The HI turbulence: temperature distribution, buildup of molecular clouds, and ineffective stellar feedback

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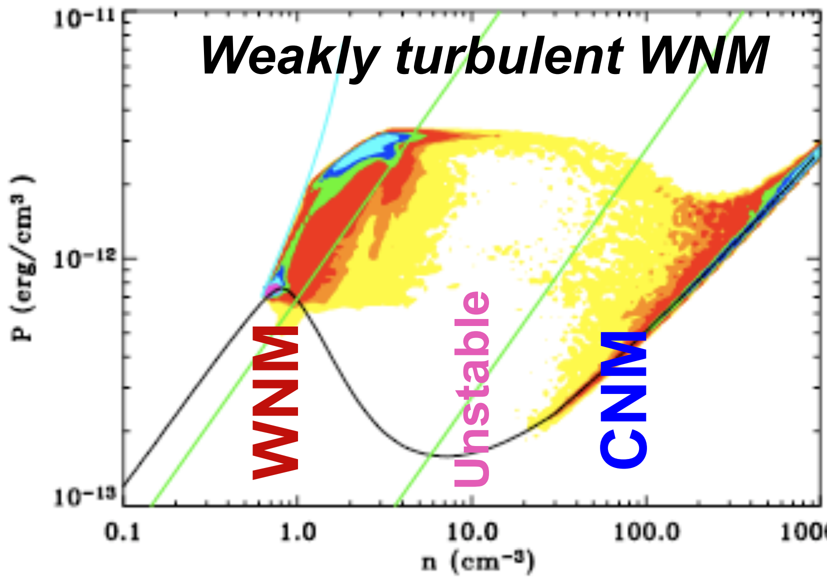
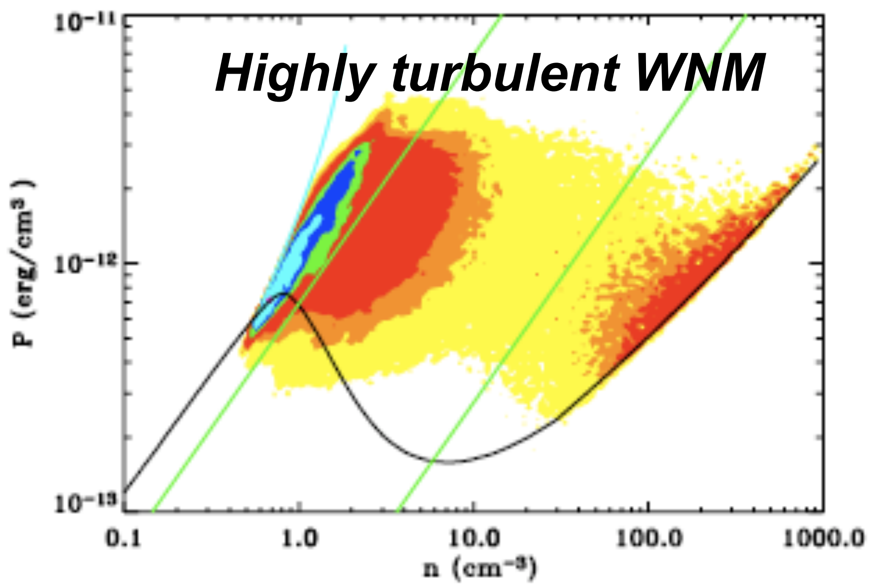
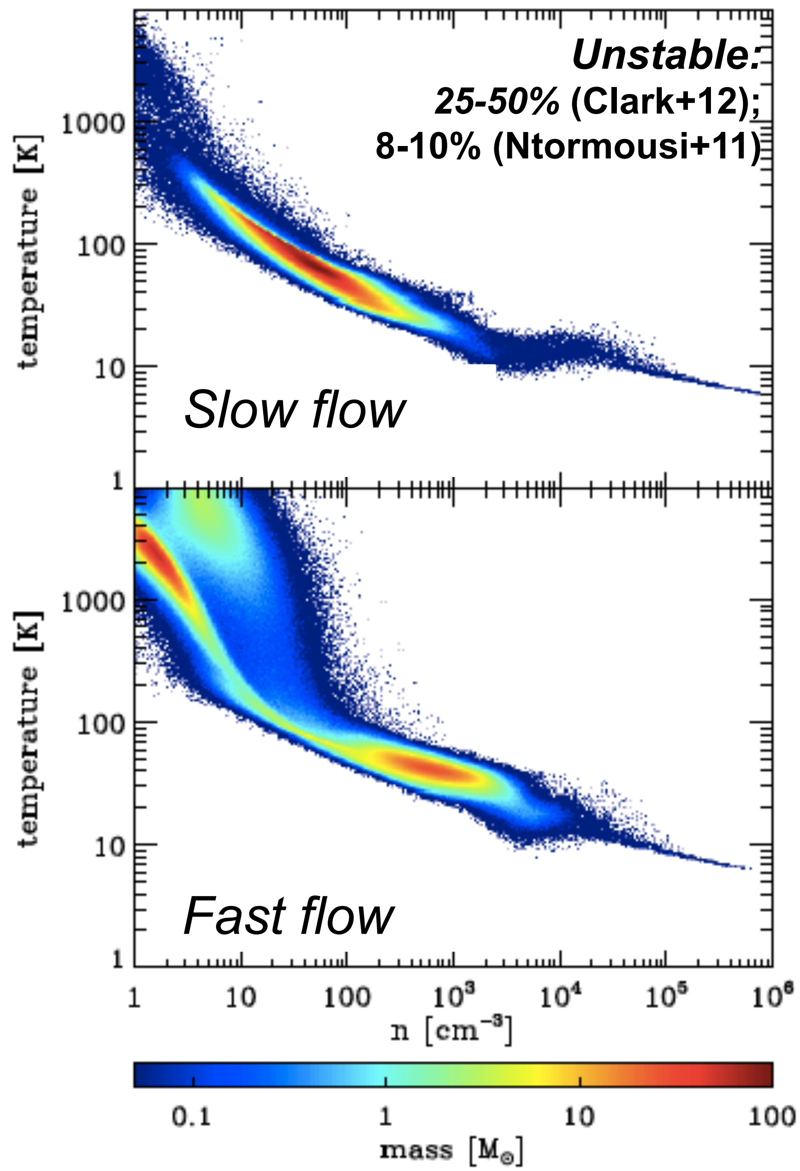
Simulations: unstable WNM depends on turbulence and its fraction varies greatly



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

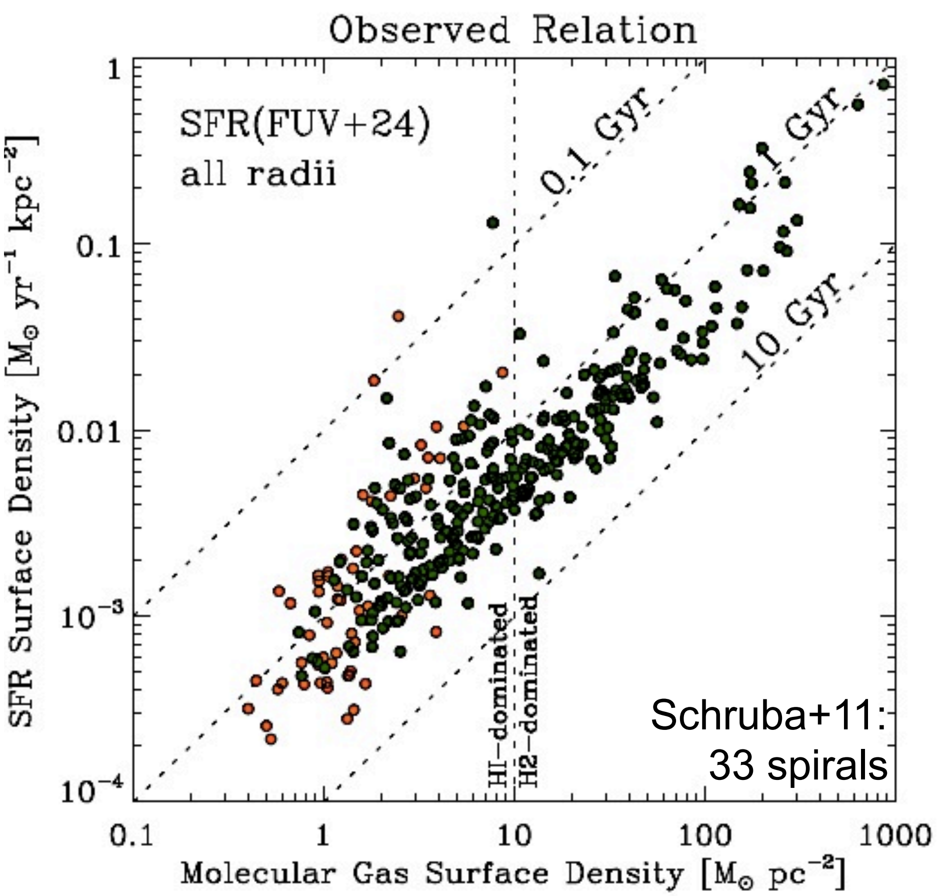


AH05, Mac Low+05, Hill+12, Clark+12



Why do we care? Want to understand galaxy's efficiency to form molecular gas?

Schinnerer+13



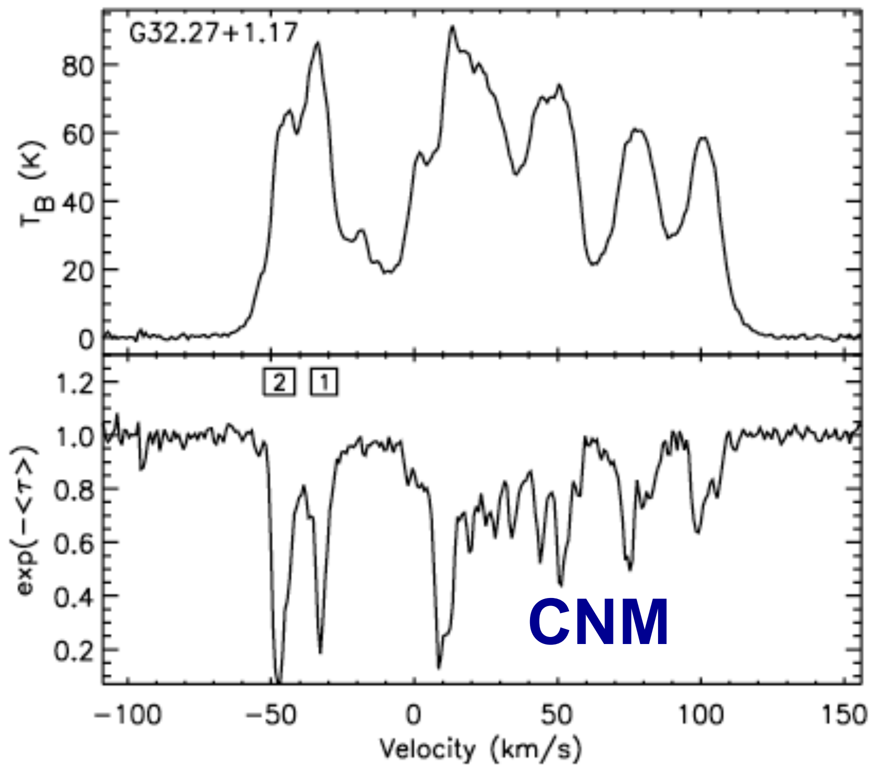
- Understand initial conditions for GMC formation: atomic reservoir (e.g. Saury+13)
- Test ISM and GMC formation models by comparing synthetic with observed spectra.
- Drivers and properties of the HI-to-H_2 transition ? What is the role of WNM?
- Role of turbulence?

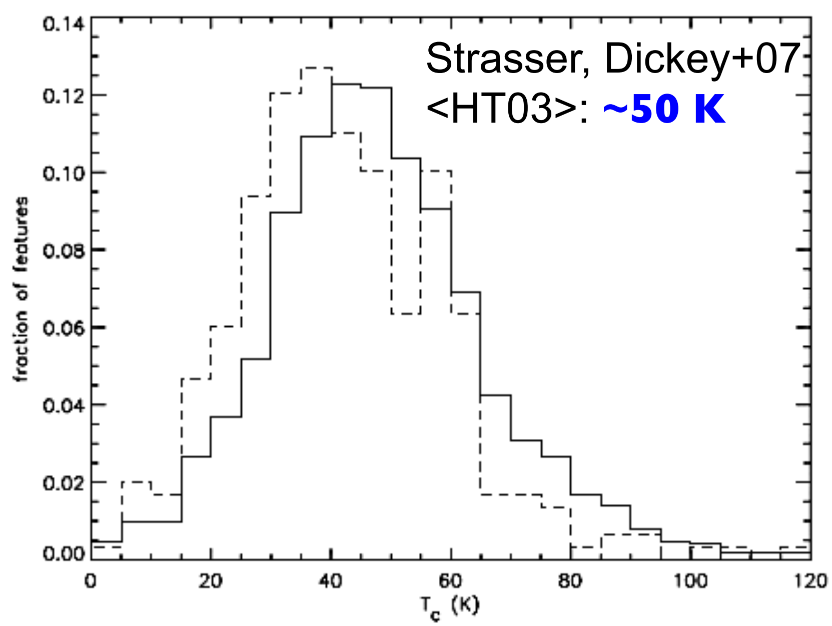
PAWS
PdBI Arcsecond Whirlpool Surve

CNM excitation or spin temperature, T_s

Puzzle: no evidence for spatial variations of Ts

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

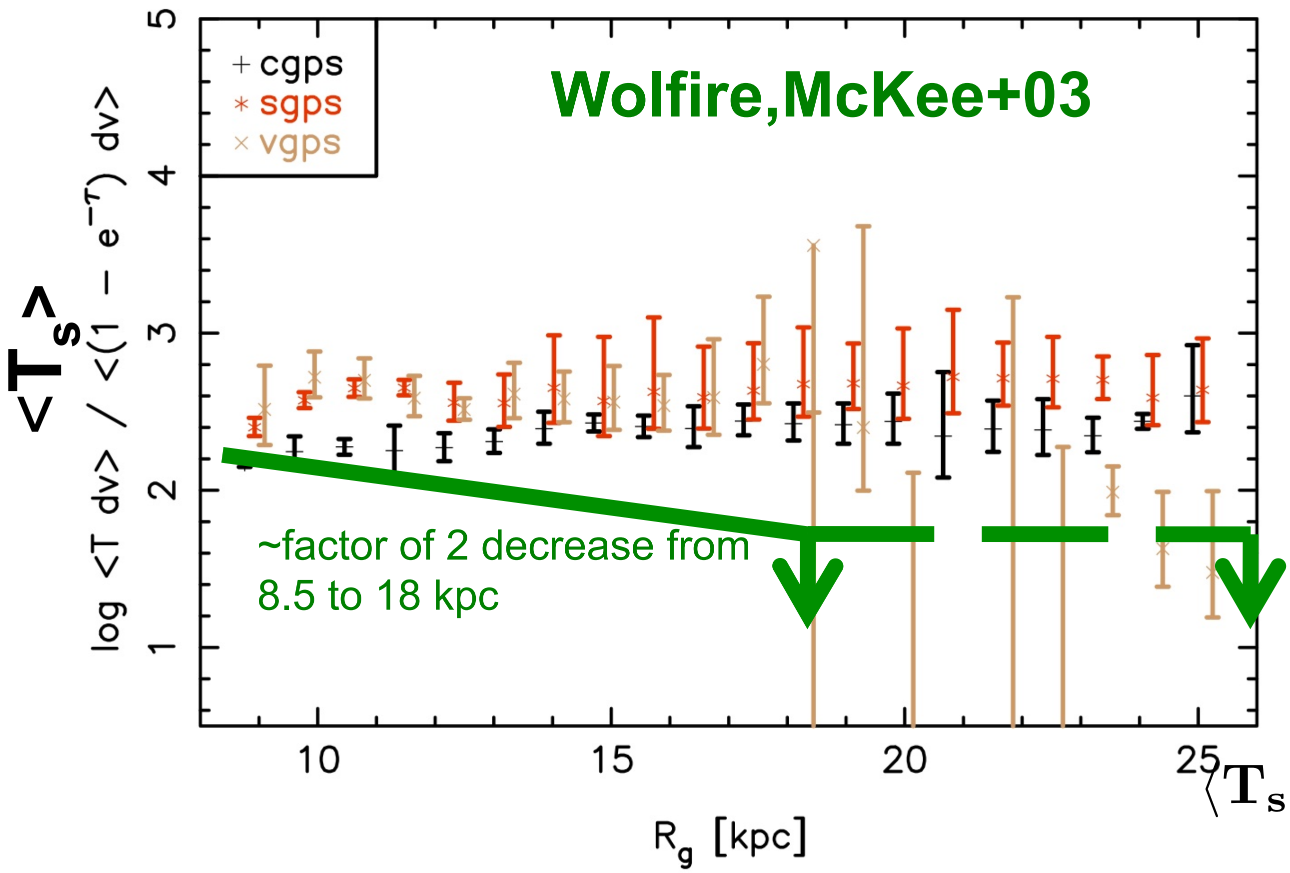




(VLA + Canadian + Southern) Galactic plane surveys

	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.

