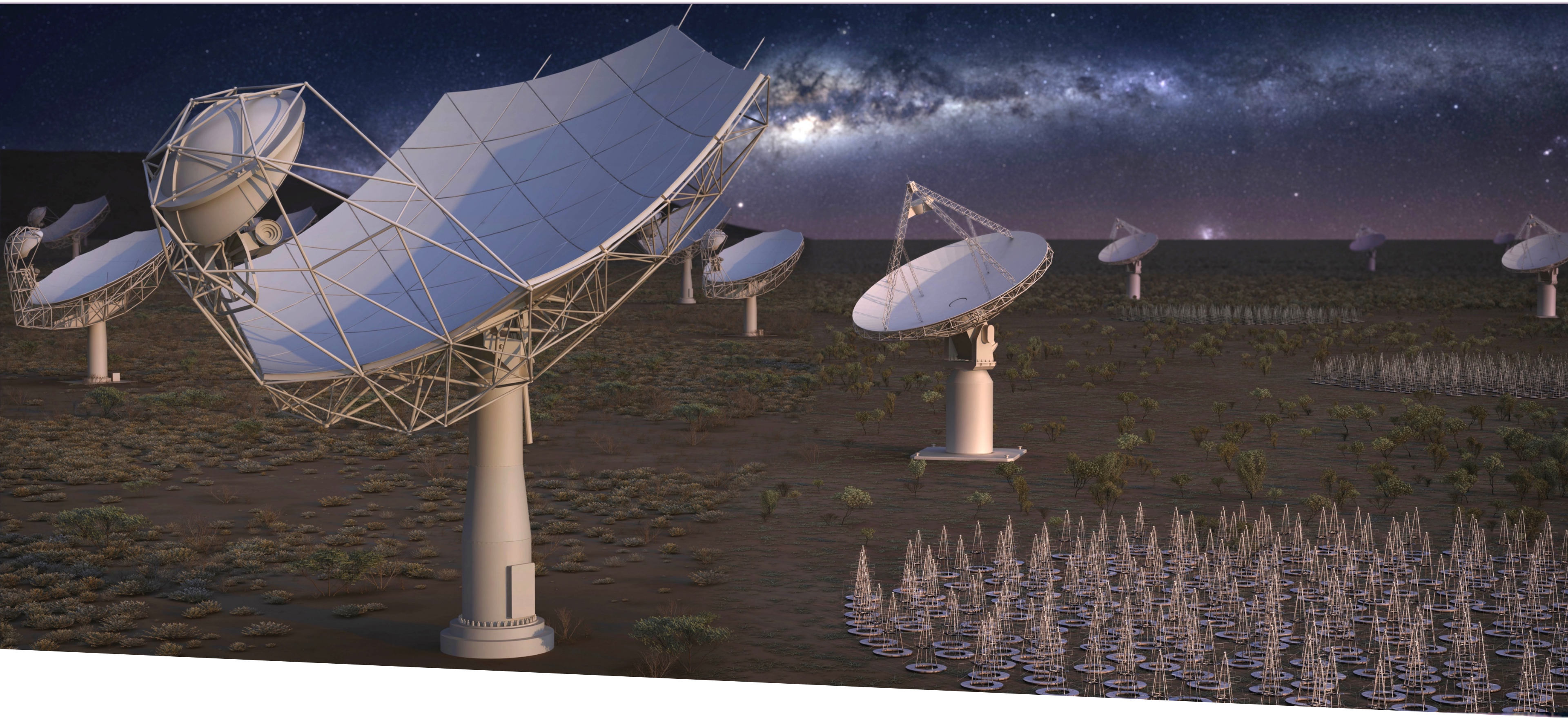
Low Frequency Science with the Square Kilometre Array



SQUARE KILOMETRE ARRAY

Exploring the Universe with the world's largest radio telescope

Robert Braun, Science Director

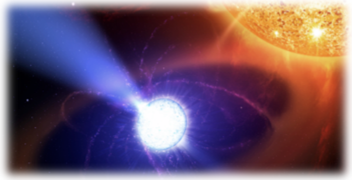
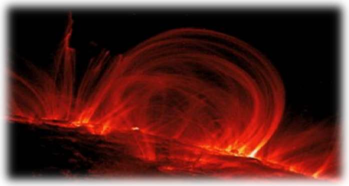
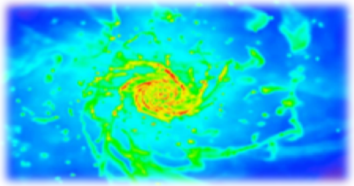
20 June 2017

SKA– Key Science Drivers: The history of the Universe

Extremely broad range of science!

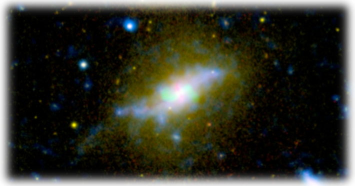
Headline Science with SKA1 and SKA2

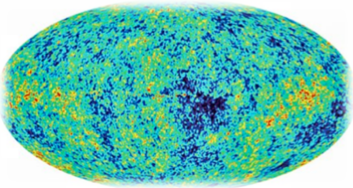
	SKA1	SKA2
The Cradle of Life & Astrobiology	Proto-planetary disks; imaging inside the snow/ice line (@ < 100pc), Searches for amino acids.	Proto-planetary disks; sub-AU imaging (@ < 150 pc), Studies of amino acids.
	Targeted SETI: airport radar 10^4 nearby stars.	Ultra-sensitive SETI: airport radar 10^5 nearby star, TV ~10 stars.
Strong-field Tests of Gravity with Pulsars and Black Holes	1st detection of nHz-stochastic gravitational wave background.	Gravitational wave astronomy of discrete sources: constraining galaxy evolution, cosmological GWs and cosmic strings.
	Discover and use NS-NS and PSR-BH binaries to provide the best tests of gravity theories and General Relativity.	Find all ~40,000 visible pulsars in the Galaxy, use the most relativistic systems to test cosmic censorship and the no-hair theorem.
The Origin and Evolution of Cosmic Magnetism	The role of magnetism from sub-galactic to Cosmic Web scales, the RM-grid @ 300/deg2.	The origin and amplification of cosmic magnetic fields, the RM-grid @ 5000/deg2.
	Faraday tomography of extended sources, 100pc resolution at 14Mpc, 1 kpc @ $z \approx 0.04$.	Faraday tomography of extended sources, 100pc resolution at 50Mpc, 1 kpc @ $z \approx 0.13$.
Galaxy Evolution probed by Neutral Hydrogen	Gas properties of 10^7 galaxies, $\langle z \rangle \approx 0.3$, evolution to $z \approx 1$, BAO complement to Euclid.	Gas properties of 10^9 galaxies, $\langle z \rangle \approx 1$, evolution to $z \approx 5$, world-class precision cosmology.
	Detailed interstellar medium of nearby galaxies (3 Mpc) at 50pc resolution, diffuse IGM down to $N_H < 10^{17}$ at 1 kpc.	Detailed interstellar medium of nearby galaxies (10 Mpc) at 50pc resolution, diffuse IGM down to $N_H < 10^{17}$ at 1 kpc.

