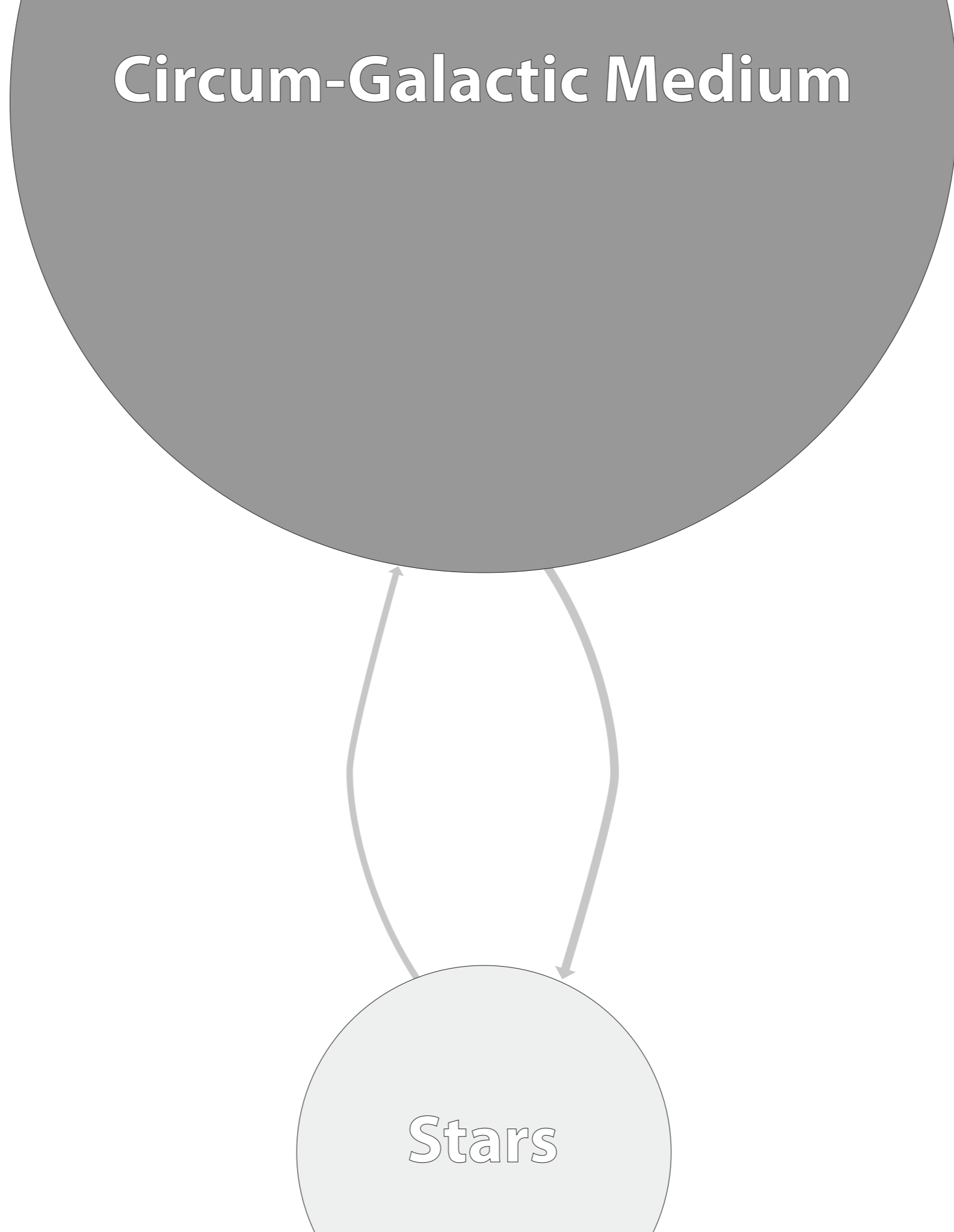


# Think Global, Act Local: HI in (and around) the Milky Way

NAOMI MCCLURE-GRIFFITHS  
Australian National University

**Circum-Galactic Medium**

**Stars**



Circum-Galactic Medium

**How do galaxies work?**

Stars

Circum-Galactic Medium

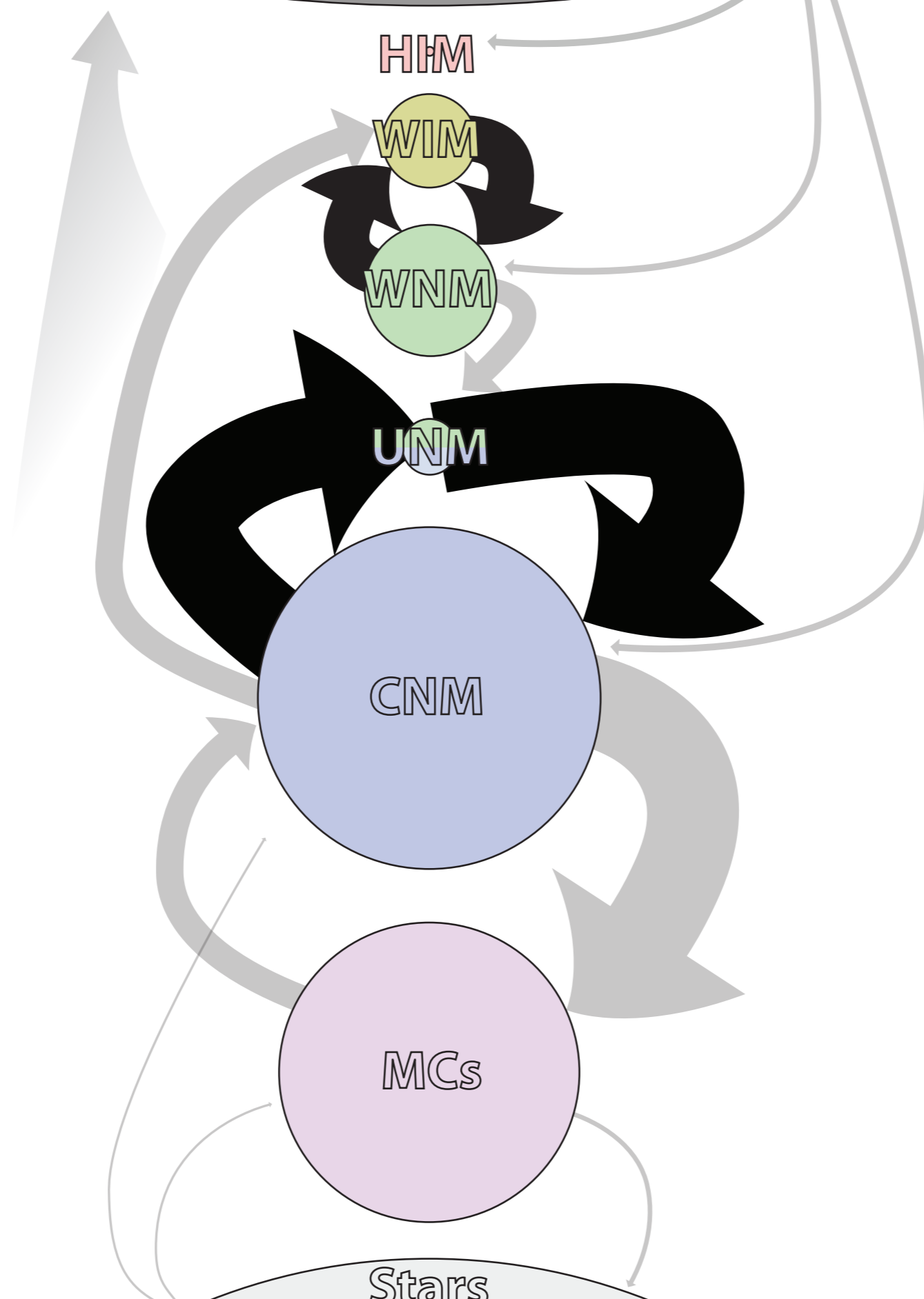
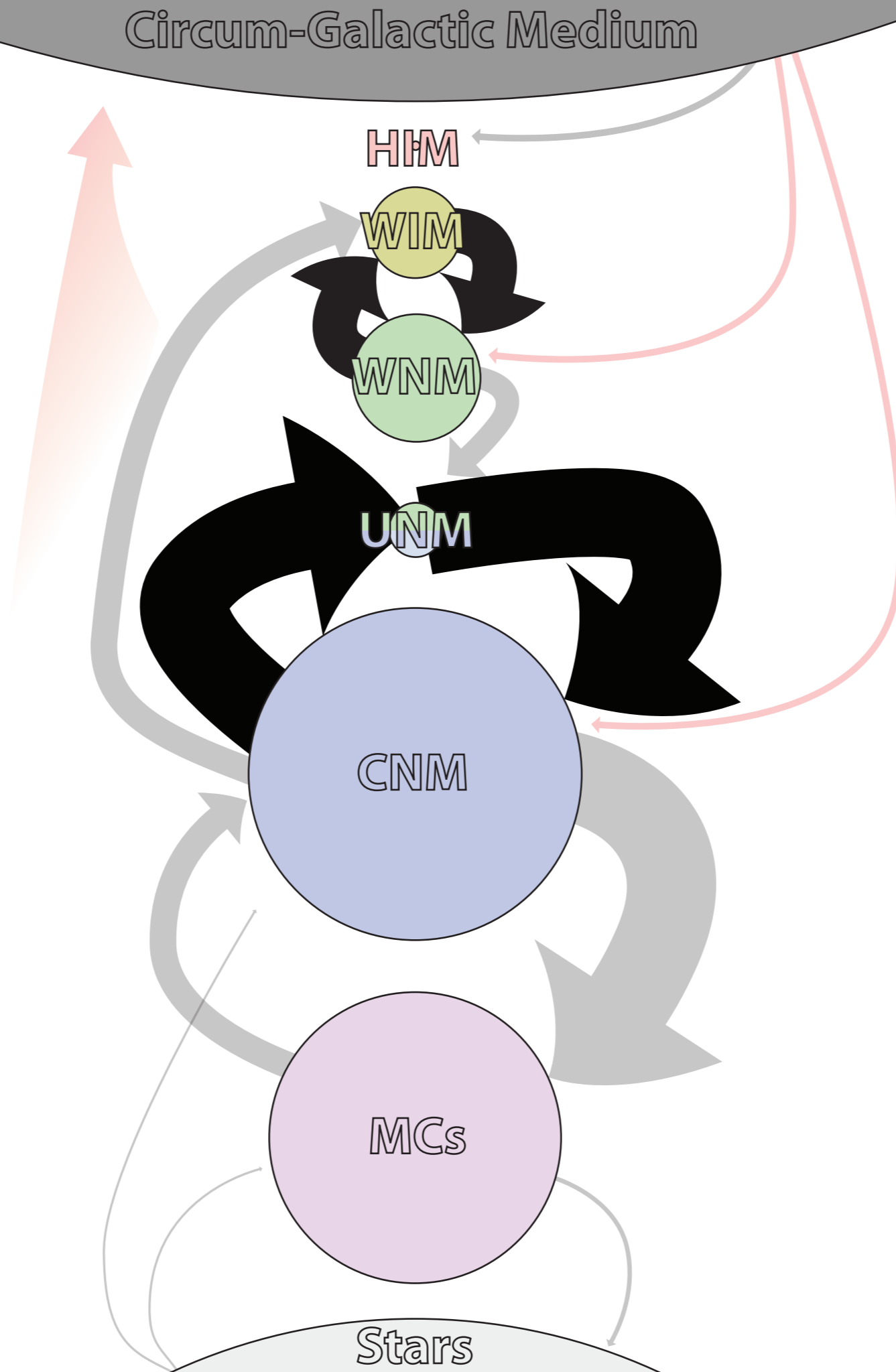
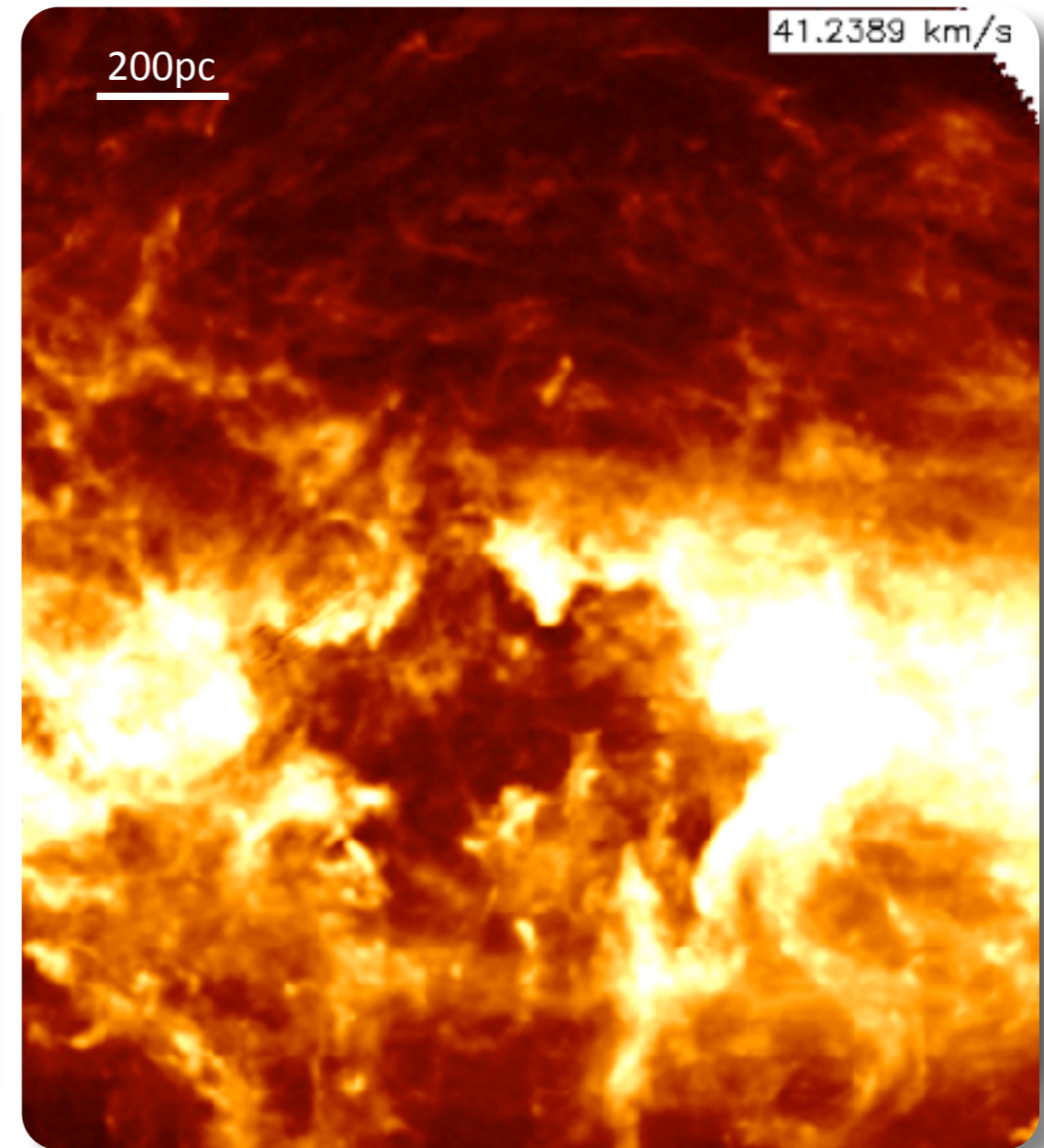


Figure by Josh Peek

How does  
MW interact  
with the  
circumgalactic  
medium?



