



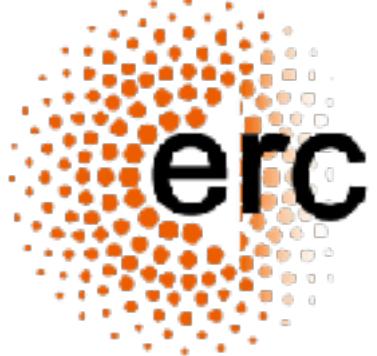
The Galactic dynamics revealed by the filamentary structure in the neutral atomic hydrogen emission

Juan Diego Soler

Istituto di Astrofisica e Planetologia Spaziali

Munich Joint Astronomy Colloquium (JAC)

March 9, 2023



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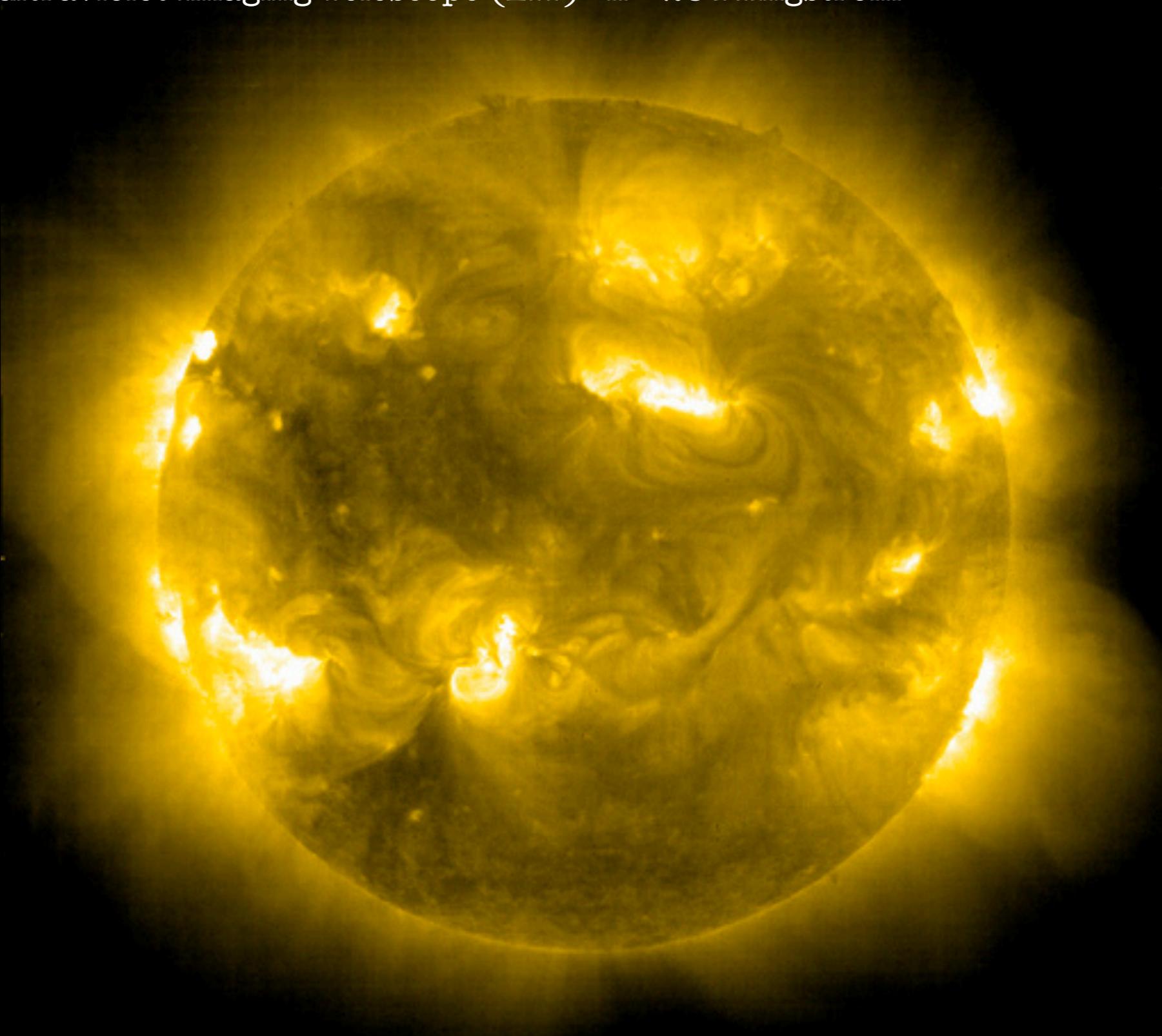
Istituto di Astrofisica e Planetologia Spaziali

THOR collaboration: H. Beuther, J. Syed, Y. Wang, Th. Henning
N. M. McClure-Griffiths, P. F. Goldsmith, M. Heyer, K. M. Menten,
L. D. Anderson, M. Rugel, R. Shanahan, J. S. Urquhart, J. Stil

ECOGAL collaboration: S. Molinari, R. S. Klessen, P. Hennebelle,
L. Testi, 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) - $\lambda = 284$ Angstrom



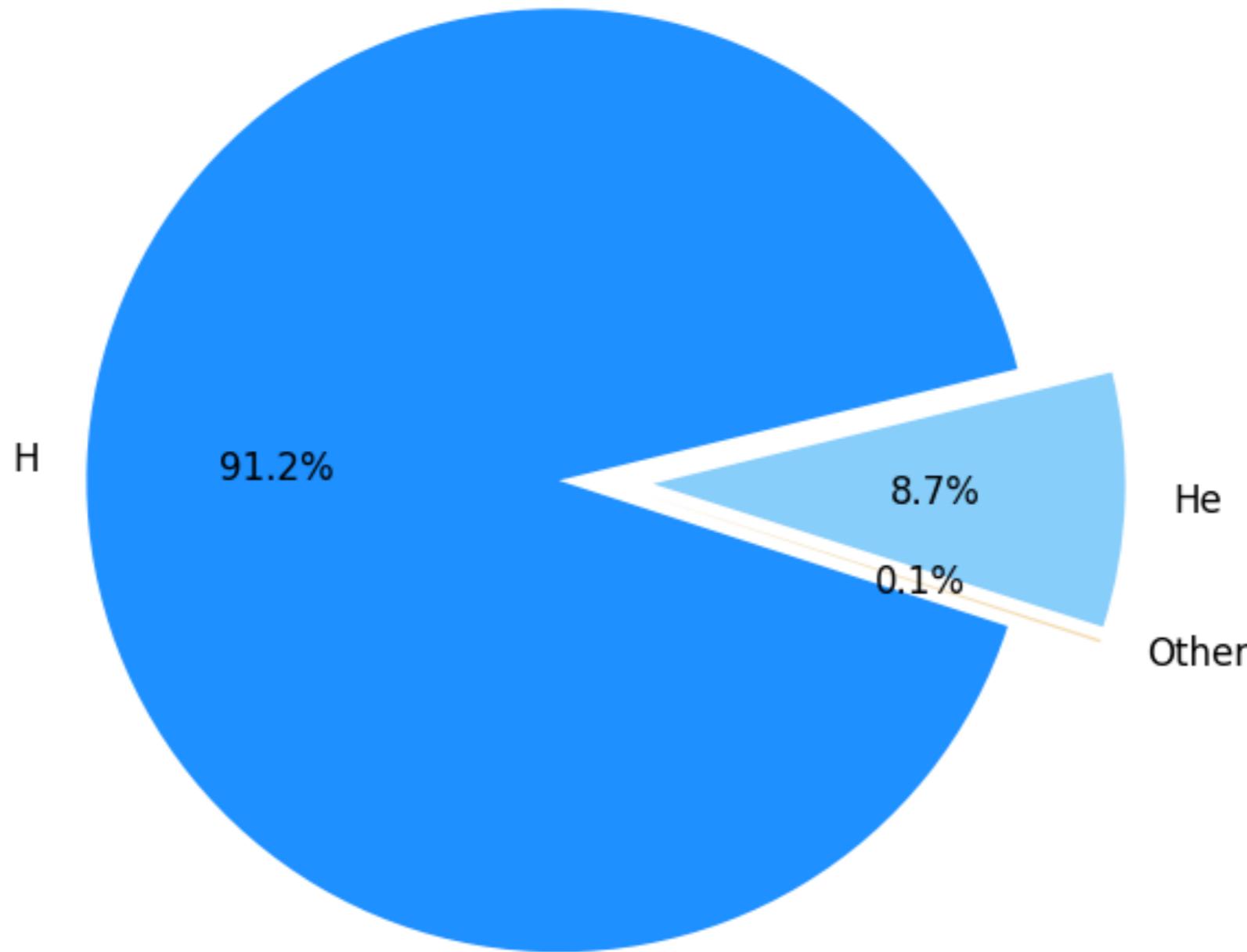
2023/03/09 01:06

Juan D. Soler (IAPS, Rome)

The Sun

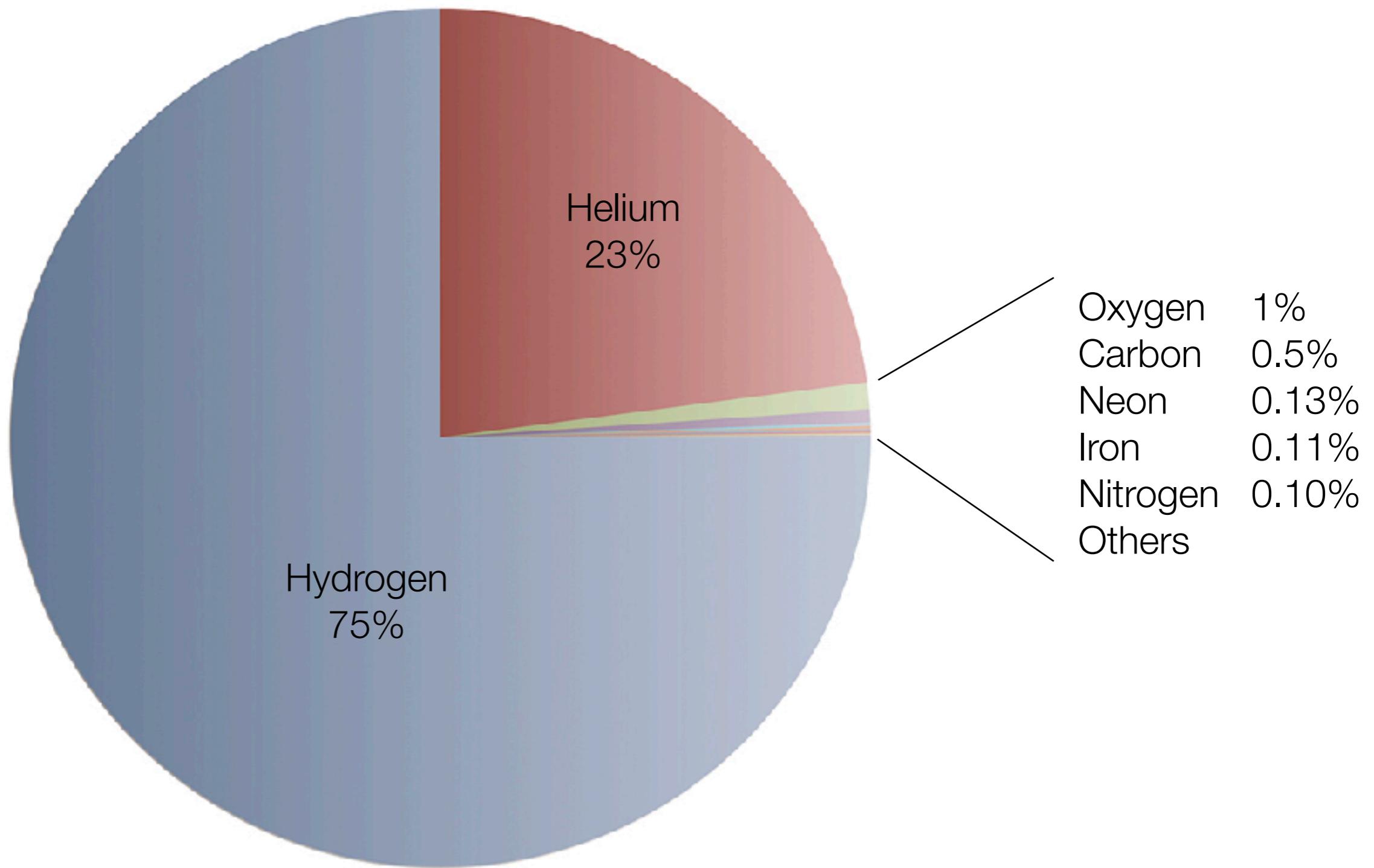
M. Asplund, A. Amarsi, and N. Grevesse. A&A (2021)

Sun composition by number of atoms



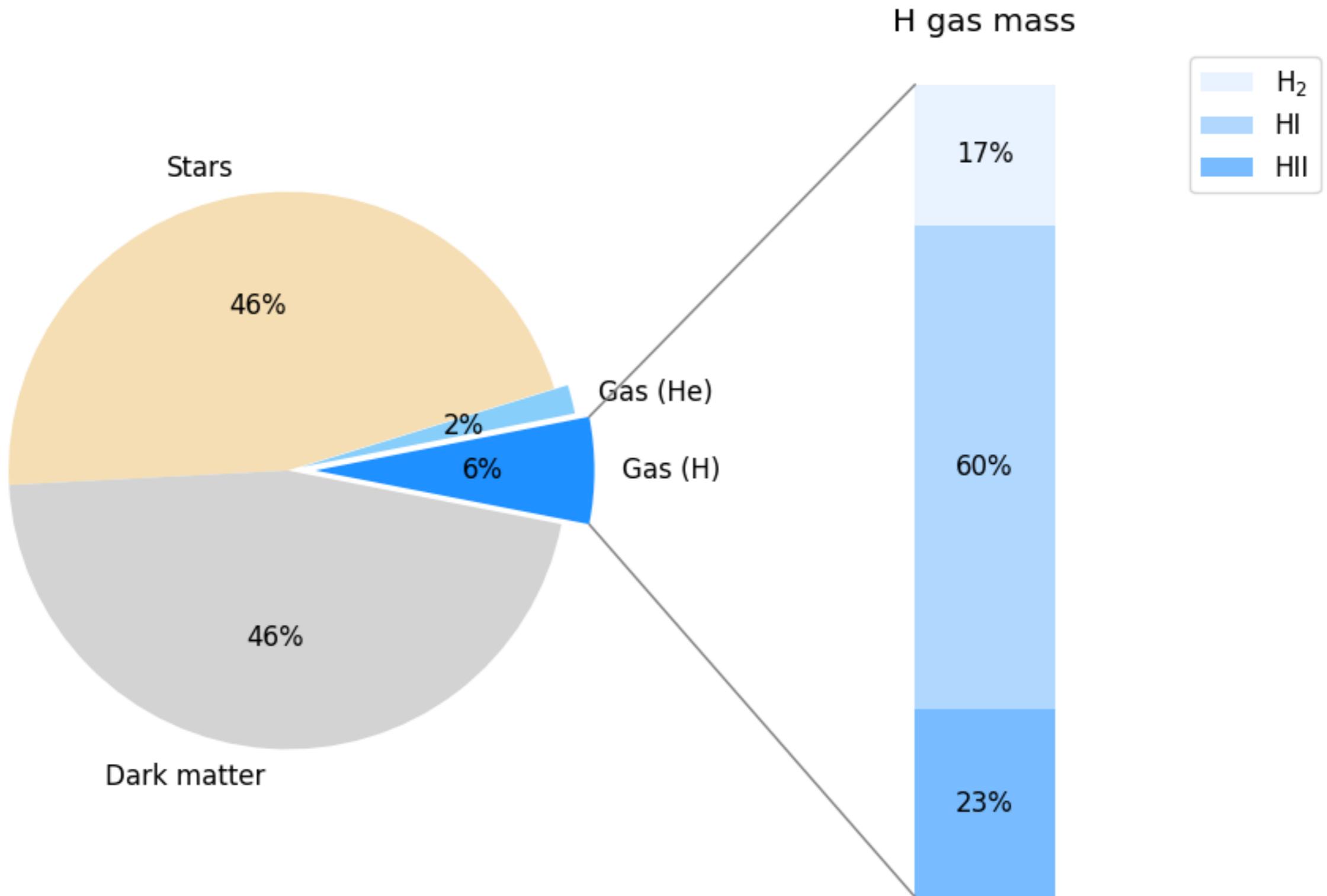
The Universe

NASA/CXC/M.Weiss

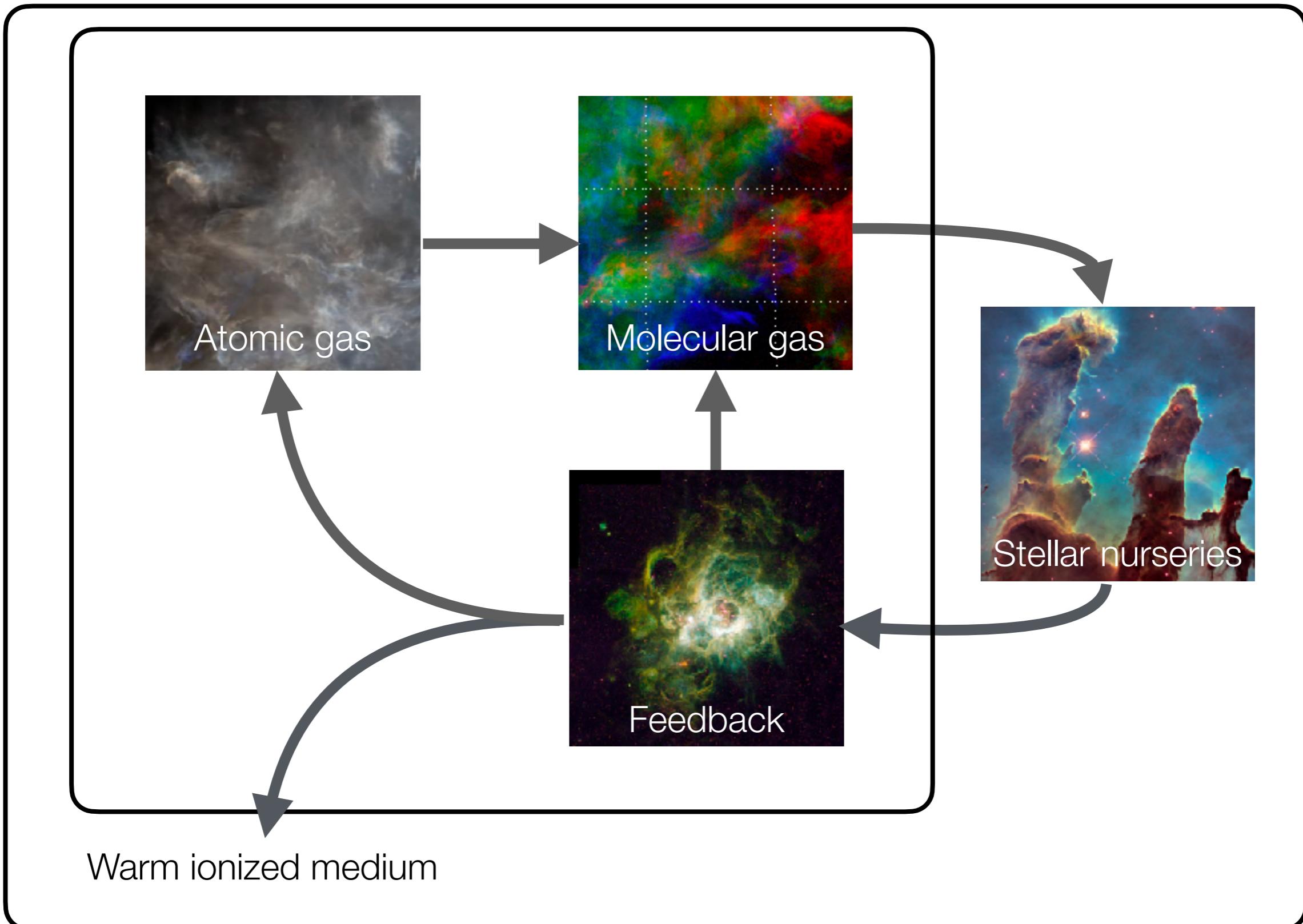


Milky Way's mass budget

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



Hydrogen lifecycle in the interstellar medium



Hot ionized medium

Neutral atomic hydrogen (HI) emission

HI4PI survey

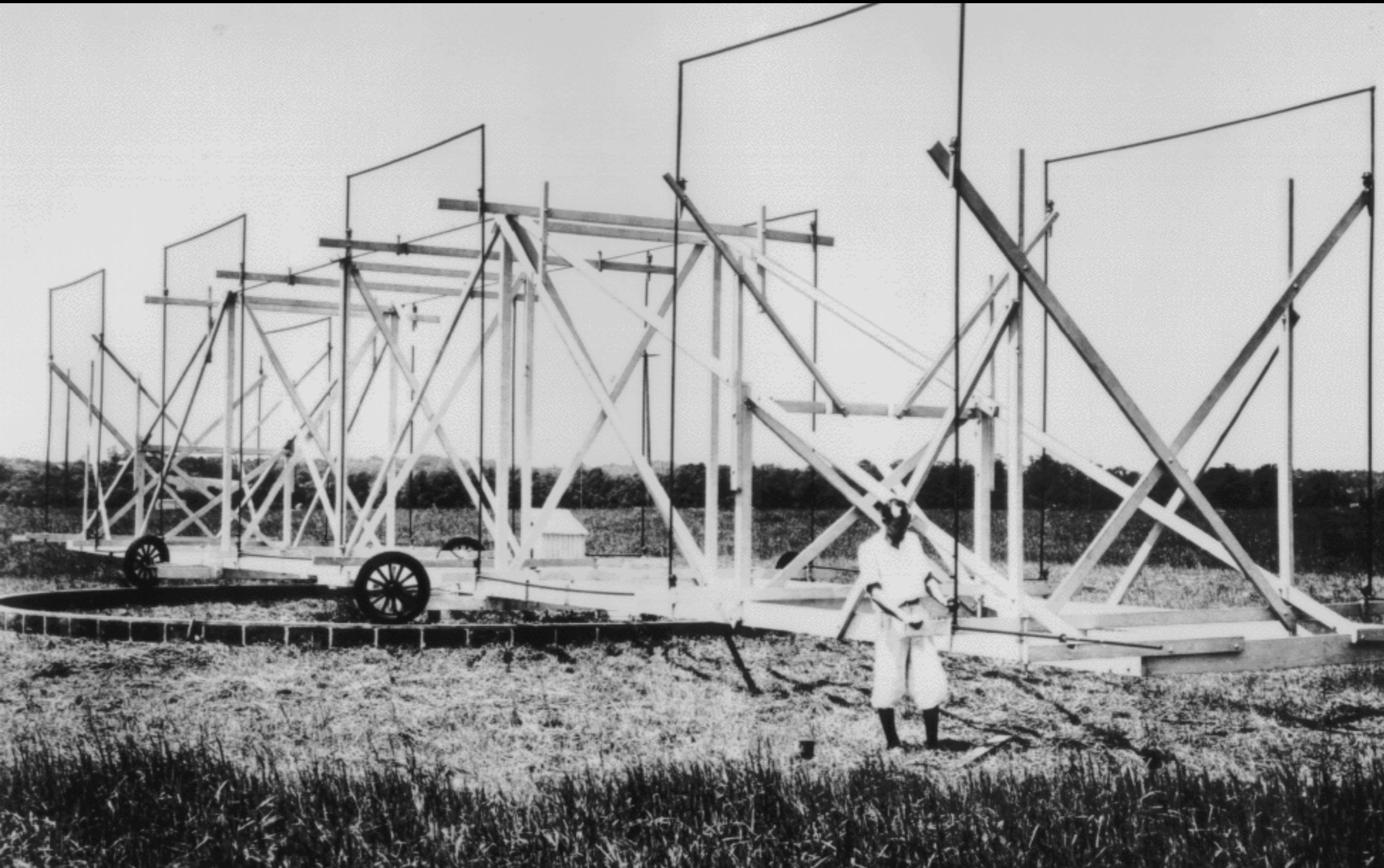
The Galactic dynamics revealed by HI

- I. Introducing the Galactic HI
 - A. Face-on Milky Way
 - B. Galactic warp
 - C. Galactic flaring
 - D. Shells and supershells
 - E. Multiphase interstellar medium (ISM) structure

- II. HI filaments and Galactic dynamics

Radioastronomy (20.5 MHz)

Karl Jansky. Bell Labs (1928-1933)



Atomic hydrogen emission

Elbers, A., The Rise of Radio Astronomy in the Netherlands (2016)

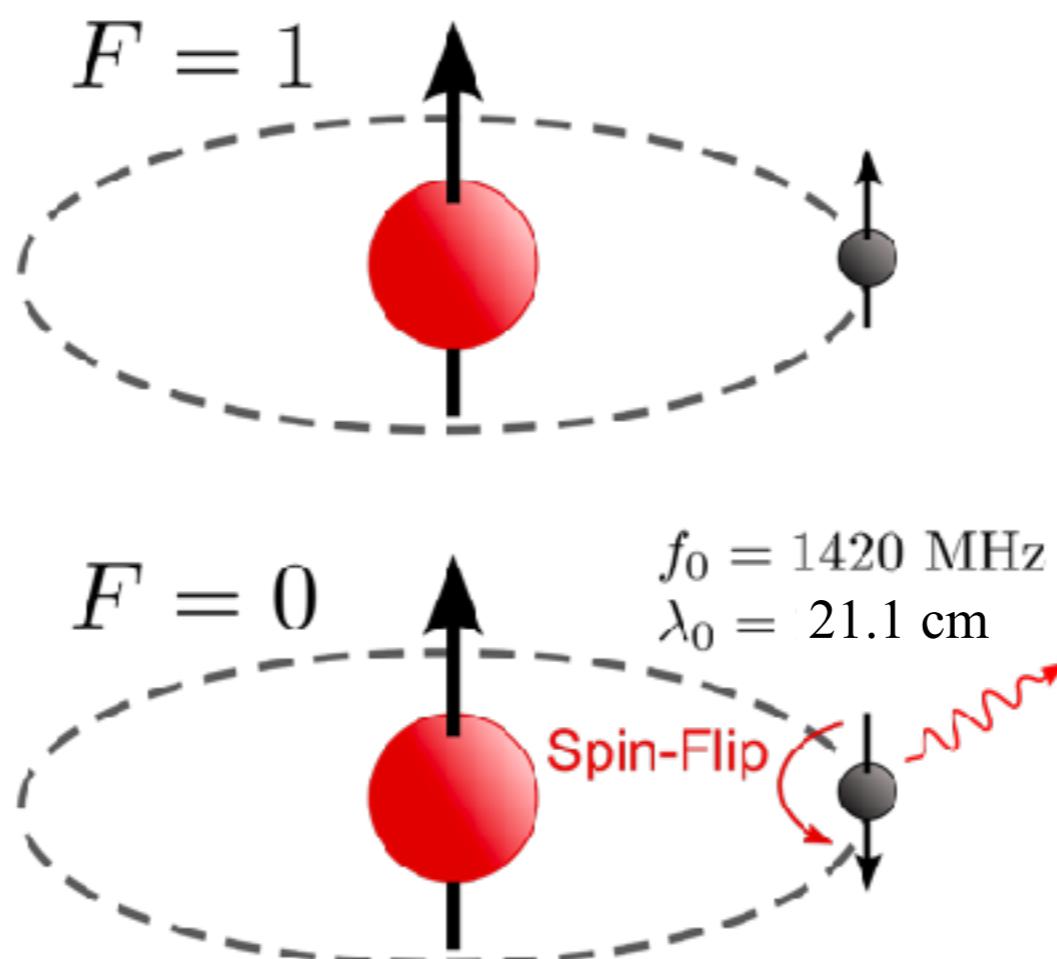


Hyperfine transition of neutral hydrogen

H.C. Van de Hulst (1945) Origin of the Radio Waves from Space*

The ground state of hydrogen is split by *hyperfine structure* into two levels

A quantum of wavelength 21.2 cm* is emitted due to a spontaneous flip of the spin.



Hyperfine transition of neutral hydrogen

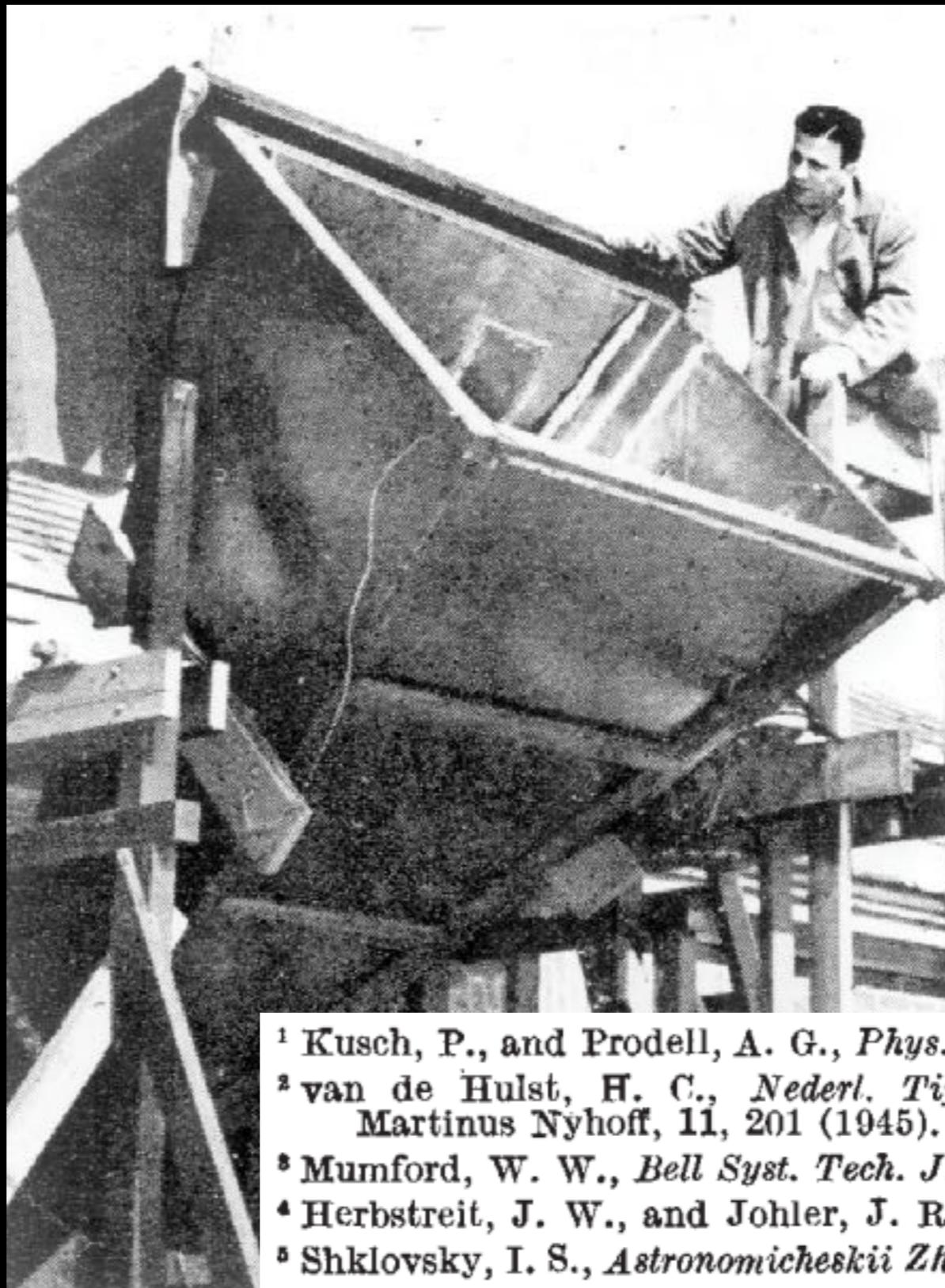
H.C. Van de Hulst (1945) Origin of the Radio Waves from Space*

Until a rigid calculation is made, the existence of this line remains speculative.

Atomic hydrogen emission

$\theta \approx 12^\circ$

Harold Ewen & Edward Purcell (1951)
Lyman Laboratory - Harvard University.

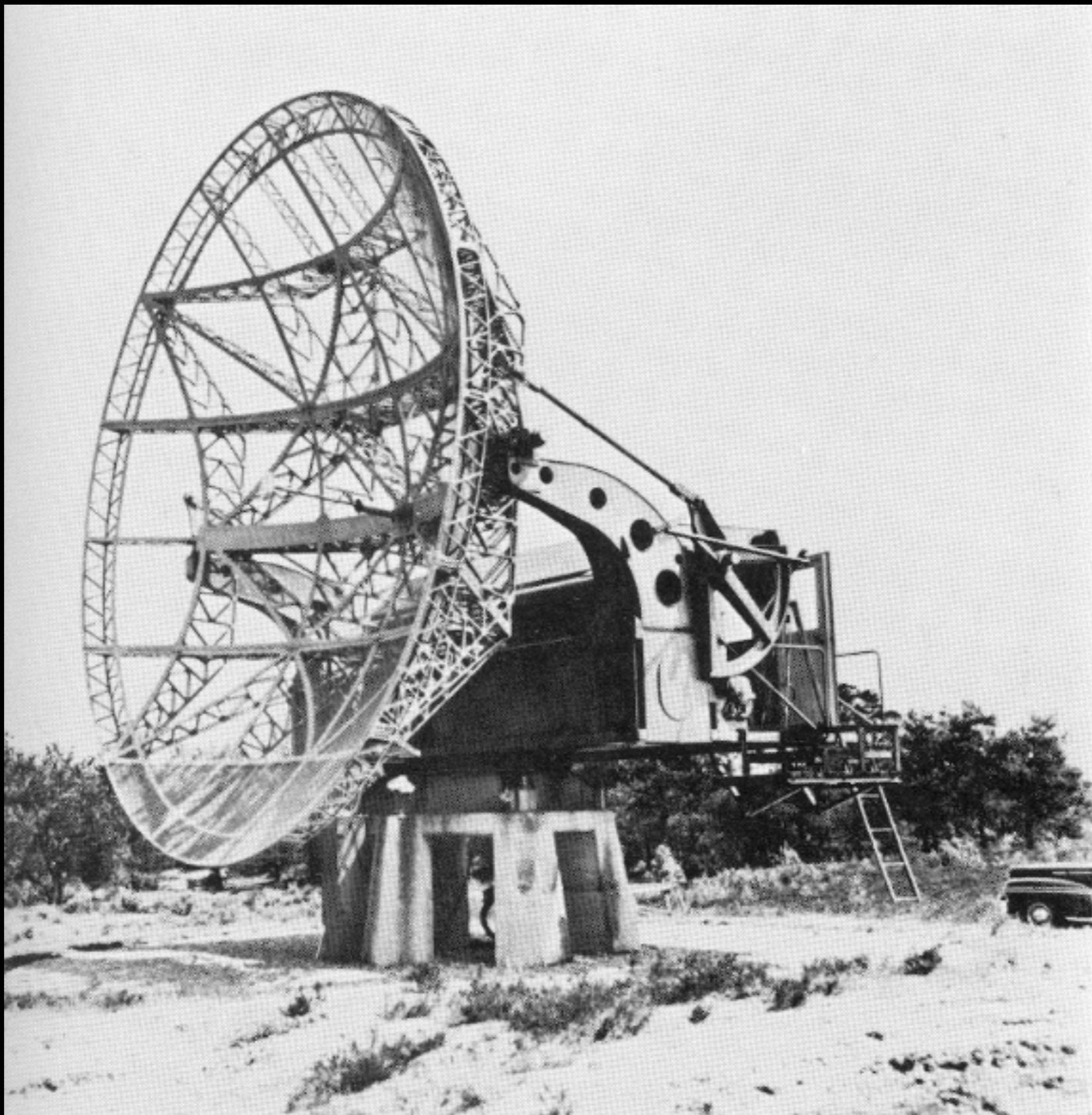


- ¹ Kusch, P., and Prodell, A. G., *Phys. Rev.*, **79**, 1009 (1950).
- ² van de Hulst, H. C., *Nederl. Tij. Natuurkunde*, 's-Gravenhage-Martinus Nijhoff, **11**, 201 (1945).
- ³ Mumford, W. W., *Bell Syst. Tech. J.*, **28**, 608 (1949).
- ⁴ Herbstreit, J. W., and Johler, J. R., *Nature*, **161**, 515 (1948).
- ⁵ Shklovsky, I. S., *Astronomicheskii Zhurnal*, **26**, 10 (1949) (in Russian).

