The ASKAP FLASH survey in 2019: Progress and challenges

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Overview

What I'll talk about:

- Motivation for the FLASH survey, and the 2009 survey plan
- Challenges for 'blind' large-area surveys
- What we've learned so far
- MWA IPS results, and relevance to the FLASH survey
- Next steps with ASKAP

Collaborators in this research include:

James Allison, Stephen Curran, Sara Ellison, Bjorn Emonts, Katinka Gereb, Marcin Glowacki, Elizabeth Mahony, Raffaella Morganti, Vanessa Moss, Sarah Reeves, Matt Whiting, Martin Zwaan

and members of the ASKAP FLASH and ACES teams

Why a radio 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*

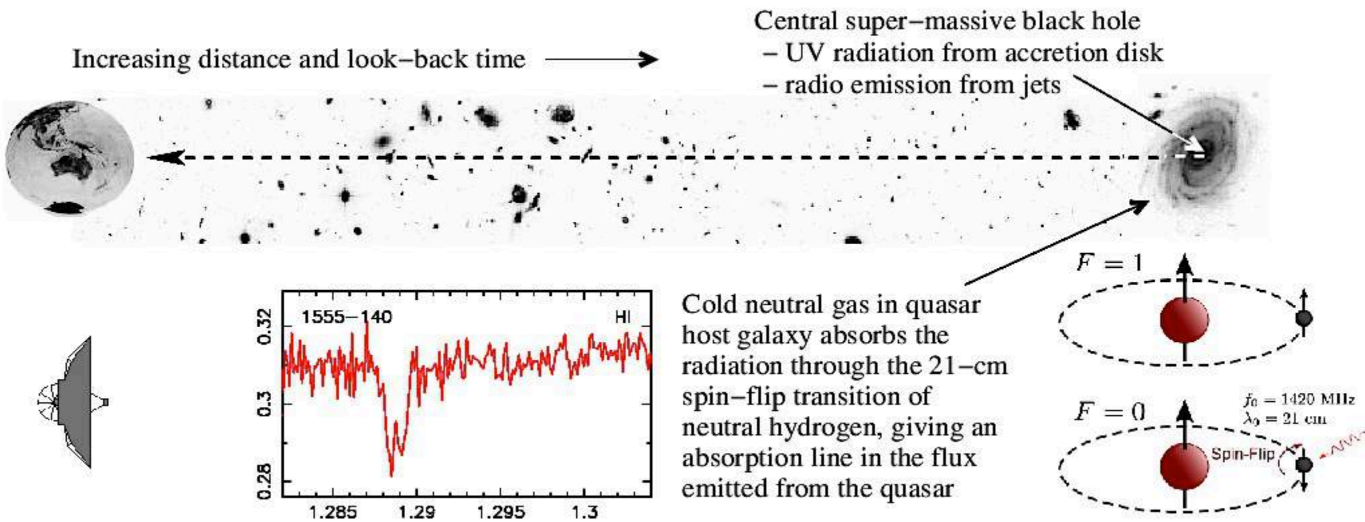

Image: S. Curran

Intervening absorbers: Cosmic evolution of HI in galaxies
Associated absorbers: AGN fuelling and feedback

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FLASH: The First Large Absorption Survey in HI

ASKAP-FLASH

FLASH Team:

50 members from 24 institutions in 10 countries

PIs : James Allison (Oxford)
Elaine Sadler (Sydney)

Our goal:

- Use ASKAP to probe the neutral hydrogen (HI) content of individual galaxies in the redshift range **$0.4 < z < 1.0$** (look-back time 4-8 Gyr)
- *Test current galaxy evolution and mass assembly models* in this redshift range

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

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The advantages of ASKAP

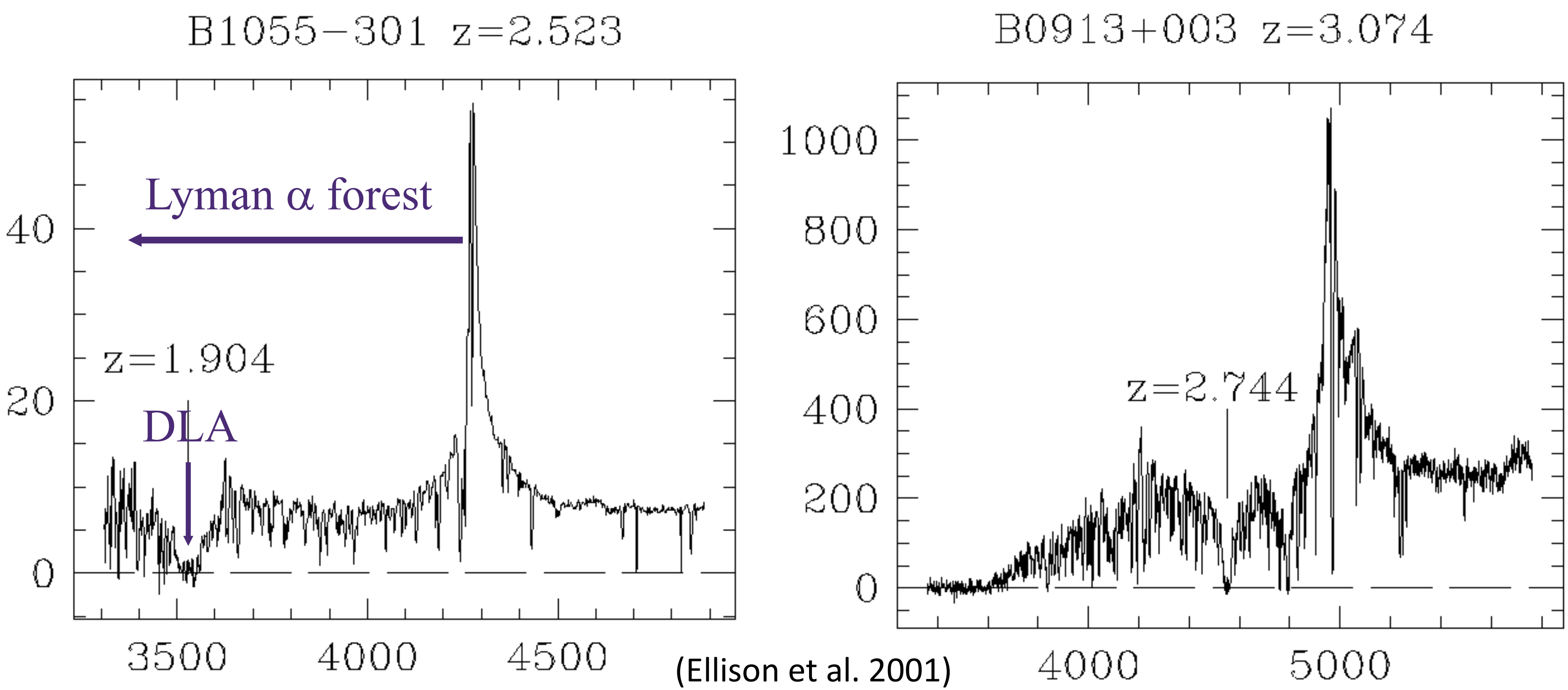
ASKAP's

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

make it possible to carry out the first *blind* large-area radio survey for HI absorption

Strategy: **All-sky survey in HI absorption!** In 2-3 months of observing time, FLASH can target over 150,000 sightlines to bright background continuum sources across the whole southern sky - *an increase of more than two orders of magnitude over previous 21cm HI absorption searches.*

