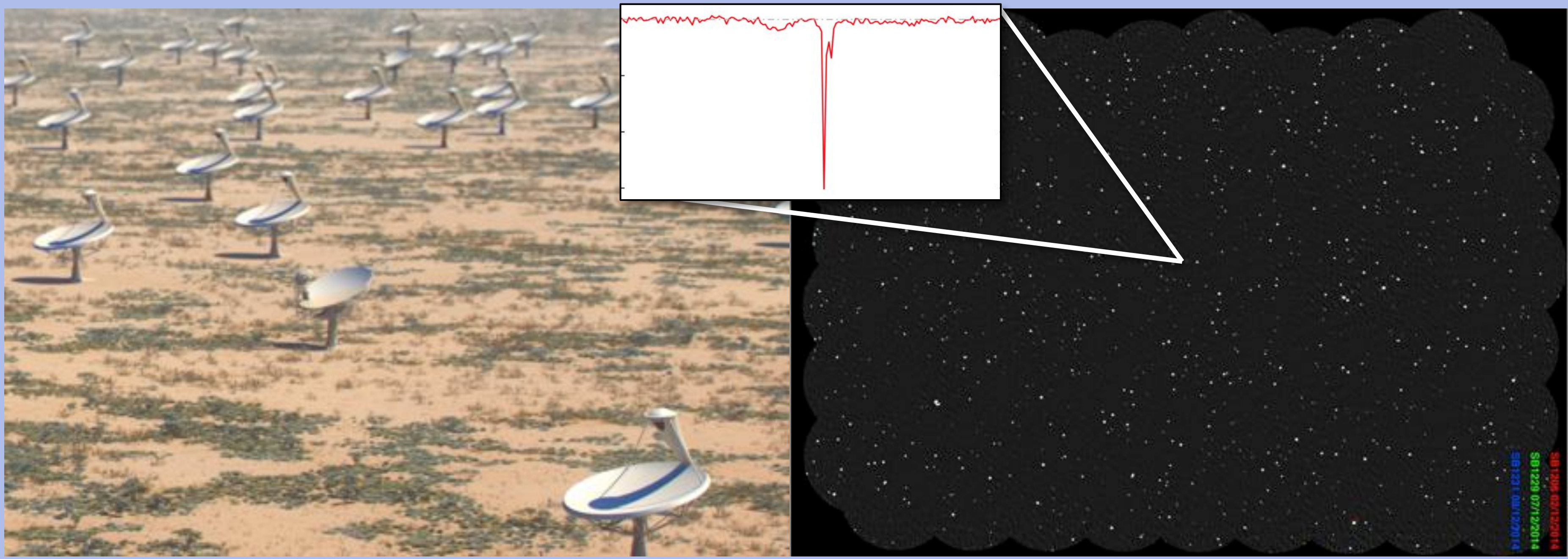


Cool outflows and HI absorbers

with the Square Kilometre Array

James Allison

2014 Science Book: "Advancing Astrophysics with the Square Kilometre Array"

HI absorption chapter by **R. Morganti**, **E. M. Sadler**, **S. J. Curran** & HI SKA Working Group Members

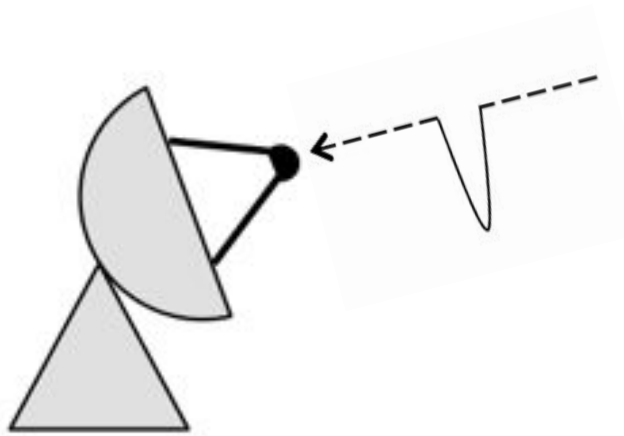
arXiv:1501.01091

Why a 21cm absorption line survey?

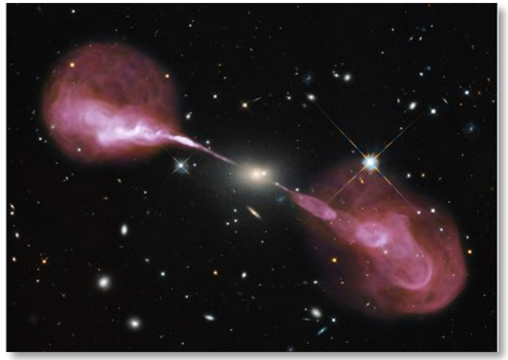
- We can use absorption against background radio sources to directly trace the evolution of HI in the Universe from the EOR to now.

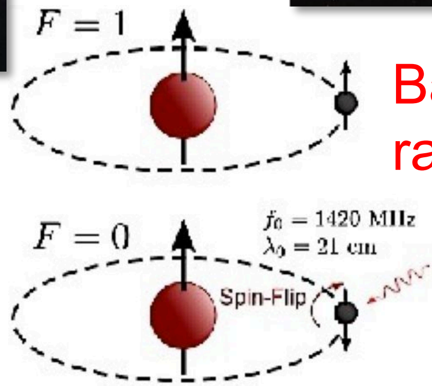
Line Strength = HI Column Density * Source Flux / Spin Temperature

Radio Telescope



High column density cold HI gas





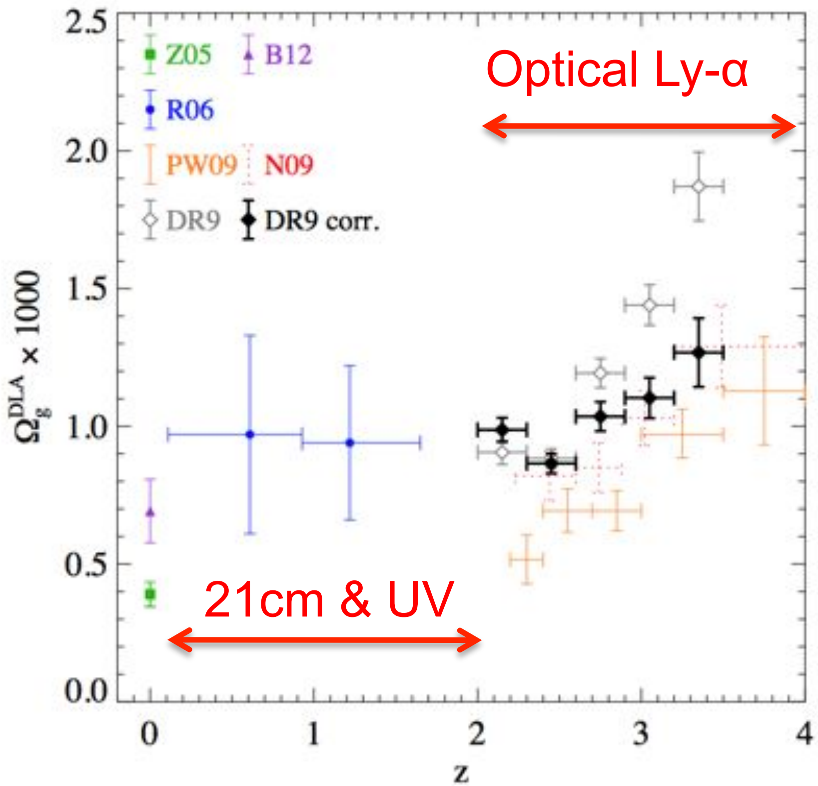
Background radio AGN

Tracing HI in galaxies over 12 billion years

- **Redshift independence** of absorption means we can trace the cold neutral hydrogen in galaxies over a huge range in redshift (potentially **0 < z < 8** with SKA1)

- At ***z* < *2*** the 21cm line is a **unique probe** of HI in the **redshift desert** c.f. Ly-α absorption at optical wavelengths

