ISM phases through HI absorption

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with thanks to:
Claire Murray, John Dickey, Carl Heiles, Miller Goss +
21-SPONGE, GALFA-HI, GASKAP

and apologies for not being able to cover all exciting work

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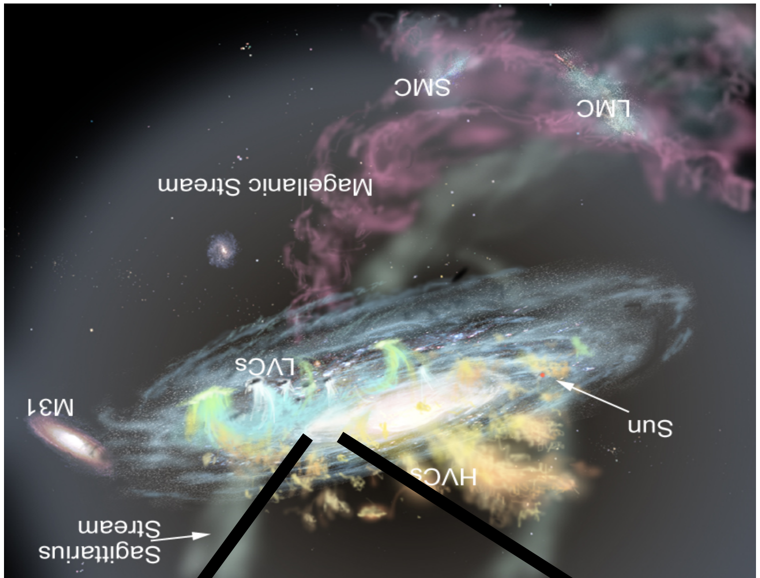
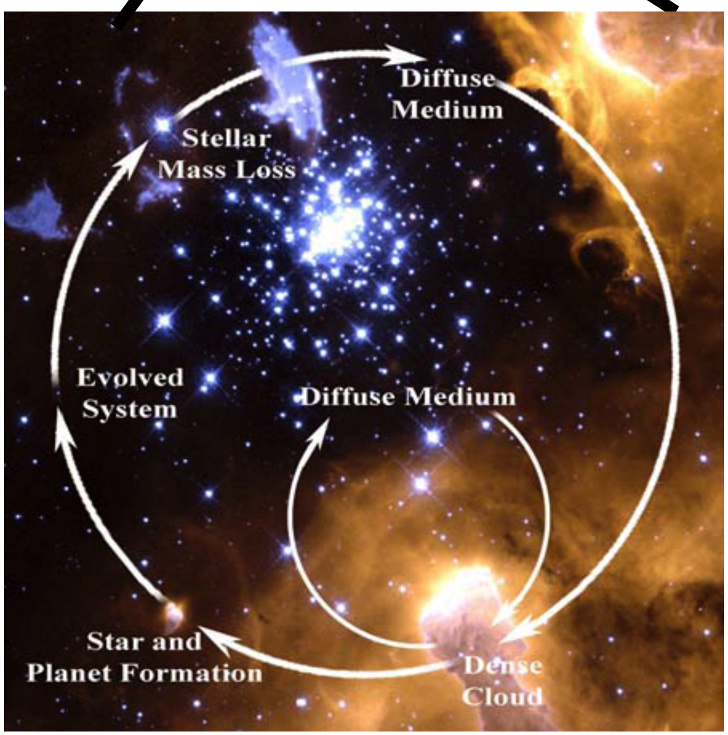




Diffuse IS gas = the 1st step in the star formation cycle in galaxies

- Diffuse gas accreted
- Atomic → molecular
- Molecular → stars
- Stars → diffuse gas

- How do we measure gas properties?

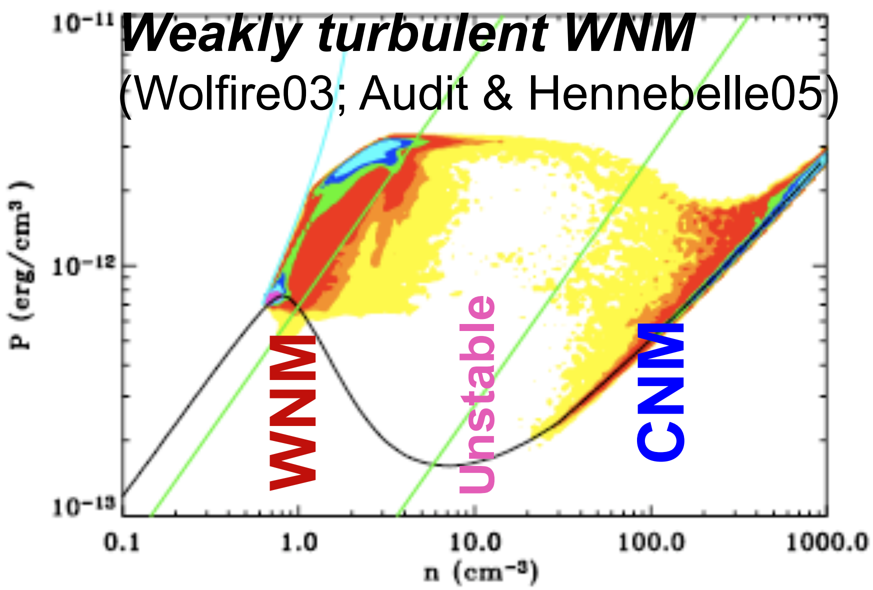
CNM:

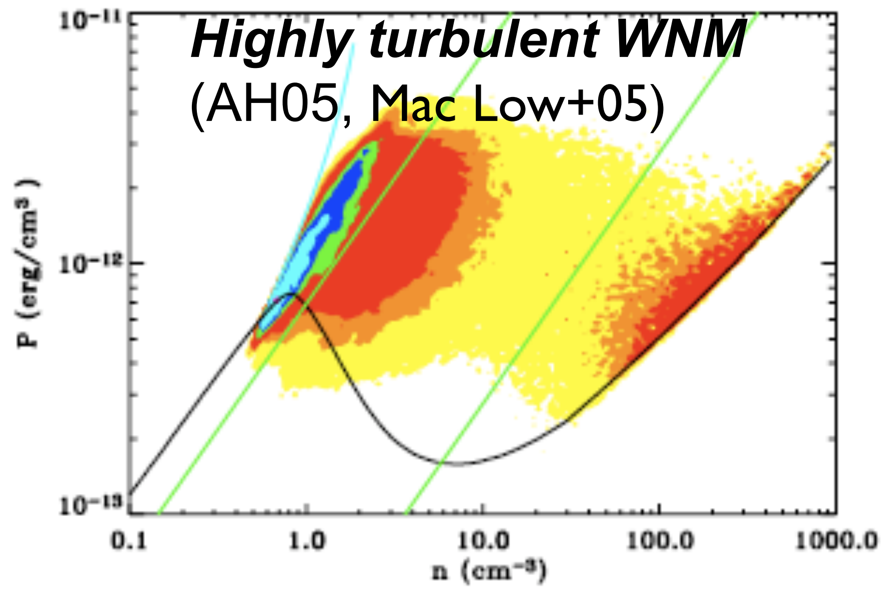
- Large-scale properties
- Variation of CNM temperature in the MW

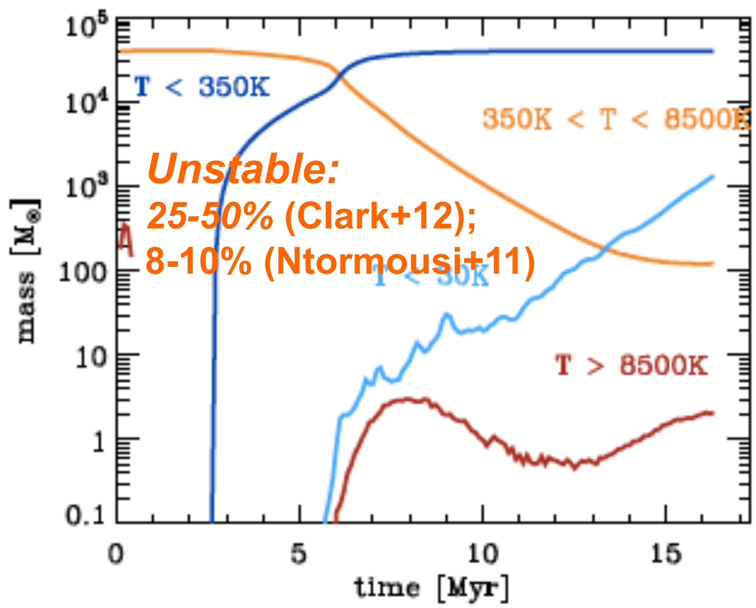
WNM:

- WNM in absorption and its temperature
- Open questions

Initial conditions for the assembly of dense clouds (T, n)?







Equilibrium Theory: 2 stable phases.

P/k ~ 1700 - 4400 cm^{-3} K

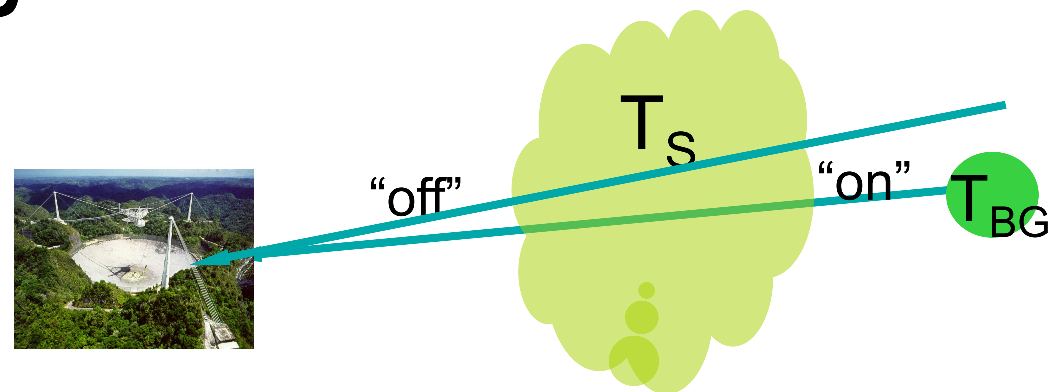
- WNM T ~ 8000 K
- CNM T ~ 50 K

MHD Simulations: Initial~8000K gas.

Fraction of cold, warm and thermally unstable gas vary hugely.

- Due to numerics and/or initial conditions?

How do we measure HI absorption? Ingredients:



1. **Background continuum source:** bright galaxy (whole LOS) or HII regions (near-side bias).

2. **Optical depth profile:**
   Interferometers: $T_{b,on}/T_{bg} = e^{-\tau}$
   but single dish needs to solve Eq (1)

$$T_b^{on} = T_{bg}e^{-\tau} + T_s(1 - e^{-\tau})$$
$$T_b^{off} = T_s(1 - e^{-\tau}) \quad (1)$$

3. **$T_{b,off}$ = “expected” emission** profile = HI emission if the source suddenly turned off

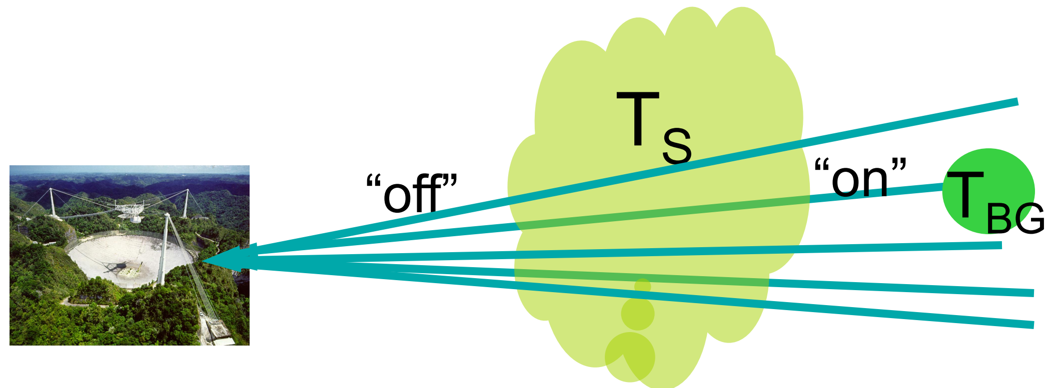
High angular resolution needed to measure emission fluctuations.
$\Delta\tau \approx \Delta T_{b,off}/T_{bg}$

How do we constrain observationally? Ingredients:

5. **Radiative transfer → Ts**
   To solve radiative transfer need similar angular resolution of emission and optical depth

   Ts derivation methods: "differences minor" (Dickey+03)

6. **Stray radiation**: affects emission spectra



$$
\begin{aligned}
\underbrace{T^*_{\mathrm{sys},n,j}(\nu) - T^*_{R,n}}_{\textit{Source temperature}} = {} & [T_{\exp}(\nu)] + \left[\frac{\partial T_{\exp}(\nu)}{\partial \alpha}\right] \Delta\alpha_j \\
& + \left[\frac{\partial T_{\exp}(\nu)}{\partial \delta}\right] \Delta\delta_j + \left[\frac{\partial T_{\exp}(\nu)^2}{\partial^2 \alpha}\right] \frac{(\Delta\alpha_j)^2}{2} \\
& + \left[\frac{\partial T_{\exp}(\nu)^2}{\partial\alpha\partial\delta}\right] (\Delta\alpha_j)(\Delta\delta_j) \\
& + \left[\frac{\partial T_{\exp}(\nu)^2}{\partial^2 \delta}\right] \frac{(\Delta\delta_j)^2}{2} \\
& + [e^{-\tau(\nu)}]\, T^*_{\mathrm{ant},n,j} \,. \qquad (8)
\end{aligned}
$$