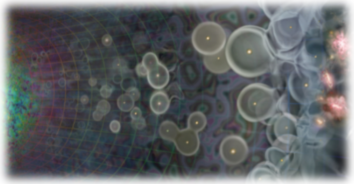





Headline Science with SKA1 and SKA2

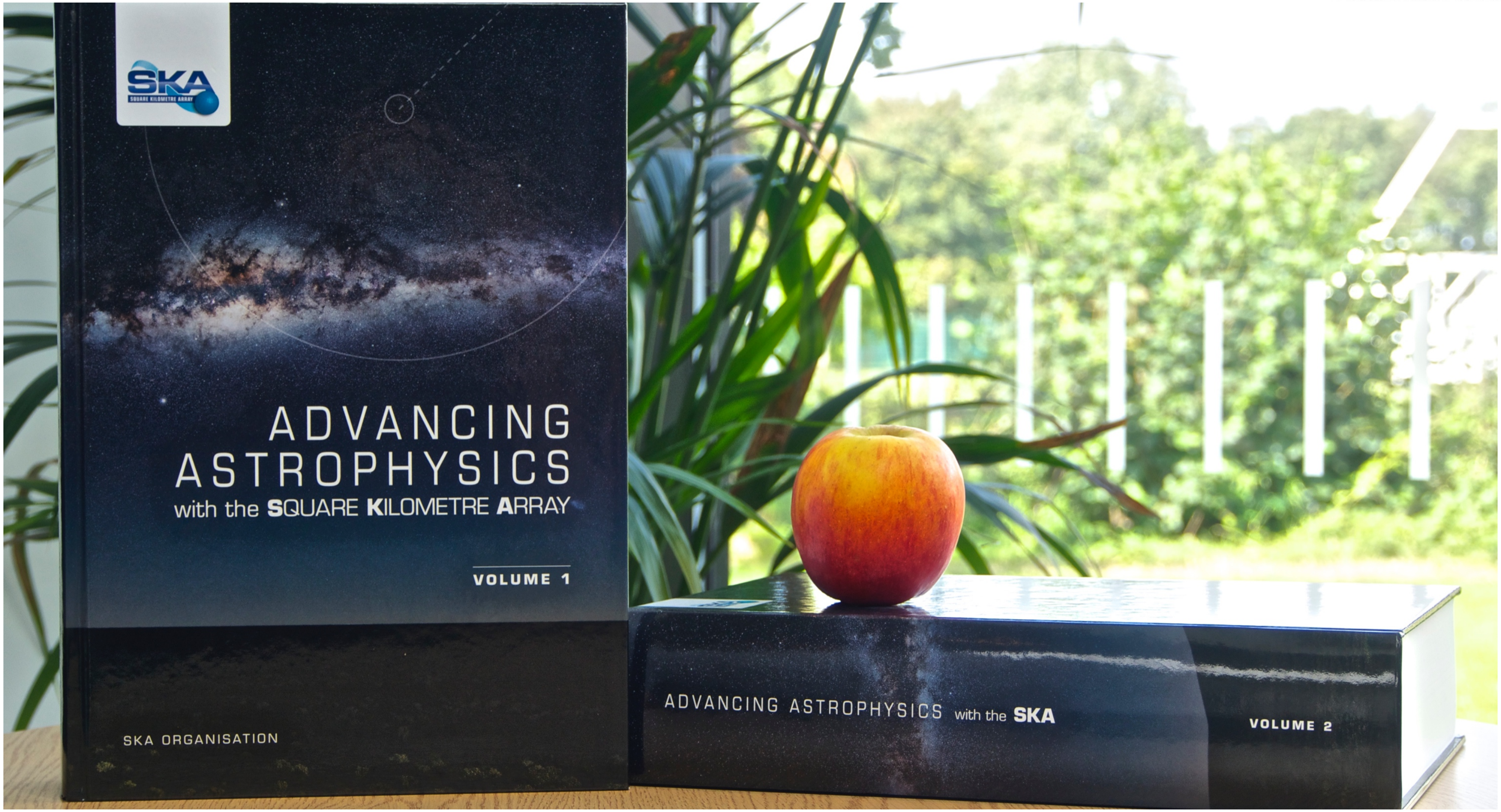
	SKA1	SKA2
The Transient Radio Sky	Use fast radio bursts to uncover the missing "normal" matter in the universe.	Fast radio bursts as unique probes of fundamental cosmological parameters and intergalactic magnetic fields.
	Study feedback from the most energetic cosmic explosions and the disruption of stars by super-massive black holes.	Exploring the unknown: new exotic astrophysical phenomena in discovery phase space.
Galaxy Evolution probed in the Radio Continuum	Star formation rates (10 M_Sun/yr to z ~ 4).	Star formation rates (10 M_Sun/yr to z ~ 10).
	Resolved star formation astrophysics (sub-kpc active regions at z ~ 1).	Resolved star formation astrophysics (sub-kpc active regions at z ~ 6).
Cosmology & Dark Energy	Constraints on DE, modified gravity, the distribution & evolution of matter on super-horizon scales: competitive to Euclid.	Constraints on DE, modified gravity, the distribution & evolution of matter on super-horizon scales: redefines state-of-art.
	Primordial non-Gaussianity and the matter dipole: 2x Euclid.	Primordial non-Gaussianity and the matter dipole: 10x Euclid.
Cosmic Dawn and the Epoch of Reionization	Direct imaging of EoR structures (z = 6 - 12).	Direct imaging of Cosmic Dawn structures (z = 12 - 30).
	Power spectra of Cosmic Dawn down to arcmin scales, possible imaging at 10 arcmin.	First glimpse of the Dark Ages (z > 30).





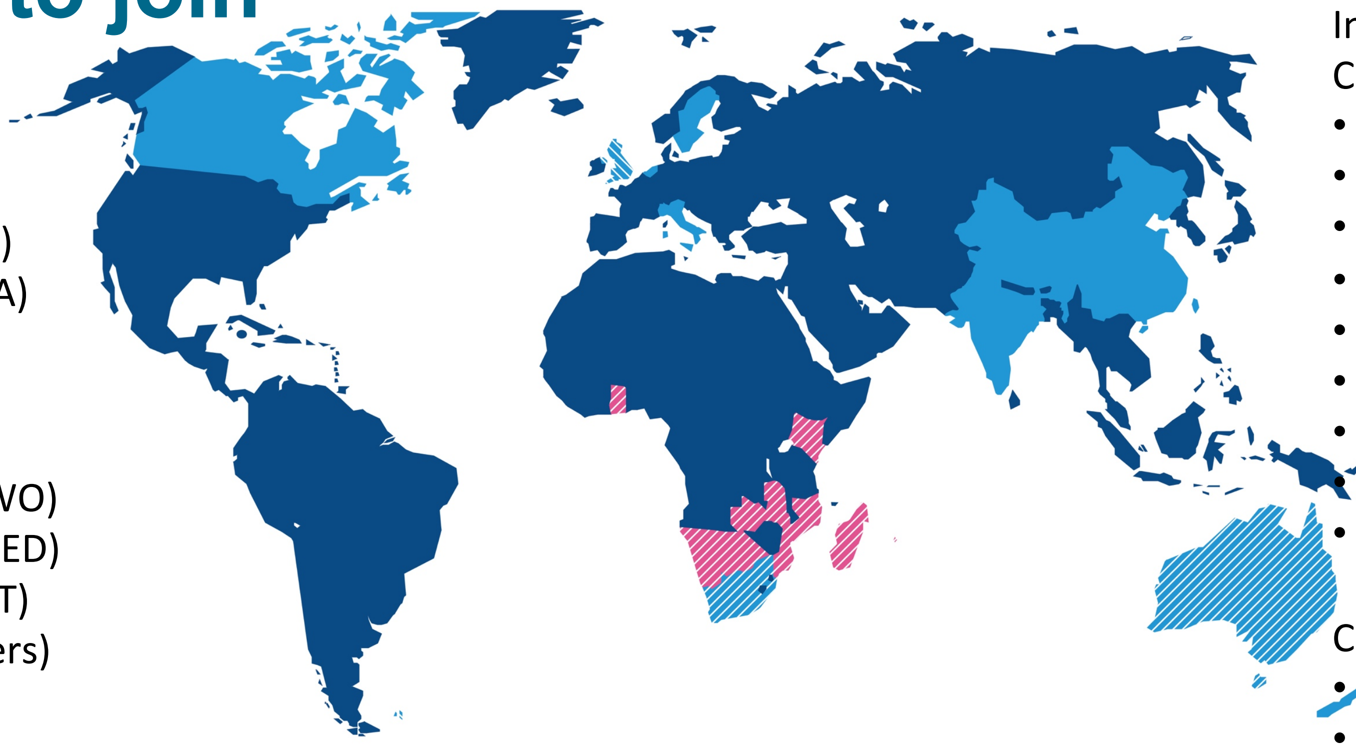


SKA Science Book 2015



- 135 Chapters, 2000 pages, 8.8 kg
- Plus new science directions that continue to emerge!

SKA Organisation: 10 countries, more to join



Australia (DoI&S)
Canada (NRC-HIA)
China (MOST)
India (DAE)
Italy (INAF)
Netherlands (NWO)
New Zealand (MED)
South Africa (DST)
Sweden (Chalmers)
UK (STFC)

Interested Countries:

- France
- Germany
- Japan
- Korea
- Malta
- Portugal
- Spain
- Switzerland
- USA

Contacts:

- Brazil
- Ireland
- Russia

Full members

SKA Headquarters host country

SKA Phase 1 and Phase 2 host countries

African partner countries (non-member SKA Phase 2 host countries)

This map is intended for reference only and is not meant to represent legal borders

Negotiations to establish SKA Inter-Governmental Organisation.

4th meeting in Rome, Sept 27-29
Text of Convention and protocols all agreed
Plan to initial documents in Q3 2017
Ministerial signing ceremony in Q4 2017

