ICRAR

International Centre for Radio Astronomy Research

HI Galaxy Science with the SKA

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on behalf of the HI SWG

Curtin University

The Government of Western Australia

The University of Western Australia

Overview

HI Galaxy Science with the SKA

- science chapters, priorities

SKA Capabilities for HI

- rebaselined SKA1

Key Science Observations

- what kinds of HI surveys do we want to carry out?

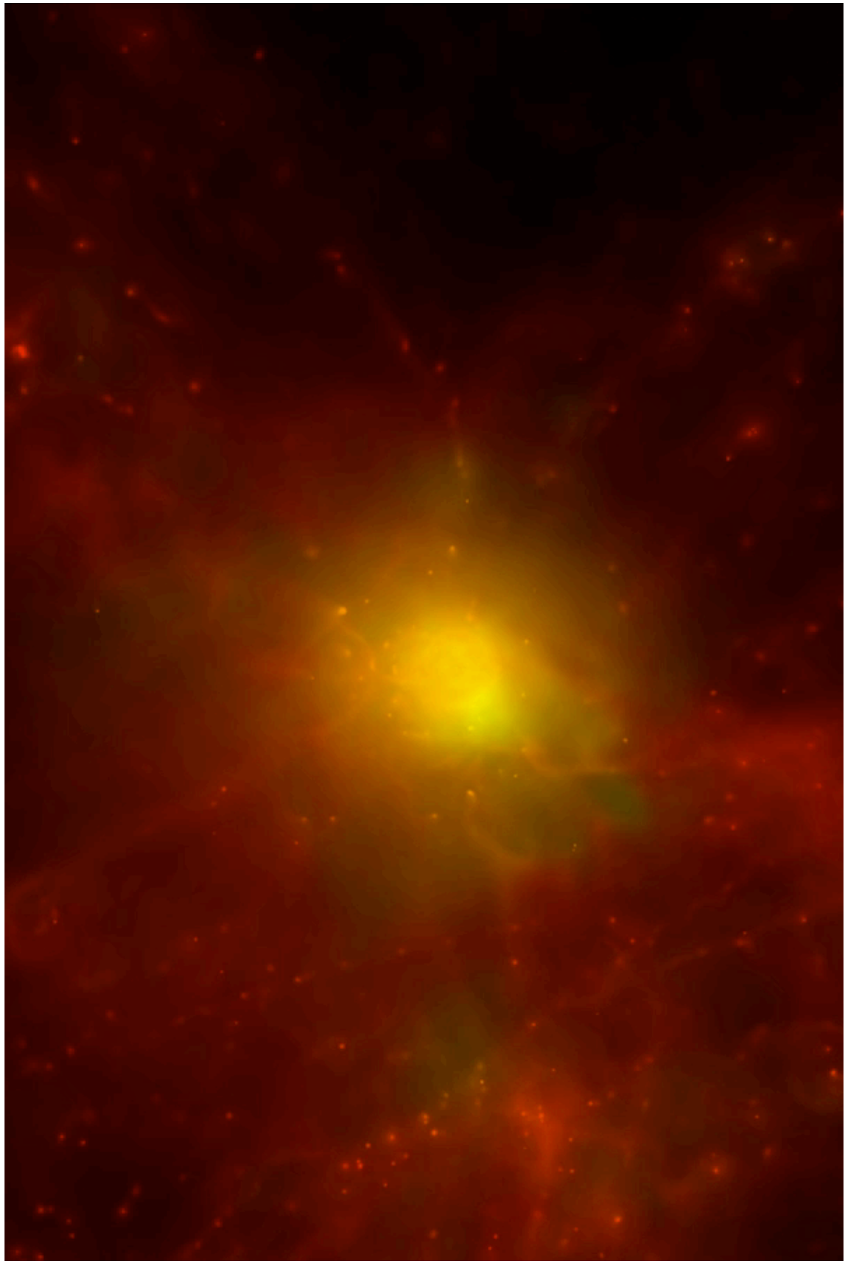
Fuelling Galaxies over Cosmic Time

HI surveys key to unlocking galaxy evolution

- galaxy evolution studies dominated by optical/NIR (stars)
- need to understand how galaxies fuelled (gas)
- HI the fundamental baryonic building block

Understanding of HI in galaxies remains limited

- HIPASS, ALFALFA: single dish, $z < 0.06$
- Only few hundred galaxies detected in HI beyond the local Universe
- SKA and its pathfinders will revolutionise



Chris Power, simulated gas distribution z=0

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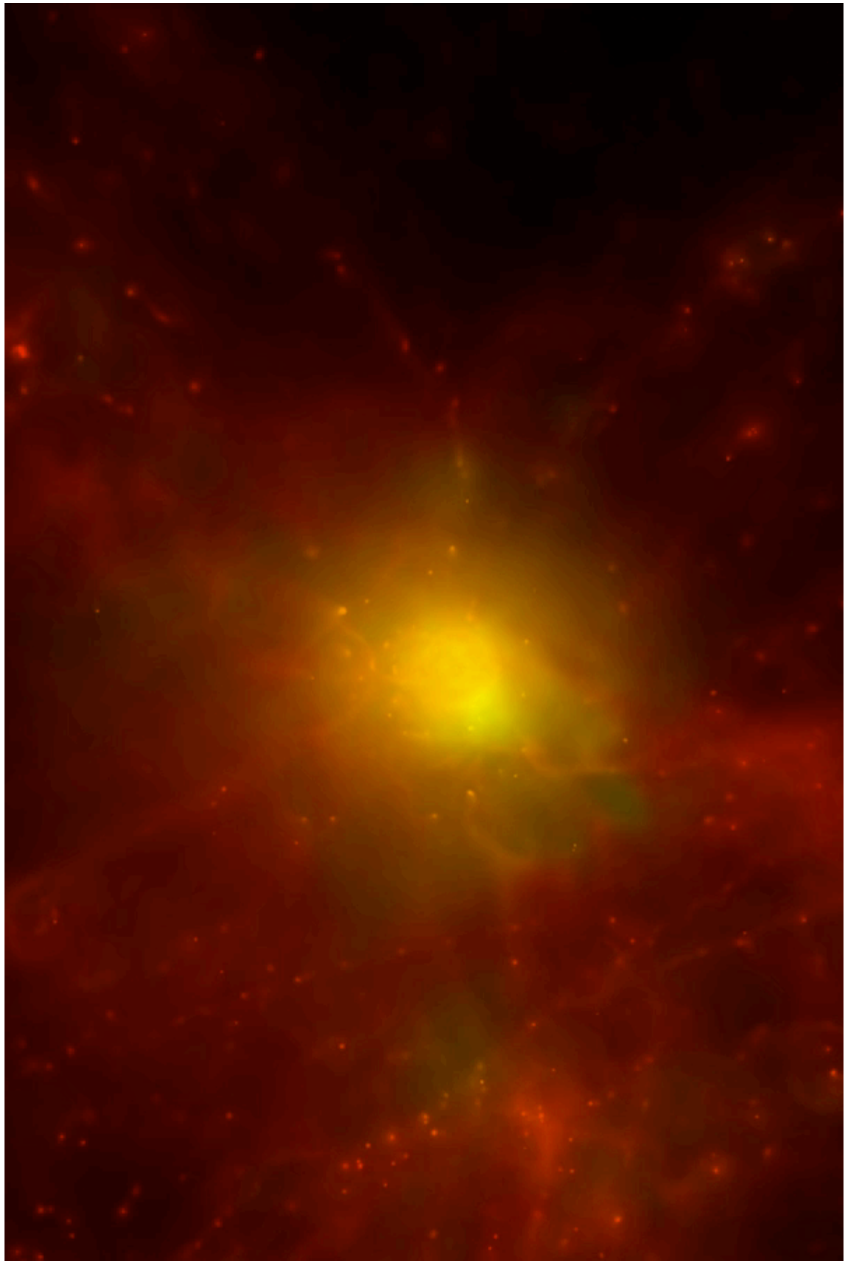

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SKA1 HI Science Priorities

- Resolved HI kinematics and morphology of ~10^{10} $M_\odot$ mass **galaxies out to z~0.8**
- High spatial resolution studies of the **ISM in the nearby Universe**.
- Multi-resolution mapping studies of the **ISM in our Galaxy**
- **HI absorption studies** out to the highest redshifts.
- 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

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priority SKA1 science goals

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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

SKA Science Case Update

New HI Chapters:

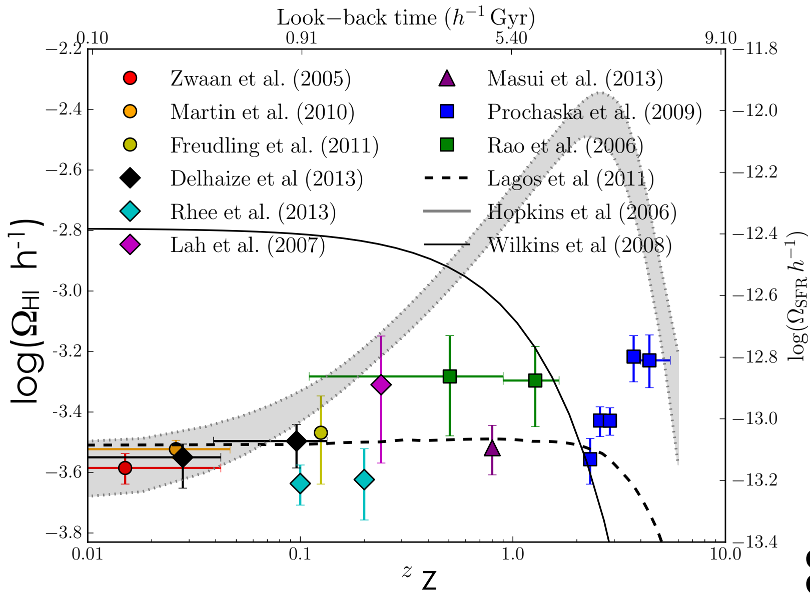
- **The Hydrogen Universe with the SKA** (Staveley-Smith) - includes rebaselining
- **Neutral Hydrogen and Galaxy Evolution** (Blyth)
- **The ISM in Galaxies** (de Blok)
- **The Galaxy and Magellanic System** (McClure-Griffiths)
- **The IGM** (Popping)
- **Cool Outflows and HI absorbers** (Morganti)
- **Galaxy Formation Models** (Power)
- **Connecting the Baryons** (Meyer)
- **SMBHs and galaxies** (Marconi)
- **SKA as Doorway to Angular Momentum** (Obreschkow)
- **Physics of Cold Neutral Medium** (Oonk)