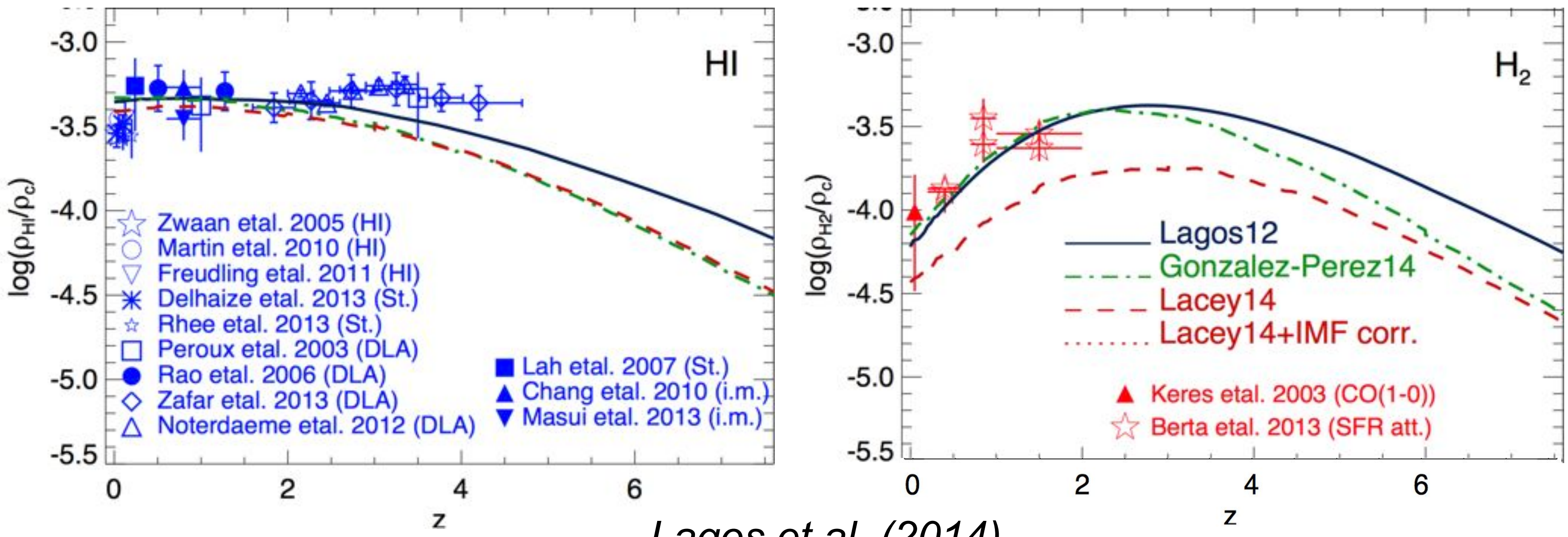
- At ***z* > *2*** radio-selected 21cm searches do not suffer from the **dust selection bias** in observations of **damped Ly-α absorption** towards colour-selected quasars



Noterdaeme (2012)

Co-evolution of HI & molecular gas

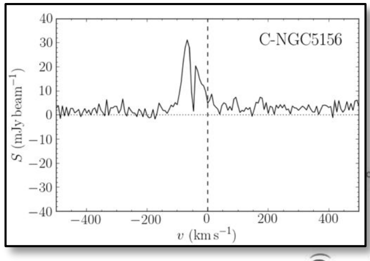
- HI and CO observations provide an important **complimentary** picture of the **evolution** of the **neutral ISM** over cosmic history
- The SKA and pathfinders, in combination with ALMA/EVLA, will allow us to directly measure the relative amounts of atomic and molecular gas in individual galaxies over a huge range of redshifts



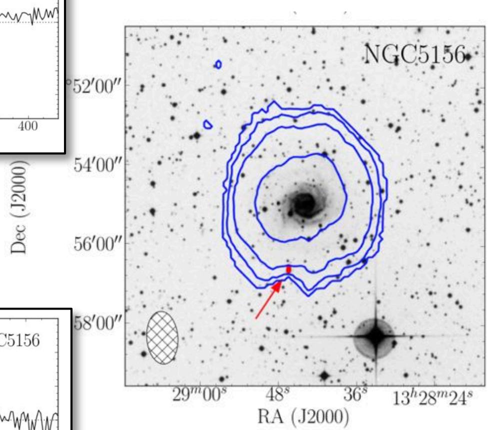
Lagos et al. (2014)

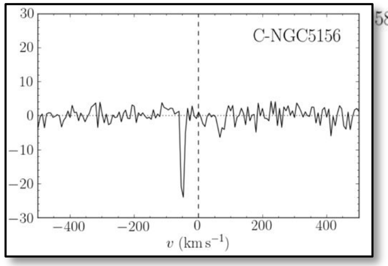
Existing searches for intervening absorption

- **Fewer than 100** detections of intervening 21cm lines known at $z > 0.1$
- Most from **targeted** searches of known Lyα and MgII absorption systems (e.g. Kanekar et al. 2014)
- A few "blind" searches with single dishes (e.g. Darling et al. 2004; 2011)
- Limited by existing **bandwidth**, radio frequency **environment,** quality of spectra (e.g. **spectral ripple** in single-dish observations)

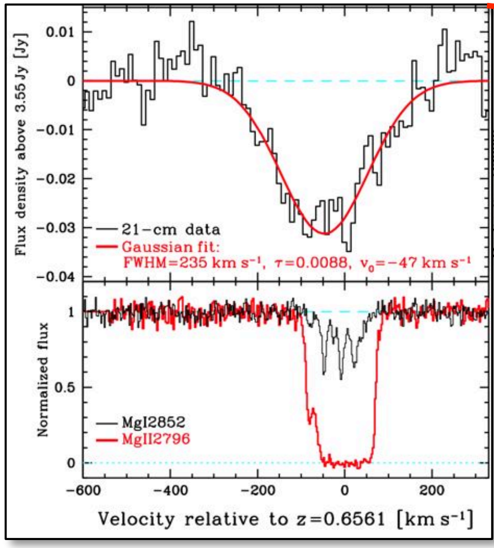


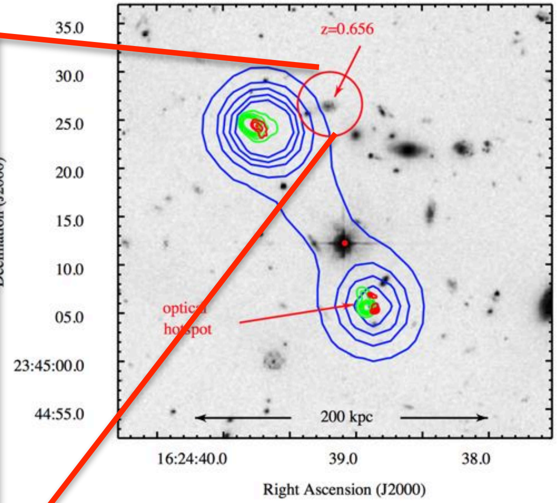
$z = 0$





Reeves et al. (in prep.)



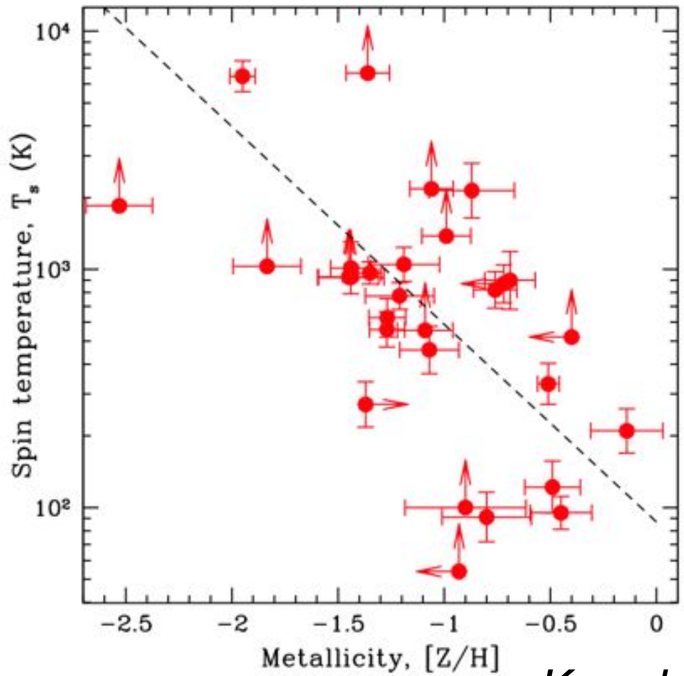


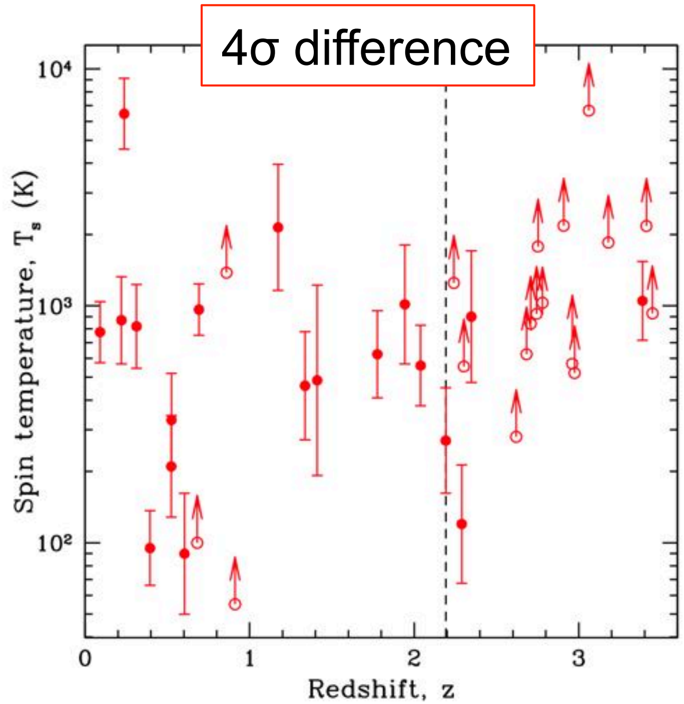
Curran et al. (2007)