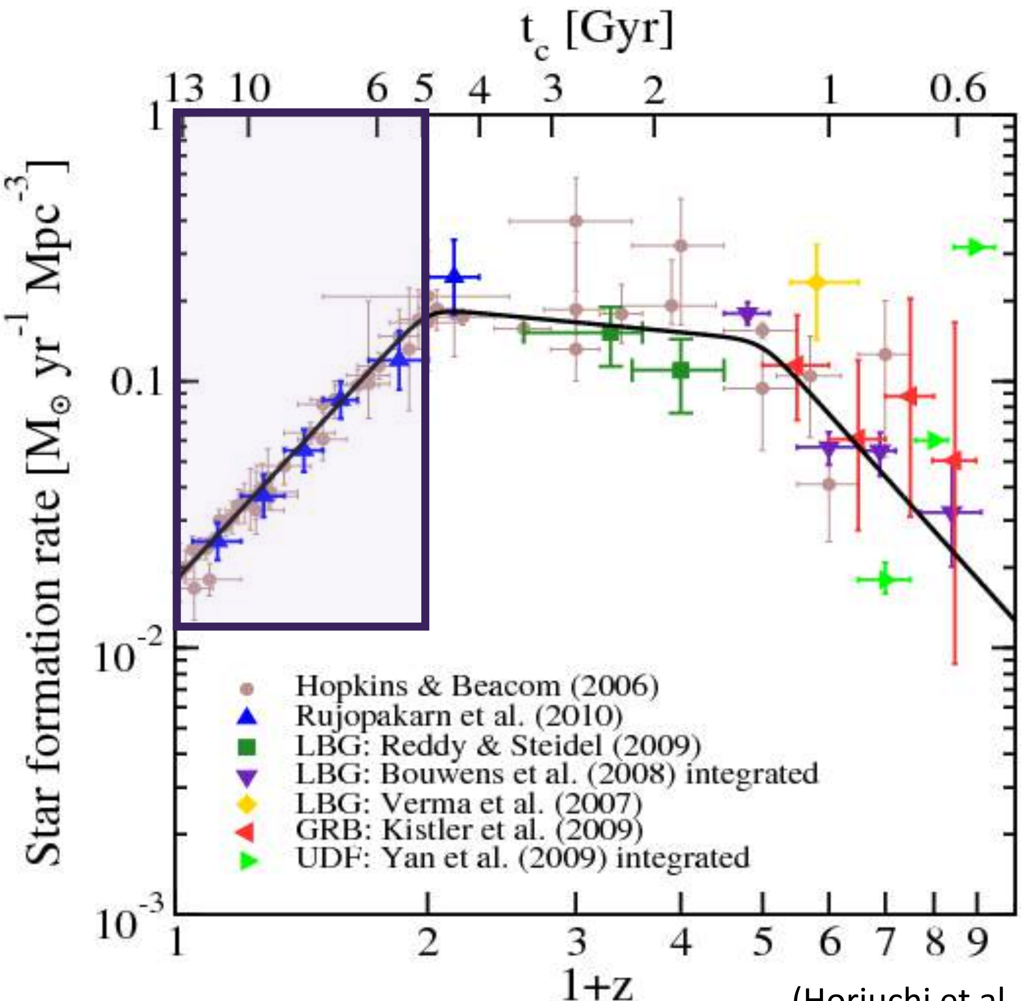
Optical: Damped Lyα Absorbers



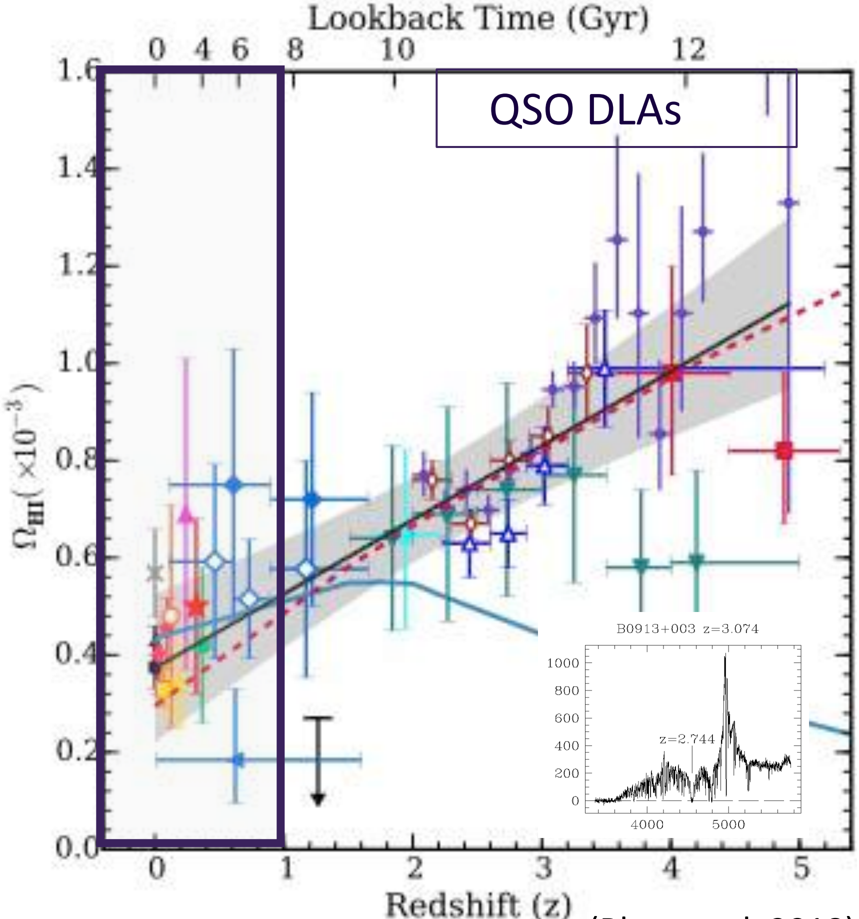
(Ellison et al. 2001)

DLAs: Intervening absorbers with high HI column density ($N_{HI} > 2 \times 10^{20}$ cm^{-2}).
Equivalent width of Lyman-α line gives a **direct measurement** of HI column density N_{HI}.

Neutral gas and galaxy evolution



(Horiuchi et al. 2010)



(Rhee et al. 2018)

Cosmic star-formation rate

Cosmic HI mass density

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

Technical requirements (2009 proposal)

	FLASH	WALLABY piggyback
Survey area (deg^2)	25,000	20,000
Observing freq. (MHz)	700-1000	1130-1430
HI redshift range	$0.4 < z < 1.0$	$0 < z < 0.26$
Angular resol. (arcsec)	30	30
Spectral resol. (kHz)	18	18
Bandwidth (MHz)	300	300
Integration time per field (hr)	2	8
Total obs. time (hr)	1600	*(9600)*
Expected detections	~470	~480

Also: Need the final calibrated channel-to-channel spectral response over the bandpass to be uniform to within 0.5%

Challenges for large multi-object HI surveys

Challenge 1: Linking observed optical depth (τ) to HI column density (N_{HI}) – need to know Tspin, *f*

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

$$N_{HI} = 1.823\times10^{18}\ [Ts\ /\ f] \int \tau\ dV$$

HI column density

HI spin temperature

Covering factor

Optical depth

Challenge 2: Redshifts (and structures) of individual continuum sources are generally unknown

- How many are background sources?
- What is the typical covering factor?

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Timeline

Period	Activity
2009-2010	Proposal submitted, FLASH selected as one of 10 ASKAP Survey Science Teams
2011-2014	Development of line finder and analysis pipeline, tests with ATCA at z < 0.12, HIPASS line search
2015-2017	Commissioning observations with 6-12 ASKAP antennas (1-9 beams), bright targets
2018	Early Science observations (12 antennas, 36 beams), measure all bright sources in field
2019	ASKAP Pilot surveys (36 antennas, 36 beams, 200hr), all sources in field
2020	Start full FLASH survey

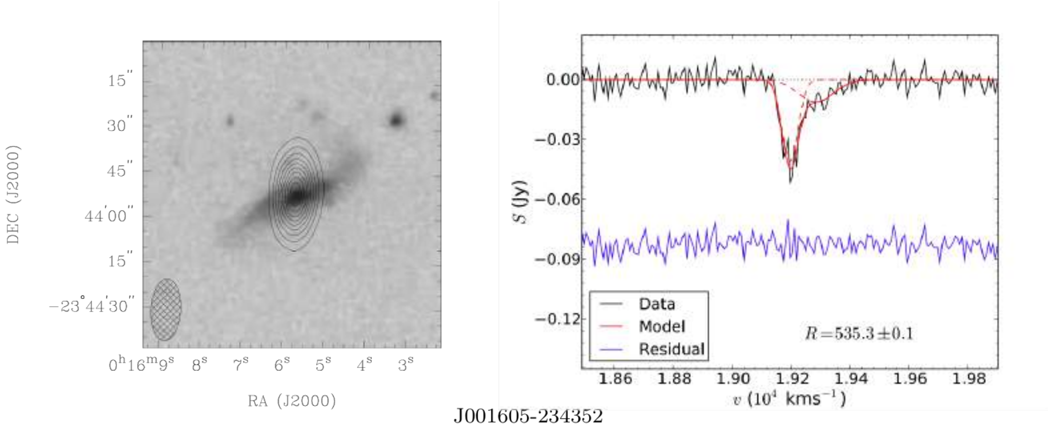
This talk (2011-2014, 2015-2017)

James Allison's talk (2018)

Next steps (2019, 2020)

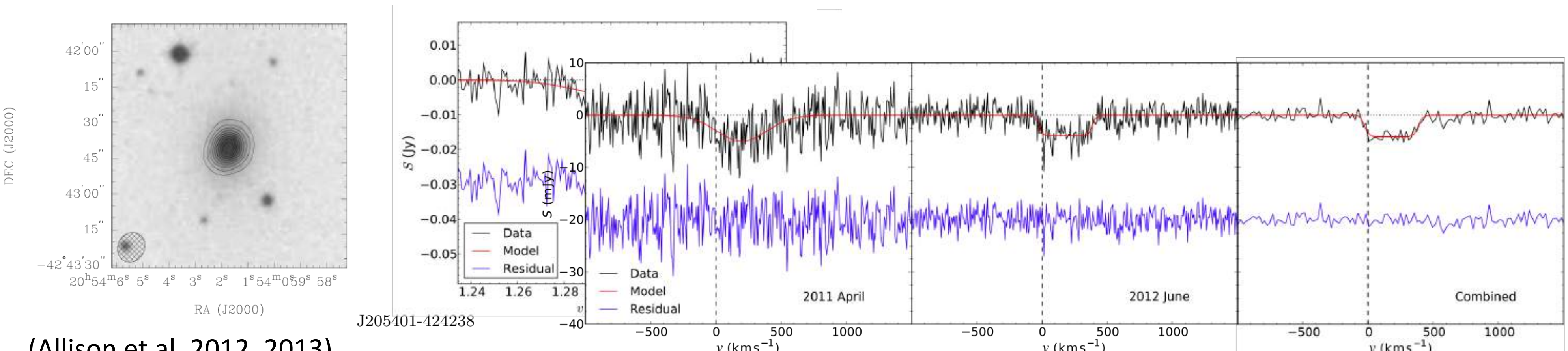
Testing the automated line finder

ATCA observations 2011-13: HI absorption in nearby compact radio sources



Associated absorption:

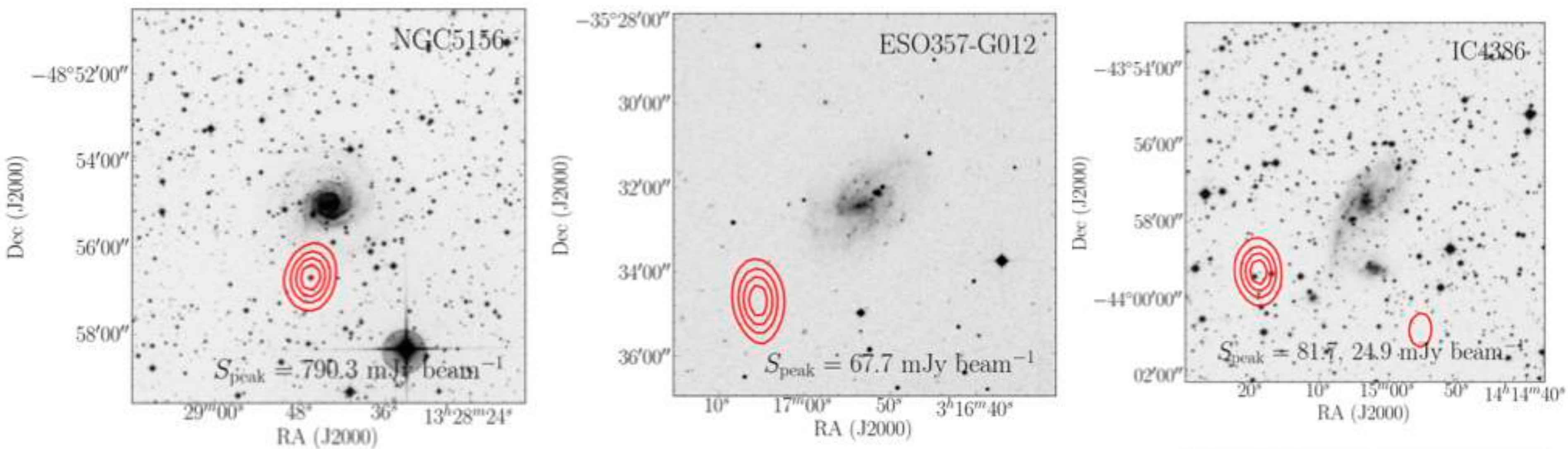
- HI detection rate ~10%, mixture of early- and late-type galaxies.
- One detection of an unusually broad and shallow line.



