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Warm ionized medium

The warm ionized medium (WIM) traces energy transport in the diffuse ISM of star-forming galaxies. For non-starburst galaxies, the fraction of the H α luminosity which is seen in the WIM is a remarkably consistent $59 \pm 19\%$ (Oey et al 2007, reproduced in Figure 1), suggesting that some universal process creates the WIM. The WIM accounts for $\approx 90\%$ of the H $^+$ mass in the Milky Way. The energy requirement can only be met by photoionization from massive stars; the complex structure established in the ISM by supernova-driven turbulence likely allows ionizing photons to propagate far enough to ionize the WIM (Wood et al 2010).

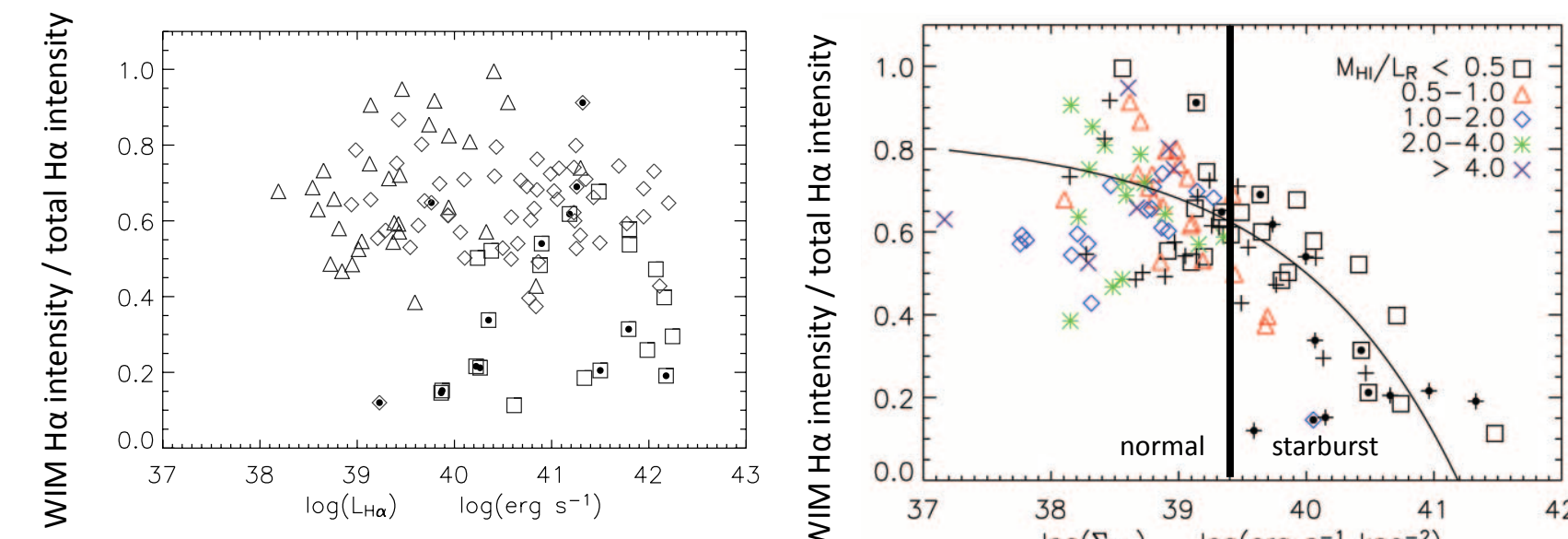


Fig. 1: Fraction of the H α luminosity in SINGS galaxies which is associated with the WIM (not H II regions) plotted as a function of total H α luminosity (left) and surface H α flux density (right). From Oey et al (2007).

Observations

We present a variety of observations obtained with the Wisconsin H α Mapper (WHAM), which is described in the adjacent poster by Haffner et al. In Figure 2, we present WHAM observations of H α and [S II] $\lambda 6716$ from Hill et al (2014). In Figure 3, we present a map of the line ratio H α /[S II].

Vertical extent

The WIM is considerably thicker than the atomic gas layer, with a typical exponential scale height of ~ 1 kpc. Locally, pulsar dispersion measures indicate a scale height of 1.4 ± 0.2 kpc (Gaensler et al 2008; Savage & Wakker 2009). Electron scale heights measured from H α emission in spiral arms are generally lower, especially in the inner Galaxy; see Fig. 4 and Table 1.

The quantity D/H_n^2 is measured by fitting H α intensity as a function of Galactic latitude. The electron-density-squared scale height H_n^2 can then be measured with an assumed distance to the arm. If the volume filling factor does not change as a function of height, the electron density scale height $H_n = 2H_n^2$. From Table 1, the implied scale heights assuming a uniform filling factor are ≈ 800 pc in the Perseus Arm outside the Solar circle, ≈ 600 pc in the Scutum-Centaurus Arm inside the Solar circle, and ≈ 200 – 300 pc in the inner Galaxy.

