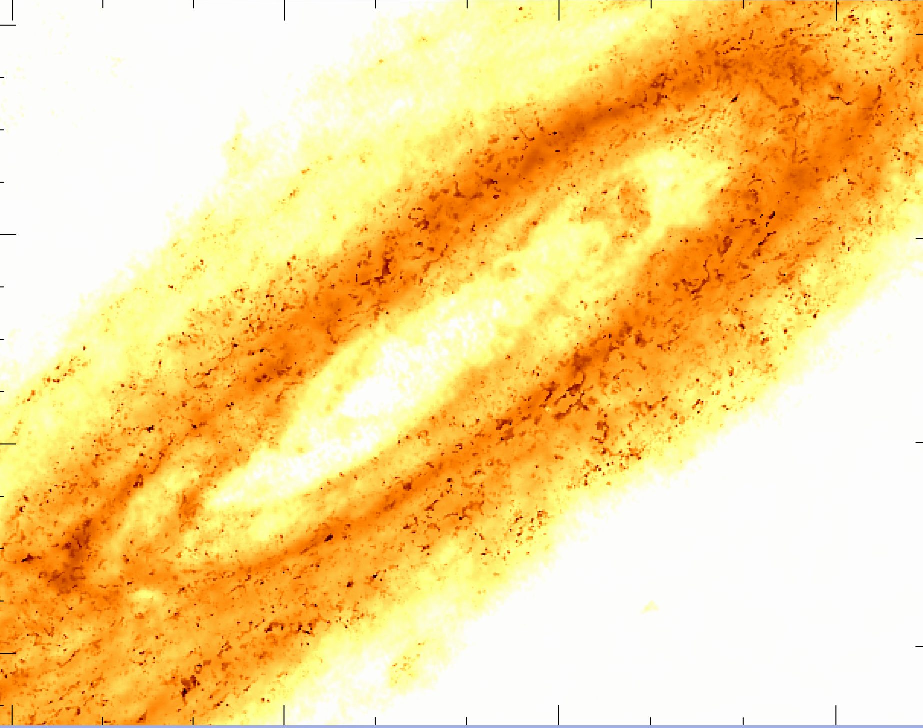
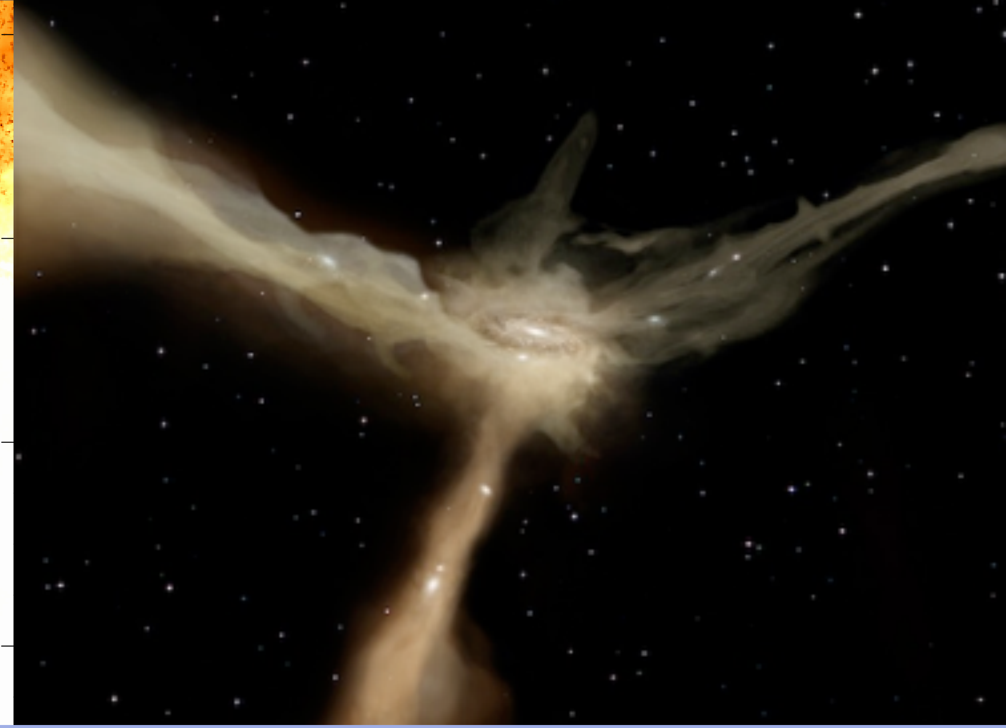




HI Galaxy Science Summary

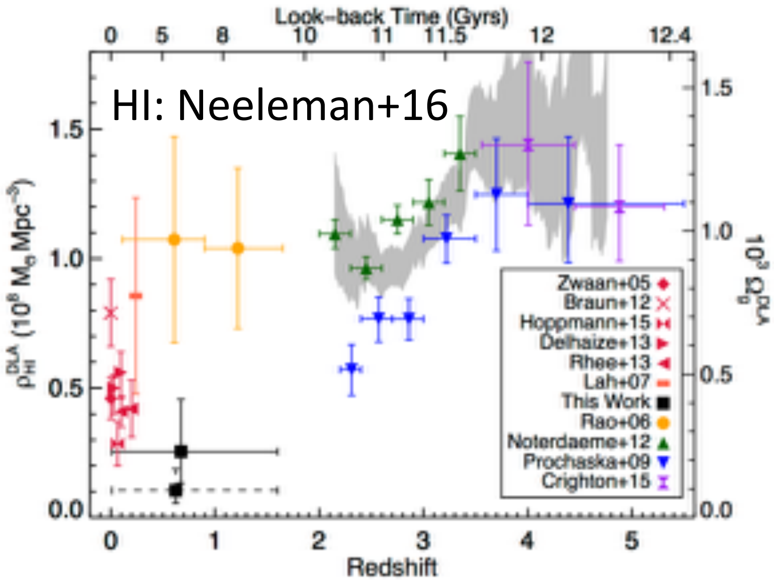
James Allison

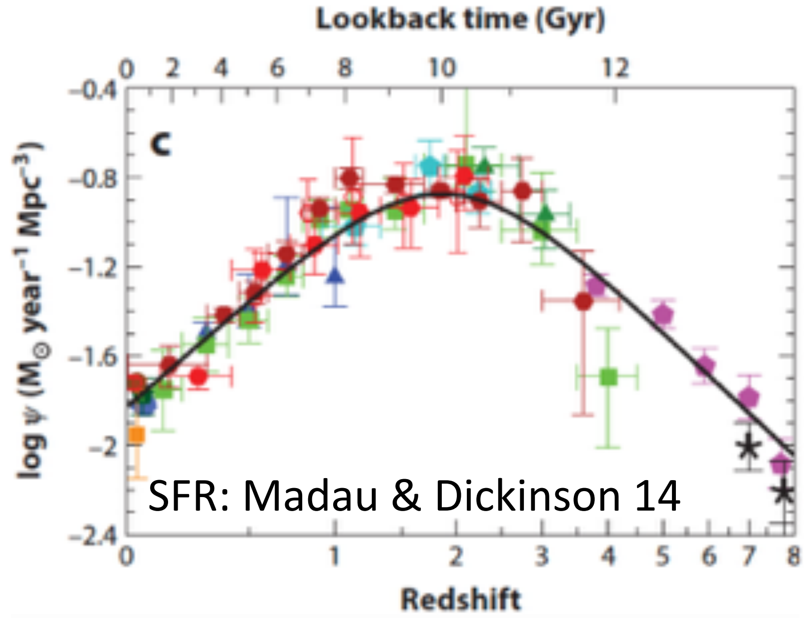
on behalf of The HI Galaxy Science Working Group

