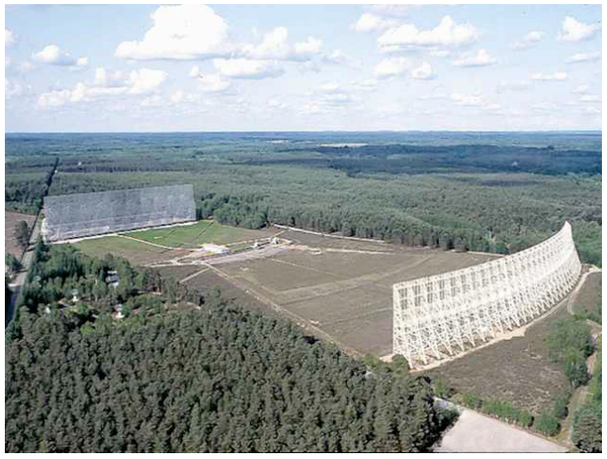
UNIVERSITY OF AMSTERDAM

Master Astronomy and Astrophysics - 5214RAAS6Y



Radio Astronomy

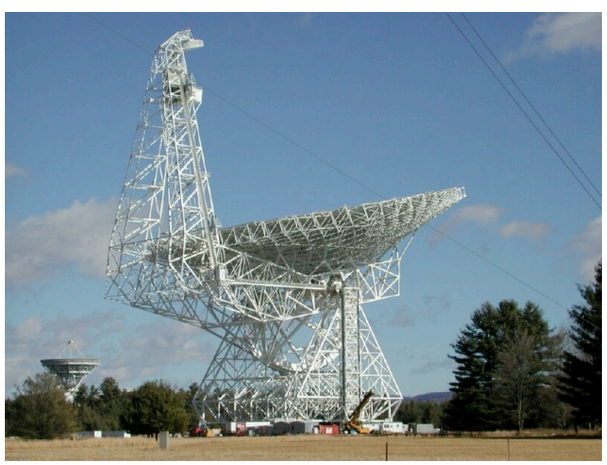
Lecture 11

The Future of Radio Astronomy

Lecturer: Michael Wise (wise@astron.nl)

May 21st, 2013



Outline

- The Square Kilometre Array (SKA)
- SKA Pathfinders
- SKA Computational Challenges
- Data Intensive Astronomy
- Beyond the SKA

The Square Kilometre Array

The Square Kilometre Array

- Next generation global radio telescope
- Frequency range: 0.1–25 GHz, 100x as sensitive as EVLA
- Being constructed in South Africa and Western AU
- Online in 2020 and expected to cost €1.5 Billion

"The Hydrogen Array"

1991ASPC...19..428W

Radio Interferometry: Theory, Techniques and Applications,
IAU Coll. 131, ASP Conference Series, Vol. 19, 1991,
T.J. Cornwell and R.A. Perley (eds.)

THE HYDROGEN ARRAY

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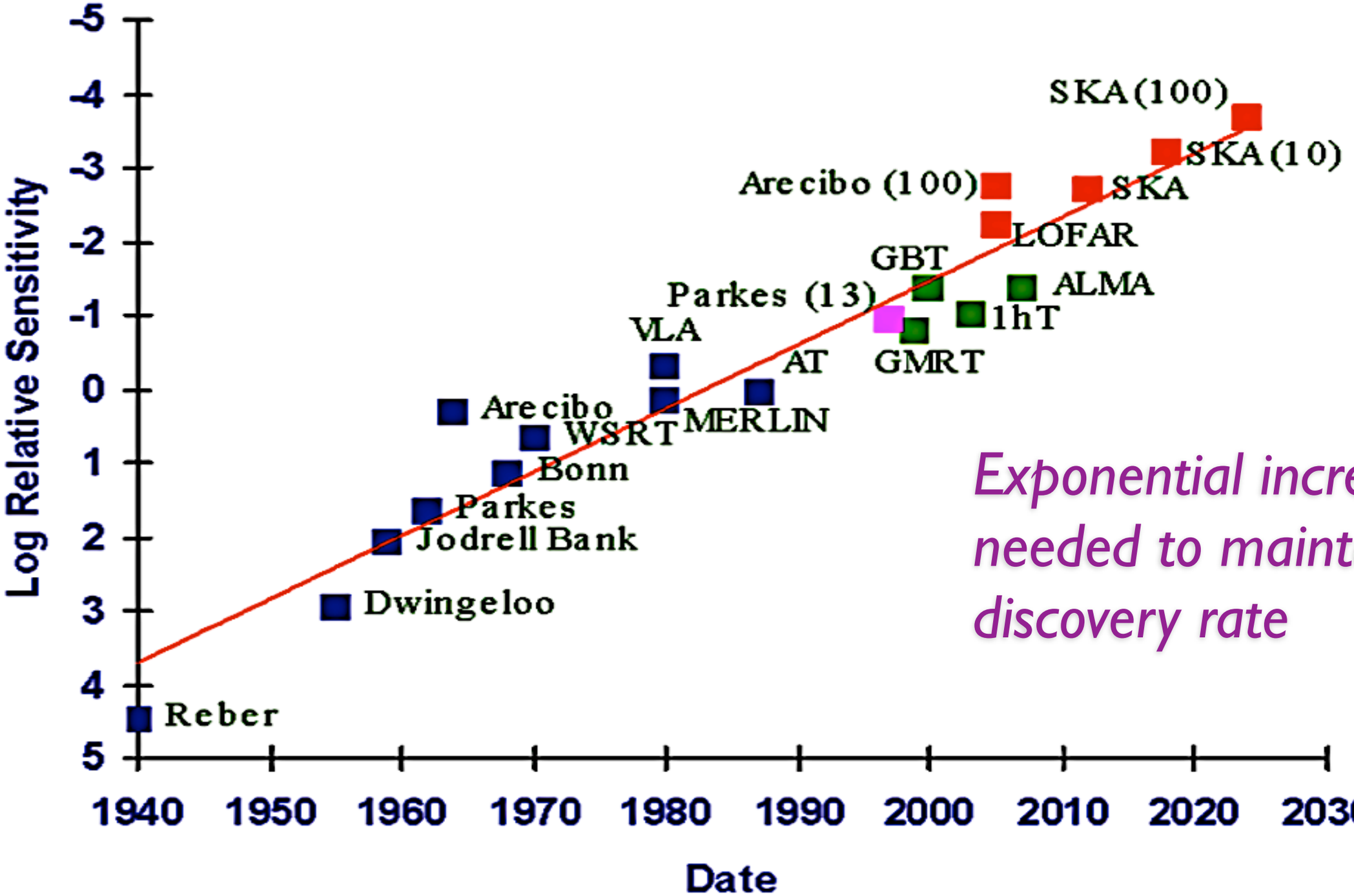
ABSTRACT The time is ripe for planning an array with a collecting area of 1 km² (14 times larger than Arecibo and 75 times larger than the VLA). In view of its major astronomical target I have dubbed this concept 'The Hydrogen Array', although 1μJy continuum sources will also be reliably detected. I present some initial thoughts about the issues involved.

