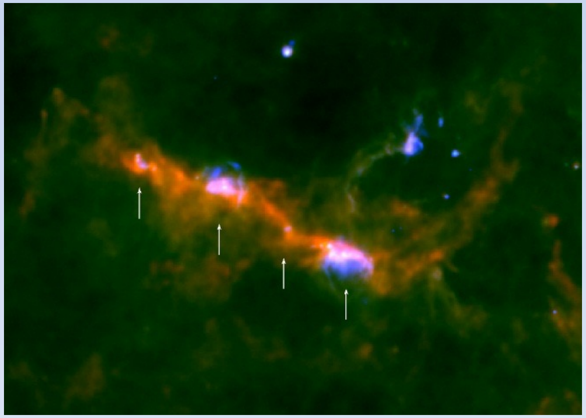
Herschel sees hidden filaments

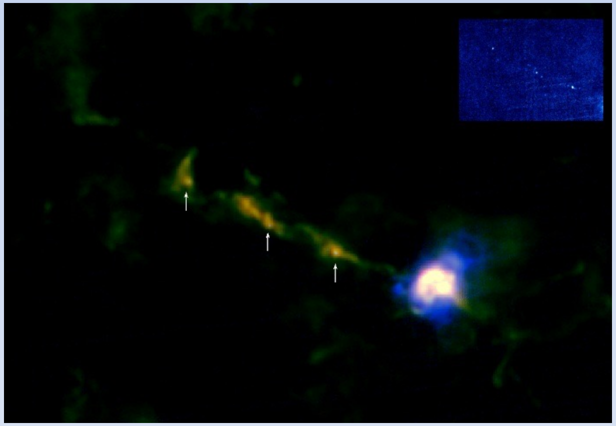
mostly on-arm





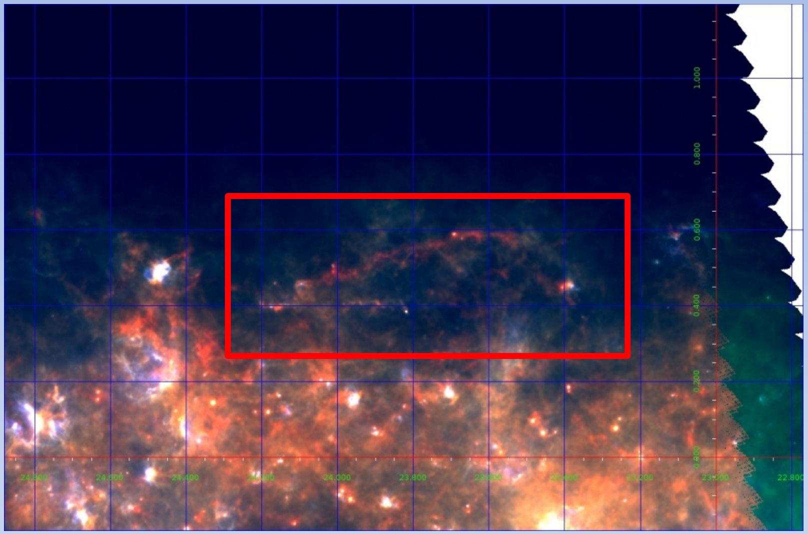




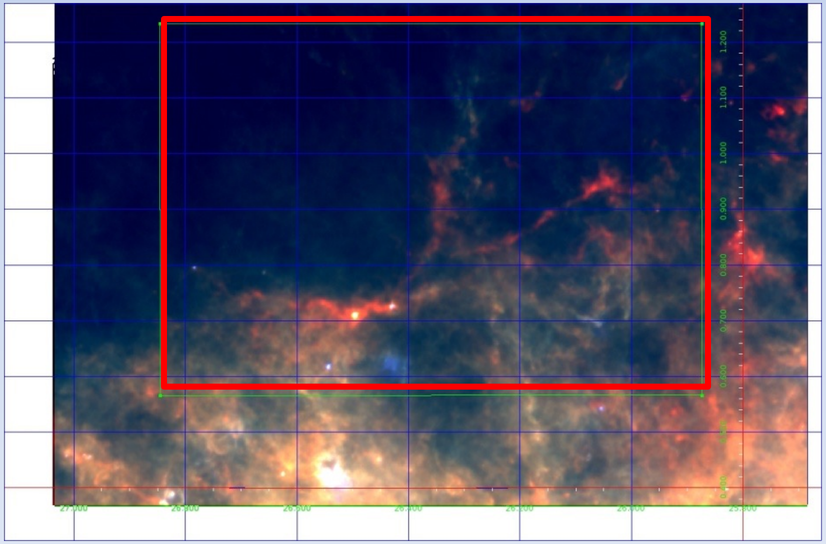


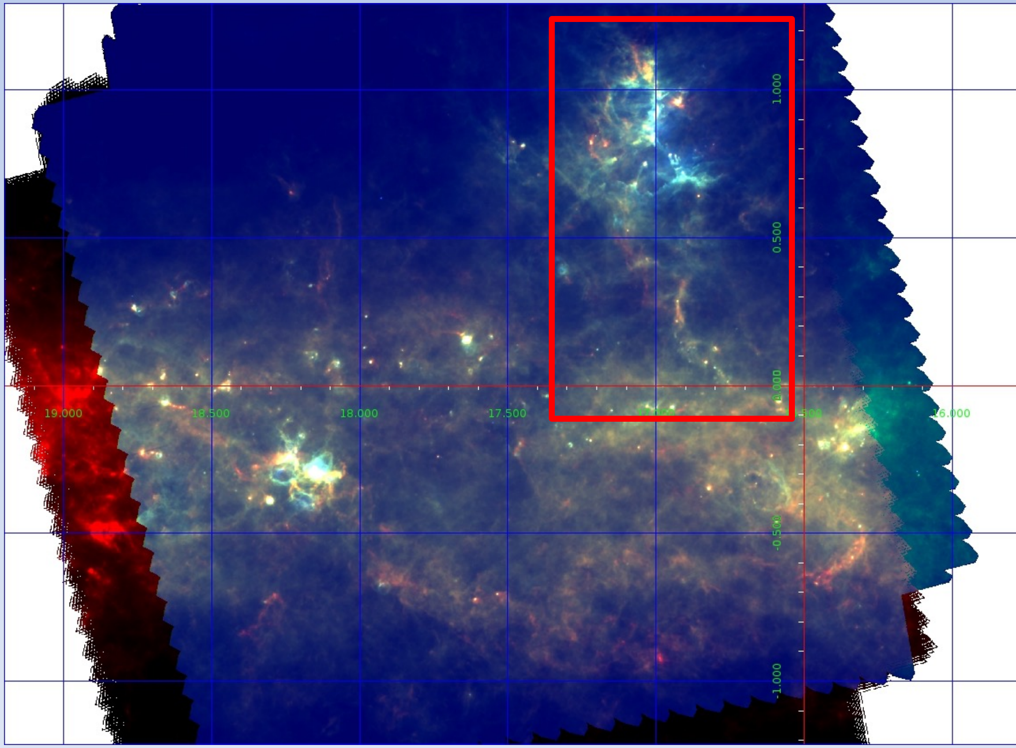
Wang et al. 2015

Step 1: visual inspection

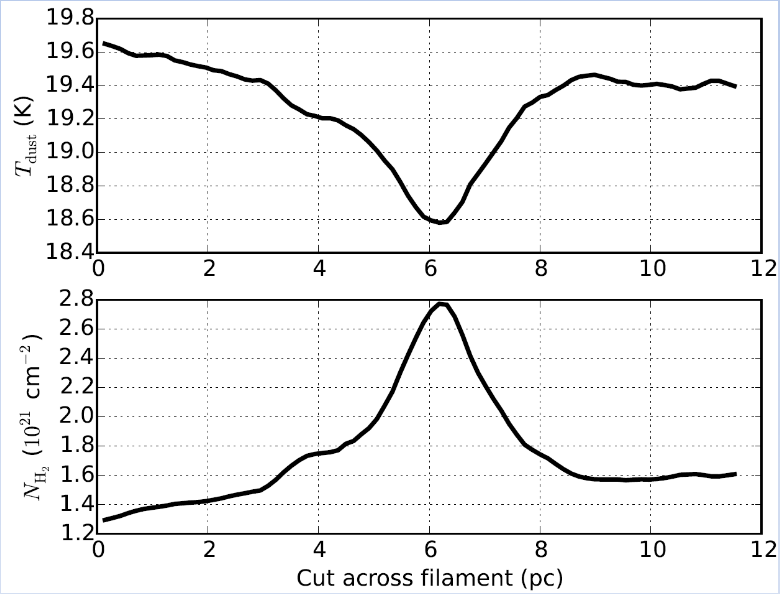


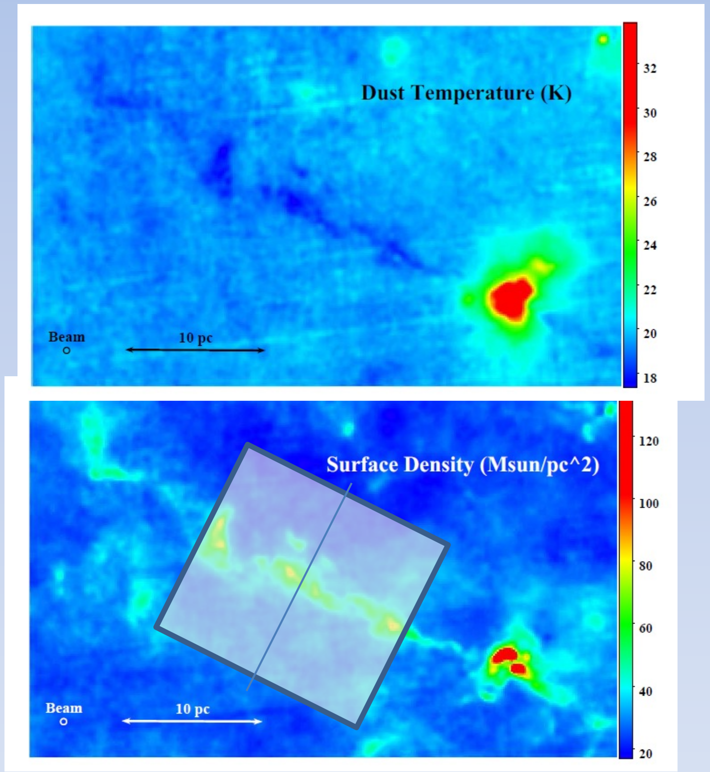
***Herschel* 70/160/350 um**





Step 2: inspect ***N, T*** maps

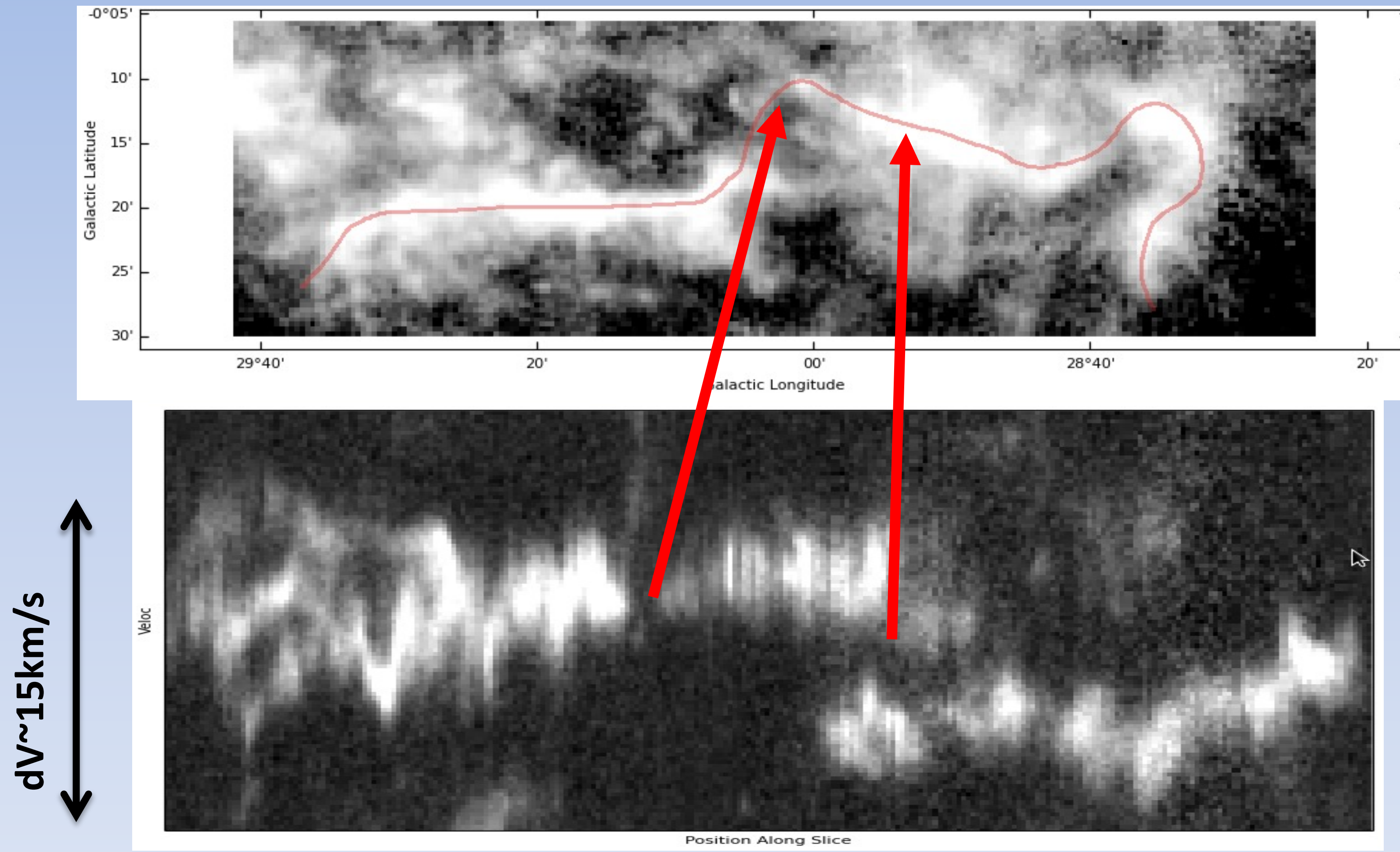