09 May 2017

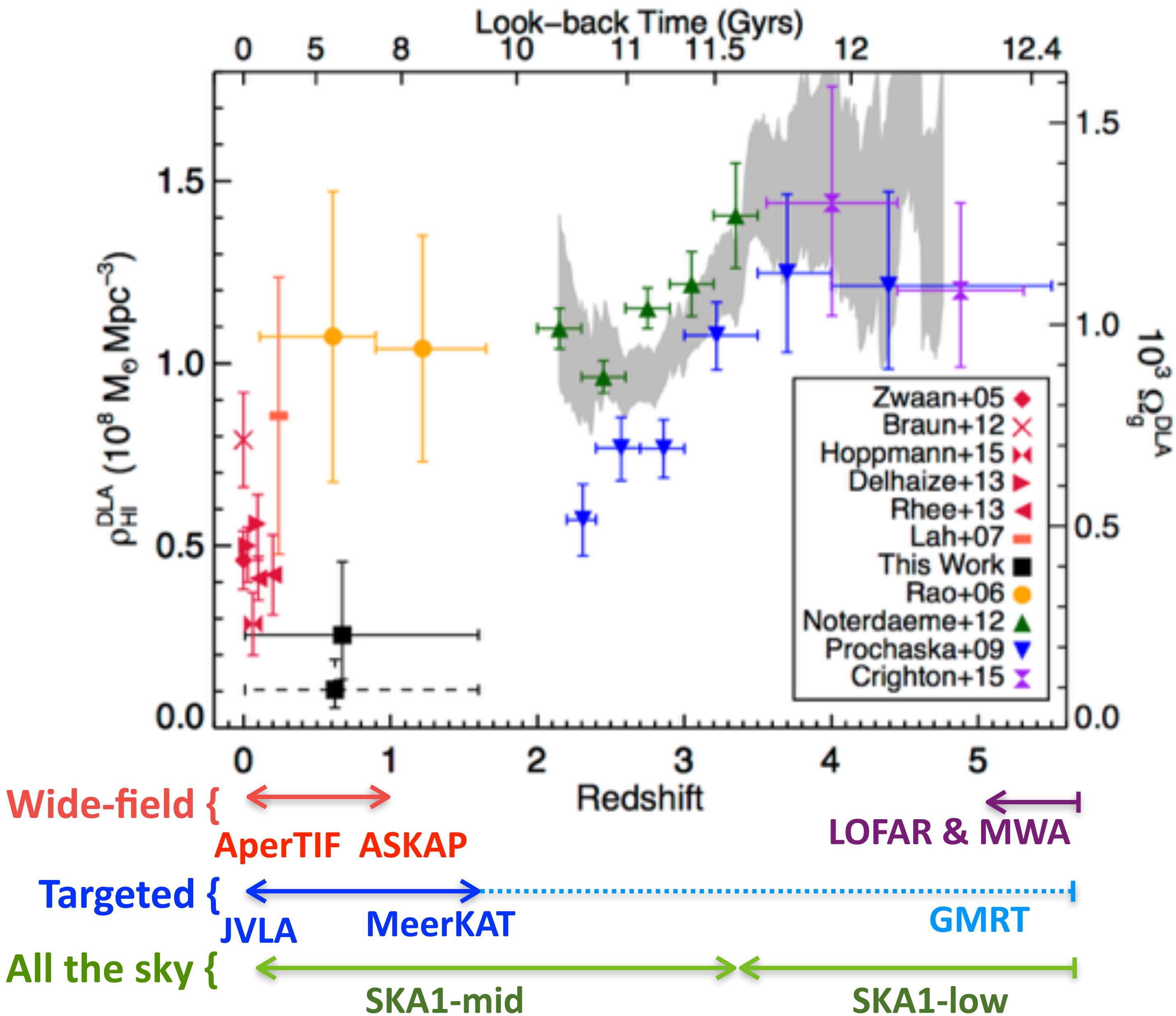
Goal: A history of the baryonic Universe in neutral hydrogen

History of the Universe in hydrogen





- How does the distribution, and kinematics, of HI in galaxies evolve over the history of the Universe?
- How is the gas that drives star formation replenished in galaxies?
- What role does neutral gas play in the processes that couple the evolution of galaxies to their black holes?



Look–back Time (Gyrs)
0
5
8
10
11
11.5
12
12.4
1.5
1.0
0.5
0.0
ρ_{HI}^{DLA} (10^8 $M_\odot$ Mpc^{-3})
10^3 Ω_g^{DLA}
0
1
2
3
4
5
Redshift
Zwaan+05
Braun+12
Hoppmann+15
Delhaize+13
Rhee+13
Lah+07
This Work
Rao+06
Noterdaeme+12
Prochaska+09
Crighton+15
Wide-field {
AperTIF ASKAP
LOFAR & MWA
Targeted {
JVLA
MeerKAT
GMRT
All the sky {
SKA1-mid
SKA1-low

HI galaxy science priorities for SKA 1

HI Science Priorities

Braun+14,
SKA1 Science Priority Outcomes

1) **Resolved HI** kinematics & morphology of ~10^{10} $M_\odot$ mass galaxies **out to z~0.8**
2) High spatial resolution studies of the **ISM in the nearby Universe**.
3) Multi-resolution imaging studies of the **ISM in our own Galaxy**
4) **HI absorption studies** out to the highest redshifts.
5) The gaseous interface and accretion physics between **galaxies and the IGM**

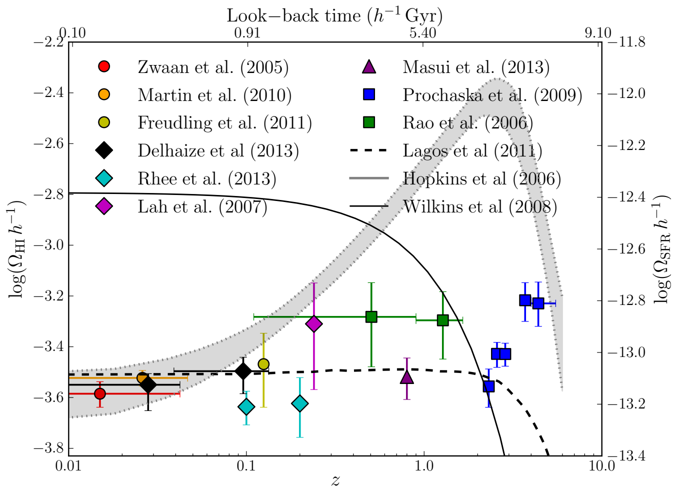
Science Goal	SWG	Objective	SWG Rank
1	*CD/EoR*	Physics of the early universe IGM - I. Imaging	1/3
2	*CD/EoR*	Physics of the early universe IGM - II. Power spectrum	2/3
3	*CD/EoR*	Physics of the early universe IGM - III. HI absorption line spectra (21cm forest)	3/3
4	*Pulsars*	Reveal pulsar population and MSPs for gravity tests and Gravitational Wave detection	1/3
5	*Pulsars*	High precision timing for testing gravity and GW detection	1/3
6	*Pulsars*	Characterising the pulsar population	2/3
7	*Pulsars*	Finding and using (Millisecond) Pulsars in Globular Clusters and External Galaxies	2/3
8	*Pulsars*	Finding pulsars in the Galactic Centre	2/3
9	*Pulsars*	Astrometric measurements of pulsars to enable improved tests of GR	2/3
10	*Pulsars*	Mapping the pulsar beam	3/3
11	*Pulsars*	Understanding pulsars and their environments through their interactions	3/3
12	*Pulsars*	Mapping the Galactic Structure	3/3
13	*HI*	Resolved HI kinematics and morphology of ~10^10 M_sol mass galaxies out to z~0.8	1/5
14	*HI*	High spatial resolution studies of the ISM in the nearby Universe.	2/5
15	*HI*	Multi-resolution mapping studies of the ISM in our Galaxy	3/5
16	*HI*	HI absorption studies out to the highest redshifts.	4/5
17	*HI*	The gaseous interface and accretion physics between galaxies and the IGM	5/5
18	*Transients*	Solve missing baryon problem at z~2 and determine the Dark Energy Equation of State	=1/4
19	*Transients*	Accessing New Physics using Ultra-Luminous Cosmic Explosions	=1/4
20	*Transients*	Galaxy growth through measurements of Black Hole accretion, growth and feedback	3/4
21	*Transients*	Detect the Electromagnetic Counterparts to Gravitational Wave Events	4/4
22	*Cradle of Life*	Map dust grain growth in the terrestrial planet forming zones at a distance of 100 pc	1/5
23	*Cradle of Life*	Characterise exo-planet magnetic fields and rotational periods	2/5
24	*Cradle of Life*	Survey all nearby (~100 pc) stars for radio emission from technological civilizations.	3/5
25	*Cradle of Life*	The detection of pre-biotic molecules in pre-stellar cores at distance of 100 pc.	4/5
26	*Cradle of Life*	Mapping of the sub-structure and dynamics of nearby clusters using maser emission.	5/5
27	*Magnetism*	The resolved all-Sky characterisation of the interstellar and intergalactic magnetic fields	1/5
28	*Magnetism*	Determine origin, maintenance and amplification of magnetic fields at high redshifts - I.	2/5
29	*Magnetism*	Detection of polarised emission in Cosmic Web filaments	3/5
30	*Magnetism*	Determine origin, maintenance and amplification of magnetic fields at high redshifts - II.	4/5
31	*Magnetism*	Intrinsic properties of polarised sources	5/5
32	*Cosmology*	Constraints on primordial non-Gaussianity and tests of gravity on super-horizon scales.	1/5
33	*Cosmology*	Angular correlation functions to probe non-Gaussianity and the matter dipole	2/5
34	*Cosmology*	Map the dark Universe with a completely new kind of weak lensing survey - in the radio.	3/5
35	*Cosmology*	Dark energy & GR via power spectrum, BAO, redshift-space distortions and topology.	4/5
36	*Cosmology*	Test dark energy & general relativity with fore-runner of the 'billion galaxy' survey.	5/5
37	*Continuum*	Measure the Star formation history of the Universe (SFHU) - I. Non-thermal processes	1/8
38	*Continuum*	Measure the Star formation history of the Universe (SFHU) - II. Thermal processes	2/8
39	*Continuum*	Probe the role of black holes in galaxy evolution - I.	3/8
40	*Continuum*	Probe the role of black holes in galaxy evolution - II.	4/8
41	*Continuum*	Probe cosmic rays and magnetic fields in ICM and cosmic filaments.	5/8
42	*Continuum*	Study the detailed astrophysics of star-formation and accretion processes - I.	6/8
43	*Continuum*	Probing dark matter and the high redshift Universe with strong gravitational lensing.	7/8
44	*Continuum*	Legacy/Serendipity/Rare.	8/8