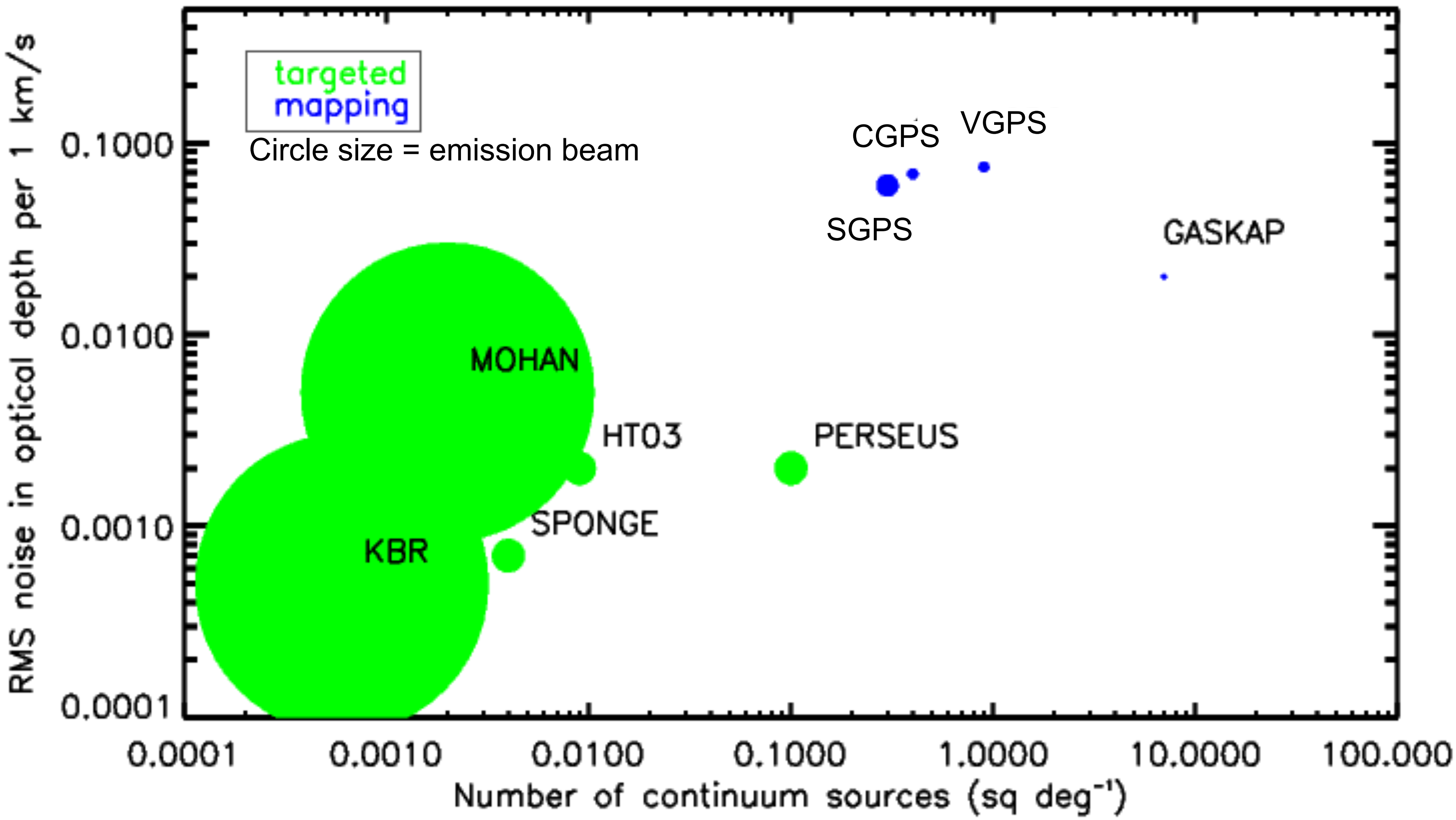
Heiles & Troland03

Recent HI absorption surveys

Survey	Area (deg)	Emission Angular Resolution (‘)	Velocity Resolution (km/s)	Sensitivity 1-σ_τ per 1 km/s	Number of spectra	Telescopes
VGPS	|b|<1.3 l=18-67	1	1.56	0.025-0.125	113	VLA + GBT
CGPS	-3.6<b<5.6 l=65-175	1	1.32	0.023-0.115	364	DRAO + DRAO 26m
SGPS	|b|<1.5 l=253-358	2	1.0	0.02-0.1	96	ATCA+ Parkes
HT03	9060 sq deg	4	0.16	0.002	78	Arecibo
3C	20830 sq deg	4	0.16	0.002	23	Arecibo
Perseus	270 sq deg	4	0.16	0.002	27	Arecibo
Mohan04	|b|>15	36	3.3	0.005	102	GMRT+LDS
Kanekar	56500 sq deg	36	1.0	0.0005	35	WSRT/ GMRT/ATCA +LDS
SPONGE	|b|>15	4	0.4	<0.00073	58	VLA+Arecibo

Taylor+03, Heiles & Troland03, McClure-Griffiths+05, Stil+06, Mohan+04, Kanekar, Braun, Roy 11, SS & Heiles05, Murray+13, SS+, in prep.

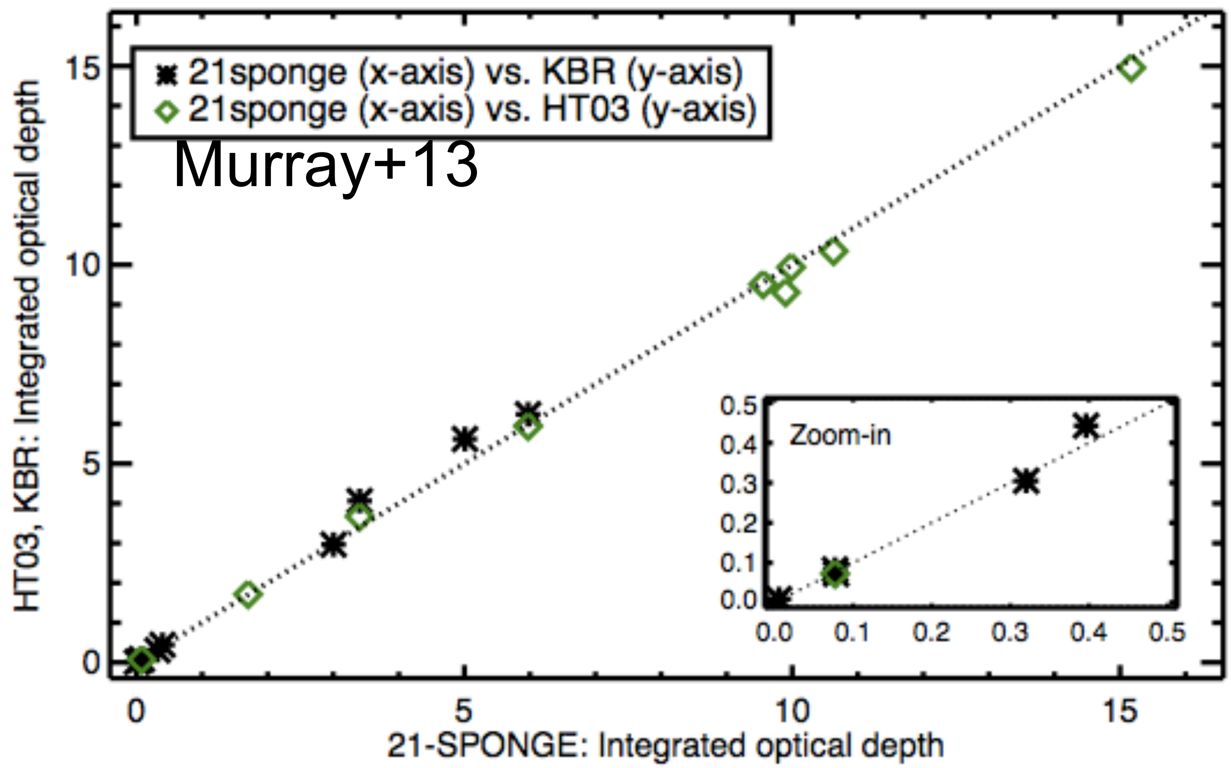
Survey comparison



Interferometric (CGPA, VGPS, SGPS, GASKAP): large samples but low sensitivity.
Kanekar, Braun & Roy (2011) and 21-SPONGE (SS+): the most sensitive.

Survey comparison

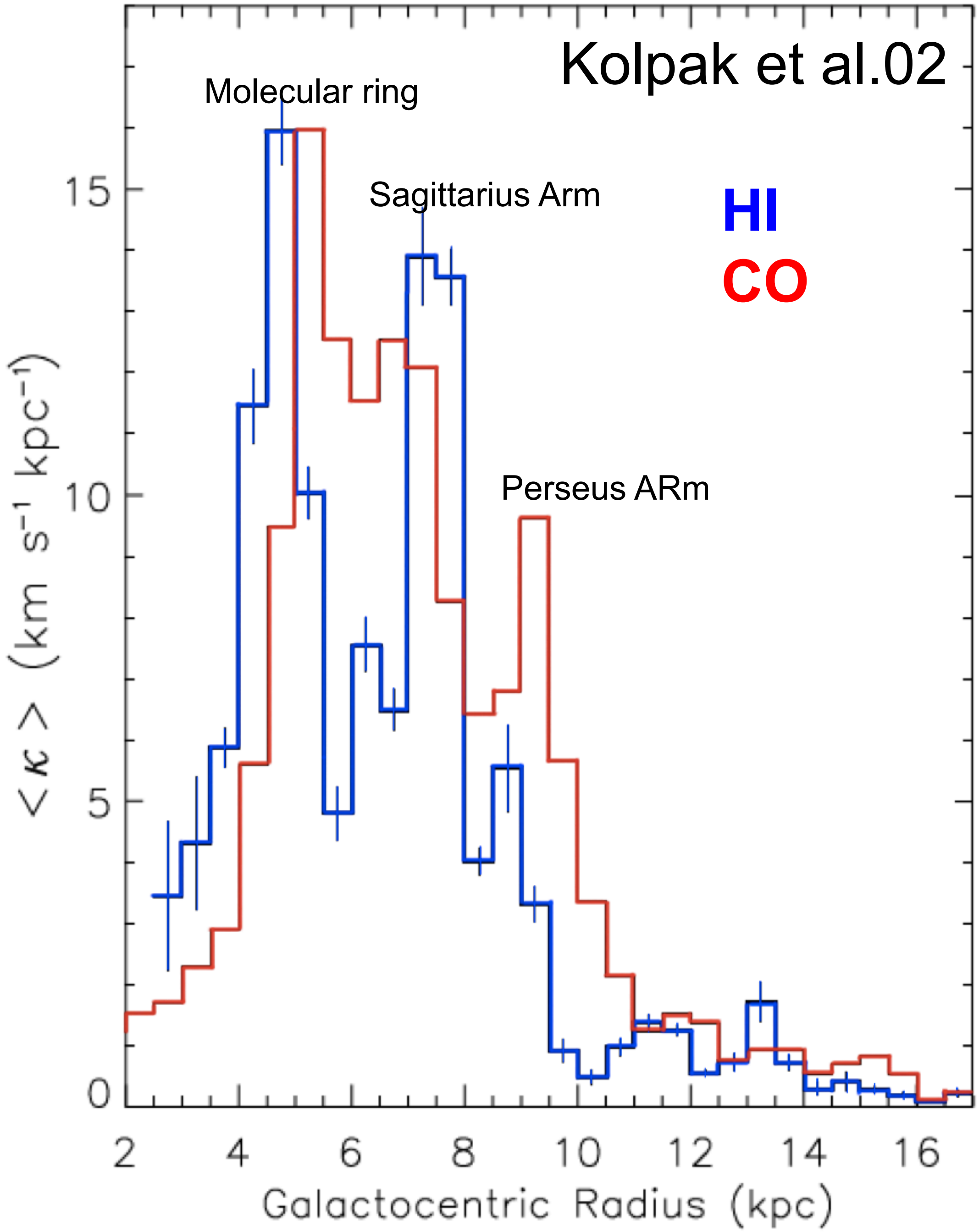
Good agreement btw VLA/WSRT and Arecibo at |b|>10deg.



Low-b: Interferometers (with 0 spacings) more accurate in obtaining absorption spectra, but spectra complicated and large blending (effects Ts derivation).

High-b: profiles not affected by Galactic rotation + less complicated so less blending and fitting uncertainties.

Highly complementary!



Absorption coefficient at |b|<a few deg

$$\kappa(R_{gal}) = \frac{\int \tau \, dv}{\Delta s(R_{gal})}$$

Peaks at 4 and 7kpc independent on rotation curve.

