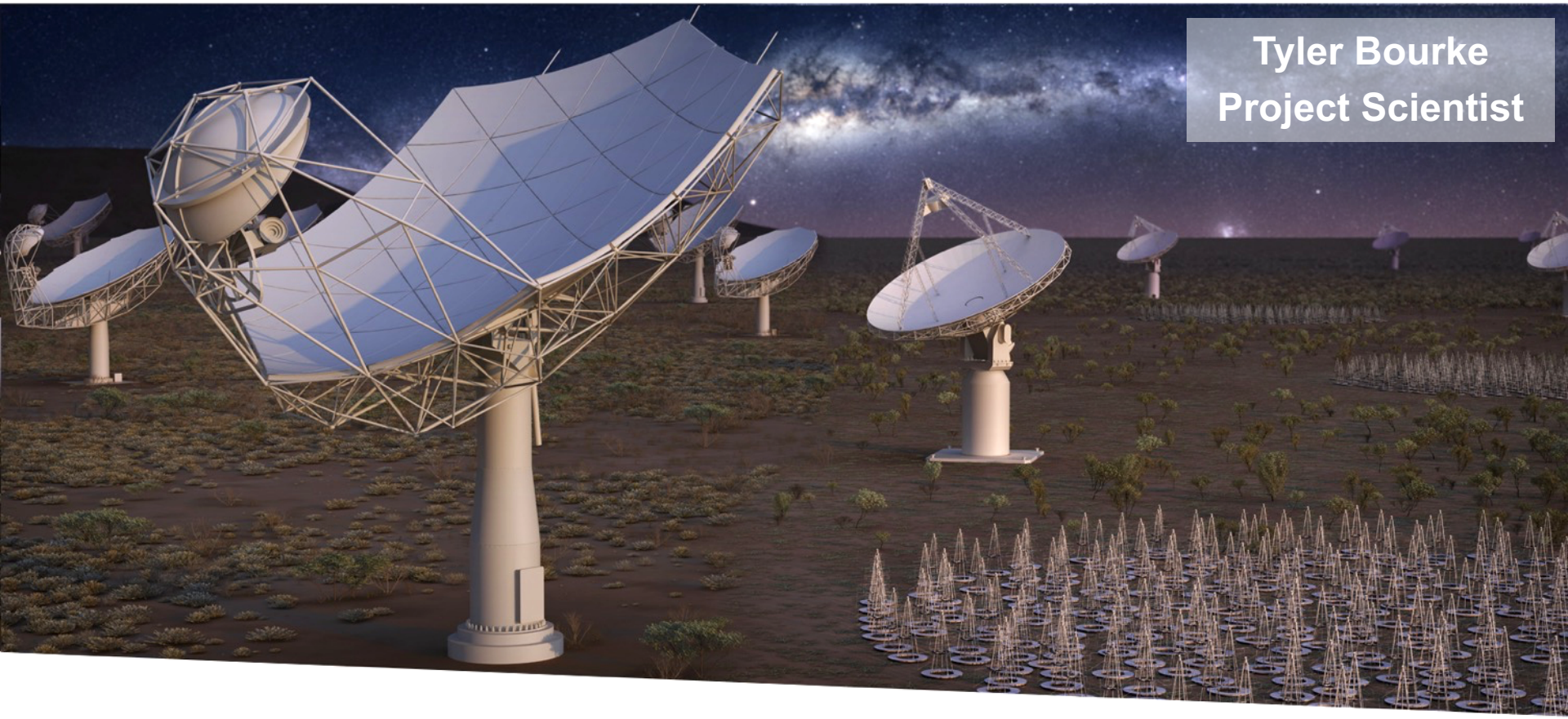
# SKA Science Planning

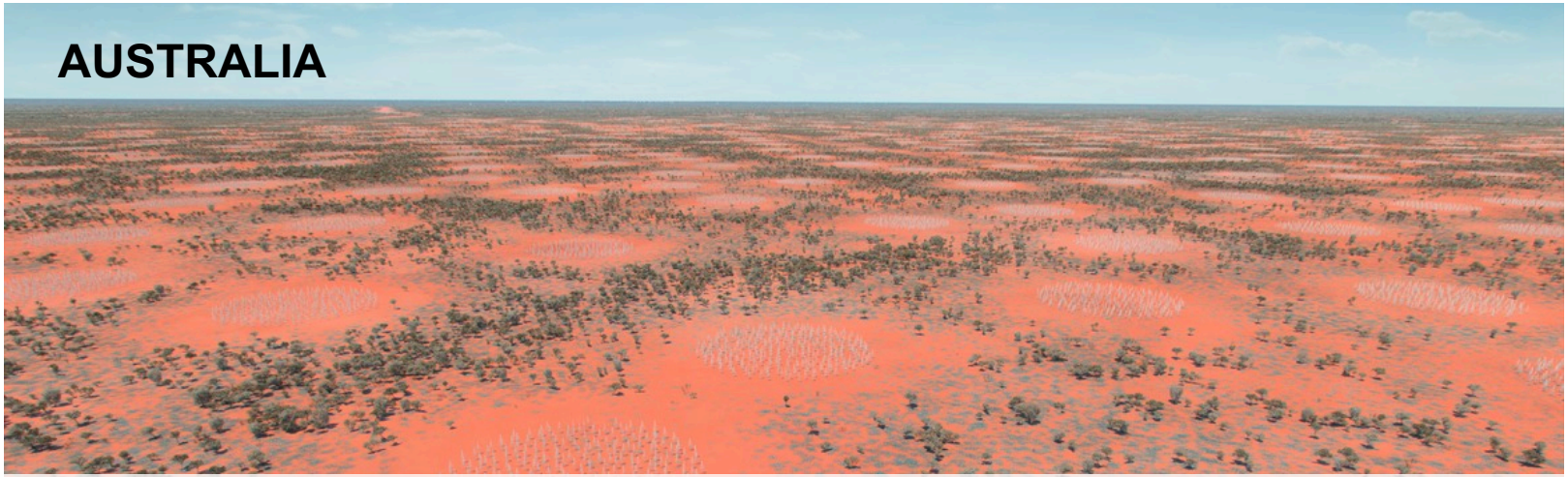


Tyler Bourke
Project Scientist

SQUARE KILOMETRE ARRAY

Exploring the Universe with the world's largest radio telescope

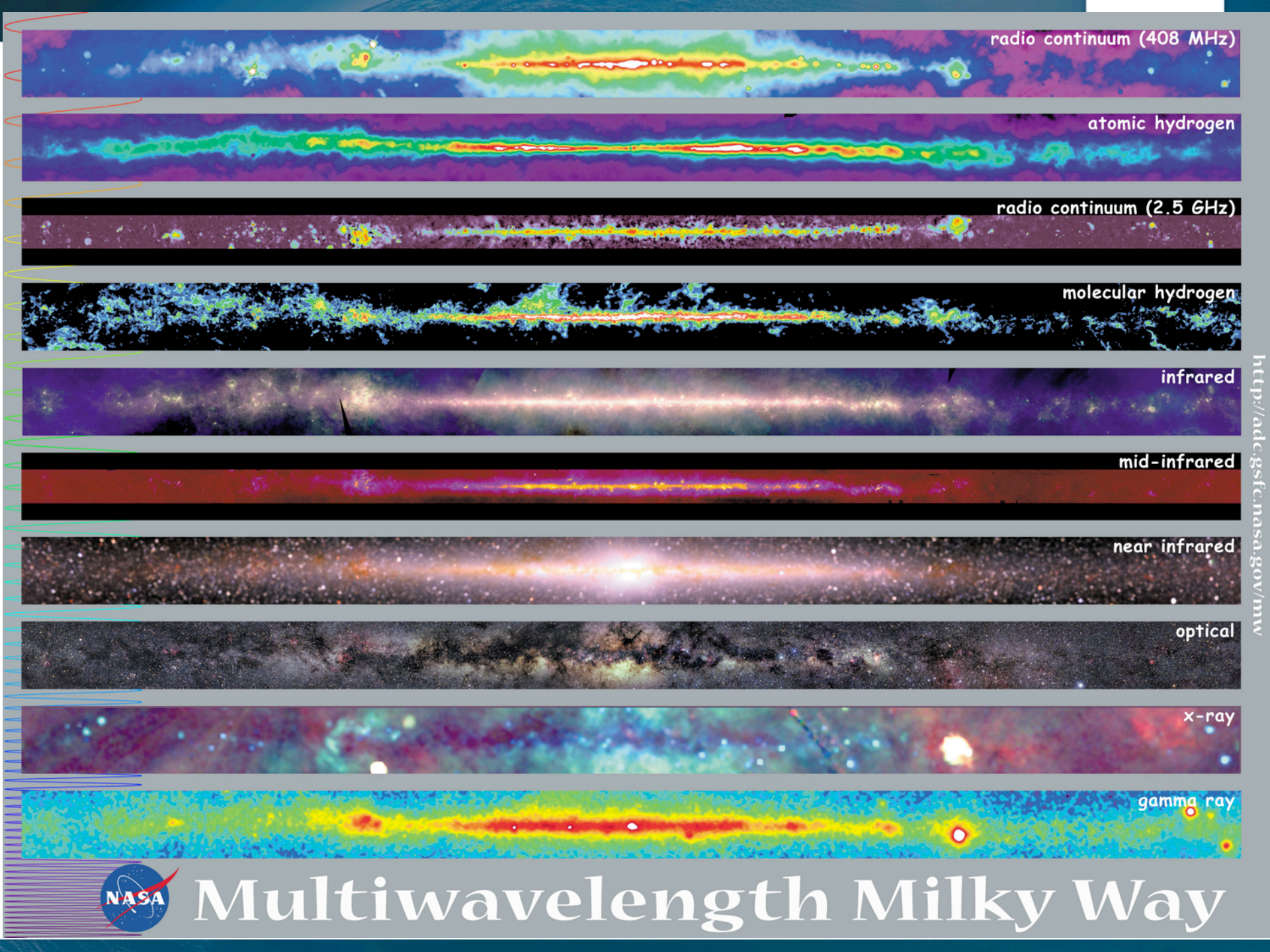
SKA Swiss Days, Brugg
12/6/2018




International effort to build the World's largest radio telescope

Prime Motivation: Study the history of the Universe in Hydrogen

Will enable transformational science in many other areas


radio continuum (408 MHz)
atomic hydrogen
radio continuum (2.5 GHz)
molecular hydrogen
infrared
mid-infrared
near infrared
optical
x-ray
gamma ray
http://adc.gsfc.nasa.gov/mw
NASA
Multiwavelength Milky Way

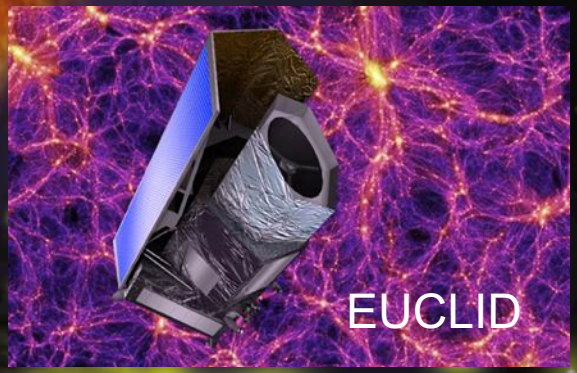

LIGO/VIRGO

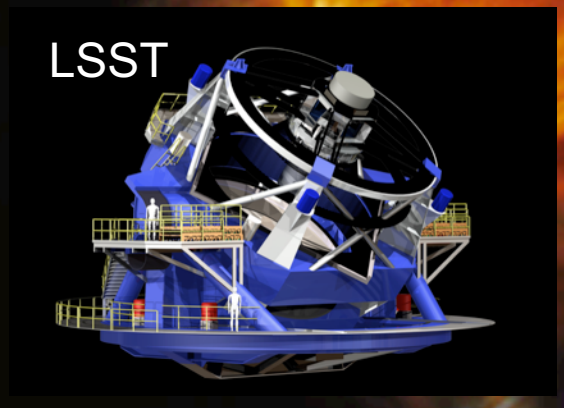

JWST: 2020


ATHENA: 2028+


ALMA


SKA


EUCLID


LSST


E-ELT: 2024


CTA: 2024


Radio waves
Microwaves
Infrared
Ultraviolet
X-rays
Gamma

# 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
(Planets, Molecules, SETI)

Cosmology
(Dark Matter, Large Scale Structure)

Cosmic Magnetism
(Origin, Evolution)