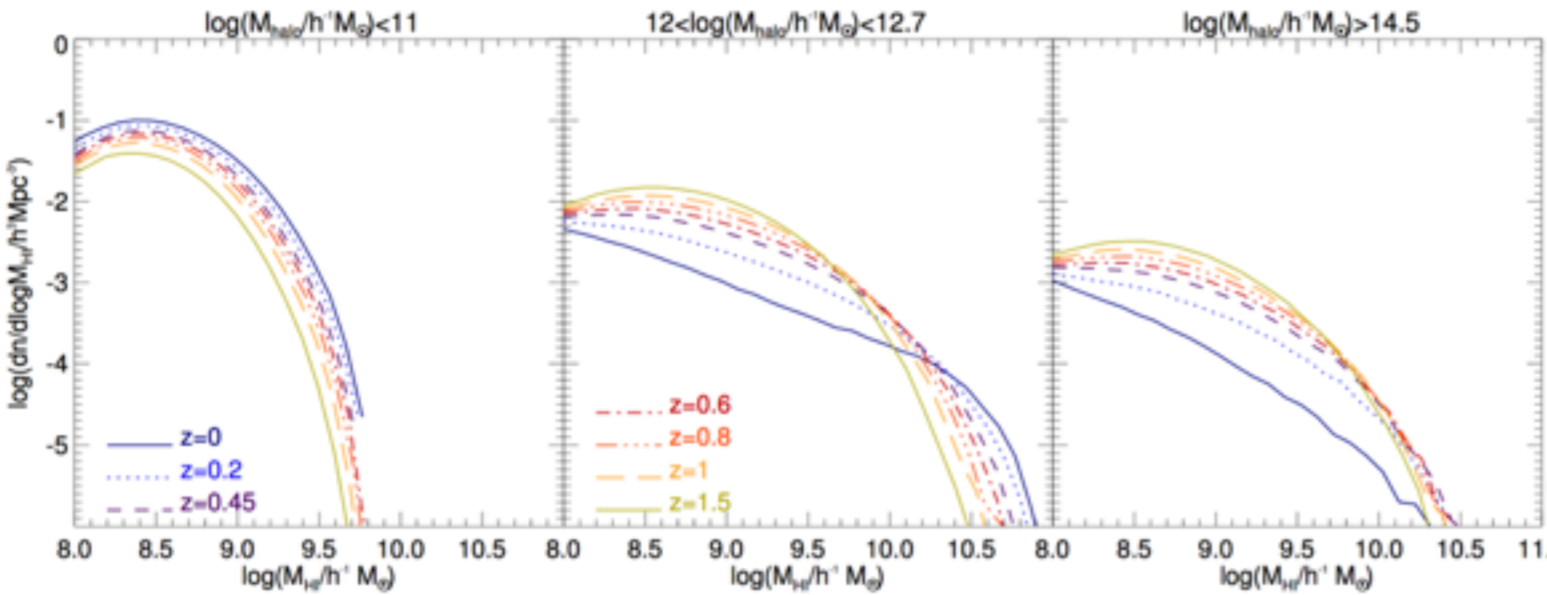
Table 1. Collated list of science goals. Within each science area, the entries are ordered in the rank provided by the SWG Chairs. The eight different groups of SWG contributions are listed in the Table in an arbitrary sequence.

Blyth+15

Science goals - Galaxy evolution z < 0.8

Mass properties - **evolution** of **Ω_{HI}** & **HI mass function** as a function of environment

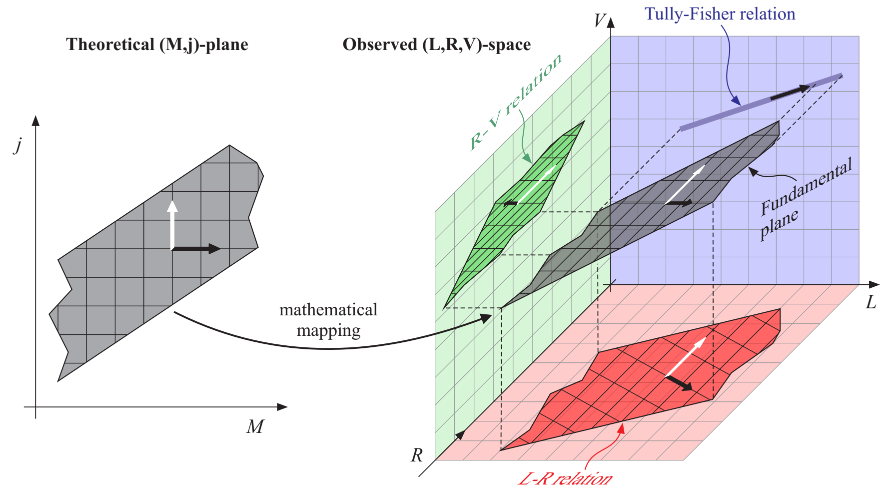




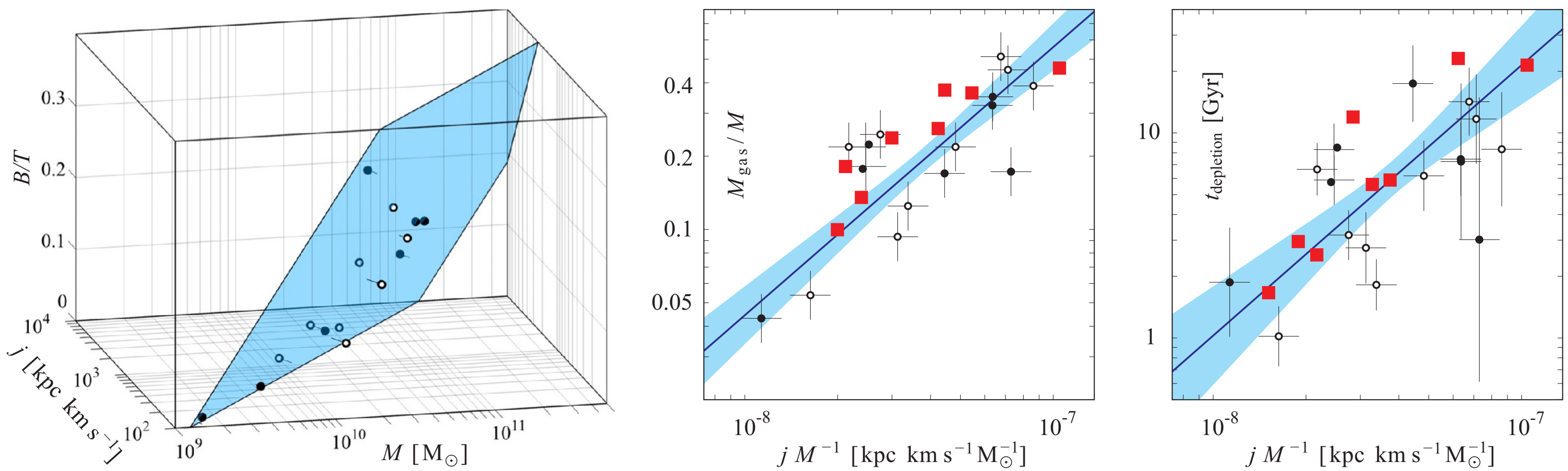
Obreschkow+15

Science goals - Galaxy evolution z < 0.8

Kinematic properties-
Angular momentum
scaling relations, Tully-Fisher relation



(a) Morphology (b) Gas fraction (c) Star formation

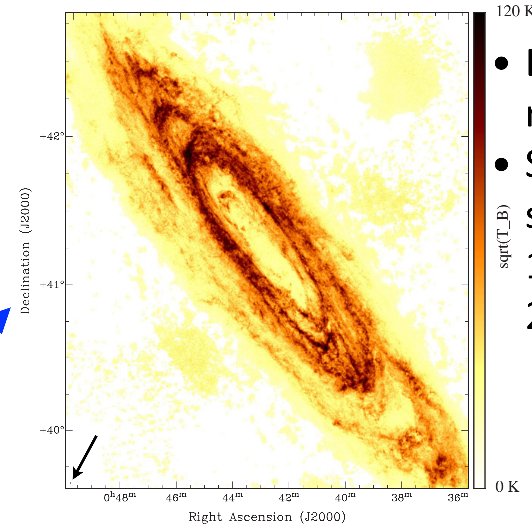


Science goals - ISM in nearby galaxies

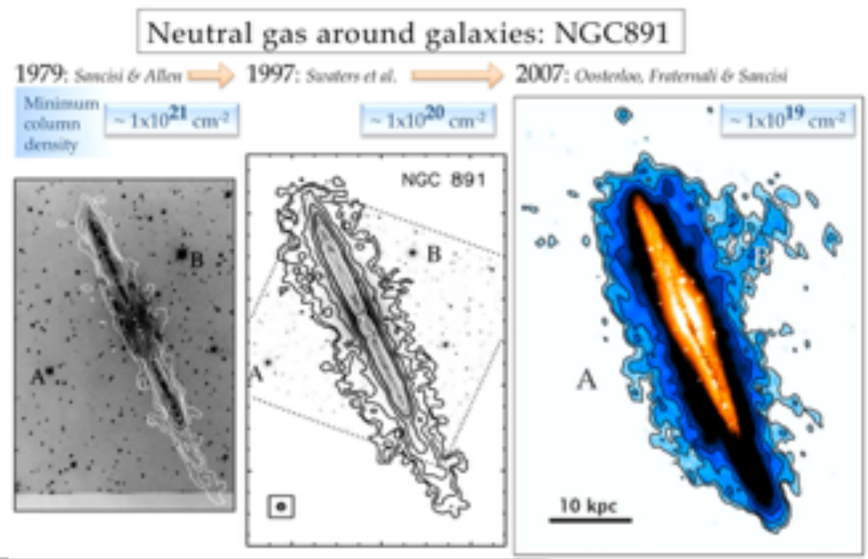
- Very **high spatial resolution** (sub-kpc) and **column density sensitivity** (sub 10^{20} cm^{-2})

- What is the **connection** between **star formation** on small scales and **global scaling laws** (origin of the Kennicutt-Schmidt law)?

