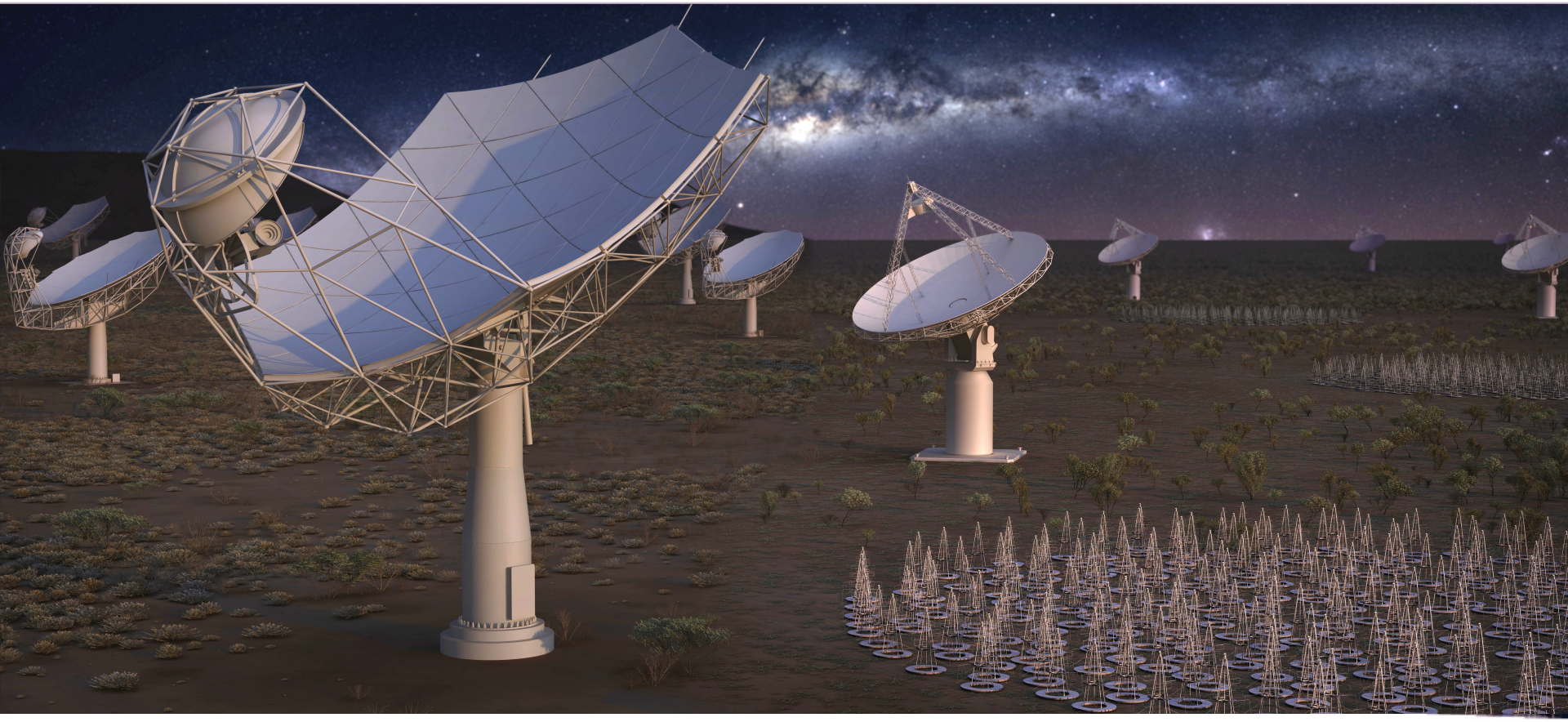
The SKA Project and its Science



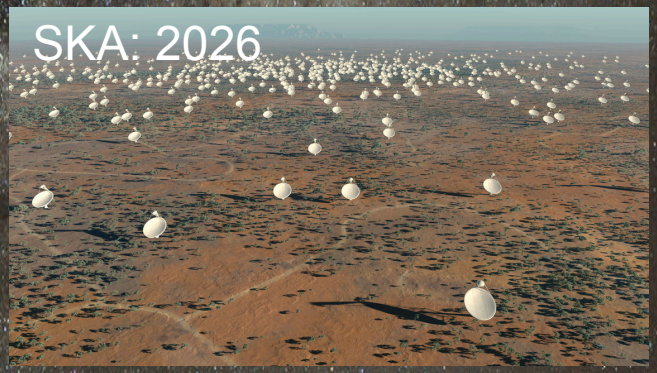
SQUARE KILOMETRE ARRAY

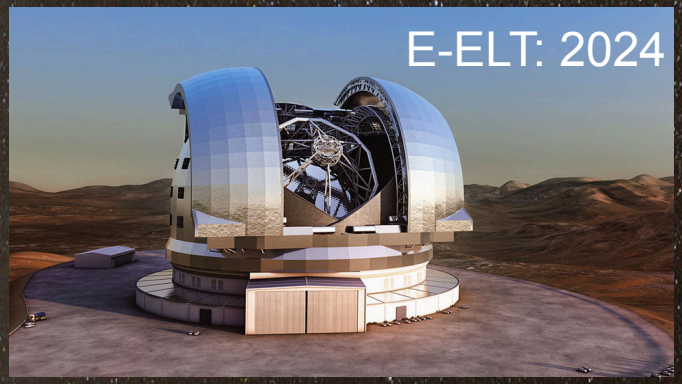
Exploring the Universe with the world's largest radio telescope

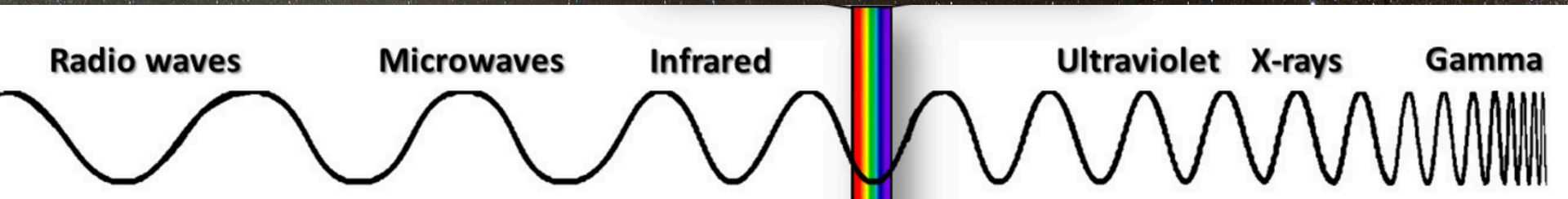
Robert Braun, SKA Science Director

3 December 2018

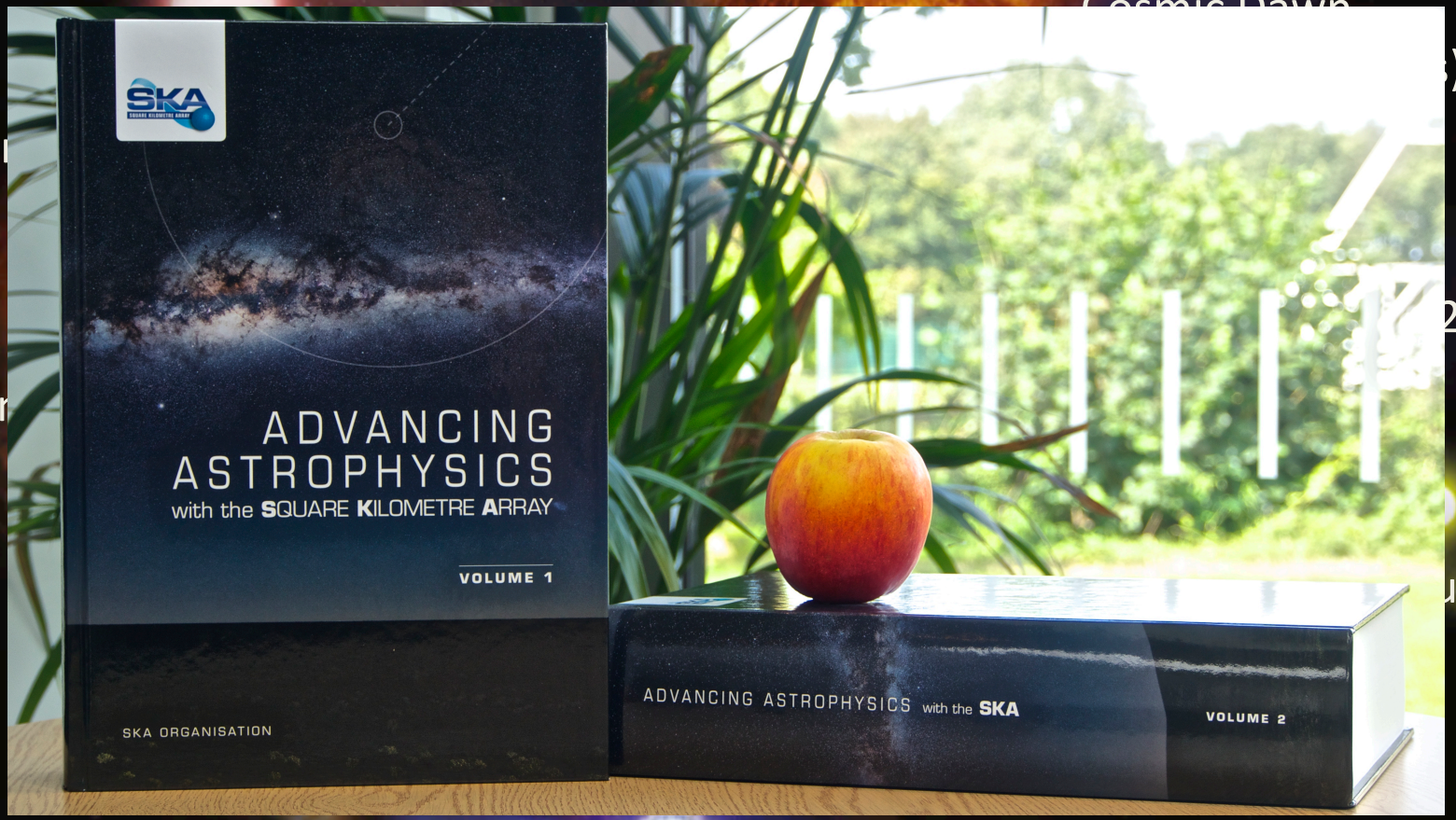
21st Century Observatories







SKA– Key Science Drivers: The history of the Universe



Broadest science range of any facility on or off the Earth.

The SKA Observatory

SKA: A global Research Infrastructure

Members
Host Countries: Australia, South Africa, United Kingdom

Observers

African partner countries

SKA: A global Research Infrastructure

Current Members

Potential Future Members

Members
Host Countries: Australia, South Africa, United Kingdom

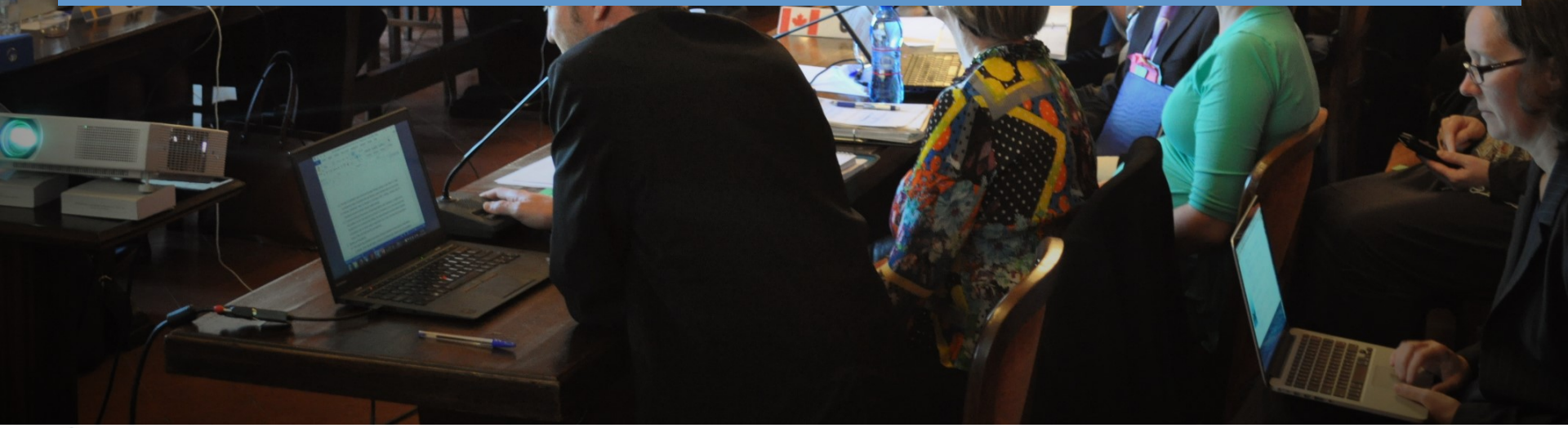
Observers

African partner countries

Negotiations to establish SKA Inter-Governmental Organisation.

Text of Convention and protocols now agreed
Initialing of documents completed
Ministerial signing ceremony in early 2019

Transition planning underway



Square Kilometre Array

3 sites; 2 telescopes + HQ
1 Observatory

Design Phase: ~€170M; 600 scientists+engineers

Phase 1
Construction: 2020 – 2025
Construction cost cap: €650M (2013€)

MeerKat integrated
Observatory Development Programme

SKA Regional Centres out of scope of centrally-funded SKAO

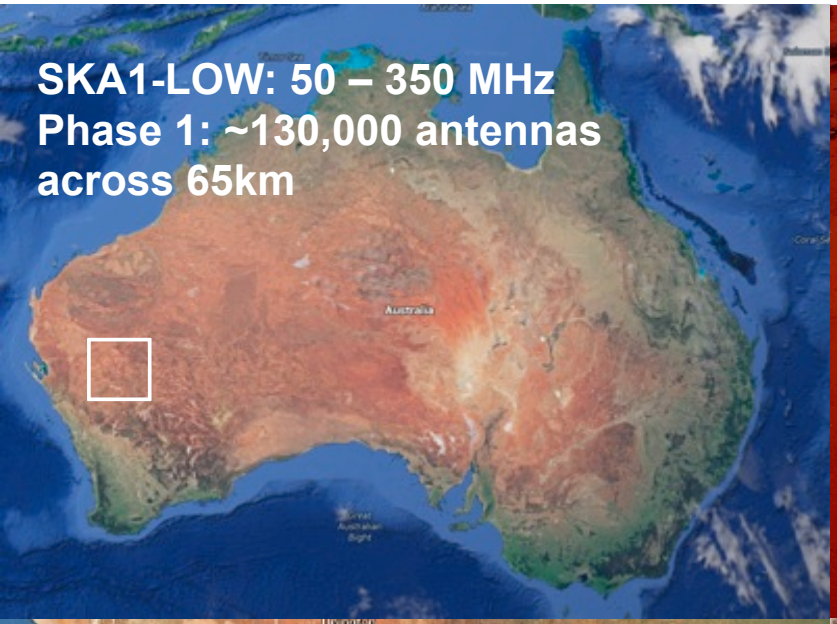
SKA HQ: Jodrell Bank, UK

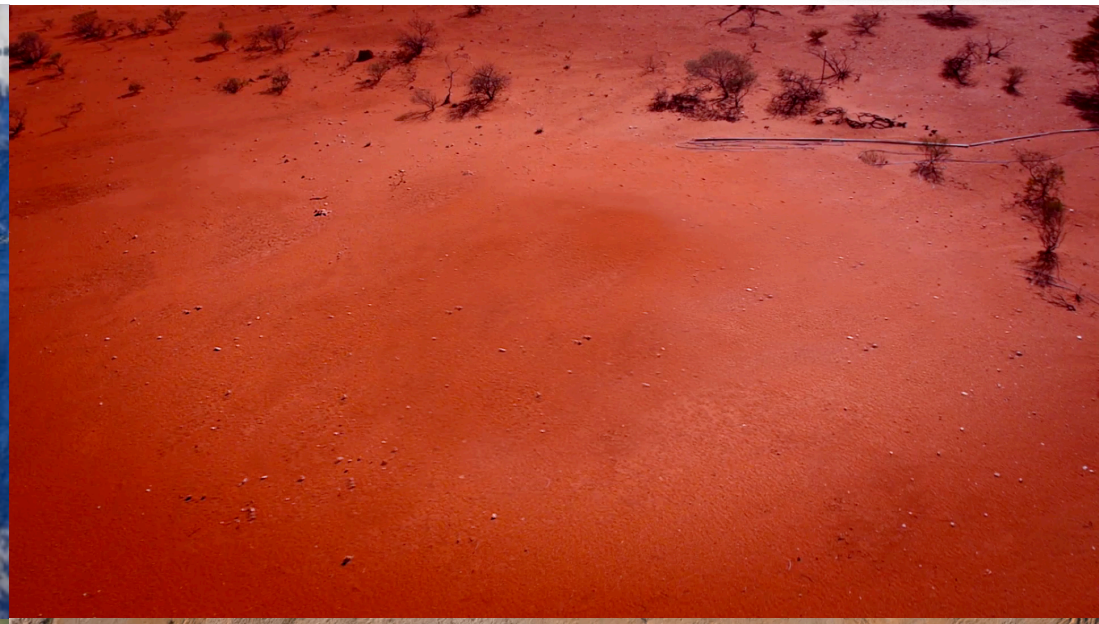
€20M project.

Completed Sept 2018

A ‘nexus for radio astronomy’

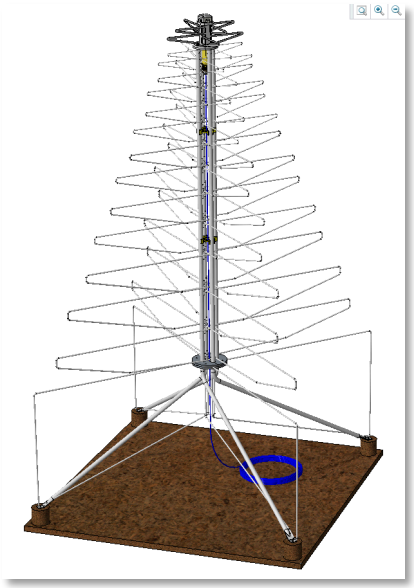
SKA: Telescopes in AUS & RSA



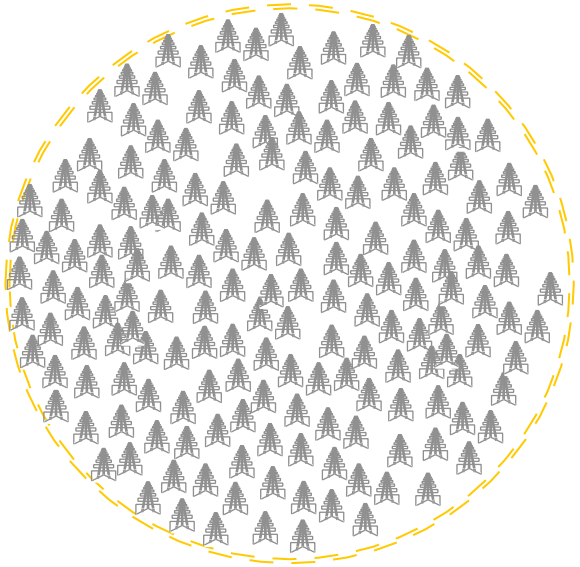


Construction: 2020 – 2025; Cost cap: €650M (2013€)

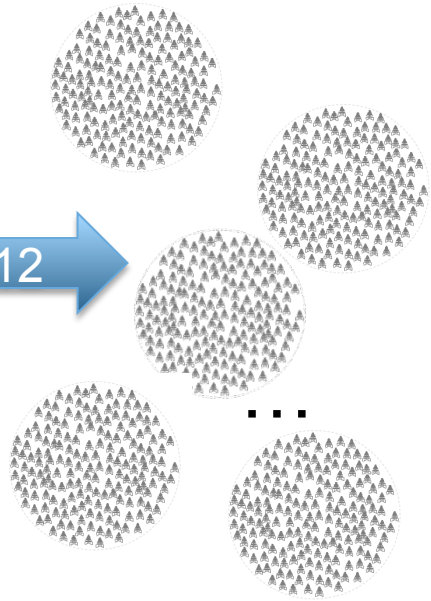
SKA1-Low: Array of Arrays



256



512



SKA1-Low Antenna/Receptor

Antenna Beam

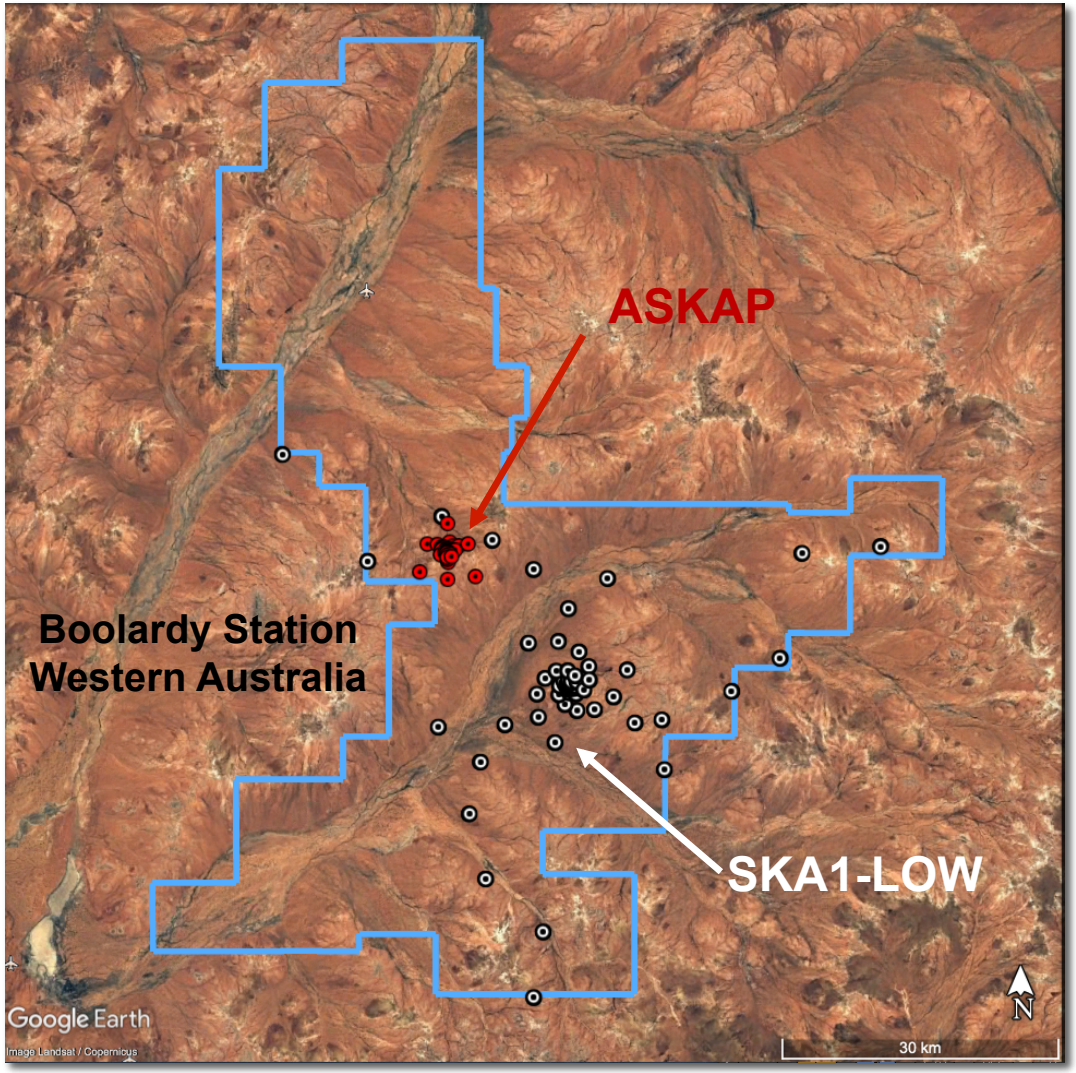
SKA1-Low *"Station"*

Station Beam

SKA1-Low "Array"