Transition planning underway

Square Kilometre Array

3 sites; 2 telescopes + HQ
1 Observatory

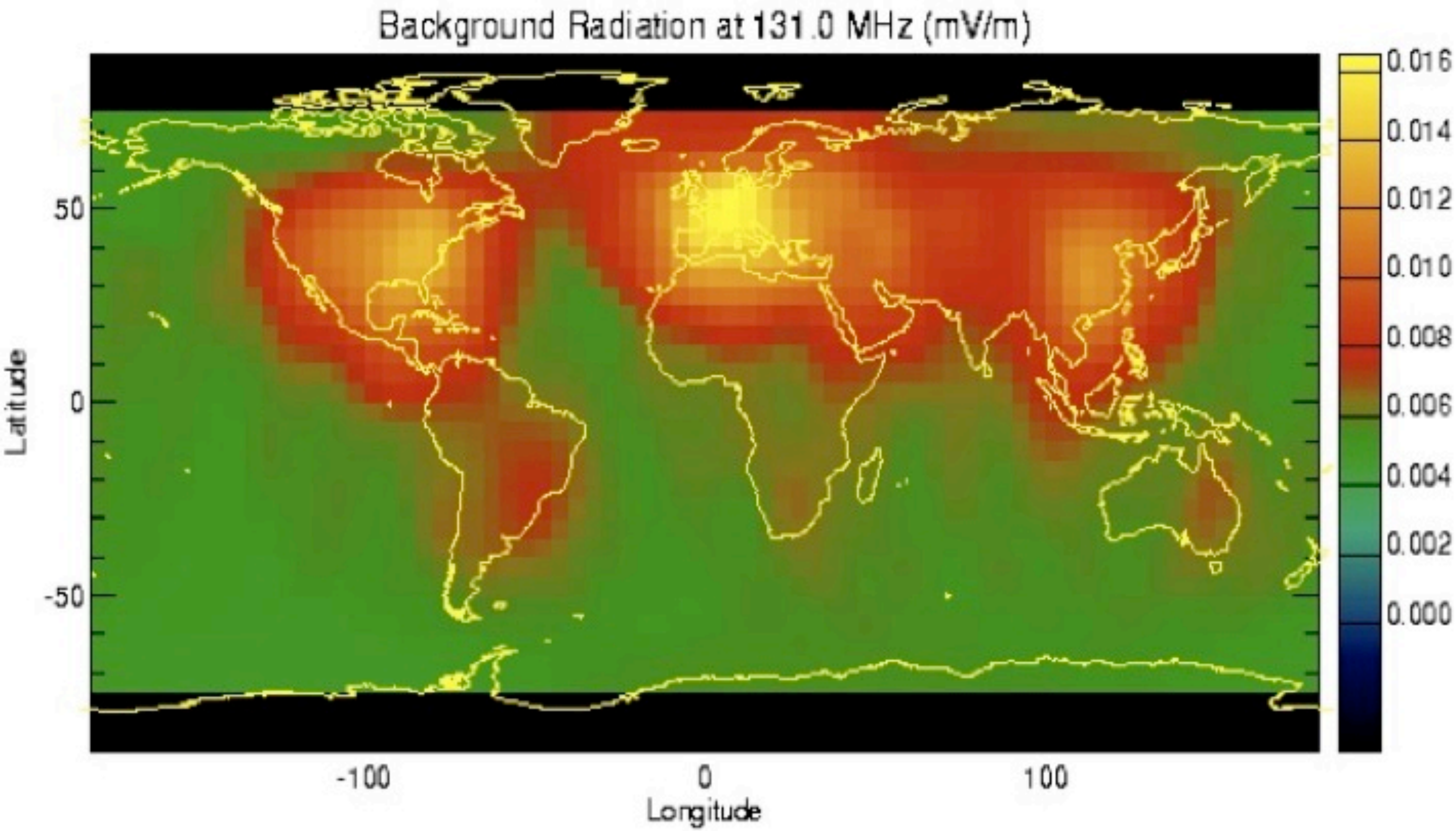
Design Phase: ~€170M; 600 scientists+engineers

Phase 1
Construction: <u>2018/19 – 2023</u>
Construction cost cap: €674M (inflation-adjusted)

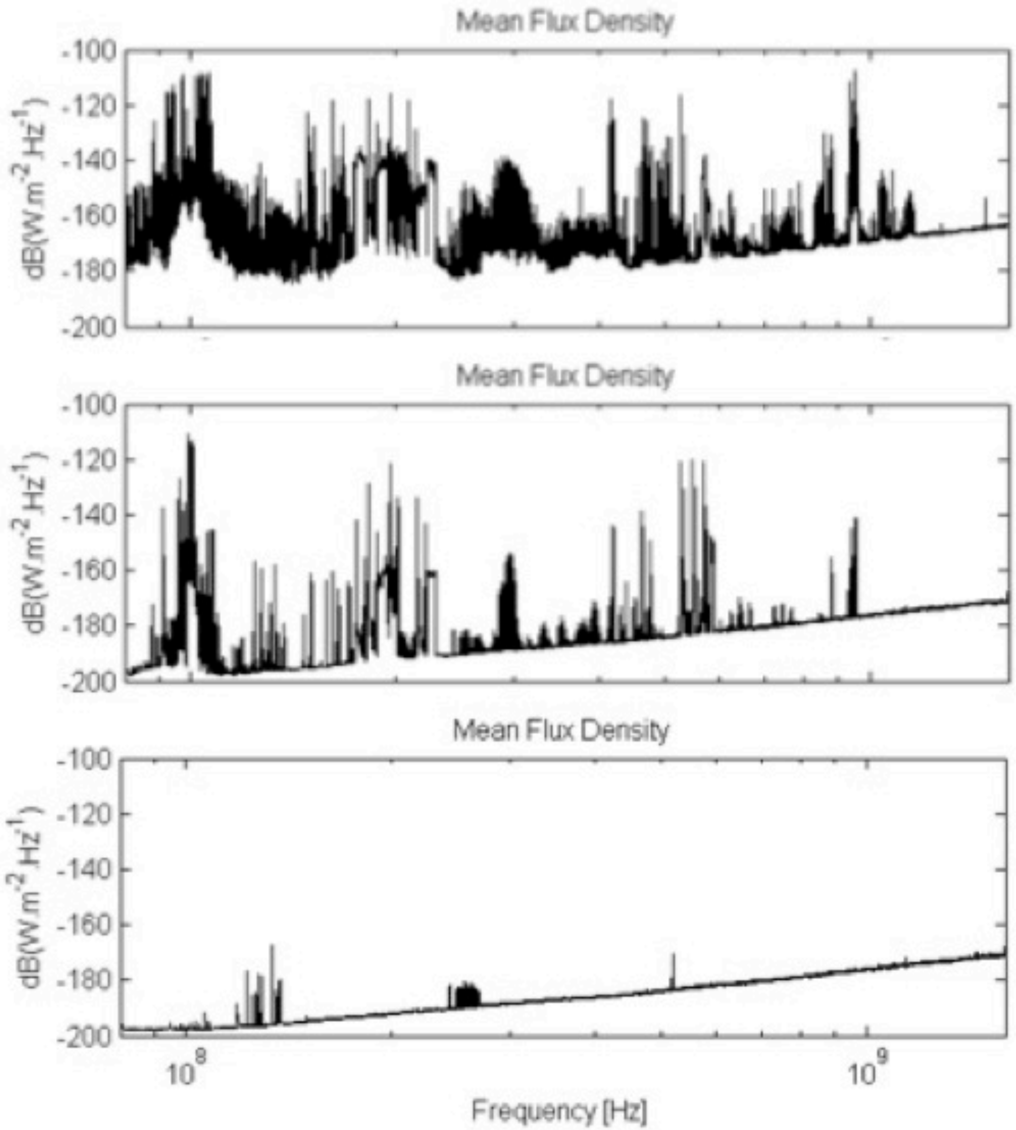
MeerKat integrated
Observatory Development Programme

