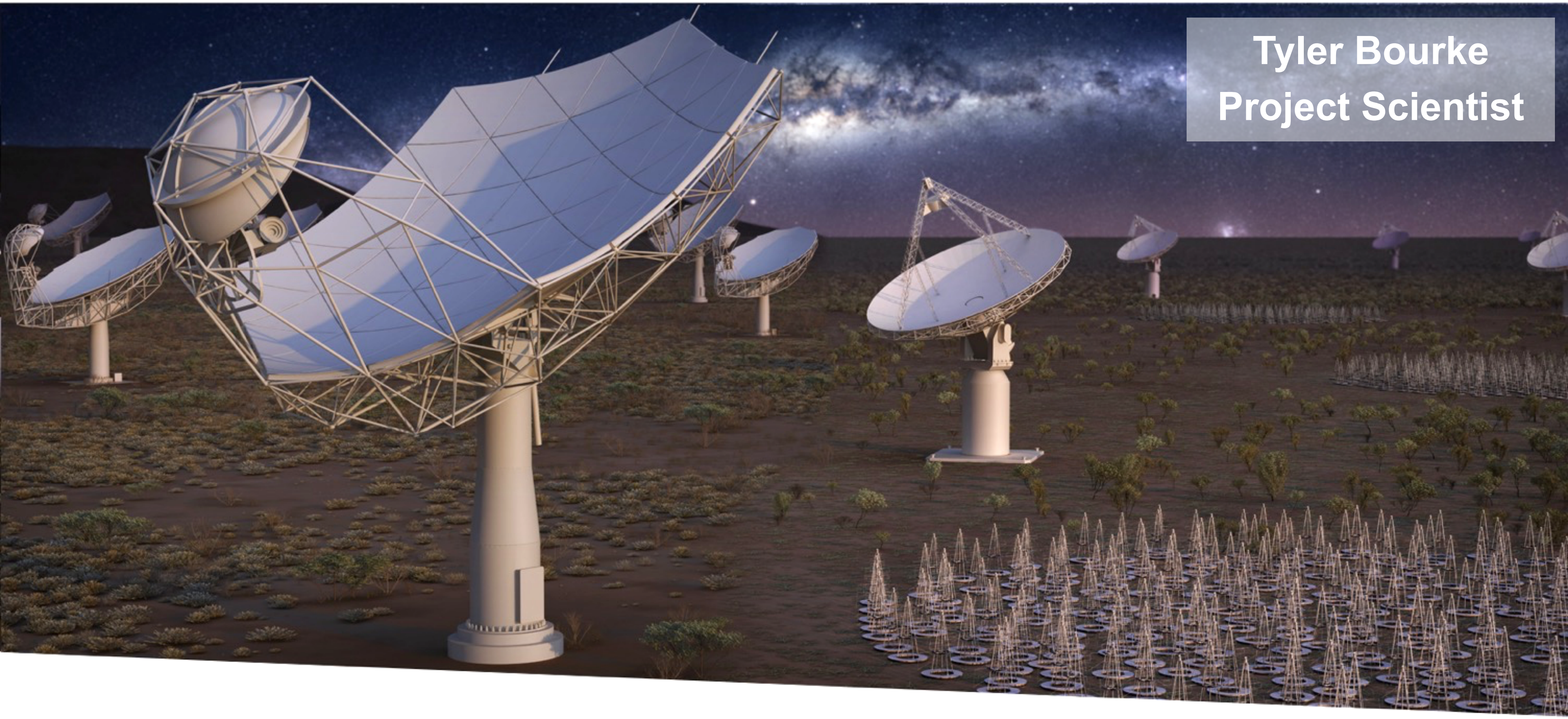
SKA Science Planning



Tyler Bourke
Project Scientist

SQUARE KILOMETRE ARRAY

Exploring the Universe with the world's largest radio telescope

SKA SWG Our Galaxy f2f
11/7/2018

SKA– Key Science Drivers:
The history of the Universe

Cosmic Dawn
(First Stars and Galaxies)

Testing General Relativity
(Strong Regime, Gravitational Waves)

Galaxy Evolution
(Normal Galaxies z~2-3)

Cradle of Life
(Exo-planets, Molecules, SETI)

Cosmology
(Dark Matter, Large Scale Structure)

Cosmic Magnetism
(Origin, Evolution)

The Milky Way
(Stellar Evolution, ISM, 3D structure)

Exploration of the Unknown

Broadest range of science of any facility, worldwide

SKA Phase 1

3 sites (AUS, RSA, UK-HQ) **2 telescopes (LOW, MID)** **one Observatory (SKAO)**

Construction Cost-cap: €675M (2016)

Construction: 2020-2026

SKA1-Low: 512 x 256 low-freq dipoles,
50 – 350 MHz
65 km baselines (11" @ 110 MHz)
Murchison, Western Australia

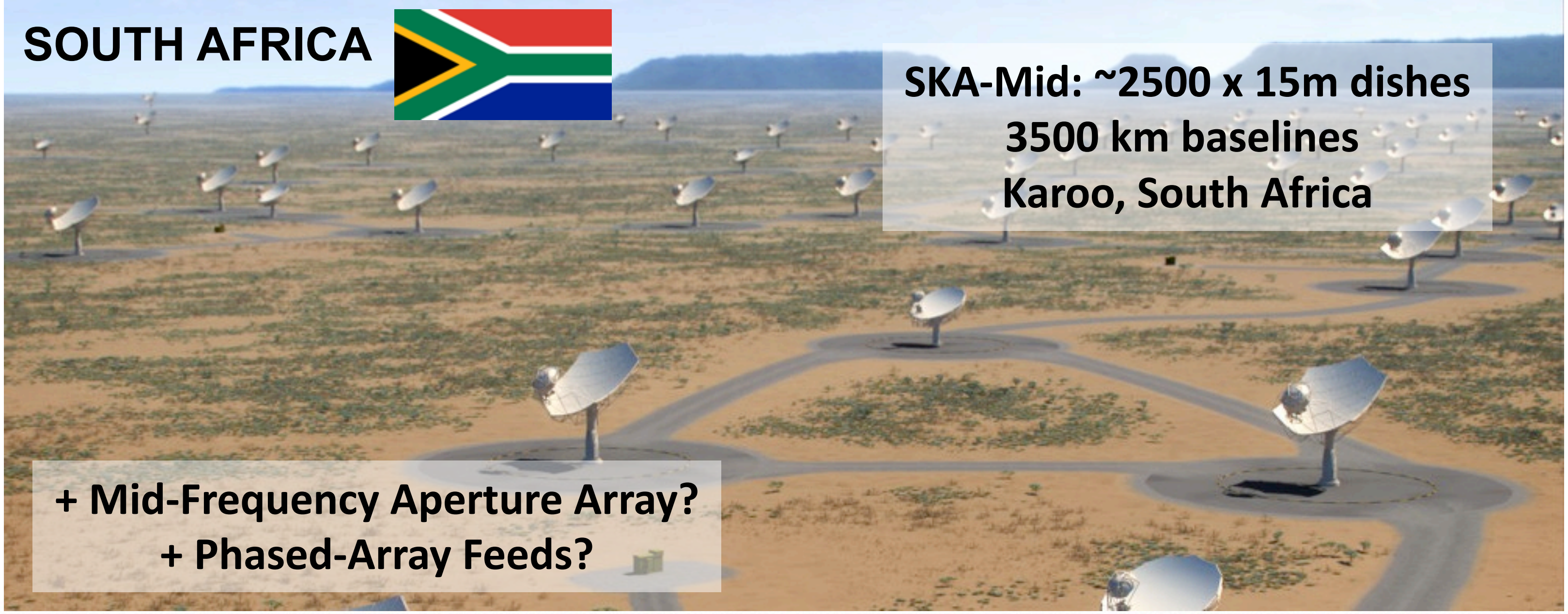
SKA1-Mid: 133 x 15m + 64 x 13.5m dishes,
0.35 – 15 (24) GHz
150 km baselines
(0.22" @ 1.7 GHz; 34 mas @ 15 GHz)
Karoo, South Africa

SKA Phase 2

Start Mid-2020s

AUSTRALIA

SKA-Low: ~500,000 low-freq dipoles,
200 km baselines
Murchison, Western Australia



SOUTH AFRICA

SKA-Mid: ~2500 x 15m dishes
3500 km baselines
Karoo, South Africa

+ Mid-Frequency Aperture Array?
+ Phased-Array Feeds?

SKA1 Bands and Spectral Resolution

Band	Frequency Range	Bandwidth
Low	50 – 350 MHz	300 MHz
Mid Band 1	0.35 – 1.05 GHz	1 GHz
Mid Band 2	0.95 – 1.76 GHz	1 GHz
Mid Band 3	1.65 – 3.05 GHz	1 GHz
Mid Band 4	2.80 – 5.18 GHz	2.5 GHz
Mid Band 5a	4.6 – 8.5 GHz	2 x 2 GHz
Mid Band 5b	8.3 – 15.3 GHz	2 x 2.5 GHz
65,536 channels maximum across any band, zoom windows possible		

Possible Wide-Band and/or High Frequency upgrade paths

Band	Frequency Range	Bandwidth
Mid Band A	1.6 – 5.2 GHz	2 x 2 GHz
Mid Band B	4.6 – 24 GHz	2 x 2.5 GHz
Mid Band 6	15 – 24 GHz	2 x 2.5 GHz

SKA1 Bands and Spectral Resolution

Nominal Frequency	110 MHz	300 MHz	770 MHz	1.4 GHz	6.7 GHz	12.5 GHz
Range [GHz]	0.05-0.35	0.05-0.35	0.35-1.05	0.95-1.76	4.6-8.5	8.3-15.3
Channel width (uniform resolution across max. bandwidth) [kHz]	5.4	5.4	15.2	15.2	61.0	79.3
Channel width (uniform resolution across max. bandwidth) [km/s]	14.7	5.4	6.5	3.3	2.7	1.9
Spectral zoom windows X narrowest bandwidth [MHz]	4 X 4.0	4 X 4.0	4 X 3.125	4 X 3.125	4 X 3.125	4 X 3.125
Finest zoom channel width [Hz]	244	244	190	190	190	190
Finest zoom channel width [km/s]	0.67	0.24	0.08	0.04	0.009	0.004

Band 5a/b maximum zoom results in very fine velocity channels

- generally impractical
  - spectrally average within zoom windows to reduce number of channels
  - use broader zoom windows for more bandwidth with wider channels

65,536 channels maximum across any band, zoom windows possible

16,384 channels maximum within a zoom window

SKA1 Spectral Resolution

SKA1-Mid

- Frequency Slice Approach ➔ Frequency Slice Processors (FSP) 200 MHz
- Each FSP contains ~16k channels
- Each FSP offers zoom windows 100, 50, 25, 12, 6, 3 MHz
- Maximum of 4 zoom windows
- Maximum processed channels (to SDP) is 65,536 (correlator is not the limitation, but data amount sent to SDP)