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

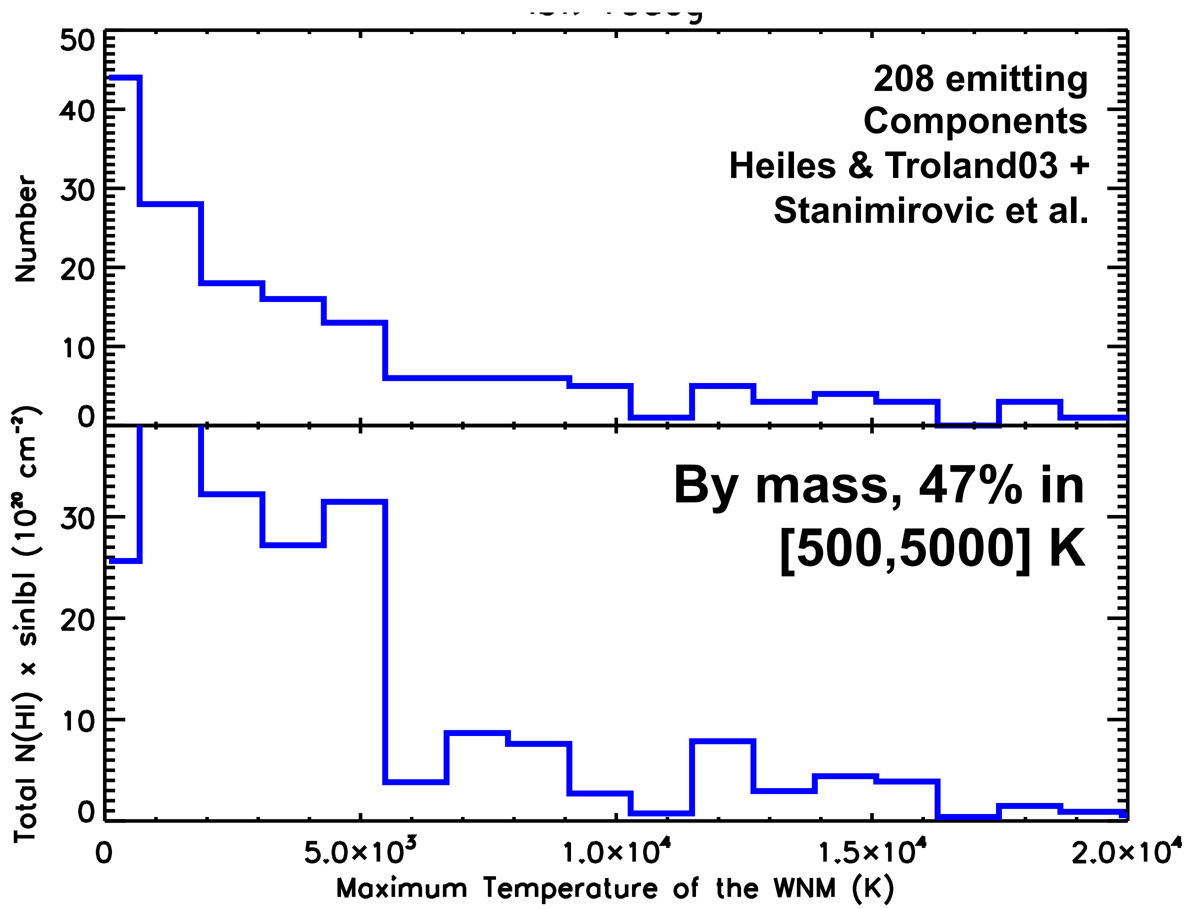
$\langle T_s \rangle$~300 K → CNM fraction constant in the MW from R_0 to $3 \times R_0$.

Contradicts theoretical predictions

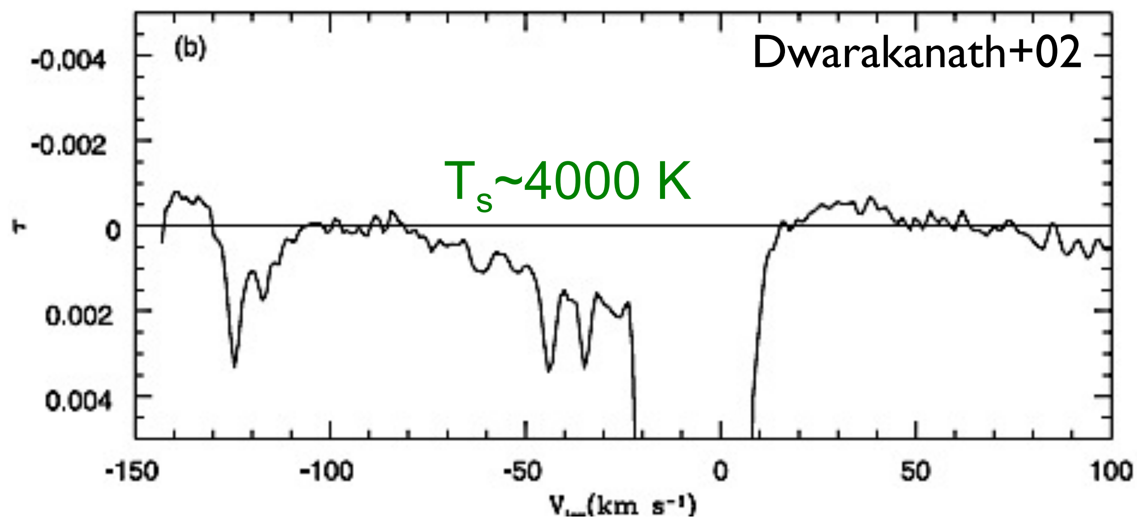
Indirect WNM temperature

	Unstable WNM Fraction
Heiles & Troland03	0.4-0.5
Roy+13	0.3

Dickey+77, Kalberla+85, etc

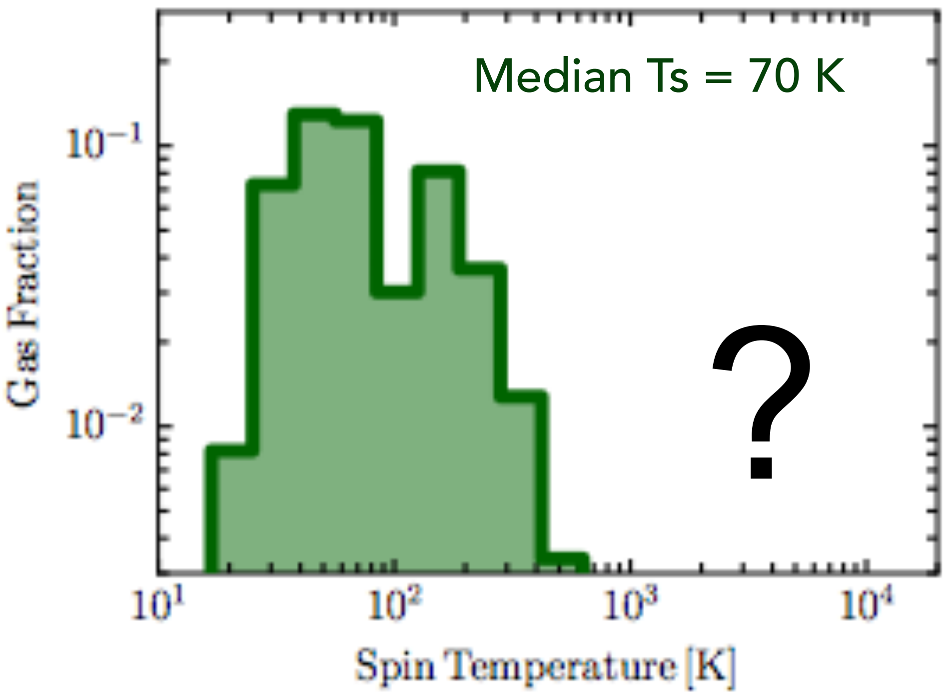


Direct WNM temperature difficult & rare as optical depth ~ $1/T_s$

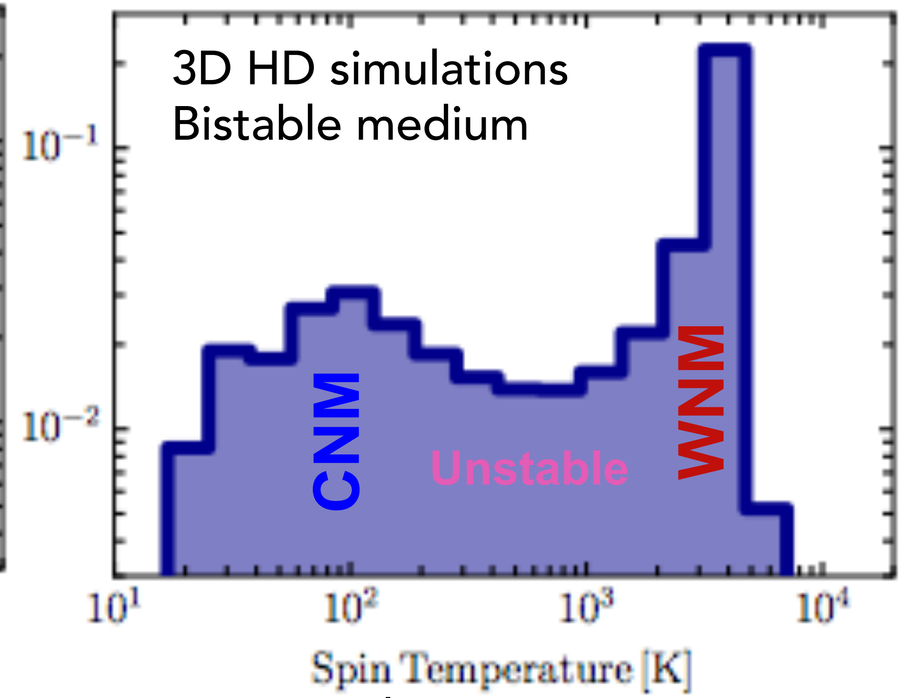


HI temperature distribution for the Milky Way as of 2003

Arecibo Millennium Survey
79 HI absorption+emission pairs



Heiles & Troland 2003, ApJS, 145, 329H

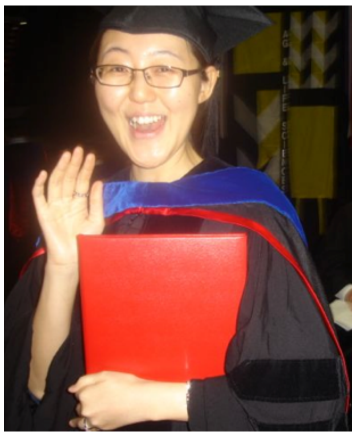


Kim et al. 2014, ApJ, 786, 64

Questions:

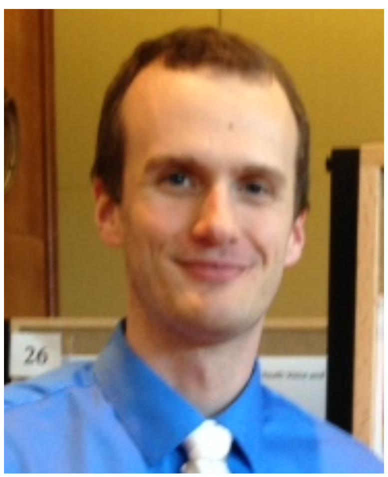
1. Measure WNM temperature and thermally unstable fraction. Constrain ISM models. → 21-SPONGE

Claire Murray, Bob Lindner, M. Goss, J. Dickey, C. Heiles, P. Hennebelle, A. Begum, C.-G. Kim, E. Ostriker + UW ugrads



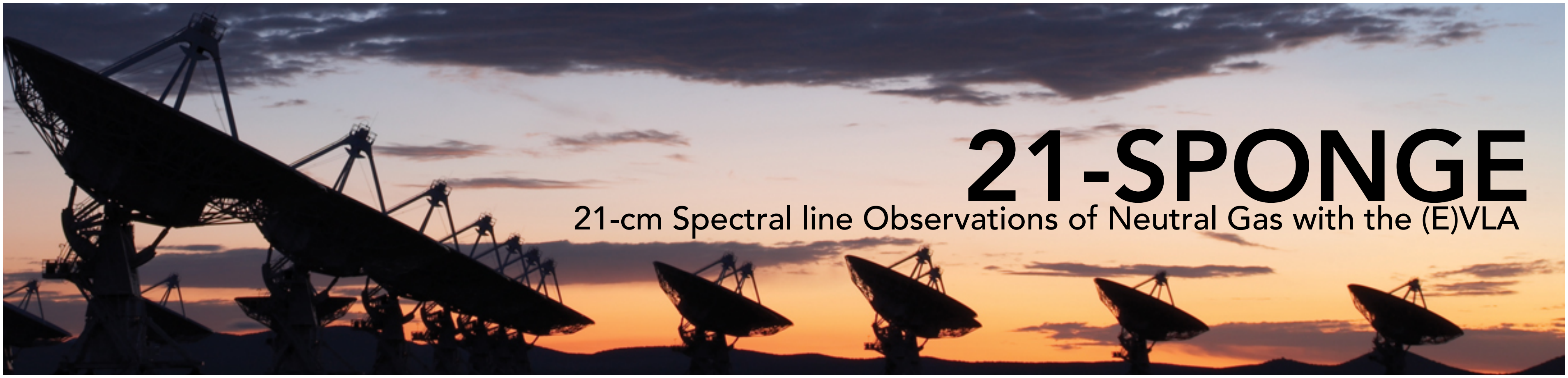
2. Probe the HI-H_2 transition in the Perseus molecular cloud. Phase transformation and properties close to GMCs?