SKA Regional Centres out of scope of centrally-funded SKAO

The SKA sites and RFI



The SKA sites and RFI

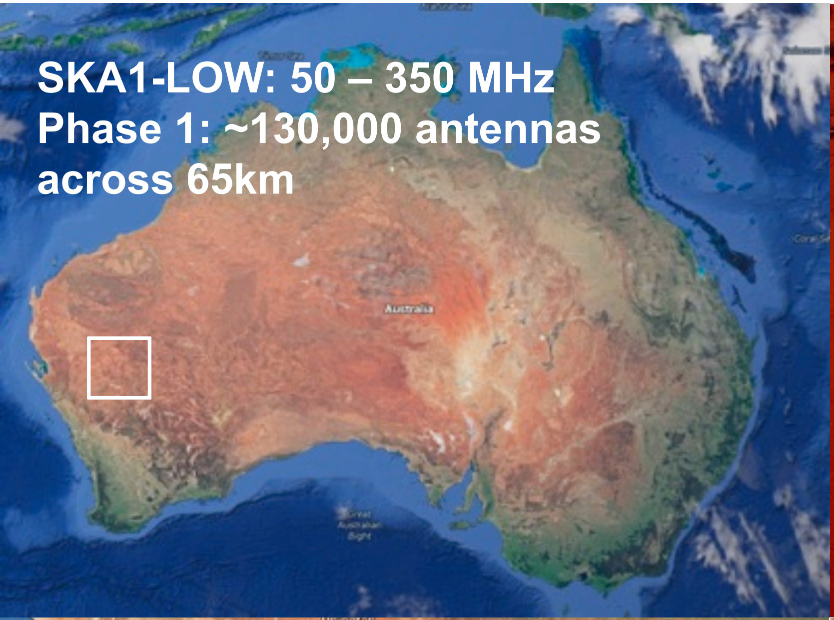


Sydney:
population 4 million

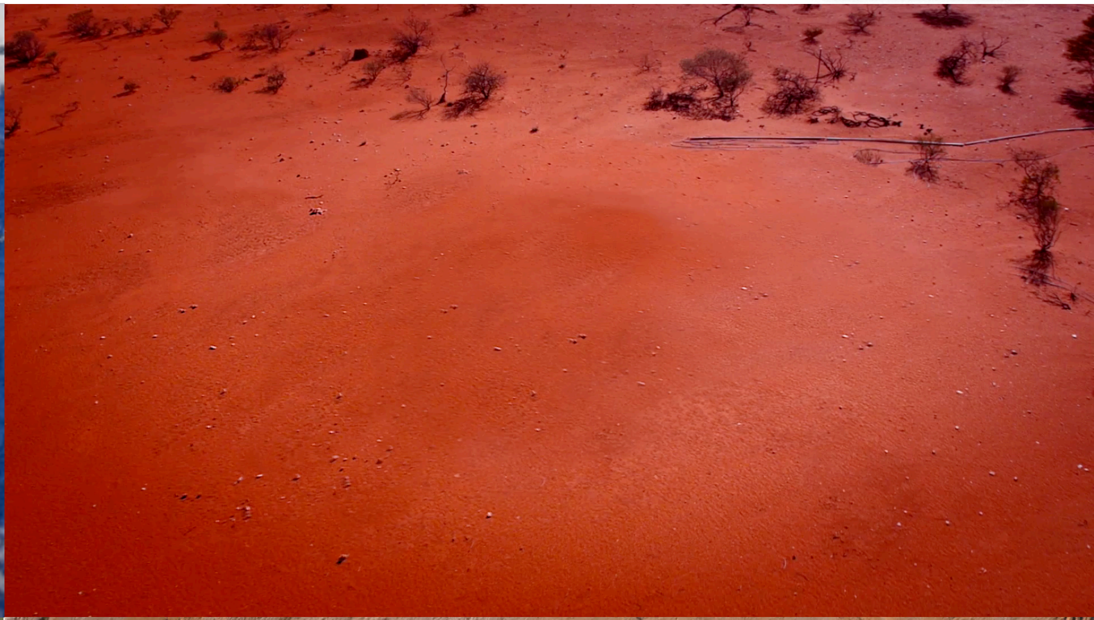
Narrabri:
population 4000

Mileura:
population 4

SKA: Telescopes in AUS & RSA



SKA1-LOW: 50 – 350 MHz
Phase 1: ~130,000 antennas across 65km

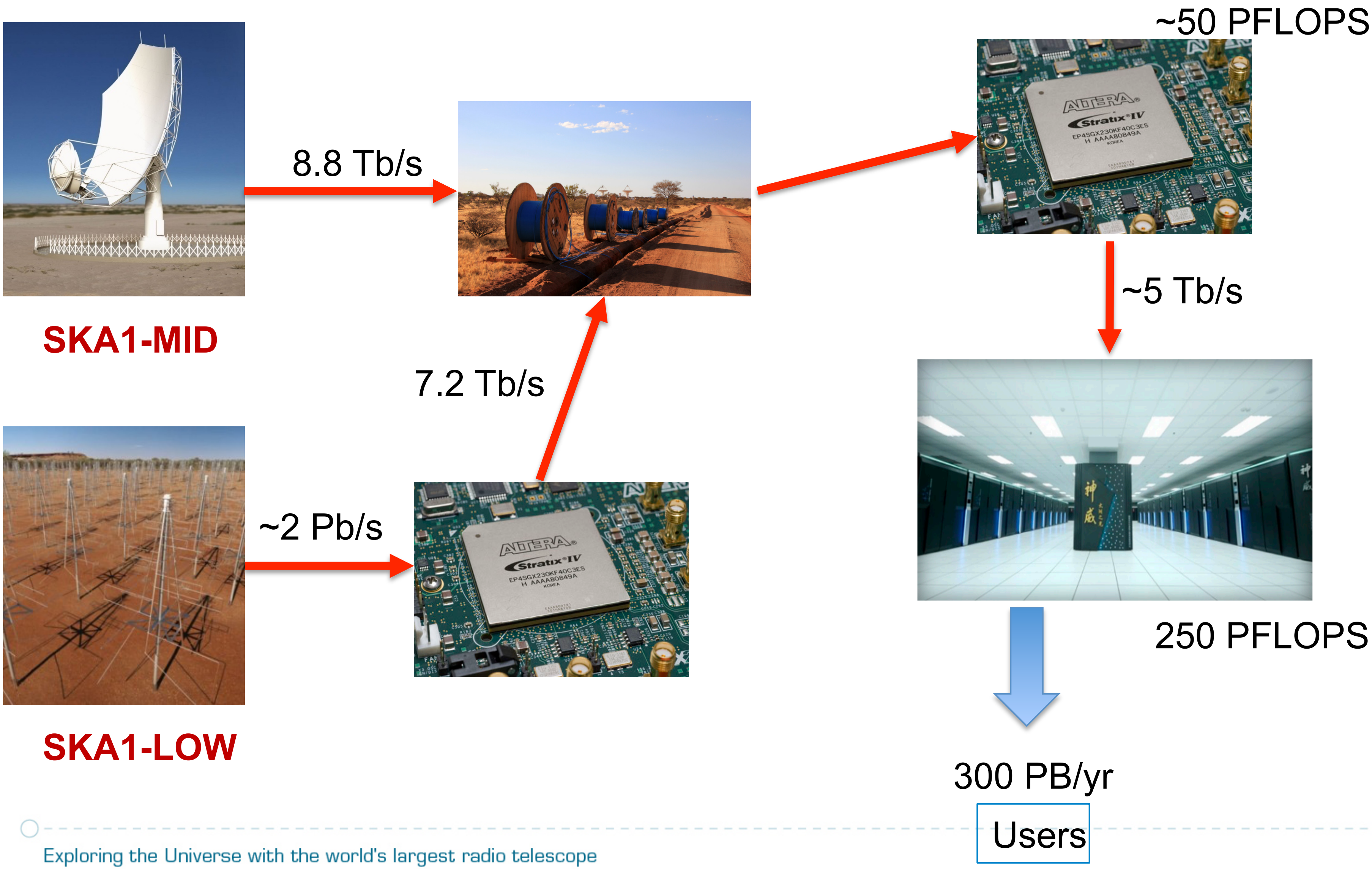


SKA1-Mid: 350 MHz – 24 GHz
Phase 1: 200 15-m dishes across 150 km

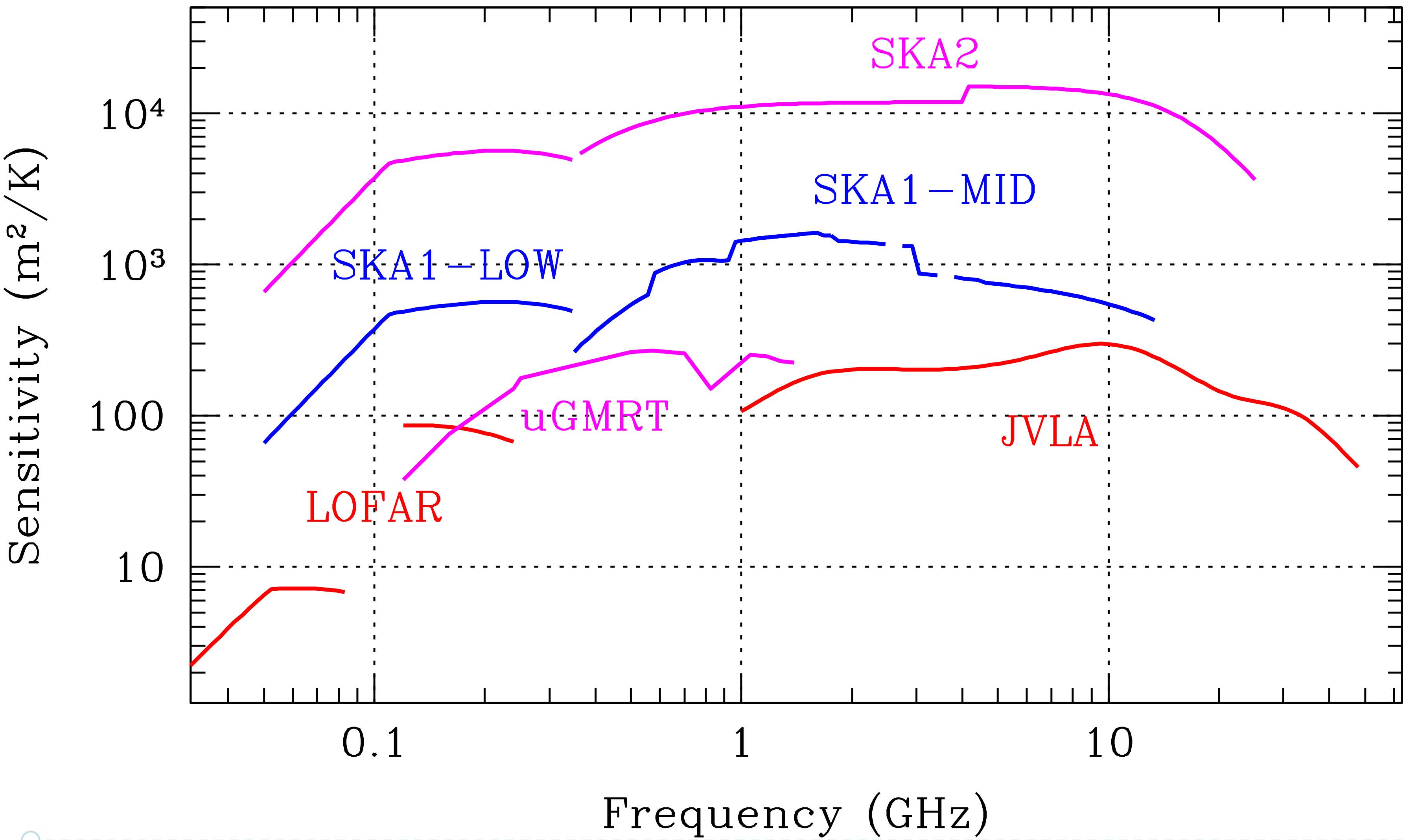
Construction: 2018/19 – 2023; Cost cap: €674M