Table 1: Scale Height Measurements					
$b_{\min}$	$b_{\max}$	R_G (kpc)	$\ln(I_0/R)$	D/H_n^2	H_n^2 (pc)
Scutum-Centaurus Arm (Hill et al 2014)					
5°	21°	5.5	1.34 ± 0.12	8.1 ± 0.4	430 ± 50
-21°	-5°	5.5	1.41 ± 0.16	9.5 ± 0.6	370 ± 40
Scutum-Centaurus Arm, extinction-corrected (Hill et al 2014)					
3°	21°	5.5	2.52 ± 0.10	10.7 ± 0.4	330 ± 40
-21°	-3°	5.5	2.86 ± 0.11	13.1 ± 0.5	270 ± 30
Perseus Arm (Haffner et al. 1999)					
-30°	-15°	10	1.73 ± 0.19	4.91 ± 0.39	400 ± 30
Inner Galaxy, extinction-corrected (Madsen & Reynolds 2005)					
-5°	$-0:8$	6.0	4.9 ± 0.5	32^{+7}_{-10}	95^{+30}_{-20}
-5°	$-0:8$	4.9	5.5 ± 0.5	33^{+6}_{-11}	135^{+45}_{-25}
-5°	$-0:8$	4.1	6.3 ± 0.9	40^{+1}_{-24}	150^{+90}_{-40}

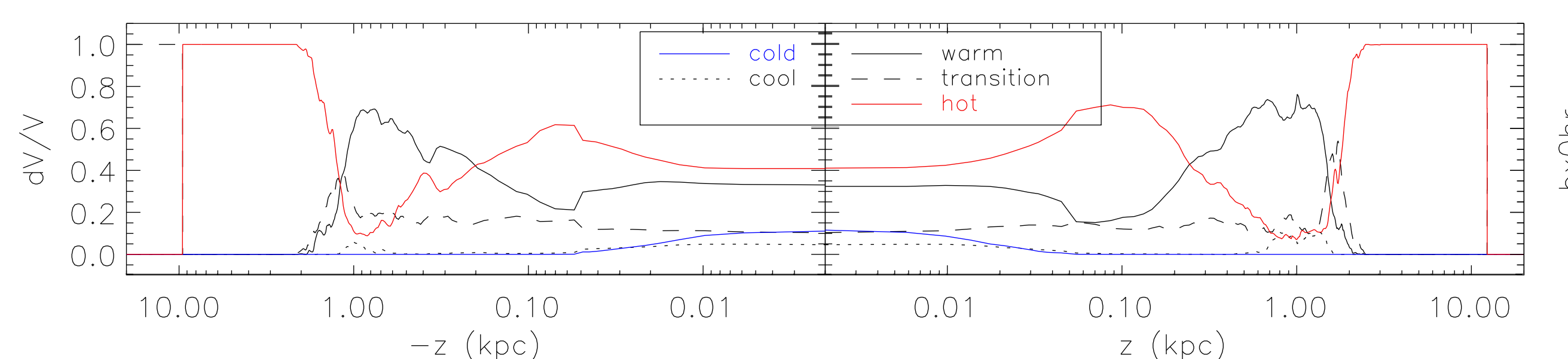


Fig. 7: Volume filling factor of the phases of the ISM as a function of height in simulations. The simulations incorporate supernovae, parameterized photoelectric heating, and line cooling appropriate for the ISM near the Sun. From Hill et al (2012).

