HI Galaxy Science with the SKA

Erwin de Blok
(ASTRON/UCT/Kapteyn)

Martin Meyer (ICRAR),
Lourdes Verdes-Montenegro (IAA) (co-chair),
Sarah Blyth (UCT) (co-chair)

on behalf of HI SWG

SKA-NL 2018

The HI Galaxy Science Working Group

HI emission/absorption and galaxy evolution from our Milky Way to high-redshift

~70 members from 16 countries (7 NL)

co-chairs: Lourdes Verdes-Montenegro (lourdes@iaa.es) and Sarah Blyth (blyth@ast.uct.ac.za)

open membership

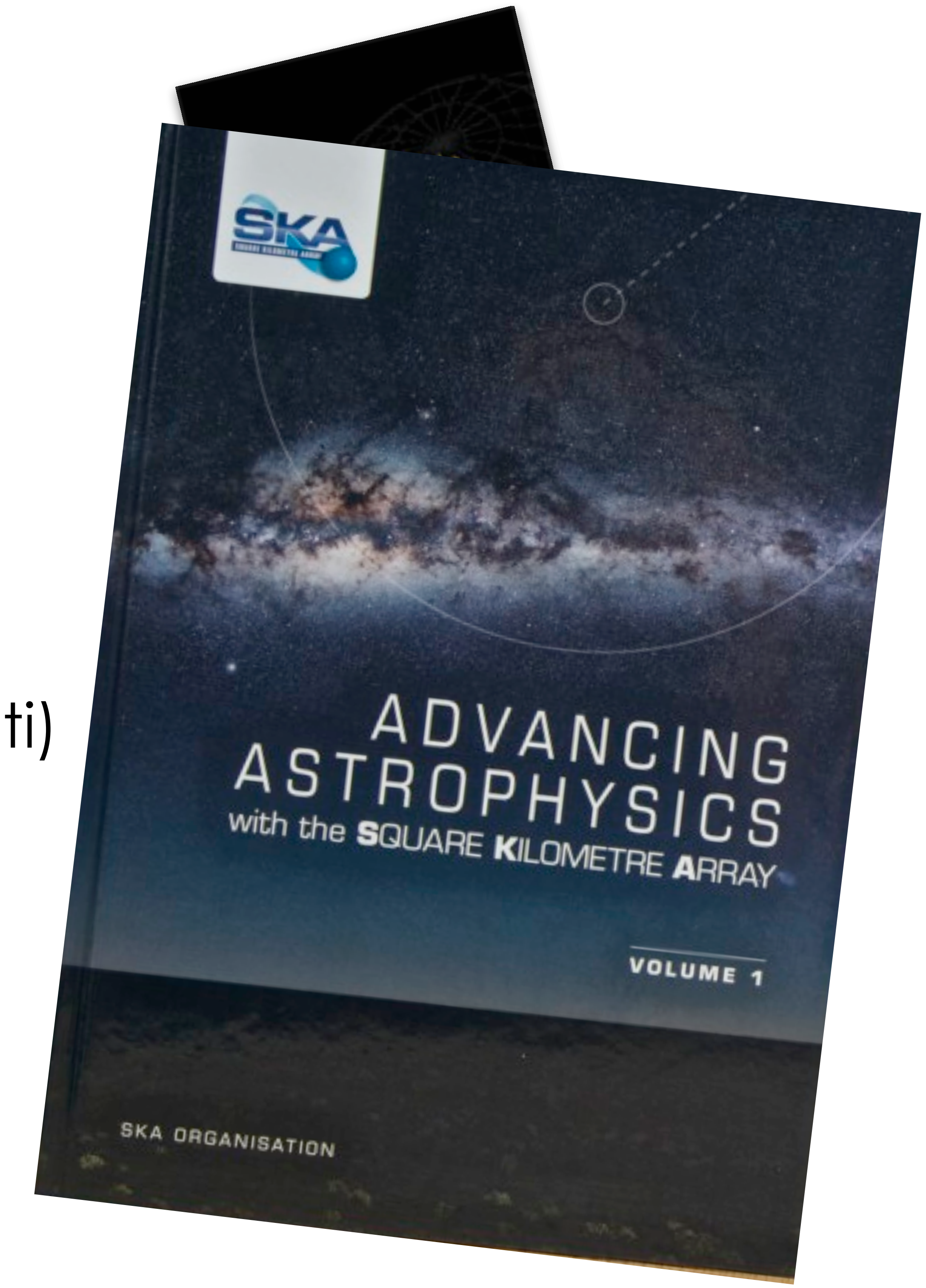
annual PHISCC workshops to coordinate precursor and SKA science (next one in 3 weeks @ FAST)

more information at http://astronomers.skatelescope.org/science-working-groups/galaxy-evolution/

The SKA Science Book

HI Chapters:

- **The Hydrogen Universe with the SKA** (Staveley-Smith/Oosterloo)
- **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)



HI Science

The connection between star formation, HI, gas dynamics and accretion, is one of the main issues to address through HI surveys of the local and distant Universe

- ***How do galaxies get their gas?***
- ***How is star formation regulated?***
- ***How are outer disks and cosmic web linked?***
- ***How does all of this evolve with redshift?***
- ***…***

SKA1 HI Science Goals

- 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 imaging 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

SKA1 HI Science Priorities

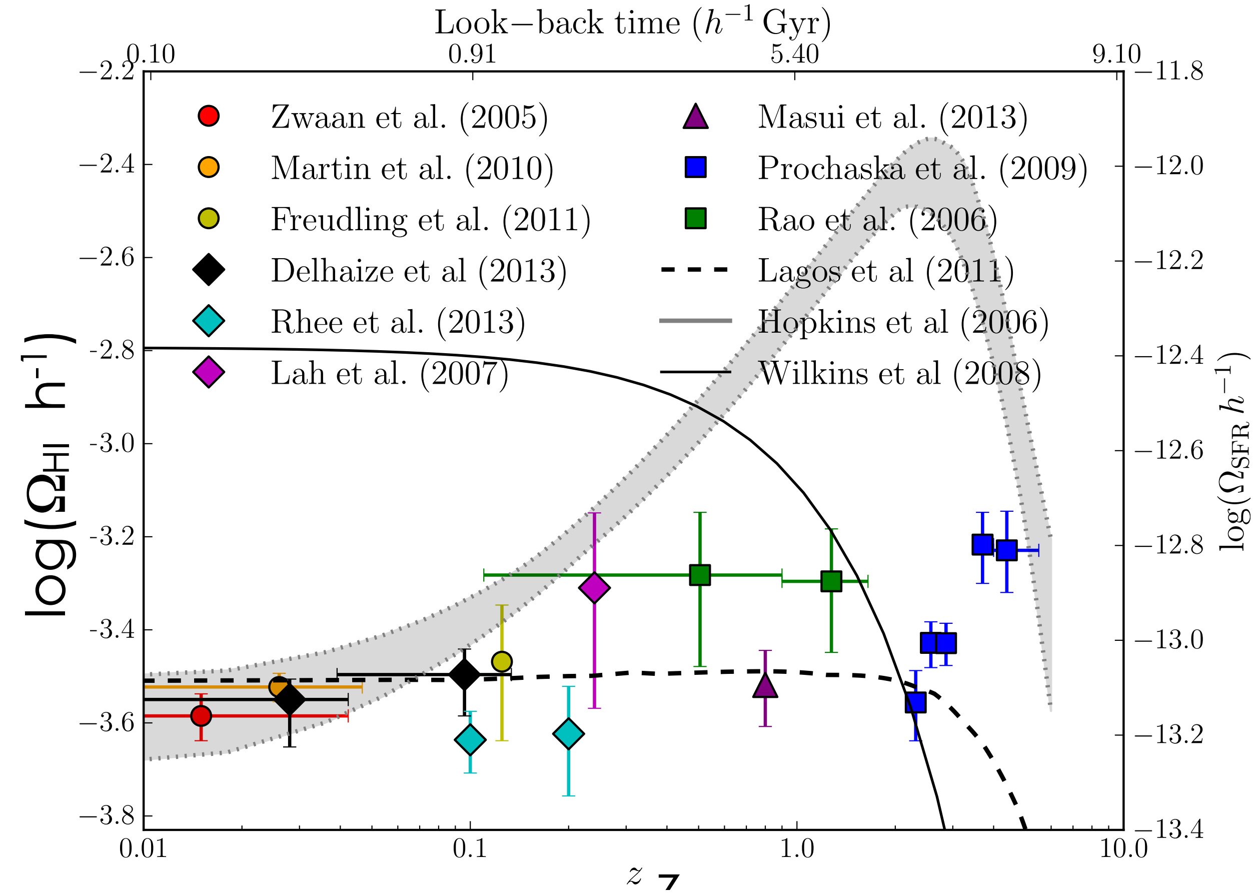
- Resolved HI kinematics and morphology of ~10^{10} $M_\odot$ mass **galaxies out to z~0.8**
- High spatial resolution studies of the **ISM in the nearby Universe**.
- Multi-resolution imaging studies of the **ISM in our Galaxy**
- **HI absorption studies** out to the highest redshifts.
- The gaseous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