Background removal: github.com/esoPanda/FTbg

SED fitting: hi-gal-sed-fitter.readthedocs.org

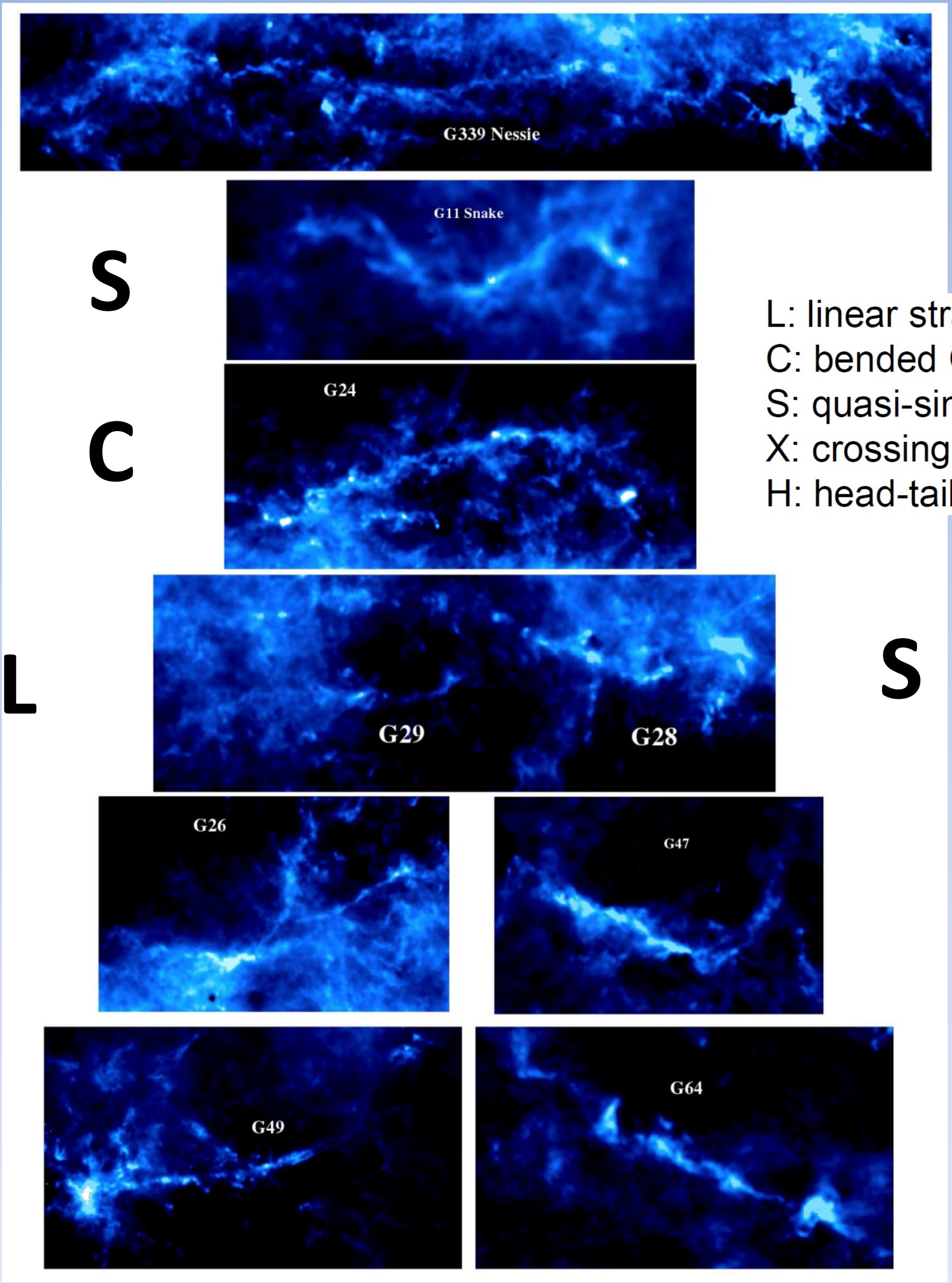
Step 3: velocity coherence



Position along filament

Herschel Hi-GAL
SED fitted column density

Code available at
https://ascl.net/code/v/1837



S,H

S

C

L

S

X

L

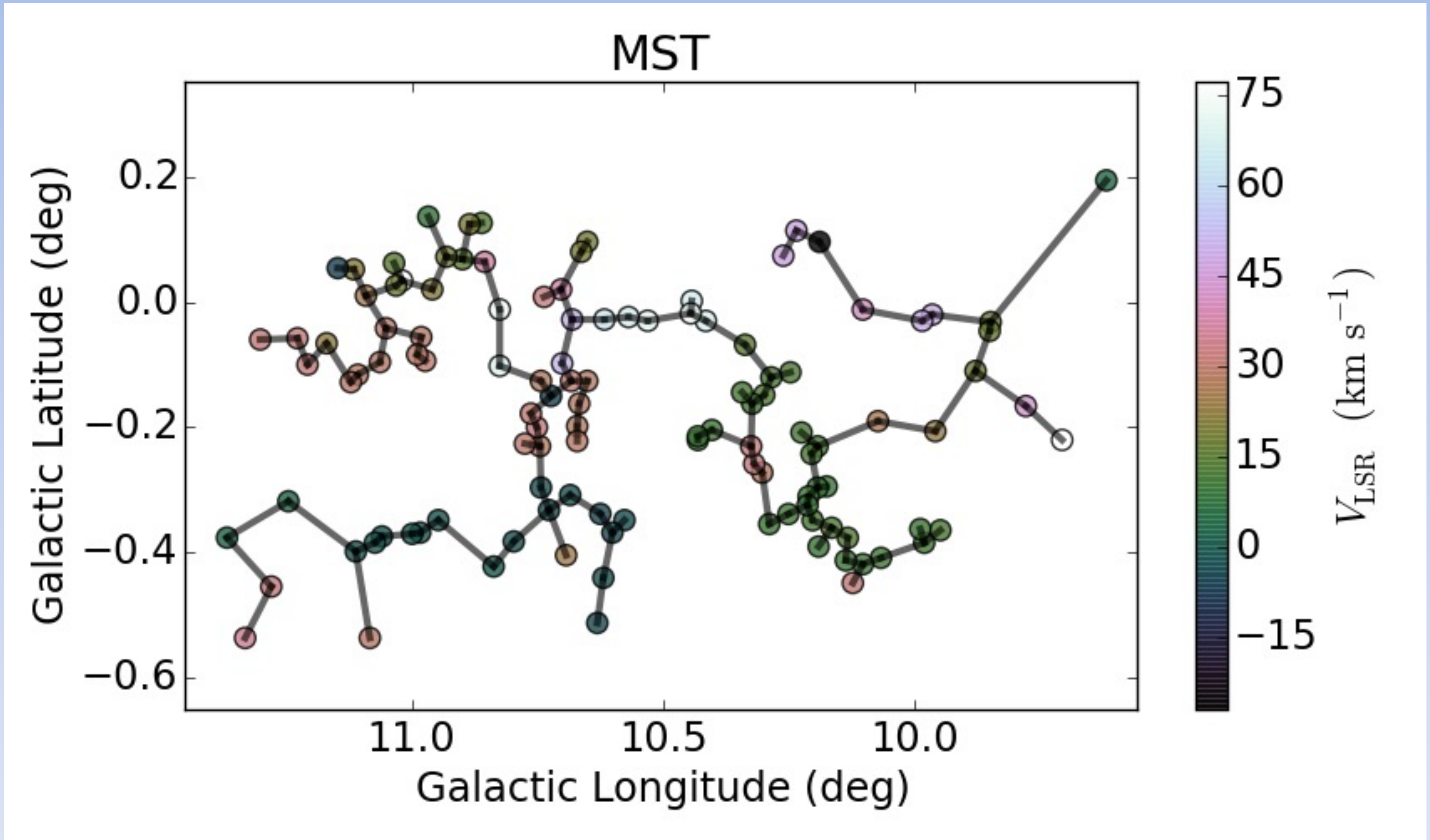
H,X

L,H

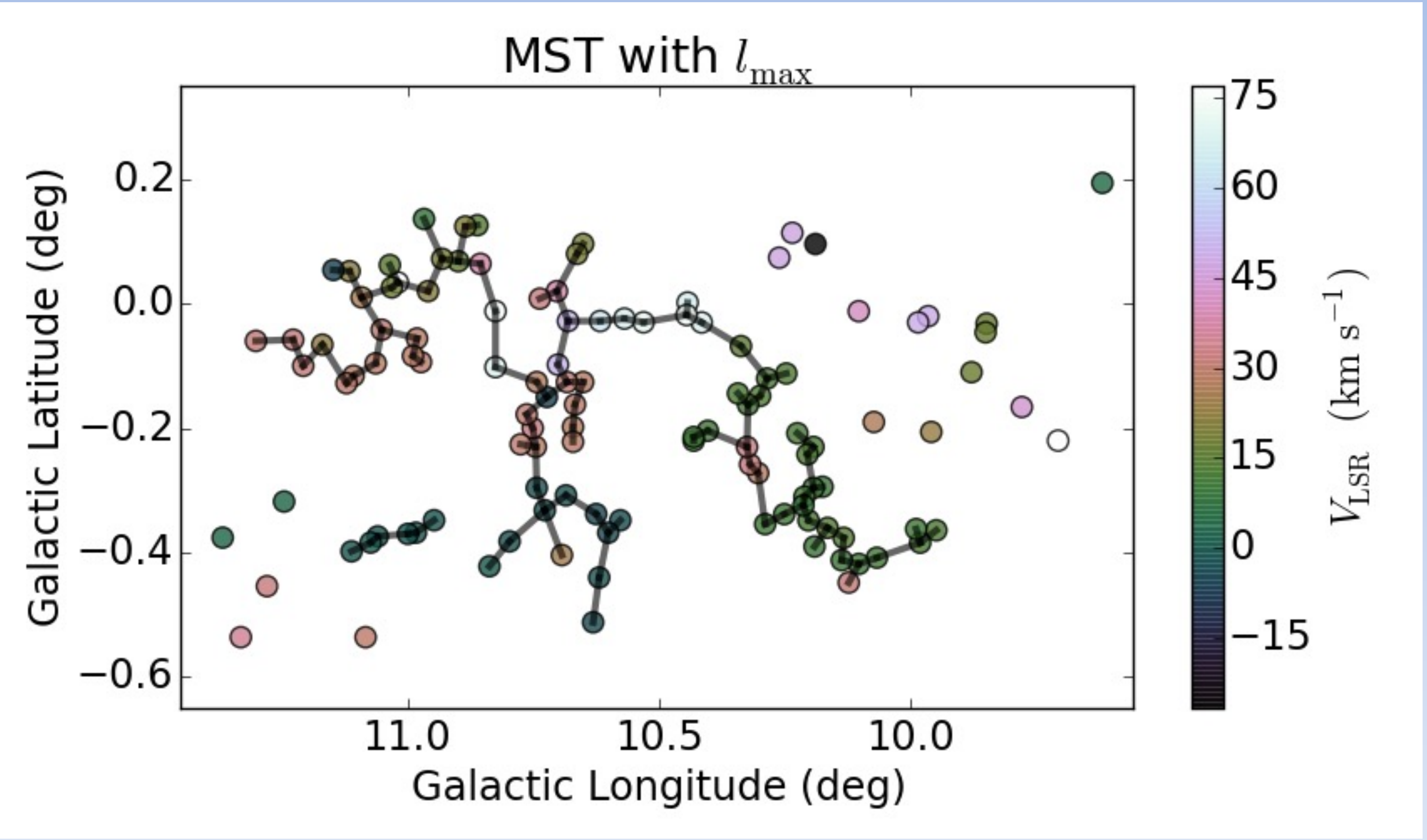
L: linear straight or L-shape;
C: bended C-shape;
S: quasi-sinusoidal shape;
X: crossing of multiple filaments;
H: head-tail or hub-filament system

