The Milky Way Halo – 29 May, 2007

Physical Conditions of Plasma in the Milky Way Halo

Results from the Wisconsin H-Alpha Mapper

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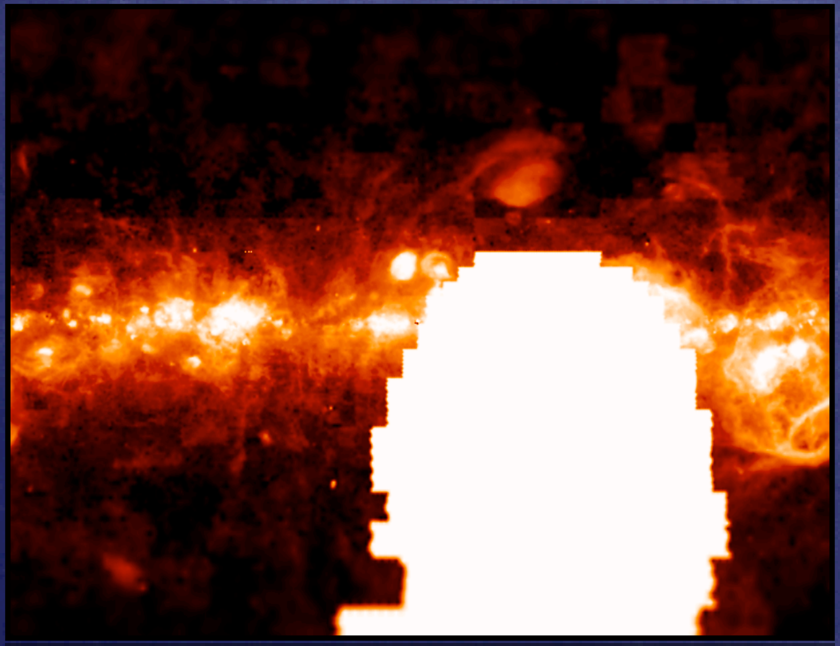

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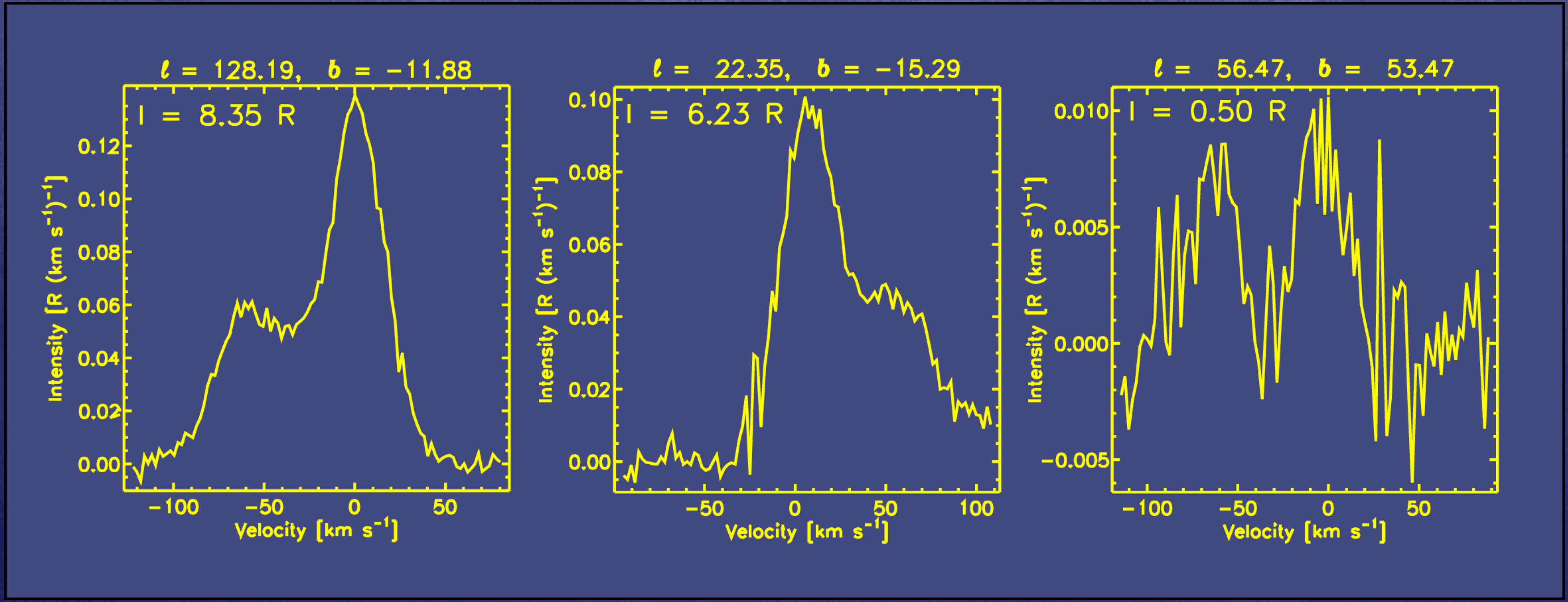
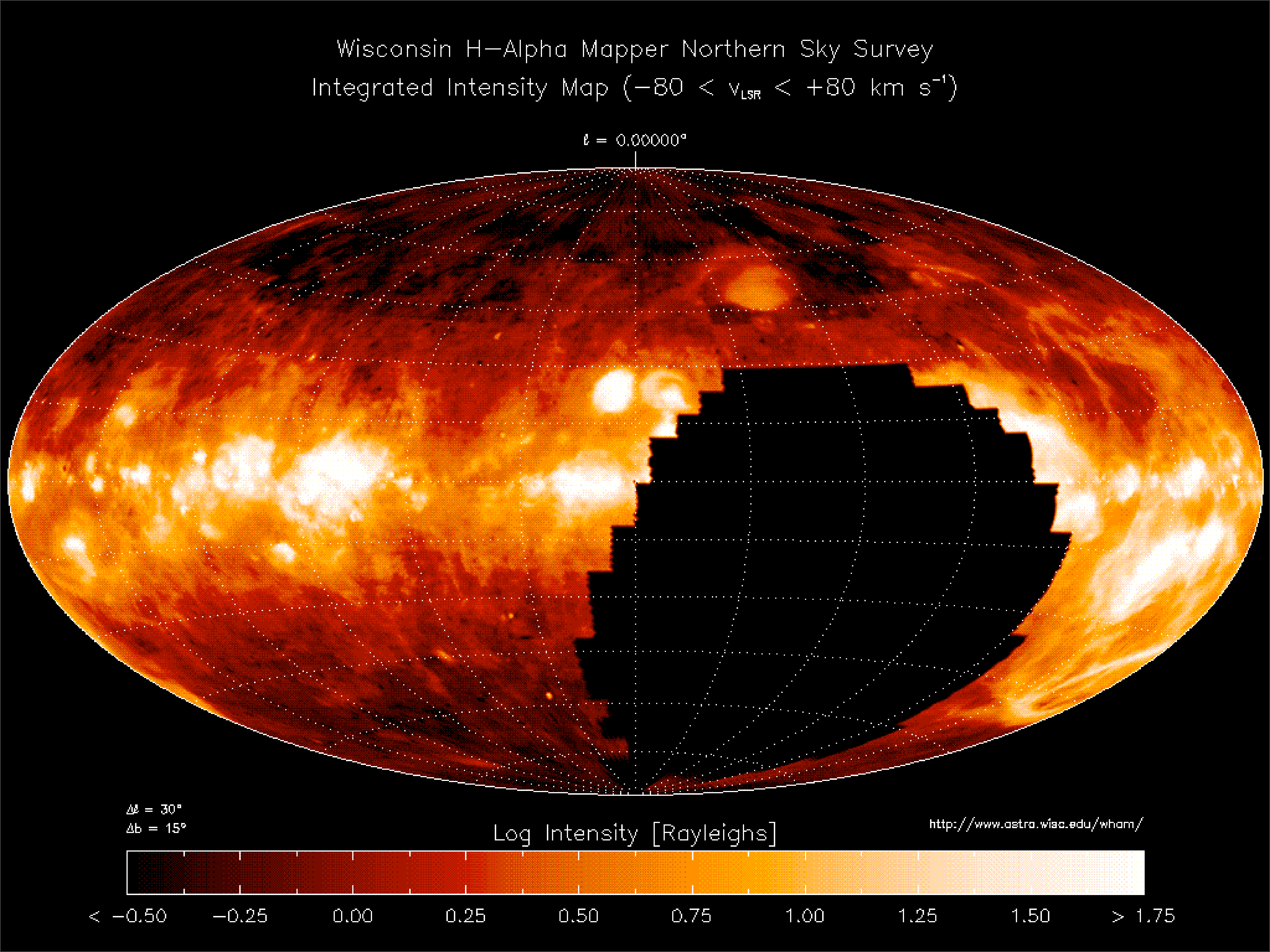
WHAM Northern Sky Survey

