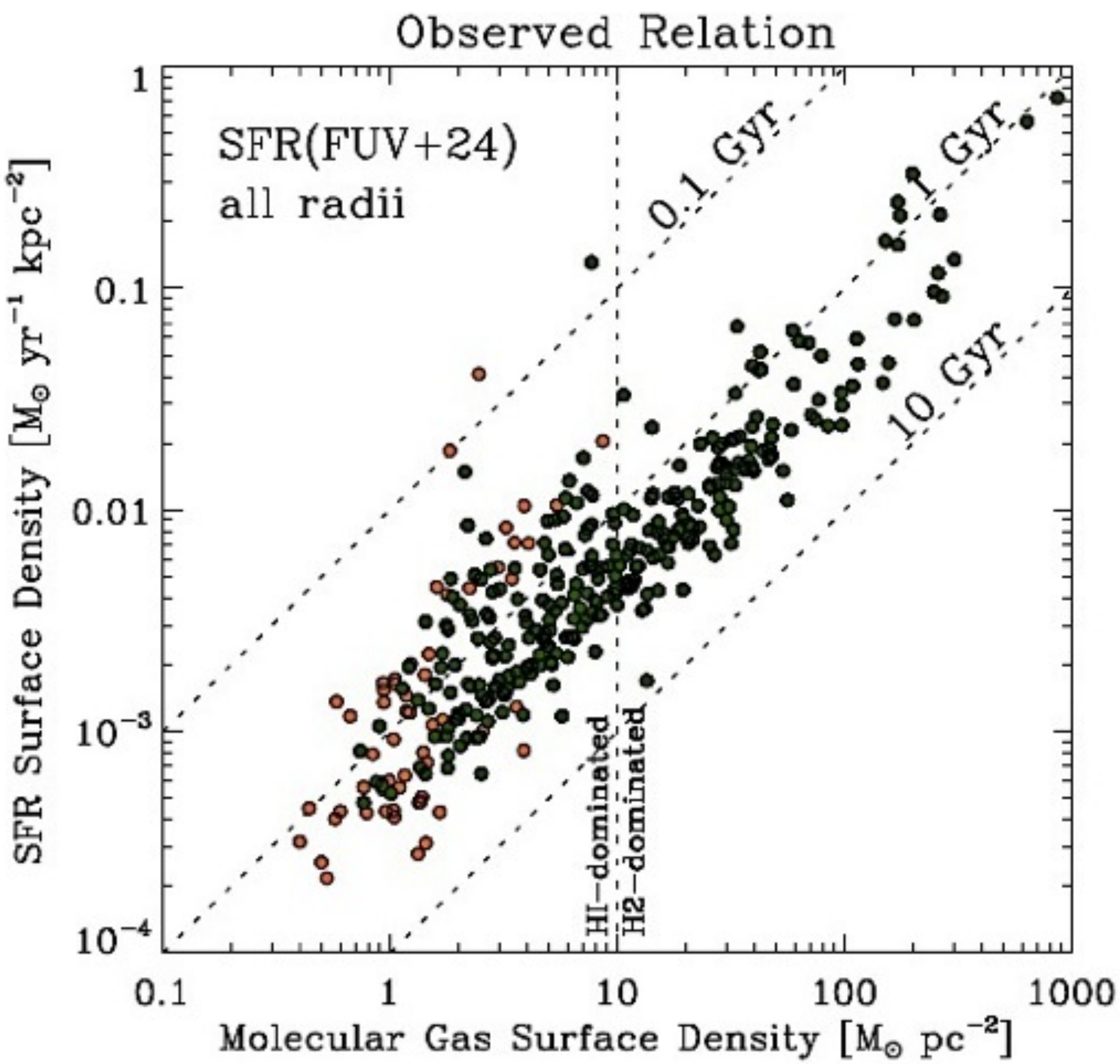
Deciphering Local, Multiphase HI with 21-SPONGE and Artificial Intelligence

Claire Murray

University of Wisconsin - Madison

Snežana Stanimirović (UW Madison), Robert Lindner (UW Madison), W. M. Goss (NRAO), Carl Heiles (UC Berkeley), John Dickey (UTas), Brian Babler (UW Madison), Patrick Hennebelle (CEA) + the rest of the **21-SPONGE** team

What sets a galaxy's efficiency to form molecular gas?



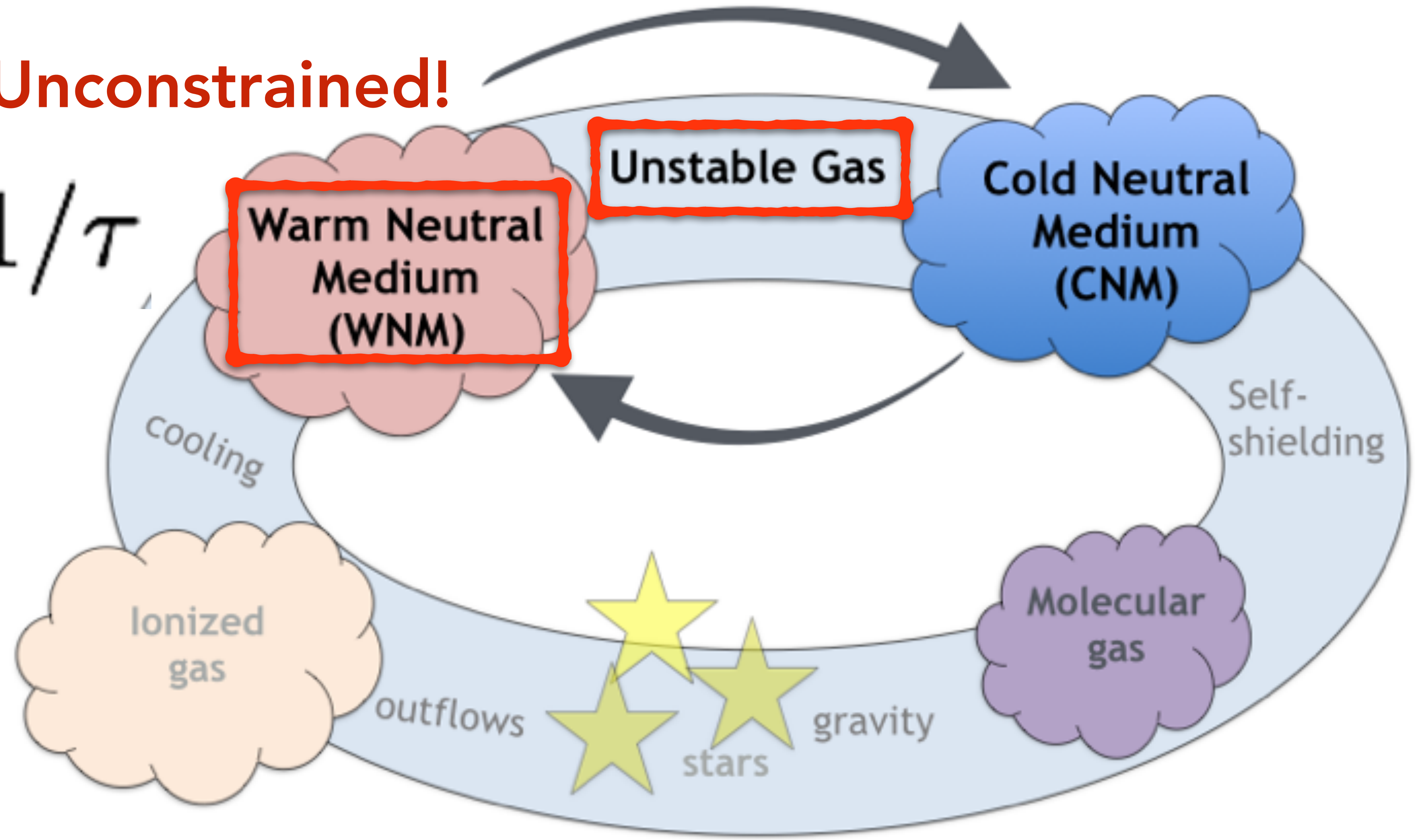
Schruba et al. 2011

Initial conditions for GMC formation: ***atomic reservoir***

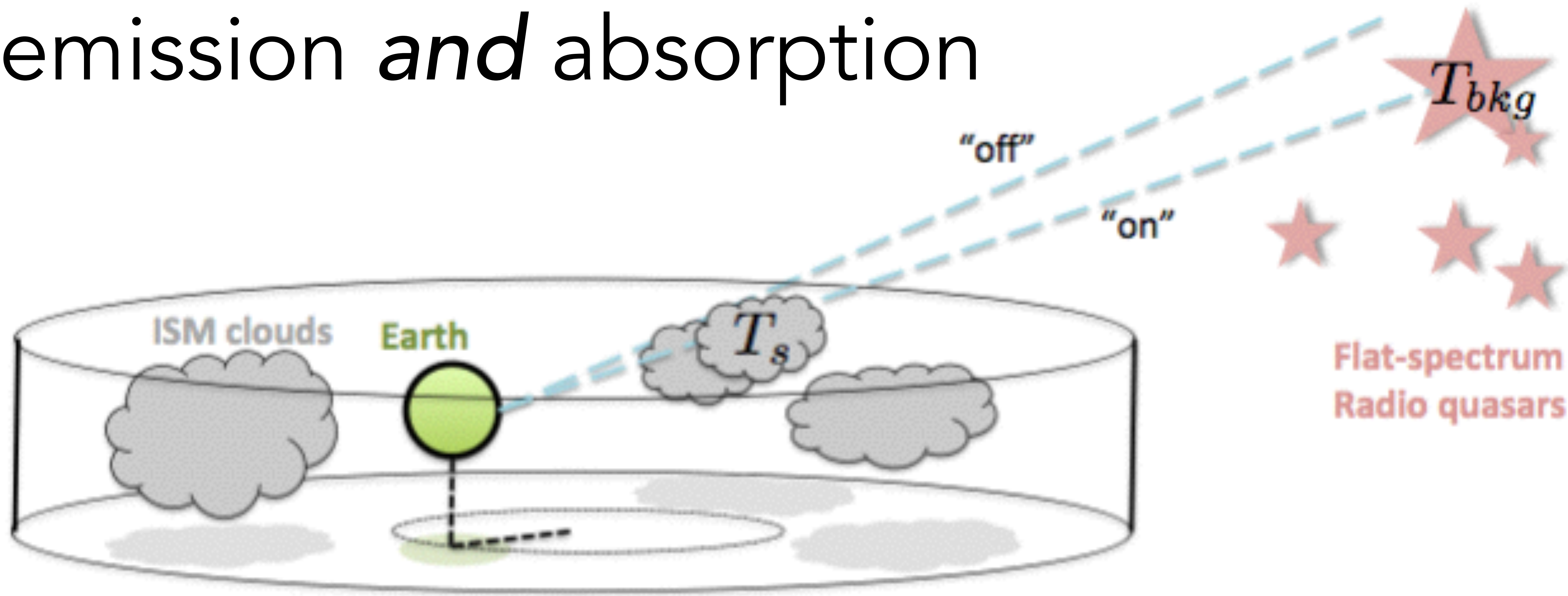
What are the properties (T_s, N(HI), etc…) of the HI phases?

Unconstrained!

$$T_s \sim 1/\tau$$



Measuring T_s : need HI emission *and* absorption



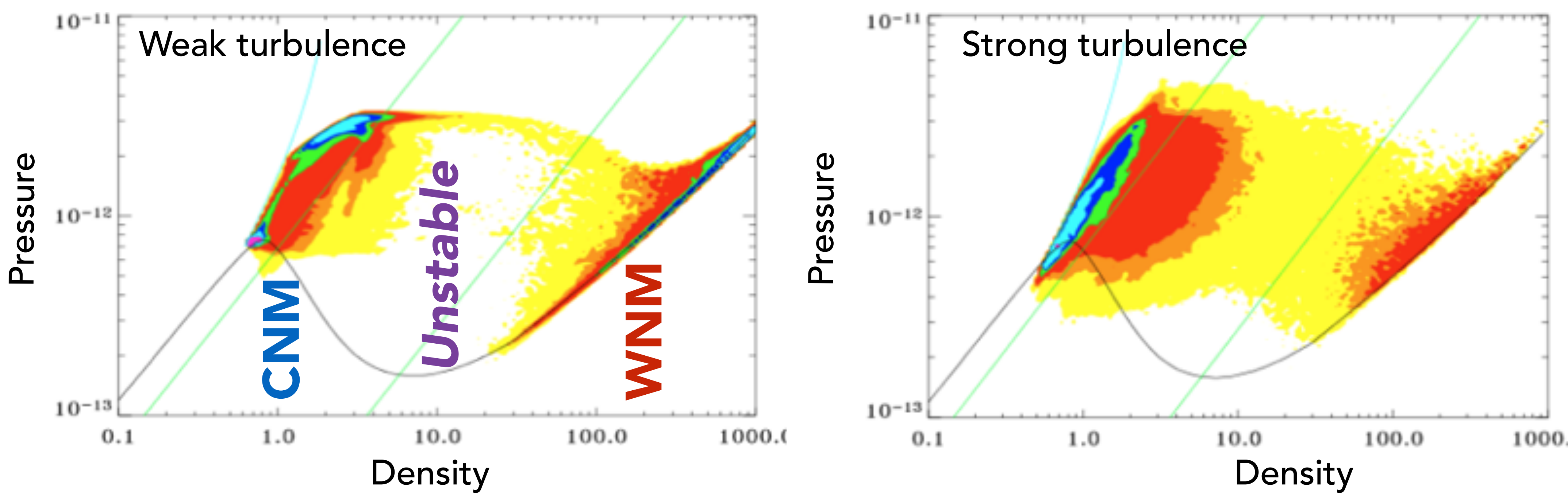
$$T_b^{on} = T_{bkg} e^{-\tau} + T_s (1 - e^{-\tau})$$

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

How much mass exists in each HI phase of the ISM?