Atomic hydrogen emission

$$\theta \approx 2^\circ$$

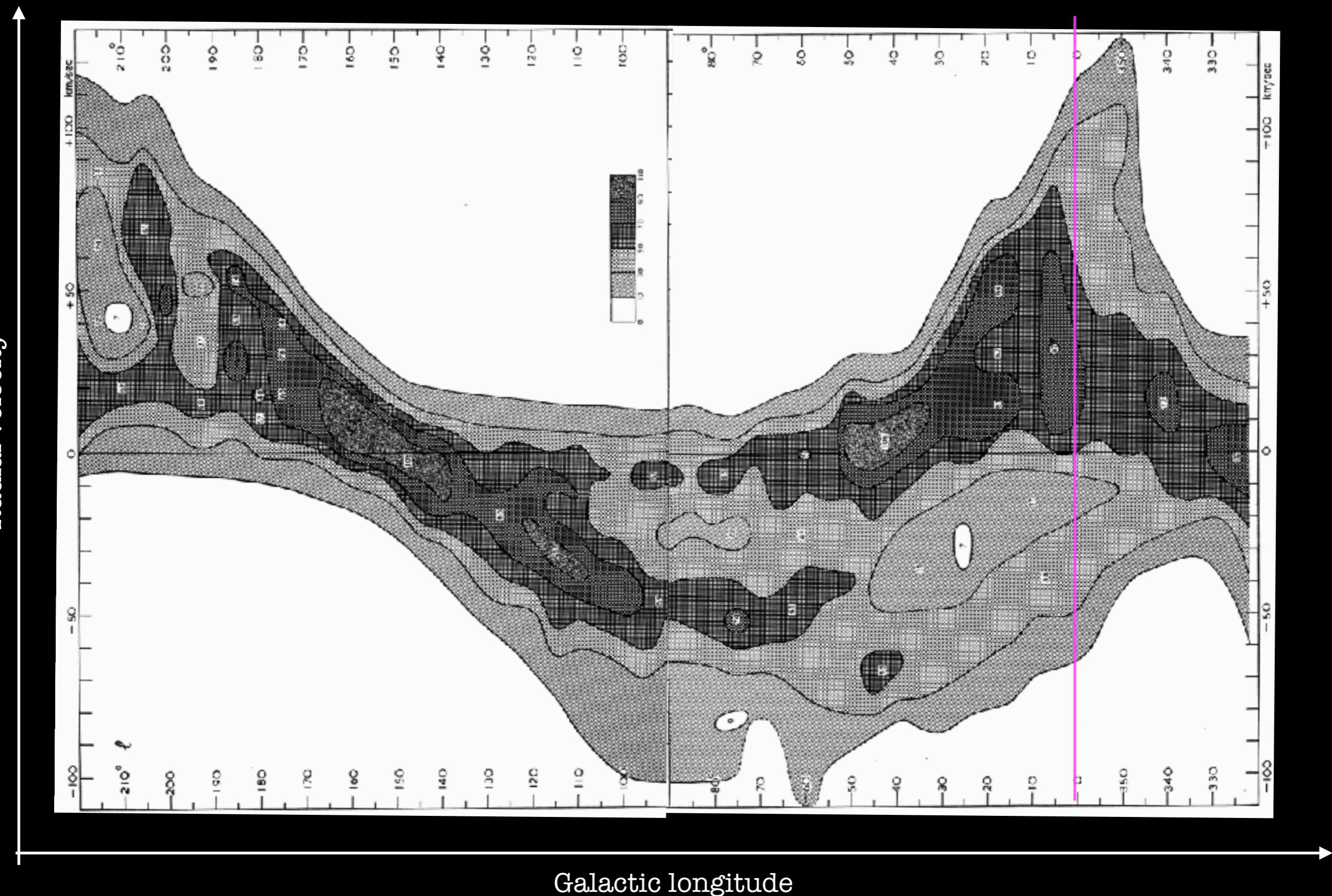
Würzburg radar antenna (7.5 m)



HI emission toward the Milky Way

$\theta \approx 2^\circ$

van de Hulst, Muller & Oort. BAN (1954)

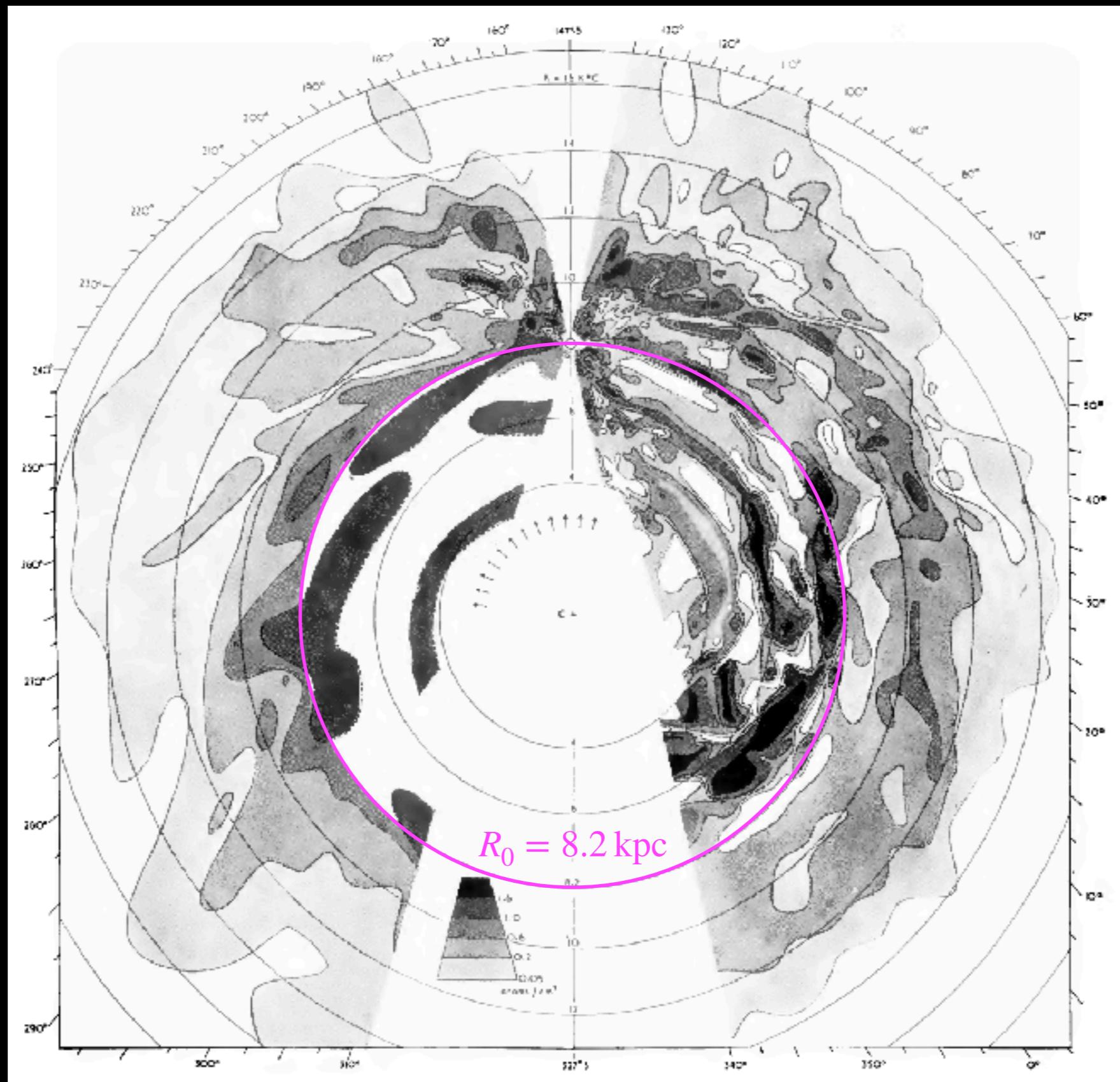


Galactic longitude

A. HI mapping face-on Milky Way

$$\theta \approx 2^\circ$$

Oort; Kerr & Westerhout. MNRAS (1958)



A. HI mapping face-on Milky Way

$\theta \approx 0.6^\circ$

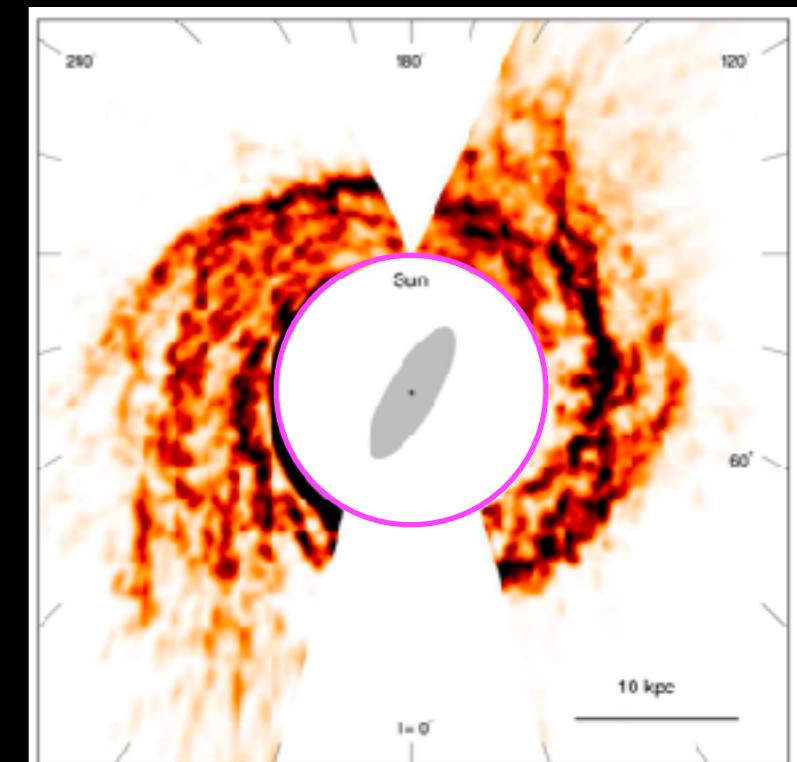
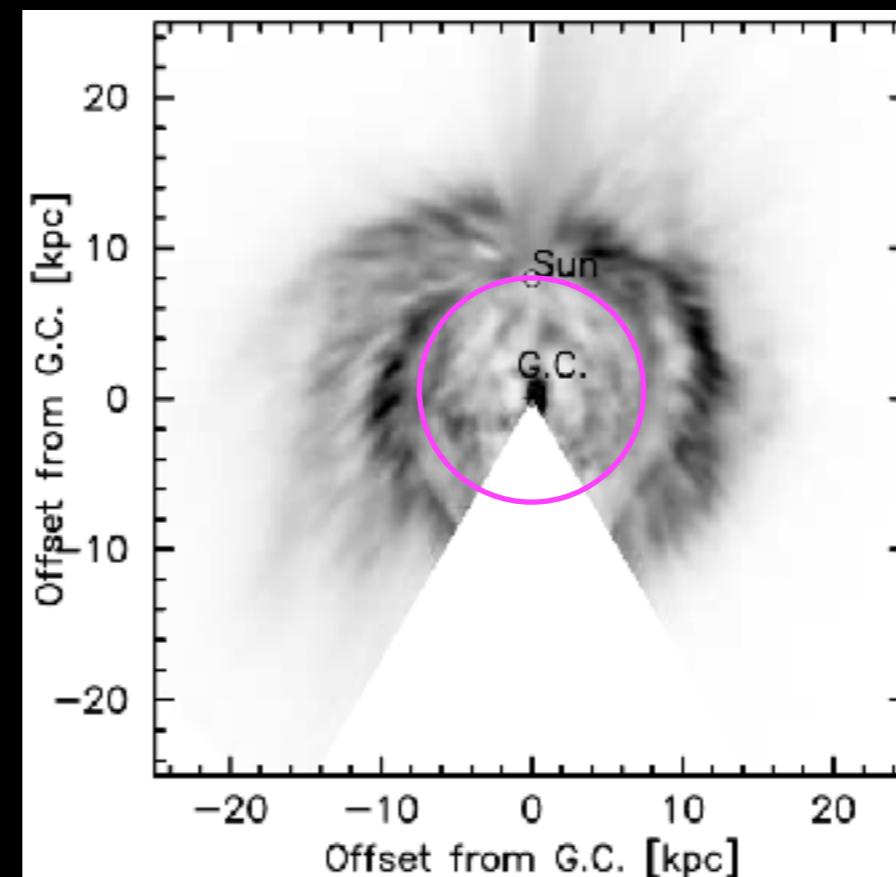
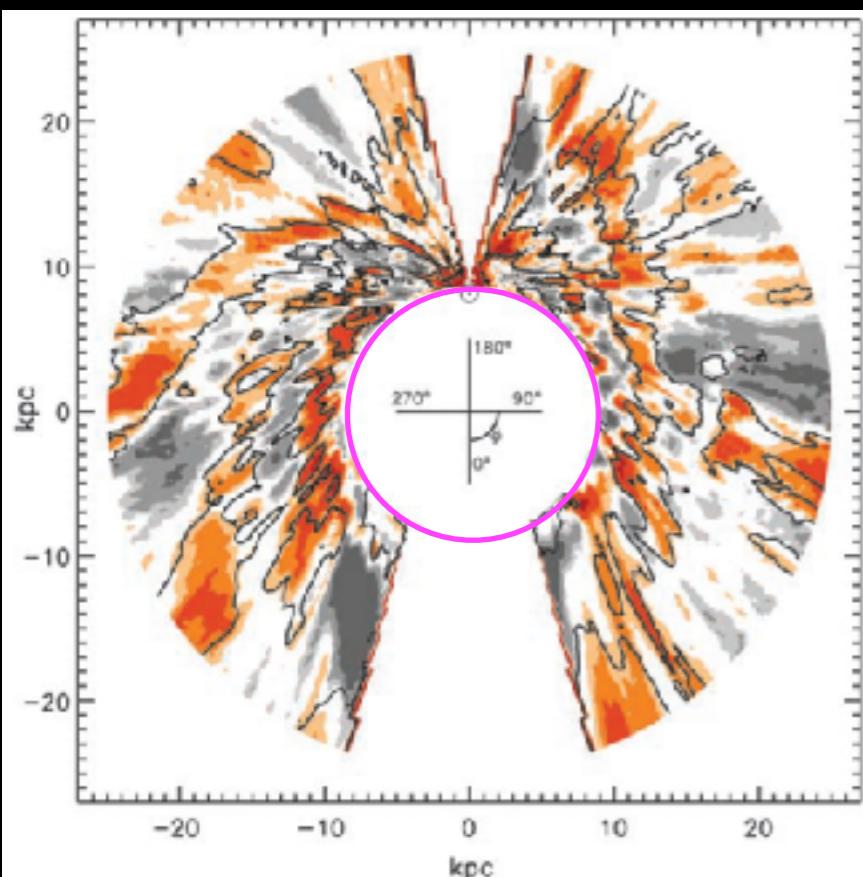
LAB survey

HI surface density

Levine, Blitz & Heiles (2006)

Nakanishi & Sofue. PASJ (2016)

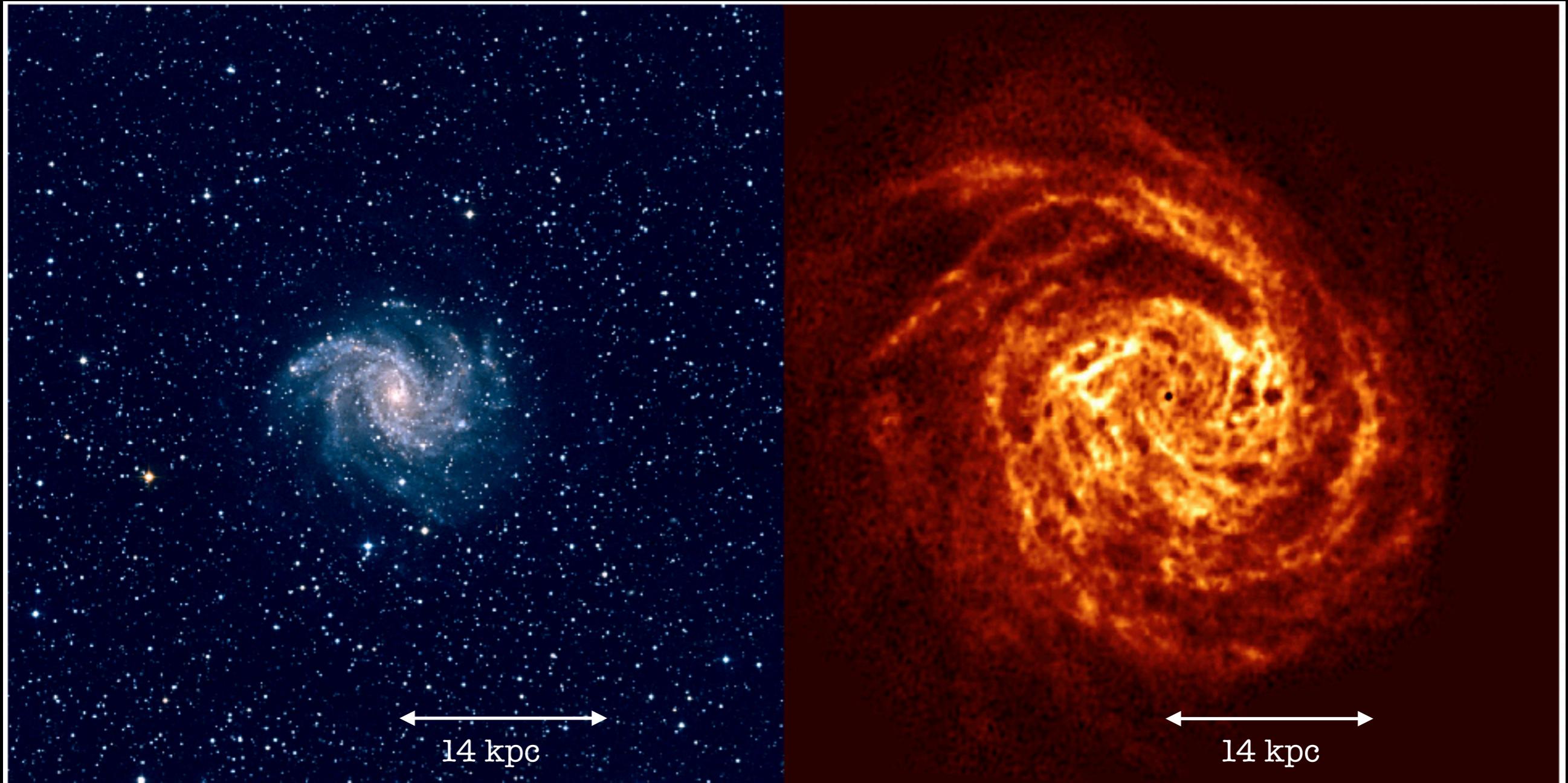
Koo et al. PASP (2017)



A. HI mapping face-on Milky Way

Boomsma et al. A&A (2008)

NGC6946 ($d = 6$ Mpc)

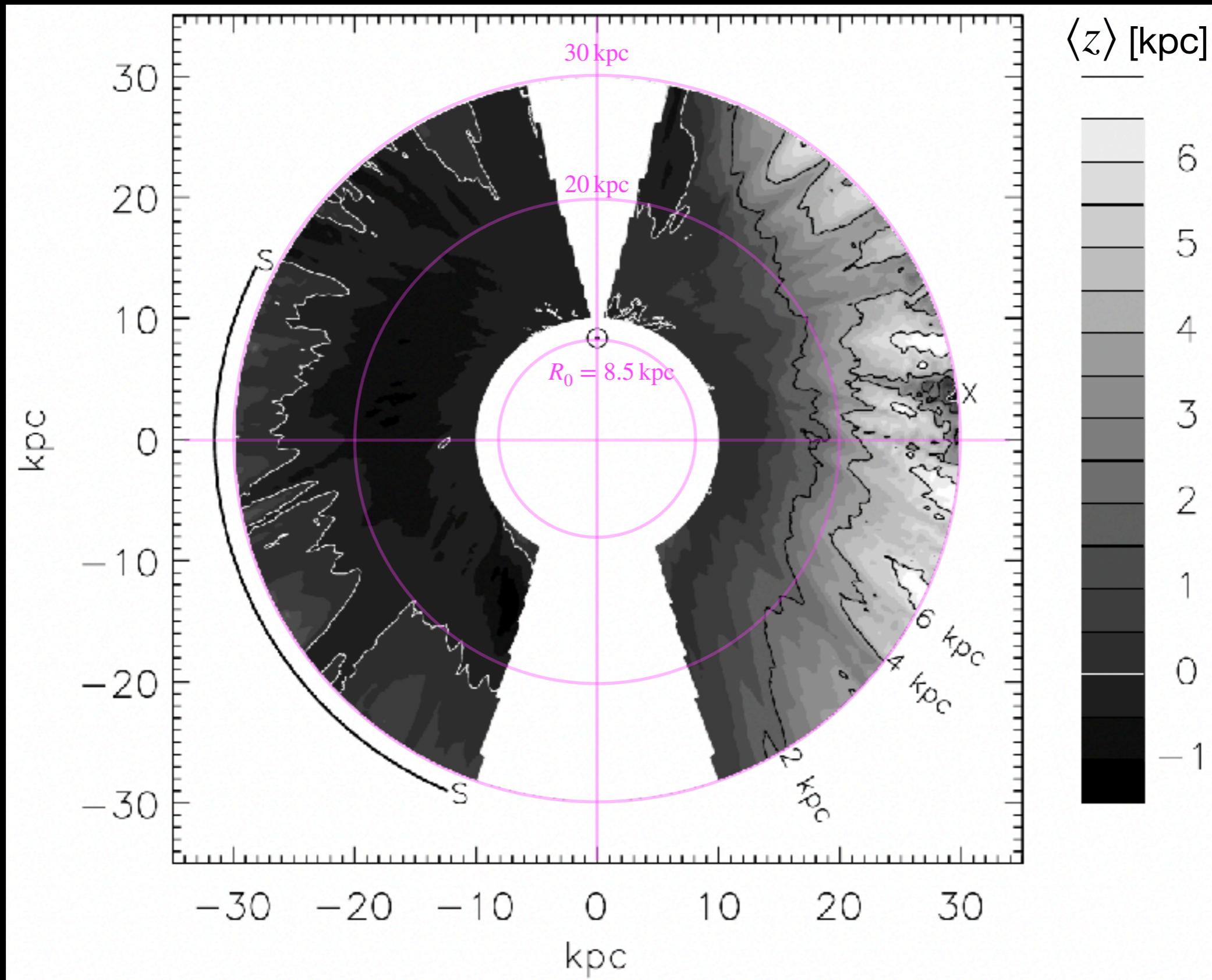


B. HI mapping Galactic disk warp

$\langle z \rangle$

$\theta \approx 30'$

Levine, Blitz & Heiles (2006).

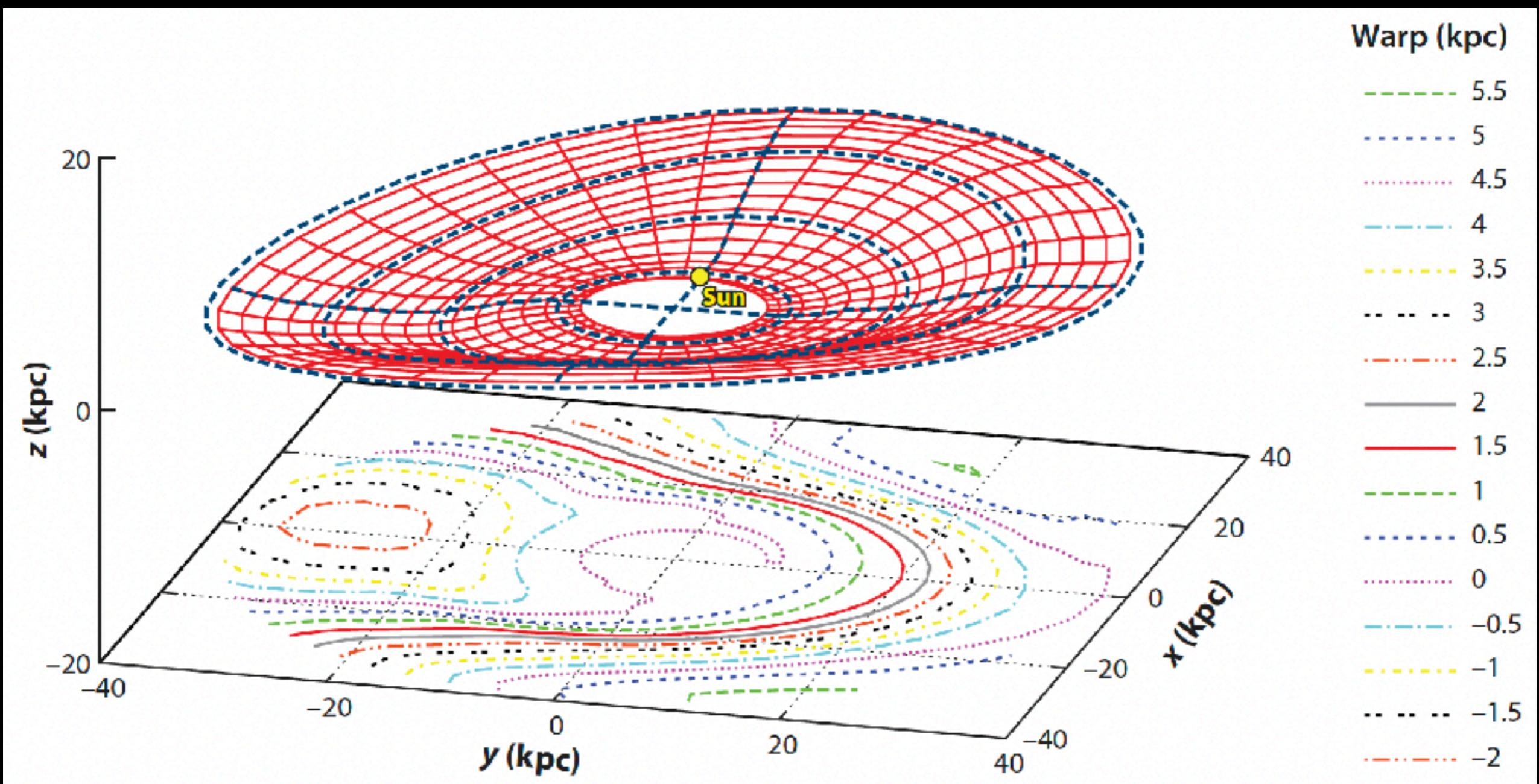


B. HI mapping Galactic disk warp

$$\langle z \rangle$$

$$\theta \approx 48'$$

Kalberla & Kerp. ARA&A. (2009).

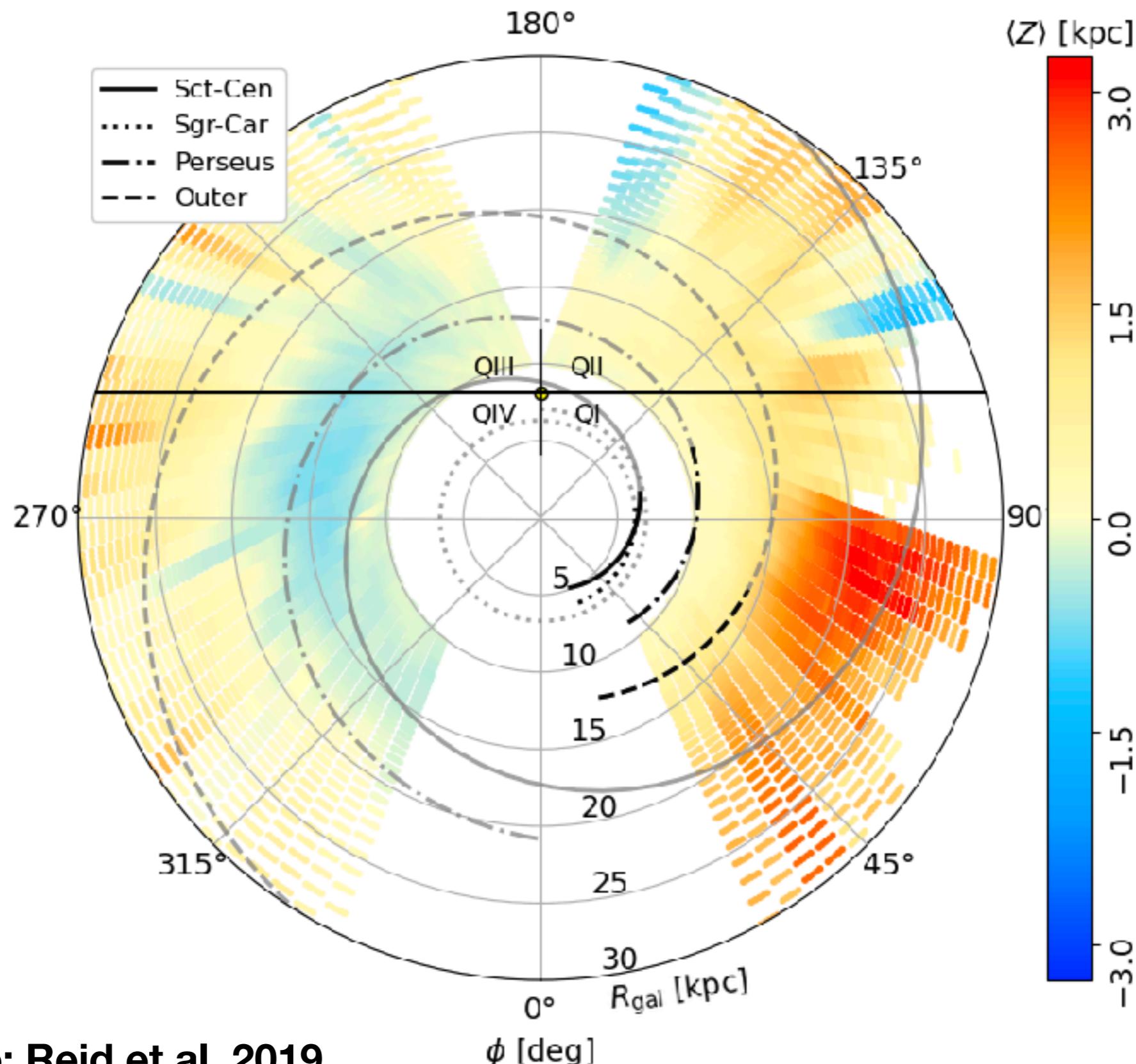


B. HI mapping Galactic disk warp

$$\langle z \rangle$$

$$\theta \approx 16.4'$$

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



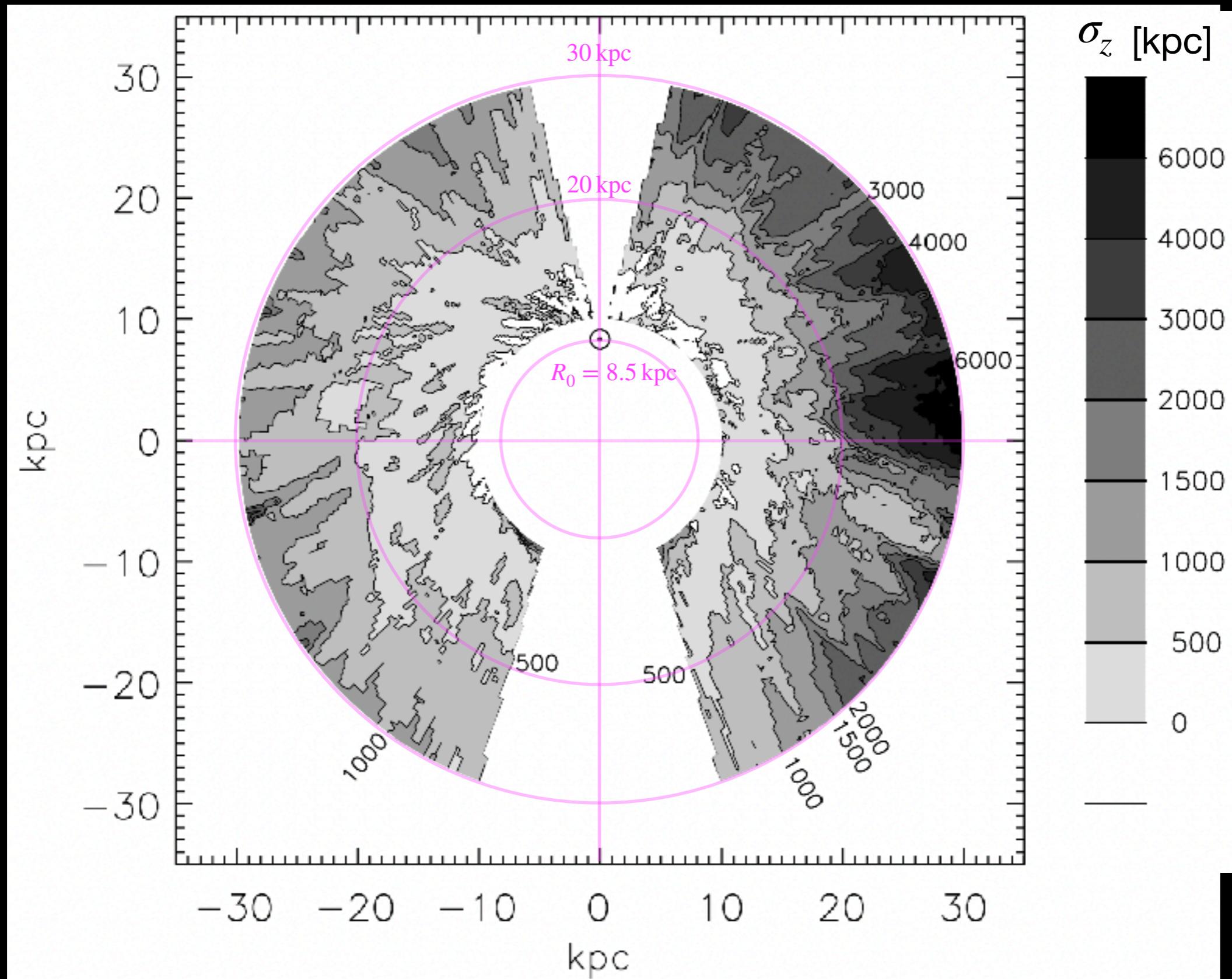
Rotation curve: Reid et al. 2019

C. HI mapping Galactic disk flaring

σ_z

$\theta \approx 30'$

Levine, Blitz & Heiles (2006).

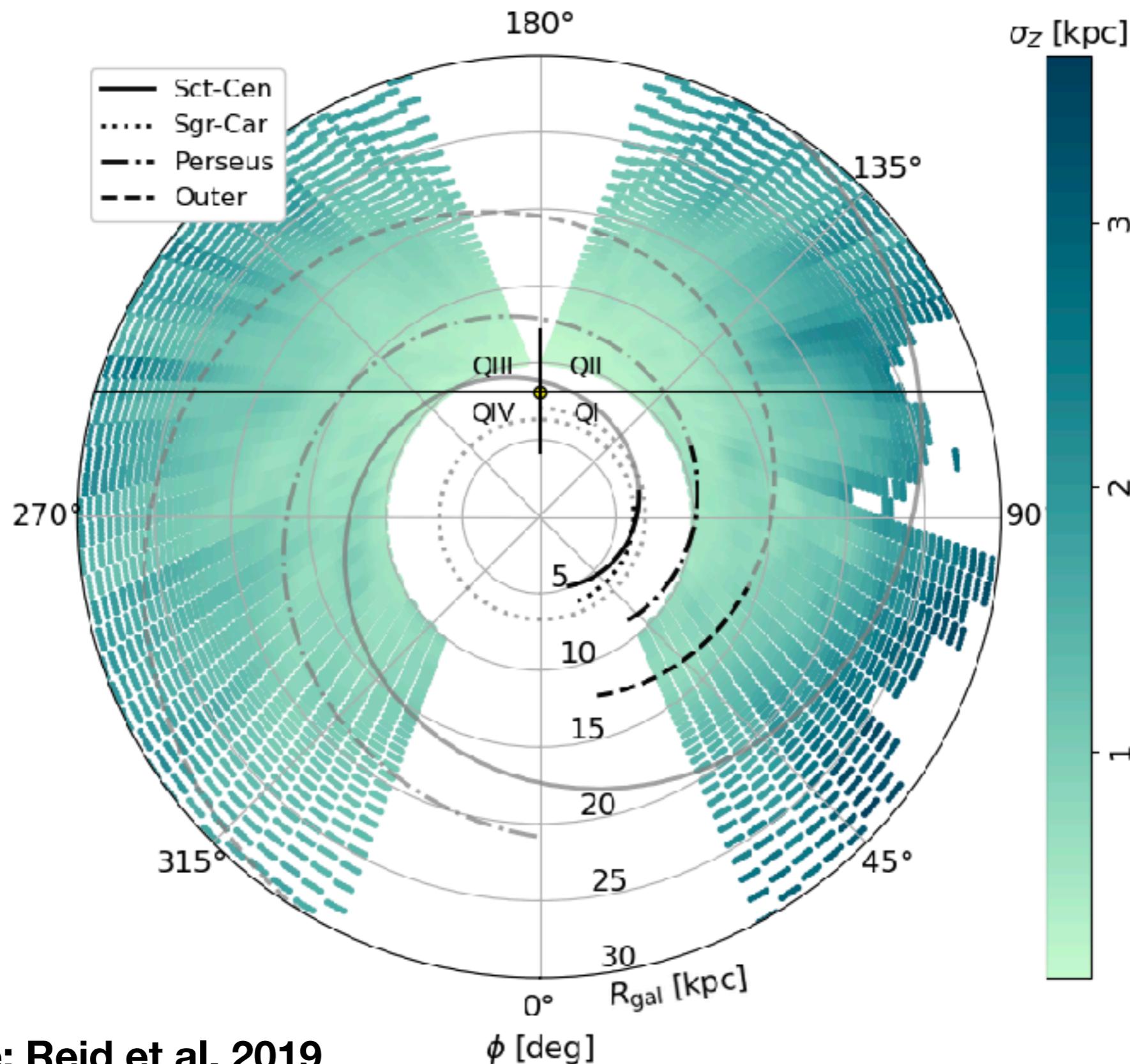


C. HI mapping Galactic disk flaring

σ_z

$\theta \approx 16.4'$

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



Rotation curve: Reid et al. 2019

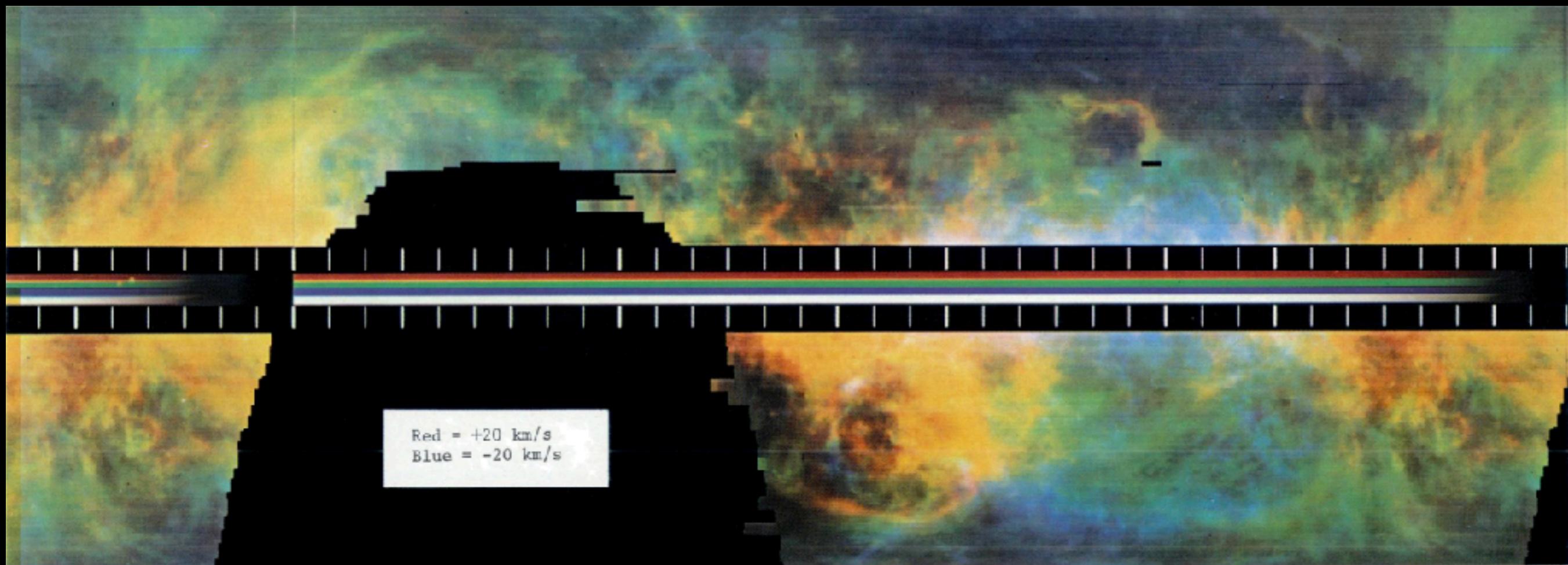
ϕ [deg]

D. HI mapping shells and supershells

$\theta \approx 0.6^\circ$

Heiles & Jenkins. A&A (1976)

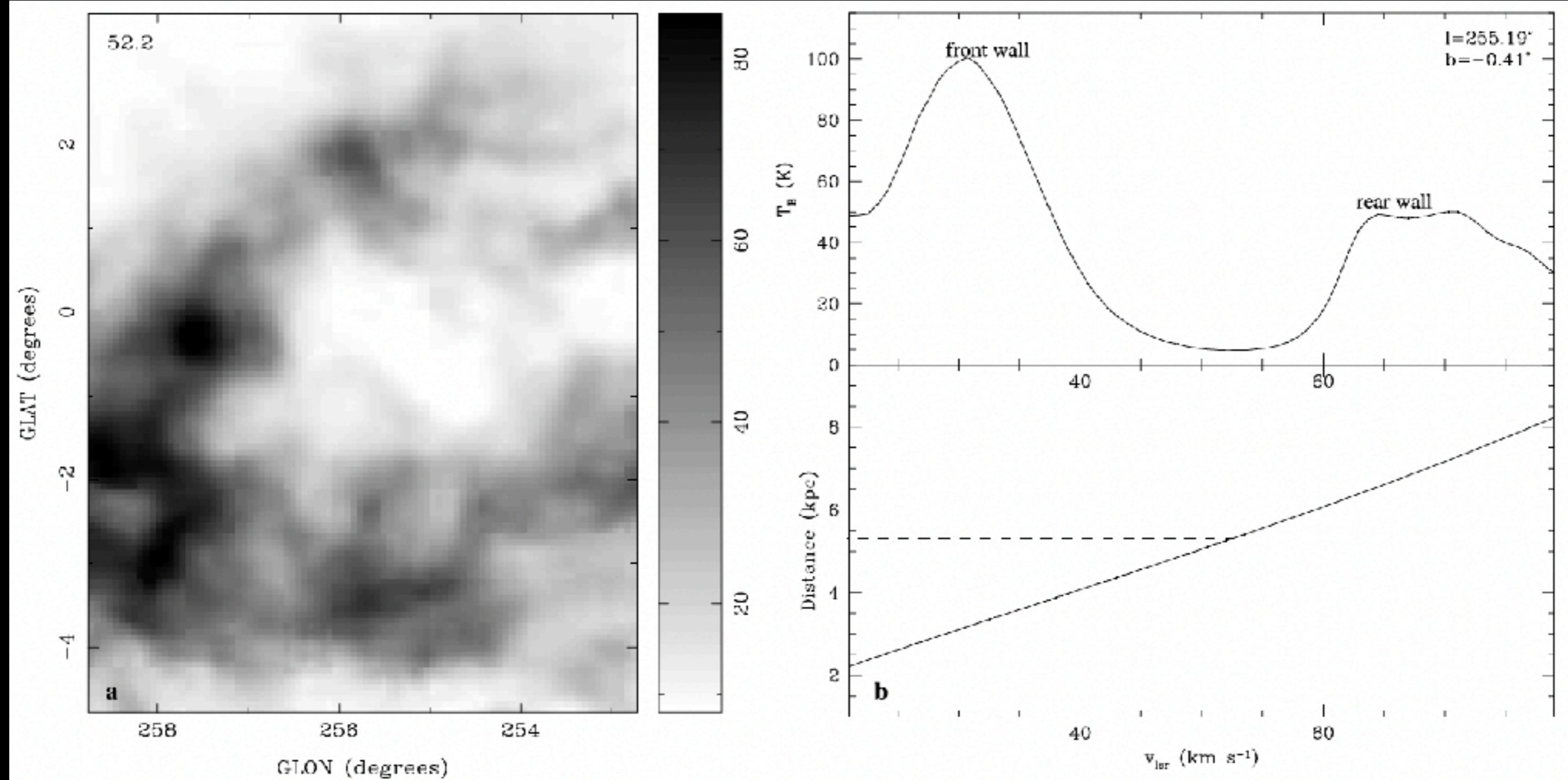
$b = +60^\circ$



$b = -60^\circ$

D. HI mapping shells and supershells

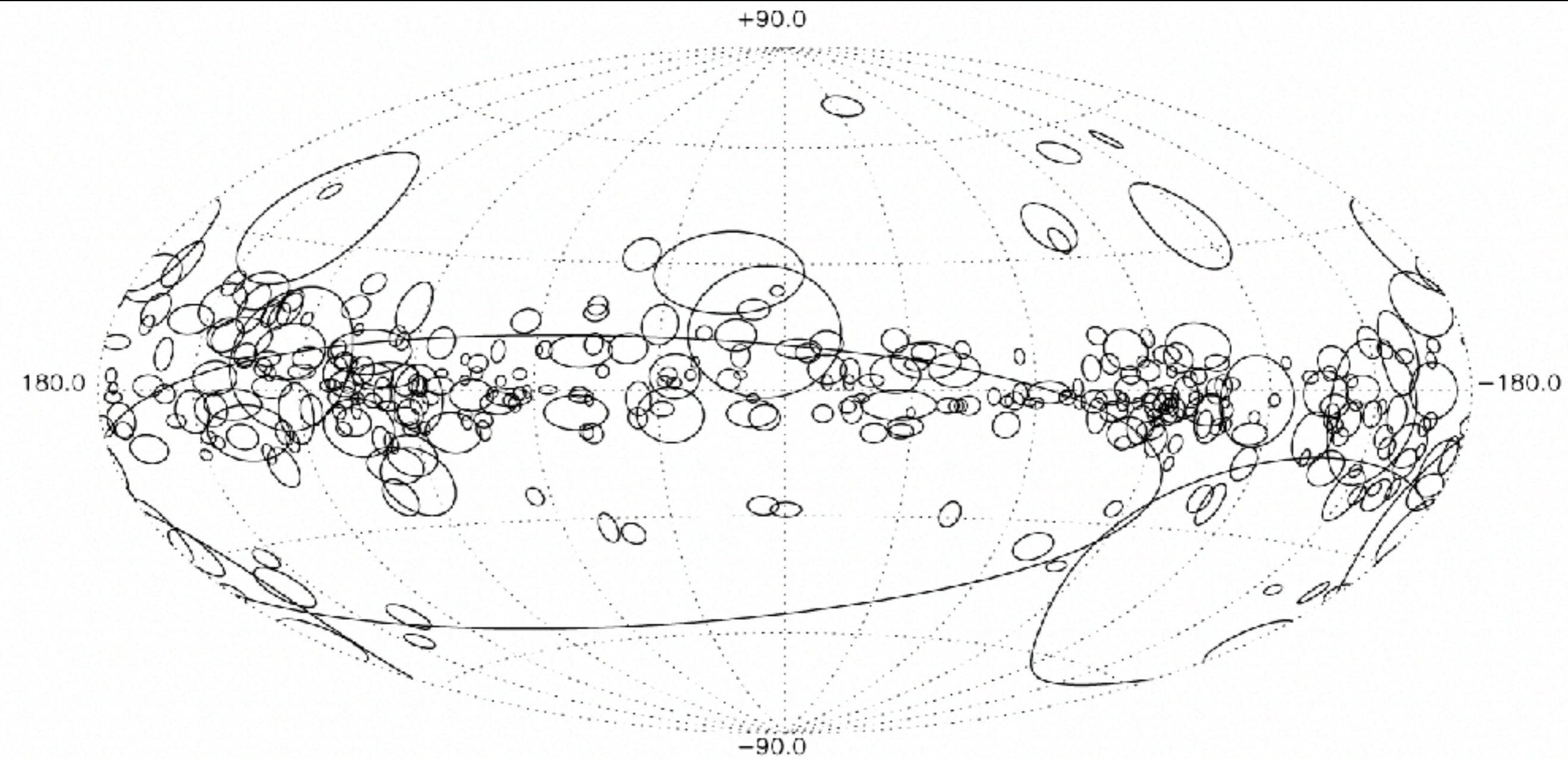
McClure-Griffiths et al. ApJ (2006)



