HI studies with the SKA: from the EoR, to intensity mapping and beyond …

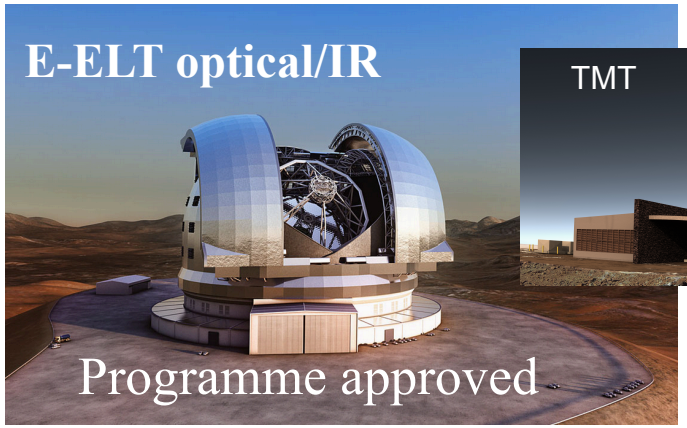
Jeff Wagg
SKAO
UK

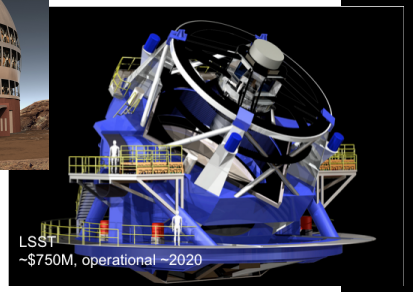
Robert Braun, Tyler Bourke, Jimi Green

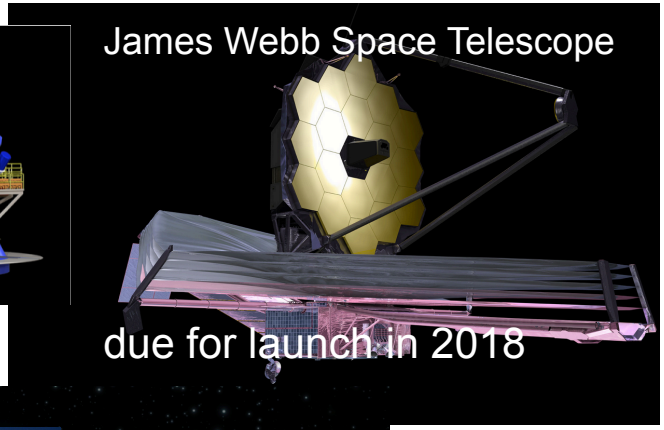
21cm Paris Intensity Mapping Workshop, SF2A

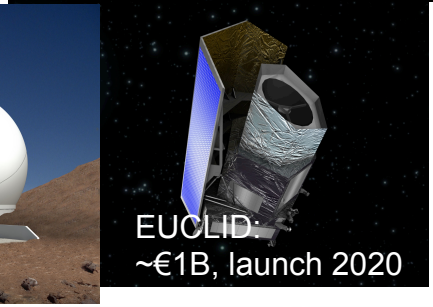
June 4, 2014

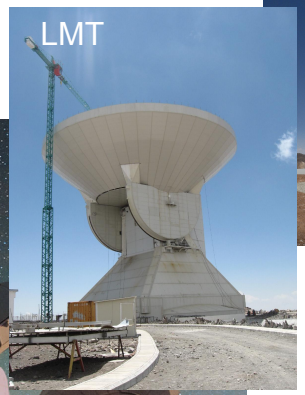
Great observatories for the coming decades





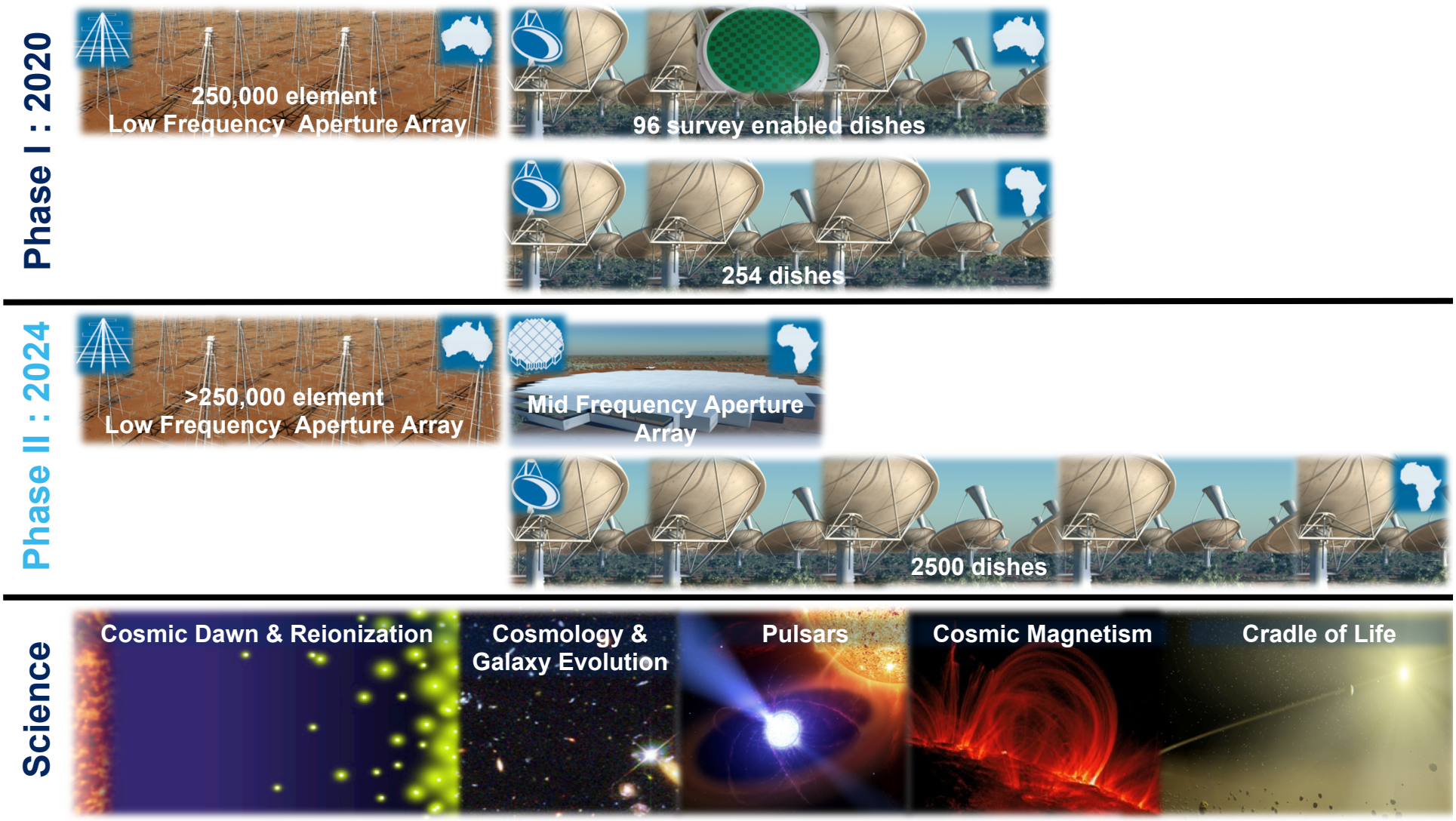






The next major radio observatory …

Exploring the Universe with the world's largest radio telescope



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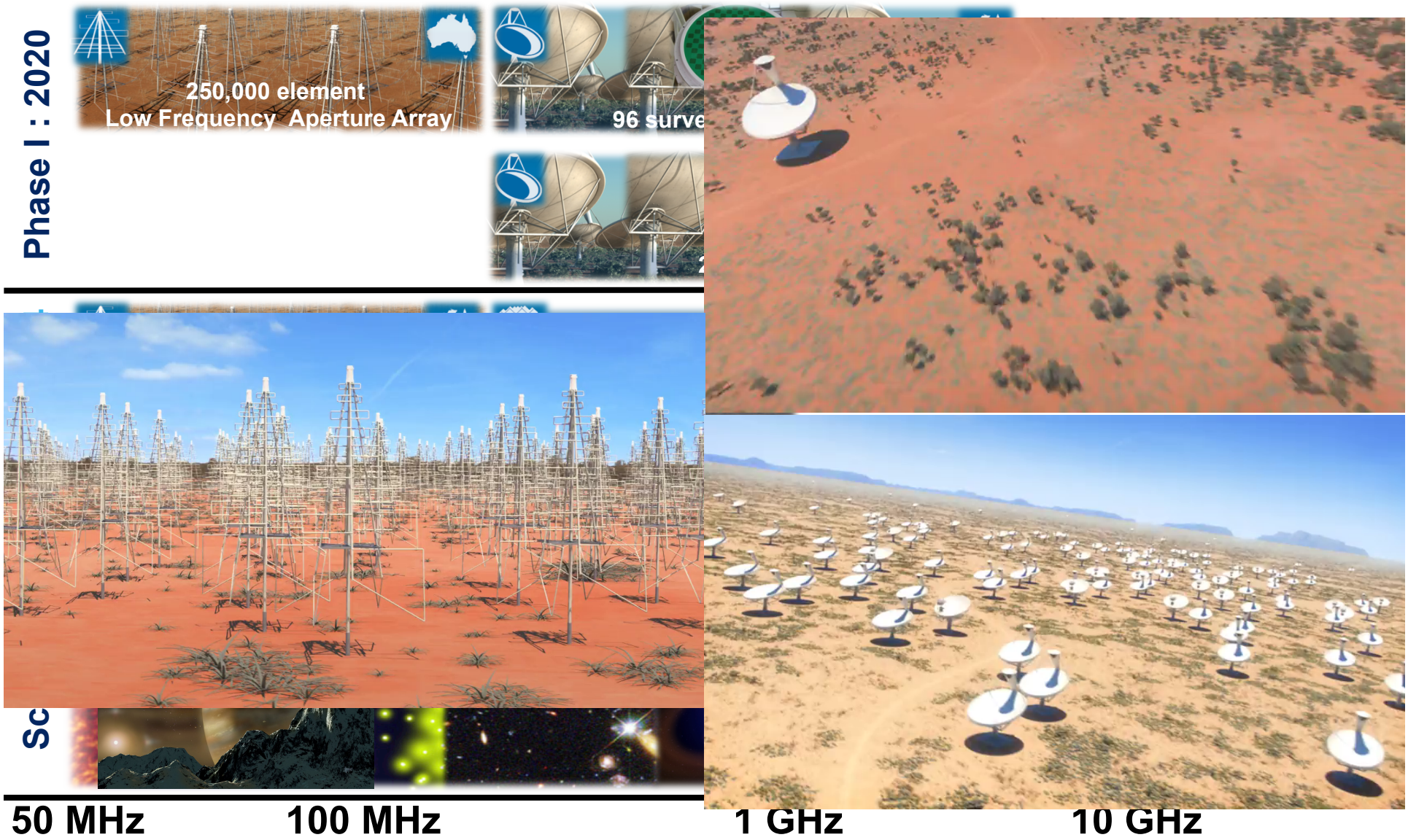