- Deepest, kinematically resolved map of the Warm Ionized Medium (WIM)[1].
- 37,565 pointings covering the Northern sky down to $\delta = -30°$.
- Each one-degree pointing captures an Hα spectrum over a 200 km s^{-1} region centered near v_{LSR} = 0 km s^{-1}.
- Sensitivities reach below 0.1 R (EM ~ 0.2 cm^{-6} pc) in all spectra, with extended spatial regions detected below 0.03 R.
- Available at http://www.astro.wisc.edu/wham/.




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

Ionization in the WIM

General Observations

- [O I] λ6300: $H^+/H_{tot} > 90\%$.[2]
- He I λ5876: $He^+/He < 60\%$.[3]
- [N II] and [S II] are bright compared to H II regions, ratio to Hα typically 0.1 to 1.0.[4]
- [O III] is faint, ratio to Hα typically << 0.1.[3]

Ionization in the WIM

General Conclusions

- Power requirement is high[5]: Hα observations imply a disk surface recombination rate of ~ 4×10^6 s^{-1} cm^{-2}.
  - 15% OB Lyman continuum flux.
  - 100% kinematic input from SN.
- N^+, S^+, and O^+, etc. are dominant ions.
  - Ionizing spectrum is soft?
  - Photon/gas ratio is low?

Temperature in the WIM

General Observations

- [S II]/Hα and [N II]/Hα are strongly correlated with each other, especially within a localized region.[4]
- [N II]/Hα and [S II]/Hα increase with decreasing $I_{H\alpha}$.[4]
- [N II] λ5755/[N II] λ6584 is about three times larger in the WIM than in H II regions.[6,3]
- [O II]/Hα increases faster than [N II]/Hα with decreasing $I_{H\alpha}$. [See poster by Reynolds et al.]

Temperature in the WIM

General Conclusions

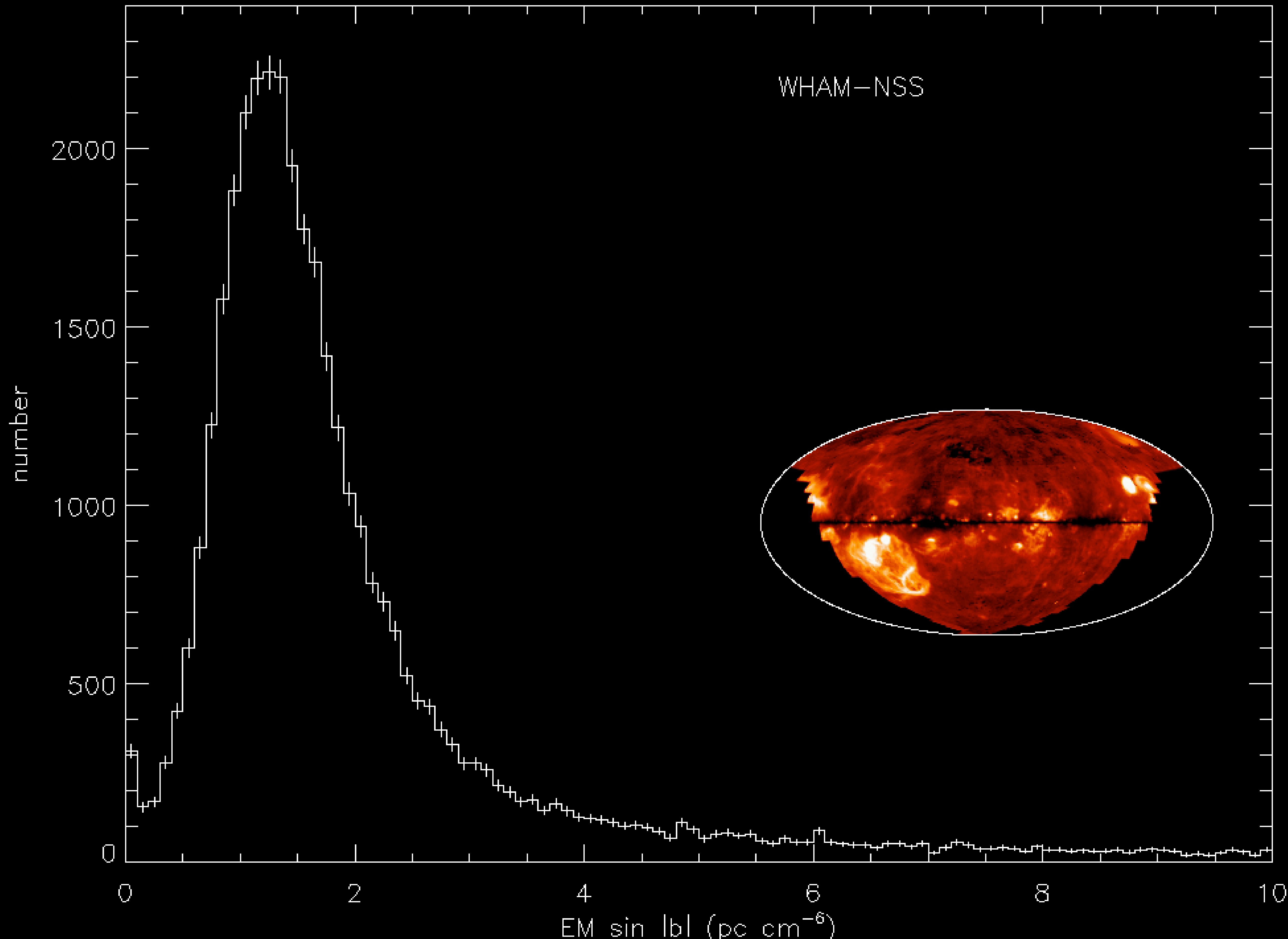
- T_e is elevated in the WIM compared to classical H II regions: 8,000–12,000 K.
- Variation in optical forbidden line radiation is dominated by changes in T_e rather than changes in ionic fractions or elemental abundances.[4]
- T_e rises with decreasing EM and, as a result, with increasing |z|.[4]

