HI Galaxy Science with the SKA

Martin Meyer &
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on behalf of the HI SWG

ICRAR
International Centre for
Radio Astronomy Research

ASTRON

HI galaxy science

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

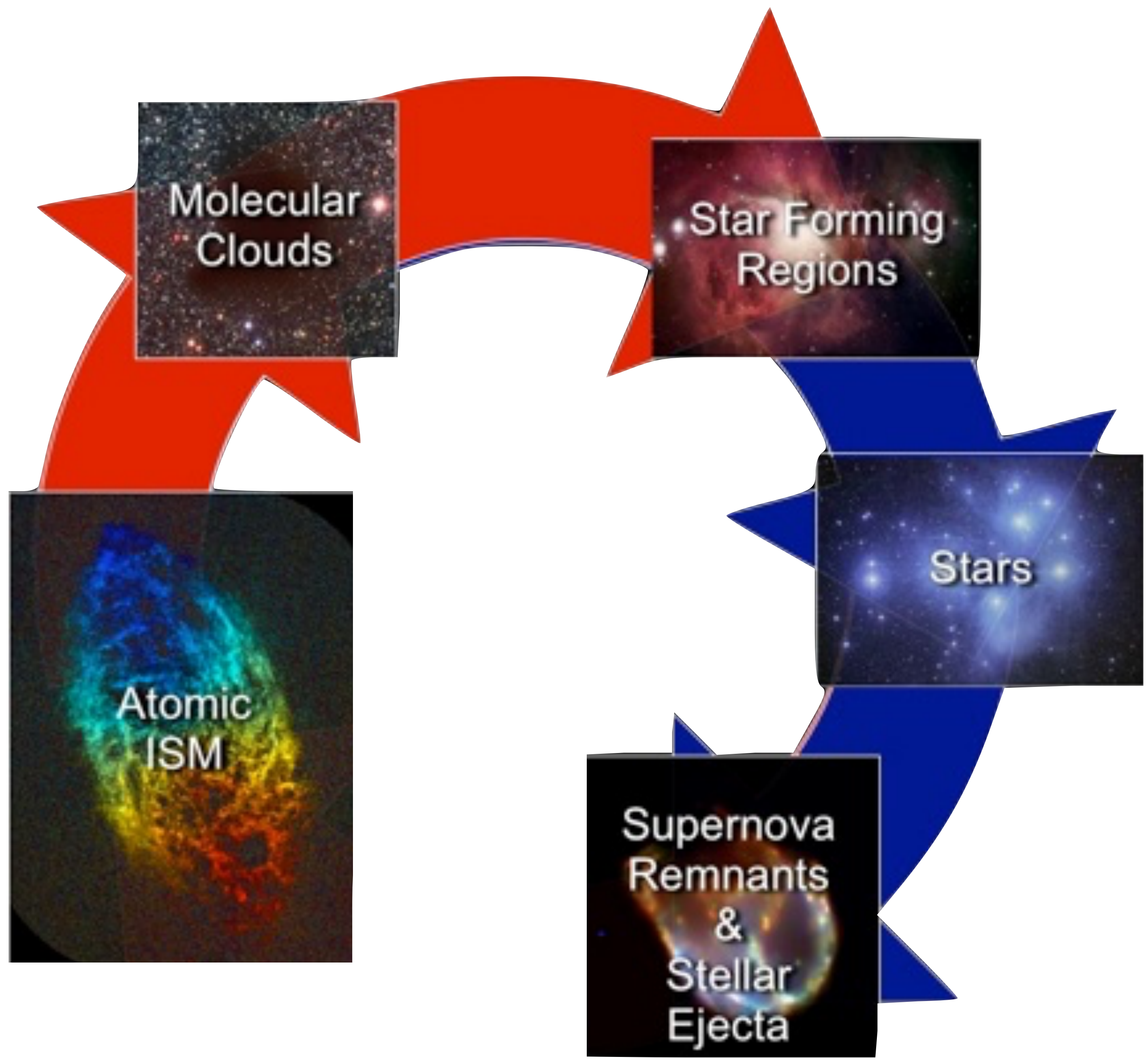
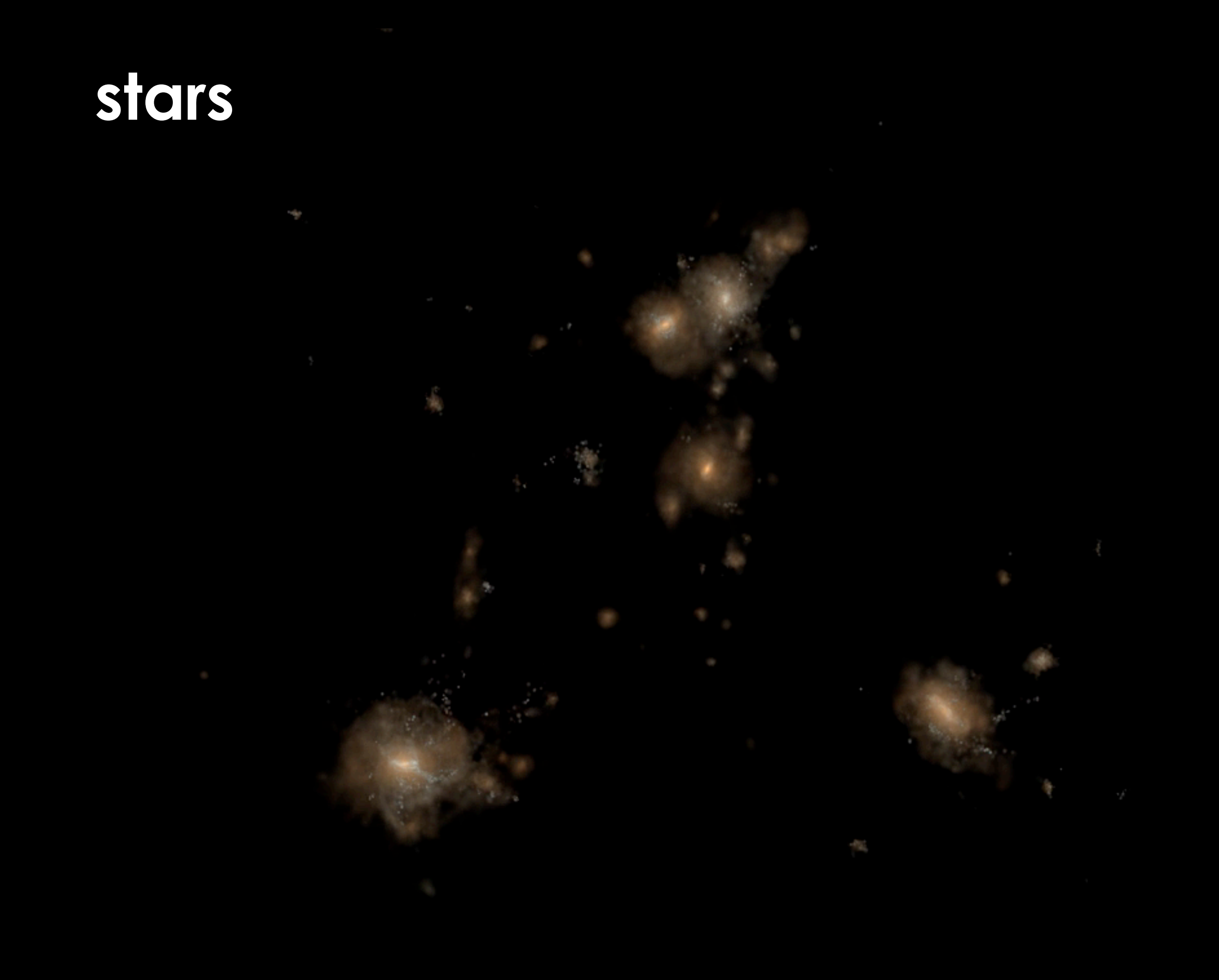
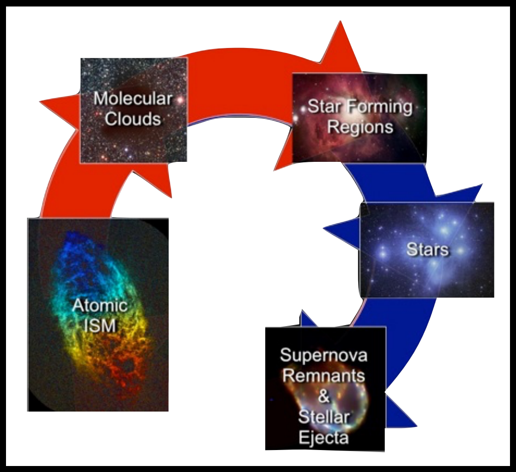


Image: Rosolowsky

HI galaxy science





SKA1 HI Science Priorities

- 13: Resolved HI kinematics and morphology of ~10^{10} $M_\odot$ mass **galaxies out to z~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 ~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.