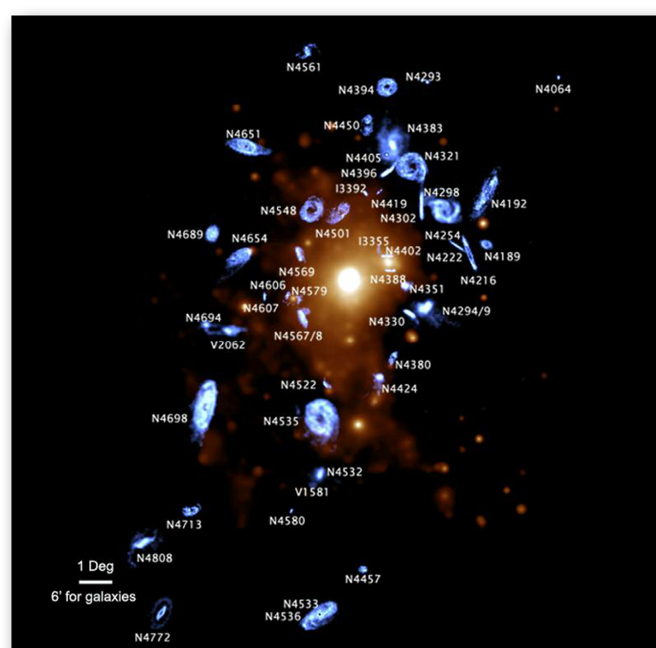
13 priority SKA1 science goals

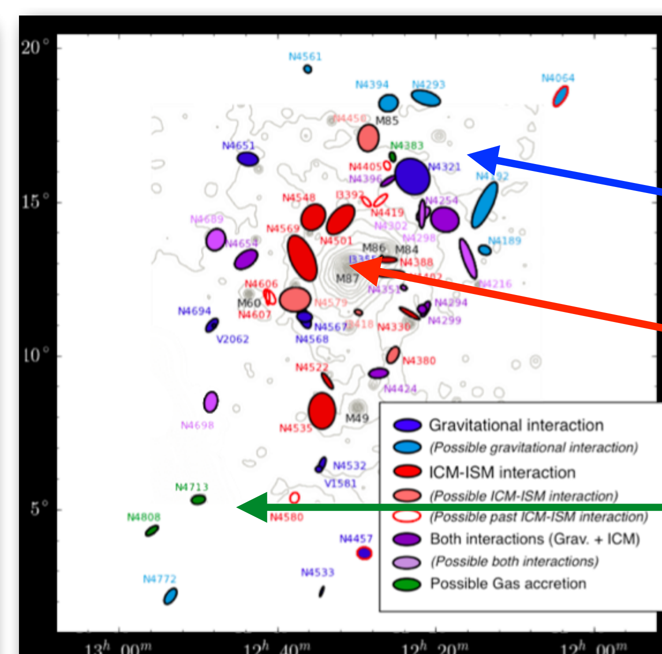
Science Goal	SWG	Objective	SWG Rank
1	*CD/EoR*	Physics of the early universe IGM - I. Imaging	1/3
2	*CD/EoR*	Physics of the early universe IGM - II. Power spectrum	2/3
4	*Pulsars*	Reveal pulsar population and MSPs for gravity tests and Gravitational Wave detection	1/3
5	*Pulsars*	High precision timing for testing gravity and GW detection	1/3
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
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 & 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