Min-Young Lee, M. Wolfire, J. Miller, C. Heiles, L. Knee, J. Di Francesco, A. Leroy, R. Shetty, S. Glover, F. Molina, R. Klessen + GALFA-HI team



3. Test the importance of stellar feedback for driving HI turbulence?

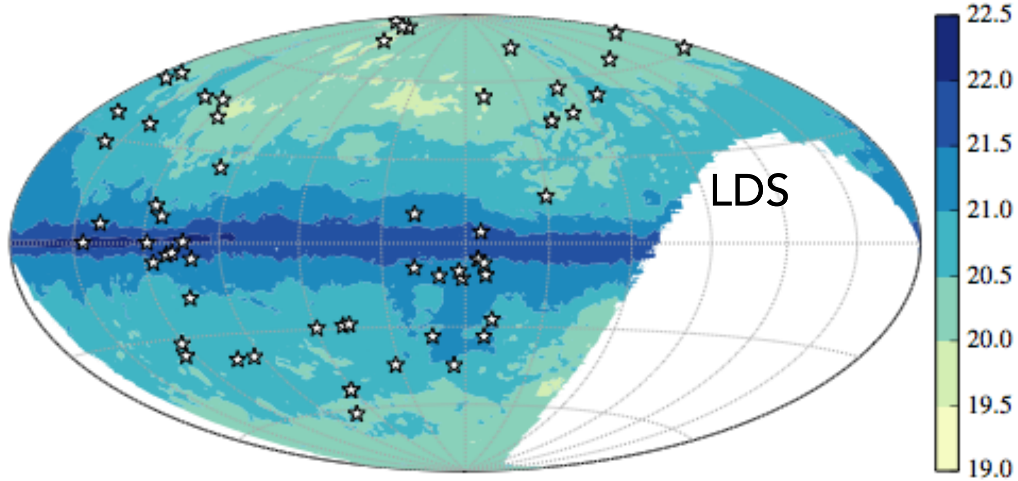
David Nestingen-Palm, D. Gonzales-Casanova, B. Babler, A. Bolatto, K. Jameson



21-SPONGE

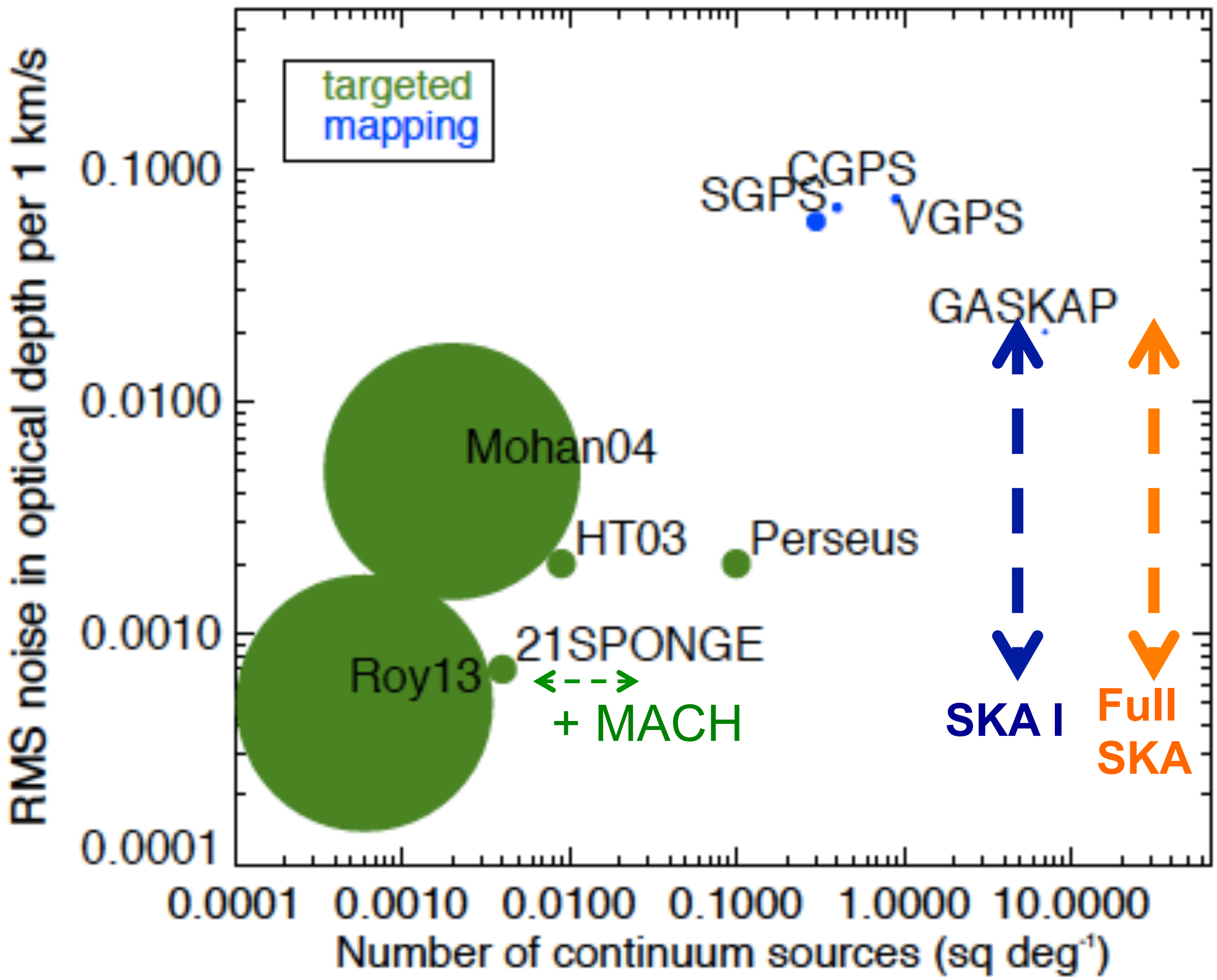
21-cm Spectral line Observations of Neutral Gas with the (E)VLA

- 52 continuum sources, S >3 Jy, high latitudes
- 571 VLA hours: $\boldsymbol{\sigma_\tau}$ < 0.001 per 0.4 km/s channels
- Matching HI emission from Arecibo
- High detection rate (49/52)



Murray et al. 2015, ApJ, 804, 89

21-SPONGE in perspective

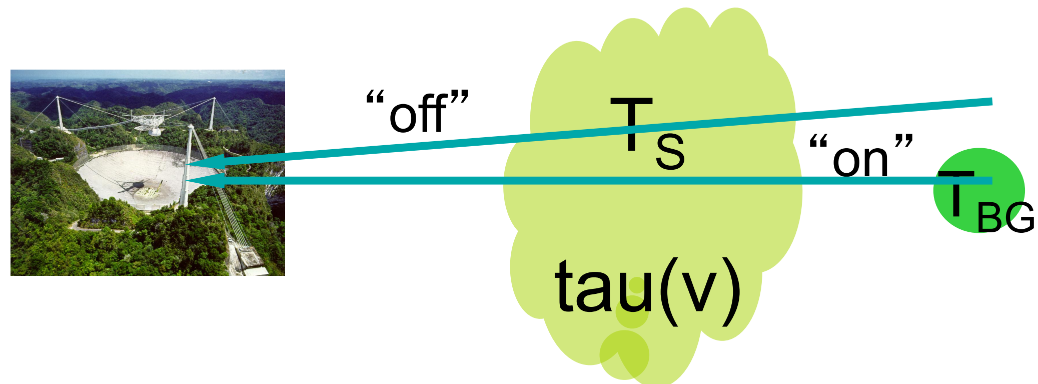


Goal: high angular resolution, high sensitivity, many sources

Observational constraints: measuring Ts

$$T_b^{on} = T_{bg} e^{-\tau}$$

$$T_b^{off} = T_s(1 - e^{-\tau})$$



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

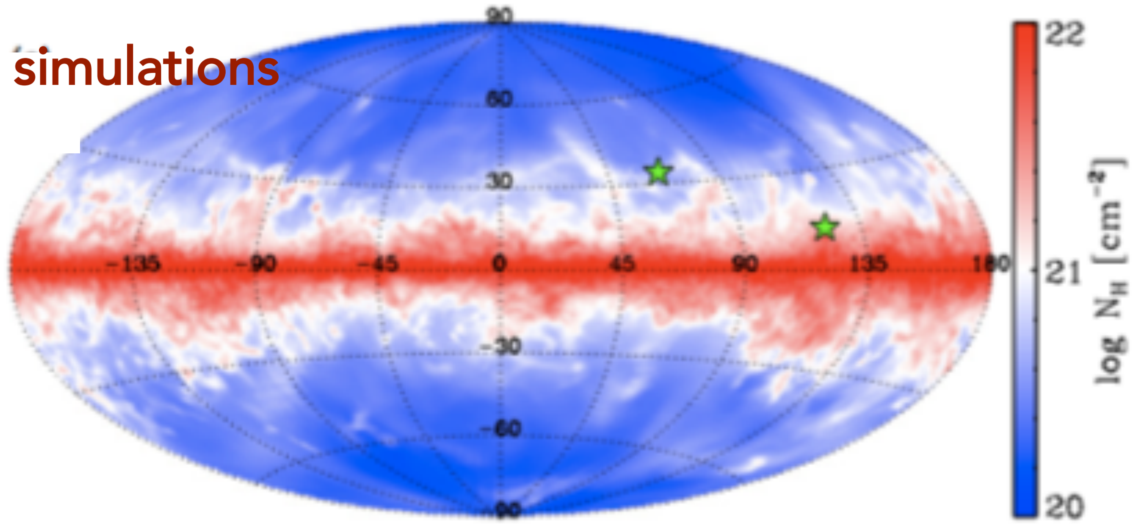
Measure: optical depth and Ts, N(CNM), N(WNM), CNM fraction along the LOS. Ts → Tk requires understanding of HI excitation processes

- Marc-Antoine’s talk – observations are likely not resolving individual CNM/WNM structures
- Fitting Gaussian components

Dickey+77, Taylor+03, Heiles & Troland03, McClure-Griffiths+05, Stil+06, Mohan+04, Kanekar, Braun, Roy 11, SS & Heiles05, Murray+14, etc etc

Understanding Observational Biases

1. Compare with numerical simulations



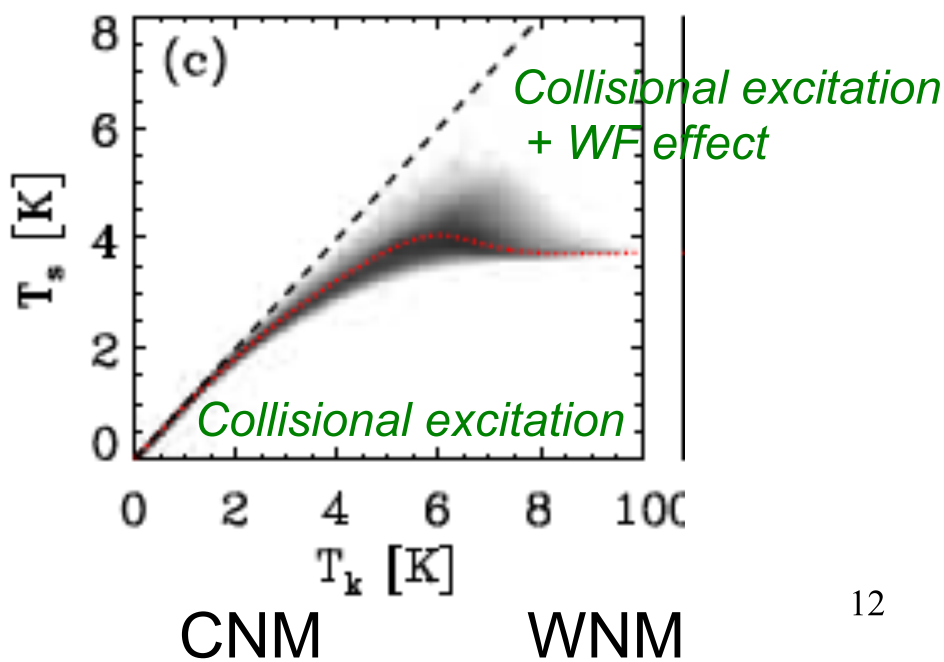
- 3D hydrodynamic simulation:
  - Supernova feedback
  - Self gravity
  - ISM heating, cooling
  - 2pc spatial resolution
  - Galactic rotation

→ Have 10^4 synthetic HI spectra

- HI excitation: Collisions, radiative, scattering of Lyalpha photons (Wouthuysen-Field effect)

Assume n_alpha=10^{-6} cm^{-3} (not well constrained observationally).

→ Expect Ts<4000 K

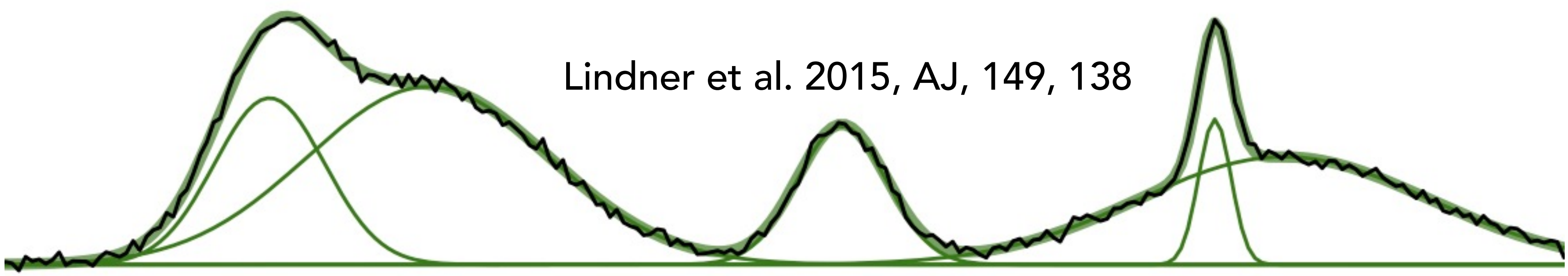


Understanding Observational Biases

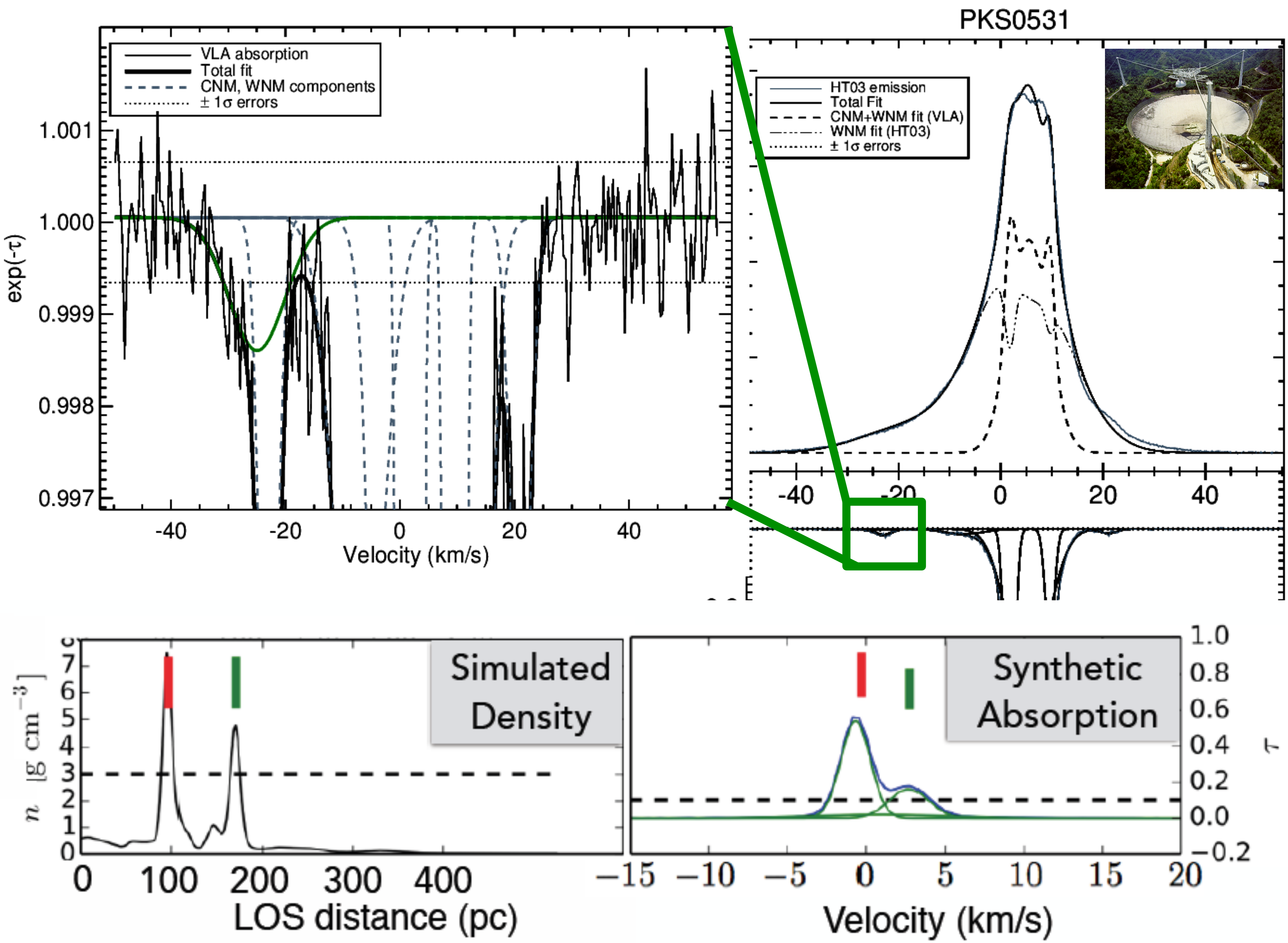
1. Develop analysis tools for objective comparisons

