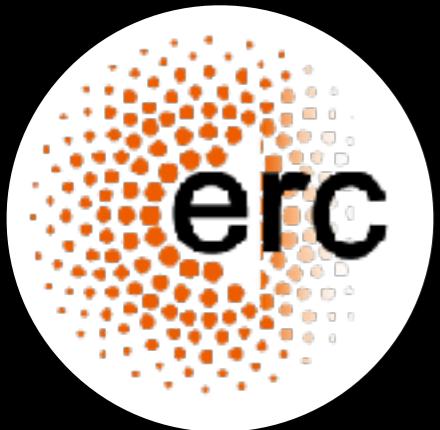




Lorentz
center

Mapping the Milky Way with neutral atomic hydrogen (HI)



a (biased) review by Juan Diego Soler
IAPS-INAF (Rome, Italy)
ECOGAL collaboration

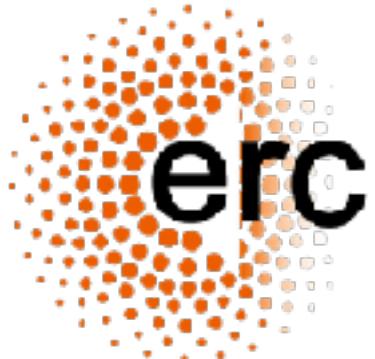
Mapping the Milky Way with neutral atomic hydrogen (HI)

Juan Diego Soler

Istituto di Astrofisica e Planetologia Spaziali (Rome, Italy)

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

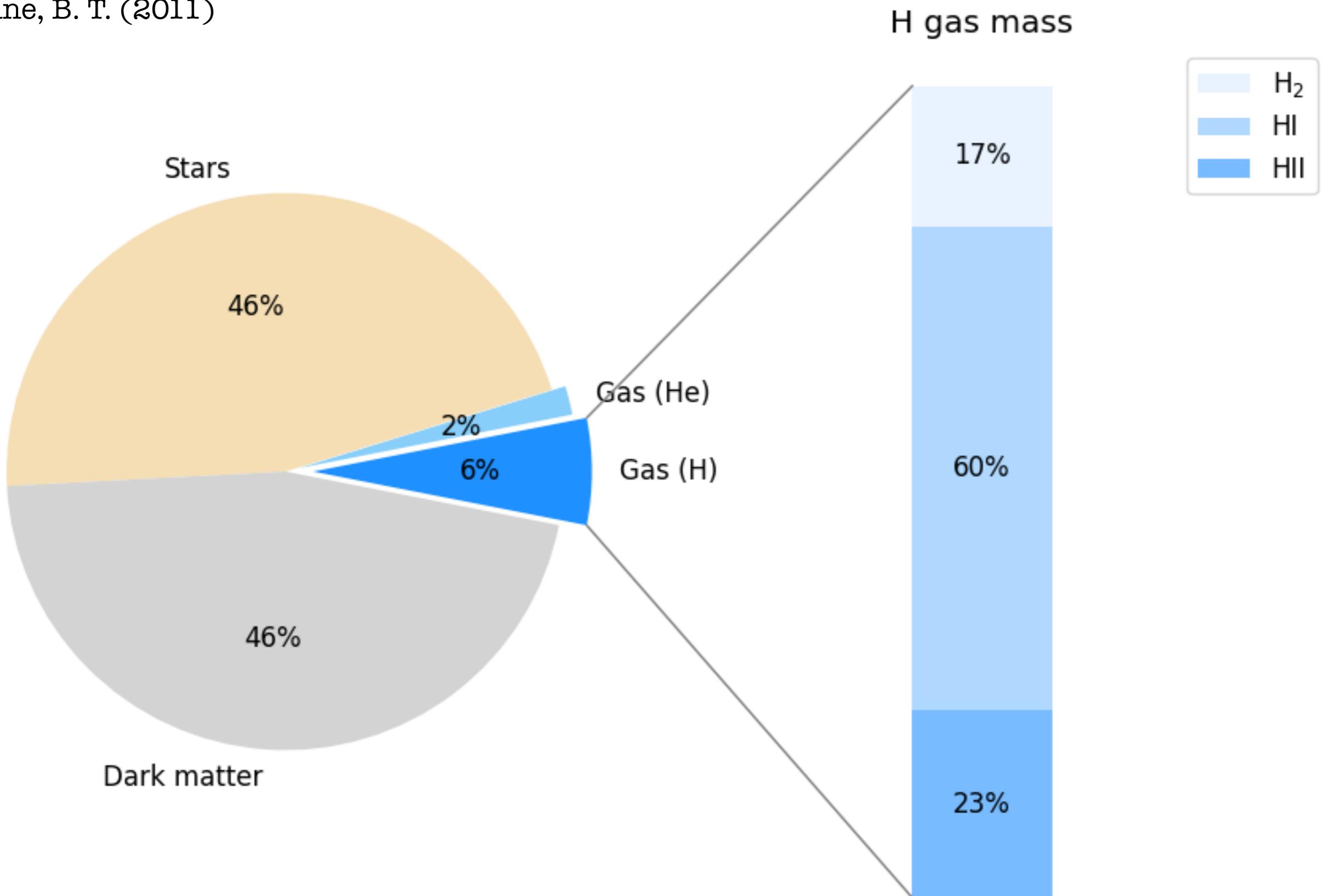
ECOgal collaboration: S. Molinari, R. S. Klessen, P. Hennebelle, L. Testi,
A. Trafficante, E. Schisano, D. Elia, M.-A. Miville-Dêschenes, T. Colman
S. C. O. Glover, M. Sormani, R., Treß, P. Girichidis, R. J. Smith



Why do we care about neutral atomic hydrogen (HI)?

Milky Way's mass budget

Draine, B. T. (2011)



Atomic hydrogen emission

HI4PI survey



Mapping the Milky Way with HI

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

Atomic hydrogen emission

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

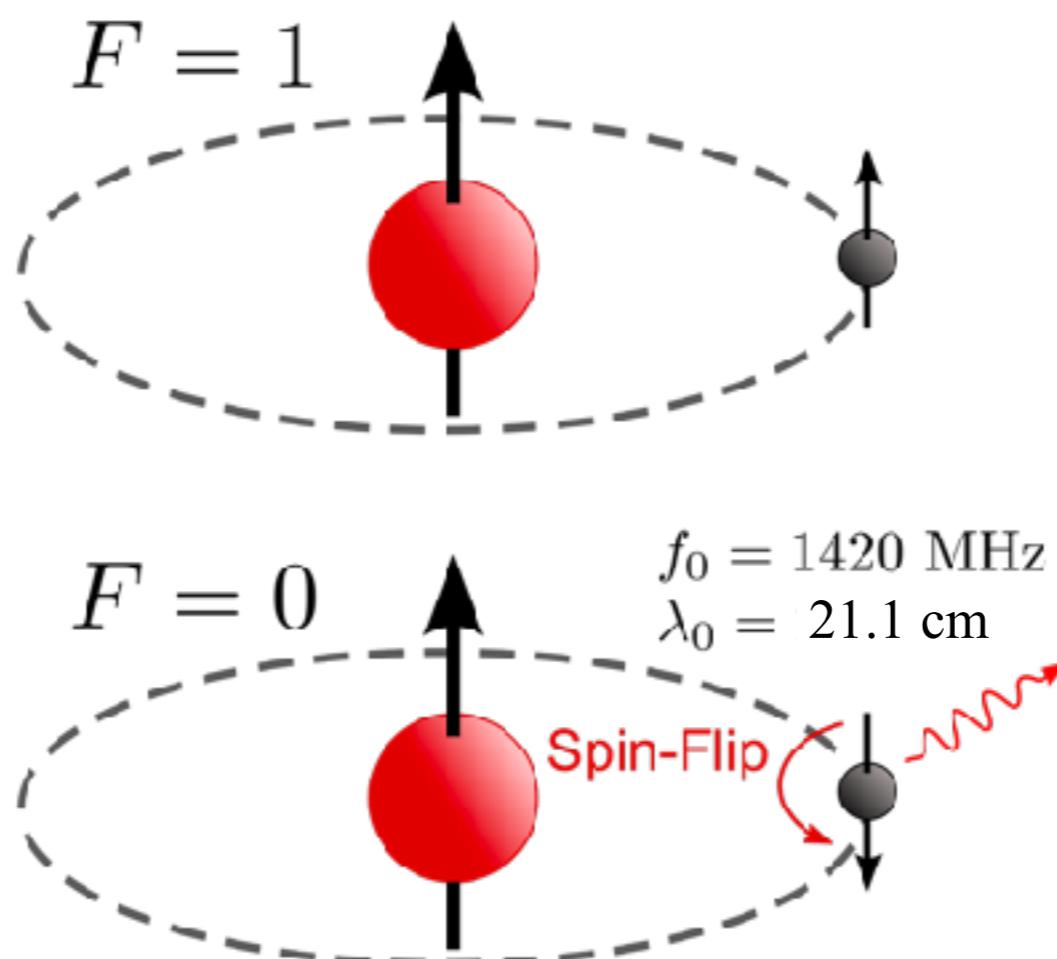


Hyperfine transition of neutral hydrogen

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

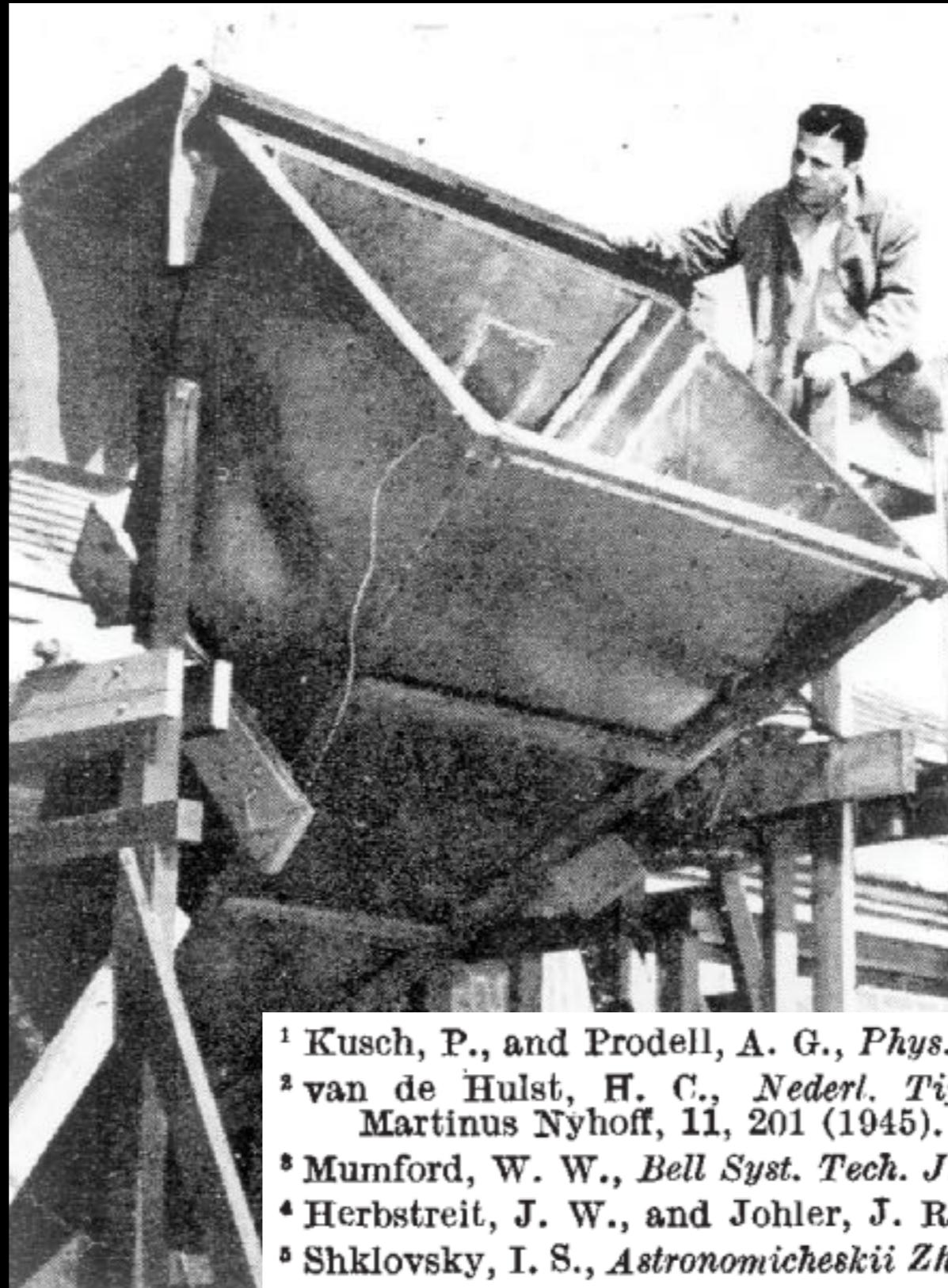
H.C. Van de Hulst (1945) Origin of the Radio Waves from Space*

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.

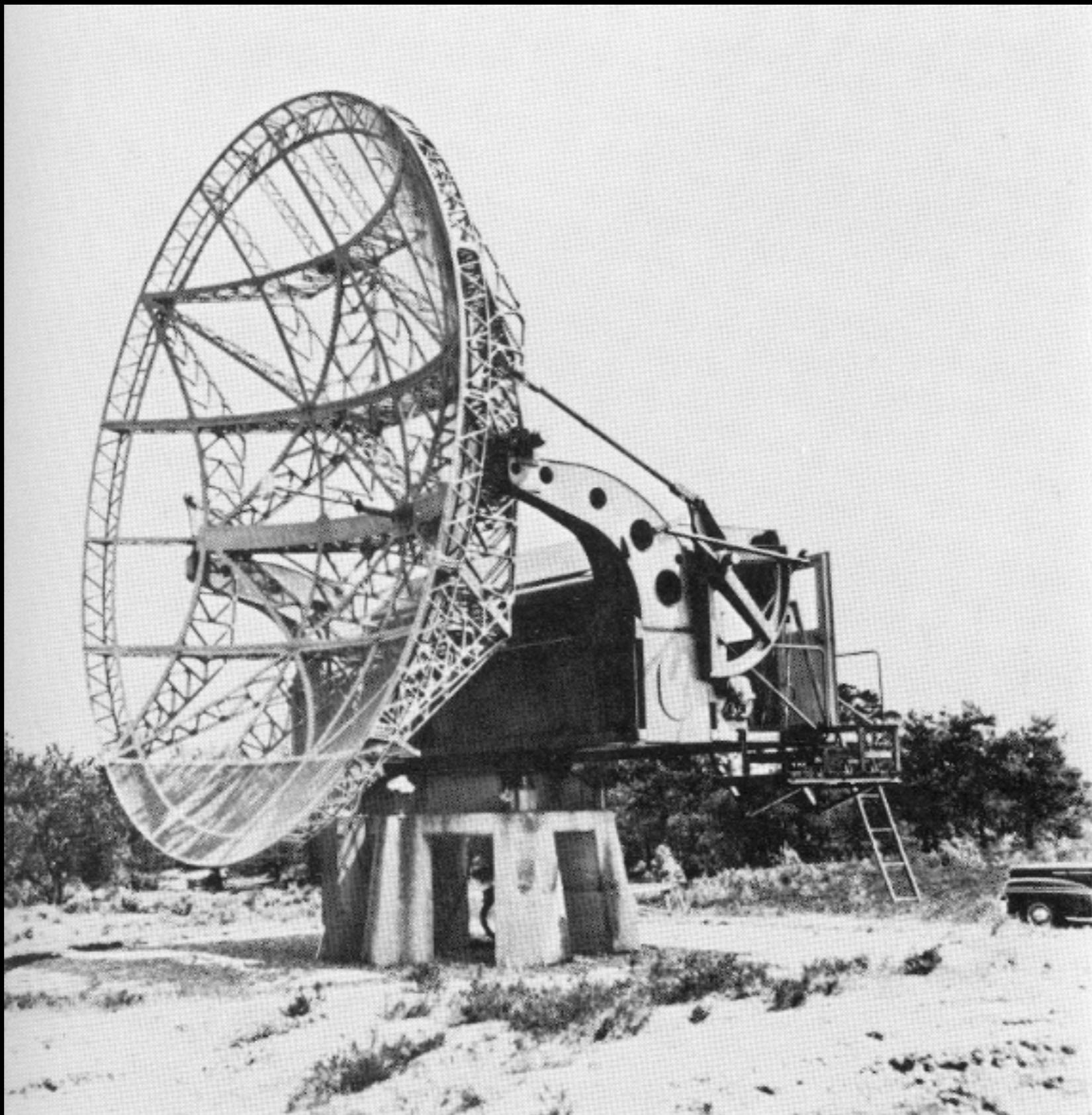


- ¹ Kusch, P., and Prodell, A. G., *Phys. Rev.*, **79**, 1009 (1950).
- ² van de Hulst, H. C., *Nederl. Tij. Natuurkunde*, 's-Gravenhage-Martinus Nijhoff, **11**, 201 (1945).
- ³ Mumford, W. W., *Bell Syst. Tech. J.*, **28**, 608 (1949).
- ⁴ Herbstreit, J. W., and Johler, J. R., *Nature*, **161**, 515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

Atomic hydrogen emission

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

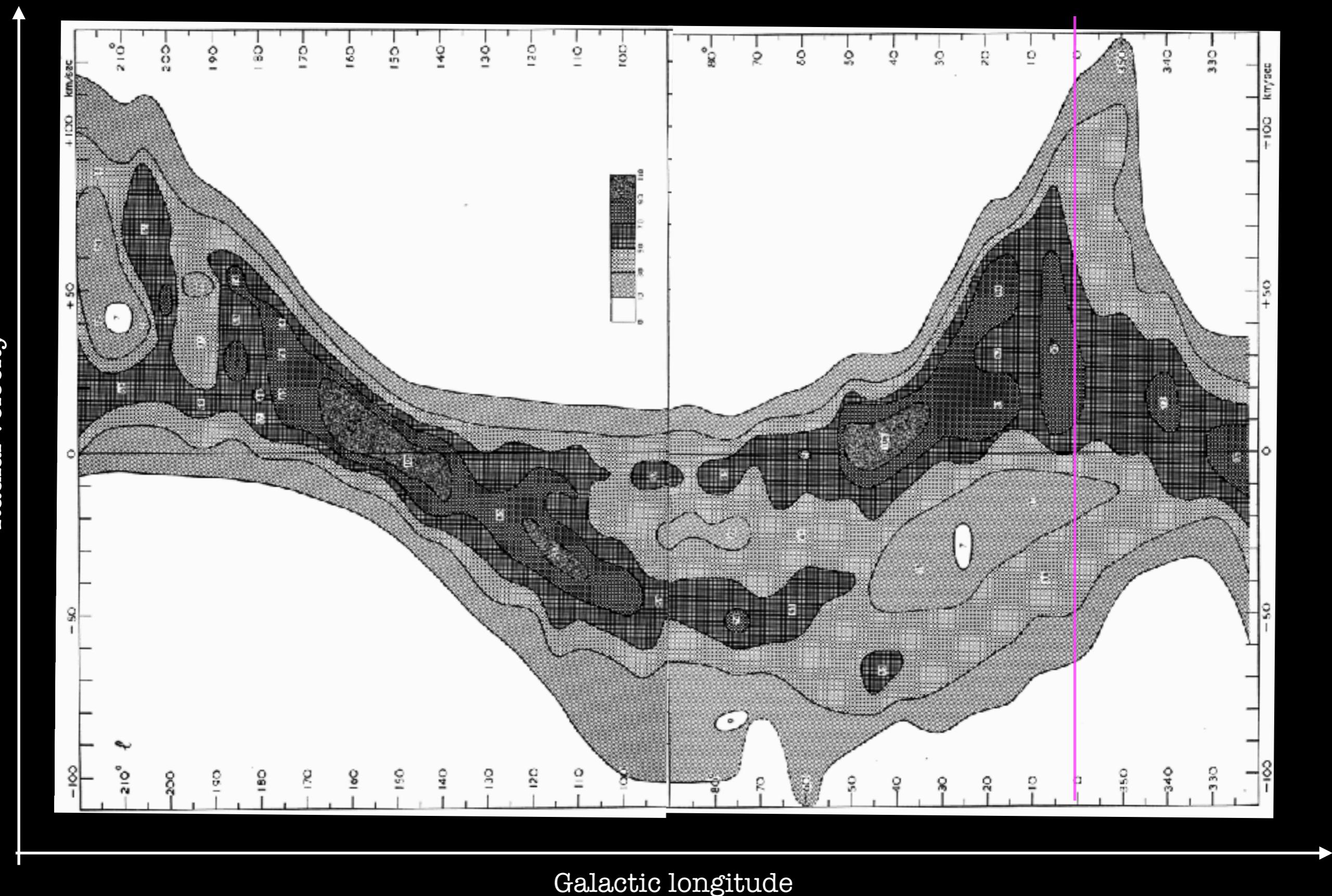
Würzburg radar antenna (7.5 m)



HI emission toward the Milky Way

$\theta \approx 2^\circ$

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

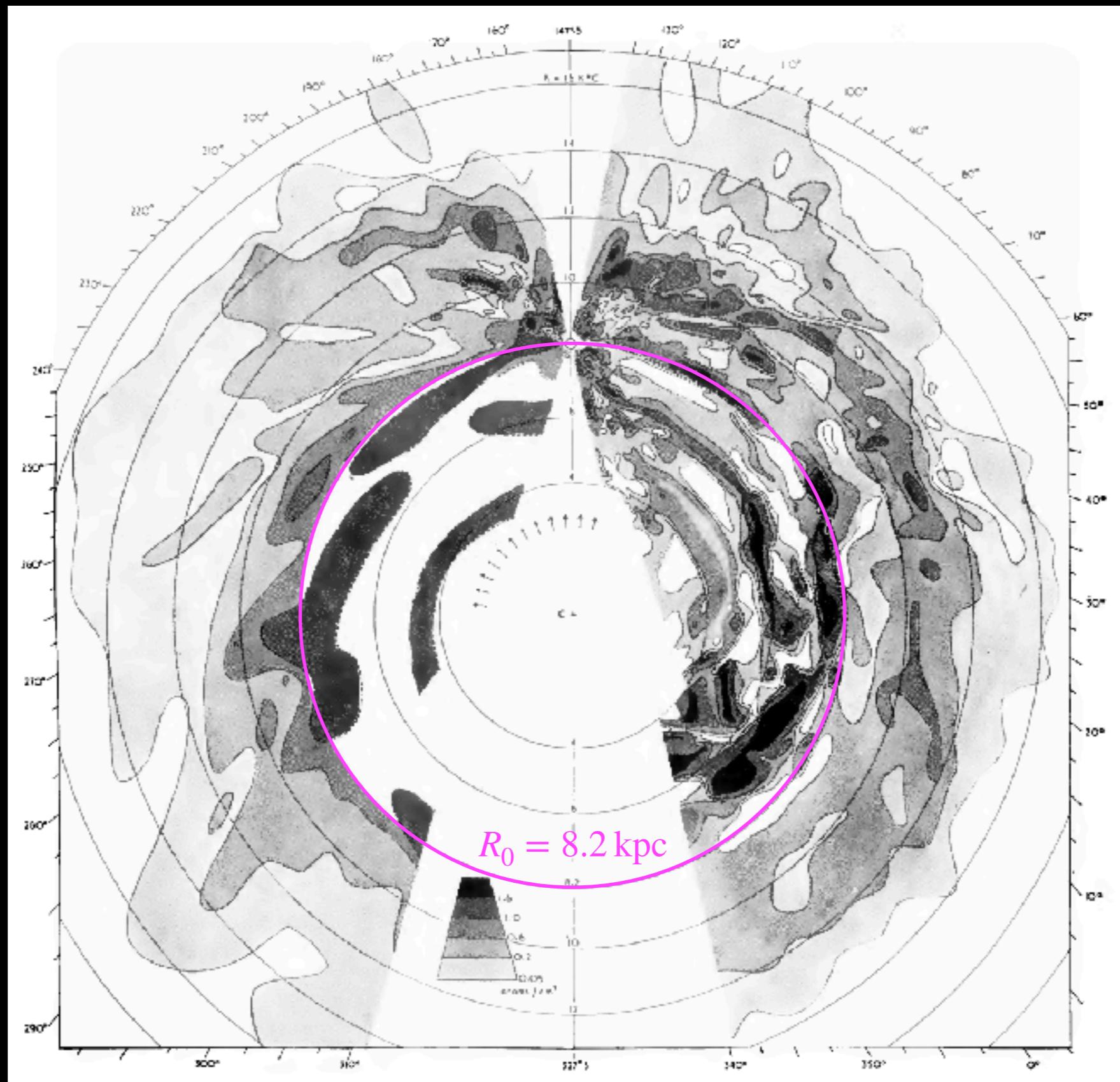


Galactic longitude

A. HI mapping face-on Milky Way

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

Oort,; Kerr & Westerhout. MNRAS (1958)



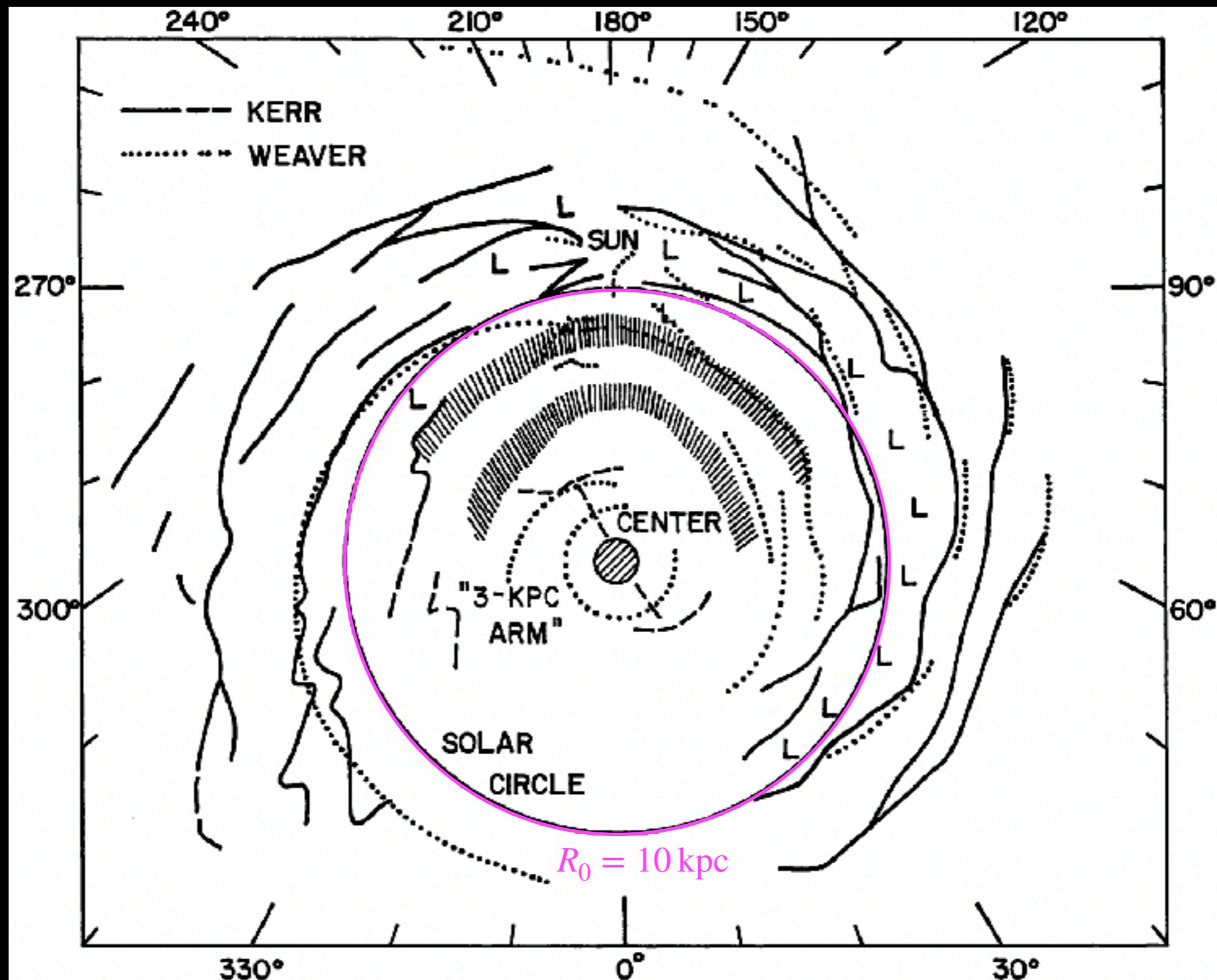
A. HI mapping face-on Milky Way

$\theta \approx 0.6^\circ$

Simonson. A&A (1970)