D. HI mapping shells and supershells

$\theta \approx 36'$

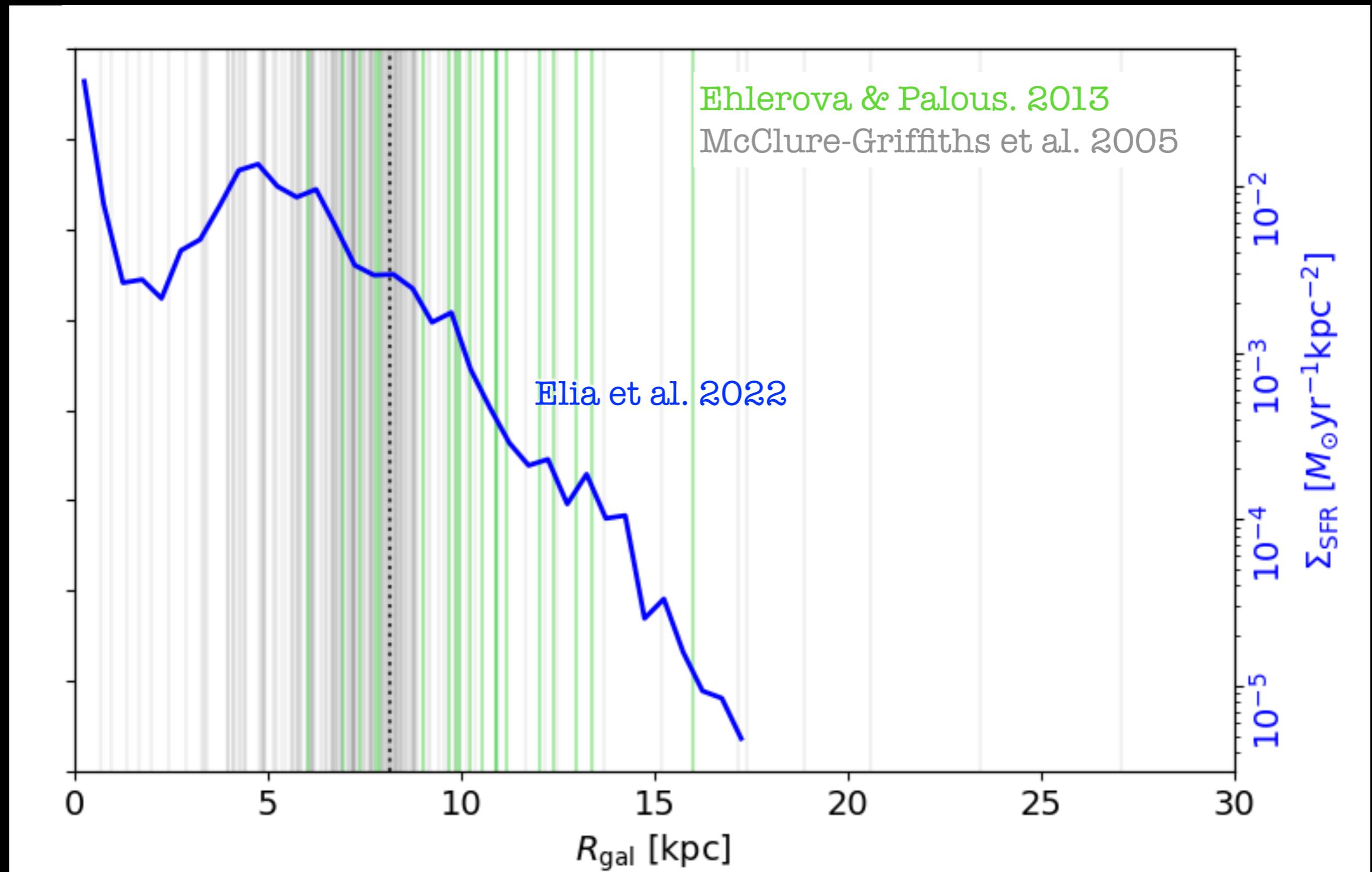
Ehlerová & Palouš. A&A (2013)



D. HI mapping shells and supershells

$\theta \approx 36'$

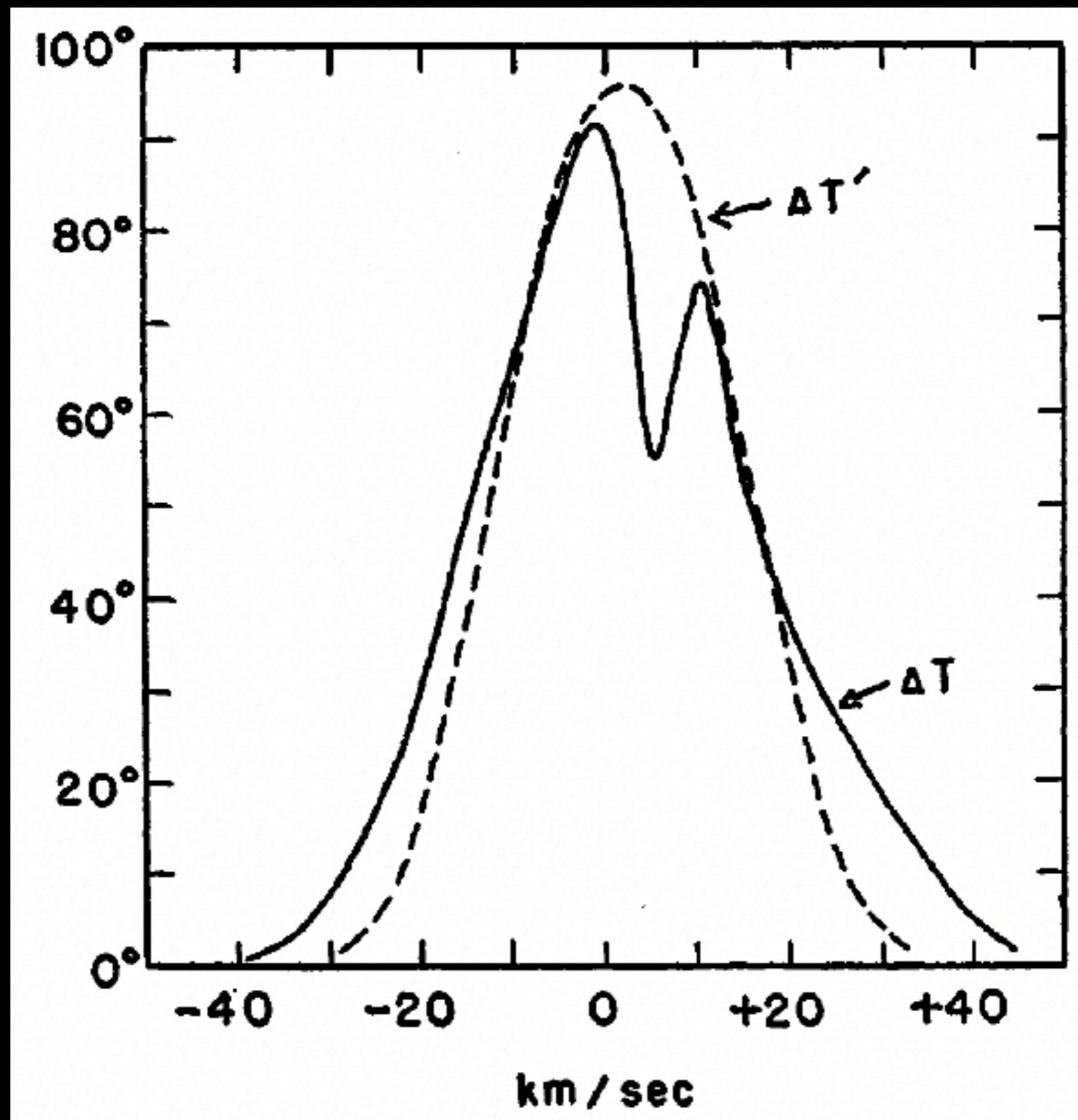
Soler, J.D. et al. A&A (2022)



E. HI mapping the multiphase ISM structure

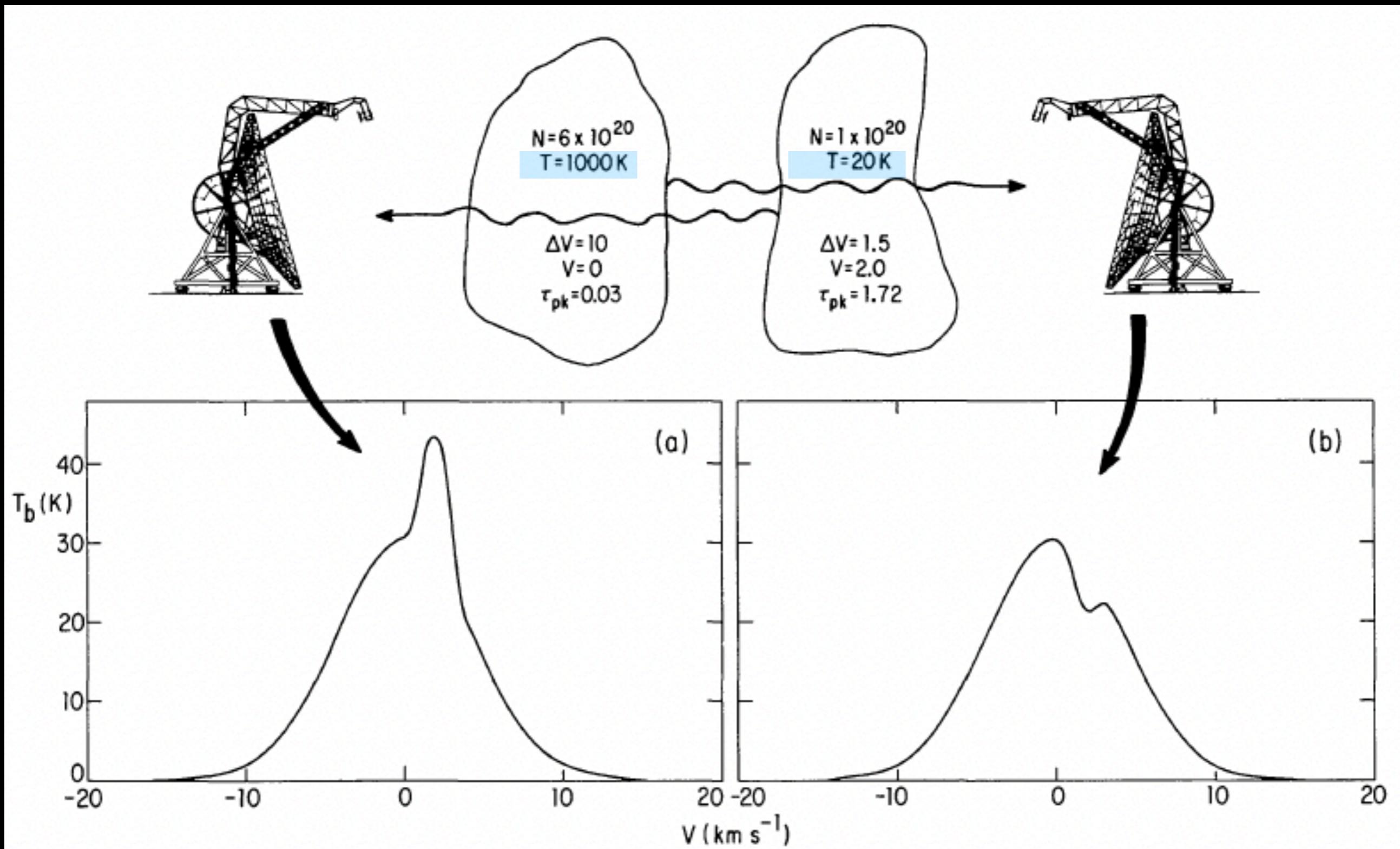
$\theta \approx 1.7^\circ$

Heeschen. ApJ (1955)



E. HI mapping the multiphase ISM structure

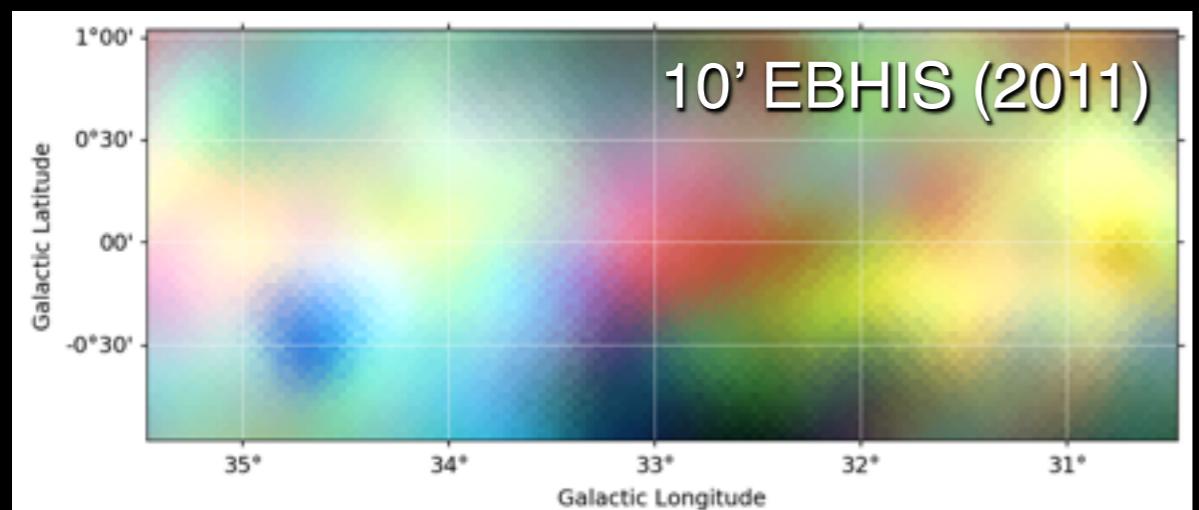
Dickey & Lockman (1990) ;Heeschen (1955).



Atomic hydrogen emission toward the Milky Way

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

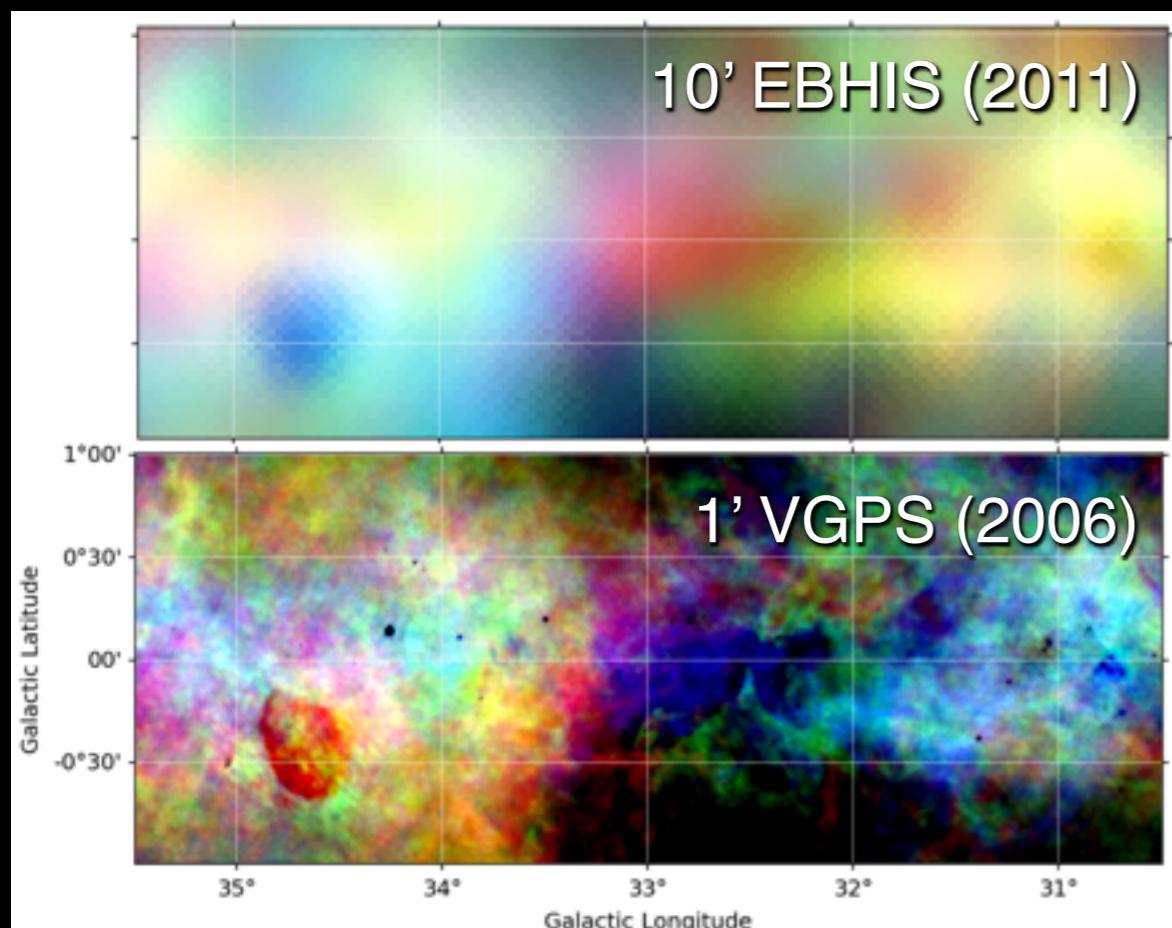
Effelsberg 100-m Telescope



Atomic hydrogen emission toward the Milky Way

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

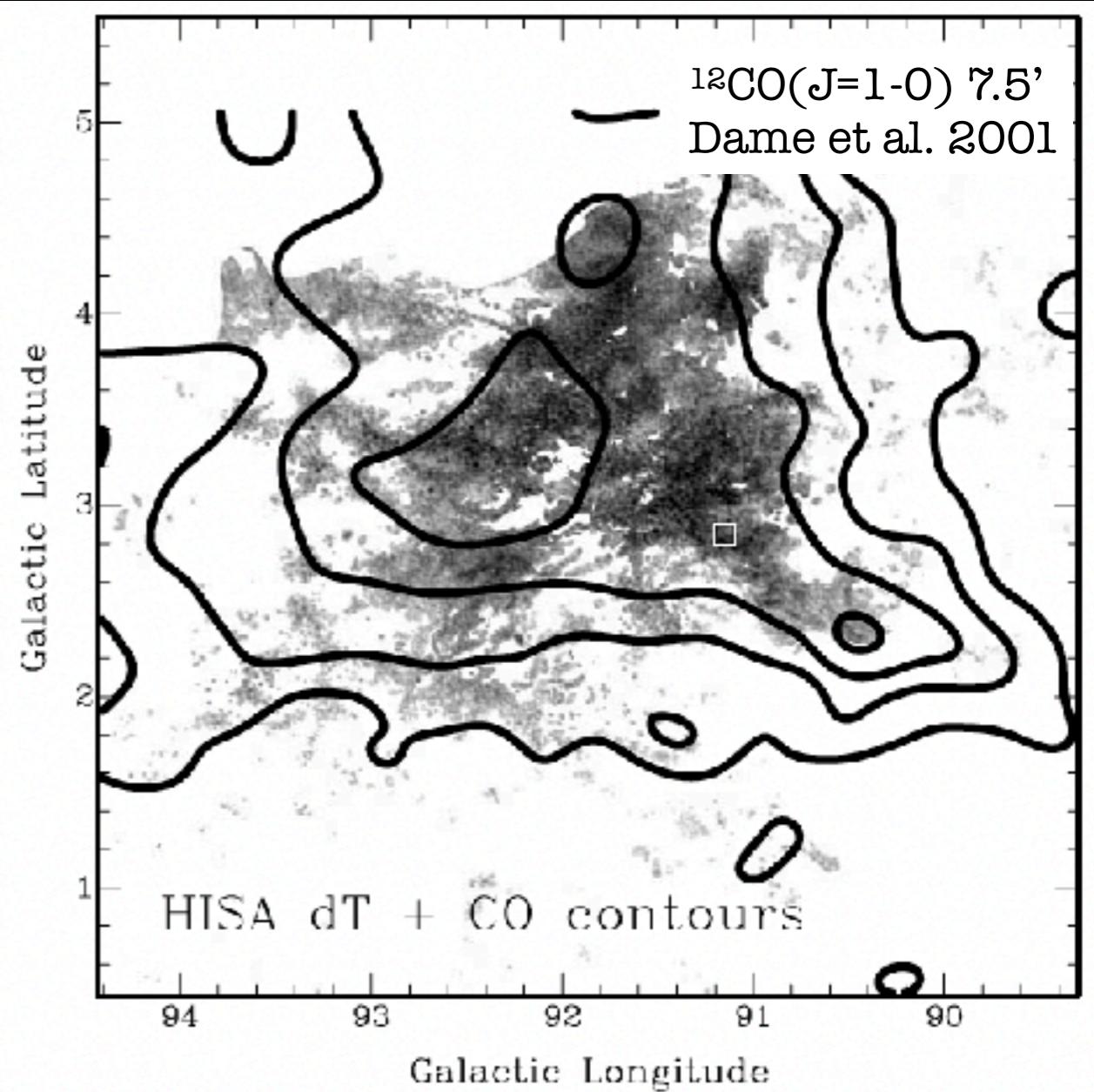
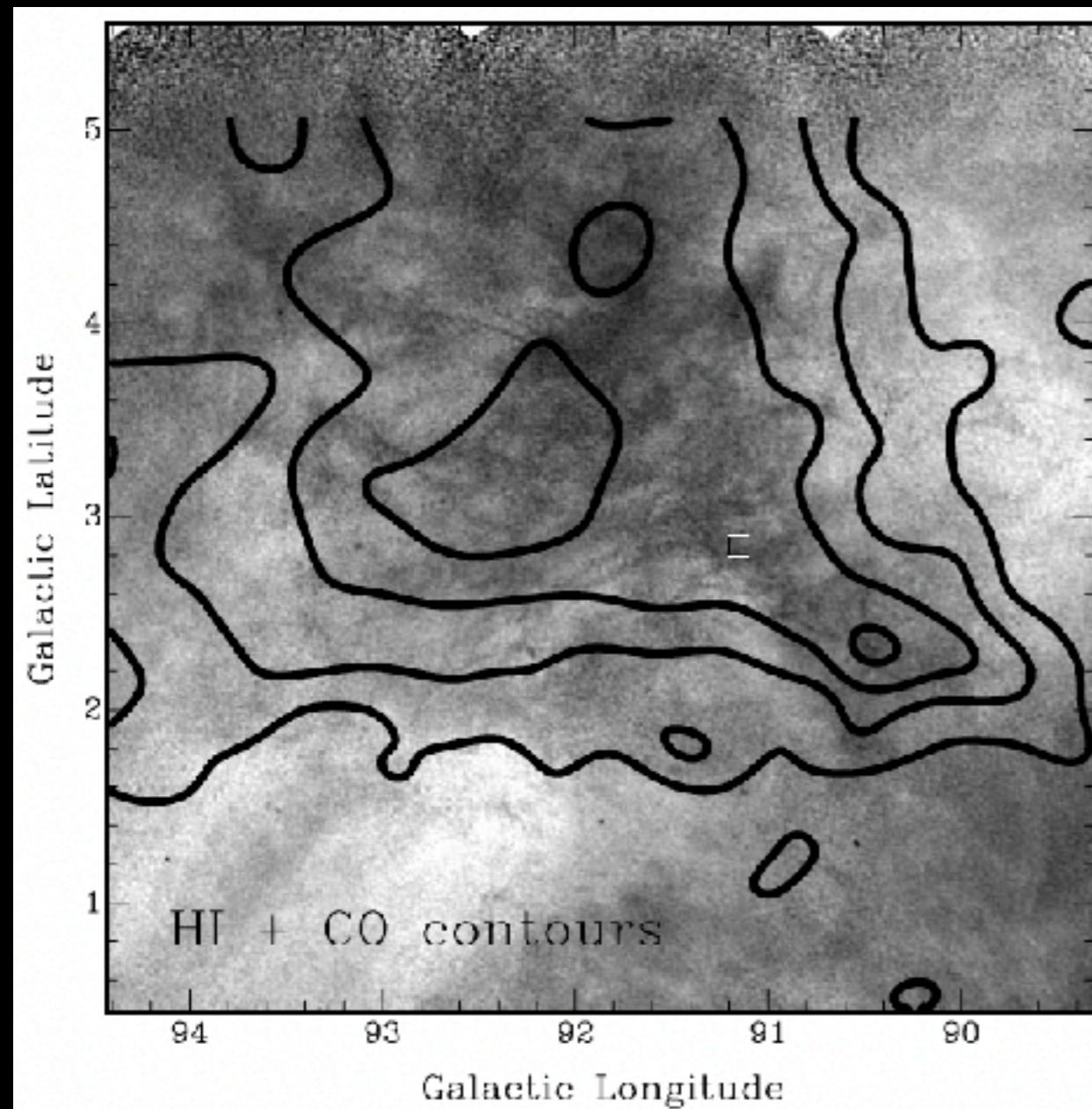
Jansky Very Large Array (VLA)



E. HI mapping the multiphase ISM structure

$\theta \approx 1'$

Gibson et al. ApJ (2000)



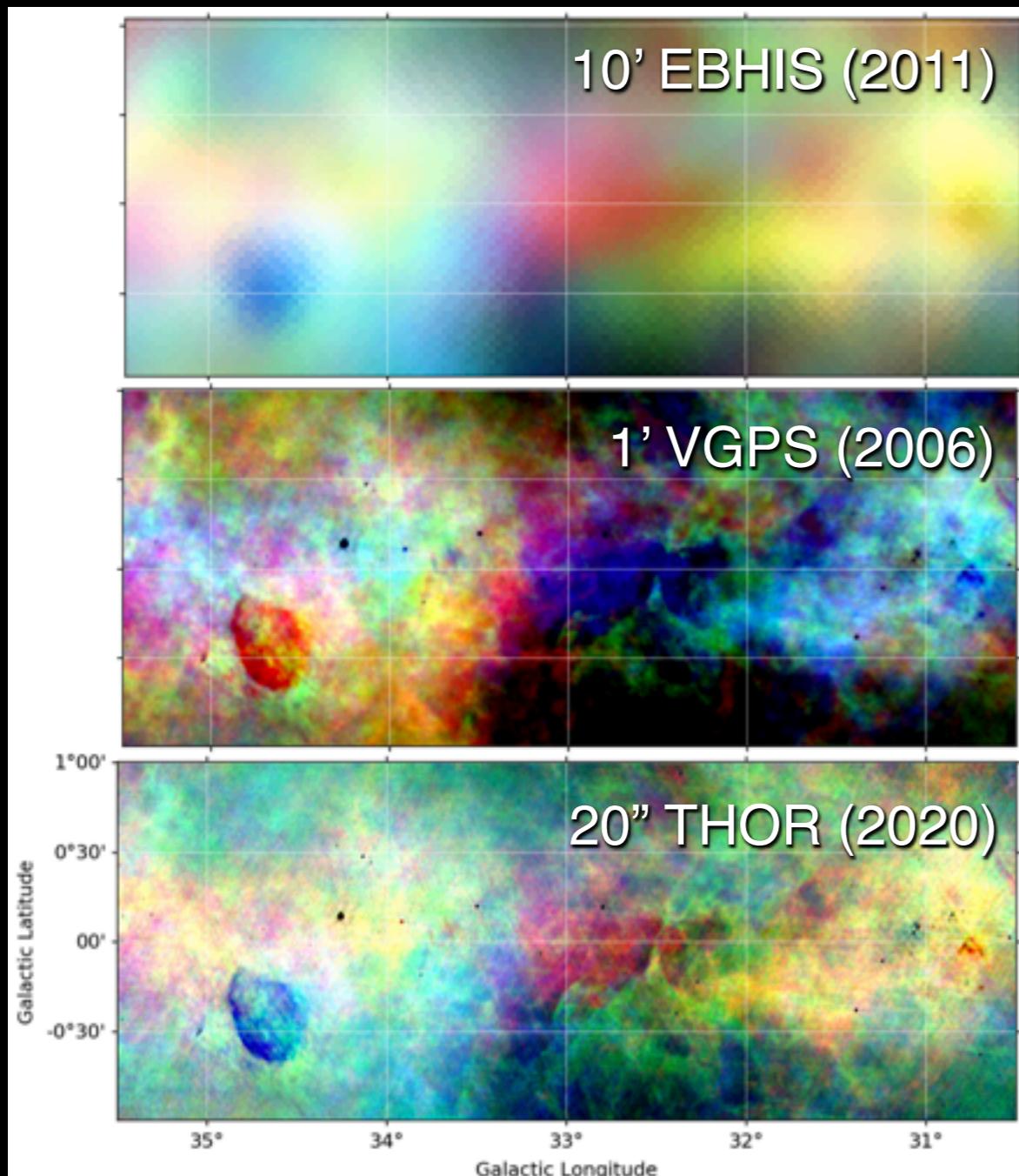
Atomic hydrogen emission toward the Milky Way

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/Recombination line (THOR) survey

$\theta \approx 20''$

Beuther et al. A&A (2016); Wang et al. A&A (2020)

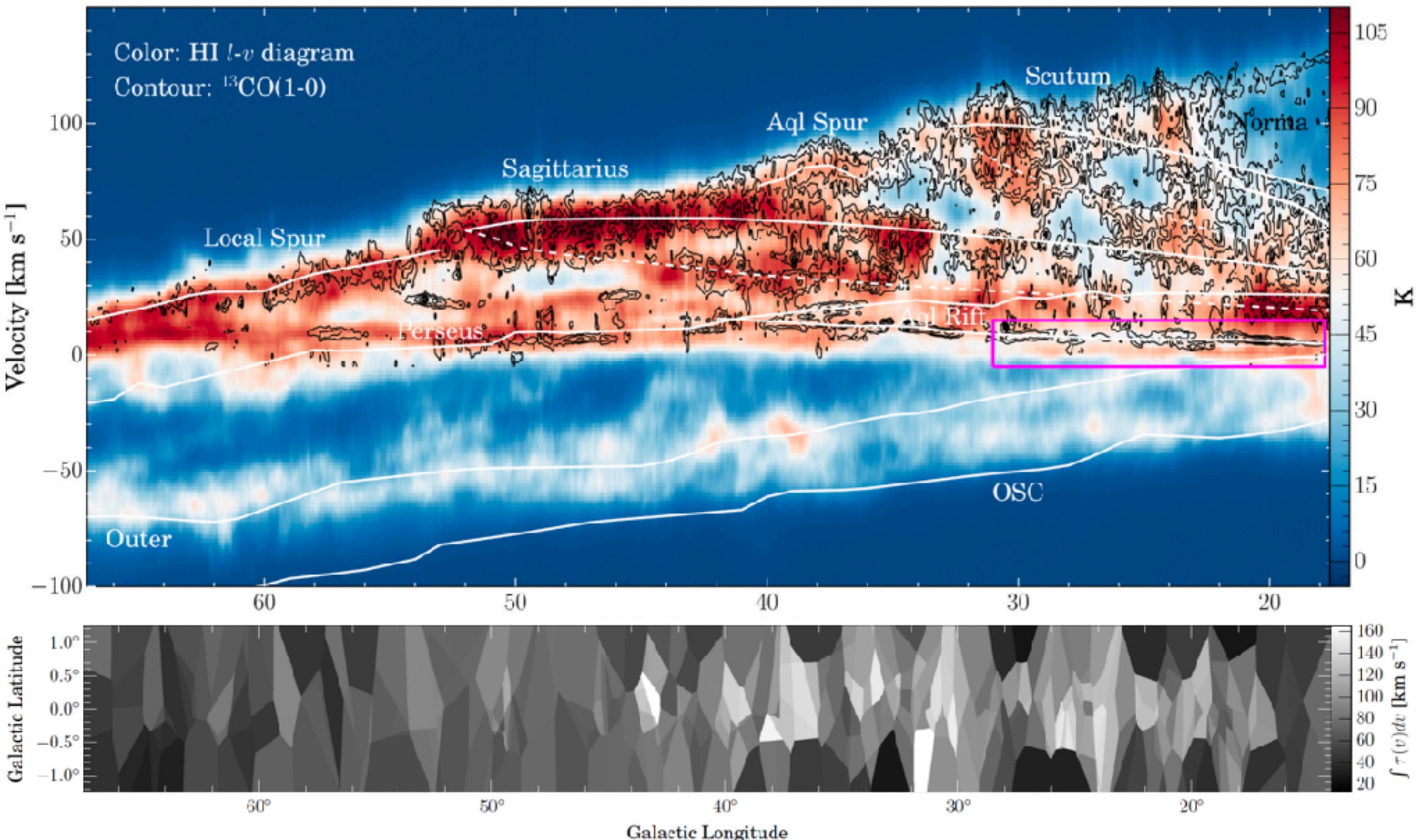


All-sky visible light [ESA/Gaia/DPAC]

E. HI mapping the multiphase ISM structure

$$\theta \approx 20''$$

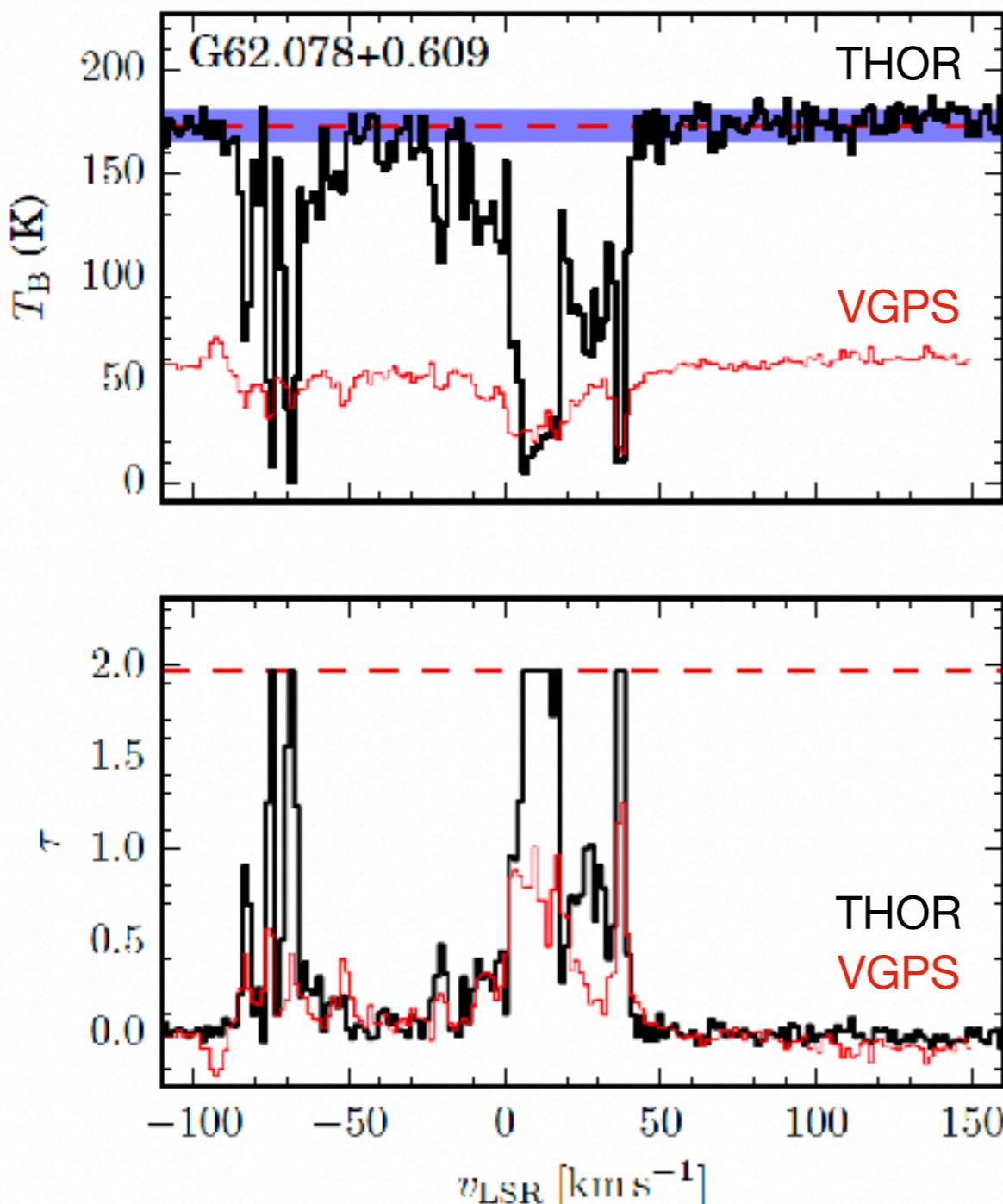
Wang, Y., Beuther, H. et al (including JDS). A&A (2020)



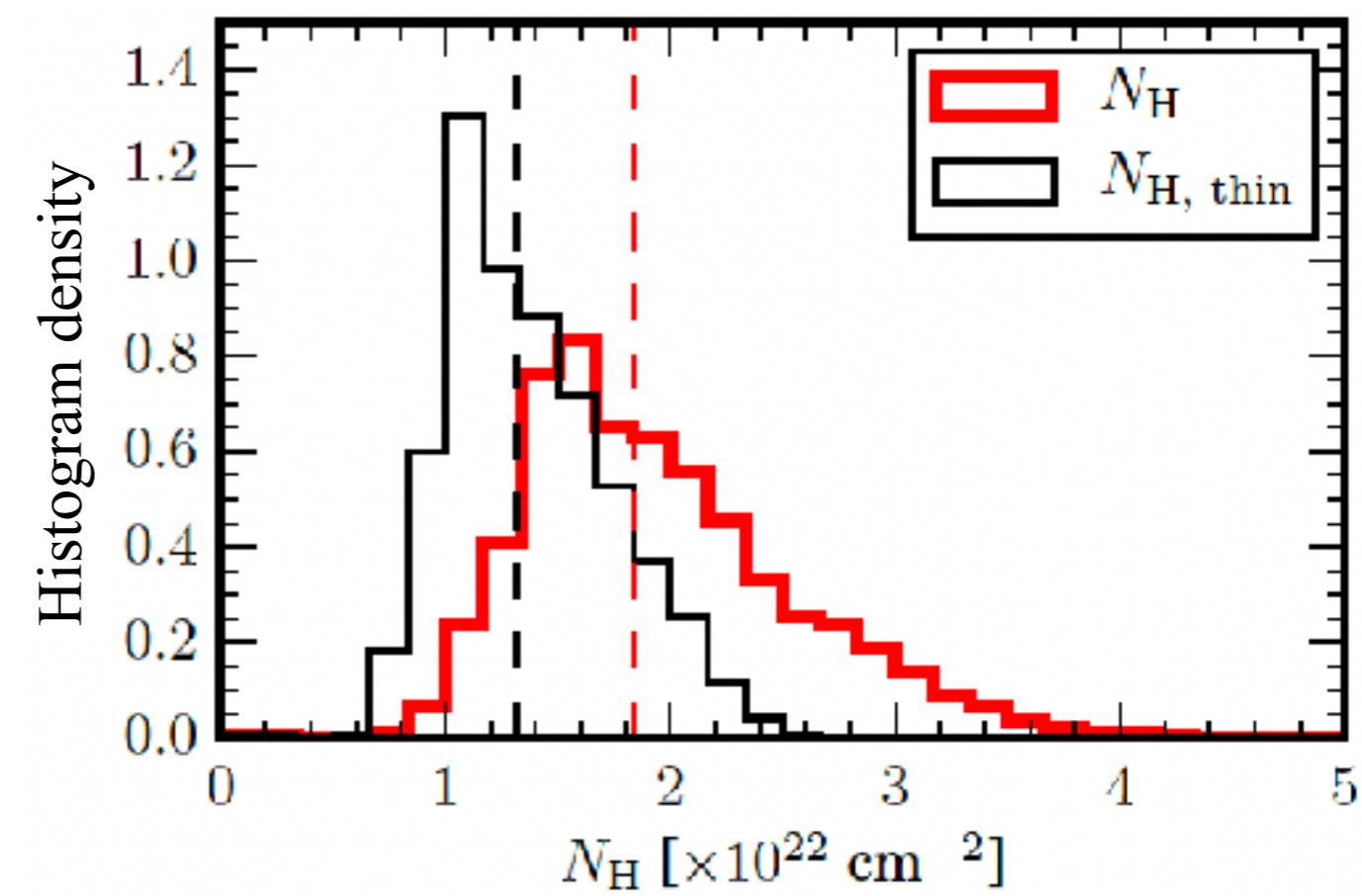
E. HI mapping the multiphase ISM structure

