

# HI Galaxy Science with the SKA

Martin Meyer &  
Erwin de Blok

on behalf of the HI SWG



International Centre  
for  
Radio Astronomy Research



# HI galaxy science

HI is a prime tracer for the assembly of mass, structure, and angular momentum

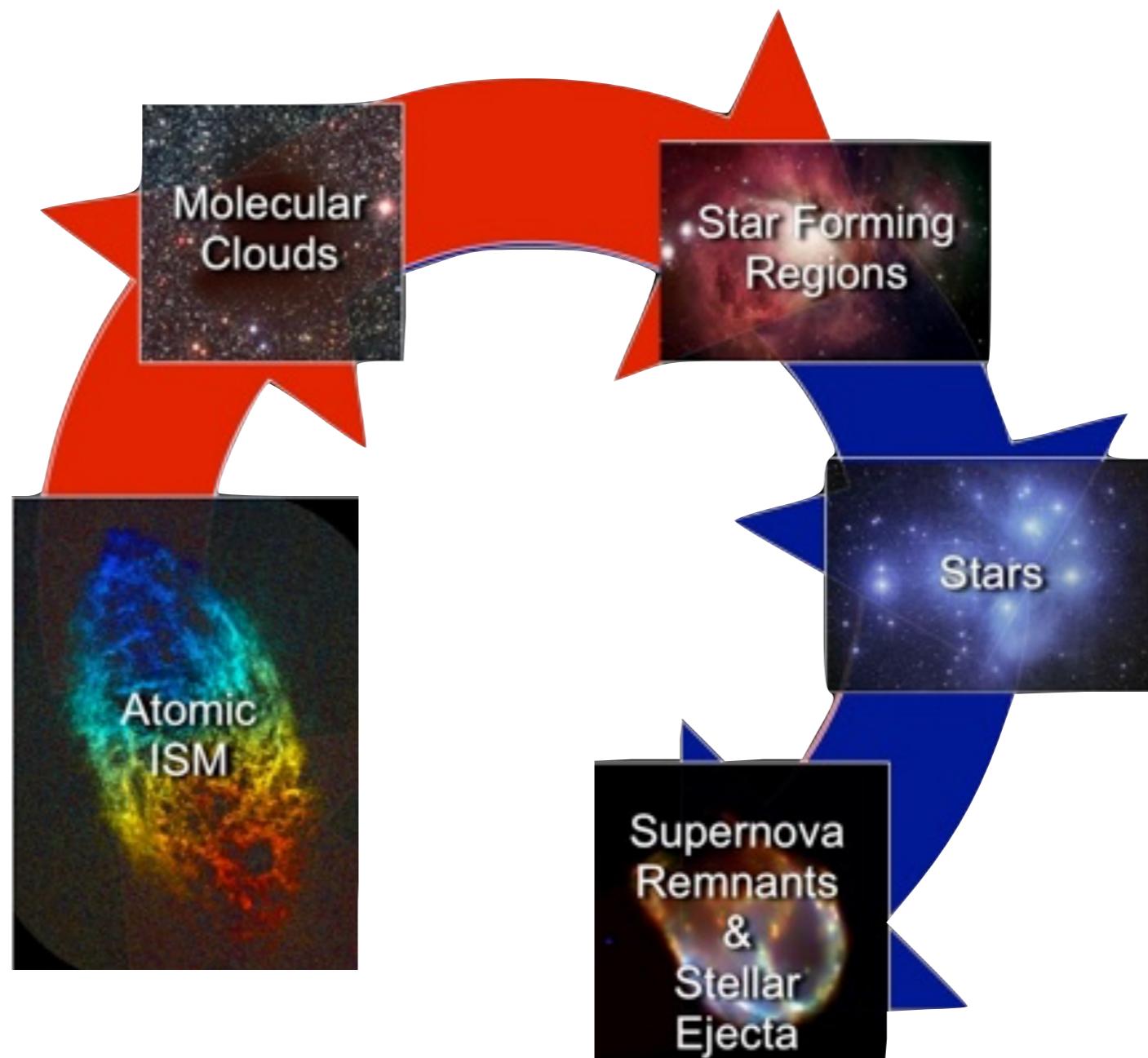
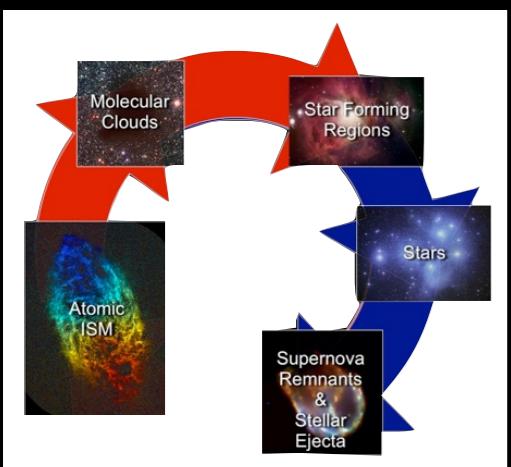
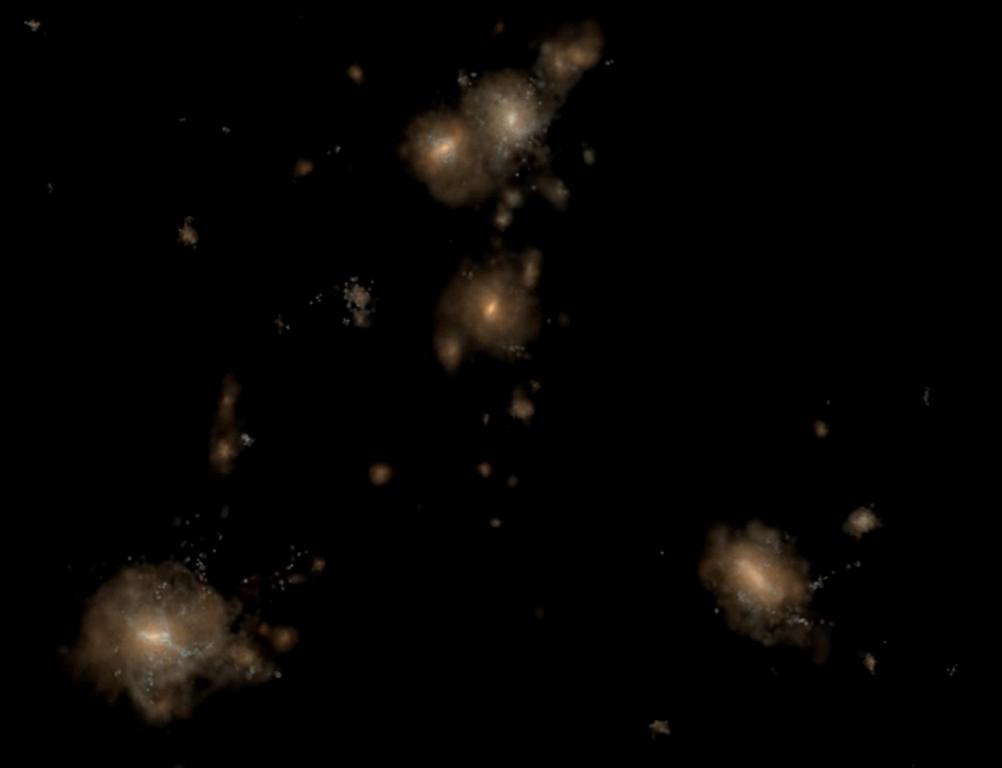