# Multi-phase gas-loss from galaxies

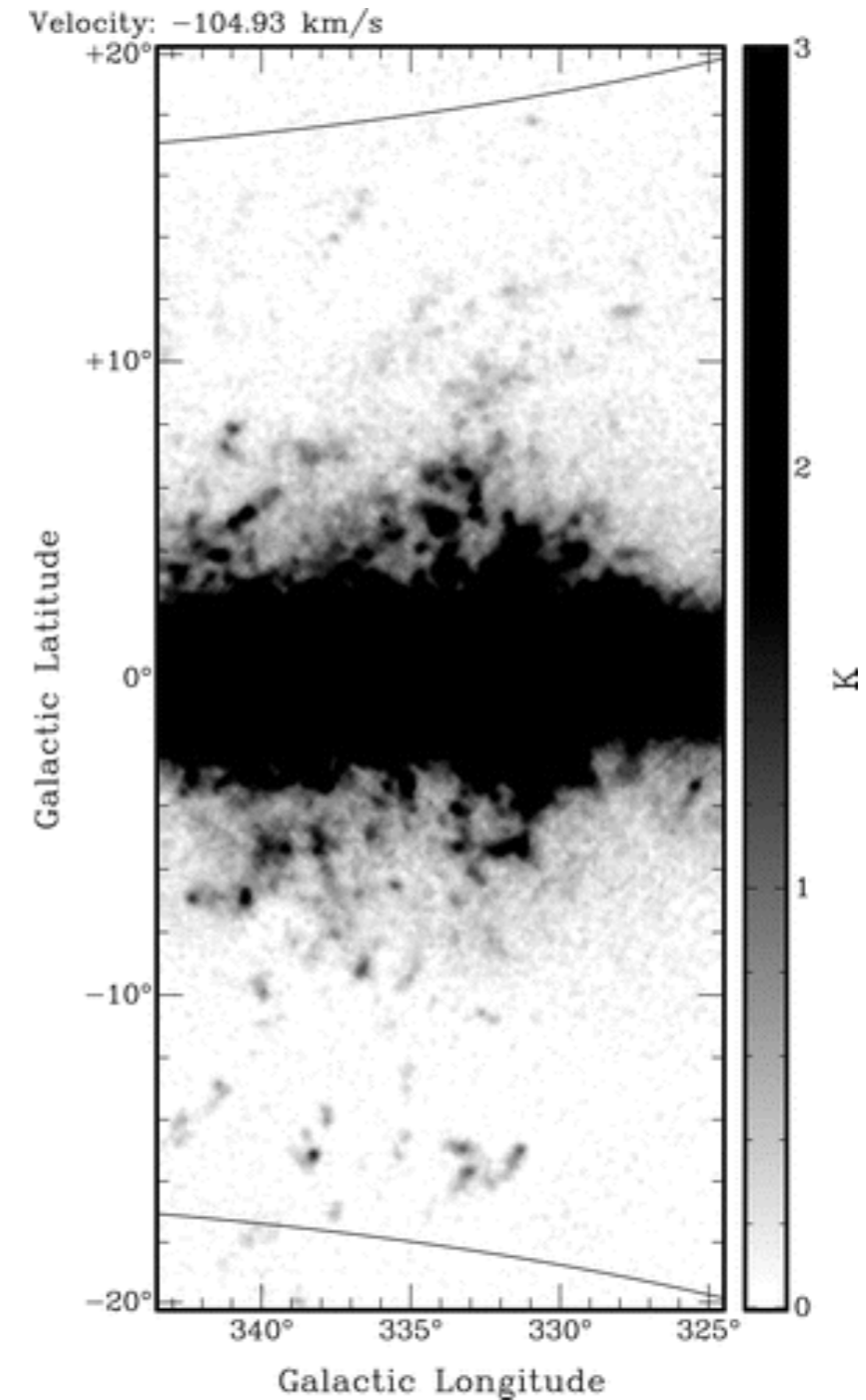
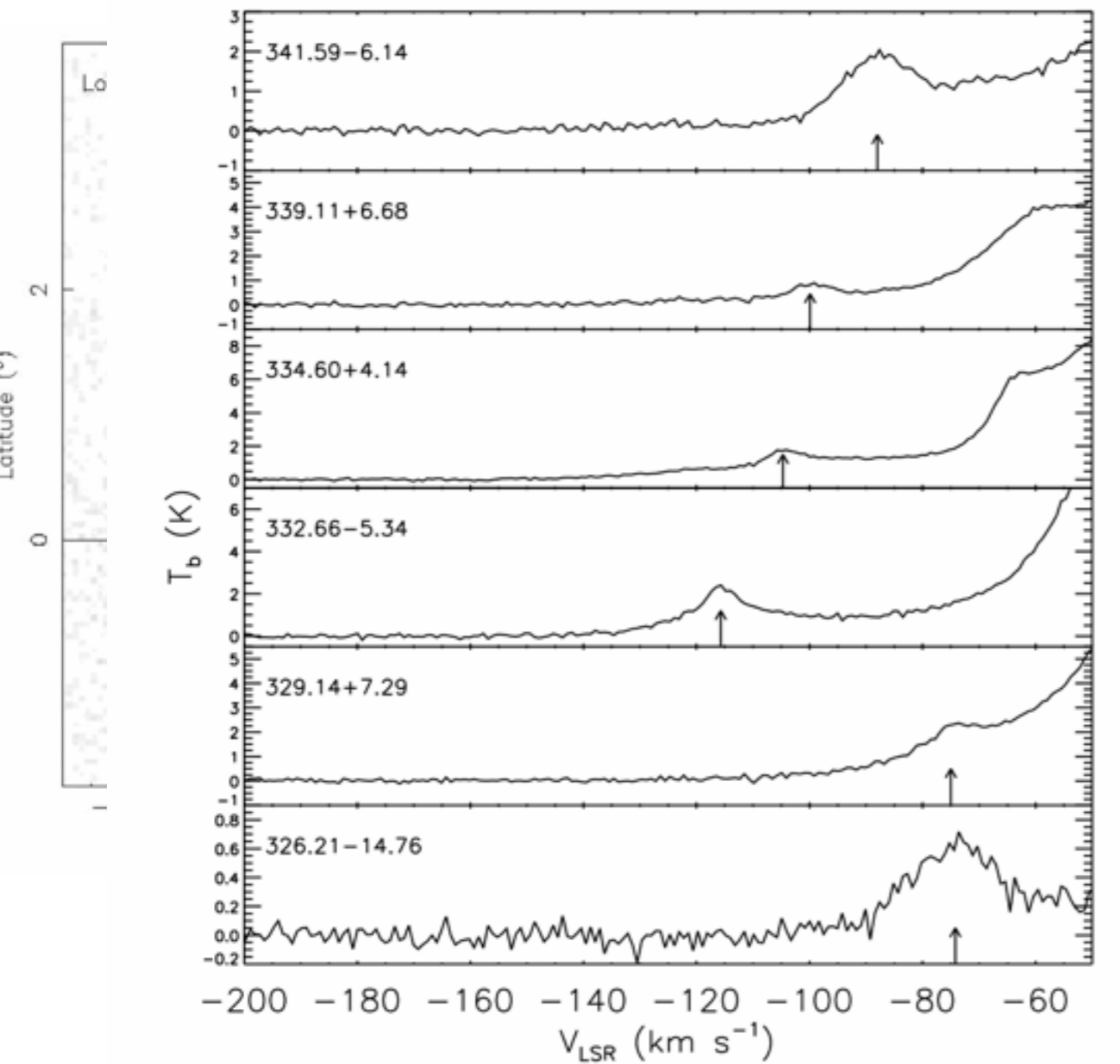


M82. Credit: NASA, ESA, and The Hubble Heritage Team (STScI/AURA)

MW HI GSH277+00+36: McClure-Griffiths et al. (2003)

# Cool HI halo structure

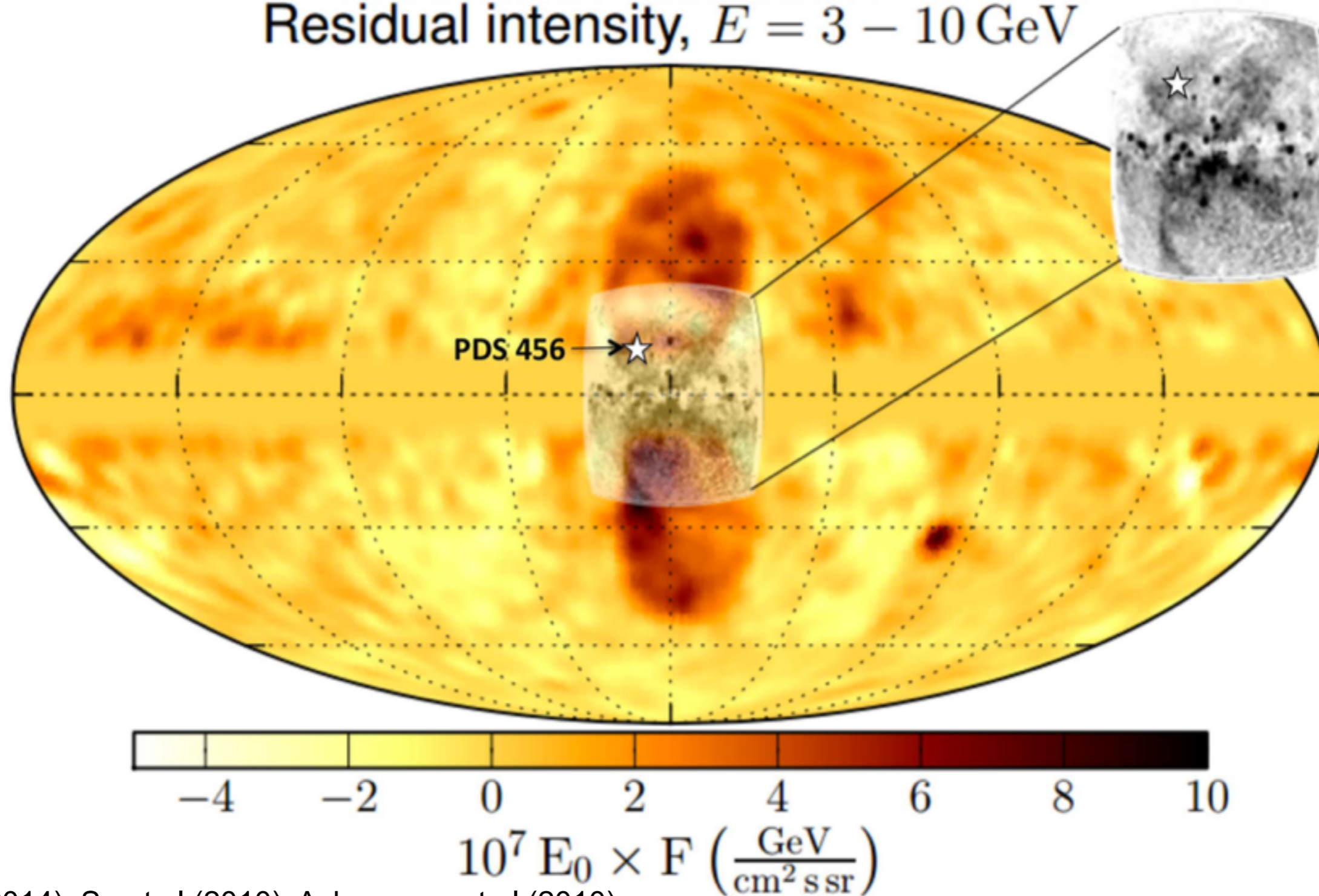
**GALFA examples:**  
 Stanimirovic et al. (2006)  
 Begum et al (2010)  
 Saul et al (2012)



Ford et al (2008)

# Galactic Wind: Fermi Bubbles

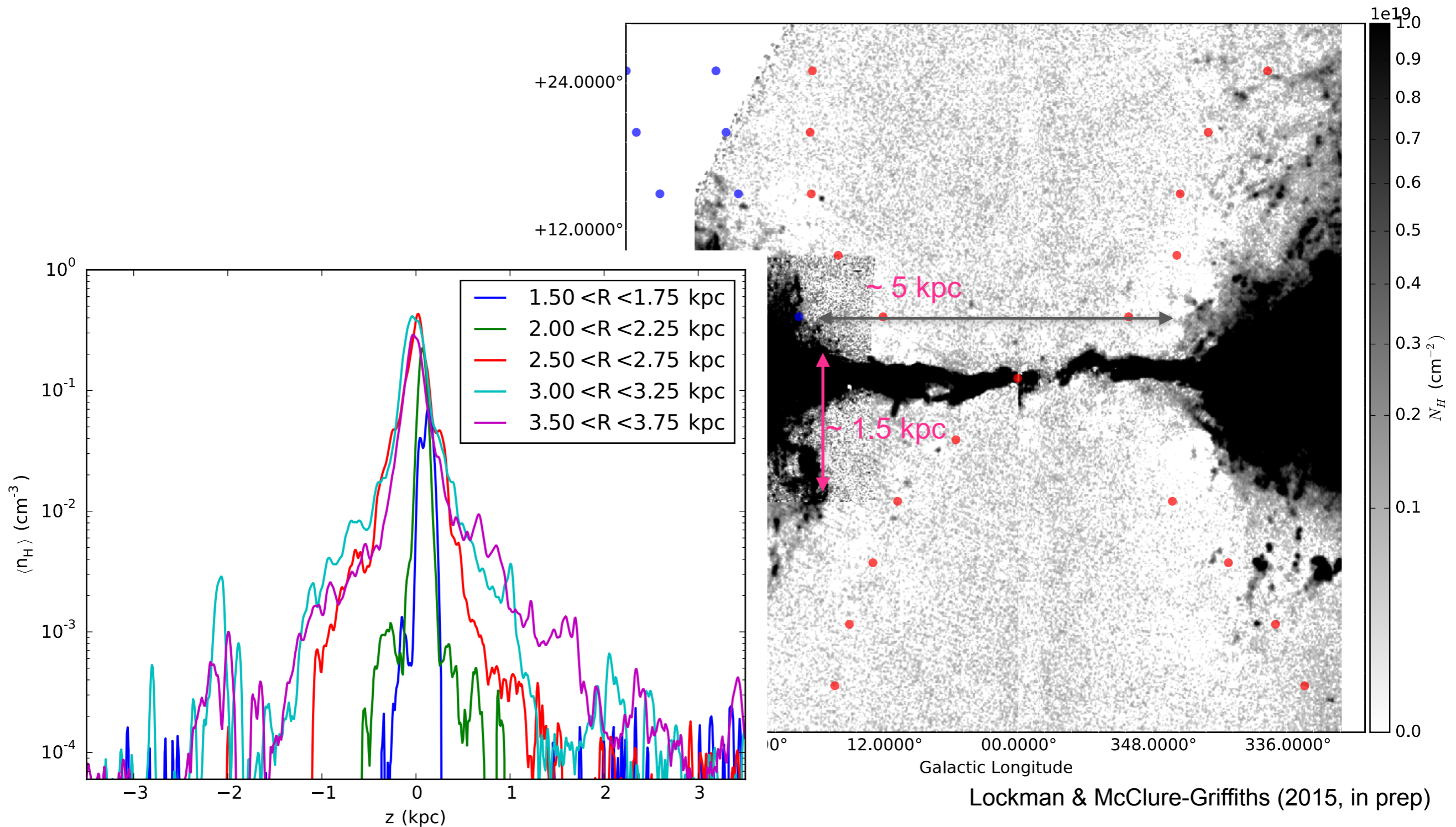
Residual intensity,  $E = 3 - 10$  GeV



Fox et al (2014); Su et al (2010); Ackermann et al (2010);  
Bland-Hawthorn & Cohen (2003)



