Cold gas evolution with the SKA pathfinders

A statistical method for measuring the spin temperature in distant galaxies

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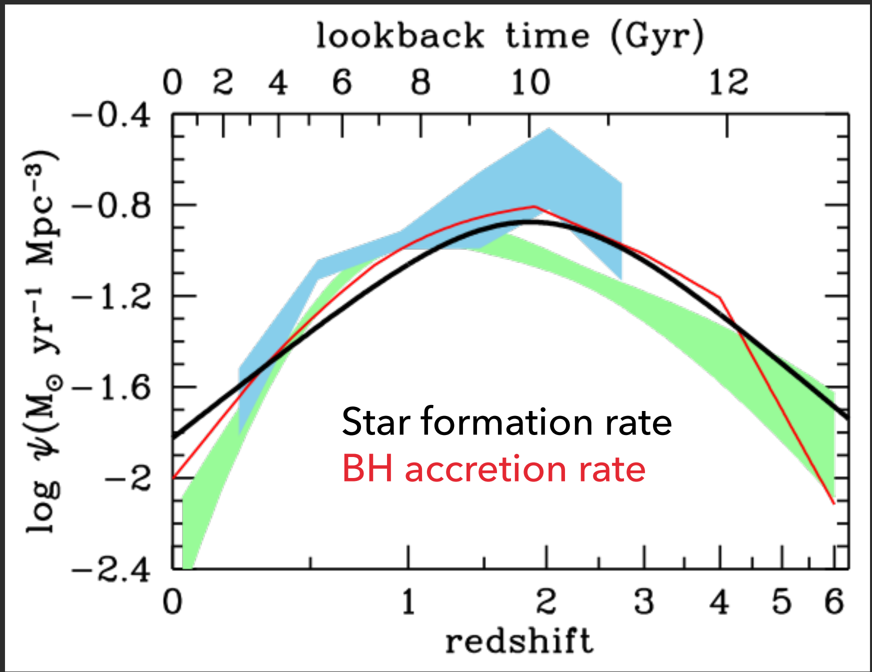
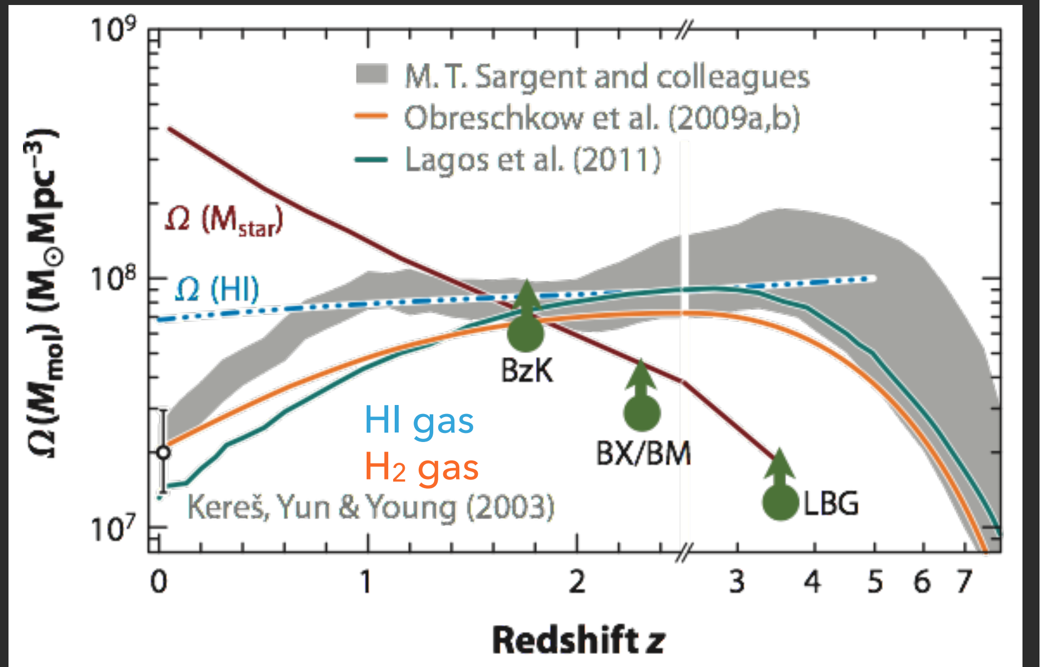
FUELLING THE RISE AND FALL OF STAR FORMATION & BH GROWTH



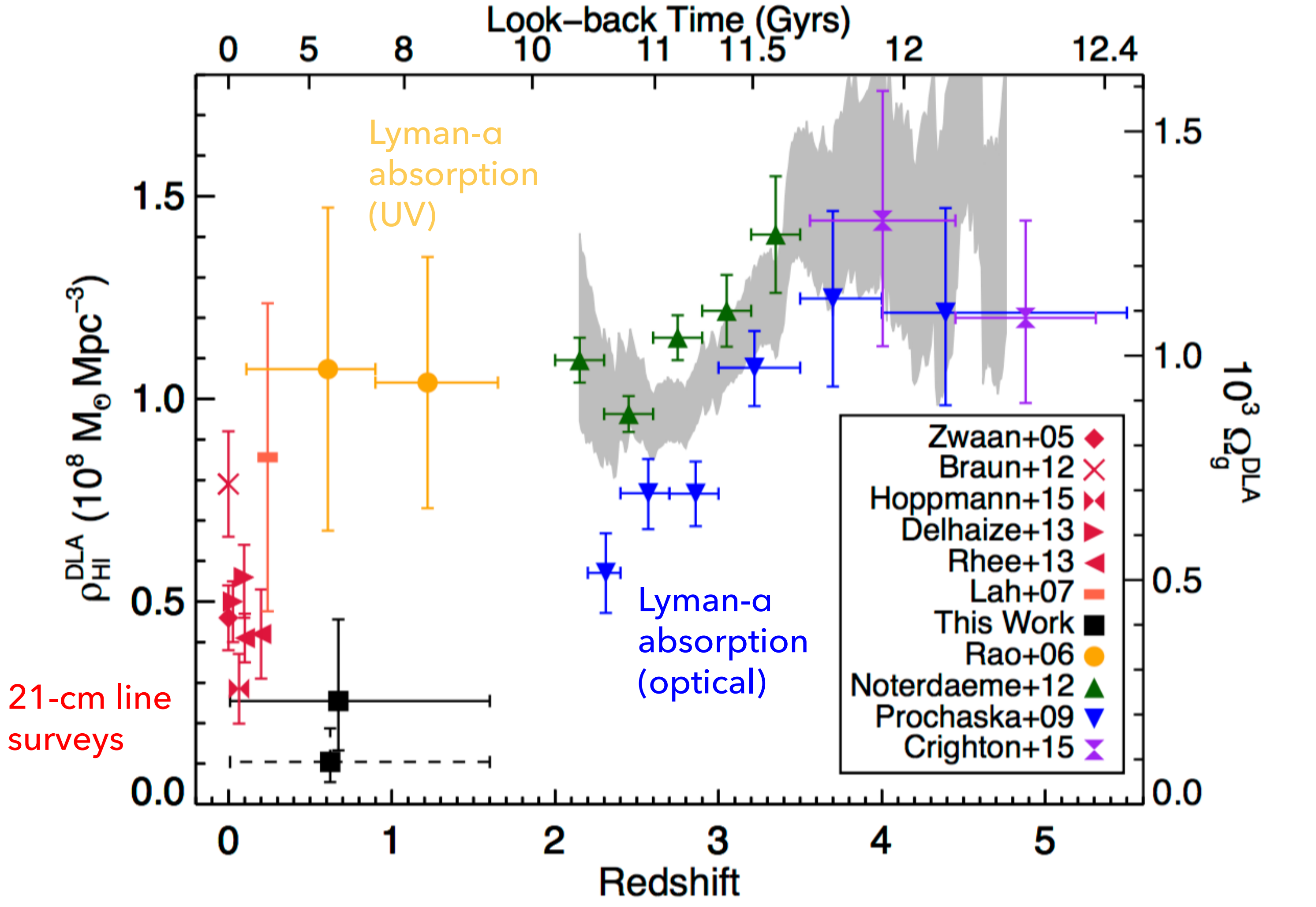
Madau & Dickinson 14



Carilli & Walter 13

- Dramatic decline in star formation and black hole growth rate over last 10 billion years
- Do we see a similar cosmological decline in the neutral gas - is the fuel drying up?

