Kinetic tomography of the Galactic disk

Local ISM motions using 3D dust, line emission, and machine vision

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In collaboration with
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G. Edenhofer, E. Zari, C. Swiggum, & C. Zucker

Soler et al. A&A (2025)

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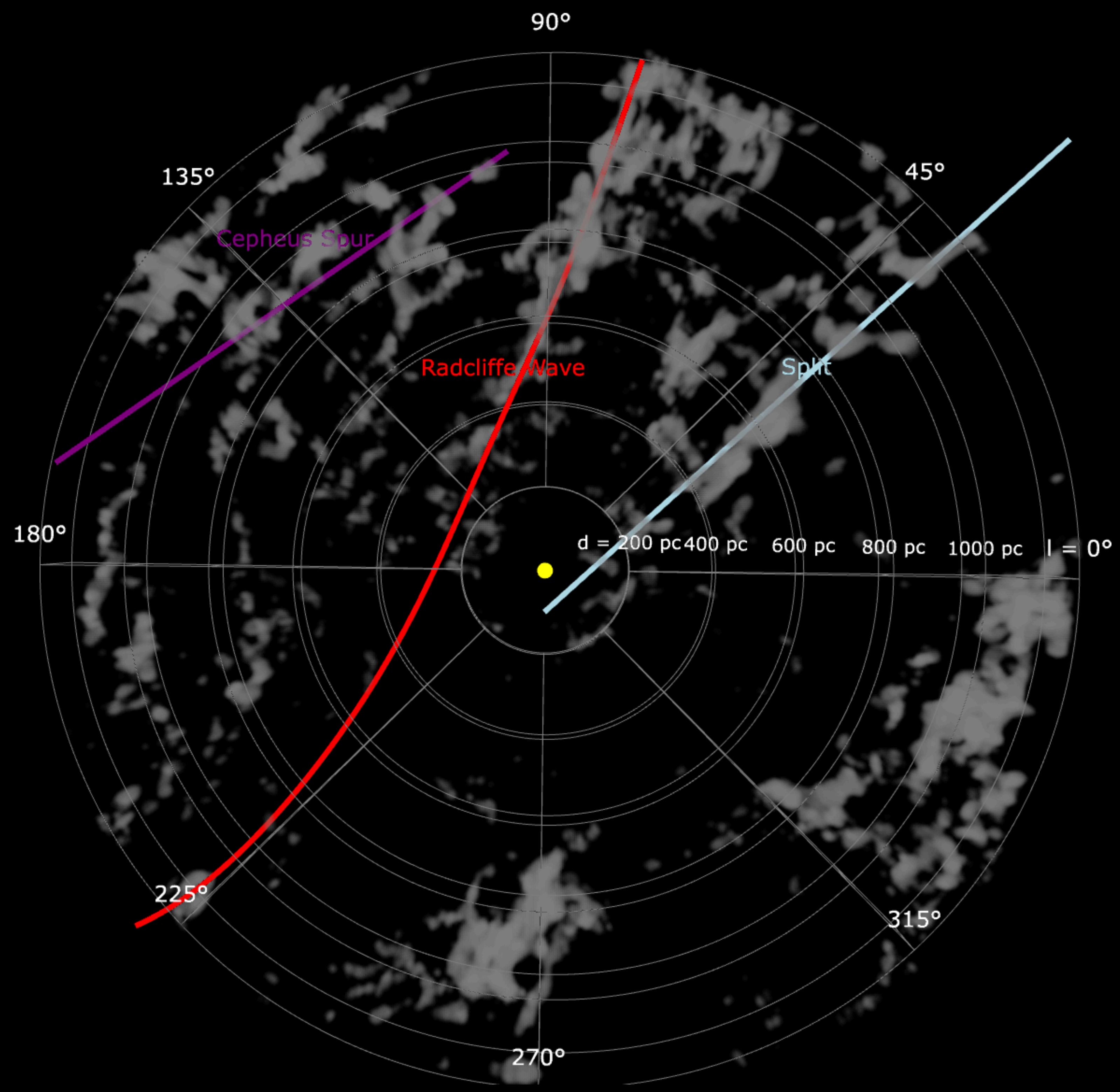
Soler et al. A&A (2025)

Galactic 3D dust map out to 1.25 kpc from the Sun

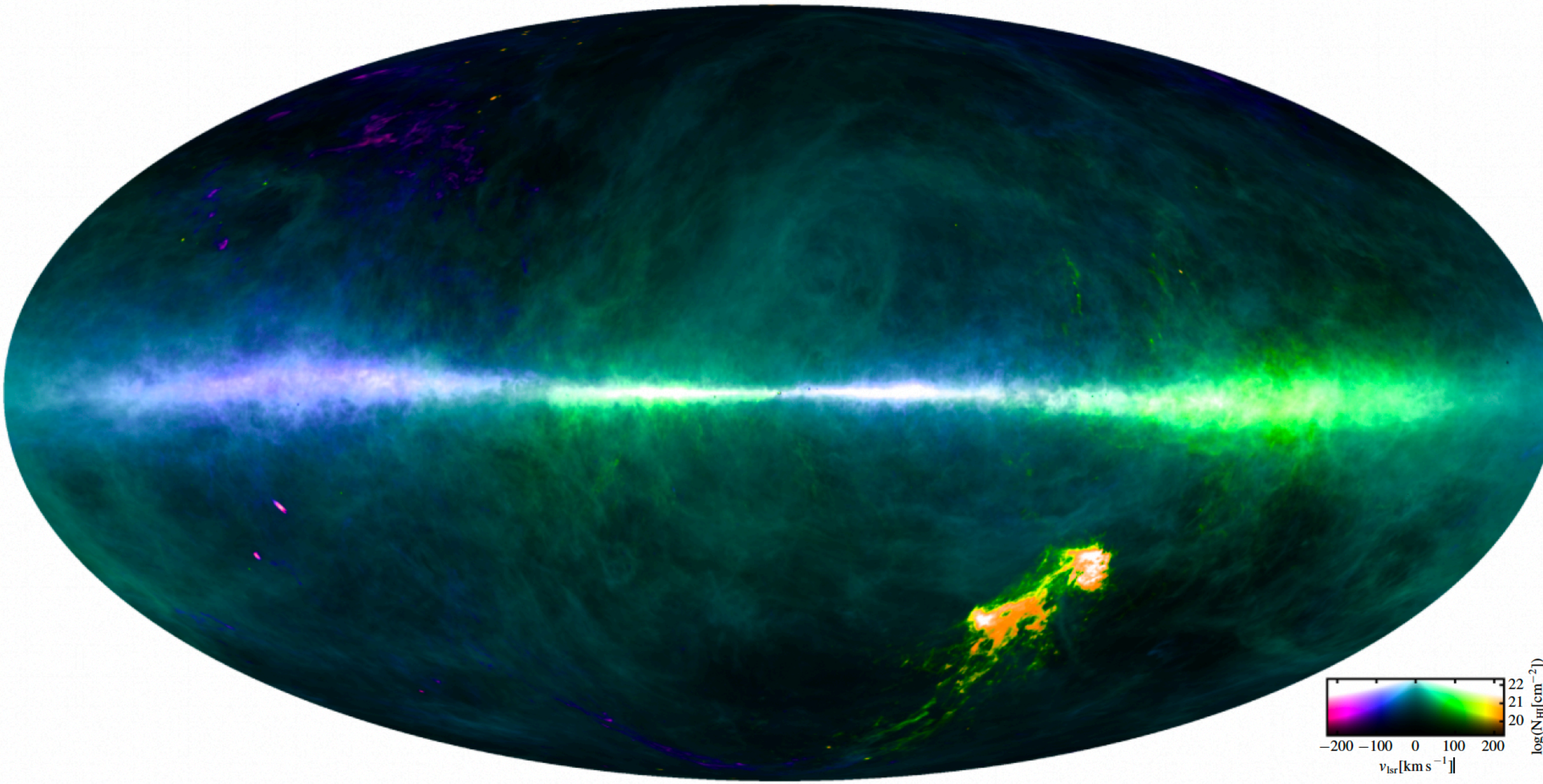
Edenhofer et al. (2024)



Neutral atomic hydrogen (HI) emission

$\theta \approx 16.2'$

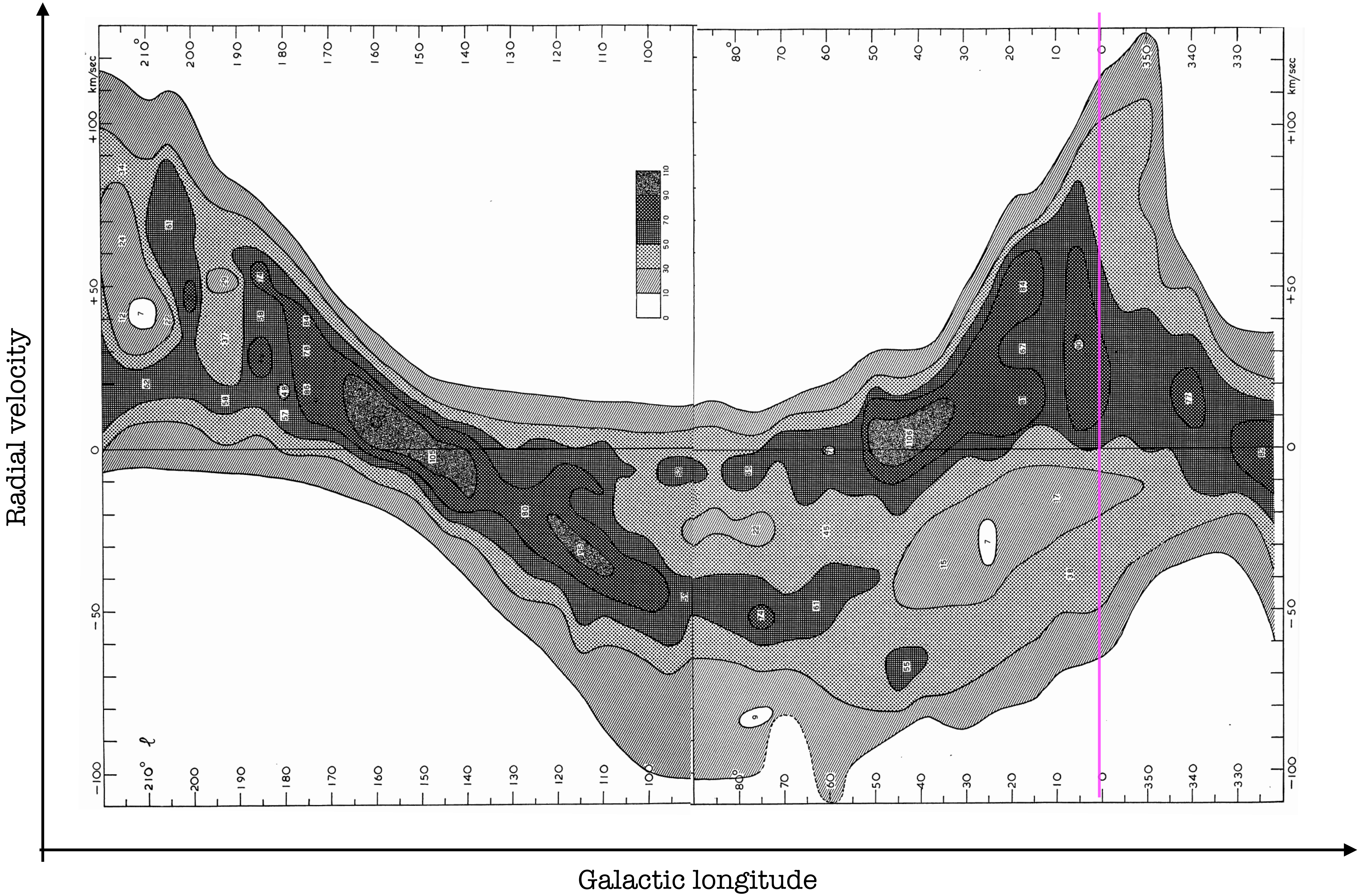
HI4PI Collaboration. A&A (2016)



HI emission toward the Milky Way

$\theta \approx 2°$

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



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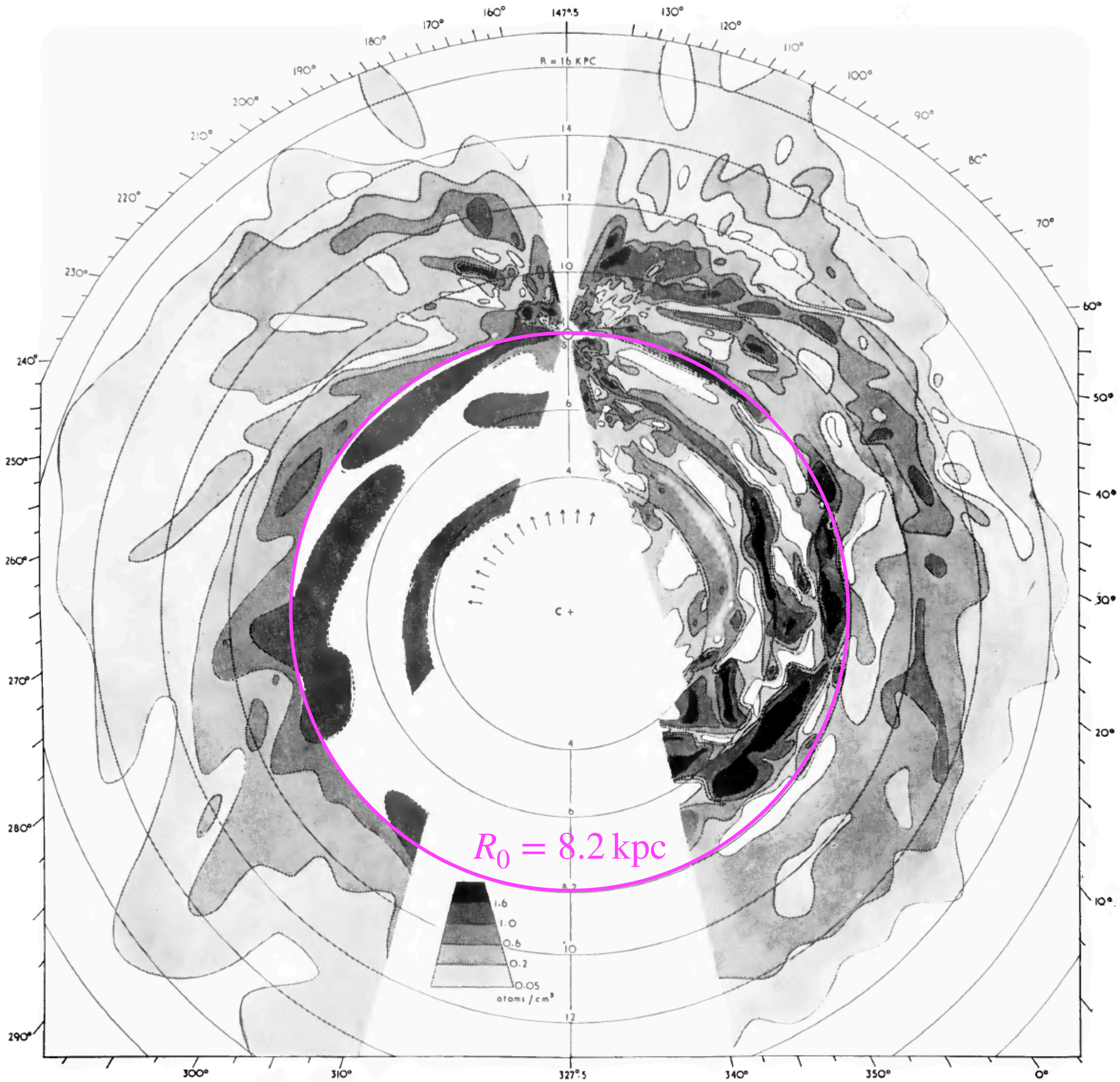
Soler et al. A&A (2025)

Face-on mapping of the Milky Way using HI

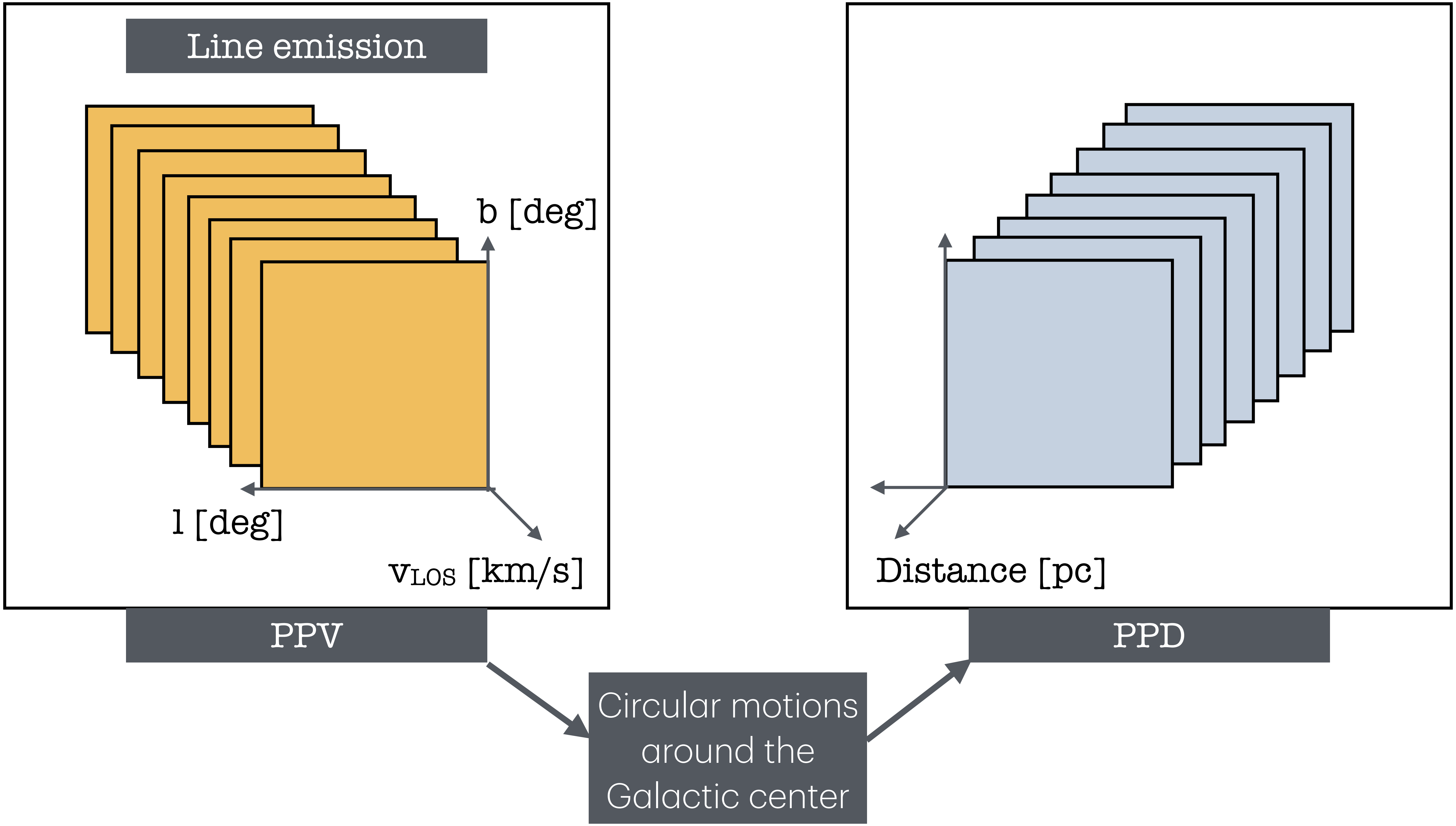
$\theta \approx 2^{\circ}$

Oort, Kerr & Westerhout. MNRAS (1958)