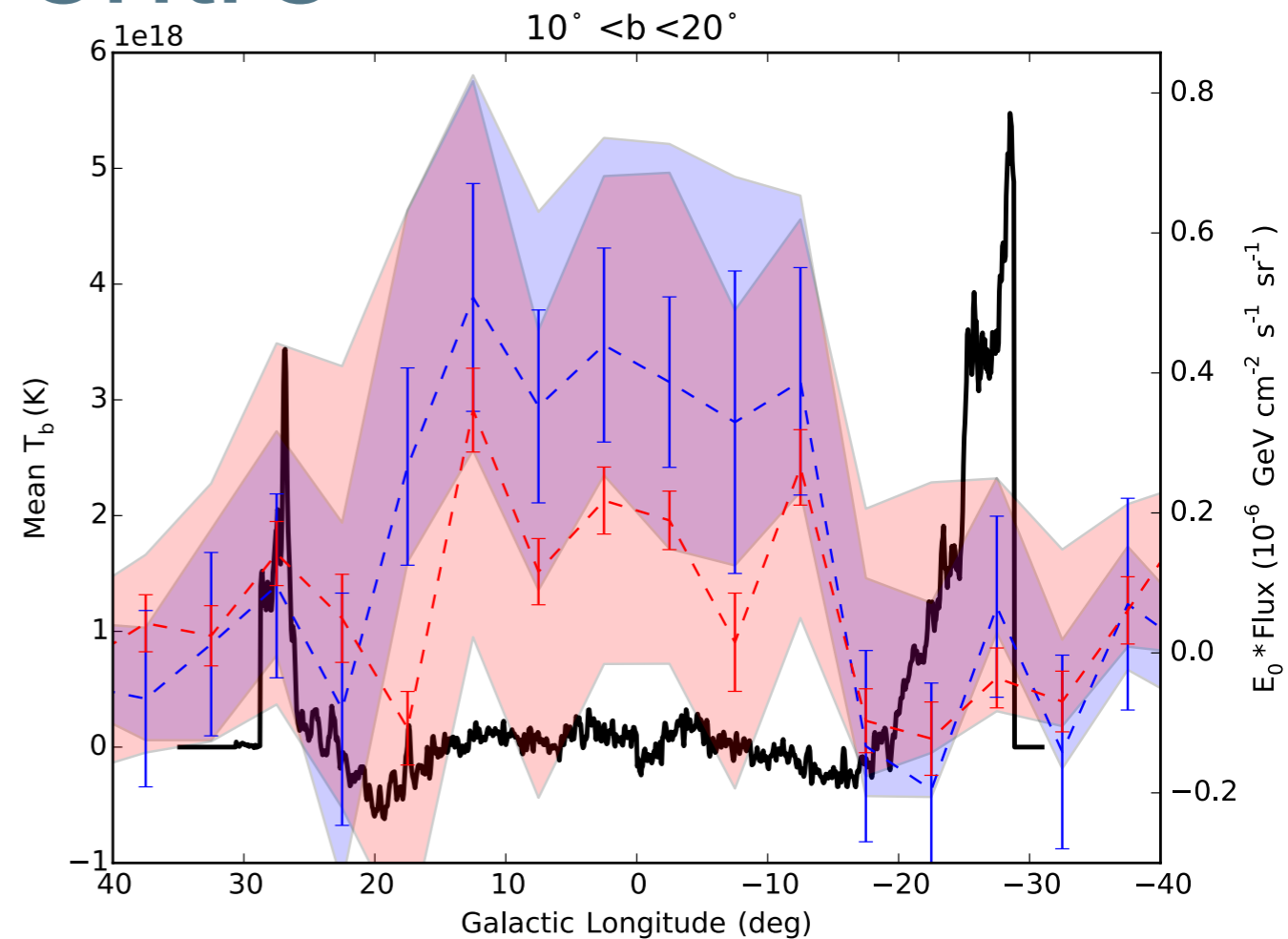
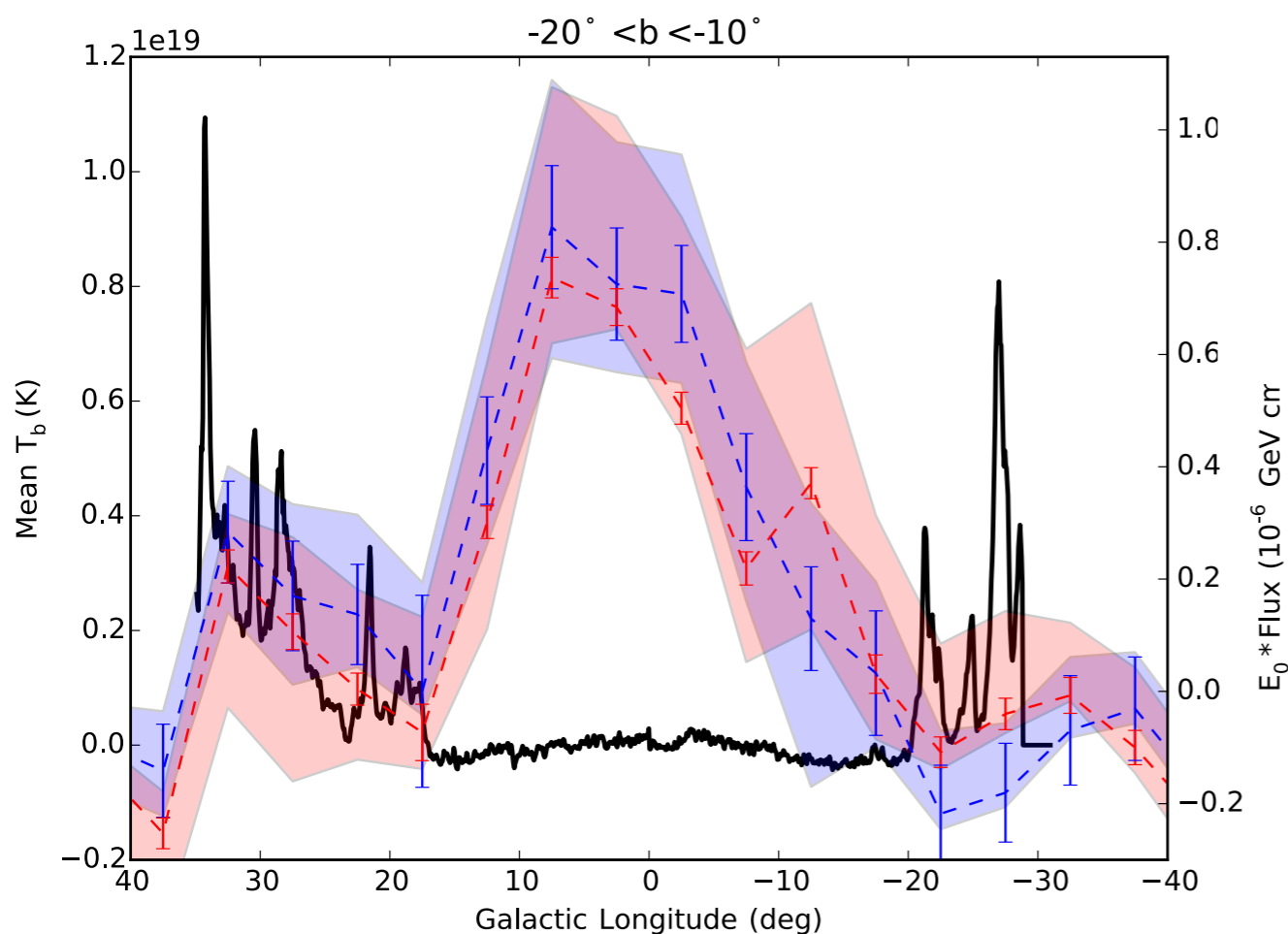
# (Lack-of) HI in the Galactic Centre



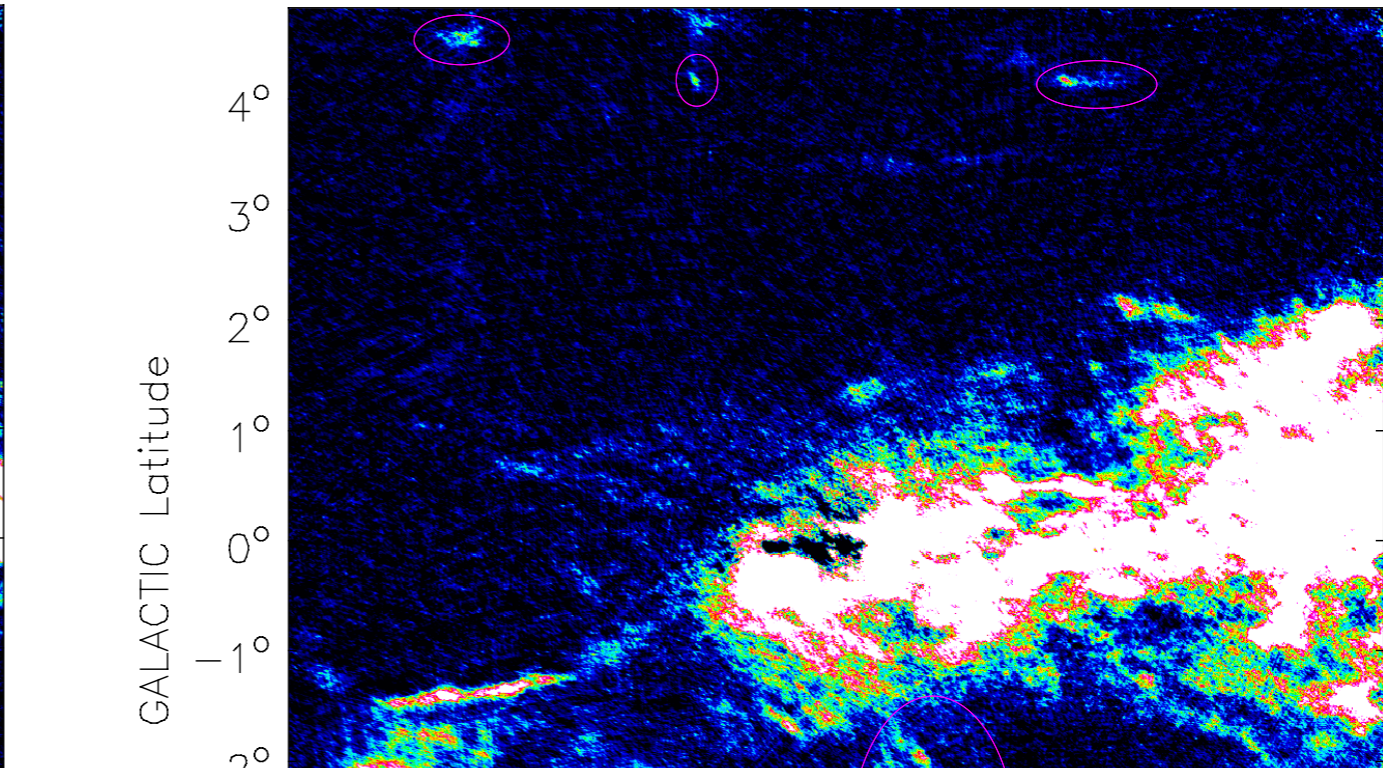
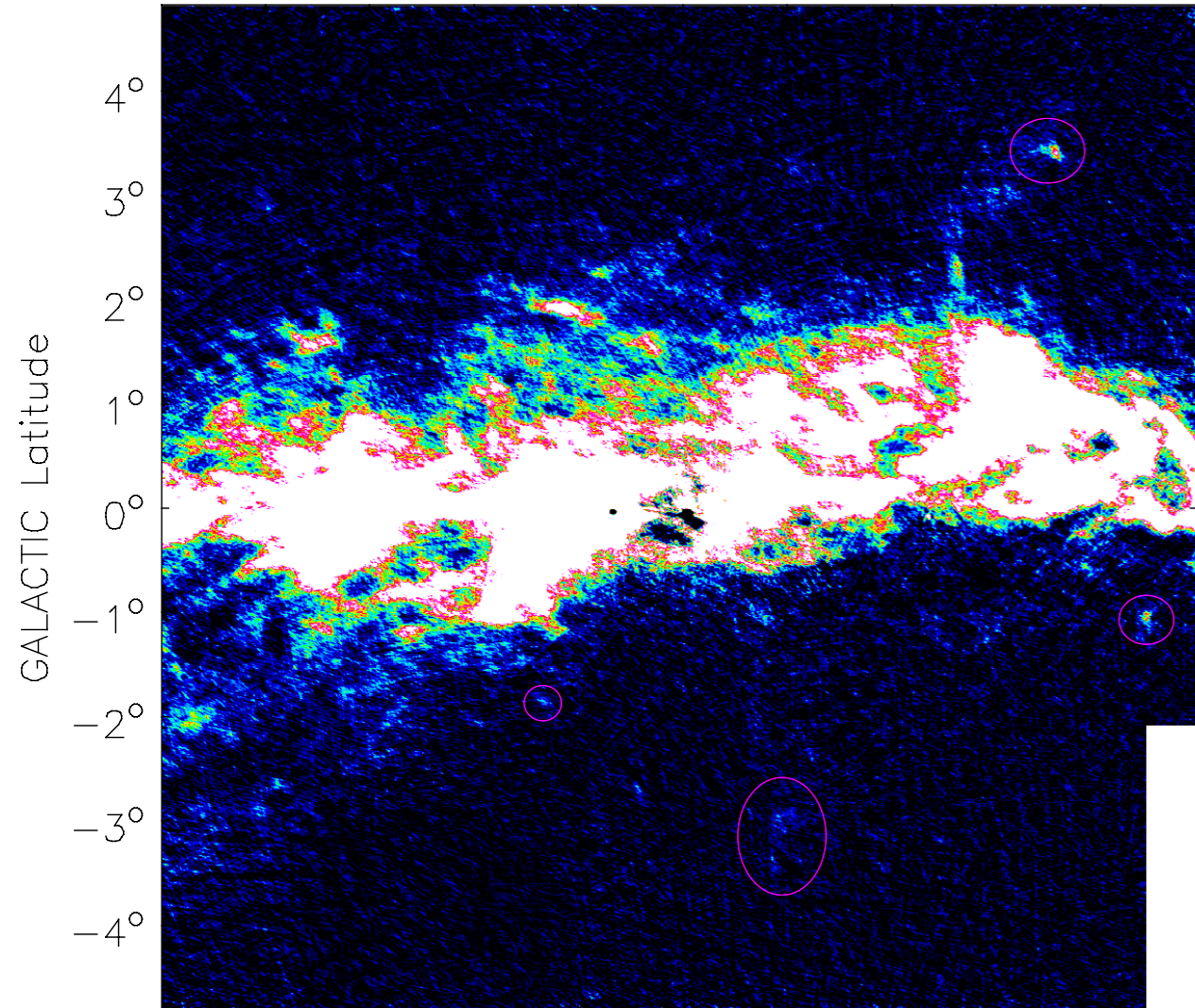
# HI in the Galactic Centre

Fermi: Ackermann et al 2014  
 HI: Lockman & McClure-Griffiths (2015)