NEUTRAL HISTORY OF THE UNIVERSE IN HI



Neeleman+ 16

THE MULTIPHASE ISM

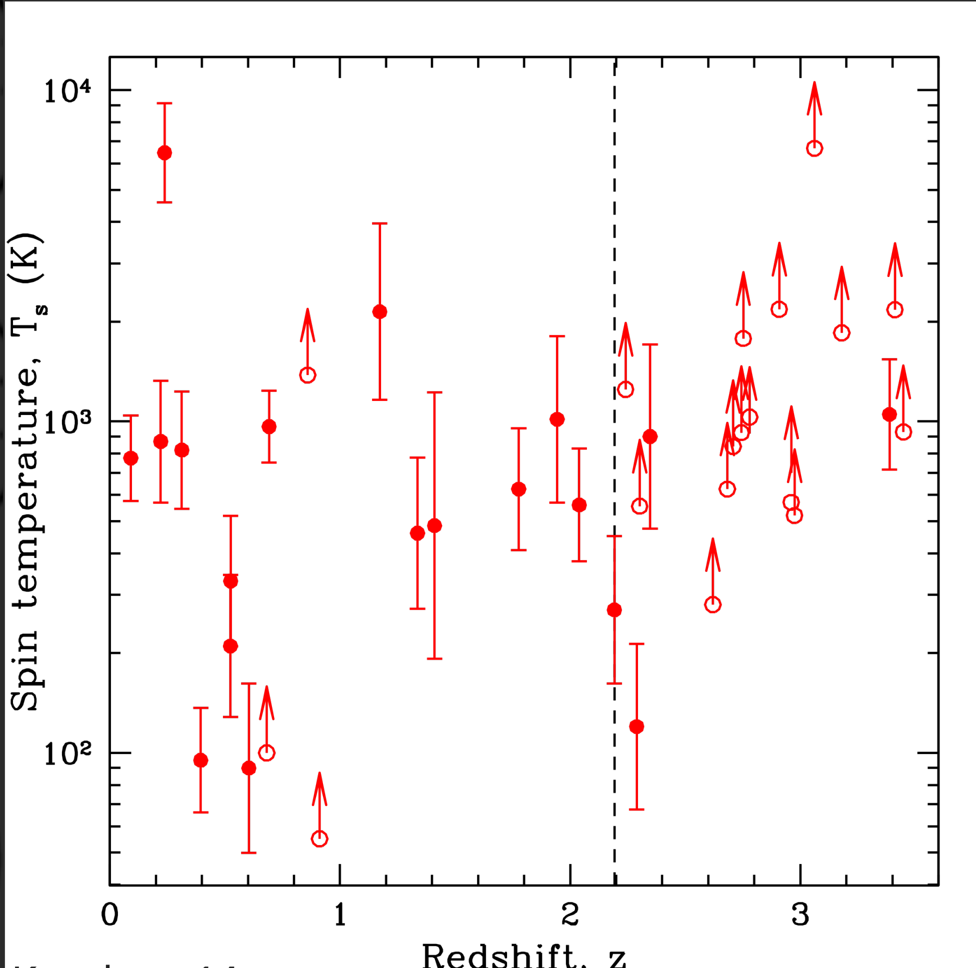
- Classical ISM model has two stable neutral phases in pressure equilibrium with differing spin temperatures (e.g. Field+ 69)
- Cold (T_{spin}~100K) and Warm (T_{spin}~1000-5000K; e.g. Liszt 01)
- The balance of these phases depends on cooling (e.g. metallicity), heating (e.g. star formation)

21-CM ABSORPTION AS A PROBE OF THE COLD GAS FRACTION

- CNM is the phase in which molecular clouds and stars form, which we suspect might evolve with redshift
- 21-cm absorption strength dependent on inverse harmonic mean of line-of-sight T_{spin} and so sensitive to cold gas
- Combining 21-cm absorption with either emission or Lyman-alpha absorption provides a direct measure of $< T_{\mathrm{spin}} >$

DIRECTLY MEASURING THE SPIN TEMPERATURE IN DLAS

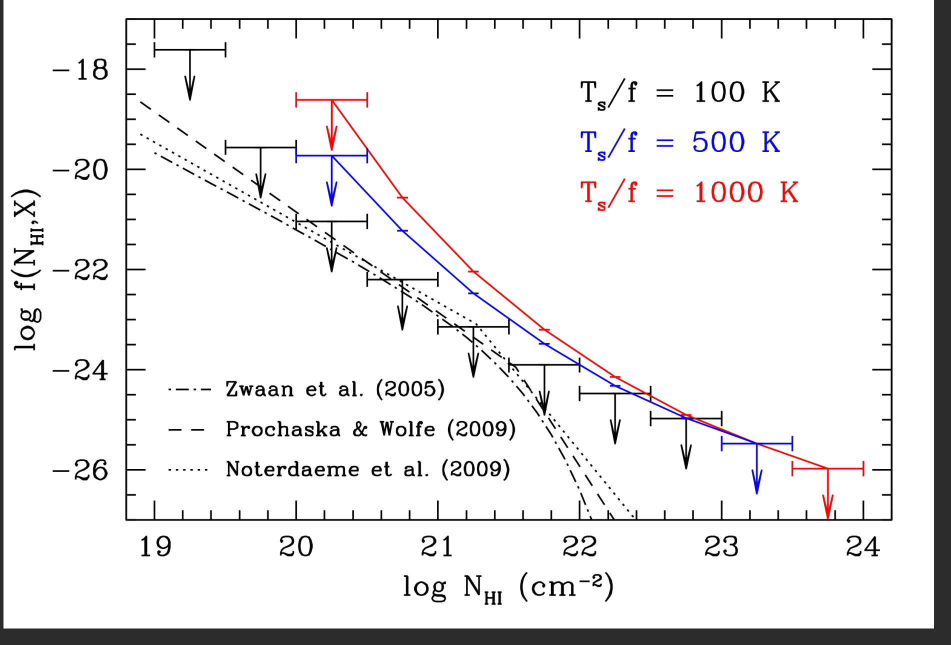
- Decades of targeted 21-cm absorption observations of optical DLAs has yielded a tentative 4-sigma evolution in $\langle T_{spin} \rangle$ (Kanekar+ 14)
- Improvement in statistics requires simultaneous 21-cm line and Optical/UV of a larger sample
- This is observationally expensive, especially at intermediate redshifts where the Lyman-alpha line is in UV



Kanekar+ 14

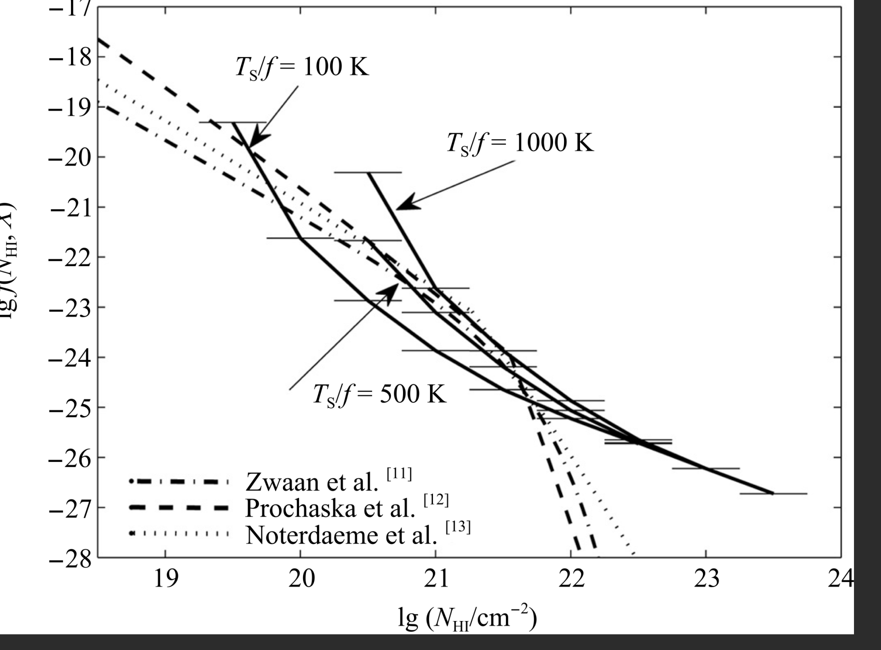
SPIN TEMPERATURE LOWER BOUNDS USING ALFALFA

ALFALFA Pilot Absorption Survey (7%)



Darling+ 11

ALFALFA 40% data release



Wu+ 15

CAN WE INFER $<T_{\rm SPIN}>$ JUST FROM 21-CM LINE ABSORPTION?

