MANCHESTER 1824

The University of Manchester

The Square Kilometre Array: the radio telescope of the XXI century

Friends of the RAS

2nd October 2019

Keith Grainge, SKA SADT Lead
University of Manchester

Talk Overview

- SKA Science
- Outline of SKA telescope
- Data transport
- Time and frequency distribution
- Summary

Time since Big Bang

0 yr

300 000 yr

100 000 000 yr

1 000 000 000 yr

5 000 000 000 yr

9 000 000 000 yr

13 800 000 000 yr

Big Bang

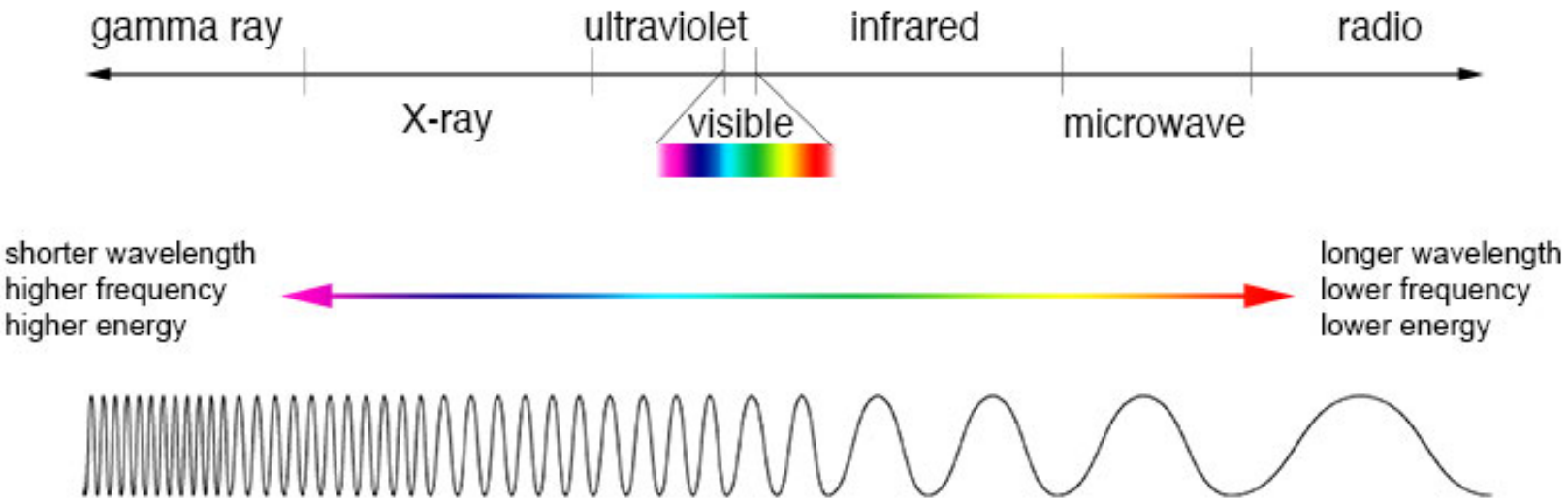
First stars

Galaxies Evolve

Solar System Forms

Humans Appear

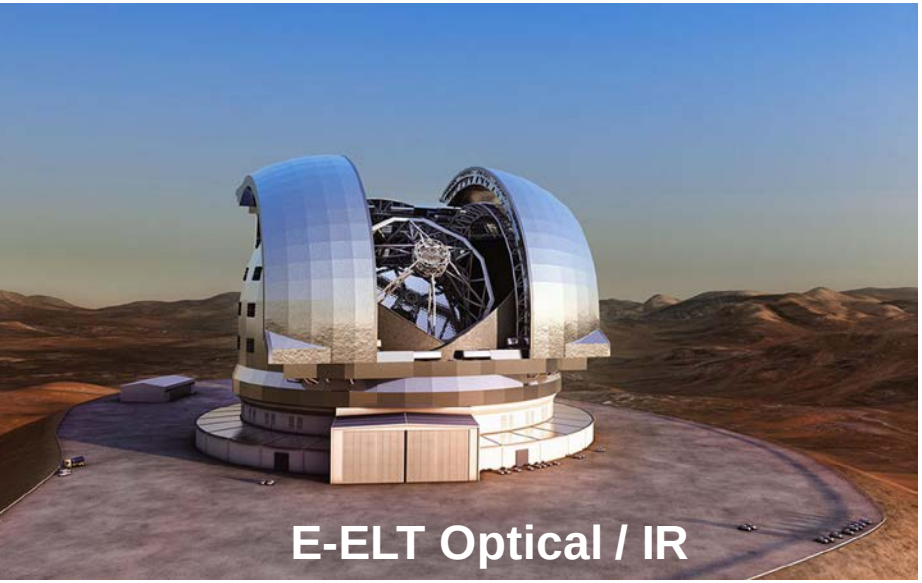
The electromagnetic spectrum

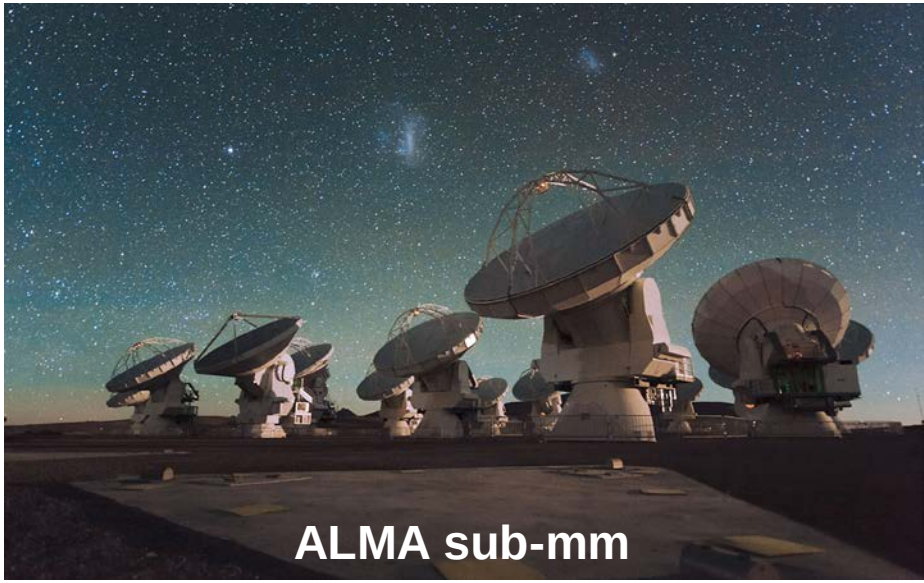


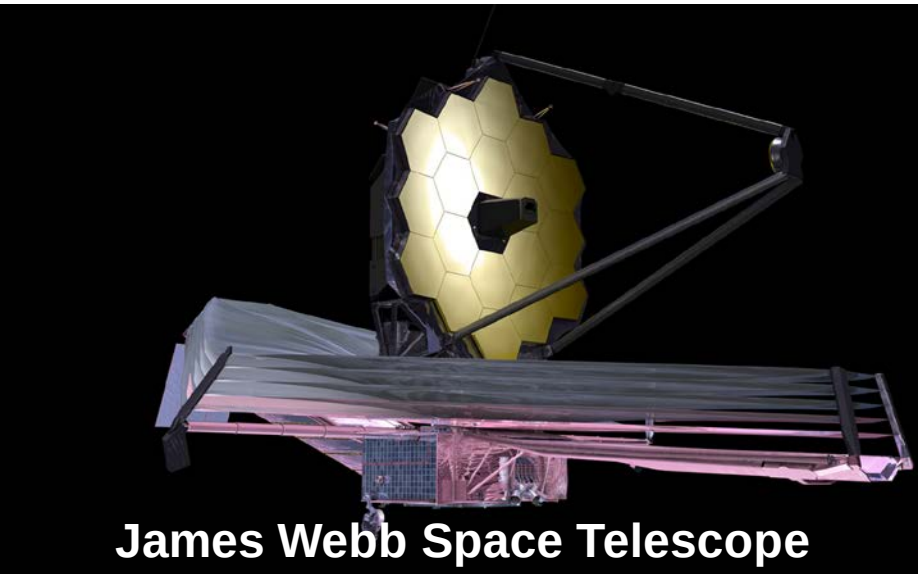
- Many advances made outside optical band
- Many outstanding mysteries
- Need for a next generation of observatories

