The ISM phases: an observational perspective

recent highlights and open questions

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with thanks to:
Dan McCammon, Matt Haffner, Brian Babler, Blair Savage

and apologies for not being able to cover all exciting work

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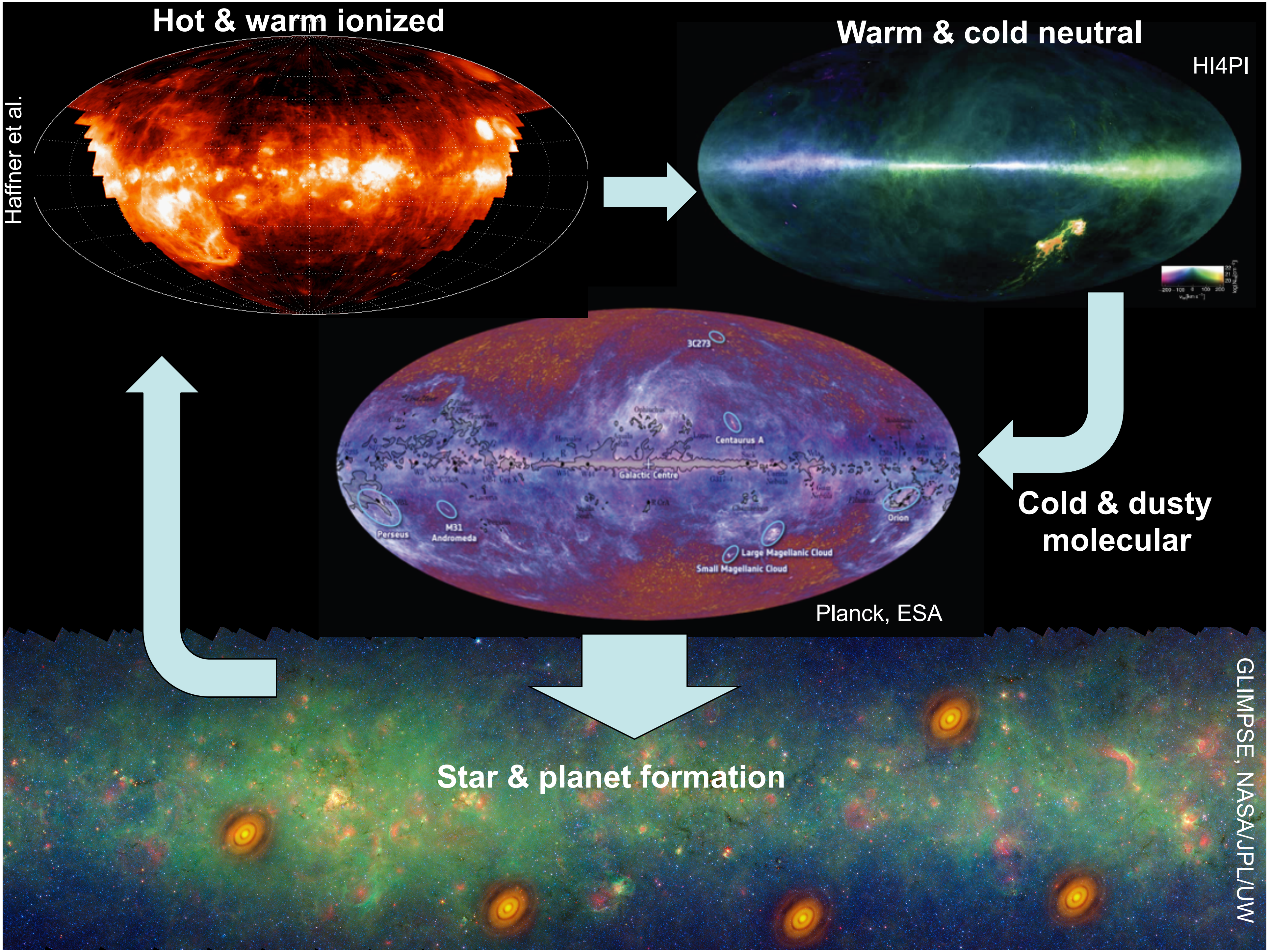
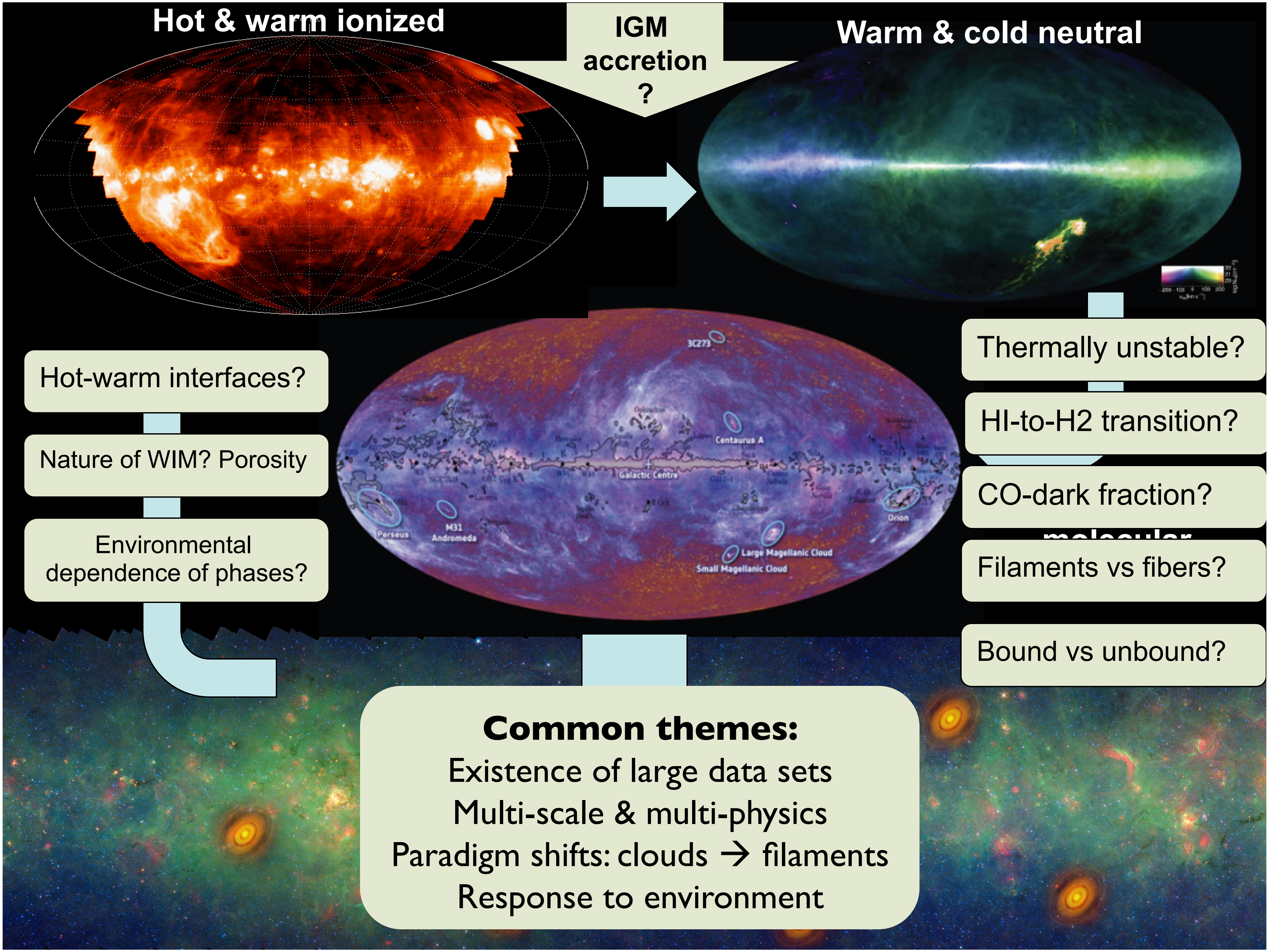
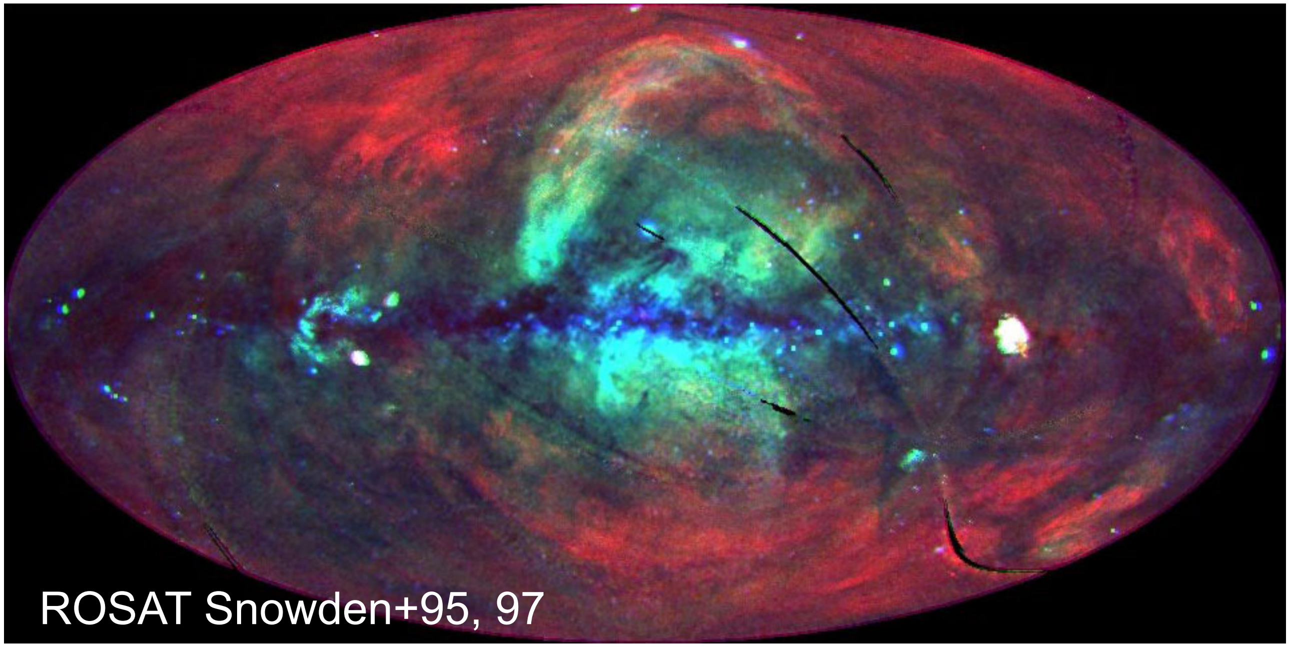


Hot & warm ionized
Haffner et al.
Warm & cold neutral
HI4PI
3C273
Centaurus A
Galactic Centre
Perseus
M31
Andromeda
Orion
Large Magellanic Cloud
Small Magellanic Cloud
Planck, ESA
Cold & dusty
molecular
Star & planet formation
GLIMPSE, NASA/JPL/UW



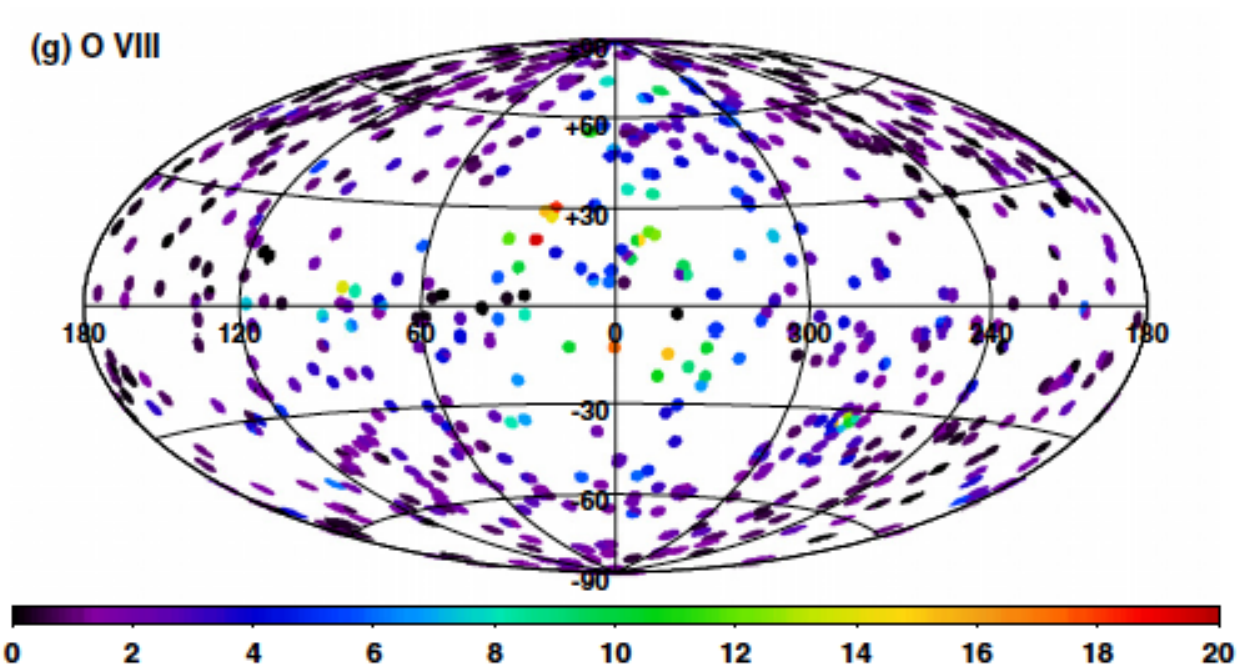
Hot & warm ionized
IGM accretion ?
Warm & cold neutral
Hot-warm interfaces?
Nature of WIM? Porosity
Environmental dependence of phases?
3C273
Centaurus A
Galactic Centre
Perseus
M31 Andromeda
Orion
Large Magellanic Cloud
Small Magellanic Cloud
Thermally unstable?
HI-to-H2 transition?
CO-dark fraction?
Filaments vs fibers?
Bound vs unbound?
Common themes:
Existence of large data sets
Multi-scale & multi-physics
Paradigm shifts: clouds → filaments
Response to environment



Galactic Diffuse X-ray Emission

weak + includes:

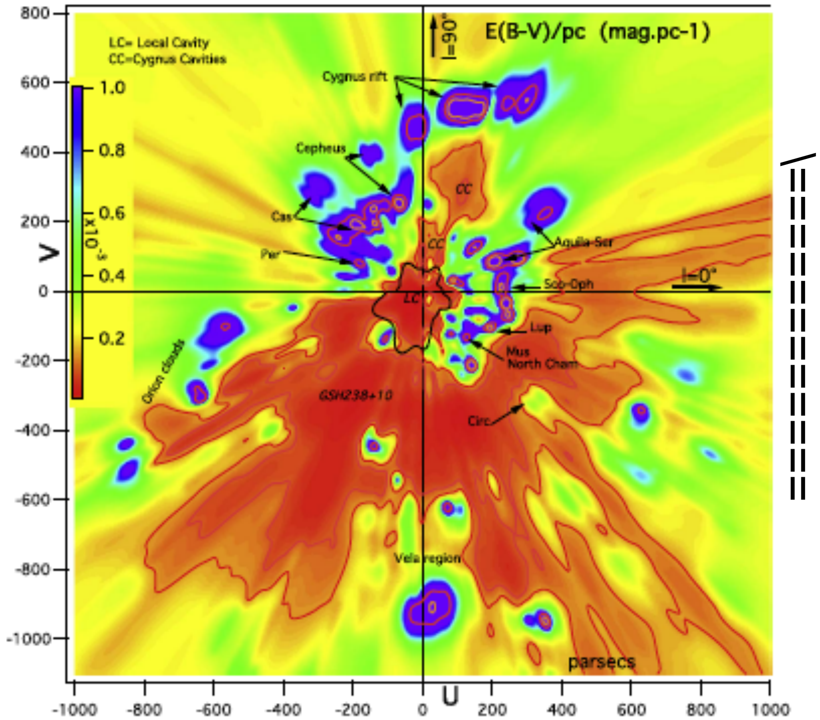
- Solar Wind Charge Exchange
- Local Hot Bubble
- Possibly faint stars (Mitsuishi & Sato 2013)
- Disk component
- Galactic Halo



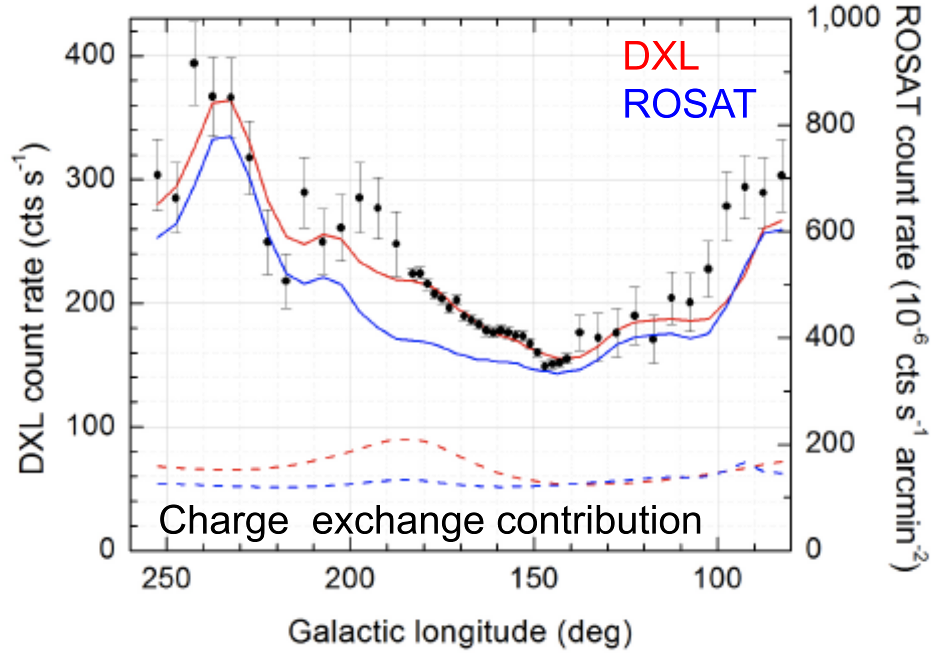
Henley+13, 15

XMM-Newton observations of 600+ sightlines with OVII and OVIII emission lines
→ T<= $3x10^6$ K

Existence of ~10^6 K gas within Galactic disk? Local Hot Bubble is really hot!



Liu+17: R2/R1 → ~10^6 K gas inside The Local Bubble

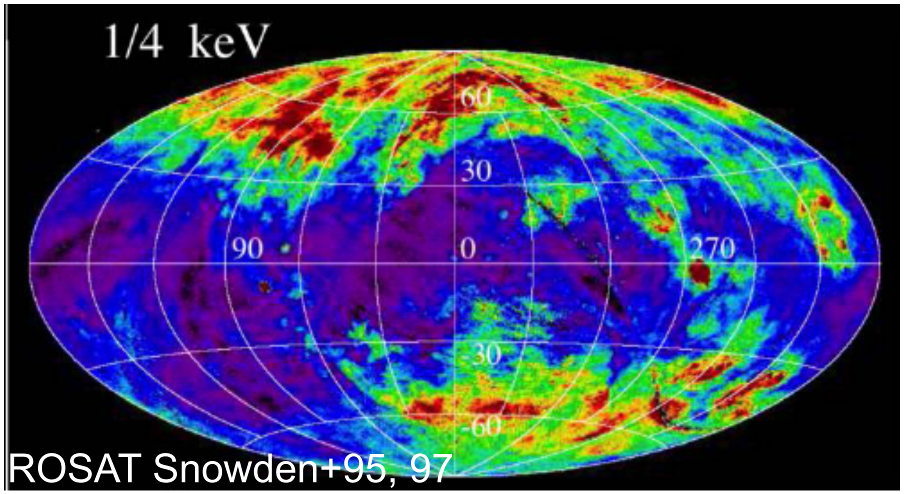


Thanks to Dan McCammon

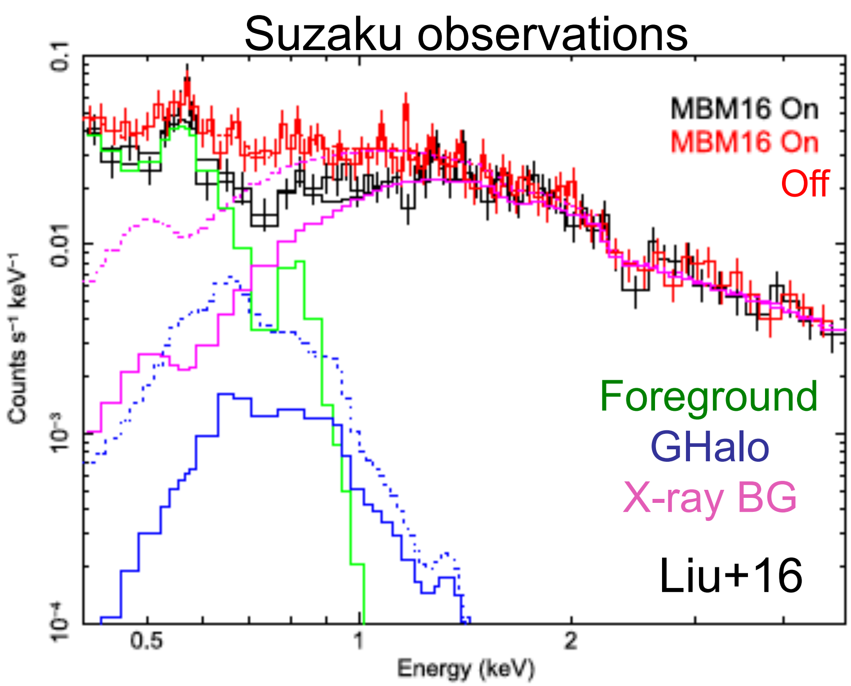
Galeazzi+14: Charge exchange contribution to ROSAT 40% → hot gas fills the Local Bubble

LB structure still unclear.
Disk component fraction and distribution unknown.