SKA HQ: Jodrell Bank, UK

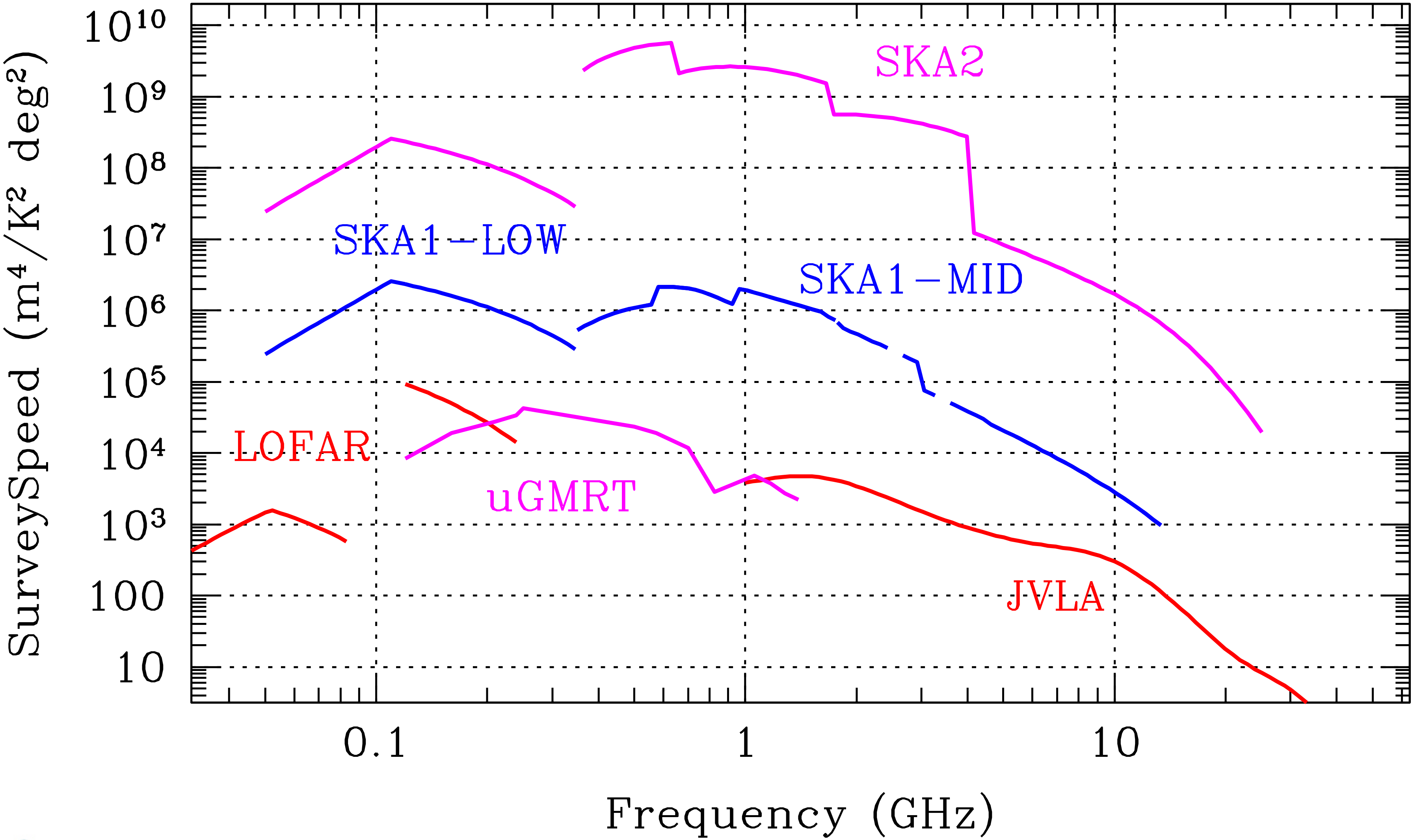
Data Flow through the SKA



Sensitivity Comparison



Survey Speed Comparison



Resolution Comparison

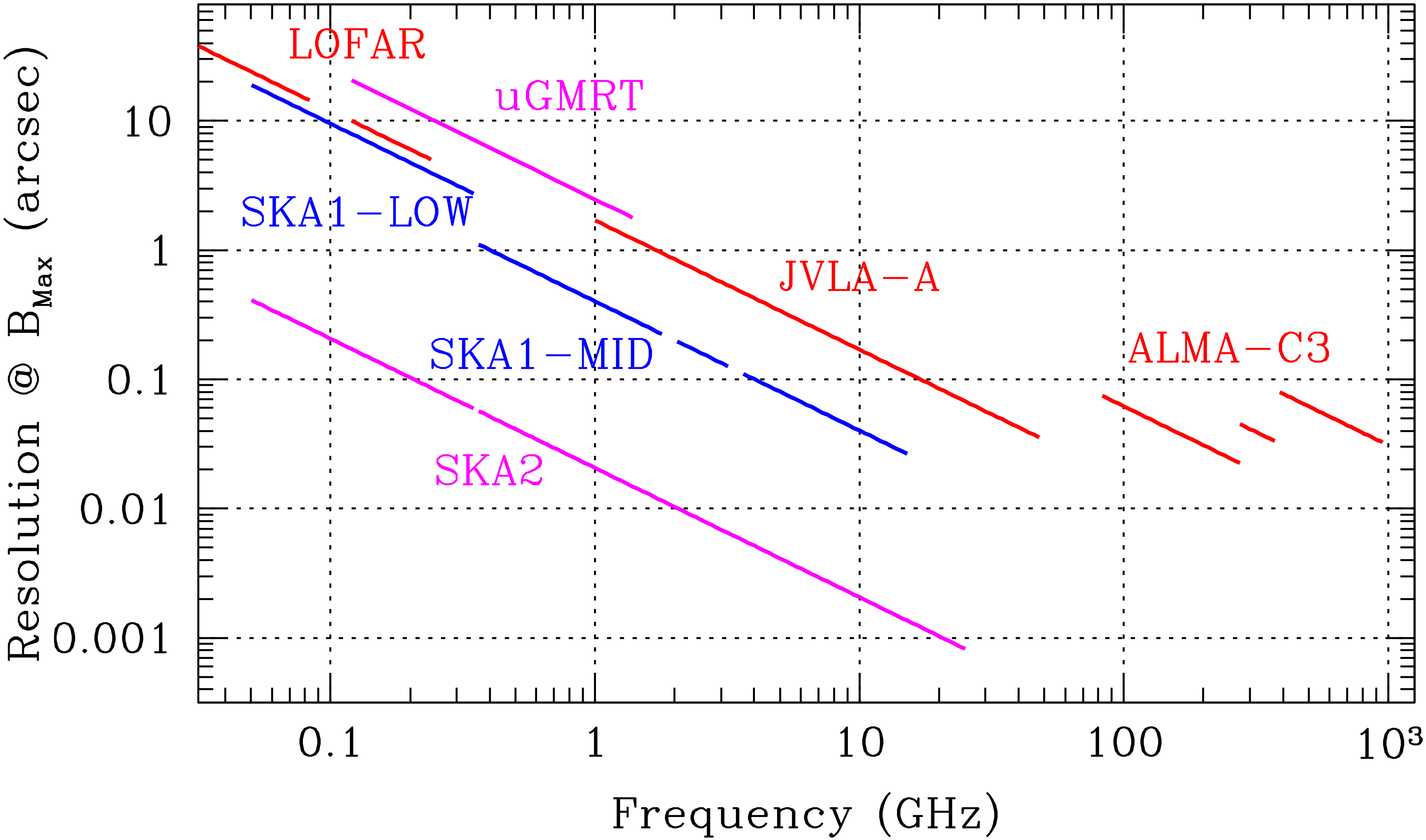


Image Quality Comparison

- Single SKA1 track equivalent to VLA A+B+C+D + **E+A⁺**
- "Structural" dynamic range of ~1000:1 rather than ~3:1 per track
- Beam quality ~100 times better than VLA