Future Great Observatories

SIGNAL AND DATA TRANSPORT



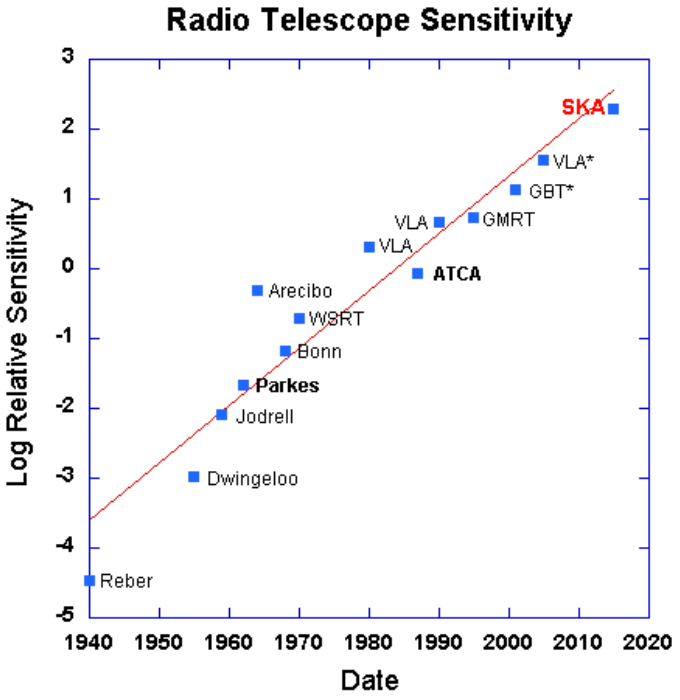




The SKA

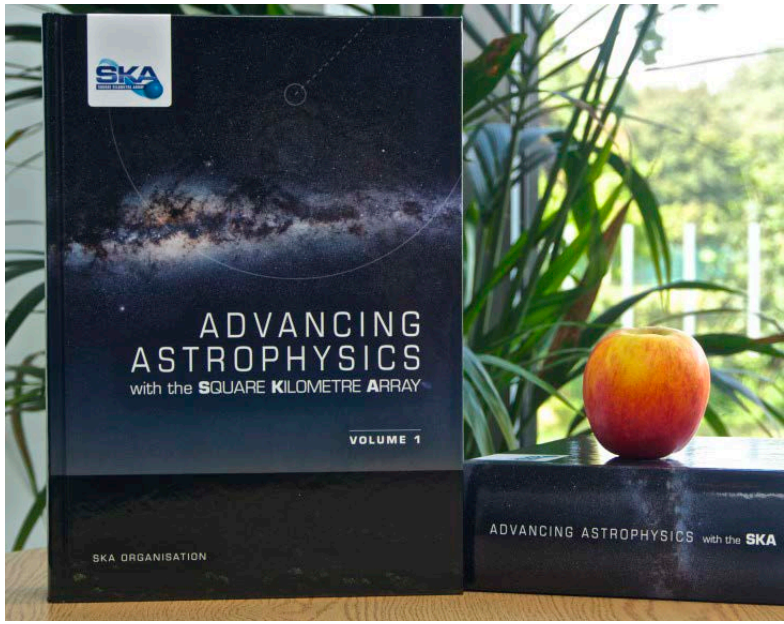
SIGNAL AND DATA TRANSPORT

- Large radio telescope for transformational science
- > 1 million m^2 collecting area
- Baselines 3000+ km
- Wide-field interferometer
- Frequencies from 50 MHz to 15 GHz
- Aperture Arrays and 15m Dishes
- High performance correlator(s)
- HPC Science Data Processor
- Optical fibre network
- 2 Phases; SKA1 cost cap €650M
- 100 time survey speed increase
- 2 Continents; 2 telescopes



SKA Science

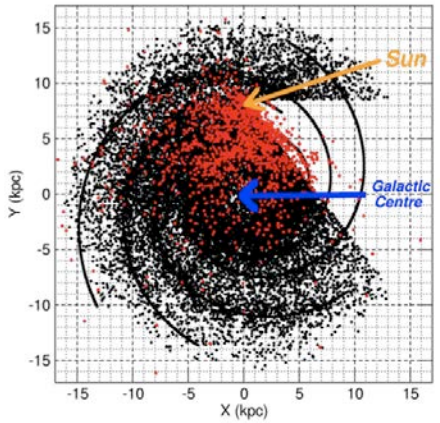
- Cosmology
- Our Galaxy
- Cosmic Magnetism
- Cradle of Life/AstroBiology
- Extragalactic Continuum
- Epoch of Reionisation
- Extragalactic Spectral Line
- H I Galaxy Science
- Radio Transients
- Fundamental Physics with Pulsars
- Solar & Heliospheric Physics



135 Chapters; 1200 contributors

Finding all pulsars in the Milky Way…

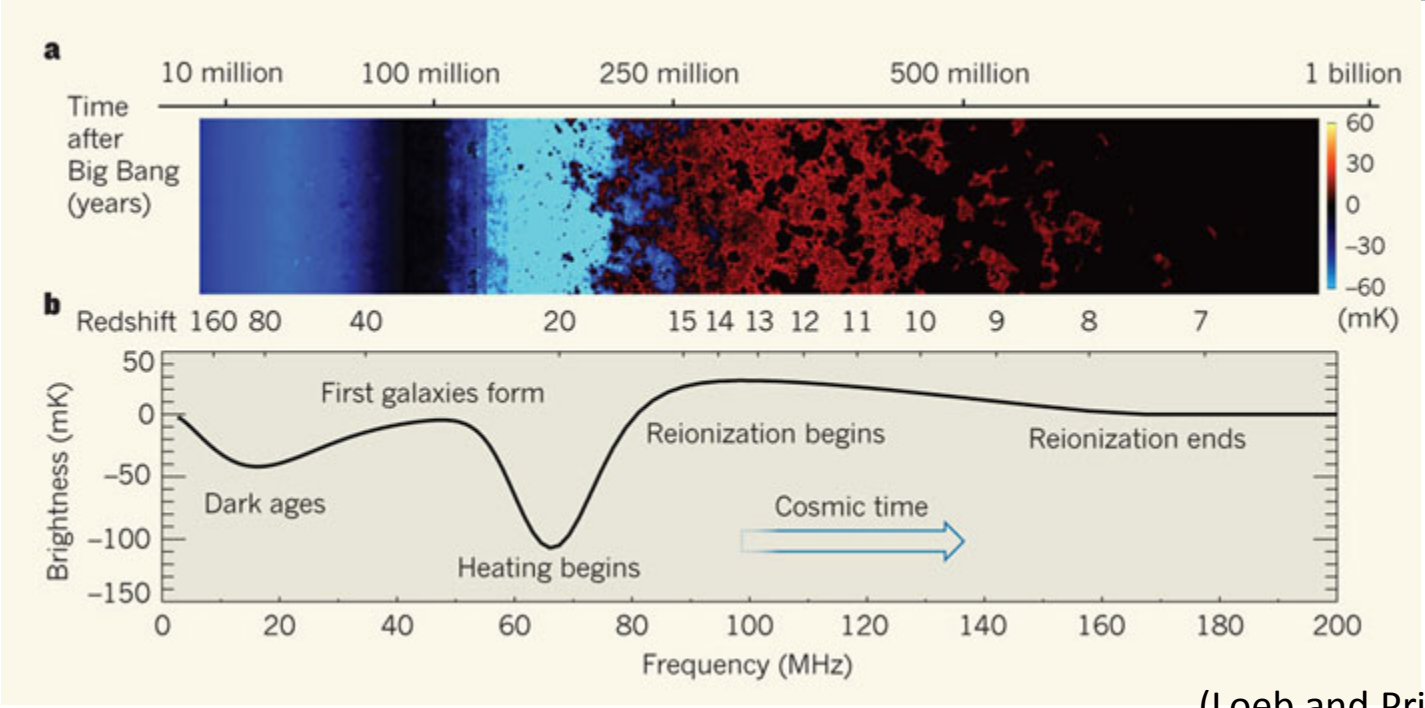
(Cordes et al. 2004, Kramer et al. 2004, Smits et al. 2008)



- ~30,000 normal pulsars
- ~2,000 millisecond pulsars
- ~100 relativistic binaries
- first pulsars in Galactic Centre
- first extragalactic pulsars

- Timing precision is expected to increase by factor ~100
- Rare and exotic pulsars and binary systems: including PSR-BH systems!
- Testing cosmic censorship and no-hair theorem
- **Current estimates are that >50% of entire Galactic population in reach of SKA1**
- **Pulsar timings across galaxy → nHz gravitational waves**

The Early Universe with HI



(Loeb and Pritchett)

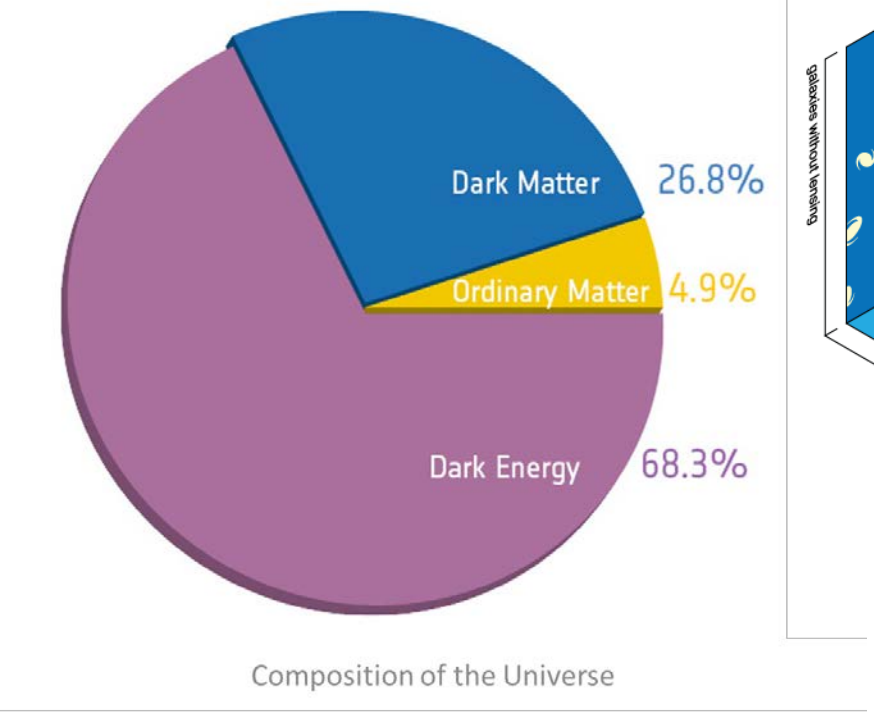
- Neutral hydrogen 21cm spin flip transition
- Probe neutral IGM before and during formation of first stars
- Tomography as well as statistical detection
- “HI Forest” towards high-z sources