- How do galaxies **acquire** sufficient **gas** to sustain their star formation rates?



- Braun+09 - M31 at 50pc resolution
- SKA1 will allow similar studies of the ISM in 100s galaxies out to 20Mpc

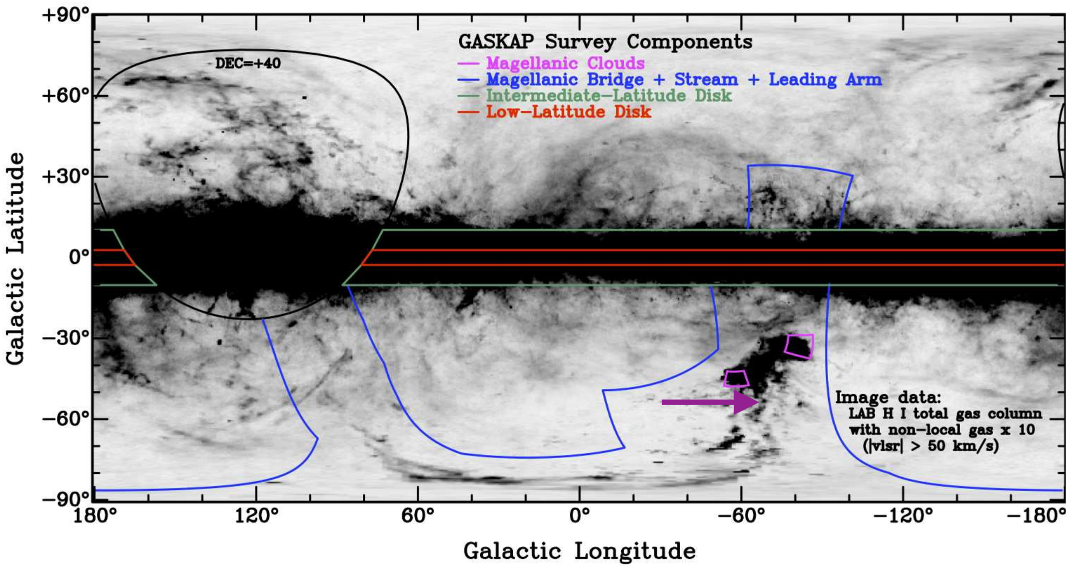


McClure-Griffiths+15

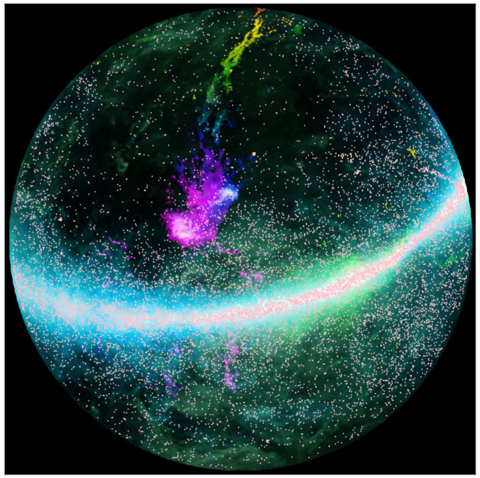
Science goals - The Galaxy & Magellanic System

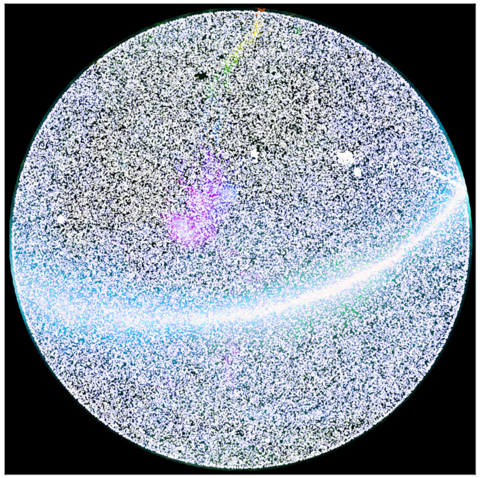
MW and Magellanic clouds allow studies of gas content **in greater detail than anywhere else**

- How is **gas exchanged with** surrounding **IGM**?
- How is **warm surrounding diffuse gas cooled** into molecular clouds, stars?
- SKA will have surface brightness sensitivity, point source sensitivity and angular resolution to understand Milky Way gas **all the way from the halo down to the formation of individual molecular clouds.**



HI emission





HI absorption

Morganti+15

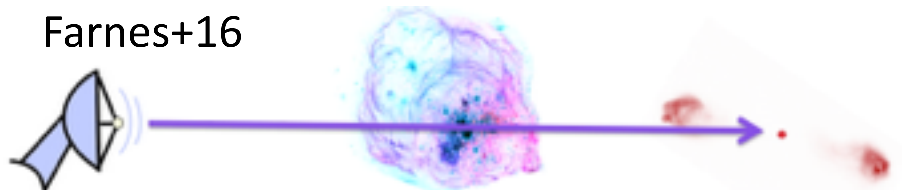
Science goals - HI absorption and AGN at z < 6

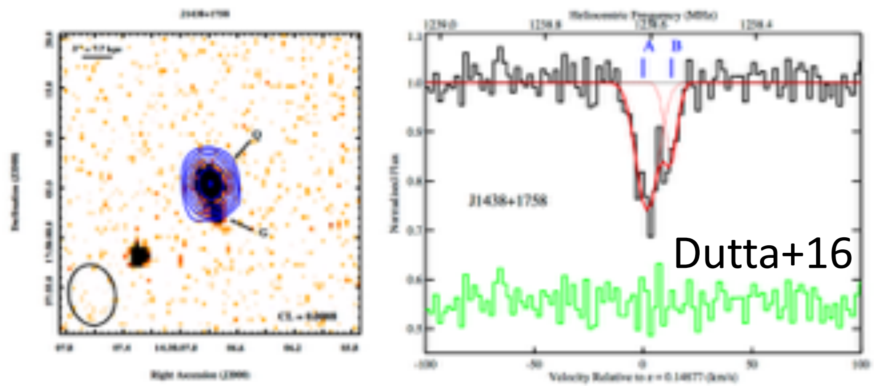
- HI in absorption connecting the epoch of re-ionisation to the present day —> “21-cm forest”
- How does the **cold phase gas** in galaxies evolve over the past **12 billion** years?

AGN Feedback and Fuelling

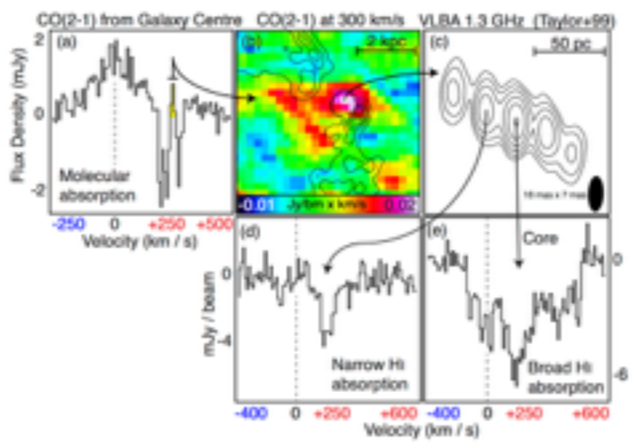
- What are the mechanisms by which gas **accretes** onto **AGN**?
- Are **neutral outflows** a common feature of all radio AGN?