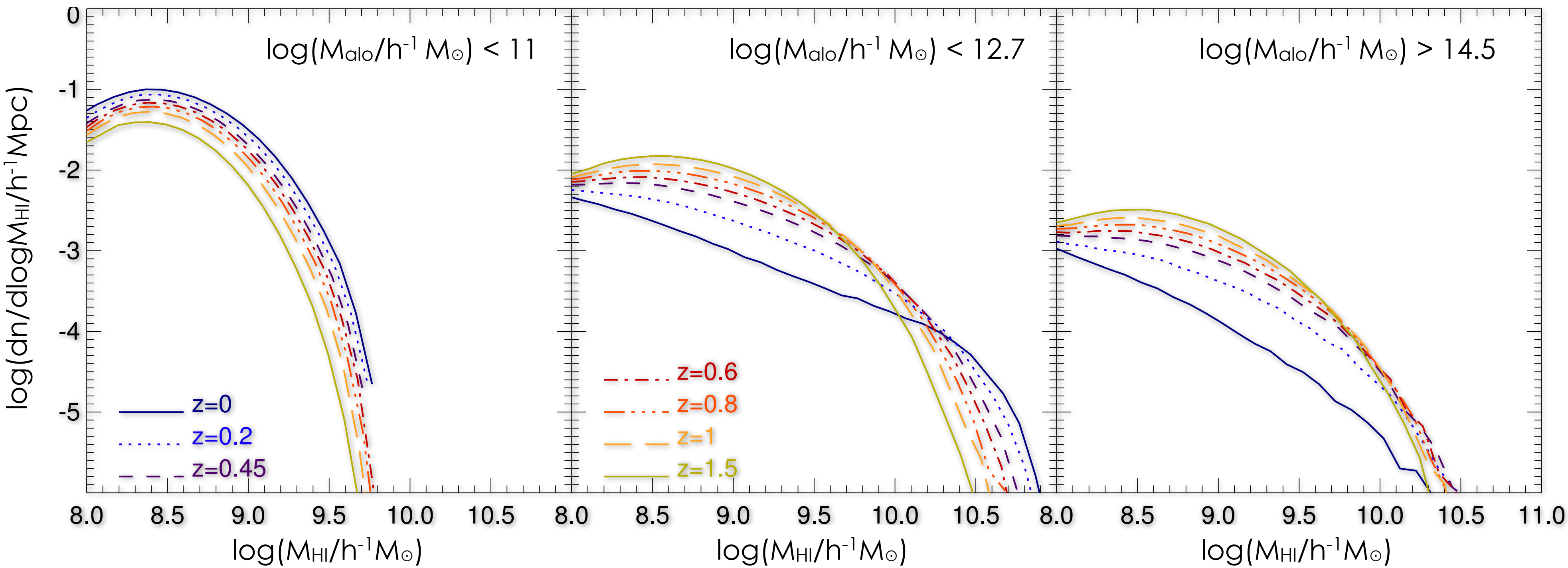
update

PoS(AASKA)

HI & Galaxy Evolution

- **Mass properties**: Ω_{HI} & HI mass function; baryon cycle; DM dependencies
- Environment: gas inflow and removal
- Angular momentum/kinematics: scaling relations, Tully-Fisher relation





Blyth et al, 2015, PoS, AASKA14, 128

HI & Galaxy Evolution

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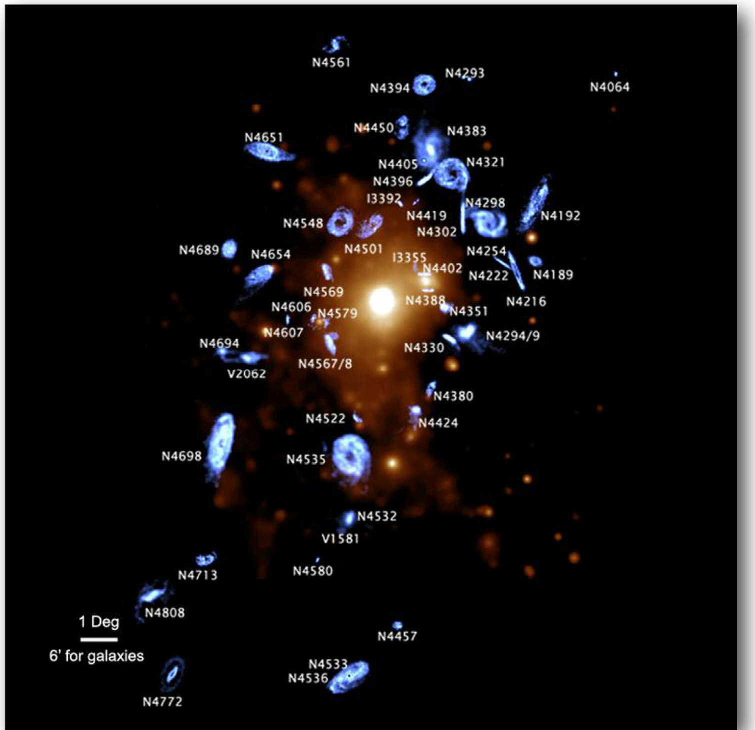
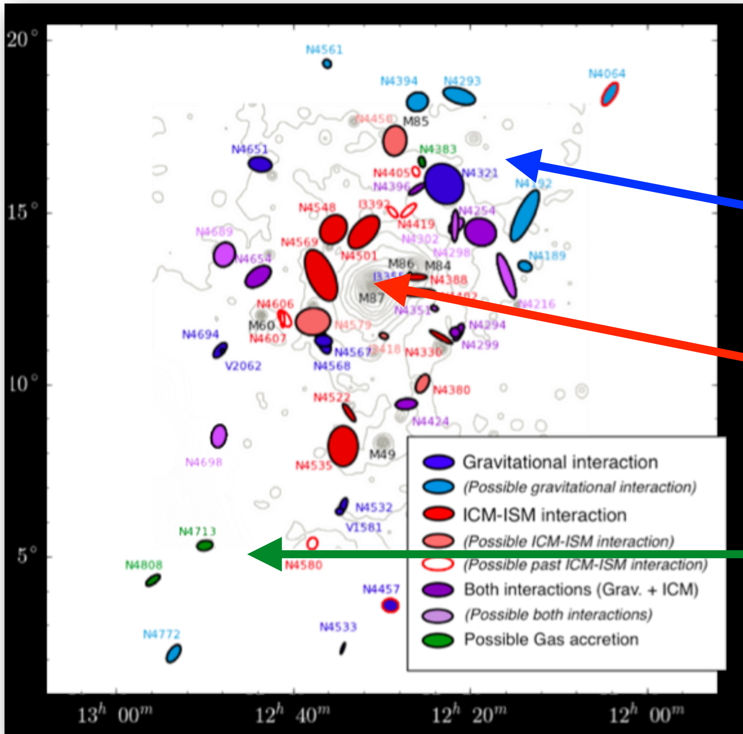
SKA will enable unprecedented **resolved** image analyses





gravitational interaction

current ICM-ISM interaction

accretion

VIVA survey; Chung, 2009; Yoon in prep;

HI & Galaxy Evolution

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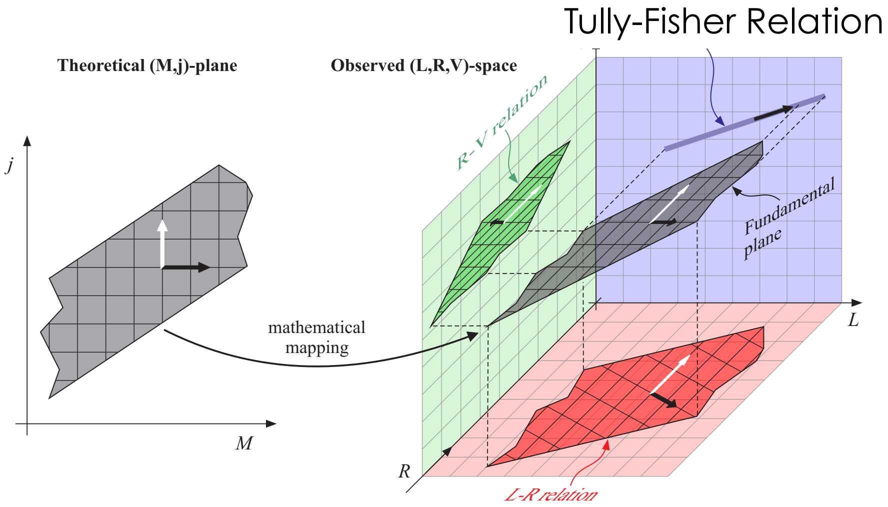
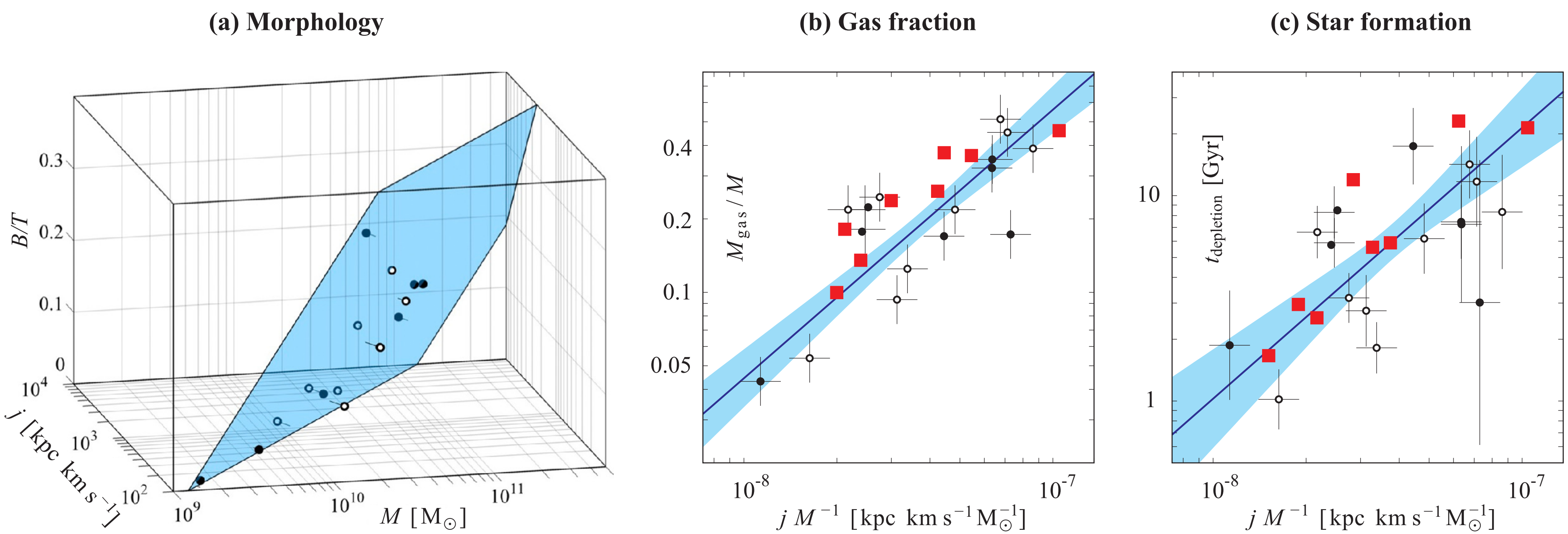




