The Galactic dynamics

revealed by the filamentary structure in the

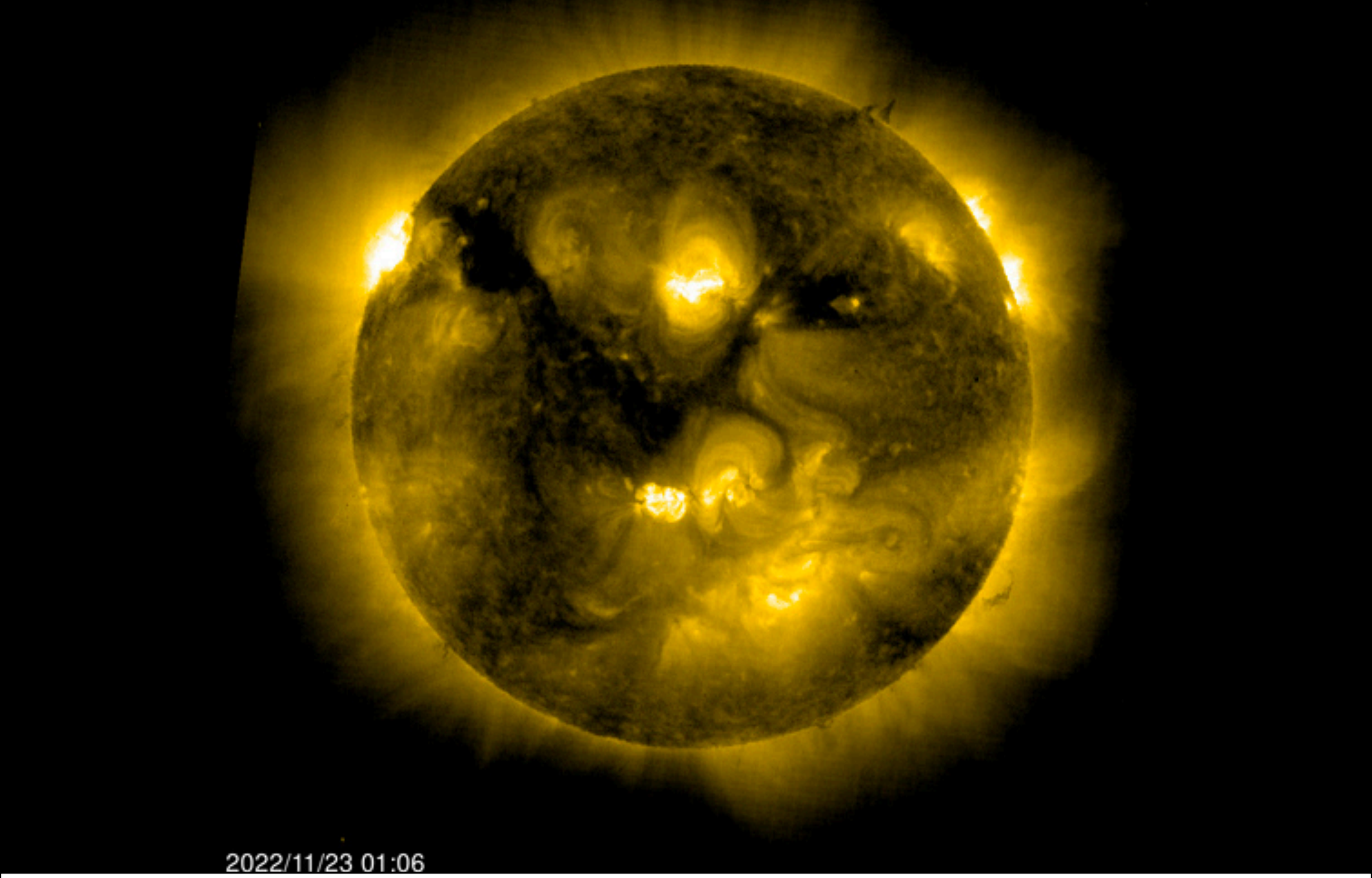
atomic and molecular gas emission

Juan Diego Soler
Istituto di Astrofisica e Planetologia Spaziali

THOR collaboration: H. Beuther, J. Syed, Y. Wang, Th. Henning, L. D. Anderson, N. M. McClure-Griffiths, P. F. Goldsmith, M. Heyer, K. M. Menten, M. Rugel, S. N. Longmore, J. S. Urquhart, J. Stil, R. Shanahan
ECOgal collaboration: S. Molinari, R. S. Klessen, P. Hennebelle, S. C. O. Glover, A. Trafficante, E. Schisano, D. Elia, M. Sormani, R., Tress, P. Girichidis, R. J. Smith, T. Colman

The Sun

SOHO Extreme ultraviolet Imaging Telescope (EIT) - λ = 284 Angstrom



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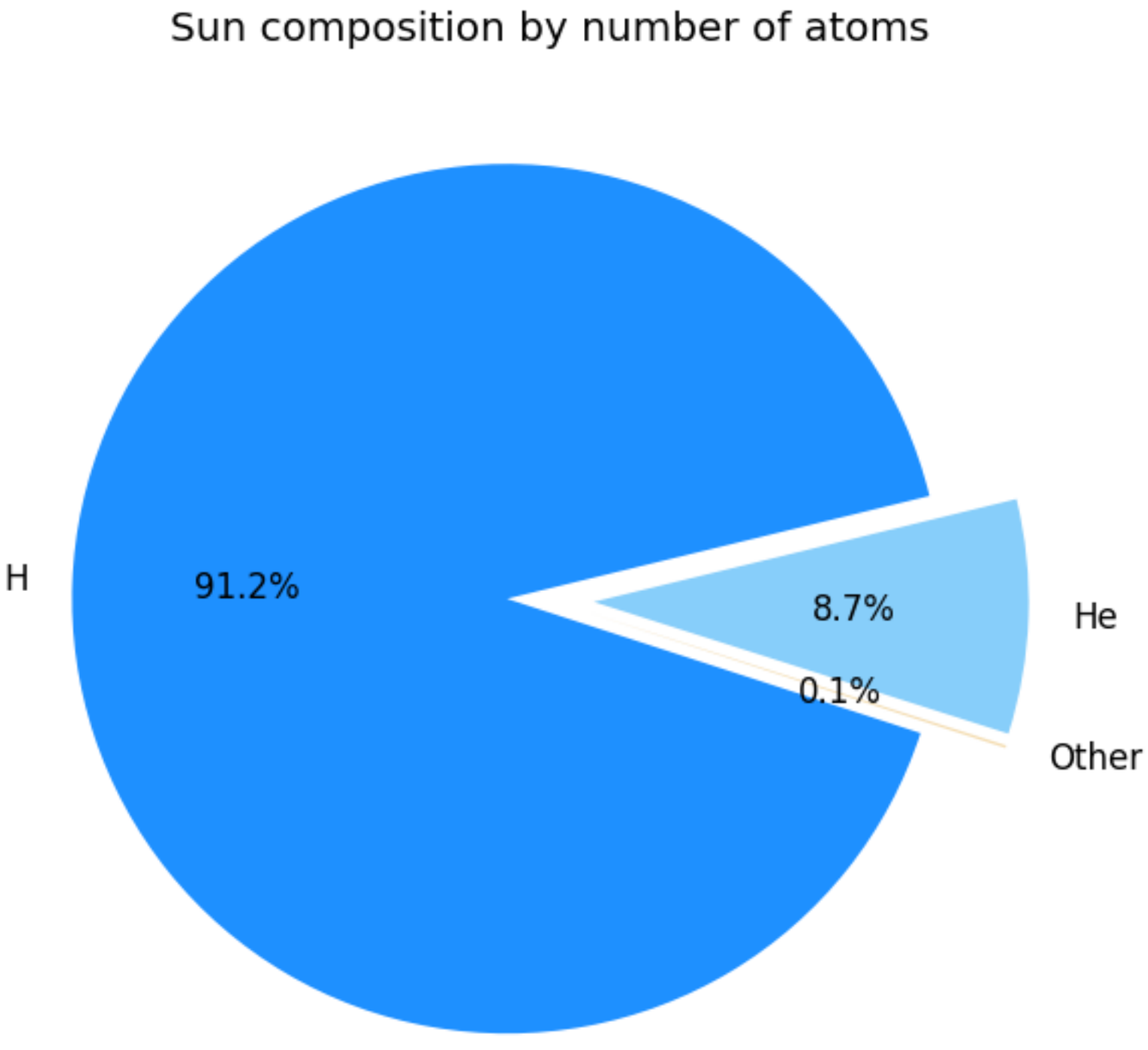
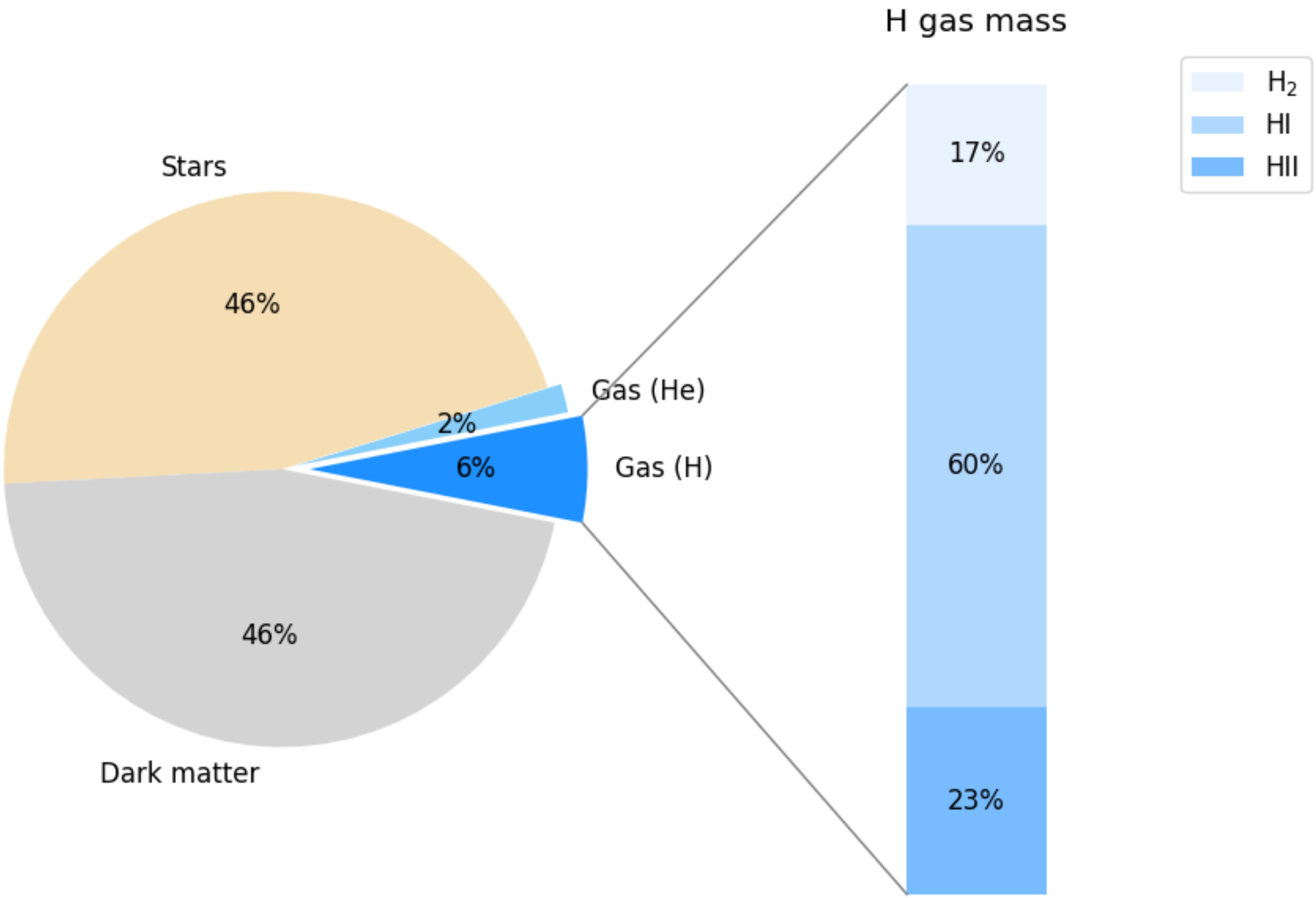
The Sun

M. Asplund, A. Amarsi, and N. Grevesse 2021, A&A, 653, A141

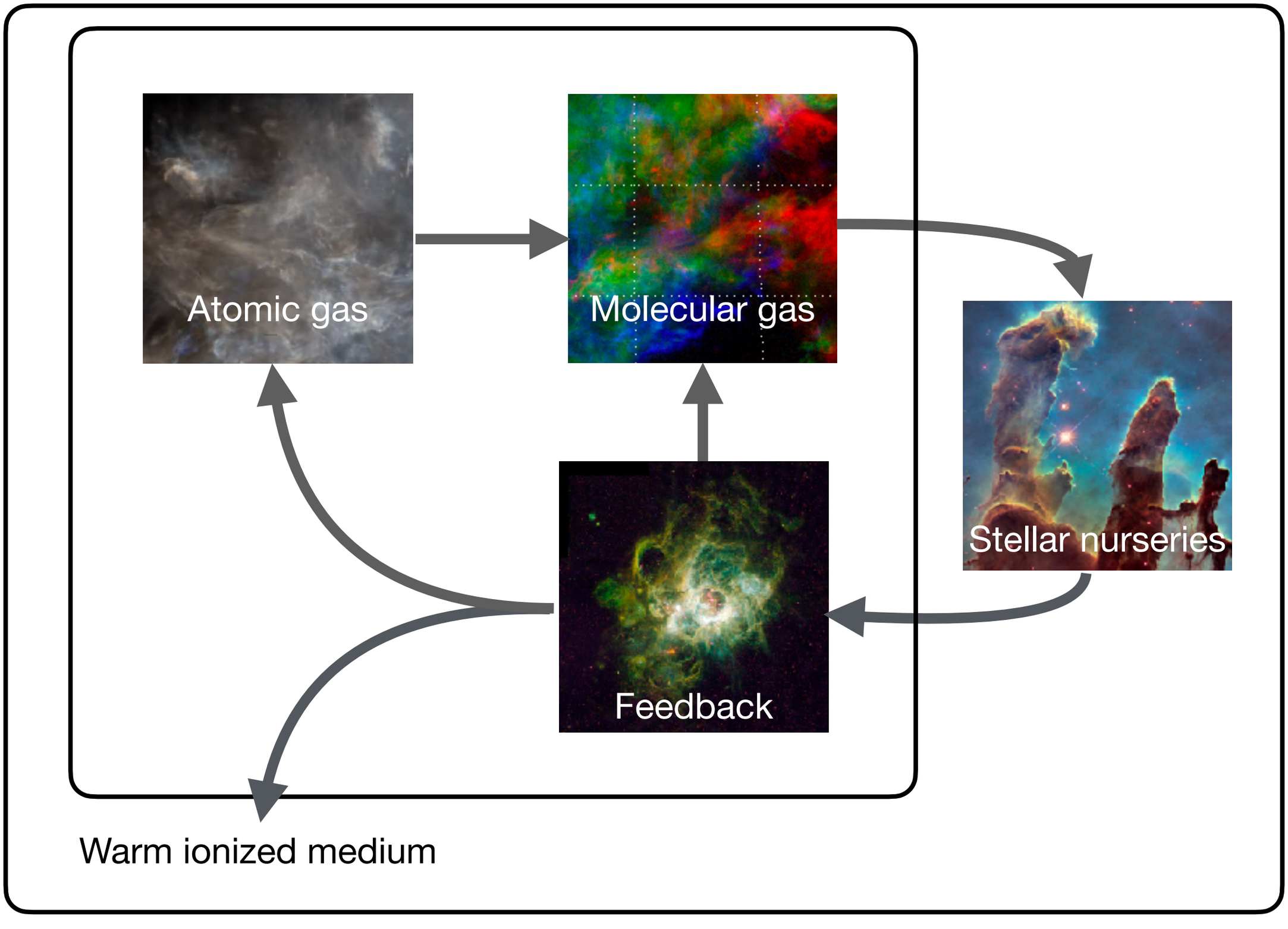


Milky Way's mass budget

Draine, B. T. Physics of the Interstellar and Intergalactic Medium (2011)

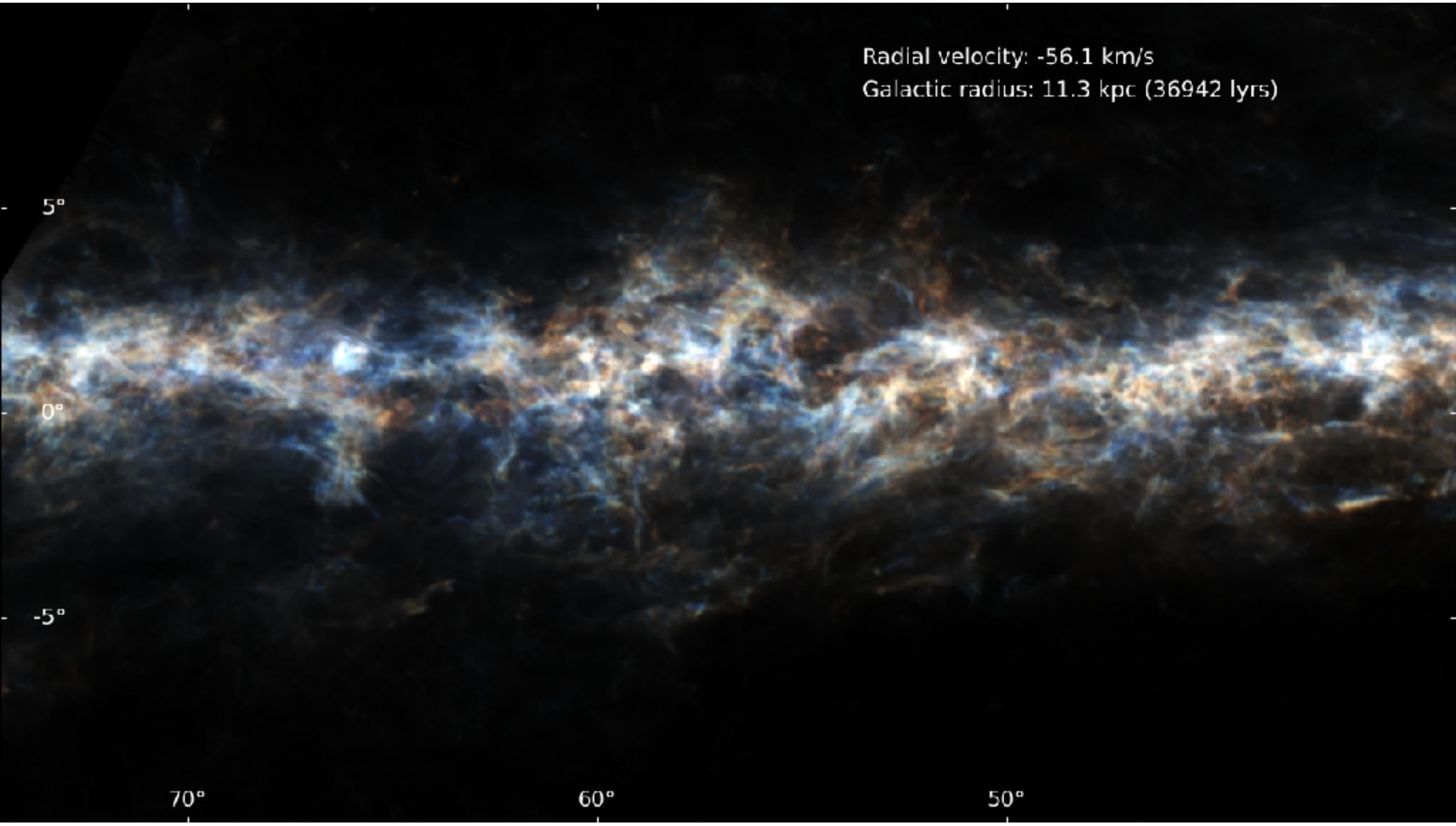


Hydrogen lifecycle in the interstellar medium



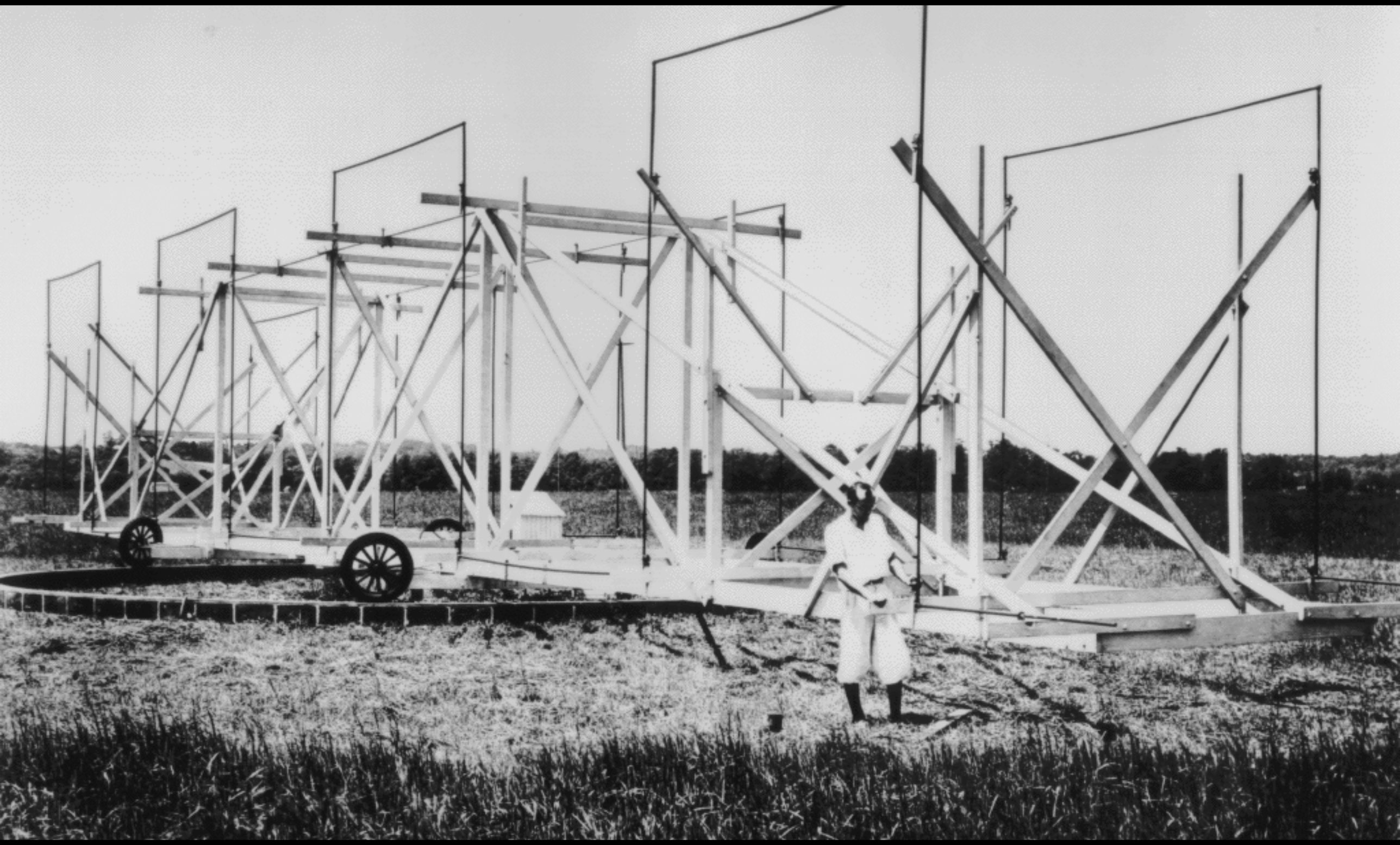
Atomic hydrogen clouds

J.D. Soler; GALFA-HI, Peek et al, 2018



Radioastronomy (20.5 MHz)

Karl Jansky. Bell Labs (1928-1933)



Atomic hydrogen emission

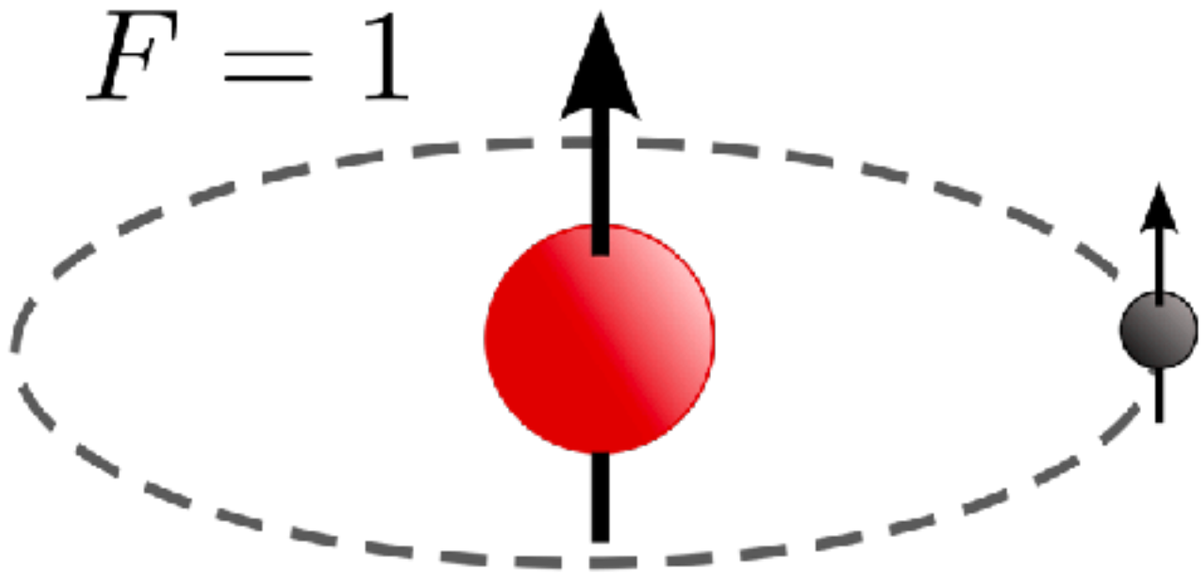
Netherlands. June, 1941.

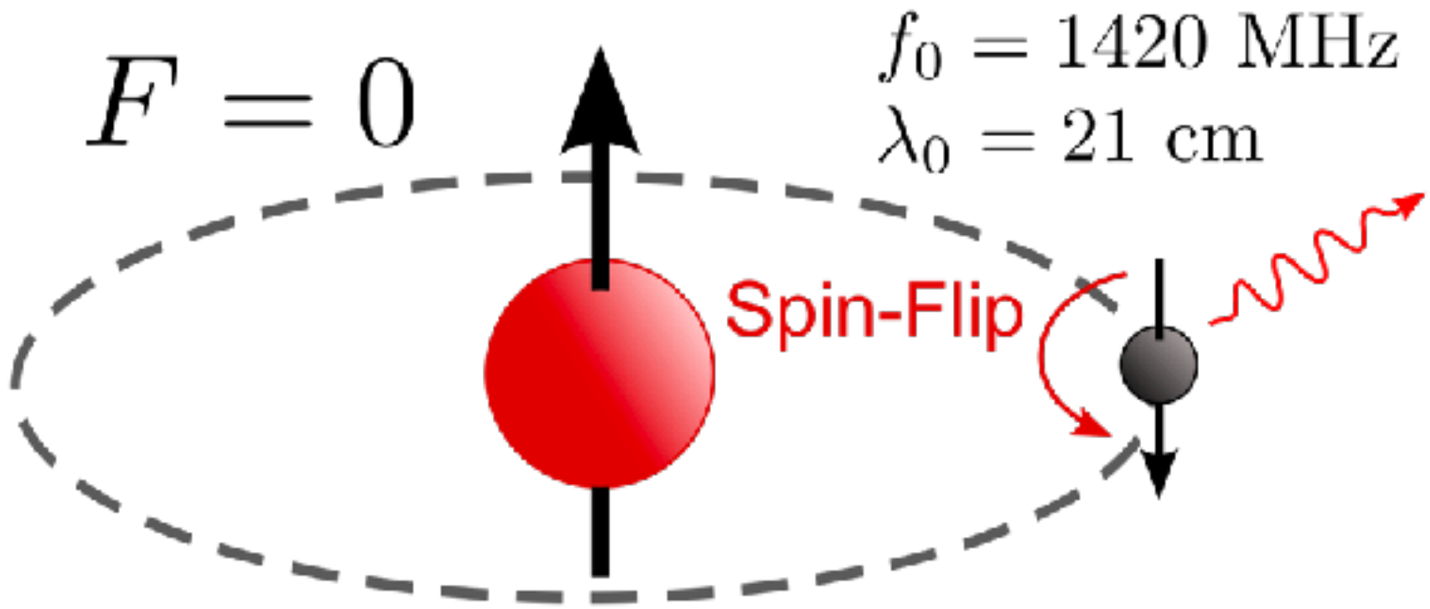
Photo: Nationaal Archief

Juan D. Soler (IAPS, Rome)

Hyperfine transition of neutral hydrogen

Origin of the radio waves from space. H.C. Van de Hulst (1945)





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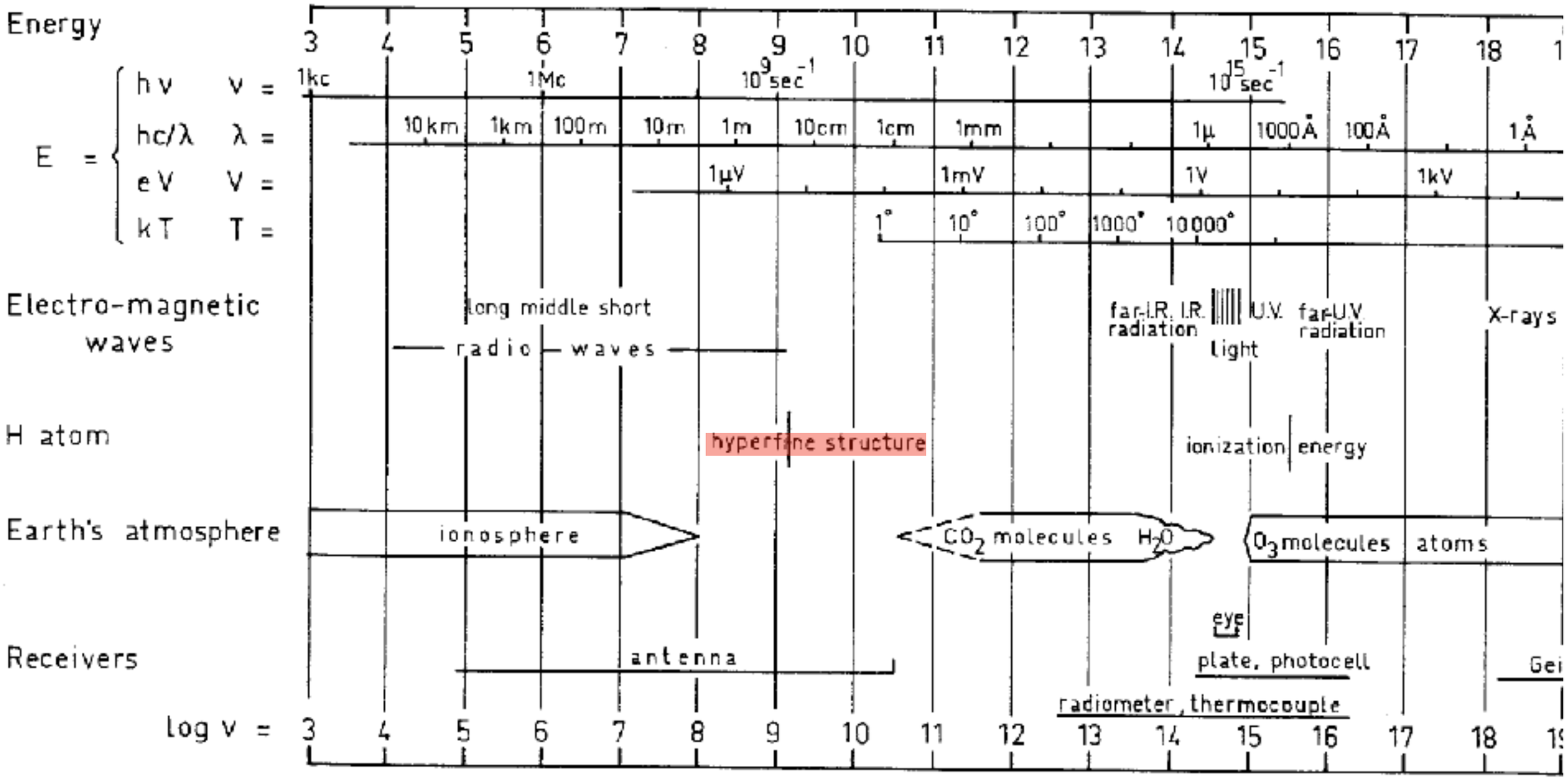