INTRODUCTION

Since the late 1960s radioastronomers have increased the capability of their instruments many fold. The maximum resolution achieved with interferometry has increased from ~ 50 milliarcsec to ~ 50 microarcsec; the highest frequency in use has gone from ~ 10 GHz to > 350 GHz and the aperture plane coverage has improved from that of the One–Mile Telescope to that of the multi–configuration VLA. However, in terms of raw sensitivity the improvement has been less dramatic. The Arecibo telescope remains the world's largest and the improvements to system noise temperatures at decimetric and centimetric wavelengths have been relatively small ($\leq$ 5). Despite its limitations in sky and frequency coverage, the scientific output of the Arecibo telescope amply demonstrates the advantage of a collecting area 5–10 times larger than that of

- Originally motivated by high redshift HI studies
- Detect 21cm hydrogen emission line ("H I") from normal galaxies anywhere in Universe (z~2)
- Current science case is much broader

Radio Telescope Sensitivity

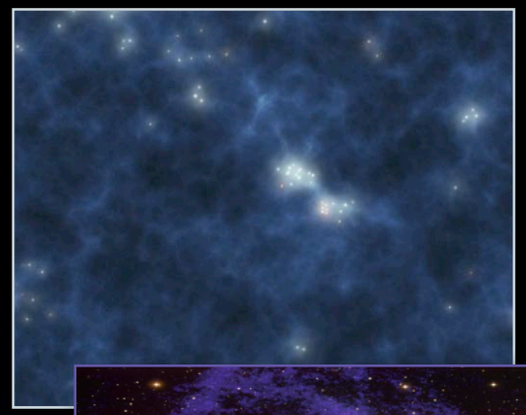


Exponential increase needed to maintain discovery rate

Formation and Evolution of Galaxies • The Dawn of Galaxies: Searching for the Epoch of First Light • 21-cm Emission and Absorption Mechanisms • Preheating the IGM • **SKA Imaging of Cosmological HI** • Large Scale Structure and Galaxy Evolution • A Deep SKA HI Pencil Beam Survey • Large scale structure studies from a shallow, wide area survey • The Ly-α forest seen in the 21-cm HI line • **High Redshift CO** • Deep Continuum Fields • Extragalactic Radio Sources • The SubmicroJansky Sky • Probing Dark Matter with **Gravitational Lensing** • Activity in Galactic Nuclei • The SKA and Active Galactic Nuclei • Sensitivity of the SKA in VLBI Arrays • Circum-nuclear MegaMasers • H_2O megamasers • OH Megamasers • Formaldehyde Megamasers • The **Starburst** Phenomenon • **Interstellar Processes** • HII Regions: High Resolution Imaging of Thermal Emission • Centimetre Wavelength Molecular Probes of the ISM • **Supernova Remnants** • The Origin of Cosmic Rays • Interstellar Plasma Turbulence • Recombination Lines • Magnetic Fields • Rotation Measure Synthesis • Polarization Studies of the Interstellar Medium in the Galaxy and in Nearby External Galaxies • Formation and Evolution of Stars • Continuum Radio Emission from Stars • Imaging the **Surfaces of Stars** • Red Giants and Supergiant Stars • Star Formation • Protostellar Cores • Protostellar Jets • Uncovering the Evolutionary Sequence • Magnetic Fields in Protostellar Objects • Cool Star Astronomy • The Radio **Sun** • Observing Solar Analogs at Radio Wavelengths • Where are the many other Radio Suns? • Flares and Microflares • X-ray Binaries • Relativistic Electrons from X-ray Transients • The Faint Persistent Population • Imaging of Circumstellar Phenomena • Stellar Astrometry • Supernovae • Radio **Supernovae** • The Radio After-Glows of **Gamma-ray Bursts** • Pulsars • Pulsar Searches • **Pulsar Timing**• Radio Pulsar Timing and General Relativity • Solar System Science • Thermal Emission from Small Solar System Bodies • Asteroids • Planetary Satellites • **Kuiper Belt Objects** • Radar Imaging of Near Earth Asteroids • The Atmosphere and Magnetosphere of Jupiter • Comet Studies • Solar Radar • Coronal Scattering • Formation and Evolution of Life • Detection of **Extrasolar Planets** • Pre-Biotic Interstellar Chemistry • The Search for **Extraterrestrial Intelligence**