Scale Height

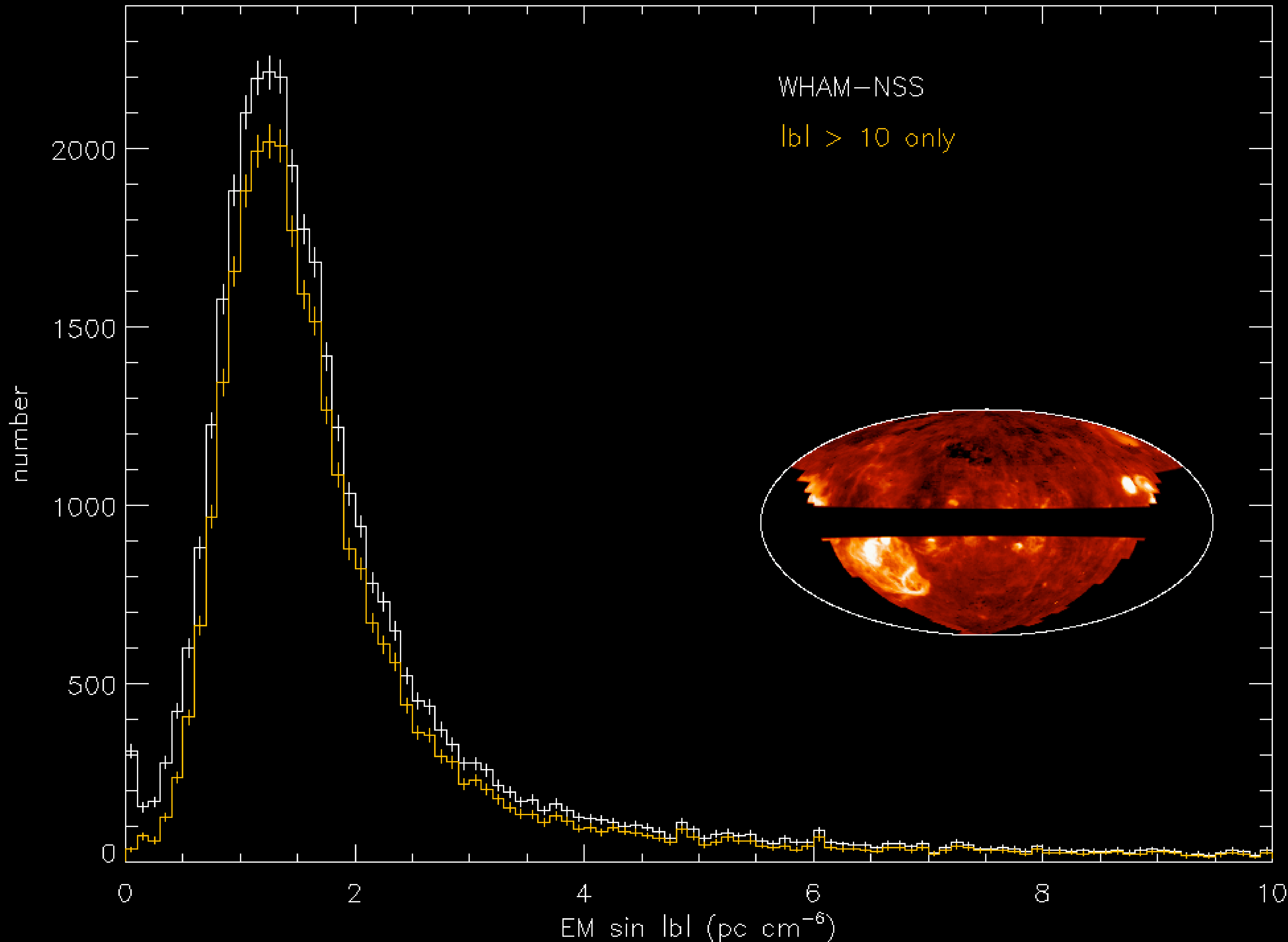
- Two independent observational methods:
  - Examining the DM distribution of high-latitude pulsars with known distances.[7]
  - Kinematically separating and tracing EM vs. |z| in Perseus Arm.[4]
- Both studies give H_{WIM} = 1 kpc.

EM Distribution

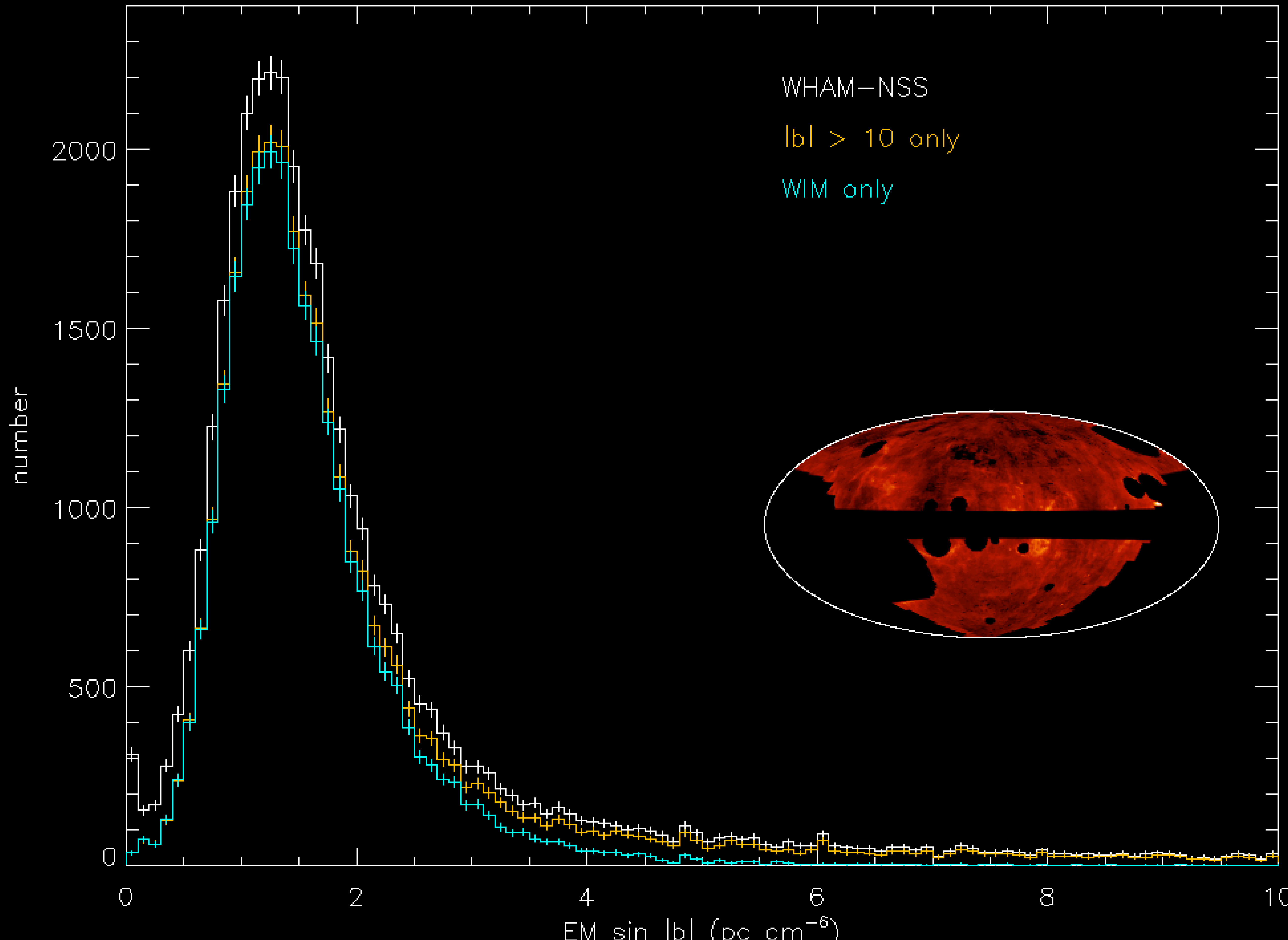
- Smooth, plane-parallel ionized layer would result in EM sin |b| = constant.
- What does the real distribution of EM sin |b| tell us about the WIM?
- Hill, et al., in prep.