Obreschkow et al, 2015, PoS, AASKA14, 138

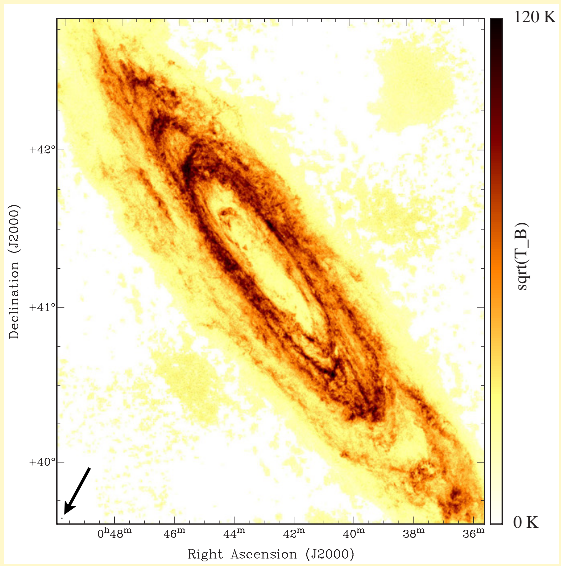
ISM in the Nearby Universe

Deep studies in local Universe also needed to understand HI physics

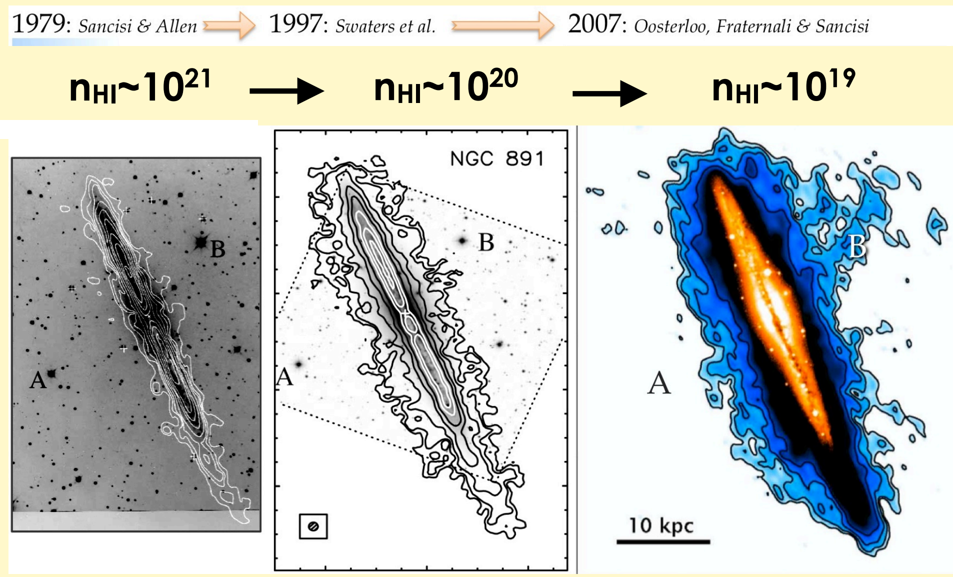
- Enable <u>high spatial resolution</u> (sub-kpc) and <u>low column density sensitivity</u> (sub 10^{20})

- What is the connection between star formation on small scales and global scaling laws?

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



M31, Braun et al, 2009, 50pc resolution

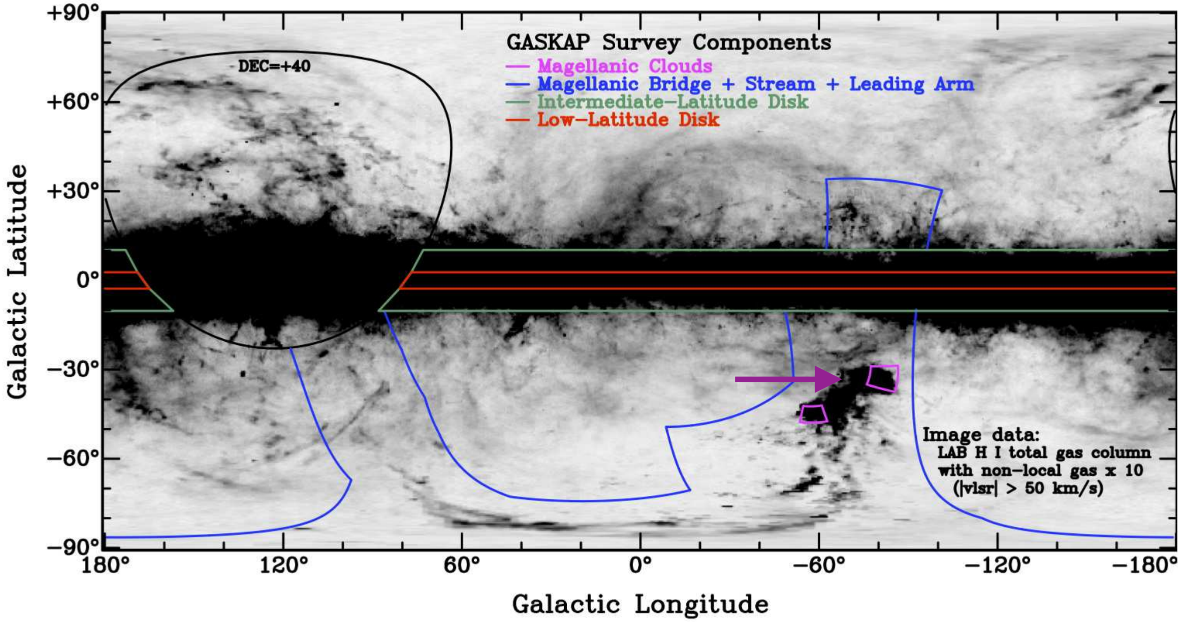


de Blok et al, 2015, PoS, AASKA14, 129

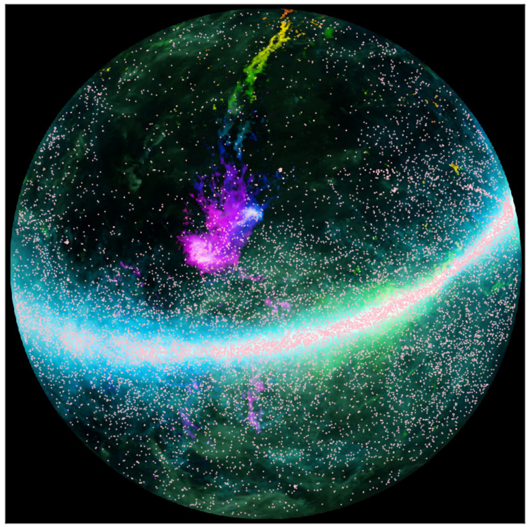
Milky Way & Magellanic Clouds

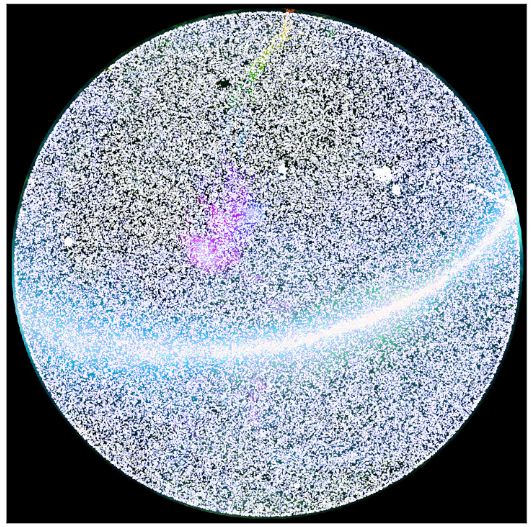
MW and Magellanic clouds allow studies of gas content **in greater detail than anywhere else**