Galactic Halo



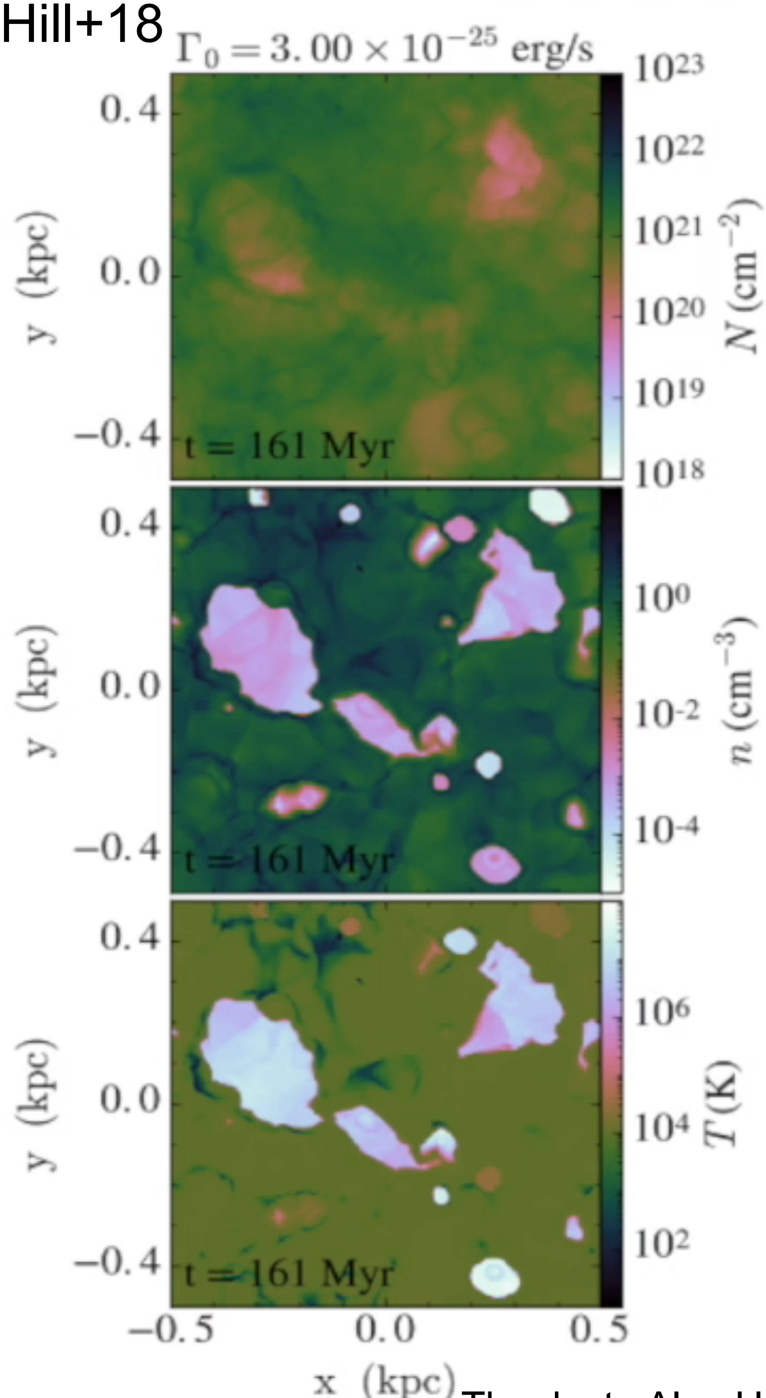
Widespread, smooth X-ray emission indicative of the ubiquitous Halo.
Li & Bregman17: *modeling* of X-ray emission based on 648 OVII and OVIII emission lines →
vertical scale height ~1.3 kpc a
M~$3x10^{10}$ Msun,
<n>~$5x10^{-5}$ cm^{-3} (Faerman+17)



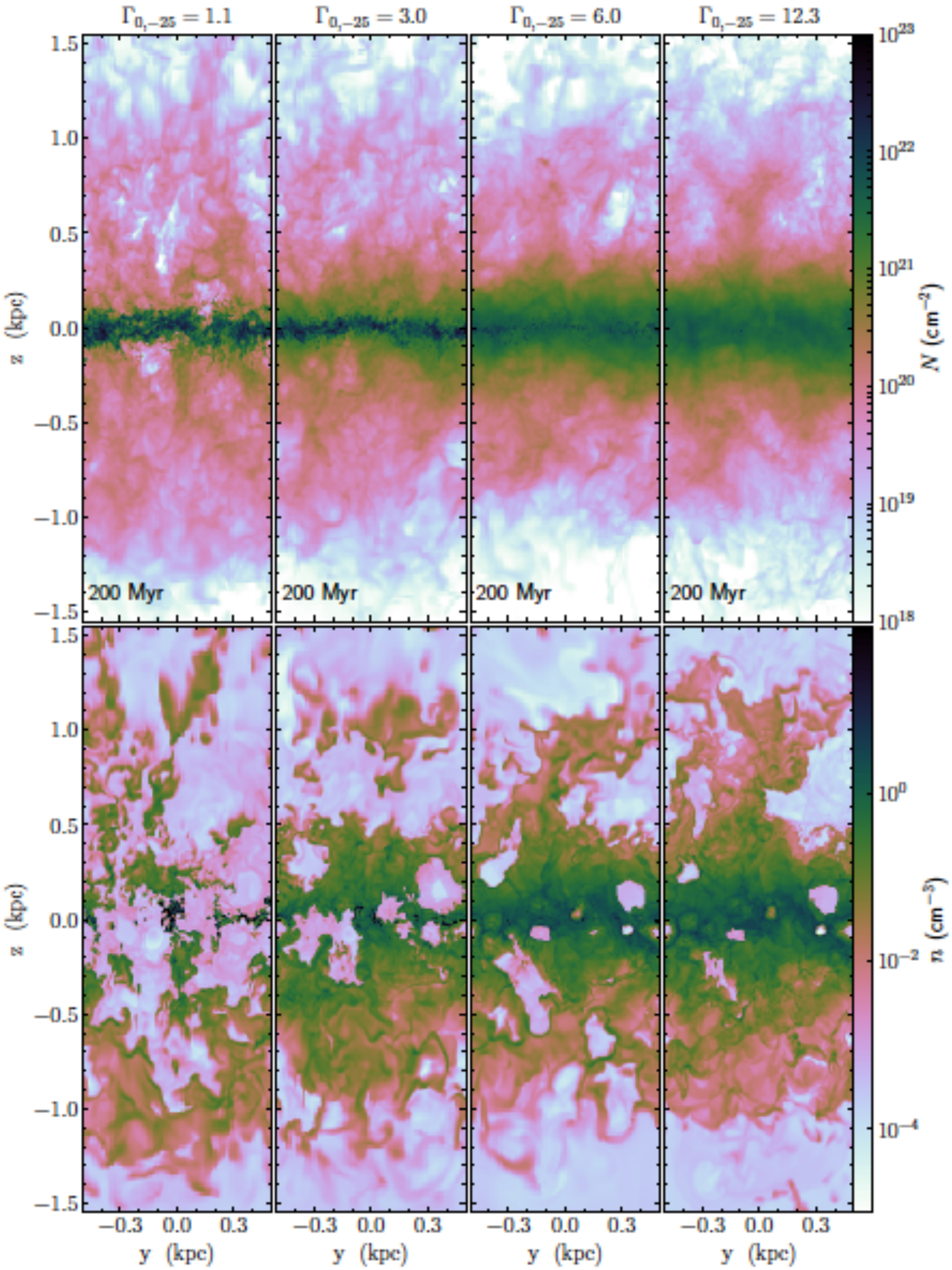
Some X-ray shadow observations (best way to constrain foregrounds) do not support a global Halo. ***Patchy Halo?*** Very limited sample of shadow measurements.

Still know very little due to weak X-ray emission and massive foregrounds (Local Bubble and Solar Wind charge exchange)!

Hill+18

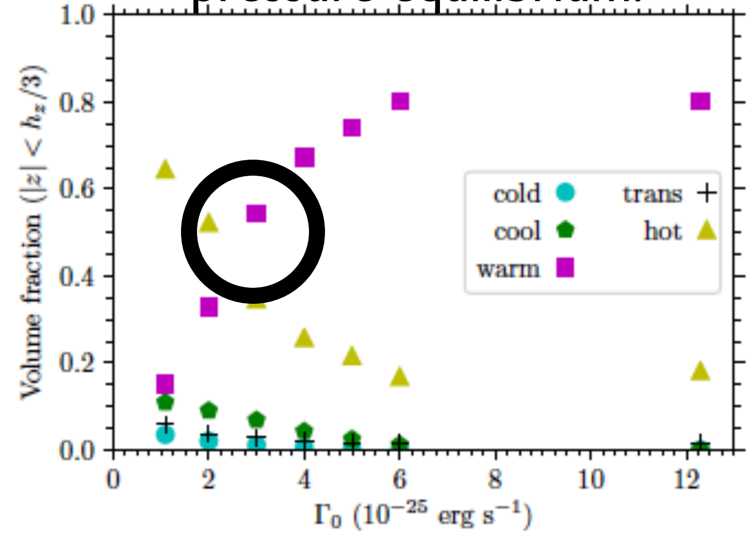


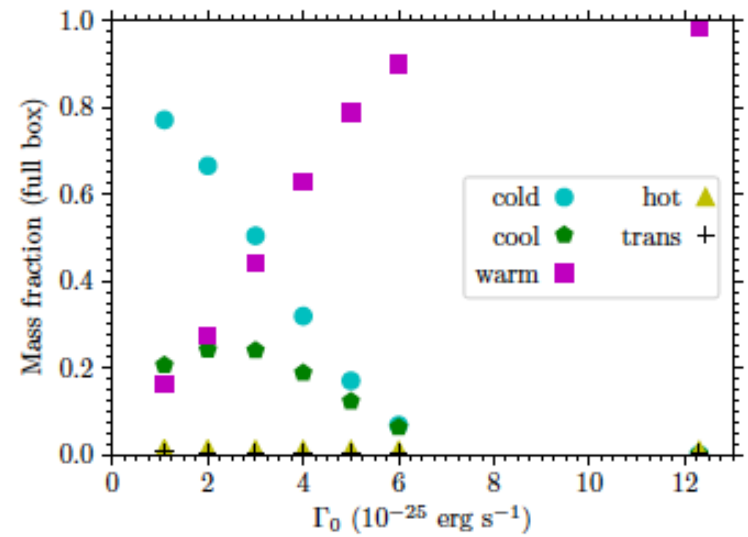
Thanks to Alex Hill



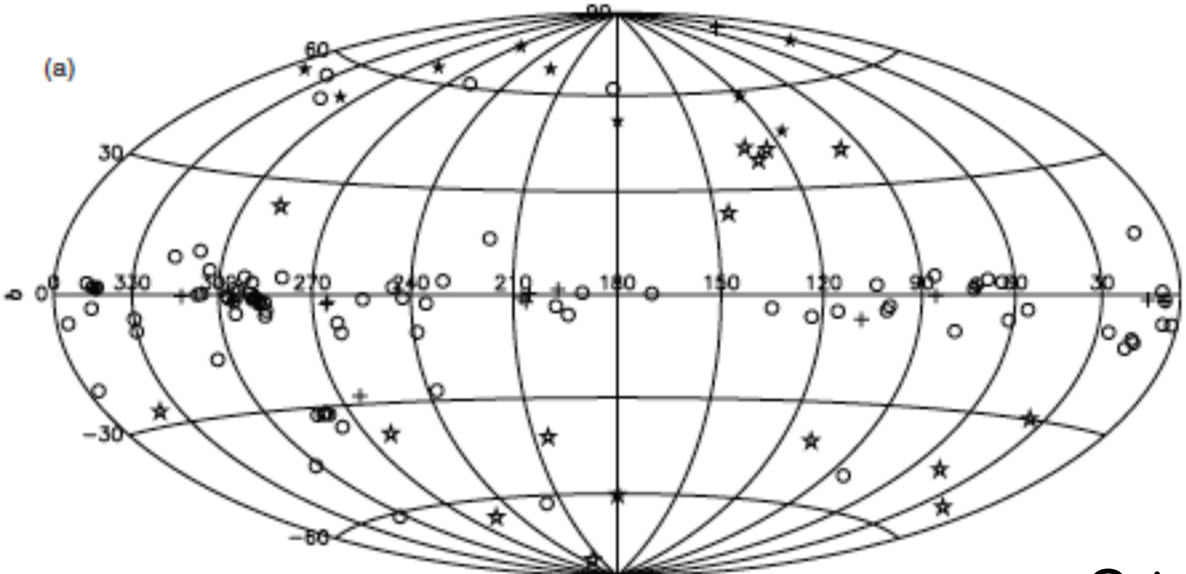
Hill+18 **Simulations**

Shock-heated HIM formed in SNe explosions is in thermal pressure equilibrium.



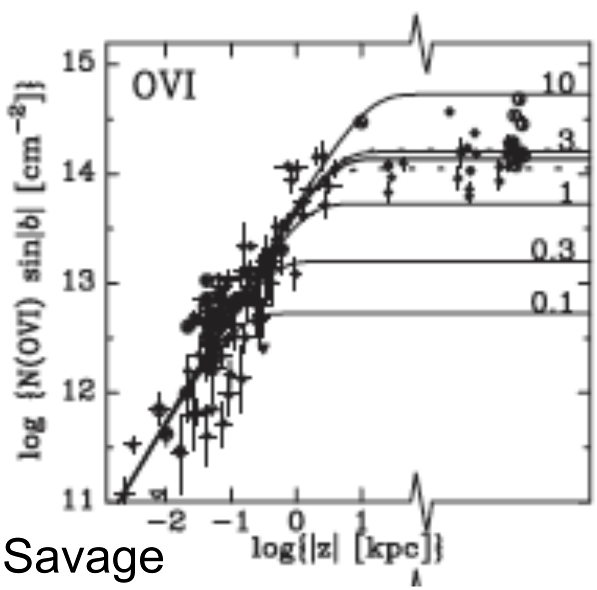


Transition gas ~10^5-10^6 K: HIM to WIM via OVI + SiIV, CIV, AlIII



~140 HST and FUSE observations

Savage & Wakker 09

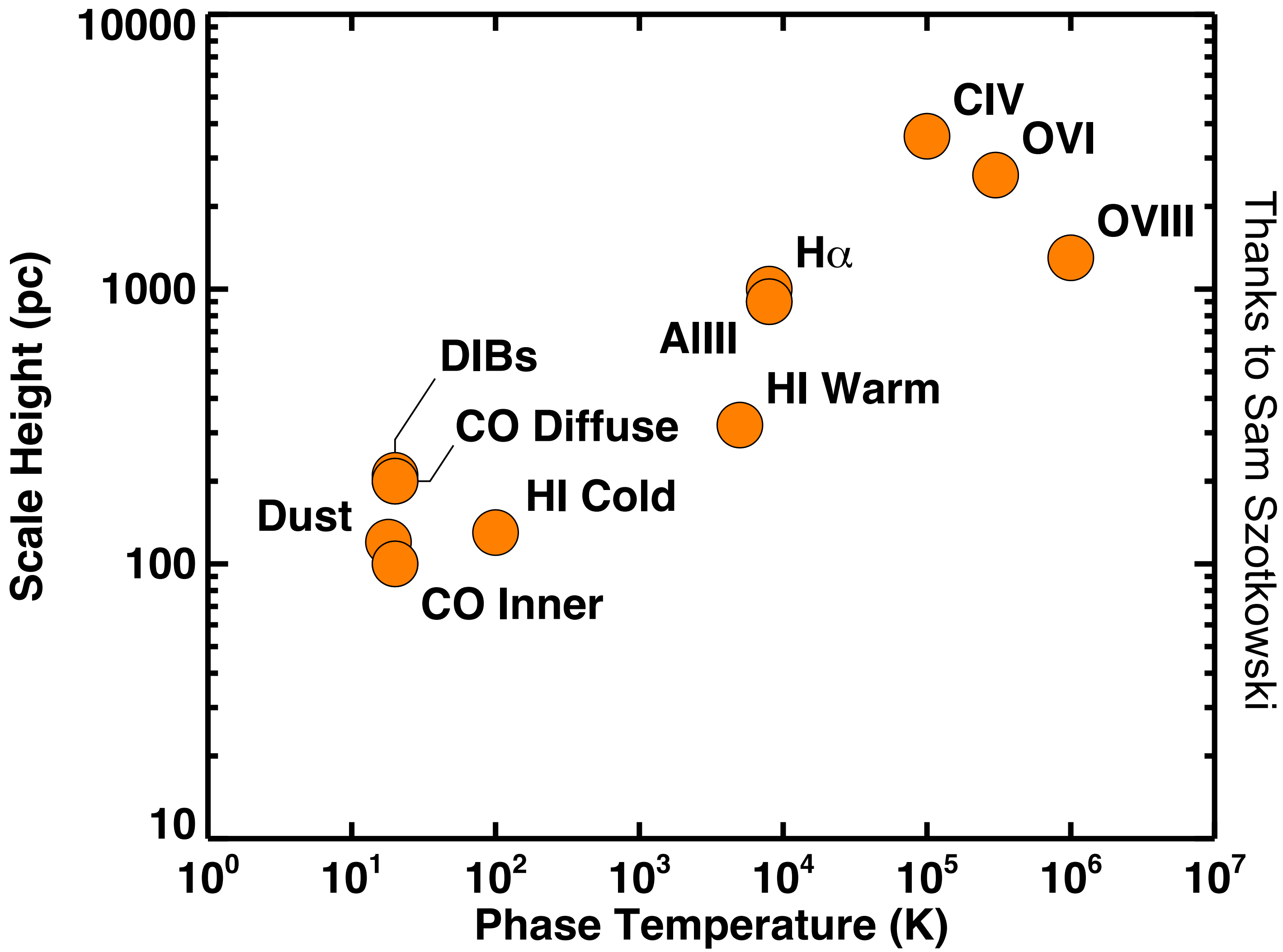


Thanks to Blair Savage

Origin: Hot to warm conductive interfaces or cooling of Hot gas.

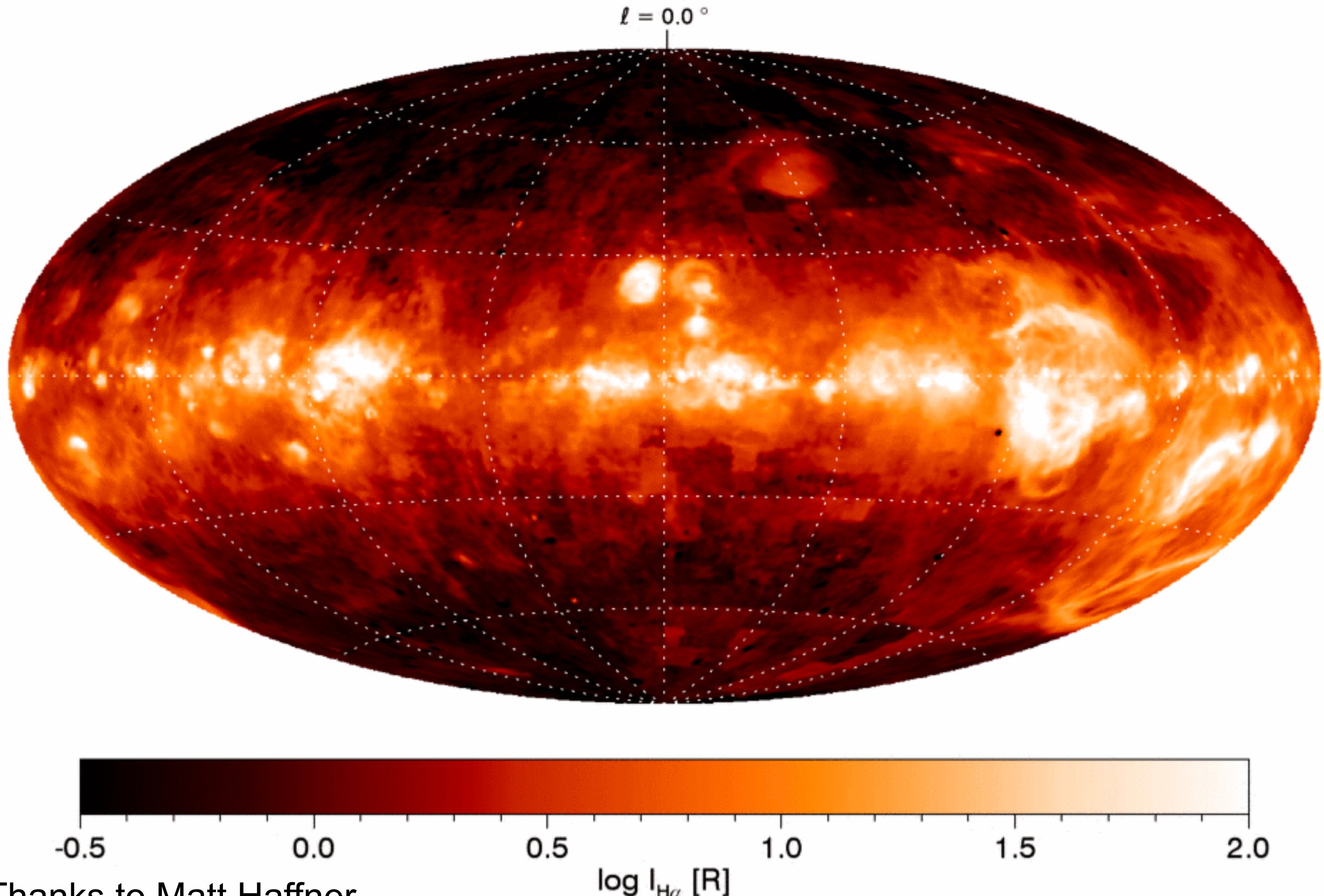
Most species show significant patchiness, up to 87% for HIM (Savage & Wakker 2009). Al III traces WIM, SiIV and CIV trace both photoionized and transition gas, OVI traces collisionally ionized transition gas.

Scale heights



WIM with Wisconsin H-Alpha Mapper (WHAM):

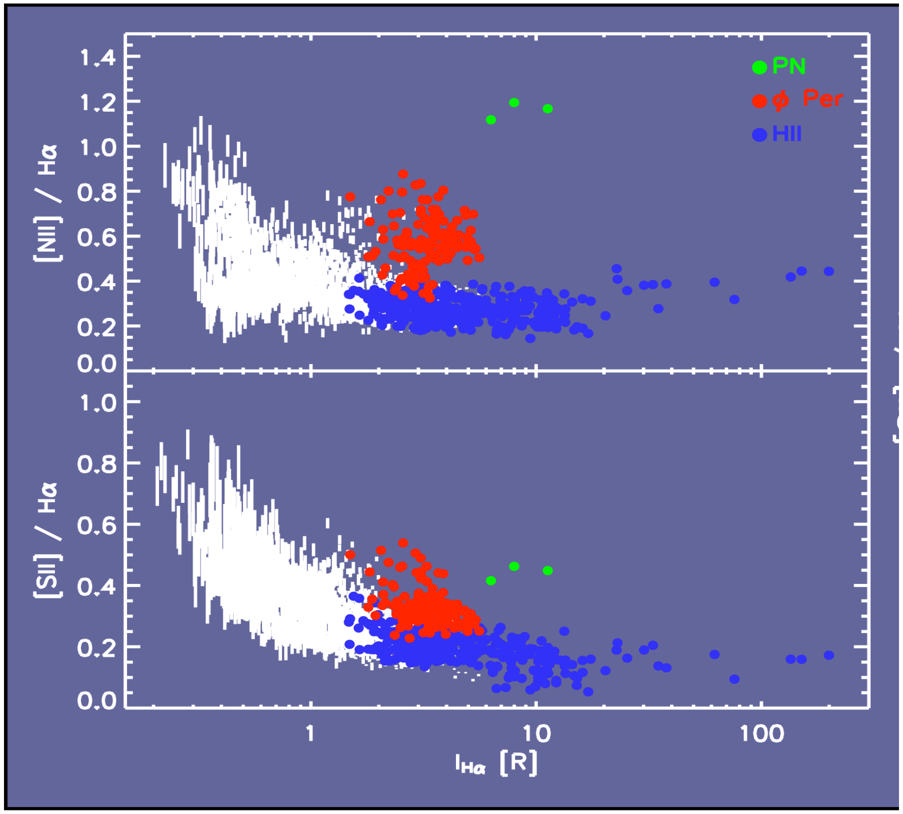
$\Delta S = 0.1$ R ($\Delta EM \sim 0.2$ cm^{-6} pc), $\Delta v = 12$ km/s, FWHM = 1°



Thanks to Matt Haffner

WIM Properties:

~T_e



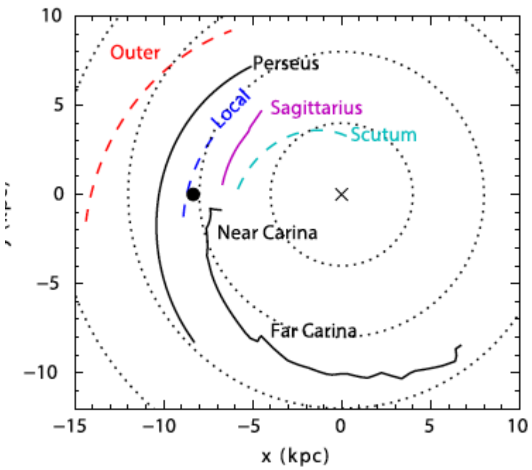
~n_e^2

$$\frac{I_{6583}}{I_{H\alpha}} = 1.63\times10^5 \left(\frac{H^+}{H}\right)^{-1} \left(\frac{N}{H}\right) \left(\frac{N^+}{N}\right) T_4^{0.426}\, e^{-2.18/T_4}, \quad (2)$$

