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FOR ALL-SKY ASTROPHYSICS

A successful search for intervening 21 cm HI absorption at 0.4 < z < 1 with ASKAP

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on behalf of the ASKAP FLASH team

ASKAP-FLASH

THE UNIVERSITY OF SYDNEY

Outline of this presentation

Credit: CSIRO

- Goals of the ASKAP FLASH survey
  - An HI-selected galaxy sample at $0.4 < z < 1$
  - Cross-calibration of N_{HI} at z=0
- Earlier work - what we expect to see
- First results from ASKAP
- Interpretation and challenges
- Follow-up and next steps

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The FLASH team

ASKAP-FLASH

<u>Team members:</u> *Currently 50 members from 24 institutions in 10 countries*

At this meeting: Elaine Sadler (Sydney, PI), James Allison (CSIRO), Stephen Curran (NZ), Alastair Edge (UK), Bjorn Emonts (USA), Elizabeth Mahony (Sydney), Martin Meyer (UWA), Raffaella Morganti (Netherlands), Vanessa Moss (Netherlands), Tom Oosterloo (Netherlands), Lister Staveley-Smith (UWA), Martin Zwaan (ESO)

http://www.physics.usyd.edu.au/sifa/FLASH

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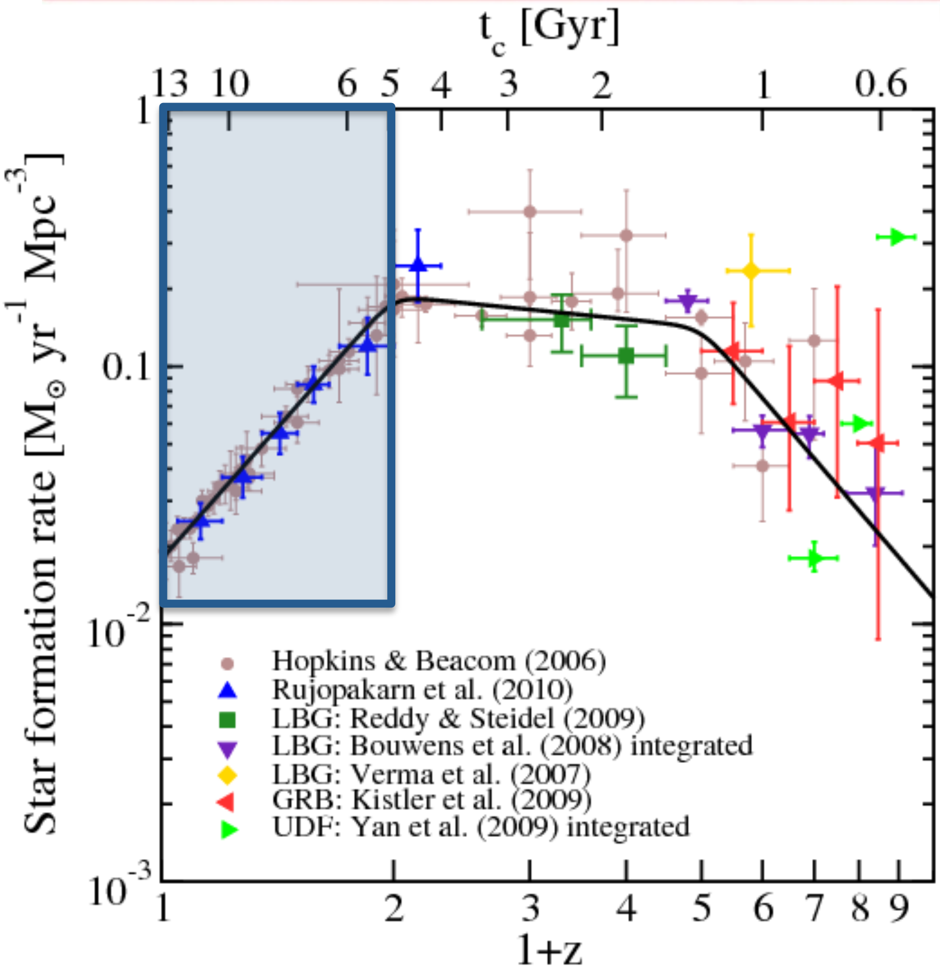
FLASH key science goals

The ASKAP FLASH survey will provide the *first systematic probe* of the neutral hydrogen (HI) content of individual galaxies in the redshift range 0.4 < z < 1.0

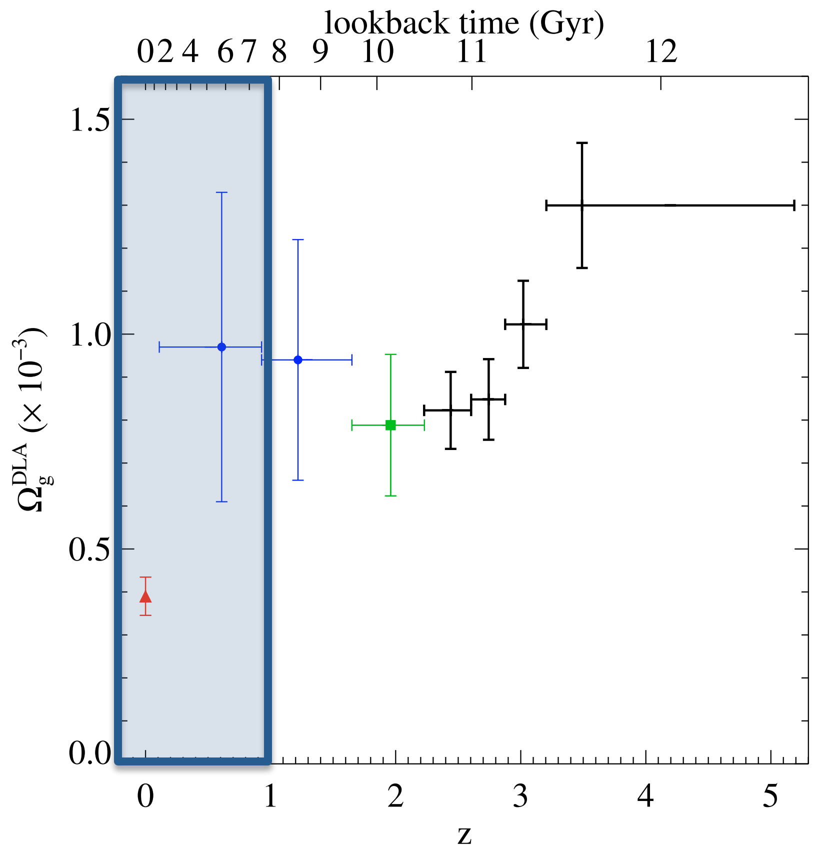
- **Intervening absorbers:** *Test current galaxy evolution and mass assembly models* in this redshift range, using the observed and predicted distributions of quantities like HI optical depth and line width
- **Associated absorbers:** Study the processes of *AGN fuelling and feedback* in massive galaxies across a wide range in redshift

Gas and galaxy evolution



(Horiuchi et al. 2010)

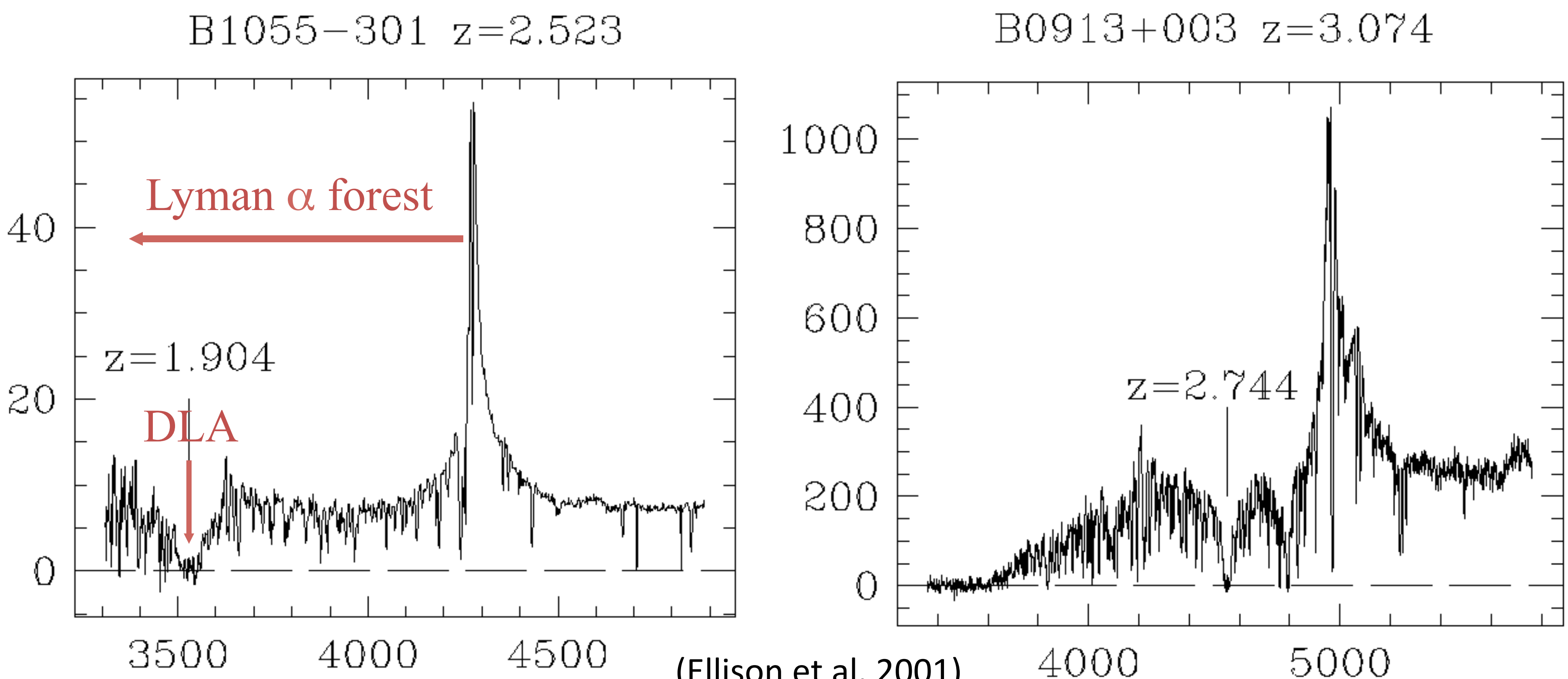
Cosmic star-formation rate



(Noterdaeme al. 2009)

Cosmic HI mass density

Optical: Damped Lyα Absorbers



(Ellison et al. 2001)

DLAs: Intervening absorbers with high HI column density ($N_{HI} > 2 \times 10^{20}$ cm^{-2}) can be used to detect and study neutral hydrogen in the very distant universe.
Ground-based observations of the Lyman-α line are only possible at redshift z > 1.7

Why a 21cm HI absorption survey?

Motivation: Use 21cm HI absorption to probe neutral atomic hydrogen in distant galaxies - unlike HI emission, *sensitivity is independent of z*