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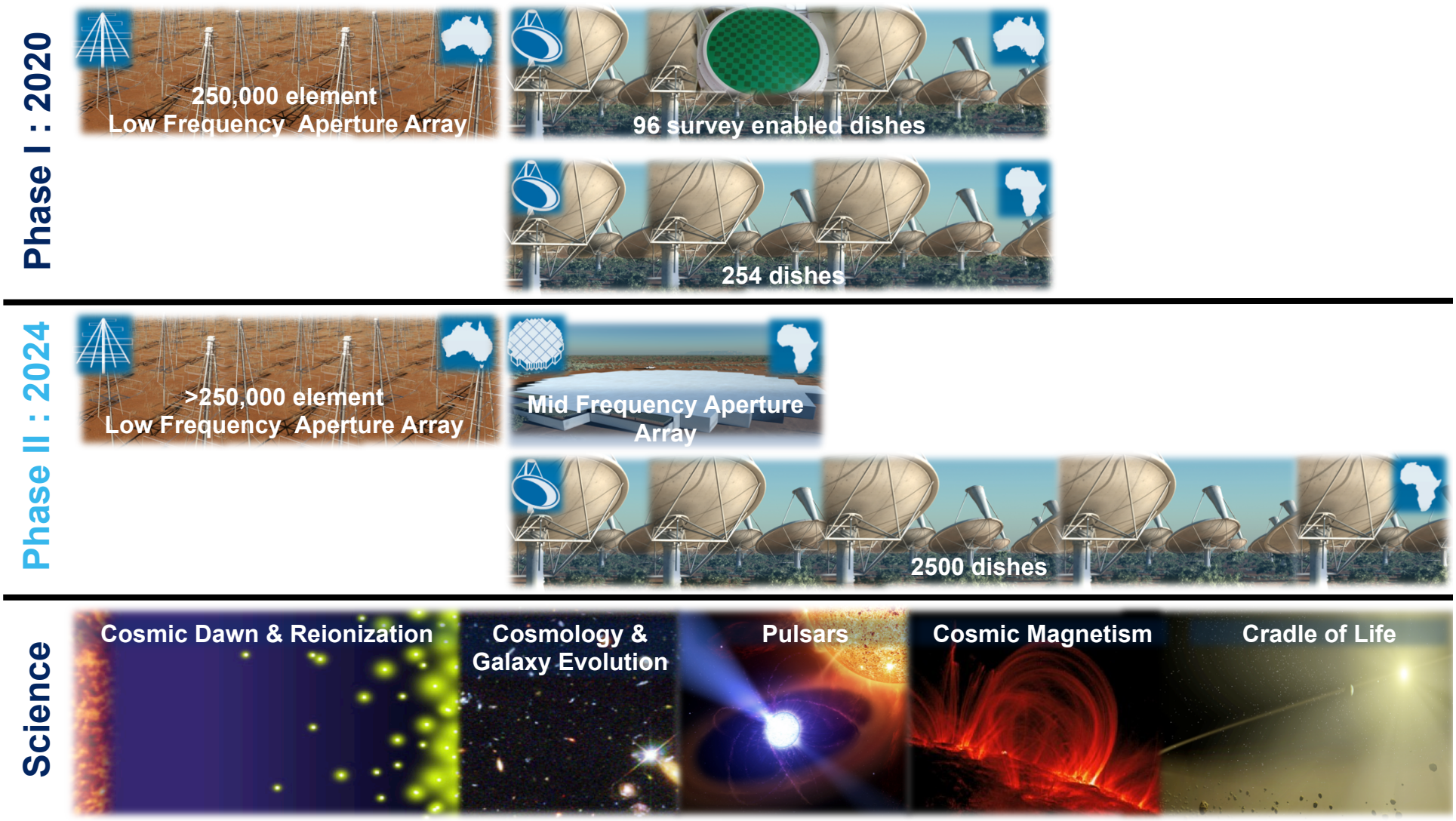
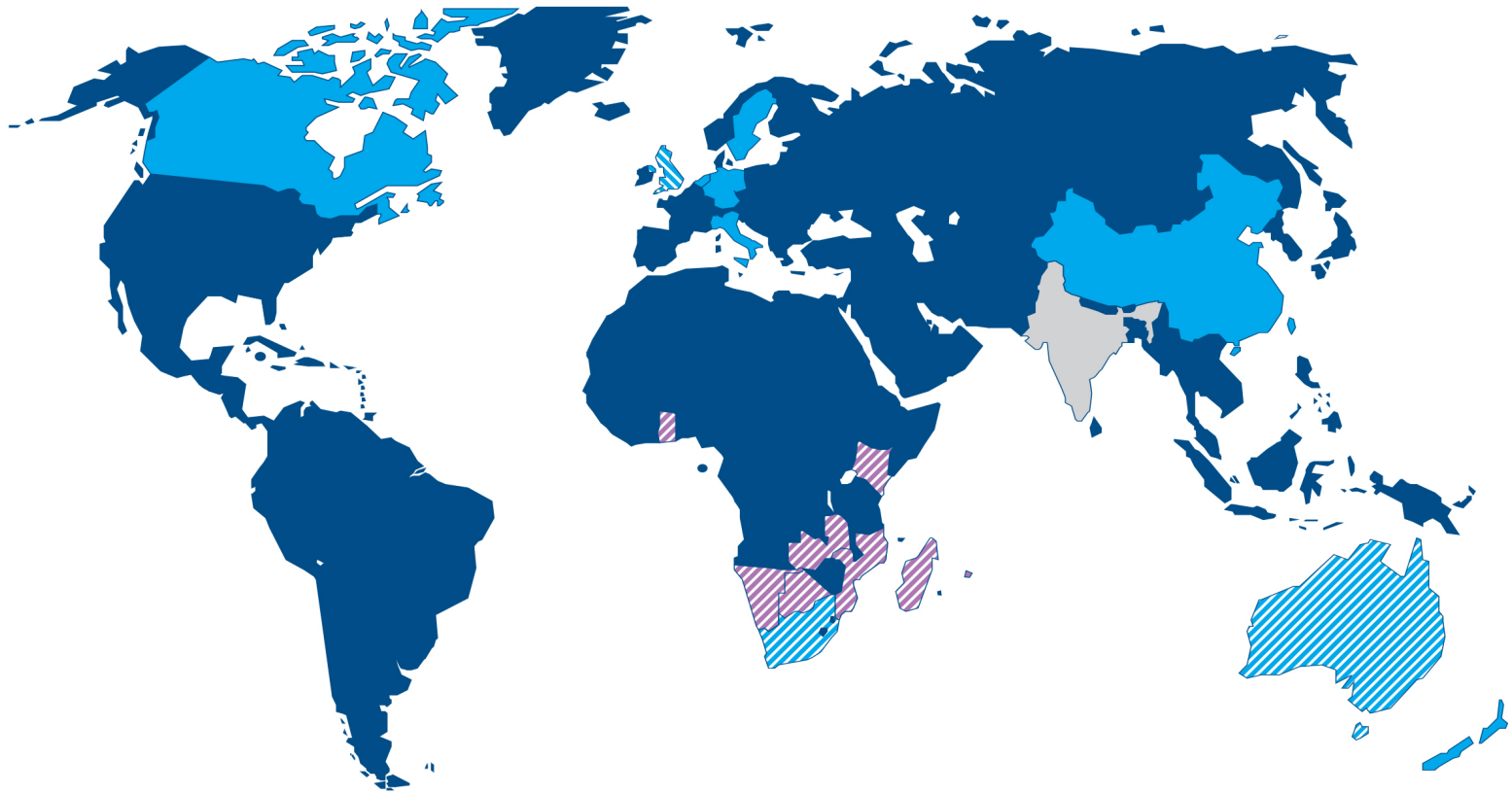


SKA global community



Full members

Associate members

Member SKA Phase 1 and Phase 2 host countries

Non-member SKA Phase 2 host countries

SKA Headquarters host country

SKA science drivers

- Emerging from the Dark Ages and the Epoch of Reionization
  - **Sensitive EoR imaging capability in Phase 1**
  - **Possibly Reaching to Cosmic Dawn in Phase 2**
- Galaxy Evolution, Cosmology, & Dark Energy
  - **Cutting edge contributions in non-Gaussianity and Dark Energy**
  - **Complementarity to Euclid, LSST in Phase 1 (reduced systematics)**
  - **Unmatched performance in Phase 2 (Billion Galaxy Surveys)**
- Strong-field Tests of Gravity with Pulsars and Black Holes
  - **Unique GR constraints, major contributions in Phase 1 and Phase 2**
- The Cradle of Life & Astrobiology
- The Origin and Evolution of Cosmic Magnetism

With design philosophy of *Exploration of the Unknown*

Unmatched prospects (complement to LSST) in Phase 1 and Phase 2

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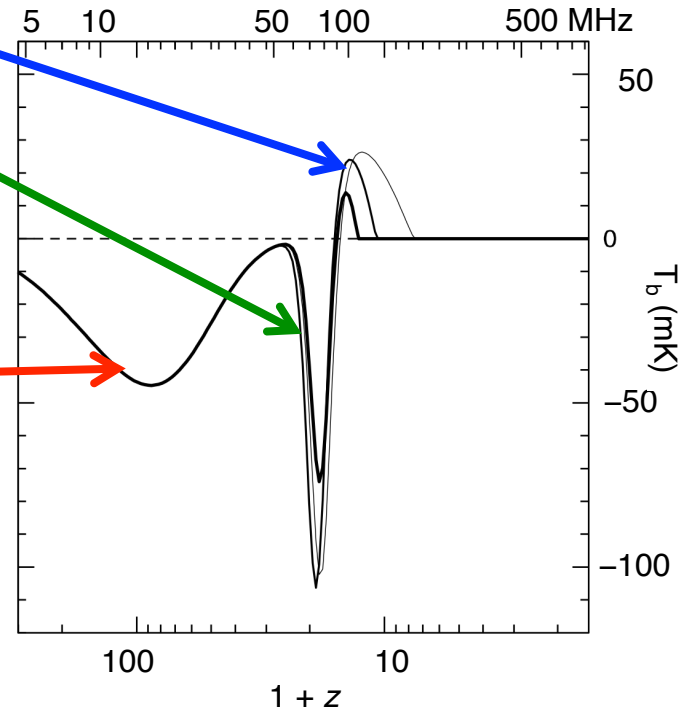
The first galaxies and AGN: Probing the early universe with the 21cm HI Line

EoR

Cosmic Dawn

Dark Ages

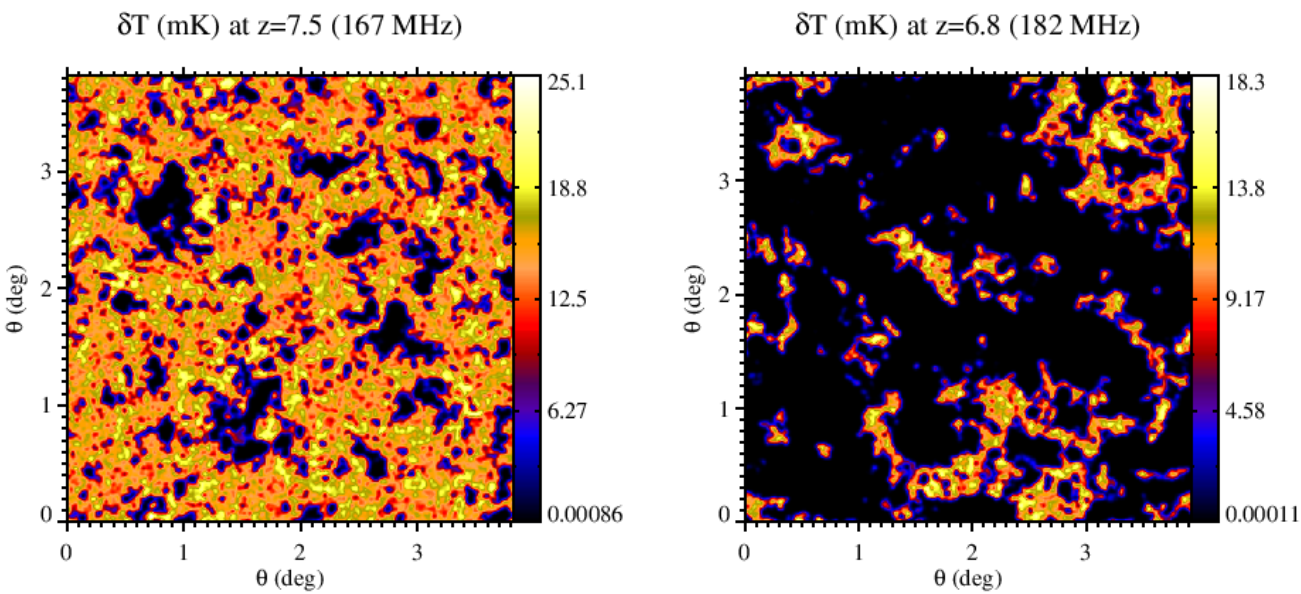


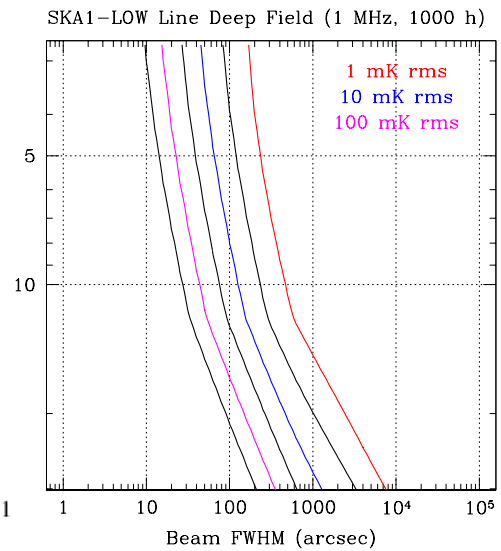
Neutral Hydrogen 21 cm spin-flip transition provides probe of neutral intergalactic medium before and during formation of first stars

$\nu = 1420\ \mathrm{MHz}/(1 + z)$

$\lambda = 21\ \mathrm{cm}\ (1 + z)$

HI surveys of the EoR/Cosmic-Dawn in the early Universe



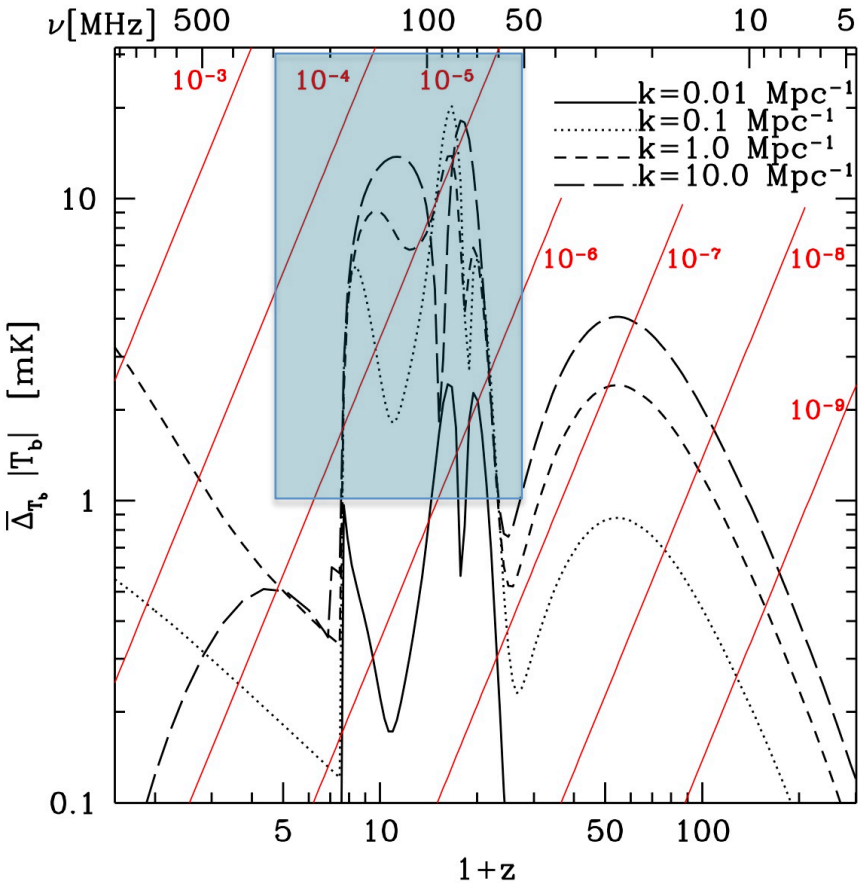


Review by Mellema et al. 2013

- Detecting EoR structures in imaging mode (as distinct from statistically) on ~5 arcmin scales with 1 mK RMS

- Probing the Cosmic Dawn statistically or possibly even imaging in ultra-deep through the power spectrum of fluctuations

HI surveys of the EoR/Cosmic-Dawn in the early Universe



Pritchard and Loeb 2008, 2010

- Probing the Cosmic Dawn statistically (to z < 27) through fluctuations in the power spectrum, sensitive to:

<u>Density of baryons (cosmology)</u>

<u>Peculiar velocities (cosmology)</u>

<u>Neutral fraction (reionization)</u>

<u>Gas temperature (X-ray heating)</u>

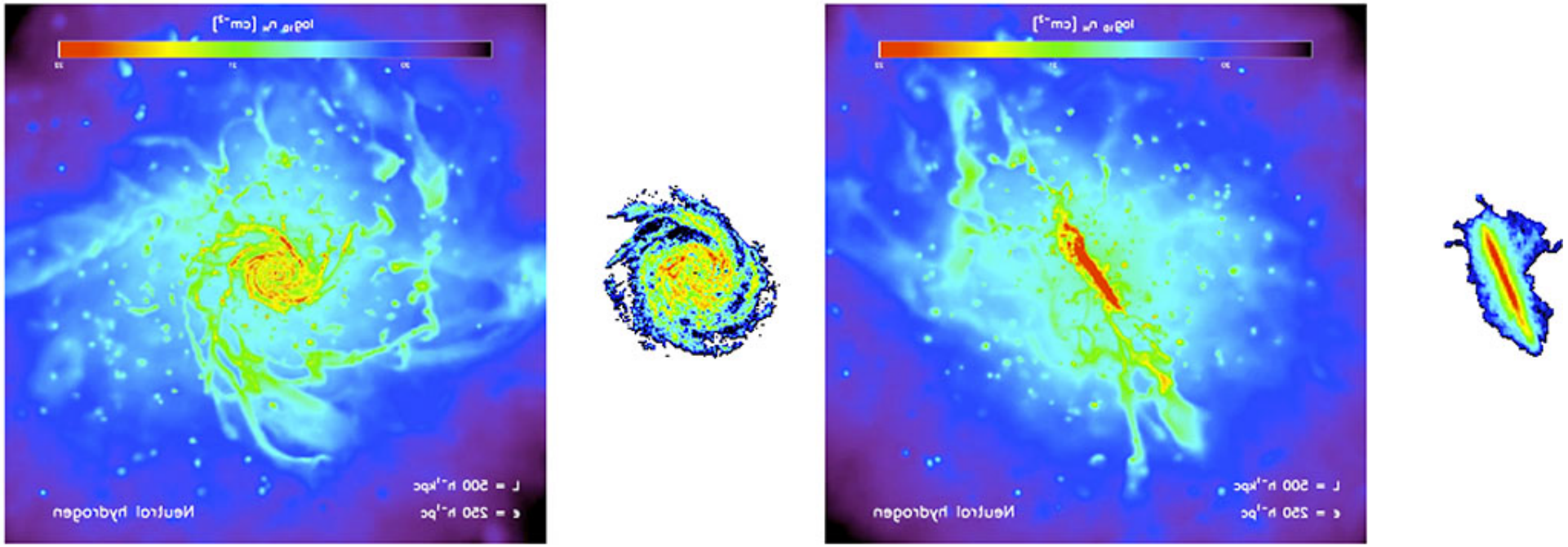
<u>Lyman Alpha flux (Lyα sources)</u>

- SKA EoR science working group

https://indico.skatelescope.org/conferenceDisplay.py?confId=259

SKA HI emission line studies of galaxies

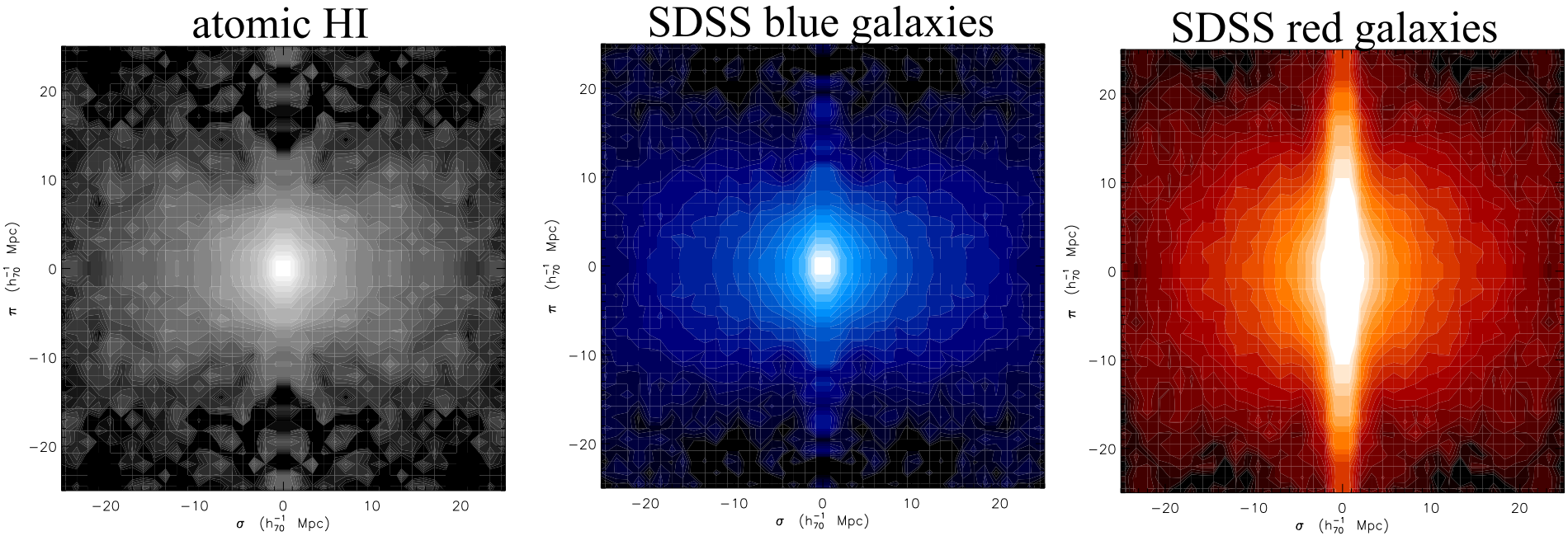
simulation observed simulation observed



Images courtesy of Tom Oosterloo

- How do galaxies interact with the surrounding `Cosmic Web' (feeding and feedback)
- SKA will probe low column density HI in nearby Universe ($n_{HI} < 10^{18}$ cm^{-2})
- Complementary to high-resolution observations of molecular gas and stellar light with ALMA and the E-ELT/TMT

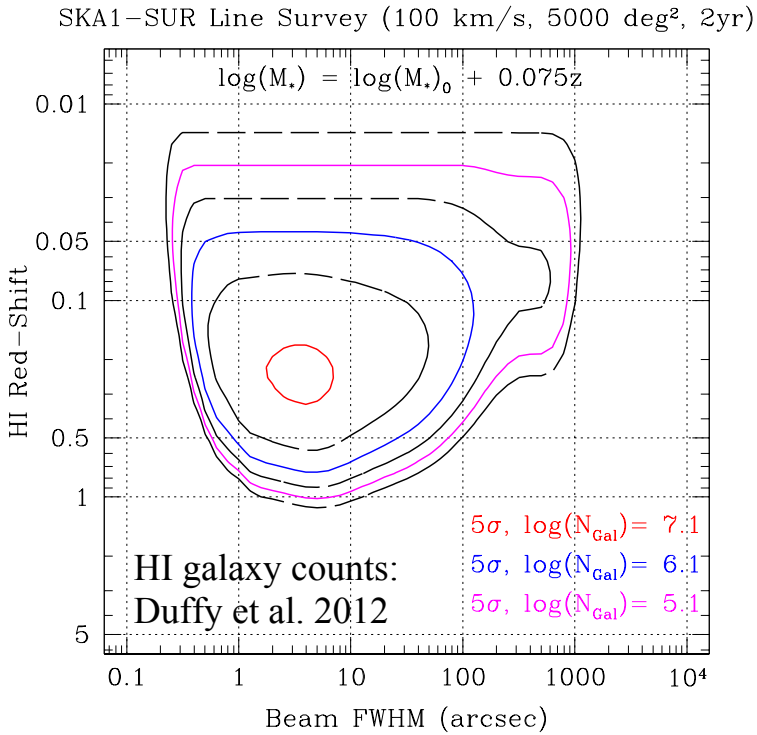
HI emission line surveys with SKA: complementarity with optical surveys

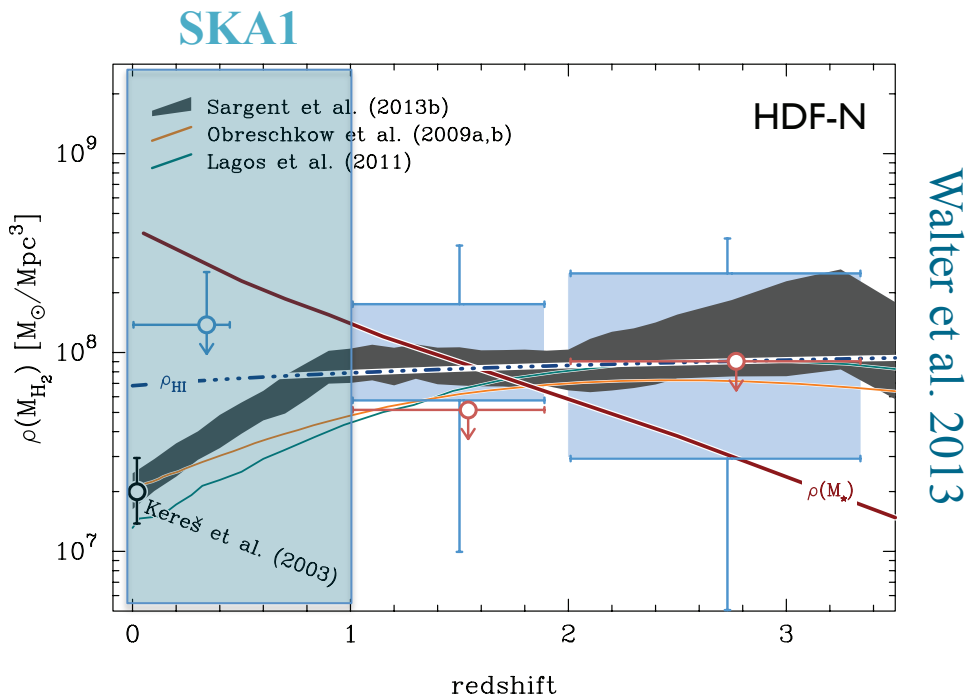


(Papastergis et al. 2013) ALFALFA HI versus SDSS blue and red samples

- Two-dimensional correlation functions of HI detections demonstrate much lower bias and excellent prospects for Redshift-space distortion measurements once interesting sample sizes are achieved with SKA

A wide-field HI emission survey to measure evolution of the HI mass function and galaxy kinematics

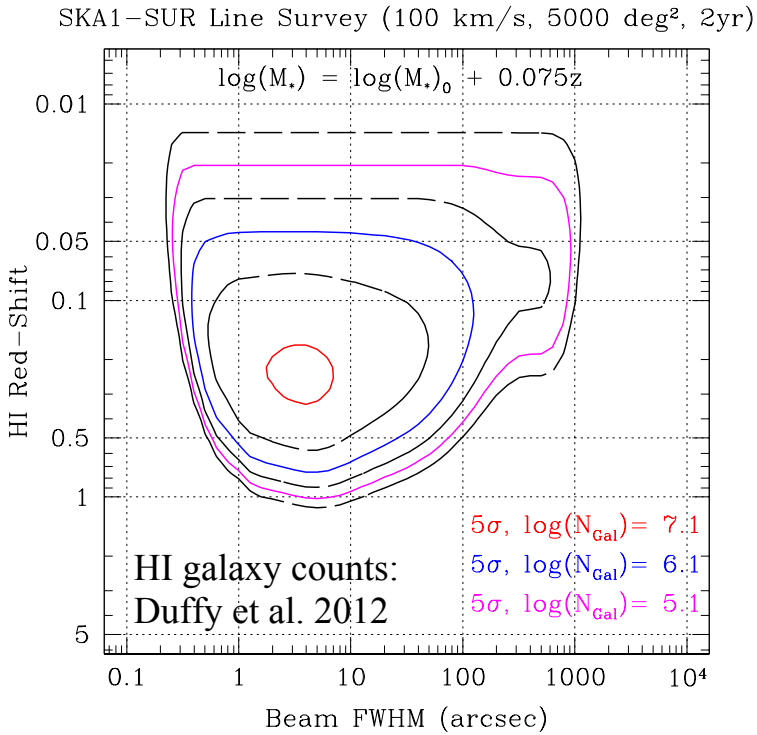


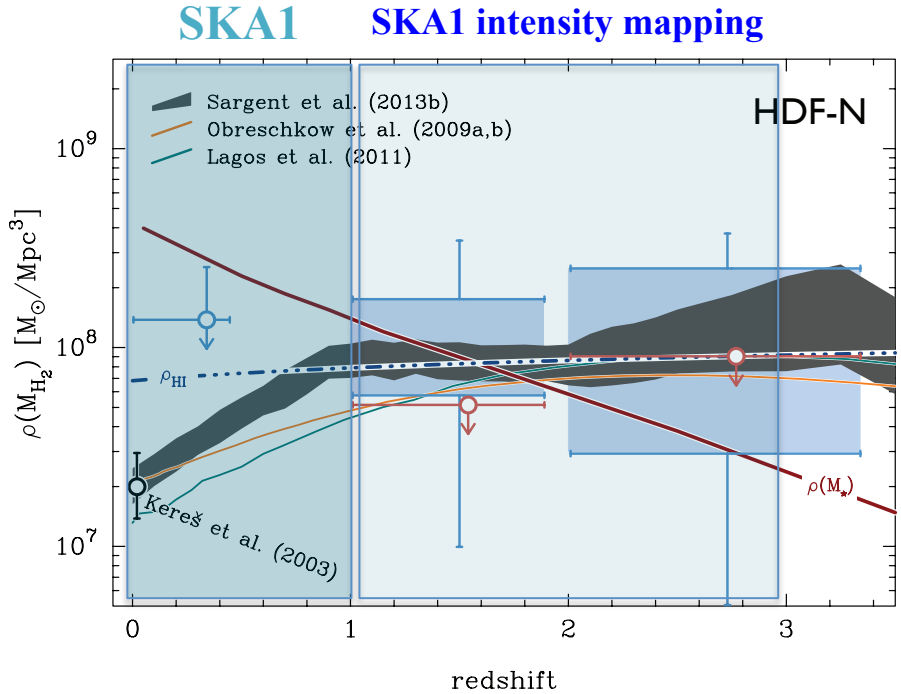


Walter et al. 2013

- Detect $10^{7.1}$ galaxies <z> ≈ 0.3, $10^{5.1}$ galaxies <z> ≈ 1
- Density ≈ 2500 galaxies deg^{-2} , 1 $arcmin^{-2}$
- Compare SDSS: $10^{6.2}$ galaxies with <z> ≈ 0.1 over 15,000 deg^2
- Compare WigglesZ $10^{5.2}$ galaxies with <z> ≈ 0.6
- **Redshifts, HI gas content and galaxy kinematics -> dynamical masses**