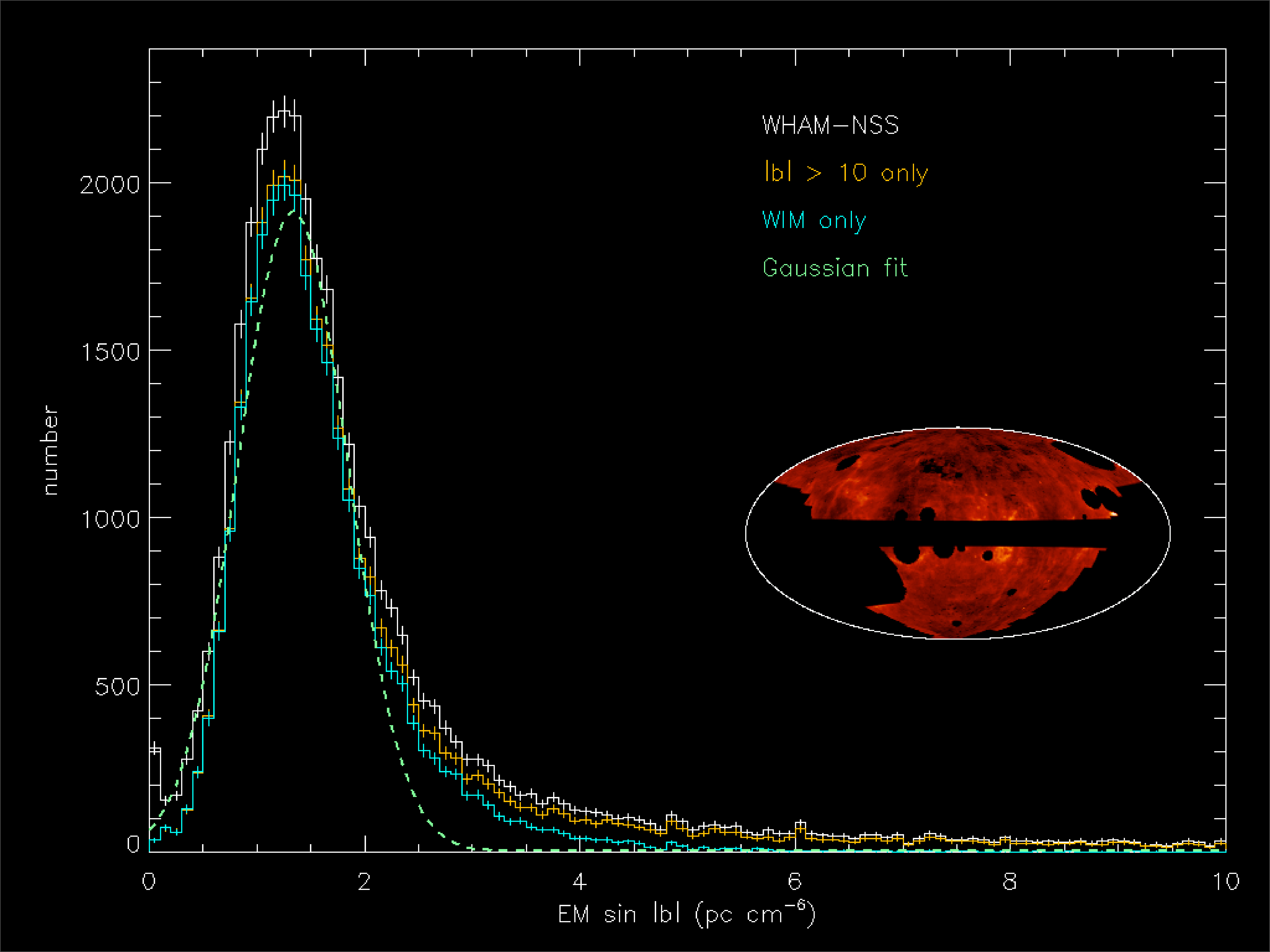
WHAM–NSS
number
2000
1500
1000
500
0
0
2
4
6
8
10
EM sin |b| (pc cm^{-6})



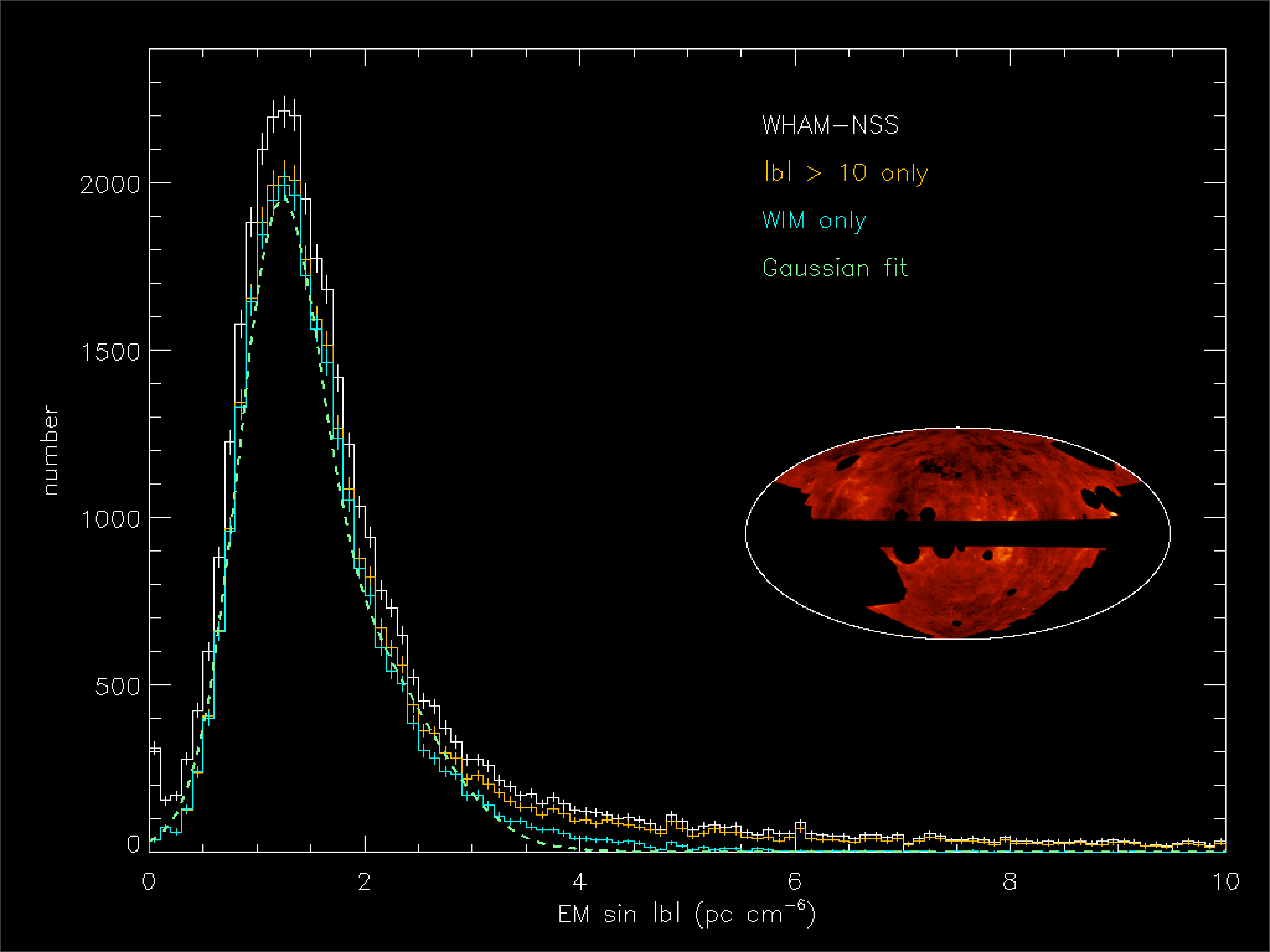
WHAM–NSS
|b| > 10 only
number
0
500
1000
1500
2000
0
2
4
6
8
10
EM sin |b| (pc cm^{-6})