Autonomous Gaussian Decomposition (AGD)

- Efficient decomposition of 1D spectral data into Gaussian functions via derivative spectroscopy and machine learning
- Fit parameters are chosen without human interaction
- On the way to fully automate Ts derivation

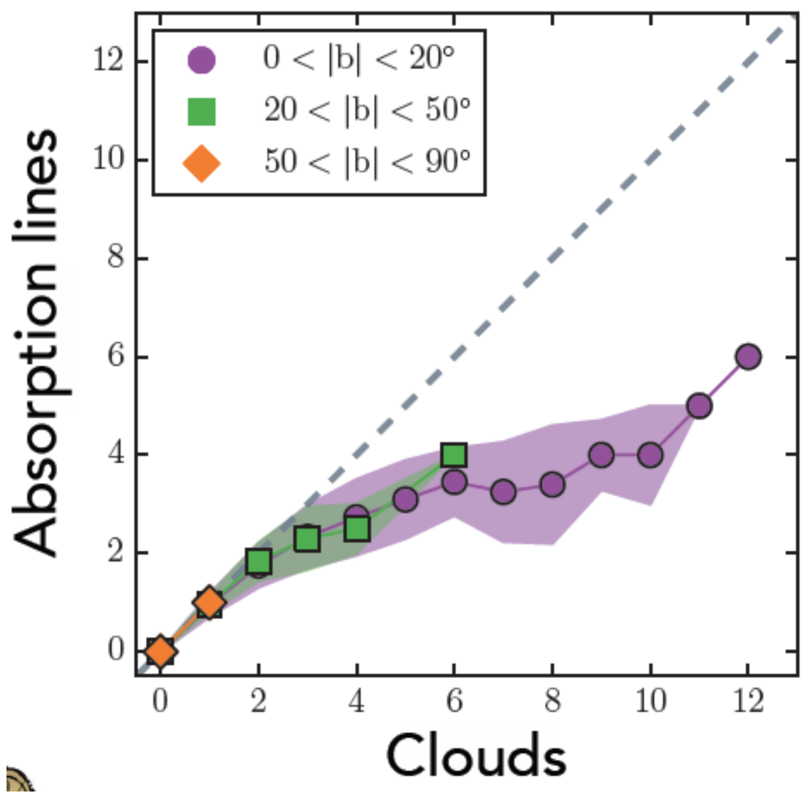


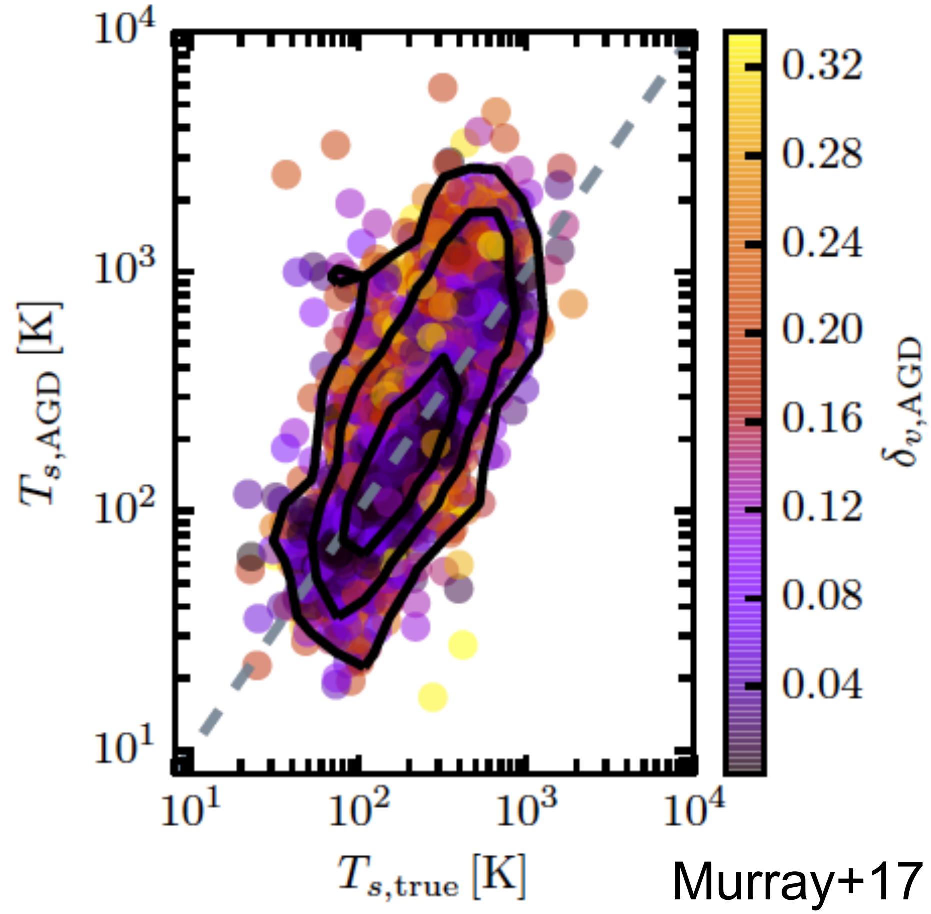
Lindner et al. 2015, AJ, 149, 138



VLA absorption
Total fit
CNM, WNM components
± 1σ errors
exp(-τ)
Velocity (km/s)
PKS0531
HT03 emission
Total Fit
CNM+WNM fit (VLA)
WNM fit (HT03)
± 1σ errors
Simulated Density
LOS distance (pc)
Synthetic Absorption
Velocity (km/s)

Accuracy of observational Ts derivation





Murray+17

Recovery Completeness

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

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

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

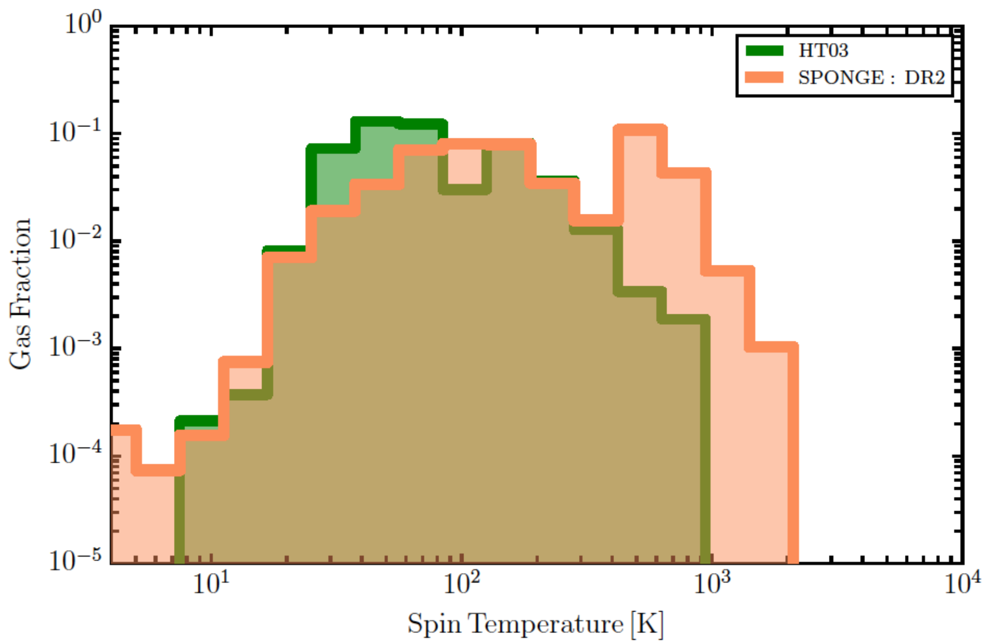
Issues at low-b: line blending and many components

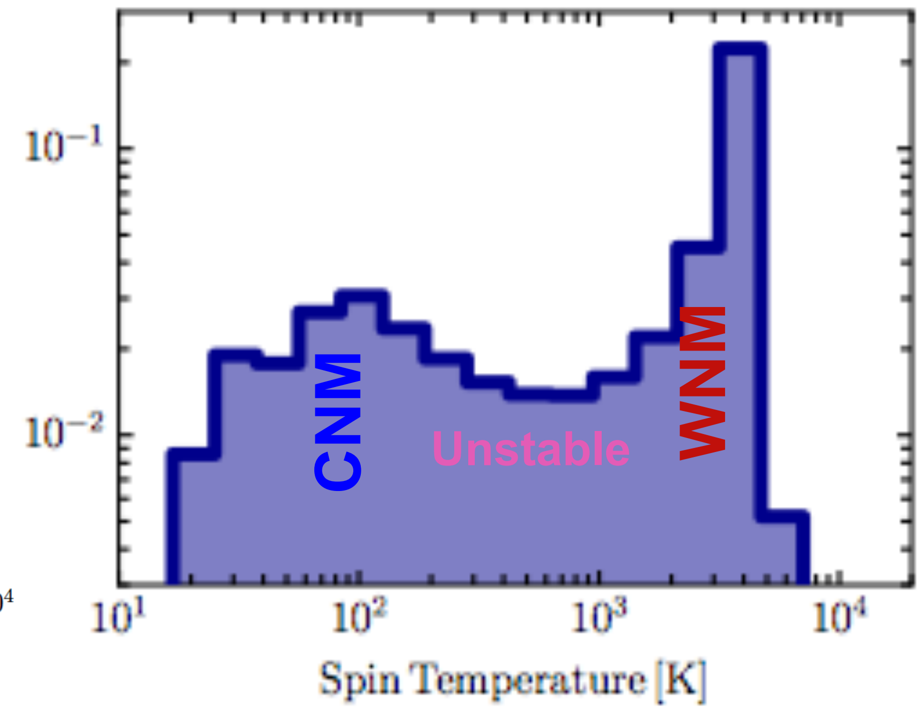
Ts: generally good agreement, at Ts>400K AGD overestimates temp.

Thermally-unstable WNM?

Have sensitivity to see full range of Ts
yet no detections with Ts>2000 K

Arecibo Millennium Survey
21-SPONGE (full survey)



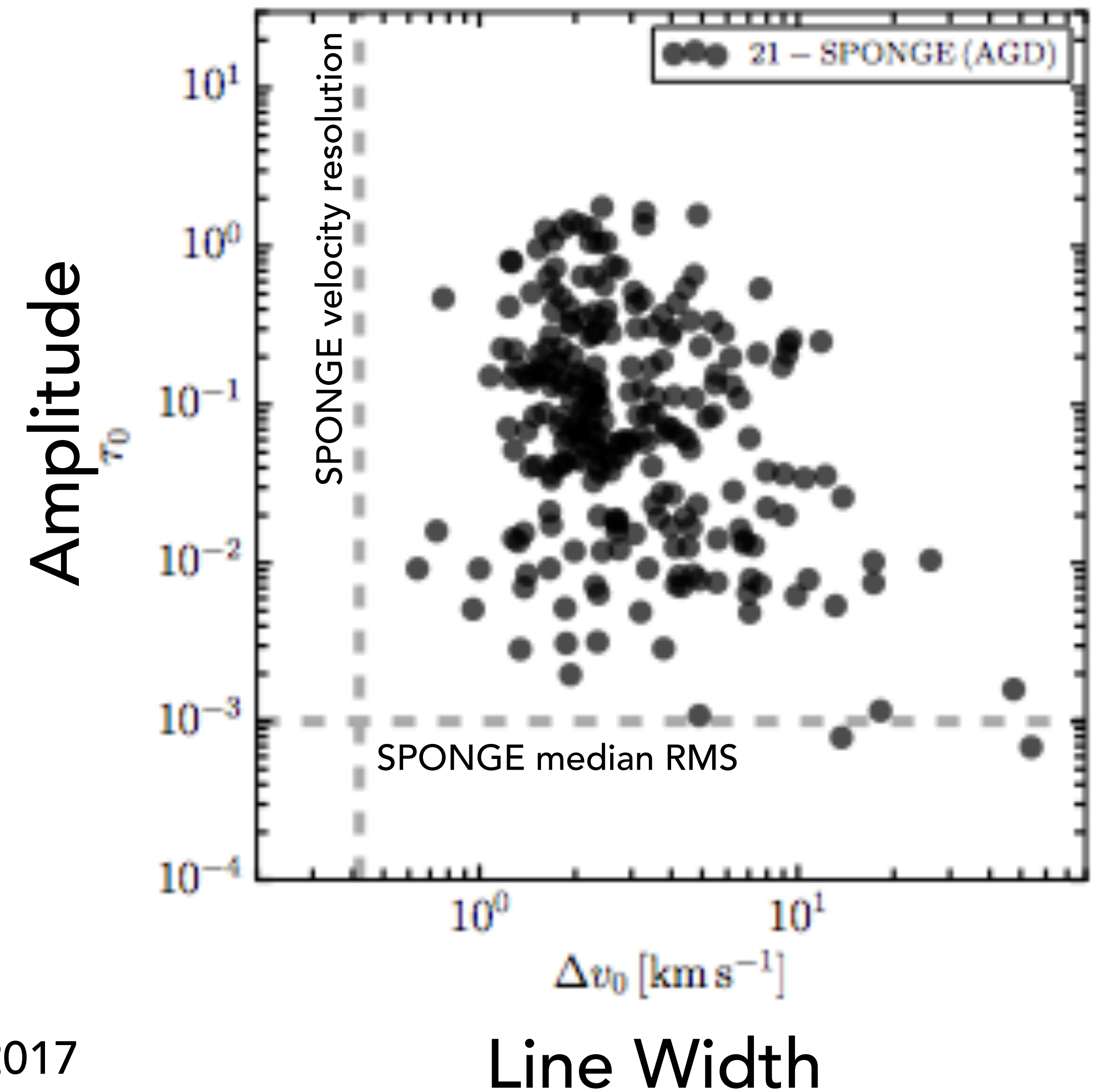


Unstable fraction ~40% (preliminary)