Image: Rosolowsky

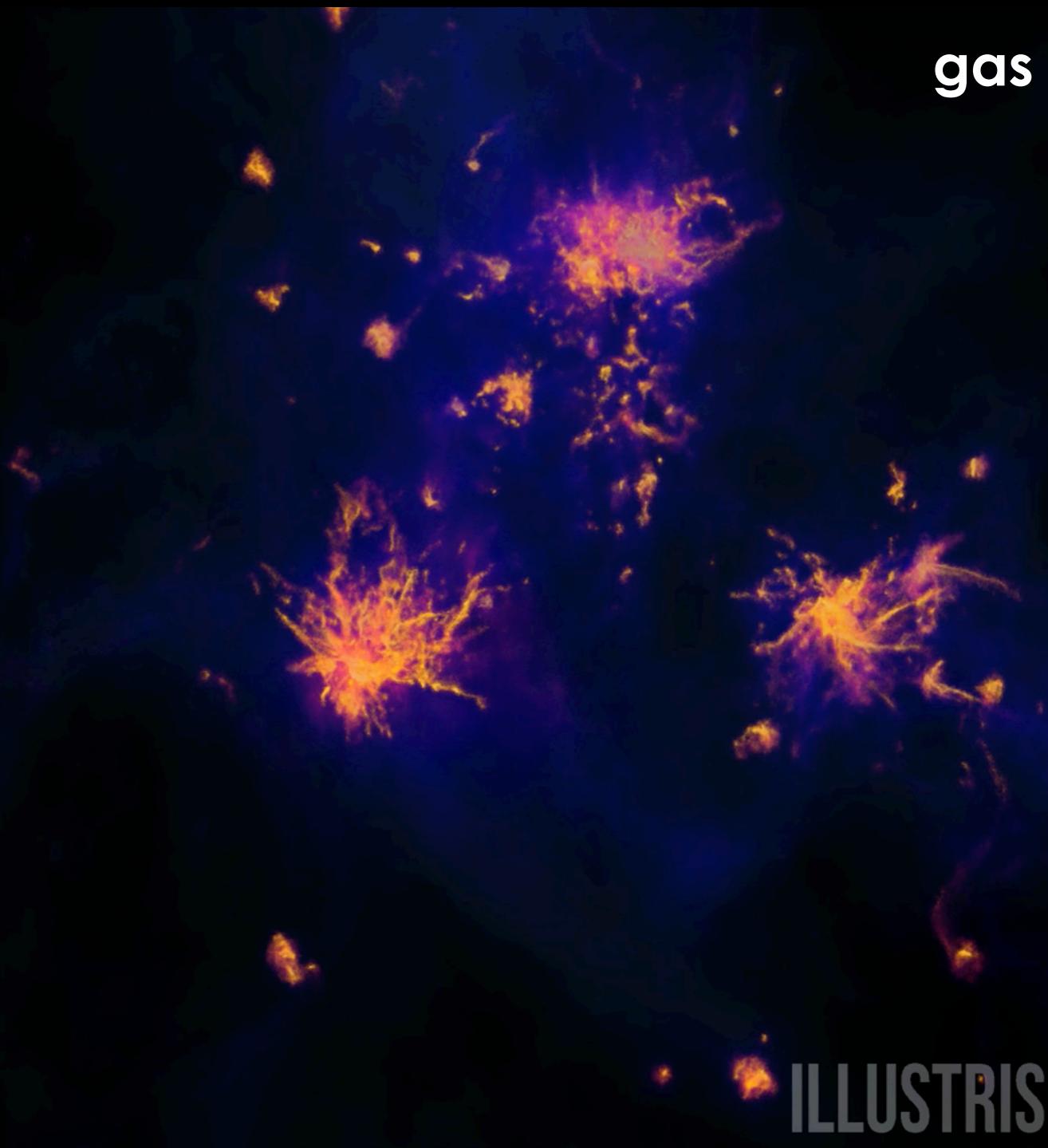


# HI galaxy science

stars

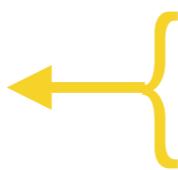


gas



# SKA1 HI Science Priorities

- 13: Resolved HI kinematics and morphology of  $\sim 10^{10} M_{\odot}$  mass **galaxies out to  $z \sim 0.8$**
- 14: High spatial resolution studies of the **ISM in the nearby Universe.**
- 15: Multi-resolution mapping studies of the **ISM in our Galaxy**
- 16: **HI absorption studies** out to the highest redshifts.
- 17: The gaseous interface and accretion physics between **galaxies and the IGM**



## SKA1 science goals

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 $\sim 10^{10} M_{\odot}$ mass galaxies out to $z \sim 0.8$	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 $z \sim 2$ 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 ( $\sim 100$ 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.



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## High Priority Science Objectives

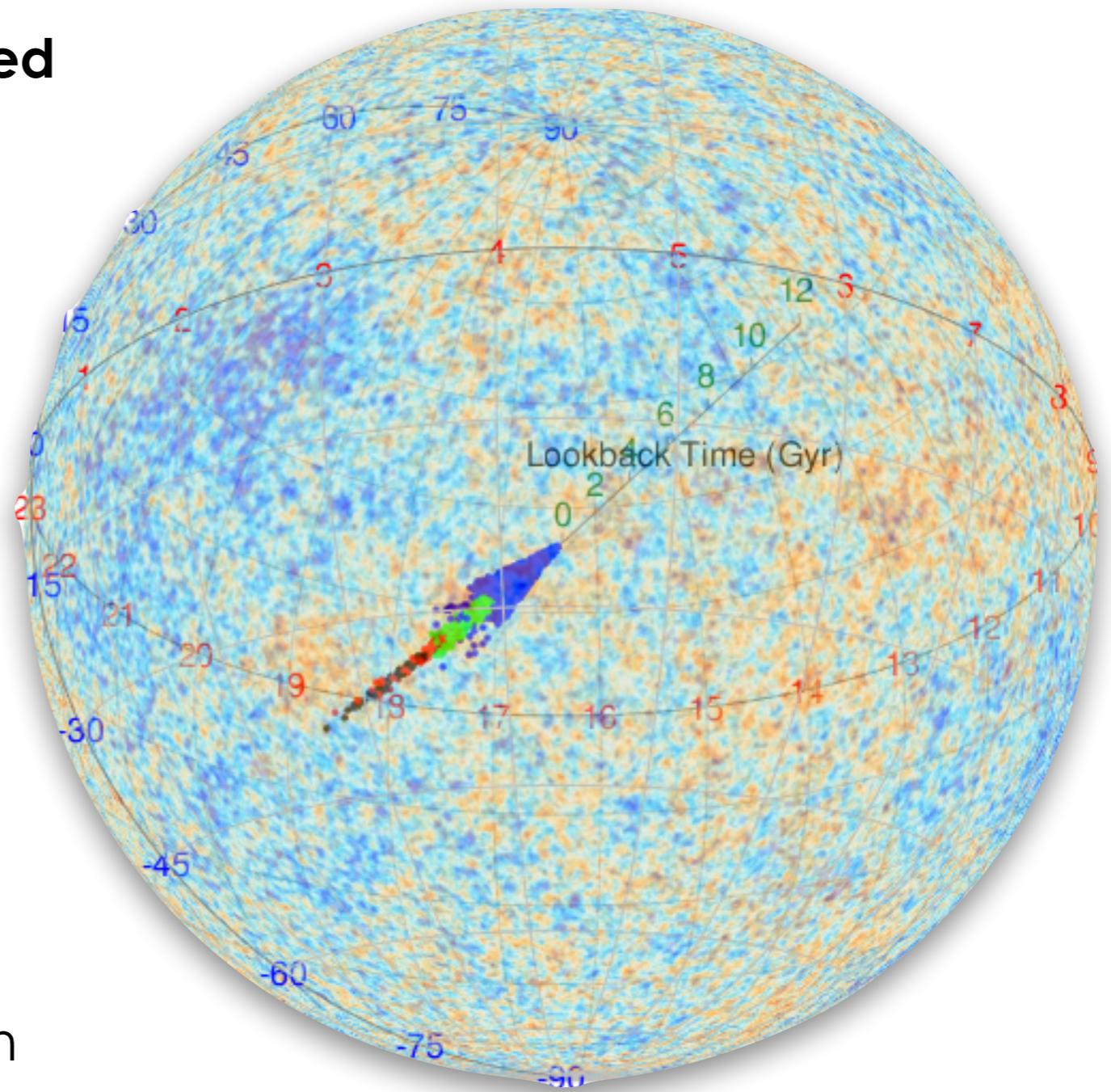


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13	HI	Resolved HI kinematics and morphology of $\sim 10^{10} M_{\odot}$ mass galaxies out to $z \sim 0.8$	1/5
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15	HI	Multi-resolution mapping studies of the ISM in our Galaxy	3/5
18	Transients	Solve missing baryon problem at $z \sim 2$ and determine the Dark Energy Equation of State	=1/4
22	Cradle of Life	Map dust grain growth in the terrestrial planet forming zones at a distance of 100 pc	1/5
27	Magnetism	The resolved all-Sky characterisation of the interstellar and intergalactic magnetic fields	1/5
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
37 + 38	Continuum	Star formation history of the Universe (SFHU) – I+II. Non-thermal & Thermal processes	1+2/8

- 16: **HI absorption studies** out to the highest redshifts.
- 17: The gaseous interface and accretion physics between **galaxies and the IGM**

## HPSO-13

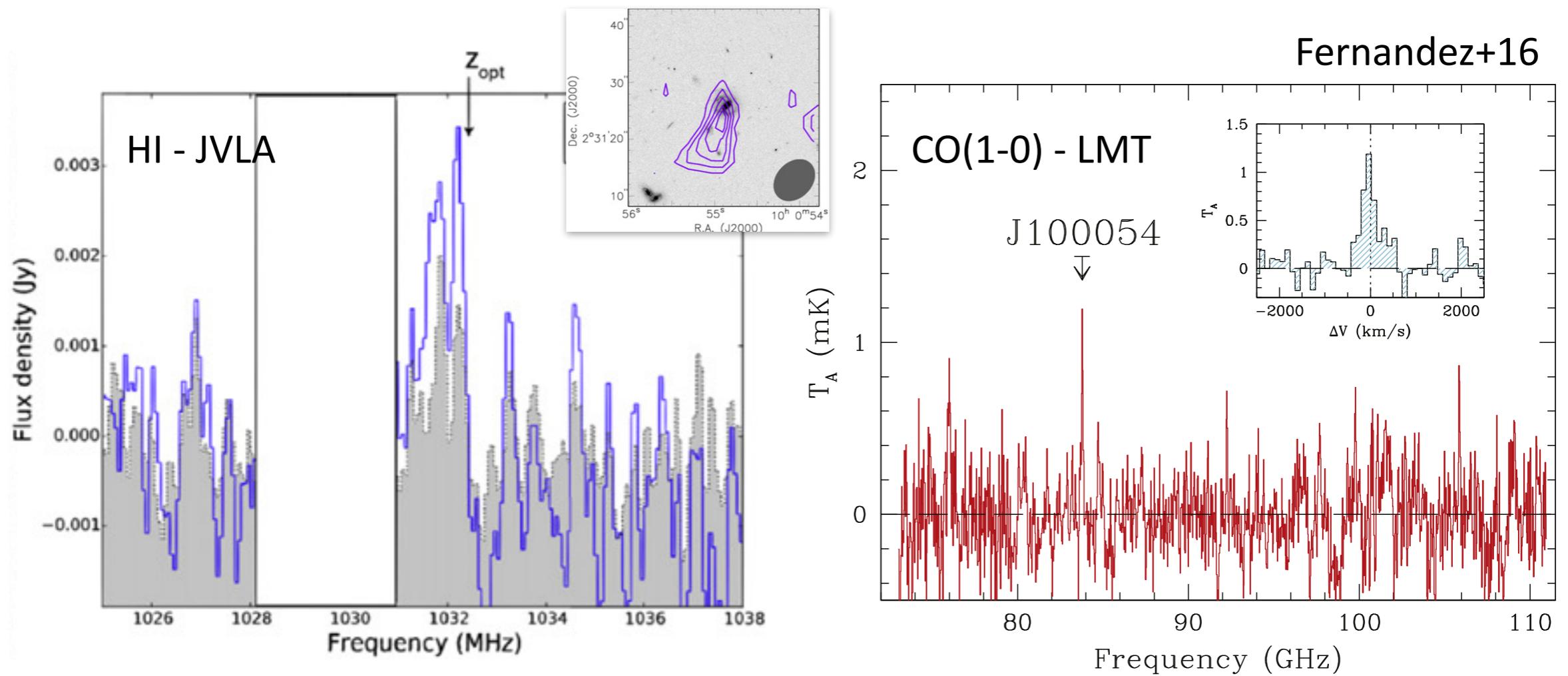
- Only few hundred galaxies detected in HI beyond the local Universe
- SKA1 and its pathfinders will revolutionise
- Unique opportunity for SKA1 to **resolve**  $M_{\text{HI}} \sim 10^{10} M_{\odot}$  gals to  $z < 0.8$
- Mass Assembly:  $\Omega_{\text{HI}}$  & HI mass function; baryon cycle; DM dependencies
- Impact of Environment: gas inflow and removal
- Angular momentum/kinematics: scaling relations, Tully-Fisher relation