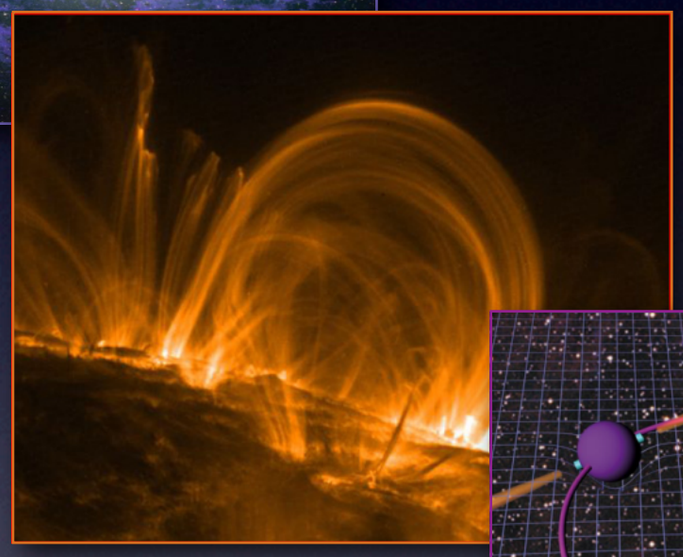
SKA Science

The Science Case



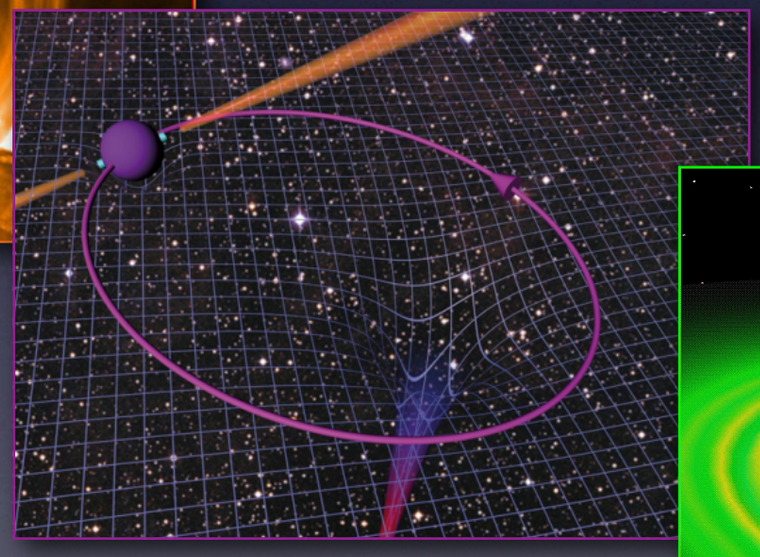
The First Stars

Cosmic Evolution

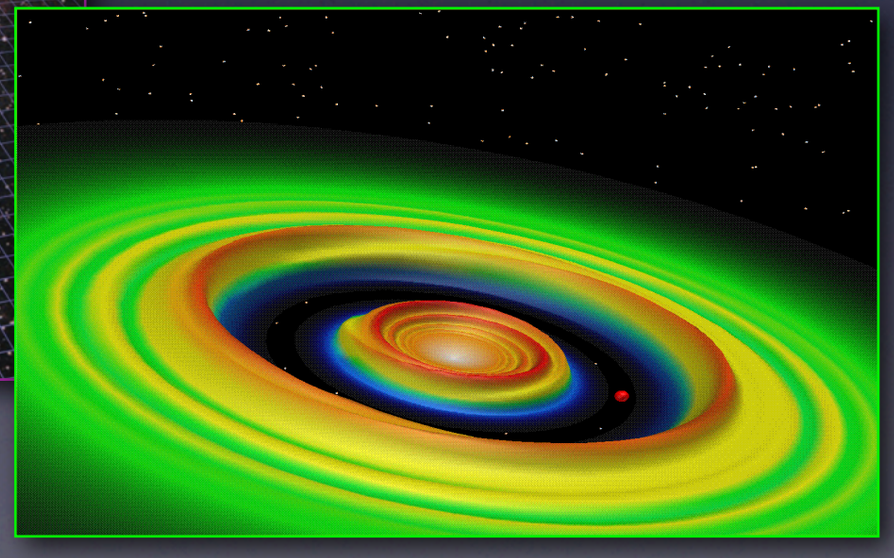


Cosmic Magnetism

Gravitational Physics



Origins of Life



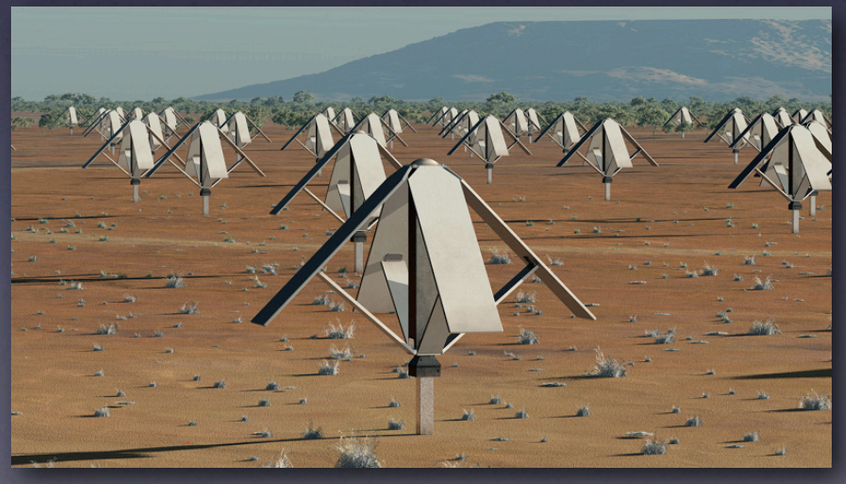
SKA Specifications

- Frequency range: 0.1-25 GHz
- Bandwidth: 0.3 -10 GHz
- Sensitivity (Aeff /Tsys): 2×10^4 m^2 K^{-1}
- Baseline distribution: 50% within 5 km, some baselines beyond 3000 km

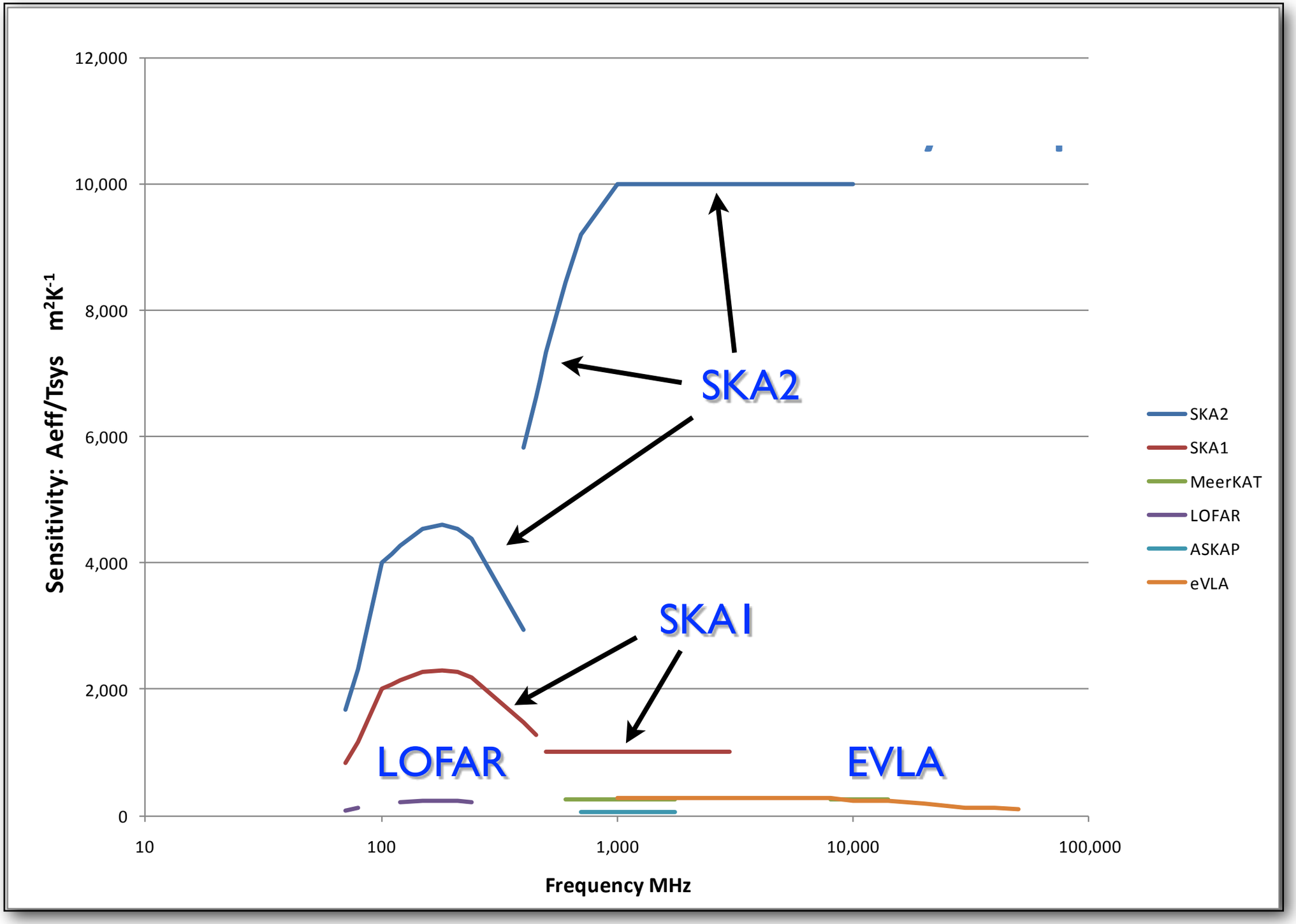
- Imaging Field Of View: 1° @ 1.4 GHz
- Angular Resolution: 0.1" @ 1.4 GHz
- Image Dynamic Range: 10^6 @ 1.4 GHz

- SKA 1: 300 dishes, 50 AA fields
- SKA 2: 2700 dishes, 250 AA fields

- Estimated cost: ~ €1.5 billion
- Operations in 2019 (SKA1), 2024 (SKA2)