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



HI emission



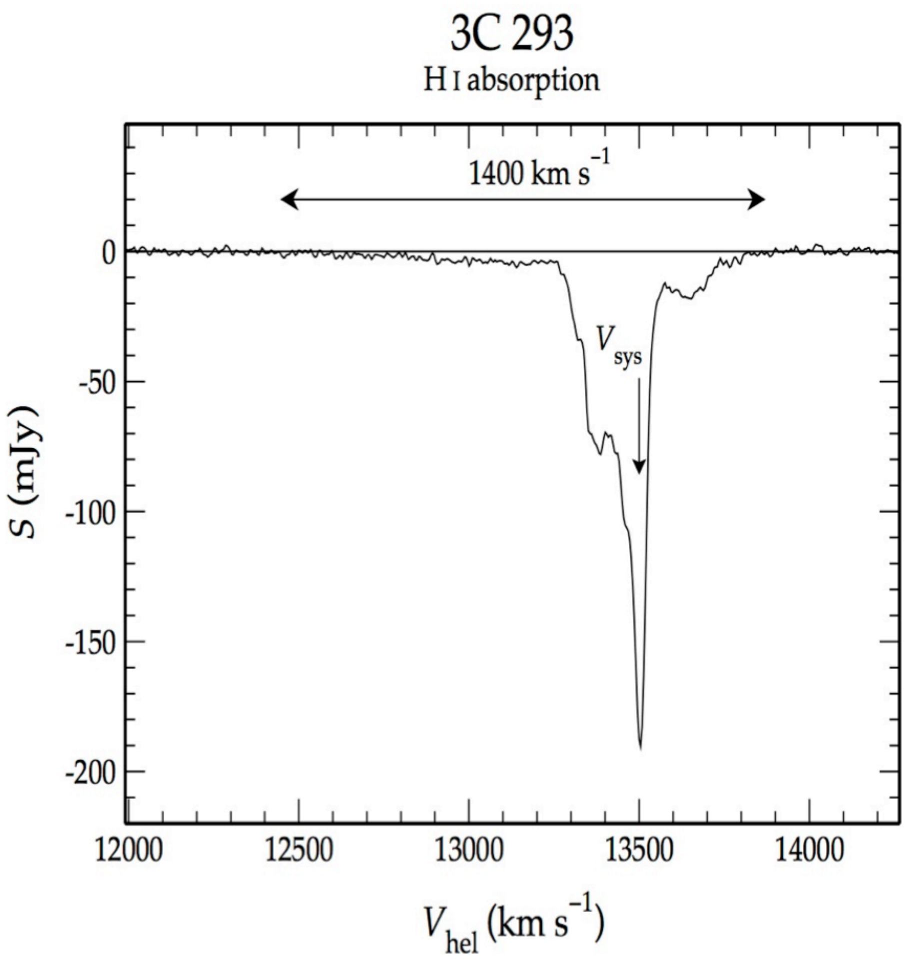


HI absorption

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

HI at High-z: Absorption Studies

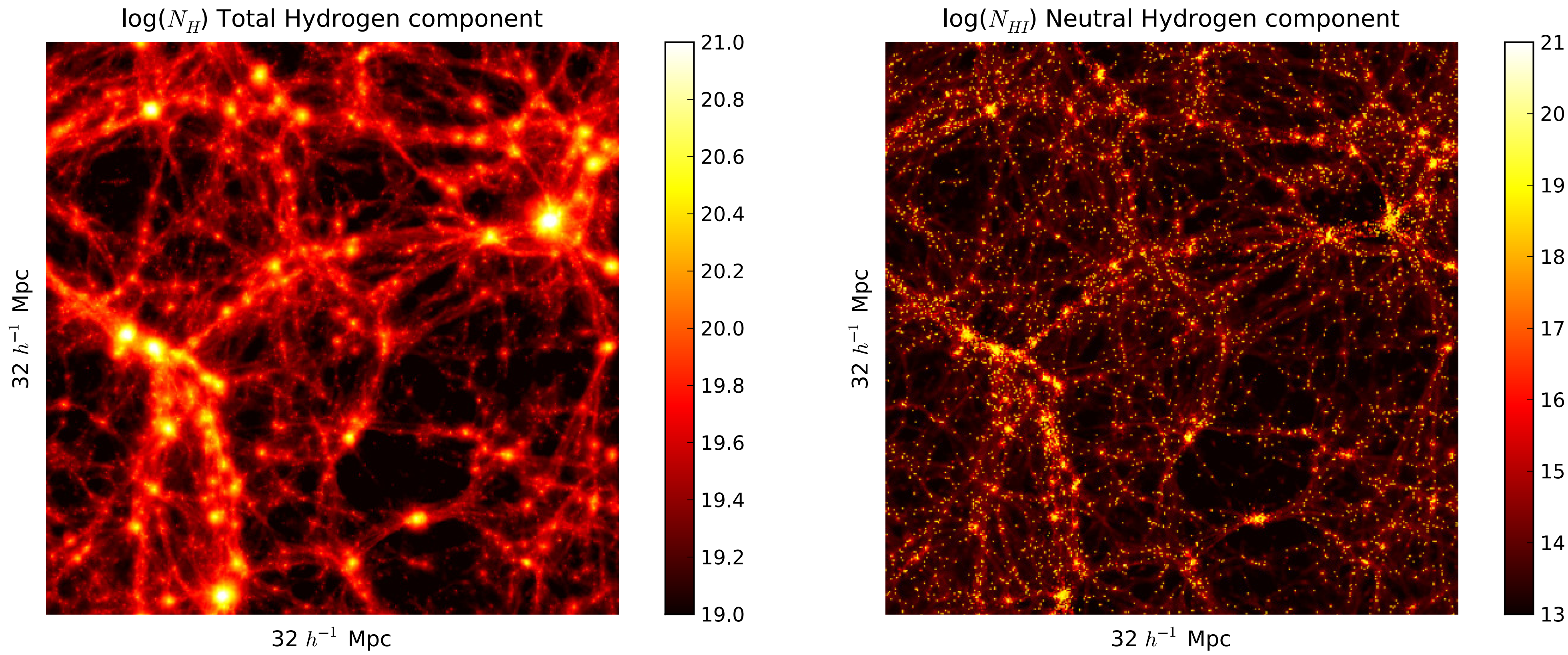
- HI 21-cm absorption spectroscopy provides a unique probe of cold neutral gas in normal and active galaxies *from redshift z > 6 to the present day*.
- Associated HI 21cm absorption → content of individual galaxies, structure of the central regions and the feeding and feedback of AGN.
- Intervening HI 21cm absorption → constrain the evolution of cold gas in normal galaxies over more than 12 billion years of cosmic time.