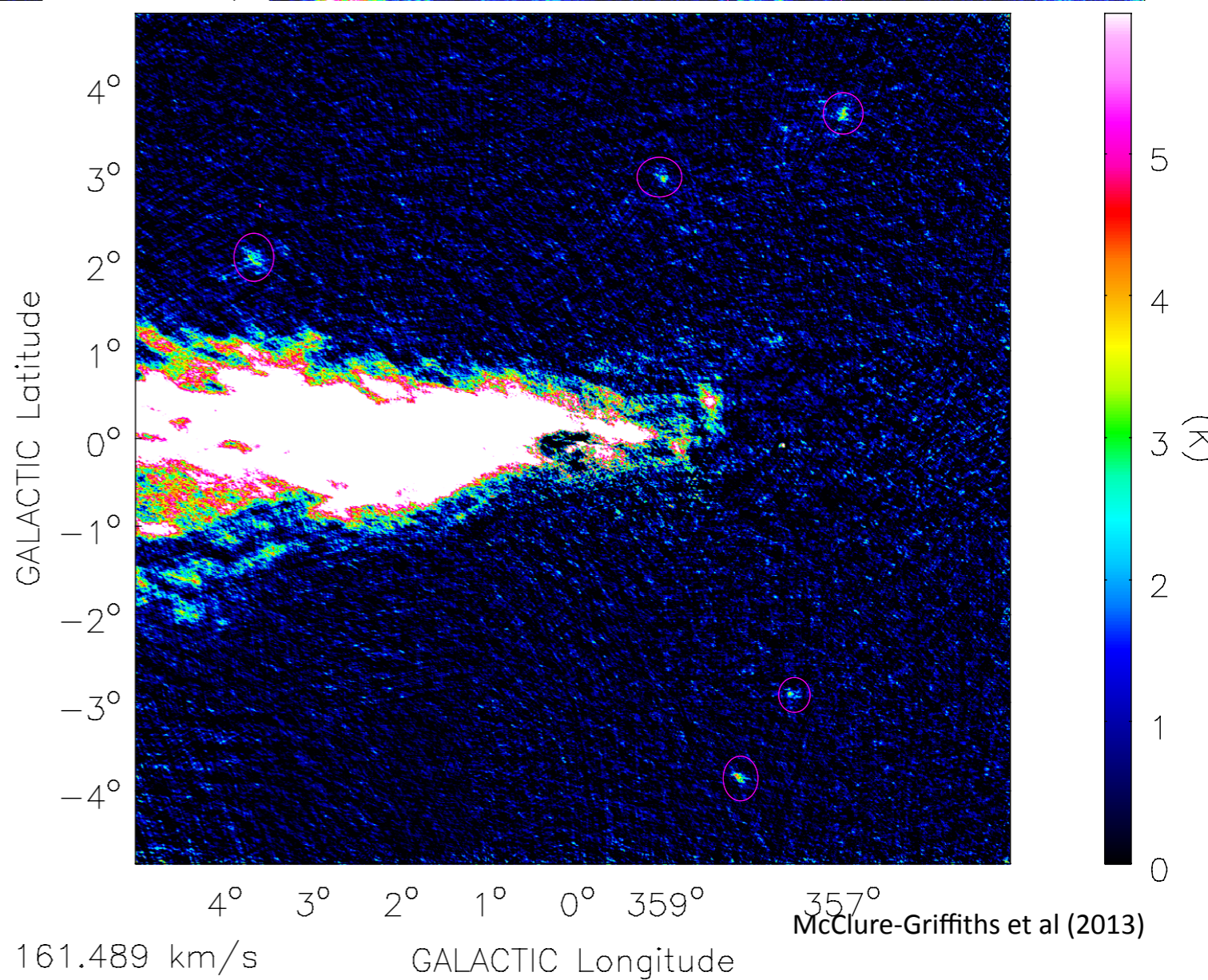
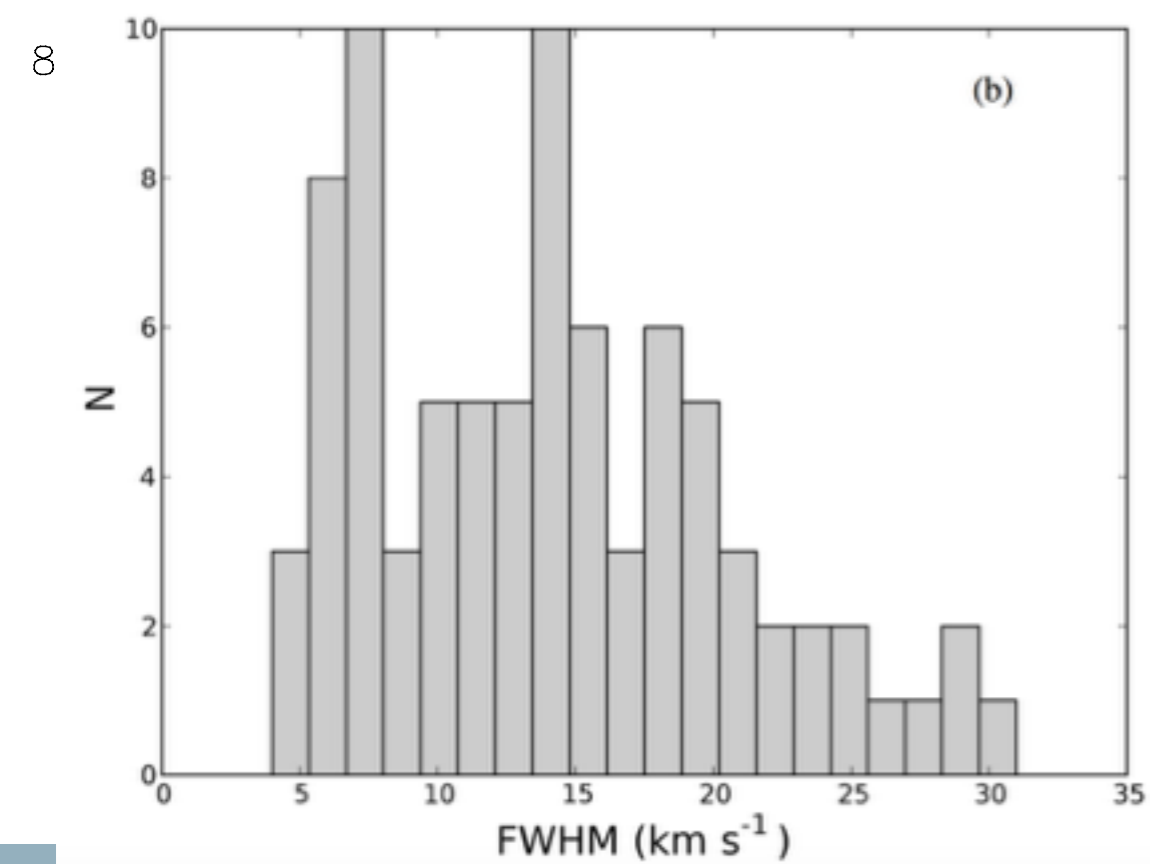
HI anti-correlated  
 with  $\gamma$ -ray at  $|b| > 10$   
 deg



HI halo missing -  
 typical of spirals?



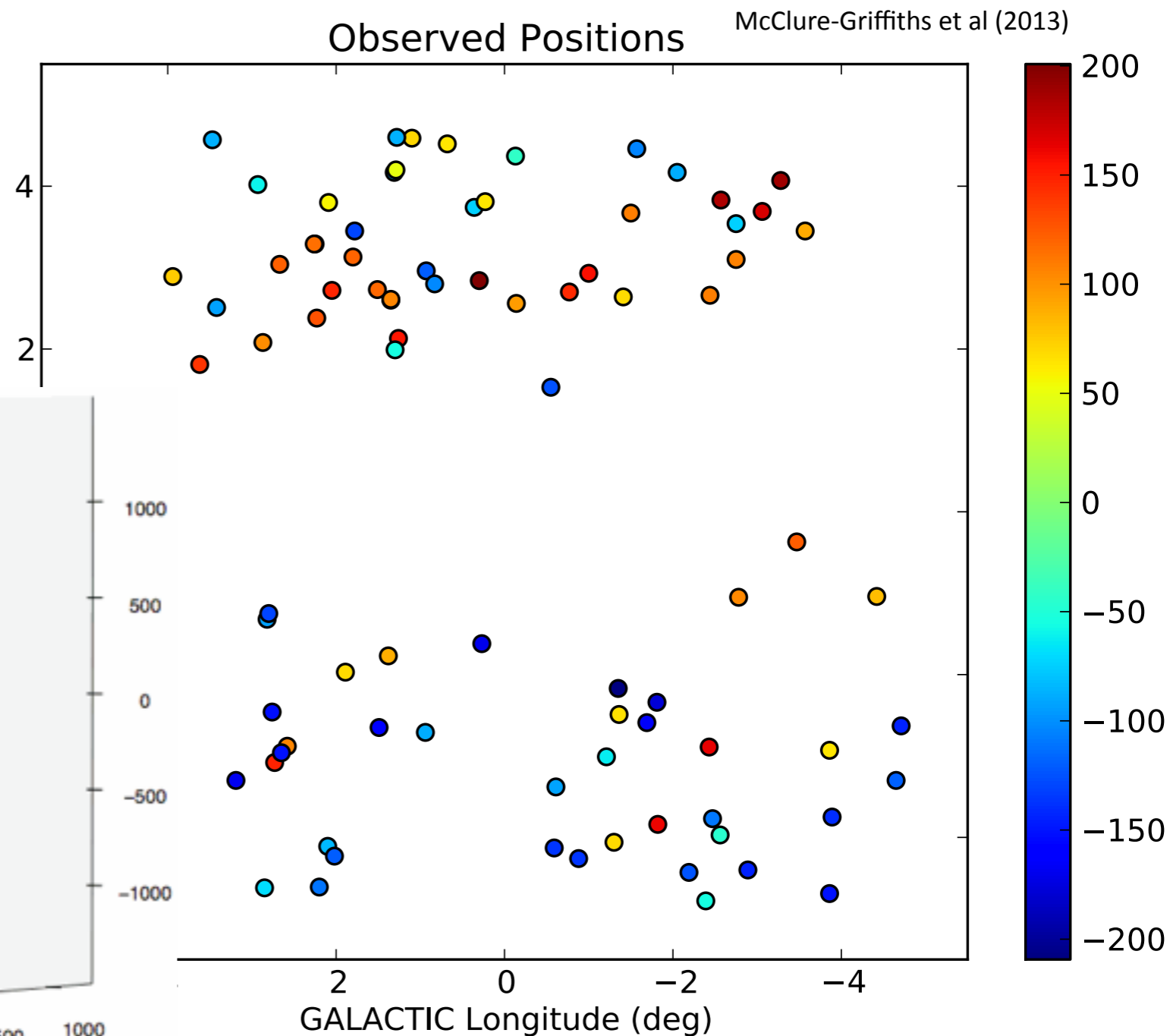
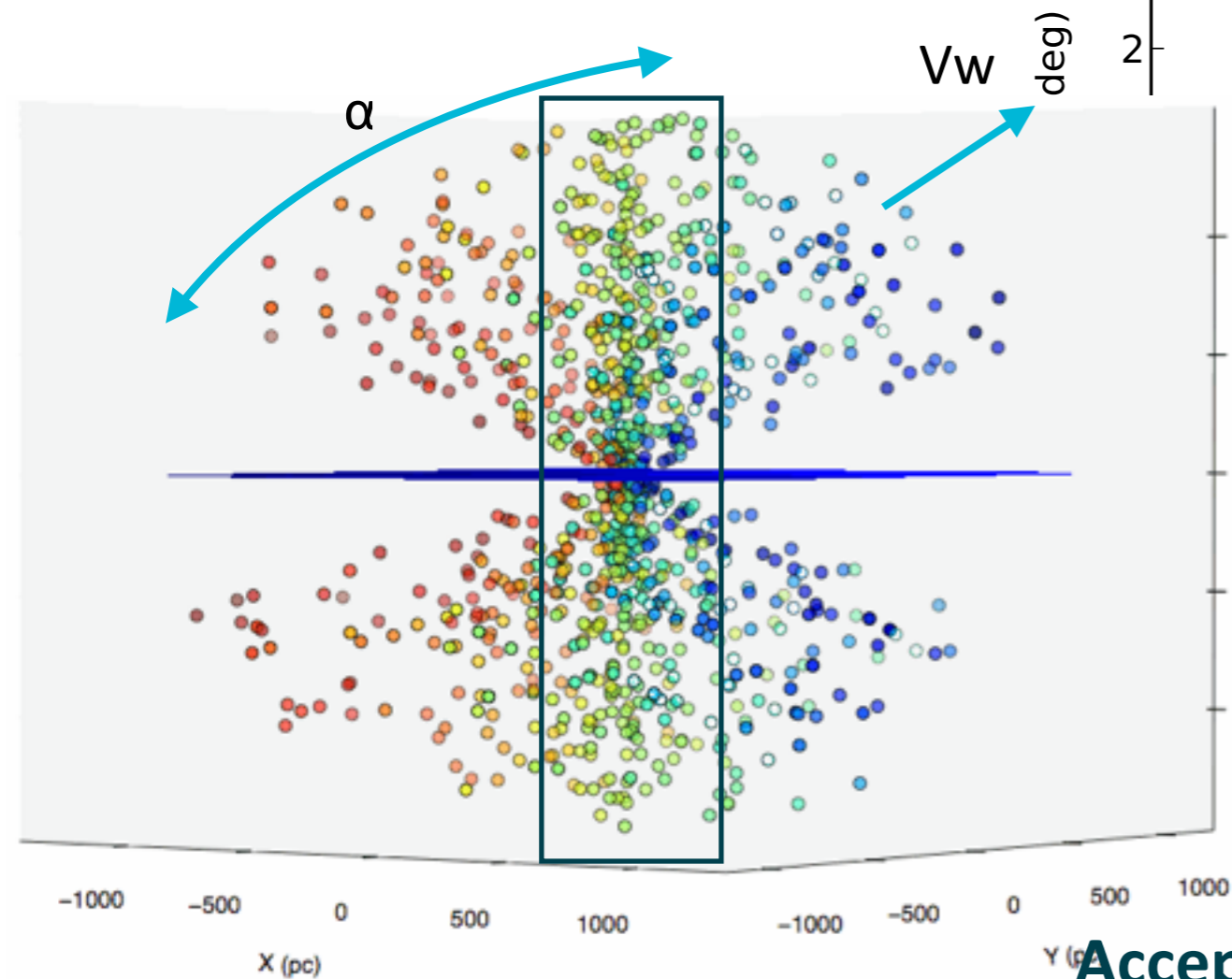
Histogram of FWHM