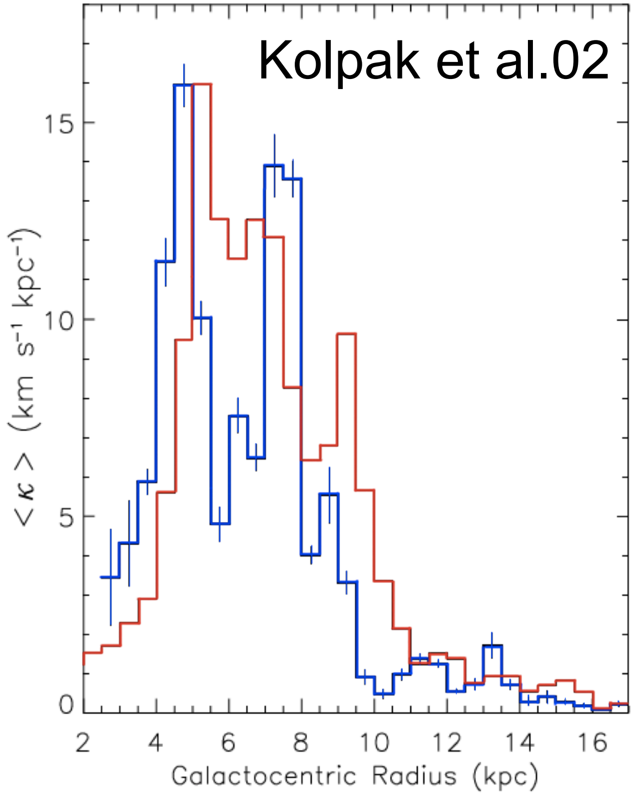
Increase in CNM abundance in the inner Galaxy. Low optical depth for R>10 kpc, sharp decrease at R~4kpc.

Good correlation with molecular mass not HI surface density → molecular gas is associated with regions of highest opacity

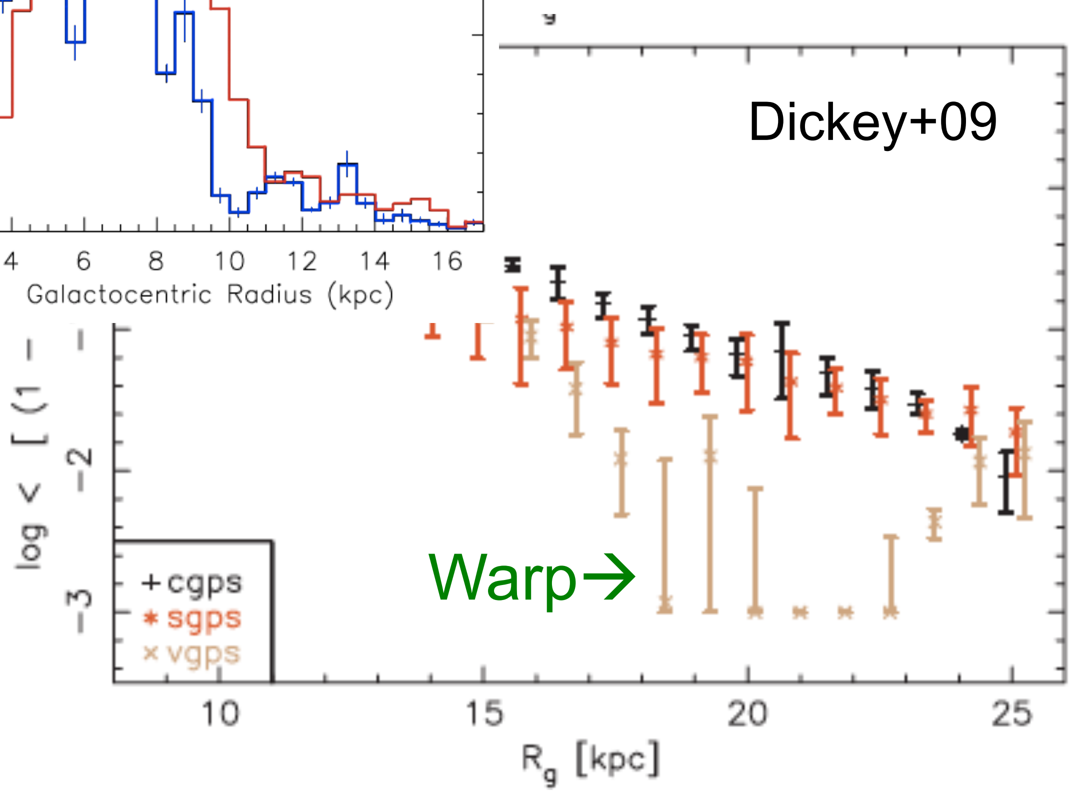
Further along the disk...

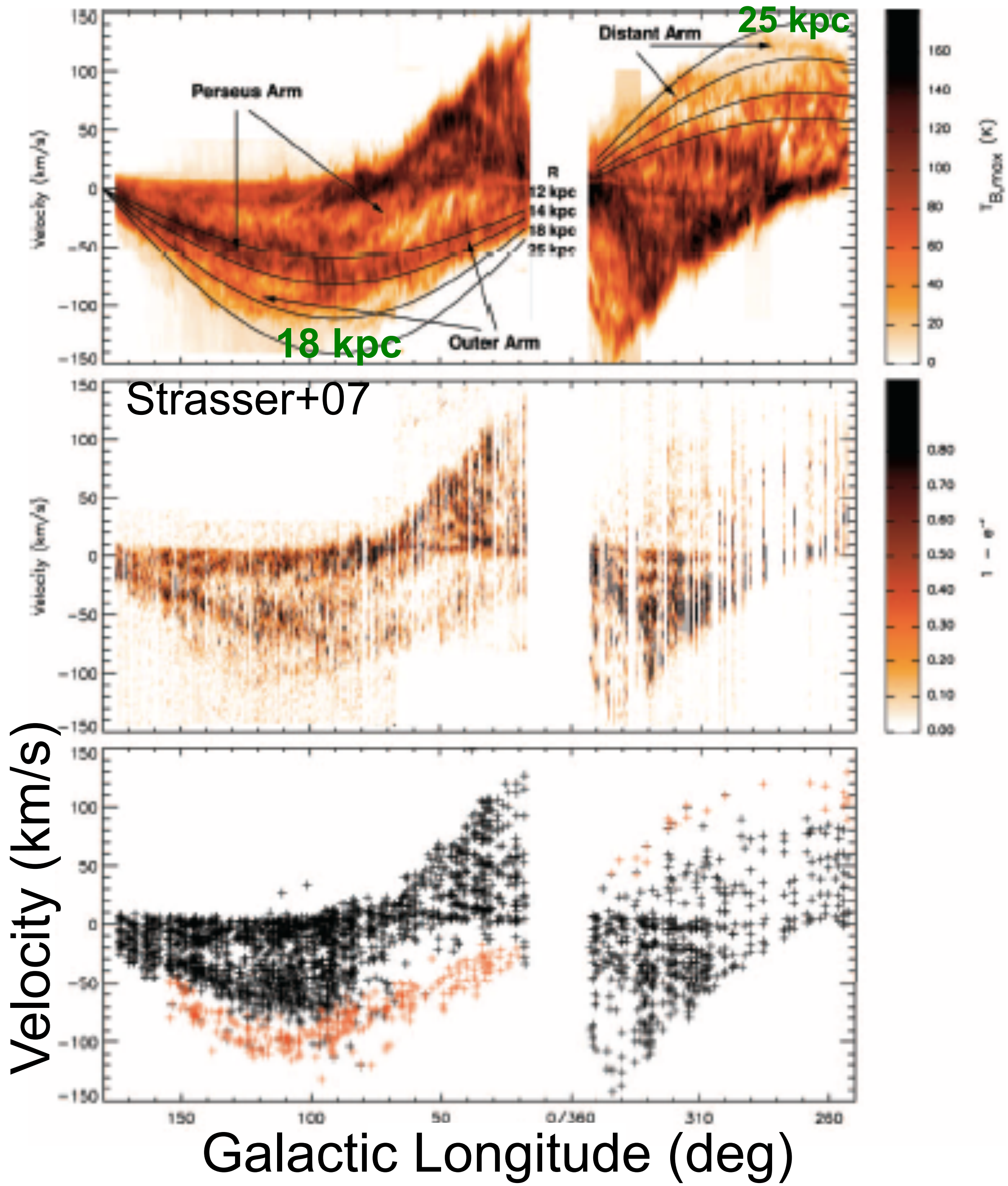
Decrease by >100x from 8 to 25 kpc, detected to R_g~25kpc

from Individual "clouds"



from Integrated properties



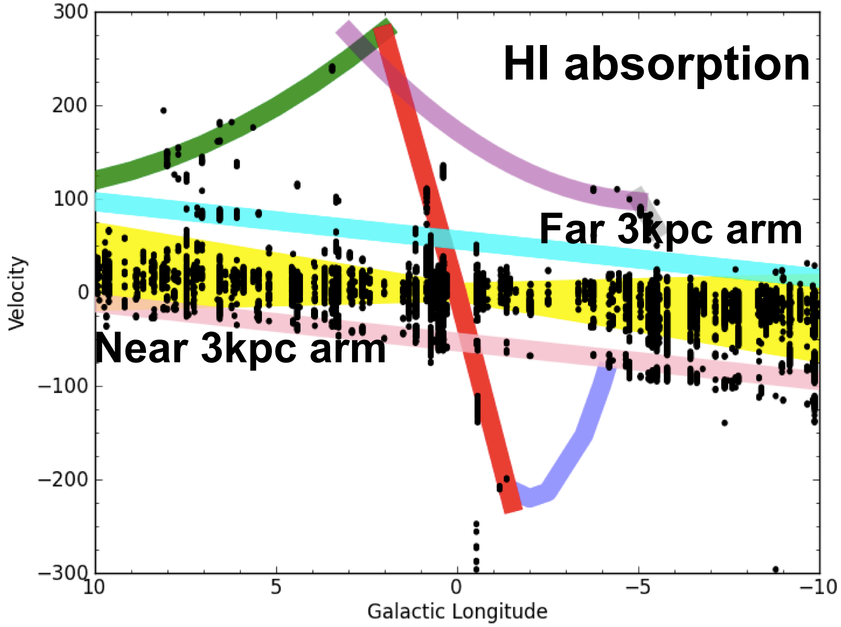


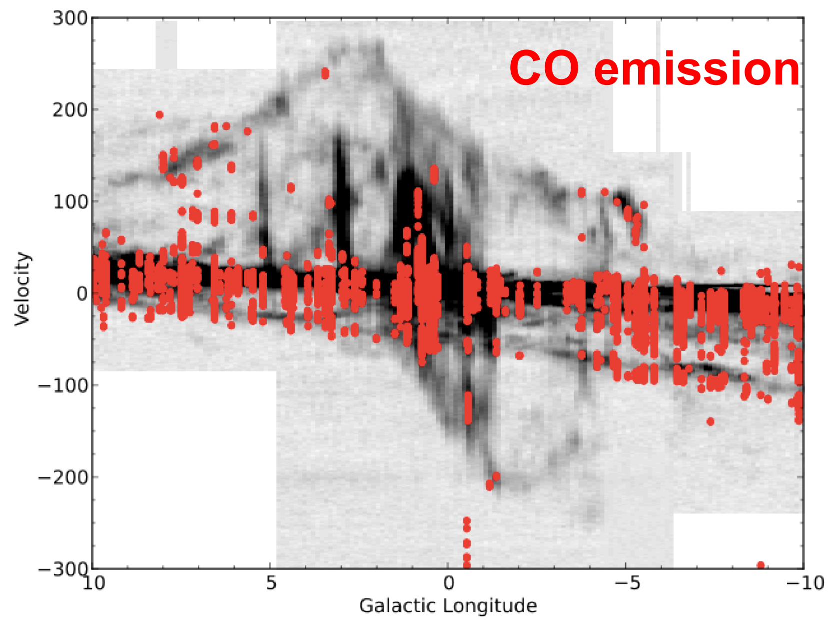
Cold HI in the outer MW?

All the way to R~18-25kpc and in spiral arms

- 557 background sources + IGPS survey
- Clear detection of HI absorption in the Outer Arm (R~18 kpc) and the Distant Arm (R~18-25 kpc)
- Wolfire03: CNM/WNM equilibrium exists for R = 3 to 18 kpc.