Cosmic origins

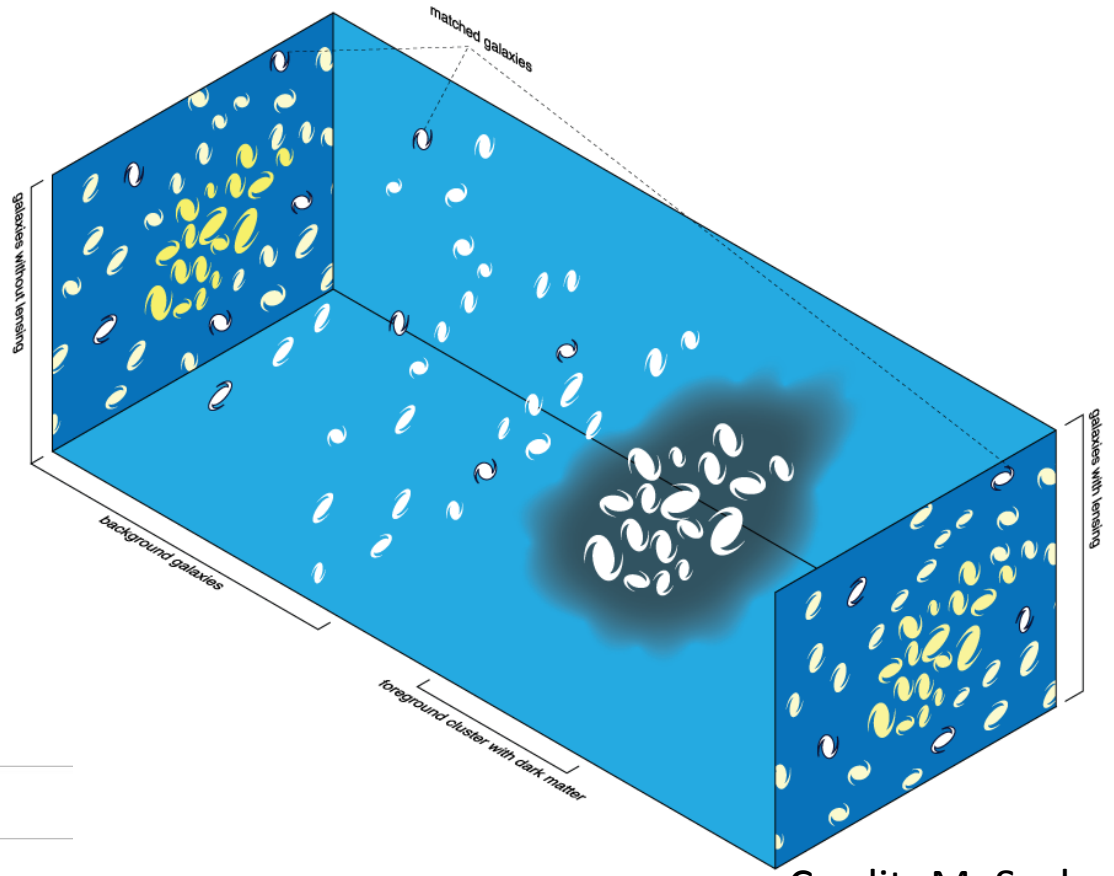
Credit: M. Alvarez, R. Kaehler, and T. Abel

- Lyman-α from first stars couples spin and gas temperatures; first absorption then emission of CMB
- Gradually neutral hydrogen is ionised

Cosmology



Credit: ESA

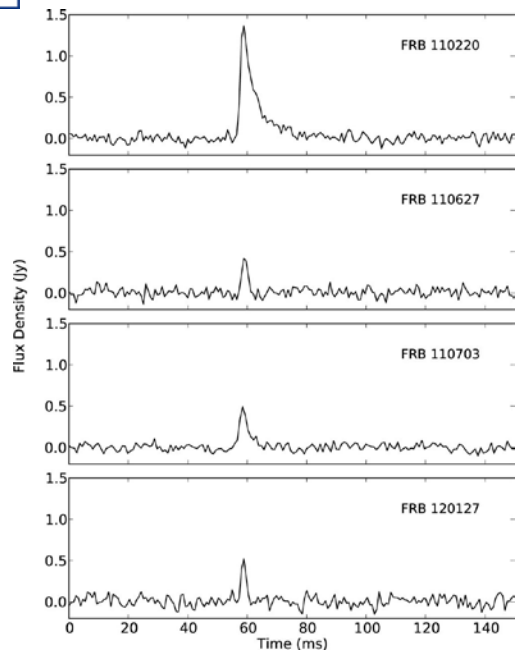


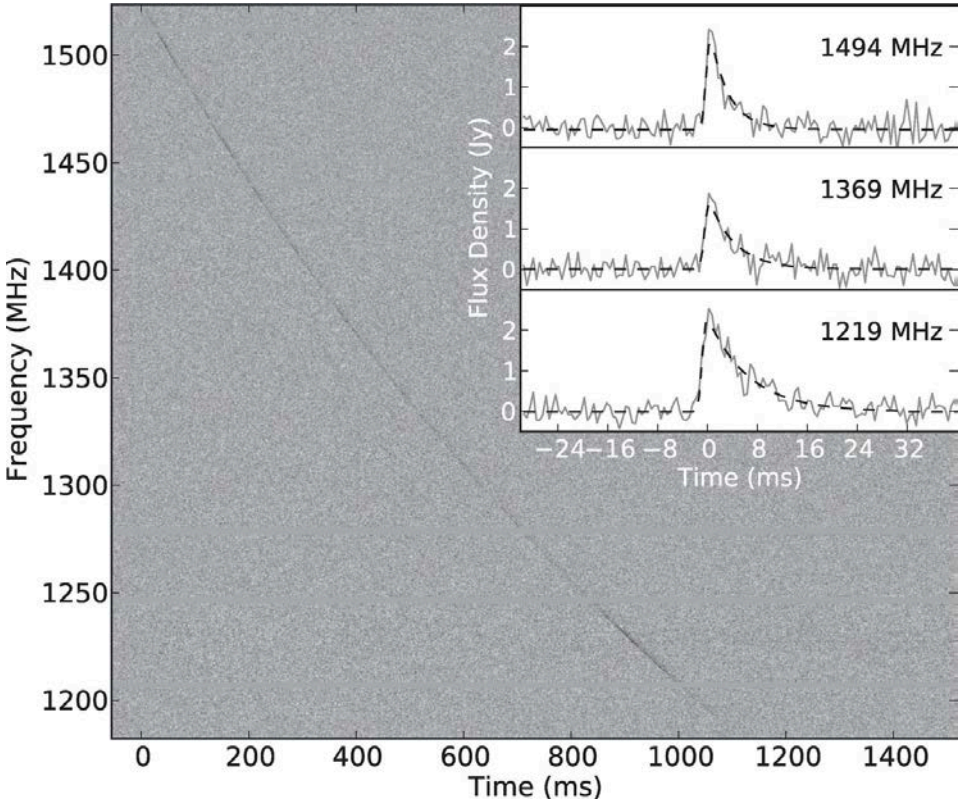
Credit: M. Sachs

- Baryon acoustic oscillations
- Weak gravitational lensing allows mapping of structure
- Constrain Dark Matter and Dark Energy

The transient radio sky

A Population of Fast Radio Bursts at Cosmological Distances
D. Thornton *et al.*
Science **341**, 53 (2013);
DOI: 10.1126/science.1236789





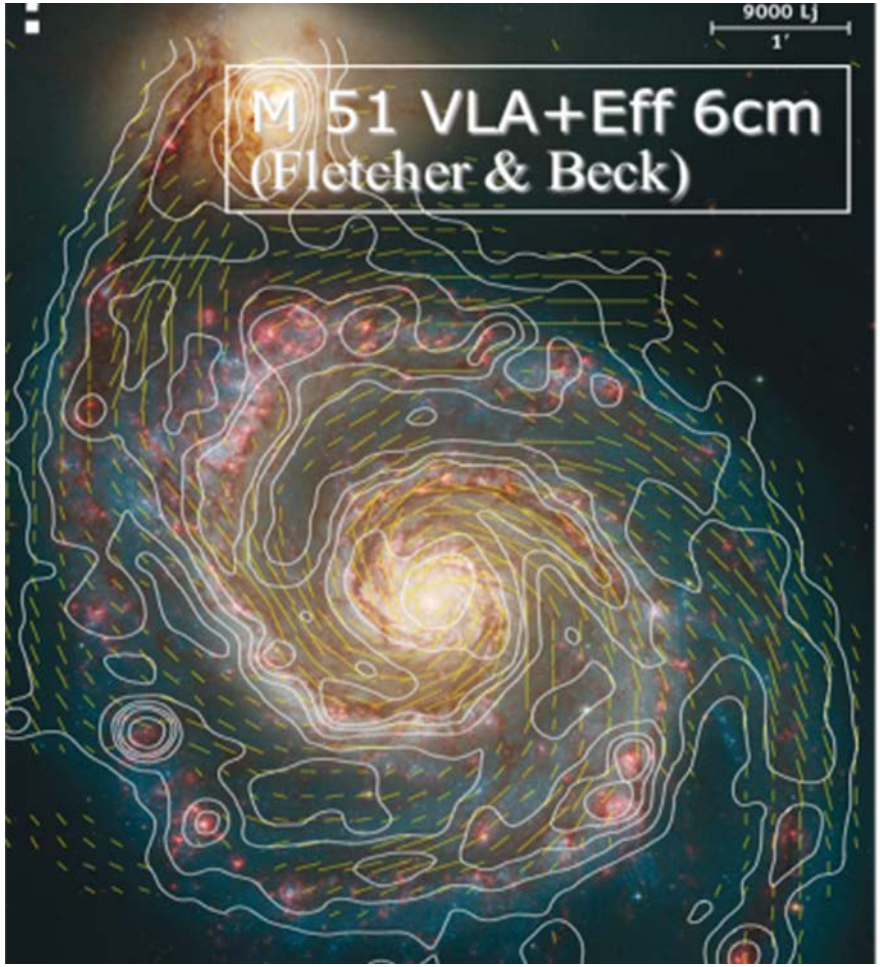
- Recent discovery of Fast Radio Bursts
- Hundreds now detected
- Completely unknown origin, at cosmological distances