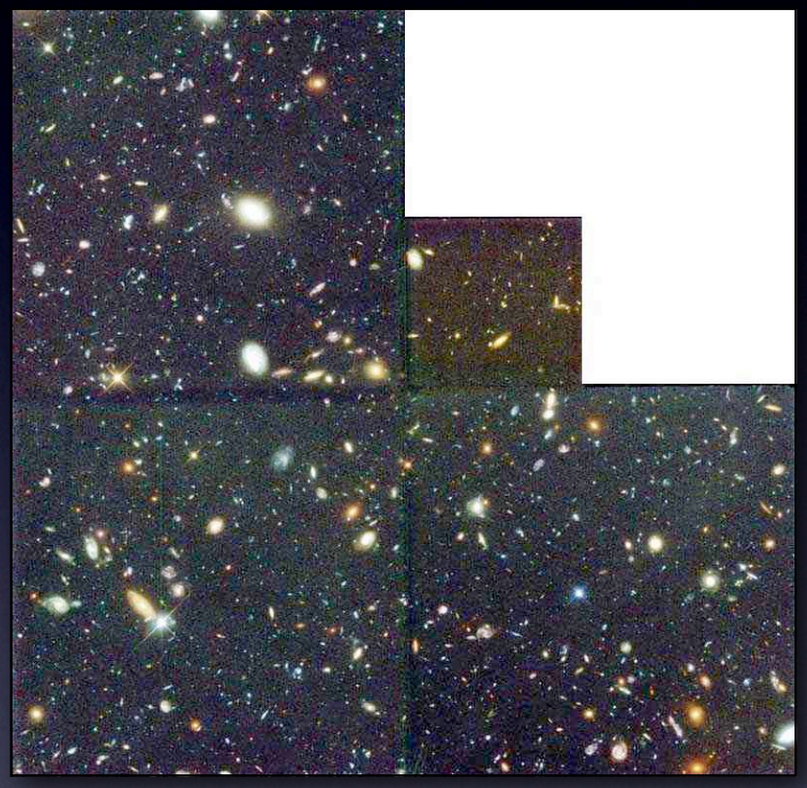


Sensitivity Comparison



Expected Sensitivity

Hubble Deep Field

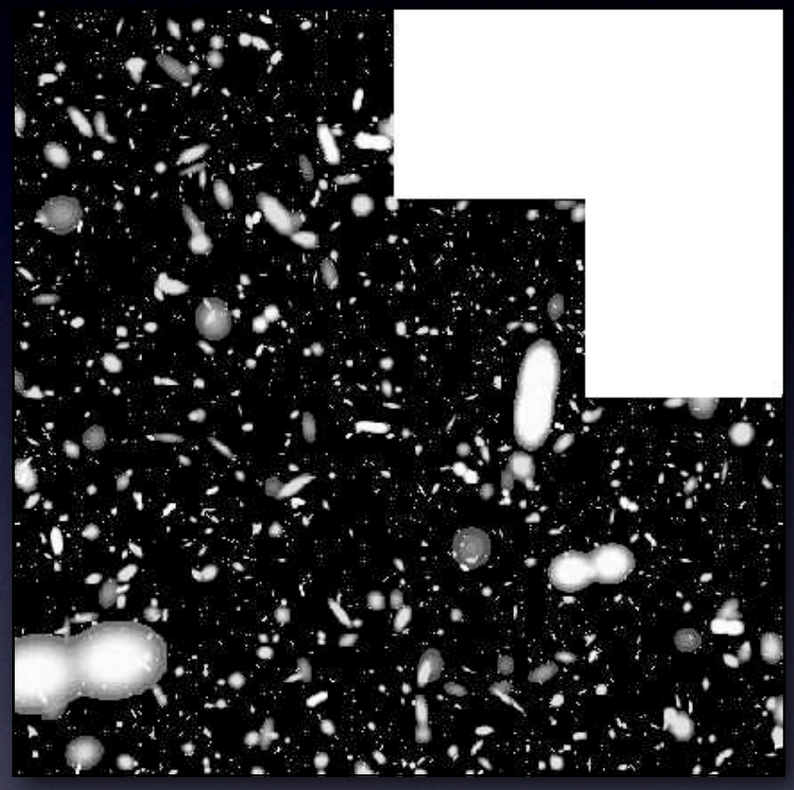


2.5 arcmin x 2.5 arcmin
~3000 galaxies

EVLA

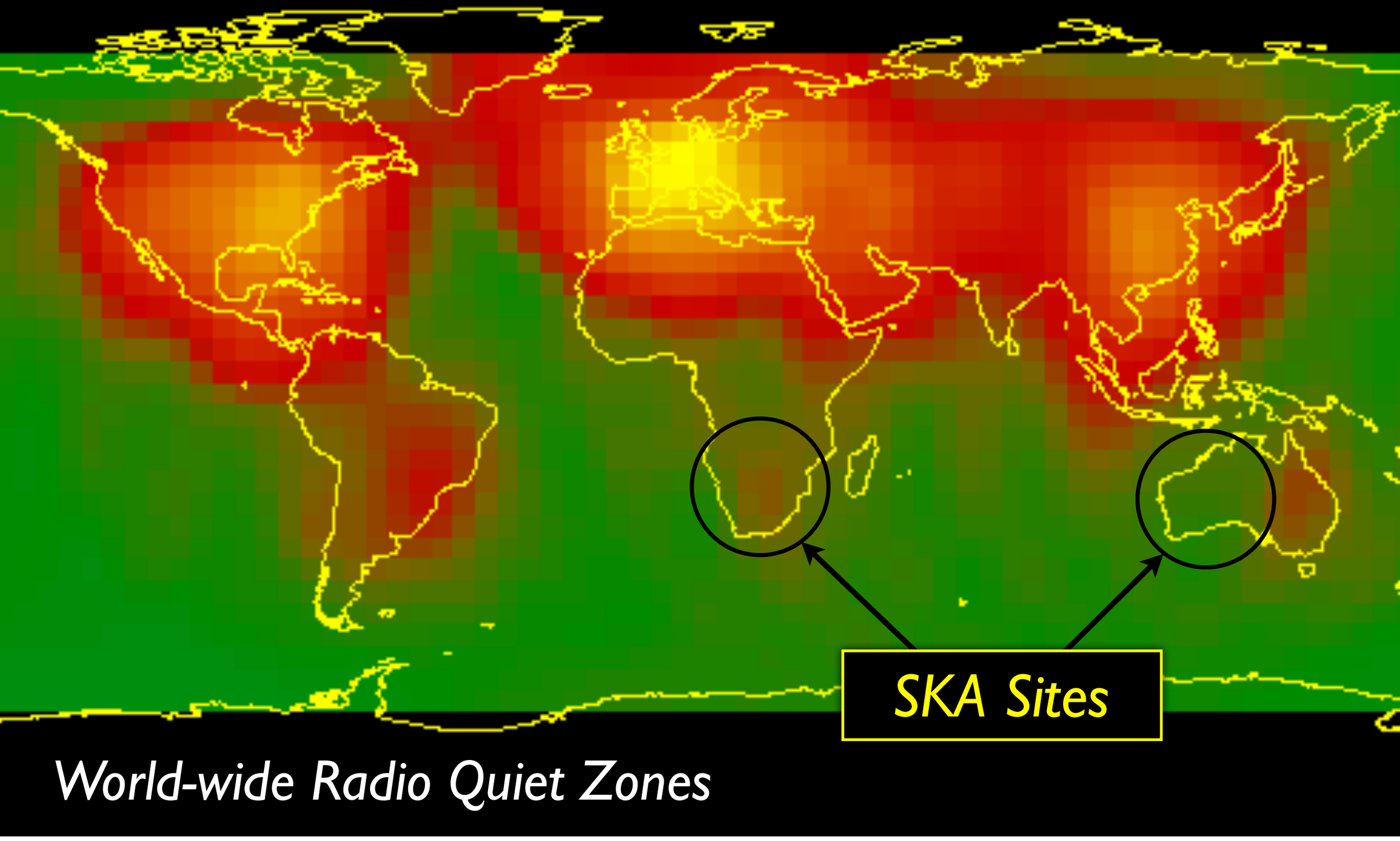
50 hours at 8.7 GHz gives
6 sources at >12 μJy