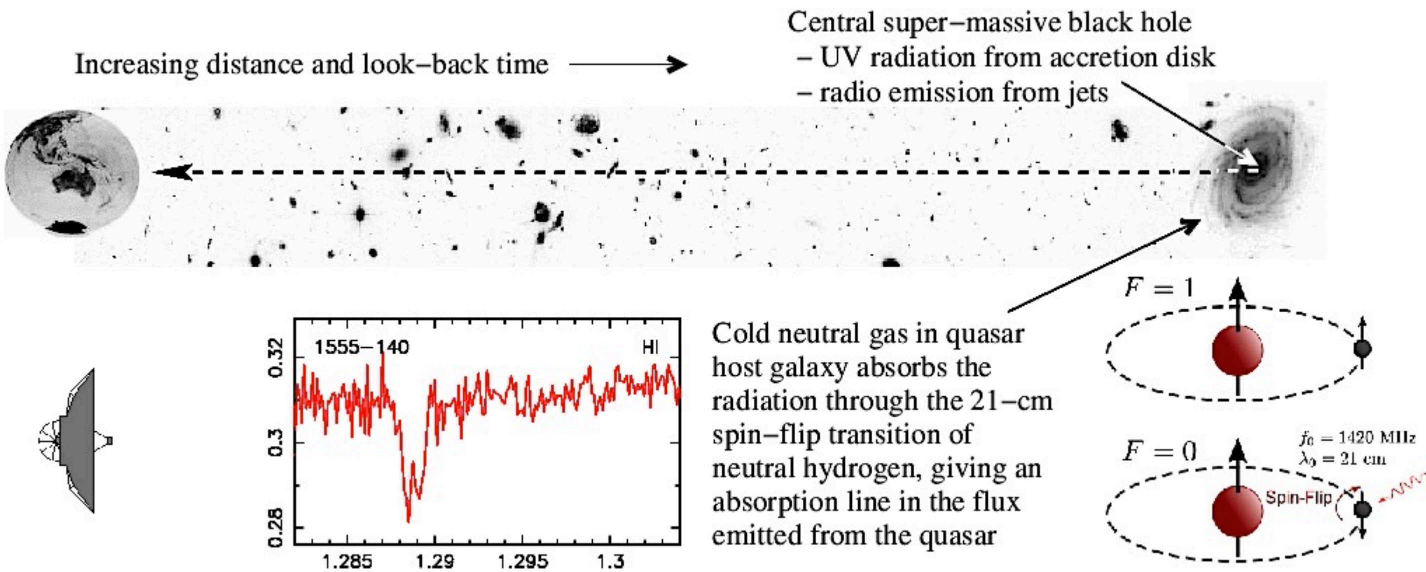
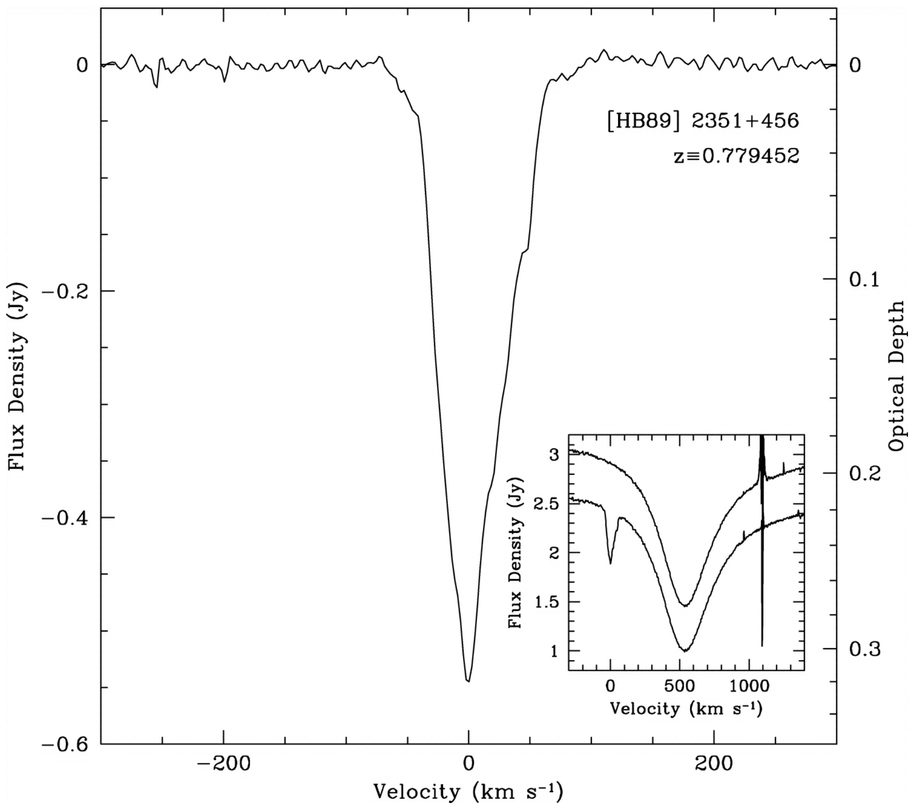


Image: S. Curran

Radio: Intervening HI absorption



(Darling et al. 2004)

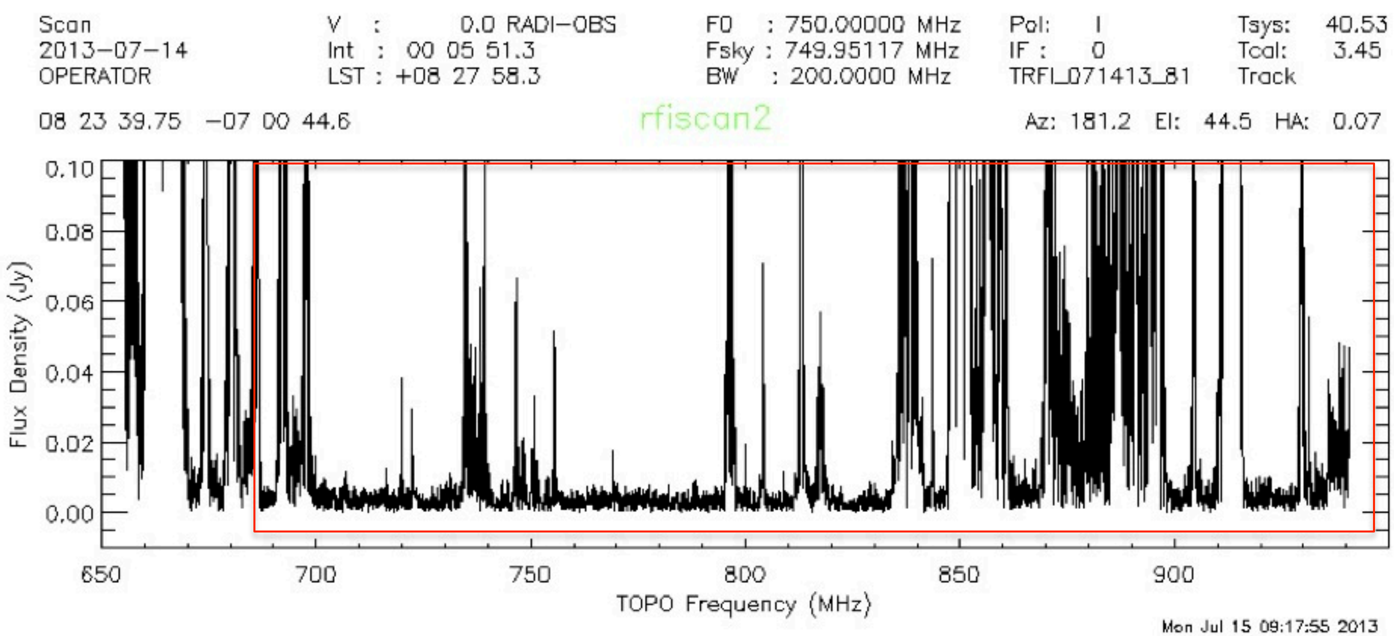
Radio 21cm measurements are particularly sensitive to cold HI (spin temp. T_S < 200K) .

$\tau \propto N_{HI} / f.\ T_s.\ \Delta V$ for observed optical depth τ, line width ΔV

RFI spectrum at the GBT site

(via NRAO web pages)

GBT RFI Plots http://www.gb.nrao.edu/IPG/rfiarchive_files/GBTDataImage...

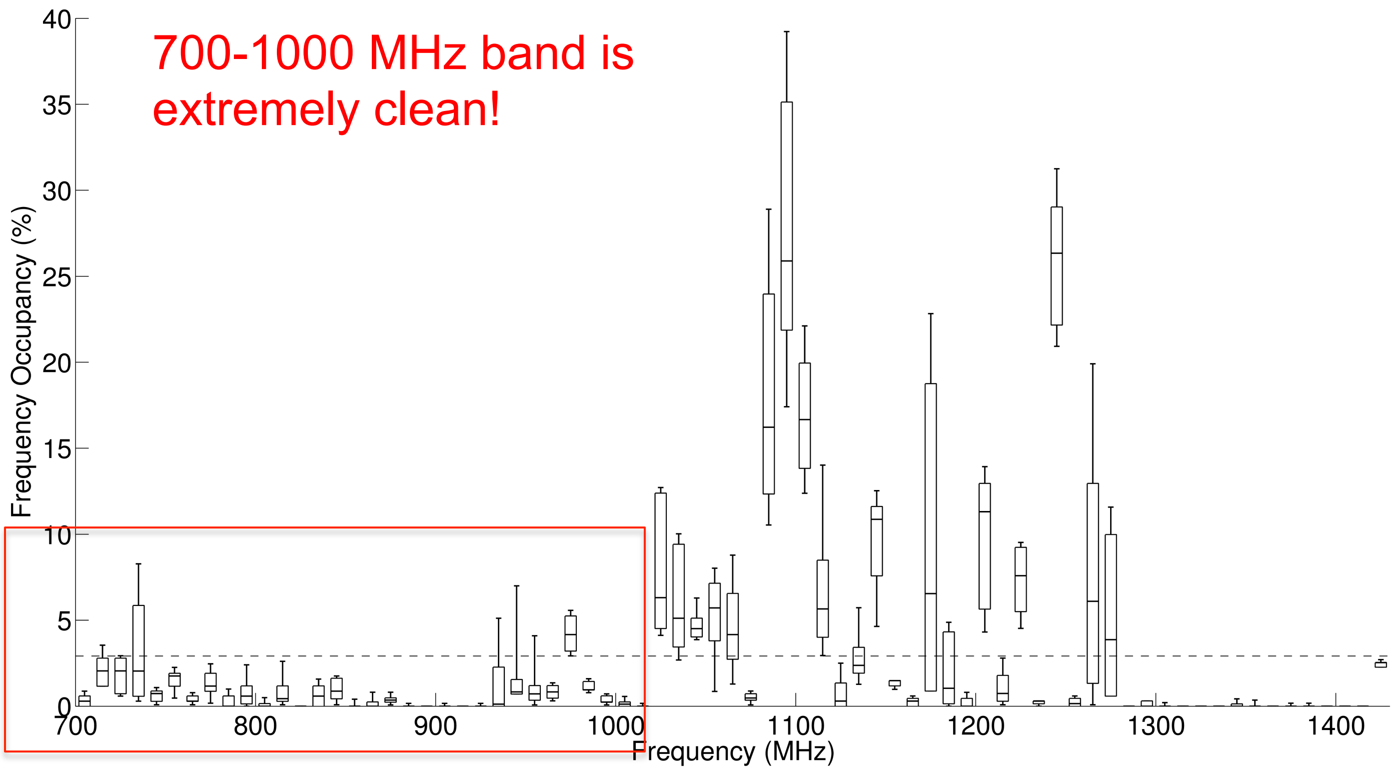


Roughly half the GBT band below 1 GHz is lost to RFI.
700-1000 MHz is considered one of the better regions.

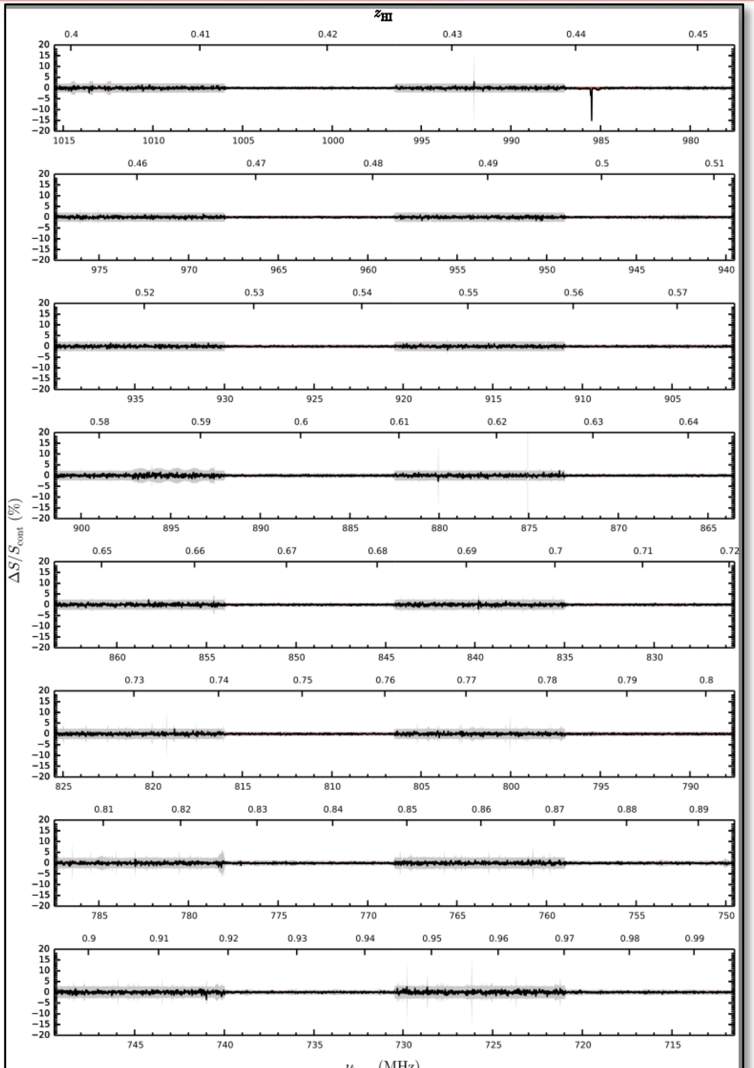
RFI spectrum at the ASKAP site

Measured Frequency Occupancy (plot from Aaron Chippendale)

Percentage of occupied 27.4 kHz channels in 10 MHz blocks in 2hr spectra



The advantages of ASKAP



ASKAP's

- Wide field of view
- Wide spectral bandwidth
- Radio-quiet site

make it possible to carry out a *large and unbiased* radio survey for HI absorption

Will observe ~150,000 sightlines to bright (>50 mJy) radio sources, an increase of almost **two orders of magnitude** over earlier studies

ASKAP Band 1 (700 – 1000 MHz) provides continuous coverage of the 21cm HI line from $0.4 < z < 1$ (lookback times of 4 to 8 Gyr)

What do we expect to see?