Heiles & Troland 2003a
Murray et al. 2015, 2017

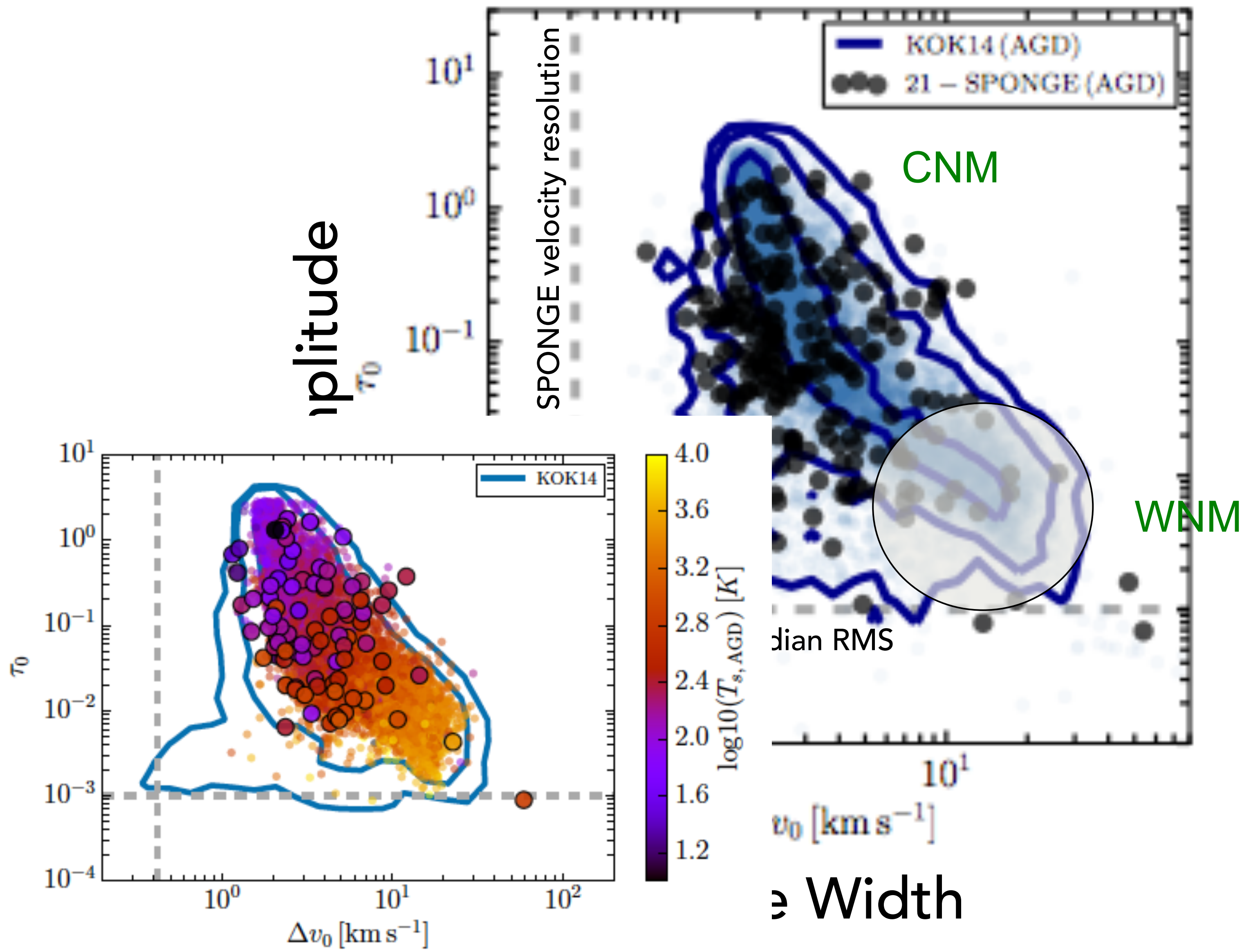
3D HD numerical simulations
Kim et al. 2014, ApJ, 786, 64

Where is the WNM?

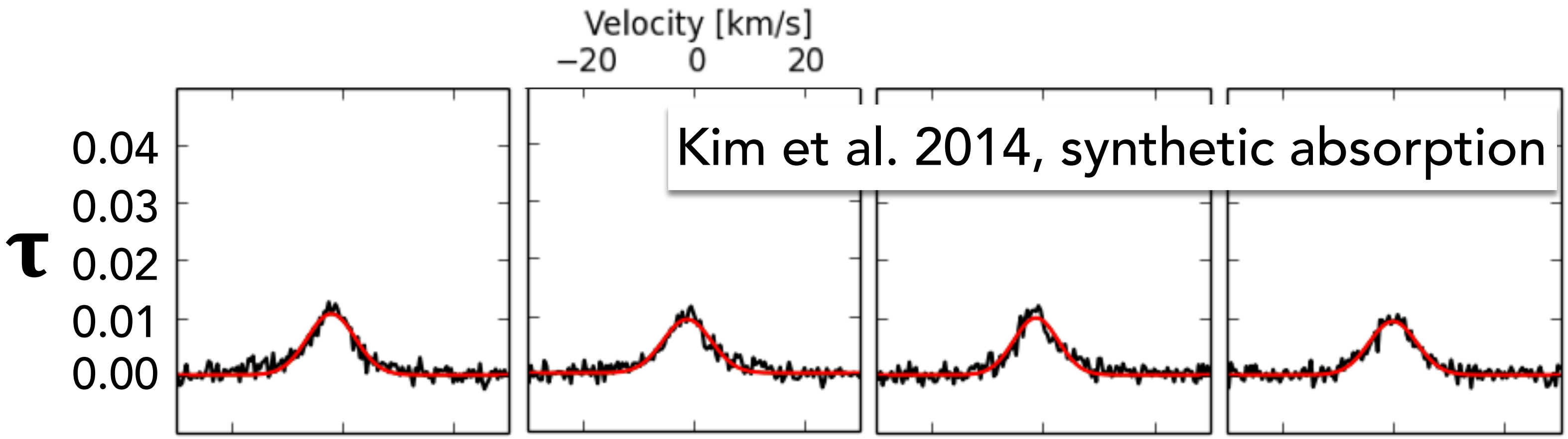


Murray et al. 2017

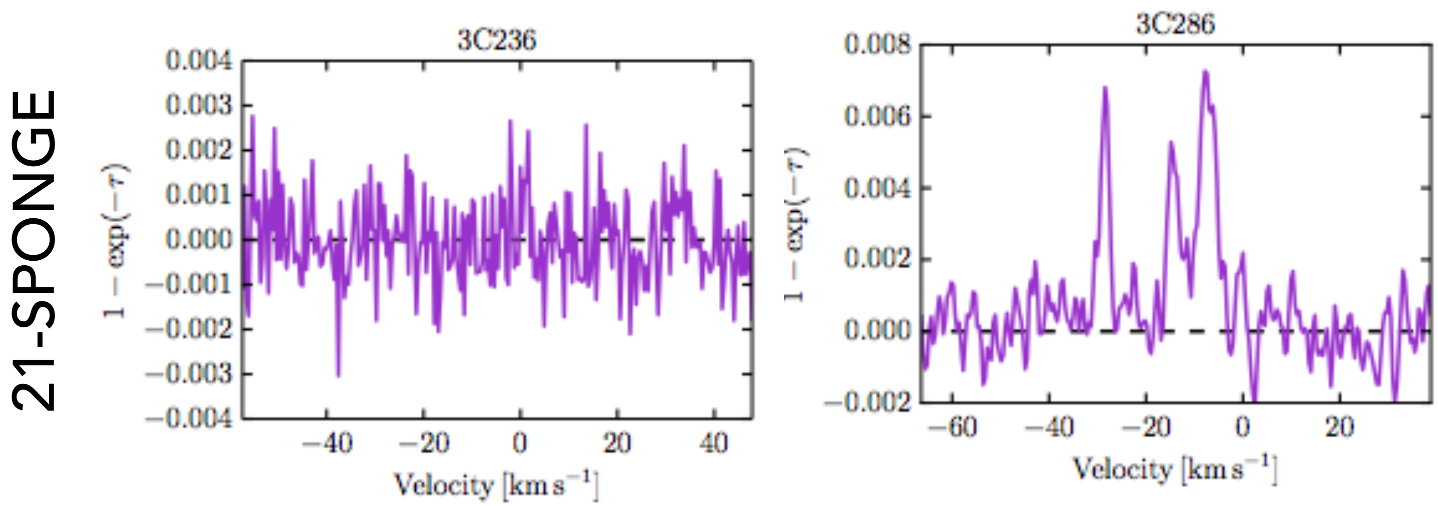
Observed vs. Simulated HI Absorption



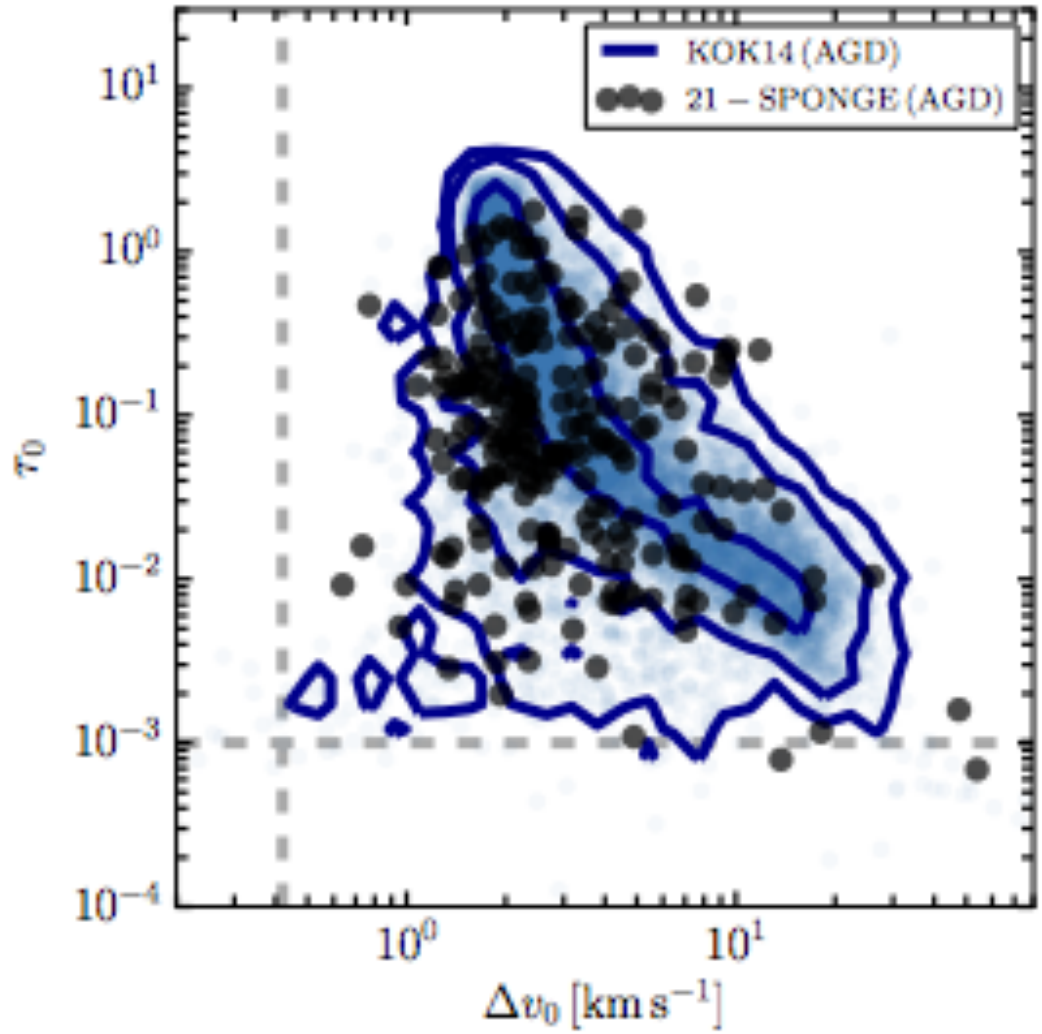
Observed vs. Simulated WNM Absorption



Strong, broad, WNM absorption lines, without CNM, are NOT seen in observations! → clear disagreement btw simulations and observations



WNM temperature depends on turbulence but also detailed physics: Lya scattering

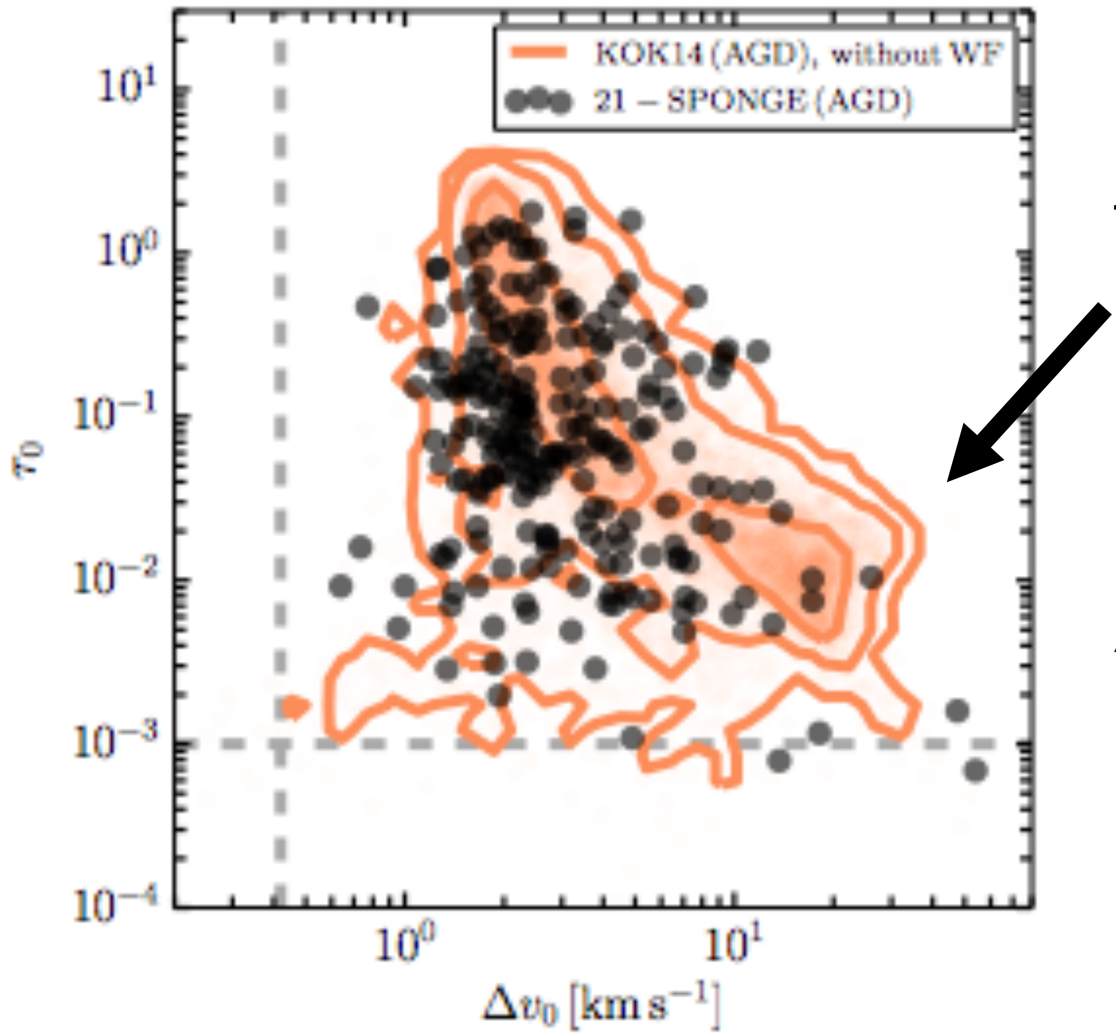


Resonant Lyα scattering included

(Wouthuysen-Field effect)