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
120 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* | | |

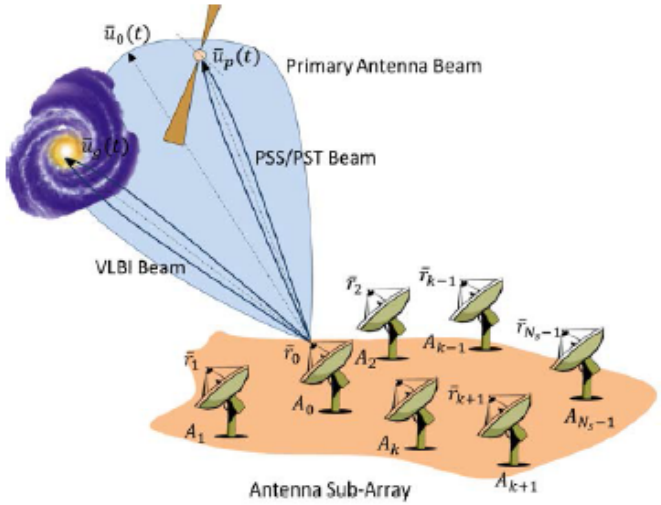
**Possible Wide-Band and/or High Frequency upgrade paths**

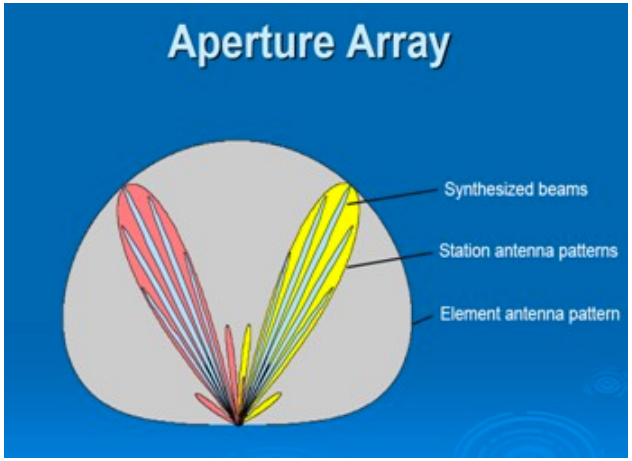
| Band | Frequency Range | Bandwidth |
|---|---|---|
| Mid Band A | 1.6 – 5.2 GHz | 2 x 2 GHz |
| Mid Band B | 4.6 – 24 GHz | 2 x 2.5 GHz |
| Mid Band 6 | 15 – 24 GHz | 2 x 2.5 GHz |

# SKA1 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)*



# SKA Configurations

Fixed positions

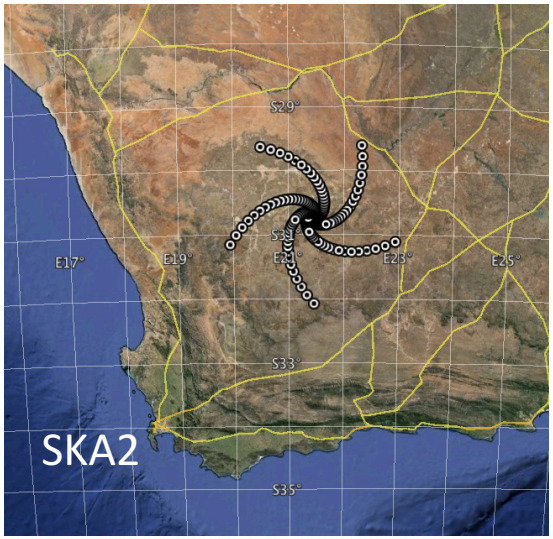
Dense inner-core (~2 km diam., 50%)

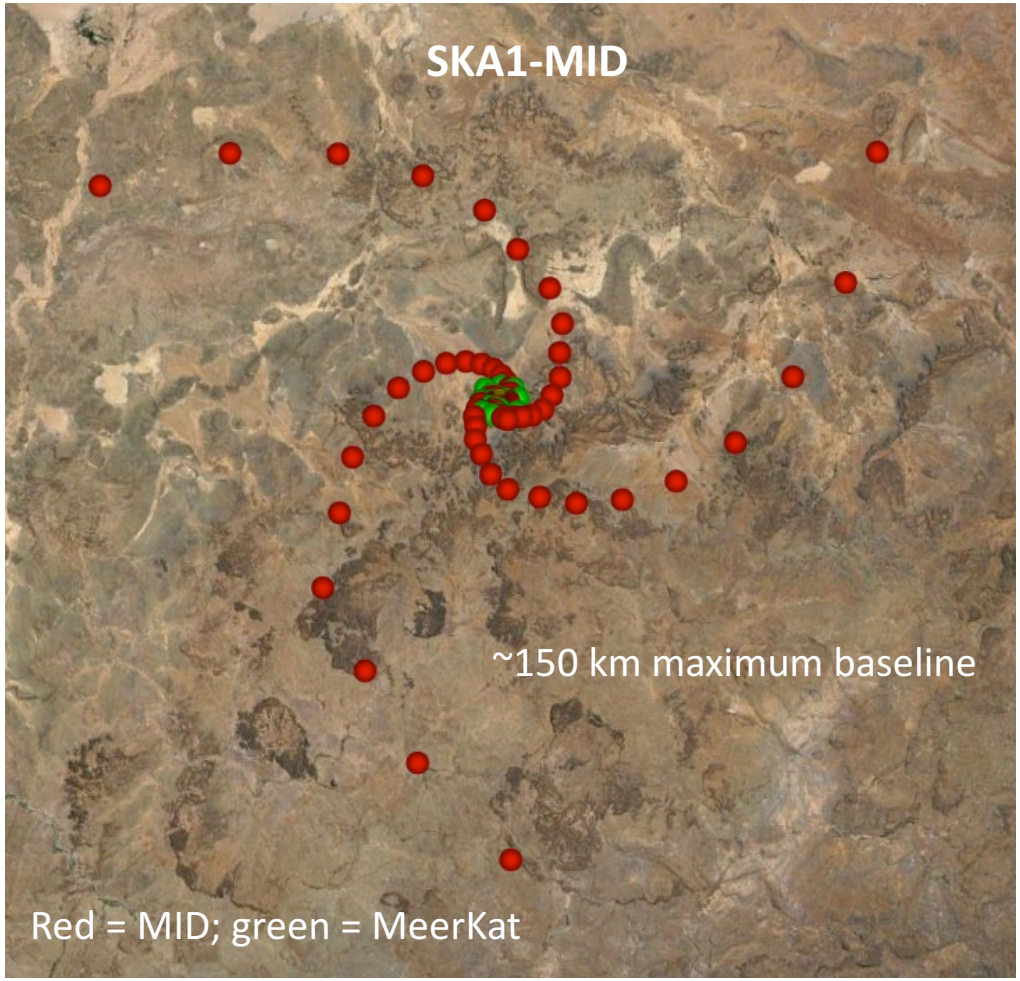
→ Brightness Sensitivity

→ Pulsar Sensitivity

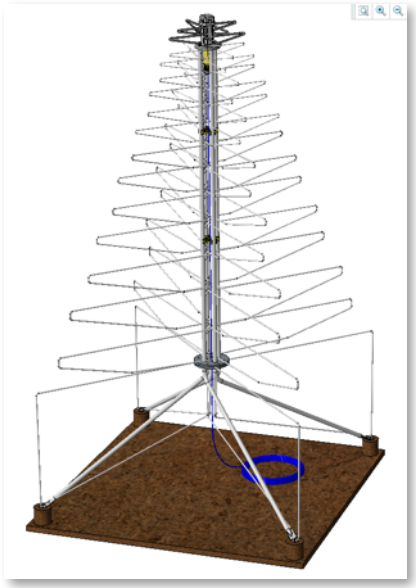
Logarithmic spiral arms

→ Imaging a range of angular scales (“scale-free”)



# SKA1-Low: Array of Arrays



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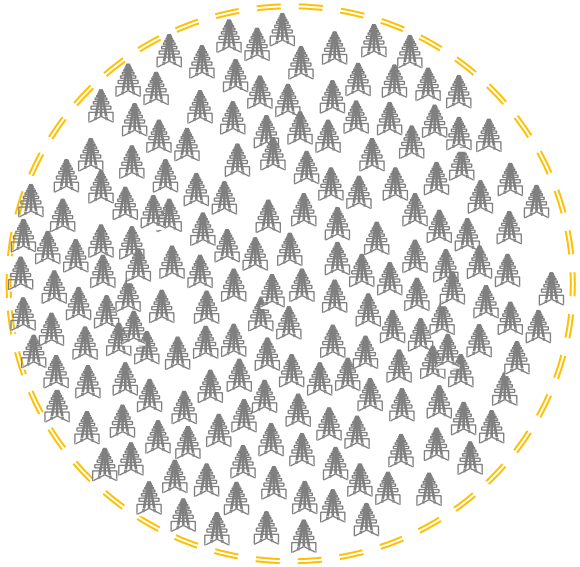

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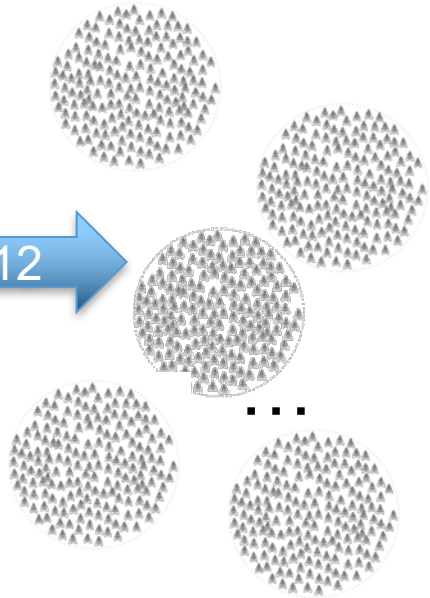


## SKA1-Low Antenna/Receptor

**Antenna Beam**

## SKA1-Low *"Station"*

**Station Beam**

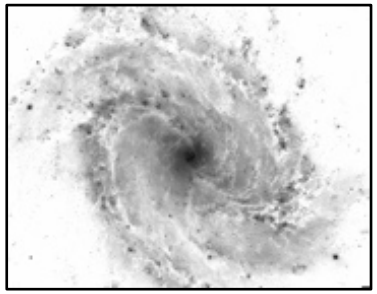
## SKA1-Low "Array"