Leiden survey

Problems in Galactic Spiral Structure



A. HI mapping face-on Milky Way

$\theta \approx 0.6^\circ$

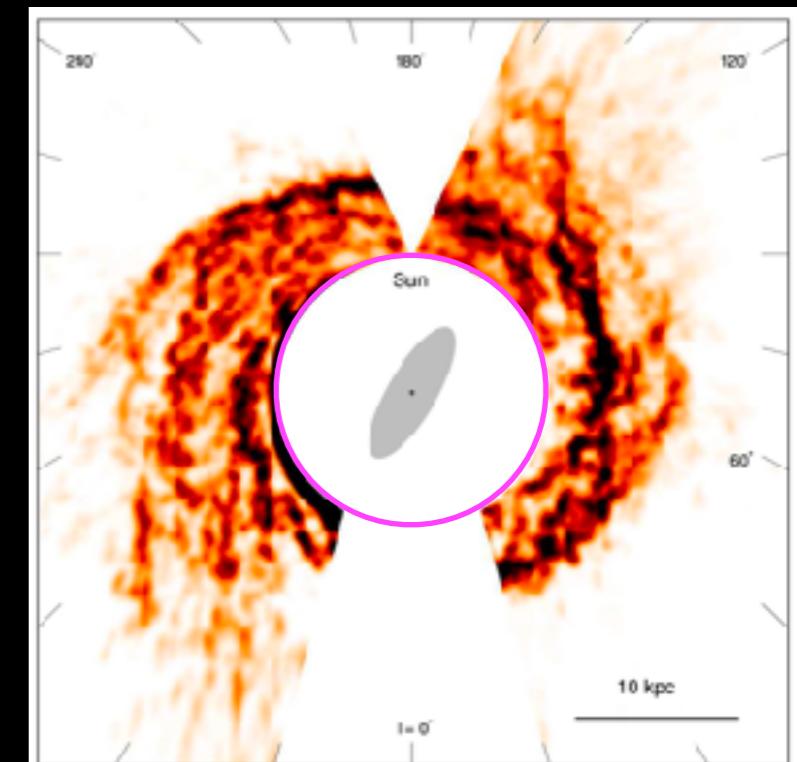
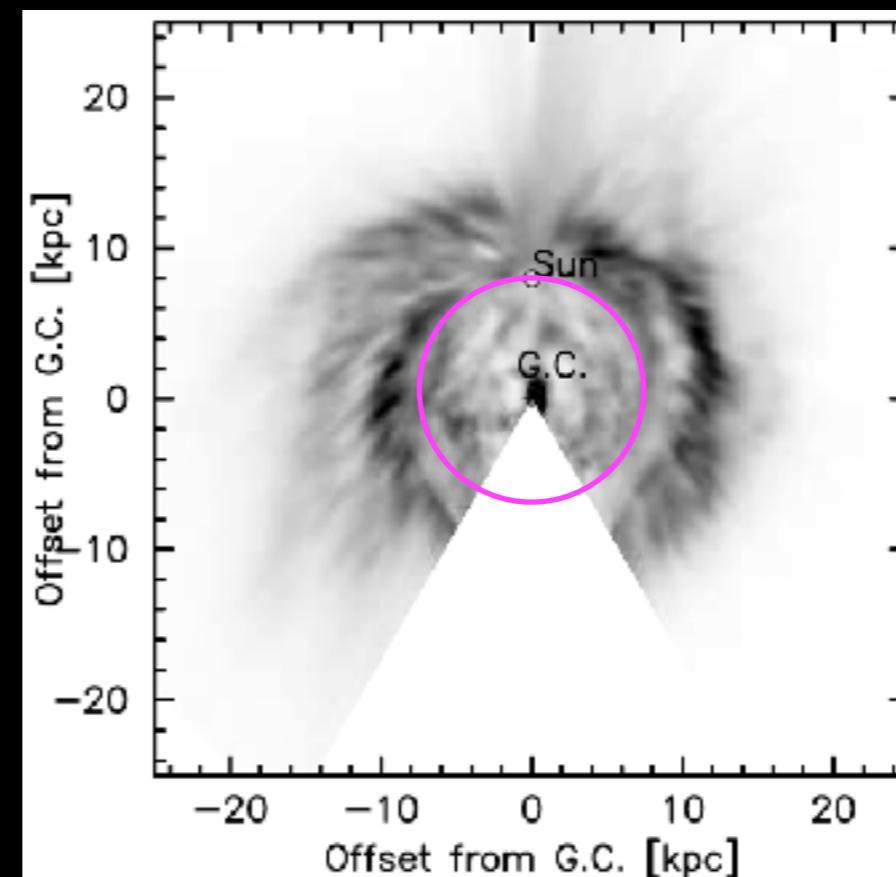
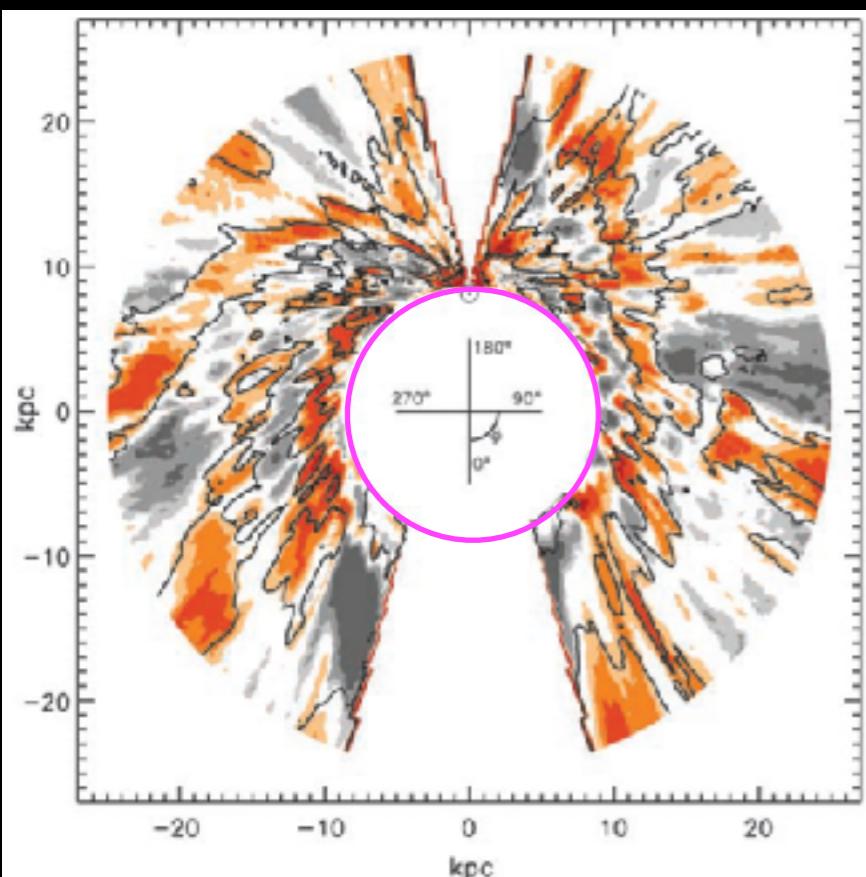
LAB survey

HI surface density

Levine, Blitz & Heiles (2006)

Nakanishi & Sofue. PASJ (2016)

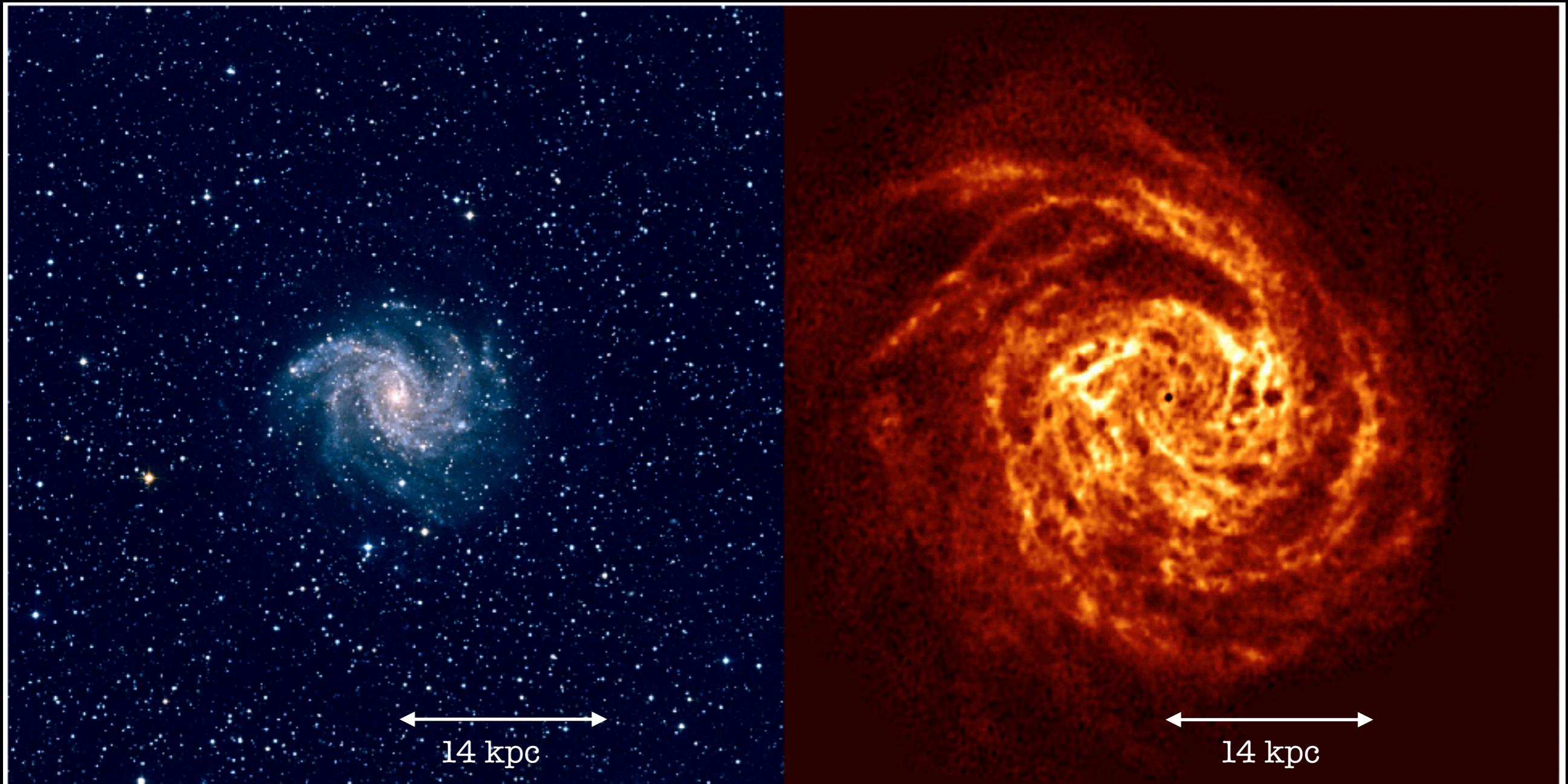
Koo et al. PASP (2017)



A. HI mapping face-on Milky Way

Boomsma et al. A&A (2008)

NGC6946 ($d = 6$ Mpc)

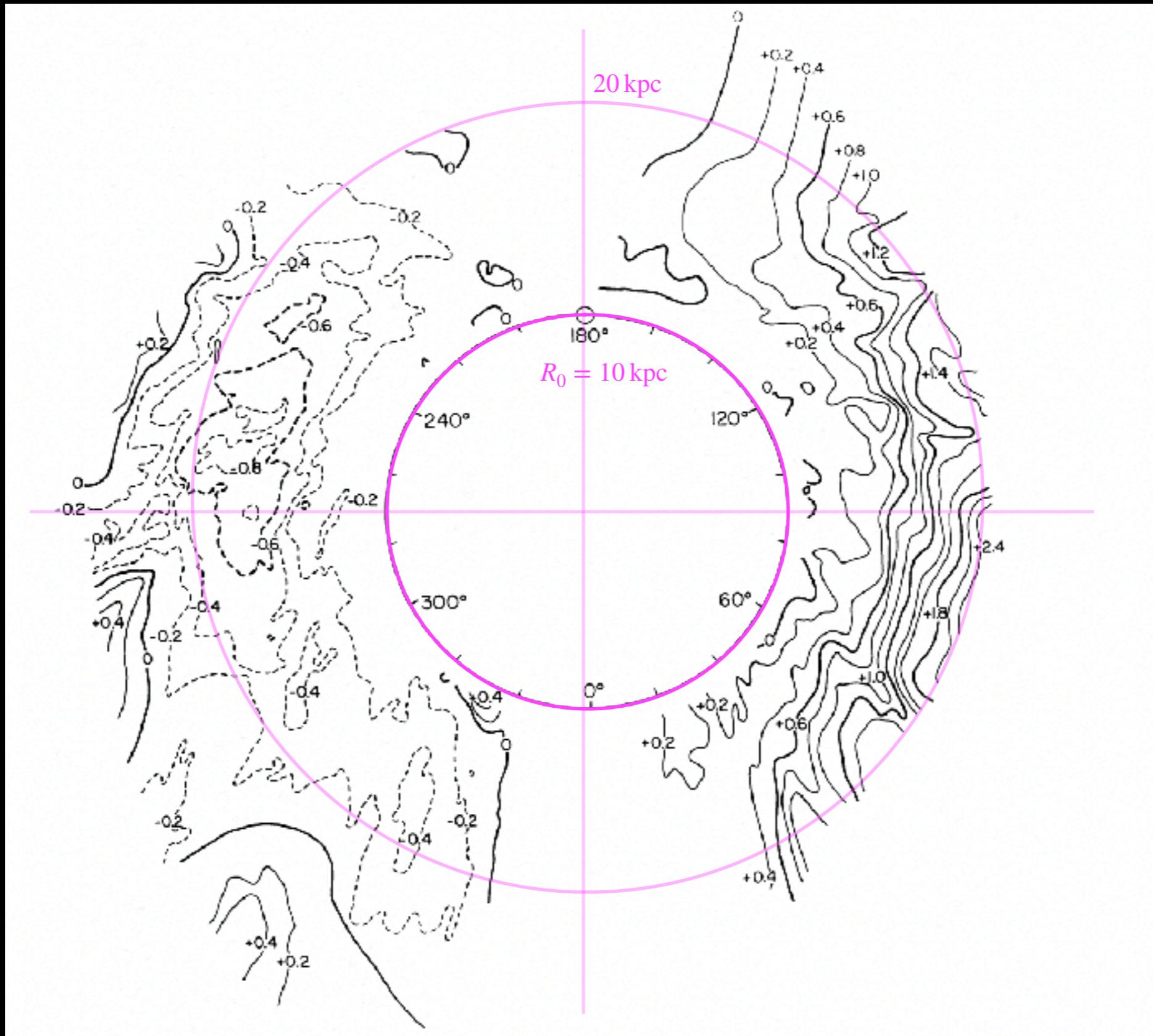


B. HI mapping Galactic disk warp

$$\langle z \rangle$$

$$\theta \approx 48'$$

Henderson, Jackson & Kerr (1982)

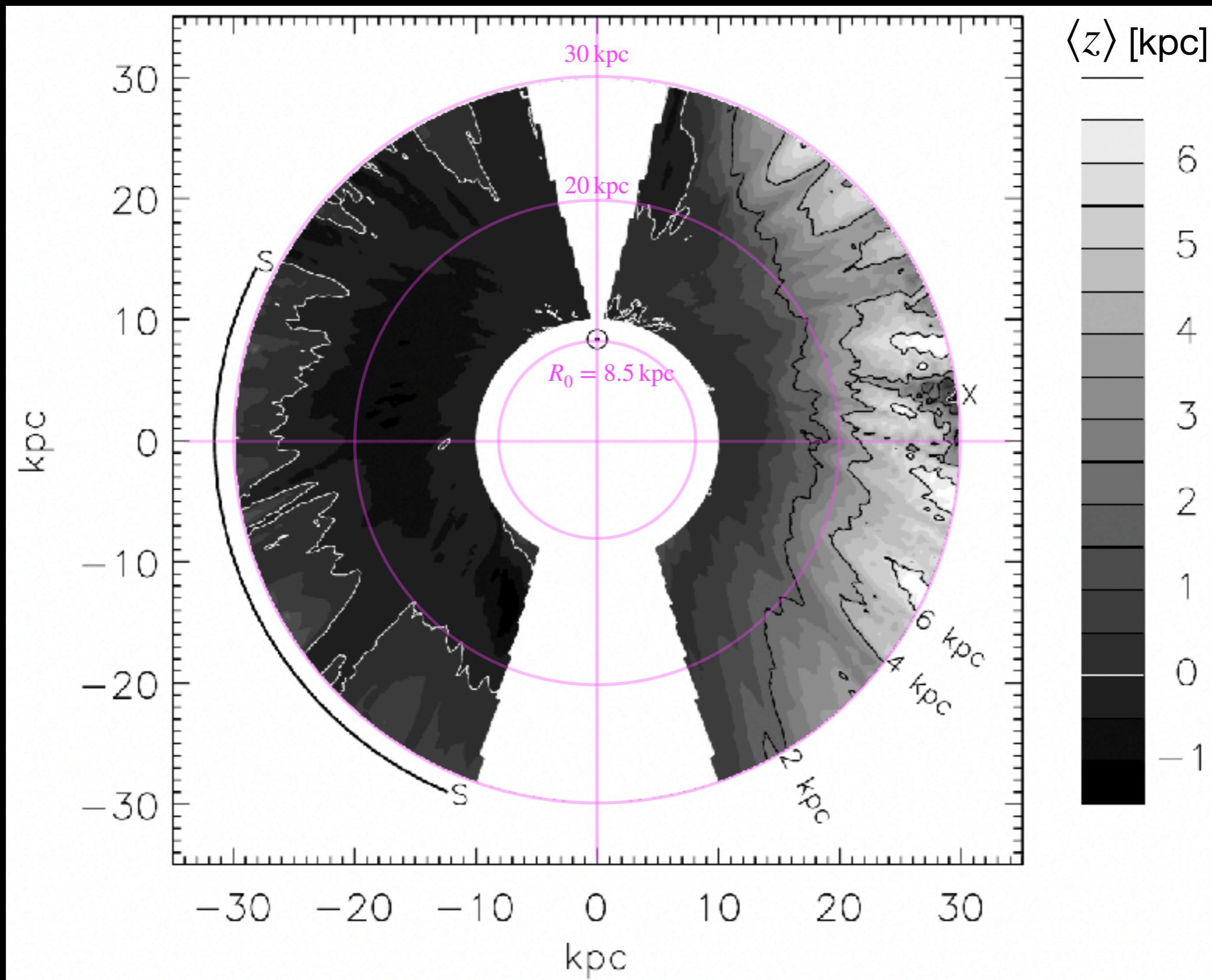


B. HI mapping Galactic disk warp

$\langle z \rangle$

$\theta \approx 30'$

Levine, Blitz & Heiles (2006).

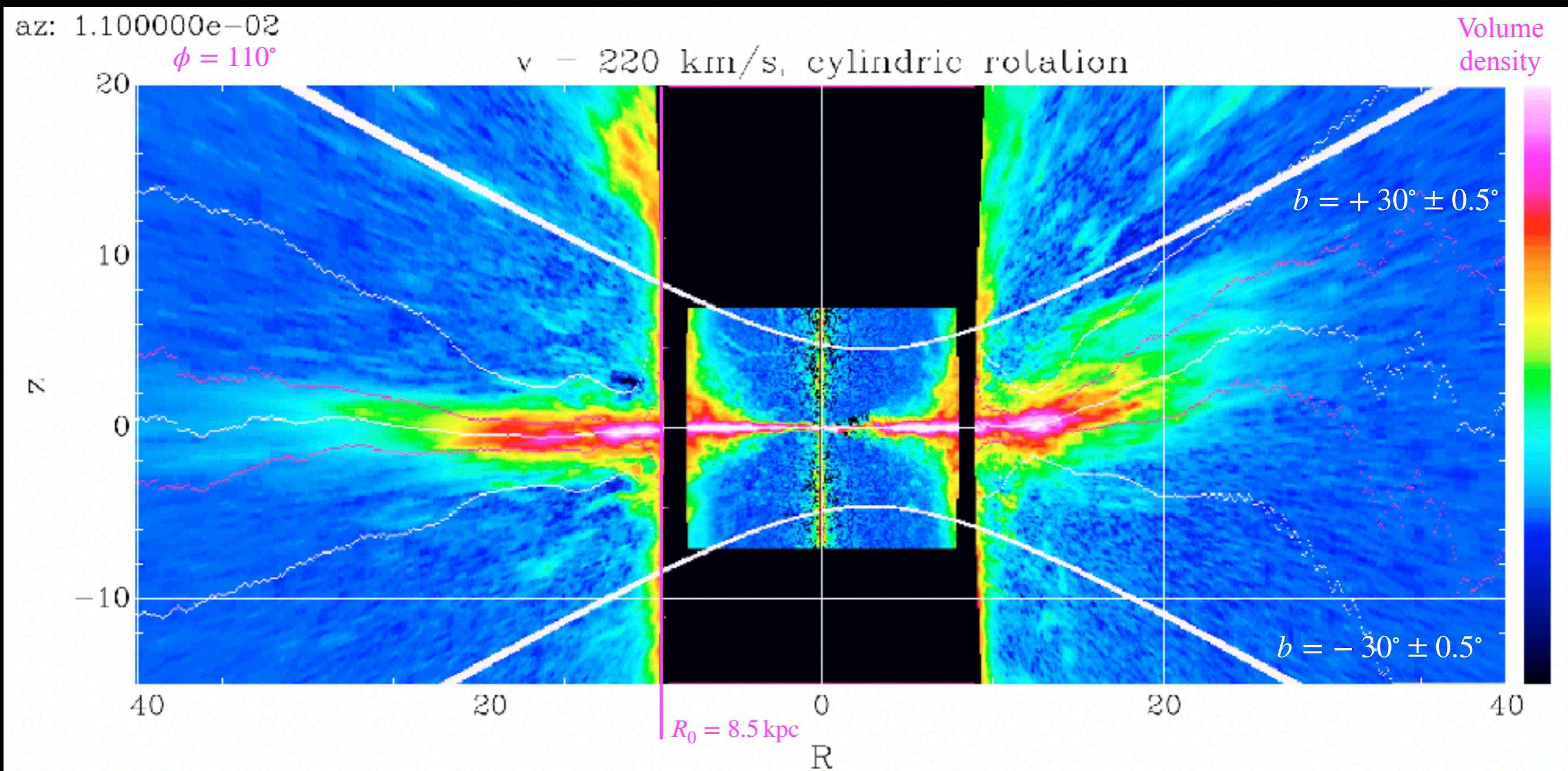


B. HI mapping Galactic disk warp

$$\langle z \rangle$$

$$\theta \approx 48'$$

Kalberla, Dedes, Kerp & Haud (2007).

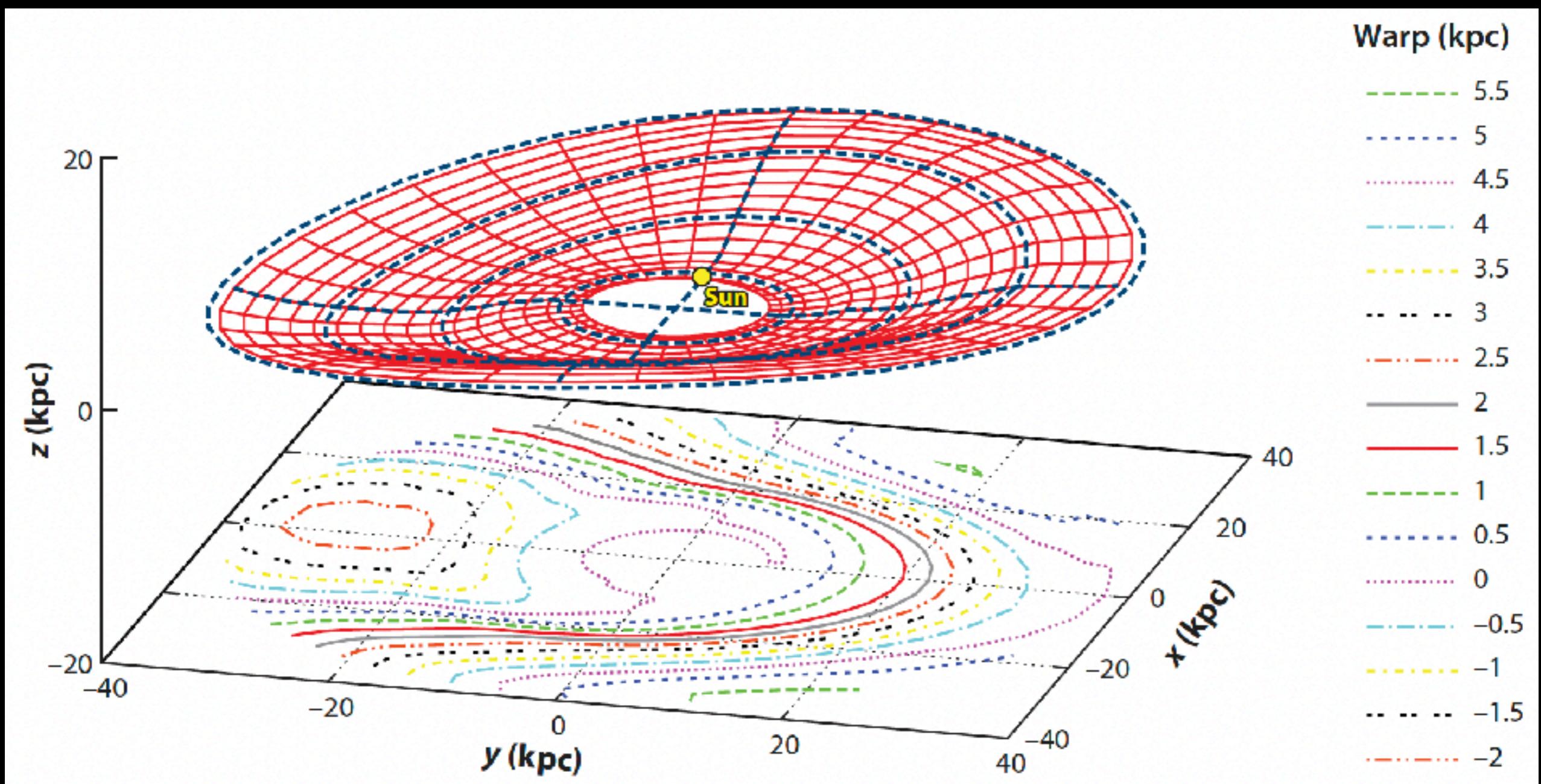


B. HI mapping Galactic disk warp

$$\langle z \rangle$$

$$\theta \approx 48'$$

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

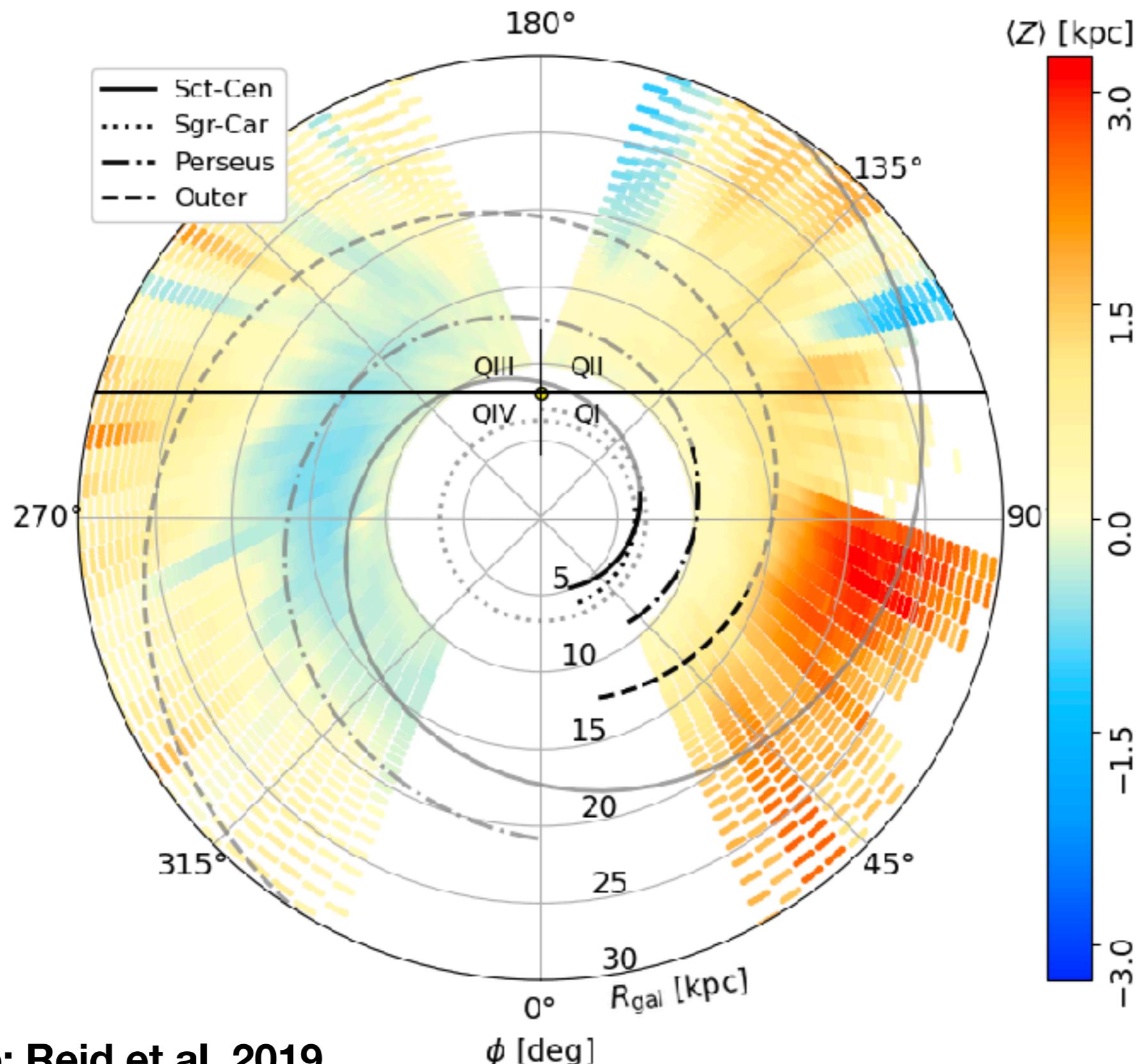


B. HI mapping Galactic disk warp

$$\langle z \rangle$$

$$\theta \approx 16.4'$$

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



Rotation curve: Reid et al. 2019

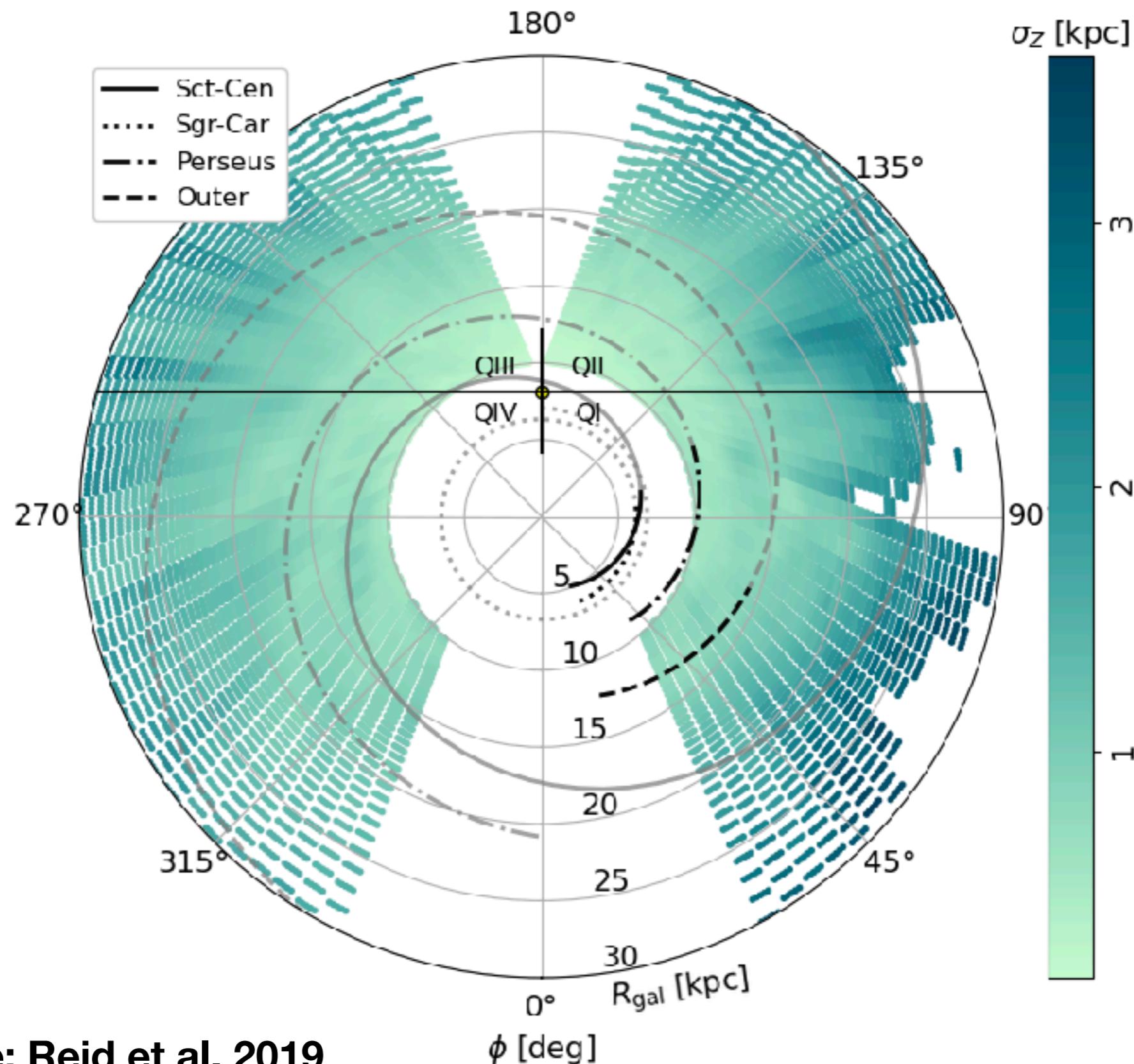
ϕ [deg]

C. HI mapping Galactic disk flaring

σ_z

$\theta \approx 16.4'$

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



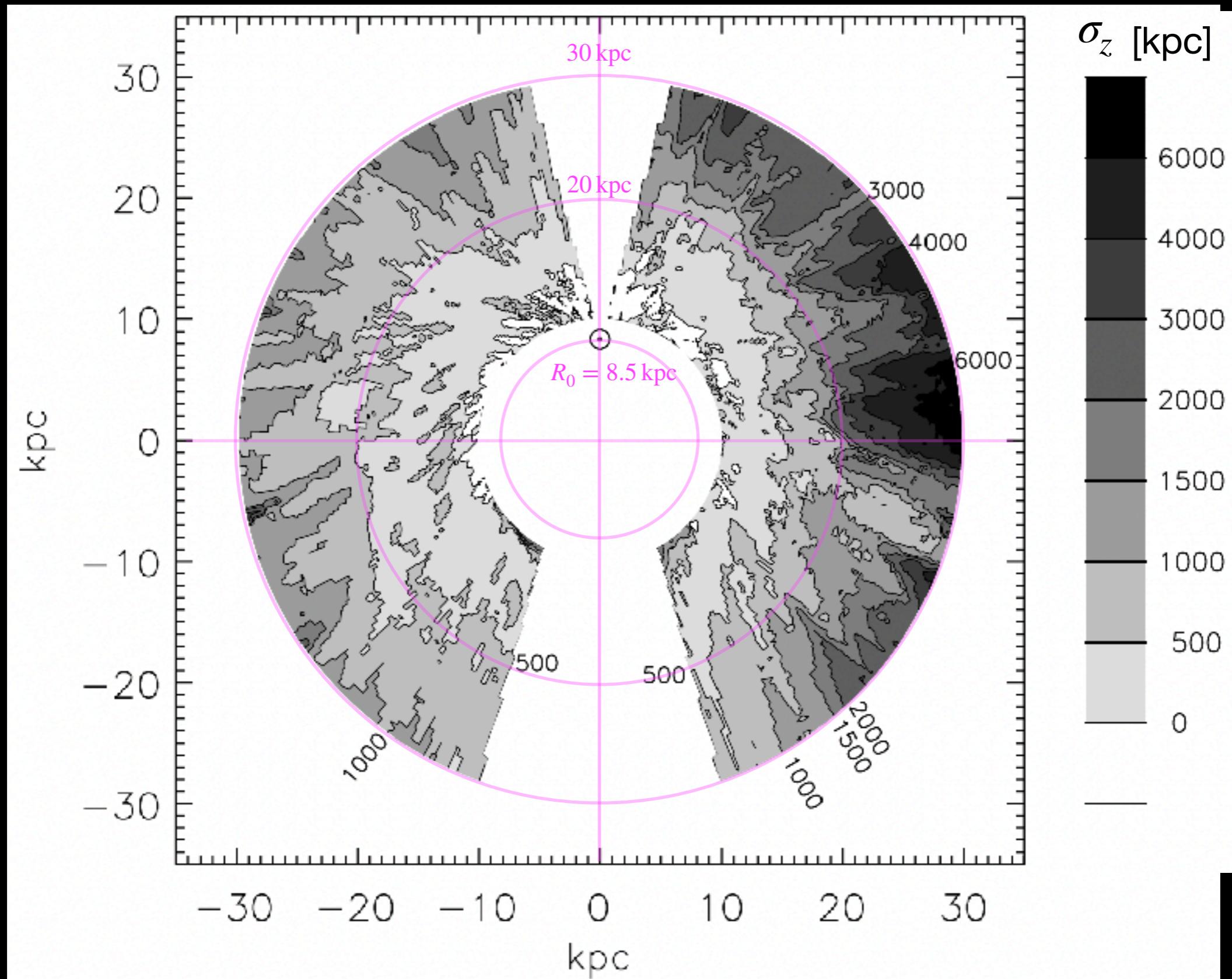
Rotation curve: Reid et al. 2019

C. HI mapping Galactic disk flaring

σ_z

$\theta \approx 30'$

Levine, Blitz & Heiles (2006).

