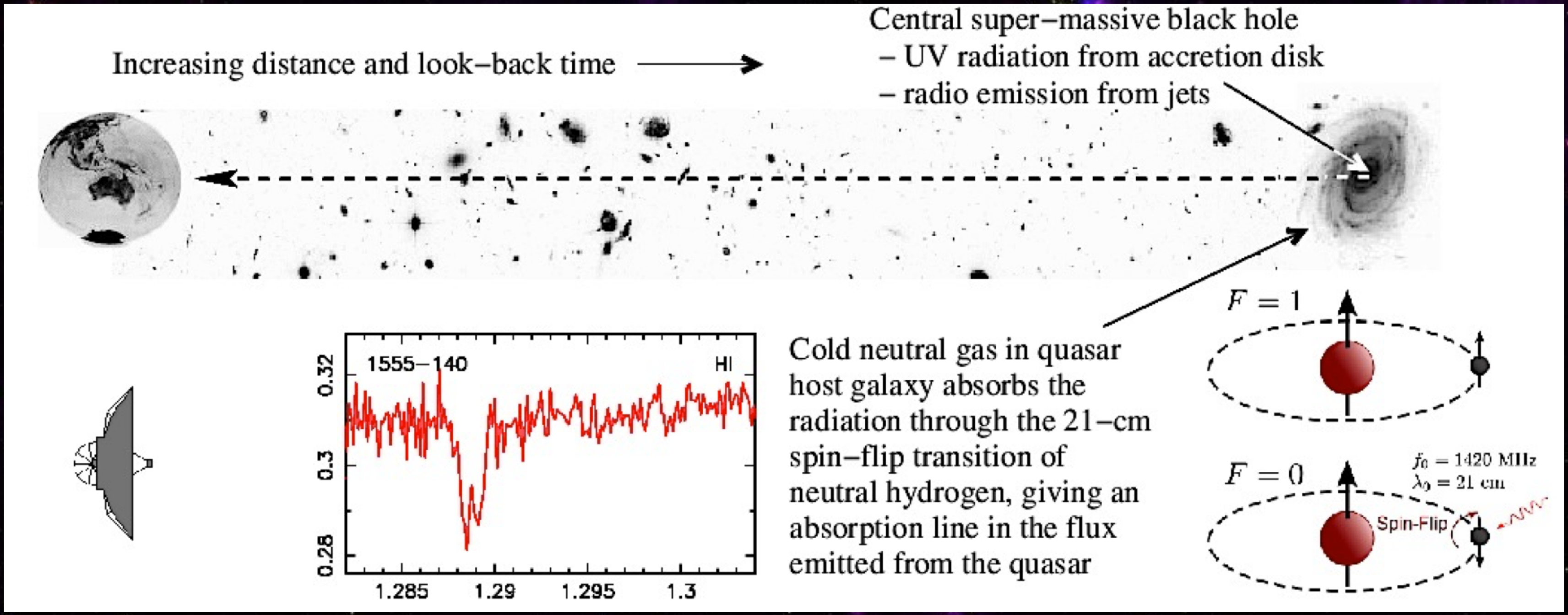
Absorption of the 21-cm transition of neutral hydrogen (HI) traces the cool component of the neutral gas, the reservoir star formation history. Also provides a useful probe of

- Baryonic mass density
- Evolution of large-scale structure
- Epoch of Reionisation
- Variations on the fundamental constants (α, μ, g_p)

Unlike the Lyman-α transition of HI (λ = 1216 Å), 21-cm can be observed at $z = 0$ by ground-based telescopes day or night (cf. $z > 1.7$).

Unlike 21-cm emission, can be readily detected at $z \gtrsim 0.2$, since absorption strength only dependent upon column density and background flux.