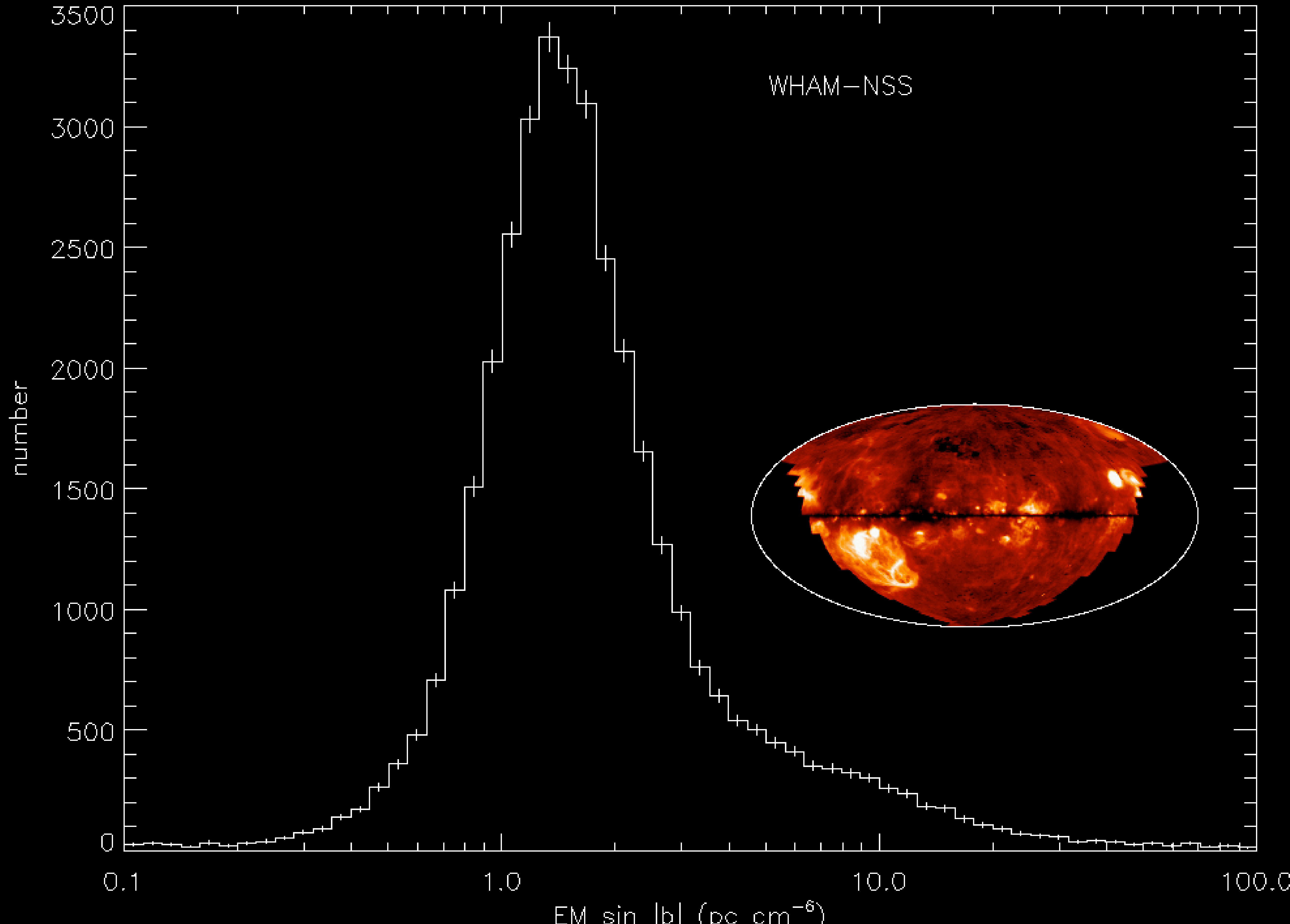


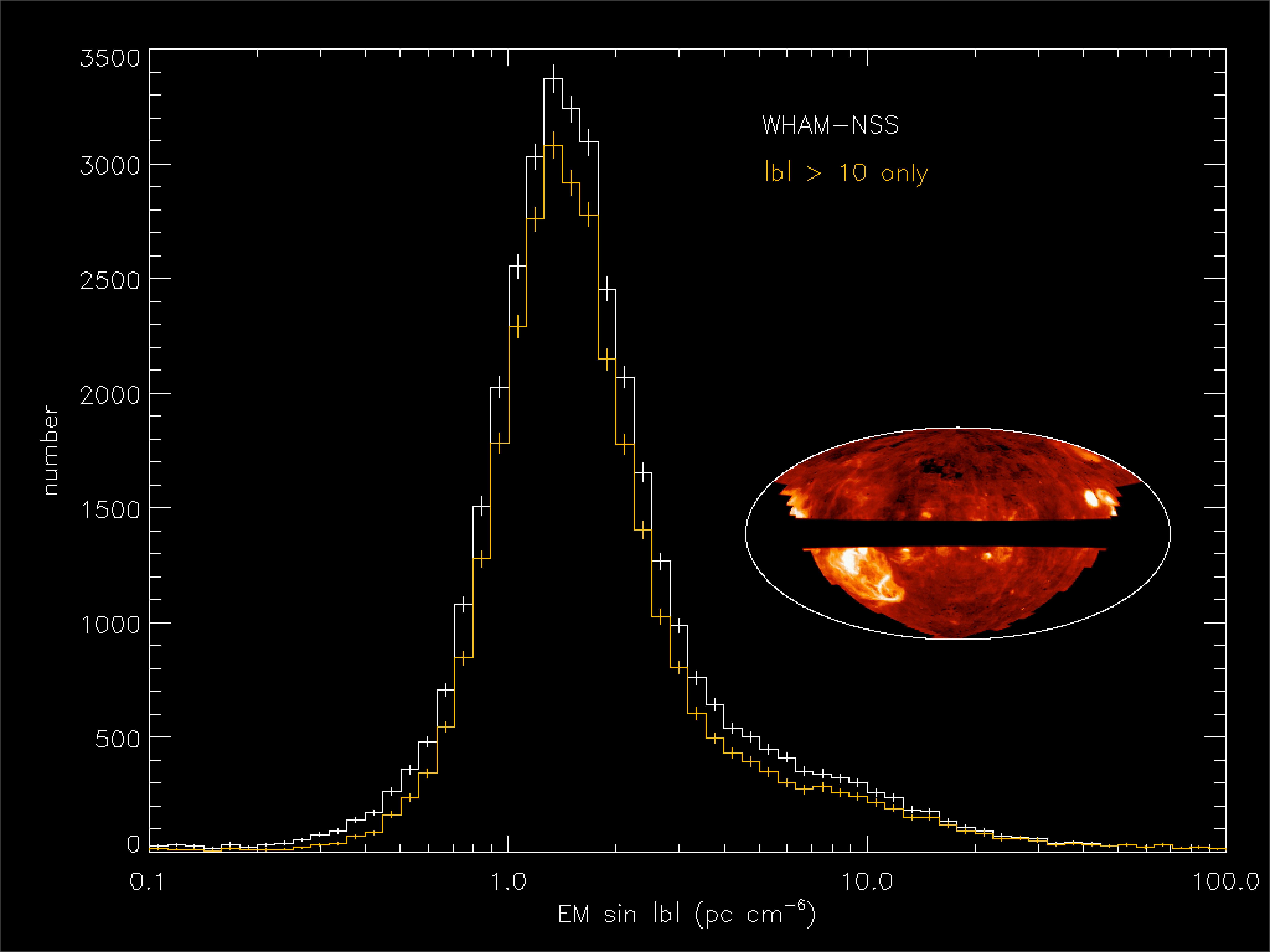
WHAM−NSS
|b| > 10 only
WIM only
number
EM sin |b| (pc cm^{-6})
0
500
1000
1500
2000
0
2
4
6
8
10