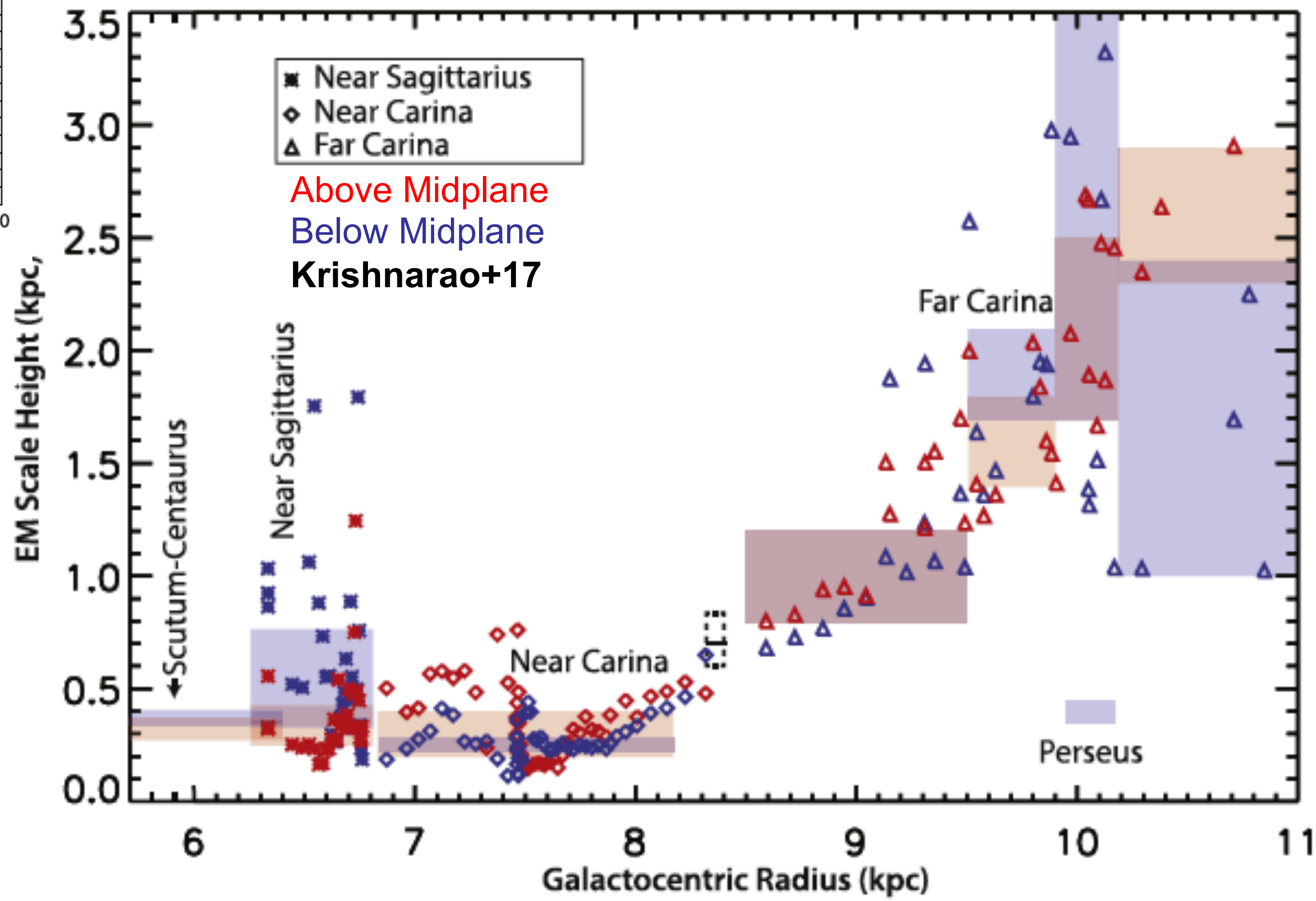
- [N II]/Hα and [S II]/Hα increase with decreasing $I_{H\alpha}$ due to changes in T_e (Haffner et al. 1999).
- **Te~8000-12,000 K, hotter than HII regions**
- Significant variations: Higher T_e at lower n_e and higher |z| - not understood
- n_e ~ 0.03-0.08 cm^{-3}
- H^+/H~0.9
- 90% of H+ is in WIM
- Origin: Requires 1 x 10^{-4} erg s^{-1} cm^{-2} to sustain the 5 x 10^6 s^{-1} cm^{-2} recombination rate.

→ ionizing radiation from O stars via leaky HII regions

- Anderson+15: RCW120 leaking fraction ~25%

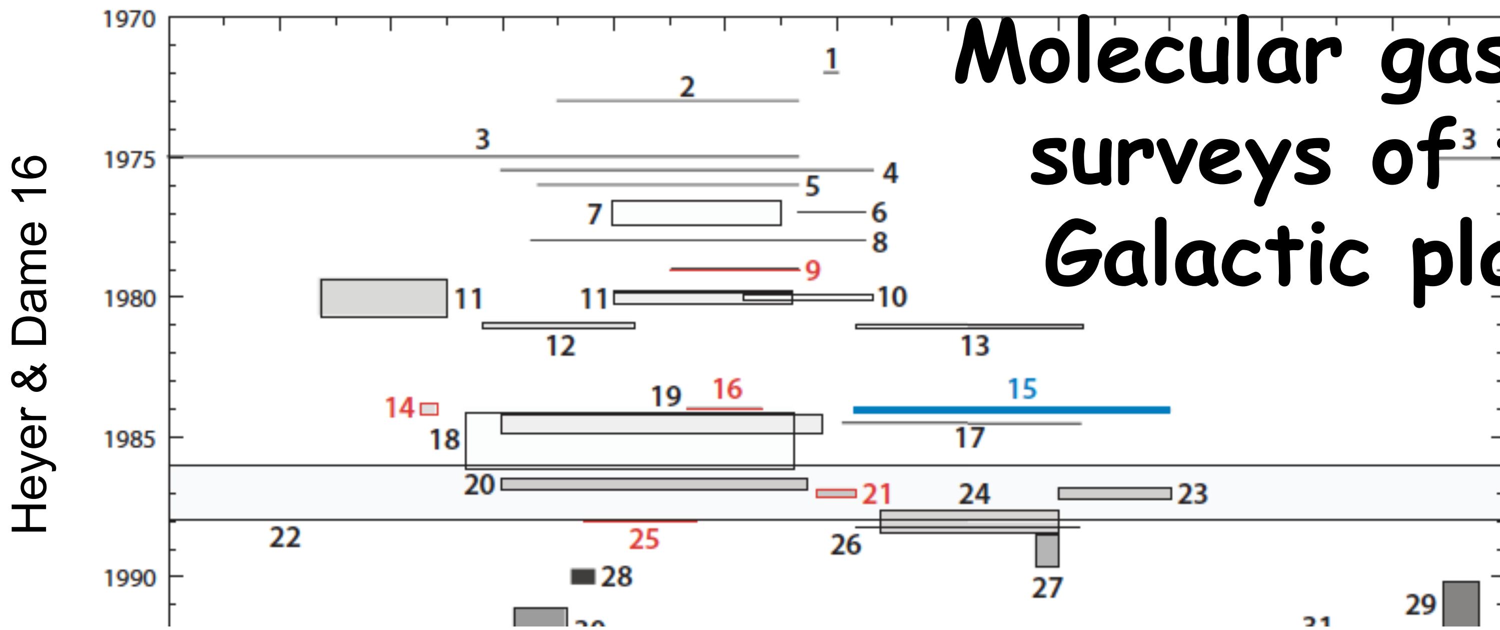


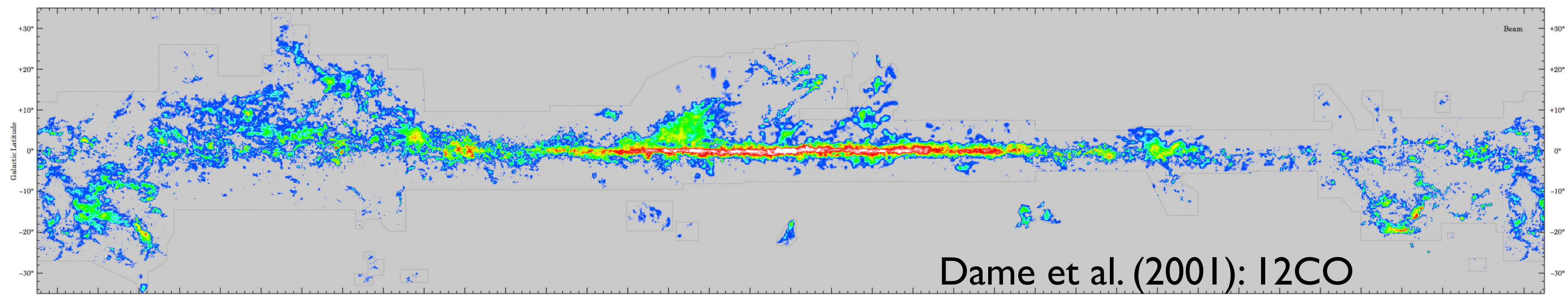
WIM in spiral arms

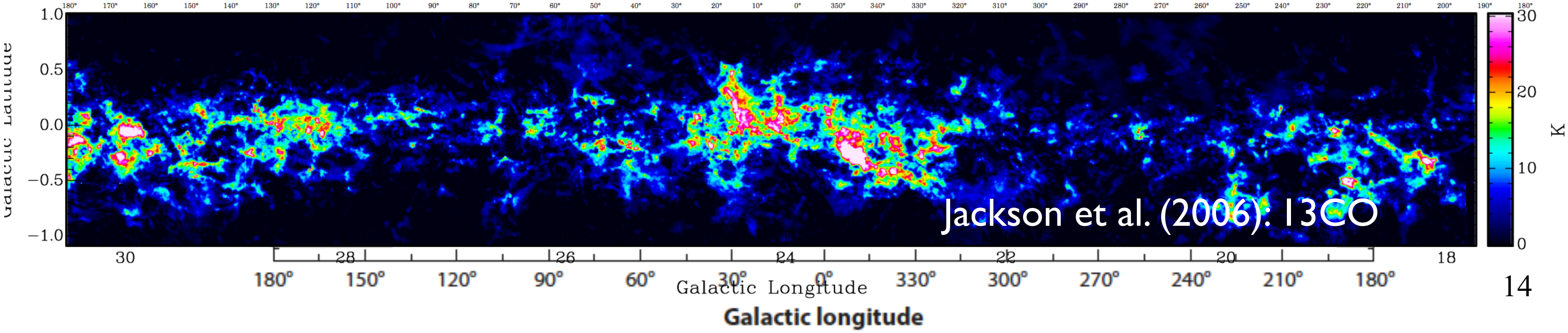


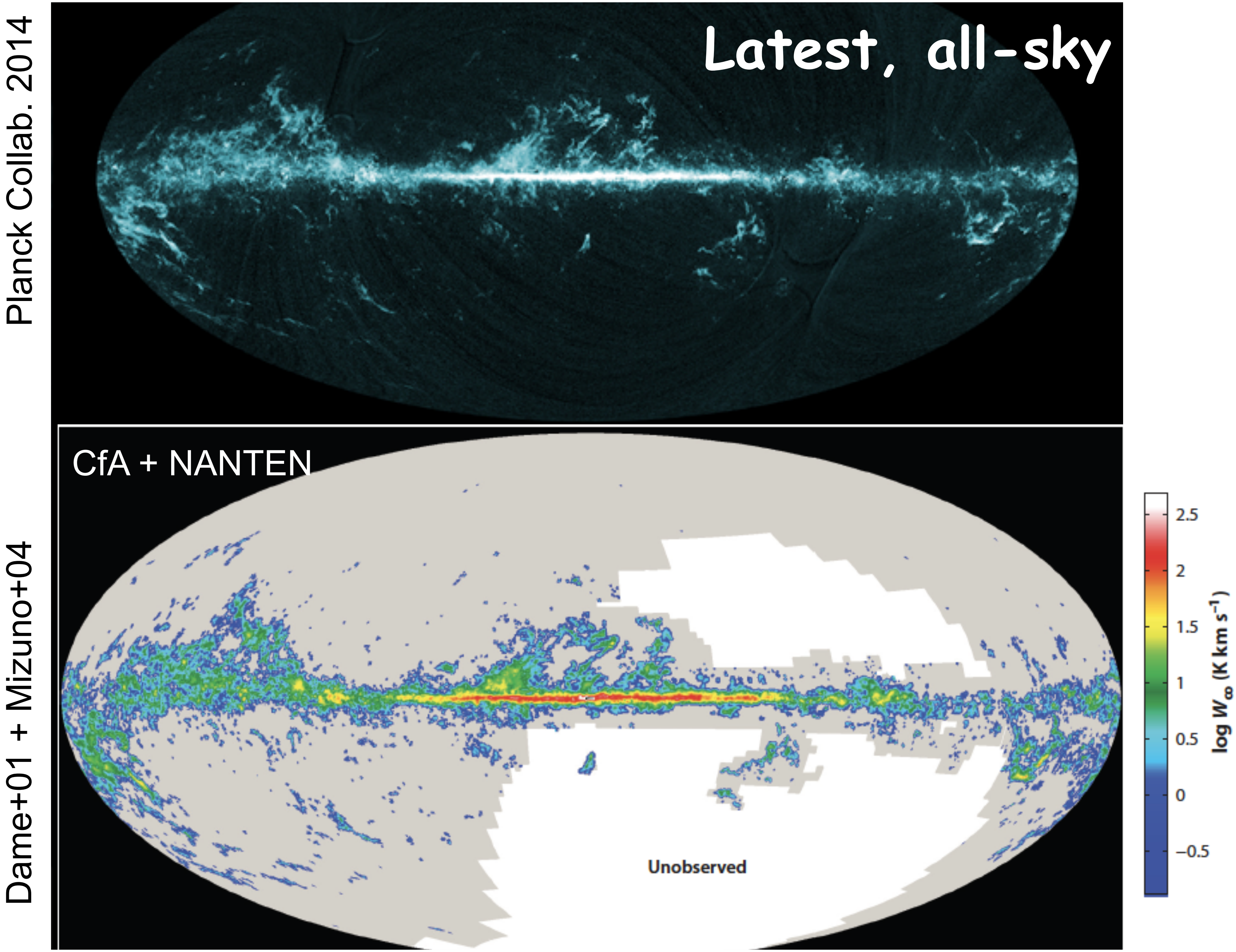
Far Carina arm much higher scale height, >1 kpc.
Line ratios → local ne enhancement via star formation more likely than scattered light from HII regions.

Molecular gas: CO surveys of the Galactic plane



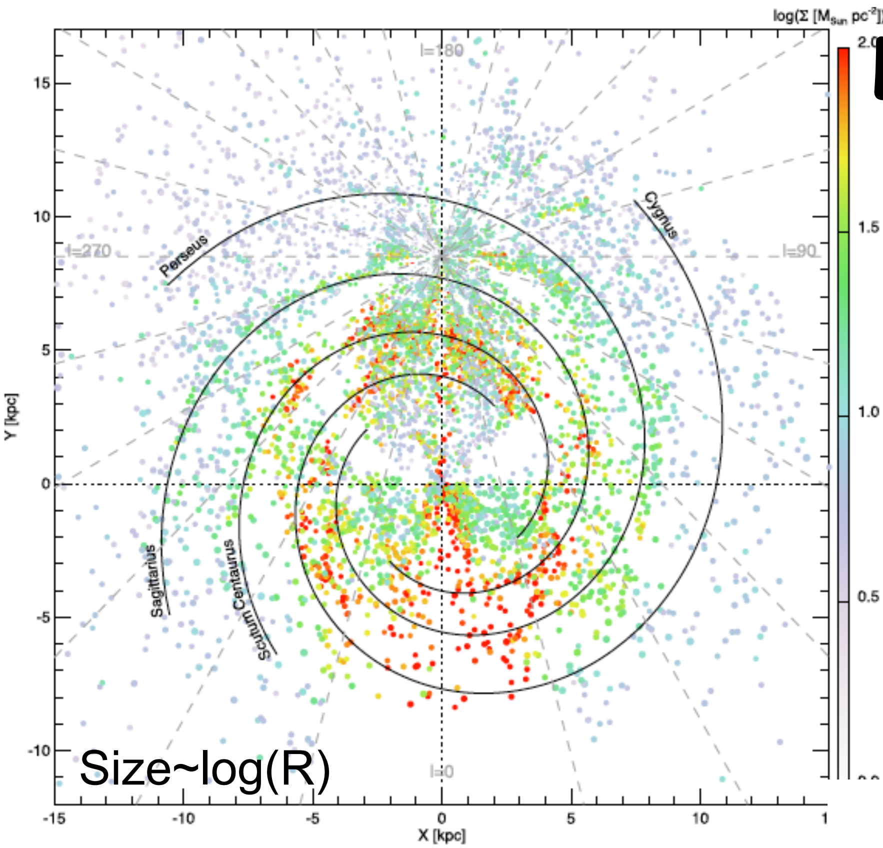






Planck Collab. 2014
Latest, all-sky
Dame+01 + Mizuno+04
CfA + NANTEN
Unobserved
2.5
2
1.5
1
0.5
0
−0.5
log W_{CO} (K km s^{-1})

Large-scale properties of molecular gas

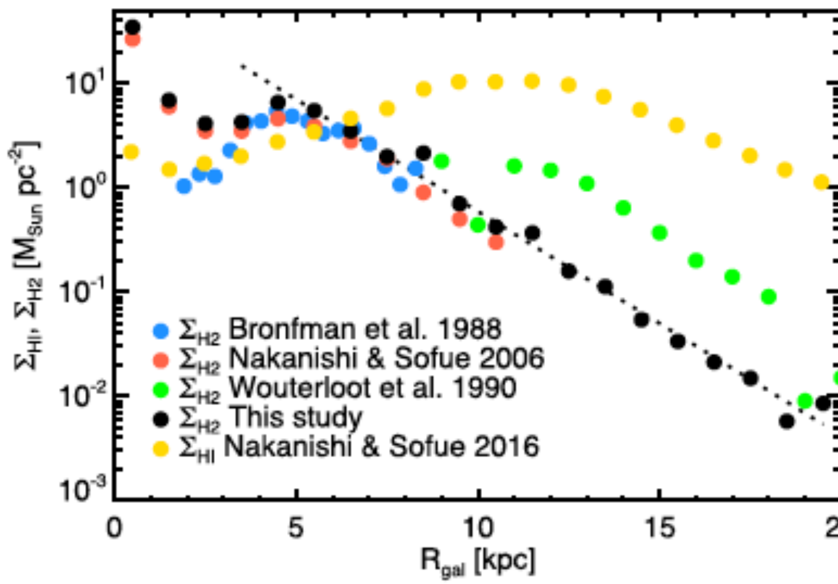


Miville-Deschenes+17

8107 Gaussian cloud clusters, correspond to 98% of CO emission from Dame+01.

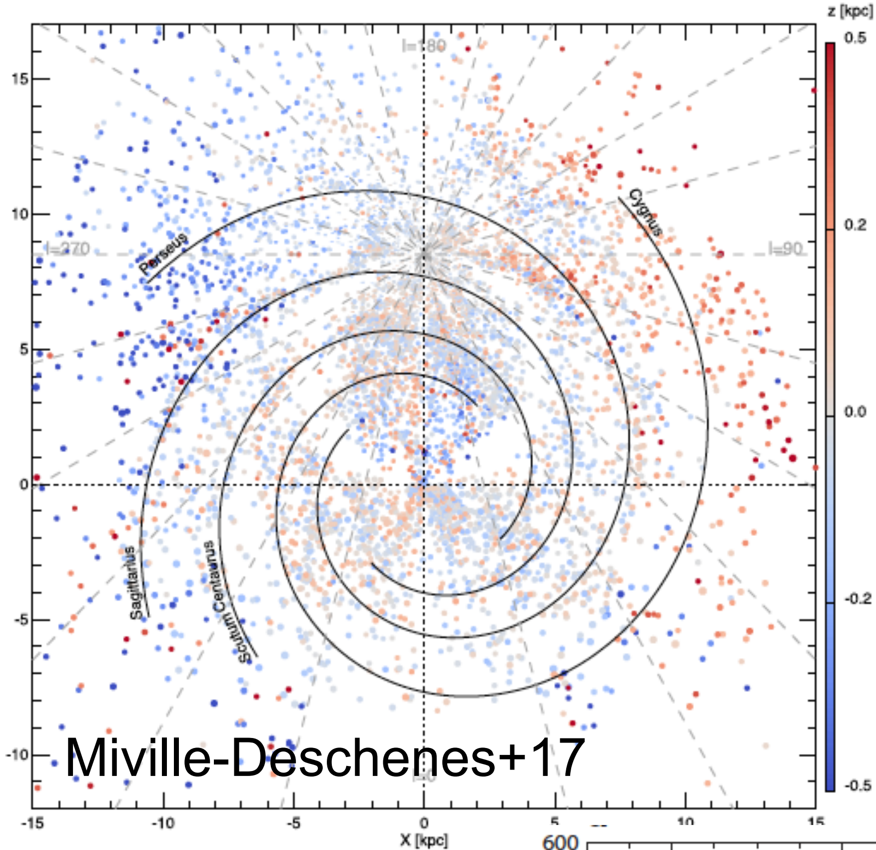
Assumed a constant X_{CO}.

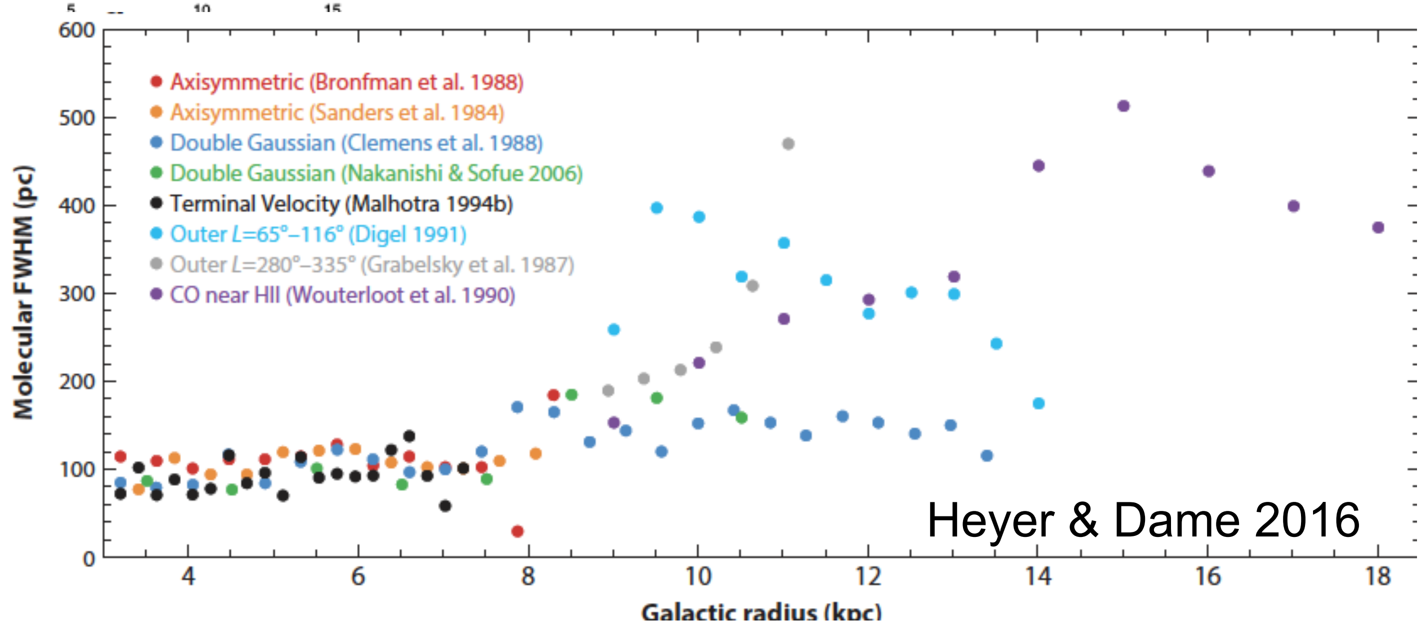
Surface density increases close to major spiral arms.