gravitational interaction

current ICM-ISM interaction

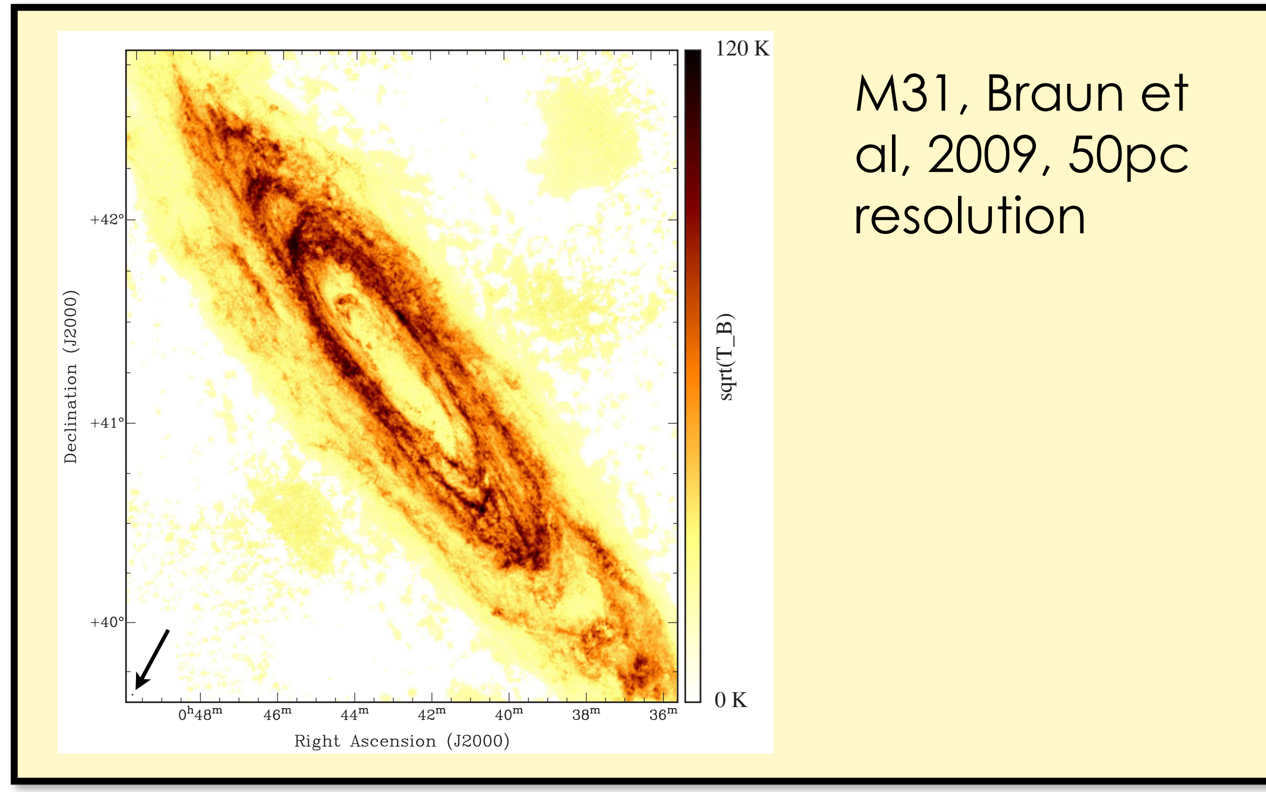
accretion

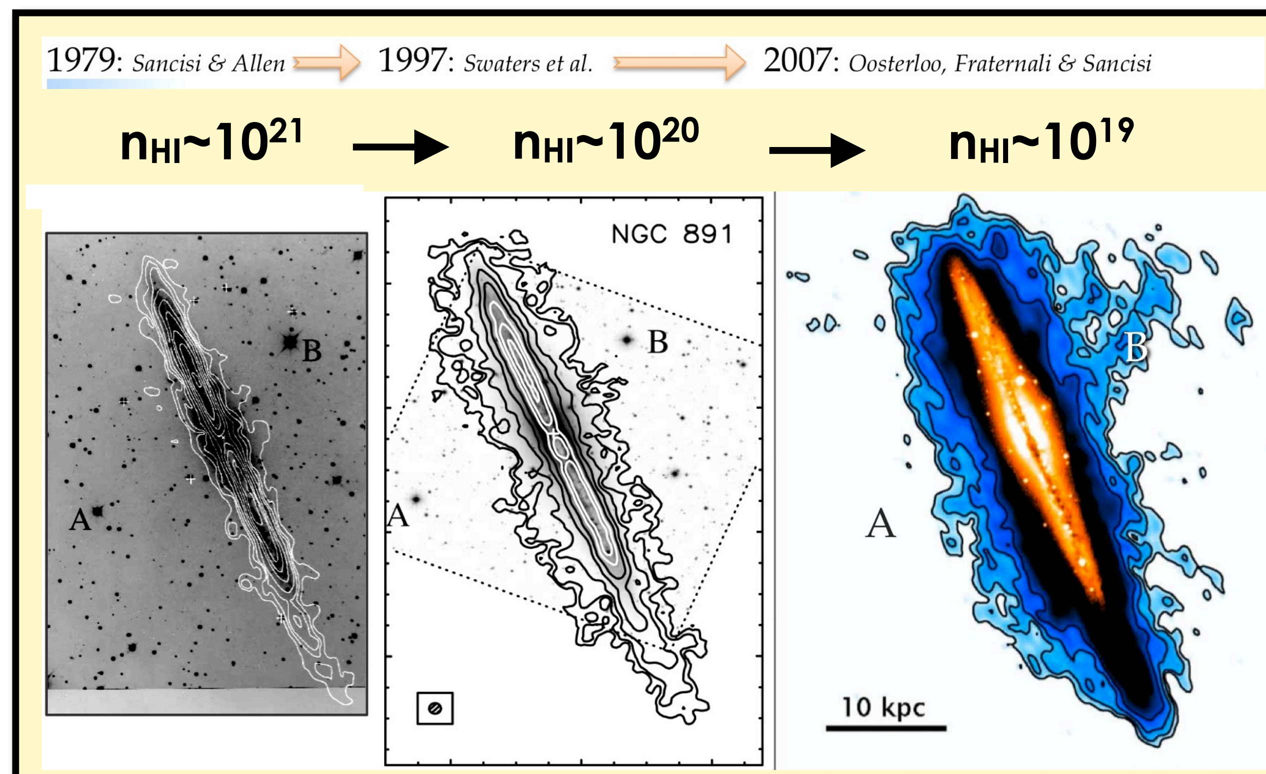
Blyth et al, 2015, PoS, AASKA14, 128

ISM in the Nearby Universe

Deep studies in local Universe also needed to understand HI physics

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



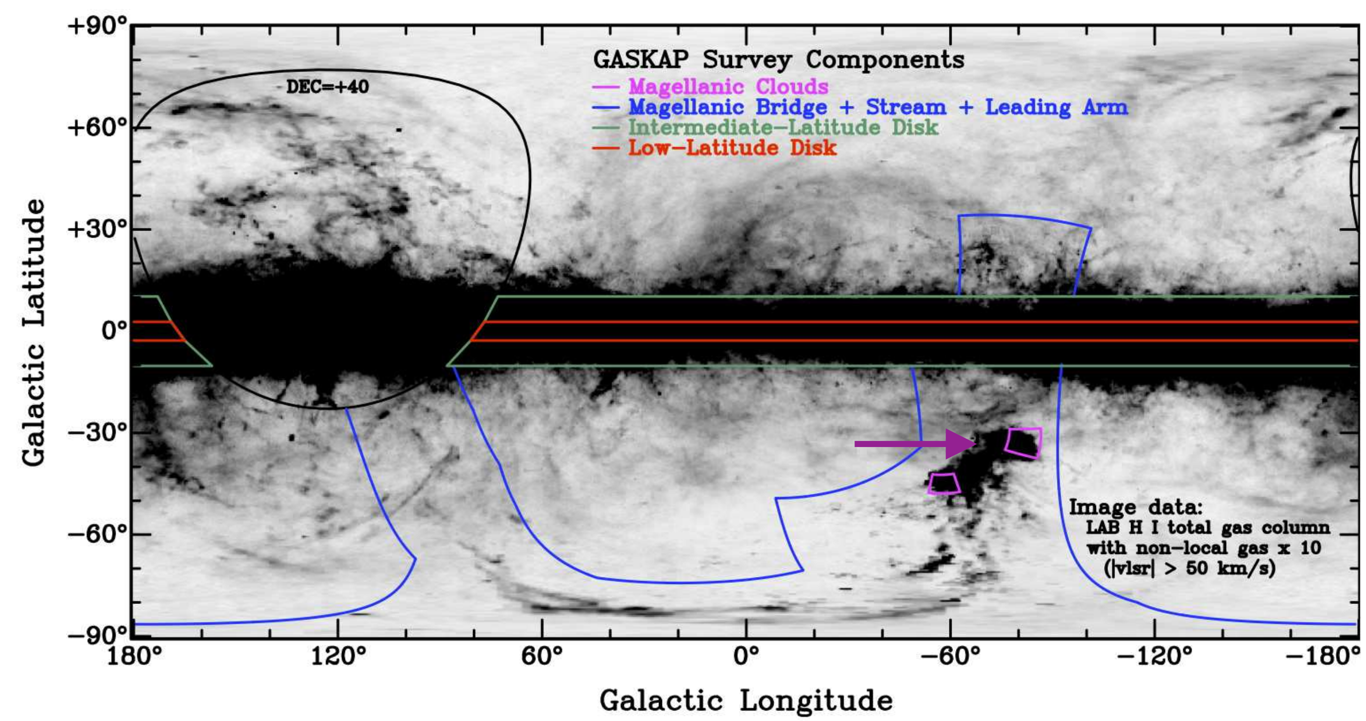


dB et al, 2015, PoS, AASKA14, 129

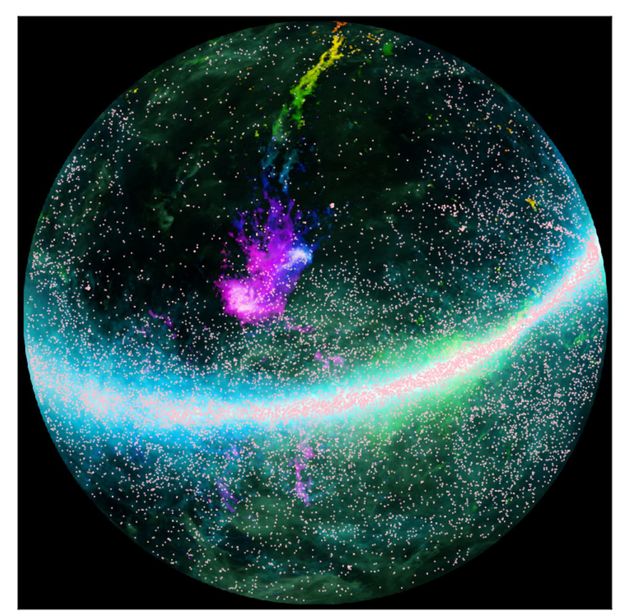
Milky Way & Magellanic Clouds

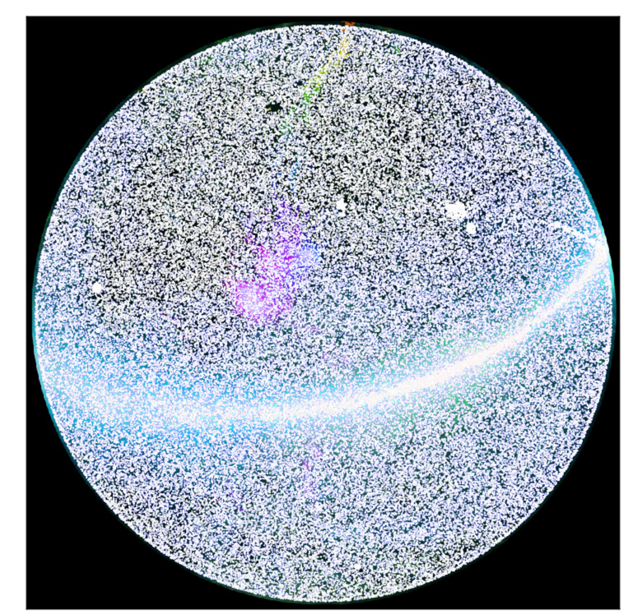
MW and Magellanic clouds allow studies of gas content **in greater detail than anywhere else**

- How is <u>gas exchanged</u> with surrounding <u>IGM</u>?
- How is <u>warm surrounding diffuse gas</u> cooled 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

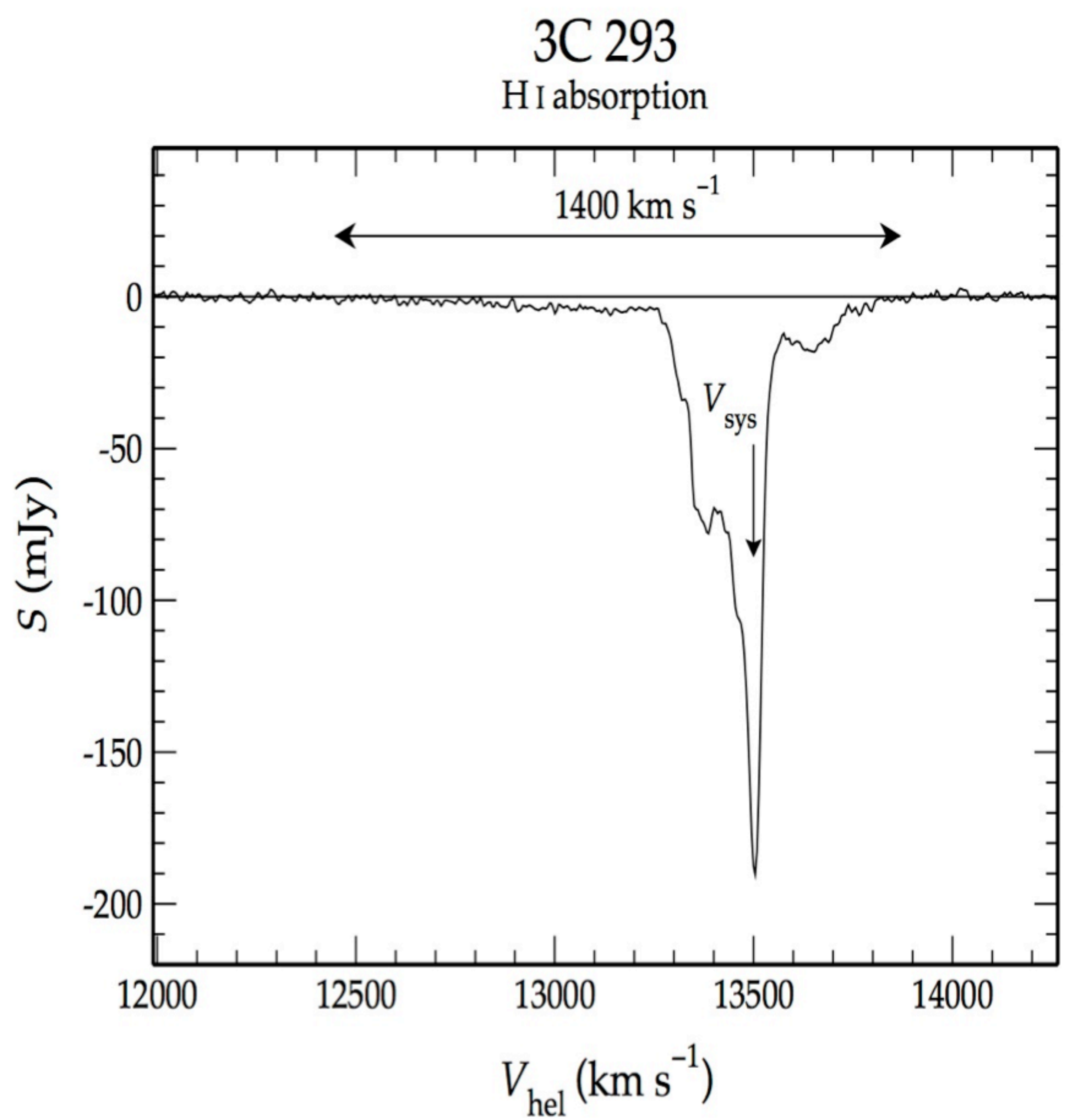
McClure-Griffiths et al, 2015, PoS, AASKA14, 130