Simulated SKA

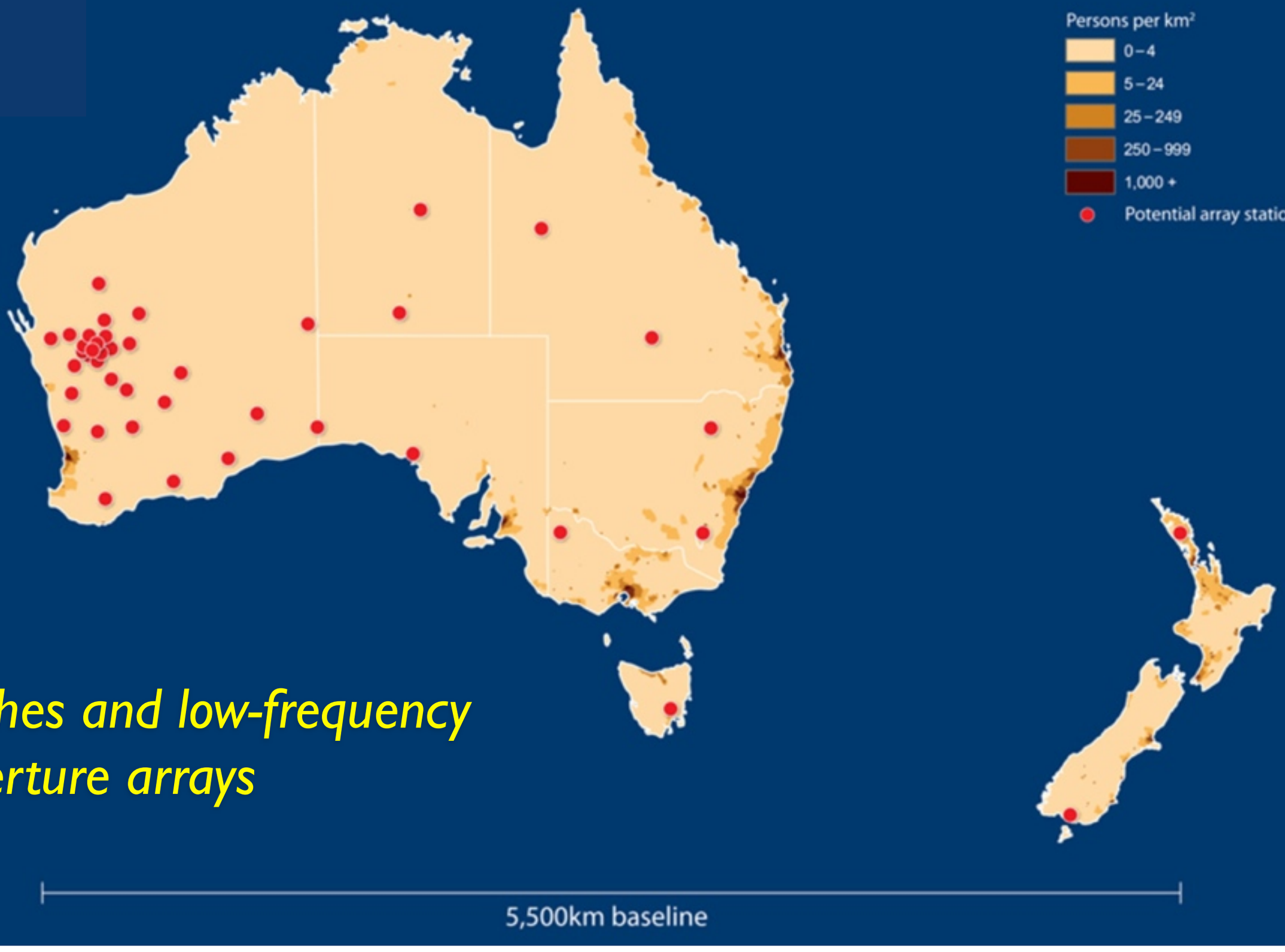


1000's of sources at 1 μJy @
1.4 GHz (fraction of total FoV)

Where do we build it?



