Diffuse neutral interstellar medium: temperature and turbulence
(from H I 21 cm absorption studies)

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The multiphase atomic ISM

THE ASTROPHYSICAL JOURNAL, Vol. 155, March 1969

COSMIC-RAY HEATING OF THE INTERSTELLAR GAS

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Department of Astronomy, University of California, Berkeley
Received December 16, 1968; revised January 17, 1969

ABSTRACT

We present a model of the interstellar medium based on detailed calculations of heating by low-energy cosmic rays. The model contains two thermally stable gas phases that coexist in pressure equilibrium, one at $T = 10^4$ ° K and one at $T < 300$° K. The hot gas occupies most of interstellar space. Gravitation in

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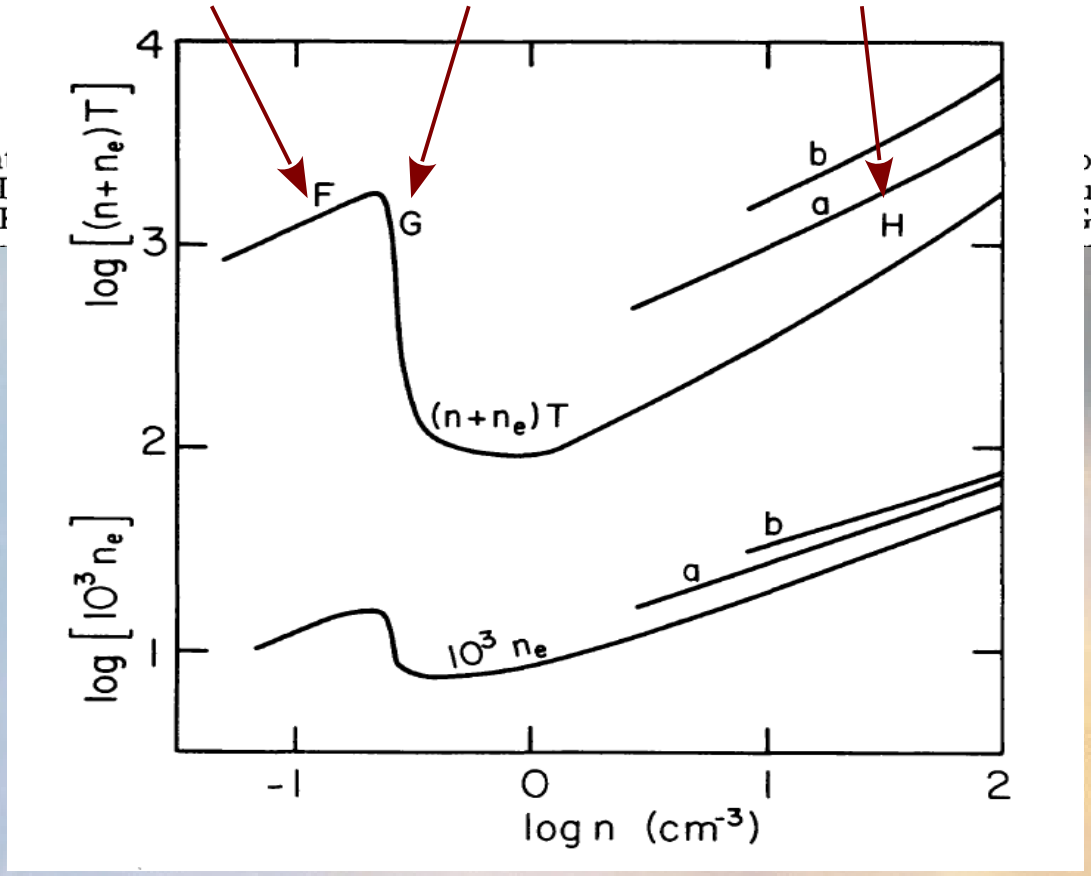

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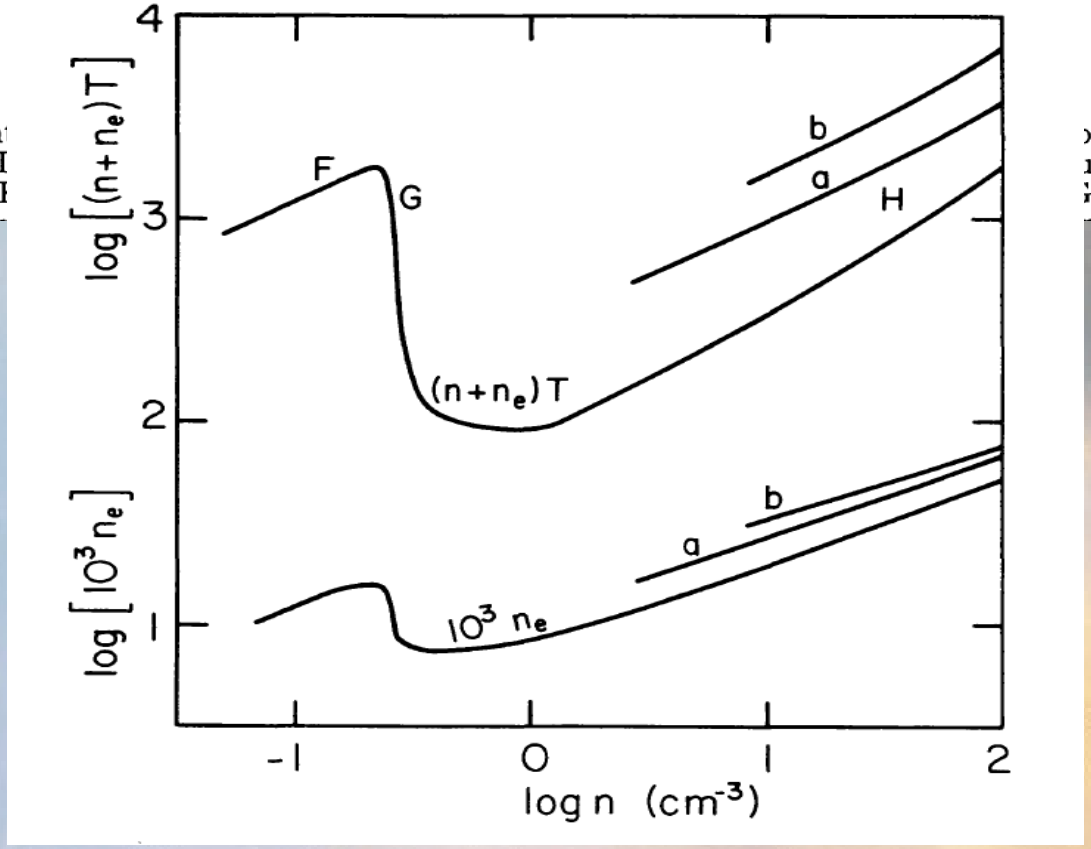
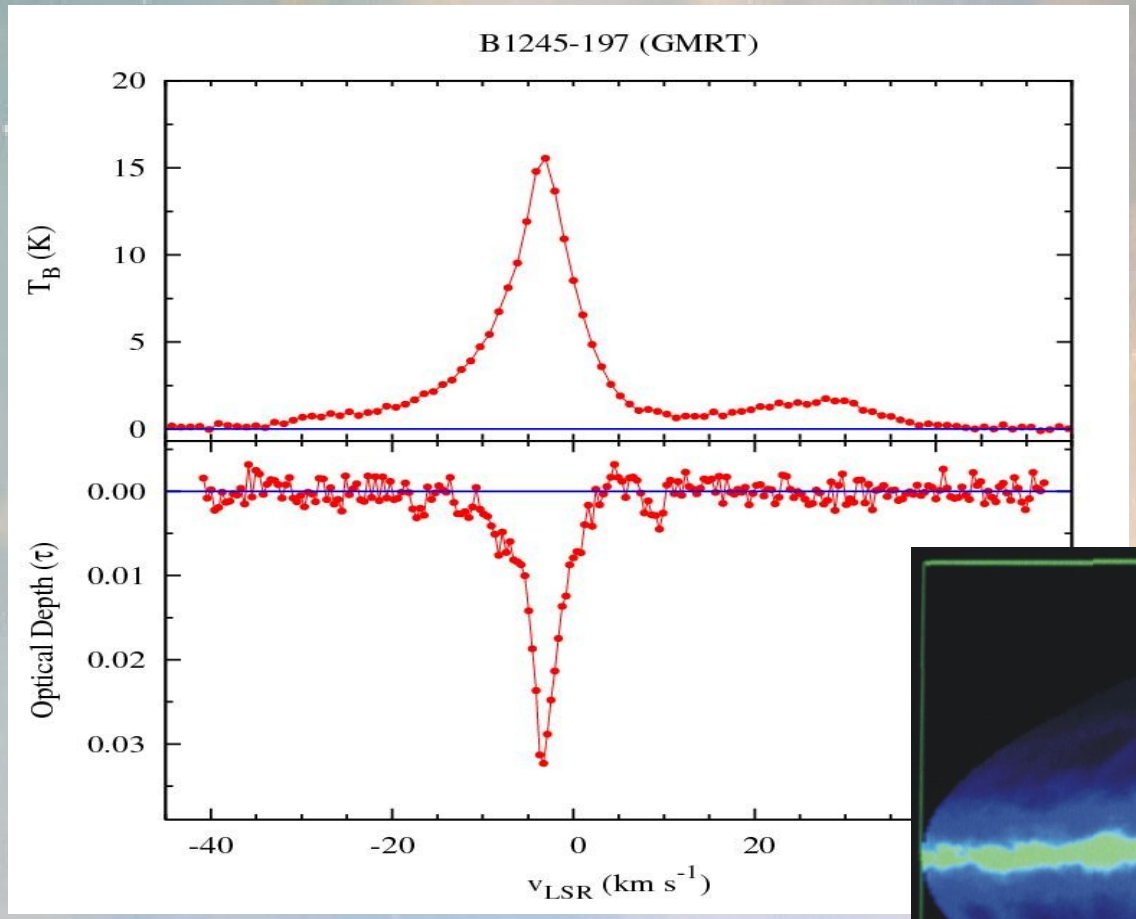
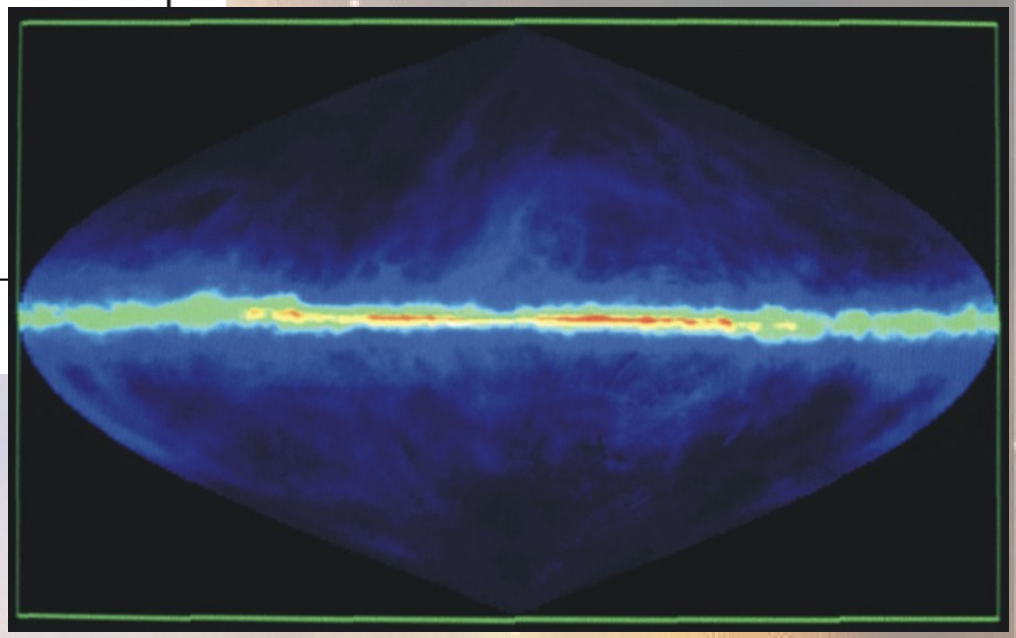


Atomic hydrogen 21 cm transition



Roy et al. (2013)



Credit: NRAO/AUI, Dickey & Lockman (1990)