$\theta \approx 20''$

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



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

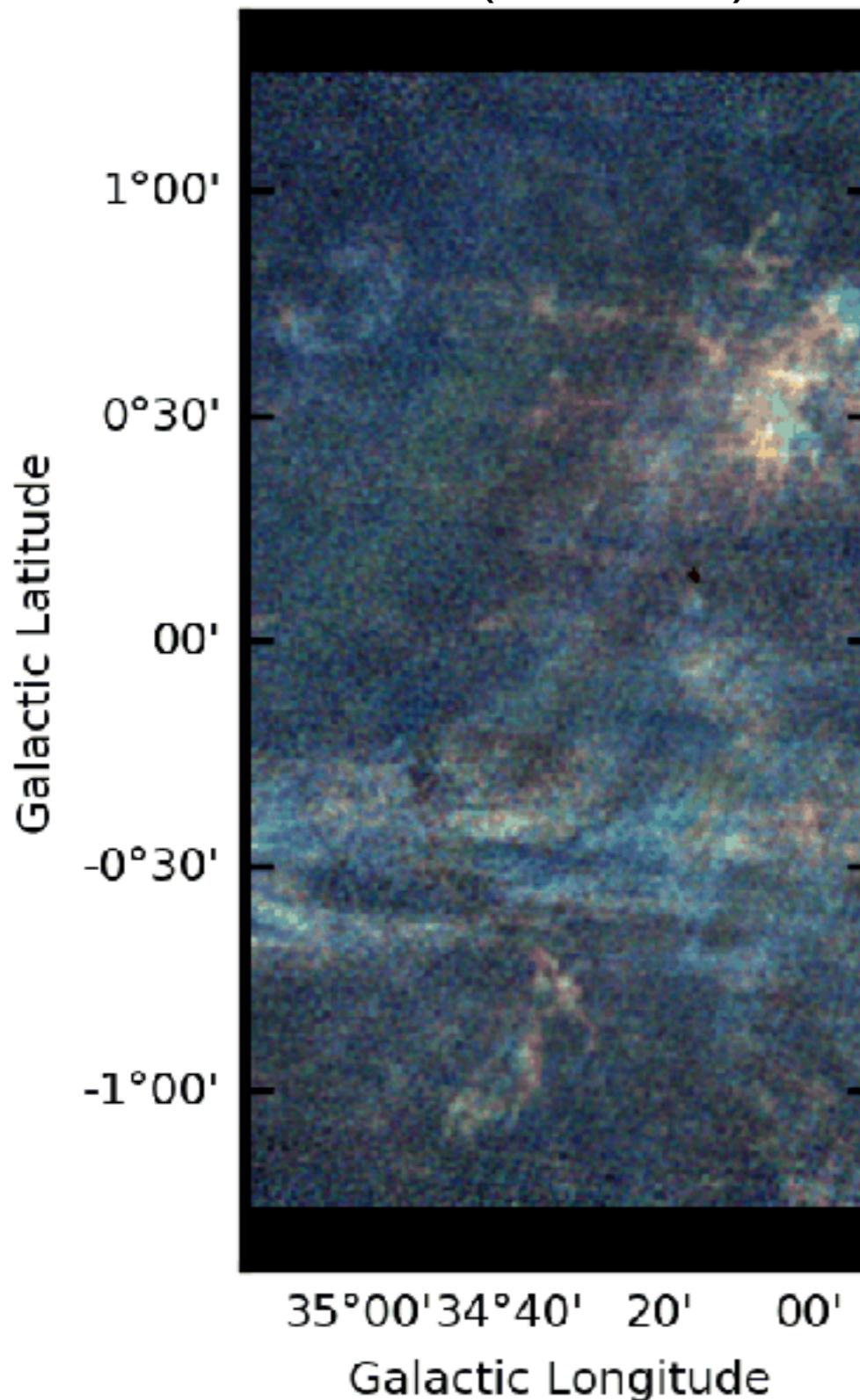


Histogram of relative orientations (HOG)

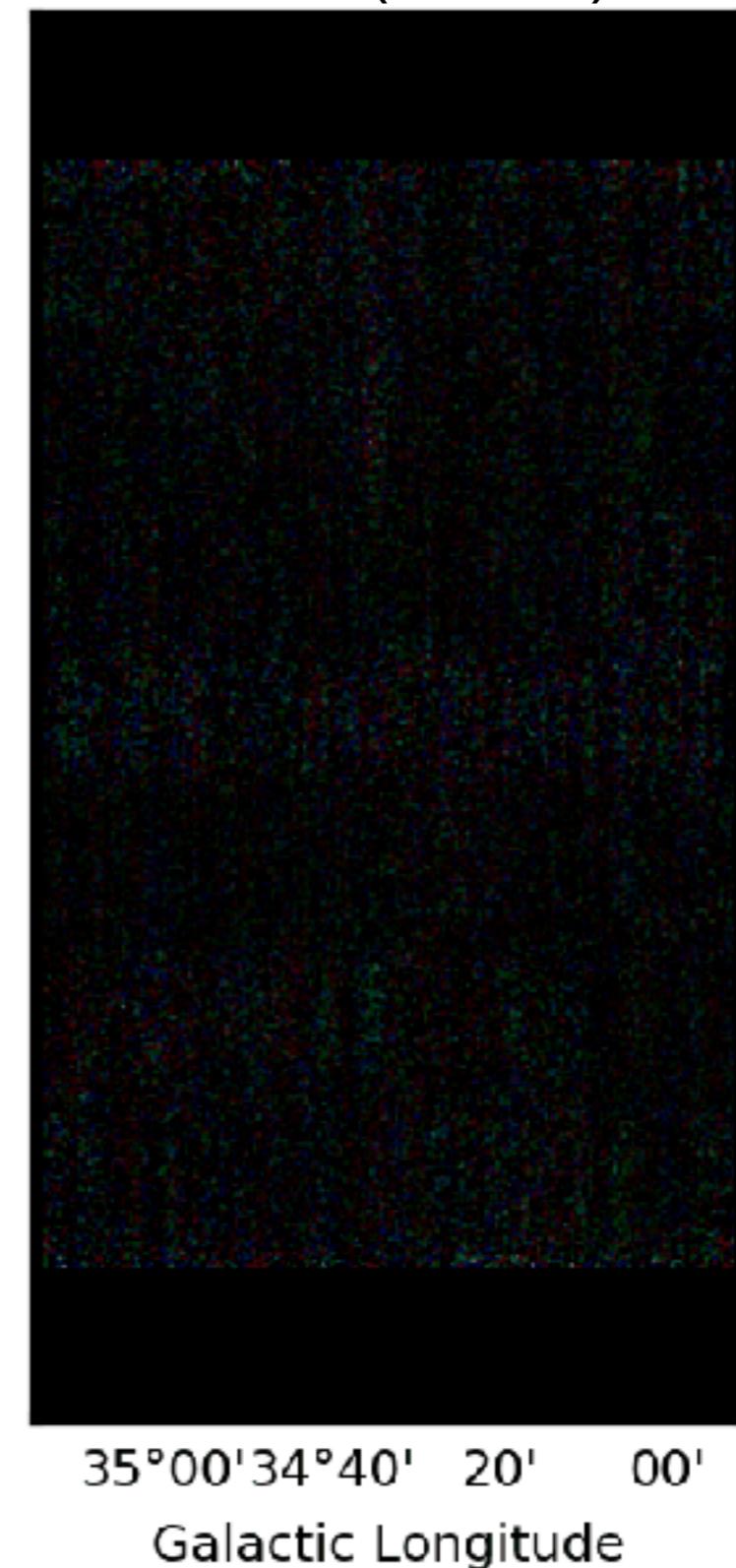


Soler, J.D. et al. A&A (2019)

HI (THOR)

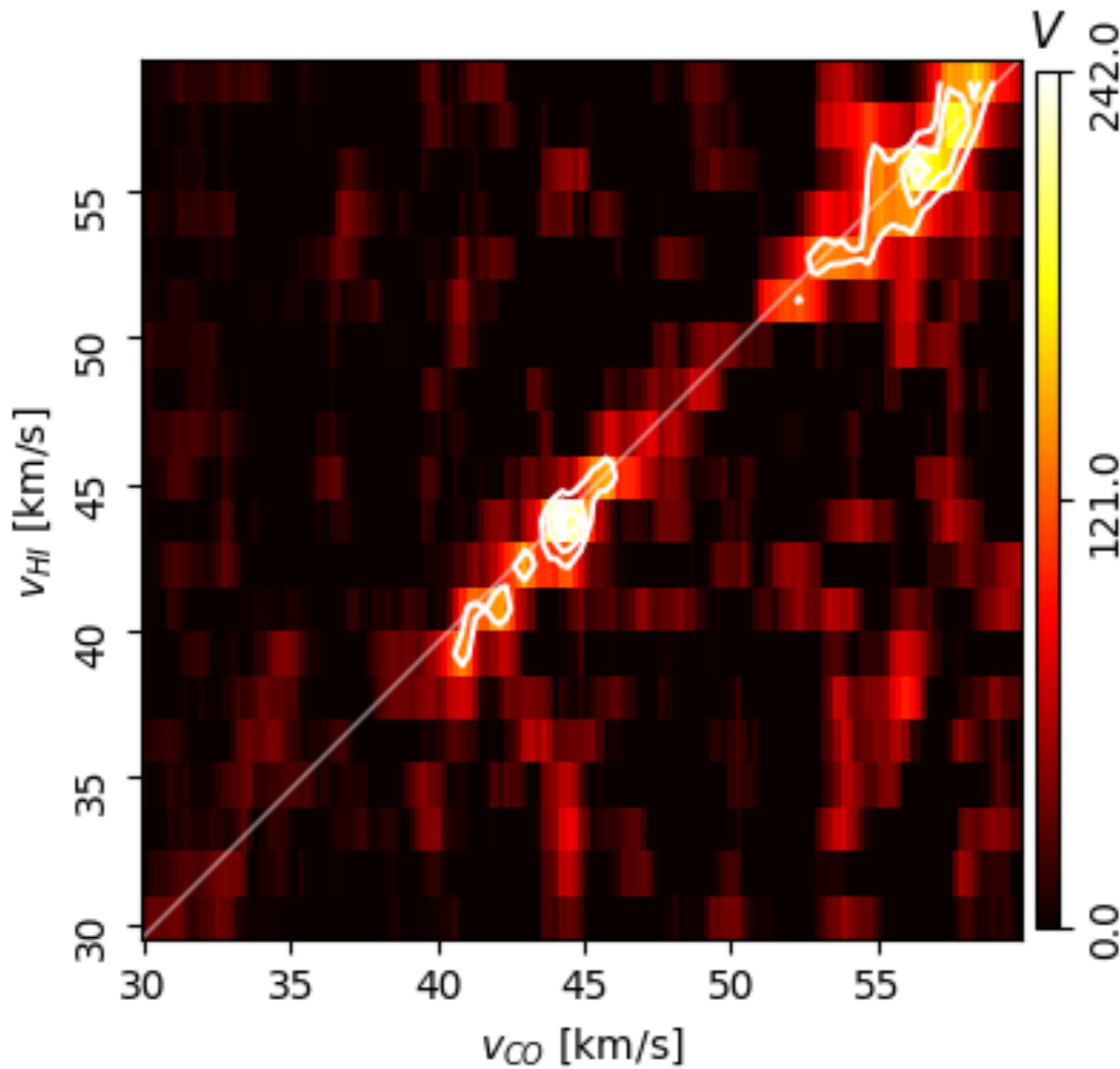


^{13}CO (GRS)



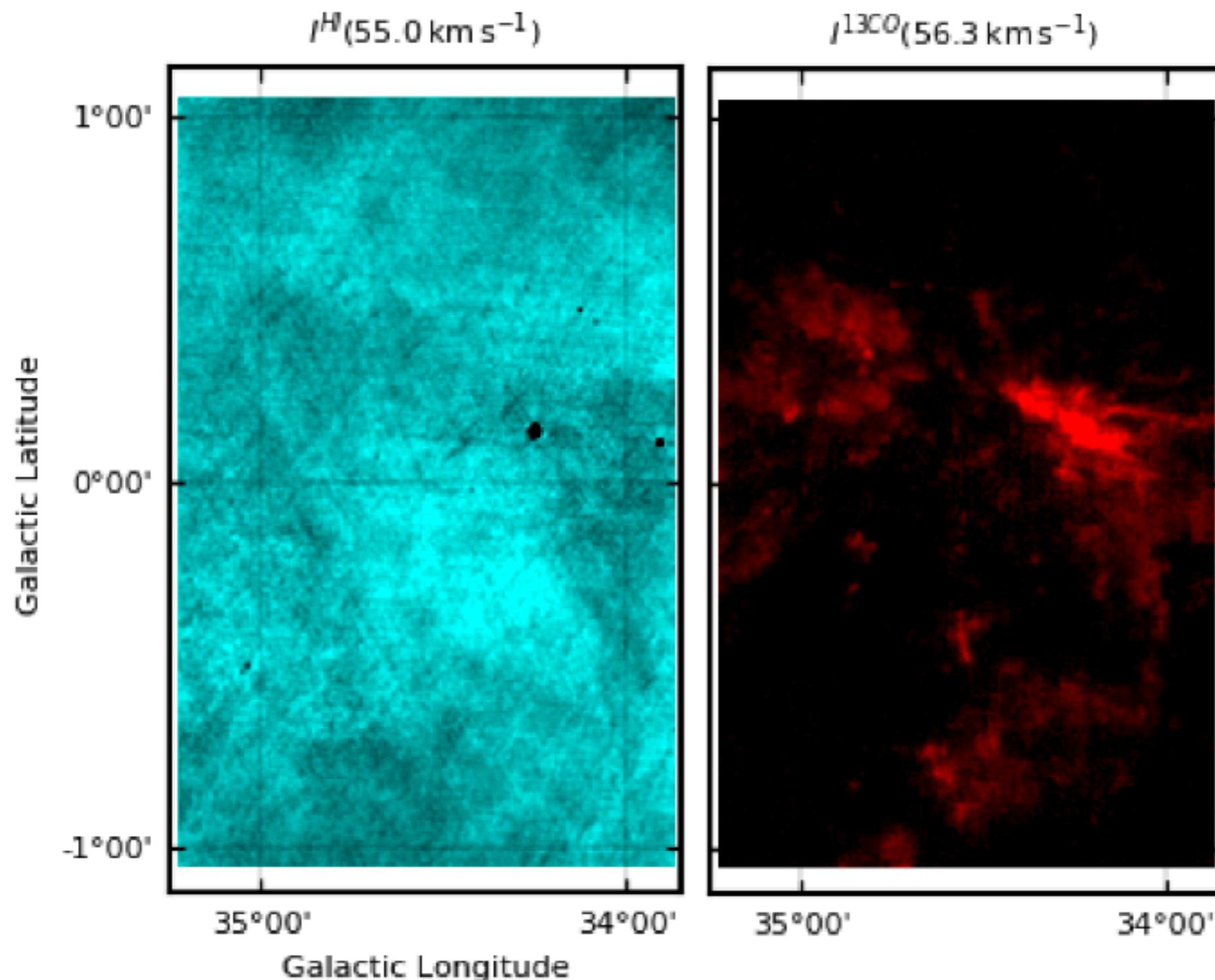
Histogram of relative orientations (HOG)

Soler, J.D. et al. A&A (2019)



E. HI mapping the multiphase ISM structure

Soler, Beuther, et al. A&A (2009)

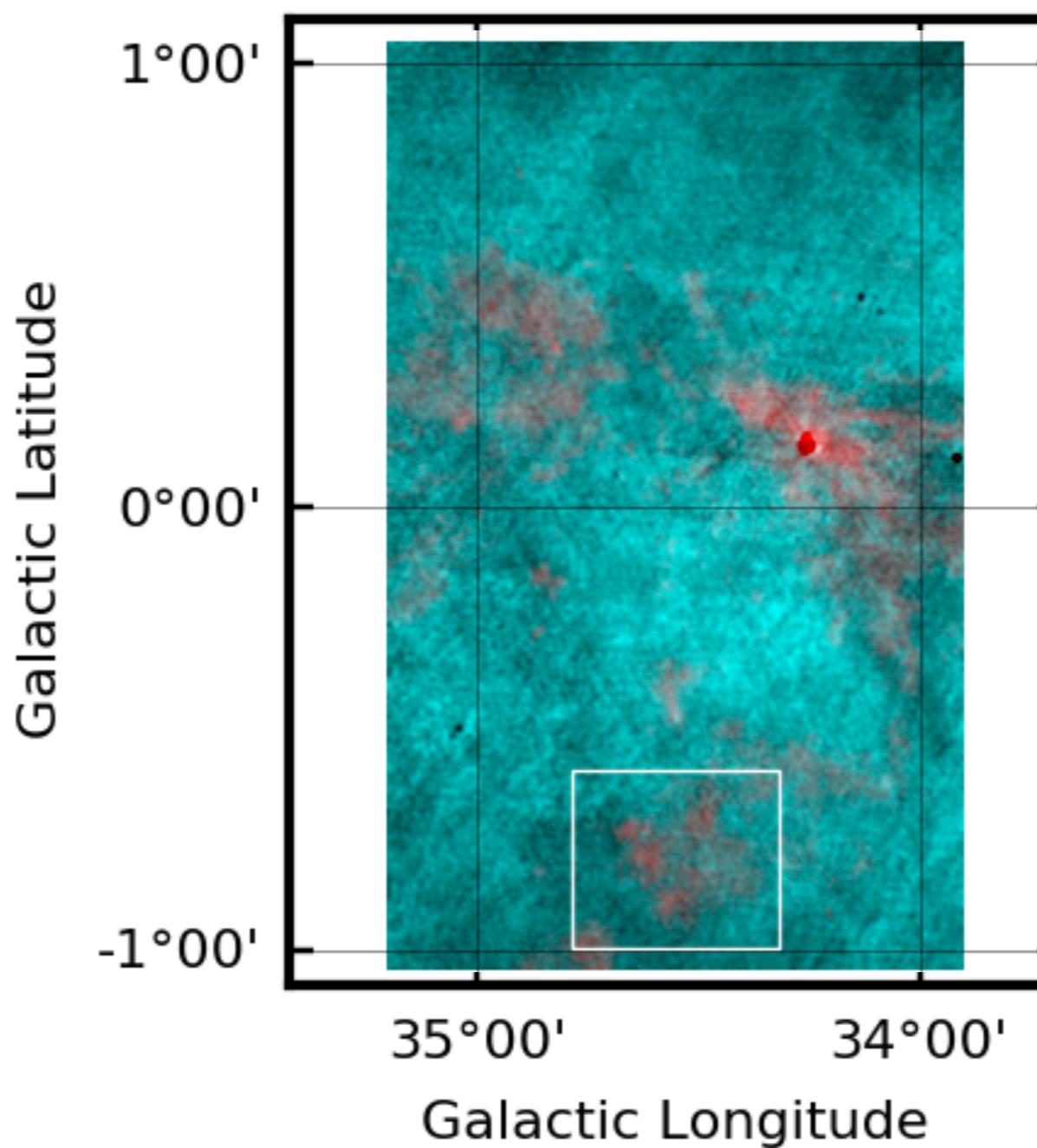


E. HI mapping the multiphase ISM structure

Soler, Beuther, et al. A&A (2009)

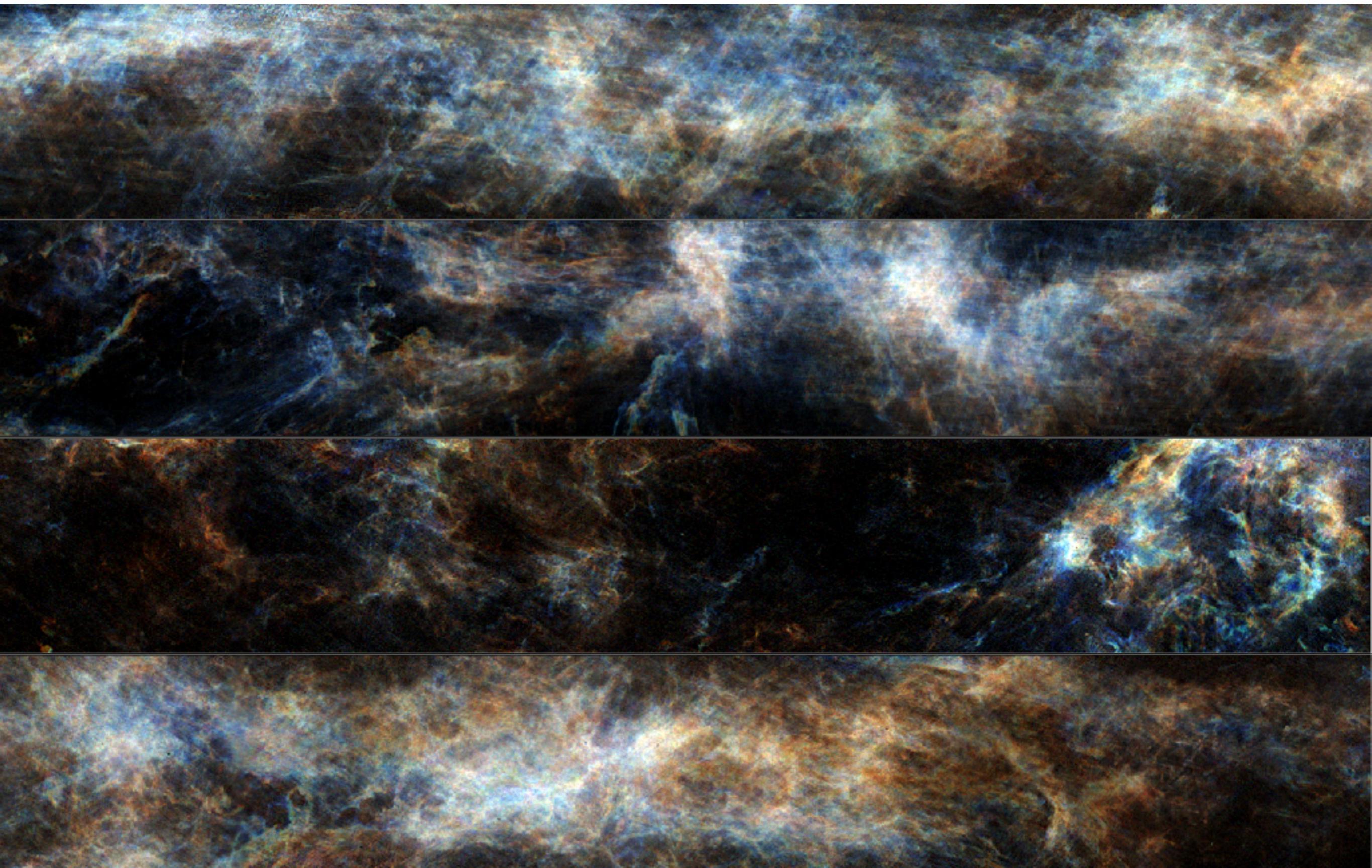


$I^{HI}(55.0 \text{ km s}^{-1})$, $I^{^{13}CO}(56.3 \text{ km s}^{-1})$



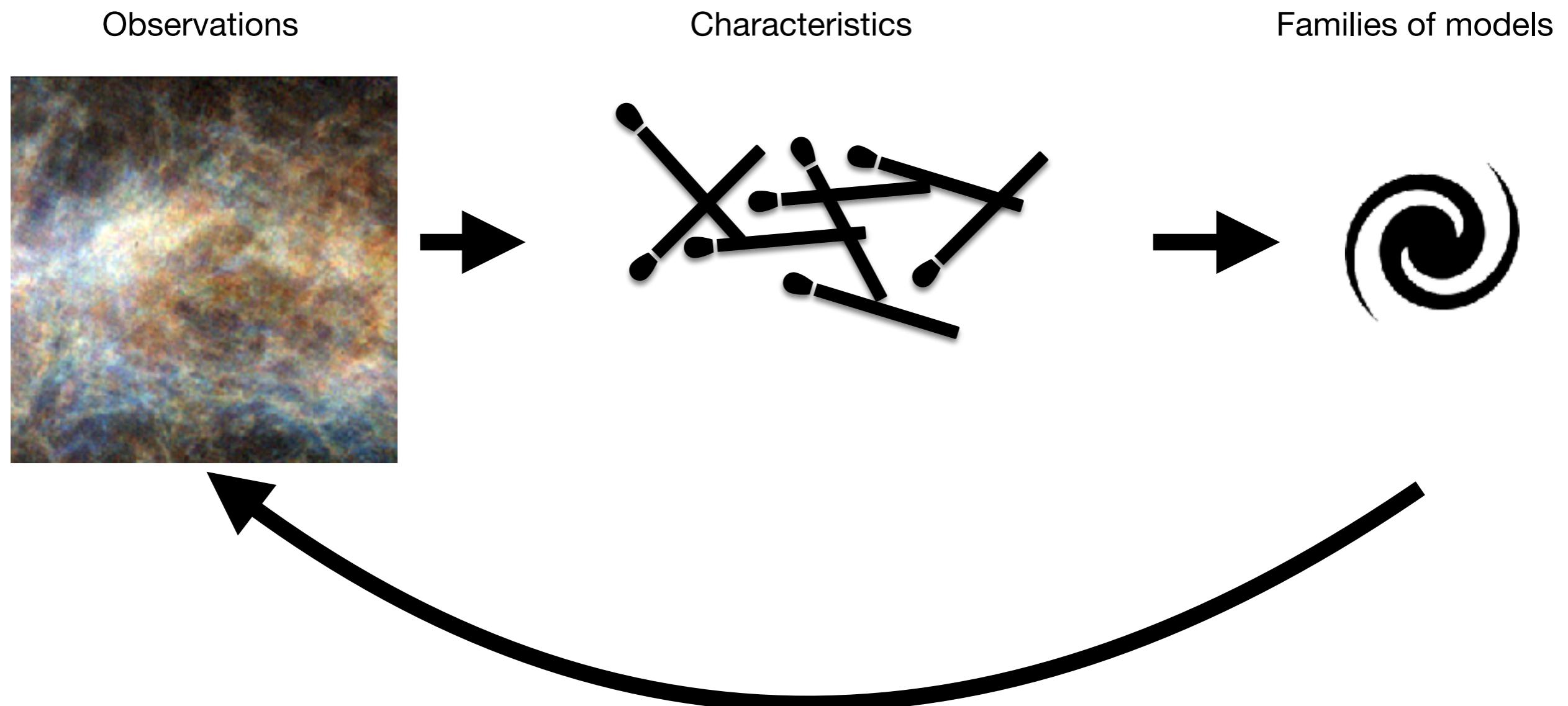
HI filaments and Galactic dynamics

J.D. Soler; THOR collaboration



HI filaments and Galactic dynamics

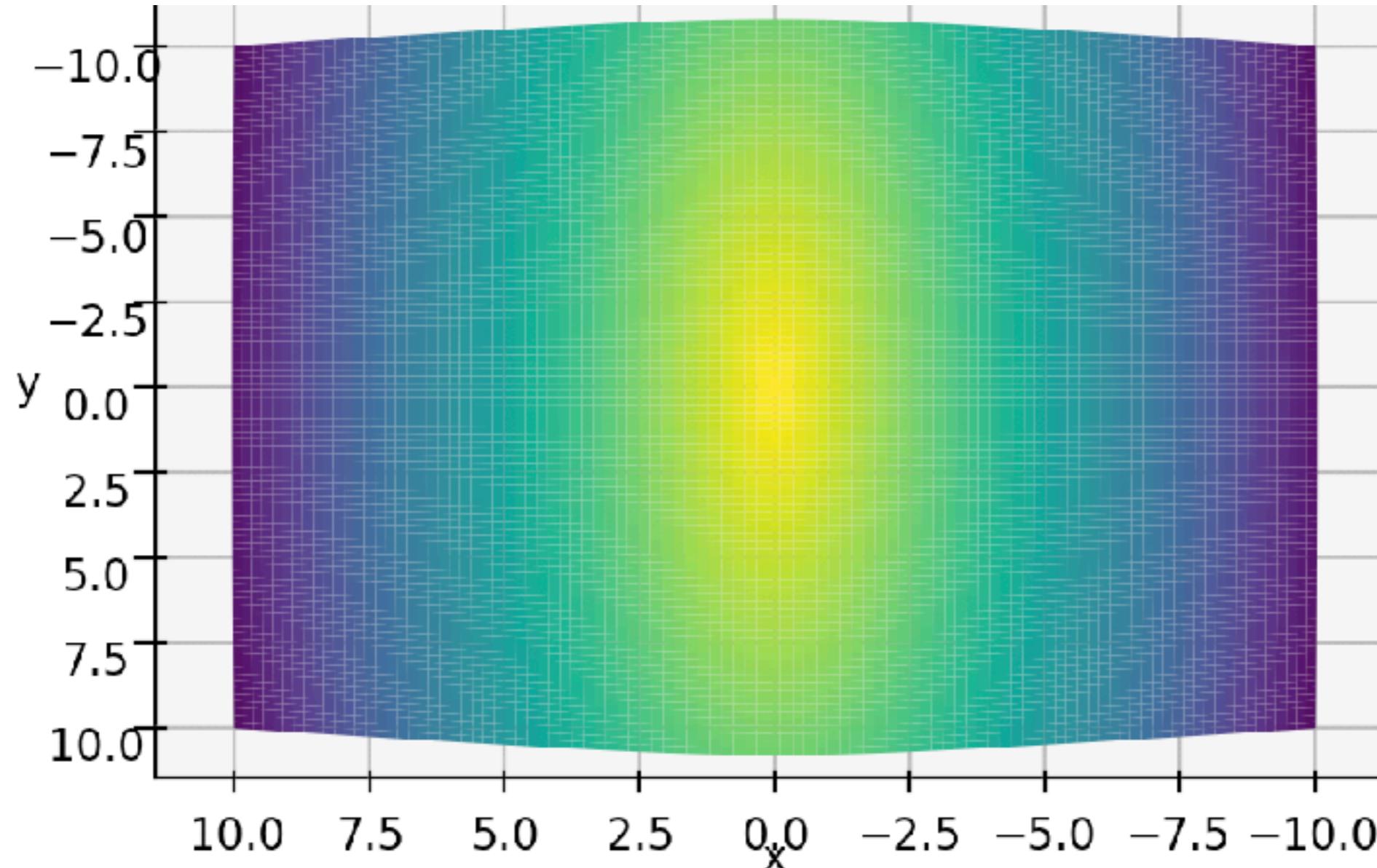
Soler, J.D. et al. A&A (2020)



Hessian matrix method

Polychroni et al. 2013

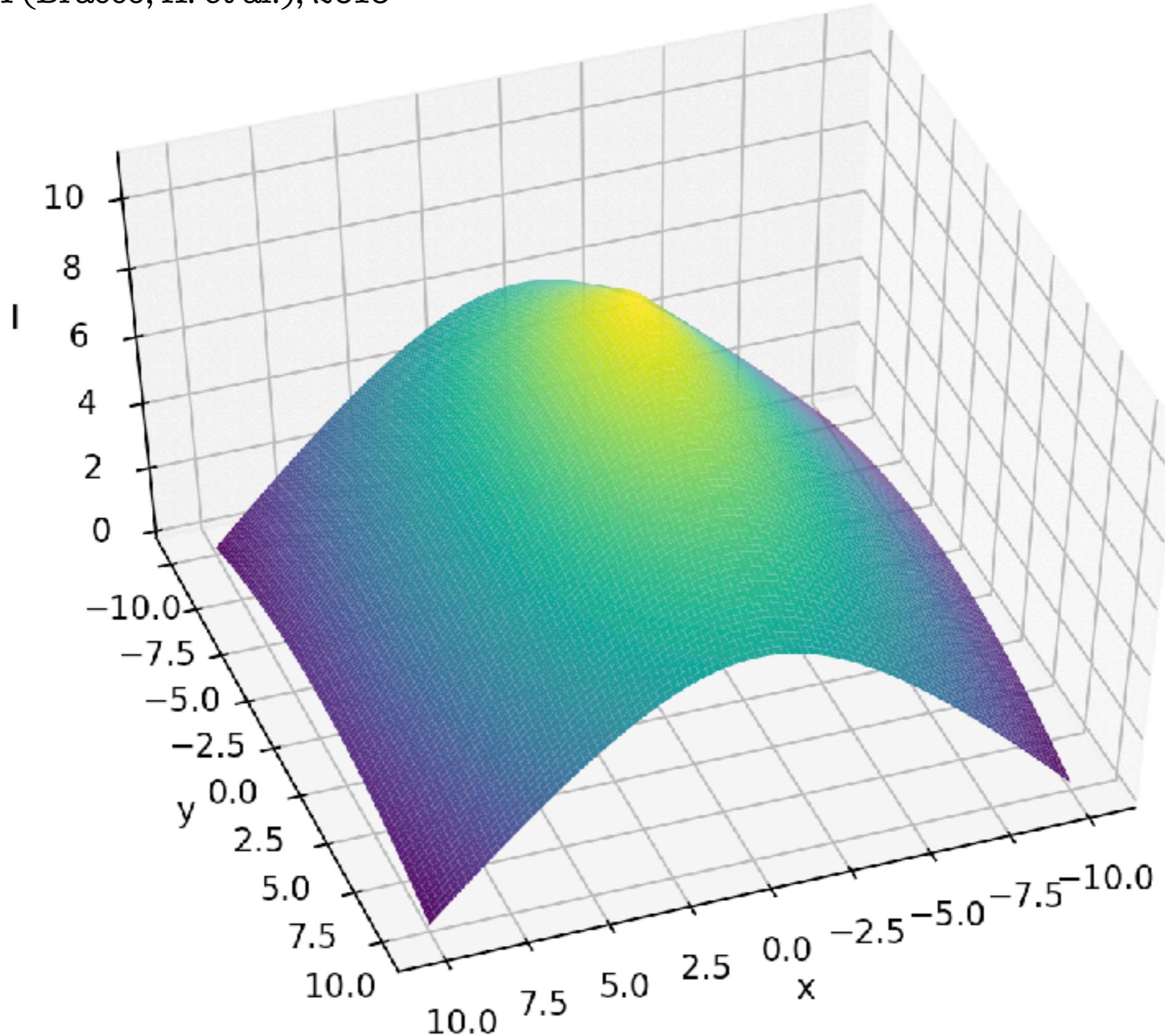
Planck XXXII (Bracco, A. et al.), 2016



Hessian matrix method

Polychroni et al. 2013

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

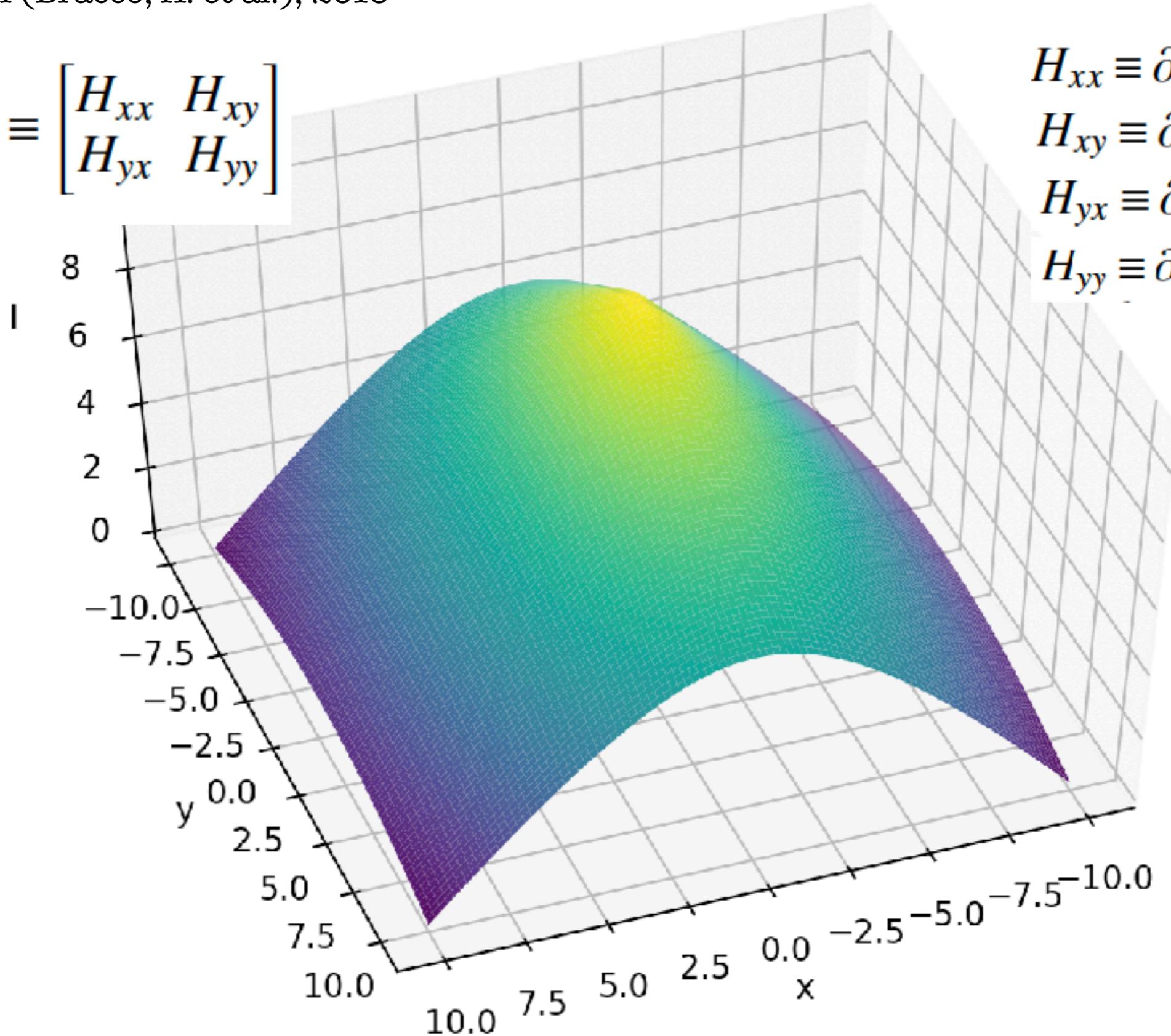


Hessian matrix method

Polychroni et al. 2013

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

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



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

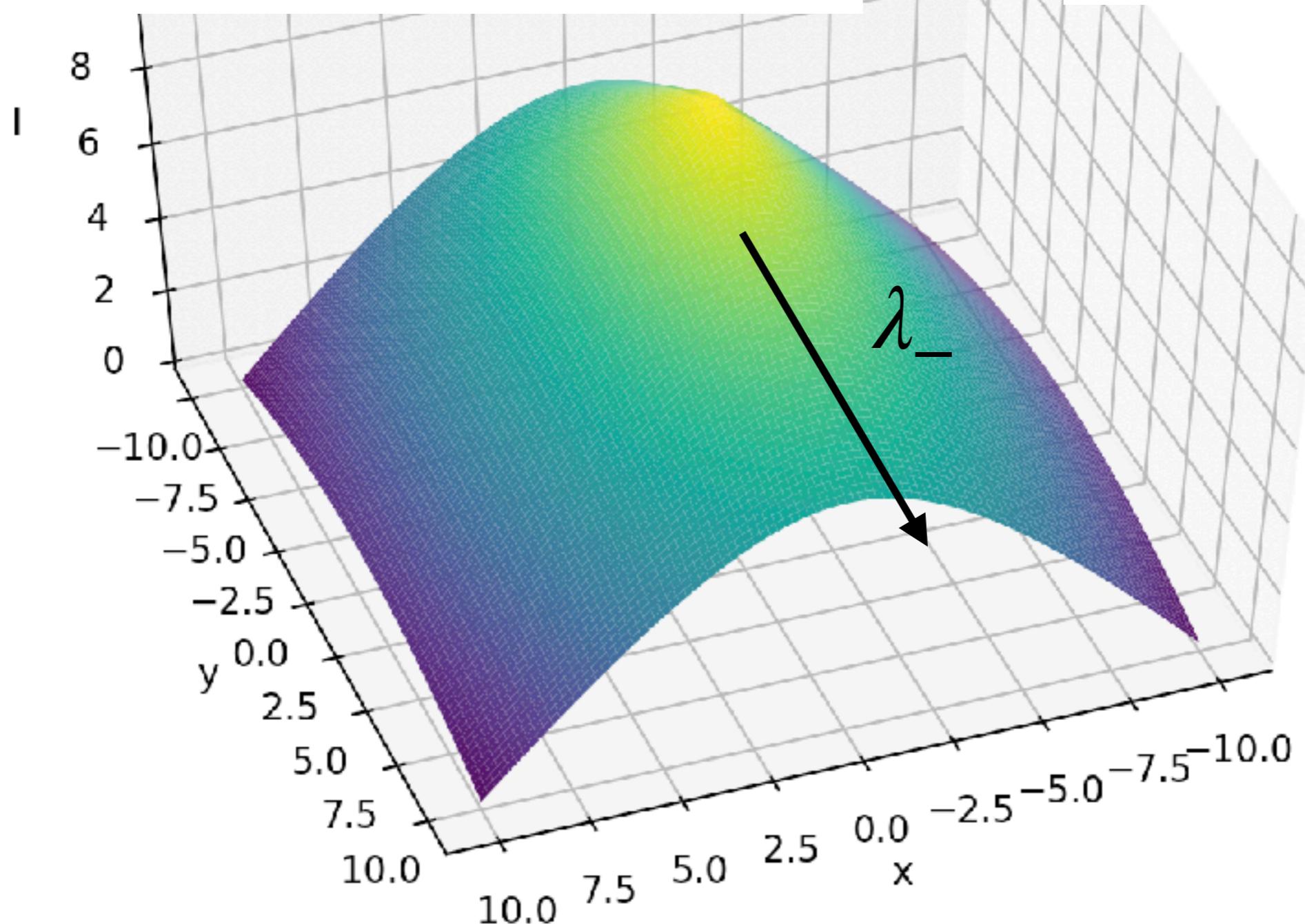
Hessian matrix method

Polychroni et al. 2013

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

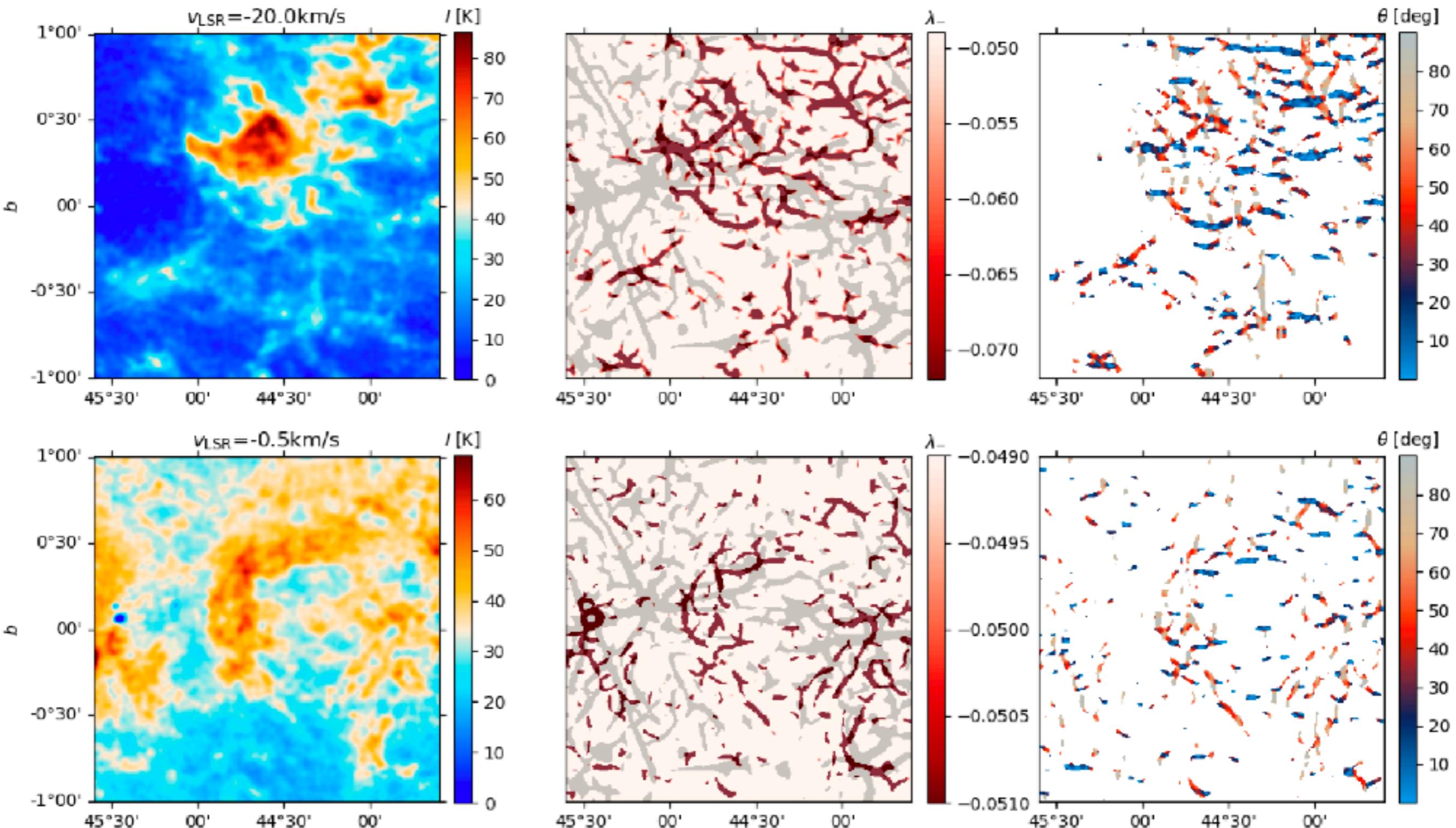
$$\lambda_{\pm} = \frac{(H_{xx} + H_{yy}) \pm \sqrt{(H_{xx} - H_{yy})^2 + 4H_{xy}H_{yx}}}{2}$$