A wide-field HI emission survey to measure evolution of the HI mass function and galaxy kinematics





Walter et al. 2013

Talk by Mario Santos

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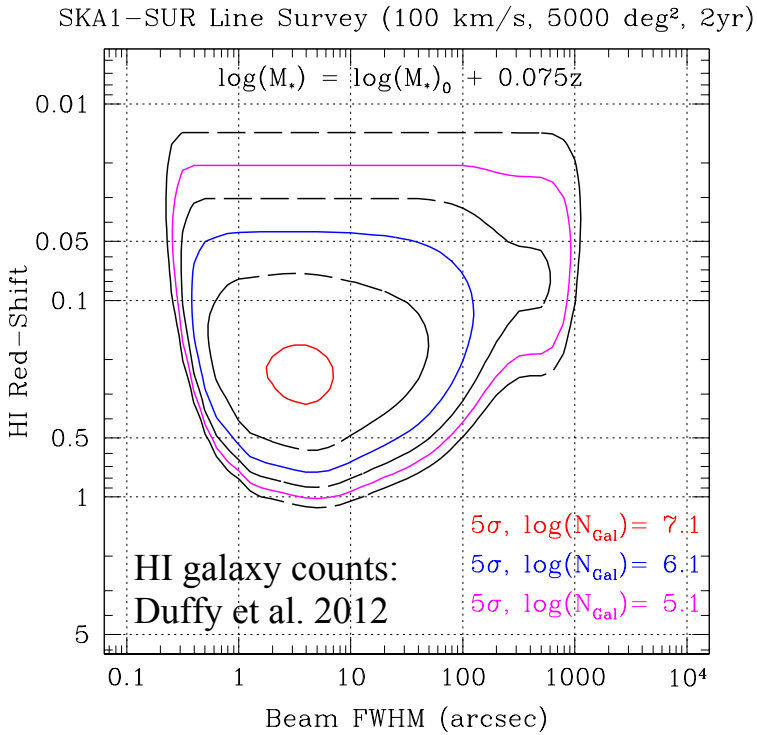

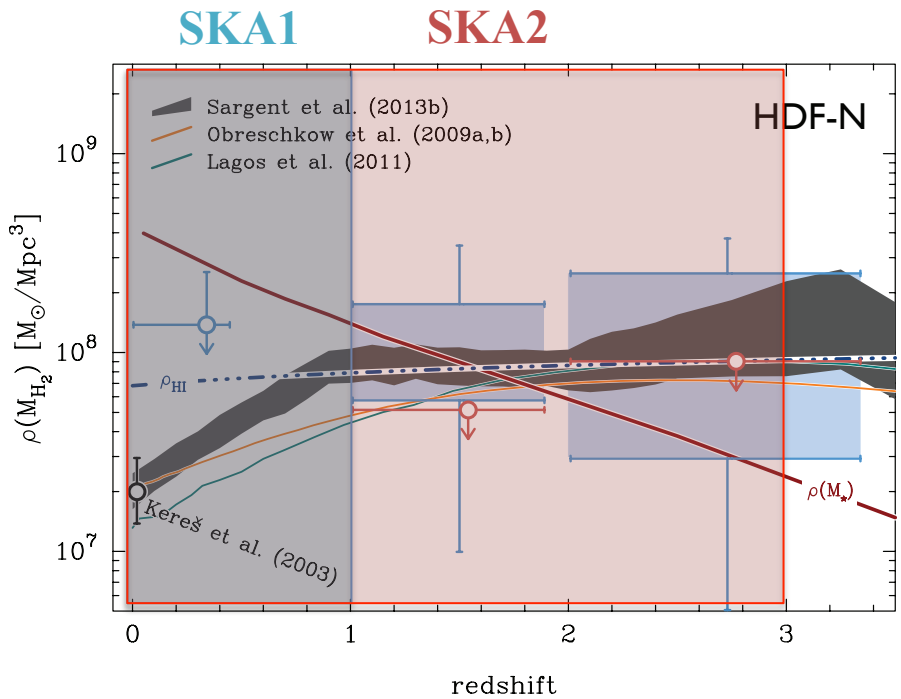

Walter et al. 2013

$M_{HI} > 5\times10^9\ M_\odot$ at z=2 in ~1000h

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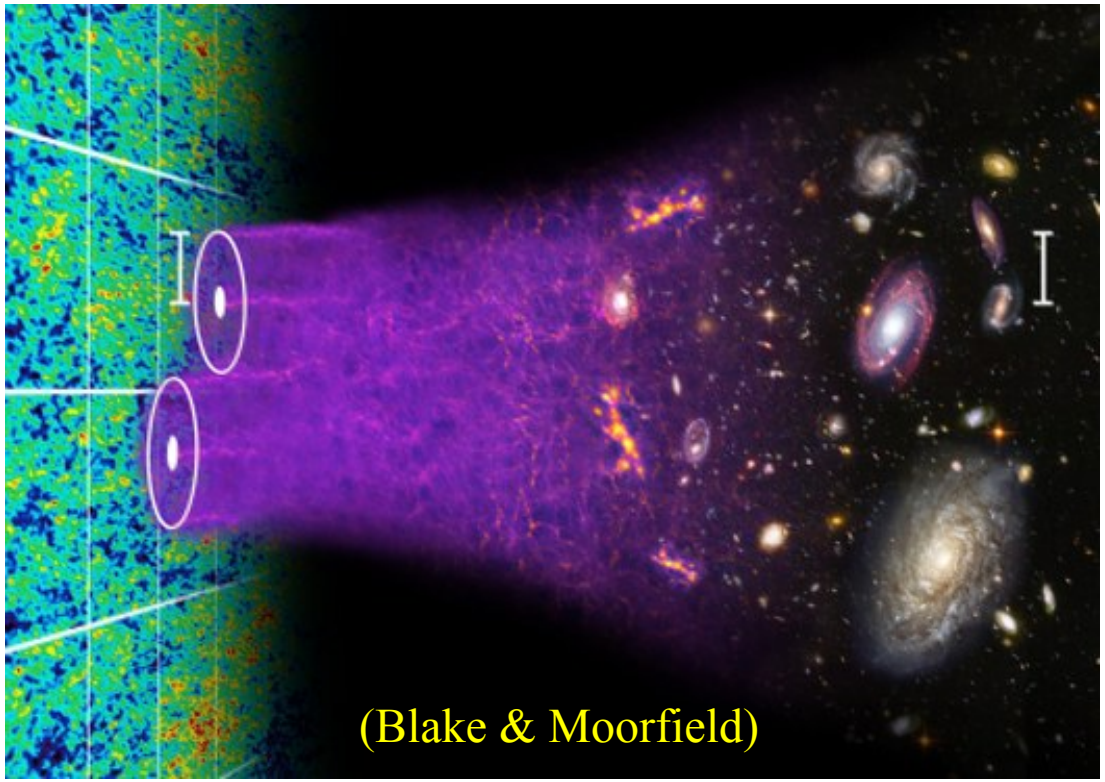
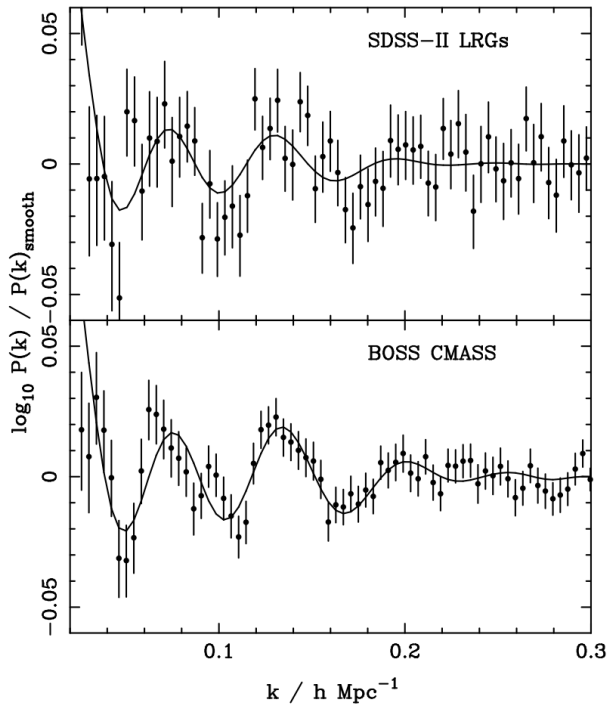
Cosmology with SKA1 HI: Baryon Acoustic Oscillations



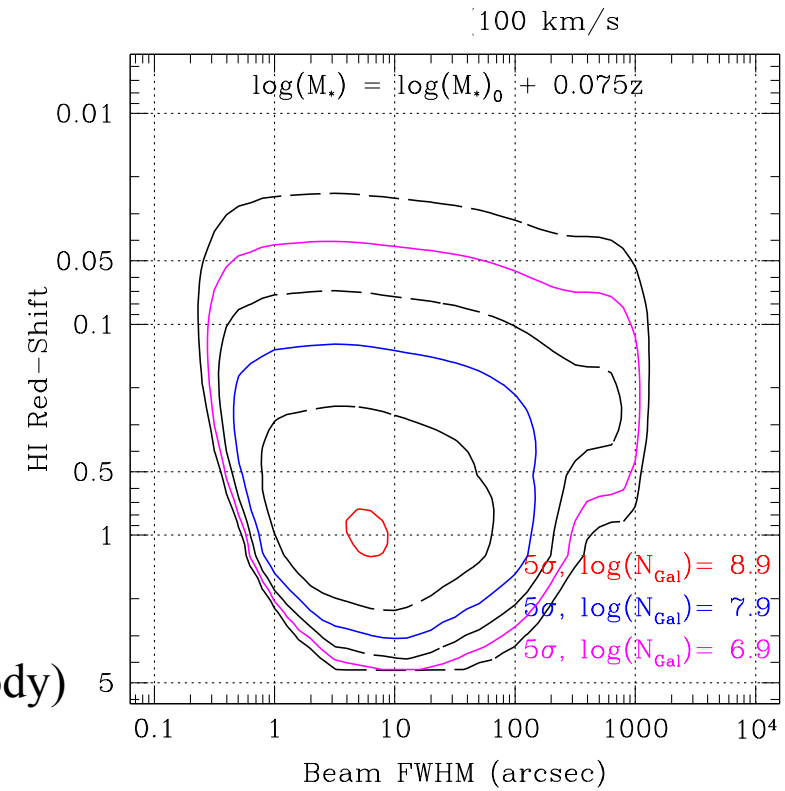


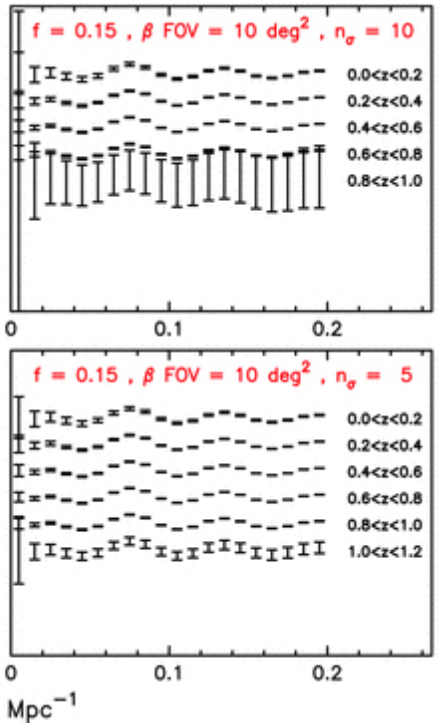
Anderson et al. 2012

- Constraining Dark Energy models with redshift-resolved BAO measurements

An SKA2 HI emission survey to study the evolution of atomic gas content and BAOs

HI galaxy counts:
Duffy et al. 2012
(semi-analytic + N-body)