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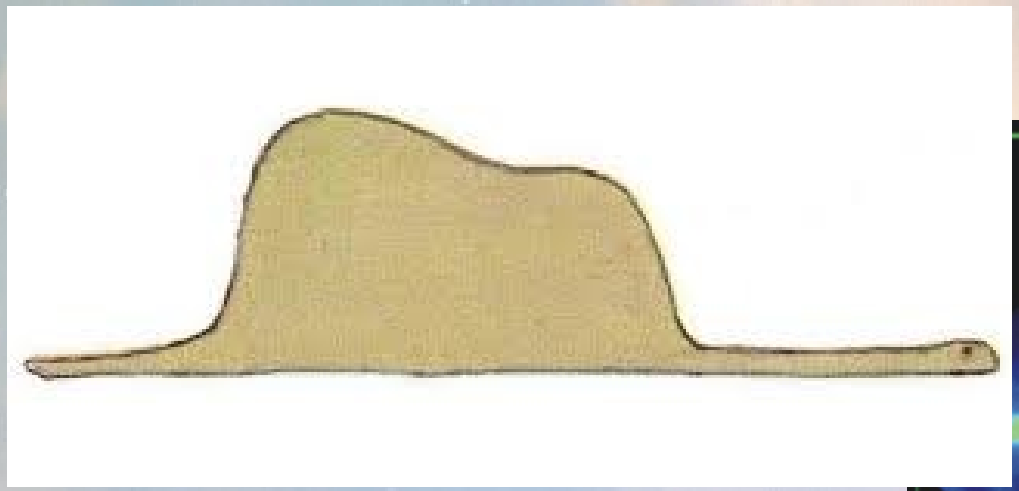
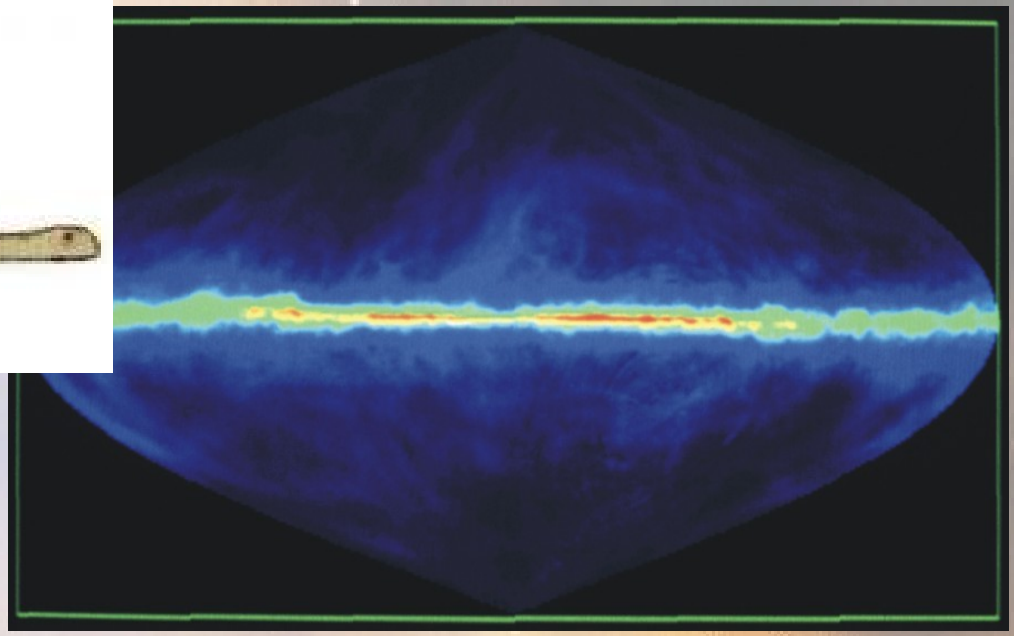


Antoine de Saint-Exupery (1943)



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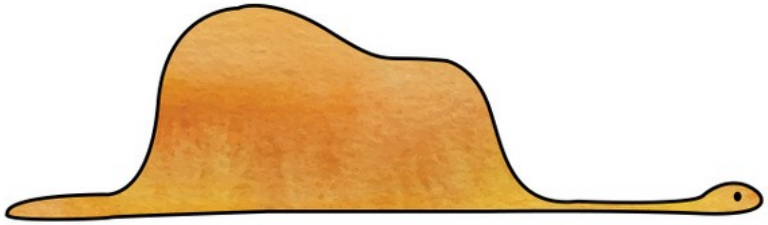
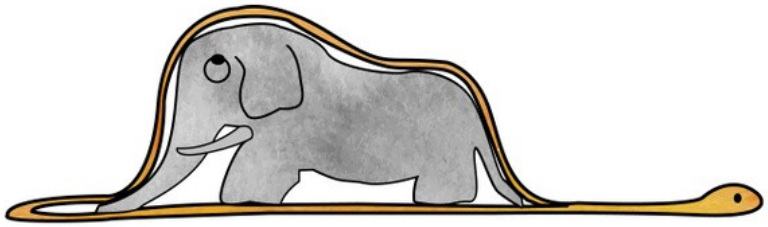


"My drawing was not a picture of a hat.
It was a picture of a boa constrictor digesting an elephant."



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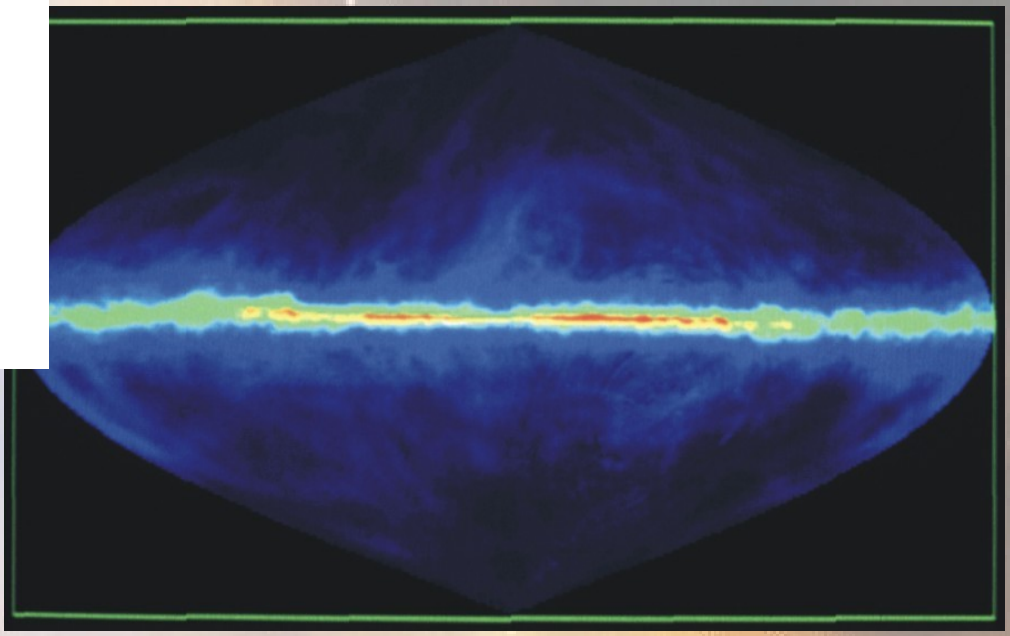
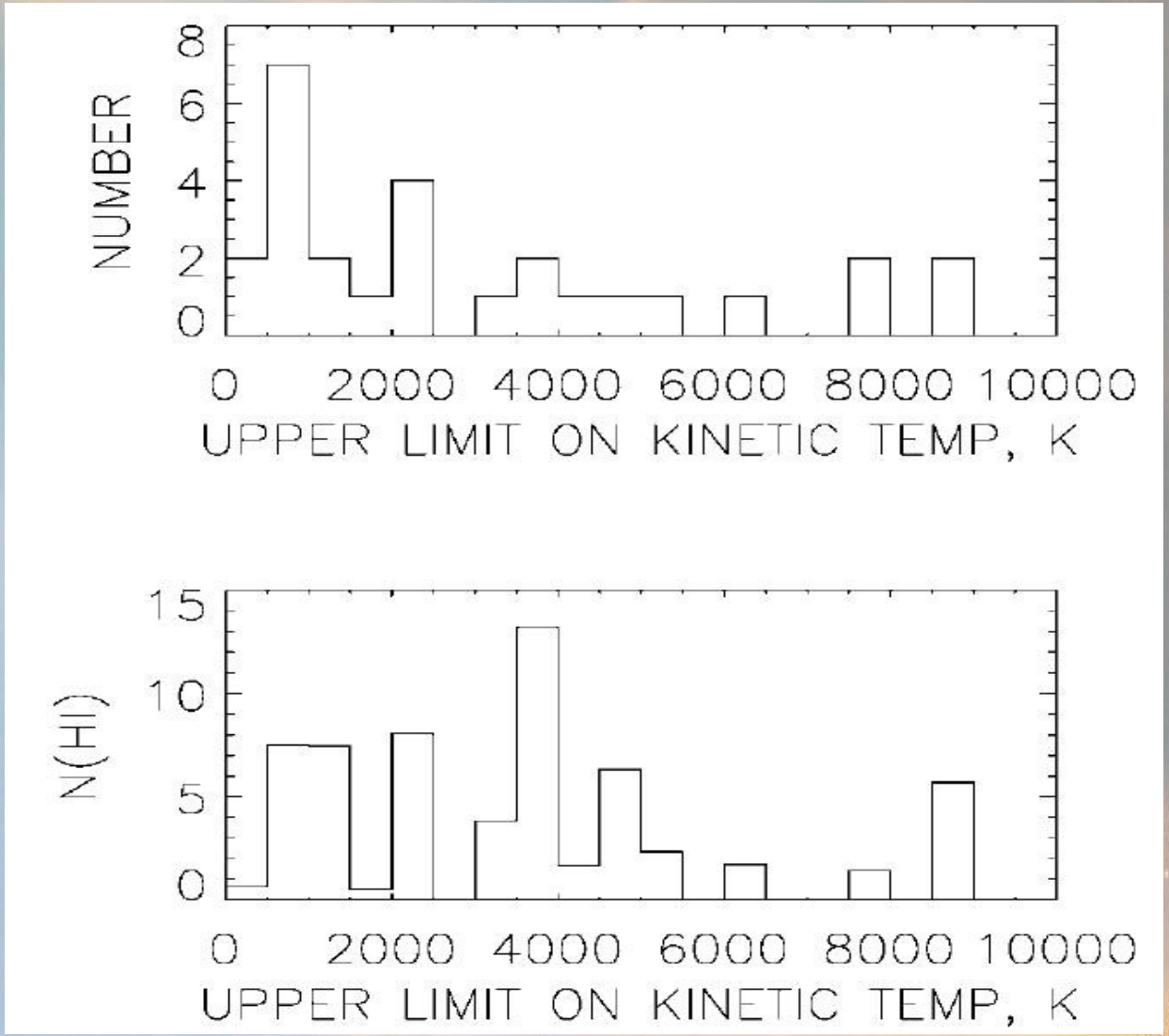


Credit: NRAO/AUI, Dickey & Lockman (1990)

Elephant in the room: A large fraction of unstable gas?



Heiles (2001)