$z = 0.66$

Possible evolution of the spin temperature

- Existing high redshift 21cm studies towards DLAs are providing possible evidence for **evolution** in the **HI spin temperature** (e.g. Kanekar et al. 2014; but see also Curran 2012 for alternatives)
- Increasing T_{spin} with redshift has important implications for the detectably of HI at $z > 3$



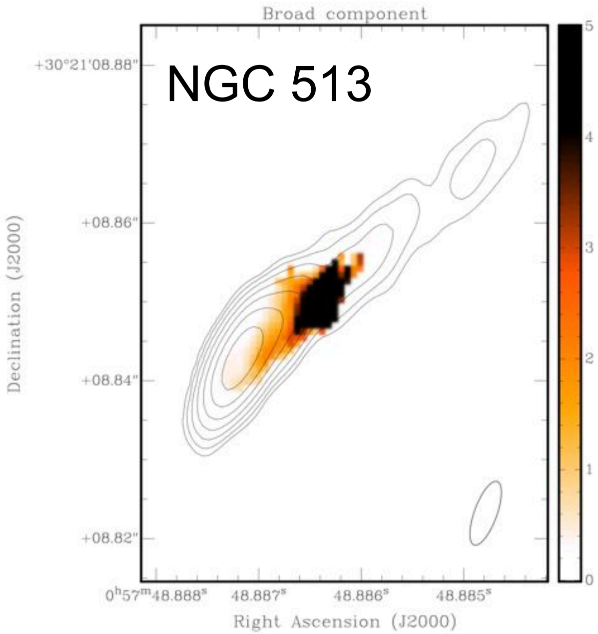


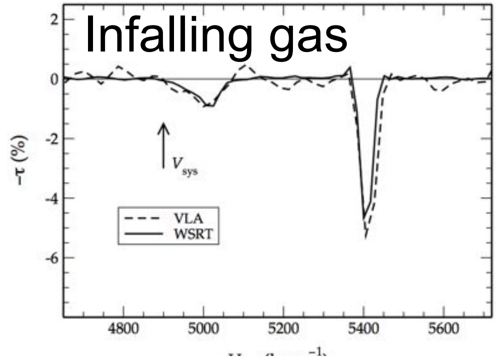
Kanekar et al. (2014)

Radio AGN and Cool Outflows

Tracing the inner gas in radio galaxies

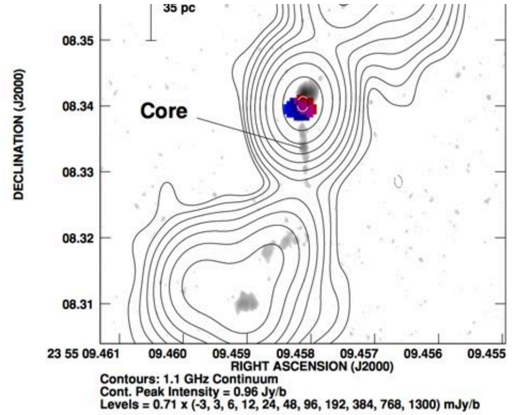
- HI absorption can trace the inner neutral gas near to radio AGN
- Existing studies have suggested that HI absorption can trace infalling neutral gas (e.g. van Gorkom 1989)
- Regularly rotating sub-100pc structures have been found in compact radio sources
- True interpretation of the results requires high spatial resolution imaging on 10mas scales

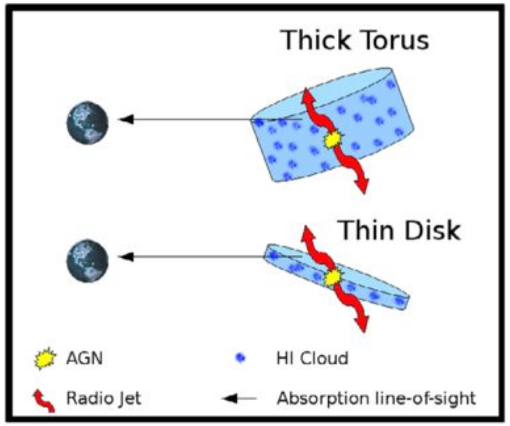




Morganti et al. (2009)

Compact symmetric radio source B2352+495



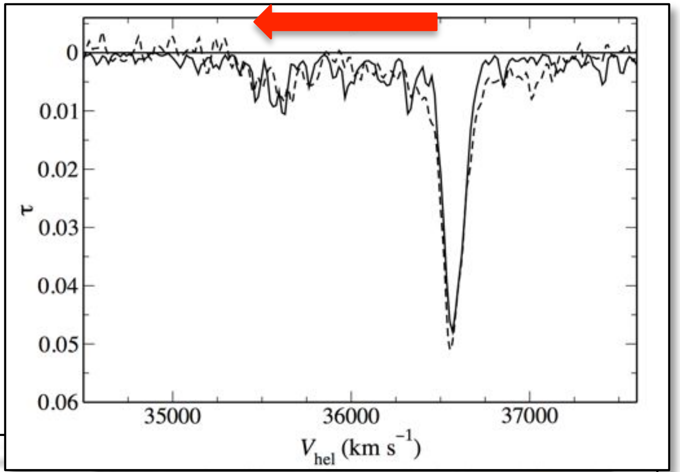


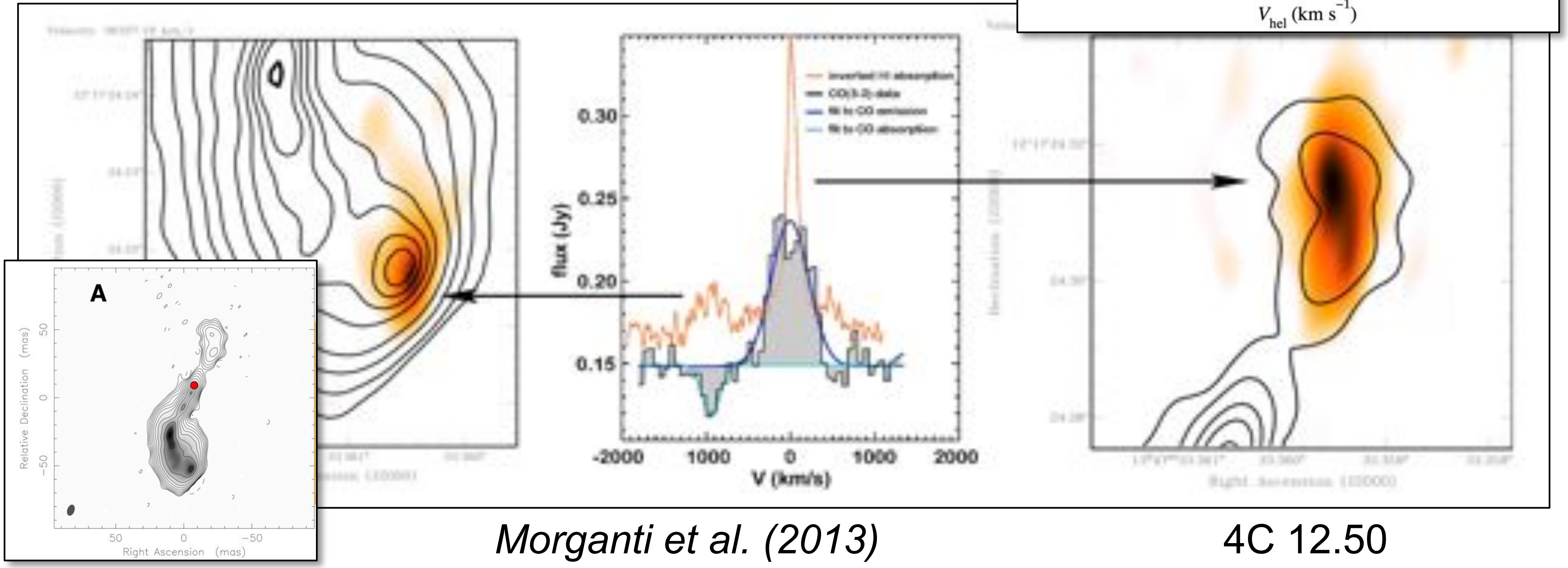
Araya et al. (2010)