Murray et al. 2017

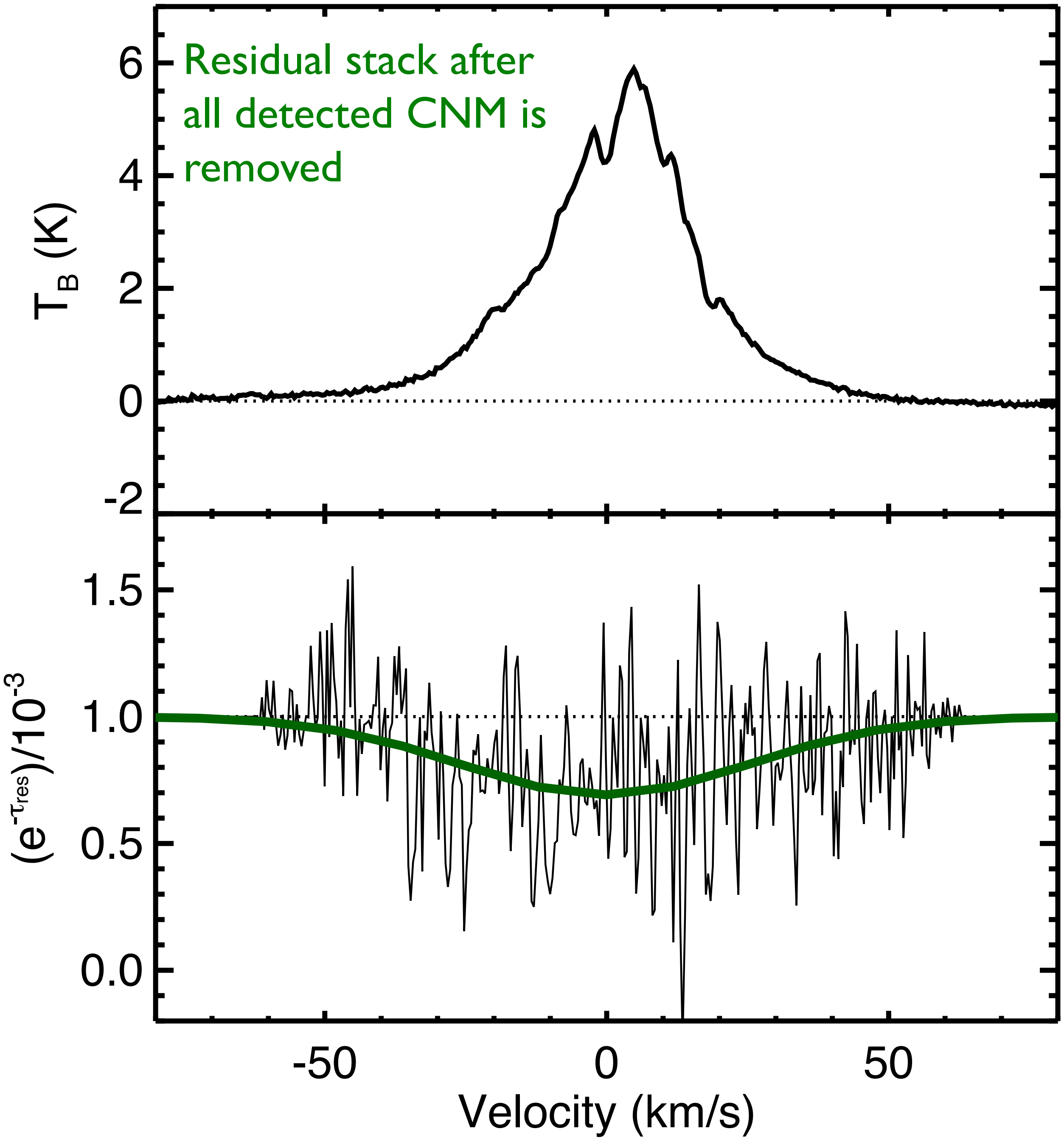
Without Lya scattering



Omitting the WF effect lowers WNM temperature and exacerbates the difference between synthetic and observed absorption lines.

Another issue: absence of hot phase in the simulation

Murray et al. 2017



21- 

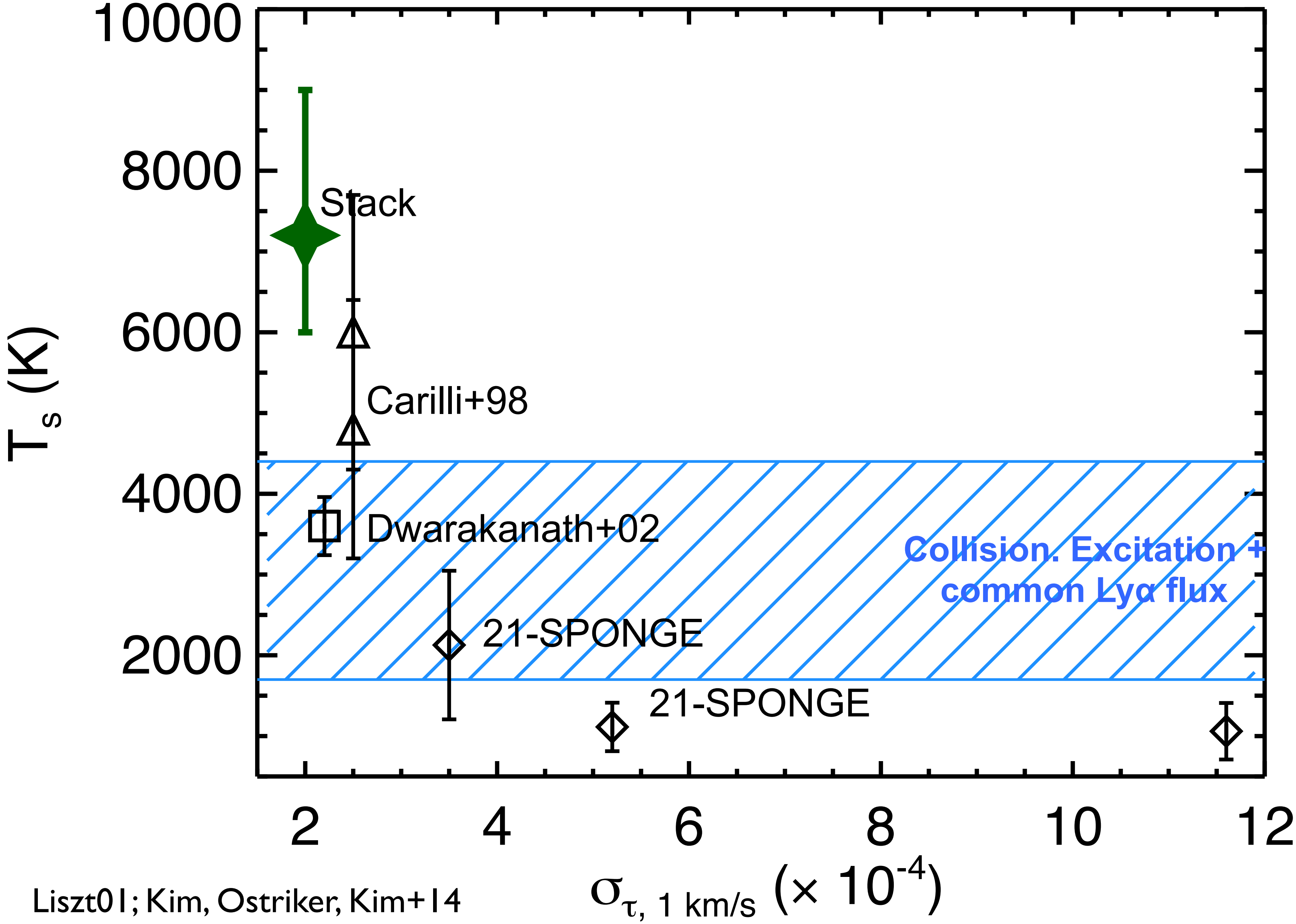
How warm is the WNM?

Stacking analysis of 19 HI absorption spectra

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

Murray+14: 5σ statistical detection

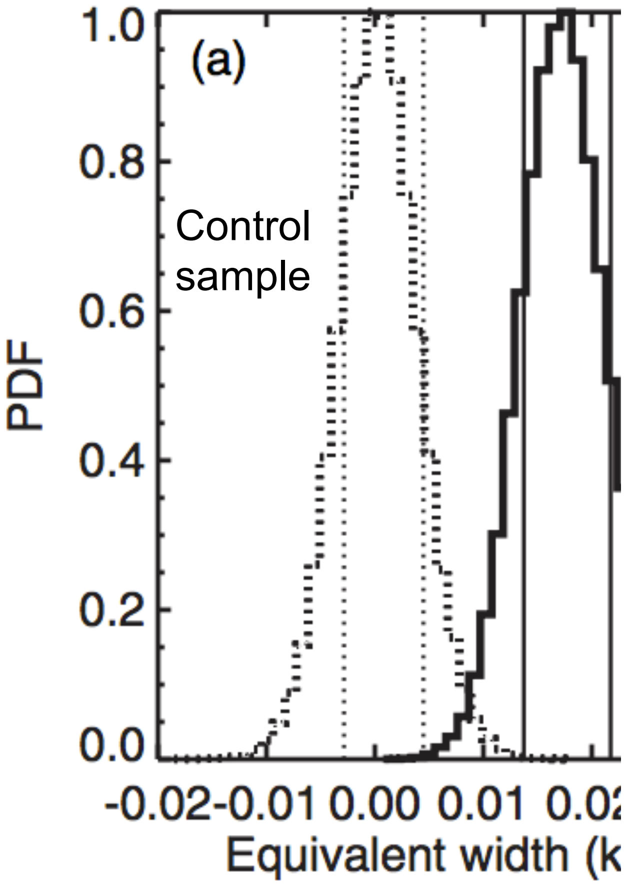
WNM warmer than expected?



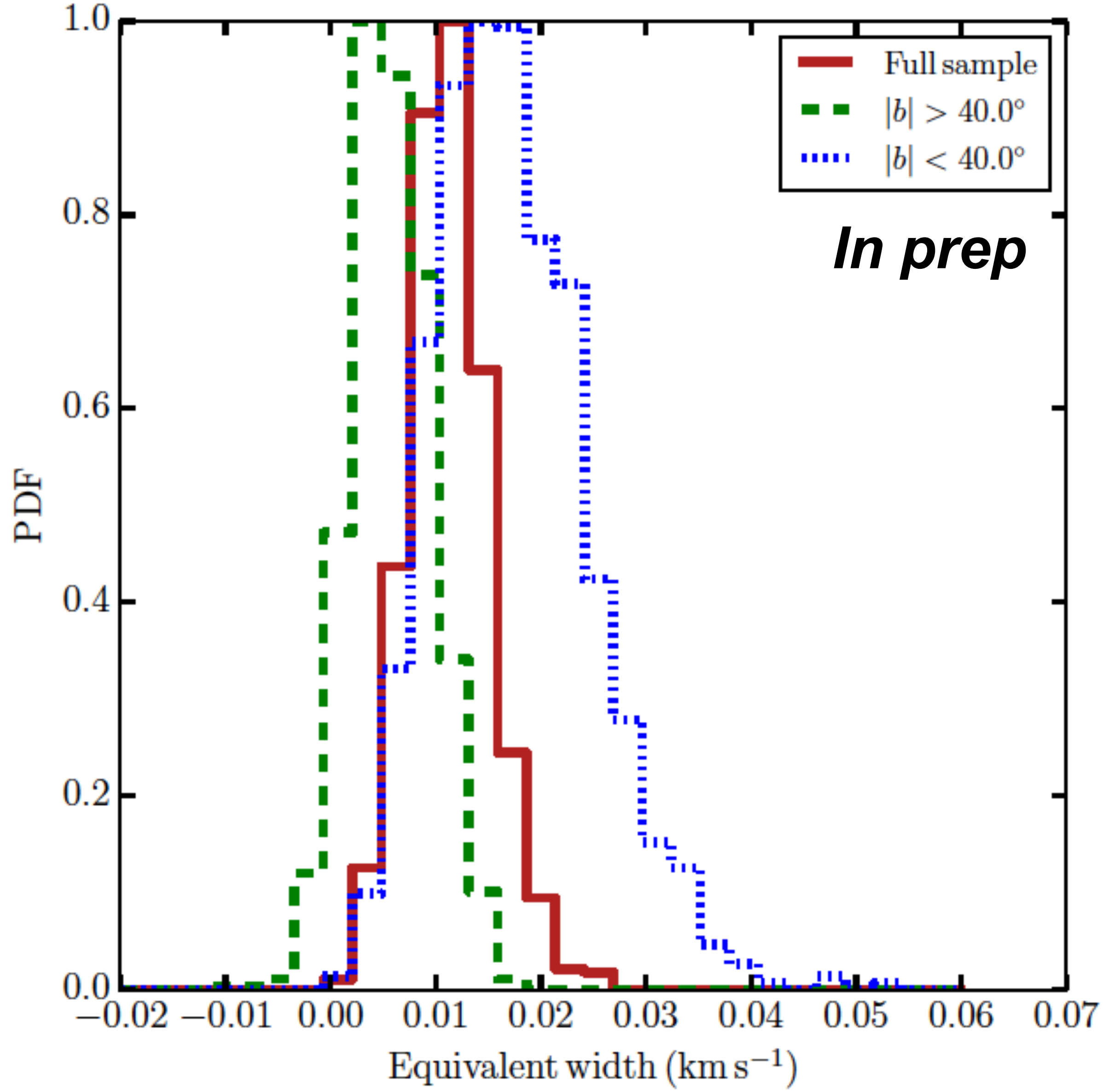
Liszt01; Kim, Ostriker, Kim+14

$$\langle T_s \rangle = 7200^{+1800}_{-1200}\,K$$

44 sources: Ts (WNM) higher at low-b?