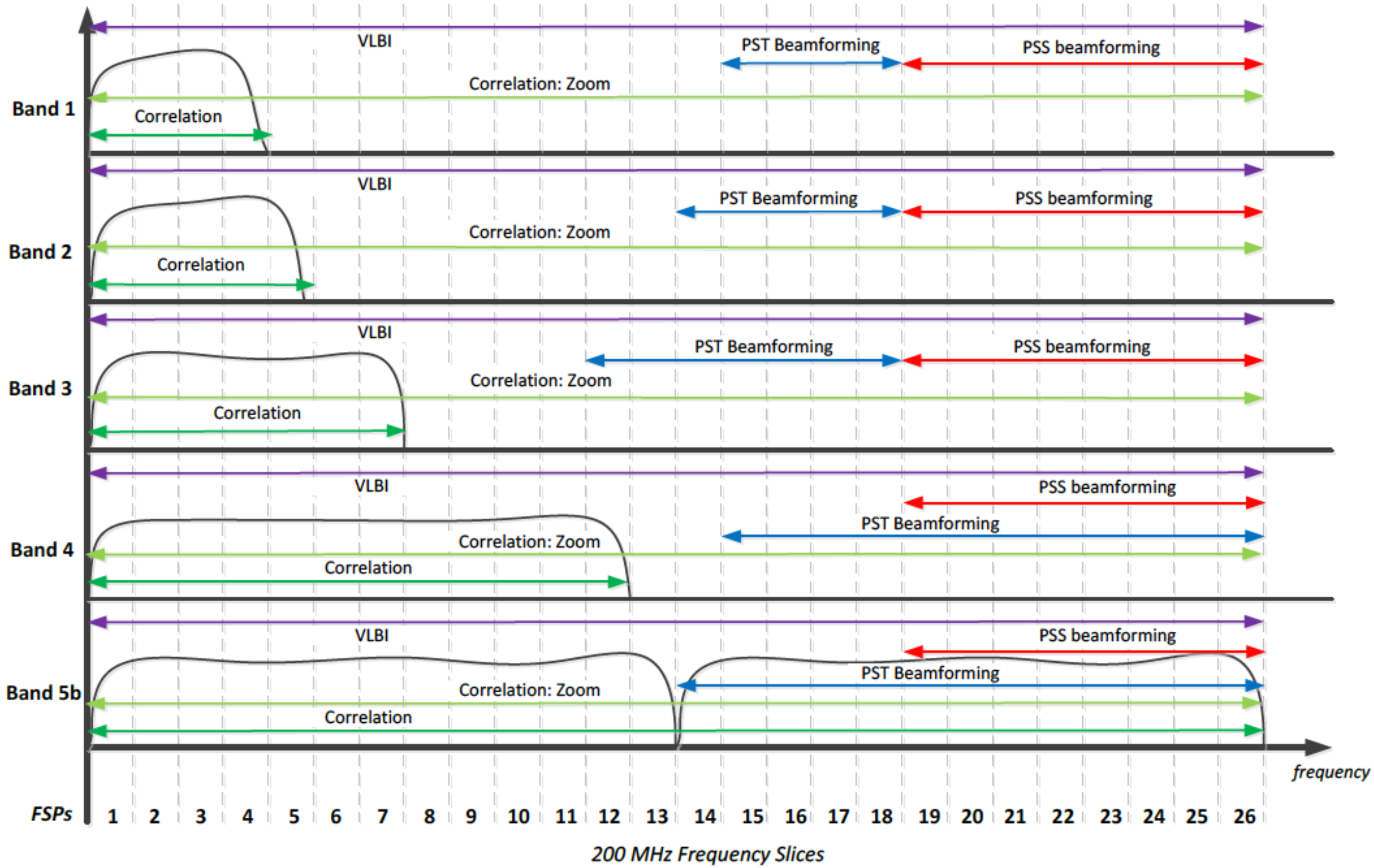
SKA1-Low

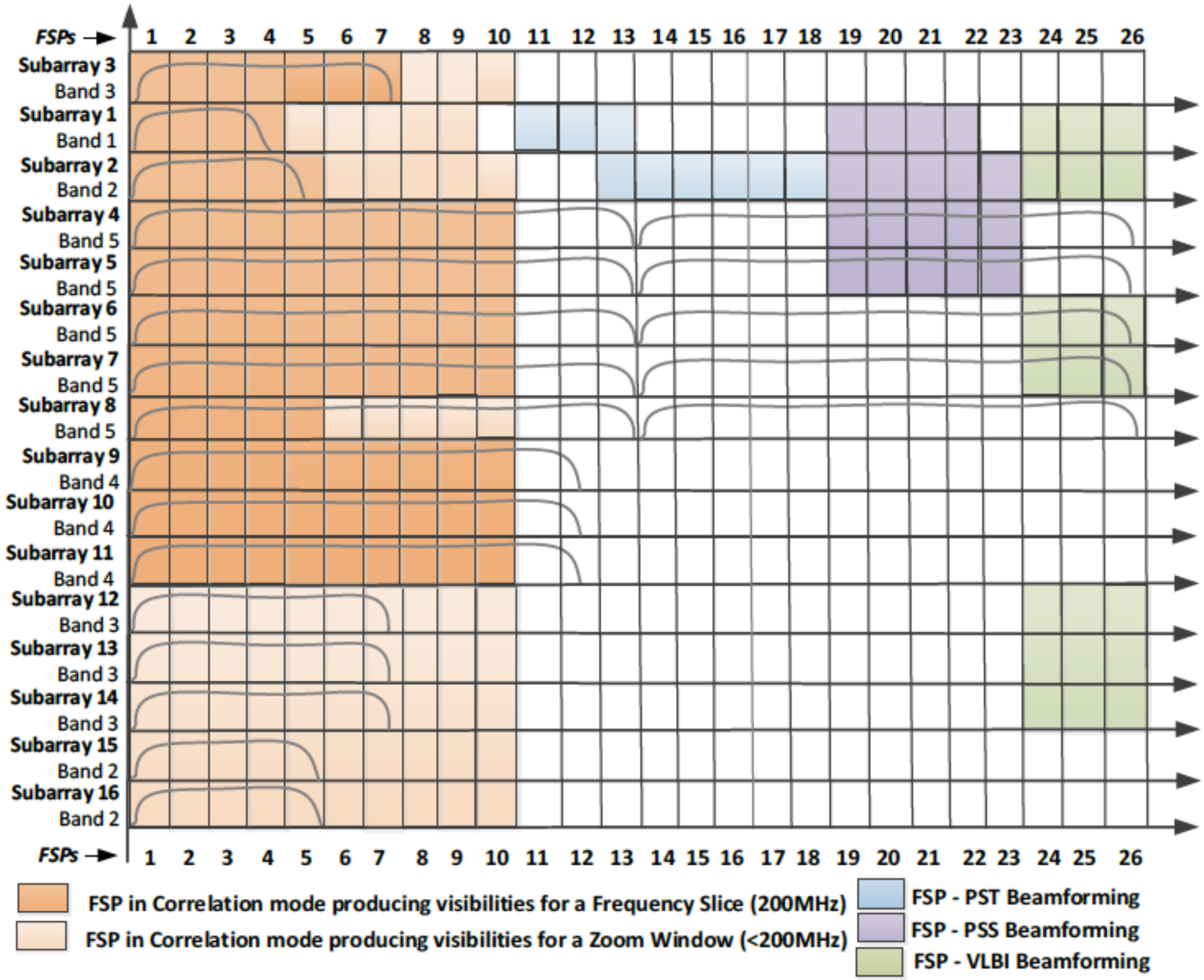
- 65k (55k) channels over 300 MHz (Requirements *at least* 55k channels)
- Zooms of 4, 8, 16, 32, 64, 128 MHz
- Maximum 4 zoom windows of 16k channels each

65,536 channels maximum across any band, zoom windows possible

16,384 channels maximum within a zoom window

Example of correlator possibilities for Mid (this page and next)





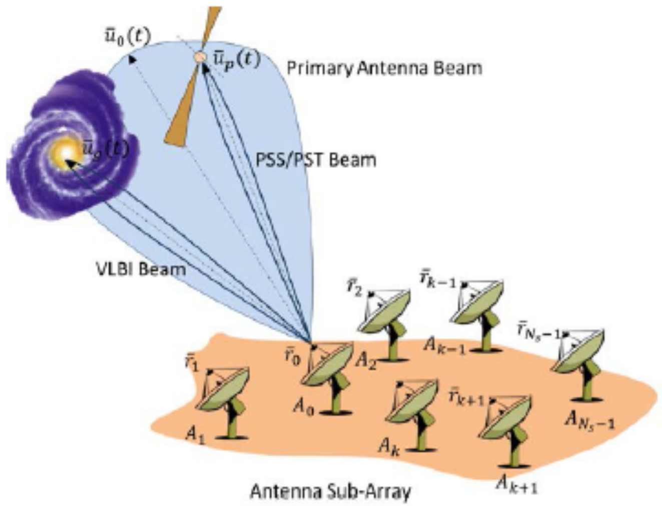
Bandwidth for each Band is shown to illustrate how much of the Band is correlated in units of Frequency Slices: portions shown are illustrative and configurable.

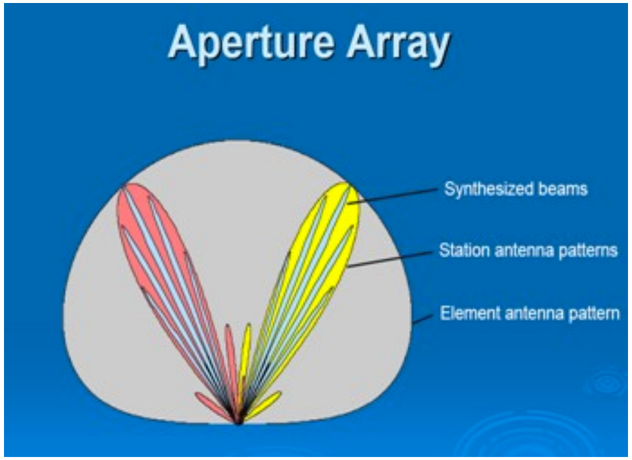
SKA1 Pulsar Search & Timing

	Search		Timing		Bandwidth
	Beams	Subarrays	Beams	Precision (1 sigma)	
SKA1-Mid	1500	up to 16	16 (8 on B5)	5 ns	300 MHz
SKA1-Low	500	up to 16	16	10 ns	100 MHz

Simultaneous imaging, VLBI, pulsar search & pulsar timing possible (commensal/sub-arrays)