Braun et al, 2014,
SKA1 Science Priority Outcomes

SKA1 HI Science Priorities

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High Priority Science Objectives

Science Goal	SWG	Objective	SWG Rank
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13	*HI*	Resolved HI kinematics and morphology of ~10^10 M_sol mass galaxies out to z~0.8	1/5
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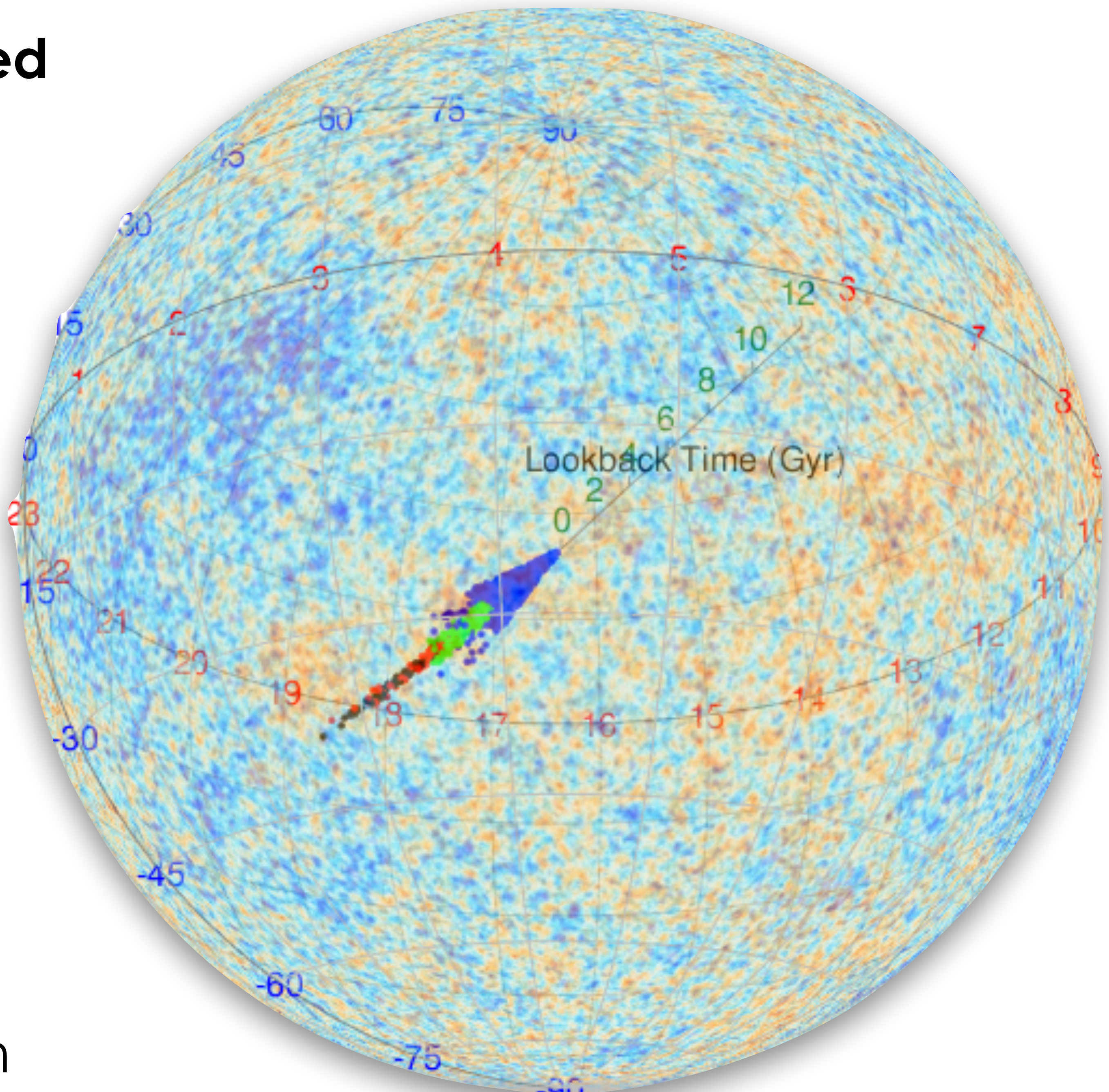
15	*HI*	Multi-resolution mapping studies of the ISM in our Galaxy	3/5
18	*Transients*	Solve missing baryon problem at z~2 and determine the Dark Energy Equation of State	=1/4
22	*Cradle of Life*	Map dust grain growth in the terrestrial planet forming zones at a distance of 100 pc	1/5
27	*Magnetism*	The 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

HI and Galaxy Evolution

HPSO-13

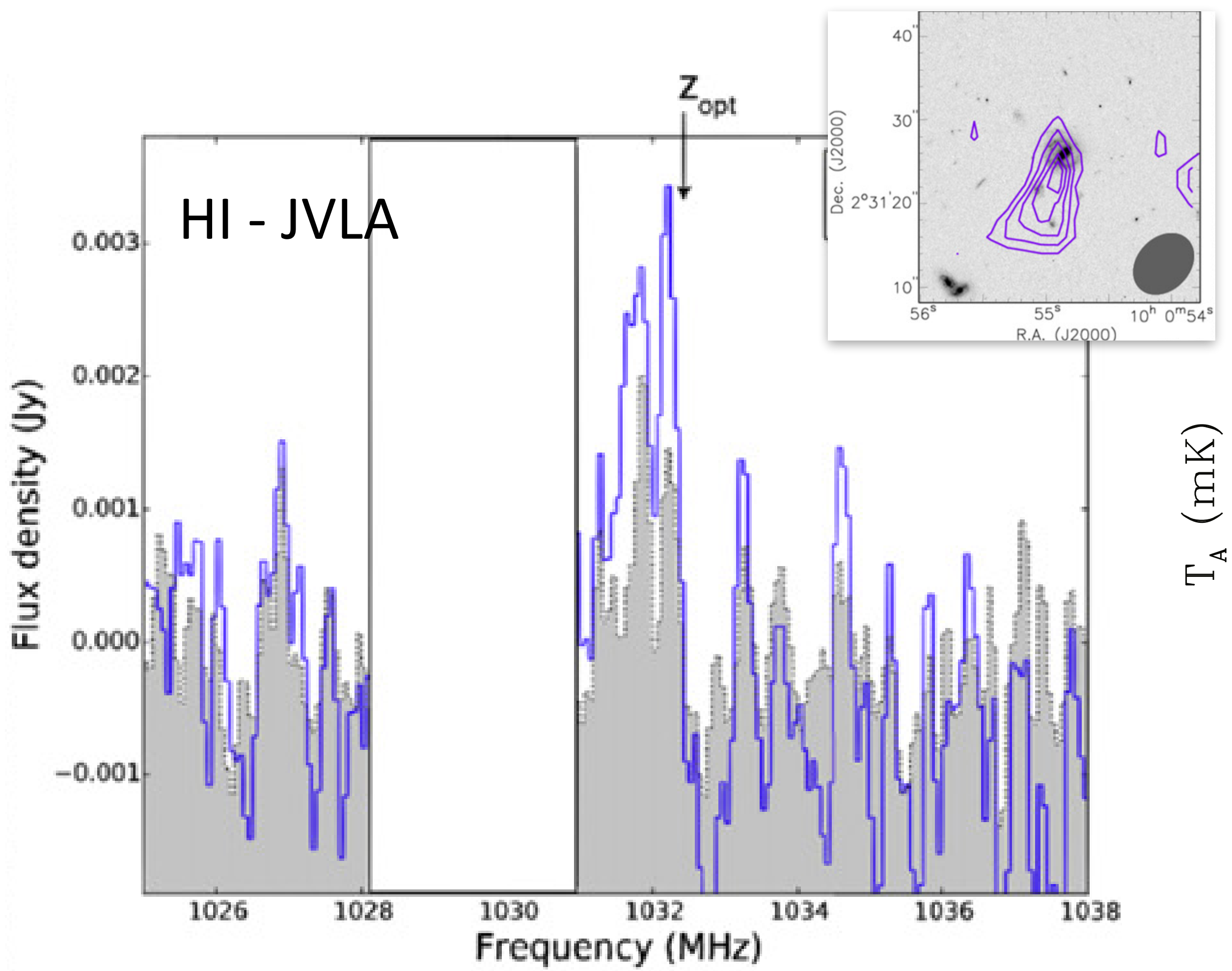
- **Only few hundred galaxies detected in HI beyond the local Universe**
- SKA1 and its pathfinders will revolutionise
- Unique opportunity for SKA1 to ***resolve*** $M_{HI}\sim10^{10}M_{\odot}$ gals to z<0.8
- *Mass Assembly*: Ω_{HI} & HI mass function; baryon cycle; DM dependencies
- *Impact of Environment*: gas inflow and removal
- *Angular momentum/kinematics*: scaling relations, Tully-Fisher relation