The extreme inner Galaxy (R_{gal}<4 kpc)



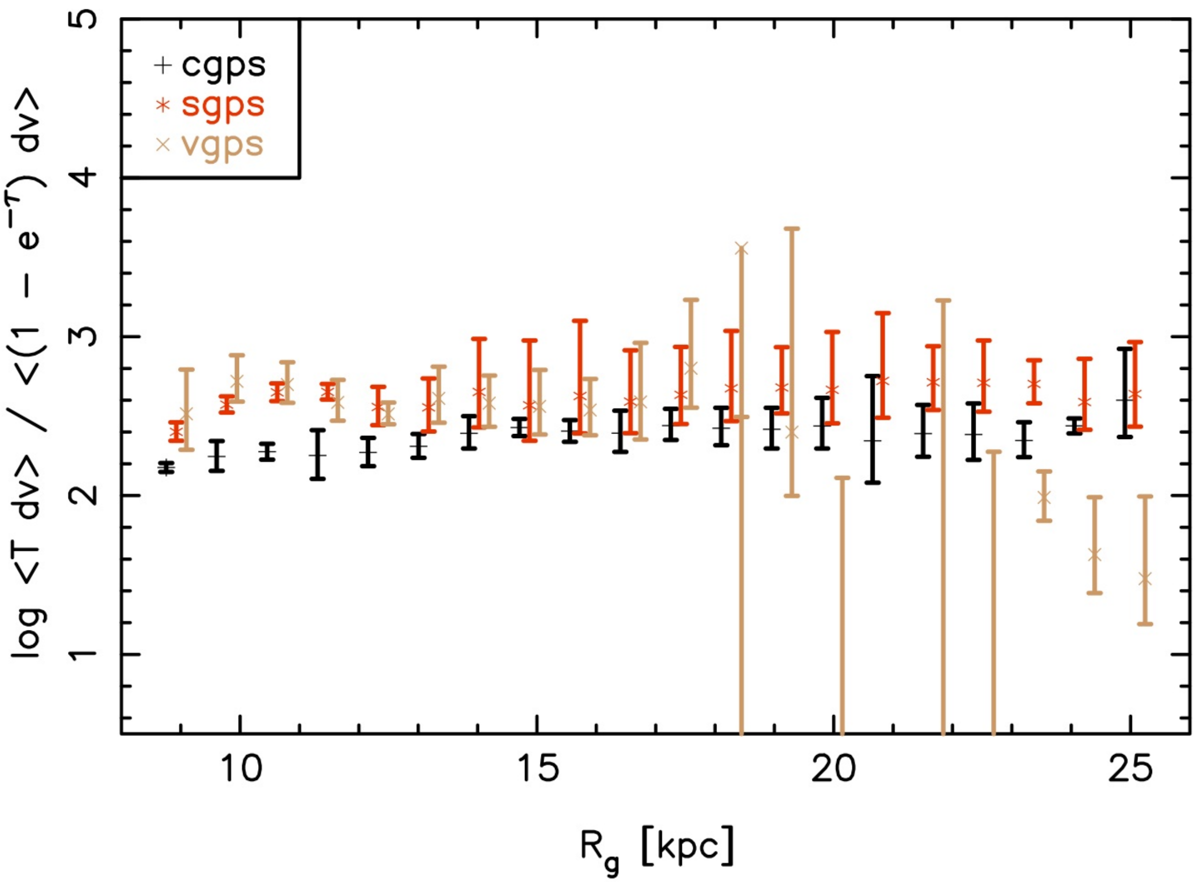


- Southern Galactic Plane Survey + ATCA HI Galactic Center Survey
- 151 HI absorption spectra extracted in the direction of HII regions
- Significant HI absorption detected.
- Relative to CO, HI absorption and HII regions less abundant in 3kpc Arms. Photodissociation product?

Jones et al. 2013

Does T_{sp} vary across the MW disk?

"T_{sp}"



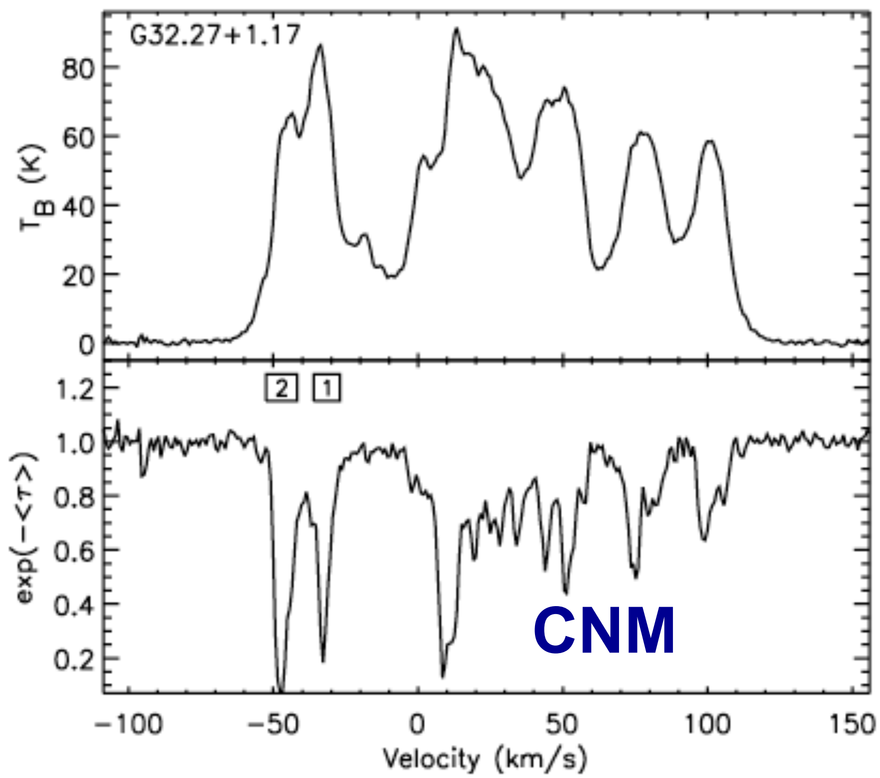
Dickey et al. 09:
290 spectra from SGPS, CGPS, VGPS.
Integrated properties.

$$\langle T_{sp} \rangle = \frac{T_{EM}}{(1-e^{-\tau})} = \frac{\int n\, ds}{\int \frac{n}{T_{kin}}\, ds},$$

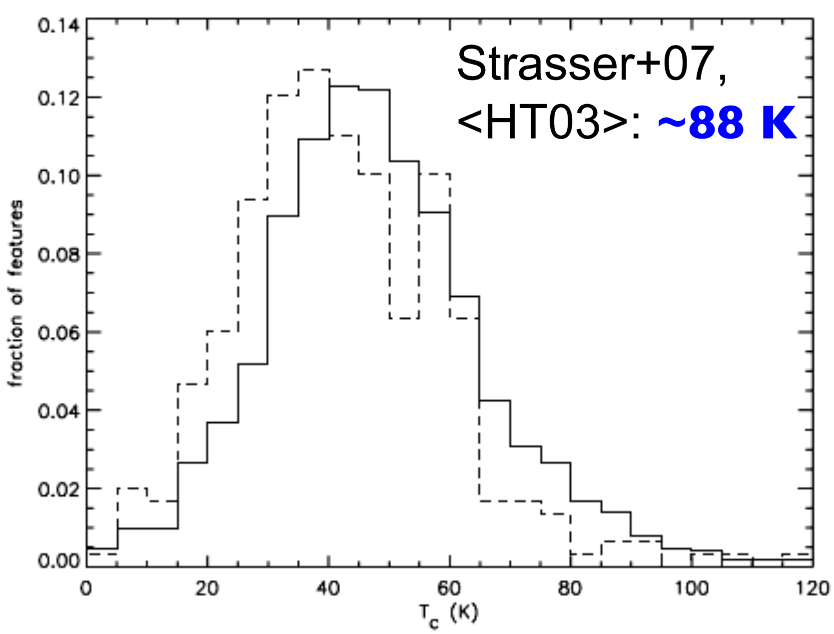
$$\langle T_{sp} \rangle = T_{cool} \frac{n_{WNM} + n_{CNM}}{n_{CNM}},$$

"T_{sp}"~300 K. As no evidence that T_{cool} varies across the disk → Mixture of CNM & WNM (or CNM fraction) is constant in the MW all the way to 25 kpc.

CNM temperature: inner vs outer MW



Strasser06 (PhD):
Do not observe a strong dependence on R_{gal} in the northern Galaxy (from individual absorption features)



	Inner Galaxy	Outer Galaxy
<Tc>	48 +/- 10 K	38 +/- 10 K
# per kpc	0.03-1	0.02-0.08

Wolfire et al. (2003): properties of thermally stable CNM & WNM

TABLE 3

RANGE OF PHYSICAL CONDITIONS FOR TWO-PHASE MEDIUM

~8000K

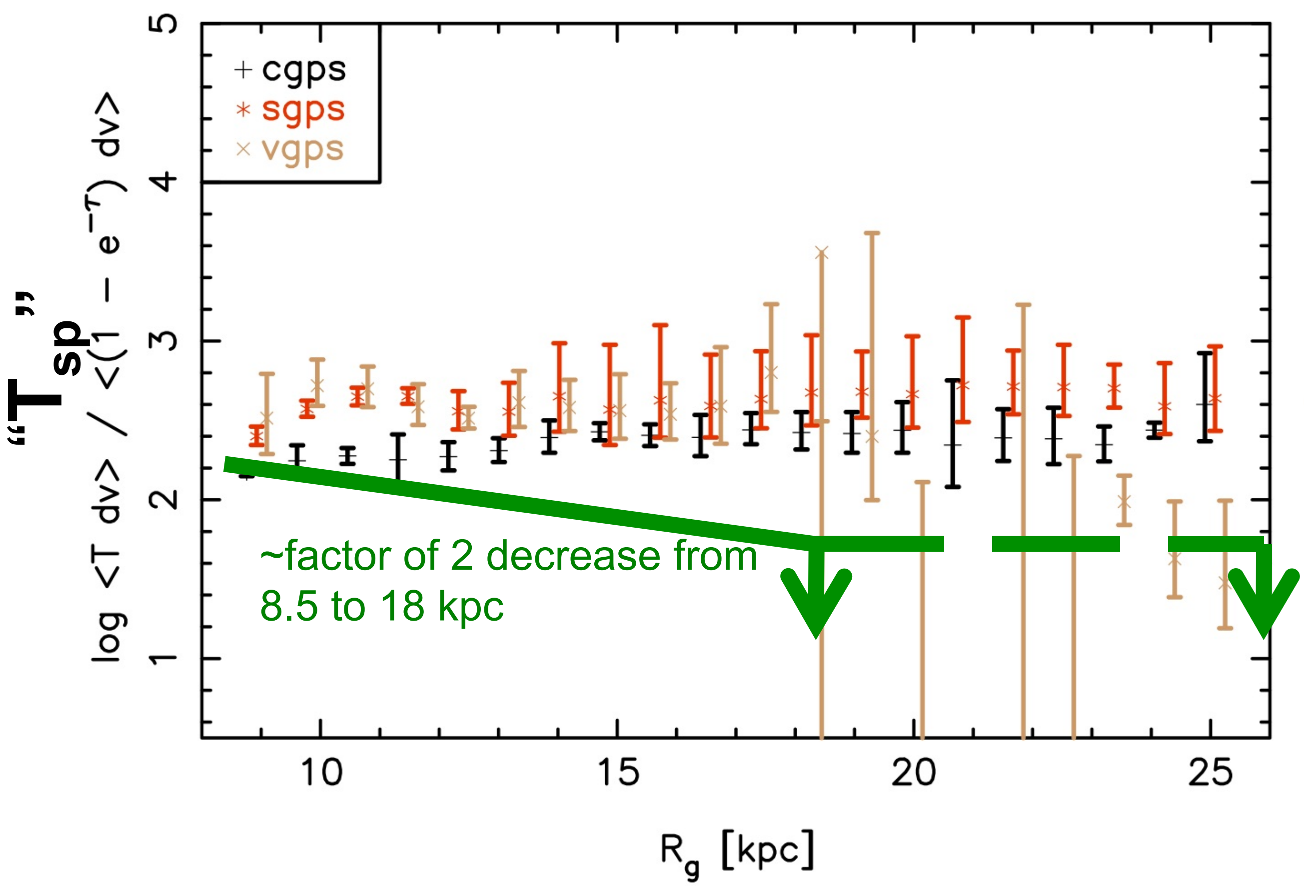
				WNM				CNM			
N_{cl} (cm^{-2})	R (kpc)	$P_{min}/k - P_{max}/k$ ($K\ cm^{-3}$)	$P_{th,ave}/k$ ($K\ cm^{-3}$)	T (K)	n (cm^{-3})	T_{ave} (K)	n_{ave} (cm^{-3})	T (K)	n (cm^{-3})	T_{ave} (K)	n_{ave} (cm^{-3})
1×10^{19}	3	5580–12100	8220	8530–5030	0.579–2.17	7960	0.922	345–88.8	14.6–124	124	60.2
	4	4910–10600	7210	8430–4930	0.516–1.93	7880	0.817	323–87.5	13.9–110	121	54.2
	5	4000–8850	5950	8410–4910	0.422–1.63	7880	0.675	312–80.6	11.6–100	111	48.6
	8.5	1960–4810	3070	8310–5040	0.209–0.860	7860	0.349	258–61.6	6.91–71.0	85.0	32.9
	11	995–2420	1550	8130–5080	0.109–0.430	7700	0.180	247–56.5	3.65–39.0	78.4	18.0
	15	487–1400	825	8080–5540	0.0534–0.227	7690	0.0958	229–43.8	1.93–29.0	62.3	12.0
	17	374–1360	713	8190–5690	0.0403–0.215	7800	0.0815	197–35.7	1.72–34.6	51.4	12.6
	18	272–1220	575	8320–6050	0.0287–0.180	7880	0.0648	180–30.7	1.37–36.0	44.1	11.8
1×10^{20}	3	3150–5330	4090	7820–4410	0.359–1.09	7080	0.519	411–136	6.95–35.5	180	20.6
	4	2800–4690	3620	7700–4360	0.325–0.971	6960	0.467	410–133	6.19–32.1	174	18.9
	5	2300–3910	3000	7670–4320	0.268–0.817	6950	0.387	401–122	5.20–29.1	161	17.0
	8.5	1240–2310	1690	7750–4300	0.142–0.485	7150	0.212	324–86.2	3.47–24.4	117	13.2
	11	652–1200	886	7560–4240	0.0770–0.257	6990	0.113	322–77.4	1.84–14.1	106	7.57
	15	329–674	471	7620–4470	0.0385–0.136	7170	0.0588	291–59.6	1.03–10.3	84.6	5.06
	17	253–629	399	7830–5260	0.0287–0.108	7440	0.0480	250–47.3	0.917–12.1	68.2	5.32
	18	179–548	313	8010–5760	0.0198–0.0855	7610	0.0367	223–39.3	0.727–12.7	57.4	4.96
3×10^{18}	3	7340–19900	12100	8800–5370	0.732–3.33	8320	1.29	280–66.6	23.8–271	95.0	115
	4	6490–17300	10600	8700–5260	0.655–2.97	8240	1.15	277–66.1	21.2–238	93.5	103
	5	5290–14500	8770	8670–5560	0.537–2.36	8210	0.950	269–61.9	17.8–214	87.0	91.6
	8.5	2560–7830	4480	8520–5650	0.264–1.25	8100	0.491	233–49.6	10.0–144	69.2	58.9
	11	1300–3940	2260	8330–5380	0.137–0.660	7940	0.253	223–46.0	5.29–77.8	64.3	31.9
	15	635–2300	1210	8240–5910	0.0678–0.349	7860	0.137	194–36.8	2.97–56.7	52.5	20.9
	17	495–2220	1050	8310–6040	0.0521–0.329	7890	0.118	180–31.1	2.50–64.8	44.4	21.5
	18	371–1970	856	8390–6020	0.0385–0.293	7940	0.0953	152–27.5	2.22–65.0	39.1	19.9

P_{th} drops by factor of ~10 from R = 3kpc to R = 18 kpc.