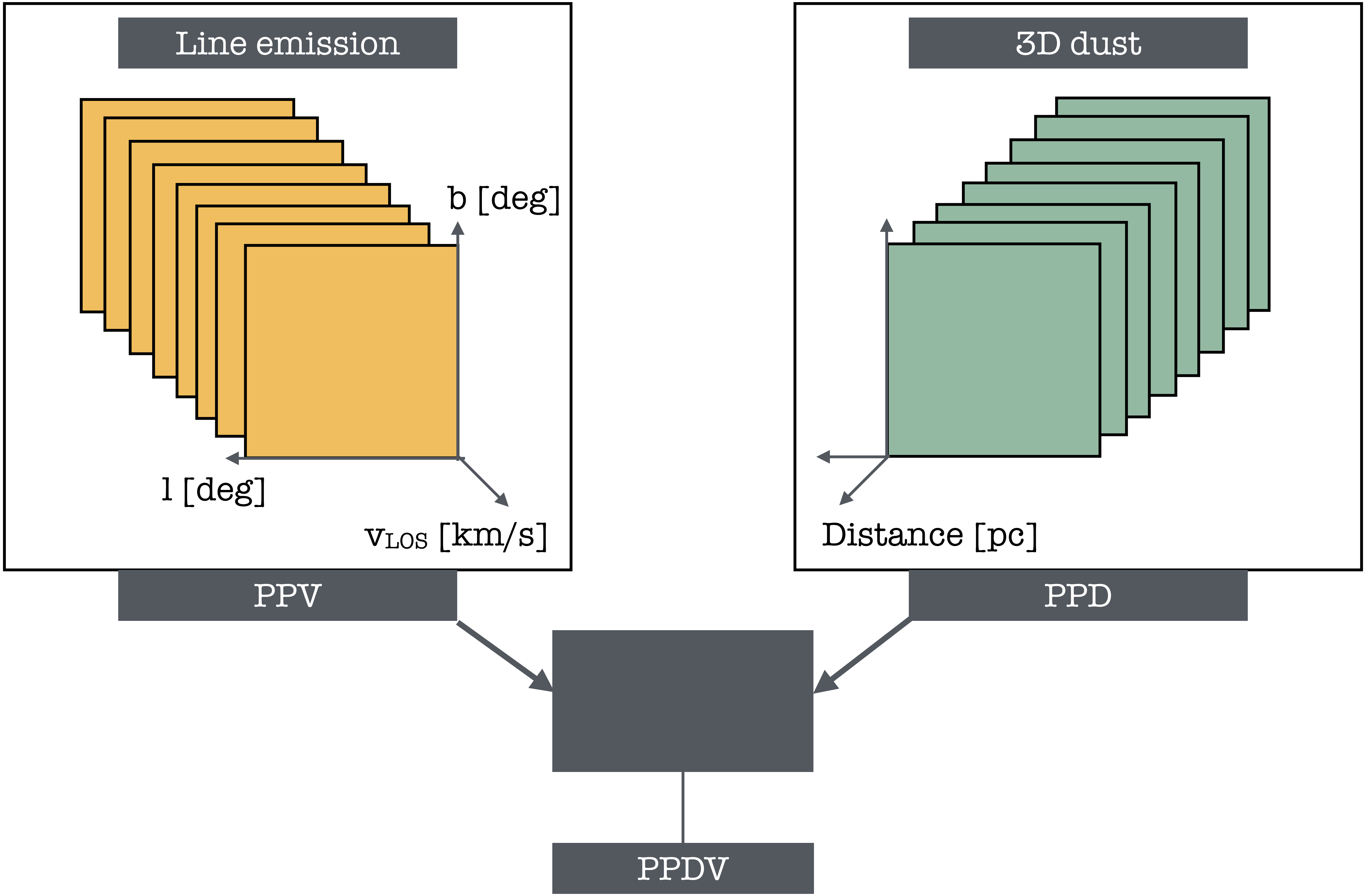
Face-on mapping of the Milky Way (kinematic distances)

Oort, Kerr & Westerhout. MNRAS (1958)



Kinetic tomography

Tchernyshyov & Peek. ApJ (2017)



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Soler et al. A&A (2025)

Histogram of oriented gradients (HOG)

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

Histogram of oriented gradients (HOG)

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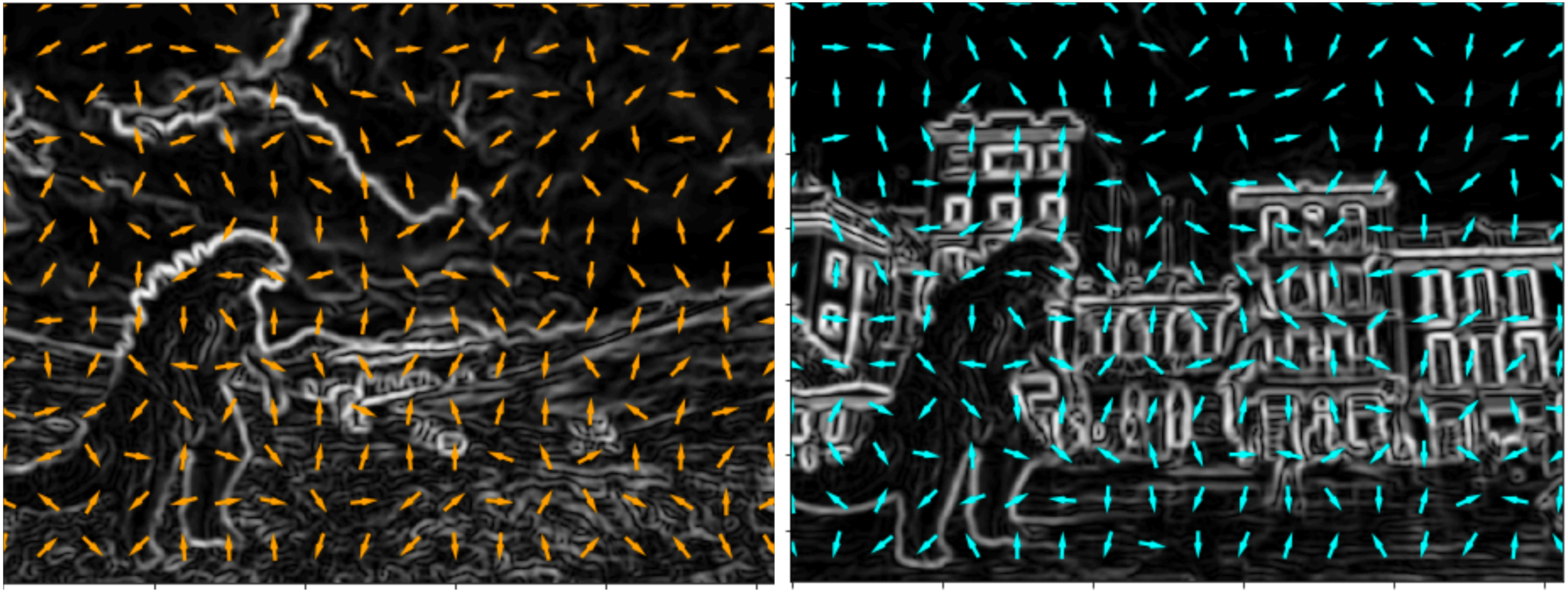
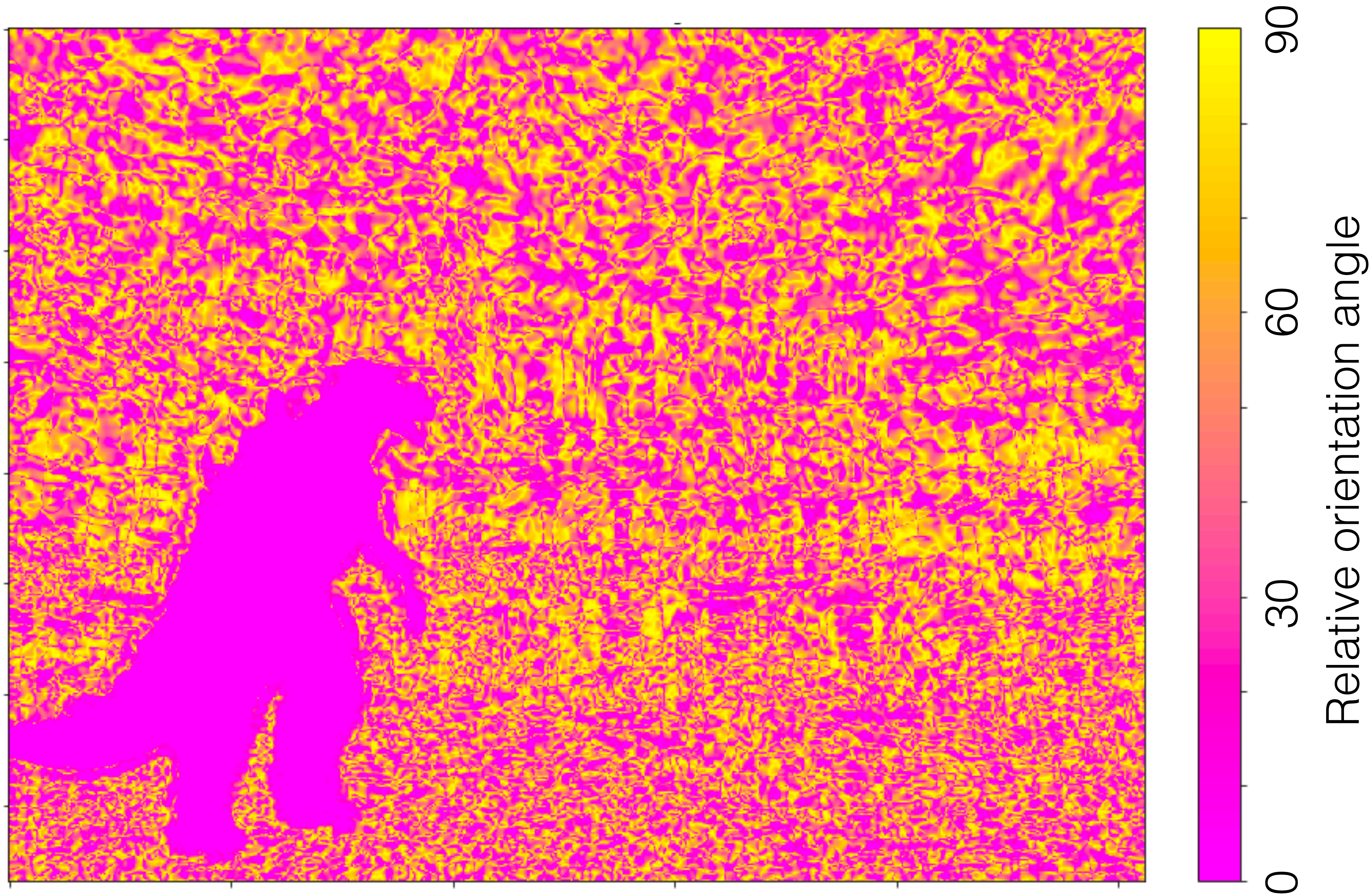
Soler, J.D. et al. A&A (2019)



Histogram of oriented gradients (HOG)

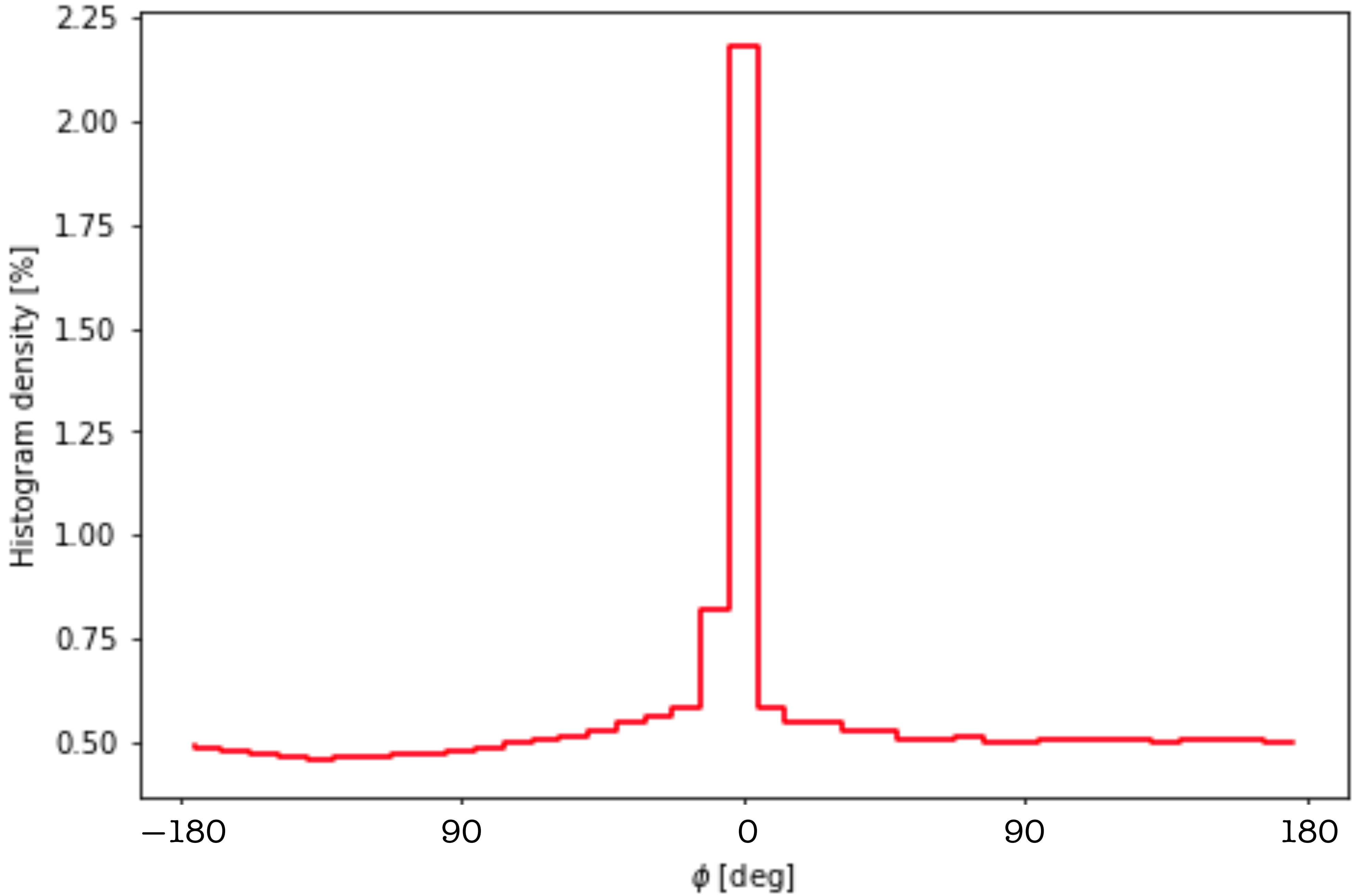
Soler, J.D. et al. A&A (2019)