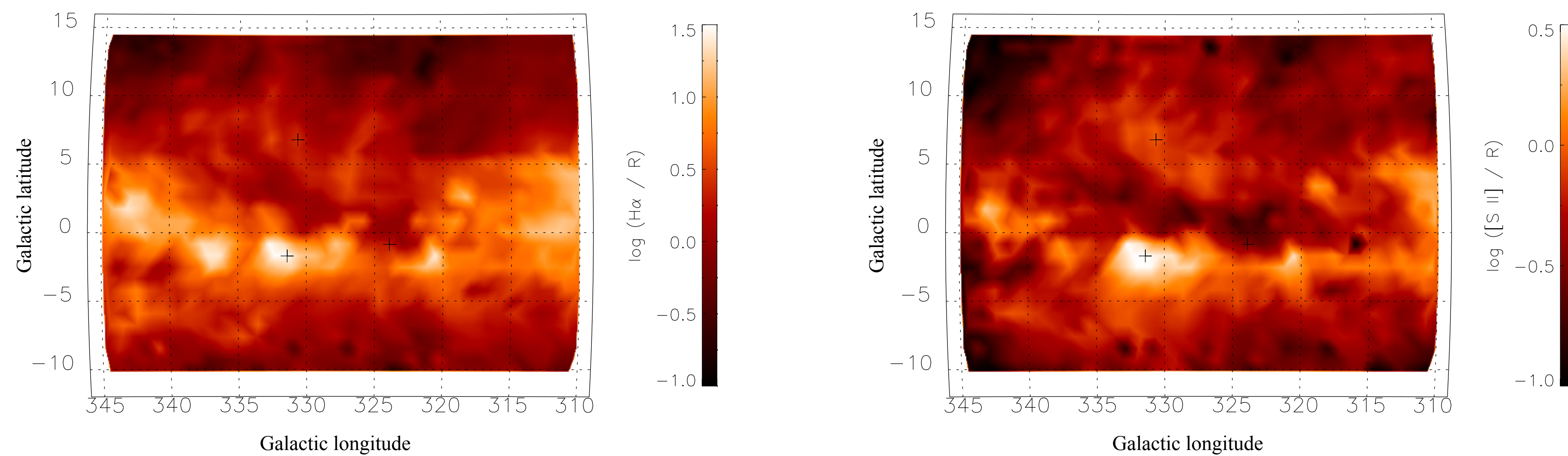


Fig. 2: Maps of H α and [S II] $\lambda 6716$ intensity in the Scutum-Centaurus Arm observed with WHAM (Hill et al 2014).