T_{cnm} and n_{cnm} decrease, n_{wnm} decreases while T_{wnm}~const.

→ "T_{sp}" expected to decrease by a factor of ~3 (up to 18 kpc).

Does T_{sp} vary across the MW disk?



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290 spectra from SGPS, CGPS, VGPS.
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$$\langle T_{sp} \rangle = T_{cool} \frac{n_{WNM} + n_{CNM}}{n_{CNM}},$$

"T_{sp}"~300 K. As no evidence that T_{cool} varies across the disk → Mixture of CNM & WNM (or CNM fraction) may be constant in the MW from R_0 to $3xR_0$.

Surprising from equilibrium perspective!

Recent HI absorption surveys

Survey	Area (deg)	Emission Angular Resolution (‘)	Velocity Resolution (km/s)	Sensitivity 1-σ_{τ} per 1 km/s	Number of spectra	Telescopes
VGPS	|b|<1.3 l=18-67	1	1.56	0.025-0.125	113	VLA
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SPONGE	|b|>15	4		<0.00073	58	VLA+Arecibo

Updated Arecibo

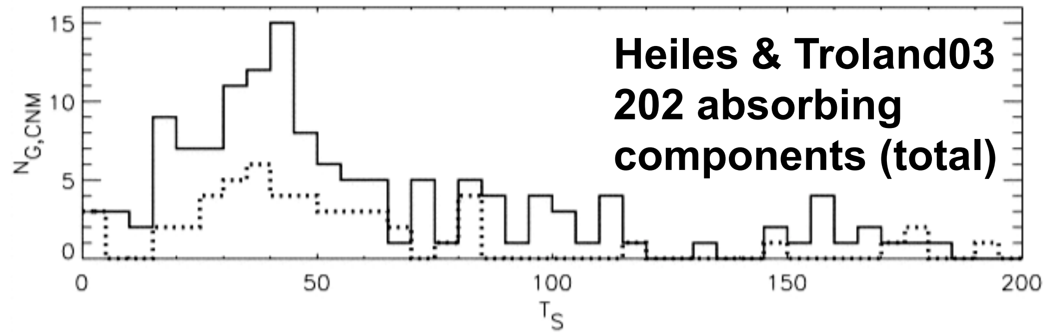
Taylor+03, Heiles & Troland03, McClure-Griffiths+05, Stil+06, Mohan+04, Kanekar, Braun, Roy 11, SS & Heiles05, Murray+13, SS+, in prep.

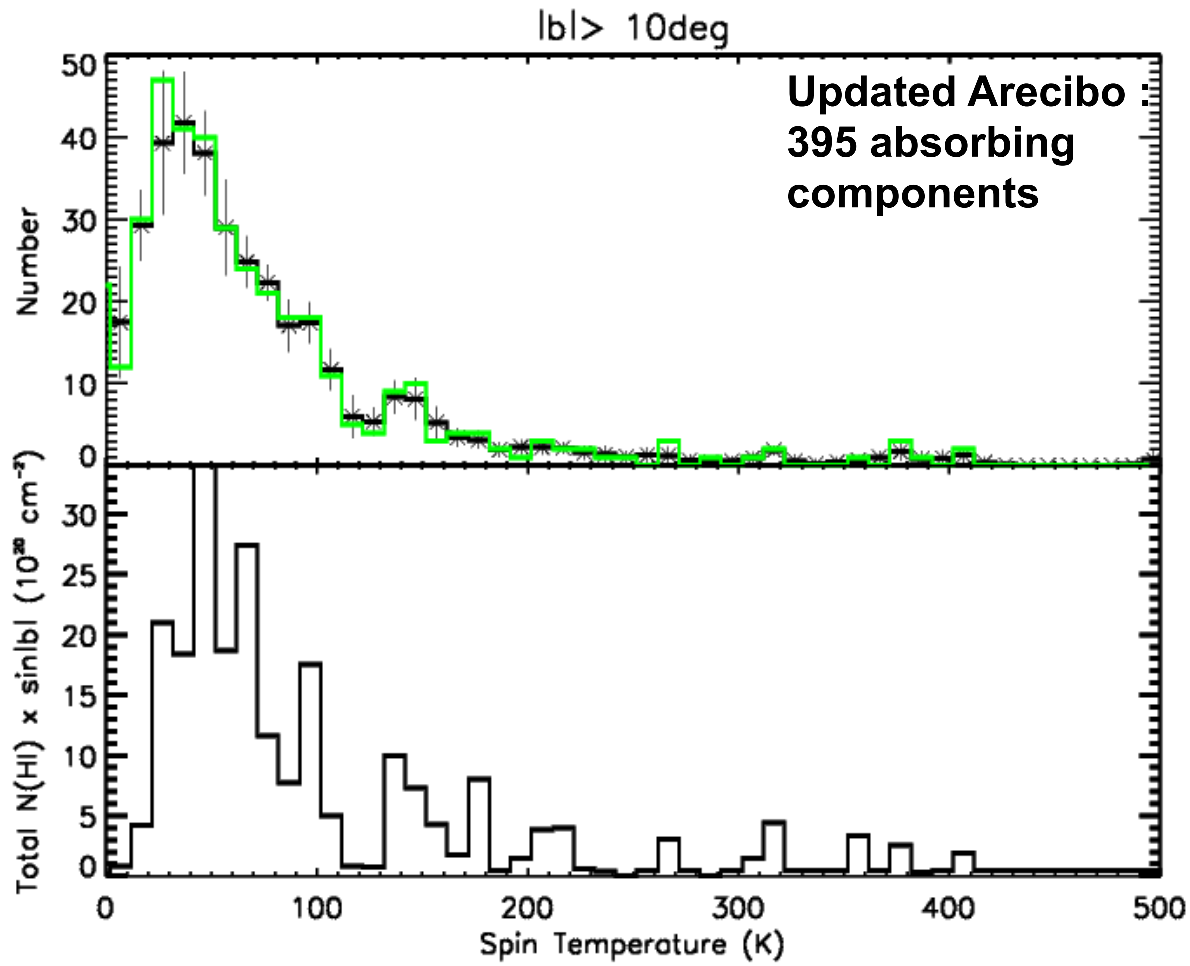
T_{sp} @ |b| >10deg:

In agreement with other studies although a more pronounced high-T_{sp} tail.

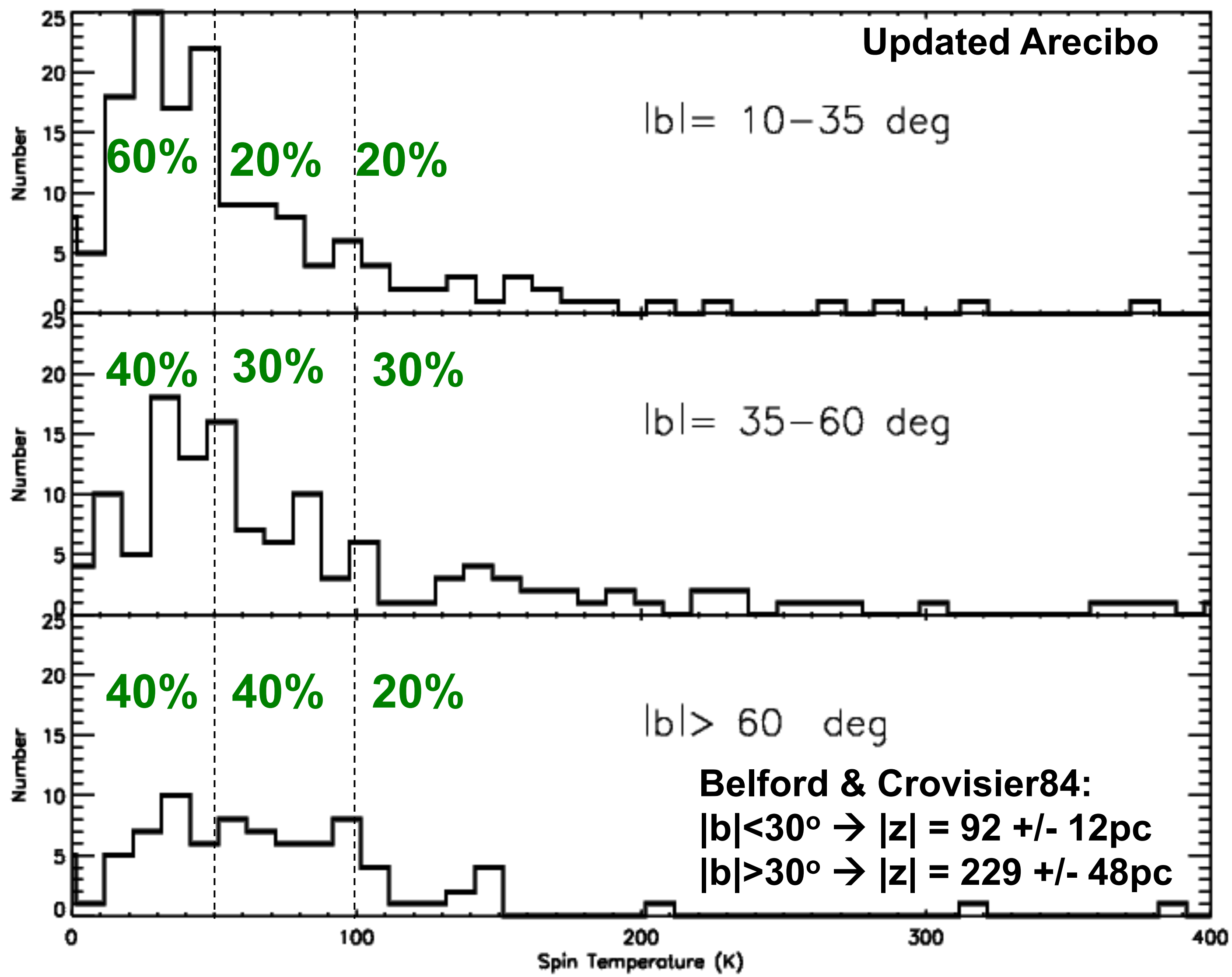
	All Arecibo	Heiles & Troland 2003
Median Ts	59 K	48 K
Median Ts weighted by N(HI)	136 K	70 K
Fraction with Ts<100K	0.7	0.77
Fraction with Ts<25K	0.16	0.17
Fraction with Ts>200K	0.10	0.08
Max Ts	1800 K	656
Mean N(HI)	$2x10^{20}$ cm^{-2}	$2x10^{20}$ cm^{-2}