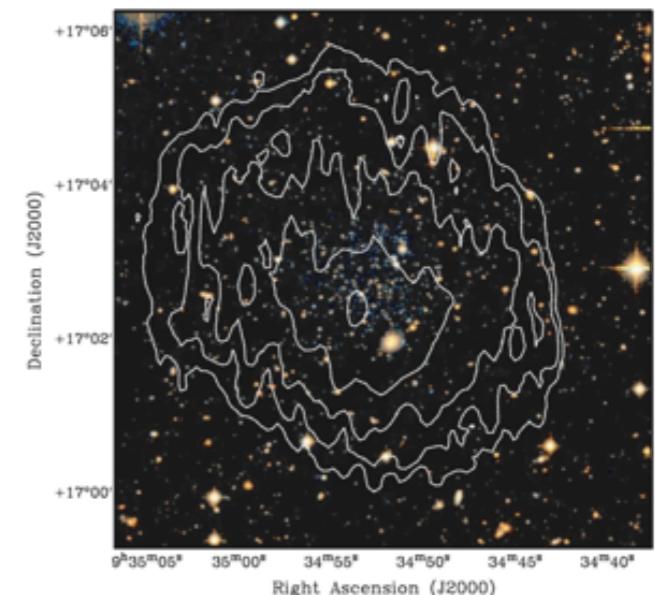
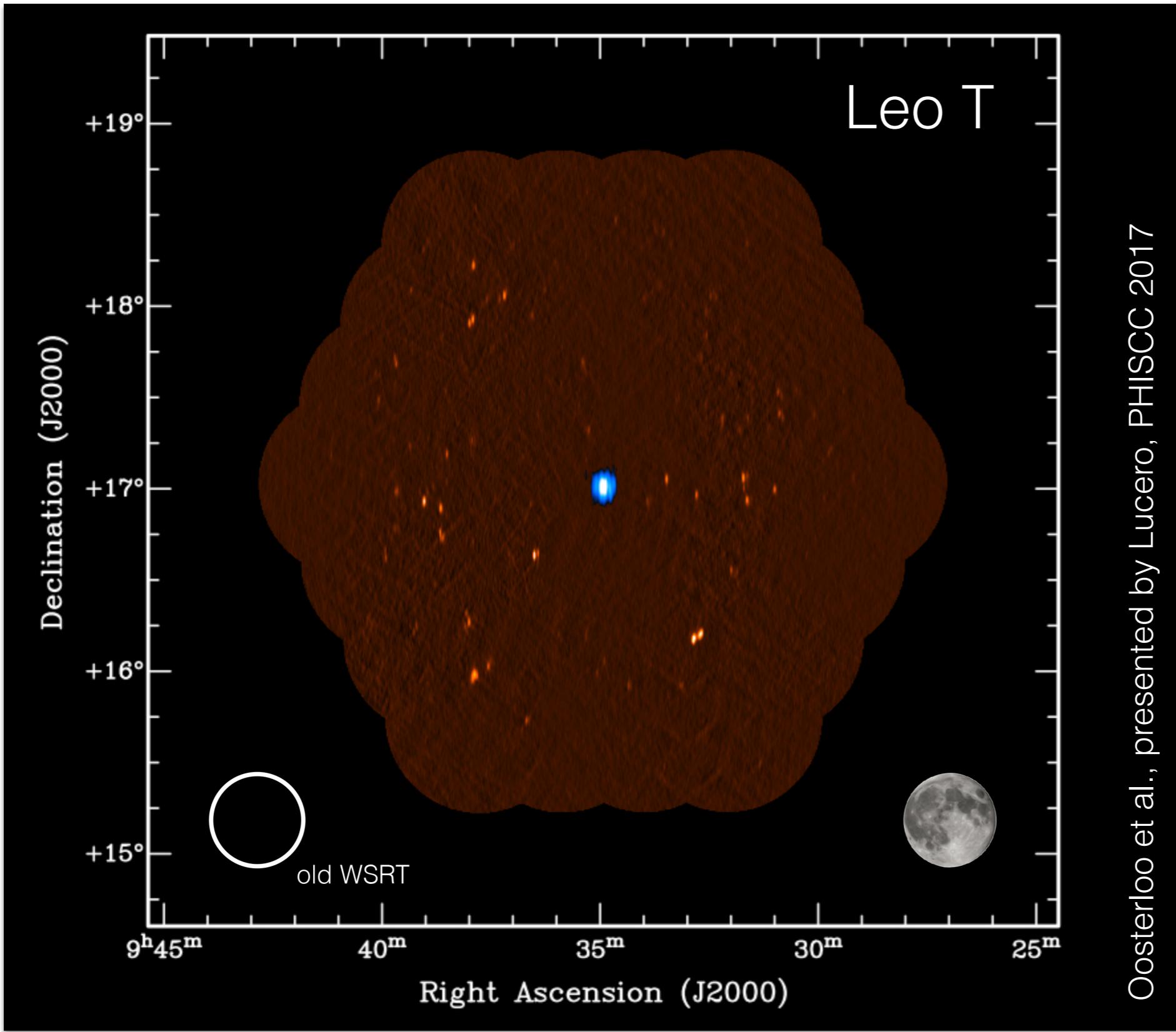
# Recent Progress: JVLA CHILES



- The COSMOS HI Large Extragalactic Survey, Pl. van Gorkom
- 1000hr,  $\sim 300$  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<sub>2</sub> gas ( $M_{\text{HI}} = 3 \times 10^{10} M_{\odot}$ )



# Recent Progress: Apertif

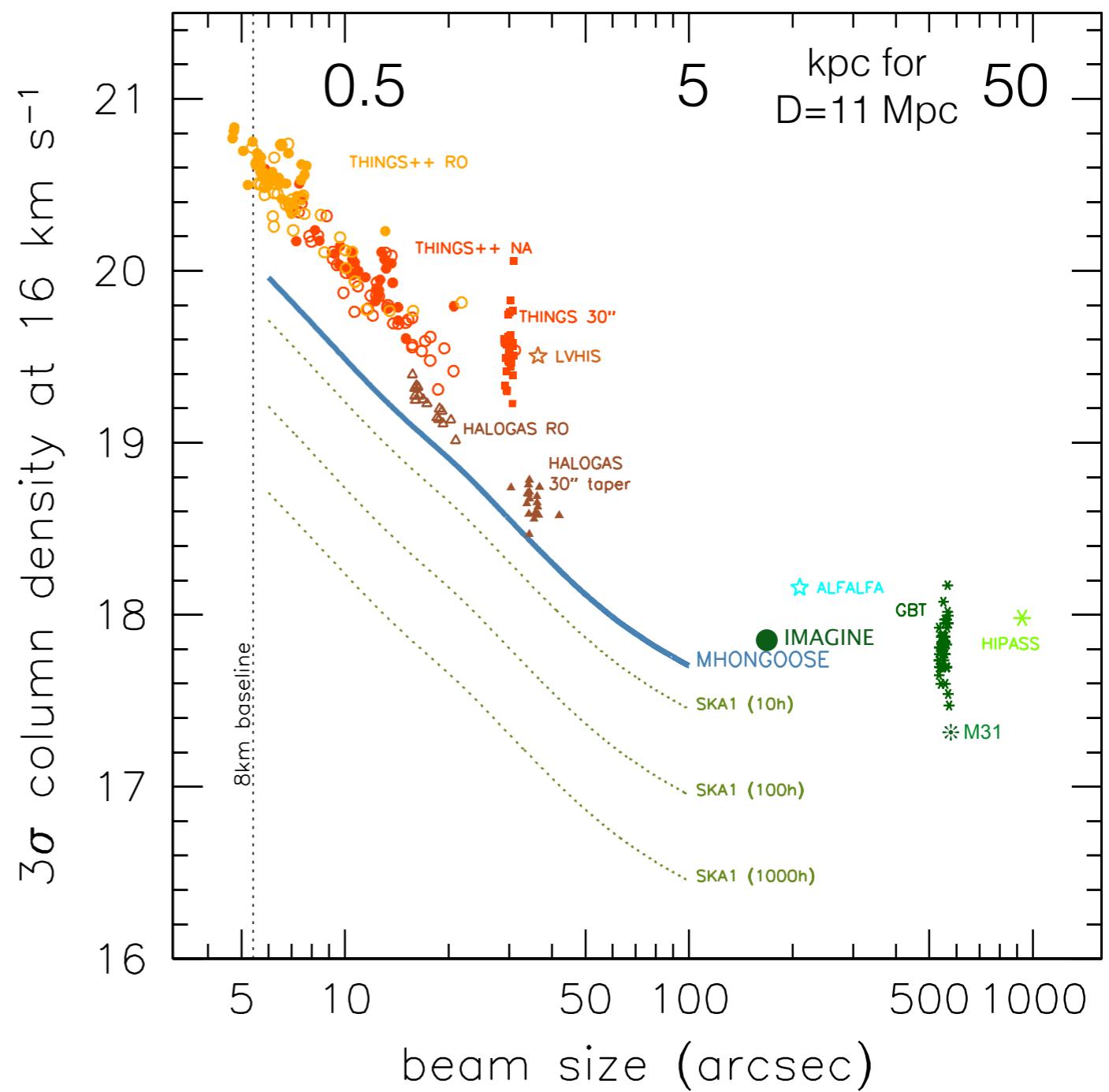


$$\bullet M_{\text{HI}} = 2.8 \times 10^5 M_{\odot}$$

## HPSO-14 and PSO-17

**Deep HI studies in the local Universe will give new understandings of gas fuelling and the ISM**

- SKA will enable high spatial resolution ( $\sim 100\text{pc}$ ) and low column density sensitivity (sub  $10^{20}$ )
- Understand the connection between star formation on small scales and global scaling laws
- Understand how galaxies acquire sufficient gas to sustain their star formation rates?