Cosmic Magnetism

Credit: SKAO

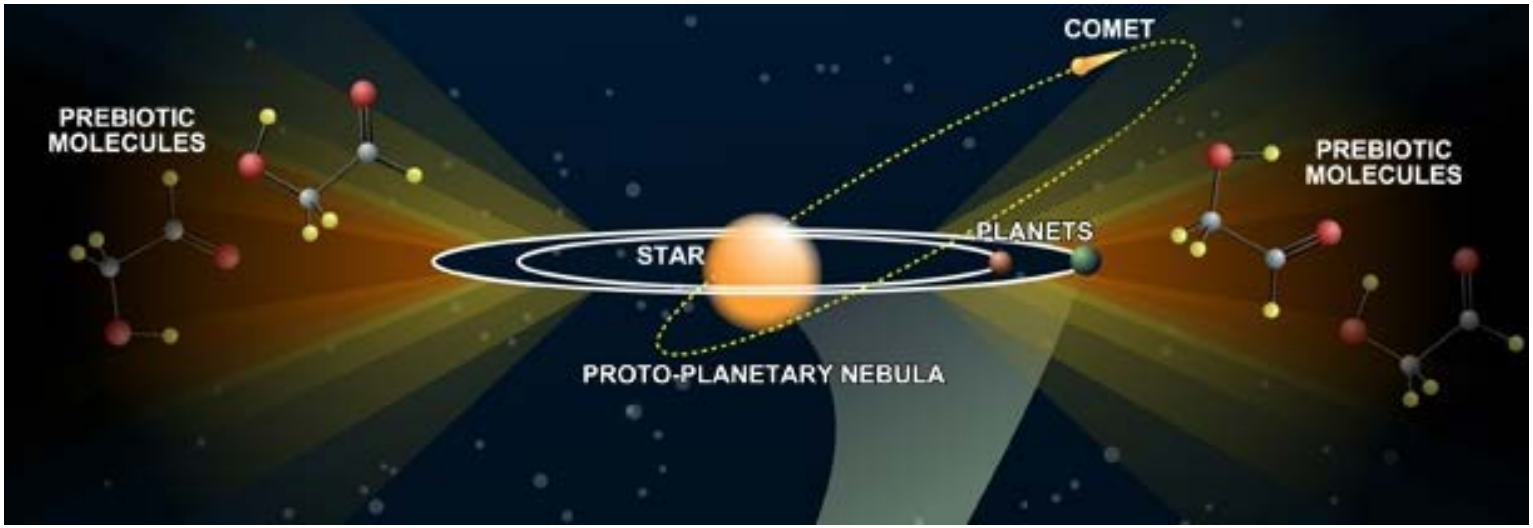
- Faraday rotation
  - B-fields rotate polarisation of background radio sources
  - Effect is proportional to λ^2
  - unique tool for measuring magnetic fields

Cosmic Magnetism



- SKA is polarisation sensitive
- Origin of cosmic B-fields?
- B-fields in Galaxy Clusters
- Role in galaxy formation

Cradle of life



- Protoplanetary disks and the dawn of planets
- Magnetospheric emissions from extrasolar planets
- Complex organic molecules around protostars
- OH masers in the Milky Way and the Local Group
- Searching for Extra-Terrestrial Intelligence
  - detect airport radar on a planet tens of light years away

Radio Interferometery

- Combine signals from multiple antennas
- Telescope size → resolution
- e.g. e-MERLIN
  - 7 telescope across England
  - 220km baseline
  - 0.01 arcsec resoln possible
- But telescope sensitivity depends on *collecting area*
- Many key science areas require ~ 1 km^2 area
- e-MERLIN will enable pathfinder observations

SKA Phase 1

SIGNAL AND DATA TRANSPORT

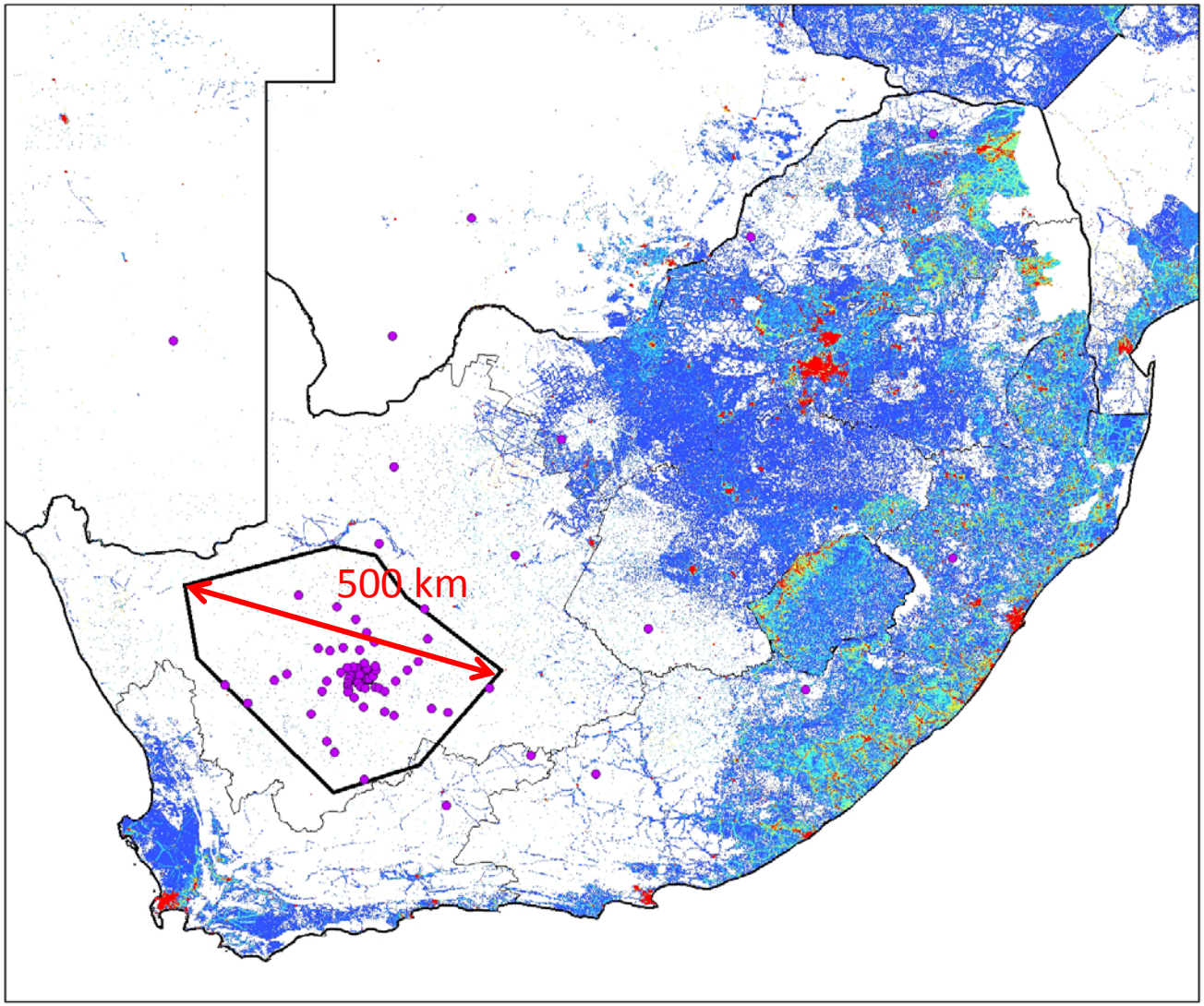
South Africa

SKA1_Mid 350 MHz – 15 GHz
64 MeerKAT dishes
133 SKA1 dishes.

Australia

SKA1_Low 50 – 350 MHz
131,000 aperture array dipole
512 stations of 256 antennas

Karoo Radio Astronomy Reserve



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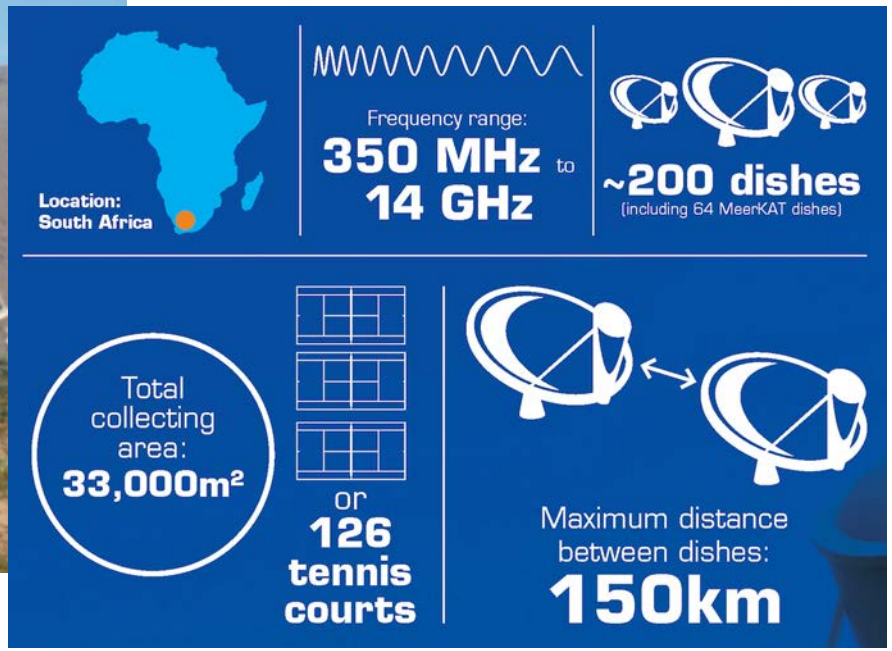
Design: SKA-Mid