# HI entrained in a Galactic wind

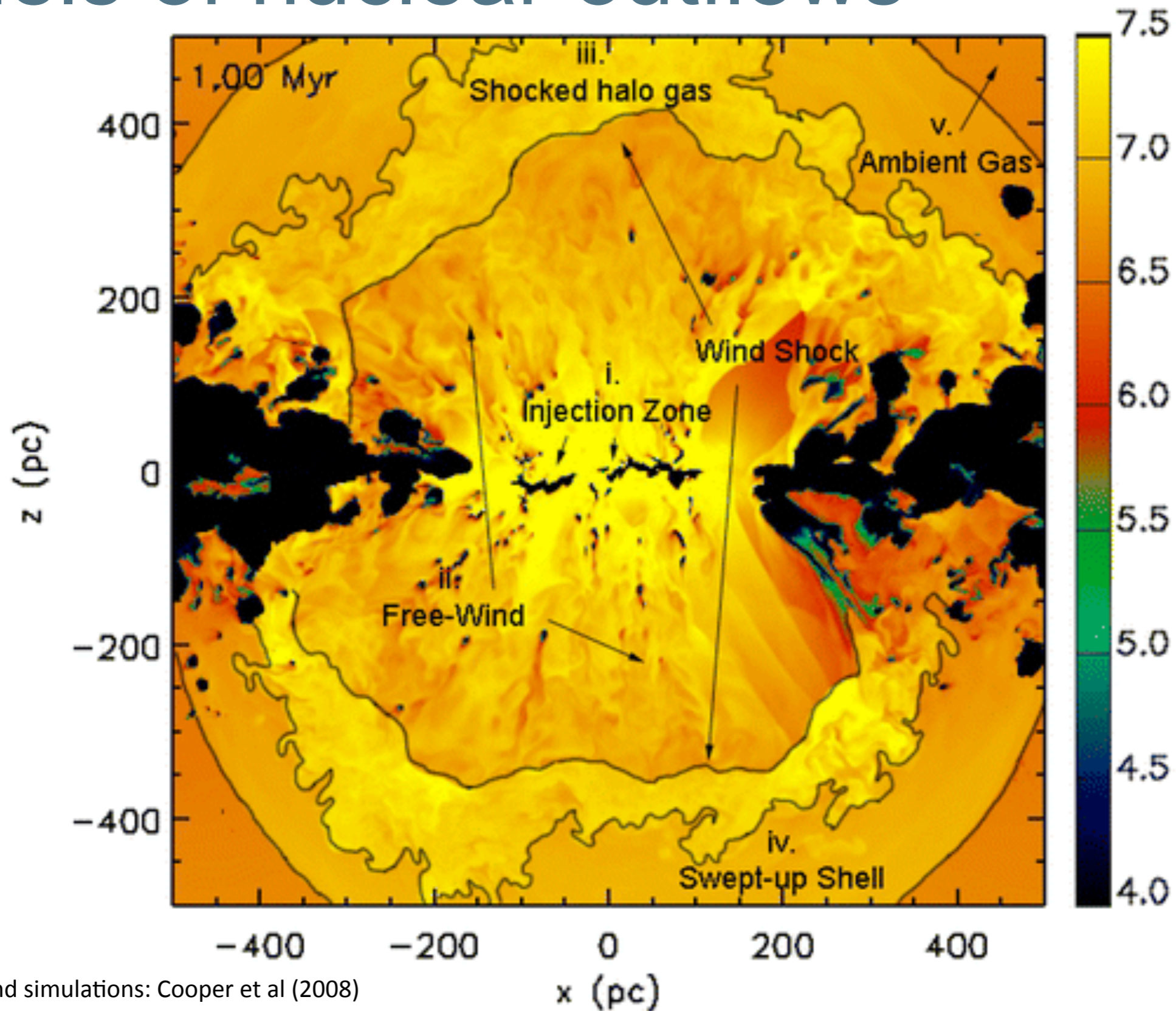
Typical clouds:

- $\sim 15$  pc
- $\sim 270 M_{\text{sun}}$



**Acceptable wind velocities: 150 km/s to 270 km/s**

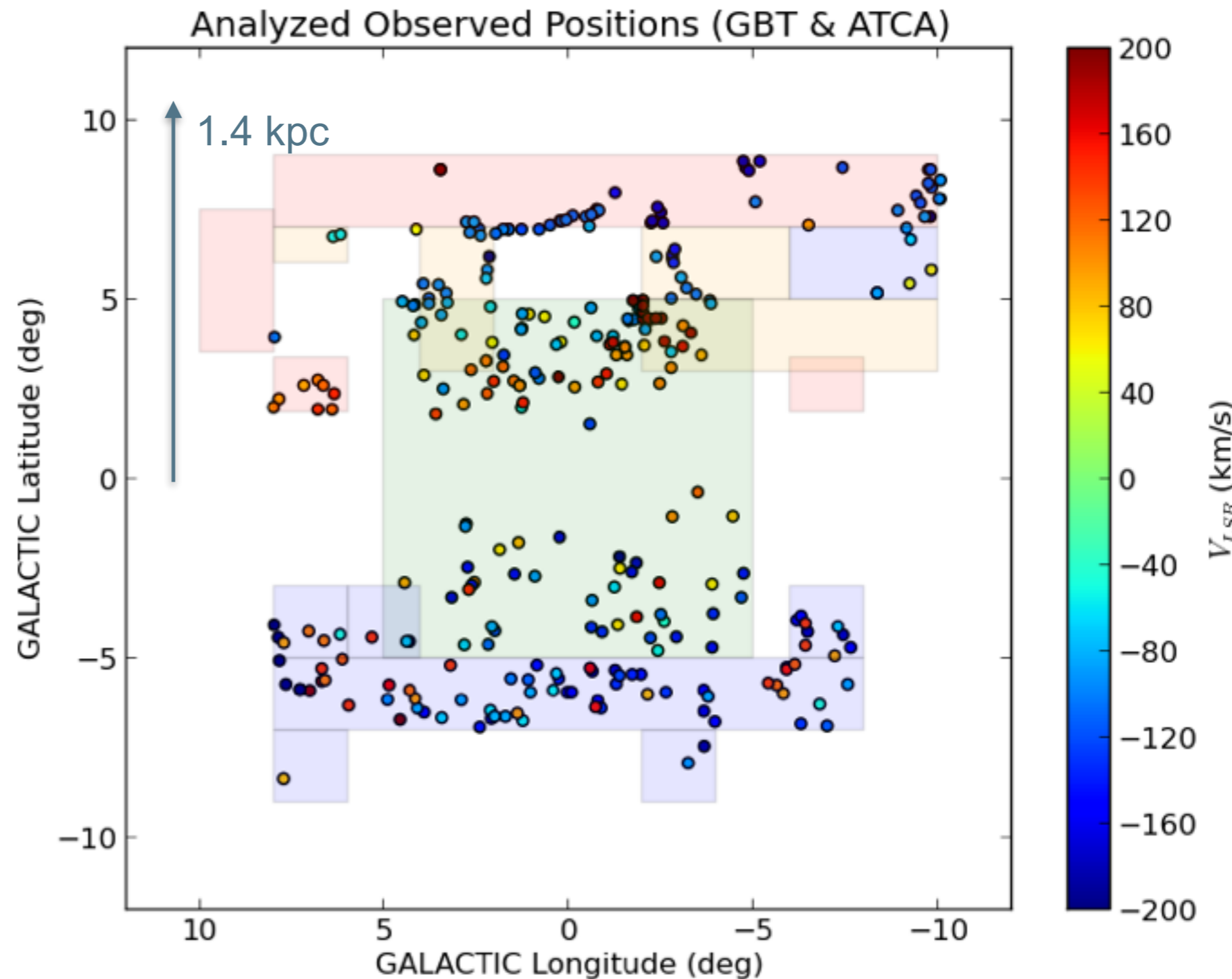
# Models of nuclear outflows



M82 wind simulations: Cooper et al (2008)

- Improve estimates of:
  - opening angle and velocity
  - cloud lifetime
  - entrained mass

Where do they go and what are their properties?



Circum-Galactic Medium

HIM

WIM

WNM

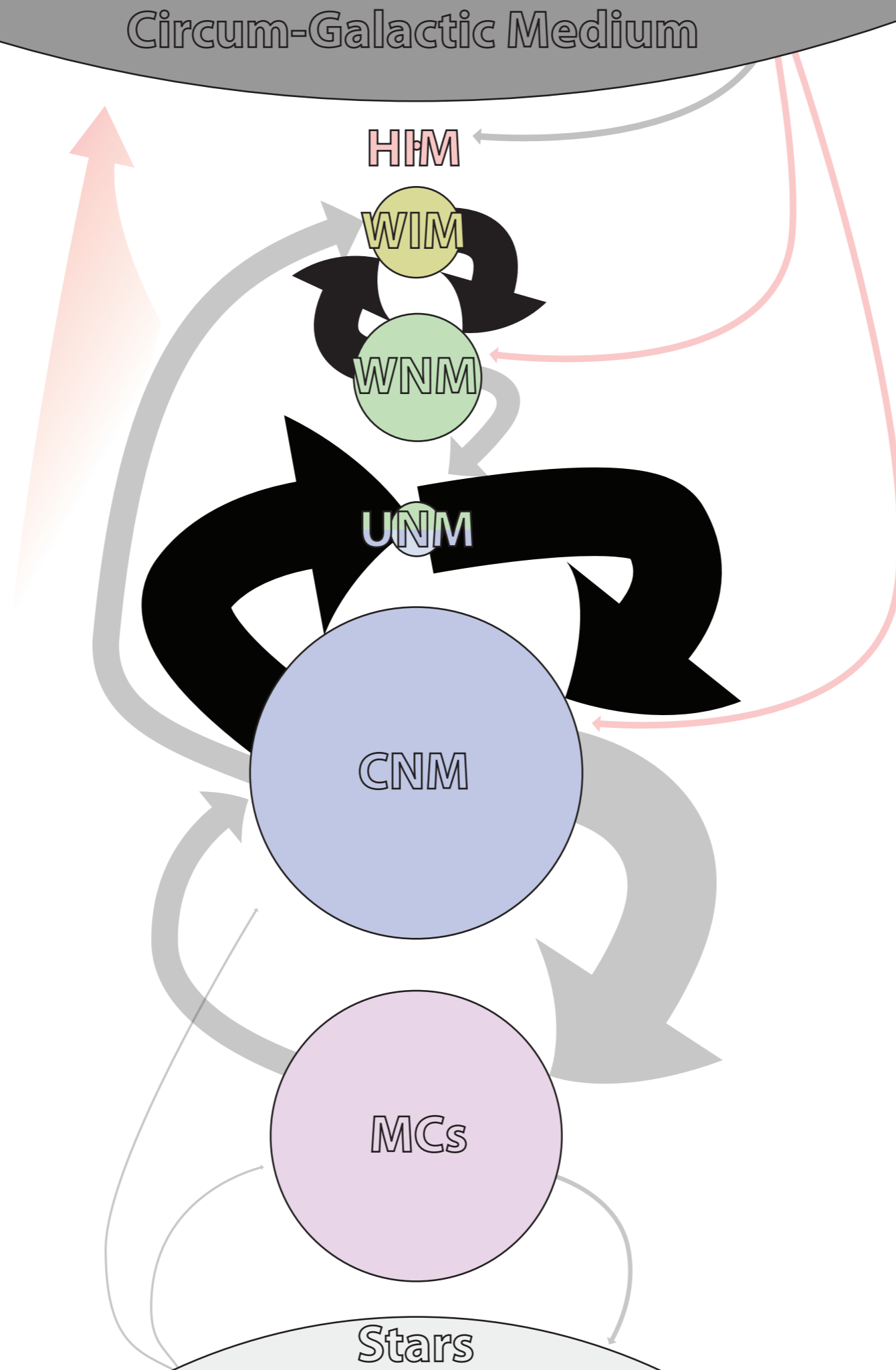
UNM

CNM

MCs

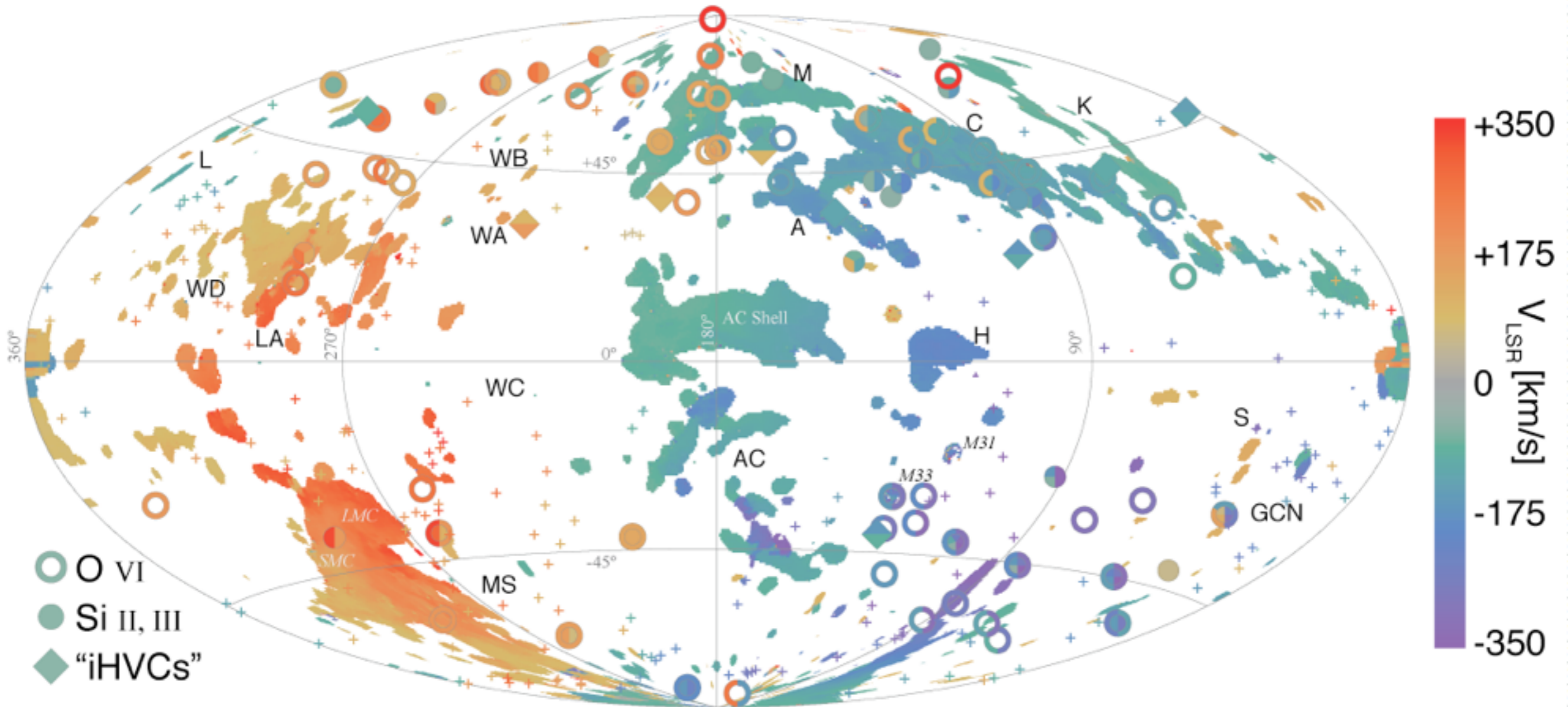
Stars

Gas  
circulation?  
Infall?