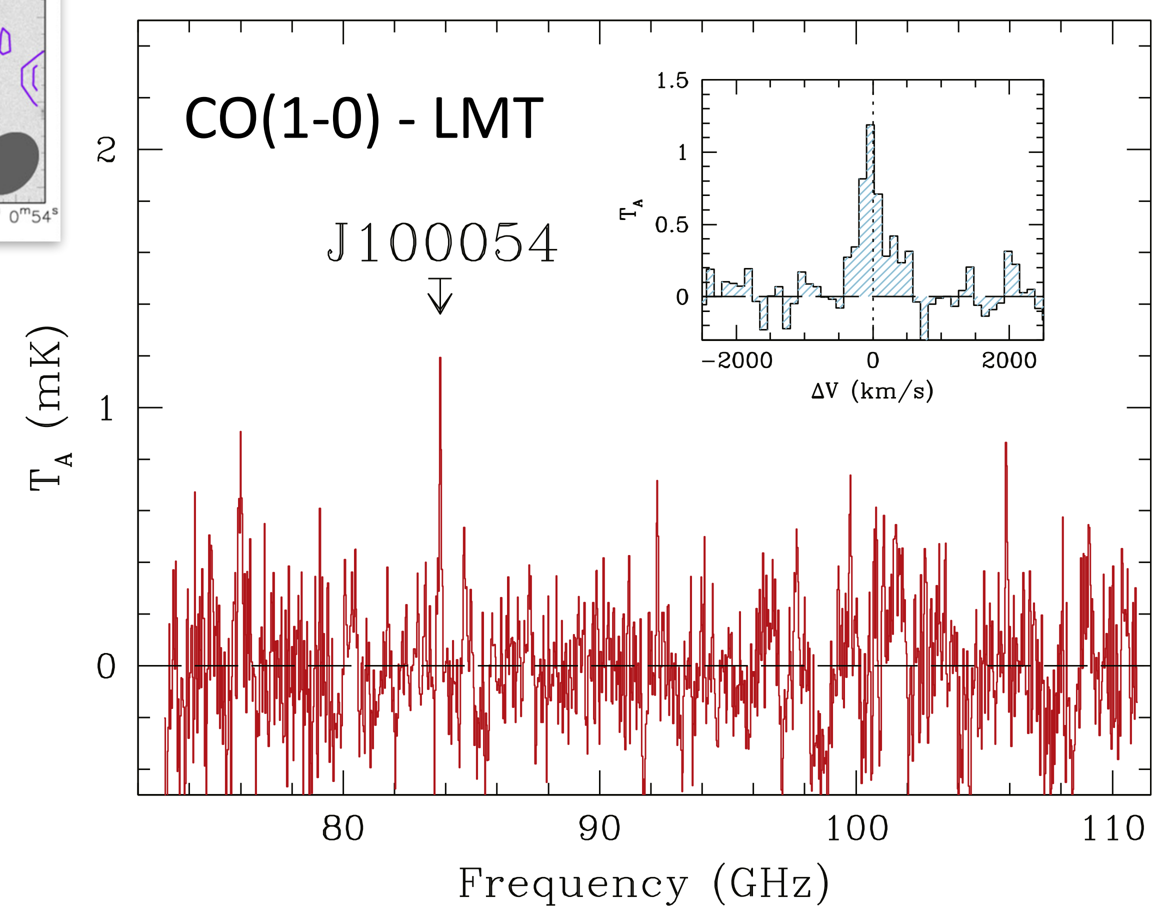
Blyth et al, 2015, PoS, AASKA14, 128

Recent Progress: JVLA CHILES

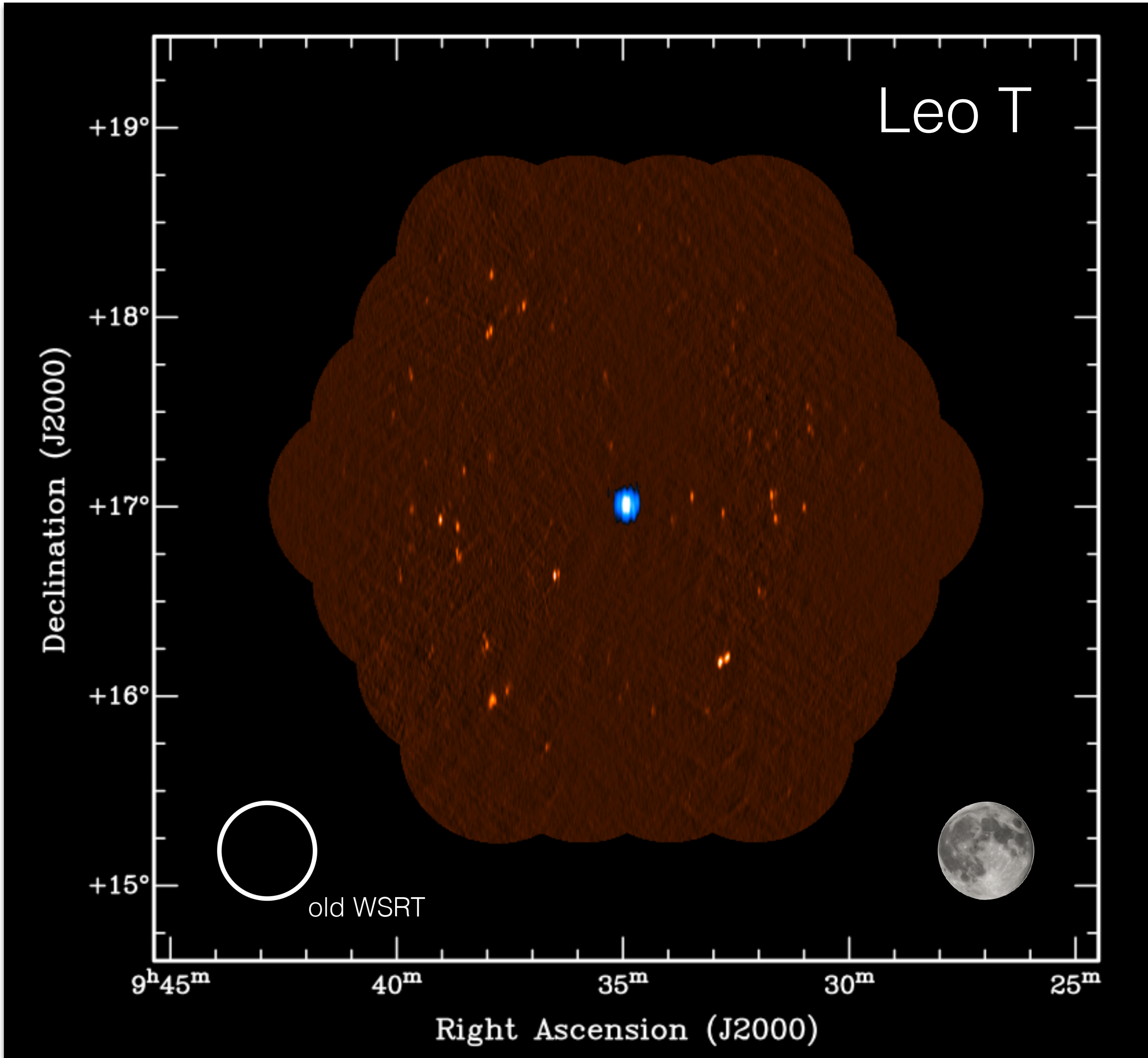
- The COSMOS HI Large Extragalactic Survey, PI. van Gorkom
- 1000hr, ~300 galaxies at $0 < z < 0.5$
- Most distant detection of 21-cm line emission at **$z = 0.376$**
- Large starbursting galaxy rich in HI & H_2 gas ($M_{HI} = 3 \times 10^{10}\ M_\odot$)