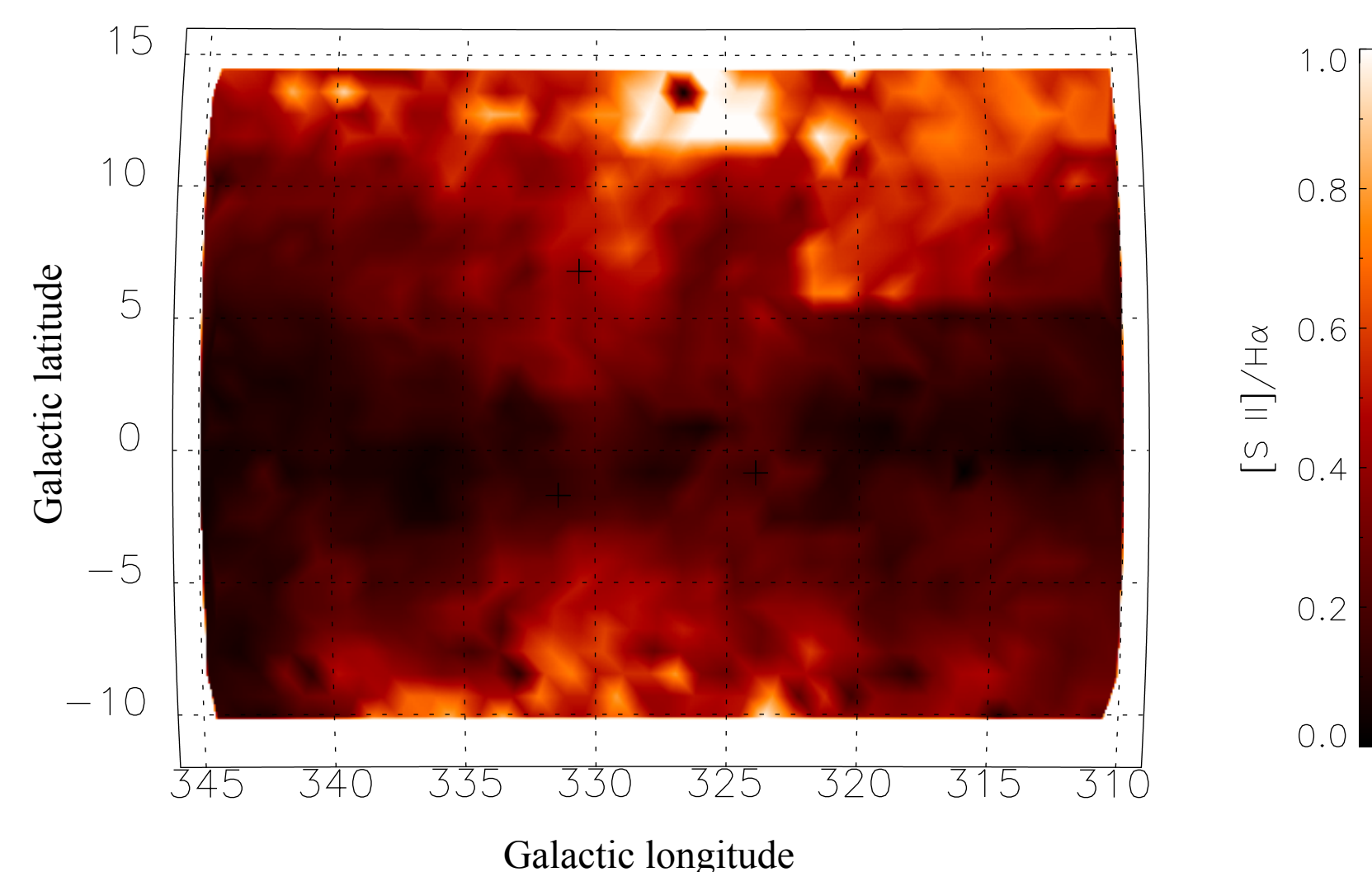


Fig. 3: Map of the line ratio H α /[S II] $\lambda 6716$ intensity in the Scutum-Centaurus Arm (Hill et al 2014).