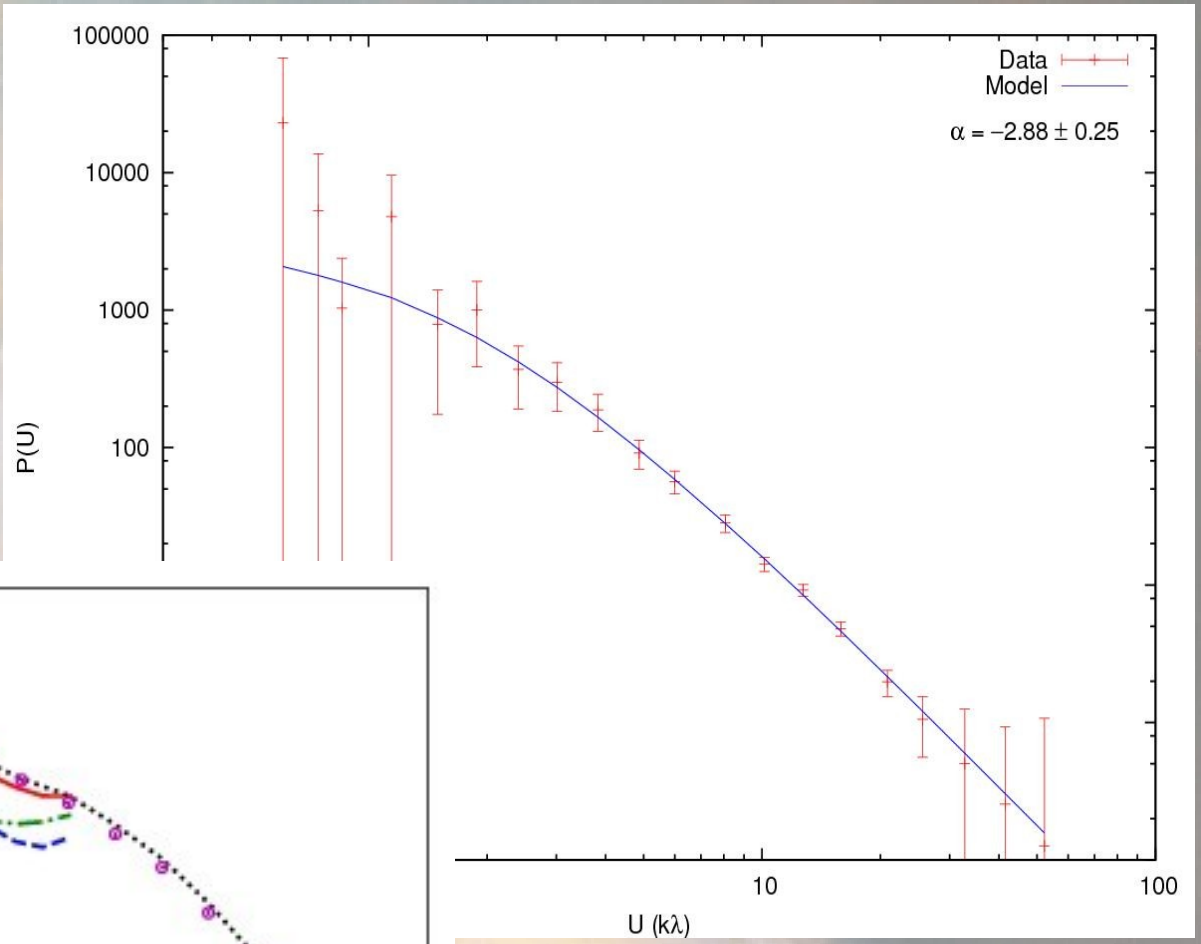
Caution: a variety of temperatures …

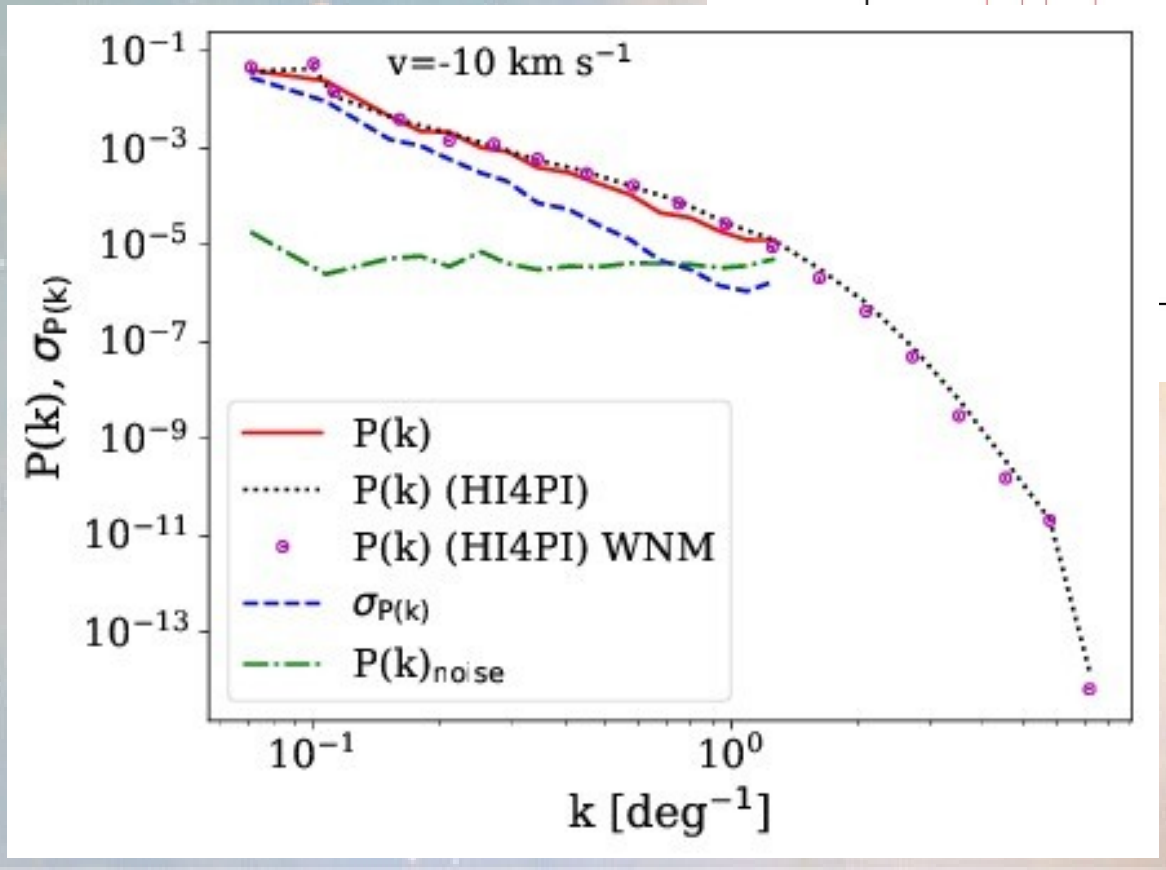
- **Kinetic temperature (T_K)**
  - velocity distribution of the thermalized gas
- **Spin temperature (T_S)**
  - Boltzmann distribution of population
- **Doppler temperature (T_D)**
  - thermal and non-thermal broadening of line

Structures in diffuse ISM

- **Galactic H I emission (Crovisier & Dickey 1983, Green 1993)**
- **Other galaxies (Stanimirovic et al. 1999, Elmegreen et al. 2001, Begum et. Al 2006, Dutta et al. 2009a,b)**
- **H I absorption – pc/sub-pc scale (Deshpande et al. 2000, Roy et al. 2010)**
- **Tiny scale H I opacity fluctuations (Faison et al. 2001, Brogan et al. 2005, Lazio et al. 2009, Dutta et al. 2014)**
- **With pulsars at AU scale (Frail et al. 1994, Johnston et al. 2003)**

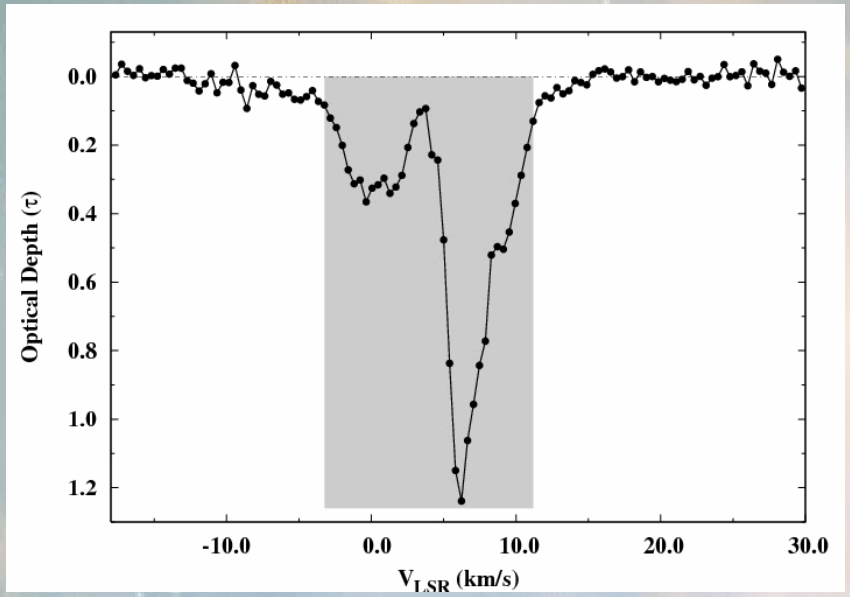
Choudhuri and Roy (2019)

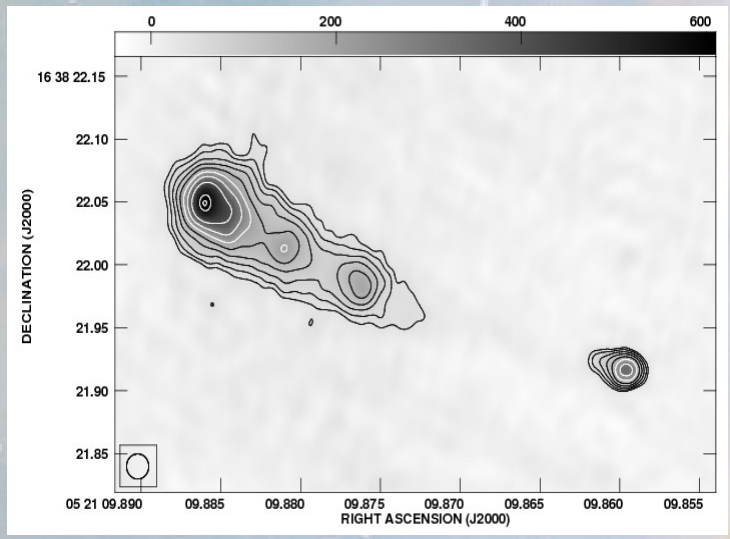


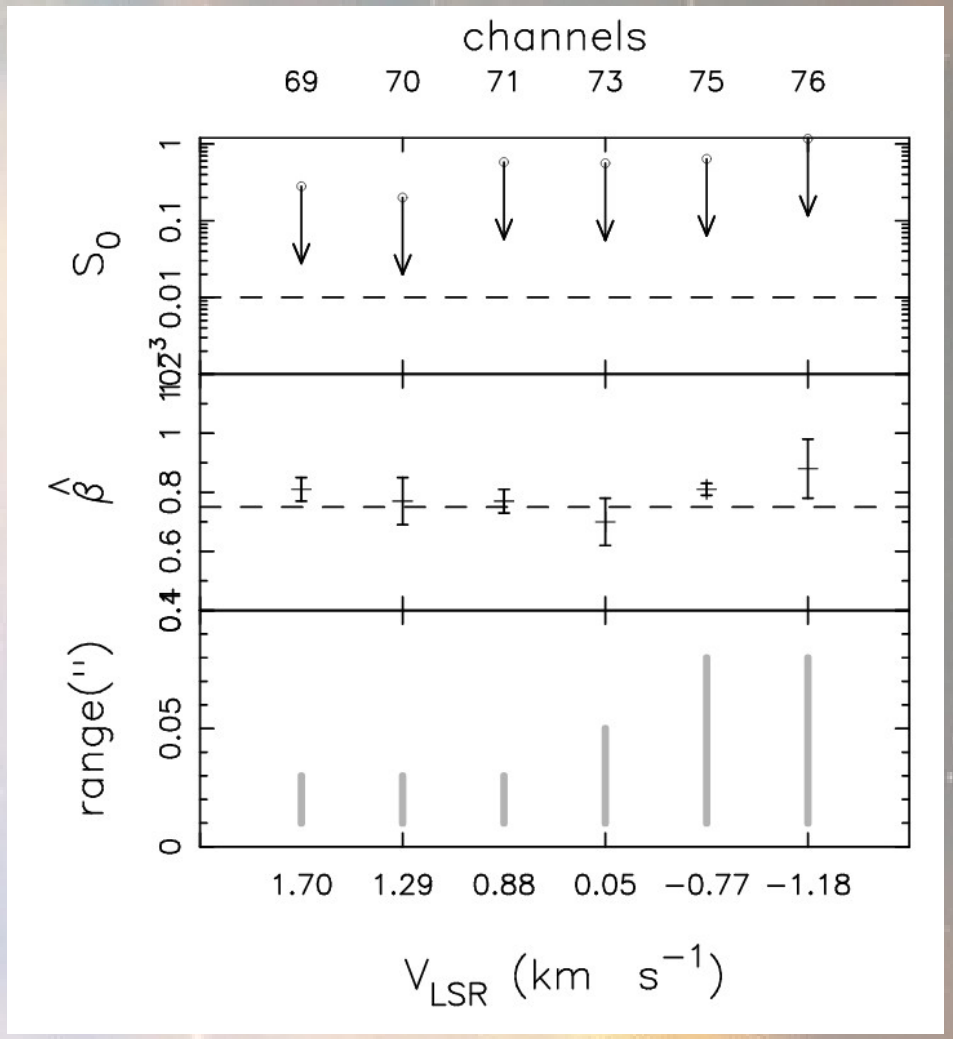


Roy et al. (2009); Roy, Chengalur, Dutta & Bharadwaj (2010)

Hint of a single power law power spectrum from ~AU to > pc scale!



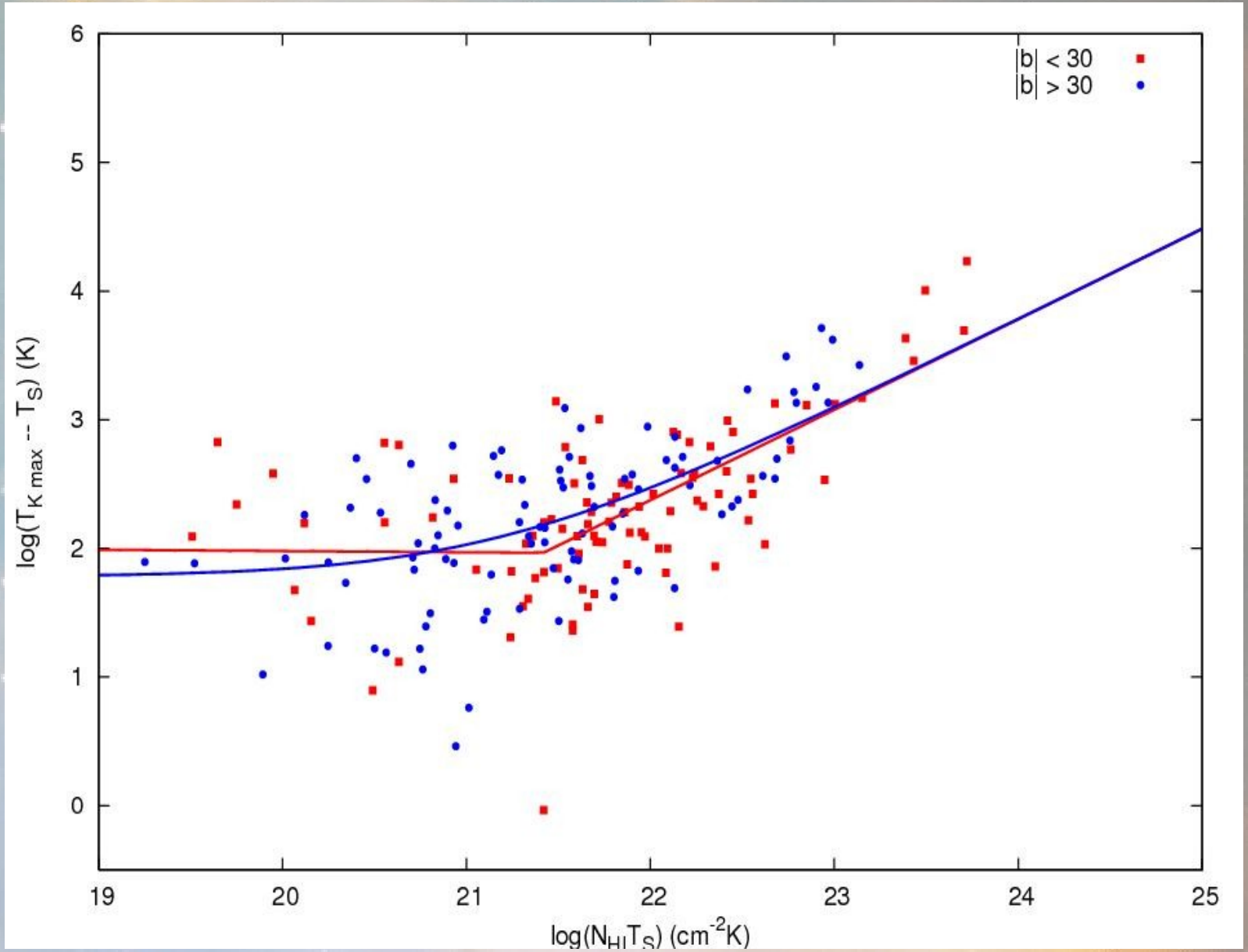




Dutta et al. (2014)

Please see Pavan K. Vishwakarma's poster!