Farnes+16





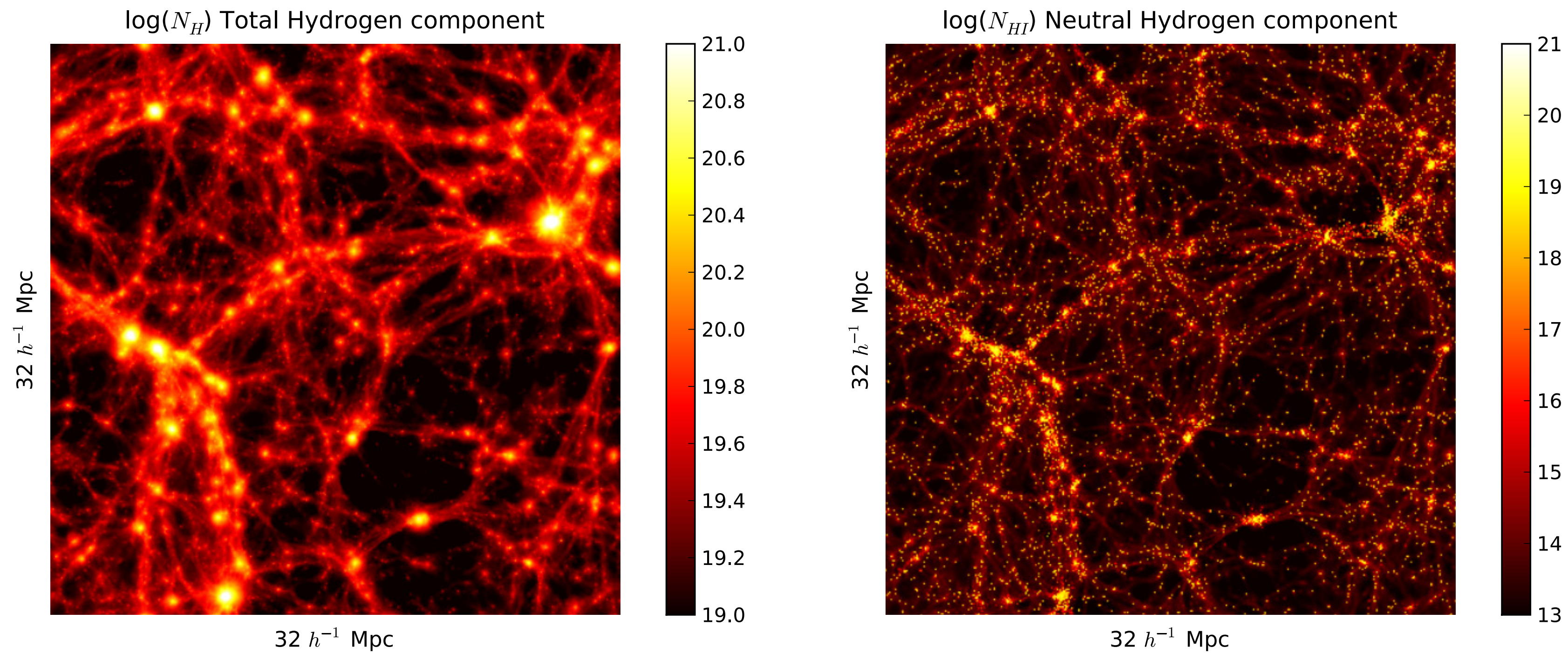
Dutta+16



Tremblay+16

Science goals - The Cosmic Web & IGM

- Commensal with the ISM KSP
- How are galaxies **re-fuelled** from the surrounding IGM?
- What is the nature of diffuse **intergalactic** gas?
- Requires **extremely sensitive** observations at column densities $n_{HI} \lesssim 10^{18}$



Proposed SKA1 HI surveys

Survey	Area (deg²)	Freq MHz	HI Resolution	<z> (z_{lim})	T (hrs)	N_{gal}
Medium wide	400	950-1420	10"	0.1 (0.3)	2000	~30,000
Medium deep	20	950-1420	5"	0.2 (0.5)	2000	~25,000
Deep	1 pointing	600-1050	2"	0.5 (1)	3000	~3000
Targeted ISM	30 targets	1400-1420	3"-30"	0.002 (0.01)	3000	30
Targeted Accretion	30 targets	1400-1420	30"-1'	0.002 (0.01)	3000	30
Galaxy/MS	500	1418-1422	10"-1'	0 (0)	4,500	1
Galaxy Abs	(5000)	1418-1422	2"	0 (0)	(10,000)	(~4,000)
Absorption	1000+	350-1050	2"	1 (3)	1,000+	~5,000
	1000	200-350	10"	4 (6)	1,000	Unknown

Commensality, commensality, commensality.

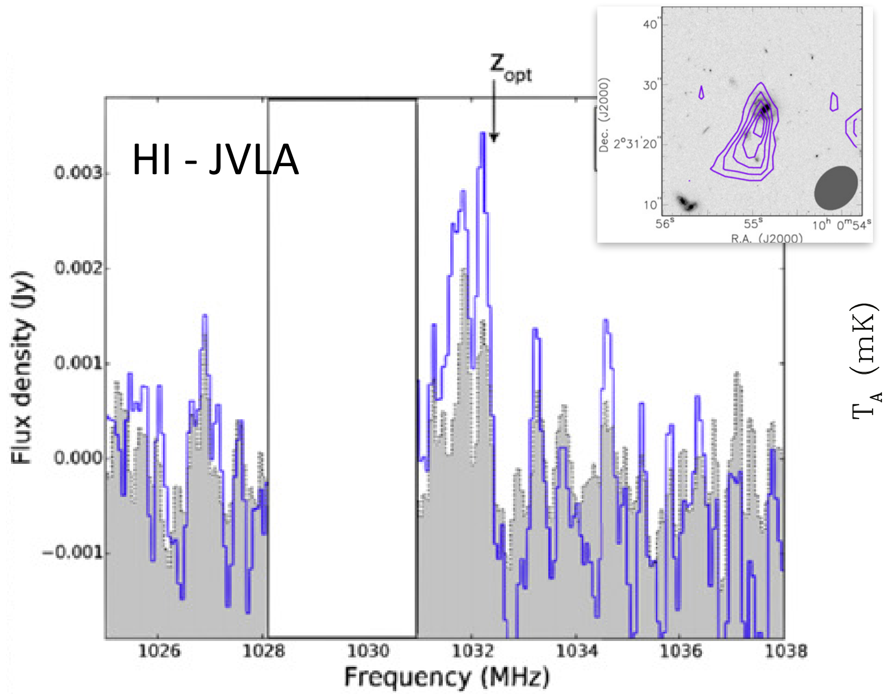
Survey	Area (deg^2)	Freq MHz	T (hrs)	Magnetism	Cosmology/ EoR	Continuum
Medium wide	400	950-1420	2000		1000 sq deg 5000 hours weak lensing	similar strategy
Medium deep	20	950-1420	2000	100 deg2 tracing cosmic web, similar depth		similar strategy
Deep	1 pointing	600-1050	3000	compatible; magn. plans wider		useful only if in band 1
Targeted	30 targets	1400-1420	3000	good match in sample, res and depth		
Targeted (Accr)	(30 targets)	1400-1420	(3000)		fully commensal with ISM Accretion	
Galaxy/MS	500	1418-1422	4500	commensal with Galaxy + Magn WG to get optimum 1200 deg2 and 11500 hours		
Galaxy Abs	(5000)	1418-1422	(10000)	fully commensal with "Galaxy/MS", continuum, magnetism		
Absorption	1000+	350-1050	1,000+	all sky, optimum commensality if band 1		
	1000	200-350	1.000		fully commensal 5000 deg2 absorption survey	

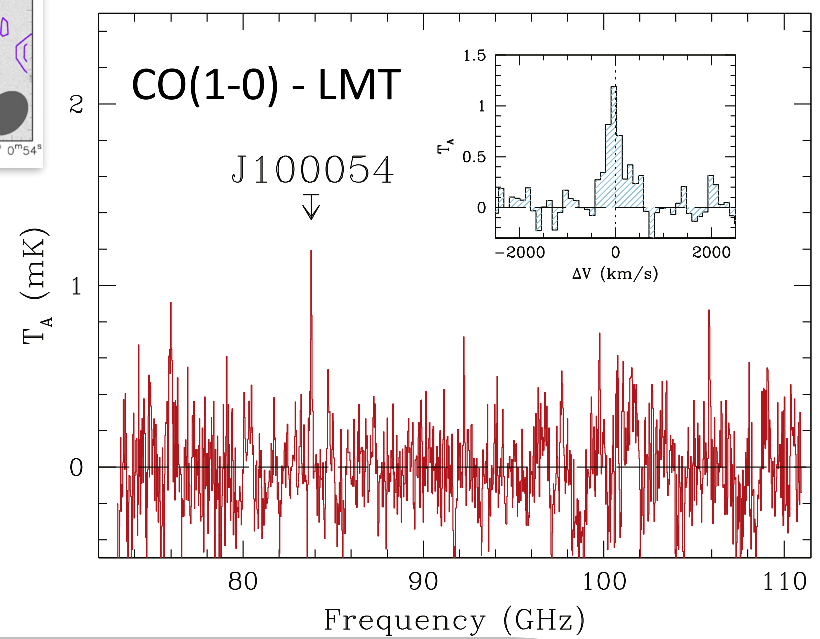
and commensal with medium-wide HI band 2

Recent activities: precursor SKA HI science

Recent activities - JVLA CHILES project

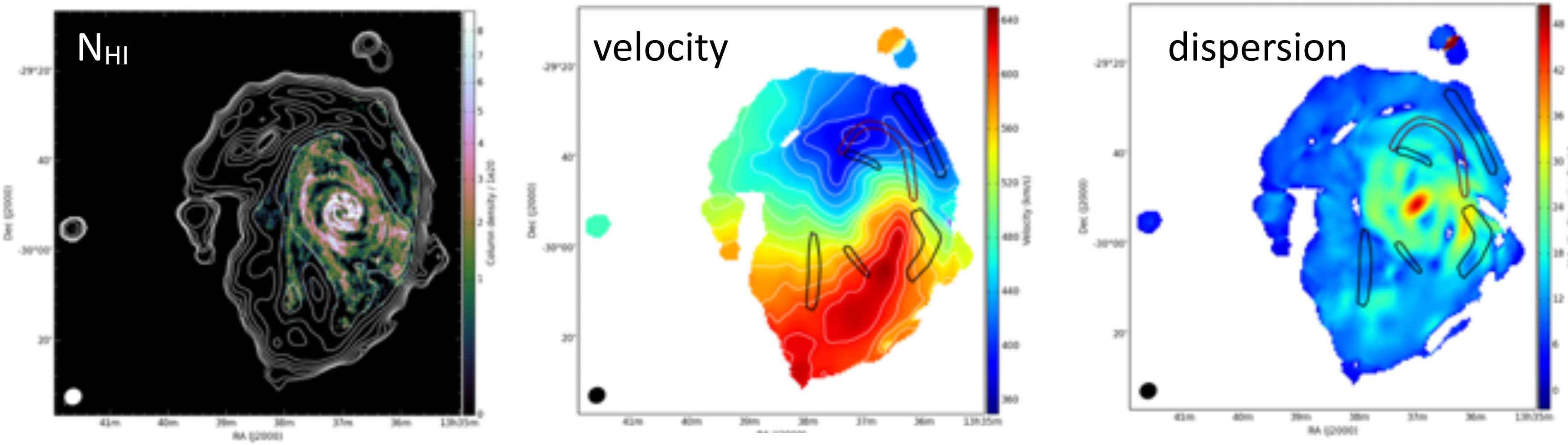
- **CHILES - Deep 21-cm emission**
- **1000hr HI survey, ~300 galaxies at 0 < *z* < 0.5**
  - Most distant detection of 21-cm line emission at ***z* = 0.376**
  - Large starbursting galaxy rich in HI & H_2 gas ($M_{HI} = 3 \times 10^{10}\ M_{solar}$)