FLASH survey science proposal 2009

Intervening 21cm absorbers:

- **Probability** of intercepting a DLA system with $N_{HI} > 2 \times 10^{20}$ cm^{-2} is
  $dN/dZ = 0.055\,(1+z)^{1.11}$ (Storrie-Lombardi & Wolfe 2000)

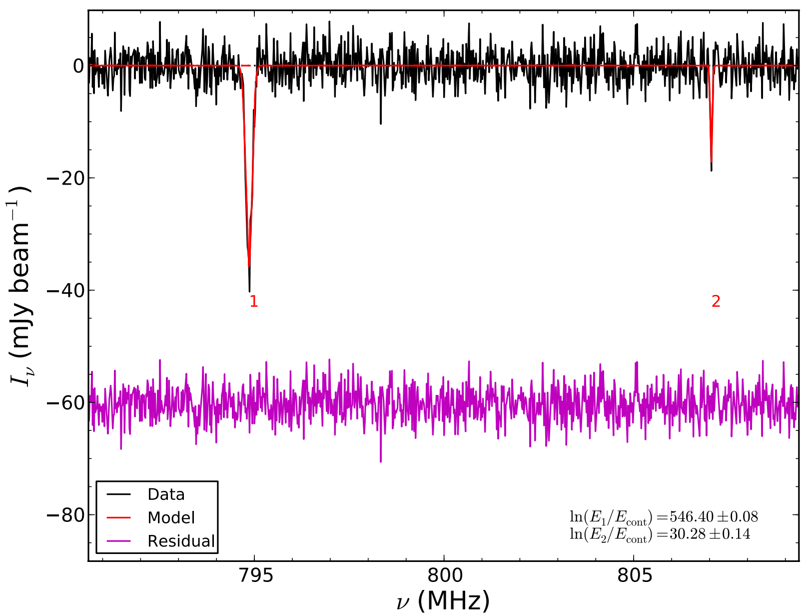
i.e. 6% for a sightline in the 700-1000 MHz ASKAP band (0.4 < z < 1.0)

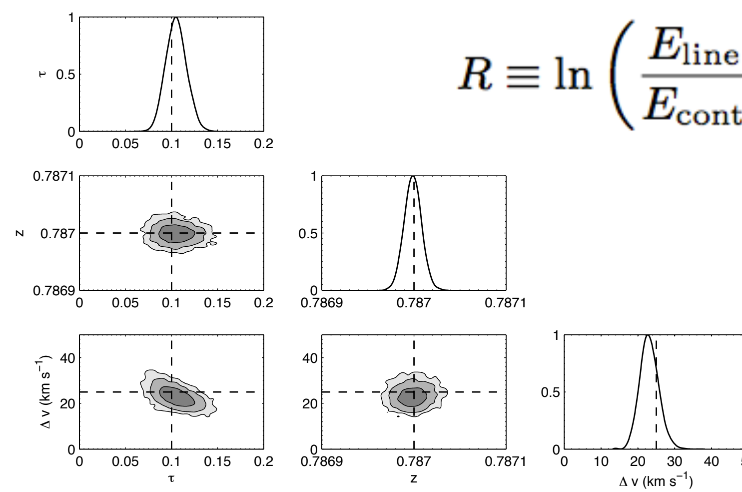
- **Optical depth** of these lines is expected to be ~1.5% for a minimal DLA and 10% or higher for sightlines with much higher HI column density (Braun 2012)
- **Surface density** (and approximate redshift distribution) of suitably bright background continuum sources is already known

Implies that an all-sky 21cm HI absorption survey with ASKAP is feasible, and should yield several hundred detections of intervening lines

Tools and techniques

- Positions and flux densities of background sources are already known
- Use Bayesian *line-finding tool* (Allison et al. 2012) to identify lines and quantify their significance – tested on both real and simulated data



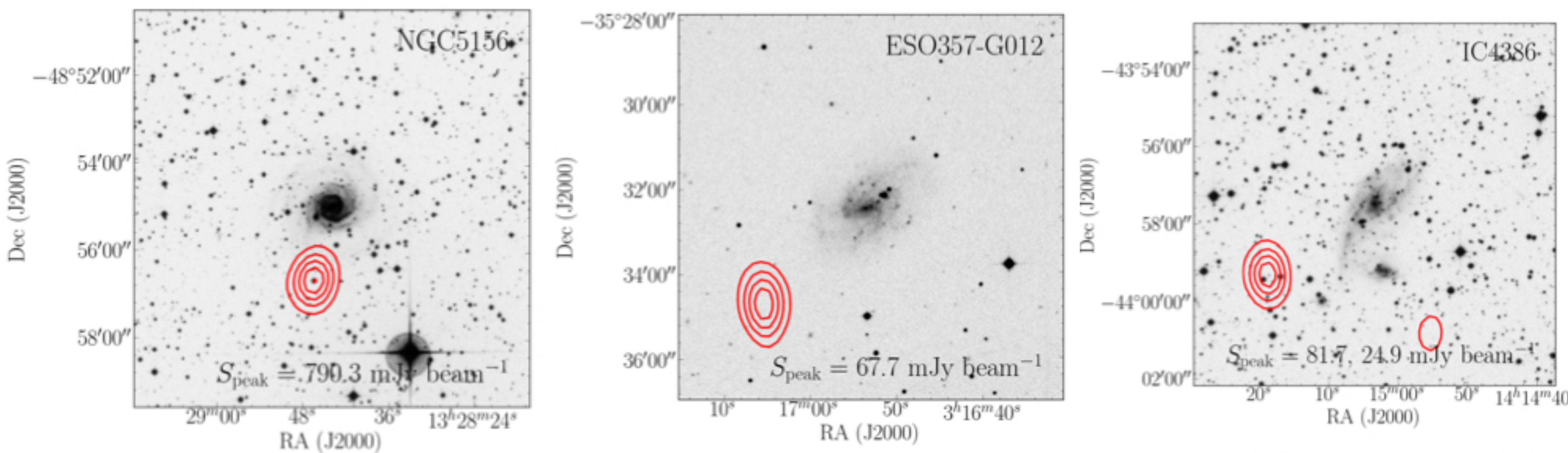


$$R \equiv \ln\left(\frac{E_{line}}{E_{cont}}\right)$$

Model using single Gaussian profiles, detection significance given by the ratio of Evidence for Gaussian spectral-line and Continuum-only models (Allison et al. 2012)

ATCA: low-redshift intervening lines

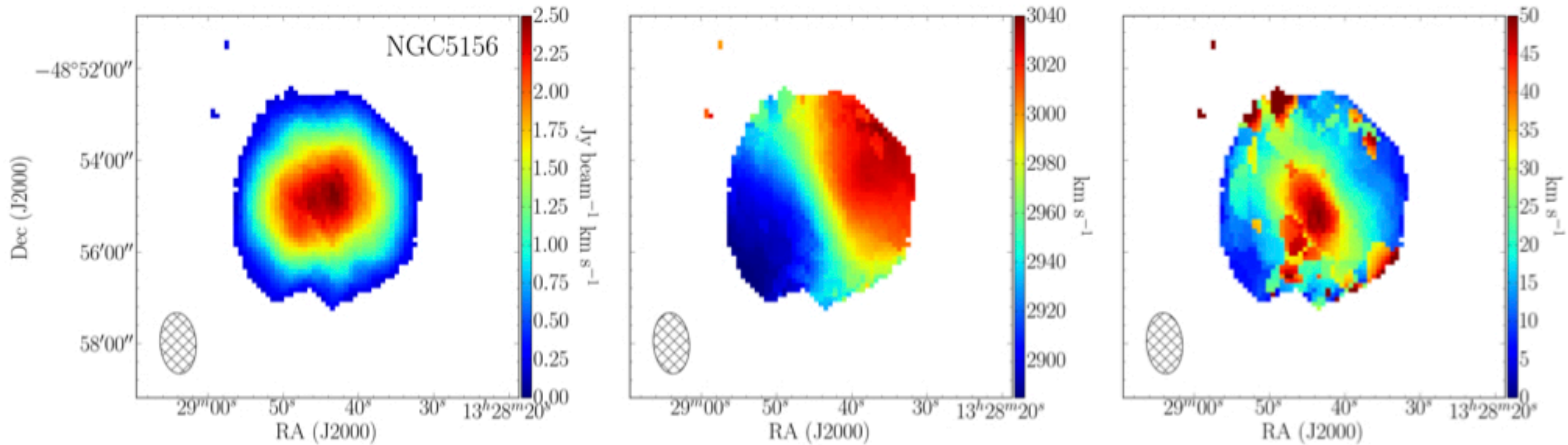
Sarah Reeves PhD thesis: Background radio sources behind 12 nearby gas-rich galaxies from HIPASS, impact parameter < 20 kpc

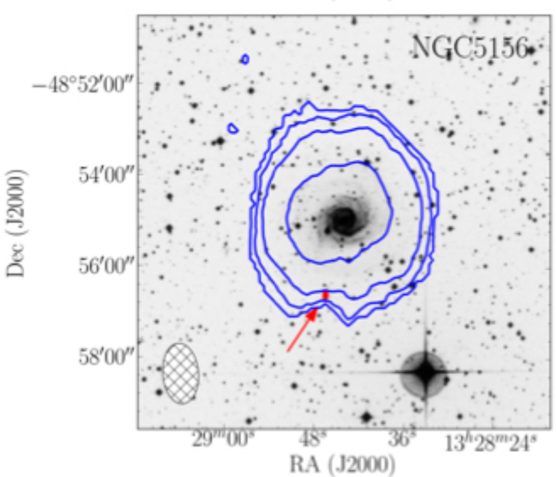


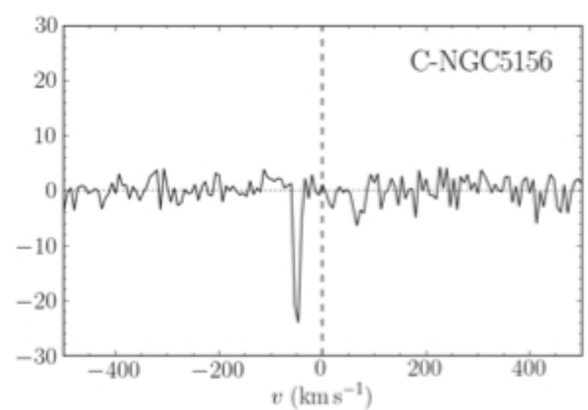
ATCA: Searching for **intervening** HI absorption

(Reeves et al. 2015, 2016)

ATCA detection: NGC 5156



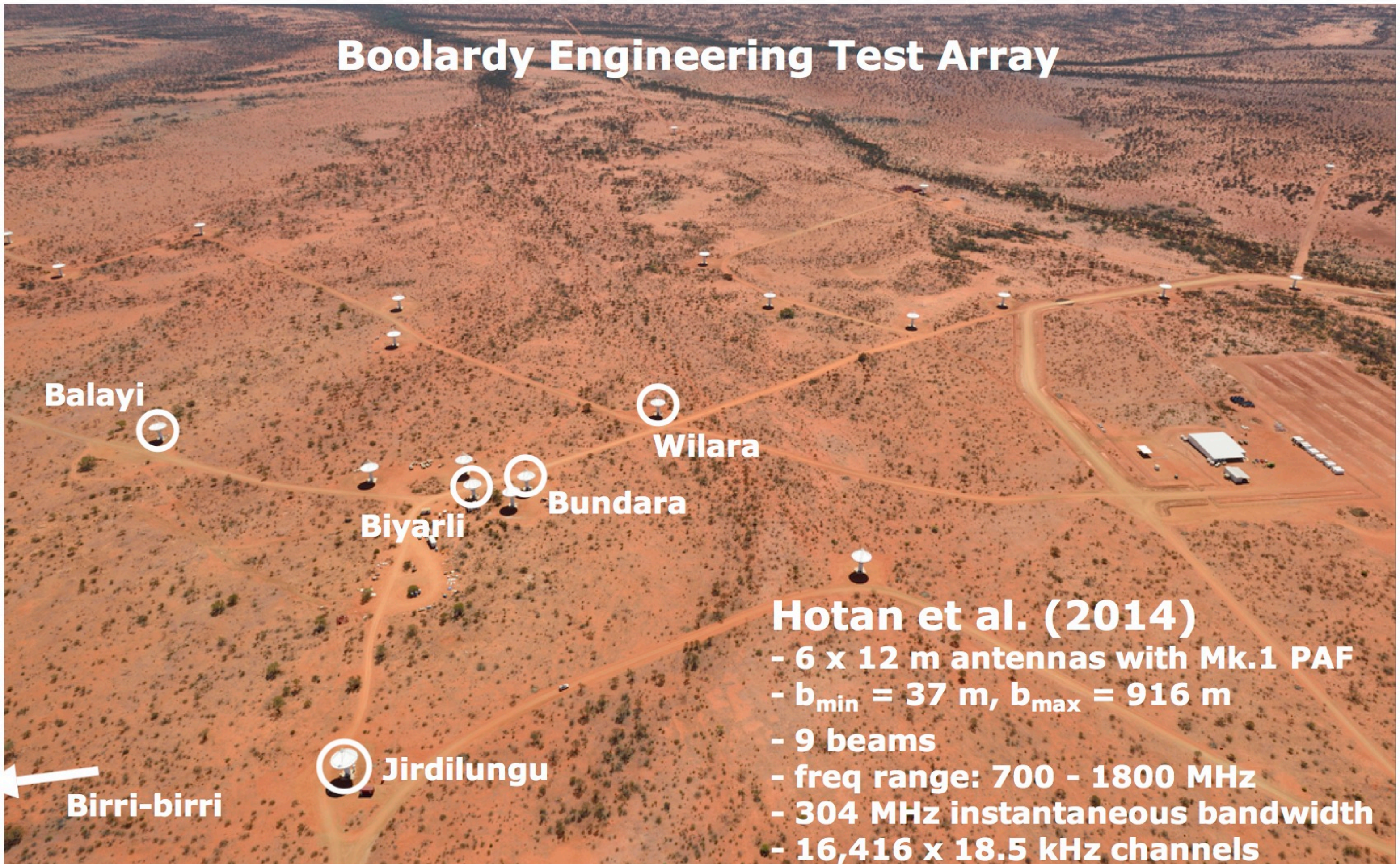




Intervening HI absorption line seen against the background source – 19 kpc from the centre