Non-thermal broadening: estimate from the Arecibo survey …



Roy et al. 2008

Key Questions

- **Can we detect "WNM" in H I 21 cm absorption?**
  - **Carilli et al. (1998), Dwarakanath et al. (2002), Heiles & Troland (2003), Mohan et al. (2004a,b) …**
  - **Kanekar et al. (2003), Braun & Kanekar (2005) …**
- **What is the "true" temperature distribution?**
- **How much gas, if any, is in unstable phase?**
  - **Heiles & Troland (2003) …**
  - **McKee & Ostriker (1977), Wolfire et al. (1995, 2003) …**

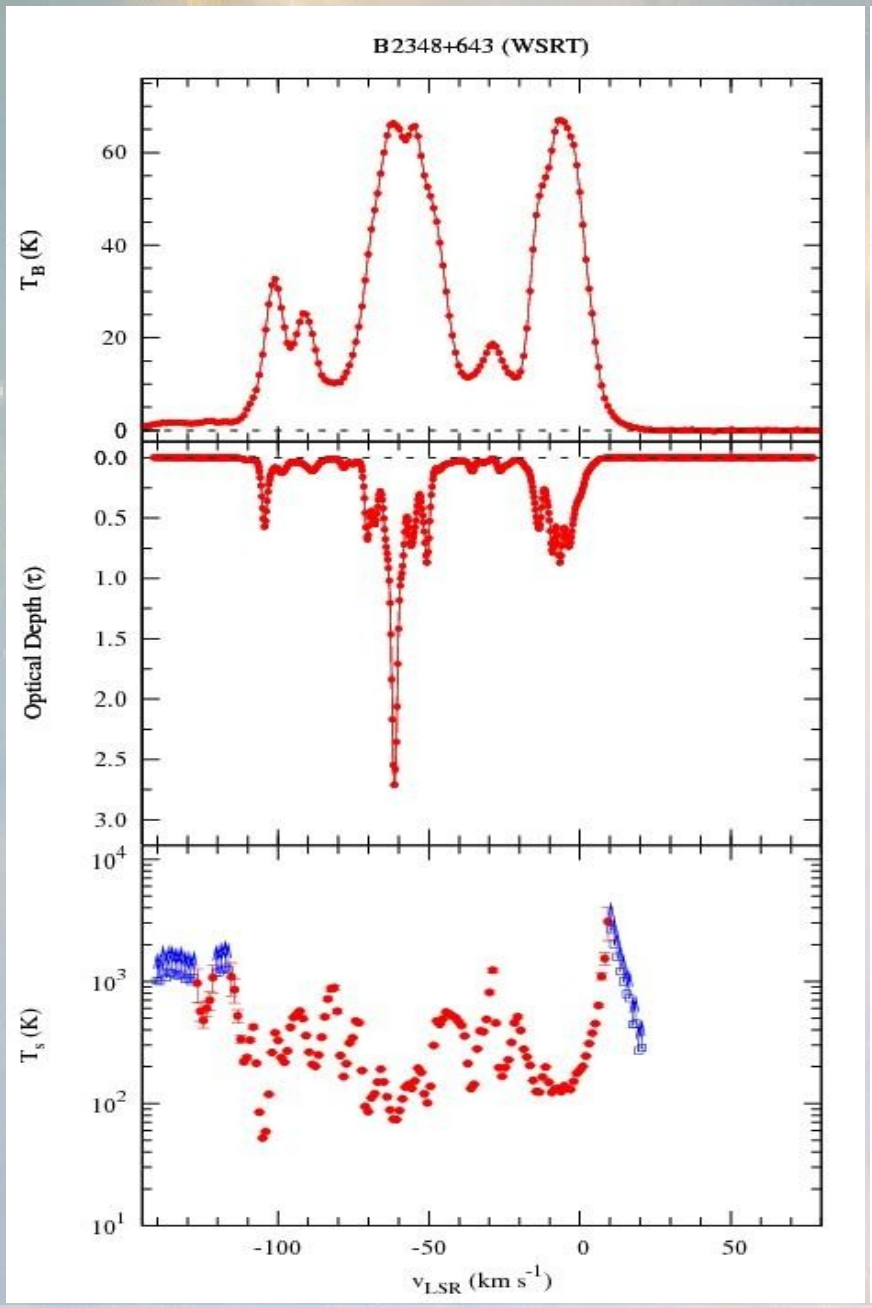
Atomic hydrogen absorption study

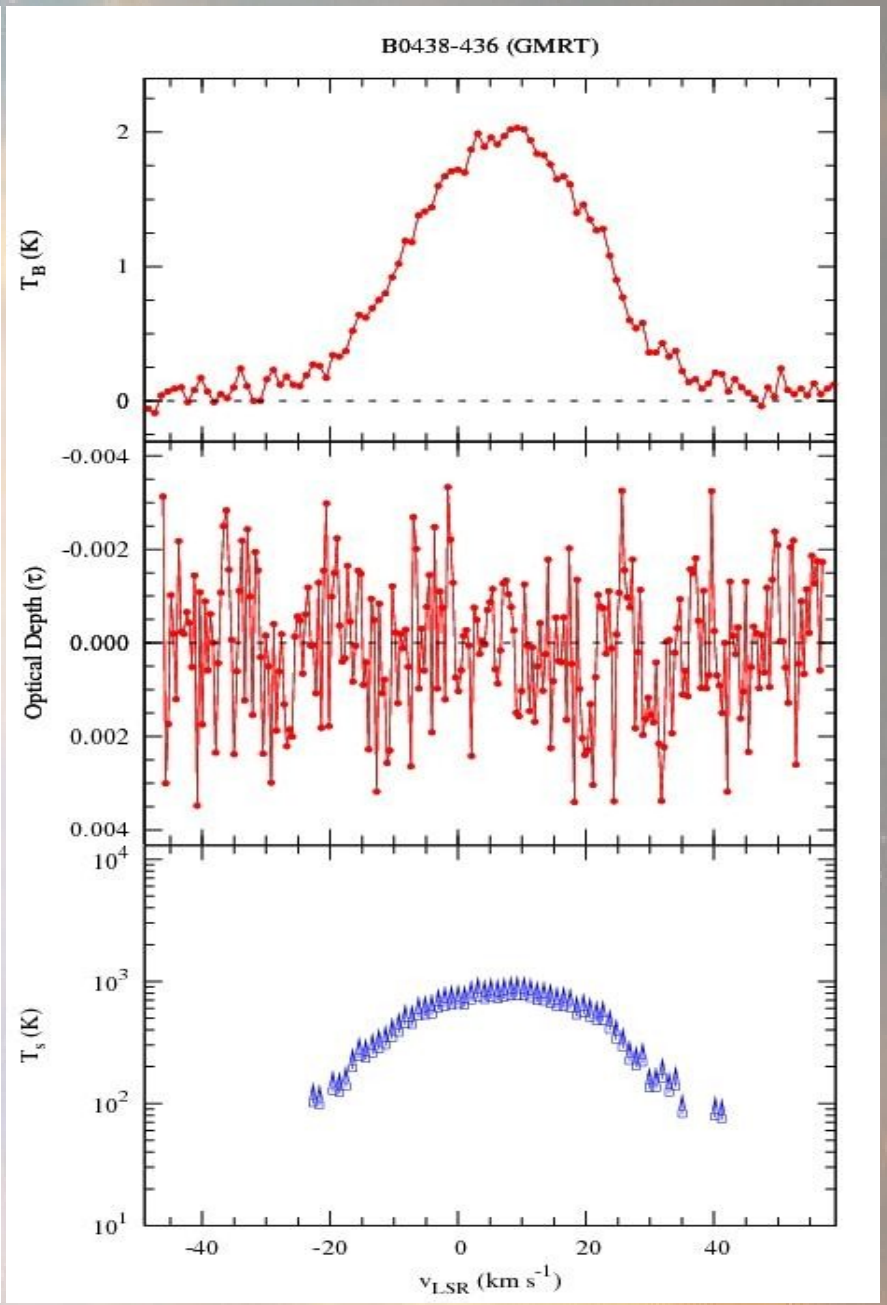
"WNM–in–absorption"

- H I absorption study with GMRT & WSRT
- 34 sources: 23 (WSRT), 11 (GMRT), [+2 (ATCA)]
- Bright, compact sources; deep integration …
- High spectral resolution, good bandpass
- Aim to detect 8000 K gas for $N_{HI} \sim 10^{20}\,cm^{-2}$