Mohan+04: peak ~75K



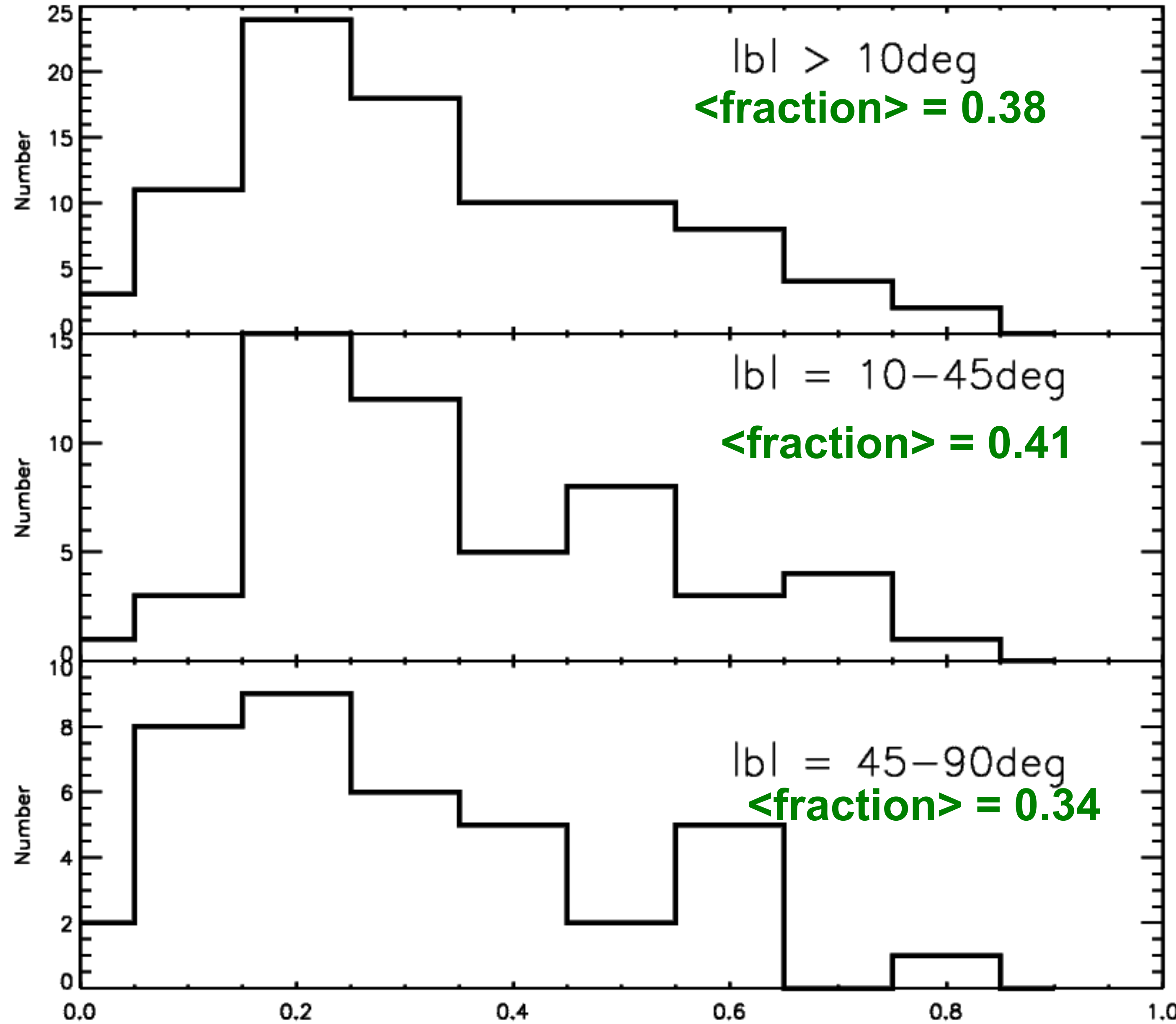


CNM temperature as function of |b|



Flatter T_{sp} distribution at high-b as the relative number of warmer clouds increases.
Blending? – NO. Deficiency of cold CNM clouds due to the Local Cavity?
+ Increase in Tsp with |z|?

CNM/WNM fraction

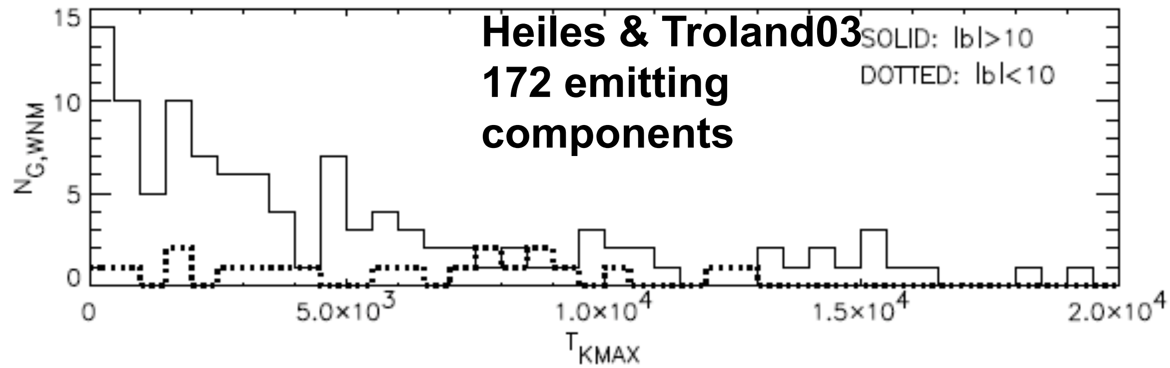


CNM Fraction = $N_{CNM}/[N_{CNM} + N_{WNM}]$

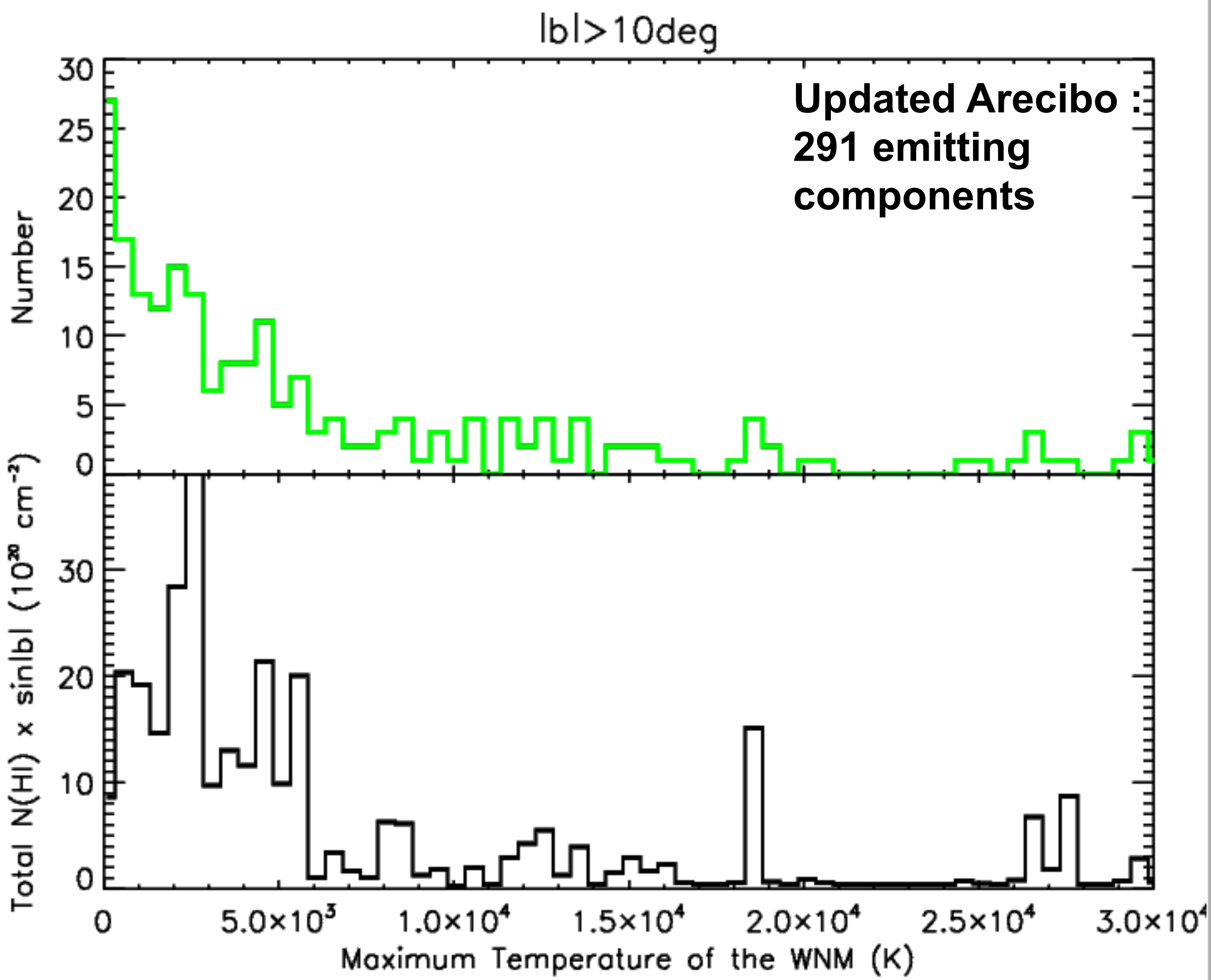
No significant change with |b|, although slightly higher # of clouds with low fraction.

fcnm = 0.25-0.45% for Tsp = 60 K Dickey+09

(Indirect) WNM temperature



Fraction	All Arecibo	Heiles & Troland 2003
500-5000K (number)	0.41	0.39
500-5000K (mass)	0.44	0.50

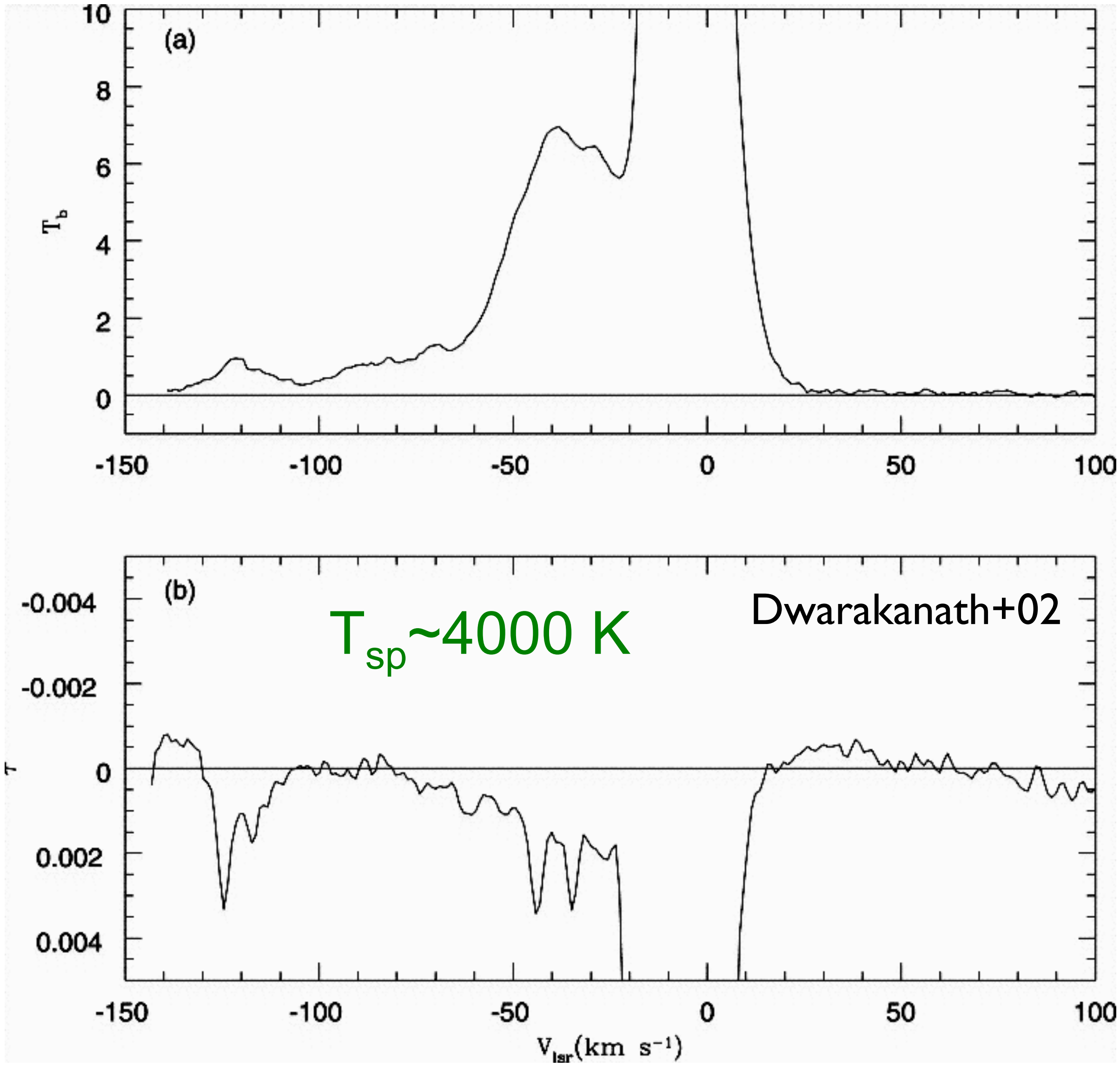


Wolfire10: low-b distribution thermally stable?