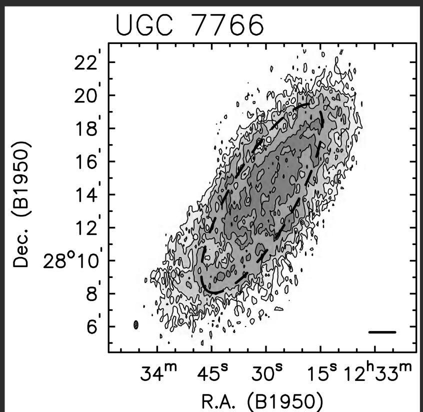
- The expected number of detections in any survey for intervening absorption is dependent on the spin temperature
- By comparing the expected number of detections with the actual yield we can infer what the average spin temperature must be for HI rich galaxies in that redshift interval
- With a sufficiently large number of sight-lines can we achieve reasonable constraints on $<T_{\rm spin}>$?

THE EXPECTED NUMBER OF 21-CM ABSORBERS

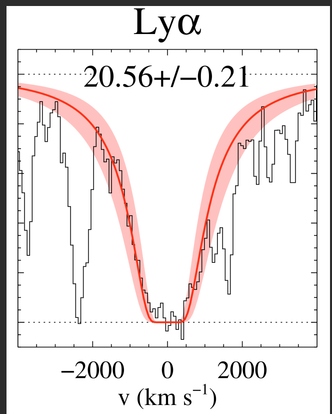
- The expected number of intervening HI clouds is given by

$$\mu = \iint f(N_{\mathrm{HI}}, X)\, \mathrm{d}X\, \mathrm{d}N_{\mathrm{HI}}$$

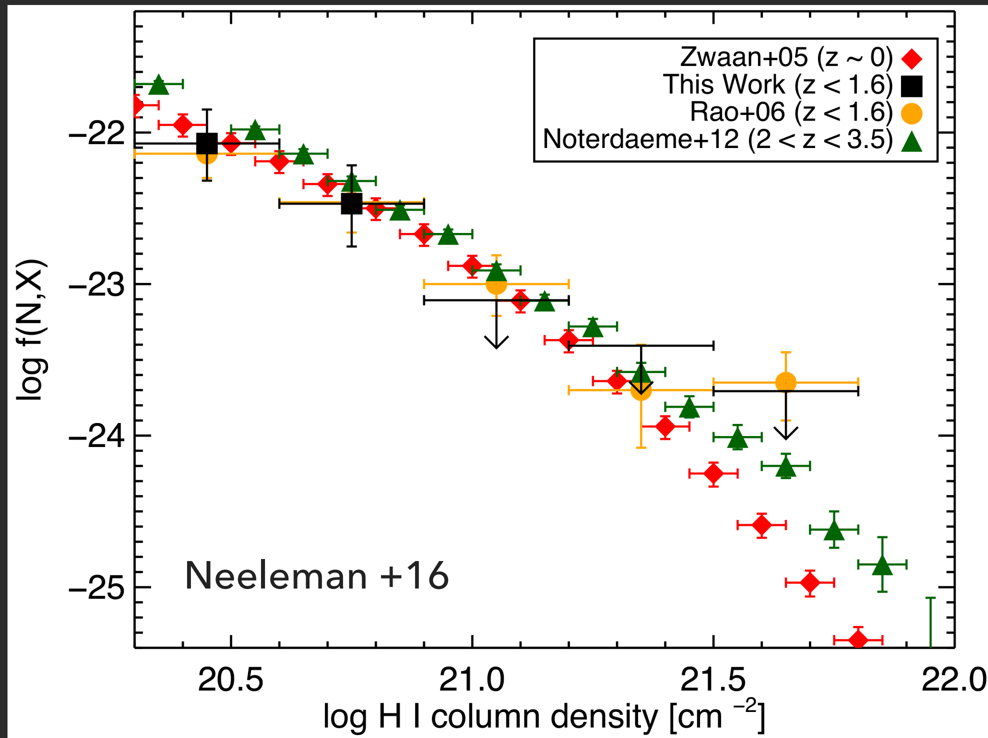
- Use measured $f(N_{HI}, X)$



Zwaan +05



Noterdaeme +09



THE EXPECTED NUMBER OF 21-CM ABSORBERS

- For each sight-line element probed by the survey we define a 5-sigma N_{HI} sensitivity so that the integral is now equal to the expected number of detections

$$\delta X(z) = \begin{cases} \frac{\delta z\,(1+z)^2}{\sqrt{(1+z)^2(1+z\Omega_{\mathrm{M}})-z(z+2)\Omega_{\Lambda}}}, & \text{if } N_{\mathrm{HI}} \geq N_{5\sigma}, \\ 0, & \text{otherwise.} \end{cases}$$

$$N_{5\sigma} \approx 1.941 \times 10^{18}\, T_{\mathrm{spin}}\, \tau_{5\sigma}\, \Delta v_{\mathrm{conv}}$$

$$\tau_{5\sigma} \approx -\ln\left[1 - \frac{5\,\sigma_{\mathrm{chan}}}{c_{\mathrm{f}}\, S_{\mathrm{cont}}}\sqrt{\frac{\Delta v_{\mathrm{chan}}}{\Delta v_{\mathrm{conv}}}}\right]$$

