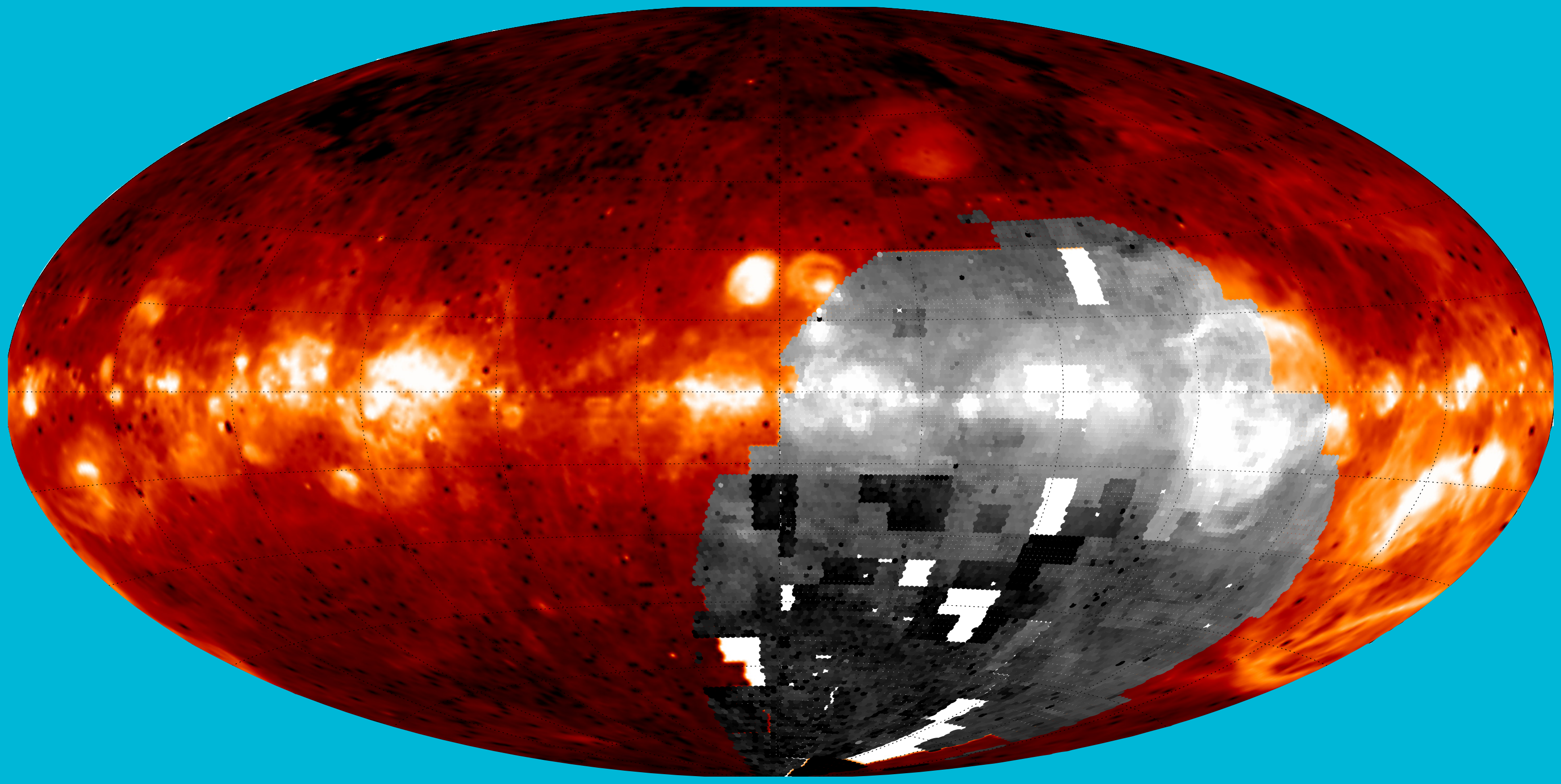

The warm ionised medium

Alex S Hill

Matt Haffner, Ron Reynolds, Bob Benjamin, Kenny Wood, & Jo Barnes

ON THE EXISTENCE OF AN IONIZED LAYER ABOUT THE GALACTIC PLANE

By F. Hoyle* and G. R. A. Ellis†

[*Manuscript received November* 8, 1962]
Australian J. Phys.

Summary

The radio frequency spectrum observed in directions towards the galactic pole shows a maximum near 5 Mc/s. It seems unlikely that the synchrotron process responsible for the emission can give such a maximum and it is suggested that the observed fall in the flux density at lower frequencies is caused by absorption in an ionized layer parallel to the galactic plane.

To avoid an excessive value of the calculated electron density the kinetic temperature is taken as low as is consistent with the maintenance of ionization, about 10^4 °K. At this temperature the gas cannot fill the galactic halo but must form a layer along the galactic plane, the layer having a half-width of the order of 10^{21} cm. (~325 pc)

The electron density is found to be about $0 \cdot 1$ cm^{-3} so that along a line of sight to the galactic pole there are of the order of 10^{20} electrons. The mass of the layer is $\sim 5 \times 10^8 M_\odot$ and its rate of radiation in the Balmer continuum is $10^7 L_\odot$. The radiation rate per unit volume is $\sim 10^{-26}$ erg cm^{-3} s^{-1} in the Balmer continuum and the total radiation rate is $\sim 5 \times 10^{-26}$ erg cm^{-3} s^{-1}, a value close to the average emission of ionizing radiation by O and B stars.

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OBSERVATIONS OF DIFFUSE GALACTIC Hα AND [N II] EMISSION

R. J. Reynolds* and F. Scherb†
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AND

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Physics Department, University of Wisconsin, Madison

Received 1973 March 5; revised 1973 June 12

ABSTRACT

A study has been made of the intensities and radial velocities of faint galactic Hα and [N II] λ6584 emission lines not associated with any known bright H II regions. Although some (~10 percent) of the observed radiation may be scattered galactic light from bright H II regions in the galactic plane, most of the radiation appears to be produced by an ionized component of the interstellar gas which is distributed throughout the interstellar medium within the three nearby galactic spiral arms. In the local Orion arm the emitting gas has a temperature between 3000° and 8000° K and mean square electron density $\langle n_e^2\rangle \simeq 0.05$ cm^{-6} in the galactic plane, while in the Perseus and Sagittarius arms $\langle n_e^2\rangle \simeq 0.1$ and 0.9 cm^{-6}, respectively.

Subject heading: interstellar matter

Warm ionised medium (WIM)

Often called the “diffuse ionised gas” (DIG) or “Reynolds Layer”

Pervasive component of star-forming galaxies

≈90% of the H^+ and ≈1/4 of the total atomic H mass of the Milky Way ISM

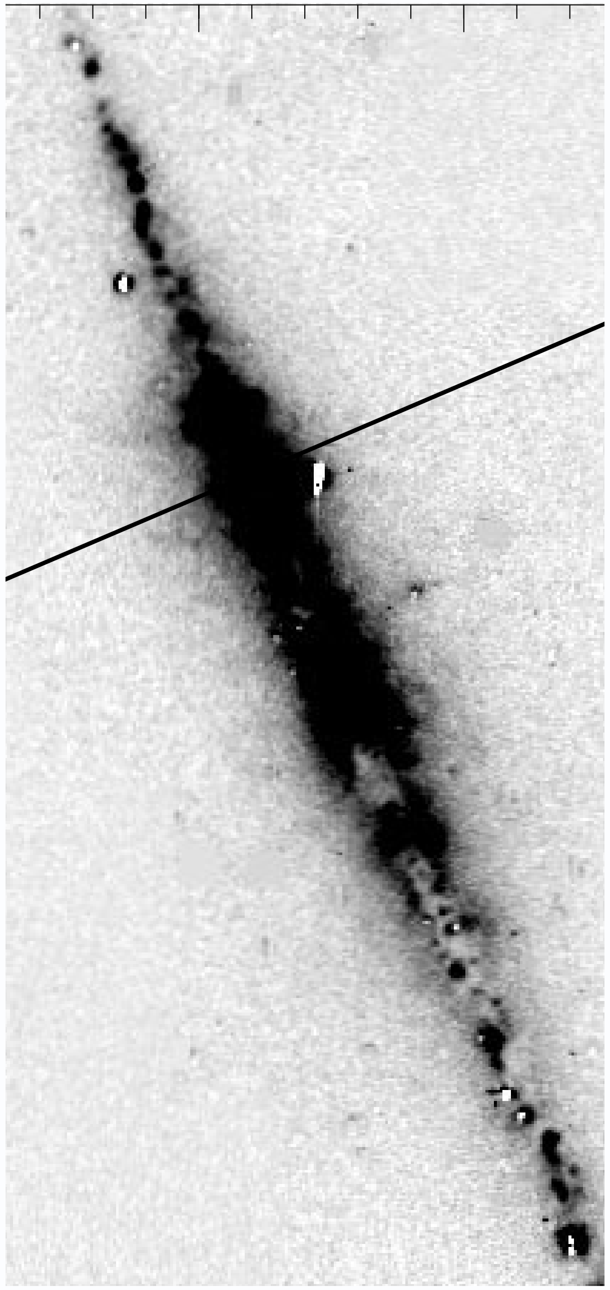
Nearly fully ionised, T = 6000 – 10000 K

Extends to more than 1 kpc above the midplane

Observationally distinct from classical H II regions

Primarily photoionised by OB stars in the plane

- turbulent structure makes this possible



NGC 891
Rand et al (1990)

Observations

Observational diagnostics

Pulsar dispersion

$$\mathrm{DM} = \int_0^D n_e \, ds$$

Faraday rotation

$$\mathrm{RM} = \int n_e \mathbf{B} \cdot d\mathbf{s}$$

Emission measure

- Hα and other emission lines
- free-free

$$\mathrm{EM} = \int_0^\infty n_e^2 \, ds$$

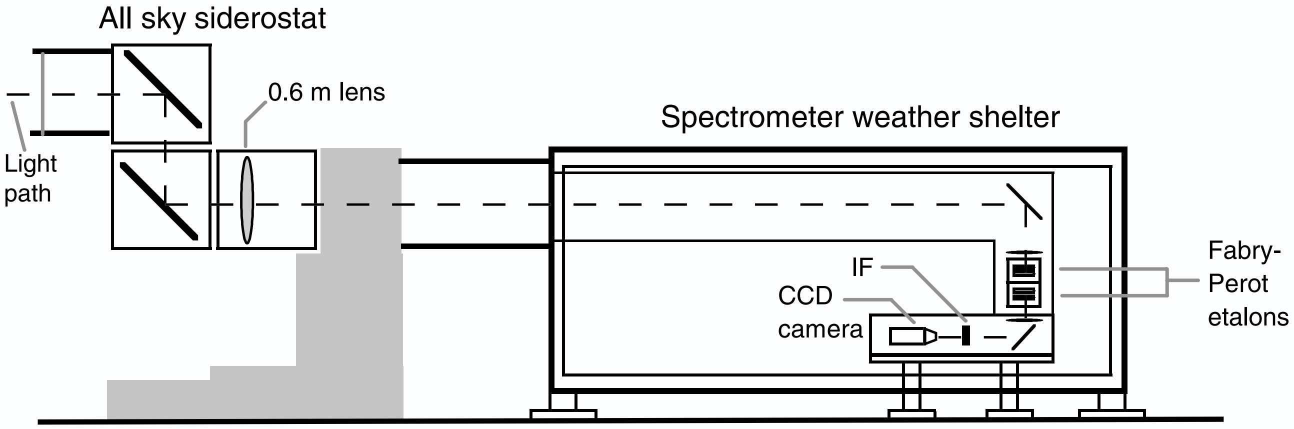
WIM optical surveys

Survey	Sky coverage	δV	Lines	δθ	σ
WHAM-NSS (Haffner et al 2003 ApJS)	$\delta > -30°$	12 km s^{-1}	Hα	1°	0.15 R
WHAM-SSS (in prep)	$\delta < +30°$	12 km s^{-1}	Hα	1°	0.15 R
WHAM (Haffner et al 1999; Madsen et al 2005, 2006)	partial	12 km s^{-1}	[N II] λ6584, [S II] λ6716, others 4800 A < λ < 7300 A	1°	<0.15 R
SHASSA (Gaustad et al 2001 PASP)	$\delta < +15°$	imaging	Hα + [N II] contamination	0.8′	2 R
VTSS (Dennison et al 1998 PASP)	partial $\delta > -30°$	imaging	Hα + [N II] contamination	1.6′	~1 R
Finkbeiner (2003 ApJS) composite of WHAM-NSS, SHASSA, and VTSS	Full	imaging	Hα + [N II] contamination	6′	Varies