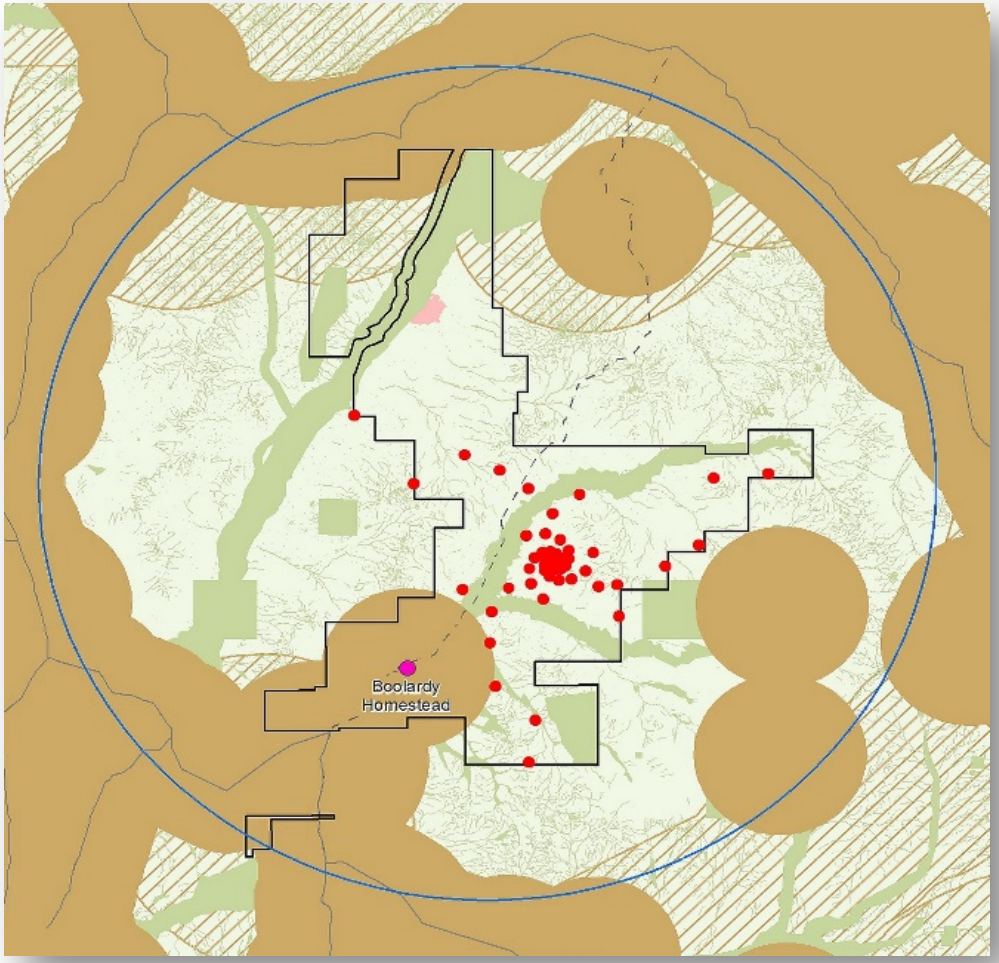
Correlation and *Tied-array Beams*

SKA1 – Low: Layout



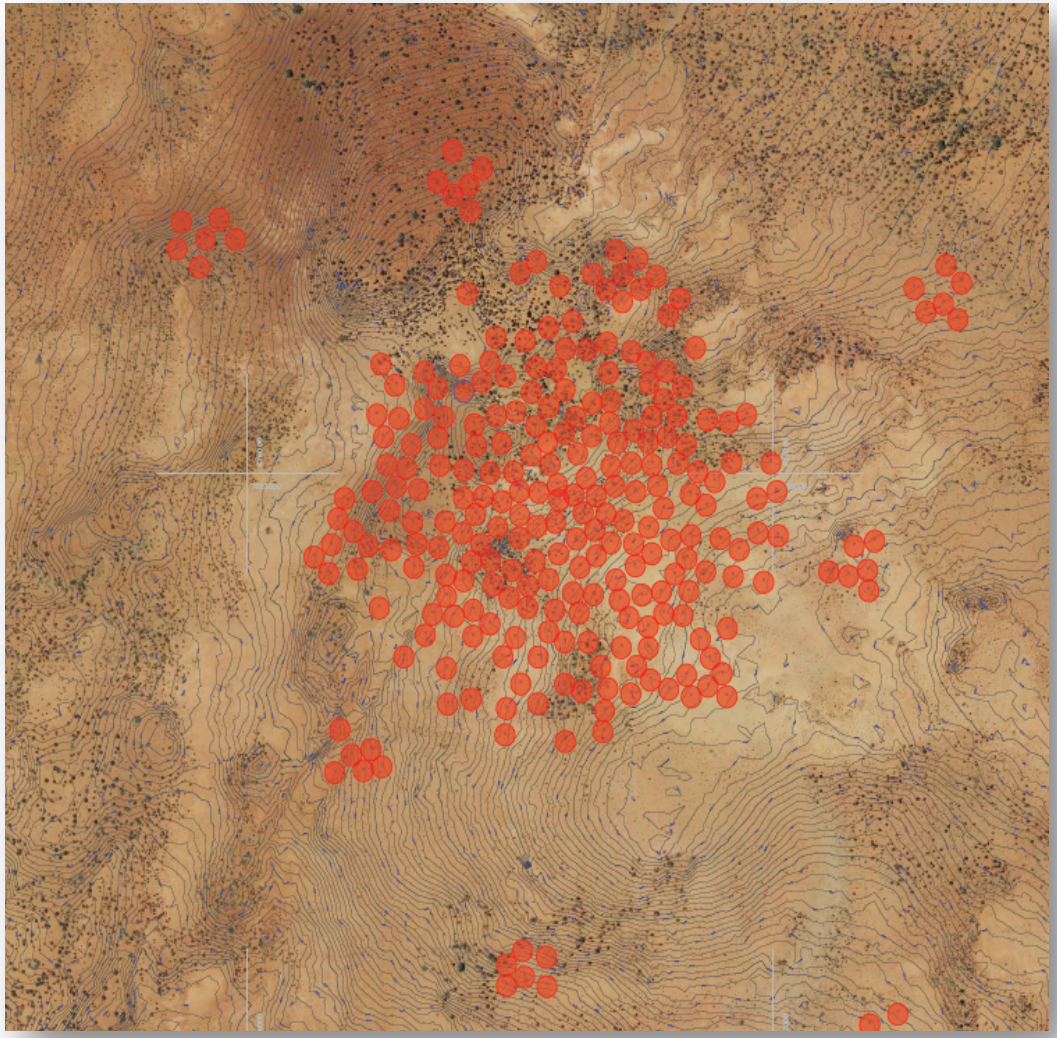
- 512 aperture array stations
- Maximum baseline 65 km
- 3 modified spiral arms

SKA1 – Low: Layout

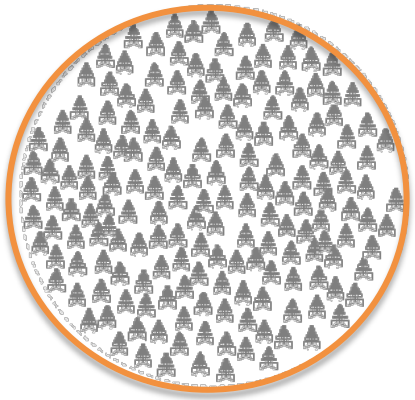


- 512 aperture array stations
- Maximum baseline 65 km
- 3 modified spiral arms
- Respect site constraints

SKA1 – LOW: Layout

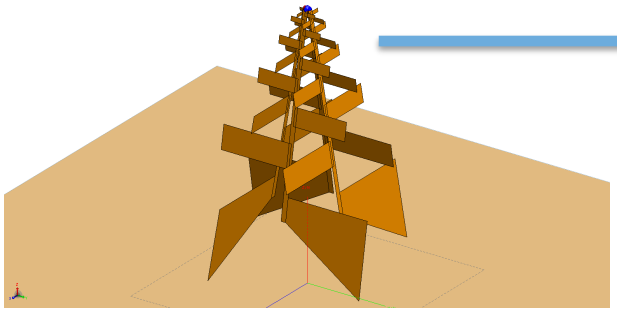


- 512 aperture array stations
- Maximum baseline 65 km
- 3 modified spiral arms
- Respect site constraints
- ~ 50% within ~1 km randomly distributed
- Others in clusters of 6 stations arranged randomly over an area 100 to 150 m in diameter

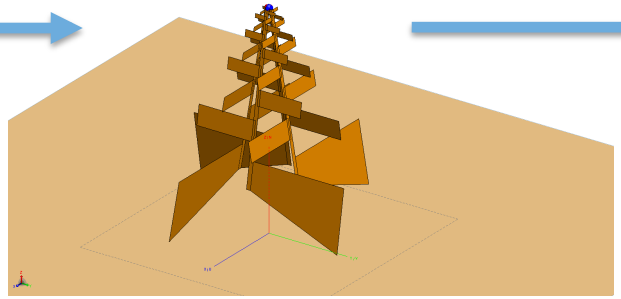


- 256 antennas per station
- 38m station diameter

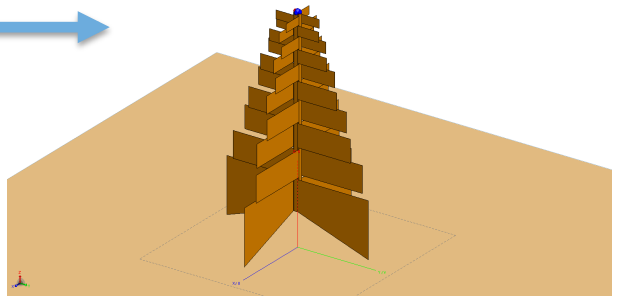
SKA1-Low Antenna Development



SKALA1-2: Open boom, 9 dipoles

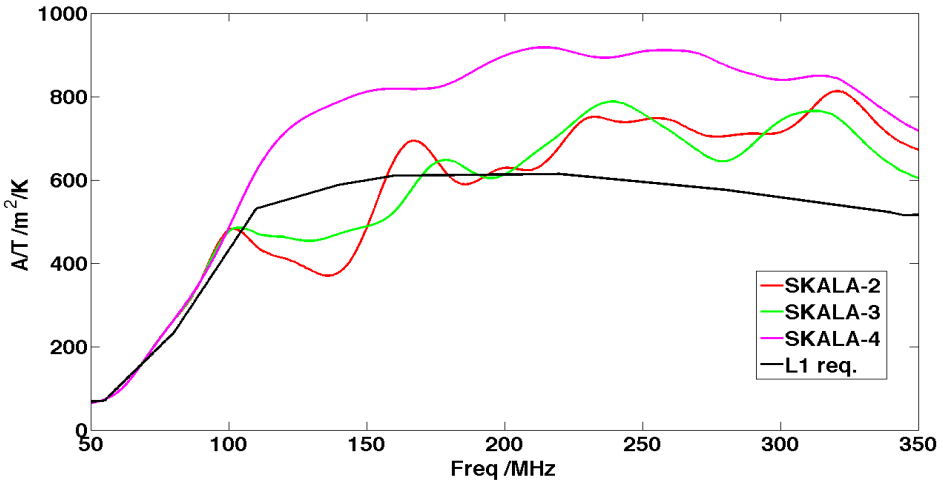


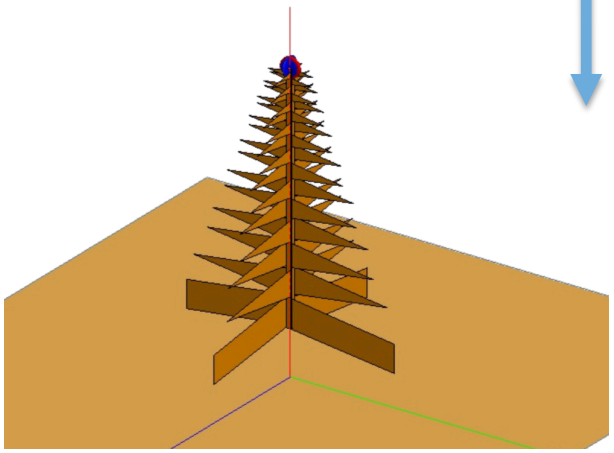
SKALA3: Open boom, 9 dipoles



SKALA4: Closed boom, 11 – 18 dipoles

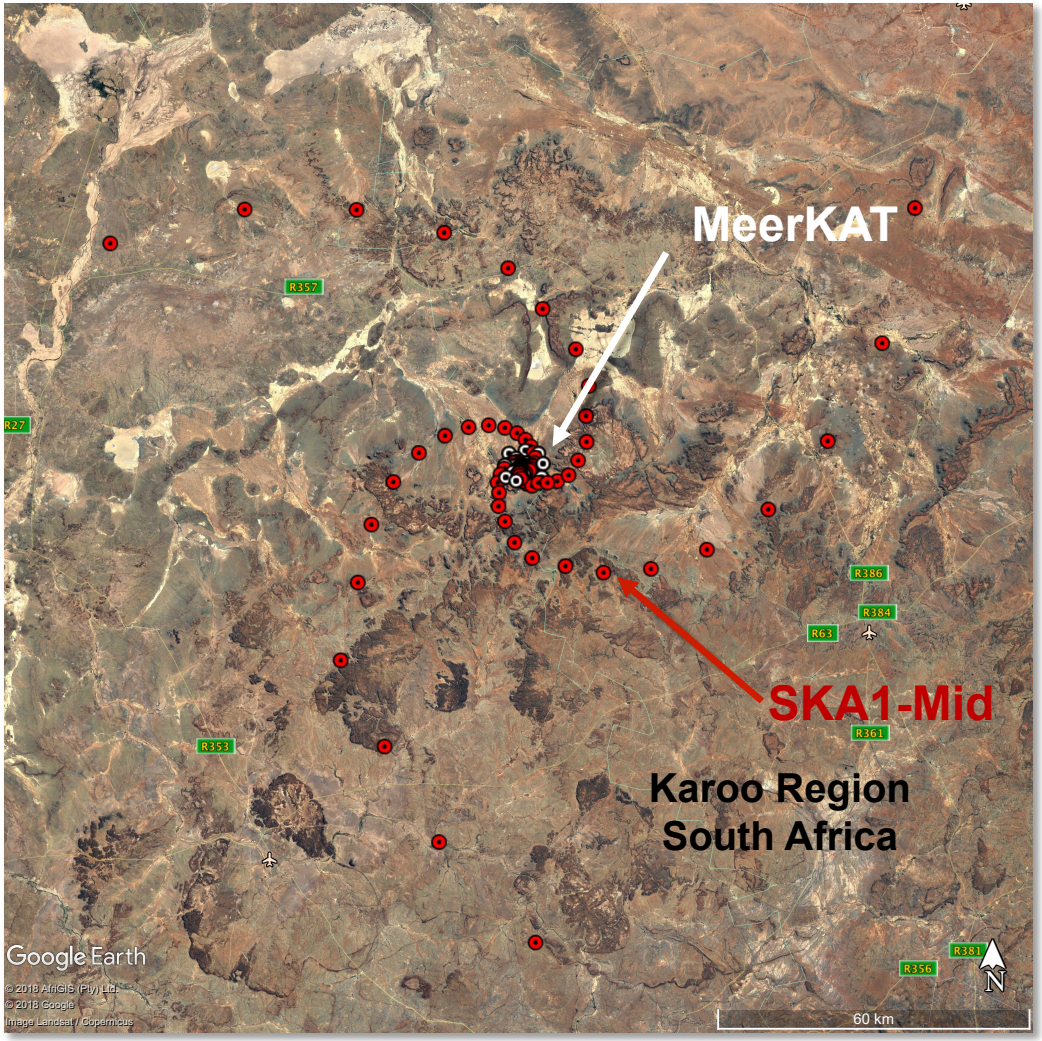
- SKALA4 design for SKA1-Low antenna
  - Improved: sensitivity, smoothness, polarisation purity, beam shape



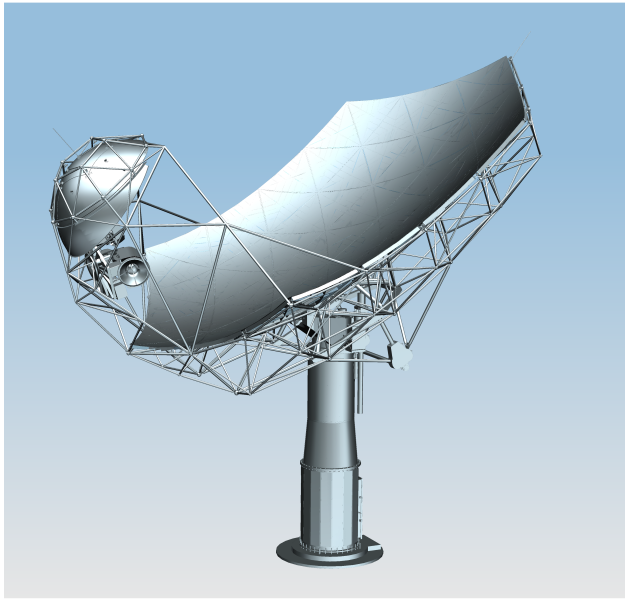


SKALA4: Closed boom, optimised

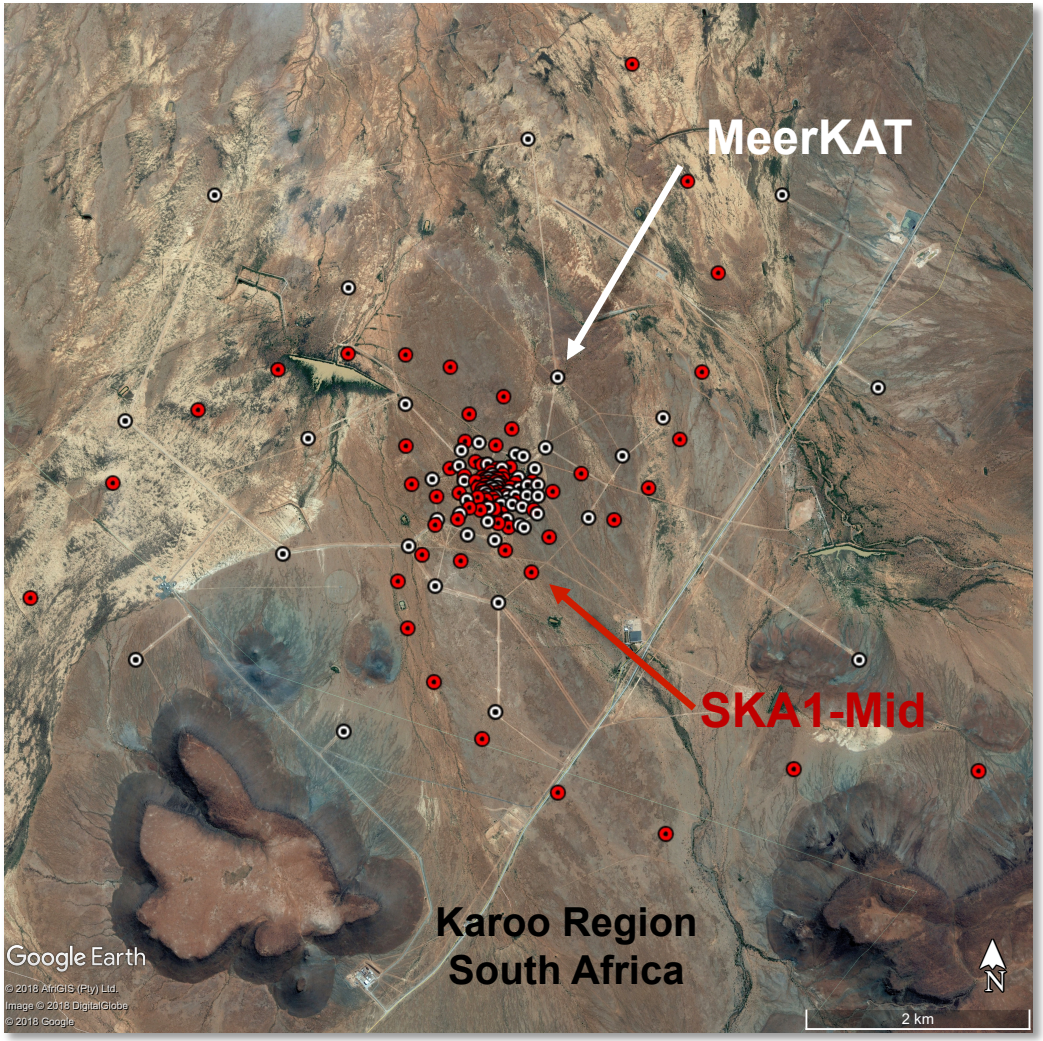
SKA1 –Mid: Layout



- 133 SKA 15m dishes
- 64 MeerKAT 13.5m dishes
- Maximum baseline 150 km
- 3 logarithmic spiral arms