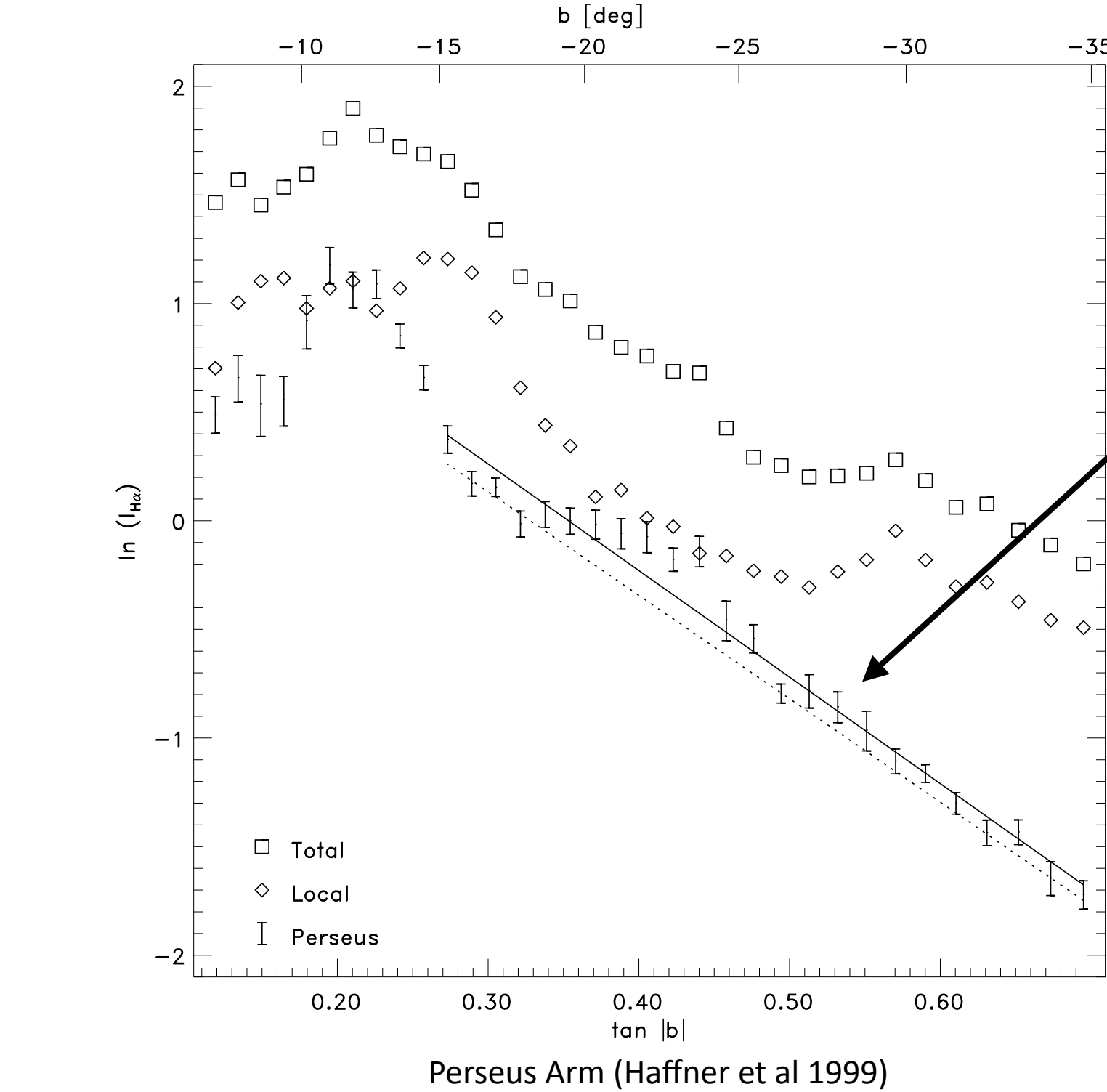
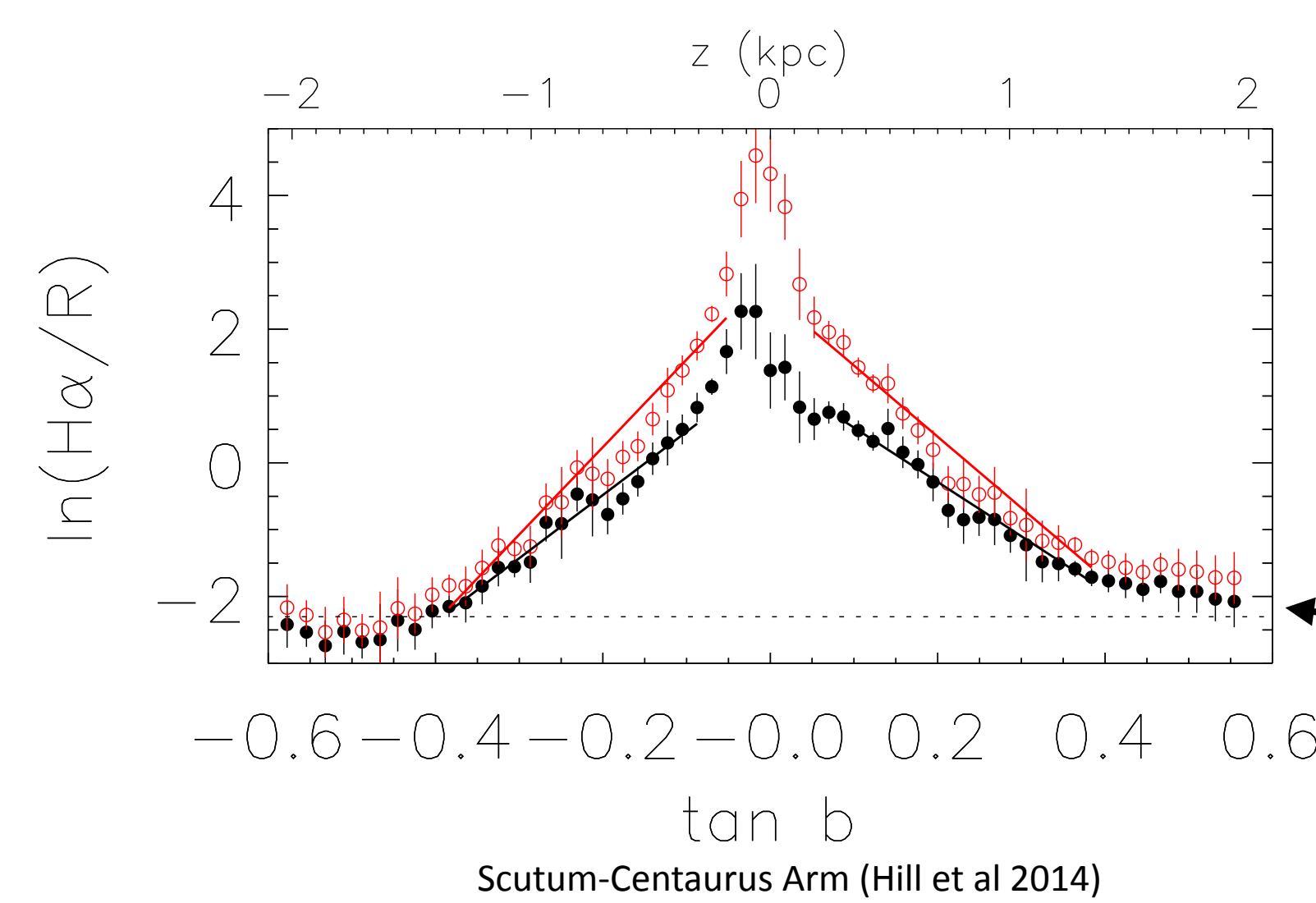


Fig. 4: H α intensity as a function of height in two spiral arms with the position of the arms on the artist's conception of the Milky Way by R. Hurt. In the top panel, black symbols show the H α intensity, while red symbols show the H α intensity with an estimated extinction correction. Derived scale heights are listed in Table 1.