**Correlation and *Tied-array Beams***

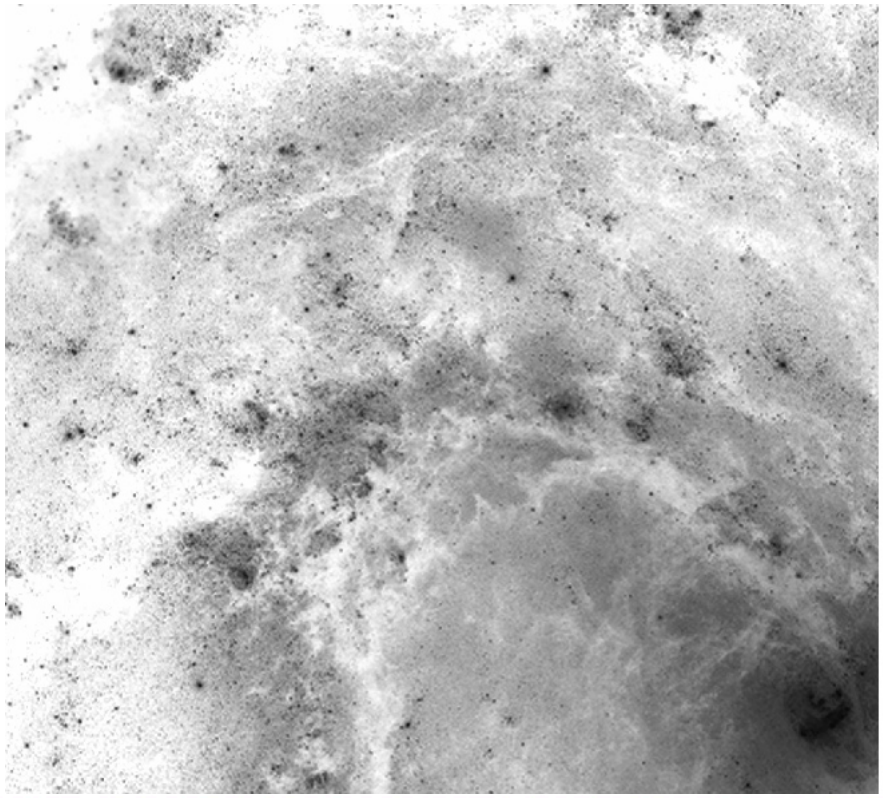
# Imaging Performance (Mid)*

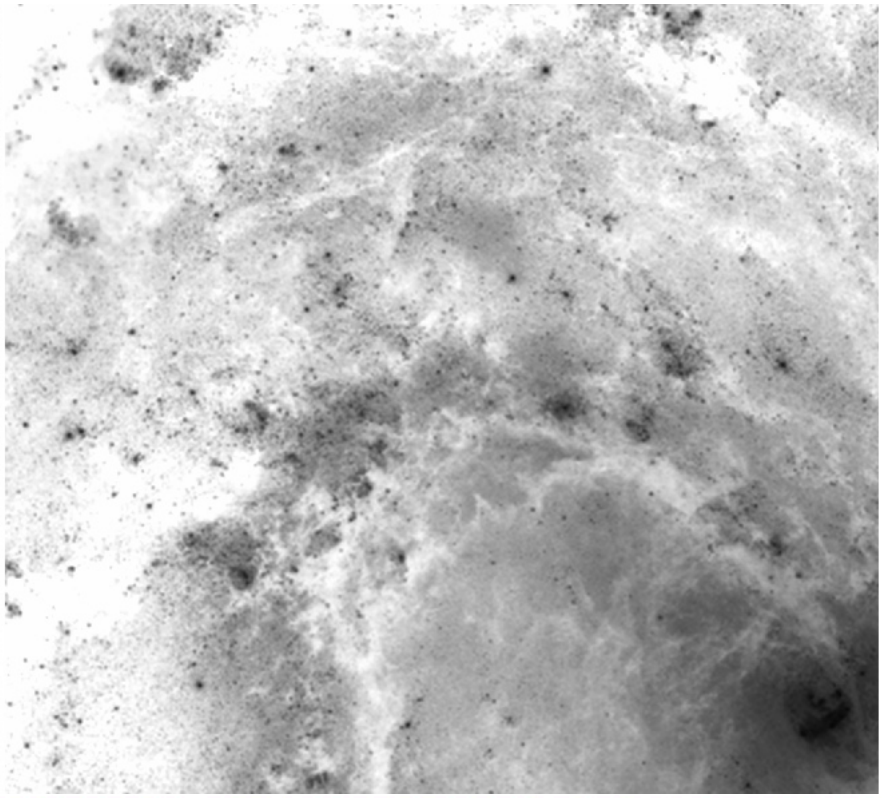
*Noiseless

Input Model Image



SKA1-Mid, 8h track

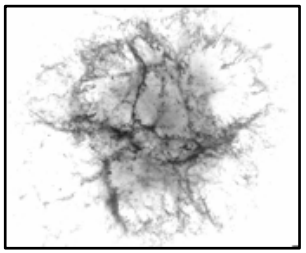




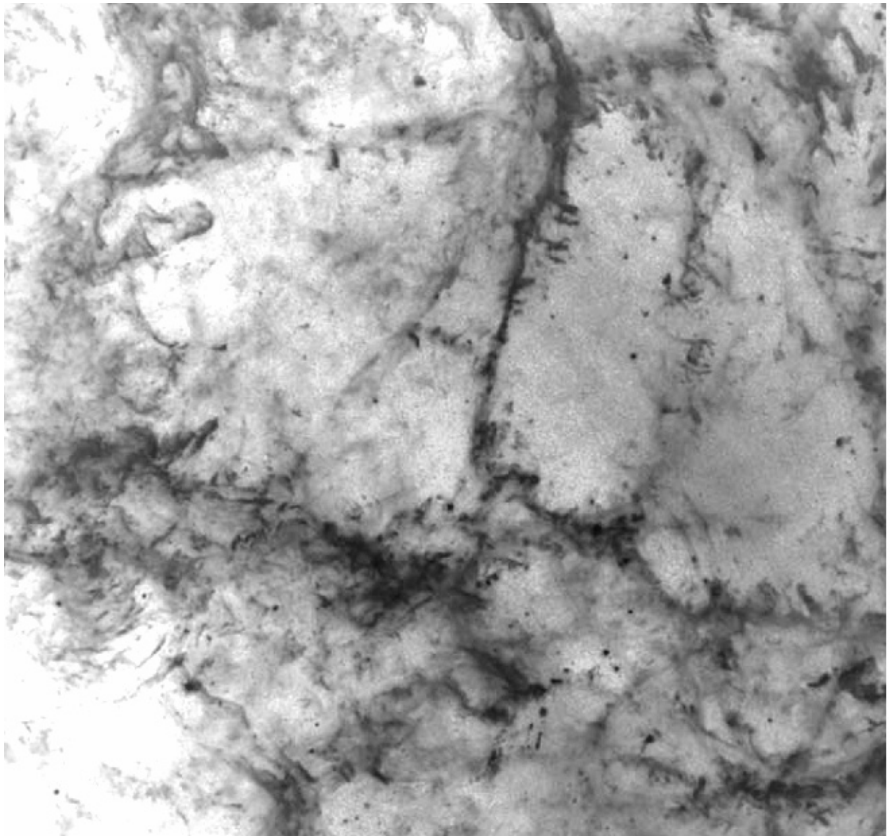
# Imaging Performance (Low)*

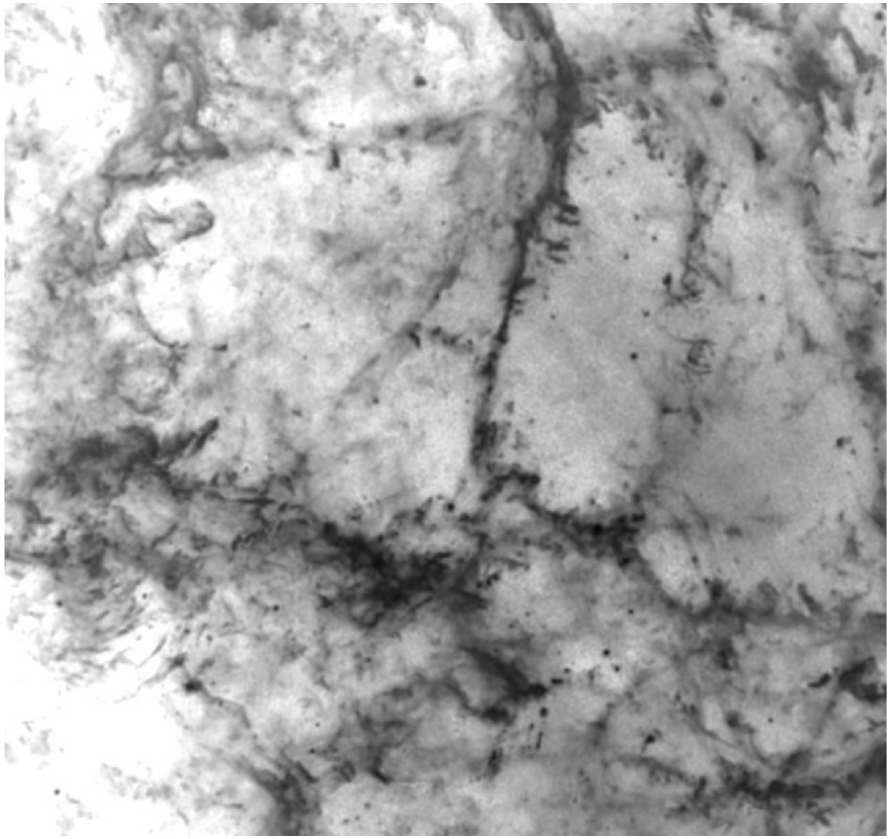
*Noiseless

Input Model Image

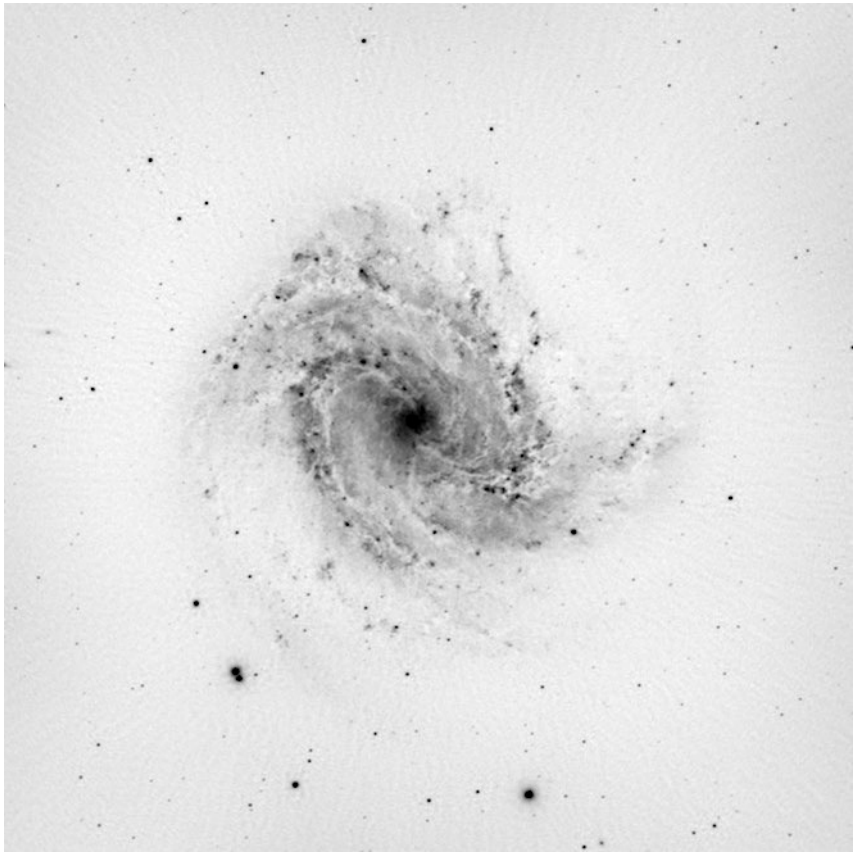


SKA1-Low, 4h track



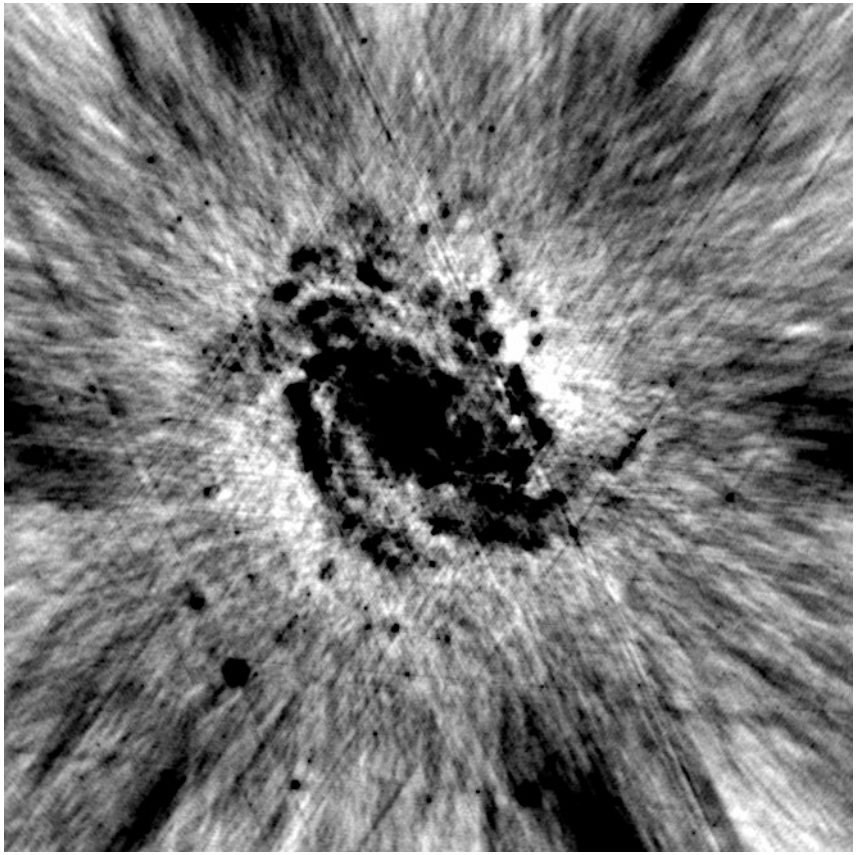


# Imaging Performance*



SKA1-MID Snapshot observation

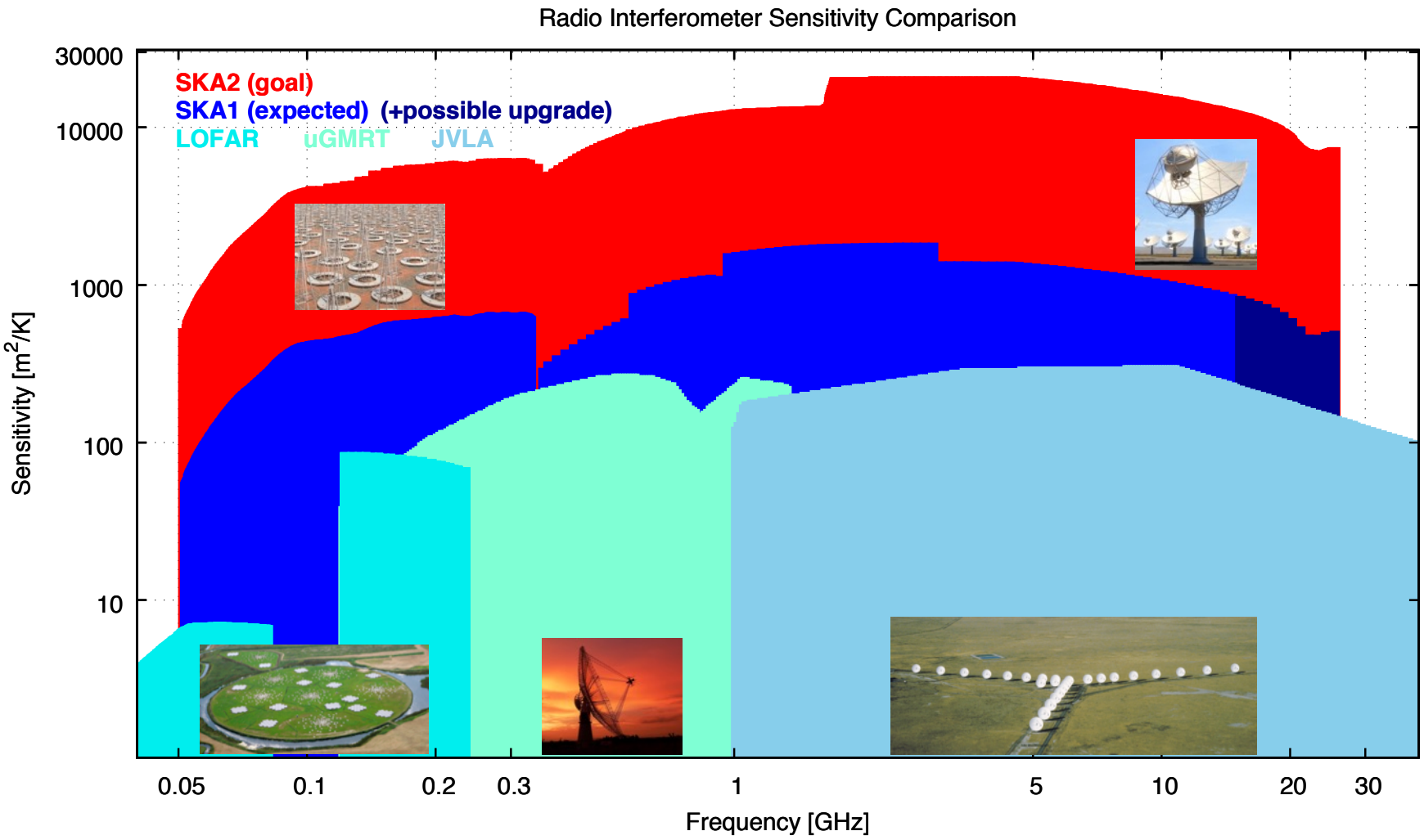
*Noiseless



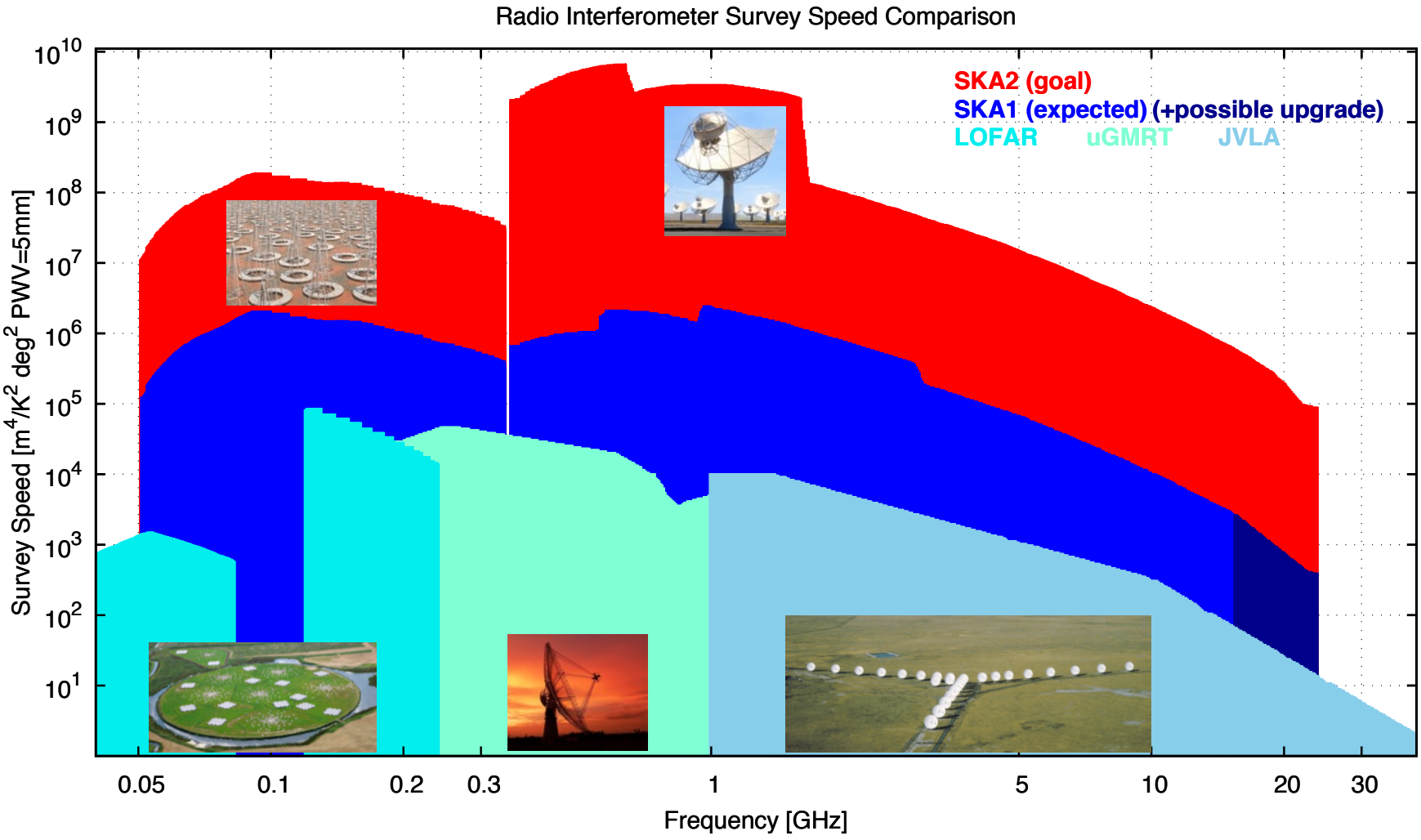
VLA Combination Snapshot
A+B+C+D array configuations