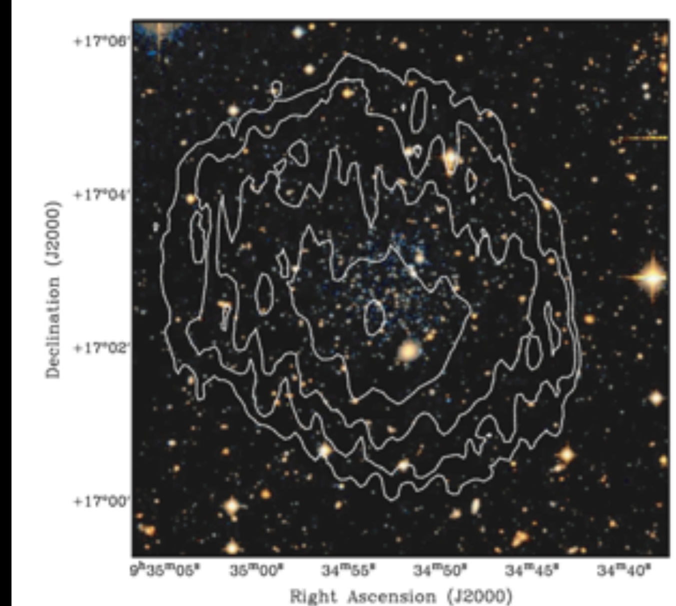
Fernandez+16



Recent Progress: Apertif



Oosterloo et al., presented by Lucero, PHISCC 2017



cf. WSRT, Rayn-Weber

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

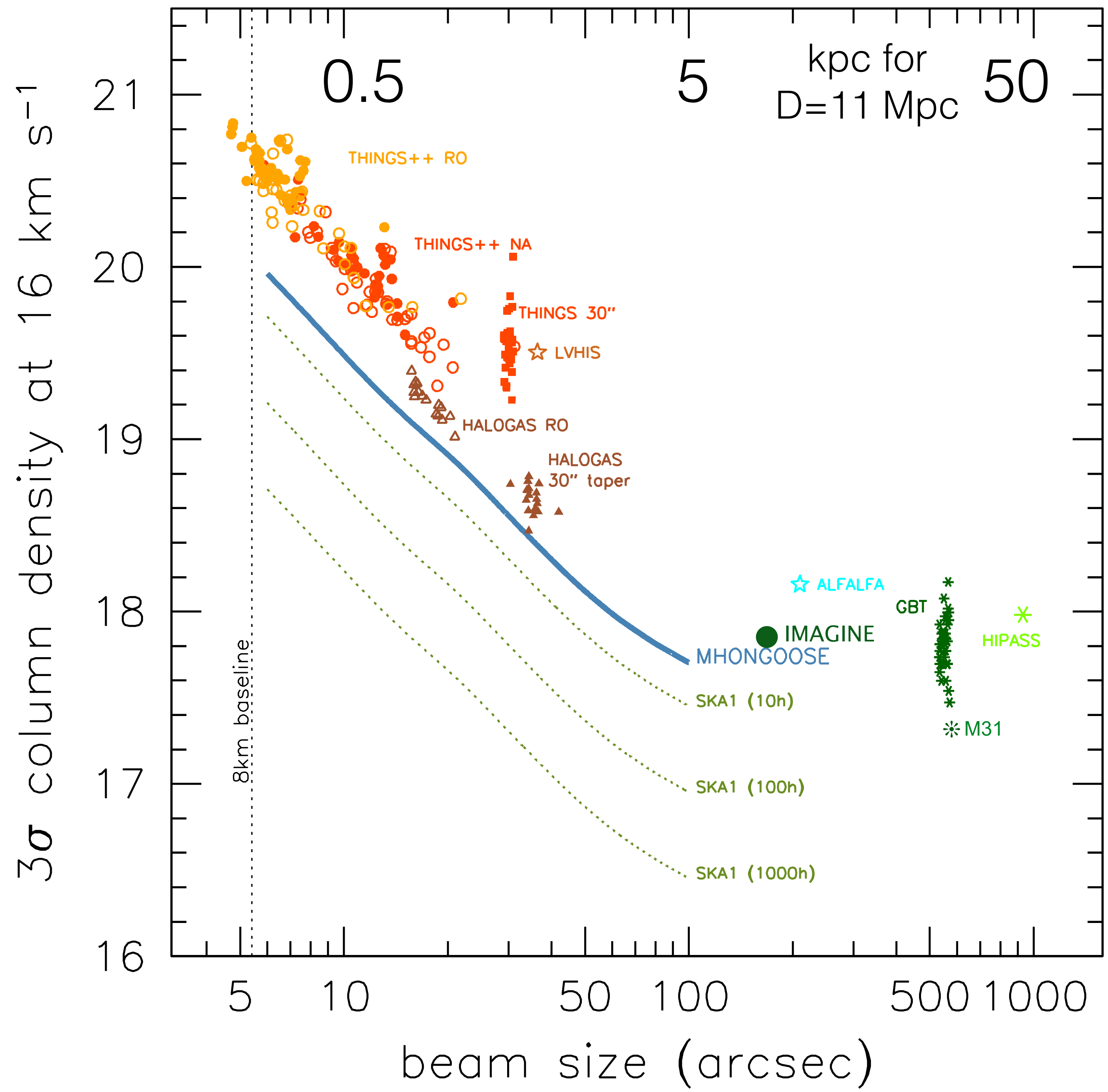
ISM and Gas Fuelling in the Nearby Universe

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 <u>high spatial resolution</u> (~100pc) and <u>low column density sensitivity</u> (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?

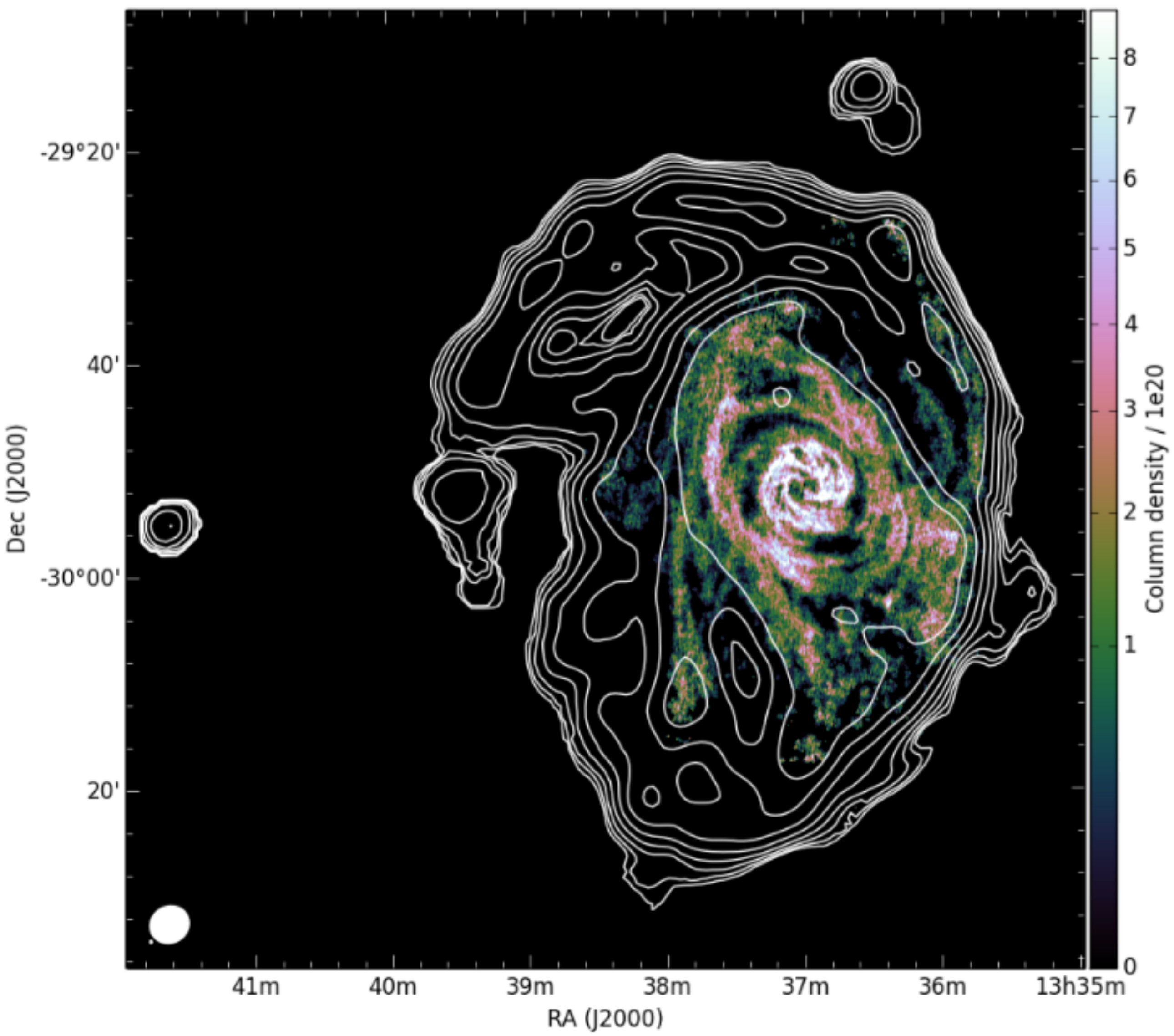
de Blok et al, 2015, PoS, AASKA14, 129
Popping et al, 2015, PoS, AASKA14, 132



