The SKAO: Science & Status

Philippa Hartley, SKAO Project Scientist

University of Catania, 27th November 2023

The Fourth National Workshop on the SKA Project - Sharpening the Italian science case for the SKAO

The SKA Observatory

*Building and operating the largest **radio** telescopes in the world*


Born February 2021
One Observatory
Two Telescopes
Three Continents
SKAO Global HQ, Jodrell Bank, UK

The **Low** telescope

131,072 x 2 metre log-periodic dipole antennas
Grouped into 256 stations
50-350 MHz
Murchison, **Western Australia**
Located on the traditional lands of the **Wajarri Yamaji**

Credit: SKAO/CSIRO

The **Mid** telescope

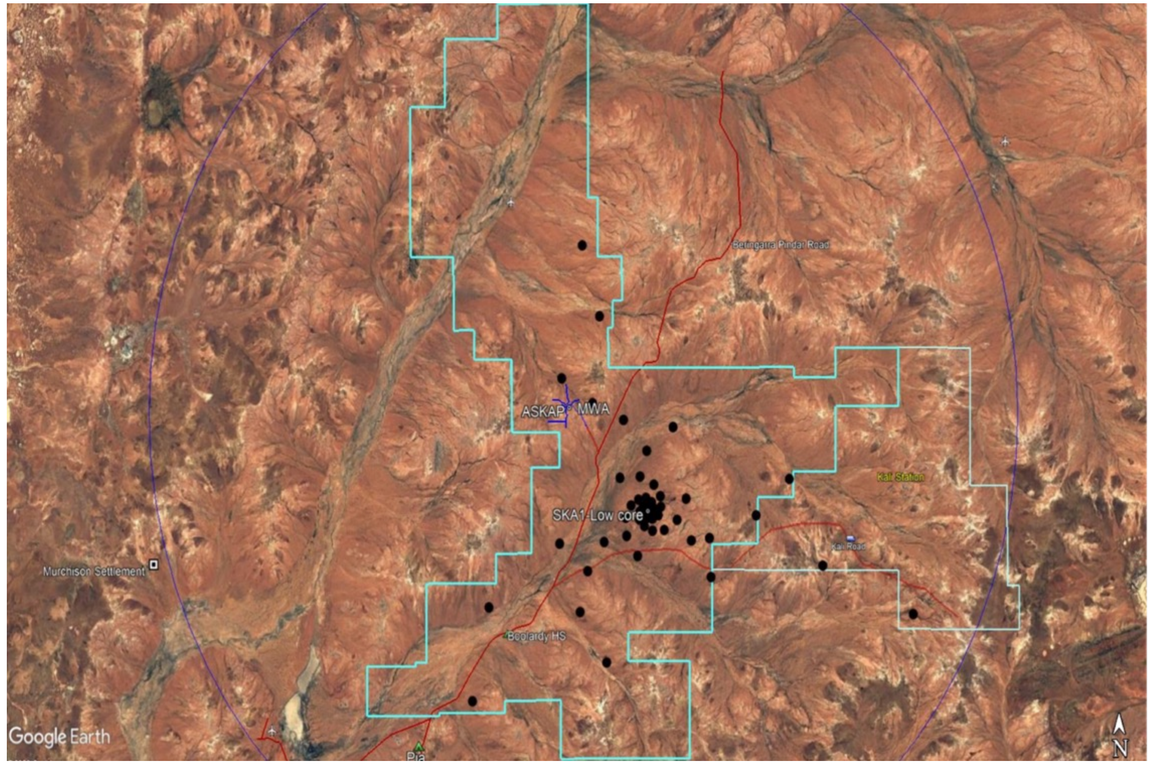
SKAO

197 dishes
(133 x 15m + 64 x 13.5m dishes)
0.35-15 GHz
Karoo, **South Africa**

64 MeerKAT dishes

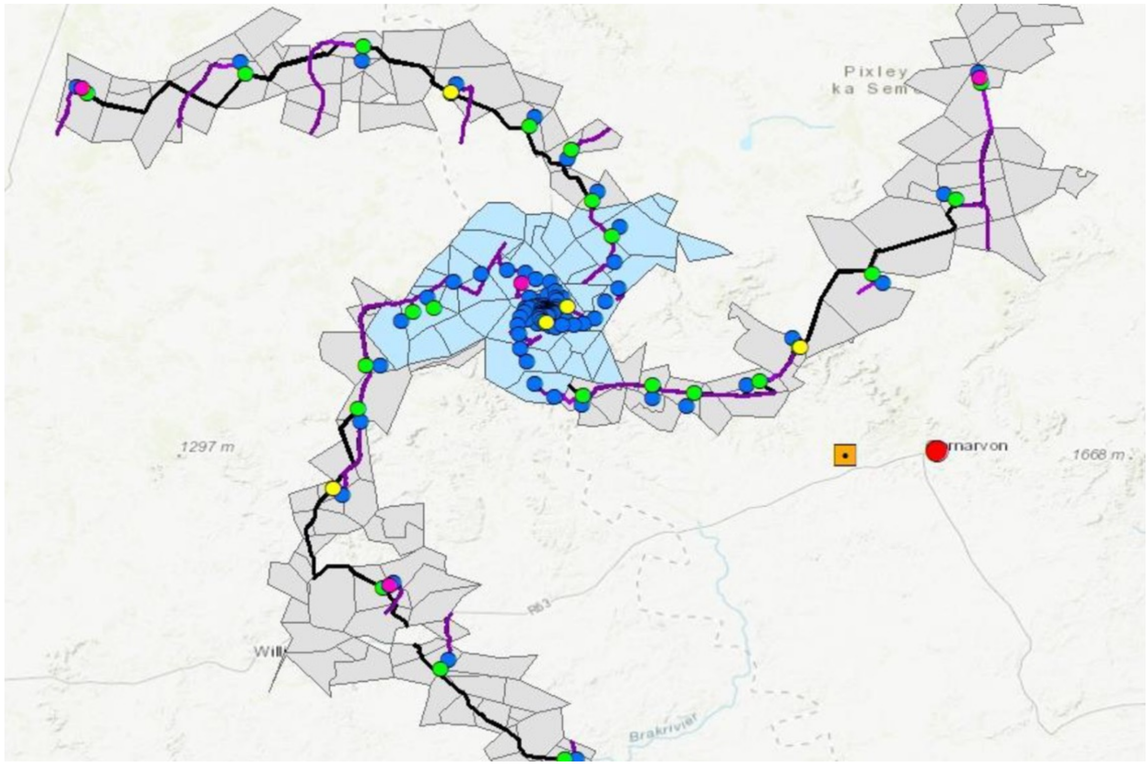
Baselines

Murchison, **Western Australia**



SKA-Low$_i$
74 km max baseline
(11” @ 110 MHz)

Karoo, **South Africa**



SKA-Mid
150 km max baseline
(0.22” @ 1.7 GHz; 34 mas @ 15 GHz)

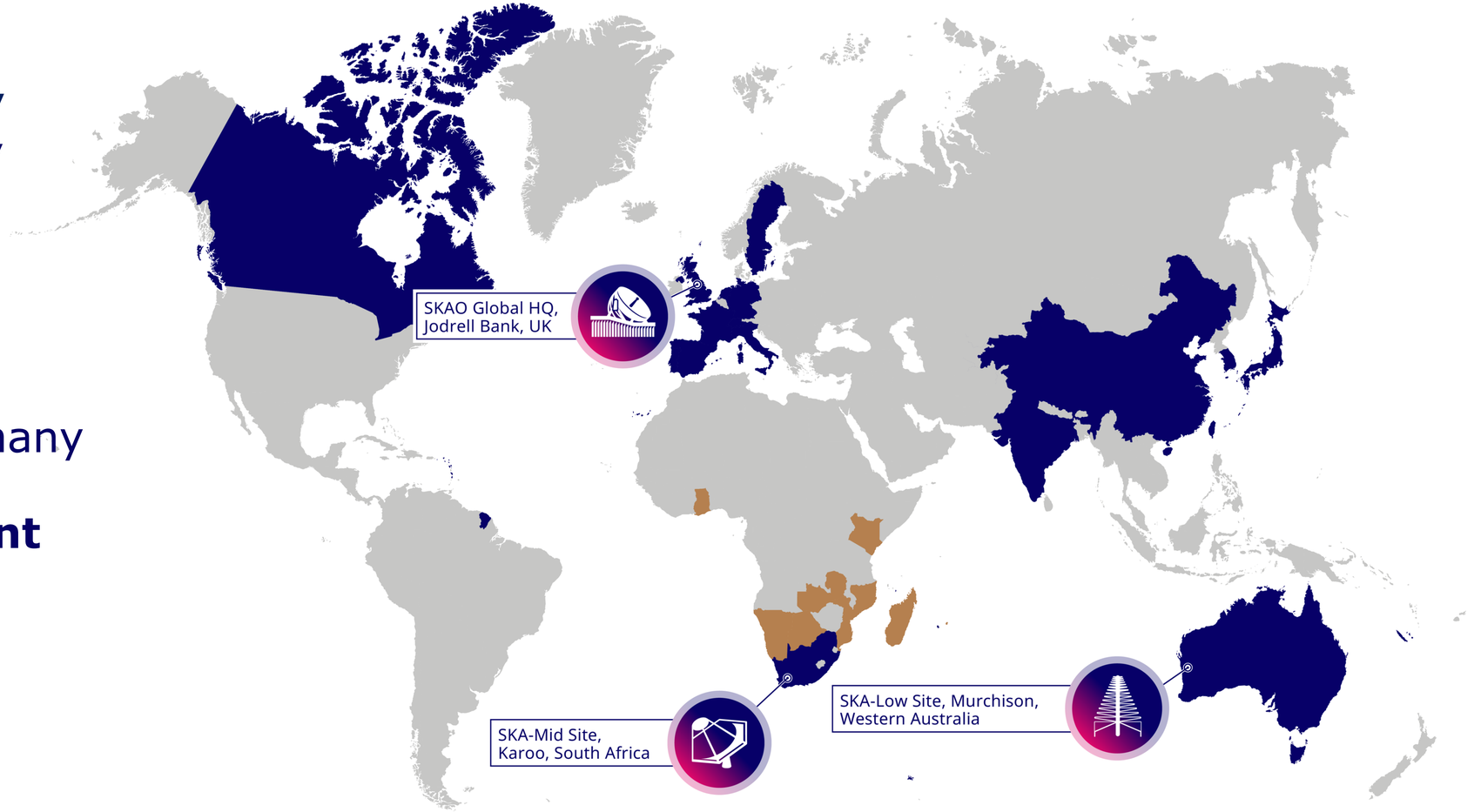
A global collaboration

Full membership:
Australia, China, Italy, Netherlands, Portugal, South Africa, Spain, Switzerland, United Kingdom.

Accession stage:
Canada, France, Germany

Awaiting government decisions:
India, Sweden, South Korea

Early stages:
Japan, South Korea.



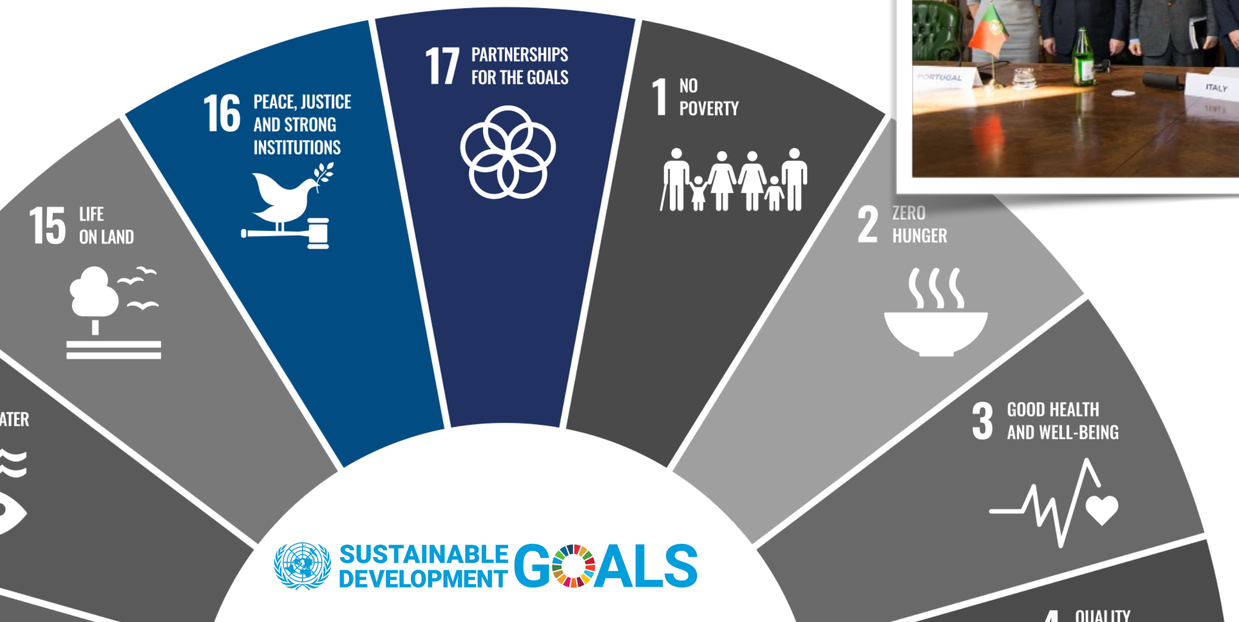
SKAO Partnership - includes SKAO Member States* and SKAO Observers (as of April 2023)

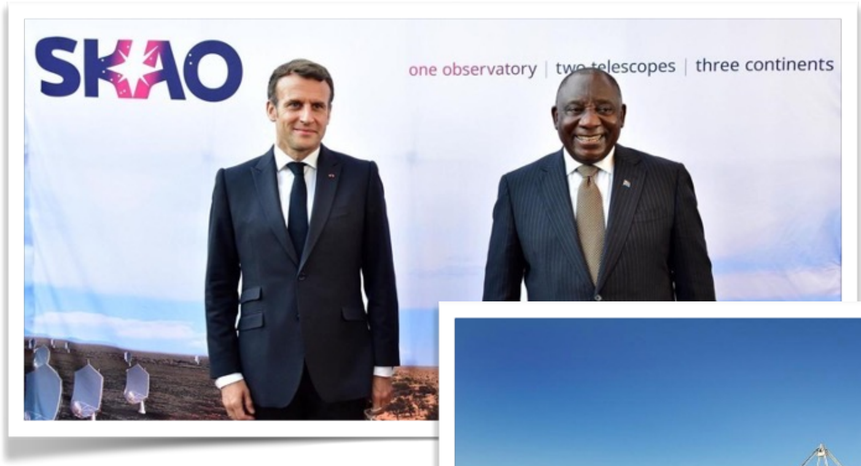
African Partner Countries

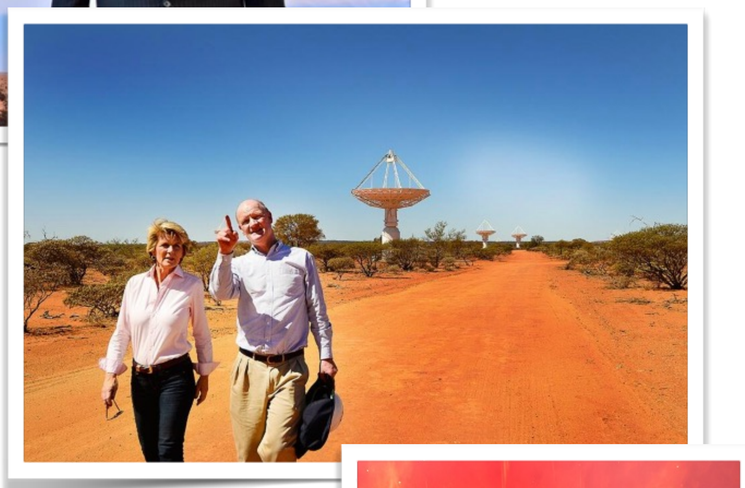
SKAO’s mission is to build and operate cutting-edge radio telescopes to transform our understanding of the Universe and to deliver benefits to society through global collaboration and innovation.