4 independently steerable VLBI beams available



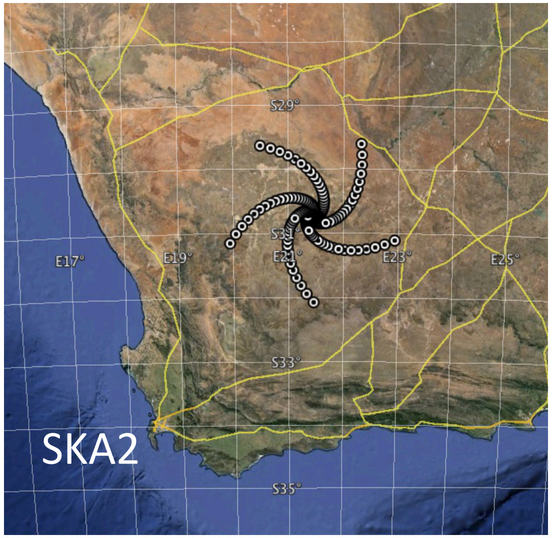


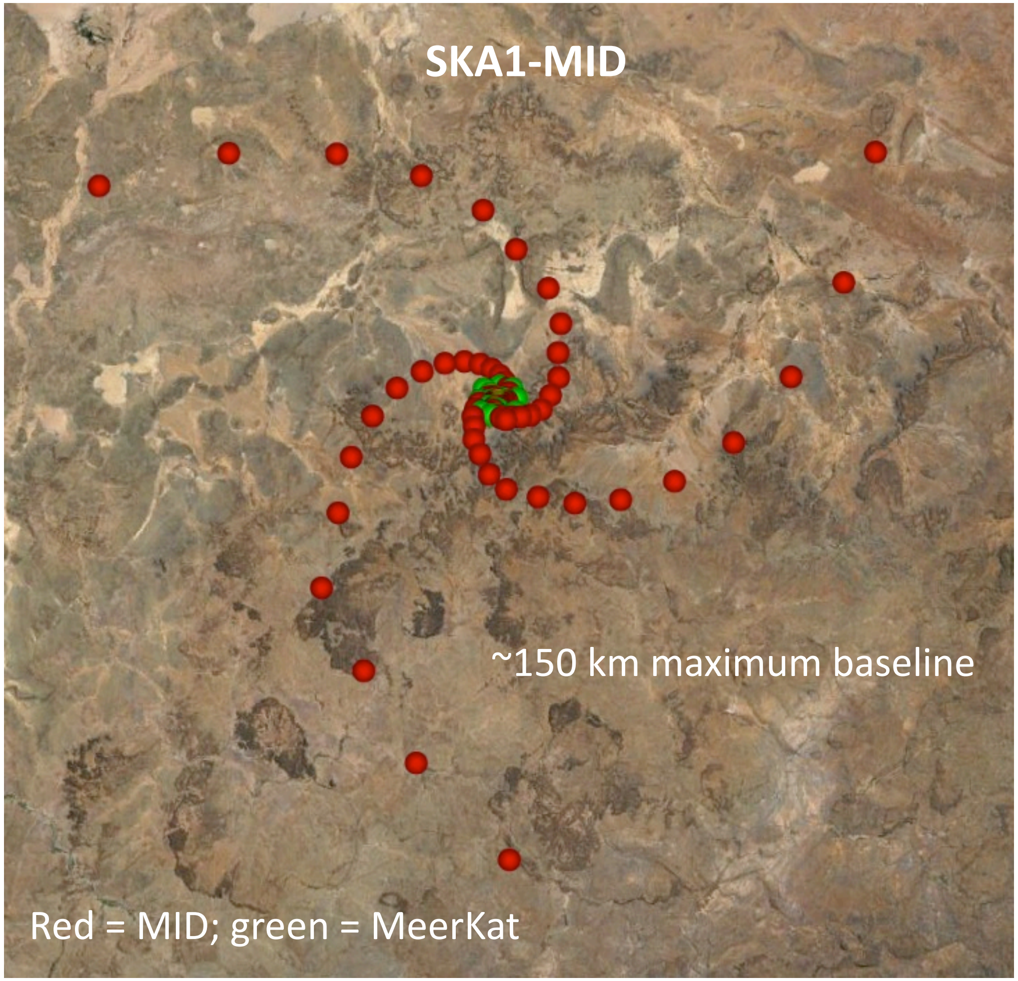
SKA Configurations

Fixed positions

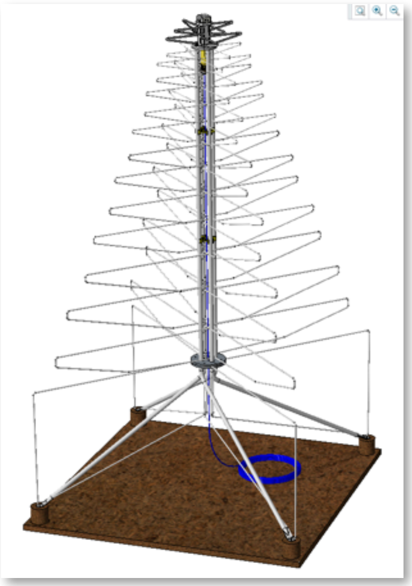
Dense inner-core (~2 km diam., 50%)
→ Brightness Sensitivity
→ Pulsar Sensitivity

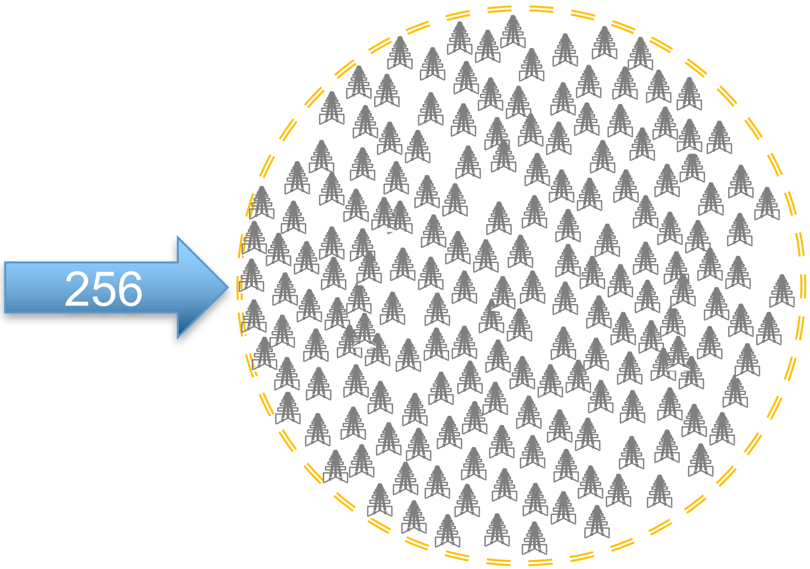
Logarithmic spiral arms
→ Imaging a range of angular scales ("scale-free")

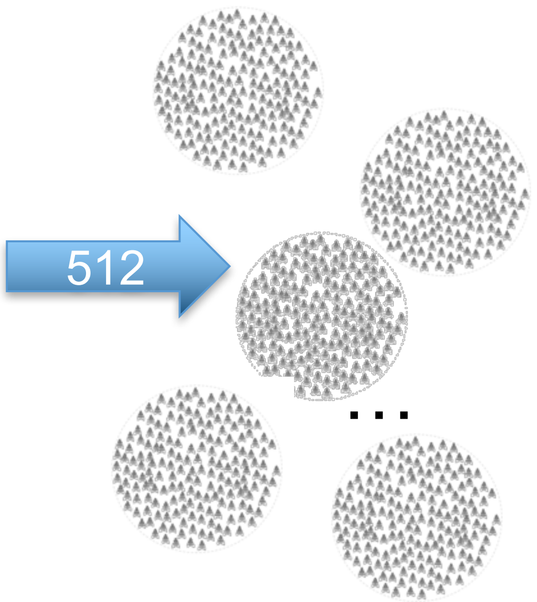




SKA1-Low: Array of Arrays







SKA1-Low
Antenna/Receptor

Antenna Beam

SKA1-Low
"Station"

Station Beam

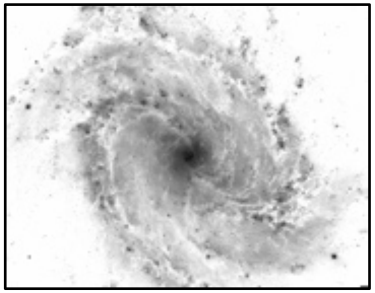
SKA1-Low
"Array"