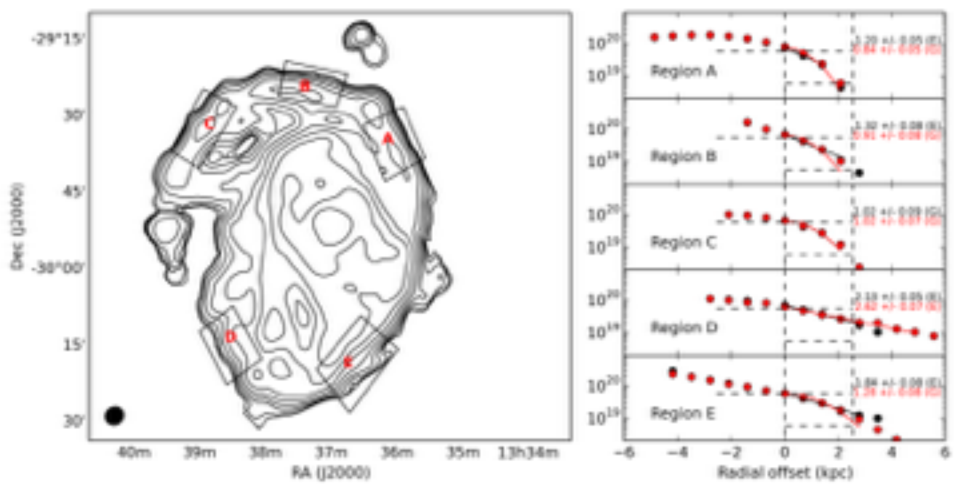




Recent activities - KAT-7

- **Revealing the edge of M83 & interaction with IGM (Heald+16)**





Recent activities - ASKAP wide field

- **First wide-field HI images with ASKAP-12 using 36-beams**
- Resolved kinematics of IC 5201 (Karen's talk)

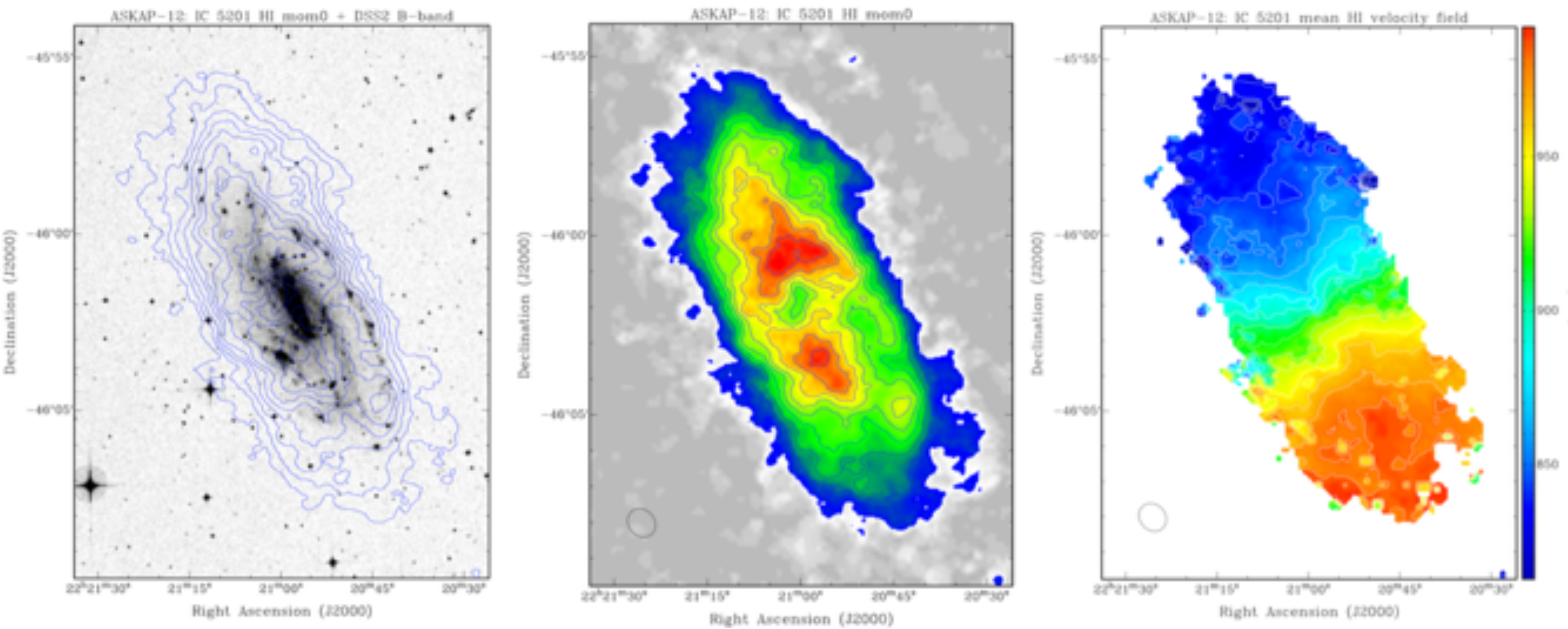
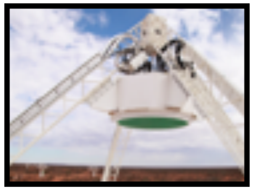


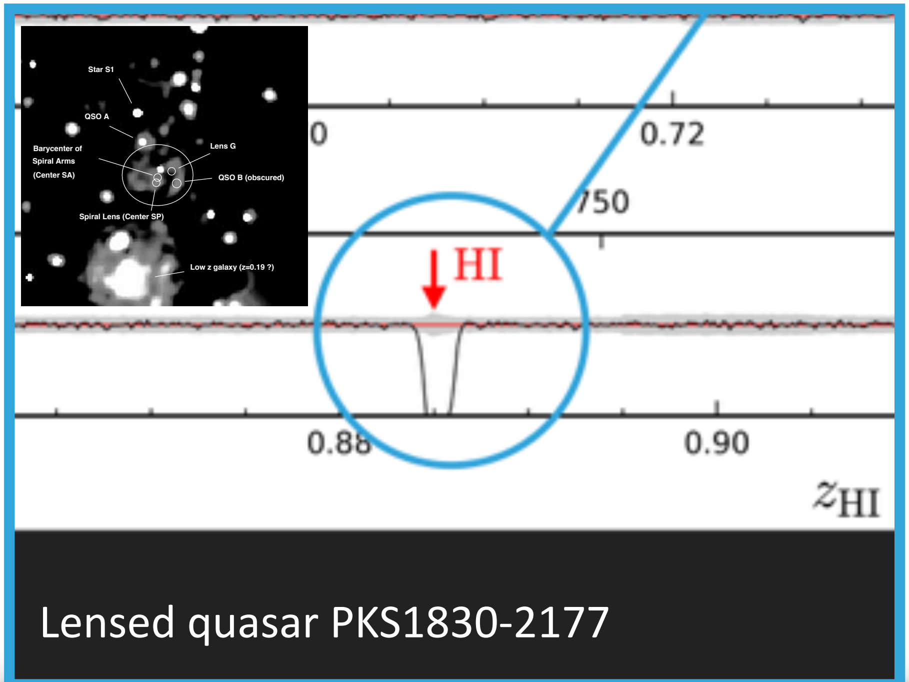
Image Credit: WALLABY Survey Science Team