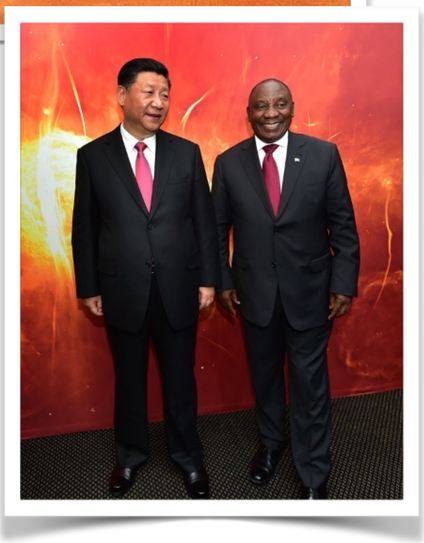
SKAO partnership as a science diplomacy tool

- Build international connections
- Encouraging government-level interaction
- A vehicle for collaboration





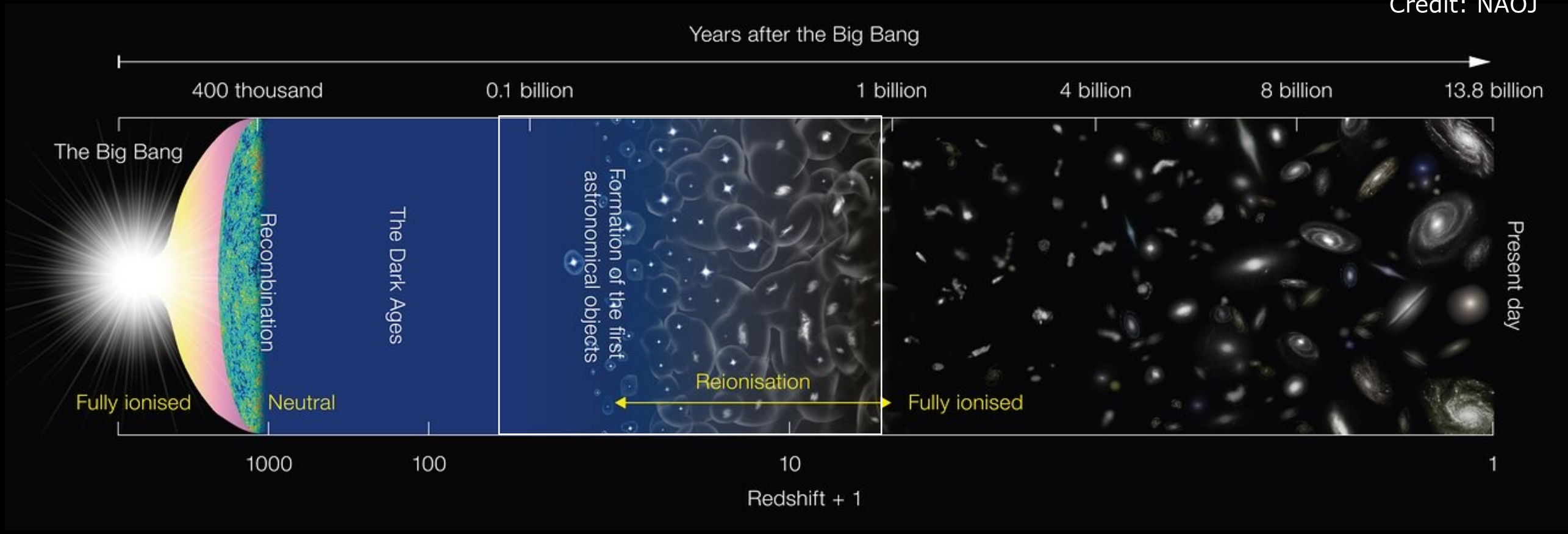




SKAO Science Capabilities


The M81 group
Credit: Keesscherer; NRAO

Credit: NAOJ



Born from an ambition to explore the Cosmic Dawn…

How and when did the first stars, galaxies and black holes form?

…built to answer all kinds of questions

Galaxy evolution, cosmology and dark energy
What is dark matter? How do galaxies form and grow?

Origin and evolution of cosmic magnetism
What is the role of magnetism across cosmic history?

Cradle of life: planets, molecules, SETI
How do planets form? Are we alone?

Exploration of the unknown

Testing gravity using pulsars
Was Einstein right?

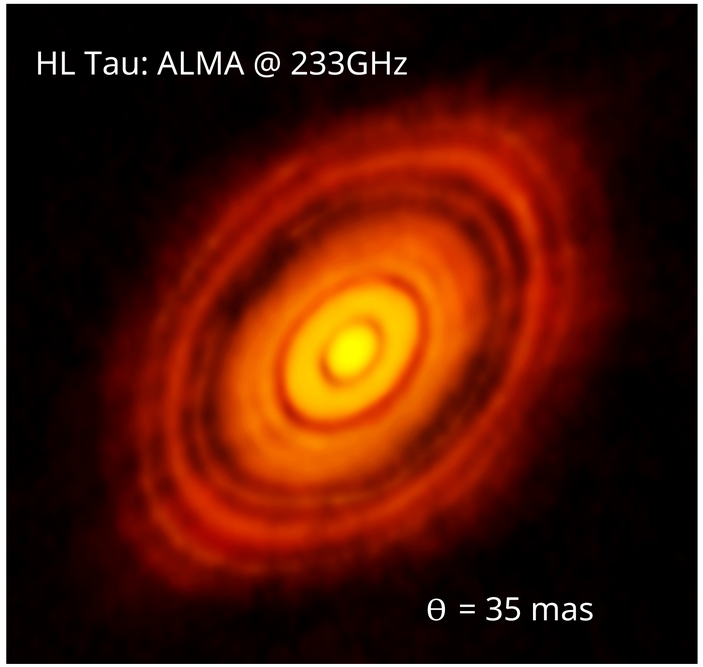
Transient Radio Sky
What are Fast Radio Bursts?

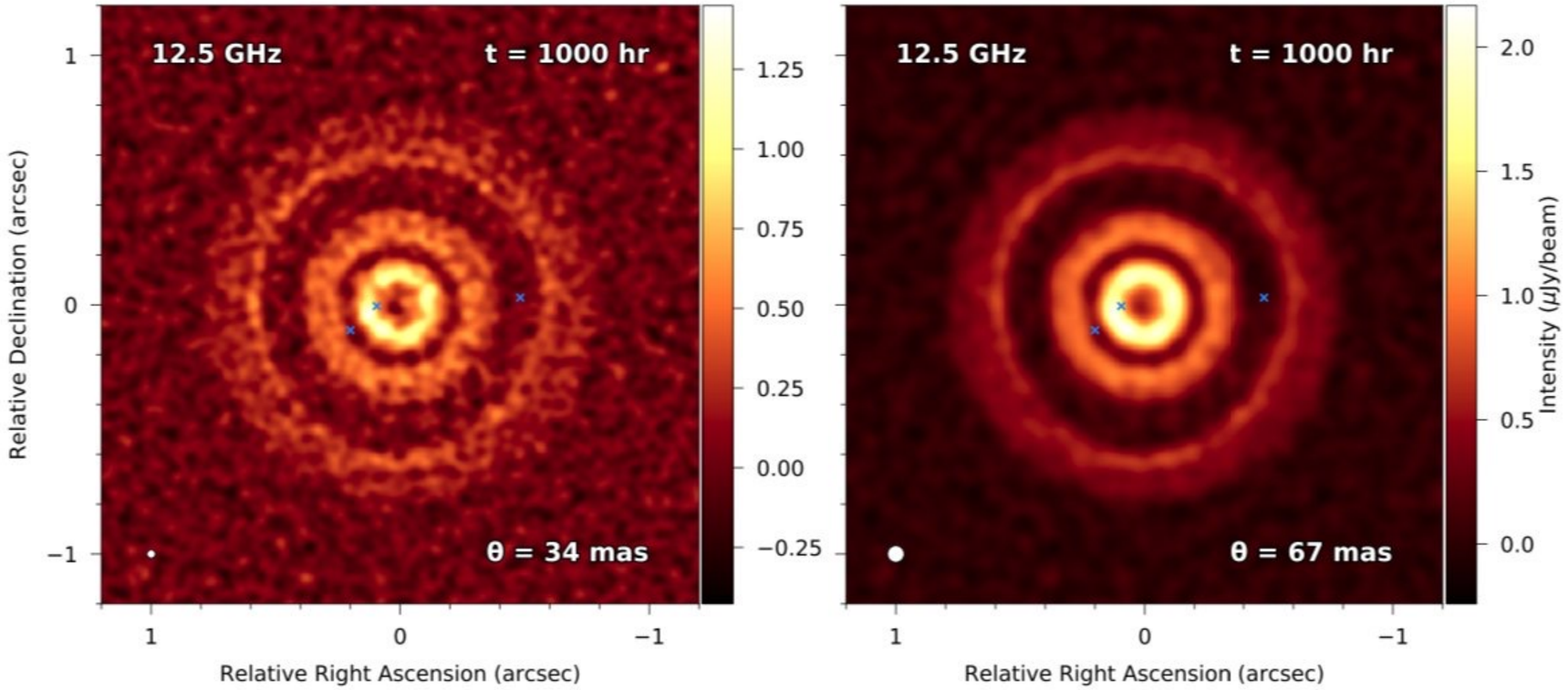
Our Galaxy, the Milky Way
How does matter cycle between stars and the Interstellar Medium?

Huge range of transformational science enabled by SKAO

When/Where do Earth-like Planets form in Disks

- Formation of cm+ sized grains is a crucial step on the road to terrestrial planet formation
- Where and how does grain growth proceed?





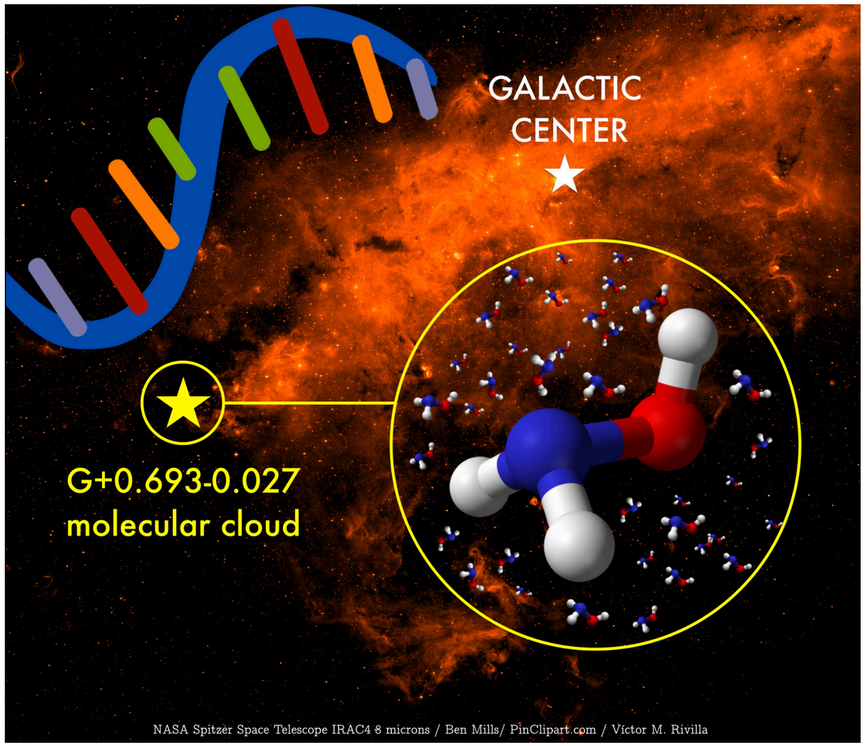
SKA-Mid wavelength range will enable study of cm-size grains

- Simulations clearly show deep SKA observations will be able to observe pebbles in disks, and gaps/ring structure due to forming planets
  (Band 5 simulation – Ilee et al. 2020MNRAS.498.5116I)

Pre-biotic molecules in star-forming regions

Building blocks for life on Earth may have arrived from space (panspermia hypothesis)

Detection of key pre-biotic molecules (e.g. amino acids, complex sugars) in interstellar space is a “holy grail” of Cradle of Life studies

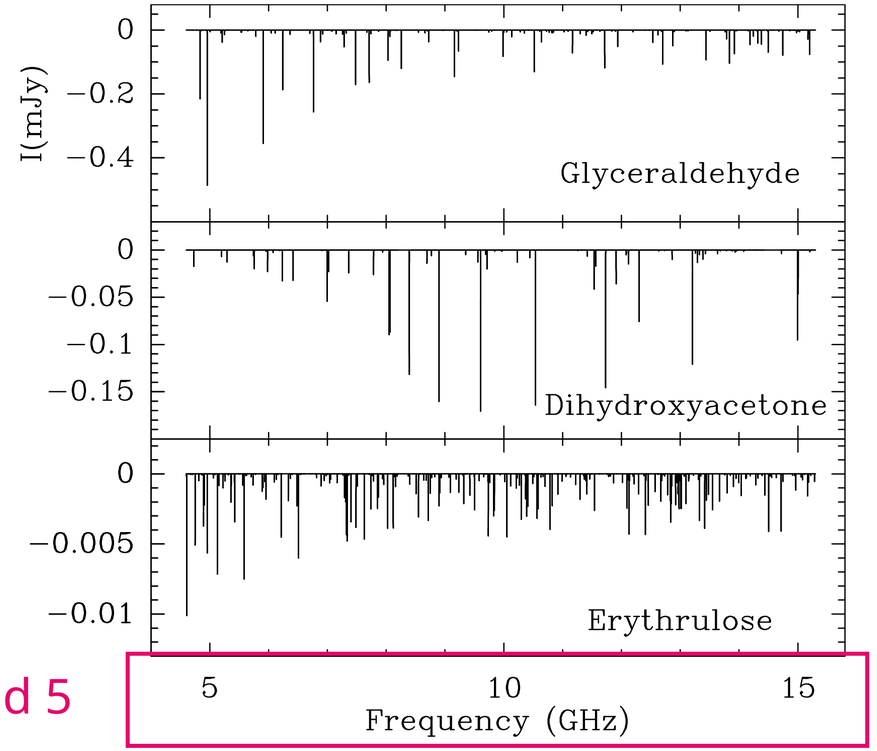


Detection of hydroxylamine (NH_2OH), key precursor to RNA
(IRAM 30-m; Rivilla et al. 2020)

$CHOCHOHCH_2OH$

$CH_2OHCOCH_2OH$

$C_4H_8O_4$



SKA Band 5

Predicted spectrum of key large sugars toward G+0693.

Detection of the brightest (i.e. deepest) lines requires **10s of hours integration with SKA** (Jimenez-Serra et al. 2022)

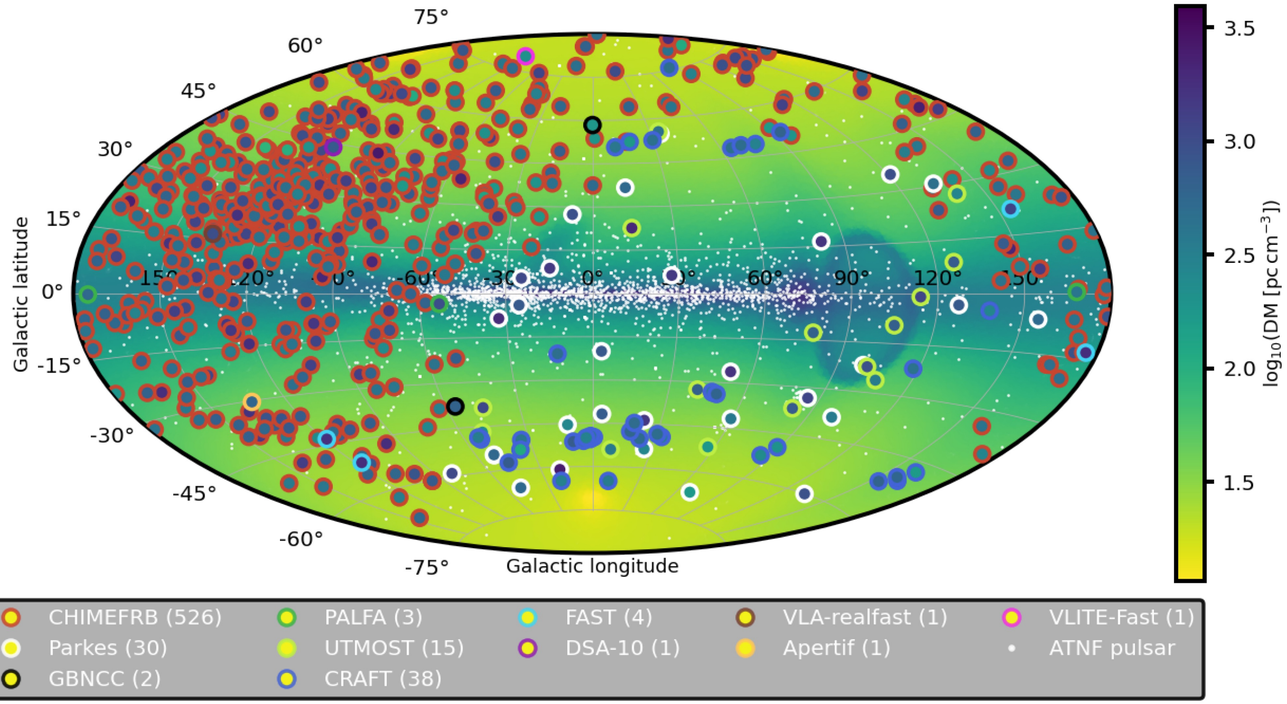
Fast Radio Bursts (FRBs)

Bright: (~1 Jy), Short period: (1–6 msec),

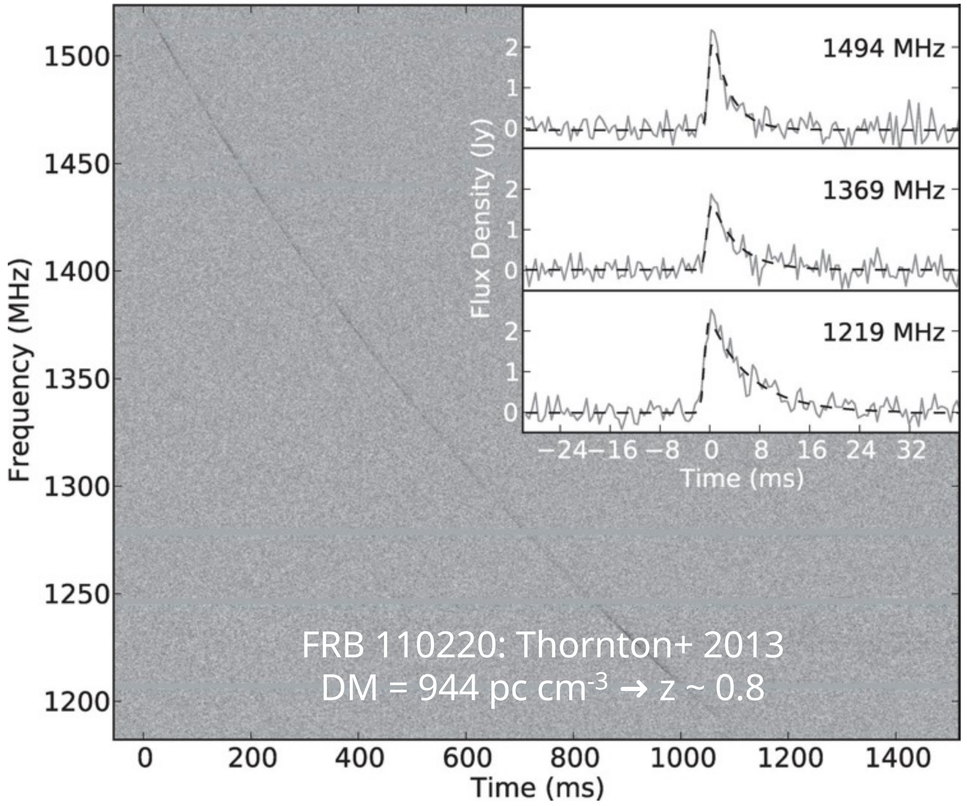
Extragalactic: DM = 100 – 2500 cm^{-3} pc