Atomic hydrogen emission

Harold Ewen y Edward Purcell.
Lyman Laboratory - Harvard University. March, 1951

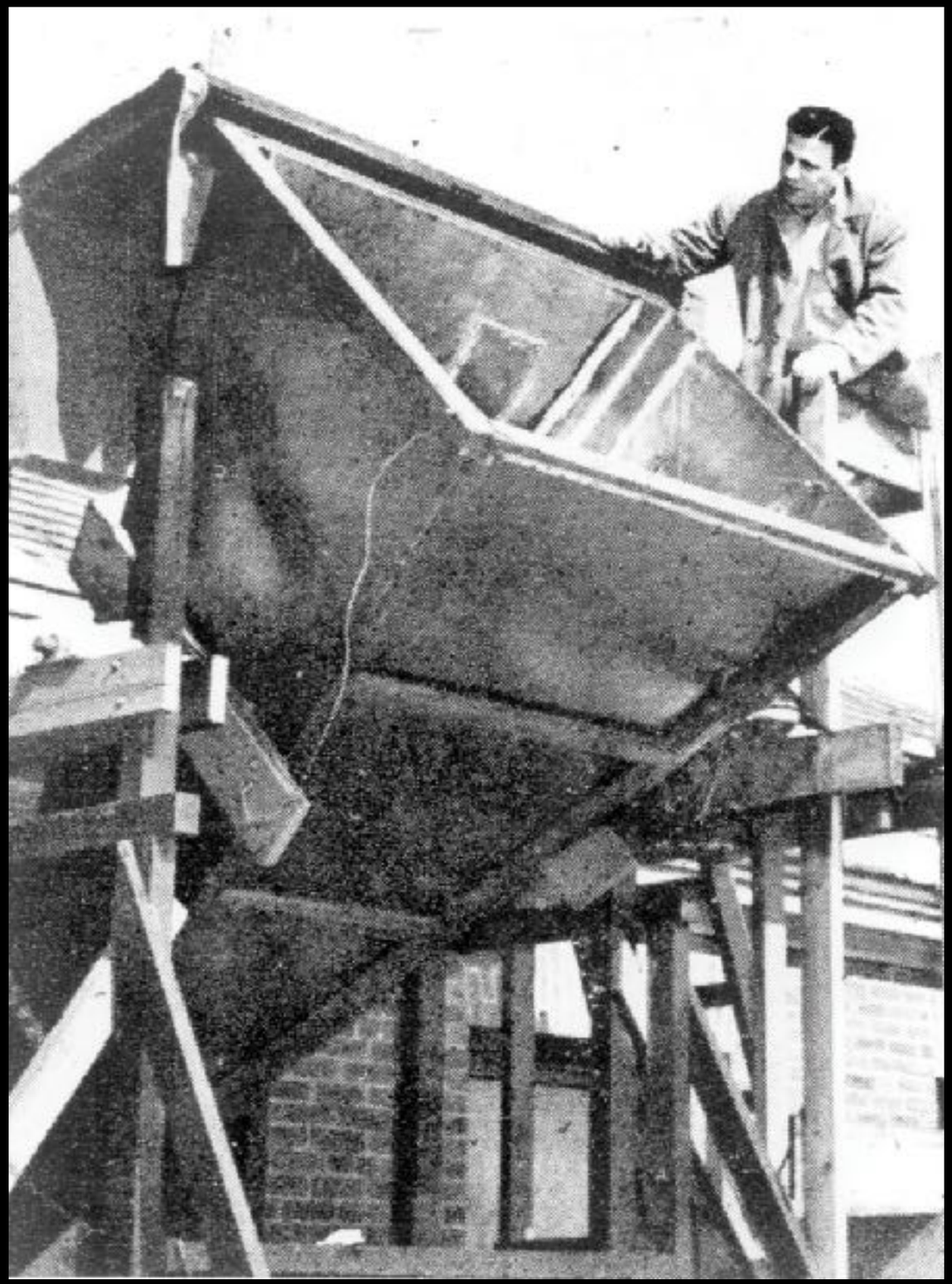


Photo: NRAO

Atomic hydrogen emission

Würzburg radar antenna (7.5 m)

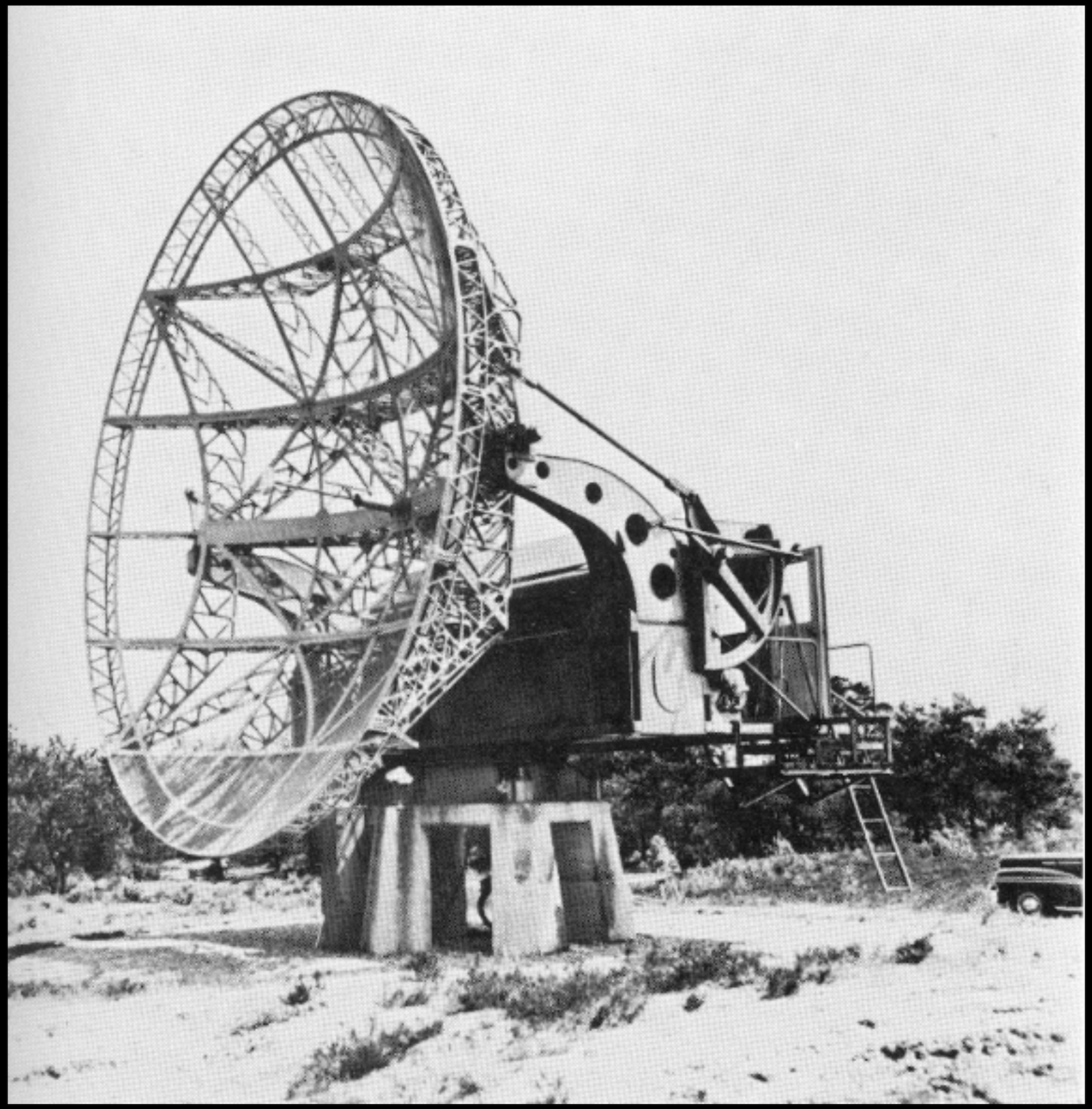
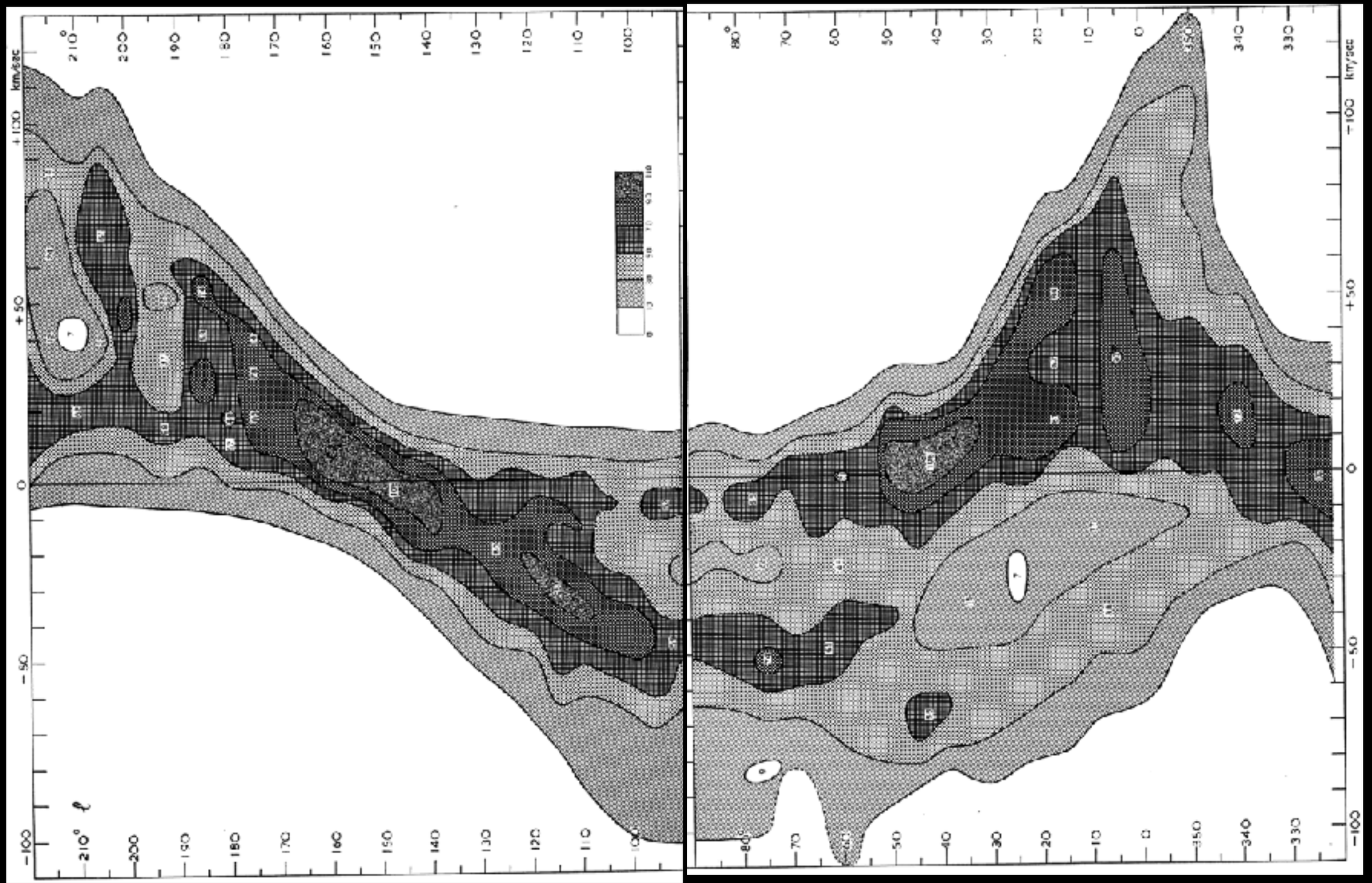


Photo: Leiden Observatory

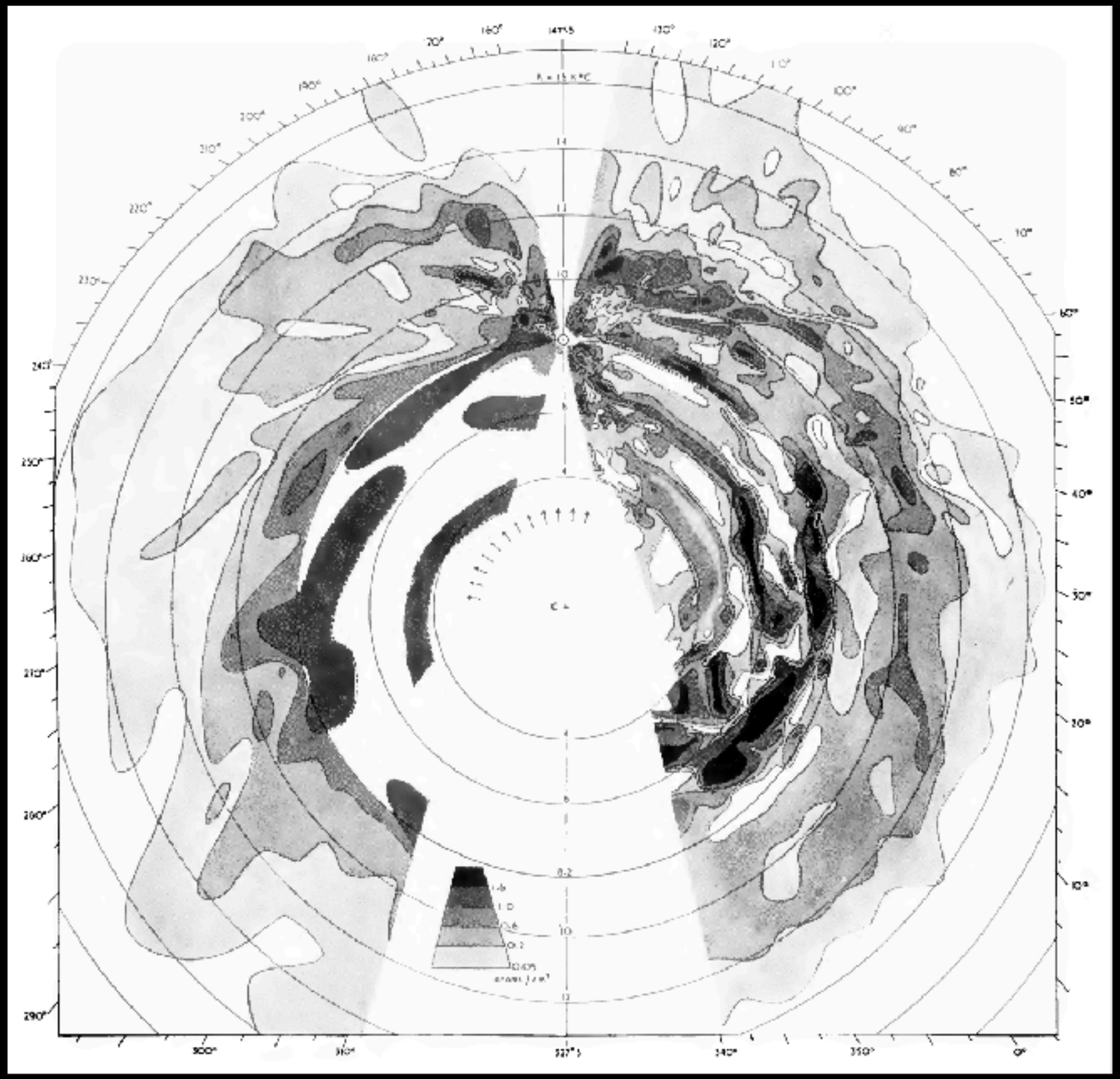
Atomic hydrogen emission toward the Milky Way

van de Hulst, Muller & Oort (1954).



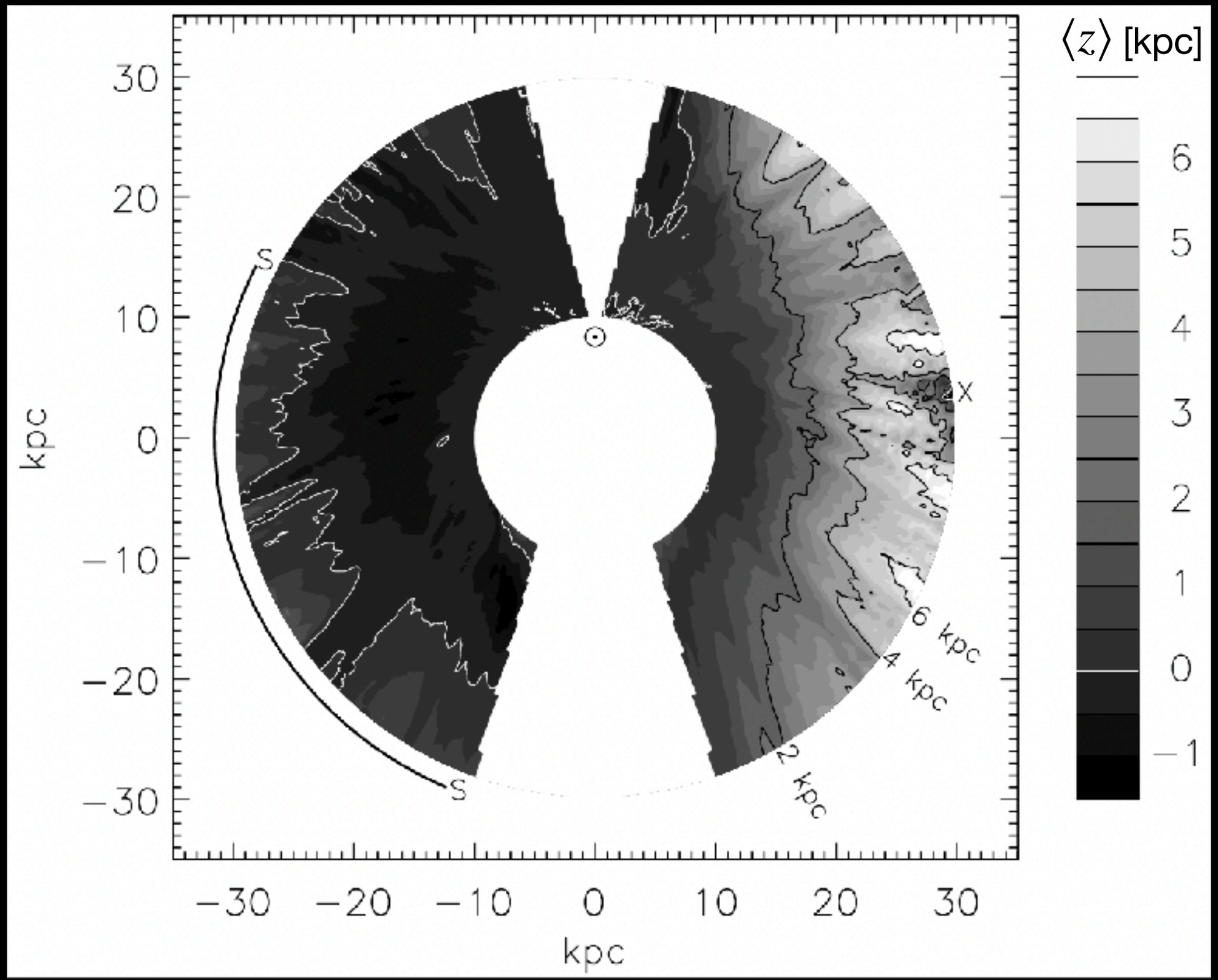
Atomic hydrogen emission toward the Milky Way

Oort,; Kerr & Westerhout (1958)



HI highlights: 1. Galactic disk warp and flaring

Levine, Blitz & Heiles (2006).



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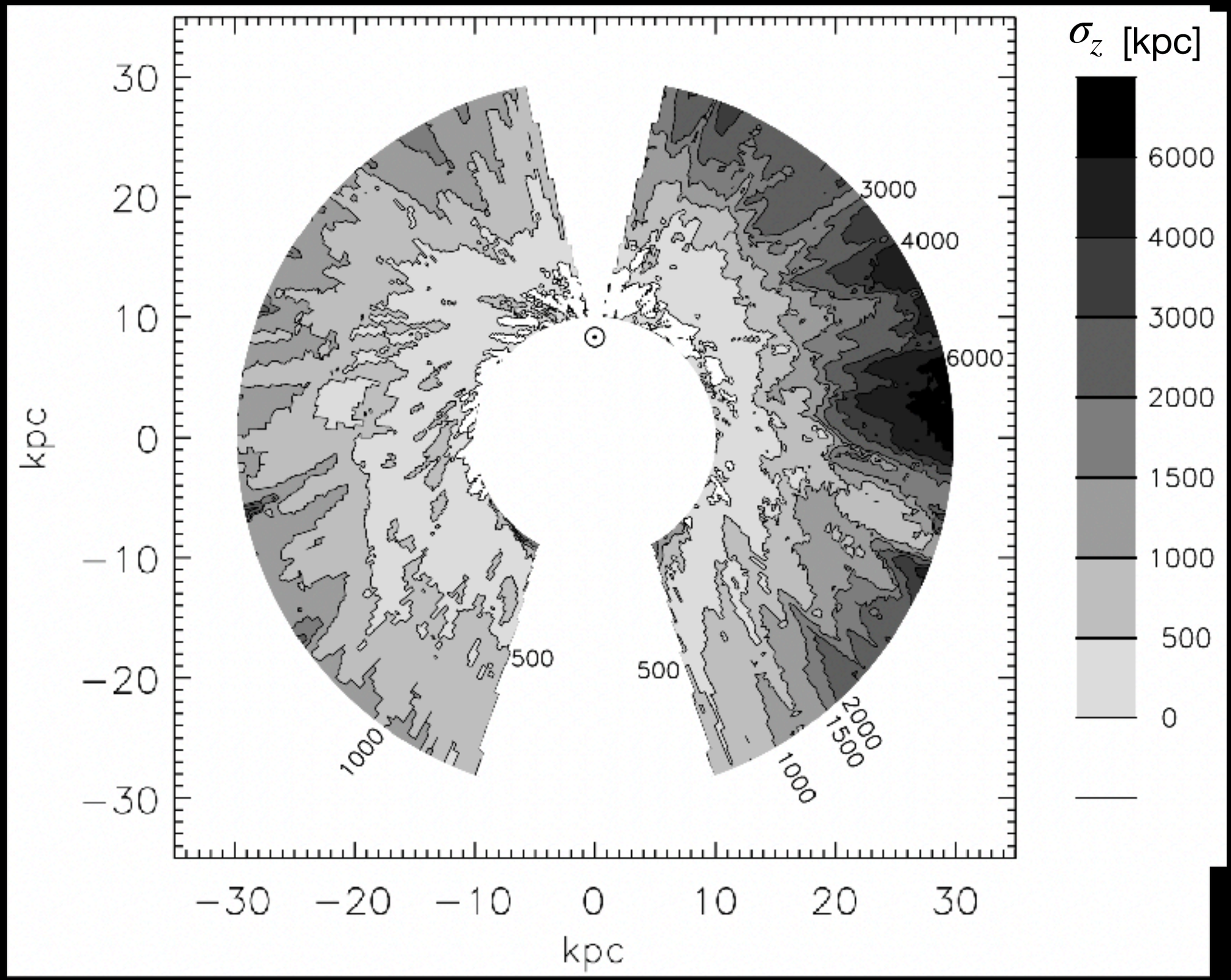
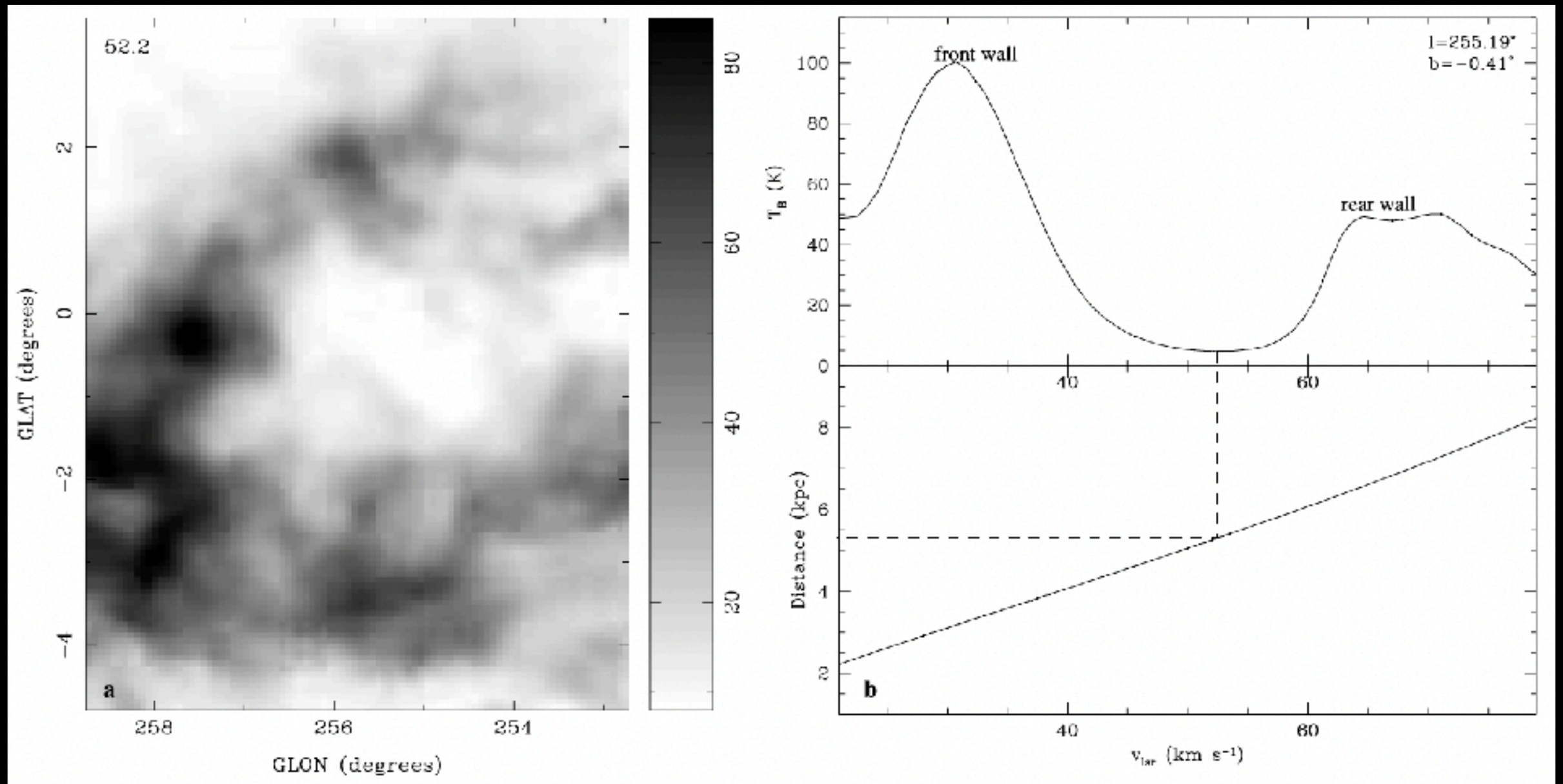


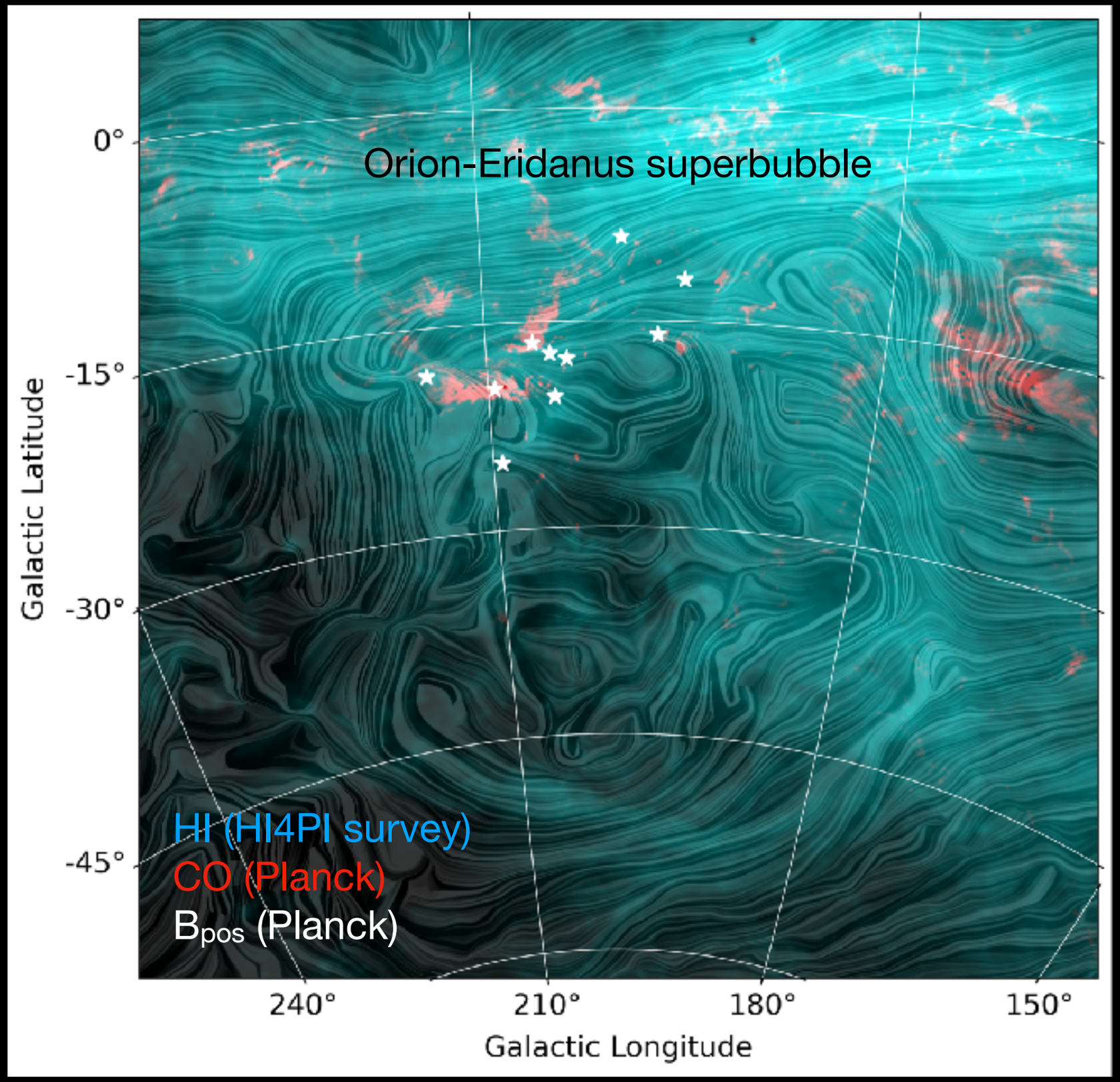
HI highlights: 2. Shells and supershells

Heiles (1984); McClure-Griffiths et al. (2006).



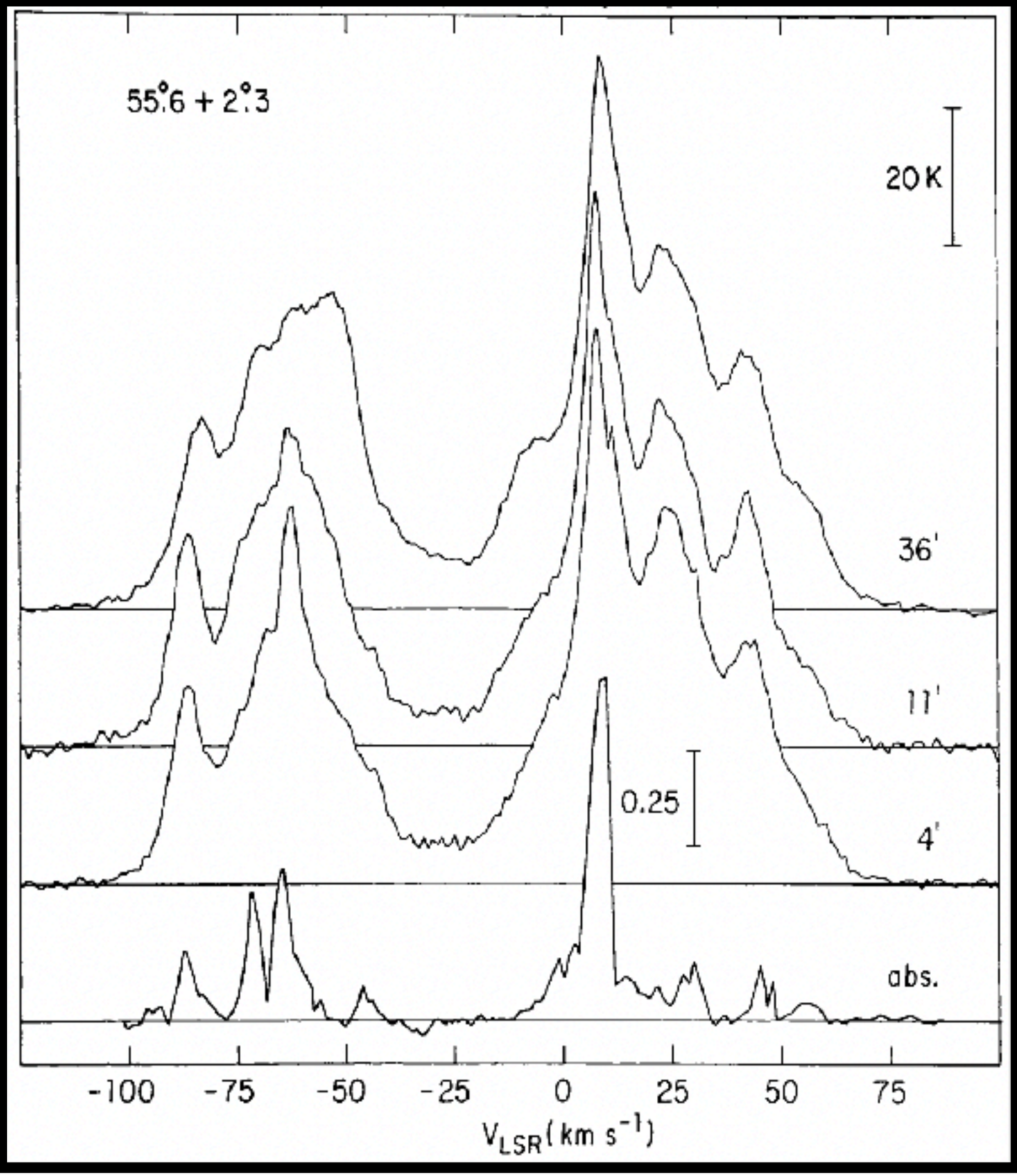
HI highlights: 2. Shells and supershells

Soler, Bracco & Pon (2018).