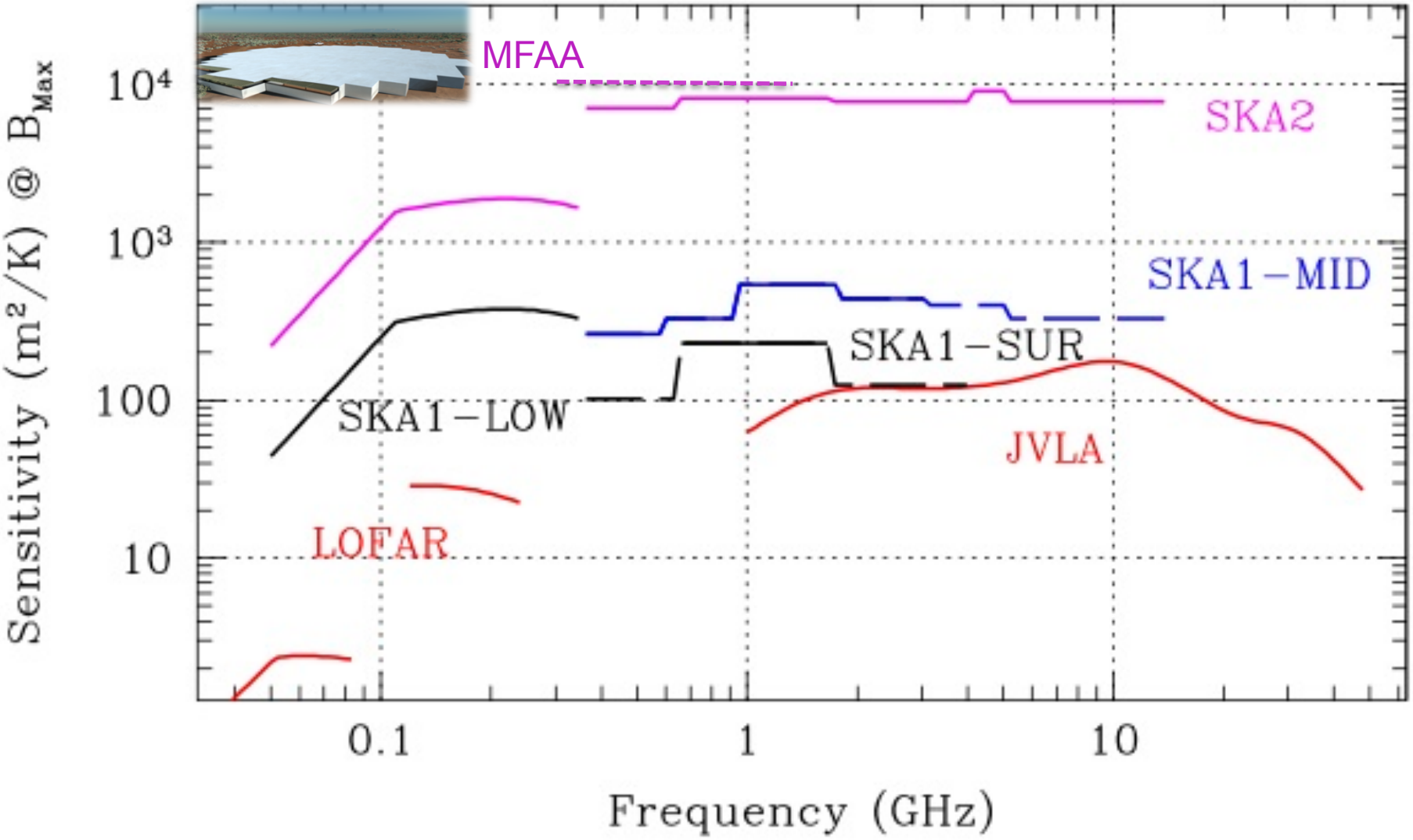




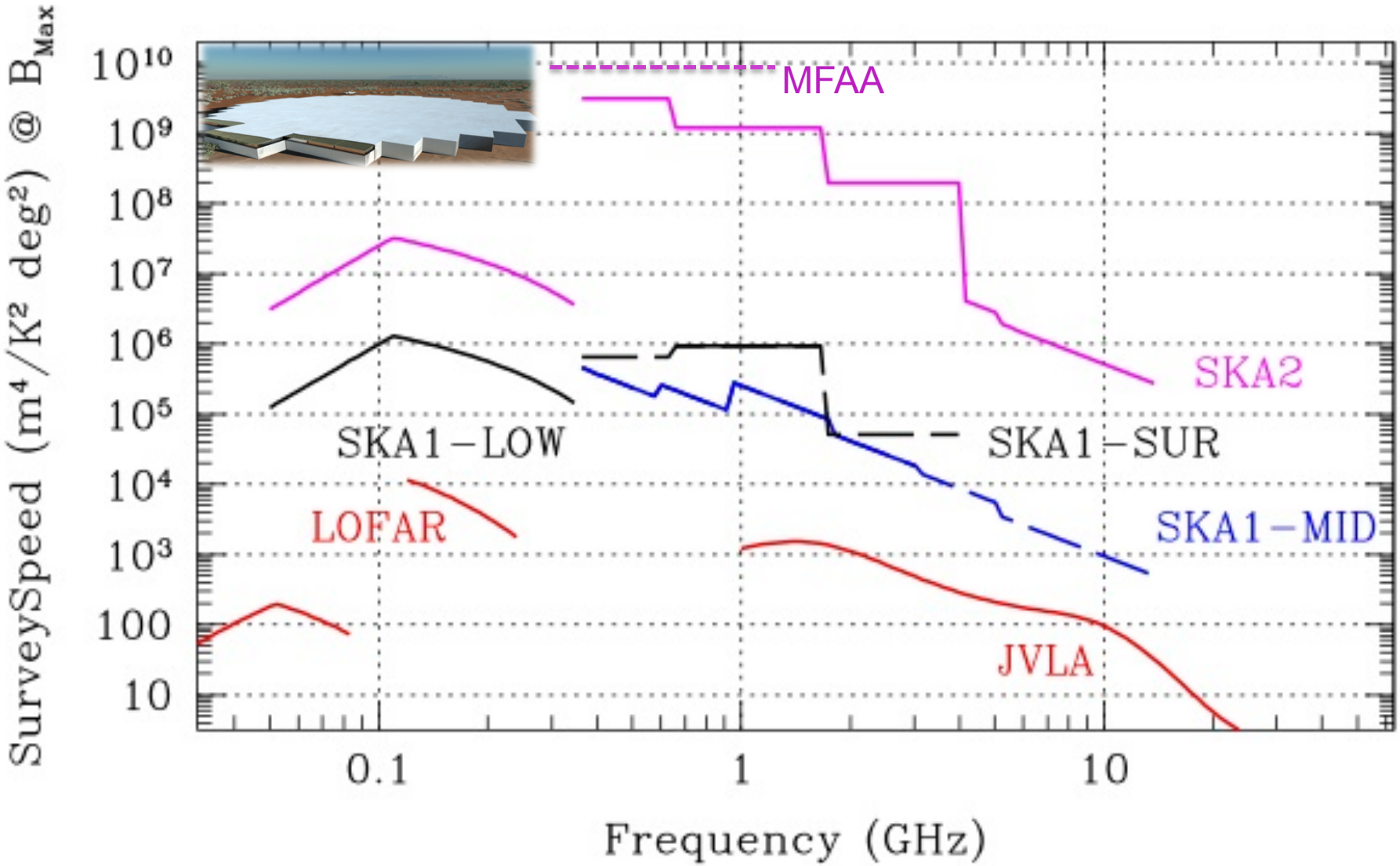
(Abdalla et al 2010)

- Detect $10^{8.9}$ galaxies with $\langle z \rangle \approx 1$, $10^{7.9}$ with $\langle z \rangle \approx 2$
- Compare Euclid target of 10^8 spectra with $\langle z \rangle \approx 1$
- **SKA2 with MFAA will be a unique facility for studying the evolution of atomic Hydrogen in galaxies**

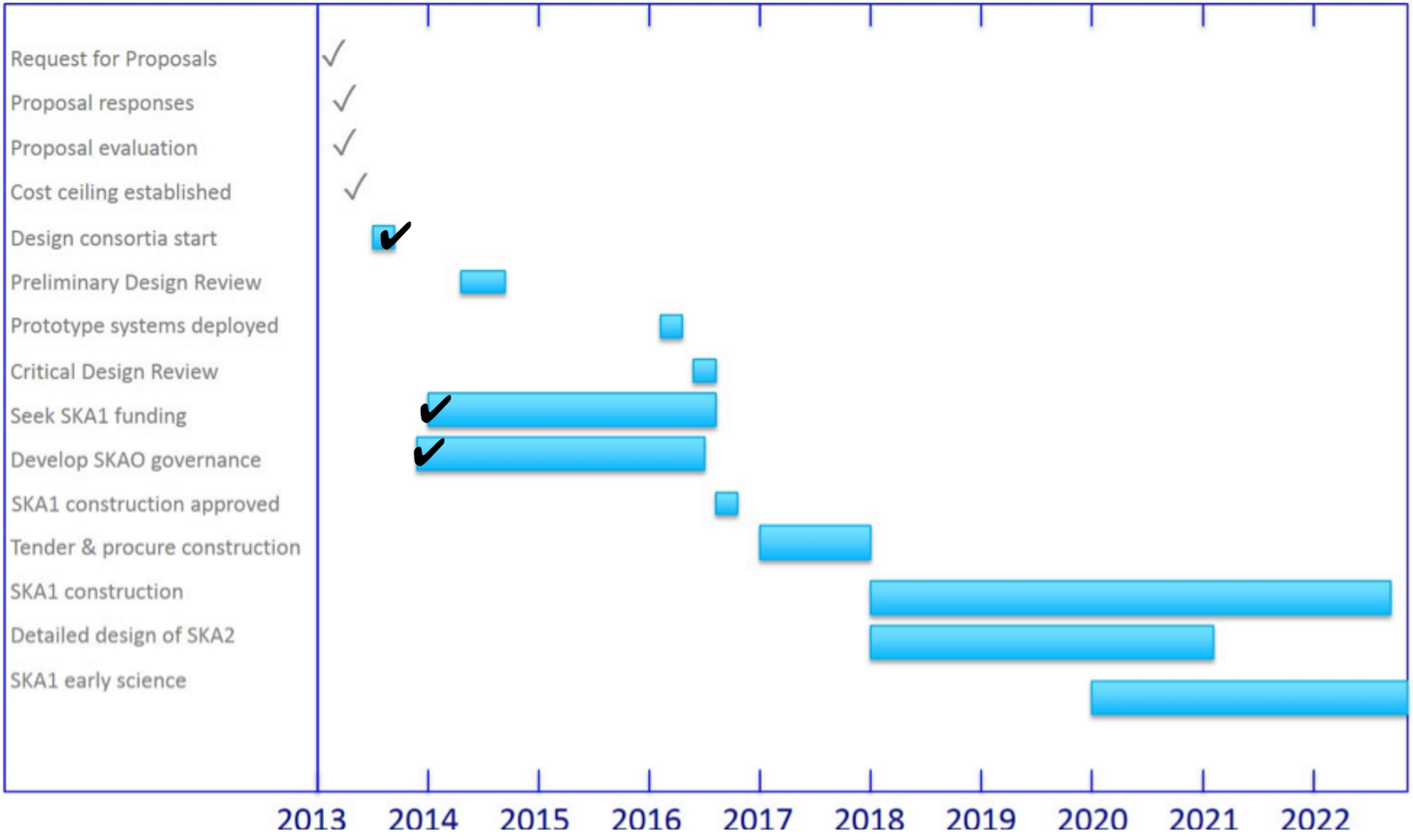
Sensitivity comparison



Survey speed comparison

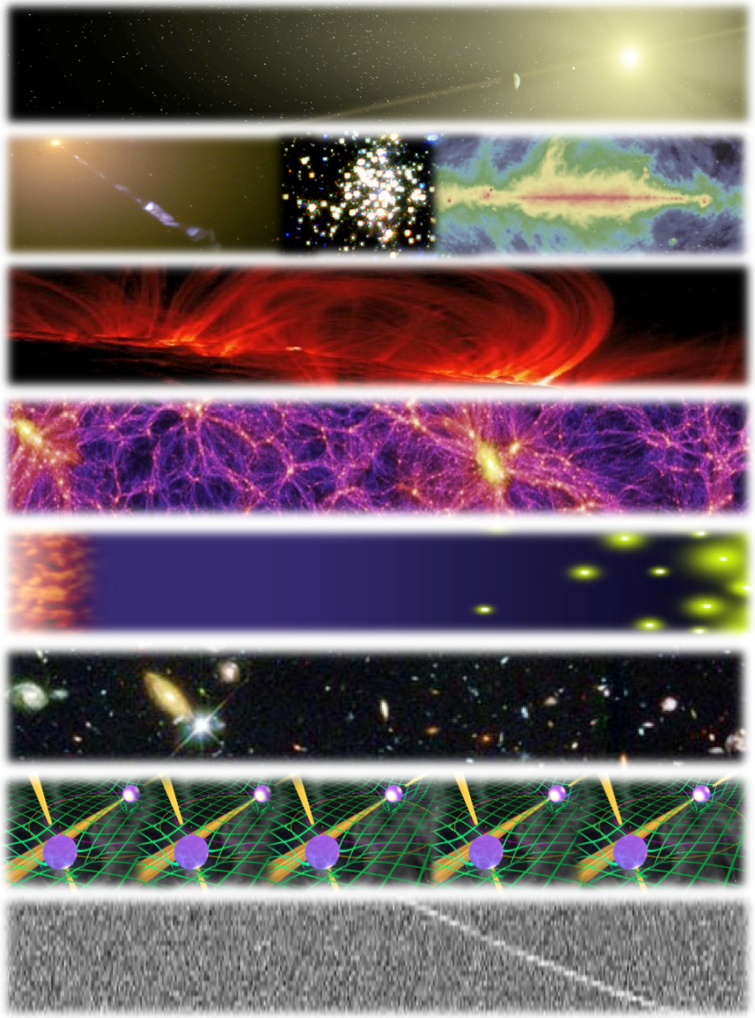


Timeline


Request for Proposals
Proposal responses
Proposal evaluation
Cost ceiling established
Design consortia start
Preliminary Design Review
Prototype systems deployed
Critical Design Review
Seek SKA1 funding
Develop SKAO governance
SKA1 construction approved
Tender & procure construction
SKA1 construction
Detailed design of SKA2
SKA1 early science
2013
2014
2015
2016
2017
2018
2019
2020
2021
2022

The Science Working Groups

- **Astrobiology ("The Cradle of Life")**
  - *Project Scientist:* Tyler Bourke
  - *Working Group Chair:* Melvin Hoare
- **Continuum**
  - *Project Scientist*: Jeff Wagg
  - *Working Group Chairs:* Nick Seymour & Isabella Prandoni
- **Cosmic Magnetism**
  - *Project Scientist:* Jimi Green
  - *Working Group Chairs:* Melanie Johnston-Hollitt & Federica Govoni
- **Cosmology**
  - *Project Scientist:* Jeff Wagg
  - *Working Group Chair:* Roy Maartens & Mario Santos
- **Epoch of Reionisation & the Cosmic Dawn**
  - *Project Scientist:* Jeff Wagg
  - *Working Group Chair:* Leon Koopmans
- **HI Galaxies**
  - *Project Scientist:* Jimi Green
  - *Working Group Chairs:* Lister Staveley-Smith & Tom Osterloo
- **Pulsars ("Strong field tests of gravity")**
  - *Project Scientist:* Jimi Green
  - *Working Group Chairs:* Ben Stappers & Michael Kramer
- **Transients**
  - *Project Scientist:* Tyler Bourke
  - *Working Group Chair:* Rob Fender and J-P Macquart