Hundreds of FRBs now detected

Estimated event rate: $1x10^4$ sky^{-1} day^{-1}



credit: Laura Driessen

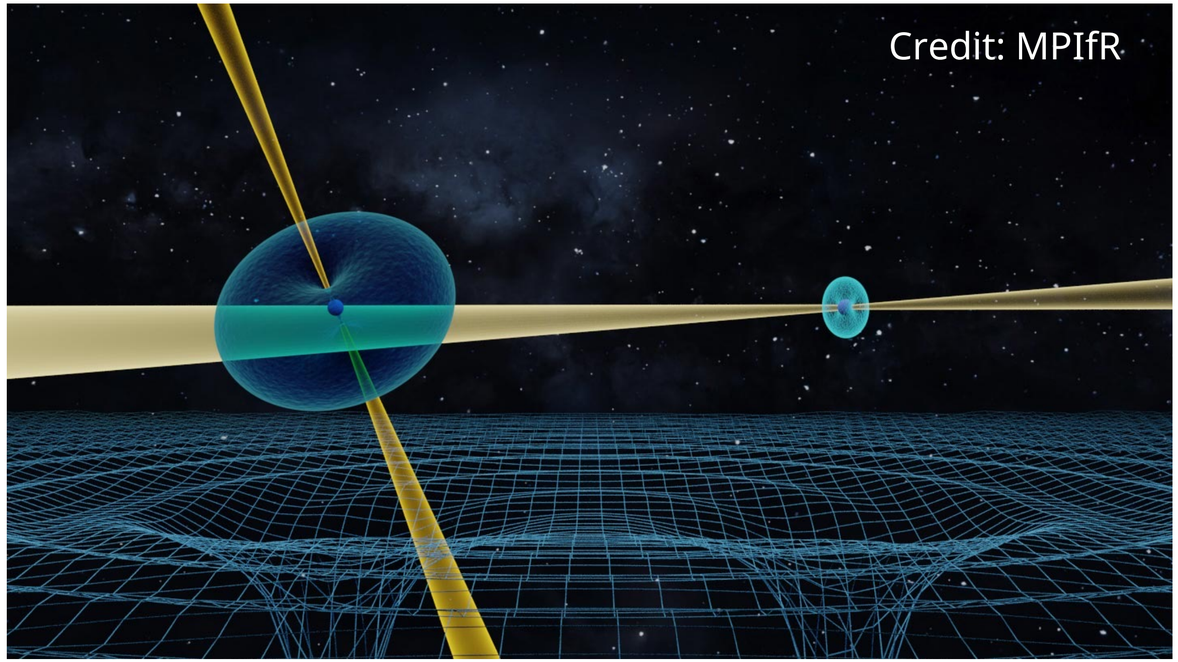


Probe Baryon content along line-of-sight:
Missing Baryon Question

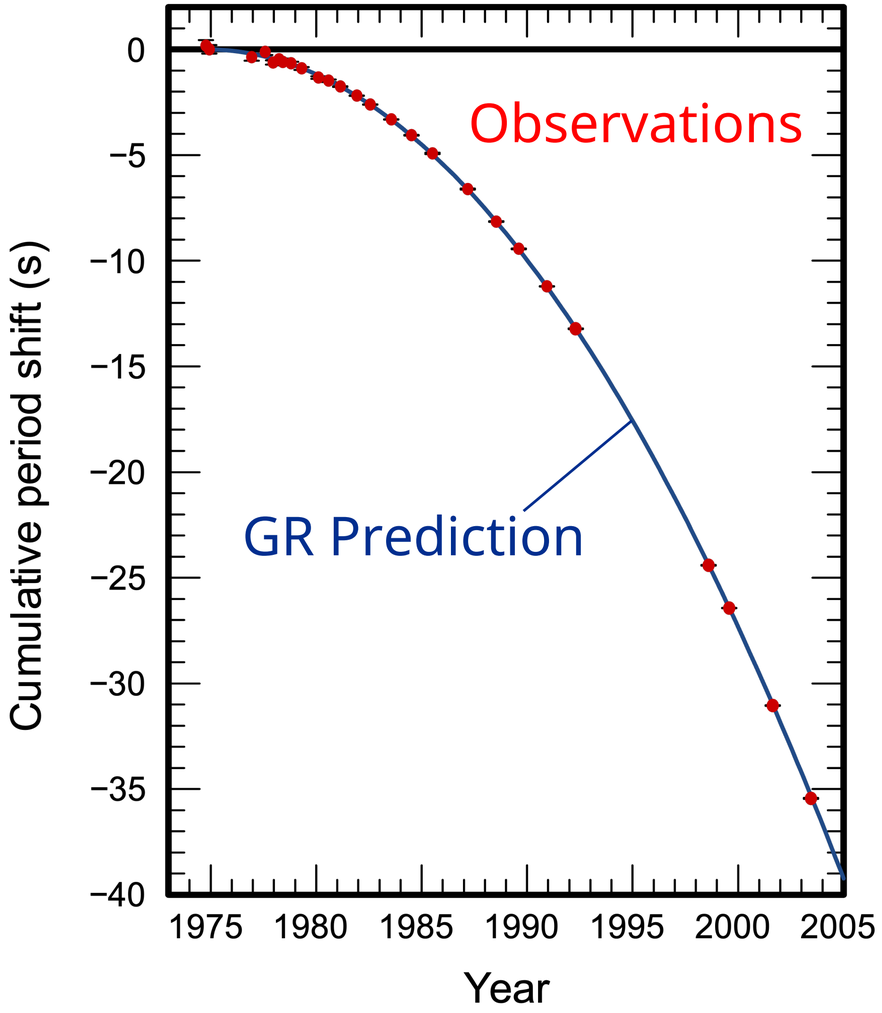
Test General Relativity in strong field regime

Tests of GR in strong field regime via:

- Pulsar – White Dwarf binaries
- Pulsar – Neutron Star binaries
- **Pulsar – Pulsar binaries**
- Pulsars around Galactic Centre
- **Pulsar – Black Hole binaries**



Pulsar (Neutron Star) Binary Orbital Decay – Obs. v Theory

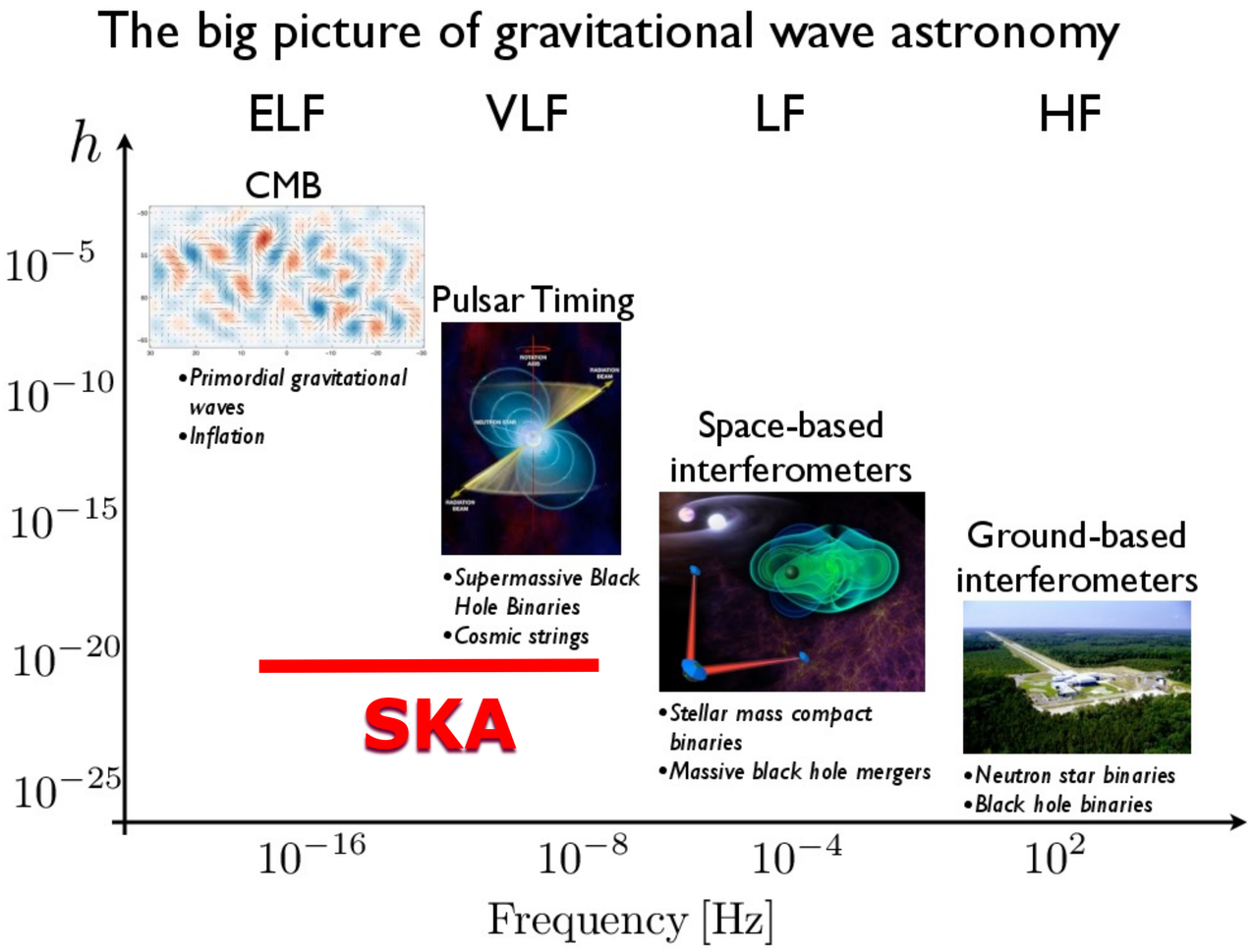


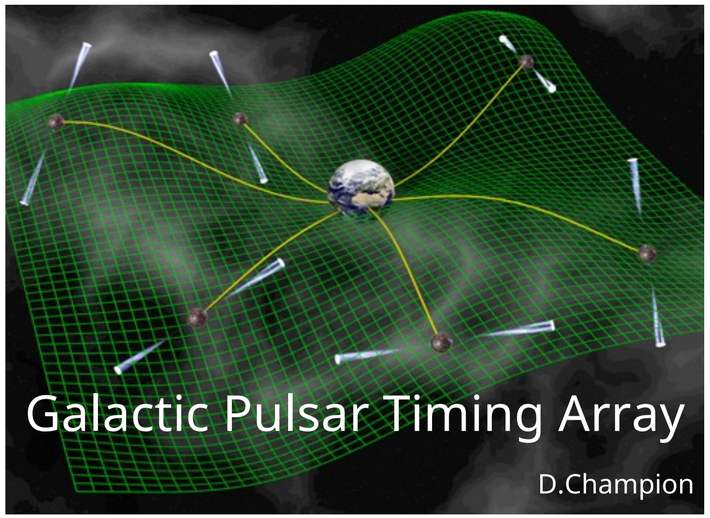
99.99% agreement with GR

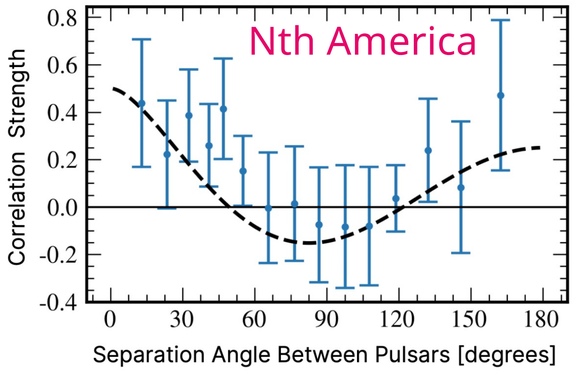
(e.g., Kramer+ 2021 Phy. Rev. X)

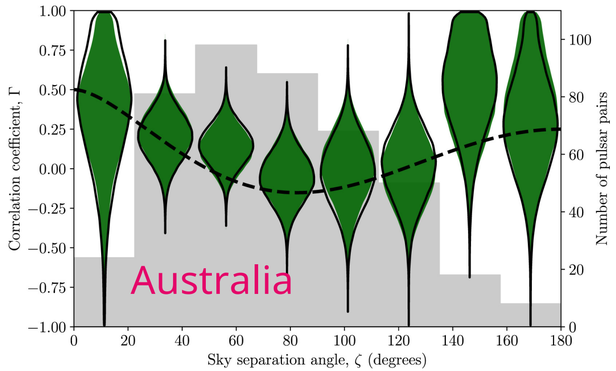
Gravitational Waves with Pulsars

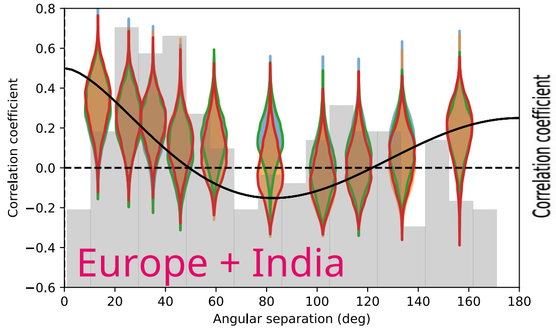
(Multi-messenger Physics)

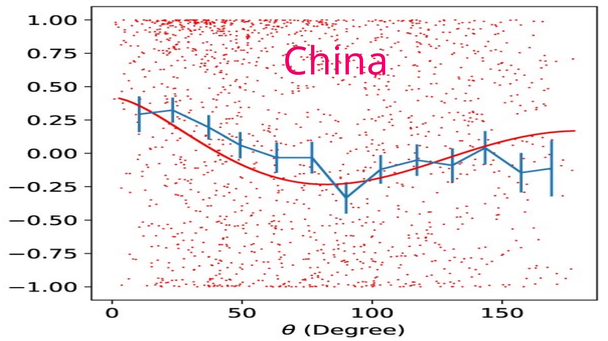






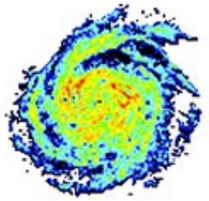


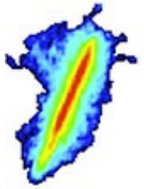


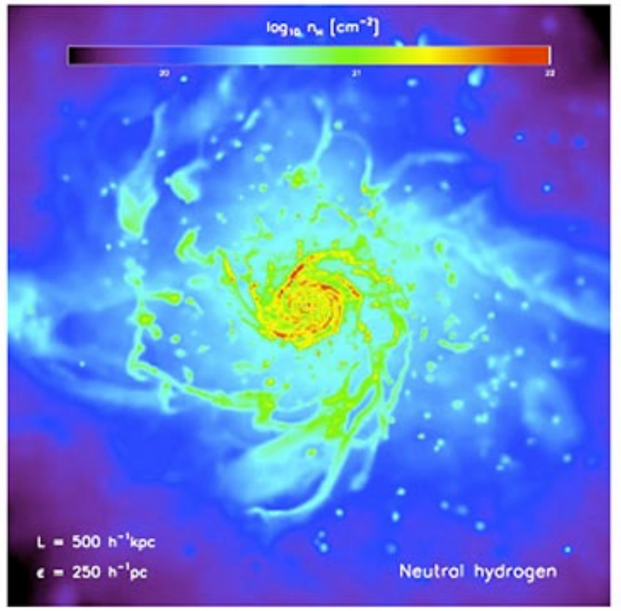


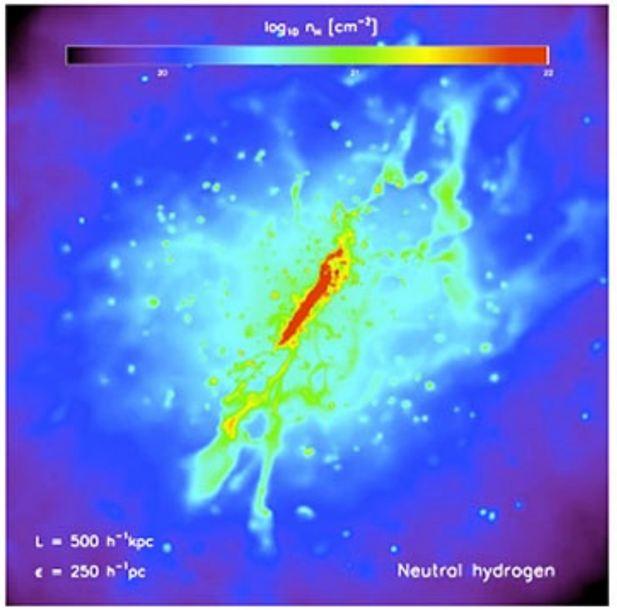
Galaxy evolution

- How do galaxies accrete and grow from the `Cosmic Web' ?
- Observations miss the low-density IGM
- SKA will provide resolved observations out to z ~ 0.8
- Measure angular momentum build-up (rotation curves out to large radius)
- *SKA will probe low column density HI in nearby Universe ($N_{HI} < 10^{18}$ cm^{-2})*