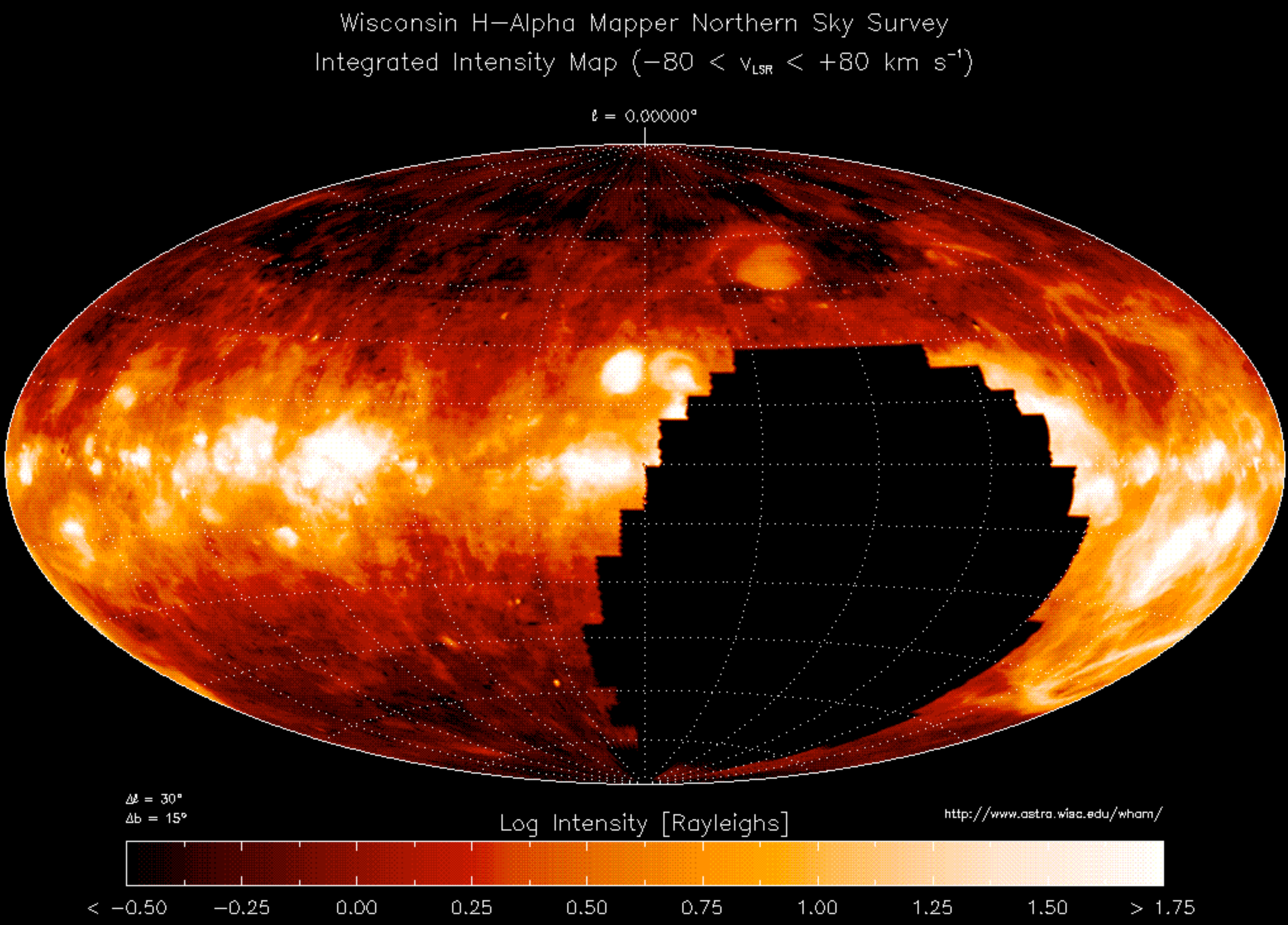
Observing the WIM

Hα emission very faint

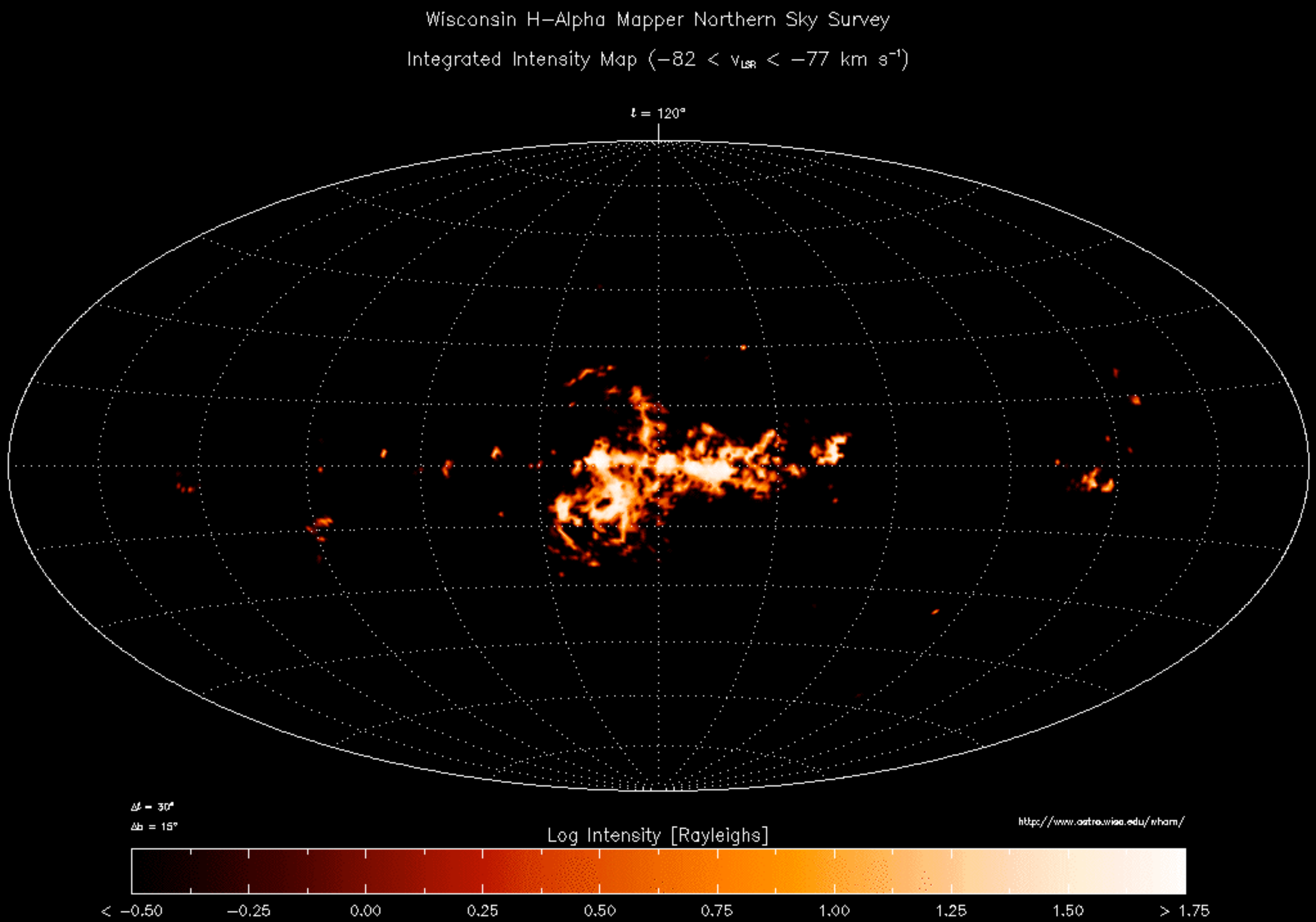
- Need highly sensitive spectrometer
- Wisconsin Hα Mapper (WHAM)
  - Dual-etalon Fabry Perot spectrometer
  - Can observe 4800 – 7300 A
    - Hα, Hβ, [N II] λ6584, [S II] λ6716, [N II] λ5755, He I λ5876, [O III] λ5007, [O I] λ6300, etc
  - One degree pointings capture a spectrum
    - Spectral resolution of 12 km s^{-1} (R = 25,000)
    - 200 km s^{-1} wide tunable window
    - Sensitivity ≈0.15 R in a 30 s exposure
- Kitt Peak 1996 – 2008; now at Cerro Tololo



Haffner et al (2003 ApJS)



Wisconsin H-Alpha Mapper Northern Sky Survey
Integrated Intensity Map (-80 < v_LSR < +80 km s^-1)
ℓ = 0.00000°
Δℓ = 30°
Δb = 15°
Log Intensity [Rayleighs]
http://www.astro.wisc.edu/wham/
< -0.50
-0.25
0.00
0.25
0.50
0.75
1.00
1.25
1.50
> 1.75


Wisconsin H-Alpha Mapper Northern Sky Survey
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http://www.astro.wisc.edu/wham/
Log Intensity [Rayleighs]
< −0.50
−0.25
0.00
0.25
0.50
0.75
1.00
1.25
1.50
> 1.75

H II region or WIM?

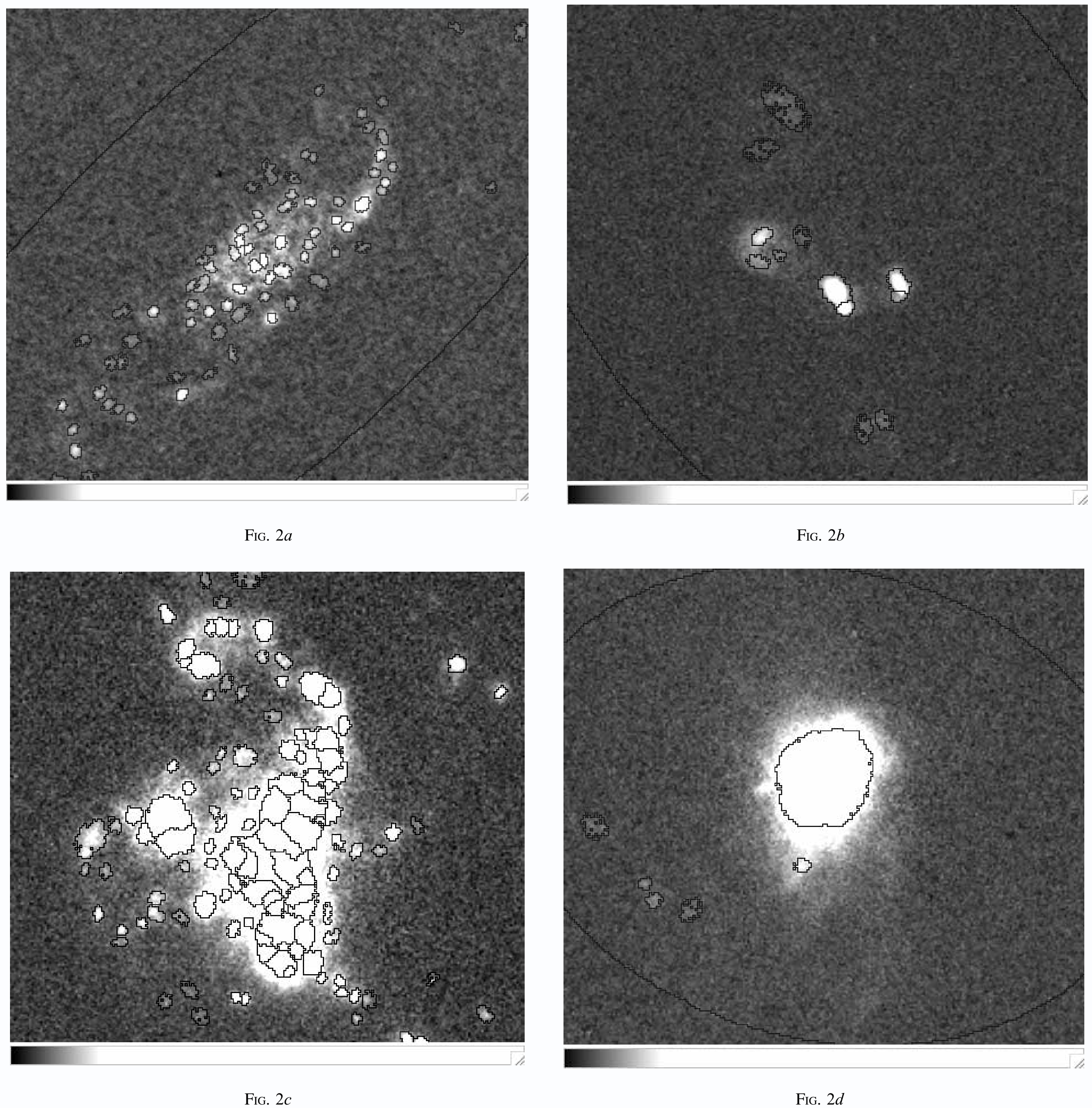
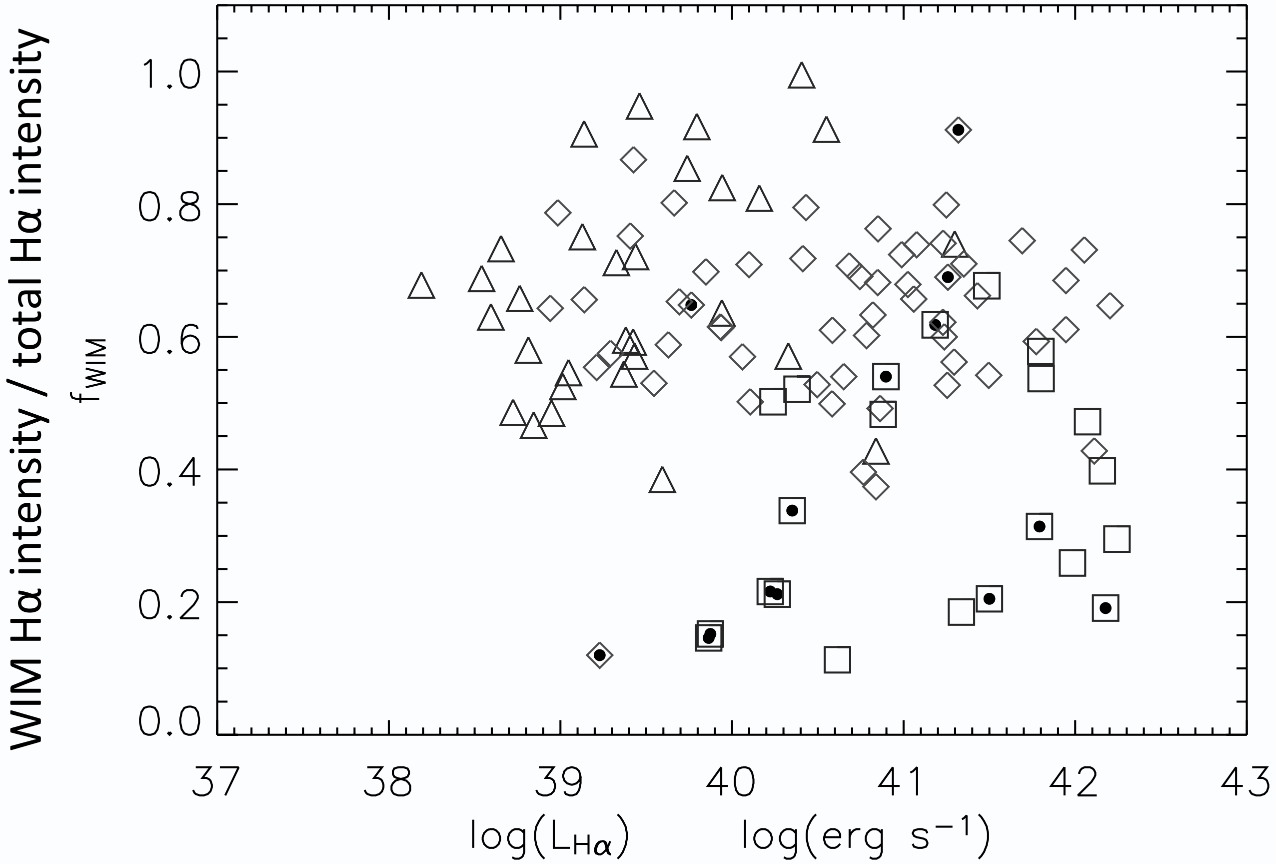


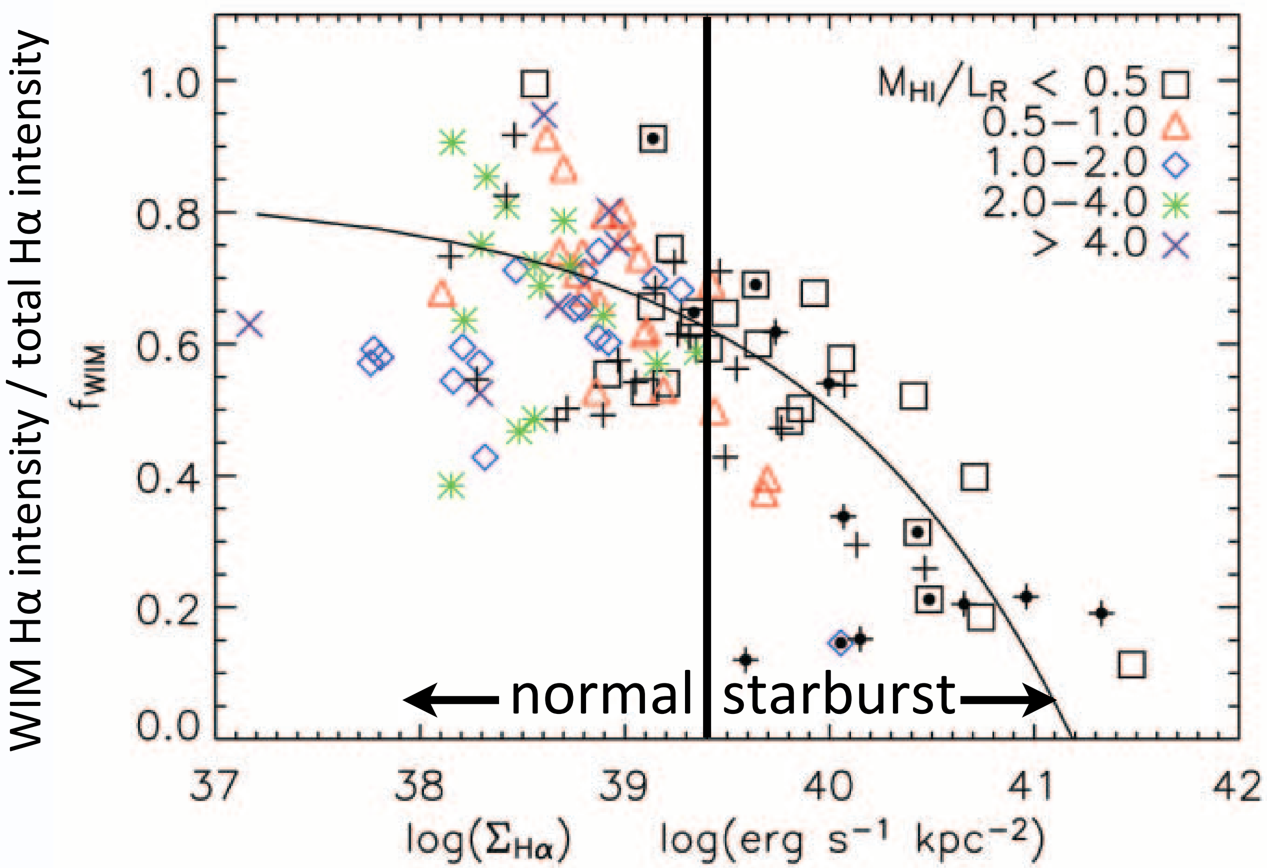
Fig. 1.—Representative examples of the galaxy categories. (*a*) "Normal": J0412+02, $\log \Sigma_{\mathrm{H}\alpha} = 38.92$. (*b*) "Sparse": J0031−22, $\log \Sigma_{\mathrm{H}\alpha} = 38.26$. (*c*) "Starburst": J0355−42, $\log \Sigma_{\mathrm{H}\alpha} = 39.40$. (*d*) "Nuclear Starburst": J0209−10:S2. $\Sigma_{\mathrm{H}\alpha}$ is quoted in units of erg s^{-1} kpc^{-2}. H II region boundaries defined by HIIphot are outlined in black. The large elliptical apertures indicated by the black lines around the galaxies are those defined from *R*-band images by Paper I (their r_{max}) for the total galaxy flux measurements. The images are roughly 1.8′ square, with north up and east to the left; all are displayed with the same gray scale.

Oey et al (2007 ApJ)

H II region or WIM?