Projected Rayleigh statistic

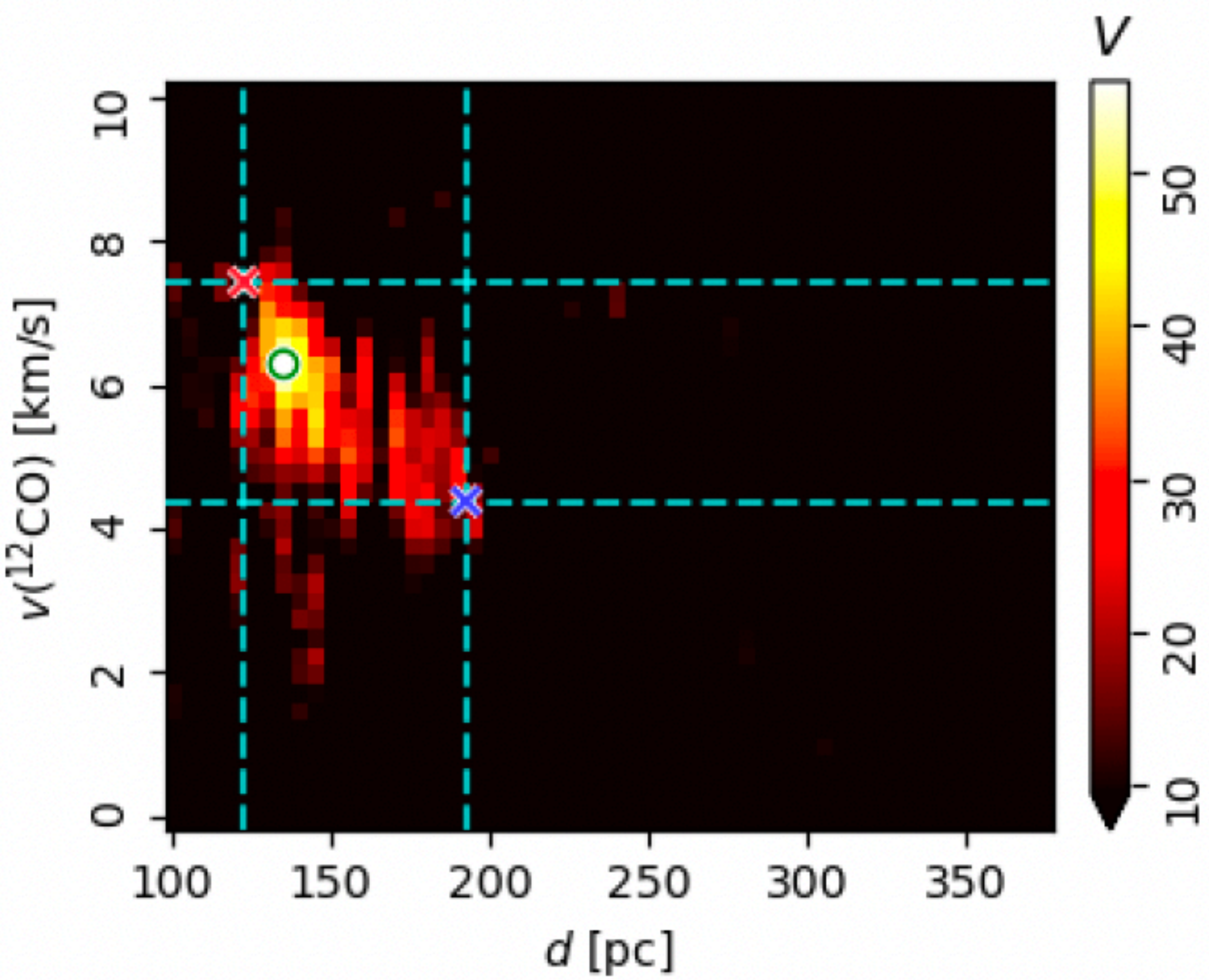
Soler, J.D. et al. A&A (2019); Jow et al. MNRAS (2018)

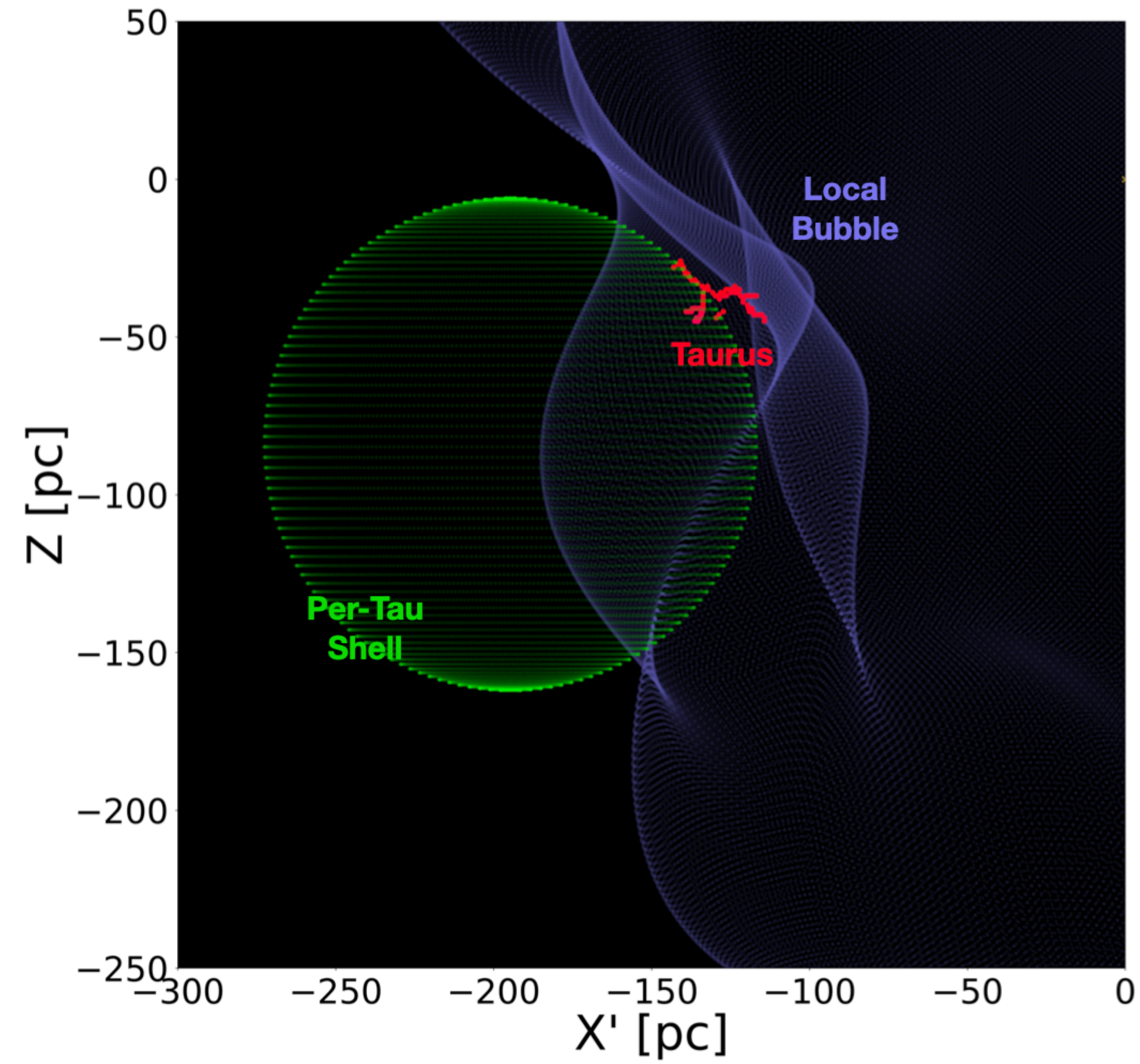
$$\boxed{V_{\mathrm{d}} = \frac{\sum_i^N w_i \cos(\phi_i)}{\sqrt{\sum_i^N w_i^2/2}}}$$

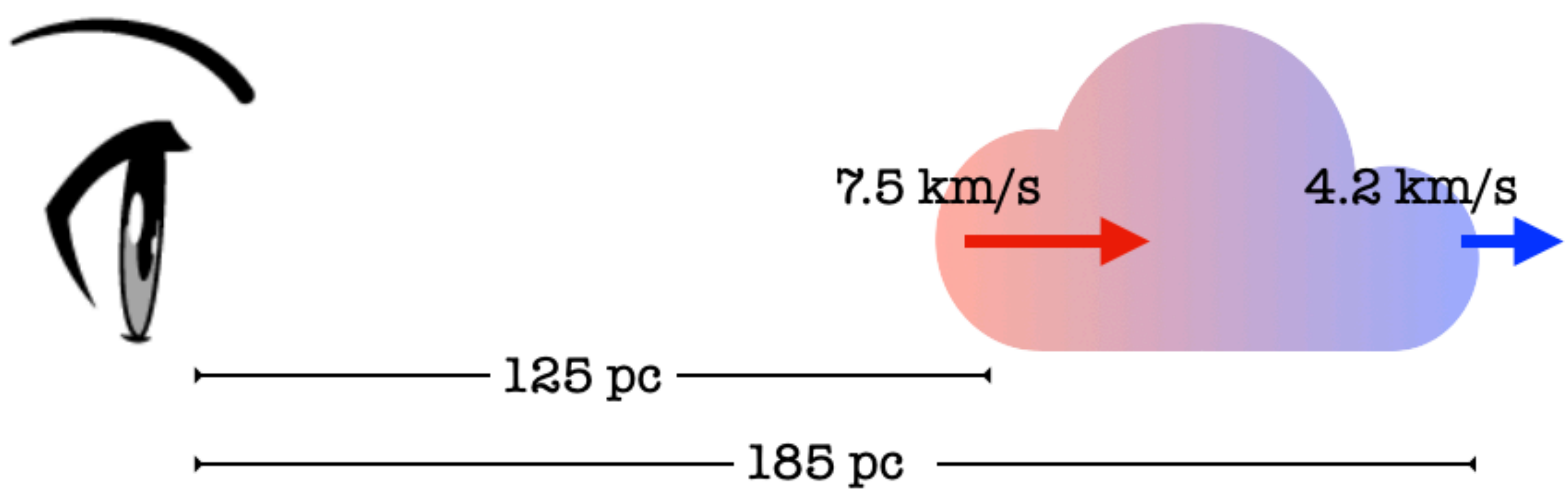


Pilot study: dynamics of the Taurus molecular cloud

Soler, Zucker, et al. A&A (2023)







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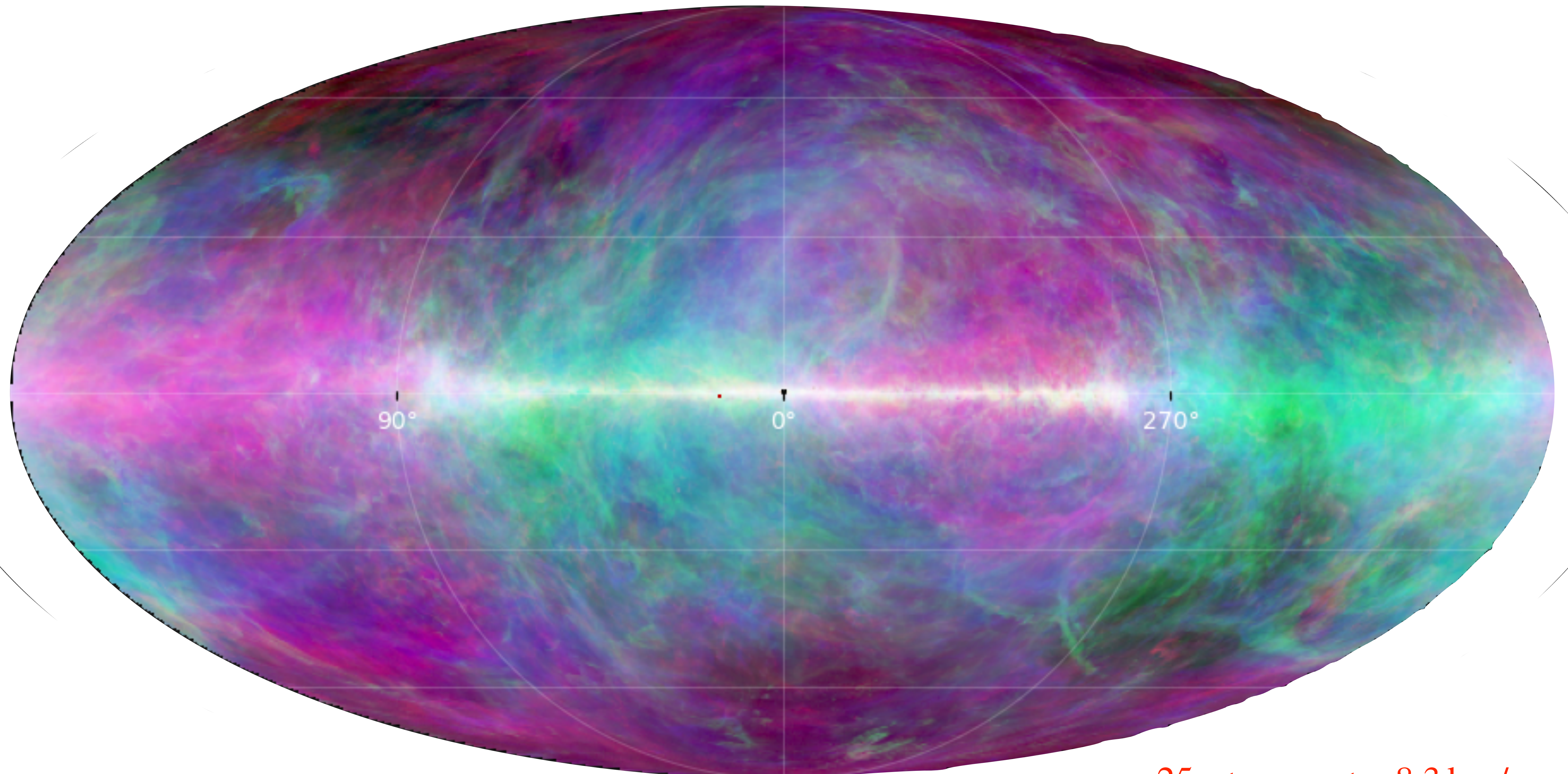
Soler et al. A&A (2025)

HI emission

$\theta \approx 16.2'$

Soler et al. (2025) A&A



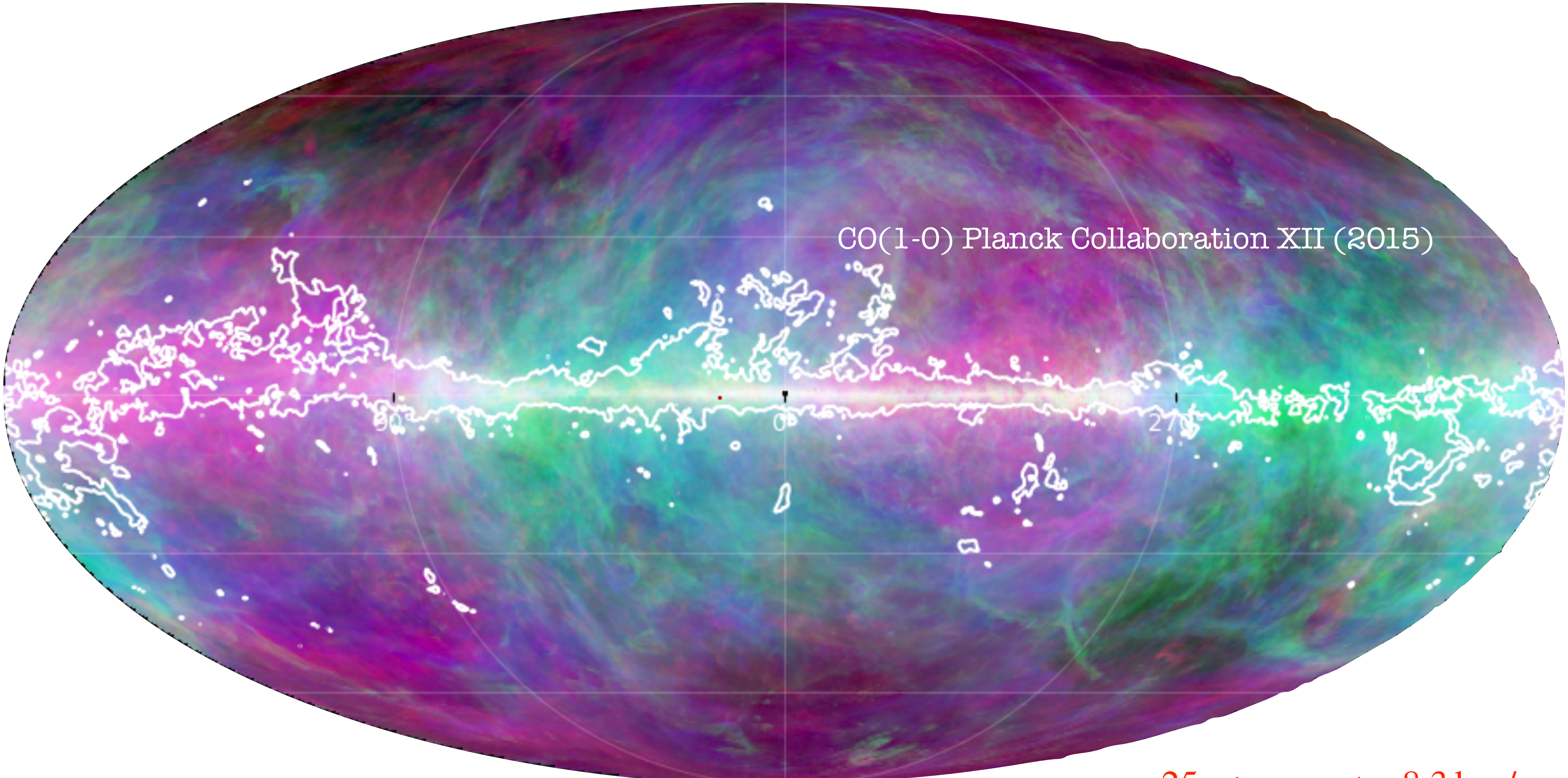
HI4PI Collaboration. A&A (2016)

$-25 < v_{LSR} < -8.3\,\mathrm{km/s}$
$-8.3 < v_{LSR} < 8.3\,\mathrm{km/s}$
$8.3 < v_{LSR} < 25\,\mathrm{km/s}$

HI and CO emission

$\theta \approx 16.2'$

Soler et al. (2025) A&A



HI4PI Collaboration. A&A (2016)