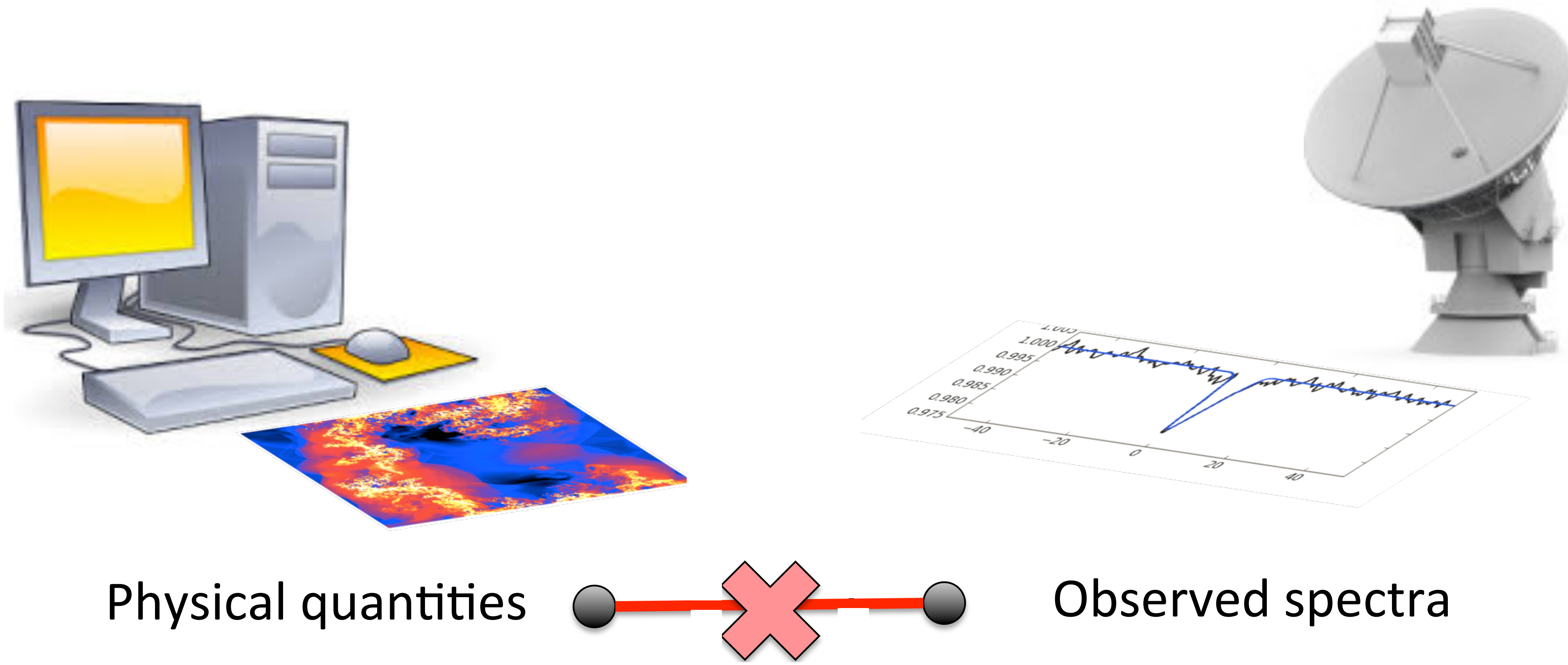
CNM, WNM, and unstable fractions depend on input physics

(e.g. MacLow et al. 2005, Audit & Hennebelle 2005, Hill et al. 2012)



Audit & Hennebelle 2005

Comparing observations with theory is essential, but difficult!



Needed:

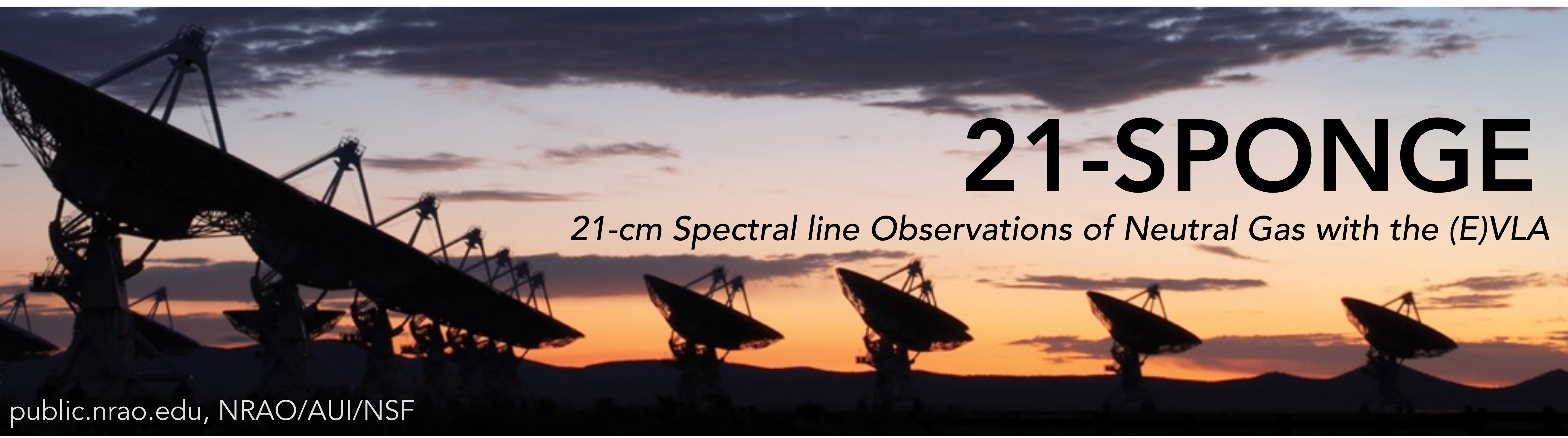
1. Deeper, statistically significant observational constraints

2. Comparison strategy

3. Synthetic observations of simulations

Needed:

1. Deeper, statistically significant observational constraints



21-SPONGE

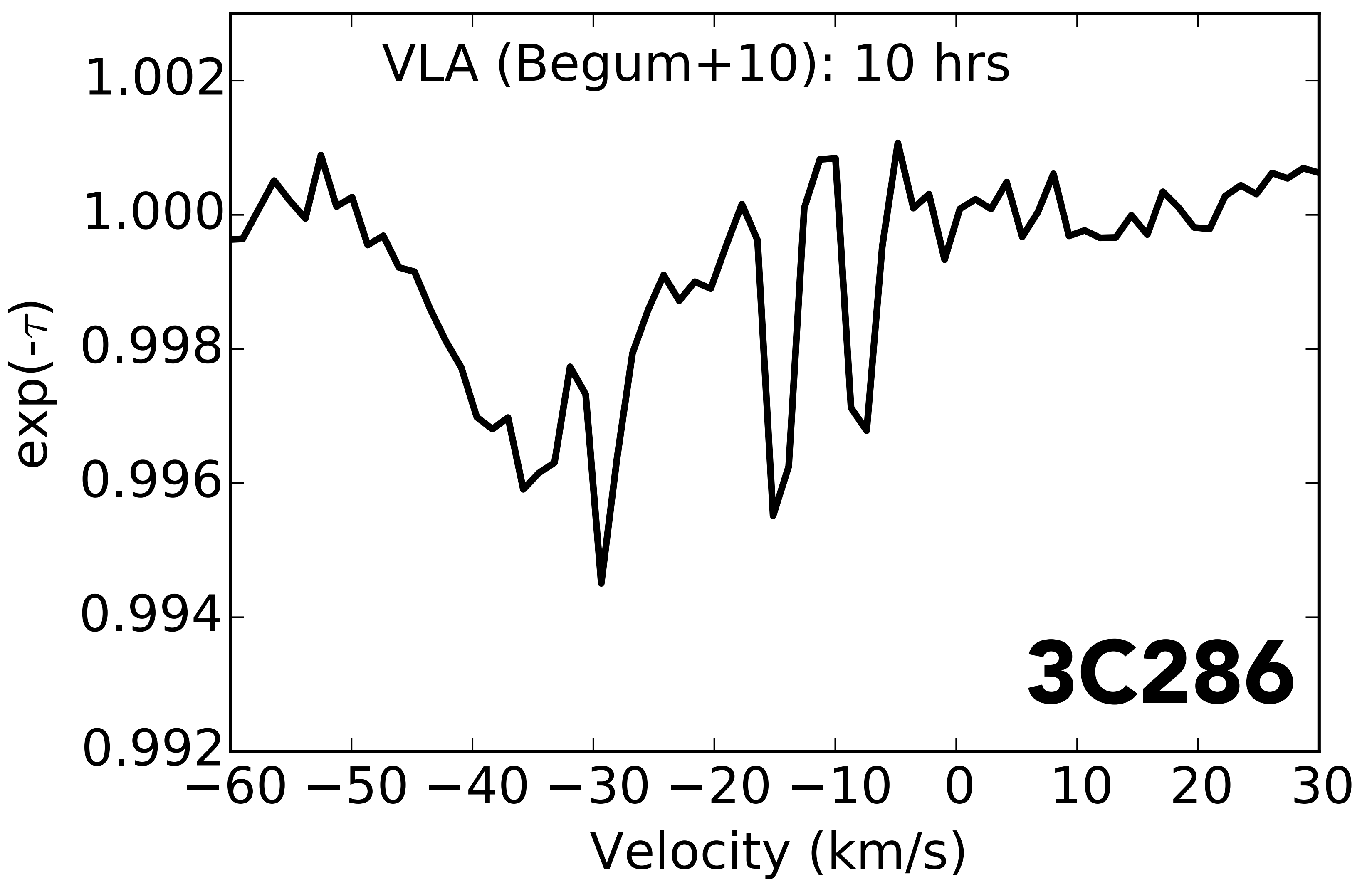
21-cm Spectral line Observations of Neutral Gas with the (E)VLA

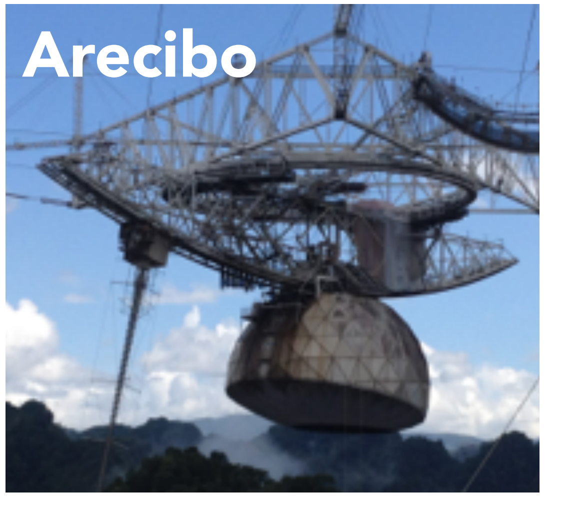
- 57 sources (37 complete): S>3 Jy, |b|>10
- High-sensitivity HI absorption: σ_τ ~7 x 10^{-4}
- New time-averaged bandpass calibration dramatically improves RMS and efficiency
- Filler project! 571 VLA hours / 3 years
- High detection rate: 36/37