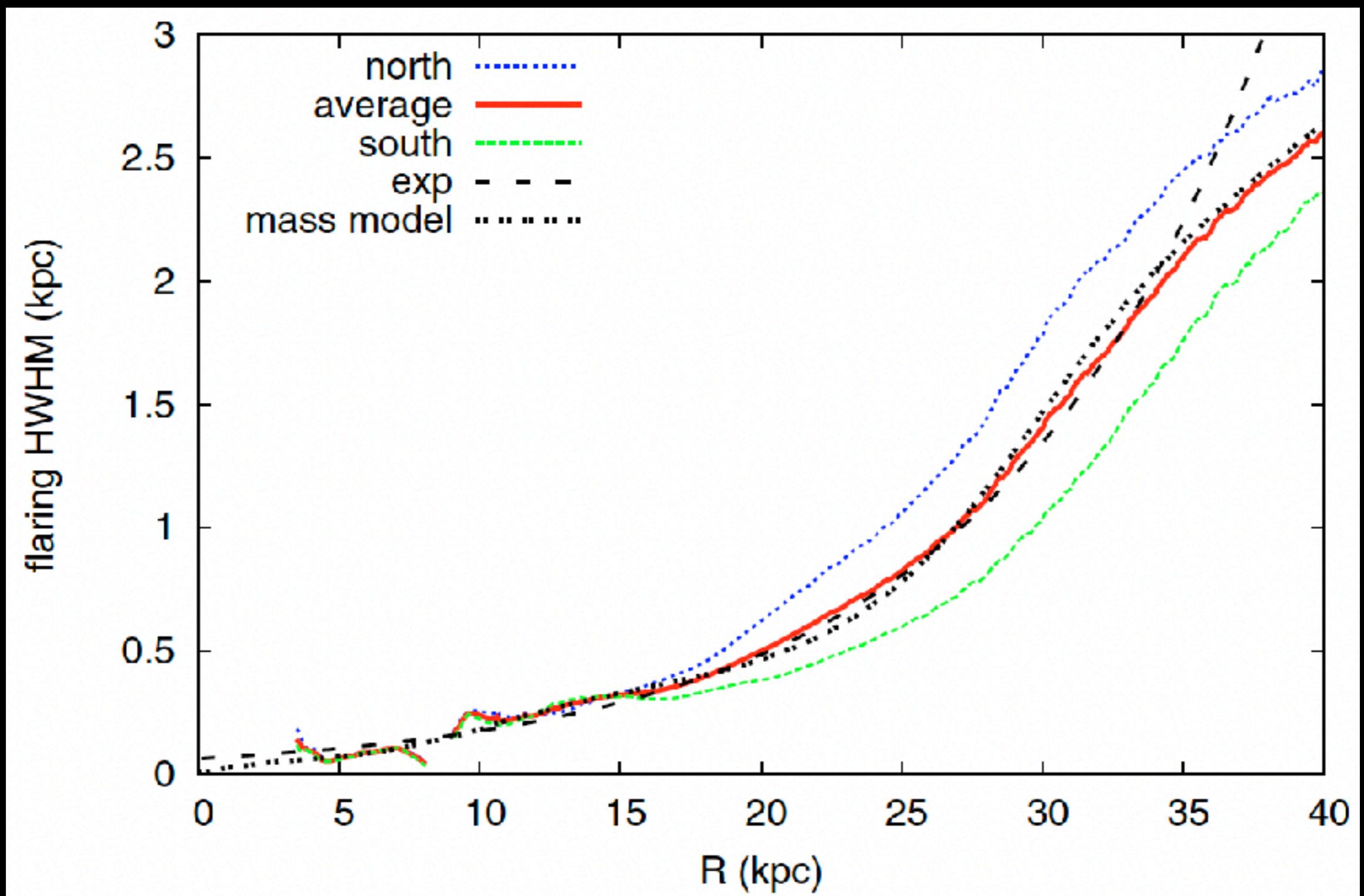


C. HI mapping Galactic disk flaring

σ_z

$\theta \approx 30'$

Kalberla & Dedes. A&A (2008)

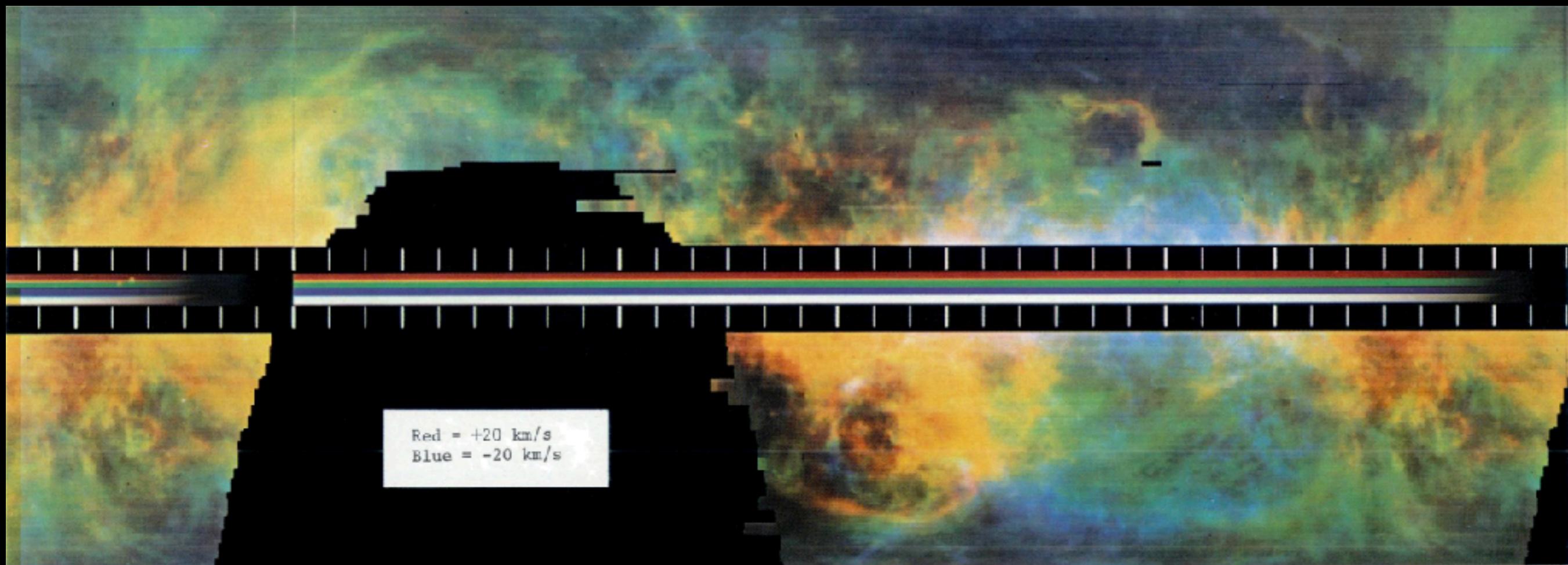


D. HI mapping shells and supershells

$\theta \approx 0.6^\circ$

Heiles & Jenkins. A&A (1976)

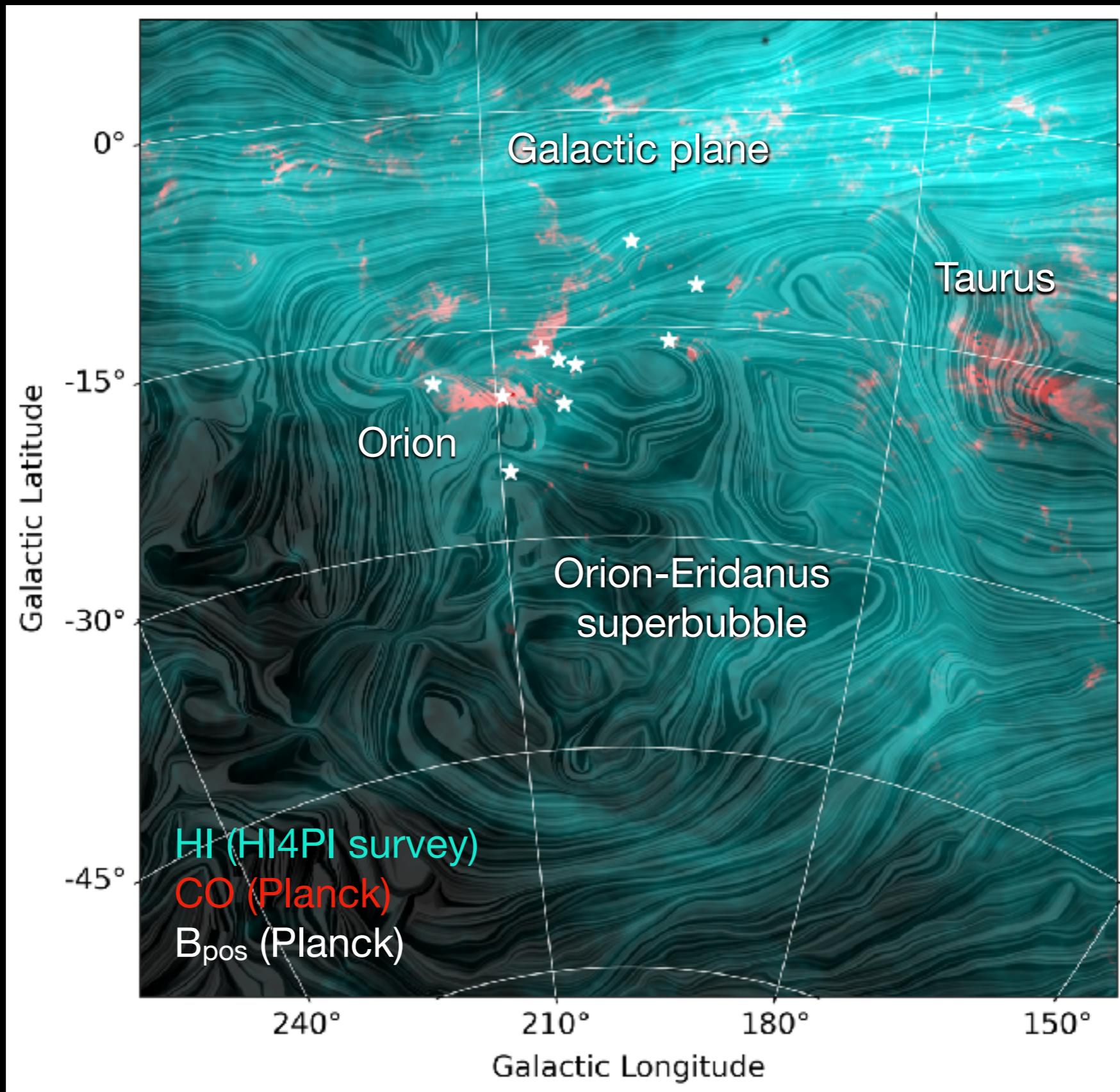
$b = +60^\circ$



$b = -60^\circ$

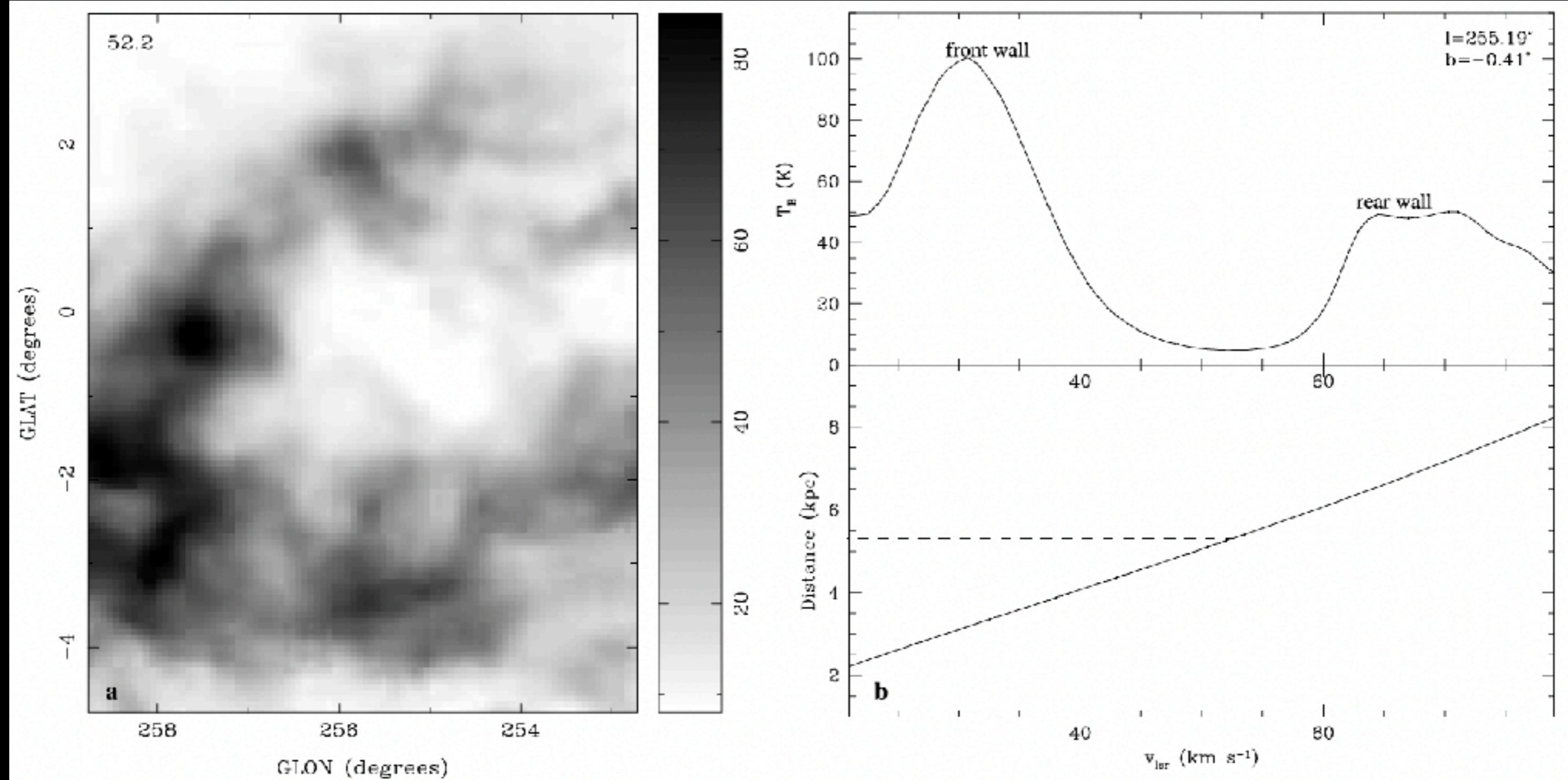
D. HI mapping shells and supershells

Soler, Bracco & Pon. ApJ (2018)



D. HI mapping shells and supershells

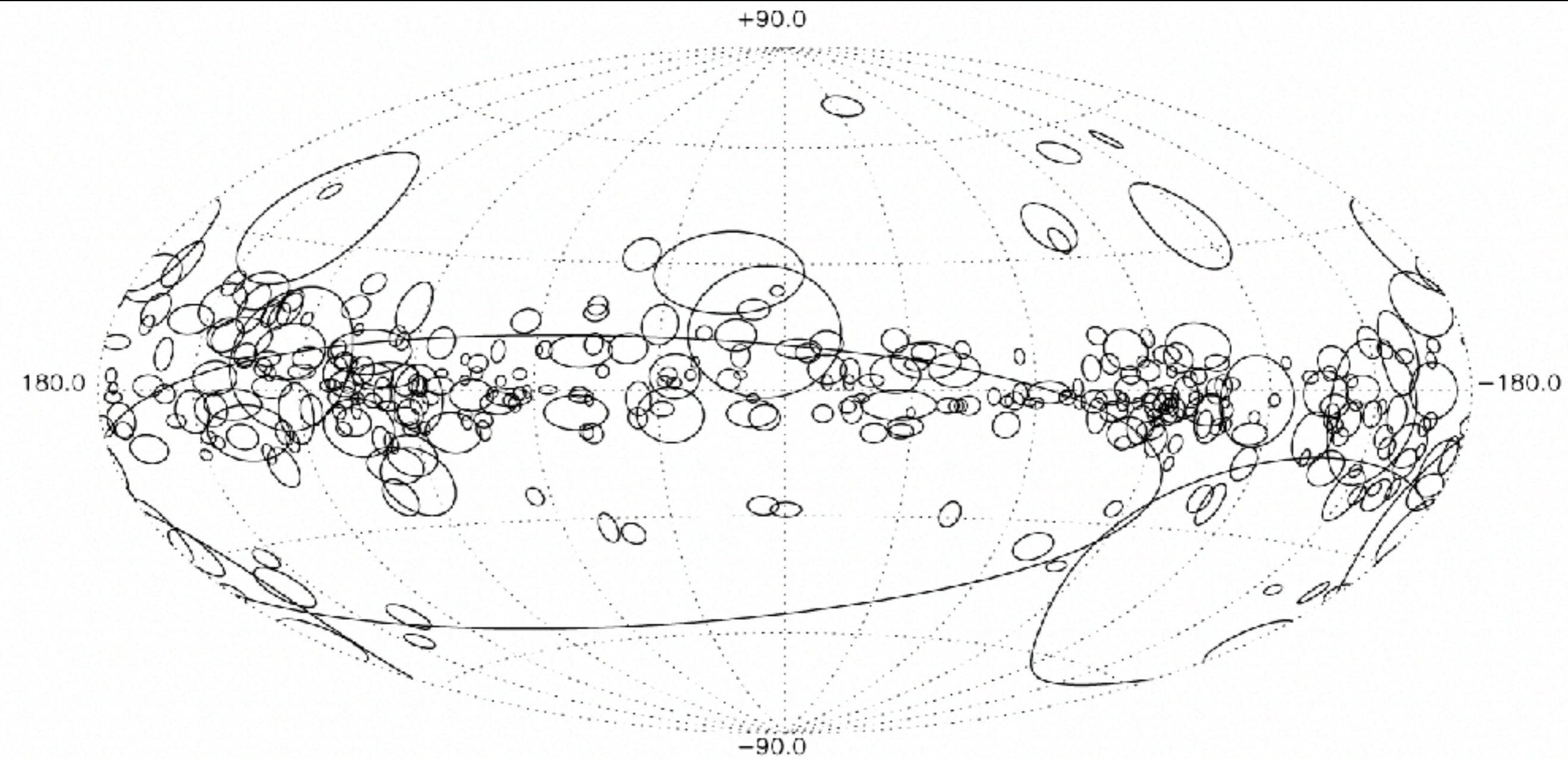
McClure-Griffiths et al. ApJ (2006)



D. HI mapping shells and supershells

$\theta \approx 36'$

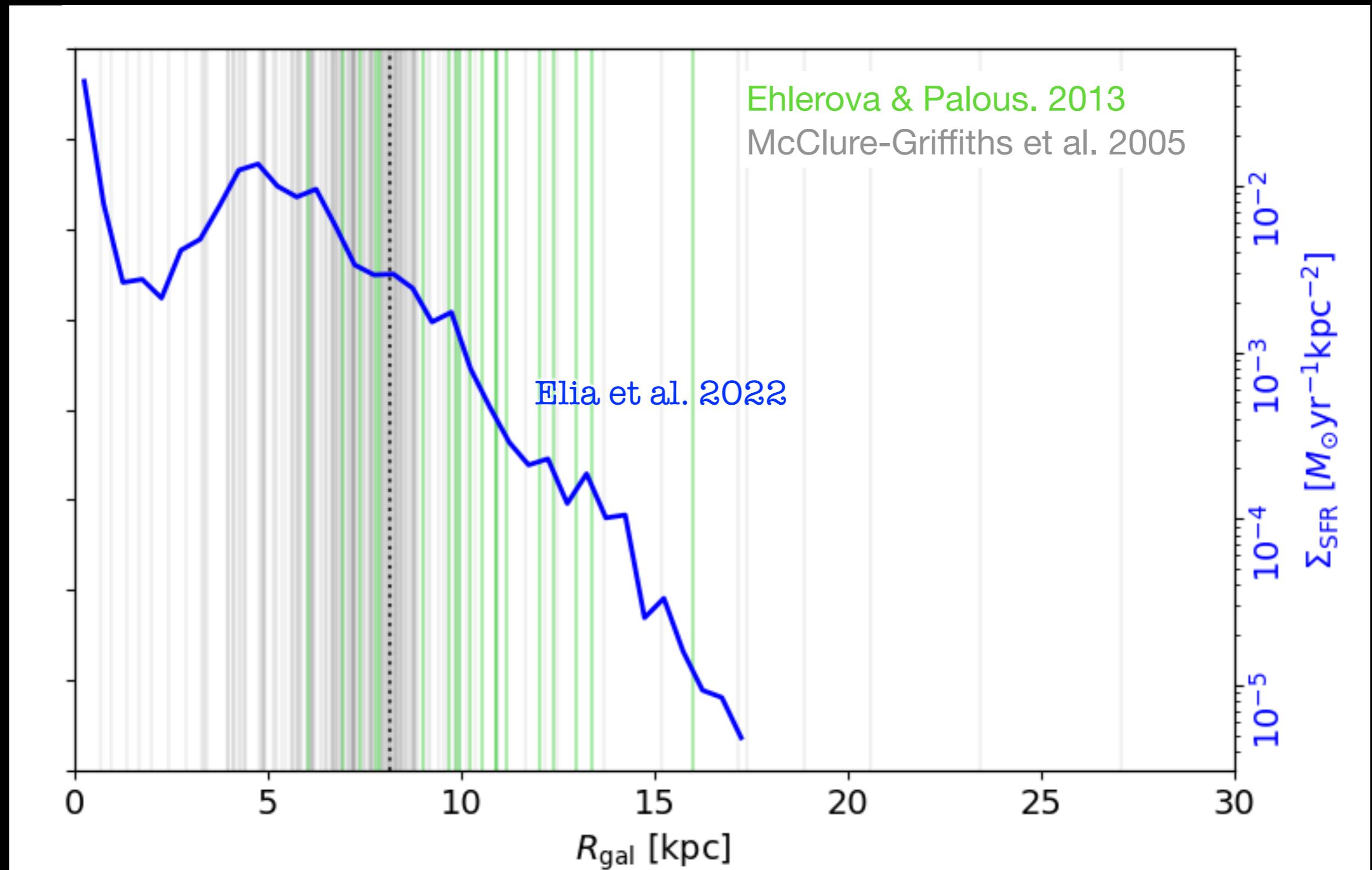
Ehlerová & Palouš. A&A (2013)



D. HI mapping shells and supershells

$\theta \approx 36'$

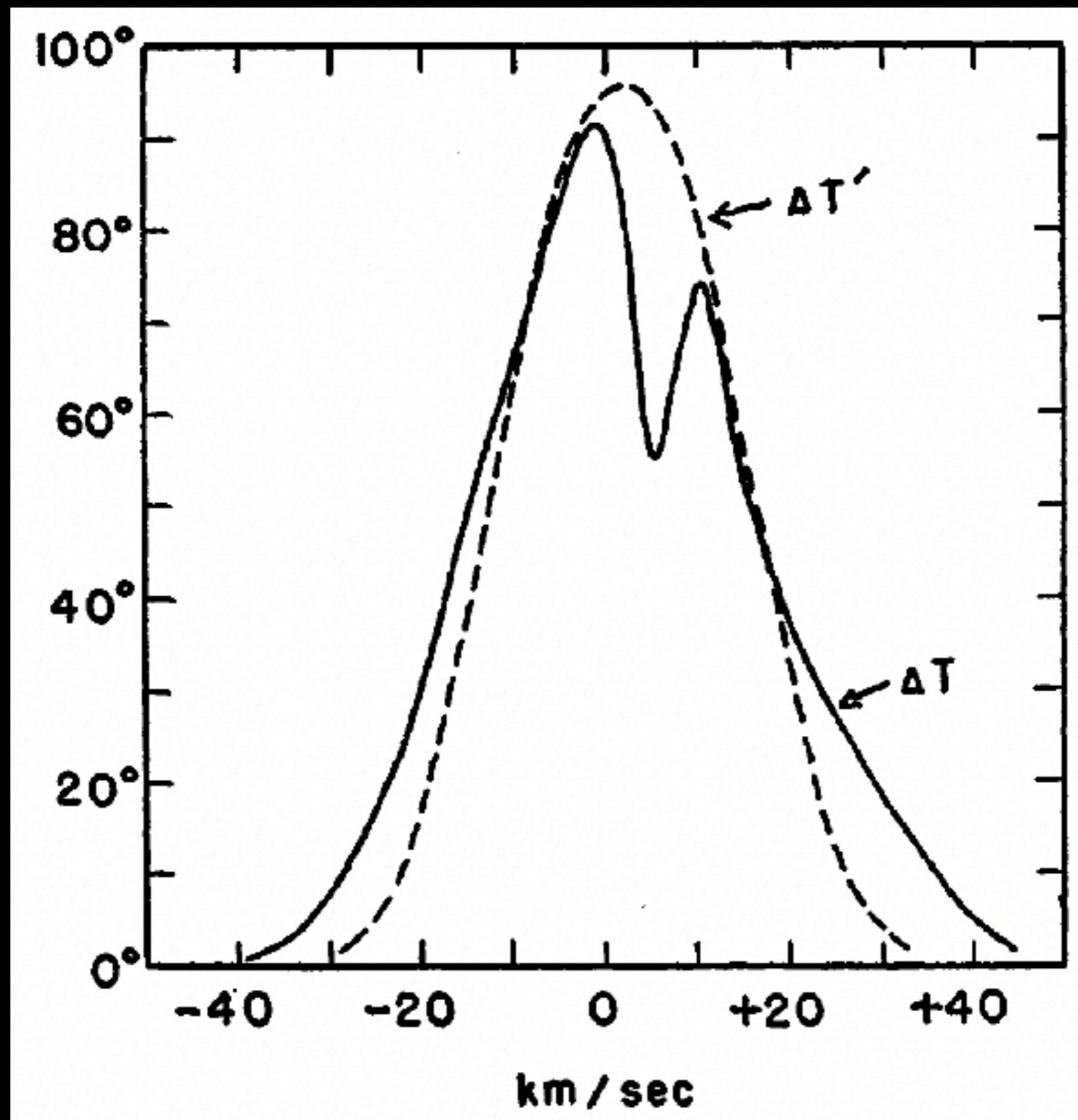
Soler, J.D. et al. A&A (2022)