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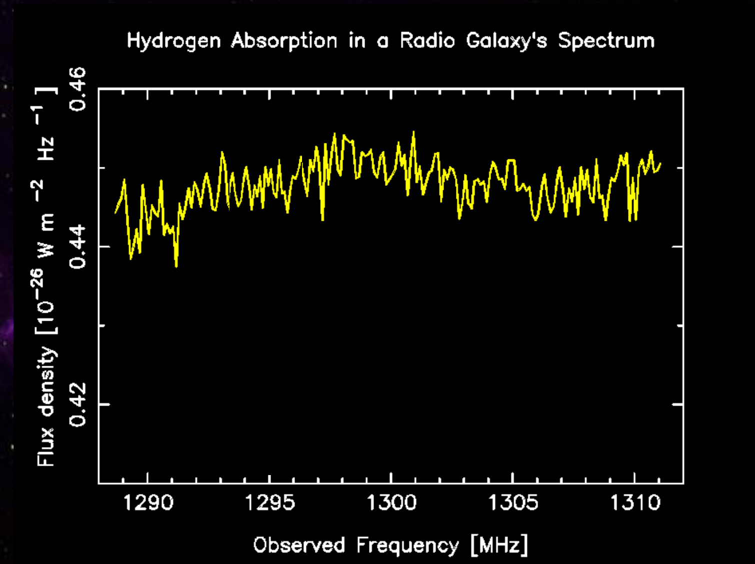
$$N_{\rm HI} = 1.823 \times 10^{18}\, T_{\rm spin} \int \tau \, dv. \qquad (1)$$

The observed optical depth is the ratio of the line depth, ΔS, to the observed background flux, $S_{\rm obs}$, and is related to the intrinsic optical depth via

$$\tau \equiv -\ln\left(1 - \frac{\tau_{\rm obs}}{f}\right) \approx \frac{\tau_{\rm obs}}{f}, \text{ for } \tau_{\rm obs} \equiv \frac{\Delta S}{S_{\rm obs}} \lesssim 0.3, \qquad (2)$$

where the covering factor, f, is the fraction of $S_{\rm obs}$ intercepted by the absorber. Therefore, in the optically thin regime (where $\tau_{\rm obs} \lesssim 0.3$), Equ. 1 can be rewritten as

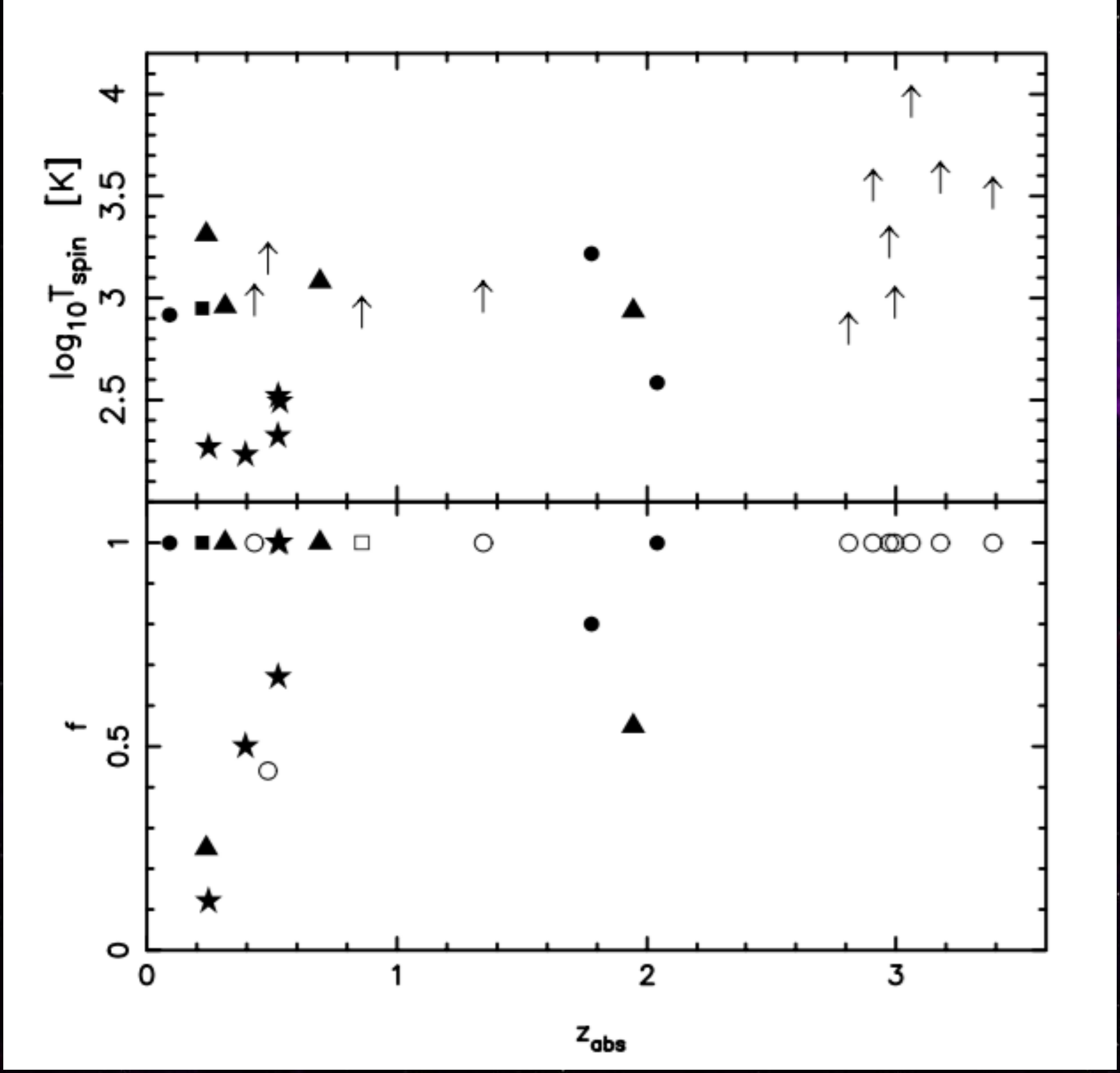
$$N_{\rm HI} \approx 1.823 \times 10^{18}\, \frac{T_{\rm spin}}{f} \int \tau_{\rm obs} \, dv, \qquad (3)$$