HI highlights: 3. Cold and warm neutral medium

Dickey & Lockman (1990) ;Heeschen (1955).



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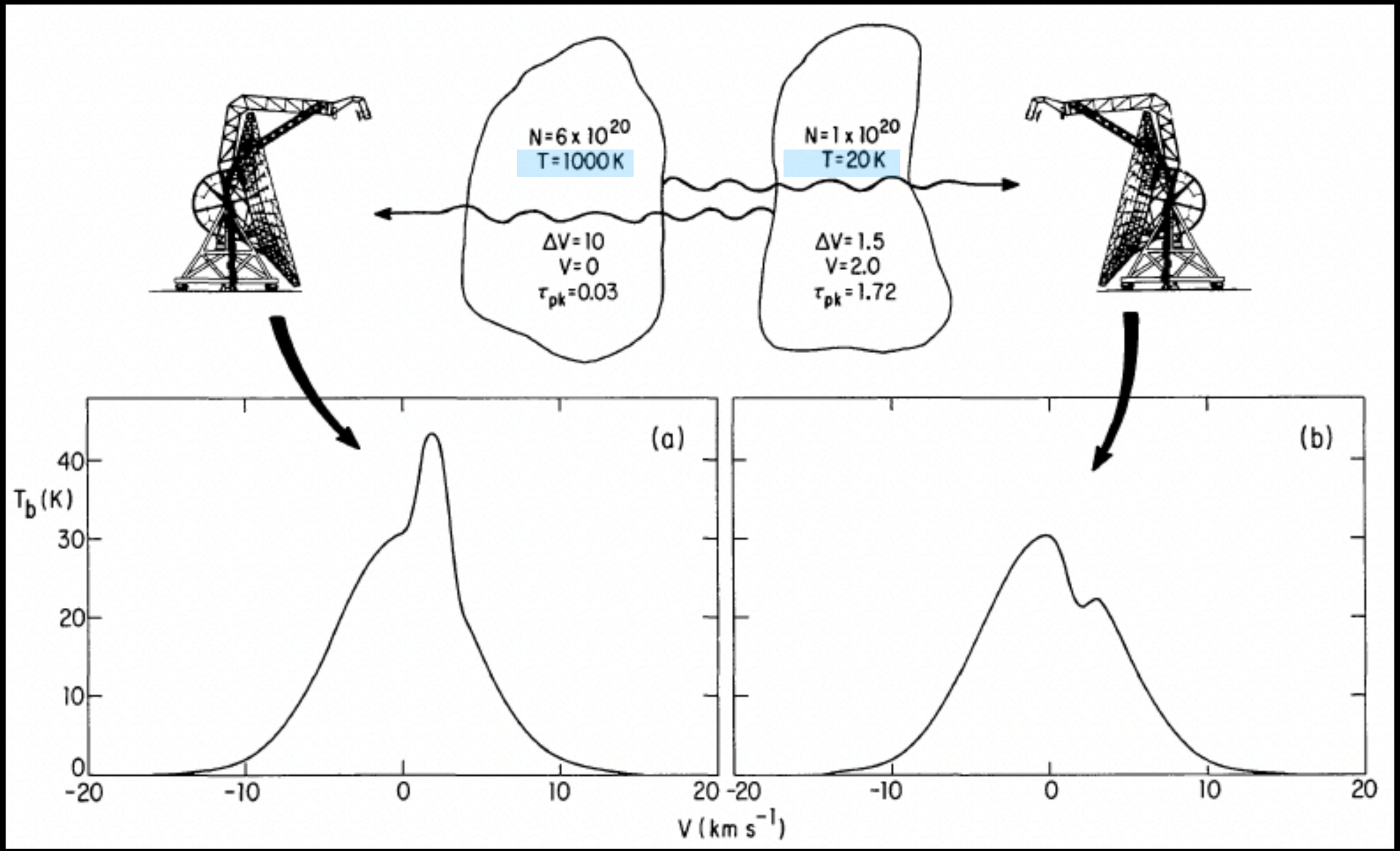
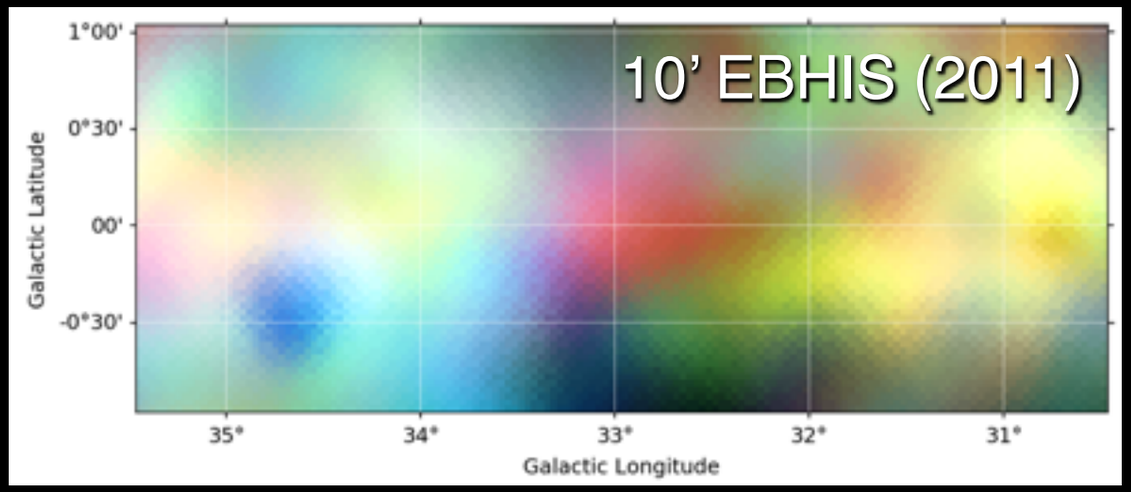


Atomic hydrogen emission toward the Milky Way

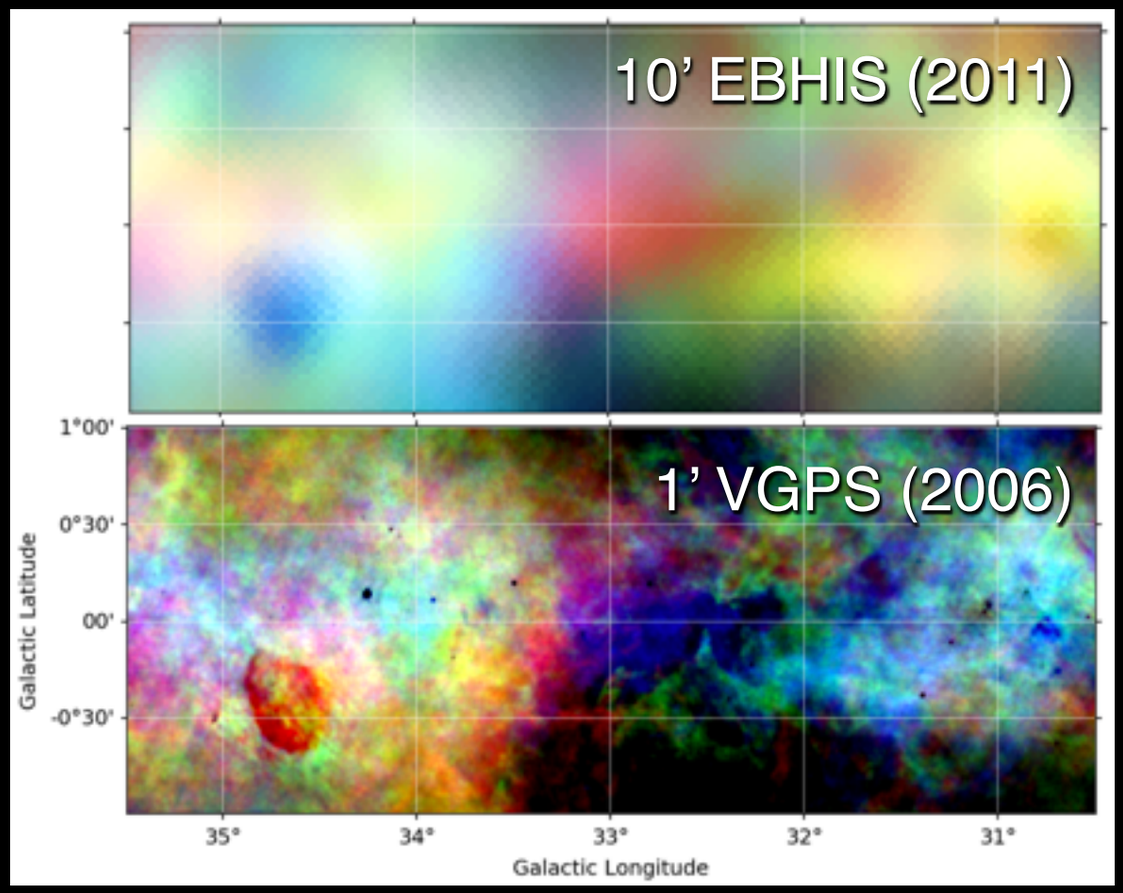
The Effelsberg-Bonn HI Survey (EBHIS)
Kerp et al. 2011



Effelsberg 100-m Telescope

Atomic hydrogen emission toward the Milky Way

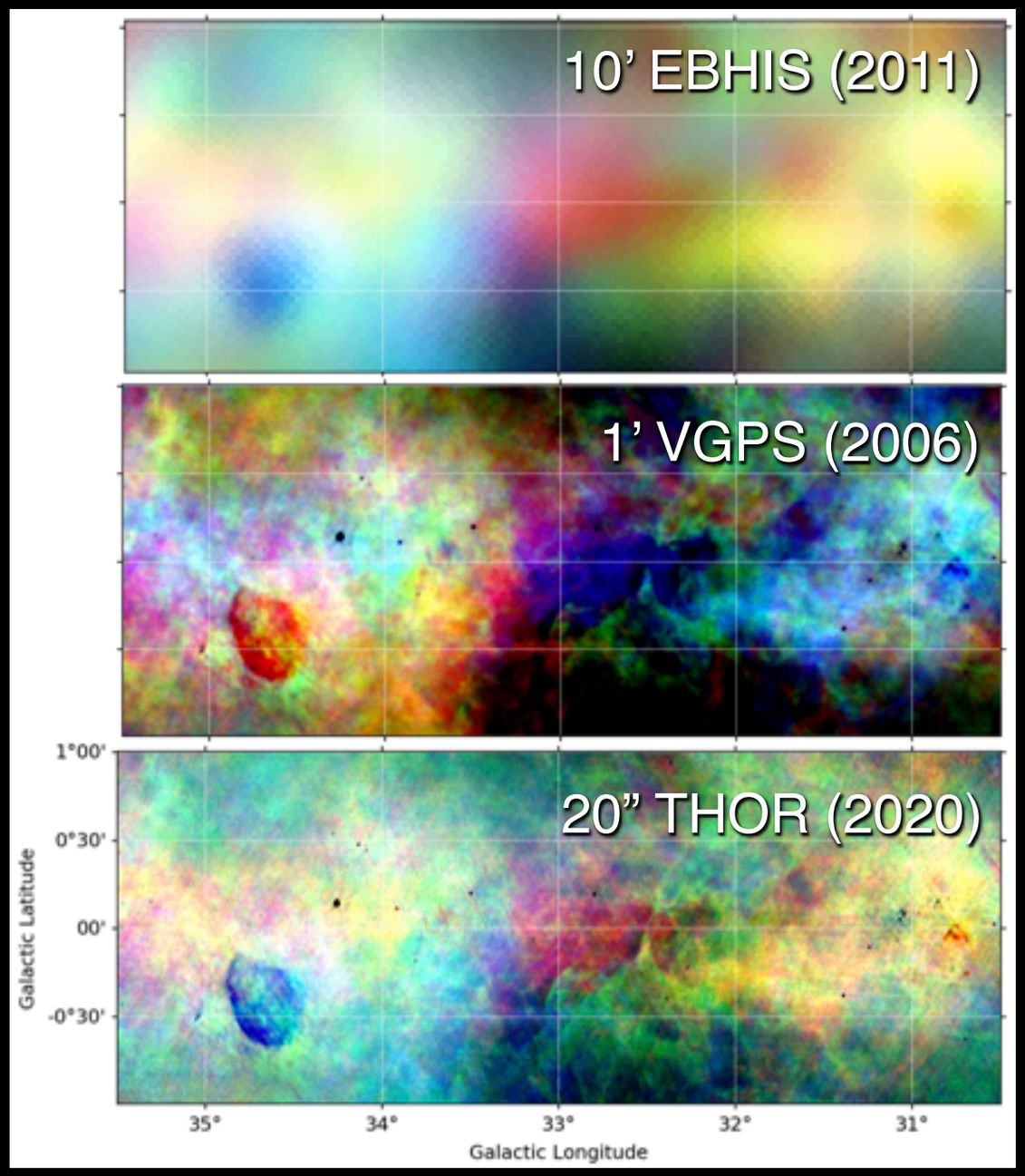
VLA Galactic Plane Survey (VGPS)
Stil et al. 2006



Jansky Very Large Array (VLA)

Atomic hydrogen emission toward the Milky Way

The HI, OH, and Recombination-line (THOR) survey
Beuther, JDS et al., 2016
Wang, JDS, et al., 2020.



Jansky Very Large Array (VLA)

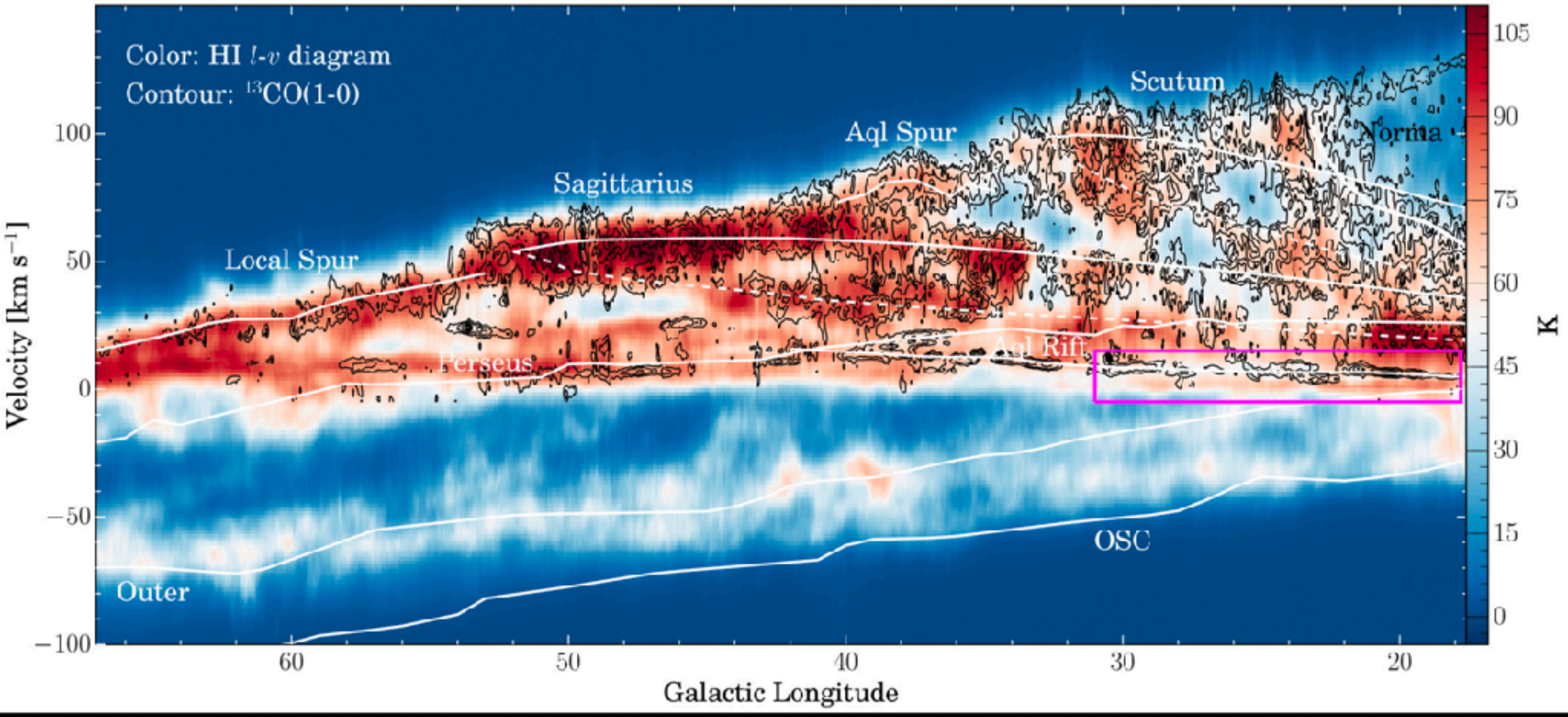
The HI, OH, and Recombination-line (THOR) survey

Wang, Y., et al. A&A 2020.

Video: J.D. Soler & T. Müller

Atomic hydrogen emission toward the Milky Way

Wang, Y., Beuther, H. et al (including JDS). A&A (2020)

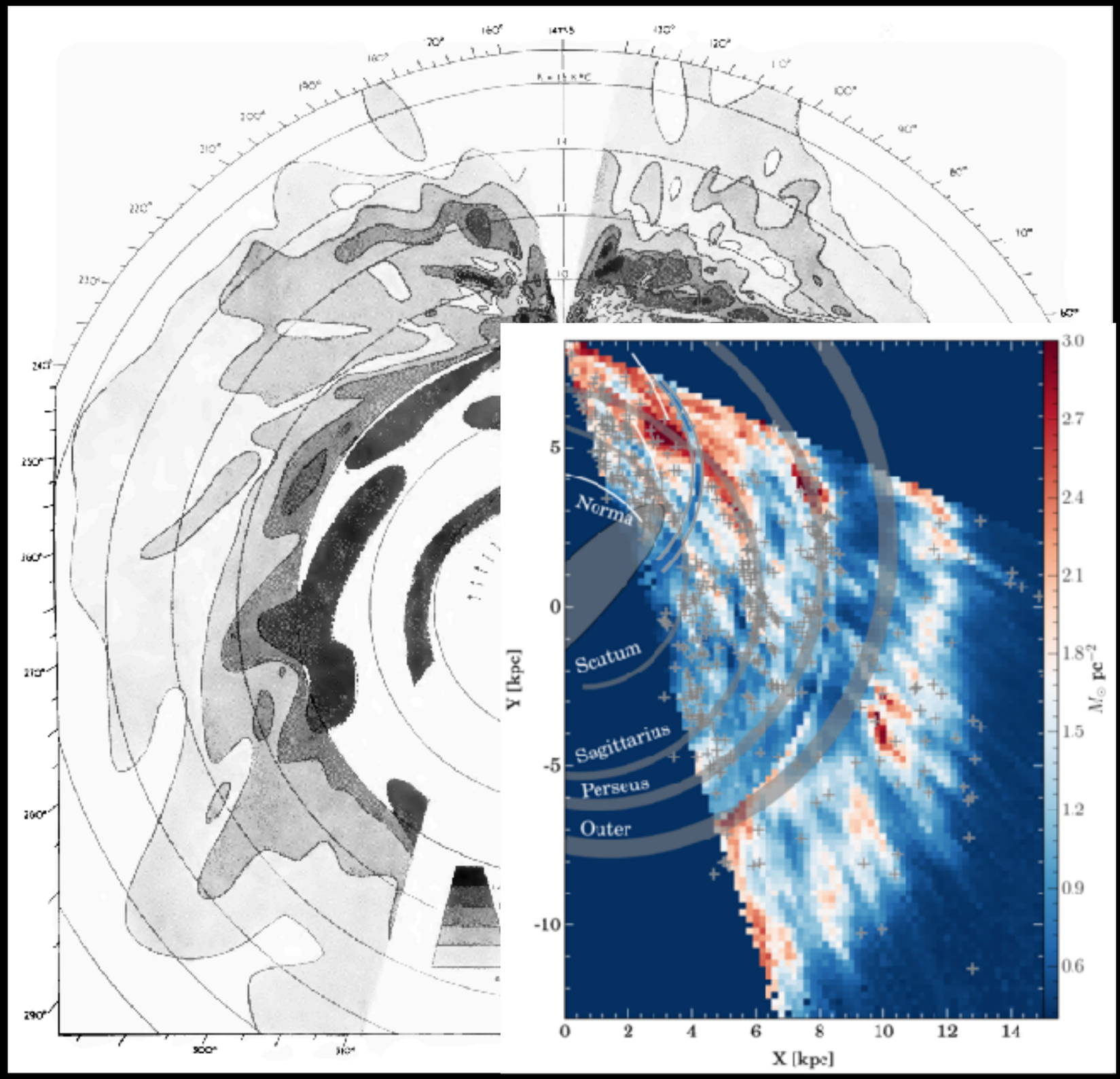


Spiral arm model: Reid et al. 2016

Juan D. Soler (IAPS, Rome)

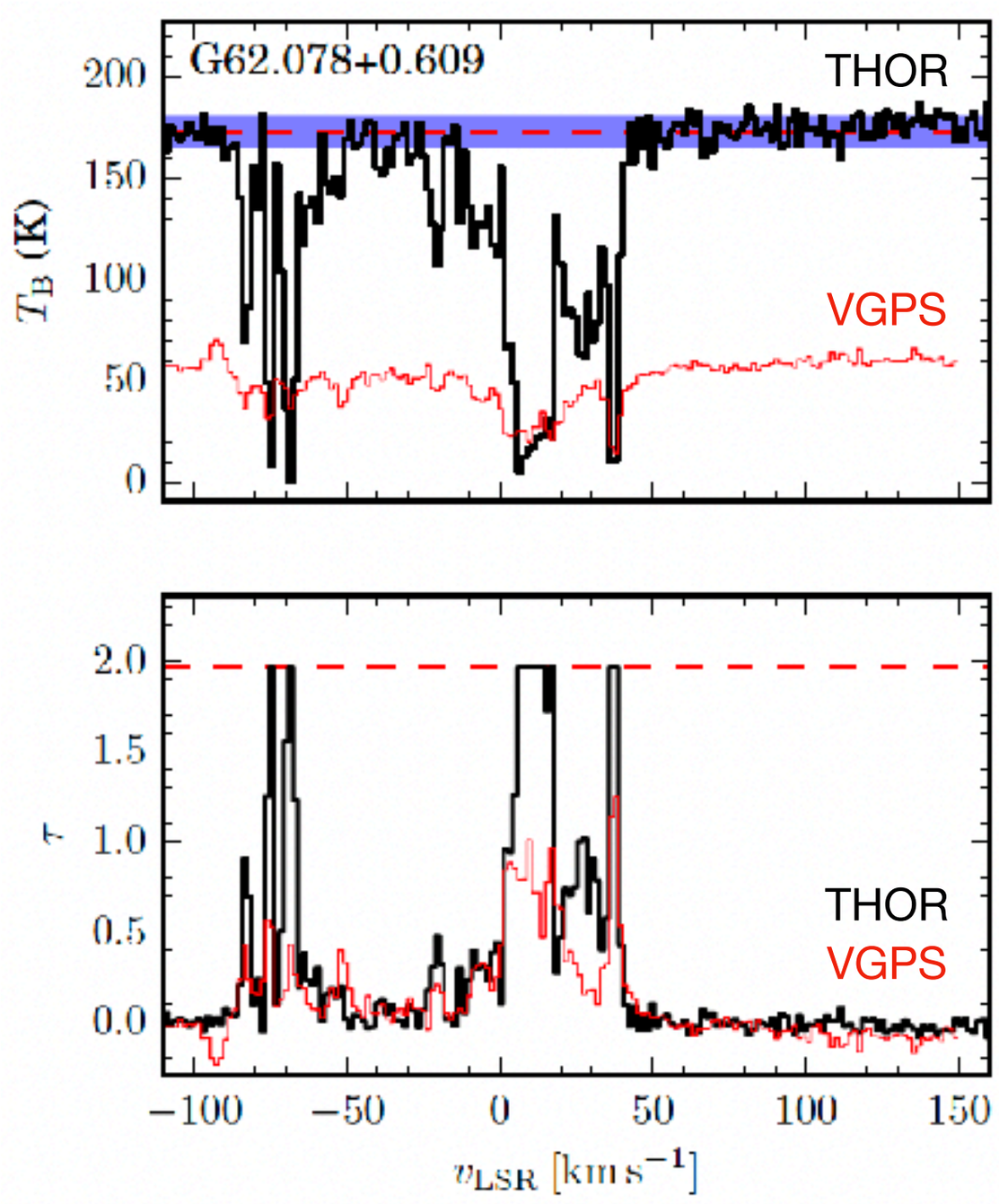
Atomic hydrogen emission toward the Milky Way

Wang, Y., Beuther, H. et al (including JDS). A&A (2020)

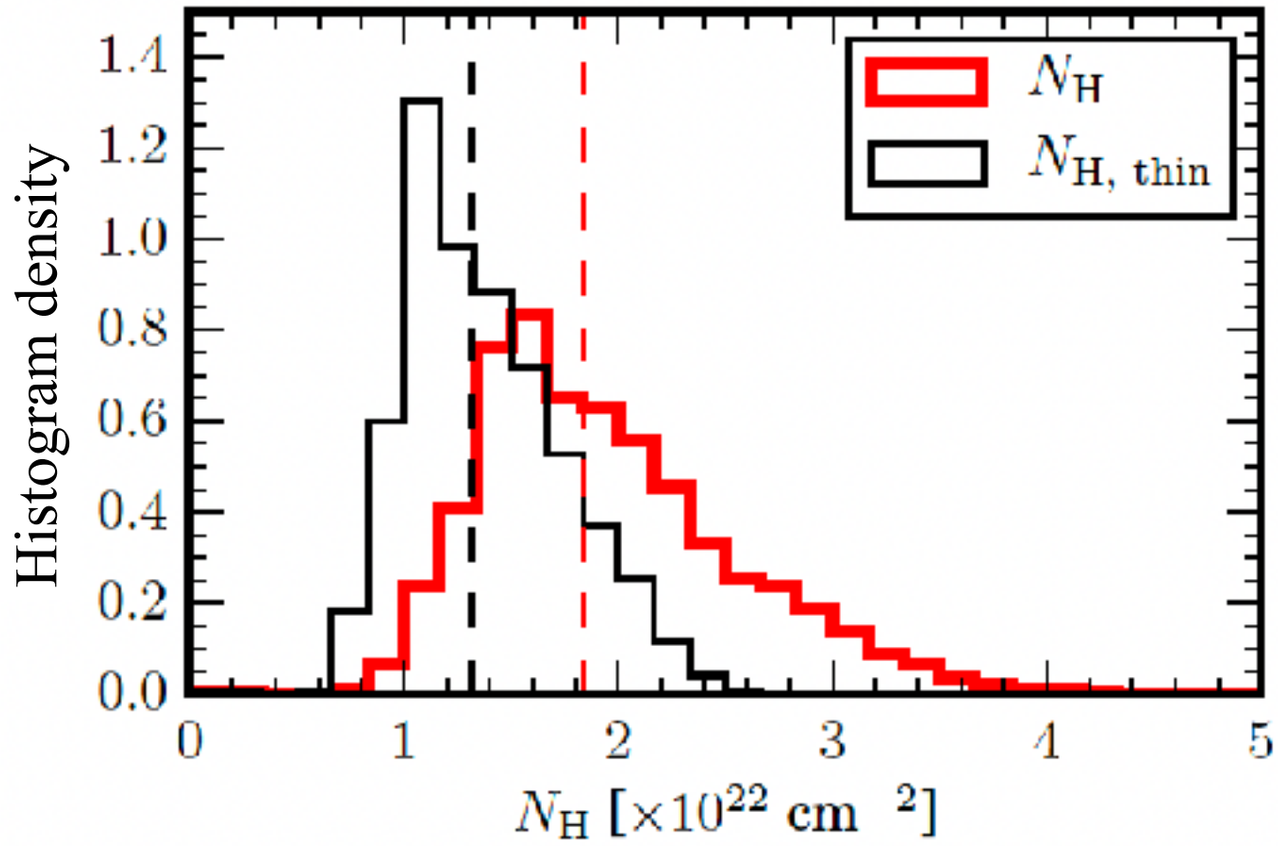


Mass of Galactic hydrogen

Wang, Y., Beuther, H. et al (including JDS). A&A (2020)

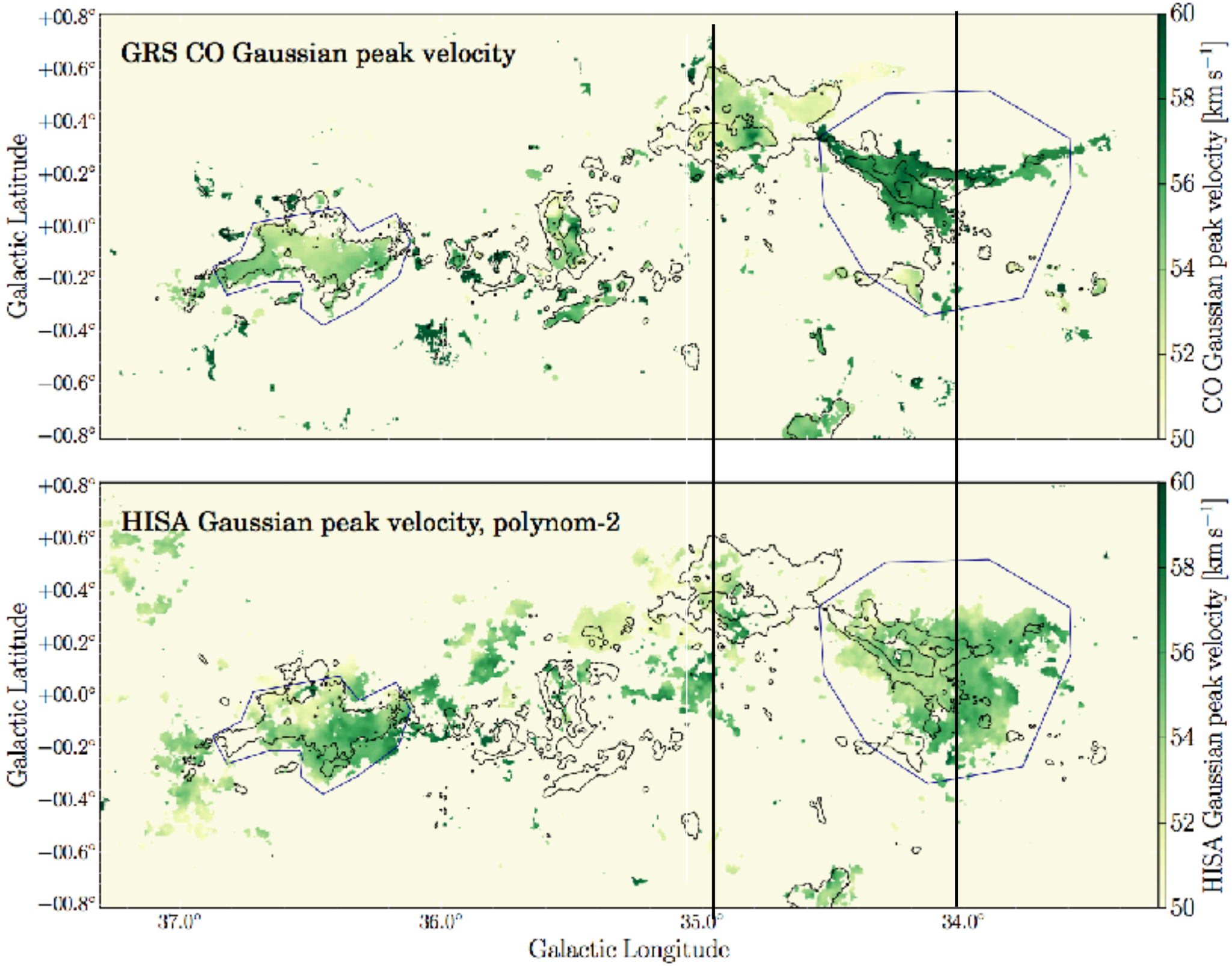


$$M_{\rm HI} \approx 9.4 \times 10^9 M_\odot$$



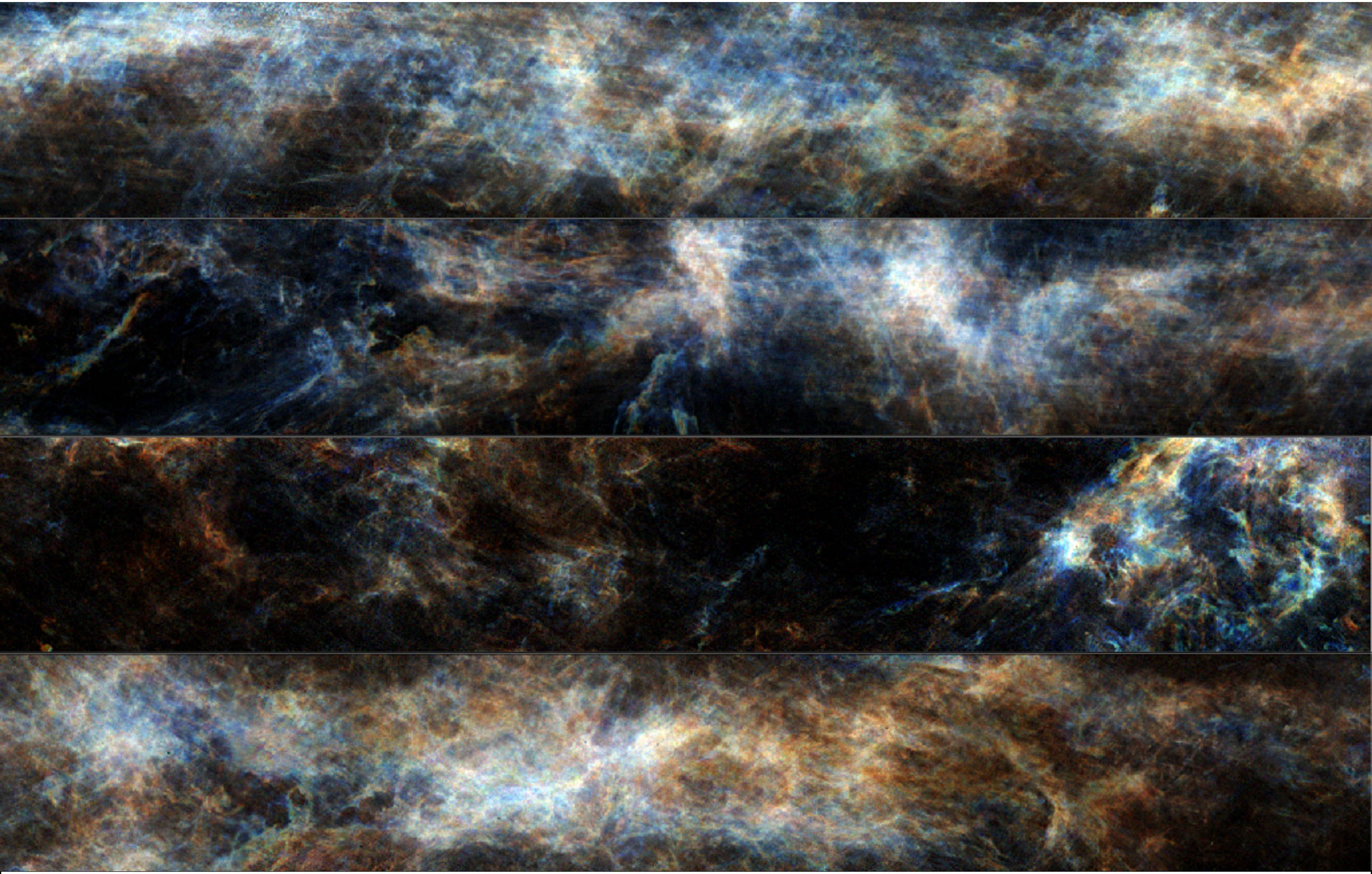
HISA and ^{13}CO

Wang, Y., Beuther, H. et al (including JDS). A&A (2020)