(Reeves et al. 2016)

BETA observations 2015-16



Six-antenna engineering test array

BETA target sources

Six-antenna BETA engineering test array, 700-1000 MHz band

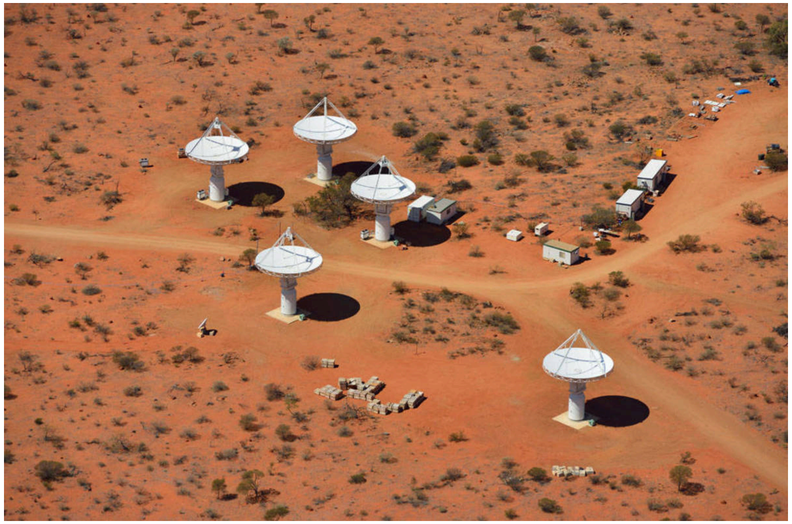
(with James Allison, Marcin Glowacki, Elizabeth Mahony, Vanessa Moss, Matt Whiting and the ASKAP ACES team)

Total of ~100 objects observed

Observed **bright** (> 1Jy) and **compact** (VLBI-scale) radio sources in the southern sky

Several sub-samples observed:

- GPS/CSS radio galaxies
- Red quasars
- X-ray AGN
- 2 Jy radio sample
- **Intervening line search**



Selection of intervening targets

Complete sample selected from the AT20G Bright Source catalogue (Massardi et al. 2008)

- Dec < -15 deg
- S > 1.0 Jy at 20 GHz
- Redshift z > 0.4 or unknown
- S > 2.0 Jy in NVSS (1.4 GHz) or SUMSS (843 MHz) survey

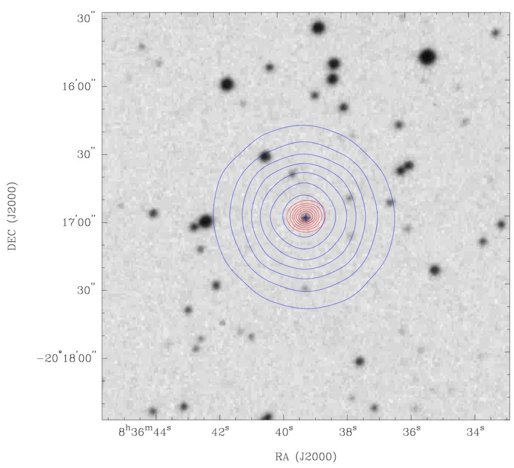
BETA intervening sample:

✧ 32 sources, 27 with known optical redshift

✧ Total redshift path $\Delta z = 12.5$

✧ Integration times of 3-5 hours per source

✧ Two detections of intervening lines



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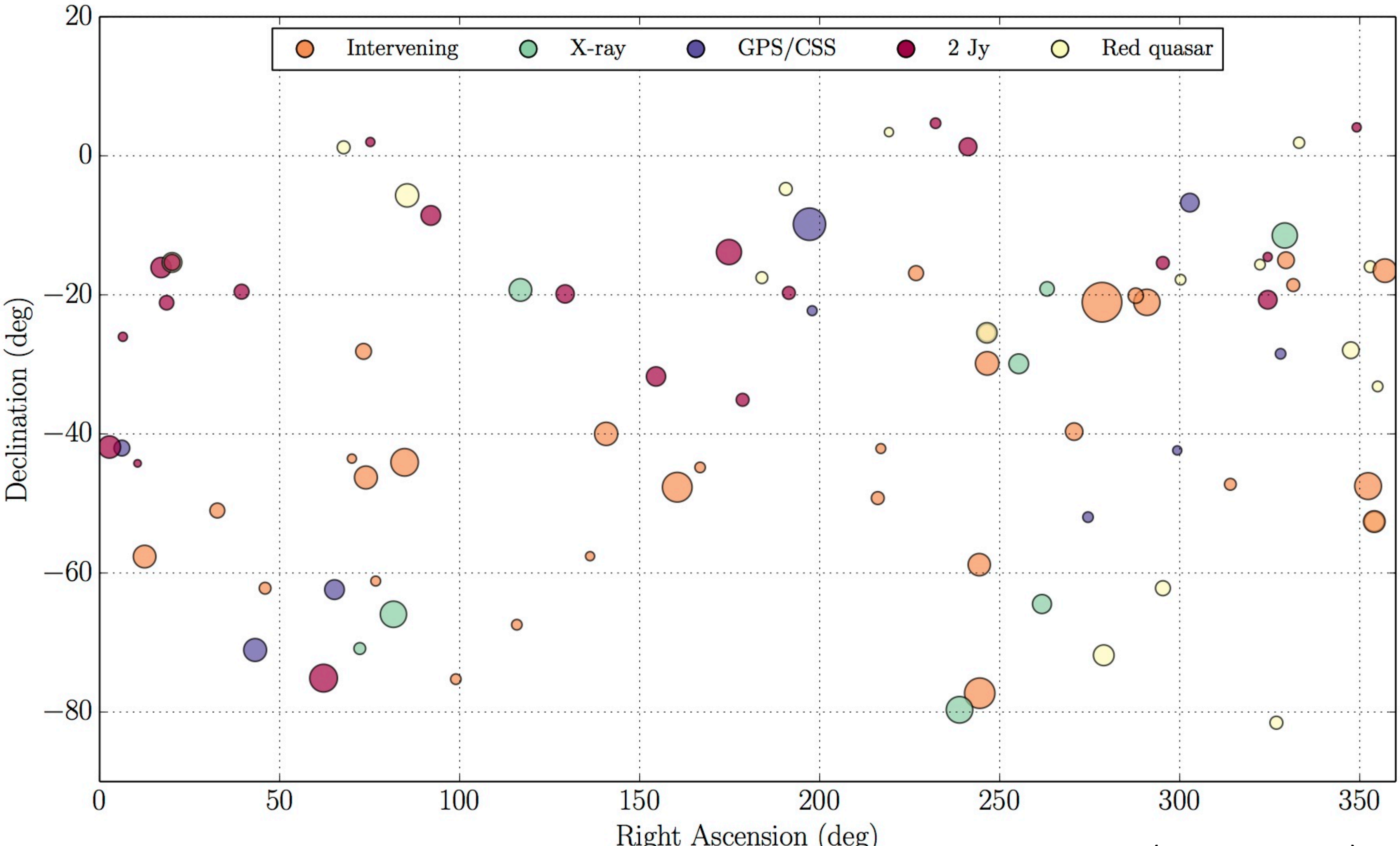
Summary of BETA observations



(Vanessa Moss)

ASKAP-12 observations 2017

ASKAP-12 intervening sample:

- ✧ 21 more sources, all with known optical redshift
- ✧ Total redshift path $\Delta z = 7.9$
- ✧ Integration time of 2 hours per source
- ✧ One new detection of an intervening line

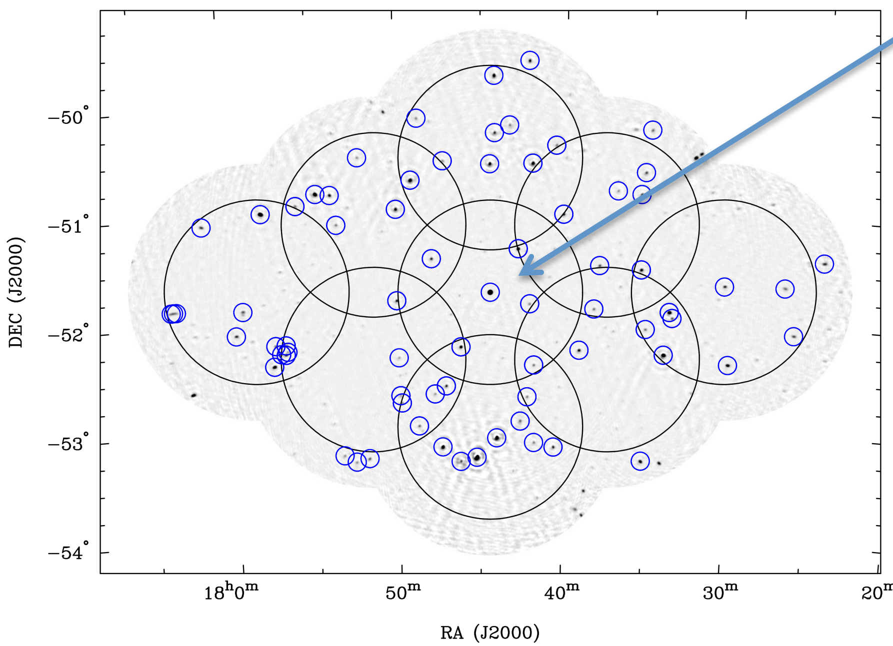
<u>ASKAP-12 commissioning Feb 2017</u>

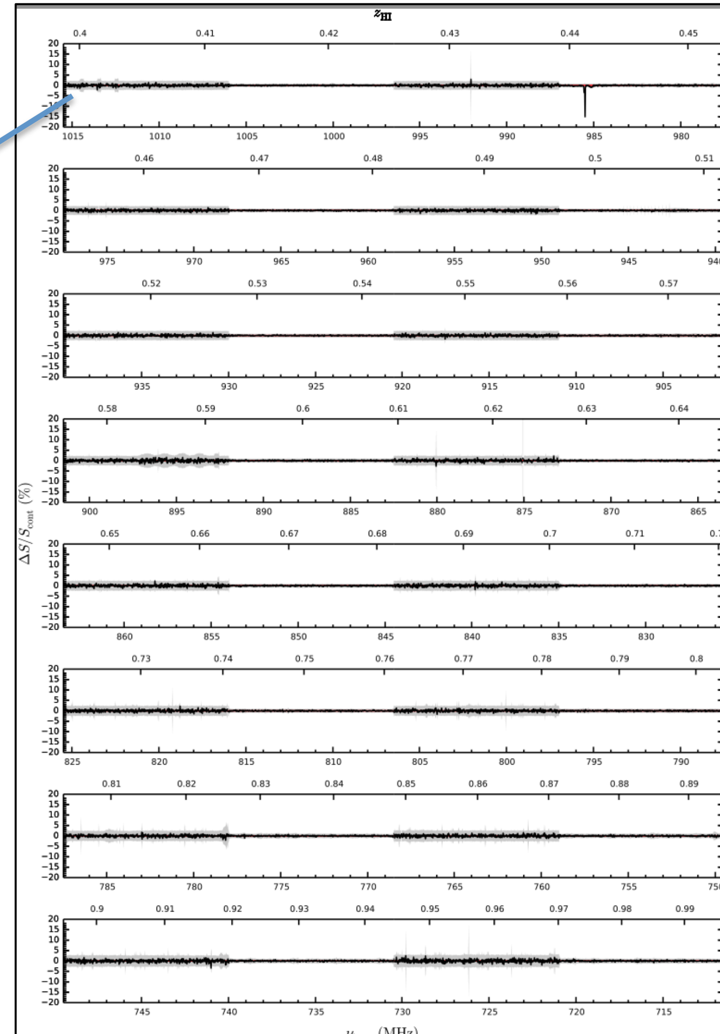
- Target selection similar to BETA sample, but with slightly relaxed Dec and flux density limits (Dec limit 0^{o})
- Frequency restricted to 240 MHz BW and single beam (data ingest issues)