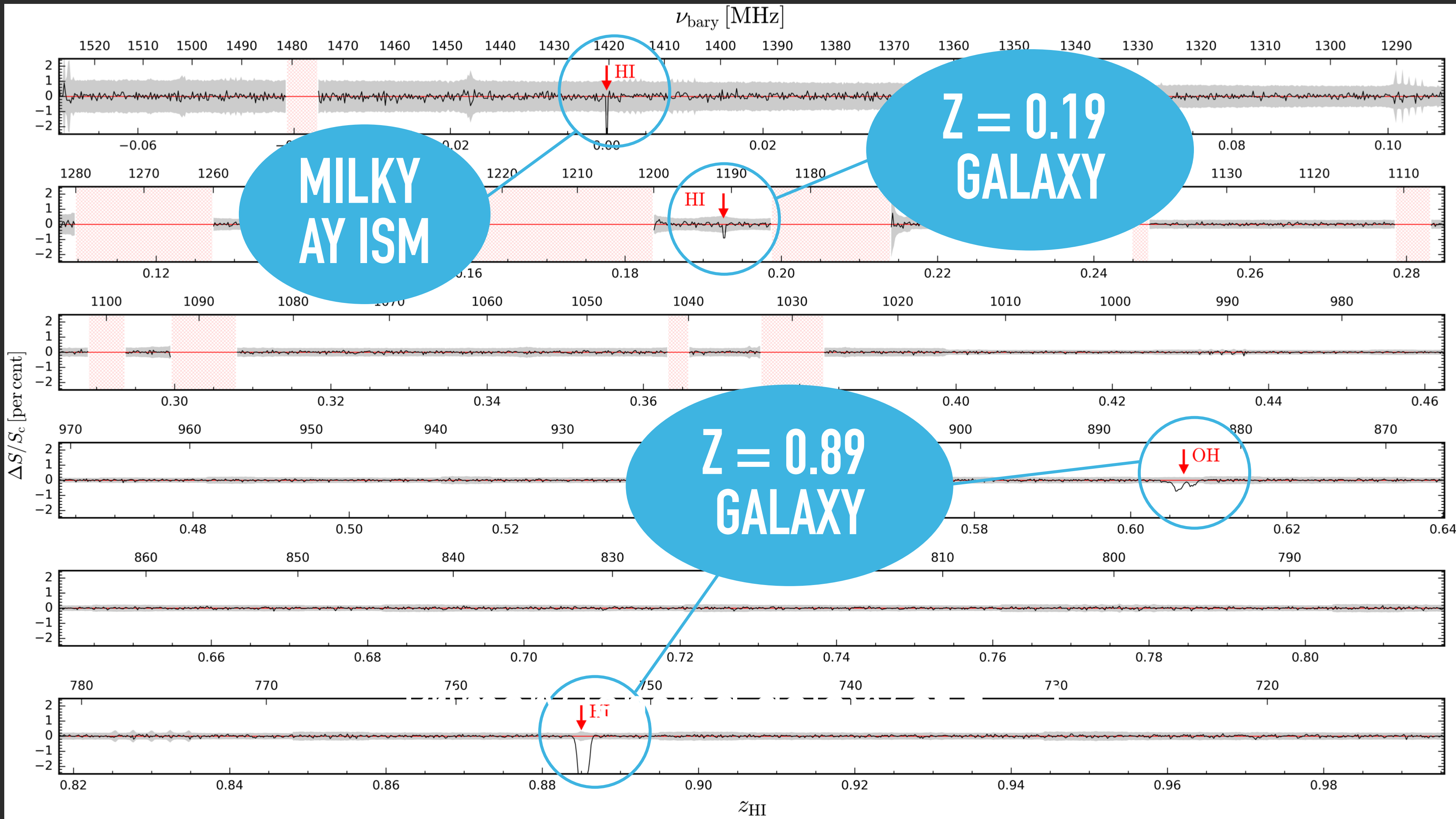
DETECTION YIELD PROBABILITY

- We assume that the number of detections *N* follows a Poisson distribution with mean and variance given by the expected number of detections
- The probability of obtaining a detection yield *N* absorbers from any given observation or survey is then given by

$$p(\mathcal{N}|\overline{\mu}) = p(\mathcal{N}|\overline{T}_{\mathrm{spin}}) = \frac{\overline{\mu}^{\mathcal{N}}}{\mathcal{N}!}\mathrm{e}^{-\overline{\mu}}$$