Wang et al. 2015
“Bones” of Milky Way
Morphological classification

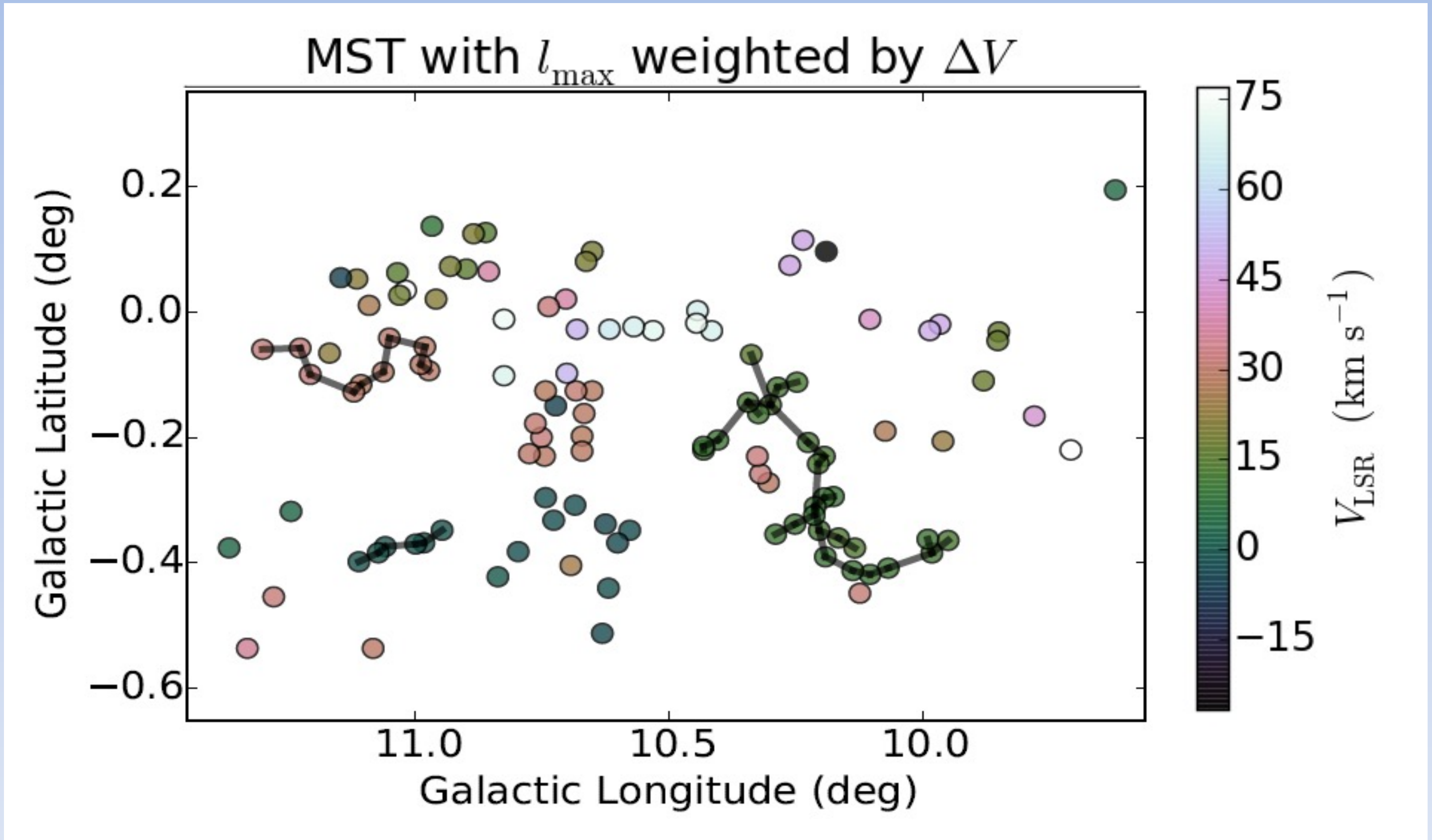
Automated identification: connecting (p,p,v) points using minimum spanning tree (MST)



Automated identification: connecting (p,p,v) points using minimum spanning tree (MST)



Automated identification: connecting (p,p,v) points using minimum spanning tree (MST)



Definition of filament

(1) The accepted MST must contain at least five BGPS clumps: $N_{\rm cl} \geqslant 5$.
(2) Only edges shorter than a maximum length can be connected ($\Delta L < 0\overset{\circ}{.}1$, Figure 1(b)).
(3) For any two clumps to be connected, the difference in line-of-sight velocity (Δv) must be less than $2\,{\rm km\,s^{-1}}$ (Figure 1(c)).

(4) Linearity $f_L > 1.5$

(5) Projected length $\geqslant$10 pc

Definition of “bone”

A large filament that:

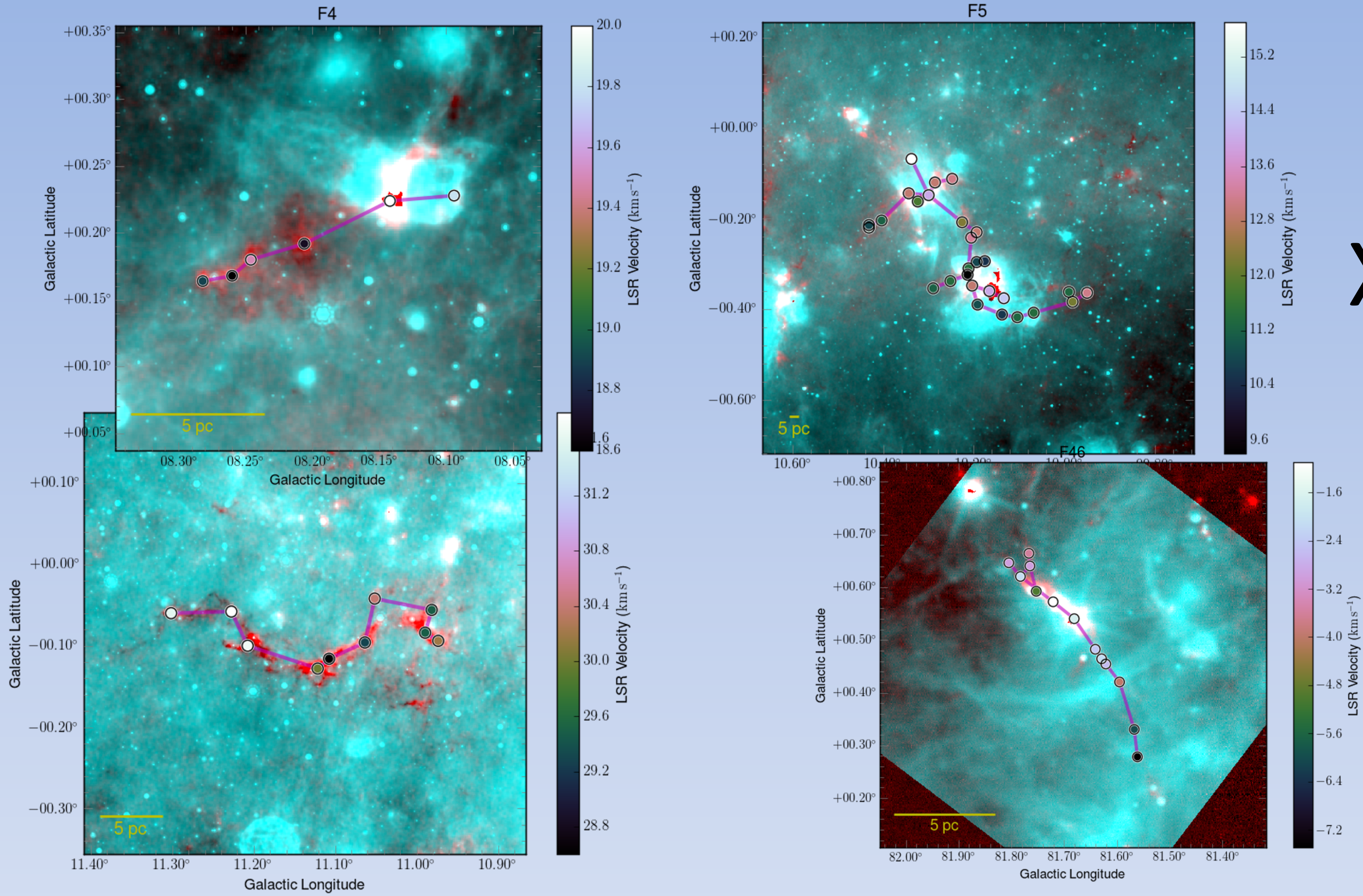
(6) Lies in the very center of the physical Galactic mid-plane, with $|z| \leq 20$ pc.

(7) Runs almost parallel to arms in the projected sky, with $|\theta| \leq 30°$.

(8) The flux weighted LSR velocity $v_{\rm wt}$ is within ±5 km $\rm s^{-1}$ from spiral arms.

L

X



S

C

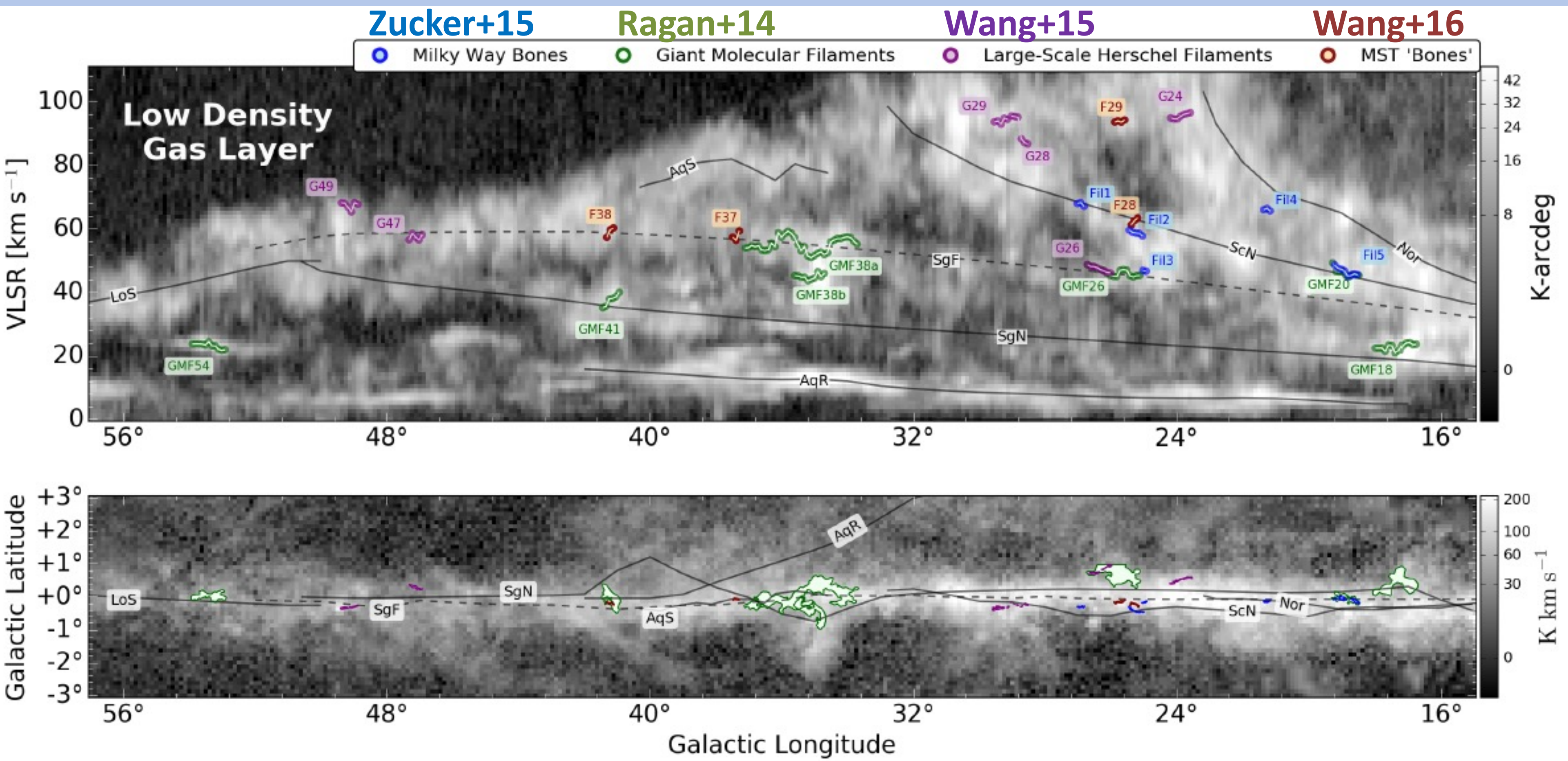
Red: 0.87mm
Cyan: Spitzer MIR

Wang et al. [2016ApJS..226....9W]

AAS NOVA Science highlight

Zucker, Battersby, & Goodman 2018: a "standardized" analysis of large filaments using the Reid+16 arm model:

- 1/3 are bones, consistent with Wang+16
- Highly elongated filaments can trace spiral arms
- Observation-driven simulations now catching up (e.g., Smith et al.)



Current status of the bone-hunting game

Filament Class	From	λ of Initial Detection	Longitude Range	Velocity Reference	Spectral Lines	Velocity Contiguity Criterion	Aspect Ratio or Linearity Criterion	Min. Length	Spiral Arm Association Criterion	Spiral Arm Reference	Galactic Altitude Criterion	Position Angle Criterion
Milky Way Bone	Goodman et al. 2014, Zucker et al. 2015	Mid-IR	60° < l < 60°	HOPS MALT90 BGPS GRS ThrUMMS	NH_3 N_2H+ HCO+ ^{13}CO	Δv < 3 km/s per 10 pc	>50:1		Within 10 km/s of p-v fit	Dame et al. 2011 Reid et al. 2016 Sanna et al. 2014 Vallee 2008 Shane 1972	<20 pc	<30° from midplane
Giant Molecular Filament ("GMF")	Ragan et al. 2014 Abreu-Vicente et al. 2015	Mid-IR Near-IR	18° < l < 56°	GRS ThrUMMS	^{13}CO	"Continuous" velocity gradient		1°	Intersects p-v fit within arm errors	Vallee 2008, Reid et al. 2014		
Large-Scale Herschel	Wang et al. 2015	Far-IR	18° < l < 56°	GRS	^{13}CO	"Continuous, not broken" emission in p-v diagram	>>10		Intersects Galactocentric fit within arm/ filament errors	Reid et al. 2014		
MST "Bone"	Wang et al. 2016	Radio	7° < l < 194°	BGPS	N_2H+ HCO+	Δv < 2 km/s between connected clumps	$\sigma_{major}/\sigma_{minor}$ > 1.5	10 pc	Within 5 km/s of p-v fit	Reid et al. 2016	<20 pc	< 30° from midplane

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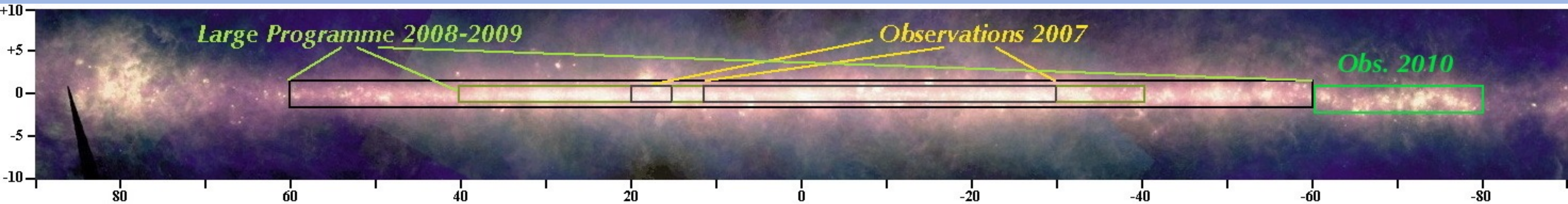
Table from Zucker, Battersby, & Goodman 2018

We have developed two independent methods to search for large filaments:

(1) Find the coldest structure directly in FIR emission

(2) Unbiased automated search using MST

ATLASGAL - The APEX Telescope Large Area Survey of the Galaxy

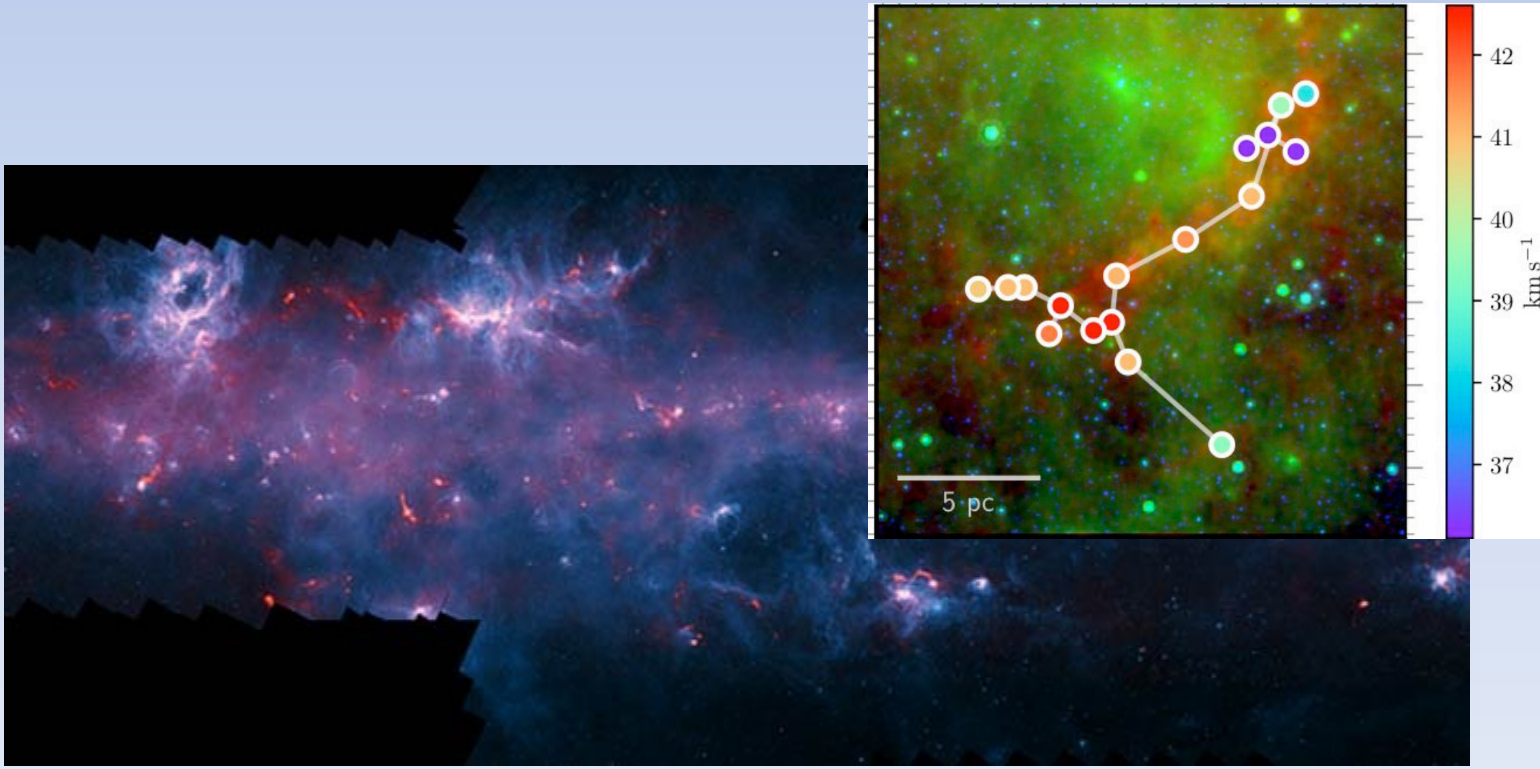


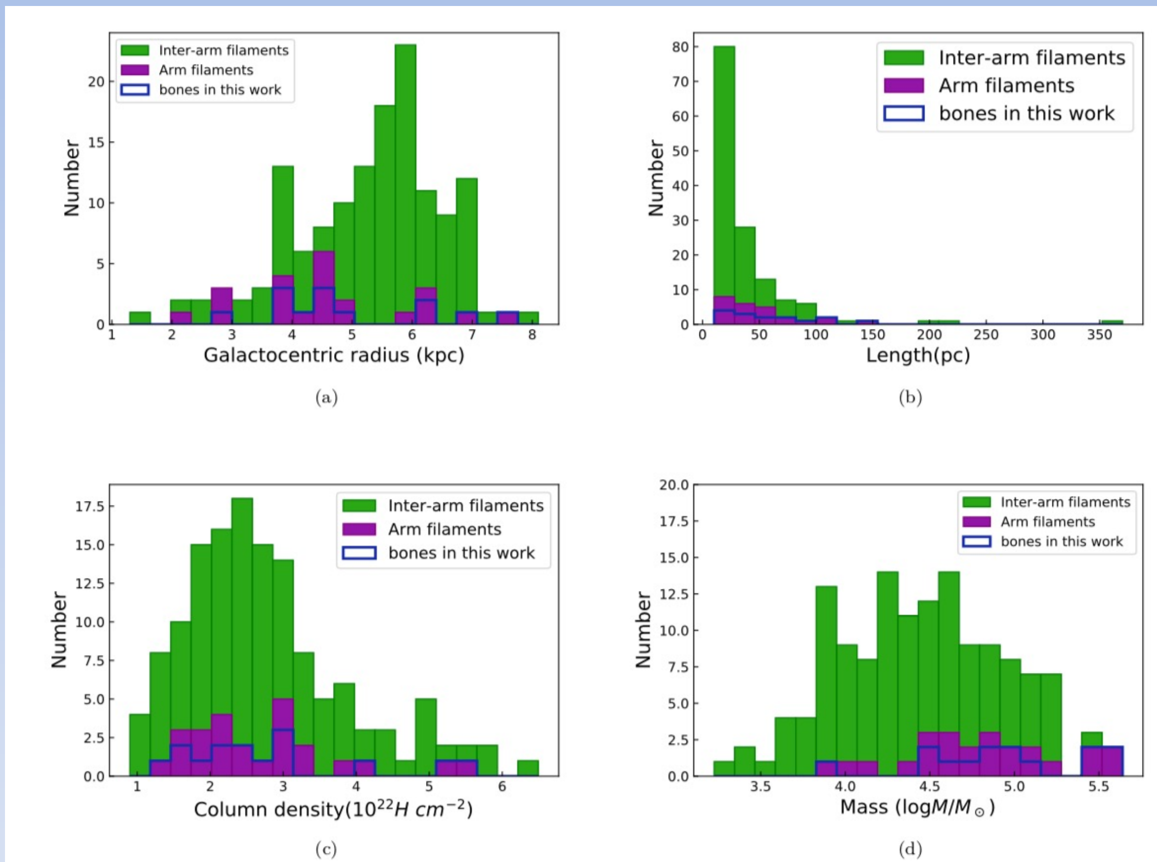
Yifei Ge (盖逸飞), PKU student

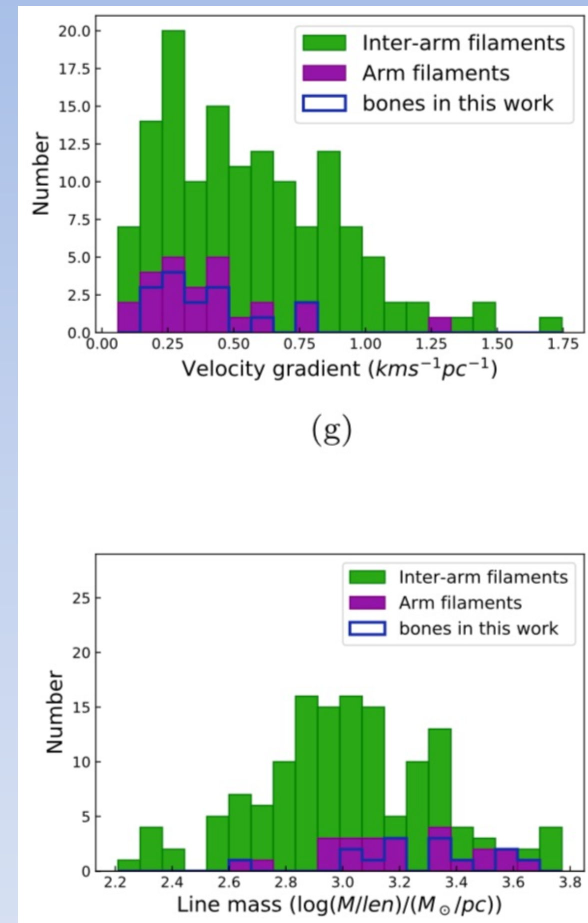
PhD project: full census of filaments and characterization

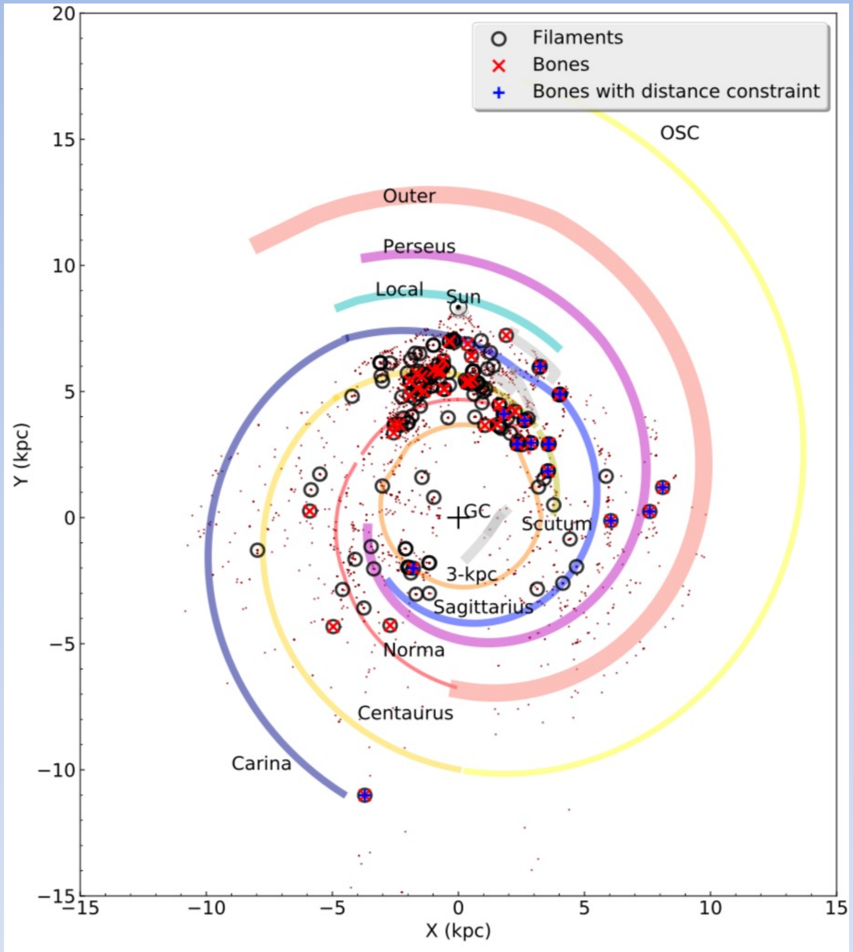
Finished: auto identified 160+ large-scale filaments (Ge & Wang, ApJS, submitted)

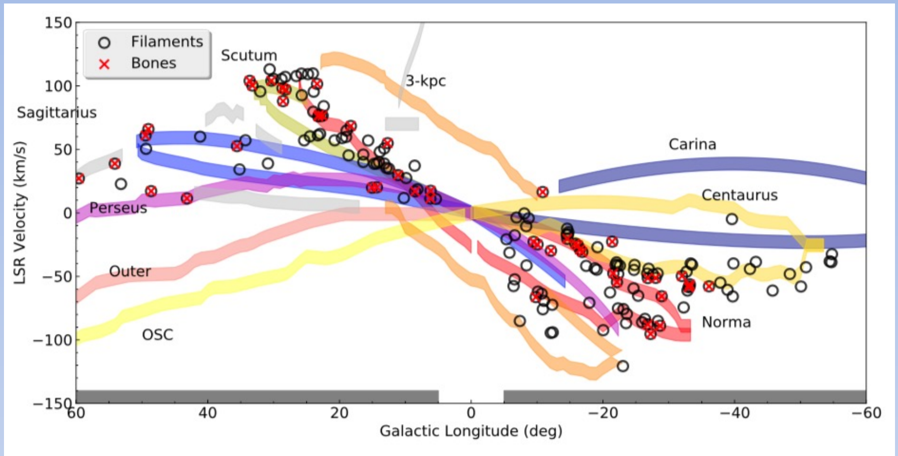
Ongoing: structure and kinematics analysis



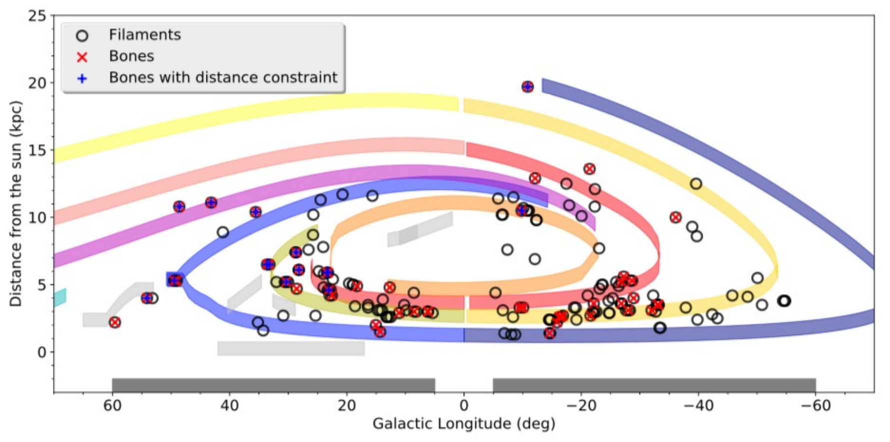

Inter-arm filaments
Arm filaments
bones in this work
Number
Galactocentric radius (kpc)
(a)
Length(pc)
(b)
Column density($10^{22} H\ cm^{-2}$)
(c)
Mass ($\log M/M_\odot$)
(d)