de Blok et al, 2015, PoS, AASKA14, 129

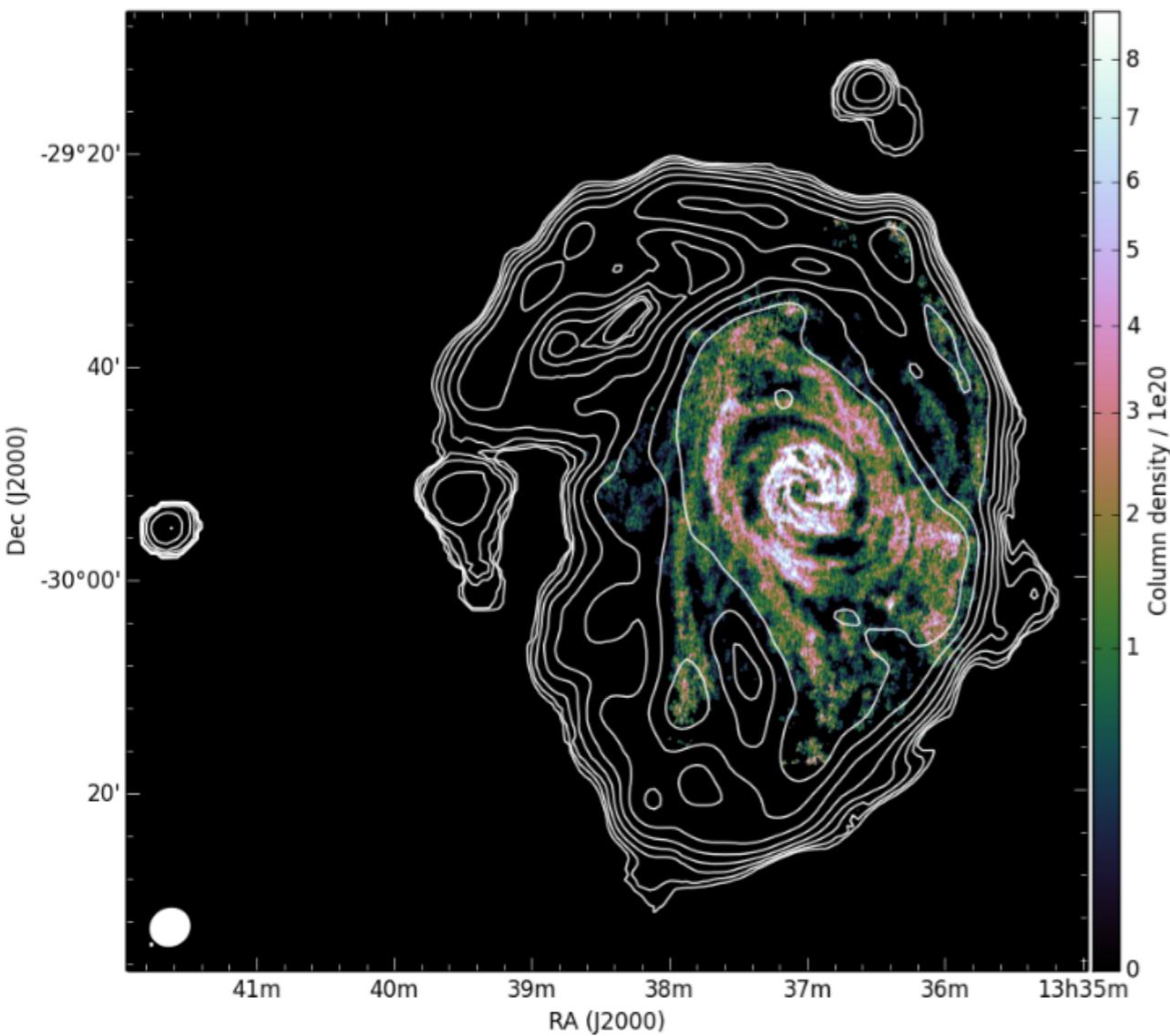
Popping et al, 2015, PoS, AASKA14, 132

Credit: de Blok, ASTRON

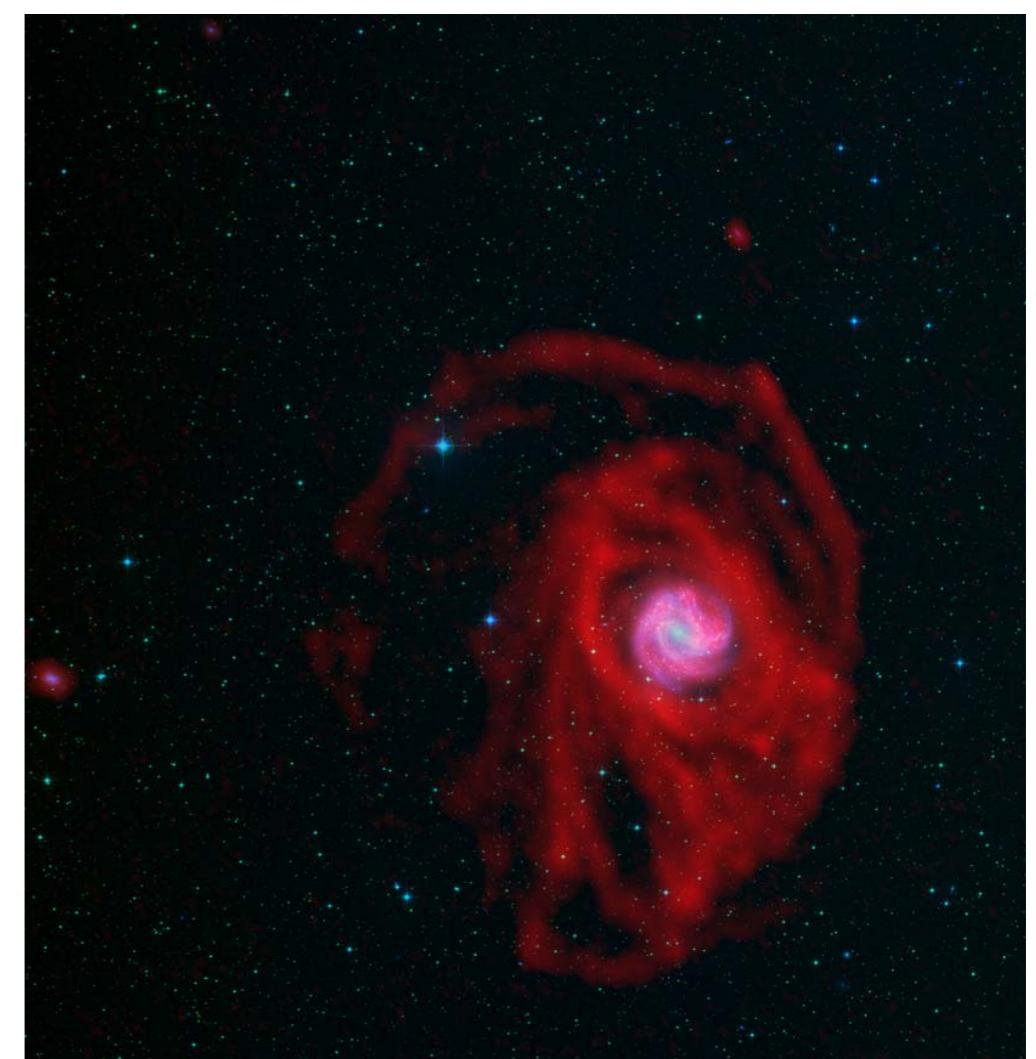
# Recent Progress: MeerKAT



**Revealing the edge of M83 & interaction with IGM (Heald+ 2016)**



KAT-7



MeerKAT, April 2017

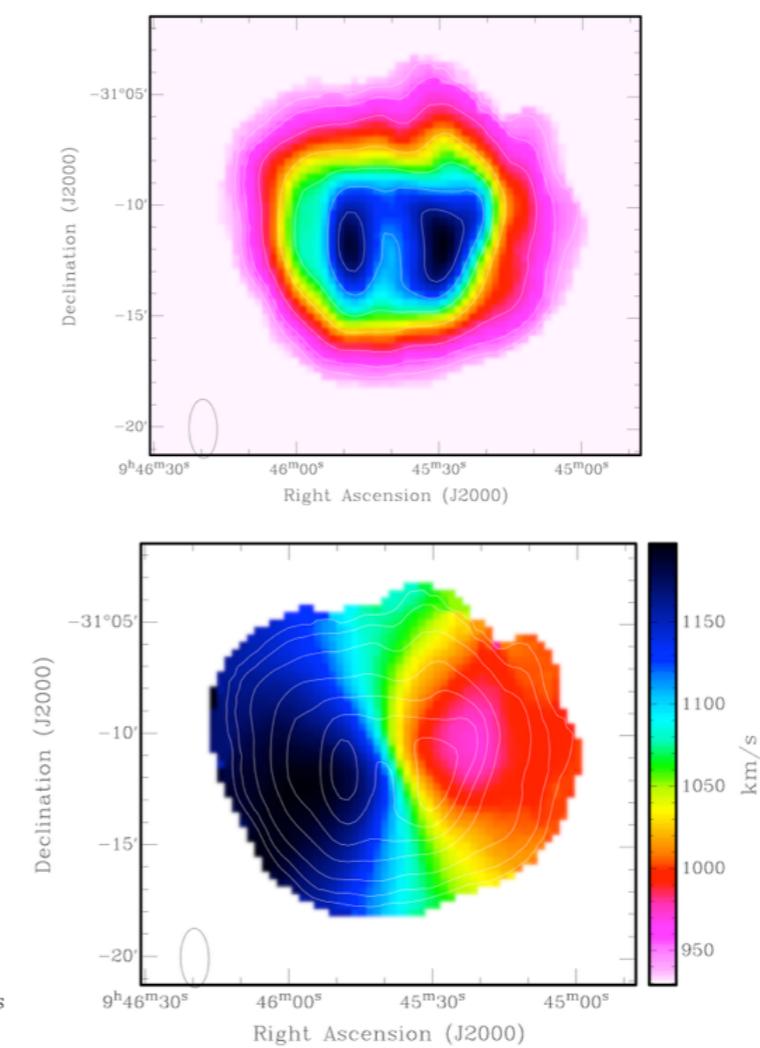
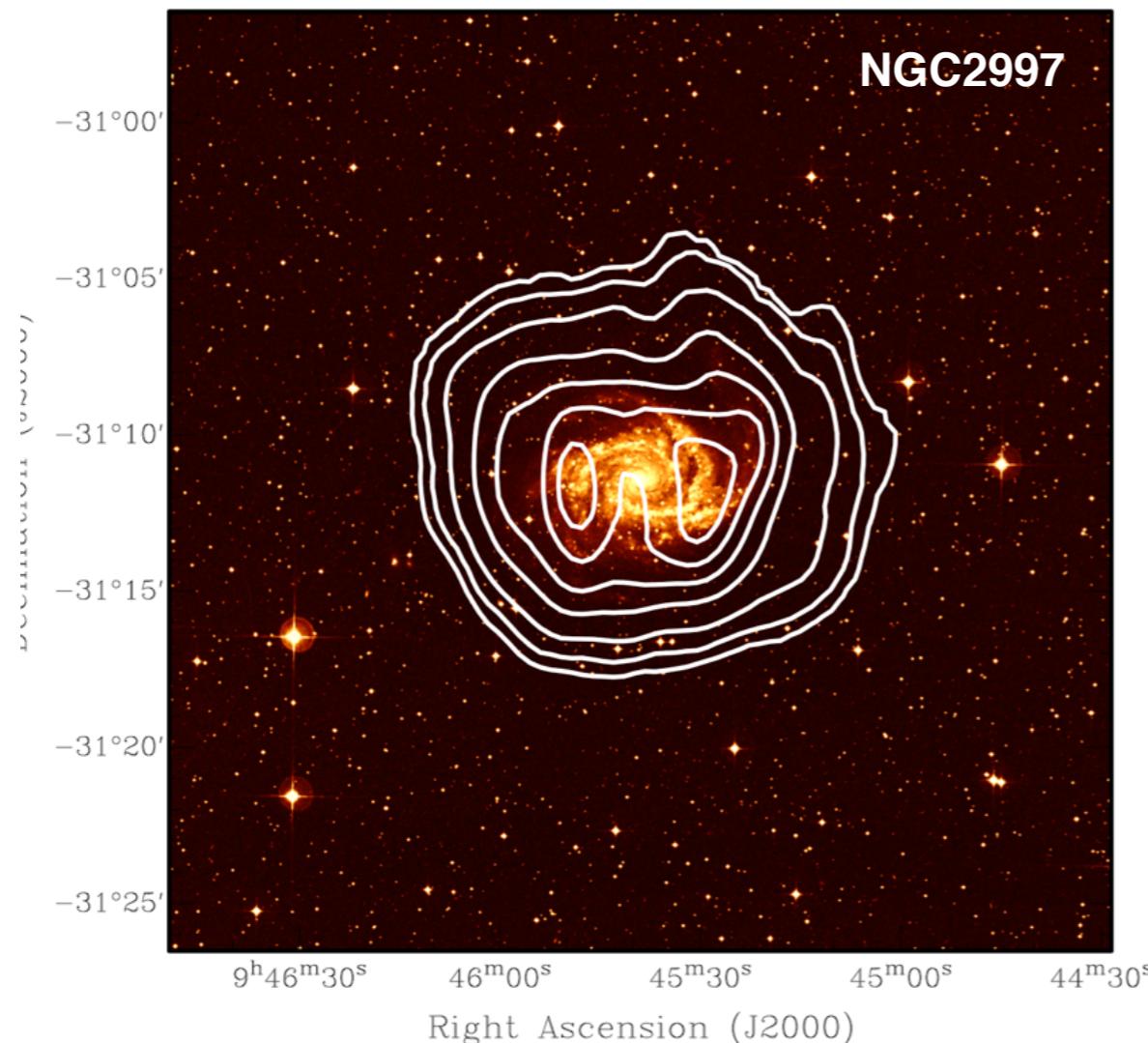