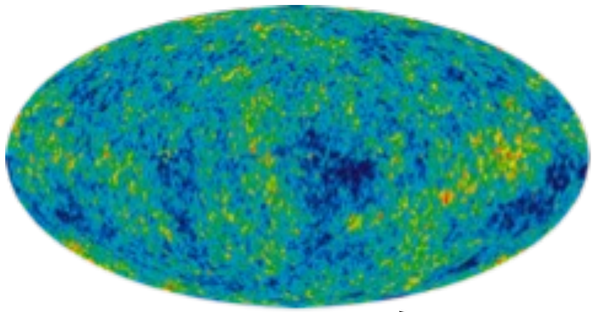


observed simulated

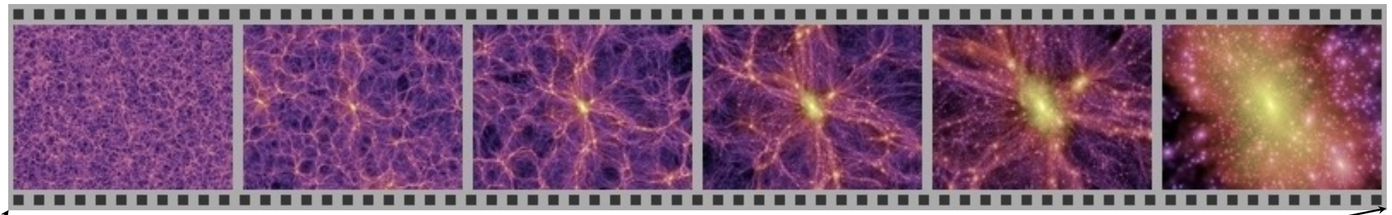
Images courtesy of Tom Oosterloo (SKA HI science working group)

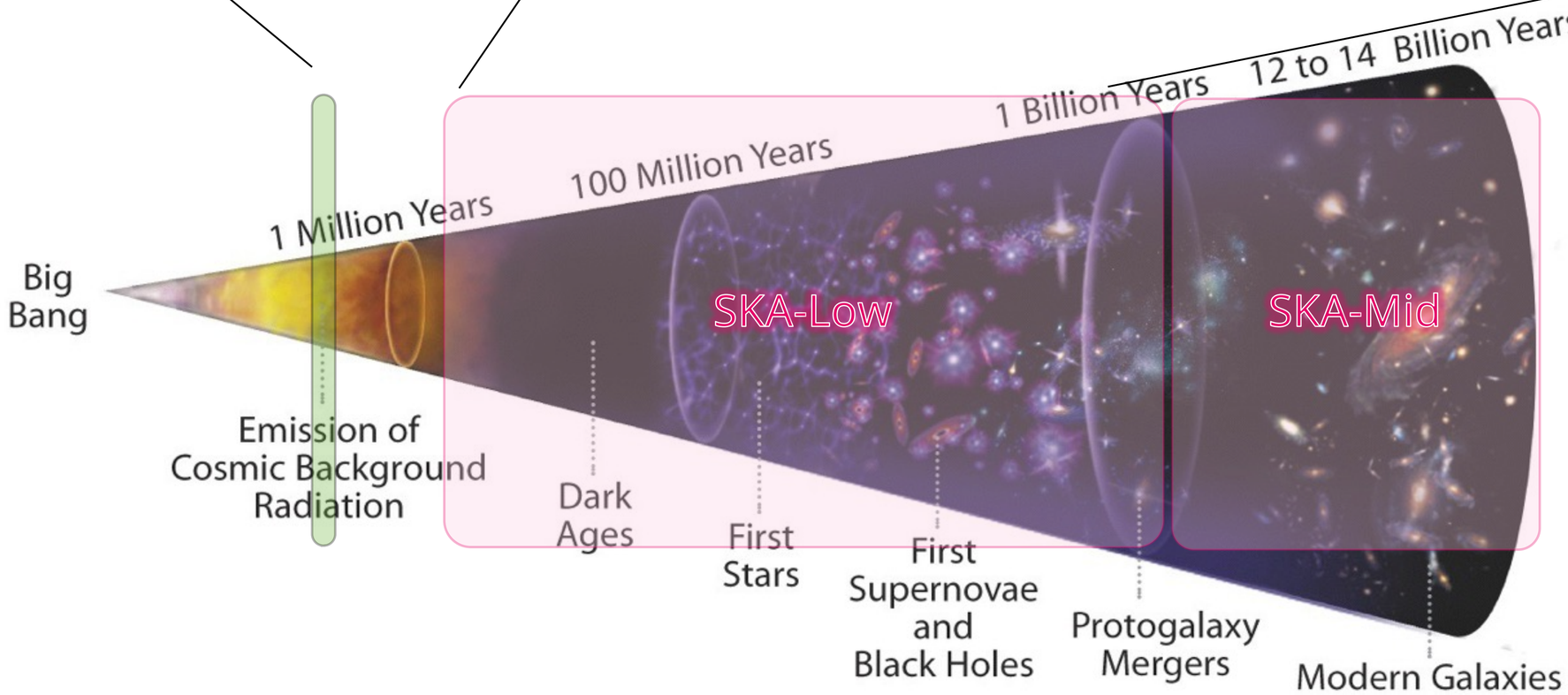
The Epoch of Reionisation

CMB snapshot at ~400,000 yrs



SKA-Low will observe the evolution of HI emission to make a movie of the Universe from its Dawn until the formation of the first modern galaxies





14 Science Working Groups cover the science areas that will be addressed with the SKA telescopes

Extragalactic Continuum
Science Workin

Our Galaxy
Science Workin

Extragalactic Spectral Lines
Science Work

High Energy Cosmic Particles
Focus Group

Cosmology
Science Working

VLBI with the SKA
Science Working Group

HI Galaxy Science
Science Working Group

Cosmic Magnetism
Science Working Group

Transients
Science Workin

Cradle of Life
Science Working Group

Solar and Heliospheric Physics
Science Working Gro

Epoch of Reionization
Science Workin

Pulsars
Science Working Group

(Gravitational Waves SWG poster coming soon)

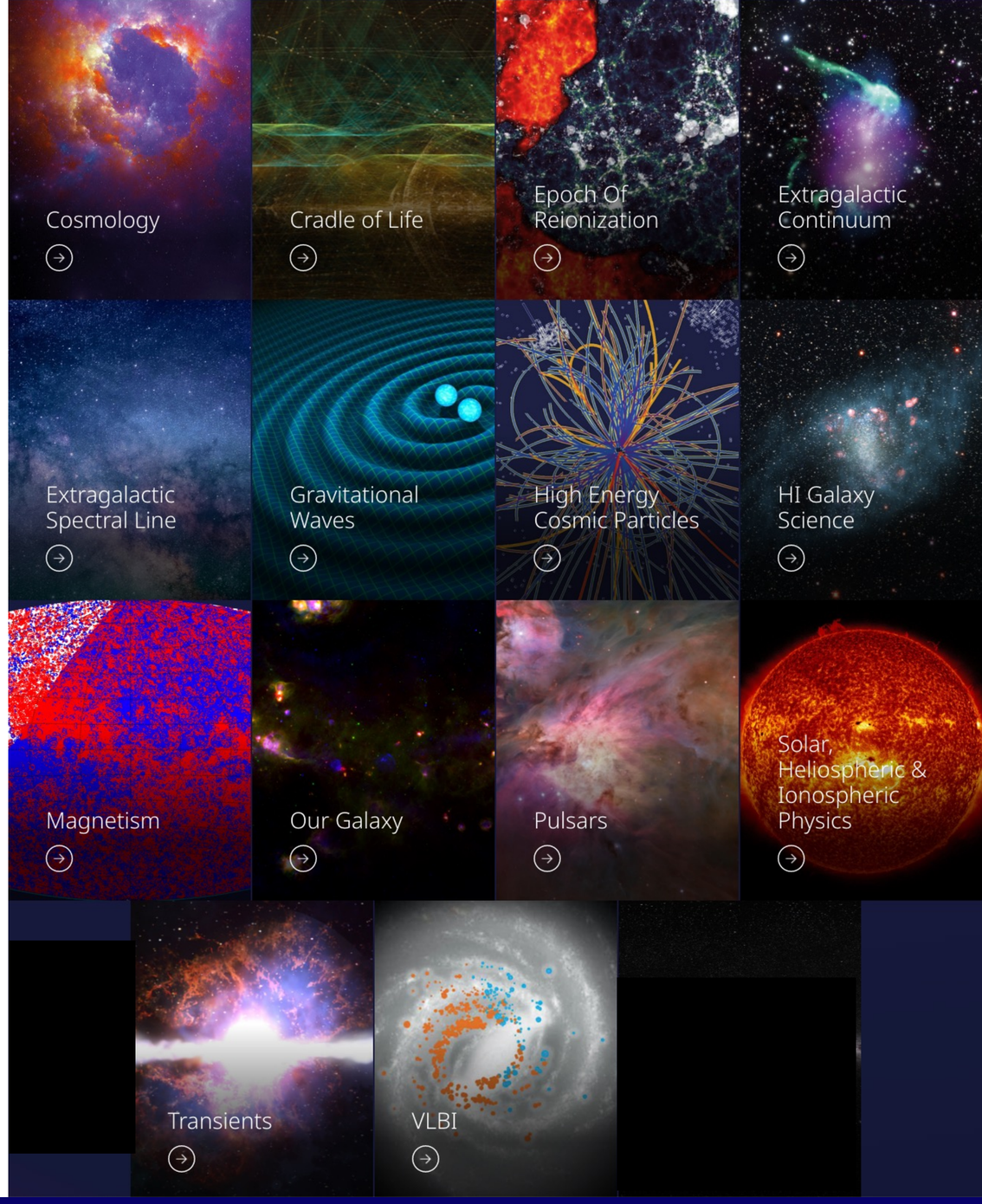
www.skao.int

SKAO Science Working Groups (SWGs)

- Provide a forum for discussion on possible SKAO science projects
- Will facilitate Key Science Project (KSP) collaborations
- Are the best way to receive up-to-date information regarding the road to science and operations

To join a SWG

- Send a request via email to the relevant SWG co-chairs
- Contact details of the co-chairs available on the website
- www.skao.int/en/science-users/science-working-groups-focus-groups



SKA Science Case

(2015 snapshot ; continuous evolution)

https://pos.sissa.it/cgi-bin/reader/conf.cgi?confid=215

135 chapters,
2000 pages,
31 countries

Capabilities & performance estimates

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	8.3-15.4
Telescope	Low	Low	Mid	Mid	Mid	Mid
FoV [arcmin]	327	120	109	60	12.5	6.7
Max. Resolution [arcsec]	10	3.5	0.55	0.3	0.06	0.03
Max. Bandwidth [MHz]	300	300	700	810	3900	2 x 2500
Cont. rms, 1hr [μJy/beam] [a]	26	14	4.4	2	1.3	1.2
Line rms, 1hr [μJy/beam] [b]	1850	800	300	140	90	85
Resolution range for Cont. & Line rms. [arcsec] [c]	12-600	6-300	1-145	0.6-78	0.13-17	0.07-9
Channel width [kHz]	5.4	5.4	13.4	13.4	80.6	80.6
Spectral zoom windows x narrowest bandwidth [MHz]	4 x 3.9	4 x 3.9	4 x 3.1	4 x 3.1	4 x 3.1	4 x 3.1
Finest zoom channel width [Hz]	226	226	210	210	210	210

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 Science Performance: https://arxiv.org/abs/1912.12699

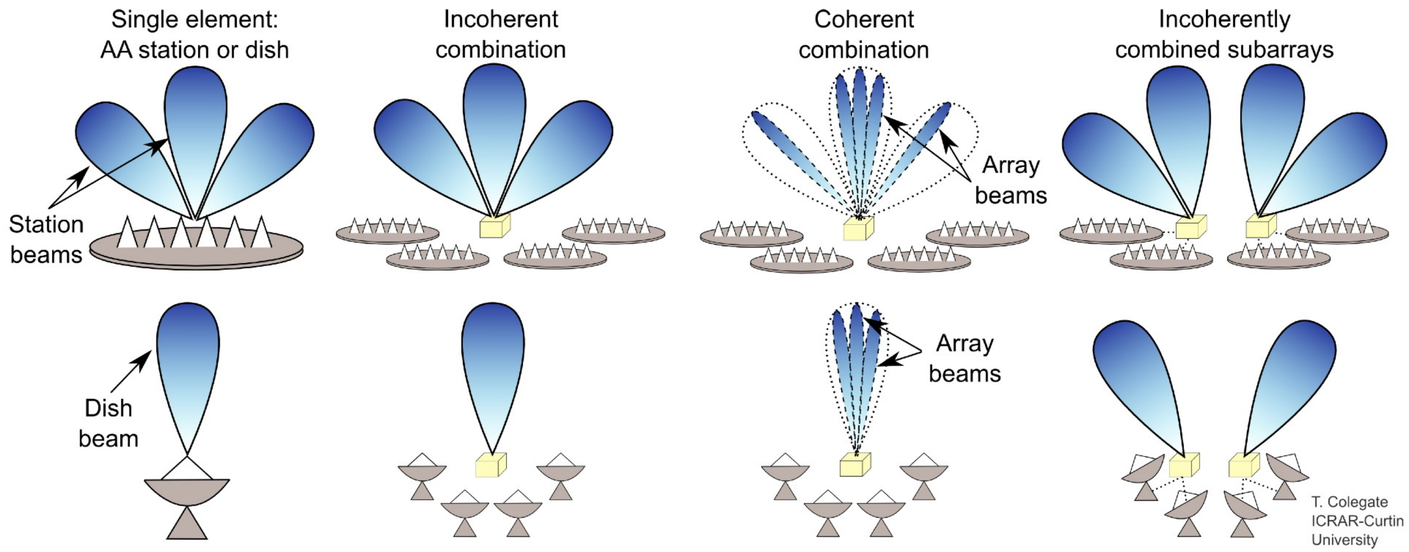
Non-imaging (Pulsars, Fast Radio Bursts, VLBI, …)

	Search		Timing		Bandwidth (Max)
Telescope	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	300 MHz

Possible simultaneously:

- imaging
- VLBI
- pulsar search
- pulsar timing

via commensal / sub-arrays



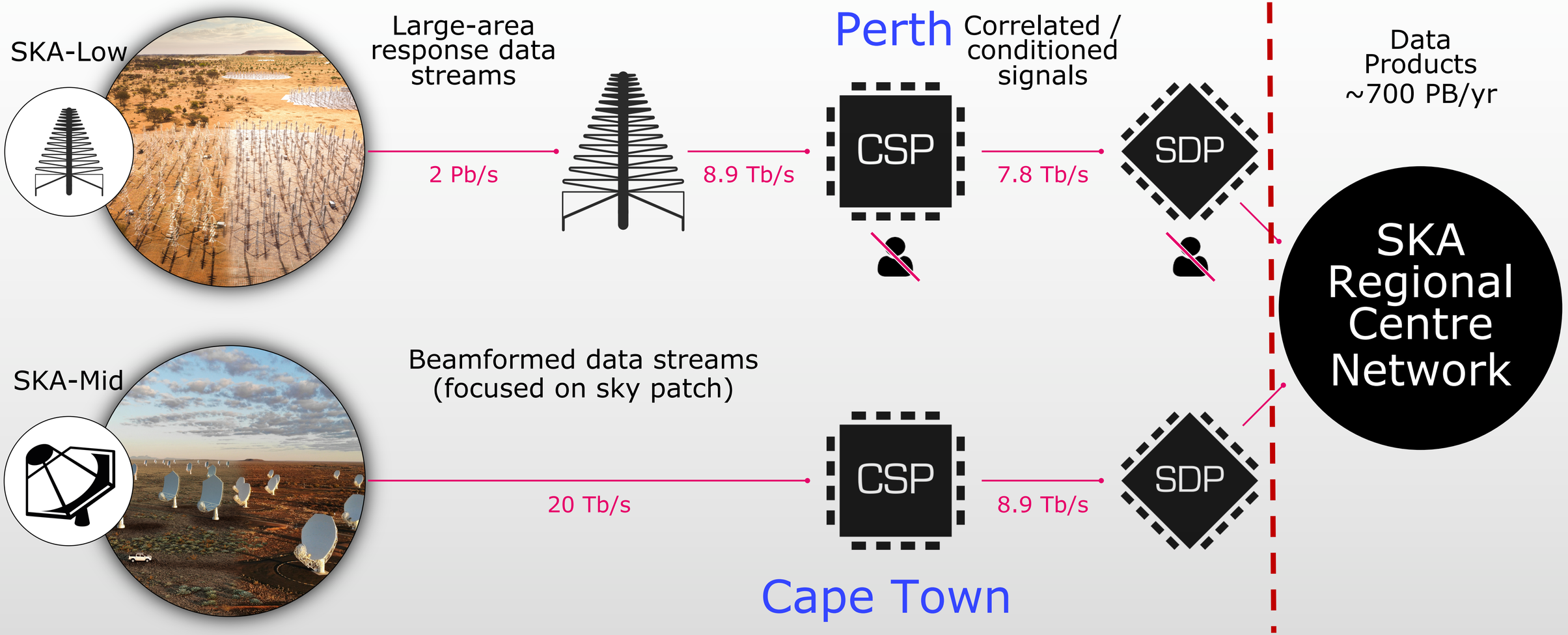
Exploration of the Unknown

Hubble (Lallo: arXiv:1203.0002; Norris AASKA14)