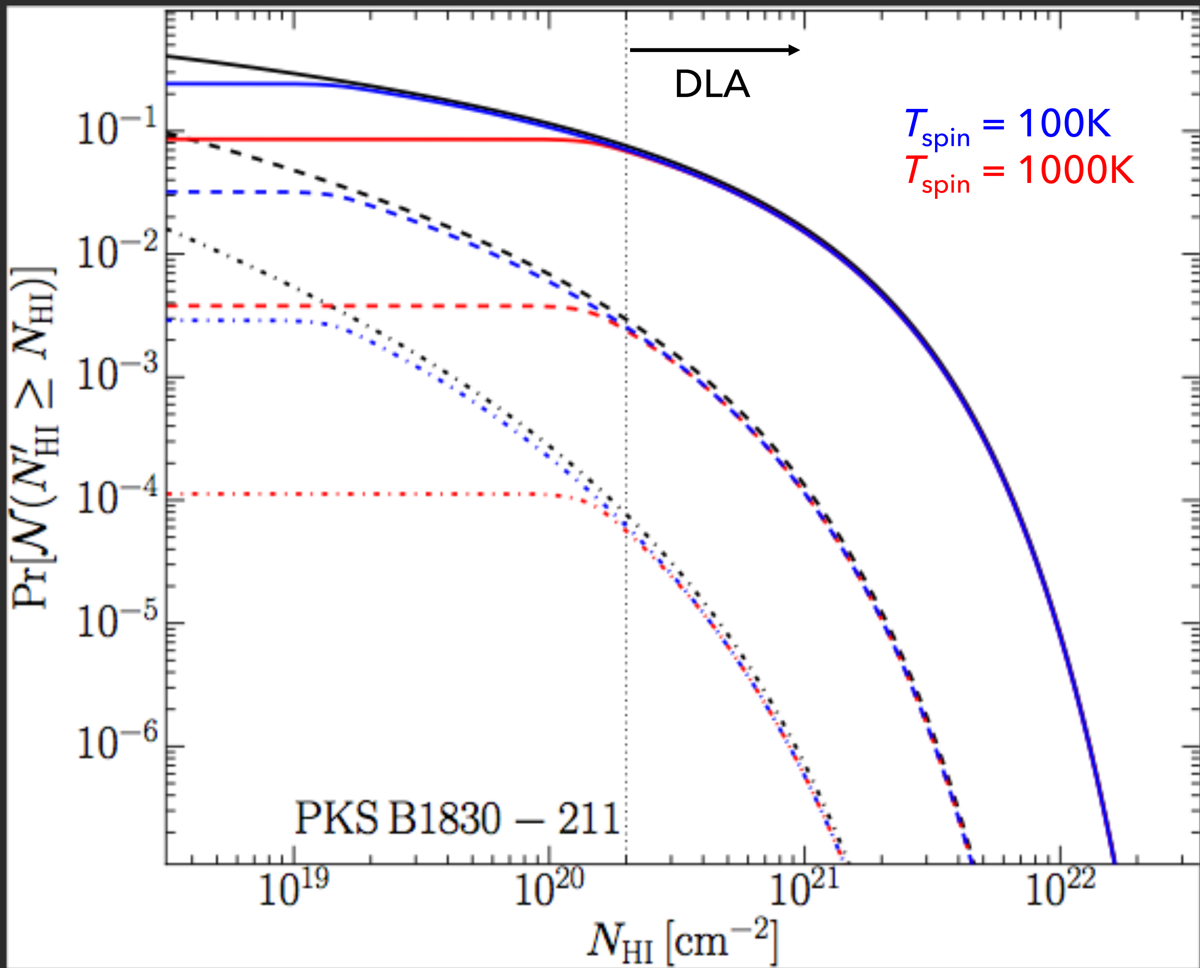
SINGLE SIGHT LINE EXAMPLE

ASKAP HI ABSORPTION SPECTRUM



Allison+17

ASKAP HI ABSORPTION SPECTRUM

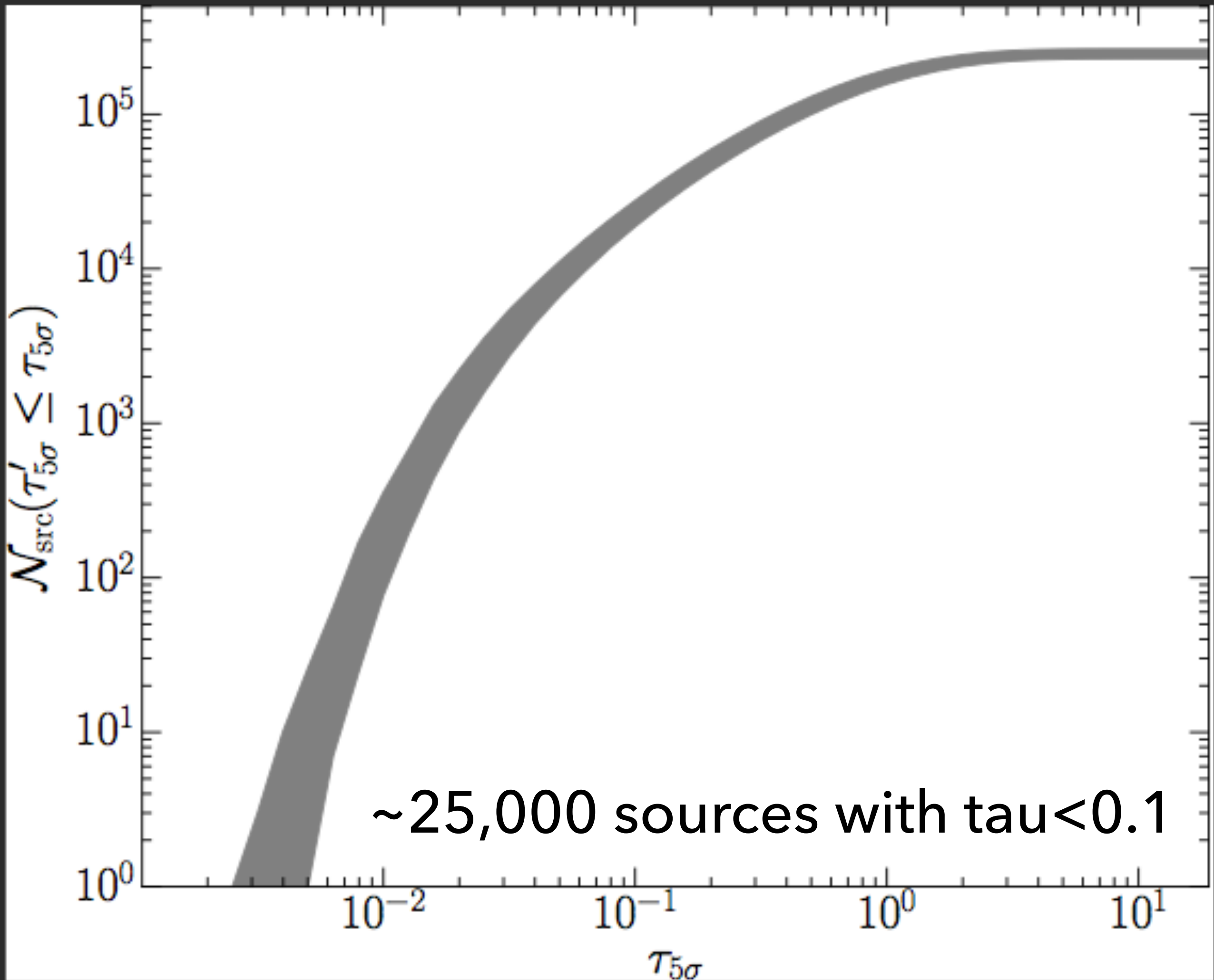


Allison+17

ALL-SKY 21-CM ABSORPTION SURVEY WITH ASKAP

- Simulate radio sky using NVSS (1.4GHz; Condon+ 98), SUMSS (843MHz; Mauch+ 03), MGPS-2 (843MHz; Murphy +07)
- Assume spectral index of -0.7 to extrapolate in frequency
- Choose sources between 10 mJy and 1Jy (~500,000 sight-lines)
- All-sky below +10 degrees
- 2hrs per pointing and use predicted telescope sensitivity from recent engineering tests by Chippendale+ 15

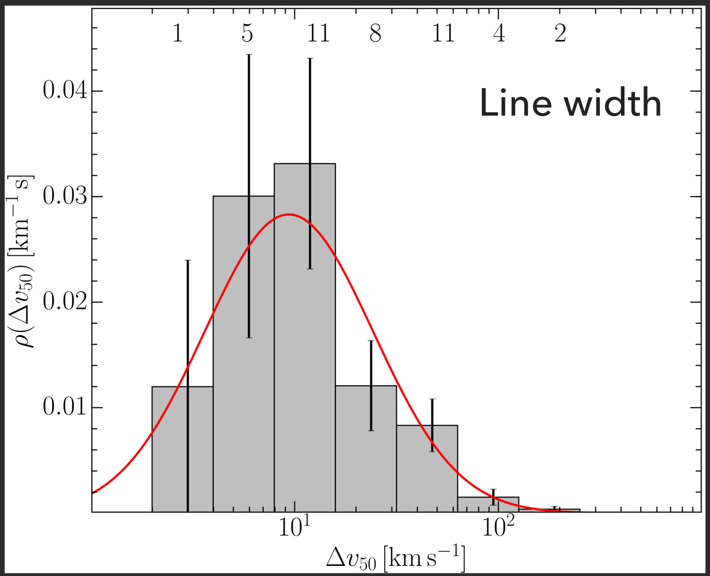
EXPECTED SURVEY SENSITIVITY

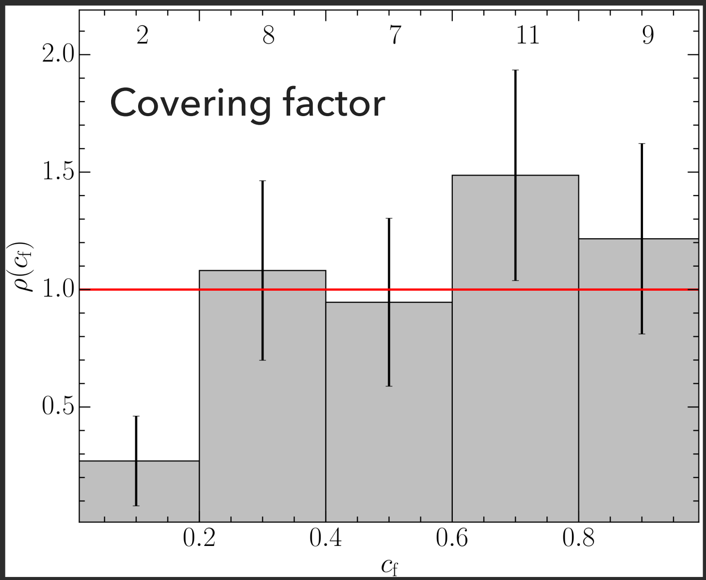


Allison+ 67

ACCOUNTING FOR COVERING FACTOR AND LINE WIDTH

- The detection sensitivity depends not only on the telescope, survey and source (known), but also the spin temperature, covering factor and line width (unknown)
- We marginalise over the last two properties, by drawing random samples assuming distributions for both

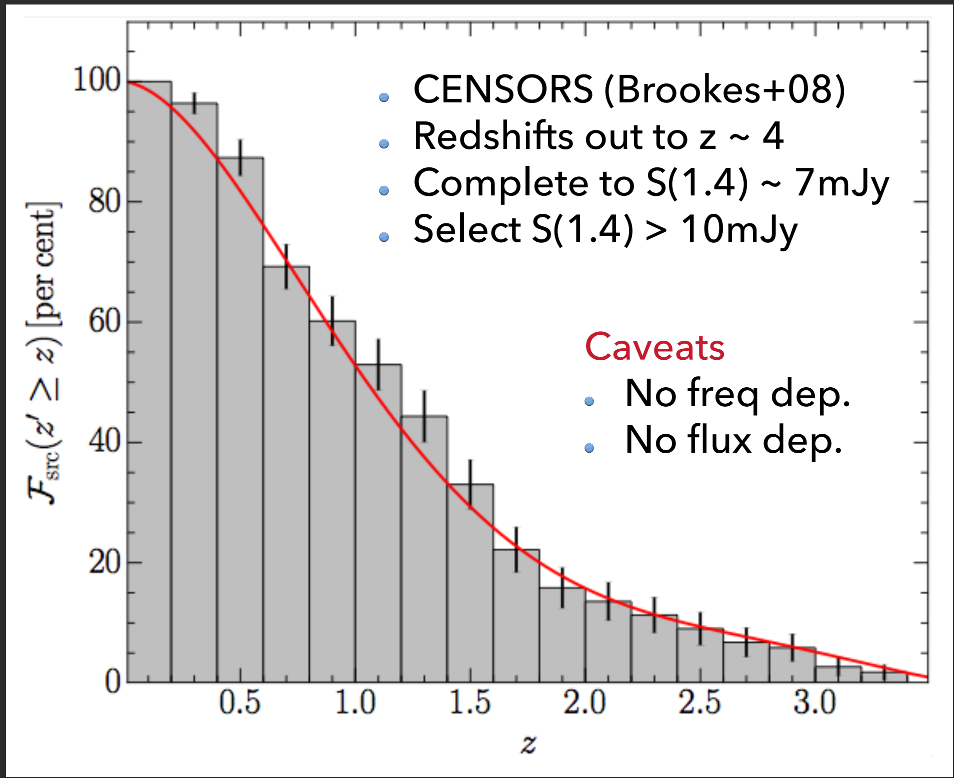




Allison+ 16

ACCOUNTING FOR UNKNOWN SOURCE REDSHIFTS

- The number of detections also depends on the available comoving path to each source
- We don't have have spectroscopic redshifts for every radio source in the sample
- But we can weight the comoving path length using the known distribution of source spectroscopic redshifts