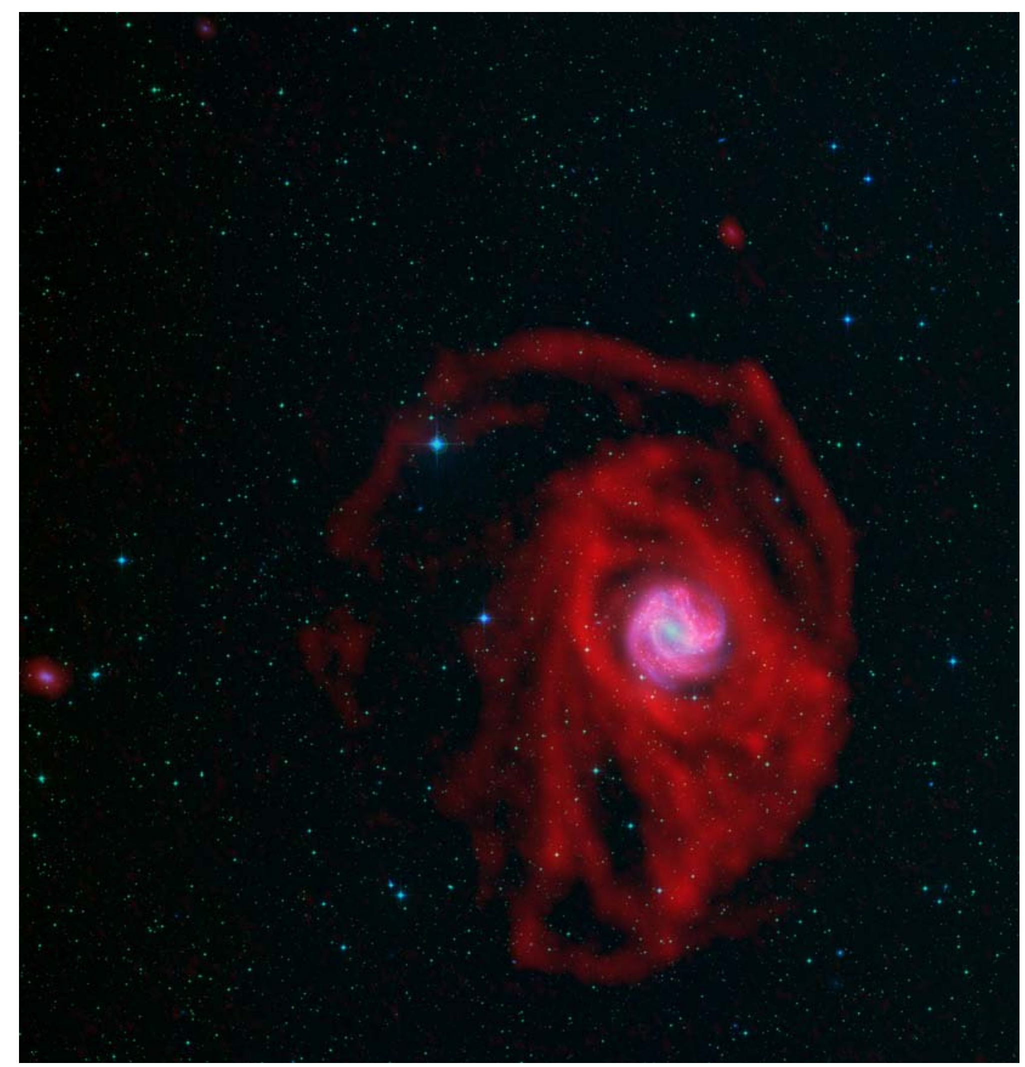
Credit: de Blok, ASTRON

Recent Progress: MeerKAT

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



KAT-7

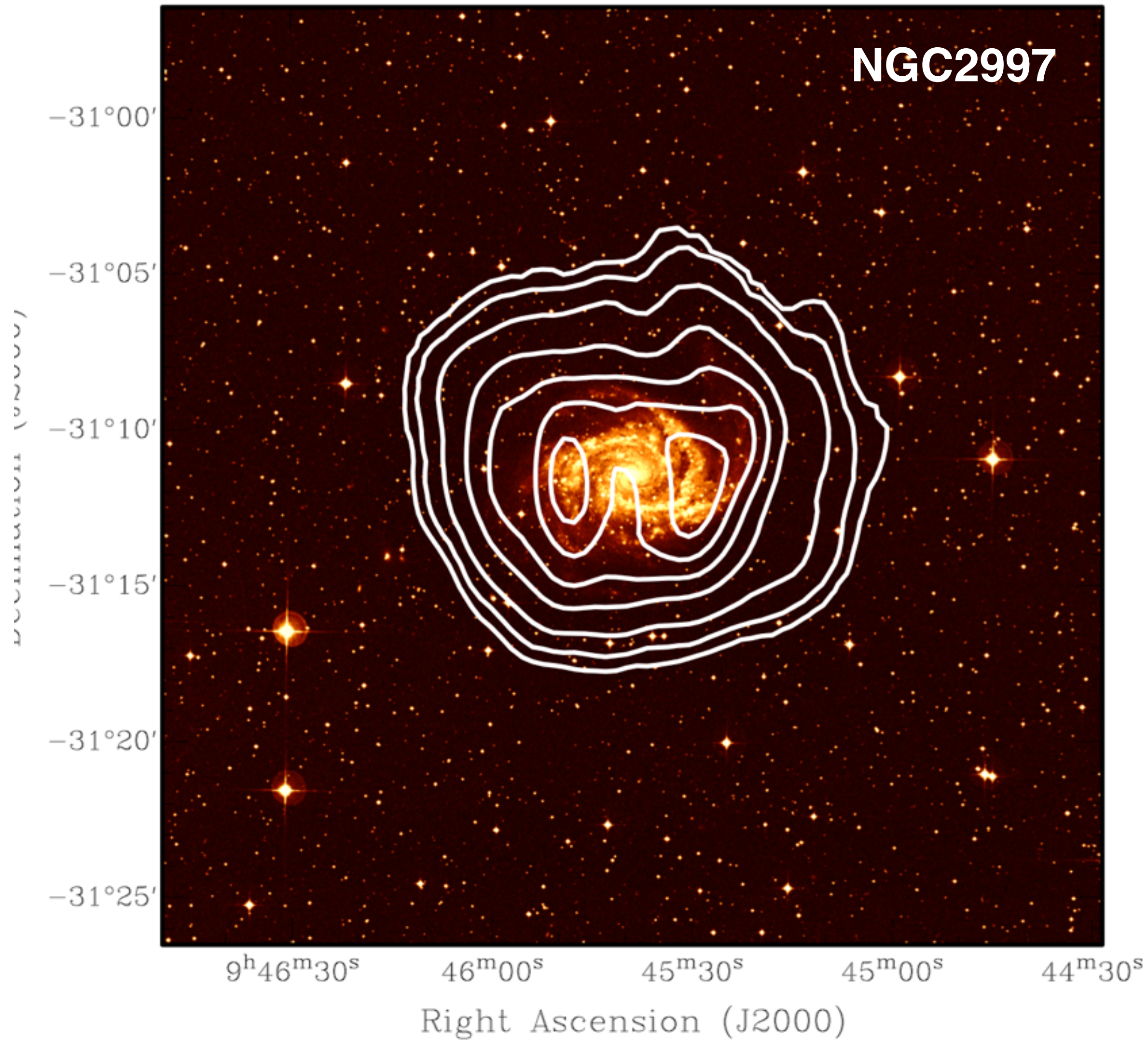


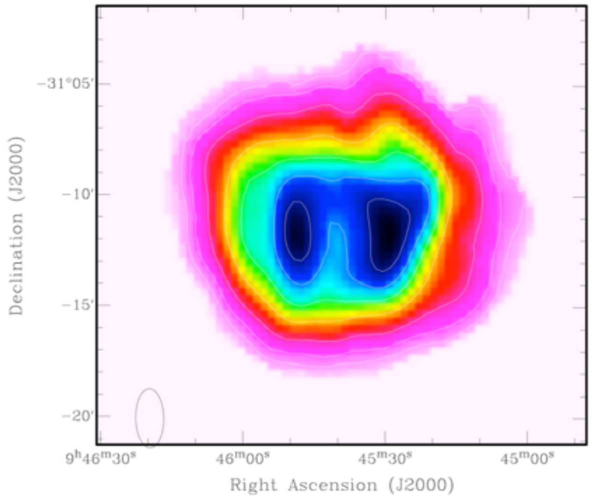
MeerKAT, April 2017

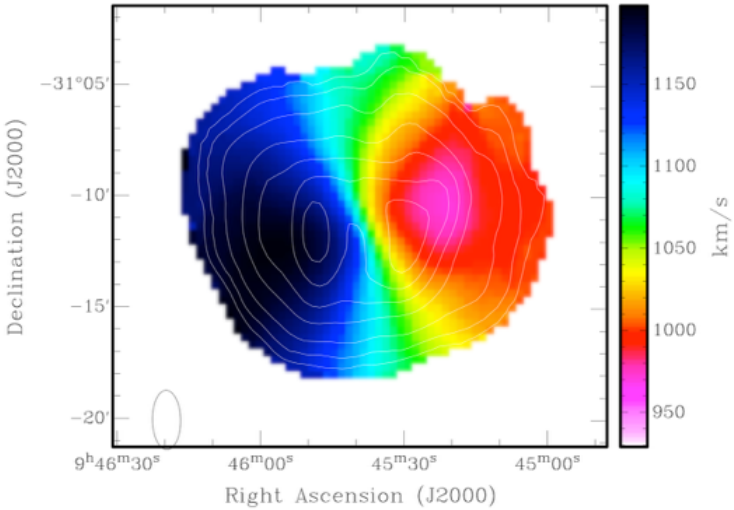
Recent Progress: IMAGINE

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_{HI}~$2.5x10^{17}$ cm^{-2} over 20 km s^{-1}
- resolution 1' to 2.5'
- SKA PSO-17 precursor experiment