SKA1 –Mid: Layout



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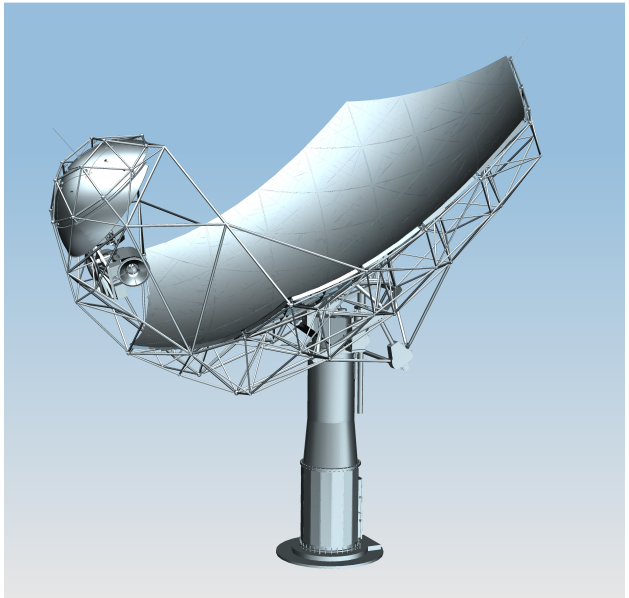
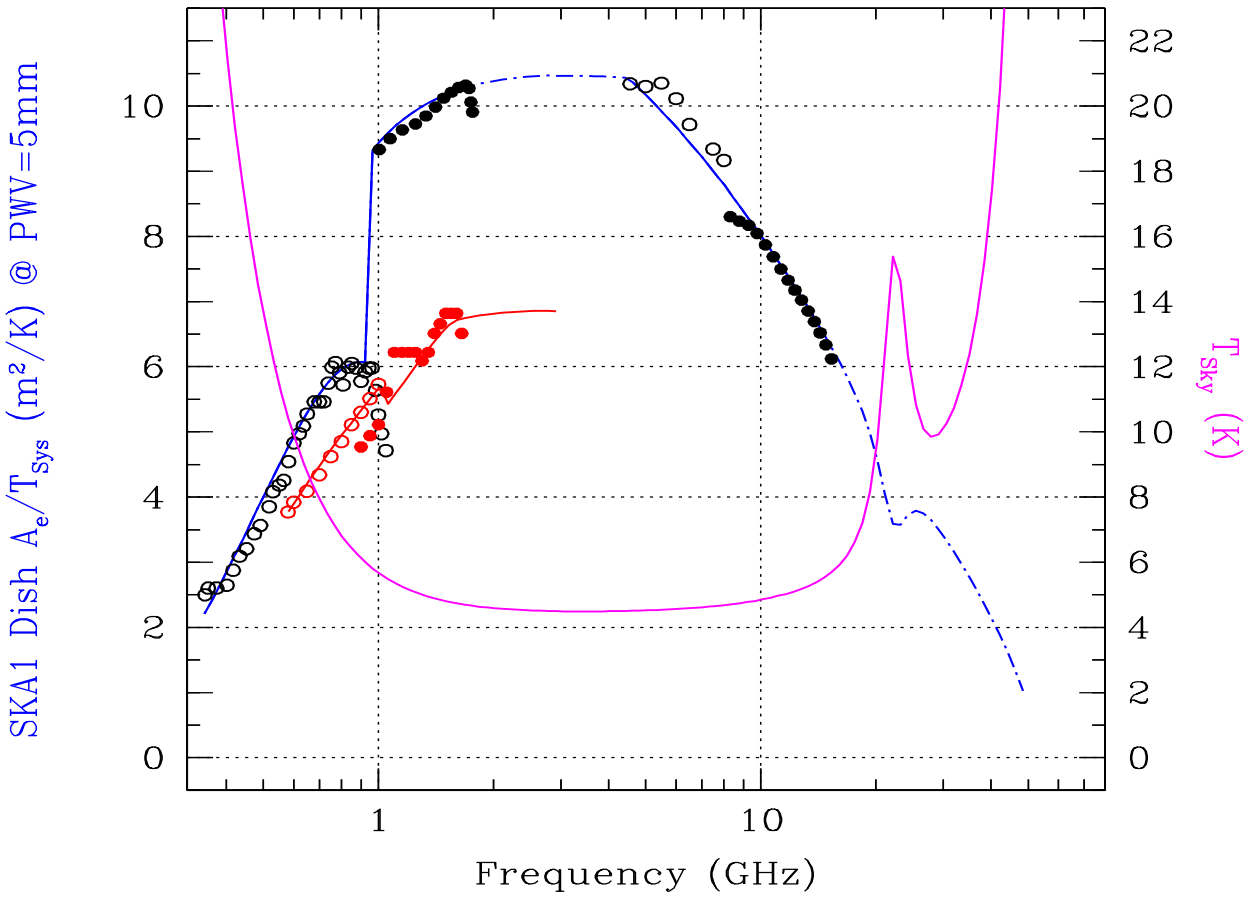
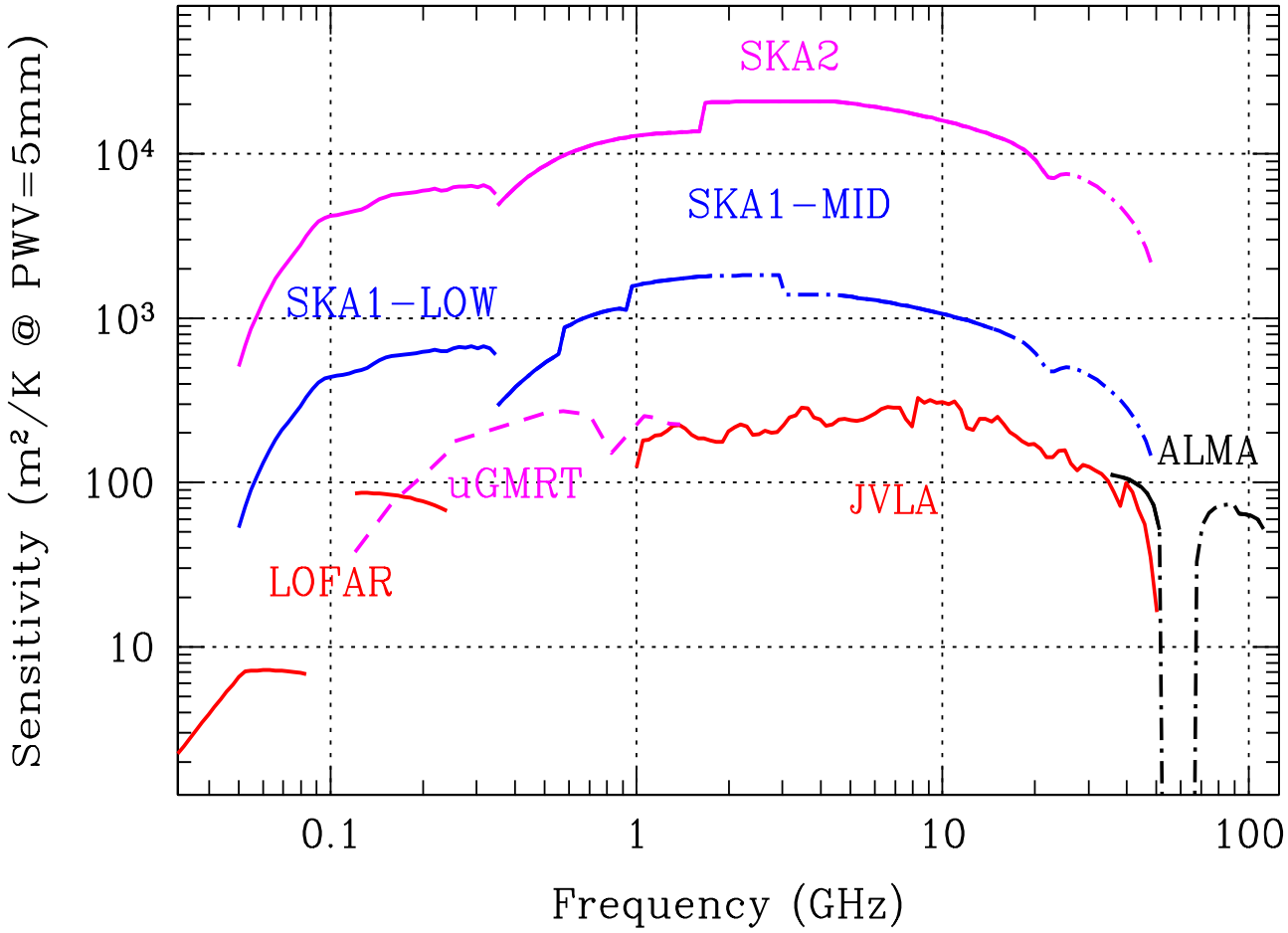


SKA1-Mid Anticipated Performance



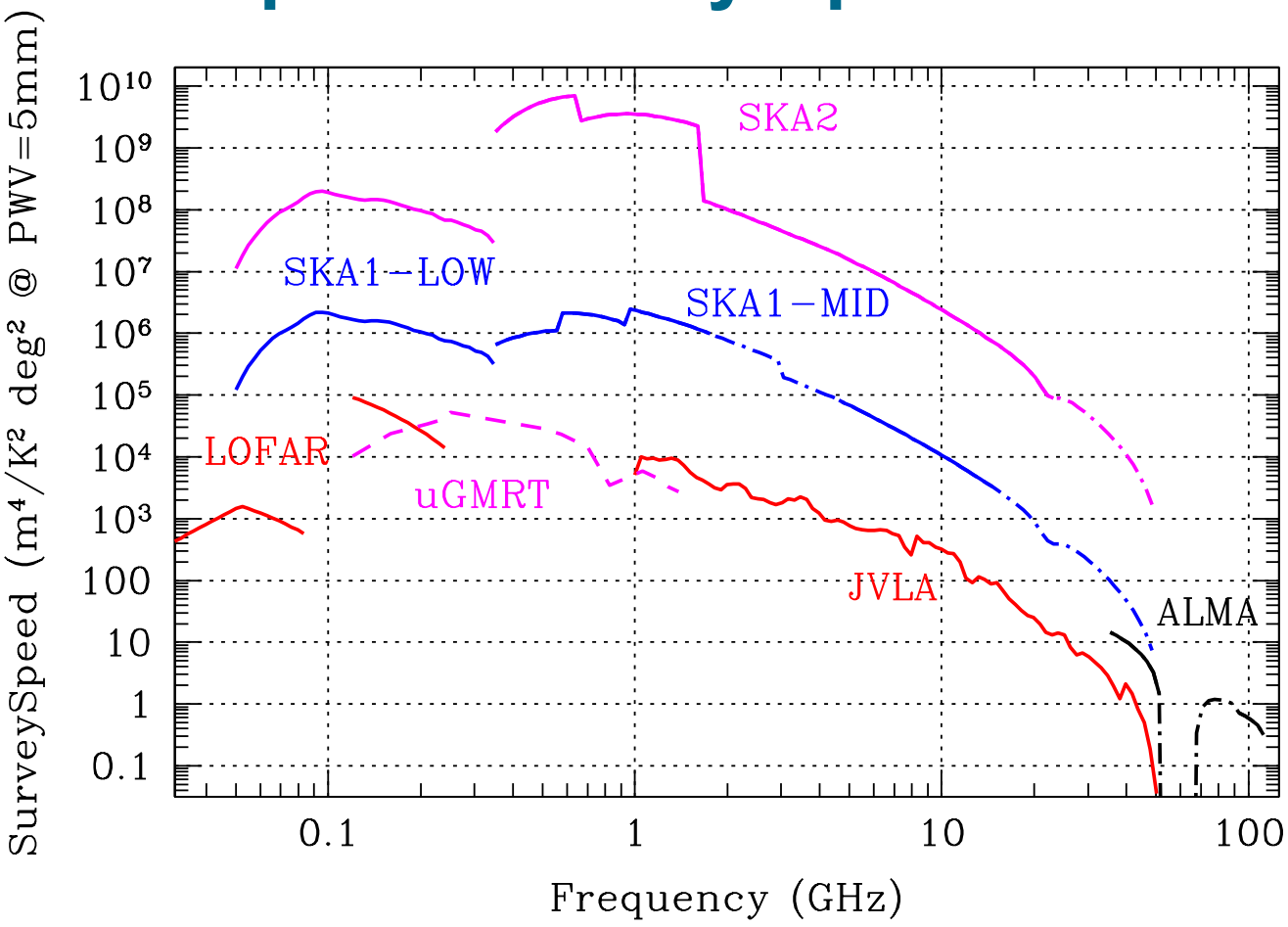
- SKA1-Mid and MeerKAT dish performance at Karoo site
  - SKA surface RMS < 350 μm, relative pointing RMS <1.3 arcsec

SKA1 Anticipated Sensitivity



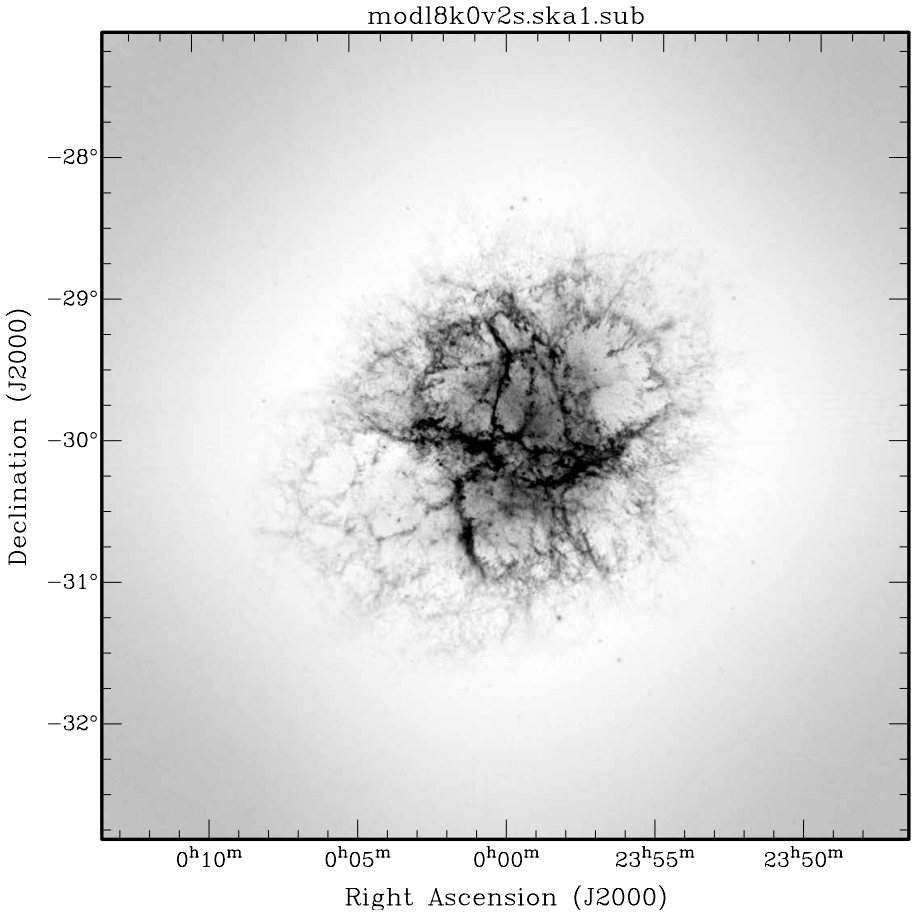
- Improved performance predictions now available at all frequencies
- Opportunity for seamless interface of SKA to ALMA capabilities

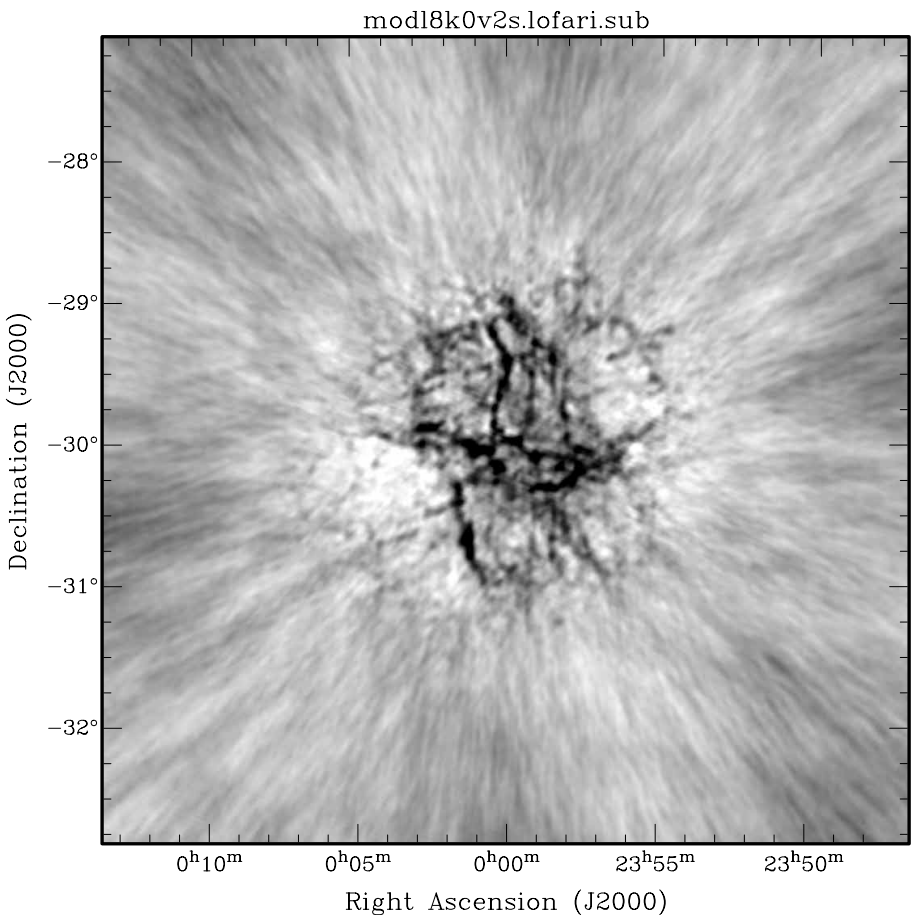
SKA1 Anticipated Survey Speed



- Improved performance predictions now available at all frequencies
- Opportunity for seamless interface of SKA to ALMA capabilities

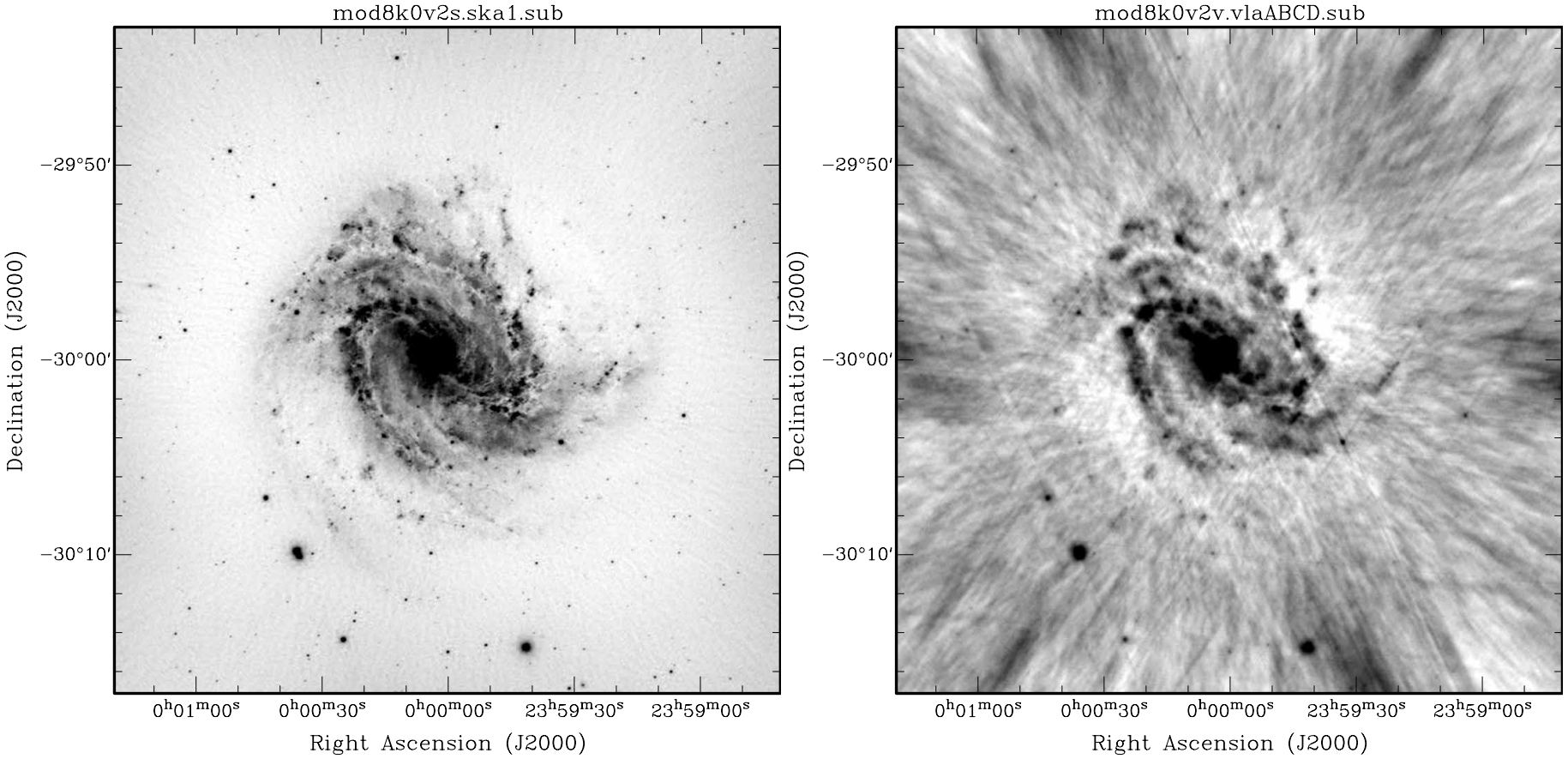
SKA1 Image Quality Comparison





- Between 10 and 100 times the image quality of current facilities
- Single SKA1-Low “dirty” snap-shot compared to LOFAR “dirty” snap-shot