Recent activities - ASKAP HI absorption

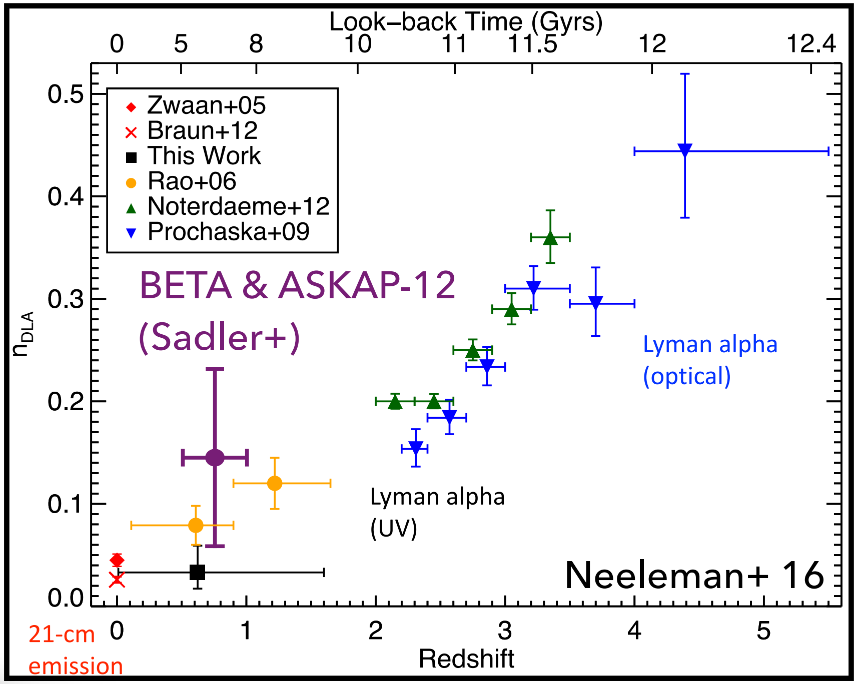


- **Discoveries of HI absorption at cosmological redshifts**

Lensed quasars illuminating cold gas throughout 8 billion years (Allison +17)



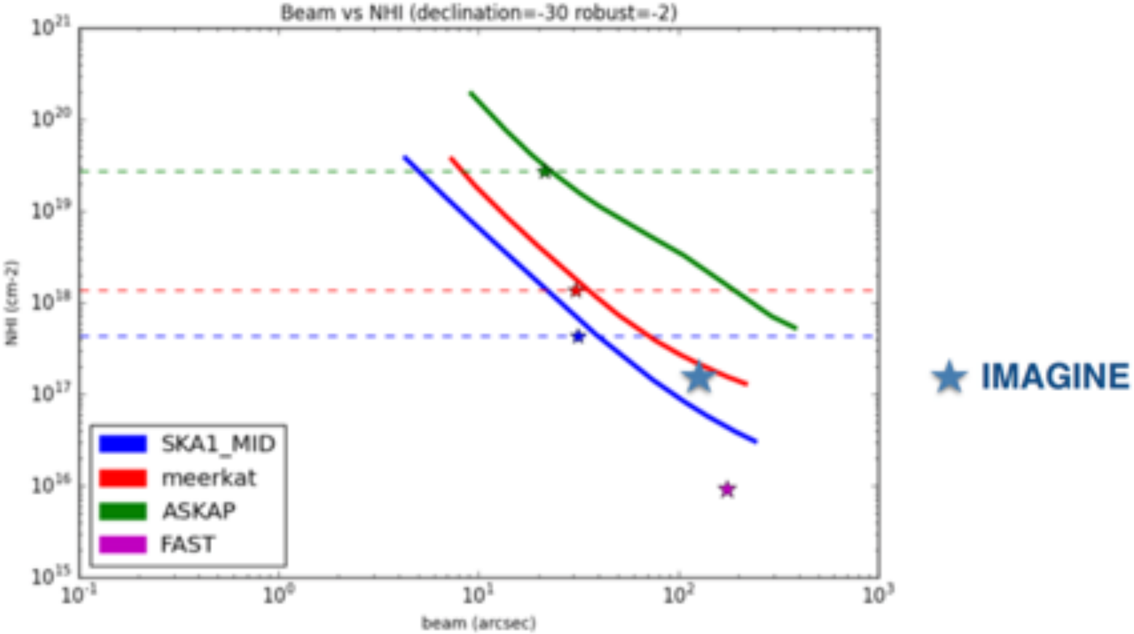
The first radio-selected 21-cm line DLA survey (Sadler +)



Recent activities - ATCA Legacy Project

- **Deep Imaging of the circumgalactic medium (Popping+)**
  - Observe 28 spiral Galaxies and their direct environments
  - 2500hr Legacy Program
- Precursor to SKA Accretion KSP

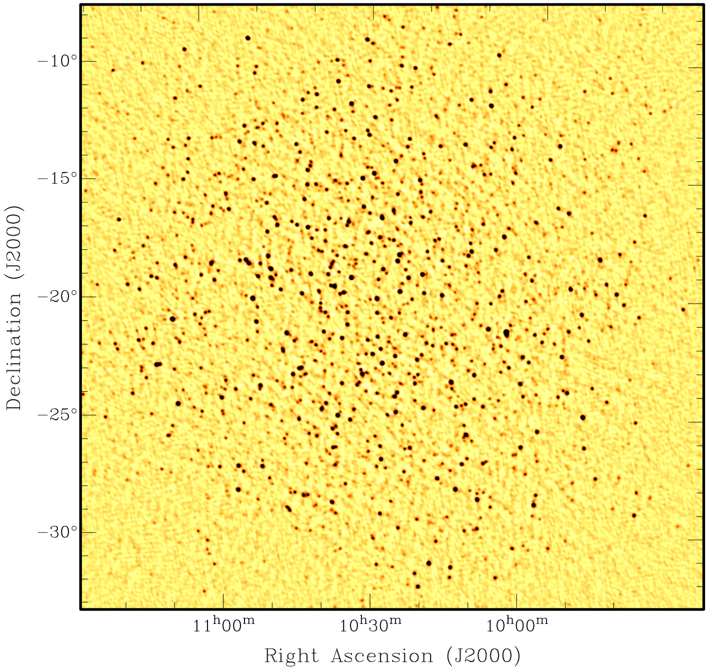
Brightness sensitivity after 8 hours observing

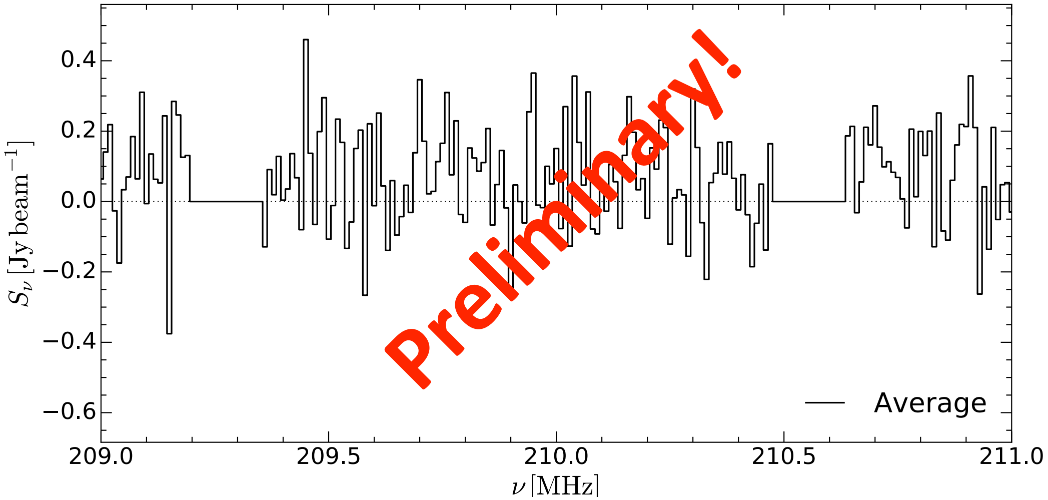


- Measure the extended gas content of galaxies to detect gas accretion and outflows.
- Determine the environment of gas accretion
- Detect the densest peak of the underlying Cosmic Web.

Recent activities - MWA: HI @ z > 5

- **HIghz: HI absorption search for high-*z* radio galaxies (Allison +)**
  - Luminous radio galaxies at centres of early cluster formation
  - Optically and infrared faint (z >> 1)
  - Bright steep spectrum, peaked radio sources (Callingham +17)