# Recent Progress: IMAGINE



## Imaging Galaxies Intergalactic and Nearby Environment

- PI: Attila Popping
- 28 spiral Galaxies and their direct environment
- 8 most compact ATCA configs
- Total time 2688 hours
- $N_{\text{HI}} \sim 2.5 \times 10^{17} \text{ cm}^{-2}$  over  $20 \text{ km s}^{-1}$
- resolution 1' to 2.5'
- SKA PSO-17 precursor experiment

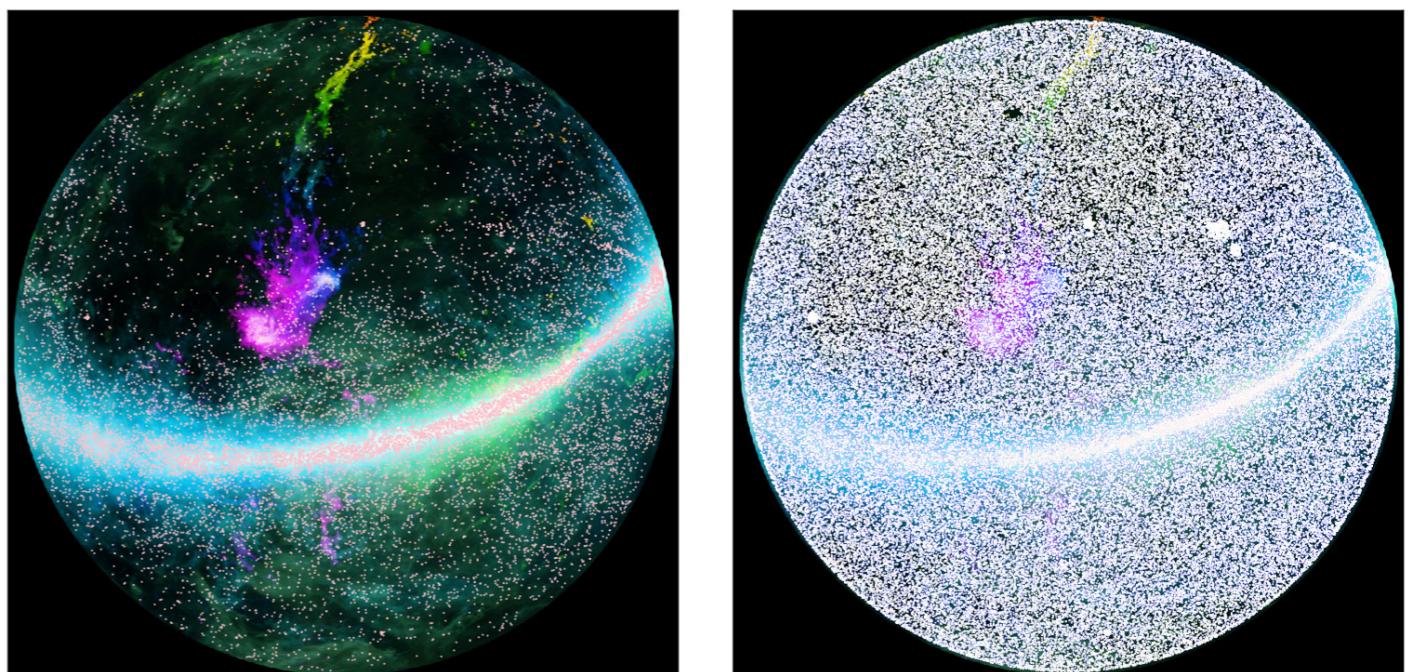
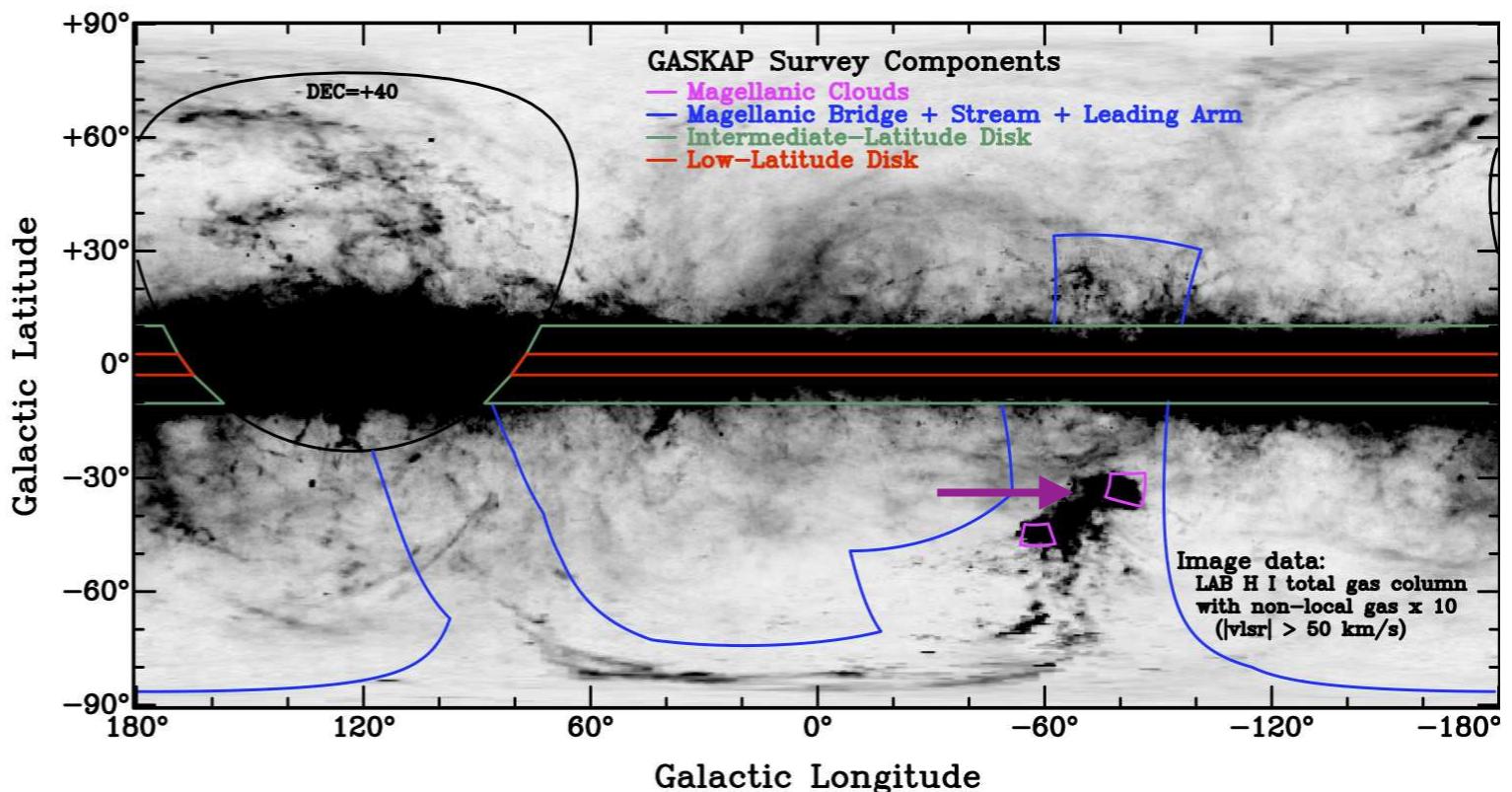