Morganti et al, 2015, PoS, AASKA14, 134

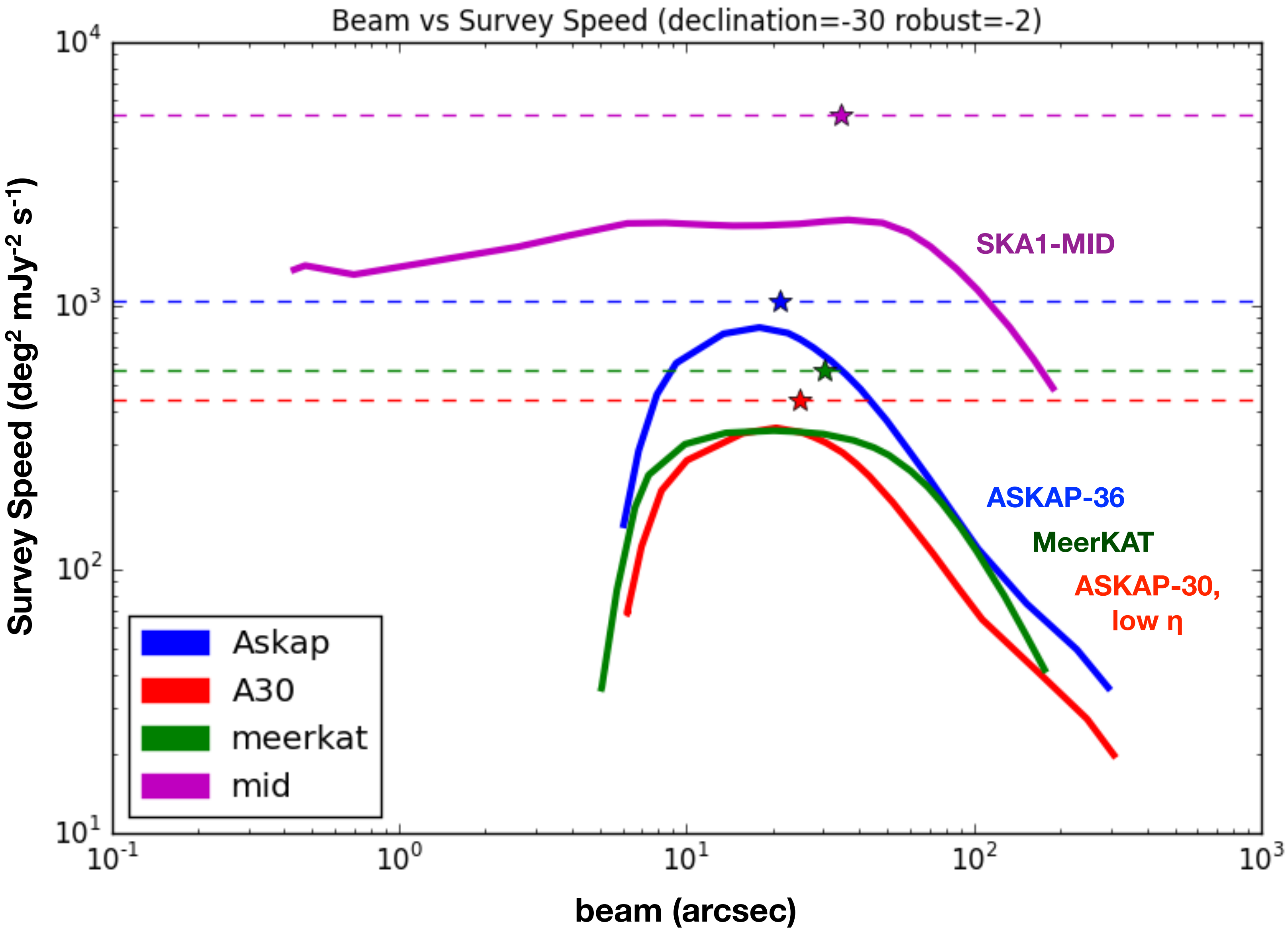
Galaxy-IGM Connection

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



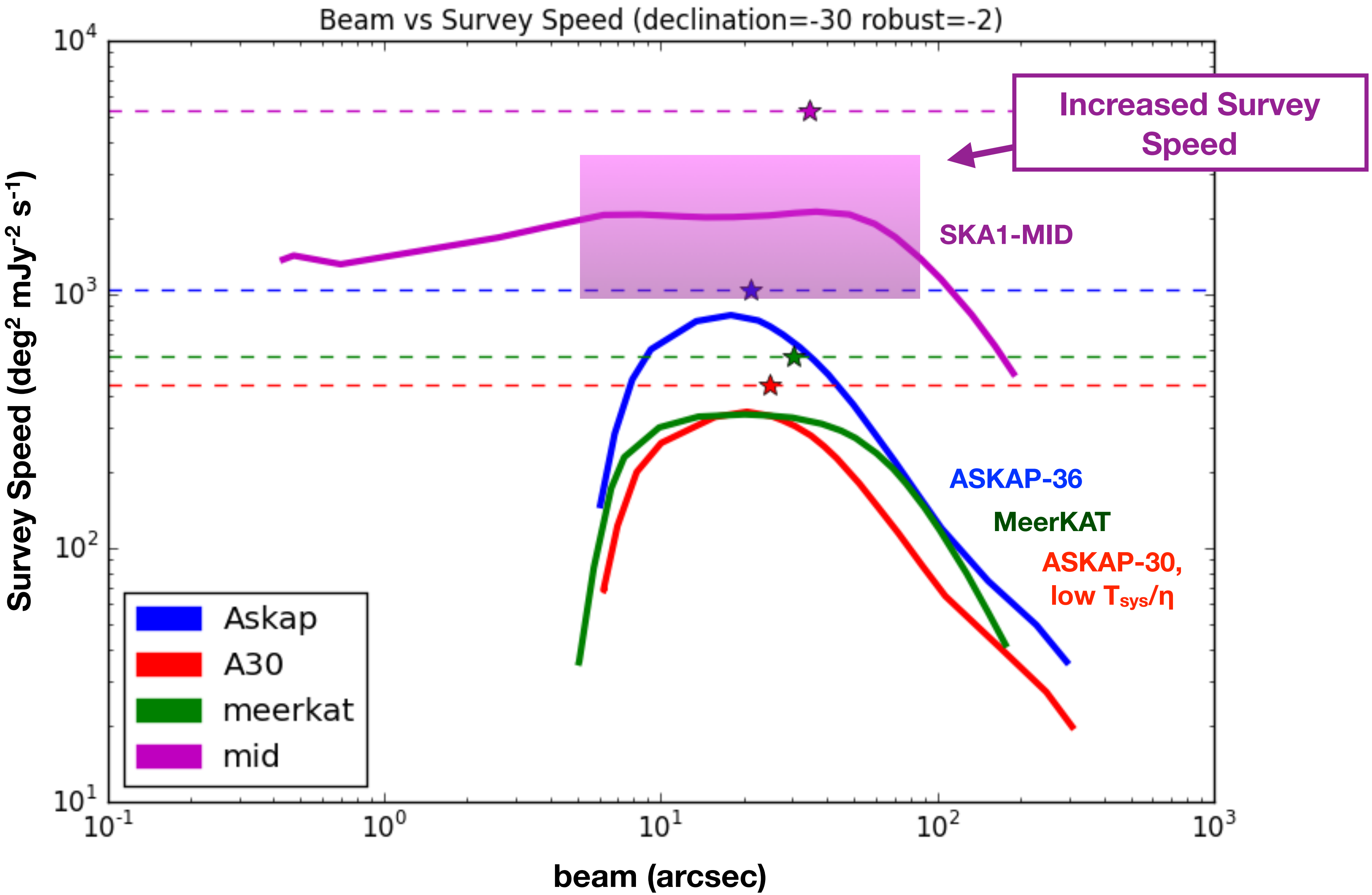
Popping et al, 2015, PoS, AASKA14, 132

SKA1 Capabilities



Popping performance plots

SKA1 Capabilities



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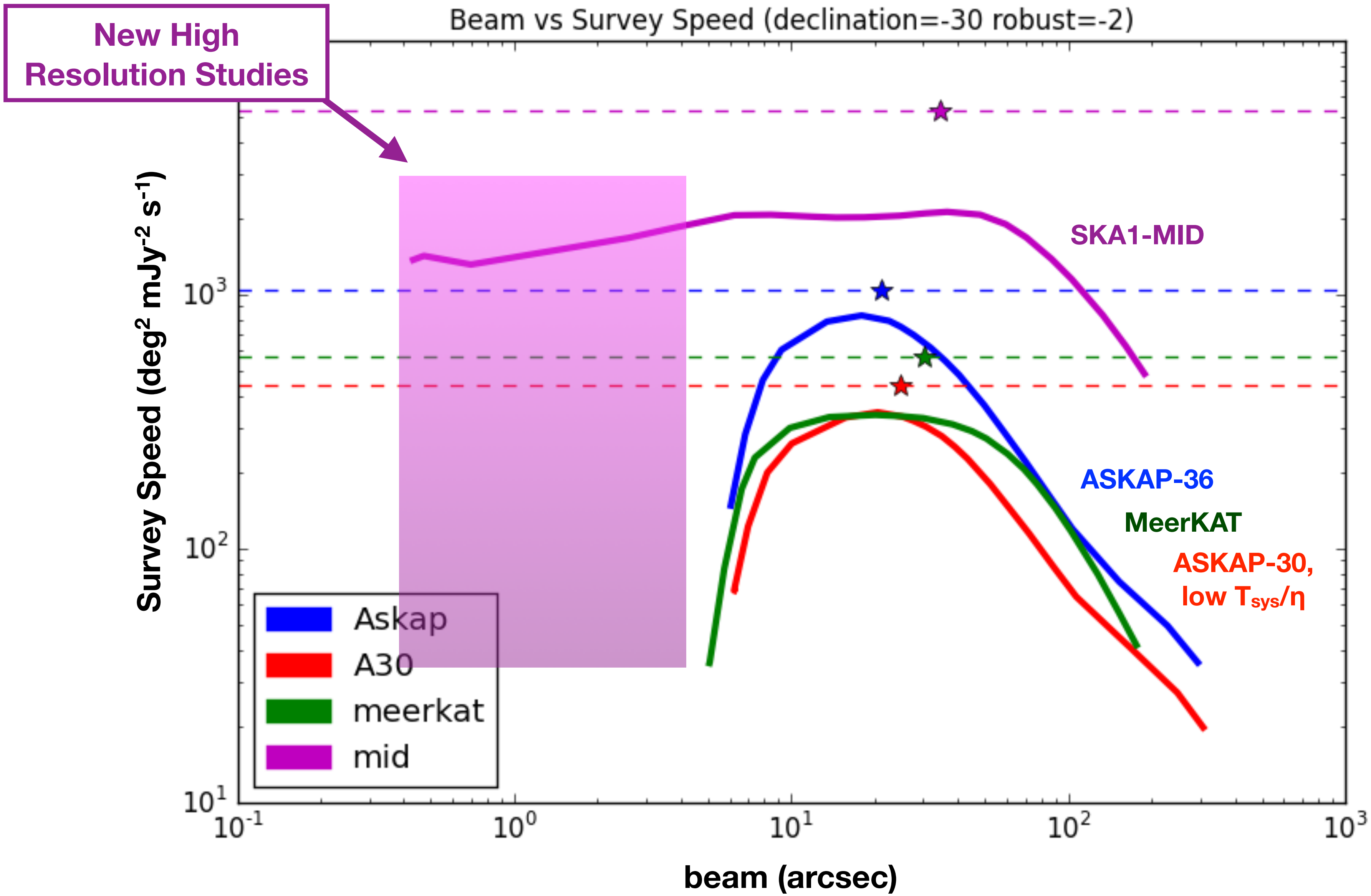
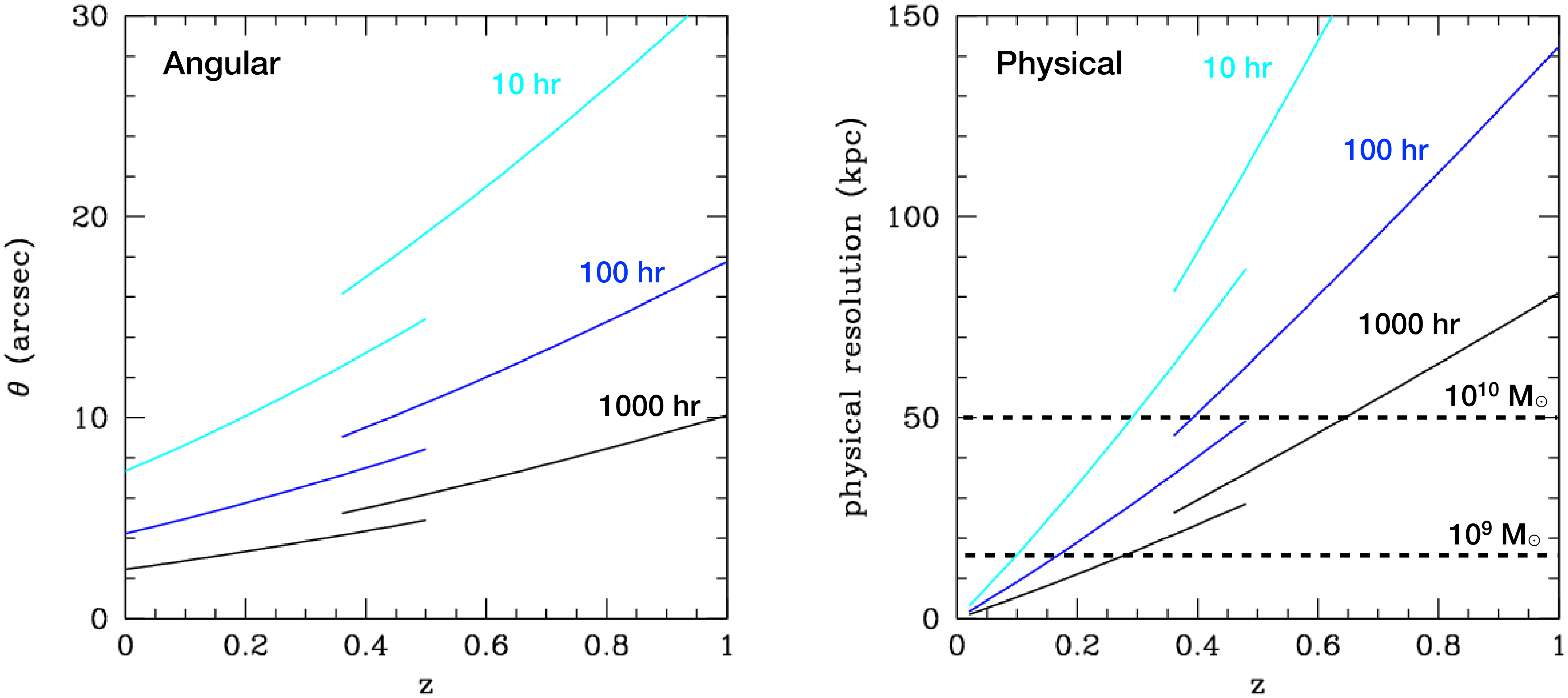
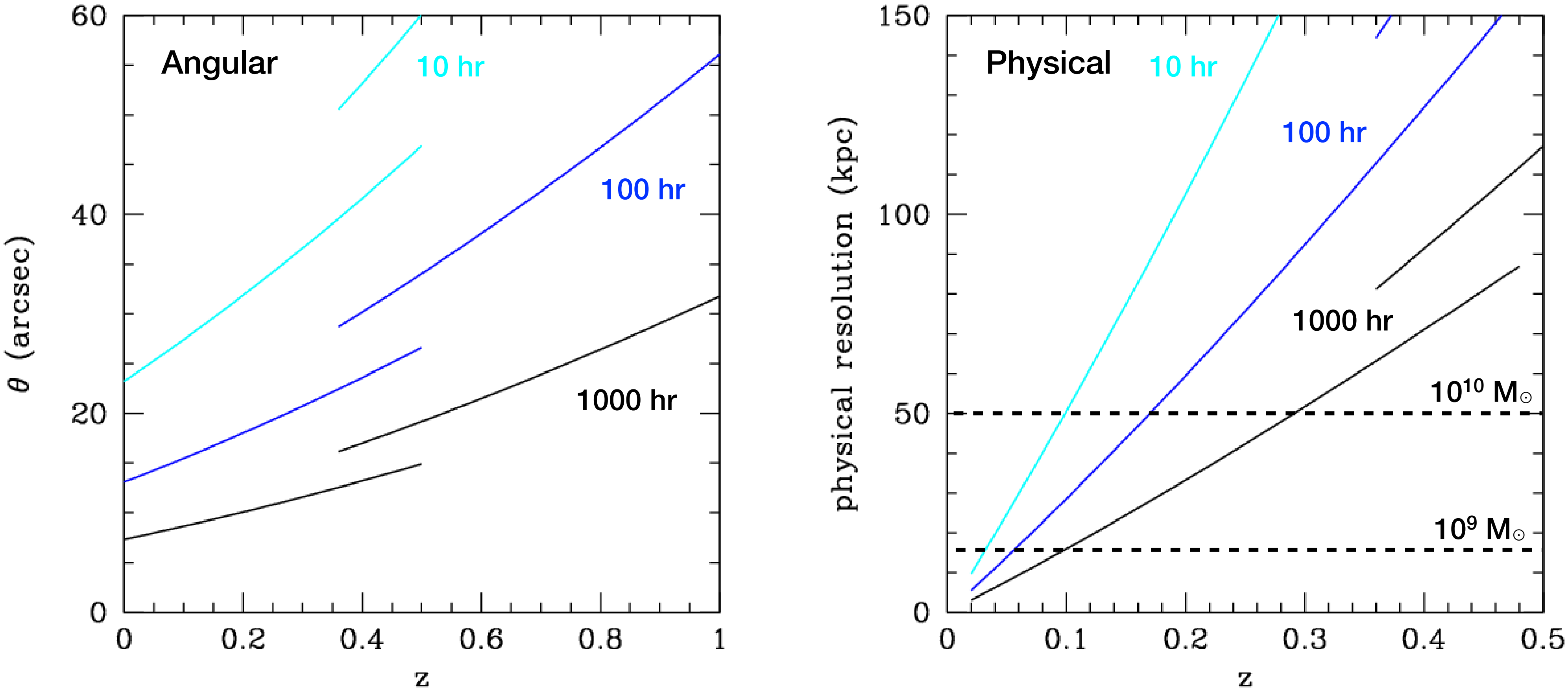