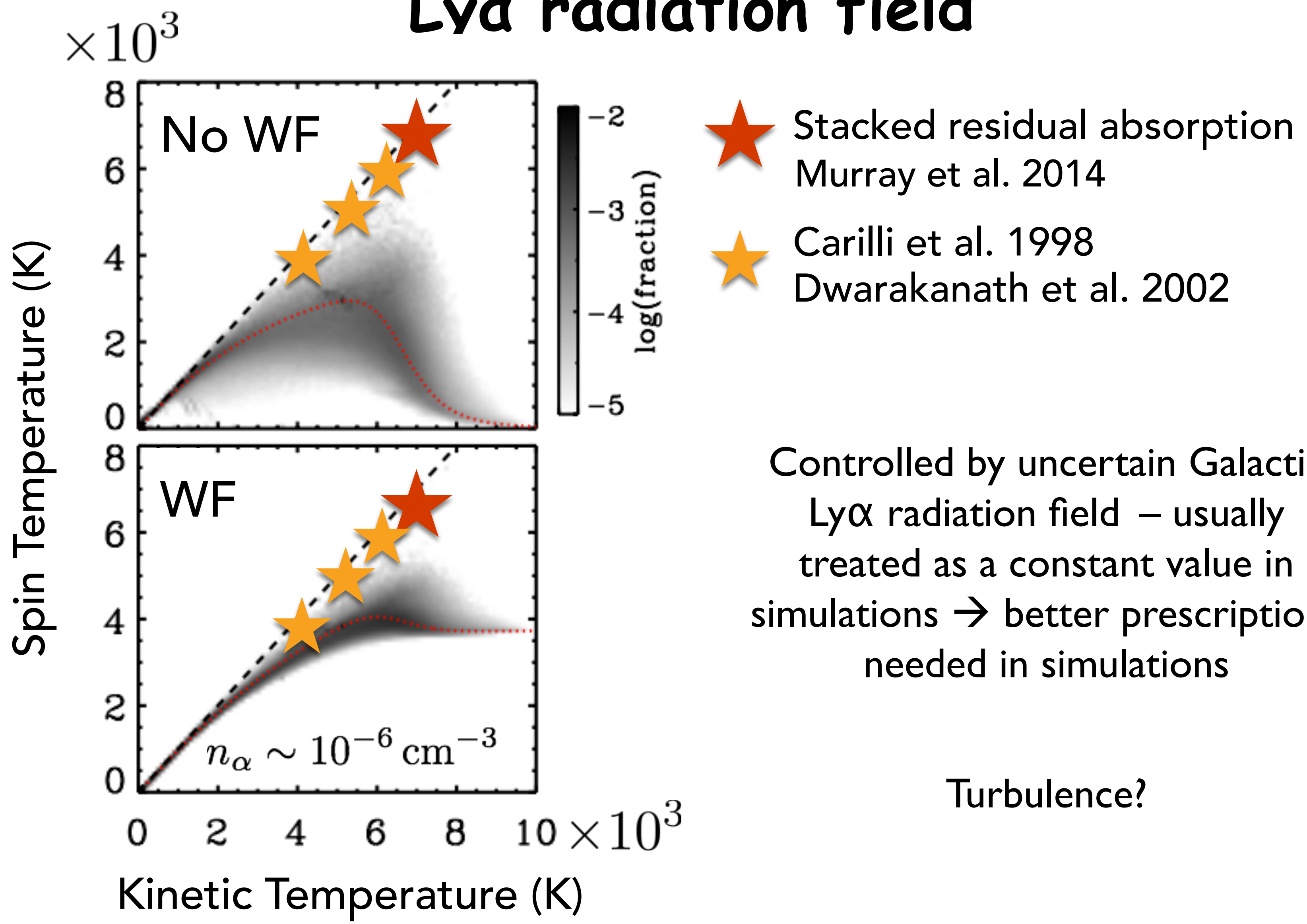


Bootstrap MC simulation, 19 sources



Murray et al. 2014, ApJ, 781

To explain WNM temperature need significant Lya radiation field



Controlled by uncertain Galactic Lyα radiation field – usually treated as a constant value in simulations → better prescriptions needed in simulations

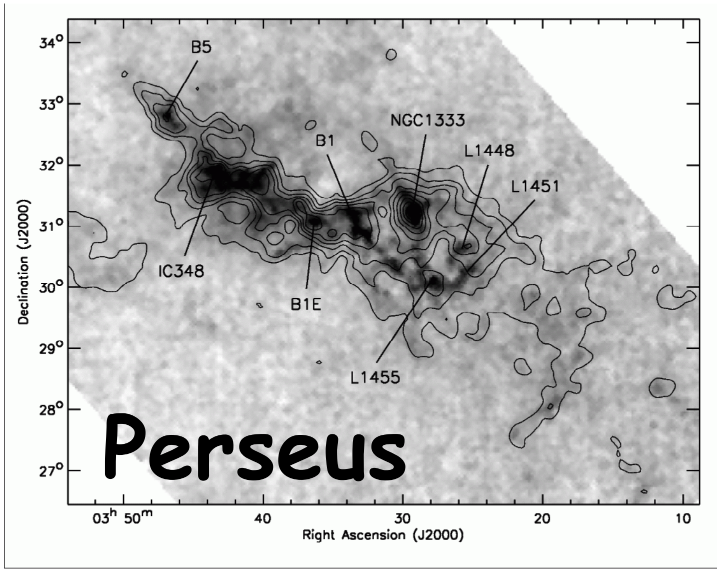
Turbulence?

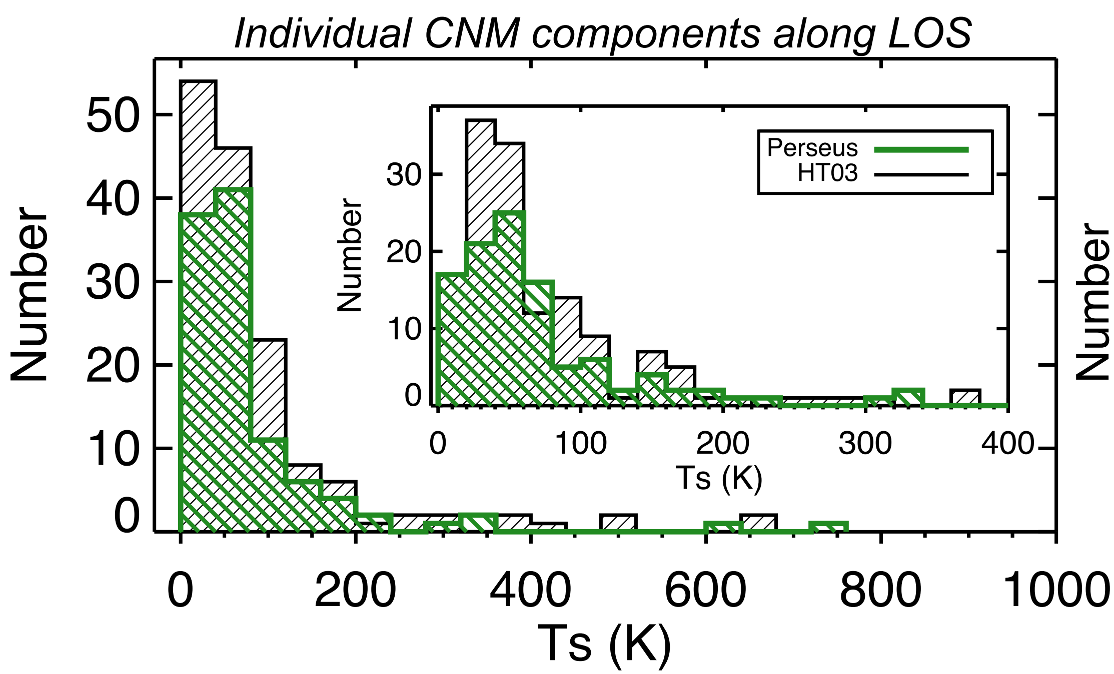
Kim et al. 2014

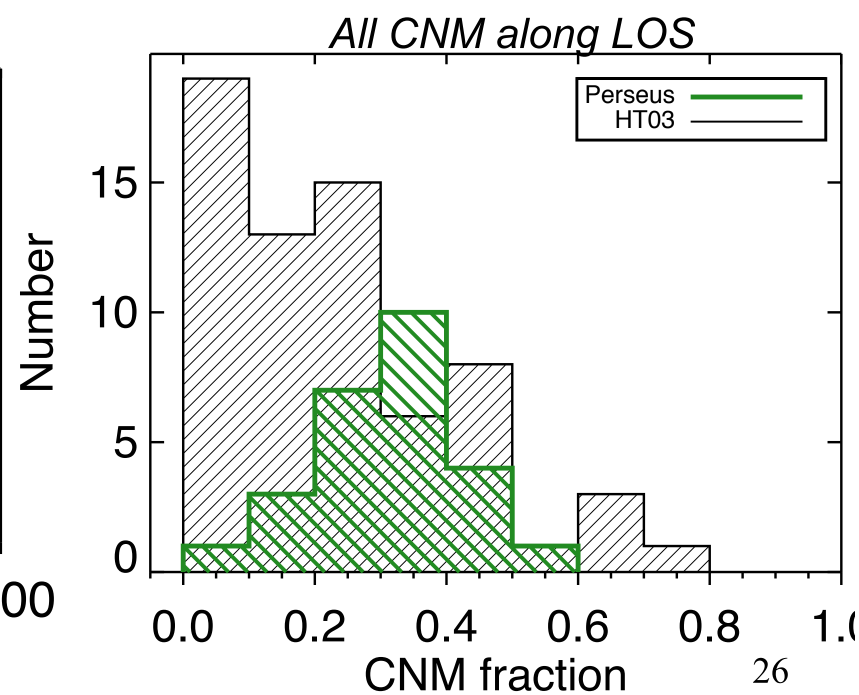
2. Are HI phases different close to GMCs?

- ~30 HI absorption lines in the vicinity of Perseus
- CNM clouds in/around GMCs typical.
- Higher CNM fraction than in a random ISM field.
- 50% WNM → lots of warm gas!
- 10% mass increase when cold HI included

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







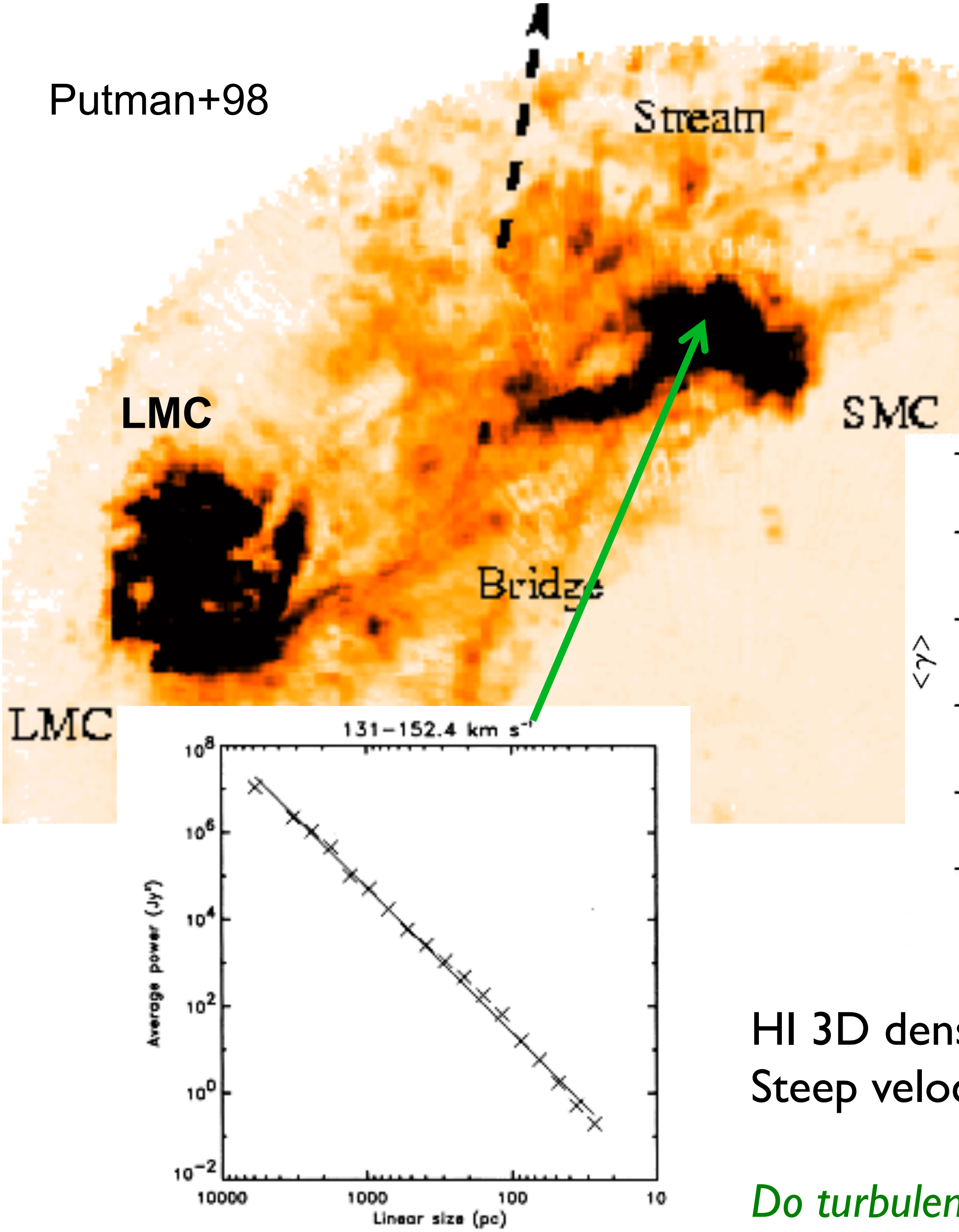
Summary/future:

1. Importance of turbulence for HI phase structure?

- 21-SPONGE is the highest sensitivity HI absorption-line survey constraining Ts of neutral gas.
- 21-SPONGE: lack of components with Ts>2000 K relative to the simulations. Possible reasons: WNM is hotter than expected as suggested by stacking analysis.
- Detailed physics of HI excitation (Galactic Lyα flux) still need to be understood to match observations with simulations.
- CNM fraction around Perseus higher than in random ISM. Buildup of molecular clouds and geometry of CNM?
- Future: additional sources with more SPONGE, GASKAP, SKA

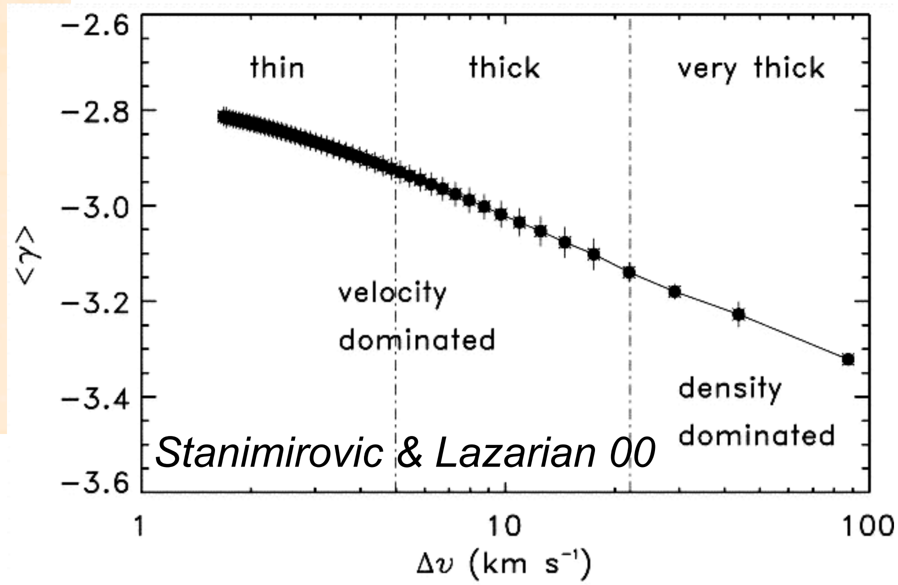
Small Magellanic Cloud

Putman+98



Stanimirovic+99

No preferred spatial scales from 30 pc to 4 kpc! No turnover on largest scales.