Project	Key project	Planned?	Nat. Geo. top ten?	Highly cited?	Nobel prize?
Use Cepheids to improve value of H0					
Study intergalactic medium with uv spectroscopy					
Medium-deep survey					
Image quasar host galaxies					
Measure SMBH masses					
Exoplanet atmospheres					
Planetary Nebulae					
Discover Dark Energy					
Comet Shoemaker-Levy					
Deep fields (HDF, HDFS, UDF, FF, etc)					
Proplyds in Orion					
GRB Hosts					

Science Access

SKA Regional Centres: SKAO data processing stages



Telescope Access, based on contribution level

Key Science Projects (KSPs)

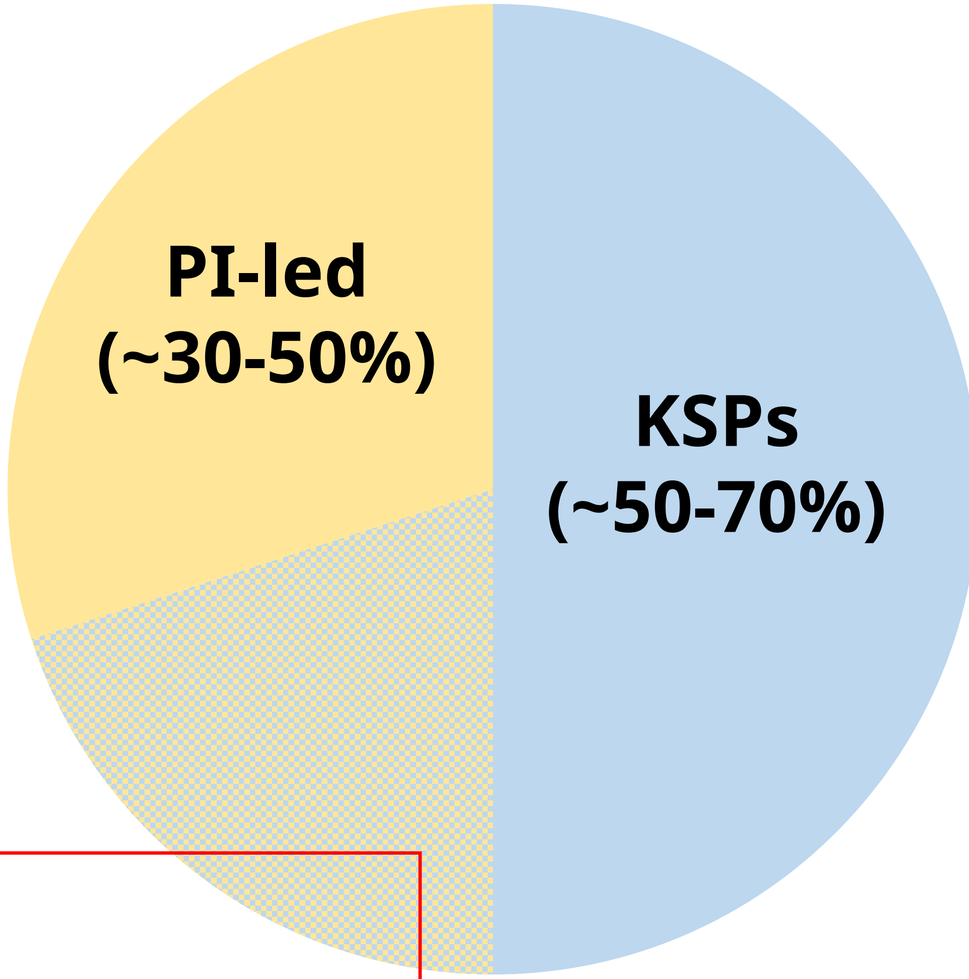
- Large programs (>500 h ?) performed over multiple cycles
- PI & leadership team from SKA-member countries; co-Is from any country (latter may be limited)

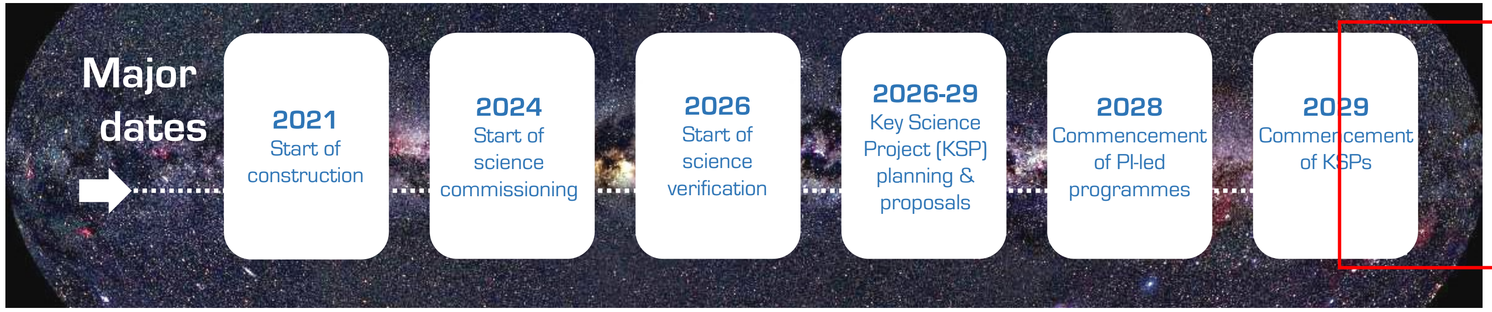
Principal Investigator (PI) Projects

- Small programs (<500 h ?) performed within a single cycle

Director-General's Discretionary Time

- Time allocated by the D-G outside of the normal TAC process





Telescope Access

Commensal Science

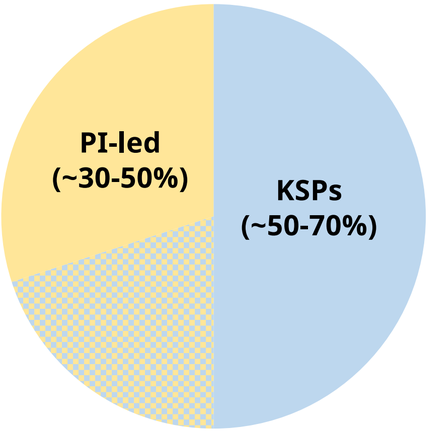
- Different observing projects utilizing the same telescope time (pointing direction); may use same or different observing mode (i.e., continuum imaging, spectral line imaging, pulsar/transient search)
- Maximizes the use of SKA resources
- Commensal science is not ”free”, will be counted against member share

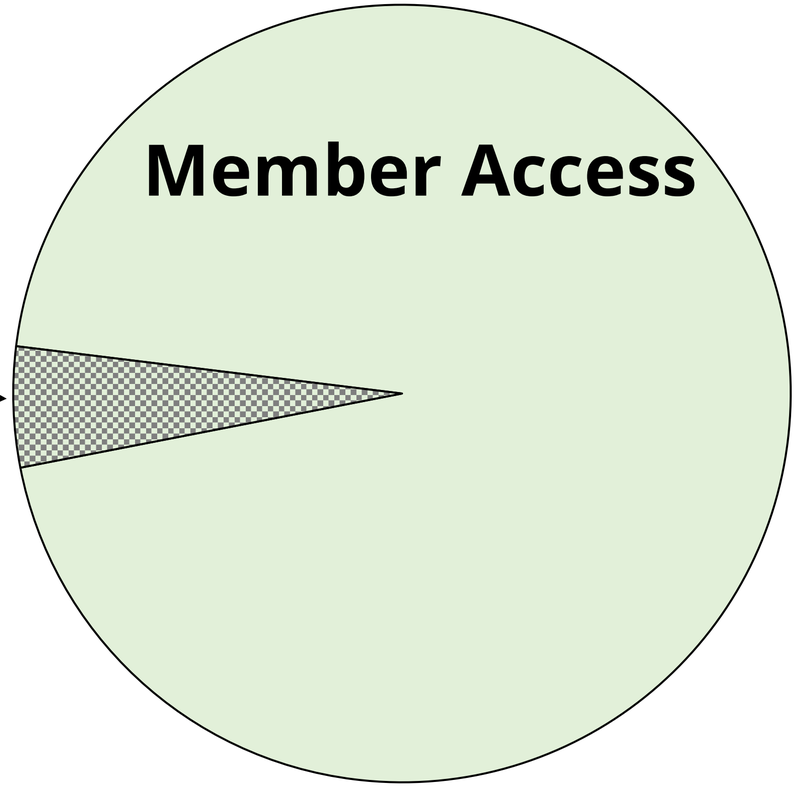
Members (and Associate Members)

- Can lead any program (KSP, PI)
- Can be part of KSP leadership teams
- Access in proportion to member share

Non-Members

- Can lead PI programs
- Can be team members of KSPs, but not part of leadership team
- Access capped at **5% (”Open Time”;** TBC by Council)
- Access to any individual non-member entity may be capped



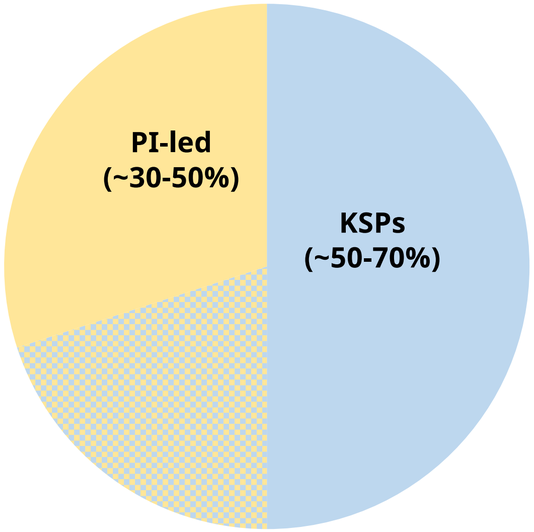


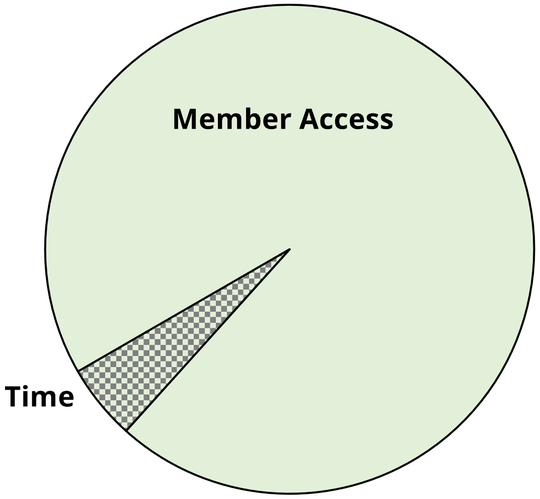
Telescope access

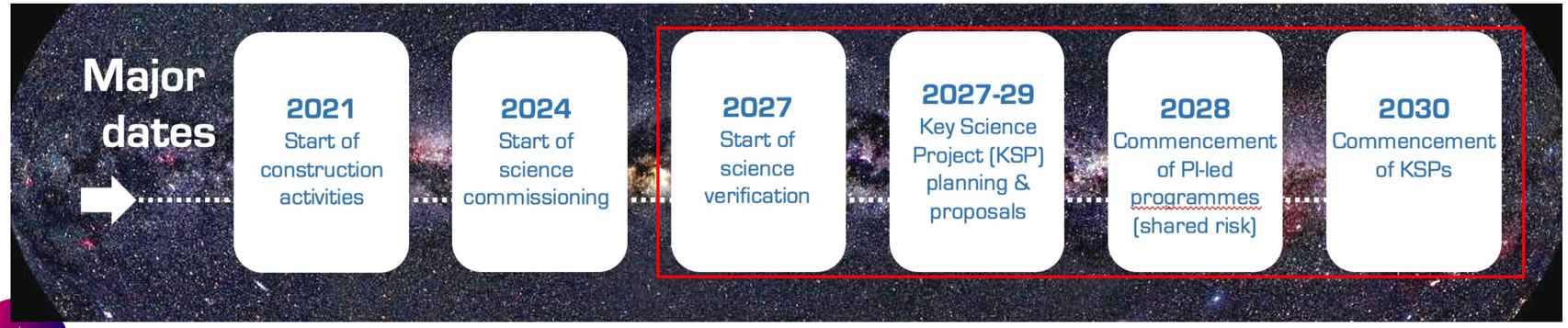
- **No time has been allocated for any project**
- Science Working Groups are not proto-KSPs
- High Priority Science Objectives are not KSPs
- There are no guaranteed KSPs
- Time allocation will be based on

  SCIENTIFIC MERIT

  and technical feasibility through a common proposal review process







Construction Strategy
(Staged Delivery - Target: Design Baseline)

Array Assemblies (AA)

- Capable as acting as an end-to-end telescope system with pre-defined functionality
- Used to commission the telescopes, and verify against requirements
- Different objectives for different assemblies
- **Science commissioning**: on-sky observations for testing and debugging the system
- **Science verification**: observations to ensure the system meets the needs of the science users (e.g., test observing modes, verify science requirements)
- **AA 0.5** – test array for interferometry, using prototype dishes and (in some cases) receivers; discover system level issues and develop procedures (pointing, tracking, holography)

Milestone Event (earliest)		SKA-Mid (date)	SKA-Low (date)
AA0.5 (test array)	4 dishes 6 stations	2025 Q1	2024 Q4
AA1	8 dishes 18 stations	2026 Q1	2025 Q4
AA2	64 dishes 64 stations	2027 Q1	2026 Q4
Science Verification begins		**2027+**	**2027+**
AA*	144 dishes (80+64 MK) 307 stations	2027 Q4	2028 Q1
Operations Readiness Review		2028 Q1	2028 Q2
End of Staged Delivery Programme		2028 Q3	2028 Q3
Early Operations begin (shared risk)		**2029+**	**2029+**
AA4	197 dishes 512 stations	TBD	TBD

Updated August 2023

Construction Strategy
(Staged Delivery - Target: Design Baseline)

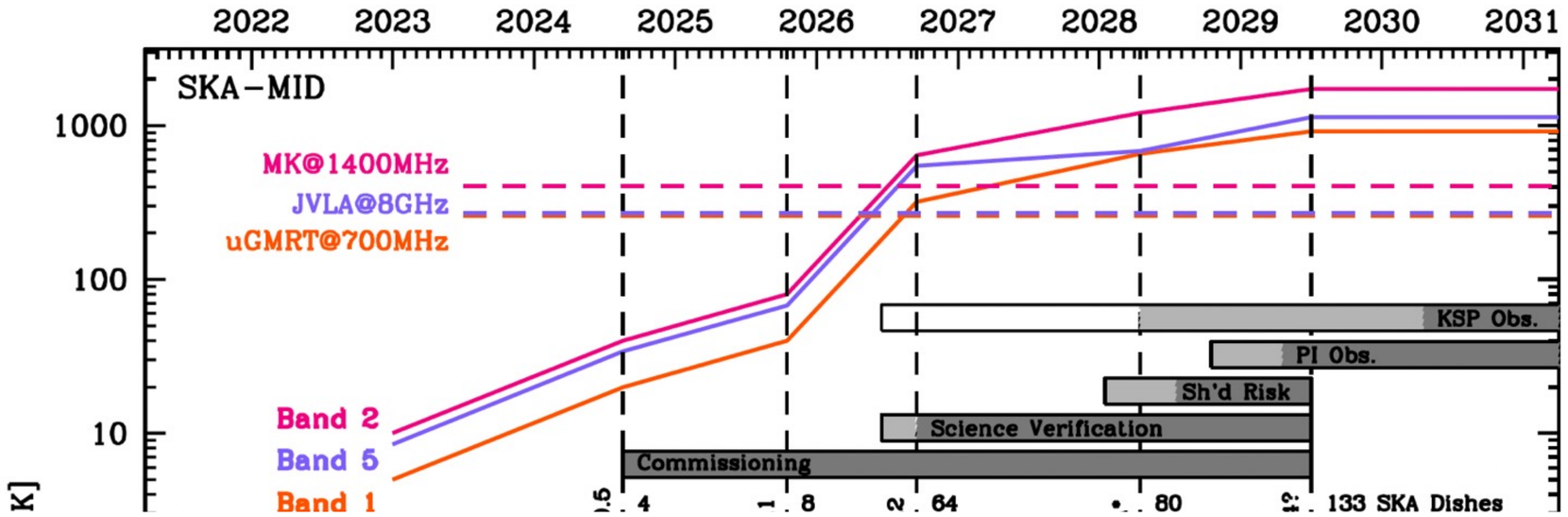
- **Goal – SKA-Mid with 197 dishes & SKA-Low with 512 stations**
- Not all funding yet secured, therefore following Staged Delivery Plan (AA*)
- Roll out the array in stages (Array Assemblies – AAs)
- Maintain a continuously working and expanding facility that demonstrates the full performance capabilities of the SKA Design.
- **AA2 – Start science verification**: observations to ensure the system meets the needs of the science users (e.g., test observing modes, verify science requirements)

First data release to community after AA2 in 2026/27 time-frame
(similar to ALMA SV model)