SKA1 Surveys: Resolution @ 10^{20} cm^{-2}



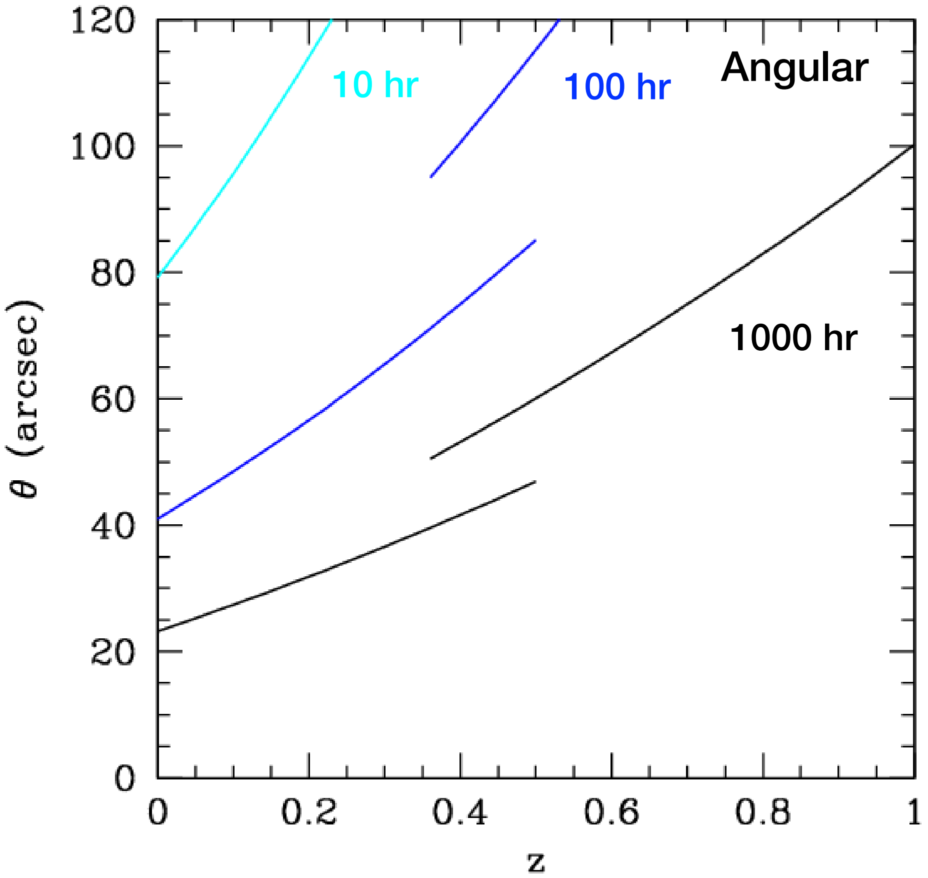
- **Resolve** galaxies over large redshift range
- Study role of mergers, feedback, local environment
- carry out detailed studies of galaxy kinematics & angular momentum
- high resolution studies of ISM in nearby galaxies (< 100 pc)

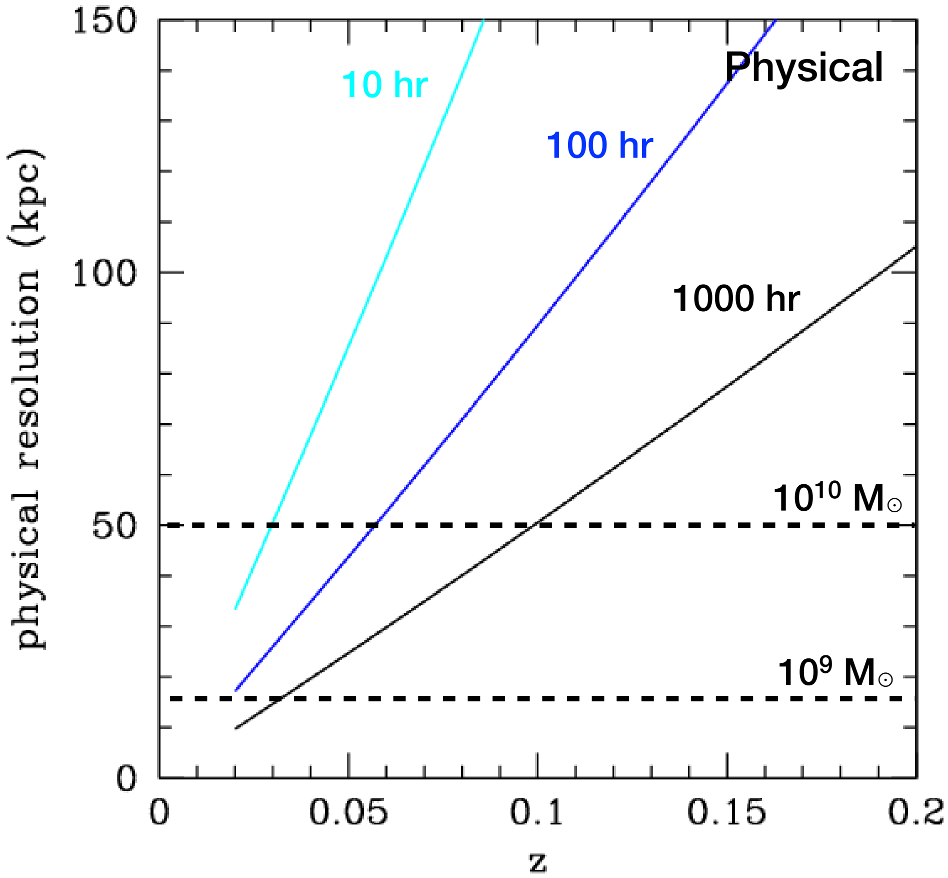
SKA1 Surveys: Resolution @ 10^{19} cm^{-2}



- HALOGAS type studies beyond local Universe
- understand how galaxies acquire their gas: role of environment/accretion

SKA1 Surveys: Resolution @ 10^{18} cm^{-2}





- New studies of the disk-halo-IGM interface

Possible SKA1 Surveys

1,000 hour projects

Survey	Area (deg	Freq MHz	Resolution	N	<z> (z
Medium wide	400	950-1420	10"	34,000	0.1 (0.3)
Medium deep	20	950-1420	5"	25,000	0.2 (0.5)
Deep	1	600-1050	2"	2,600	0.5 (1)
Targeted	-	1400-1420	3"-1'	50	0.002 (0.01)
Galaxy Emiss.	600	1418-1422	10"-1'	-	0 (0)
Galaxy Absorp.	400	1418-1422	5"	4,000	0 (0)
ExGal Absorp.	1000	350-1050	2"	5,000	1 (3)
	1000	200-350	10"	?	4 (6)