**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))

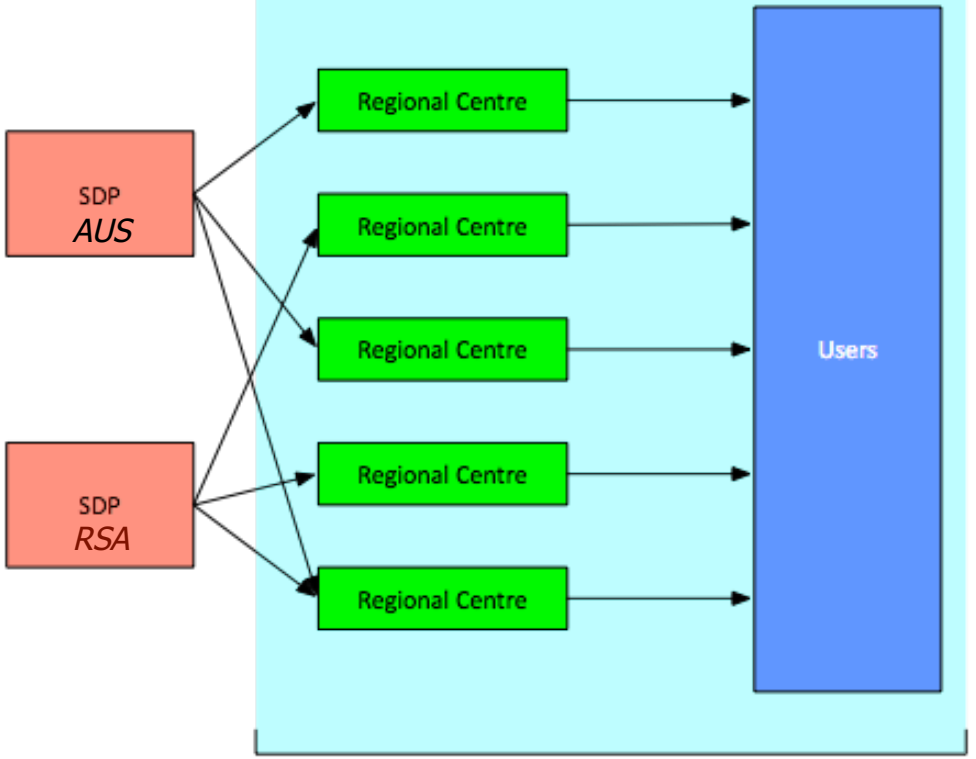
# SKA Regional Centres – outside SKAO scope

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

# 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
(Planets, Molecules, SETI)

Cosmology
(Dark Matter, Large Scale Structure)

Cosmic Magnetism
(Origin, Evolution)

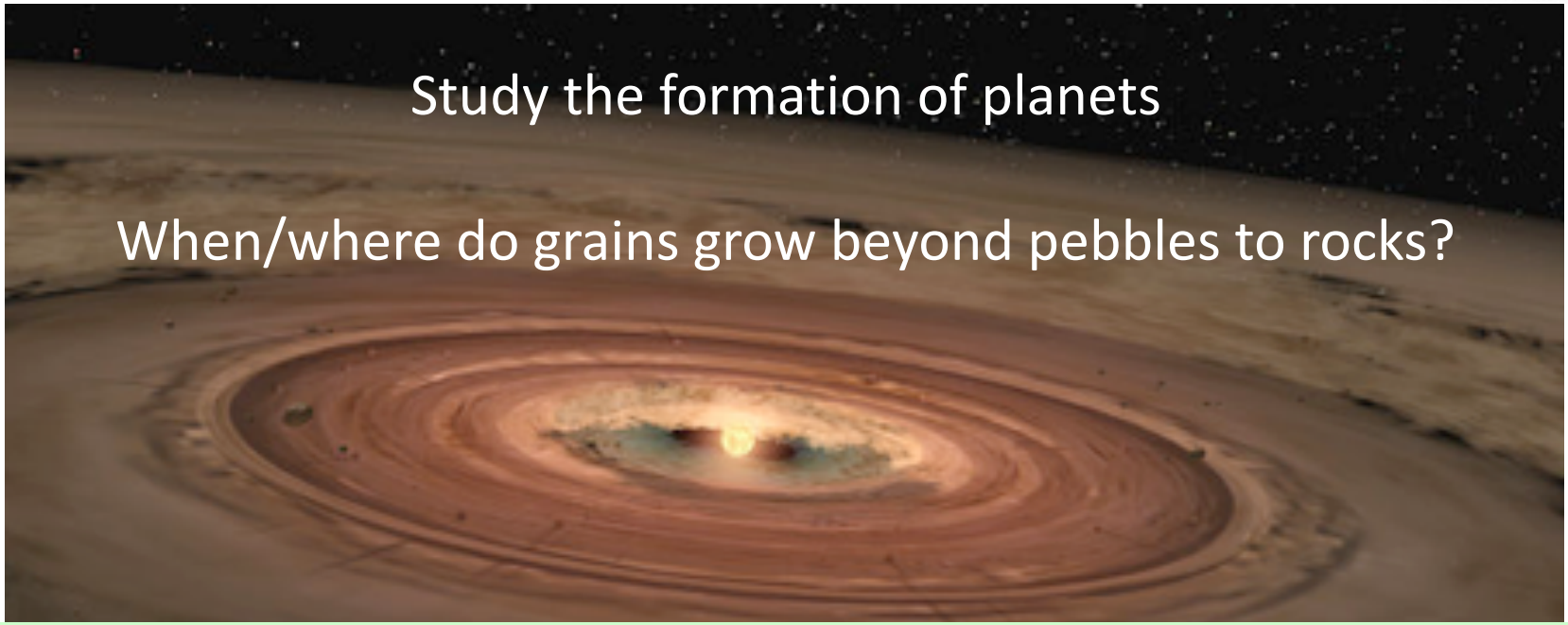
Exploration of the Unknown

**Broadest range of science of any facility, worldwide**

# 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?*

# Grain Growth in Protoplanetary Disks




Resolved disk observations allow for separation of free-free and thermal dust emission