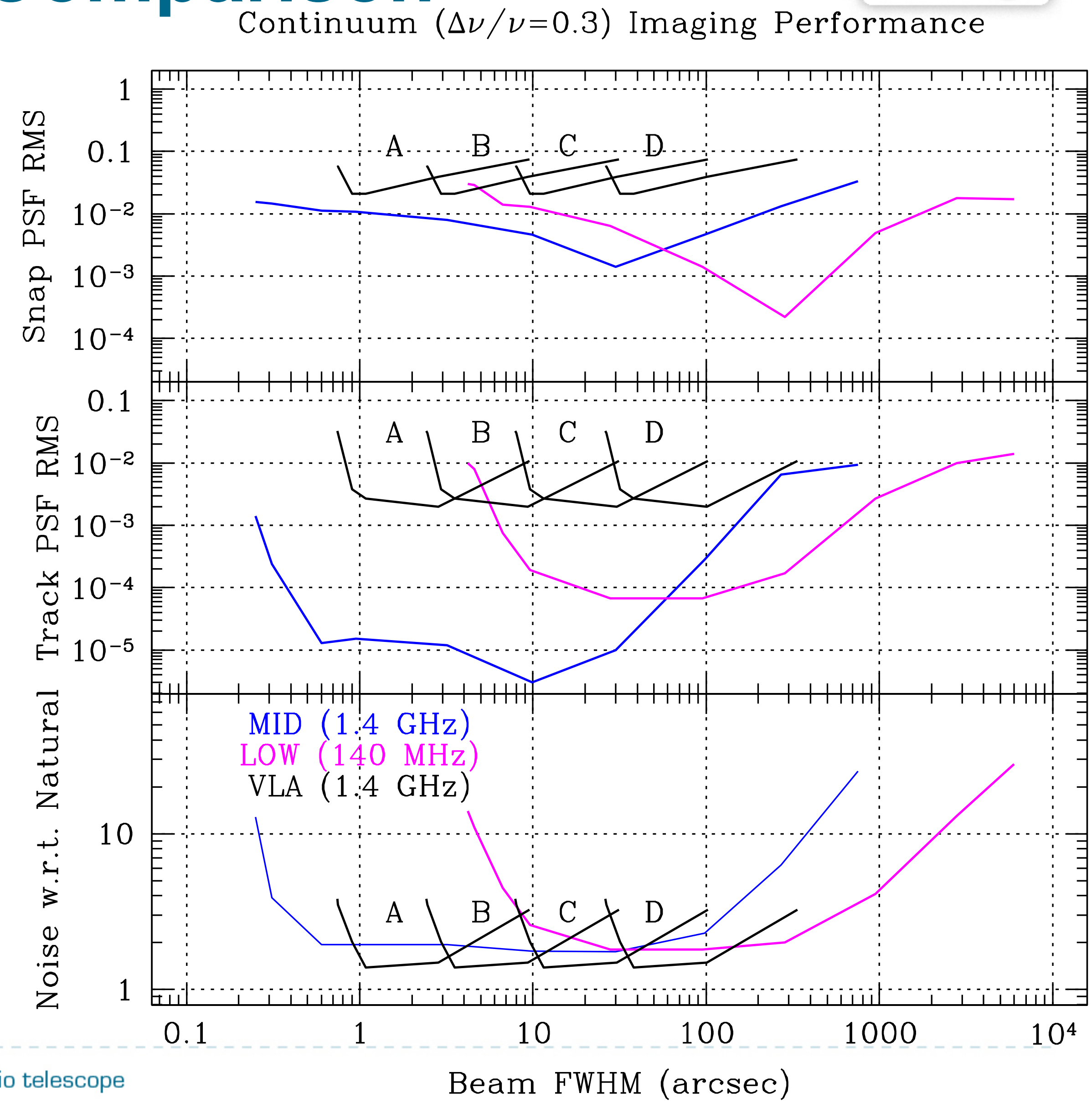
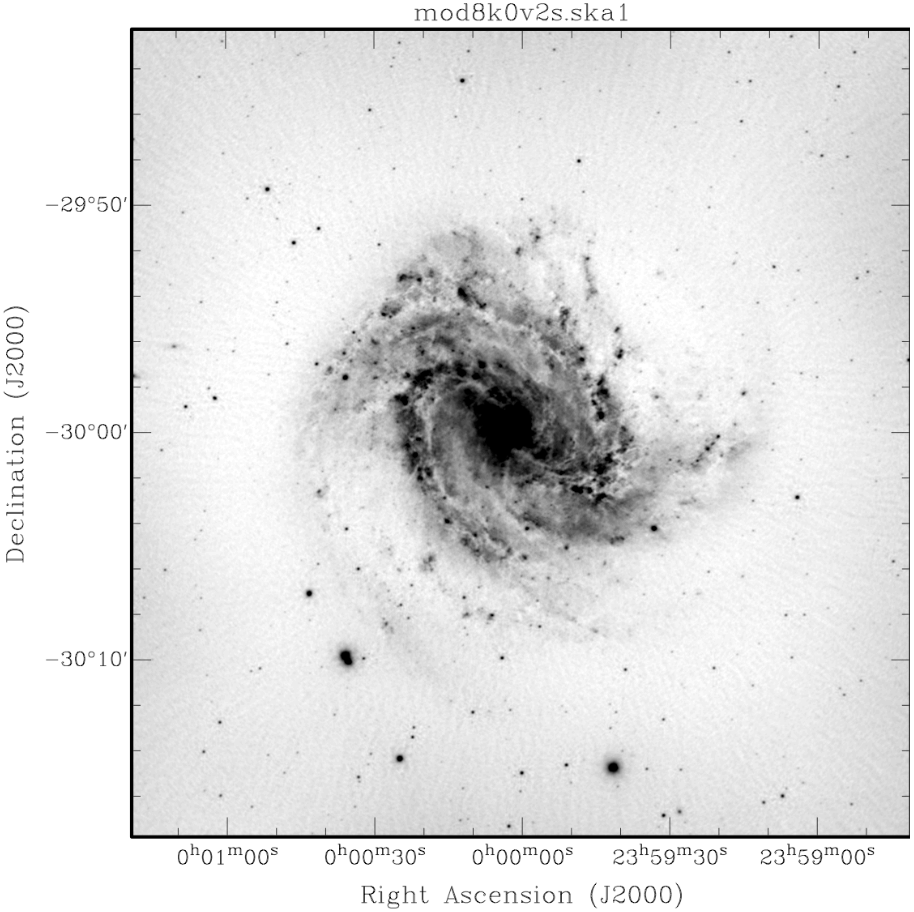
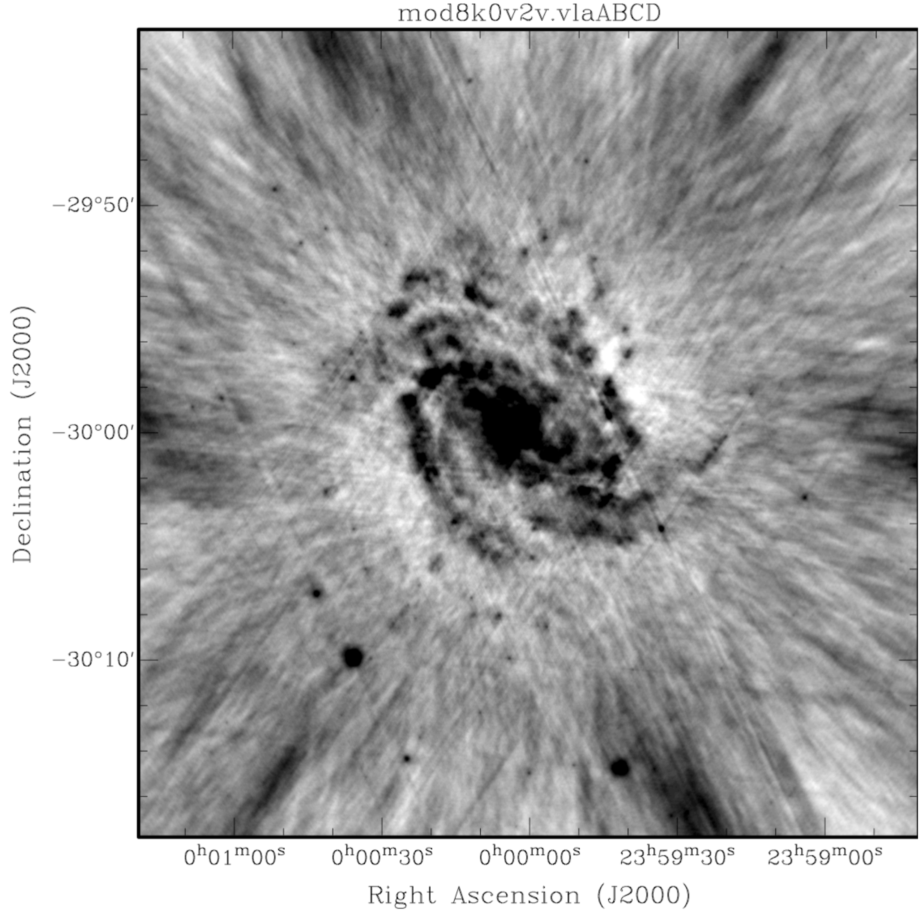