Staveley-Smith & Oosterloo, 2015, PoS, AASKA14, 167

Possible SKA1 Surveys

10,000 hour projects

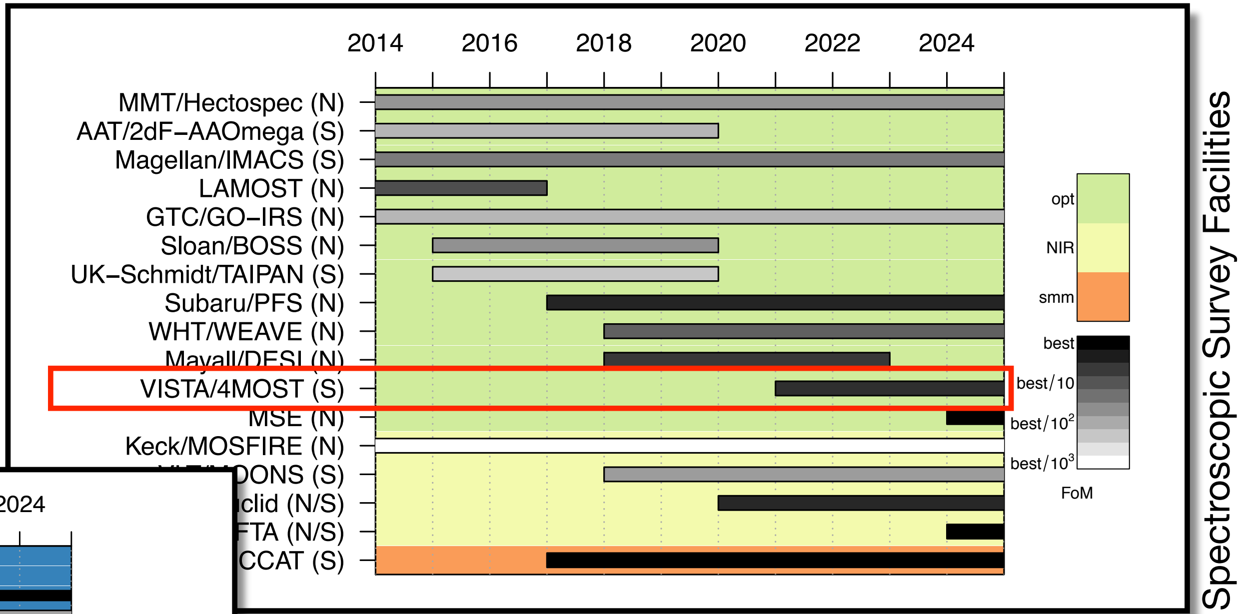
Survey	Area	Freq	Resolution	N	<z> (z
	(deg	MHz			
All-sky	20,000	950-1420	15”	550,000	0.06 (0.3)
Wide	5,000	950-1420	10”	340,000	0.1 (0.5)
Ultra deep	1	450-1050	2”	23,000	0.7 (2)

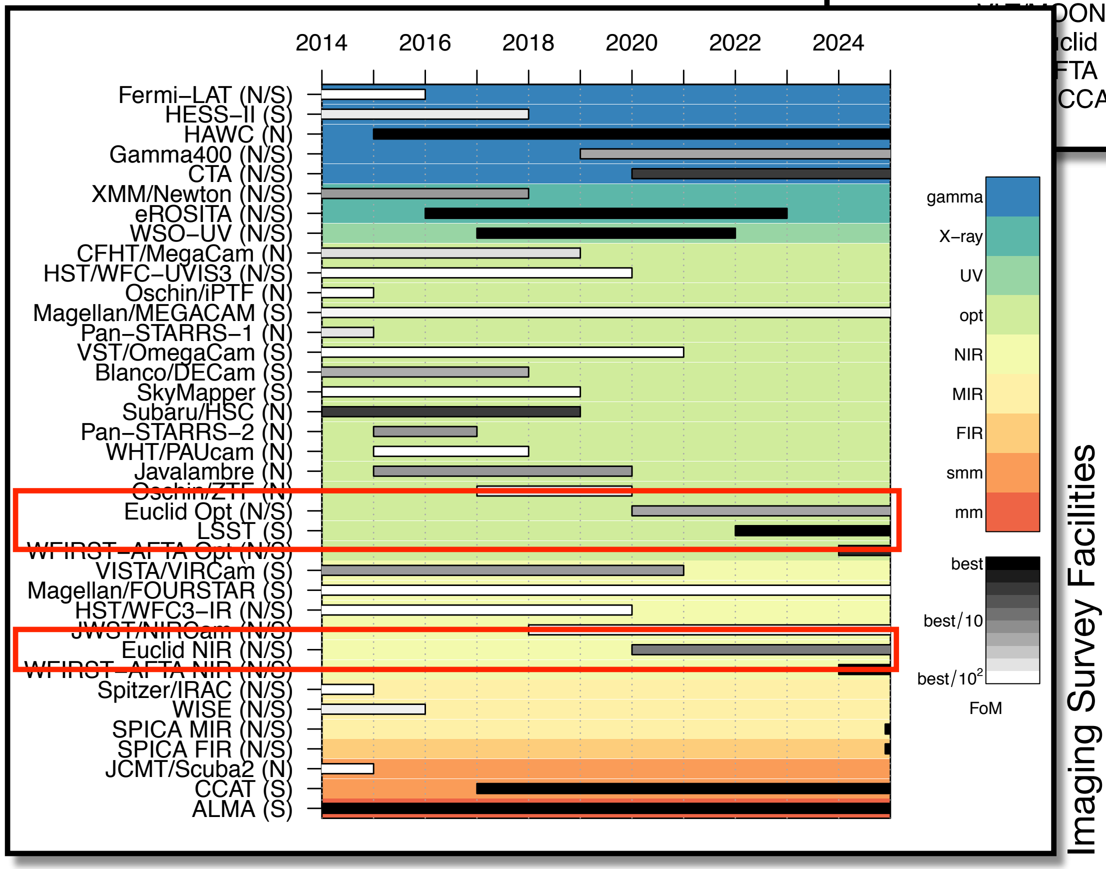
Staveley-Smith & Oosterloo, 2015, PoS, AASKA14, 167

Multi-λ for the SKA

“Connecting the Baryons”
Meyer, Robotham, et al, 2015, PoS, AASKA14, 131

https://asgr.shinyapps.io/ganttshiny



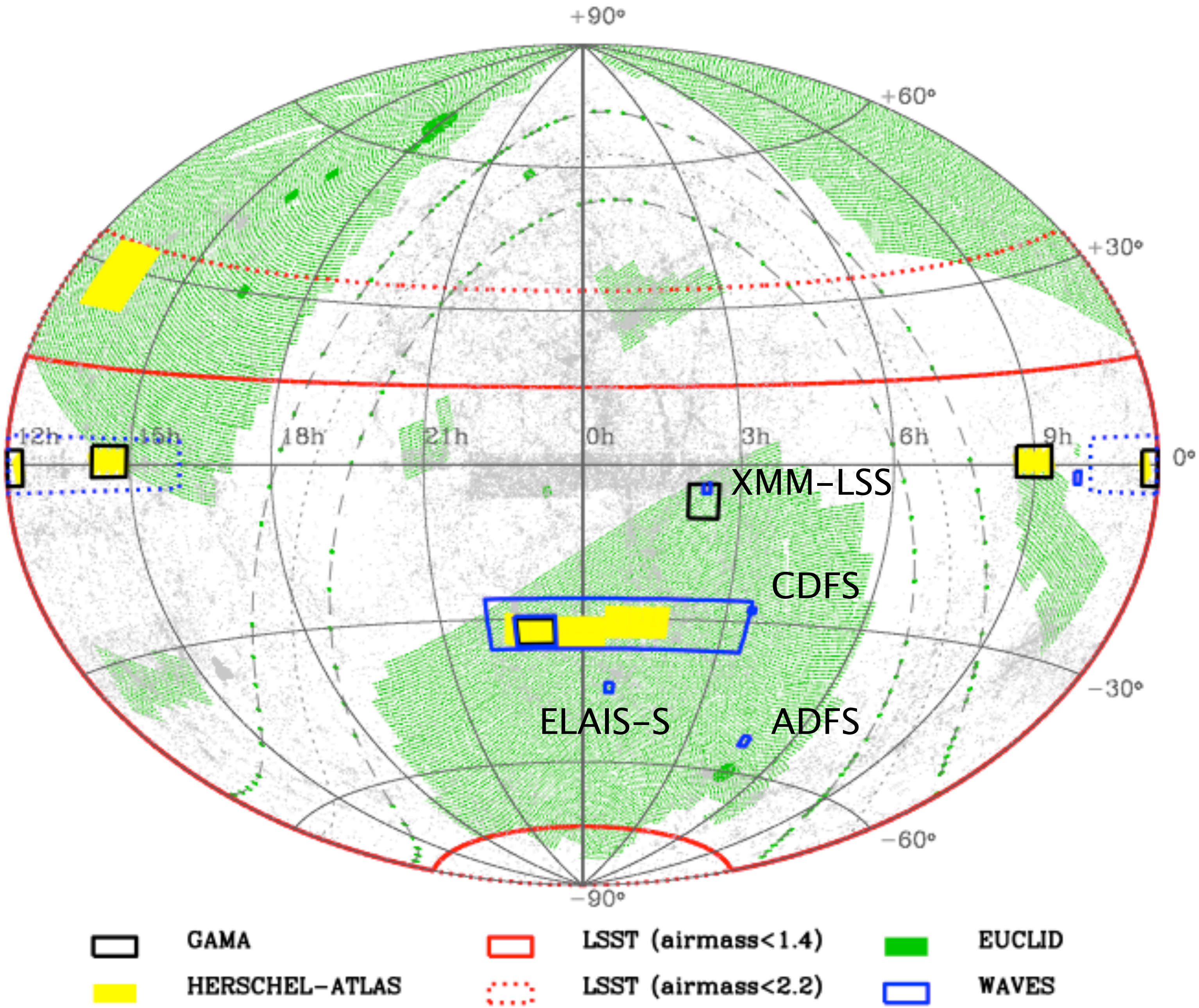


<u>excellent coverage</u>: optical and NIR imaging (LSST and Euclid/W- FIRST), low S/N redshift emission spectra (4MOST)