SKA1 at 15 GHz will have 34 mas resolution, so 4-5 AU at 140 pc

Probing very large grains trapped in the terrestrial planet regime

→ SKA resolution and sensitivity at longer wavelengths sensitive to larger grain sizes

Hoare+ 2015, Testi+ 2015

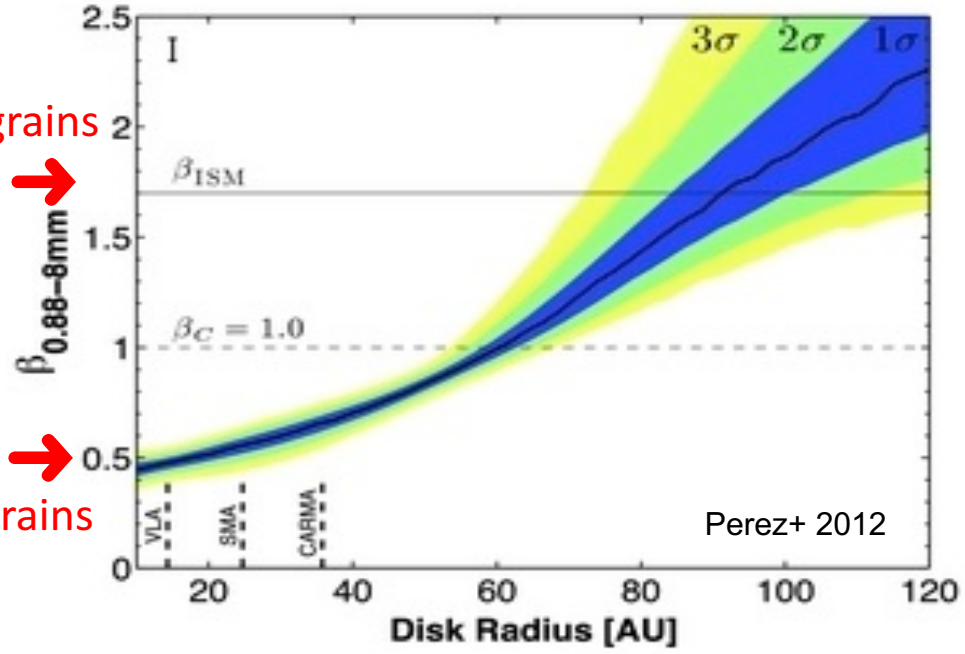
# Grain Growth in Protoplanetary Disks

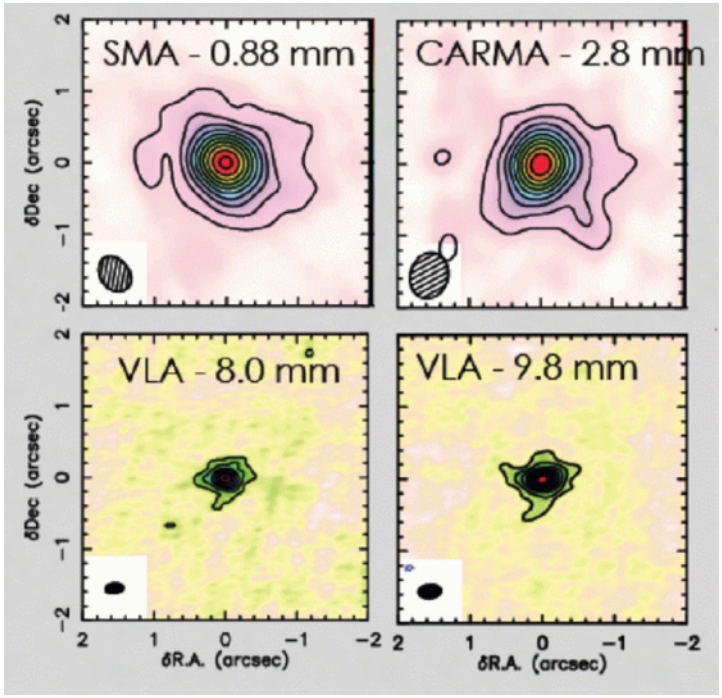
Resolved observations at cm wavelengths

- constrains dust opacity slope
- sensitive to larger grains

small grains →

→ large grains




SKA1 at 15 GHz will have 34 mas resolution, so 4-5 AU at 140 pc

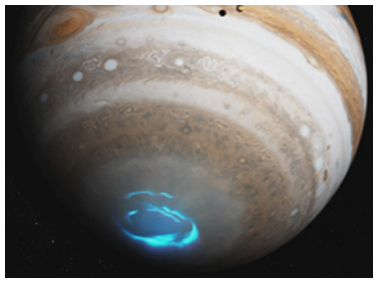
Probing very large grains trapped in the terrestrial planet regime

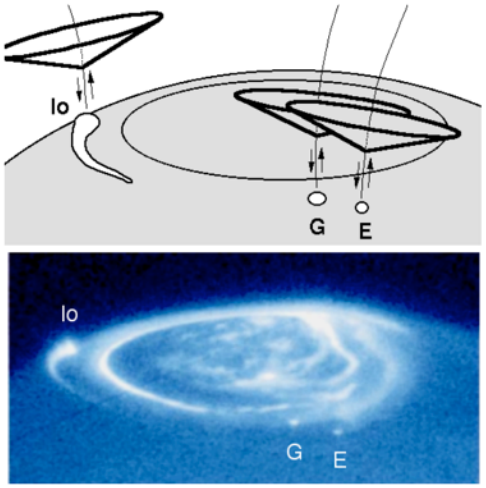
# Characterisation of Exoplanets

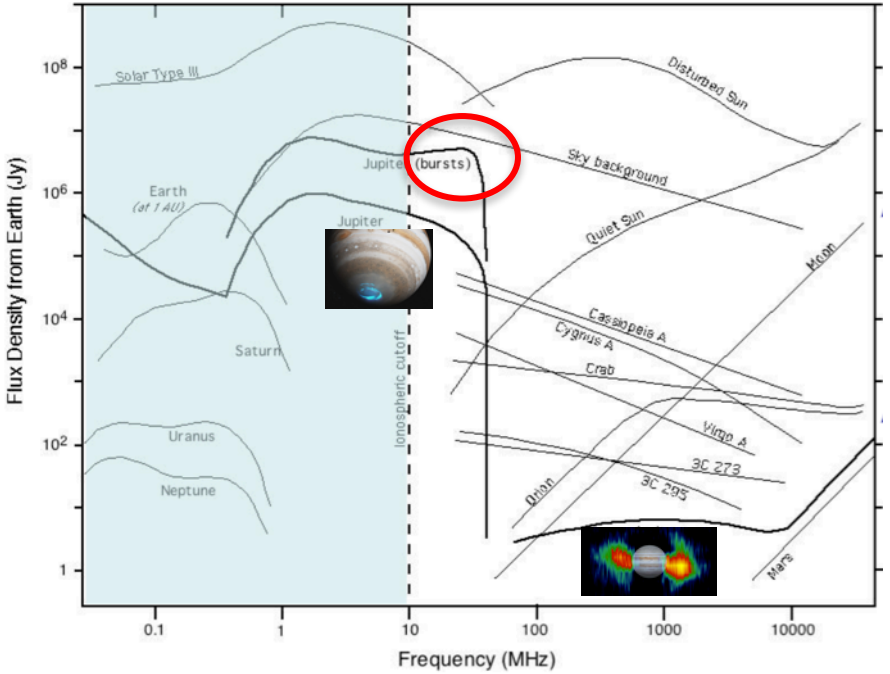
- Magnetospheric auroral radio emissions due to coherent Plasma processes

  Emission is extremely bright (up to 1020 K), highly polarized & beamed

- **Direct detection method for exoplanets**:
  - measurement of rotation rate
  - measurement of magnetic field strengths
  - leads to constraints on scaling laws
  - probes internal structure