public.nrao.edu; naic.edu

21-SPONGE

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

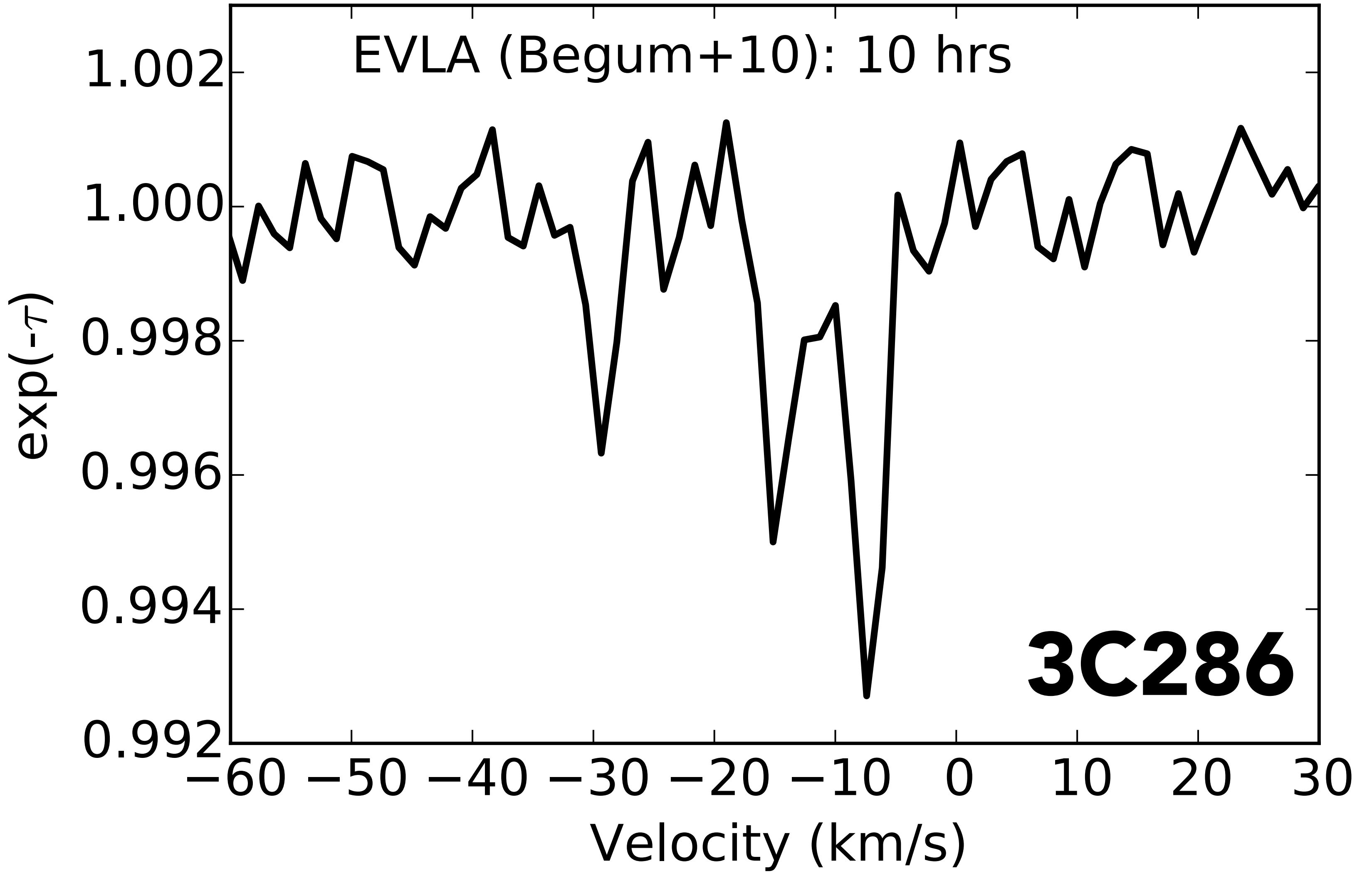


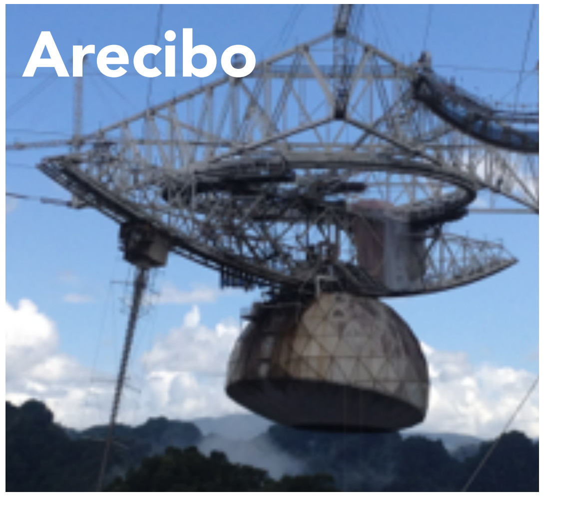


public.nrao.edu; naic.edu

21-SPONGE

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

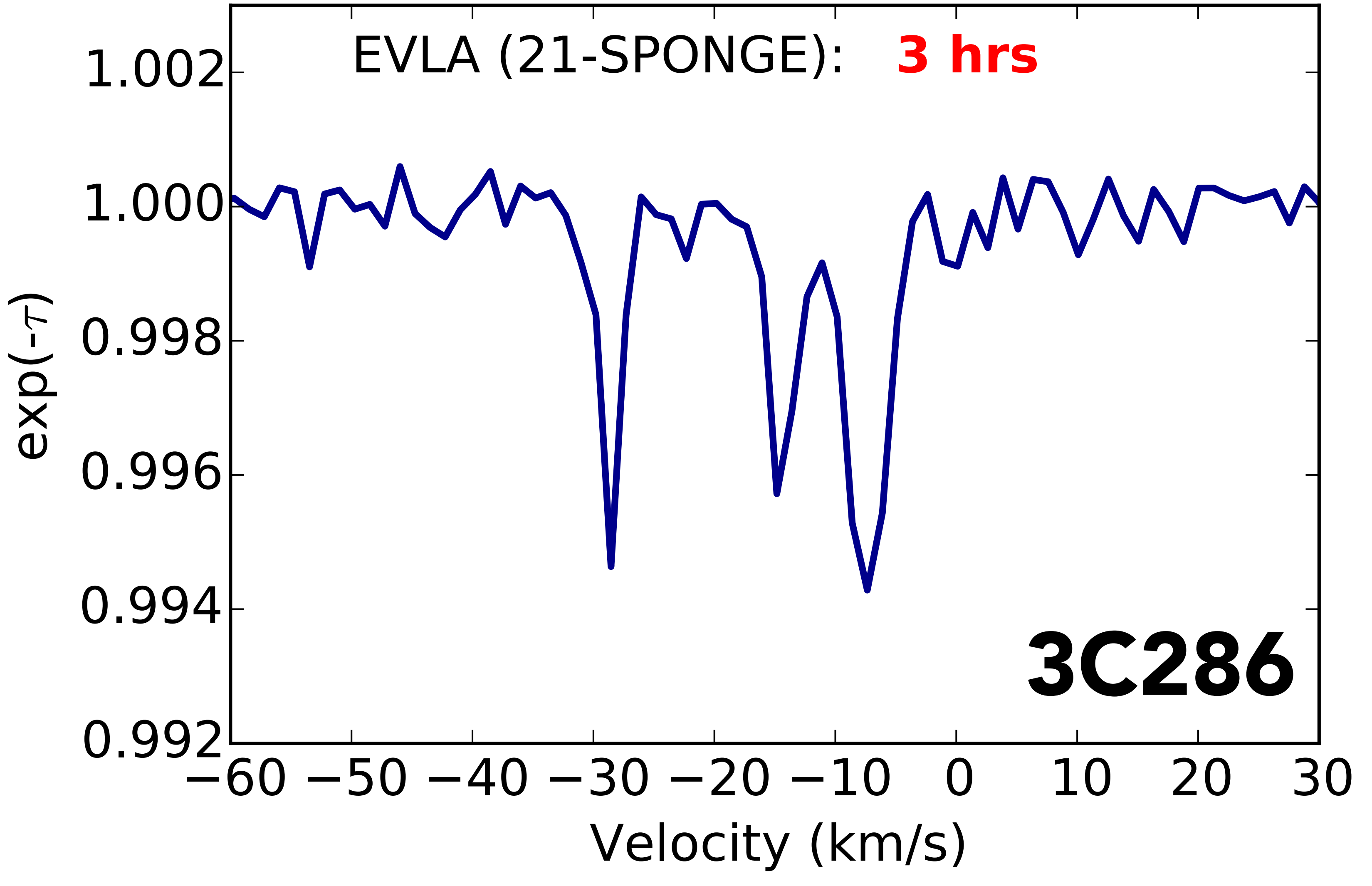


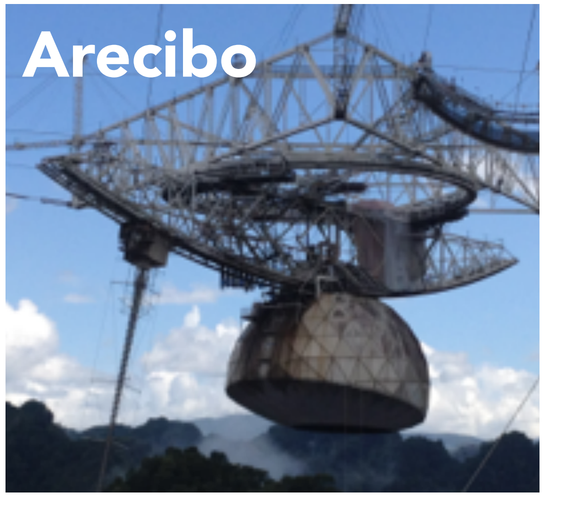


public.nrao.edu; naic.edu

21-SPONGE

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

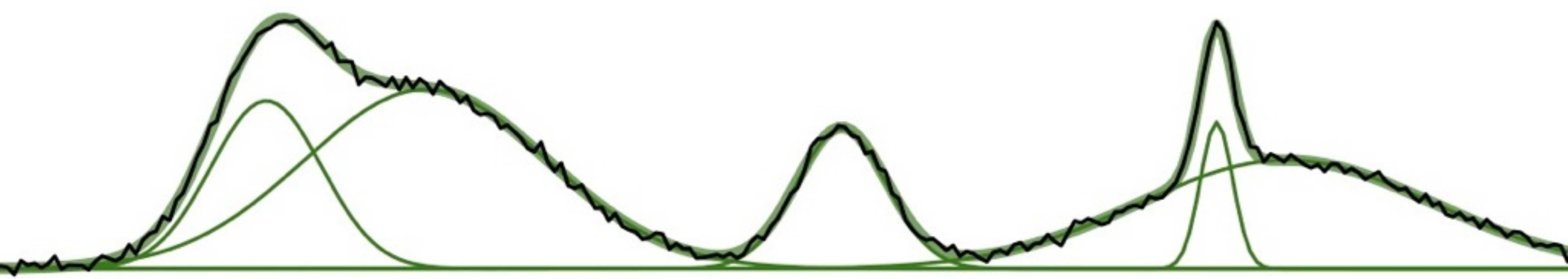




public.nrao.edu; naic.edu

2. Comparison strategy

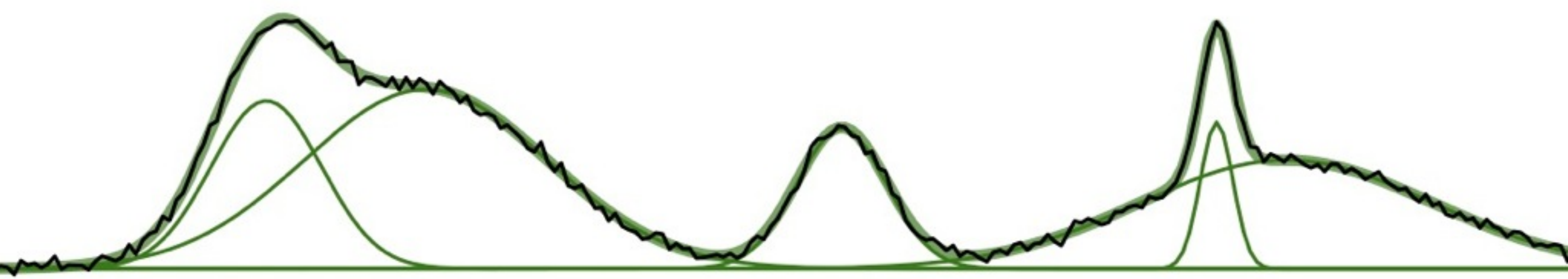
AUTONOMOUS GAUSSIAN DECOMPOSITION (AGD)



Lindner et al. 2015, AJ, 149, 138

AUTONOMOUS GAUSSIAN DECOMPOSITION (AGD)

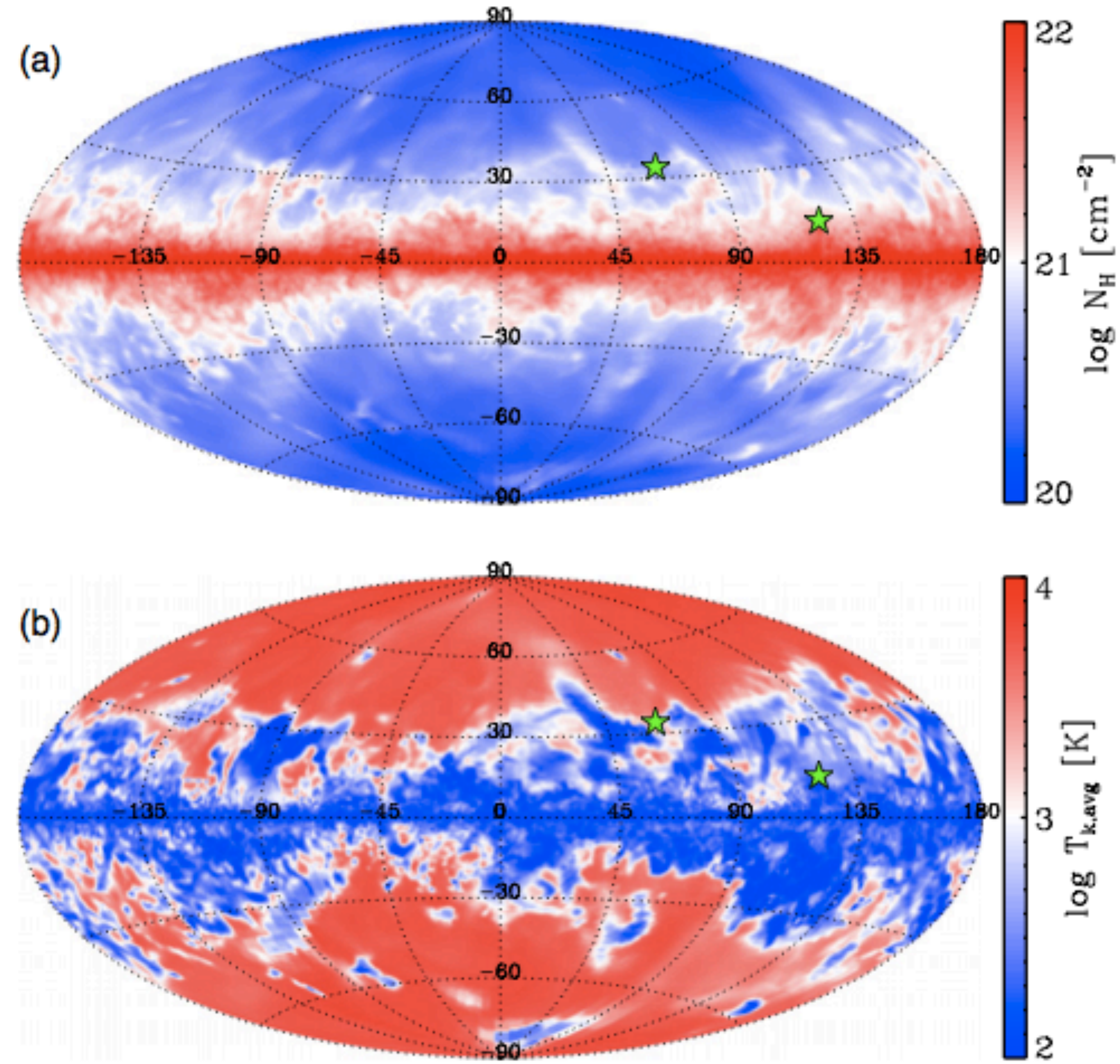
- Automatic, efficient decomposition of 1D spectral data into Gaussian functions via derivative spectroscopy
- Initial guesses are chosen without human interaction