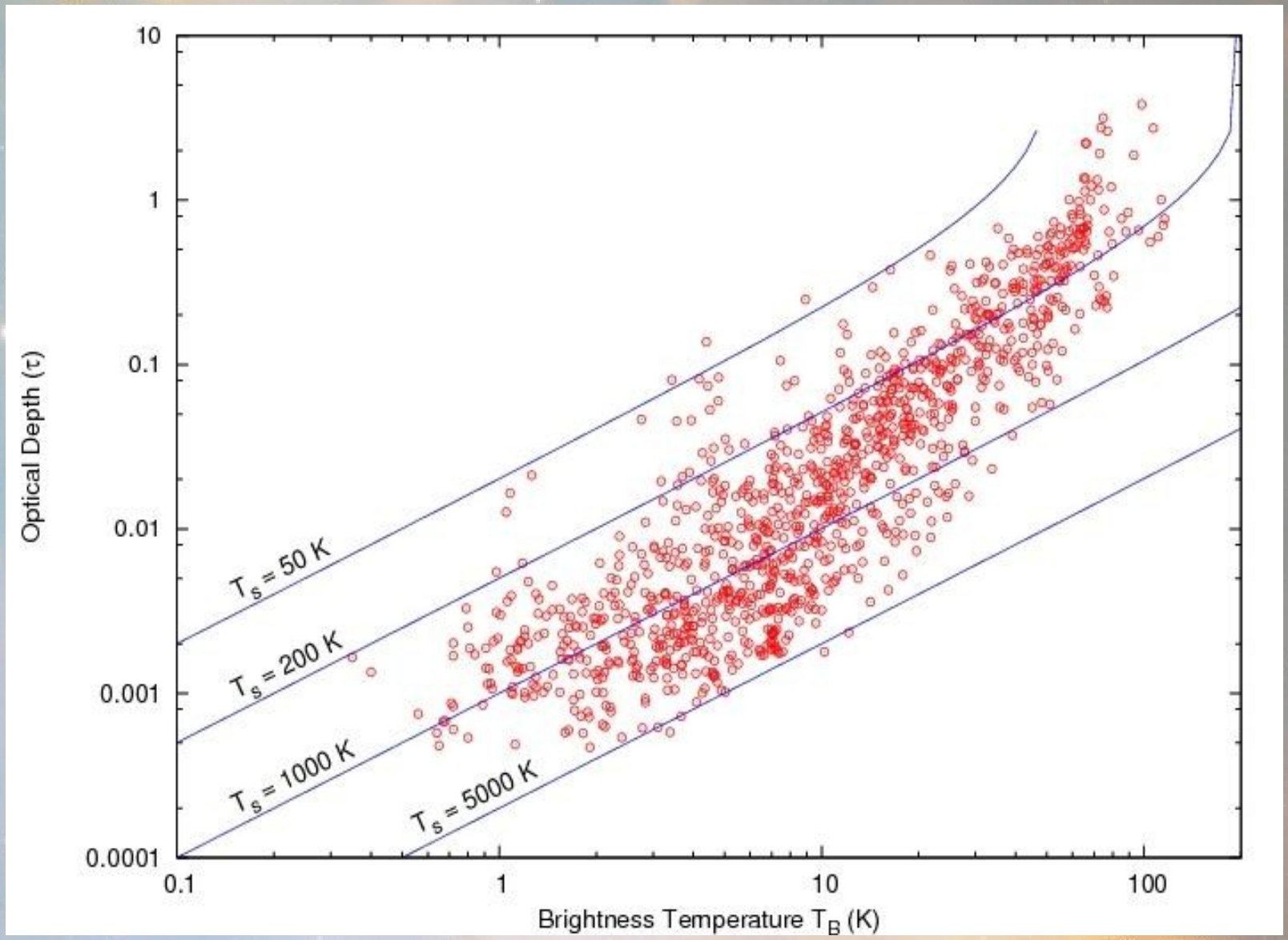


Emission/absorption and T_S spectra

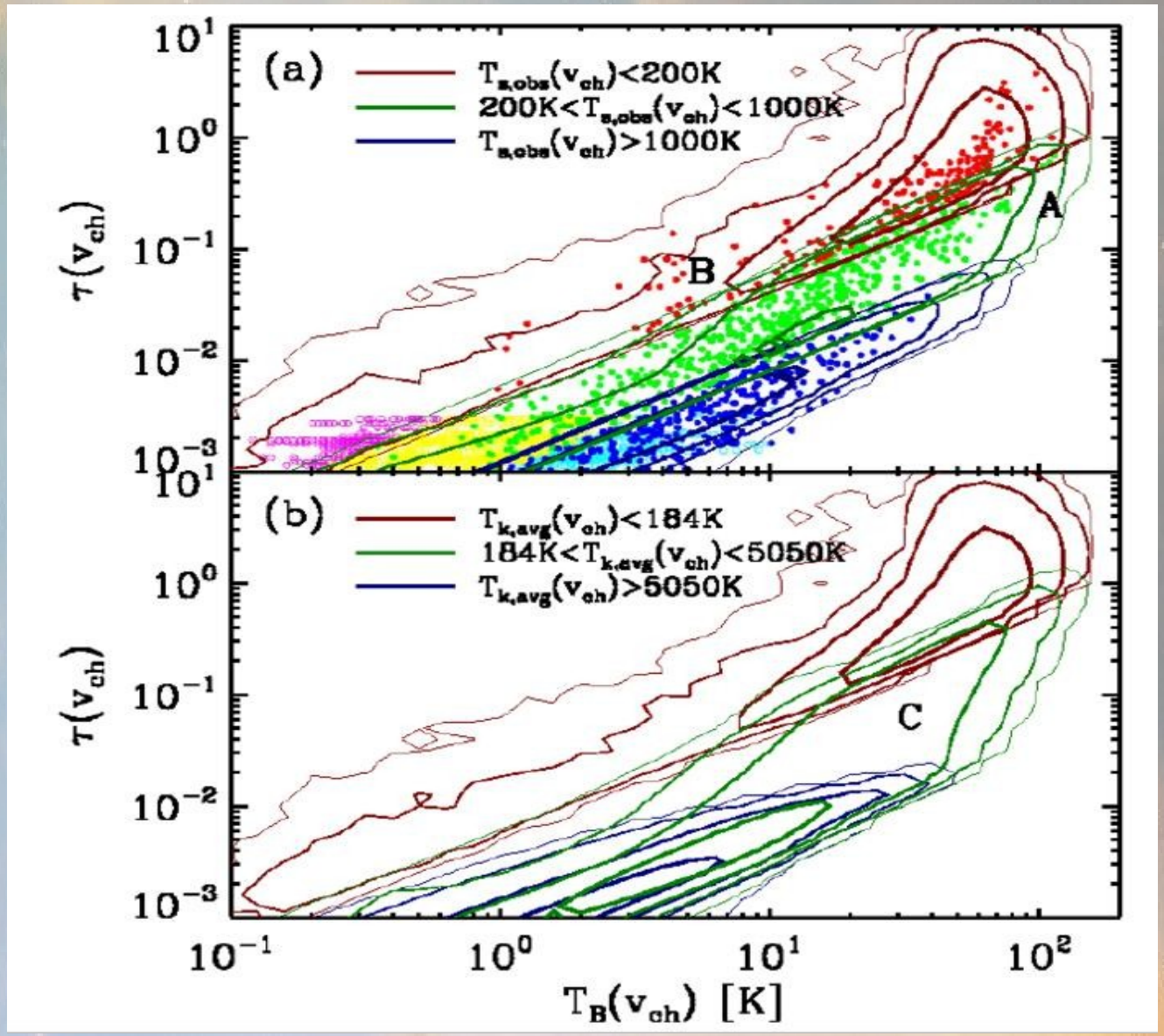




$T_B - \tau - T_S$ relation (~1 km/s resolution)

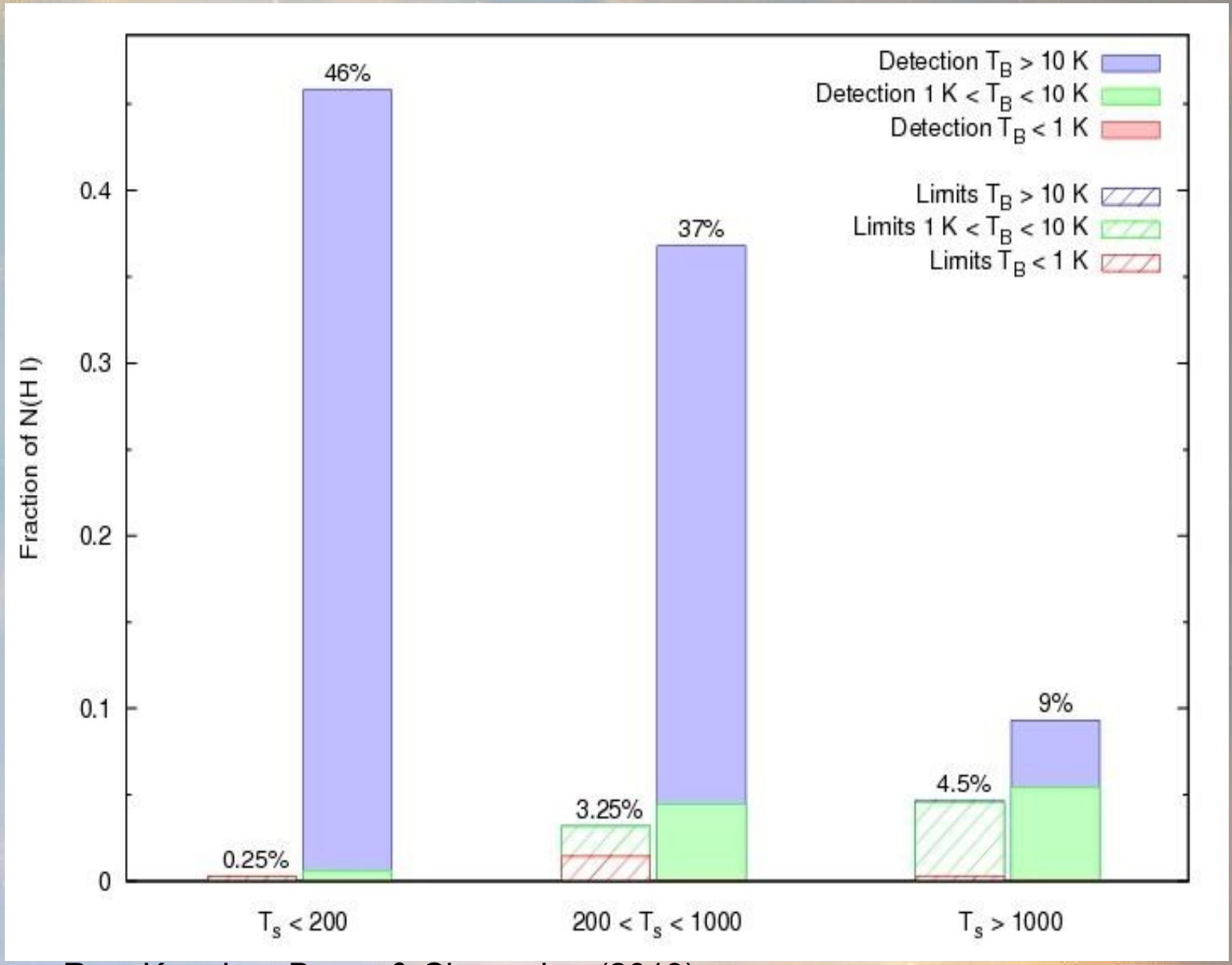


Observation vs. theory: dynamical effects



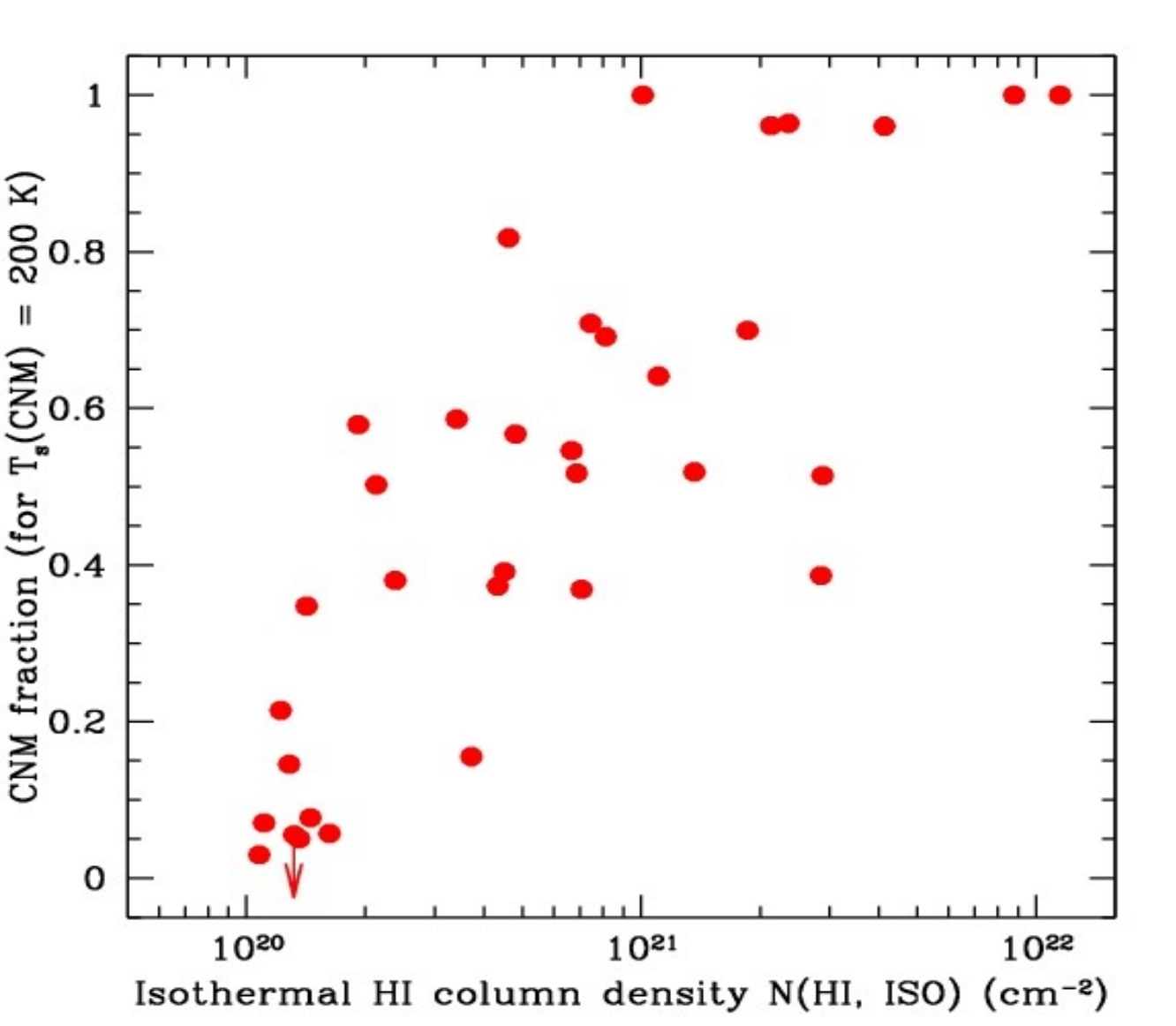
Kim, Ostriker & Kim (2014): Synthetic spectra from simulation

Column density distribution (~1 km/s resolution)



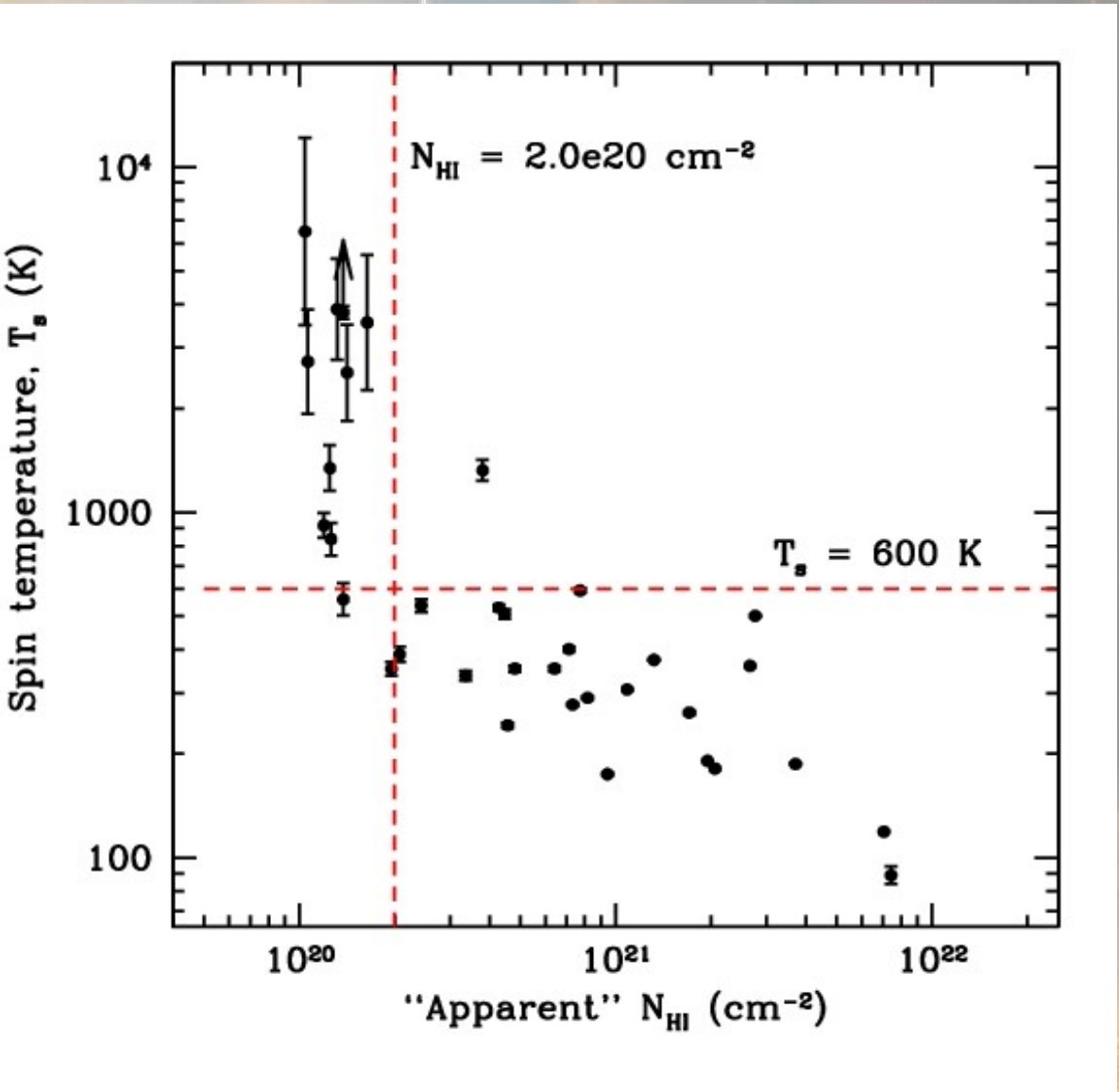
Roy, Kanekar, Braun & Chengalur (2013)

Cold gas fraction for individual lines of sight



Roy, Kanekar & Chengalur (2013)

Line of sight integrated properties



Kanekar, Braun & Roy (2011)

All absorption is definitely NOT from cold gas …

Multi-Gaussian fitting*

Drawing an elephant with four complex parameters

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(Received 20 August 2008; accepted 5 October 2009)

We define four complex numbers representing the parameters needed to specify an elephantine shape. The real and imaginary parts of these complex numbers are the coefficients of a Fourier coordinate expansion, a powerful tool for reducing the data required to define shapes. © *2010 American Association of Physics Teachers.*

[DOI: 10.1119/1.3254017]

A turning point in Freeman Dyson's life occurred during a meeting in the Spring of 1953 when Enrico Fermi criticized the complexity of Dyson's model by quoting Johnny von Neumann:[1] "With four parameters I can fit an elephant, and with five I can make him wiggle his trunk." Since then it has become a well-known saying among physicists, but nobody has successfully implemented it.