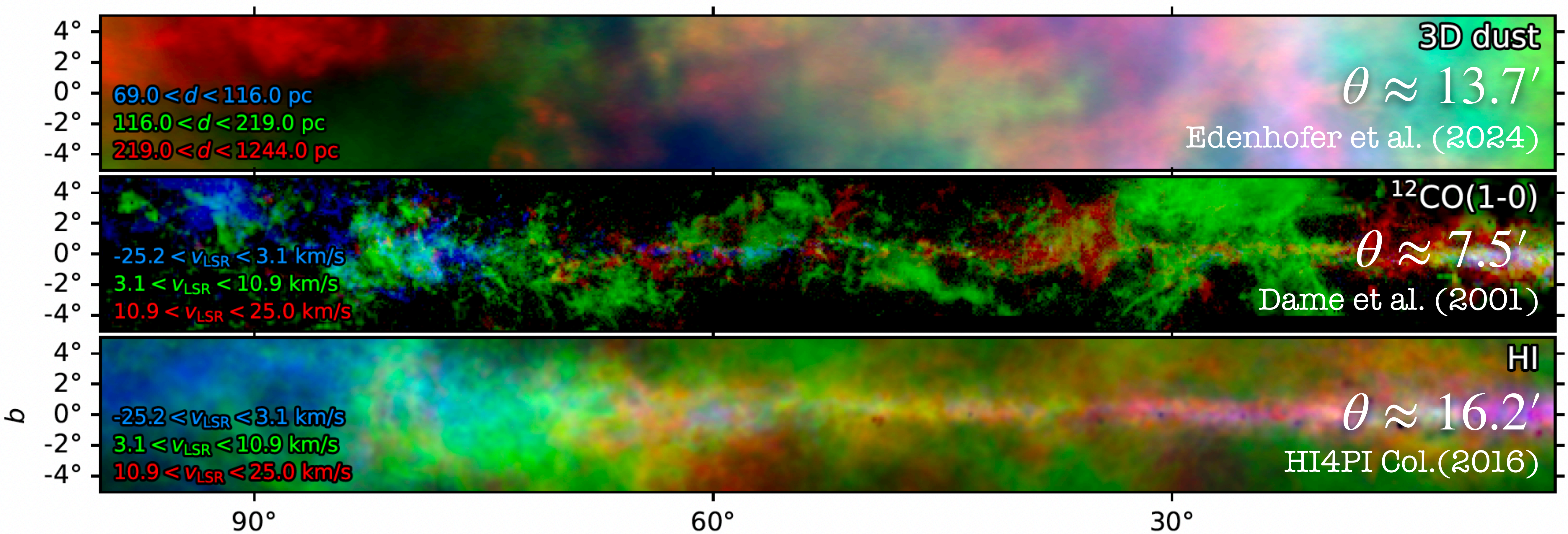
$-25 < v_{\rm LSR} < -8.3\,{\rm km/s}$

$-8.3 < v_{\rm LSR} < 8.3\,{\rm km/s}$

$8.3 < v_{\rm LSR} < 25\,{\rm km/s}$

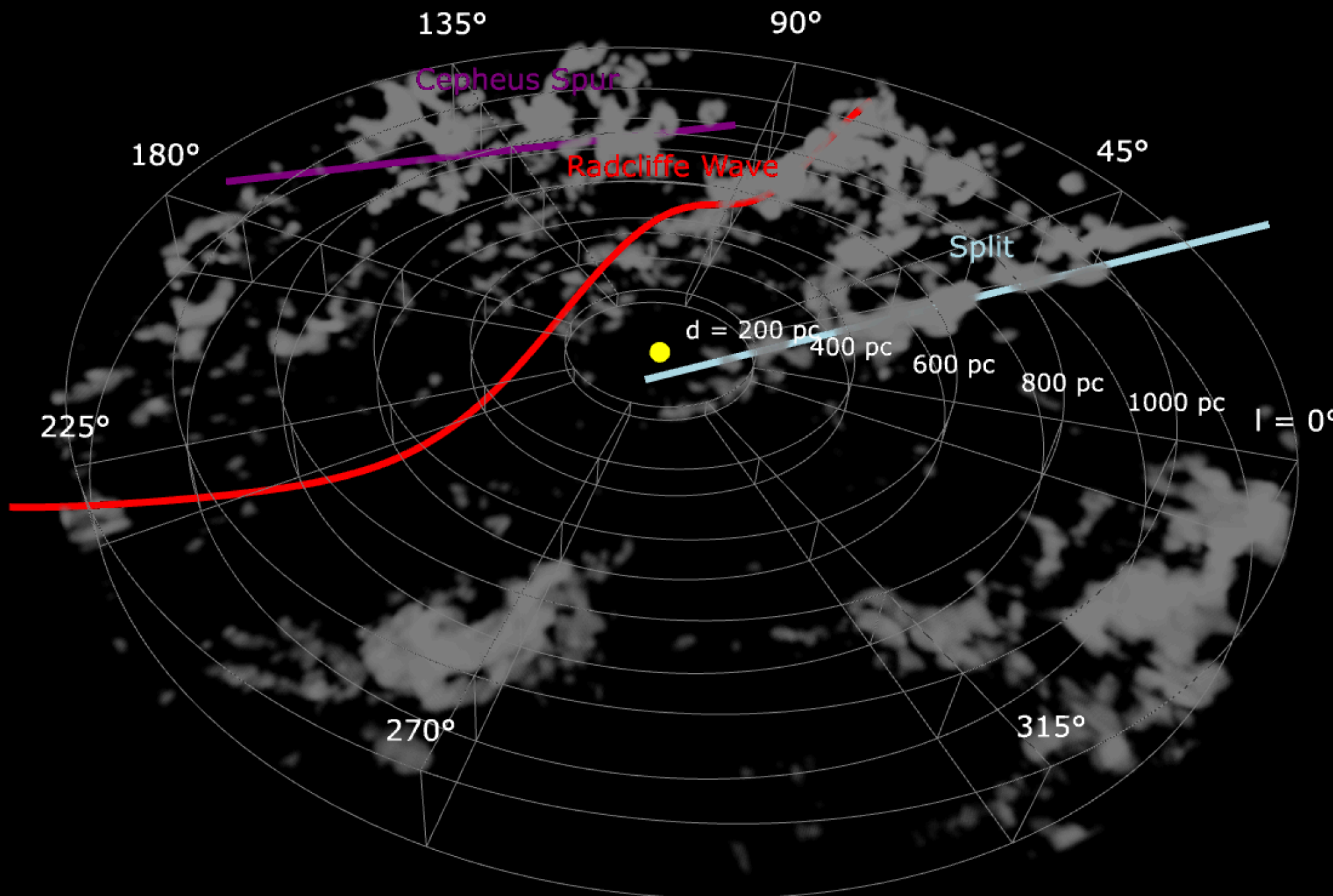
3D dust and line emission toward the Galactic plane

Soler et al. (2025) A&A



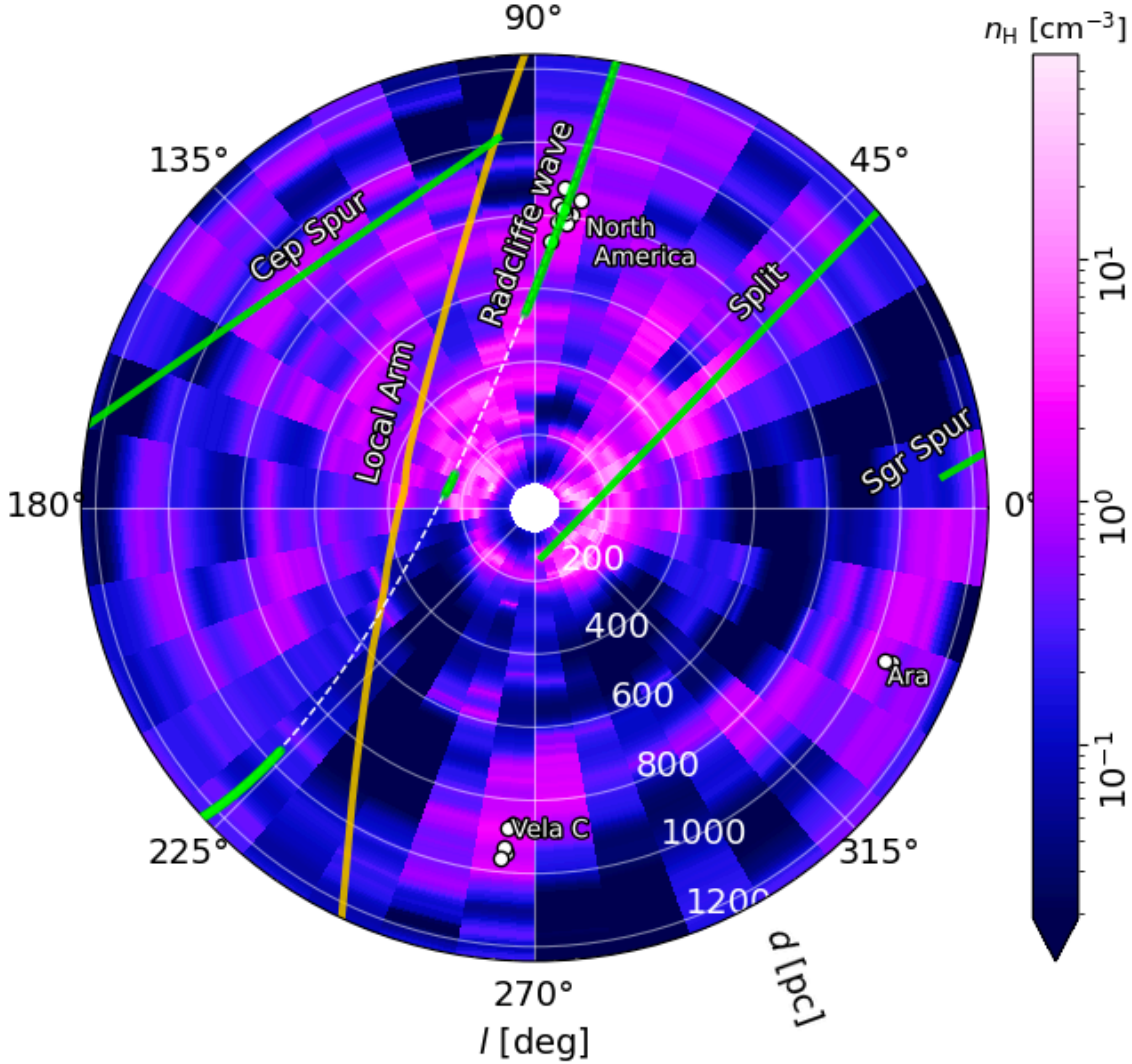
3D dust within $|b| \leq 5°$

Soler et al. (2025) A&A



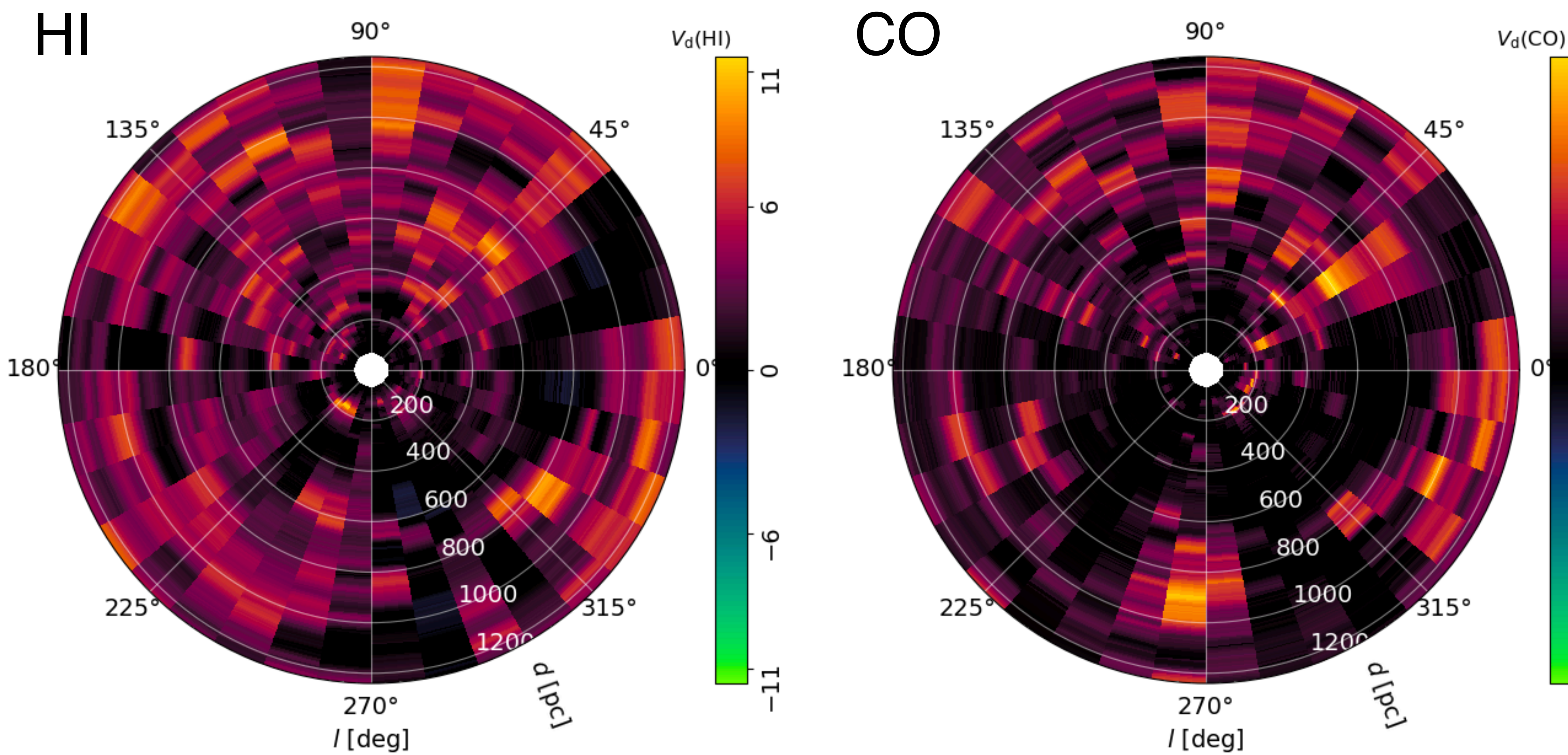
Segmentation of the local Galactic plane

Soler et al. (2025) A&A



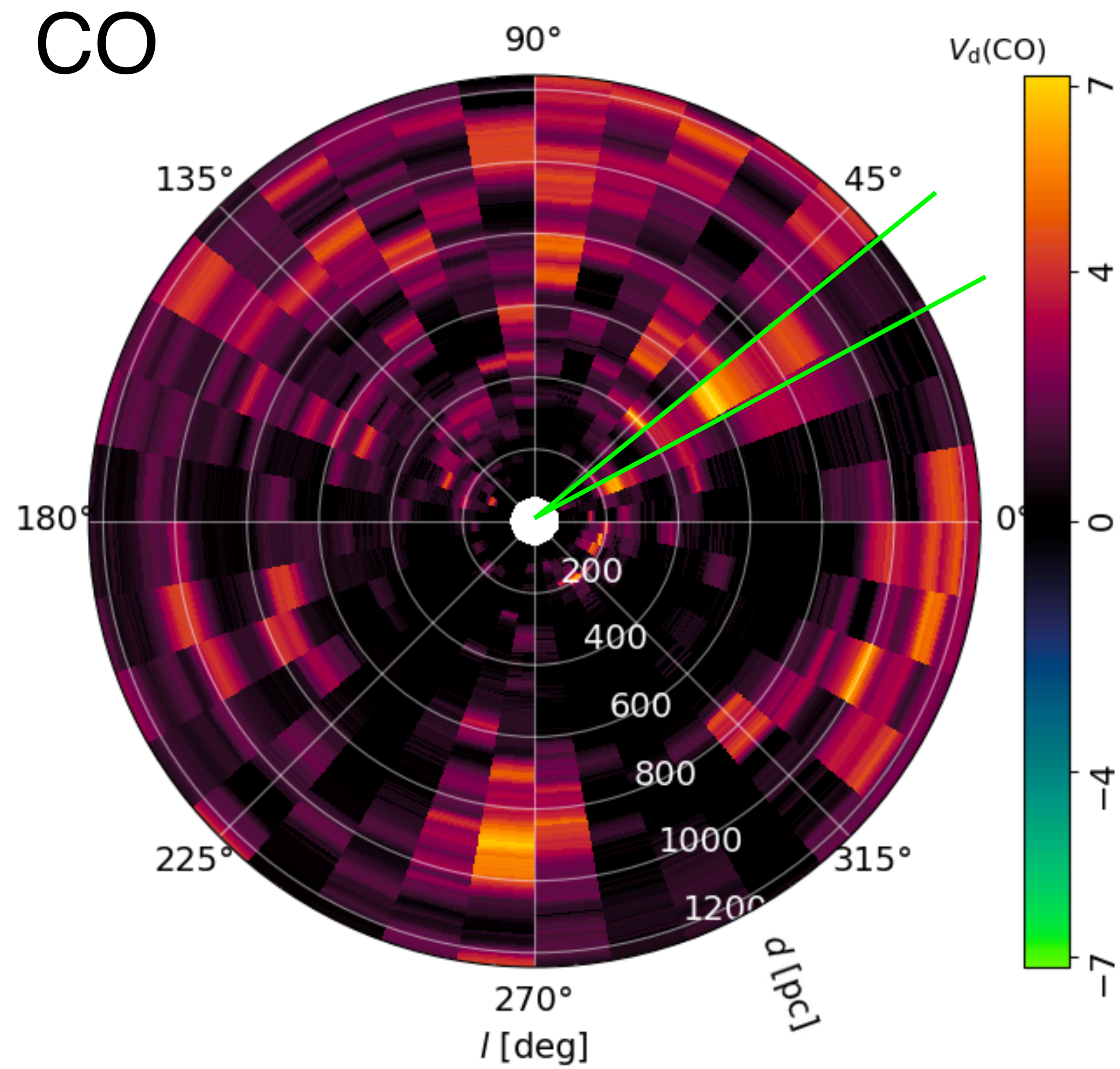
Morphological correlation between 3D dust and line emission