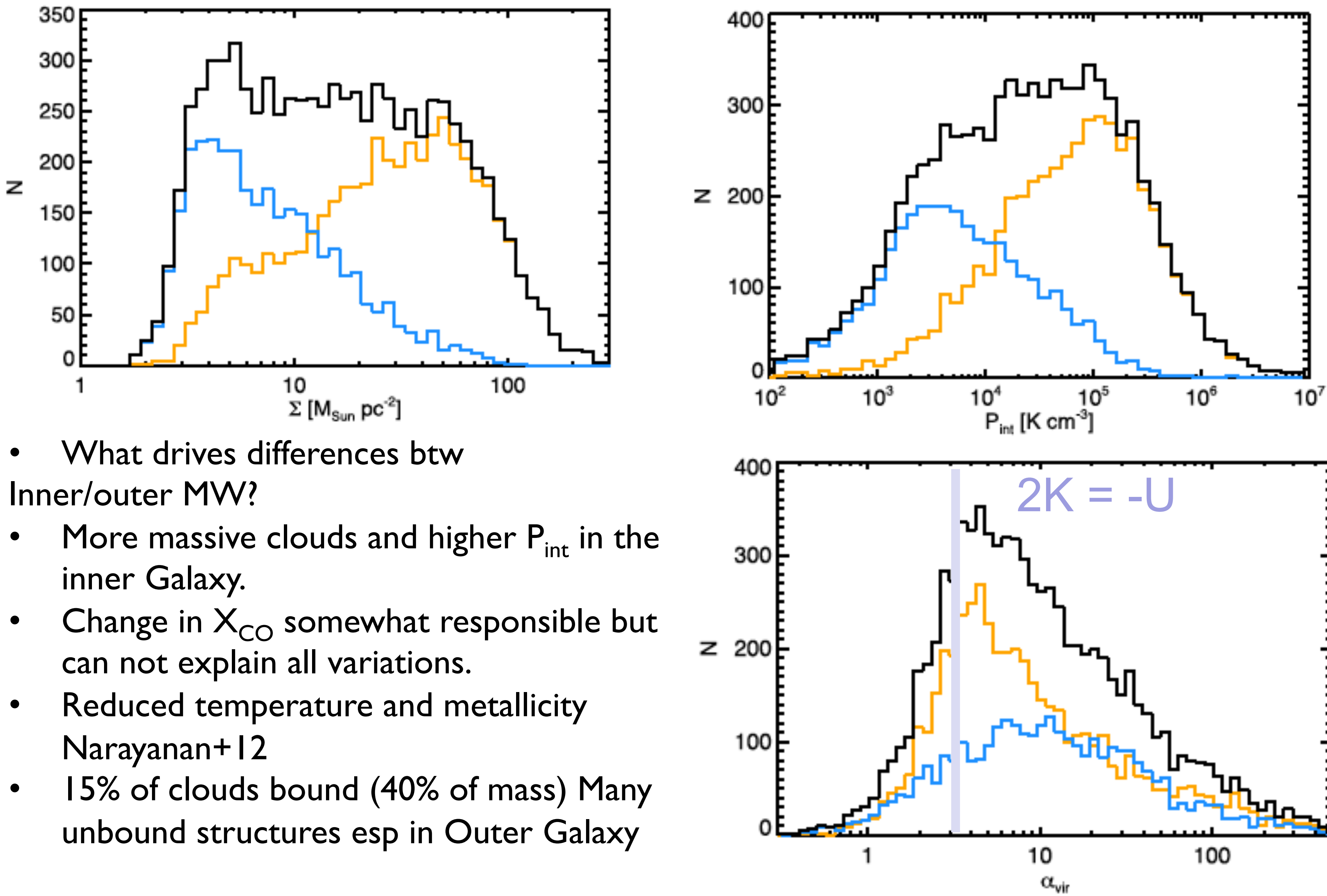
Large-scale properties of molecular gas

Inner Galaxy: CO in a thin layer
Outer Galaxy: flaring and warp, and significant regional variations





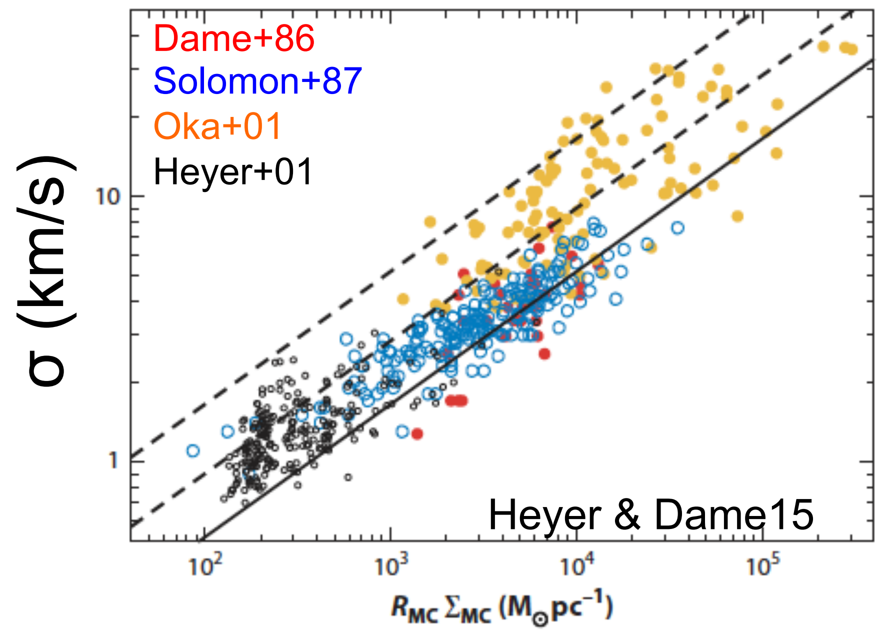
Inner vs Outer Galaxy



Miville-Deschenes+17

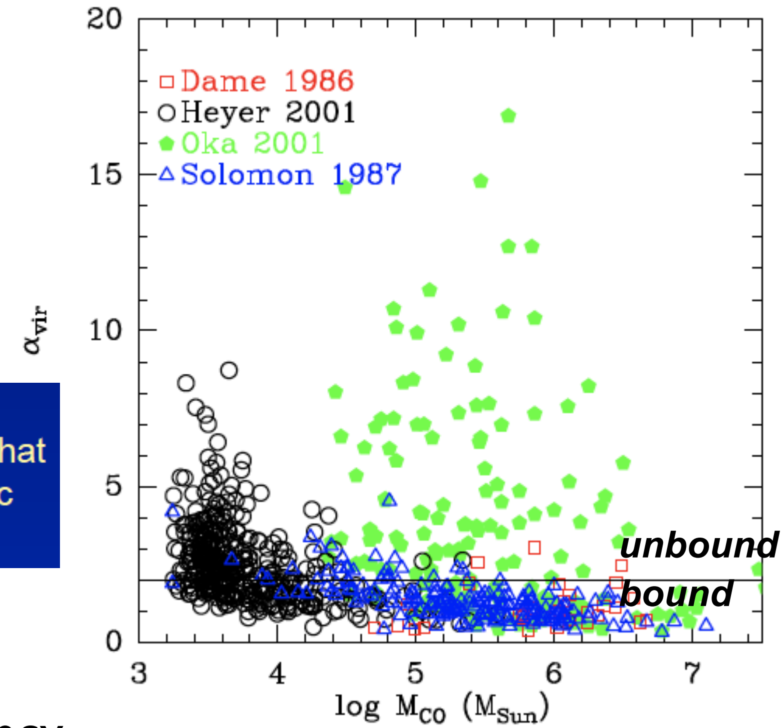
- What drives differences btw Inner/outer MW?
- More massive clouds and higher P_{int} in the inner Galaxy.
- Change in X_{CO} somewhat responsible but can not explain all variations.
- Reduced temperature and metallicity Narayanan+12
- 15% of clouds bound (40% of mass) Many unbound structures esp in Outer Galaxy

Bound vs unbound molecular clouds?



Evans18

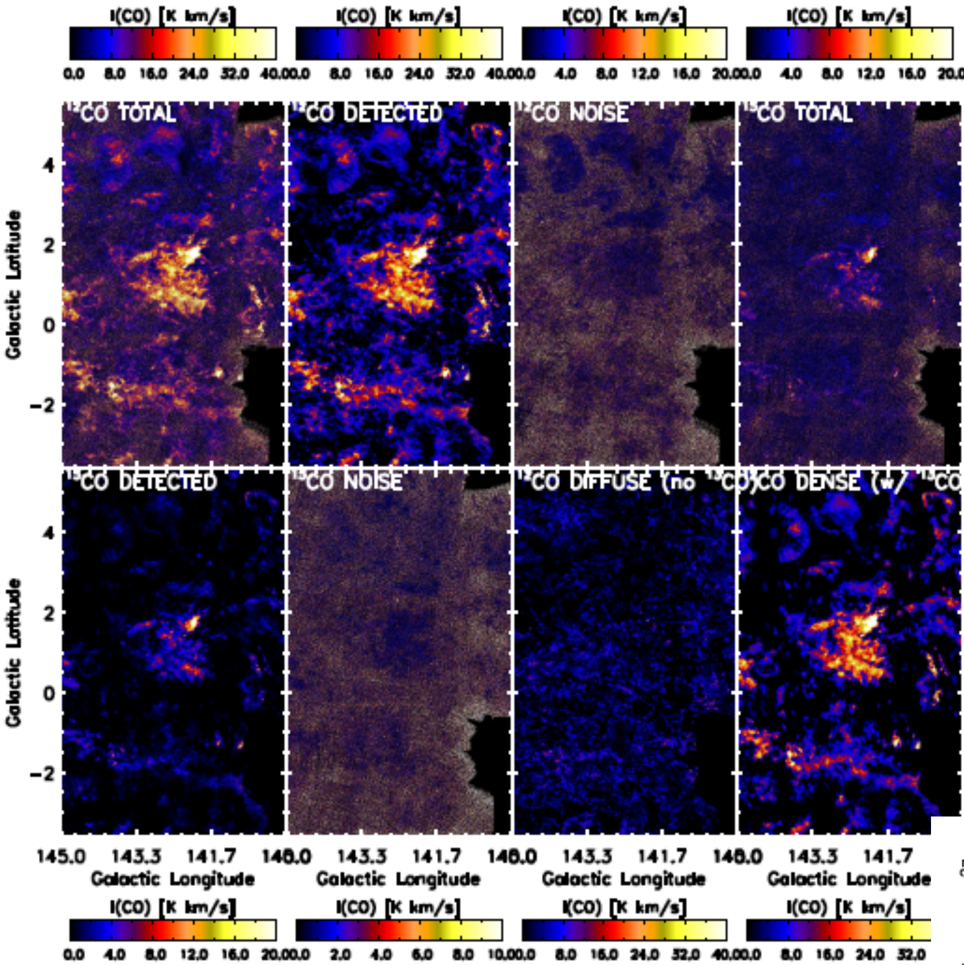
Intrinsic uncertainties in α_{vir} are factor of 3
Almost all could be either bound or not bound!



Heyer and Dame comment:
"Clouds within the Galactic disk have virial ratios between 1 and 3 that are consistent with being gravitationally bound, given the systematic errors of recovering cloud properties.".

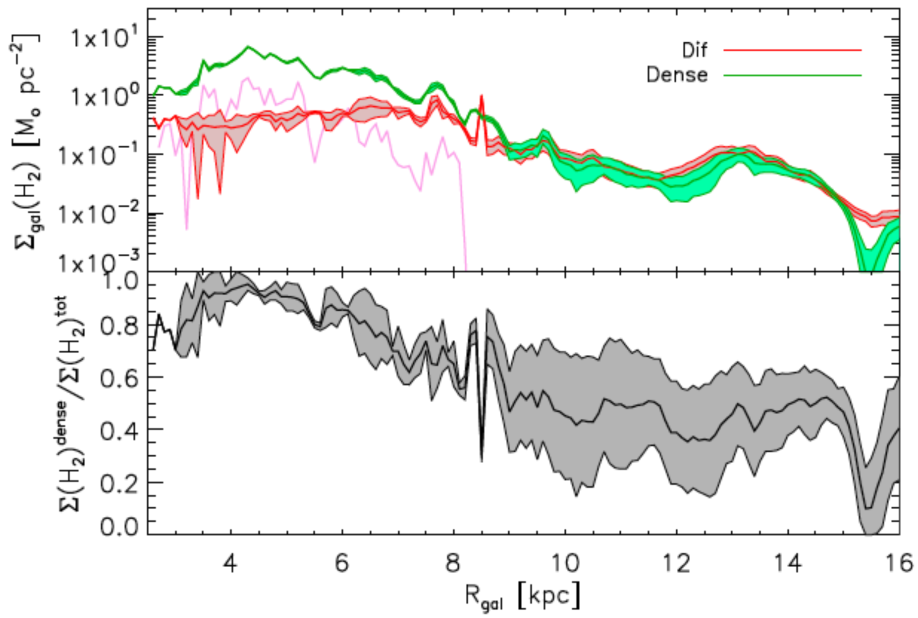
α~1 for gravitationally bound

Key to understanding low star formation efficiency

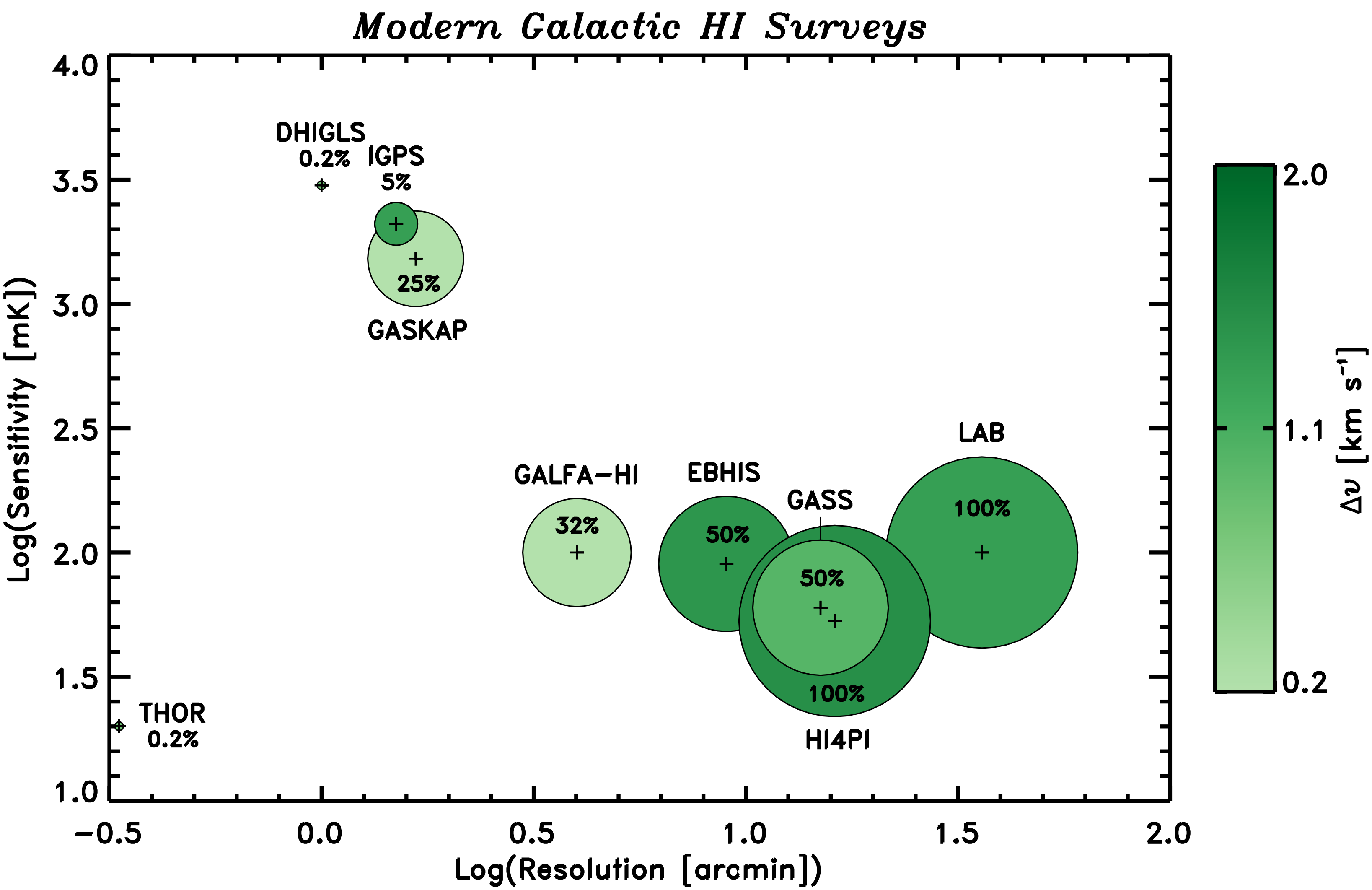


The role of diffuse molecular gas?

- A significant fraction of CO in diffuse, unbound, non-star-forming gas.
- 10-20% at R = 3 kpc, 50% at R = 15 kpc (Roman-Duval+16, Liszt+10, Goldmisth+08).
- Diffuse CO has higher scale height and originates in a thick disk.