Total star formation rate



Star formation intensity

59±19% of Hα luminosity of normal galaxies is WIM

- Little trend among normal galaxies

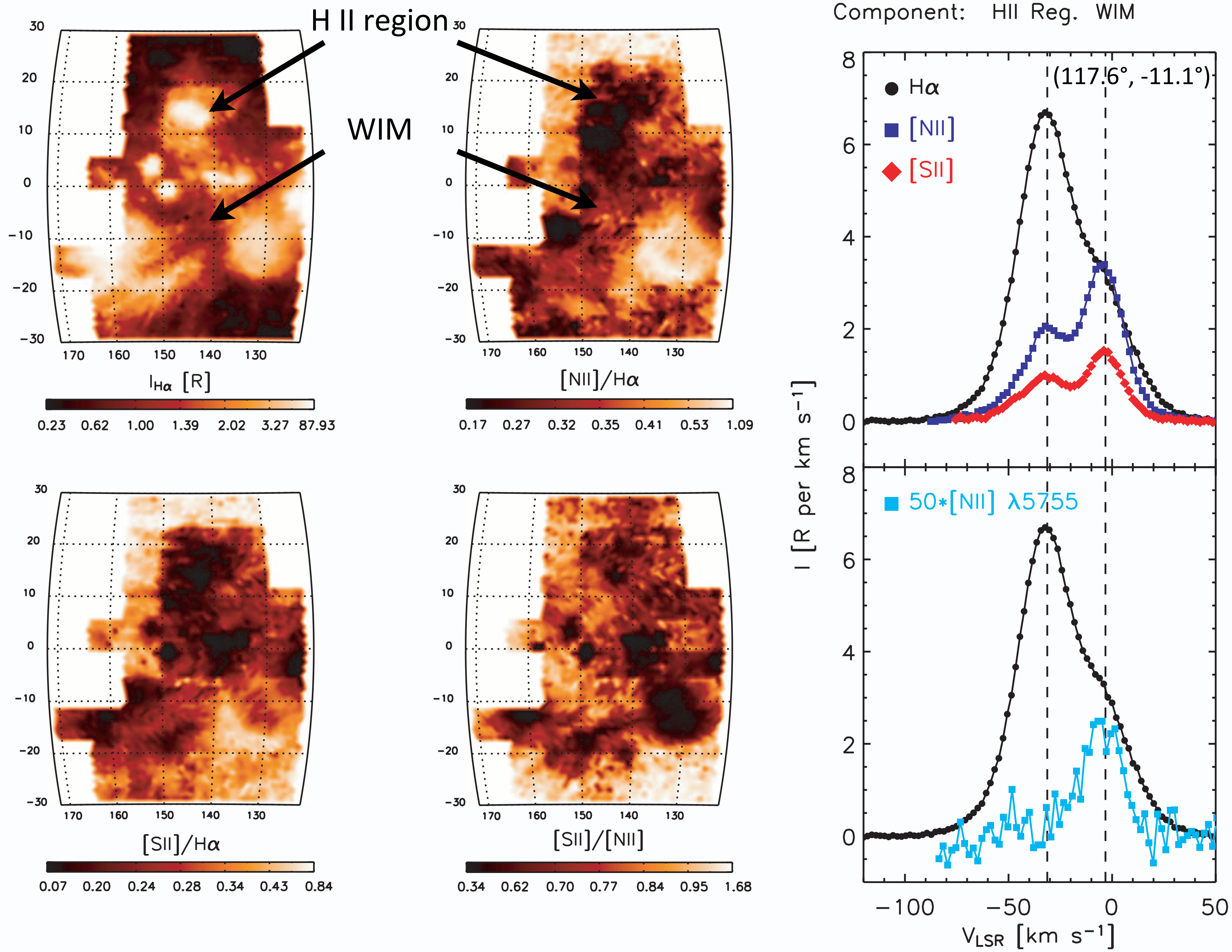
Lower WIM fraction in starbursts

Oey et al (2007 ApJ)

Comparison to H II regions

Forbidden line emission

- WIM is distinct from locally-ionised classical H II regions (Reynolds 1985 ApJ)
  - Elevated [N II] / Hα and [S II] / Hα



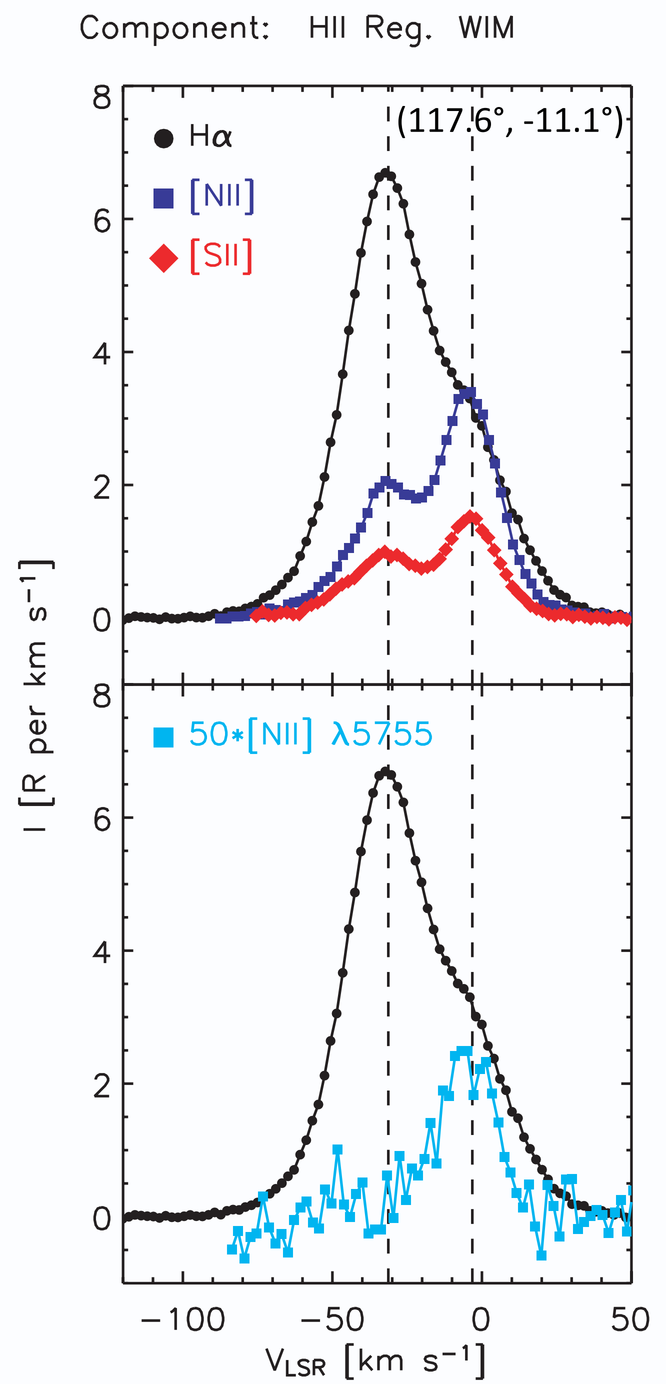
Madsen, Reynolds, & Haffner (2006 ApJ)

Temperature

Elevated [N II]/Hα indicates higher temperature in WIM than H II regions

$$\frac{[\mathrm{N\ II}]}{\mathrm{H}\alpha} = 1.62 \times 10^5\, T_4^{0.4}\, e^{-2.18/T_4} \left(\frac{\mathrm{N}}{\mathrm{H}}\right) \left(\frac{\mathrm{N}^+}{\mathrm{N}}\right) \left(\frac{\mathrm{H}^+}{\mathrm{H}}\right)^{-1}$$

- Interpretation confirmed with [N II]λ 5755 line



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known ~1

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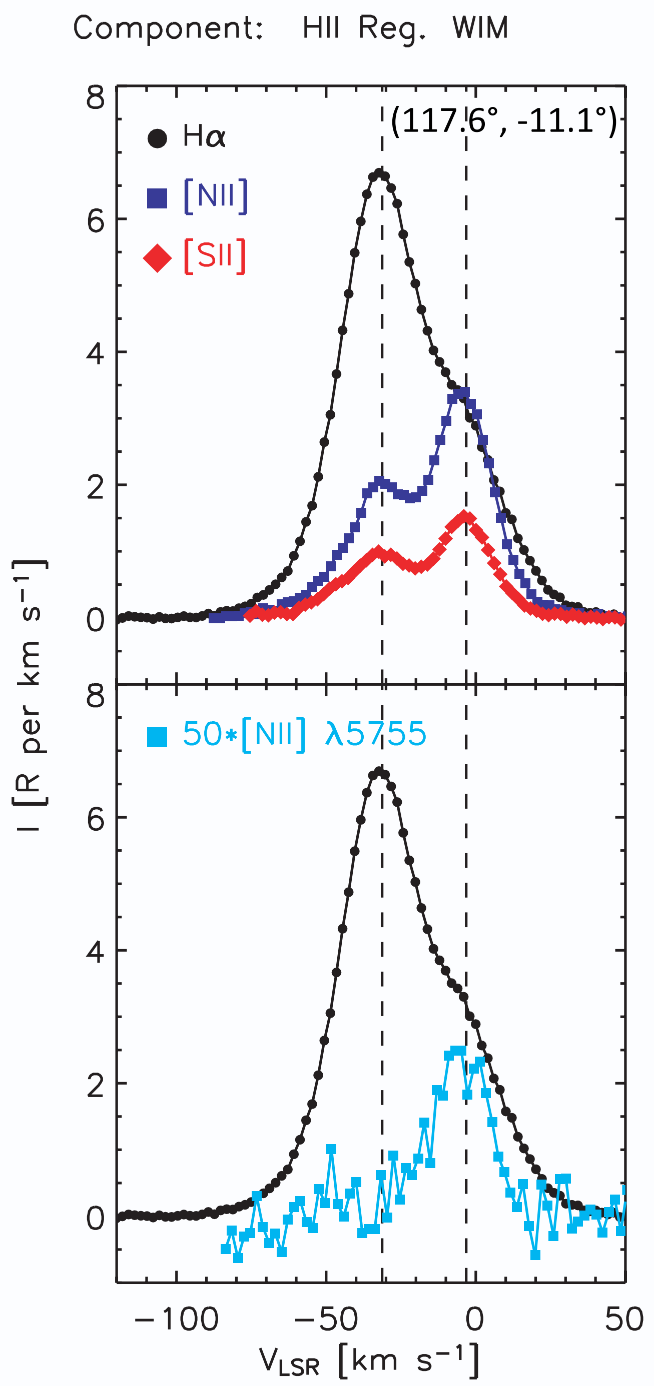
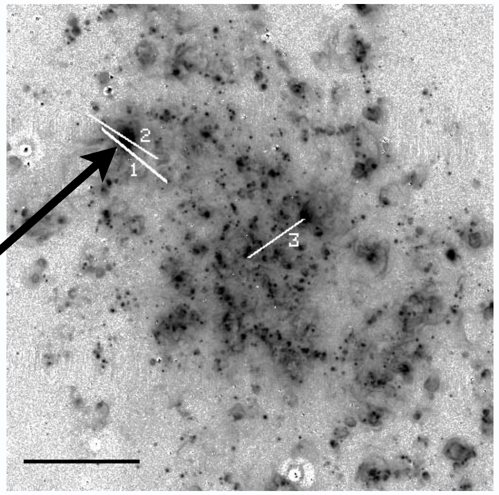
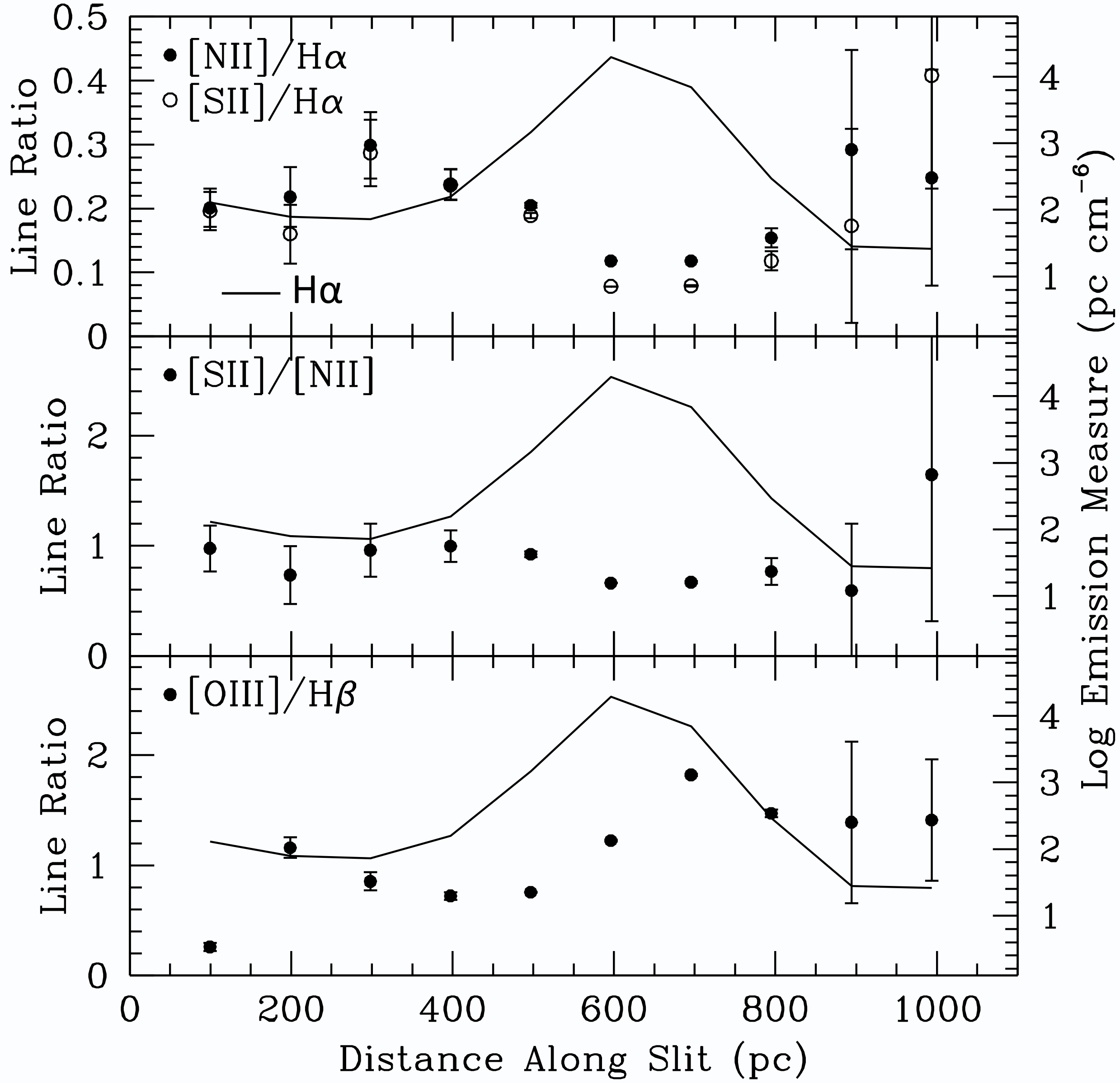


Spectral properties



NGC 604 in M33



Hoopes & Walterbos (2003 ApJ)

WIM Observations (Reynolds et al 1998 ApJ, Haffner et al 1999 ApJ, Madsen et al 2006 ApJ)

- [O I], [O III], and He I all very faint
- 0.1 ≲ [O II] / Hα ≲ 0.6 (Mierkiewicz et al 2006 ApJL)
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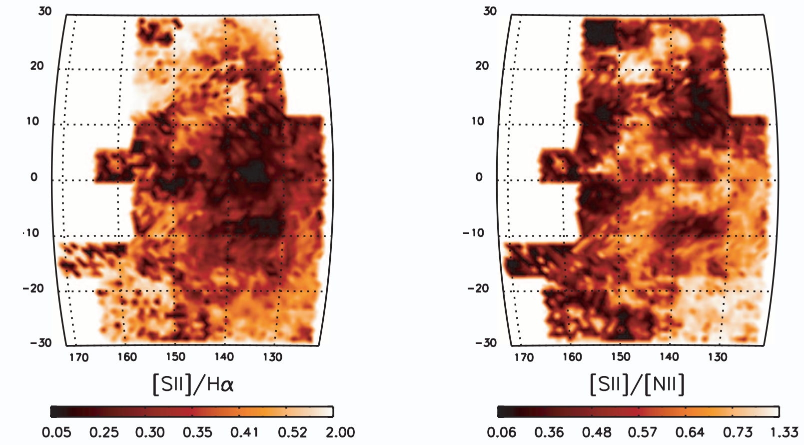