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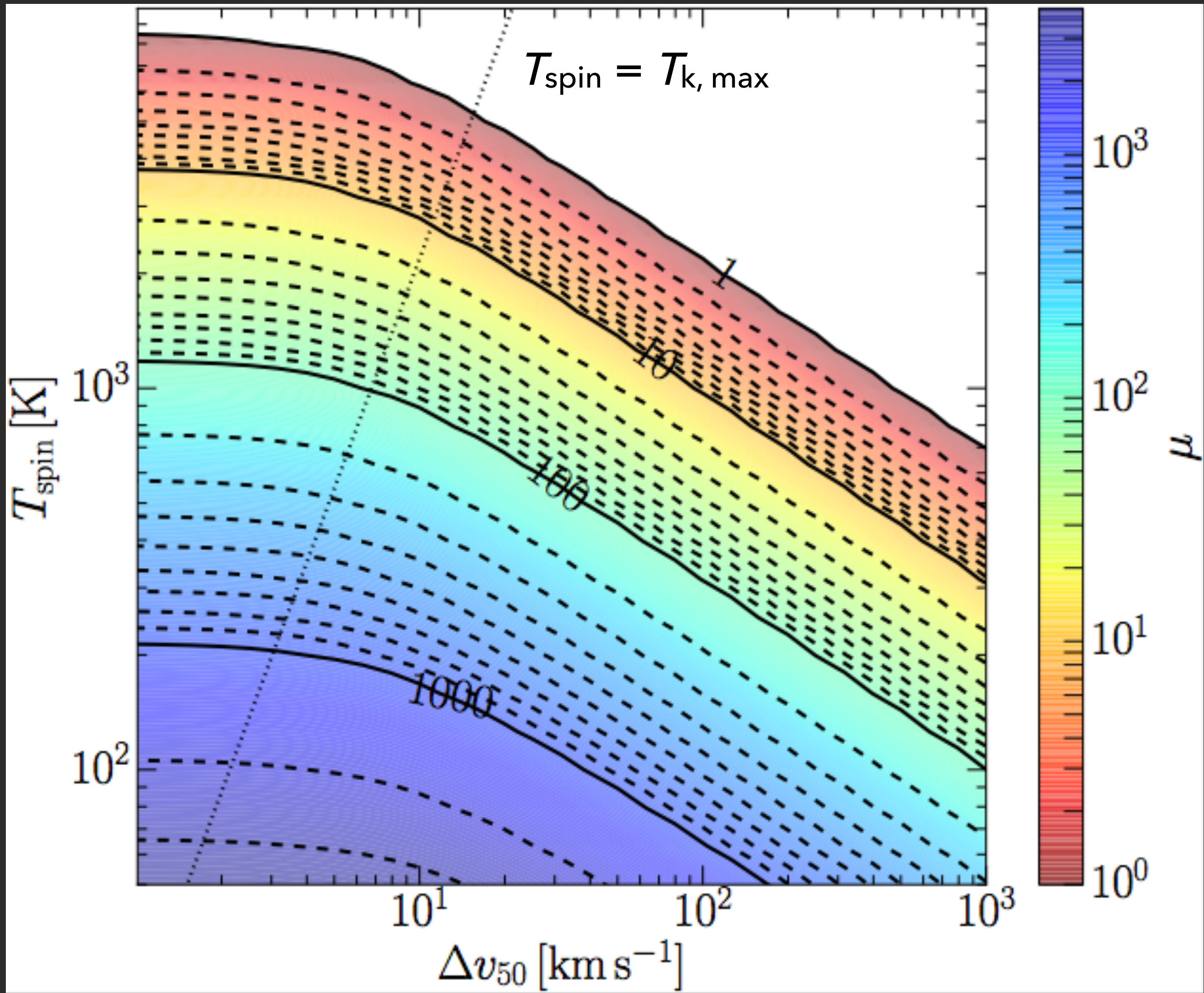
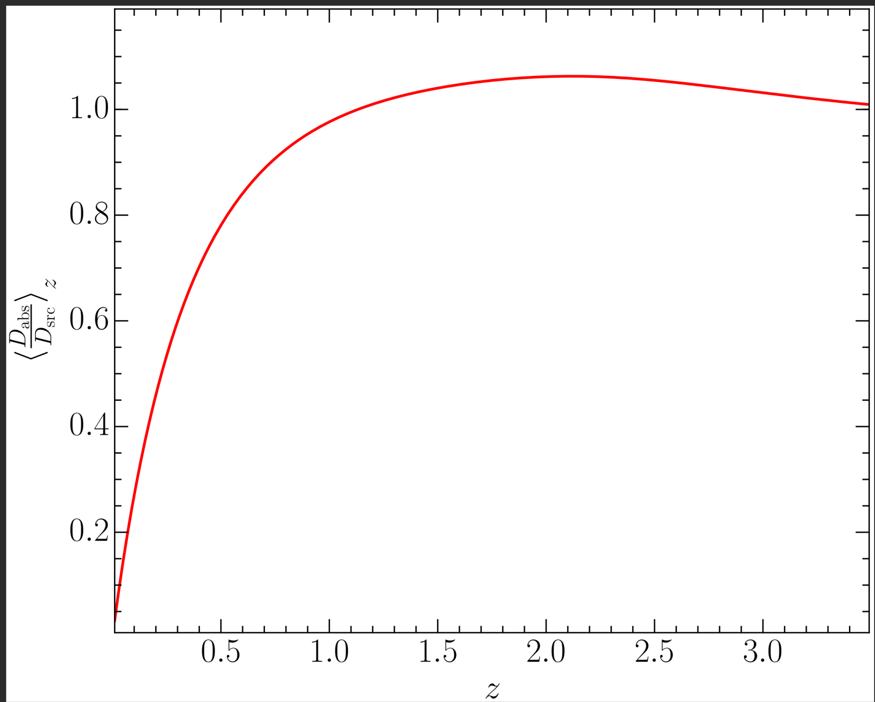
EXPECTED NUMBER OF DETECTIONS AS A FUNCTION OF T_{spin}



Allison+ 16

ERRORS IN THE EXPECTED DETECTION RATE

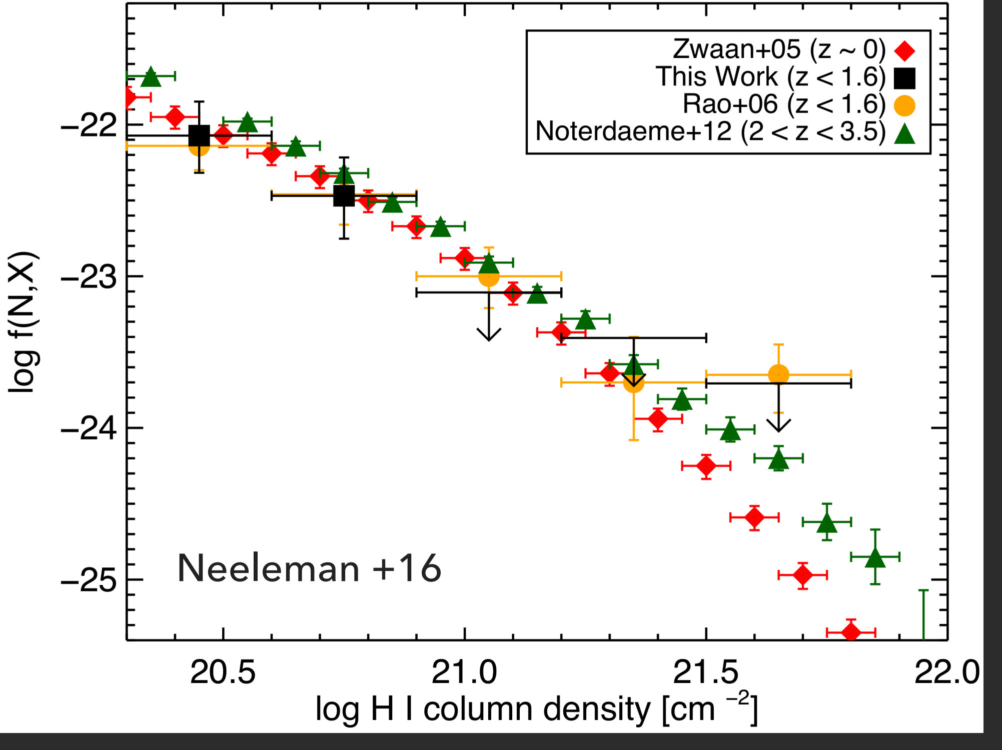
- How certain are we about the source covering factor?
  - Could deviate from uniform distribution: **+/-10%**
  - Could evolve with *z* (Curran+08): **+30%**