SKA1 Image Quality Comparison



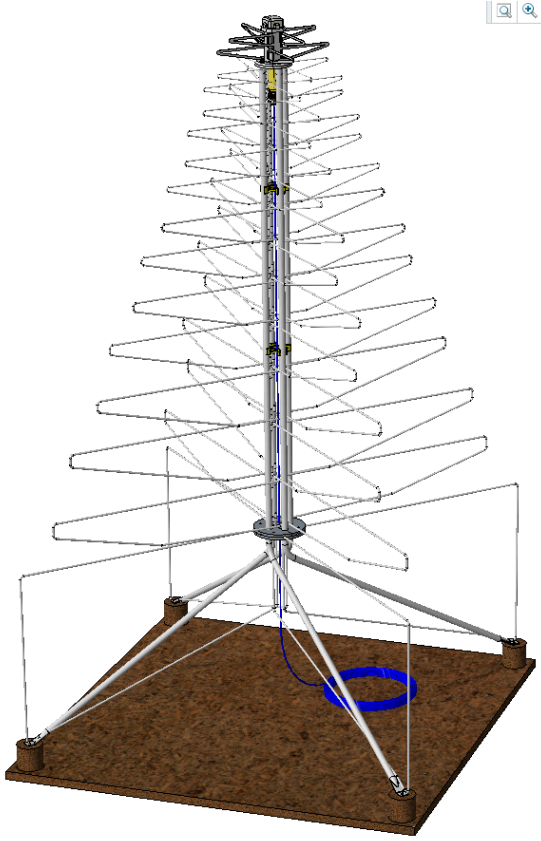
- Between 10 and 100 times the image quality of current facilities
- Single “dirty” SKA1-Mid snap-shot compared to combination of four “dirty” snap-shots, one in each of VLA A+B+C+D

Current status

CDR Activity – Update Nov 2018

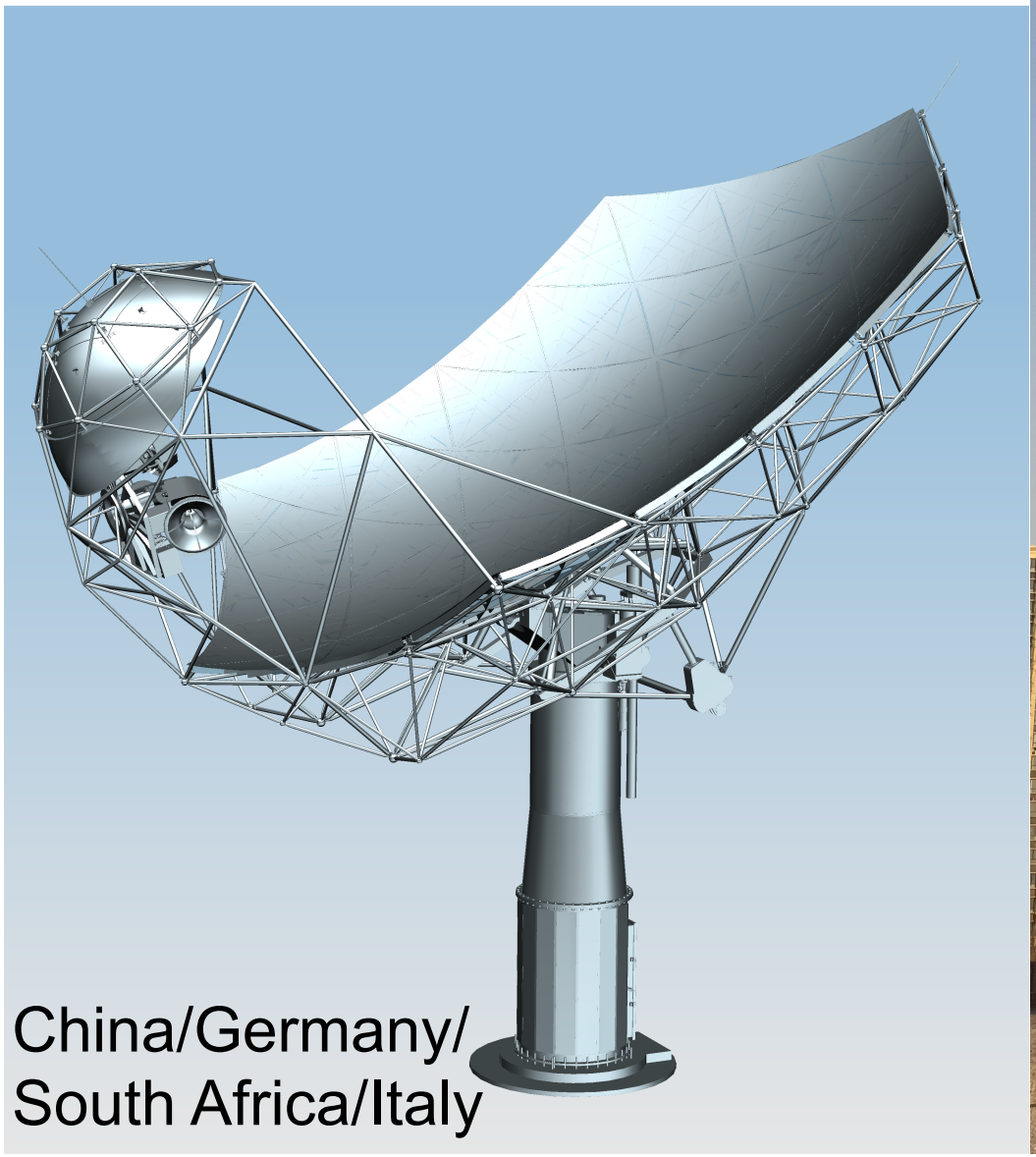
Element	RRN Submission	CDR Submission	CDR Meeting
TM	29 January 2018	28 February 2018	17-20 April 2018
SaDT & SAT	17 January 2018	28 February 2018	15-18 May 2018
INAU	19 March 2018	30 April 2018	27-29 June 2018
INSA	19 March 2018	30 April 2018	2-4 July 2018
CSP	18 May 2018 - PSS, PST, CBF-Low, CBF-Mid Sub-Element CDRs	30 June 2018	25 – 28 September 2018 !!
MeerKAT Integration			22 October 2018
SDP Pre-CDR SDP CDR	9 March 2018 17 September 2018	25 April 2018 31 October 2018	20 – 22 June 2018 15 – 18 January 2019
LFAA	15 October 2018	5 November 2018	11 – 13 December 2018
AIV	29 October 2018	30 November 2018	4 March 2019
DSH Pre-CDR DSH CDR	17 September 2018 1 Apr 2019 - Band 1, LMC Sub-CDR 20 Sept 2018 - DSH Struct Sub-CDR 1 Apr 2019 - Band 2 Sub-CDR 1 Apr 2019 - Band 5 Sub-CDR 27 Aug 2019	28 September 2018 13 September 2019 (B2)	26 – 27 November 2018 Aug 2019 (DSH, B2) Oct 2019 (B1, B5)
System			Q2/3 2019

Testing of SKALA4 Prototypes



- Two different implementations of new optimised EM design tested at MRO during 2018

Building SKA : dishes

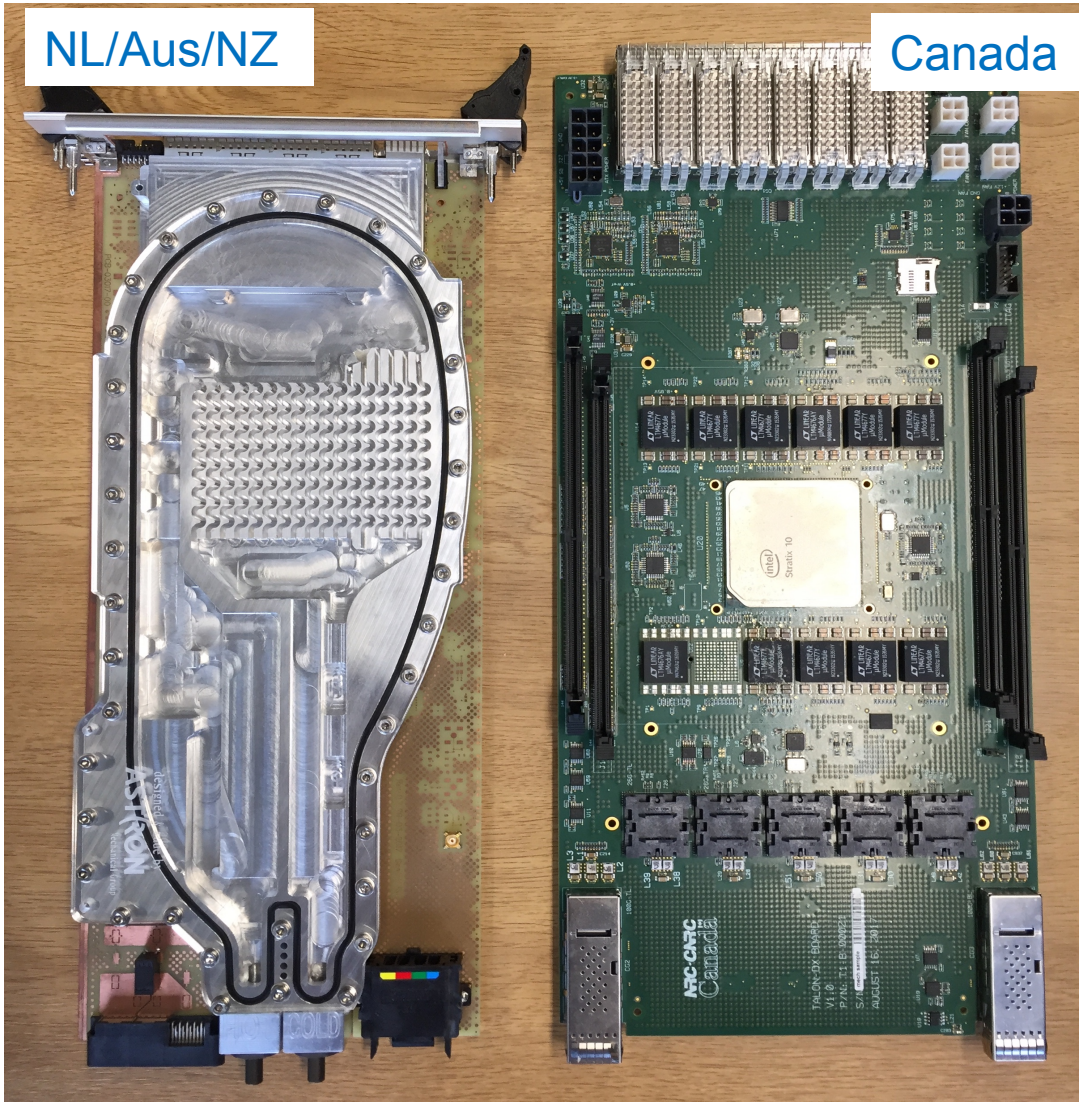


China/Germany/
South Africa/Italy

Building SKA: prototypes

NL/Aus/NZ

Canada



UK/Aus

RSA/UK/India/NZ/Aus

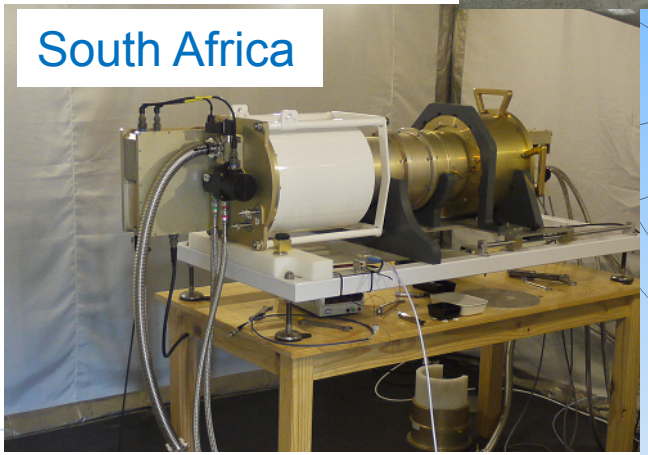
Building SKA: prototypes

Band 1 receiver, leaving Sweden…

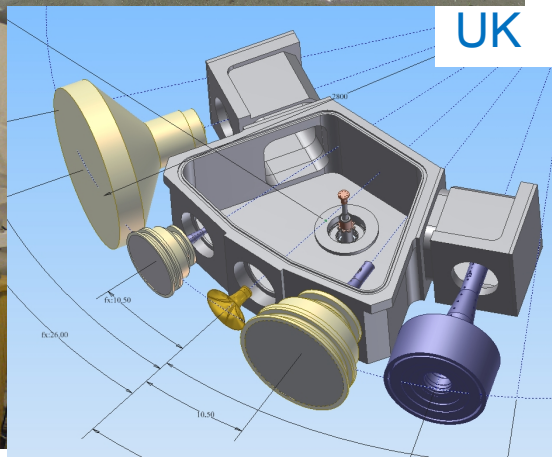
…being tested at MeerKAT.

Italy

South Africa



UK

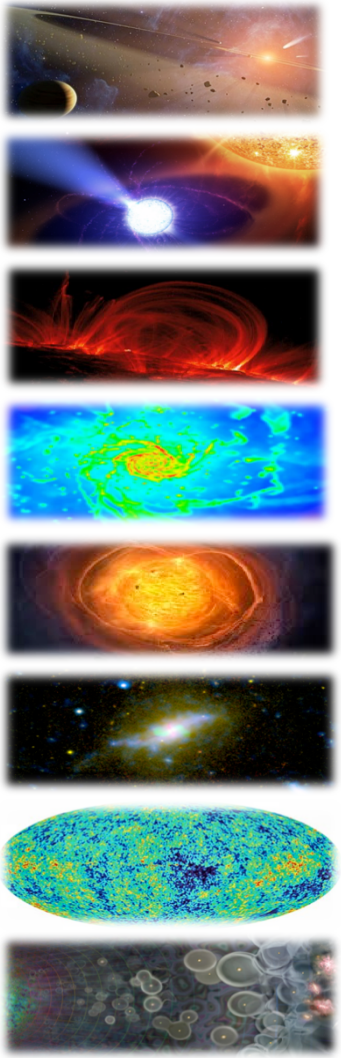


elescope

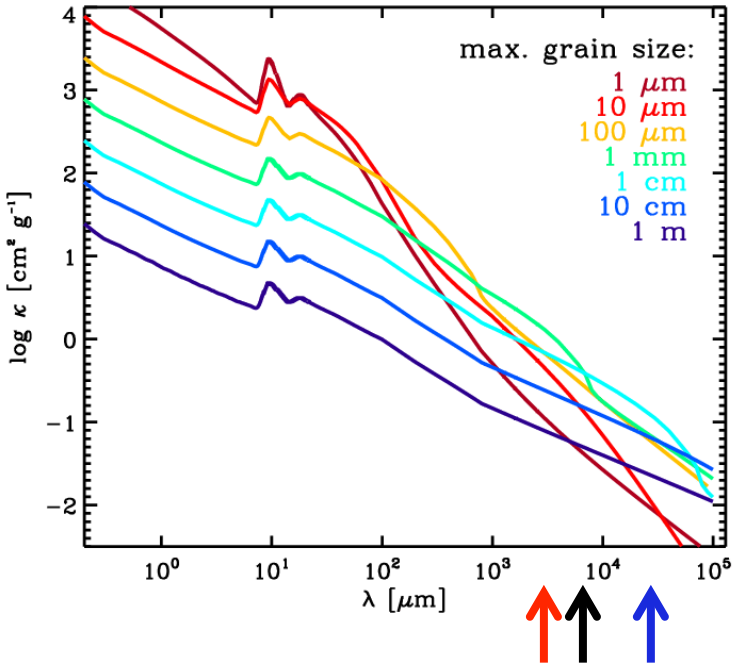
The Science

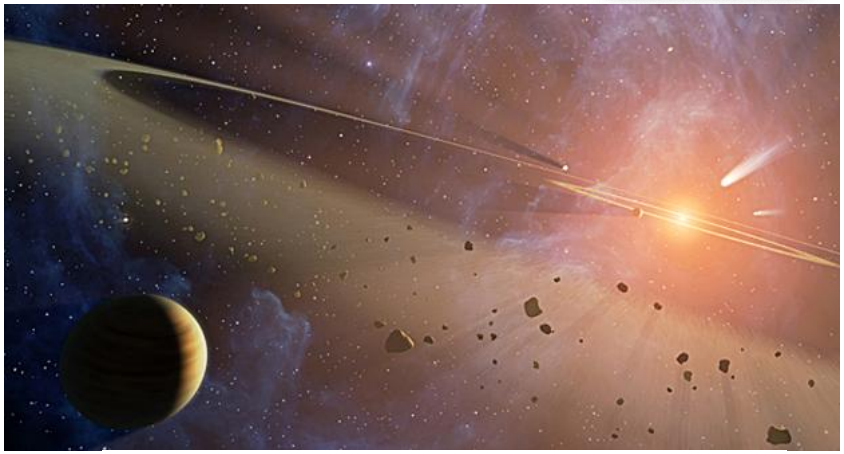
SKA Big Questions

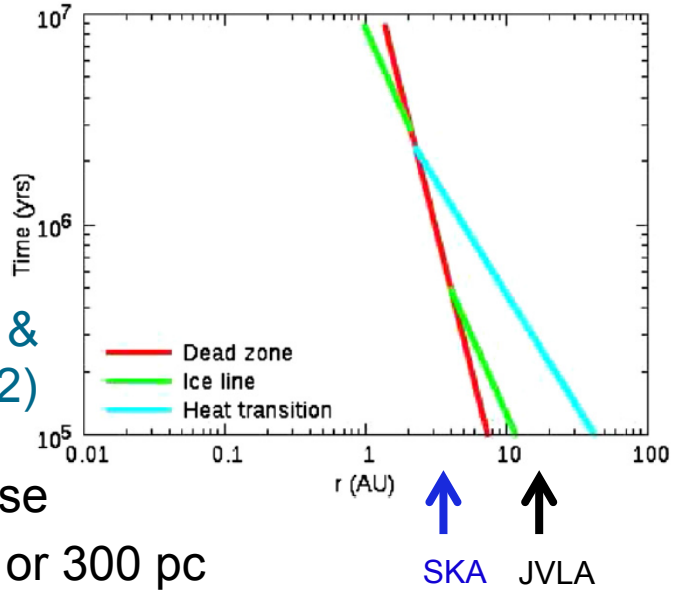
- **The Cradle of Life & Astrobiology**
  - *How do planets form? Are we alone?*
- **Strong-field Tests of Gravity with Pulsars and Black Holes**
  - *Was Einstein right with General Relativity?*
- **The Origin and Evolution of Cosmic Magnetism**
  - *What is the role of magnetism in galaxy evolution and the structure of the cosmic web?*
- **Galaxy Evolution probed by Neutral Hydrogen**
  - *How do normal galaxies form and grow?*
- **The Transient Radio Sky**
  - *What are Fast Radio Bursts? What haven't we discovered?*
- **Galaxy Evolution probed in the Radio Continuum**
  - *What is the star-formation history of normal galaxies?*
- **Cosmology & Dark Energy**
  - *What is dark matter? What is the large-scale structure of the Universe?*
- **Cosmic Dawn and the Epoch of Reionization**
  - *How and when did the first stars and galaxies form?*



The Cradle of Life: Understanding planet formation





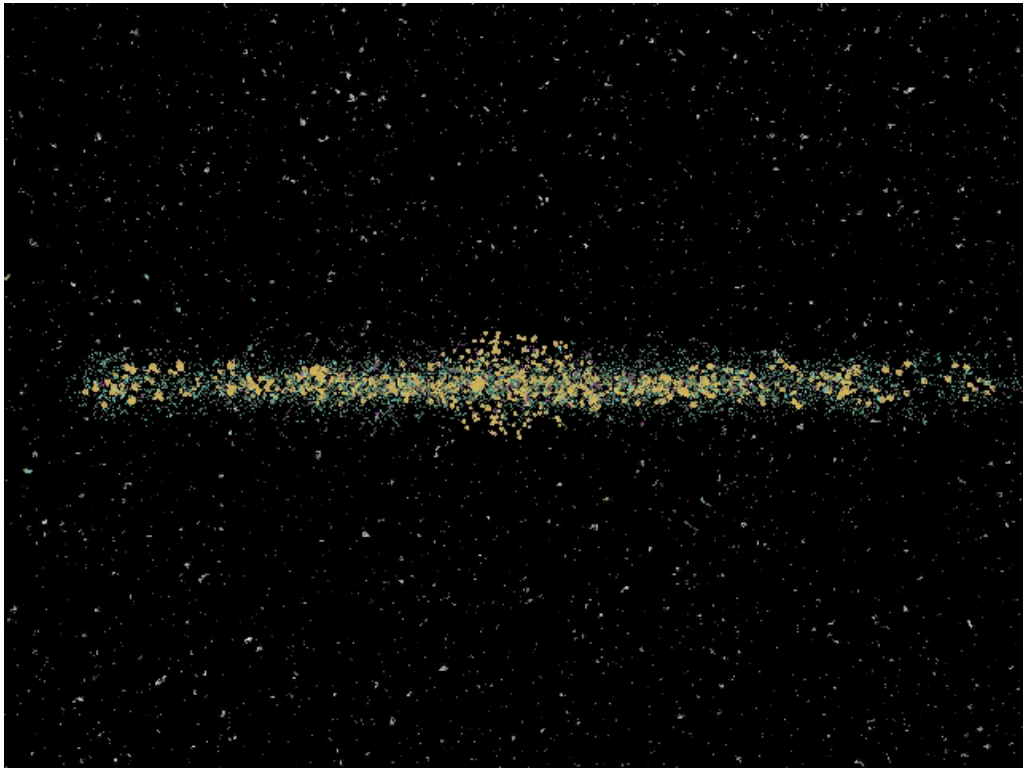


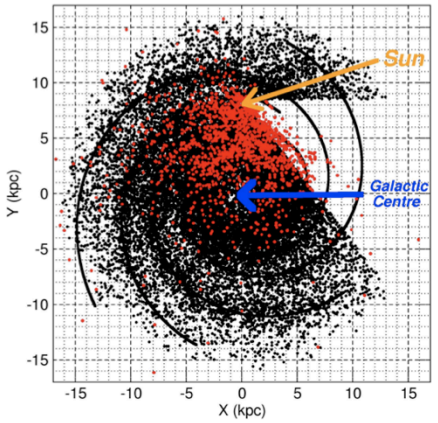
(Hasegawa & Pudritz 2012)