E. HI mapping the multiphase ISM structure

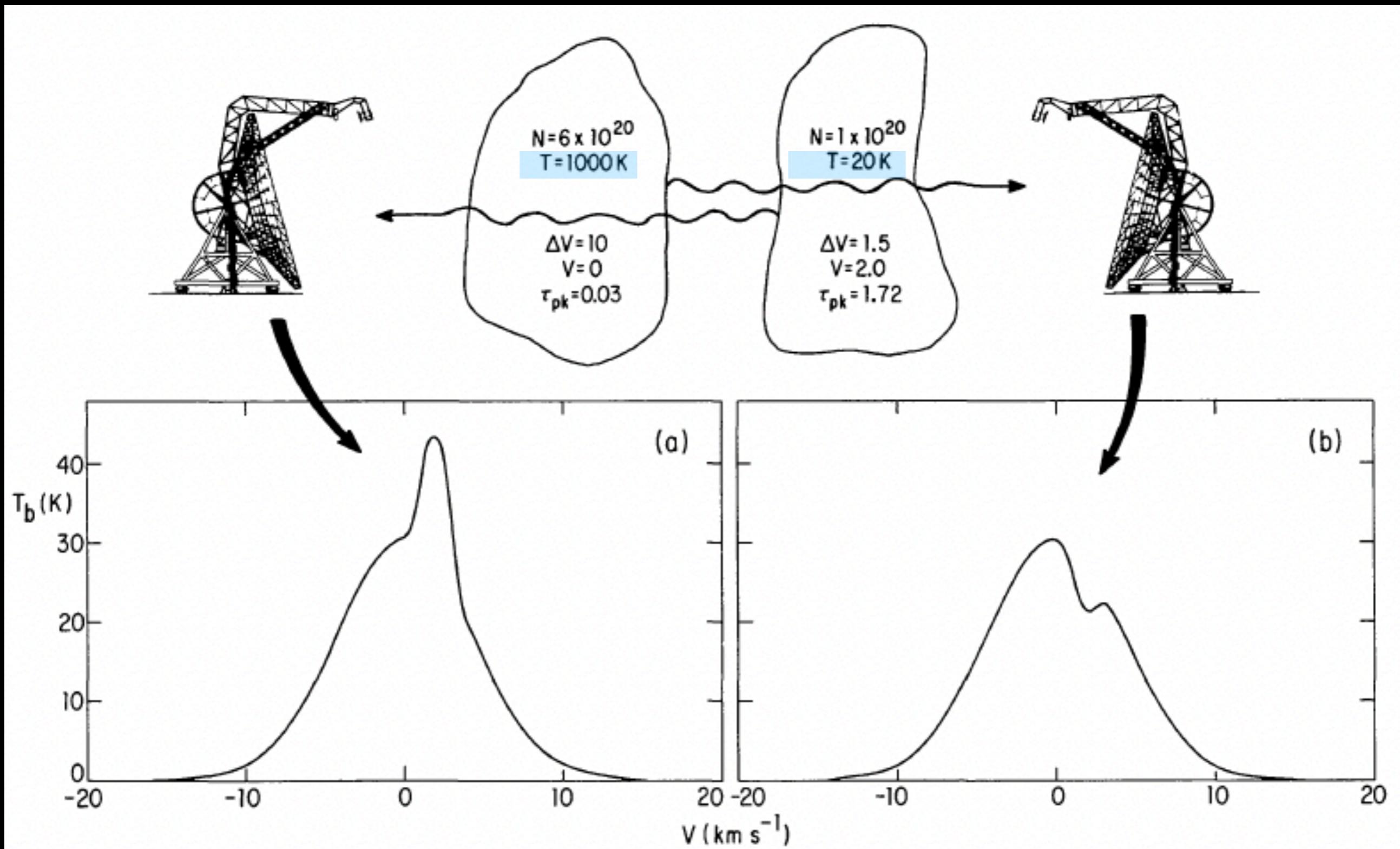
$\theta \approx 1.7^\circ$

Heeschen. ApJ (1955)



E. HI mapping the multiphase ISM structure

Dickey & Lockman. ARA&A (1990)

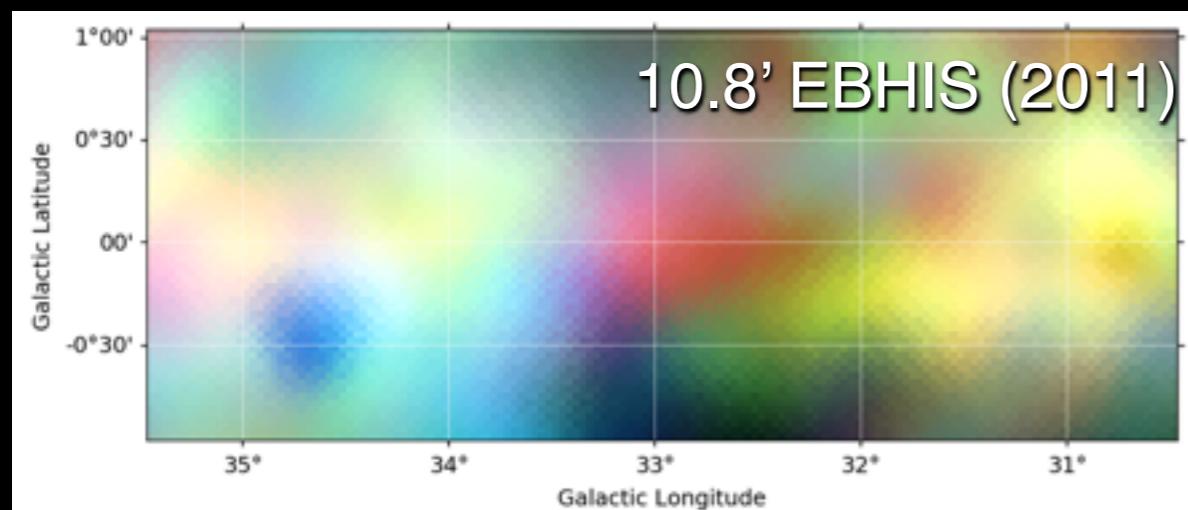


Intermission: the resolution problem

$$\theta \approx 10.8'$$

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

Effelsberg 100-m Telescope

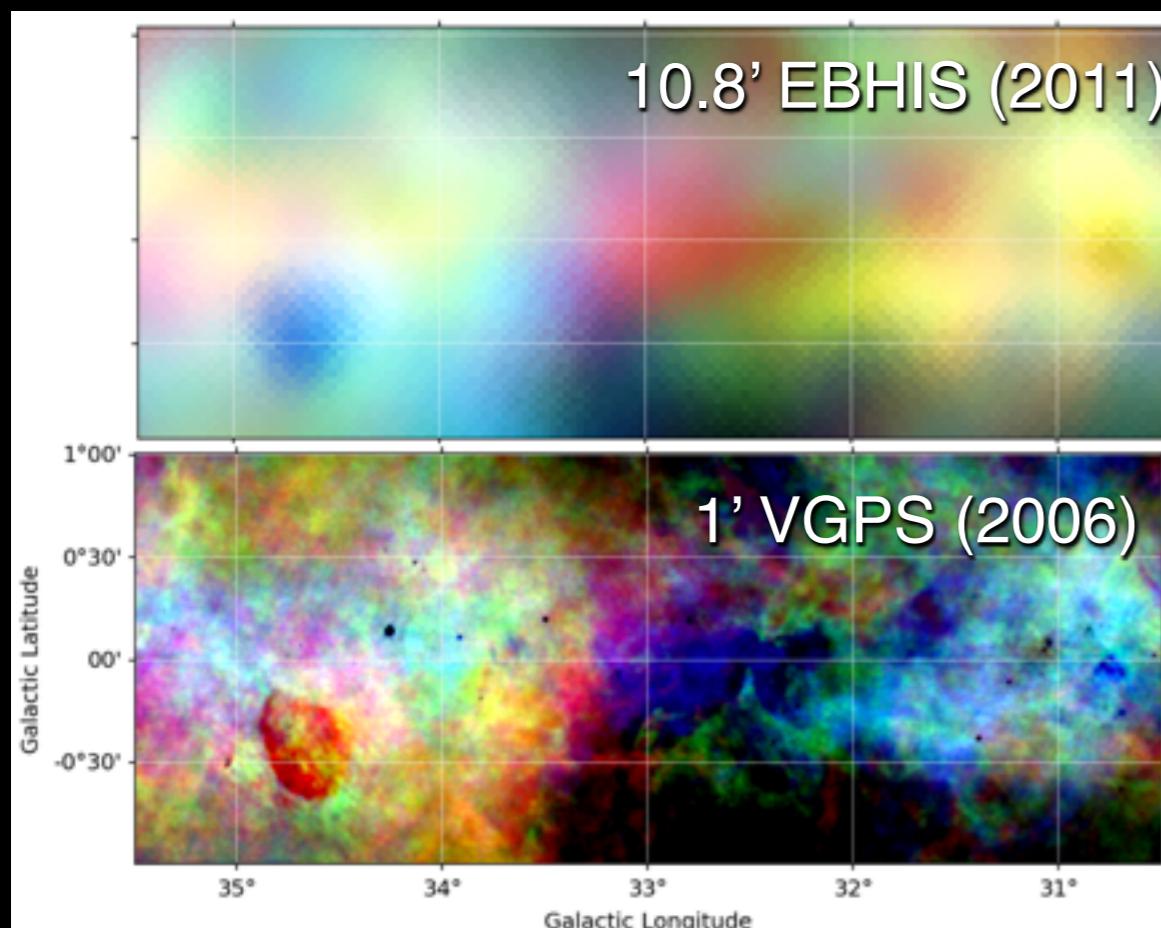


Intermission: the resolution problem

$$\theta \approx 1'$$

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

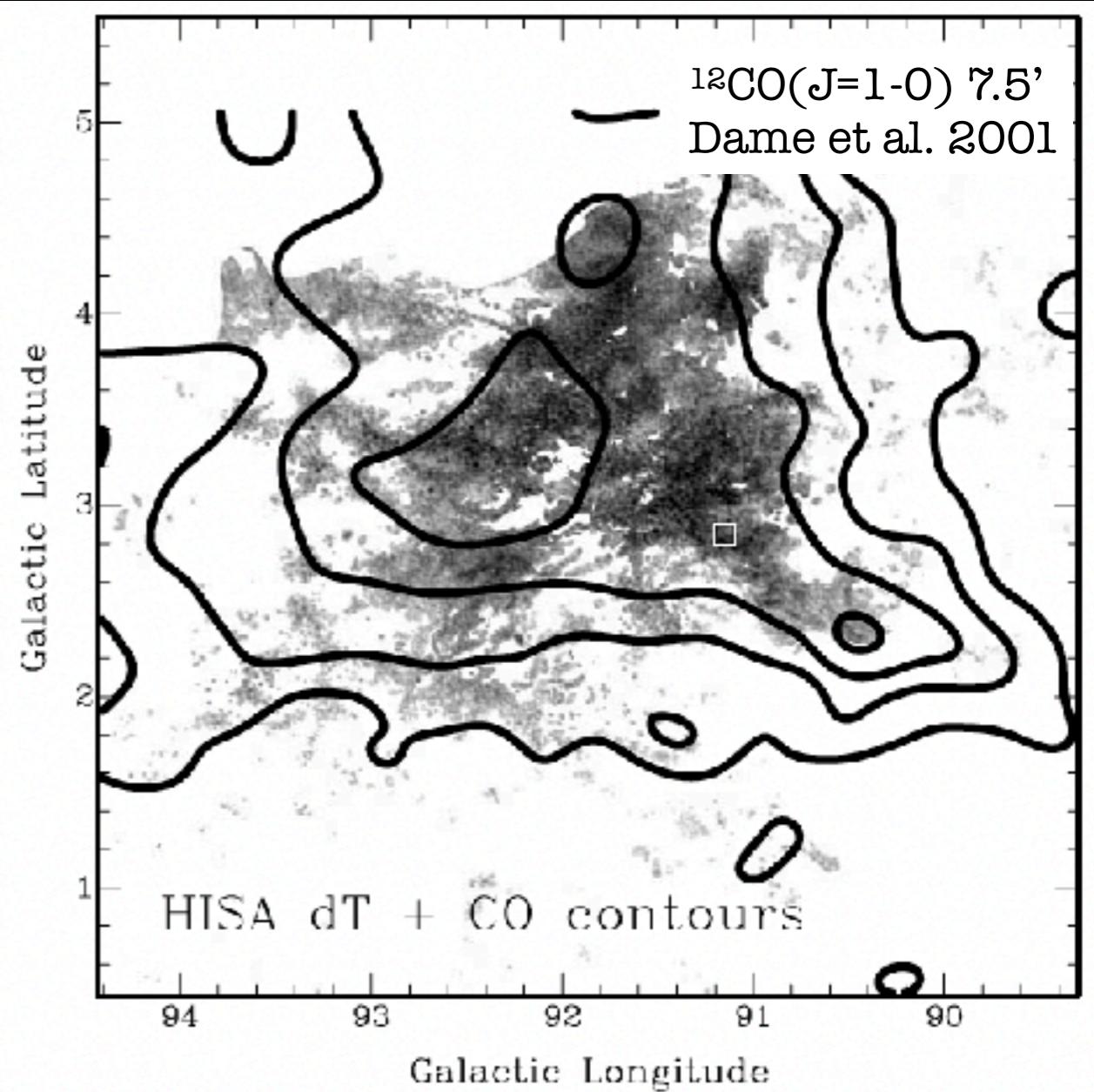
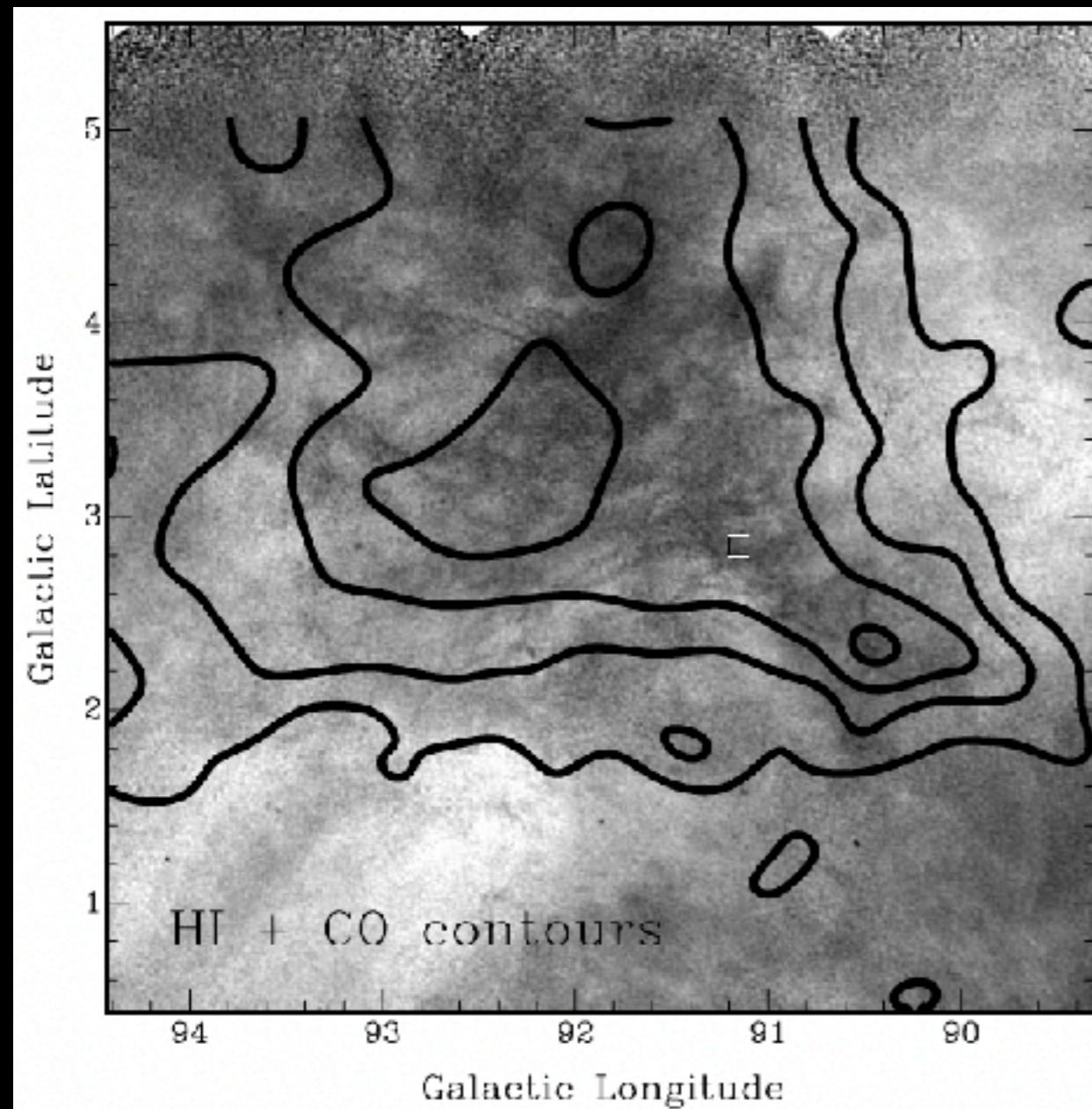
Jansky Very Large Array (VLA)



E. HI mapping the multiphase ISM structure

$\theta \approx 1'$

Gibson et al. ApJ (2000)



Intermission: the resolution problem

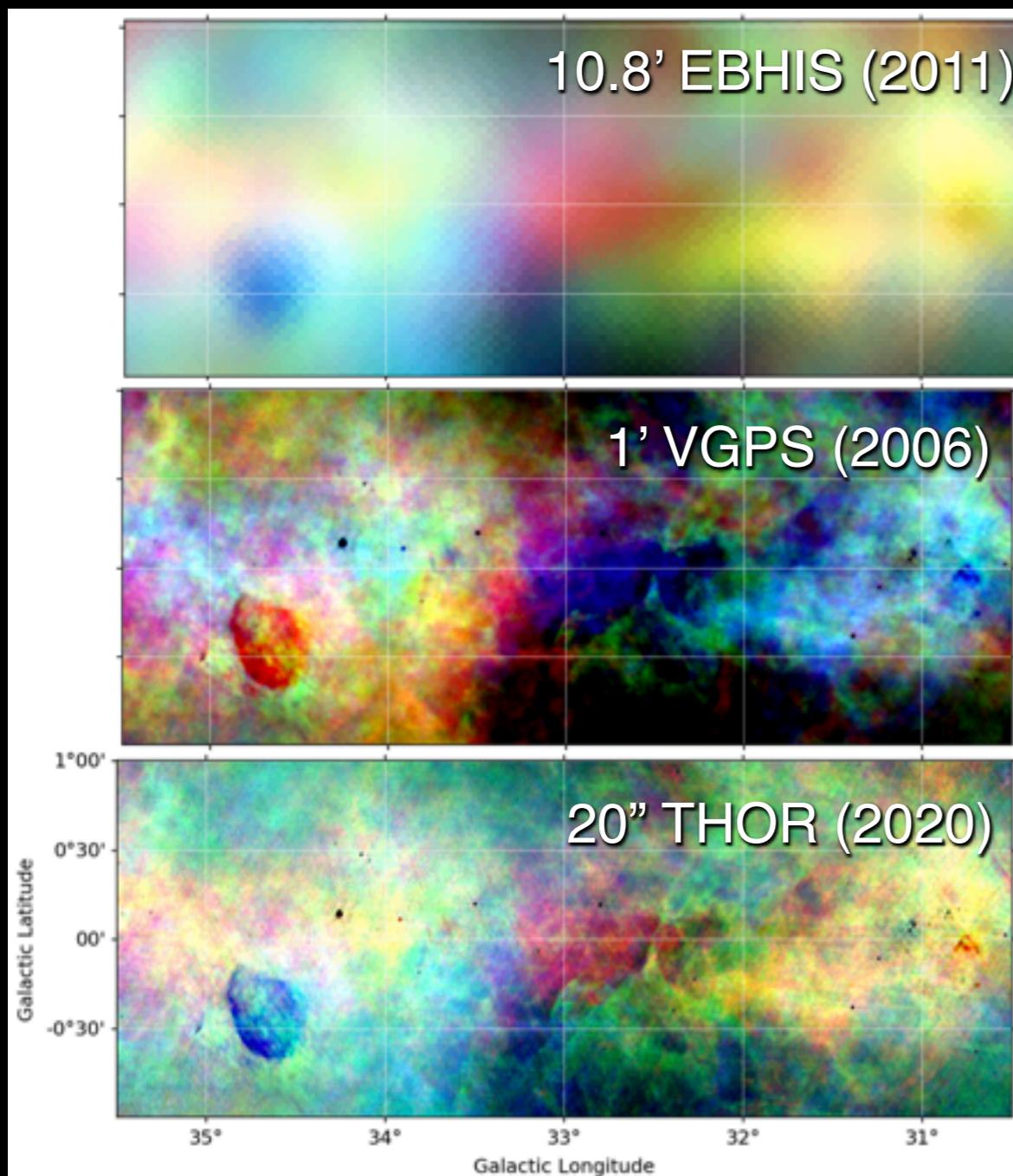
$$\theta \approx 20''$$

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

Beuther et al. (including JDS), 2016

Wang et al. (including JDS) 2020

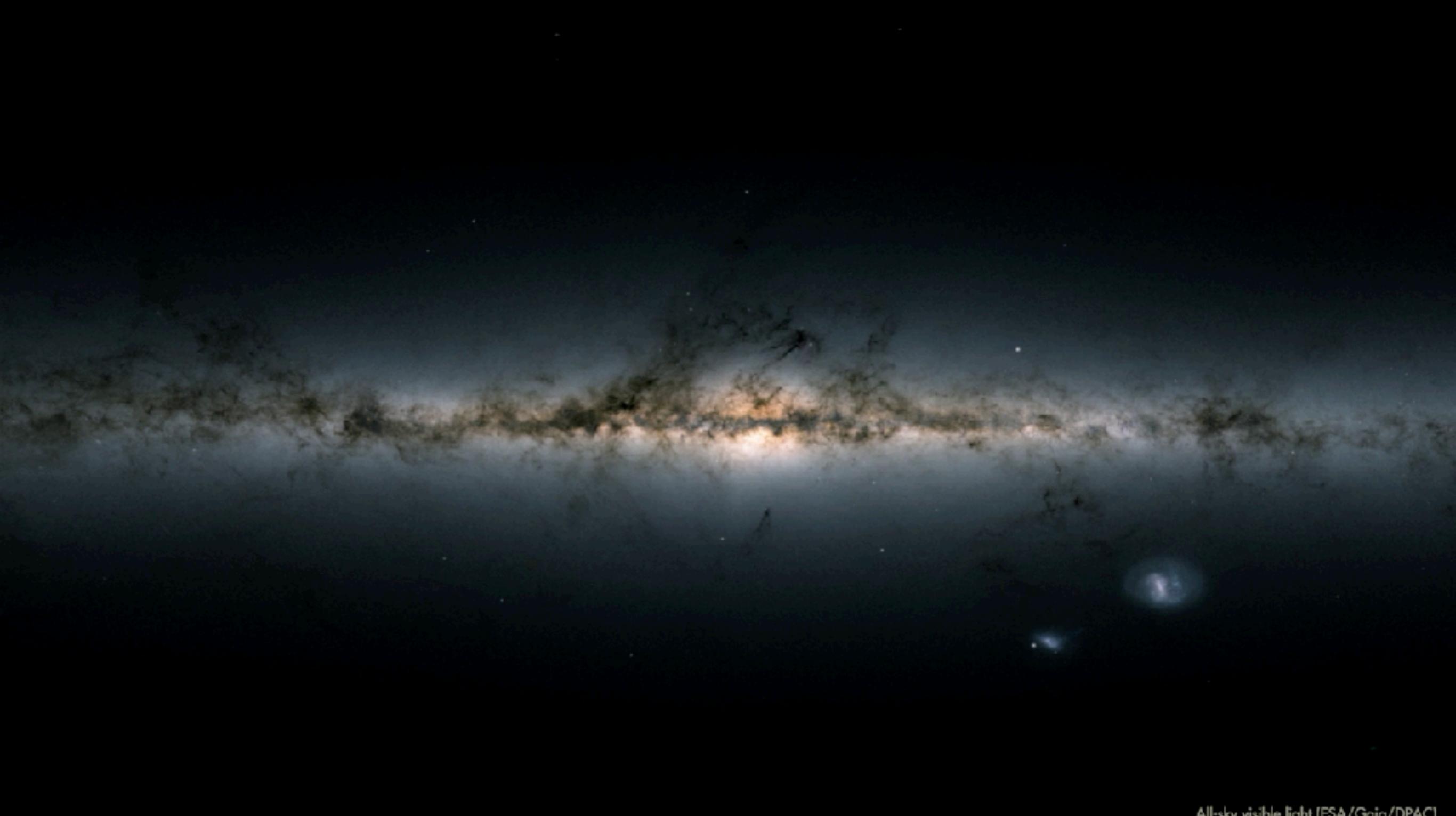
Jansky Very Large Array (VLA)



Intermission: the resolution problem

$\theta \approx 20''$

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

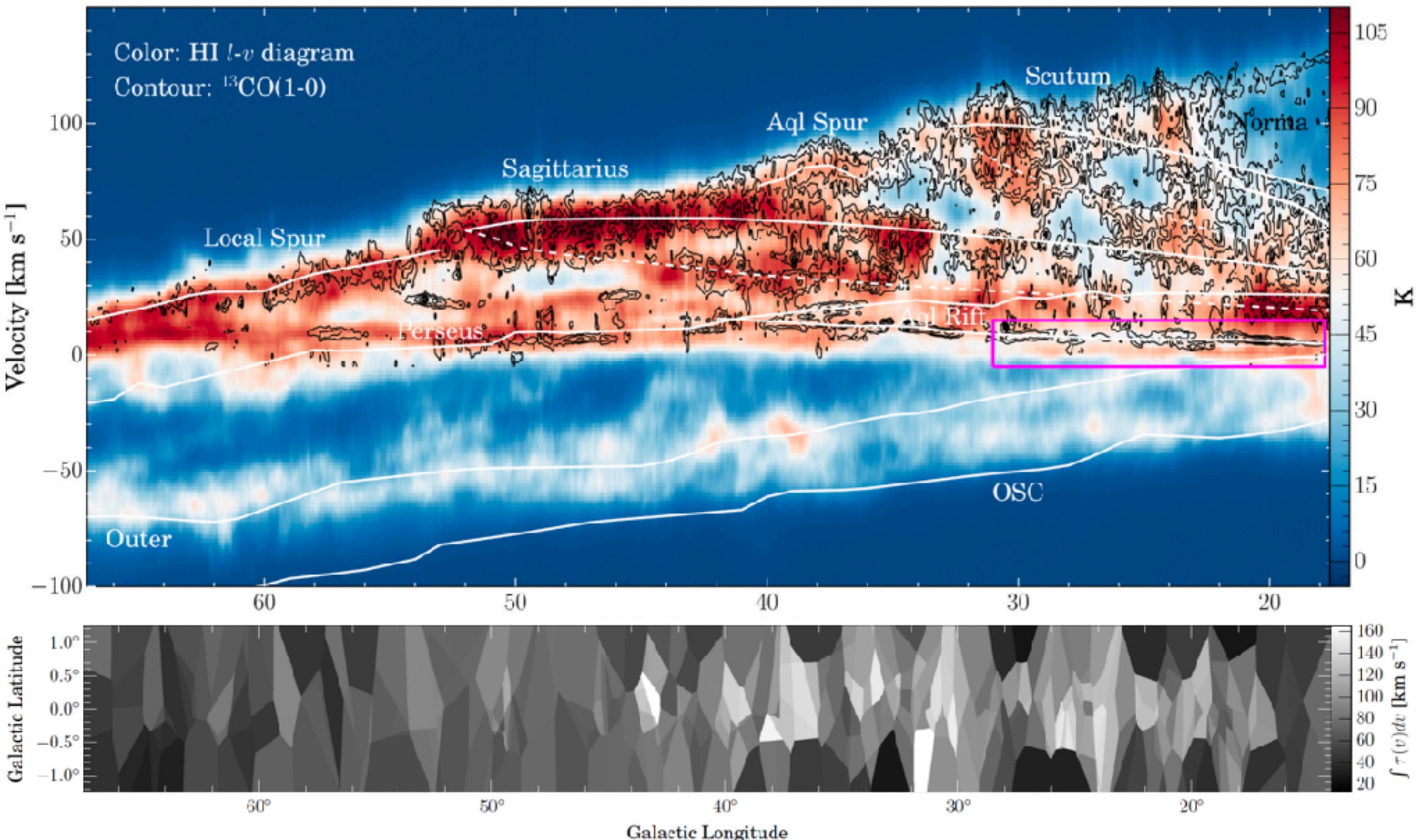


All-sky visible light [ESA/Gaia/DPAC]

E. HI mapping the multiphase ISM structure

$$\theta \approx 20''$$

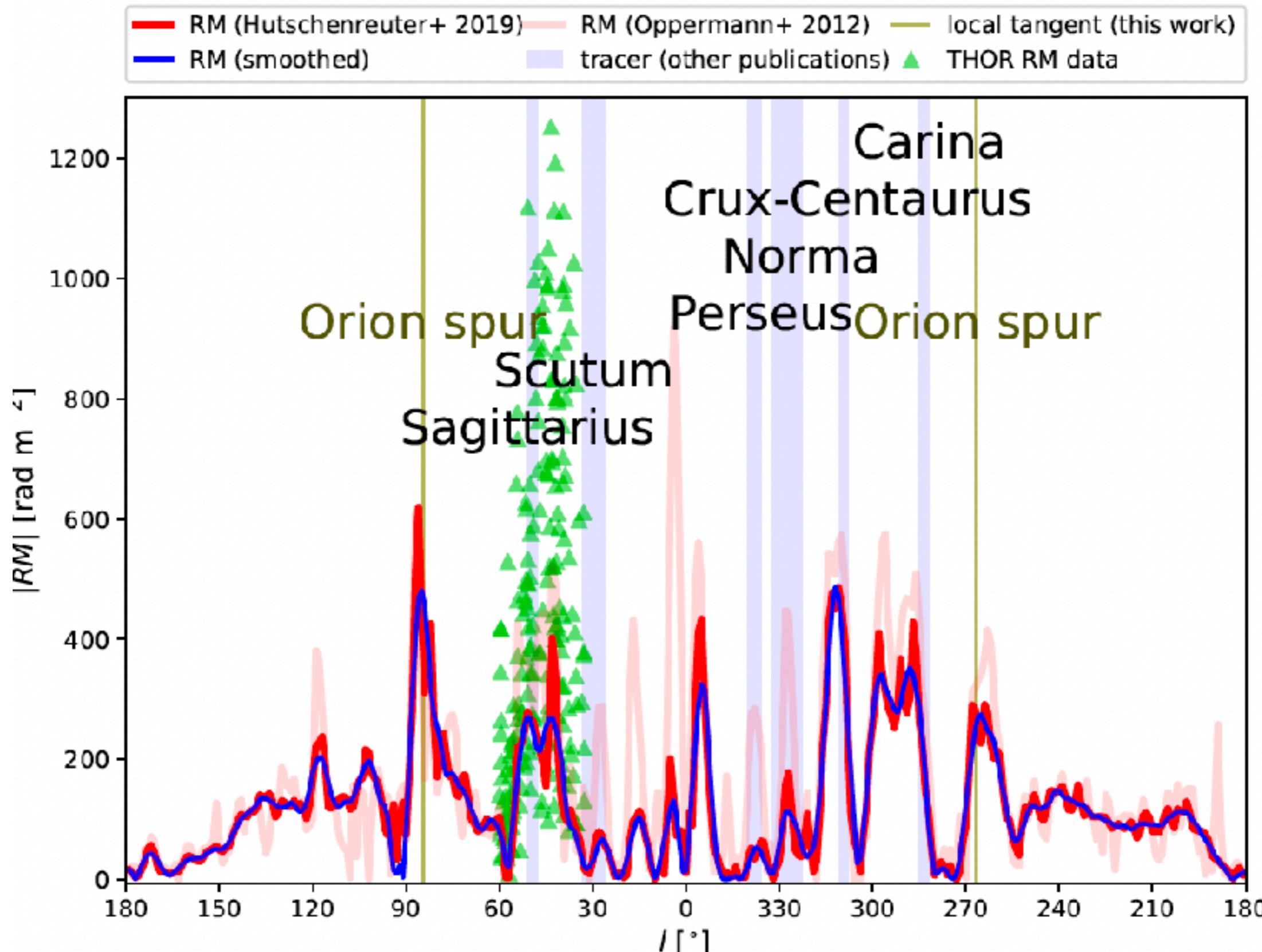
Wang, Y., Beuther, H. et al (including JDS). A&A (2020)