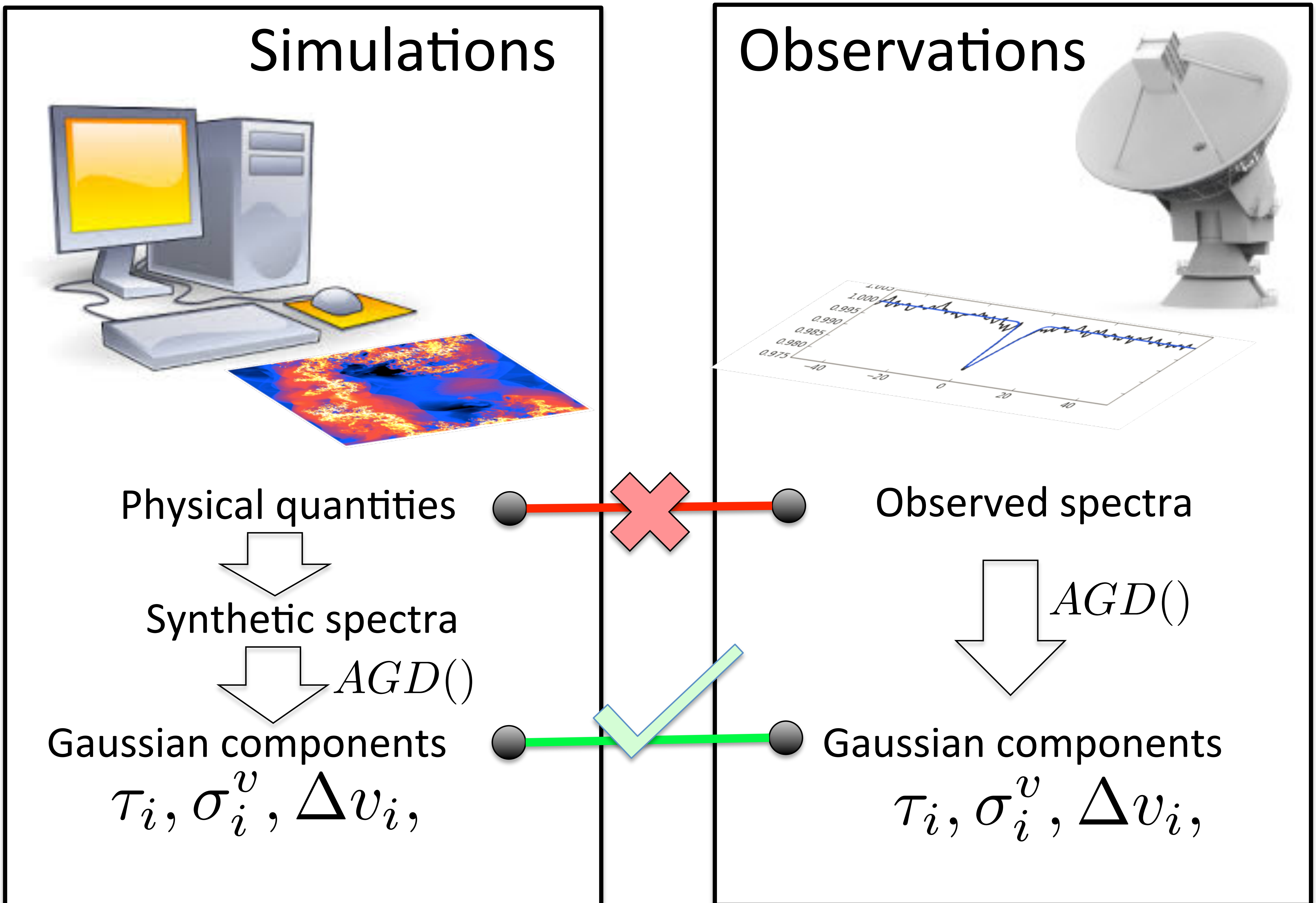
Lindner et al. 2015, AJ, 149, 138

3. Synthetic Observations

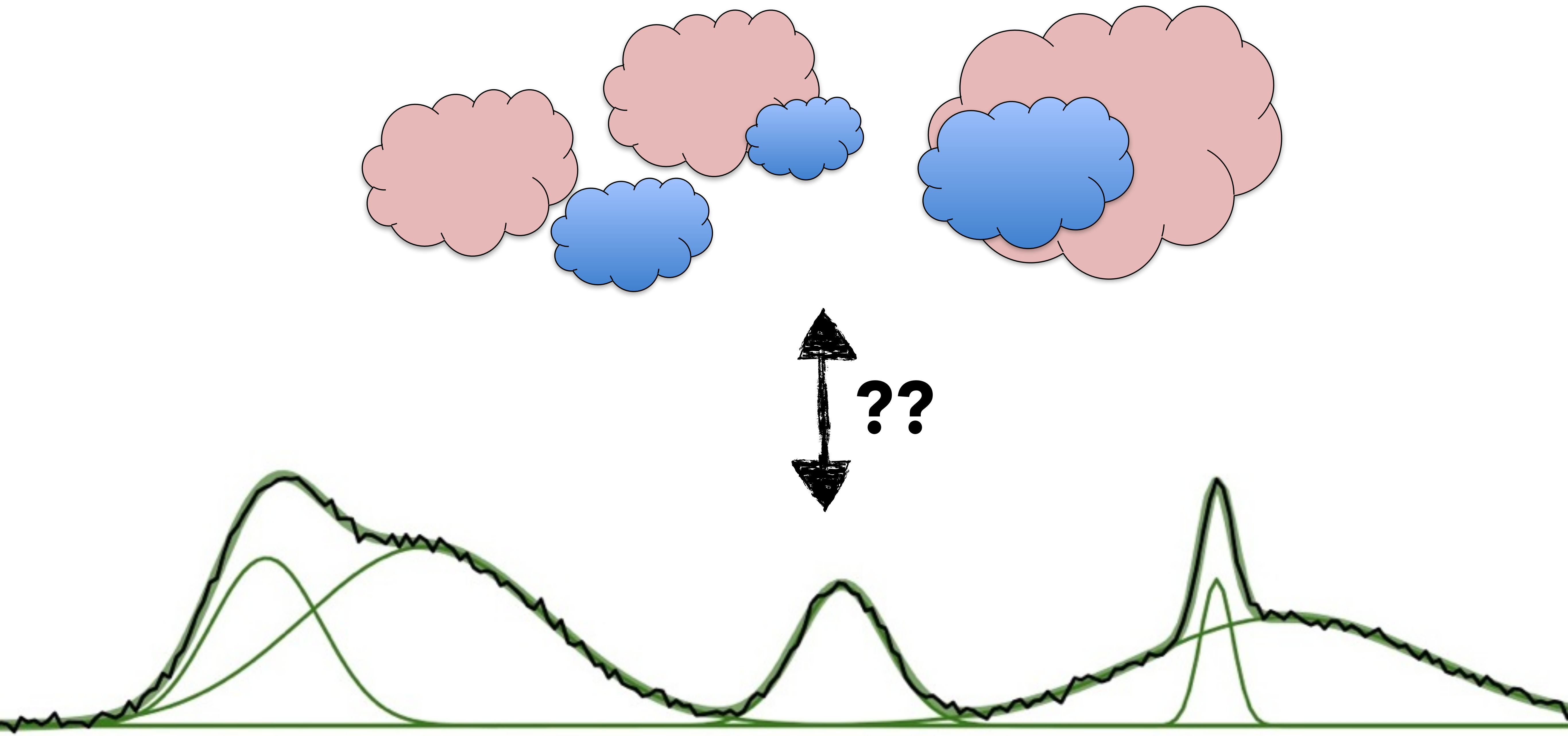
- 3D hydrodynamical Galactic ISM simulation (Kim et al., 2013, 2014)
- Includes:
  - Supernova feedback
  - Self gravity
  - ISM heating and cooling
  - 2pc spatial resolution
- **10^4 synthetic HI spectra**



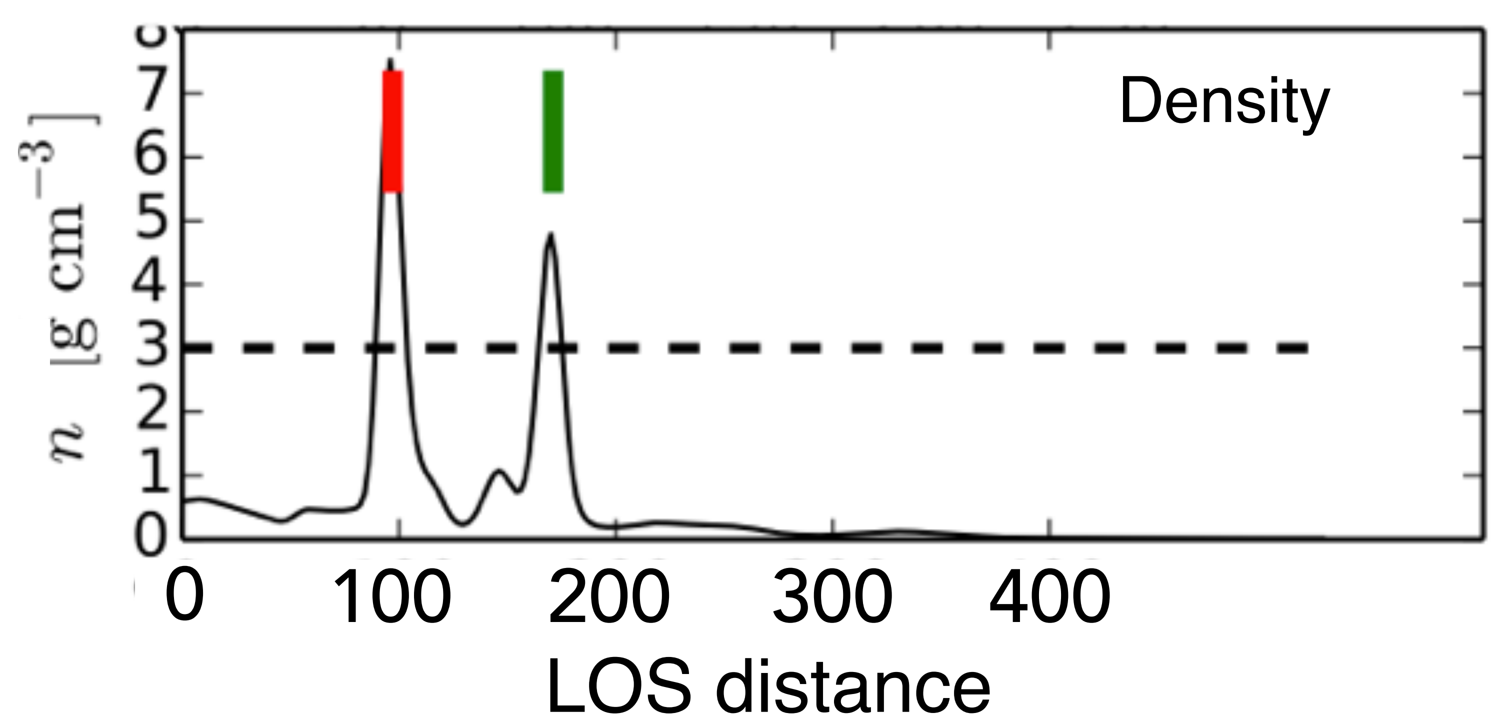
Kim et al. 2014, ApJ, 786, 64

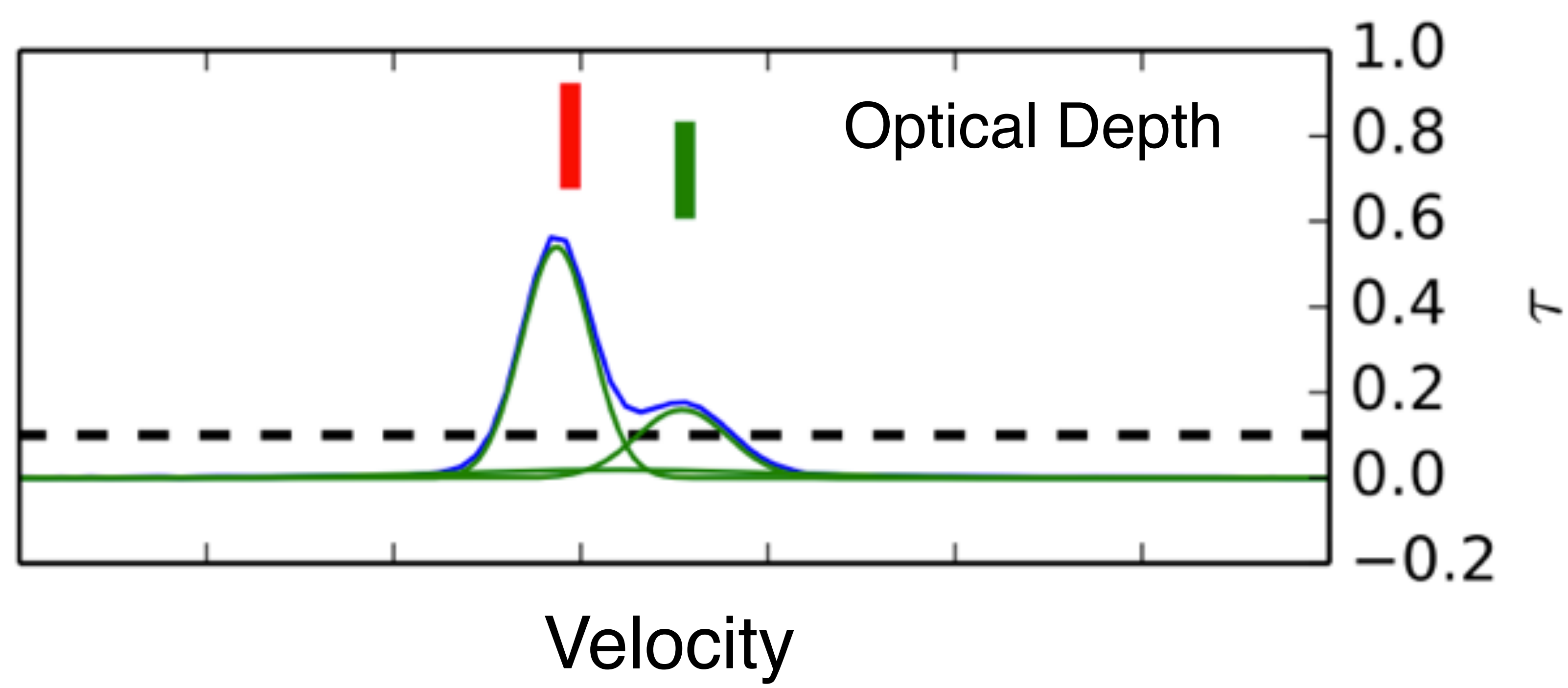

Simulations
Observations
Physical quantities
Synthetic spectra
$AGD()$
Gaussian components
$\tau_i, \sigma_i^v, \Delta v_i,$
Observed spectra
$AGD()$
Gaussian components
$\tau_i, \sigma_i^v, \Delta v_i,$

Do Gaussians Correspond to Clouds?