- Measuring grain growth through planetesimal phase
- Resolving proto-planetary disks at 100 pc (SKA1) or 300 pc (SKA2) inside the snow/ice line, sub-AU scales with SKA2

Finding all the pulsars in the Milky Way…

(Cordes et al. 2004, Kramer et al. 2004, Smits et al. 2008)

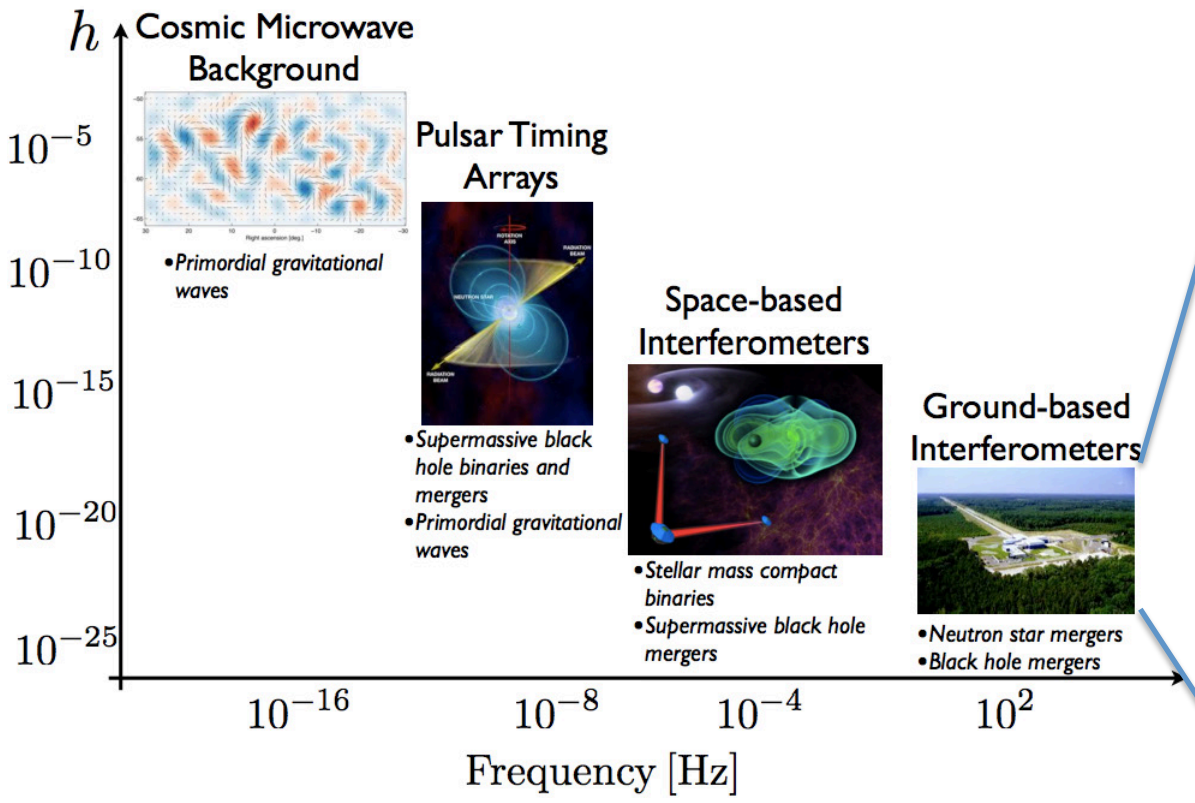


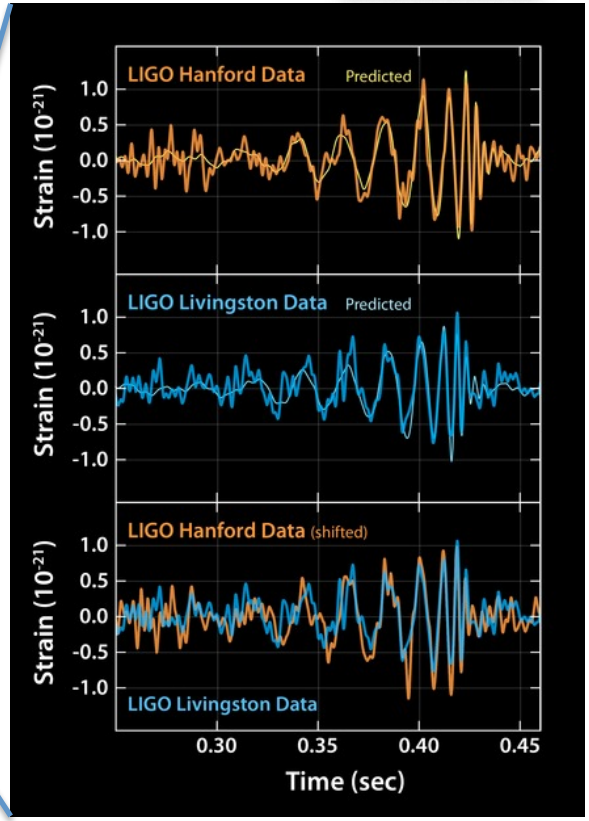


- ~40,000 normal pulsars
- ~2,000 millisecond psrs
- ~100 relativistic binaries
- first pulsars in Galactic Centre
- first extragalactic pulsars

- Timing precision is expected to increase by factor ~100: nHz Grav. Waves
- Rare and exotic pulsars and binary systems: including PSR-BH systems!
- Testing cosmic censorship and no-hair theorem
- **Current estimates are ~50% of population with SKA1, 100% with SKA2**

Finding all the pulsars in the Milky Way…





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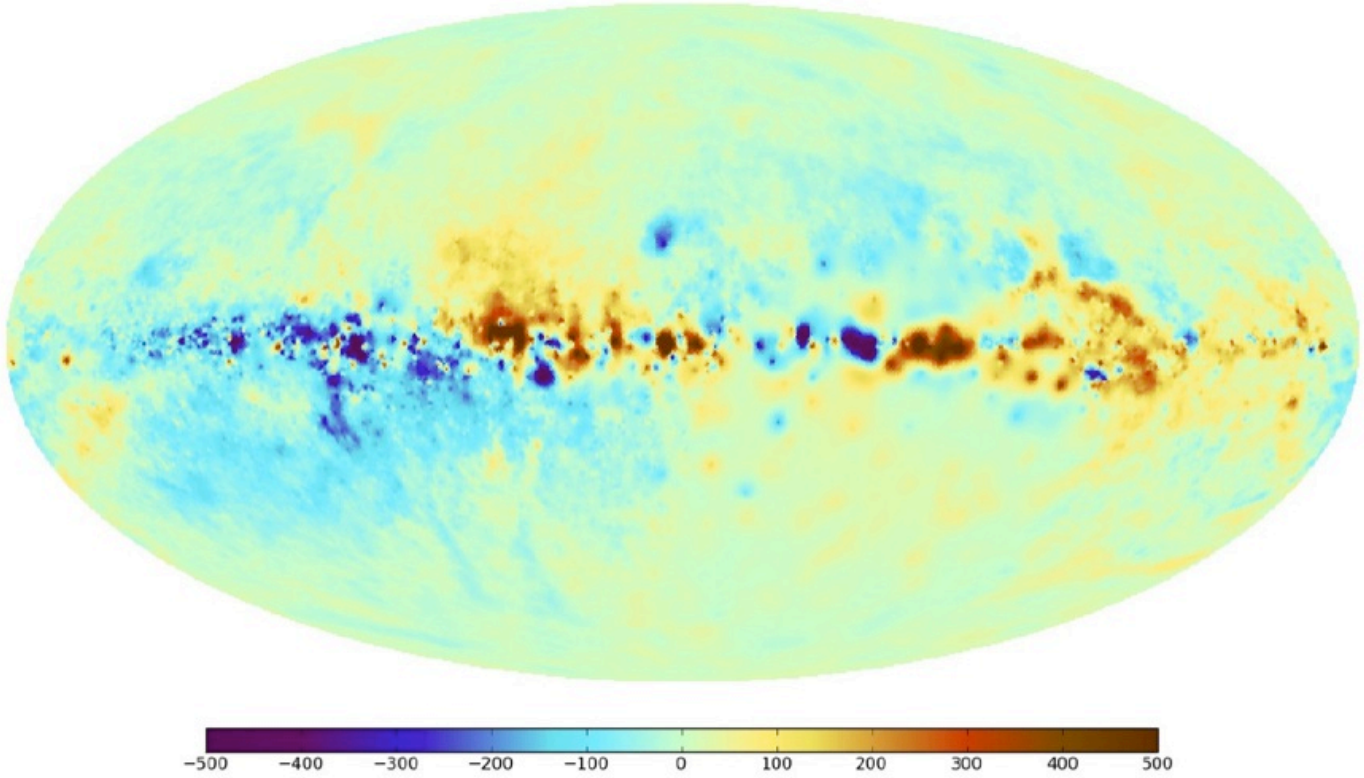
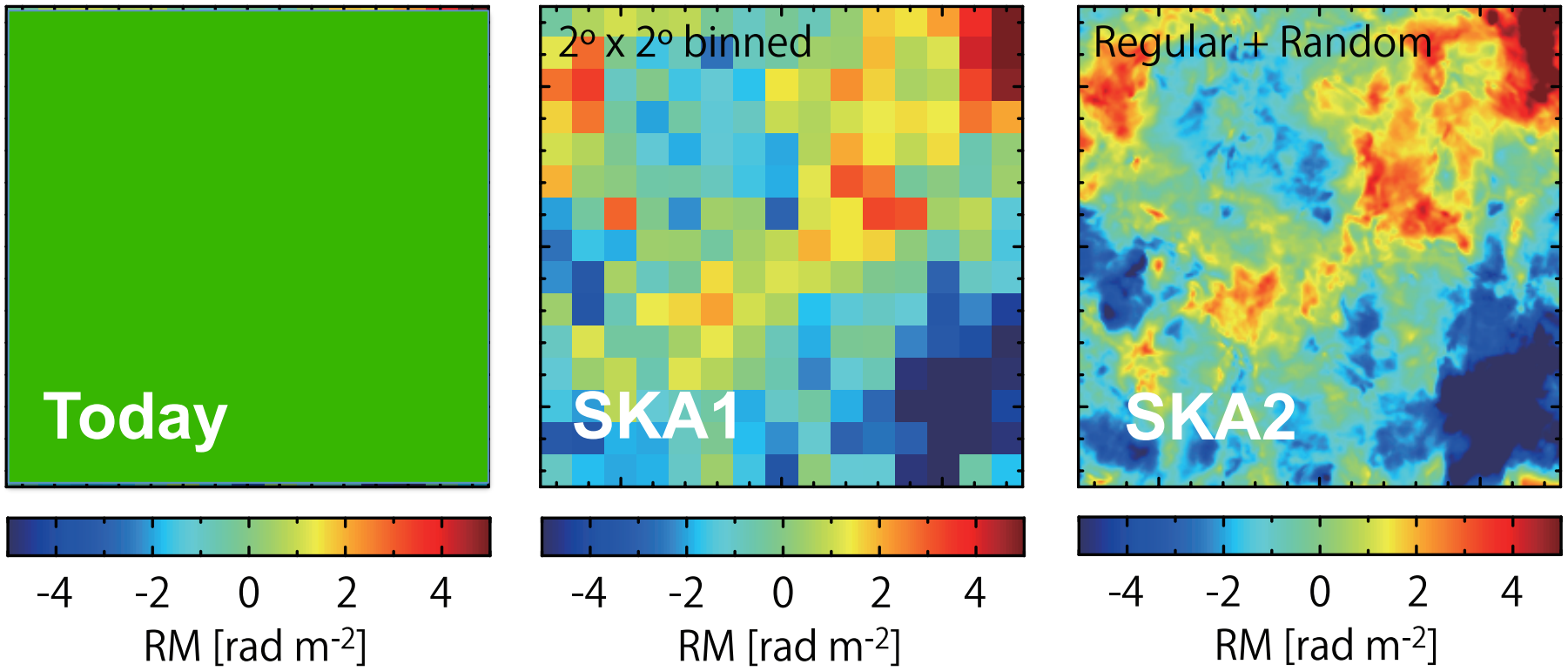
Headline Magnetism Science



Oppermann et al. (2012) ~40,000 extra-galactic RMs over 4π sr

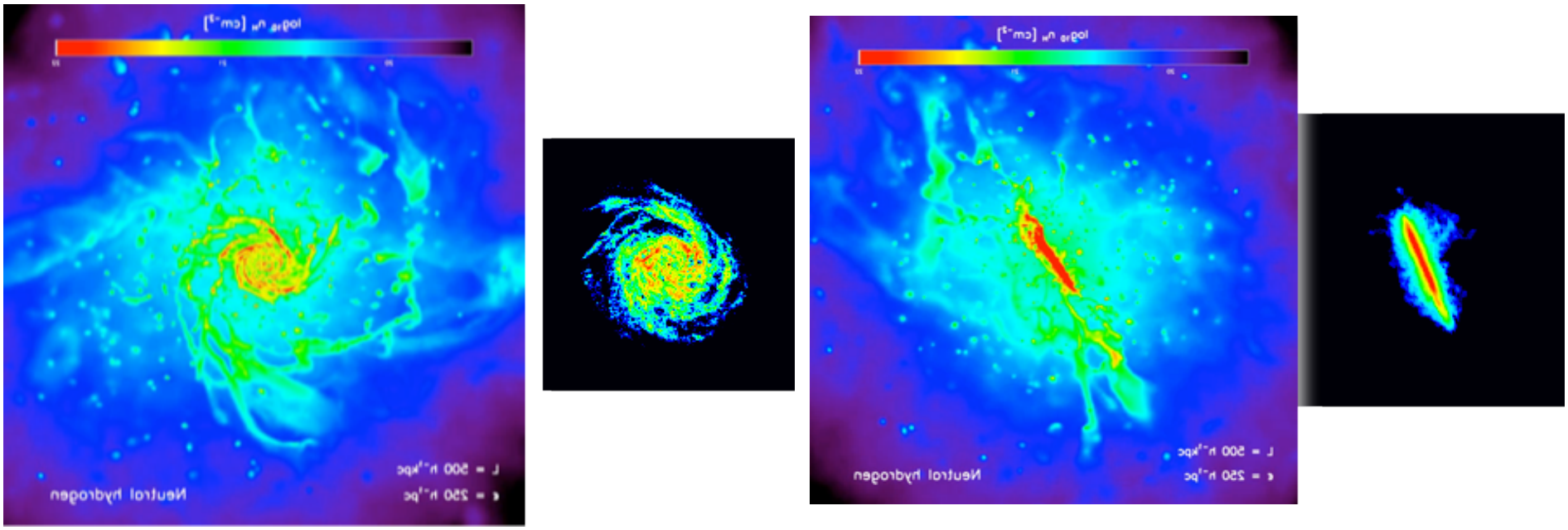
- 3D magnetic tomography of the Galaxy and distant universe; from current 1 RM deg^{-2}, SKA1: 300 deg^{-2} to SKA2: 5000 deg^{-2}

Headline Magnetism Science



- 3D magnetic tomography of the Galaxy and distant universe; from current 1 RM deg^{-2}, SKA1: 300 deg^{-2} to SKA2: 5000 deg^{-2}

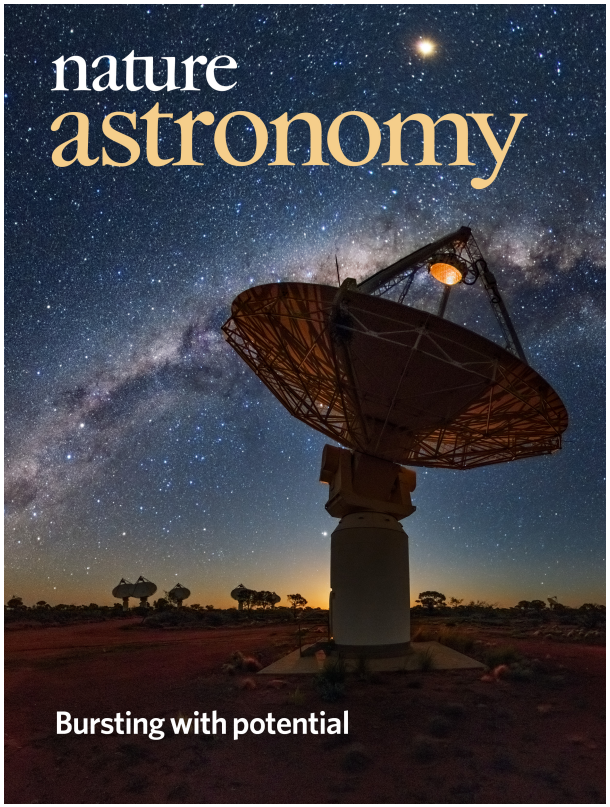
Galaxy HI Evolution:
out to z ~ 1 with SKA1 and z ~ 5 with SKA2

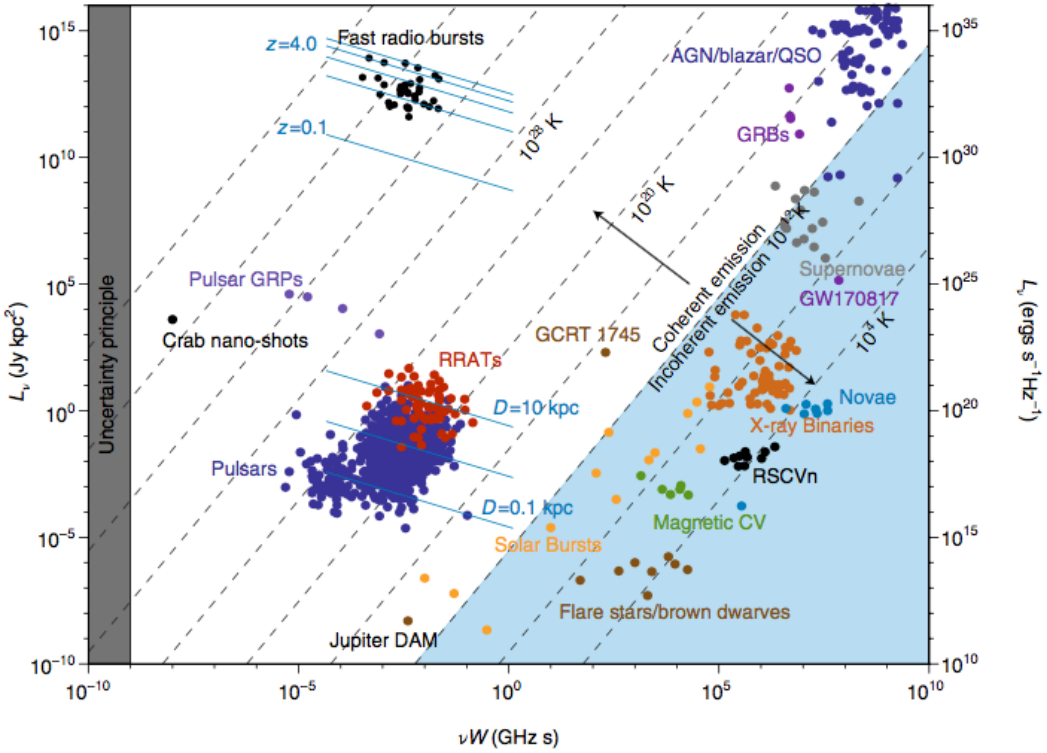


(Simulations: Schaye et al. 2010, Images: Oosterloo 2014)

- Understanding galaxy assembly and the baryon cycle
  - Determine the impact of galaxy environments
  - Probe gas inflow and removal, diffuse gas $N_{HI} < 10^{17}$ cm^{-2}
  - Measure angular momentum build-up