I still love the magnetic field

$$\theta \approx 20''$$

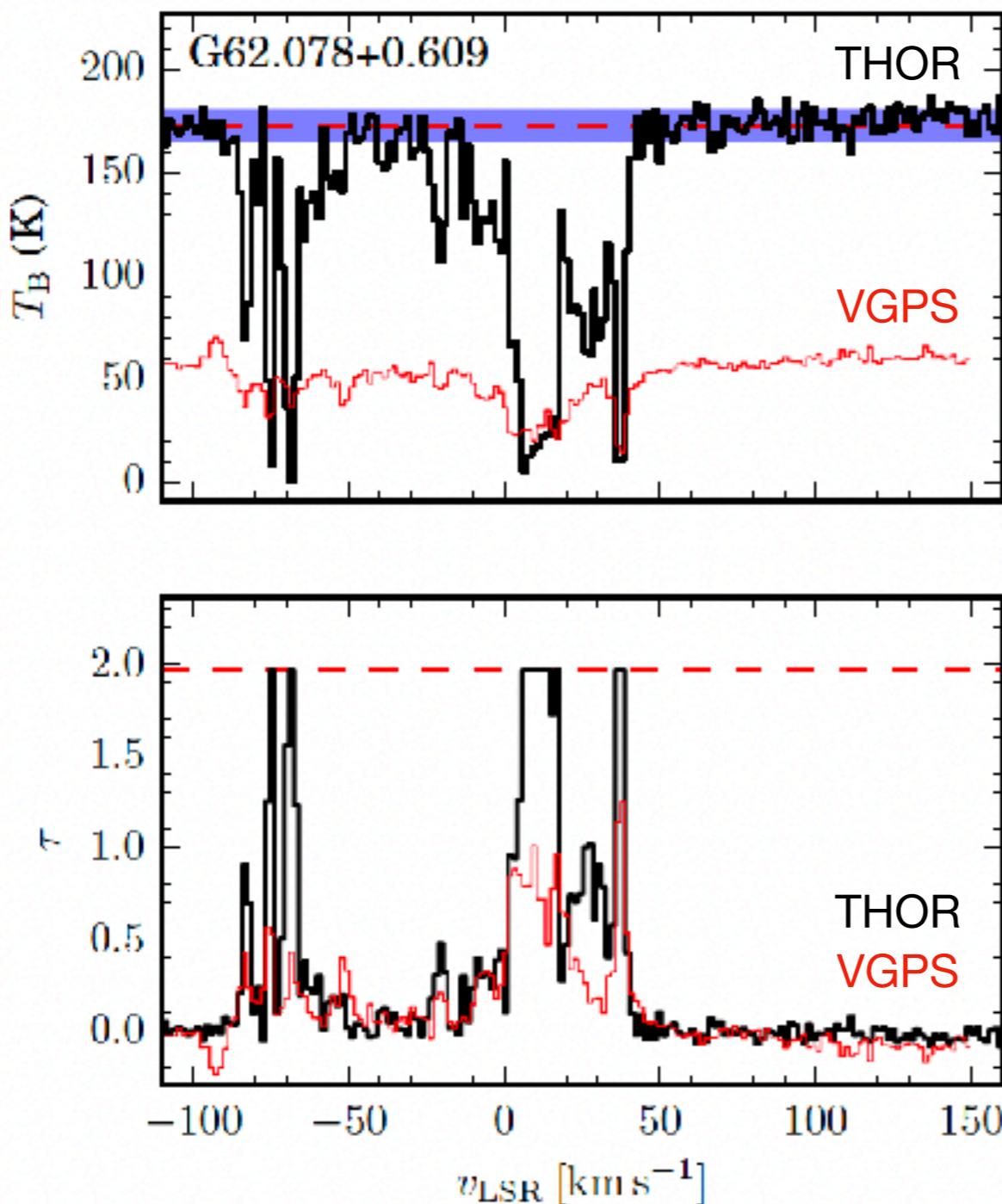
Reissl, JDS, et al. A&A (2020); Shanahan, JDS, et al. (2019)



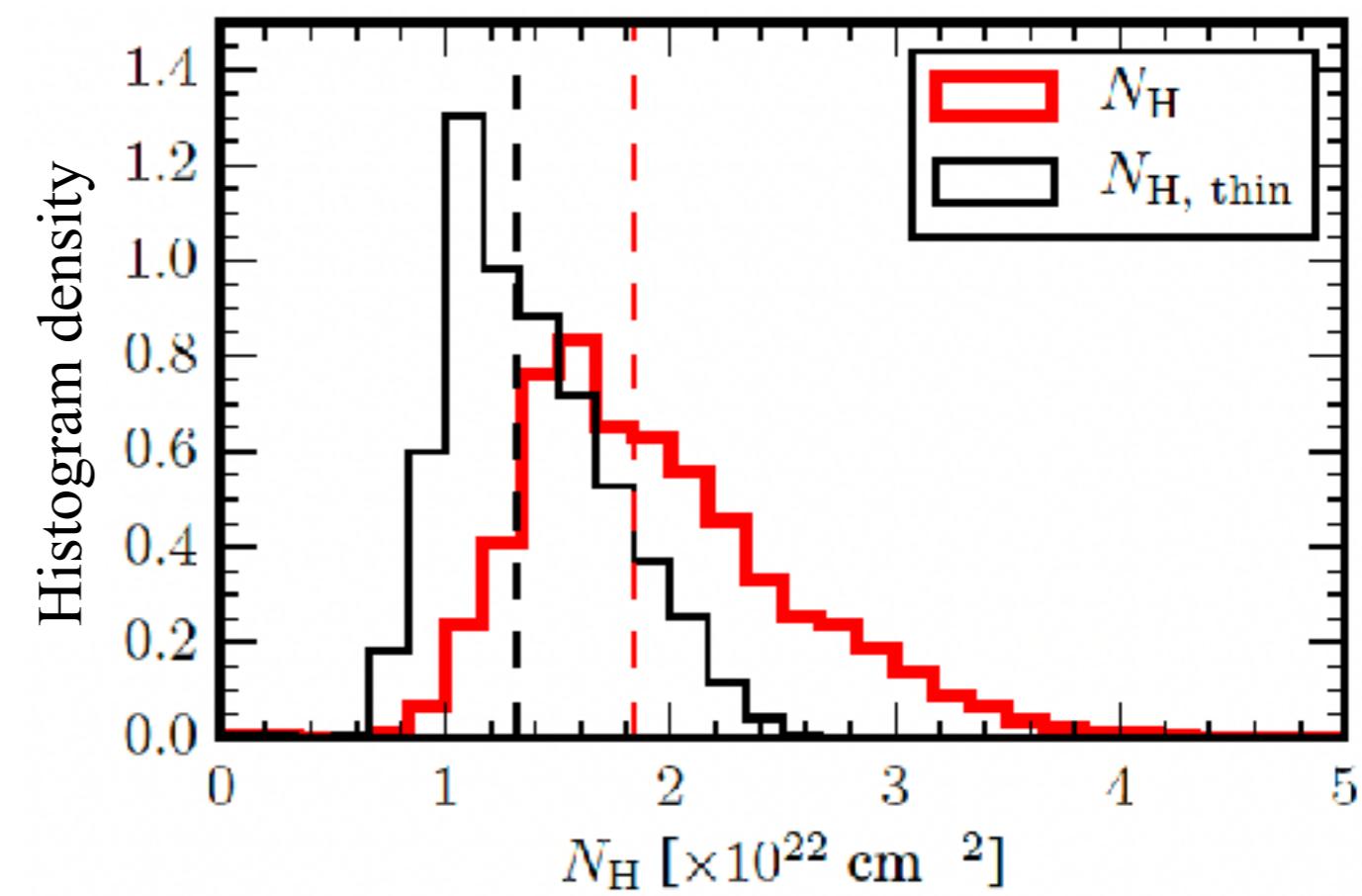
E. HI mapping the multiphase ISM structure

$\theta \approx 20''$

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



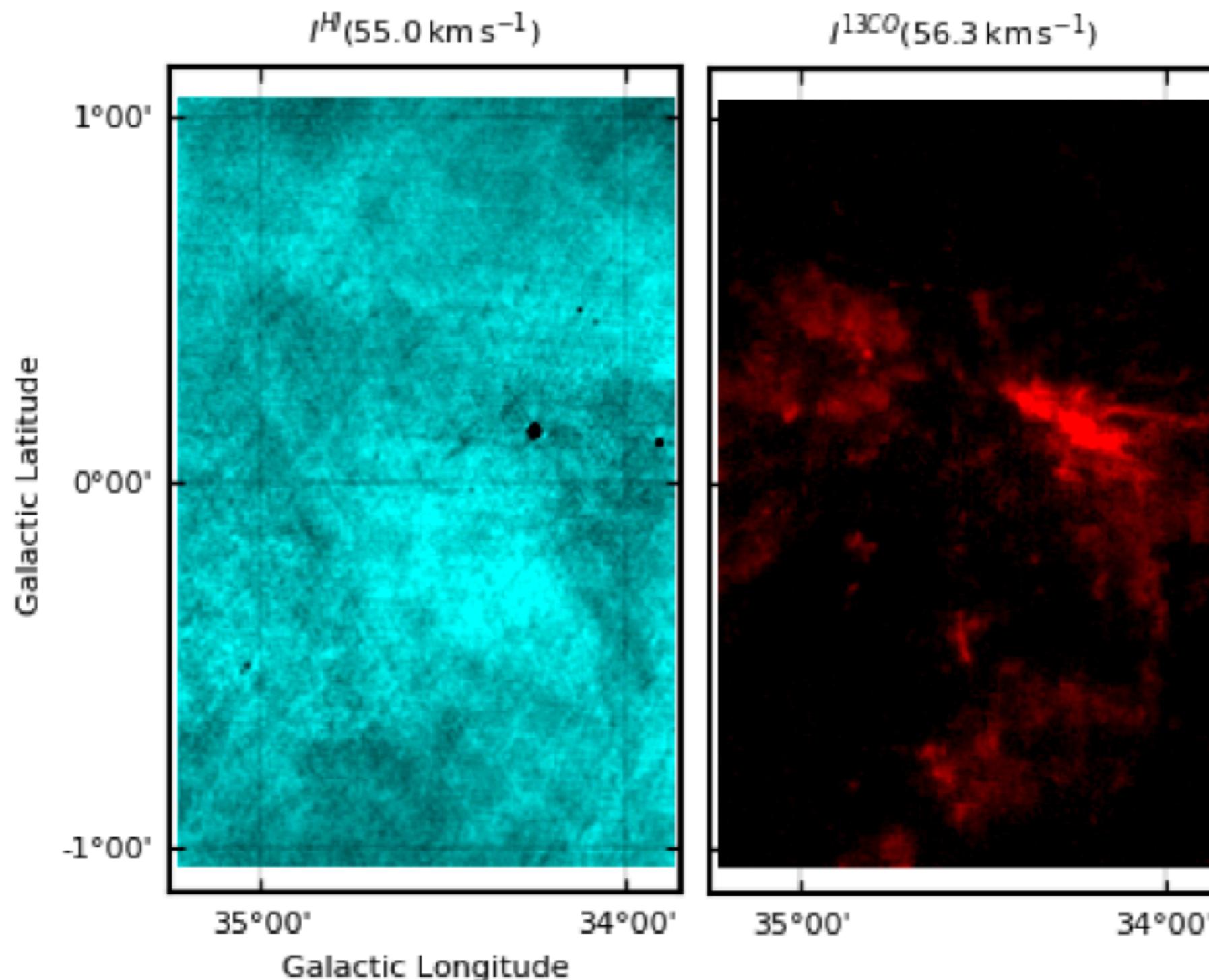
$$M_{\text{HI}} \approx 9.4 \times 10^9 M_{\odot}$$



E. HI mapping the multiphase ISM structure

$$\theta \approx 20''$$

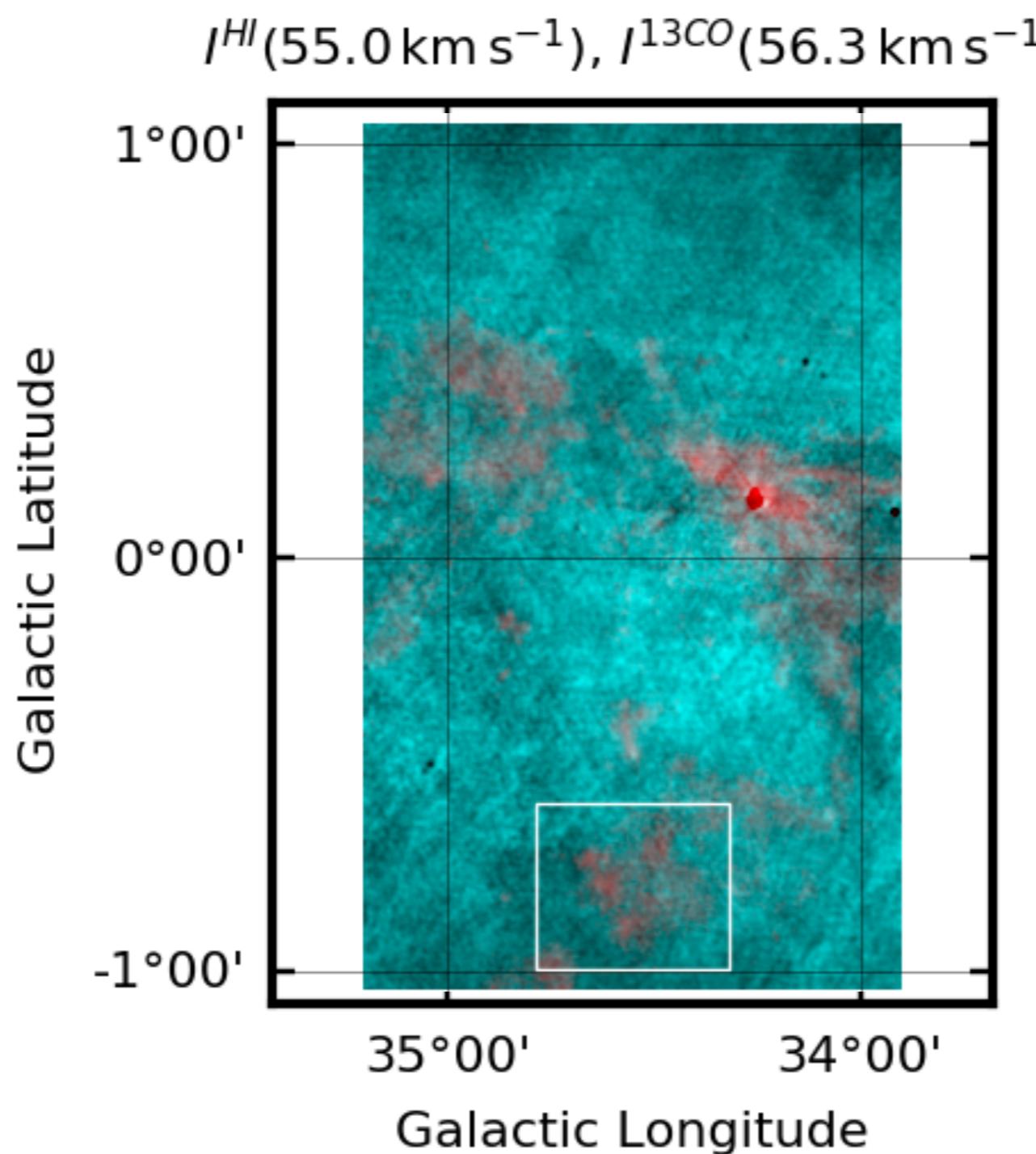
Soler, Beuther, et al. A&A (2009)



E. HI mapping the multiphase ISM structure

$\theta \approx 20''$

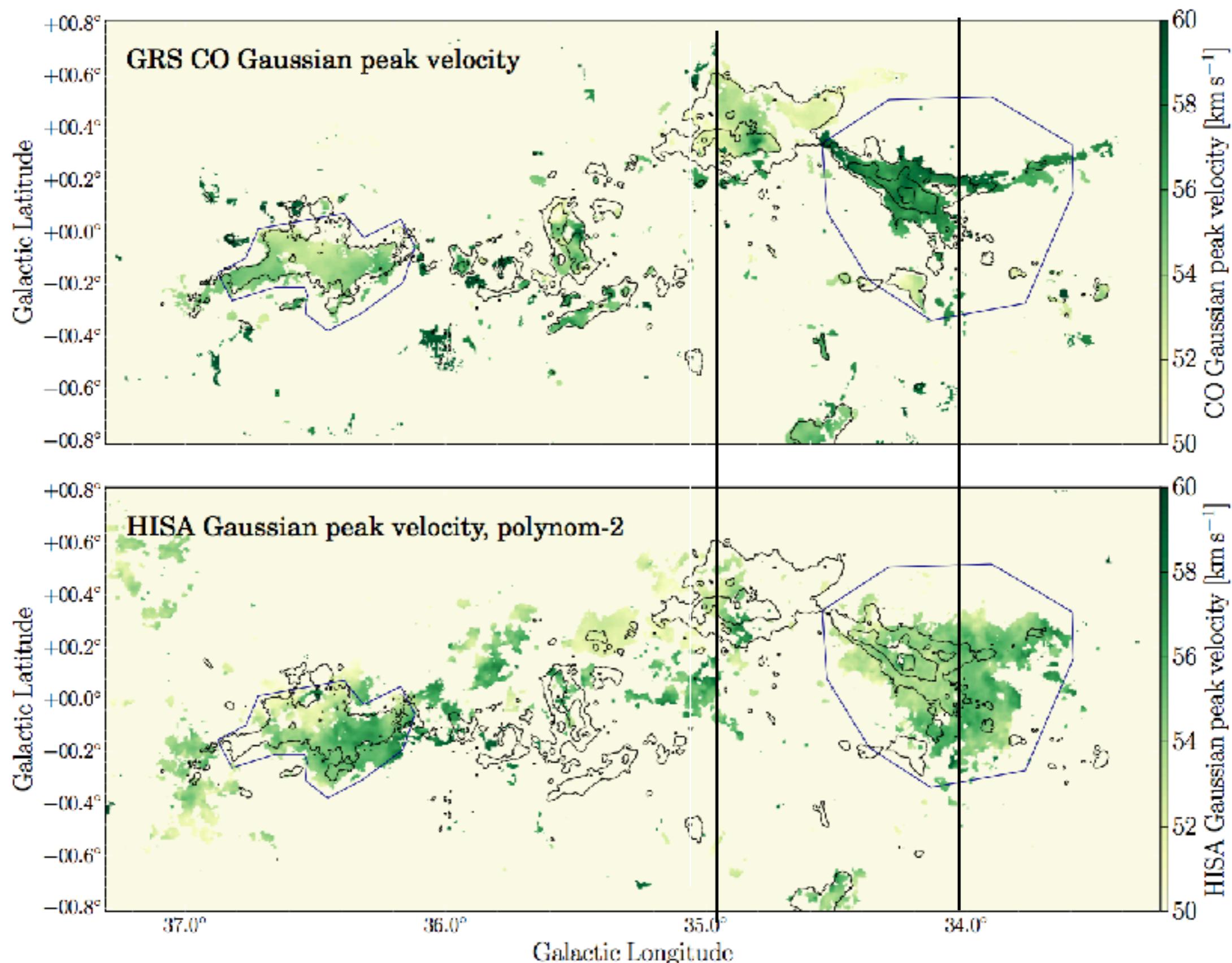
Soler, Beuther, et al. A&A (2009)



E. HI mapping the multiphase ISM structure

$$\theta \approx 20''$$

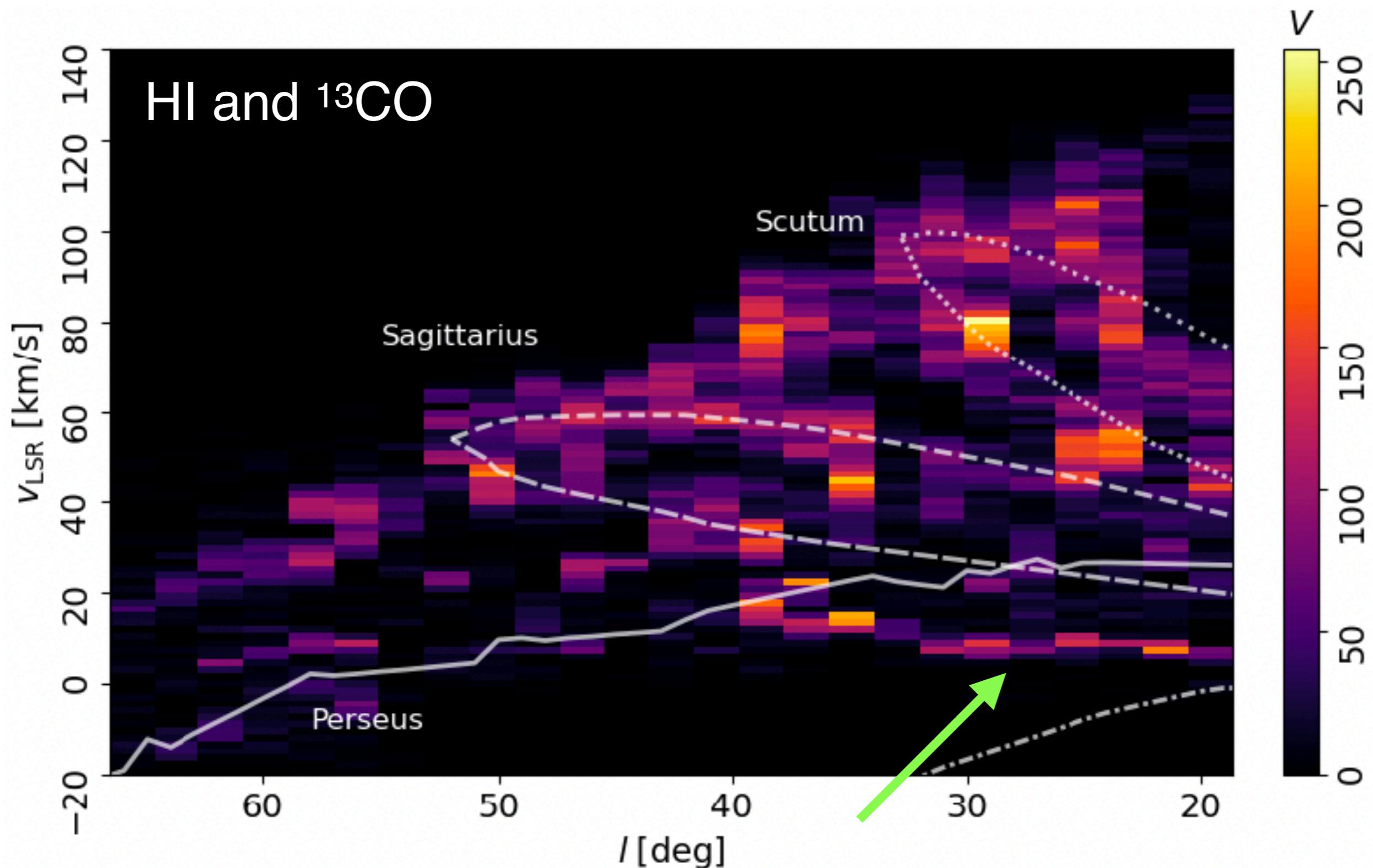
Wang, Y., Beuther, H. et al (including JDS). A&A (2020)



E. HI mapping the multiphase ISM structure

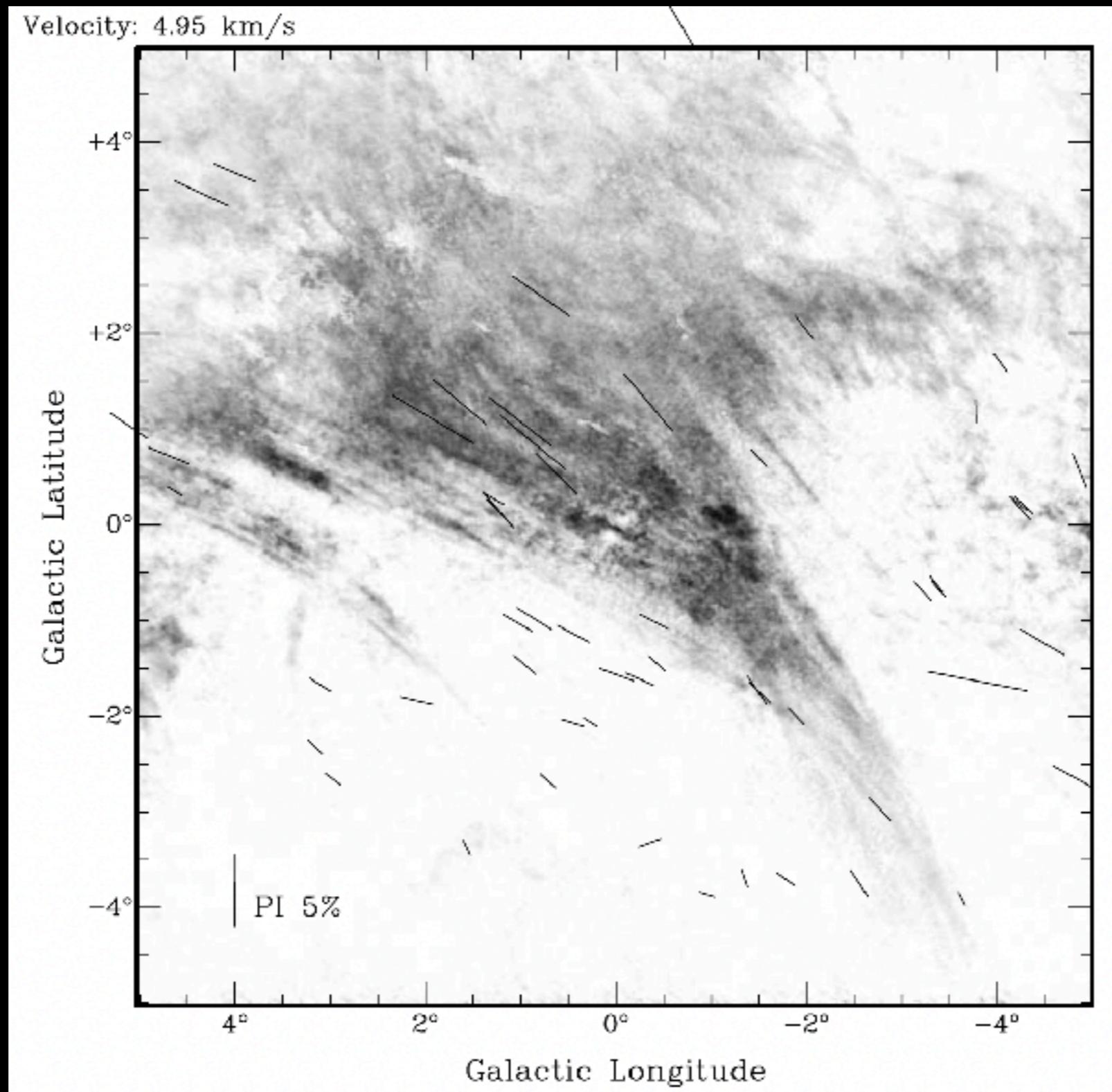
$\theta \approx 20''$

Soler, Beuther, Syed, et al. In preparation.



F. HI mapping ISM dynamics

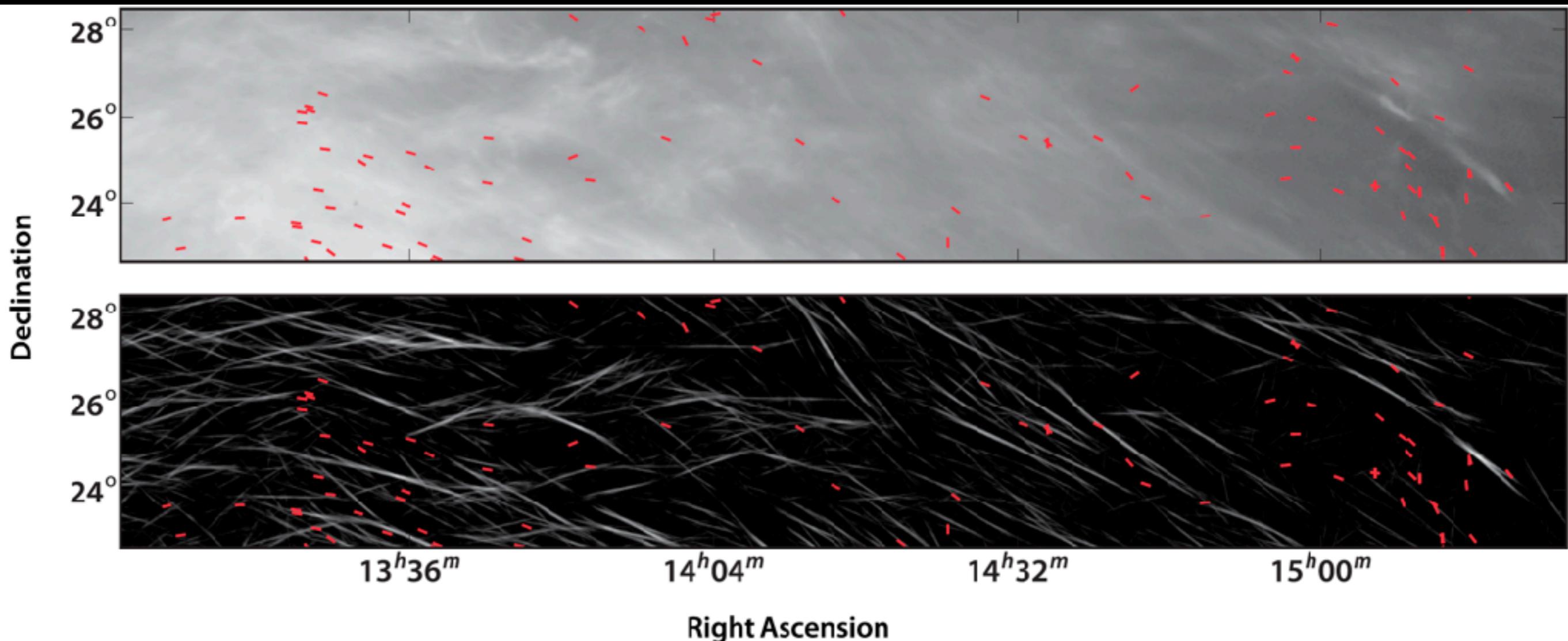
McClure-Griffiths, Dickey, et al. ApJ (2006)