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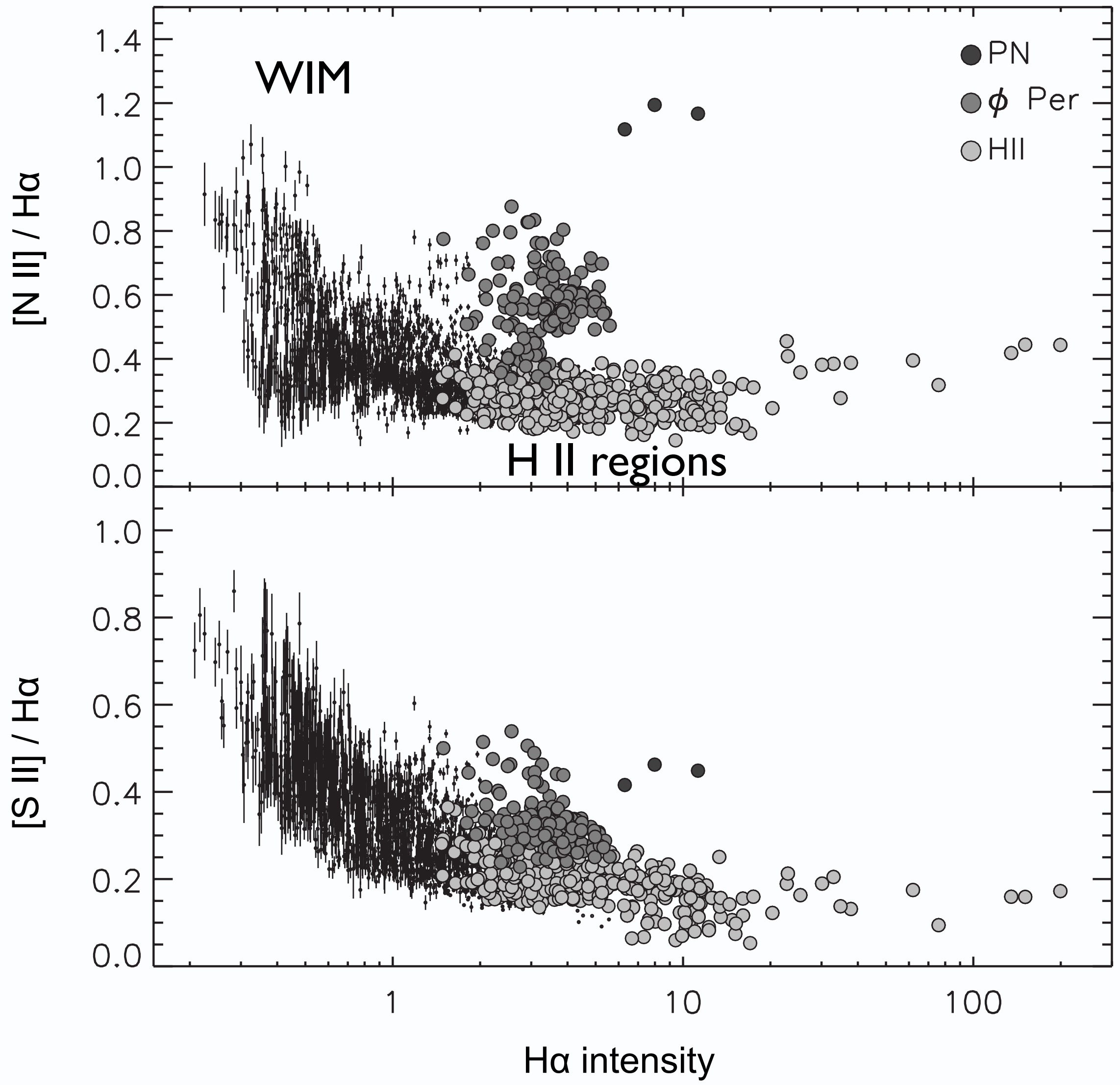
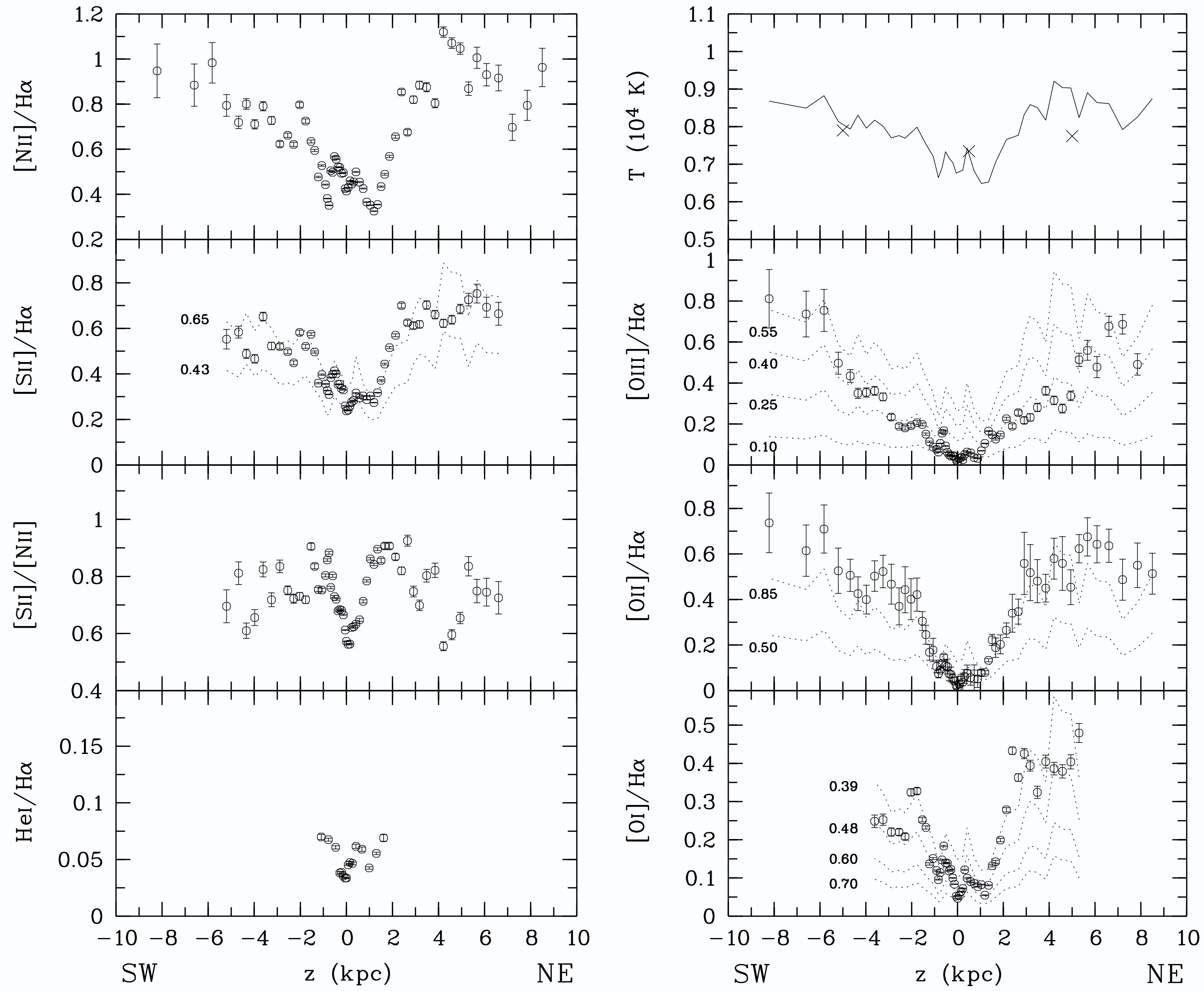


Haffner et al (2009 Rev Mod Phys)

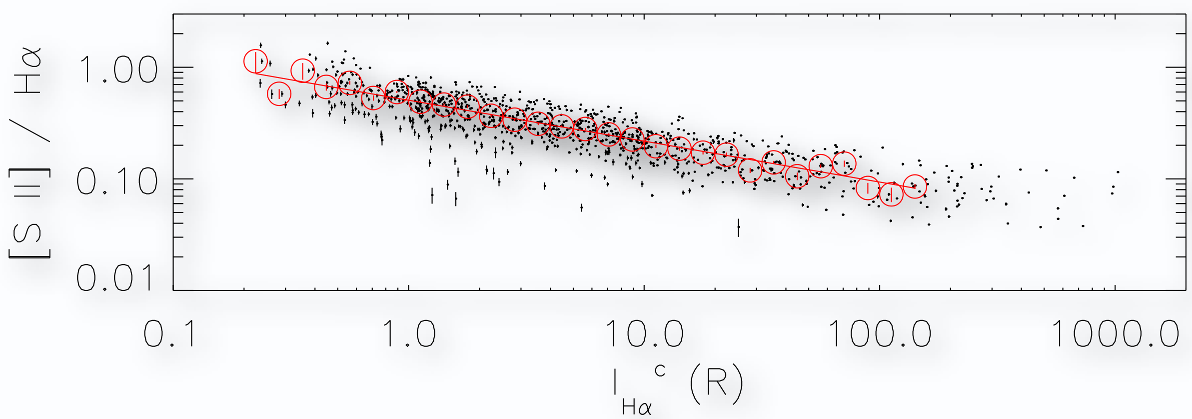
Trends with height

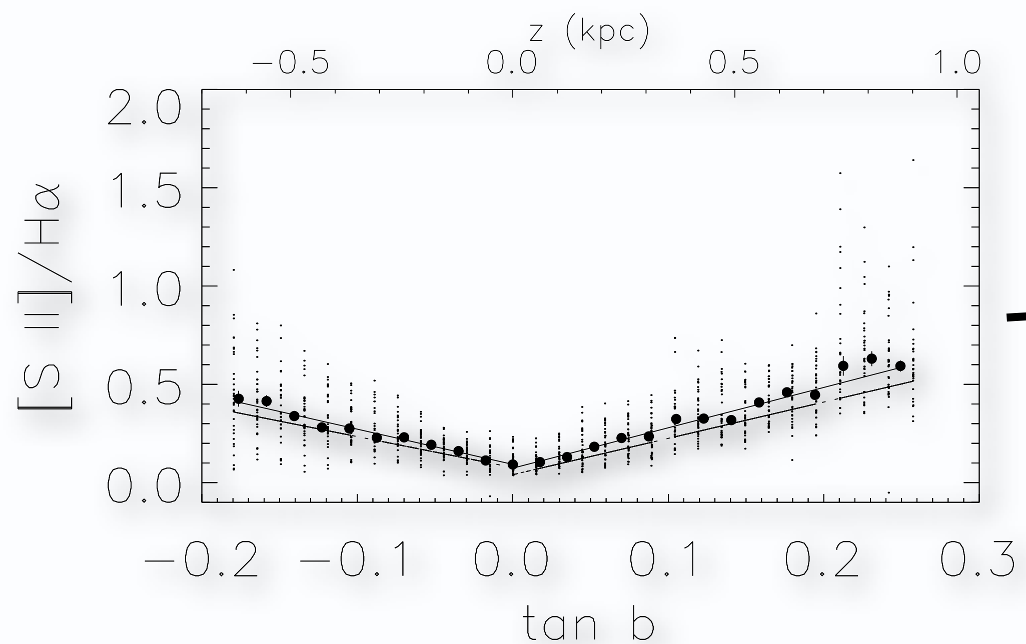


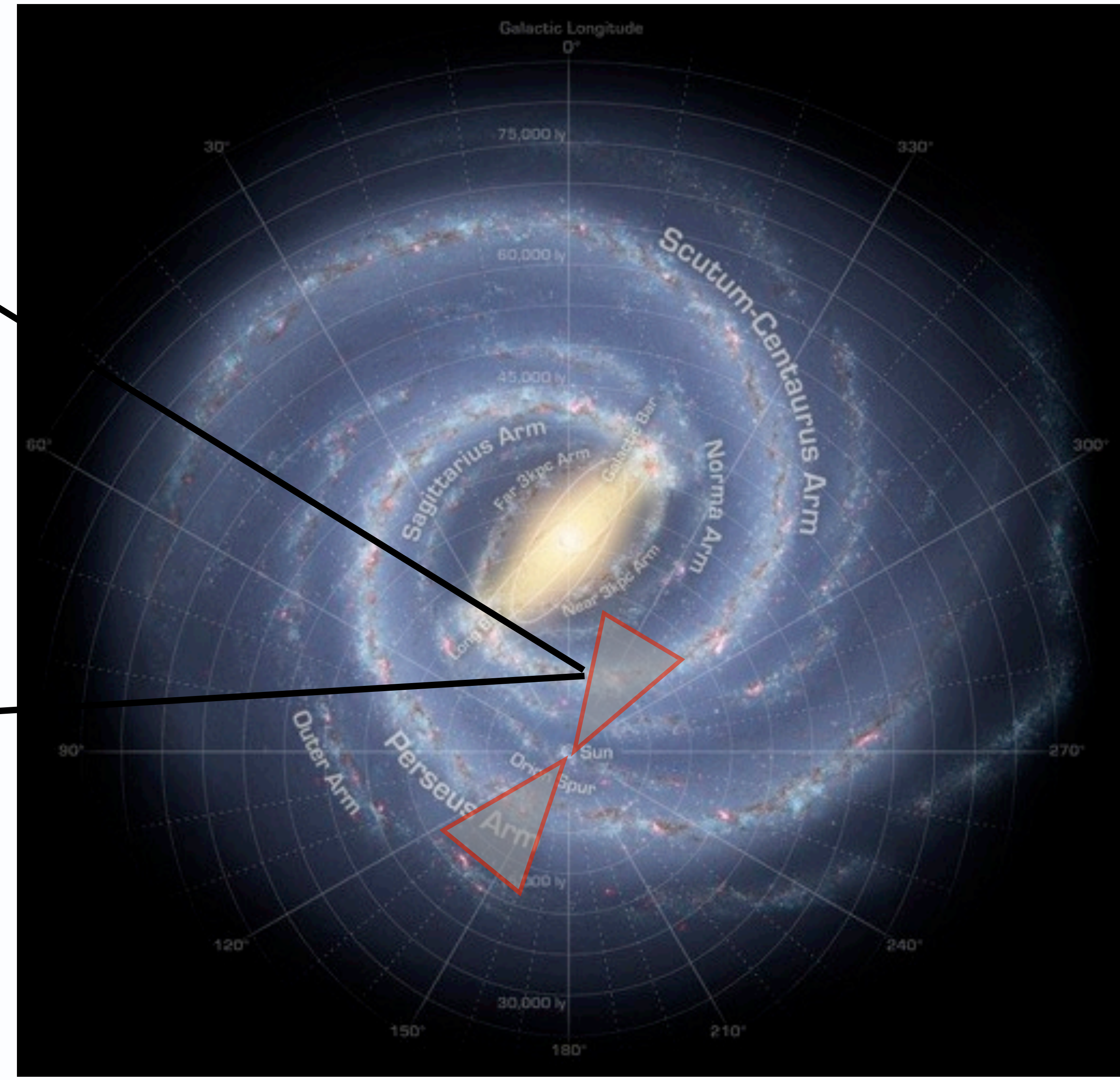
NGC 5775 (Tüllman et al 2000 A&A)

Fig. 2. Line ratios (corrected for interstellar extinction) plotted as a function of $|z|$. Theoretical line ratios (dotted lines) based on temperature profiles (measured from nitrogen emission, upper right) are fitted to the data by variing the corresponding ionization fraction. "x"-symbols are from temperature determinations using upper limits of [N II]λ5755 emission and are given as a consistency check.

Scutum-Cen Arm



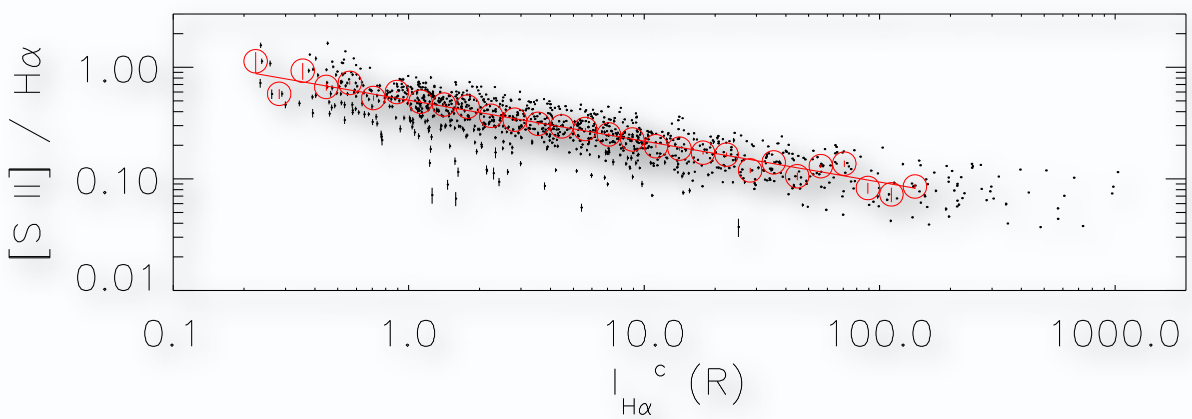




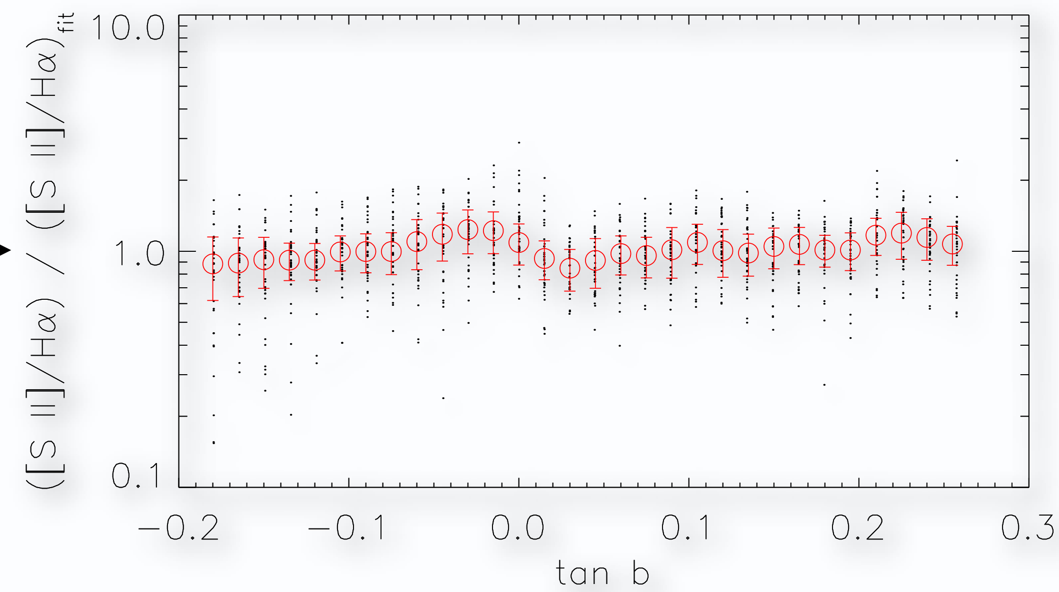
Hill, Haffner et al (in prep)

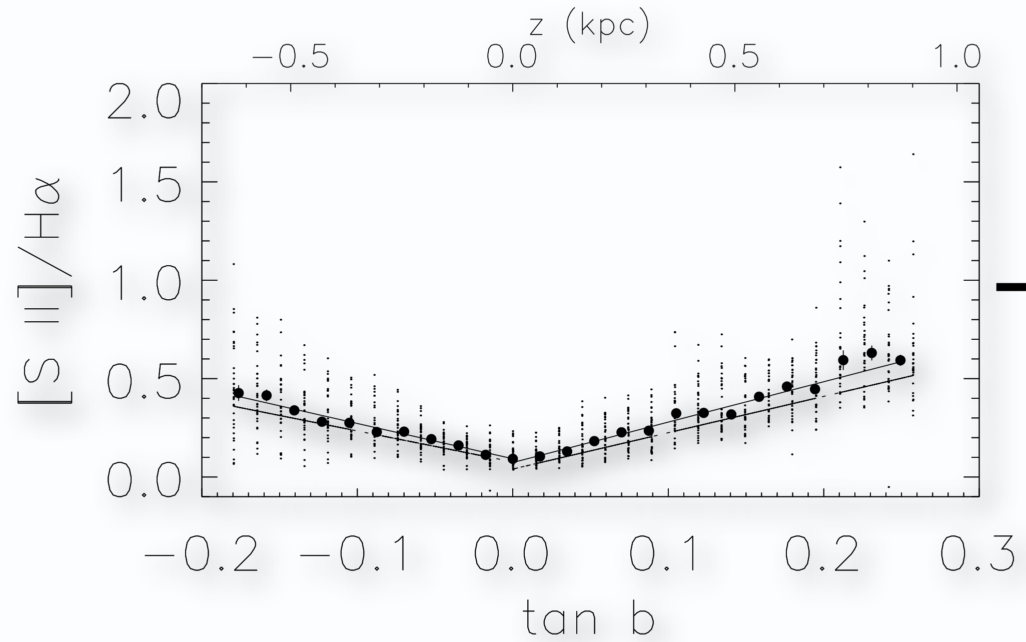
CSIRO

Intensity or height?