Total intervening sample (BETA + ASKAP-12):
53 sightlines,
3 intervening detections

BETA commissioning data

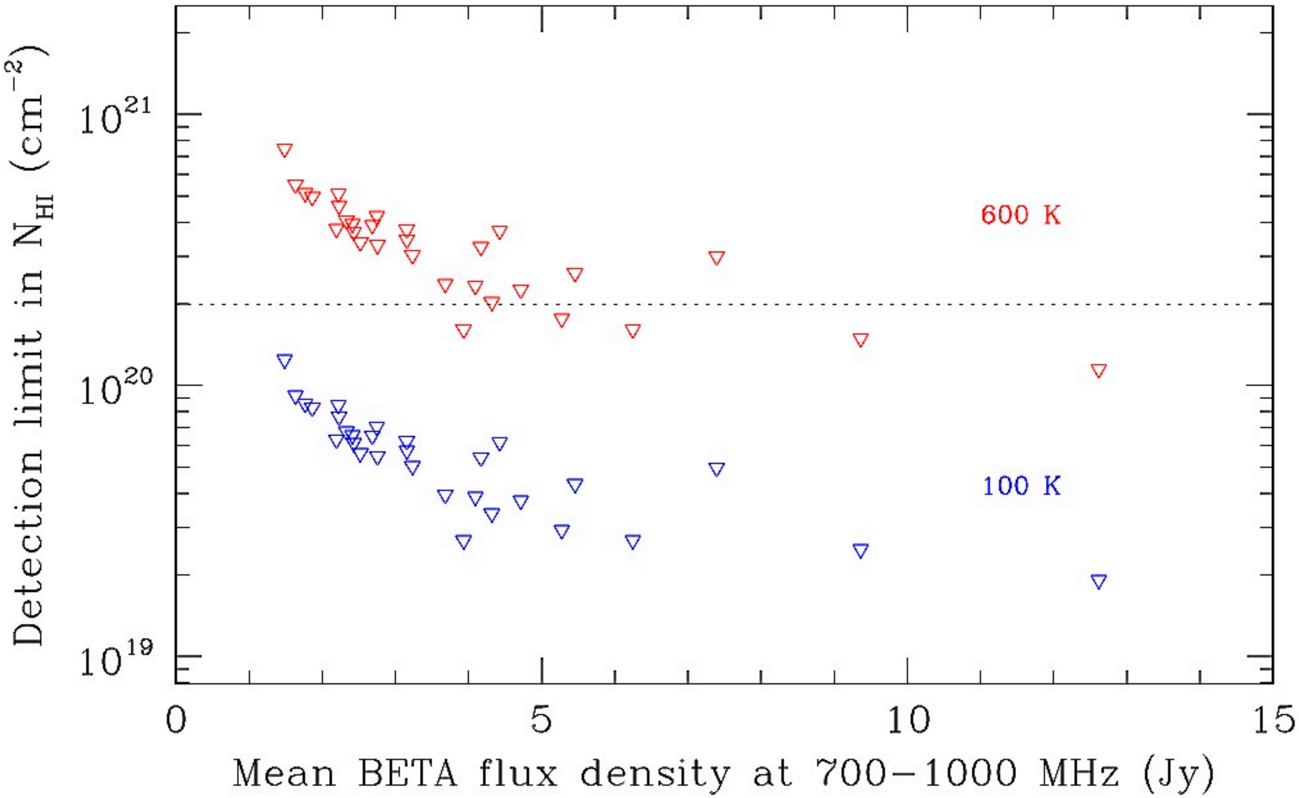
- 711.5-1015.5 MHz Band
- 16,416 x 18.5 kHz (~5 km/s) channels





Spectrum is completely free of RFI!

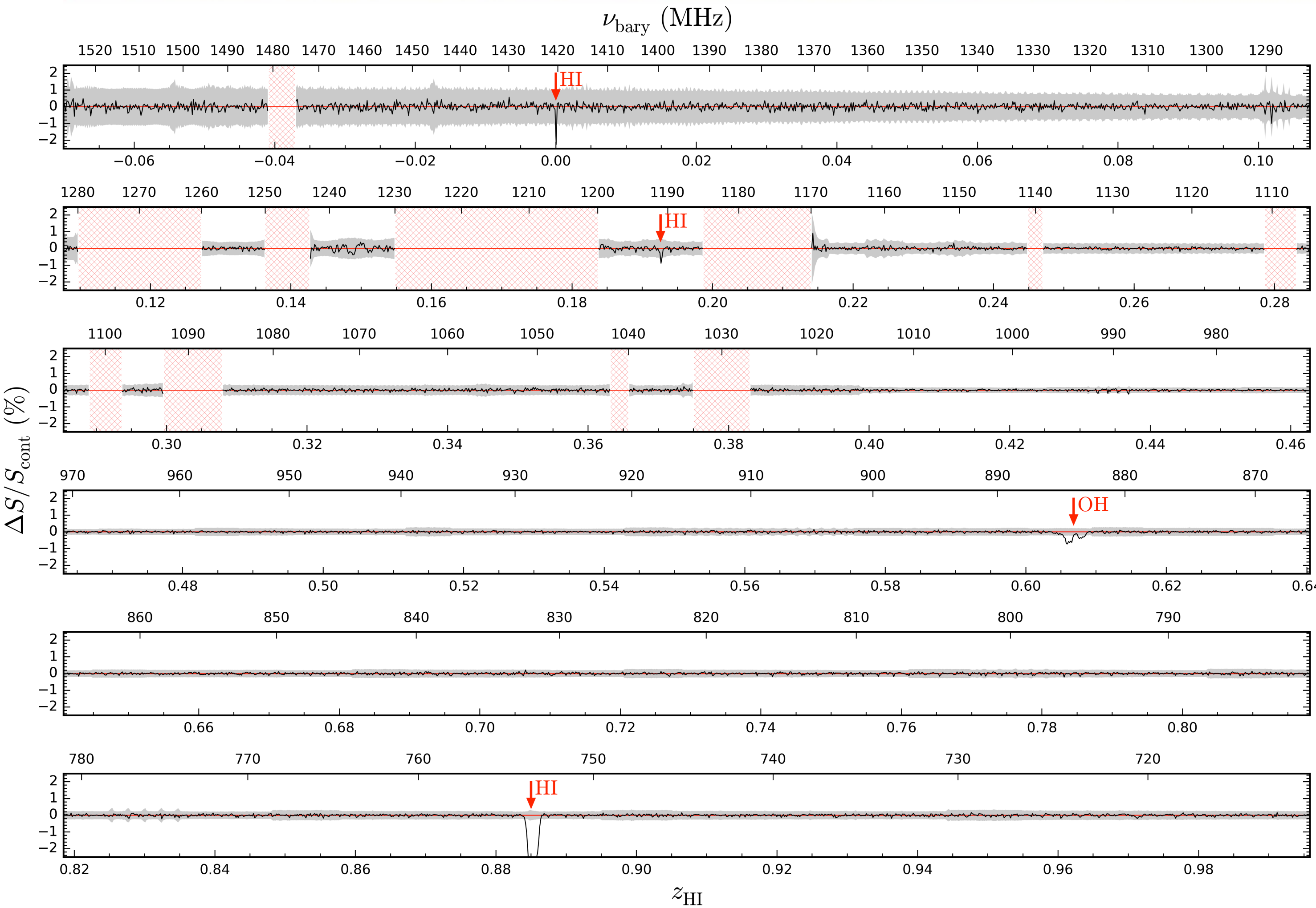
Detection limits in HI column density

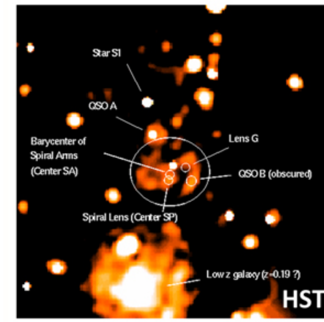


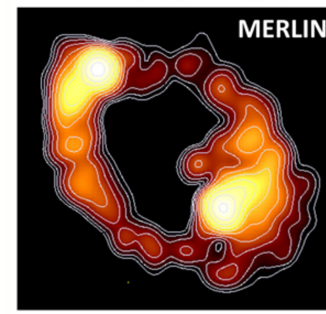
BETA observations: Sensitive to DLA-like HI column densities for cool neutral gas (spin temperature Ts below 200-600 K)

(assumes covering factor f=1)

Known absorber: PKS 1830-211



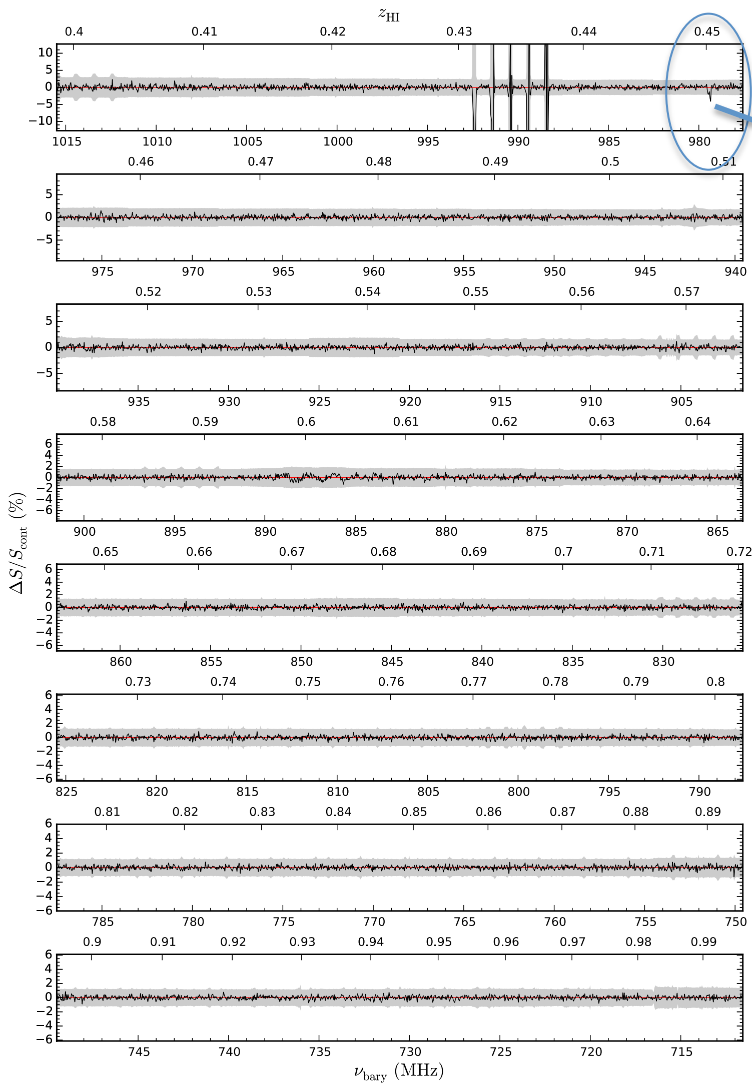


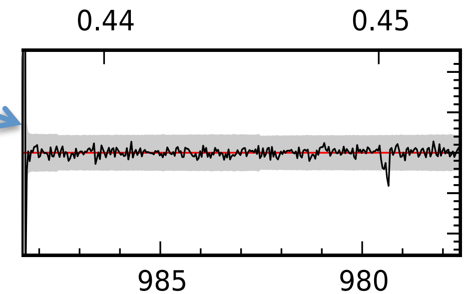


QSO at z=2.51 lensed by foreground galaxy at z=0.89

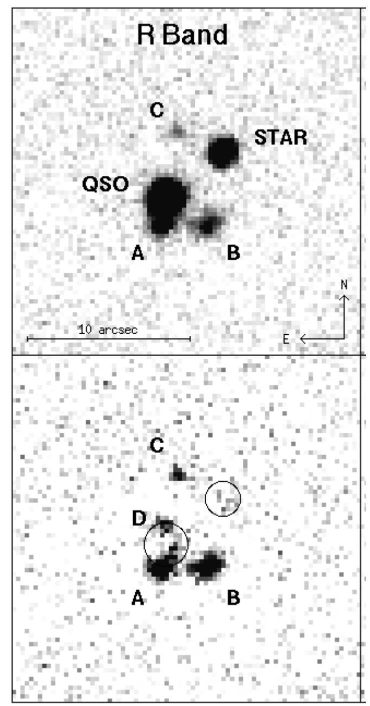
(Jauncey et al. 1991; Lidman et al. 1999)