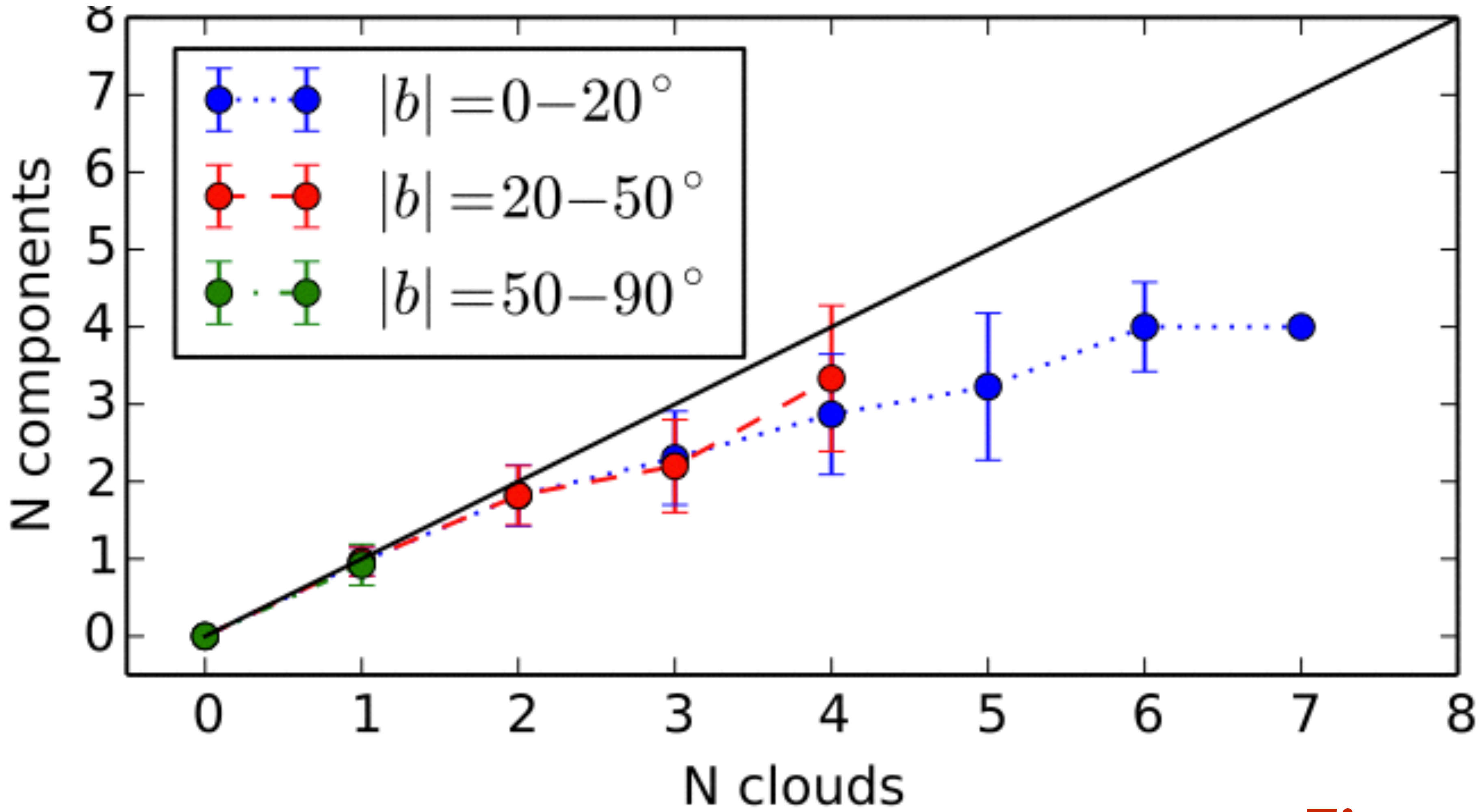


Matching Gaussians to Clouds in Simulations





Matching Gaussians to Clouds in Simulations



Unique cloud recovery fraction:

$$|b| = 0 - 20^\circ \rightarrow 69\%$$

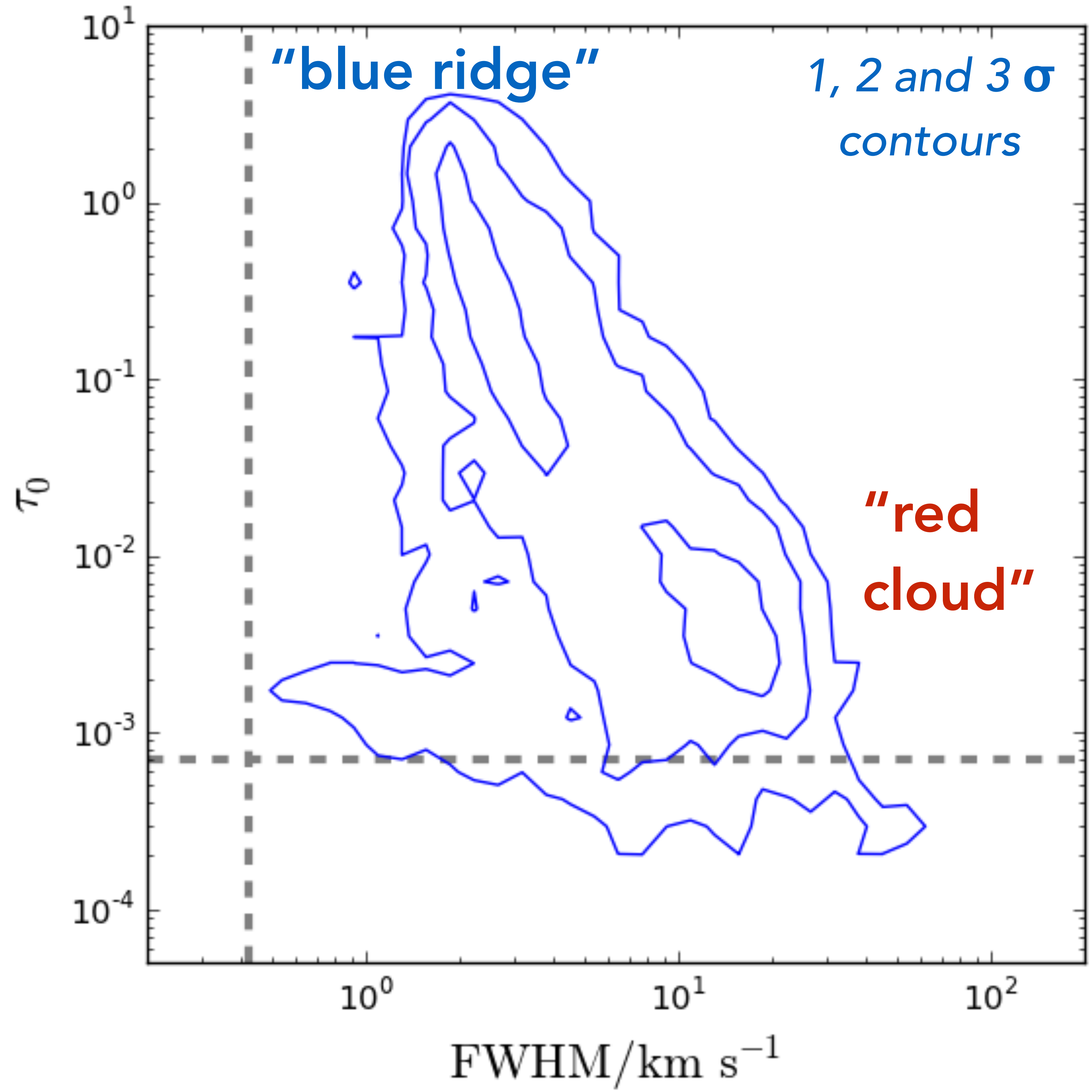
$$|b| = 20 - 50^\circ \rightarrow 83\%$$

$$|b| = 50 - 90^\circ \rightarrow 92\%$$

First statistically-robust quantification of cloud-component correspondence!

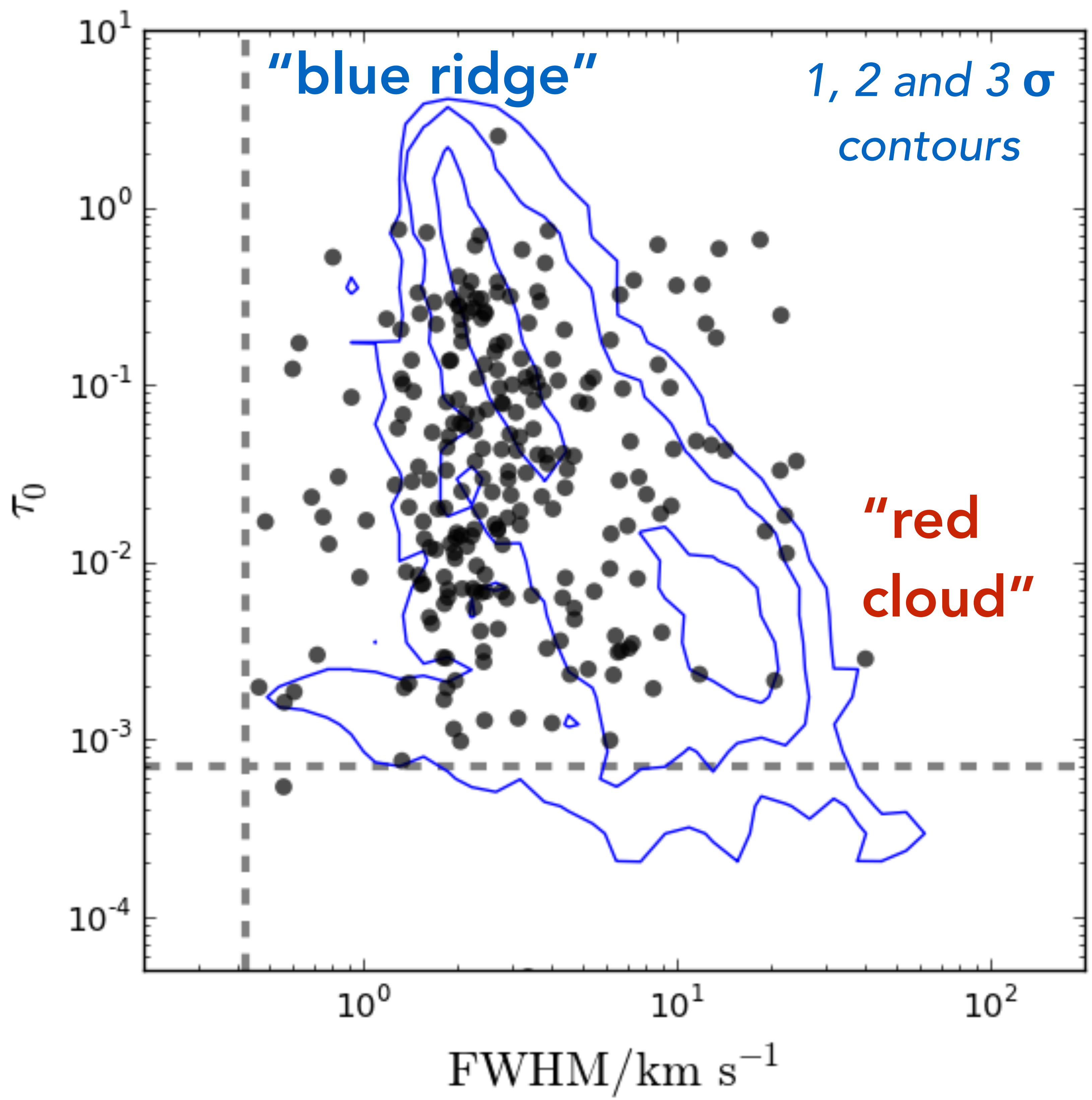
Comparing AGD Absorption Parameters

- **BLUE CONTOURS:** 10^4 AGD-processed synthetic HI absorption lines (Kim et al. 2014)