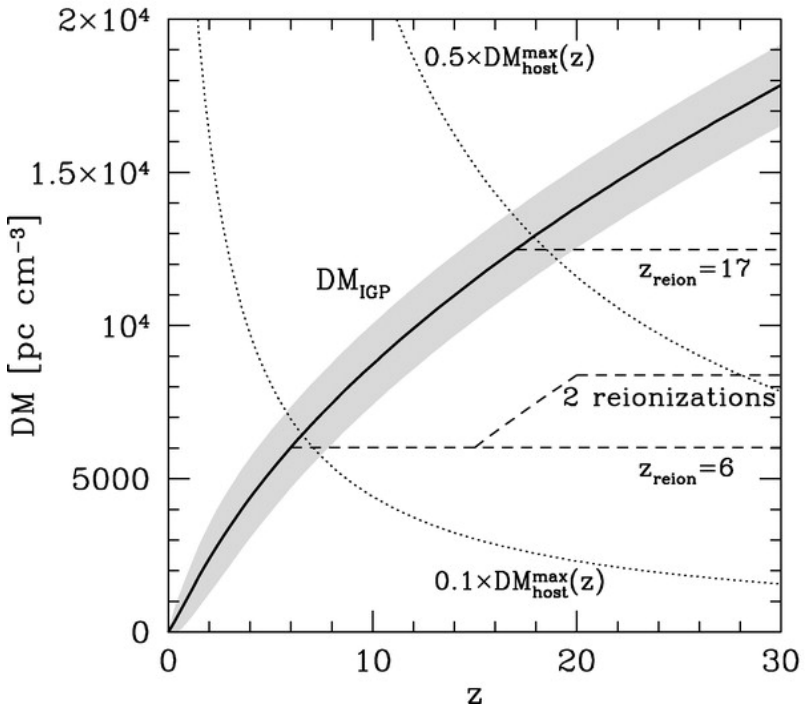
The Transient radio sky



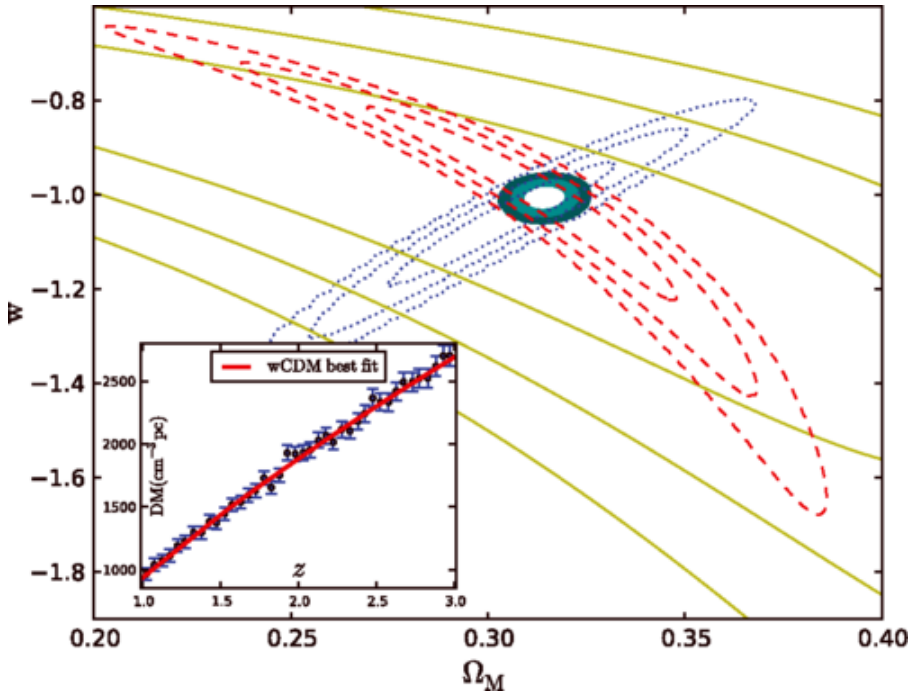


- More than 60 celestial “FRB” events now detected (after first “Lorimer” burst):
  S = 0.5 – 2 Jy, Δt = 1 – 6 msec, DM = 500 – 2000 cm^{-3} pc
- Estimated event rate: $3x10^3$ sky^{-1} day^{-1}
- Unknown origin – some, probably all at cosmological distances

Transients headline science: Fast Radio Bursts as a cosmological probe



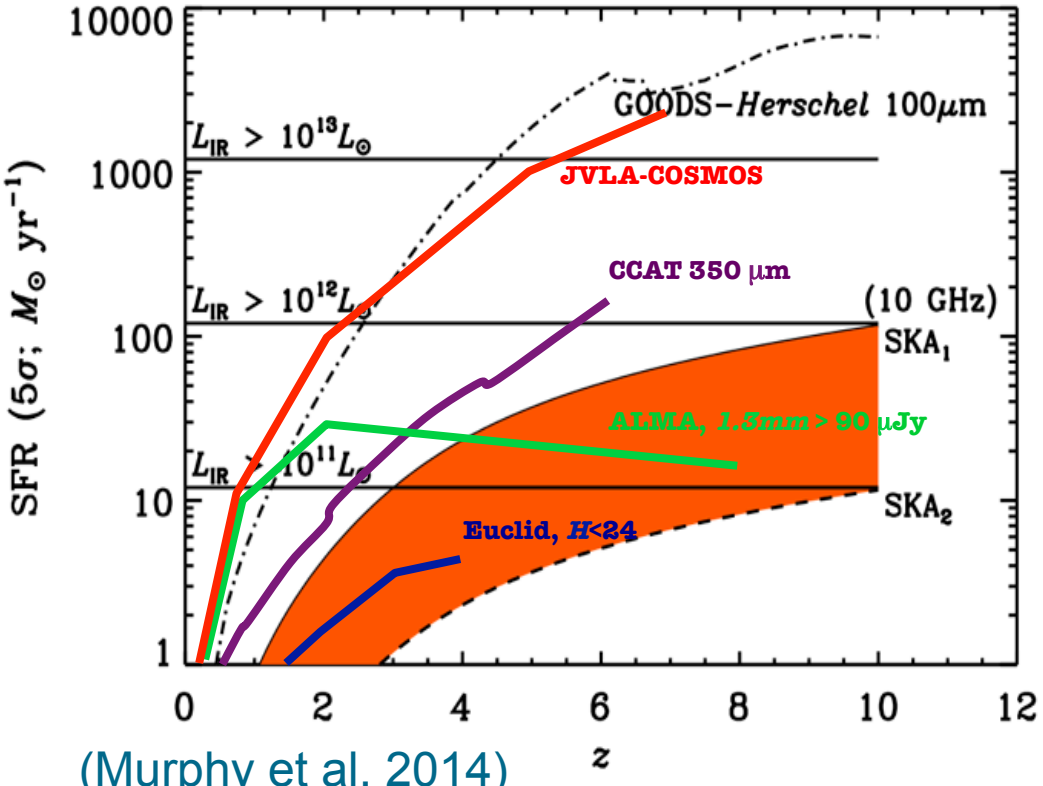
(Ioka 2003)



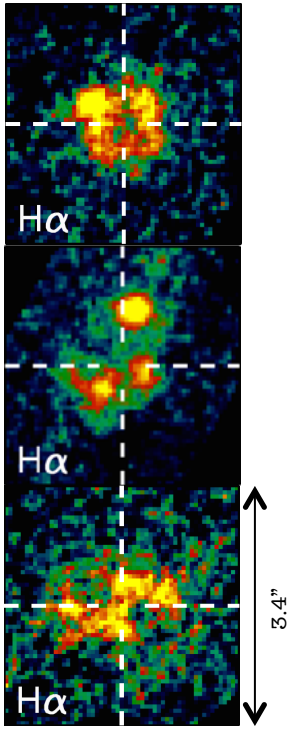
(Zhou et al. 2014)

- Prospects for fundamental contributions to cosmology with large samples (~1000) of spectroscopically identified FRBs out to z ~ 2 with SKA1 and z ~ 5 with SKA2

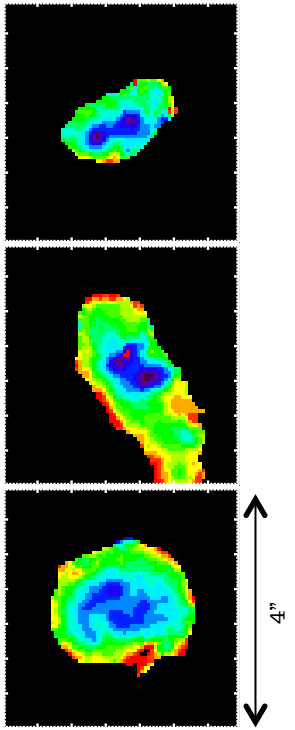
Galaxy Evolution Studies in the Radio Continuum: Understanding the Star Formation History of the Universe



(Murphy et al. 2014)



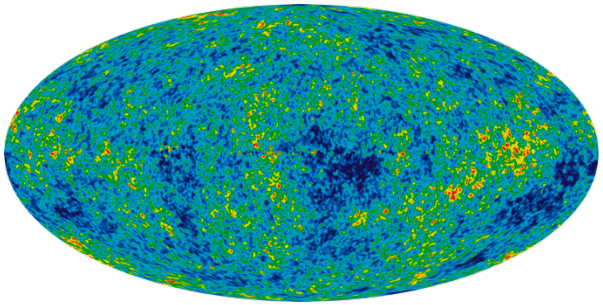
Wuyts et al 2013, **z~1**
Hα–based SFR-maps

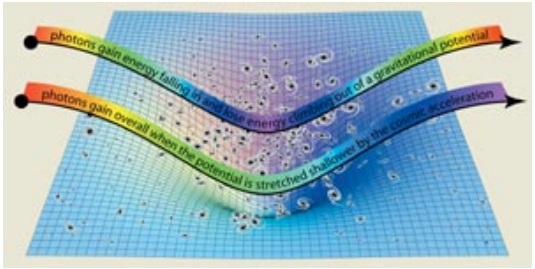


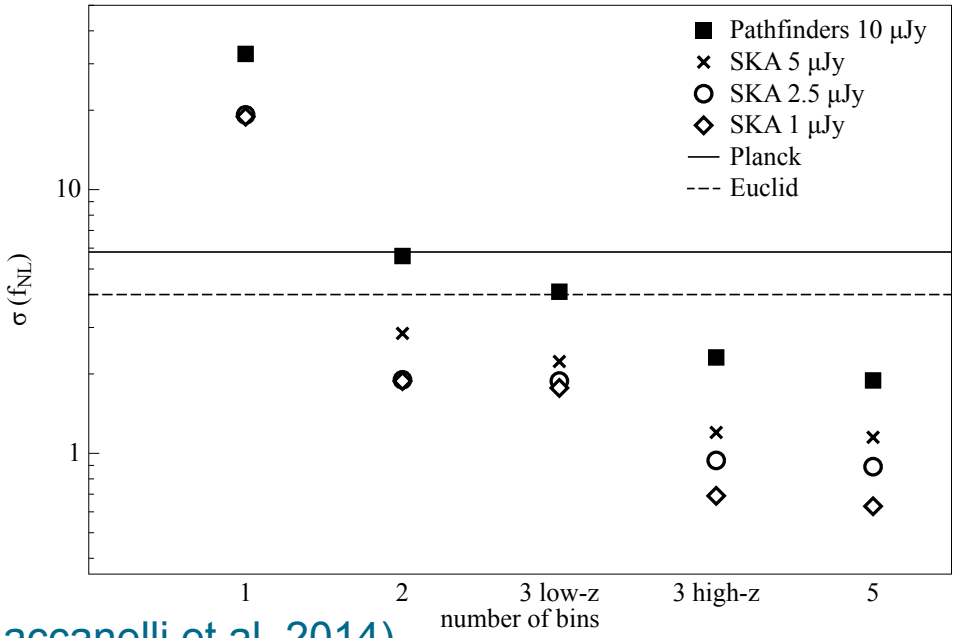
Cibinel et al 2014, **z~2**
UV-based SFR-maps

- Unmatched sensitivity to star formation rates (10 $M_\odot$/yr) out to z ~ 4 with SKA1 and z ~ 10 with SKA2
- Resolved (sub-kpc) imaging of star forming disks out to z ~ 1 with SKA1 and z ~ 6 with SKA2

Cosmology with SKA: Integrated Sachs-Wolfe effect



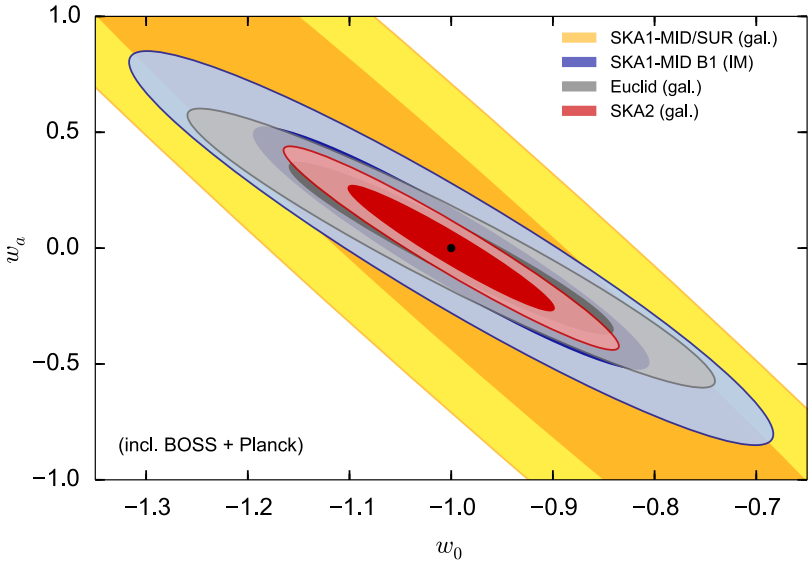




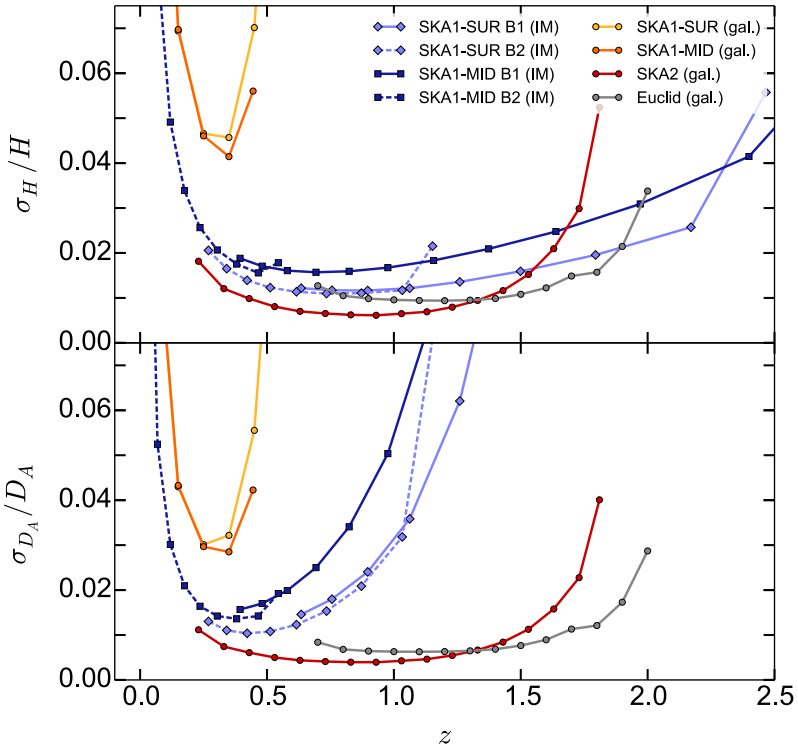
(Raccanelli et al. 2014)

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

Cosmology with SKA: Baryon Acoustic Oscillations

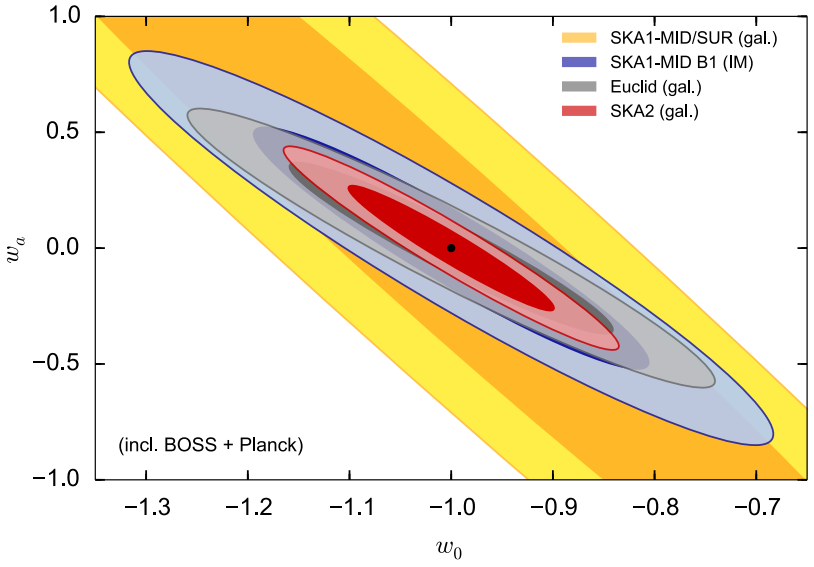


(Bull et al 2014)

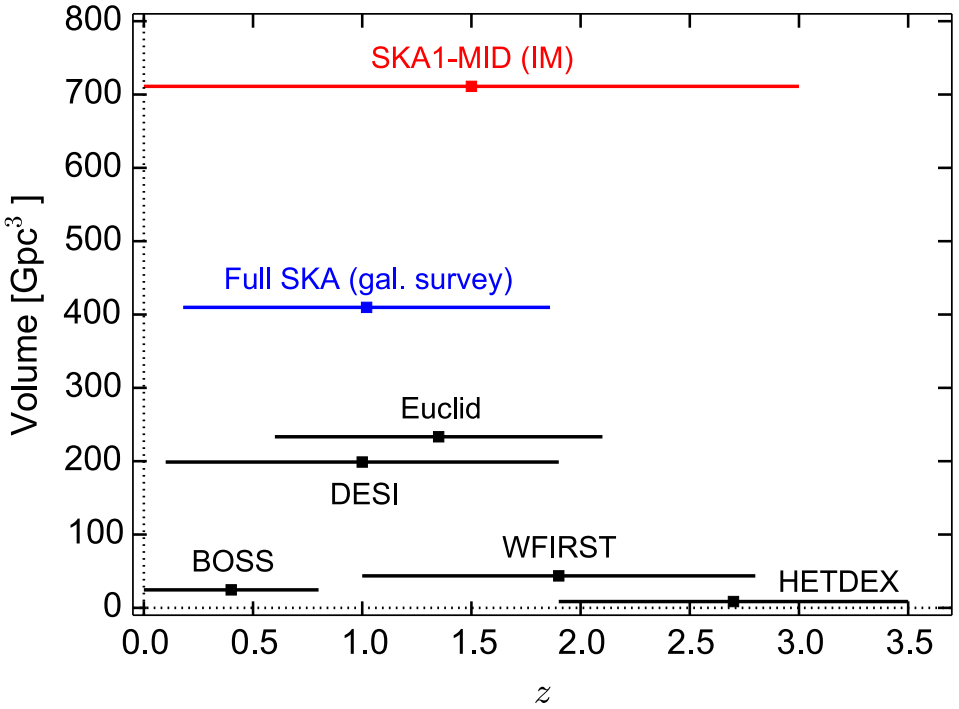


- Constraining Dark Energy models with redshift-resolved BAO measurements
  - Discrete detection is complementary with SKA1, cutting edge with SKA2
  - Intensity mapping is higher risk but world-class, even with SKA1

Cosmology with SKA: Baryon Acoustic Oscillations



(Bull et al 2014)

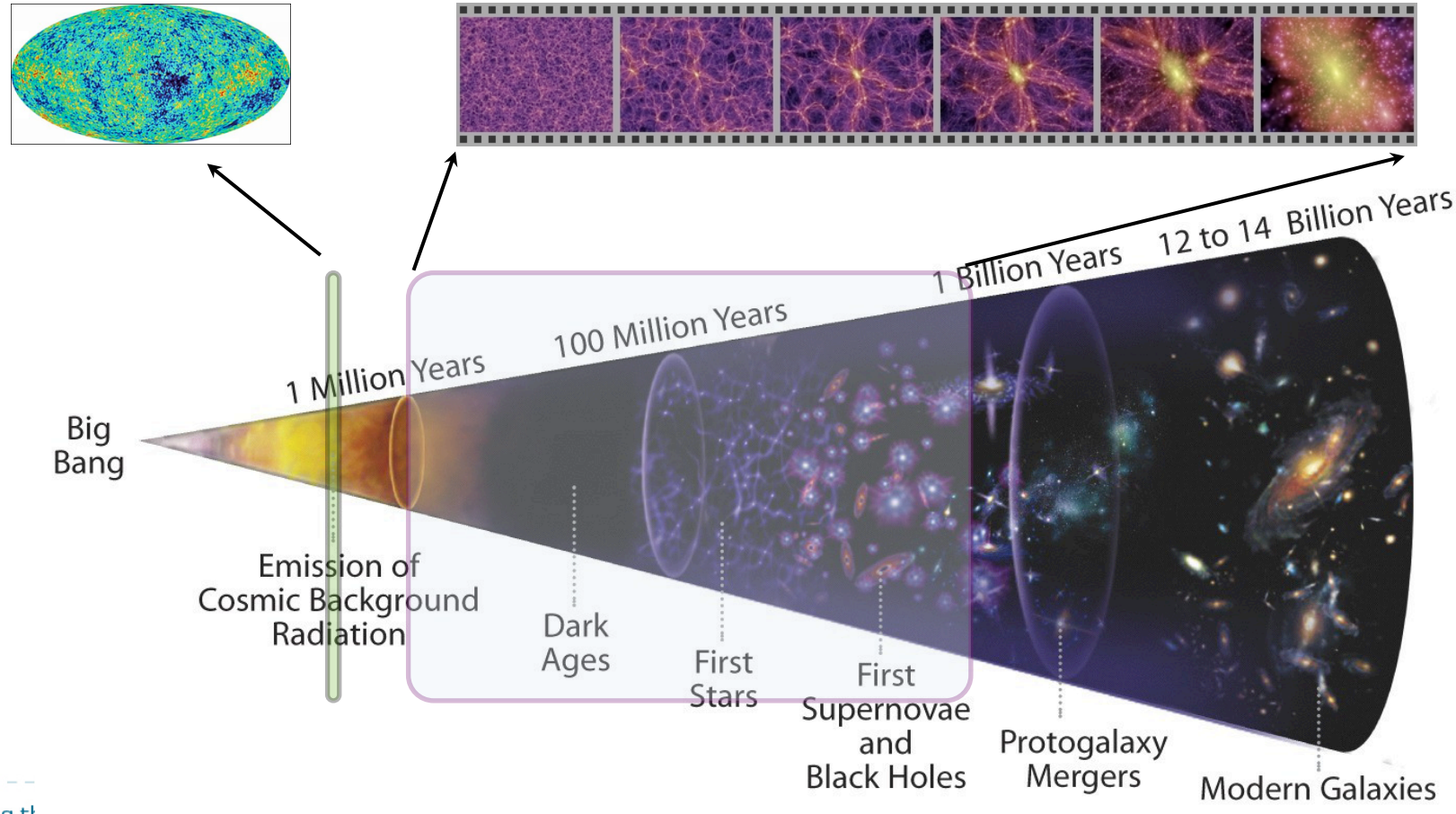


- Constraining Dark Energy models with redshift-resolved BAO measurements
  - Discrete detection is complementary with SKA1, cutting edge in SKA2
  - Intensity mapping is higher risk but world-class, even with SKA1

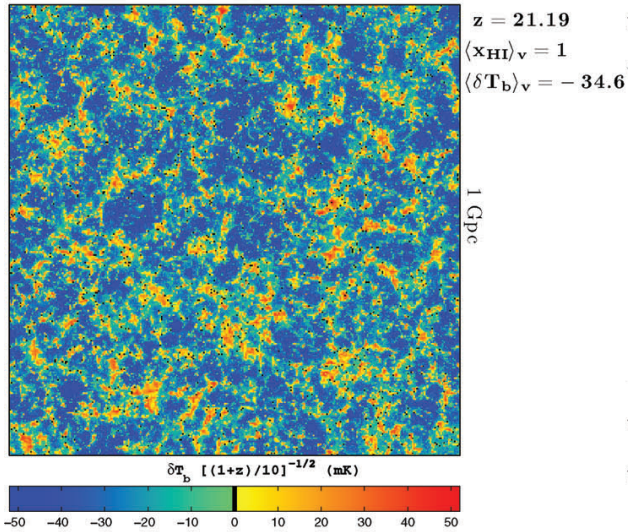
HI surveys of the Dark Ages, Cosmic-Dawn & EoR

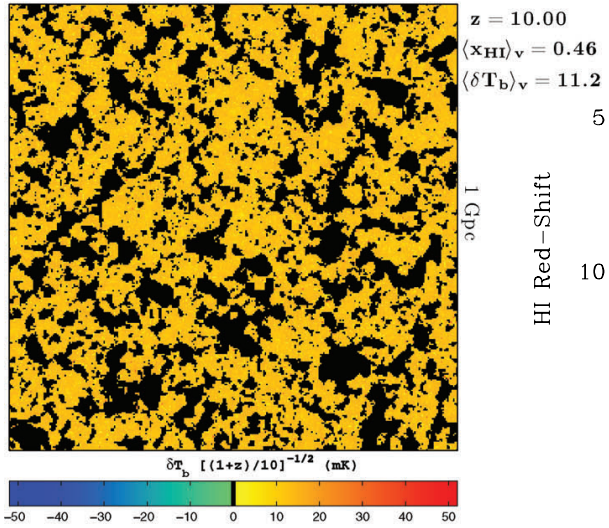
CMB displays a single moment of the Universe. Its initial conditions at ~400,000 yrs

HI emission from the Dark Ages, Cosmic Dawn & EoR traces an evolving “movie” of baryonic and DM structure formation at $t_{univ}<10^9$ years.