New intervening absorber with BETA





PKS 1610-77

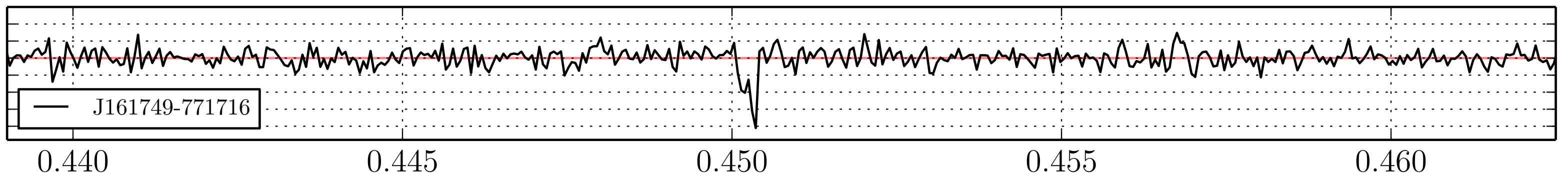


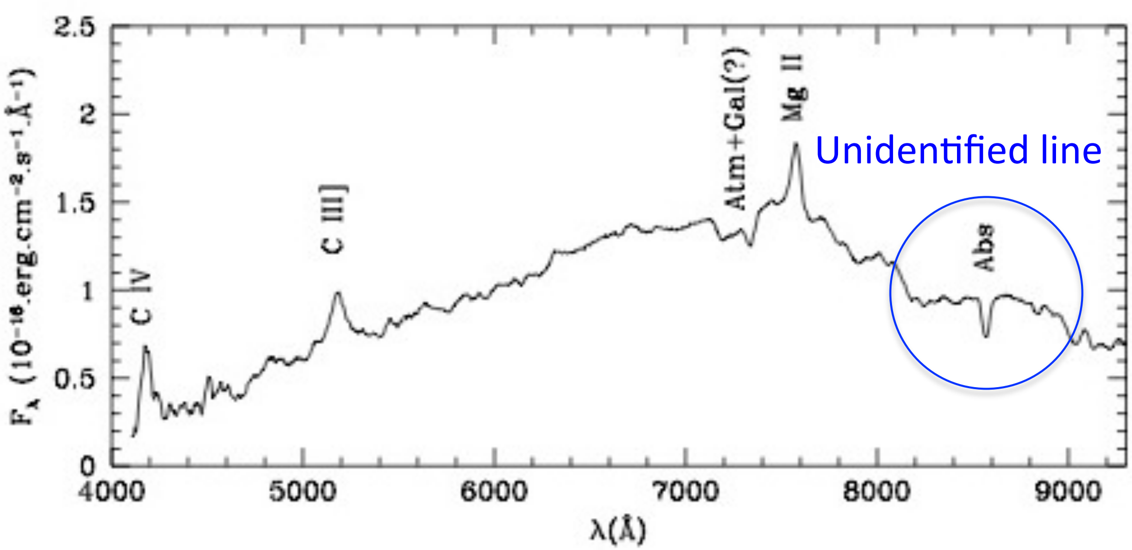
Detection of neutral hydrogen in a galaxy at z=0.45 along the line of sight to a powerful QSO at z=1.71

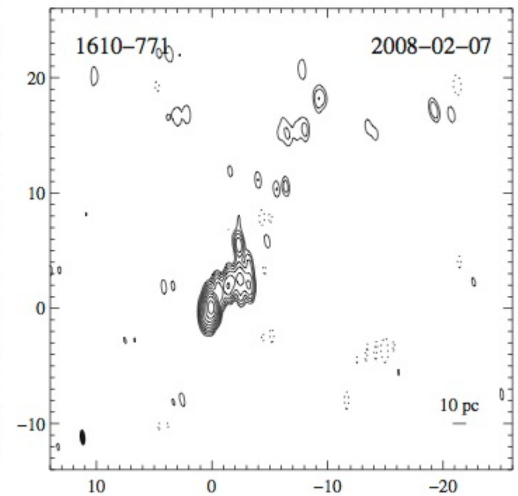
(Courbin et al. 1997)

PKS 1610-77 optical spectrum

ASKAP spectrum







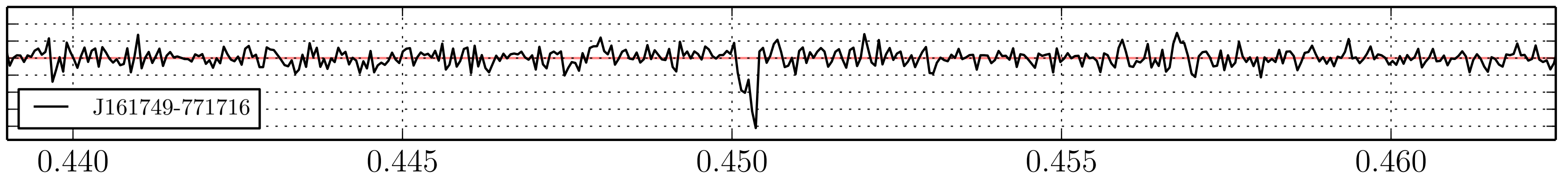
Optical spectrum: Courbin et al. (1997)

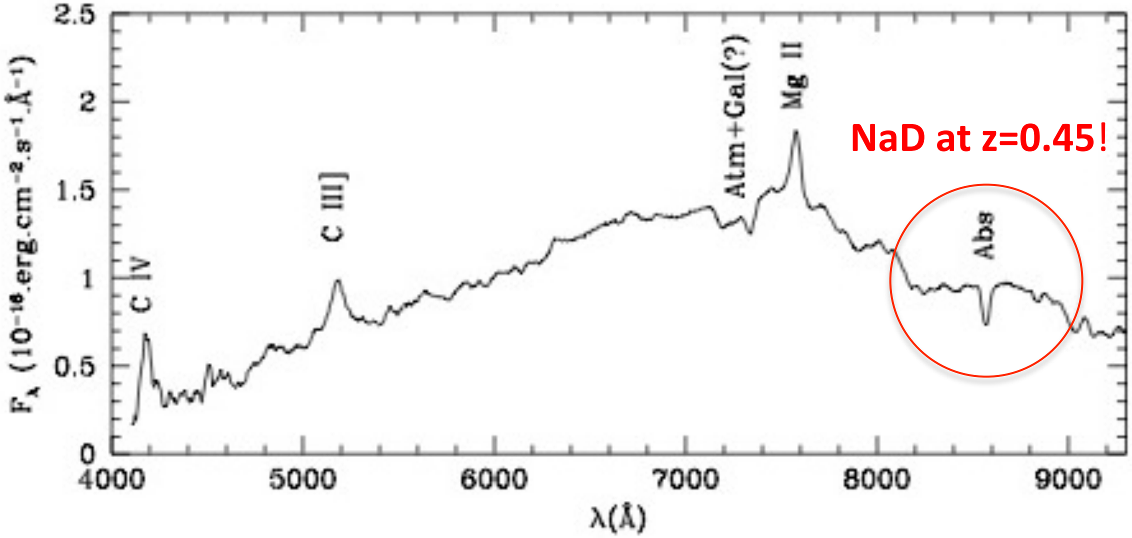
VLBI image: Ojha (2010)

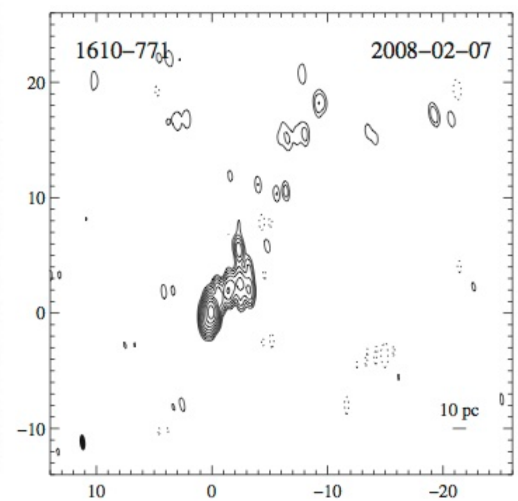
Unidentified absorption line at 8552 A

PKS 1610-77 optical spectrum

ASKAP spectrum



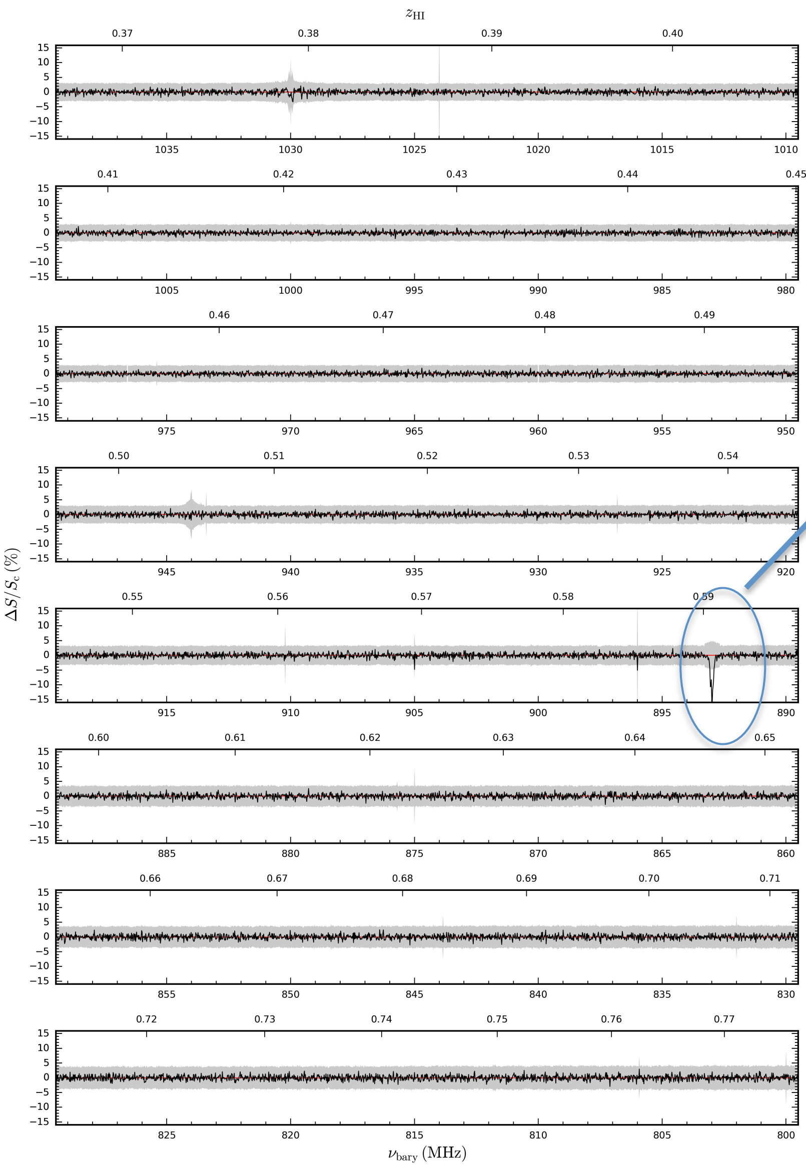


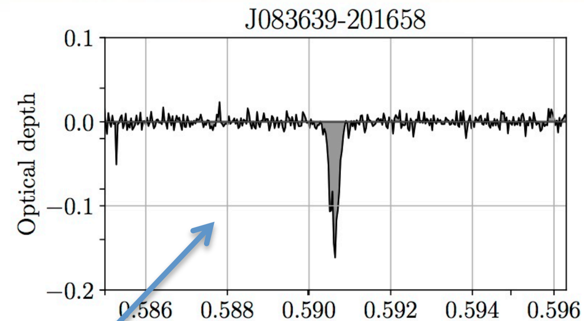


Optical spectrum: Courbin et al. (1997)

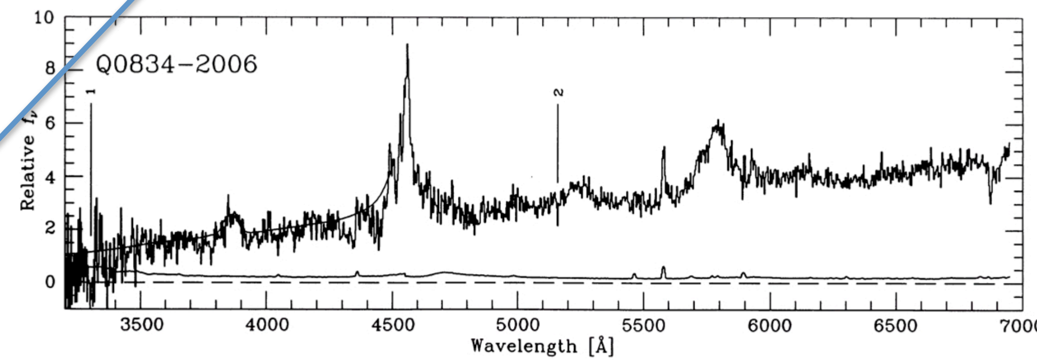
VLBI image: Ojha (2010)