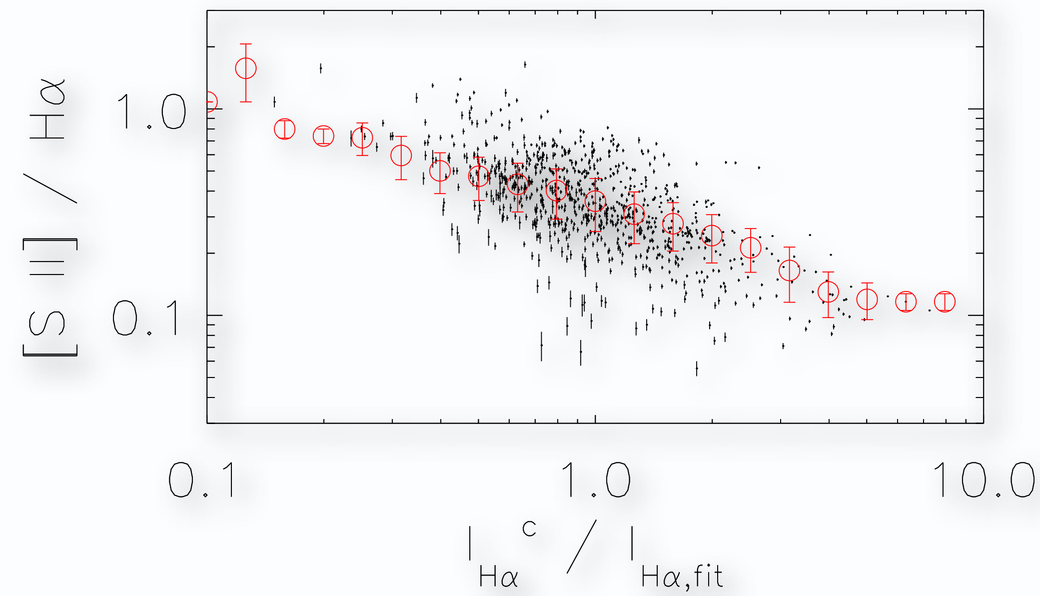


Divide [S II]/Hα by fit





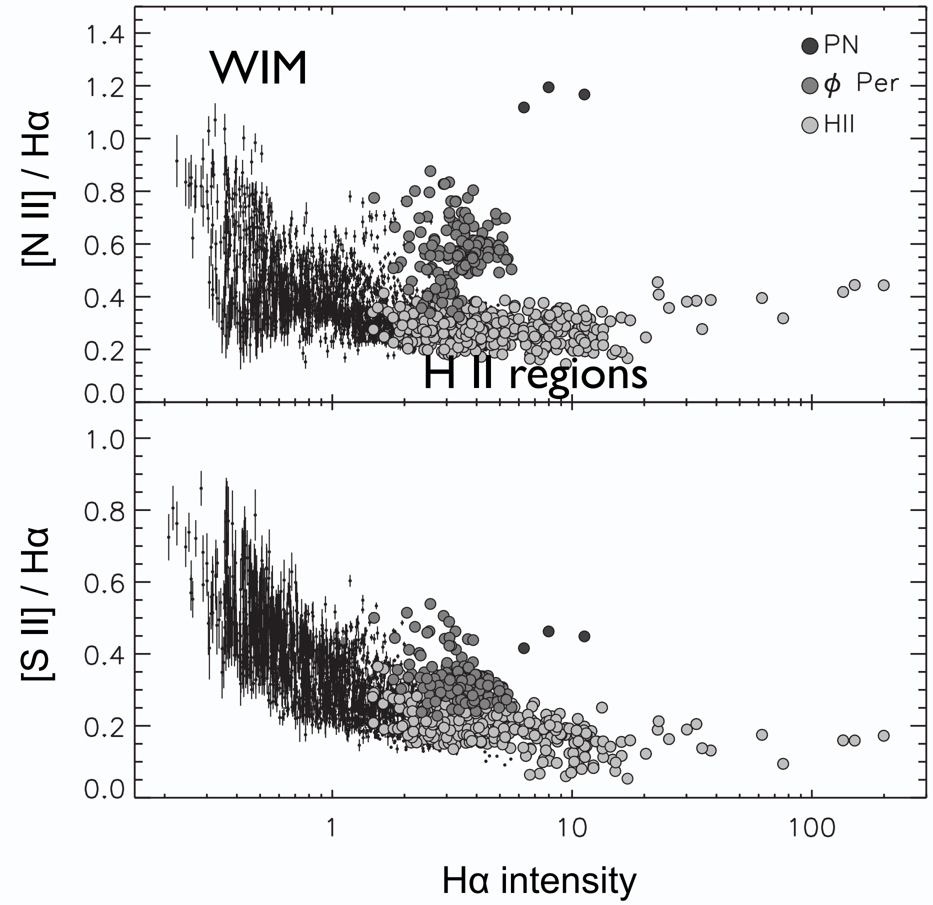
Divide $I_{H\alpha}$ by fit



Hill, Haffner et al (in prep)

Ionisation state

Forbidden line ratios probe temperature and physical conditions in the gas



Haffner et al (2009 Rev Mod Phys)

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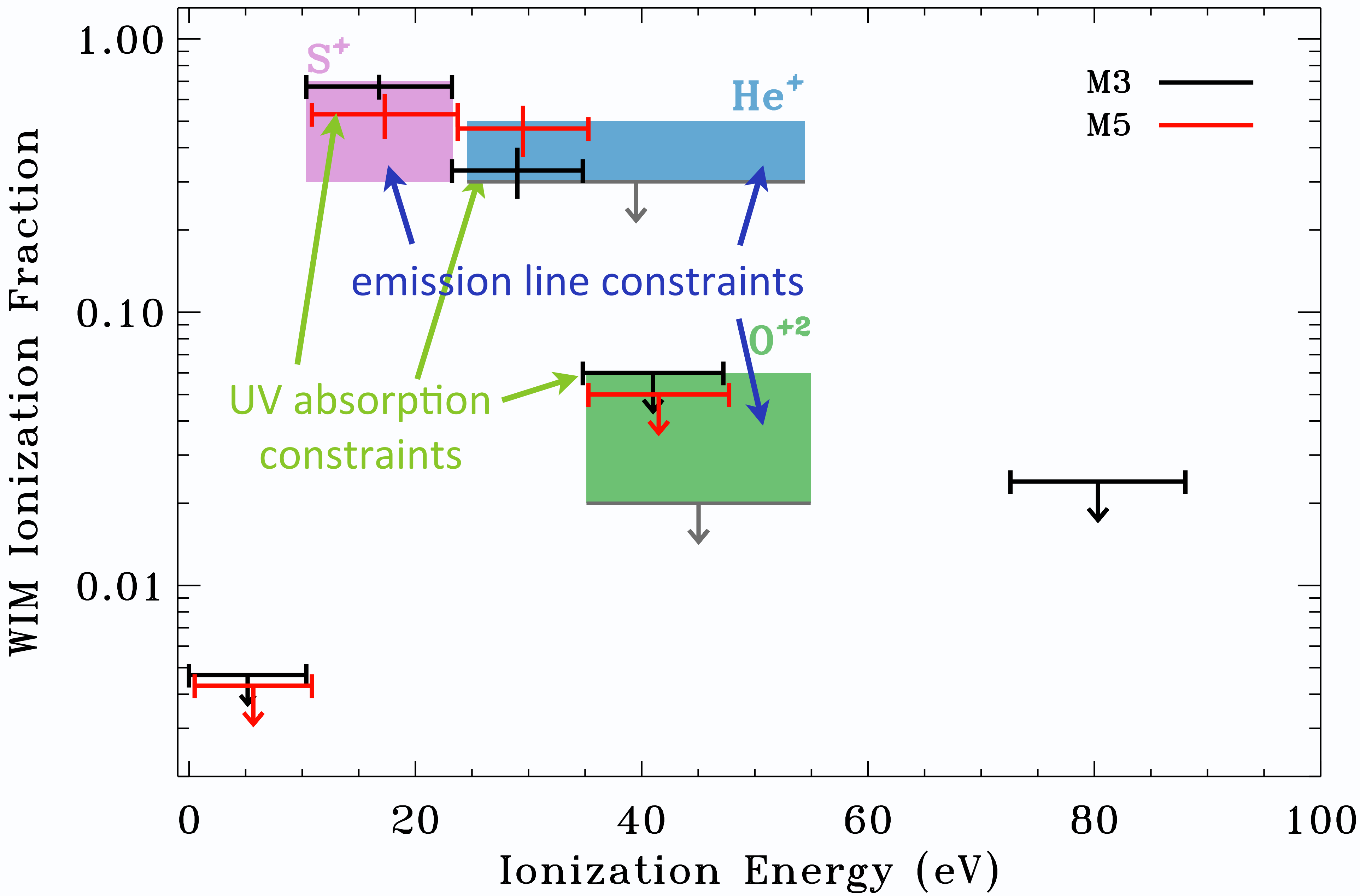
Conclusions

- He^0, O^+, N^+, and S^+ are dominant ions in WIM
- H II regions contain significant He^+, O^{++}, N^{++}, and S^{++}

Ionization Potentials (eV)		
Element	0→+	+ → ++
S	10.4	23.3
H	13.6	
O	13.6	35.1
N	14.5	29.6
He	24.6	54.4

Ionisation state



Howk & Consiglio (2012 ApJ)

Heating

Photoionisation heating dominant

Observed temperature can't be explained by photoionisation heating alone

- requires additional heat source ∝ n_e
- $\sim 1 \times 10^{-25}\, n_e$ ergs cm^{-3} s^{-1}

Possible mechanisms

- Dissipation of turbulence? (Minter & Spangler 2007)
- Magnetic reconnection?
- Cosmic rays? (Weiner, Zweibel, & Oh 2013 ApJ)

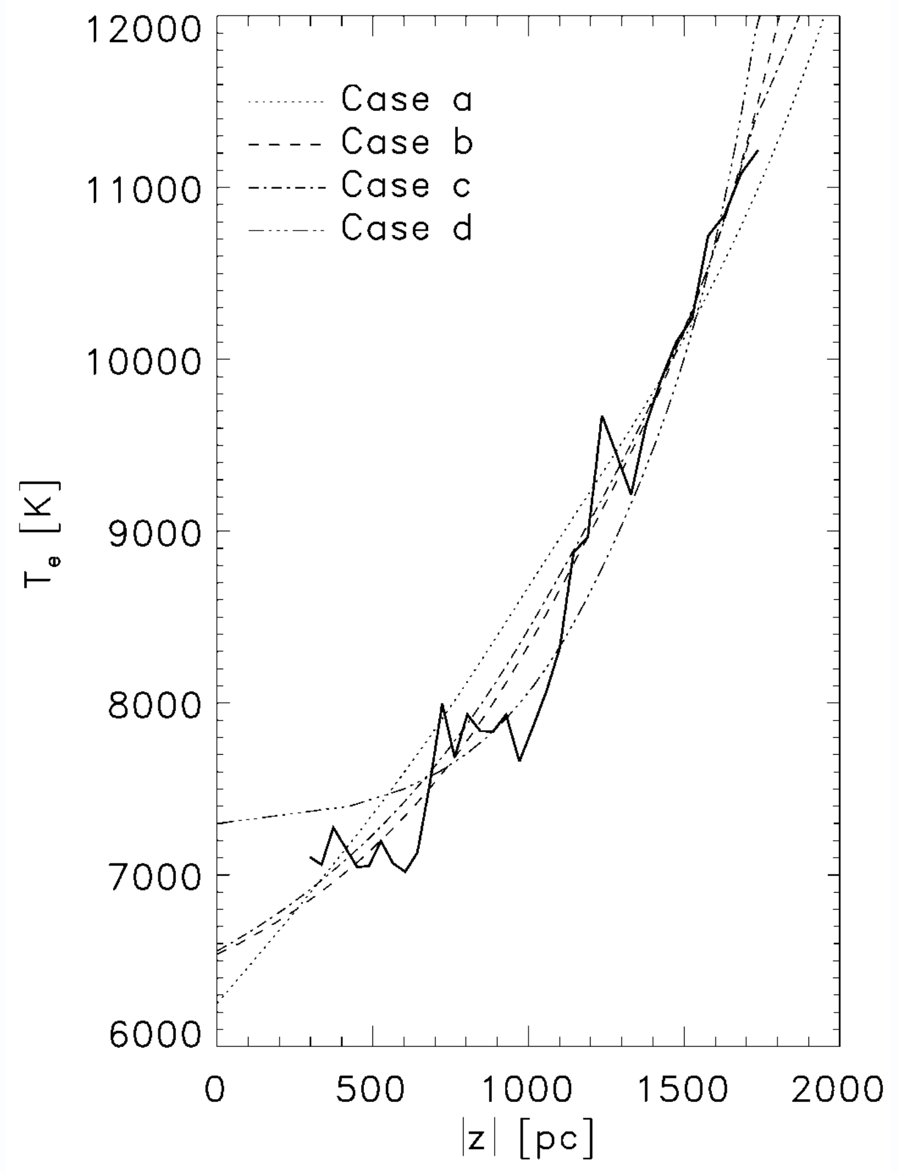


FIG. 1.—Electron temperatures T_e inferred from the [N II]/Hα line intensity ratios plotted vs. the distance $|z|$ from the Galactic midplane in the Perseus spiral arm (*thick line*). Also plotted are the best fits to this T_e vs. $|z|$ relation for four cases in which the gas is heated by photoionization plus an additional nonionizing source (see text).

Reynolds et al (1999 ApJL)

Place in the multi-phase ISM

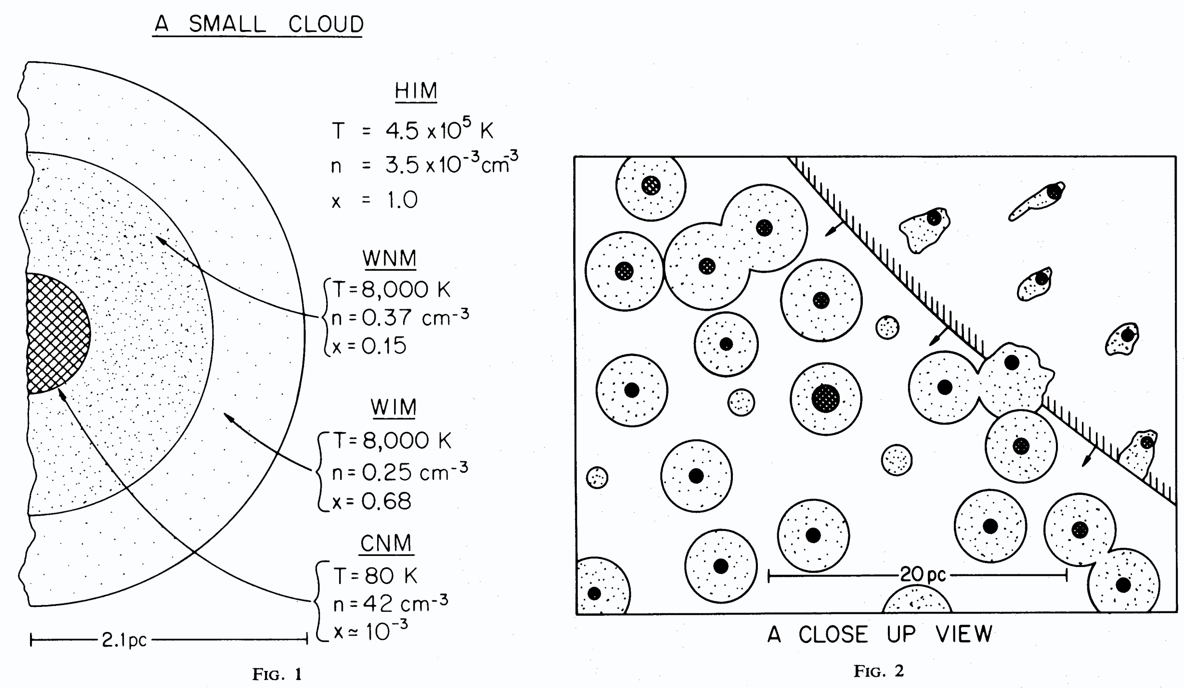
Geometry

McKee & Ostriker picture

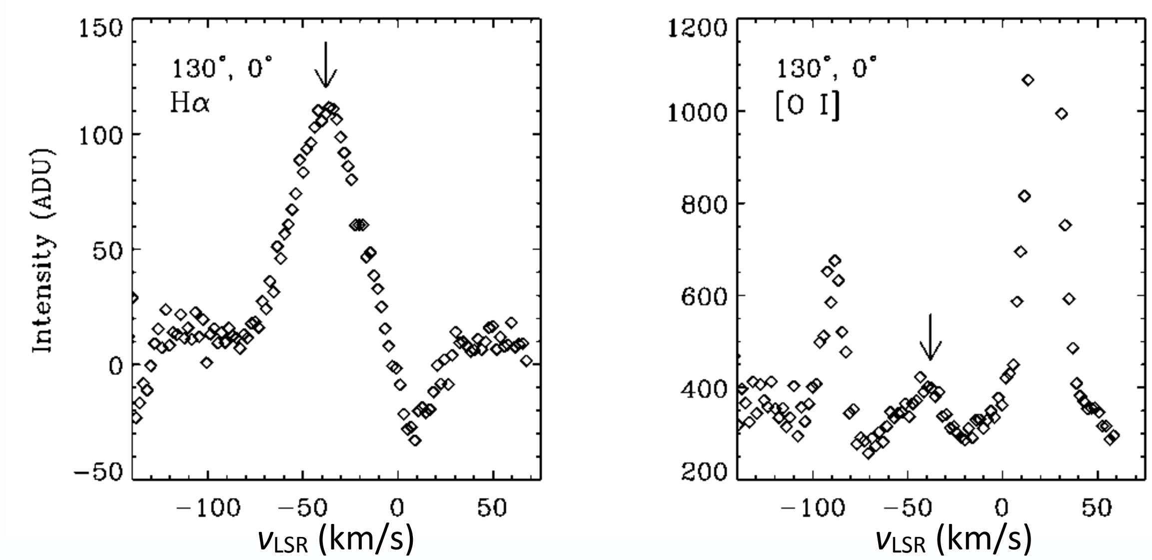
- WIM is an envelope around cold clouds
- Partially ionised ($x_e \sim 0.7$)