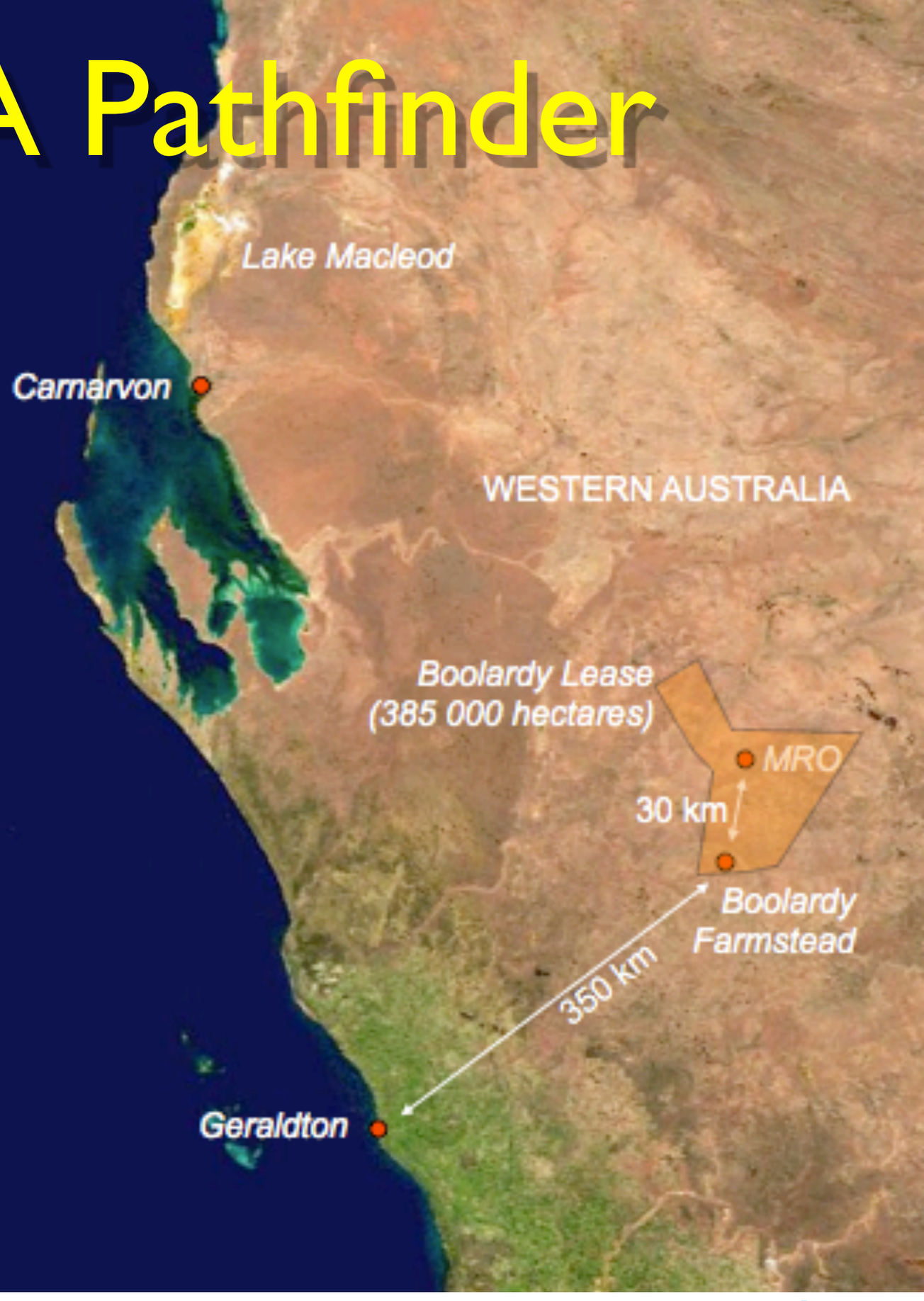
SKA Site 1: Australia



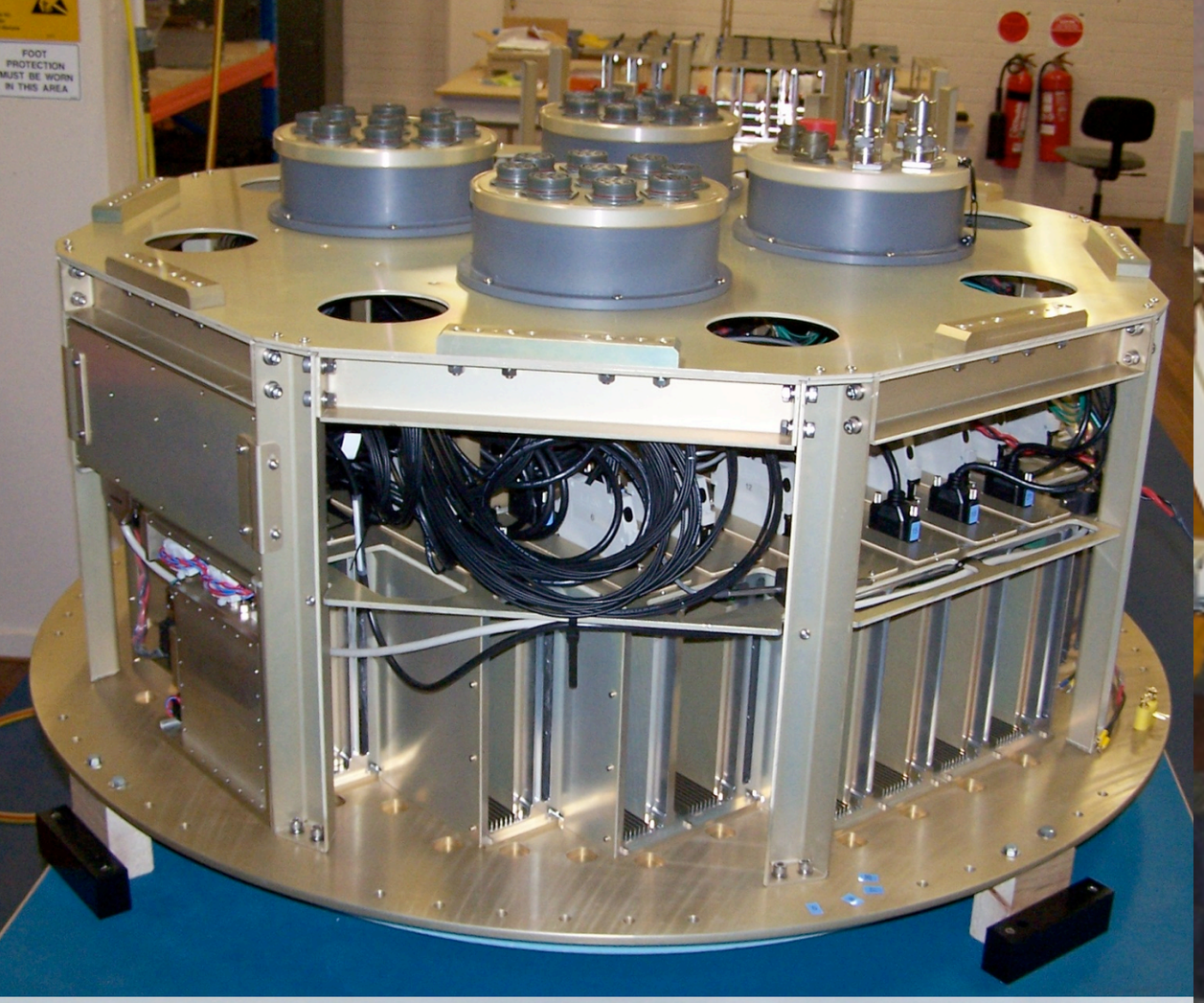
Dishes and low-frequency aperture arrays

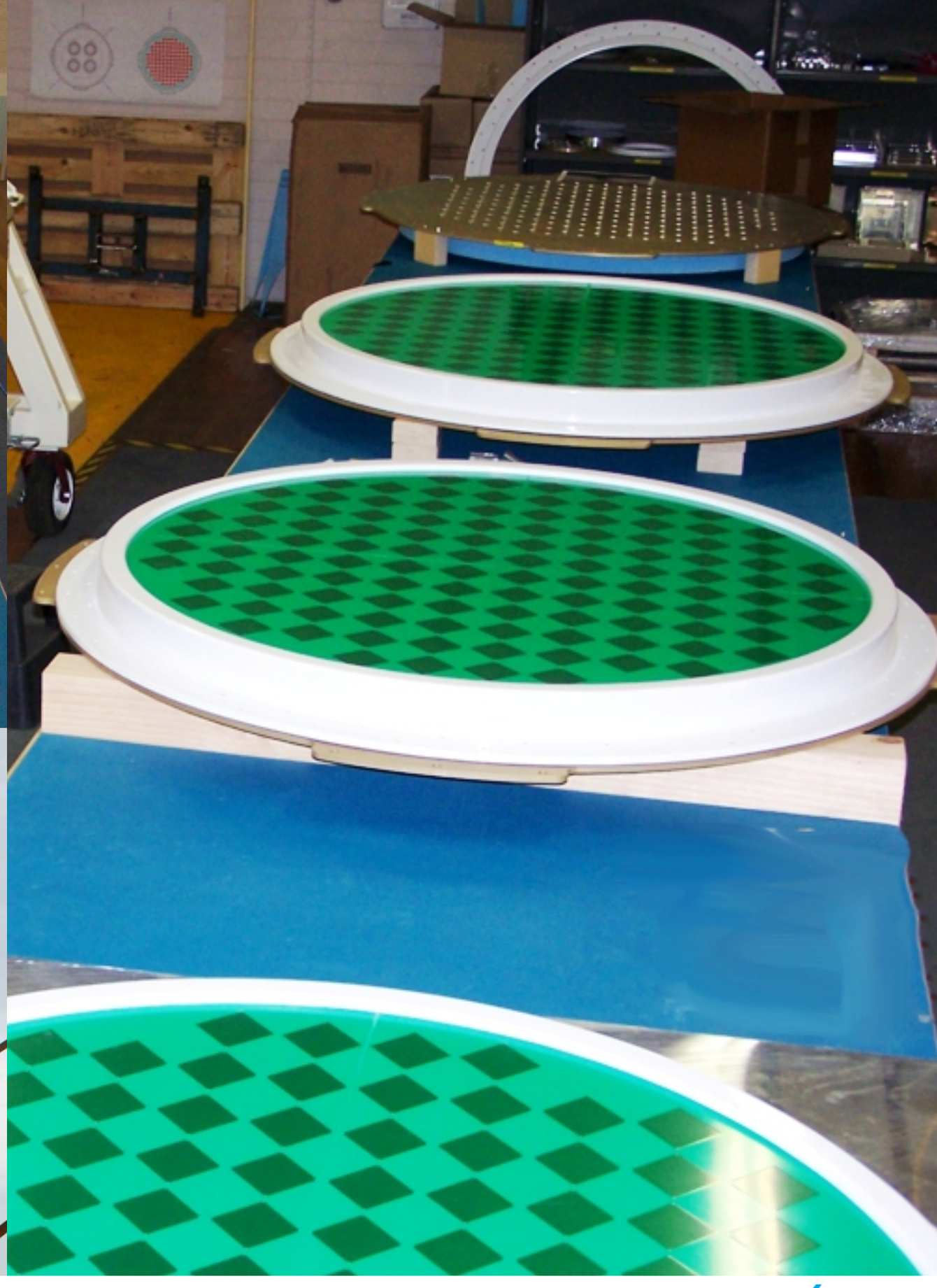
Australian SKA Pathfinder (ASKAP)