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.

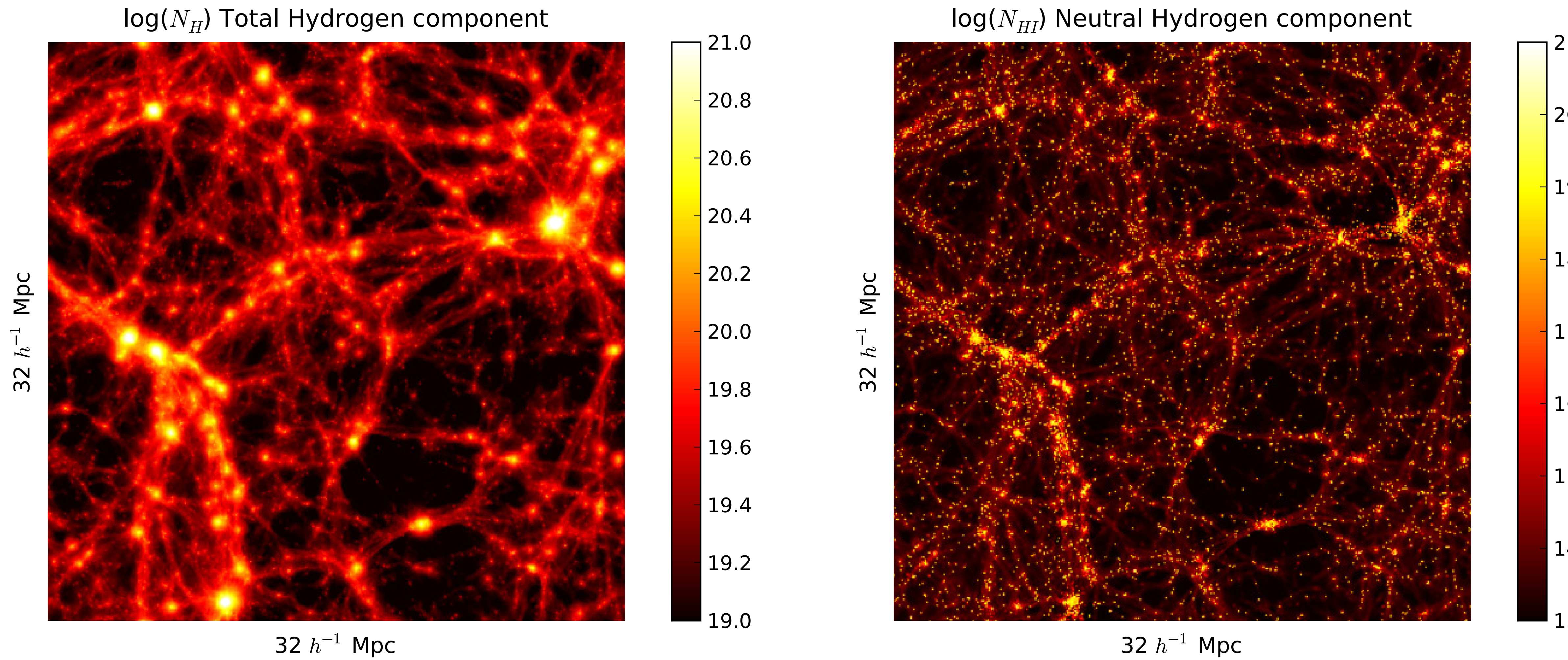
- Intervening HI 21cm absorption → constrain the evolution of cold gas in normal galaxies over more than 12 billion years of cosmic time.