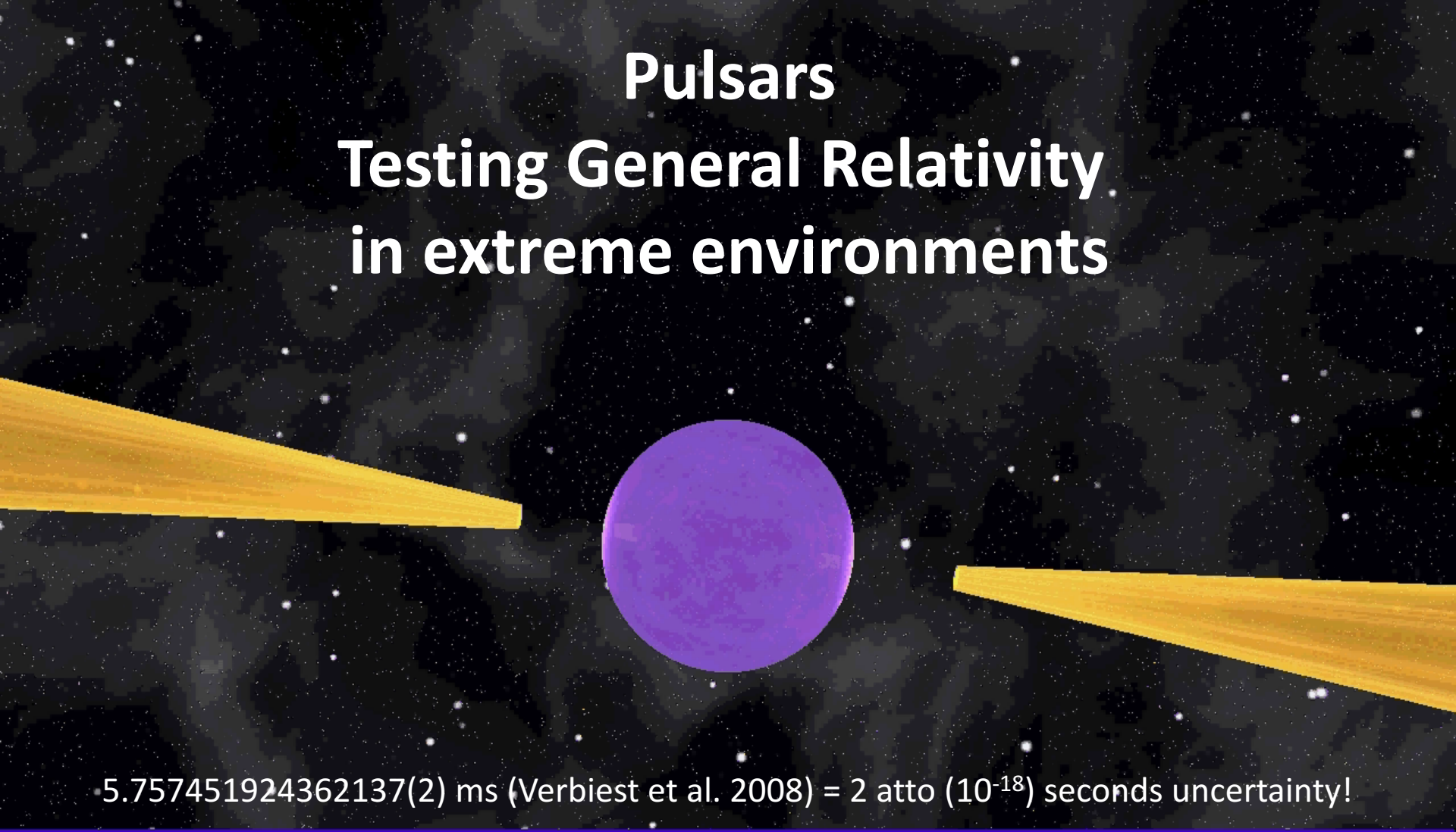




Zarka+ 2015

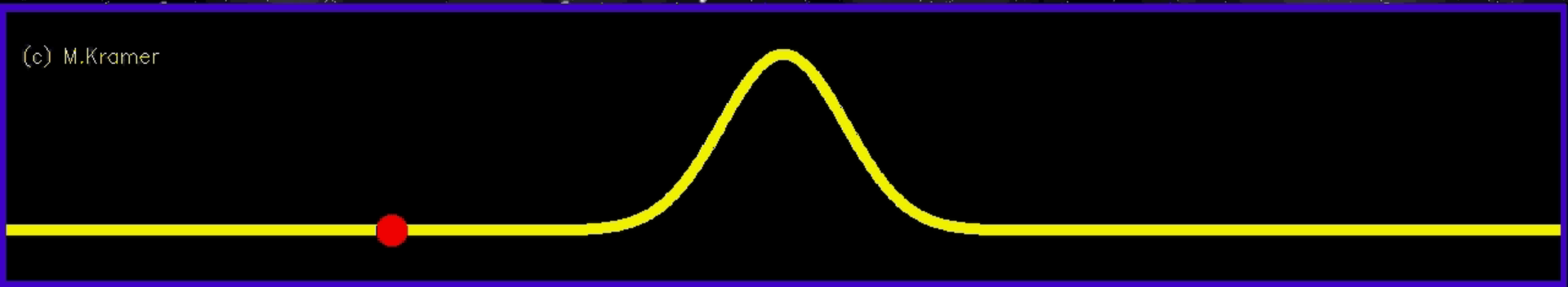
**SKA1-LOW at ~50 MHz will detect polarised bursts of emission!**

**SKA1-LOW able to detect hot-Jupiters out to 10 pc (~200 stars, ~35 known exoplanets)**

# Pulsars
# Testing General Relativity
# in extreme environments

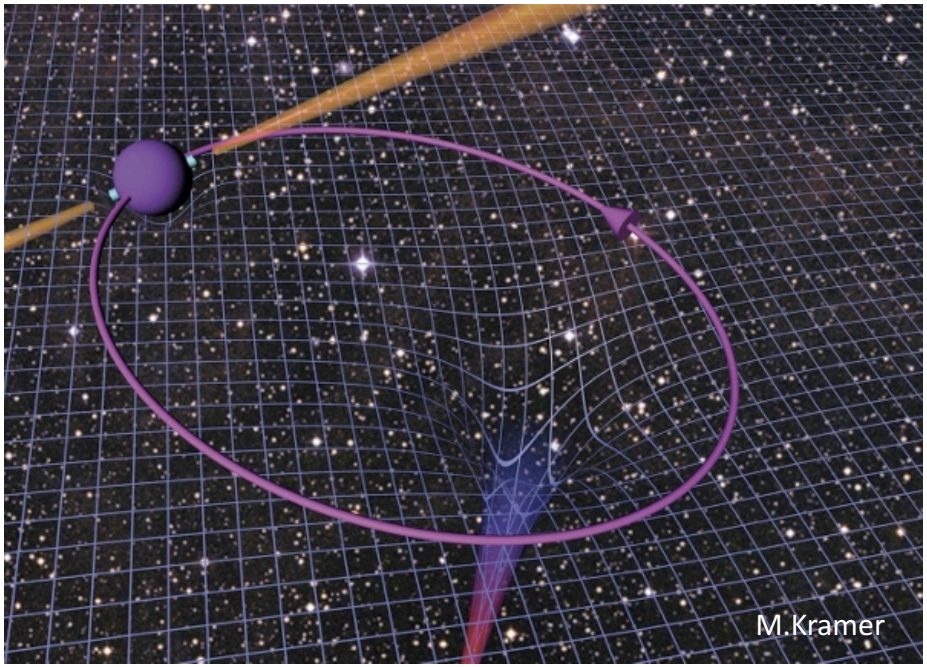


5.757451924362137(2) ms (Verbiest et al. 2008) = 2 atto ($10^{-18}$) seconds uncertainty!



# Test GR in strong field regime

Tests of GR in strong field regime via:
Neutron Star – White Dwarf binaries
Neutron Star – Neutron Star binaries
Pulsars around Galactic Centre
Neutron Star – Black Hole binaries




## No Hair Theorem

Black Holes can be described by 3 classical parameters:

- Mass
- Electric Charge
- Angular Momentum (Spin)

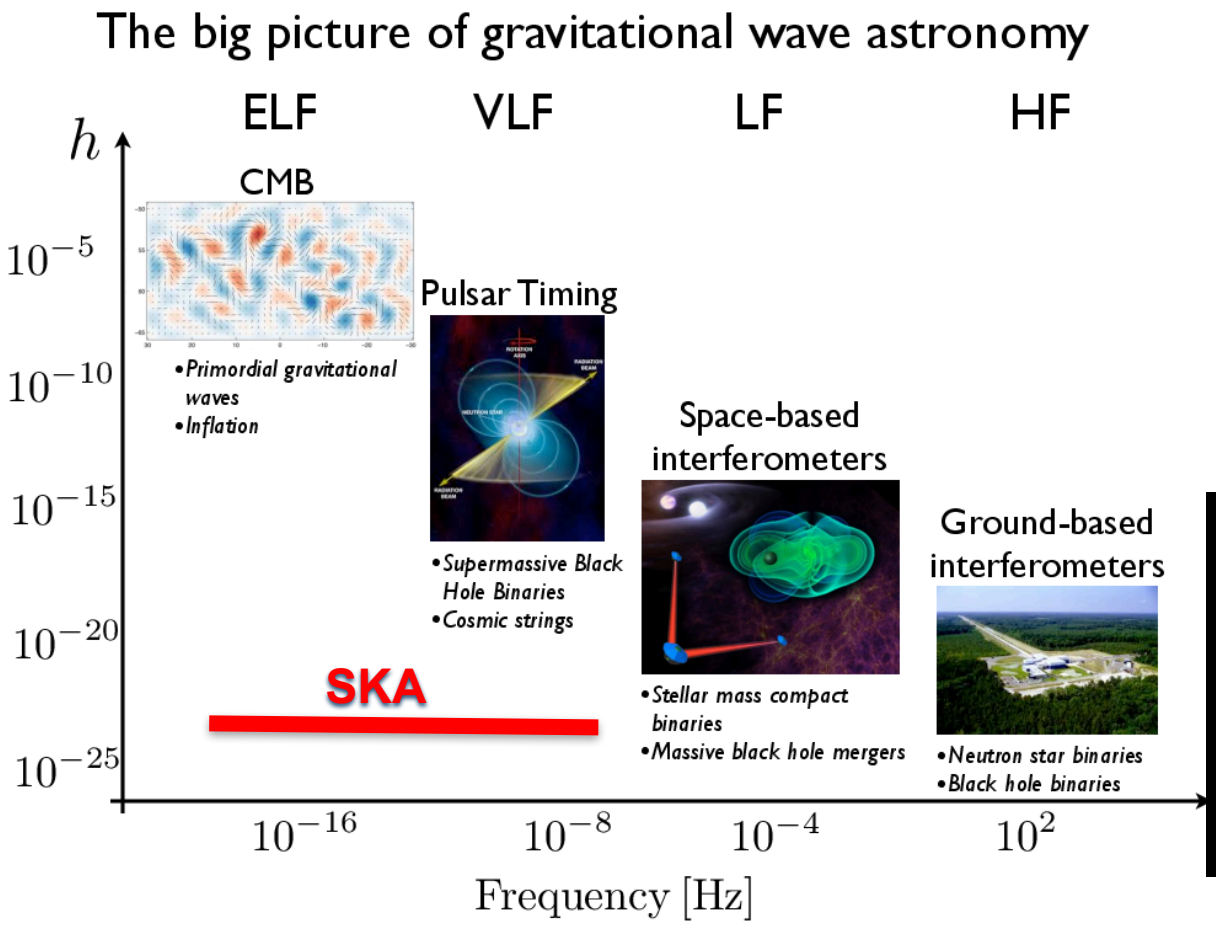
## Cosmic Censorship

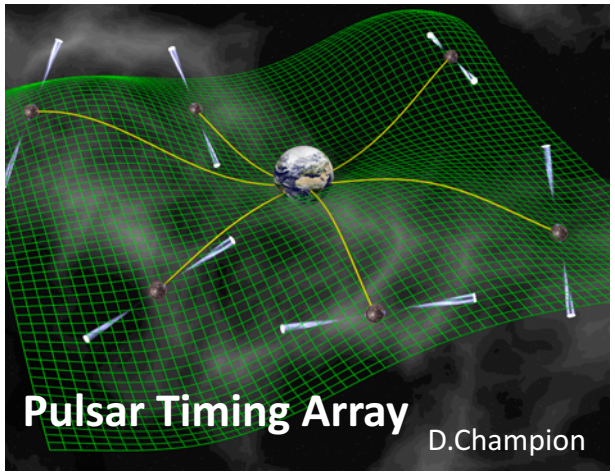
BHs have an event horizon which hides the singularity, i.e.., there are **no naked singularities**