Atomic hydrogen clouds

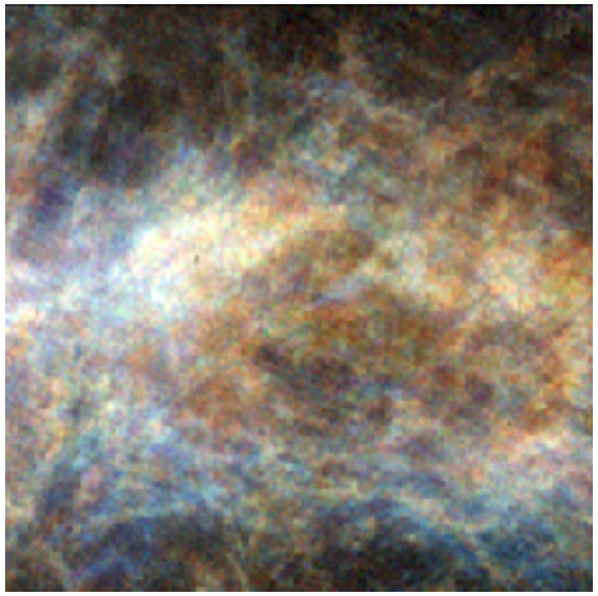
J.D. Soler; THOR collaboration



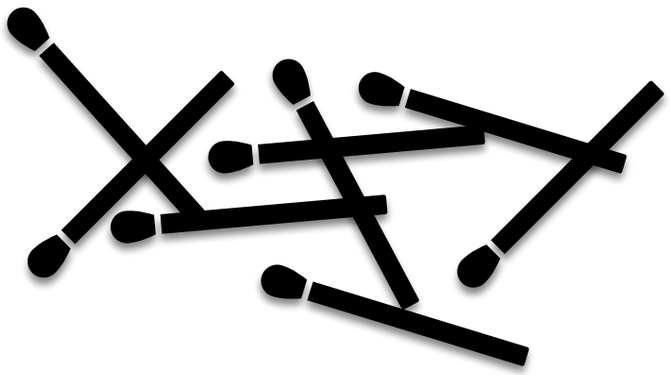
Data-driven analysis

Soler, J.D. et al. A&A (2020)

Observations



Characteristics

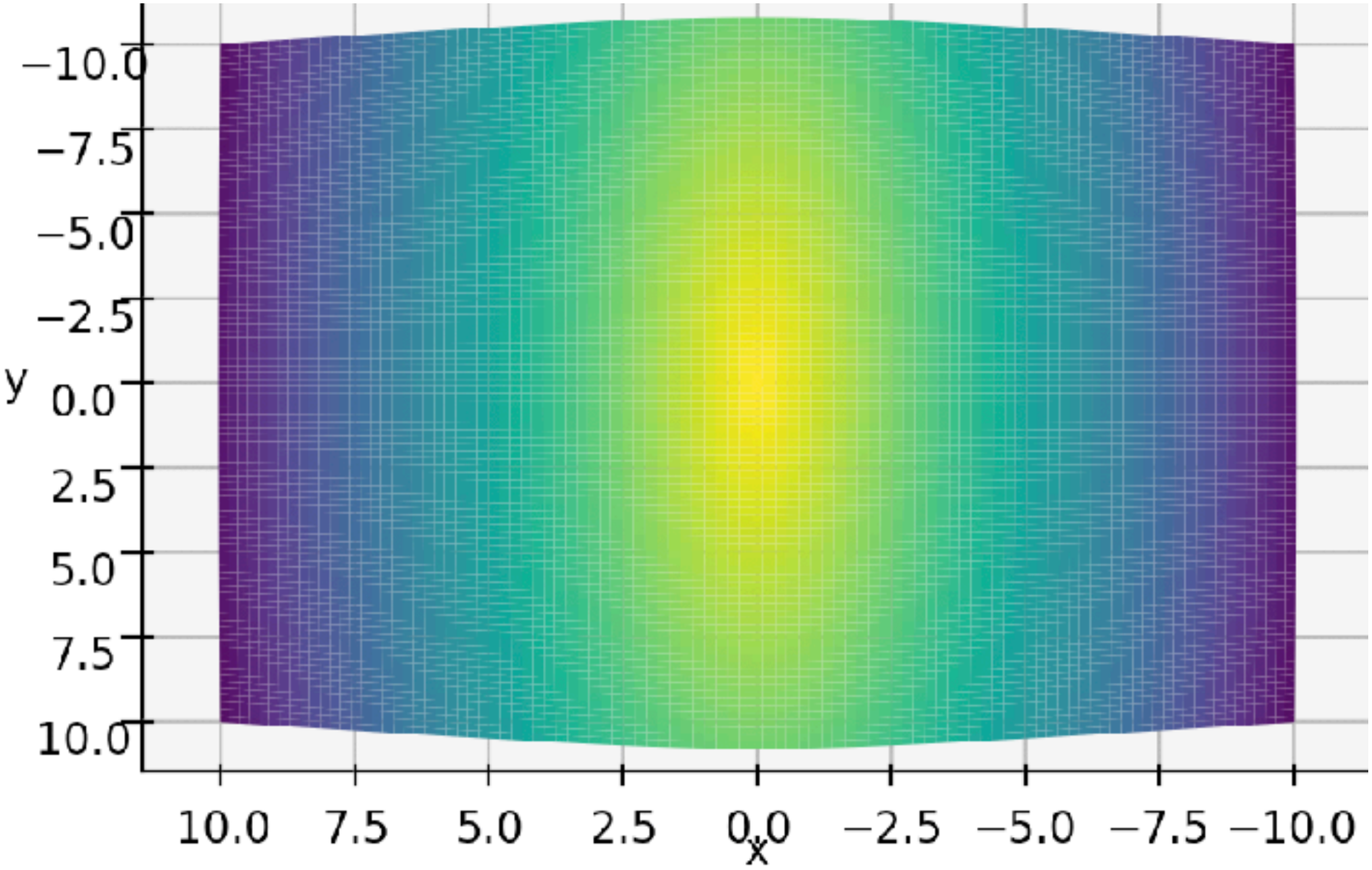


Families of models

Machine vision: Hessian matrix method

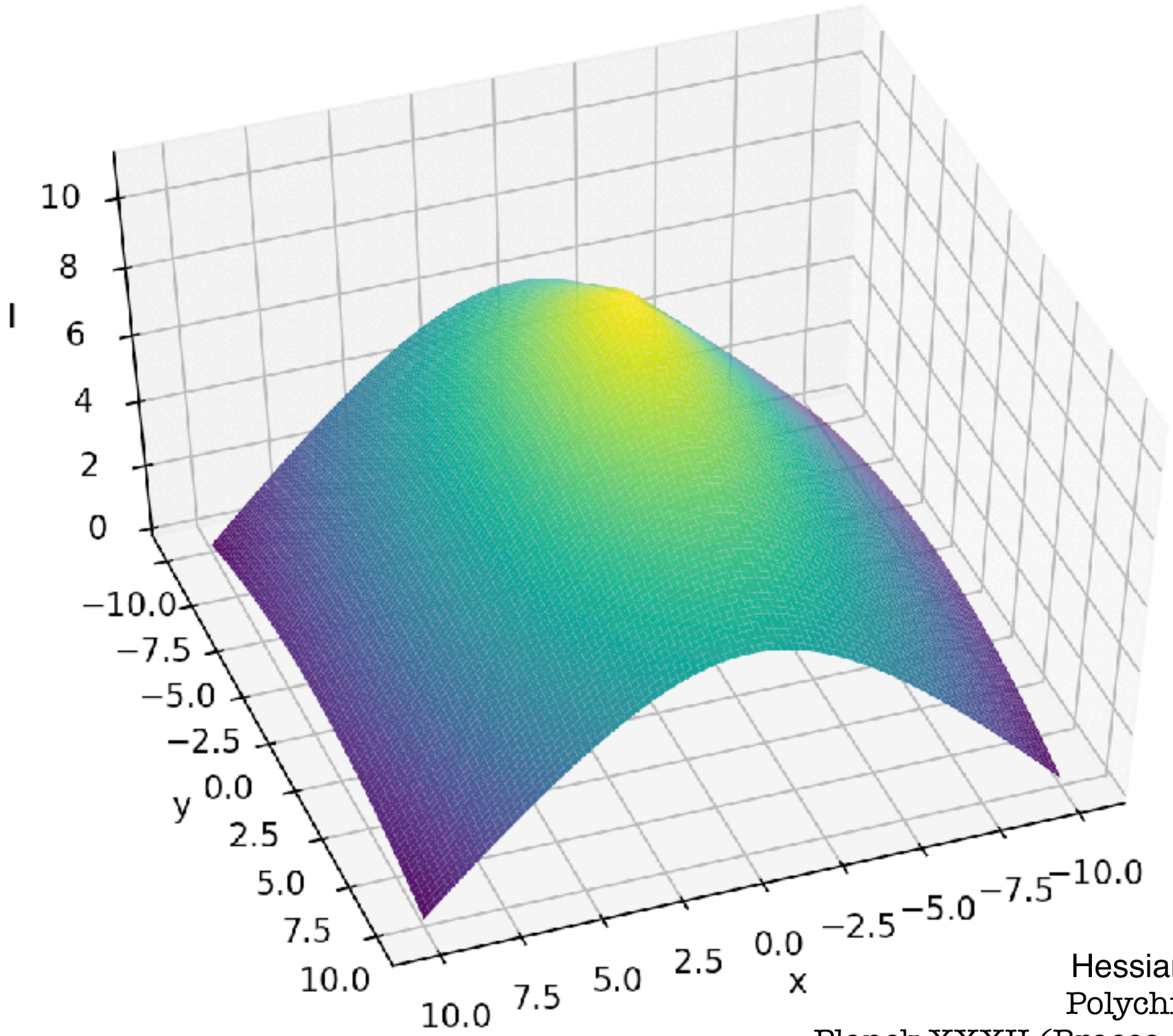
Soler, J.D. et al. A&A. 2020

Polychroni et al. 2013
Planck XXXII (Bracco, A. et al.), 2016



Machine vision: Hessian matrix method

Soler, J.D. et al. A&A. 2020



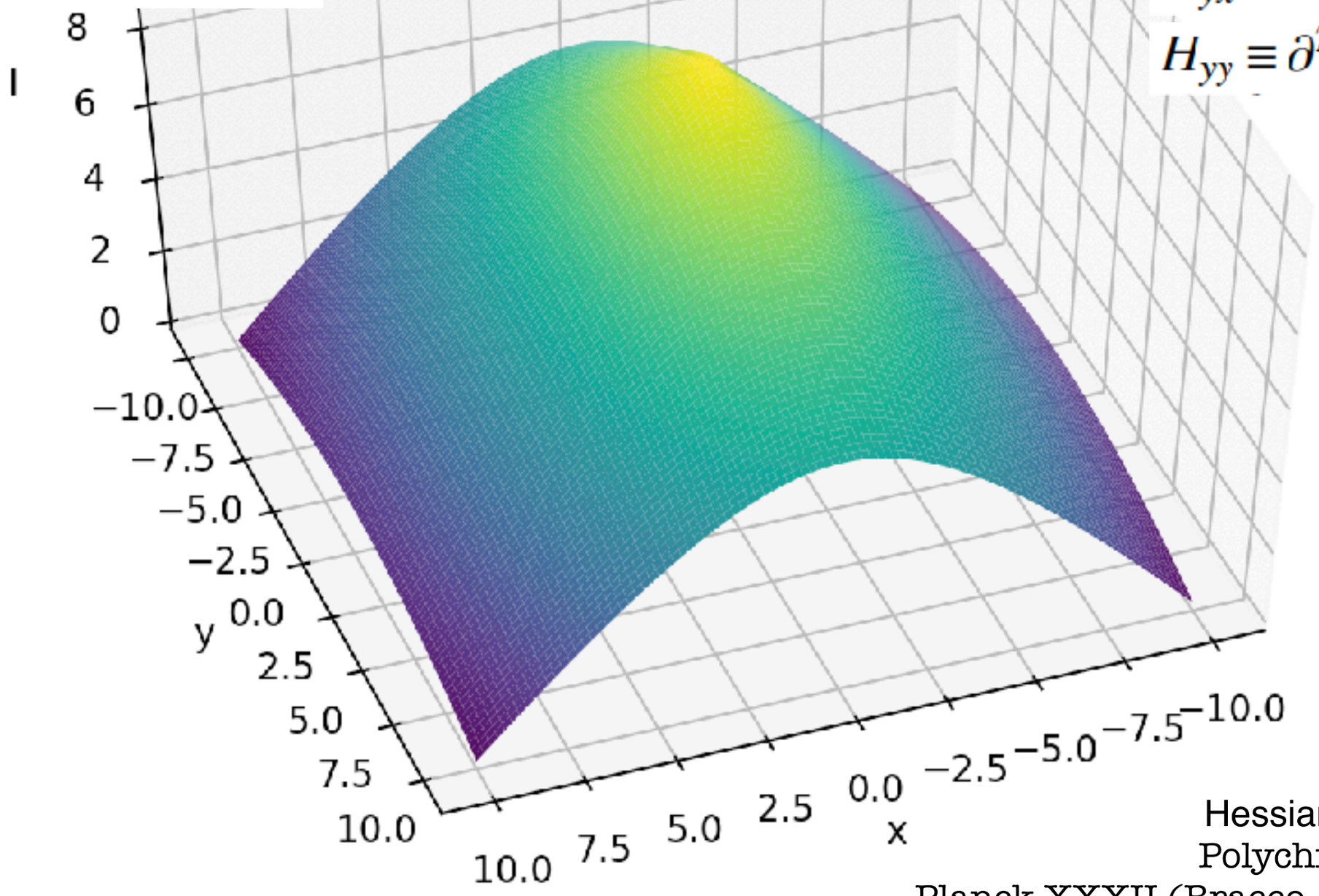
Hessian matrix method
Polychroni et al. 2013
Planck XXXII (Bracco, A. et al.), 2016

Machine vision: Hessian matrix method

Soler, J.D. et al. A&A. 2020

$$\mathbf{H}(x,y) \equiv \begin{bmatrix} H_{xx} & H_{xy} \\ H_{yx} & H_{yy} \end{bmatrix}$$

$$H_{xx} \equiv \partial^2 I / \partial x^2$$
$$H_{xy} \equiv \partial^2 I / \partial x \partial y$$
$$H_{yx} \equiv \partial^2 I / \partial y \partial x$$
$$H_{yy} \equiv \partial^2 I / \partial y^2$$



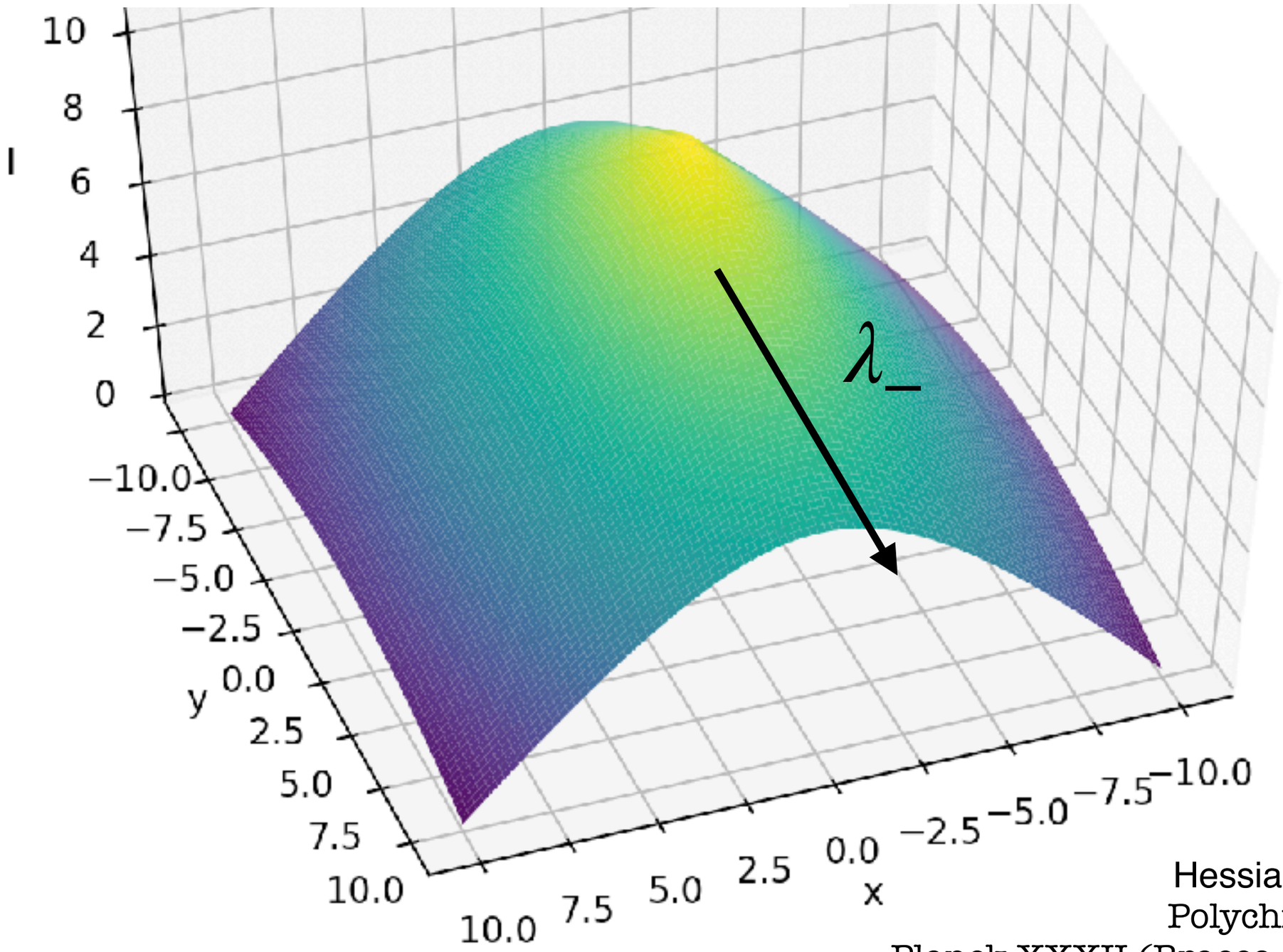
Hessian matrix method
Polychroni et al. 2013
Planck XXXII (Bracco, A. et al.), 2016

Machine vision: Hessian matrix method

Soler, J.D. et al. A&A. 2020

$$\lambda_{\pm} = \frac{(H_{xx} + H_{yy}) \pm \sqrt{(H_{xx} - H_{yy})^2 + 4H_{xy}H_{yx}}}{2}$$

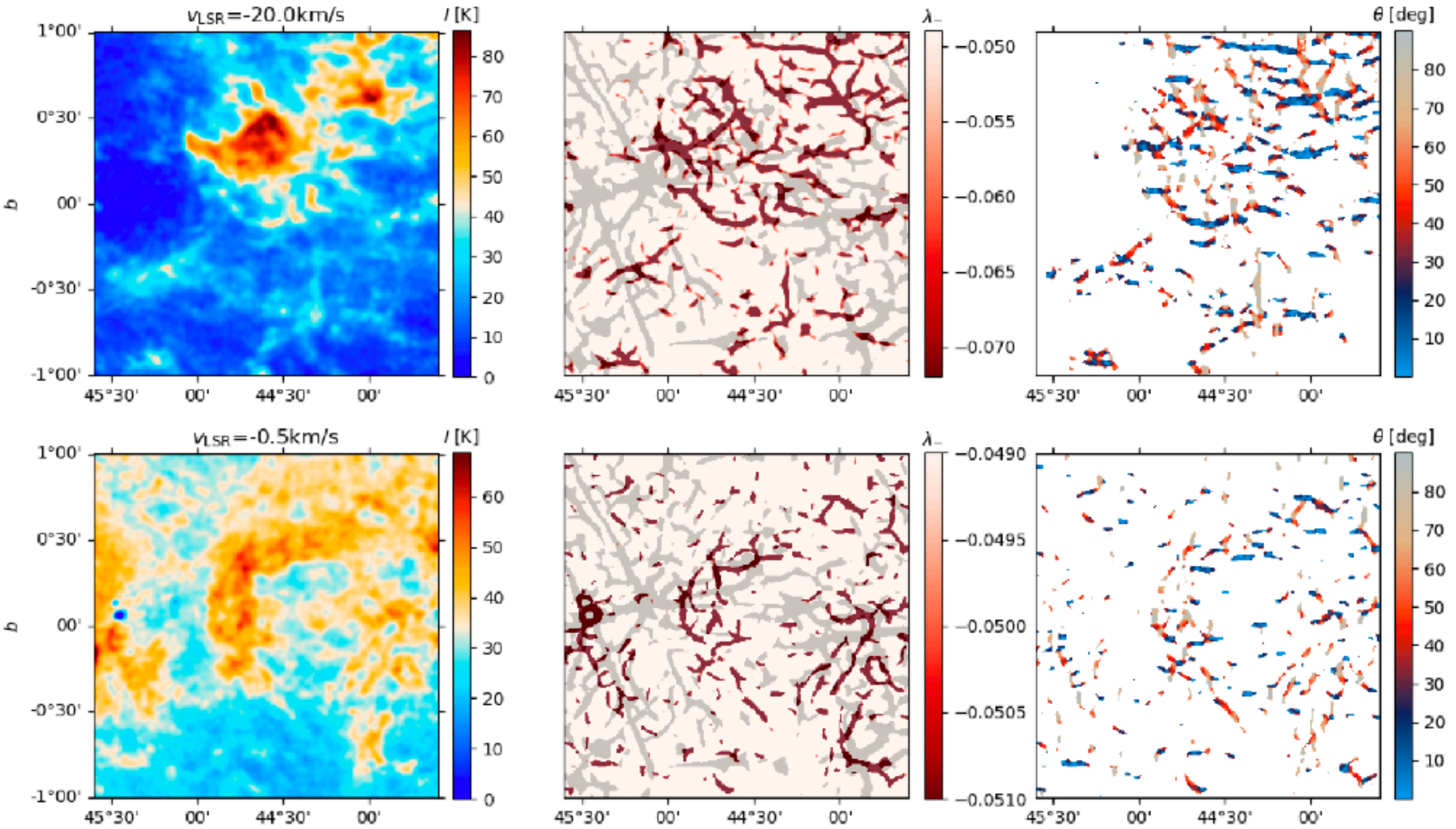
$$\theta = \frac{1}{2} \tan^{-1} \frac{H_{xy} - H_{yx}}{H_{xx} - H_{yy}}$$



Hessian matrix method
Polychroni et al. 2013
Planck XXXII (Bracco, A. et al.), 2016