Morganti et al, 2015, PoS, AASKA14, 134

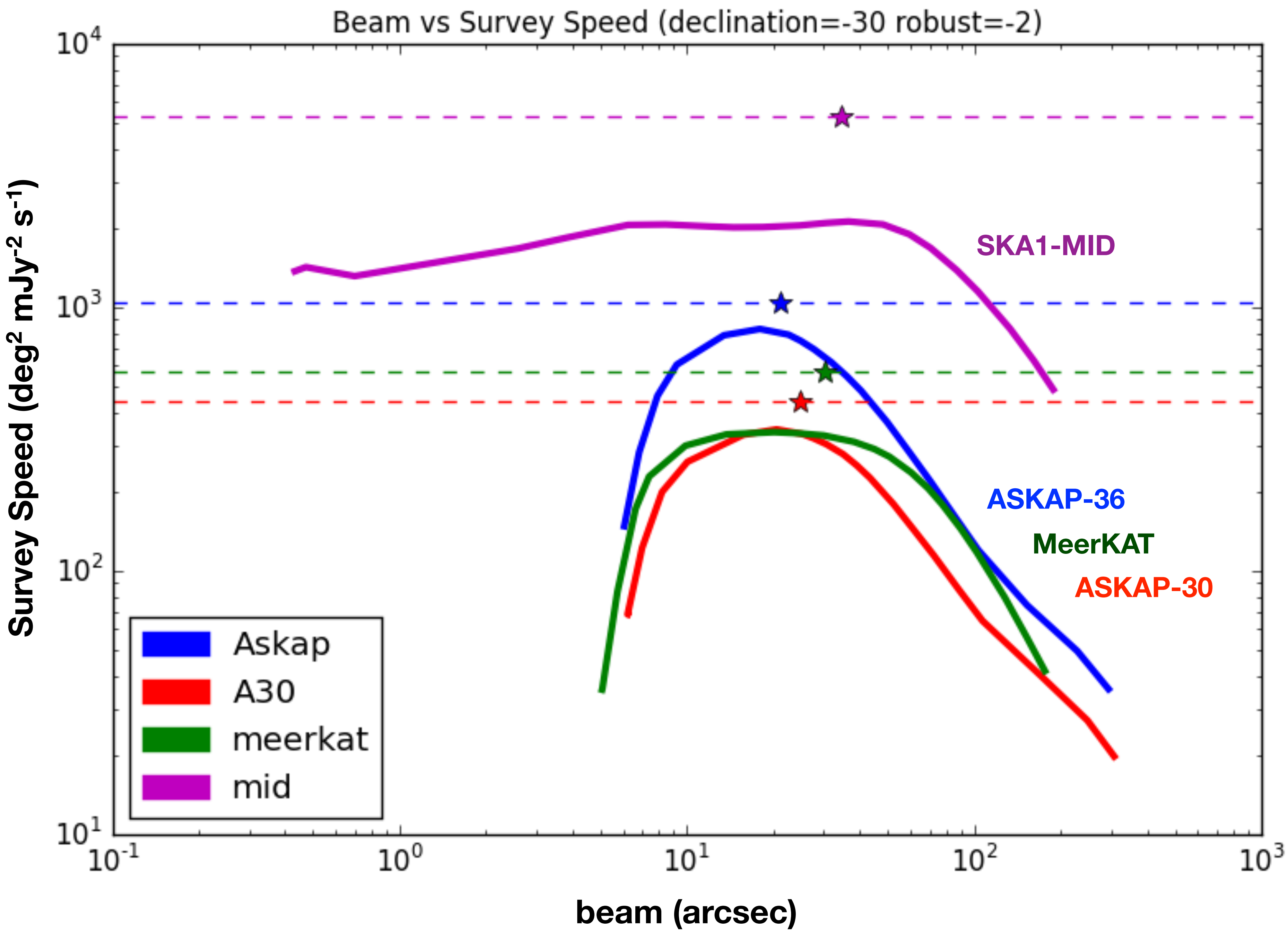
Galaxy-IGM Connection

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



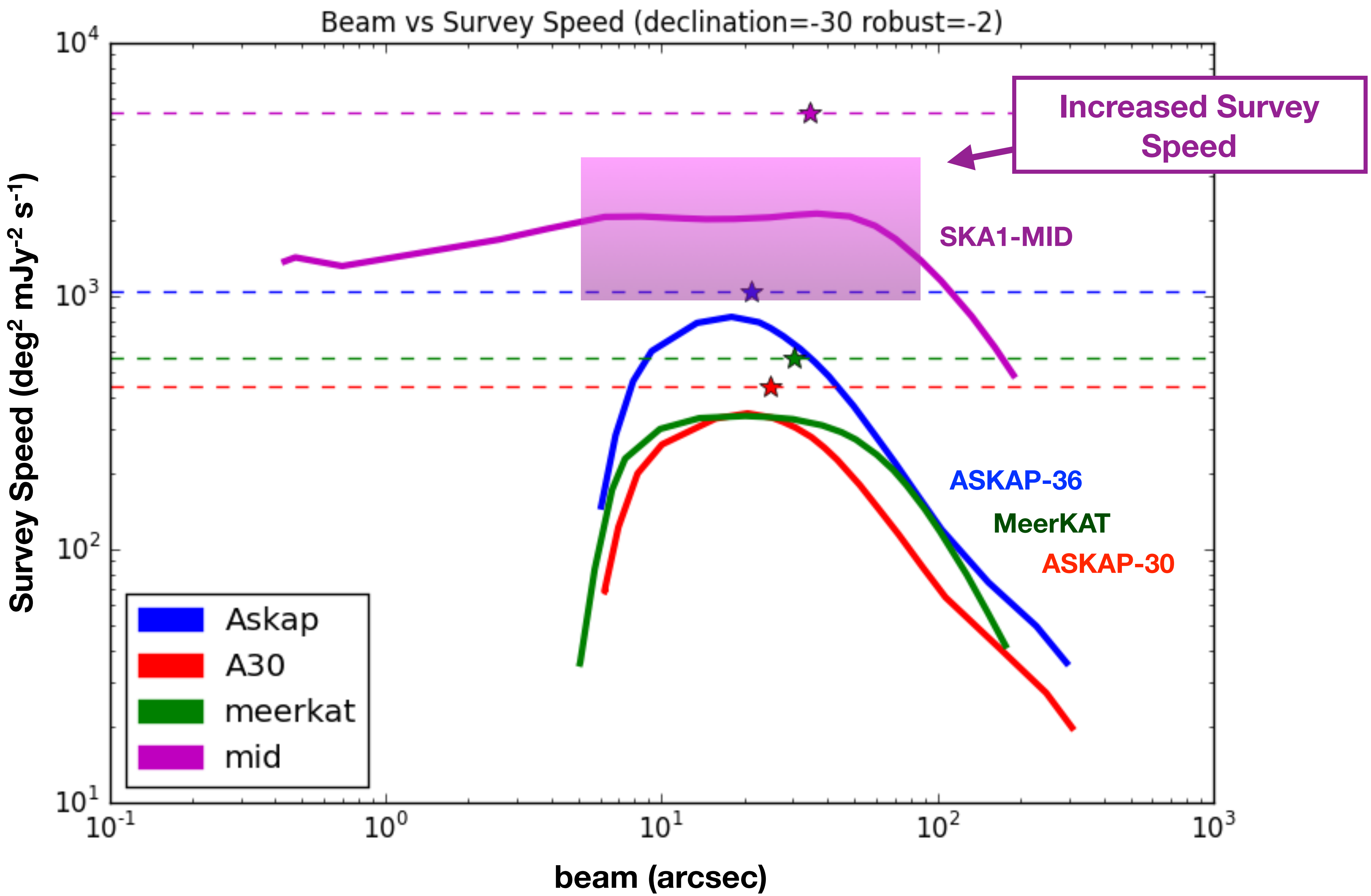
Popping et al, 2015, PoS, AASKA14, 132

SKA-1 Capabilities

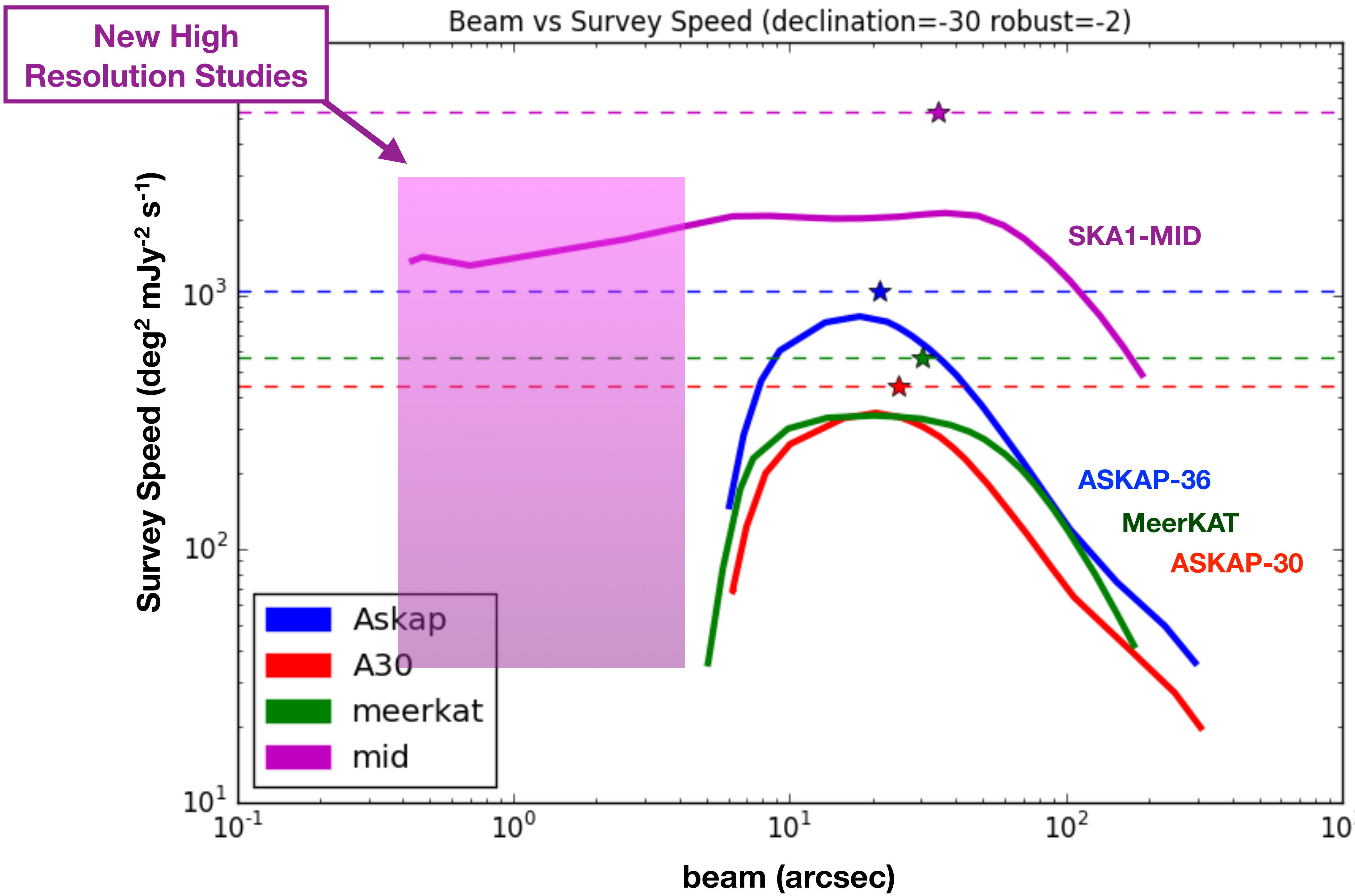


(courtesy A. Popping)