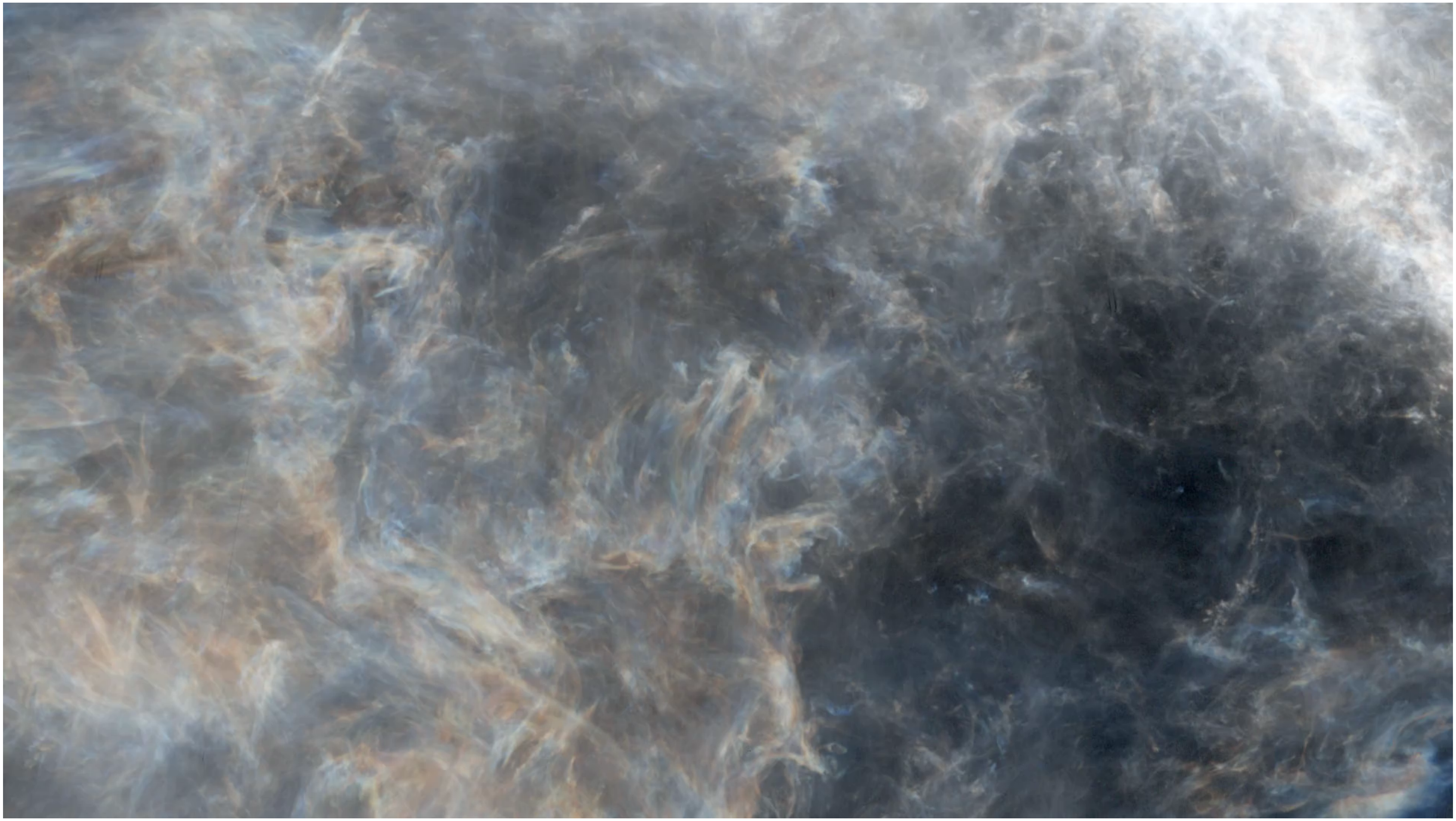


Neutral gas: key HI emission surveys



Thanks to Sam Szotkowski

GALFA-HI DR2: 13,000 deg^2 at 4′

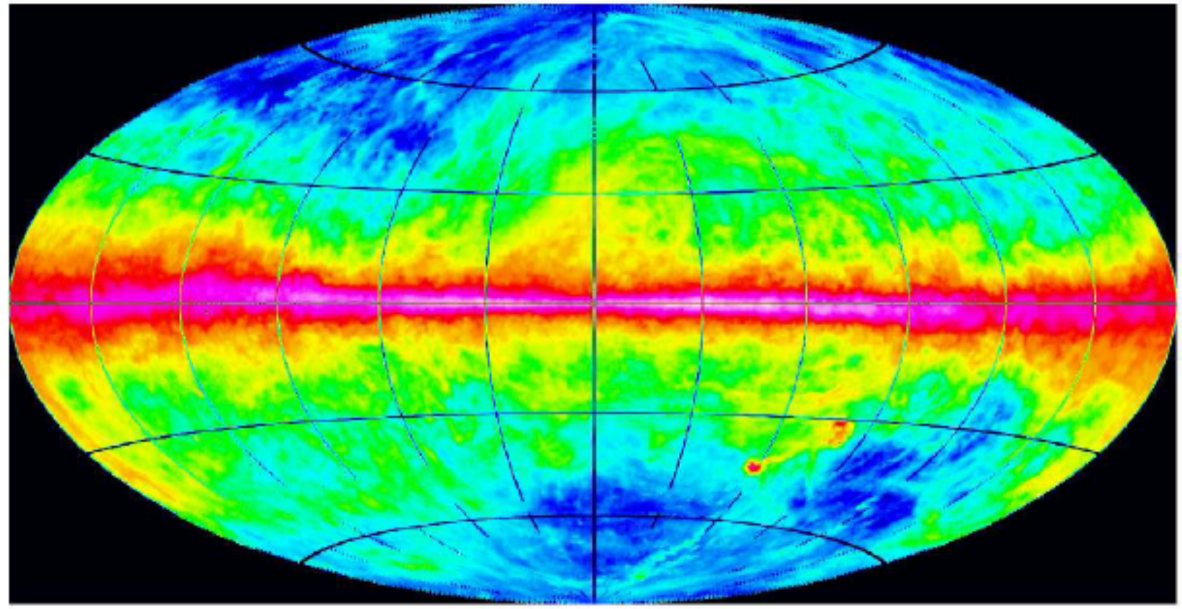


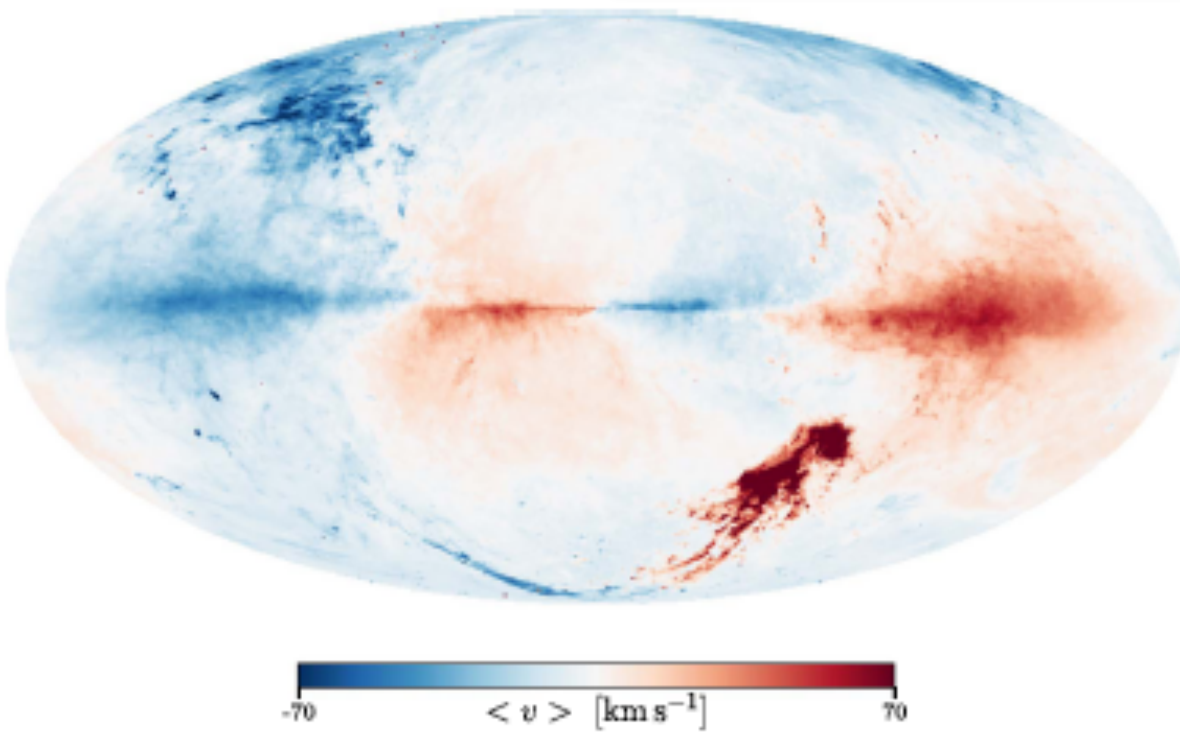
90% of data obtained commensally

Courtesy Josh Peek

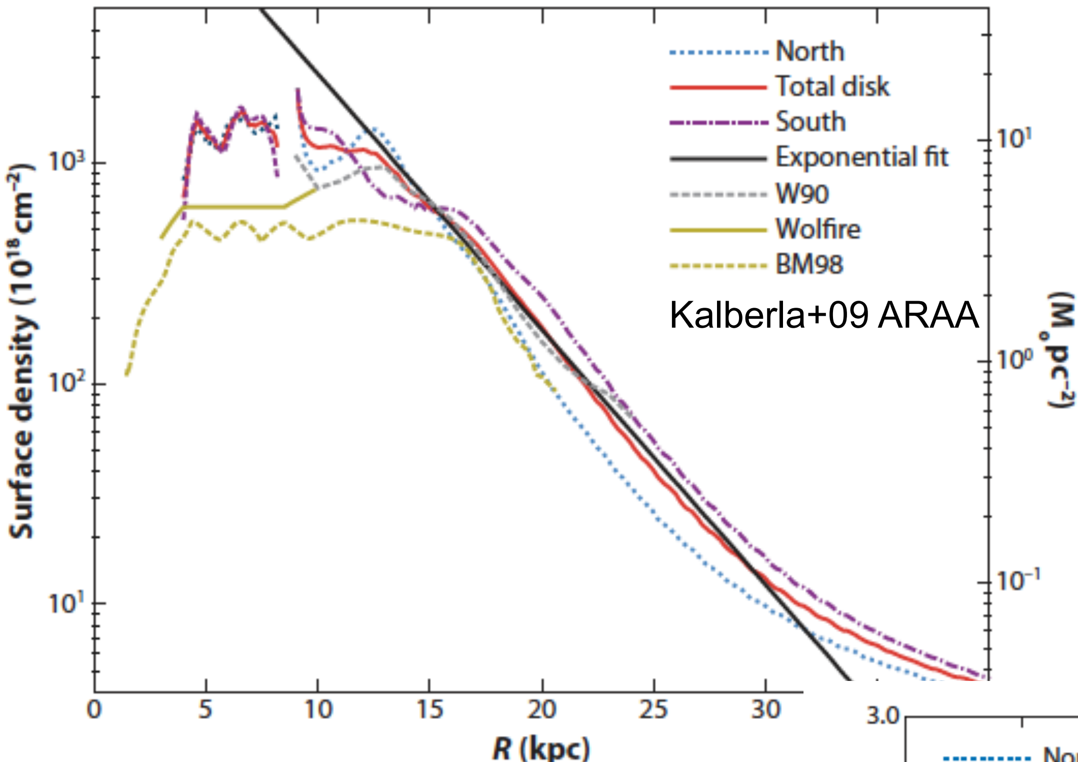
All-sky HI

LAB at 36’

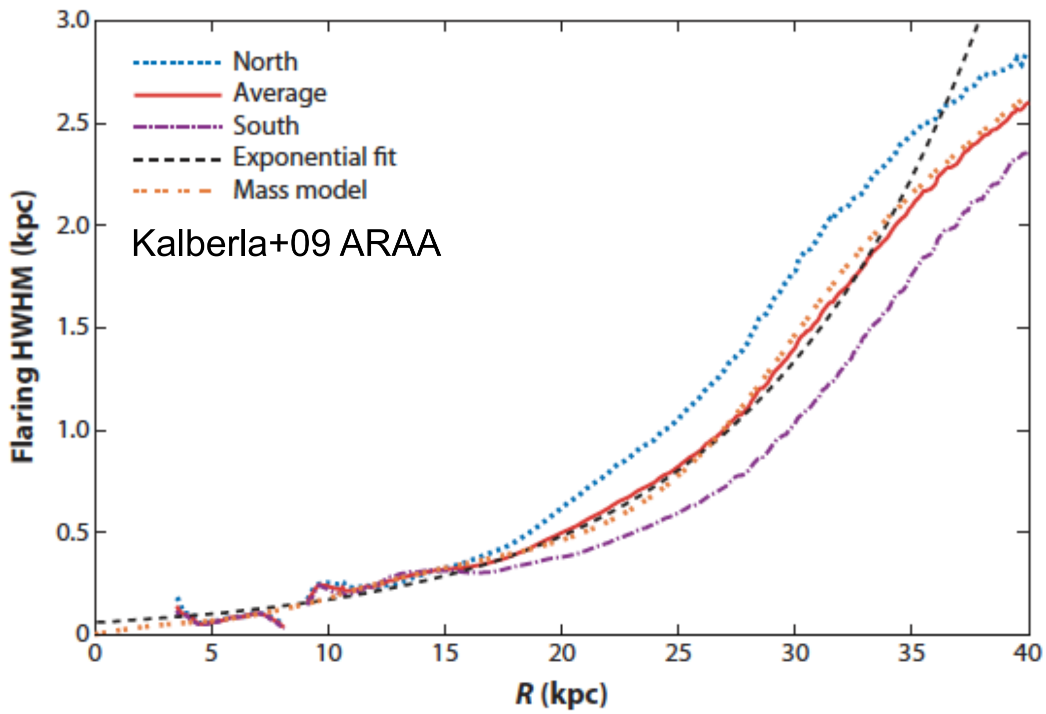


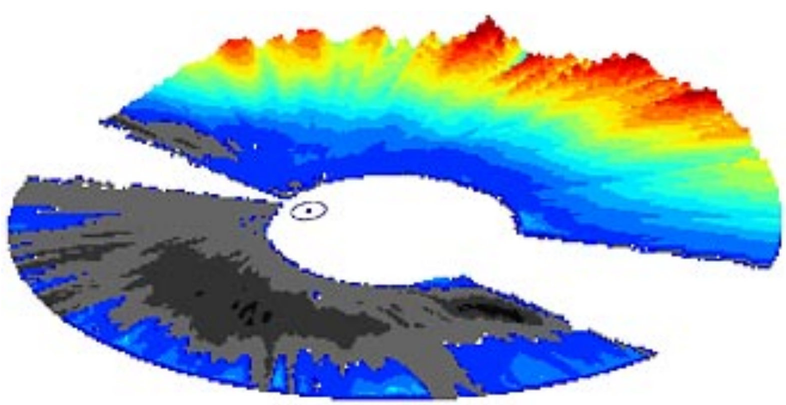


HI4PI (Effelsberg + Parkes) at 9’-16’

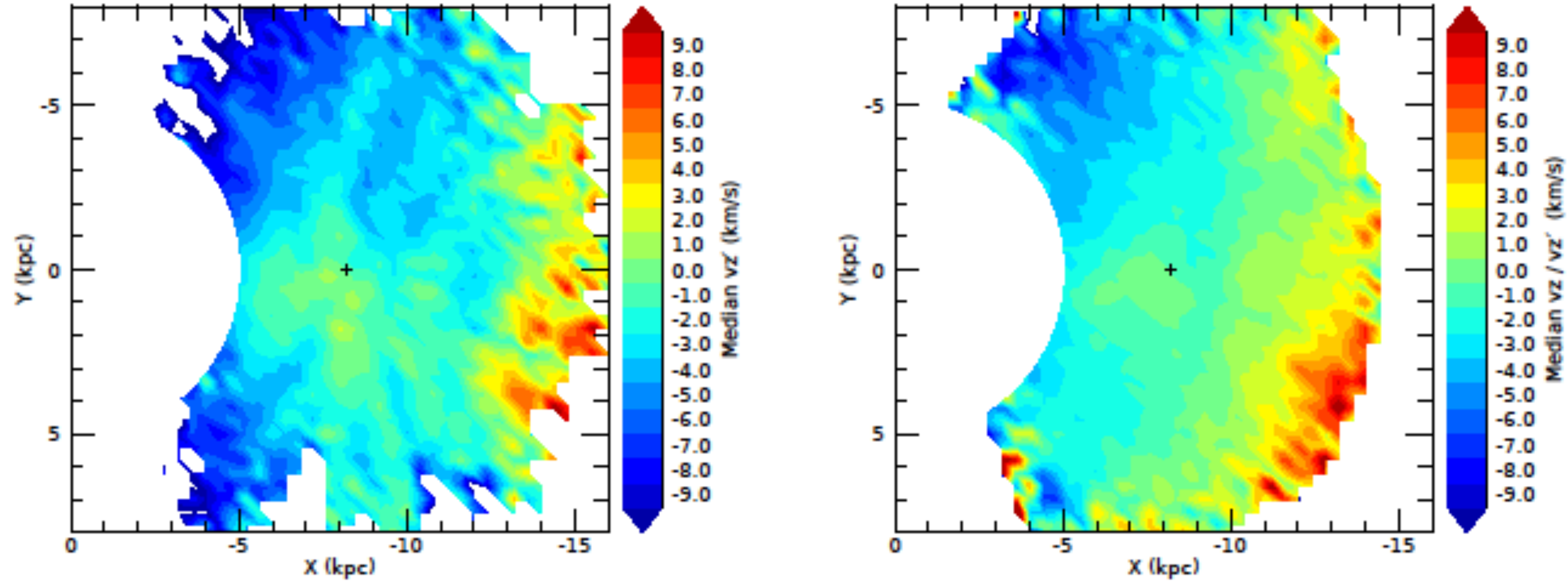


HI scale height:
At least 2 components with h ~ 120 and ~300pc (Dickey & Lockman 1990)

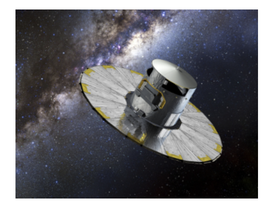




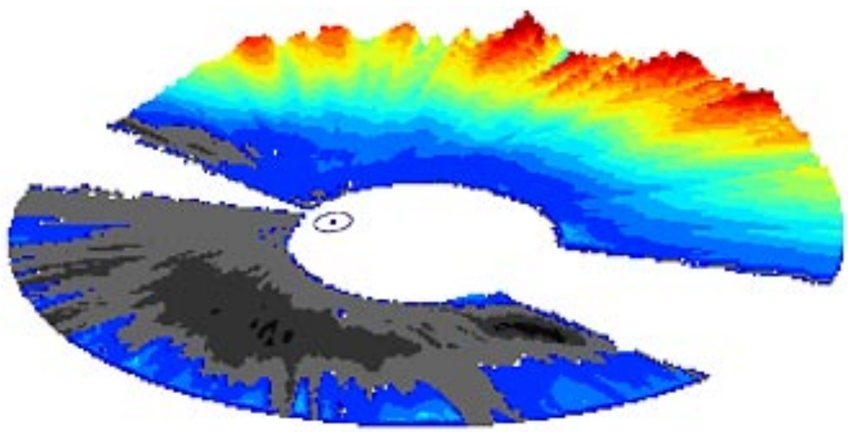
Levine+06



Vertical motion Vz of stars: upper MS and giants from Gaia (Poggio+18)

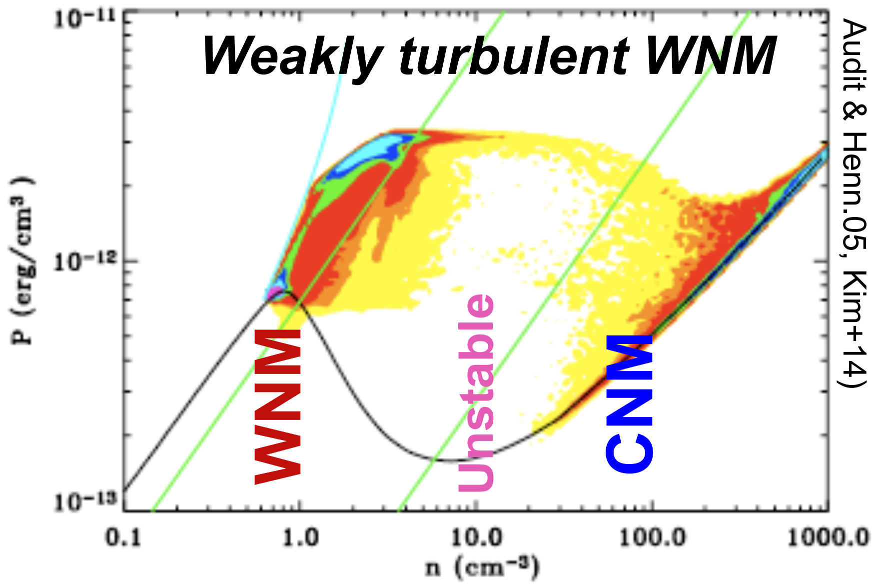


Need distance information – GAIA and other stellar surveys: <u>a lot more to come about the vertical structure of the Milky Way disk!</u> Connecting stellar and gaseous disk structure.

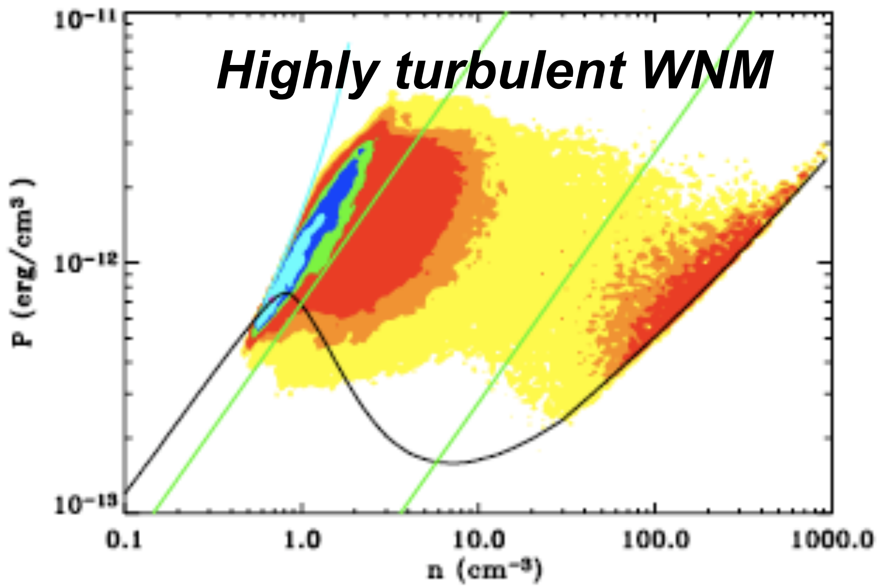


HI: Levine+06

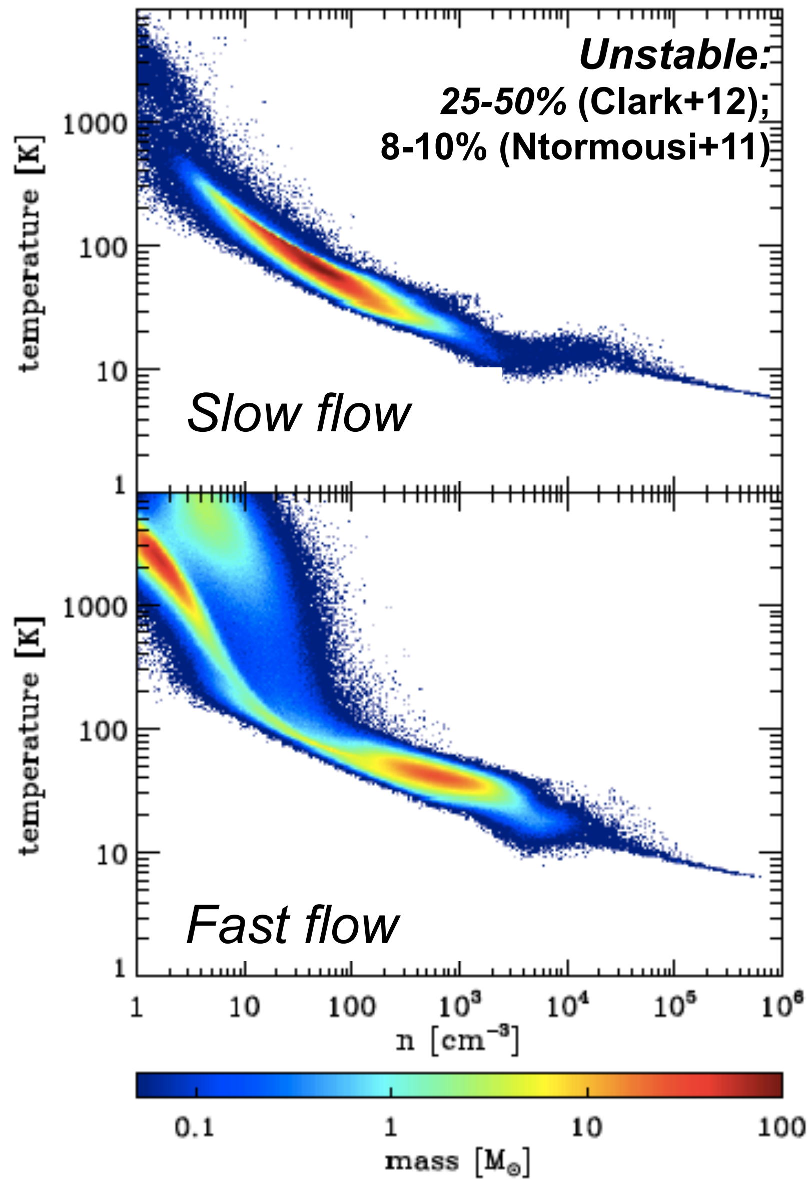
HI: CNM, WNM, and feedback-driven unstable neutral medium



(McKee & Ostriker77;Wolfire03; Audit & Henn.05, Kim+14)

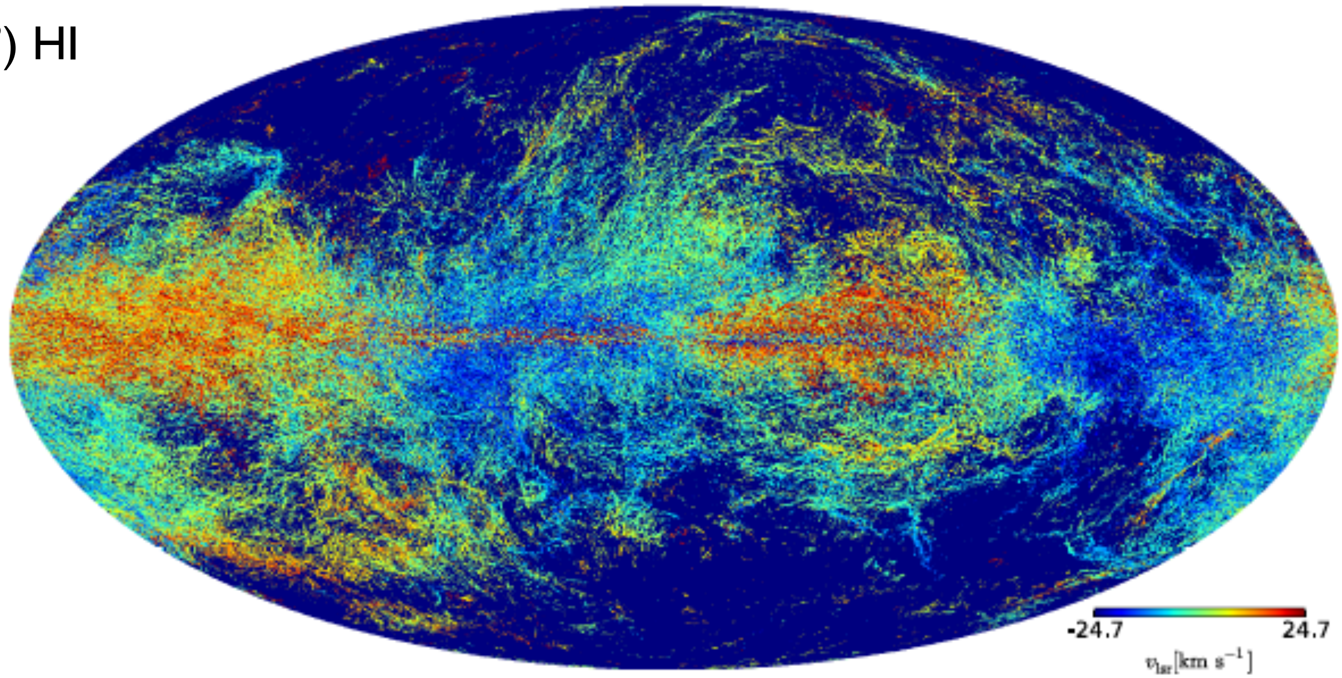


AH05, Mac Low+05, Hill+12, Clark+12

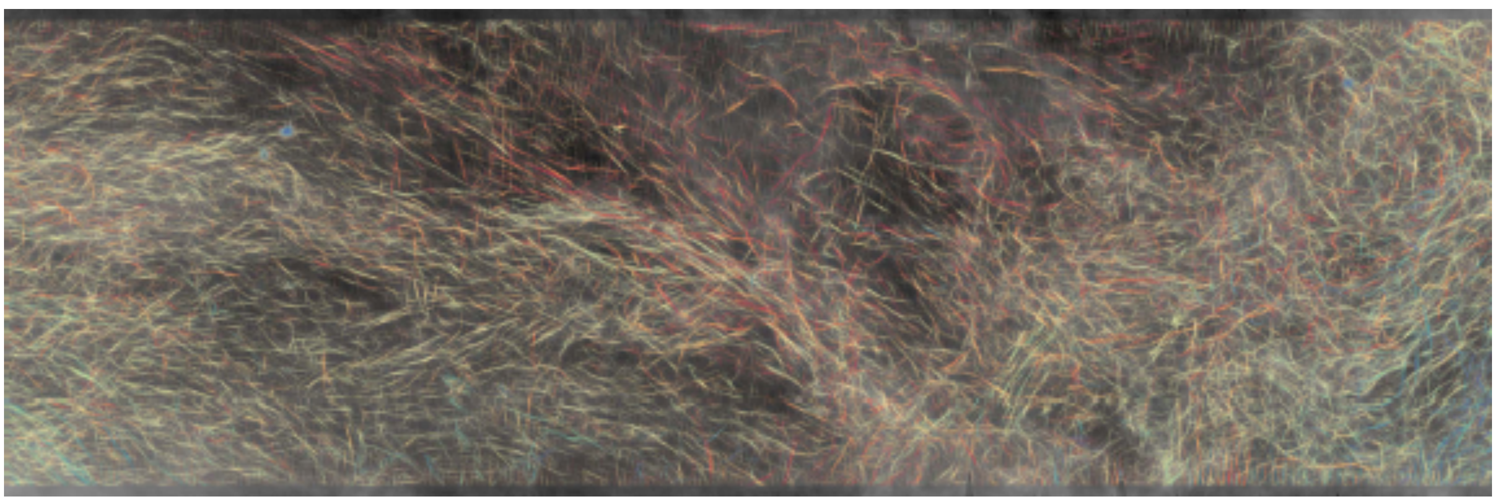


Morphology of the CNM?