[O I] λ6300

- Strong $O^+ + H^0 \Leftrightarrow O^0 + H^+$ charge exchange
- Hα-emitting gas is nearly fully ionized
  - if $T \gtrsim 8000$ K ($x_e > 0.9$)
  - in both WIM and H II regions



McKee & Ostriker (1977)



Reynolds et al (1998)

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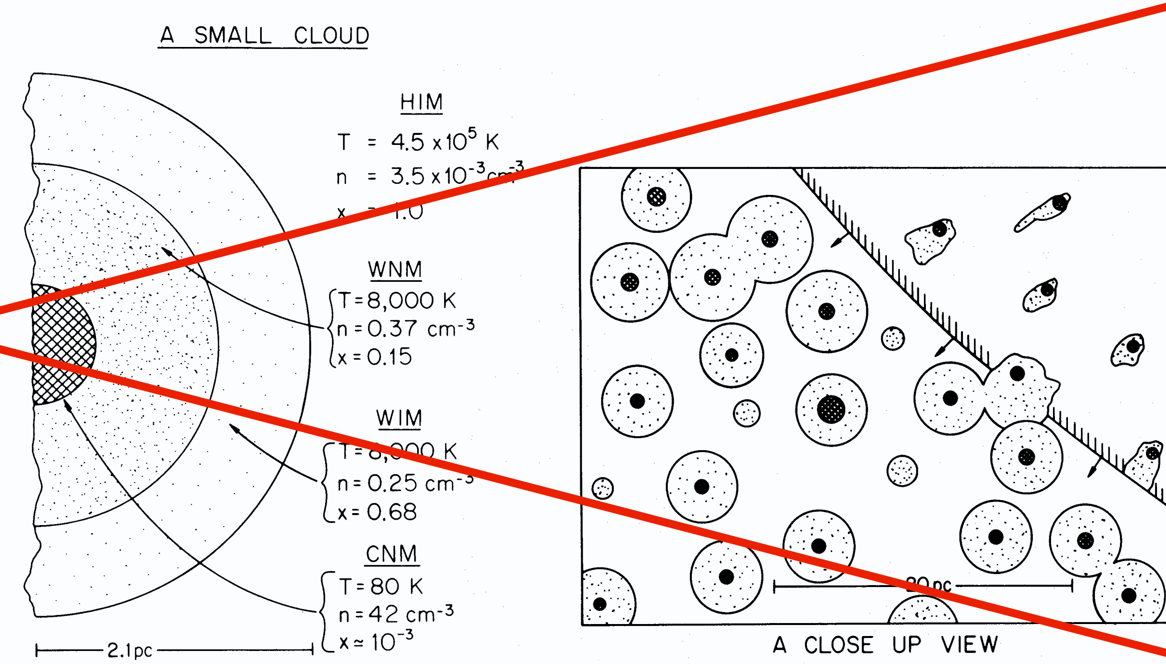
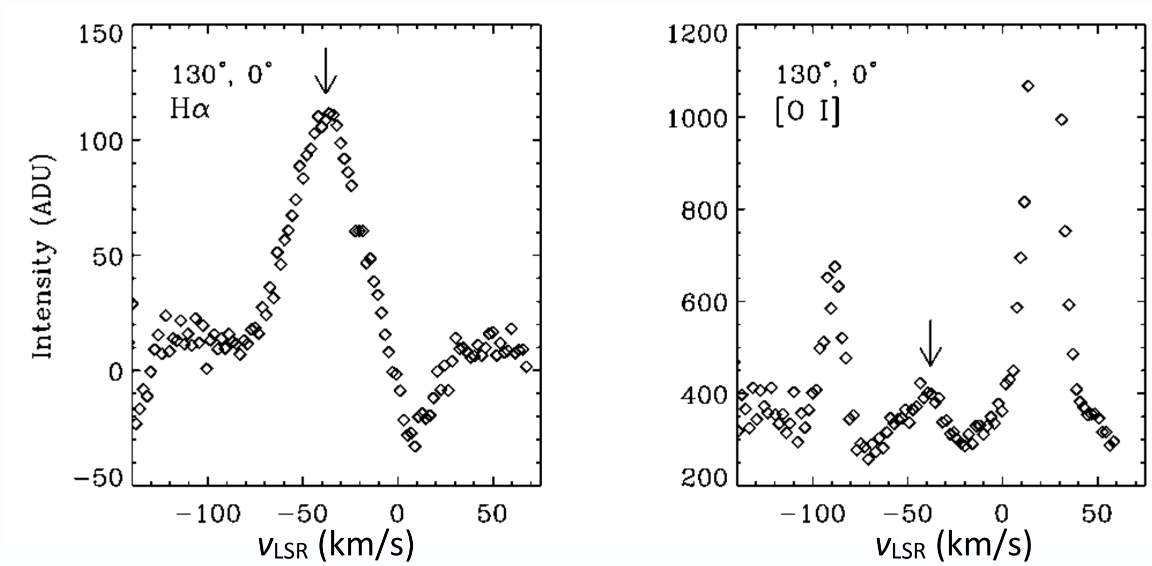


FIG. 1 FIG. 2

McKee & Ostriker (1977)

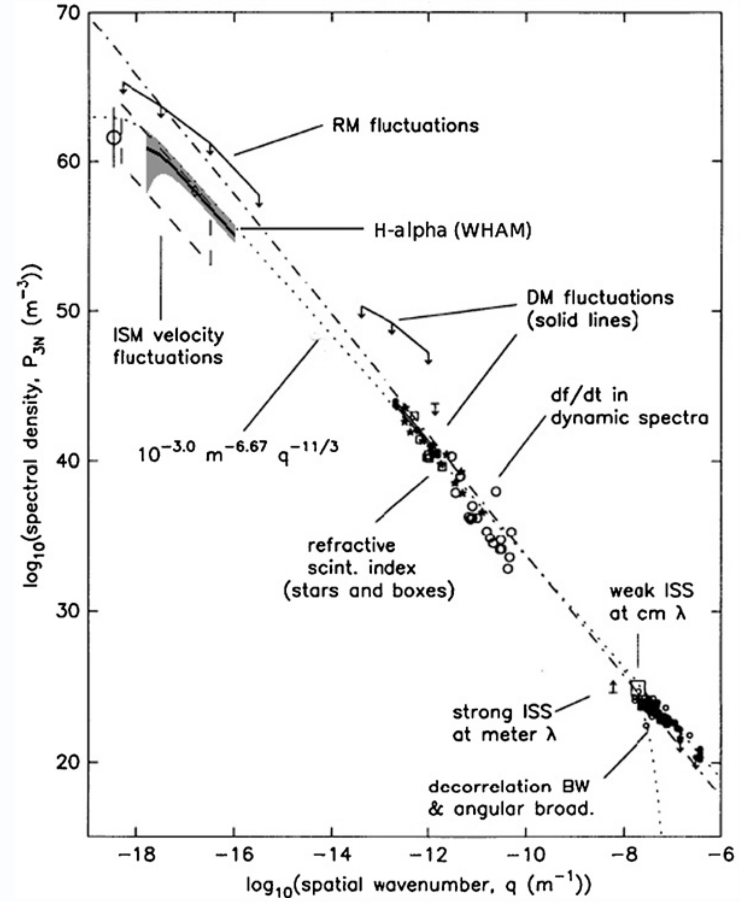


Reynolds et al (1998)

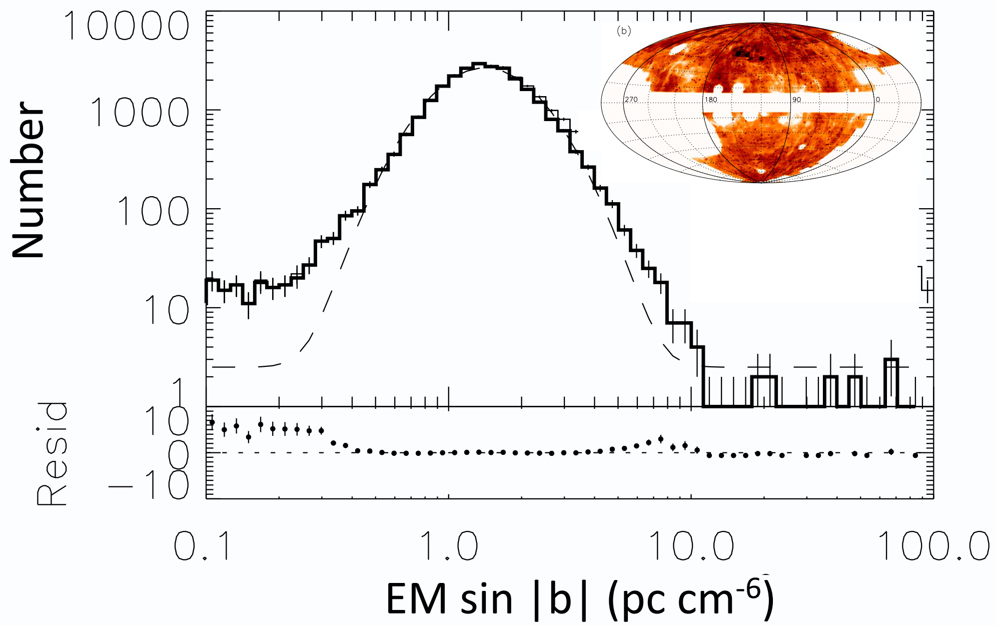
Turbulence

Variety of observations and theoretical expectations indicate that the WIM is turbulent (Rickett 1990 ARA&A, Benjamin 1999)

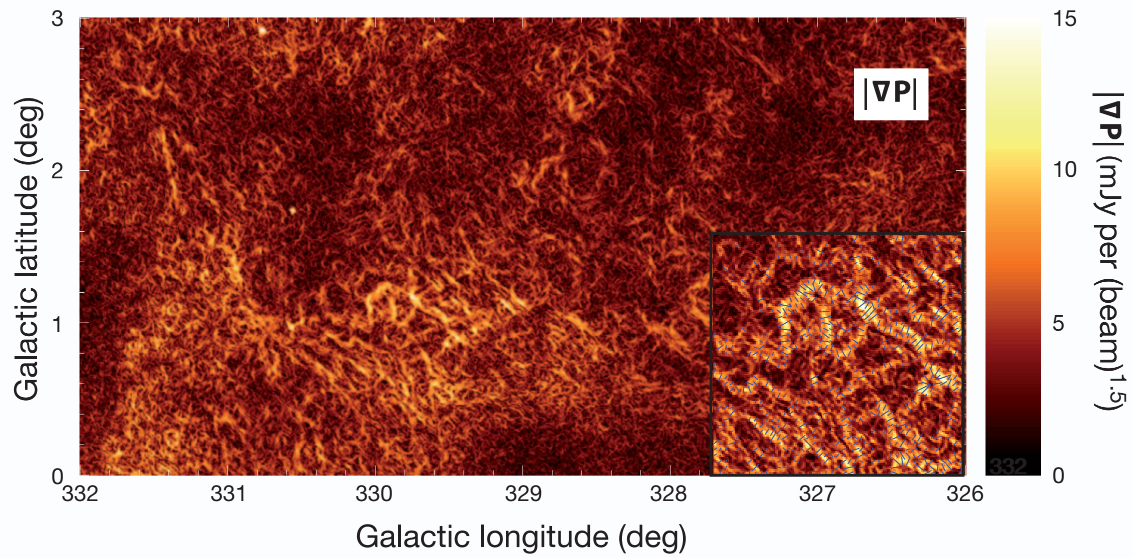
- Mach ~2 (Hill et al 2008 ApJ; Berkhuijsen & Fletcher 2008 MNRAS; Gaensler et al 2011 Nature; Burkhart et al 2012 ApJ)



Armstrong et al (1995 ApJ); Chepurnov & Lazarian (2010 ApJ)



WHAM data (Hill et al 2008)



Gaensler et al (2011 Nature); Burkhart et al (2012 ApJ)

Scale height

$n_e(|z|) = n_0 \exp(-|z|/H)$

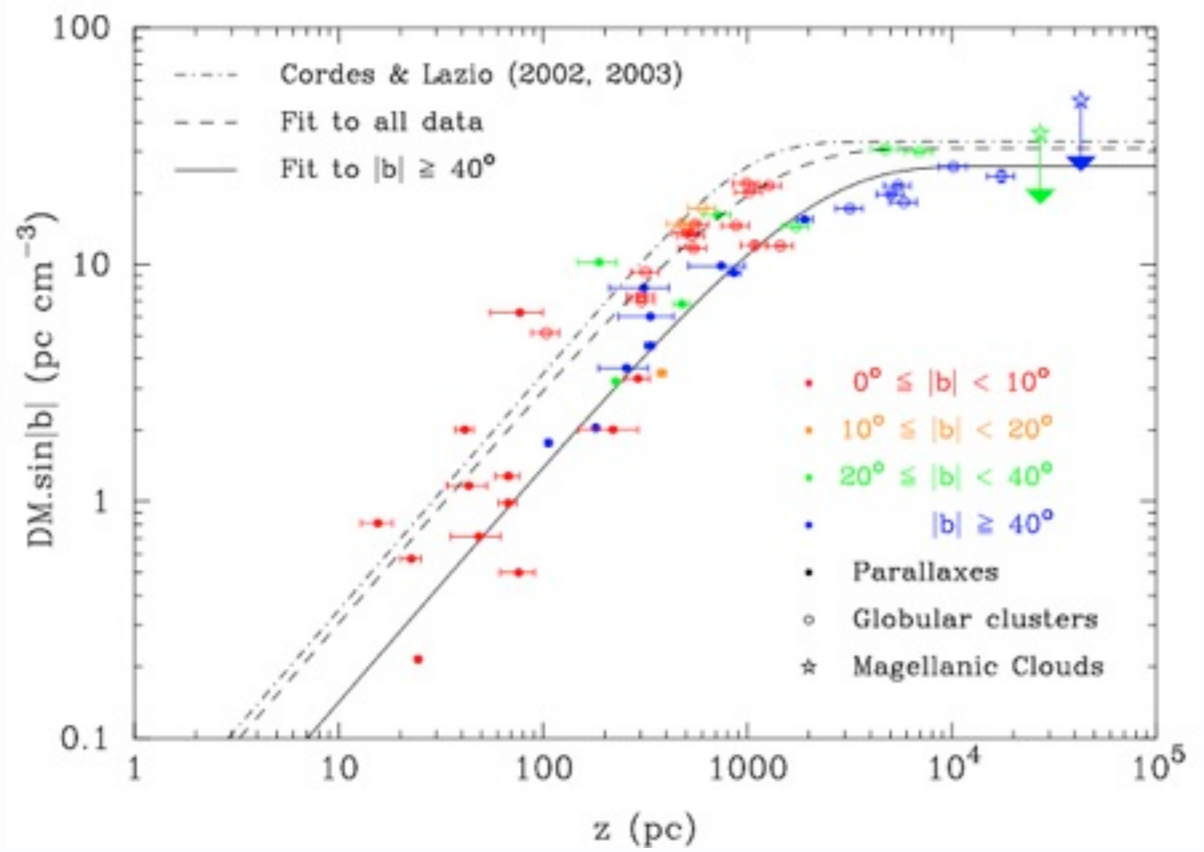
- Assume constant filling fraction

Pulsars

- Measure DM sin $|b| = \int_0^{D \sin |b|} n_e \, dz$ vs z
- $H_n = 1.4 \pm 0.3$ kpc (Savage & Wakker 2009) locally

Al III

- Measure $N(\mathrm{Al}^{++}) = \int n(\mathrm{Al}^{++}) \, dz$ vs z
- $H_n = 0.9^{+0.6}_{-0.3}$ kpc (Savage & Wakker 2009)



Gaensler et al (2008 PASA)