# Milky Way & Magellanic System

## HPSO-15

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

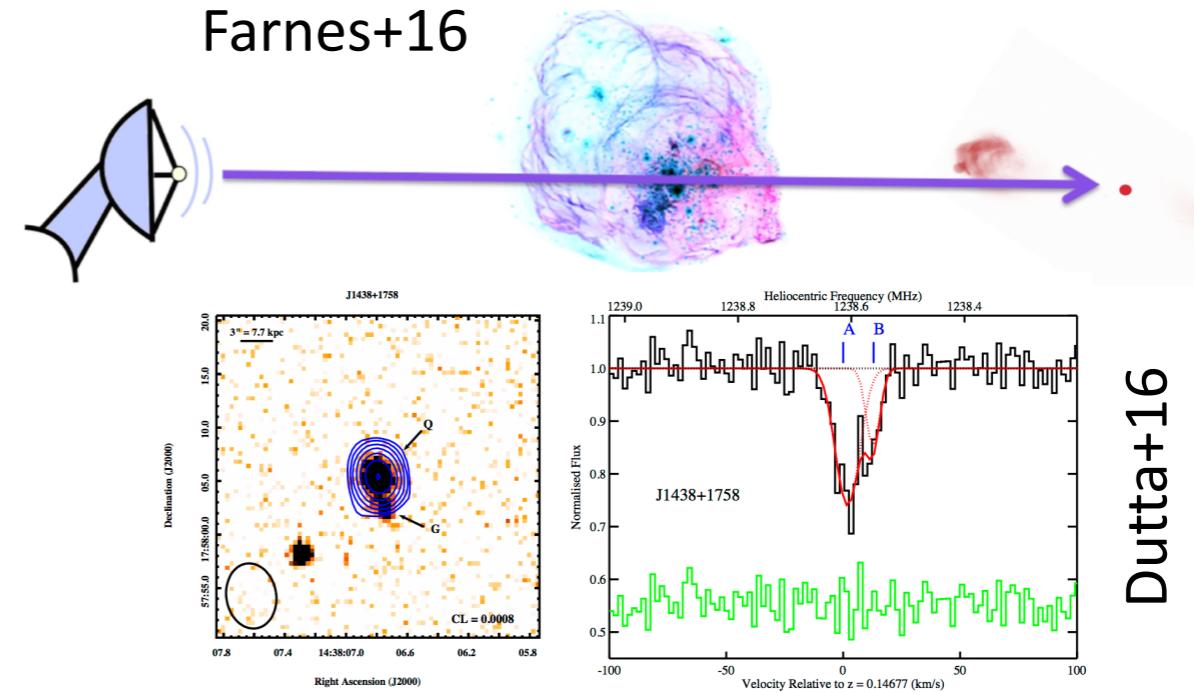
- How is gas exchanged with surrounding IGM?
- How is warm surrounding diffuse gas cooled into molecular clouds, stars?
- SKA will have surface brightness sensitivity, point source sensitivity and angular resolution to understand Milky Way gas all the way from the halo down to the formation of individual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



# HI absorption and AGN at $z < 6$

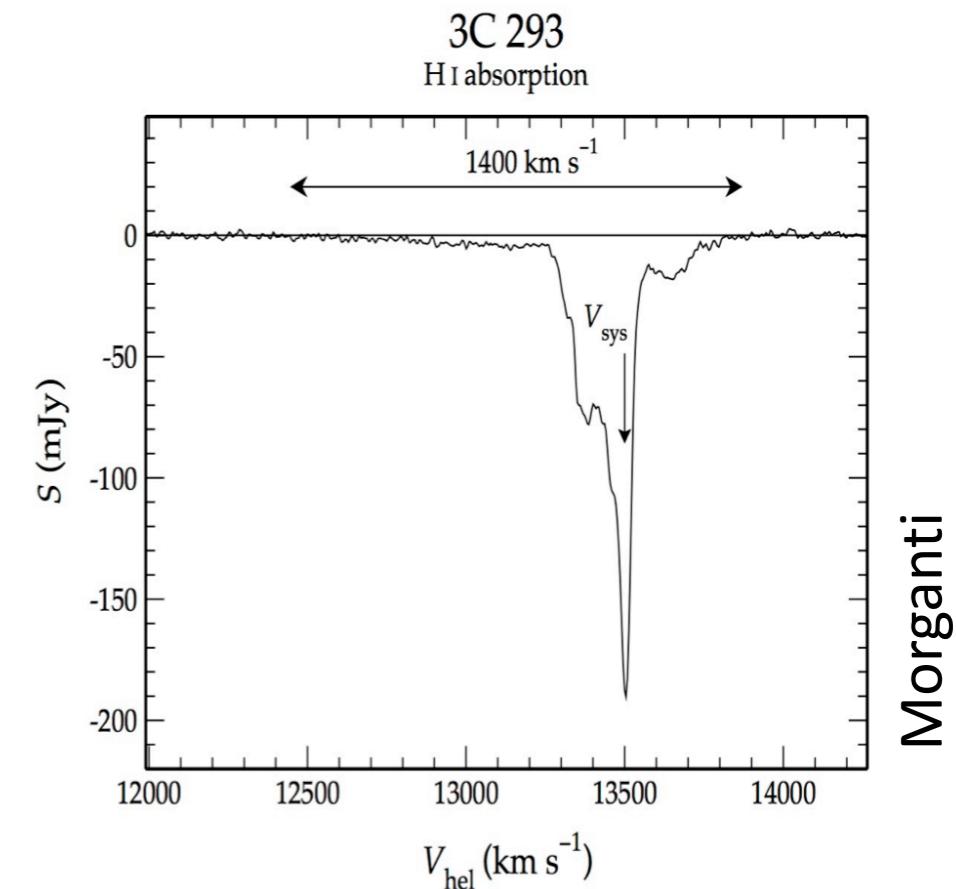
## PSO-16

HI 21-cm absorption spectroscopy provides a unique probe of cold neutral gas in normal and active galaxies from redshift  $z \sim 6$  to the present day.

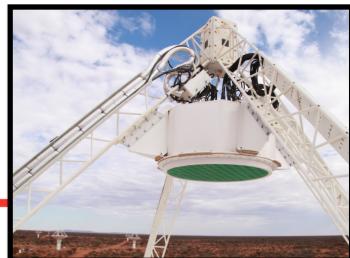


- Intervening HI 21cm absorption → constrain the evolution of cold gas in normal galaxies over more than 12 billion years of cosmic time.
- Associated HI 21cm absorption → content of individual galaxies, structure of the central regions and the feeding and feedback of AGN.