(Allison et al. 2012, 2013)

ATCA: low-redshift intervening lines

Sarah Reeves PhD thesis: Background radio sources behind 16 nearby gas-rich galaxies from HIPASS, impact parameter < 20 kpc



Searching for **intervening** absorption in nearby spiral galaxies with detected HI emission

(Reeves et al. 2015, 2016)

The effects of background source structure

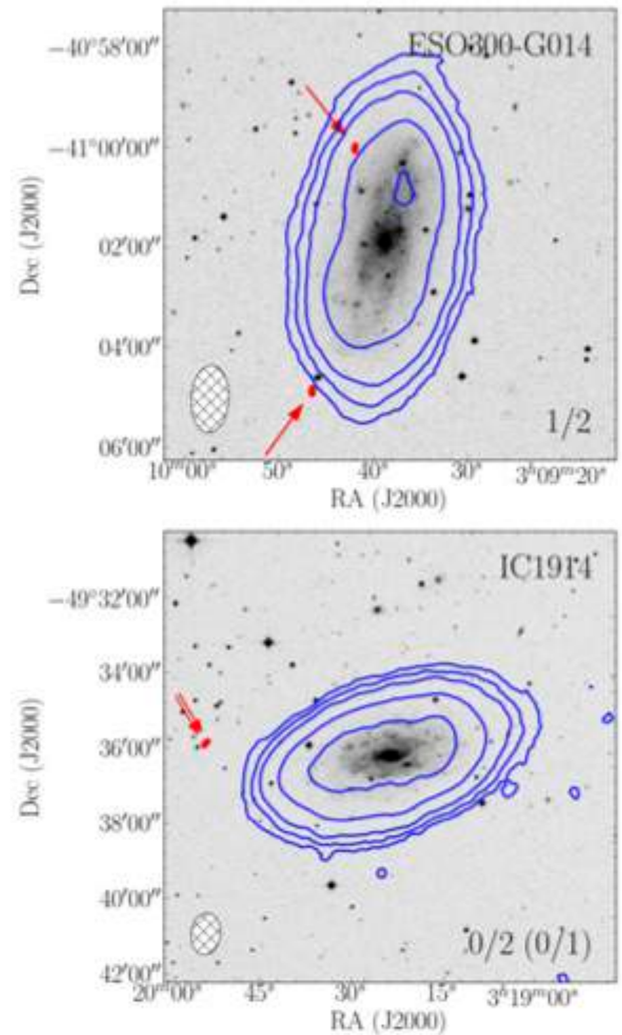
- Observed **16 galaxies**, with **23 sightlines** to background continuum sources
- Background continuum sources generally unresolved in SUMSS (45 arcsec beam)
- ATCA observations map HI emission, provide HI column density contours
- 7 arcsec ATCA beam for continuum sources

Results:

- 14/23 sightlines missed the HI disk

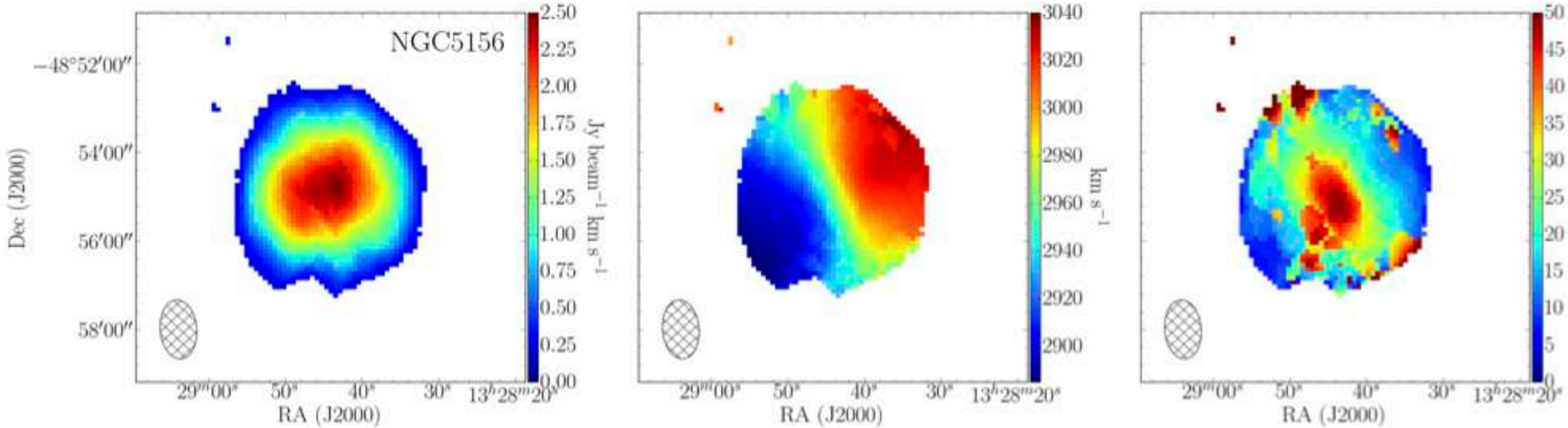
Of the 9 sightlines that intersected an HI disk:

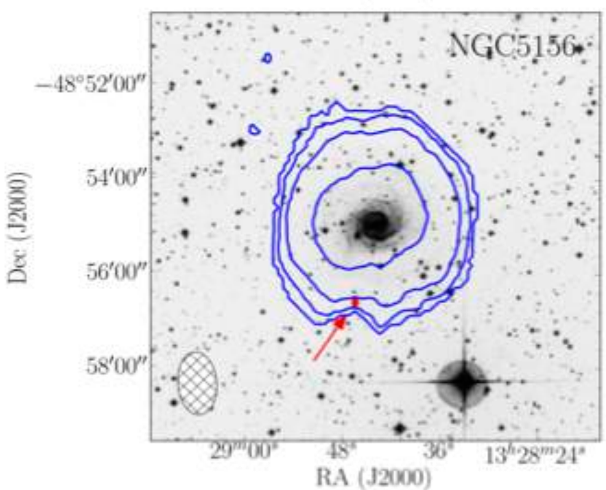
- **5/9 continuum sources were resolved by ATCA** (i.e ~50% of sources had lower peak flux density than expected)
- 3/9 objects were bright sources with no detected line (Tspin/*f* >> 100 K)
- 1/9 with detected absorption (NGC 5156)

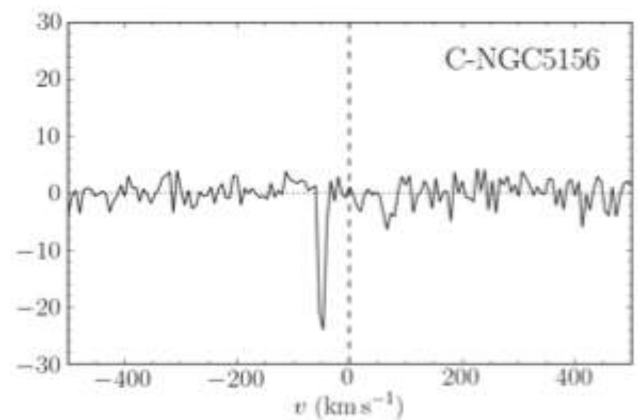


(Reeves et al. 2016)

HI absorption in a nearby spiral: NGC 5156







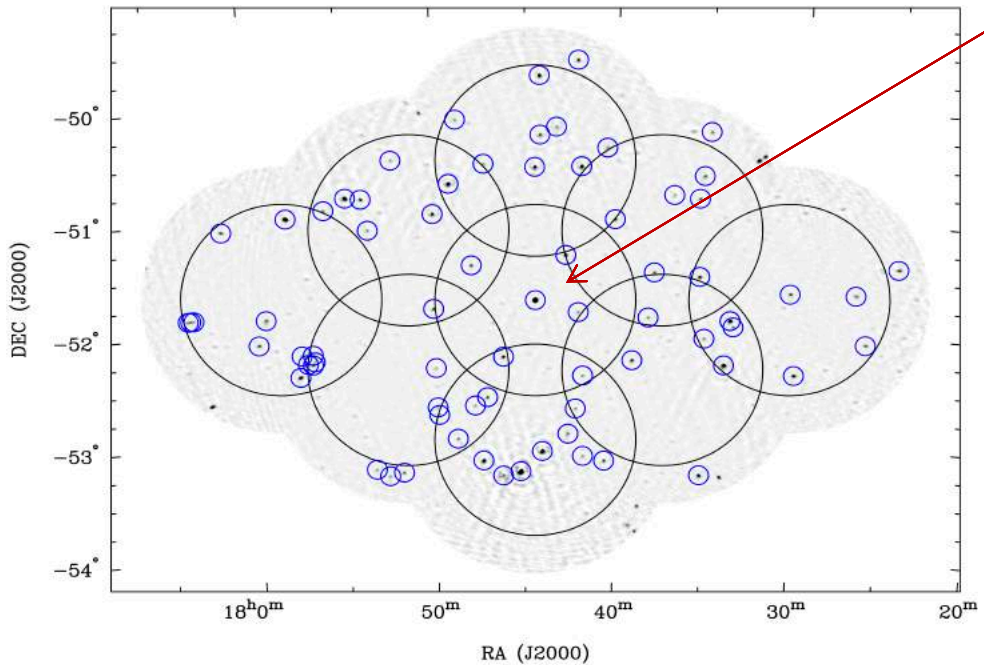
Intervening HI absorption line 19 kpc from the centre, source is a 2.6" double:

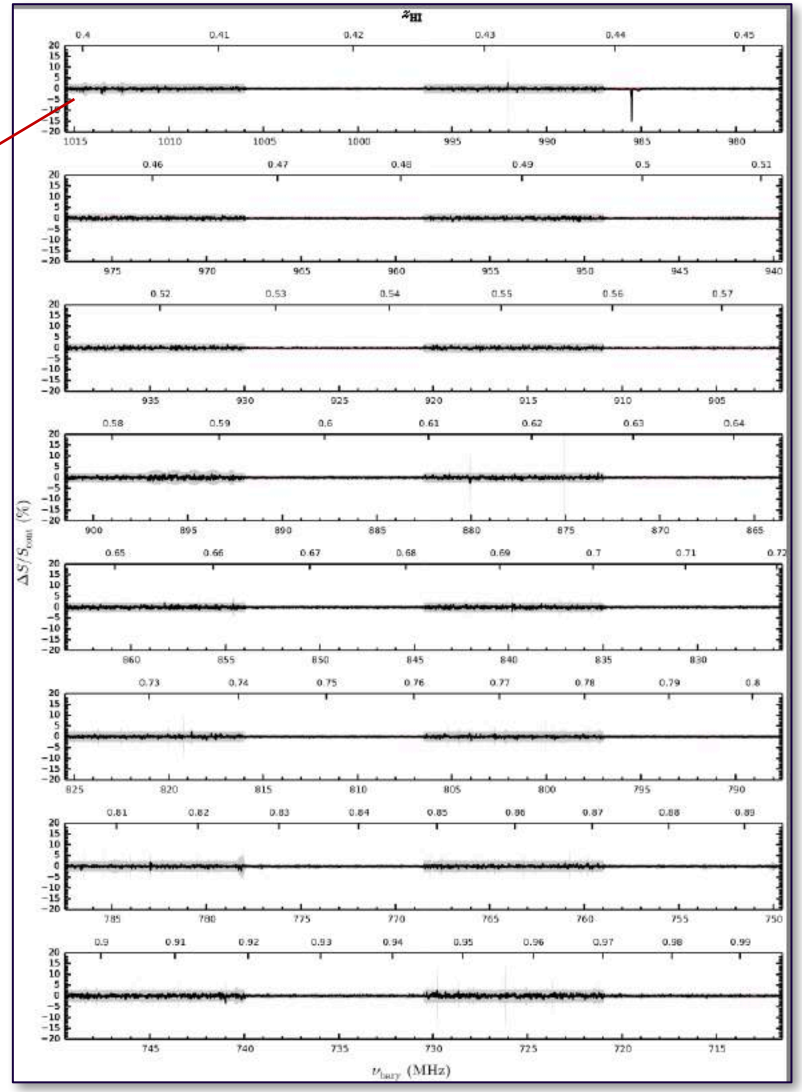
- Line width 7.2 km/s
- Int. τ = 0.82 km/s
- Ts/*f* ~ 950 K (*f* < 0.5?)

ASTROPHYSICS IN 3D (Reeves et al. 2016)

ASKAP commissioning data

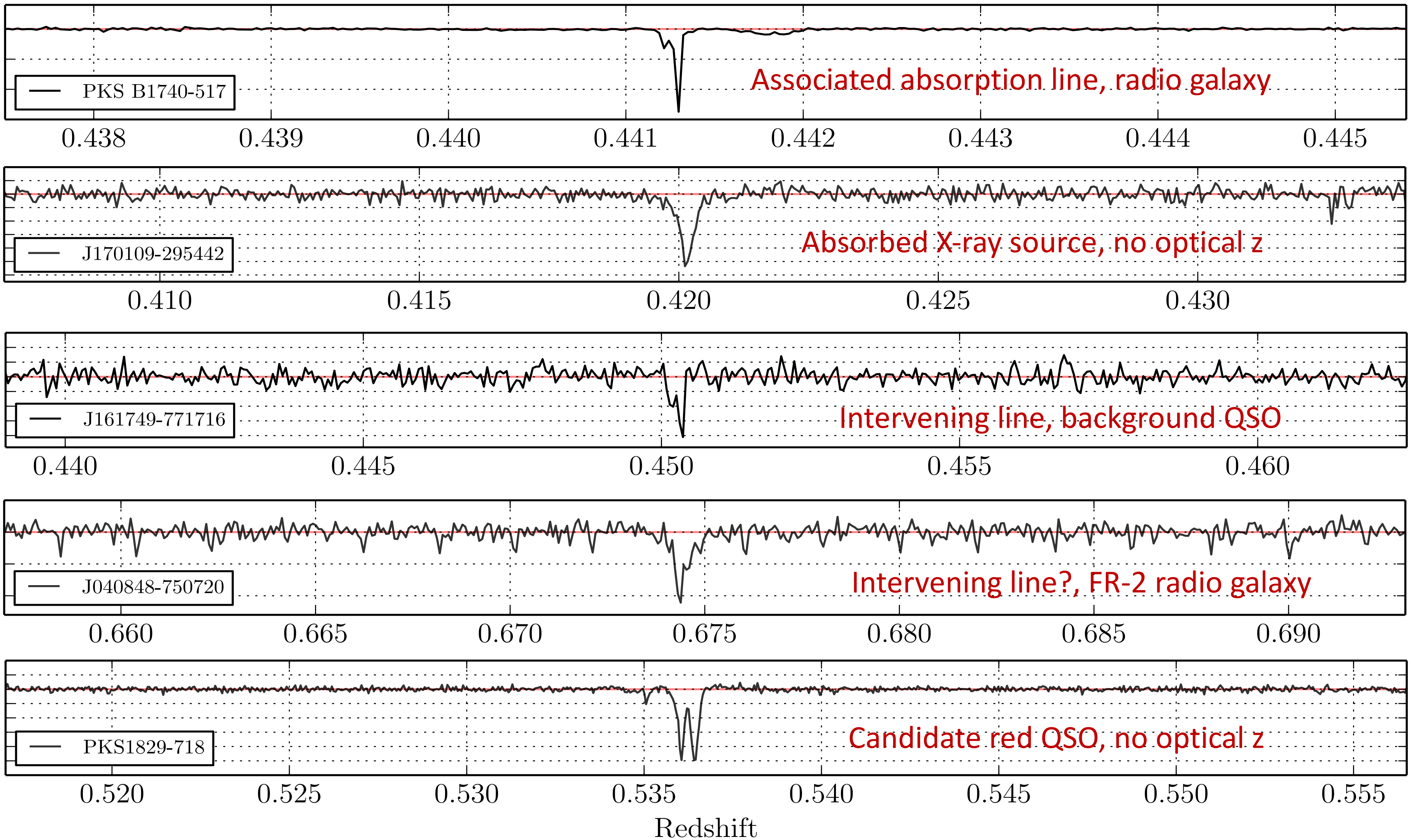
- 711.5-1015.5 MHz Band
- 16,416 x 18.5 kHz (~5 km/s) channels





ASKAP band 1 spectrum is completely free of RFI!

New HI detections (ASKAP commissioning)

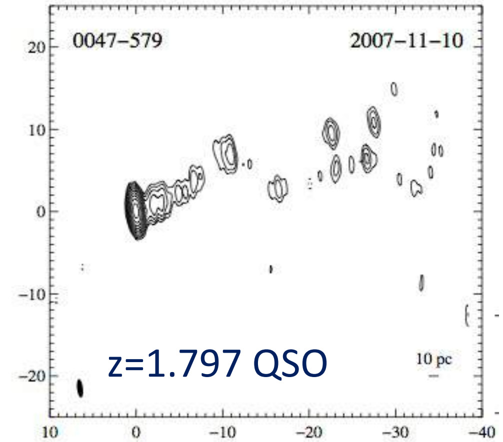


ASKAP pilot intervening source sample

ASKAP commissioning observations 2016-17 (with 6-12 antennas)

Radio flux-limited sample of 53 sources:

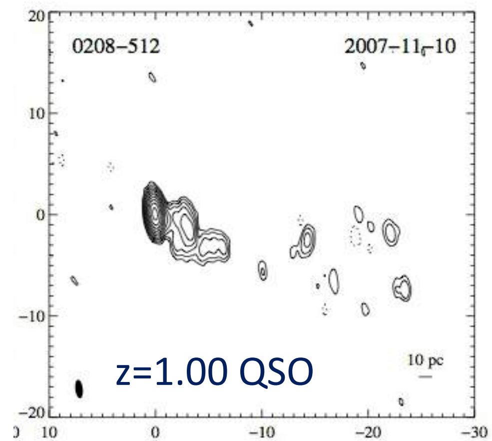
- Flux density > 1.5 Jy at 1 GHz *and* > 0.5 Jy at 20 GHz
- Redshift z > 0.4 *or* no published z
- Declination south of 0 deg
- Many with 8 GHz VLBI images (Ojha et al. 2010)



Redshift distribution:

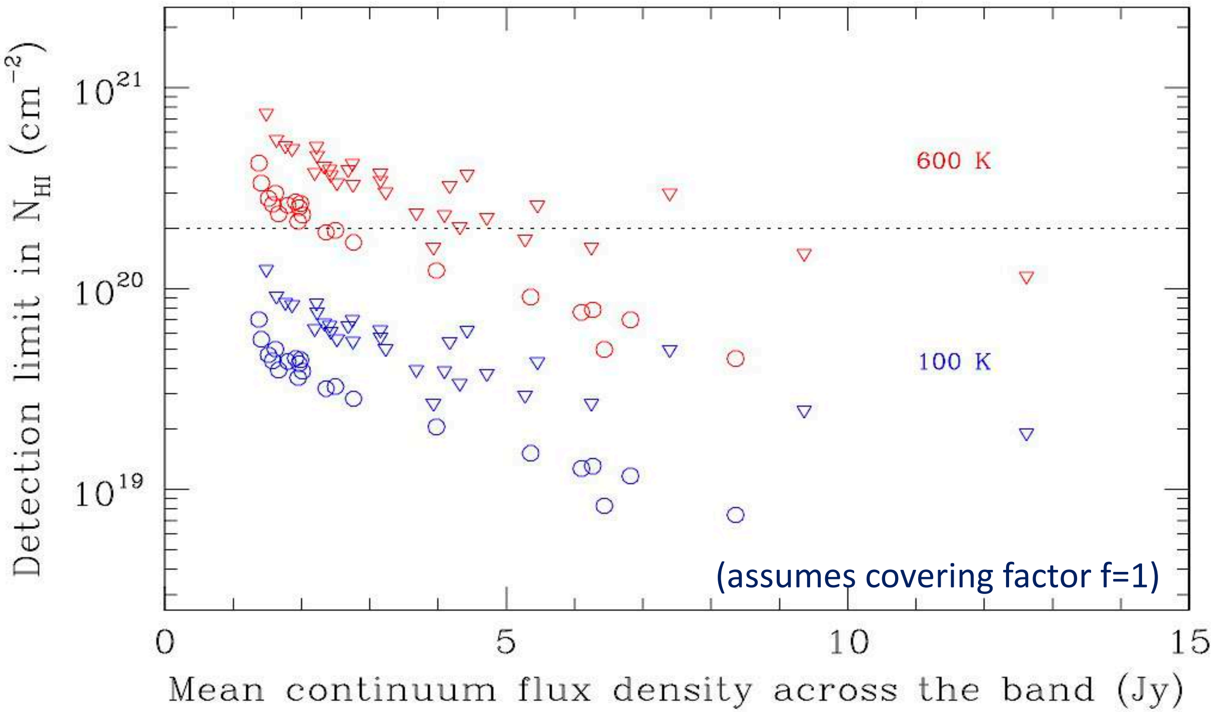
- 35 with z > 1.0
- 14 with 0.4 < z < 1.0
- 4 with no reliable redshift

<u>Total redshift path length Δz = 21.4</u>



Detection limits in HI column density

Targeted observations of 53 bright sources



Our ASKAP pilot study: Sensitive to DLA-like HI column densities for cool neutral gas (spin temperature Ts < 200-300 K).

Optical depth and HI column density:

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

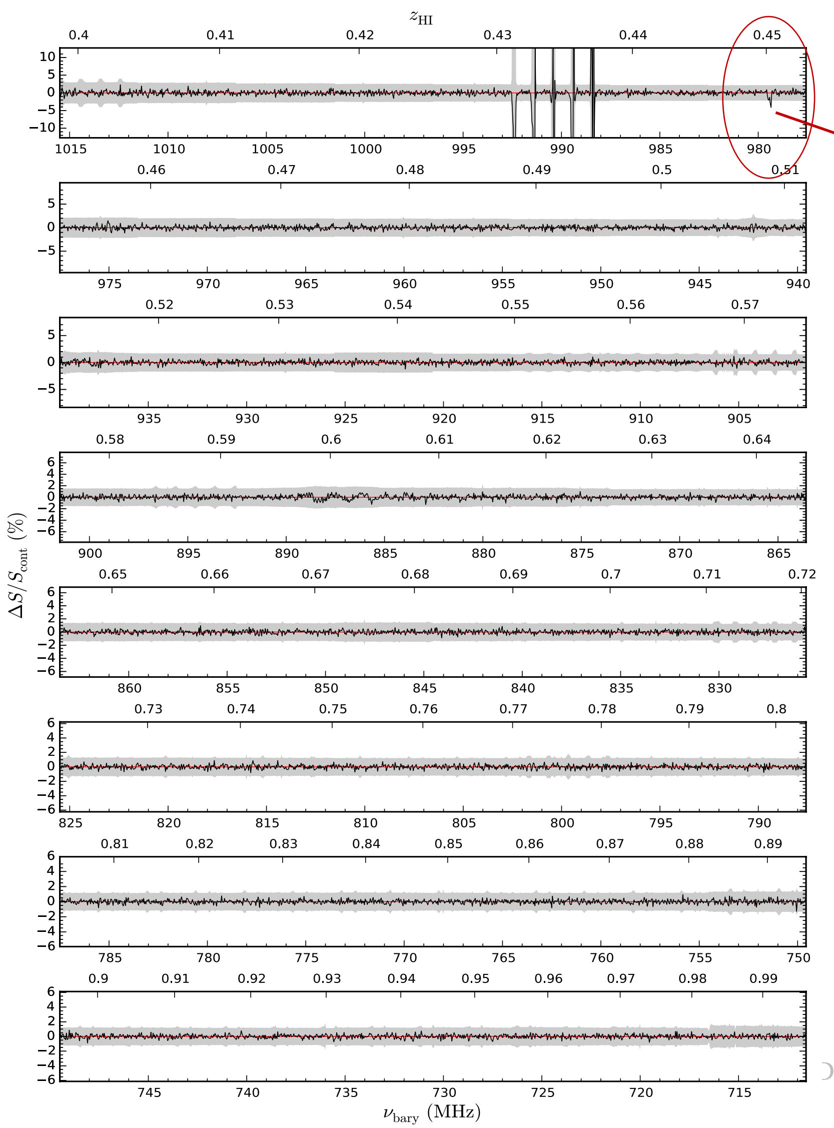
Probability of intercepting a DLA system (N_{HI} > 2 x 10^{20} cm^{-2}) on a random sightline:

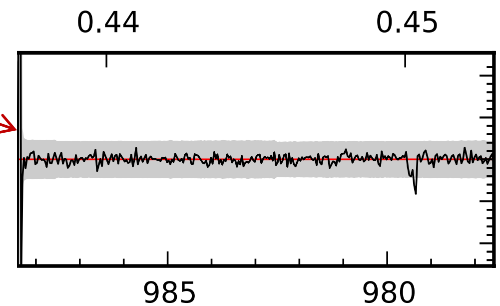
$$dN/dZ = 0.055\ (1+z)^{1.11}$$

(Storrie-Lombardi & Wolfe 2000)

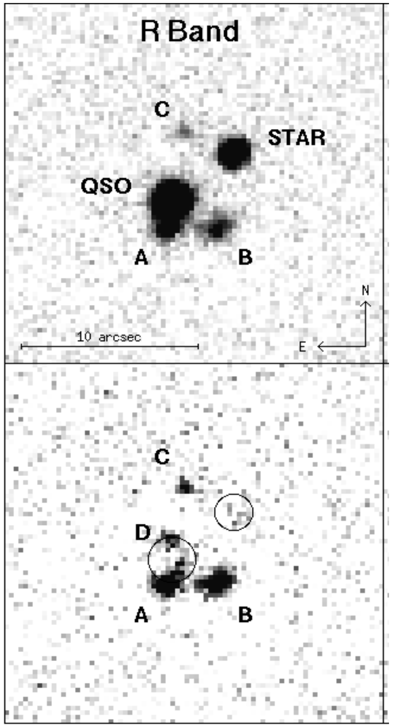
i.e. ~6% for z=0.7, 300 MHz

New intervening detection: PKS 1610-77





Important 'proof of concept' for the FLASH survey!

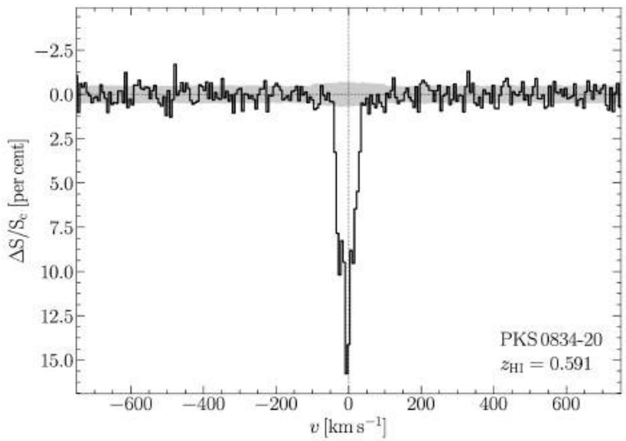


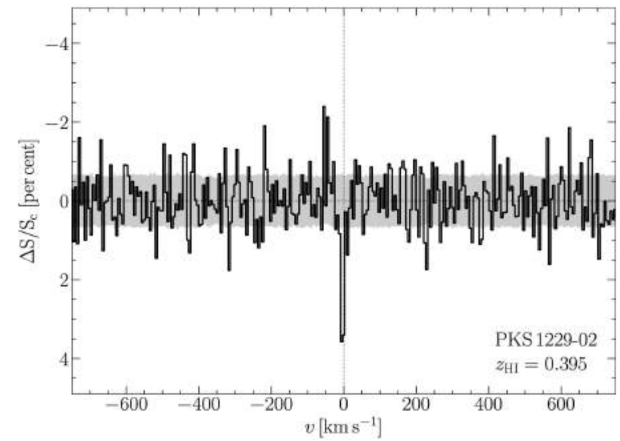
Detection of neutral hydrogen in a distant galaxy at z=0.45, along the line of sight to a powerful QSO at z=1.71

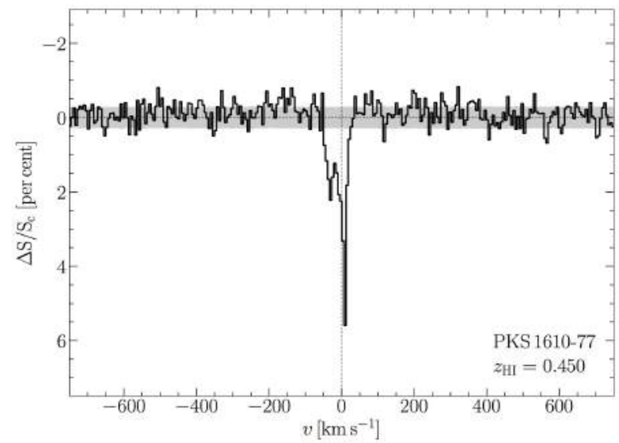
Optical images from ESO NTT (Courbin et al. 1997)