Cool outflows of gas

- High sensitivity HI absorption reveals evidence of **jet-driven** neutral gas **outflows** at 10s $M_{\odot} yr^{-1}$
- Multi-wavelength observations show concurrent **molecular** and **ionised gas** outflows
- Requires better than **10 milli-arcsec resolution** for interpretation – Important for future surveys

1000 km/s



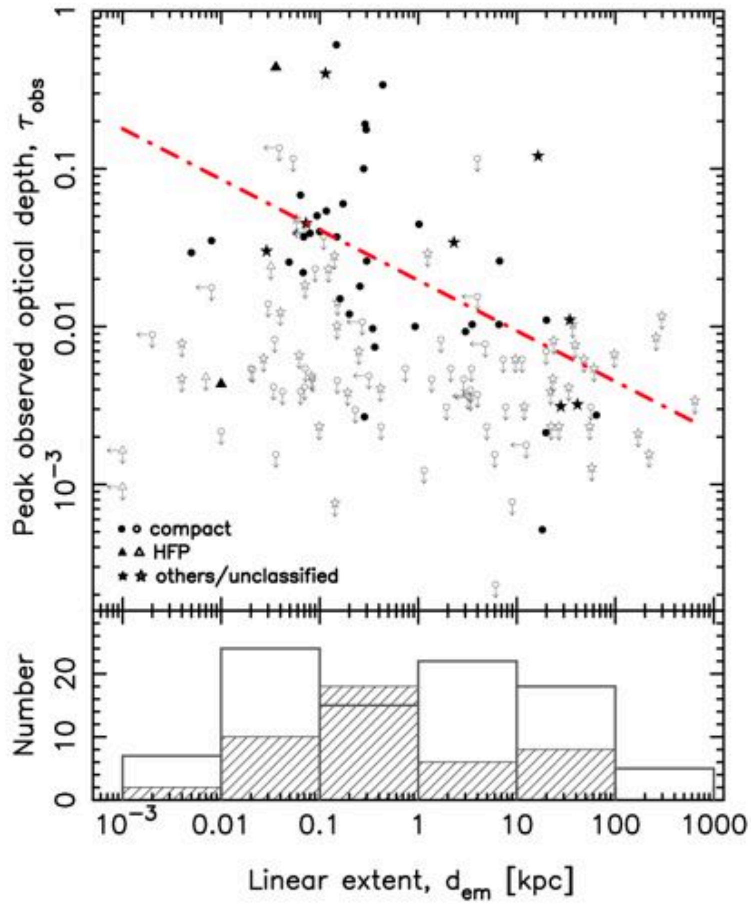


Morganti et al. (2013)

4C 12.50

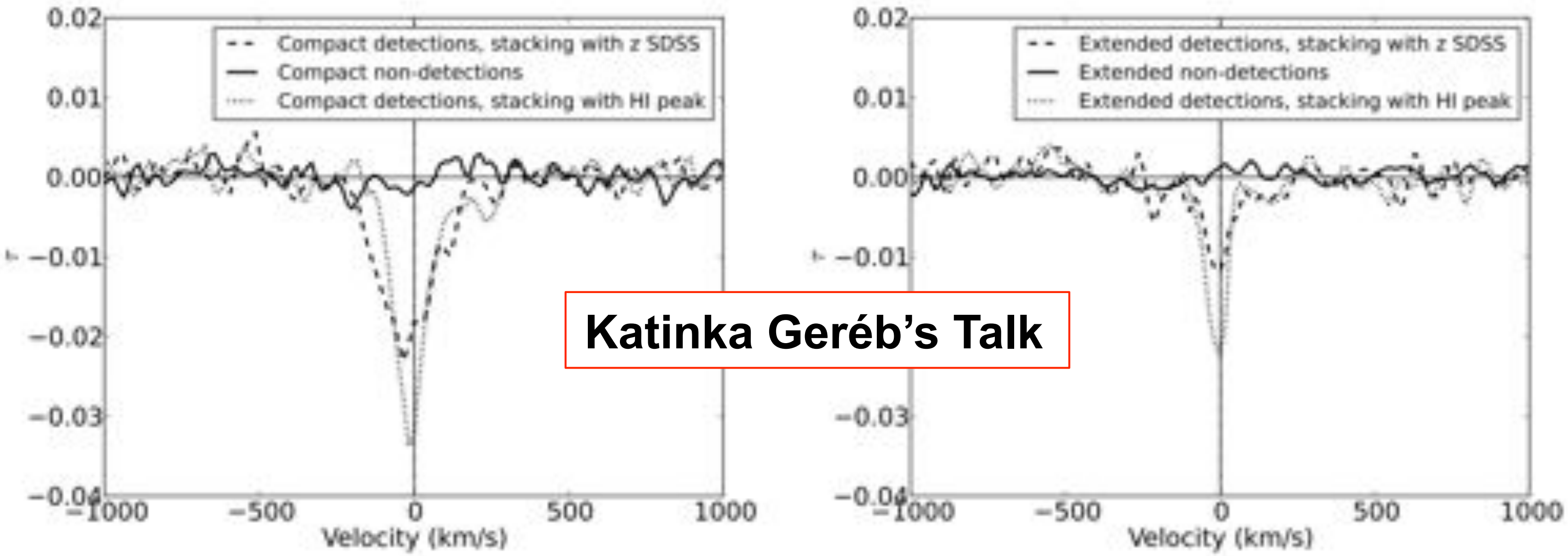
Existing searches for associated absorption

- About **100** known radio sources with associated HI absorption (most at $0.1 < z < 1$)
- **Rapidly increasing** as preparation is made for the pathfinder surveys
- All targeted towards specific populations (e.g. young, compact versus extended sources) so results effected by **selection bias**
- Higher detection rates achieved towards compact “young” radio sources – intrinsic gas properties or just an effect of geometry?



The "dichotomy" of associated absorbers

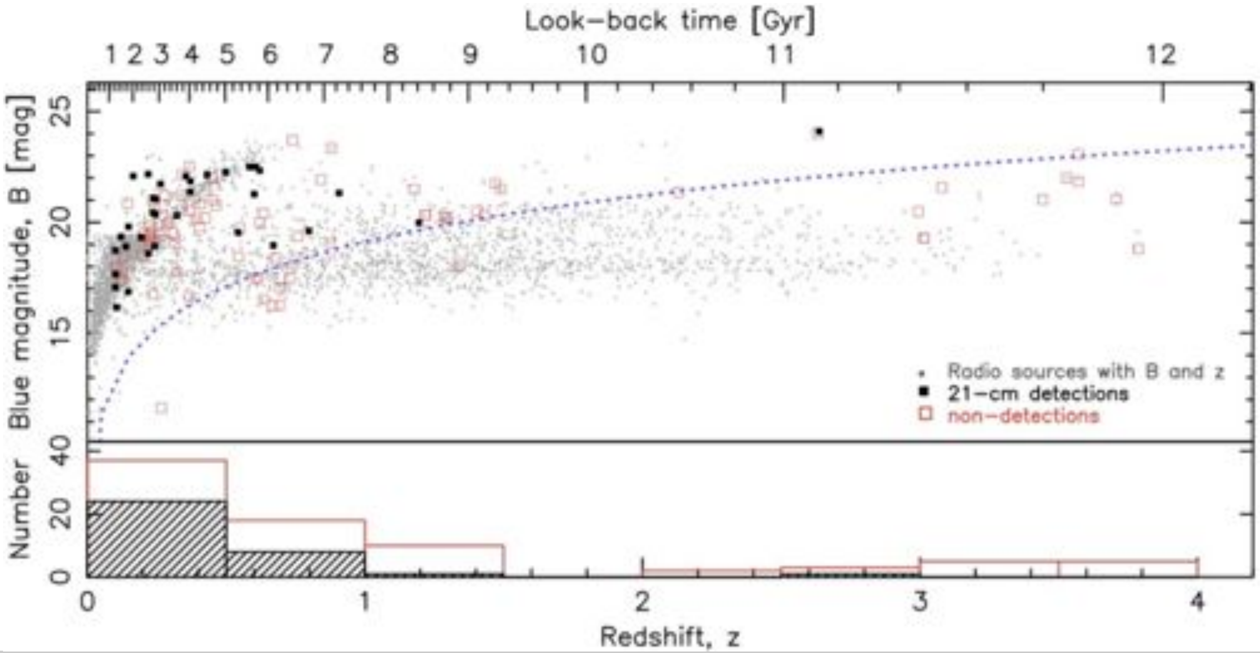
- WSRT observations of 93 radio sources (> 50 mJy) by Geréb et al. (2014) revealed an apparent dichotomy in the HI content of radio galaxies – orientation effects & gas depletion possible explanations