# A deceptive view of the HI sky?

$3.2 \times 10^8 M_{\odot}$  HI halo (Marasco & Fraternali 2010)



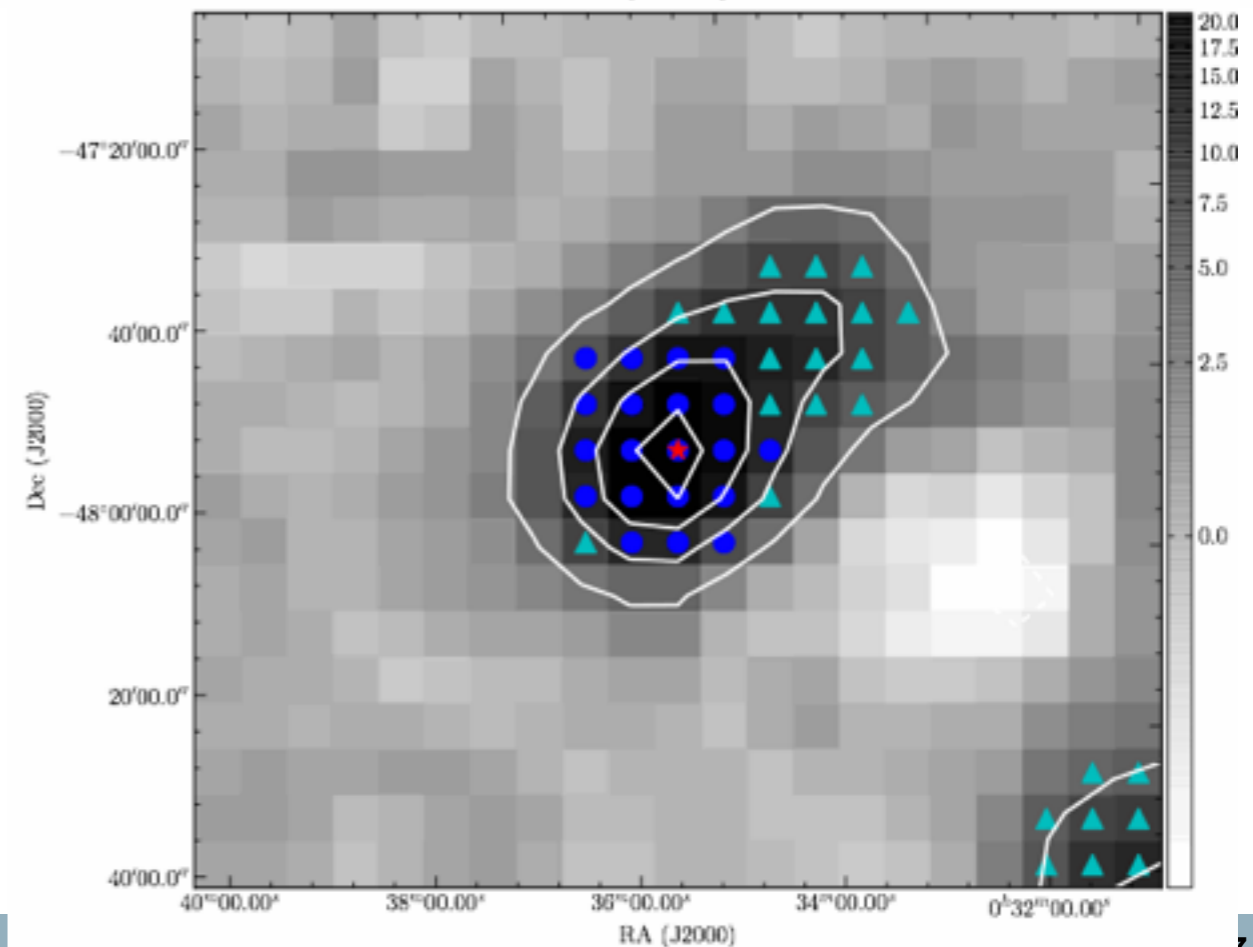
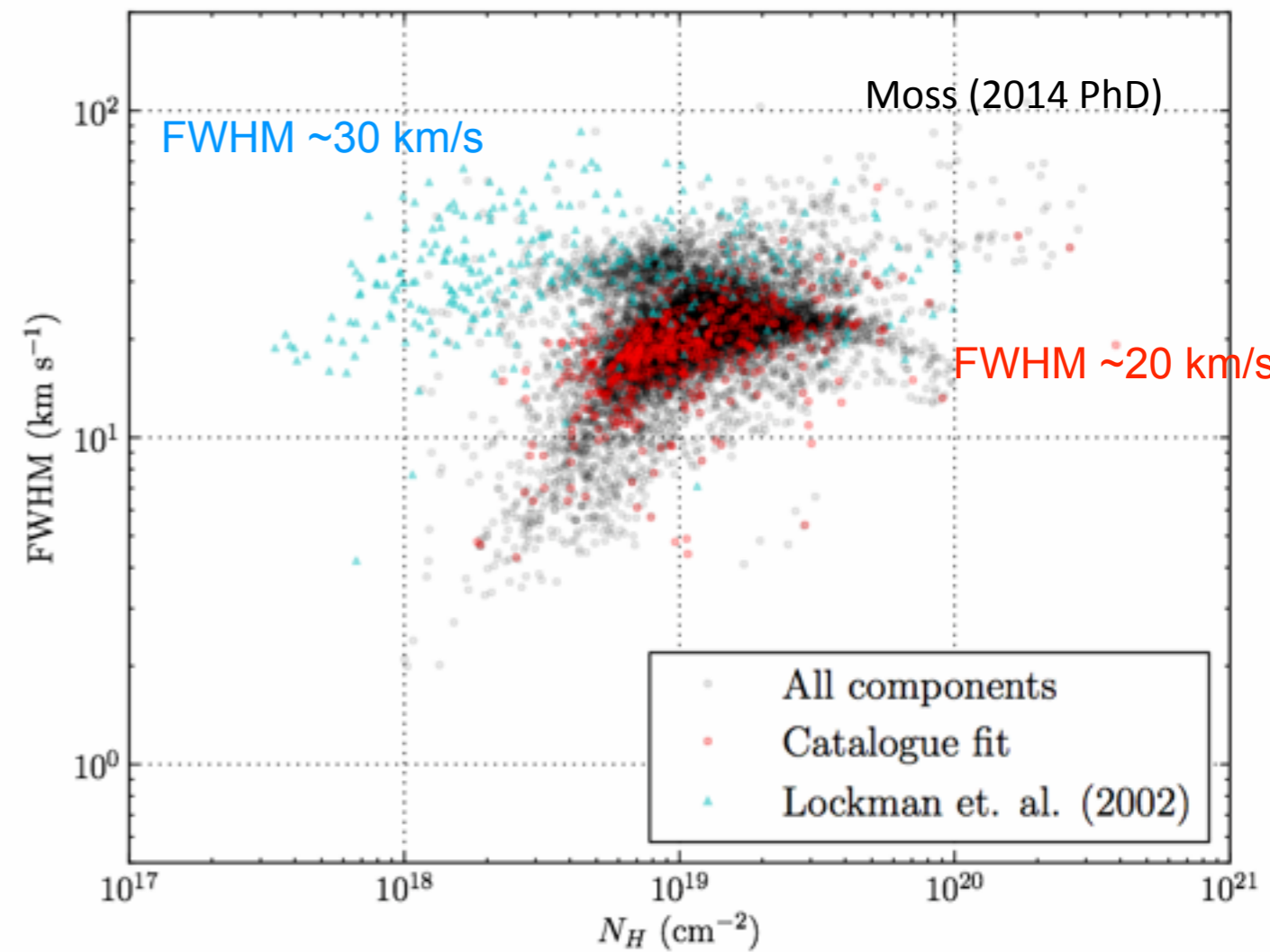
Putman, Peek, & Joung (2012 ARA&A); Westmeier (2007); LAB data

reservoir of  $<10^{18} \text{ cm}^{-2}$  HI gas?  
 significant optically thick HI?

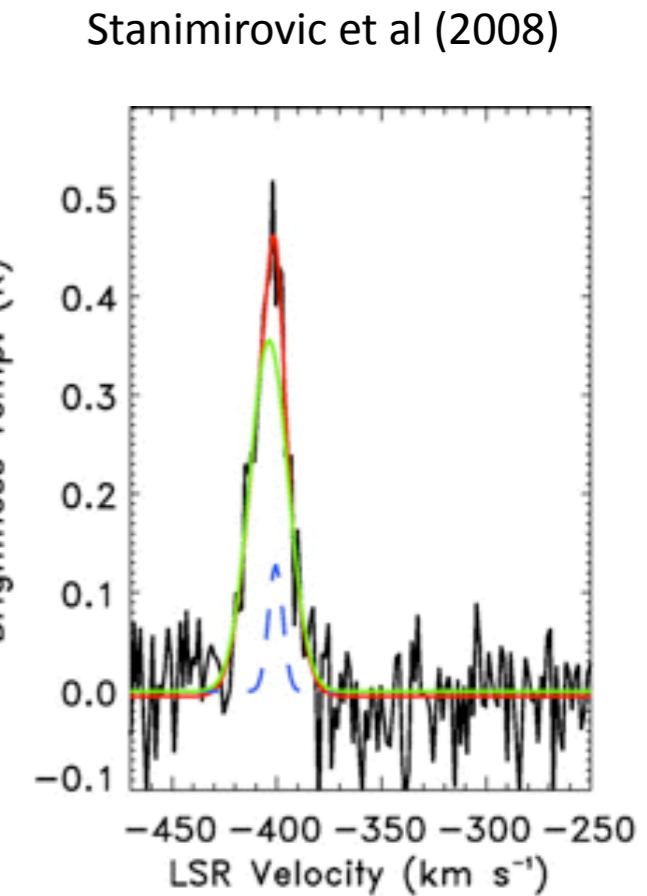
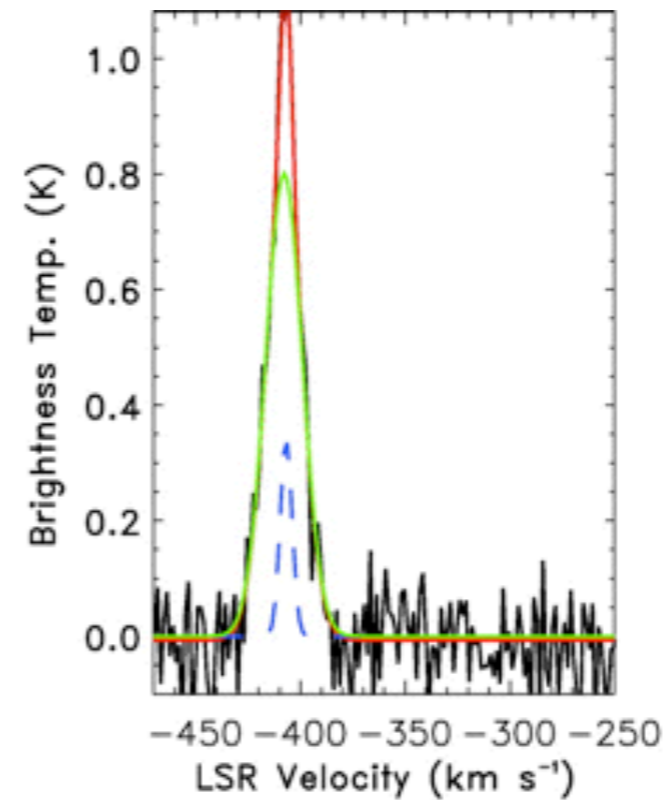
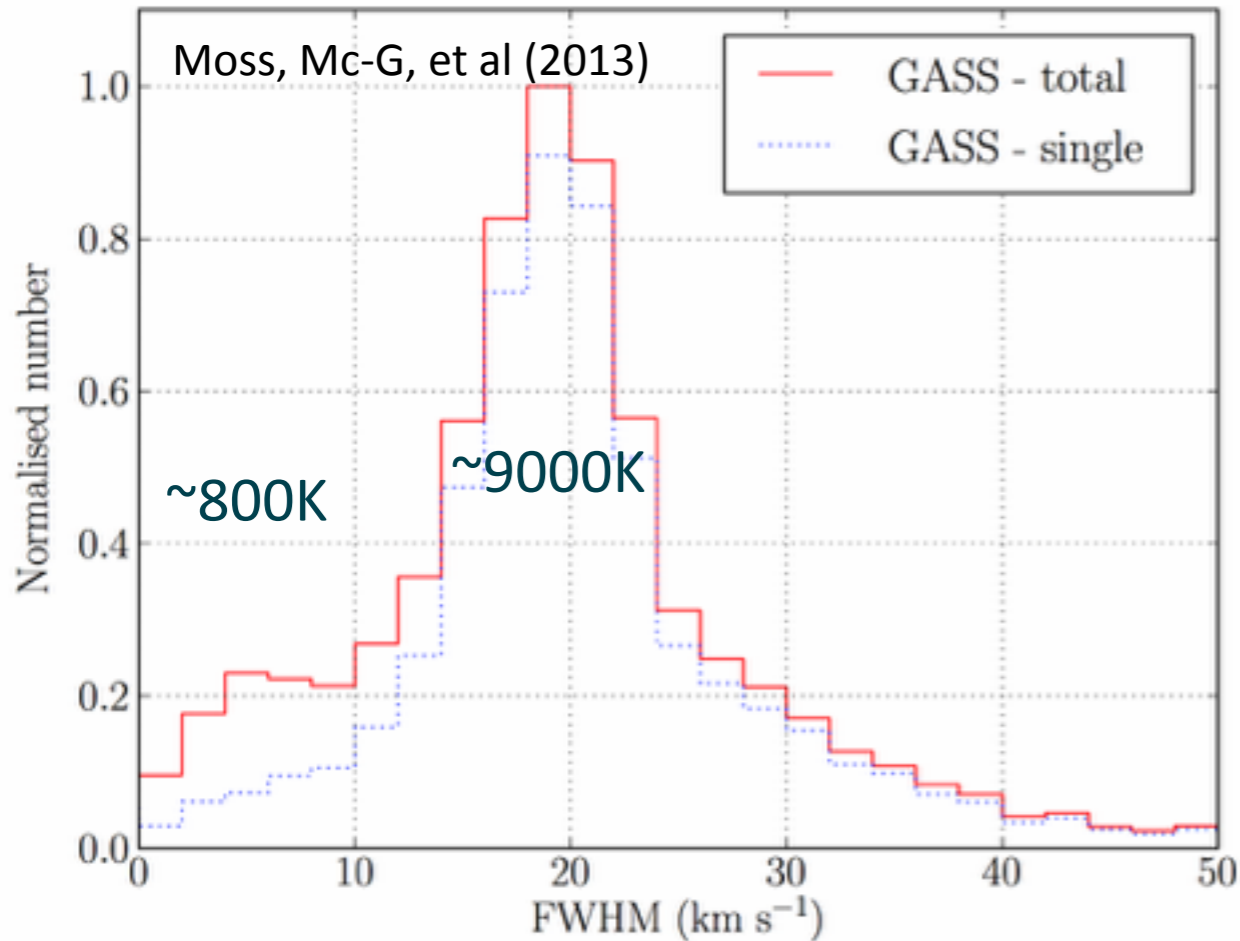


# HI Halo: Wide vs Deep

- Deep HI obs (Lockman et al 2002) compared with wide (Moss et al 2013)
- Ratio of dense to diffuse gas is: 0.2 - 0.8, consistent with lots of “undetected” HI (Moss et al, 2015)