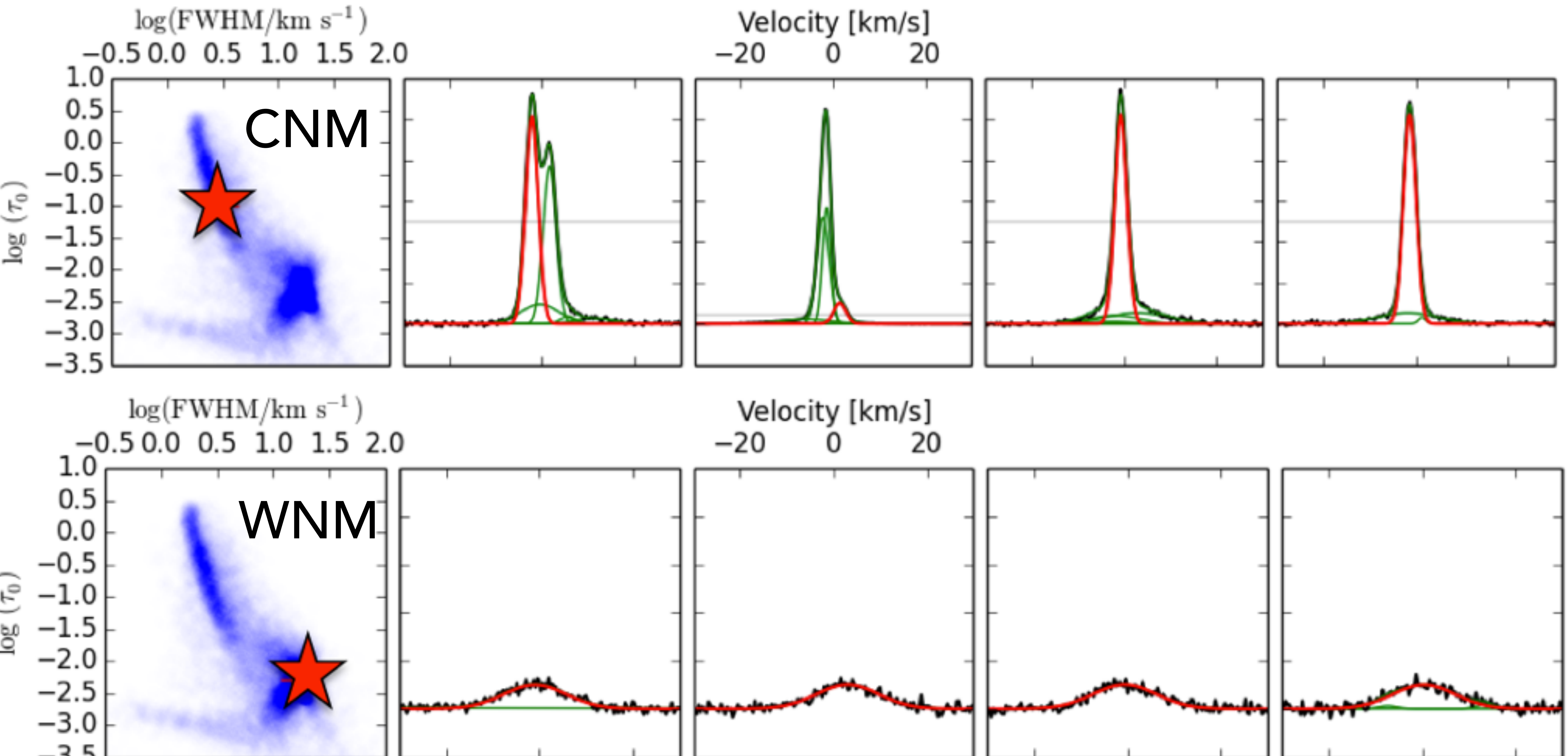


Comparing AGD Absorption Parameters

- **BLUE CONTOURS:** 10^4 AGD-processed synthetic HI absorption lines (Kim et al. 2014)
- **BLACK**: 37 AGD-processed 21-SPONGE VLA HI absorption lines (Murray et al. 2015)



Comparing CNM and WNM Absorbing LOS

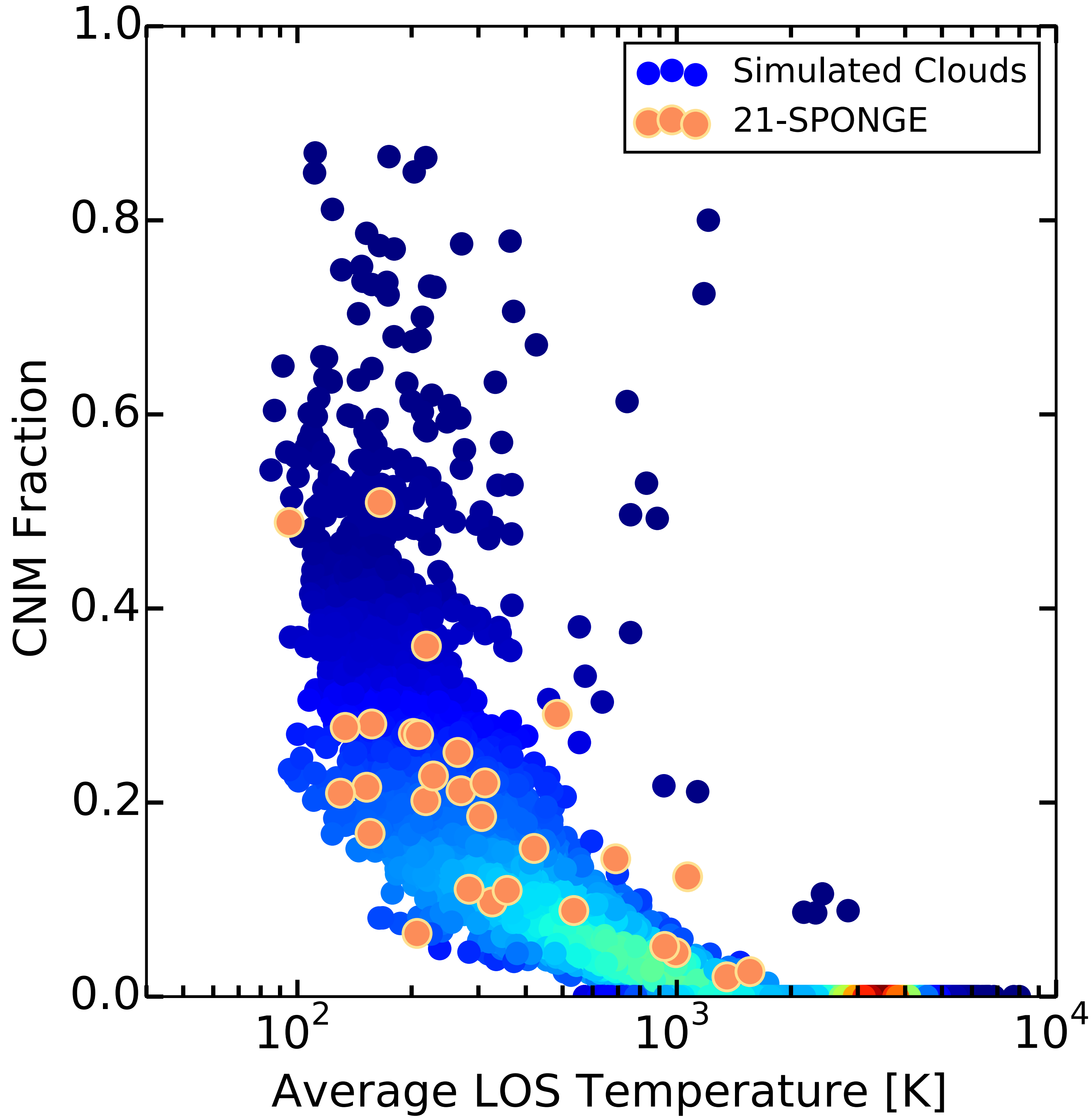


Such absorption lines, with no CNM, are RARE!

How much CNM is there?

How much CNM is there?