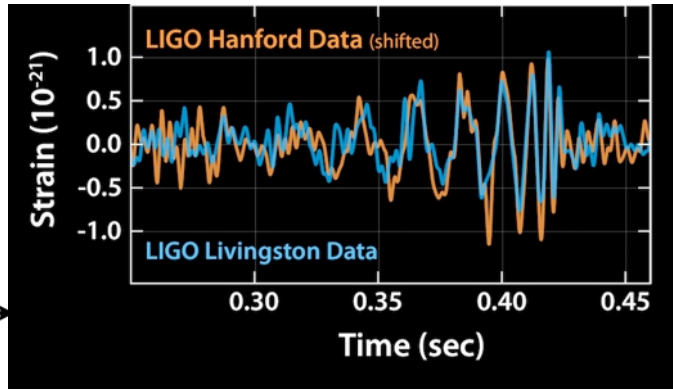
## Order of Magnitude Improvement

Kramer & Stappers 2015

# Gravitational Waves with Pulsars

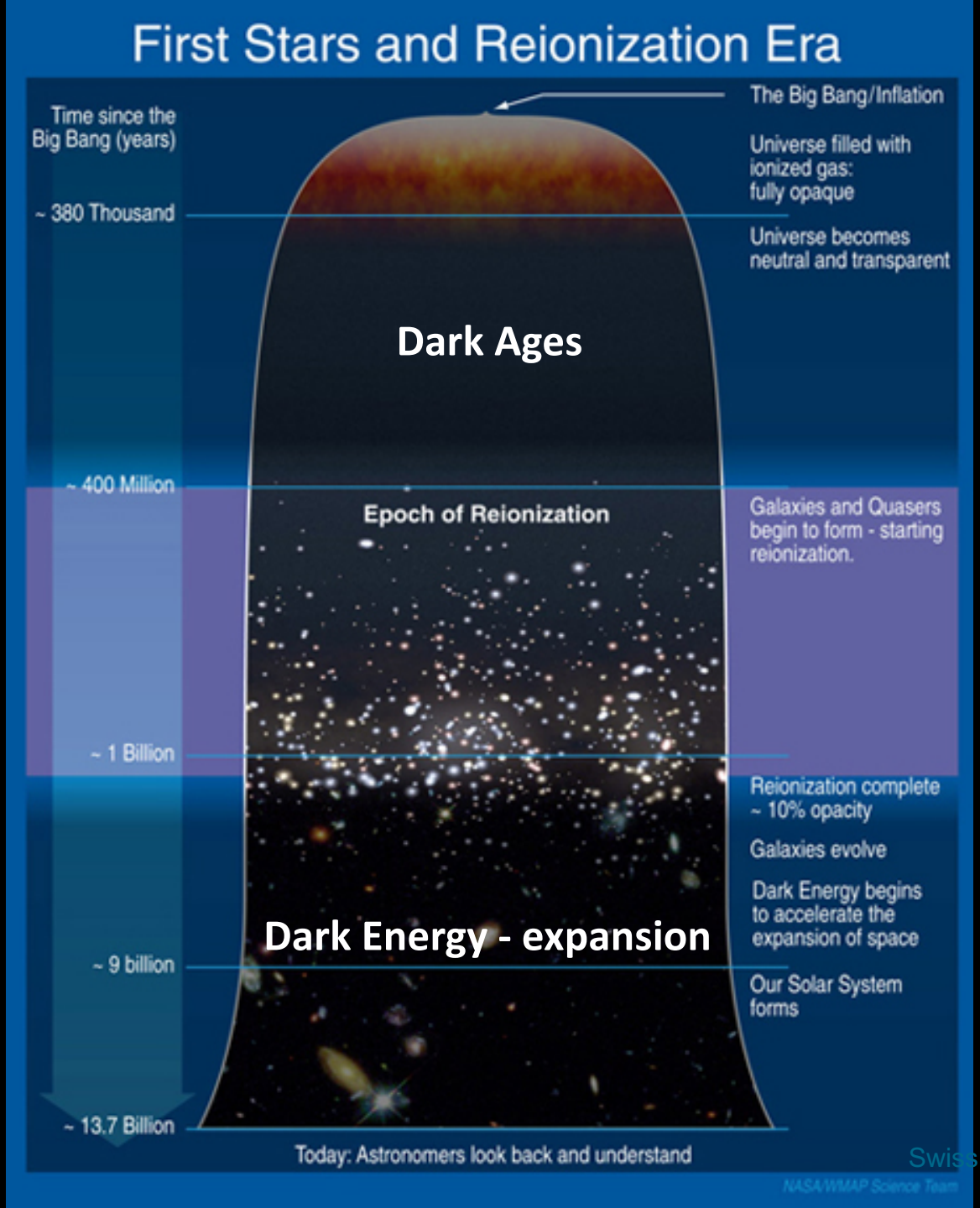



**Discoveries with SKA1 (SMBH mergers, Primordial GWs)**

**"GW astronomy" with SKA2 (discrete sources)**




380,000 yrs — CMB

400 million yrs — Stars form

1 Billion yrs — Galaxies evolve

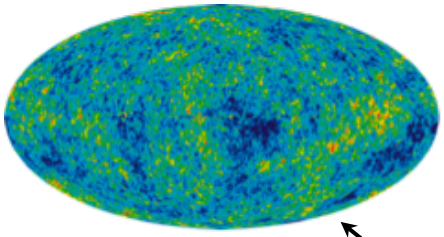
9 Billion yrs — Solar System forms

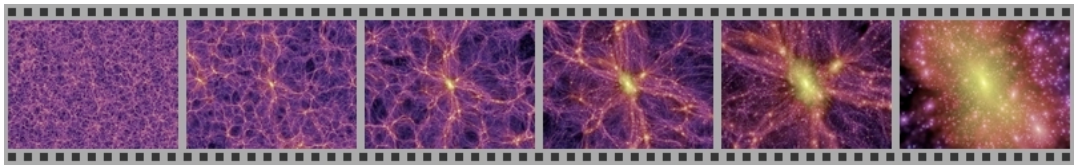
13.7 Billion yrs — Humans

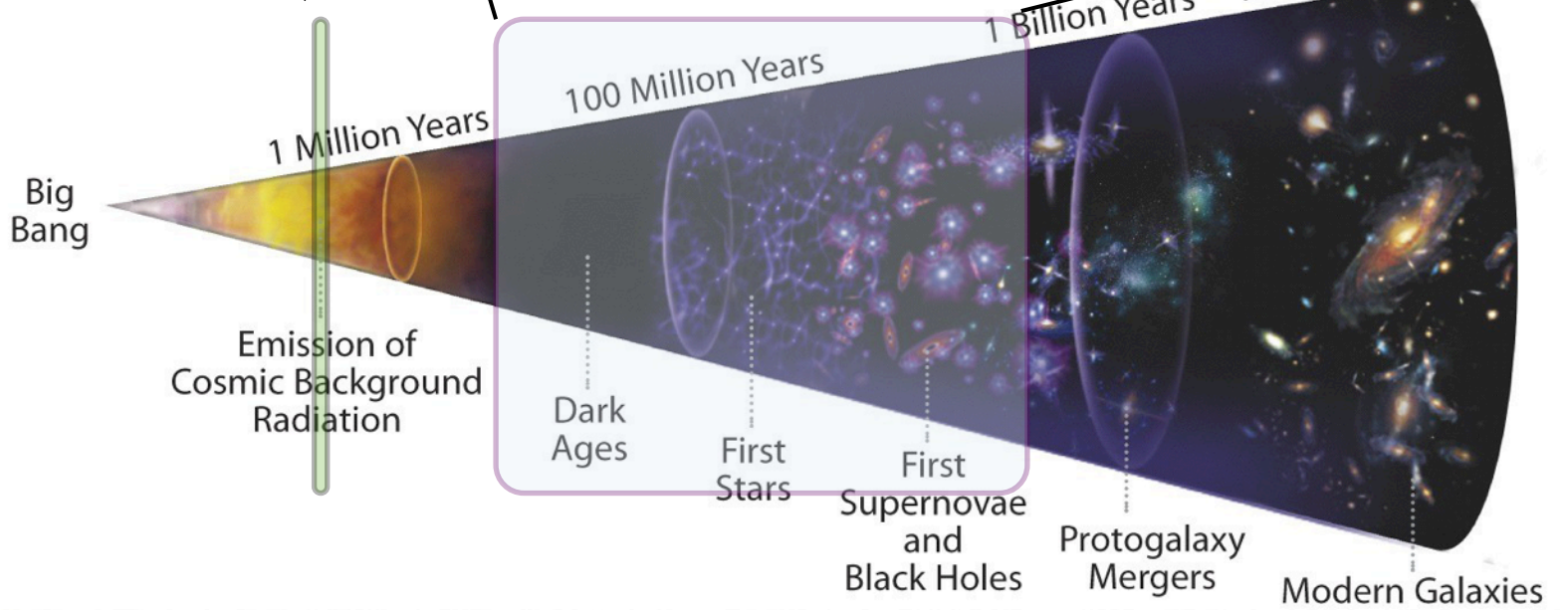
# Revealing the Epoch of Reionisation

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.







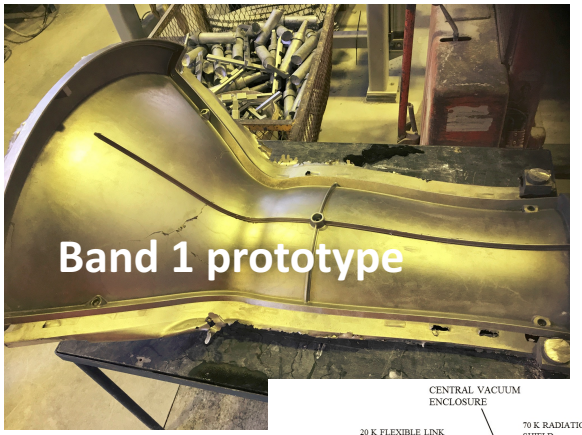
# The Unknowns (cf. HST)

| 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 | | | ✔ | | |

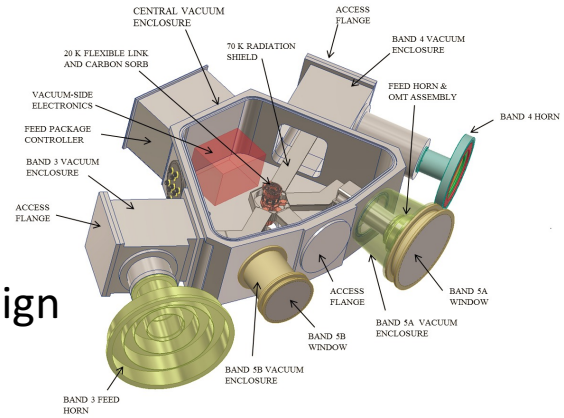
(Lallo: arXiv:1203.0002; Norris AASKA14)