- 30% detection rate; detections $N_{HI} \sim 10^{21}$ cm^{-2}, non-detections $N_{HI} < 10^{19}$ cm^{-2}
- No apparent bias with radio continuum flux, indicating that future surveys will be able to detect HI absorption in faint sources

Selection bias in high redshift radio-AGN

- Existing limitations in bandwidth and radio frequency environments require **optical redshifts** to probe the neutral ISM of high redshift radio-AGN
- This introduces a **selection bias** towards the brightest optical sources, i.e. **highly ionising** sources in the rest-frame UV (Curran & Whiting 2012 and ***Steve Curran's Talk***)

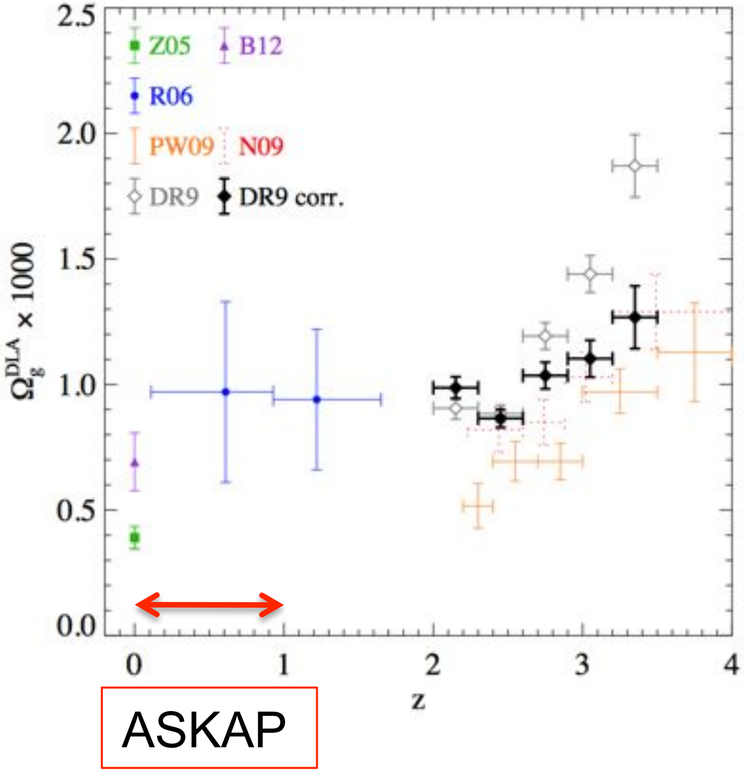


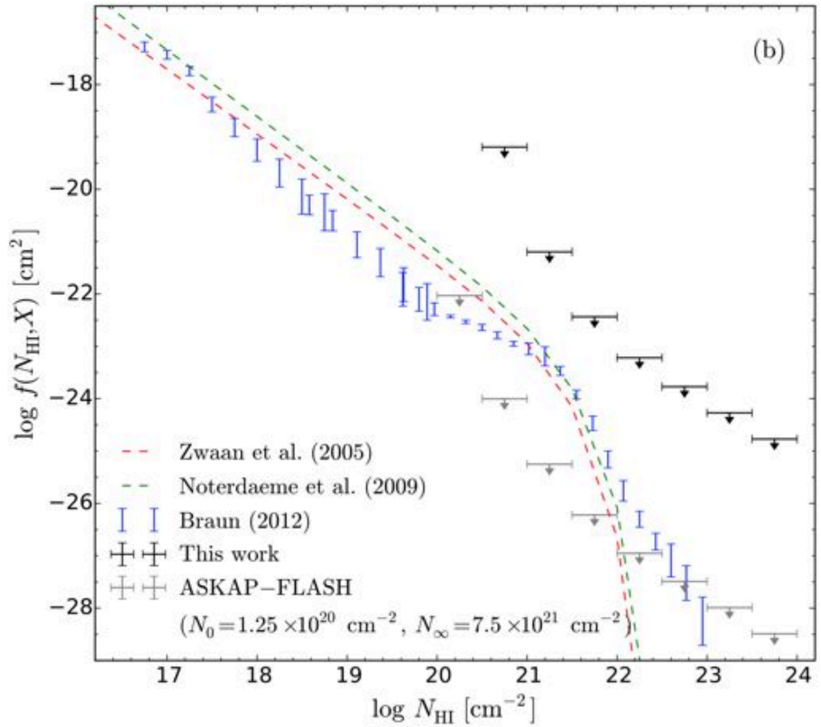
No 21cm associated absorption systems detected at z > 3

With the **SKA** we will be able to **blindly search** for the signature of HI towards flux limited sample

Absorption with SKA Pathfinders

Radio-selected surveys with the Pathfinders

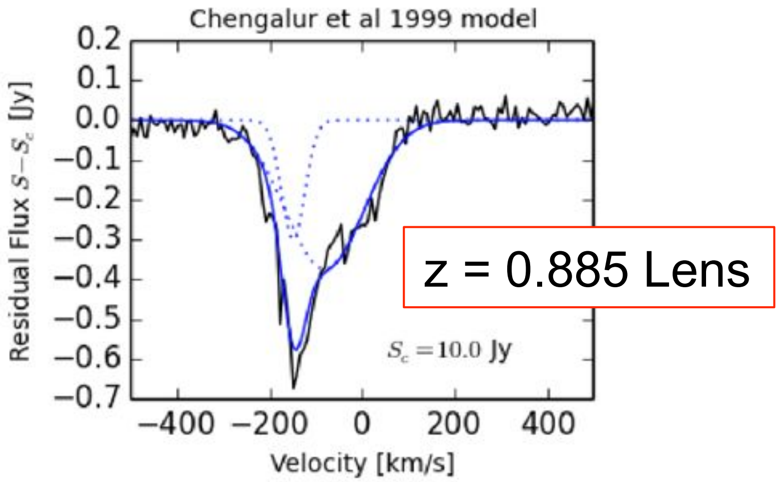


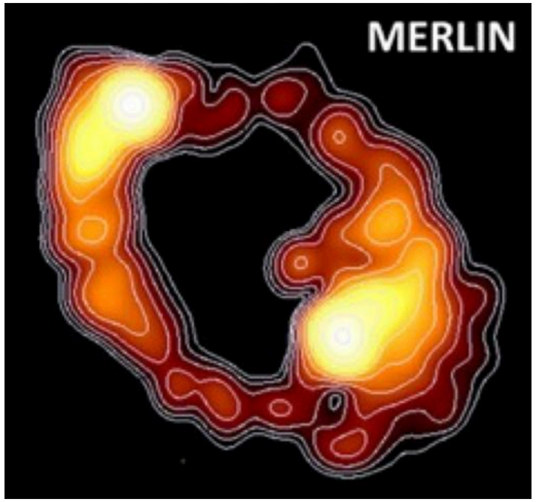


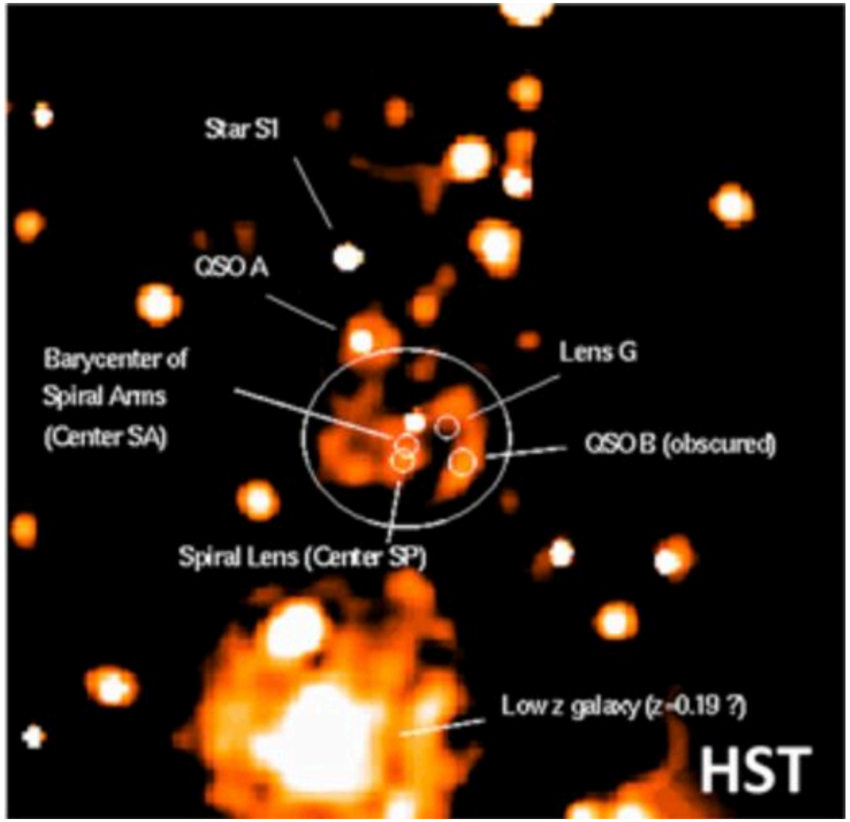
Allison et al. (2015; arXiv:1503.01265)