<u>significant follow-up possible</u>: IFU, gas-phase emission spectra, mm

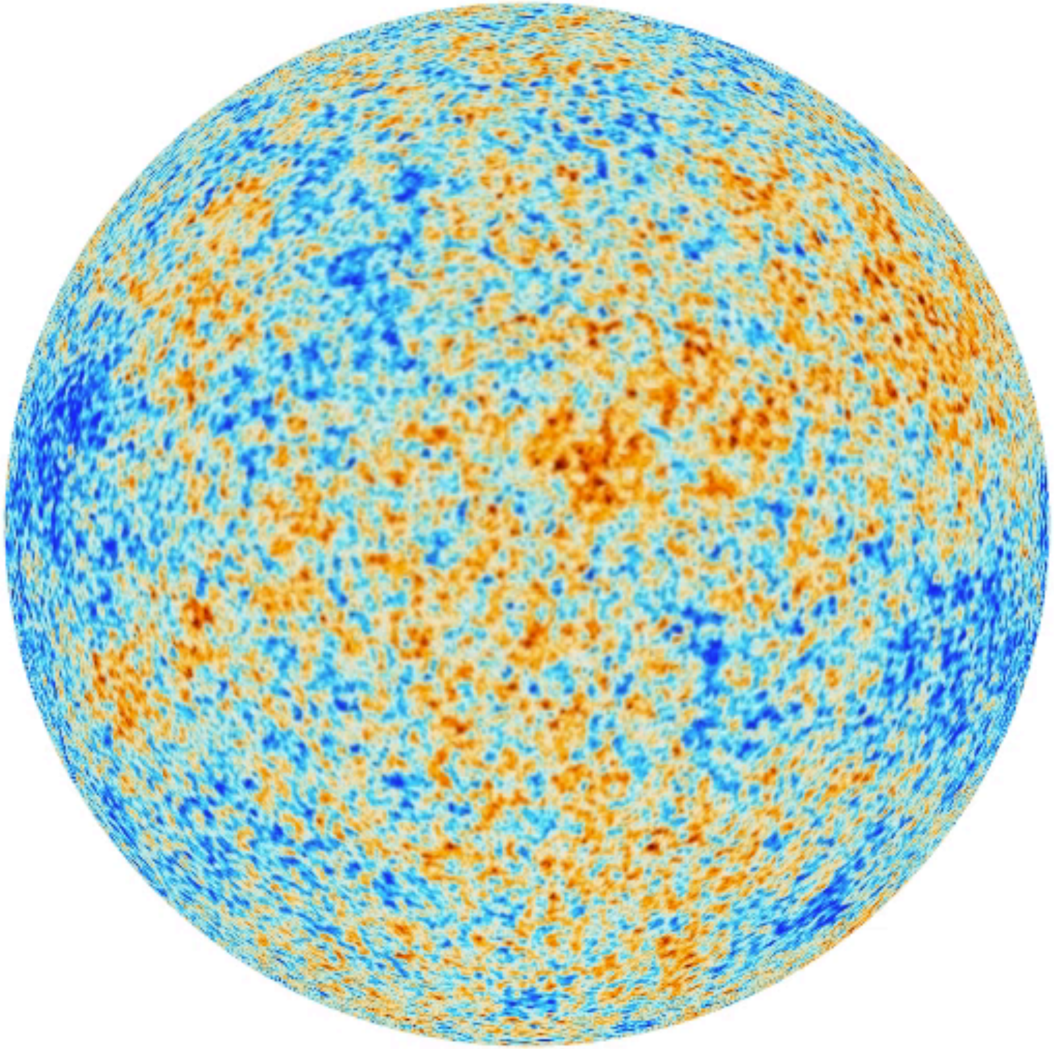
<u>potential weaknesses</u>: UV/FIR imaging, stellar-phase absorption spectra

SKA / WAVES / LSST / Euclid

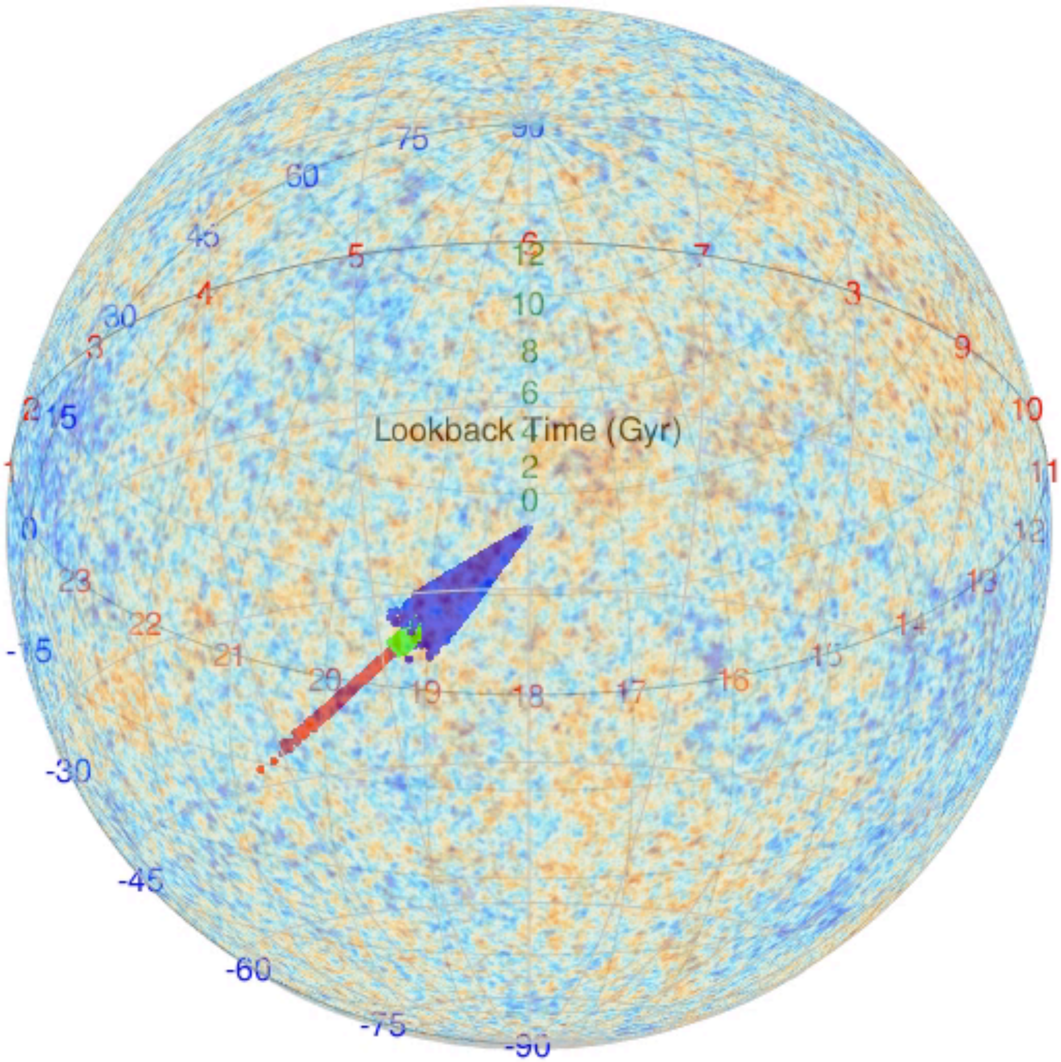


LSST
Euclid
WAVES
H-ATLAS

SKA Surveys



SKA1 1,000 hr surveys



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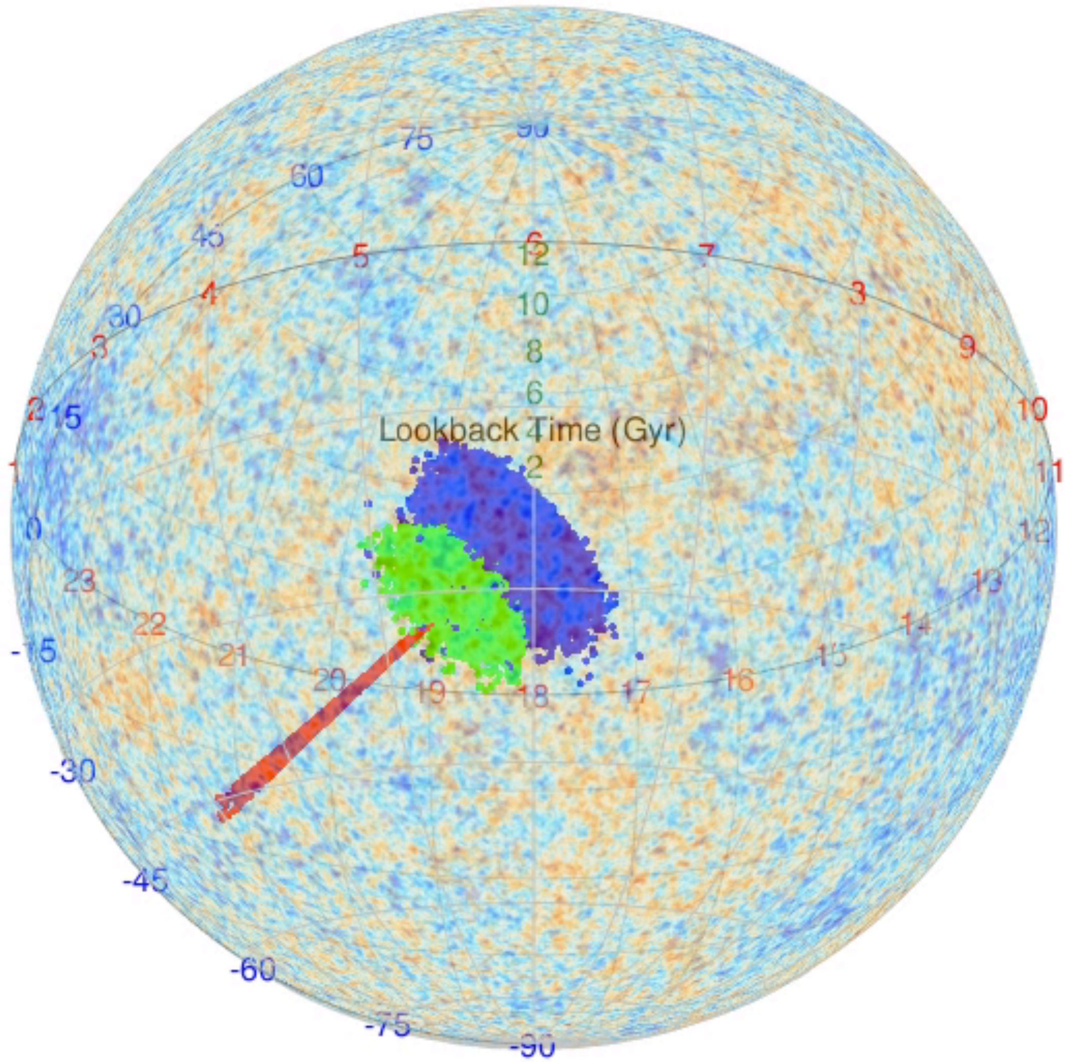

Full SKA Surveys