Soler et al. (2025) A&A



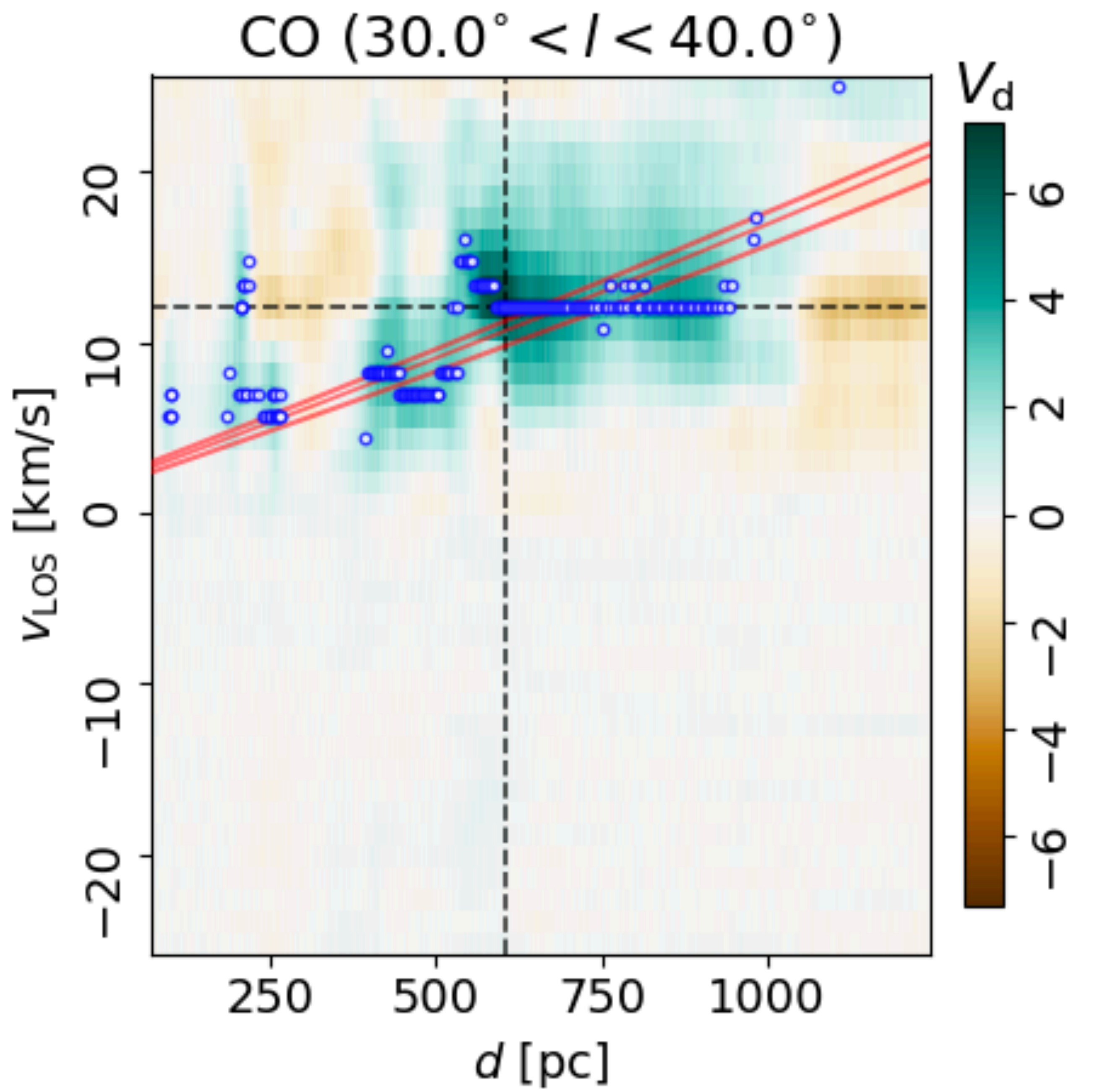
Morphological correlation between 3D dust and CO emission

Soler et al. (2025) A&A



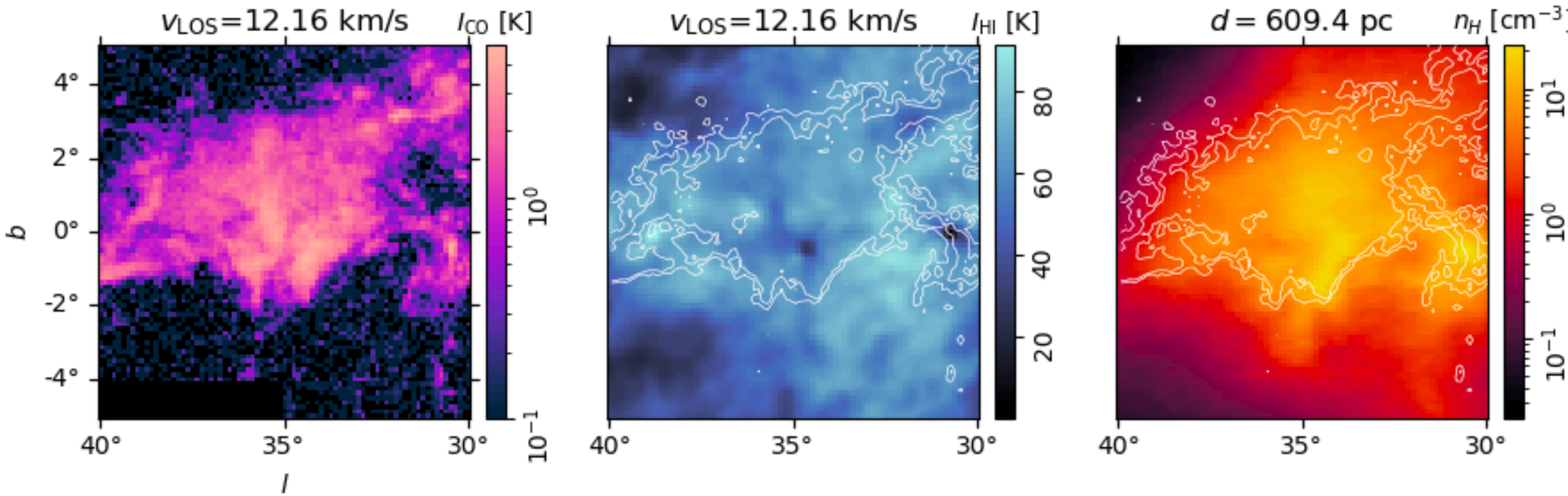
Morphological correlation between 3D dust and CO emission

Soler et al. (2025) A&A



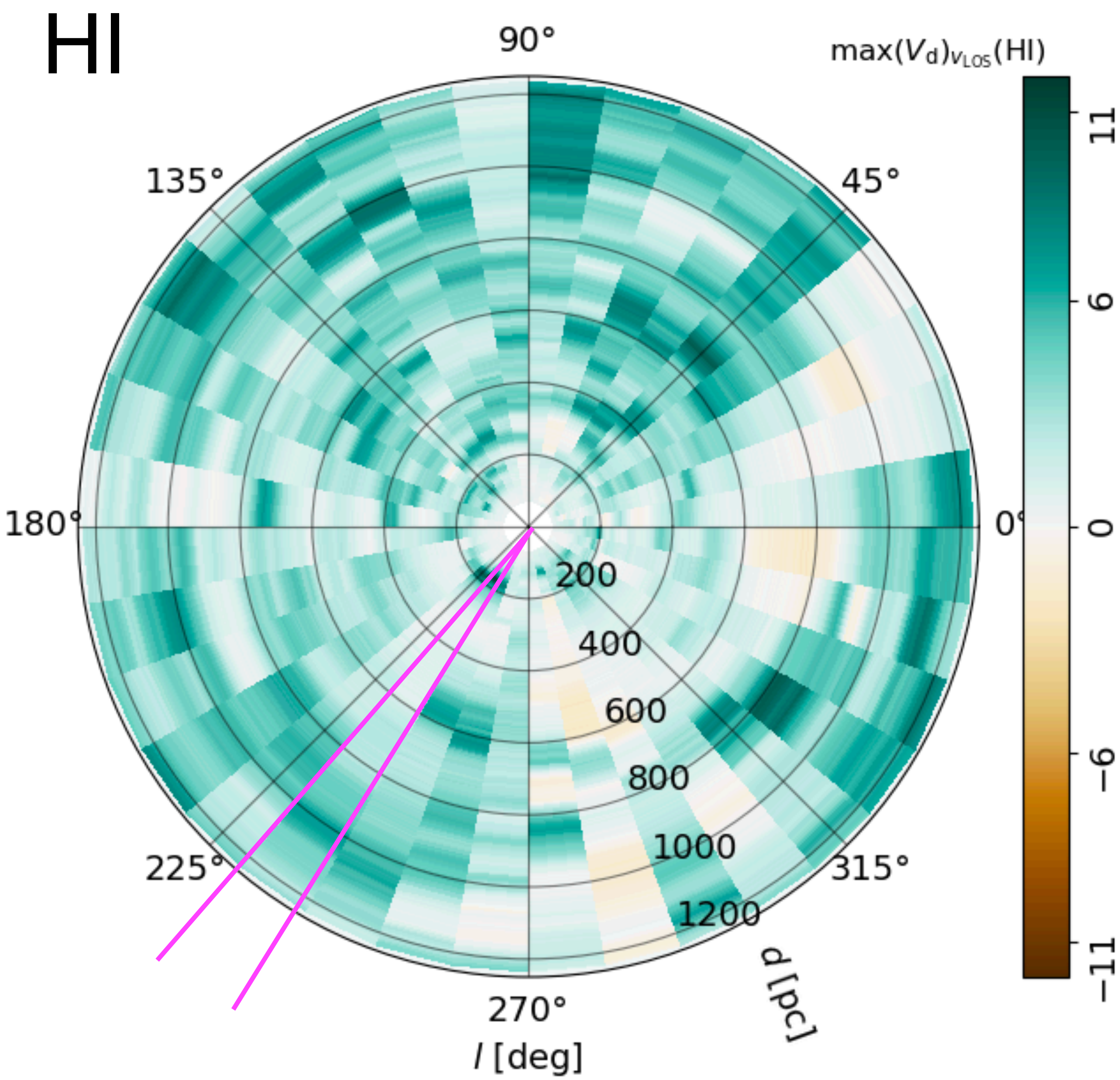
Morphological correlation between 3D dust and CO emission

Soler et al. (2025) A&A



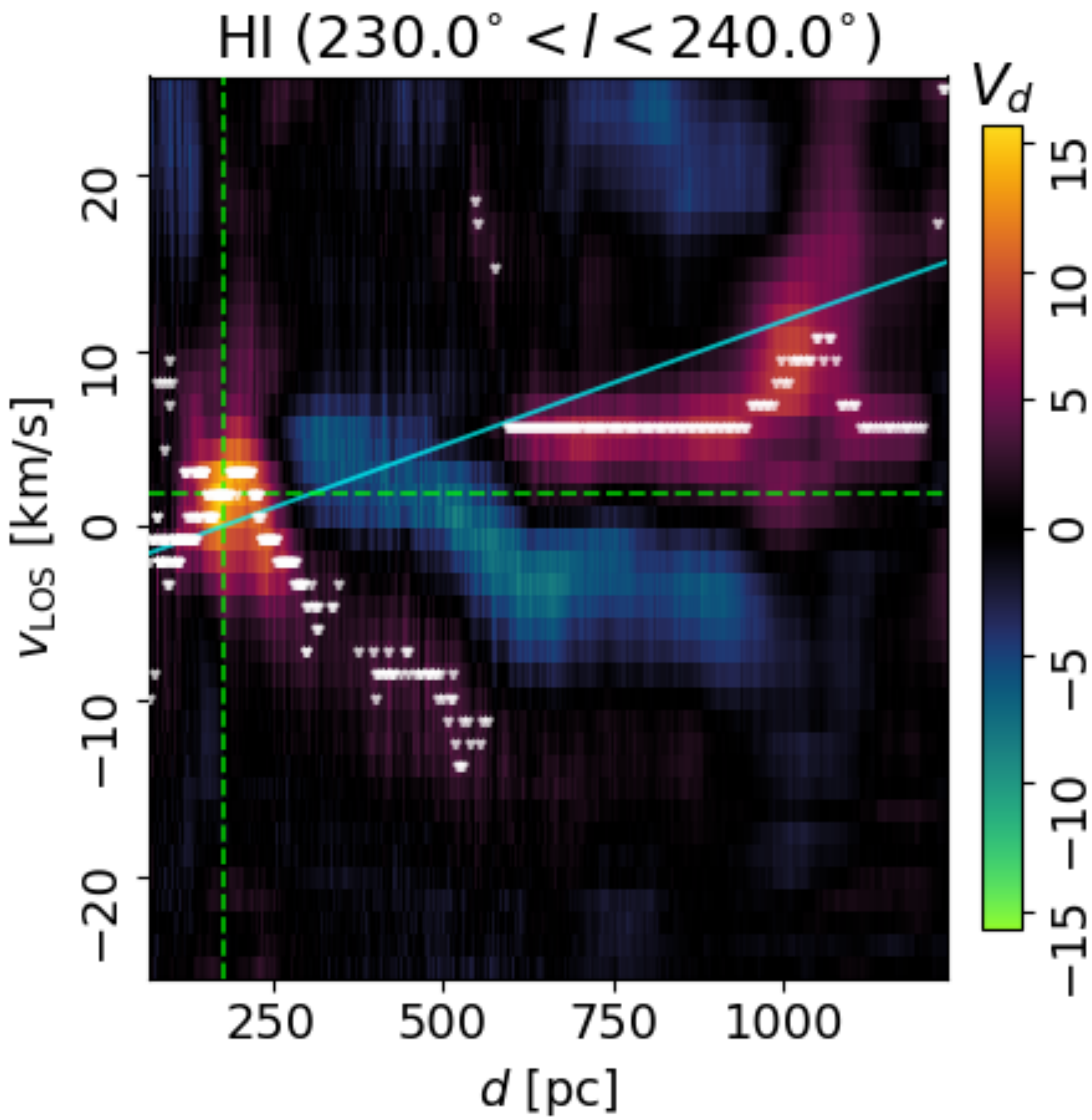
Morphological correlation between 3D dust and HI emission

Soler et al. (2025) A&A



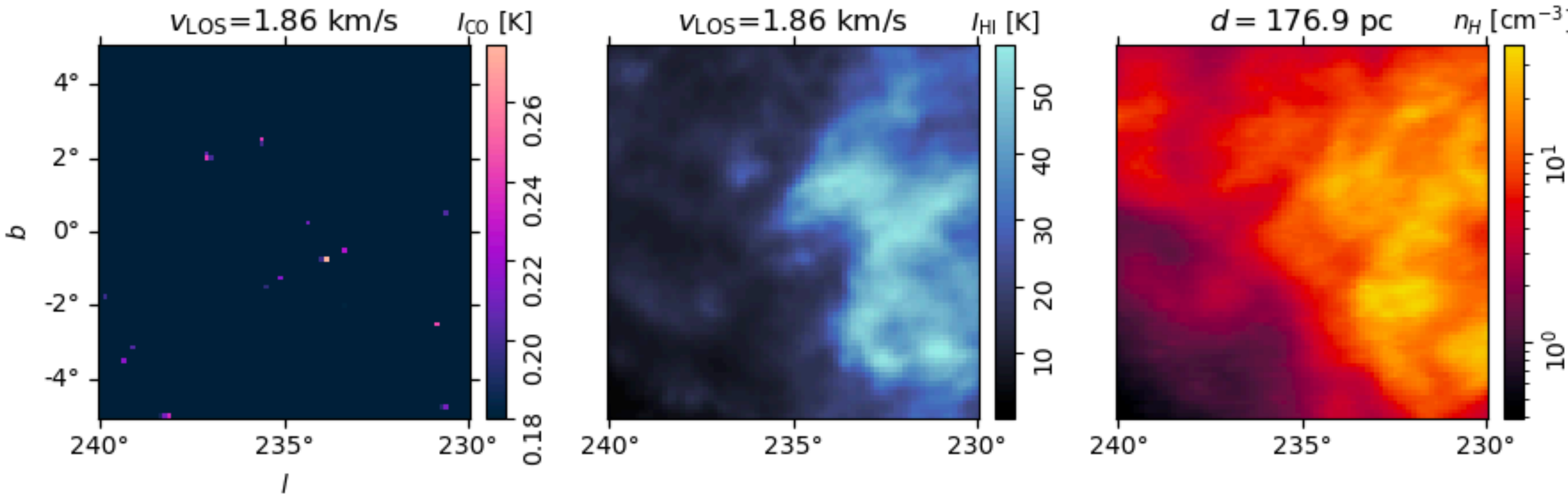
Morphological correlation between 3D dust and HI emission