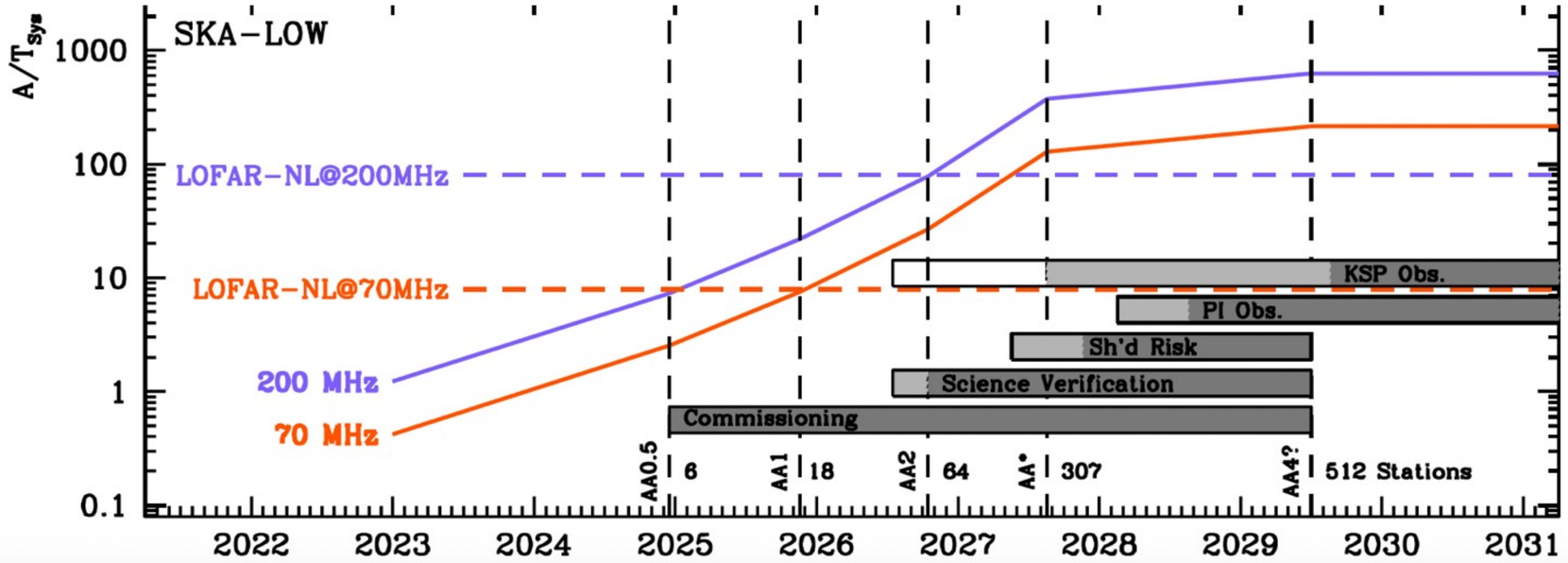
Milestone Event (earliest)		SKA-Mid (date)	SKA-Low (date)
AA0.5 (test array)	4 dishes 6 stations	2025 Q1	2024 Q4
AA1	8 dishes 18 stations	2026 Q1	2025 Q4
AA2	64 dishes 64 stations	2027 Q1	2026 Q4
Science Verification begins		**2027+**	**2027+**
AA*	144 dishes (80+64 MK) 307 stations	2027 Q4	2028 Q1
Operations Readiness Review		2028 Q1	2028 Q2
End of Staged Delivery Programme		2028 Q3	2028 Q3
Early Operations begin (shared risk)		**2029+**	**2029+**
AA4	197 dishes 512 stations	TBD	TBD

Updated August 2023

Evolution of Performance

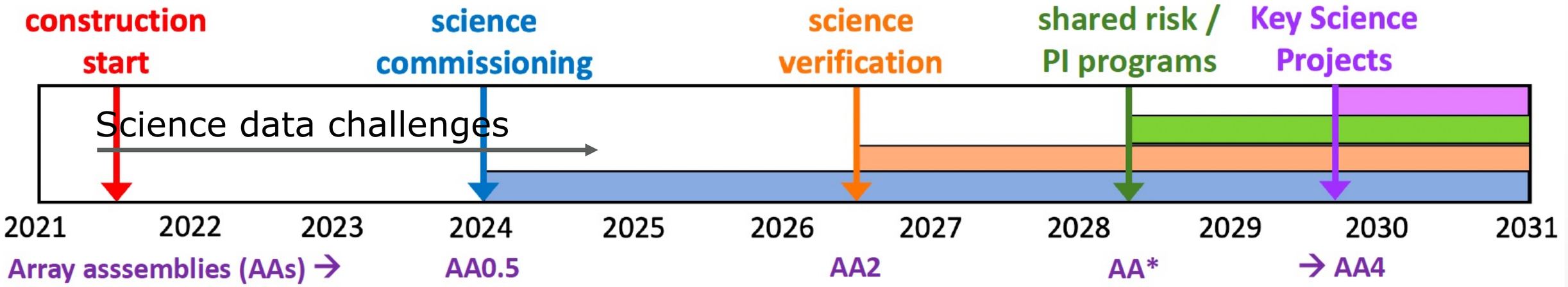


Around the end of 2026, SKAO becomes the most powerful radio observatory on Earth



Credit: Mark Sargent

SKAO Science Timeline

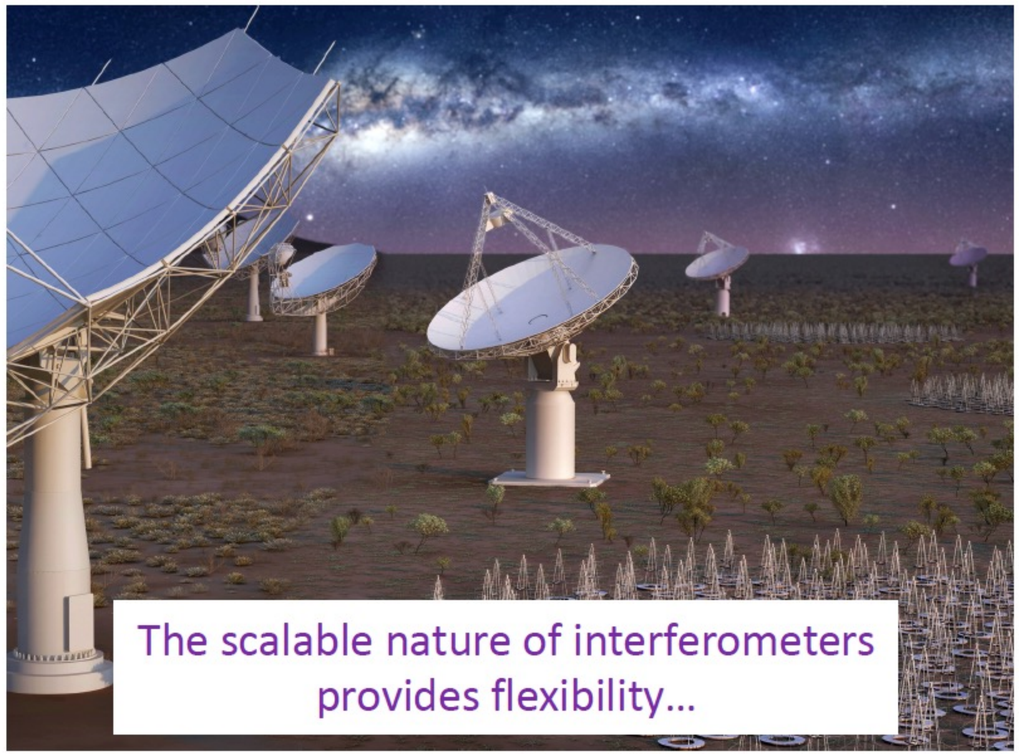


Scientifically competitive facilities > mid-2026 (= AA2):

- → Calibrated science data demonstrating capabilities will be publicly released
- → Call for community "ideas" by ~mid 2025

Shared-risk observations ("cycle 0") in early 2028 (= AA*):

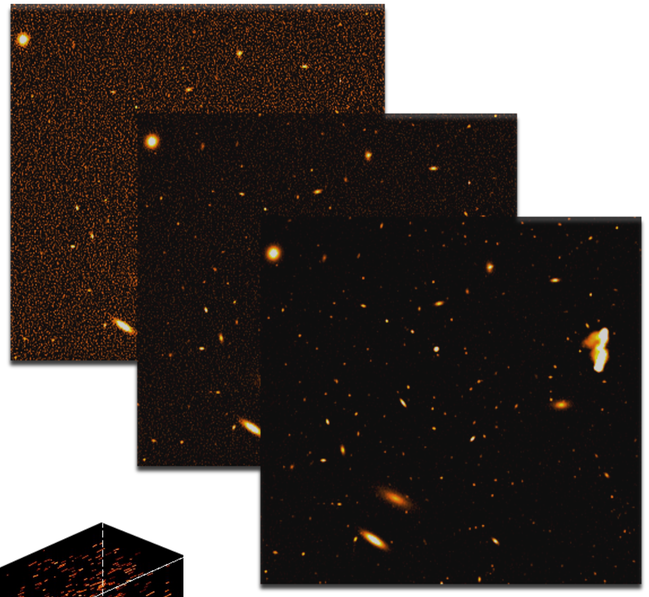
- → Full proposal solicitation/allocation process
- → Call for proposals in by ~mid 2027
- → Key Science Projects planning starts in 2026



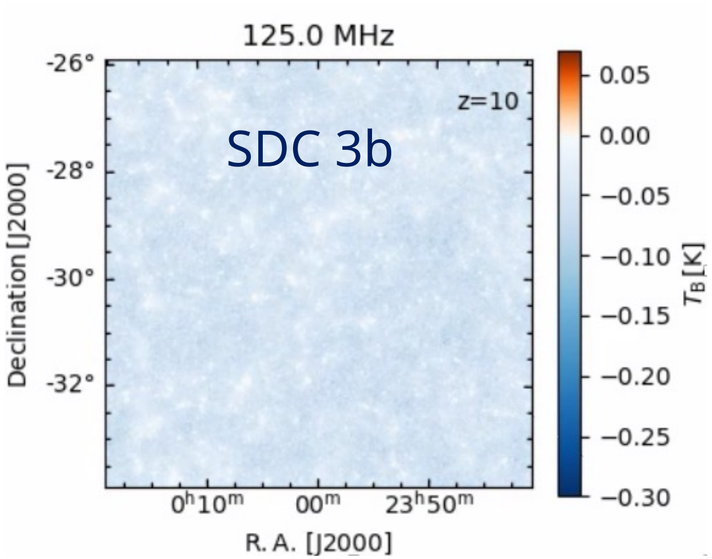
SKA Science Data Challenges (SDCs)

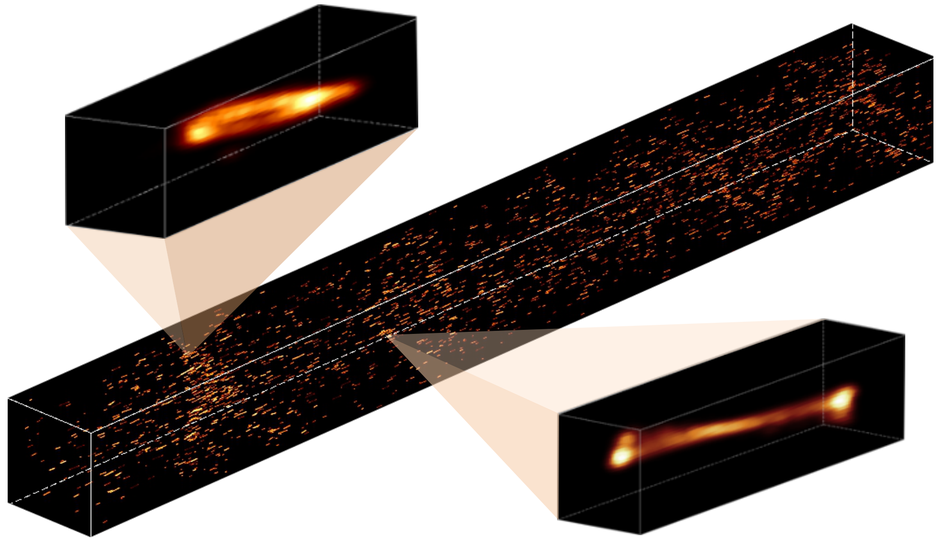
"The purpose of SDCs is to prepare the astronomical community, and SKAO itself, for the novel, yet challenging, nature of SKA data"

- ✓ SDC 1 – Radio Continuum Emission
- ✓ SDC 2 – Neutral Hydrogen Spectral Line Emission
- ✓ SDC 3a – EoR Foreground Removal ("Foregrounds")
- ▽ SDC 3b – Extraction of Cosmological Parameters ("Inference")
- ▽ SDC 4 – Magnetised continuum (Rotation Measure …)



SDC1, Bonaldi et al., 2021





SDC2, Hartley et al., 2023

Growing repository of sky models and simulation code for community re-use

SKAO Science Data Challenge 3

MAP OF WORLDWIDE PARTICIPATION

THE CHALLENGE IN NUMBERS

Teams analysing

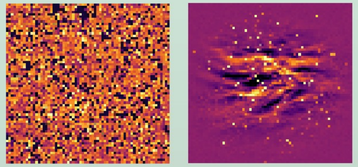
7.5 TB
of simulated telescope data and a corresponding

60 GB
of image cubes representing different radio frequencies

234
registered participants in

16
countries

12
supercomputing centres providing resources globally



Teams are analysing data which simulates observations of the Epoch of Reionisation signal (left; bright areas are neutral hydrogen, and dark patches are ionised gas). It is obscured by foreground emission (right; orange dots are galaxies, and the ribbon-like shape is diffuse gas in our galaxy). While the features of each image appear equally bright here, in the data cube the background is millions of times fainter than the foreground.

Upcoming SKA-related Science Meetings

- Science at Low Frequencies (SALF) IX, 11-15 Dec **2023** – Amsterdam, NL

  https://salfconference.org/2020-9th-annual-science-at-low-frequencies-salf-conference
- MeerKAT @ 5, 20-23 February **2024** – Stellenbosch, RSA
- Interstellar Frontiers: Bridging SETI, Astrobiology, and the SKA, 11-15 March **2024**, Perth, AU
- Cosmology in the Alps, 18 – 22 March **2024**, Les Diablerets, CH

  https://indico.skatelescope.org/event/1098/
- SPARCS (SKA Pathfinder Radio Continuum Surveys) XII, May 6-10 **2024**, Bologna, IT
- Cosmic Magnetism in the Pre-SKA Era, 27-31 May **2024** – Japan

  http://ska-jp.org/ws/SKAJP_MAGWS2024/
- IAU GA, August **2024**, Cape Town, various SKA Science events planned and related sessions
- **SKAO Science Conference, Summer 2025, Germany, planning underway**

SKAO construction update

Construction Commencement Ceremonies

Consecutive ceremonies took place at the telescope sites in Australia and South Africa on 5th December 2022

SKA-Mid foundations

Packing and shipping the first SKA-Mid pedestal

Shipping from the China Electronics Technology Group Corporation (CETC)

Testing the dish lift

Environmental inspections at the SKA-Mid site

Roadbed preparation at the SKA-Mid site

SKA-Low trenching has begun

And here are all the cables


CAPE
THINK

Path to Array Assembly 0.5 (AA0.5): Aperture Array Verification System

Thank you to Jess Broderick for these AAVS slides

AAVS1

- Pre-Critical Design Review, 1st-gen digitiser, 'SKALA2' antenna

AAVS2

- 'SKALA4' antenna and Engineering Development Array 2 (EDA2) with Murchison Widefield Array (MWA) antennas

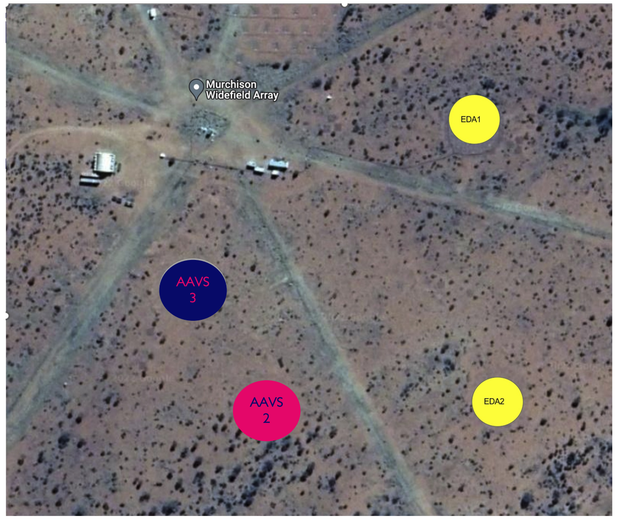
AAVS2.5

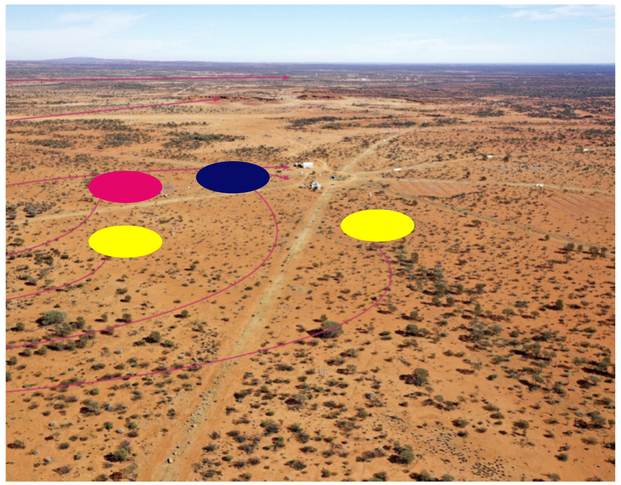
- Upgrades and improvements (heatsinking, network, firmware, antenna power and control)