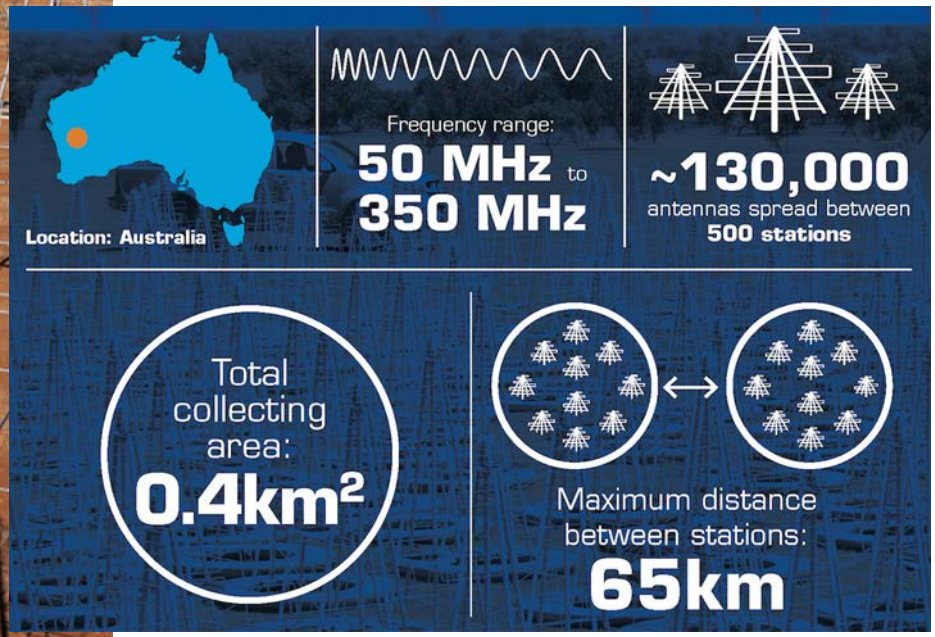
Murchison Radio Astronomy Observatory

SIGNAL AND DATA TRANSPORT

Shire of Murchison:

- 50,000 km²; size of the Netherlands
- 0 gazetted towns
- 29 sheep/cattle stations
- 110 population

Design: SKA-Low



SKA across the world

SIGNAL AND DATA TRANSPORT

International SKA Headquarters

Credit: J. Santander-Vela

- Phase 1 €650M cost cap
- HQ at Jodrell Bank; opened 10th July 2019
- 9 international Consortia performing the telescope design
  - UK lead SADT, SDP
- UK has committed £100M towards build

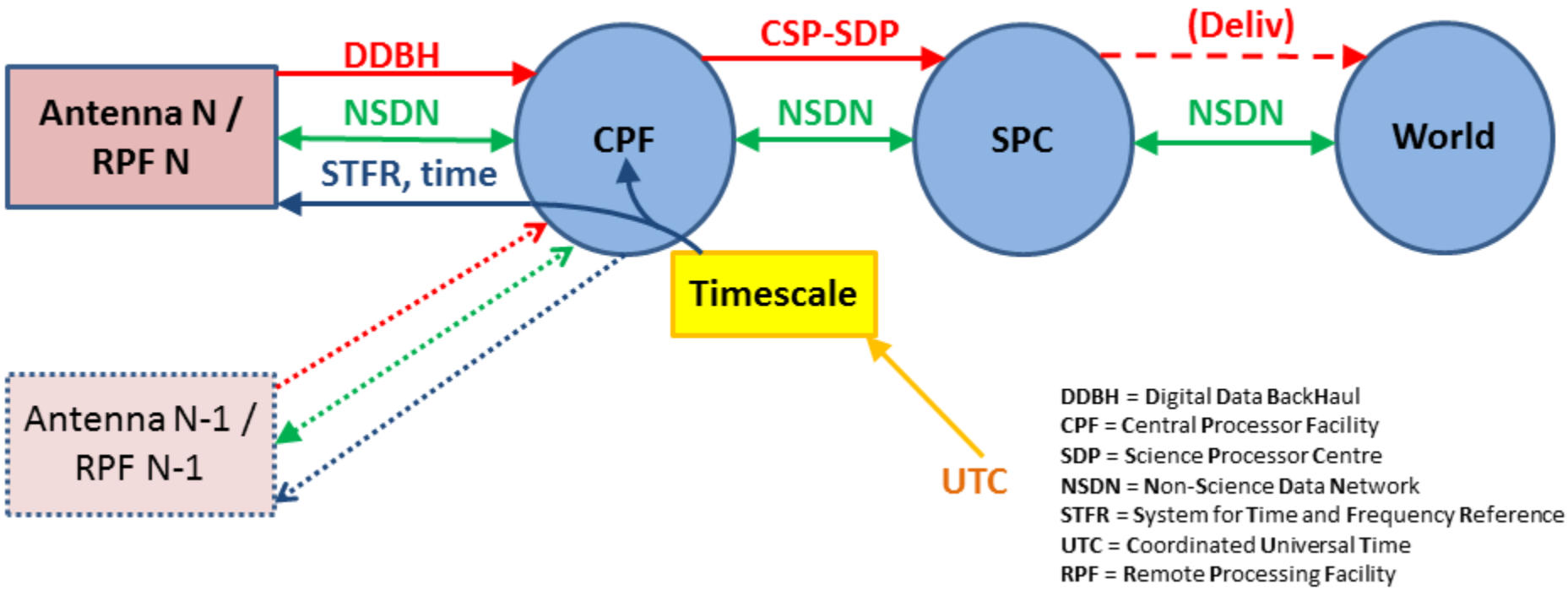
SKA IGO

- SKA to become an Inter-Governmental Organisation
- IGO Treaty signed in Rome on 12th March 2019
  - To be ratified by Parliaments

SKA Design Consortia

- 9 Design Consortia for Phase 1 SKA
  - Majority have now passed Critical Design Review

SADT Overview



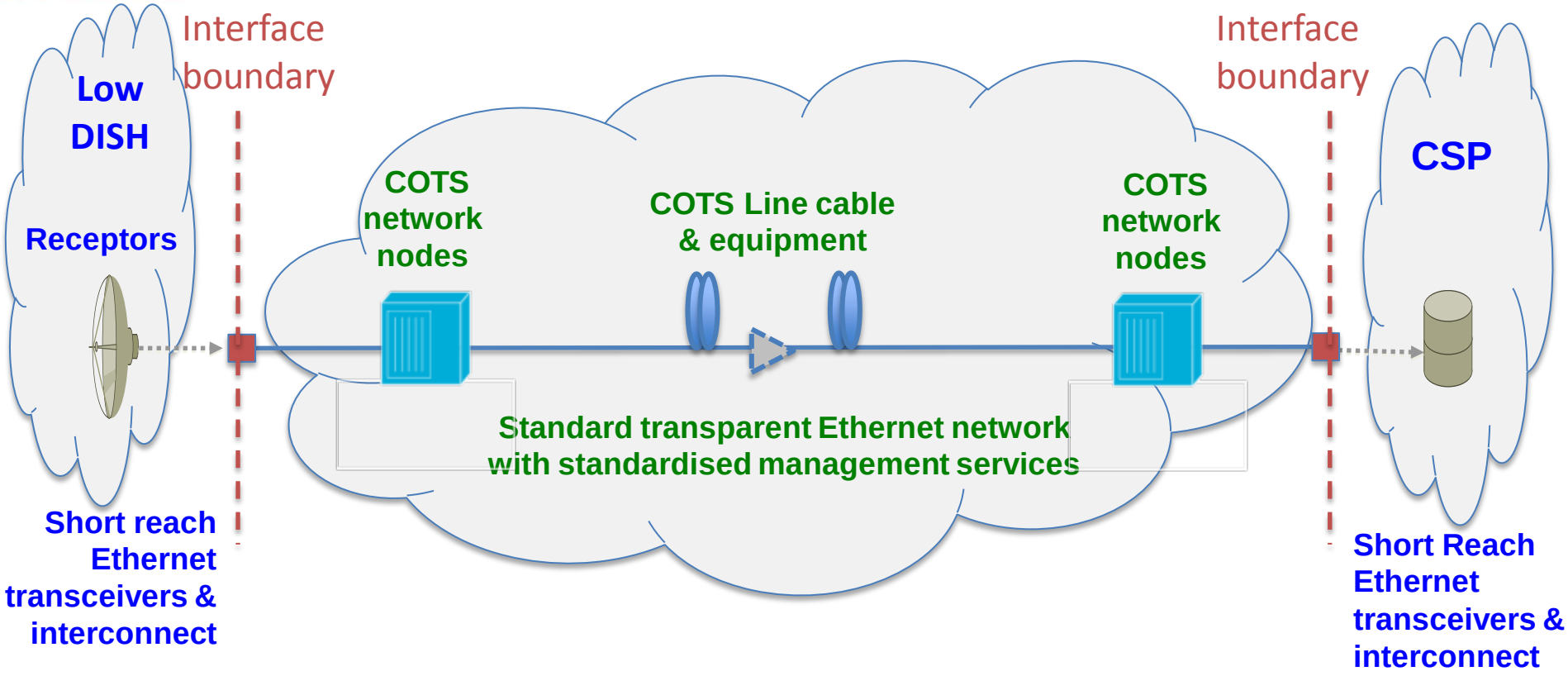
- The astronomy data network
- The synchronisation and timing network (SAT)
- The general purpose network (NSDN)
- Each has its own set of challenges