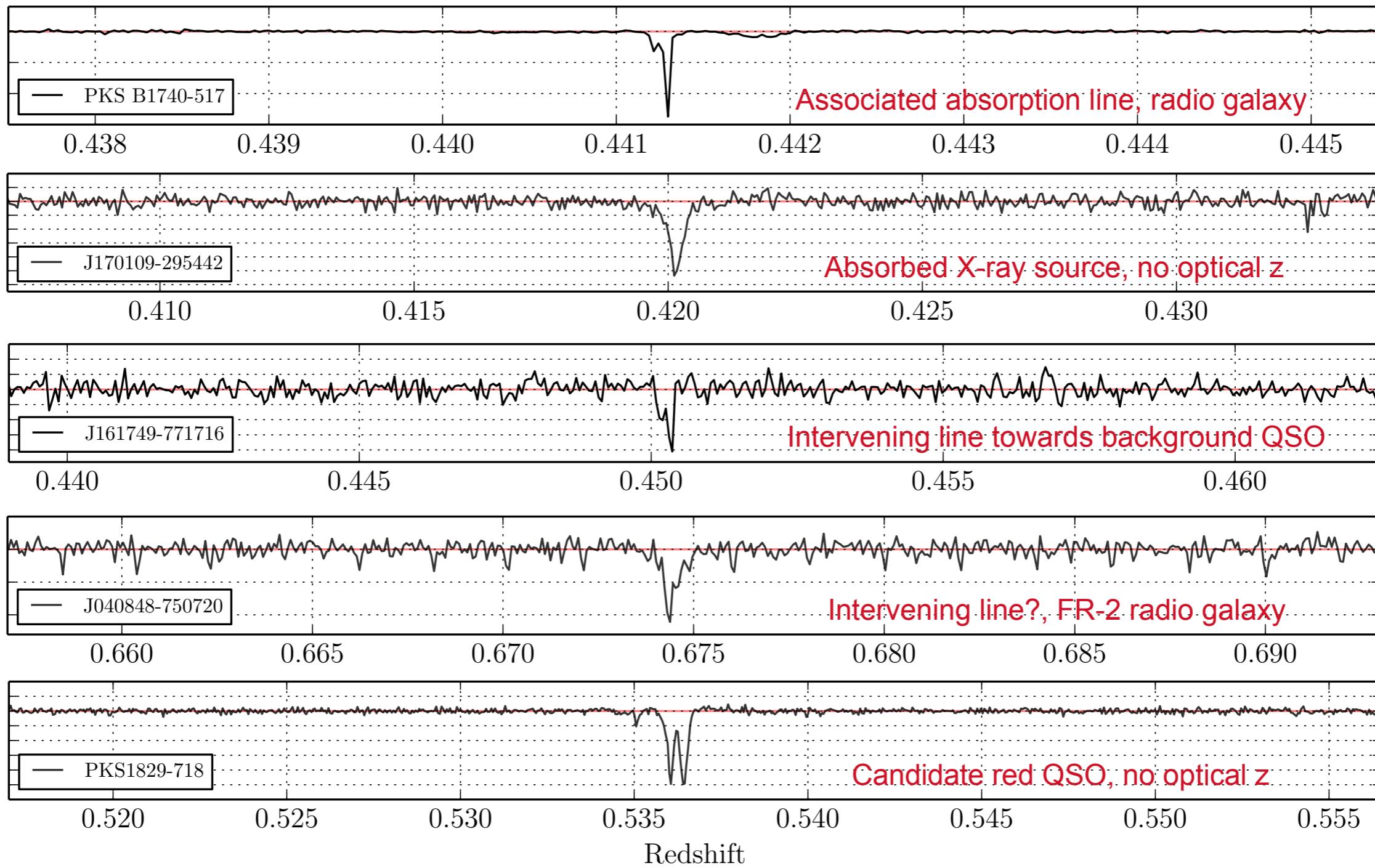
Morganti et al, 2015, PoS, AASKA14, 134



# Recent Progress: ASKAP HI



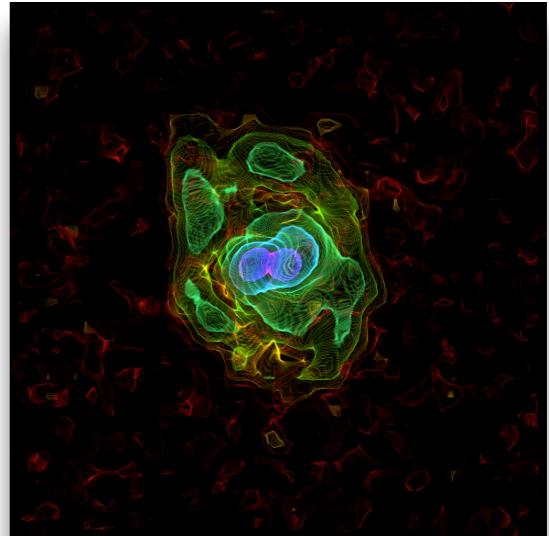
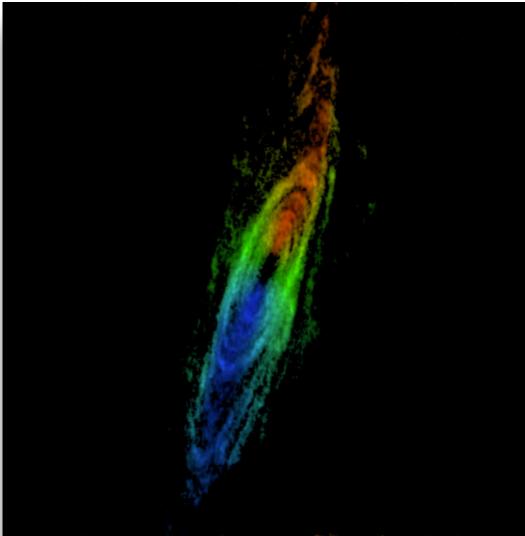
## Discoveries of HI absorption at cosmological redshifts



# Recent Activities: HI Analysis Tools

## Source Finding:

-  **SoFiA**  
Source Finding Application



## Kinematic Analysis:

-   **2DBAT** **TiViFiC**

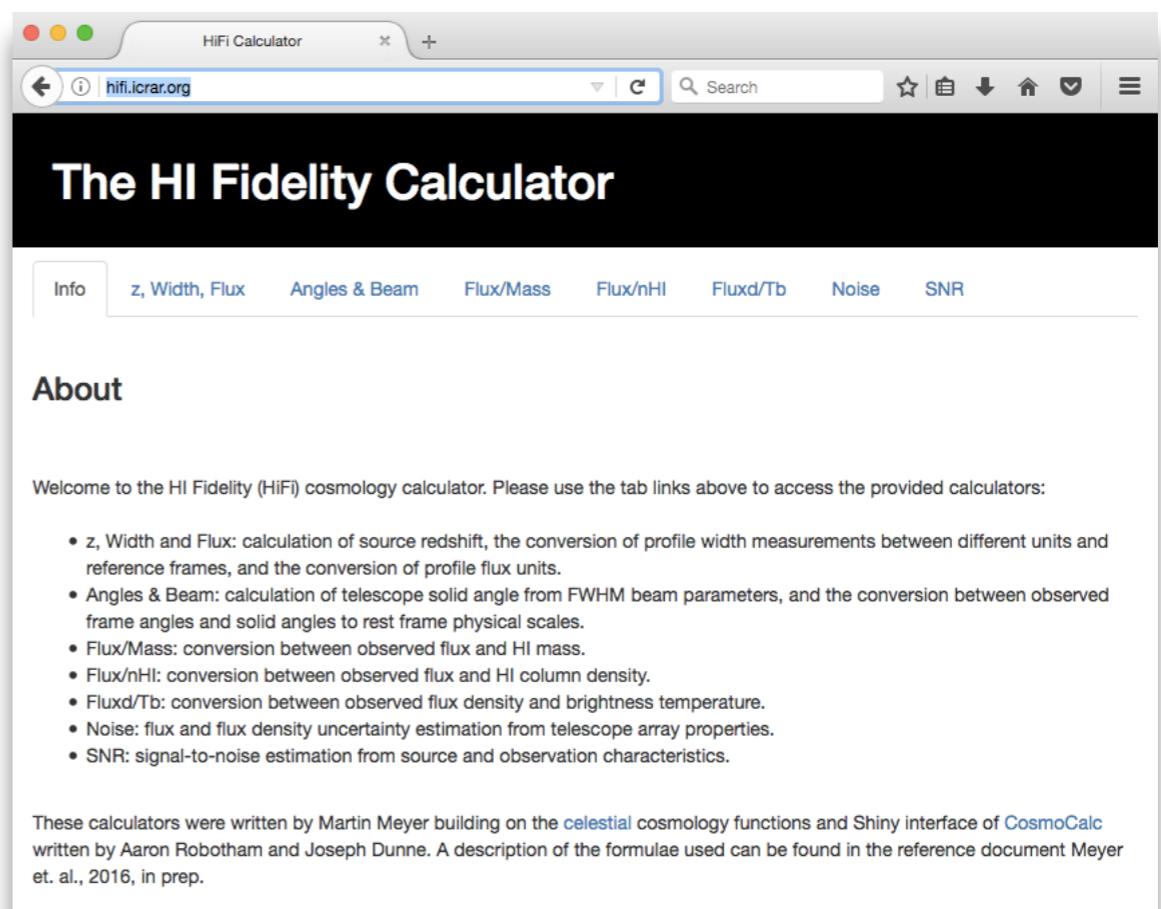
## Visualisation:

- SlicerAstro

## Analysis:

- HI stacking, IM
- HiFi Calculator

Davide Punzo 2016: **SlicerAstro**



The HI Fidelity Calculator

Welcome to the HI Fidelity (HiFi) cosmology calculator. Please use the tab links above to access the provided calculators:

- z, Width and Flux: calculation of source redshift, the conversion of profile width measurements between different units and reference frames, and the conversion of profile flux units.
- Angles & Beam: calculation of telescope solid angle from FWHM beam parameters, and the conversion between observed frame angles and solid angles to rest frame physical scales.
- Flux/Mass: conversion between observed flux and HI mass.
- Flux/nHI: conversion between observed flux and HI column density.
- Fluxd/Tb: conversion between observed flux density and brightness temperature.
- Noise: flux and flux density uncertainty estimation from telescope array properties.
- SNR: signal-to-noise estimation from source and observation characteristics.