Soler et al. (2025) A&A



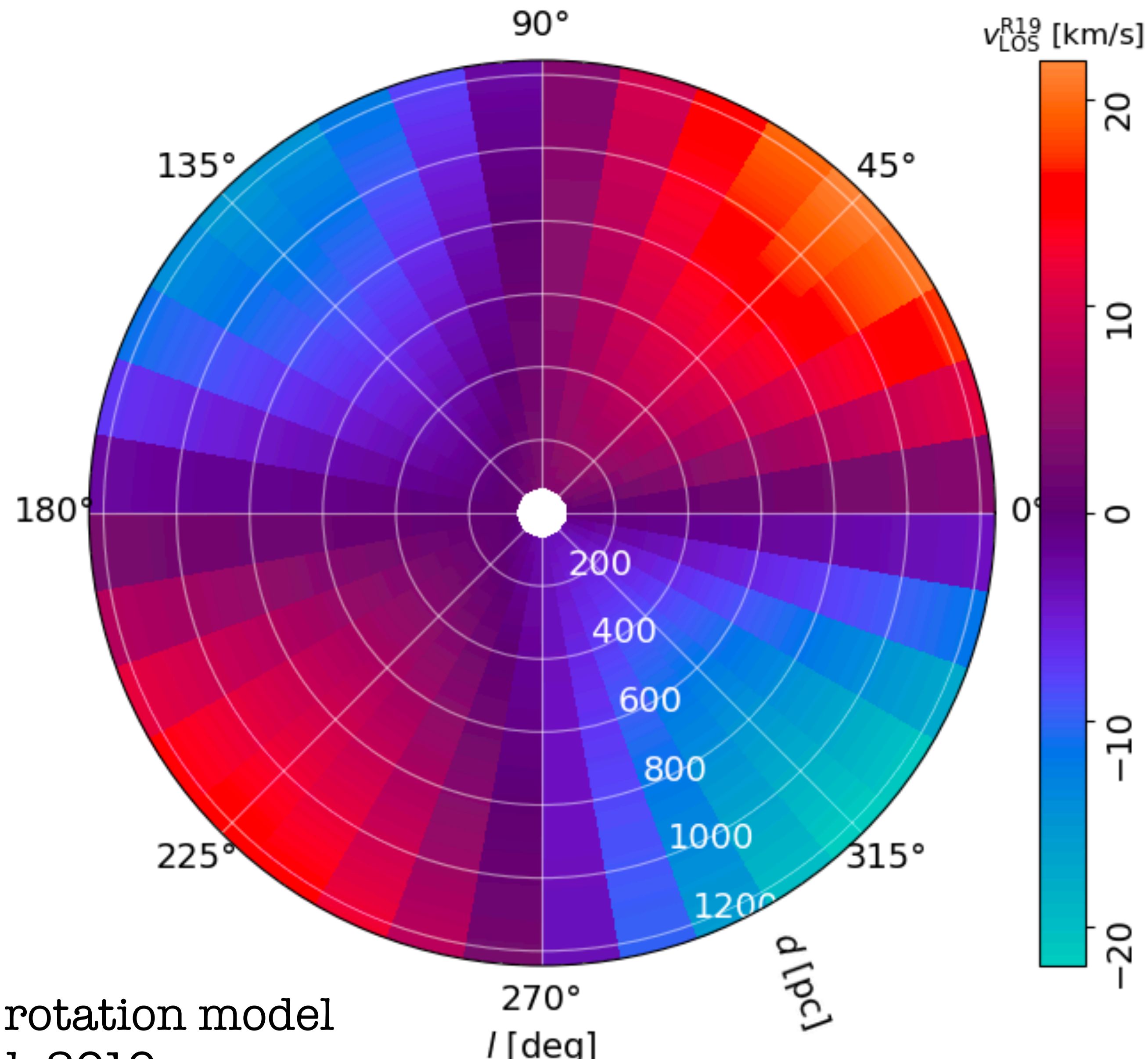
Morphological correlation between 3D dust and HI emission

Soler et al. (2025) A&A



Expected LOS velocities

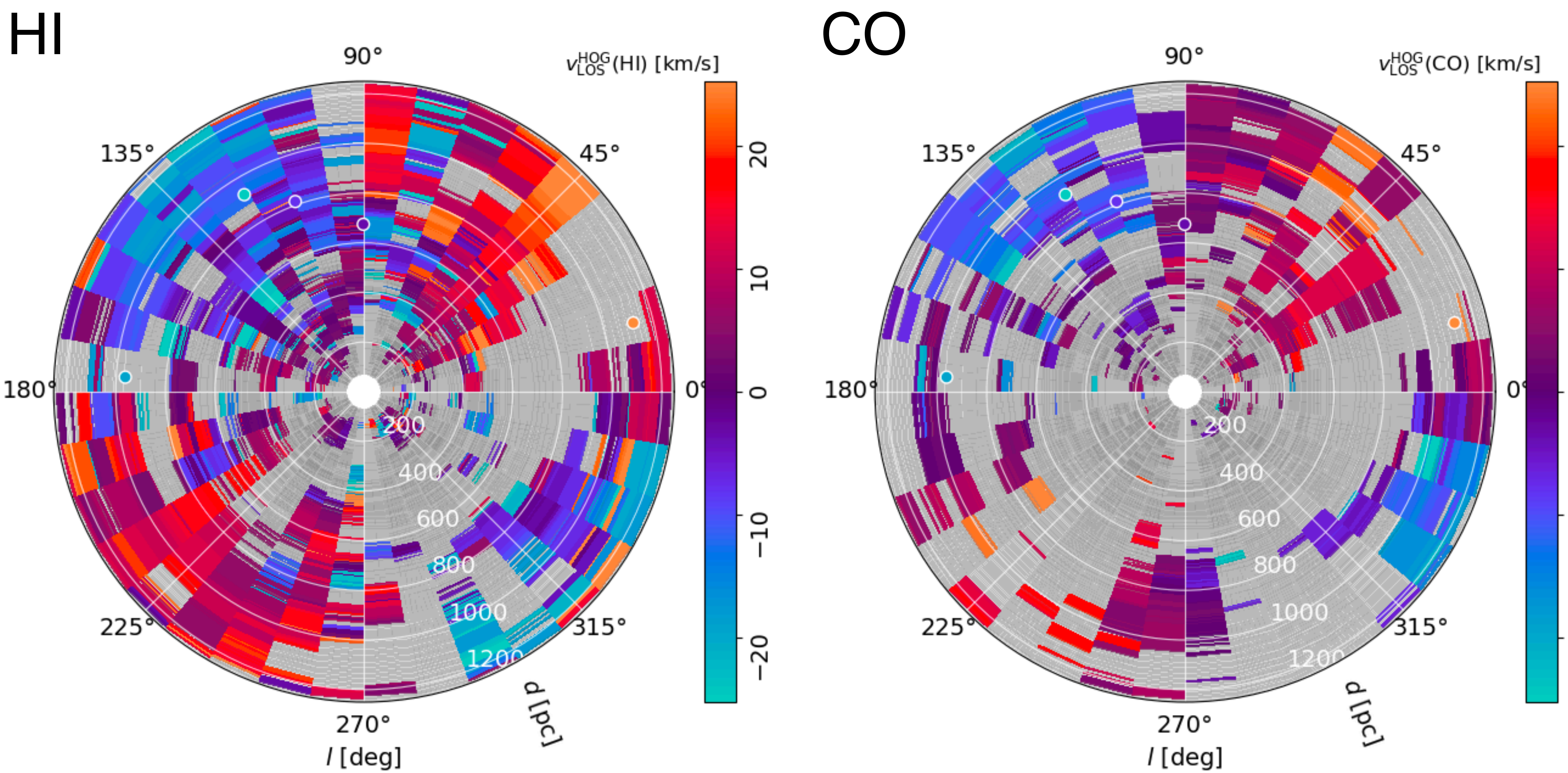
Soler et al. (2025) A&A



Galactic rotation model
Reid et al. 2019

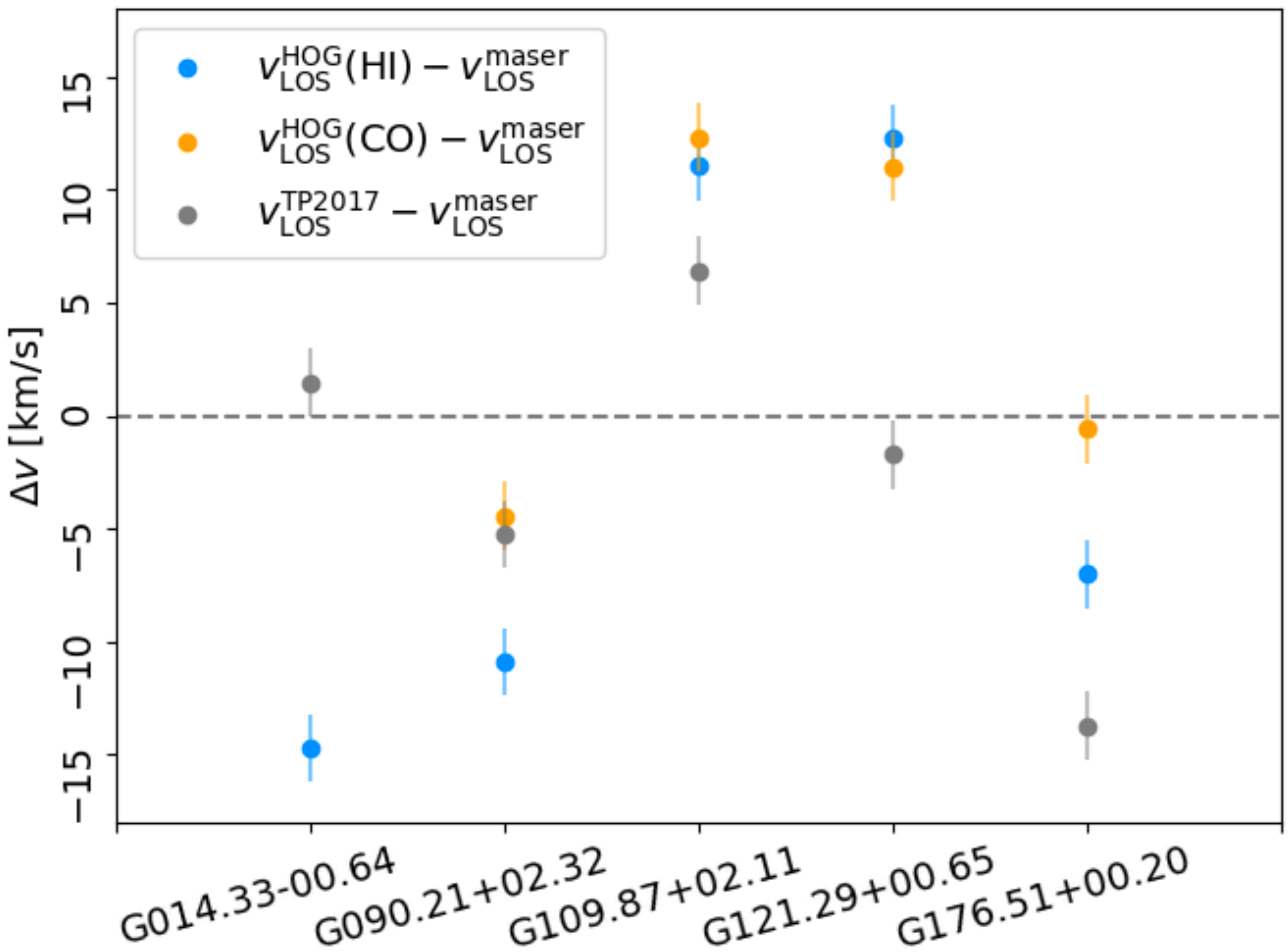
Reconstructed LOS velocities

Soler et al. (2025) A&A



Comparison to masers

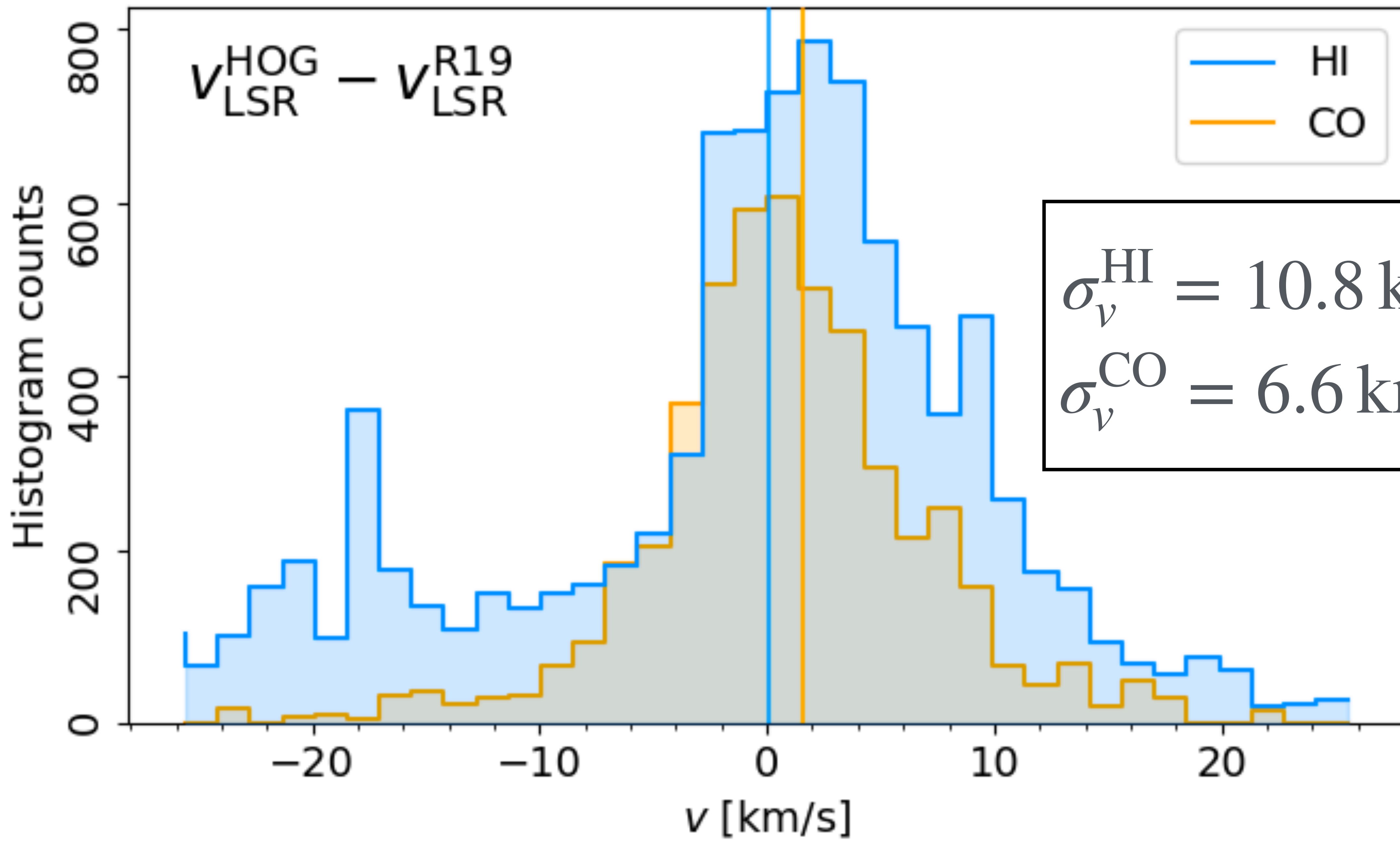
Soler et al. (2025) A&A



TP2017 - Tchernyshyov & Peek. ApJ (2017)

Residual velocities (streaming motions)

Soler et al. (2025) A&A

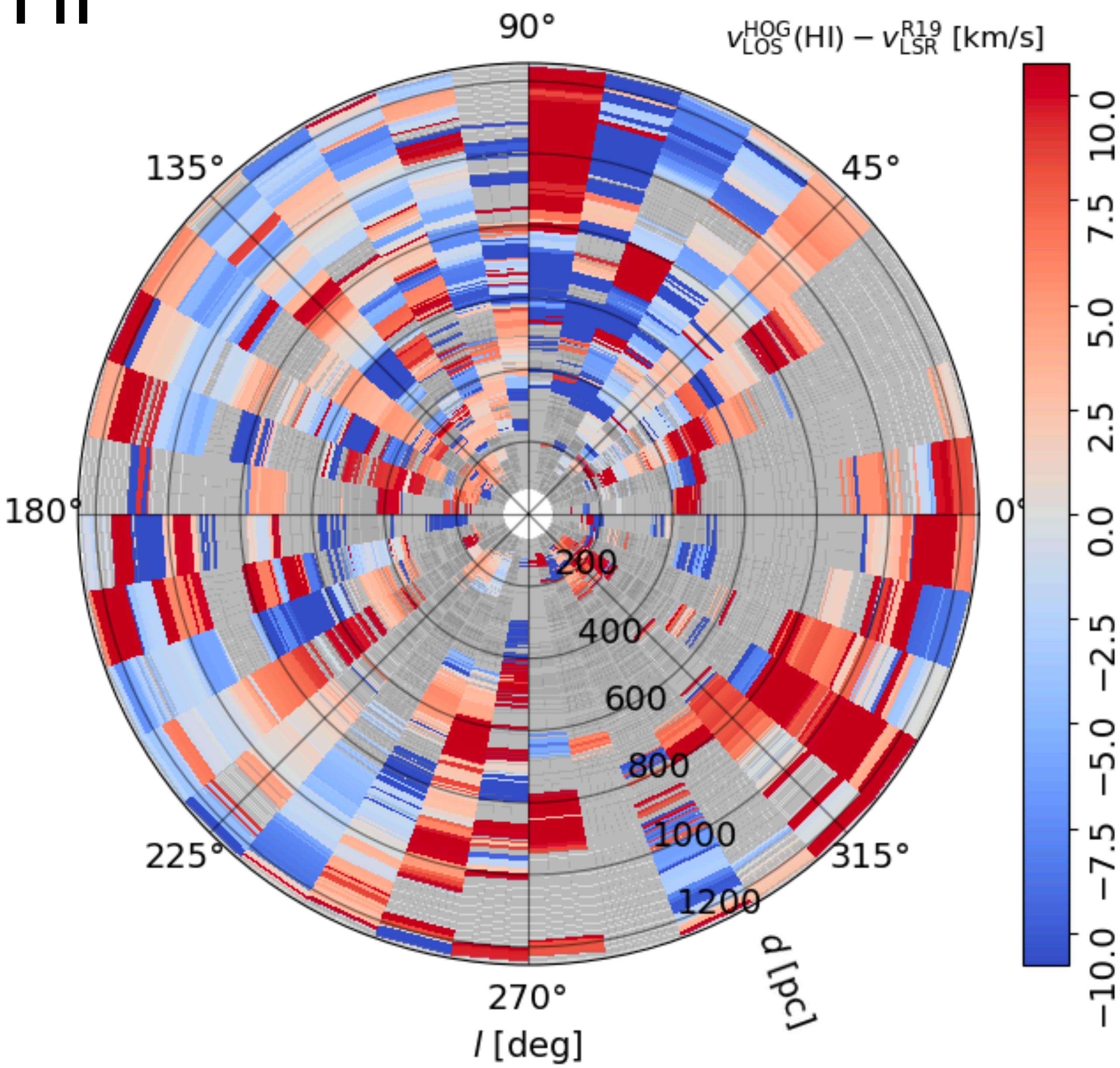


$$\sigma_v^{\mathrm{HI}} = 10.8\,\mathrm{km/s}$$
$$\sigma_v^{\mathrm{CO}} = 6.6\,\mathrm{km/s}$$