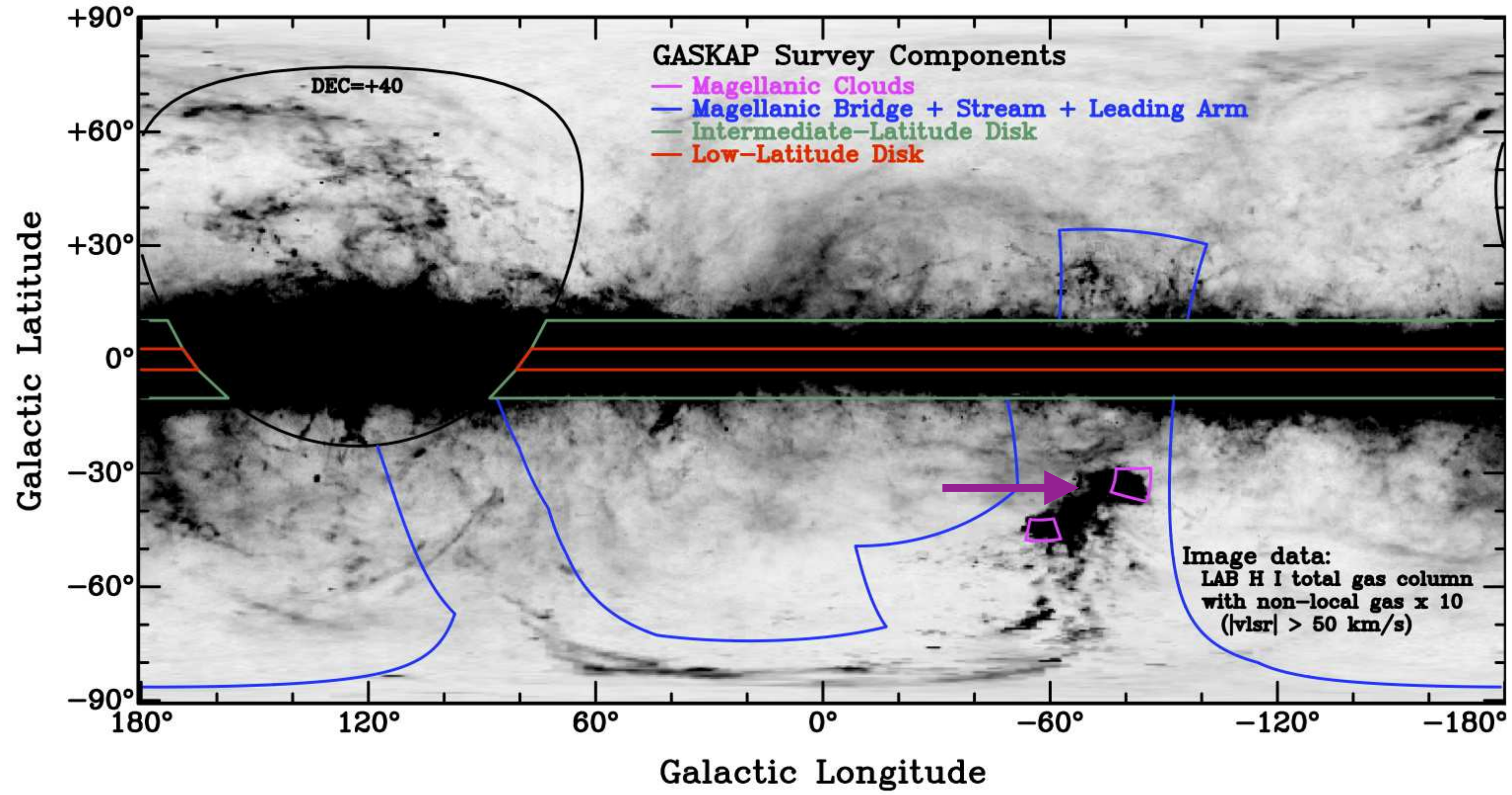


Milky Way & Magellanic System

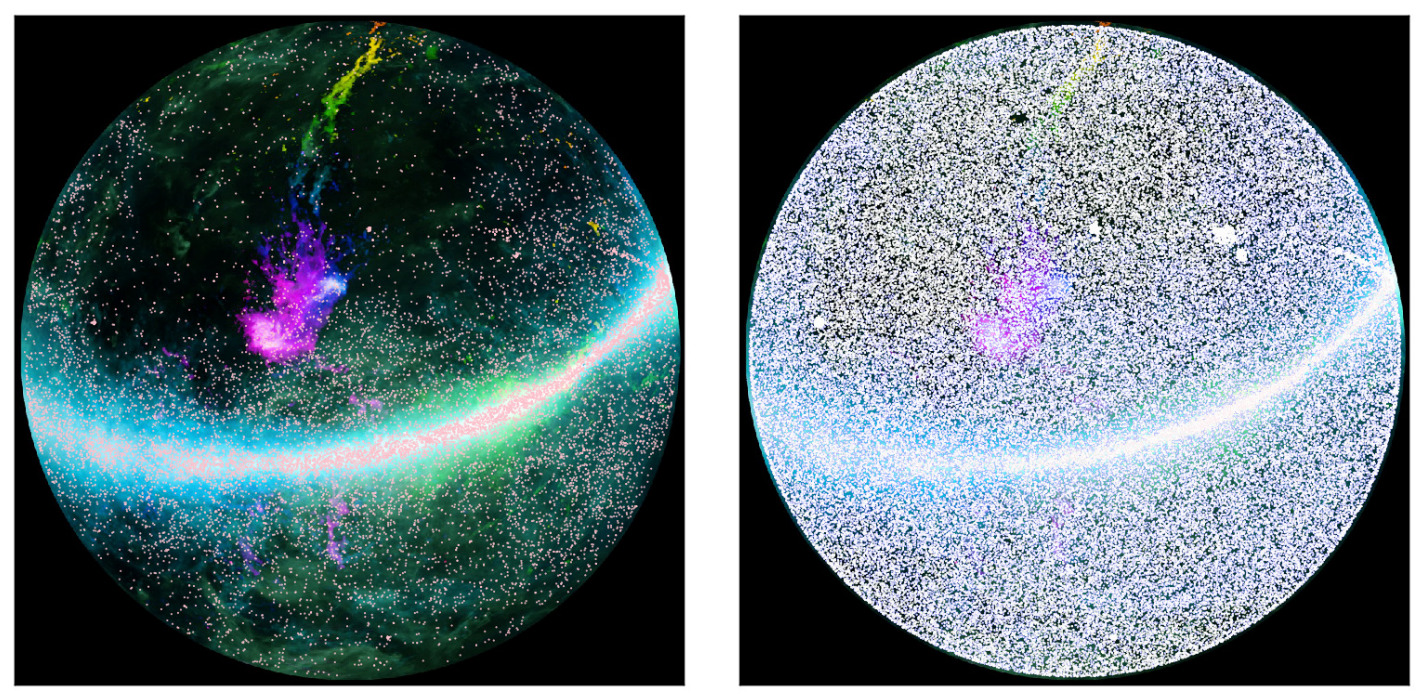
HPSO-15

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 emission



HI absorption

McClure-Griffiths et al, 2015, PoS, AASKA14, 130

HI absorption and AGN at z < 6

PSO-16

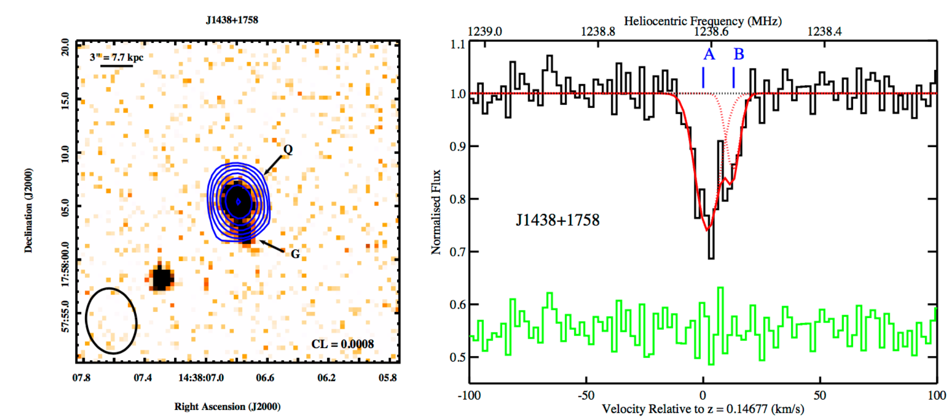
HI 21-cm absorption spectroscopy provides a unique probe of cold neutral gas in normal and active galaxies *from redshift z ~ 6 to the present day*.

- Intervening HI 21cm absorption → constrain the evolution of cold gas in normal galaxies over more than 12 billion years of cosmic time.