Advancing Astrophysics with the Square Kilometre Array

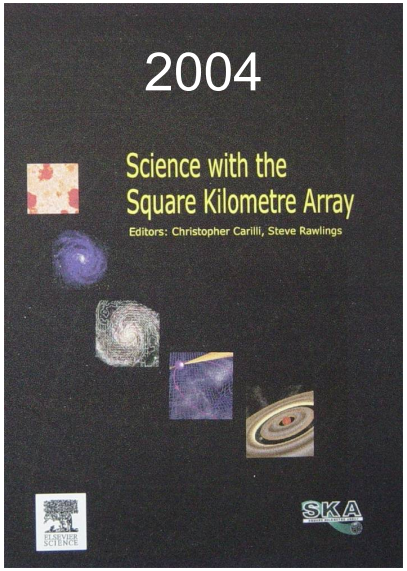
8 – 14 June, 2014, Giardini Naxos, Italy

http://indico.skatelescope.org/event/AdvancingAstrophysics2014

Aims:

- Update the 2004 Science Case
- document the scientific advances enabled by SKA-1,
- … and by the full SKA with
  - ✓4-5 x SKA-1 sensitivity < 350 MHz, 10 x SKA-1 at > 350 MHz
  - ✓frequency coverage extending to ~24 GHz

Contributed chapters will form the basis for presentations and discussion at the meeting, with SWGs providing overview chapters



Feb 7 – Call for chapter proposals open **NOW**

Feb 28 – Deadline for submission of chapter proposals
– Registration open ~~SOON~~ Now

May 9 – Draft chapters due (i.e., before the meeting)

End 2014 – Science Book published

Extragalactic continuum studies with SKA1

'nested' survey strategy (ν_{obs} ~1 GHz):

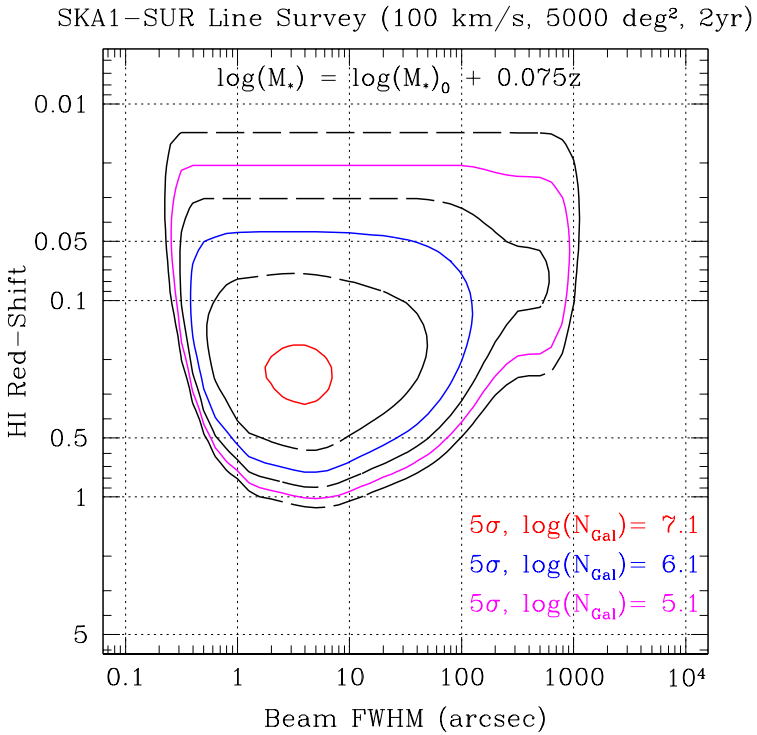
- all-sky (3π sr, ~2 μJy per 2'' beam): legacy survey near confusion limit -> power spectrum, local Universe, cluster/diffuse emission, cosmic magnetism

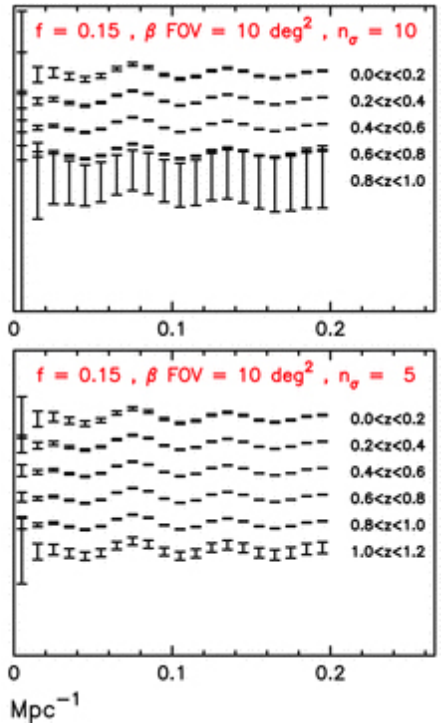
- Wide (~5000 sq. degrees, ~0.4 μJy per 0.5'' beam): constraining the Dark Energy Equation of State with Weak Gravitational Lensing

- Deep (~30 sq. degrees, ~40 nJy per 0.5'' beam): galaxy evolution and the evolution of star-formation rate density out to z~5, complementarity with Euclid, LSST, (ALMA)

- SKA continuum working group
https://indico.skatelescope.org/conferenceDisplay.py?confId=261

A wide-field HI emission survey to measure $\Omega_{HI}(z)$ and BAOs





(Abdalla et al 2010)

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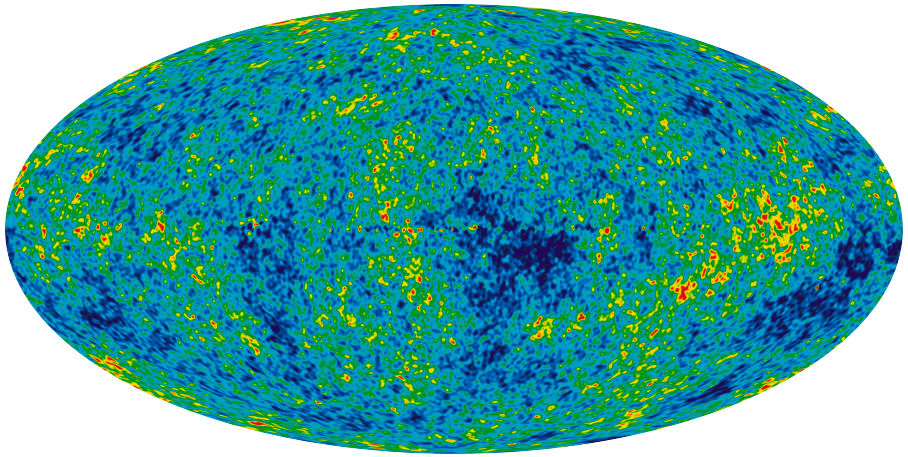
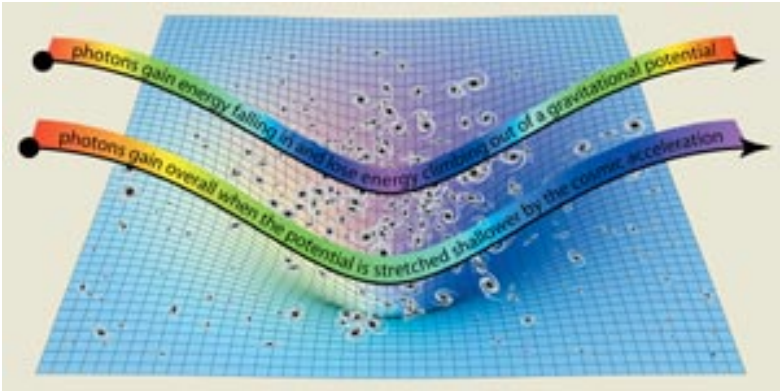
- **Major contribution to BAO science, complementary systematics versus Opt/IR**

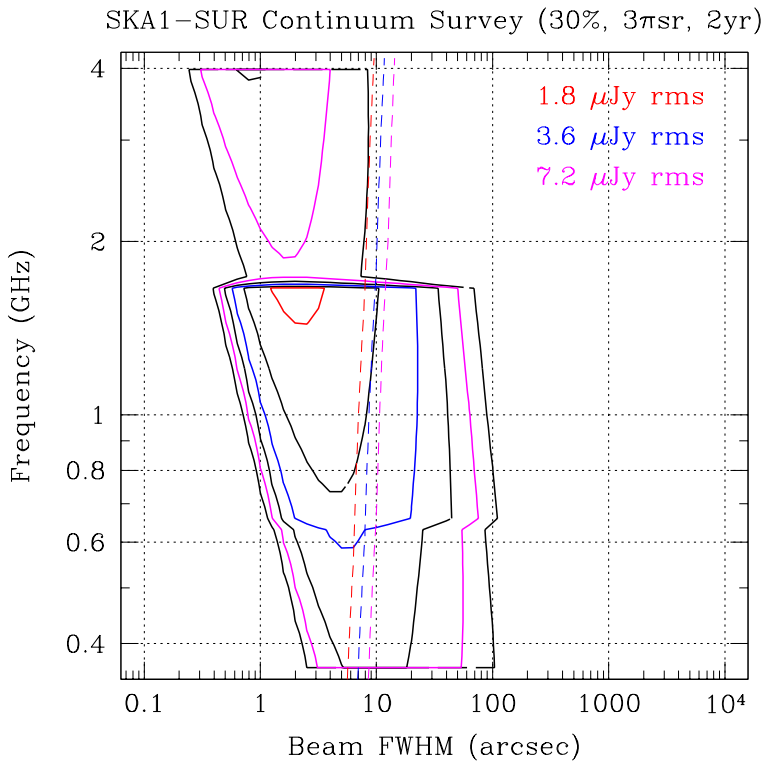
Cosmology with SKA1 continuum: Integrated Sachs-Wolfe effect

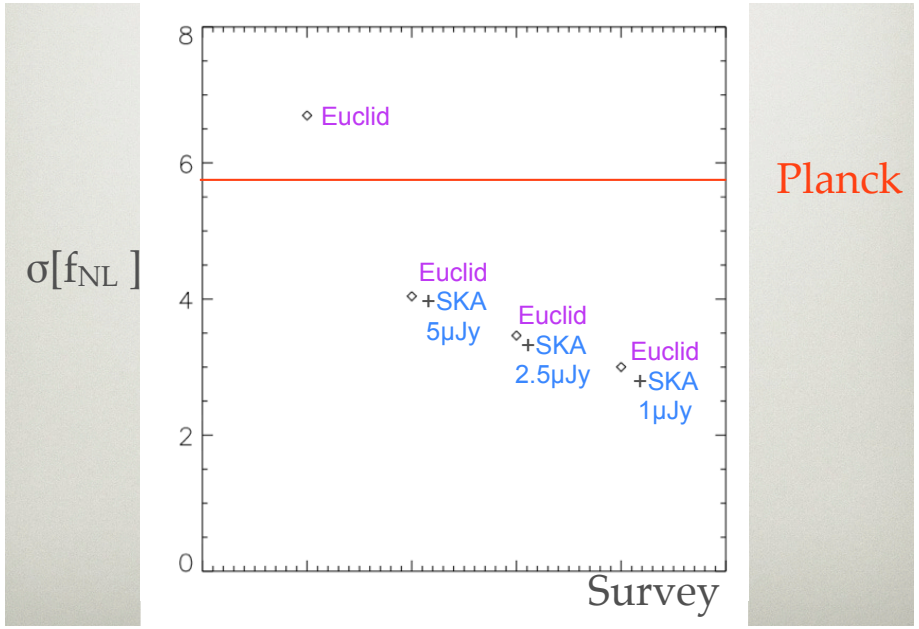




- Constraining non-Gaussianity of primordial fluctuations with the Integrated Sachs-Wolfe effect: correlation of foreground source populations with CMB structures

Cosmology with SKA1: Complementarity with Euclid





(D. Bacon)

- Constraining non-Gaussianity of primordial fluctuations with the Integrated Sachs-Wolfe effect
- Achieving 2 μJy rms would provide ≈4 galaxies arcmin^{-2} (>10σ)
- Almost uniform sky coverage of 3π sr is exceptional
- **Major enhancement over Euclid alone**