- ASKAP will target 150,000 sources above 50 mJy at 0.5 < *z* < 1.0 (using HI emission surveys at z < 0.5)
- Will target the higher column density absorbers
- MeerKAT and Apertif will cover smaller areas of the sky to greater sensitivity

ASKAP Example: z = 2.5 quasar PKS1830-211



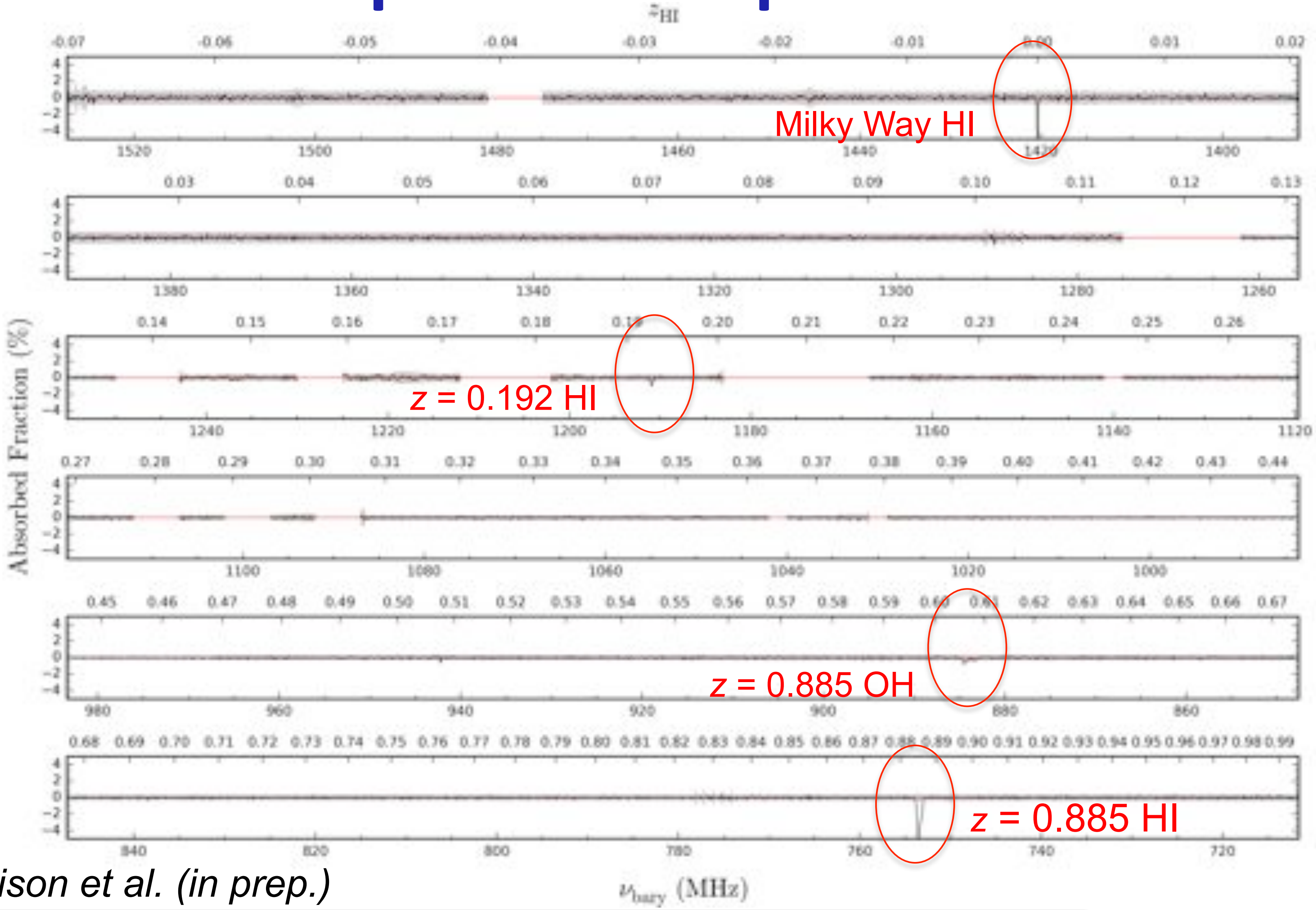




ASKAP is now in **early commissioning phase**, allowing limited sensitivity (S_{cont} > 1Jy) science observations with **six antennas**

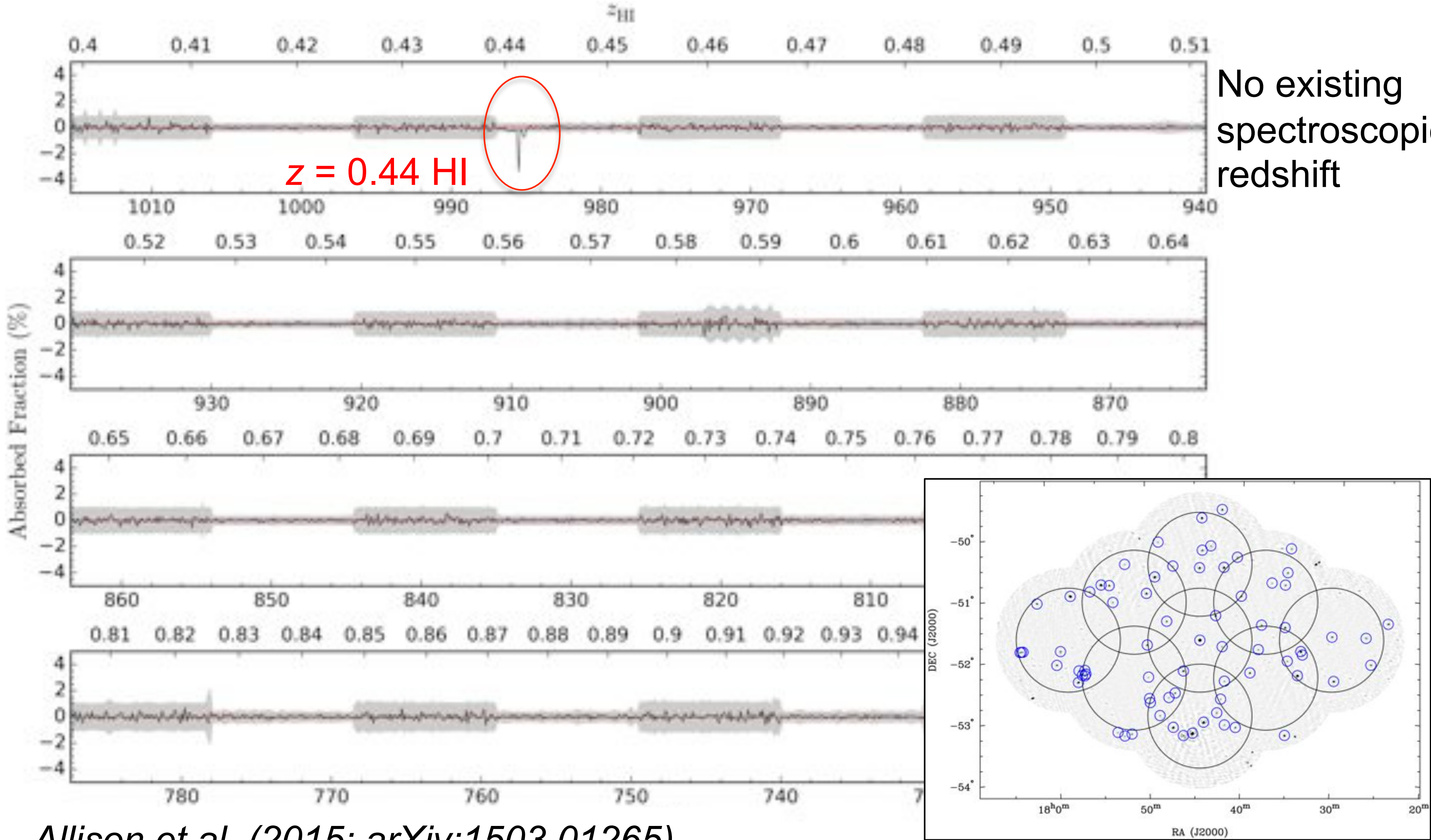
Allison et al. (in prep.)