Over 12,000 damped Ly-α absorbers (DLAs) and sub-DLAs known - up to 80% $\Omega_{\rm baryons}$

With neutral hydrogen column densities of $N_{\rm HI} > 10^{20}$ cm^{-2} and precisely determined redshifts, the detection of 21-cm in DLAs should be like shooting fish in a barrel .

However, only ~ 50 intervening 21-cm absorbers known, which tend to be detected at low redshift – in MgII absorbers ($0.2 < z_{\rm abs} < 2.2$) rather than DLAs ($z_{\rm abs} > 1.7$)



Kanekar & Chengalur (2003)

Mix of spin temperatures at low-z, exclusively high at high-z ⟹ evolution in spin temperature

$$N_{\rm HI} \approx 1.823 \times 10^{18} \frac{T_{\rm spin}}{f} \int \tau_{\rm obs}\, dv,$$

Curran et al. (2005)

At high-z, covering factor estimated/assumed to be $f = 1$, which results in the maximum possible T_{spin}.

Curran (2012)

$< T_{spin} / f > = 1800$ K at $z_{abs} < 2$

$< T_{spin} / f > = 3600$ K at $z_{abs} > 2$

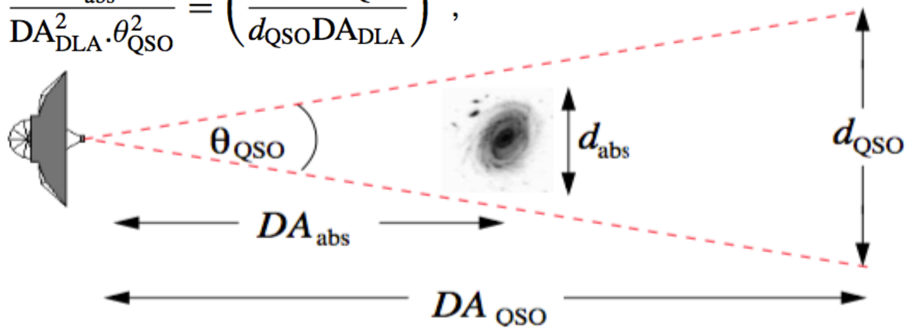
Factor of two can be accounted by the geometry of an expanding Universe (standard Λ cosmology)

It is usually assumed that the covering factor is given by the ratio of the flux from the compact unresolved component of the radio emission to the total radio continuum flux (e.g. *Briggs & Wolfe* 1983; *Kanekar et al.* 2014).