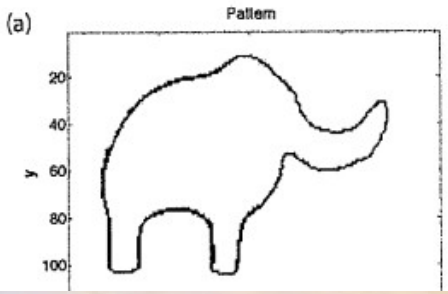
To parametrize an elephant, we note that its perimeter can be described as a set of points $(x(t),y(t))$, where t is a parameter that can be interpreted as the elapsed time while going along the path of the contour. If the speed is uniform, t becomes the arc length. We expand x and y separately[2] as a Fourier series

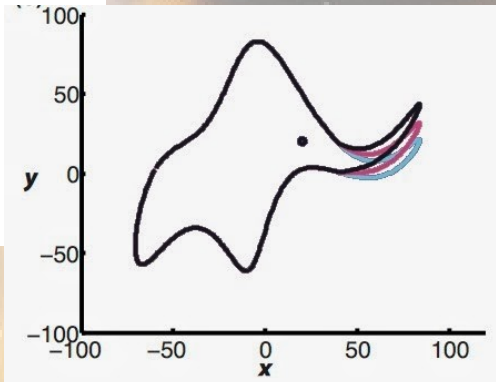
$$x(t)=\sum_{k=0}^{\infty}\left(A_k^x\cos(kt)+B_k^x\sin(kt)\right), \quad (1)$$

$$y(t)=\sum_{k=0}^{\infty}\left(A_k^y\cos(kt)+B_k^y\sin(kt)\right), \quad (2)$$

trace out elliptical corrections analogous to Ptolemy's epicycles.[5] Visualization of the corresponding ellipses can be found at Ref. 6.

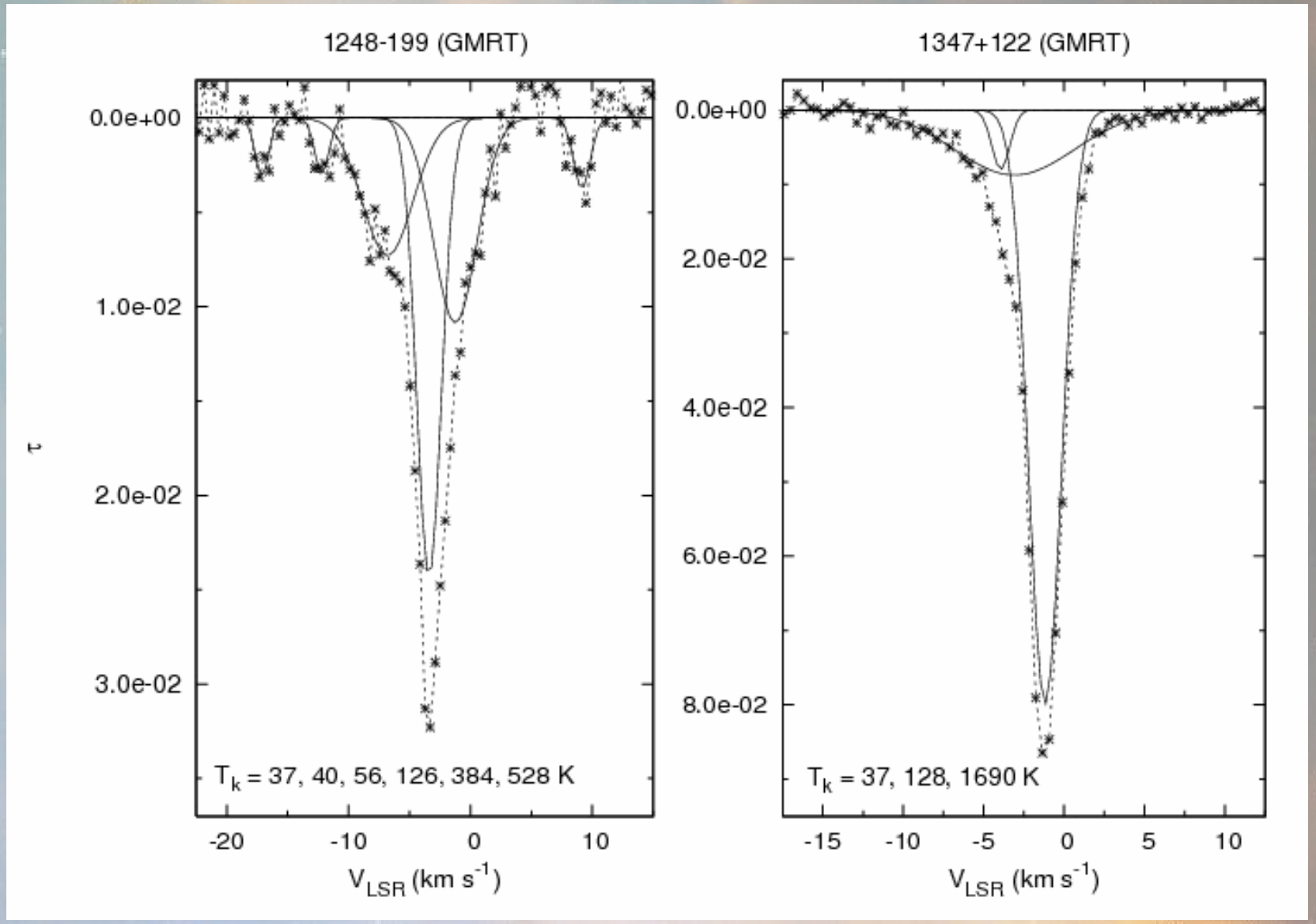
We now use this tool to fit an elephant with four parameters. Wei[7] tried this task in 1975 using a least-squares Fourier sine series but required about 30 terms. By analyzing the picture in Fig. 1(a) and eliminating components with amplitudes less than 10% of the maximum amplitude, we obtained an approximate spectrum. The remaining amplitudes were





* Fine print warning: Beaware, you may mess up everything!

HI 21 cm absorption survey (GMRT/WSRT/ATCA)



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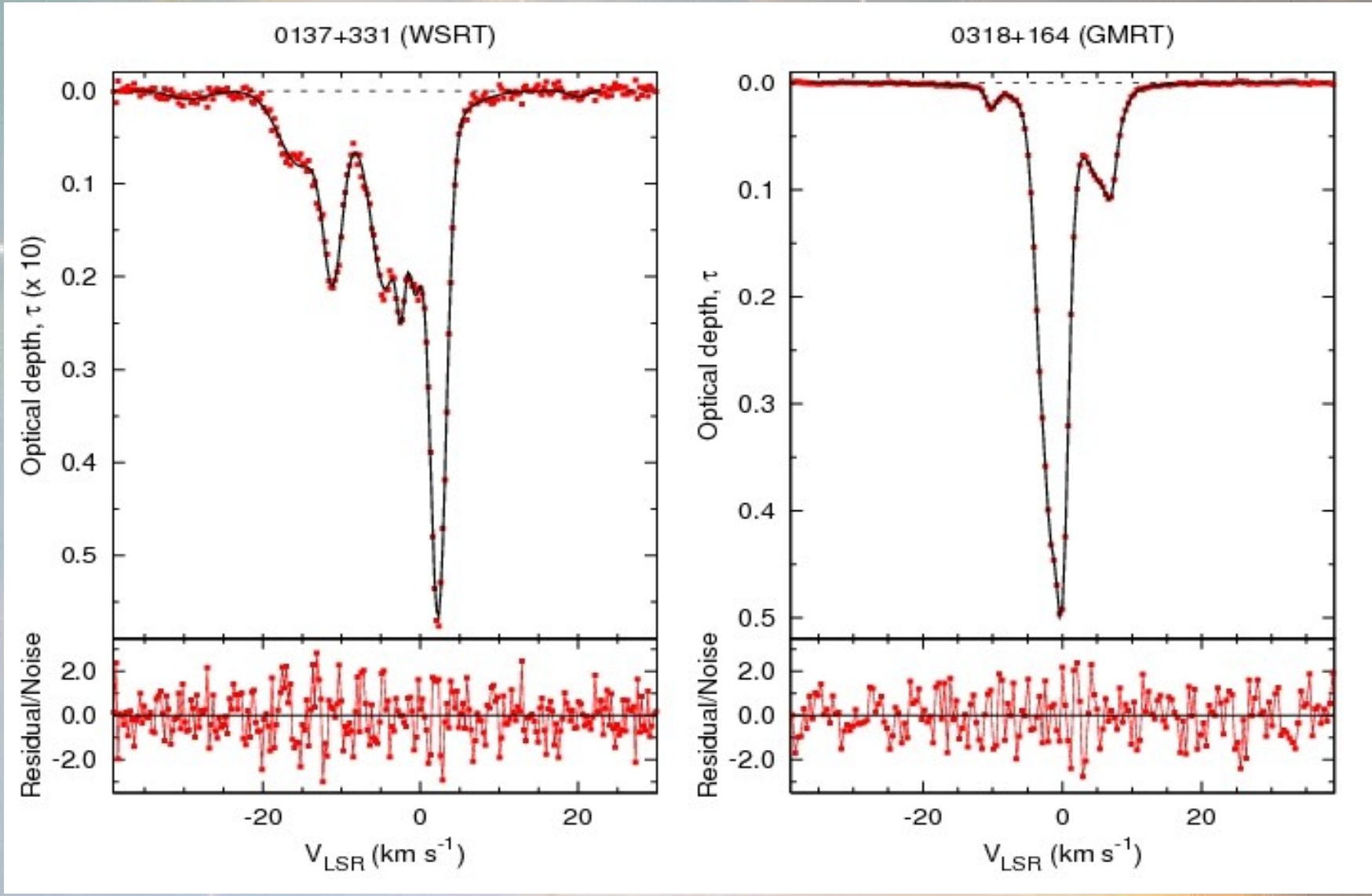
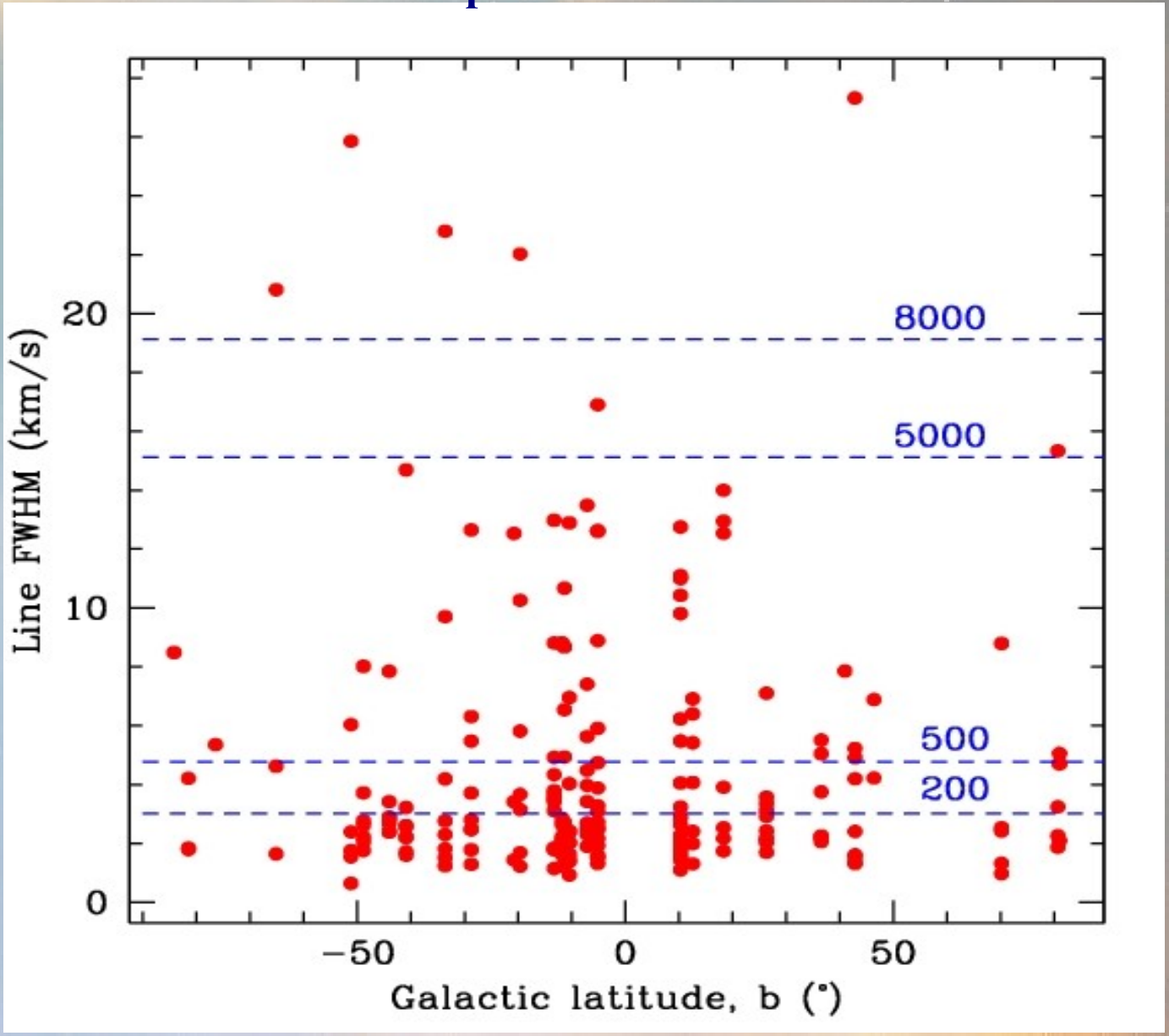