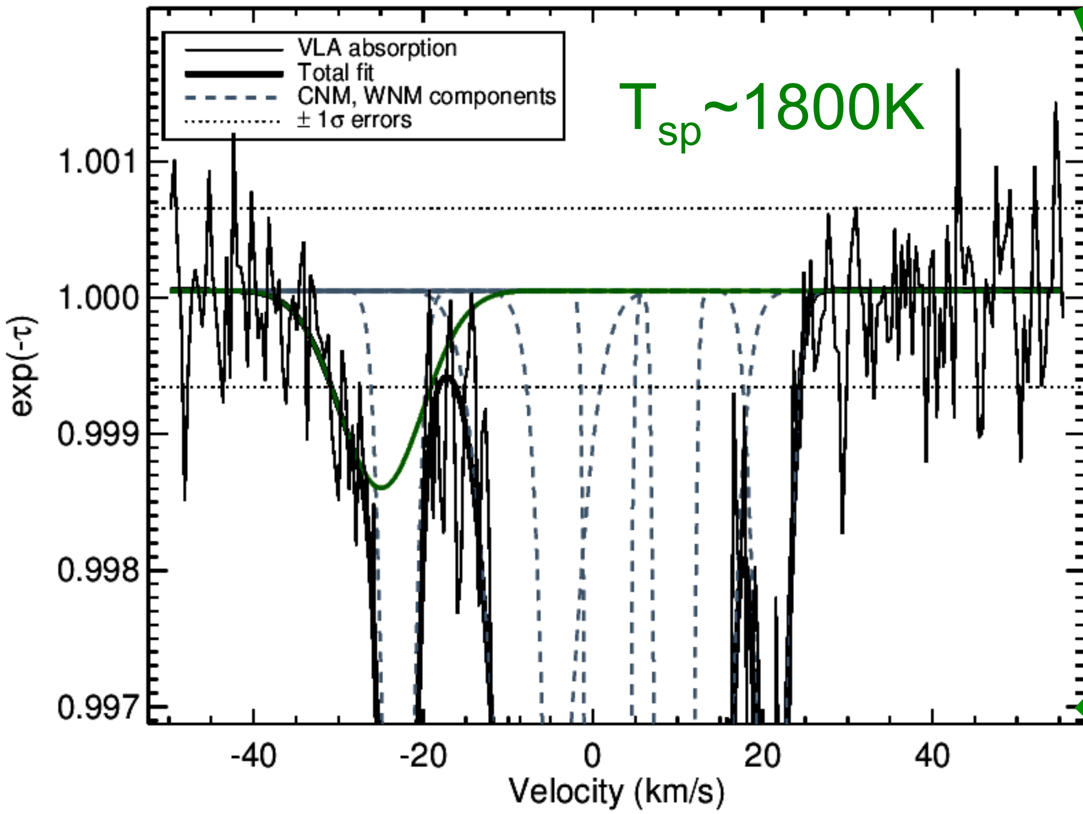
WNM temperature from direct observations:

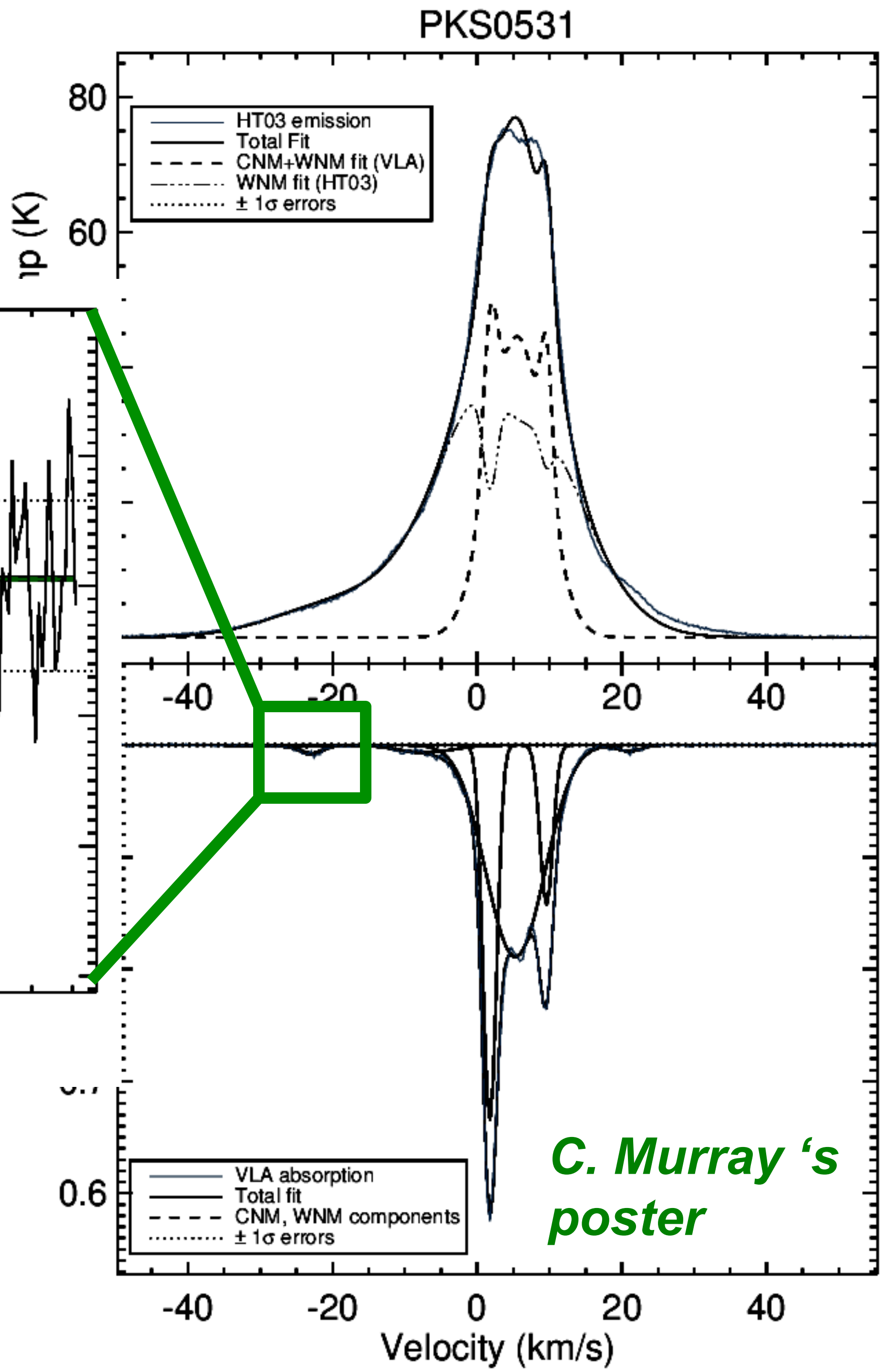
- Very sensitive observations required

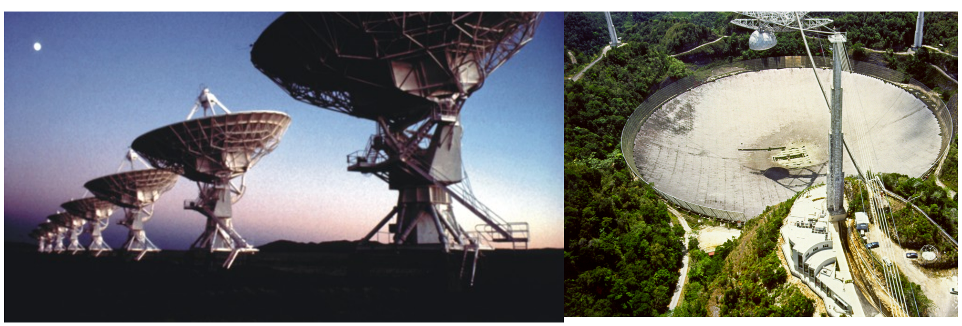
- Only a handful of measurements exist



21-SPONGE: 21cm Spectral line Observations of Neutral Gas with the





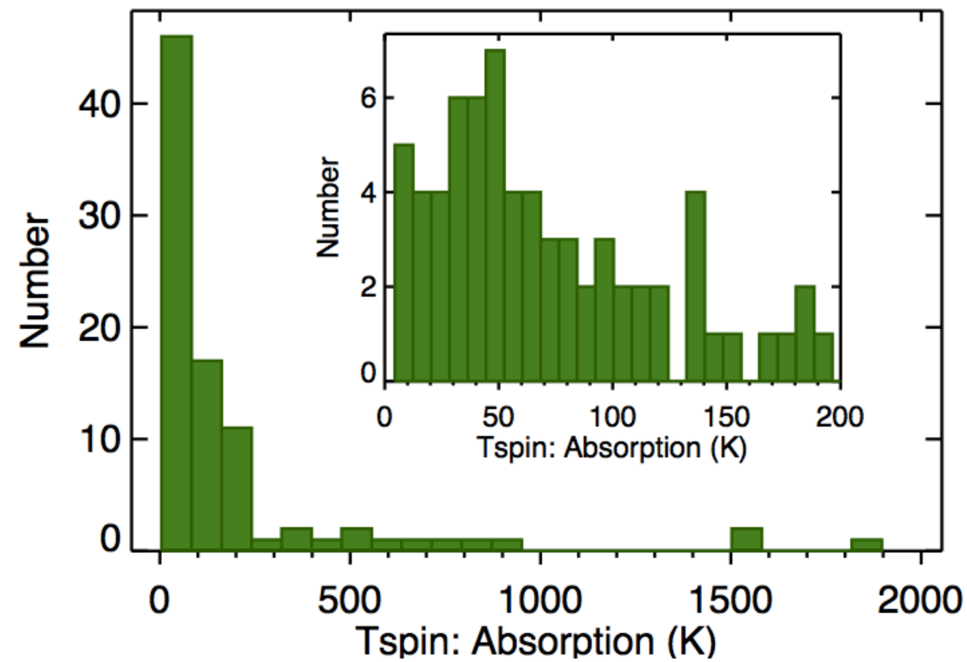


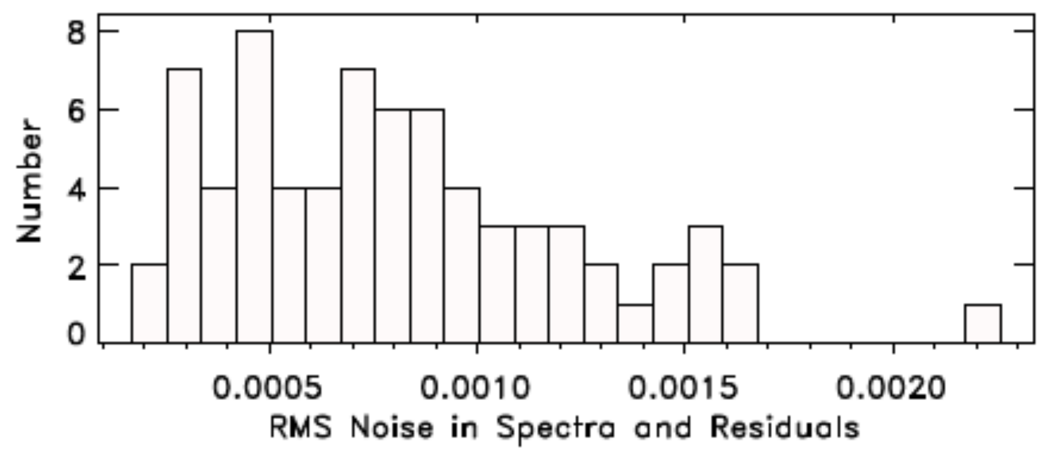
WNM direct detections from 21-SPONGE (1/3 of the survey)

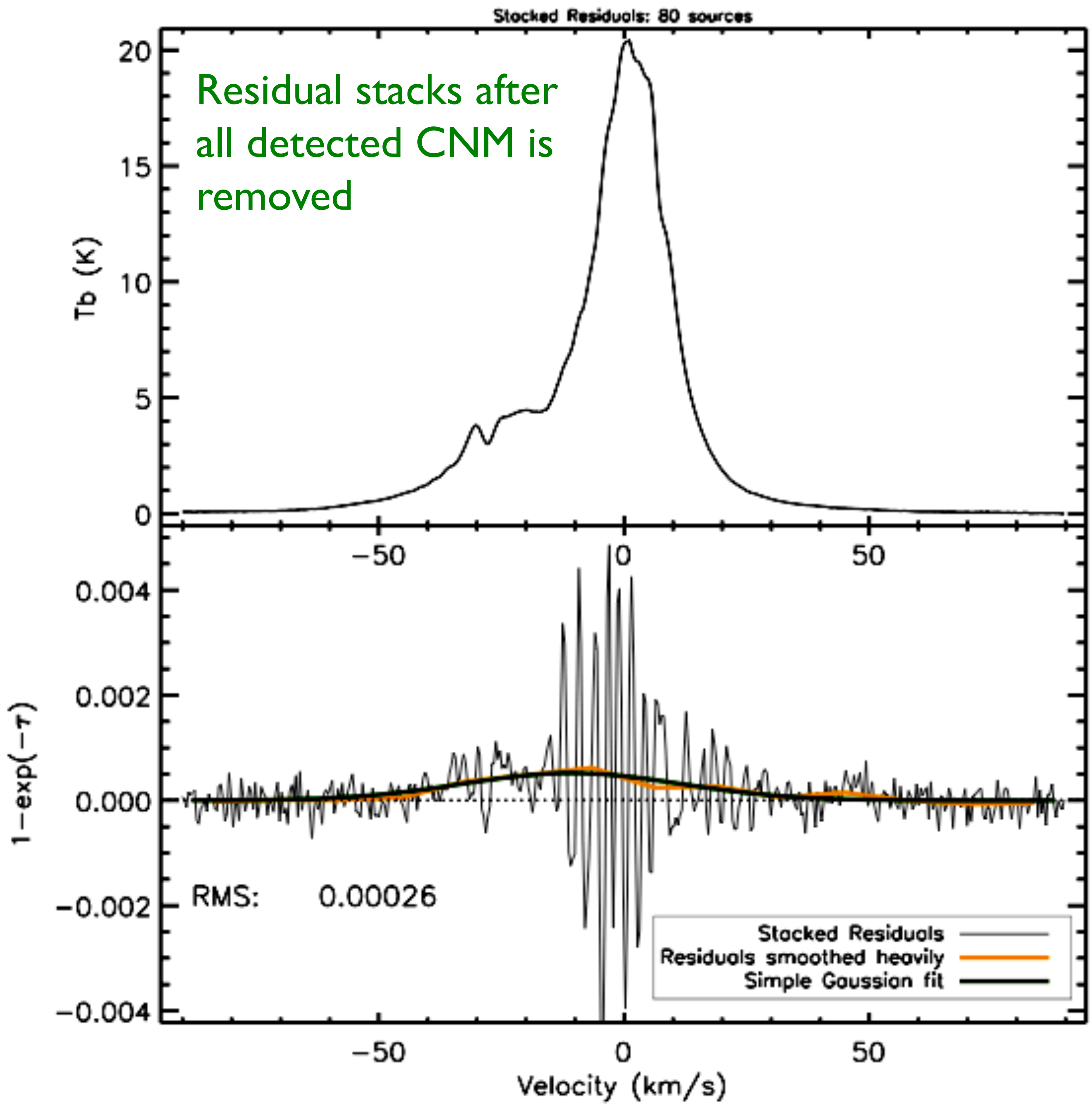
- Long tail to ~2000K.
- 23% of detections have Ts>200K (HT03 – 8%)