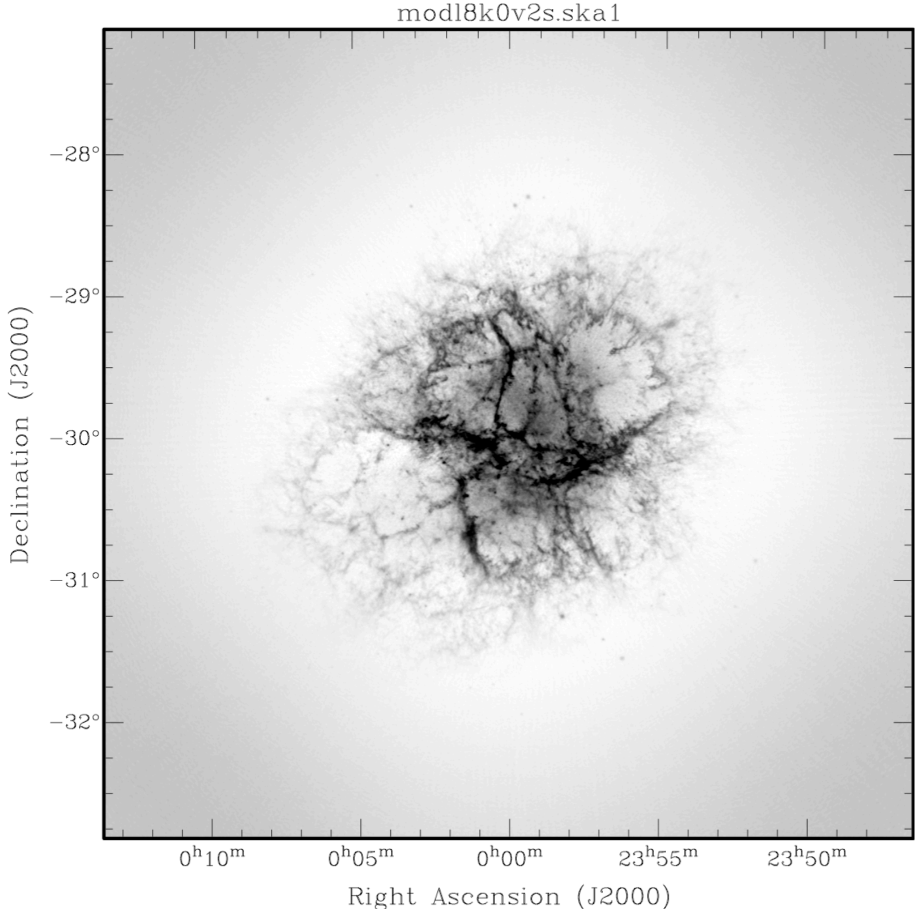
Image Quality Comparison

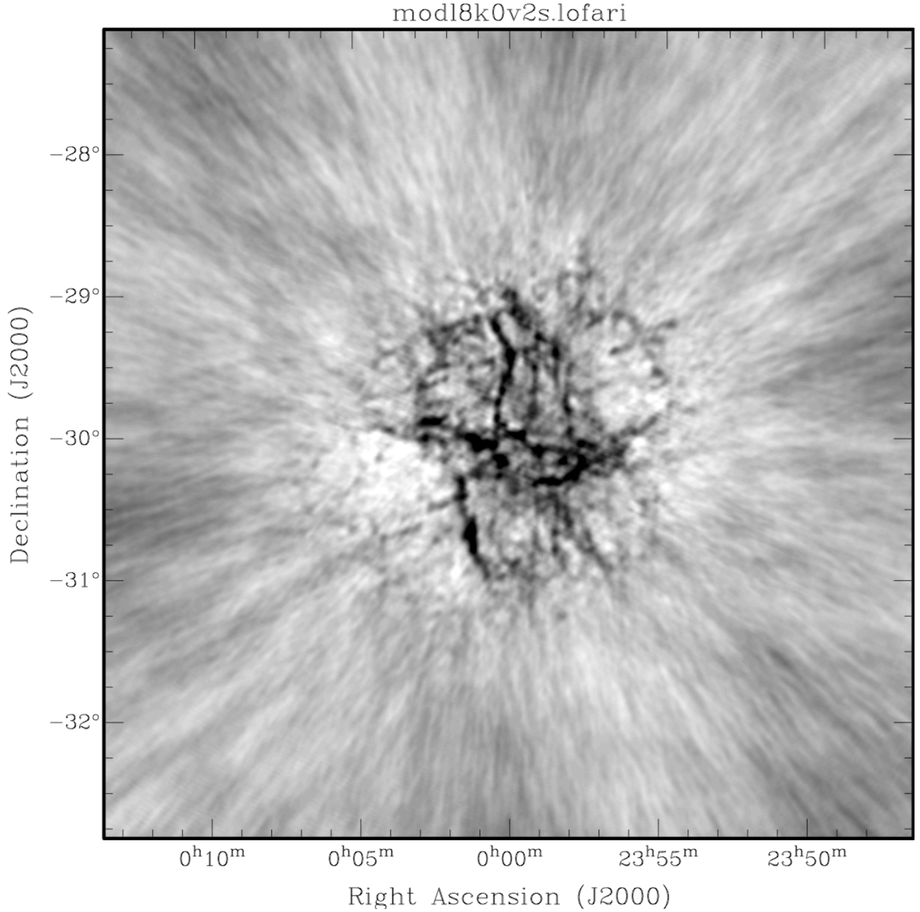




- Single SKA1-Mid snap-shot compared to combination of snap-shots in each of VLA A+B+C+D

Image Quality Comparison

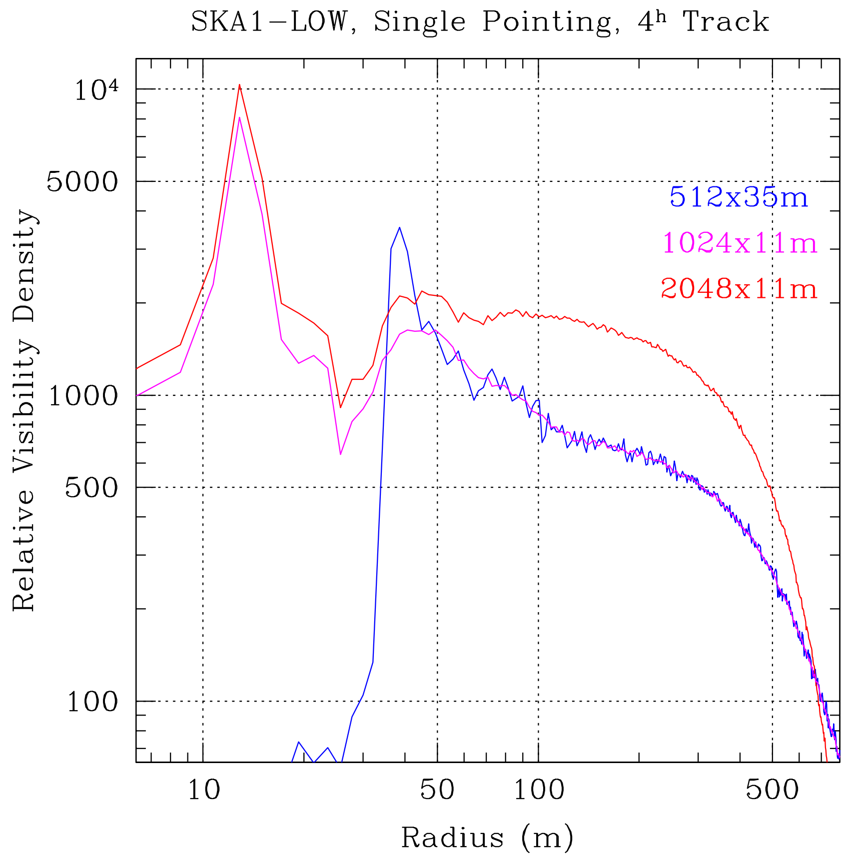




- Single SKA1-Low snap-shot compared to LOFAR snap-shot

SKA1-Low Sub-station correlation modes

- Virtual sub-stations can be defined of arbitrary size
- Support for standard correlation modes for 512, 768, 1024, 1536 and 2048 virtual stations
- Can customise (u,v) sampling to match needs
- Extreme brightness sensitivity for imaging
- Extreme sensitivity and k-mode sampling for EoR power spectra



SKA Board Meeting, Nov. 2016

- In order to ensure the delivery of SKA1 against the defined cost cap of 674M€ (2016 Euros):
  - Review of the existing design, explore and capitalise on a range of cost-saving measures
  - With the objective of preserving the transformational science capabilities of SKA1, minimising impact on the project schedule, and allowing expansion of the telescopes as additional funding becomes available.

Cost Control Plan

- Sequence of reinstatable (via extra funding) measures to achieve construction Cost Cap
- Ordering of measures (top to bottom) is attempt to reflect science impact
- Some line items represent "competing" options for which a future down-select would occur based on complete technical assessment

How was preliminary CCP order determined?

- Minimise negative science impact, using the “High Priority Science Objectives” as indicative measure
  - Wide review and endorsement of the HPSOs
- Maximise straightforward re-instatement potential given additional funding
  - Recognise the anticipated **full** refresh cycle for High Performance Computing and Pulsar Search hardware is 3 – 5 years
  - Recognise ramp up in post-construction phase to full volume of science data products (and hence HPC requirements)
  - Additional feeds (given mature design) are easier to deploy than new dishes
  - Major infrastructure re-instatement work is both costly and disruptive

SKA Science Town Hall Meeting 18 & 19 May

- Preliminary reports from the three Science Assessment Teams
- Preliminary Science Assessments from each SWG / FG which:
  1. Endorse or suggest reordering of items in the cost savings measures list
  2. Affirm or not the transformational science capability of the cost-capped observatory
- Programme for Town Hall
  - Reps provided by each SAT, SWG/FG based on availability (very short lead time between 1st announcement and meeting)
  - Q&A opportunities after each talk and in four Q&A sessions
- Some 70 participants plus live video streaming with e-mail questions available to all 600 SWG/FG members
- Wrap-up discussion: areas of consensus and contention

SKA Science Assessment Teams: Preliminary Conclusions

1. Impact on Epoch of Reionisation / Cosmic Dawn of changes to SKA1-Low maximum baseline length
   - Resources in place for effective assessment
   - Early indications may suggest that distinctions between B_{Max} = 65, 50 and 40 km are not extreme
2. Required timing accuracy to enable successful precision pulsar timing science
   - Clock precision (~4 ns) and redundancy for MID are vital
   - LOW requirements can likely be relaxed
3. Impact of SKA-Low antenna optimised frequency coverage
   - Major capability loss if low performance above 200 MHz
   - Biggest hits to Pulsar surveys (MSP yield), but also EoR tail, Solar, and continuum imaging (particularly in combination with a B_{Max} reduction!)