SKA-1 Capabilities

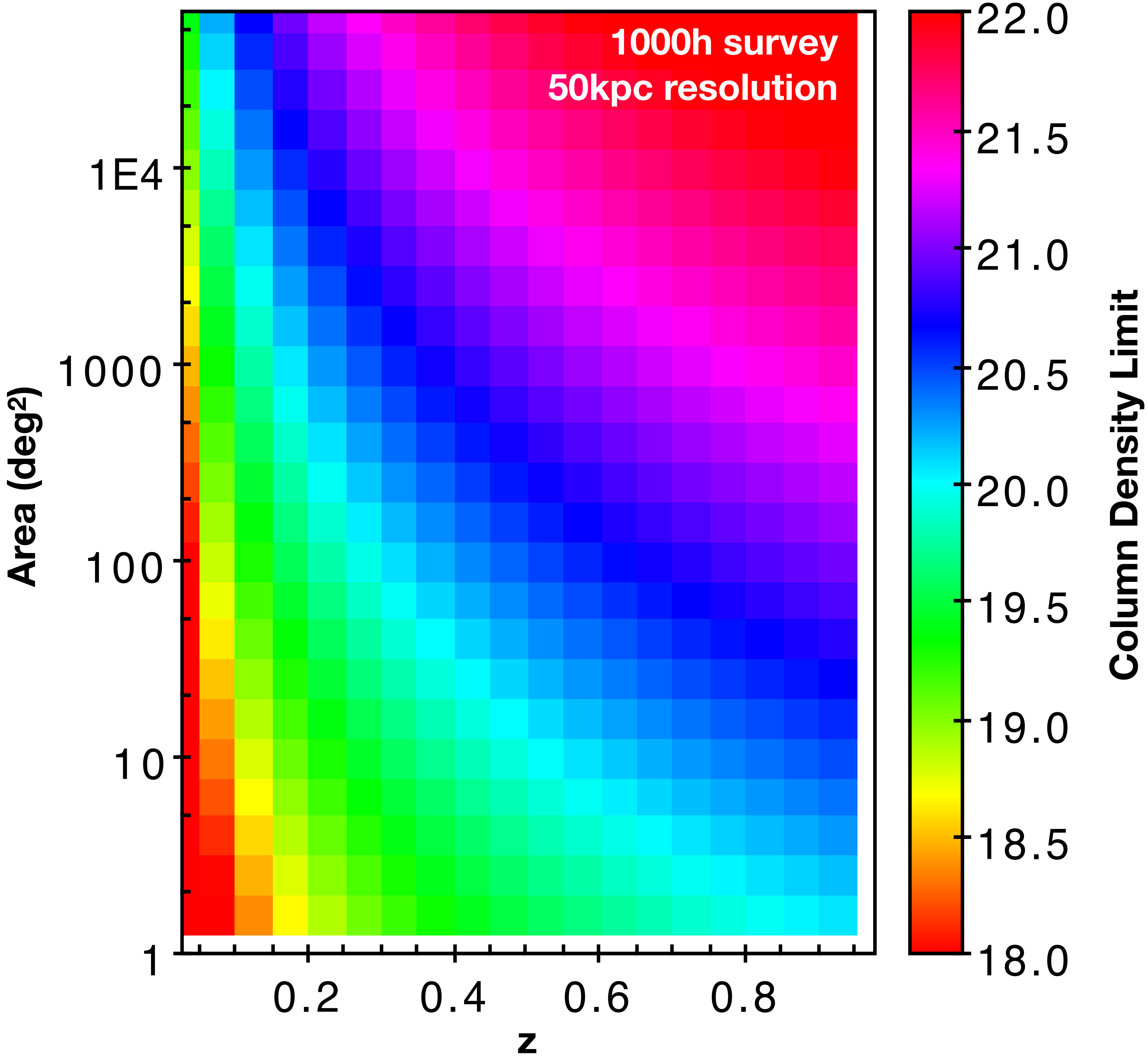


SKA-1 Capabilities



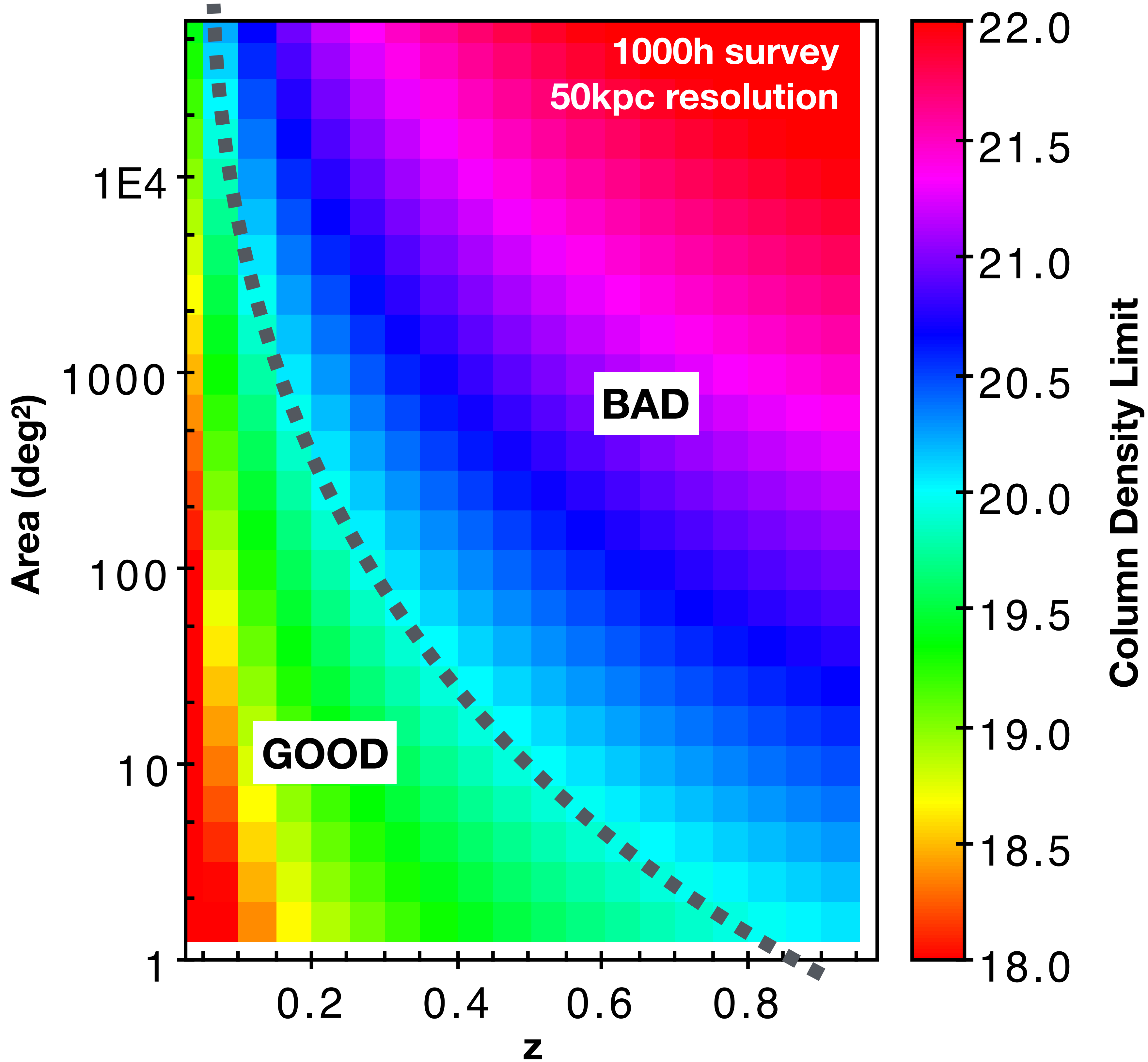
What Kind of Surveys To Do?

- **Requirements**
  - HI observations mainly <u>column-density-limited</u>
  - Want to observe HI down to at least galactic scales
  - SKA observation time is limited (~1000h KSPs)
    5 yr x 8000 h x 75% = 30000 h
  - Time+beam+z+area sets column density limit
  - Need $n_{HI} > 10^{20}$



What Kind of Surveys To Do?

- **Requirements**
  - HI observations mainly <u>column-density-limited</u>
  - Want to observe HI down to at least galactic scales
  - SKA observation time is limited (~1000h KSPs)
  - Time+beam+z+area sets column density limit
  - Need $n_{HI} > 10^{20}$



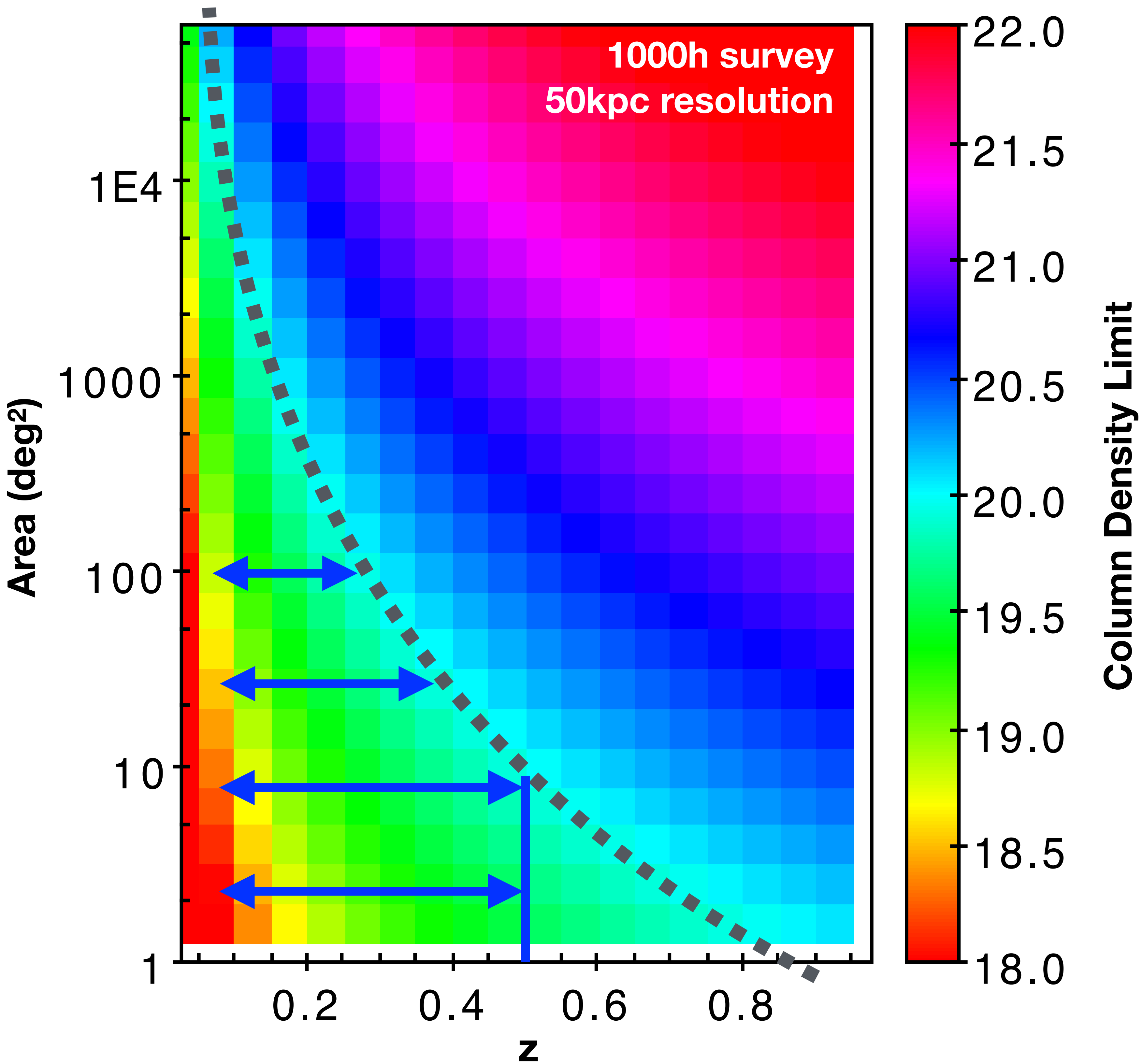
What Kind of Surveys To Do?