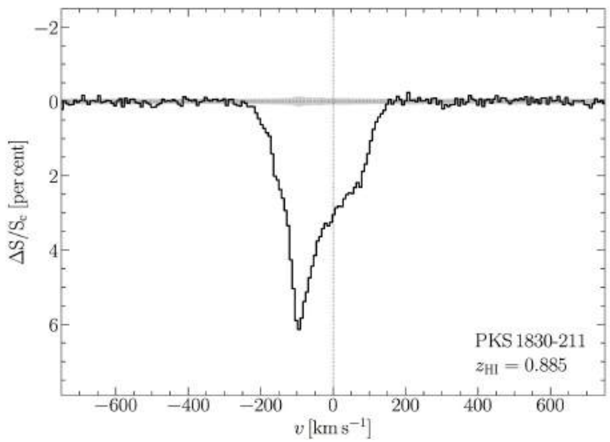
Gallery of intervening 21cm HI lines

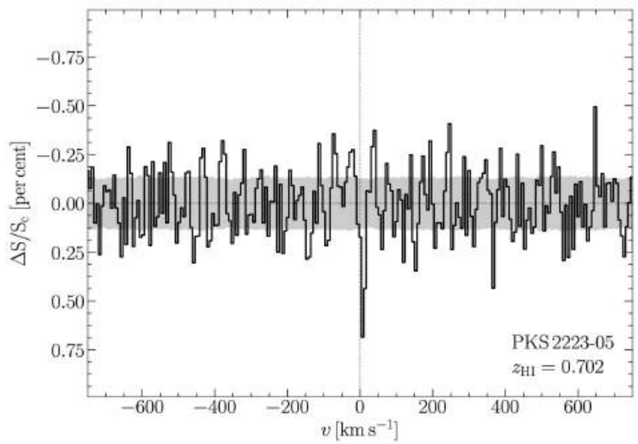
HI-selected galaxies at 0.4 < z < 0.9







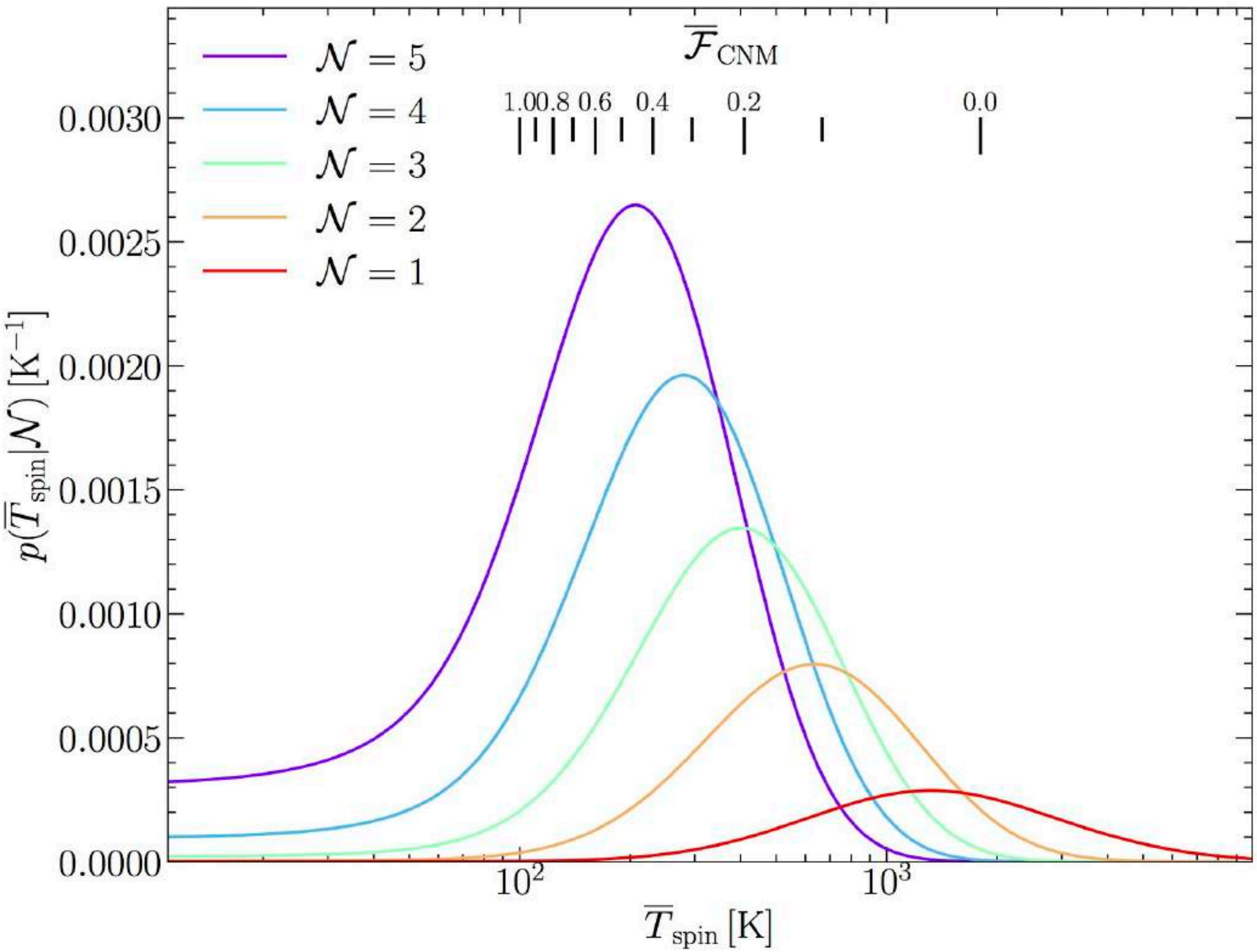




Results: 53 sightlines observed, five intervening HI abs. lines detected

- *How many of these have DLA-like HI column densities?*

Spin temperature estimate



Can estimate a characteristic **spin-temperature** based on number of intervening lines detected so far. (Allison et al. 2016)

At z ~ 0.7, estimate:
Typical Ts ~ 200K,
CNM fraction ~ 40%

Similar to Milky Way values!

Estimated HI column density

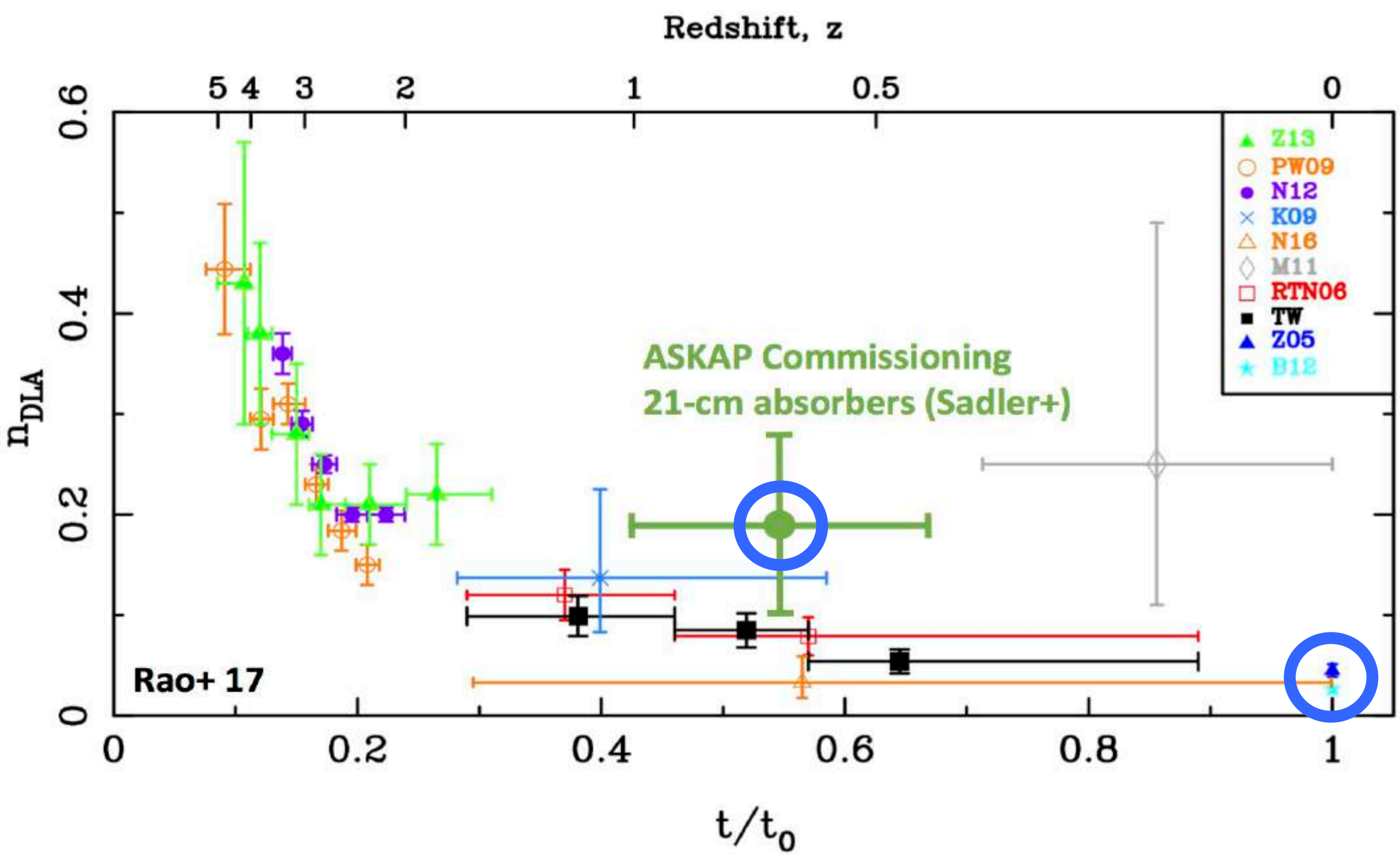
	z (abs)	N_{HI} (T_s=100K)	N_{HI} (T_s=300K)
PKS 0834-20	0.591	1.3×10^{21}	3.9×10^{21}
PKS 1229-02*	0.395	8.2×10^{19}	2.5×10^{20}
PKS 1610-77	0.452	4.1×10^{20}	1.2×10^{21}
PKS 1830-211	0.886	2.0×10^{21}	6.0×10^{21}
PKS 2223-05	0.702	1.4×10^{19}	4.5×10^{19}

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

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

HI DLA number density at z ~ 0.7

Preliminary result! 53 bright QSOs observed, redshift path length Δz ~ 21.4, five 21-cm lines detected (four with DLA-like column densities)



Large error bars for this small sample, but results appear broadly consistent with other work

Already the largest radio DLA survey in redshift path-length!