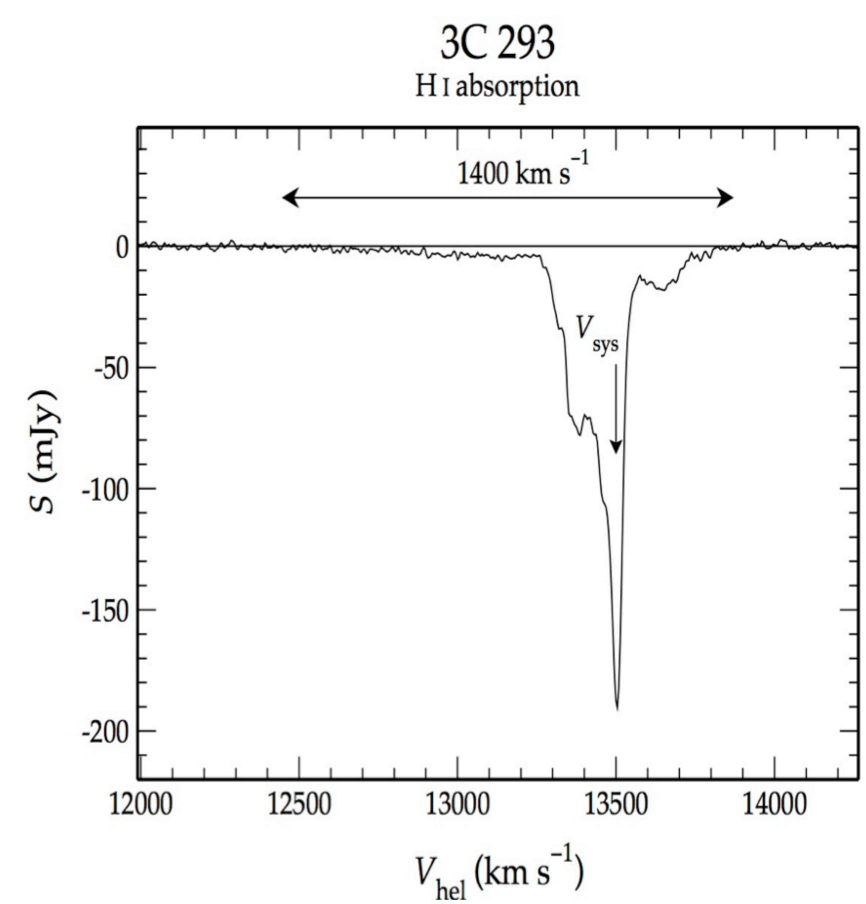
- Associated HI 21cm absorption → content of individual galaxies, structure of the central regions and the feeding and feedback of AGN.

Morganti et al, 2015, PoS, AASKA14, 134

Farnes+16

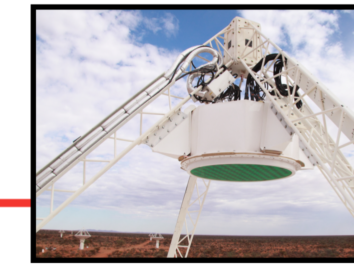


Dutta+16

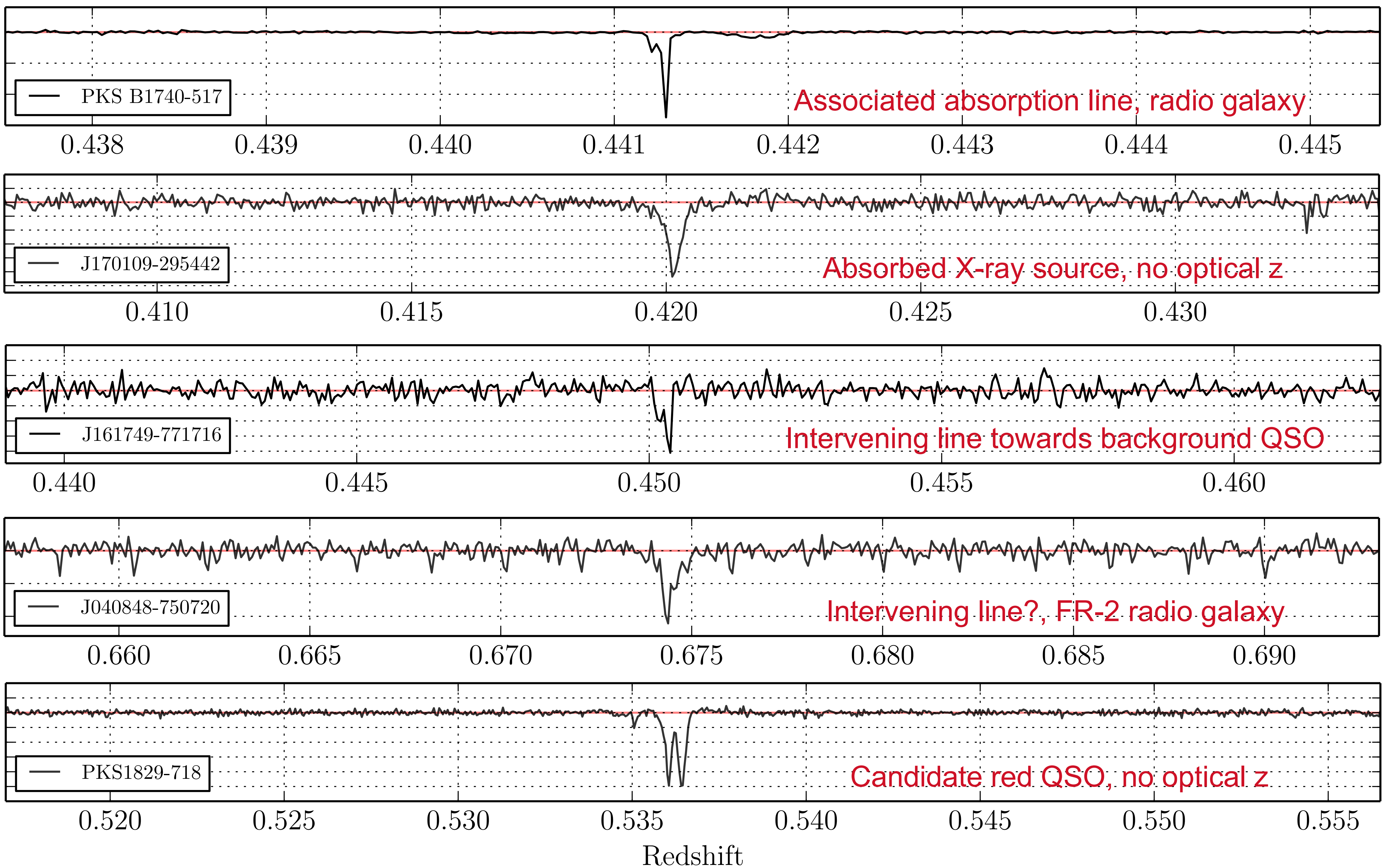


Morganti

Recent Progress: ASKAP HI



Discoveries of HI absorption at cosmological redshifts



Mahony, PHISCC 2017

Recent Activities: HI Analysis Tools

Source Finding:

- SoFiA Source Finding Application

Kinematic Analysis:

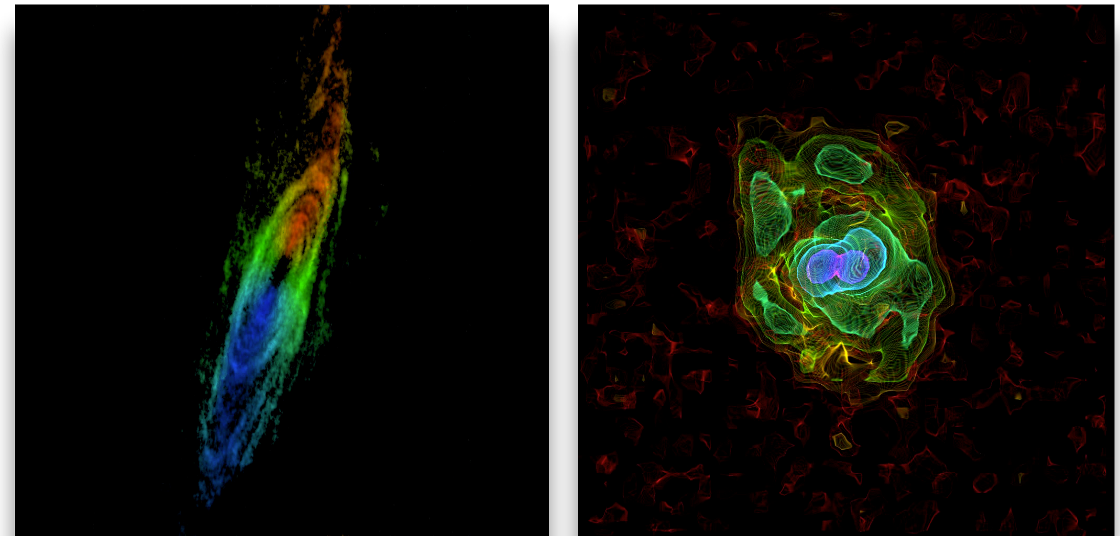
- 2DBAT TiRiFiC

Visualisation:

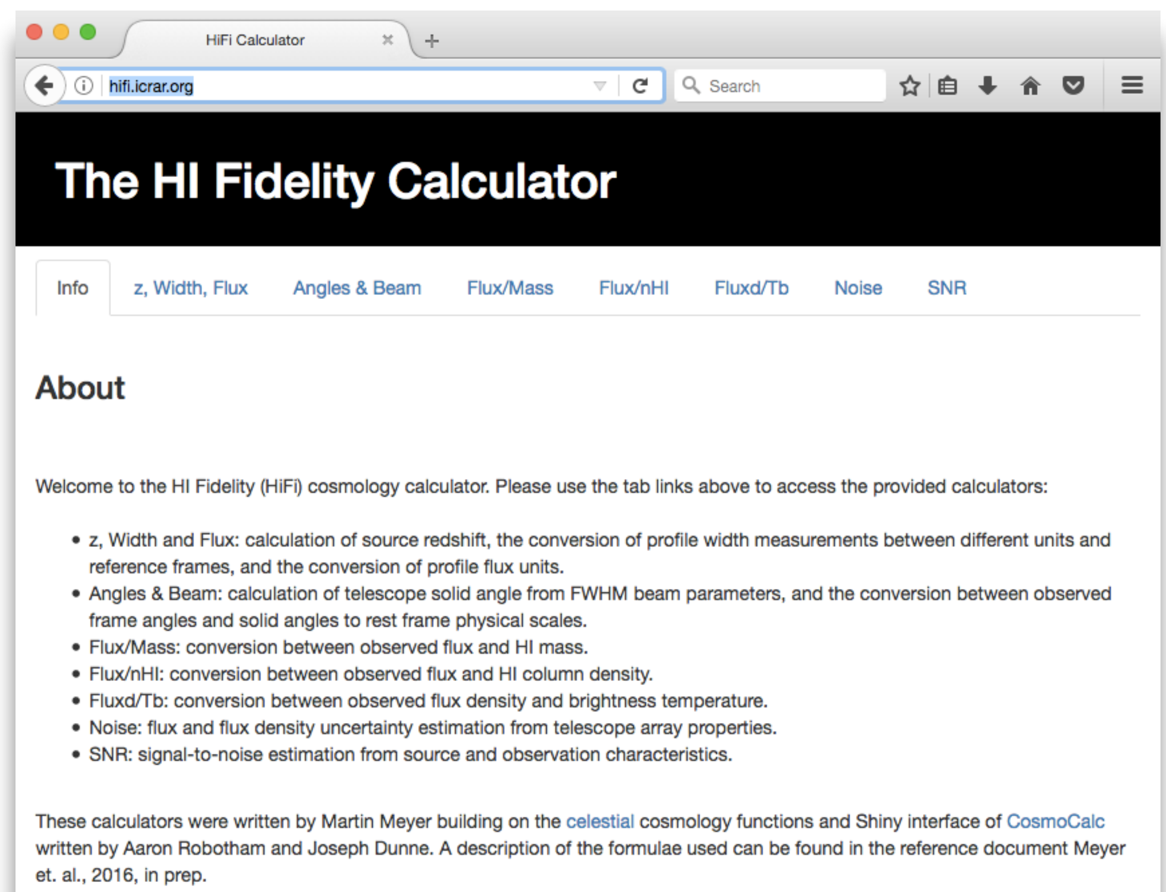
- SlicerAstro

Analysis:

- HI stacking, IM
- HiFi Calculator



Davide Punzo 2016: **SlicerAstro**



hifi.icrar.org; Meyer et. al., arXiv:1705.04210

Proposed SKA1 HI surveys

Survey	Area (deg^2)	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

Survey	Area (deg²)	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, smilar 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 transfor-mational 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 transfor-mational 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 / Deeper	Remove 54 LOW stations from core	LOW	4	31	2	28	N
5.30 / Deeper	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 transfor-mational 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 / Deeper	Remove 11 MID Dishes from core	MID	4	30	4	34	Y
5.24 / Deeper	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 transfor-mational Science Impact
8	SDP- HPC: Deploy 150 Pflops (from 200 Pflops)	COMM	3	22	3	31	M
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
5.25.2 /	Reduce PSS-LOW: C, 125 nodes to 83 nodes	LOW	3	25	1	18	N
5.25.2 /	Reduce PSS-MID: B, 375 nodes to 250 nodes	MID	3	26	1	19	N
5.30a	Reduce Bmax LOW to 40km: C, remove next 18 stations	LOW	3	27	2	27	N
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
5.30 /	Remove 54 LOW stations from core	LOW	4	31	2	28	N
5.24 /	Remove additional 11 MID Dishes from core	MID	4	32	4	35	Y
5.30 /	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
5.5.1	Remove MID Band 1 feeds: 105 to 0	MID	4	35	4	36	Y
5.5.2	Reduce MID Band 5 feeds: B, from 67 to 0	MID	4	36	1	20	N

ICRAR

Cost control: impact on HI science

“Above the black line”

- Reduction in SDP has most potential impact on HI high priority science objectives, must retain sufficient resolution capability
- Changes to LOW and reduction in angular resolution (MID & LOW) will impact HI absorption surveys

“Below the black line” - Loss of Transformational Science

- Stronger SDP cuts may render transformational science impossible due to resolution limitations
- Reduction in shorter MID baselines impacts ability to deliver *all* HI science priority objectives
- Loss of MID band 1 would mean catastrophic loss of HI science $z > 0.5$

Summary

- **Ground-breaking HI galaxy science is possible with SKA1**
  - Resolved kinematics of $M_{HI} = 10^{10}\ M_{\odot}$ 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**