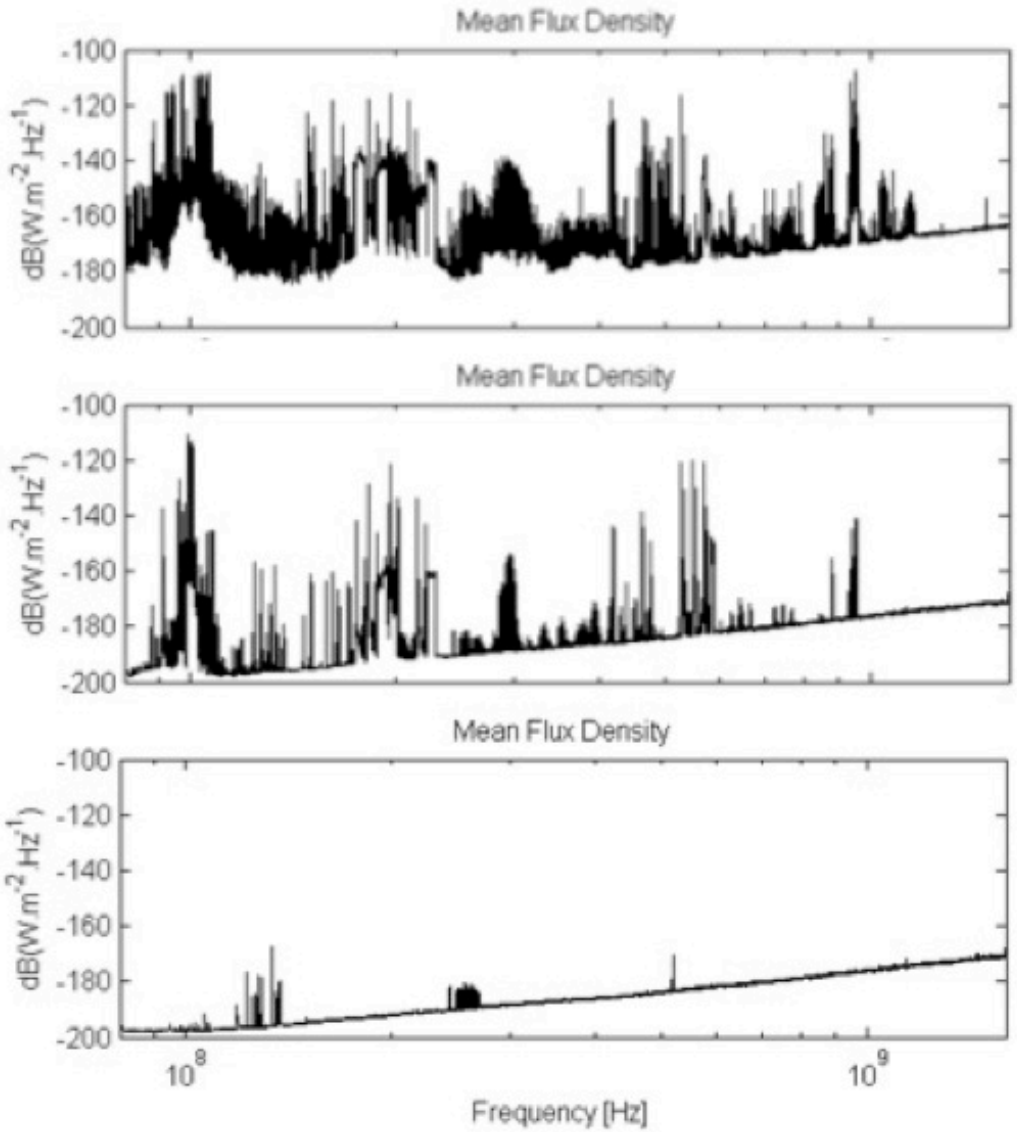
How does SKA1 compare to existing facilities?

		JVLA	MeerKAT	SKA1-mid	ASKAP	SKA1-survey	LOFAR-NL	SKA1-low
Aeff/Tsys	m^2/K	265	321	1630	65	391	61	1000
Survey FoV	deg^2	0.14	0.48	0.39	30	18	6	6
Survey Speed FoM	$deg^2\ m^4\ K^{-2}$	0.98×10^4	5.0×10^4	1.0×10^6	1.3×10^5	2.8×10^6	2.2×10^4	6.0×10^6
Resolution	arcsec	1.4	11	0.22	7	0.9	5	11

A_{eff}/T_{sys}: 6xJVLA 6xASKAP 16xLOFAR

Survey Speed: 100x 22xASKAP 270x 280xJVLA

SKA site selection

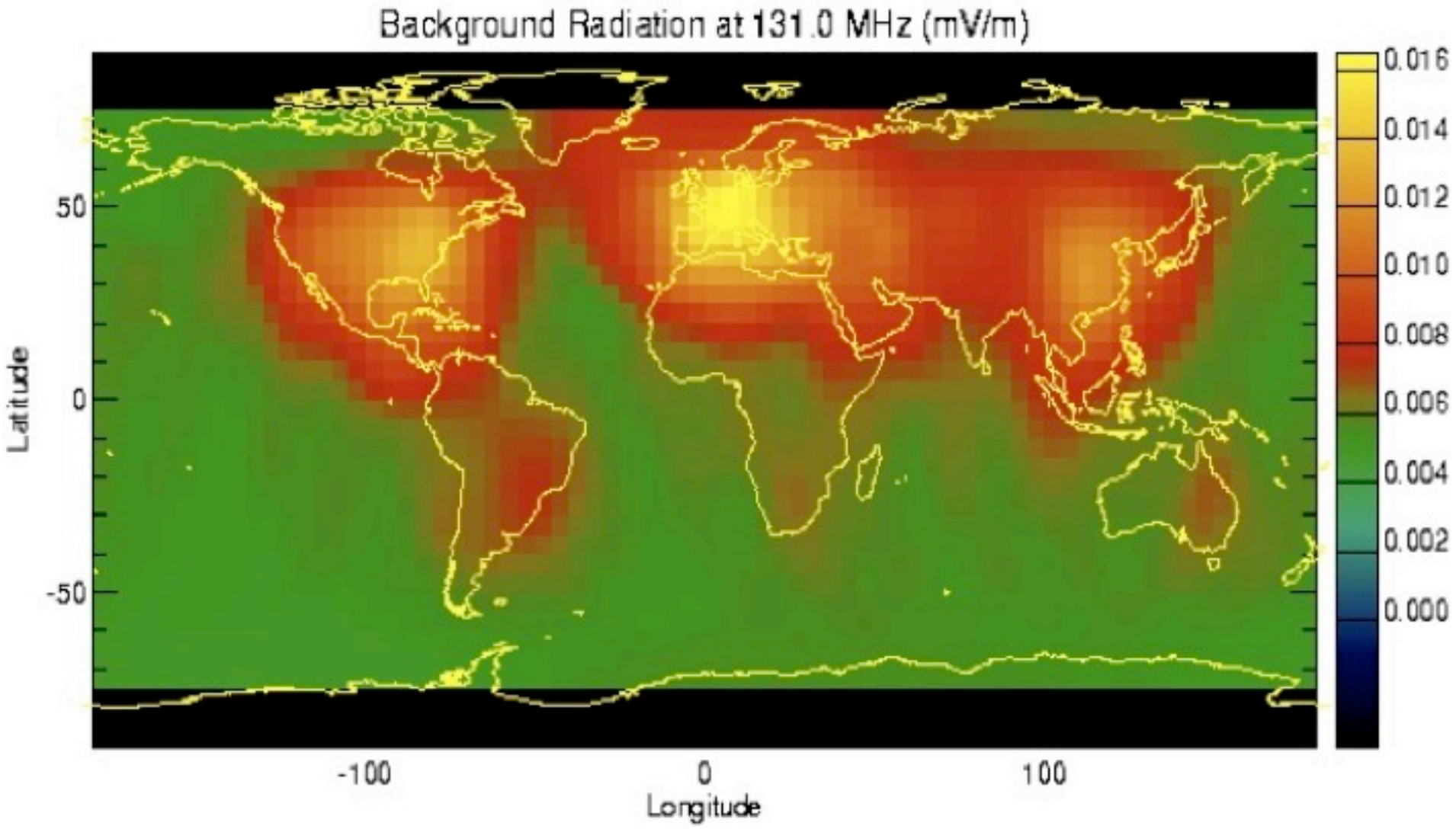


Sydney:
population 4 million

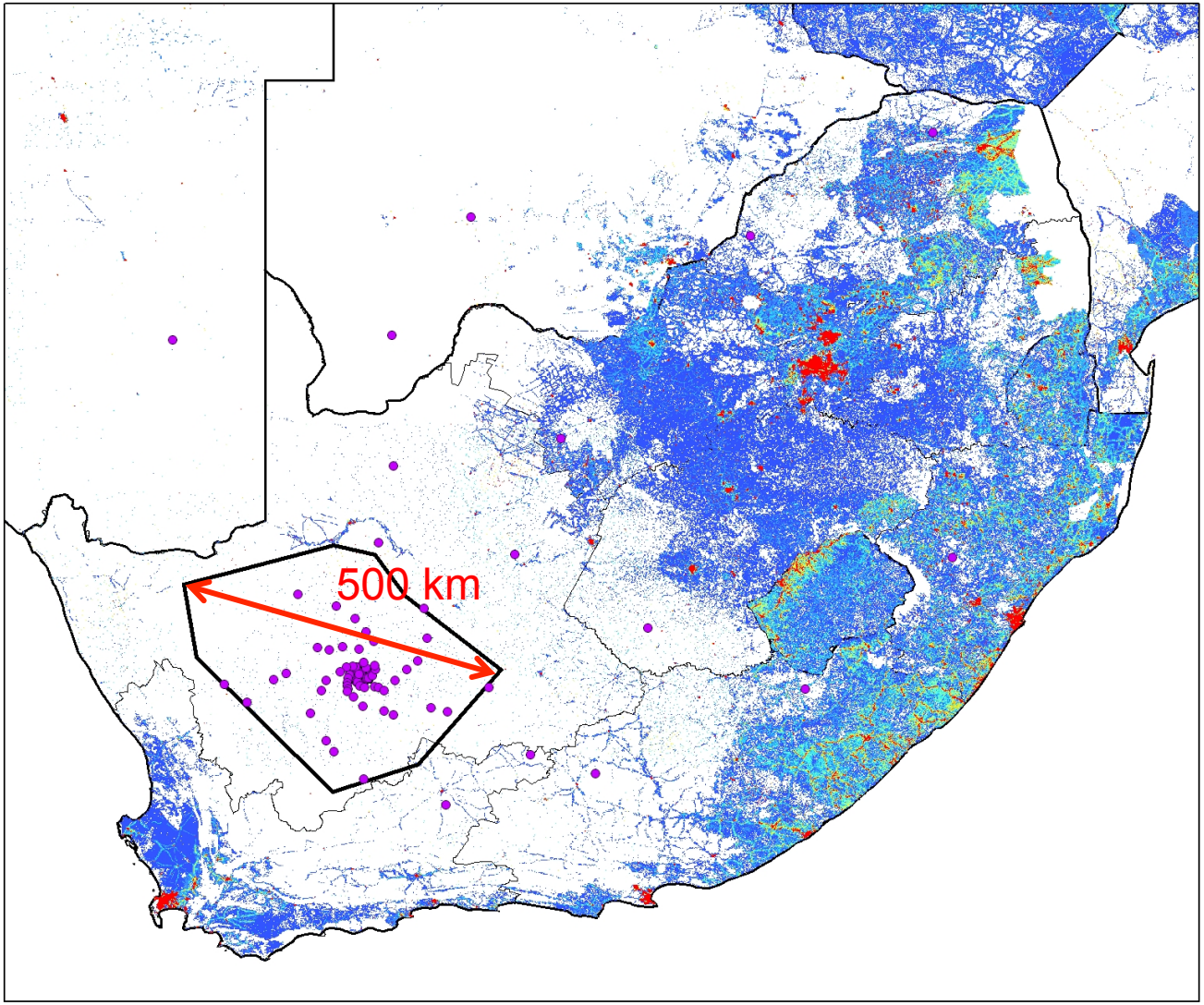
Narrabri:
population 4000

Mileura:
population 4

SKA site selection



Karoo Radio Astronomy Reserve



Legend

- SKA_Configuration_SPDO_Dish_Full
- AA1_SPDO_Version1
- AA2_SPDO_Version2
- KCAAA1

Population (per sq km)

Value

- 0 - 4
- 4.000000001 - 14
- 14.00000001 - 29
- 29.00000001 - 47
- 47.00000001 - 68
- 68.00000001 - 91
- 91.00000001 - 116
- 116.0000001 - 142
- 142.0000001 - 169
- 169.0000001 - 197
- 197.0000001 - 225
- 225.0000001 - 255