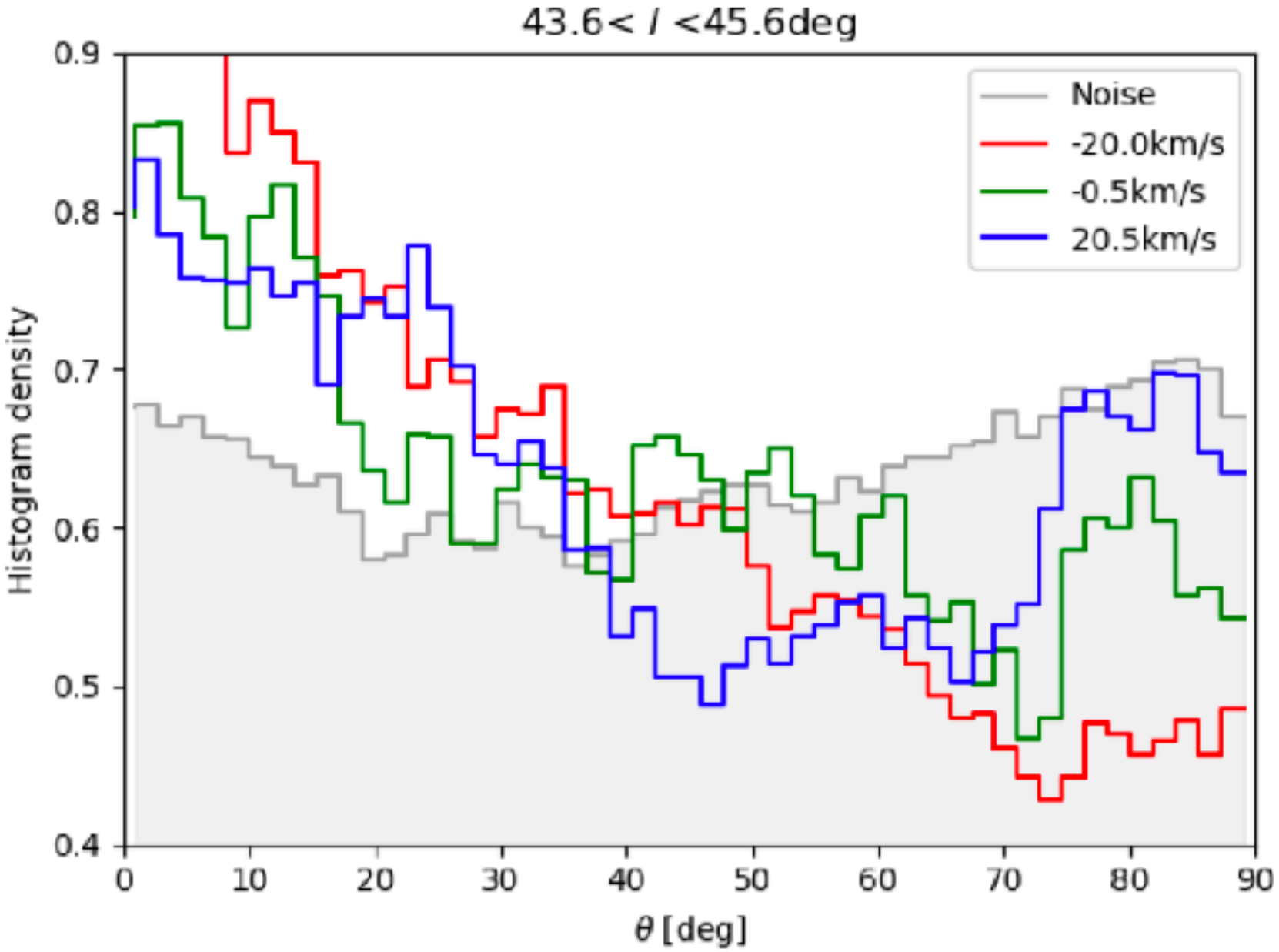
HI filaments

Soler, J.D. et al. A&A. 2020



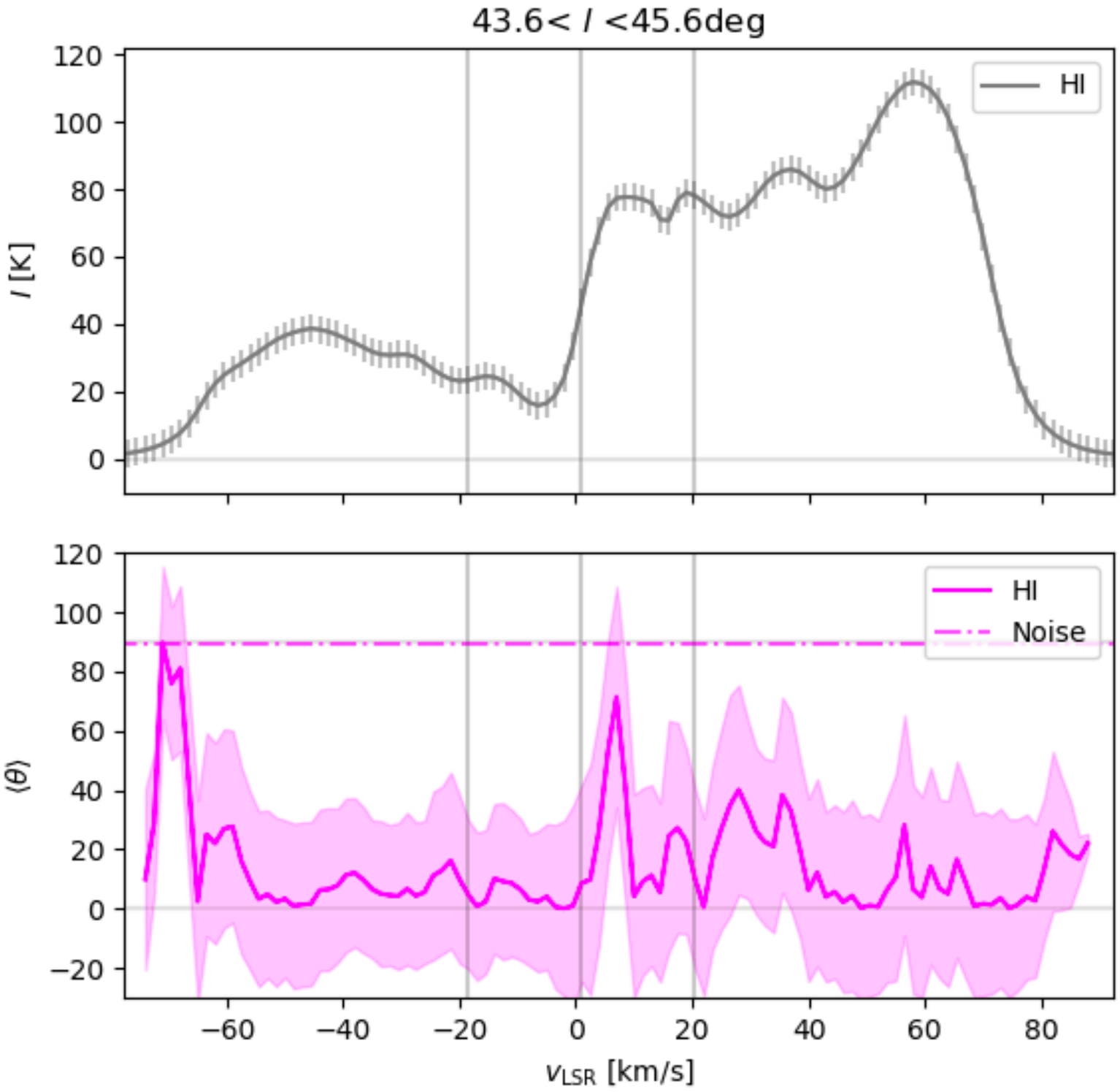
Histograms of HI filament orientation

Soler, J.D. et al. A&A. 2020



HI filament orientation

Soler, J.D. et al. A&A. 2020



HI filament orientation: random walk interpretation

Soler, J.D. et al. A&A. 2020

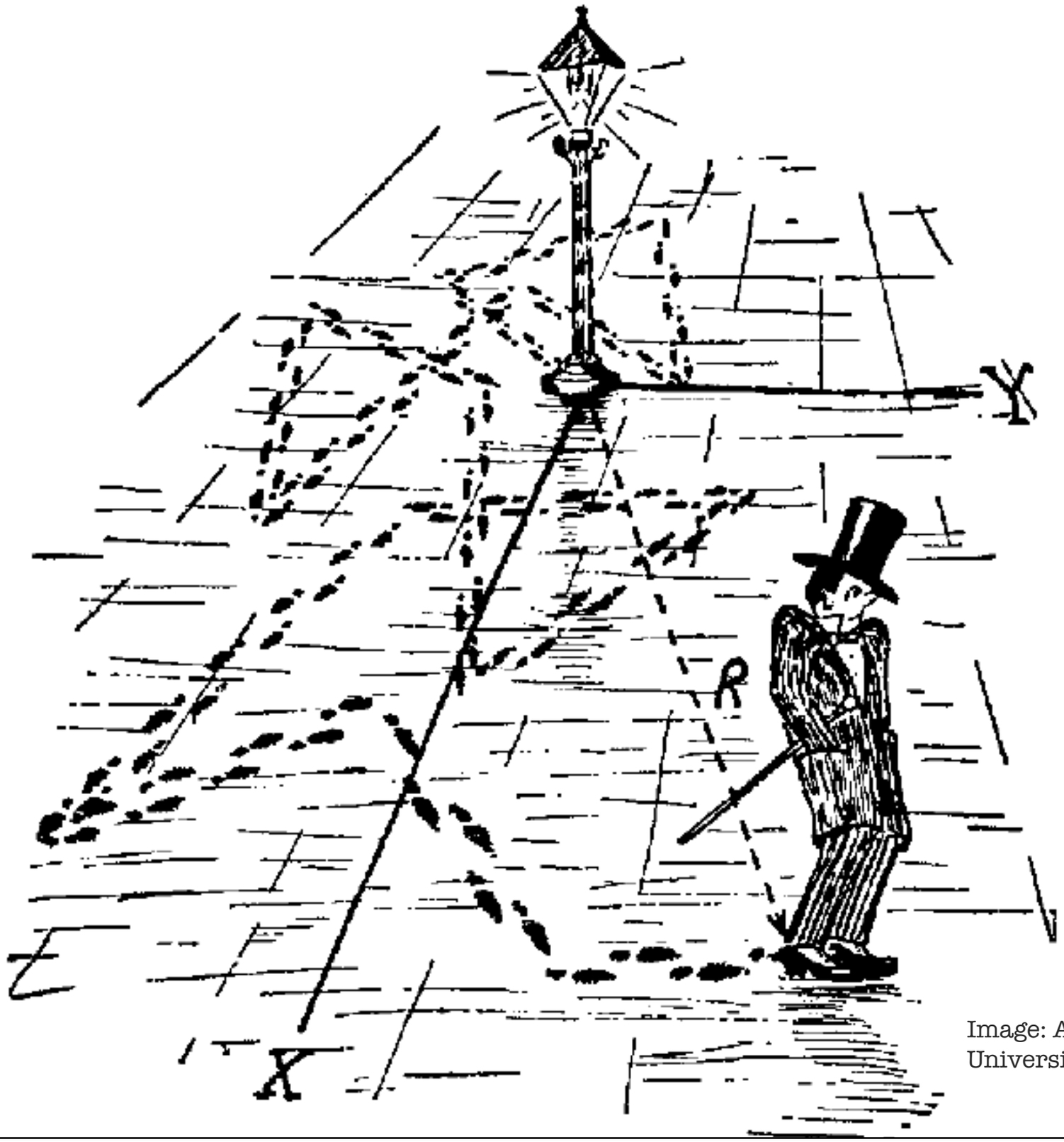
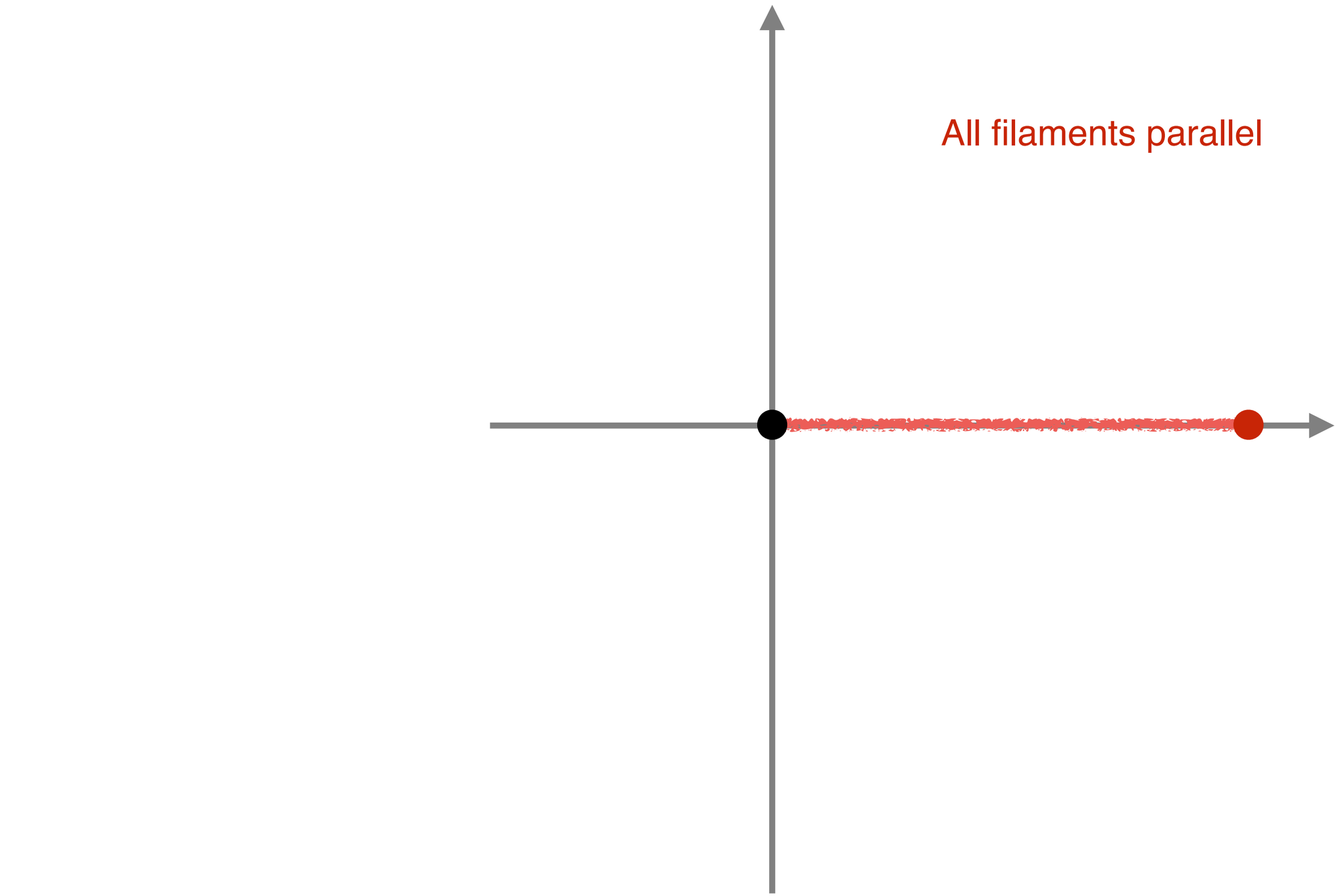


Image: Advanced Design Studies
University of Tokyo

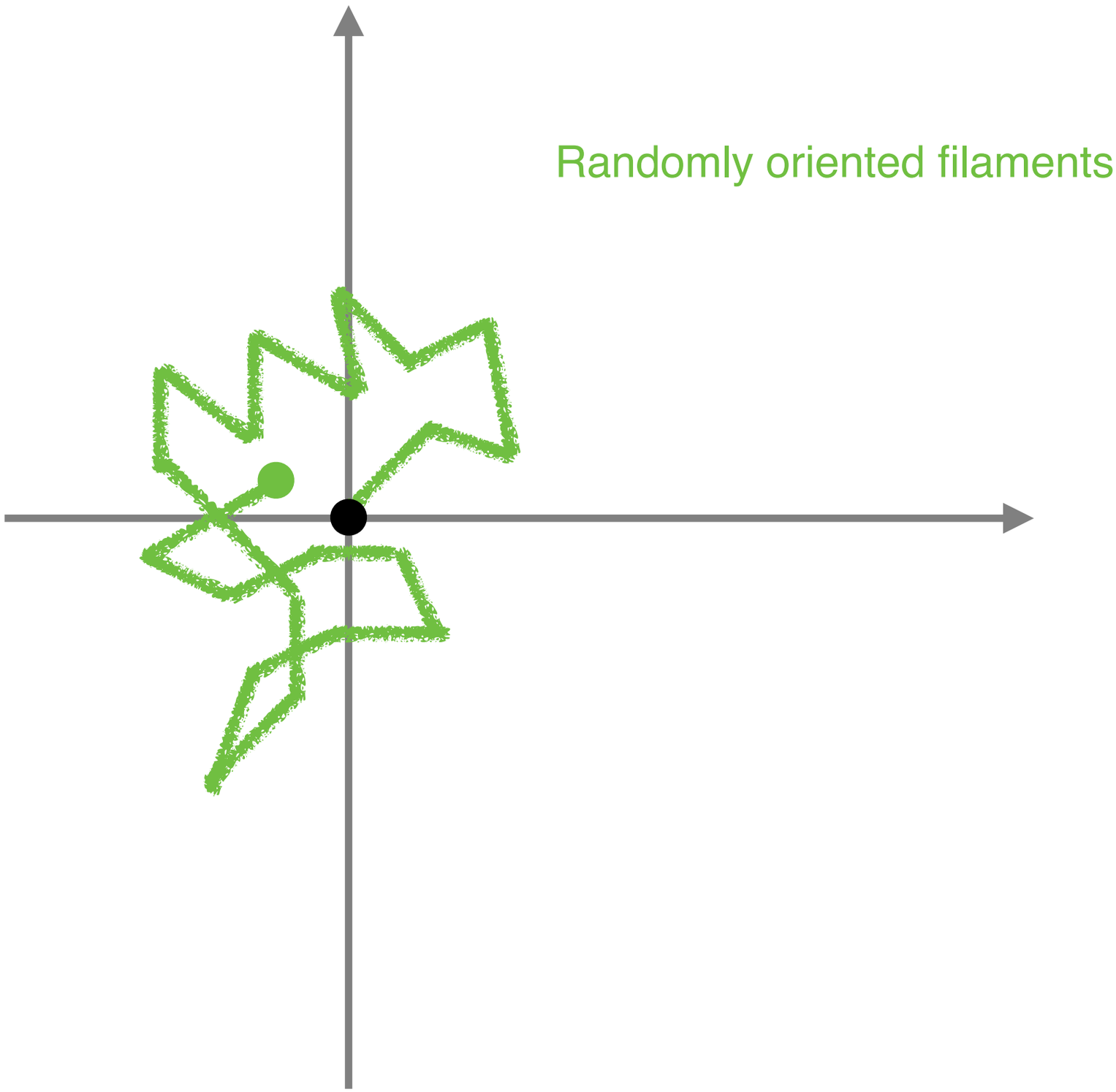
HI filament orientation: random walk interpretation

Soler, J.D. et al. A&A. 2020



HI filament orientation: random walk interpretation

Soler, J.D. et al. A&A. 2020



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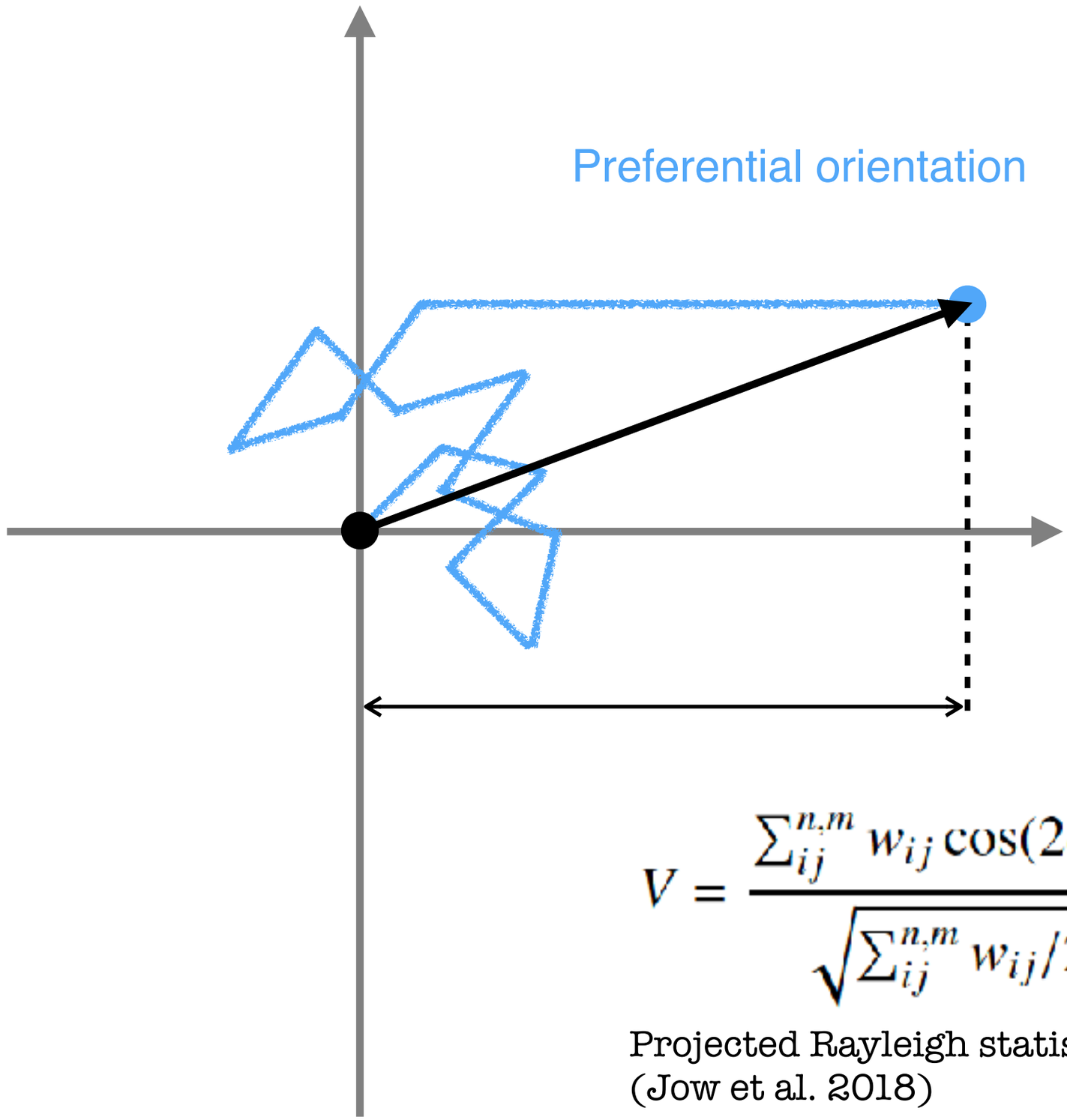
Soler, J.D. et al. A&A. 2020

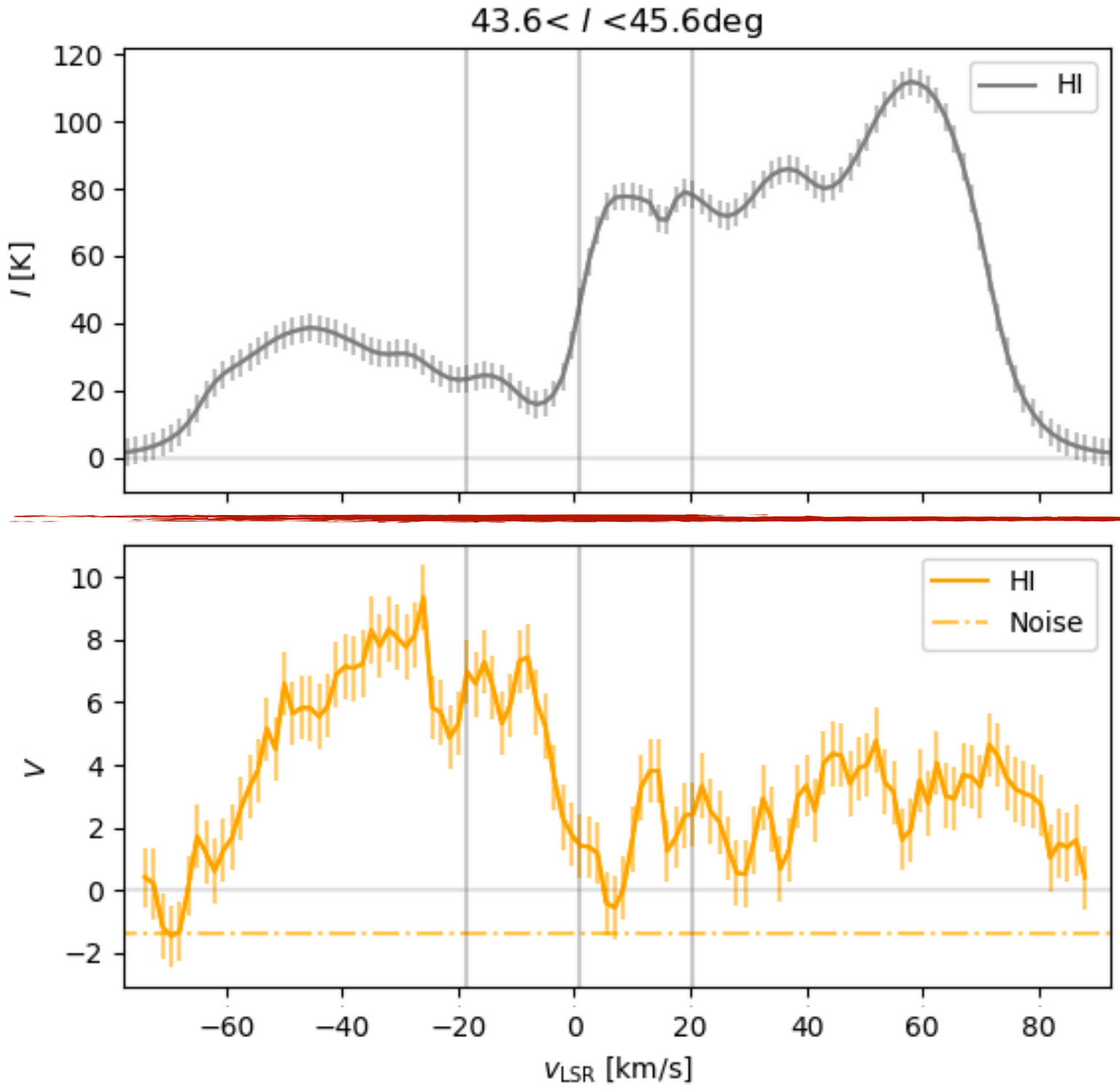


$$V = \frac{\sum_{ij}^{n,m} w_{ij} \cos(2\theta_{ij})}{\sqrt{\sum_{ij}^{n,m} w_{ij}/2}}$$

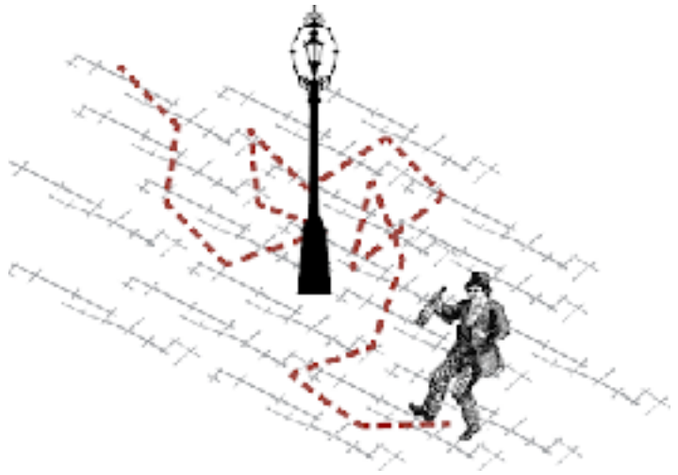
Projected Rayleigh statistic
(Jow et al. 2018)

HI filament orientation

Soler, J.D. et al. A&A. 2020



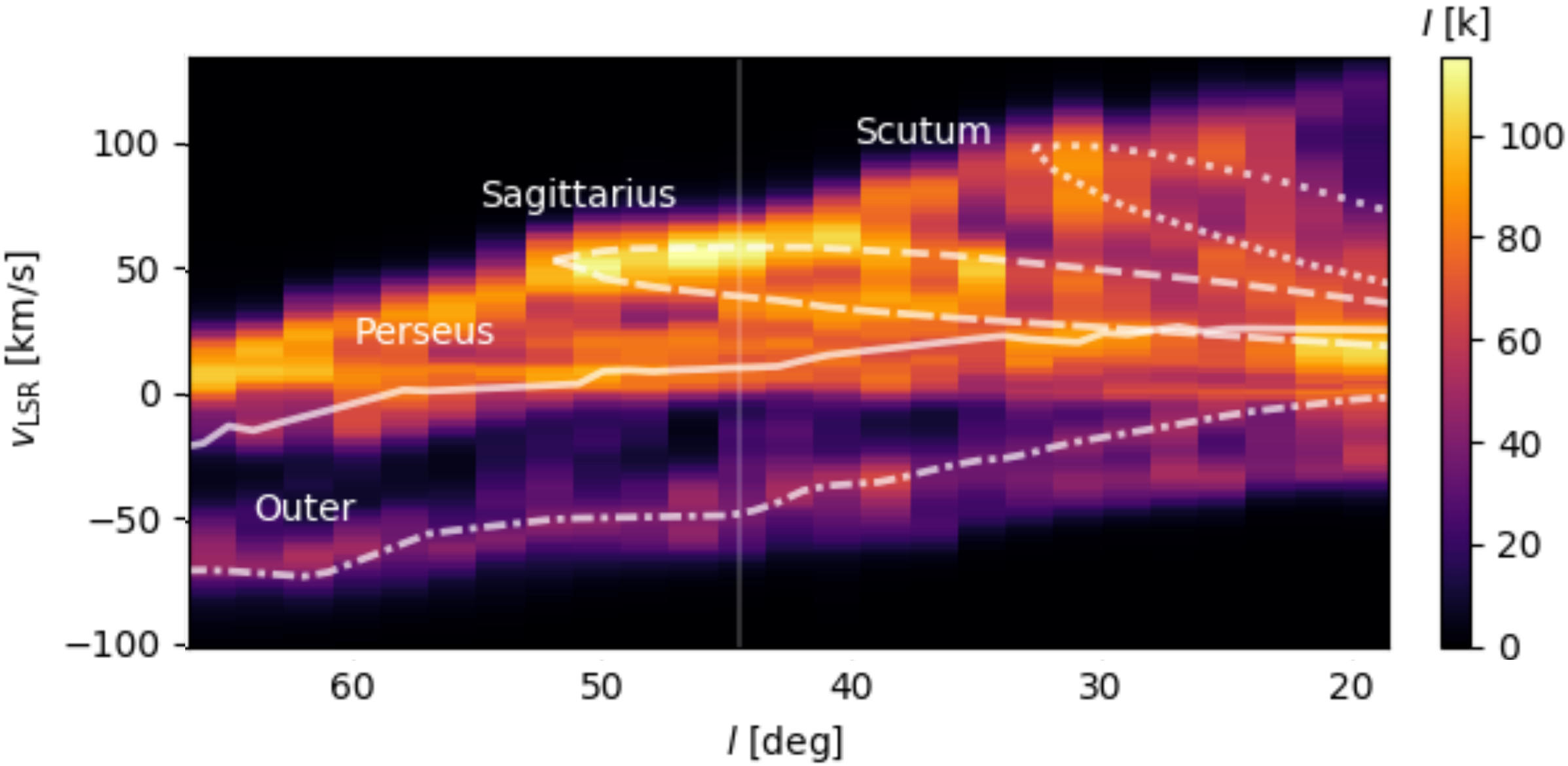
Projected Rayleigh statistic (Jow et al. 2018)



$$V = \frac{\sum_{ij}^{n,m} w_{ij} \cos(2\theta_{ij})}{\sqrt{\sum_{ij}^{n,m} w_{ij}/2}}$$

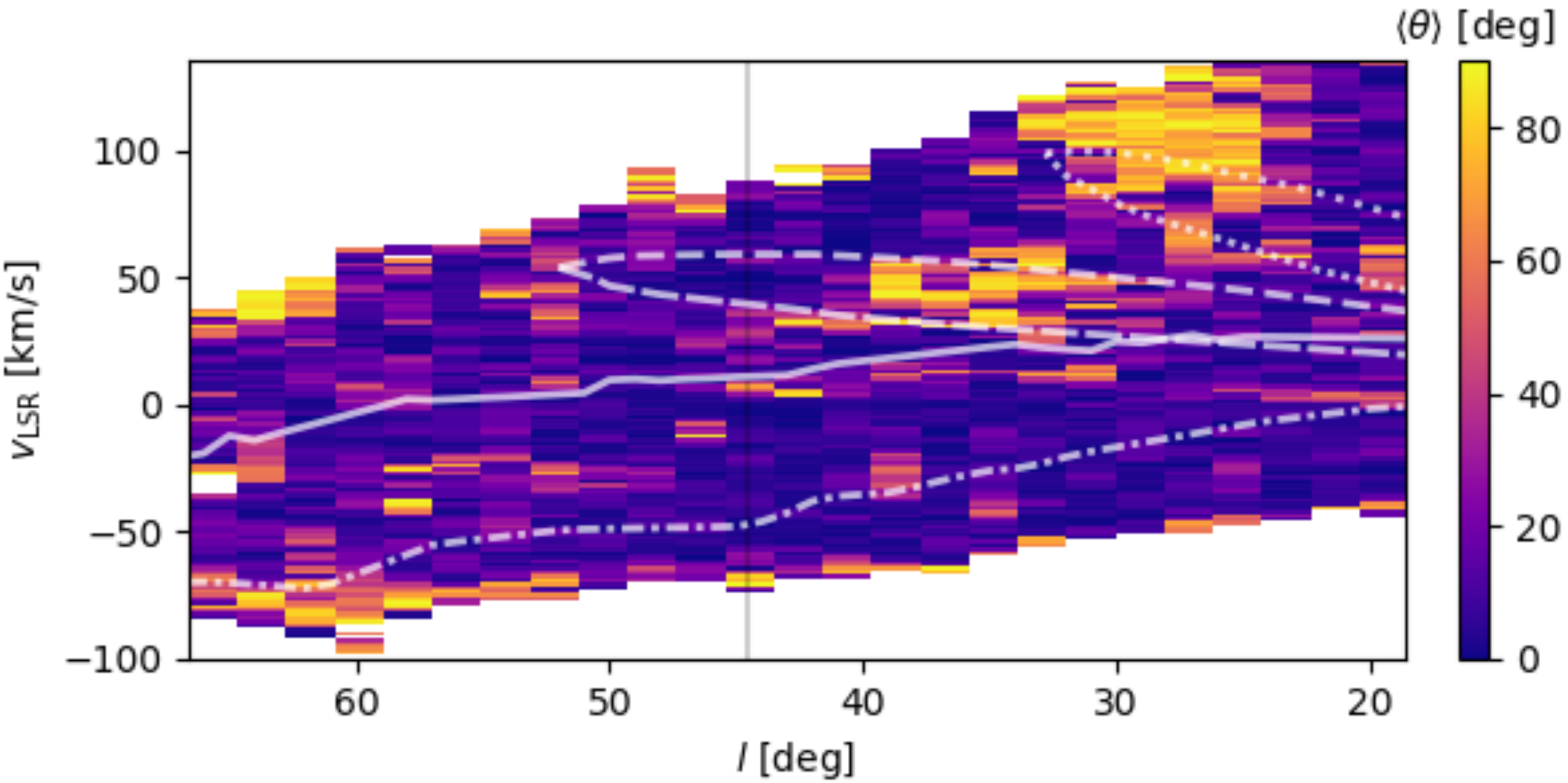
HI emission

Soler, J.D. et al. A&A (2020)



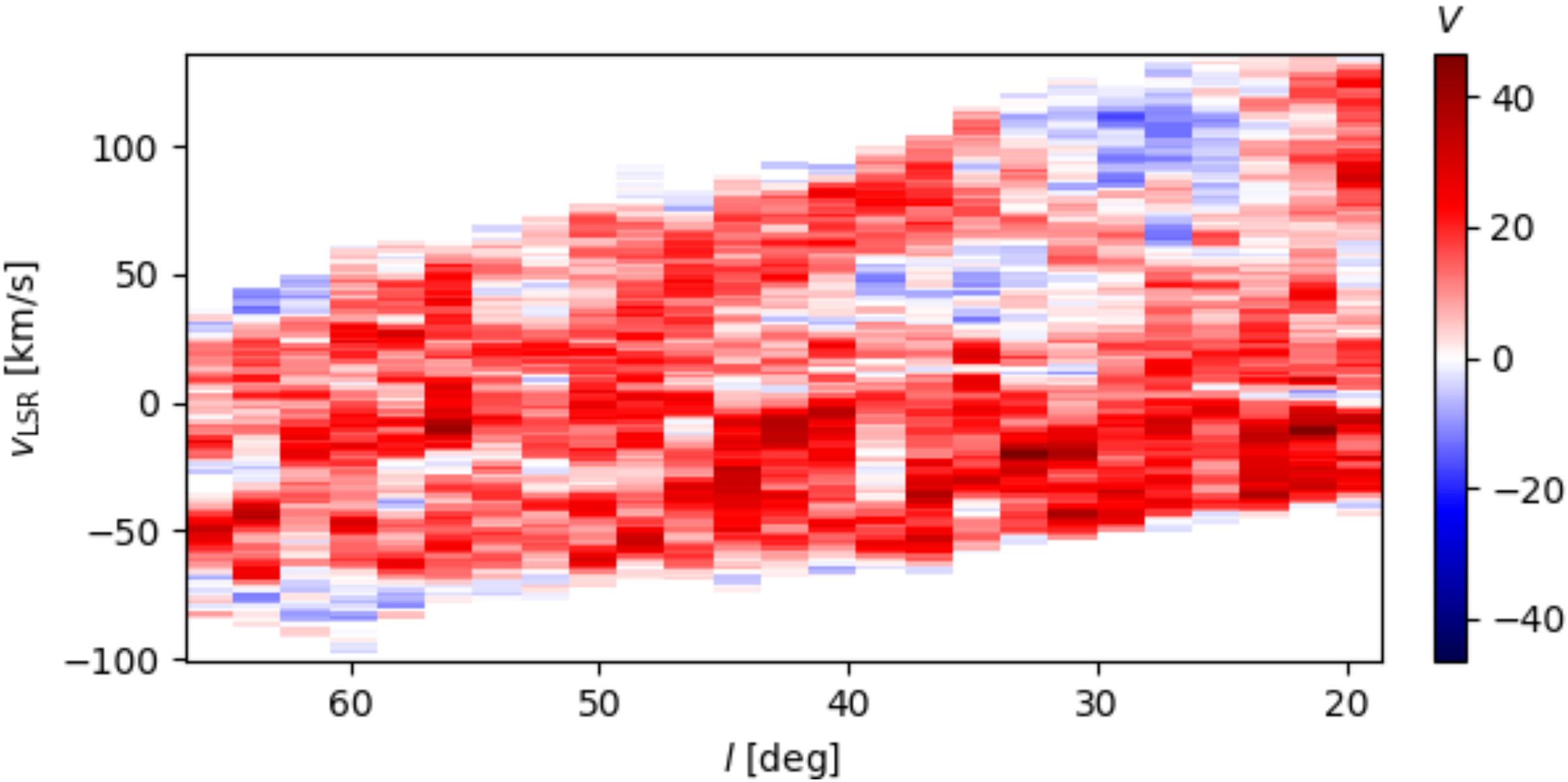
HI filament orientation

Soler, J.D. et al. A&A. 2020



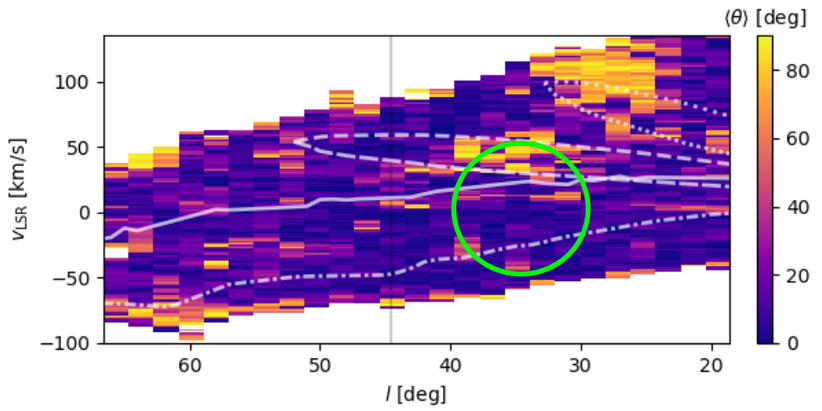
HI filament orientation

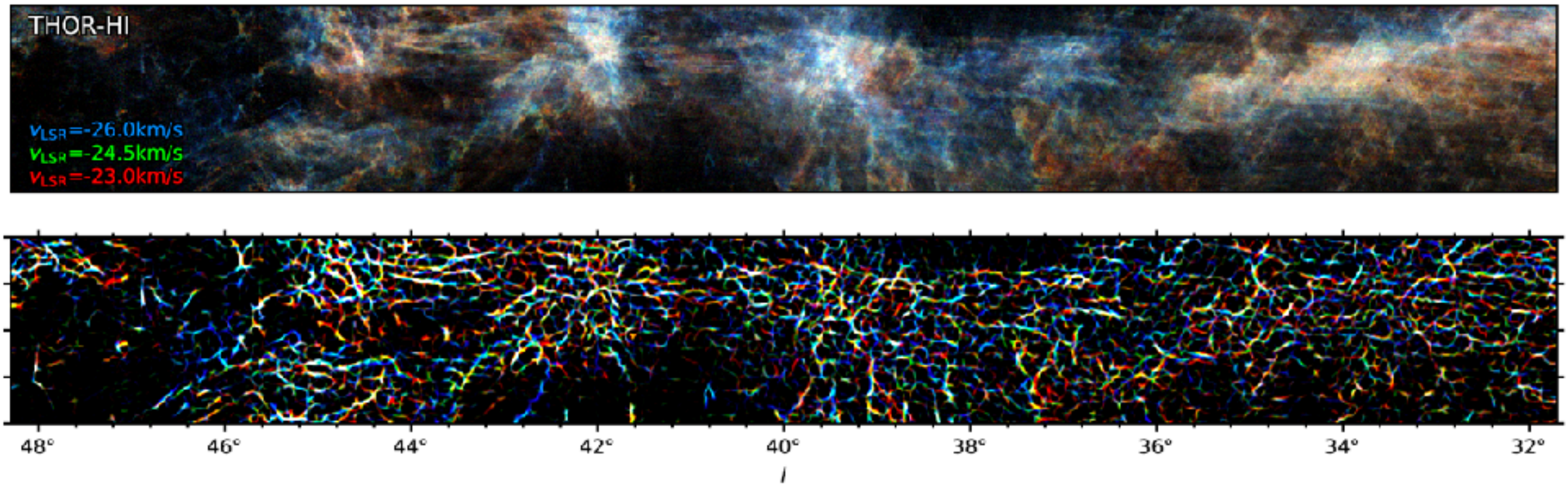
Soler, J.D. et al. A&A. 2020



HI filaments (THOR)