Allison+ 16

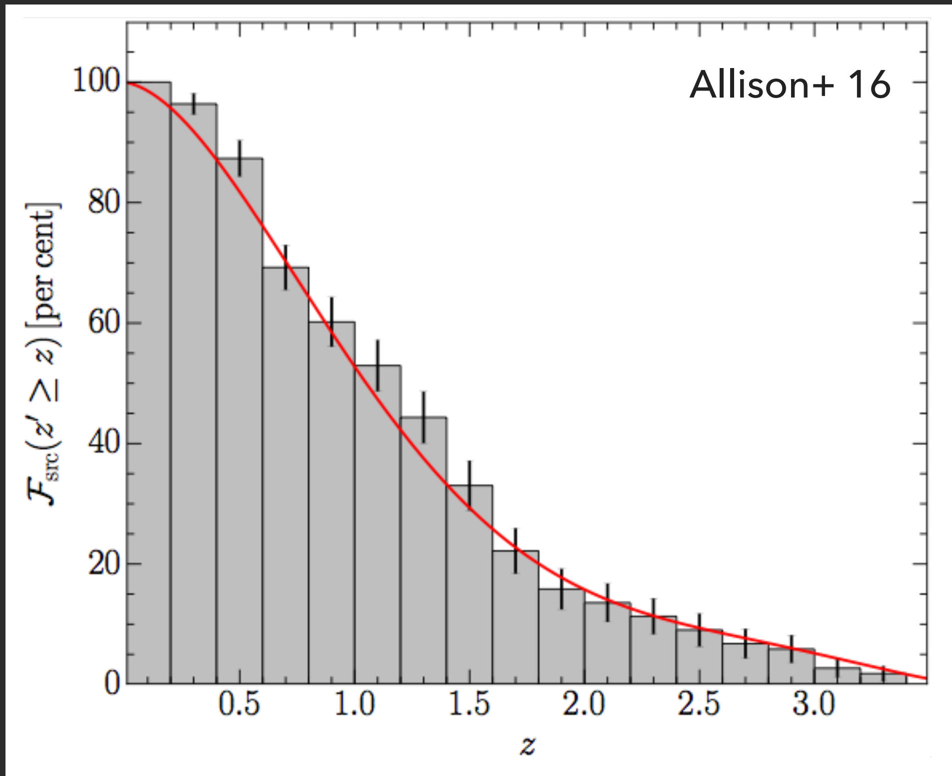
ERRORS IN THE EXPECTED DETECTION RATE

- What about $f(N_{HI}, X)$?
  - Measurement uncertainties: **+/-10%**
  - 21-cm self-absorption (Braun12): **+(10-30)%**
  - Dust obscuration bias for Ly-alpha (Pontzen+09): **+3%**



ERRORS IN THE EXPECTED DETECTION RATE

- Source redshift distribution at *z* between 0.4 and 1: **+/-5%**



INFERRING THE SPIN TEMPERATURE

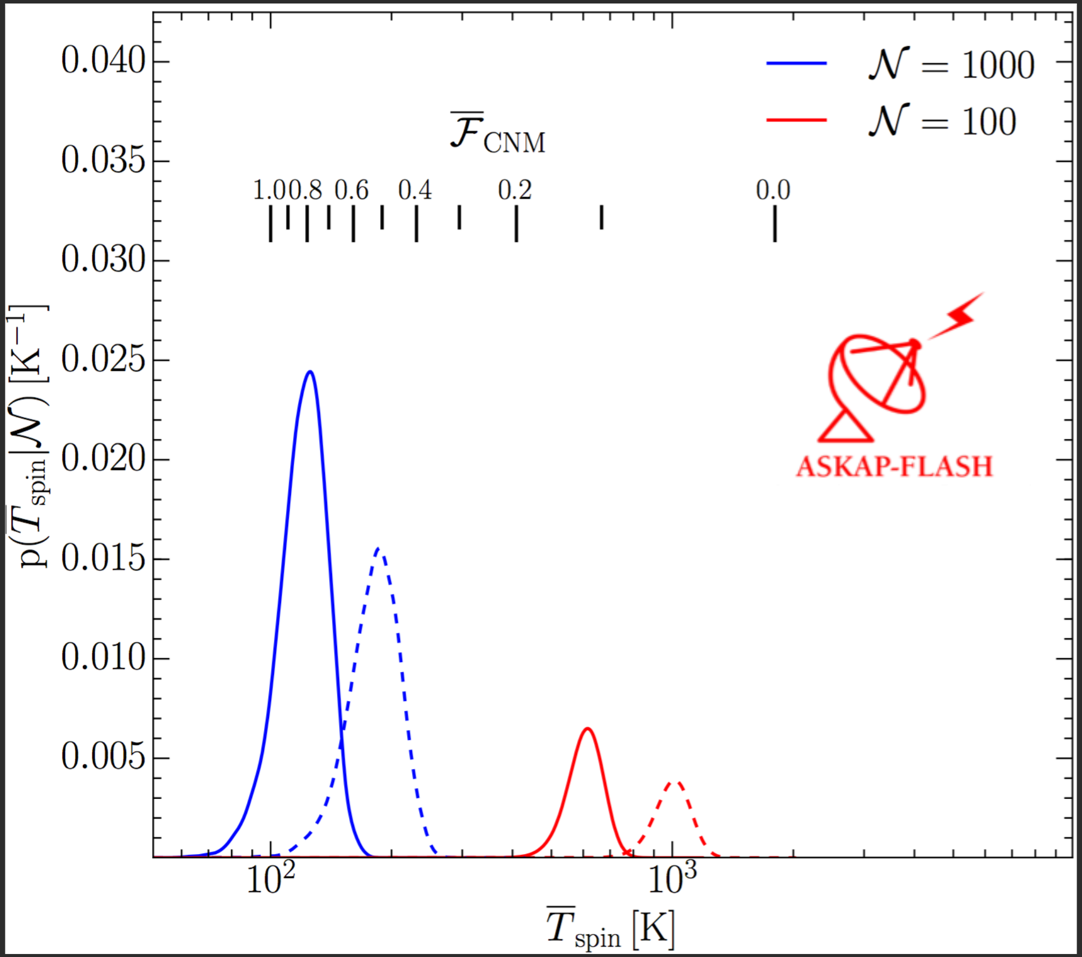
- Using Bayes' theorem for conditional probabilities to calculate the probability density of <$T_{\rm spin}$> given a detection yield N

$$p(\overline{T}_{\rm spin}|\mathcal{N}) = \frac{p(\mathcal{N}|\overline{T}_{\rm spin})p(\overline{T}_{\rm spin})}{p(\mathcal{N})}$$

- Use a minimally informative Jeffreys prior for <$T_{\rm spin}$>

$$p(\overline{T}_{\rm spin}|\mathcal{N}) = C^{-1}\,\frac{\overline{\mu}^{(\mathcal{N}-1/2)}}{\mathcal{N}!}\mathrm{e}^{-\overline{\mu}}$$