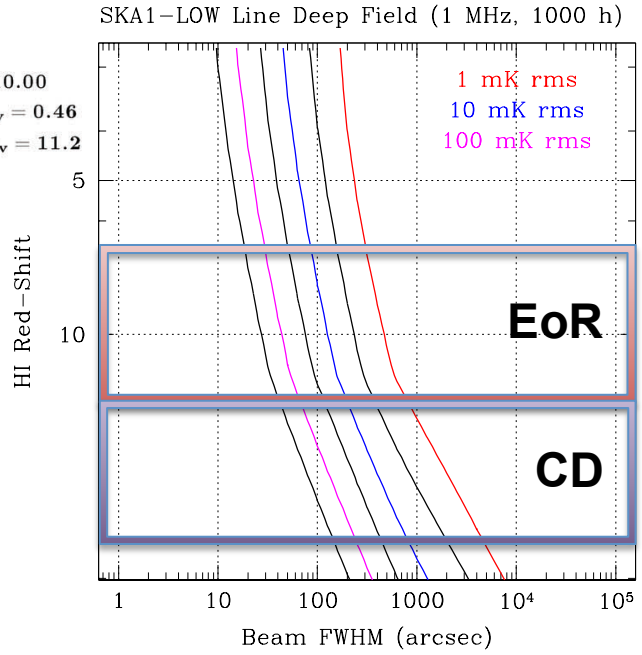


SKA1 surveys of the EoR & Cosmic-Dawn



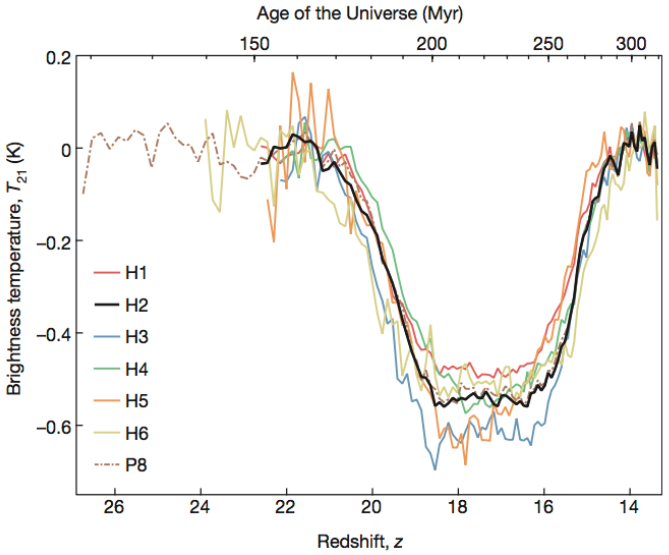


(Mesinger et al 2011)

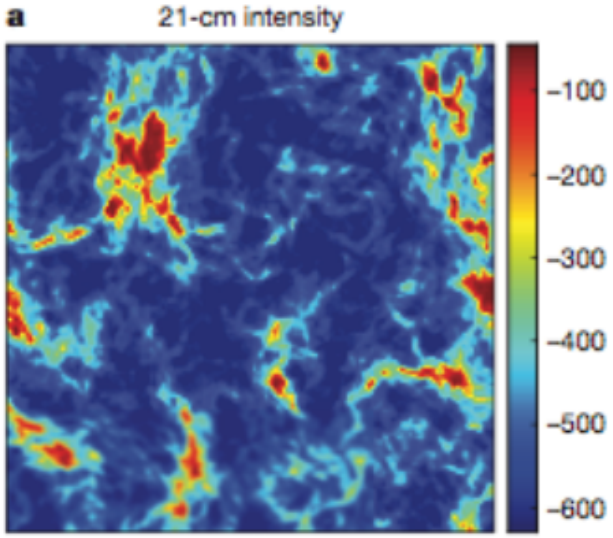


- Detecting EoR structures in imaging mode (as distinct from statistically) on 5 arcmin scales with 1 mK RMS
- Probing the Cosmic Dawn statistically (with pre-2018 predictions)

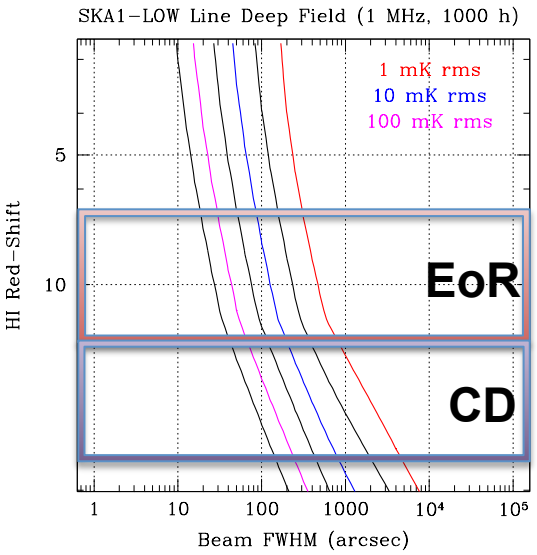
SKA1 surveys of the EoR & Cosmic-Dawn



(Bowman et al 2018)



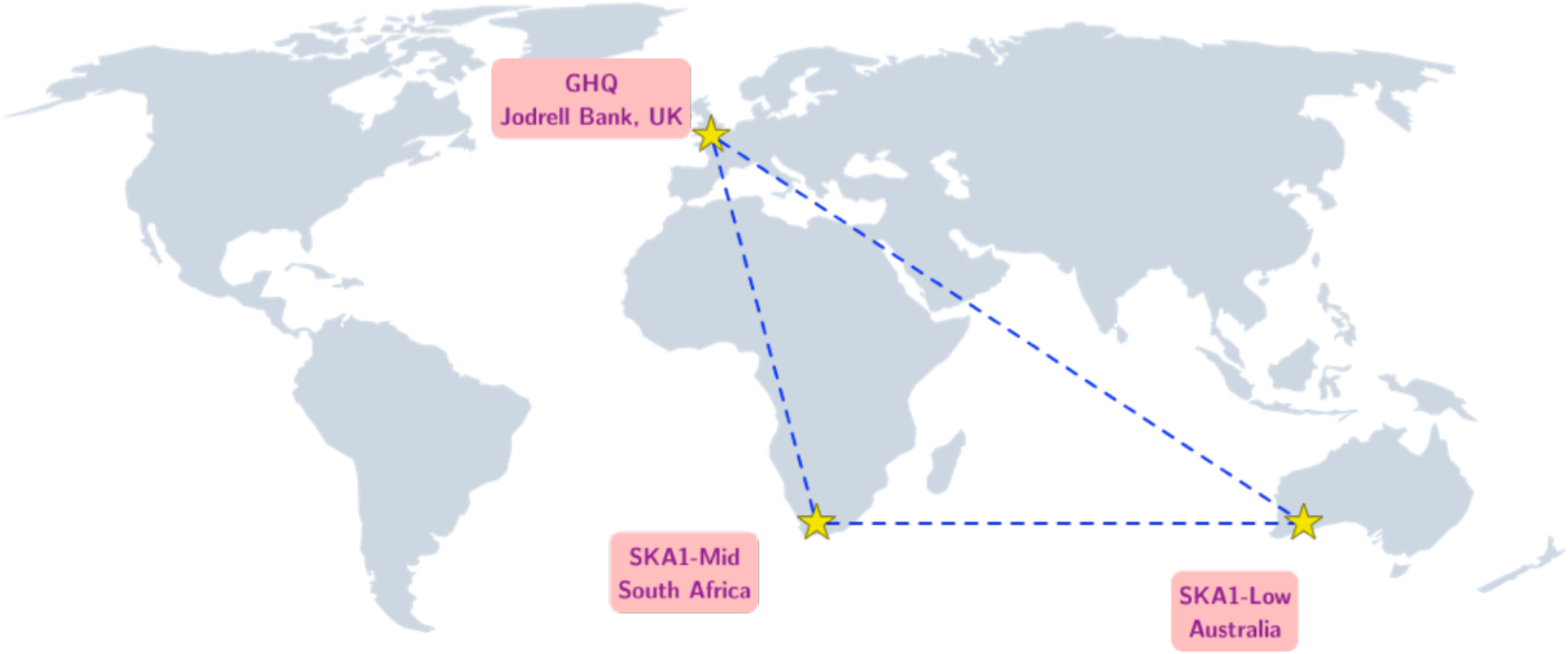
(Barkana 2018)



- Possible detection by Bowman et al (2018) of global Cosmic Dawn signature centred at 78 MHz
- If surprising depth is confirmed, then fluctuations also large:
  140 mK RMS @ 10s of arcmin predicted by Barkana (2018)
- Deep SKA integrations (3 mK RMS @ 10s of arcmin) may permit direct CD imaging: localisation in 3D of first post-big-bang heat sources

SKA and Big Data

The SKA Operational Model



1 Observatory

The SKA

2 Telescopes

SKA1-LOW
SKA1-MID

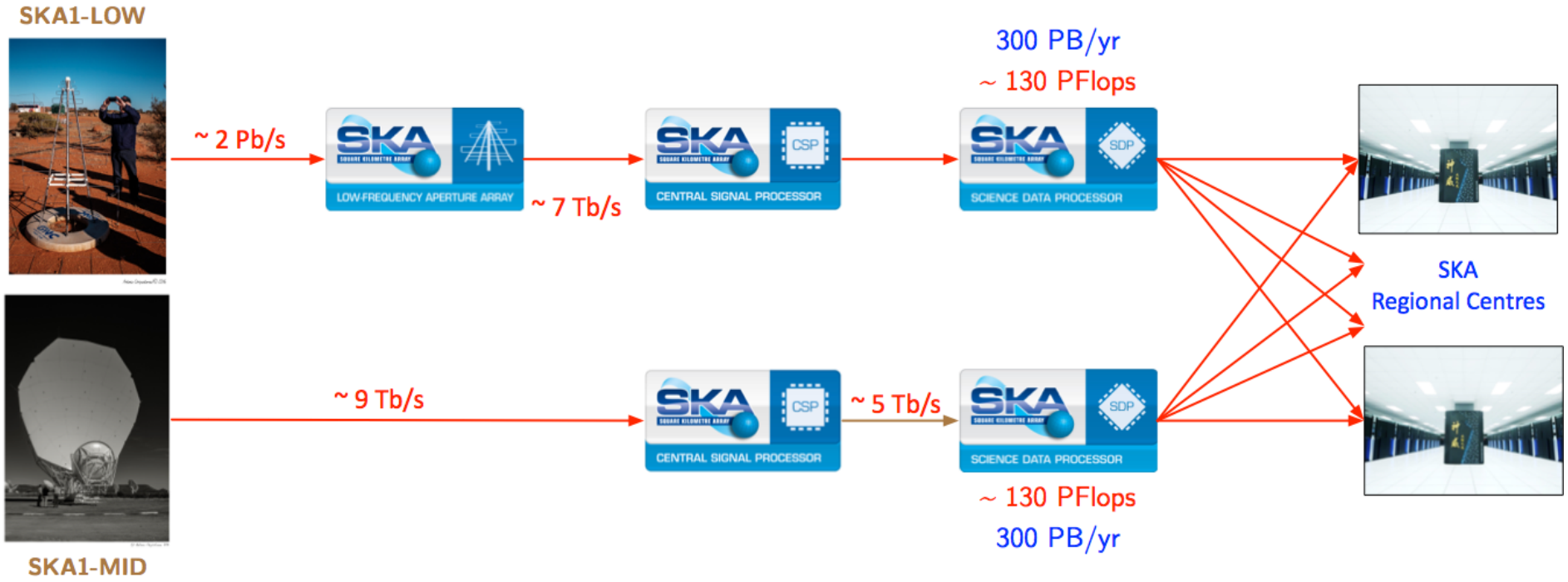
3 Sites

Australia (LOW)
South Africa (MID)
United Kingdom (GHQ)

Principles

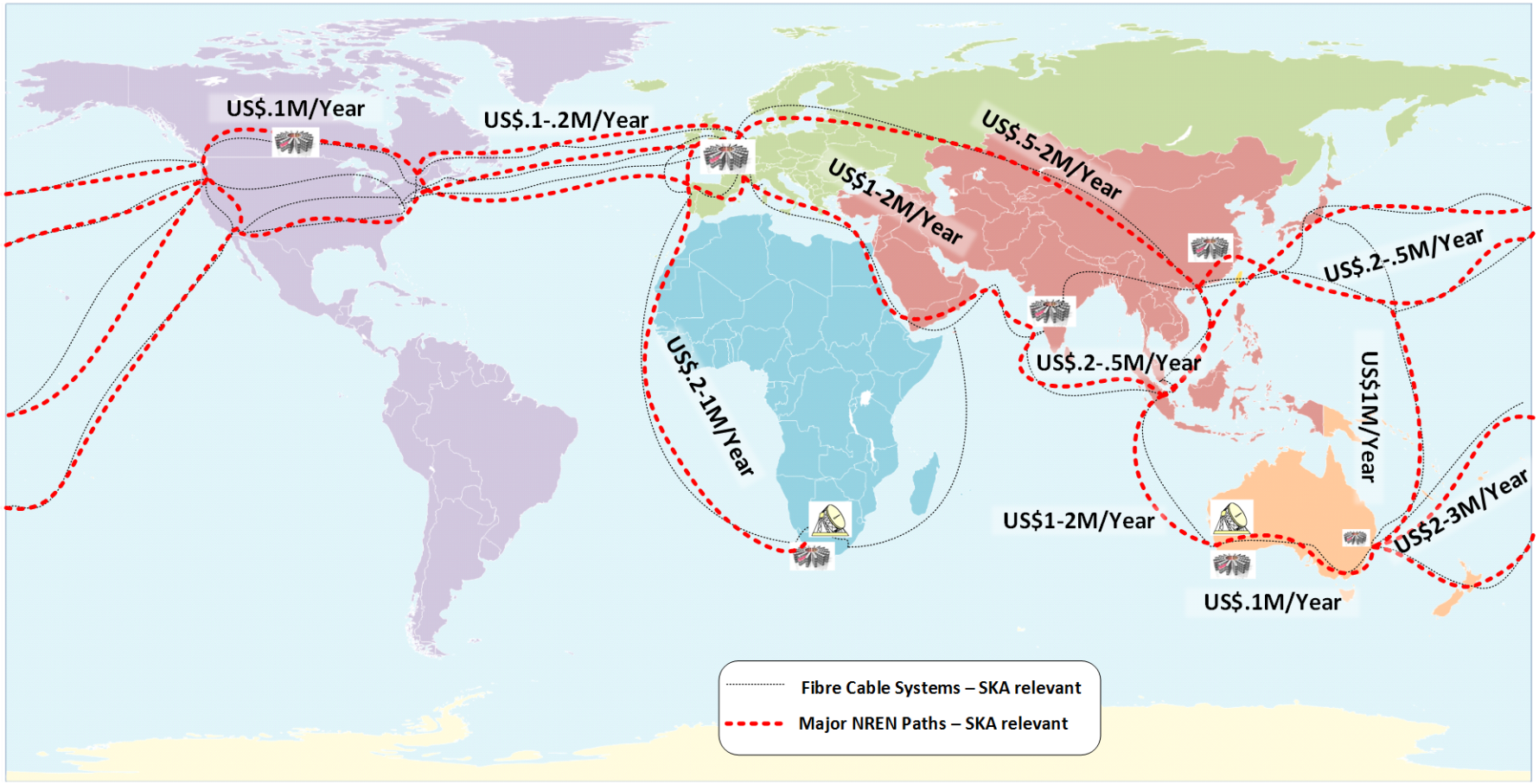
One observatory
Optimal operation
Minimise duplication
Autonomy & authority

The SKA Data Flow Challenge



- Digital data rates are reduced by factor ~100 within SDP via calibration and data product generation
- SDP output rate compatible with 100 Gb/s per site

The SKA Data Flow Challenge

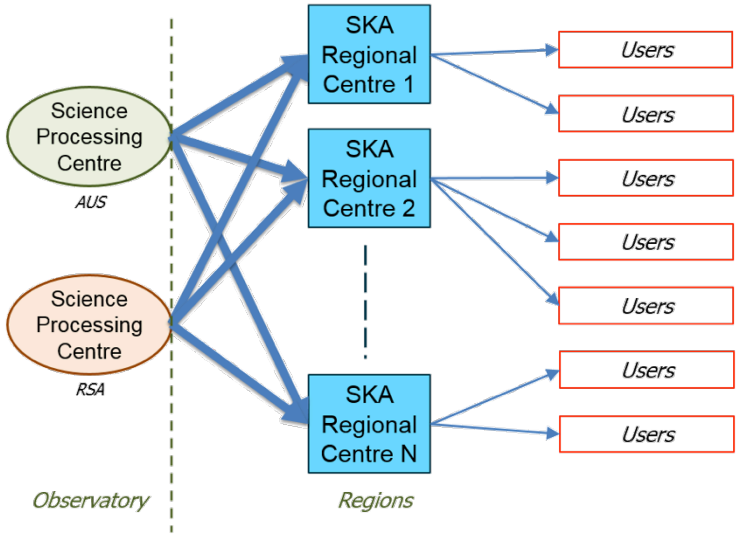


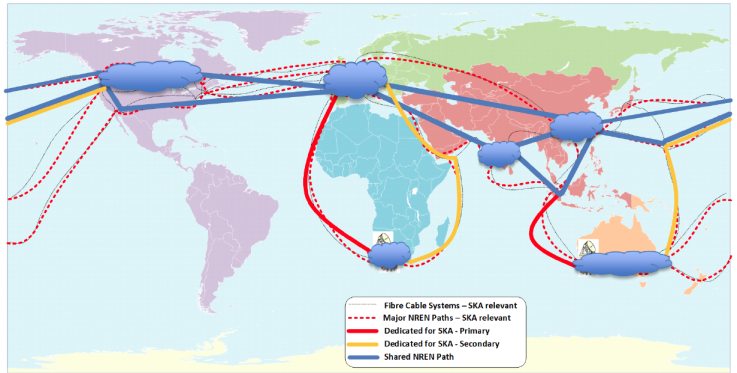
- Observatory Data Products flow from the Science Data Processors in Perth and Cape Town to SRCs around the globe