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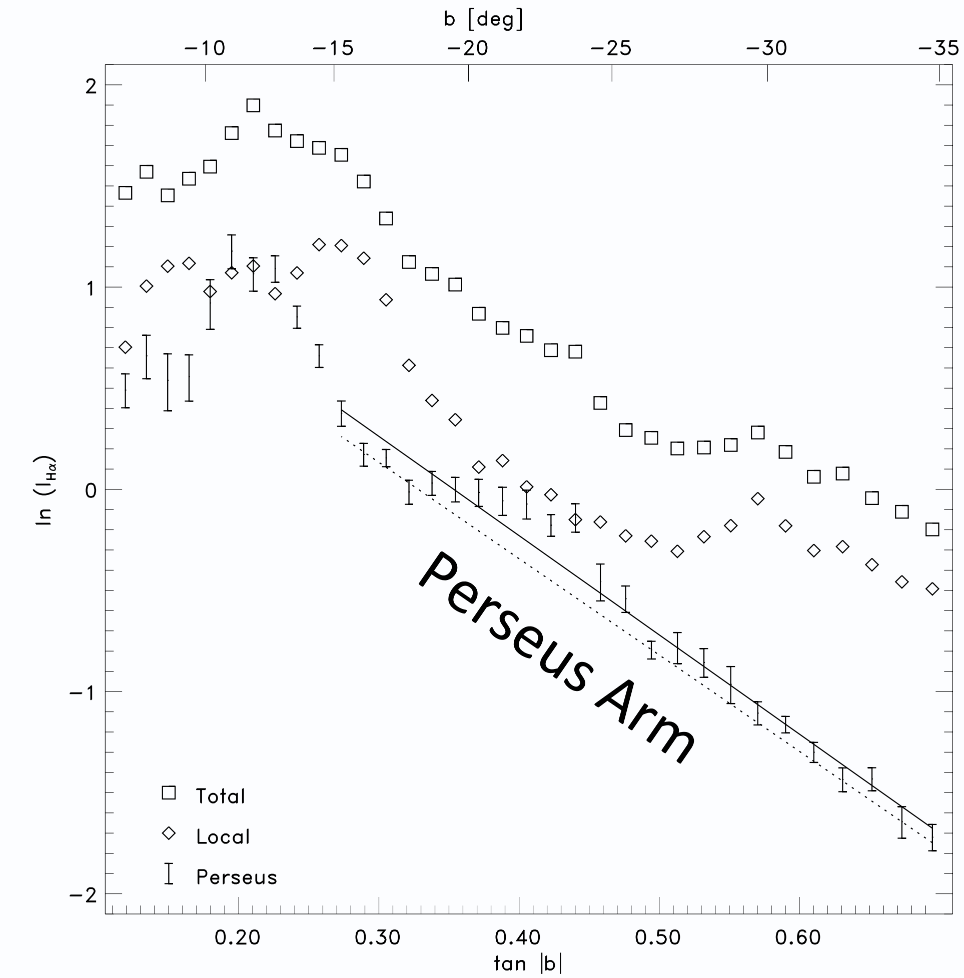
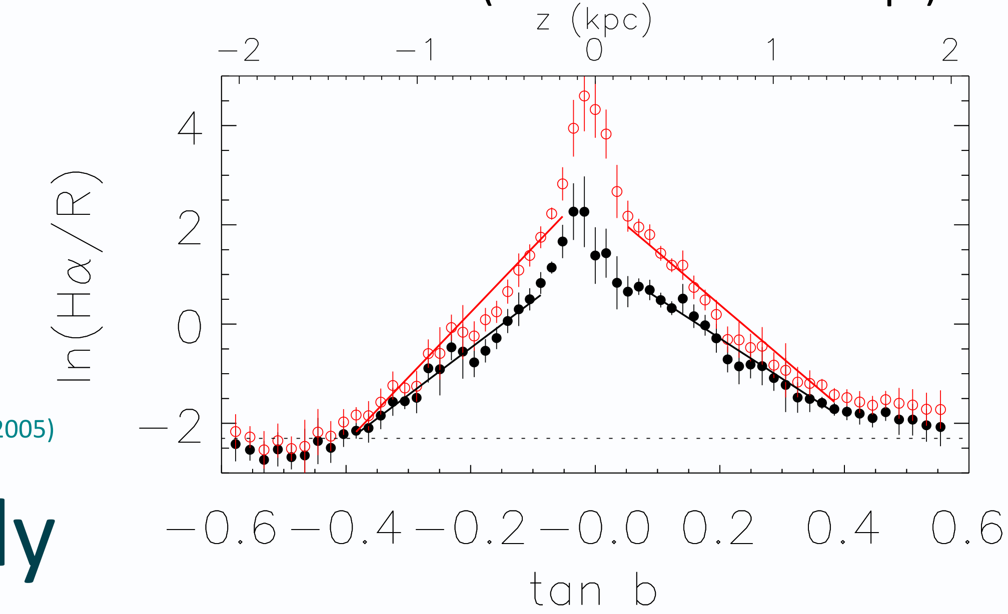
Hα from spiral arms

- Measure EM = $\int n^2 \, dz$ vs z
- $2H_{n^2}$ = 0.8 ± 0.08 kpc in Perseus Arm
- $2H_{n^2}$ = 0.6 ± 0.06 kpc in Scutum-Cen Arm
- $2H_{n^2}$ = 0.3 ± 0.1 kpc in inner Galaxy ($r_G \approx 4$ kpc) (Madsen & Reynolds 2005)

Compare to ~300 pc for WNM locally

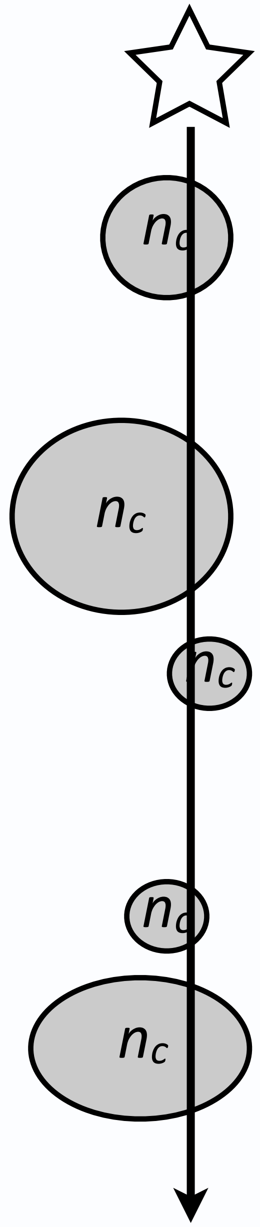


Perseus Arm (Haffner et al 1999 ApJ)



Scutum-Cen Arm (Hill et al in prep)

Filling fraction



Measure from sightlines towards high-|*z*| globular cluster pulsars

- $n_c \approx 0.07$ cm^{-3}
- $L_c \approx 390$ pc
- $f \approx 0.3$

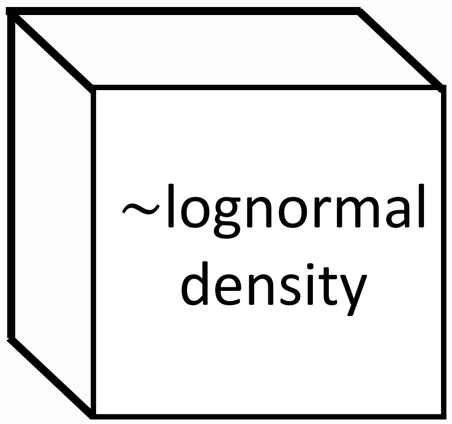
Disagreement between $2H_{n^2}$ and H_n

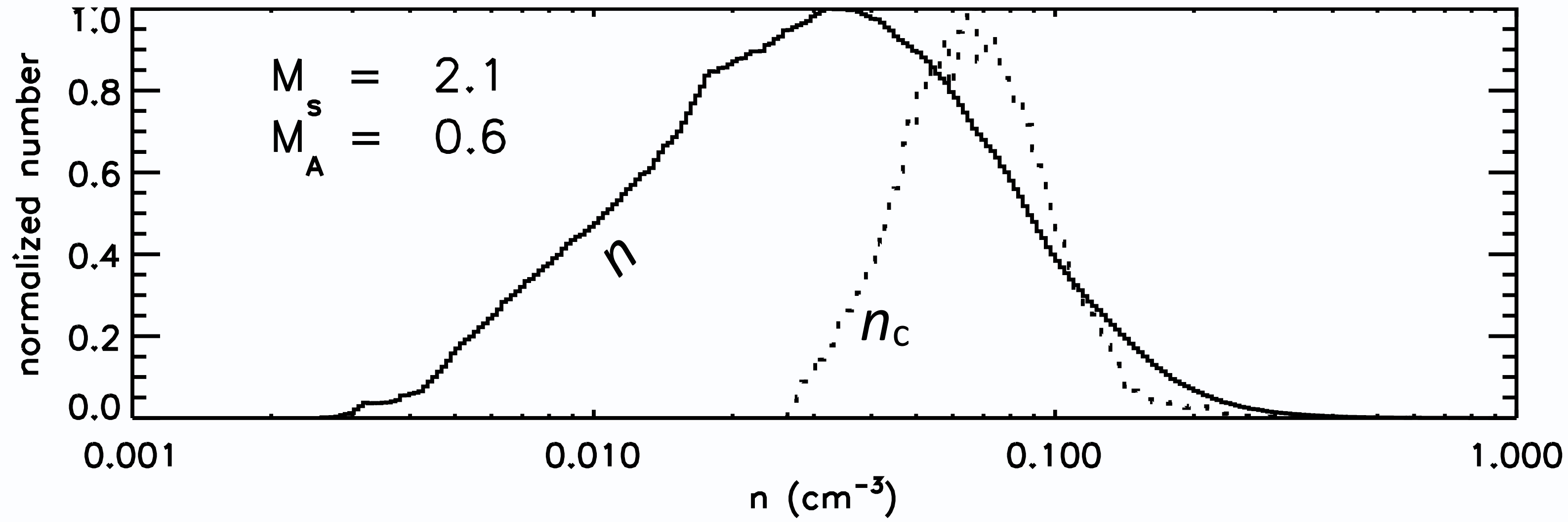
- Can be explained if $f = f(z) \propto \exp(+|z|/H_f)$ and $n_c \propto \exp(-|z|/H_{nc})$
- $f(0) \approx 0.04$; $f(1\text{ kpc}) \approx 0.3$
- midplane $n_c \approx 0.3$ cm^{-6} ($P/k \sim 4800$ cm^{-3} K at 8000 K)
- Gaensler et al (2008 PASA)
- WIM dominates over WNM at $z \sim 1$ kpc

$$n_c = \frac{\mathrm{EM}}{\mathrm{DM}} = \frac{\int n_e^2\, ds}{\int n_e\, ds} \qquad L_c = \frac{\mathrm{DM}^2}{\mathrm{EM}} = \frac{\left(\int n_e\, ds\right)^2}{\int n_e^2\, ds} \qquad f \approx \frac{L_c}{H}$$

Reynolds (1991); Hill et al (2008)

Filling fraction and turbulence





If gas density distribution is lognormal, typical density is much lower than "characteristic" density

- WIM filling fraction higher
- Ratio depends upon width of lognormal distribution

$$n_c = \frac{\mathrm{EM}}{\mathrm{DM}} = \frac{\int n_e^2\, ds}{\int n_e\, ds}$$

$$L_c = \frac{\mathrm{DM}^2}{\mathrm{EM}} = \frac{\left(\int n_e\, ds\right)^2}{\int n_e^2\, ds}$$

$$f \approx \frac{L_c}{H}$$

Hill et al (2008 ApJ)

CSIRO

Ionisation of the WIM

Ionisation of the WIM

Surface recombination rate of the WIM in the Milky Way

- 4×10^6 ionising photons s^{-1} cm^{-2} or $\approx 2 \times 10^{-4}$ ergs s^{-1} cm^{-2} (Reynolds 1990 ApJL)
  - about equal to kinetic energy input from supernovae
  - ≈1/7 of the Lyman continuum flux from OB stars
- How can ionising photons reach $|z| \sim 1$ kpc?
  - mean free path of ionising photon in $n \sim 1$ cm^{-3} WNM is ~0.1 pc

Photoionisation modeling

"Leaky" H II regions able to ionise WIM

- Smooth intercloud medium
- Lower-than-observed mean intercloud density required

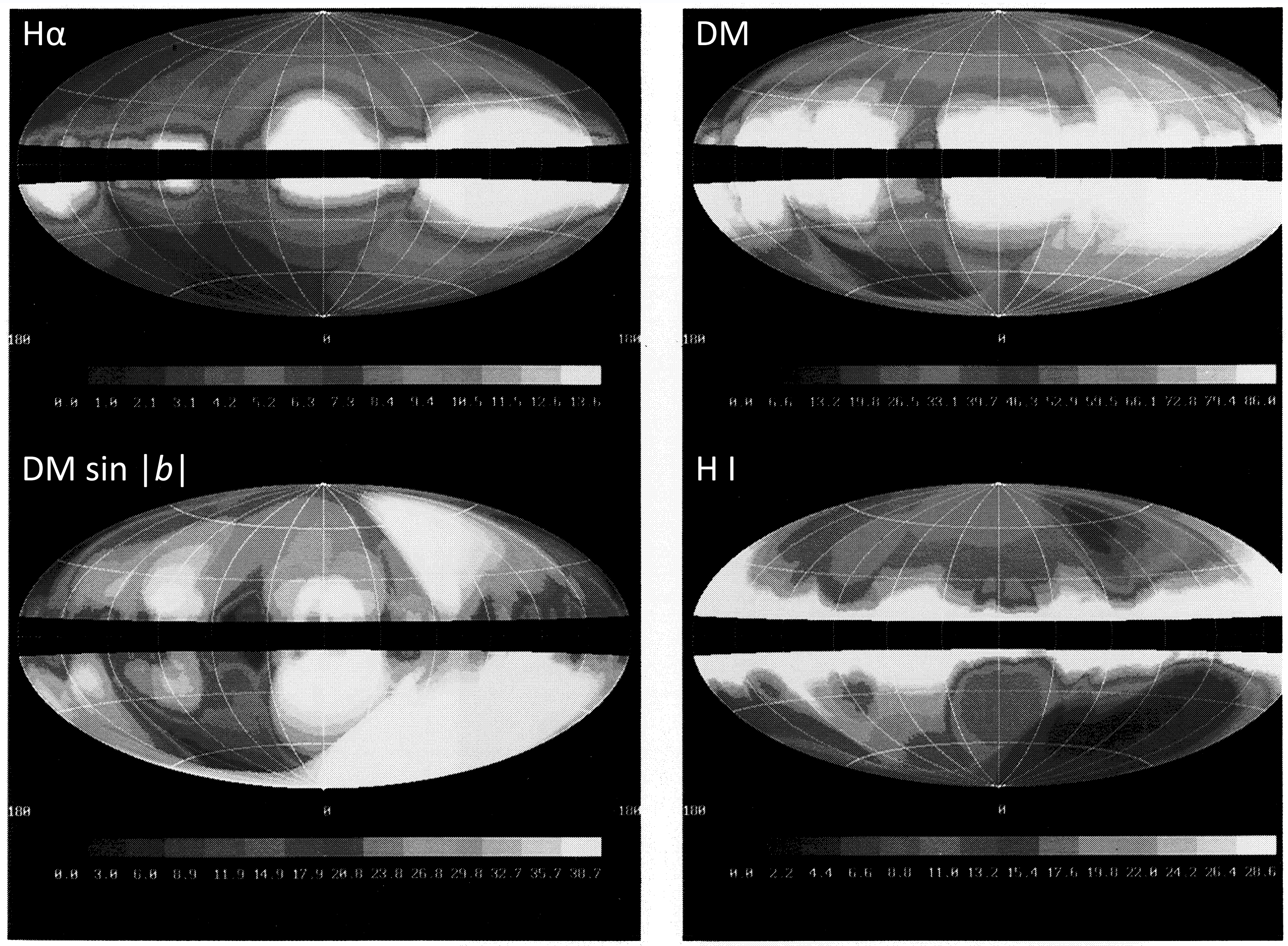


FIG. 12.—Aitoff projections from our standard cloud model of the (*upper left*) the emission measure (including ionized cloud faces), (*upper right*) the dispersion measure, (*lower left*) the vertical component of the dispersion measure (DM sin $|b|$), and (*lower right*) the residual neutral hydrogen column density. The projections are in Galactic coordinates (l, b) centered on $l = 0$ at 1° resolution. The scales are in units of cm^{-6} pc, cm^{-3} pc, cm^{-3} pc, and $cm^{-2} \times 10^{19}$, respectively. The quantities associated with each color bin represent upper limits to the bin of that color with the exception of the first bin (0.0 means truly 0.0) and the last bin (this bin contains everything greater than or equal to the bin label).

MILLER & COX (see 417, 586)

Miller & Cox (1993 ApJ)

Photoionisation in a fractal medium

Clumpy or fractal gas distribution allows ionising photons to penetrate to large heights (Elmegreen 1997 ApJ; Ciardi et al 2002 ApJ; Wood & Mathis 2004 MNRAS; Haffner et al 2009 Rev Mod Phys)

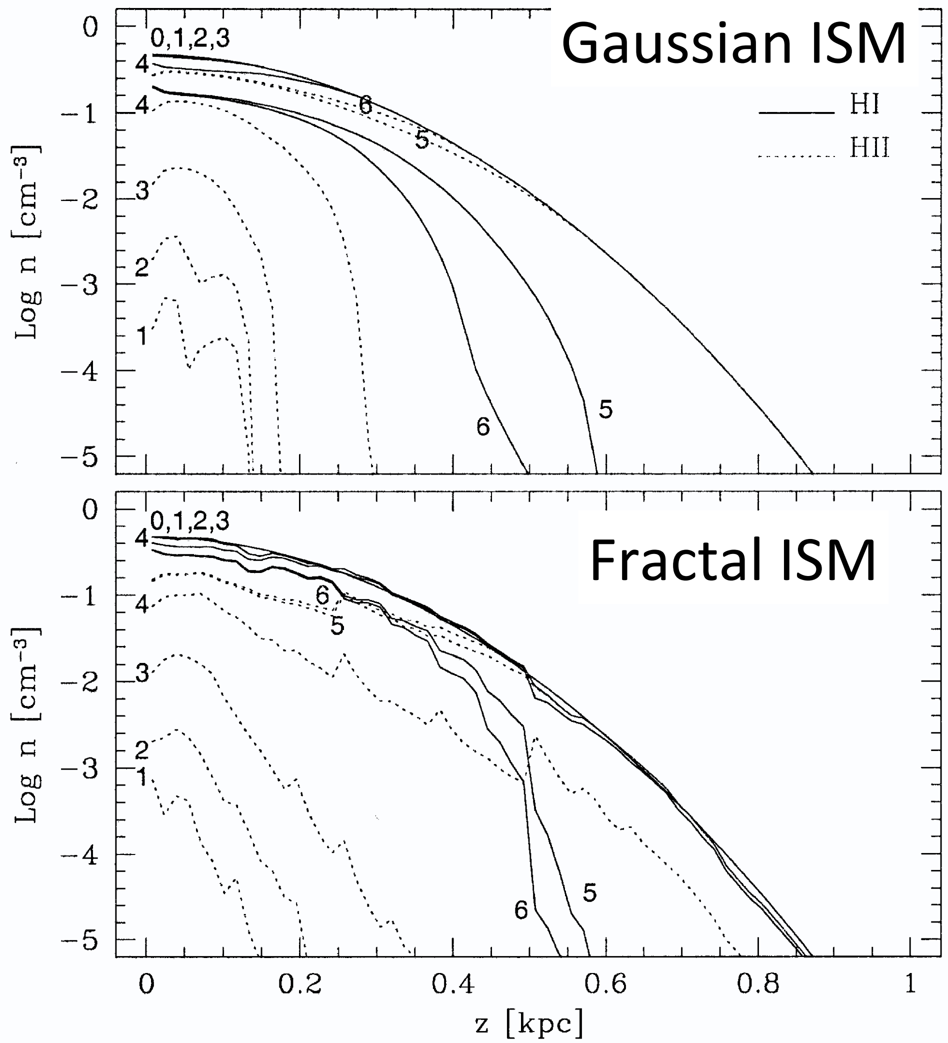


Figure 7. Vertical distribution of the mean H I (solid lines) and H II (dotted lines) number densities, in the case of a Gaussian (top panel) and fractal (bottom panel) density field. The numbers refer to different times from the source turn on: $i = 0 \ldots 6$ refers, respectively, to $t = 0$, 10^2, 10^3, 10^4, 10^5, 10^6 and 10^7 yr.