AAVS3

- Incorporating final design revisions, full power control and sensing (Power And Signal Distribution), Tile Processing Modules, Monitor Control Calibration System

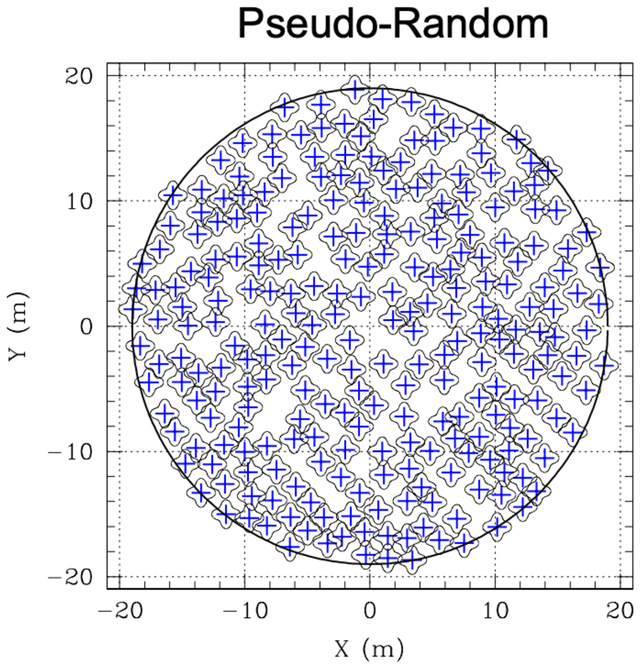
demonstrators, increasing in maturity and completeness



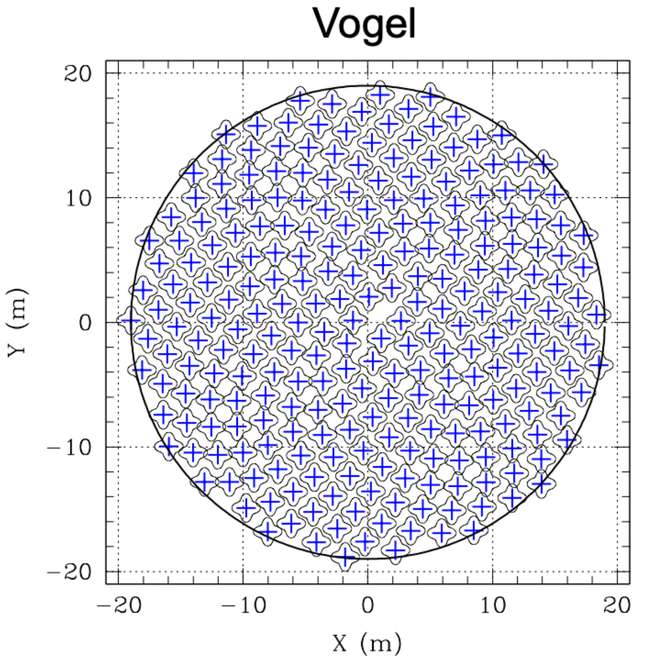


Why AAVS3?

- AAVS2: bandpass resonances (55, 78 MHz) and embedded element pattern variability.
- ‘Vogel’ maximally non-redundant spiral pattern. Larger minimum antenna separation (~2m cf. ~1.5-2m).
- Vogel configuration may offer better overall performance.



AAVS2



AAVS3

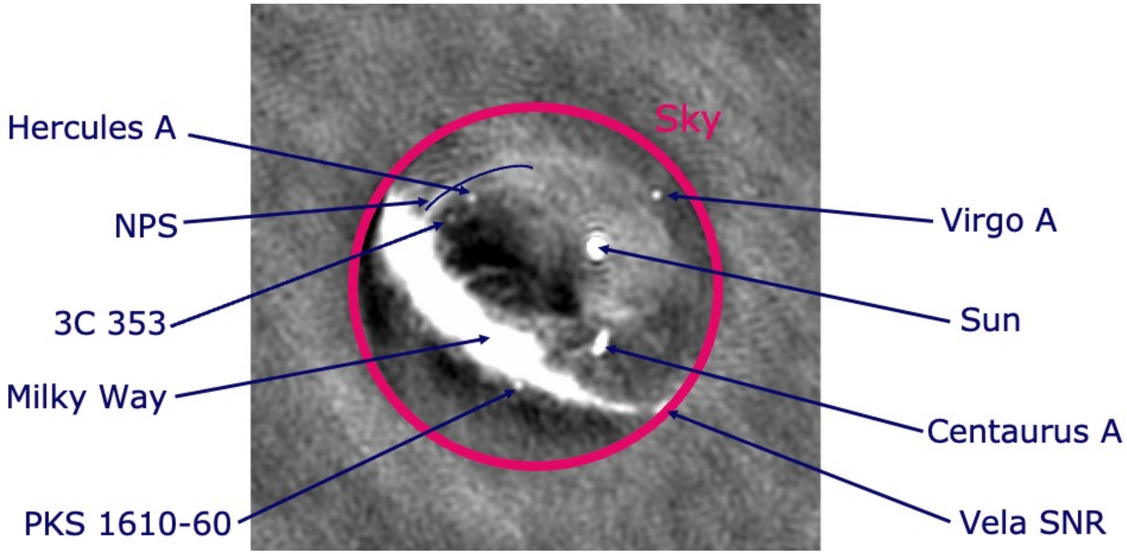
- Comparison of AAVS2 and AAVS3 data will inform a decision on the station antenna configuration for AA0.5 onwards.
- **AAVS3 is the first instrument owned, operated and maintained by SKAO staff in Australia! Ensuring continuity for product development teams and mitigating risk for the delivery of the construction phase.**

AAVS3 station rollout

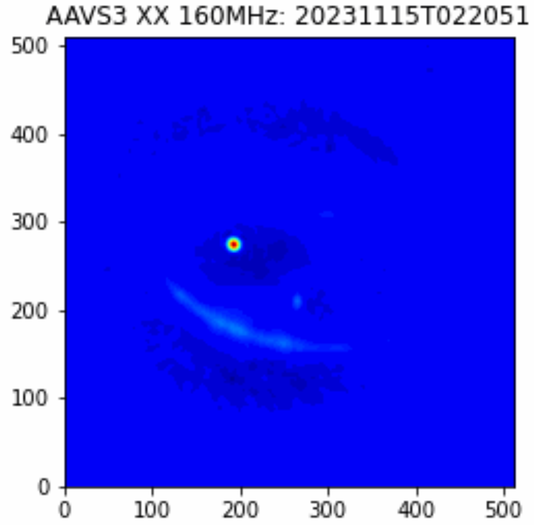

Snapshot taken mid-assembly

- **Fully deployed (256 antennas) and on schedule.**

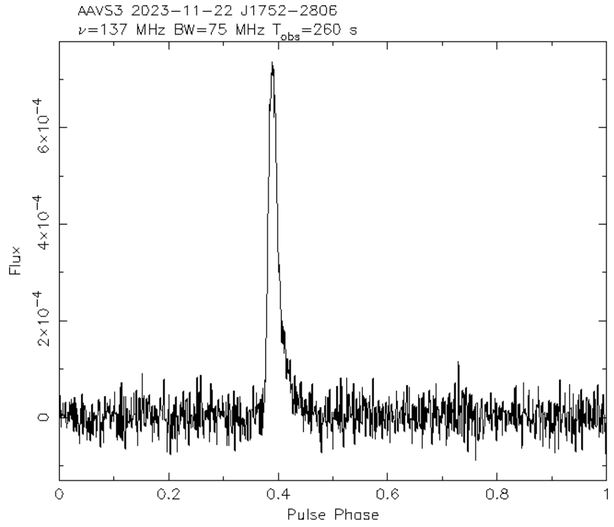
AAVS3 first light



First light: all-sky image at 159 MHz. 800-kHz bandwidth, 5-min integration, calibrated with the Sun, CLEANed. Credit: Caiazzo, Wayth et al.



Above: All-sky image movie with light CLEANing. Credit: Asayama et al.
Below: PSR J1752-2806. 137 MHz, 75-MHz bandwidth, 260-s integration. Credit: Serylak, Sobey et al.



- **Currently in the engineering commissioning phase. Science commissioning to begin soon!**

Thank you!

We recognise and acknowledge the Indigenous peoples and cultures that have traditionally lived on the lands on which our facilities are located.

SKAO

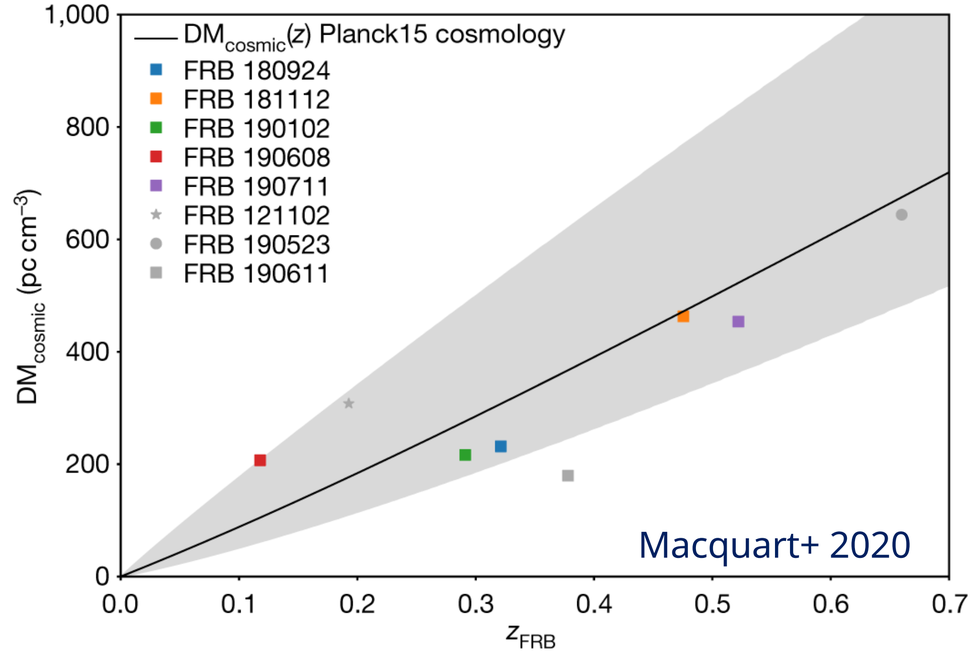
www.skao.int

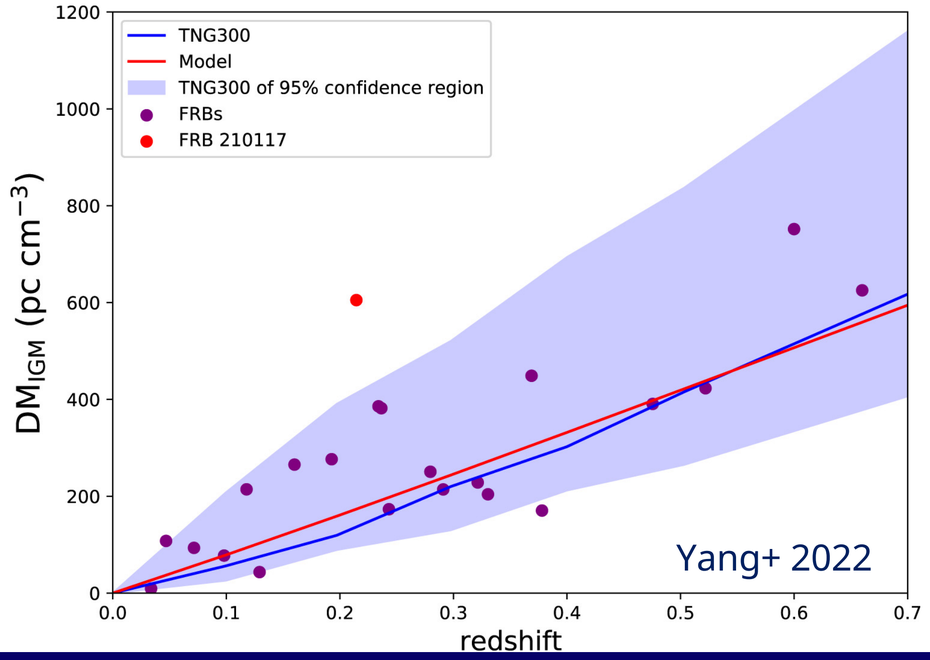
Missing Baryon Question with FRBs

- Most (3/4) baryons difficult to detect
- Small fraction directly observed, rest are "invisible"
- FRBs sensitive to total electron column density, and hence the ionized baryon content
- FRBs lie at cosmological distances
- Use FRB DM to infer baryon content
  - (DM has MW+IGM+host+FRB: IGM dominant)

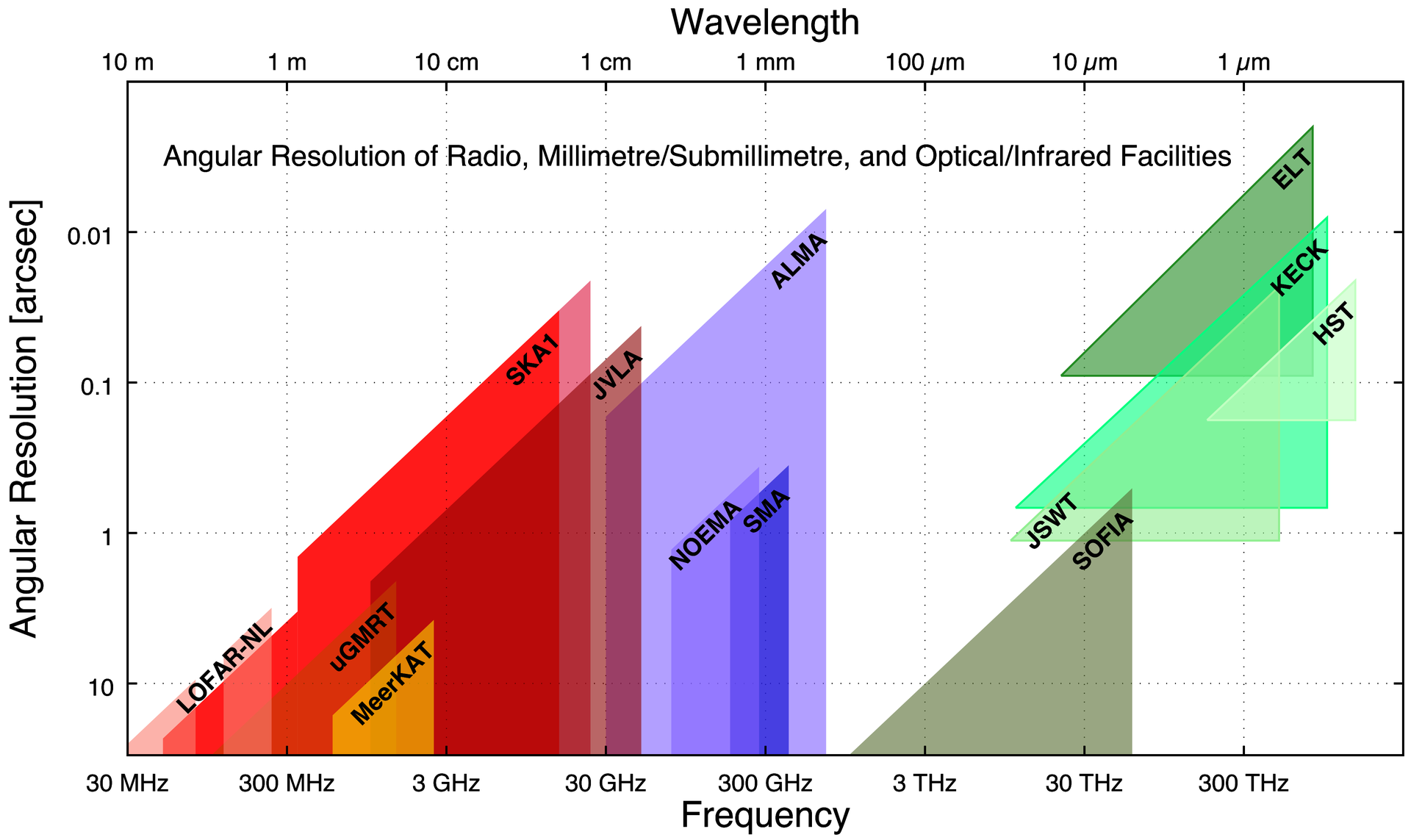
FRB localisation is difficult to date, due to small number of solid associations

Early results are consistent with CMB and Big Bang Nucleosynthesis





Angular Resolution (without VLBI)