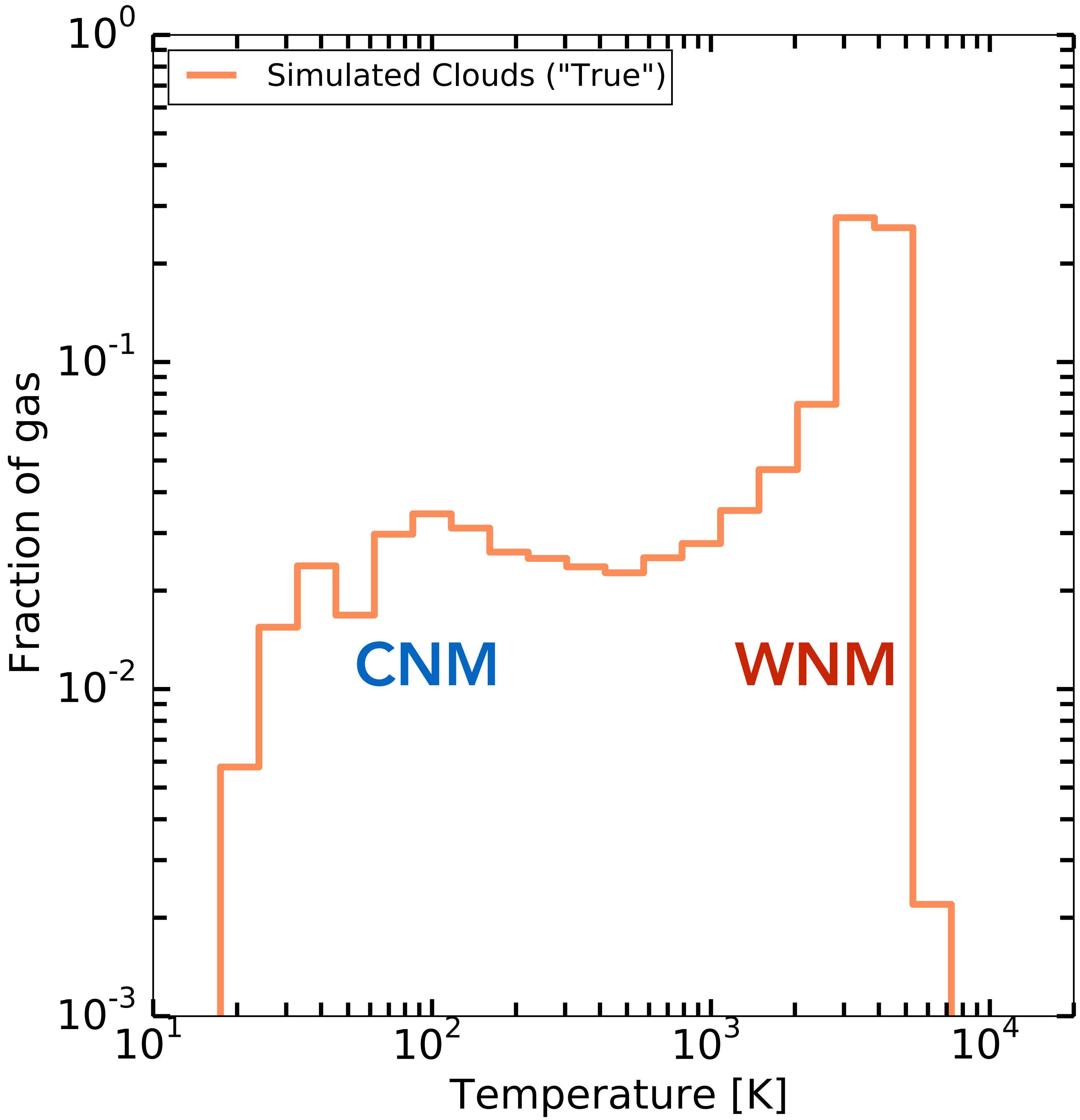
"CNM" = Ts<200 K



Murray et al. 2015, ApJ, 804, 89

Simulation data:
Kim et al. 2014

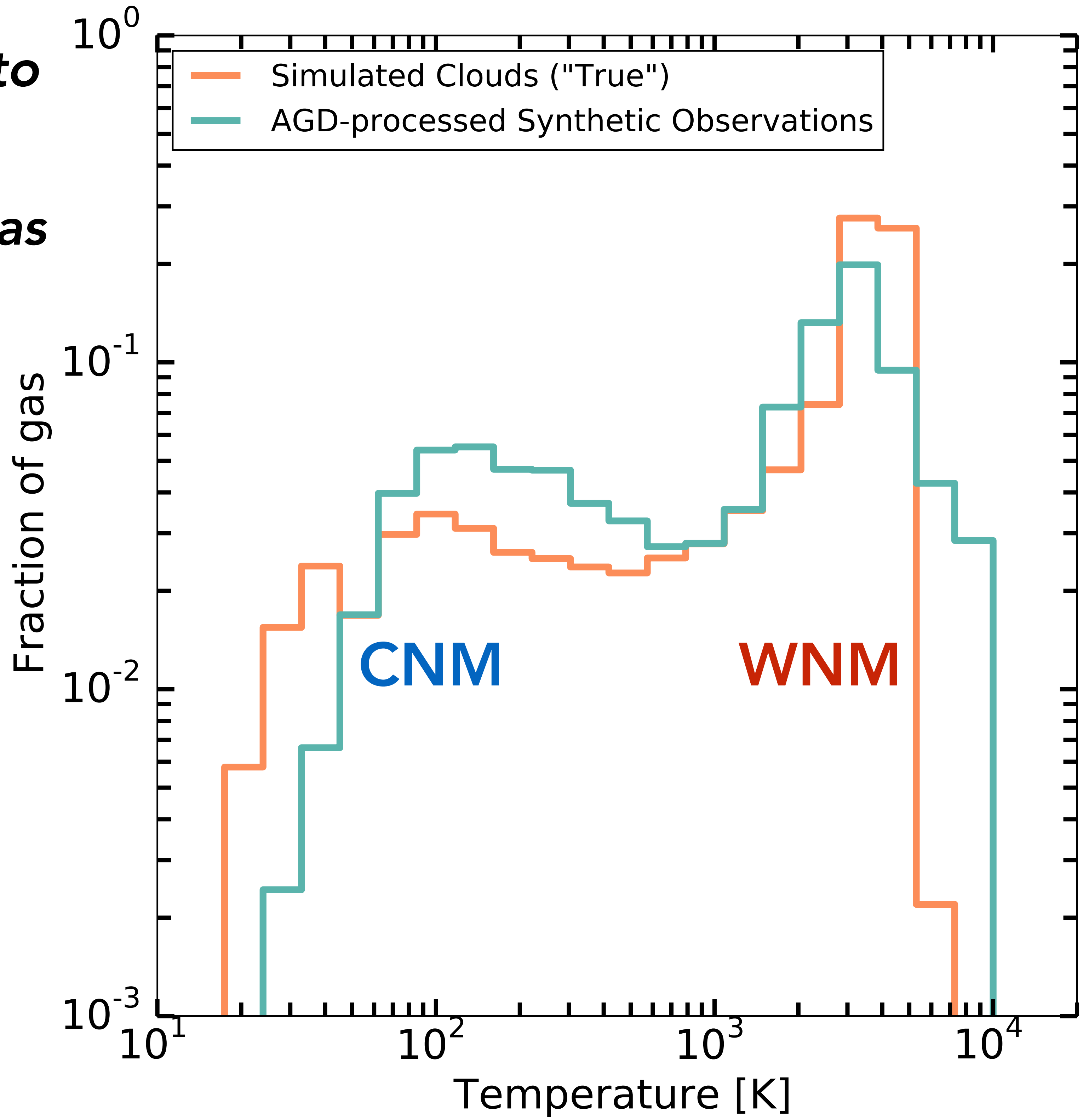
Simulated Mass Fractions by Temperature



Simulation data:
Kim et al. 2014

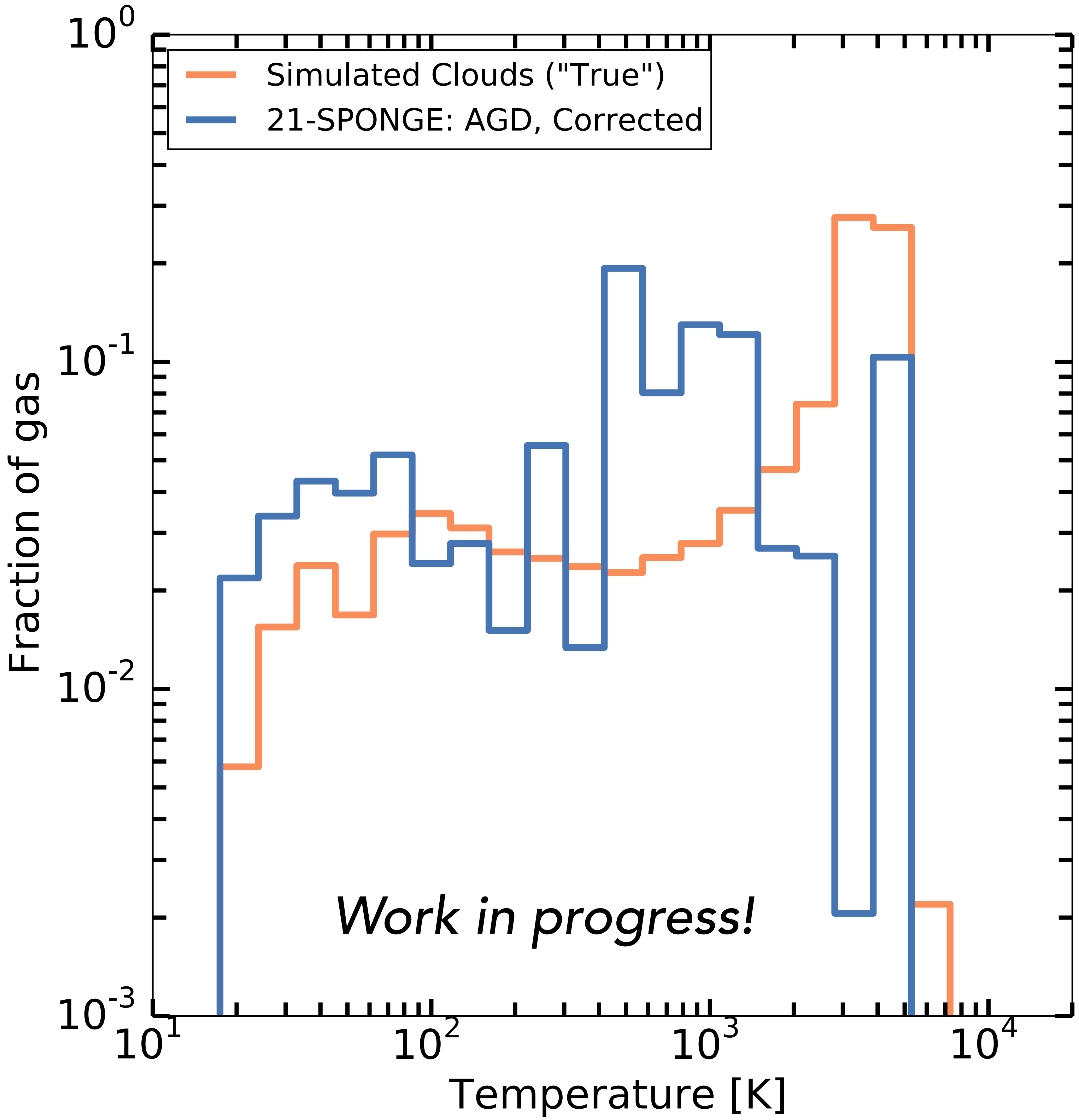
Simulated Mass Fractions by Temperature

Ratio of "true" to "observed" = observational bias correction!



Simulation data: Kim et al. 2014

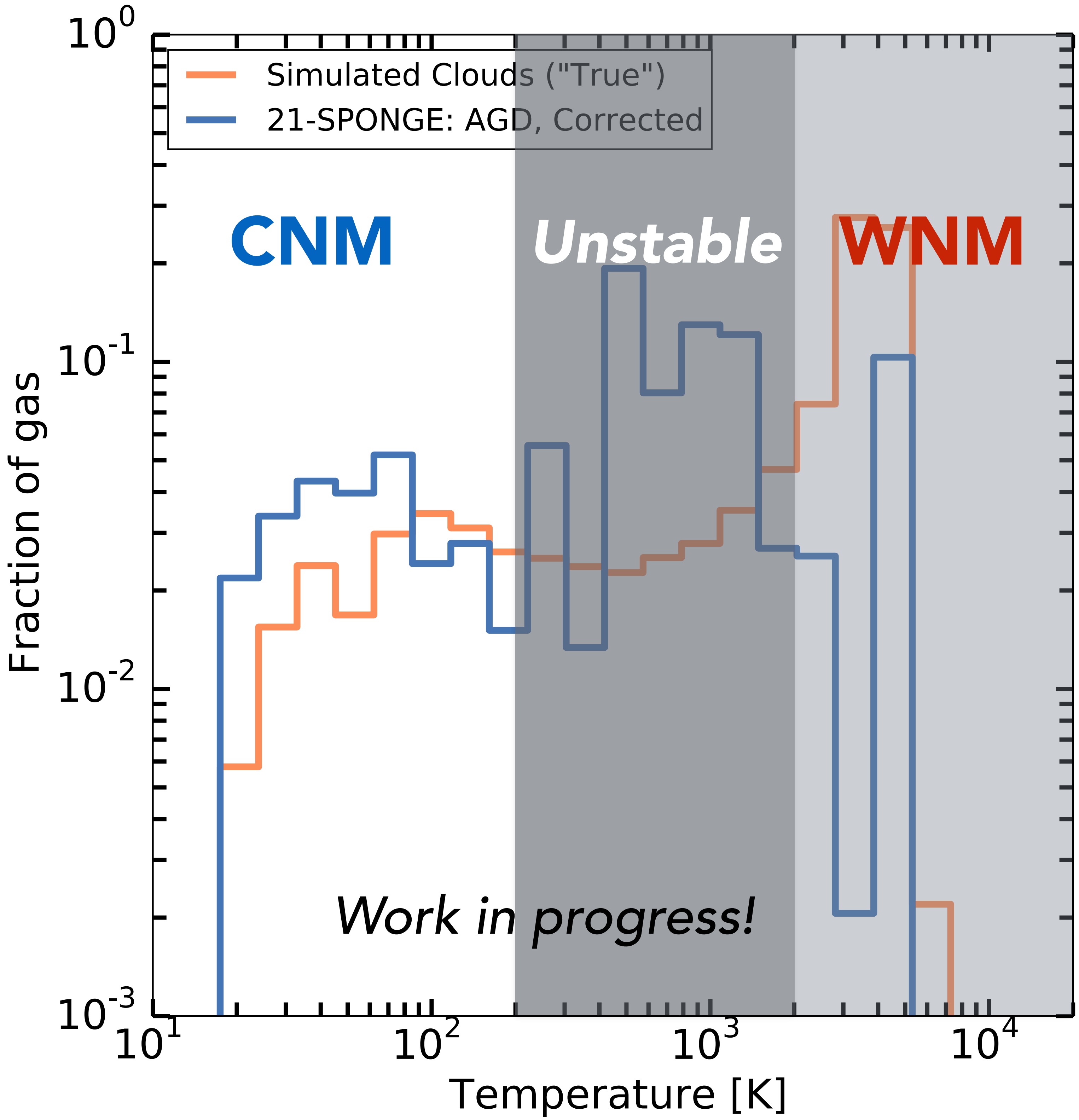
Observed Mass Fractions by Temperature



Simulation data:

Kim et al. 2014

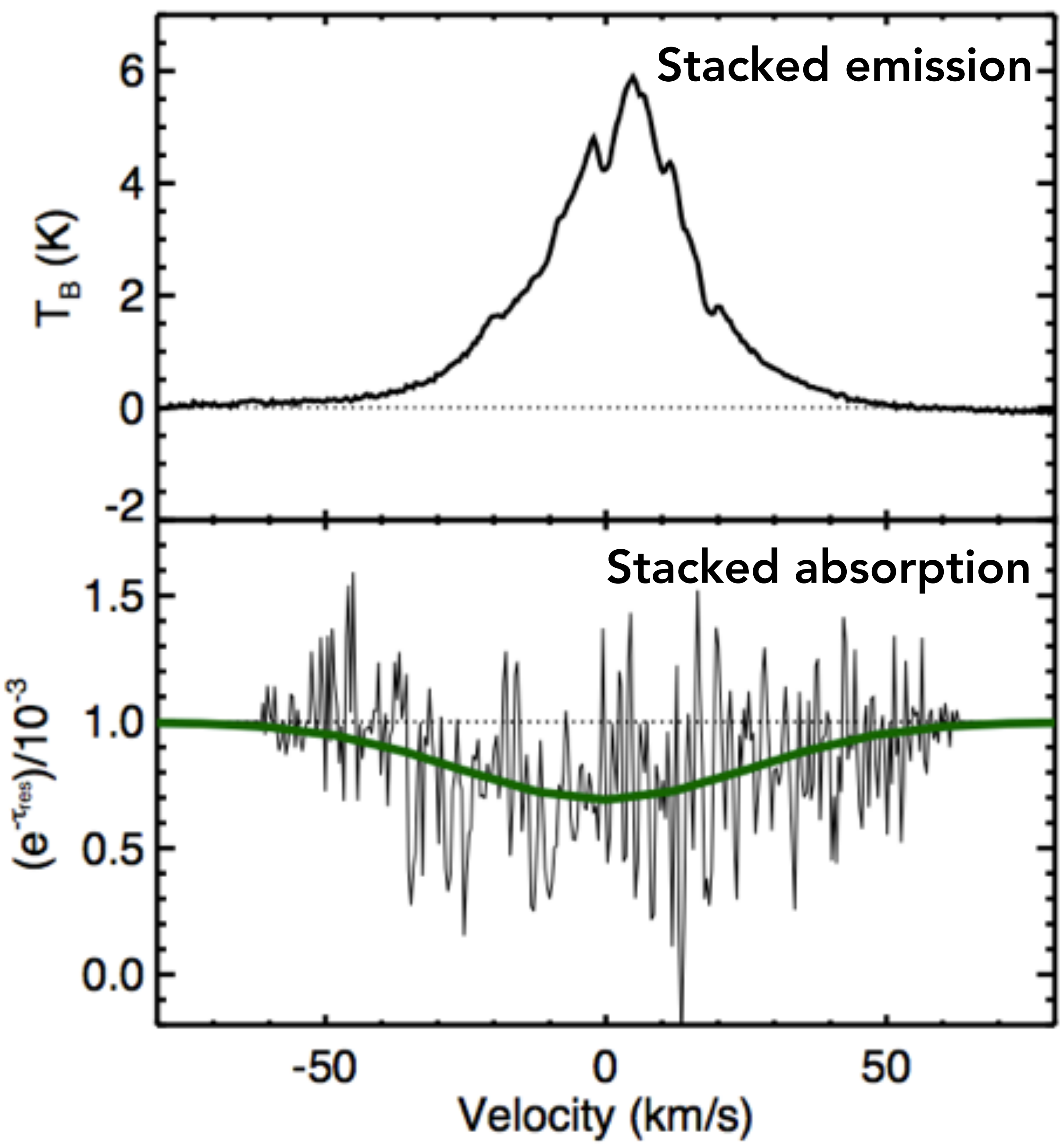
Observed Mass Fractions by Temperature



Where is the WNM?