However, the ratio of the fluxes:

- Contains no information on the depth of the line when the extended continuum emission is resolved out
- The extent of the absorber
- How this is aligned along the sight-line to the QSO
- No account for the geometry effects of an expanding Universe

$$f \equiv \frac{d_{\rm abs}^2}{{\rm DA}_{\rm DLA}^2 . \theta_{\rm QSO}^2} = \left(\frac{d_{\rm abs}\,{\rm DA}_{\rm QSO}}{d_{\rm QSO}{\rm DA}_{\rm DLA}}\right)^2,$$



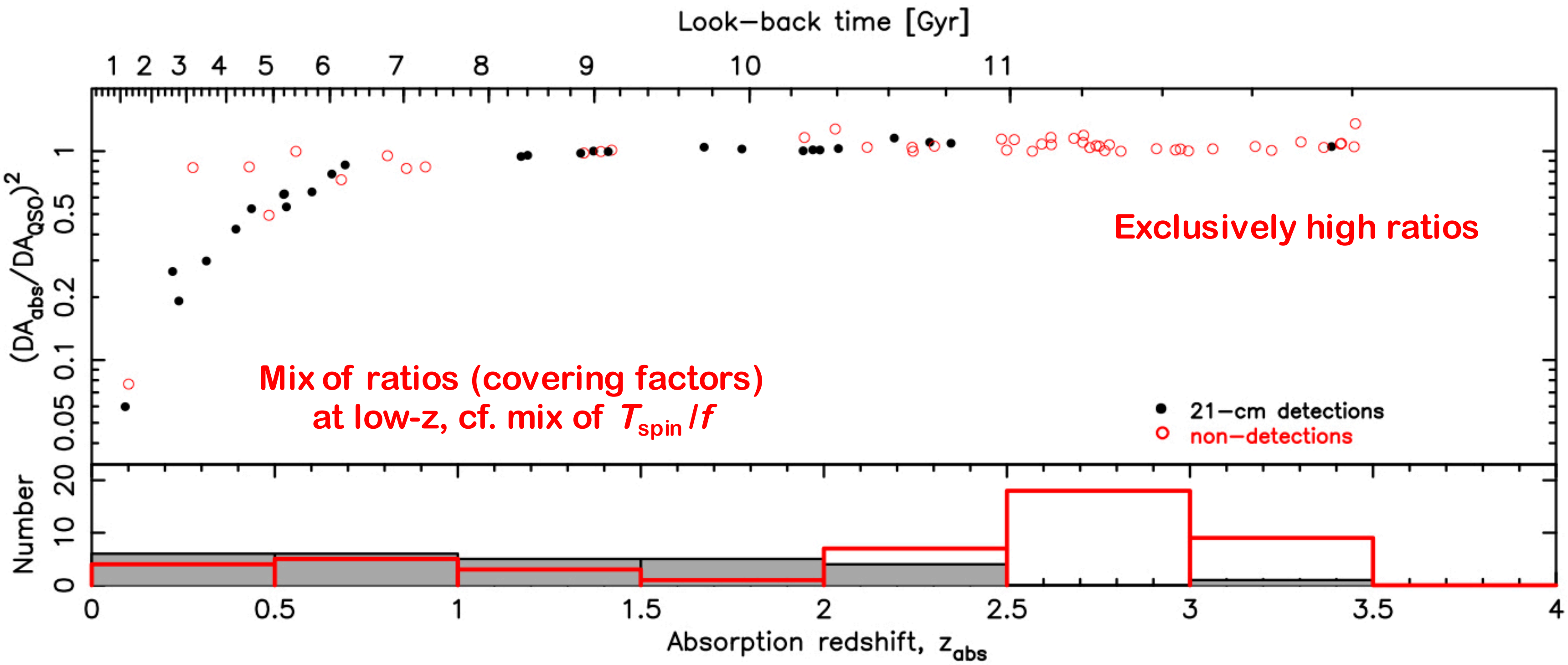
$$f = \begin{cases} \frac{d_{\rm abs}{}^2}{DA_{\rm abs}{}^2 . \theta_{\rm QSO}{}^2} & \text{if } \theta_{\rm abs} < \theta_{\rm QSO} \\ 1 & \text{if } \theta_{\rm abs} \geqslant \theta_{\rm QSO}, \end{cases} \quad (4)$$