Large-scale (10-20') HI filaments
Kalberla+16
USM
"steamrolled raisins"

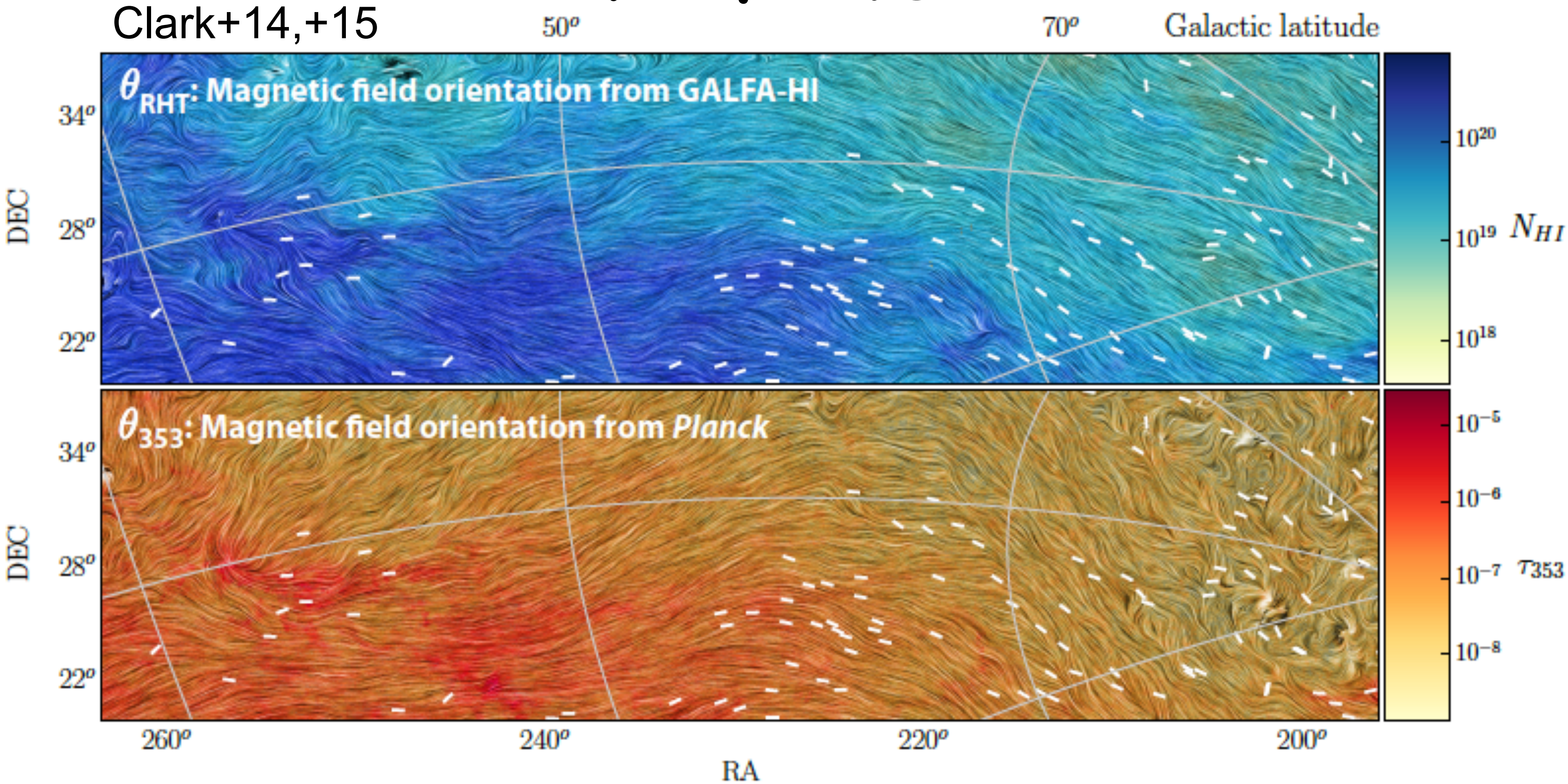


Small-scale (~few ') HI filaments;
Peek+18
RHT



HI fibers

Clark+14,+15



Fiber properties: ~10^{18-19} cm^{-2}, T_k<200 K → fibers are tracing CNM

HI-magnetic field alignment pervasive

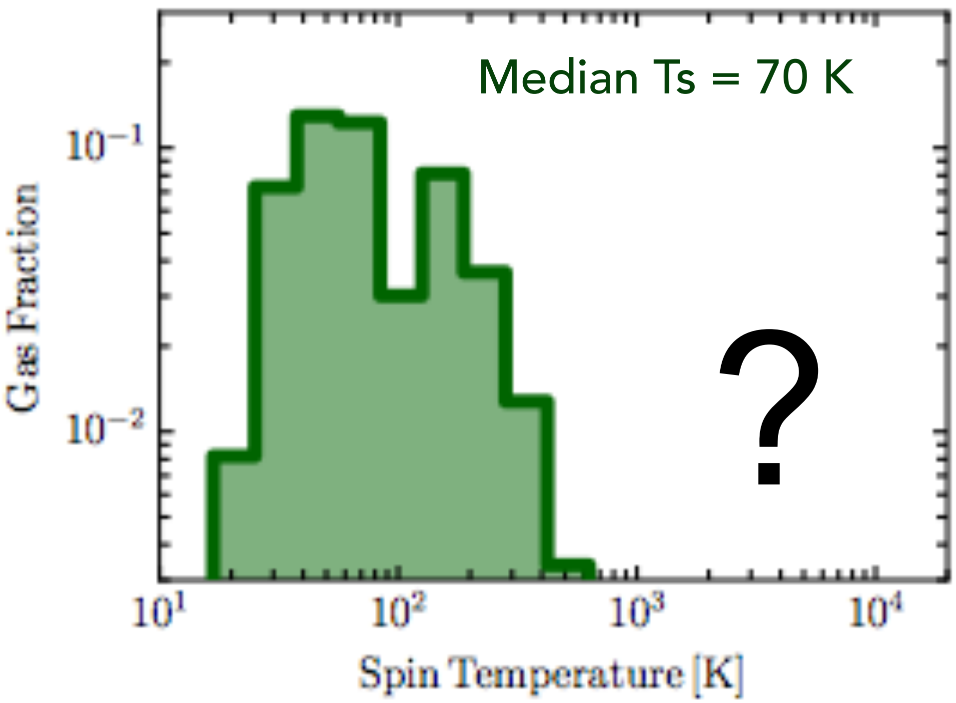
Filaments likely associated with the wall of the Local Bubble

What does this imply for the ionization fraction of HI?

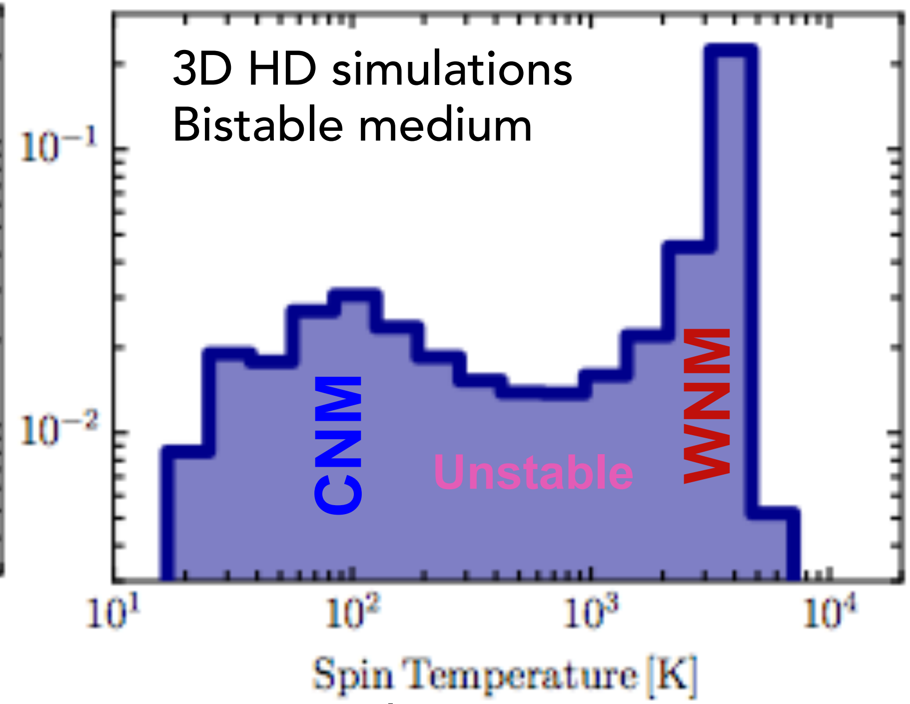
Soler+17: *magnetic field important for diffuse flows that lead to formation of molecular clouds*. More understanding needed.

Observed HI temperature distribution

Arecibo Millennium Survey
79 HI absorption+emission pairs



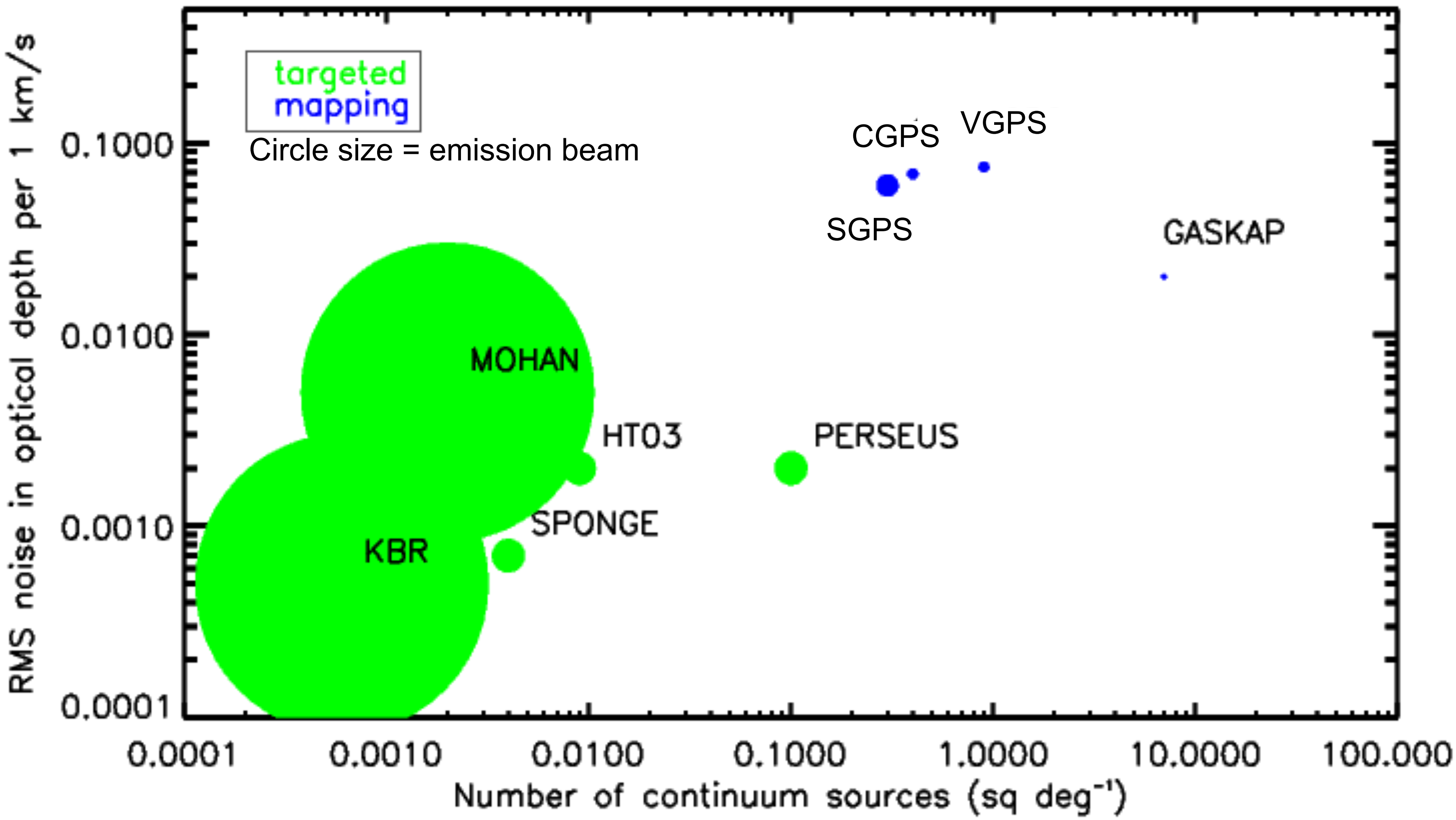
Heiles & Troland 2003, ApJS, 145, 329H



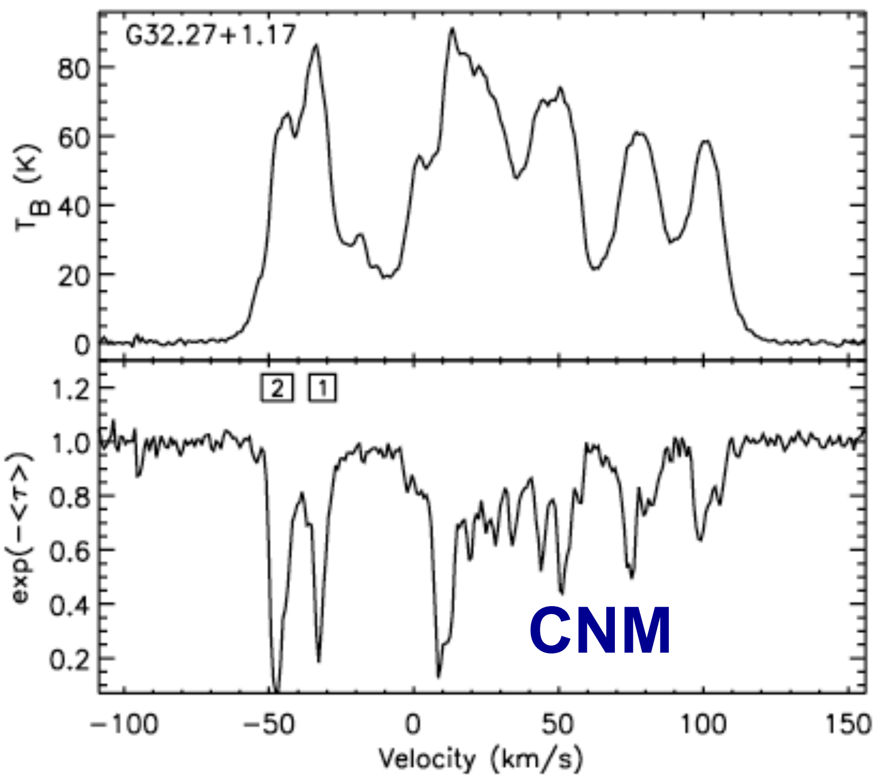
Kim et al. 2014, ApJ, 786, 64

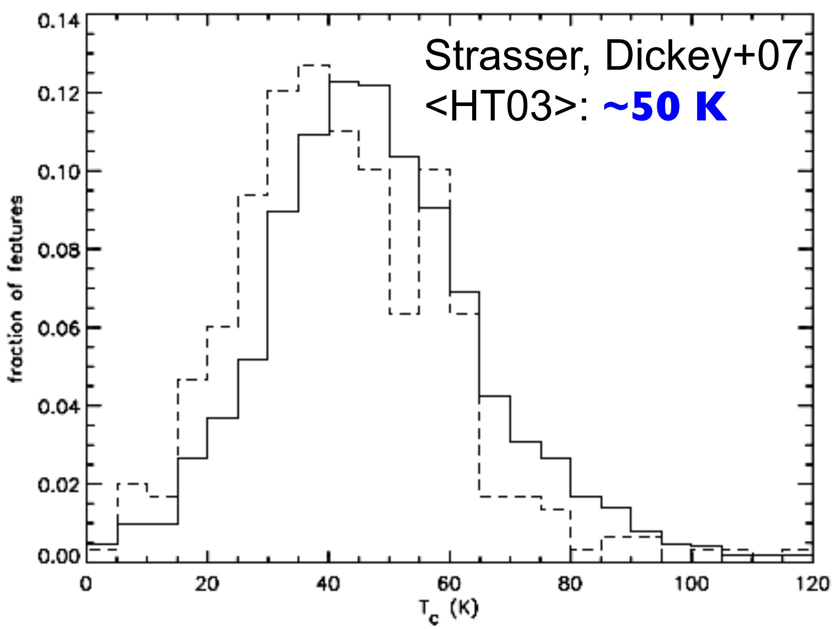
WNM temperature constraints rare and mainly indirect

Key HI absorption surveys



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





Excitation or spin temperature, Ts, of the CNM:

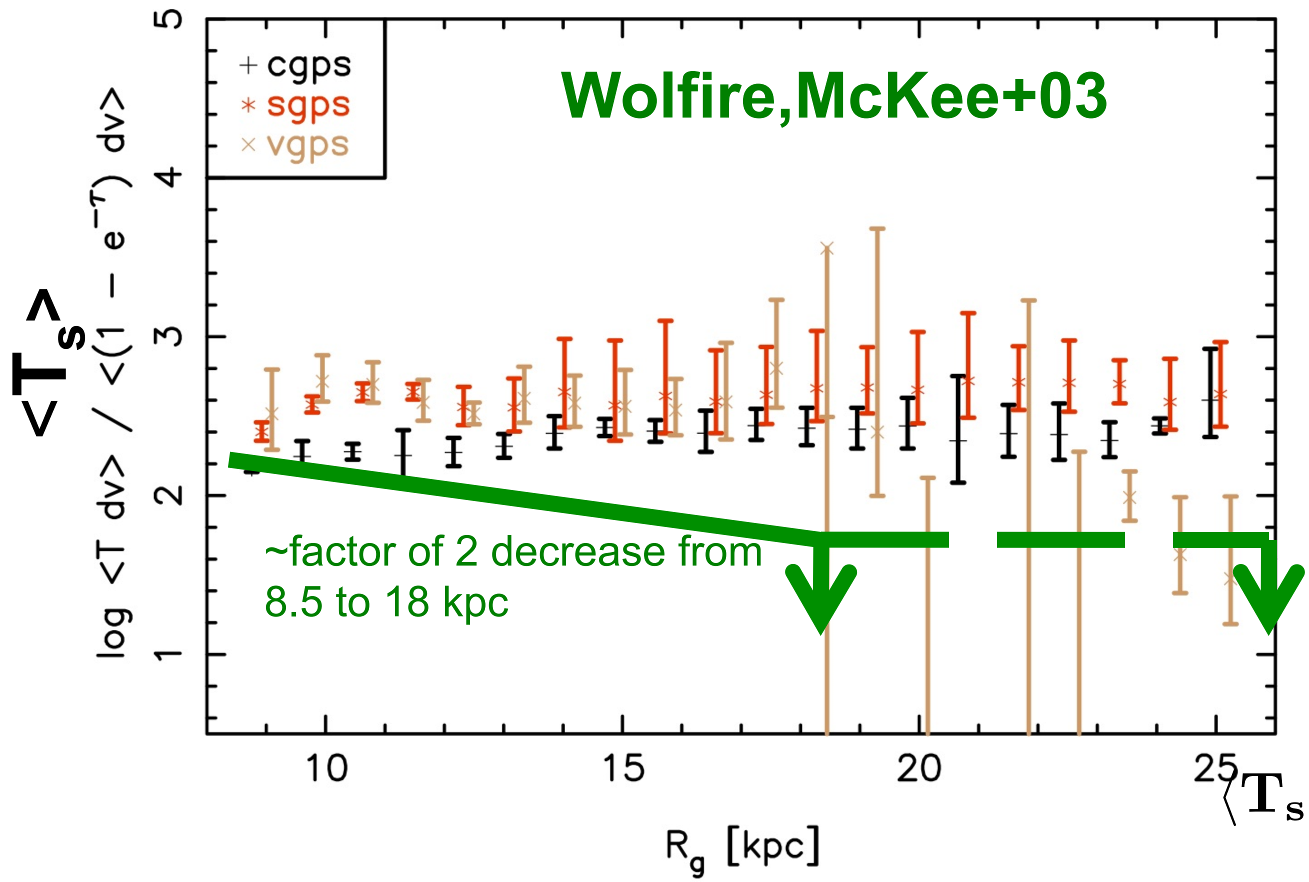
No evidence for spatial variations of Ts

E.g. <Ts>:
(Inner MW) ~ (Outer MW) !