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



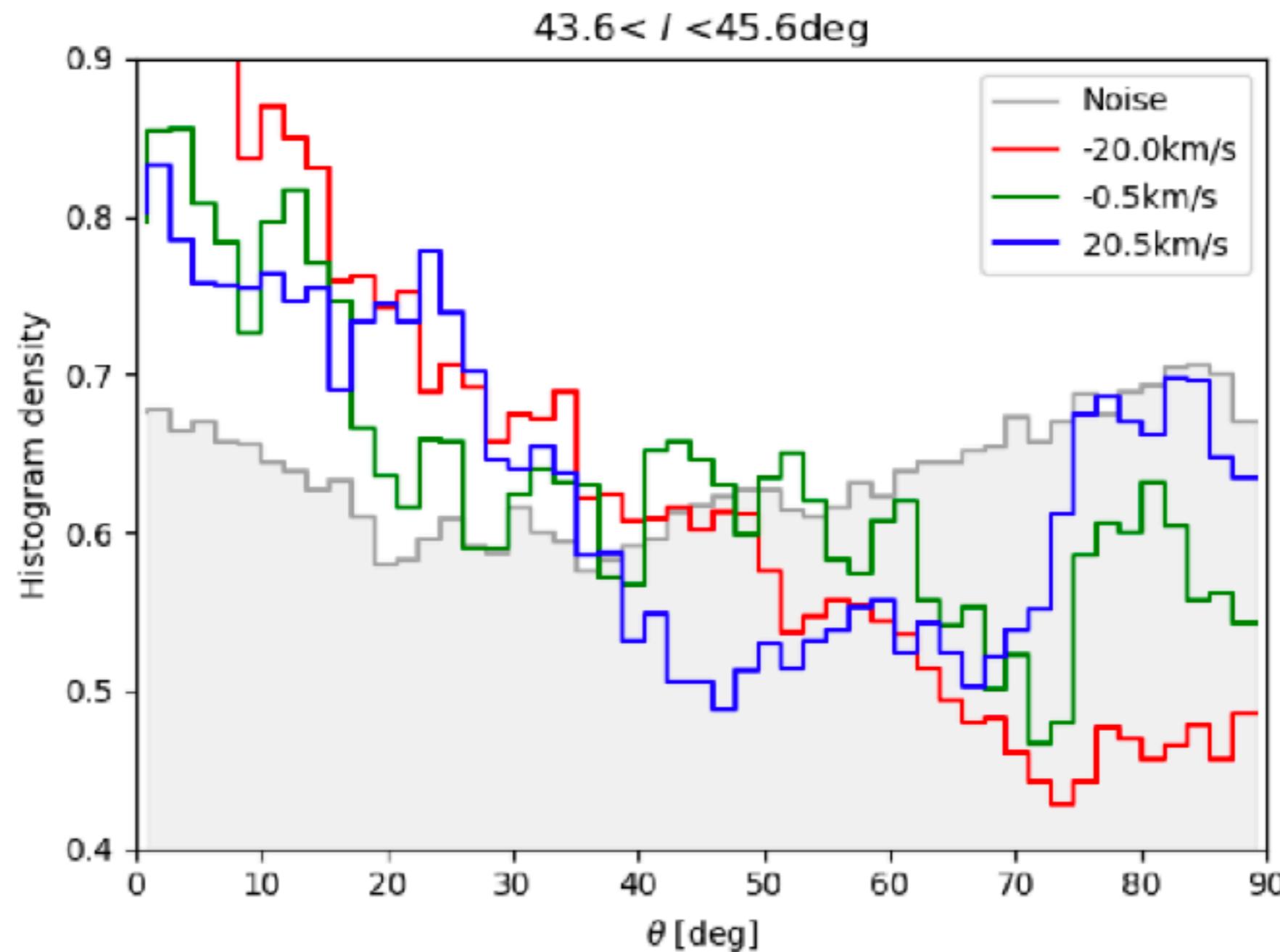
HI filaments

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



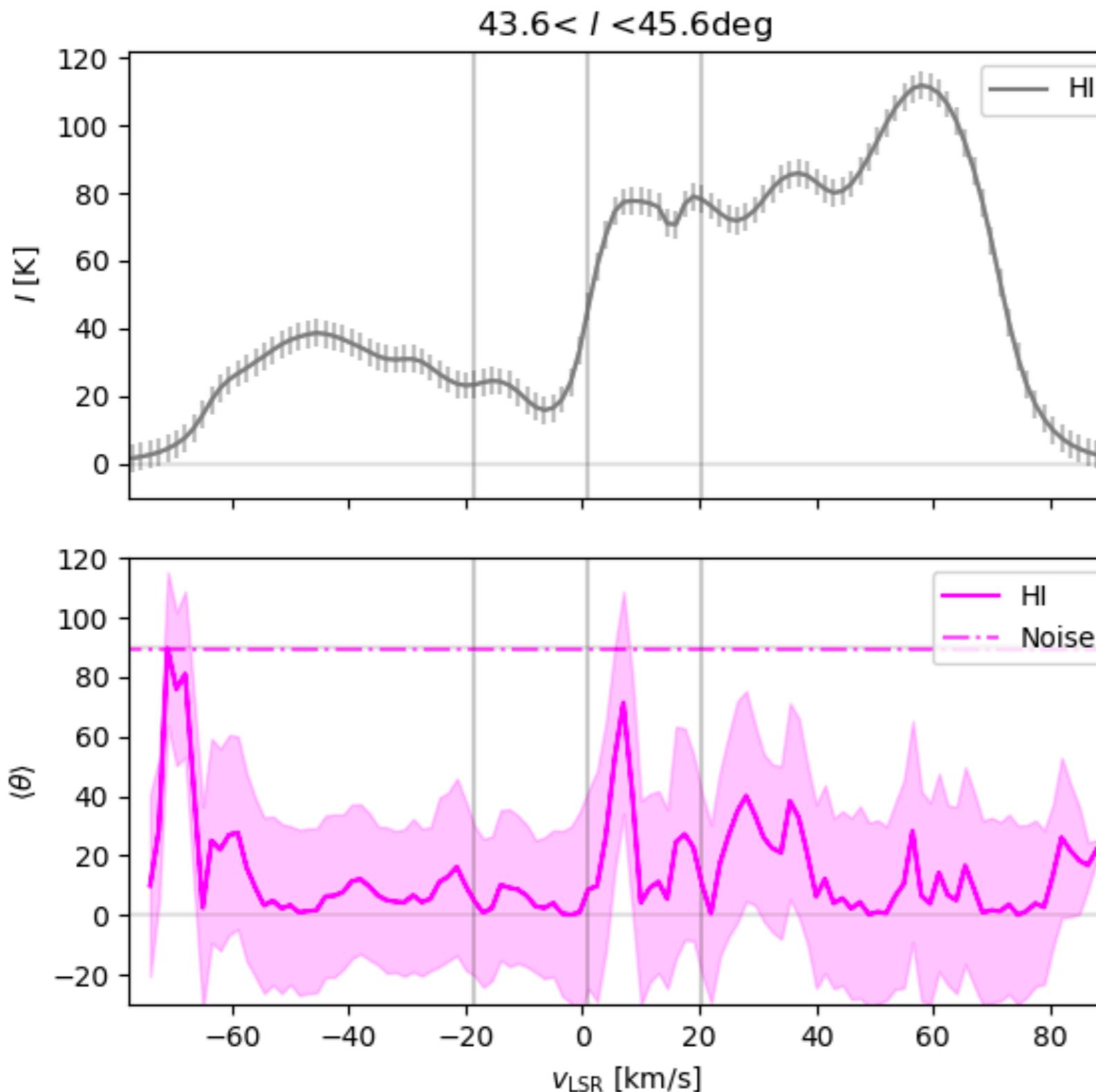
Histograms of HI filament orientation

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

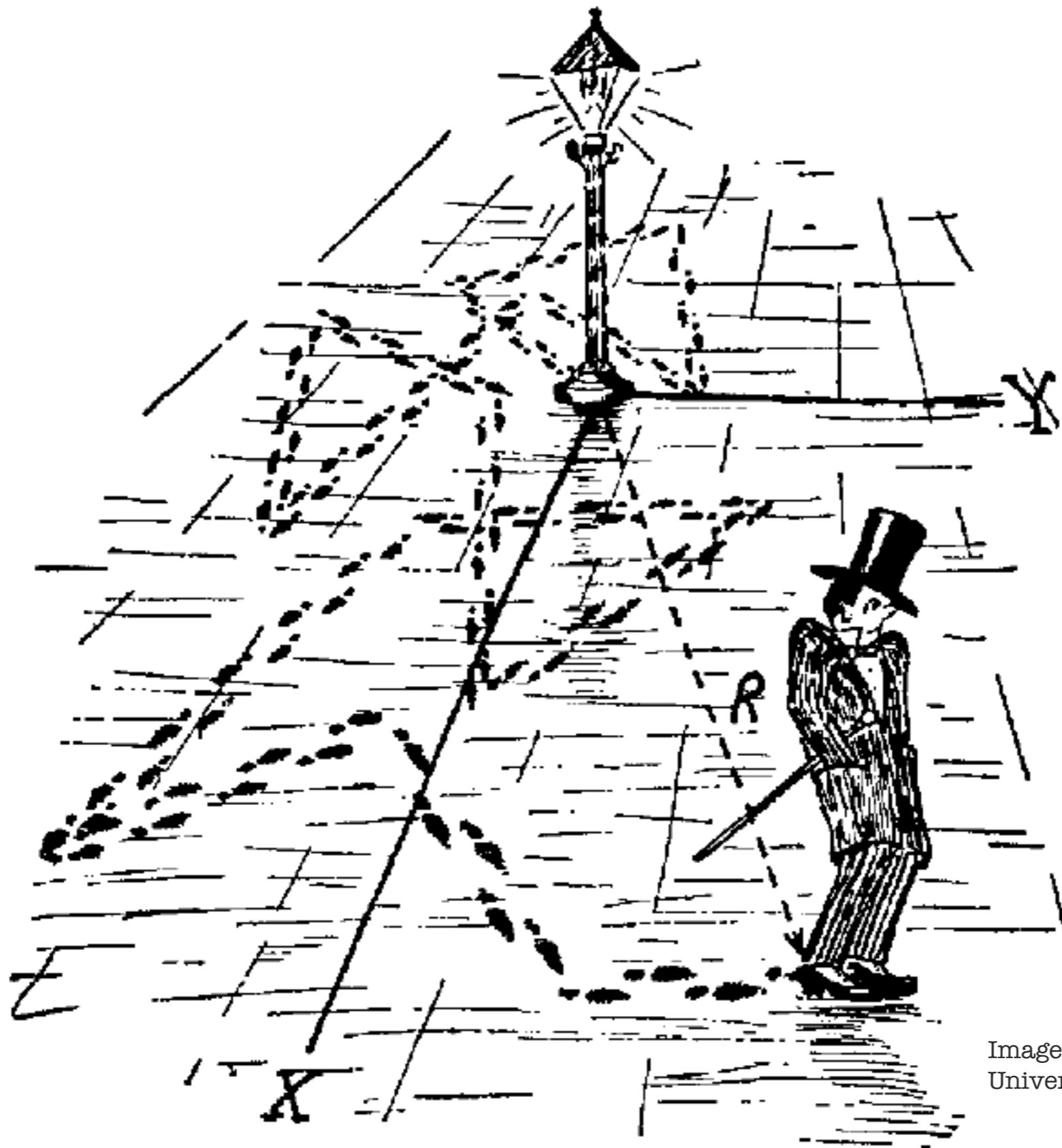
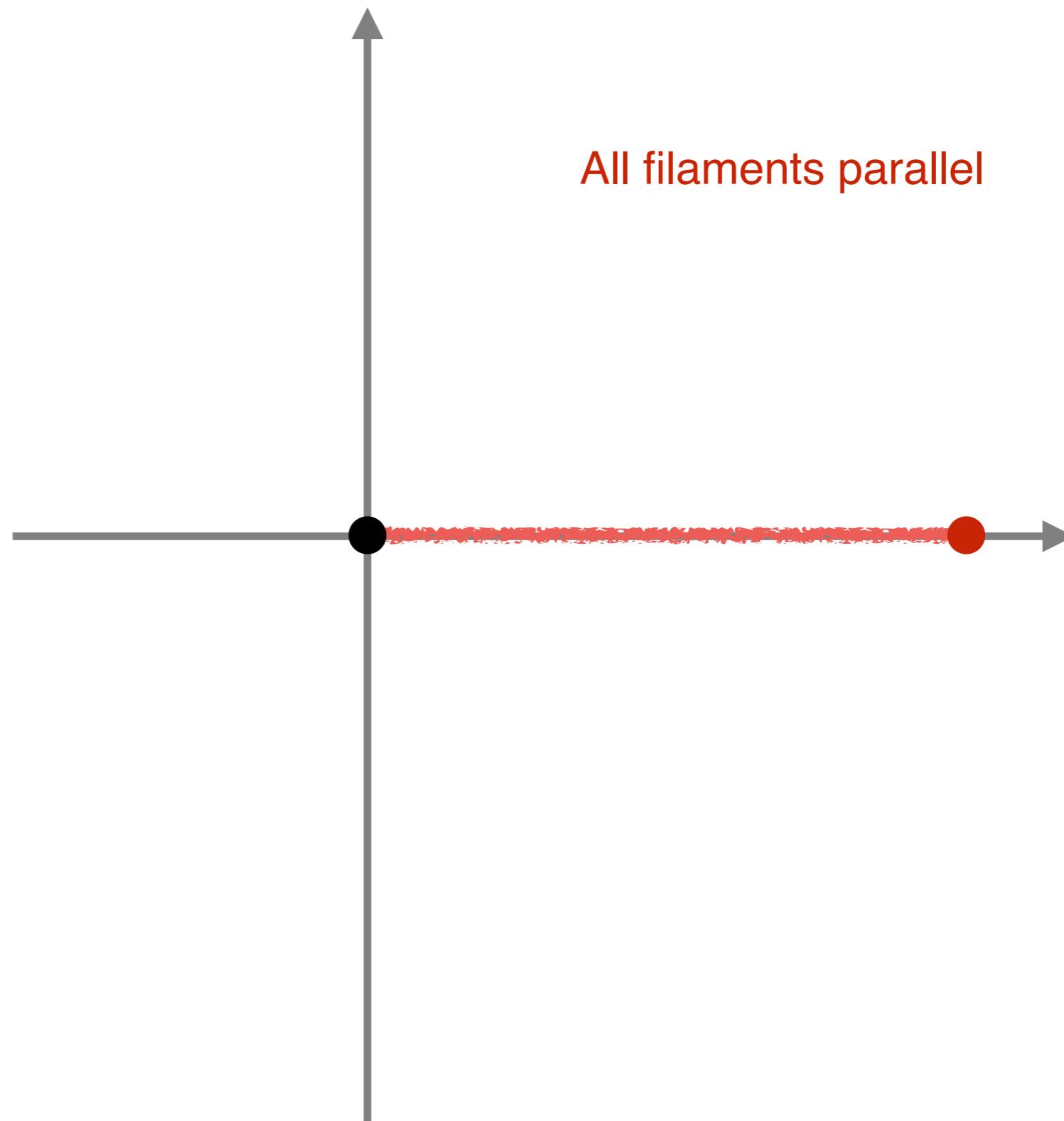


Image: Advanced Design Studies
University of Tokyo

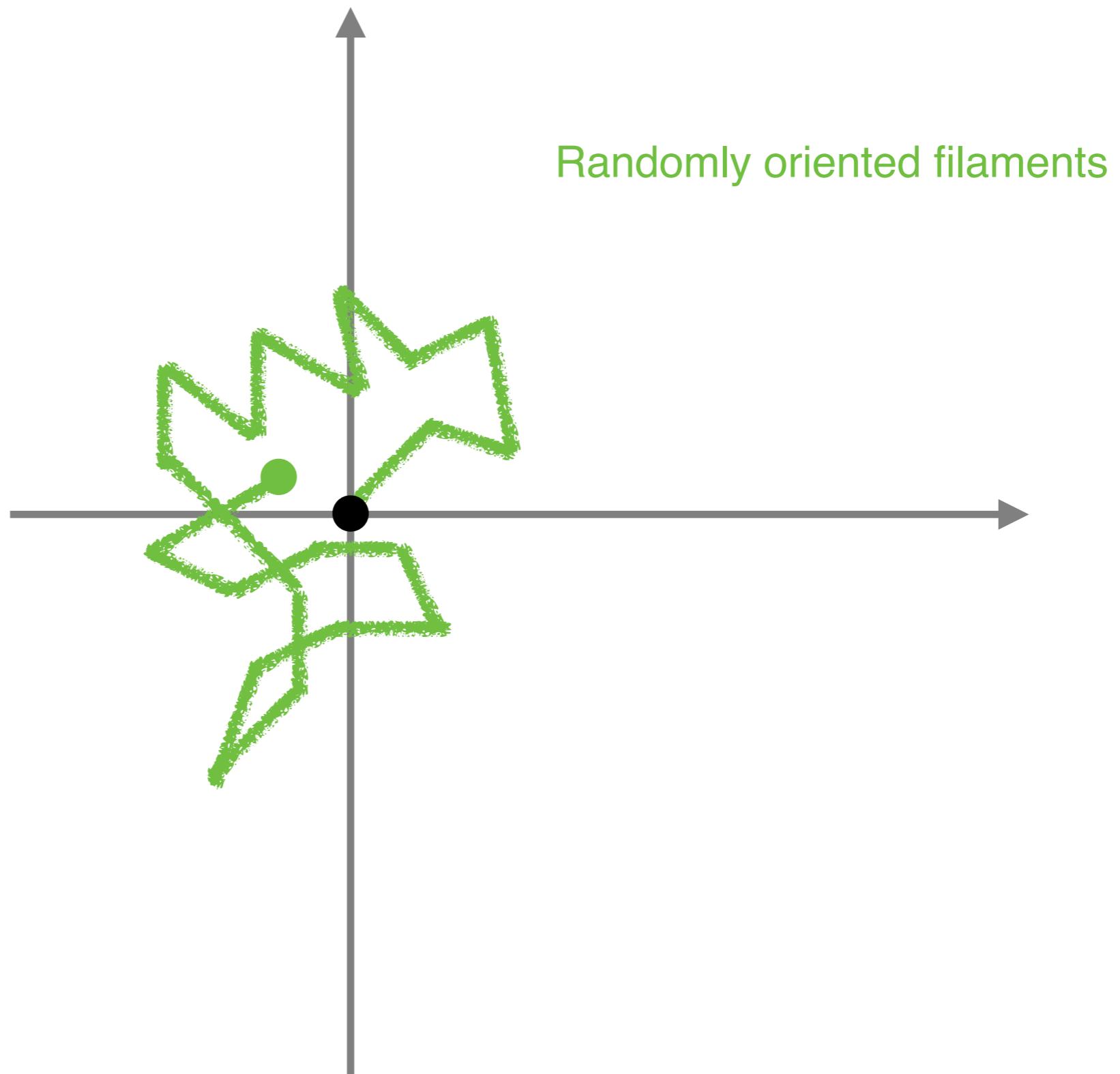
HI filament orientation: random walk interpretation

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



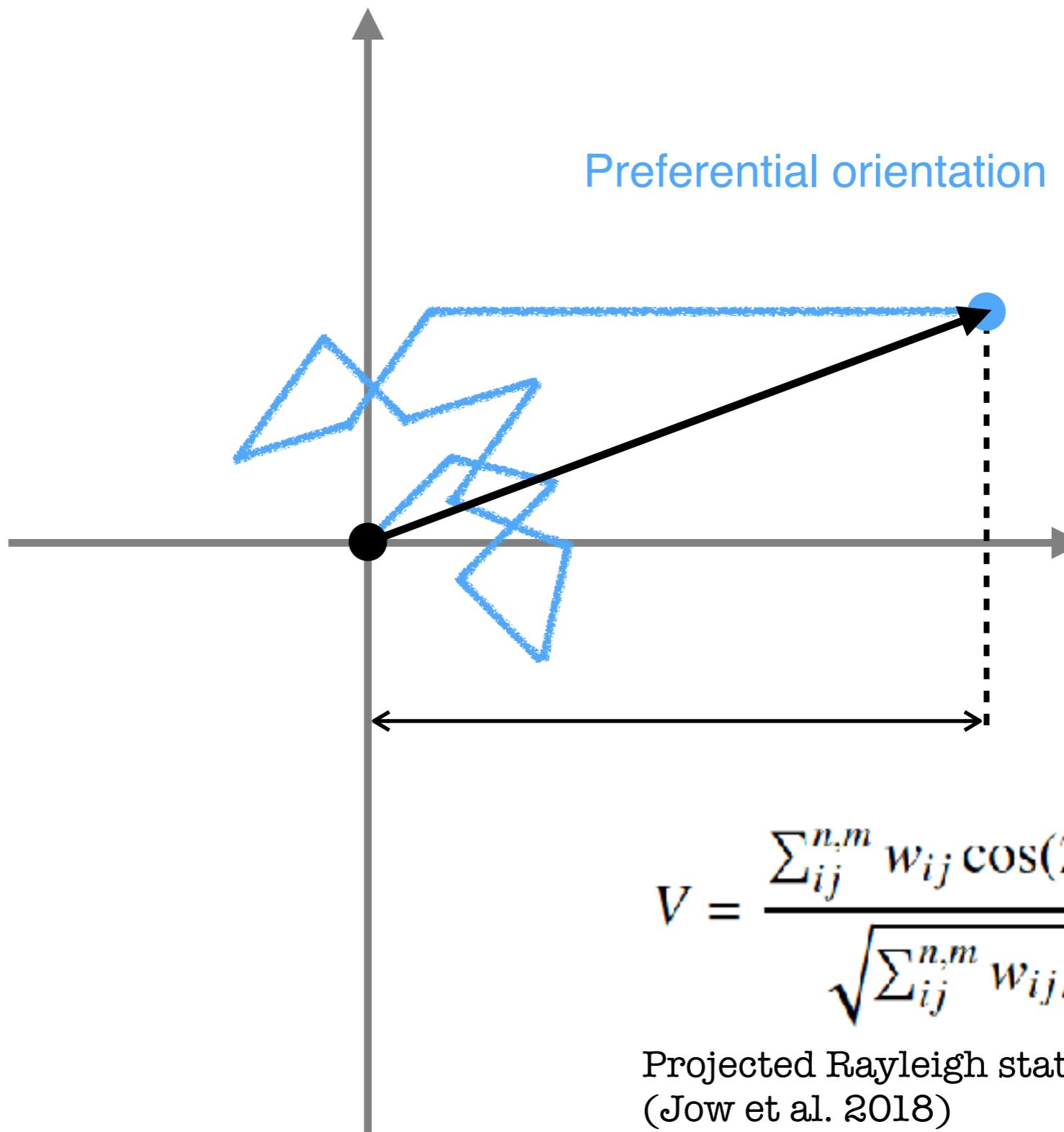
HI filament orientation: random walk interpretation

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



HI filament orientation: random walk interpretation

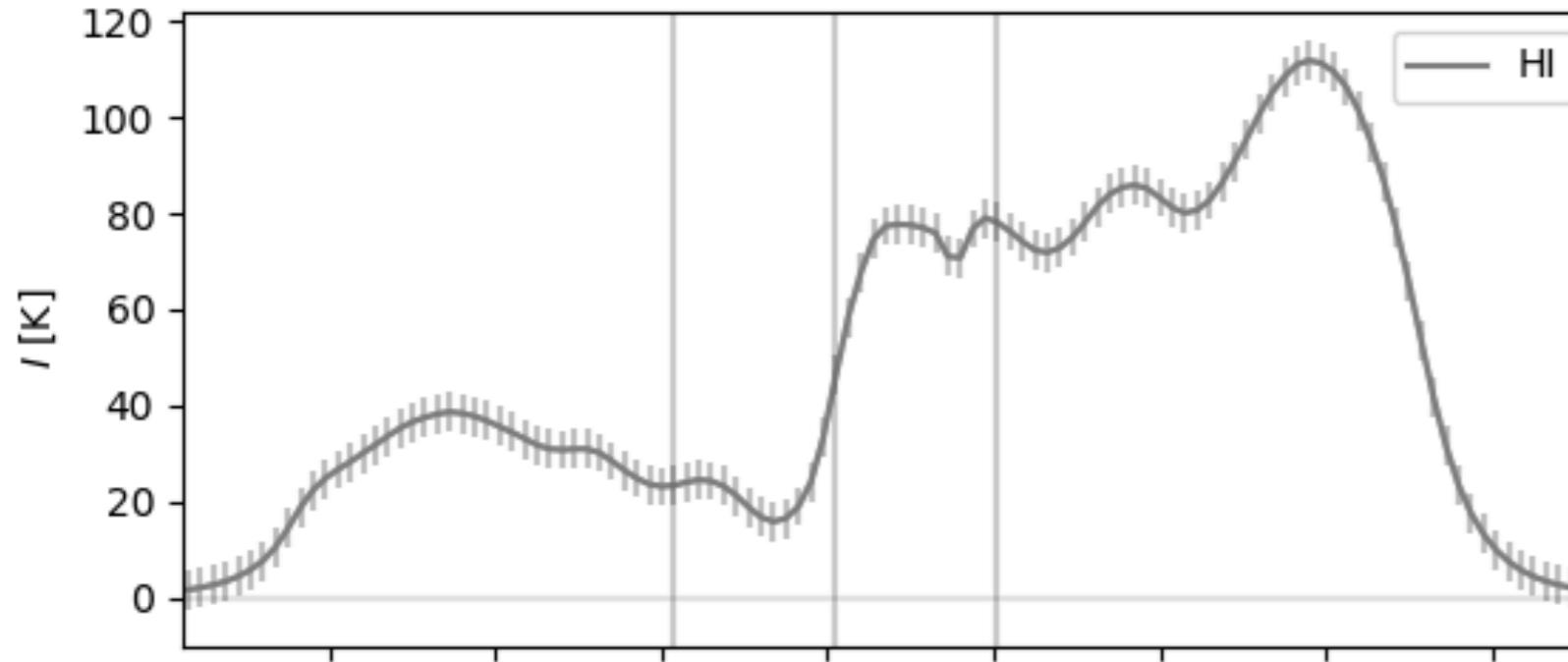
Soler, J.D. et al. A&A. 2020



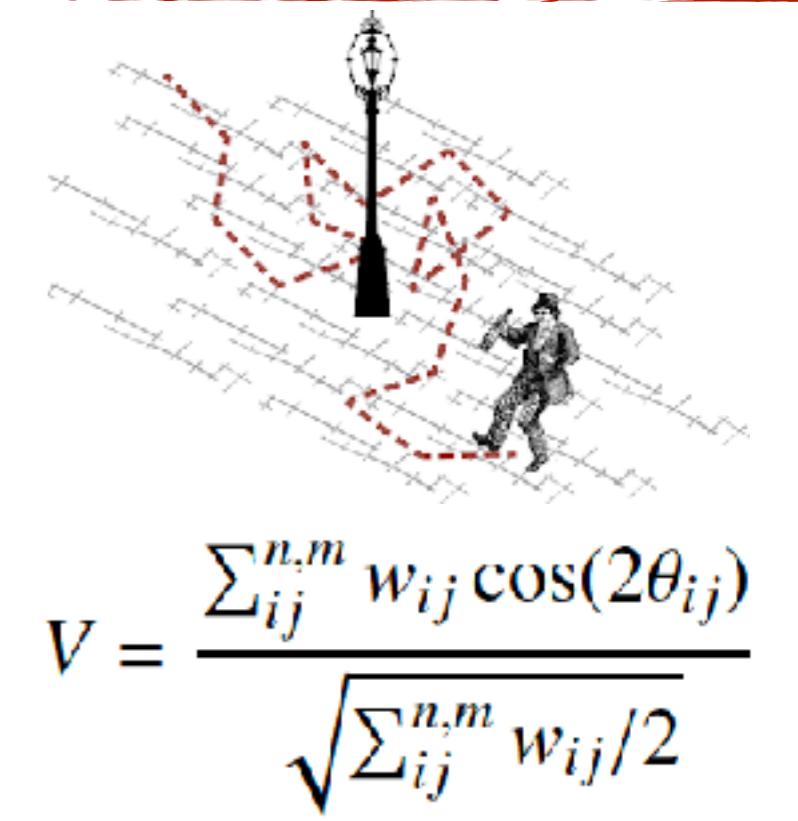
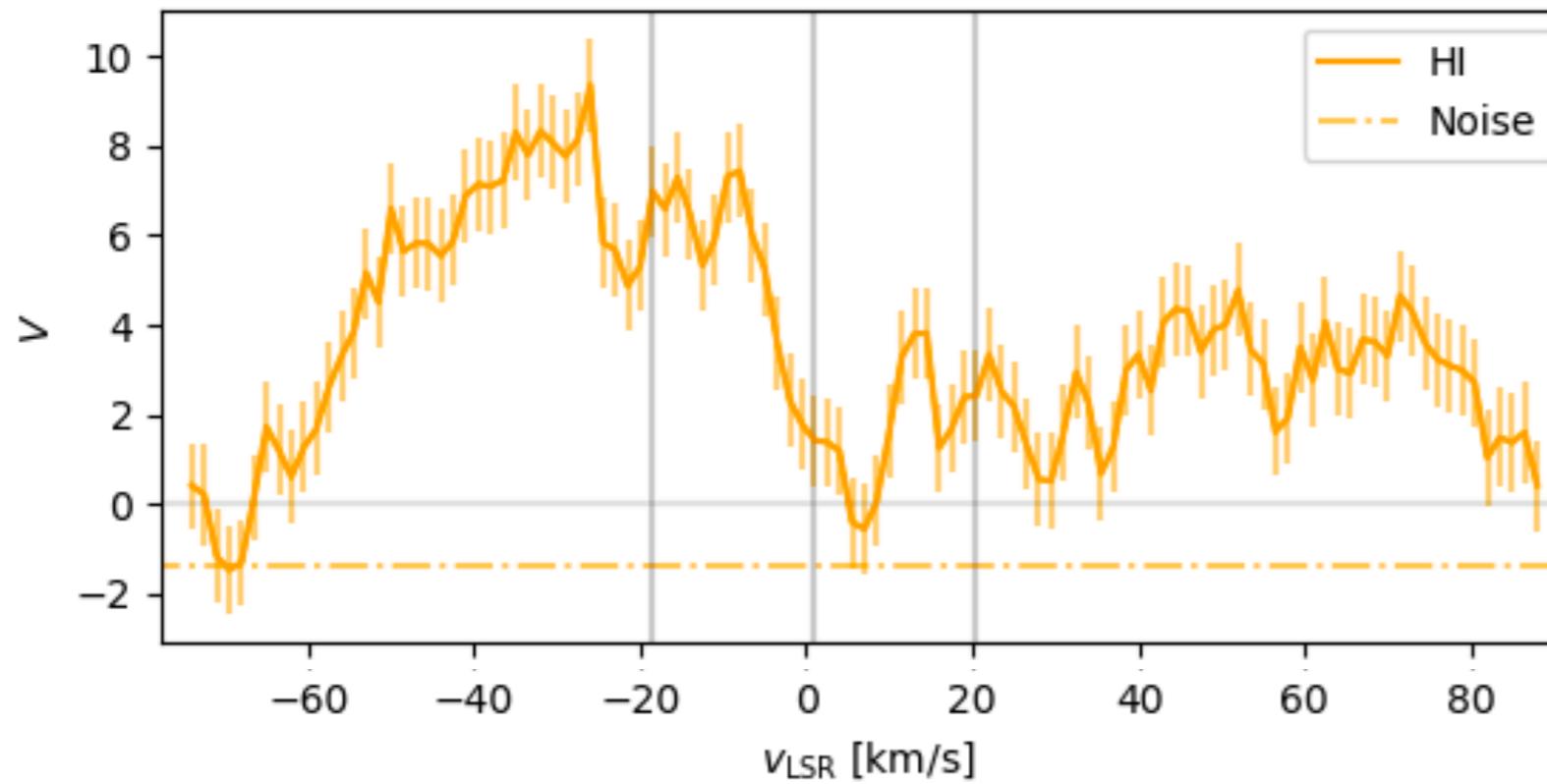
HI filament orientation

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

$43.6 < l < 45.6 \text{deg}$

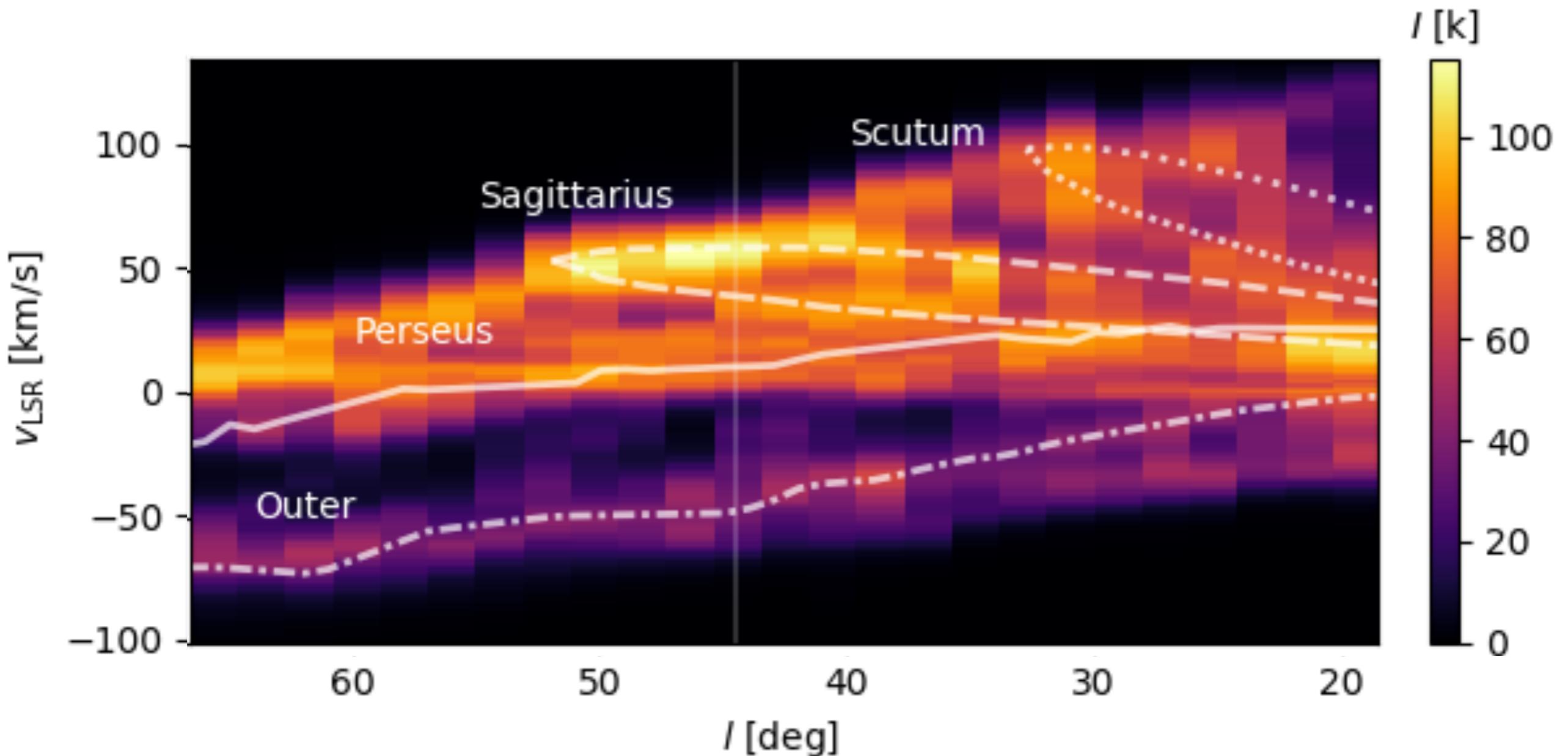


Projected Rayleigh statistic
(Jow et al. 2018)