New intervening absorber with ASKAP-12





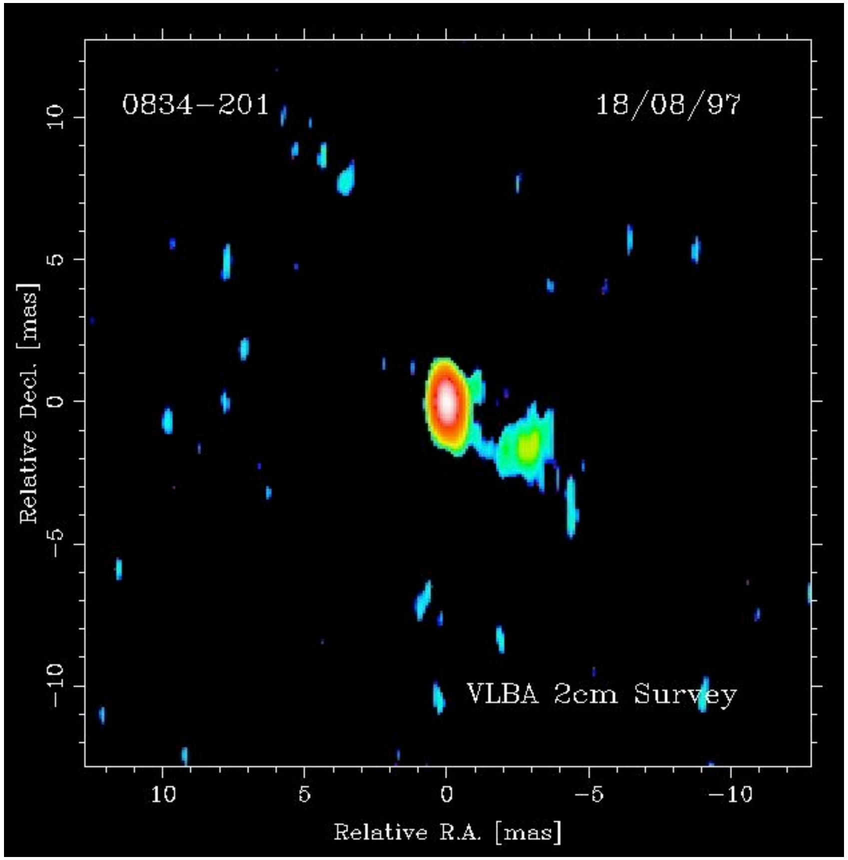
PKS 0834-20

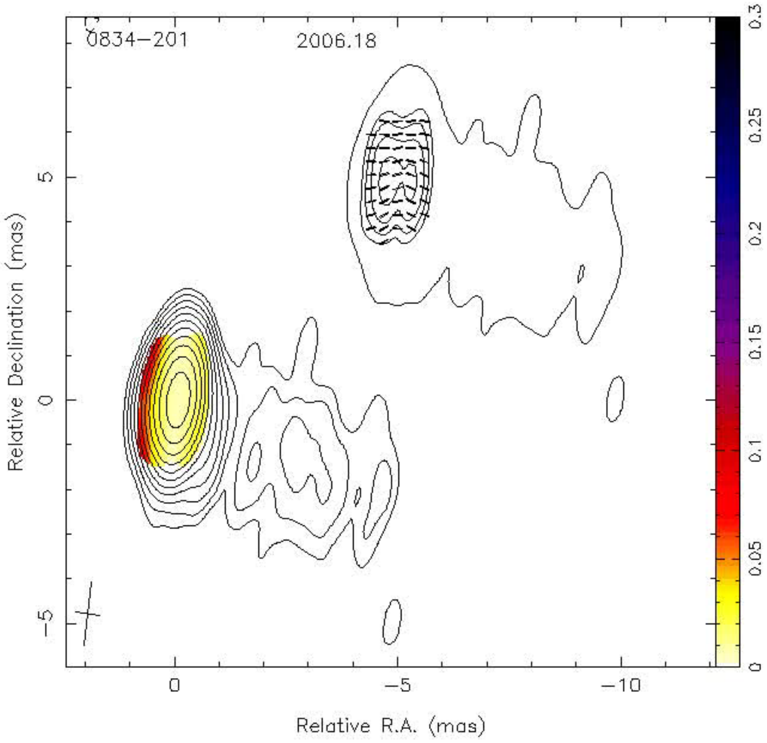


(Lanzetta et al. 1991)

Detection of neutral hydrogen in a galaxy at z=0.59 along the line of sight to a powerful QSO at z=2.7

PKS 0834-20: VLBI continuum

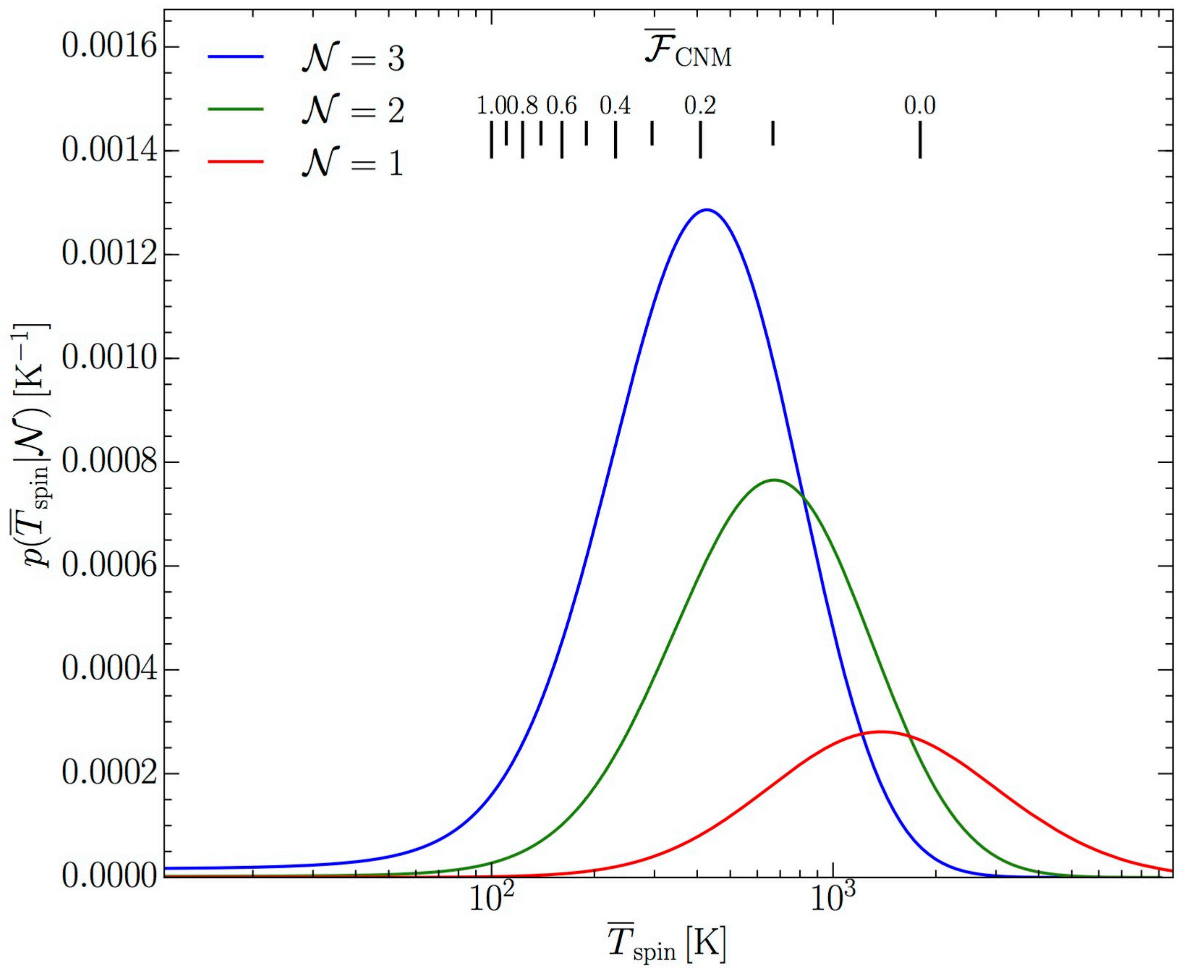




(Kellermann et al. 2004)

Detailed VLBA study by MOJAVE team (Lister et al. 2013)

Spin temperature estimate



Can now make a **spin-temperature estimate,** based on number of intervening lines detected.
(Allison et al. 2016, see James's talk yesterday)

<u>At z ~ 0.7:</u>
Ts ~ 300K,
CNM fraction ~ 20%

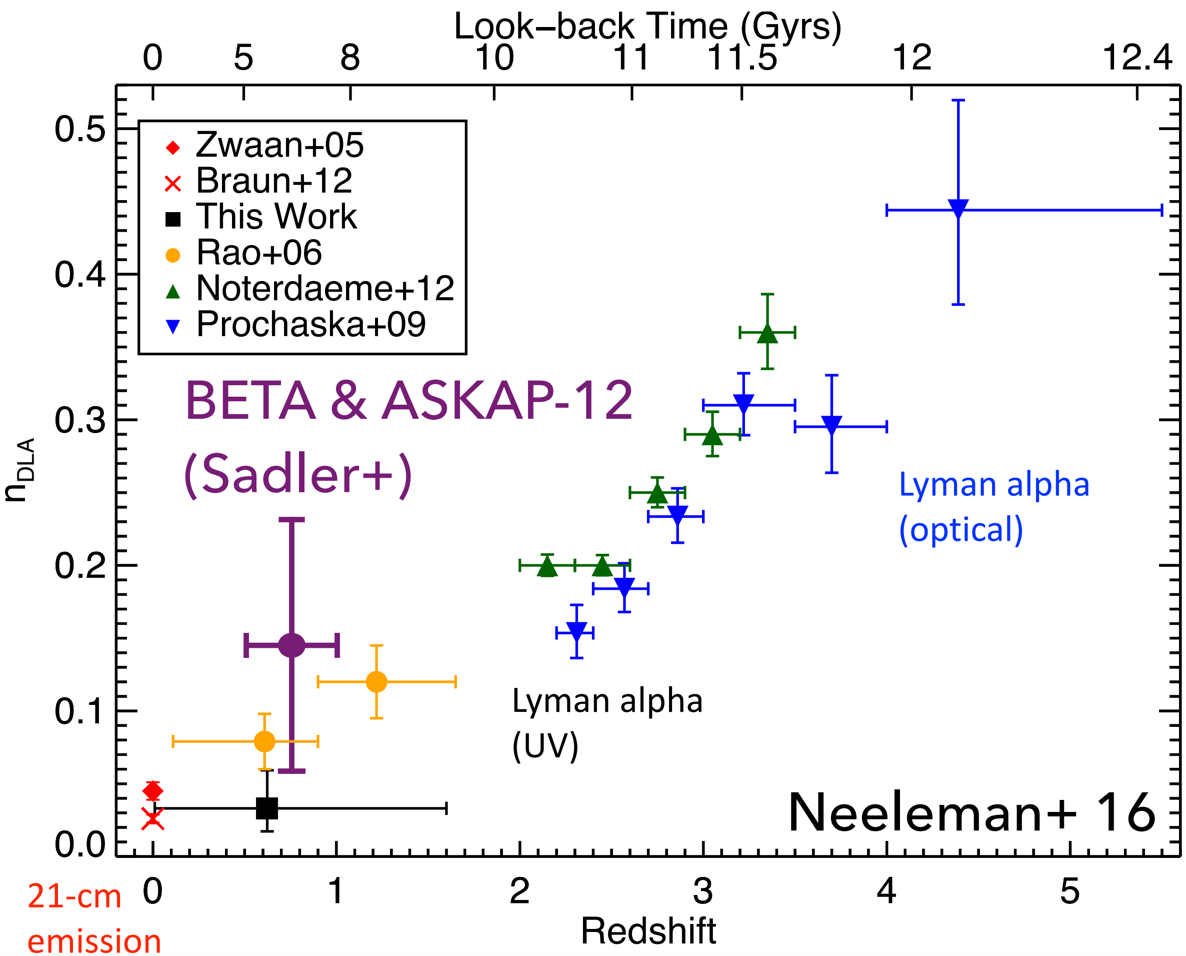
Estimated HI column density

	z (abs)	N_{HI} (T_s=100K)	N_{HI} (T_s=300K)
PKS 0834-20	0.591	1.3×10^{21}	3.9×10^{21}
PKS 1610-77	0.452	4.1×10^{20}	1.2×10^{21}
PKS 1830-211	0.886	2.0×10^{21}	6.0×10^{21}

(Assumes f = 1, uncertainties on N_{HI} are up to 20%)

i.e. Reasonable to assume that all these absorbers have HI column densities like those of optical DLA systems ($N_{HI} > 2 \times 10^{20}$ cm^{-2})