# Technical Progress

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

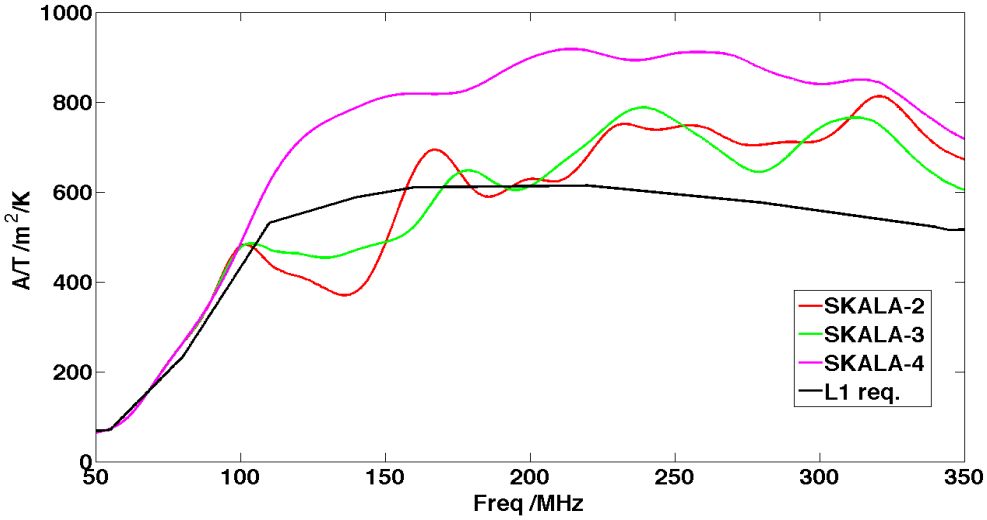


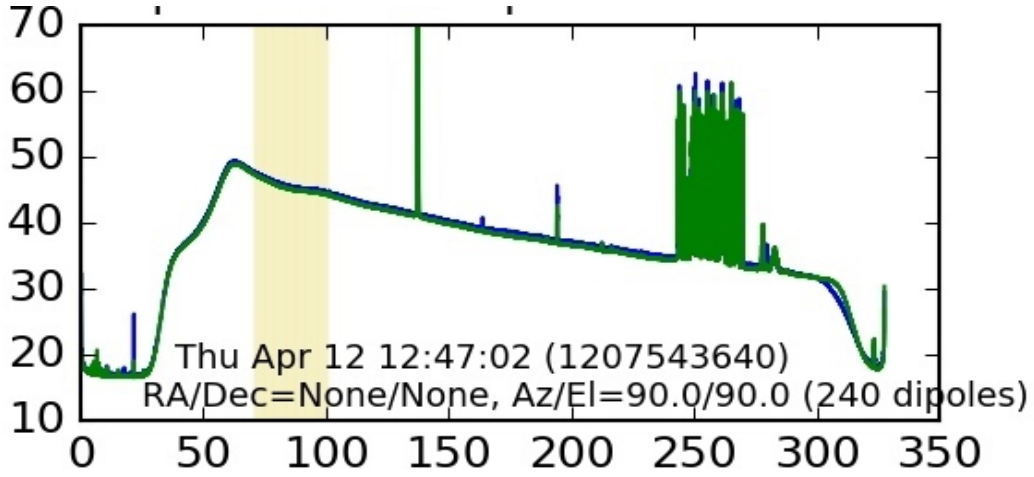





Band 3/4/5 design

# Technical Progress

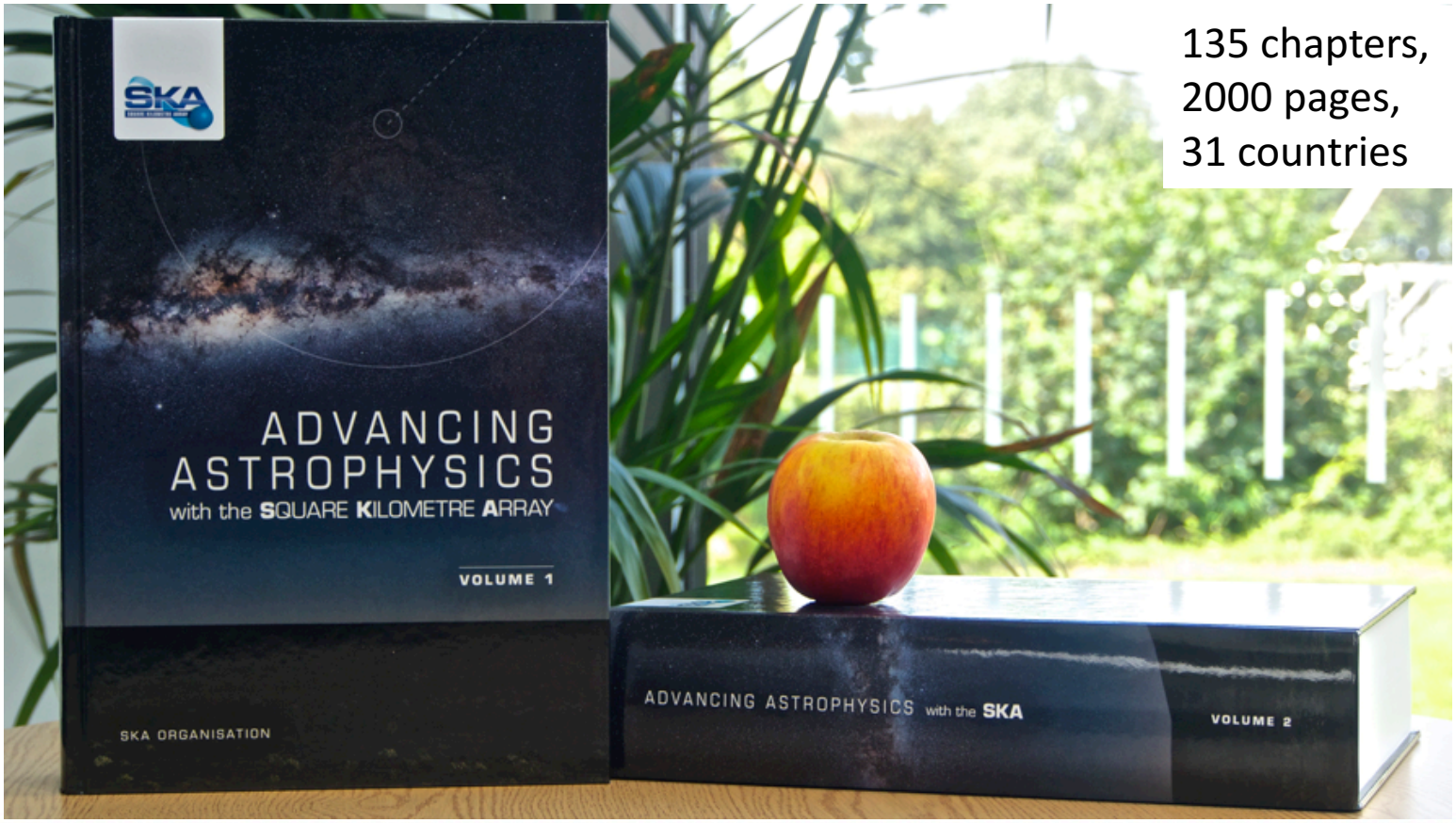


# SKA Science Case

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

www.skatelescope.org/books/

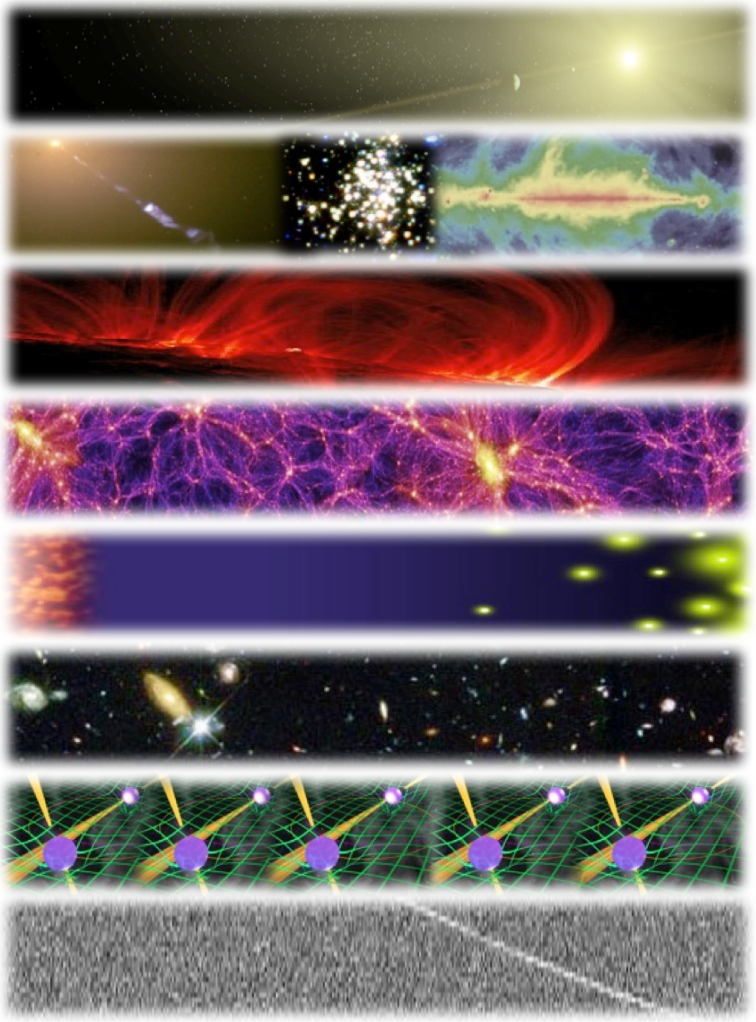



135 chapters,
2000 pages,
31 countries

# 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.

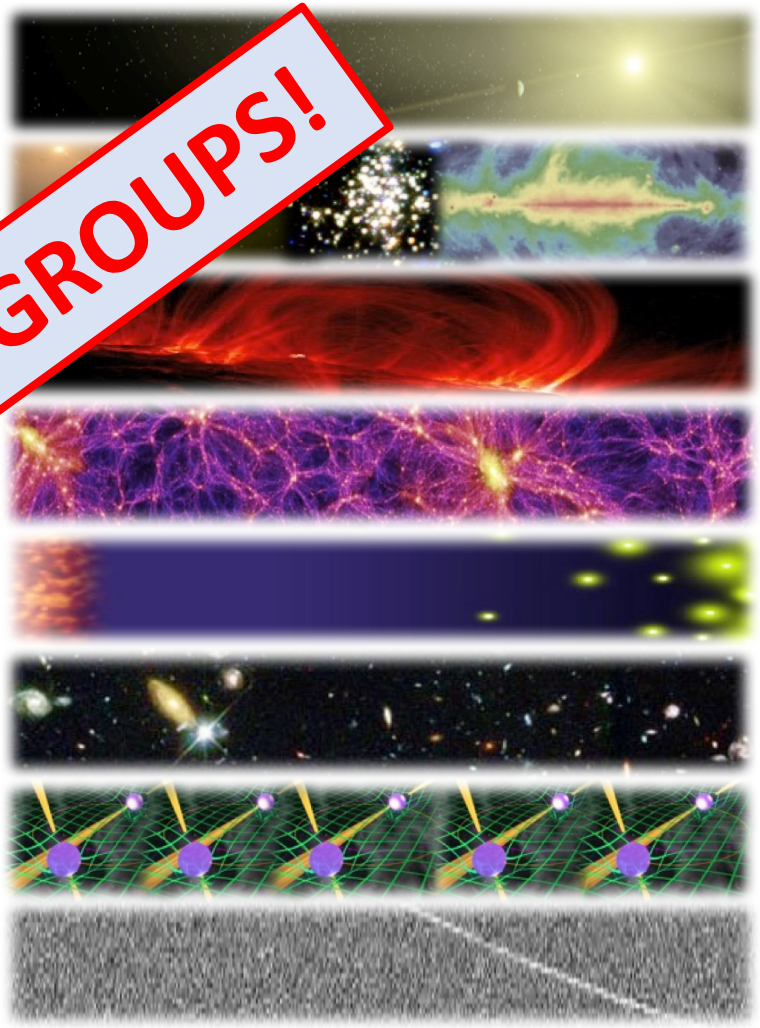
  Researchers can nominate themselves for membership by contacting the relevant SWG Chair or office project scientist. Each Science Working Group consists of two tiers of membership: Core members and Associate members.

# 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 … vity”)
- Solar and Heliosp… …cs
- Transients (E… …the Unknown)

YOU CAN JOIN THESE GROUPS!



## Focus …

- High En… …Cosmic Particles
- VLBI

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

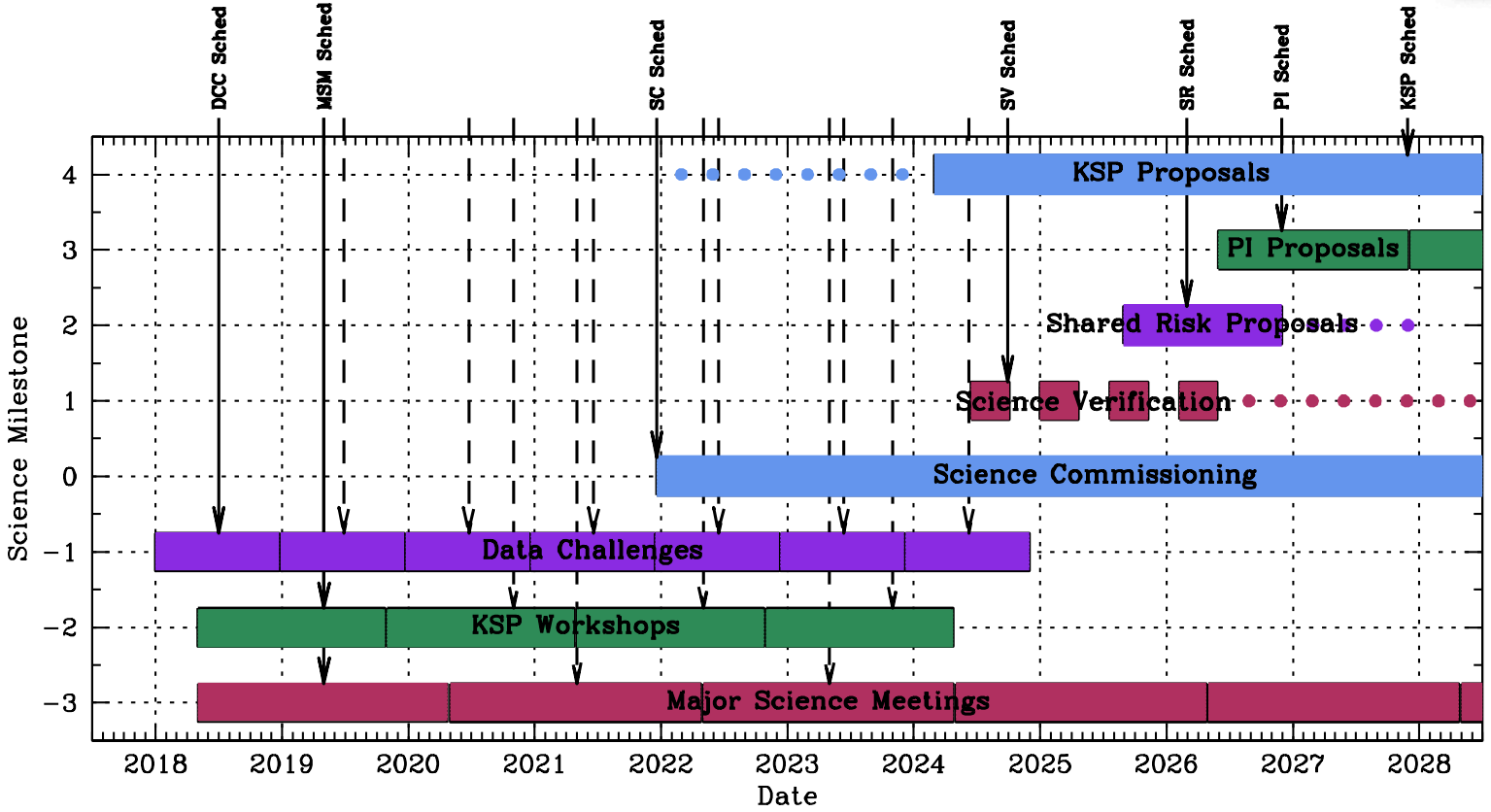
# Key Science Projects ('KSPs')


- **Notional** package of Key Science Projects developed:
  - Based on highest priority science objectives (HPSOs)
  - Consistent with capabilities of the SKA1 design
  - Consistent with a realistic observing schedule filled at approximately 50-70% for the first 5 years of scientific operations

- **Adopted KSP policy** (agreed by SKA Board, but details still under discussion)
  - **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

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

# 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

# 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 is on the Horizon

http://astronomers.skatelescope.org/