Requirements

- Want to observe HI down to at least galactic scales
- SKA observation time is limited (~1000h KSPs)
- Time+beam+z+area sets column density limit
- Need $n_{HI} > 10^{20}$

Preferred Surveys

- **band 2: ~10→100 deg²**



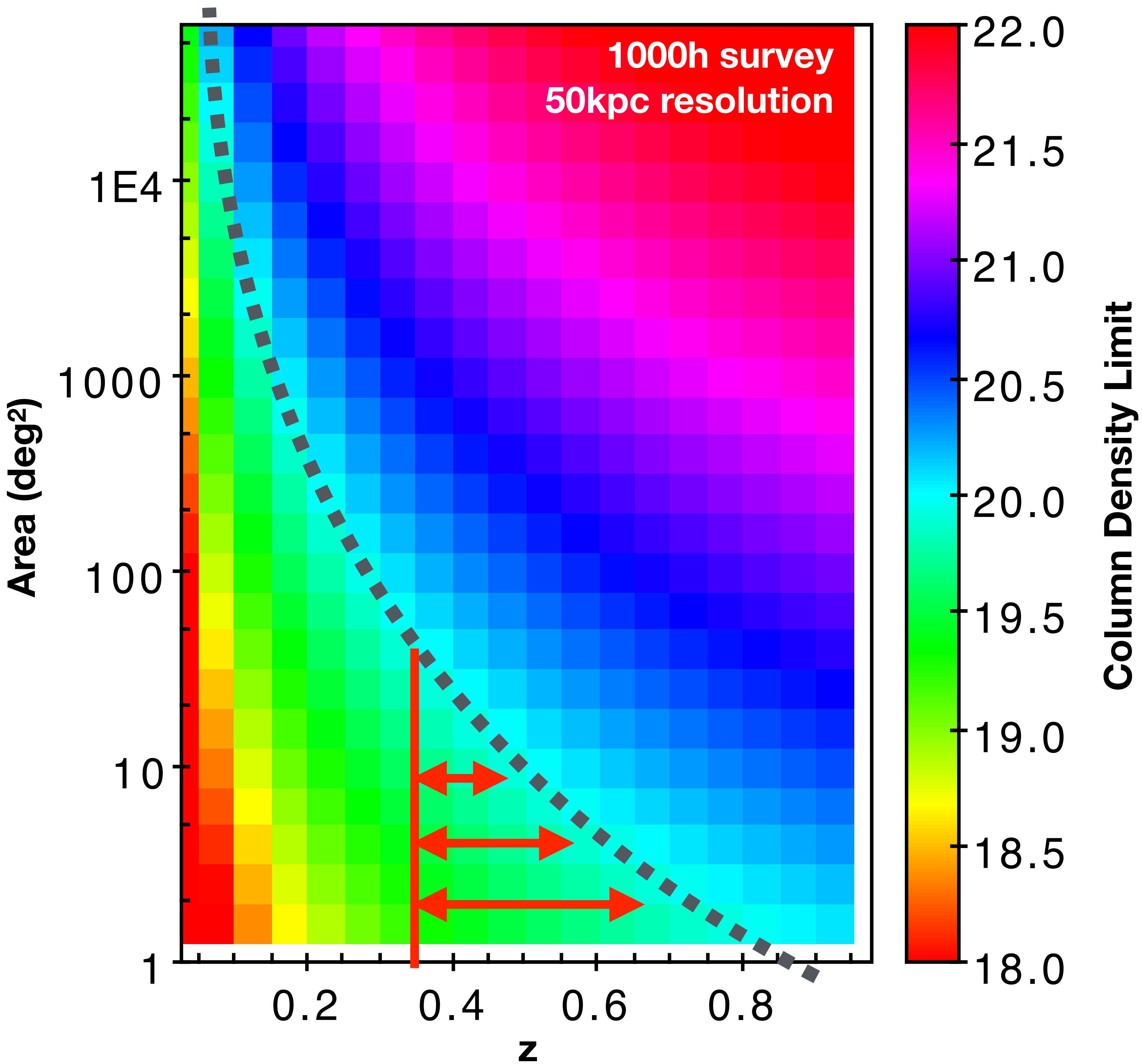
What Kind of Surveys To Do?

Requirements

- Want to observe HI down to at least galactic scales
- SKA observation time is limited (~1000h KSPs)
- Time+beam+z+area sets column density limit
- Need $n_{HI} > 10^{20}$

Preferred Surveys

- band 2: ~10→100 deg²
- band 1: SP→few deg²



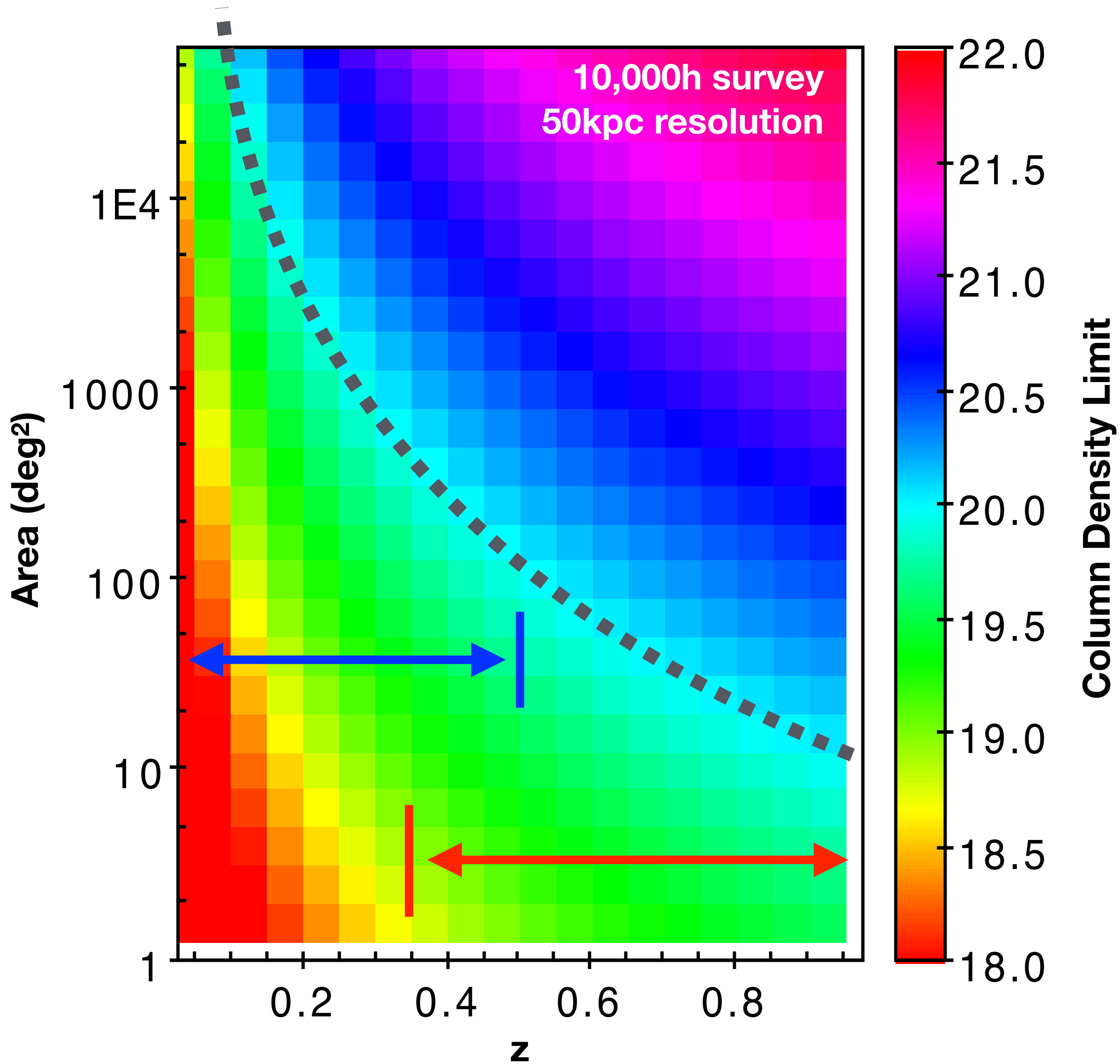
What About Commensal 10,000 h?