- Tiny fraction (4%) of detections with Ts>1000 K (HT03 – 0%) although we have sensitivity to detect them

- Future: finish the survey, uniform sensitivity HI emission spectra, <u>estimate completeness</u>



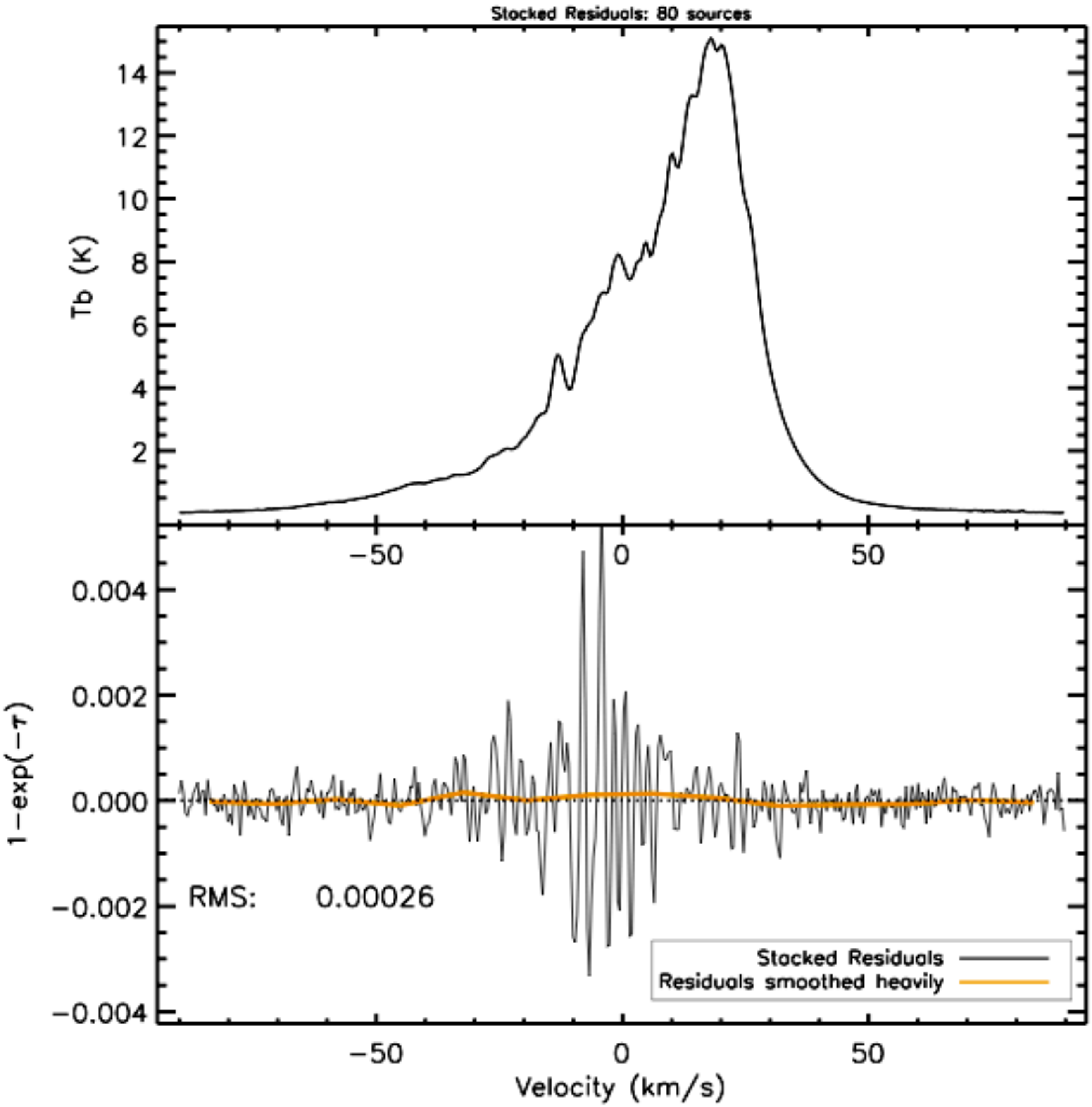




Stacking analysis of HI absorption spectra from 21-SPONGE

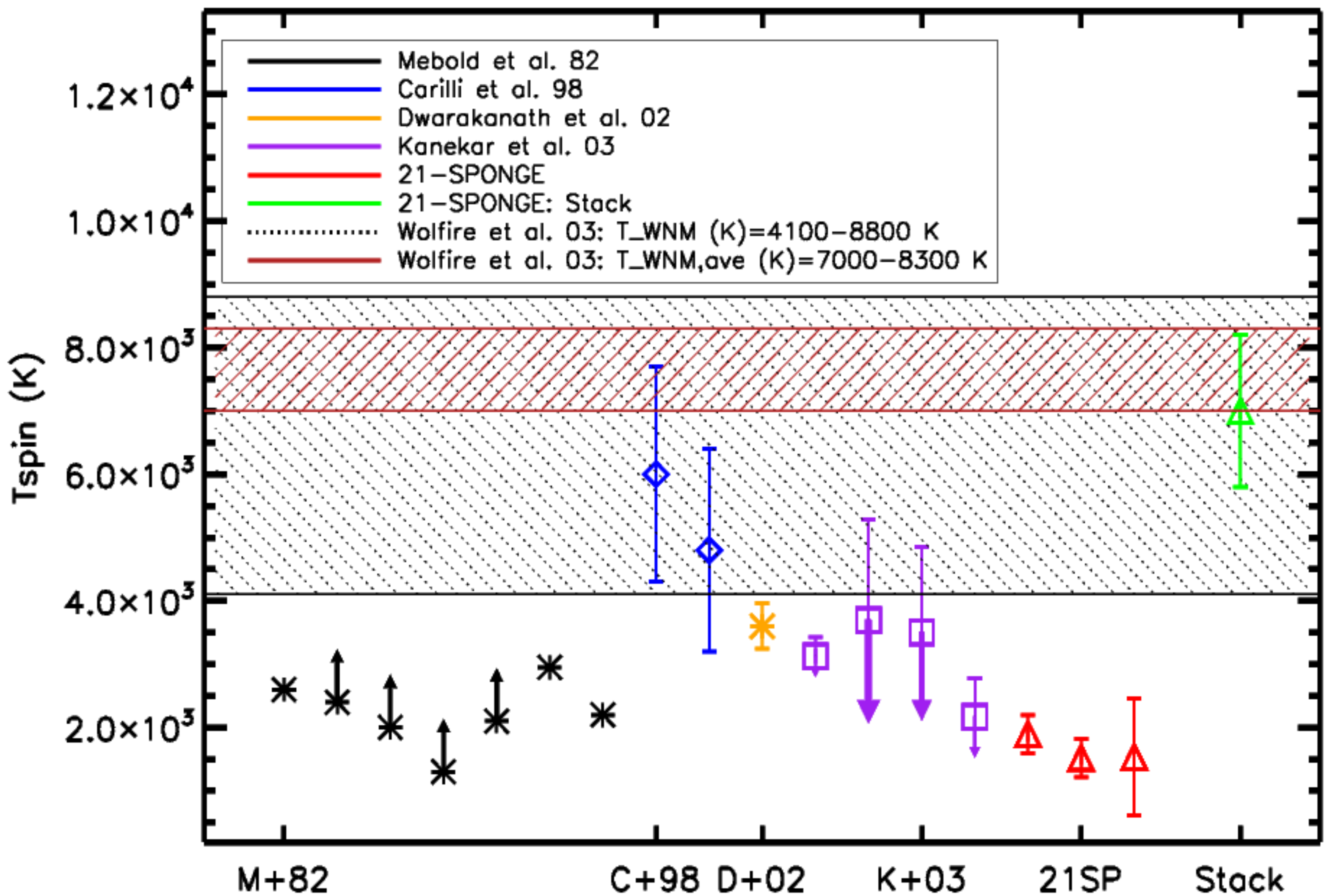
see Claire Murray's poster

Peak $\tau = 5\times10^{-4}$
FWHM ~50 km/s
Tsp ~7000 K
N(HI)~2×10^{20} cm^{-2}



Stacking analysis of HI absorption spectra from 21-SPONGE: when random velocity shits are applied

All direct WNM temperature measurements



Very few and mostly Ts~2000 K

GASKAP (PI: Dickey)**:** MW plane + Magellanic System

5000+ HI absorption spectra → build 2d images of CNM temperature and fraction

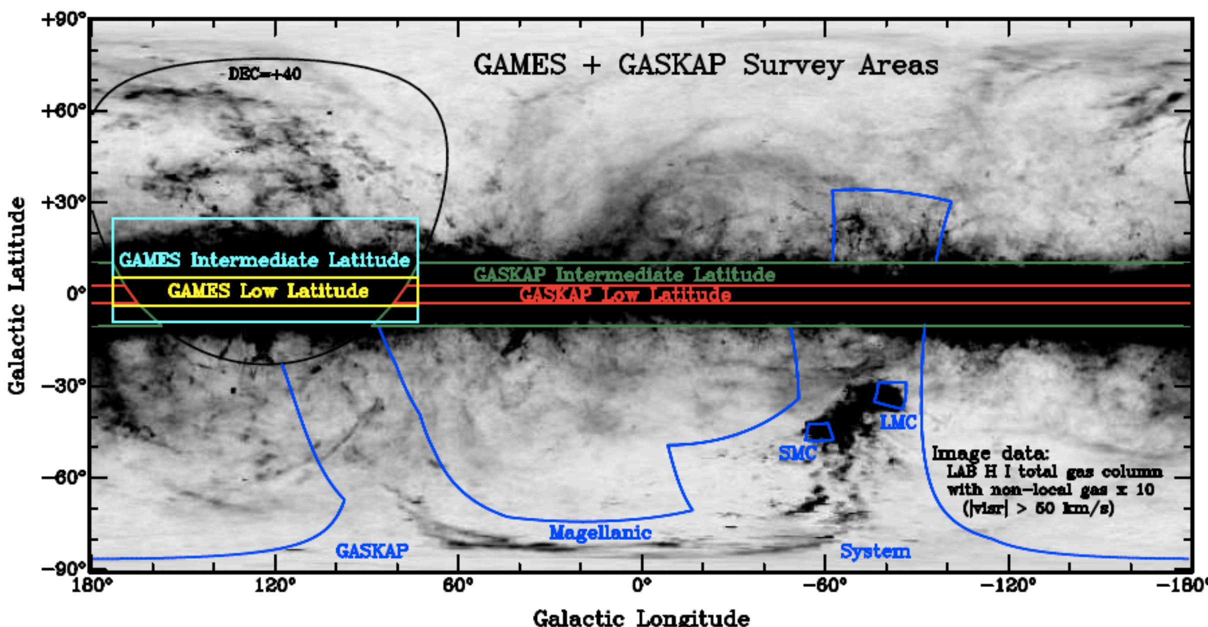
HI+OH emission → turbulent properties and atomic/molecular transition

GAMES with WSRT

(northern sister survey, PI: McClure-Griffiths):

HI absorption + HI/OH emission

Together, measure how CNM properties vary with interstellar environments (MW, LMC, SMC).



Dickey et al. (2012)
https://sites.google.com/site/gaskapproject/

Open Questions:

- Is CNM necessary for molecule formation? Physical association of CNM and molecular gas?
- Can we get further into the MW ouskirts and still detect HI absorption?
- Can we distinguish observationally between HI resulting from H2 photodissociation vs condensing out of WNM? Can this explain lack of HI in the 3-kpc arms?
- **Is T_{sp} increasing with |z|?** T_{sp} as a function of longitude? Build 2d images and fractions. Numerical predictions needed!
- **Why is T_{sp} is constant across MW**? Can we improve measurement accuracy to detect predicted factor of few decrease in T_{sp}?
- Understand discrepancy btw $T_{k,max}$ and **T_{sp} for the WNM**. Factor CNM-bias?
- Measure CNM/WNM scale heights.
- SKA & Pathfinders: zoom in and teach us about ISM properties & mix in nearby galaxies.