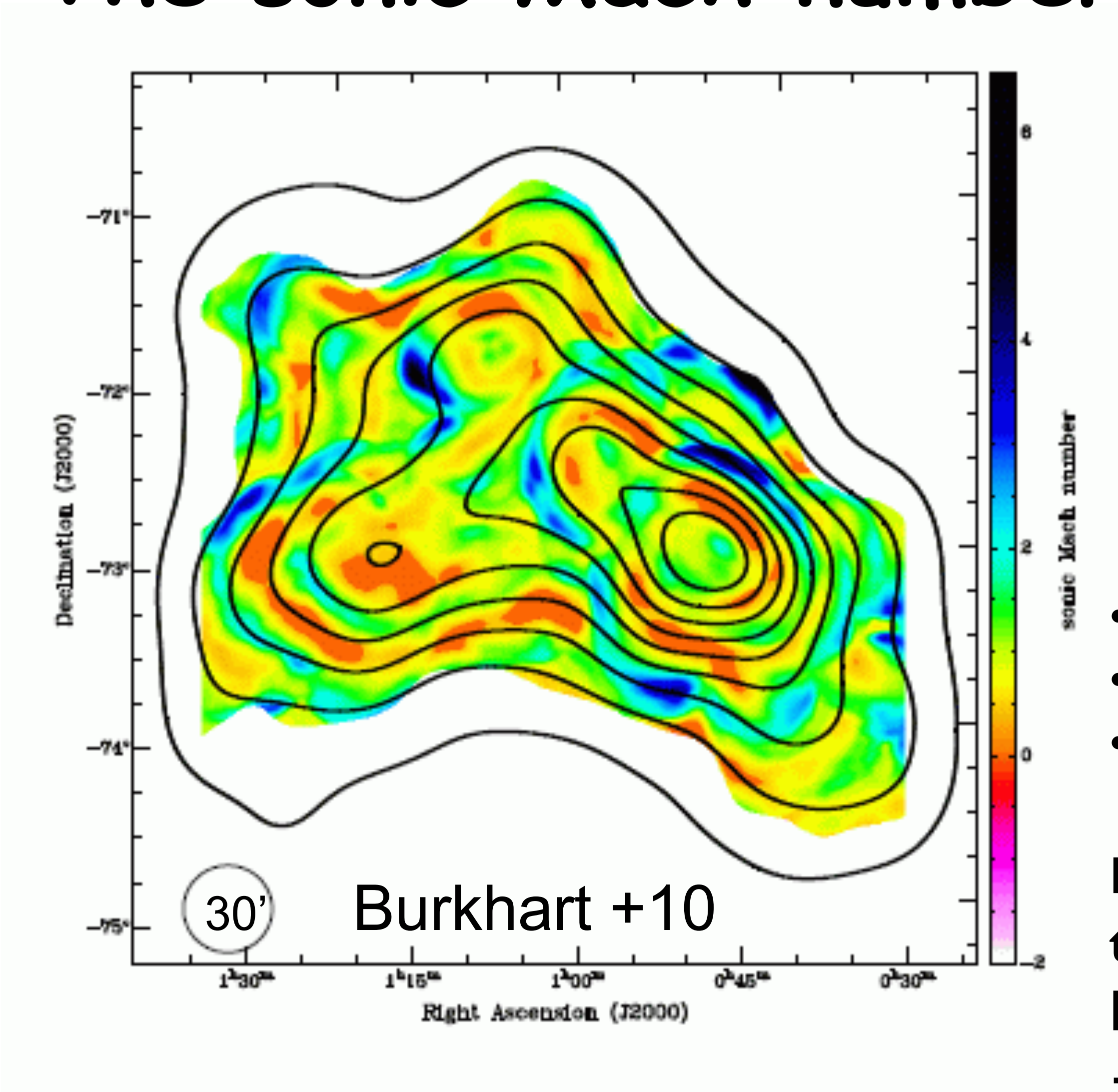


Stanimirovic & Lazarian 00

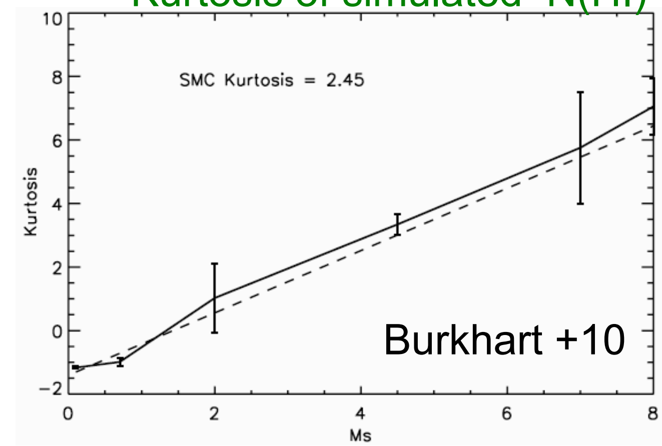
HI 3D density: -3.4
Steep velocity spectrum (Chepurnov+15): -3.7

Do turbulent properties vary spatially and can this leads us to turbulent drivers?

The sonic Mach number across the SMC



Kurtosis of simulated N(HI)



- Quiescent: ~10%
- 0<Ms<2: ~80%
- Ms>2: ~10%

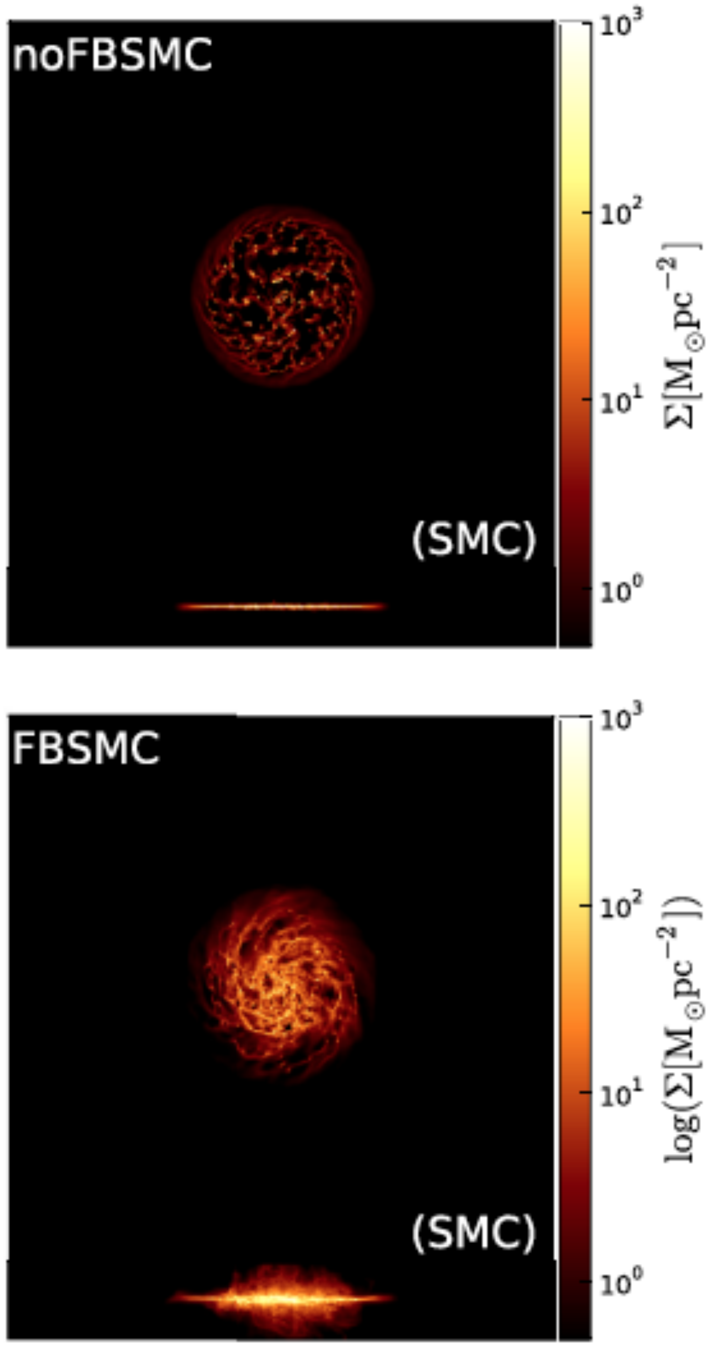
Most turbulent regions trace tidal or shearing flows.

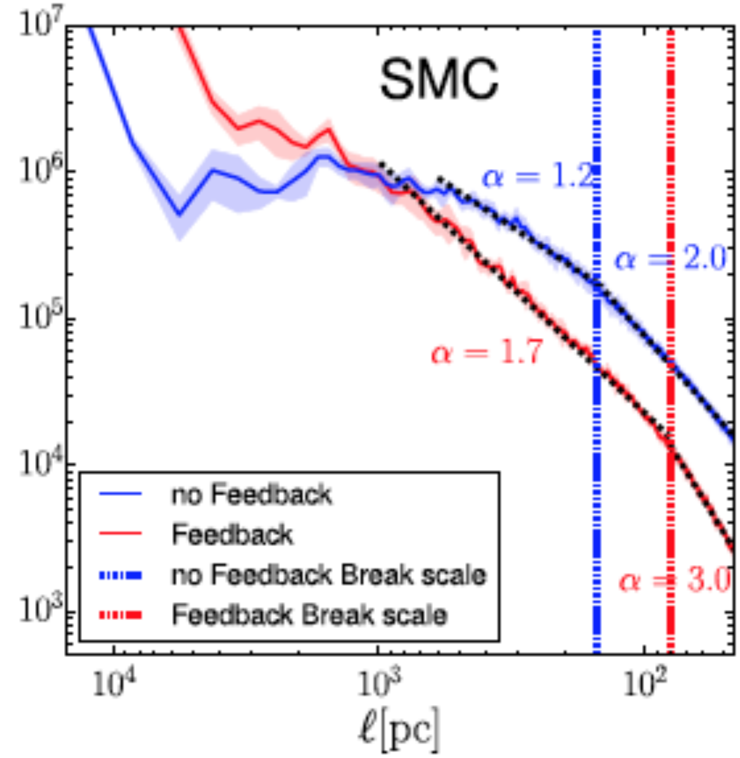
Large-scale tidal flows

→ Shearing instability?

Concerns: isothermal simulations,
High-Ms regions close to resolution limit

Stellar feedback affects the Power spectrum slope:

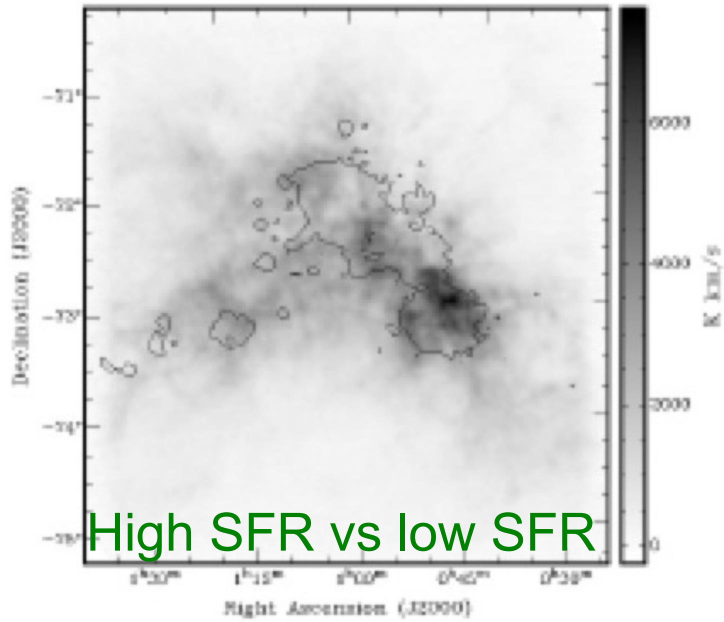


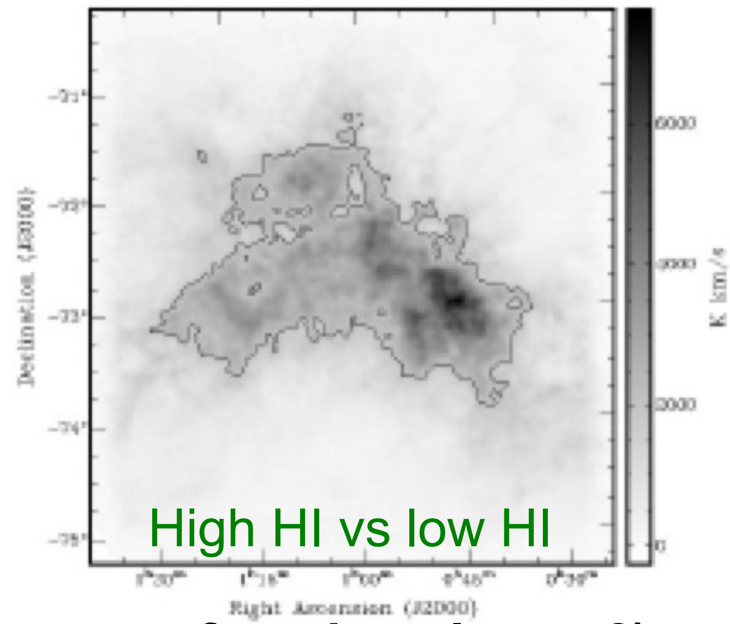


Grisdale et al. 2015

Strong feedback (stellar winds + SNe explosions) destroys clouds shifting power from small to large scales → steeper power spectra.

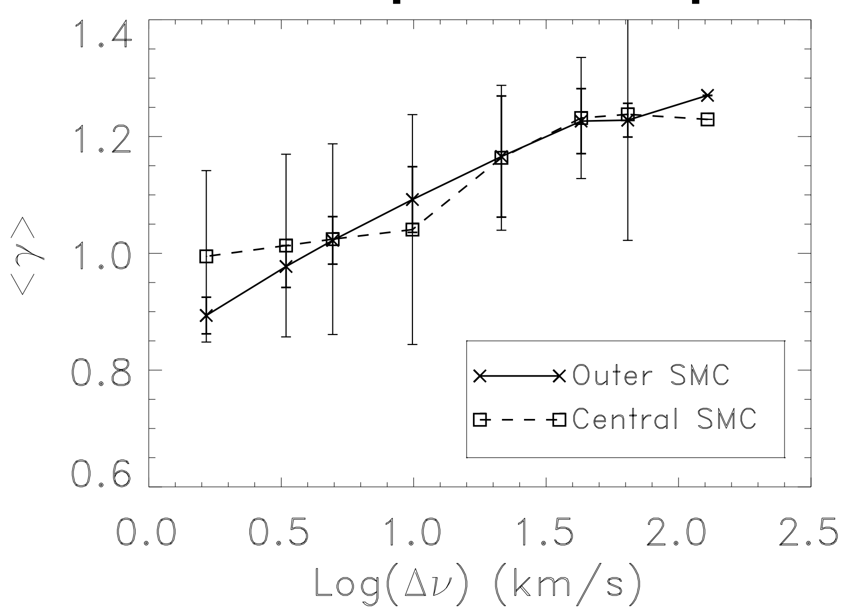
SMC Structure Function: Nestingen-Palm+, submitted

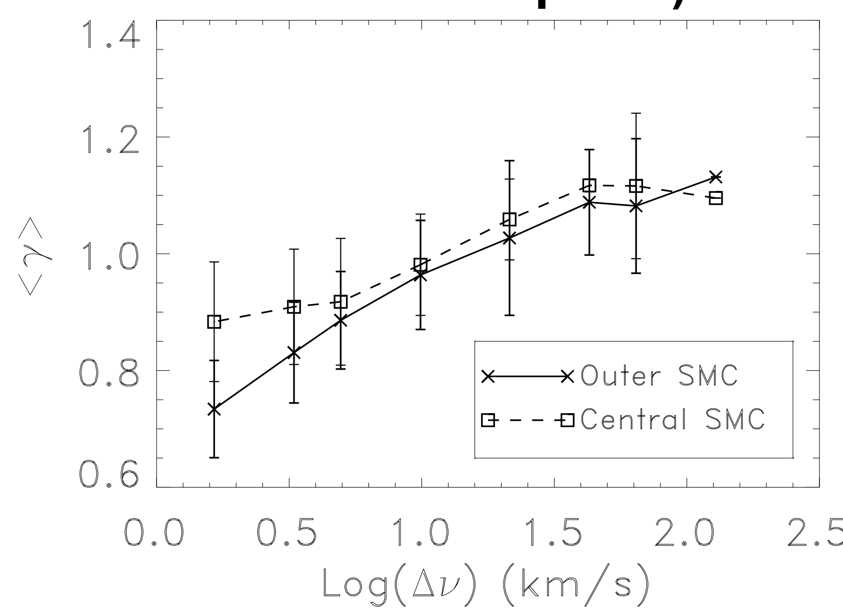




Power spectrum slope = - (structure function slope +2)

Structure function slope





Summary

- **3.** How important is stellar feedback for HI turbulence?

No difference in turbulent properties between high-SFR vs low-SFR regions → uniform turbulent properties across the SMC.

Likely large-scale turbulent driving via gravitational instabilities.

Turbulent properties decoupled from initial driving sources or stellar feedback inefficient especially at low metallicity?

SFR is not a good tracer of stellar feedback?

Enhanced turbulent properties only in highly localized regions → need higher resolution observations?