E. HI mapping ISM dynamics

Clark, Peek & Putman. ApJ (2014)

$$-7.0 < v_{\text{LSR}} < -1.1 \text{ km/s}$$

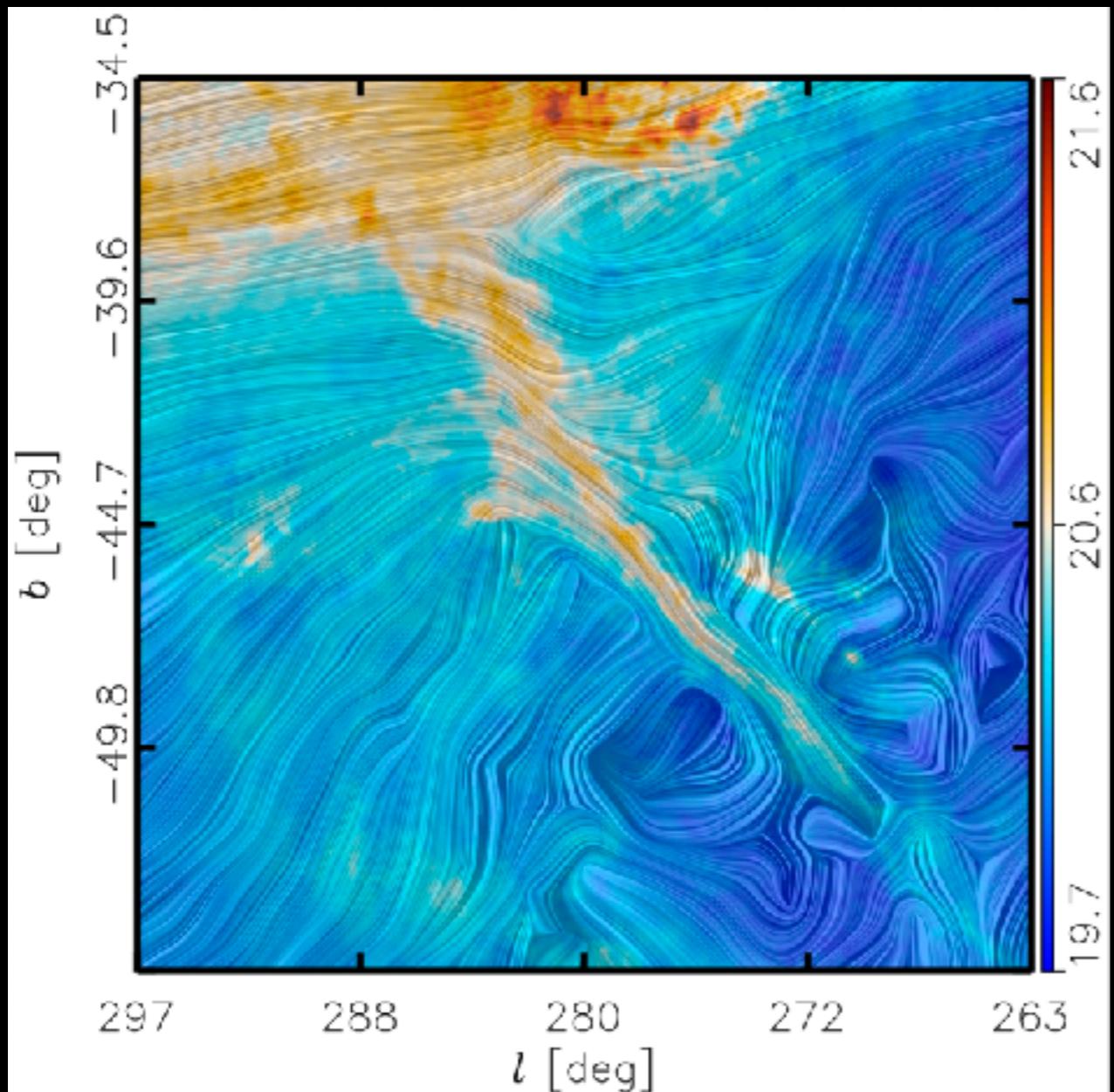


E. HI mapping ISM dynamics

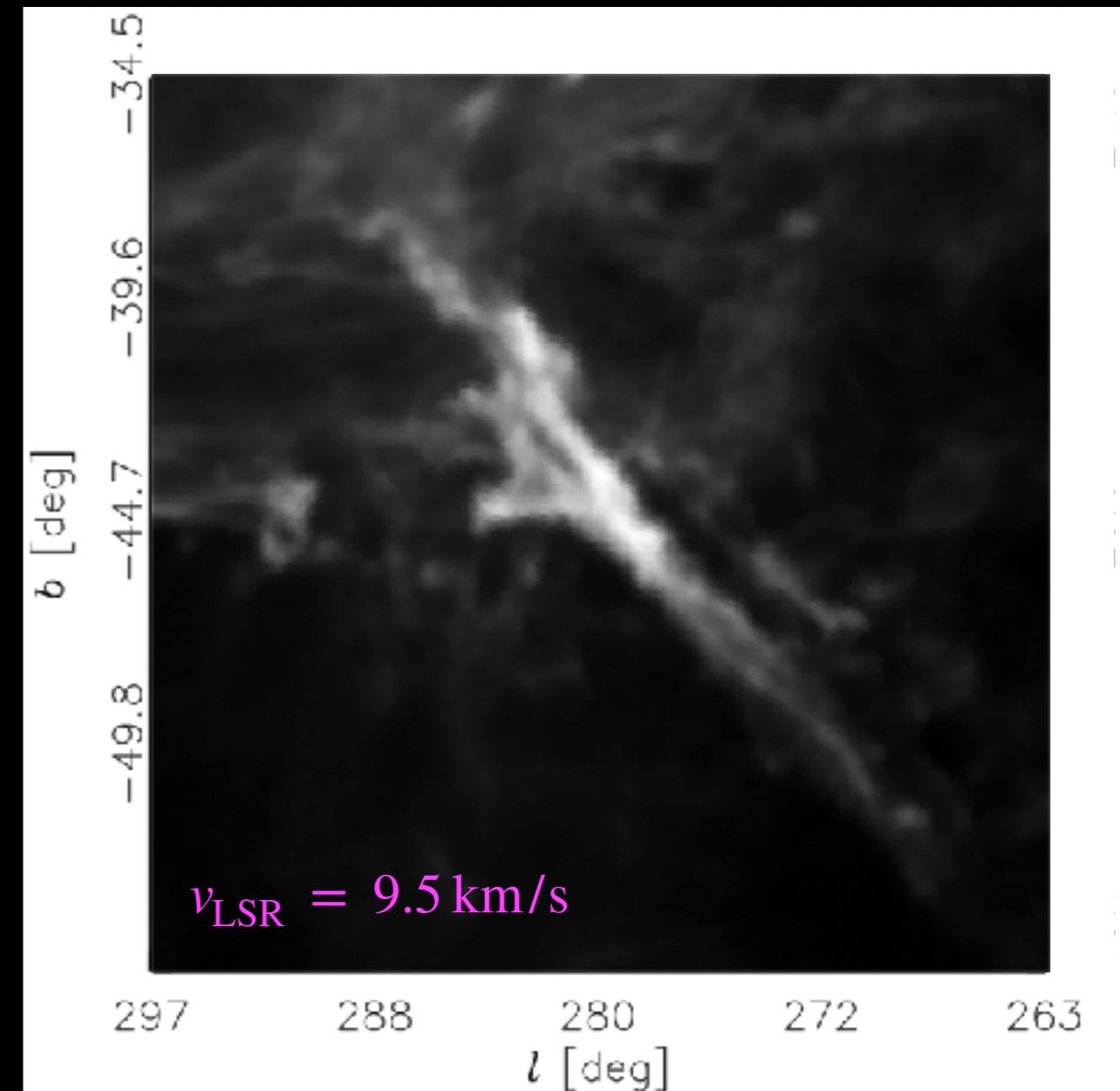
Soler, Miville-Deschénes, Santos et al. In prep.



Dust

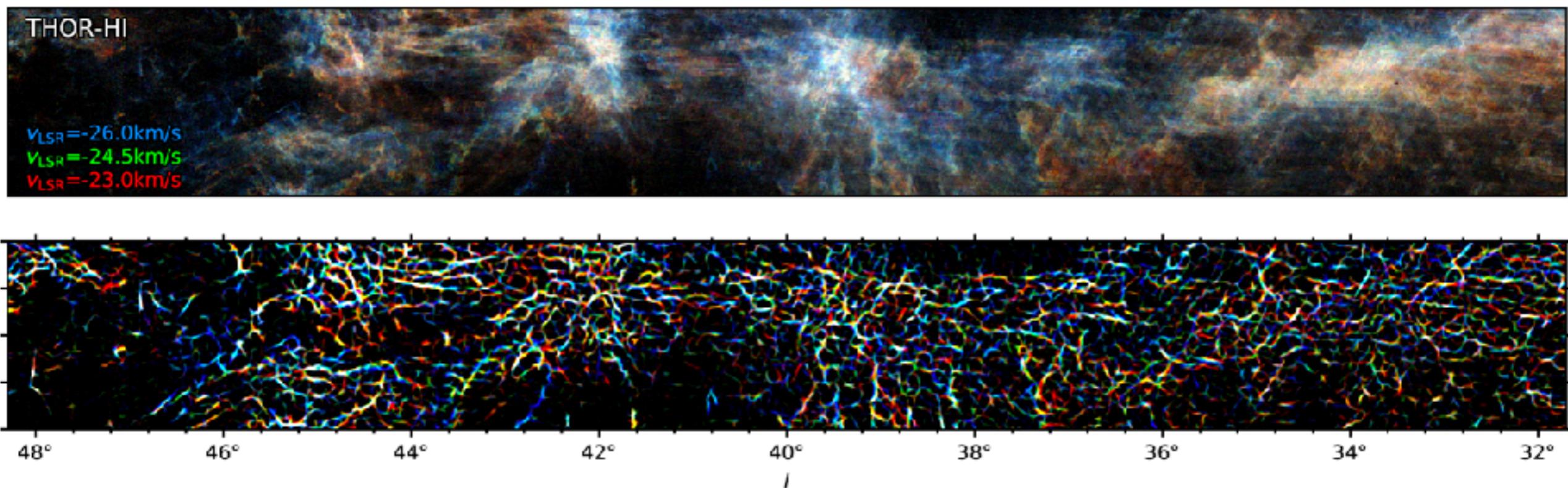


HI



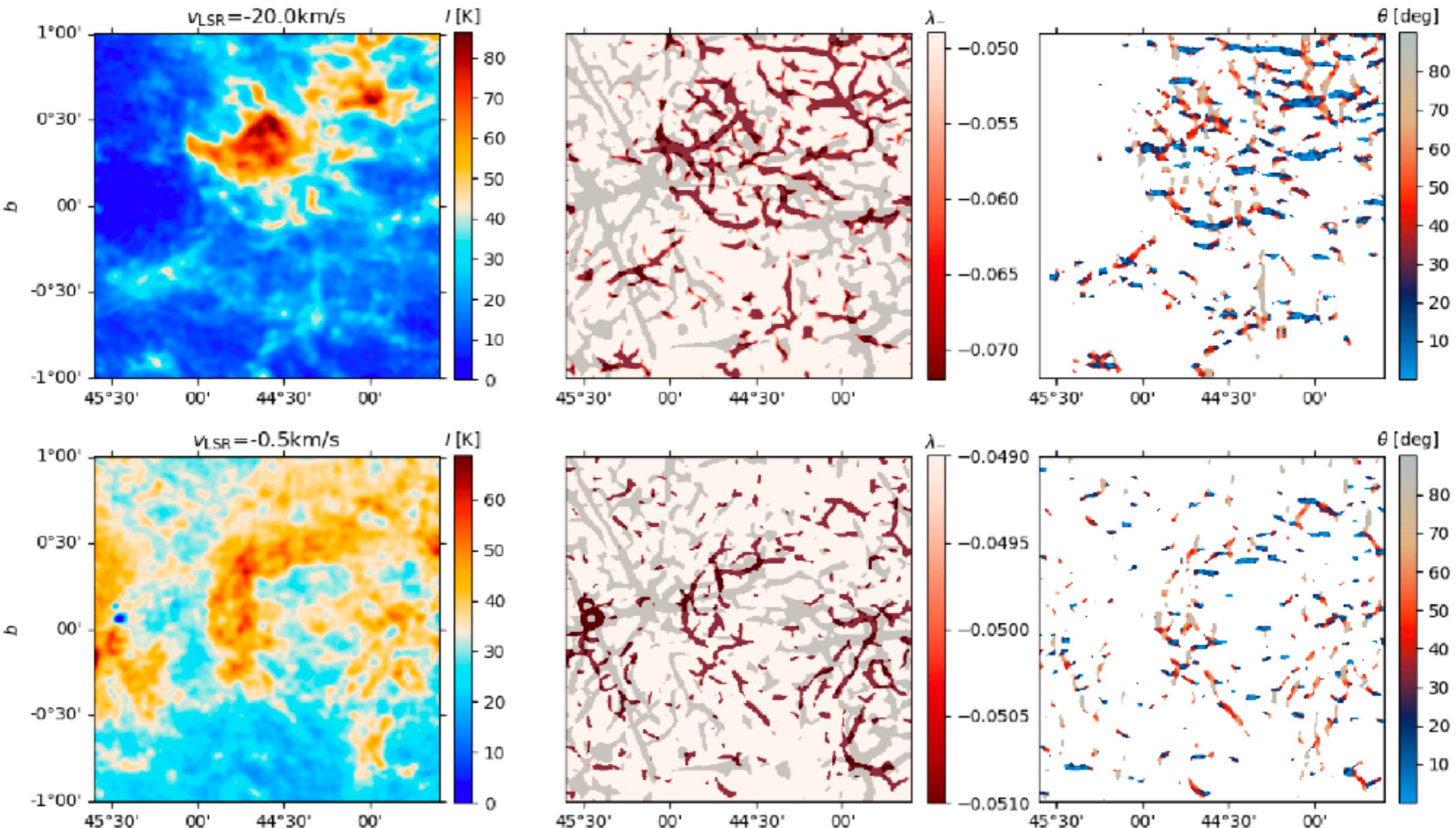
E. HI mapping ISM dynamics

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



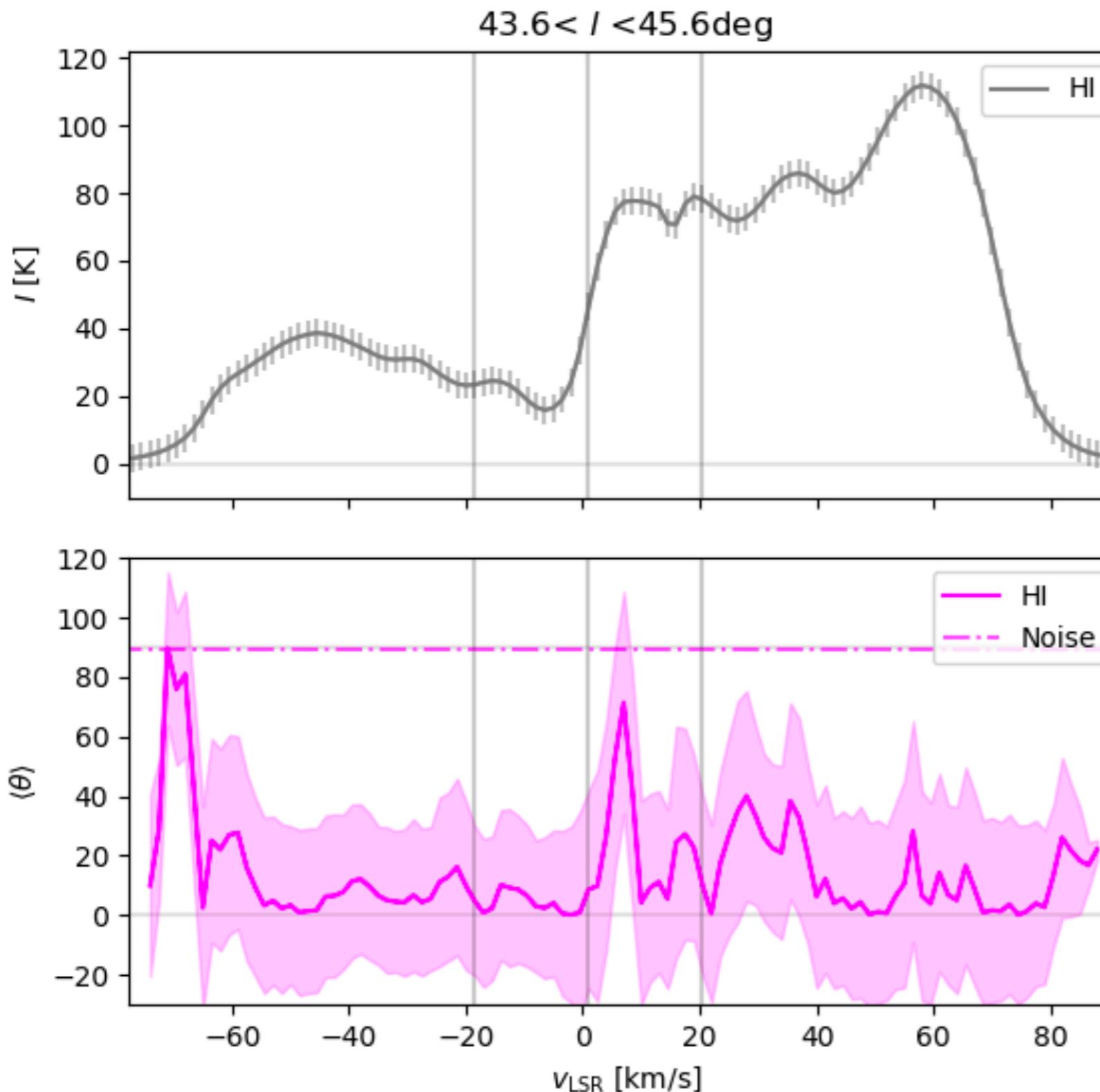
E. HI mapping ISM dynamics

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



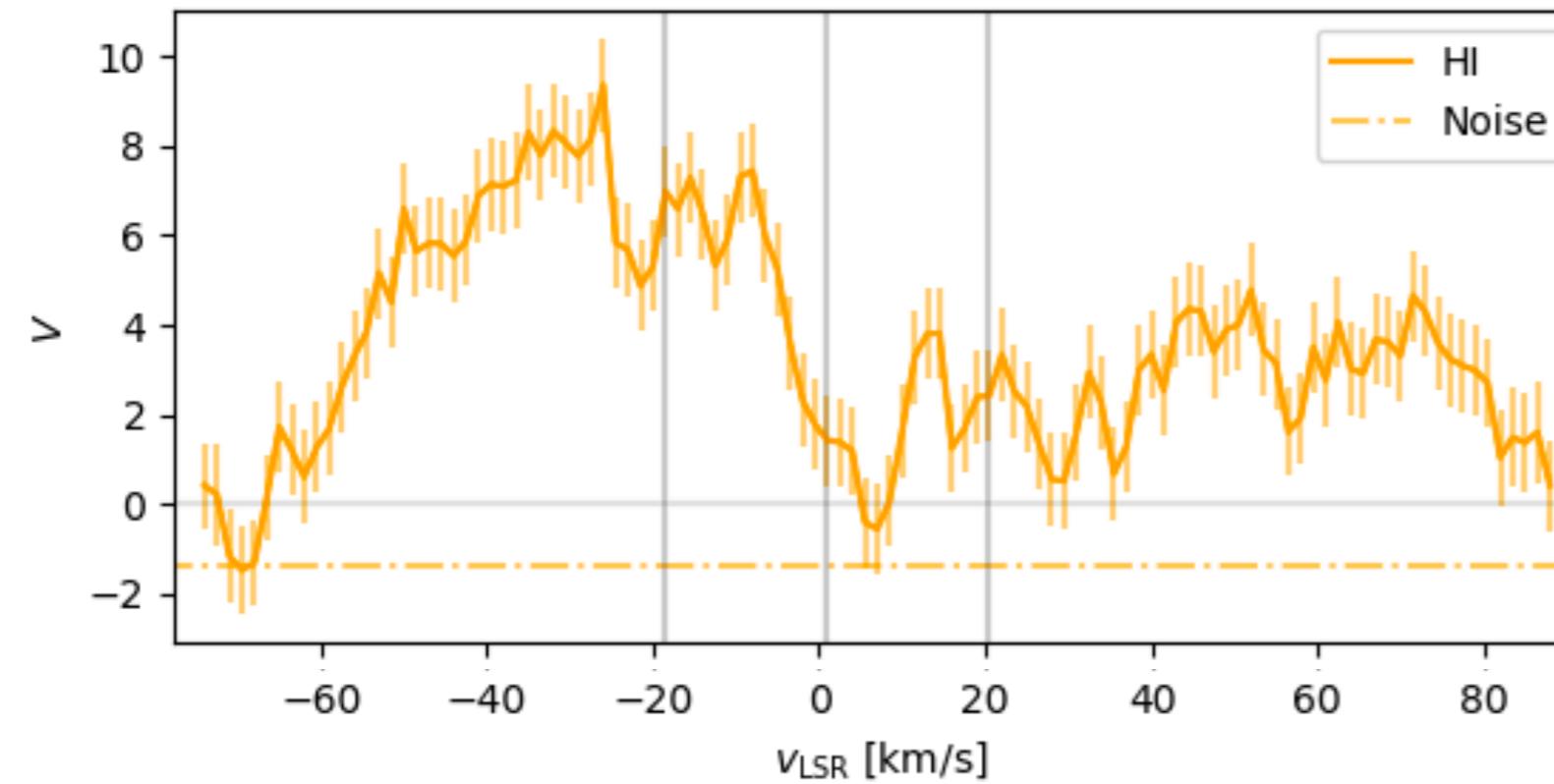
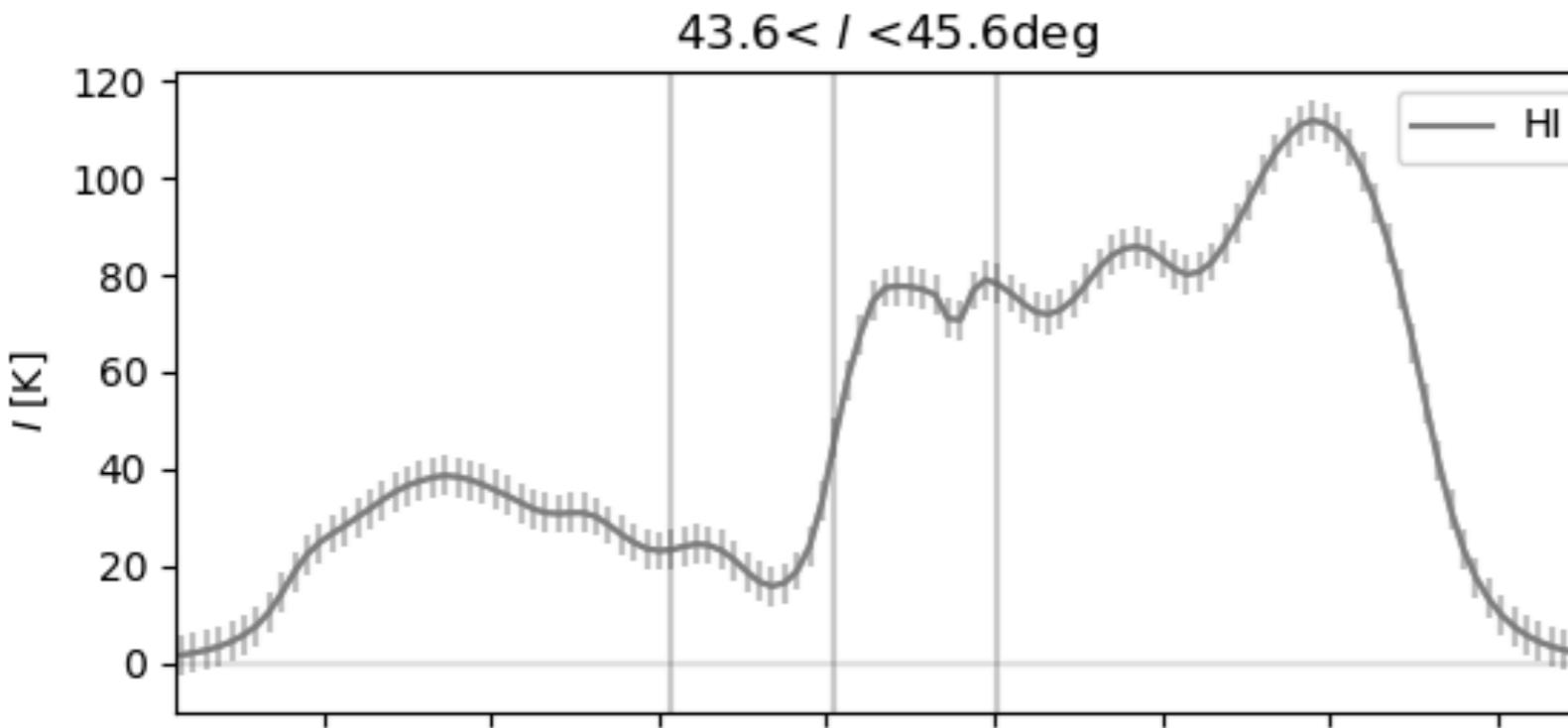
E. HI mapping ISM dynamics

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



E. HI mapping ISM dynamics

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

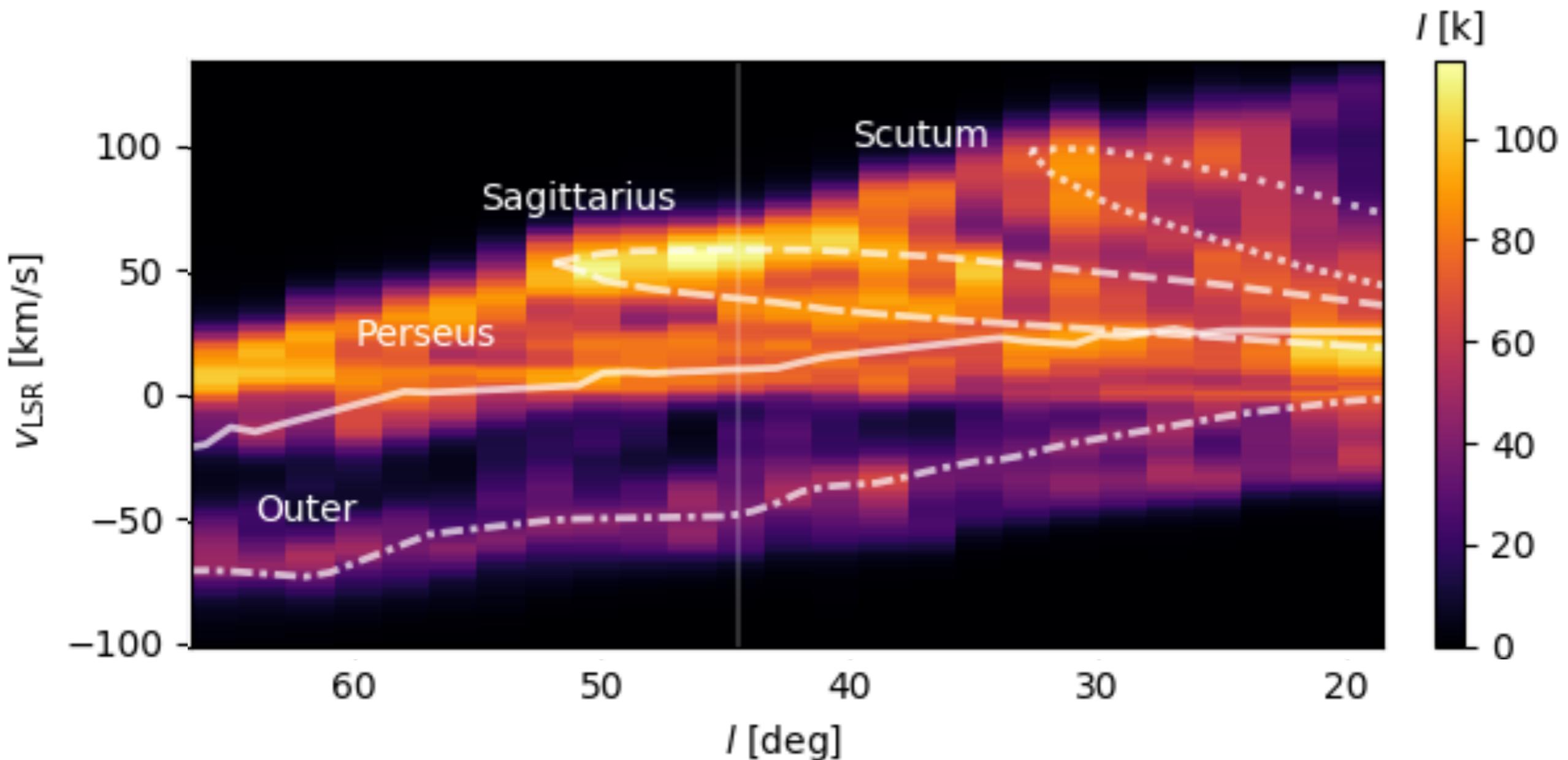


Projected Rayleigh statistic
(Jow et al. 2018)