where the angular diameter distance to a source is given by

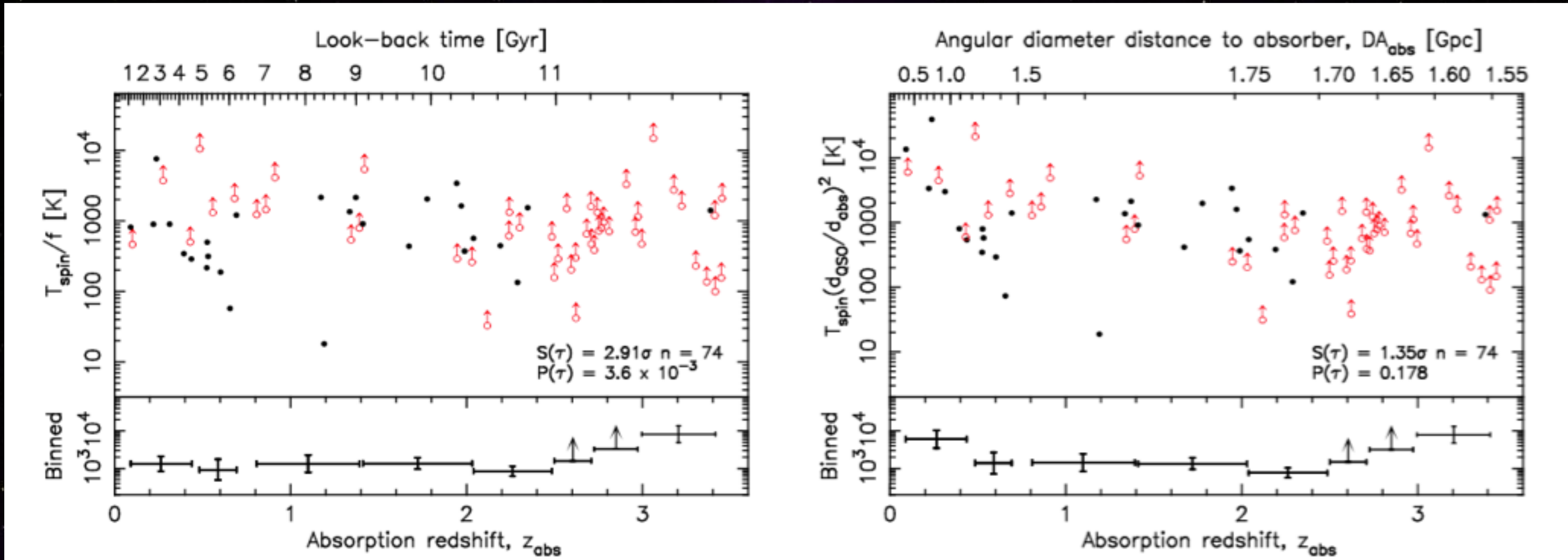
$$DA = \frac{DC}{z+1}, \text{ where } DC = \frac{c}{H_0}\int_0^z \frac{dz}{H_z/H_0} \quad (5)$$

is the line-of-sight co-moving distance (e.g. Peacock 1999), in which c is the speed of light, H_0 the Hubble constant, H_z the Hubble parameter at redshift z and

$$\frac{H_z}{H_0} = \sqrt{\Omega_{\rm m}\,(z+1)^3 + (1 - \Omega_{\rm m} - \Omega_\Lambda)\,(z+1)^2 + \Omega_\Lambda}. \quad (6)$$



Possibility that evolution in $T_{\rm spin}/f$ dominated *by f* (*Curran & Webb*, 2006)