The SADT Consortium

- 14 institutes from 8 countries

Antenna to Correlator

SIGNAL AND DATA TRANSPORT

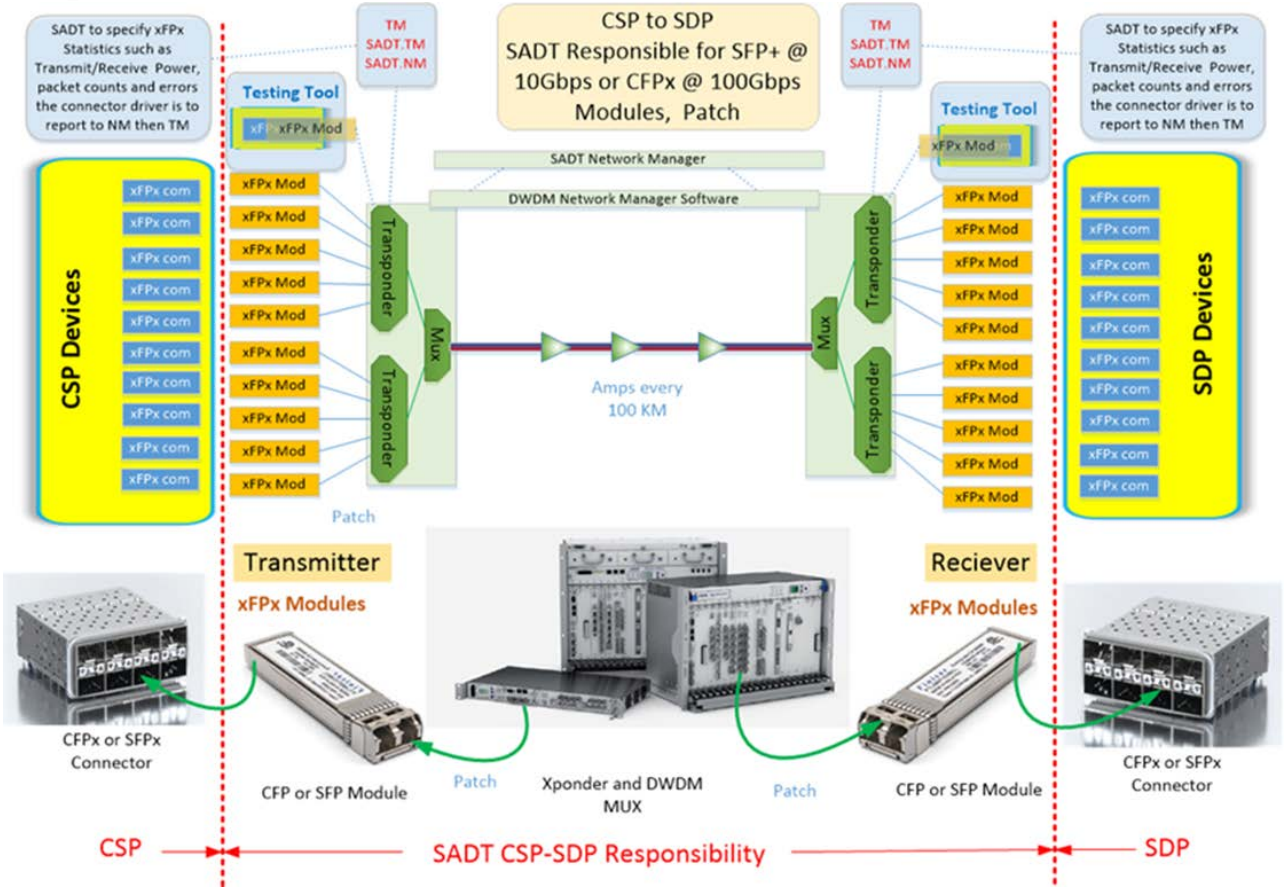


- 133 antennas; 100 Gbps from each
- Scattered across desert; 150 km baseline
- Equipment may interfere with experiment

Infrastructure

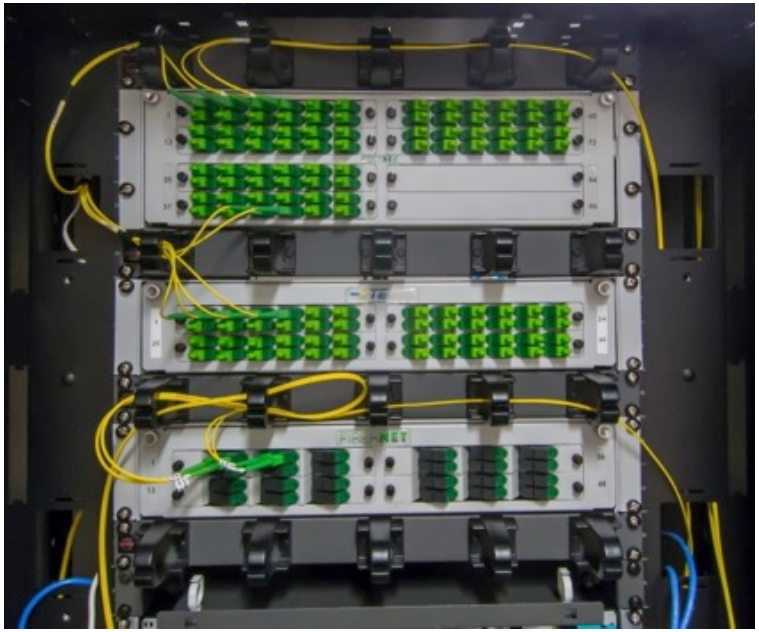
- Fibre; cable; trenching; manholes; ducts; drawpits
- Desire to combine with power reticulation
- Most expensive part of SADT

Correlator to HP Computer



- Get the data out of the desert ~ 900km
- 7.8 Tbps
- Use wavelength division multiplexing

Amplifier huts



Solar powered CEV picture (left) and communications rack (right) installed at Geraldton (WA) (courtesy of S. Amy, CSIRO)

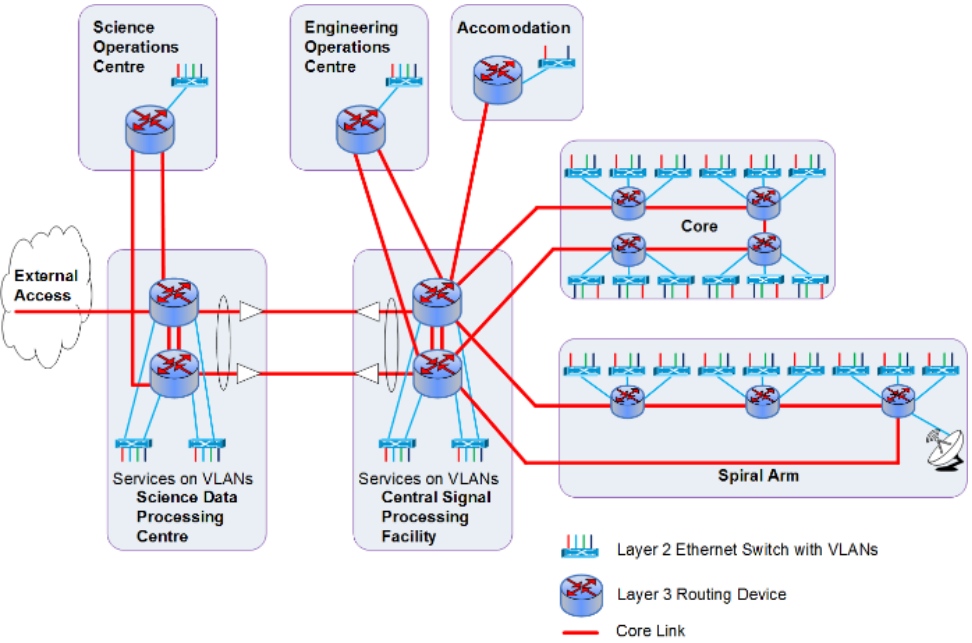
- Need amplifier huts every ~100 km
- Solar powered with diesel backup