Correlation and *Tied-array Beams*

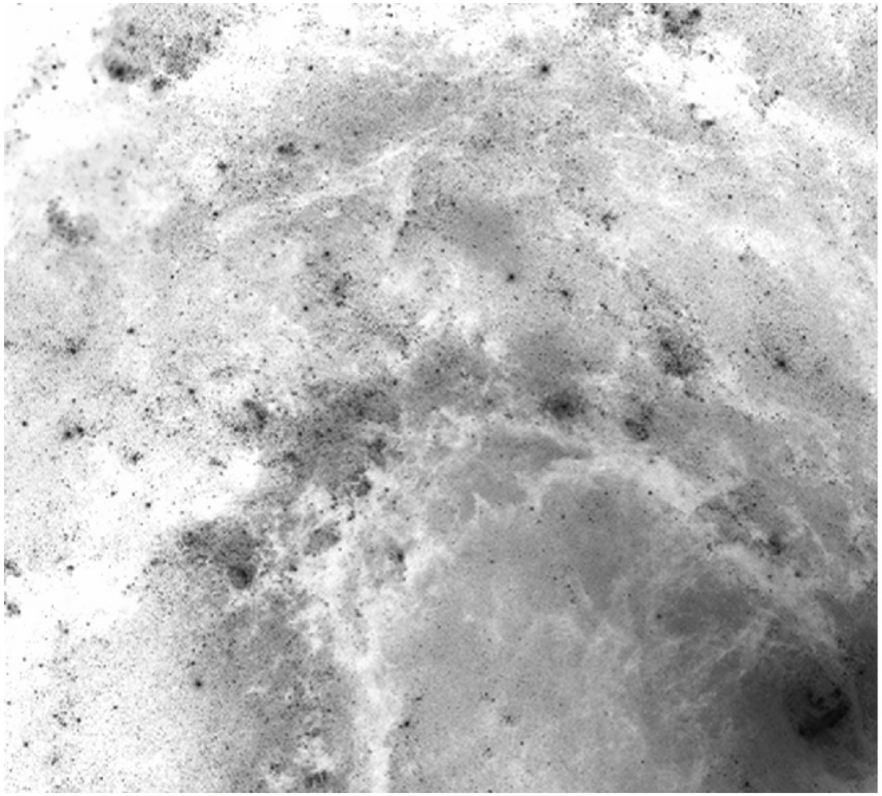
Imaging Performance (Mid)*

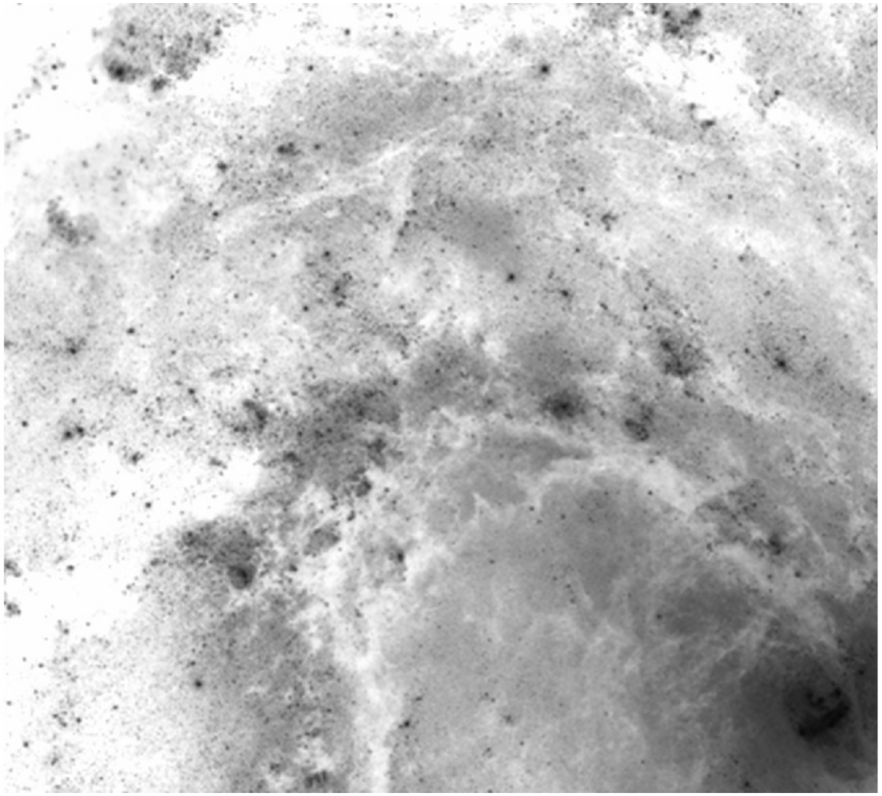
*Noiseless

Input Model Image



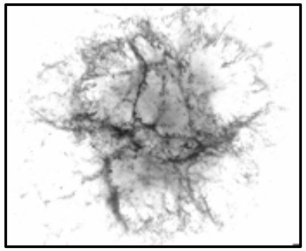
SKA1-Mid, 8h track



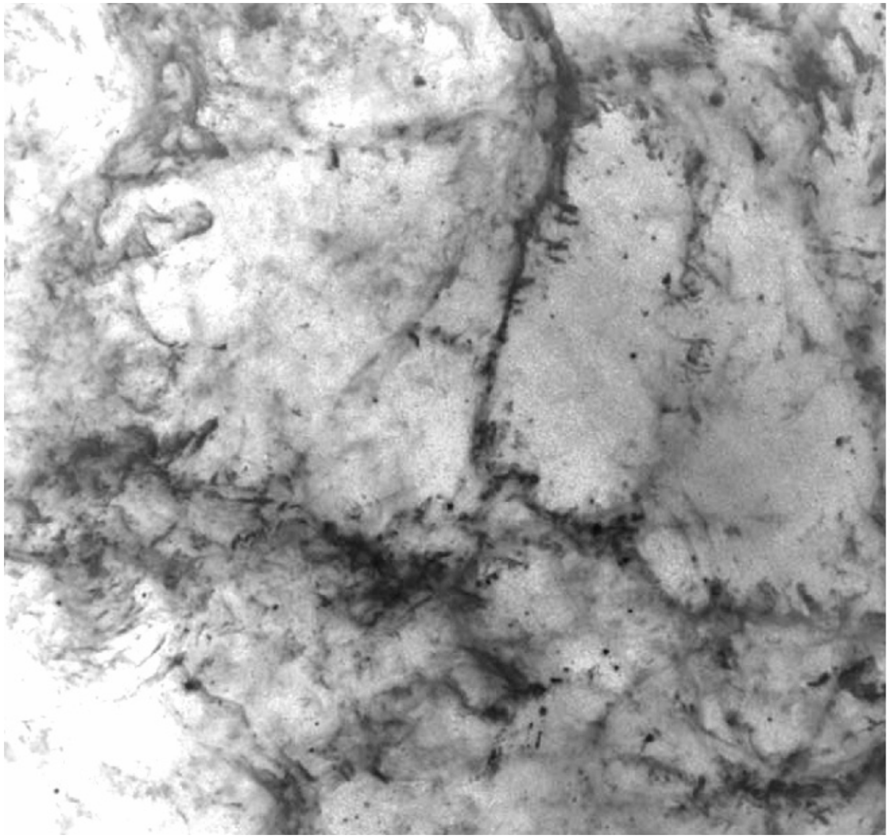


Imaging Performance (Low)*

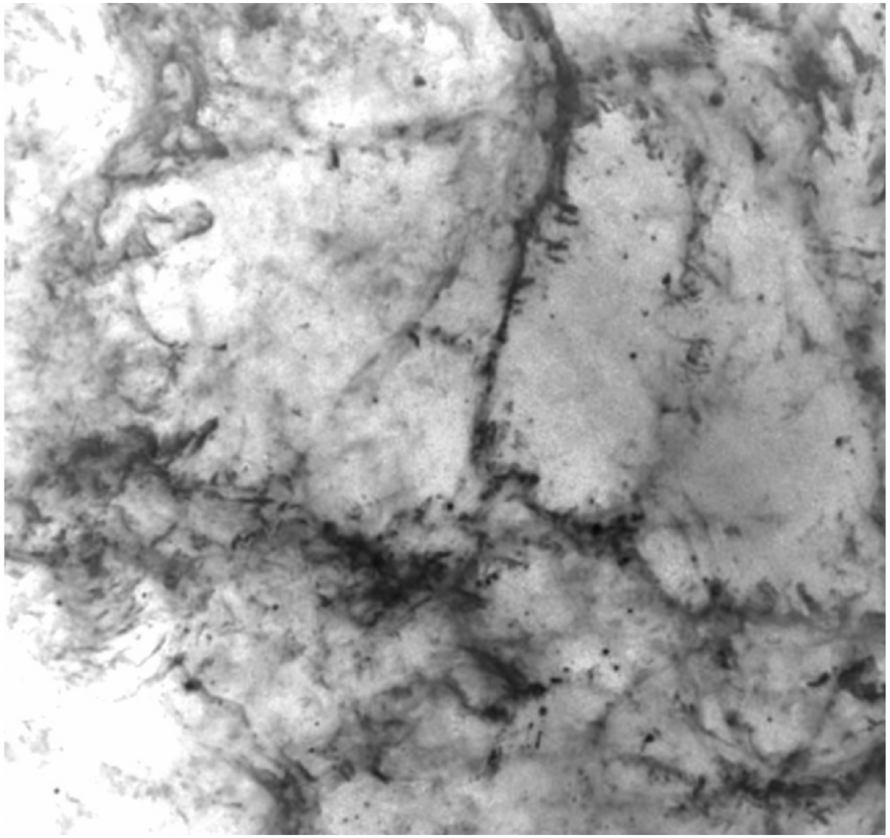
*Noiseless



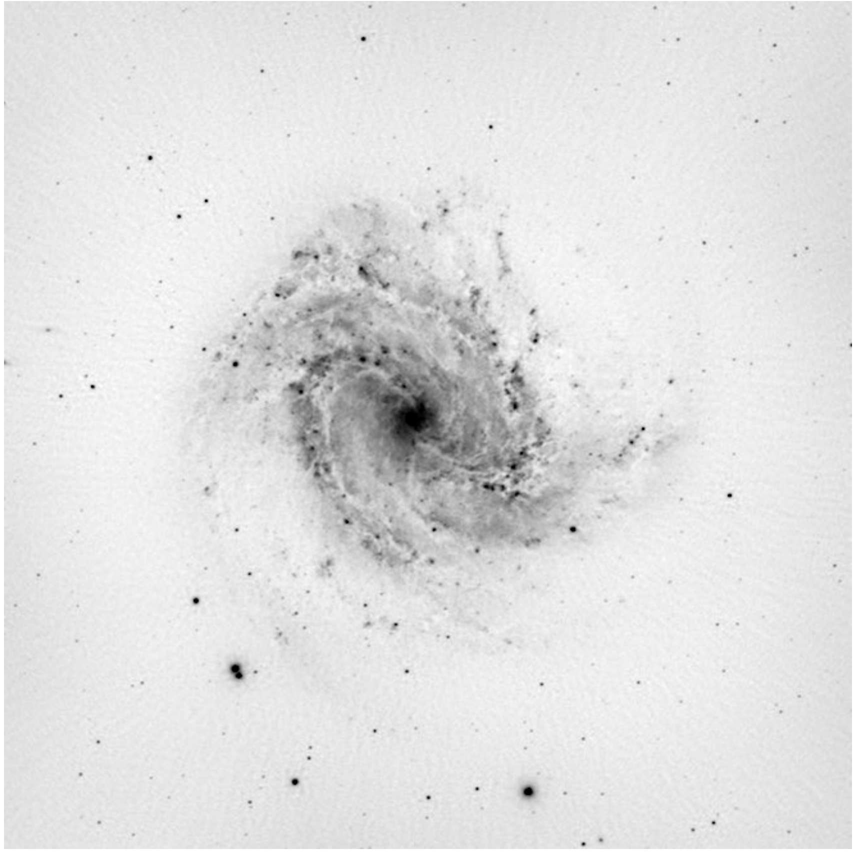
Input Model Image



SKA1-Low, 4h track

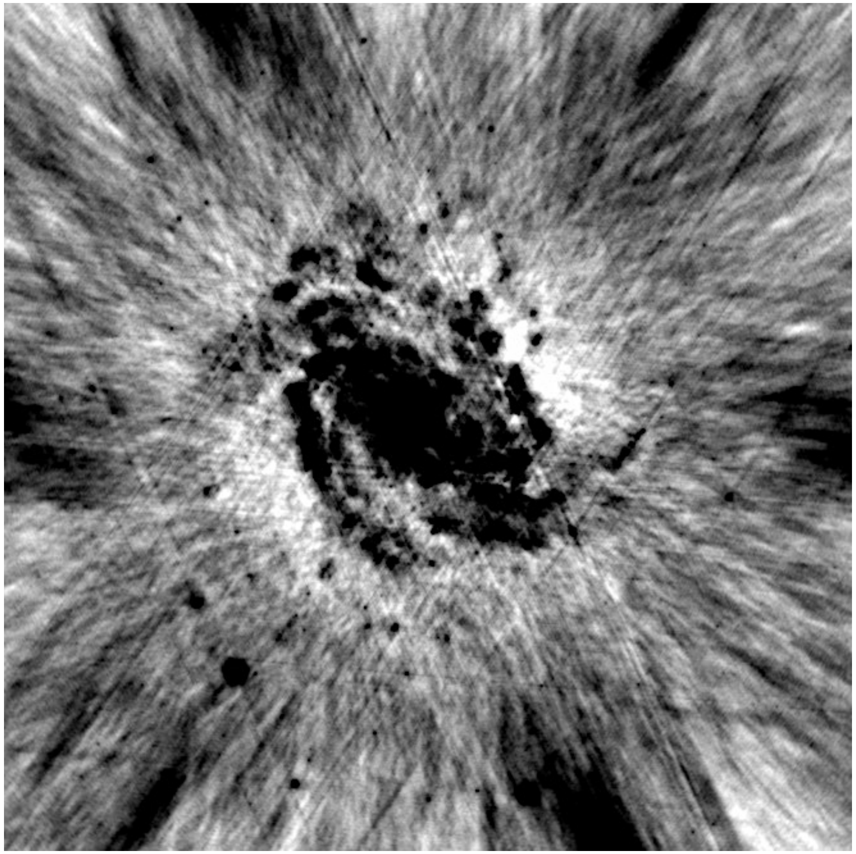


Imaging Performance*



SKA1-MID Snapshot observation

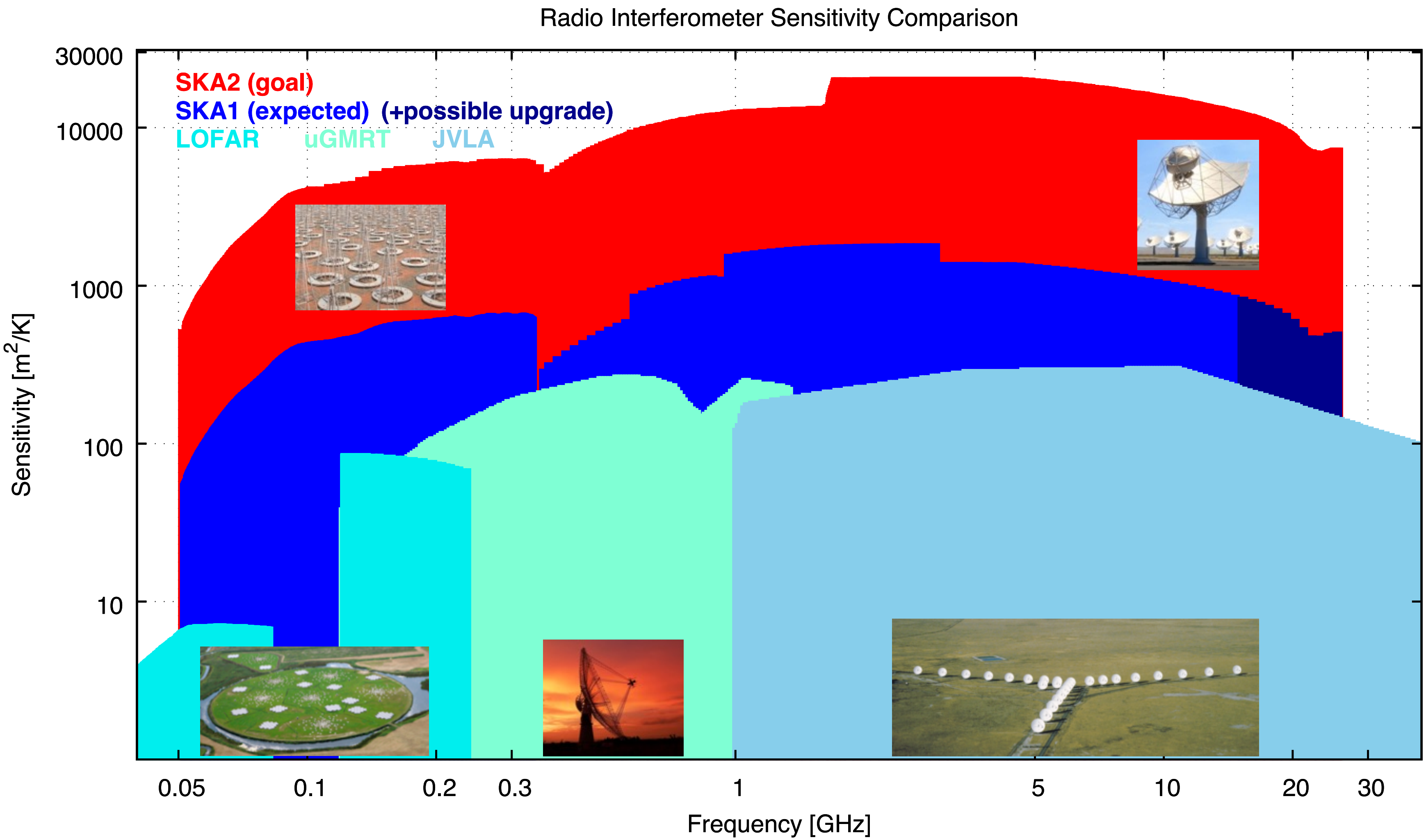
*Noiseless



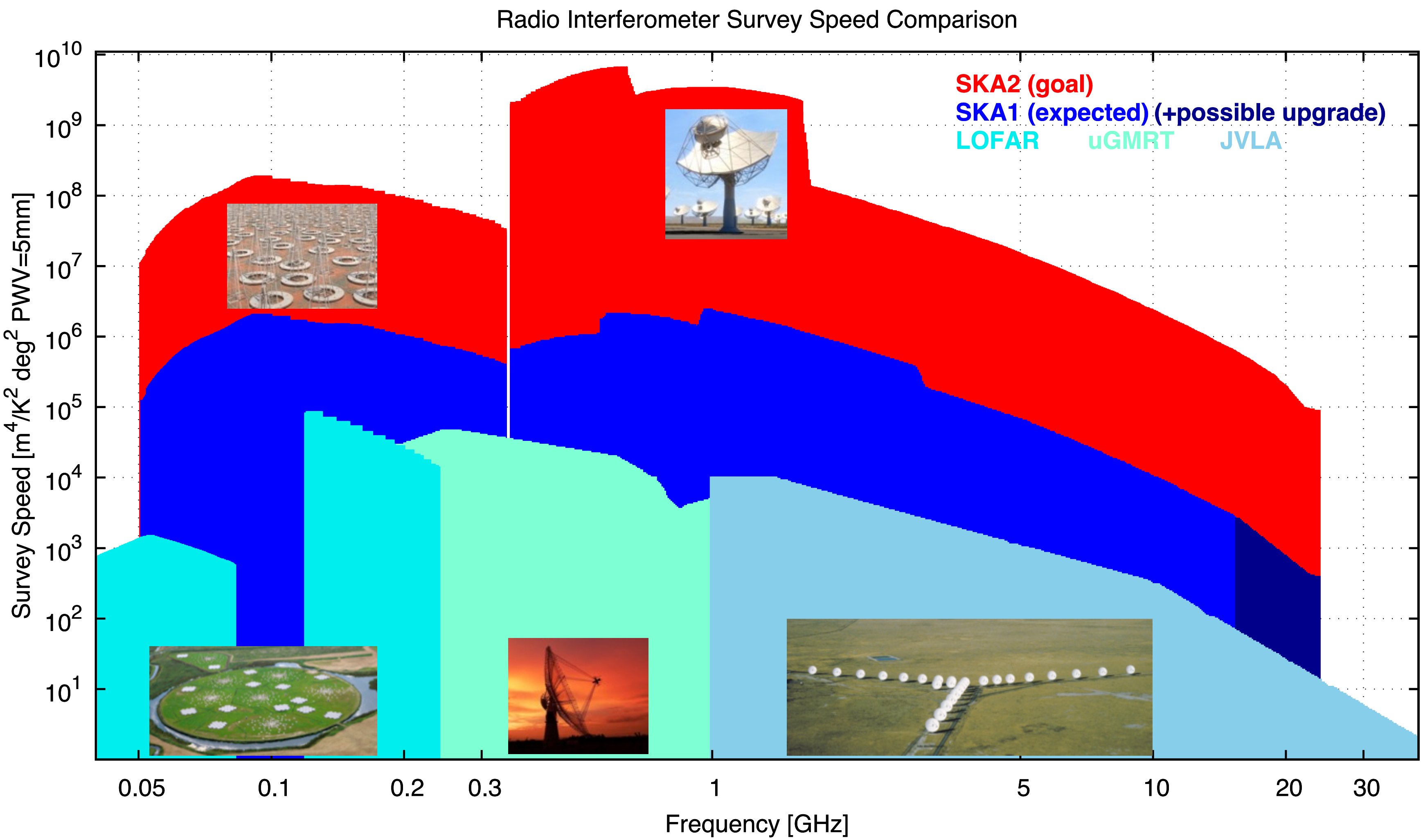
VLA Combination Snapshot
A+B+C+D array configuations

VLA Produces Amazing Science

Sensitivity Comparison



Survey Speed Comparison



Sensitivity Estimates

Frequency [GHz]	Line Sensitivity[a] [μJy per beam]	Continuum Sensitivity[b] [μJy per beam]	Min. Beam Size[c] [arcsec]	Max. Beam Size[c] [arcsec]
0.11	1850	26.0	12.00	600
0.30	800	14.0	6.00	300
0.77	300	4.4	1.00	145
1.40	140	2.0	0.60	78
6.70	90	1.3	0.13	17
12.50	85	1.2	0.07	9

One hour integrations

Table Notes:

[a] Line sensitivity assumes fractional bandwidth per channel of $\Delta\nu/\nu = 10^{-4}$ (>10^{-6} will be possible)

[b] Continuum sensitivity assumes fractional bandwidth per channel of $\Delta\nu/\nu = 0.3$

[c] The sensitivity numbers apply to the range of beam sizes given by Min. and Max. beam sizes