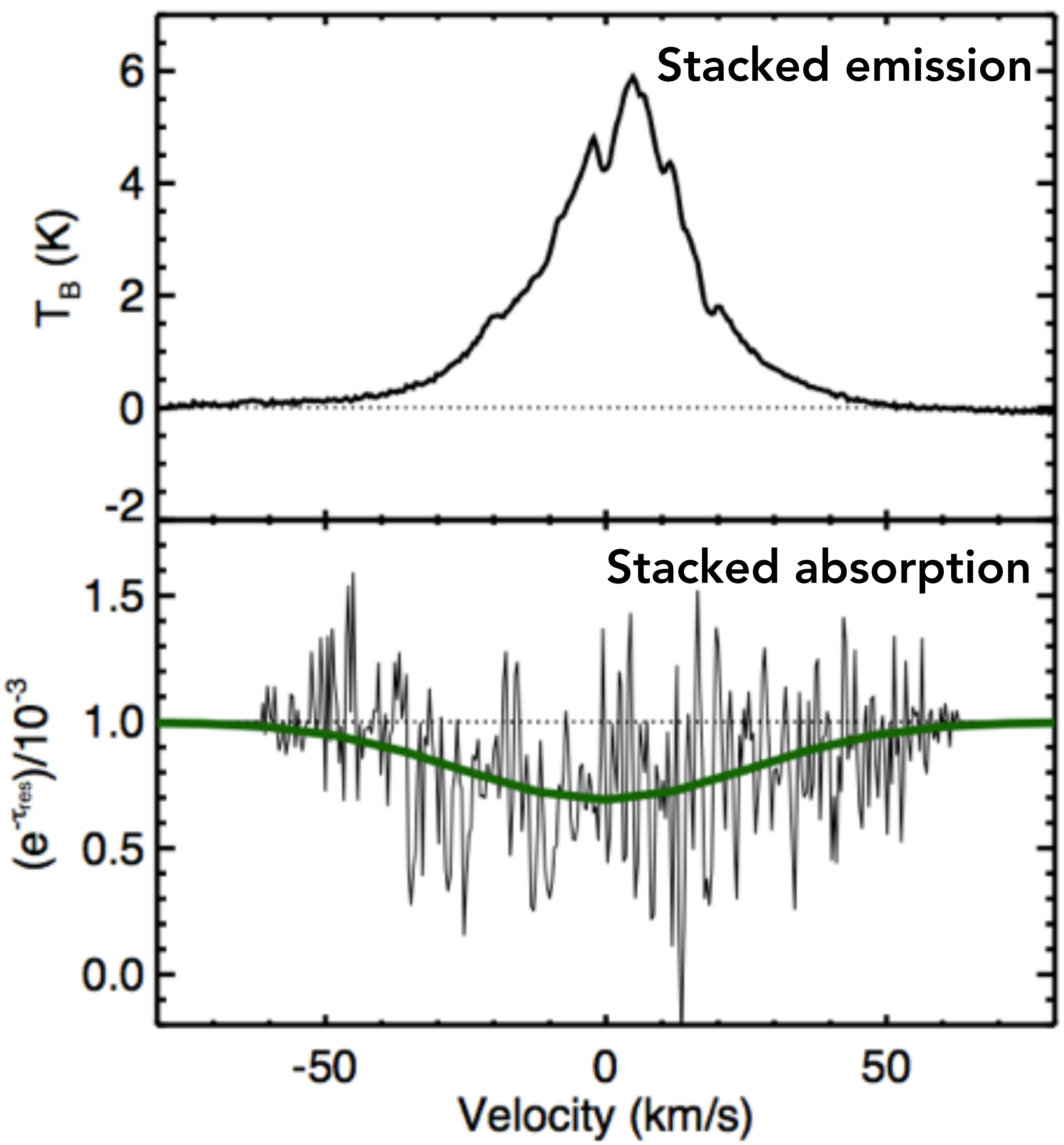
Simulation data:
Kim et al. 2014

Search for HI gas at even higher *Ts*…

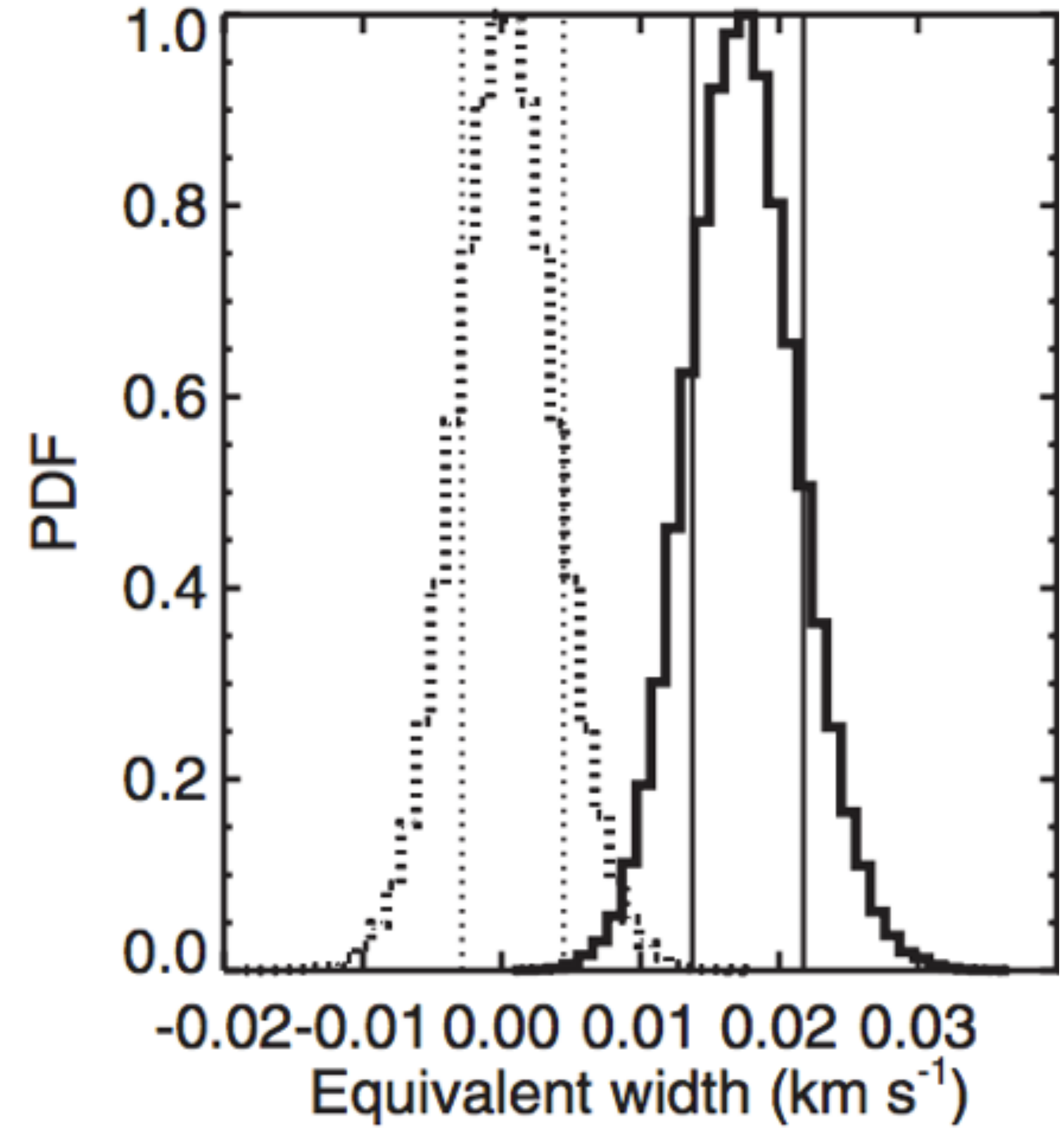


Murray et al. 2014, ApJ, 781, L41

Search for HI gas at even higher *Ts*...



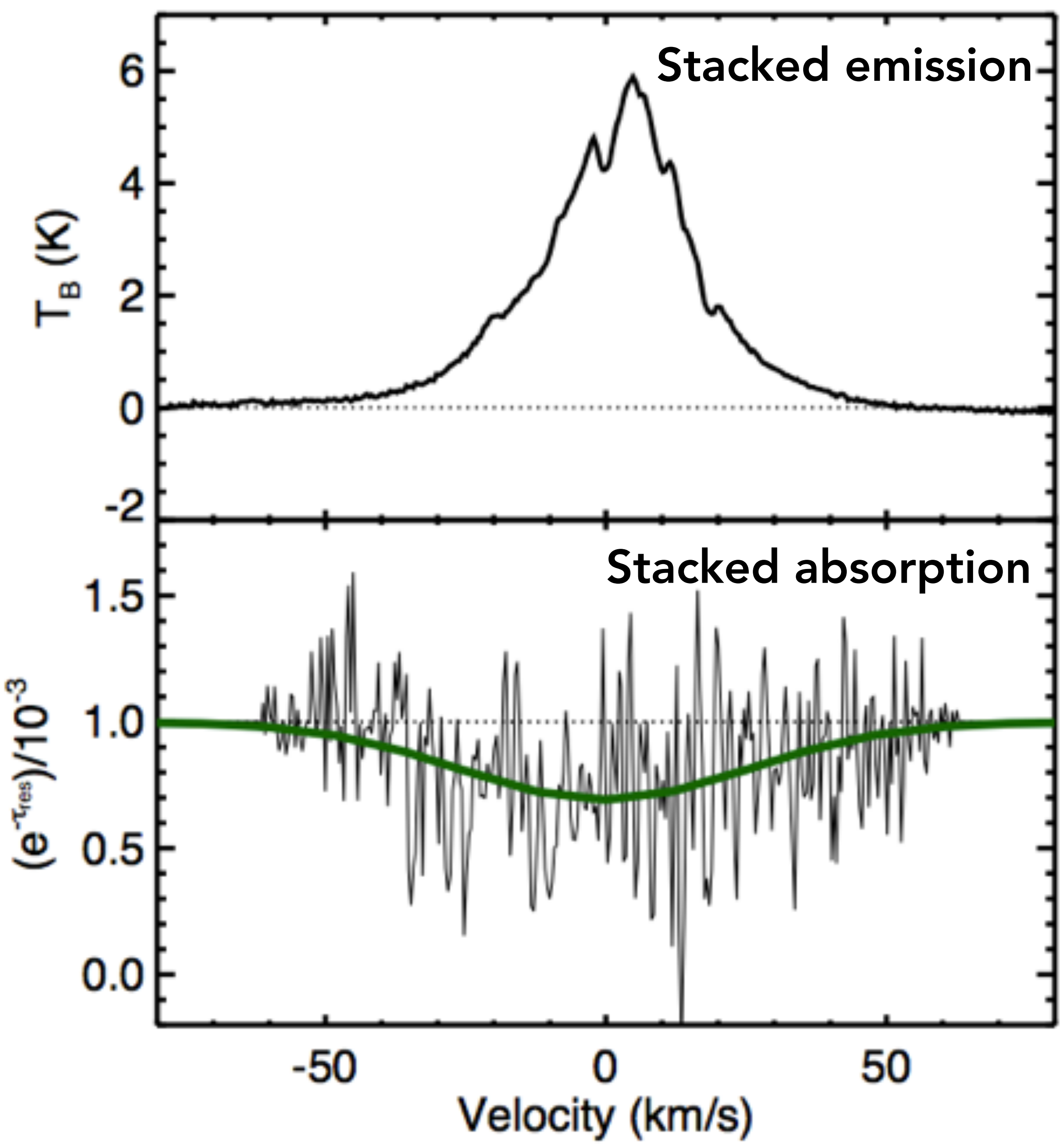
$$\langle T_s \rangle = 7200^{+1800}_{-1200}\,K$$



Murray et al. 2014, ApJ, 781, L41

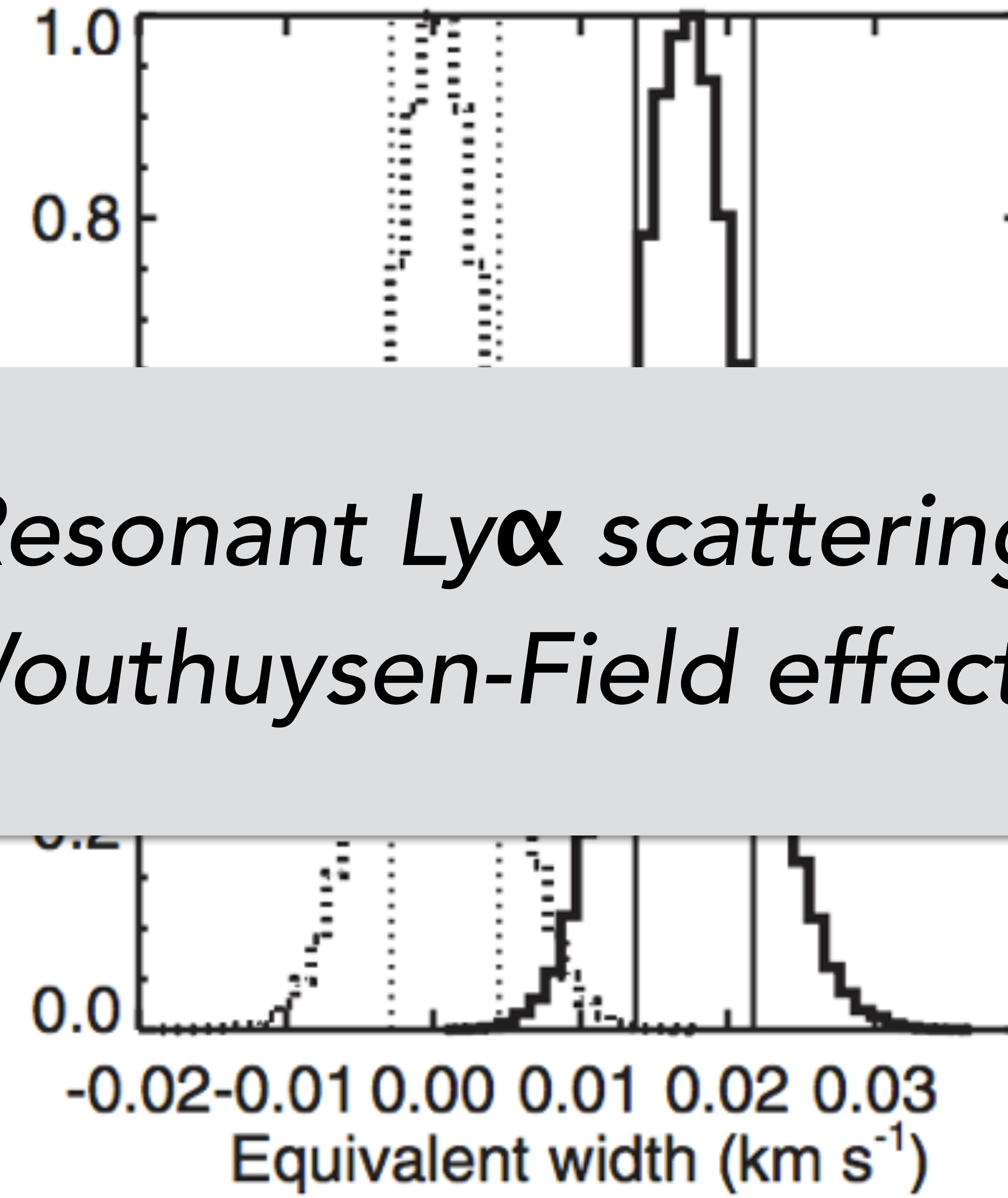
Bootstrap MC simulation, 10^5 trials

Search for HI gas at even higher *Ts*…



Murray et al. 2014, ApJ, 781, L41

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



Resonant Lyα scattering (Wouthuysen-Field effect)?

Bootstrap MC simulation, 10^5 trials

Summary

- **21-SPONGE** will constrain the uncertain mass distribution of HI as a function of $T_{s,}$ as the largest high-sensitivity HI absorption survey:
  - Sensitive to unstable and warm gas mass
  - Evidence for T_s~7000 K gas, weaker at high latitude
- **Autonomous Gaussian Decomposition (AGD)** enables fas and consistent comparisons between observations and simulations:
  - Confirms correspondence btwn HI clouds and Gaussian spectral features
  - CNM fraction agrees very well with predicted average Ts trends
  - CNM detection rate is higher in observations than simulations
- *Need more HI emission/absorption observations and synthetic observations of simulations to improve statistics!*