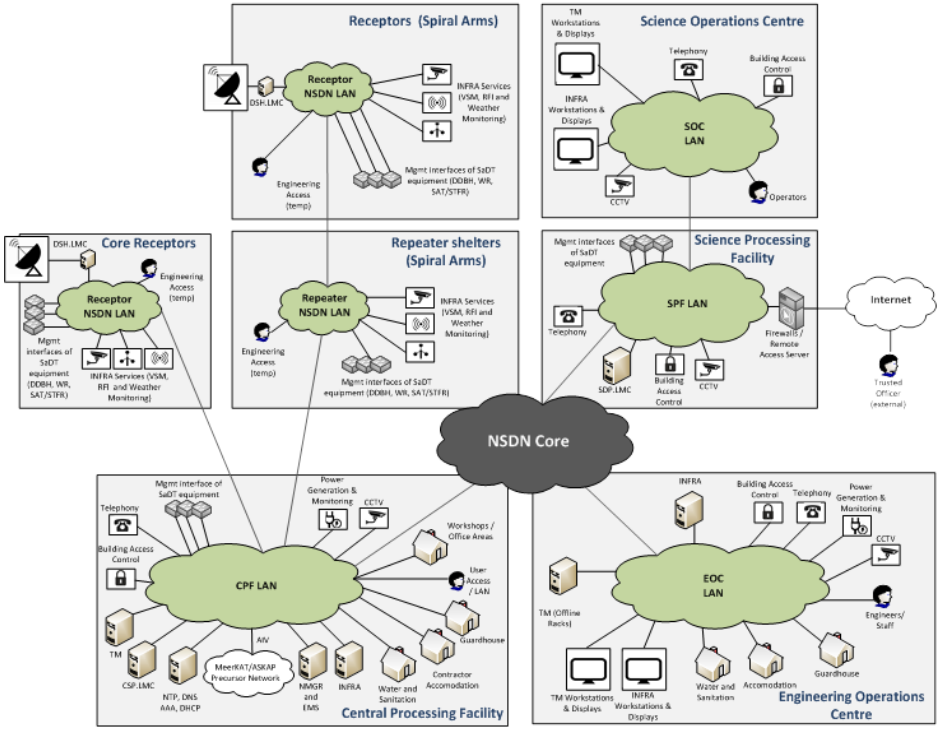
Transcontinental networks

- Work with National Research Networks
- Scope and estimate running costs

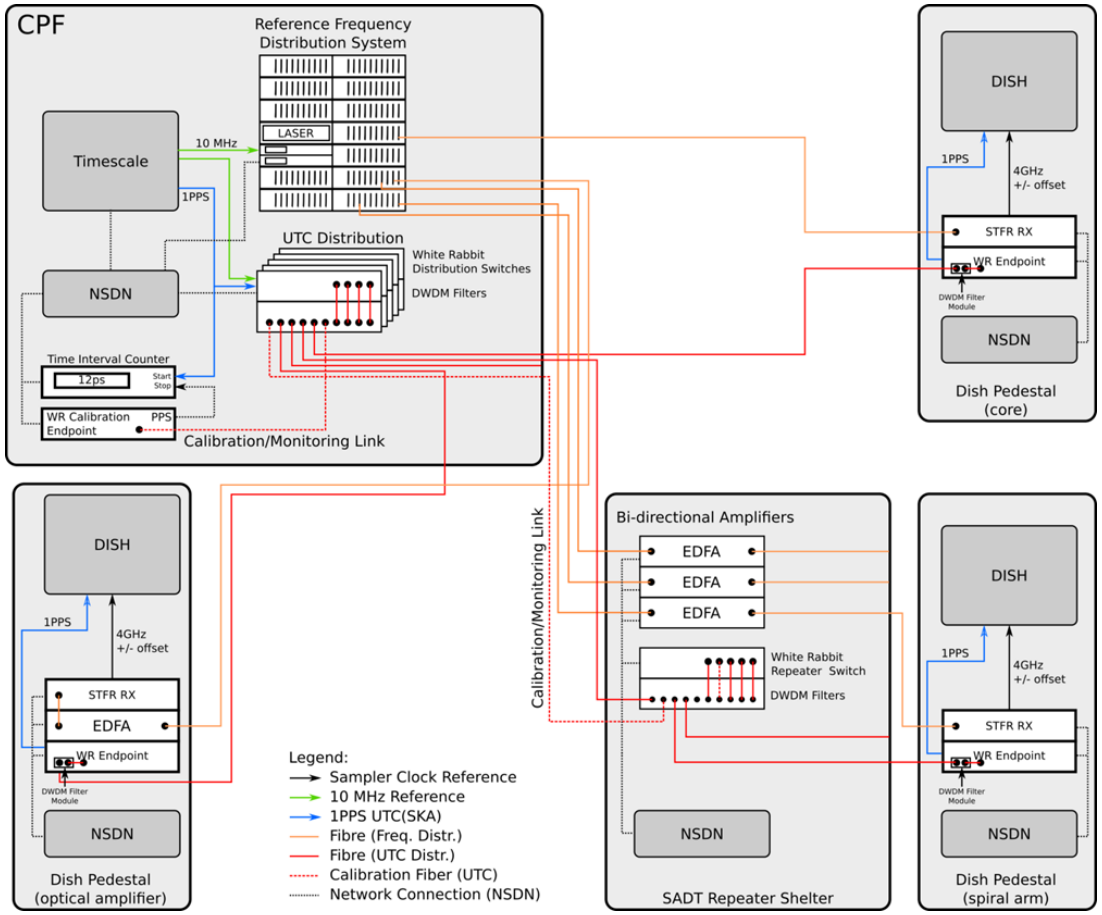
Non Science Data Network (NSDN)

- A network infrastructure with resilience – given the topology.
- The set of services include:
  - Control & Monitor
  - Internet access
  - IP phones
  - Security



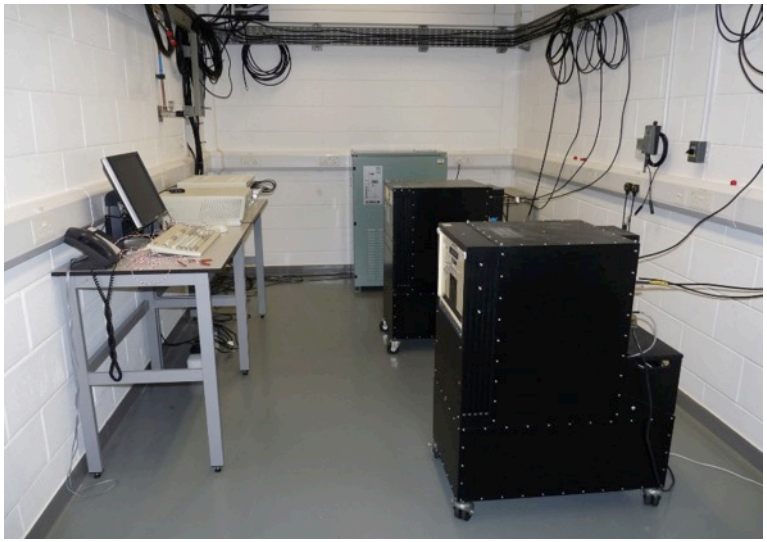


SKA Synchronisation and Timing



- Provide SKA timescale
  - Steerable timescale;
  - Traceable to UTC
  - Accuracy of 5 ns
- Distribute phase (STFR)
- Distribute time (White Rabbit)
- 197 end points (Mid)
- 36 end points (Low)

SKA Clock Ensemble



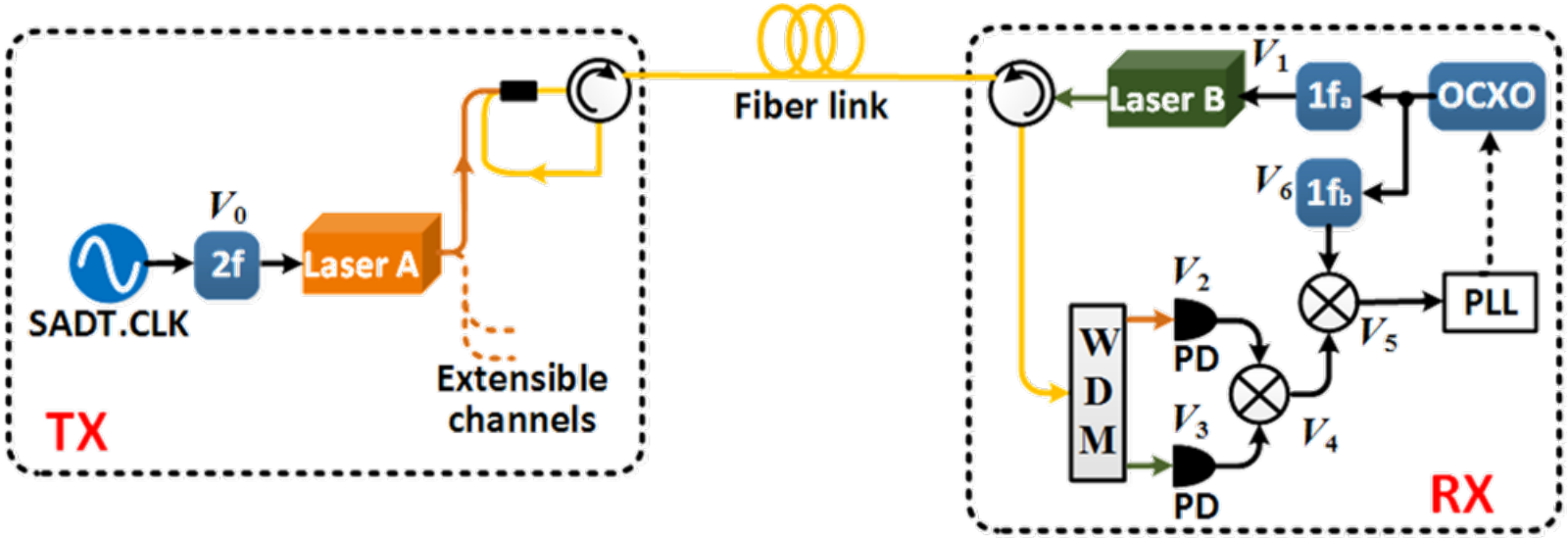
H-maser clock product example ,at NPL UK

- Requirements:
  - o Phase coherence of array
    → accuracy = 1ps
  - o Long-term timing for pulsars
    → 5 ns over 10 years
- "3 cornered hat" H-masers
- Directly traceable via GNSS PPP technique to UTC(BIPM)