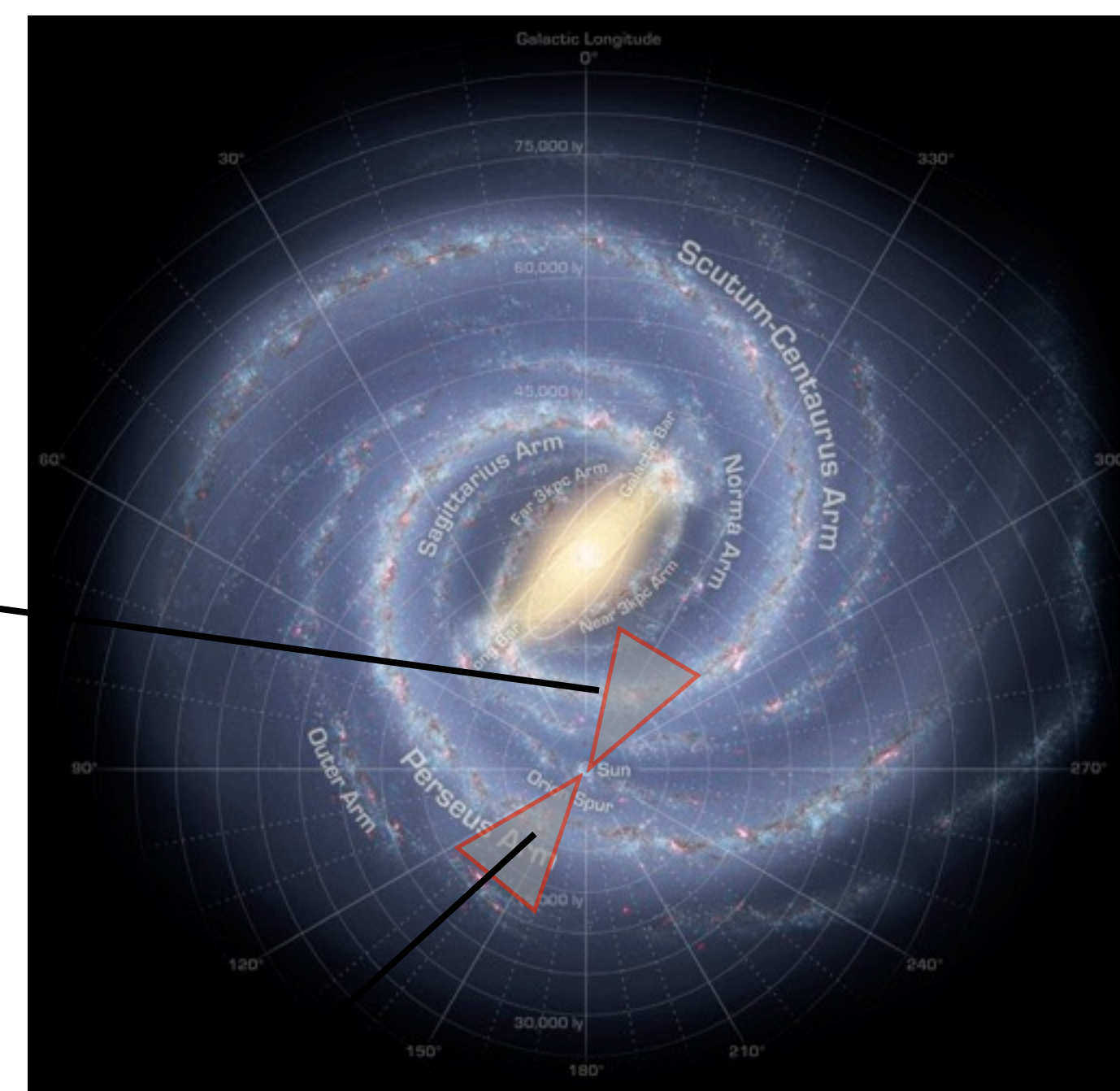


Fig. 5: Artists' conception of the spiral structure of the Milky Way with the directions probed in the surveys of the Perseus Arm and Scutum-Centaurus Arm shown in Fig. 3. NASA/JPL-Caltech/R. Hurt (SSC/Caltech).