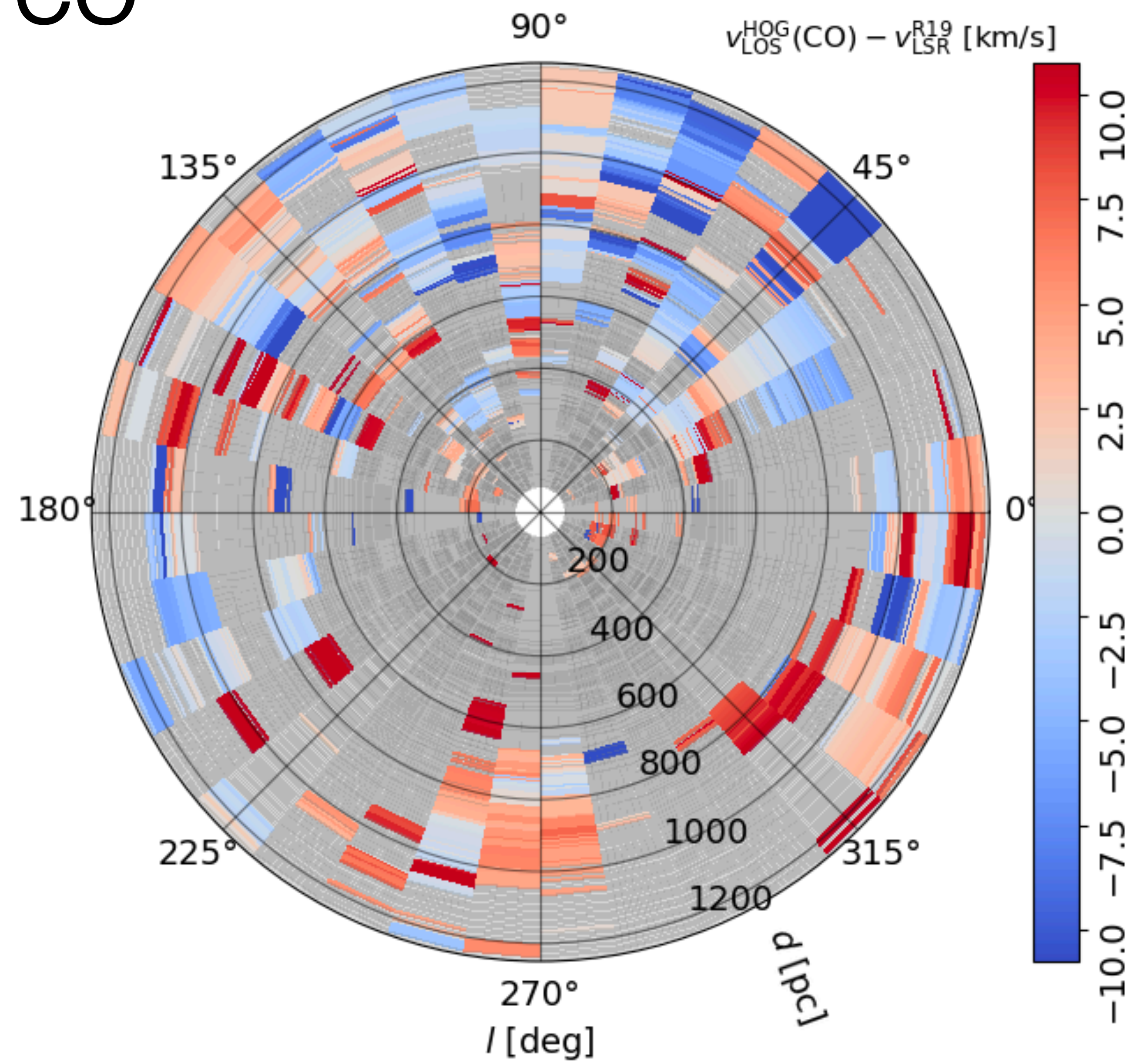
Residual velocities (streaming motions)

Soler et al. (2025) A&A

HI

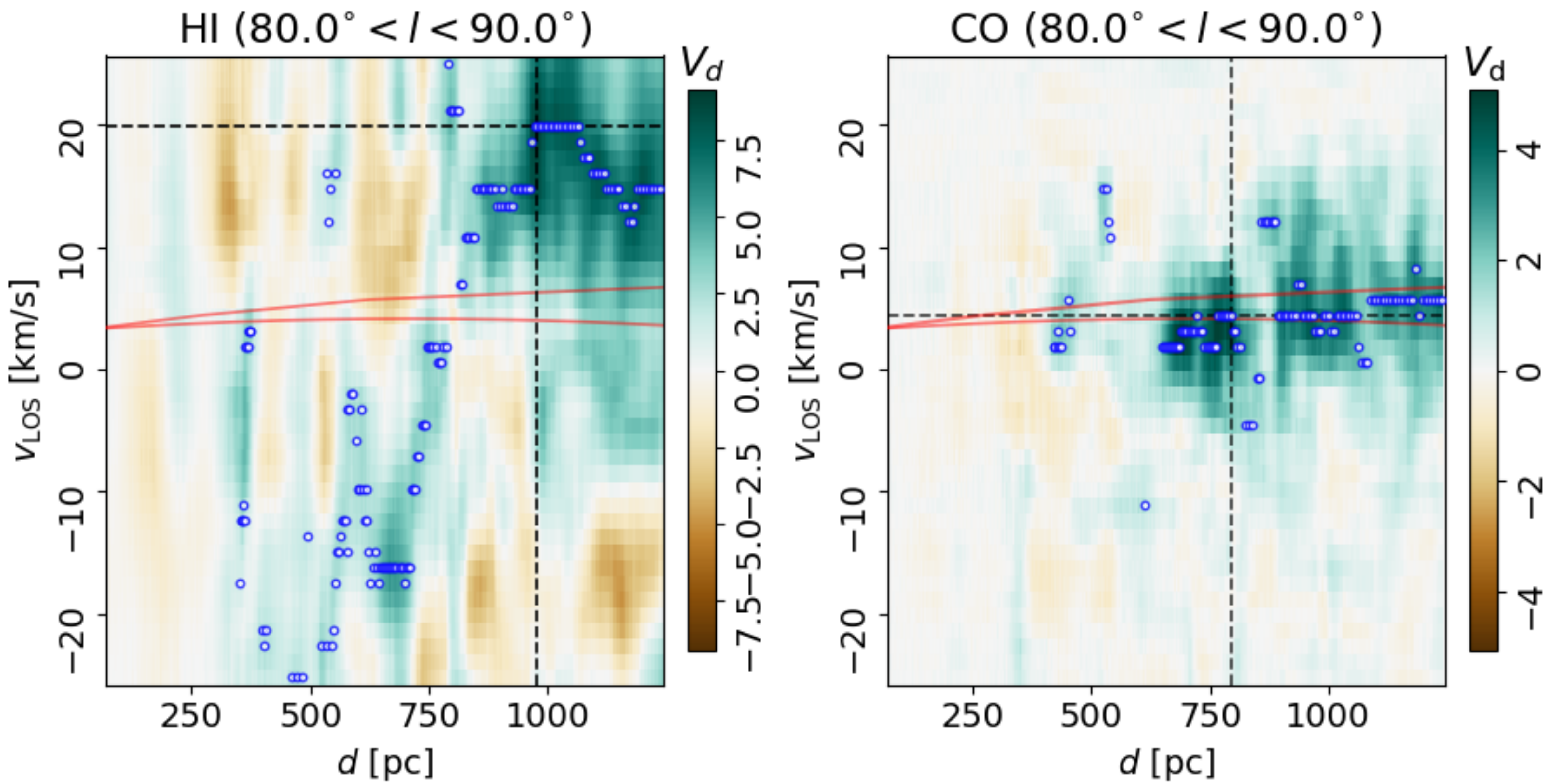


CO



Residual velocities (streaming motions)

Soler et al. (2025) A&A



“How about just good old physics?”

Unidentified ancient Roman tetrarch

Kinetic energy densities

Soler et al. (2025) A&A

$$\left\langle E_{\mathrm{K}}^{X}\right\rangle_{kq} = \frac{1}{2}\rho^{\mathrm{eff},X}_{kp^{*}q}\left[(v^{X}_{\mathrm{LOS}})_{kp^{*}q} - (v^{R19}_{\mathrm{LOS}})_{kq}\right]^{2}$$

Also momentum densities and mass flow rates!

Kinetic energy densities

Soler et al. (2025) A&A

HI or CO

Effective density

$$\left\langle E_{\mathrm{K}}^{X} \right\rangle_{kq} = \frac{1}{2} \rho_{kp^{*}q}^{\mathrm{eff},X} \left[(v_{\mathrm{LOS}}^{X})_{kp^{*}q} - (v_{\mathrm{LOS}}^{R19})_{kq} \right]^{2}$$