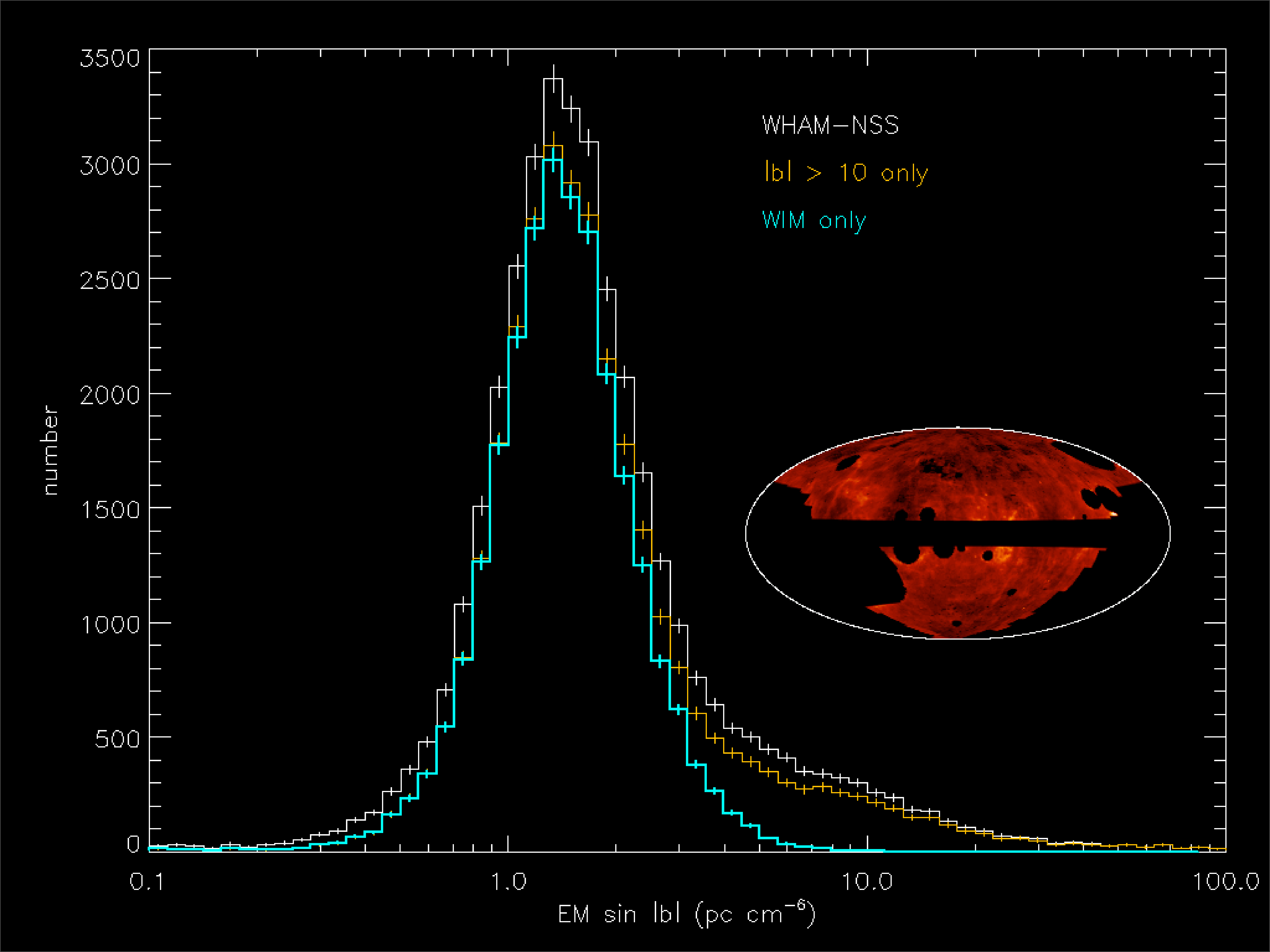
WHAM-NSS
|b| > 10 only
WIM only
Gaussian fit
number
0
500
1000
1500
2000
0
2
4
6
8
10
EM sin |b| (pc cm^{-6})


WHAM–NSS
|b| > 10 only
WIM only
Gaussian fit
number
EM sin |b| (pc cm^{-6})
0
500
1000
1500
2000
0
2
4
6
8
10