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

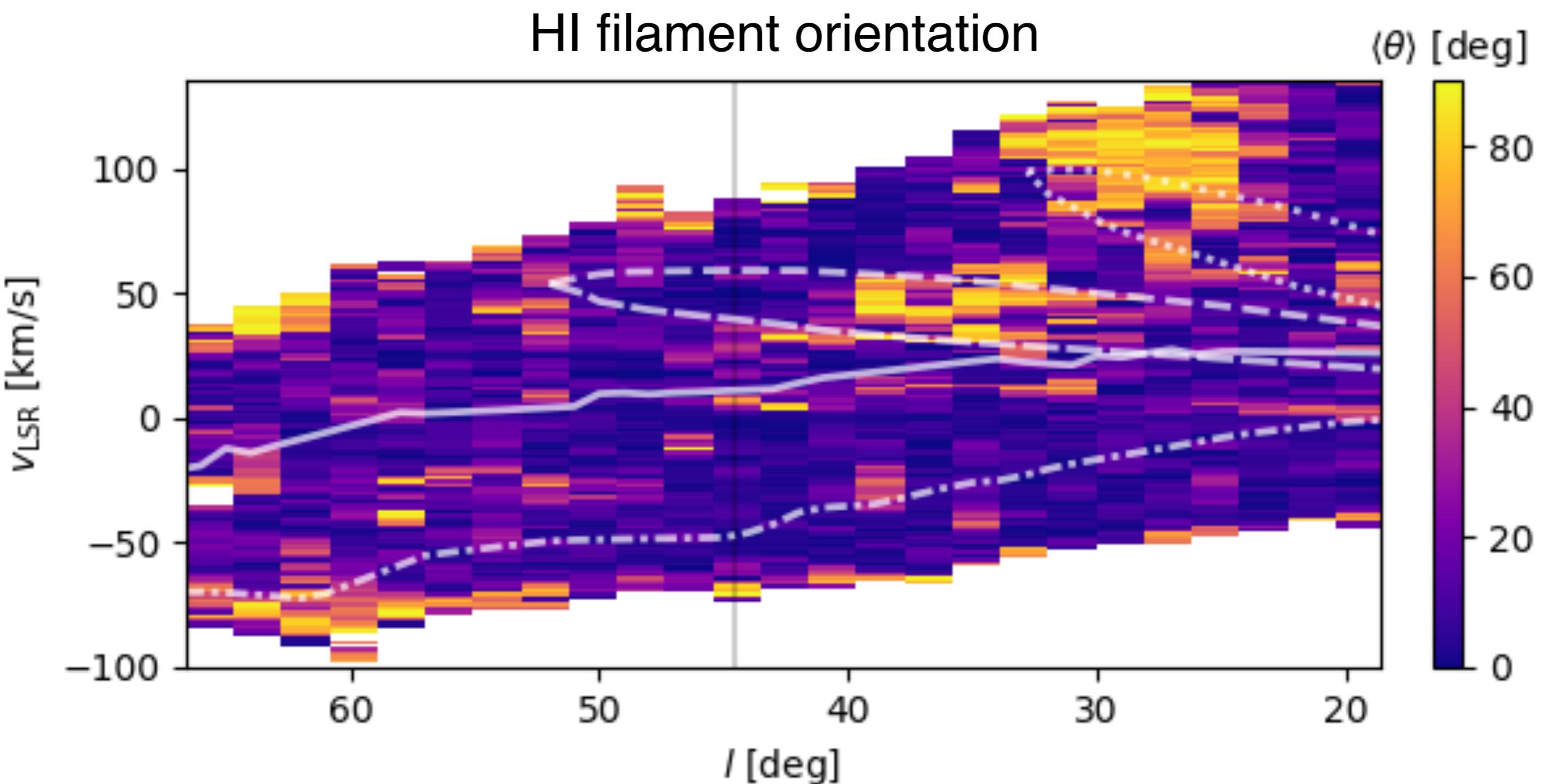
E. HI mapping ISM dynamics

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



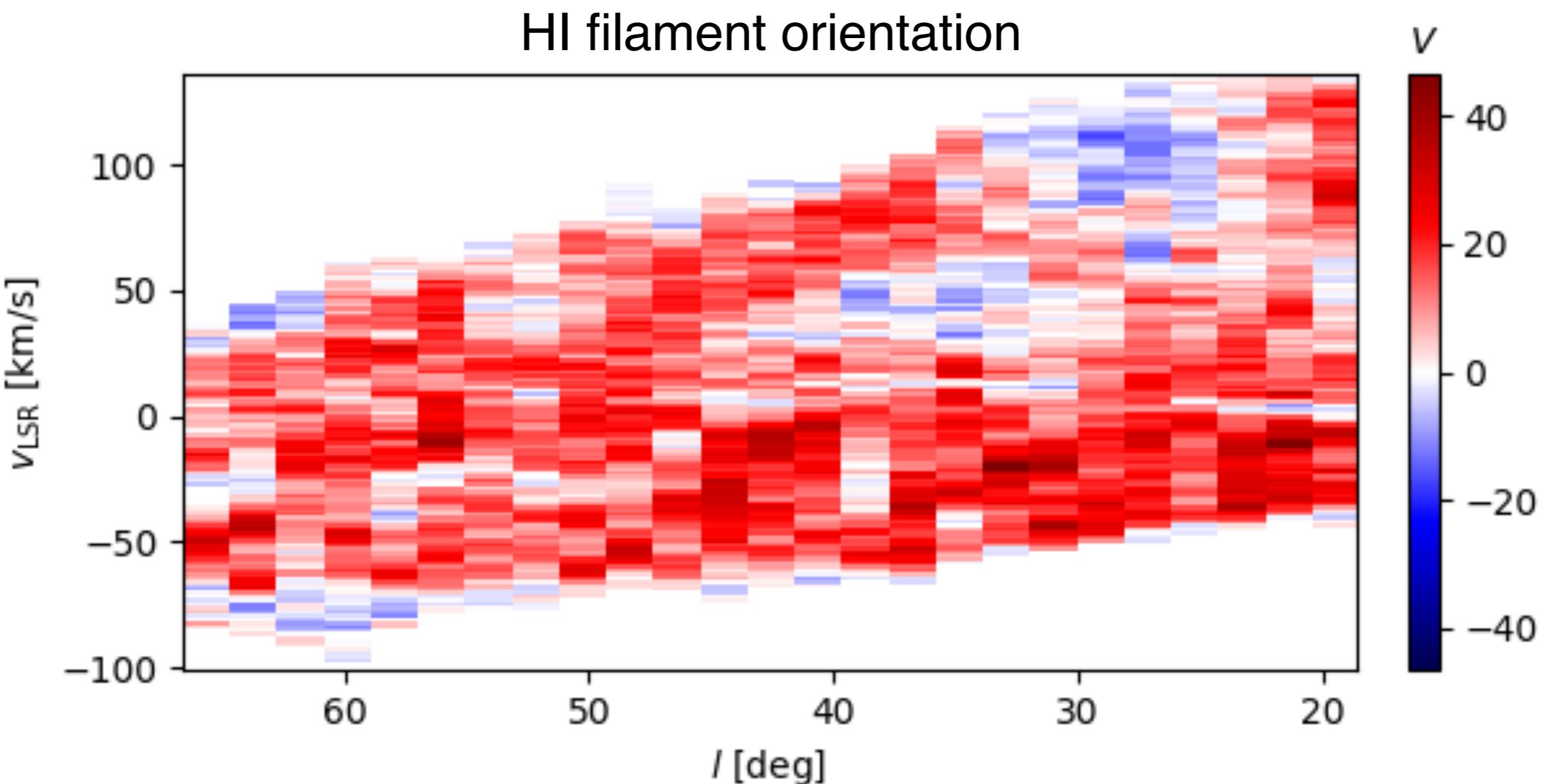
E. HI mapping ISM dynamics

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



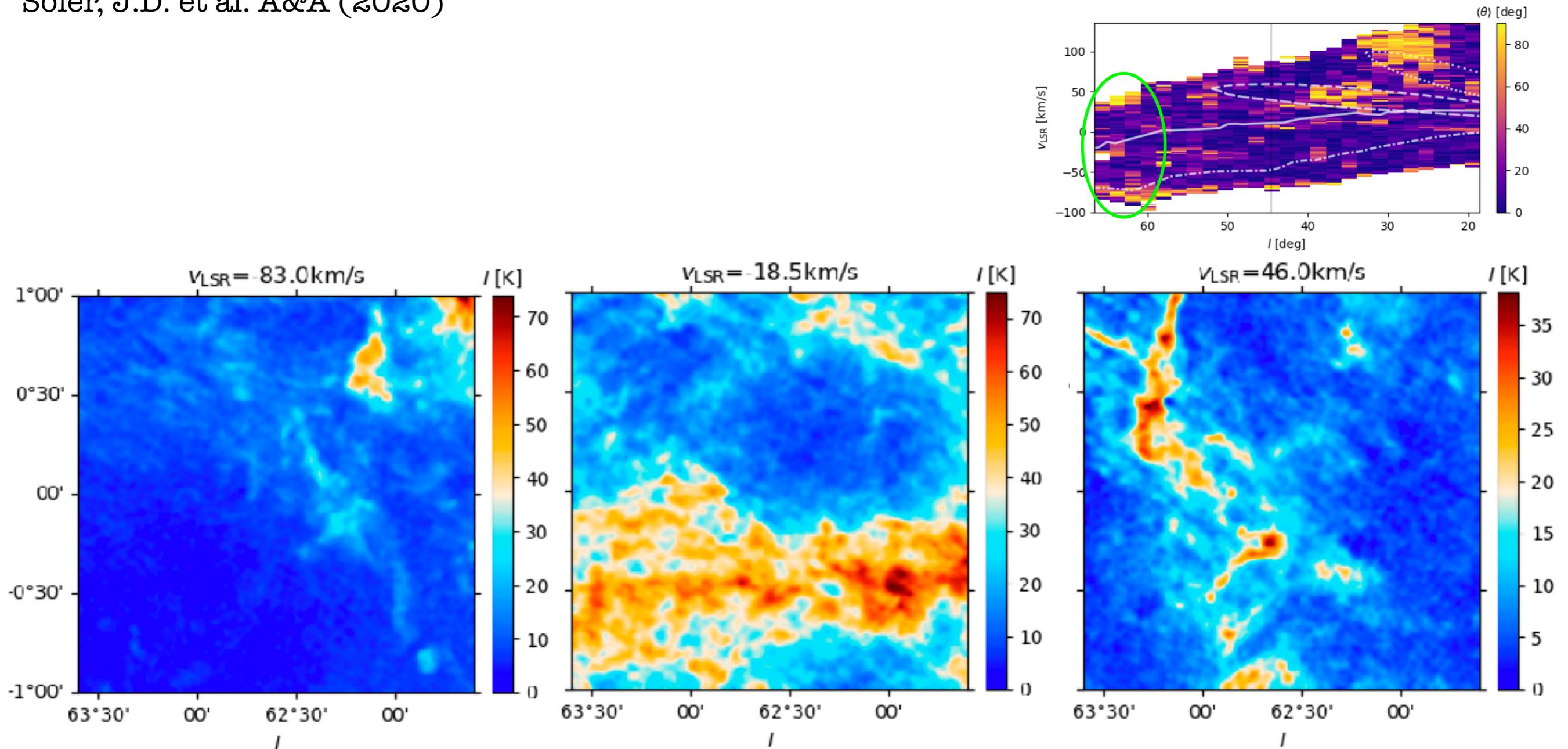
E. HI mapping ISM dynamics

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



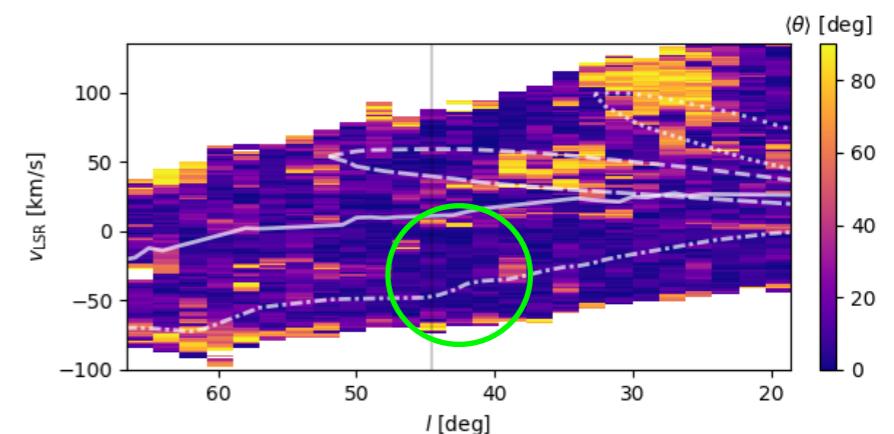
E. HI mapping ISM dynamics

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

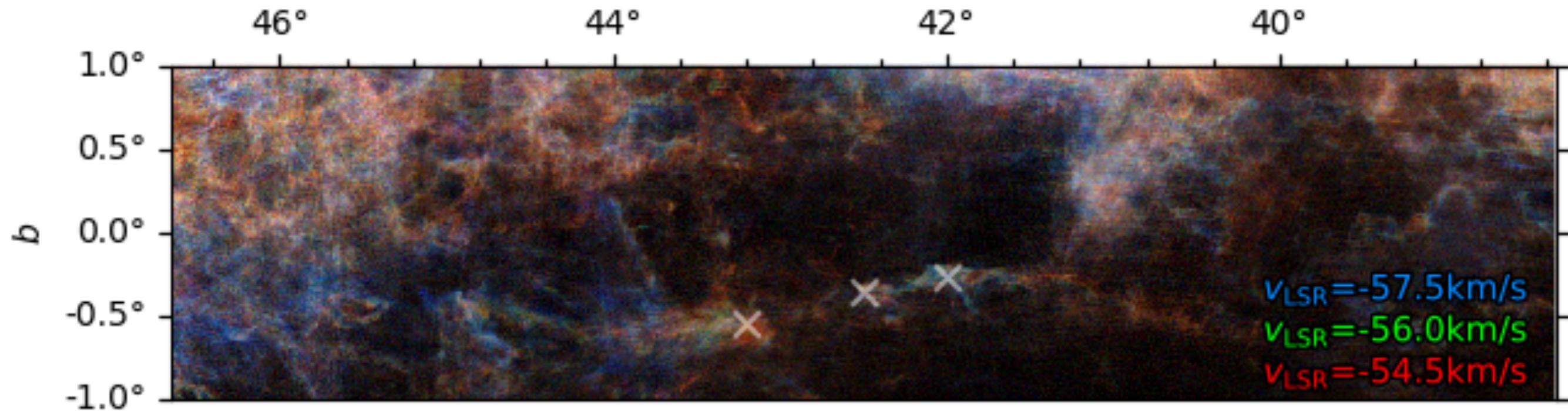


E. HI mapping ISM dynamics

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



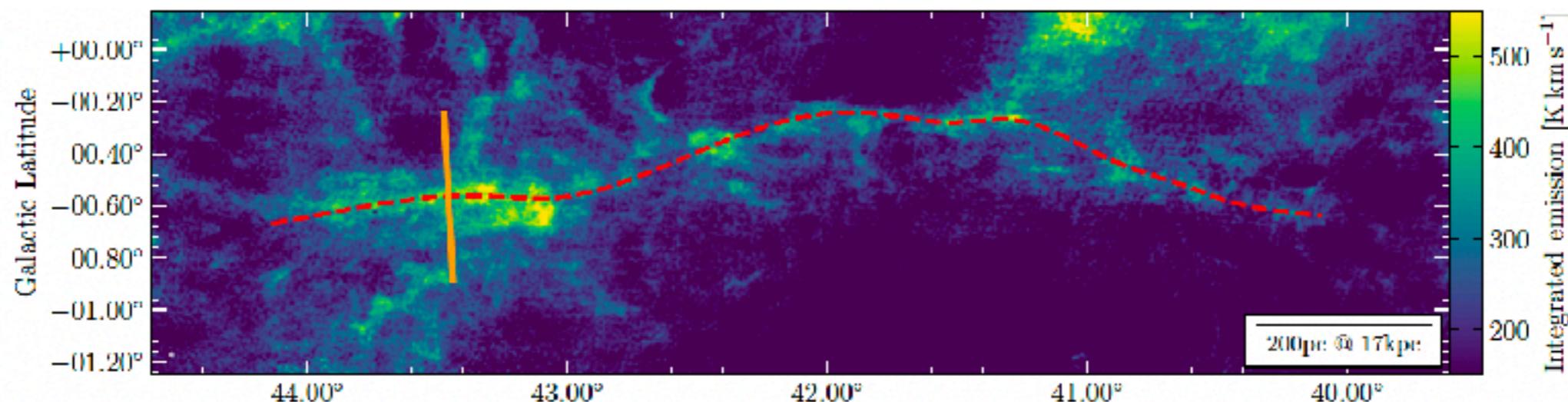
Magdalena filament



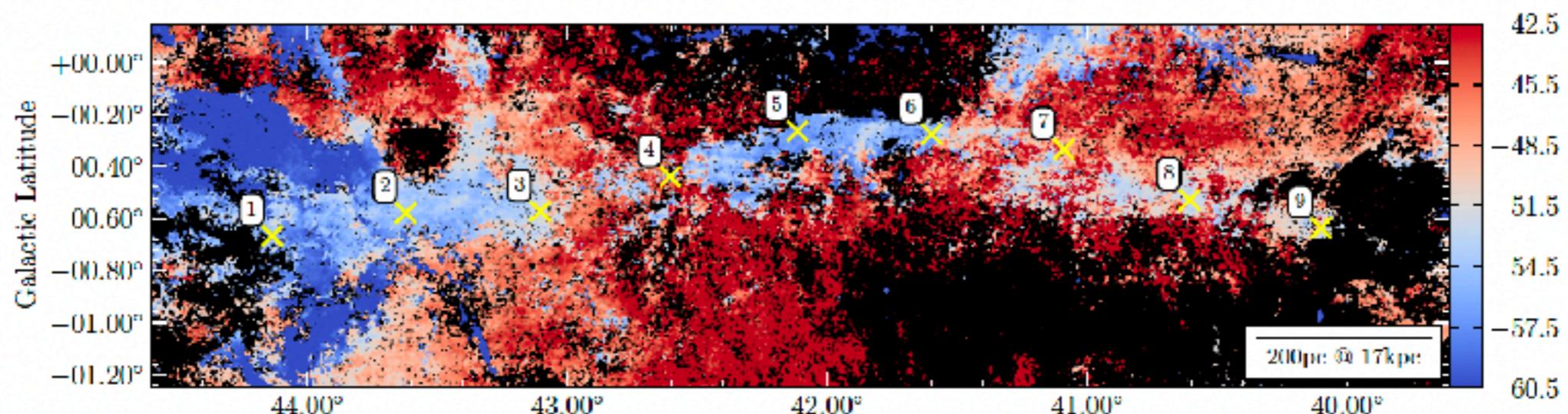
E. HI mapping ISM dynamics

Syed, J., et al. A&A (2022)

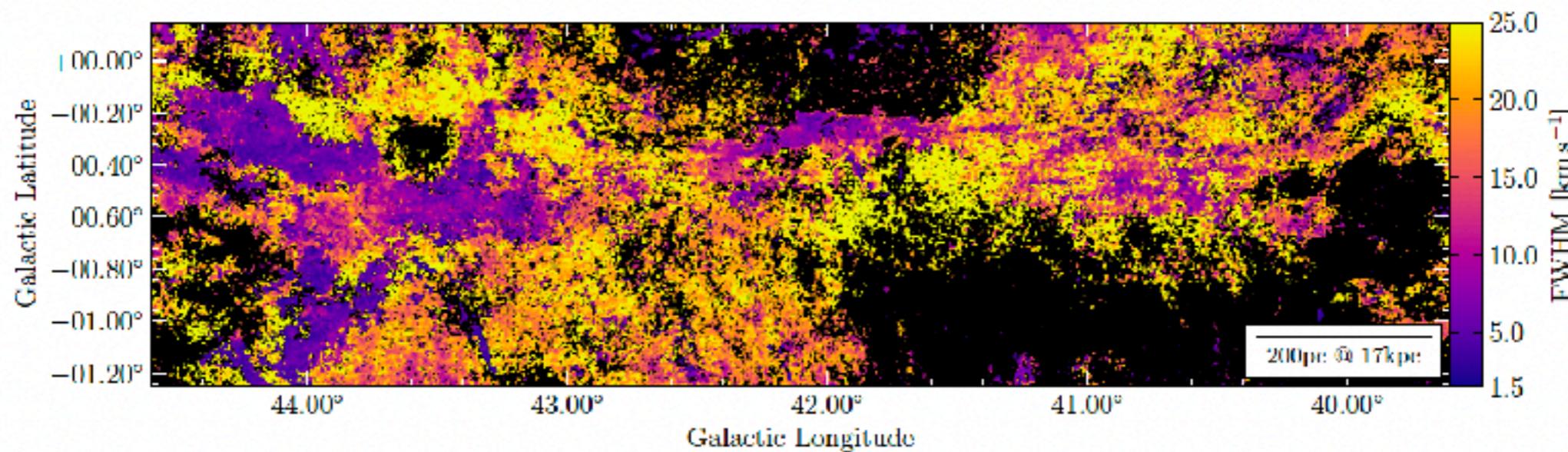
N_{H}



$\langle v \rangle$



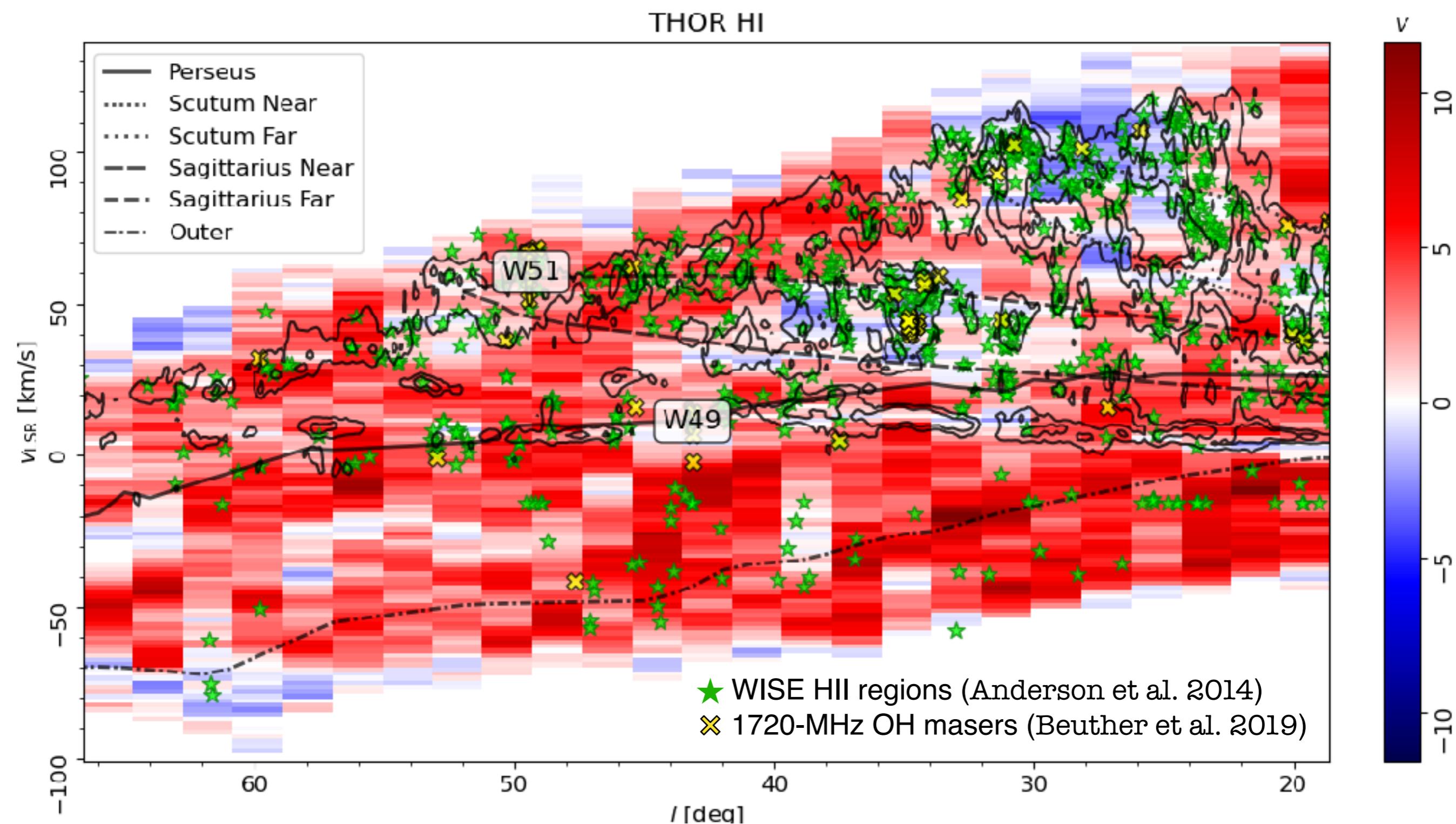
σ_v



E. HI mapping ISM dynamics

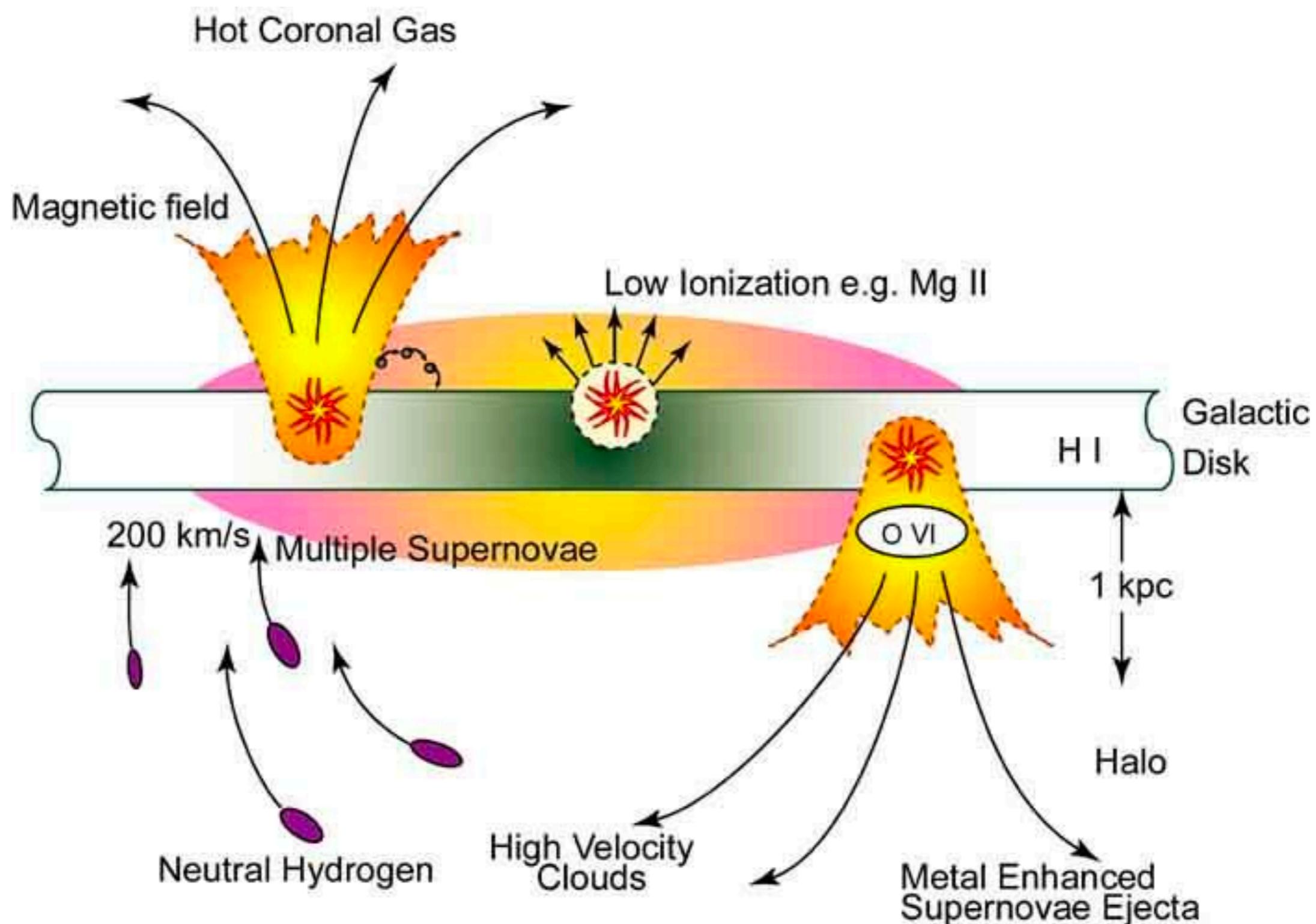
Soler, J.D. et al. A&A (2020)

THOR-HI
40" FWHM
 $\Delta v = 1.5 \text{ km/s}$



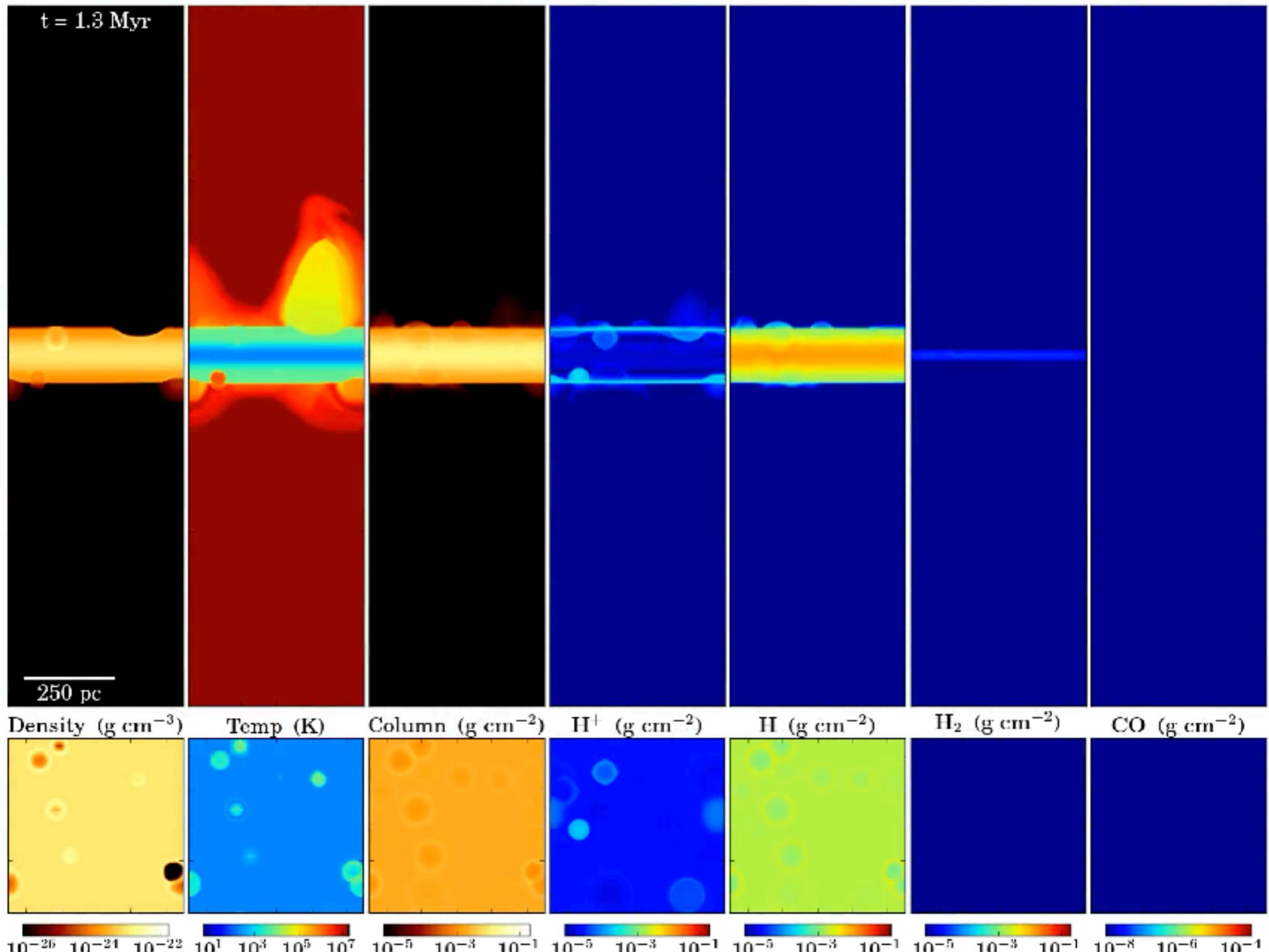
E. HI mapping ISM dynamics

Heiles, 1994



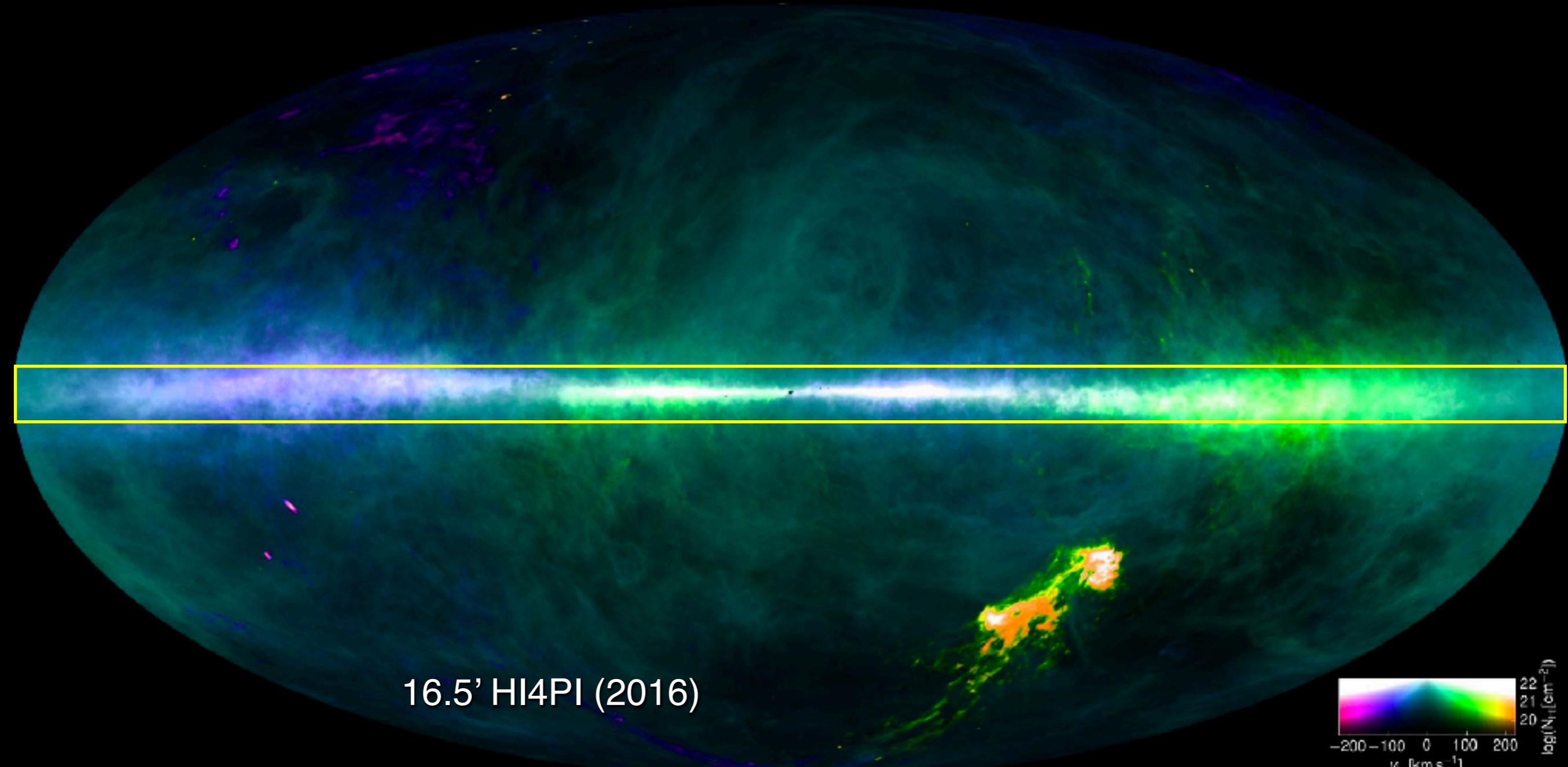
E. HI mapping ISM dynamics

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

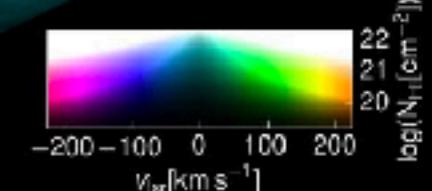


Atomic hydrogen emission

HI4PI Collaboration. A&A (2016)