Anticipated SKA1 Science Performance: https://astronomers.skatelescope.org/documents/

Science Data Products

1. Image Cubes
   - continuum, residual, clean components, line cube, residual line, psf
2. (u,v) Grids
   - gridded calibrated visibilities (FFT of dirty image)
3. Calibrated Visibilities
   - EoR, with direction dependent calibrations and time/freq. averaging
4. Local Sky Model (LSM) Catalogue
5. Transient Source Catalogue
6. Pulsar Timing Solutions
7. Transient Buffer Data
   - Voltage data
8. Sieved Pulsar and Transient Candidates
9. Science Alerts Catalogue
10. Science Product Catalogue

Data processed at SDP centres in Perth and Cape Town

Data delivered from SDP centres to SKA Regional Centres (SRCs)

Users obtain data via SRCs; Further Processing and Analysis performed at SRCs

Science Data Products

Image Products 1: Image Cubes

1. Imaging data for Continuum, as cleaned restored Taylor term images (n.b. no image products for Slow Transients detection have been specified – maps are made, searched and discarded)
2. Residual image (i.e. residuals after applying CLEAN) in continuum
3. Clean component image (or a table, which could be smaller).
4. Spectral line cube after continuum subtracted
5. Residual spectral line image (i.e. residuals after clean applied)
6. Representative Point Spread Function for observations (cutout, small in size compared to the field of view (FOV))