→ SKA time

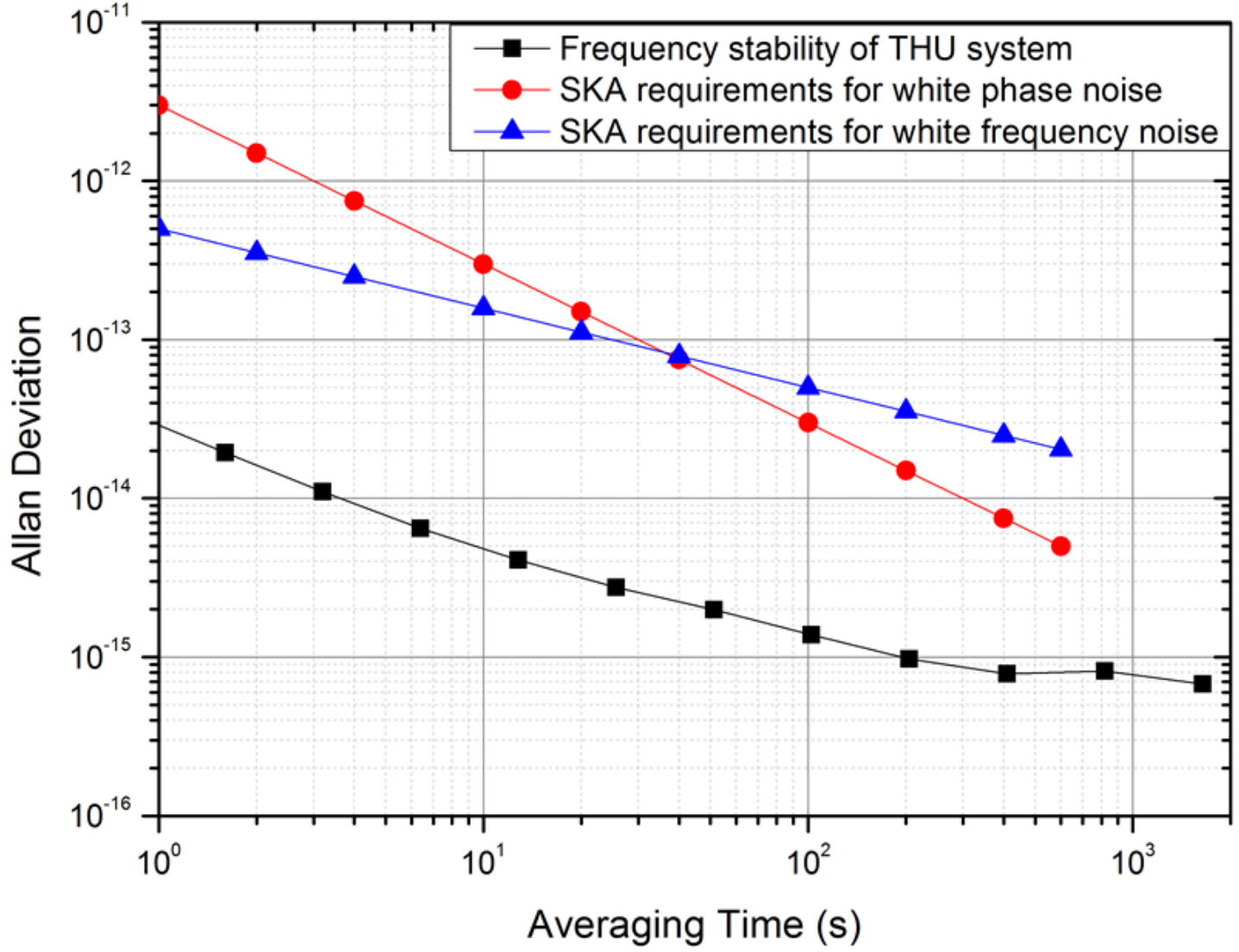
- Stringent environmental requirements

STFR Low

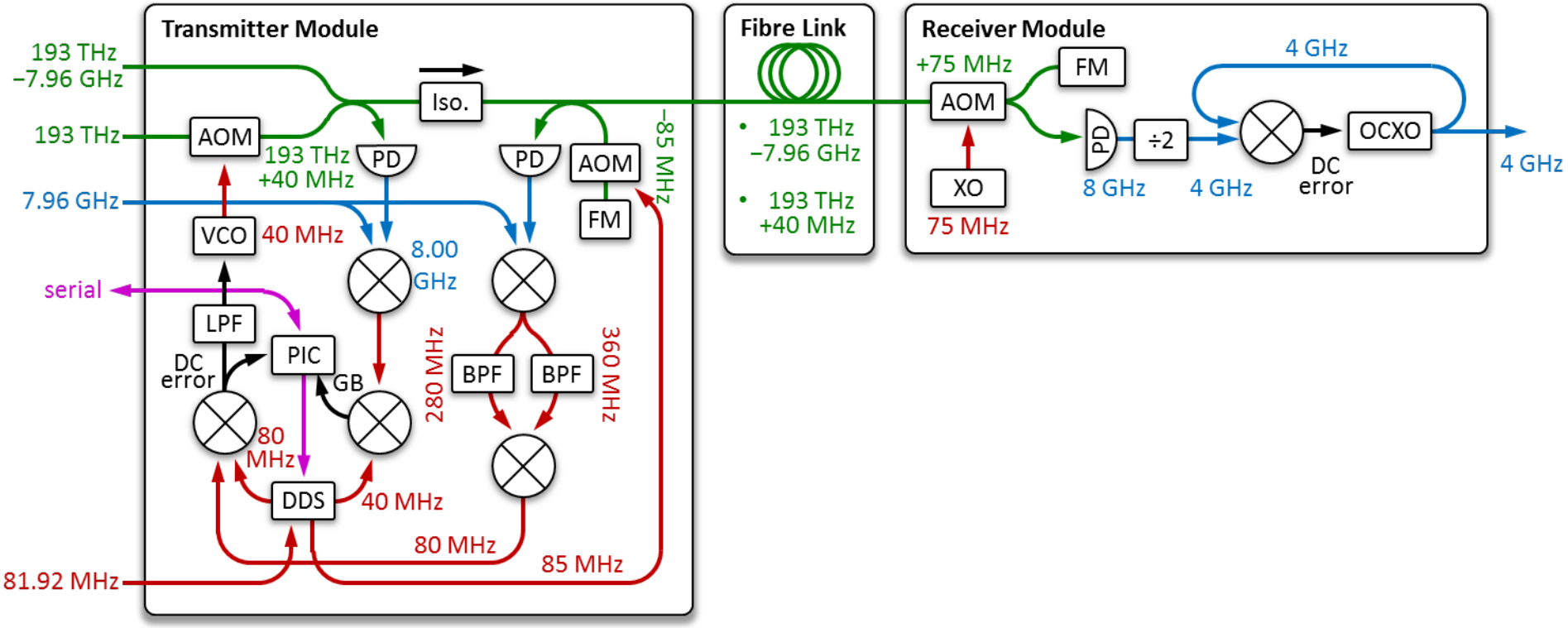


- Design developed by Tsinghua University, China
- Active, “Round-trip”, reference frequency distribution
- 1 GHz signal does a double pass
- 2 GHz signal does a single pass
- Mix to remove phase fluctuations

STFR Low performance



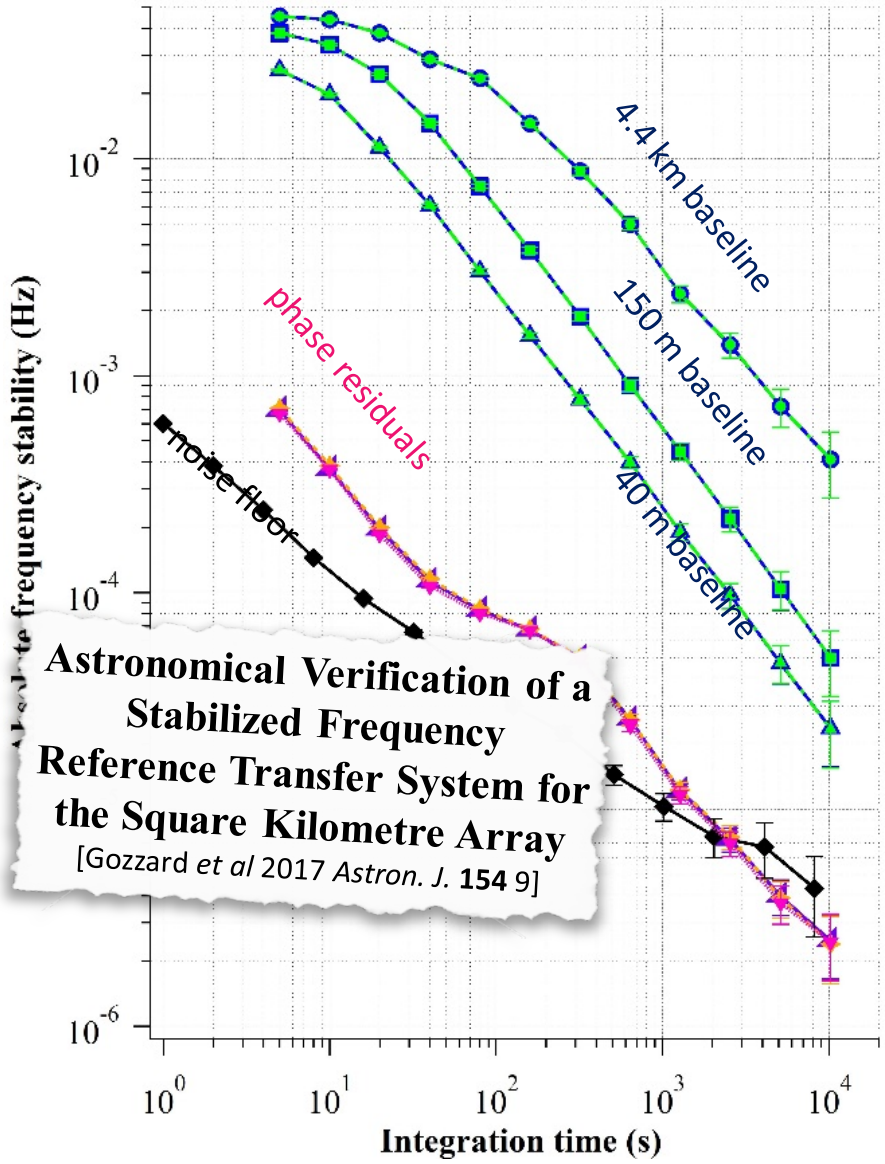
STFR Mid



- Design developed by UWA
- Mach-Zehnder interferometer distributes two optical frequencies; difference encodes reference RF
- Acoustic Optical Modulators provide active compensation

STFR Mid performance

- Astronomical confirmation of stability performance with ATCA
- Double signal chain used to remove atmospheric phase fluctuations



Astronomical Verification of a Stabilized Frequency Reference Transfer System for the Square Kilometre Array
[Gozzard *et al* 2017 *Astron. J.* **154** 9]

UTC distribution

- Design developed by JIVE together with Seven Solutions and UGR
- White Rabbit time distribution
- WR protocol is an extension of PTP, uses Ethernet
- 1200ps worst case timing uncertainty on 173km link

Current status

- SADT Critical Design Review 14th–17th May 2018
  - 1109 comments and issues on 279 documents
    - 2 days on SAT
    - 2 days NWA and data transport
    - Scenario discussion
  - Closed out; design baselined and handed over to SKAO
    - Consortium wound down; Bridging work
- Majority of other Consortia also passed CDR
- System CDR December 2019
- Construction to start Q1 2021
  - Seven years until completion
  - First science possible before then

Summary

- SKA will be the largest scientific project on Earth
- Its construction will require the industrialisation of radio astronomy.
- Major benefits to the participating countries
- Once operational, the SKA will deliver transformational science for 50 years.
- Invaluable tool for multi-wavelength / multi-messenger astronomy
- Understanding of Cosmic Dawn (earliest stages of the Universe), gravitational waves and clues as to the origins of life may all deliver Nobel Prizes.