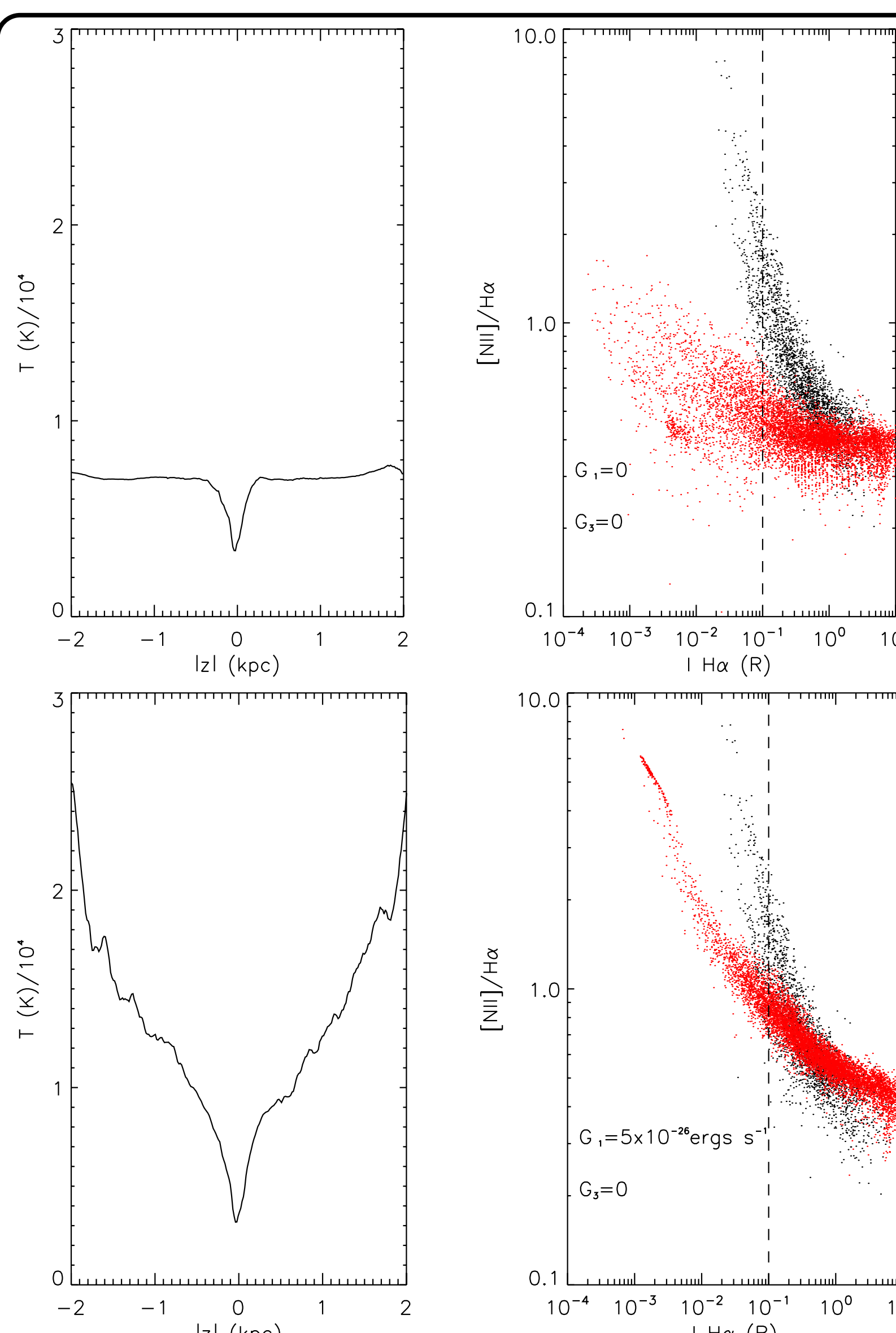


Fig. 8: Temperature and line ratio trends in numerical simulations incorporating photoionization in a fractal ISM. The top panel includes only photoionization heating ($\propto n_e^2$). The bottom panel includes a heating term which scales as n_e . From Barnes et al (2014).

Physical conditions

The combination of H α emission and emission from forbidden emission lines like [N II] and [S II] constrains the temperature and ionization state of the WIM. The line ratios [N II]/H α and [S II]/H α are both lower in classical H II regions than in the WIM (Fig. 3); these line ratios are also generally lower at higher H α intensities and closer to the mid-plane (Fig. 6).

These observations are most-readily interpreted as a higher temperature (8000 K compared to 6000 K) and lower dominant ionization state (O^+ and S^+ compared to O^{++} and S^{++} are the dominant ions) in the WIM than in H II regions. These physical conditions require a radiation field that is very dilute, with an ionization parameter $U \sim 10^{-3} - 10^{-4}$ ionizing photons per electron (Mathis 1986). A supplemental non-photoionization heating source that becomes dominant at low densities ($< 0.1 \text{ cm}^{-3}$) is also required to explain the observations (Reynolds et al 1999, Barnes et al 2014, and Fig. 8).

The cause of the different physical conditions is not obvious but is most likely related to differences in the ionizing radiation field or the local gas density. We attempt to break this degeneracy by comparing measurements of [S II]/H α as a function of height and as a function of H α intensity in Fig. 6. After dividing out the dependence on height, a dependence on H α intensity remains. After dividing out the dependence on intensity, no dependence on height remains. This suggests that local properties such as density affect the physical conditions more than global properties such as distance from the plane or ionizing radiation field.