Inter-arm filaments
Arm filaments
bones in this work
Number
Velocity gradient ($kms^{-1}pc^{-1}$)
(g)
Line mass ($\log(M/len)/(M_\odot/pc)$)

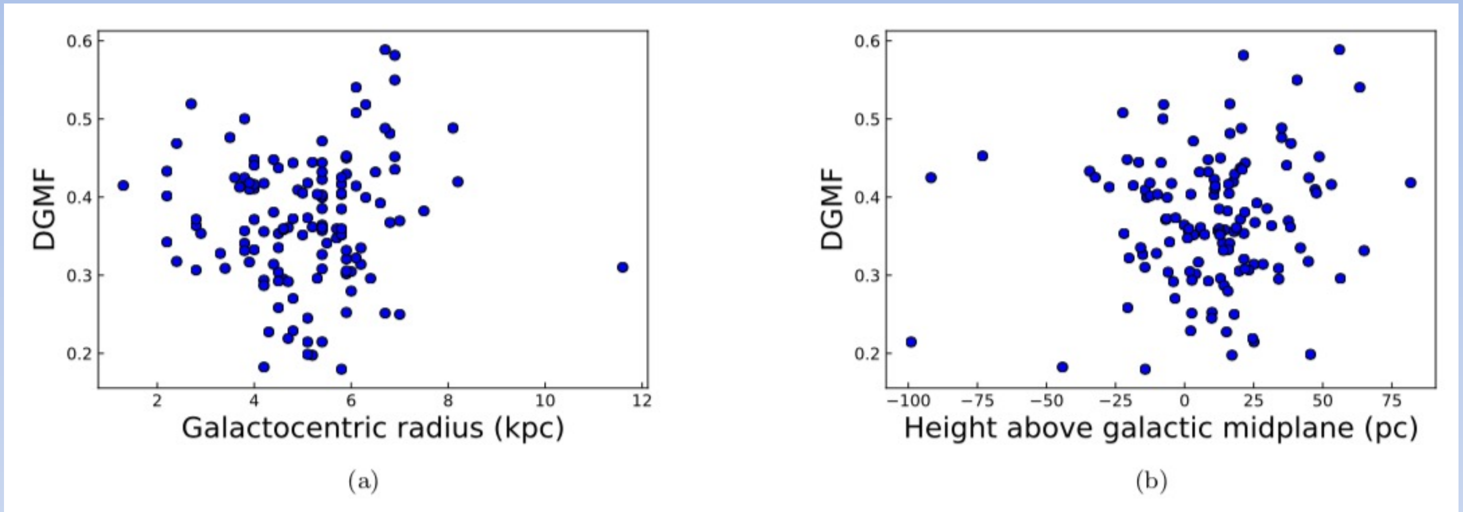

Filaments
Bones
Bones with distance constraint
OSC
Outer
Perseus
Local
Sun
GC
Scutum
3-kpc
Sagittarius
Norma
Centaurus
Carina
Y (kpc)
X (kpc)


Filaments
Bones
Scutum
3-kpc
Sagittarius
Carina
Centaurus
Perseus
Outer
OSC
Norma
LSR Velocity (km/s)
Galactic Longitude (deg)

(a)

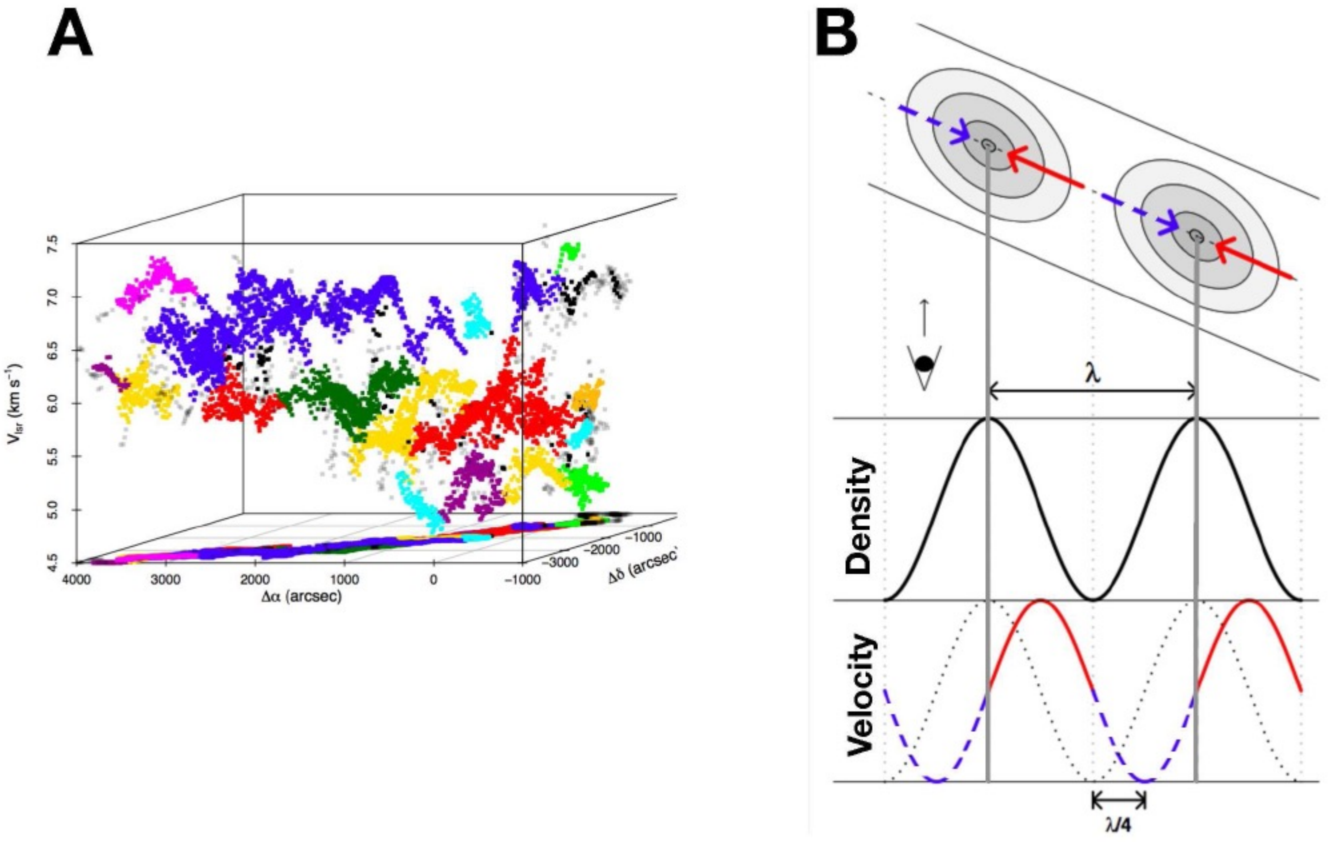

Filaments
Bones
Bones with distance constraint
Distance from the sun (kpc)
Galactic Longitude (deg)

Dense gas mass fraction

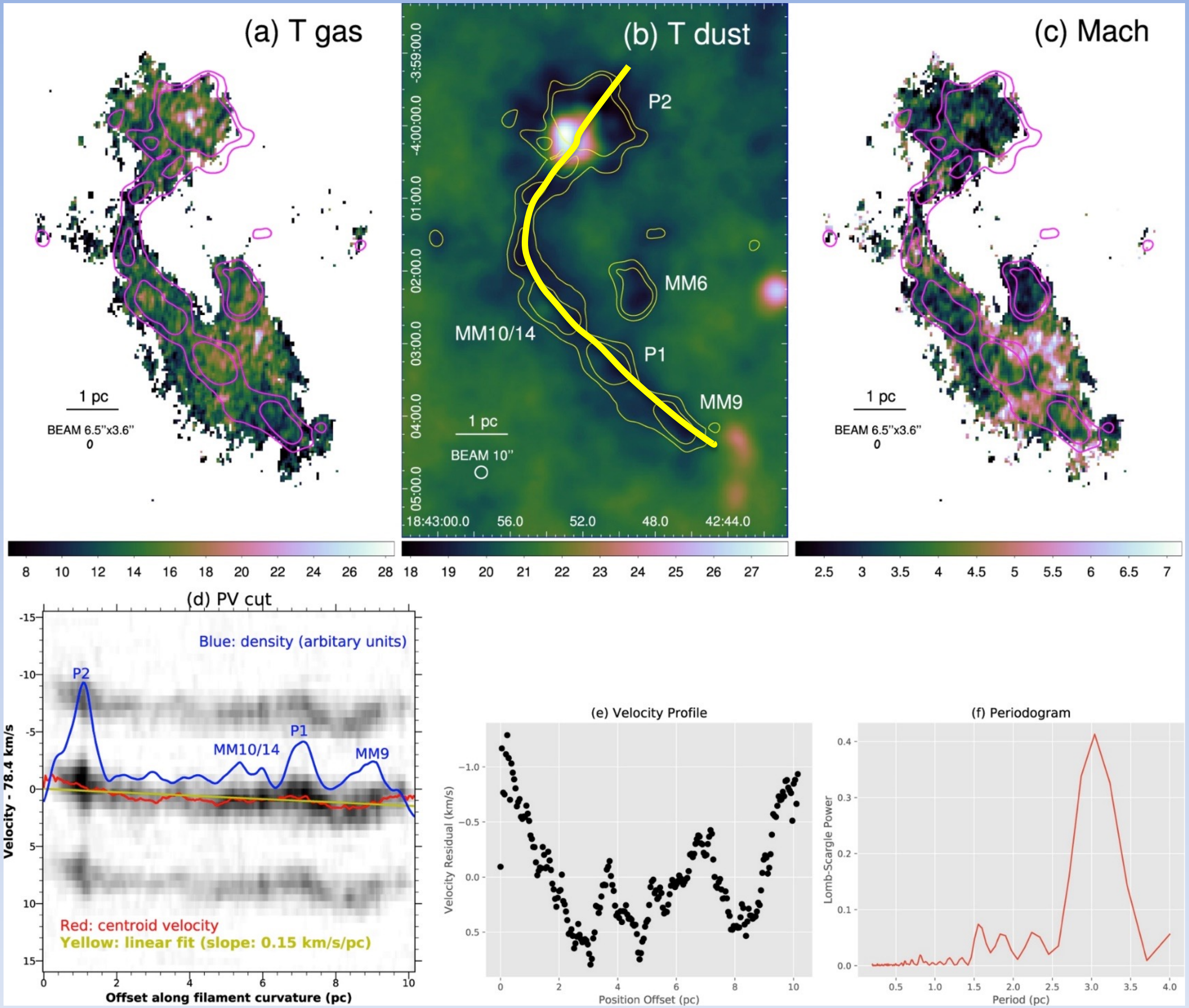


Arm	Filaments	Bones	Bones with distance constraint	Bone fraction	Mean DGMF
Norma-Outer	19 (33.3%)	9 (26.5%)	5 (50.0%)	47.4%	35.8%±0.8%
Scutum-Centaurus-OSC	12 (21.1%)	8 (23.5%)	1 (10.0%)	66.7%	41.0%±5.2%
Sagittarius-Carina	20 (35.1%)	12 (35.3%)	3 (30.0%)	60.0%	32.5%±7.0%
Perseus	6 (10.5%)	5 (14.7%)	1 (10.0%)	83.3%	44.8%
Total	57 (100%)	34 (100%)	10 (100%)	59.6%	-