(VLA + Canadian + Southern) Galactic plane surveys

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

Puzzle: the CNM fraction ~constant across the MW disk



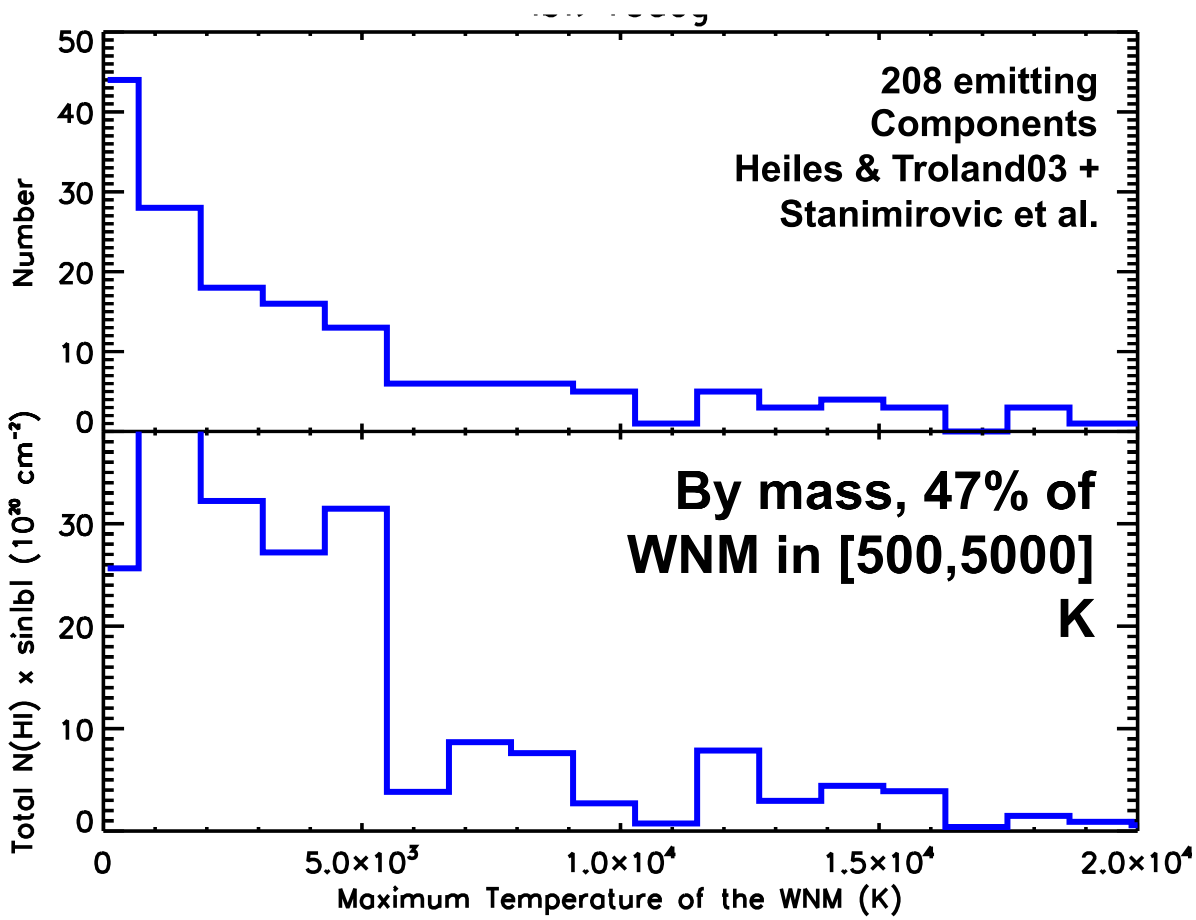
Dickey et al. 09:
290 spectra from SGPS, CGPS, VGPS.
Integrated properties.

$$\langle \mathbf{T_s} \rangle = \frac{\mathbf{T_{EM}}}{(\mathbf{1} - \mathbf{e}^{-\tau})} = \frac{\mathbf{T_{s,c}}}{\mathbf{f}_{\mathrm{CNM}}}$$

$\langle T_s \rangle$~300 K → CNM fraction constant in the MW from R_0 to $3xR_0$. CNM exists at very low thermal pressure – highly resilient?

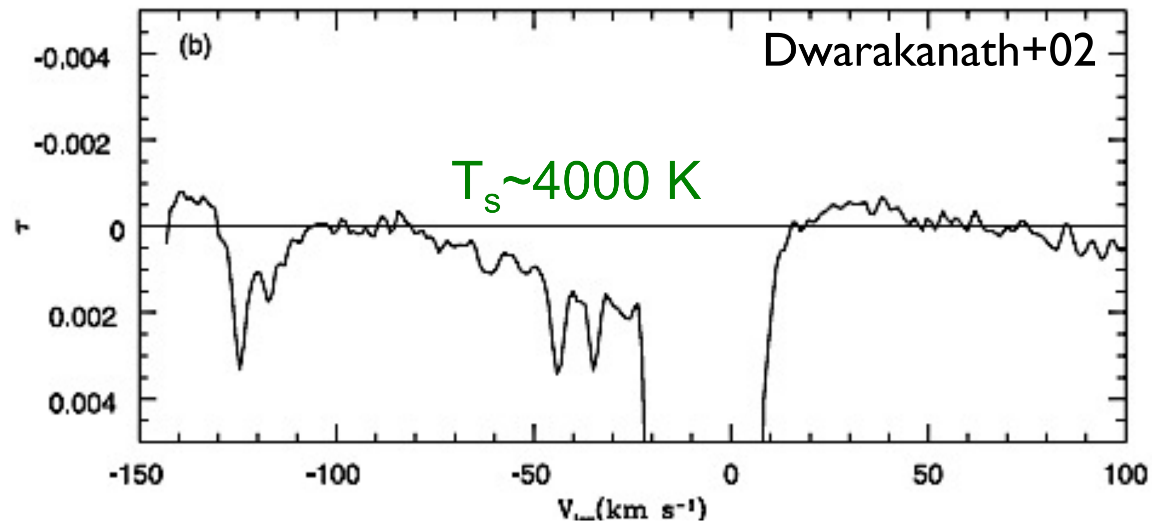
Indirect WNM temperature

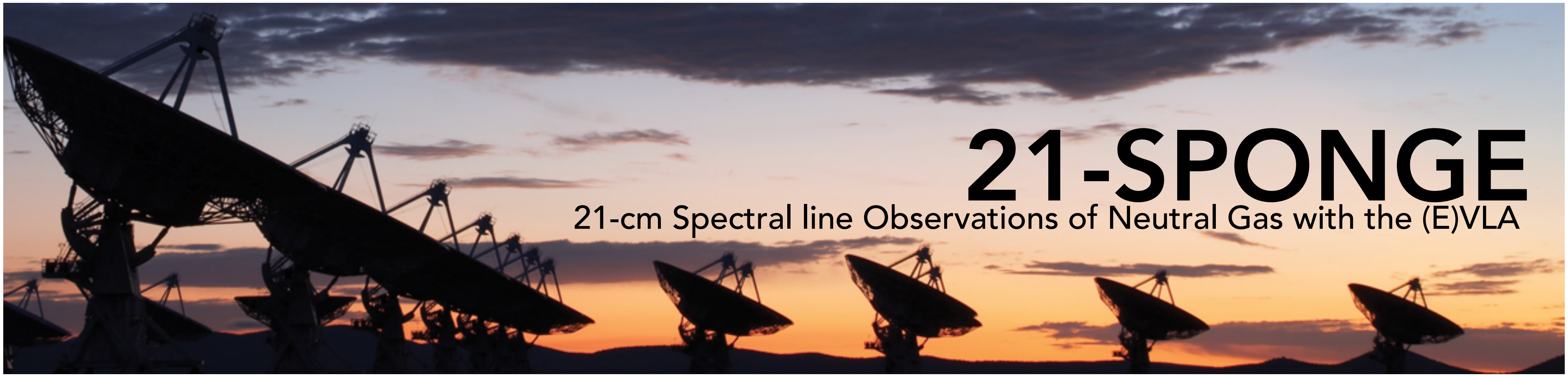
	Unstable HI mass fraction
Heiles & Troland03 Haud & Kalberla07	0.3 ~0.5
Roy+13	<0.28



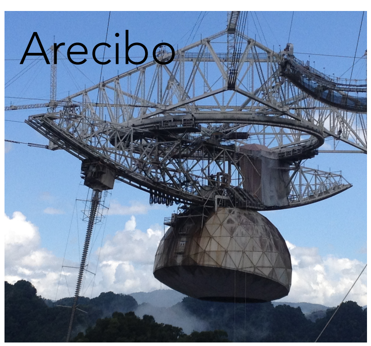
Dickey+77, Kalberla+85, etc

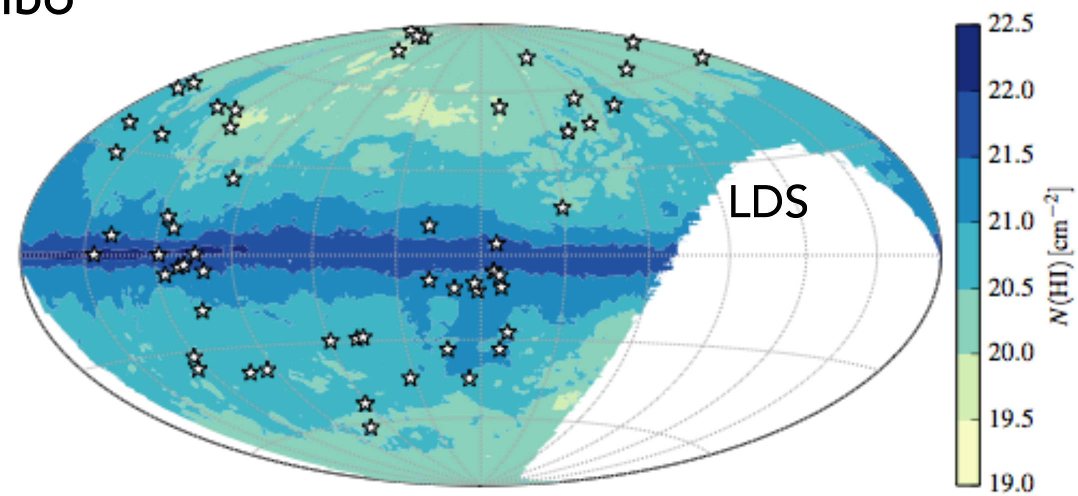
Direct WNM temperature difficult & rare





- 48 continuum sources, S >3 Jy, high latitudes
- 571 VLA hours: $\sigma_\tau < 0.001$ per 0.4 km/s channels
- 57 HI spectra as some double sources
- Matching HI emission from Arecibo
- High detection rate (52/57)!
- Claire Murray's PhD thesis

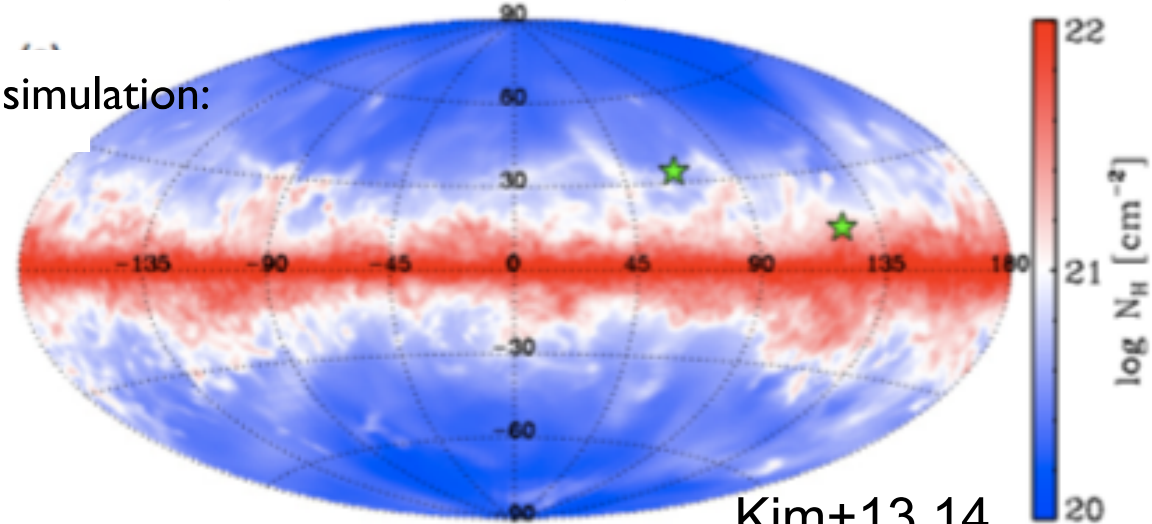




Murray et al. 2015, 2018

Understanding Observational Biases: compare with numerical simulations

- 3D hydrodynamical Galactic ISM simulation:
  - Supernova feedback
  - Self gravity
  - ISM heating, cooling
  - 2pc spatial resolution
  - Galactic rotation



Kim+13,14

- 10^4 synthetic HI spectra

~15,000 components

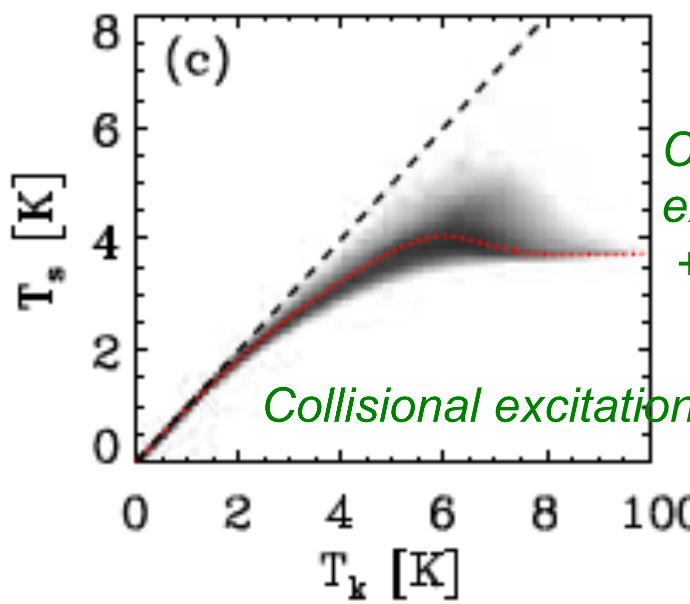
- From T_k to T_s:

Collisions, radiative excitation,

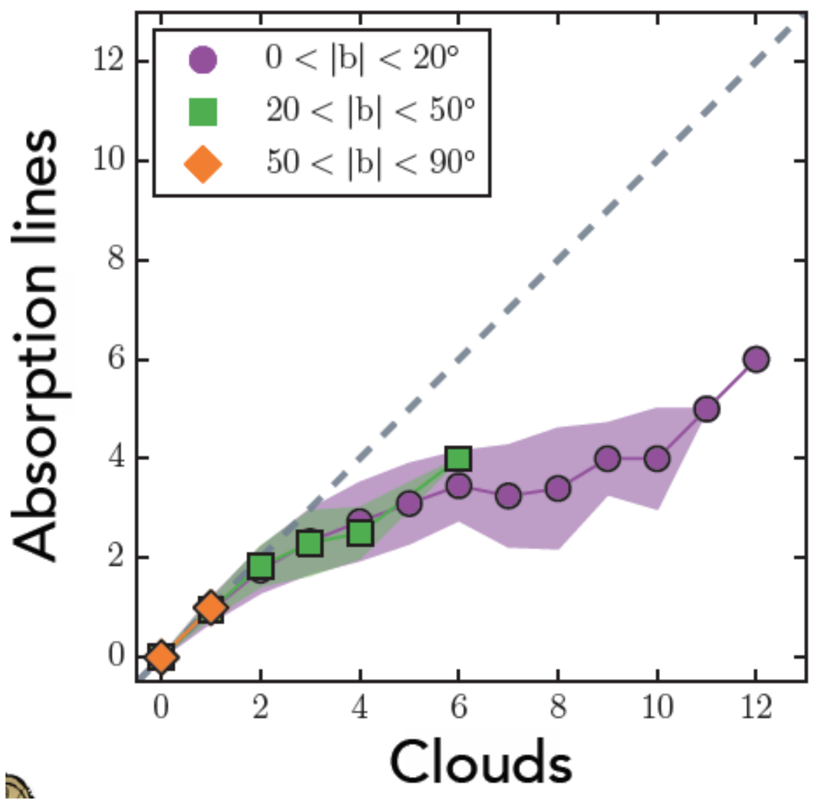
scattering of Lyalpha photons

(Wouthuysen-Field effect)

Assume n_alpha=10^{-6} cm^{-3}



Accuracy of observational Ts derivation

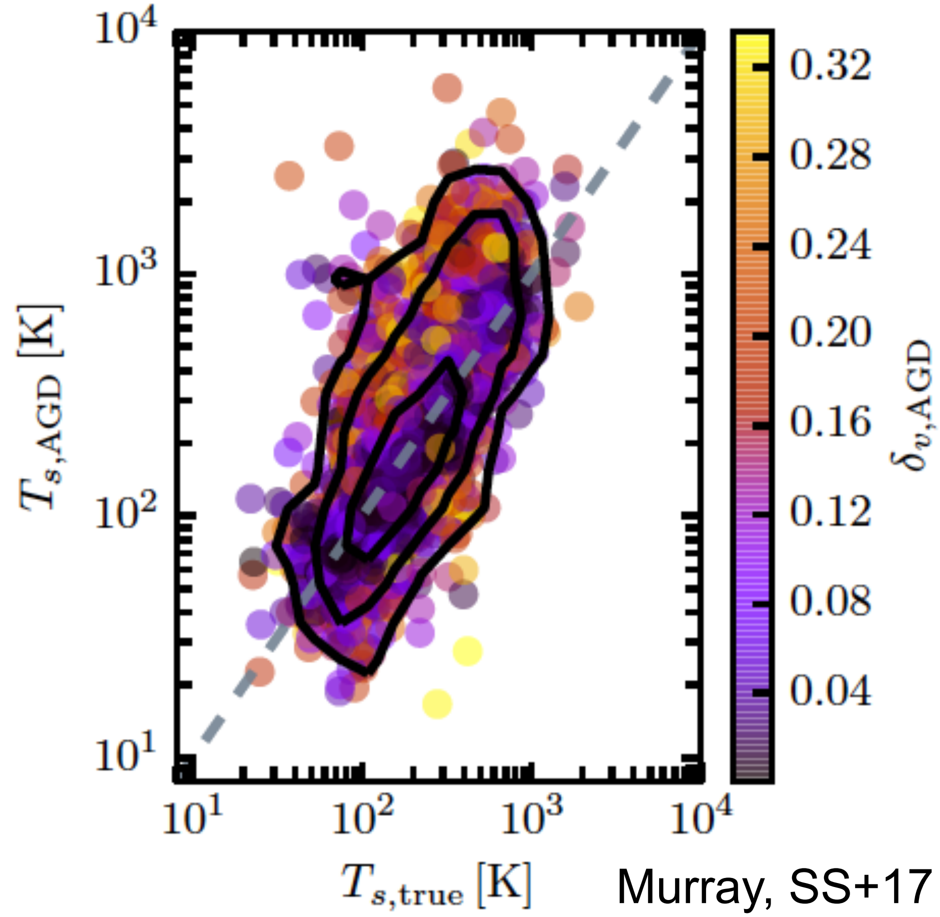


Recovery Completeness

$$0 < |b| < 20^\circ \rightarrow 51\%$$

$$20 < |b| < 50^\circ \rightarrow 73\%$$

$$50 < |b| < 90^\circ \rightarrow 100\%$$



Murray, SS+17

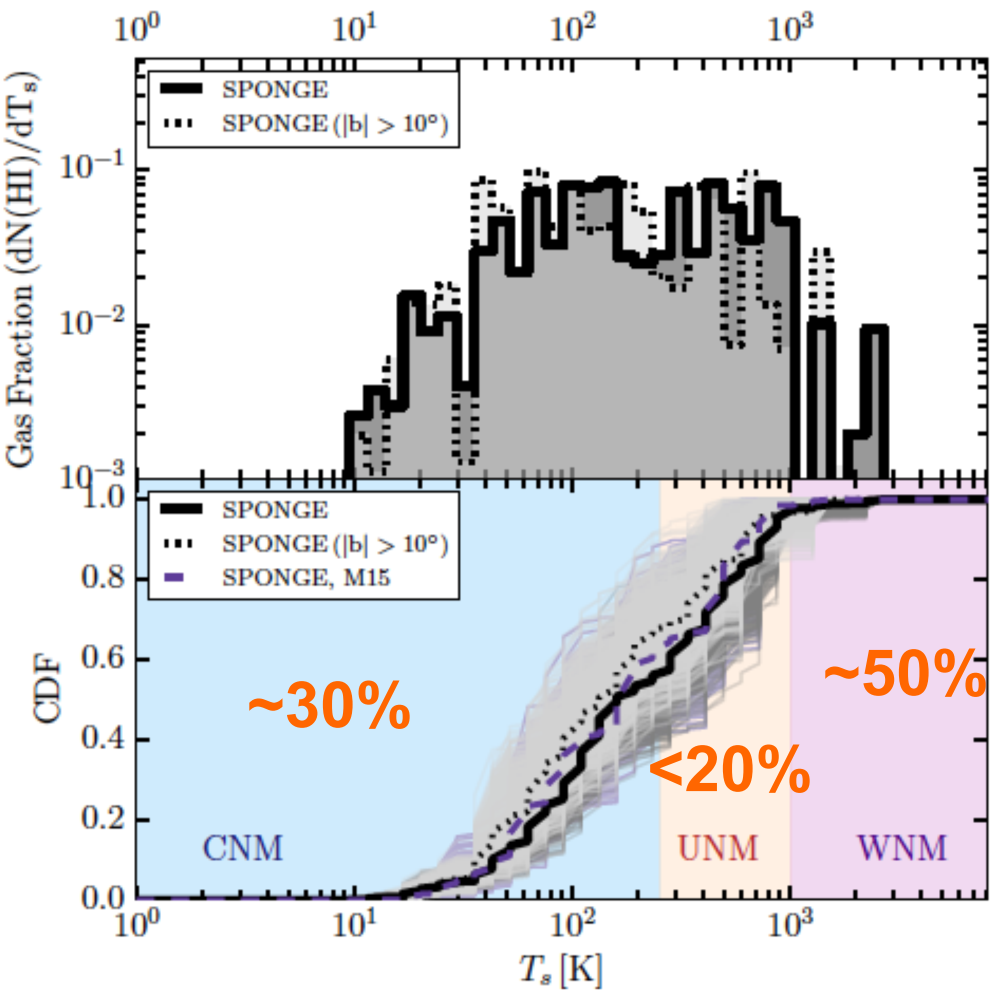
Issues at low-b: line blending and many components

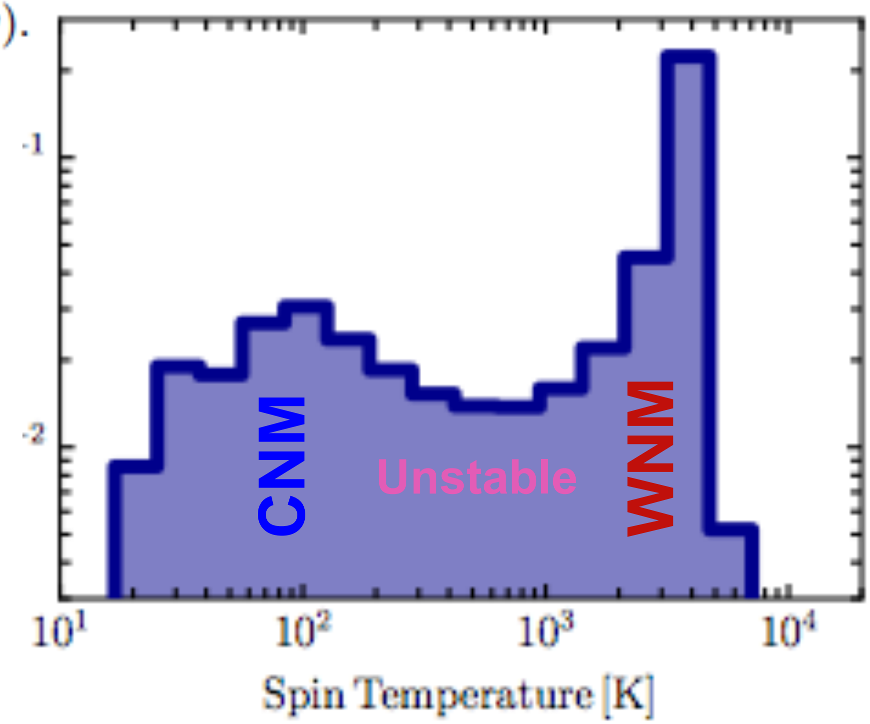
Ts: generally good agreement, but for Ts>400K AGD overestimates temp.