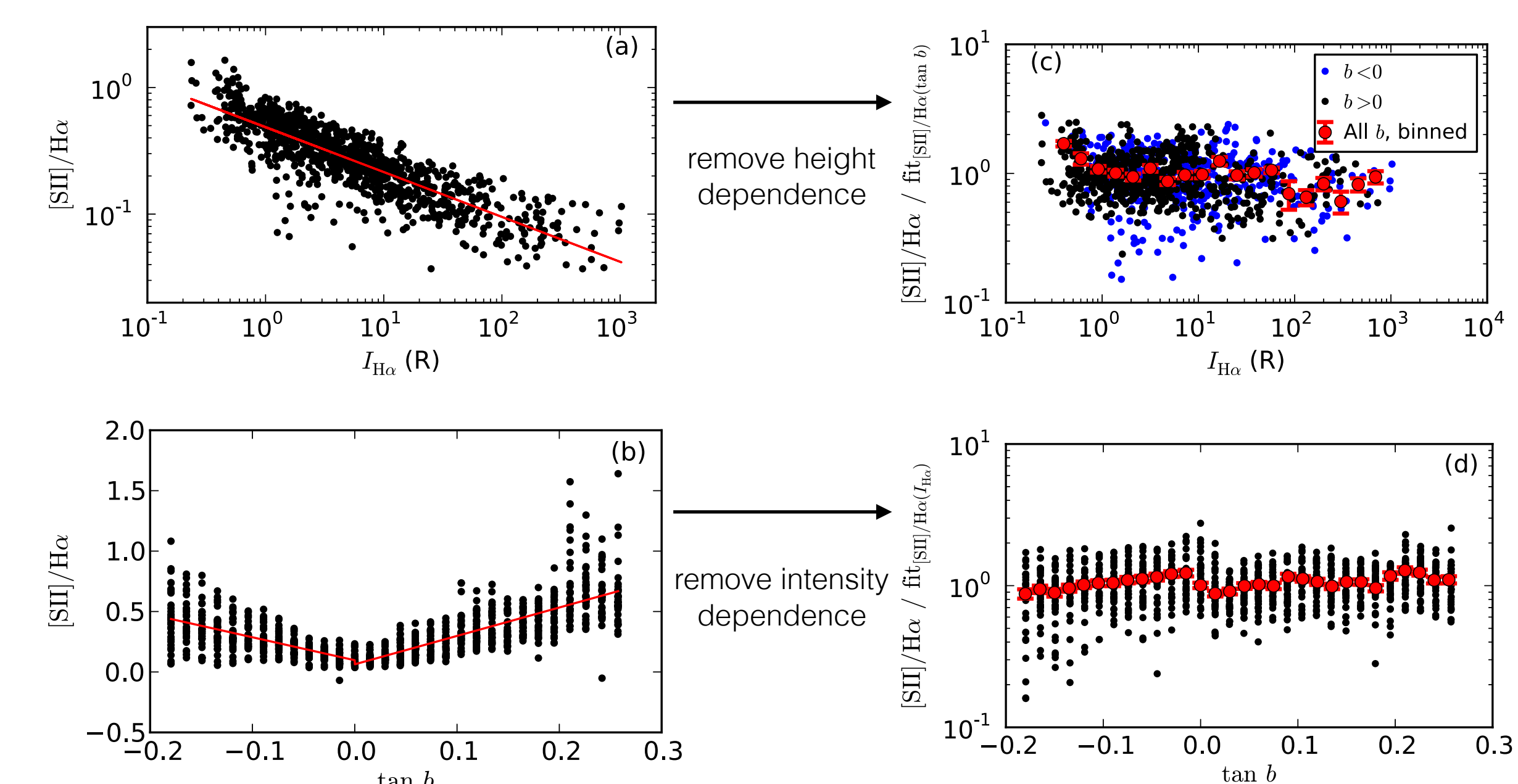


Fig. 6: [S II]/H α line ratio in the Scutum-Centaurus Arm as a function of H α intensity (top) and Galactic latitude (bottom). The left panels show the observations. In the right panels, we have divided out the dependence on the other parameter. From Hill et al (2014).

Summary

- The warm ionized medium is a universal component of star-forming galaxies, photoionized by massive stars.
- The WIM in spiral arms is more vertically extended in the outer Galaxy (~ 1 kpc) than the inner (~ 200 pc).
- The combination of H α and pulsar dispersion measurements suggest that the WIM scale height is lower in spiral arms than locally and that the volume filling fraction of the WIM is larger at ~ 1 kpc than in the disk (see also Fig. 7).
- Low-density WIM gas is likely warmer (≈ 8000 K) and in a lower ionization state than higher-density WIM gas and classical H II regions.
- Photoionization heating alone cannot explain the observed line ratio trends and implied temperature and ionization state of the WIM. A non-photoionization heating source which is important at low densities could explain the observations.

References

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