Internal structure



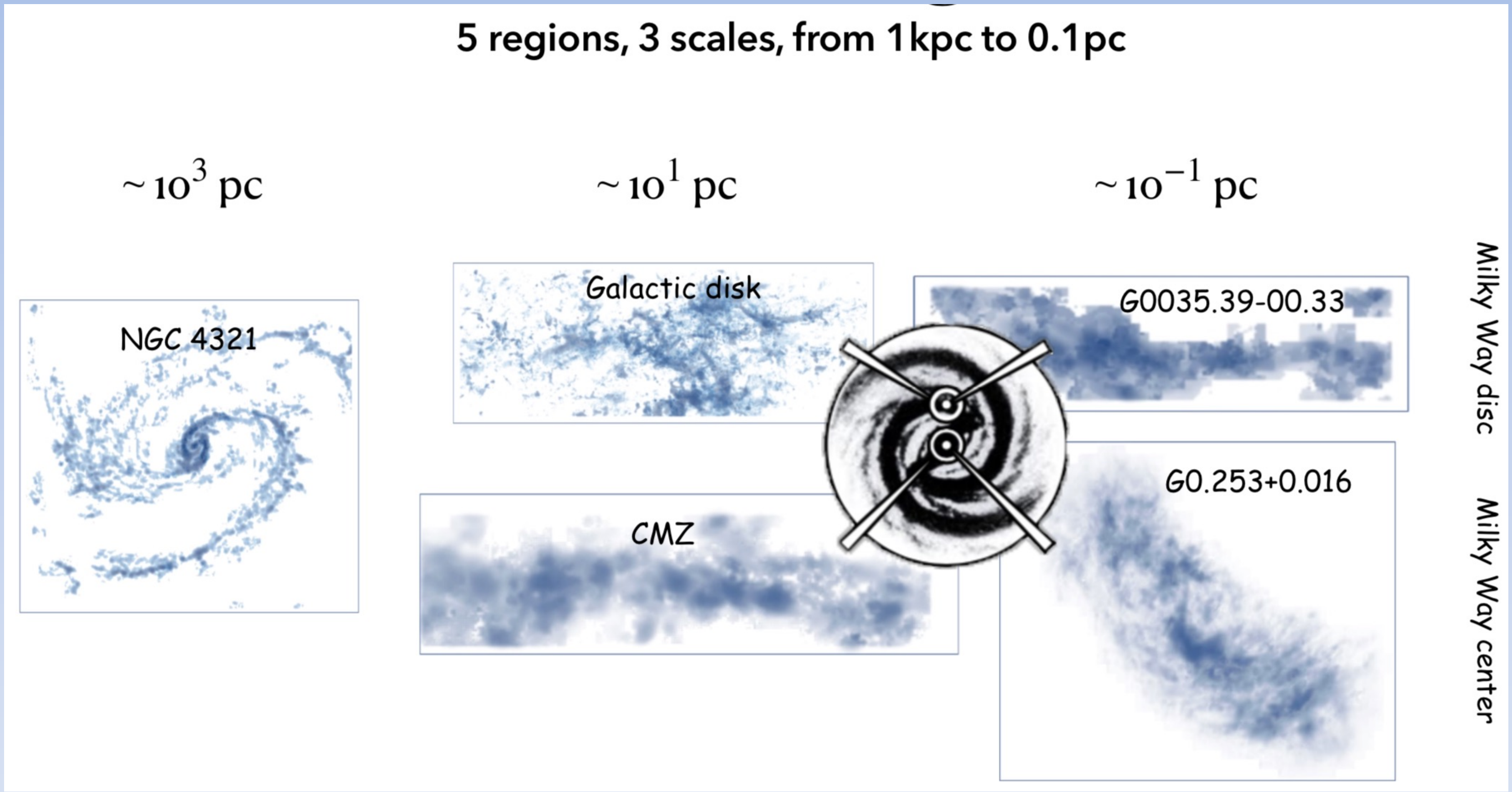
Hacar et al. 2013



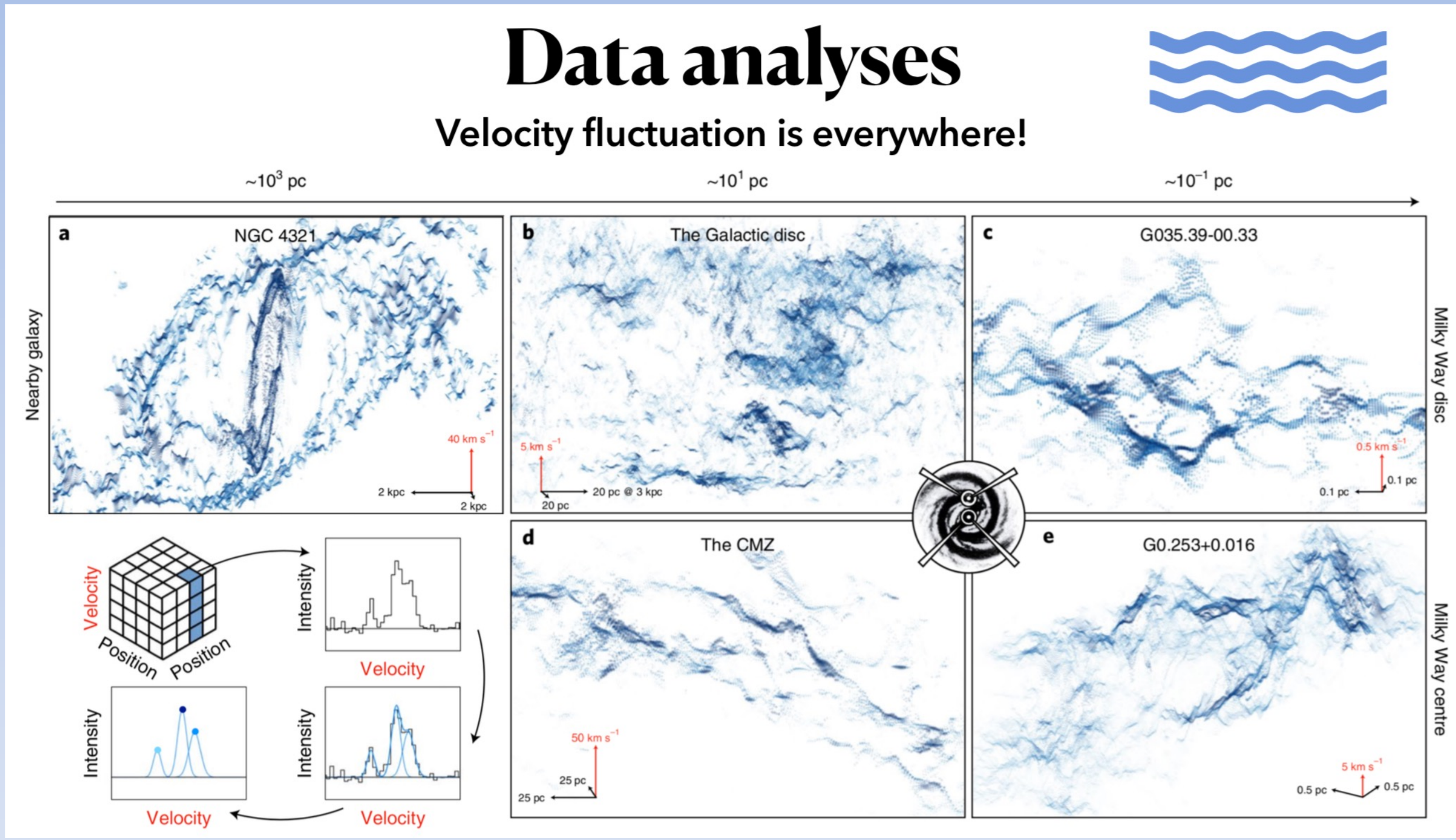
Also note the global velocity gradient shown by the yellow line

[Wang 2018]

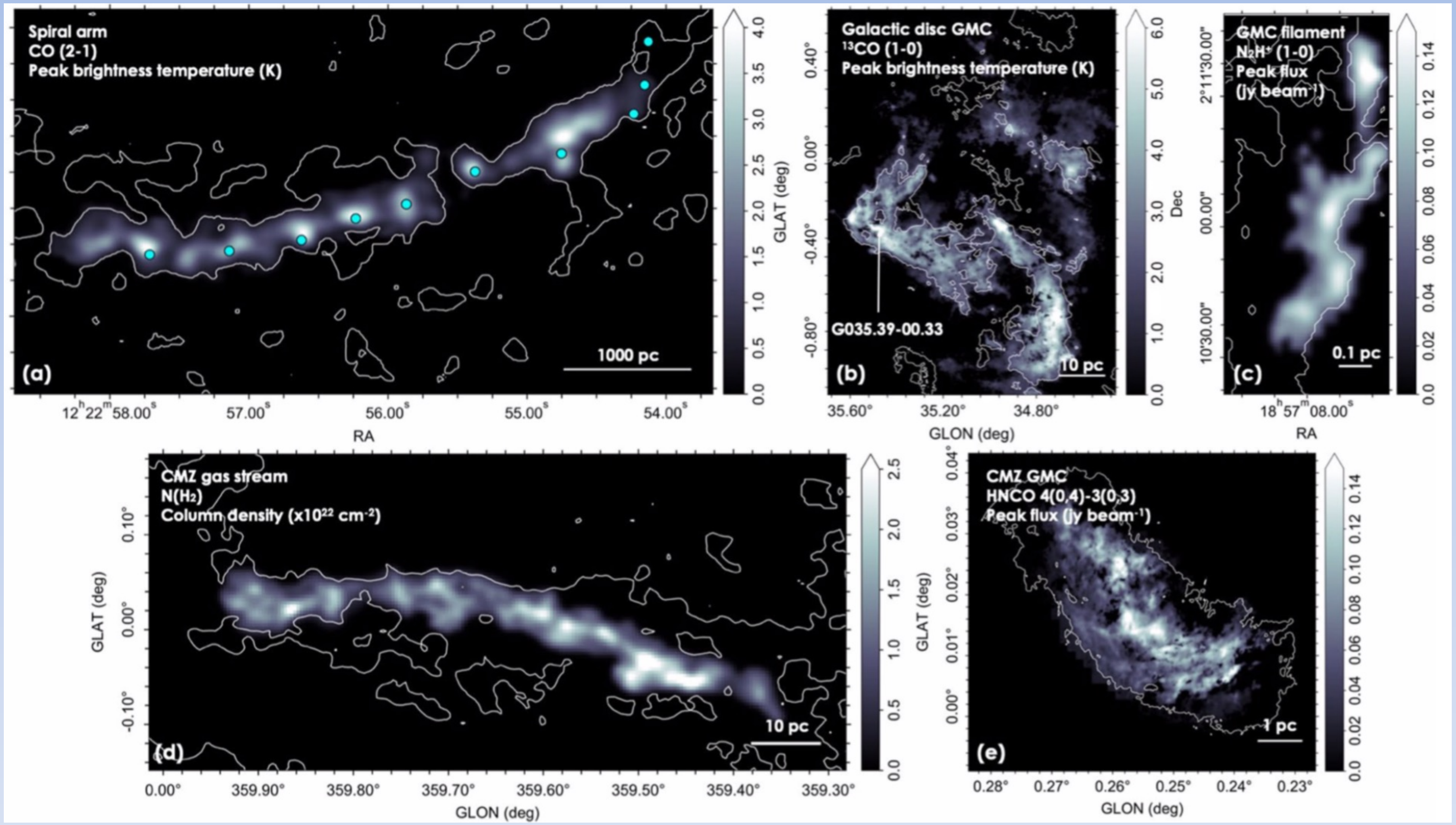
Hierarchical filaments (Henshaw et al. 2020)



Fluctuation in velocity



Fluctuation in density



Same period; phase shift

three periodic structure found in three different scale: ubiquitous fluctuations

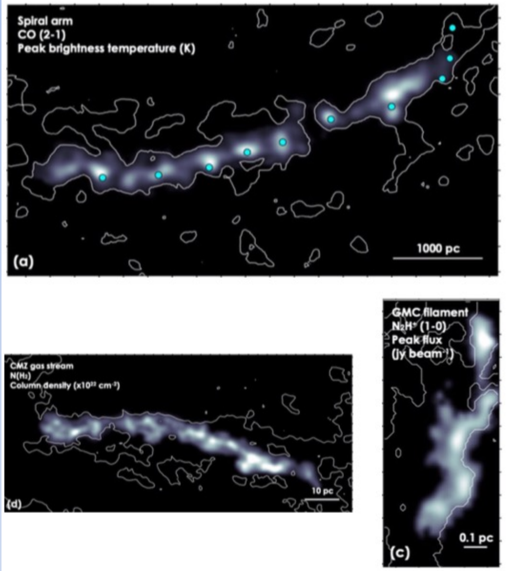
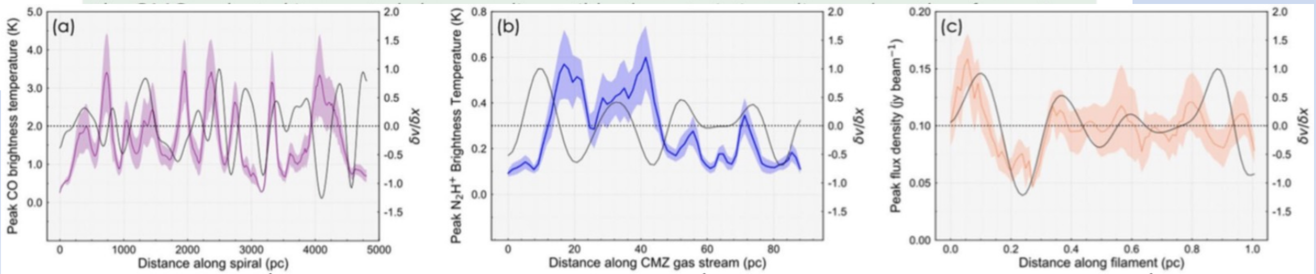


Table 1 | Characteristic length scales

Environment	Filament diameter (pc)	Density periodicity (pc)	Velocity periodicity (pc)
Spiral arm	122 ± 5	366^{+88}_{-77}	405^{+92}_{-76}
CMZ gas stream	—	$6.0^{+0.8}_{-0.6}$	—
	4.2 ± 0.2	$21.8^{+5.5}_{-6.3}$	$22.0^{+5.4}_{-6.3}$
GMC filament	0.107 ± 0.001	$0.32^{+0.01}_{-0.01}$	$0.28^{+0.06}_{-0.08}$

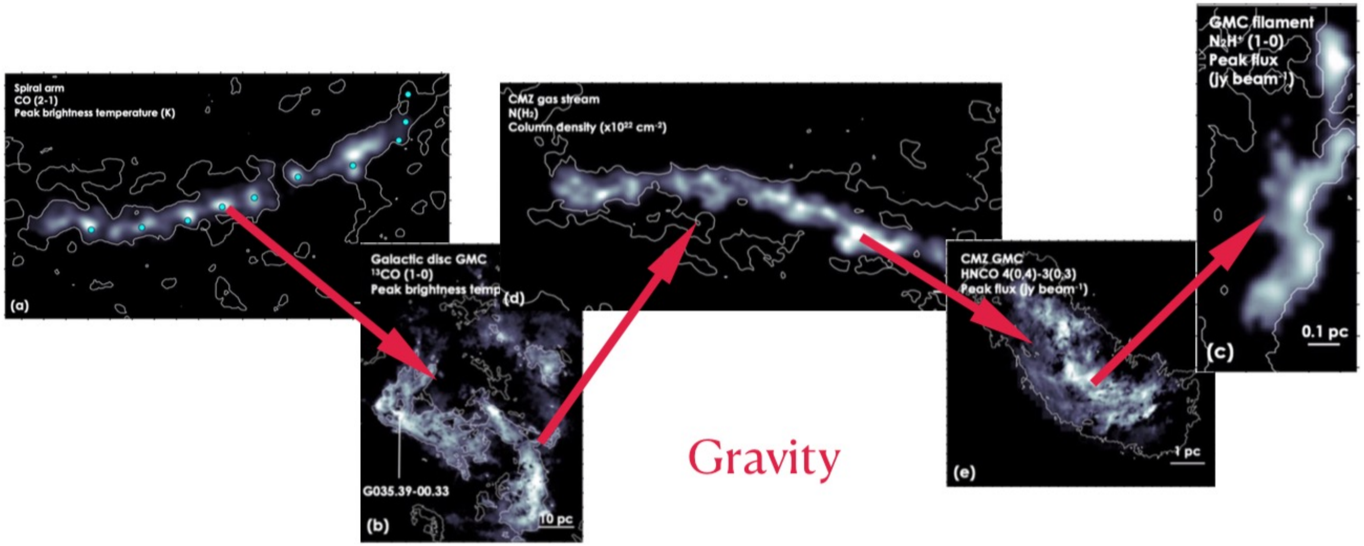
The beam-deconvolved diameters of the filamentary structures that exhibit periodicity, as well as the separation between periodically spaced density enhancements and the wavelength of the velocity oscillations determined from our structure function analysis presented in Fig. 2, are included. The two rows for the CMZ gas stream correspond to the two minima identified in the density structure function. Note that the density and velocity fluctuations observed throughout