# Multi-phase high-velocity gas

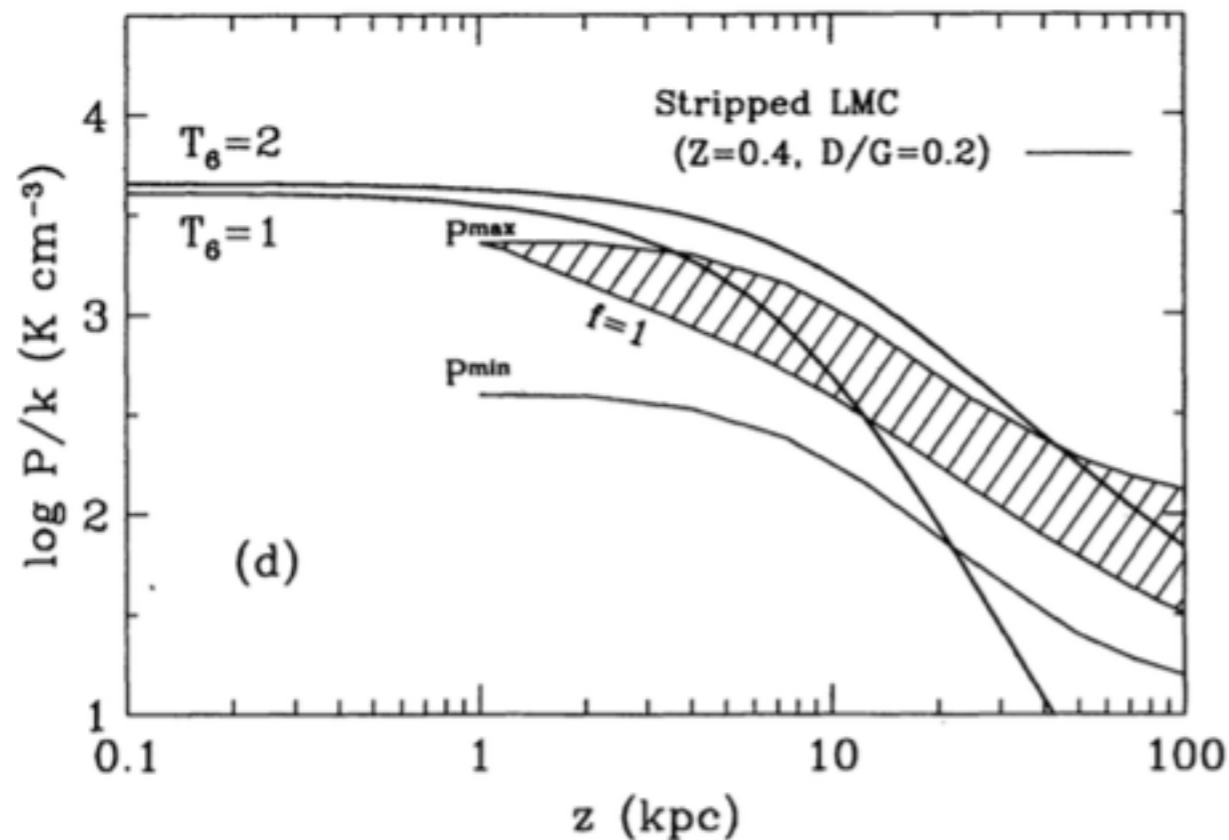
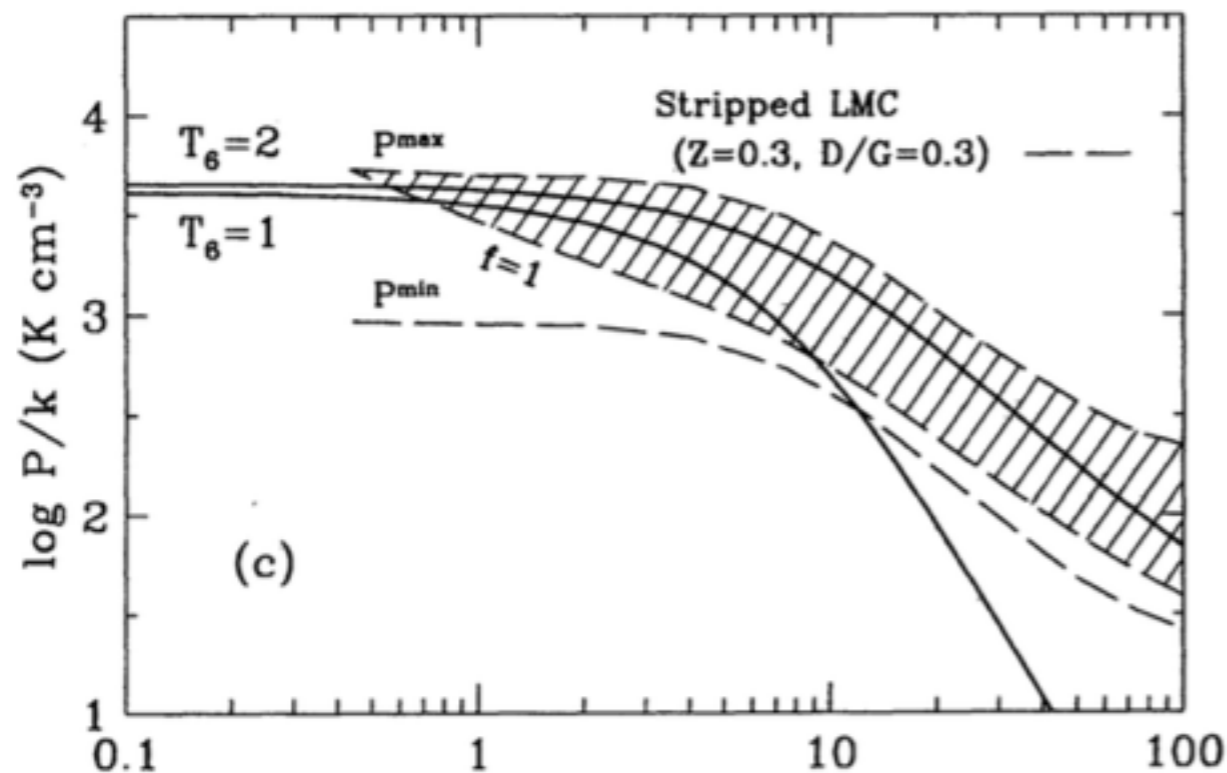


- HVCs as barometers
  - “Cold” cores: FWHM  $\sim 7$  km/s, “Warm” envelopes: FWHM  $\sim 20$  km/s
- 20 - 24 % of HVC sight-lines have multi-phase structure (Moss et al 2013, Kalberla & Haud 2006)

And ...

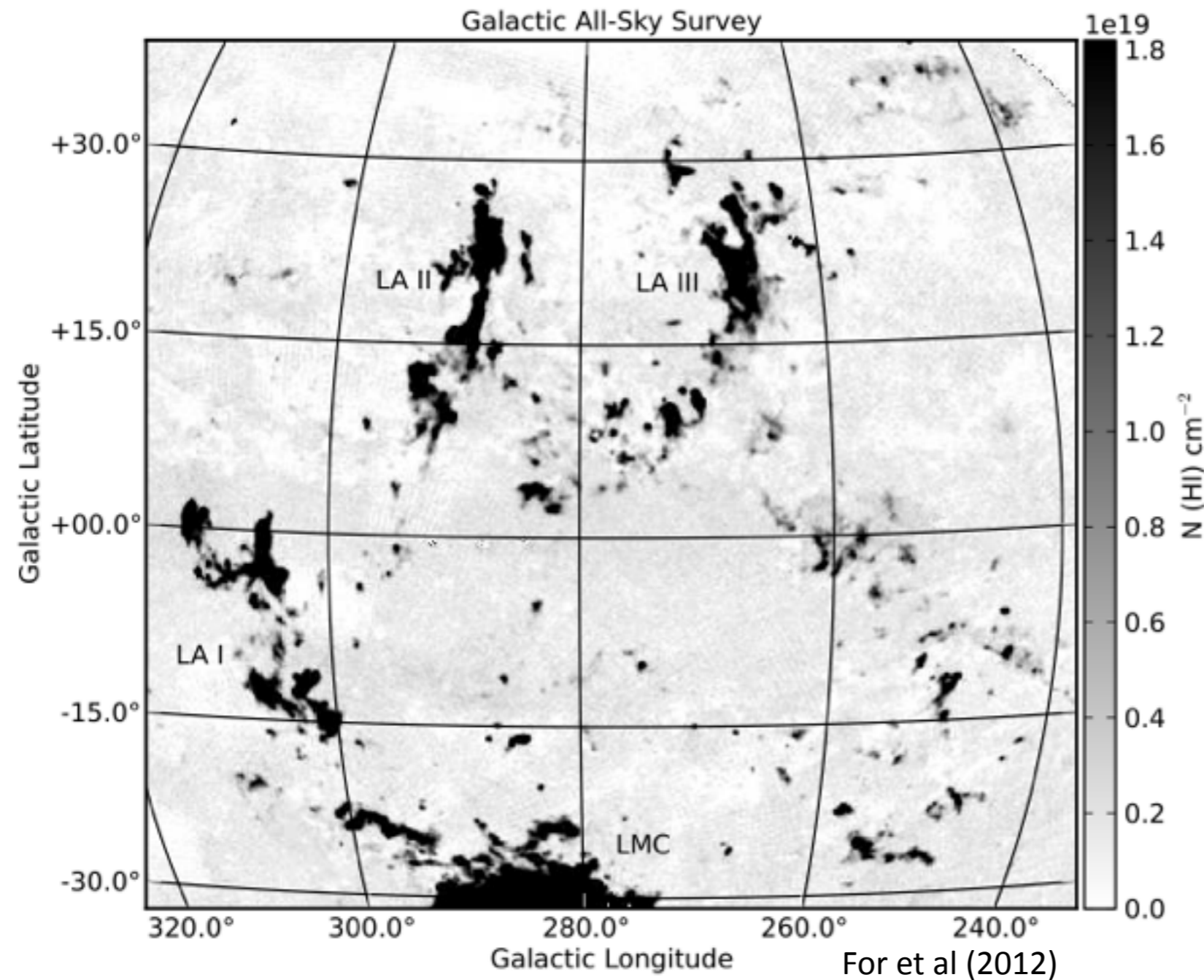
Multiphase Magellanic Steam clouds shouldn't

- Exist at 180 kpc (Stapler et al 2009)
- What other forces play a role?
- magnetic fields?



Wolfire et al (1995)

# Accretion in action?

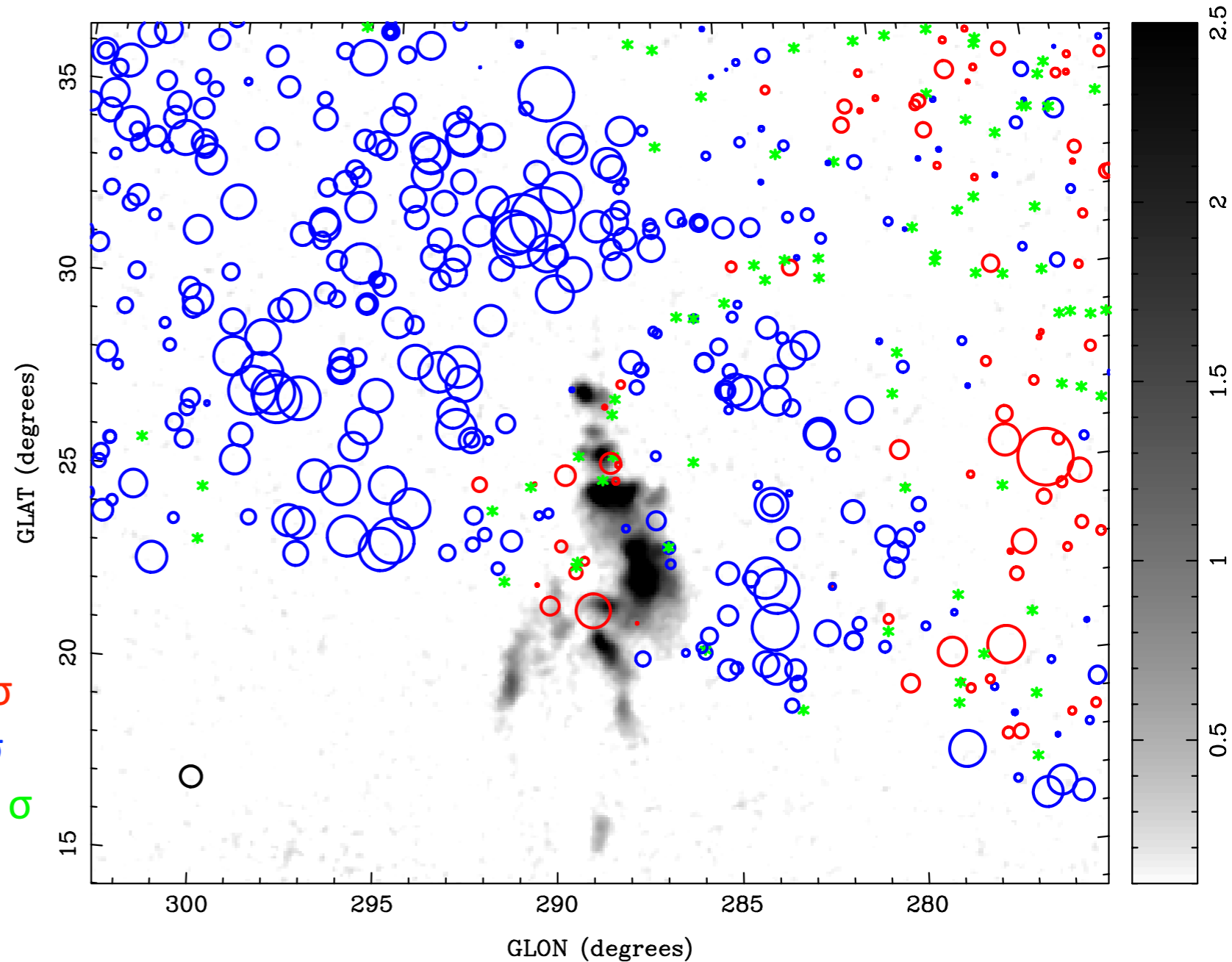


- MS travelling at  $\sim 380 \text{ km/s}$  (Kallivayelli et al 06),  $P_{\text{ram}} > 10^{2.5} \text{ K cm}^{-3}$
- Survival time  $\sim 150 \text{ Myr}$ , travel 16 kpc (Putman et al 11)

# B-fields and HVCs

- HVC in Leading Arm of Magellanic System
  - Head-tail morphology

H I  
 $RM > +\sigma$   
 $RM < -\sigma$   
 $|RM| < \sigma$



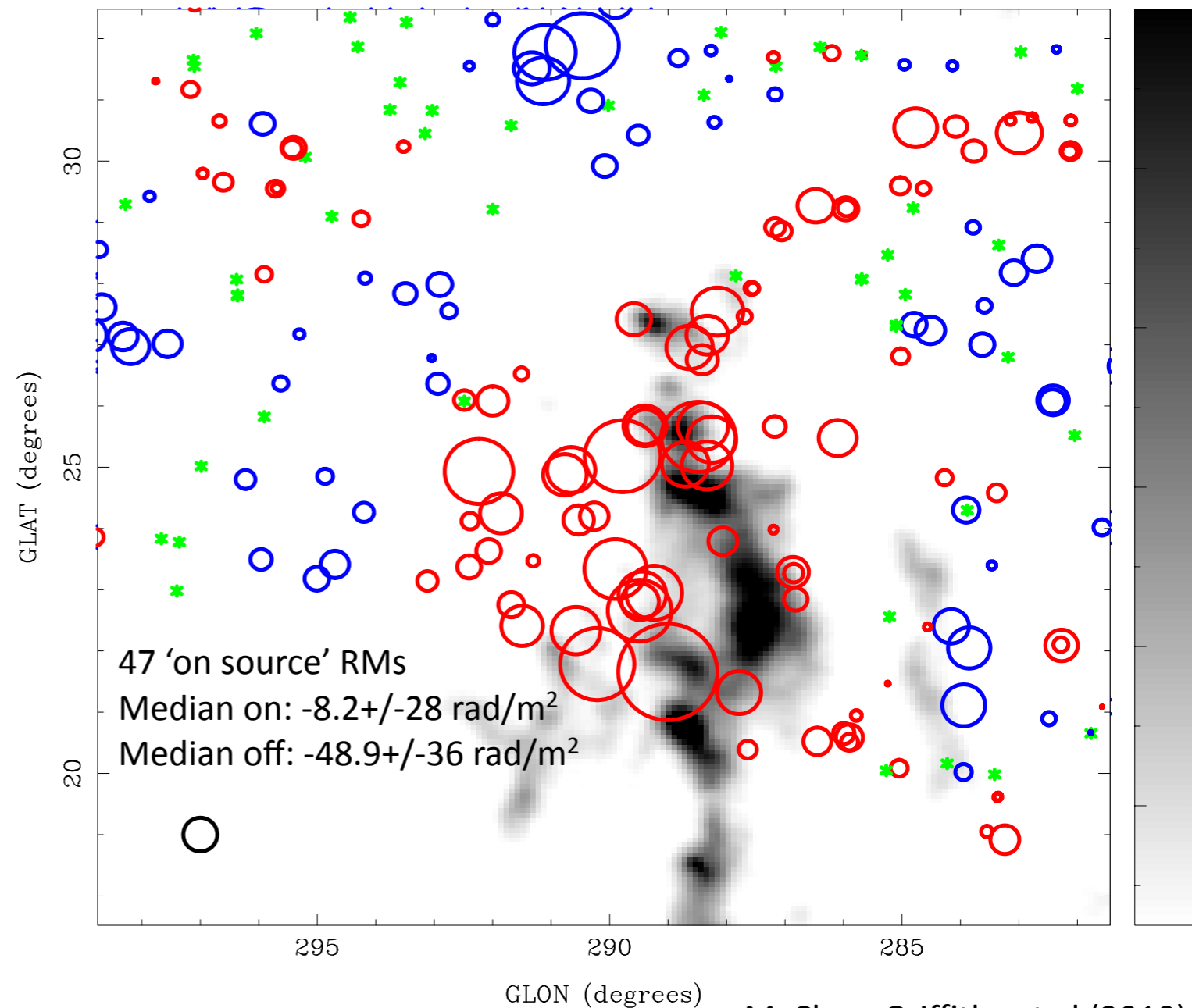
McClure-Griffiths et al (2010)