Results so far: DLA number density

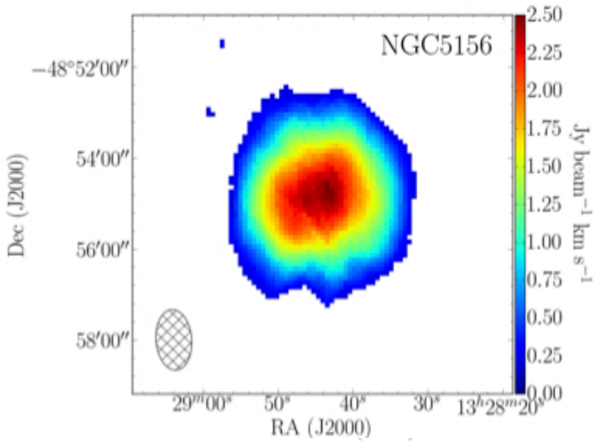


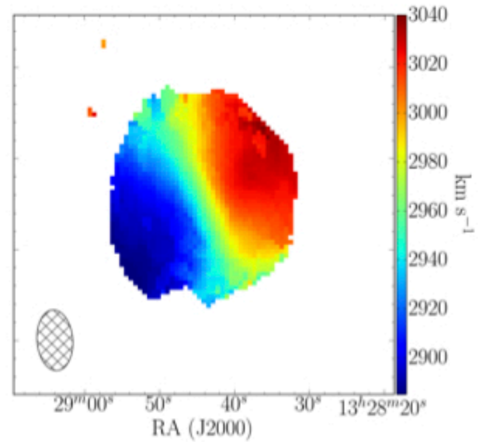
21cm DLA number density at z ~ 0.7 is *roughly consistent* (within the rather large error bars) *with the general trend of dN/dz* seen in optical DLA studies

Encouraging 'proof of concept' for future large surveys

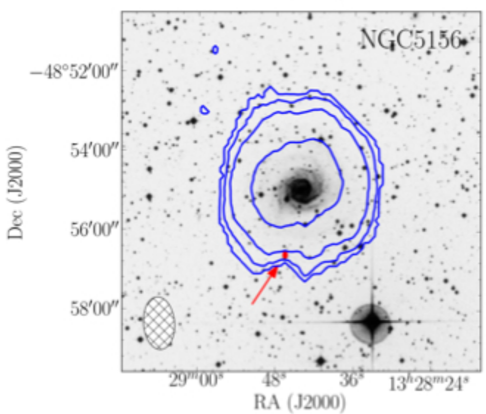
FLASH: Interpreting the data

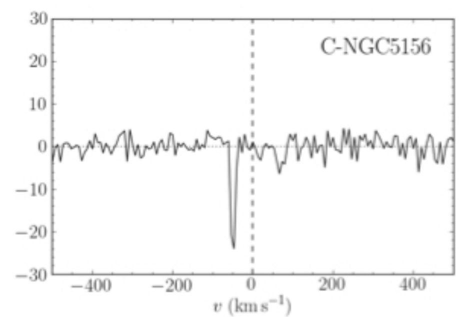
Challenge 1: Absorption-line data are highly "censored"
often have data along a single 'pencil-beam' sightline through a galaxy





Follow-up strategy:
- **ALMA CO line observations**
- Optical imaging/ IFU spectroscopy where feasible





z = 0.01
Impact parameter ~ 19 kpc
Ts/f ~ 950 K
(Reeves+ 2016)

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Interpreting the data

Challenge 2: Linking observed optical depth to HI column density

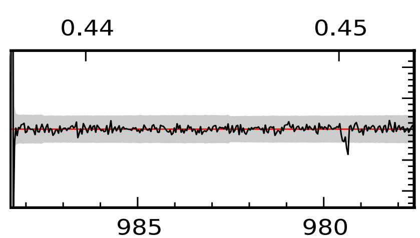
Radio 21cm measurements are particularly sensitive to cold HI (spin temperature T_S < 200K)

$$N_{HI} = 1.823 \times 10^{18} \, [T_s / f] \int \tau \, dV$$

- HI column density → N_{HI}
- HI spin temperature → T_s
- Covering factor → f
- Optical depth → τ

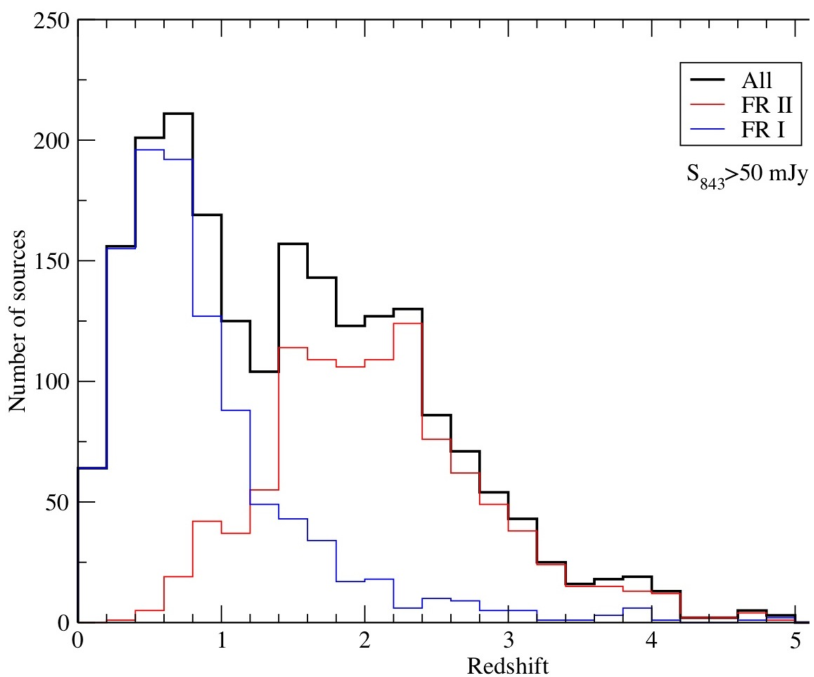
Follow-up strategy:

- **Ly-α spectroscopy** (HST, UV-bright QSOs)
- Statistical T_s estimates
- **Modelling** of full sample (SAM, hydro)
- **VLBI imaging** of sub-samples to estimate *f*



Interpreting the data

Challenge 3: Redshifts and small-scale structure of individual background continuum sources usually not known beforehand



Predicted redshift distribution for continuum sources brighter than 50 mJy at 843 MHz, from the SKADS simulated sky (Wilman+ 2008)

Follow-up strategy:

- Refine **characteristic redshift distribution** (esp. at z > 0.7)
- Optical/ALMA CO spectra of individual detections where possible
- Use **radio spectral index** as proxy for source compactness
- **Machine learning** techniques to distinguish intervening and associated lines?

Complementarity of HI surveys

Technique	Redshift	Measures	HI detection rate
HI emission-line survey **WALLABY**	z < 0.26	Individual galaxies	**Drops** with redshift
HI absorption-line survey **FLASH**	0 < z < 1.0	Individual galaxies/clouds	**Independent** of redshift
HI emission-line stacking **DINGO**	0 < z < 1.0	'Average' HI properties	Depends on redshift **and** the amount and quality of optical redshift data

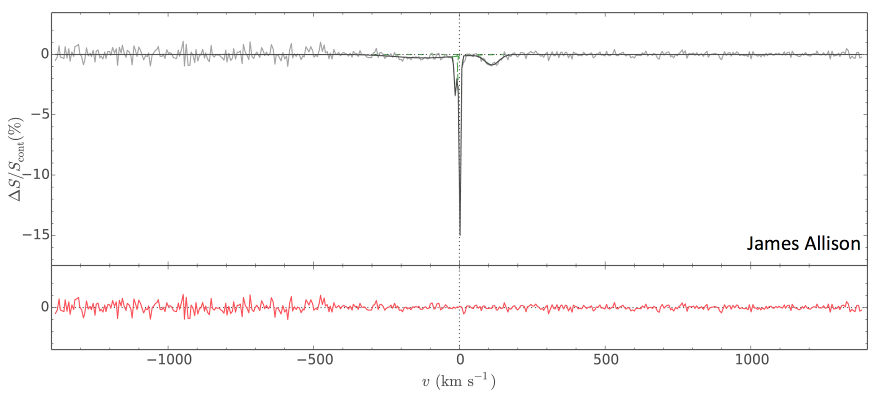
- Absorption surveys can tell us what *kinds* of galaxies (uv-bright? dusty?) dominate in an HI-selected galaxy sample at high redshift. Need to know this to design/interpret stacking surveys
- *Low-redshift data* (WALLABY at z < 0.26) are key to *cross-calibrating* all three methods

Future: Spectral-line VLBI?

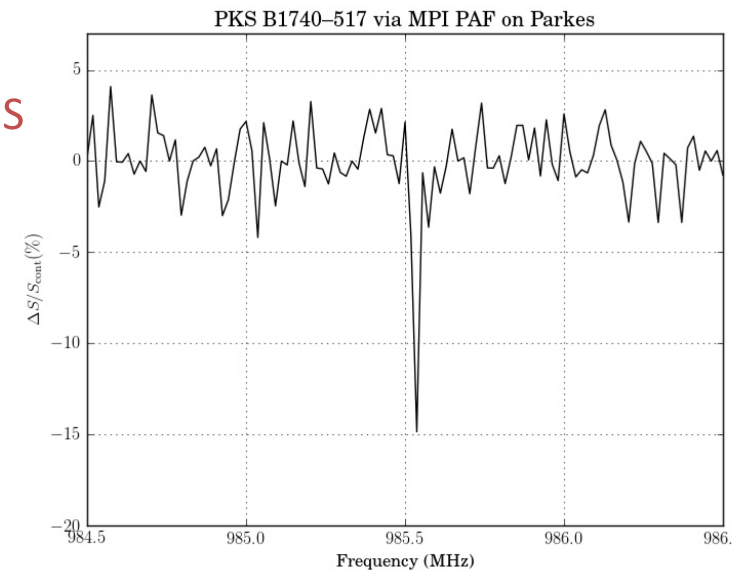
A phased-array feed (PAF) at Parkes operating down to 700 MHz opens up exciting possibilities for **spectral-line VLBI** on a PKS-ASKAP baseline.
Spatial resolution would be ~25 mas (0.025 arcsec) at 850 MHz, corresponding to ~180 parsec in an absorbing galaxy at z=0.7.

HI absorption at z = 0.44 in PKS 1740-517

ASKAP

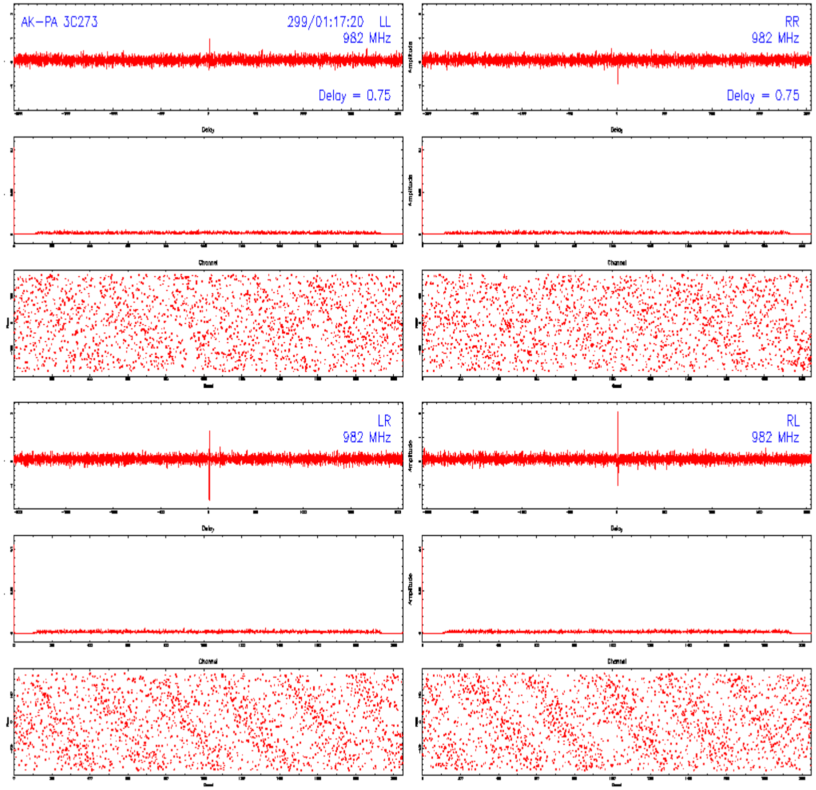


PARKES



Parkes-ASKAP VLBI with PAFs

Successful Parkes PAF – ASKAP PAF fringes, Oct 2016:
First VLBI observations with Phased Array Feeds



Opens the way for VLBI spectral-line observations of HI in the distant Universe

http://www.atnf.csiro.au/news/news.php?action=show_item&item_id=1571

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Summary

- HI absorption is an important probe of galaxy evolution out to high redshifts. The ASKAP-FLASH survey aims to assemble the first large **HI-selected galaxy sample at z > 0.4**
- Commissioning science observations with the BETA and ASKAP-12 arrays have already yielded new and encouraging results
- ASKAP data will all be public, and collaborations are welcome!