The SKA Data Flow Challenge

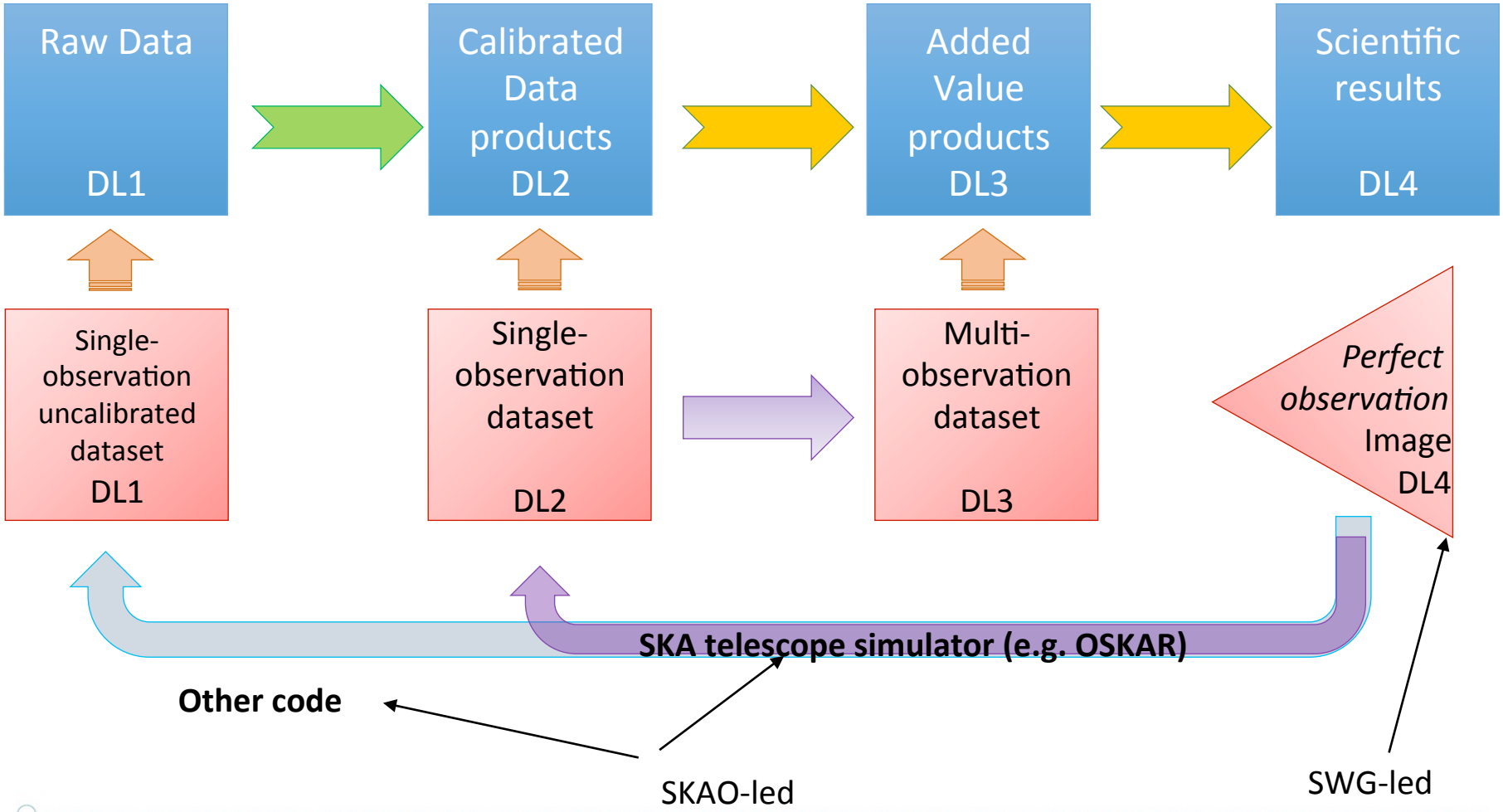
SKA Data Challenge "Flavours"

- SDP Challenges
  - Computation at scale
  - Pipeline framework
  - Network/data transport
- SRC Challenges
  - Pipeline optimisation
  - Added value data products
  - User interaction
- Science Challenges
  - Algorithms, analysis, visualisation
- Early Data Challenges by "flavour", ultimately end-to-end





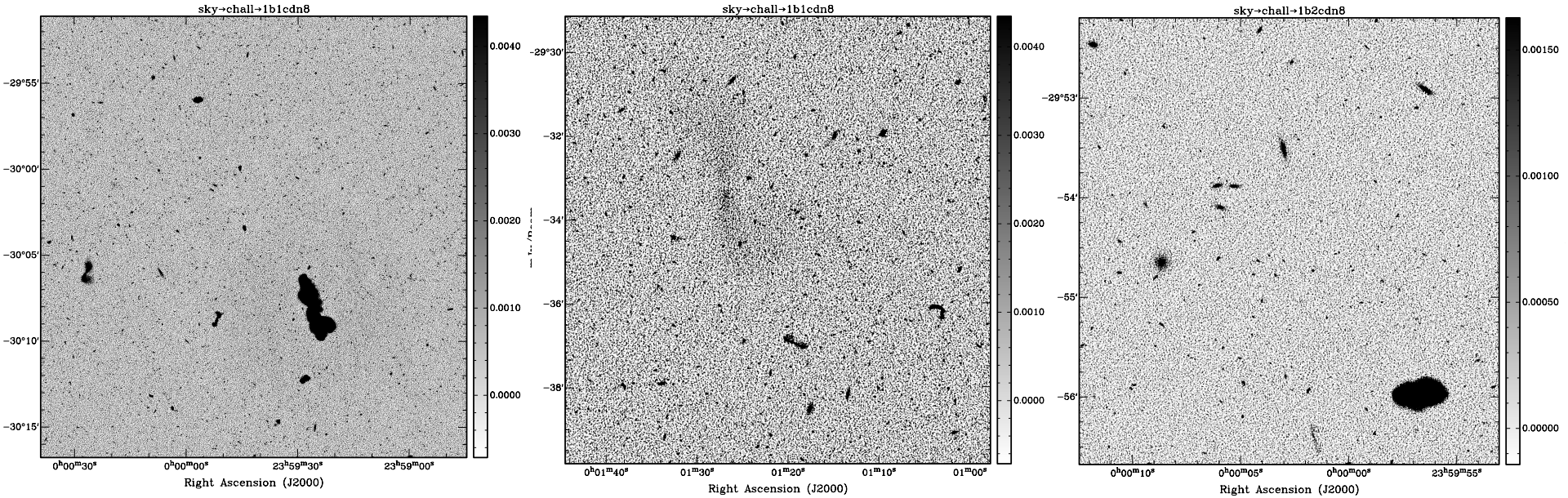
SKA Science Data Challenges: Simulations



Science Data Challenge #1

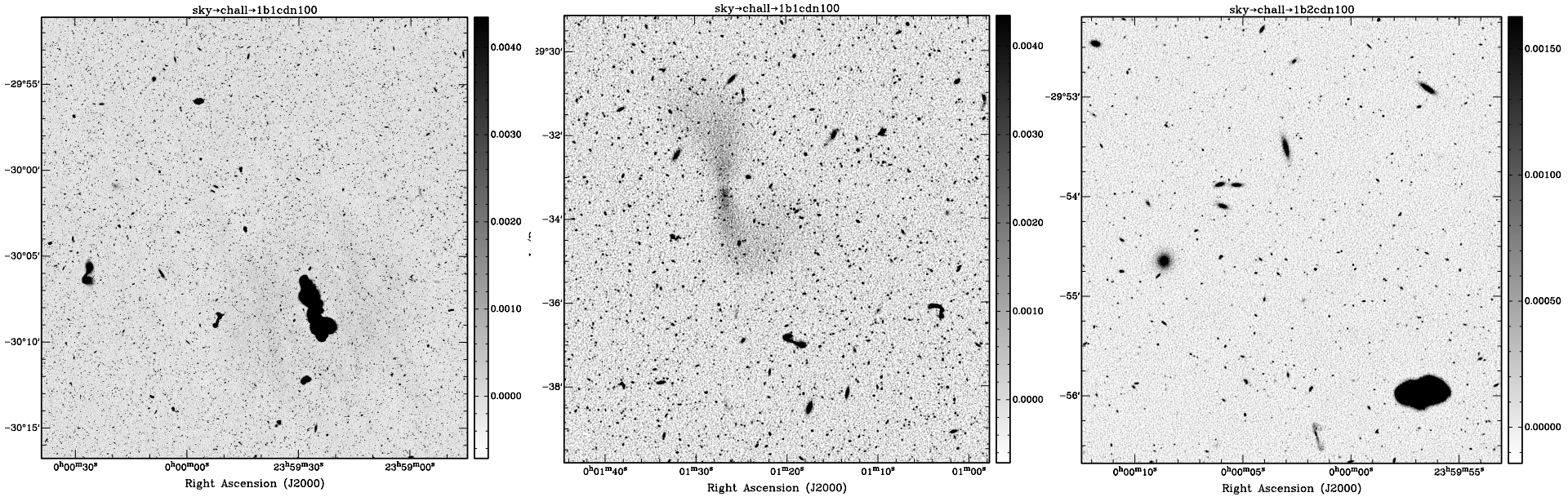
- November 26 release, March 15 deadline
- Continuum sub-band images ($\Delta\nu/\nu_c$ = 30%)
- SKA1-Mid, three frequencies: ν_c = 0.56, 1.4 and 9.2 GHz
- One pointing: 8^h, 100^h and 1000^h observations
- Data info:
  - Images of 32k pixels per side for the full FoV
  - 1.50, 0.60 and 0.091" FWHM resolution at 0.56, 1.4 and 9.2 GHz
  - Size of a single frequency slice: 4GB (x9 = 36GB total)

Science Data Challenge #1



- Sample zoom-ins
- One pointing: **8h**, 100^h and 1000^h observations
- Some 10^7 embedded sources based on state-of-the-art T-RECS sky model (Bonaldi et al. 2018)
  - Star-forming galaxies represented as projected exponential disk
  - Active galactic nuclei source morphologies drawn from DRAGNs atlas (Leahy et al.) of high resolution images

Science Data Challenge #1



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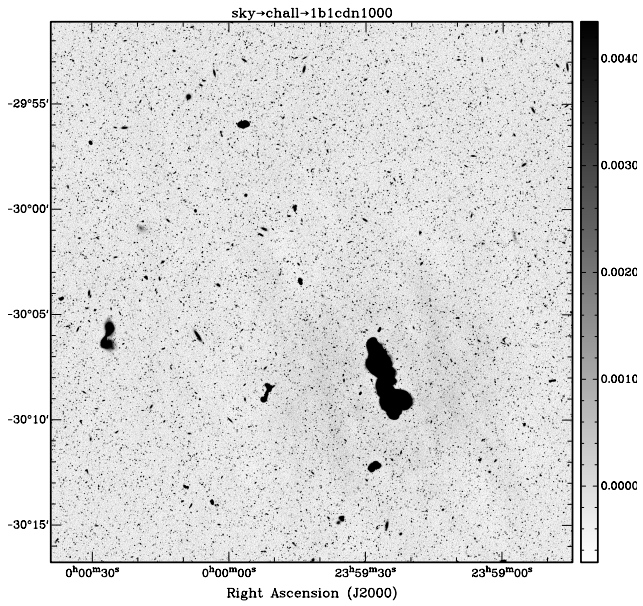

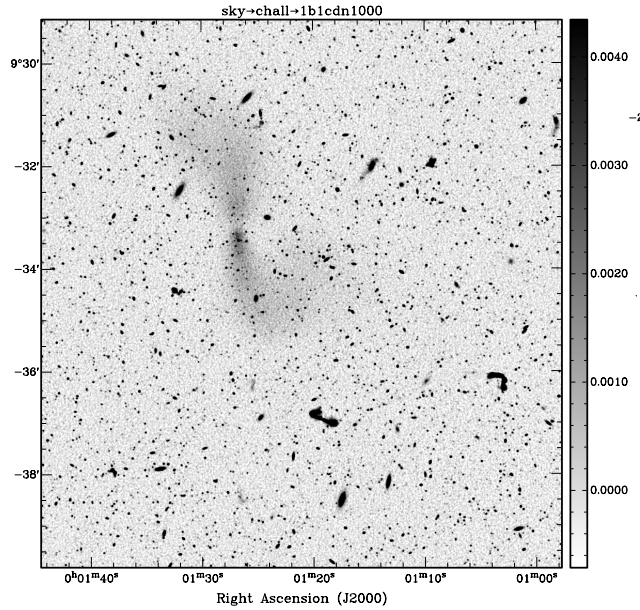

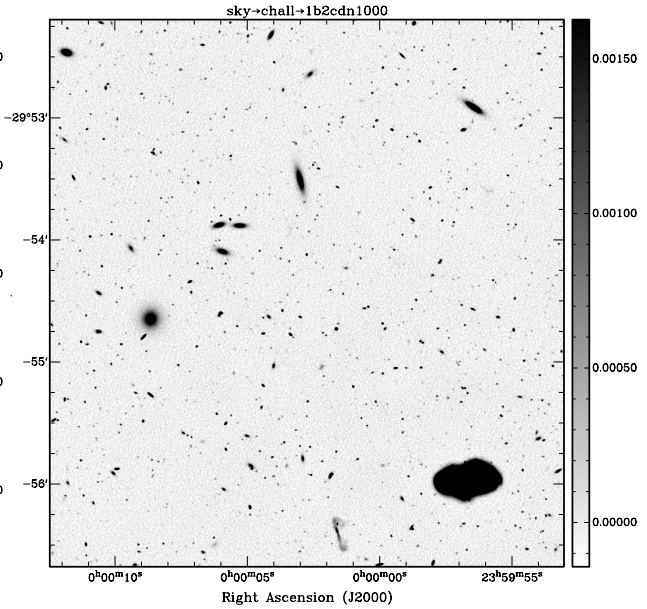

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First Science Data Challenge

- Source finding, identification, characterization etc. https://astronomers.skatelescope.org/ska-science-data-challenge-1/
- Results to be compared with simulation input catalog
- WG-specific analyses optionally done on the identified sources
- Advertising for SKAO Post-doc position for radio astronomy simulations: https://recruitment.skatelescope.org/category/ska-jobs/

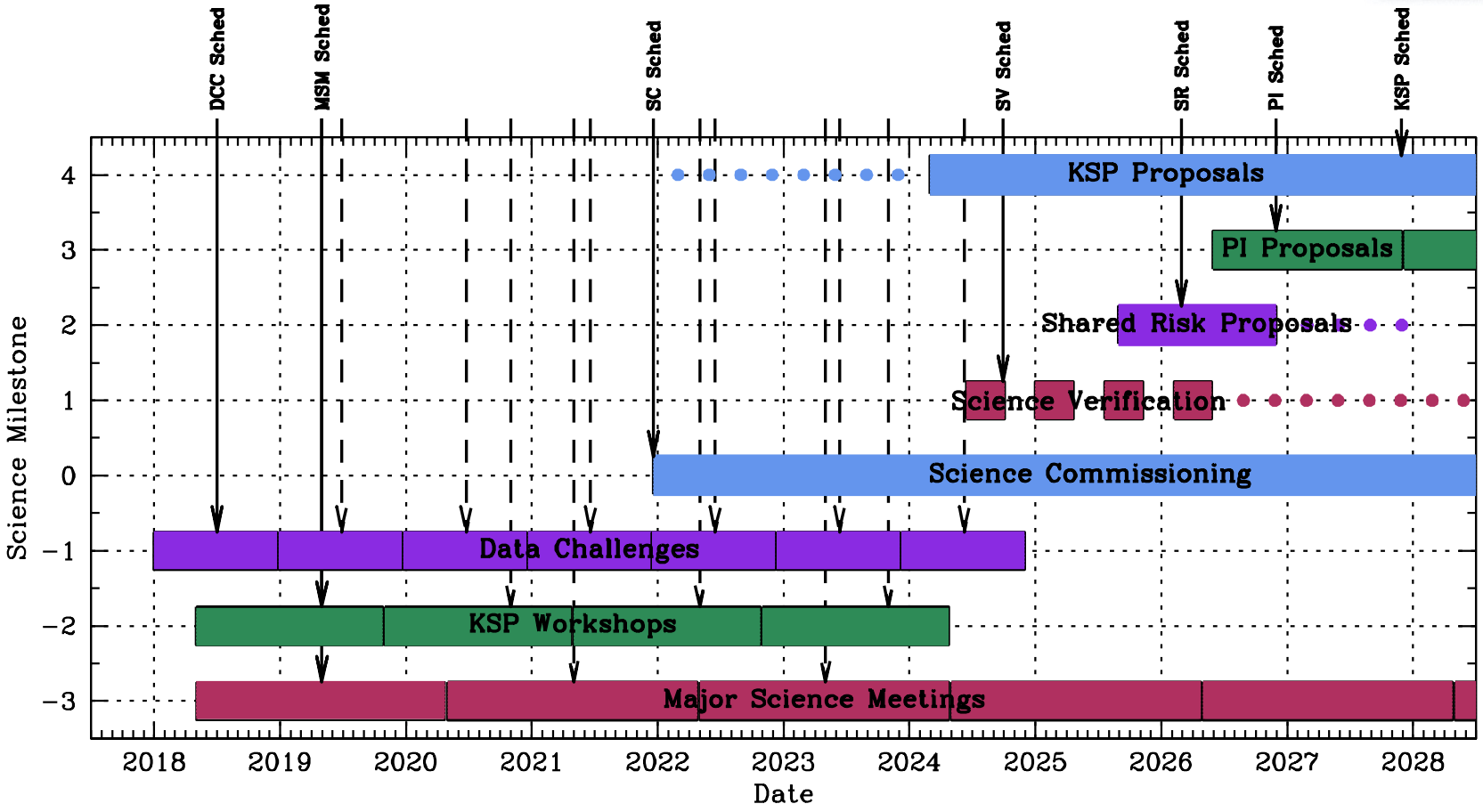
Challenge Definition

1. Source finding (RA, Dec): locate centroids and/or core positions
2. Source characterisation (integrated flux density, possible core fraction, major and minor axis size, major axis position angle) where size is one of (largest angular size, Gaussian FWHM, or exponential scale length)
3. Source identification (one of SFG, AGN-steep, AGN-flat)

Challenge Scoring

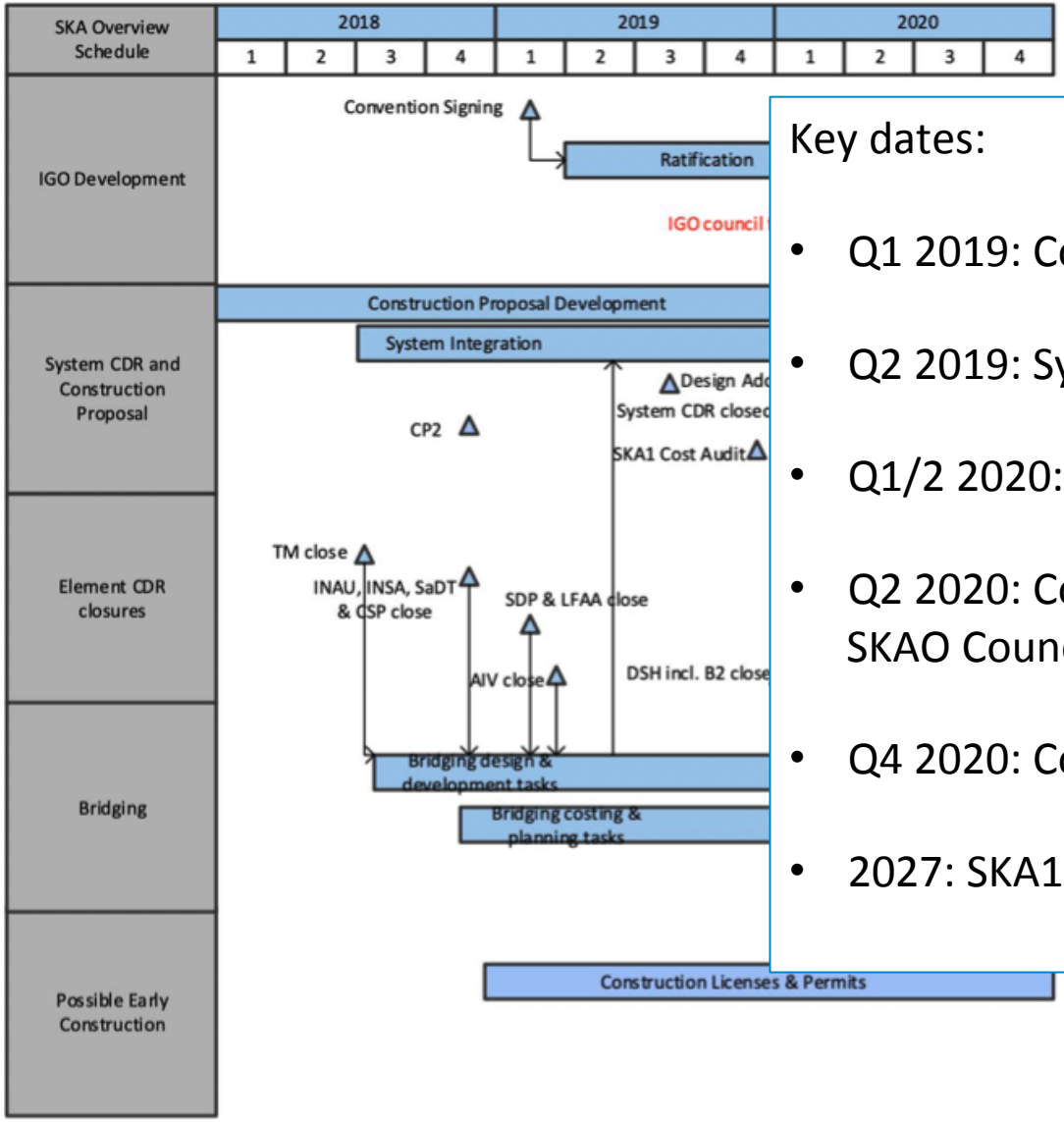
1. Reliability and completeness of sources found
2. Accuracy of property characterisation
3. Accuracy of population identification
4. Overall score based on the total number of real sources (less false positives) found in each of the three 1000h images multiplied by the fractional accuracy of the property characterisation and population identification

SKA1 Science Milestones (Doc #822)



- Overview of preparatory and scientific observing activities
- Increasingly realistic Data Challenges every 6 months

Timeline



Key dates:

- Q1 2019: Convention signing
- Q2 2019: System design final
- Q1/2 2020: SKA Observatory exists
- Q2 2020: Construction proposal submitted to SKAO Council
- Q4 2020: Construction begins
- 2027: SKA1 construction complete

Summary

- Overall progress is excellent:
  - Technical progress moving well, dealing with challenges
  - Precursors/pathfinders being delivered; delivering science
  - HQ construction complete
  - Data Challenges underway
  - Treaty establishing SKA Observatory to be signed early 2019
- SKA only possible through the drive, enthusiasm and support of the science and engineering community and governments of partner nations

SQUARE KILOMETRE ARRAY

Exploring the Universe with the world's largest radio telescope