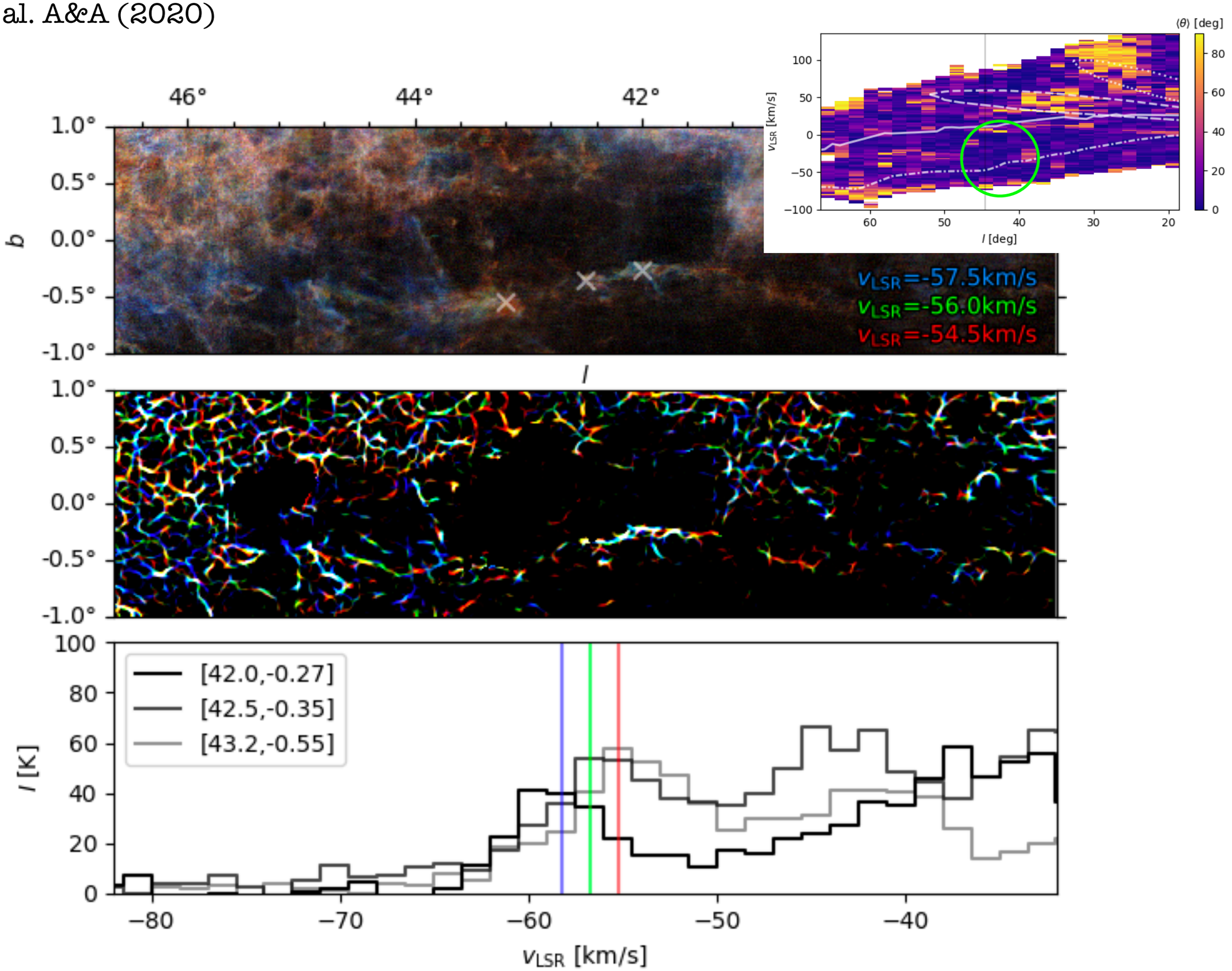
Soler, J.D. et al. A&A (2020)





The Magdalena filament

Soler, J.D. et al. A&A (2020)



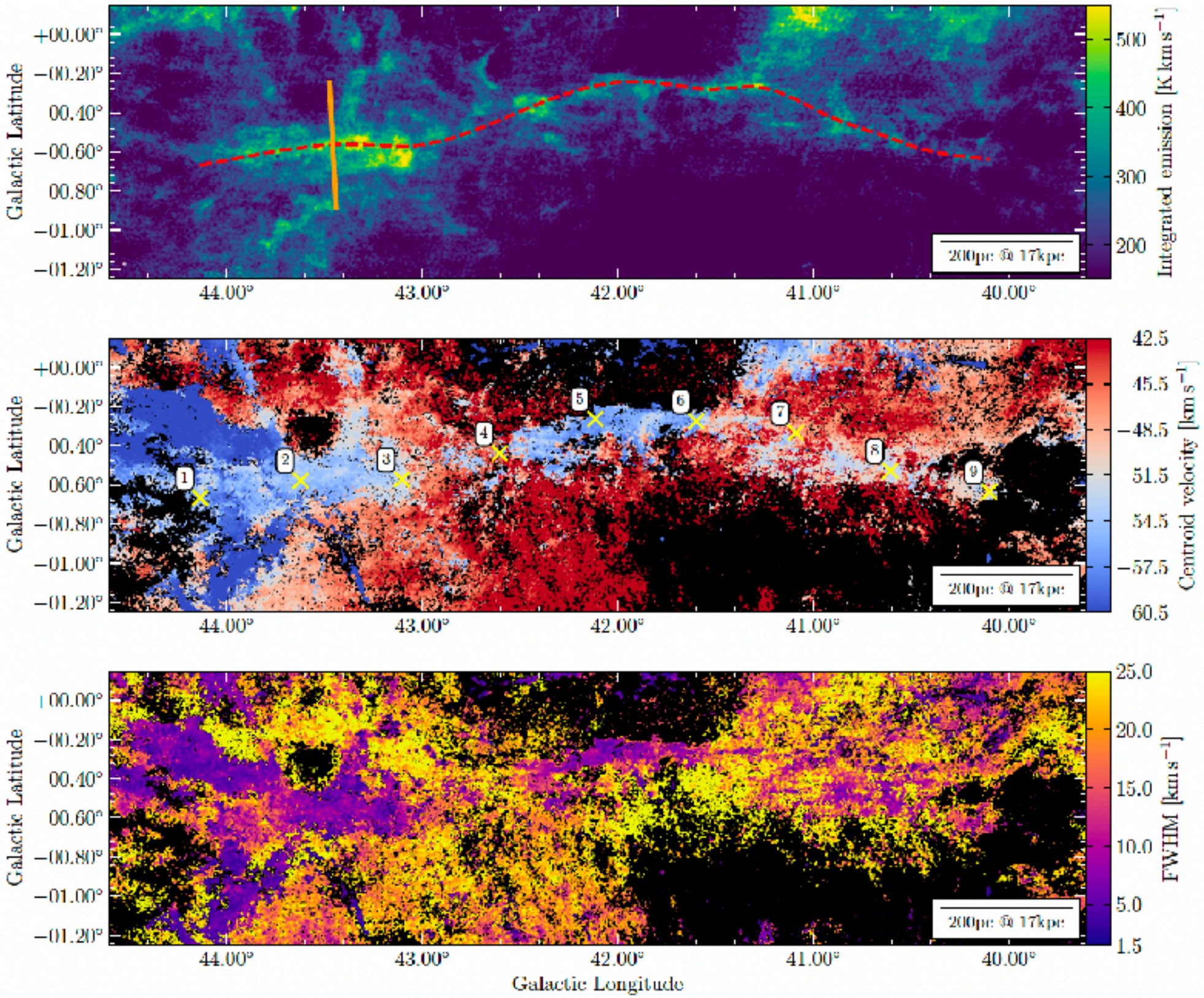
The Magdalena filament

Syed, J., et al. (2022), Soler, J.D. et al. (2020)

N_{H}

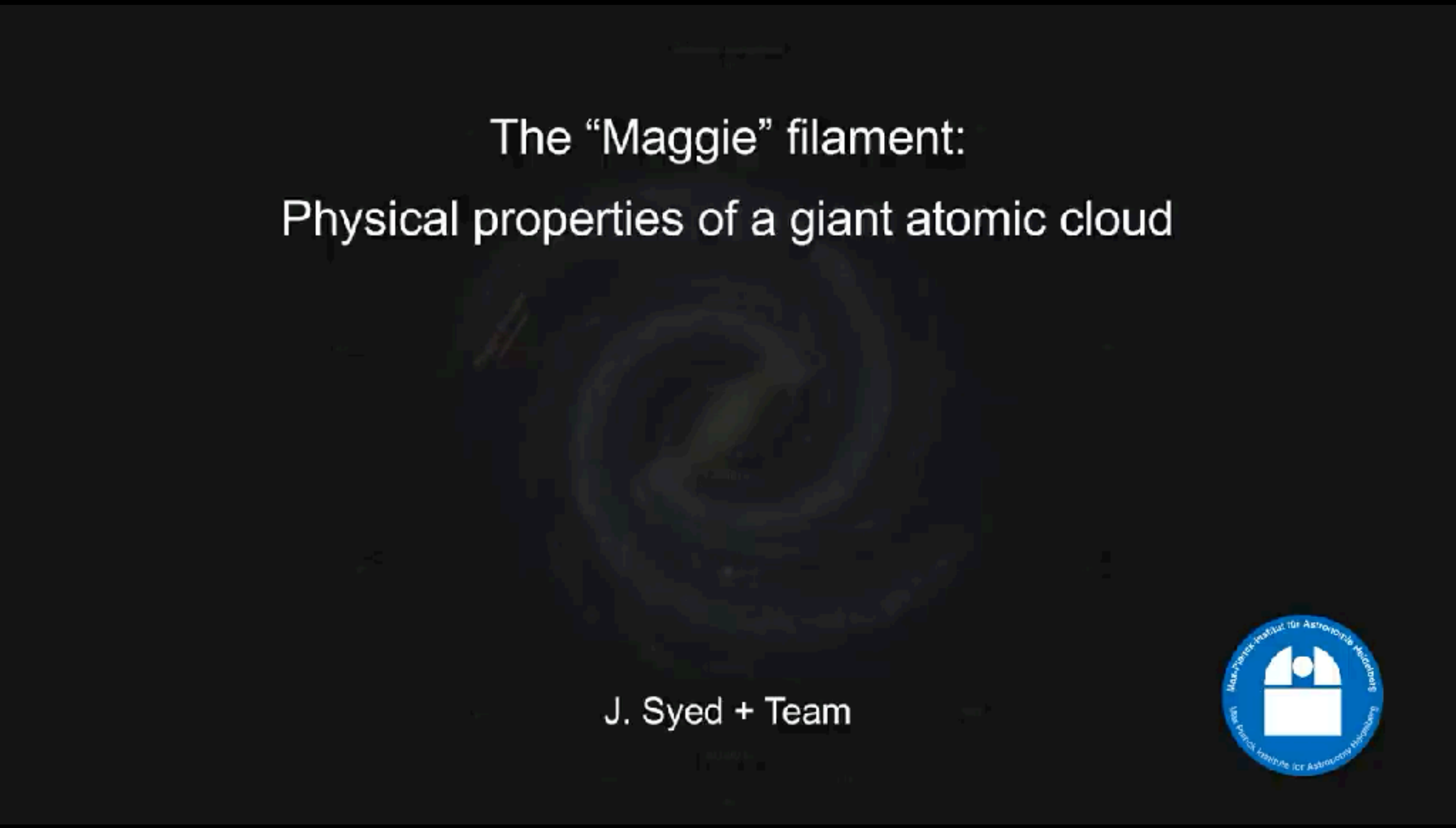
$\langle v \rangle$

σ_v



The Magdalena (Maggie) filament

Syed, J., JDS, et al. A&A 2022

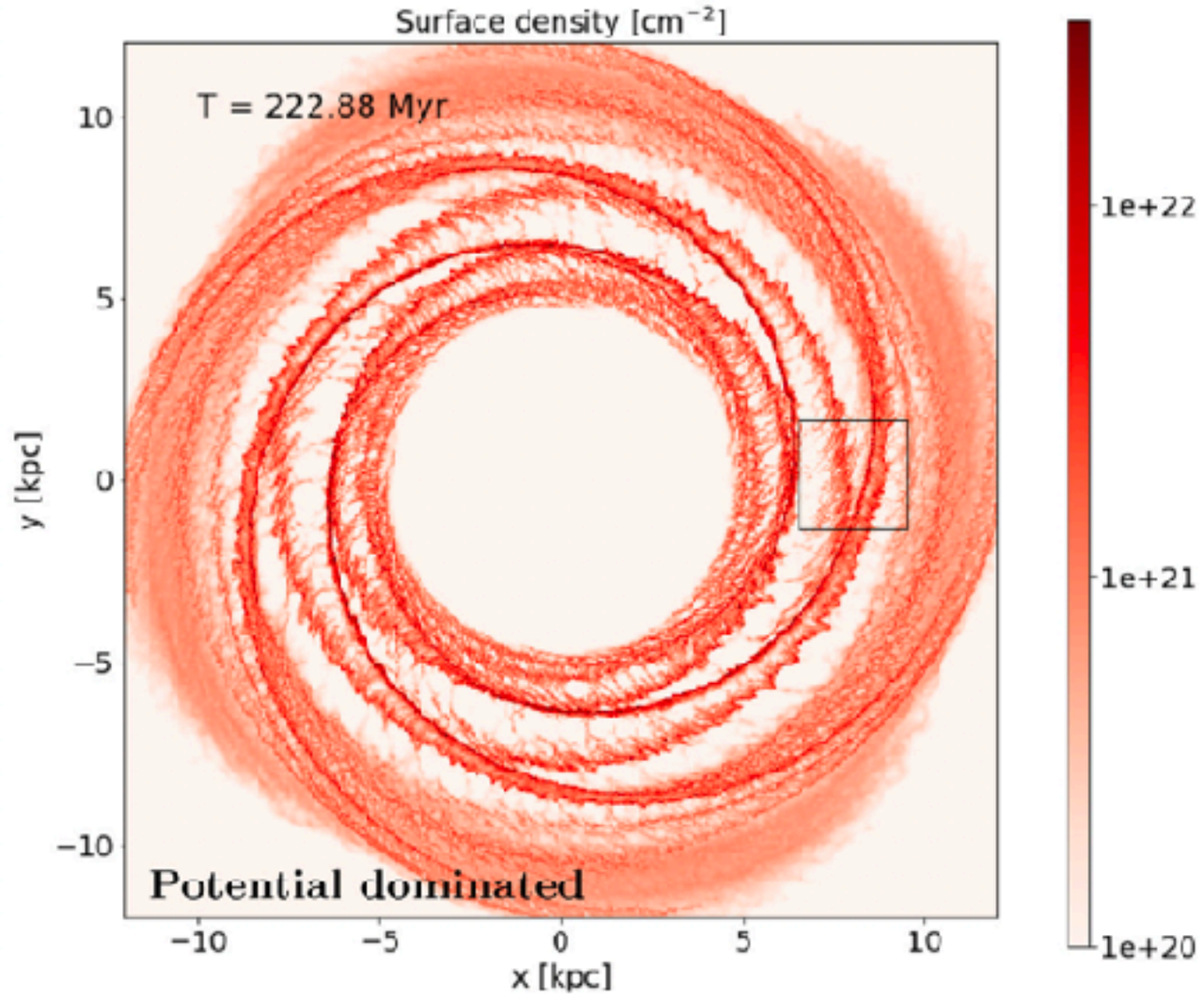


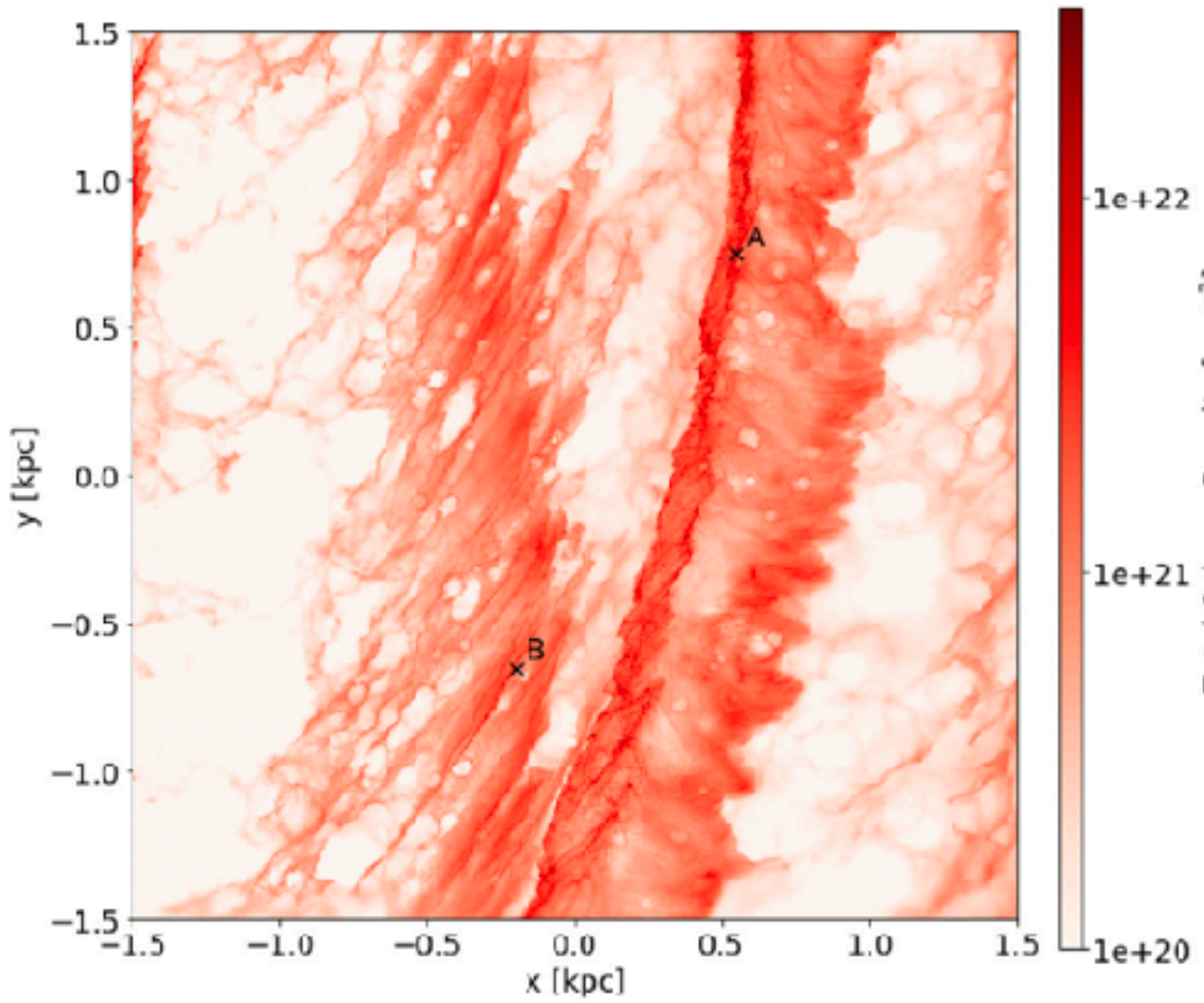
Video: J. Syed & T. Müller

Juan D. Soler (IAPS, Rome)

HI filament orientation

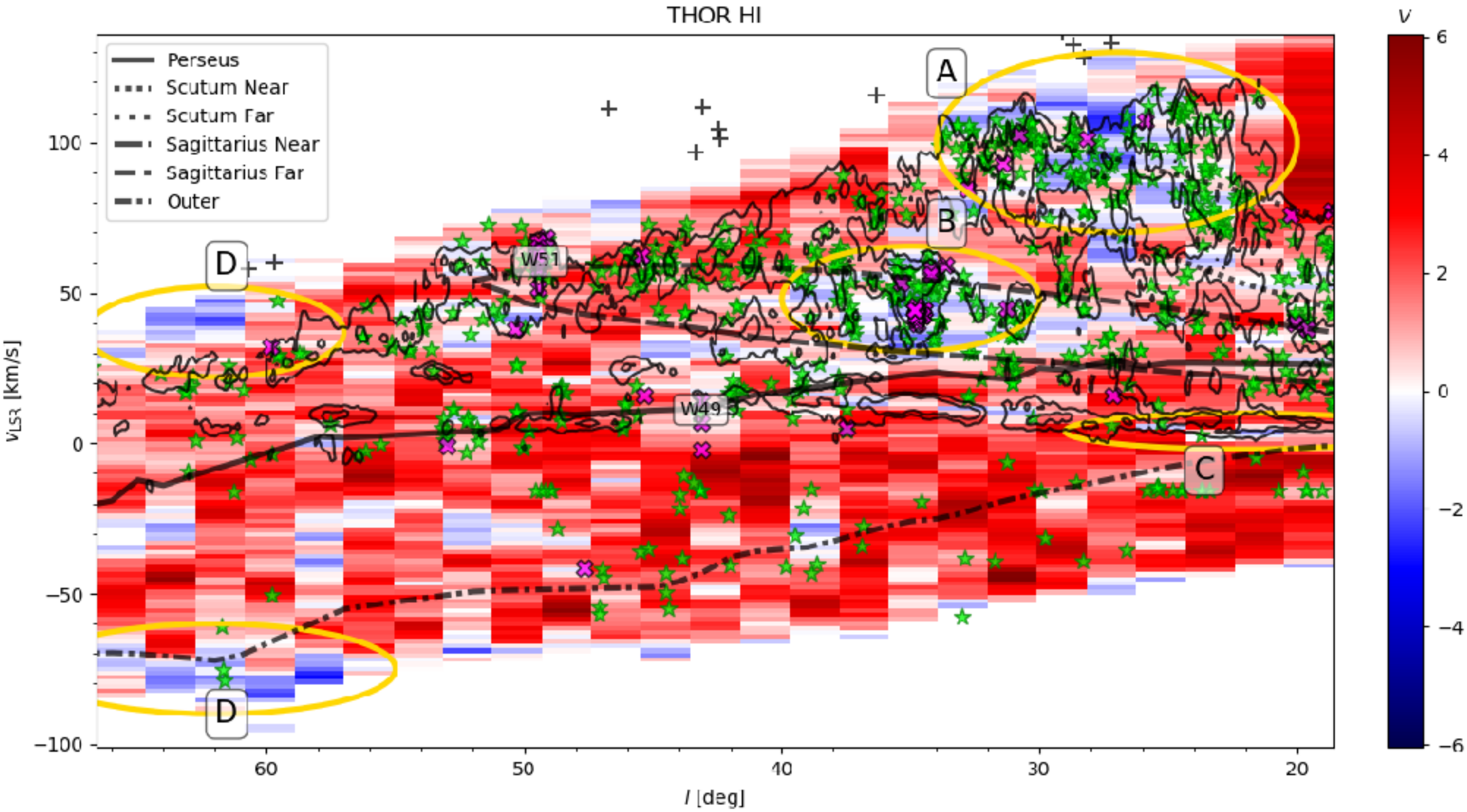
Smith, R.. et al. MNRAS. 2020





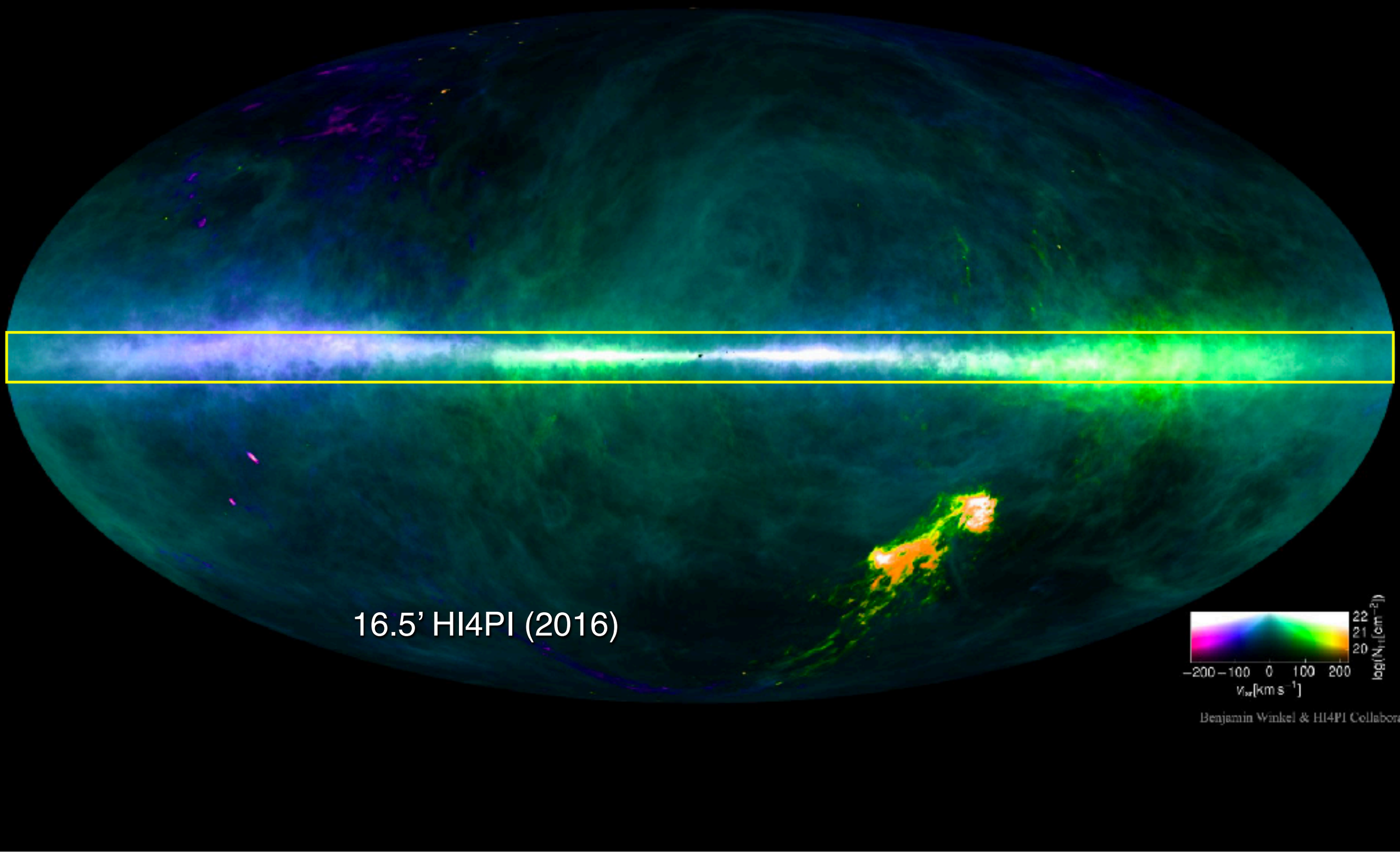
HI filament orientation

Soler, J.D. et al. A&A. 2020



Atomic hydrogen emission

HI4PI Collaboration. A&A (2016)