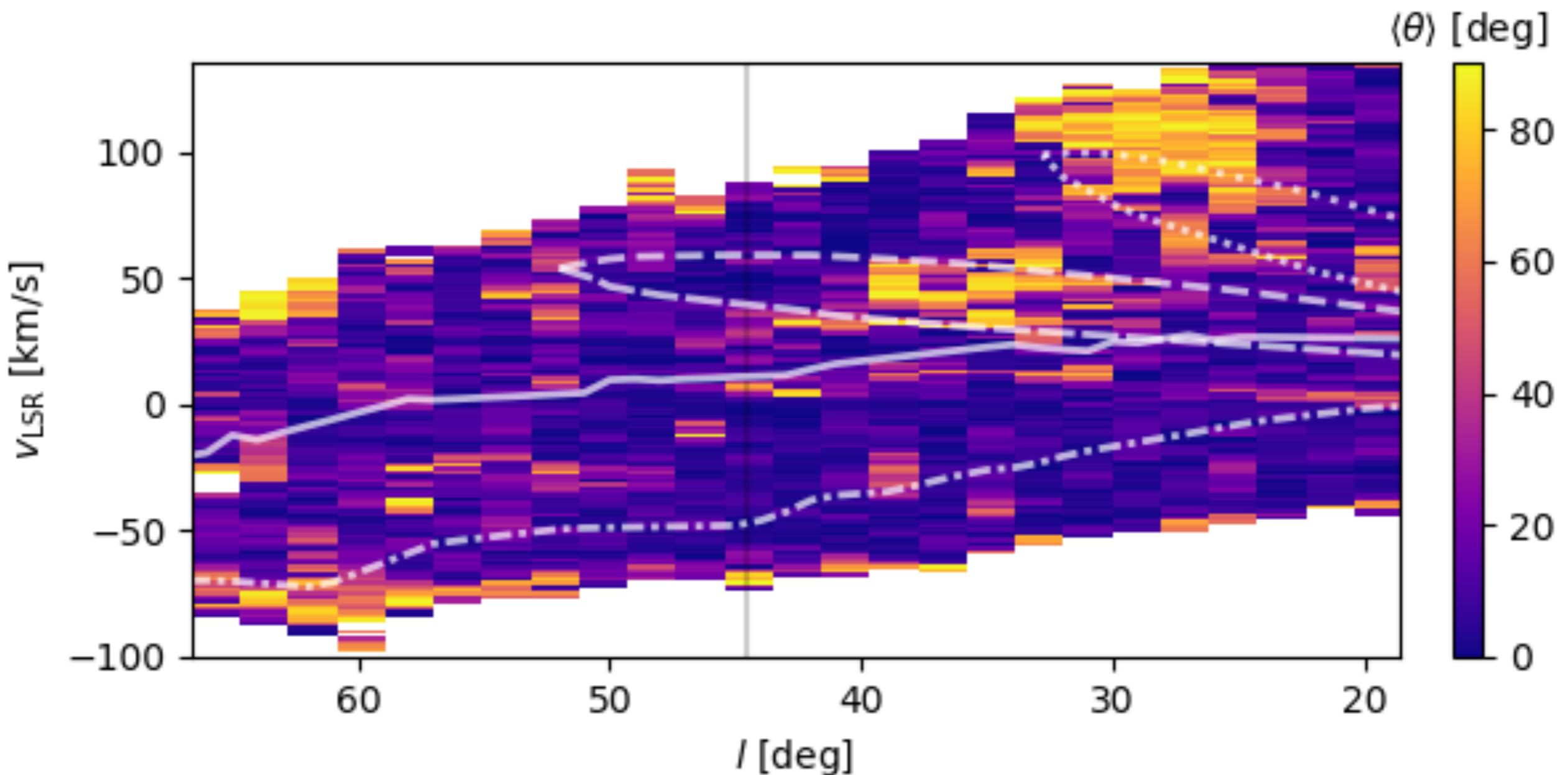
HI emission

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



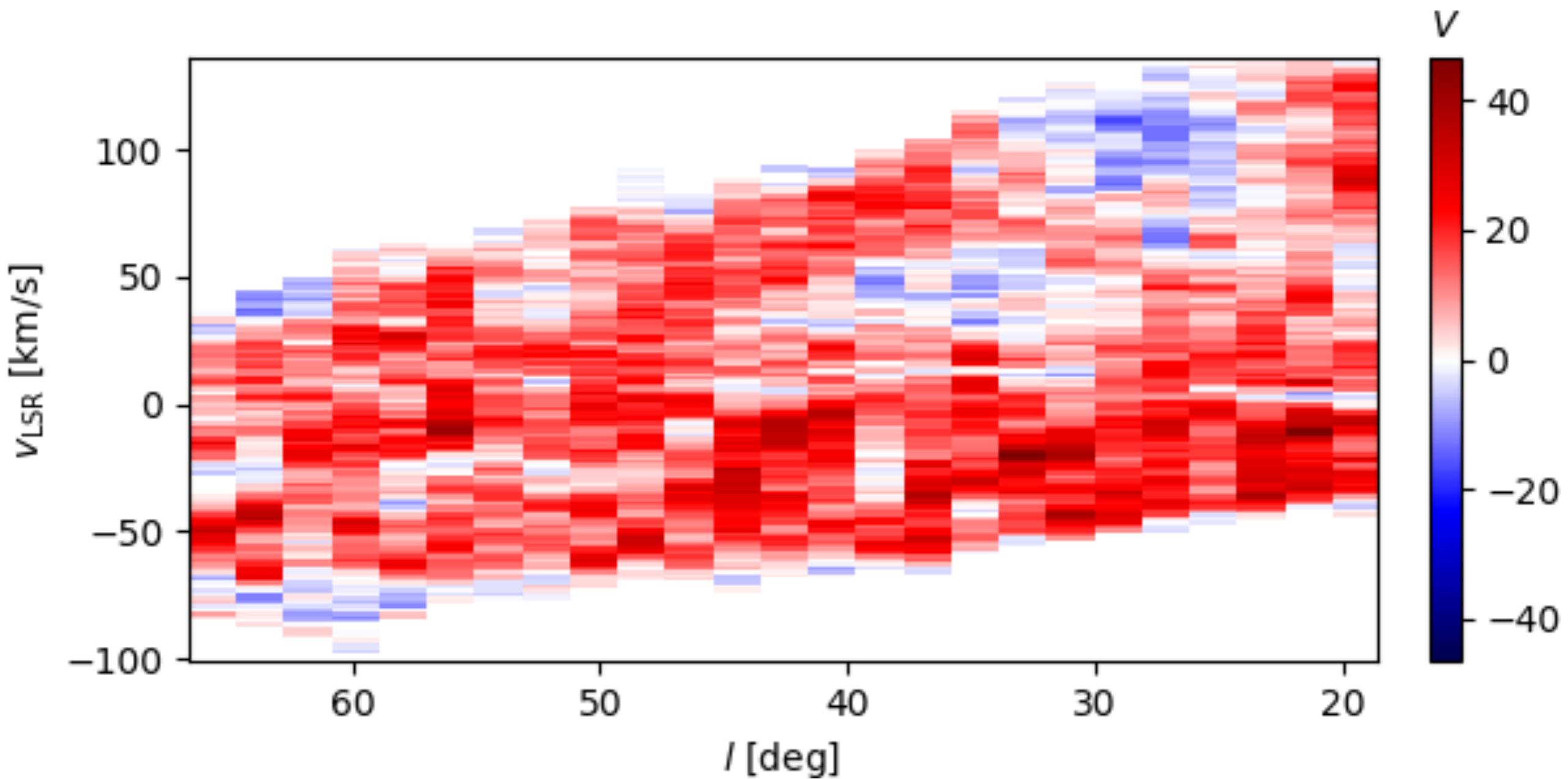
HI filament orientation

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



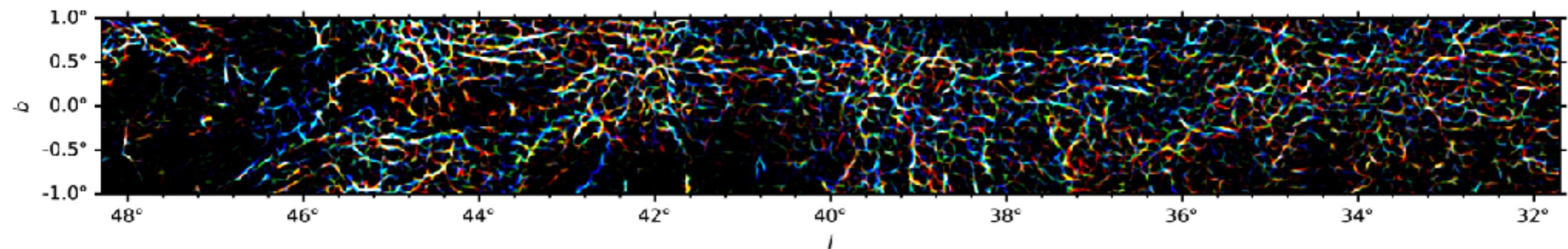
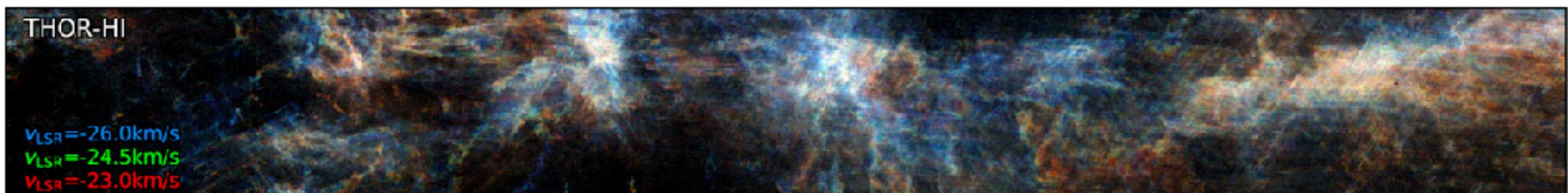
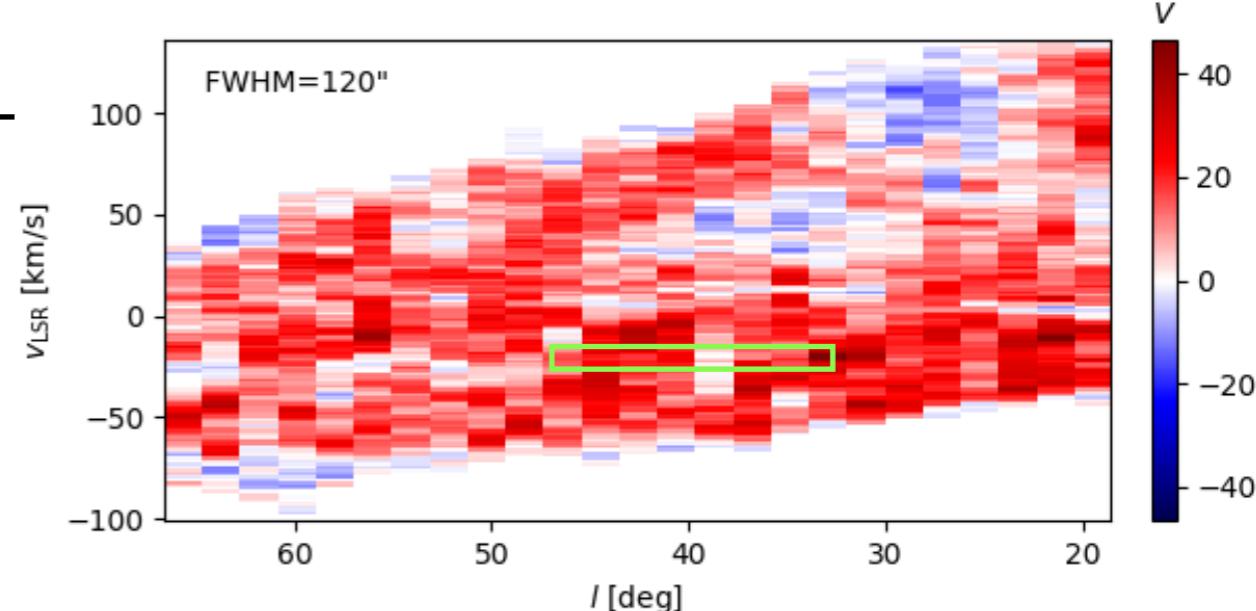
HI filament orientation

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



HI filaments (THOR)

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



The Magdalena (Maggie) filament

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

The “Maggie” filament: Physical properties of a giant atomic cloud

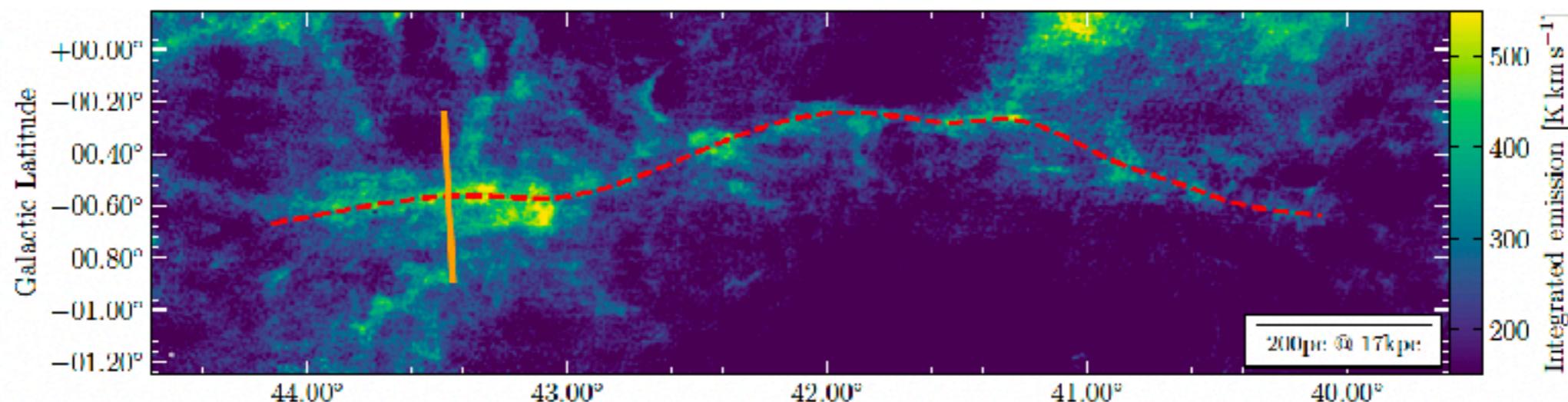
J. Syed + Team



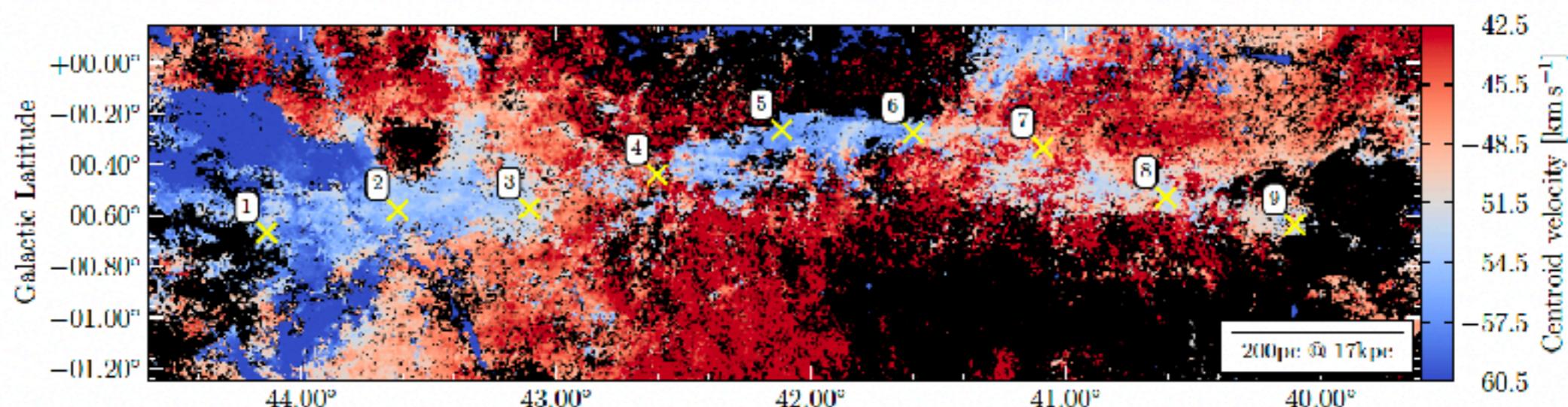
The Magdalena filament

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

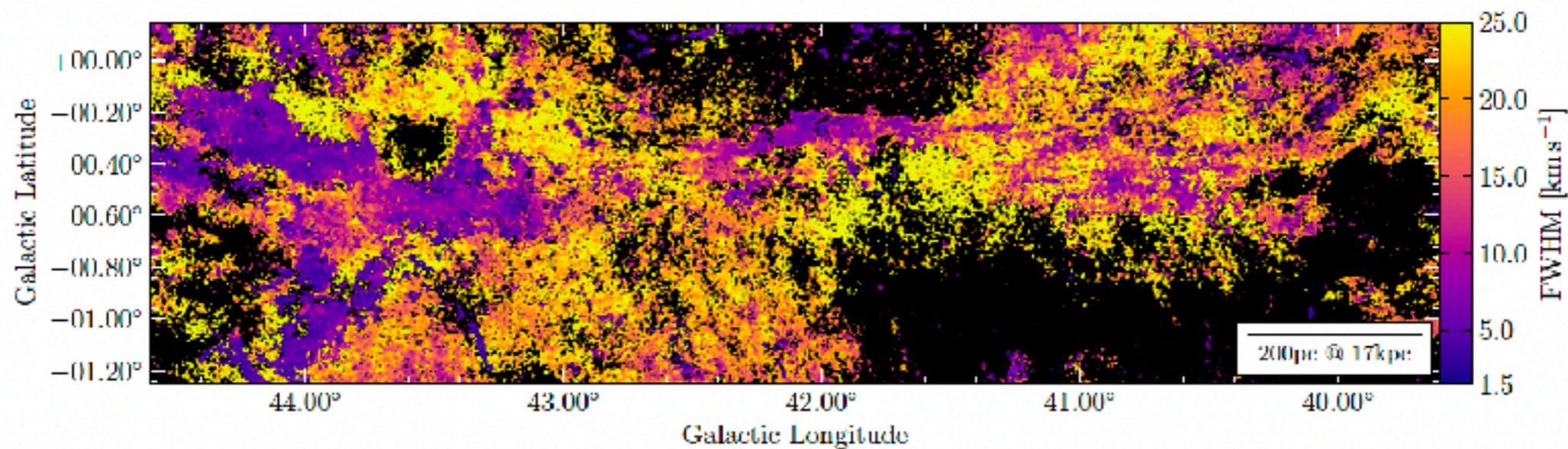
N_{H}



$\langle v \rangle$

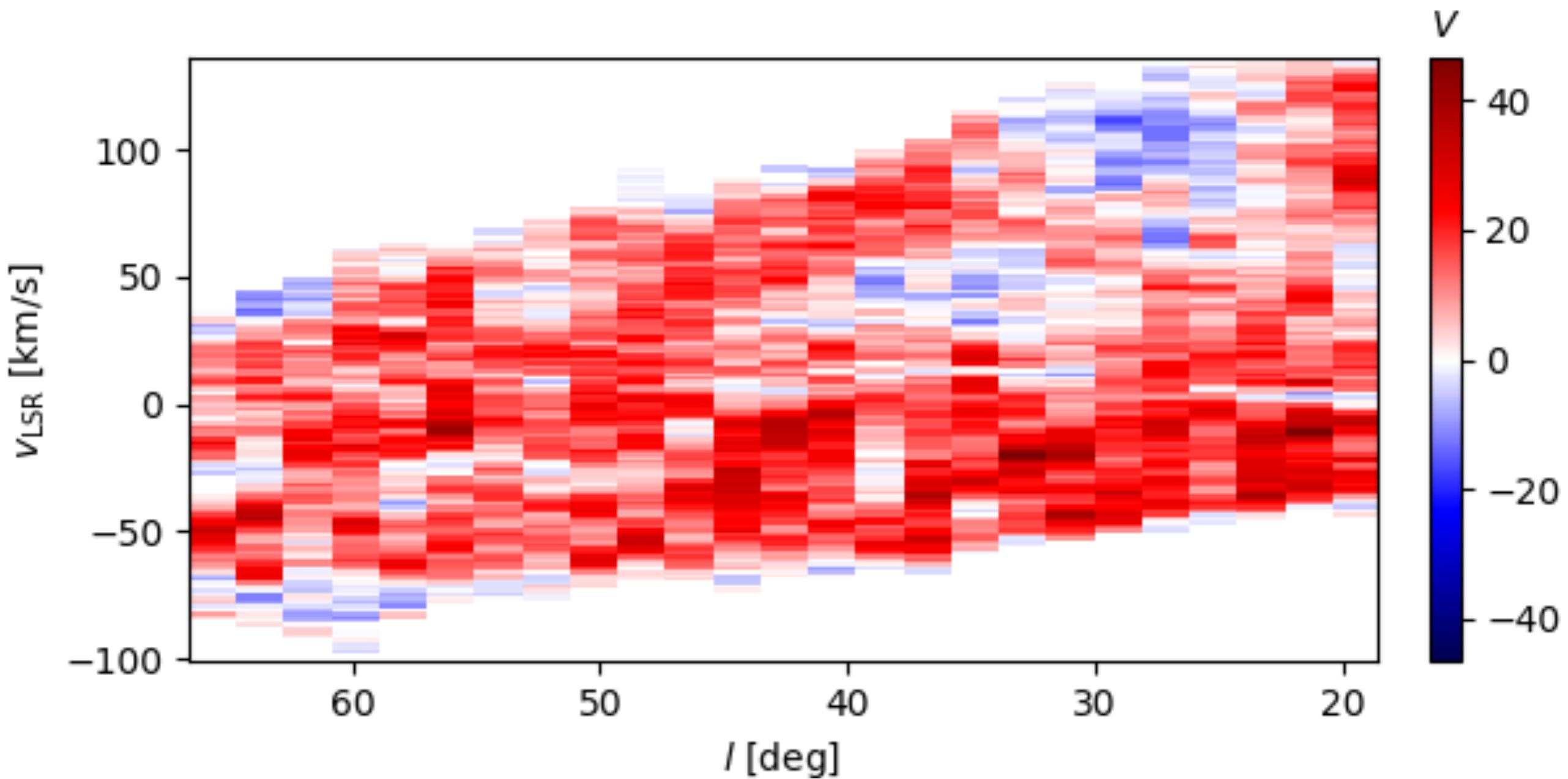


σ_v



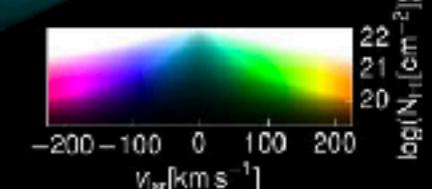
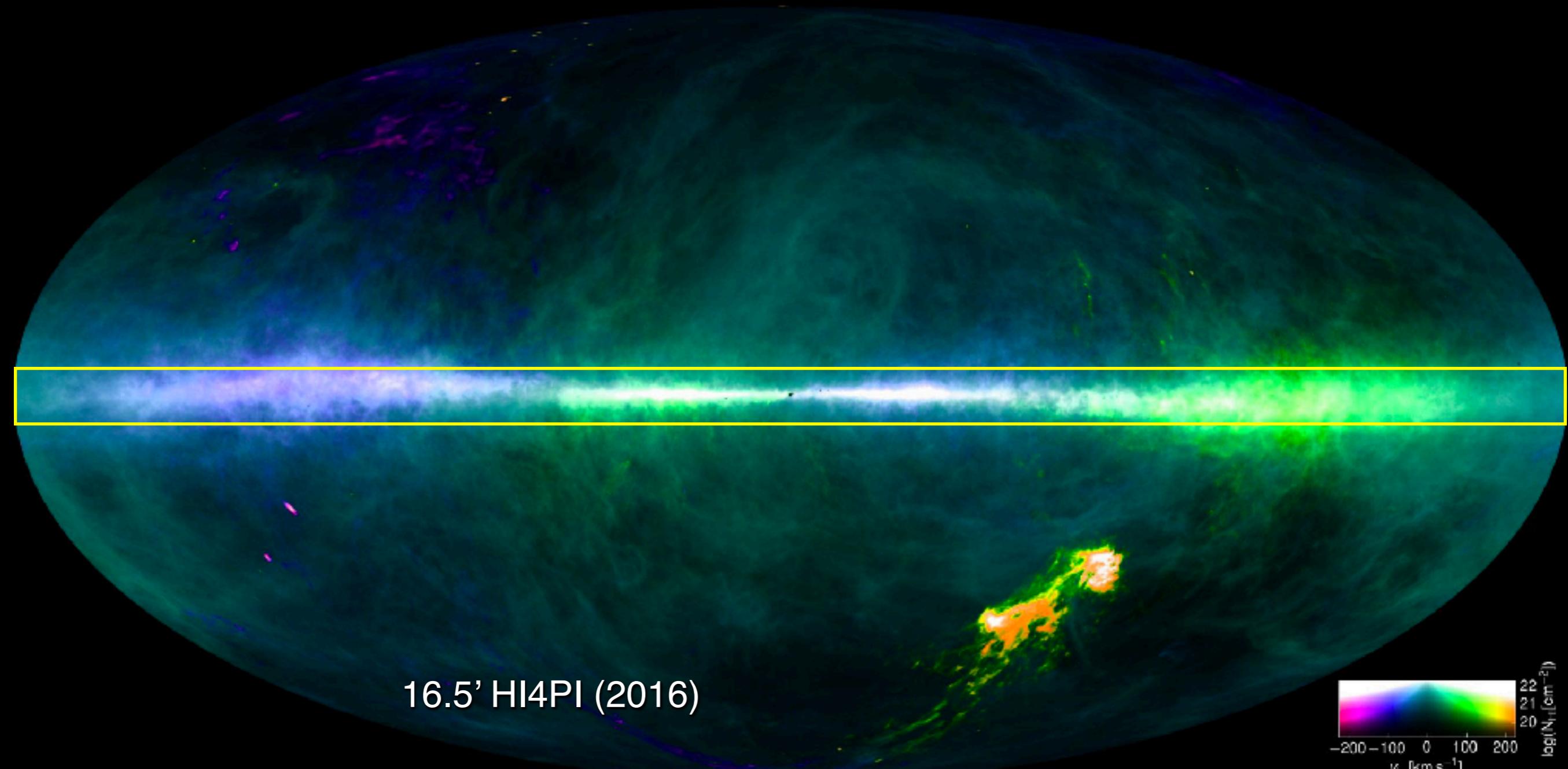
HI filament orientation

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



Atomic hydrogen emission

HI4PI Collaboration. A&A (2016)

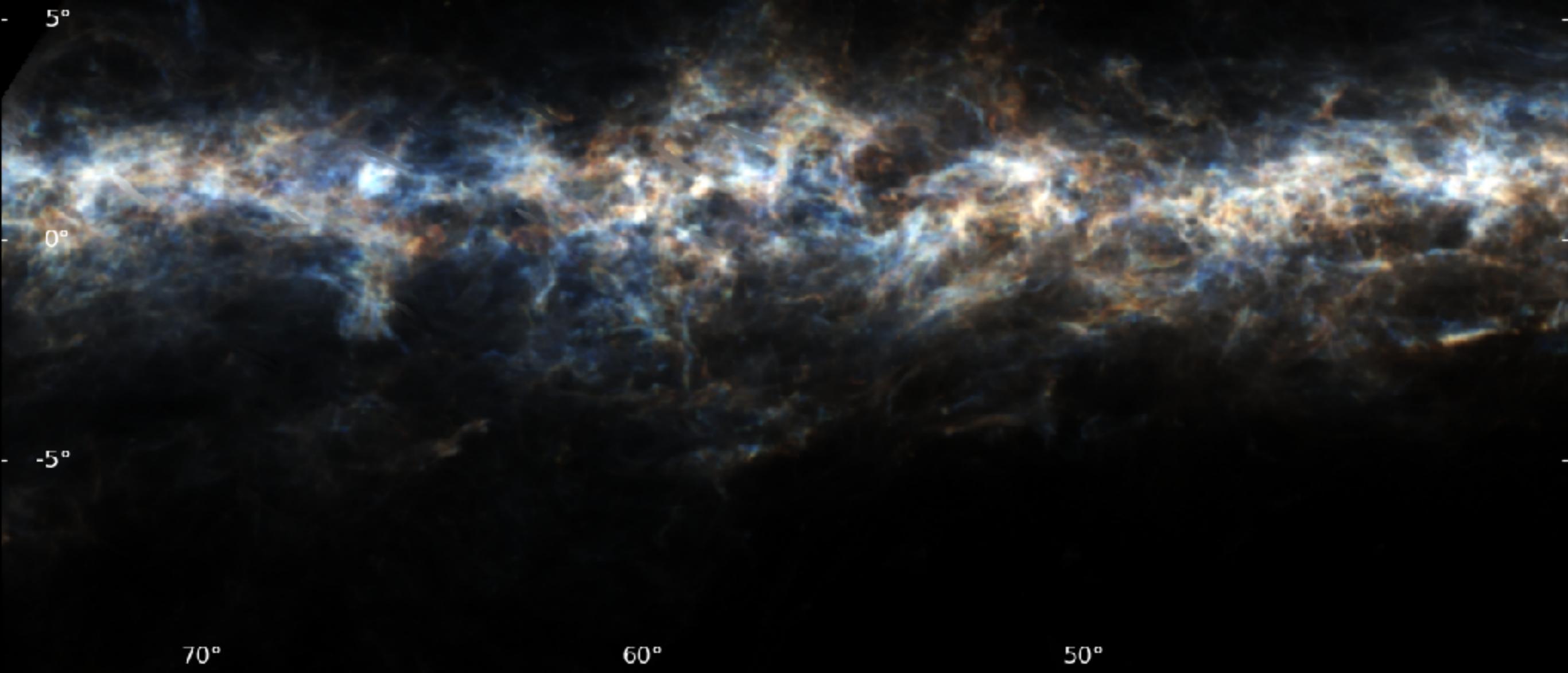


Benjamin Winkel & HI4PI Collaboration

Atomic hydrogen clouds

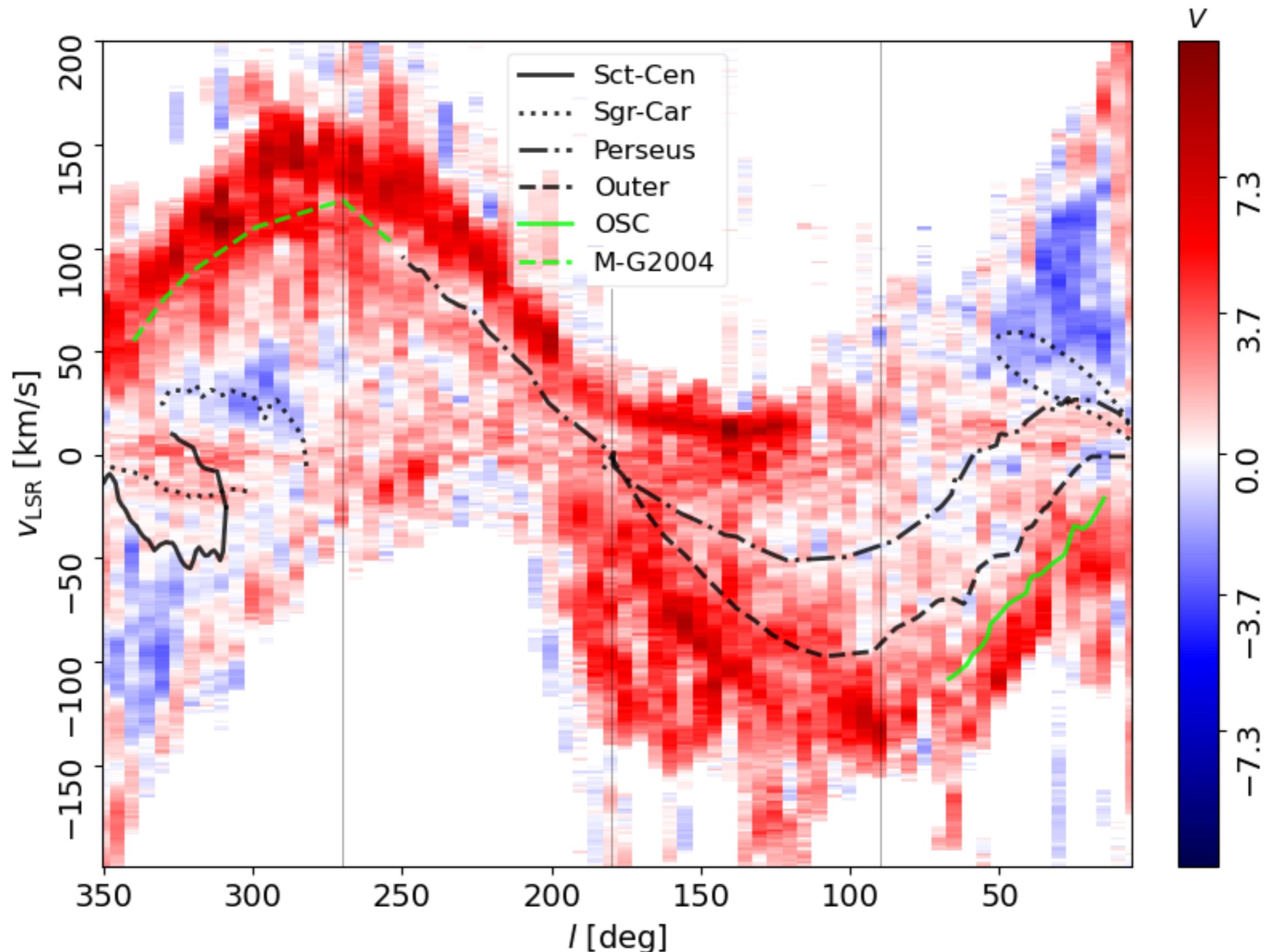
J.D. Soler; GALFA-HI, Peek et al, 2018

Radial velocity: -56.1 km/s
Galactic radius: 11.3 kpc (36942 lyrs)



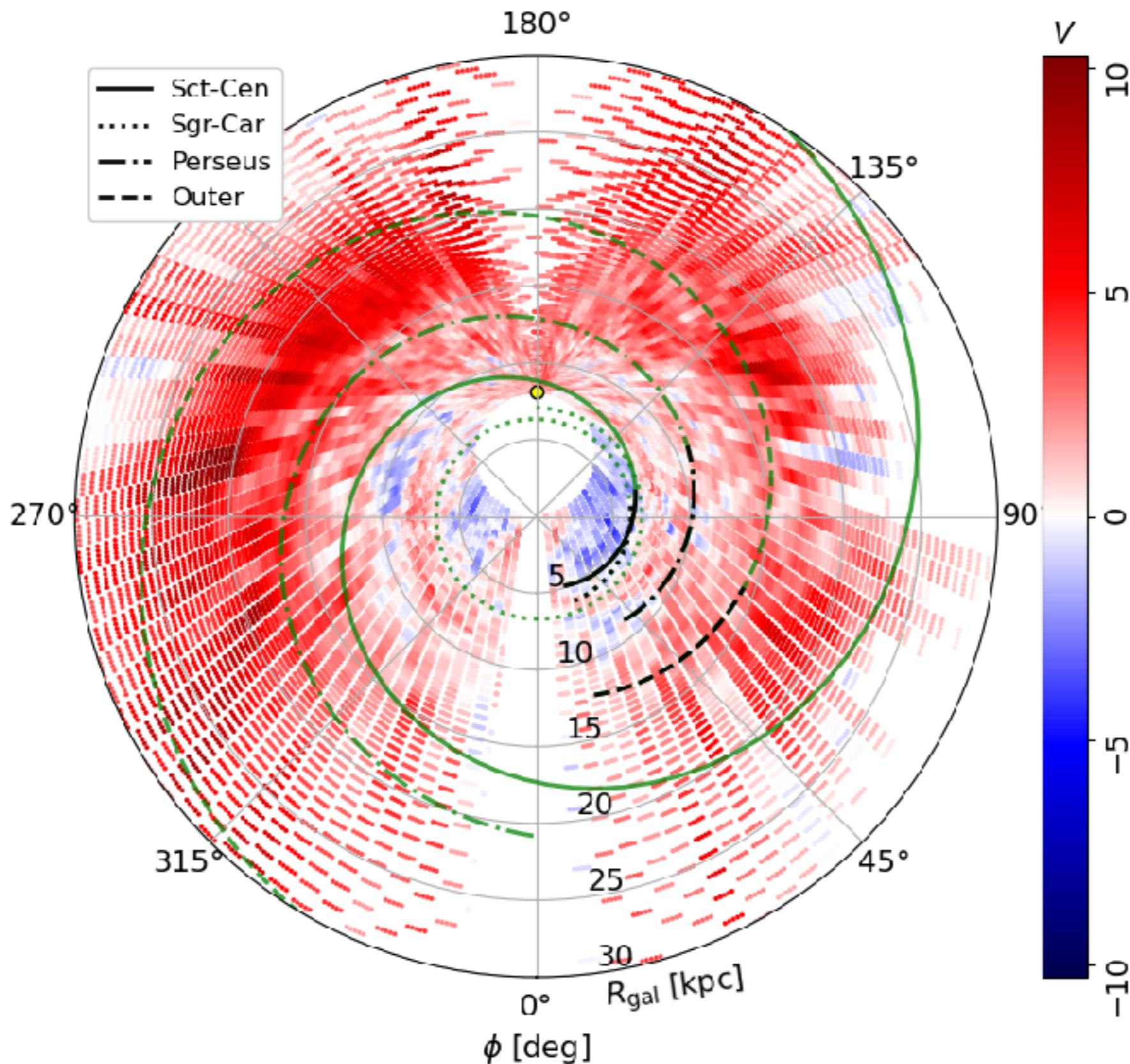
Orientation of atomic filaments

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



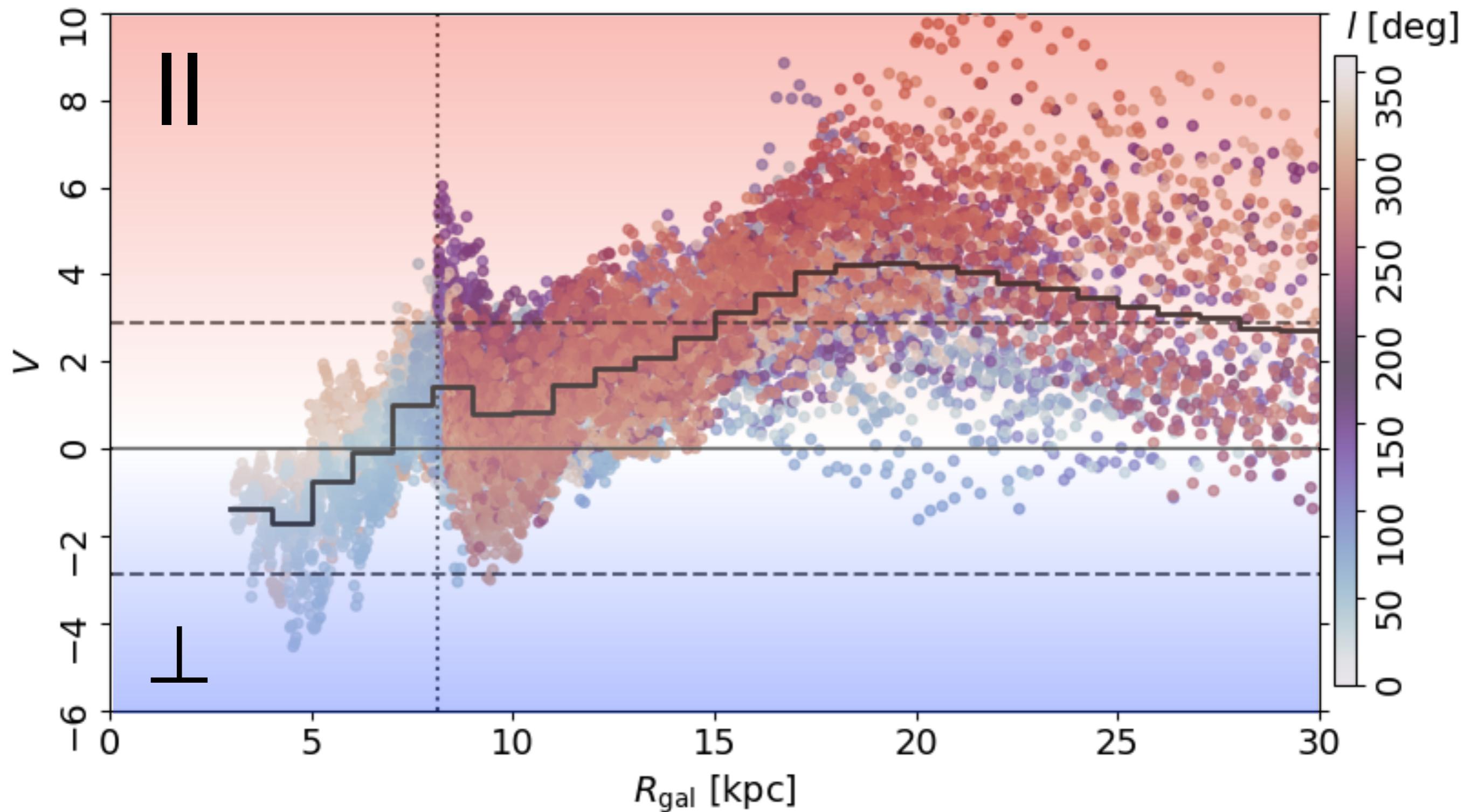
Orientation of atomic filaments

Soler, J.D. et al. 2022



Atomic filament orientation

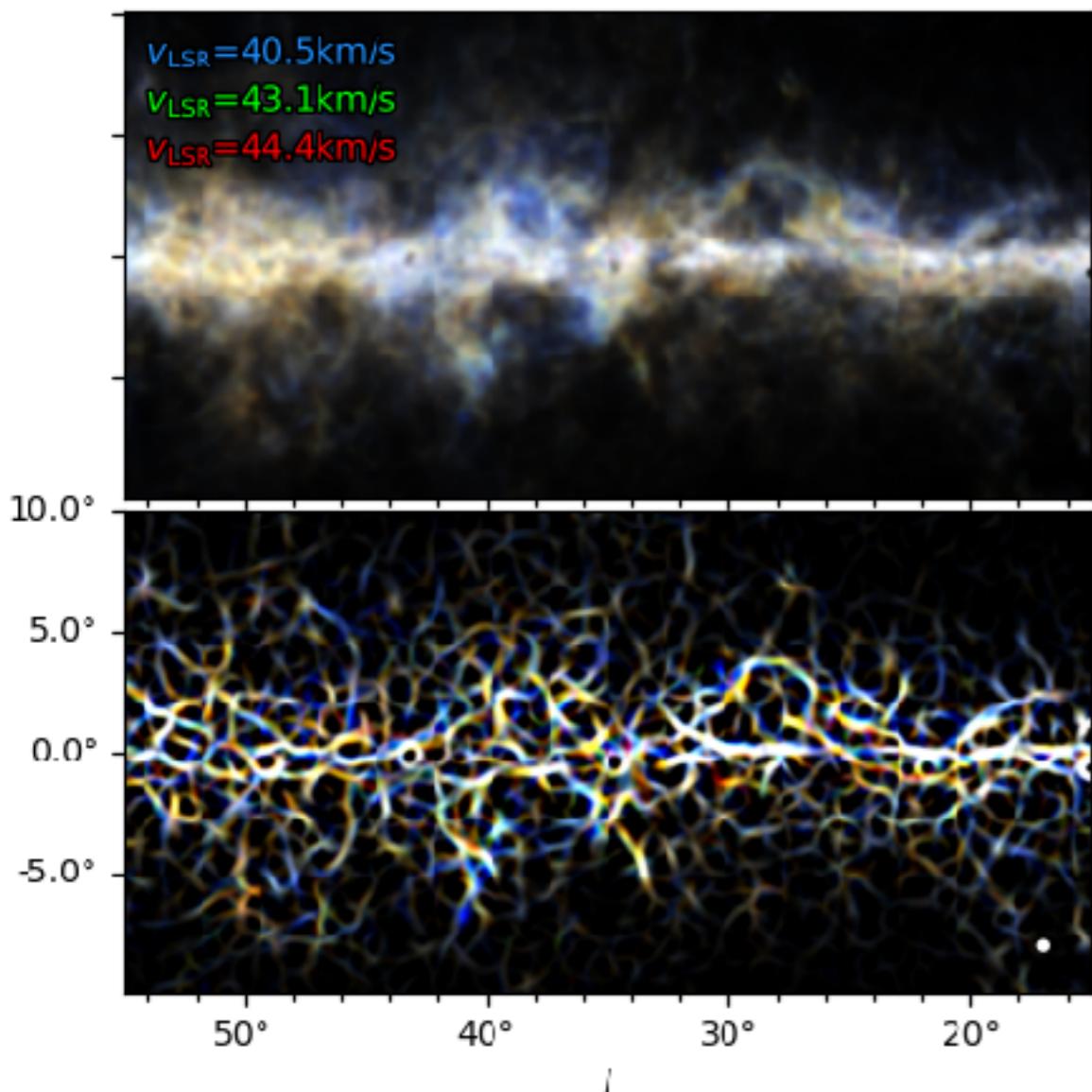
Soler, J.D. et al. 2022.



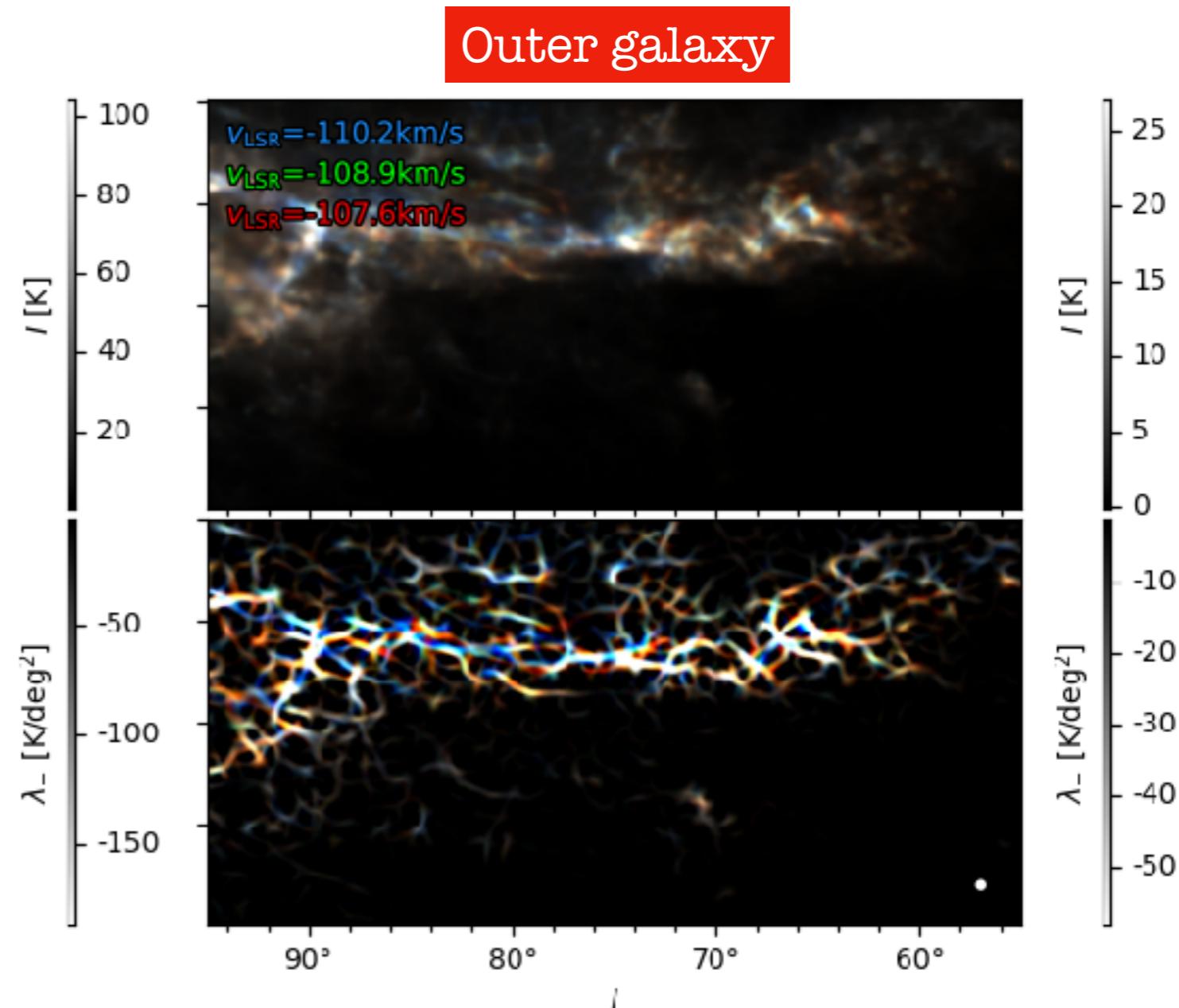
Atomic filament orientation

Soler, J.D. et al. 2022.