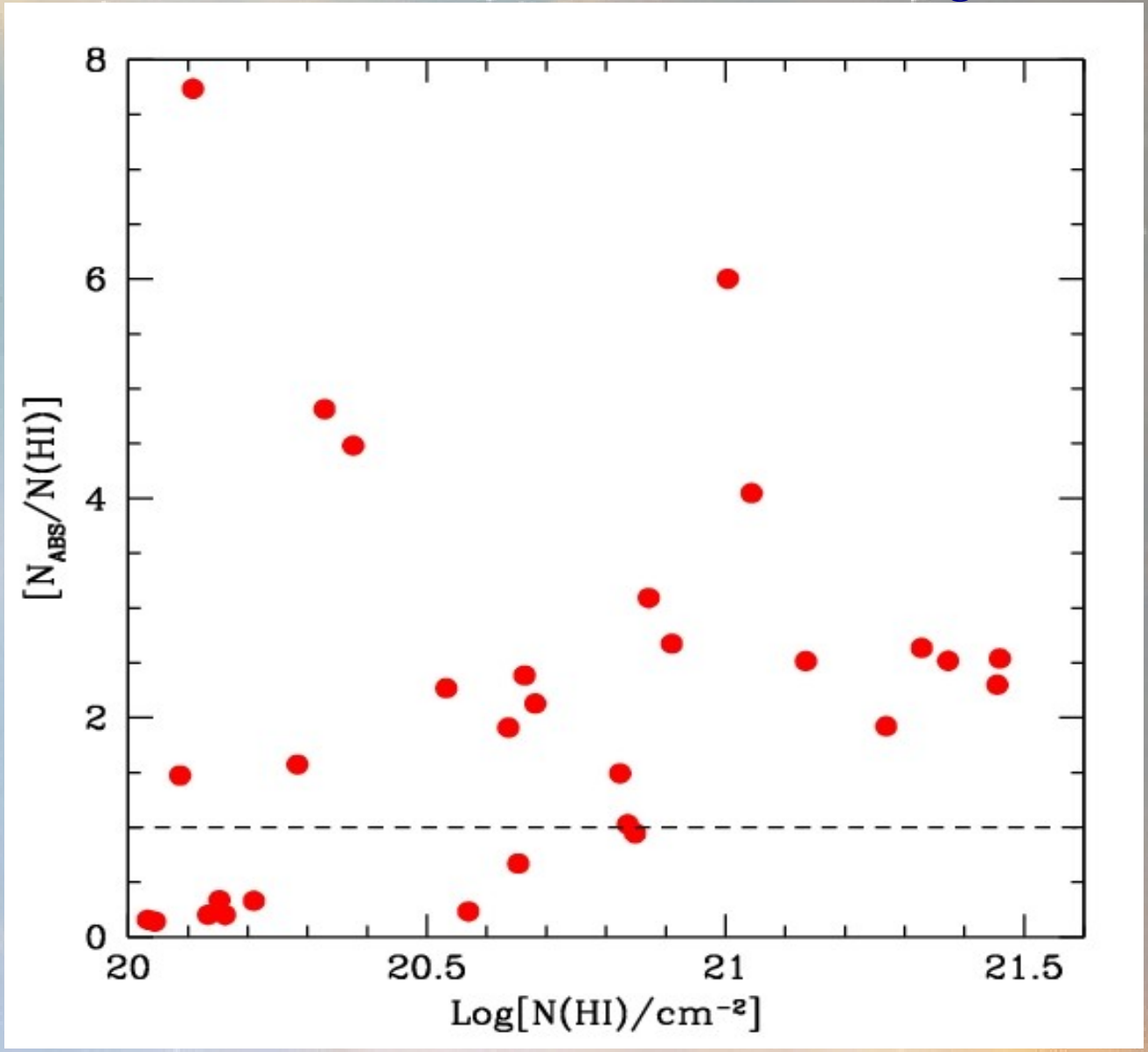
Roy, Kanekar, Chengalur (2013)

Component statistics

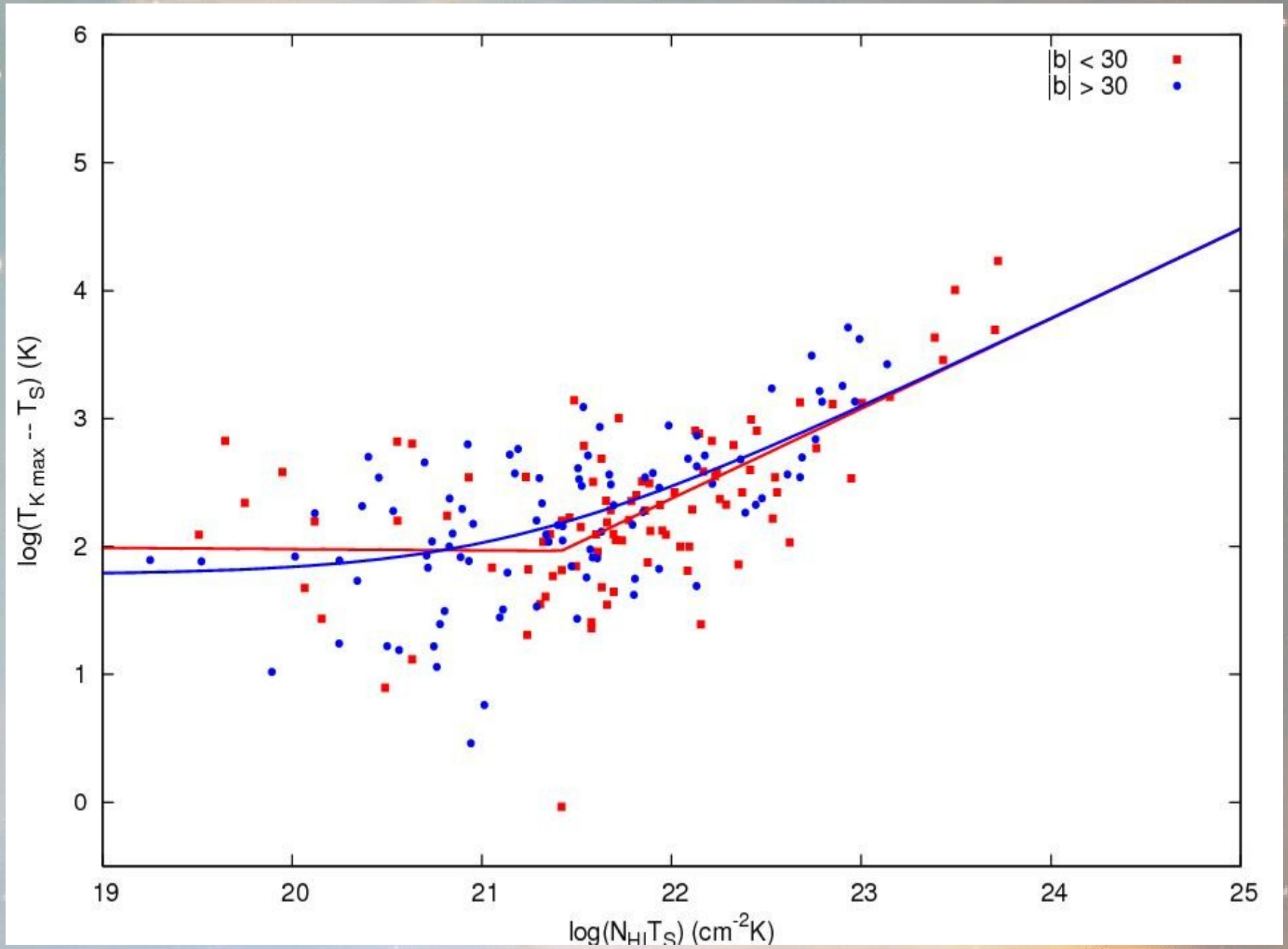


Roy, Kanekar & Chengalur (2013)

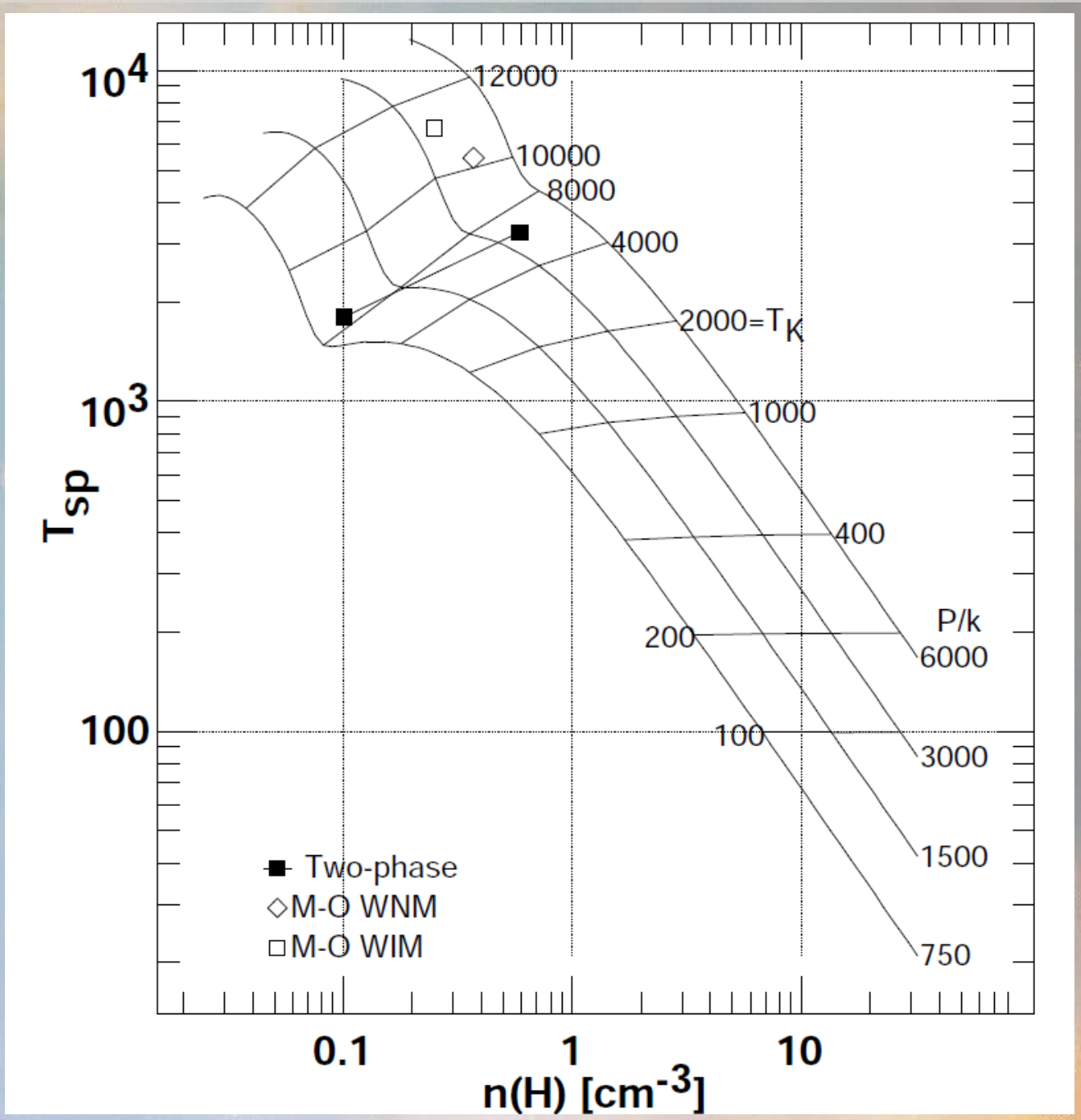
Possible handle on non-thermal broadening …



Roy, Kanekar & Chengalur (2013)