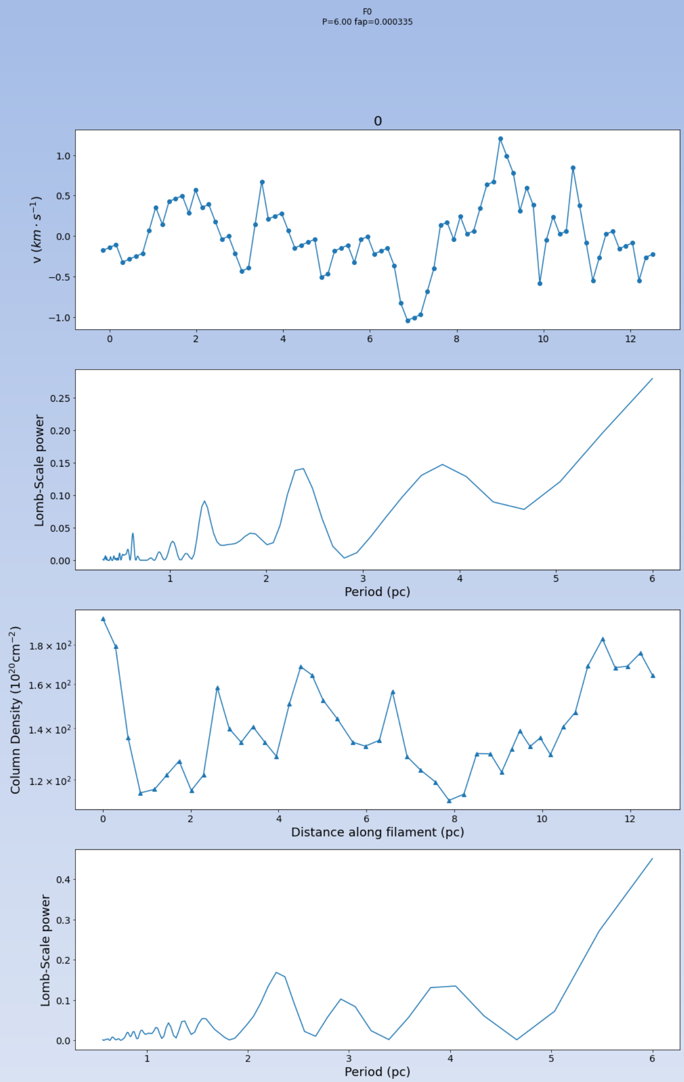
$$\Delta\phi = \frac{\lambda}{2} \qquad \Delta\phi = \frac{\lambda}{8} \qquad \Delta\phi = \frac{\lambda}{2.5}$$

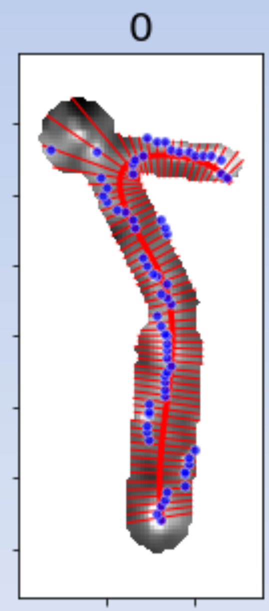
A unified view?

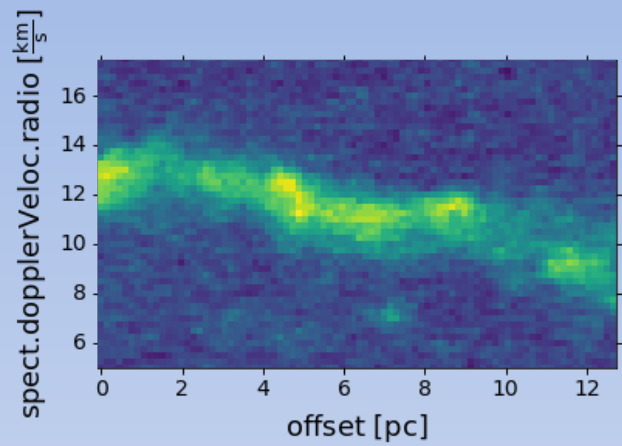
- Ubiquitous fluctuations in all-scale (0.1 pc-1 kpc) of interstellar medium.
- Density and velocity fluctuations correspond to each other well and display a phase shift, indicating sonic wave in filament structure.
- Direct observation of fragmentation due to gravity.