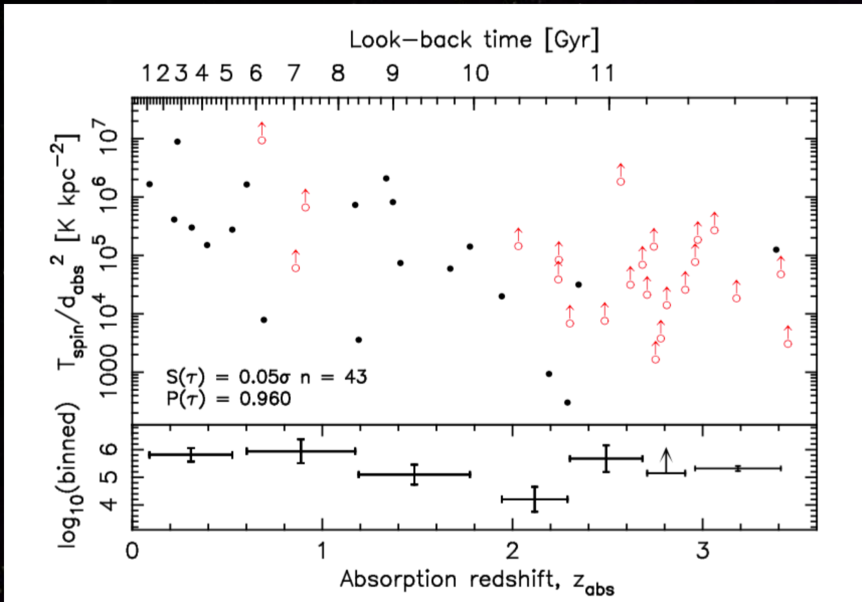
Binned data include non-detections (lower limits to $T_{\rm spin}/f$) via survival analysis

$$N_{\rm HI} \approx 1.823 \times 10^{18}\, \frac{T_{\rm spin}}{f} \int \tau_{\rm obs}\, dv,$$

$$f \equiv \frac{d_{\rm abs}^2}{{\rm DA}_{\rm DLA}^2 . \theta_{\rm QSO}^2} = \left(\frac{d_{\rm abs}\,{\rm DA}_{\rm QSO}}{d_{\rm QSO}{\rm DA}_{\rm DLA}}\right)^2,$$

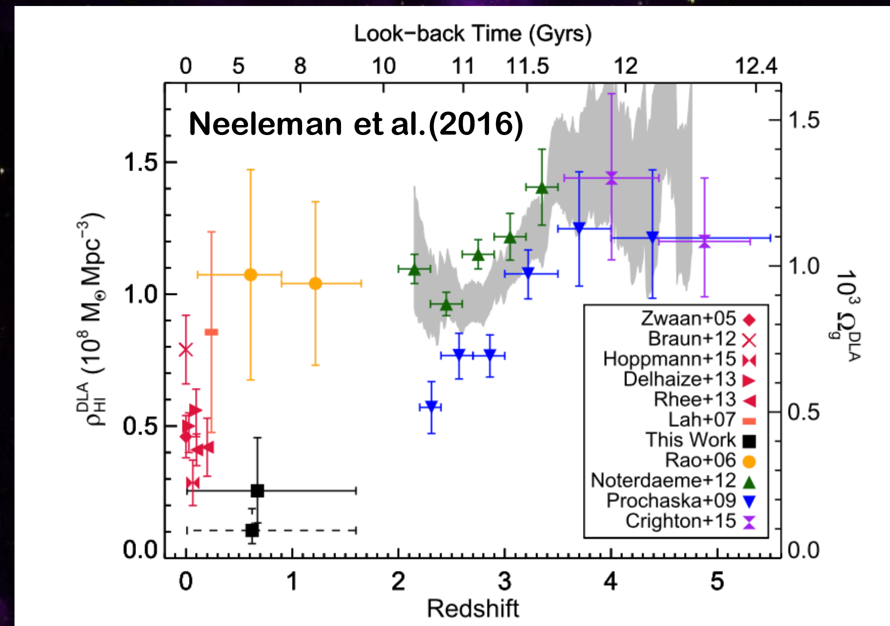
$$\int \tau_{\rm obs}\, dv \left(\frac{DA_{\rm abs}}{DA_{\rm QSO}}\right)^2 = \frac{1}{1.823 \times 10^{18}} \frac{N_{\rm HI}}{T_{\rm spin}} \left(\frac{d_{\rm abs}}{d_{\rm QSO}}\right)^2,$$