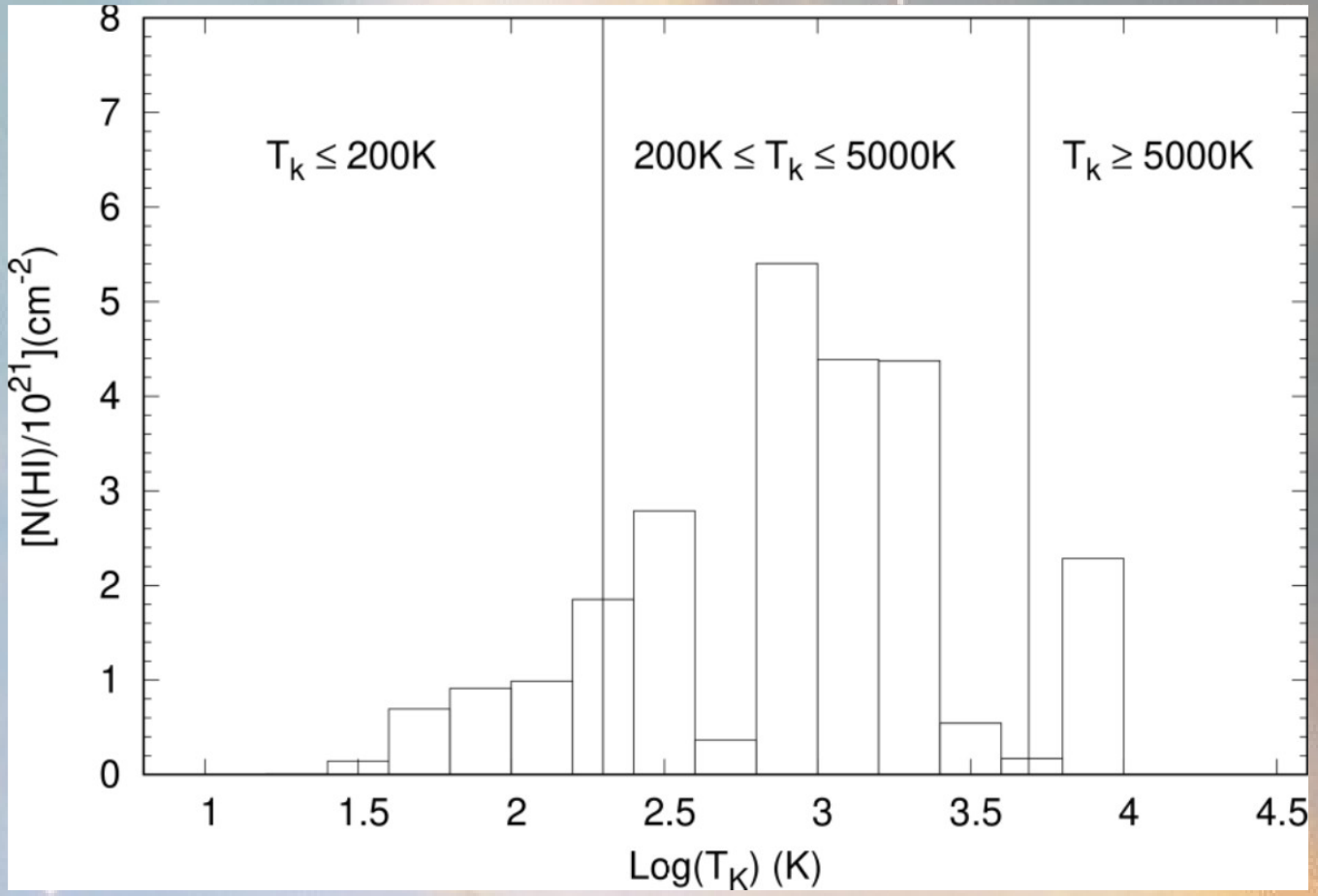
Roy et al. 2008


10^4
10^3
100
T_{sp}
12000
10000
8000
4000
2000=T_K
1000
400
200
100
P/k
6000
3000
1500
750
Two-phase
M-O WNM
M-O WIM
0.1
1
10
n(H) [cm^{-3}]

Liszt (2001)

- **Try to constrain non-thermal broadening**
- **Iterative, and model dependent**

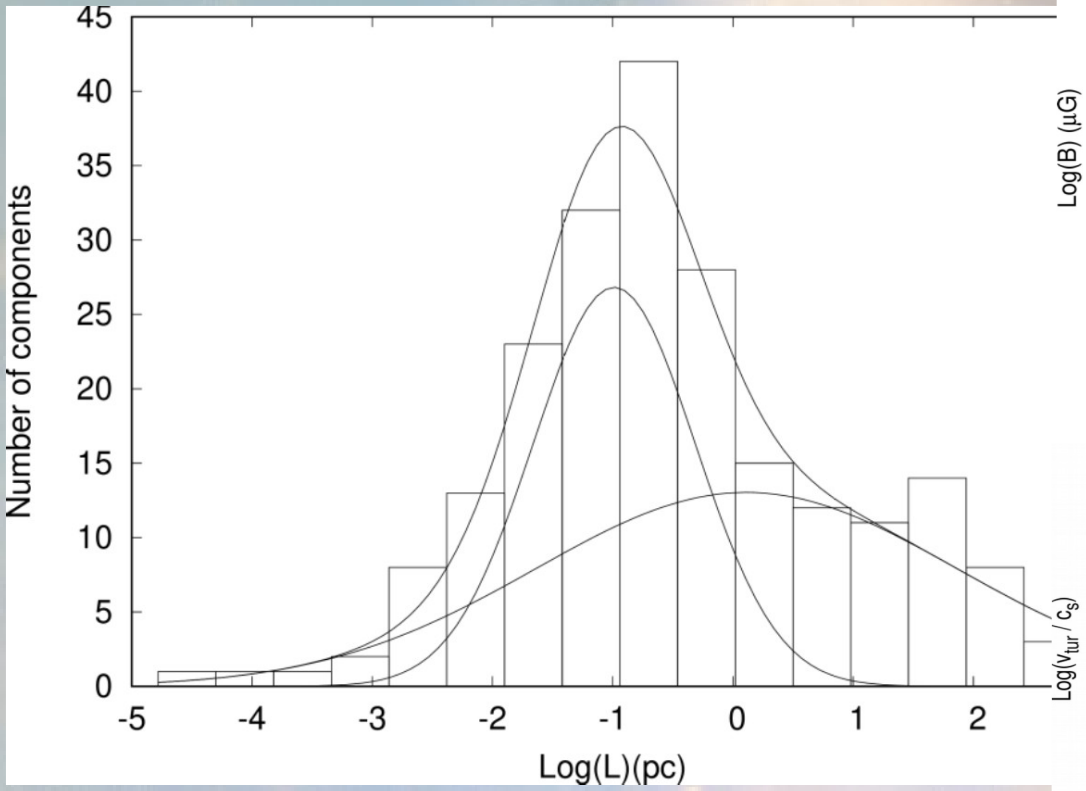
- **Try to constrain non-thermal broadening**
- **Iterative, and model dependent**



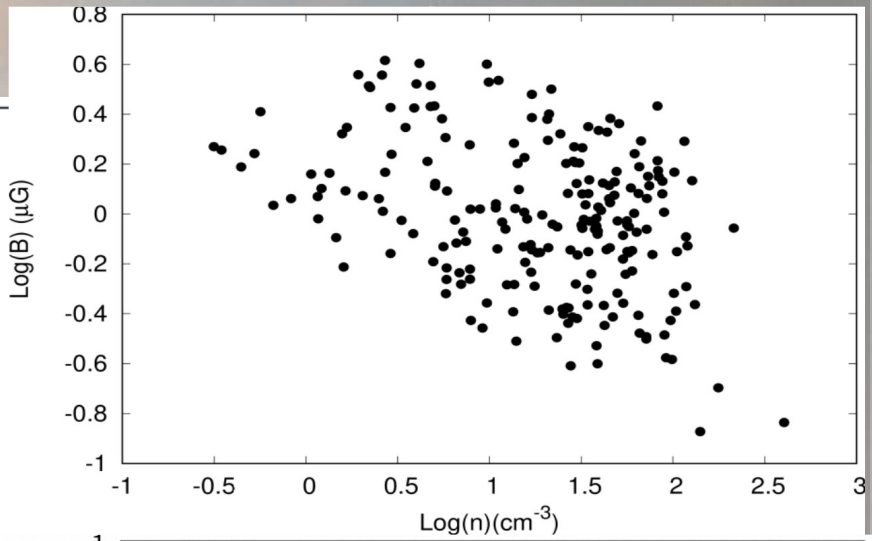
Koley and Roy (2019)

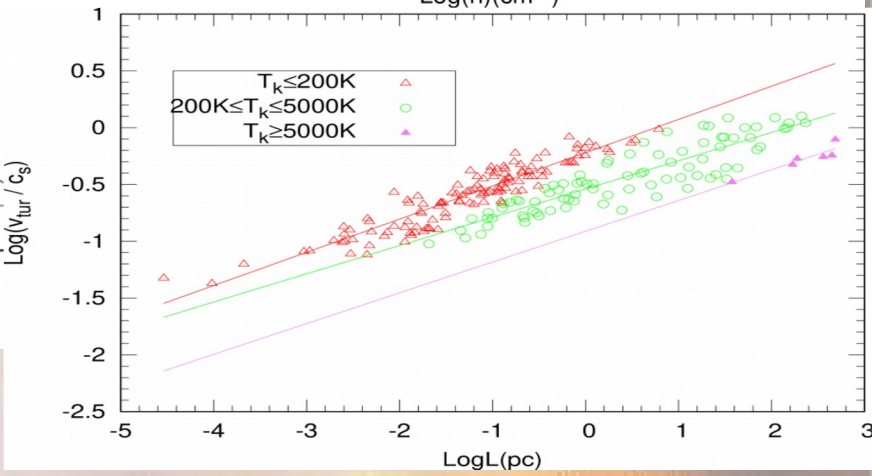
Turbulence and magnetic field from H I studies

Consistency check using total column density, spin temperature of the individual components, length scale …



Estimated B field and turbulent Mach number from H I absorption studies



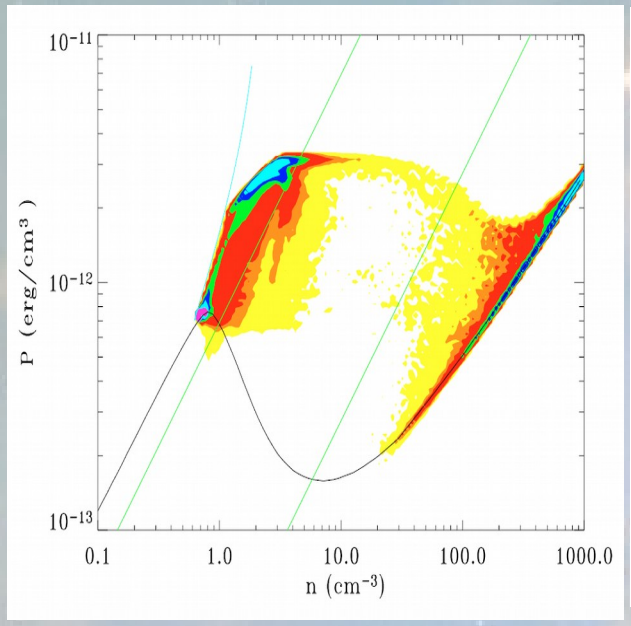


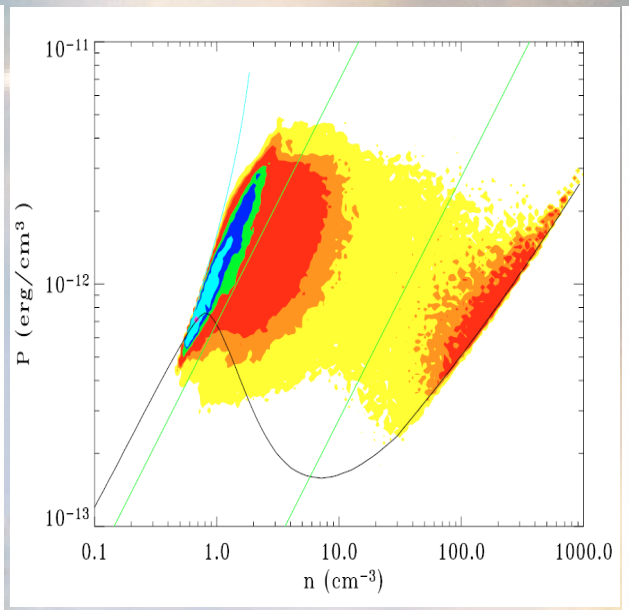
Please see Atanu Koley's poster!

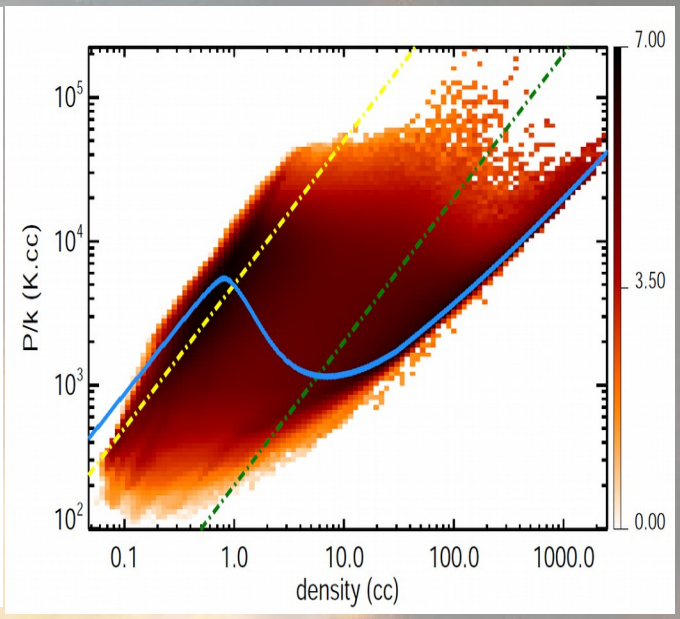
Koley and Roy (2019)

All absorption is definitely NOT from stable gas …

The inconsistency remains …







Left: Audit & Hennebelle 2005, Colliding flow with weak initial turbulence

Middle: Audit & Hennebelle 2005, Colliding flow with strong initial turbulence

Right: Saury et al. 2013, Mildly supersonic turbulence

Conclusions

- Sensitive H I observations can detect WNM in absorption
- Measured T_s values suggest a mix of cold and warm gas
- At least ~ 50% gas, on an average, is in the WNM phase
- But, very few (< 5%) stable WNM Gaussian components!
- Definite signature of "unstable" phase gas (> ~ 70%)
- Observations vs. theory: the inconsistency remains …

Thank you!

Thanks to my collaborators: J. N. Chengalur, N. Kanekar, R. Braun, P. Dutta, S. Bharadwaj, N. N. Patra, S. Choudhuri, A. Koley and others.

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Stay tuned for more results from the full sample "soon"!

Thank you!