EXPECTED ASKAP CONSTRAINTS ON $<T_{SPIN}>$



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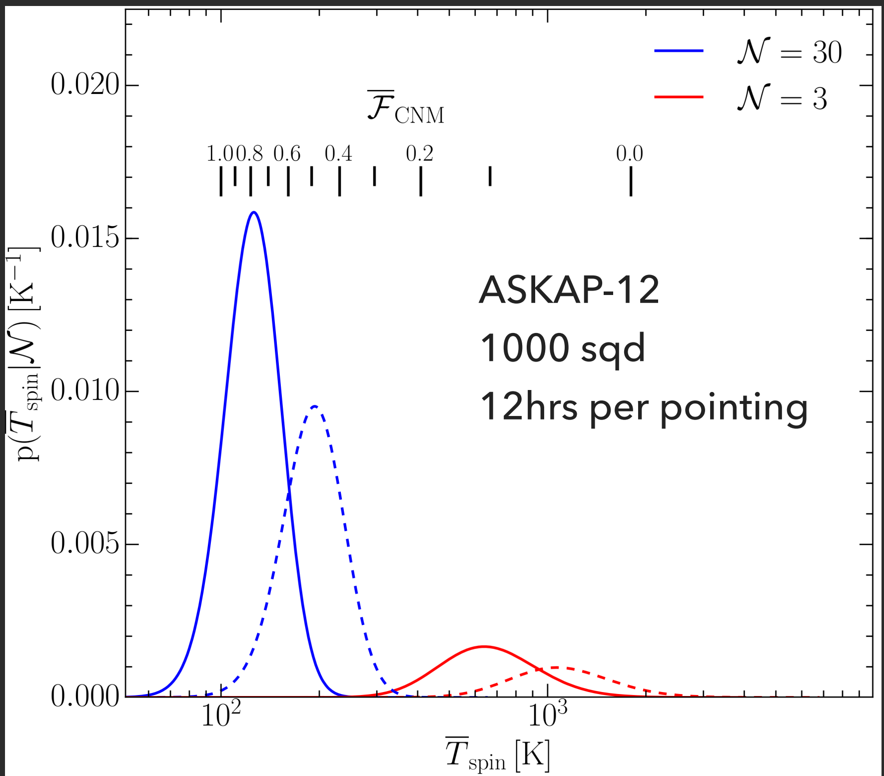
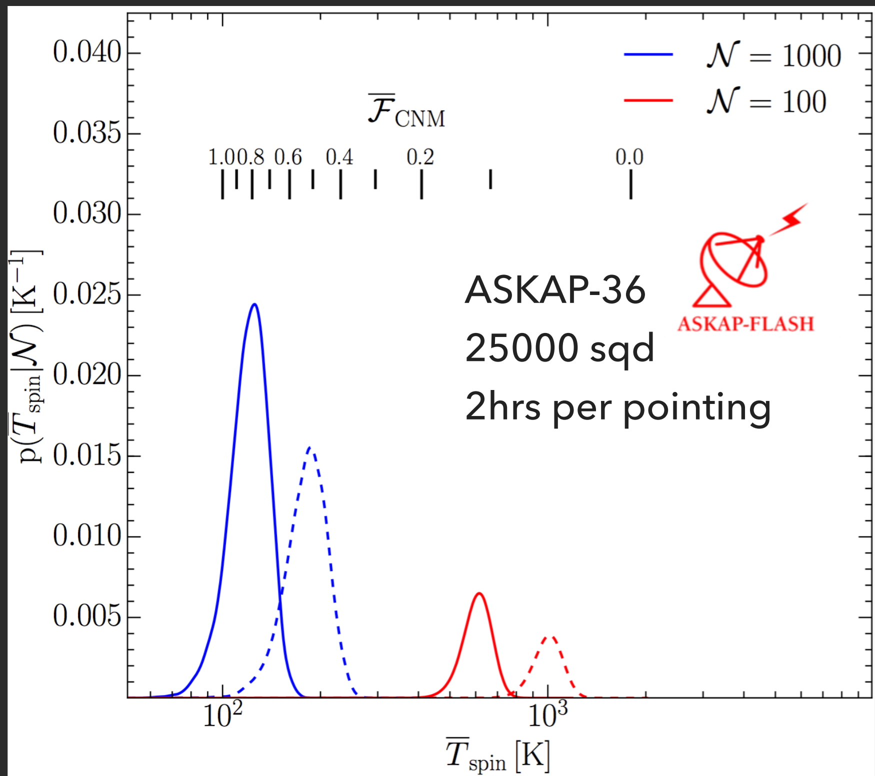
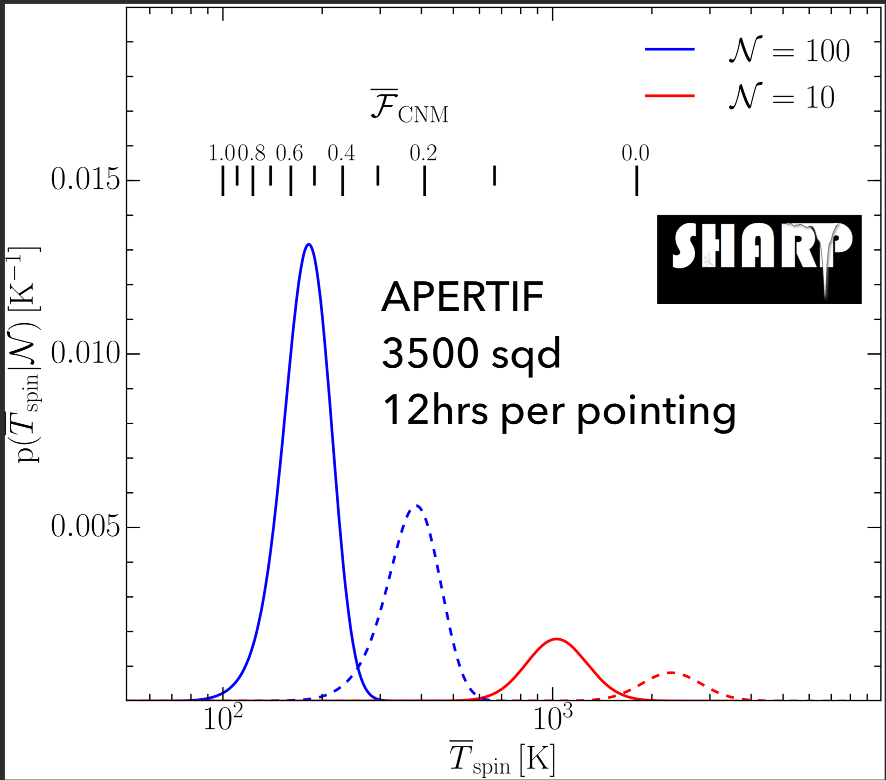
ASKAP EARLY SCIENCE

- Smaller (1000 sqd) and deeper (12hr) survey with ASKAP-12

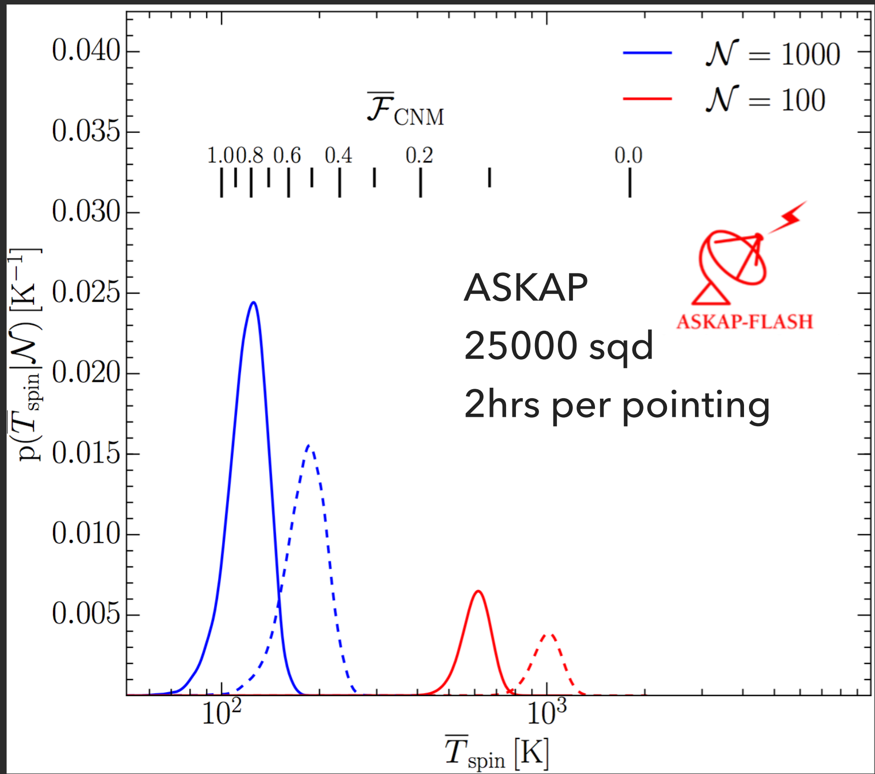




COLD GAS EVOLUTION WITH APERTIF AND ASKAP



0 < z < 0.26



0.4 < z < 1.0

SUMMARY

- Star formation and black hole growth in galaxies has declined significantly over the past 10 billion years
- It is expected that a similar decline should be seen in the cold neutral medium (CNM) where molecular clouds form
- The 21-cm line absorption is an observationally inexpensive probe of the cold neutral medium
- In the era of large 21-cm absorption surveys we can compare expected and actual detection yields to infer the average spin temperature and hence CNM fraction
- Even early science with ASKAP, MeerKAT and AperTIF should start to provide constraints on the spin temperature