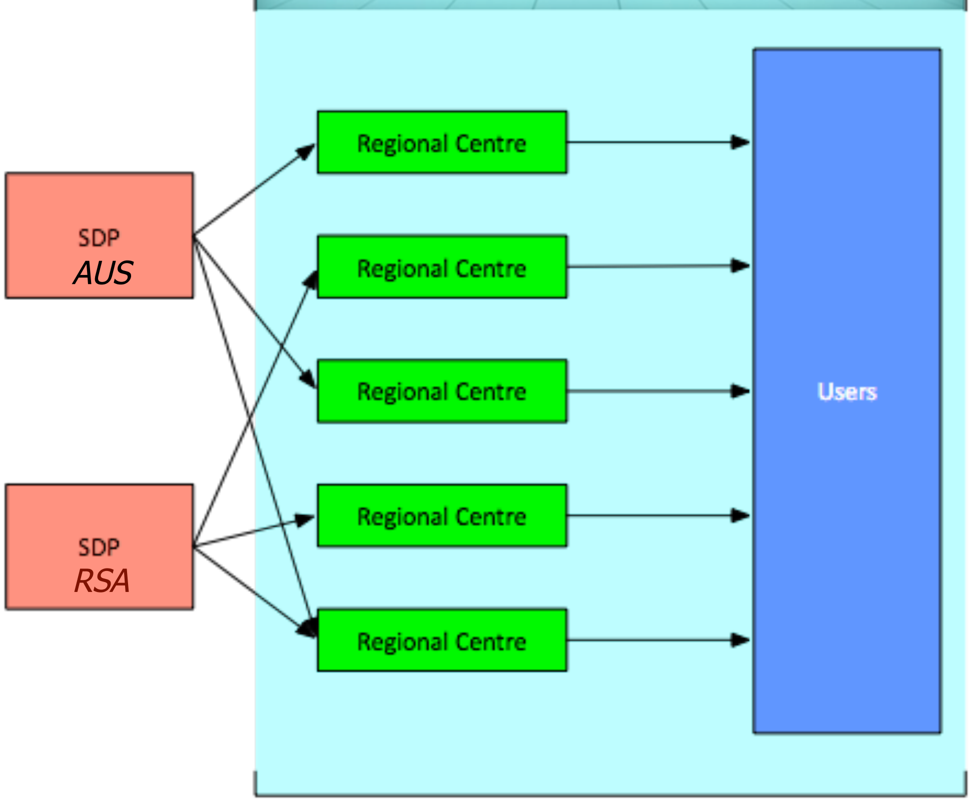
SKA Regional Centres – outside SKAO scope

Required

- ✓ capacity for reprocessing data and their analysis
- ✓ storage for a long-term archive
- ✓ local user support

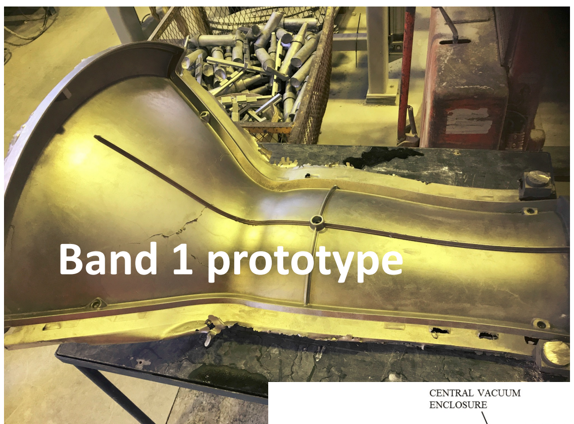
Intent

- ➢ SKA partner countries planning SKA regional Centres
- ➢ National super-computing centres
- ➢ Provide local support to scientists
- ➢ Development of new techniques, new algorithms
- ➢ Deliver SKA science

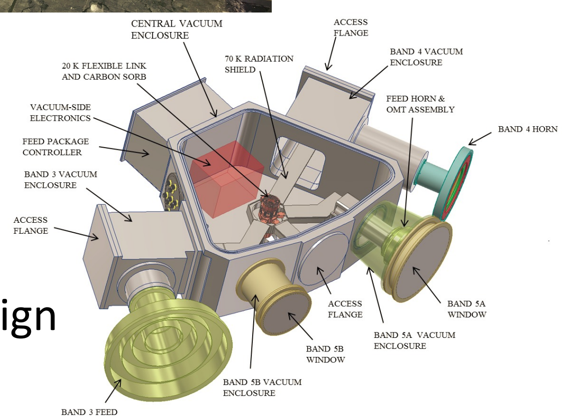


Technical Progress

- SKA-P Prototype Assembled in China
- SKA-MPI Prototype Assembly starts in South Africa mid-2018

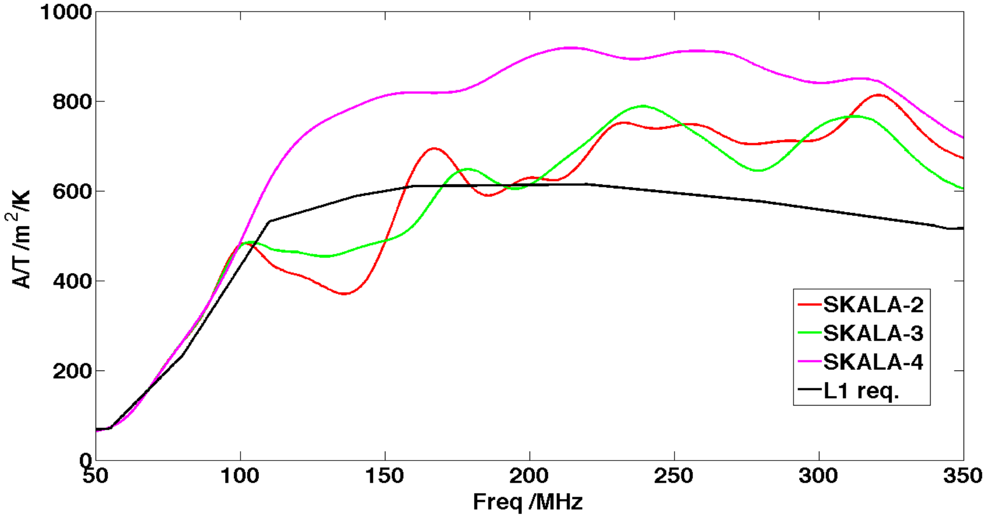


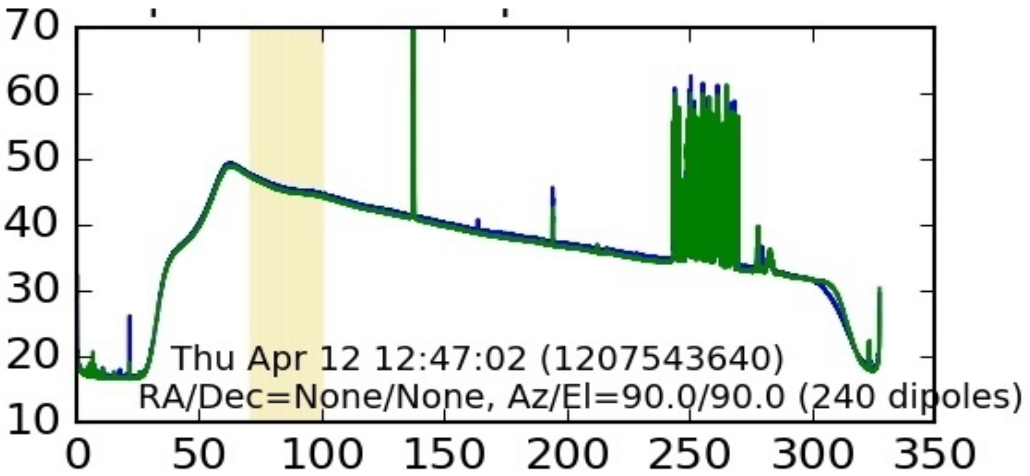
Band 1 prototype



Band 3/4/5 design

Technical Progress





SKA1 Observing Time

KEY SCIENCE PROJECTS (KSPs)

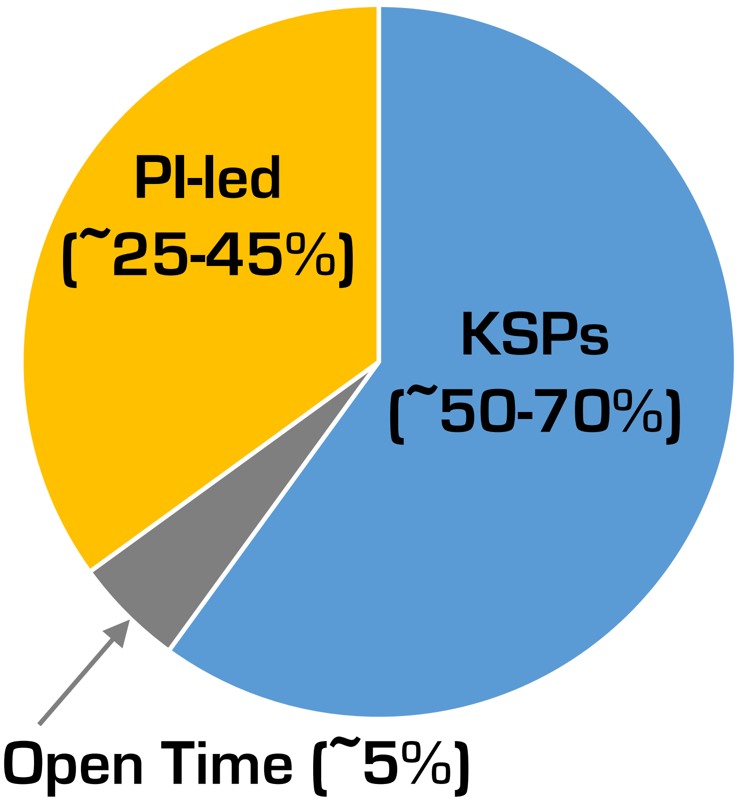
- Large programs (>1000 h) performed over multiple semesters (nominally 1 year)
- PI & management team from SKA-member countries; co-Is from any country
- Expected to provide added-value data products and tools back to SKAO

PRINCIPAL INVESTIGATOR (PI) PROJECTS

- Small programs (<1000 h) performed within a single semester
- PI and majority of co-Is from SKA-member countries

OPEN TIME (~5% of available time)

- Small programs led by PI from any country, performed with a single semester



Limited Open Skies – most time will go to astronomers from member countries

Key Science Projects ('KSPs')

Draft KSP Policy/Principles (details TBD)

- **Only** scientists from SKA member countries may lead a KSP
- KSP Leadership is guaranteed to be distributed amongst SKA members in proportion to their financial contribution
- KSP participation (at the non-Leader level) is guaranteed to be distributed amongst SKA members in proportion to their financial contribution
- KSP participation (at the non-Leader level) of SKA non-members is capped at the value defined in the Access Policy
- KSPs will be science driven and justified on scientific grounds
- KSP proposals will be reviewed by external referees, and the TAC will recommend the allocation of time
- SKAO will manage the overall observing programme, including monitoring and accessing progress of each KSP

Limited Open Skies – most time will go to astronomers from member countries

Key Science Projects ('KSPs')

Draft KSP Policy/Principles (details TBD)

- KSP proposals will include
  - a) consortium management plan
  - b) data management and processing plan
  - c) data products and algorithm release plan
  - d) regular progress reports

- The higher order data products will be made available to the SKA community under the terms of the SKA Access Policy, via Science Regions Centres (SRCs).

Limited Open Skies – most time will go to astronomers from member countries

Array Assemblies (AAs)

An **Array Assembly (AA)** event occurs when a predefined set of stand-alone dishes/stations and associated products have been *installed* and *stand-alone* tested, ie not necessarily integrated.

System level integration and verification occurs after an AA event, leading to an Array Release (AR).

An **Array Release (AR)** marks an important integration & verification milestone of an Array Assembly. It implies that the Array Assembly has been integrated into an end-to-end Telescope System and that its key engineering objectives have been achieved. An AR is available for Science Verification activities, some months after an AA event.