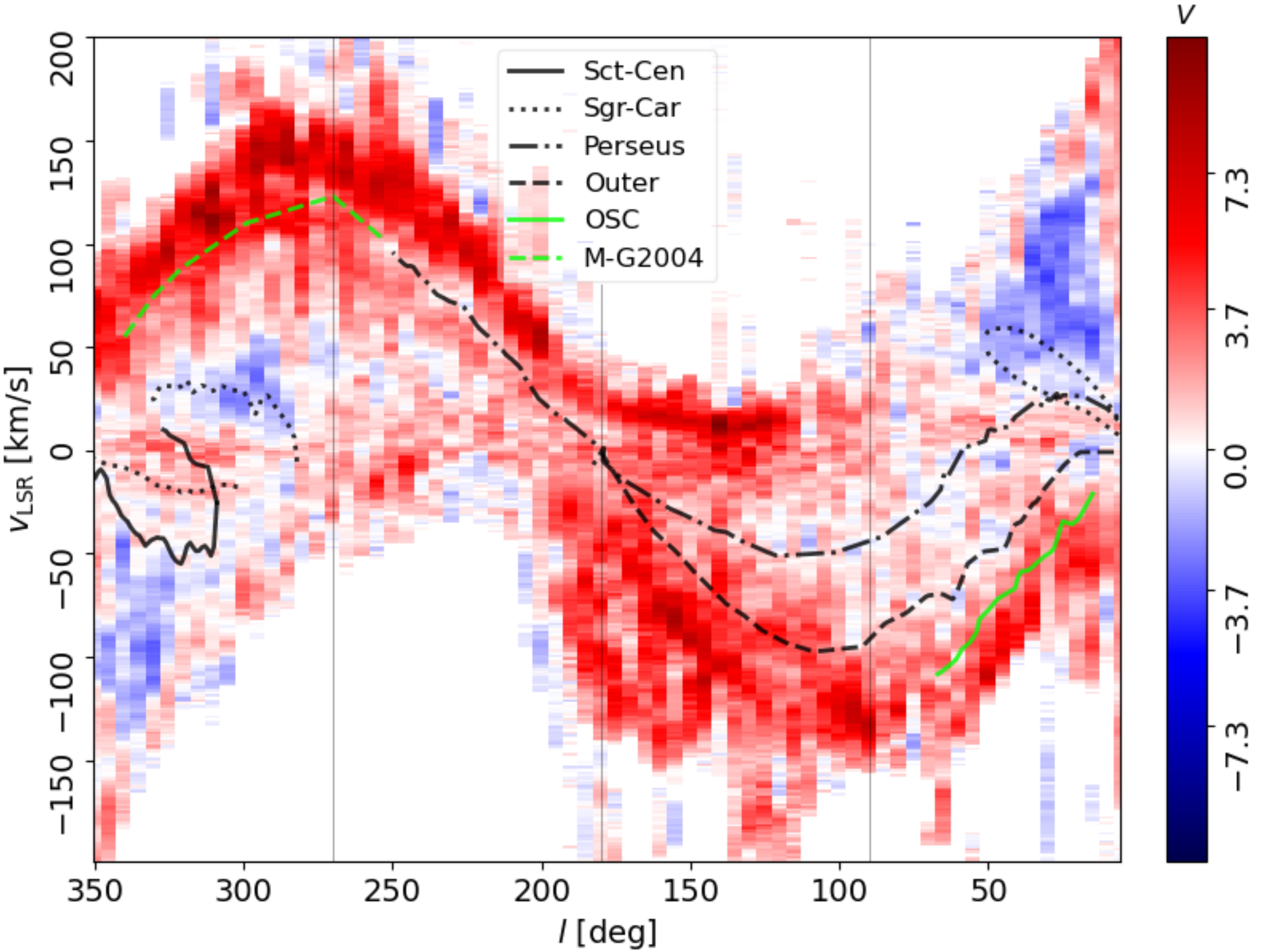


Atomic hydrogen emission

HI4PI survey

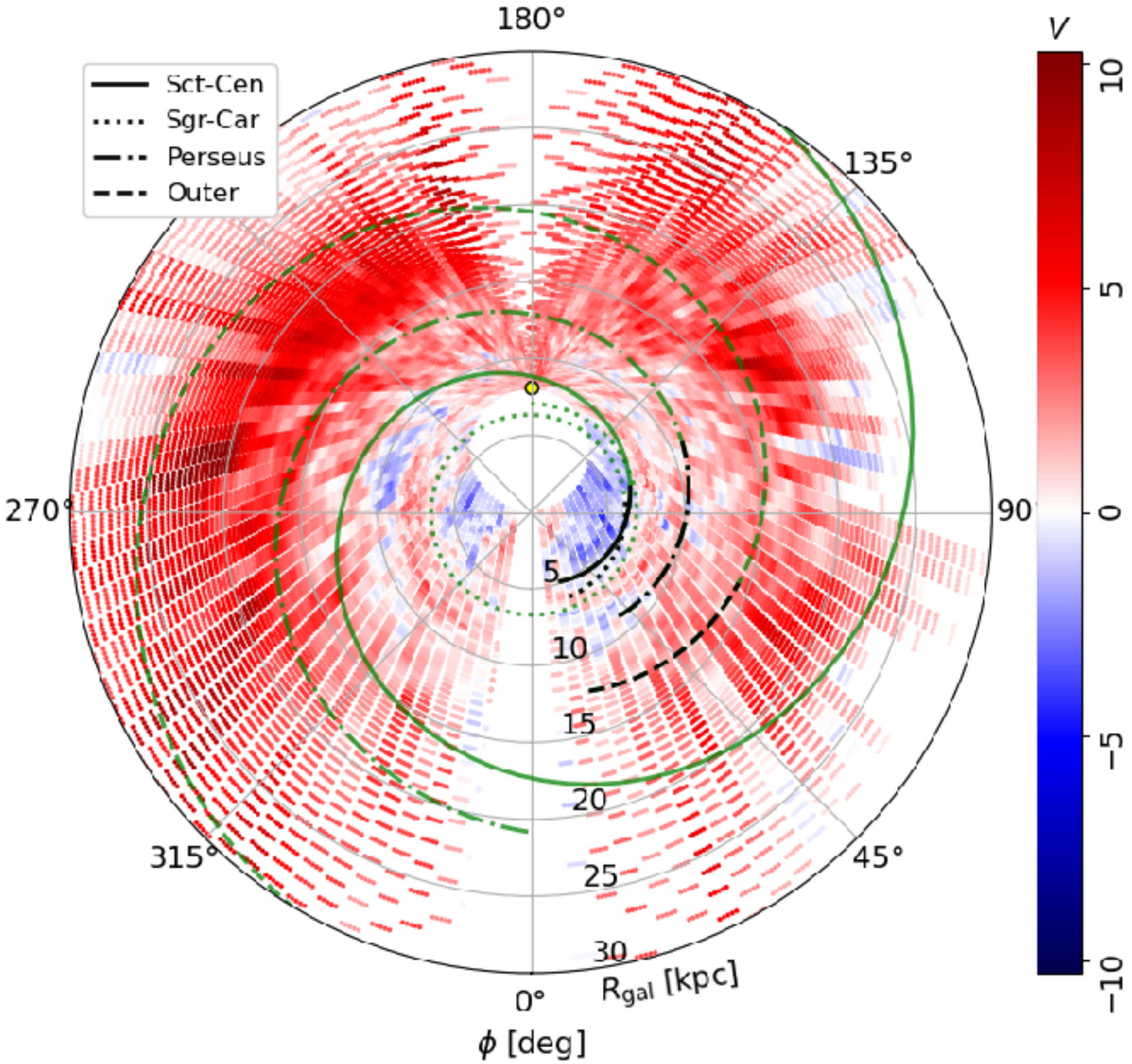
Orientation of atomic filaments

Soler, J.D. et al. 2022. A&A



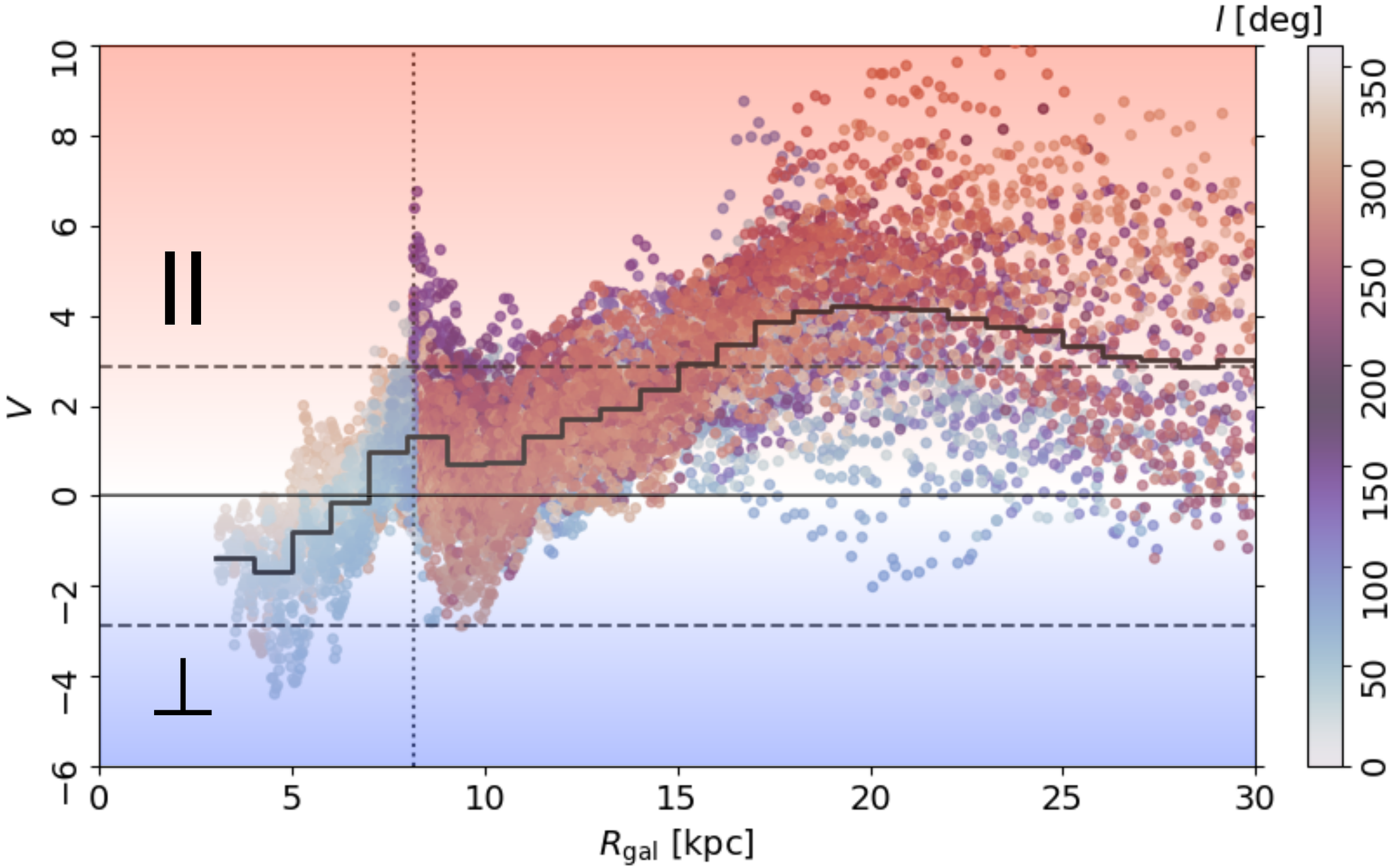
Orientation of atomic filaments

Soler, J.D. et al. 2022



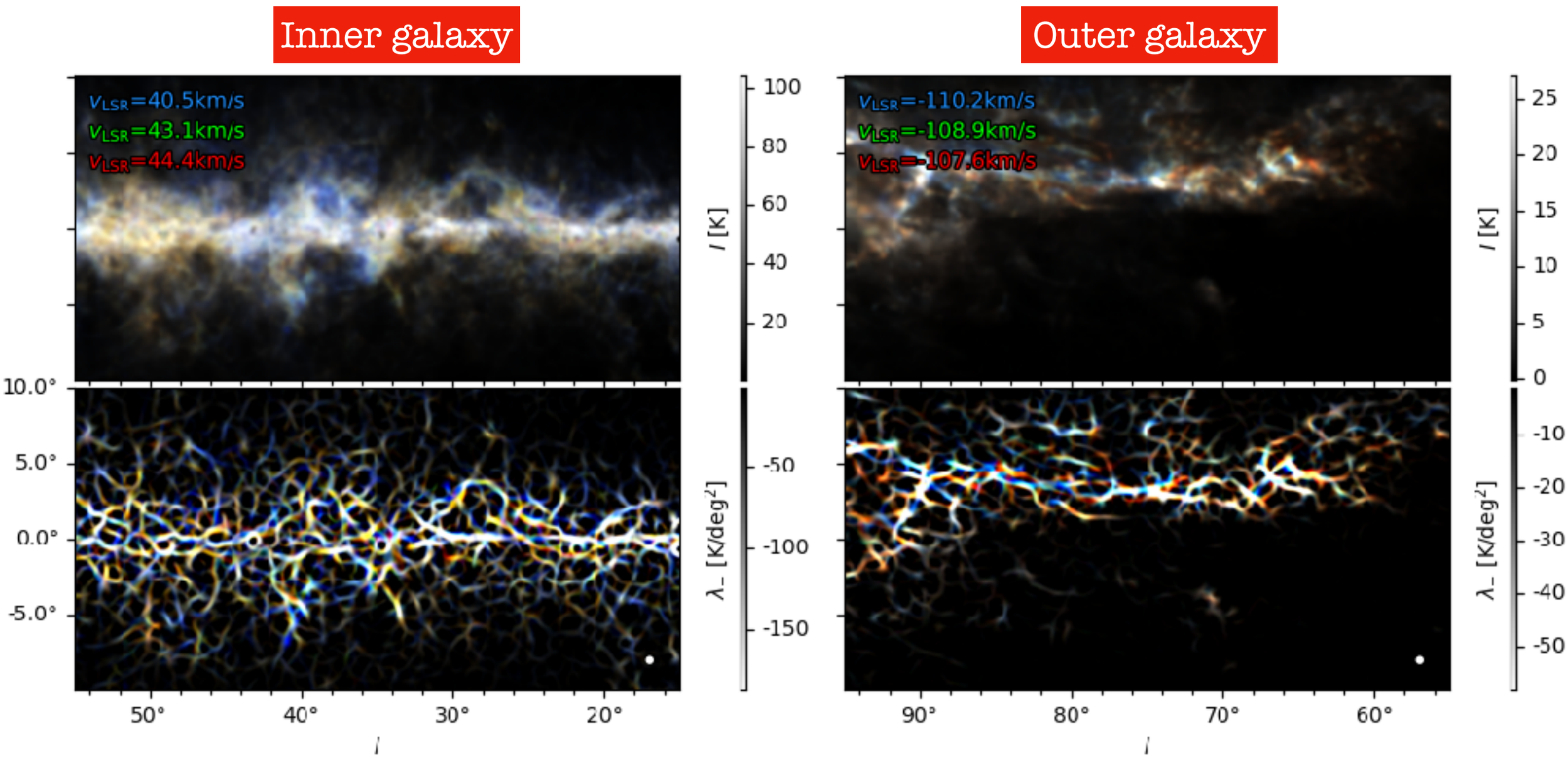
Atomic filament orientation

Soler, J.D. et al. 2022.



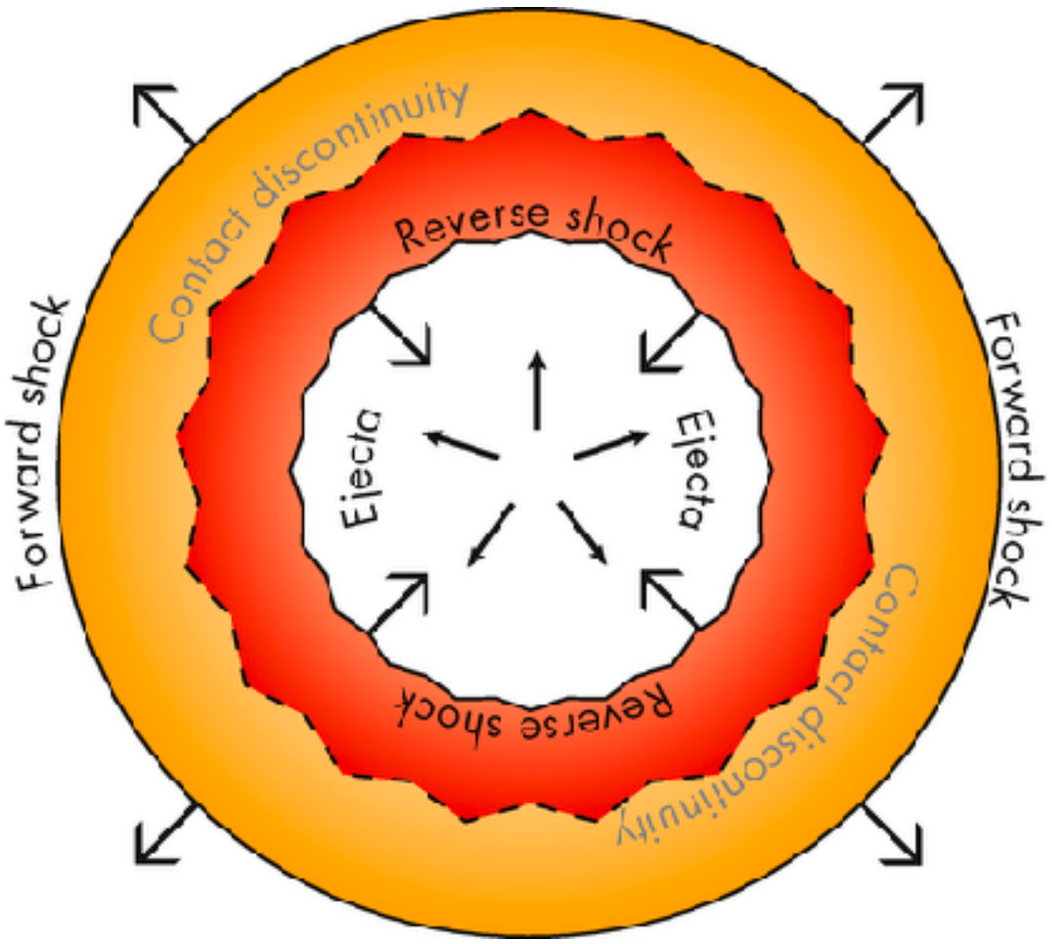
Atomic filament orientation

Soler, J.D. et al. 2022.

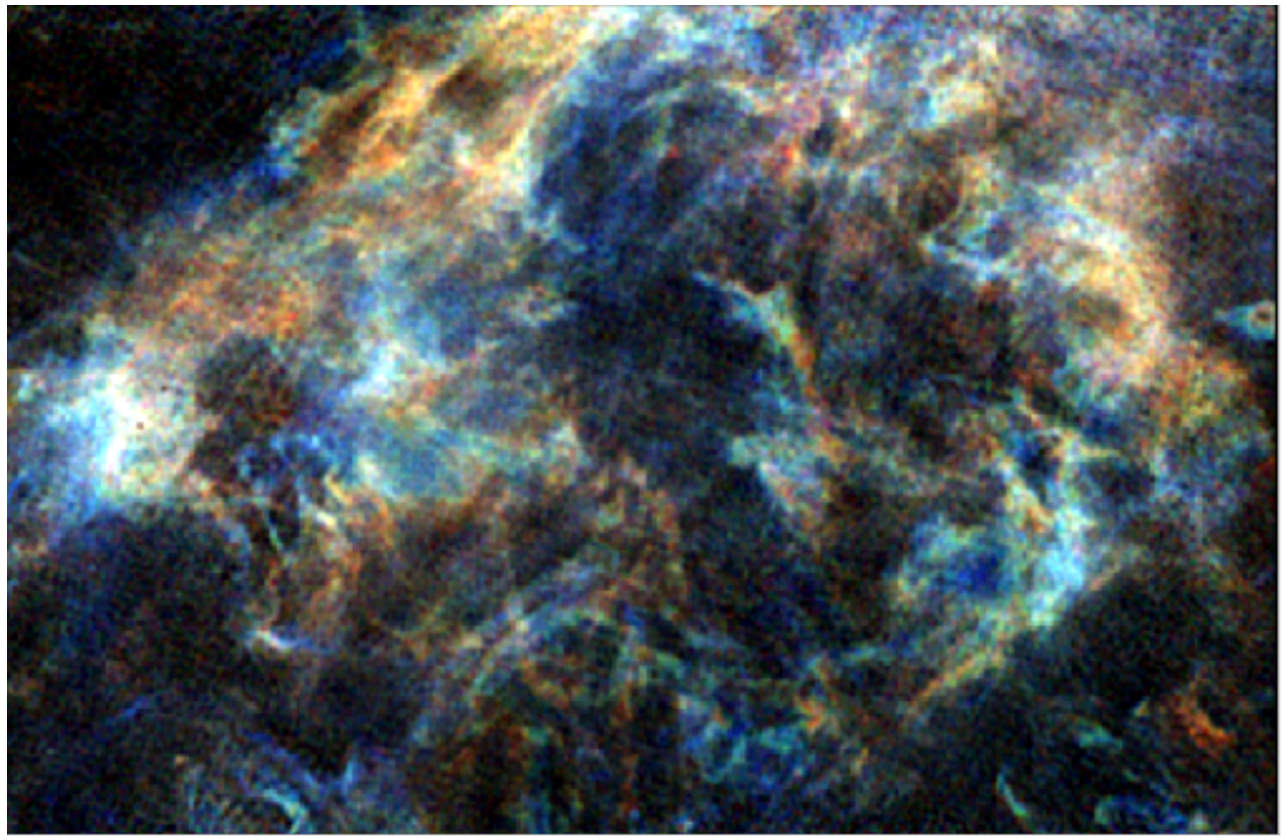


Atomic shells pushed by supernovae

Supernova Remnant Evolution. Vink, 2020.

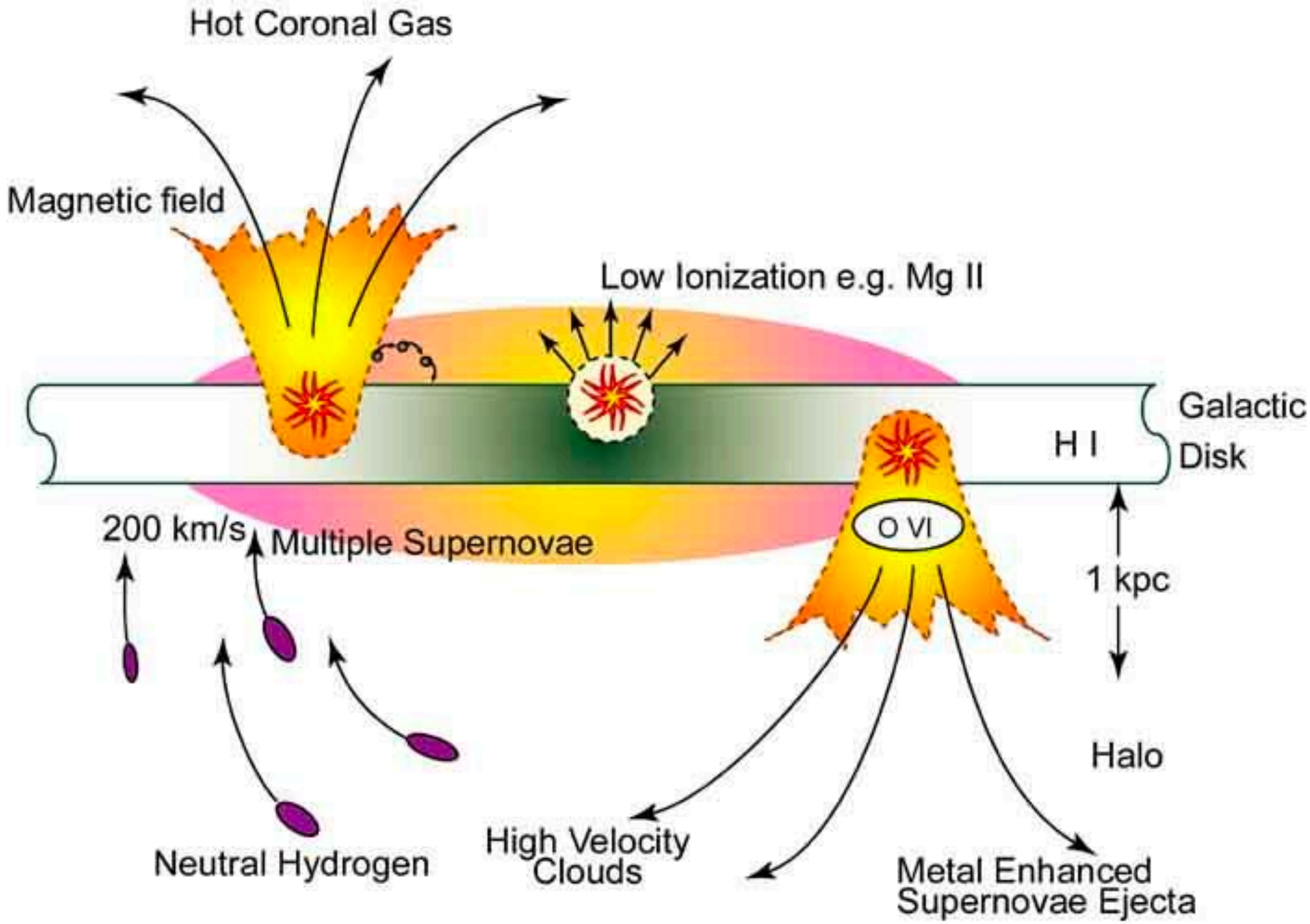


HI shell in THOR



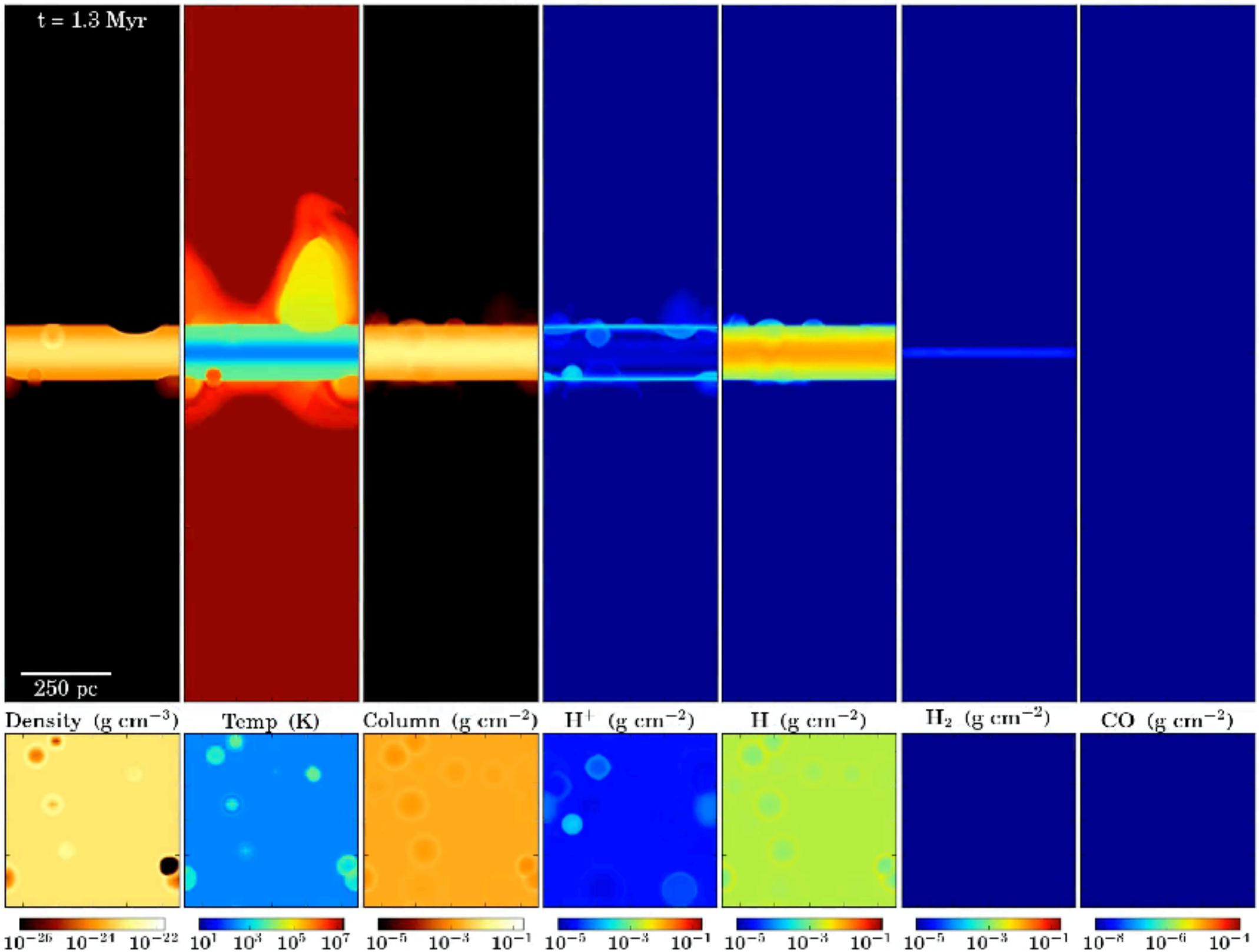
Atomic worms and chimneys

Heiles, 1994



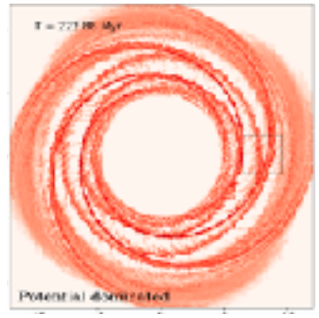
Atomic filament orientation and HI bubbles

Girichidis et al. MNRAS 2021. SILCC: Simulating the LifeCycle of molecular Clouds

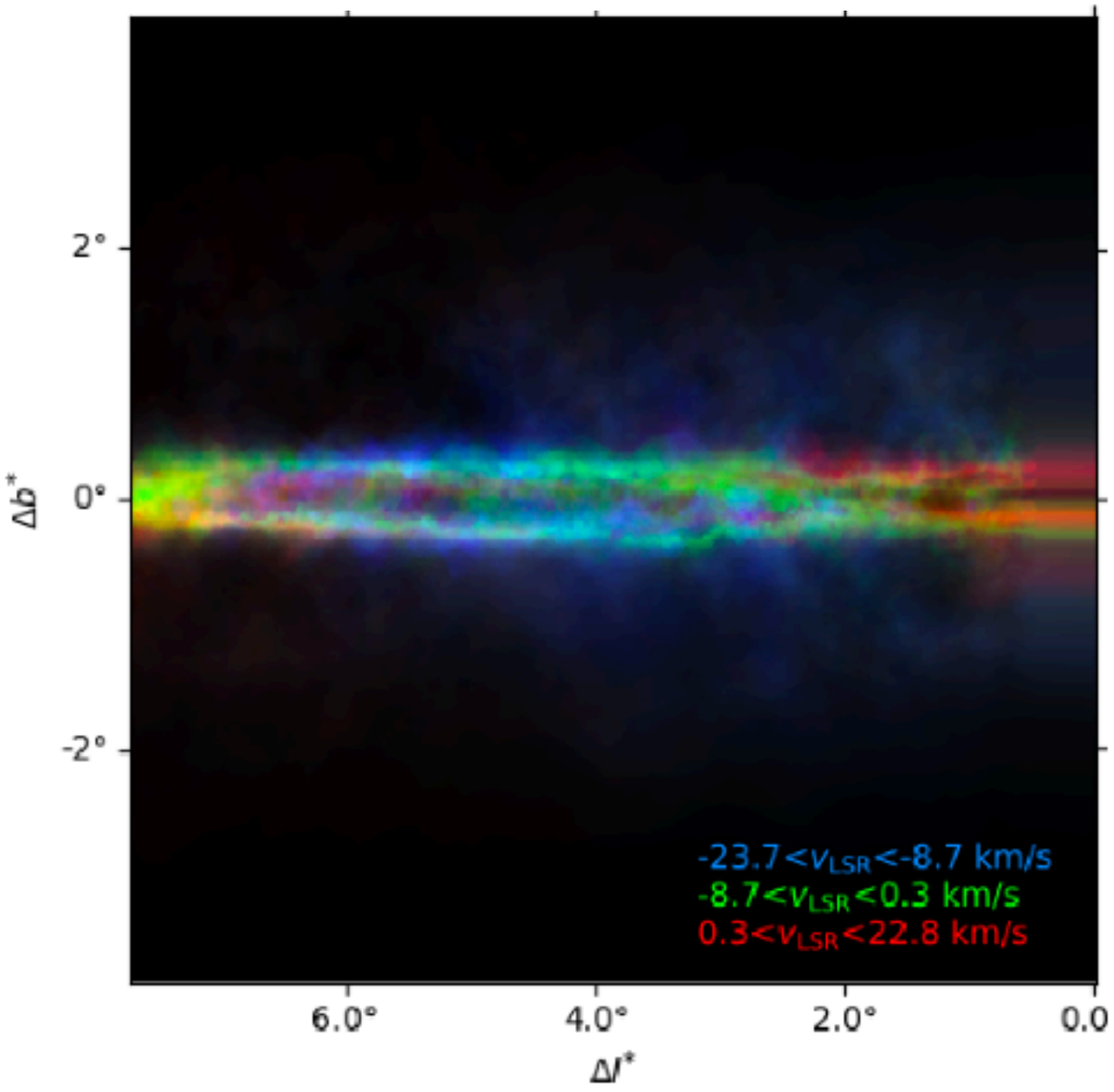


HI filaments - MHD simulations

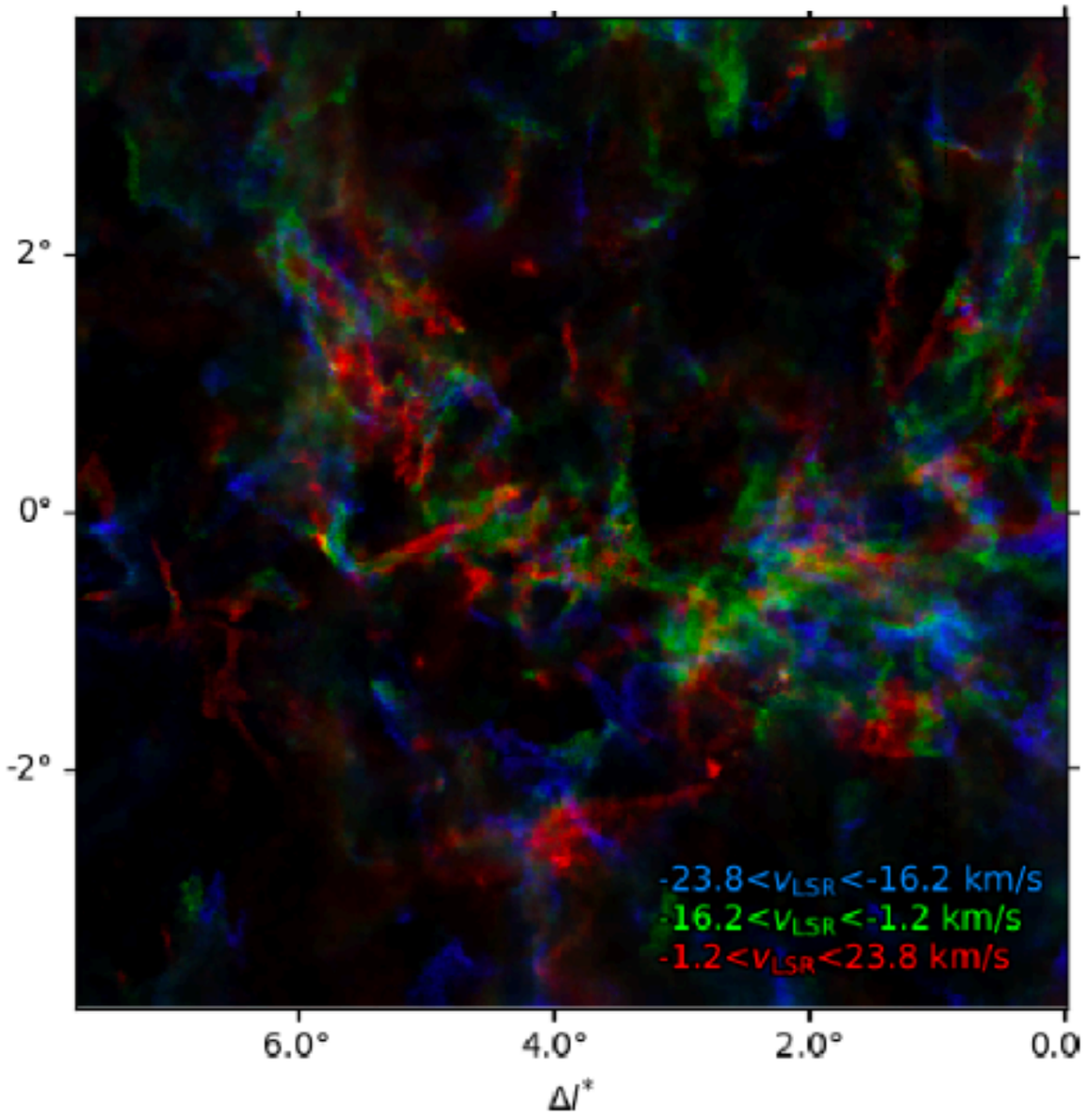
CloudFactory simulations (Smith et al. A&A 2020)
Soler, J.D. et al. A&A 2020