Areas of Consensus/Contention

- Extremely open and constructive discussion of the issues

1. Double hit to MID Band 5 (from feed number and BW) may be excessive
   – Explore methods of mitigation
2. Double hit to LOW θ_{Min} (from B_{Max} and high frequency performance) may be excessive
   – Explore methods of mitigation
3. Need for careful consideration of optimal placement of any partial Band 5 feed deployment
   – Wide consultation needed to insure all issues taken into account
4. Concern regarding deep PSS cuts
   – Explore prospects for mitigation
5. Lack of clarity around implications of HPC cuts

Adjustments to Ordered CCP List (25 May)

- LOW antenna design: Based on the major negative science impact of cuts to both the maximum baseline of SKA1-Low, as well as the higher frequency performance, the intent is to give higher priority to preserving the high frequency performance of the antenna system

- MID Band 5 partial deployment: A wide community consultation will be undertaken to ensure that any partial deployment of the Band 5 feeds takes account of all science constraints

- Reduce CBF-LOW, Reduce PSS-LOW, Reduce PSS-MID, Reduce CBF-MID: All five of these items have been moved down to below the nominal Cost Cap line, since the negative science impact of each is deemed to be too severe in relation to the anticipated cost savings

Updated CCP list (page 1/2)

WS / Origin	Description	LOW / MID / COMMON	Science Implication	Science Impact
5.39	INFRA_SA Renewable energy to outer dishes	MID	None	1
5.3	Maximise use of code produced during Pre-Construction	COMMON	None	1
5.38	Simplify DDBH LOW	LOW	None	1
5.38	Simplify DDBH MID	MID	None	1
5.25.2	Reduce PSS-MID: A, 750 nodes to 500 nodes	MID	Likely none, or small reduction of pulsar search parameter space.	1
5.25.2	Reduce PSS-LOW: A, 250 nodes to 167 nodes	LOW	Likely none, or small reduction of pulsar search parameter space.	1
5.35	Reduce CBF-MID: Freq. Slice variant of CSP design vs. MeerKAT-based design	MID	None	1
5.19	MID Frequency and Timing Standard: SaDT solution vs. MeerKAT-based solution	MID	None	1
5.36	MID SPF Digitisers: DSH solution vs. MeerKAT-based solution	MID	None	1
5.26 / 5.29	LOW RPF: Early Digital Beam Formation vs. Analogue Beam Formation	LOW	None	1
2	LOW Antenna: Log Periodic Design vs. Dipole Design	LOW	None of the current designs meet the L1 requirements	3
8	SDP- HPC: Deploy 200 Pflops (rather than 260 Pflops)	COMMON	Lower allowed duty cycle for HPC-intensive observations.	2
5.24.3	Reduce Bmax MID from 150 to 120 km: Case A, remove 3 dishes, but keep infra to 150km	MID	Reduction of maximum achievable resolution by 20%, although can be partially recovered with data weighting and longer integration times.	2
5.24.2	Reduce Bmax MID from 150 to 120 km: Case B, remove infra, but add dishes to core	MID	Reduction of maximum achievable resolution by 20%, although can be partially recovered with data weighting and longer integration times.	2
5.24.1	Reduce Bmax MID from 150 to 120 km: Case C, remove infra, remove dishes	MID	Reduction of maximum achievable resolution by 20%, although can be partially recovered with data weighting and longer integration times.	2
5.5.2	Reduce MID Band 5 feeds: A, from 130 to 67	MID	Placement to be determined based on full community consultation.	2
5.25.2	Reduce PSS-LOW: B, 167 nodes to 125 nodes	LOW	Likely reduction in processed PSS beam number (1.3x) or pulsar search parameter space	2
5.25.2	Reduce PSS-MID: B, 500 nodes to 375 nodes	MID	Likely reduction in processed PSS beam number (1.3x) or pulsar search parameter space	2

Updated CCP list (page 2/2)

8	SDP- HPC: Deploy 150 Pflops (from 200 Pflops)	COMMON	Lower allowed duty cycle for HPC-intensive observations.	3
5.30.0	Reduce Bmax LOW to 50km: A, remove infra, add 18 stations to core	LOW	Science Risk to EoR: Bmax.	3
5.30.0	Reduce Bmax LOW to 50km: B, remove 18 stations	LOW	Science Risk to EoR: Bmax	3
5.30a	Reduce Bmax LOW to 40km: C, remove next 18 stations	LOW	Science Risk to EoR: Bmax	3
8	SDP- HPC: Deploy 100 Pflops (from 150 Pflops)	COMMON	Lower allowed duty cycle for HPC-intensive observations.	4
8	SDP- HPC: Deploy 50 Pflops (from 100 Pflops)	COMMON	Lower allowed duty cycle for HPC-intensive observations.	4
5.31	Reduce CBF-LOW BW: A, 300 to 200 MHz	LOW	Longer observing times for continuum applications (1.5x)	4
5.25.2 / Deeper Savings	Reduce PSS-LOW: C, 125 nodes to 83 nodes	LOW	Likely reduction in processed PSS beam number (2x) or pulsar search parameter space	4
5.25.2 / Deeper Savings	Reduce PSS-MID: B, 375 nodes to 250 nodes	MID	Likely reduction in processed PSS beam number (2x) or pulsar search parameter space	4
5.13.2	Reduce Bandwidth output of band 5 to 2.5GHz	MID	Longer Band 5 observing times for some applications (2x)	4
5.35	Reduce MID CBF and DSH BW: 5 to 1.4 GHz	MID	Longer observing times to achieve continuum sensitivity in Band 5 (3.6x)	4
5.24 / Deeper Savings	Remove 11 MID Dishes from core	MID	10% Array sensitivity loss in core	4
5.30 / Deeper Savings	Remove 54 LOW stations from core	LOW	10% Array sensitivity loss in core	4
5.24 / Deeper Savings	Remove additional 11 MID Dishes from core	MID	20% Array sensitivity loss in core	4
5.30 / Deeper Savings	Remove additional 54 LOW stations from core	LOW	20% Array sensitivity loss in core	4
5.24.2	Reduce Bmax MID from 120 to 100 km: D, remove infra, remove next 3 dishes	MID	Lose Science (Planetary disks, High resolution Star Formation)	4
5.5.1	Remove MID Band 1 feeds: 105 to 0	MID	Lose Science (Cosmology, Galaxy Evolution)	4
5.5.2	Reduce MID Band 5 feeds: B, from 67 to 0	MID	Lose Science (Planetary disks, Star Formation)	4

Adjustments to Ordered CCP List

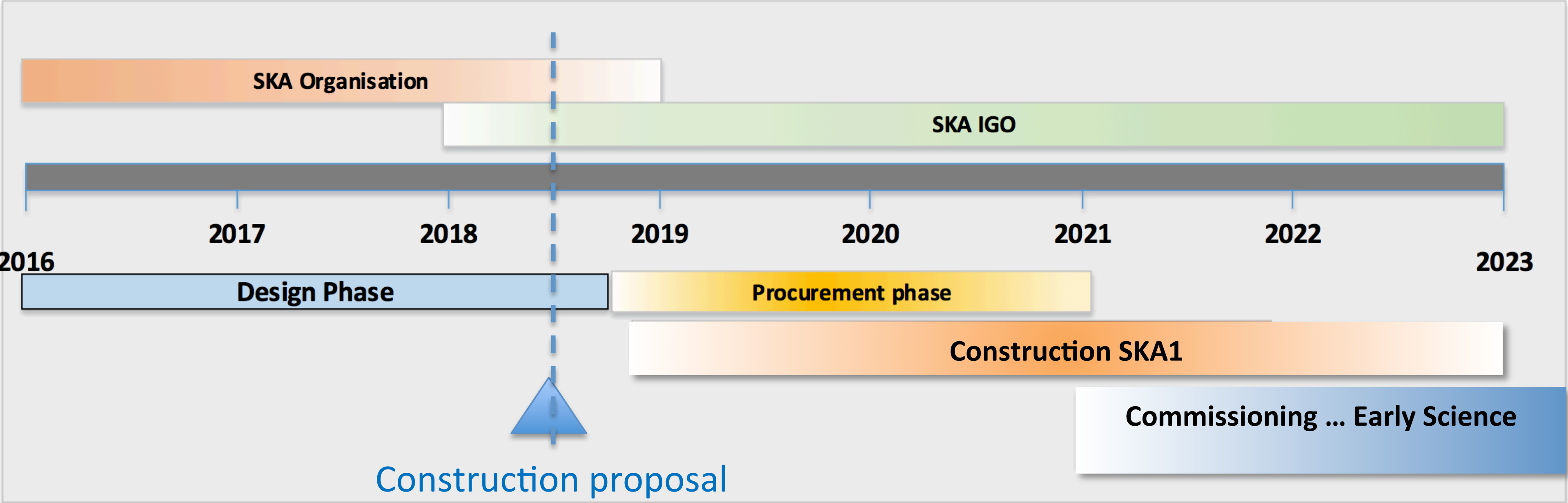
- Preserve **full ν coverage, BW and commensality** on both LOW (300 MHz) and MID (5 GHz)
- Keep PSS cuts down to only a 30% hit in search speed
- Full community consultation to optimise any partial deployment of SPF5
- Based on updated CCP list:
  - Overall consensus around ordering of measures
  - Transformational science is retained at cost-cap in essentially all areas

Critical Design Review Schedule

Milestone	Date
AIV CDR close	September 2017
CSP CDR close	December 2017
DSH CDR close (Bands 1 & 2)	October 2018
DSH CDR close (Band 5)	July 2019
INAU CDR close	December 2017
INSA CDR close	December 2017
LFAA CDR close	Under Review
SaDT CDR close	December 2017
SDP CDR close	June 2018
TM CDR close	December 2017
System CDR close	March 2018
Construction Proposal submission	June 2018
Construction Proposal approval	December 2018

- Based on “frozen” requirements in December 2016 (L1 Revision 10+)

Timeline



- Project momentum excellent:
  - Preliminary Design Reviews completed
  - Critical Design Reviews scheduled
  - IGO formal negotiations in progress
- SKA construction is on the horizon

SQUARE KILOMETRE ARRAY

Exploring the Universe with the world's largest radio telescope

www.skatelescope.org