Requirements

- Want to observe HI down to at least galactic scales
- SKA observation time is limited (~1000h KSPs)
- Time+beam+z+area sets column density limit
- Need $n_{HI} > 10^{20}$

Preferred Surveys

- **band 2: ~10→100 deg²**
- **band 1: ~1→10 deg²**



Possible SKA1 Surveys

Minimum Requirements

5 yr x 8000 h x 75% = 30000 h

Survey	Area (deg²)	Freq MHz	HI Resolution	<z> (z_{lim})	T (hrs)	
Medium wide	400	950-1420	10"	0.1 (0.3)	2000	M
Medium deep	20	950-1420	5"	0.2 (0.5)	2000	M
Deep	1 pointing	600-1050	2"	0.5 (1)	3000	L
Targeted ISM	30 targets	1400-1420	3"-30"	0.002 (0.01)	3000	M
Targeted Accretion	30 targets	1400-1420	30"-1"	0.002 (0.01)	3000	M
Galaxy/MS	500	1418-1422	10"-1'	0 (0)	4.500	M
Galaxy Abs	(5000)	1418-1422	2"	0 (0)	(10.000)	M
Absorption	1000+	350-1050	2"	1 (3)	1,000+	L
	1000	200-350	10"	4 (6)	1.000	L

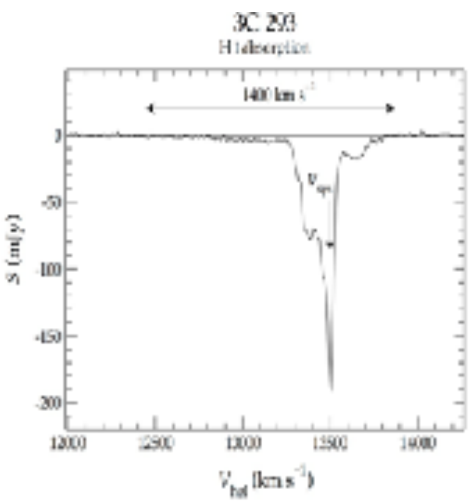
Outcomes from Stockholm/Goa
SKA Science meetings

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

Recent work

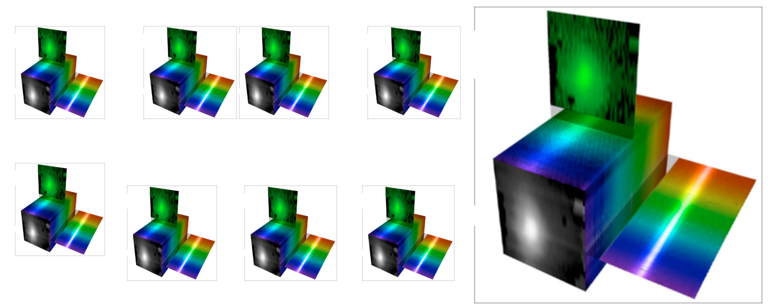
- Most activities in the last year dealt with SDP (ANEAS) and finding out requirements and responsibilities KSP, SDP, SRC
- data products, software, pipelines, …

3.3 A blind HI 21-cm absorption line survey at 3<z<6
SKA1-LOW, 5000 hrs
50 unique pointings x 100 h
3.7 An all-sky absorption survey at z~1 - 3
Mid- Band 1, 1,000 h, Individual pointings

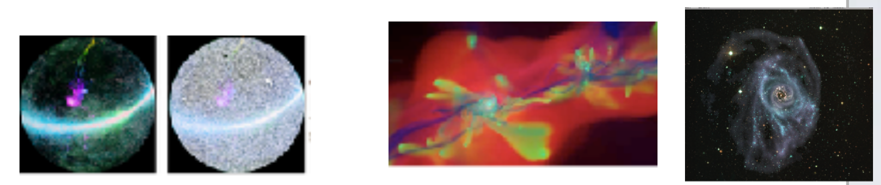


Morganti et al 2015

3.4 SKA1 All-Sky HI Survey
3.6 Medium-Deep HI Imaging Survey
3.9 Deep HI Imaging Survey
3.10 Medium-Wide HI Imaging Survey
Mid-Band 2, Mid- Band 1 x 310,000 h, 2,000 h, 3000 h, 2000h
Mosaic observations,
20,000 targets, One deep field, Single pointing



3.5 Deep Galactic and Magellanic HI Survey
Mid- Band 2, 4,500 h, Maps through multiple fields of view, 1,200 targets
3.8 Cosmic Web: The extended environment of galaxies and the IGM
Mid- Band 2, 100 h, Individual pointings with multiple objects
3.11 High spatial resolution imaging of the HI in nearby galaxies
Mid- Band 2, 300 h, multiple fields of view



McClure-Griffiths et al 2015 Agertz, Teyssier, Moore 2009

Procedures required, not in the SDP
—
Processing considerations
Reprocessing of calibrated visibilities
Data products
- Stokes I continuum visibility datasets and images at 225, 275 and 325 MHz
- Stokes I spectral-line cube over 200 – 350 MHz with 4 kHz resolution
- Cubelets and spectra towards all the sources brighter than 10 mJy in the FoV along with the RFI flags applied to the data. ?

——-
Continuum source and spectral line catalogs
Continuum image with 30% bandwidth centered at 600 MHz. This will be used to check the total flux density of the background source which should further be **logged in a public database for future sky-model reference**

Procedures required, not in the SDP
- source-finding and source parameterisation
- data combination to created integrated deep cube (uv and image domain)

Processing considerations
Large data volumes, search cube multiple times (source detection), stacking

Data products
- Stokes I data cubes
- Calibrated, imaged, continuum subtracted datacubes

———
- image cut-outs
- spectra
- minicubes
- catalogues
- moment maps
- **masks used to make mom**
- **signal-to-noise maps**

Procedures required, not in the SDP
—
- Image cubes at multiple resolutions (will SDP produce the required number?).
- Addition of single dish data for imaging.
- joint deconvolution of mosaic;
- Multi-scale deconvolution;
- Addition of single-dish data for imaging ?

Processing considerations
Large data volumes due to full spectral resolution?
Data products
- Fully calibrated I, Q, U and V cubes at full spectral resolution
- Image cubes, moment maps, images of the PS
- Data cubes, Total HI image, velocity field, velocity dispersion map. At various resol.
- **masks used to make moment maps**

Lourdes Verdes-Montenegro

MAIN CHARACTERISTICS OF THE DATA PRODUCTS

- **Volumes:**
  - SKA1MID, Band 2: Discovery cube size 2.6Pbytes. HI science a fraction down to 1/10 of the max. Extracted data products at least 10 times smaller (moment maps, pos.vel cuts, spectra)
  - continuum data products or spectral postage stamp cubes would be orders of magnitude smaller than the discovery cube
- **Formats:**
  - ongoing work by ICRAR-IT on the jp2 and jpx formats could feed perfectly into the requirements of efficiently extracting sub-cubes of various resolutions from a huge master cube.
  - …
- **Metadata:**
  - E.g. for spectra, description of the parameters that went into making them, like the size of the extraction region.

POTENTIAL SOFTWARE TO INTEGRATE IN THE SRCS SCIENCE PLATFORM

- Potential candidates:
  - Developed by SWGs, KSPs, precursors/pathfinders:
    - **Analysis**, e.g. SoFiA, TiRiFiC, GalAPAGOS, GIPSY/GuiPSY, 2DBAT, FAT, MAGMO,Barolo, GBKFit, CASA, etc (TBD)
    - **Visualization**: e.g SlicerAstro, VISIONS, X3D
  - Interaction/connection with the VO (e.g. in order to request complementary data or input data for modeling; e.g GuIPSY is connected with Topcat and Aladin)

Lourdes Verdes-Montenegro

Precursors

- *“Current plans for science with SKA precursors and pathfinders”*

- MeerKAT
  - LADUMA
  - MHONGOOSE
  - Fornax
  - MALS
- Apertif/ASKAP

These precursor projects cover much of the proposed SKA-1 HI science

- *“Some initial thoughts on how your SWG will evolve into a key science project/projects”*
- Survey concepts ready
- Precursor science can inform proposals
- HI SWG contains key people
- Early SKA science with precursors
- Connection SWG/KSP not clear
- Formalise mandate SWG in relation to KSP

- *"Approximately when can your KSP(s) get started, and, for example, is an intermediate array release sufficient?*

- Longest baselines not needed for all science

- *But* need sensitivity - i.e., close to full system

- Example: MeerKAT is “early array release”

- *“A brief comment on any key issues/concerns/roadblocks at this stage”*

- Long timescales and people are busy with Pathfinders/ Precursors

- Relation between Precursor/Pathfinder projects and KSP
  ⇨ For HI, MeerKAT = early array release
  ⇨ should inform (lead to?) KSP

- How do KSPs fit within the structure, definition and capabilities of SRCs and SDP?

- Mandate SWGs for KSP needs clarification