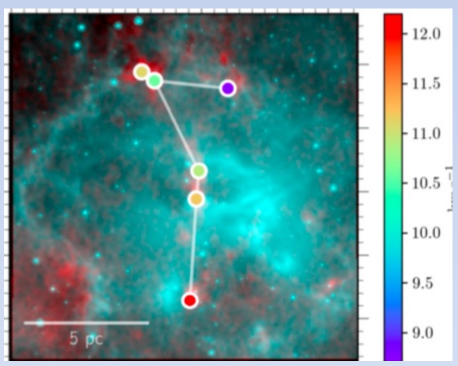


Profiling filaments using SEDIGISM

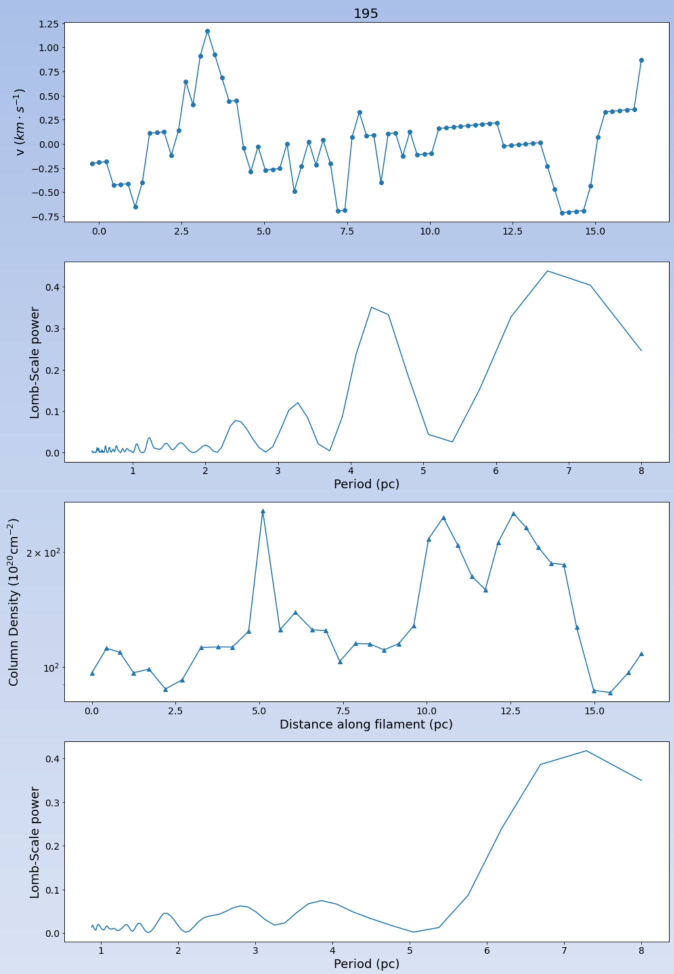


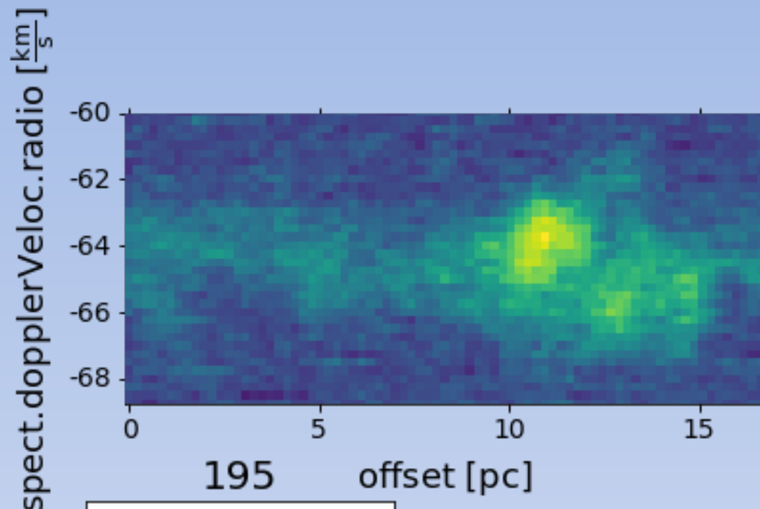


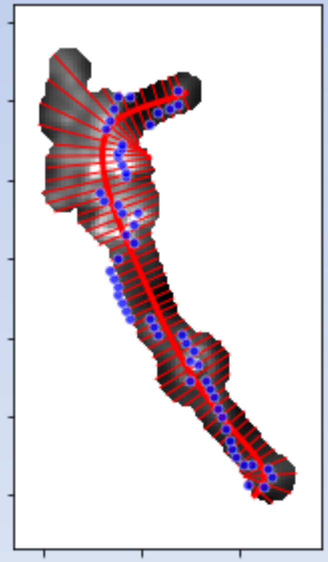


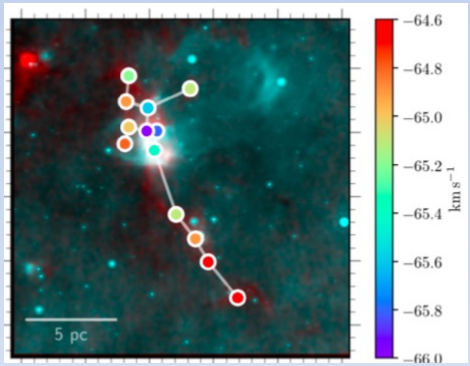


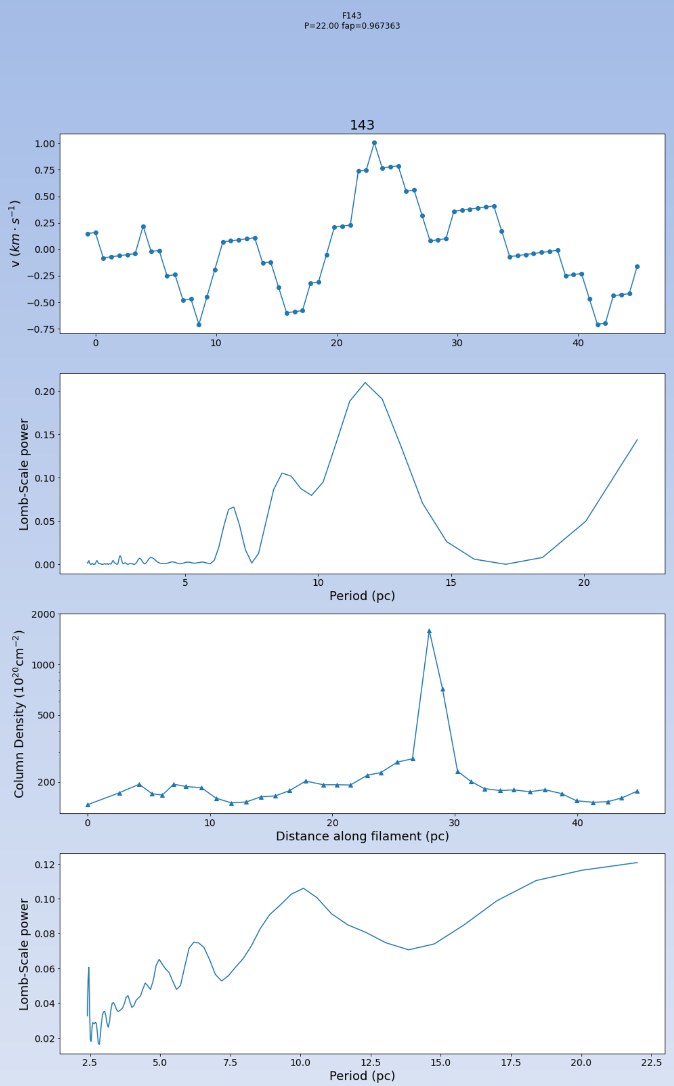
F195
P=7.29 fap=0.005429

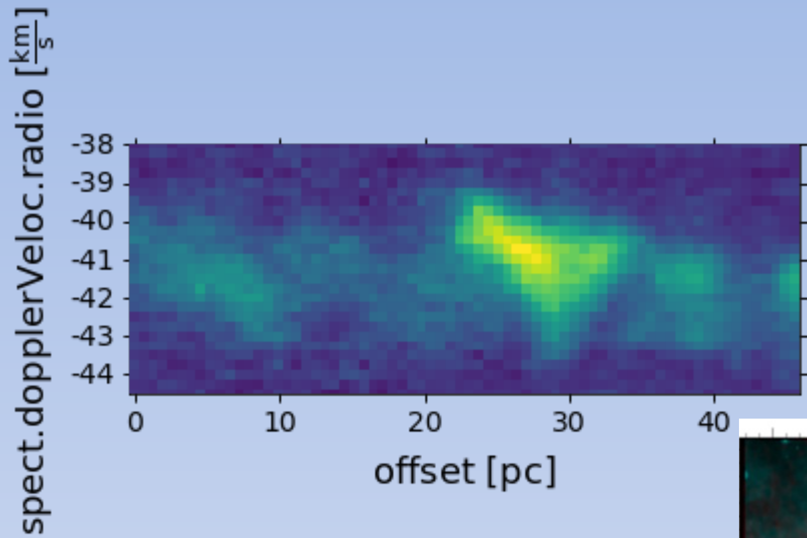


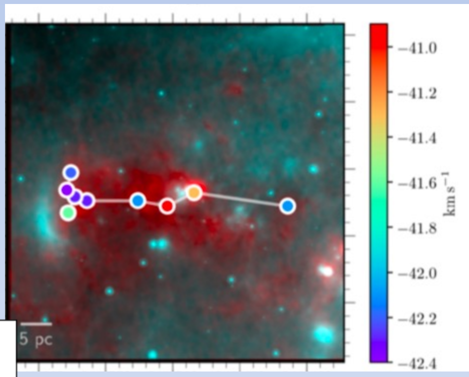


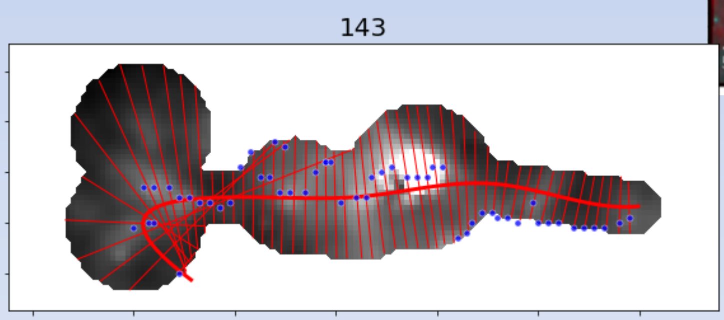


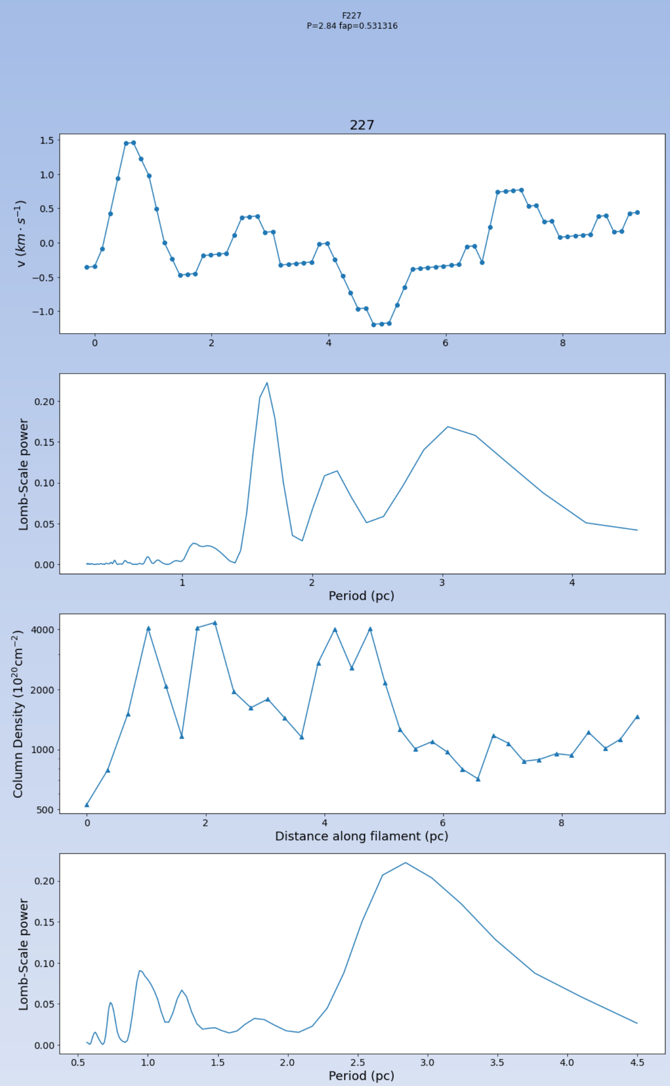


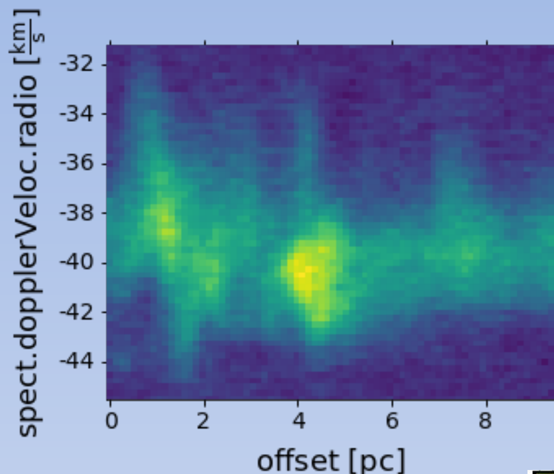

F143
P=22.00 fap=0.967363
143
v (km · s⁻¹)
Lomb-Scale power
Period (pc)
Column Density (10^{20}cm^{-2})
Distance along filament (pc)
Lomb-Scale power
Period (pc)

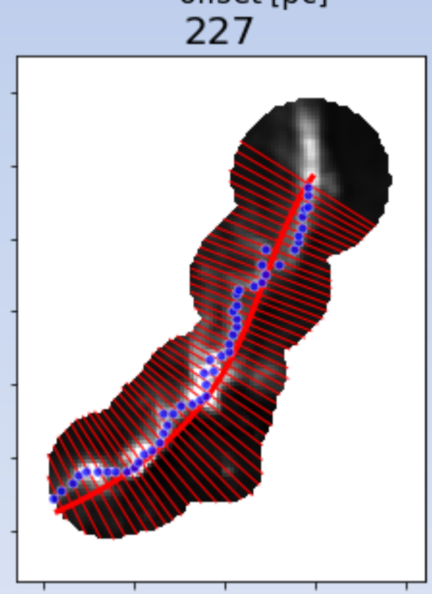

spect.dopplerVeloc.radio [km/s]
offset [pc]

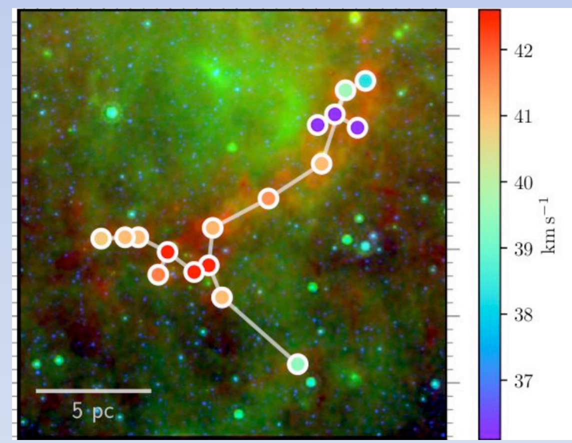

5 pc
km s^{-1}

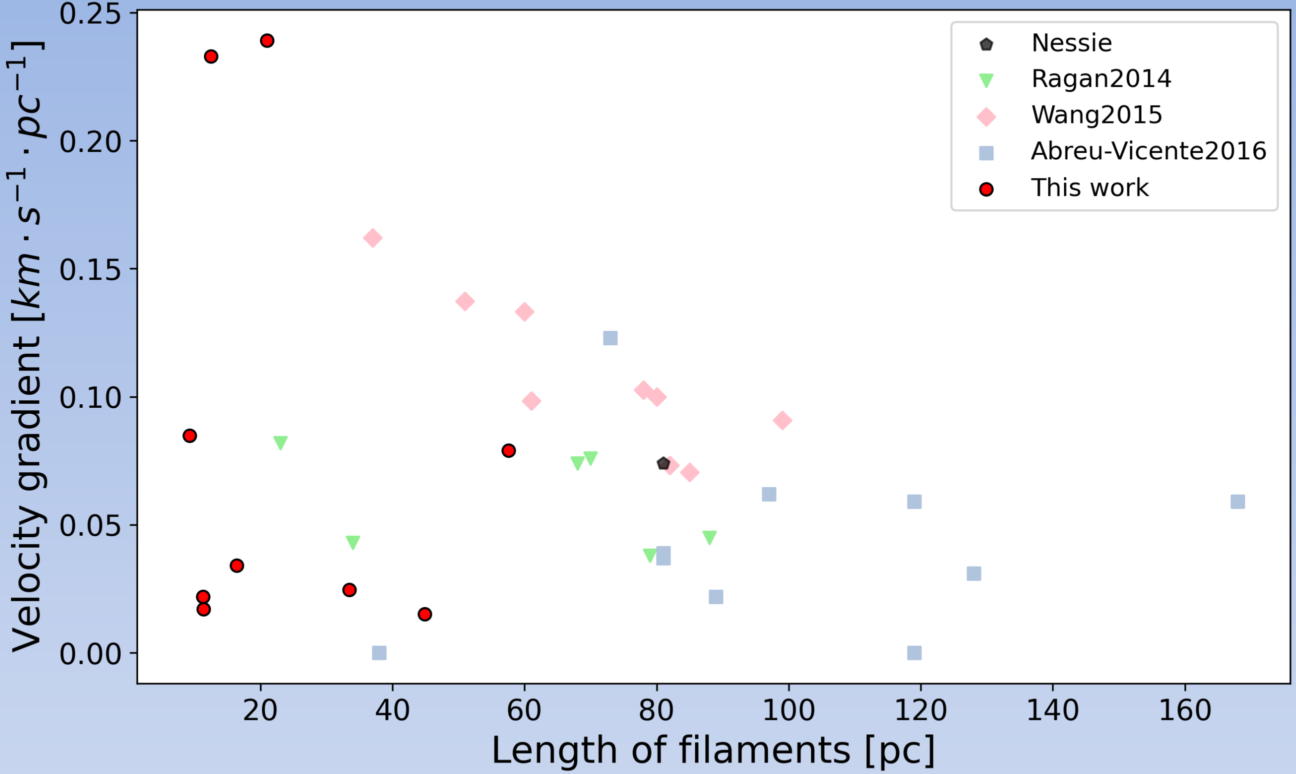

143

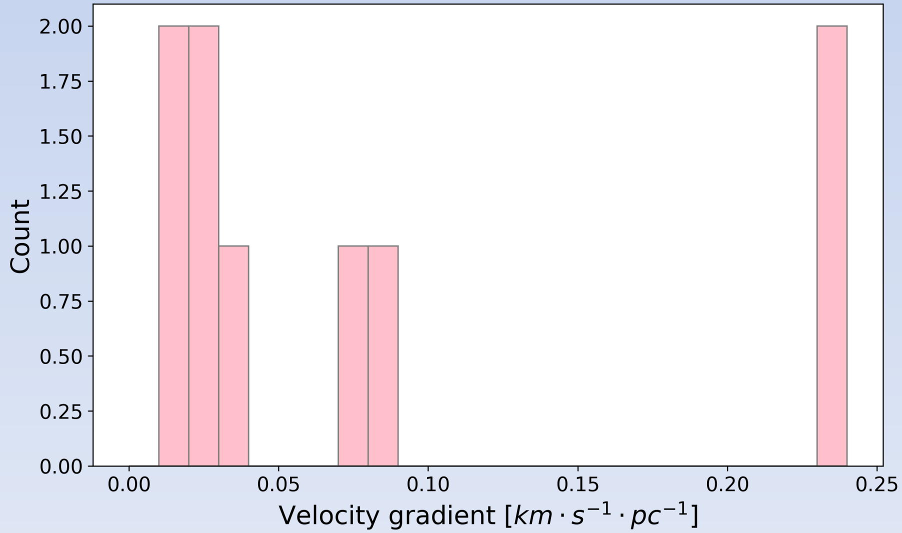

F227
P=2.84 fap=0.531316
227
v ($km \cdot s^{-1}$)
Lomb-Scale power
Period (pc)
Column Density ($10^{20}cm^{-2}$)
Distance along filament (pc)
Lomb-Scale power
Period (pc)

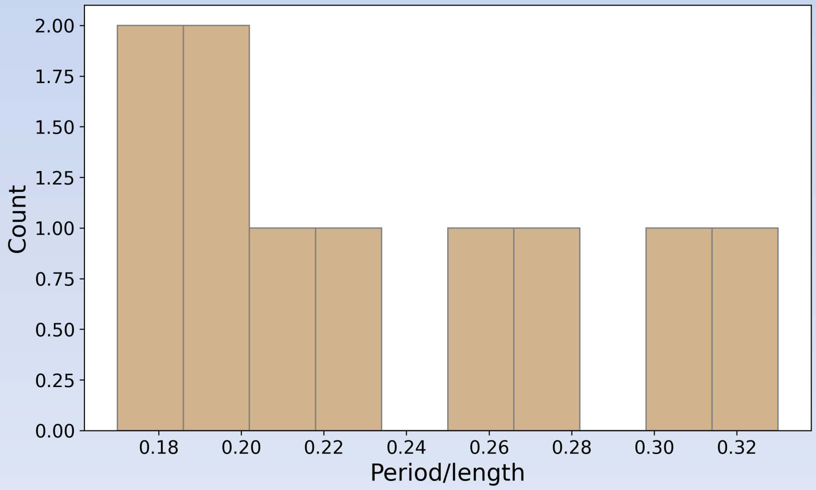

spect.dopplerVeloc.radio [km/s]
offset [pc]


227


5 pc
$km\ s^{-1}$


Nessie
Ragan2014
Wang2015
Abreu-Vicente2016
This work
Velocity gradient $[km \cdot s^{-1} \cdot pc^{-1}]$
Length of filaments [pc]
0.00
0.05
0.10
0.15
0.20
0.25
20
40
60
80
100
120
140
160


Count
Velocity gradient $[km \cdot s^{-1} \cdot pc^{-1}]$
0.00
0.25
0.50
0.75
1.00
1.25
1.50
1.75
2.00
0.00
0.05
0.10
0.15
0.20
0.25


Count
Period/length
0.00
0.25
0.50
0.75
1.00
1.25
1.50
1.75
2.00
0.18
0.20
0.22
0.24
0.26
0.28
0.30
0.32