v_{LSR} channel with maximum correlation

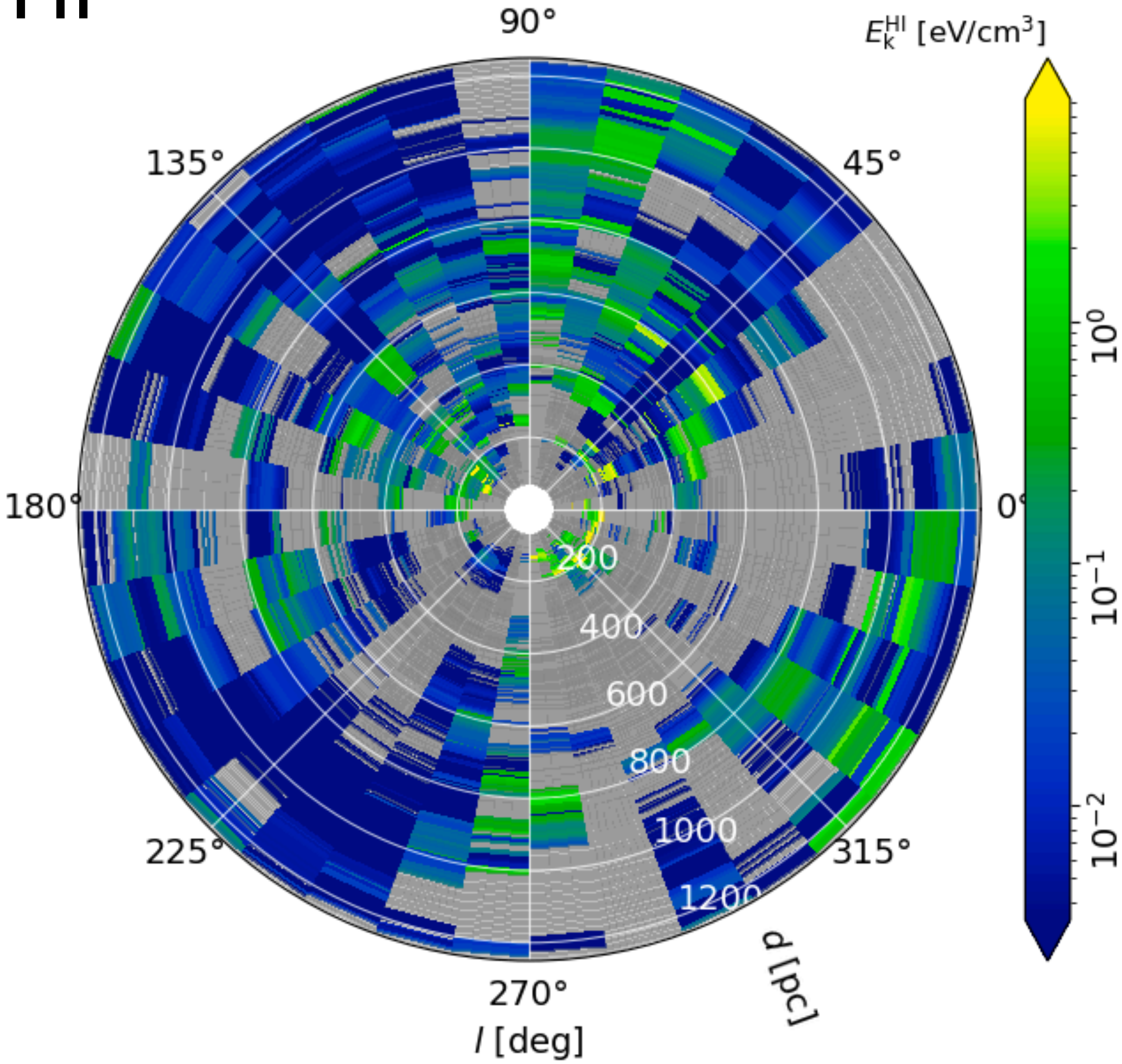
Distance channel

Galactic longitude tile

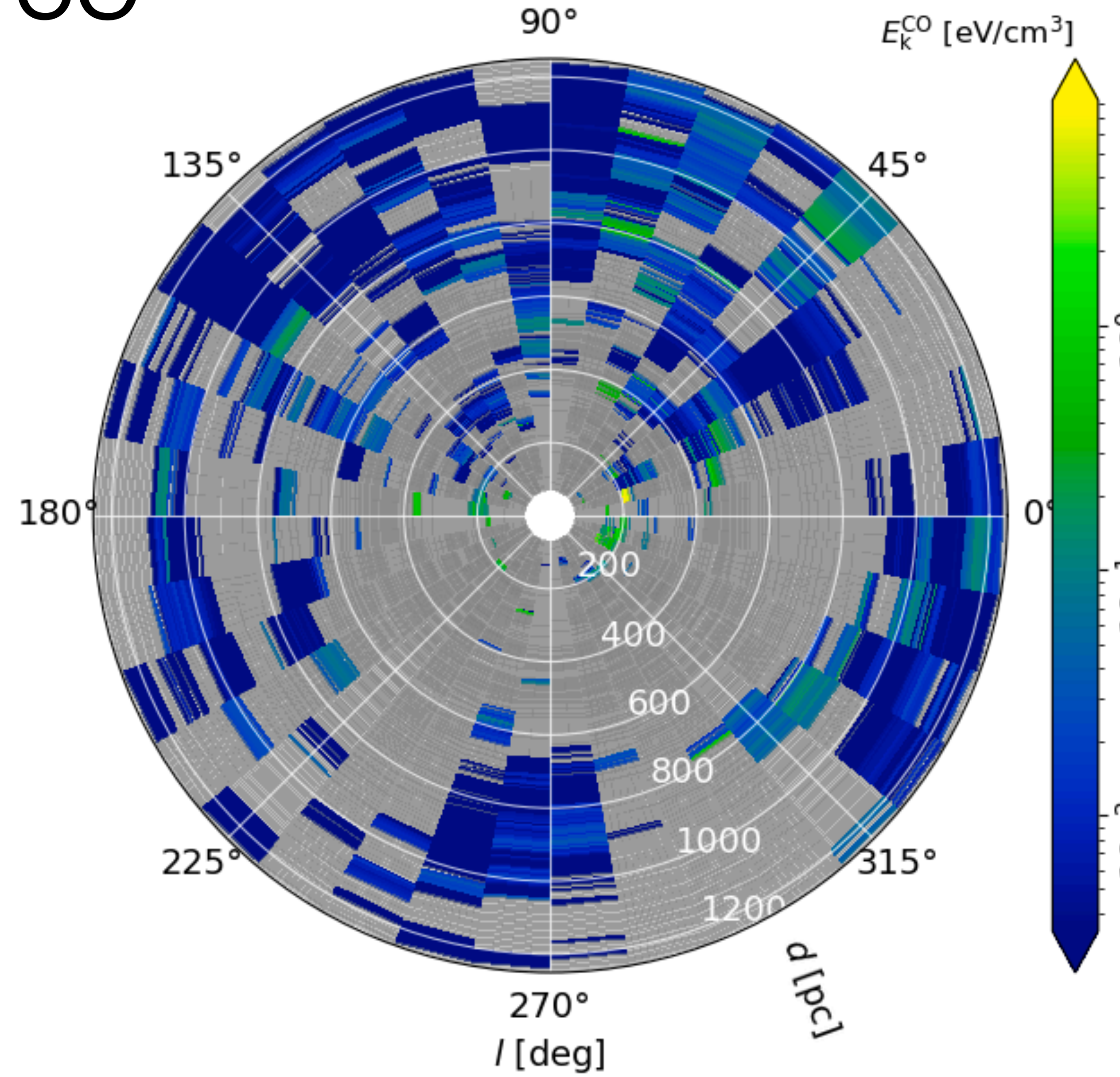
Kinetic energy densities

Soler et al. (2025) A&A

HI

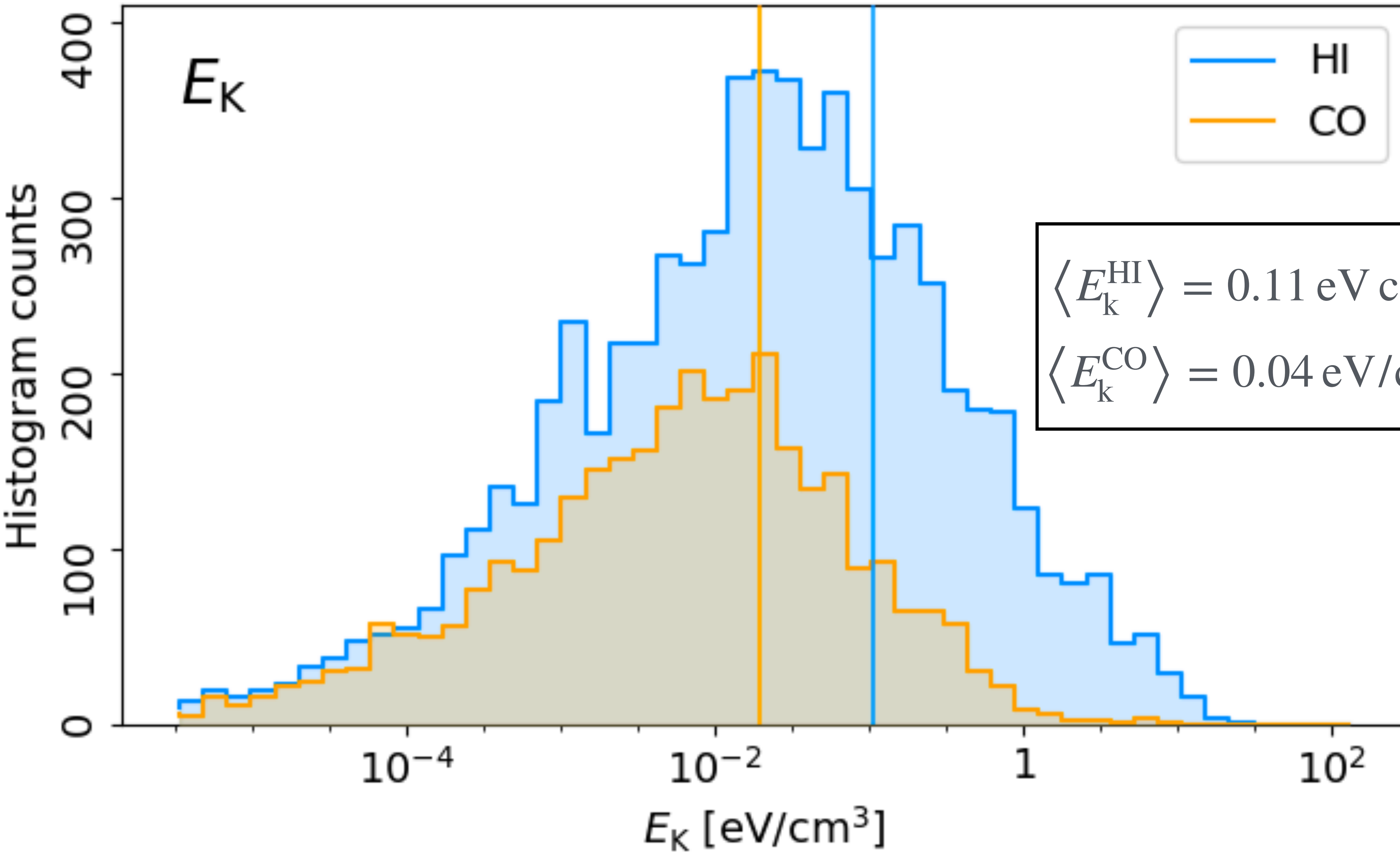


CO



Kinetic energy densities

Soler et al. (2025) A&A



$$\left\langle E_{k}^{HI} \right\rangle = 0.11\,\mathrm{eV\,cm^{-3}}$$

$$\left\langle E_{k}^{CO} \right\rangle = 0.04\,\mathrm{eV/cm^{-3}}$$

Energy densities in the ISM

Draine. Physics of the interstellar and intergalactic medium (2011)

Component	$u(\mathrm{eV\,cm^{-3}})$	Note
Far-infrared radiation from dust	0.31	*b*
Starlight ($h\nu < 13.6\,\mathrm{eV}$)	0.54	*c*
Thermal kinetic energy $(3/2)nkT$	0.49	*d*
Turbulent kinetic energy $(1/2)\rho v^2$	0.22	*e*
Magnetic energy $B^2/8\pi$	0.89	*f*
Cosmic rays	1.39	*g*

b Chapter 12.
c Chapter 12.
d For $nT = 3800\,\mathrm{cm^{-3}\,K}$ (see §17.7).
e For $n_\mathrm{H} = 30\,\mathrm{cm^{-3}}$, $v = 1\,\mathrm{km\,s^{-1}}$, or $\langle n_\mathrm{H}\rangle = 1\,\mathrm{cm^{-3}}$, $\langle v^2\rangle^{1/2} = 5.5\,\mathrm{km\,s^{-1}}$.
f For median $B_\mathrm{tot} \approx 6.0\,\mu\mathrm{G}$ (Heiles & Crutcher 2005).
g For cosmic ray spectrum X3 in Fig. 13.5.

Whodunit: supernovae

Soler et al. (2025) A&A

Energy input per SN (Martizzi et al. 2015)

$$10^{51}\,\mathrm{erg}$$

Efficiency in converting thermal to mechanical energy
(Bacchini et al. 2020)

$$10\,\%$$

SNe needed to sustain energy density in the studied volume

$$\approx 4000$$

SNe rate (Walch et al. 2015)

$$15\,\mathrm{Myr}^{-1}\,\mathrm{at}\,\Sigma = 10\,\mathrm{M}_{\odot}\,\mathrm{pc}^{-2}$$

You would have to wait

$$200\,\mathrm{Myr}$$

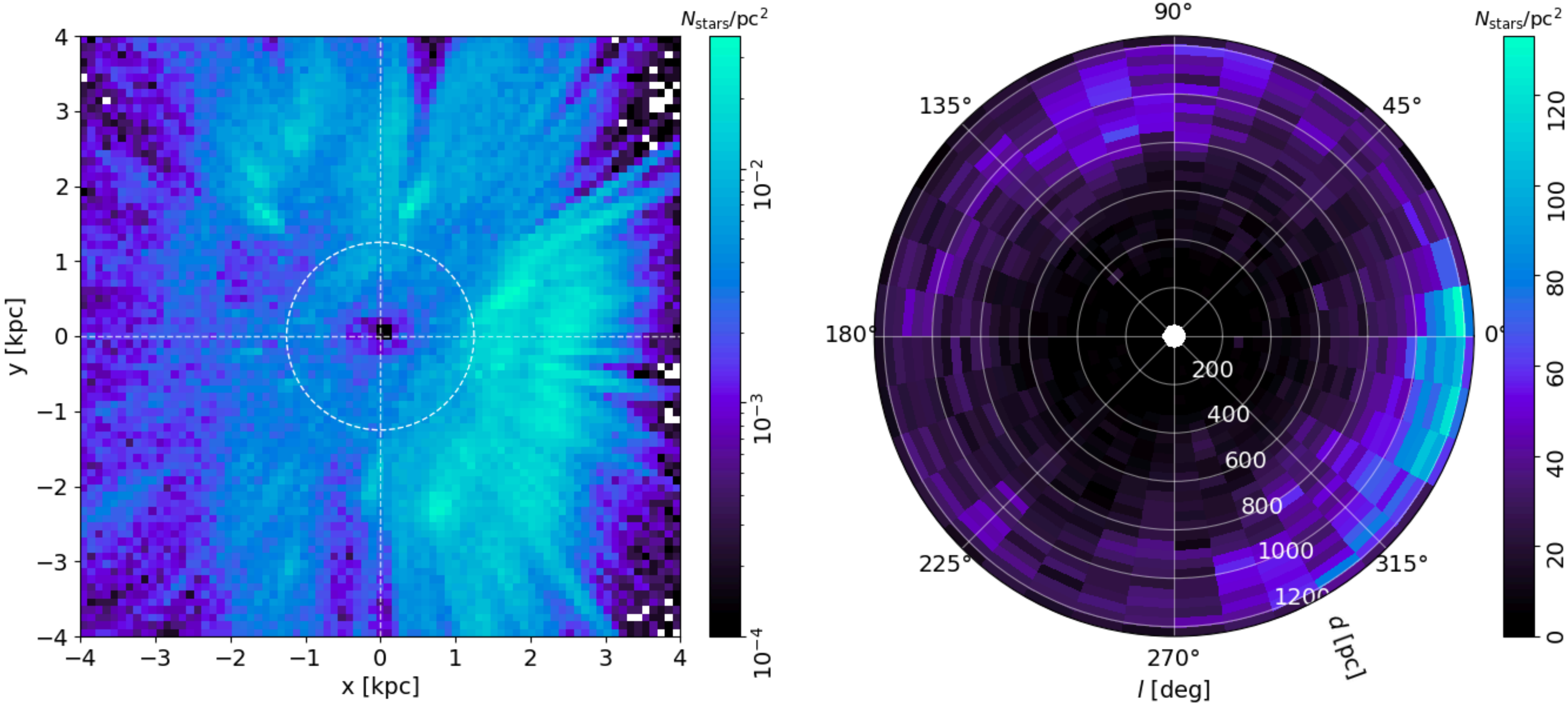
to produce enough SNe to sustain the mean energy density

$$\left\langle E_{\mathrm{k}}^{\mathrm{HI}} \right\rangle = 0.68\,\mathrm{eV/cm}^{-3}$$

$$\left\langle E_{\mathrm{k}}^{\mathrm{CO}} \right\rangle = 0.18\,\mathrm{eV/cm}^{-3}$$

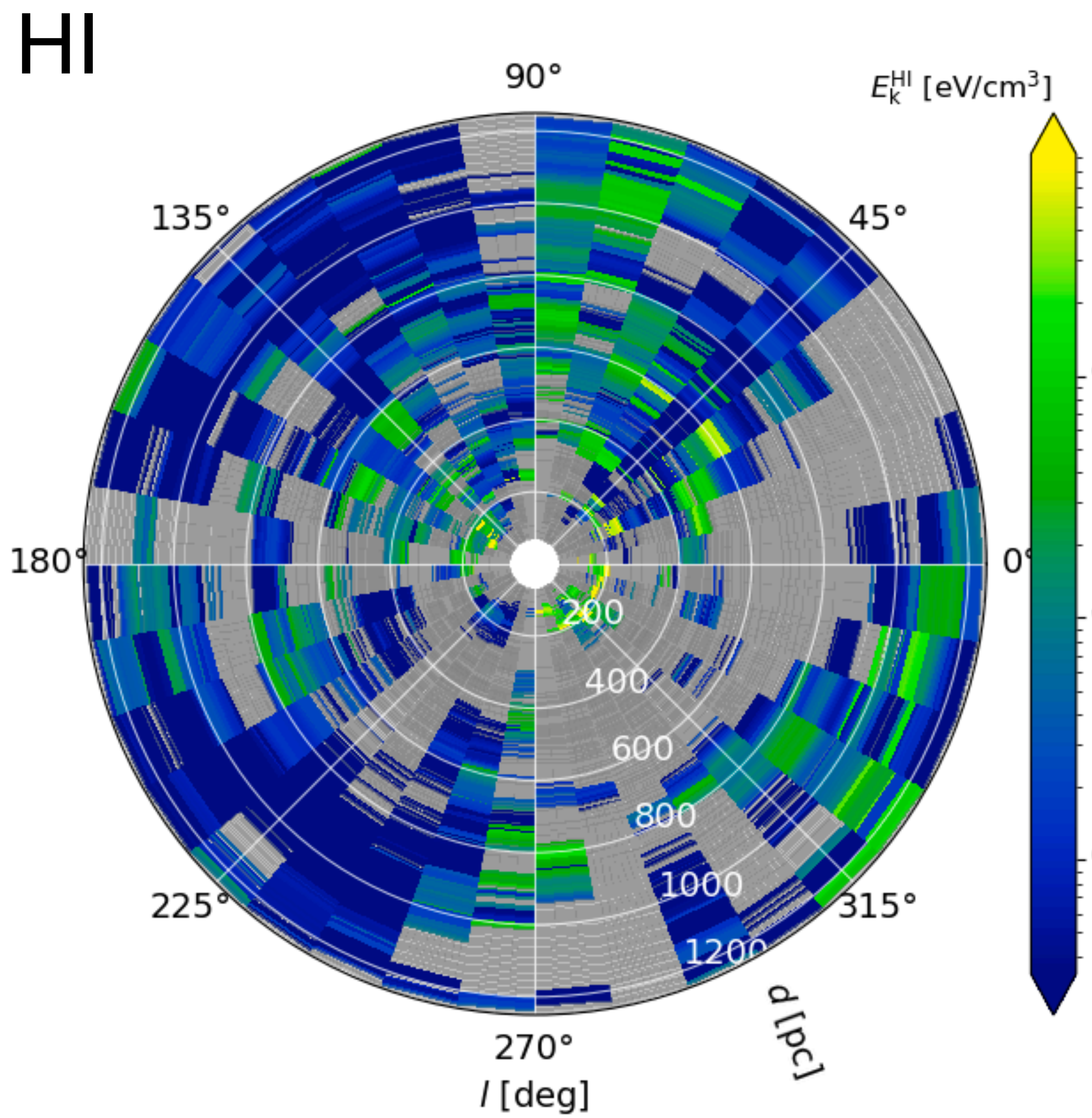
Density of O,B, and A-type stars

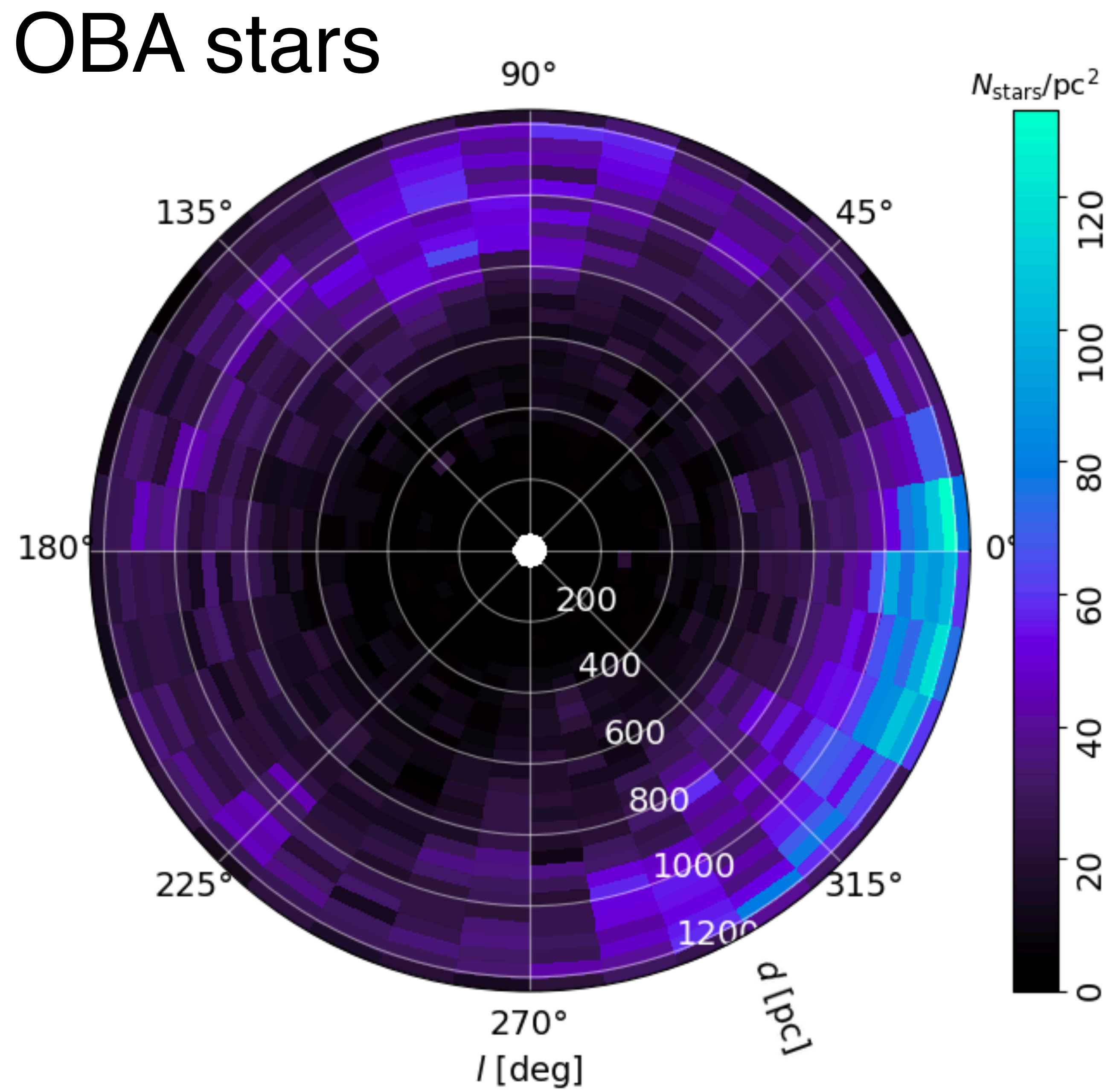
Zari et al. A&A (2021)



Whodunit: supernovae?

Soler et al. (2025) A&A





Conclusions

Soler et al. (2025) A&A

- Reconstruction of the line-of-sight (LOS) motions of the ISM based on the combination of HI and CO line emission and 3D dust.

- We used morphological correlation to assign LOS velocities to the dust across distance channels
  https://github.com/solerjuan/astroHOG

- Most of the material in the 3D dust model follows the large-scale pattern of Galactic rotation; however, we also identified streaming motions with amplitudes around 12.1 and 6.1 km/s for HI and CO, respectively.

- The mean kinetic energy densities related to these streaming motions is around 0.68 and 0.18 eV/cm^3 for either gas tracer.

- Energy overdensities appear concentrated in the Radcliffe wave and other large scale structures, suggesting they are not exclusively produced by supernova feedback.