N

0 145 290 580 870 1,160 Kilometers

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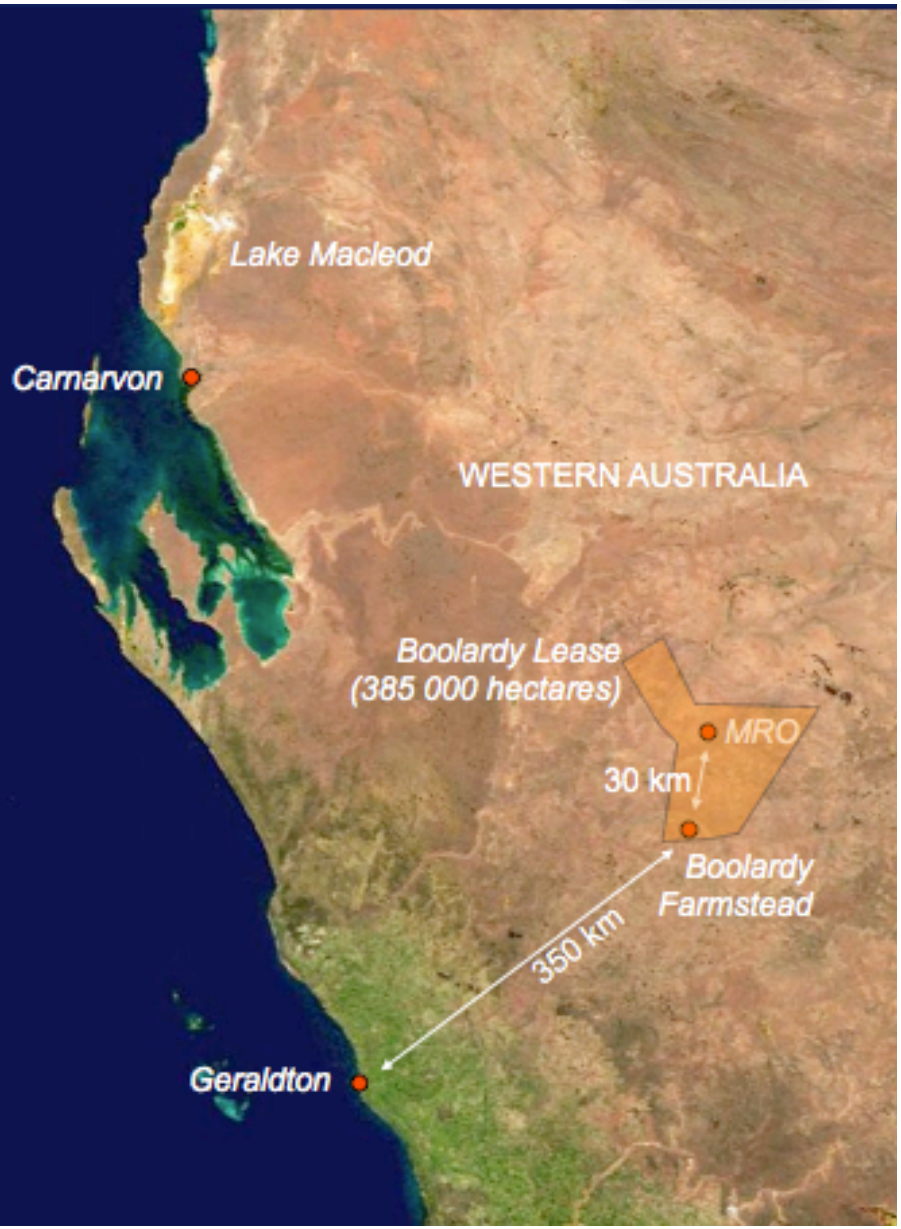
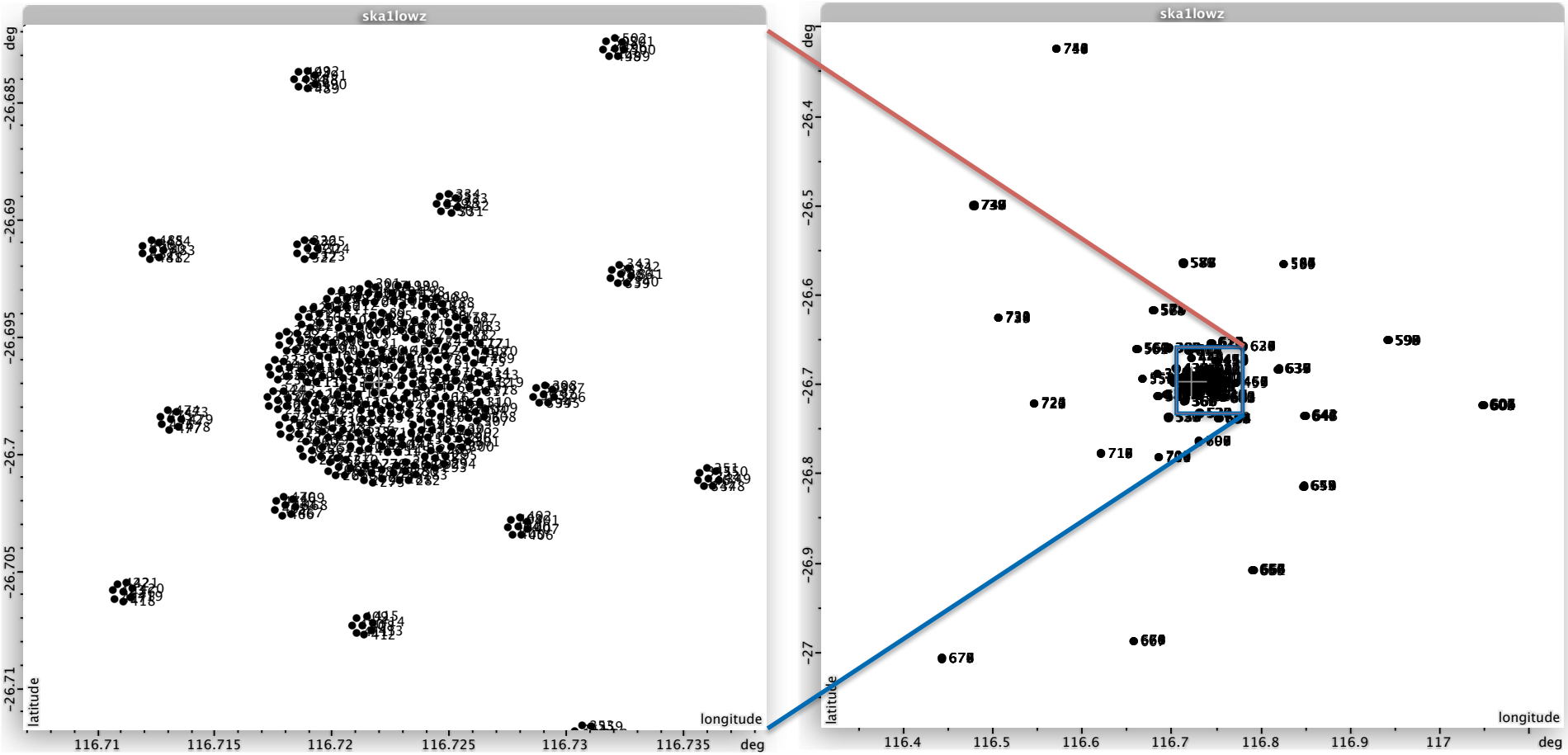
Murchison Radio Astronomy Observatory



Shire of Murchison:

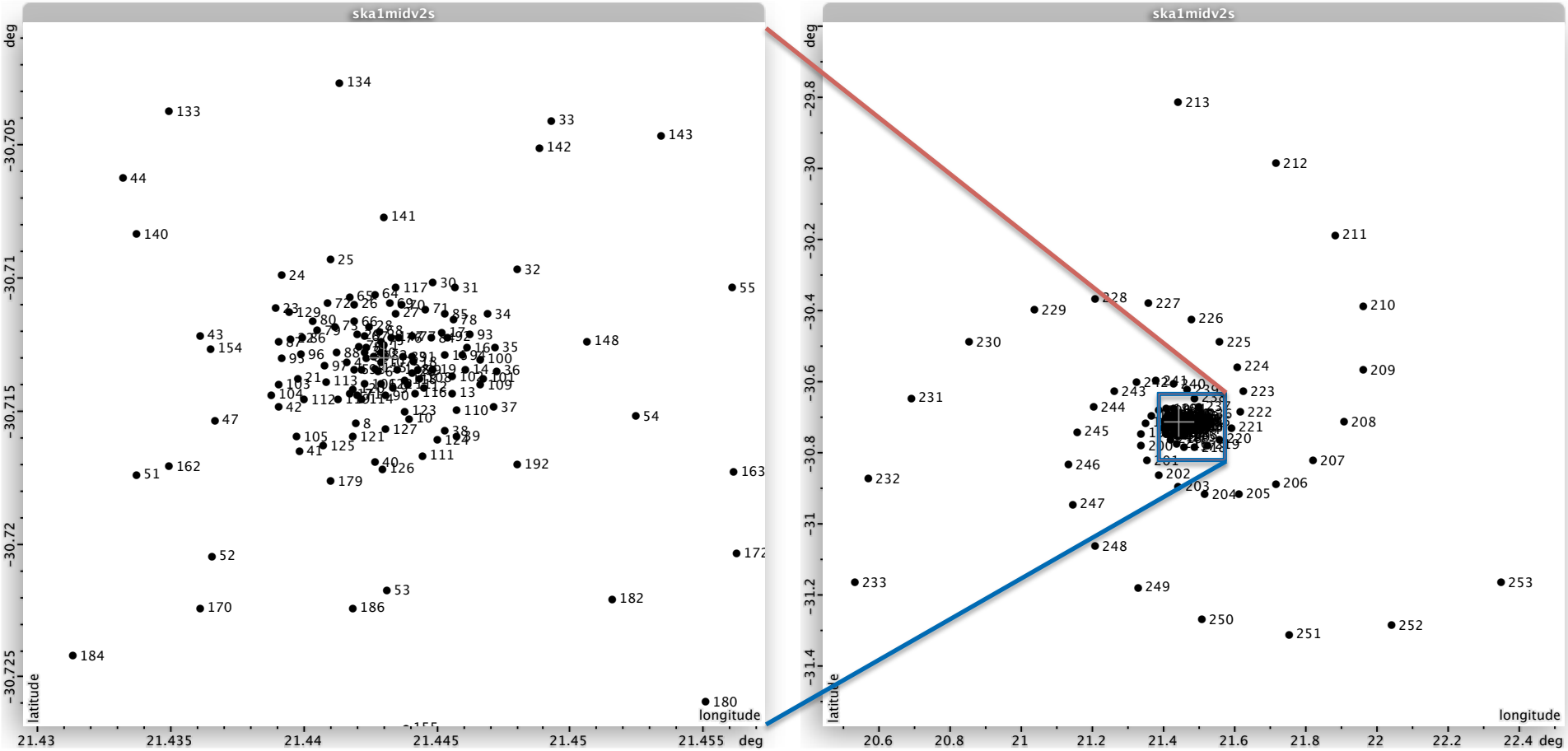
- 50,000 km² ; size of the Netherlands
- 0 gazetted towns
- 29 sheep/cattle stations
- 110 population => 0.002 km^{-2}

SKA1 configurations: LOW



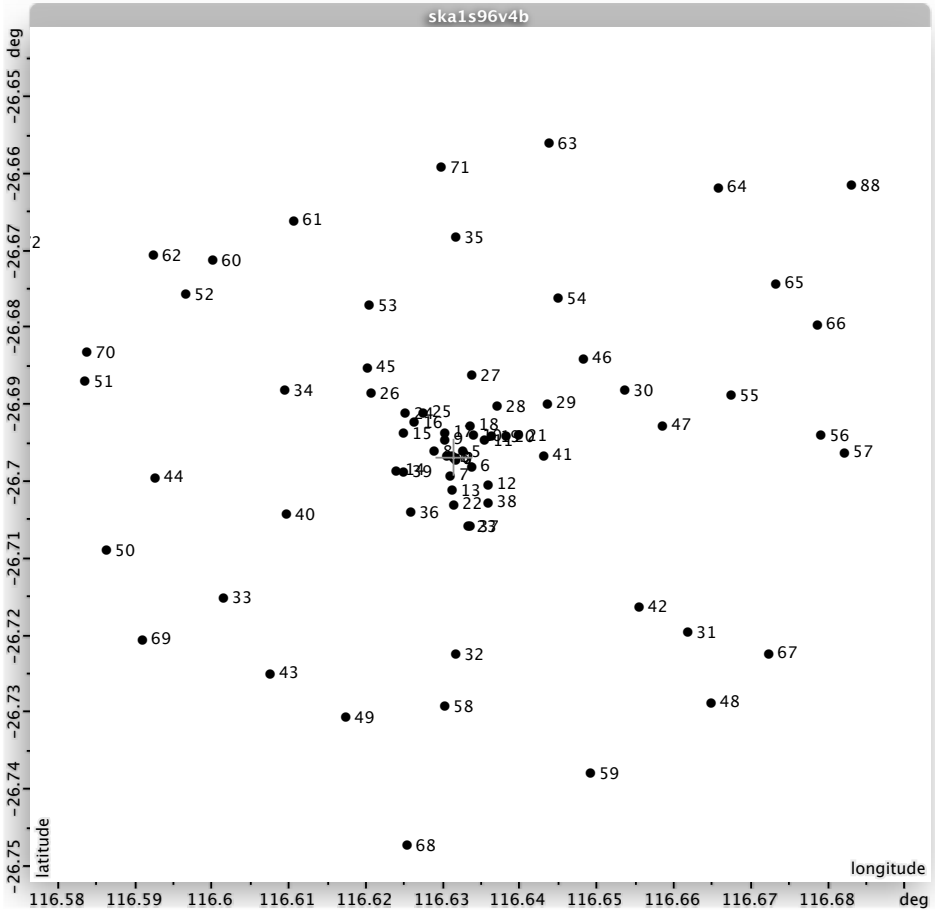
- SKA1-LOW possible configuration of core and remote spiral

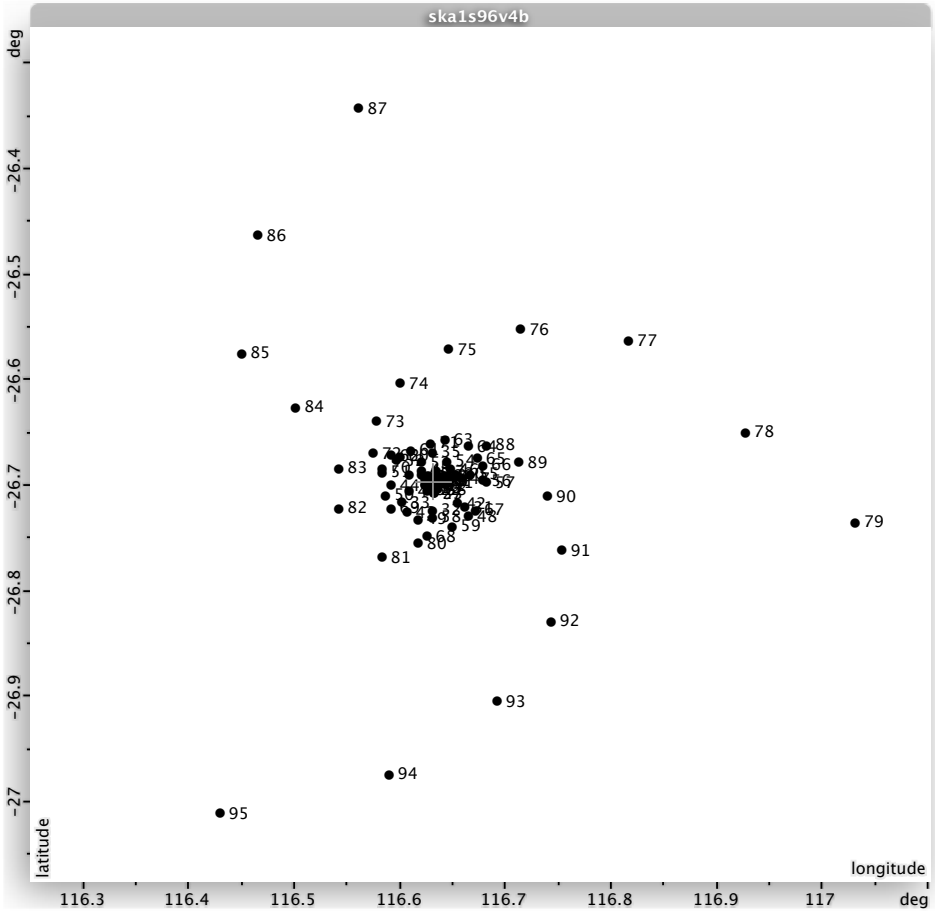
SKA1 configurations: MID



- SKA1-MID possible configuration of core and remote spiral

SKA1 configurations: SURVEY





- SKA1-SUR possible configuration of core and remote spiral