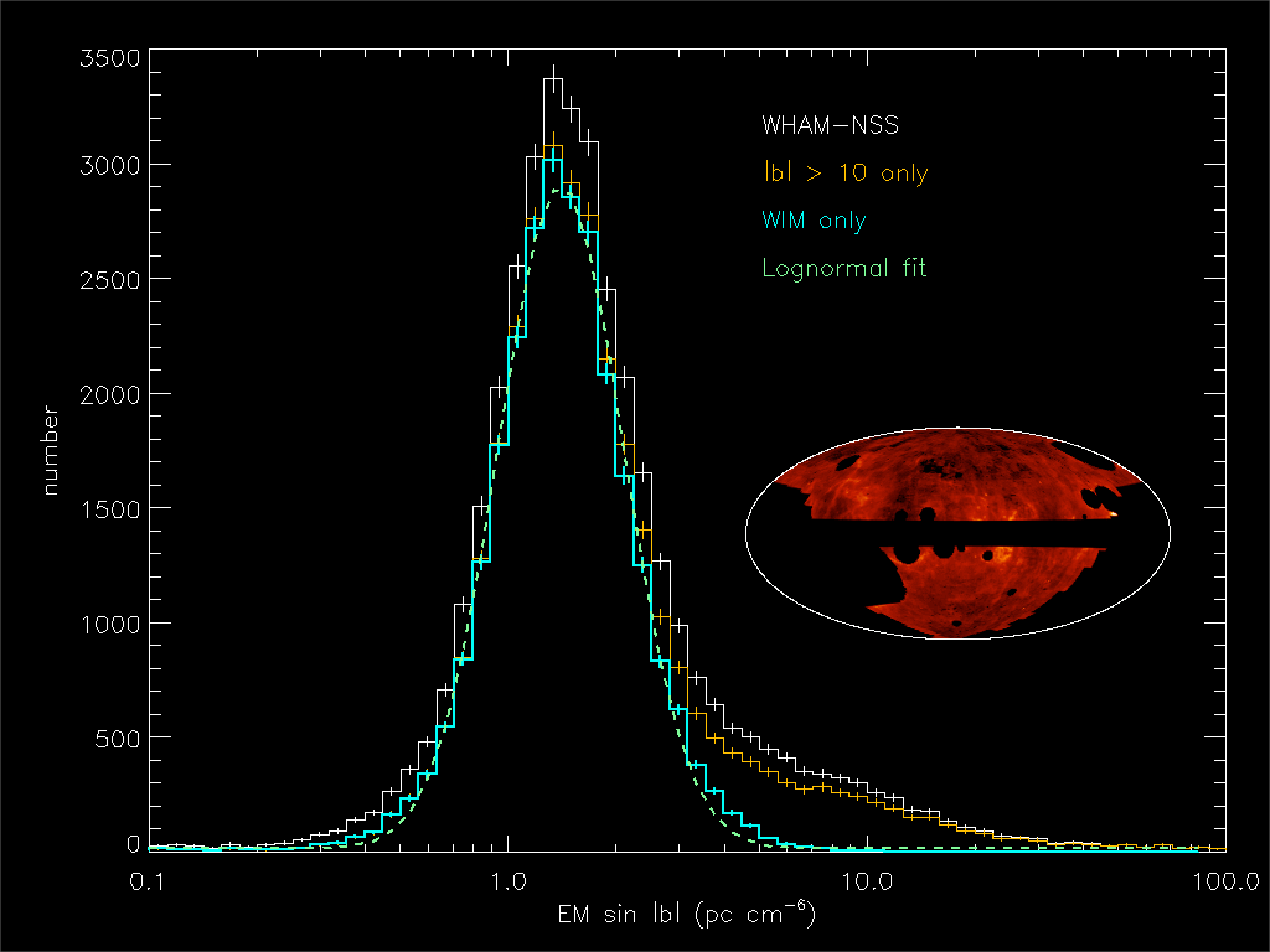

WHAM–NSS
number
EM sin |b| (pc cm^{-6})
0
500
1000
1500
2000
2500
3000
3500
0.1
1.0
10.0
100.0



WHAM-NSS
|b| > 10 only
number
EM sin |b| (pc cm^{-6})
0.1
1.0
10.0
100.0
0
500
1000
1500
2000
2500
3000
3500



WHAM-NSS
|b| > 10 only
WIM only
number
EM sin |b| (pc cm^{-6})
0
500
1000
1500
2000
2500
3000
3500
0.1
1.0
10.0
100.0



WHAM-NSS
|b| > 10 only
WIM only
Lognormal fit
3500
3000
2500
2000
1500
1000
500
0
number
0.1
1.0
10.0
100.0
EM sin |b| (pc cm^{-6})

EM Distribution

Lognormal

- Variable effects that are multiplicative rather than additive.
- PDF $\propto$ $f(\log x; \mu, \sigma) / x$, where f() is a normal distribution.

	68.3%	95.5%
Normal	$\mu \pm \sigma$	$\mu \pm 2\sigma$
Lognormal	$\mu^* \;{}^{\times}\!/\; \sigma^*$	$\mu^* \;{}^{\times}\!/\; \sigma^{*2}$

EM Distribution

- The EM sin |b| distribution of the WIM can be described by a lognormal function having:

  $\langle \log EM \sin|b| \rangle = 0.15$ $(\langle EM \sin|b| \rangle = 1.4)$

  FWHM = 0.41 $(\sigma^* = 1.5)$

- Typical result of compressions and rarefactions in fluids.
- FWHM describes the "strength" of those processes.

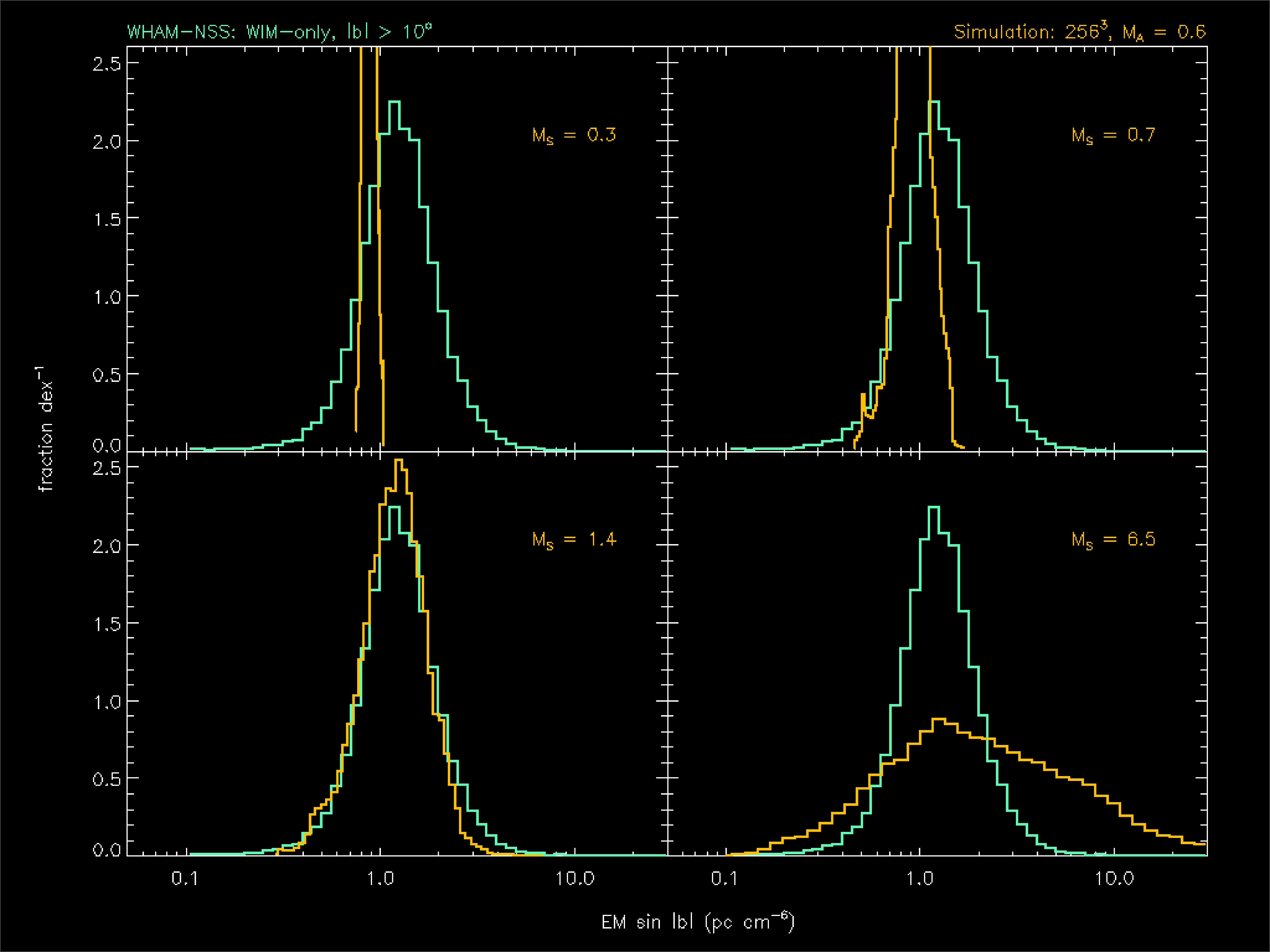
Isothermal Turbulence

Kowal, Lazarian, & Beresnyak 2007 (KLB)[8]

- 3D compressible, isothermal MHD turbulence.
- Range of resolutions (256^3 used here), sonic and Alfvénic Mach numbers (M_S, M_A).
- Analyze a range of 3D and 2D (column density) statistics after many dynamical time steps.