Thermally-unstable WNM

Have sensitivity to detect Ts <4000K
yet very few detections

$$T_{B,\mathrm{exp,\,AGD}}(v) = T_{B,\mathrm{abs,\,AGD}}(v) + T_{B,\mathrm{em,\,AGD}}(v).$$





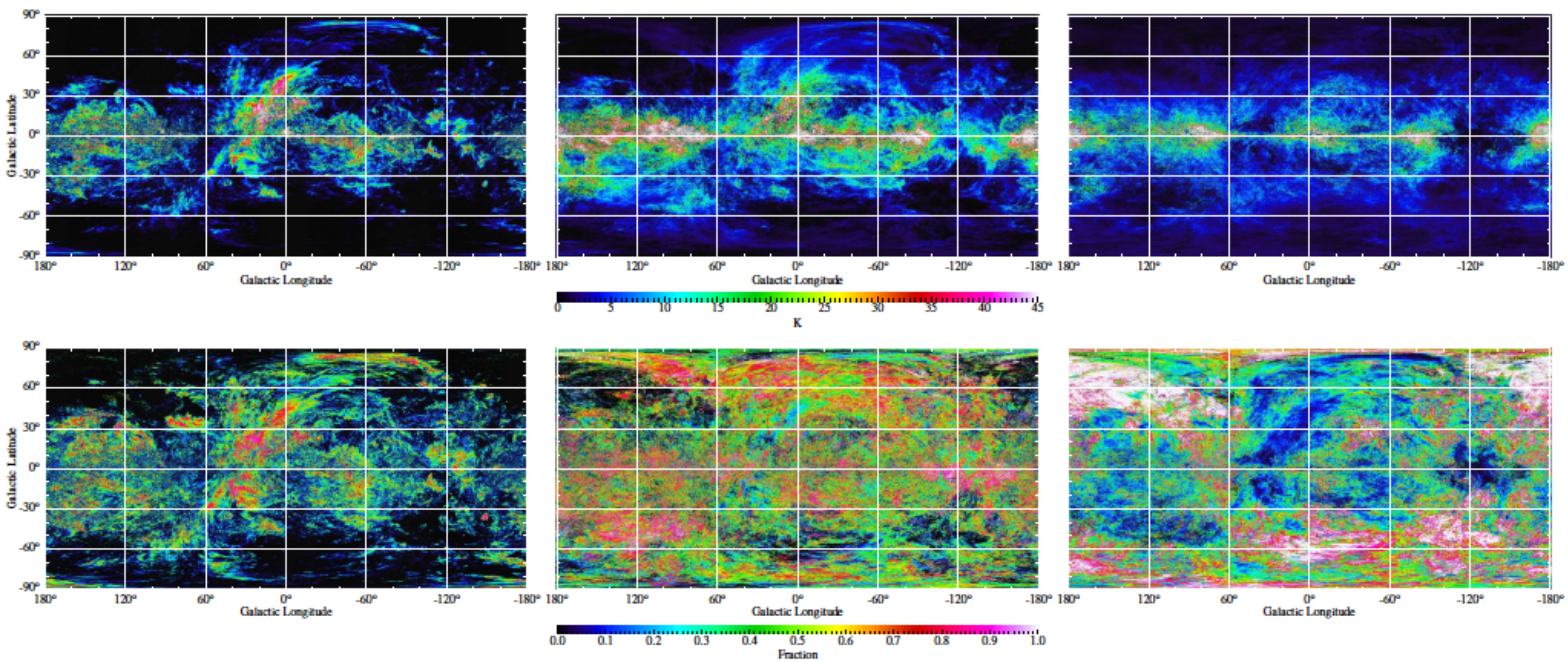
3D HD numerical simulations
Kim et al. 2014, ApJ, 786, 64

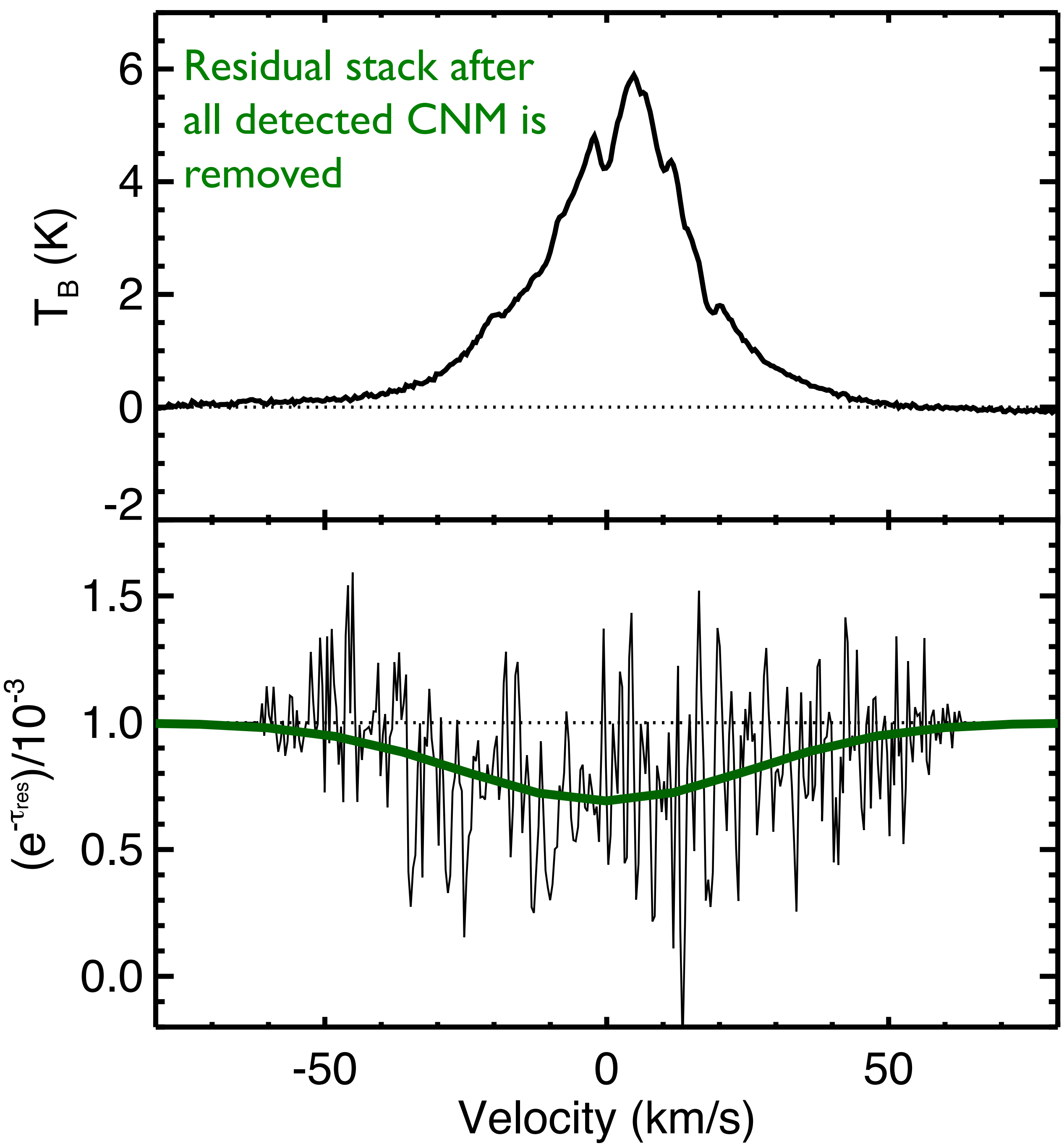
Thermally unstable HI fraction under debate

Astronomy & Astrophysics manuscript no. aa33146-18
June 12, 2018

Properties of cold and warm H I gas phases derived from a Gaussian decomposition of HI4PI data

P. M. W. Kalberla & U. Haud: Distribution of cold and warm H I gas





21- 

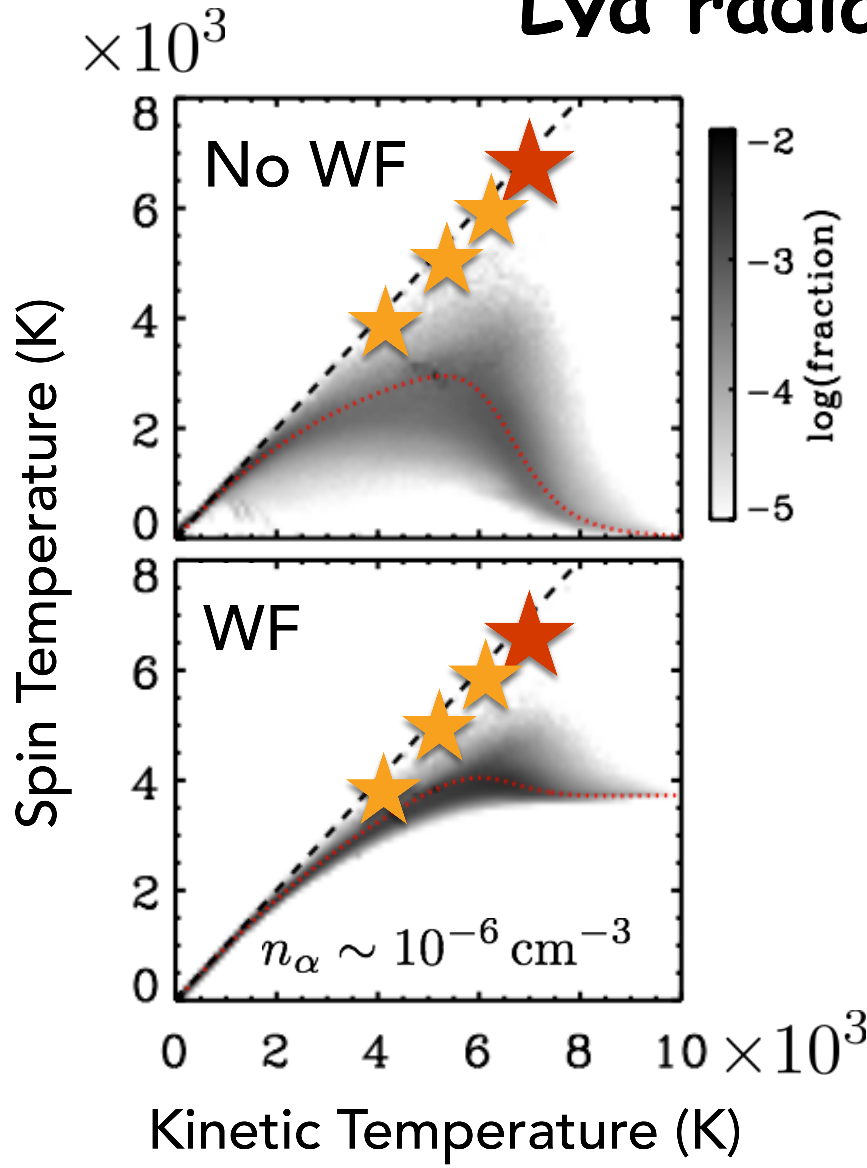
How warm is the WNM?

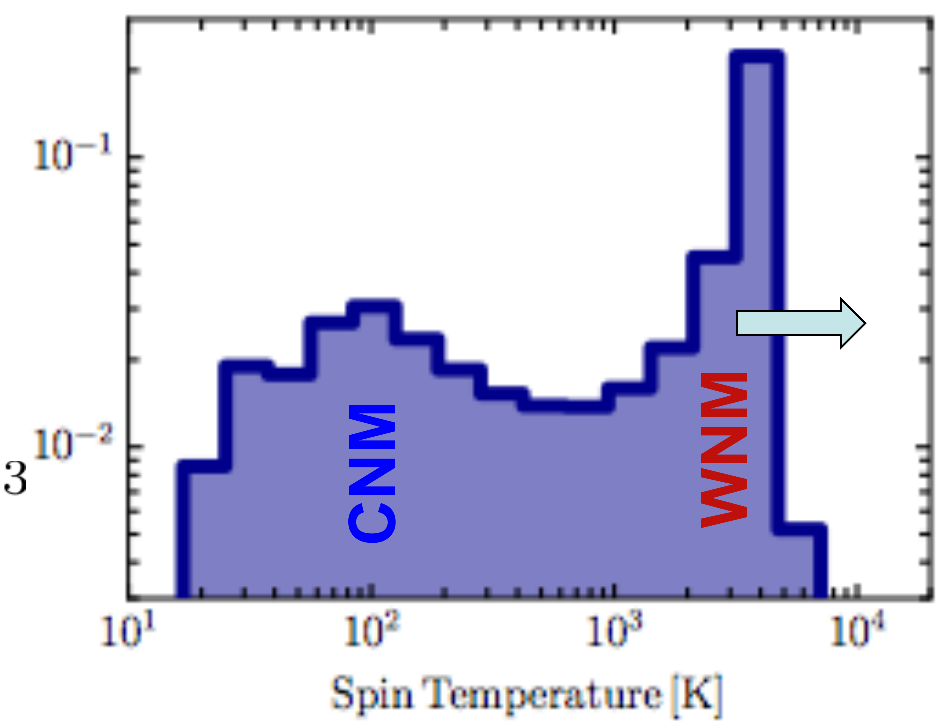
Stacking analysis of 19 HI absorption spectra

Peak $\tau = 3\times10^{-4}$
FWHM ~50 km/s
Ts ~7200 (+ 1800 – 1200) K
N(HI)~2×10^{20} cm^{-2}

Murray+14: 5σ statistical detection
Also Murray+18

To explain WNM temperature need significant Lya radiation field





Kim et al. 2014

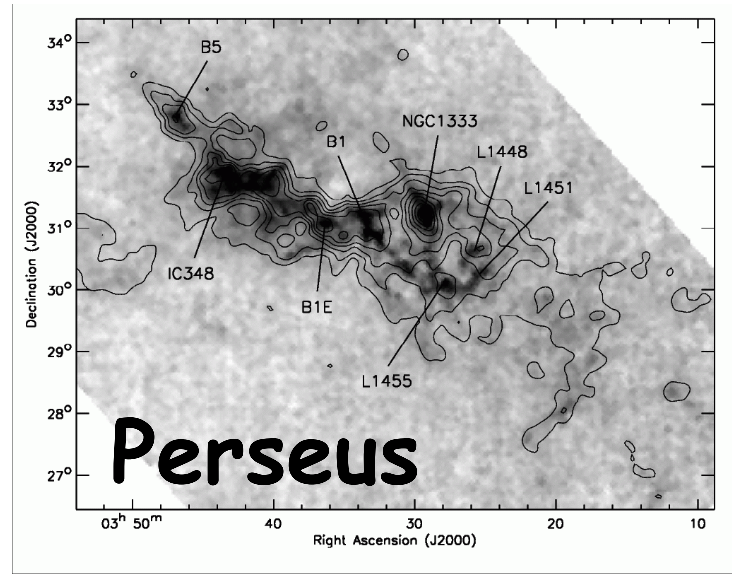
Are HI phases different close to GMCs?

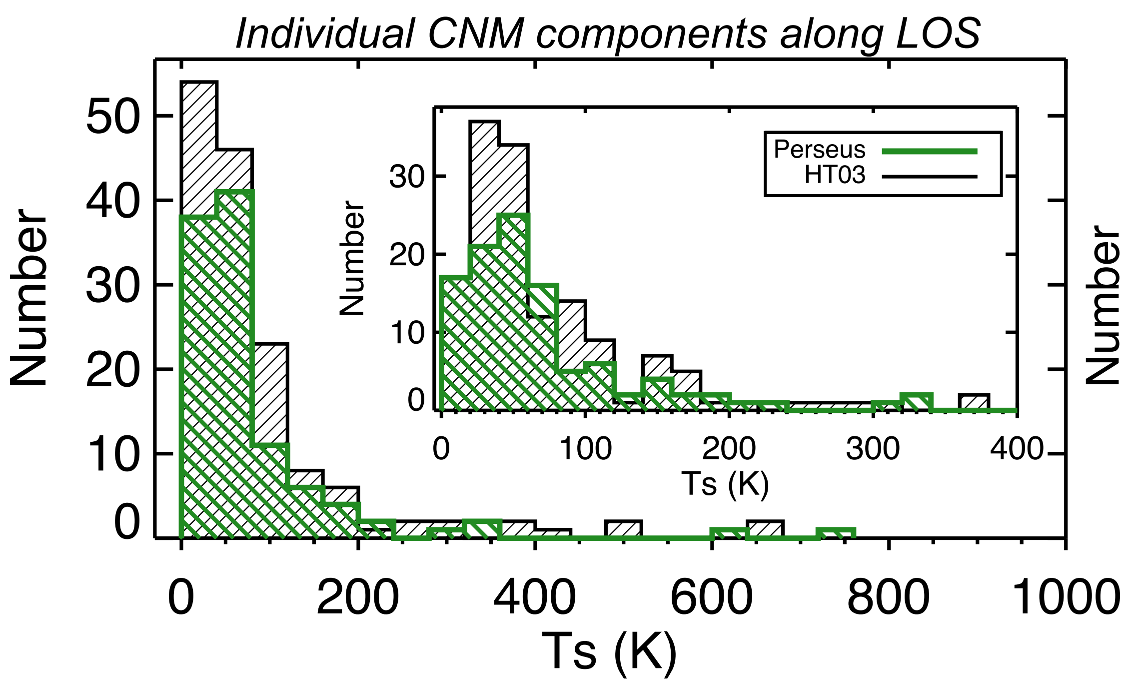
- ~30 HI absorption lines in the vicinity of Perseus
- CNM clouds in/around GMCs typical.
- Higher CNM fraction than in a random ISM field

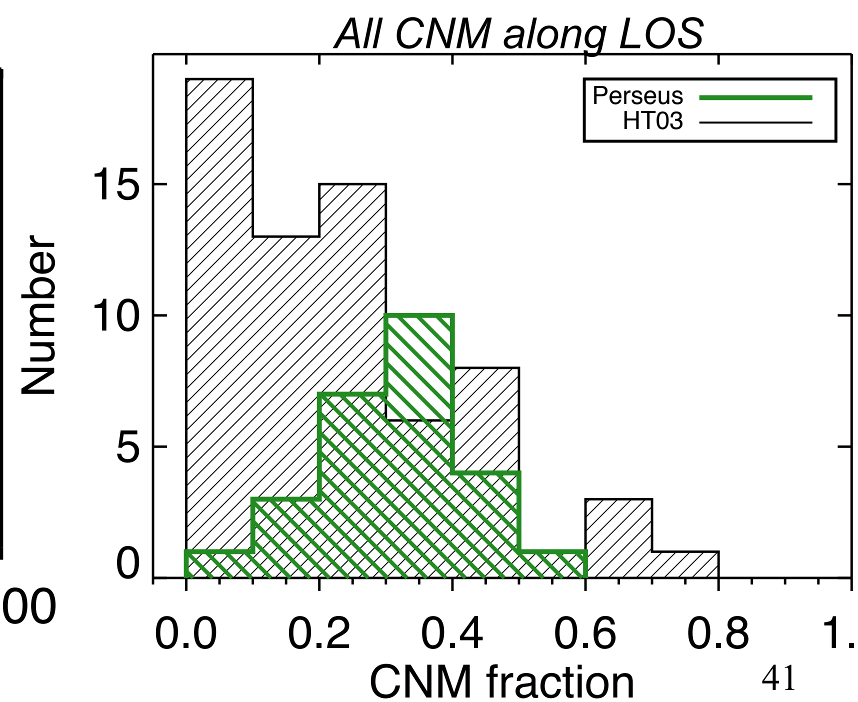
→ Buildup of cold HI that goes to make H_2

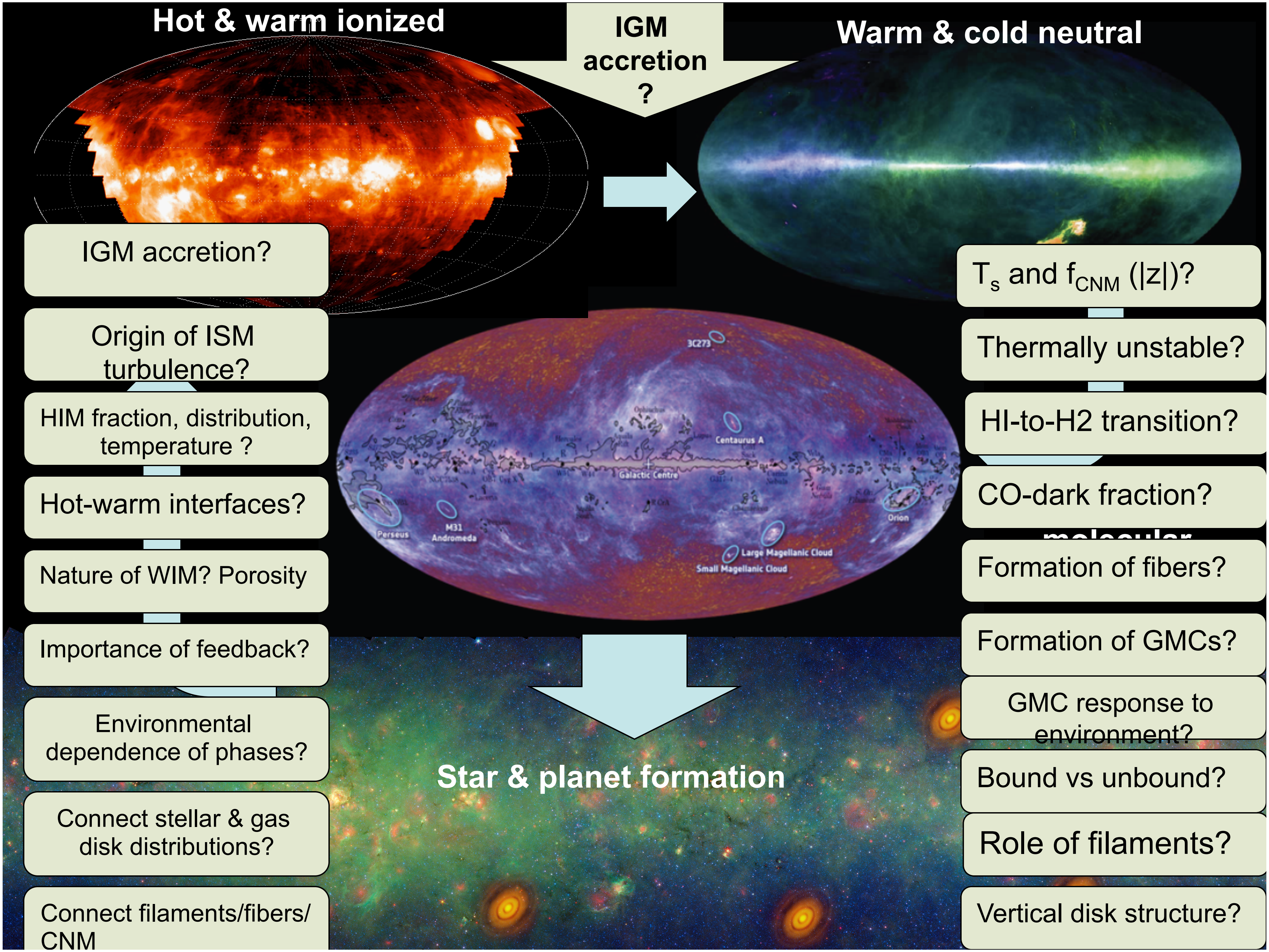
- 50% WNM → lots of warm gas! Extended HI envelopes or turbulent mixing.
- 10% mass increase when cold HI included

(SS, Murray, Lee+14; Lee+15)









Hot & warm ionized
IGM accretion ?
Warm & cold neutral
IGM accretion?
Origin of ISM turbulence?
HIM fraction, distribution, temperature ?
Hot-warm interfaces?
Nature of WIM? Porosity
Importance of feedback?
Environmental dependence of phases?
Connect stellar & gas disk distributions?
Connect filaments/fibers/ CNM
3C273
Centaurus A
Galactic Centre
Perseus
M31 Andromeda
Orion
Large Magellanic Cloud
Small Magellanic Cloud
T_s and f_{CNM} (|z|)?
Thermally unstable?
HI-to-H2 transition?
CO-dark fraction?
Formation of fibers?
Formation of GMCs?
GMC response to environment?
Bound vs unbound?
Role of filaments?
Vertical disk structure?
Star & planet formation