Assembly, Integration & Verification Event	Low Stations	Date for Low	Mid Dishes SKA+MK	Date for Mid
AA1	18	C0+35	8 + 0	C0+34
AA2	64	C0+47	64 + 0	C0+44
AA3	256	C0+58	120 + 8	C0+58
AA4	512	C0+70	133+64	C0+67

C0 = Date construction contracts awarded. End of 2020 at present

SKA1 Science Milestones (SMs)

Four major science milestones leading to steady state operations

- Science Verification (SM1)
- Shared Risk PI Observations (SM2)
- PI Observations (SM3)
- Key Science Programs (SM4)

Science commissioning At least one dish/station on site

- Begins with at least one dish/station on site(continuous activity)

[SM1] Science Verification

- AA2, observe community selected targets (i.e., ALMA SV)
- requires sufficient correlator and data processing capability (CASA++)

[SM2] Shared Risk PI Observations

- AA4, subset of Observing Modes tested, one cycle, no guarantee of data
- contribute to commissioning, testing of observing modes
- Pilot KSP observations

SKA1 Science Milestones (SMs)

Four major science milestones leading to steady state operations

- Science Verification (SM1)
- Shared Risk PI Observations (SM2)
- PI Observations (SM3)
- Key Science Programs (SM4)

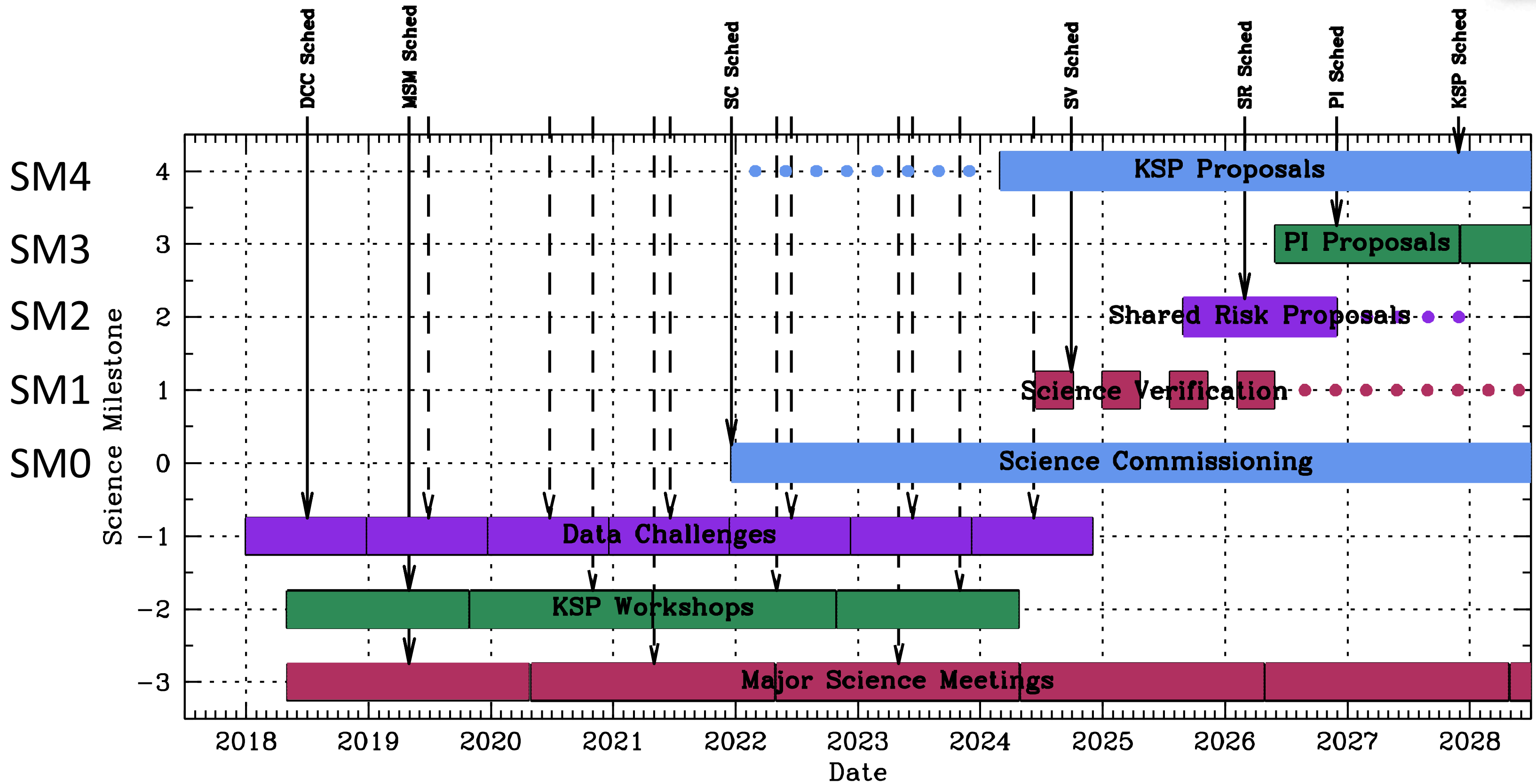
[SM3] PI Observations

- AA4+12, Observing Modes offered are fully commissioned
- similar to Cycle 0 etc on ALMA
- Pilot KSP observations

[SM4] Key Science Projects

- Stable, well-understood system, but not all Obs. modes may be ready
- at least one full cycle of successful PI observations
- Timescale might be different for Mid and Low
- Preceeded by LoI, Co-ordinations Workshops, Call for proposals

SKA1 Science Milestones



- ➢ Overview of preparatory and scientific observing activities
- ➢ KSP Preparatory Activities
  - ✓ Pilot surveys in Shared-risk and PI Proposal Cycles
  - ✓ Commissioning data to facilitate survey and pipeline design

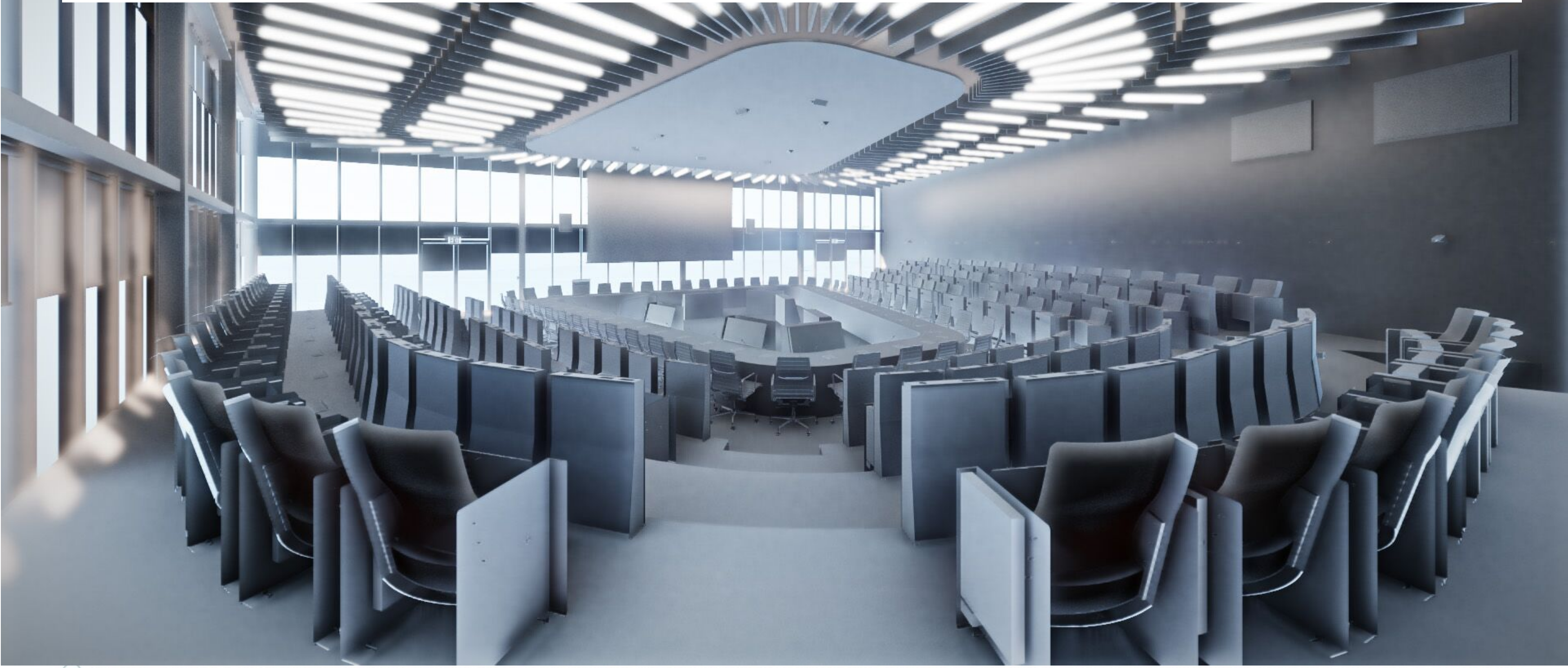
Assuming C0 is 03/2020, updated schedule has C0 = 12/2020