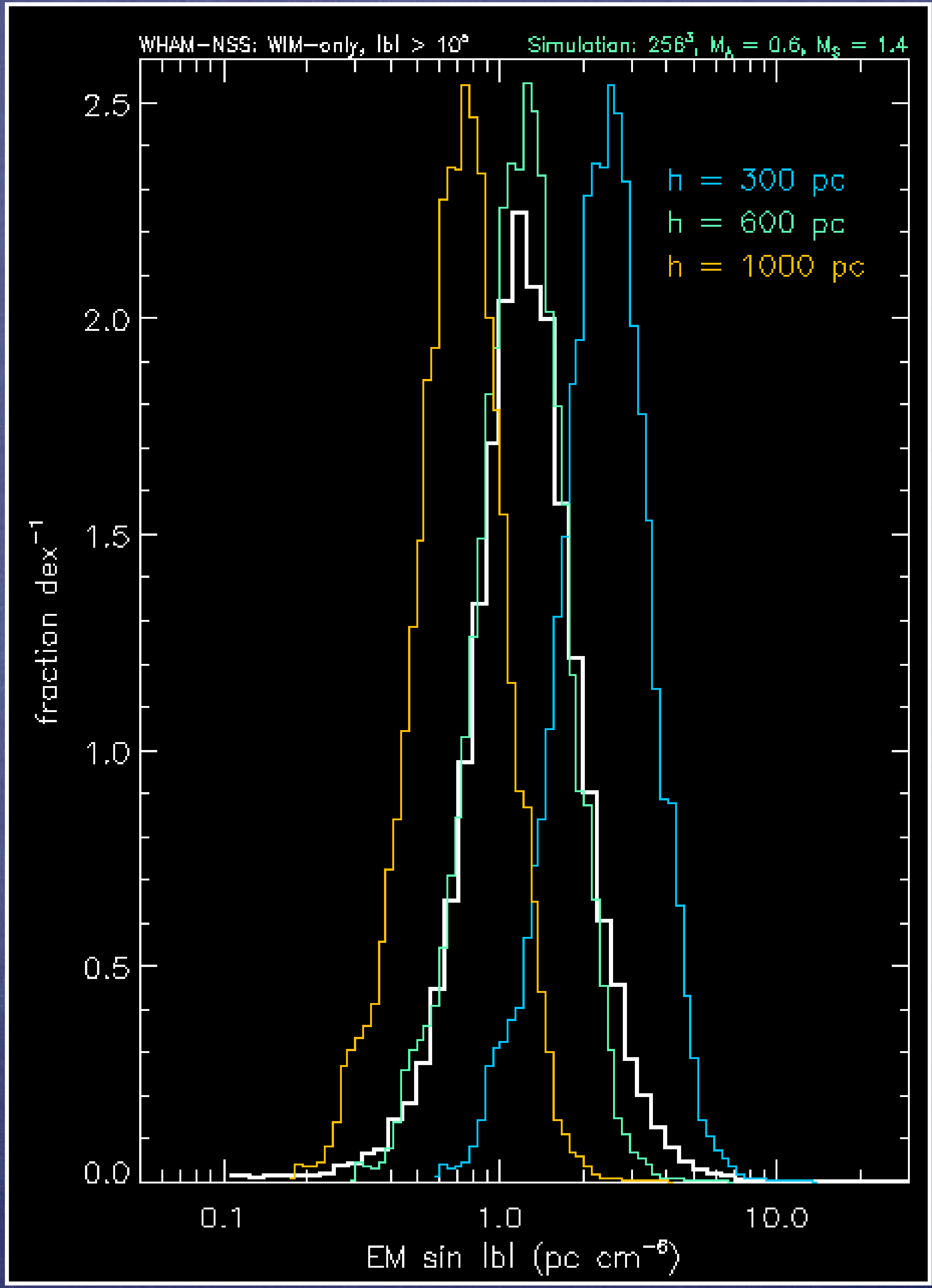
Simulations of the WIM

- KLB models with physical scaling:
  - Impose <DM> = 23 pc cm^{-6}, the mean value from globular cluster pulsars.
  - Investigate a range of box sizes (h) from 200-1000 pc.
  - T = 8000 K
- Compute simulated 2D EM maps and compare this EM distribution to that of the WIM.



WHAM-NSS: WIM-only, |b| > 10°
Simulation: 256³, M_A = 0.6
M_S = 0.3
M_S = 0.7
M_S = 1.4
M_S = 6.5
fraction dex⁻¹
EM sin |b| (pc cm⁻⁶)
0.0
0.5
1.0
1.5
2.0
2.5
0.1
1.0
10.0

- Changing the box size changes the mean of the distribution but not the shape.
- Note that the best fit box size (h = 600 pc) is 0.6 x H_{WIM}, the physical scale height of the WIM layer.



Simulations of the WIM

- EM distribution shape is very sensitive to M_S but relatively insensitive to M_A.
- Simulated EM distribution best fits the WIM EM distribution when using:
  - [FWHM] Mildly supersonic conditions: $1 < M_S < 3$.
  - [Mean] Box size (h) of 500–600 pc.

Simulations of the WIM

- With no other parameter adjustment or scaling, best-fit models also:
  - Match pulsar DM sin |b| distribution.
  - Have velocity line profiles consistent with those from the WIM.

Summary

- WHAM observations of the WIM reveal a low-ionization (H^+, O^+, N^+, S^+, ...), warm (0.8 - 1 x 10^4 K), low-density (< 0.1 cm^{-3}) plasma distributed in a thick disk (H = 1 kpc).
- New studies of the EM distribution suggest that the WIM is described well by mildly-supersonic (M_S = 1−2) isothermal, MHD turbulence models.

References

1. Haffner, Reynolds, Tufte, Madsen, Jaehnig, & Percival. 2003, ApJS, 149, 405.
2. Hausen, Reynolds, & Haffner, 2002. ApJ, 124, 3336.
3. Madsen, Reynolds, & Haffner. 2006, ApJ, 652, 401.
4. Haffner, Reynolds, & Tufte. 1999, ApJ, 523, 223.
5. Reynolds. 1984, ApJ, 282, 191.
6. Reynolds, Sterling, Haffner, & Tufte. ApJL, 548, L221.
7. Reynolds. 1991, ApJ, 372, L17.
8. Kowal, Lazarian, & Beresnyak. 2007, ApJ, 658, 423.