ASKAP Example: z = 2.5 quasar PKS1830-211



Allison et al. (in prep.)

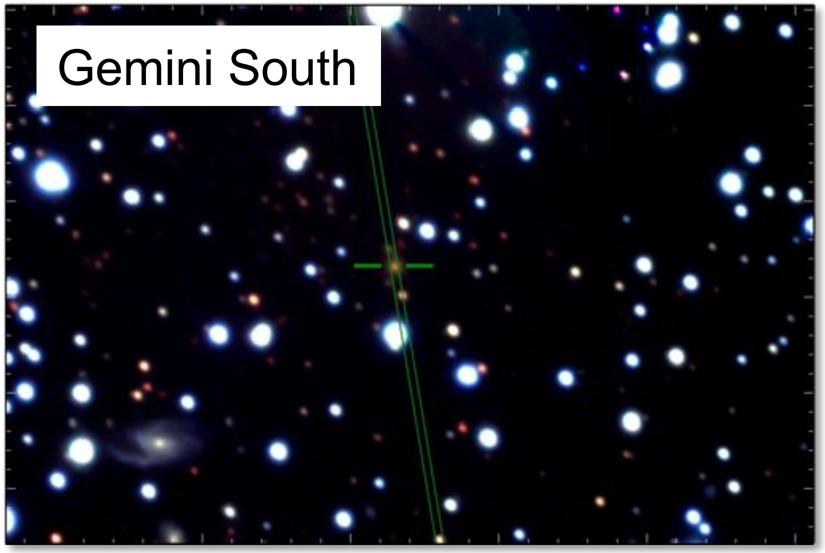
ASKAP Example: Young source PKS1740-517

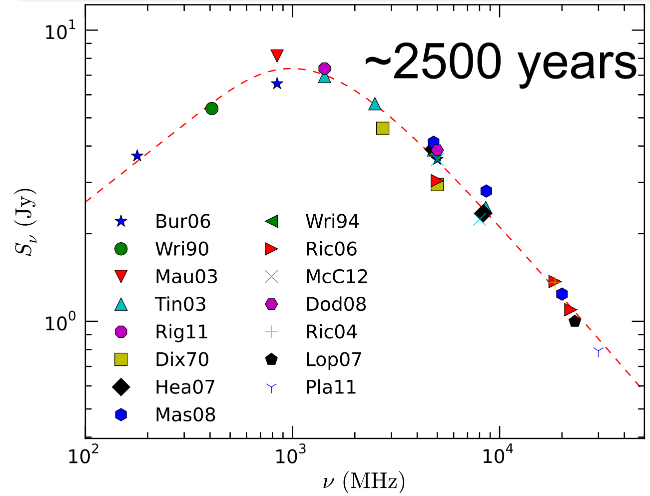


No existing spectroscopic redshift

Allison et al. (2015; arXiv:1503.01265)

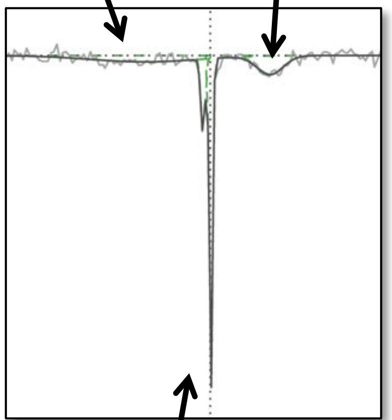
ASKAP Example: Young source PKS1740-517



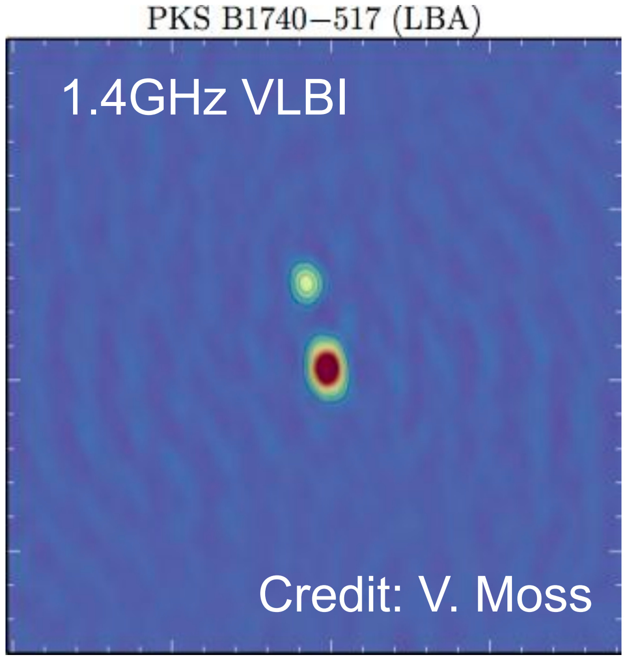


Outflow

HI disc



Cold gas cloud



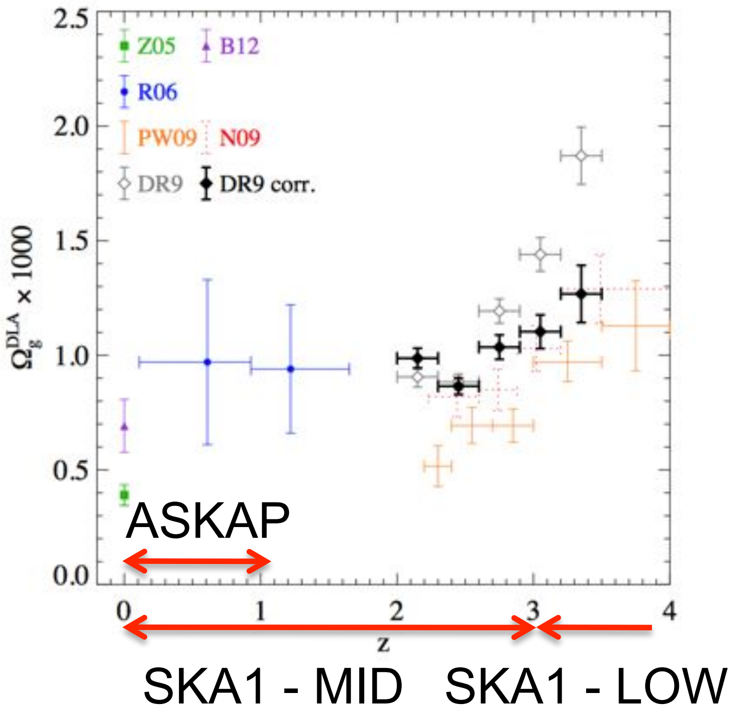
Allison et al. (2015; arXiv:1503.01265)

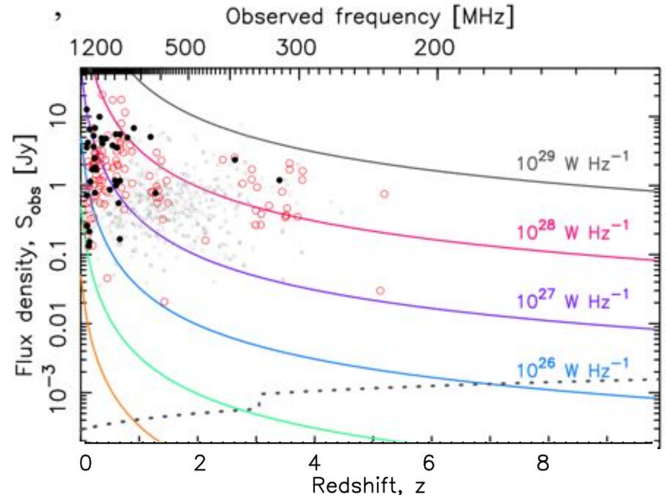
CSIRO

Absorption Surveys with the SKA

What does SKA 1 do for us?