SKA Science/KSP Meeting 2019

New Science enabled by New Techniques in the SKA Era

8-12 April 2019, SKA Headquarters, Jodrell Bank

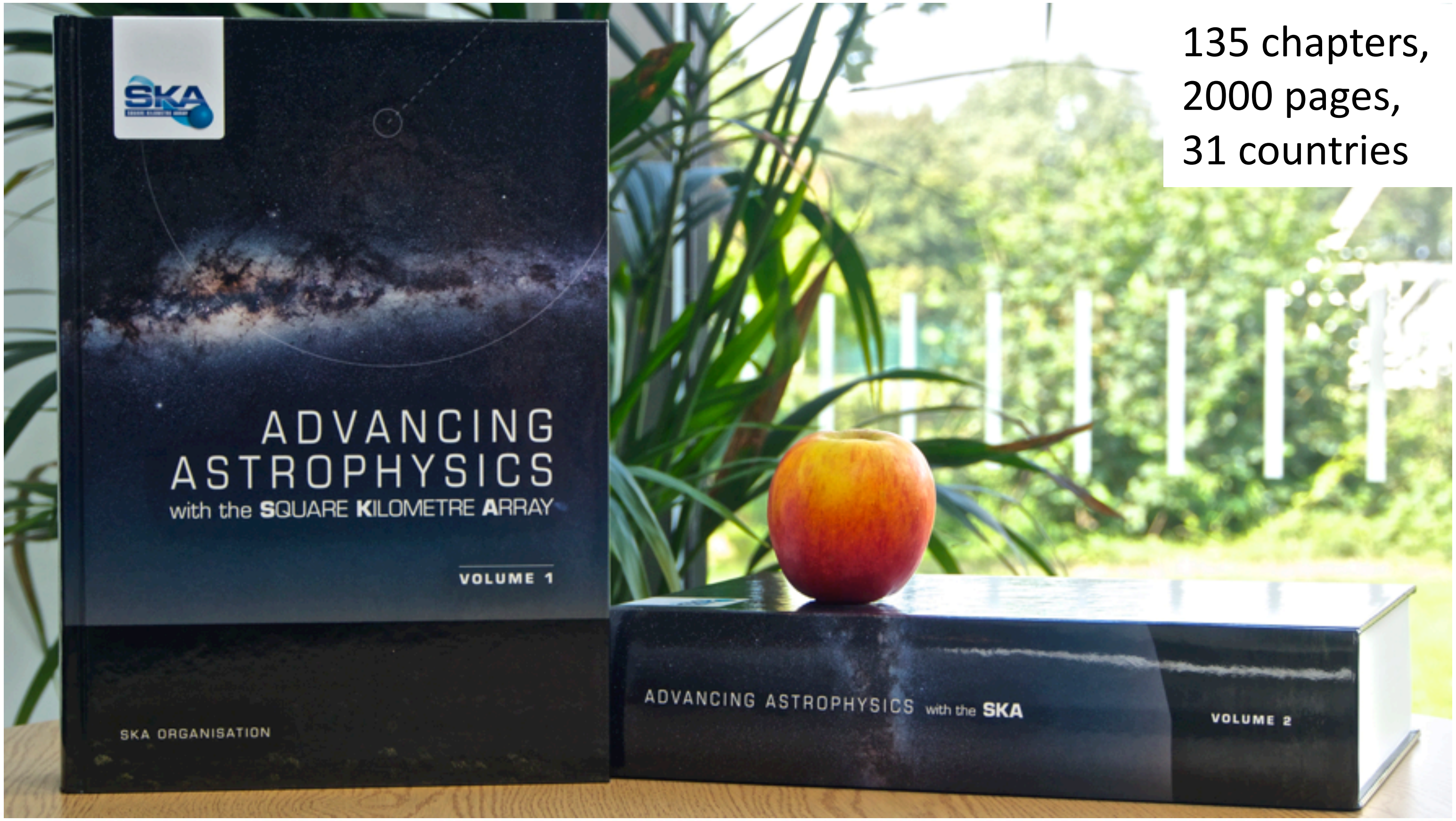
3 days Science – 2 days KSP/SWG discussions



SKA Science Case

http://astronomers.skatelescope.org/meetings-2/aaska14/

www.skatelescope.org/books/

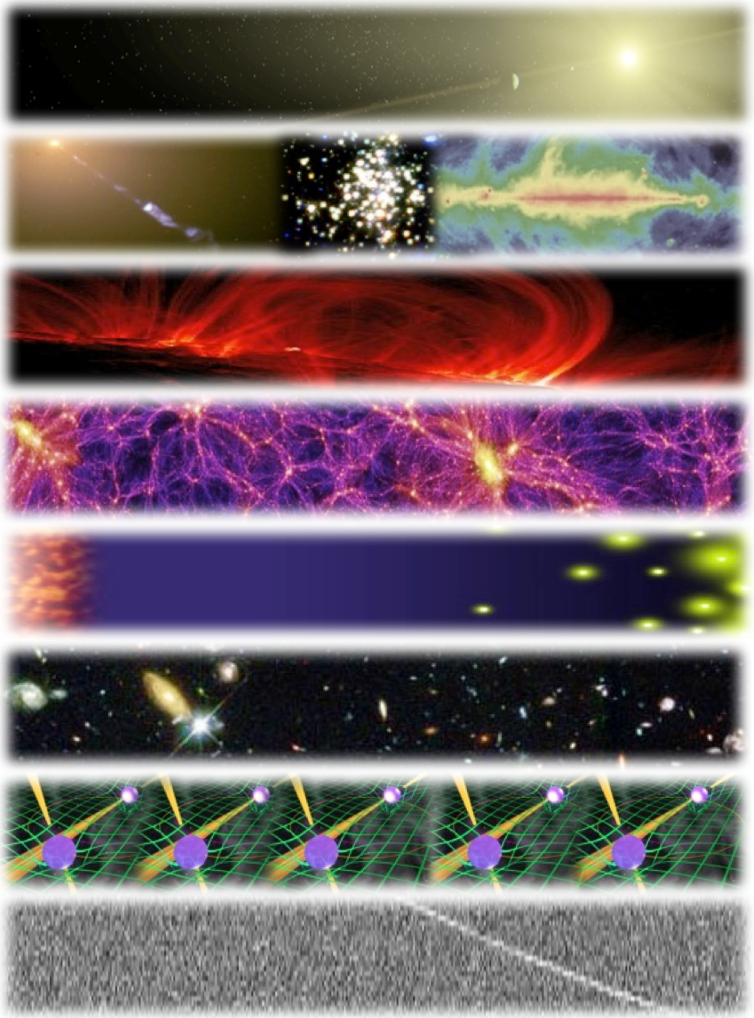


135 chapters,
2000 pages,
31 countries

SKA Science Advisory Groups

Science Working Groups (SWGs)

- Astrobiology ("The Cradle of Life")
- Cosmic Magnetism
- Cosmology
- Epoch of Reionisation & the Cosmic Dawn
- Extragalactic Continuum (+ Surveys)
- Extragalactic Spectral Line
- HI Galaxies
- **Our Galaxy**
- Pulsars ("Strong field tests of gravity")
- Solar and Heliospheric Physics
- Transients (Exploration of the Unknown)



Focus Groups

- High Energy Cosmic Particles
- VLBI

https://astronomers.skatelescope.org/science-working-groups/

SKA Science Advisory Groups

Core members are encouraged to contribute to

- the activities listed under "Charge"
    - Providing advice on the science impact of design changes to the SKA;
    - Providing advice on the expected commissioning and operation of the telescope;
    - Providing a conduit for information on nascent Key Science Projects;
    - Drawing attention to emerging research topics that may be addressed by the SKA;
    - Providing Scientific Organising Committee membership and topical speakers for SKA science meetings;
    - When possible, assisting the SKA Science Team in the dissemination and promotion of science enabled by the SKA to the broader community through presentations at major astronomy meetings, universities and research institutions.
- the day-to-day team activities such as regular participation in telecons and face-to-face meetings,
- undertaking scientific assessments, formulation of scientific use-cases, and other activities as requested by the Working Group Chair and/or Science Director.

SKA Science Advisory Groups

Membership to SWGs is

- open to any actively publishing researcher with a science interest in SKA and willingness to contribute an appropriate level of effort toward SKA science needs as described below.
- open to researchers affiliated with both SKA-member and non-member nations.

Researchers can nominate themselves for membership by contacting the relevant SWG Chair or office project scientist. Each Science Working Group consists of two tiers of membership: Core members and Associate members.

SWGs *are not* proto-KSPs.

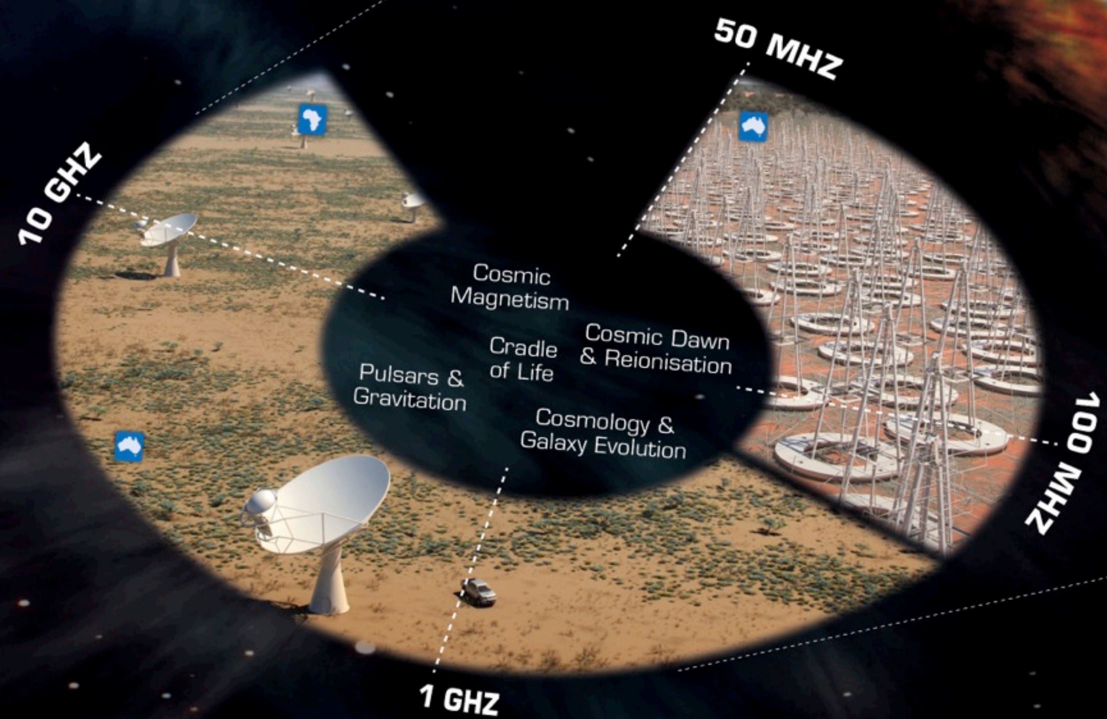
- KSPs may arise from SWGs, but are not restricted to SWGs members
- SWGs can provide a conduit for information on nascent Key Science Projects

SKA Science is on the Horizon

http://astronomers.skatelescope.org/

Useful updates:

1. Minutes/Slides from Monthly SWG Chairs telecons
astronomers.skatelescope.org/swg-chairs-meeting-minutes/
2. SKA e-newsletter
newsletter.skatelescope.org
3. SKAO Bulletin (for the SKA community)
www.skatelescope.org/skao-bulletin/



SKA1 Bands and Spectral Resolution

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Range [GHz]	0.05-0.35	0.05-0.35	0.35-1.05	0.95-1.76	4.6-8.5	8.3-15.3
Telescope	Low	Low	Mid	Mid	Mid	Mid
FoV [arcmin]	327	120	109	60	12.5	6.7
Max. Resolution (arcsec)	11	4	0.7	0.4	0.08	0.04
Max. Bandwdith [GHz]	0.3	0.3	1	1	4	5
Cont. rms, 1 hr (μJy/beam)[a]	26	14	4.4	2	1.3	1.2
Line rms, 1 hr [μJy/beam][b]	1850	800	300	140	90	85
Resolution Range for Cont. and Line rms [arcsec][c]	12–600	6–300	1–145	0.6–78	0.13–17	0.07–9
Channel width (uniform resolution across max. bandwidth) [kHz]	5.4	5.4	15.2	15.2	61.0	79.3
Spectral zoom windows X narrowest bandwidth [MHz]	4 X 4.0	4 X 4.0	4 X 3.125	4 X 3.125	4 X 3.125	4 X 3.125
Finest zoom channel width [Hz]	244	244	190	190	190	190

a. Continuum sensitivity at Nominal Frequency, assuming fractional bandwidth of $\Delta\nu/\nu = 0.3$
b. Line sensitivity at Nominal Frequency, assuming fractional bandwidth per channel of $\Delta\nu/\nu = 10^{-4}$ [$>10^{-6}$ will be possible]
c. The sensitivity numbers apply to the range of beam sizes listed

For more details refer to "Anticipated SKA1 Science Performance"