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Readiness checklist

Methodology:

1. **Automated line finder** – checked and working well ✓
2. **Uniformity and stability** of ASKAP spectral bandpass – excellent! ✓
3. **ASKAP sensitivity** – rms noise/spectral channel is ~50% higher than 2009 prediction ✓
4. **Detection rate** of intervening HI lines against bright compact sources – at least as high as predicted ✓

i.e. The FLASH survey originally proposed in 2009 is feasible as specified, possibly with increased integration time to compensate for slightly higher Tsys

Interpreting the data

Challenge 1: Linking observed optical depth (τ) to HI column density (N_{HI})

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

$$N_{\mathrm{HI}} = 1.823\times10^{18}\,[Ts\,/\,f]\int \tau\,\mathrm{d}V$$

HI column density

HI spin temperature

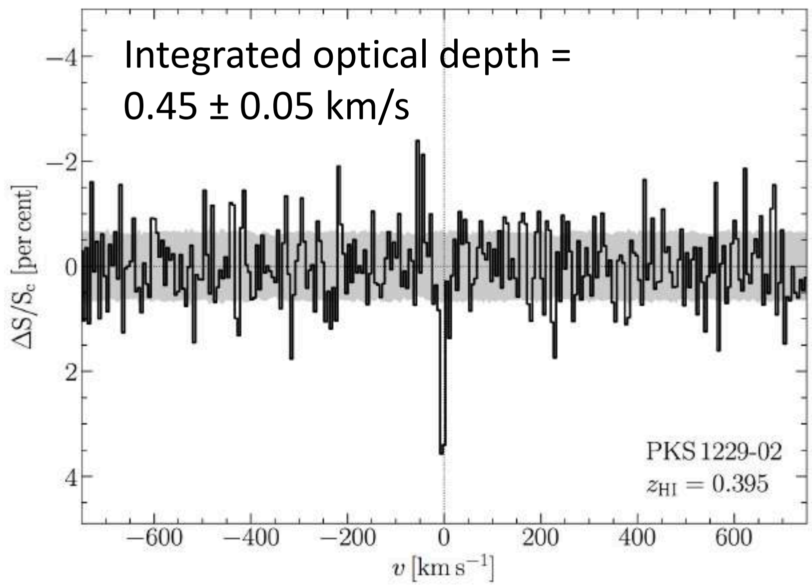
Covering factor

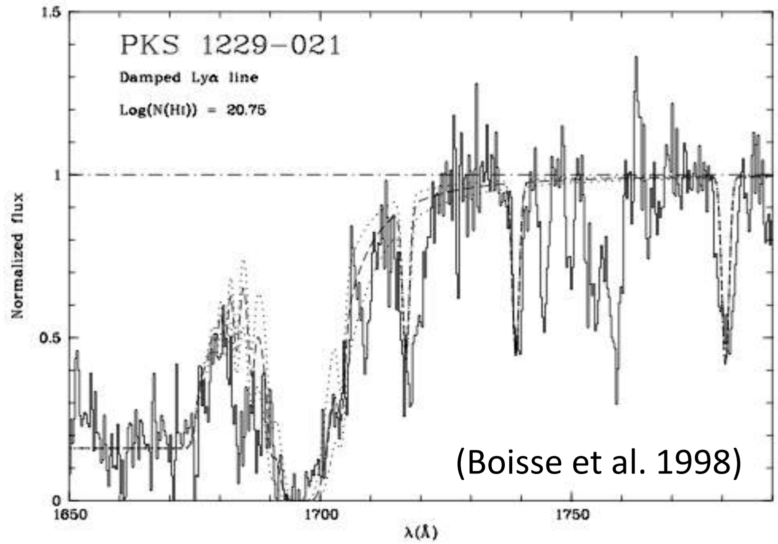
Optical depth

Possible strategies:

- **Ly-α spectroscopy** (HST, UV-bright QSOs)
- **Empirical** N_{HI} estimates (Braun 2012)
- **Statistical** T_s estimates (Allison et al. 2016)
- **VLBI imaging** of sub-samples to estimate *f*
- **Modelling** of full sample (SAM, hydro)

PKS 1229-02 – Tspin from HST DLA





PKS 1229-02: ASKAP re-discovery of known HI line at z=0.395 (Brown & Spencer 1979), MgII absorber seen in optical QSO spectrum. Boisse et al. (1998) measured N(HI) = 5.6 x 10^{20} cm^{-2} from HST Ly α line

For covering factor f = 0.42 (Kanekar et al. 2014), derive: Tspin = 286 K (+/- ~20%) for PKS 1229-02 intervening galaxy at z=0.395

N(HI) estimates for PKS 1229-02

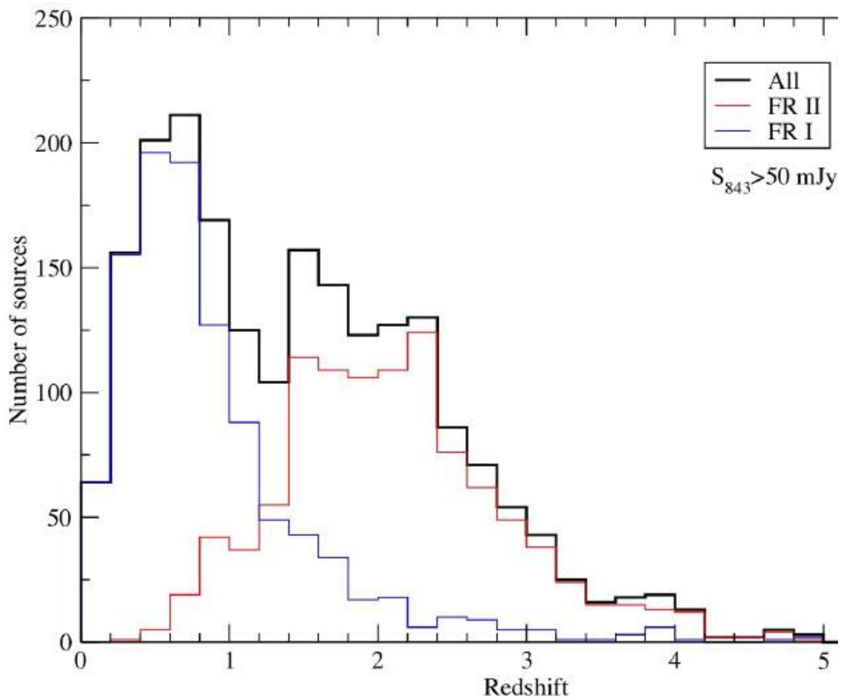
Measure: integrated optical depth of 0.45 ± 0.05 km/s

Technique	Derived HI column density	Notes
HST UV: Ly-α line (Boisse et al. 1998)	**5.6 x 10^{20} cm^{-2}**	For *f*=0.42, derive Ts= 286 K (+/- 20%)
Empirical estimate (Braun 2012)	**~ 4 x 10^{20} cm^{-2}**	Uses only the peak optical depth
Statistical estimate (Allison et al. 2016)	1.6 x 10^{20} cm^{-2} (*f*=1.0) **3.9 x 10^{20} cm^{-2} (*f*=0.42)**	Based on estimated Ts=200 K

i.e. For this object - reasonable consistency between empirical/statistical estimates of N(HI) and the value measured from Ly-α

Interpreting the data

Challenge 2: 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 et al. 2008)

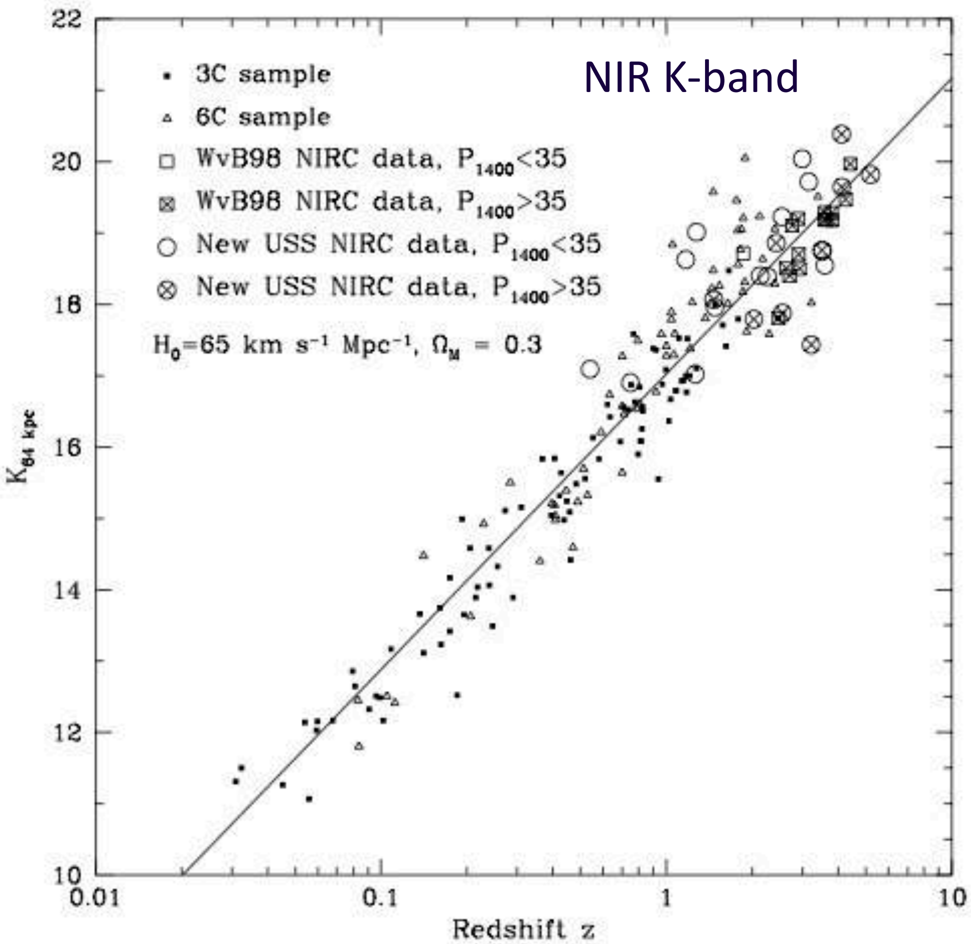
Follow-up strategy (redshifts):