Potential-dominated



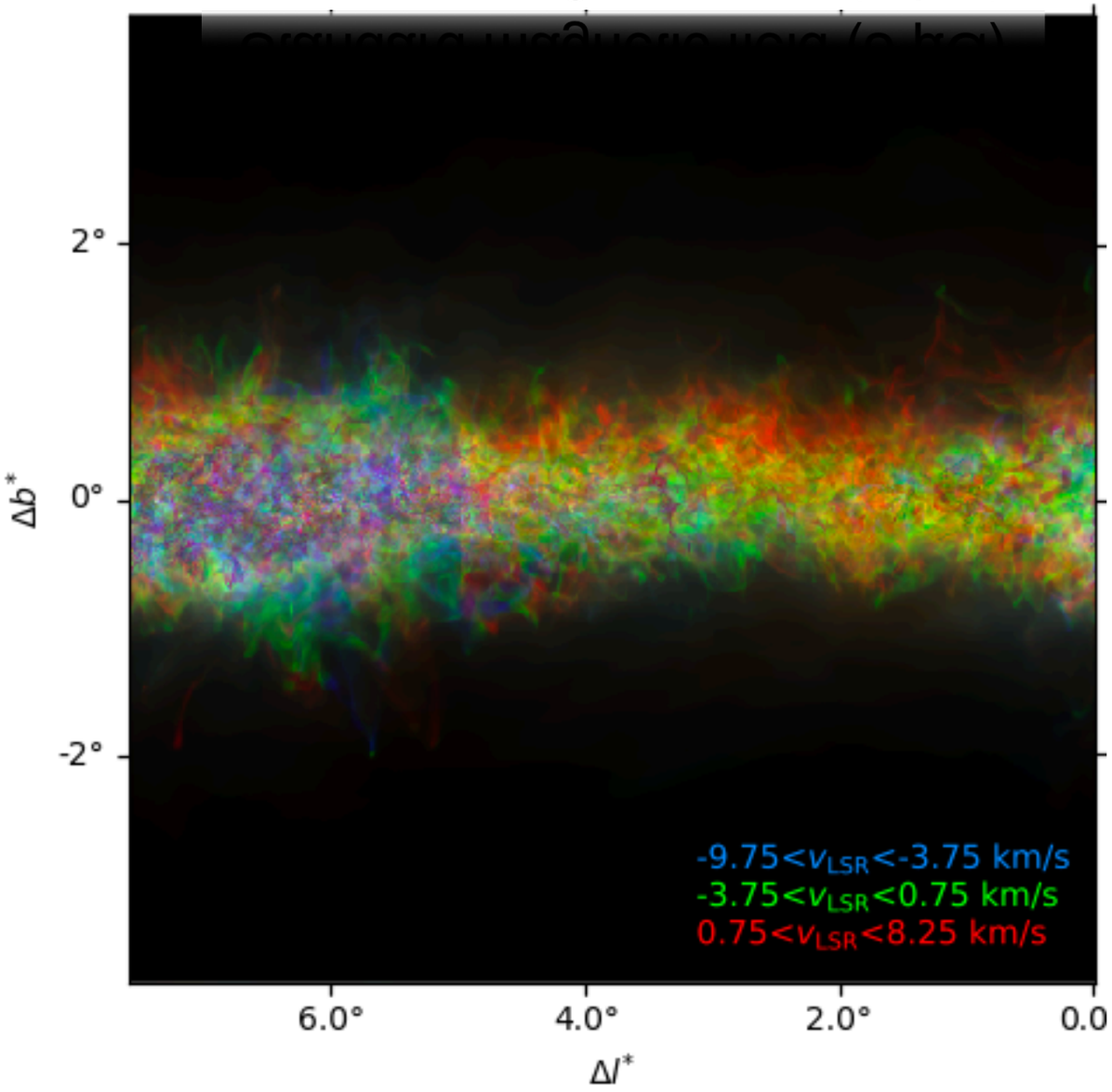
Feedback-dominated



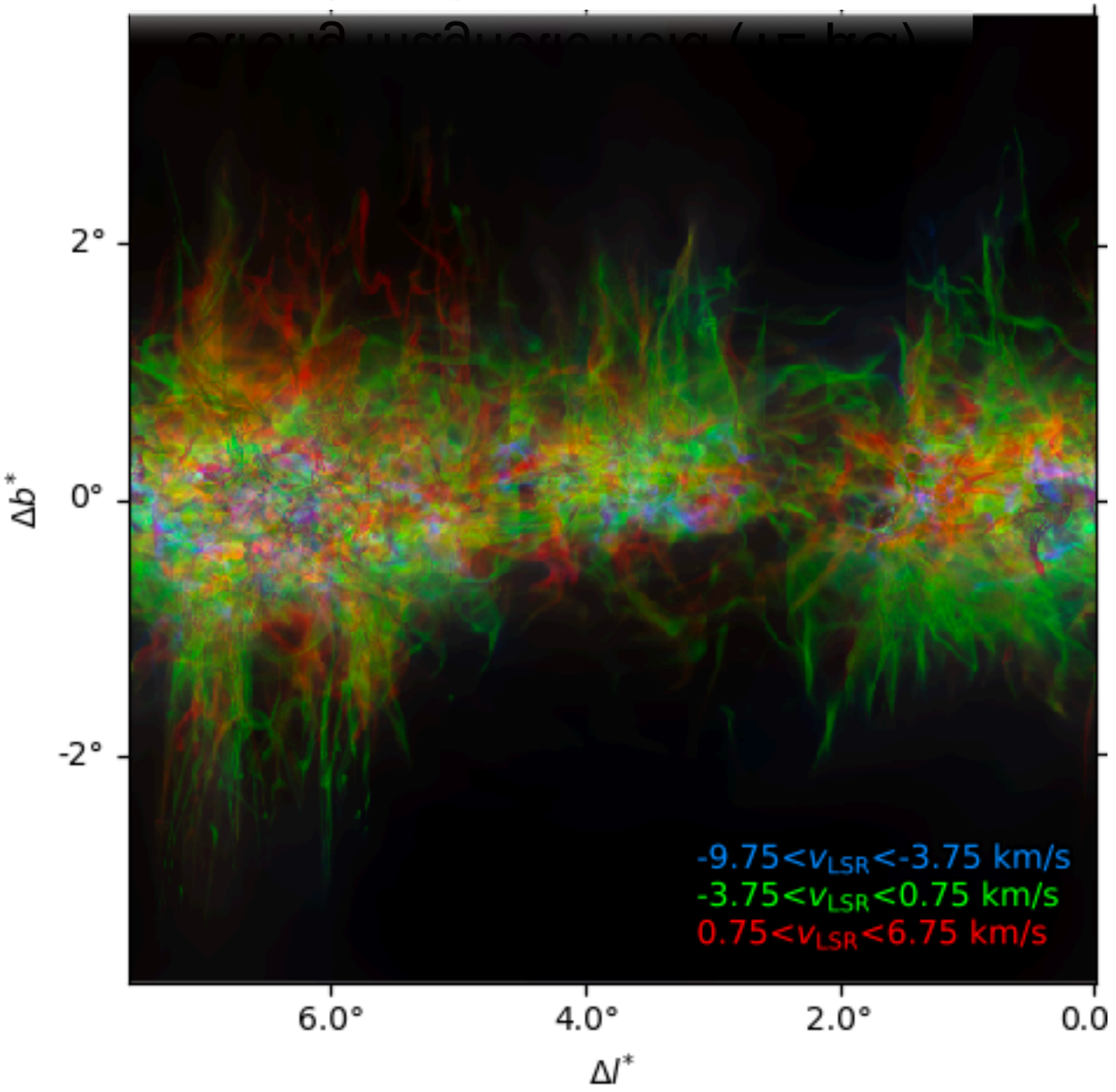
HI filaments - MHD simulations

FRIGG simulations (Hennebelle et al. A&A 2018)
Soler, J.D. et al. A&A. 2020

Standard magnetic field (3 μG)

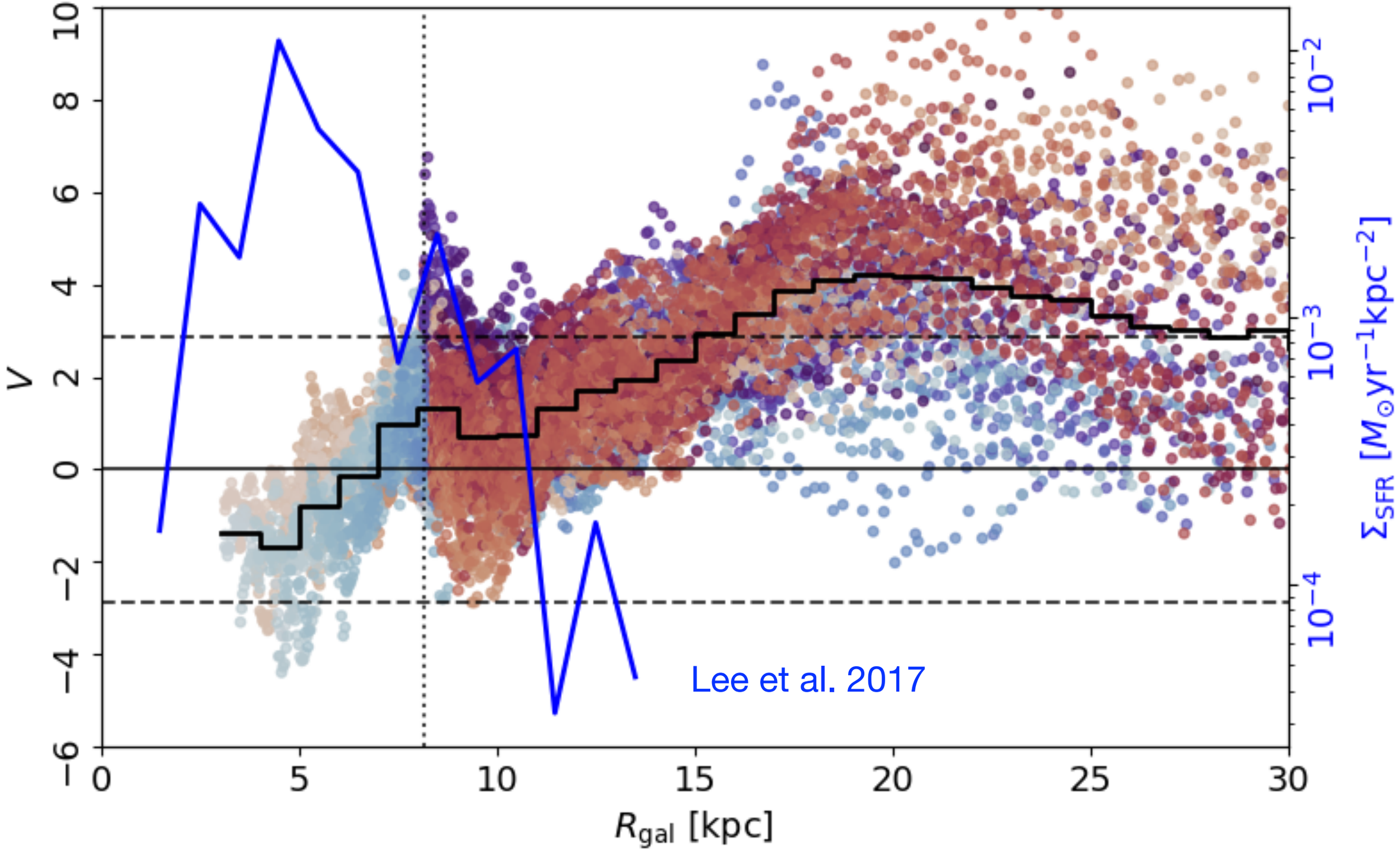


Strong magnetic field (12 μG)



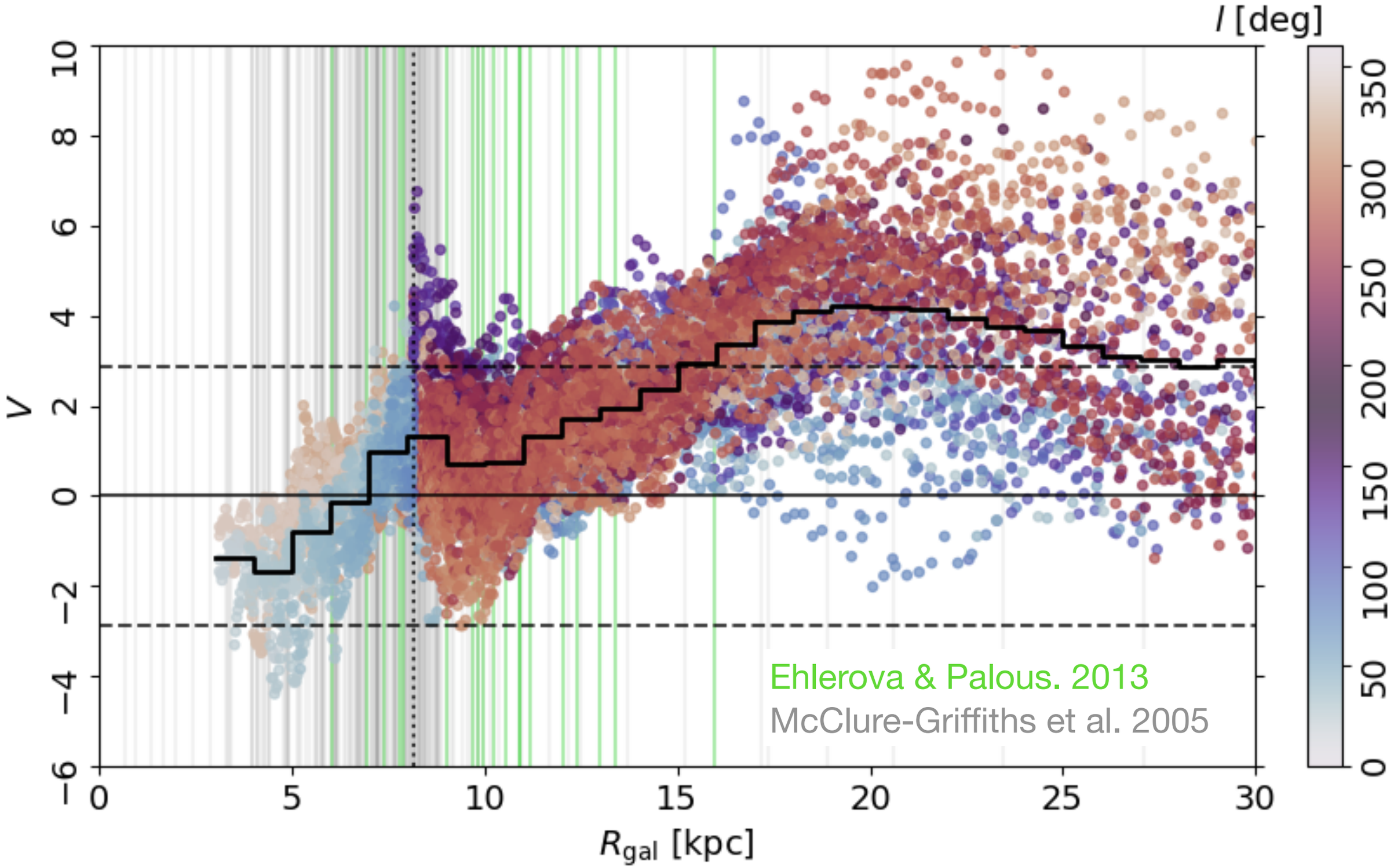
Atomic filament orientation and star formation

Soler, J.D. et al. 2022.



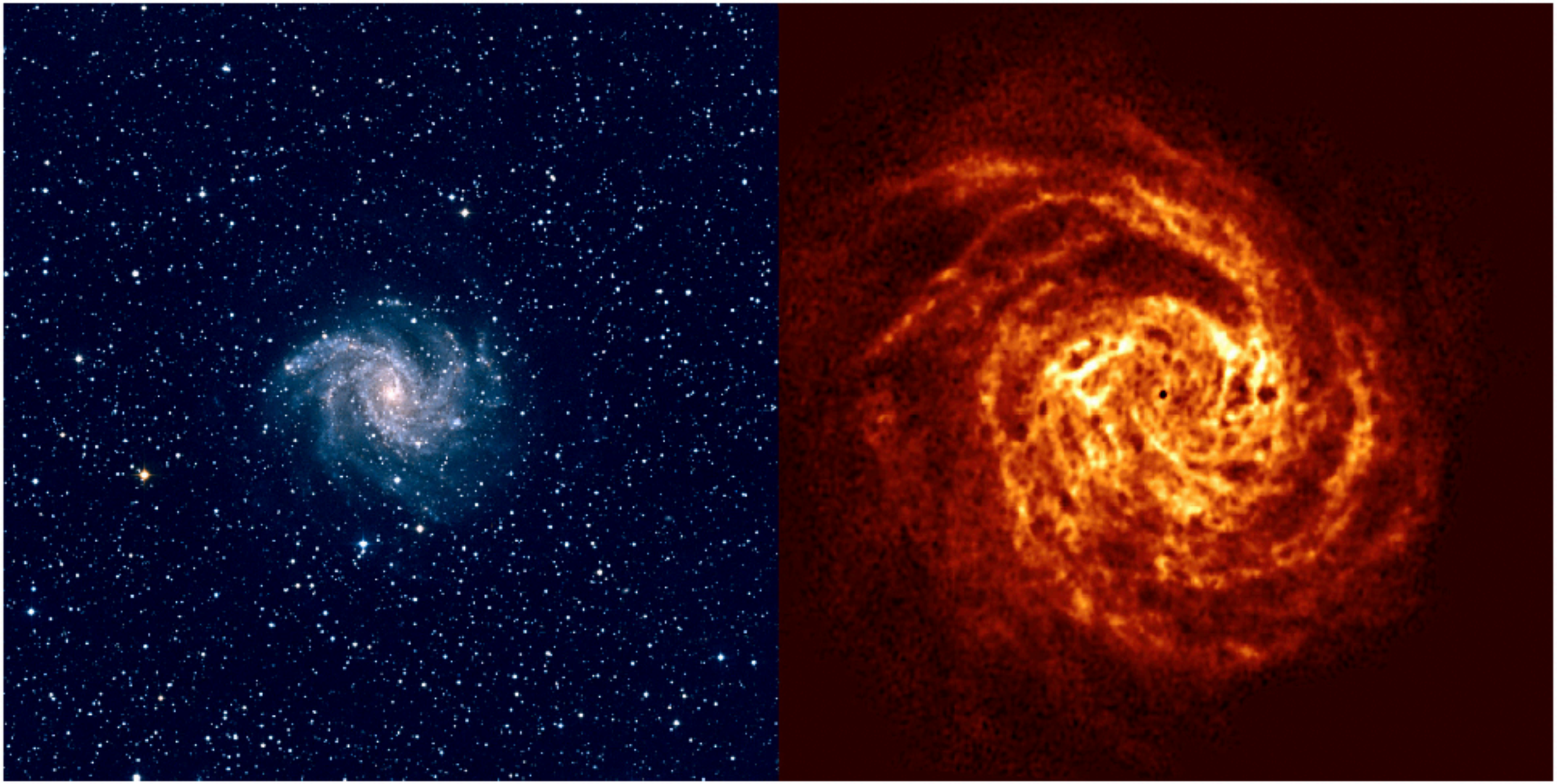
Atomic filament orientation and HI bubbles

Soler, J.D. et al. 2022.



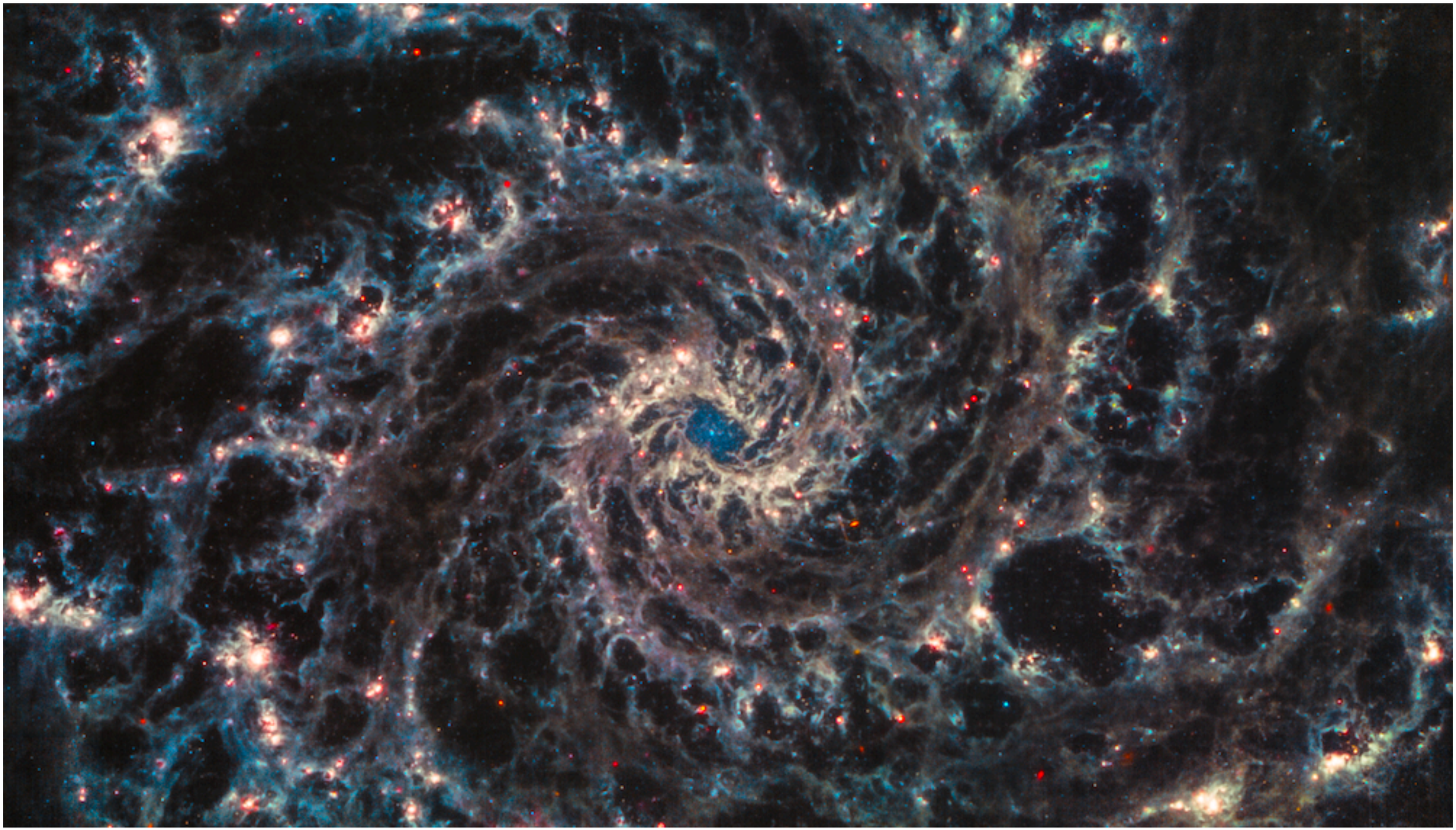
HI holes in the spiral galaxy NGC6946

Boomsma et al. A&A 2008



Holes and filaments in NGC628

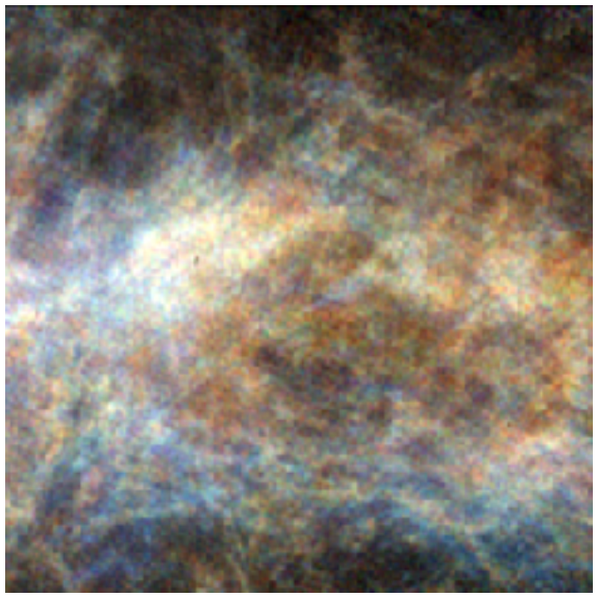
JWST/NASA/ESA/CSA/Judy Schmid



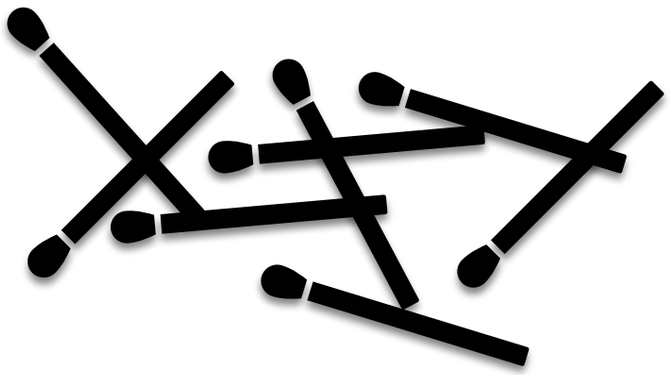
Data-driven analysis

Soler, J.D., et al. 2020. A&A
Soler, J.D., et al. 2022. A&A

Observations



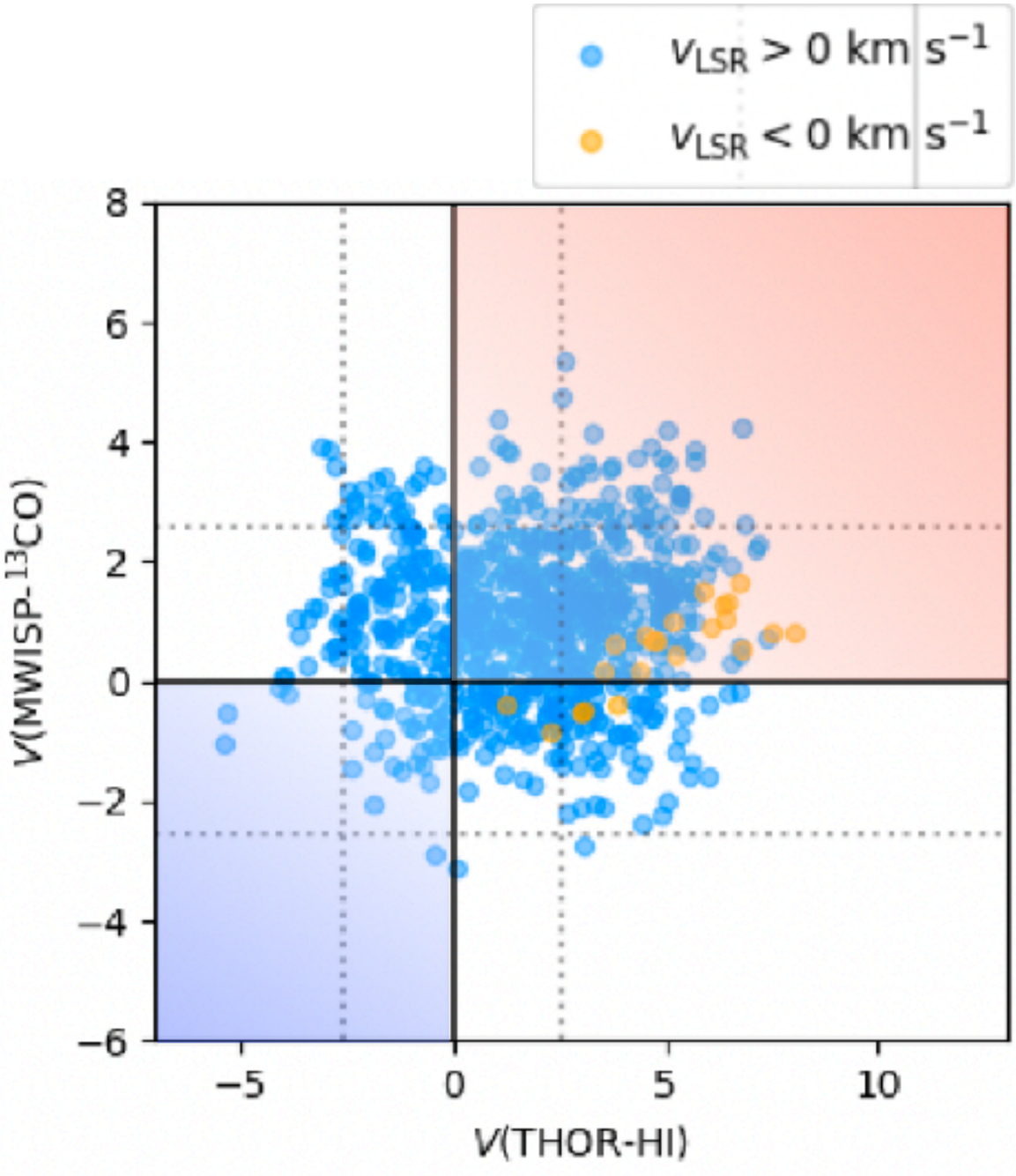
Characteristics

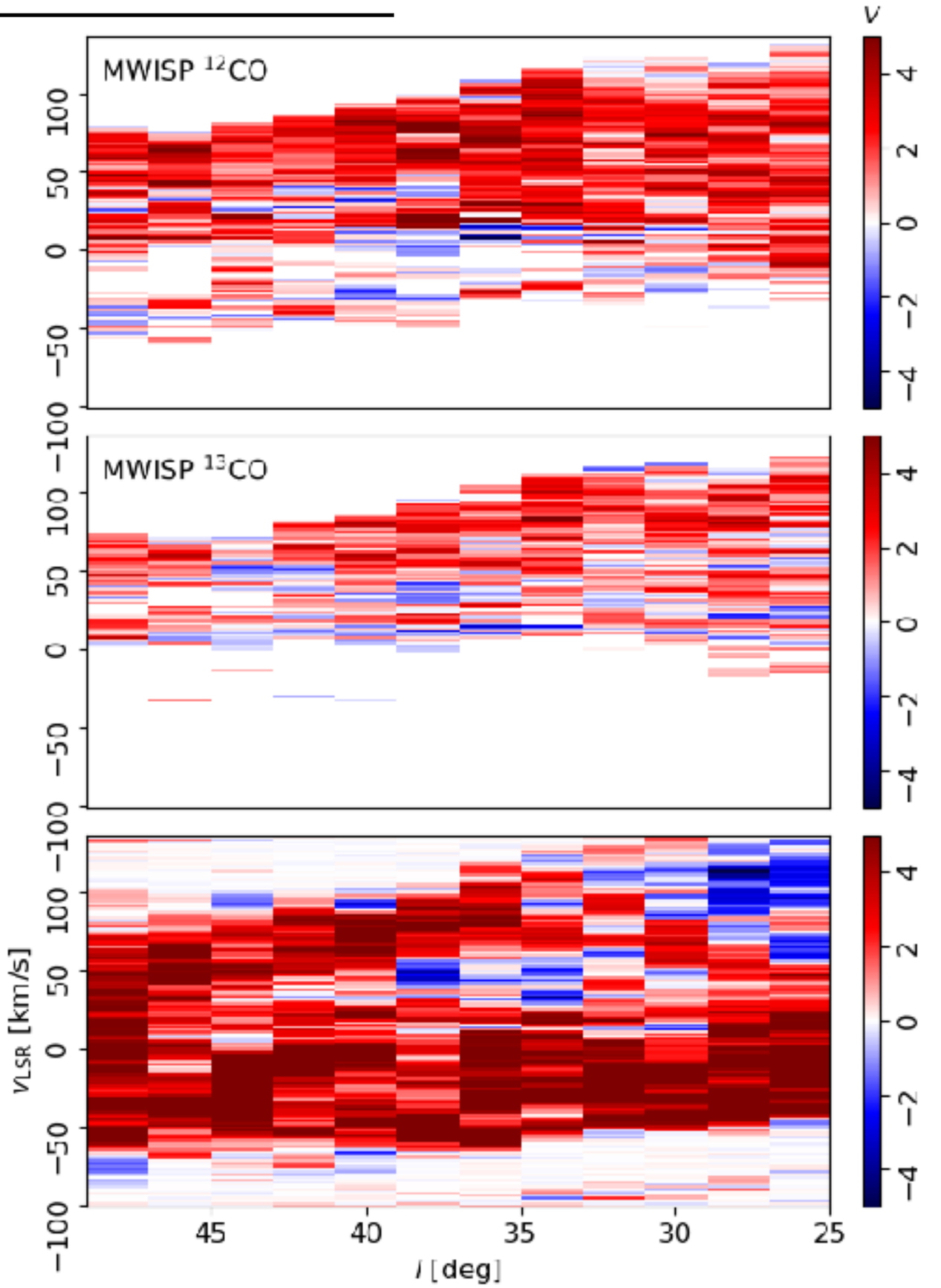


Families of models

CO filament orientation

MWISP CO survey. Sun et al. (2018)
Soler, J.D. et al. A&A (2021)





The Galactic dynamics revealed by HI and CO emission

We found that the **HI filament orientation** changes from mostly perpendicular to mostly parallel to the Galactic plane with increasing distance from the Galactic center.

The change in the **HI filament orientation** is most likely due to the energy and moment input from **supernova feedback**.

In general, the **HI filament orientation** is **not inherited** by the **CO filaments**, which may indicate the effect of stellar feedback and magnetic fields (not just gravity) shaping MCs.

Soler, J.D. et al. 2020. A&A
Soler, J.D. et al. 2021. A&A
Soler, J.D. et al. 2022. A&A

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