# Rotation Measures & HVC HI Emission

$$\langle B_{\parallel} \rangle = 3.8 \times 10^{18} \langle RM_{HVC} \rangle / N_{\text{HII}}$$

RM > 0  
RM < 0

- Average electron density from H $\alpha$  WHAM-South upper limit and Si II and Si II abs lines (Shull et al 09)
  - Given  $N_{\text{HII}} < 4 \times 10^{19} \text{ cm}^{-2}$  and  $\langle RM_{HVC} \rangle \sim 55 \text{ rad m}^{-2}$
- ➔  $B_{\parallel} > 6 \mu\text{G}$  (towards us)



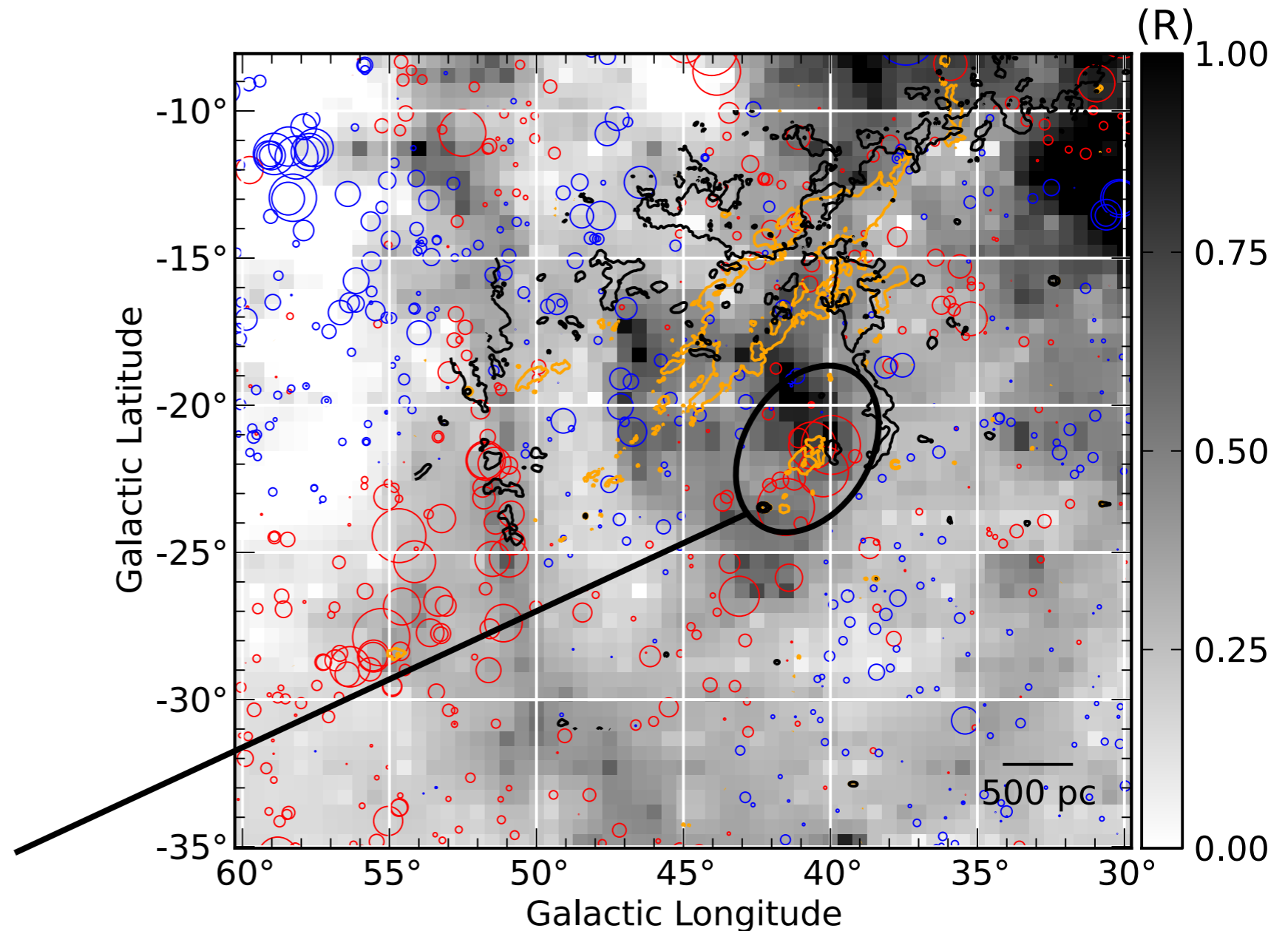
McClure-Griffiths et al (2010)

# Magnetic field in the Smith Cloud?

H I  $v_{\text{GSR}} = +247 \text{ km/s}$   
( $v_{\text{LSR}} = +100 \text{ km/s}$  at head)

RM > 0  
RM < 0

$\langle \text{RM} \rangle = +108 \pm 3 \text{ rad m}^{-2}$   
 $\langle \text{EM} \rangle = 1.22 \pm 0.04 \text{ pc cm}^{-6}$   
 $B_{\parallel} \geq +8 \mu\text{G}$  (towards observer)



Hill et al (2013)

# Summary

- Taking full multi-phase ISM into the halo:
  - Gaseous outflows in the Milky Way are multiphase
  - Galactic centre outflow evacuated HI cavity inside  $R_g < 2.5$  kpc
    - However, HI clouds of  $\sim 20$ - $30$  pc entrained in wind
  - The high velocity HI halo is devious
    - undetected diffuse HI
    - “multi-phase” clouds often shouldn’t exist
    - magnetic fields
- How to make progress:
  - Better measurements of temperature (HI absorption?)
  - More metallicities
  - Census of role of magnetic fields





# Next steps...

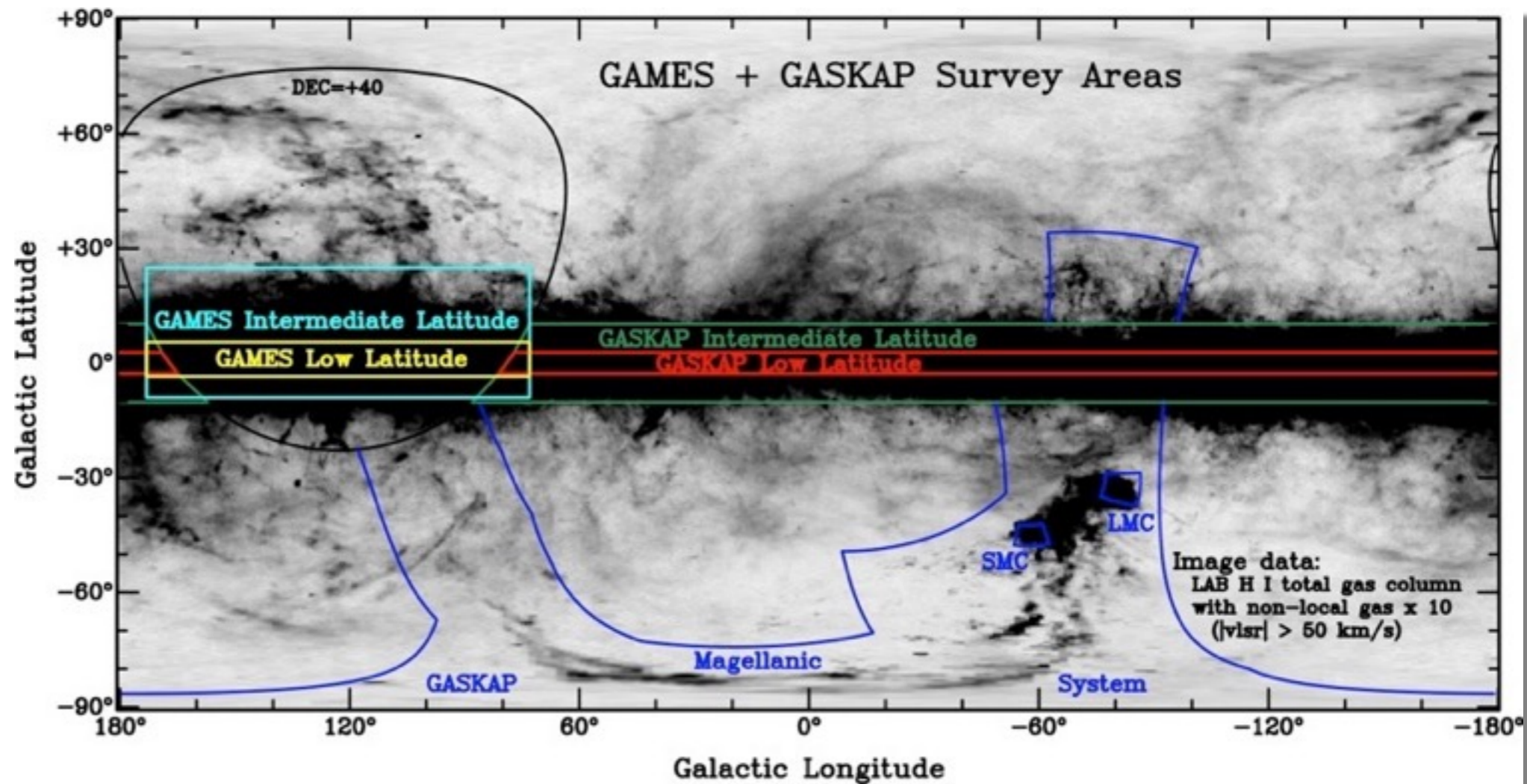
# Galactic ASKAP Survey (GASKAP)

*Aim: To study the evolution of the Milky Way and Magellanic Clouds through their interstellar gas and star formation*

Surveys of the Galactic plane and Magellanic System:

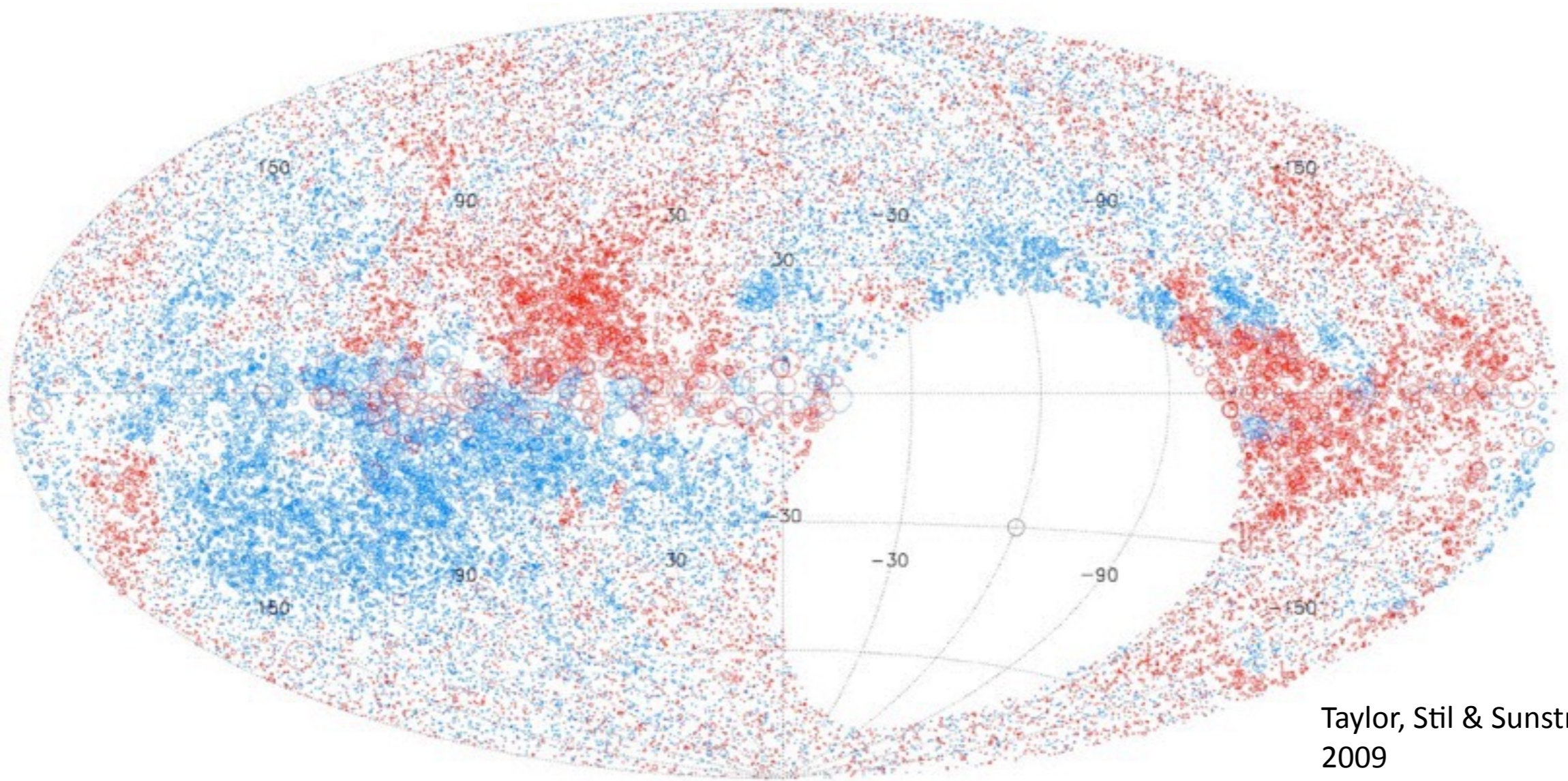
- HI  $\lambda$ 21-cm emission and absorption
- OH  $\lambda$ 18-cm diffuse emission and absorption
- OH  $\lambda$ 18-cm masers

More than order of magnitude more sensitive



Dickey, McClure-Griffiths et al (2013)

# GASKAP + POSSUM



Nidever+10