- Refine **characteristic redshift distribution** (esp. at $z > 0.7$)
- Optical/ALMA CO spectra of individual detections where possible
- **Photo-z** estimates
- **Machine learning:** separate intervening and associated lines (Curran et al. 2016)

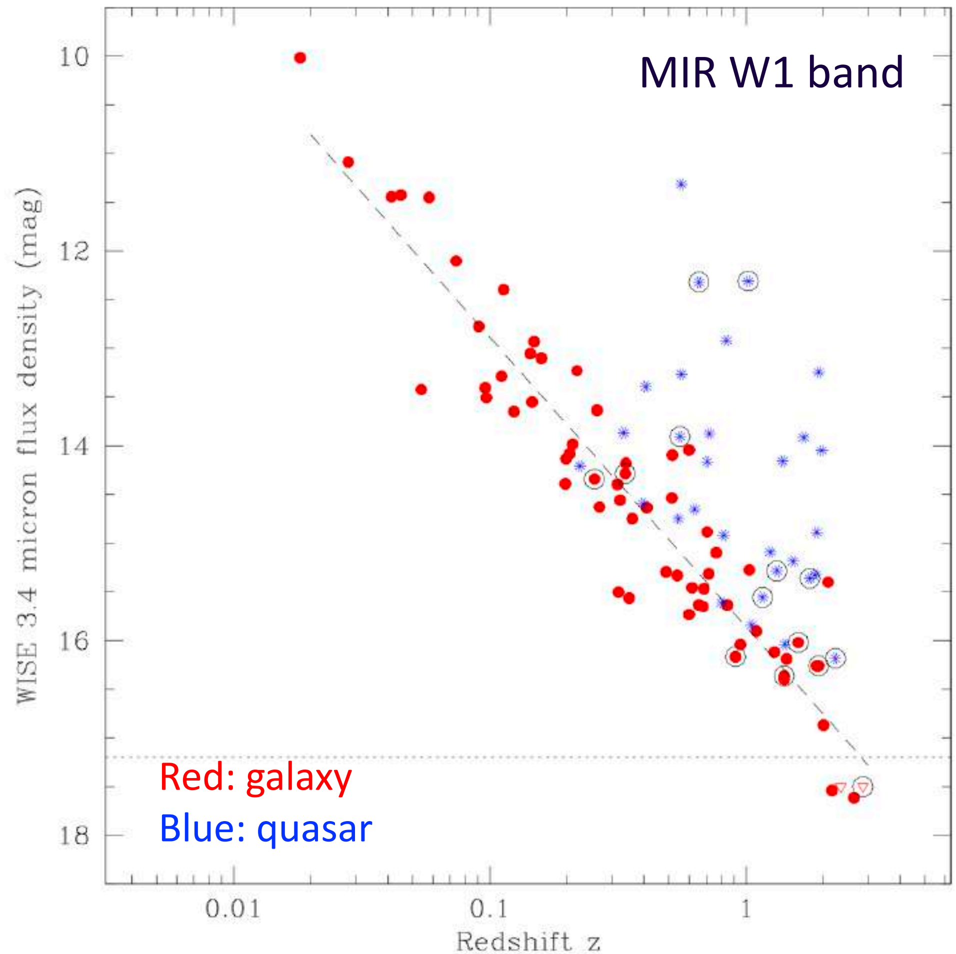
Follow-up strategy (source structure):

- Use **radio spectral index** as proxy for source compactness
- **MWA IPS survey** can identify bright compact sources

Photometric redshift estimates for radio AGN



(De Breuck et al. 2002)

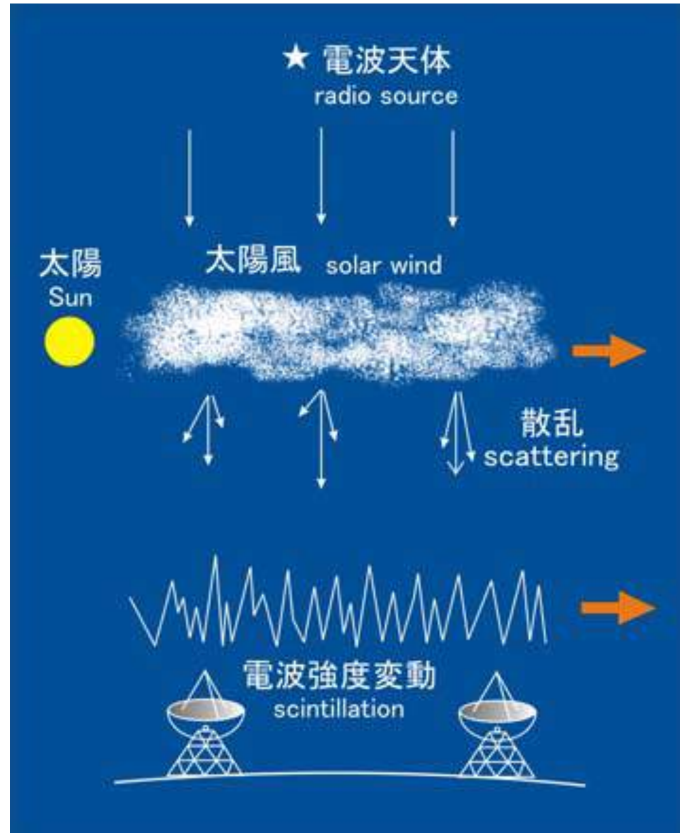


(Sadler et al. 2018)

New: Wide-field interplanetary scintillation

Interplanetary Scintillation (IPS):

- Density fluctuations in the solar wind produce random fluctuations in the intensity of compact radio sources on *timescales of a few seconds*
- For MWA, IPS is seen for sources with *angular size smaller than 0.5 arcsec* at 150-200 MHz if observed within ~30 degrees of the Sun
- Potentially a powerful tool for identifying large numbers of young and very distant radio galaxies



(Image: Nagoya Obs)

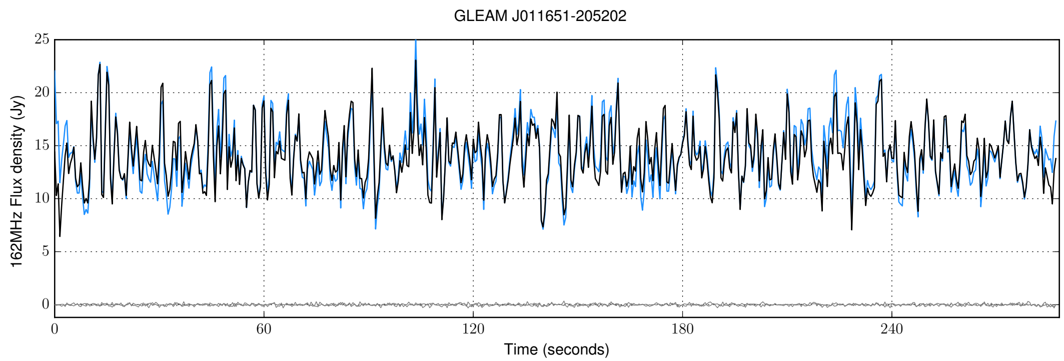
New: Wide-field Interplanetary Scintillation

Movie credit: Rajan Chhetri and John Morgan (Curtin University)

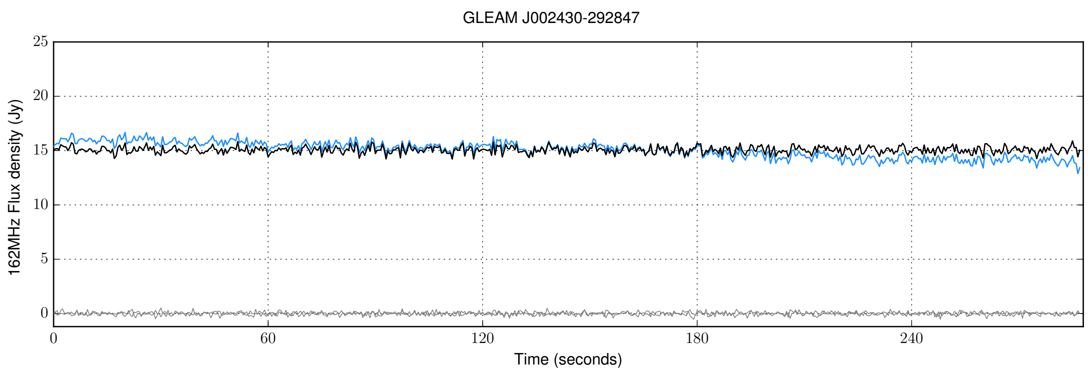
Shown here: 100 x 0.5s, 75 deg^2 field (full MWA field is 900 deg^2)

Wide-field IPS surveys with MWA

Scintillating source (compact)



Non-scintillating source



First results: (Morgan et al. 2017, Chhetri et al. 2017, Sadler et al. 2018)

- Around 12% of bright MWA GLEAM sources show strong IPS at 200 MHz
- ***Peaked-spectrum*** *sources (not QSOs)* are the **dominant population of compact sources** at low radio frequencies
- Strongly-scintillating sources are typically **distant** (median z ~ 1.5), with at least 30% at z > 2
- At z < 1, many show HI absorption

Work in progress: *All-sky IPS survey with MWA will be able to characterise the compactness of all bright southern radio sources*

Simulations: FLASH-Genesis workshop, Feb 2018

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Genesis simulations (with Claudia Lagos, Chris Power and Lilian Garratt-Smithson, UWA) – *first detailed simulations of HI absorption in distant galaxies*

See Lilian’s short talk

Summary and next steps

Results so far:
- **Successful ASKAP detection of 21cm absorption in galaxies at z > 0.4**, *at or slightly above the expected rate for intervening systems*
- Spin temperature of the cool ISM in HI-selected galaxies at z ~ 0.7 appears broadly similar to that of the Milky Way disk
- Also, many detections of **associated HI absorption** at 0.4 < z < 1
- Follow-up observations in progress with 8m telescopes, ALMA

Next steps:

Results so far mainly for single, fairly compact sources, next step is full fields with multiple sources (~150/field)
- 2019 onwards: Large-area survey with full ASKAP (36 antennas)
- Optical/CO/VLBI follow-up for larger samples
- Modelling of results (with ASTRO 3D Genesis team), tests of galaxy evolution models