These calculators were written by Martin Meyer building on the [celestial](#) cosmology functions and Shiny interface of [CosmoCalc](#) written by Aaron Robotham and Joseph Dunne. A description of the formulae used can be found in the reference document Meyer et. al., 2016, in prep.



# Proposed SKA1 HI surveys

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



# Commensality

Survey	Area	Freq	T	Magnetism	Cosmology/ EoR	Continuum
	(deg <sup>2</sup> )	MHz	(hrs)			
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

# Cost control: impact on HI science

## HI ranking scheme

1	No significant impact
2	Increased time
2	Impacts HI absorption science only
3	High risk
4	Lost capability

## Rank 1: No significant impact

- Cuts to MID baselines > 120 km
- PSS changes
- CBF-MID changes
- Band 5 (no direct HI science)

**SKAO impact      HI SWG impact**

Cost Control Option	LOW / MID / COMMON	SKAO Science Impact	SKAO Rank	HI SWG Science Impact	HI SWG Rank	HI SWG transformational Science Impact
Reduce Bmax MID from 150 to 120 km: Case B, remove infra, add dishes to core	MID	2	14	1	1	N
INFRA_SA Renewable energy to outer dishes	MID	1	1	1	2	N
Maximise use of code produced during Pre-Construction	COMM	1	2	1	3	N
Simplify DDBH LOW	LOW	1	3	1	4	N
Simplify DDBH MID	MID	1	4	1	5	N
Reduce PSS-MID: A, 750 nodes to 500 nodes	MID	1	5	1	6	N
Reduce PSS-LOW: A, 250 nodes to 167 nodes	LOW	1	6	1	7	N
Reduce CBF-MID: Freq. Slice variant of CSP design vs. MeerKAT-based design	MID	1	7	1	8	N
MID Frequency and Timing Standard: SaDT solution vs. MeerKAT-based solution	MID	1	8	1	9	N
MID SPF Digitisers: DSH solution vs. MeerKAT-based solution	MID	1	9	1	10	N
LOW RPF: Early Digital Beam Formation vs. Analogue Beam Formation.	LOW	1	10	1	11	N
LOW Antenna: Log Periodic Design vs. Dipole Design	LOW	3	11	1	12	N
Reduce Bandwidth output of band 5 to 2.5GHz	MID	2	16	1	13	N
Reduce MID Band 5 feeds: A, from 130 to 67	MID	2	17	1	14	N
Reduce PSS-LOW: B, 167 nodes to 125 nodes	LOW	2	18	1	15	N
Reduce PSS-MID: B, 500 nodes to 375 nodes	MID	2	19	1	16	N
Reduce MID CBF and DSH BW: 5 to 1.4 GHz	MID	2	20	1	17	N
Reduce PSS-LOW: C, 125 nodes to 83 nodes	LOW	3	25	1	18	N
Reduce PSS-MID: B, 375 nodes to 250 nodes	MID	3	26	1	19	N
Reduce MID Band 5 feeds: B, from 67 to 0	MID	4	36	1	20	N
Reduce Bmax MID from 150 to 120 km: Case A, remove 3 dishes, keep infra to 150km	MID	2	13	1	21	N
Reduce Bmax MID from 150 to 120 km: Case C, remove infra, remove dishes	MID	2	15	1	22	N



# Cost control: impact on HI science

## Rank 2: Time increase & Impact HI Absorption Science Only

- Mild cuts to SDP
- All cuts to LOW
- Loss of baselines > 10's of km for MID

HI SWG impact



WS / Origin	Cost Control Option	LOW / MID / COMMON	SKAO Science Impact	SKAO Rank	HI SWG Science Impact	HI SWG Rank	HI SWG transformational Science Impact
8	SDP- HPC: Deploy 200 Pflops (rather than 260 Pflops)	COMM	2	12	2	23	N
5.31	Reduce CBF-LOW BW: A, 300 to 200 MHz	LOW	2	21	2	24	N
5.30.00	Reduce Bmax LOW to 50km: A, remove infra, add 18 stations to core	LOW	3	23	2	25	N
5.30.00	Reduce Bmax LOW to 50km: B, remove 18 stations	LOW	3	24	2	26	N
5.30a	Reduce Bmax LOW to 40km: C, remove next 18 stations	LOW	3	27	2	27	N
5.30 / D	Remove 54 LOW stations from core	LOW	4	31	2	28	N
5.30 / D	Remove additional 54 LOW stations from core	LOW	4	33	2	29	N
5.24.2	Reduce Bmax MID from 120 to 100 km: D, remove infra, remove next 3 dishes	MID	4	34	2	30	N



# Cost control: impact on HI science

## Rank 3: High Risk & Rank 4: Severe

- **Major cuts to SDP:** potential to cause inability to deliver HI cubes of sufficient resolution for HPSO science (NB many factors require consideration for full assessment: flops, i/o, efficiency, commensality)
- **Cuts to MID core:** loss of sensitivity impacts all HI HPSOs
- **Loss of MID band 1:** catastrophic loss of HI science on MID  $z>0.5$

WS / Origin	Cost Control Option	LOW / MID / COMMON	SKAO Science Impact	SKAO Rank	HI SWG Science Impact	HI SWG Rank	HI SWG transformational Science Impact
8	SDP- HPC: Deploy 150 Pflops (from 200 Pflops)	COMM	3	22	3	31	M
8	SDP- HPC: Deploy 100 Pflops (from 150 Pflops)	COMM	4	28	4	32	Y
8	SDP- HPC: Deploy 50 Pflops (from 100 Pflops)	COMM	4	29	4	33	Y
5.24 /	Remove 11 MID Dishes from core	MID	4	30	4	34	Y
5.24 /	Remove additional 11 MID Dishes from core	MID	4	32	4	35	Y
5.5.1	Remove MID Band 1 feeds: 105 to 0	MID	4	35	4	36	Y



# Cost control: impact on HI science

cf. “The Black Line”

SKAO impact

HI SWG impact



WS / Origin	Cost Control Option	LOW / MID / COMMON	SKAO Science Impact	SKAO Rank	HI SWG Science Impact	HI SWG Rank	HI SWG transformational Science Impact
8	<b>SDP- HPC: Deploy 150 Pflops (from 200 Pflops)</b>	COMM	3	22	3	31	M
5.30.00	<b>Reduce Bmax LOW to 50km: A, remove infra, add 18 stations to core</b>	LOW	3	23	2	25	N
5.30.00	<b>Reduce Bmax LOW to 50km: B, remove 18 stations</b>	LOW	3	24	2	26	N
5.25.2 /	<b>Reduce PSS-LOW: C, 125 nodes to 83 nodes</b>	LOW	3	25	1	18	N
5.25.2 /	<b>Reduce PSS-MID: B, 375 nodes to 250 nodes</b>	MID	3	26	1	19	N
5.30a	<b>Reduce Bmax LOW to 40km: C, remove next 18 stations</b>	LOW	3	27	2	27	N
8	<b>SDP- HPC: Deploy 100 Pflops (from 150 Pflops)</b>	COMM	4	28	4	32	Y
8	<b>SDP- HPC: Deploy 50 Pflops (from 100 Pflops)</b>	COMM	4	29	4	33	Y
5.24 /	<b>Remove 11 MID Dishes from core</b>	MID	4	30	4	34	Y
5.30 /	<b>Remove 54 LOW stations from core</b>	LOW	4	31	2	28	N
5.24 /	<b>Remove additional 11 MID Dishes from core</b>	MID	4	32	4	35	Y
5.30 /	<b>Remove additional 54 LOW stations from core</b>	LOW	4	33	2	29	N
5.24.2	<b>Reduce Bmax MID from 120 to 100 km: D, remove infra, remove next 3 dishes</b>	MID	4	34	2	30	N
5.5.1	<b>Remove MID Band 1 feeds: 105 to 0</b>	MID	4	35	4	36	Y
5.5.2	<b>Reduce MID Band 5 feeds: B, from 67 to 0</b>	MID	4	36	1	20	N



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. non-binary pulsar search). It is considered that the change from 2 beams/node to 6 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  $167/83 = 2$ .

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. non-binary 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  $500/250 = 2$ .

- Reduction in SDP has most potential impact on HI high priority science objectives, must retain sufficient resolution capability

This scenario involves removing the second outermost cluster of (16) stations as well as the outermost cluster of (16) stations. The remaining stations in the inner 1.2 km radius will be used to support the core science objectives. This will have significant consequences for foreground continuum source characterisation and removal.

SDP- HPC: Deploy 100 Pflops (from 150 Pflops)

This is especially important for the SDP system, as it will increase the duty cycle available for observations. Therefore, re-sizing the first major purchase and assembling the 100 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.

- Changes to LOW and reduction in angular resolution (MID & LOW) will impact HI absorption surveys

MID

Likely reduction in processed PSS beam number (2x) or pulsar search parameter space

3

25

## “Above the black line” - Loss of Transformational Science

SDP- HPC: Deploy 50 Pflops (from 100 Pflops)

This is especially important for the SDP system, as it will increase the duty cycle available for observations. Therefore, re-sizing the first major purchase and assembling the 50 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

27

- Stronger SDP cuts may render transformational science impossible due to resolution limitations

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  $(T_{obs\_new}/T_{obs\_now})^3$ ) 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.

COMMON

Lower allowed duty cycle for HPC- intensive observations.

4

29

- Reduction in shorter MID baselines impacts ability to deliver all HI science priority objectives

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% impact on core sensitivity, which would need to be addressed through increased integration time to compensate.

MID

10% Sensitivity loss in core

4

30

- Loss of MID band 1 would mean catastrophic loss of HI science

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  $(T_{obs\_new}/T_{obs\_now})^3$ ) 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



# Summary

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- **Ground-breaking HI galaxy science is possible with SKA1**
  - Resolved kinematics of  $M_{\text{HI}} = 10^{10} M_{\odot}$  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**
- **Transformational science is still overall possible with “above the black line” cost control measures (caveat SDP uncertainties), and as such is globally supported by the HI SWG**