Imaging Performance SKA-Mid

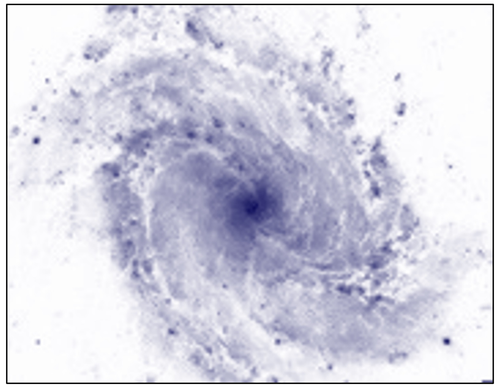
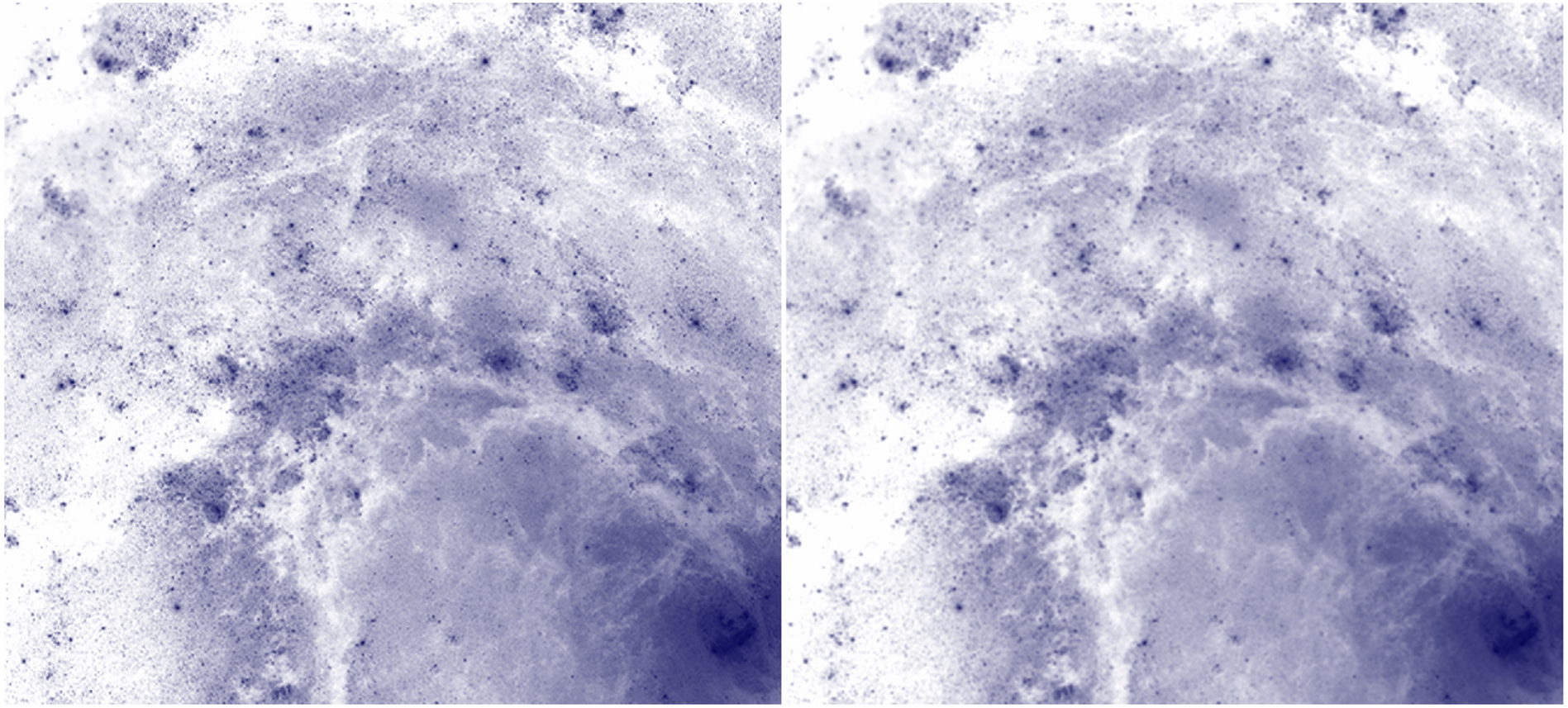


Image resample to SKA resolution ~1” @ 1.4 GHz

Input Model Image (noiseless)

SKA-Mid, 8h track



Imaging Performance SKA-Low

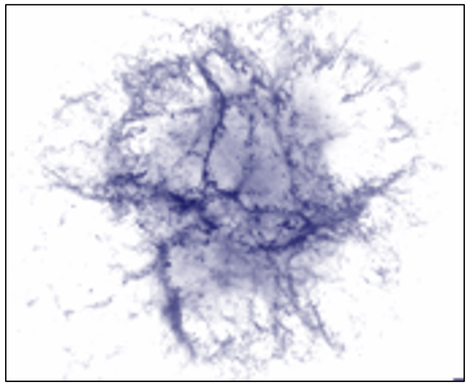
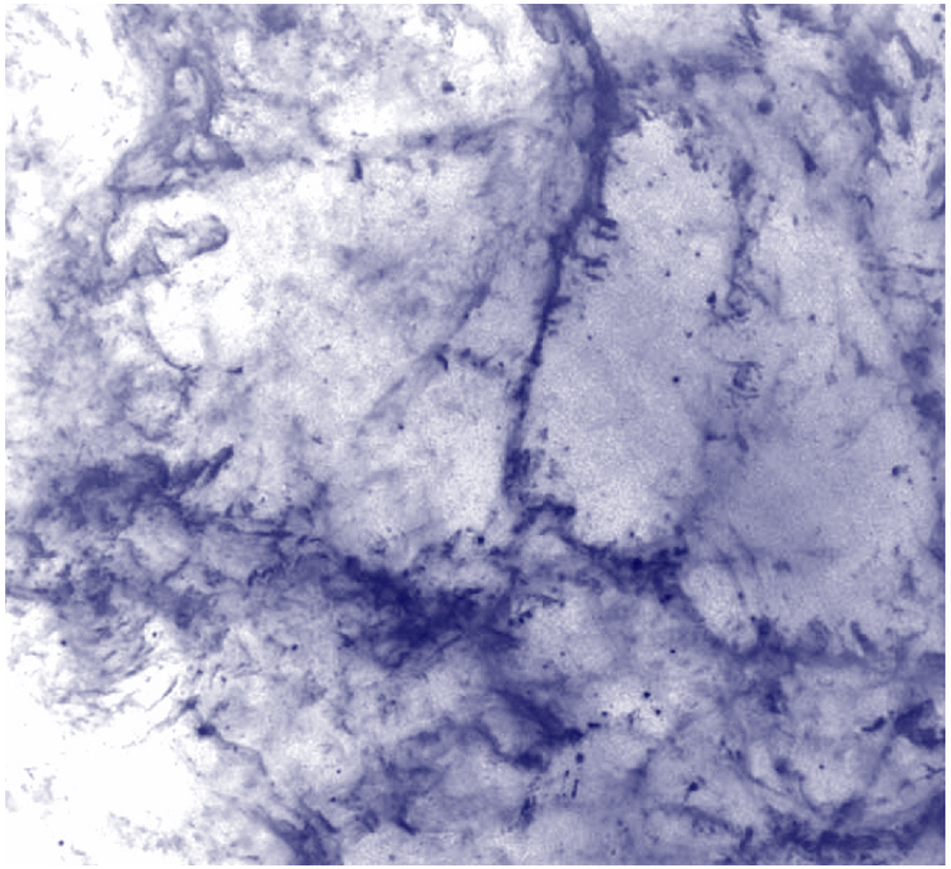
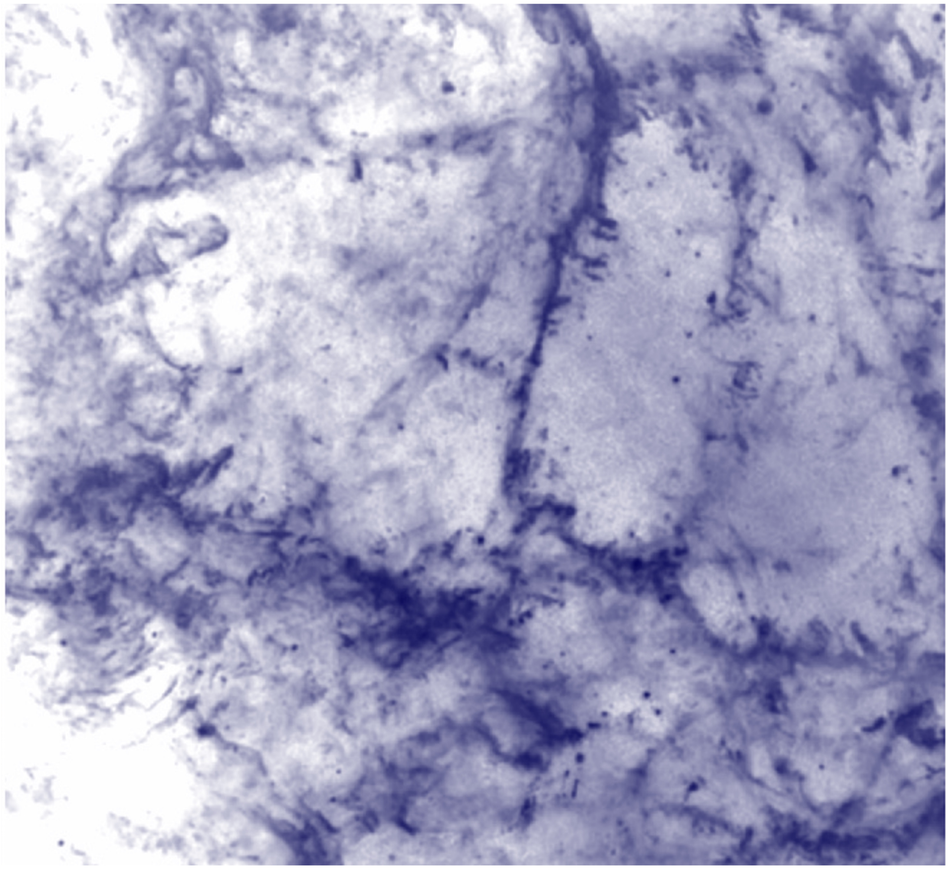


Image resample to SKA resolution
10” @ 140 MHz

Input Model Image
(noiseless)

SKA-Low, 4h track

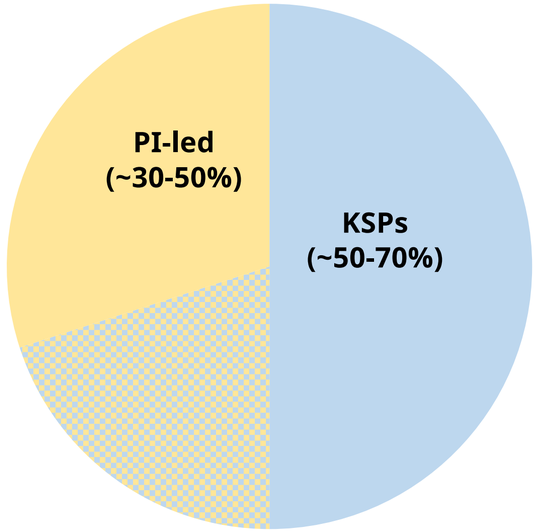




The Road to Science – Proposal Types

Key Science Projects (KSPs)

- Large programs performed over multiple cycles, requiring significant resources (e.g., observing time, computing)
- Leadership team from SKA-member countries; co-Is from any country (latter may be limited)
- Expected to provide added-value data products and tools back to SKAO
- Regular reviews to track progress toward goals

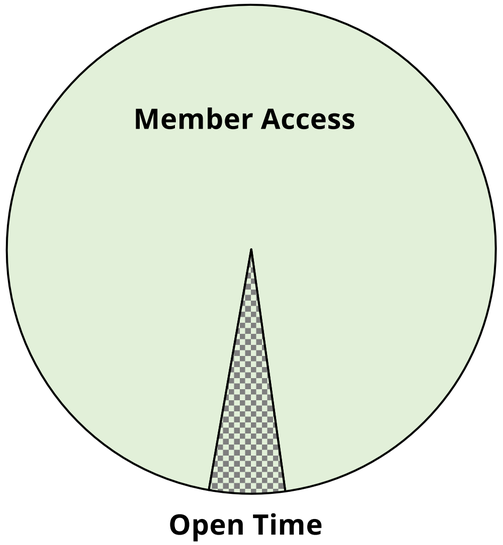


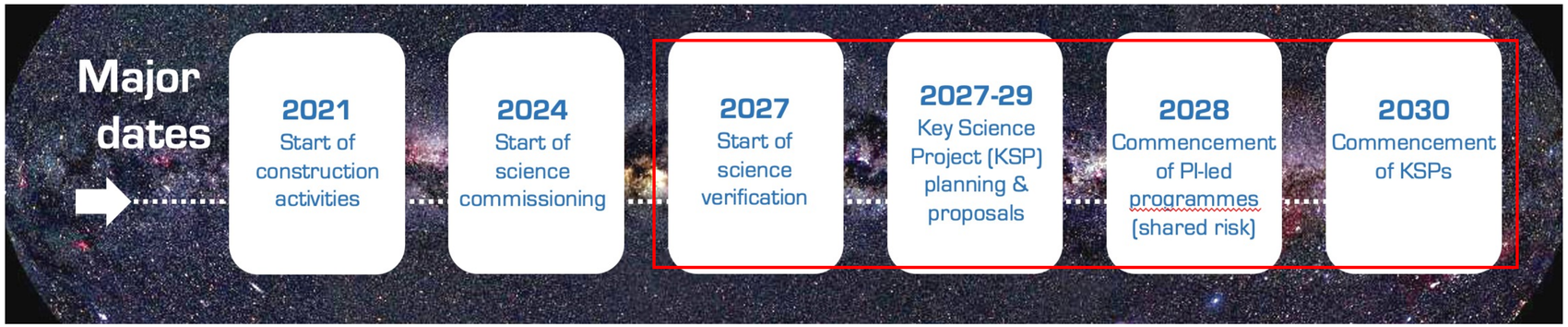
Principal Investigator (PI) Projects

- Small programs typically performed within a single cycle (1 year)

Access is proportional to member share

- e.g., UK's share currently ~15%





Spectral resolution

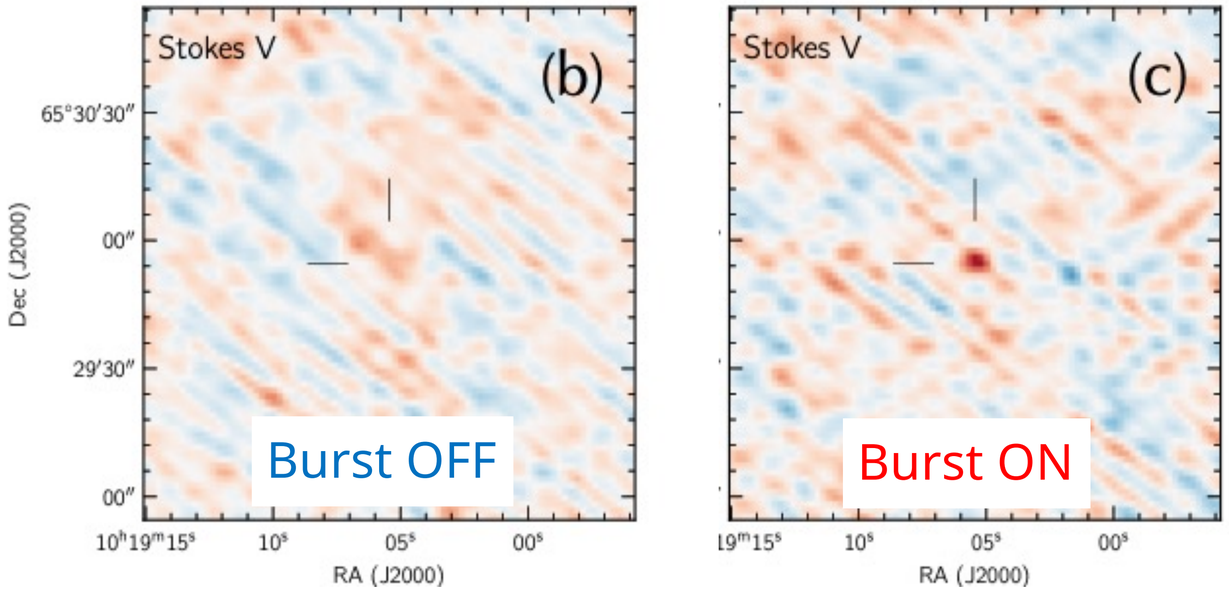
Nominal Frequency	110 MHz	300 MHz	770 MHz	1.4 GHz	6.7 GHz	12.5 GHz
Range [GHz]	0.05-0.35	0.05-0.35	0.35-1.05	0.95-1.76	4.6-8.5	8.3-15.3
Channel width (uniform resolution across max. bandwidth) [kHz]	5.4	5.4	13.4	13.4	80.6	80.6
Channel width (uniform resolution across max. bandwidth) [km/s]	14.7	5.4	5.7	2.9	3.6	1.9
Spectral zoom windows X narrowest bandwidth [MHz]	4 X 3.9	4 X 3.9	4 X 3.1	4 X 3.1	4 X 3.1	4 X 3.1
Finest zoom channel width [Hz]	226	226	210	210	210	210
Finest zoom channel width [km/s]	0.62	0.22	0.09	0.04	0.01	0.004

Anticipated Science Performance: https://arxiv.org/abs/1912.12699

Characterisation of exoplanets via direct detection

- Low frequency radio emissions from planetary aurora are very bright and highly polarized
- LOFAR detecting Brown Dwarfs – higher mass proxy (mass ~13-80 M_J) for exoplanets (<13 M_J)
- SKA-Low will enable direct detection of exoplanets (host star not polarized so not detected)
- Provides information on (i) internal structure, (ii) rotation rate, (iii) B field

Aurora on Jupiter (credit: NASA)



Circularly polarised images (Stokes V; 30s) of radio bursts from th
Brown Dwarf WISEPA J101905.63+652954.2
observed with LOFAR at **144 MHz** (LoTSS)
(Vedantham, Callingham, Zarka et al. submitted)