Impact of cost control on HI science

5.25.2 / Deeper Savings	**Reduce PSS-LOW: C, 125 nodes to 83 nodes** This cost control option involves necessitating that the CSP.PSS design processes up to 6 tied array search beams per PSS processing node on LOW. Currently the design processes 2 tied array search beams per PSS processing node on LOW. To achieve this would require improved processing algorithms (which may not be possible) or the reduction in search parameter space (i.e. not performing as complete a pulsar search). It is considered that the change from 2 beams/node to 3 beams/node will likely be possible without needing to perform an incomplete search. It is unlikely that 6 beams/node will be possible. If it is not possible, then this equates to a cut in either the number of pulsar beams or the volume of pulsar search parameter space by a factor of 167/83 = 2.	LOW	Likely reduction in processed PSS beam number (2x) or pulsar search parameter space	3	25
5.25.3 / Deeper Savings	**Reduce PSS-MID: B, 375 nodes to 250 nodes** This cost control option involves necessitating that the CSP.PSS design processes up to 6 tied array search beams per PSS processing node on MID. Currently the design processes 2 tied array search beams per PSS processing node on MID. To achieve this would require improved processing algorithms (which may not be possible) or the reduction in search parameter space (i.e. not performing as complete a pulsar search). It is considered that the change from 2 beams/node to 3 beams/node will likely be possible without needing to perform an incomplete search. It is unlikely that 6 beams/node will be possible. If it is not possible, then this equates to a cut in either the number of pulsar beams or the volume of pulsar search parameter space by a factor of 500/250 = 2.	MID	Likely reduction in processed PSS beam number (2x) or pulsar search parameter space	3	26
5.30a	**Reduce Bmax LOW to 40km: C, remove next 18 stations** This scenario involves removing the second outermost clusters of (3x6) stations as well as the supporting infrastructure. These are not added to the core region. The reduction in maximum baseline may have adverse consequences for foreground continuum source characterisation and removal.	LOW	Science Risk to EoR: Bmax	3	27
8	**SDP- HPC: Deploy 100 Pflops (from 150 Pflops)** It is e[illegible]pected that the cost of SDP processors wi[illegible]ecrease in time due [illegible] more efficient and cheaper technolog[illegible] becom[illegible] [illegible]. Th[illegible] re-si[illegible] [illegible] pur[illegible] [illegible] Pflops [illegible] deployed, computa[illegible]ionally demanding observations need to be observed for smaller fractions of time, in order for the sustained load on SDP to be compatible with the reduced system size. Those observations will still be possible, but will be accumulated more slowly.	COMMON	Lower all[illegible] duty c[illegible] observations.	4	28
8	**SDP- HPC: Deploy 50 Pflops (from 100 Pflops)** It is expected that the cost of SDP processors will decrease in time due to more efficient and cheaper technology becoming available (Moore's Law gain). Therefore, re-sizing the first major purchase and assembling the full 260 Pflops SDP system in stages, rather than in a single deployment, results in a saving. If a smaller SDP is initially deployed, computationally demanding observations need to be observed for smaller fractions of time, in order for the sustained load on SDP to be compatible with the reduced system size. Those observations will still be possible, but will be accumulated more slowly.	COMMON	Lower allowed duty cycle for HPC- intensive observations.	4	29
5.24 / Deeper Savings	**Remove 11 MID Dishes from core** This cost control option involves removing 11 SKA1 dishes from within the inner 1.2 km radius. In the current design there are 70 SKA1 (15-m) and 49 MeerKAT (13.5-m) dishes within this radius. In the case of high surface brightness imaging and pulsar searches this reduces the core collecting area by 10%. Pulsar acceleration searches require instantaneous sensitivity (or extra computing proportional to (Tobs_new/Tobs_now)^3) so they are disproportionately impacted, i.e. can not be recouped with extra Tobs. Non-binary (i.e. non-HPSO-related) pulsars and low resolution imaging are affected such that ~20% extra observing time would recoup the loss.	MID	10% Sensitivity loss in core	4	30
5.30 / Deeper Savings	**Remove 54 LOW stations from core** In this measure, 54 stations are randomly removed from the inner 1.5 km radius region (where there are currently 282 stations). There is a 20% loss in core sensitivity, which would require about 40% increased integration time to compensate.	LOW	20% Sensitivity loss in core	4	31
5.24 / Deeper Savings	**Remove additional 11 MID Dishes from core** This cost control option involves removing 22 SKA1 dishes from within the inner 1.2 km radius. In the current design there are 70 SKA1 (15-m) and 49 MeerKAT (13.5-m) dishes within this radius. In the case of high surface brightness imaging and pulsar searches this reduces the core collecting area by 20%. Pulsar acceleration searches require instantaneous sensitivity (or extra computing proportional to (Tobs_new/Tobs_now)^3) so they are disproportionately impacted, i.e. can not be recouped with extra Tobs. Non-binary (i.e. non-HPSO-related) pulsars and low resolution imaging are affected such that ~40% extra observing time would recoup the loss.	MID	20% Sensitivity loss in core	4	32

CSIRO

Cost control: Impact on HI science

"Above the black line"

- Reduction in Science Data Processor capabilities has most potential impact on high priority HI science objectives
- Reduction in angular resolution (both MID & LOW) will impact HI absorption surveys
- Reduction in LOW bandwidth will impact HI absorption surveys

"Below the black line"

- Reduction in MID core baselines will cause severe reduction in HI emission-line column density sensitivity
- Loss of MID Band 1 means no HI science with MID at z > 0.5

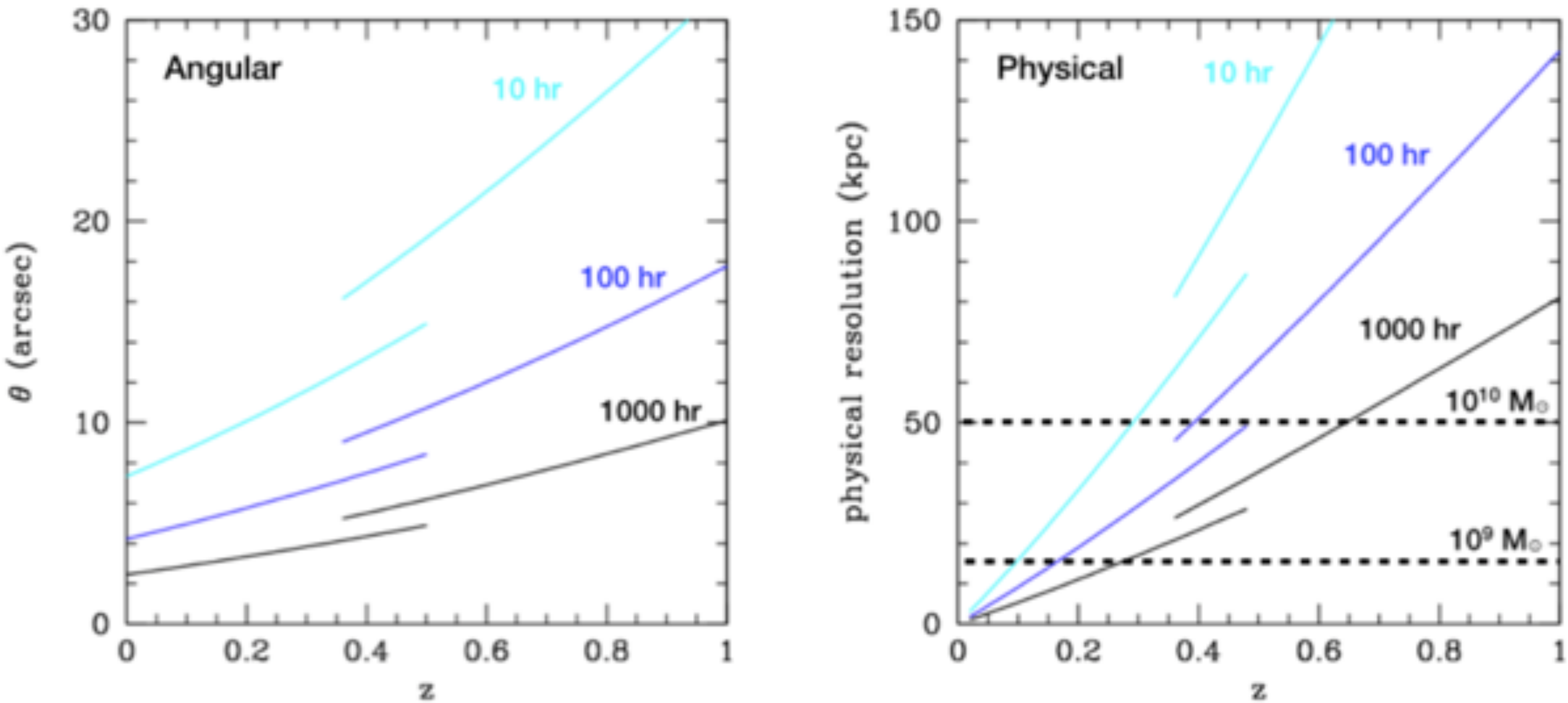
- Response currently being compiled by SWG Chairs **Martin Myer** and **Erwin de Blok** (please send **feedback by Thursday**!)

Summary

- **SKA1 will be transformational for HI galaxy science**
  - Resolved kinematics of $M_{\mathrm{HI}} = 10^{10}\ \mathrm{M}_{\odot}$ galaxies out to $z = 0.8$
  - The ISM at 50pc-scale resolution in nearby galaxies
  - Multi-resolution, multi-temperature study of the Galactic ISM
  - Cosmological evolution of cold HI (absorption) out to $z = 6$
  - The gaseous interface between galaxies and the cosmic web
- **Pathfinder telescopes are already demonstrating feasibility of achieving these goals**
- **“Above the black line” cost control measures are unlikely to have a significant impact on HI science**
- **If you want to be involved contact working group chairs Martin Meyer (UWA) and Erwin de Blok (ASTRON)**

Extra slides

SKA1-MID Resolution for $N_{HI} = 10^{20}$ cm^{-2}



HI commensality

Survey		Area (deg²)	Freq MHz	T (hrs)	Magnetism	Cosmology /EoR	Continuum
Galaxy Evolution	Medium wide	400	950-1420	2000		1000 sq deg 5000 hours weak lensing	similar strategy
Galaxy Evolution	Medium deep	20	950-1420	2000	100 deg2 tracing cosmic web, similar depth		similar strategy
Galaxy Evolution	Deep	1 pointing	600-1050	3000	compatible but plans wider		useful only if in band 1
Nearby galaxies		30 targets	1400-1420	3000	good match in sample, res and depth	*commensal with IGM accretion*	
Milky Way/MS	Emission	500	1418-1422	4500	*commensal with Galaxy + Magn WG to get optimum 1200 deg2 and 11500 hours*		
Milky Way/MS	Absorption	(5000)	1418-1422	(10000)	*fully commensal with "Milky Way/MS", continuum, magnetism*		
IGM Accretion		(30 targets)	1400-1420	(3000)	*commensal with Nearby Galaxies*		
Absorption	MID	1000+	350-1050	1,000+	*all sky, optimum commensal if band 1. Also commensal with medium-wide HI*		
Absorption	LOW	1000	200-350	1,000		fully commensal 5000 deg2 absorption survey	