Ciardi, Bianchi, & Ferrara et al (2002 ApJ)

Turbulence and ionisation

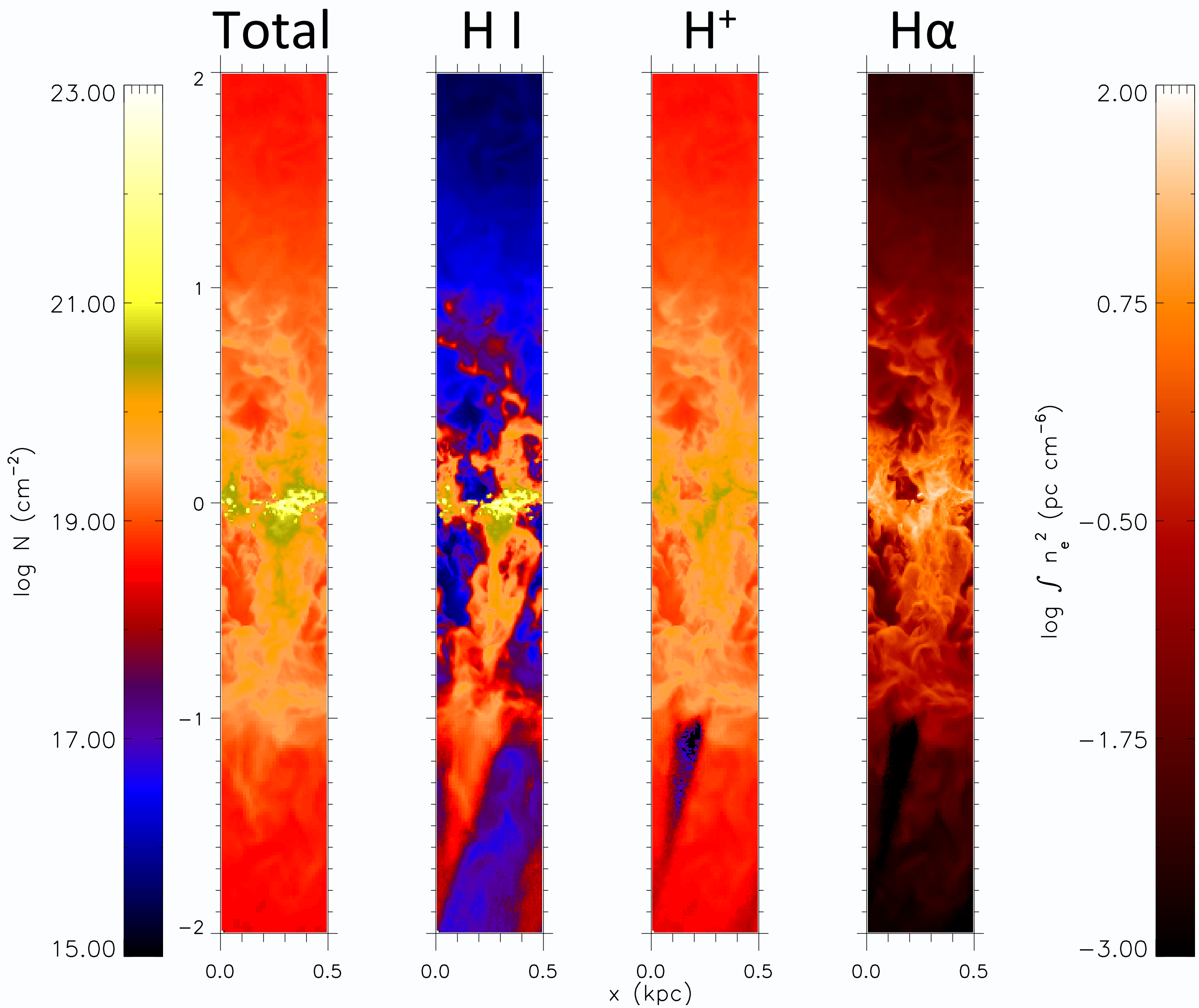
Consider hydrodynamical simulations of a multi-phase, turbulent ISM

- Supernovae drive turbulence
- Heating and cooling from 10 K to > 10^8 K
- Joung & Mac Low (2006, 2009 ApJ)

Photoionise snapshot of simulations

- Use Monte Carlo photoionisation radiative transfer code
- O stars placed near the midplane
- Ionising photons can escape the midplane through low-density paths established by turbulence
- Total ionising flux is the crucial parameter
- Wood, Hill, Joung et al (2010 ApJ)

See talk by Barnes



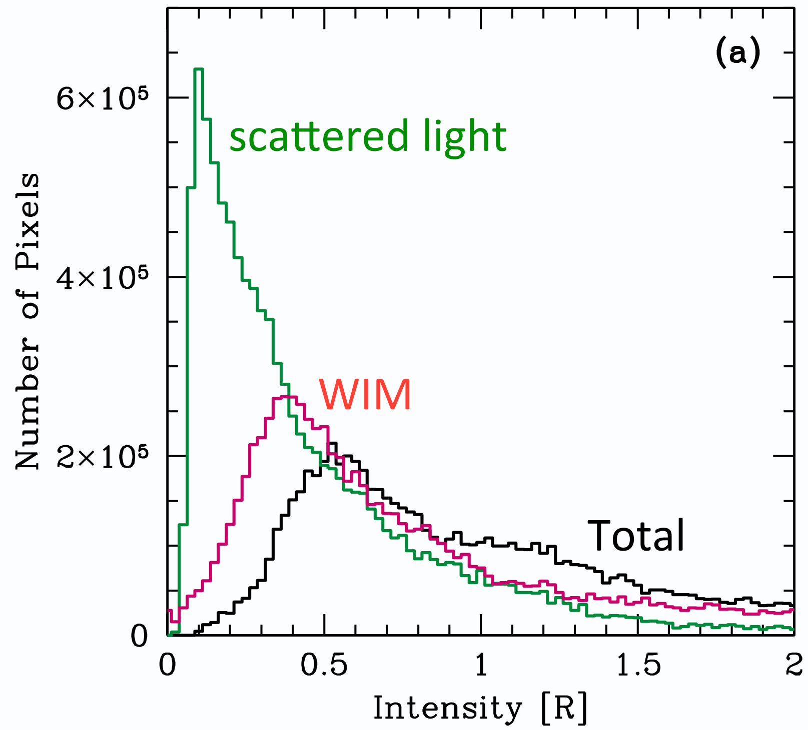
Wood, Hill, Joung et al (2010 ApJ)

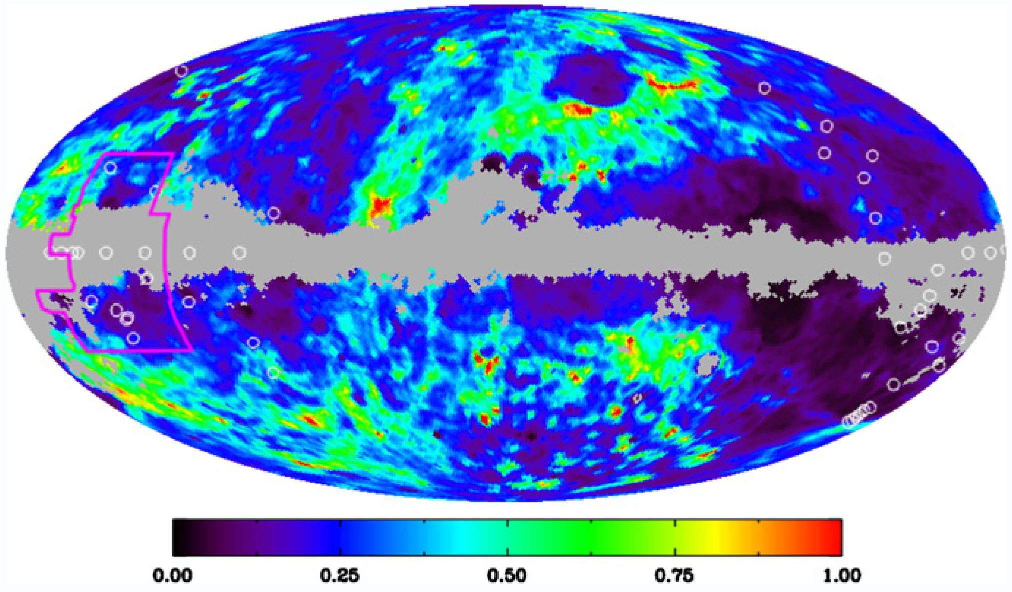
Scattered light

Scattered light

Some fraction of Hα is scattered light from midplane H II regions

- ~10% (Reynolds et al 1973)
- Up to 20% (Wood & Reynolds 1998)
  - See talk by Barnes
- ~20% on average at high latitudes
  - but up to 50% on individual sightlines (Witt et al 2010)





Witt et al (2010 ApJ)

Conclusions

Summary

Distribution

- warm ionised medium vertical column density $N(H^+) \approx 23$ pc cm^{-3} = 7×10^{19} cm^{-2} in Galaxy
  - ≈1/4 of the total hydrogen column, and 90% of H^+ mass in Milky Way ISM
- scale height 1 – 1.4 kpc
- detected in every direction in Hα
- volume filling fraction ≈20 – 40% at $|z| \sim 1$ kpc

Physical conditions

- nearly fully ionised
- optical line ratios distinct from H II regions
  - warmer (≈8000 K) than H II regions (≈6000 K)
  - lower ionisation state (S^+, O^+, N^+ are dominant ions)

Modelling

- The WIM is a natural consequence of feedback from massive stars in a star-forming galaxy.

Outstanding questions (cf Haffner et al 2009 Rev Mod Phys)

- What causes the elevated temperature (above photoionisation)?
- How much ionising radiation escapes from the Galaxy?
  - Ionisation bounded or density bounded?
- How does the WIM fit into the turbulent, multi-phase ISM?
- Why is the WIM fraction largely independent of galaxy type?

Thank You

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Temperature

$$\frac{[\mathrm{N\ II}]}{\mathrm{H}\alpha} = 1.62 \times 10^5\, T_4^{0.4}\, e^{-2.18/T_4} \left(\frac{\mathrm{N}}{\mathrm{H}}\right) \left(\frac{\mathrm{N}^+}{\mathrm{N}}\right) \left(\frac{\mathrm{H}^+}{\mathrm{H}}\right)^{-1}$$

$$\frac{[\mathrm{N\ II}]\lambda 5755}{[\mathrm{N\ II}]\lambda 6584} = 0.192\, e^{-2.5/T_4}$$

Ionisation state

13.6 eV $$\frac{[\mathrm{O\ I}]}{\mathrm{H}\alpha} \approx 2.63 \times 10^4 \left(\frac{\mathrm{H}^0}{\mathrm{H}^+}\right) \left(\frac{\mathrm{O}}{\mathrm{H}}\right) \frac{T_4^{1.85}}{1 + 0.605\, T_4^{1.105}}\, e^{-2.284/T_4}$$

23.3 eV $$\frac{[\mathrm{S\ II}]}{[\mathrm{N\ II}]} = 4.62\, e^{0.04/T_4} \left(\frac{\mathrm{S}^+}{\mathrm{S}}\right) \left(\frac{\mathrm{S}}{\mathrm{H}}\right) \left[\left(\frac{\mathrm{N}^+}{\mathrm{N}}\right) \left(\frac{\mathrm{N}}{\mathrm{H}}\right)\right]^{-1}$$

24.6 eV $$\frac{\mathrm{He\ I}}{H\alpha} = 0.47\, T_4^{-0.14} \left(\frac{\mathrm{He}^+}{\mathrm{He}}\right) \left(\frac{\mathrm{He}}{\mathrm{H}}\right) \left(\frac{\mathrm{H}^+}{\mathrm{H}}\right)^{-1}$$

35.1 eV $$\frac{[\mathrm{O\ III}]}{H\alpha} = 1.74 \times 10^5\, T_4^{0.4}\, e^{-2.88/T_4} \left(\frac{\mathrm{O}^{++}}{\mathrm{O}}\right) \left(\frac{\mathrm{O}}{\mathrm{H}}\right) \left(\frac{\mathrm{H}^+}{\mathrm{H}}\right)^{-1}$$

Reynolds et al (1998 ApJ); Haffner et al (1999 ApJ); Madsen, Reynolds, & Haffner (2006 ApJ)

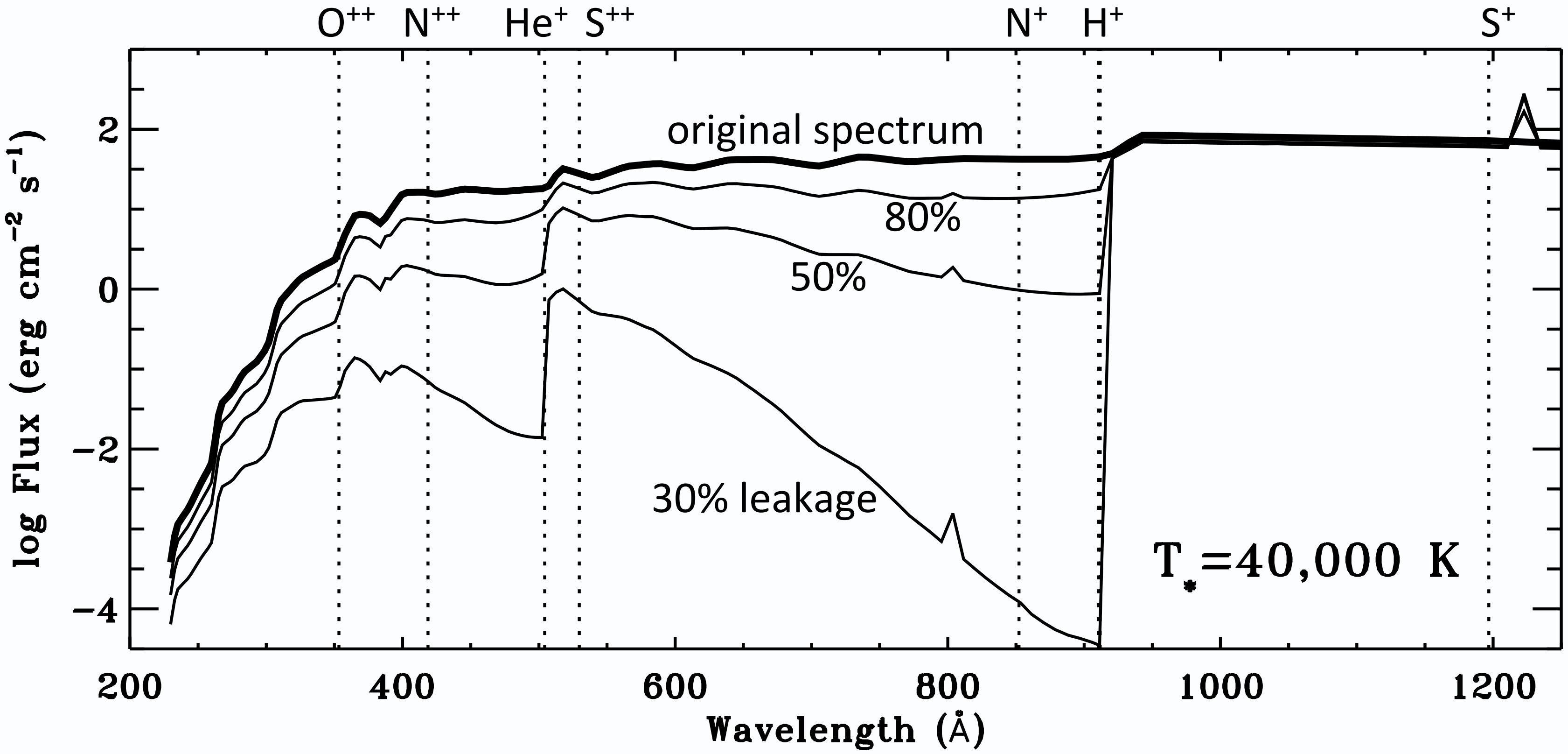
Ionising spectrum

Observations

- H^+, N^+, S^+, O^+, and He^0 are the dominant ions in WIM
- Significant N^{++}, S^{++}, O^{++}, and He^+ in H II regions

Modelling

- Requires harder spectrum with deficit of He-ionising photons in WIM
- Produced by ionising photons escaping from an H II region



Hoopes & Walterbos (2003 ApJ)