- SKA1 will be a major leap forward in:
  - **Sensitivity** = weak radio sources
  - **Redshift** = $z > 1$, beyond the SKA pathfinders
- SKA1 absorption surveys will:
  - Generate an HI-selected sample of galaxies with redshifts over a large range of redshifts
  - Open our understanding of radio feedback to higher redshifts and **weaker radio sources**
  - Constrain models for the co-evolution of atomic and molecular ISM
  - Discover a previously unknown population of heavily dust-obscured QSOs





Planned absorption surveys with SKA 1

Survey	SKA 1	Redshift range	Receiver	Spatial res.	Sky area	Spectral -line rms	Optical depth τ	Expected detections
1. Inventory of HI in distant galaxies	~~SUR~~ or MID	To z=3	Band 1	~1 arcsec*	1,000 deg^2	<0.1 mJy	<0.01 (10mJy source)	~5000 associated, several hundred intervening
2. (i) Cold outflows (assoc.), (ii) Evolution of HI in galaxies (interven.)	~~SUR~~ or MID ?	To z=3	Band 1	~1 arcsec*	10,000 deg^2	<0.1 mJy	0.001 to 0.005 (20mJy source)	A few hundred outflows, several thousand intervening absorbers
3. HI at very high redshift	LOW	3 < z < 8	220 MHz band	~5 arcsec	>1,000 deg^2	<0.5 mJy	<0.05 (10mJy source)	Unknown, new discovery space.

With Band 1 Continuum survey?

Challenges for HI absorption with SKA 1

- Interpretation of our results is strongly reliant on follow up of detections at **sub-arcsecond spatial resolution**, with VLBI capability highly recommended
- ~10^{-5} bandpass stability needed to achieve required optical depth sensitivity to weak features associated with outflows

- Consequences of rebaselining recommendation:
  - Band 1 vital to HI absorption science – therefore concern over priority order
  - will reduce the over all sensitivity significantly (~50-70%) = fewer target radio sources to achieve same optical depth sensitivity
  - the possible reduction in longer baselines for SKA-MID a concern for interpretation of results
  - However, the survey speed will still be ~20 times faster than the GMRT at 350 – 700 MHz, with a better radio frequency environment for blind searches

Looking towards SKA 2

- SKA 2 will provide a significant jump in sensitivity, allowing:
  - Direct measurement of the physical size and mass of typical galaxies at $z < 6$ using intervening absorption
  - Trace the evolution of neutral gas in the population of radio galaxies (not just the most powerful) over the whole of cosmic time
  - The higher spatial resolution will allow a more robust interpretation of associated HI absorption detections and their link the nuclear activity
  - A unique measure the HI density power spectrum at $z > 6$

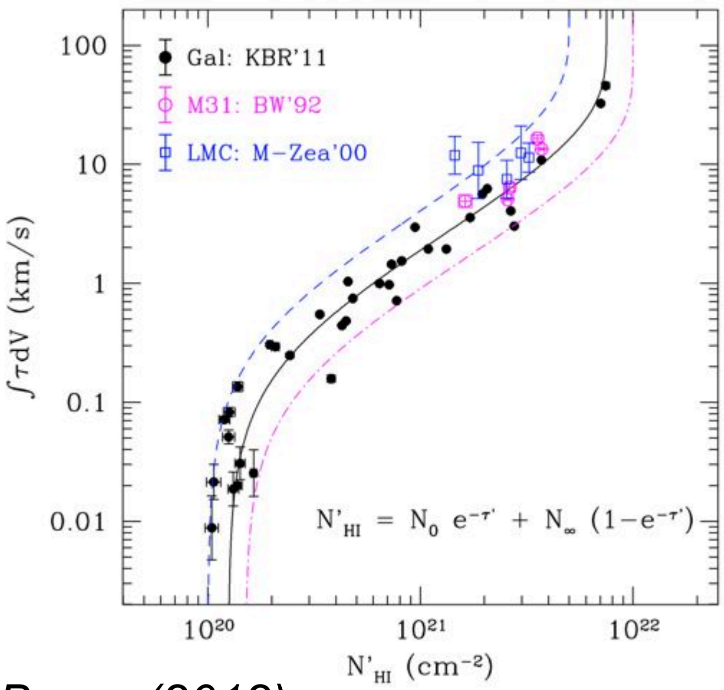
Summary

- Intervening HI absorption provides a direct study of the evolution of atomic gas in the ISM to very high redshifts
- Absorption associated with radio AGN reveals the kinematic signatures of feeding and feedback mechanisms linked to the co-evolution of galaxies and their supermassive blackholes
- The SKA (and its pathfinders) will allow us to conduct the first radio-selected surveys for HI absorption, circumnavigating existing selection biases
- With the SKA we will extend our understanding of the neutral ISM at $z < 1.0$ (using the pathfinders) to beyond $z = 3$.

Extra slides

Interpreting results from absorption surveys

- The **degeneracy** between the observed 21cm **optical depth** and the **physical properties** of the HI gas is a hurdle to interpretation of results from existing and future surveys
- This is an active field of research - very much work in progress!

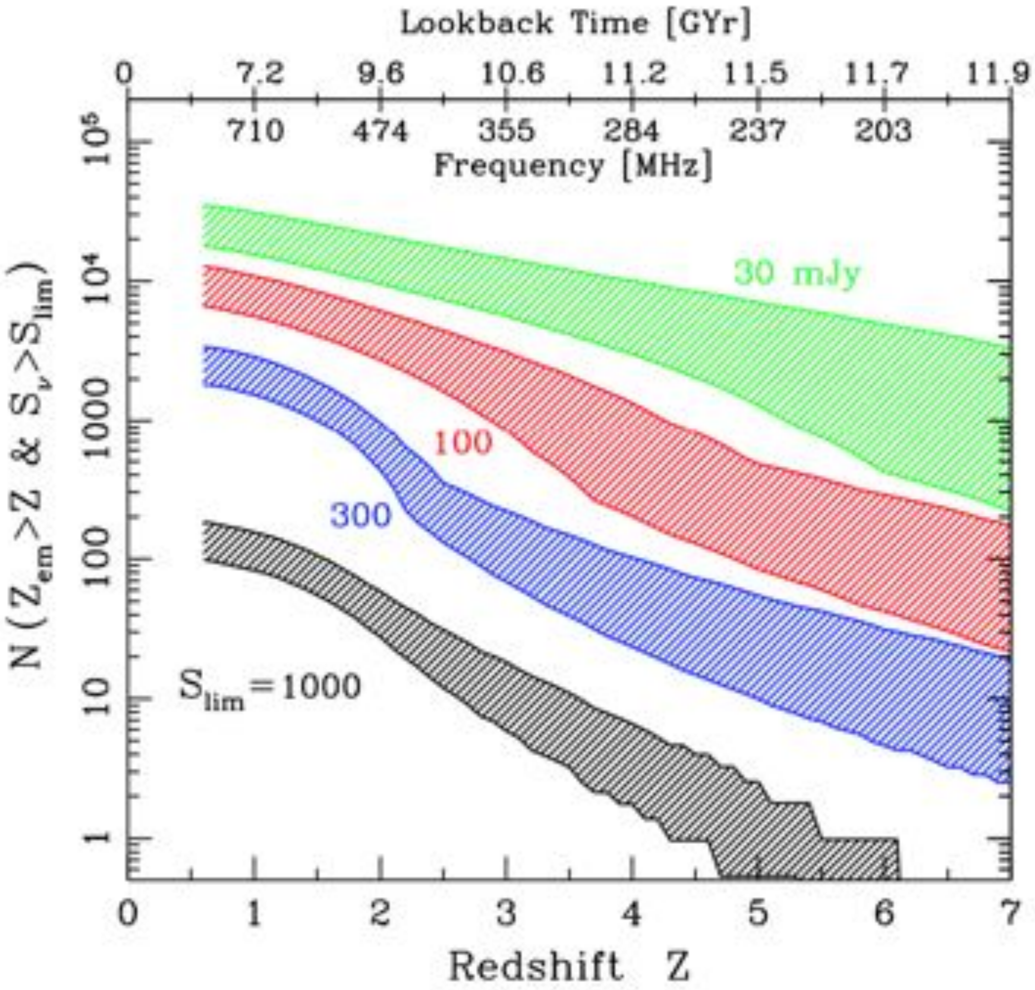


Braun (2012)

Possible solutions:

1. Extrapolation of **empirical relationship** between observed optical depth and column density for **low *z*** galaxies (e.g. Braun 2012)
2. Spectroscopic **follow up** at optical and mm wavelengths
3. Use model predictions from semi-analytic & hydro-dynamical **simulations**

Number of radio sources in 2π sr of sky



Kanekar & Briggs (2004)