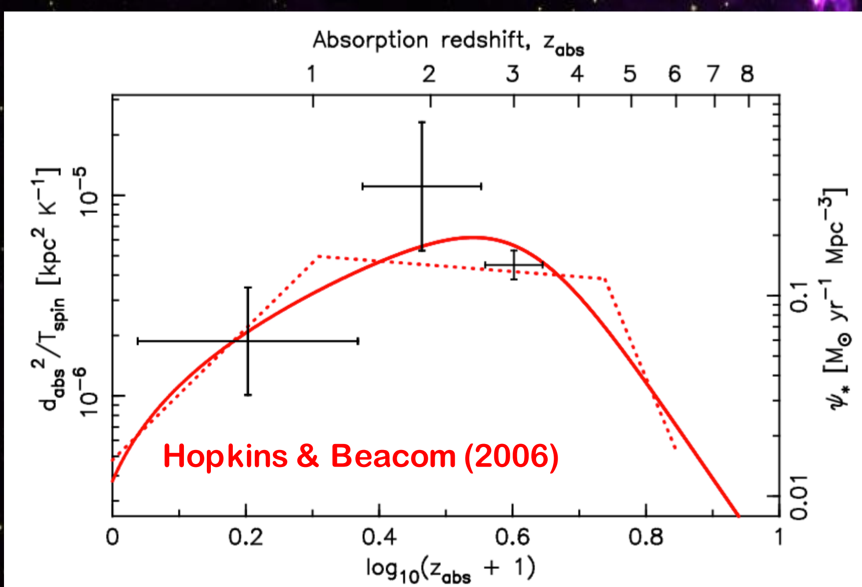
Correction for the angular diameter distance has little effect at high redshift but at $z_{\rm abs} < 1$, the spin temperature (degenerate with ratio of emitter/absorber cross-sections) exhibits a decrease with redshift $\Longrightarrow$ indicative of a dip in $T_{\rm spin}$ (*Curran,* 2017)

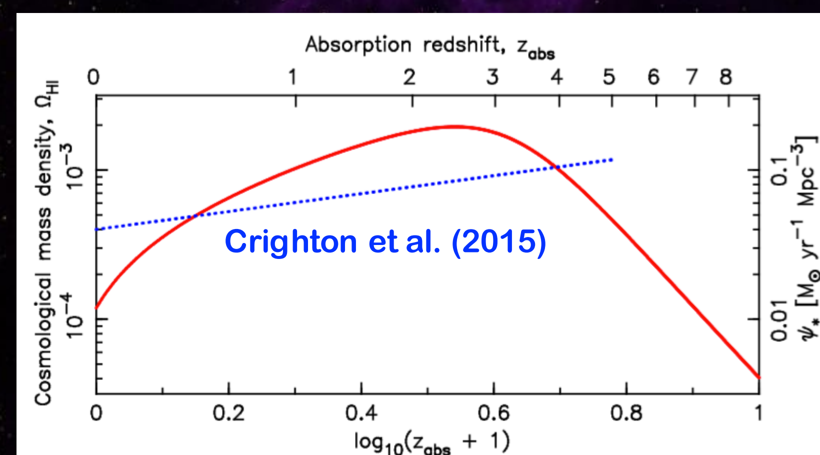


$d_{QSO} = \theta_{QSO} DA_{QSO}$, giving

$$\frac{T_{spin}}{d_{abs}^{2}} = \frac{N_{HI}}{1.823 \times 10^{18} (\theta_{QSO} DA_{abs})^2 \int \tau_{obs}\, dv},$$







Caveats

arXiv:1704.04294

- Assumes direct (or similar) alignment between absorber and QSO and uniform flux across the emitter

    Alignment for more likely when $z_{abs} << z_{QSO}$ (high f).
    Different alignments and distributions in background structure should average out in the binned data

- Assumes $\theta_{abs} < \theta_{QSO}$

    Where d_{QSO} has been measured, $f \sim 1$ is most likely at low-z, since d_{QSO} increases with $z_{abs} \Longrightarrow f$ lower at high-z

- Assumes no dominant evolution in d_{abs}/d_{QSO}

    Increase in d_{QSO} probably due to Malmquist bias and would have to be matched by corresponding increase in d_{abs}. Only likely if DLA host size evolves contrary to massive galaxies

- Limited data

    As usual, need more data – especially at $z_{abs} > 4$