Inner galaxy

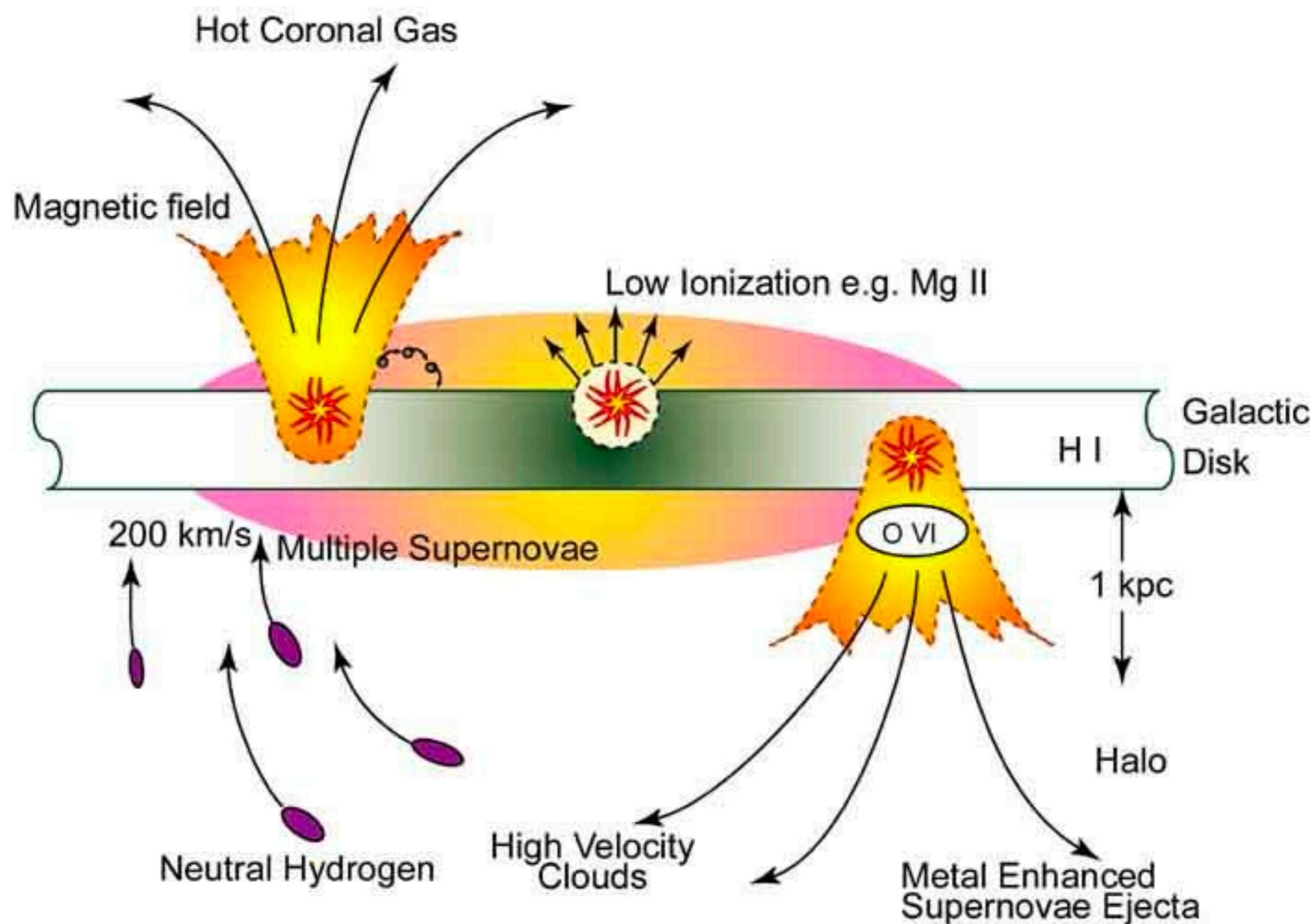


Outer galaxy



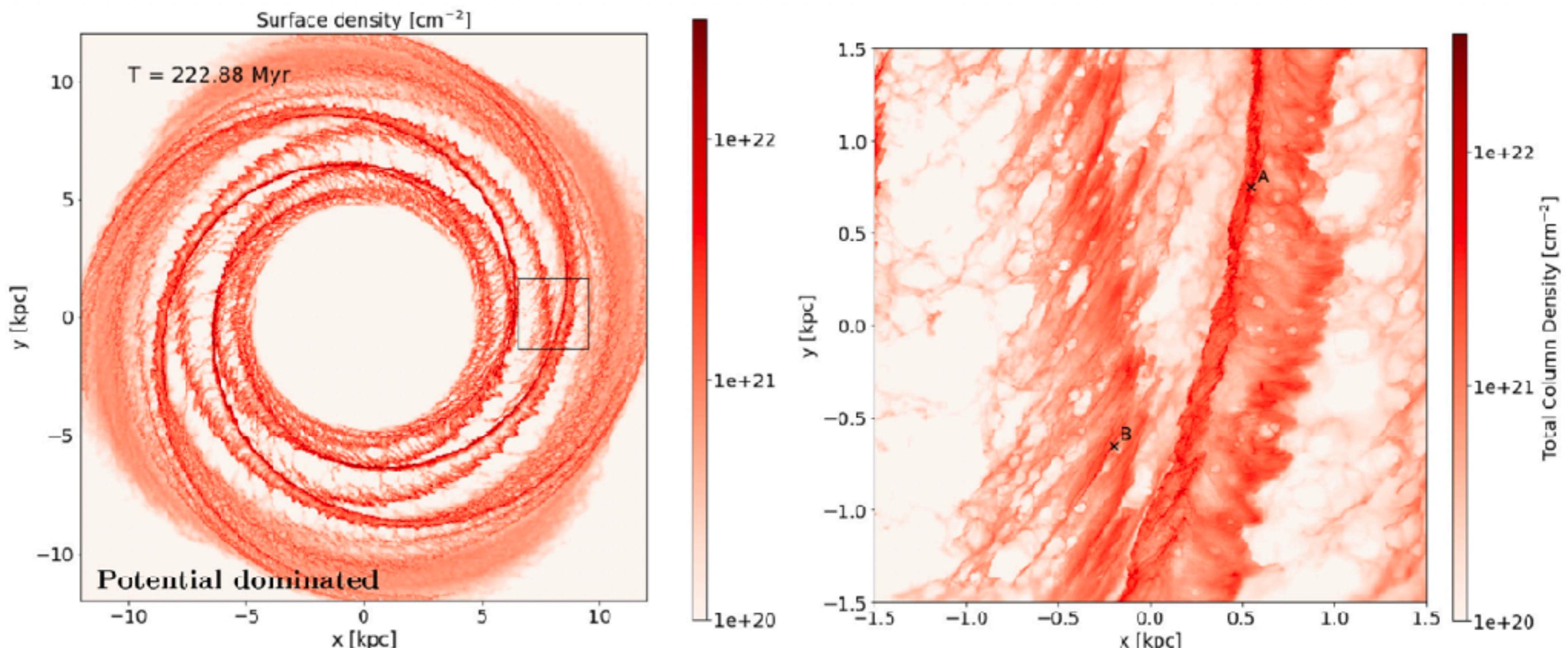
Atomic worms and chimneys

Heiles, 1994

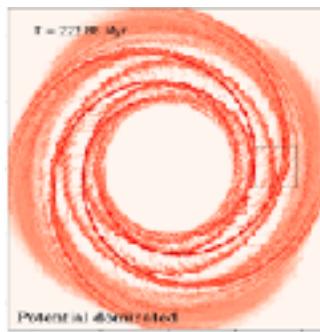


HI filaments - MHD simulations

Smith, R.. et al. MNRAS. 2020

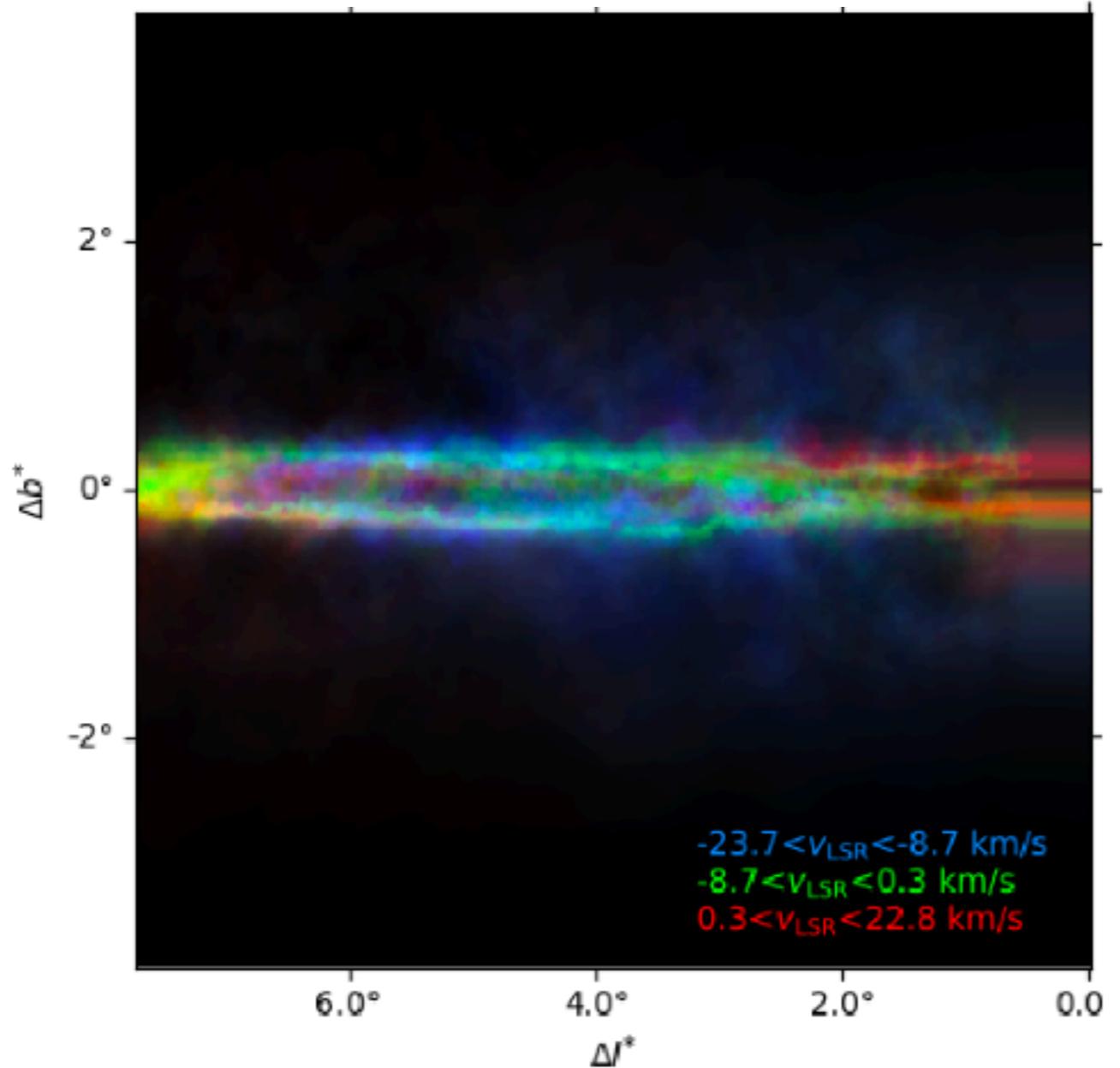


HI filaments - MHD simulations

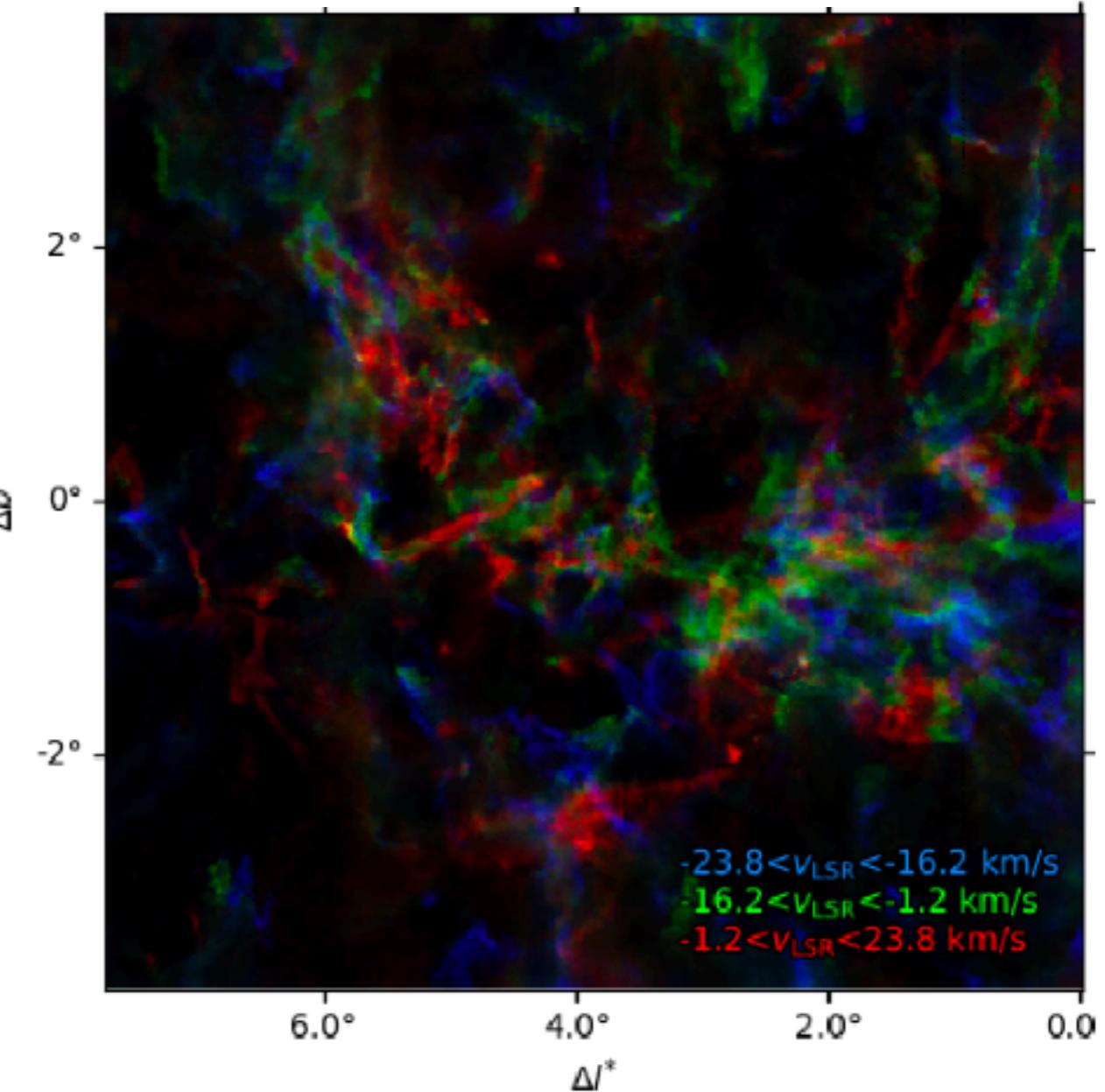


CloudFactory simulations (Smith et al. A&A 2020)
Soler, J.D. et al. A&A 2020

Potential-dominated



Feedback-dominated

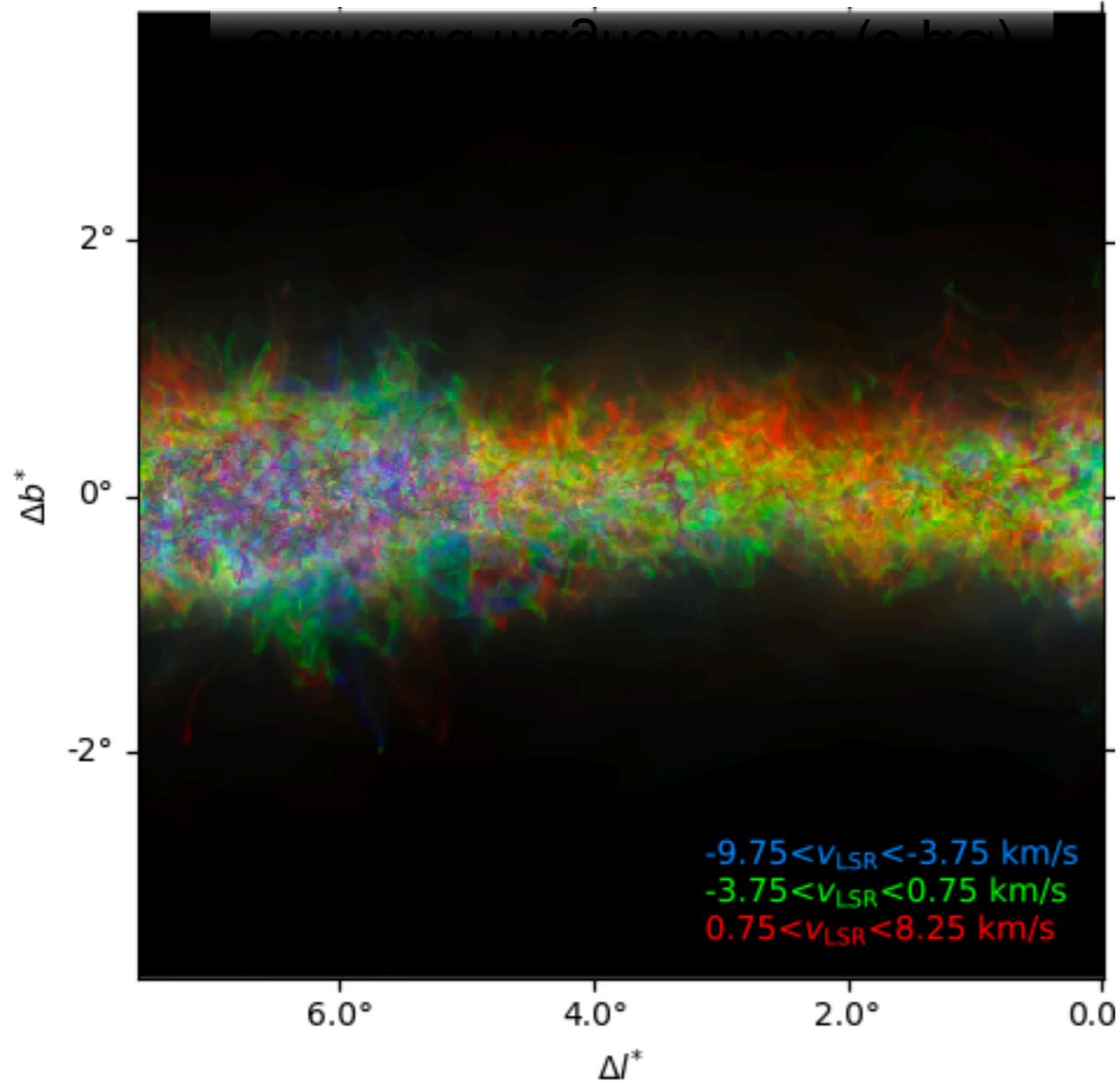


HI filaments - MHD simulations

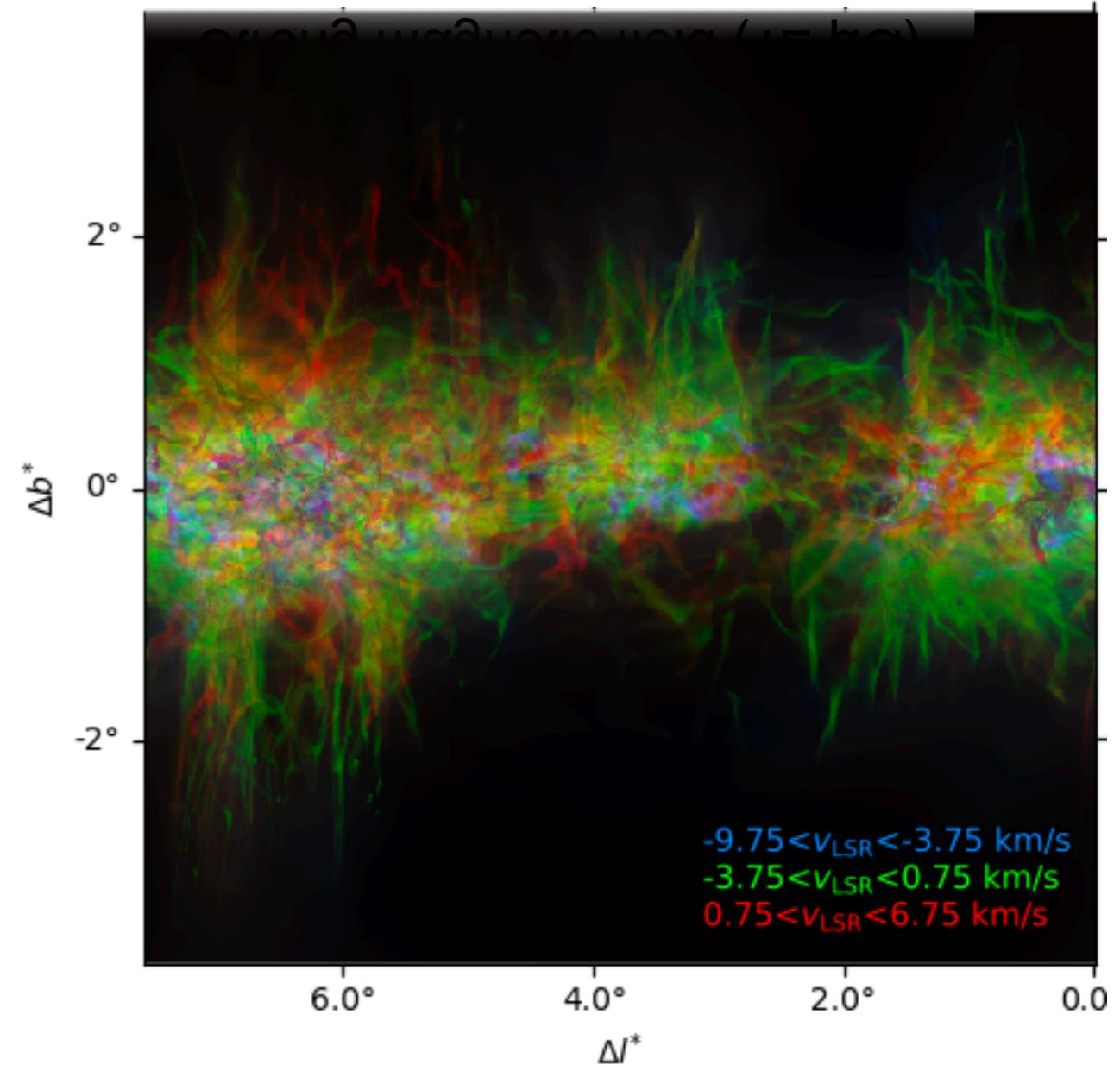
FRIGG simulations (Hennebelle et al. A&A 2018)

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

Standard magnetic field (3 μG)

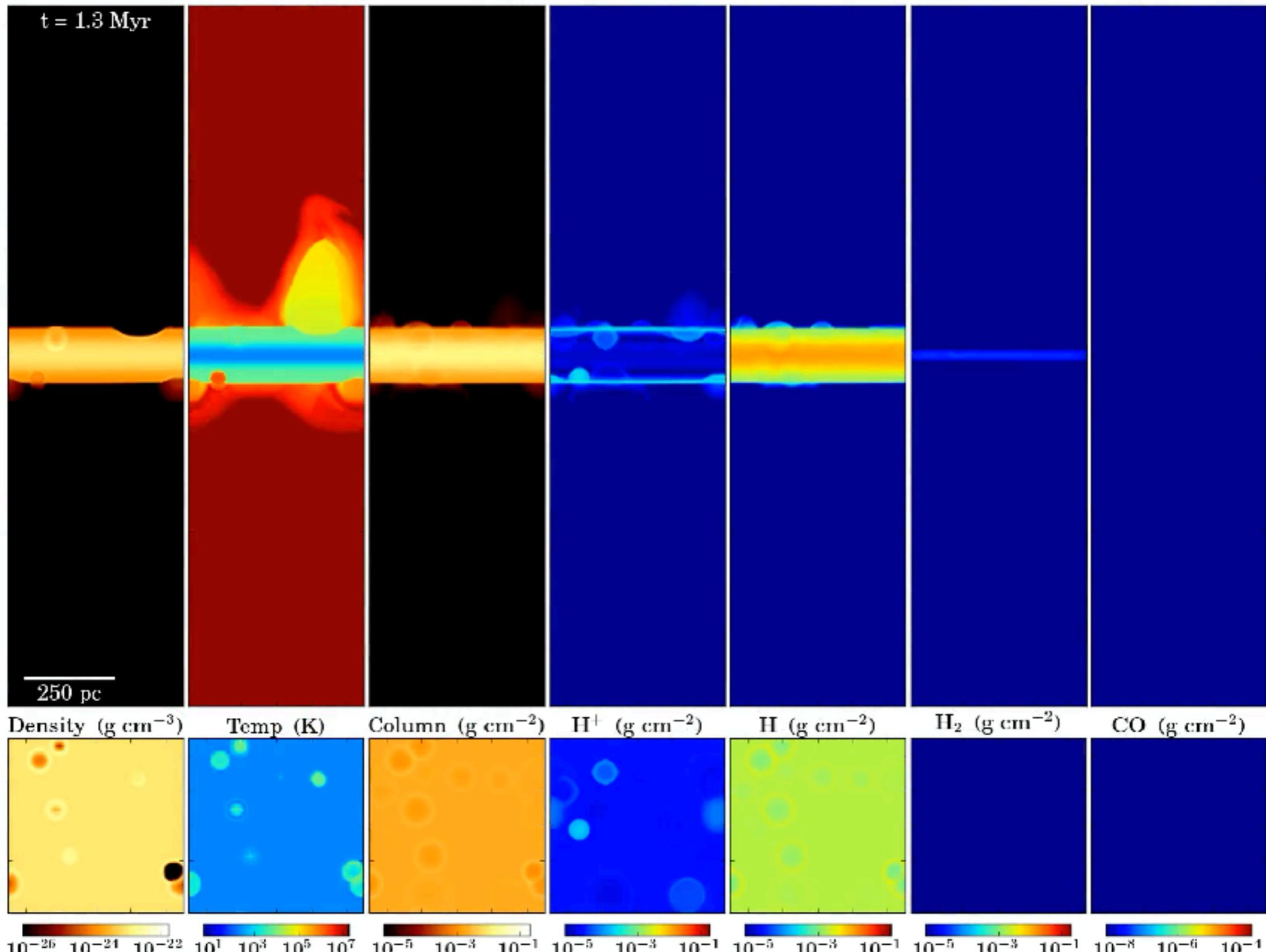


Strong magnetic field (12 μG)



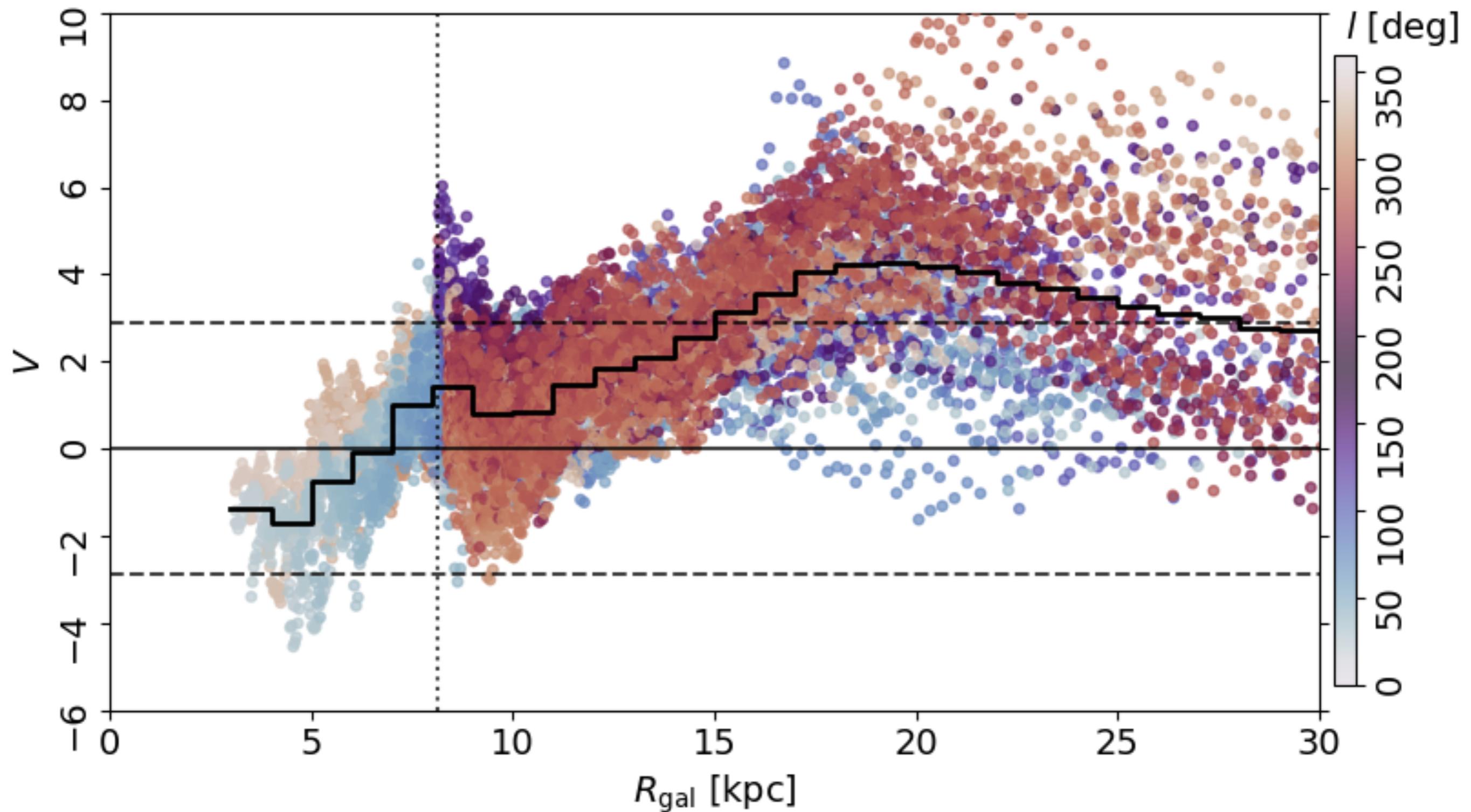
Atomic filament orientation and HI bubbles

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



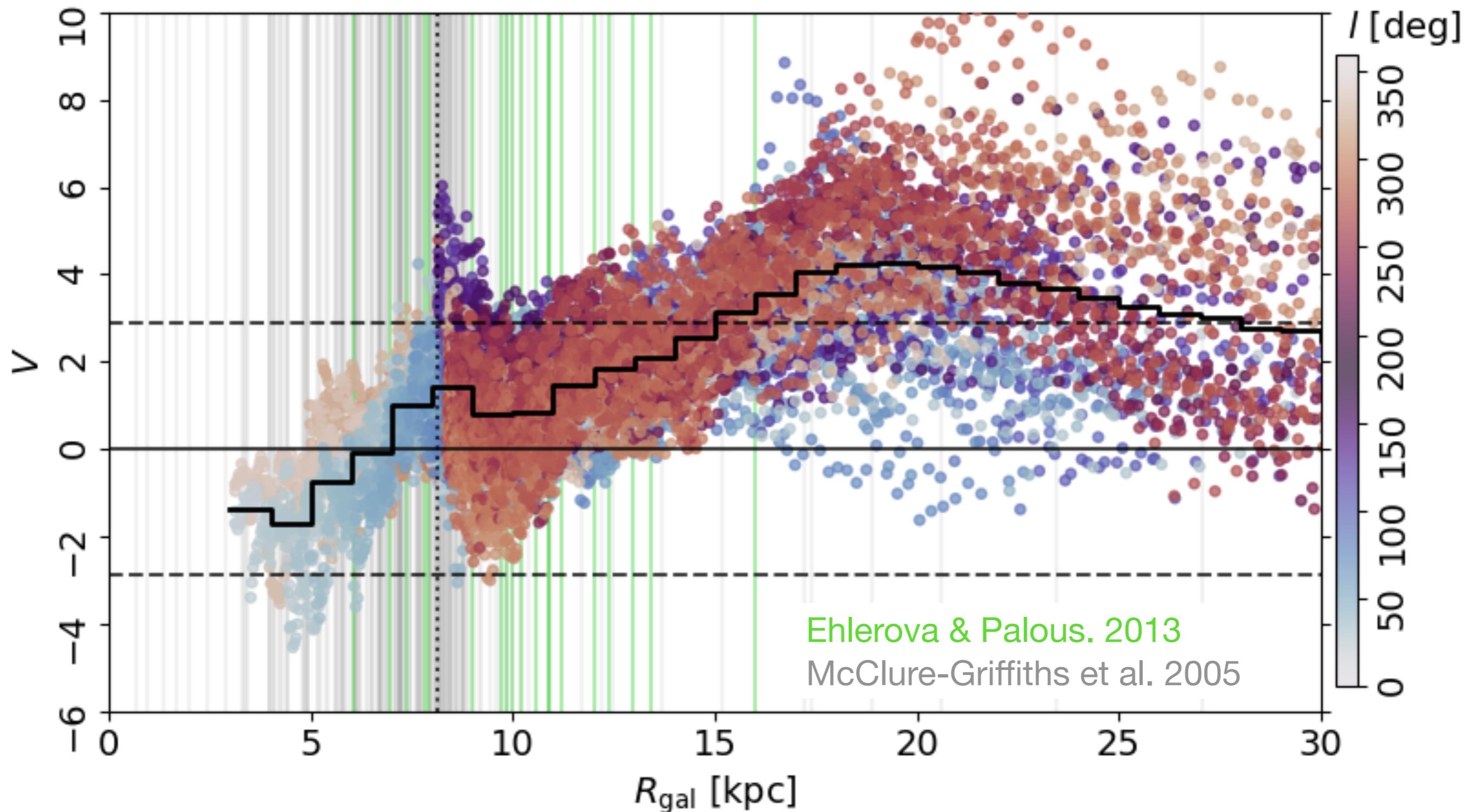
Atomic filament orientation

Soler, J.D. et al. 2022.



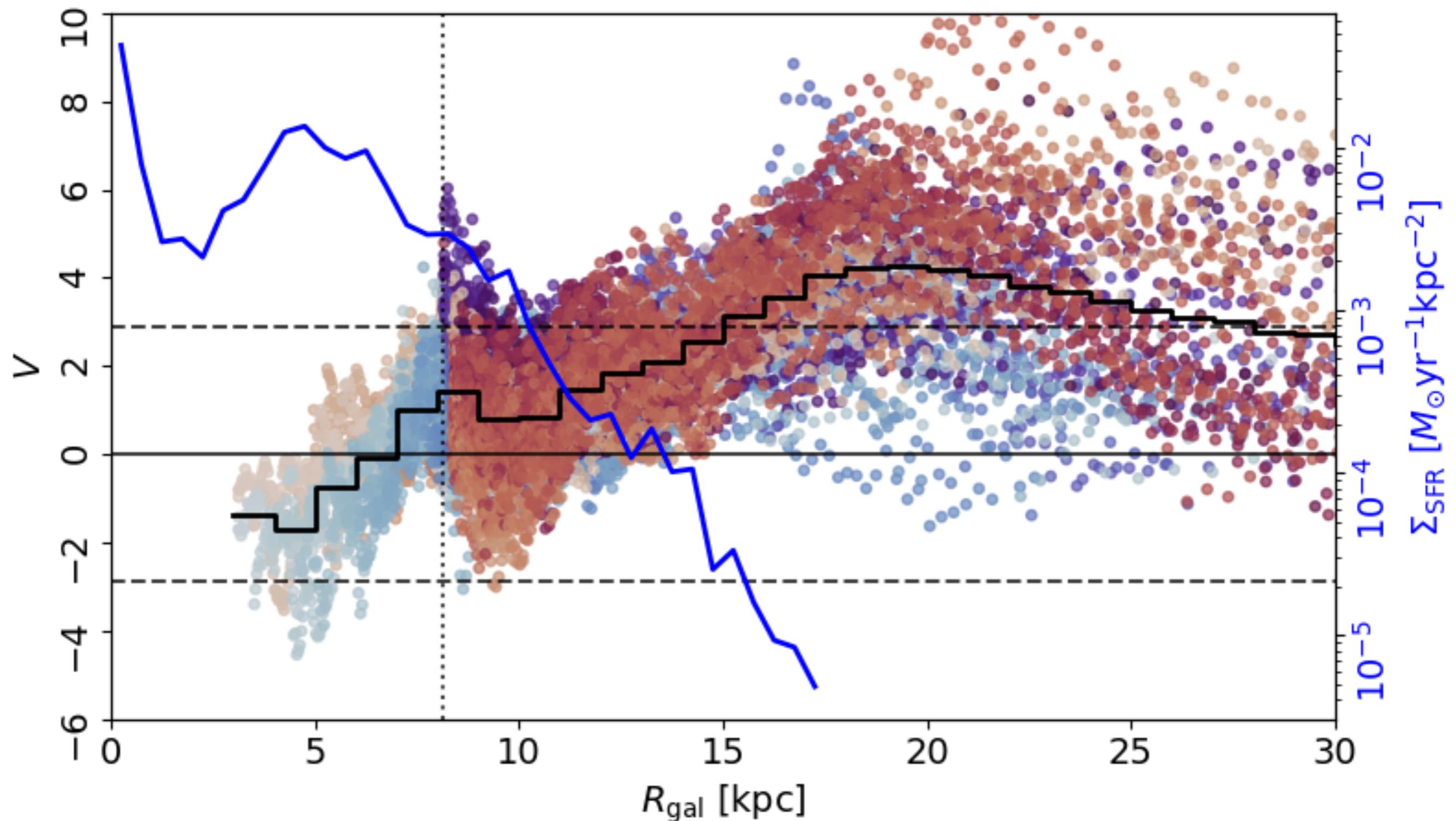
Atomic filament orientation and HI bubbles

Soler, J.D. et al. 2022.



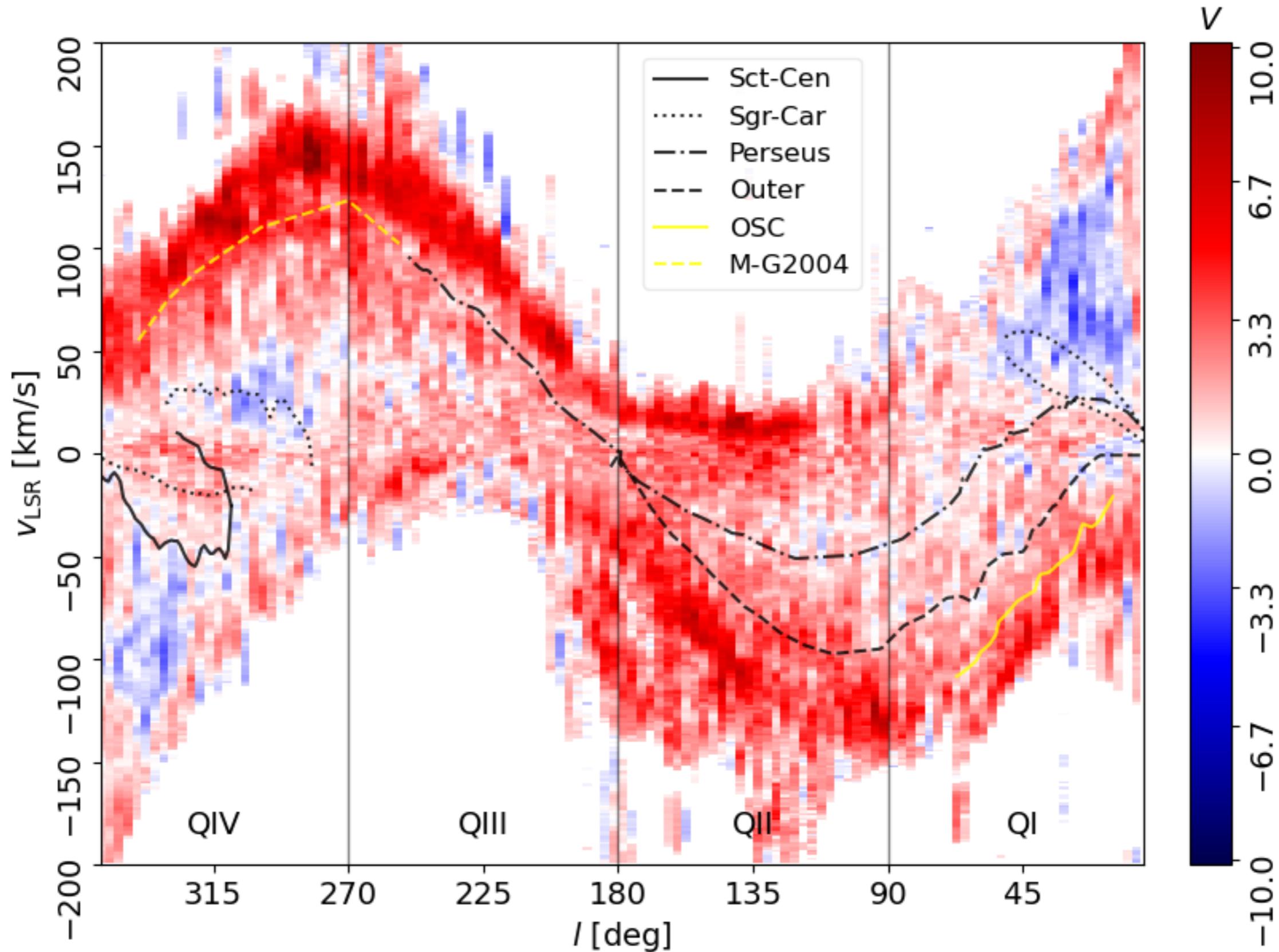
Atomic filament orientation and star formation

Soler, J.D. et al. 2022.