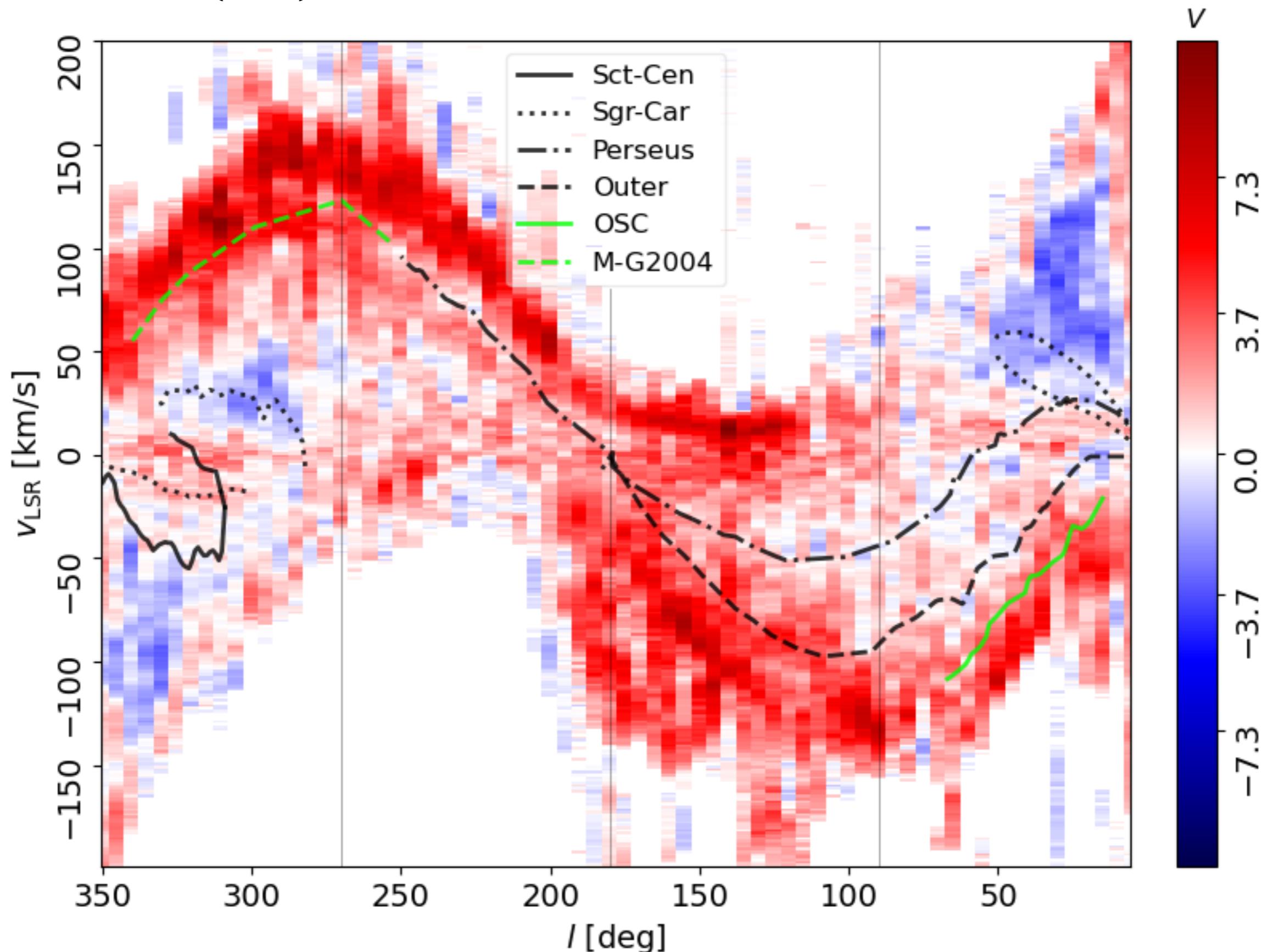
16.5' HI4PI (2016)



Benjamin Winkel & HI4PI Collaboration

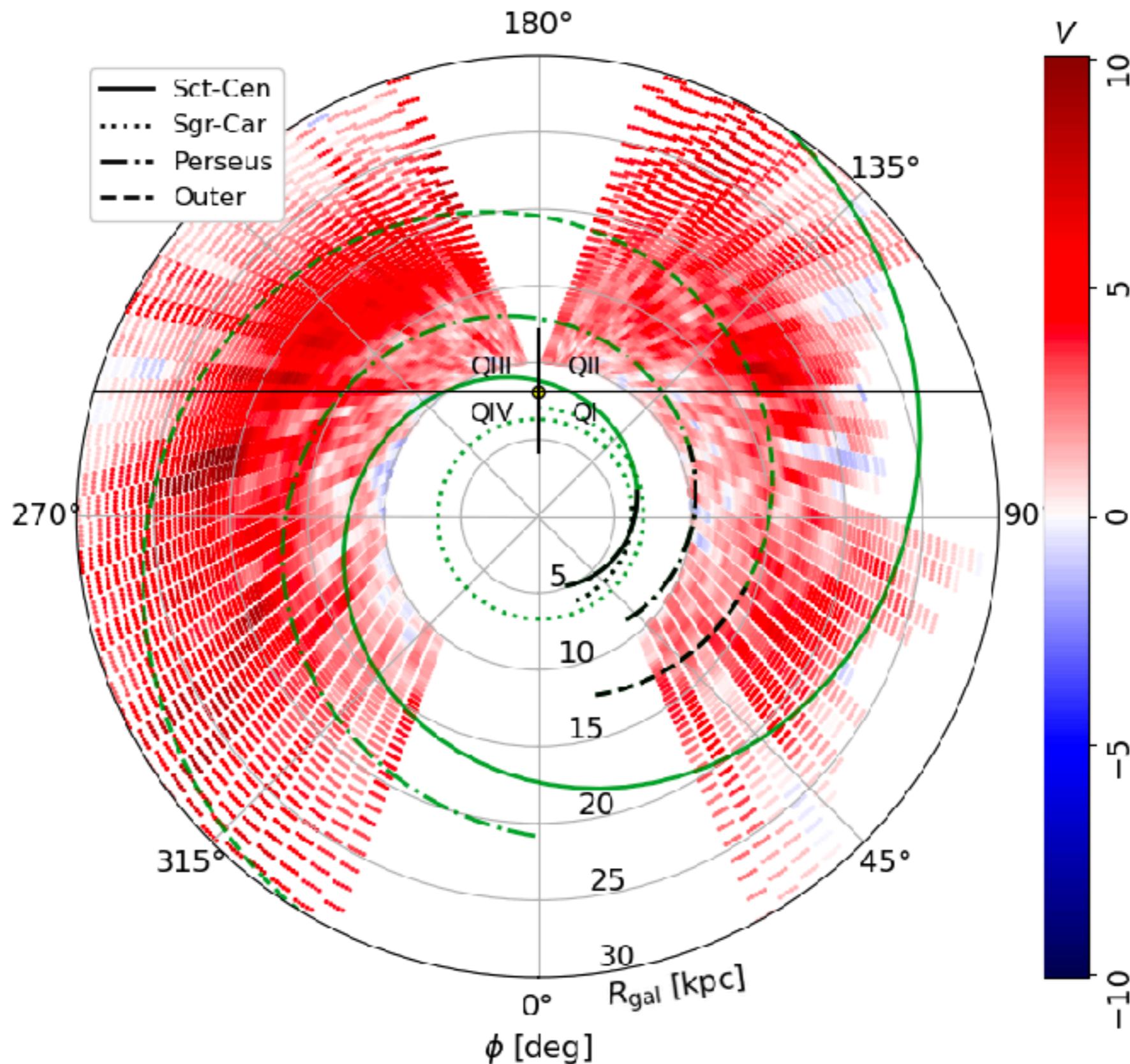
E. HI mapping ISM dynamics

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



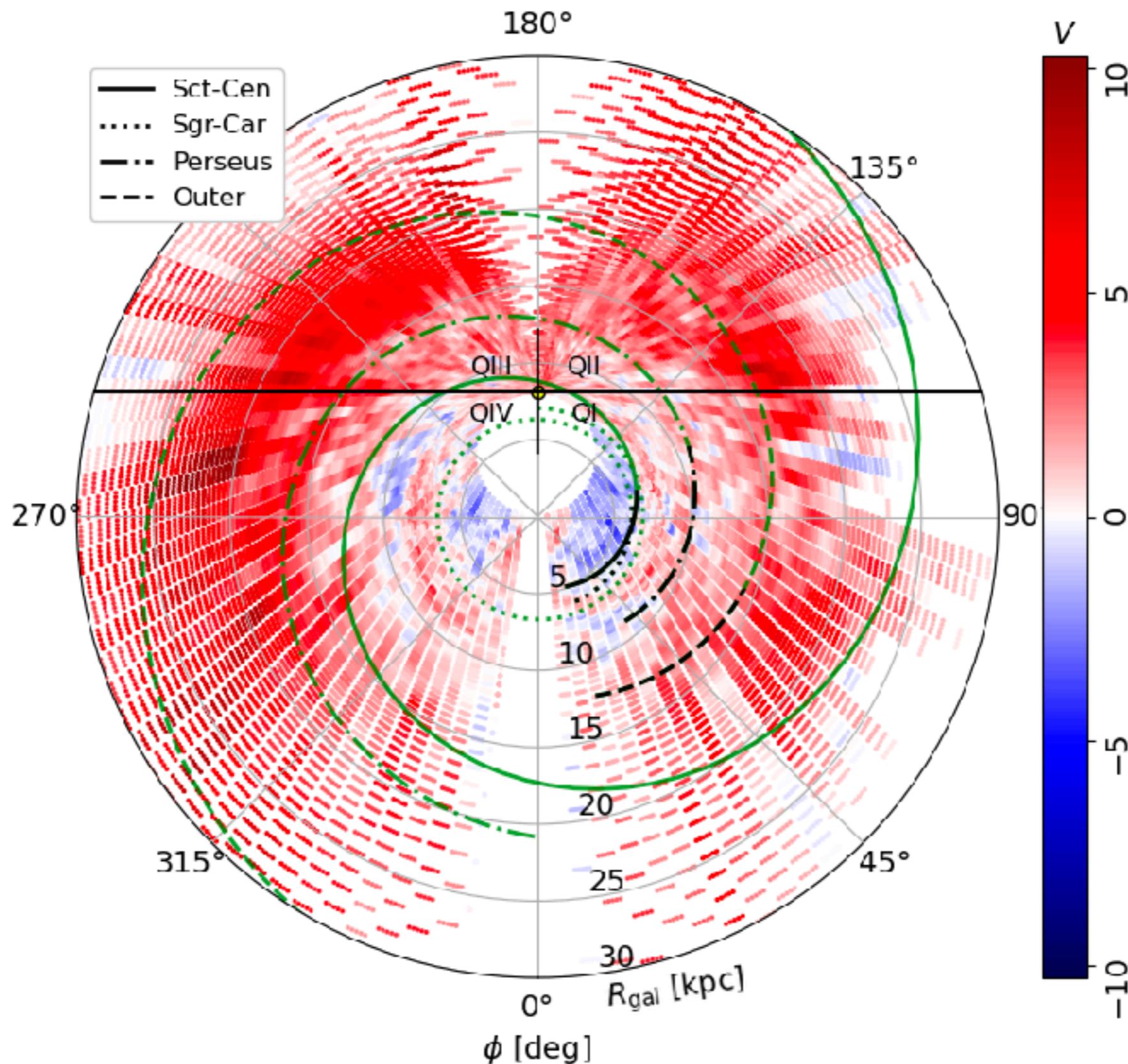
E. HI mapping ISM dynamics

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



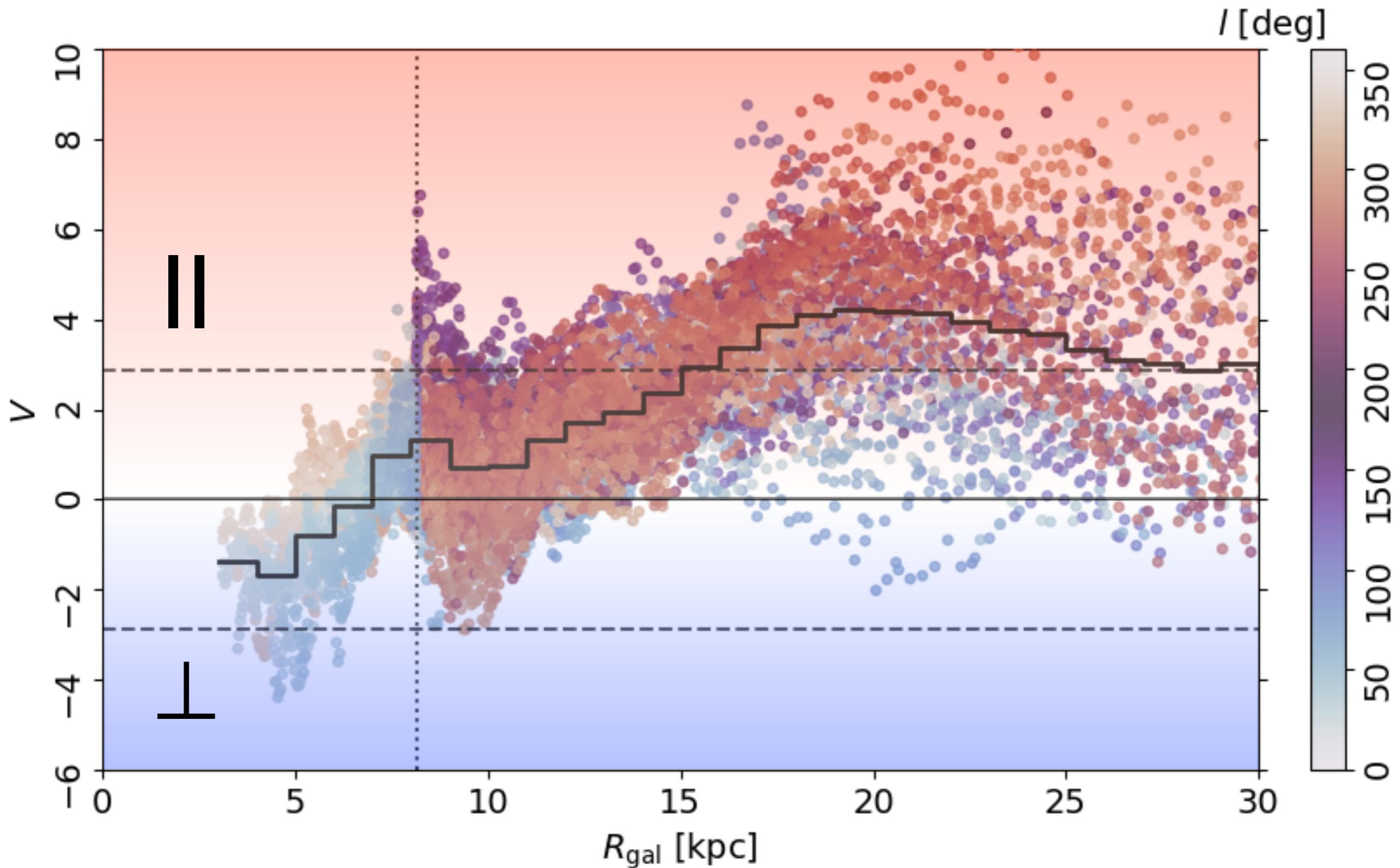
E. HI mapping ISM dynamics

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



E. HI mapping ISM dynamics

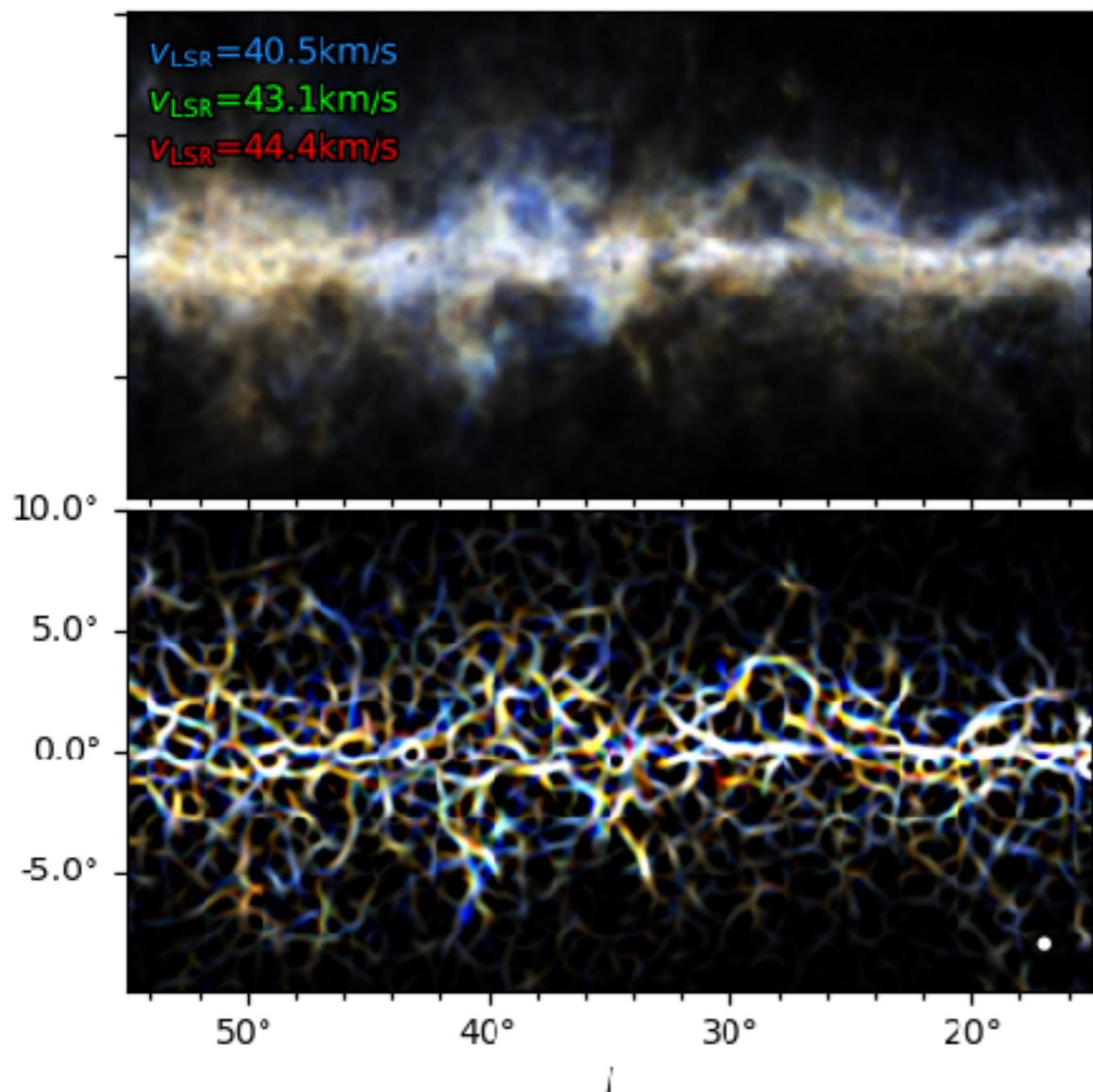
Soler, J.D. et al. A&A (2022)



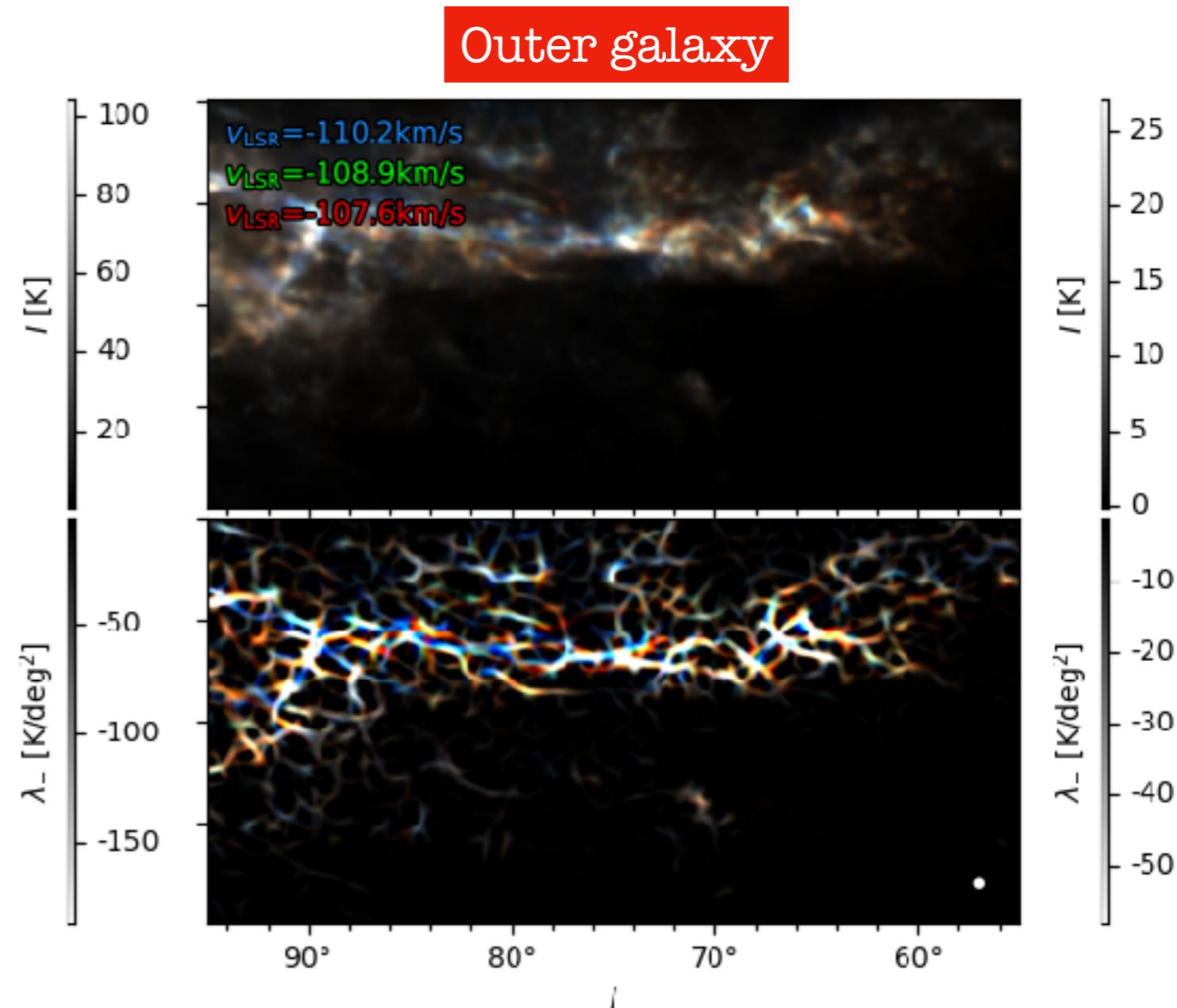
E. HI mapping ISM dynamics

Soler, J.D. et al. 2022.

Inner galaxy

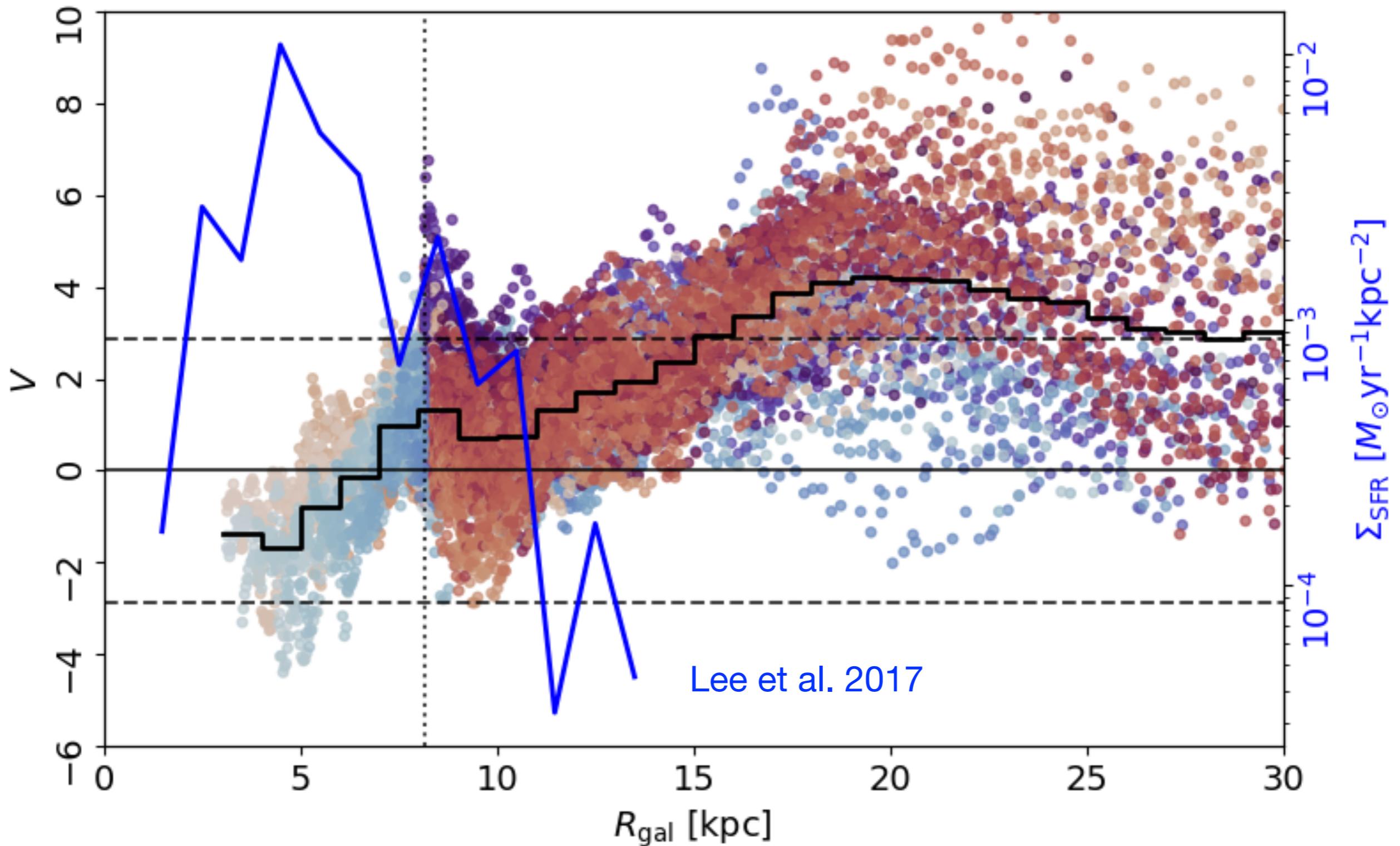


Outer galaxy



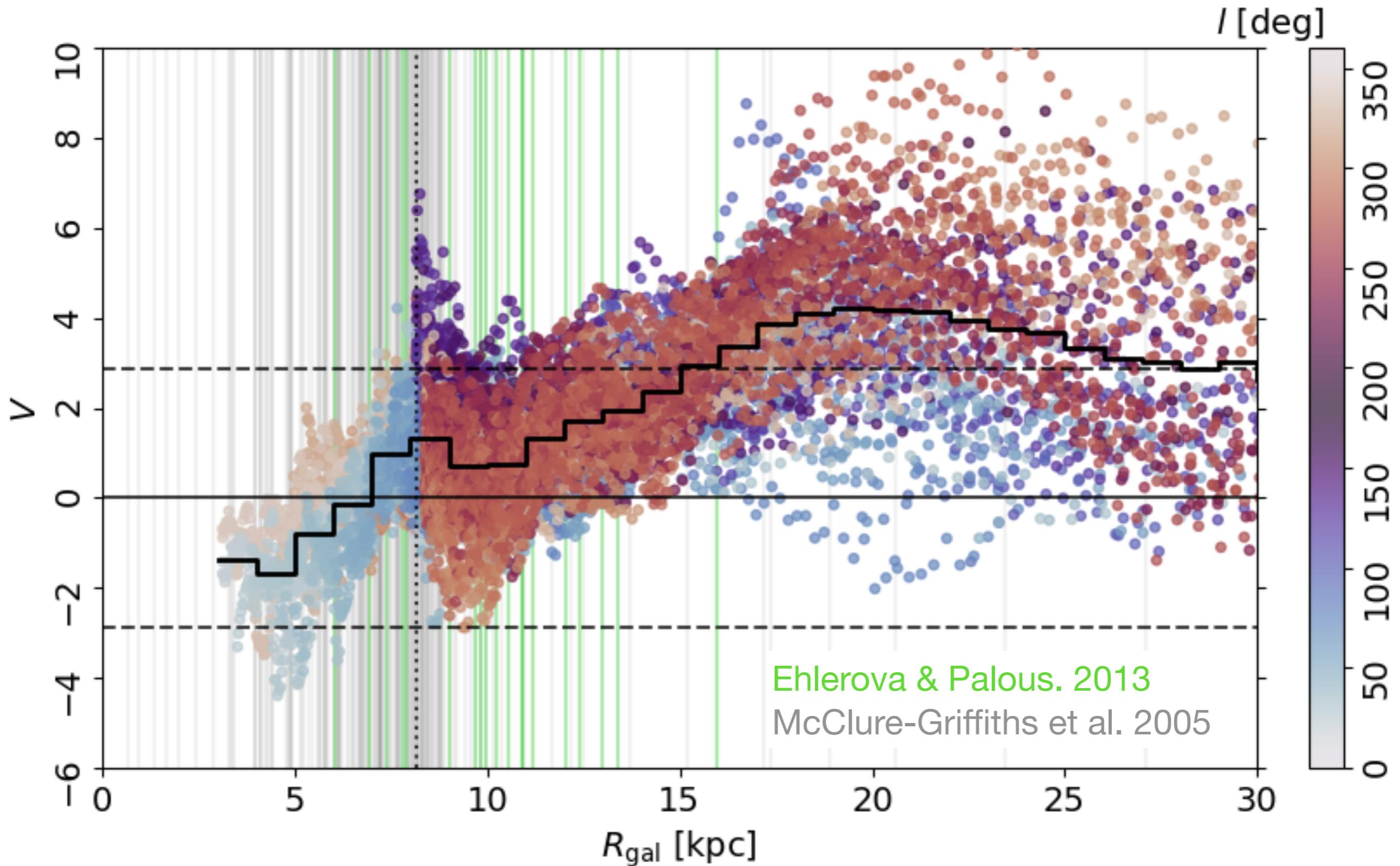
E. HI mapping ISM dynamics

Soler, J.D. et al. 2022.



E. HI mapping ISM dynamics

Soler, J.D. et al. 2022.



Mapping the Milky Way with HI

- A. Spiral arm structure
- B. Galactic warp
- C. Galactic flaring
- D. Shells and supershells
- E. Multiphase ISM structure
- F. ISM dynamics

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