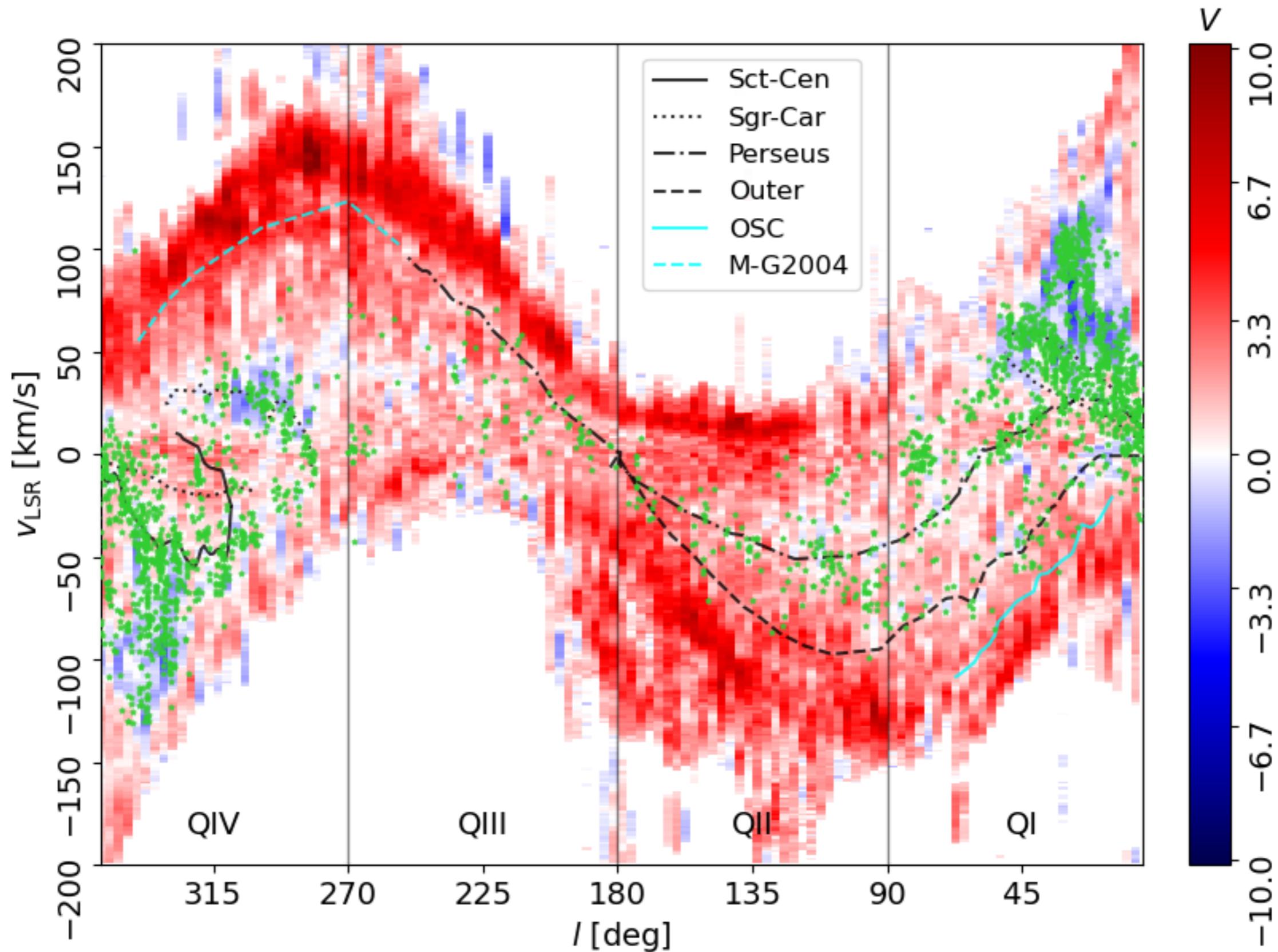
HI filament orientation

Soler, J.D., Wegner, T. et al. In prep.



HI filament orientation and HII regions (traced by RRLs)

Soler, J.D., Wegner, T. et al. In prep.

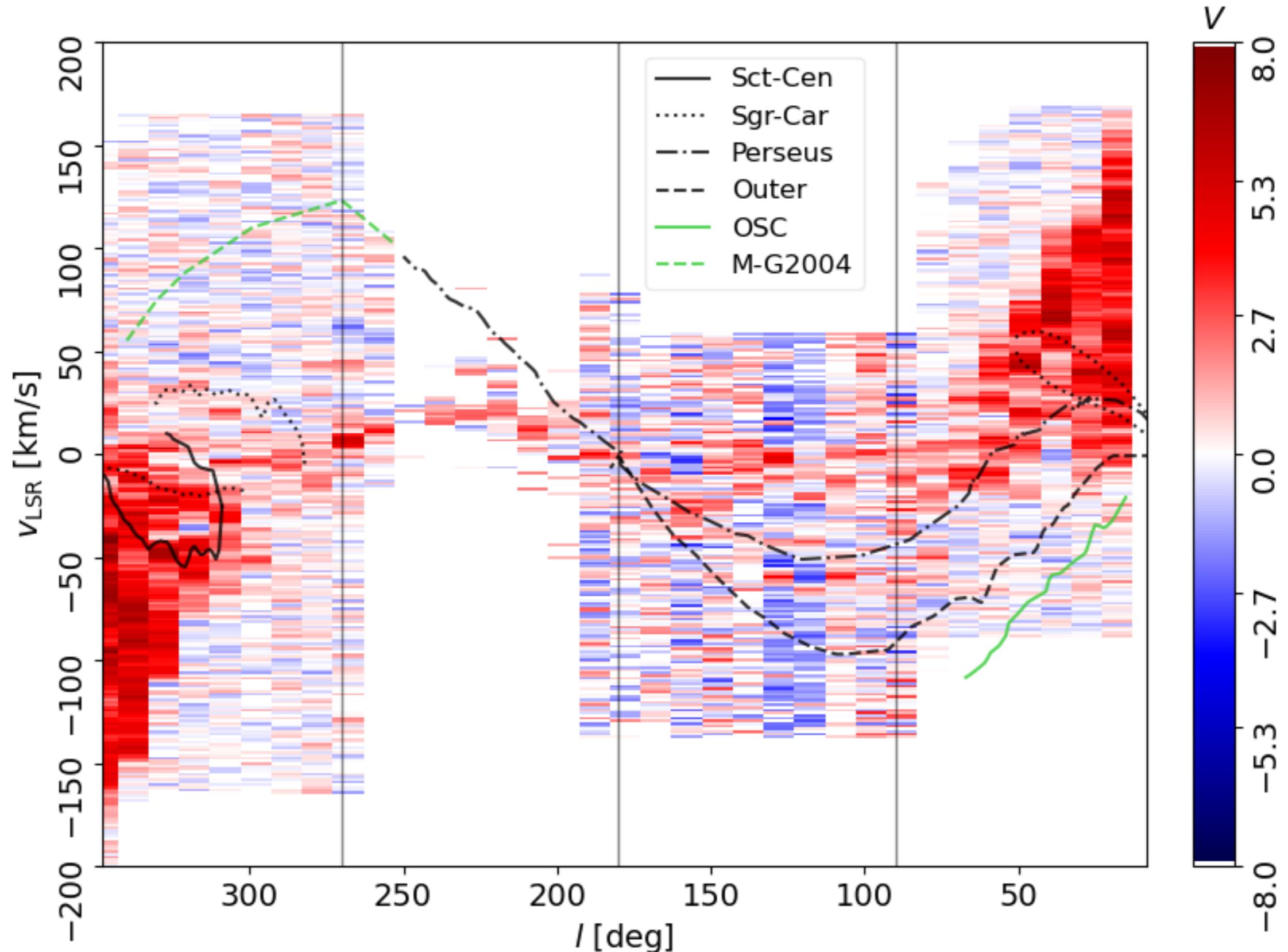


CO filament orientation

$$\theta \approx 7.5'$$

Soler, J.D., et al. In prep.

Dame et al. 2001

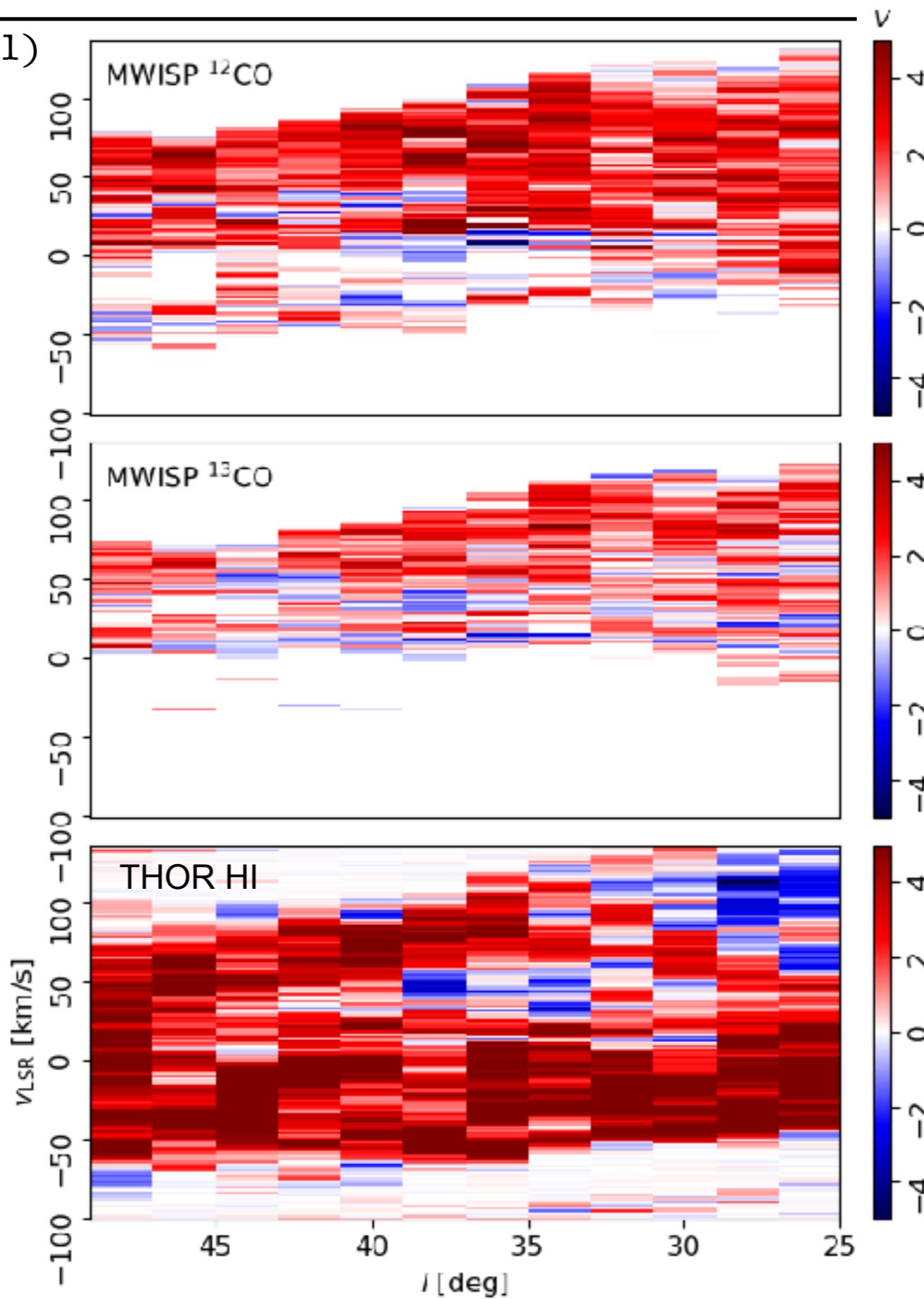


HI and CO filament orientation

$$\theta \approx 50''$$

Soler, J.D. et al. A&A (2021)

MWISP survey.
Sun et al. (2018)

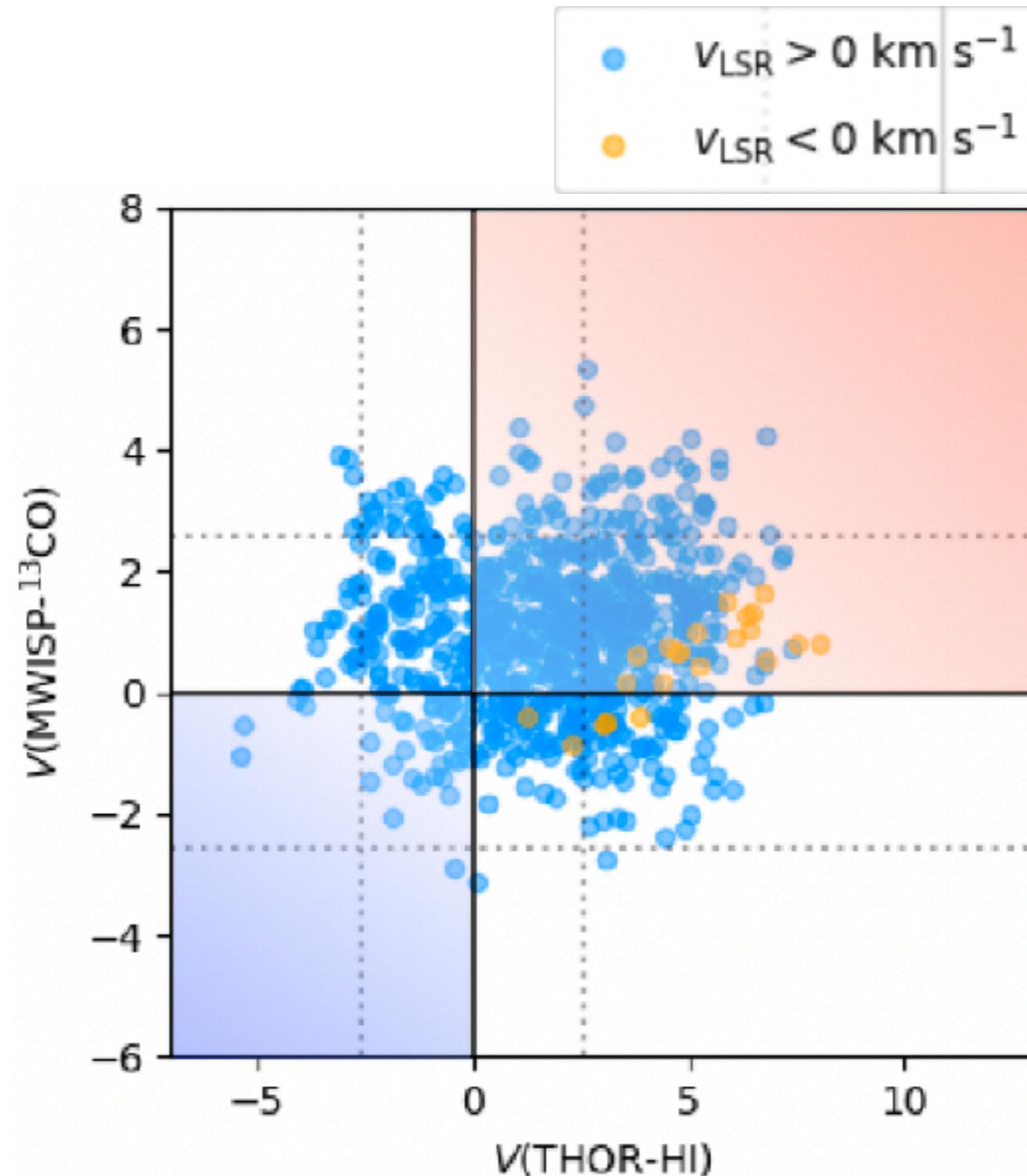


CO filament orientation

$\theta \approx 50''$

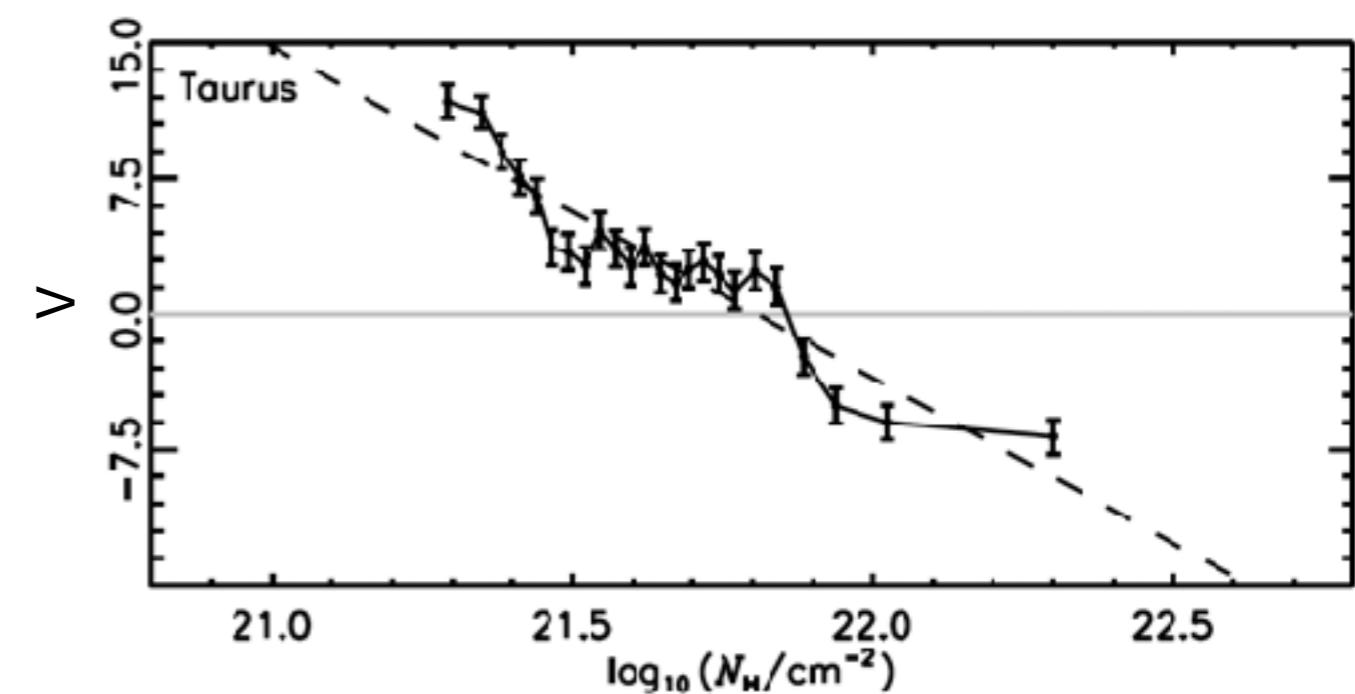
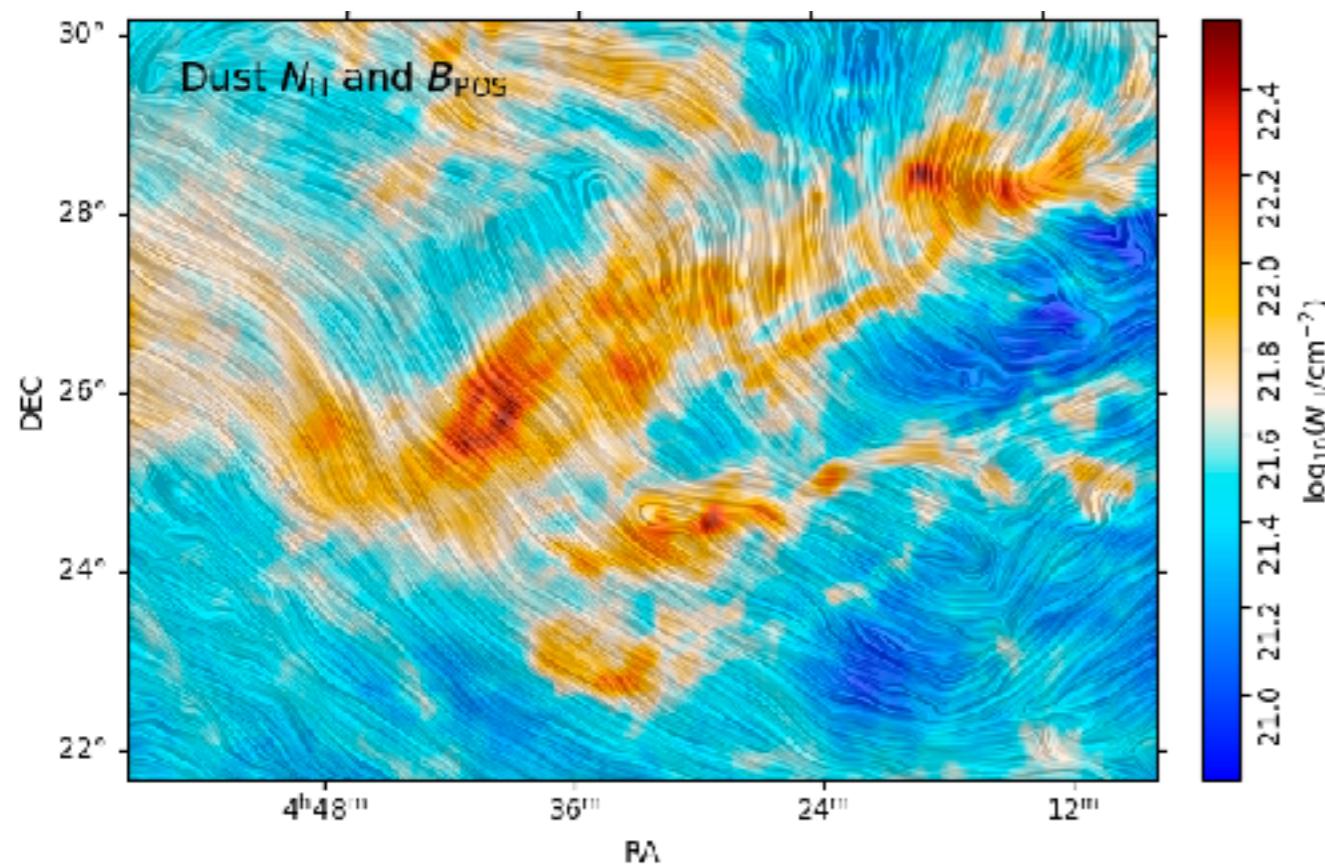
MWISP CO survey. Sun et al. (2018)

Soler, J.D. et al. A&A (2021)



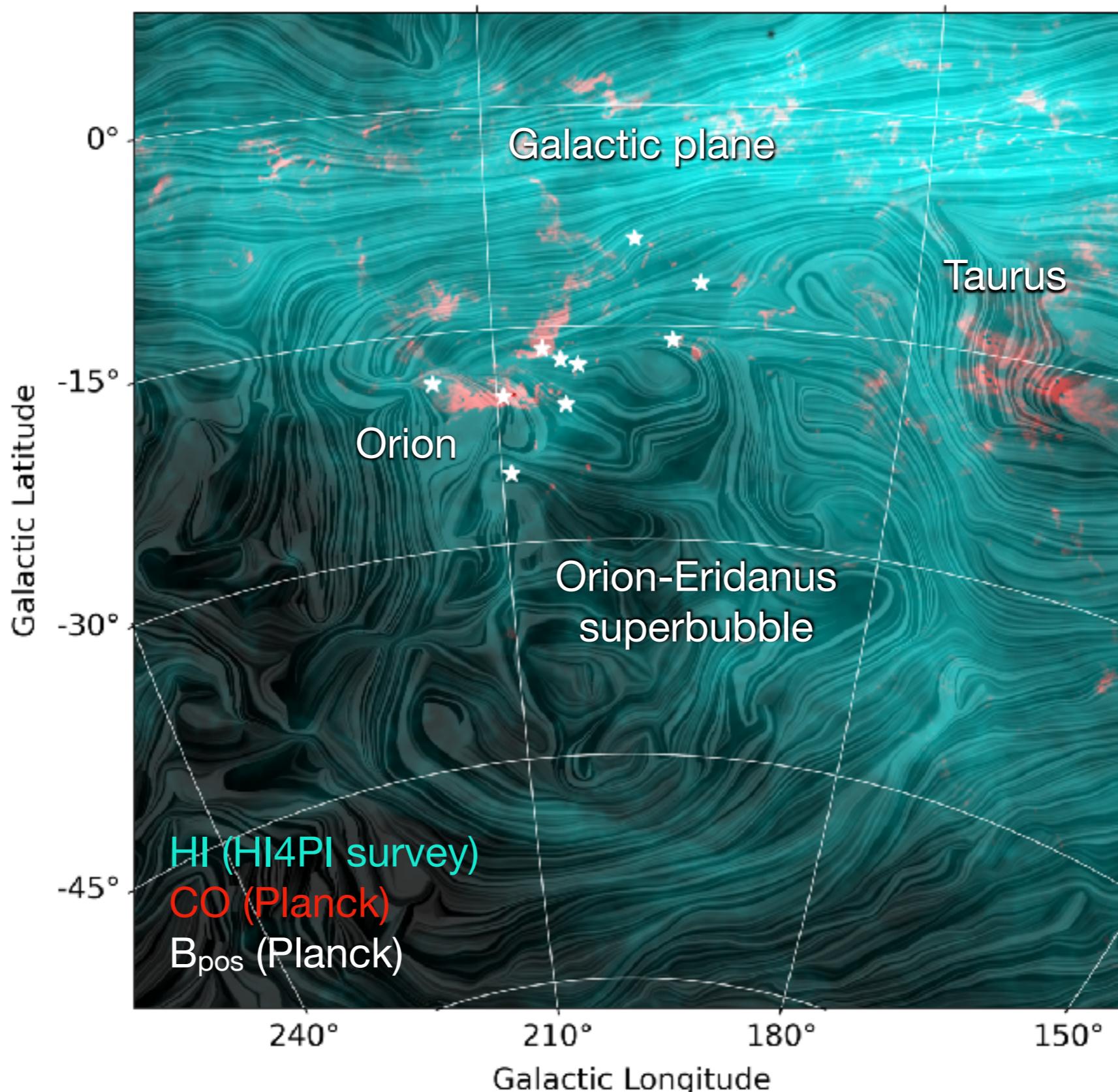
Magnetic fields and density structures in and around MCs

Planck Collaboration XXXV (corresponding author: Soler, J.D.) et al. A&A (2016)

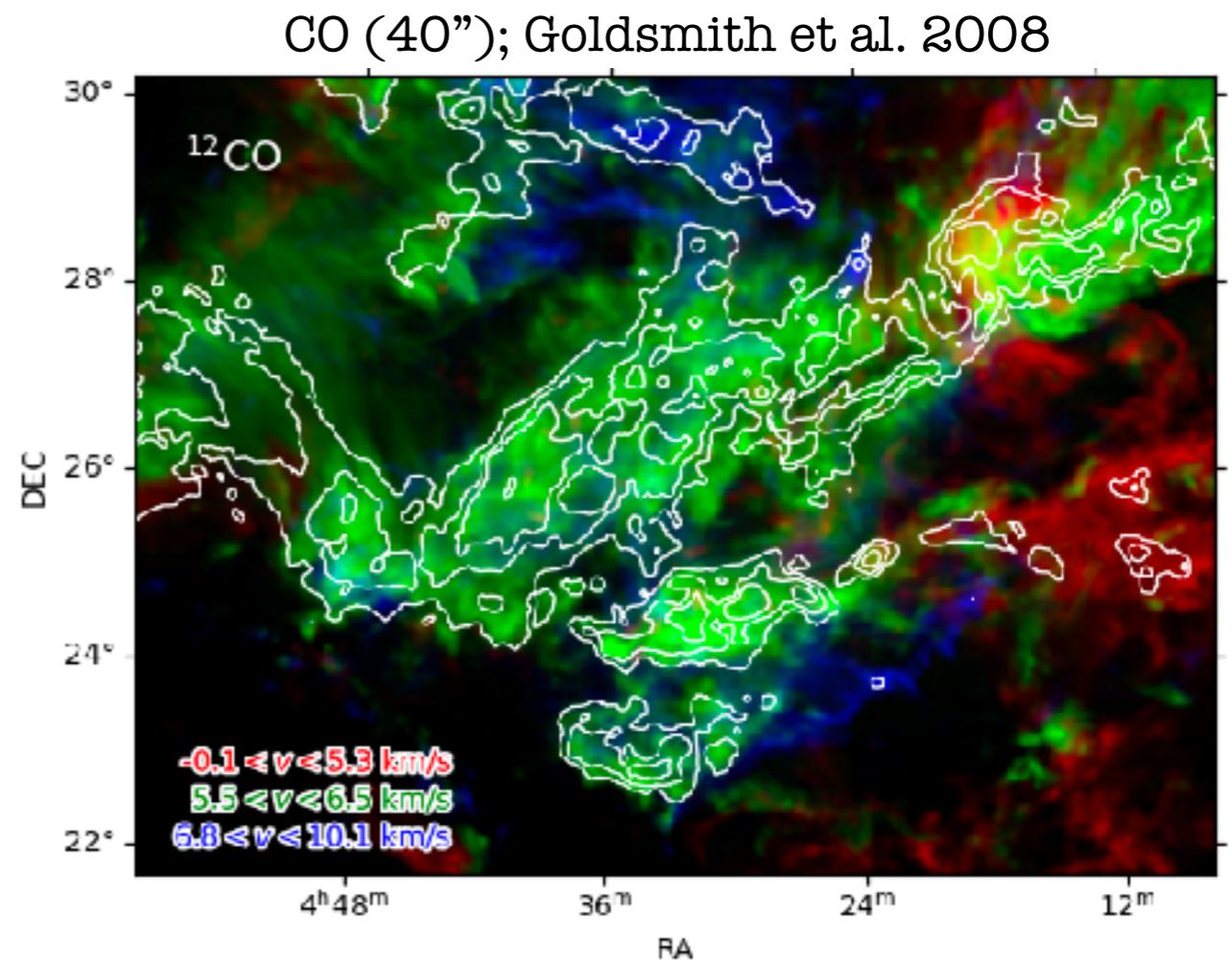
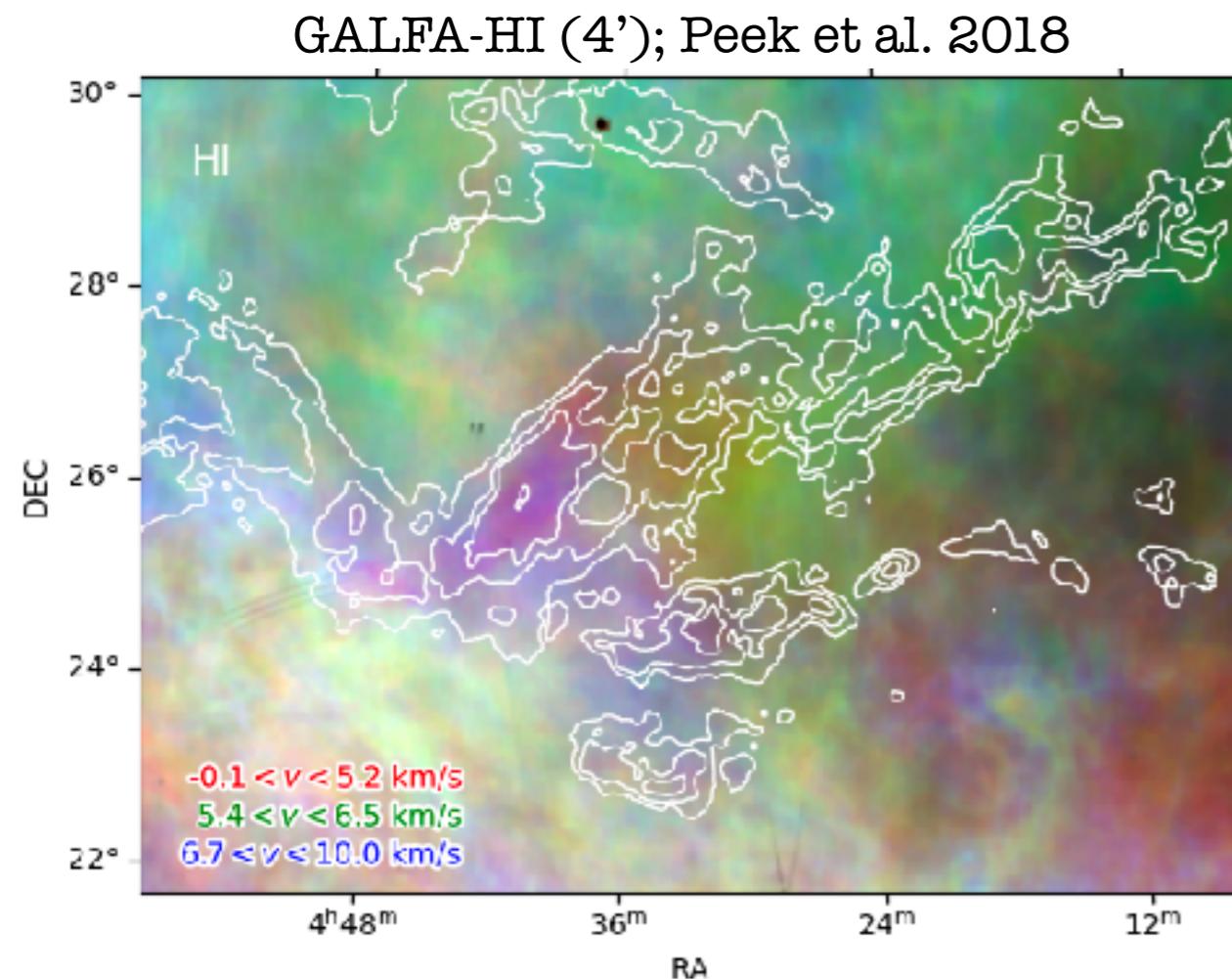


Magnetic fields and density structures in and around MCs

Soler, Bracco & Pon. ApJ (2018)

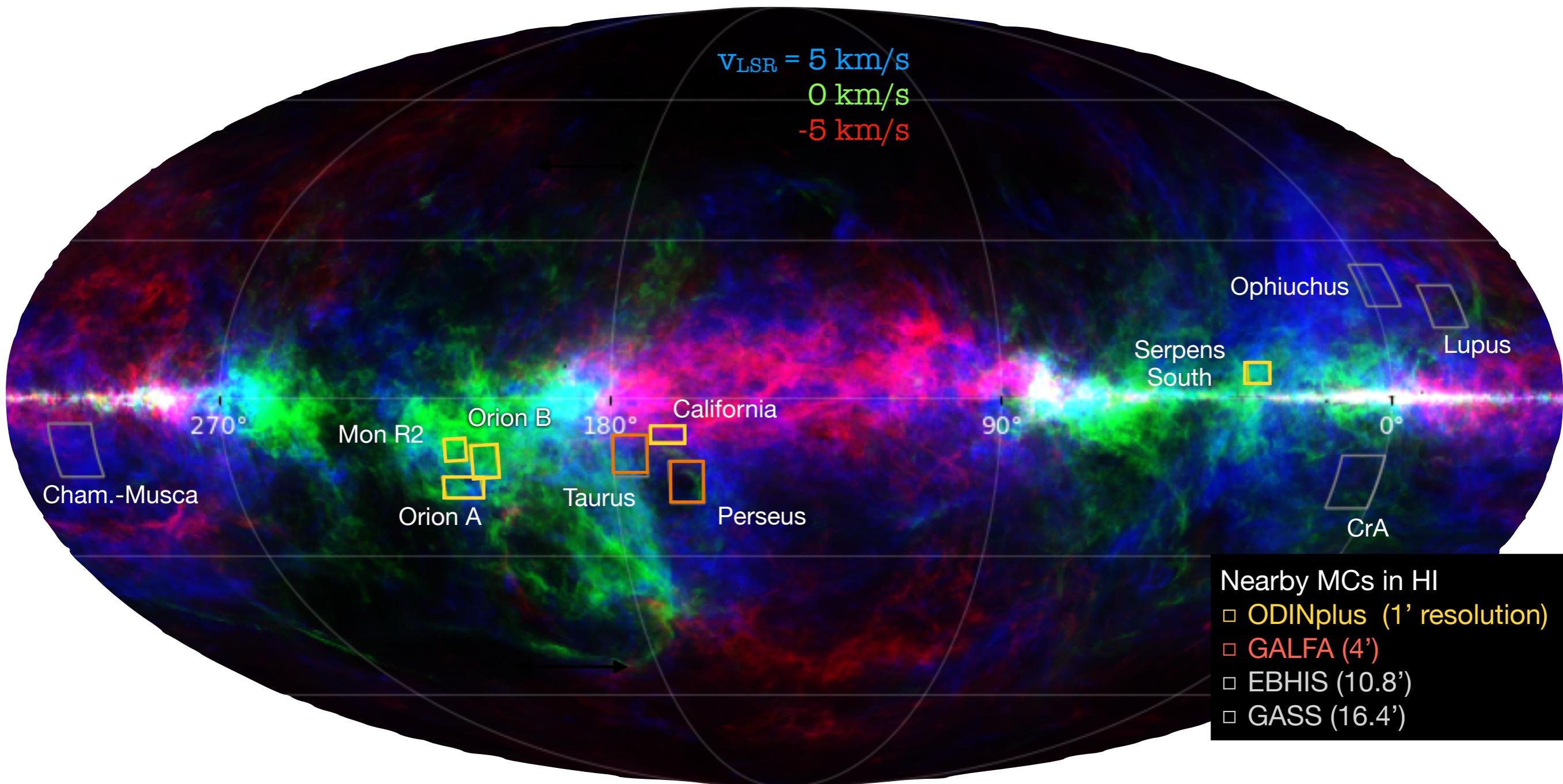


The atomic hydrogen in and around MCs



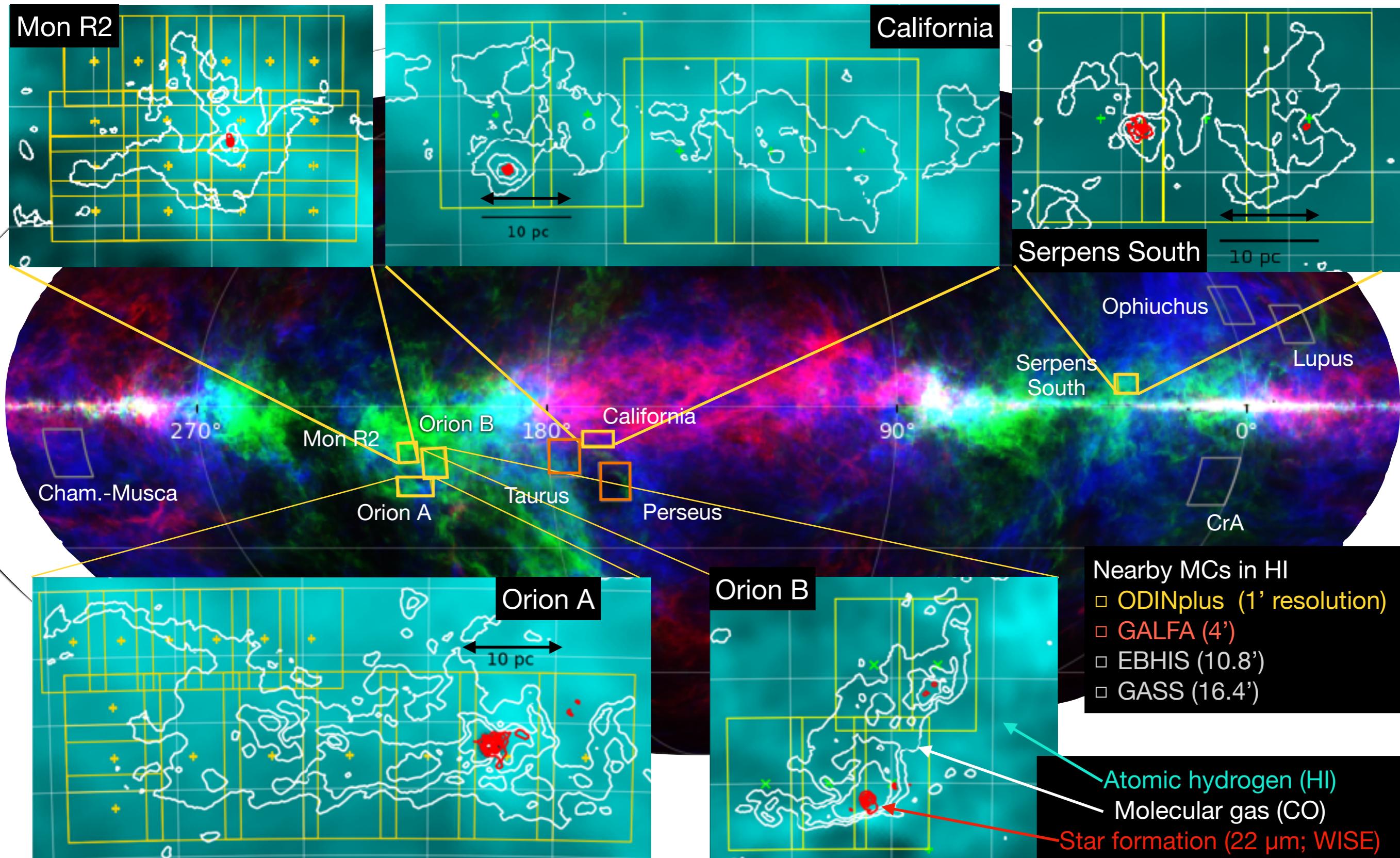
Orion and nearby clouds Dynamics of Ionized and Diffuse gas (ODIN) survey

VLA D-array (199 hours). PI: J.D. Soler



Orion and nearby clouds Dynamics of Ionized and Diffuse gas (ODIN) survey

VLA D-array (199 hours). PI: J.D. Soler



The Galactic dynamics revealed by HI 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.



Tools and data available at:

<https://github.com/solerjuan/astrohog>
juandiegosolerp@gmail.com