- Shire of Murchison
- 50,000 km^2
- 0 incorporated towns
- 29 sheep/cattle stations
- Population: 110




1
coates
coates


FOOT
PROTECTION
MUST BE WORN
IN THIS AREA



Australian SKA Pathfinder

Design goals:

- **High-dynamic range imaging**
- **Wide field-of-view science**

Number of dishes	**36**
Dish diameter	**12 m**
Maximum baseline	**6 km**
Resolution	**30”**
Sensitivity	**65 m^2/Kelvin**
Survey Speed	**1.3x10^5 m^4/kelvin^2/deg^2**
Tsys/η	**63 Kelvin**
	(e.g. Tsys = 50K, η = 80%)
Observing frequency	**700 – 1800 MHz**
Field of view	**30 deg^2**
Processed bandwidth	**300 MHz**
Spectral channels	**16384**
Focal Plane Phased Array	**188 channels (94 beams)**

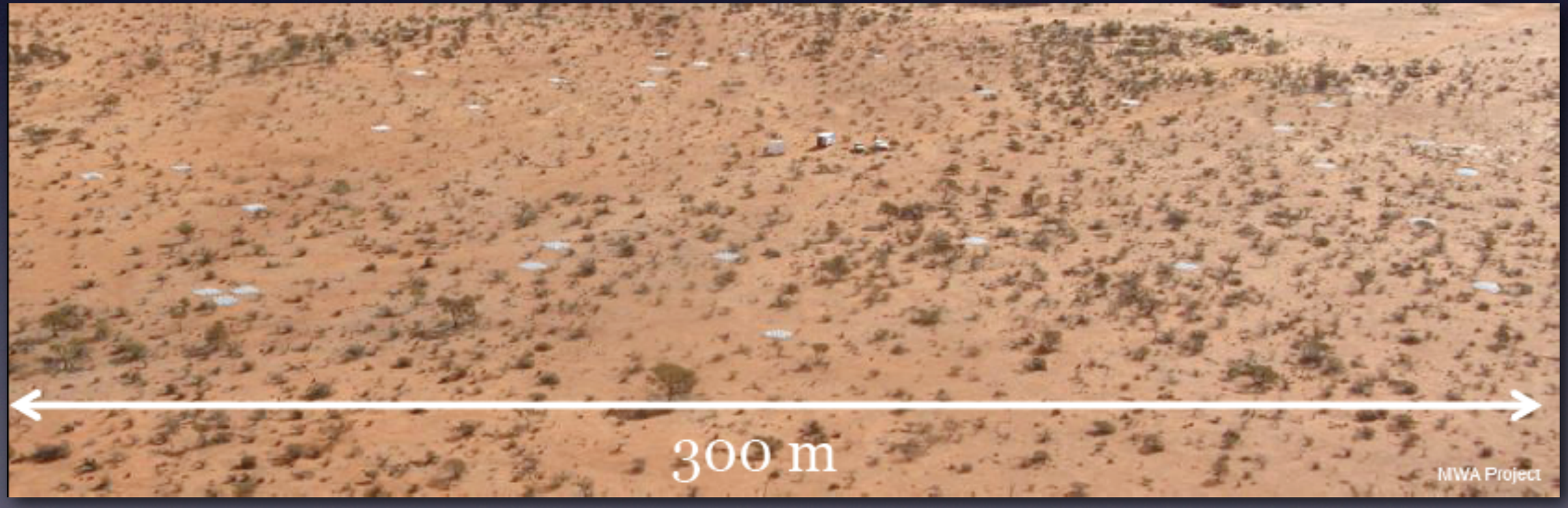
Australian SKA Pathfinder

Quick summary:

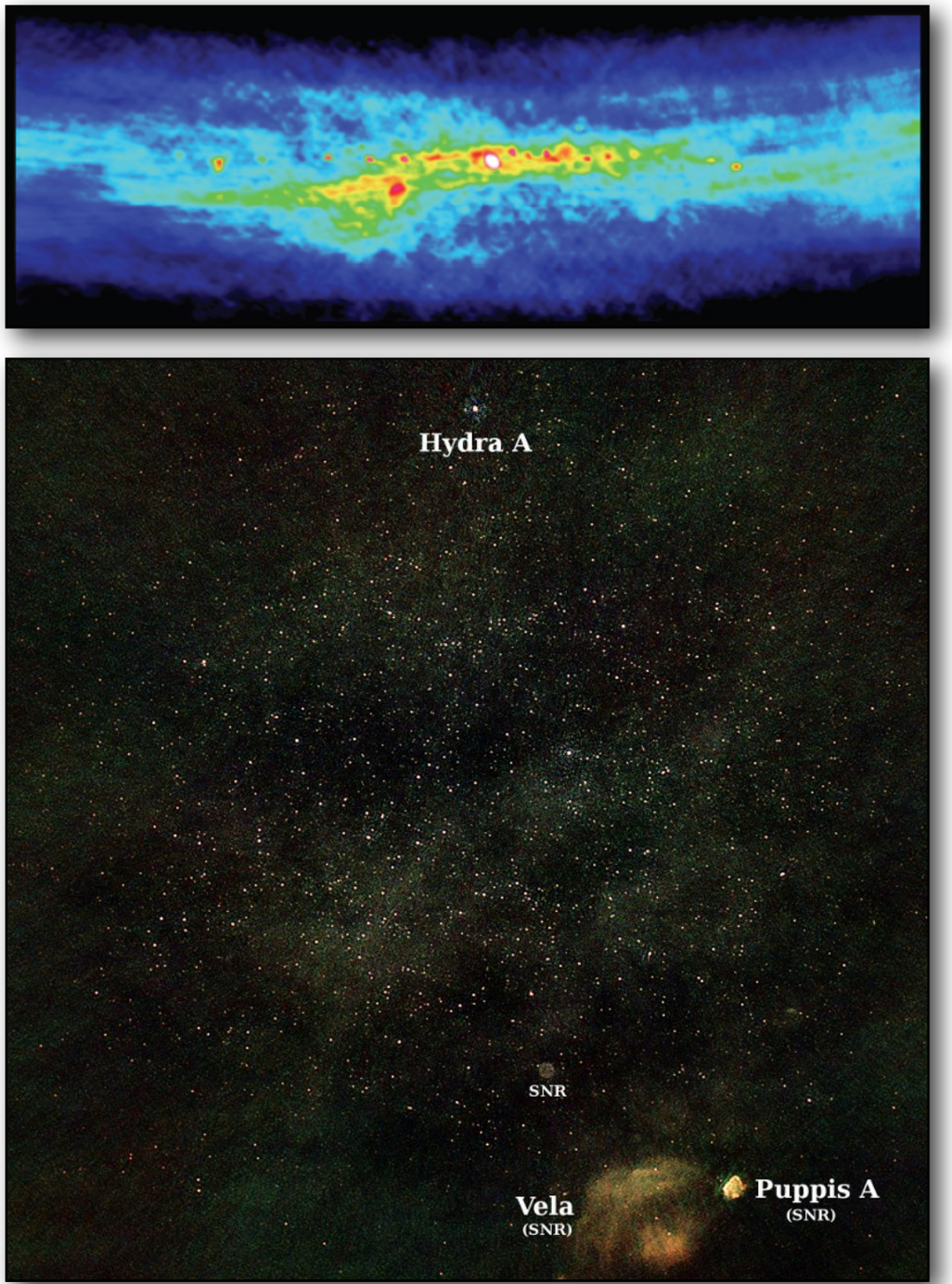
- **Design and build the world's premier radio survey telescope**
- **Located in Western Australia**
- **Total cost: ~$170M**
- **Status:**
  - **Construction well-advanced**
  - **6 antenna sub-array being equipped with phased-array feeds**
  - **Next-generation MkII phased-array feed under development**
  - **Engineering commissioning to start in May**
  - **ASKAP complete by end 2013**
  - **Early science in Q1 2014**

Murchison Widefield Array (MWA)

- Low-frequency AA
- 128 tile array
- SKA low precursor

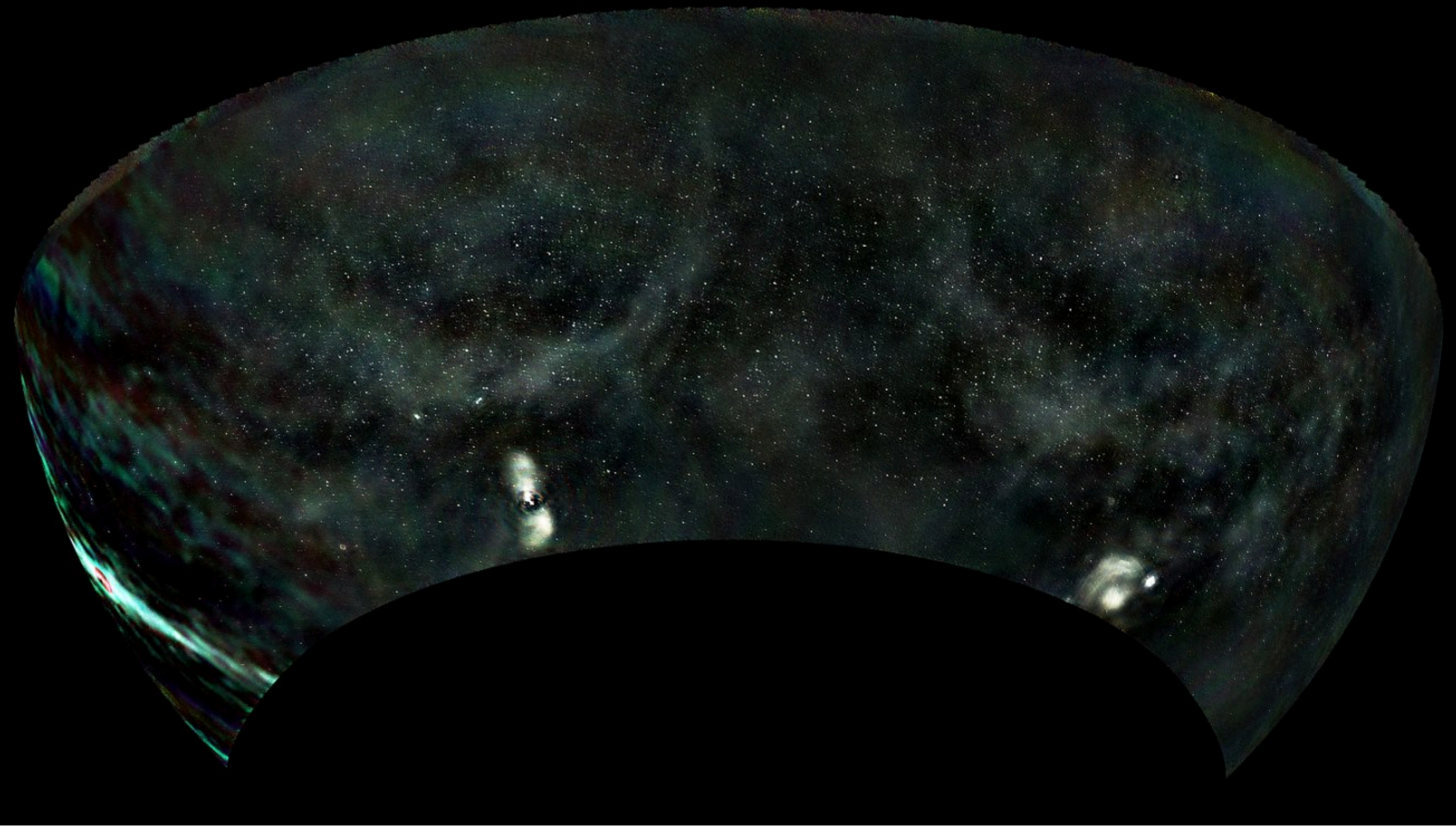


Murchison Widefield Array (MWA)



Parameter	Value
Frequency range	80 – 300 MHz
Number of receptors	2,048 dual-pol. dipoles
Number of "tiles"	128 (expandable to 256)
Number of baselines	8,128
Collecting area	~2500 m^2 @ 200 MHz
T_{sys}	25 K (Rx); 125 K (sky) @ 200 MHz
Field of view (diameter)	~40° @ 200 MHz
Configuration	Core: 1.5 km in diameter (87% of collecting area) Extended: 3 km in diameter (13% of collecting area)
Bandwidth	220 MHz sampled, 30.72 MHz processed
Spectral channels (correlator)	768 (40 kHz resolution)
Temporal resolution (correlator)	0.5 s uncalibrated; 8 s calibrated
Polarisations correlated	Full Stokes
Continuum point source sensitivity	80 mJy in 1 s @ 200 MHz
	1.3 mJy in 1 hr @ 200 MHz
Voltage capture for full array	yes

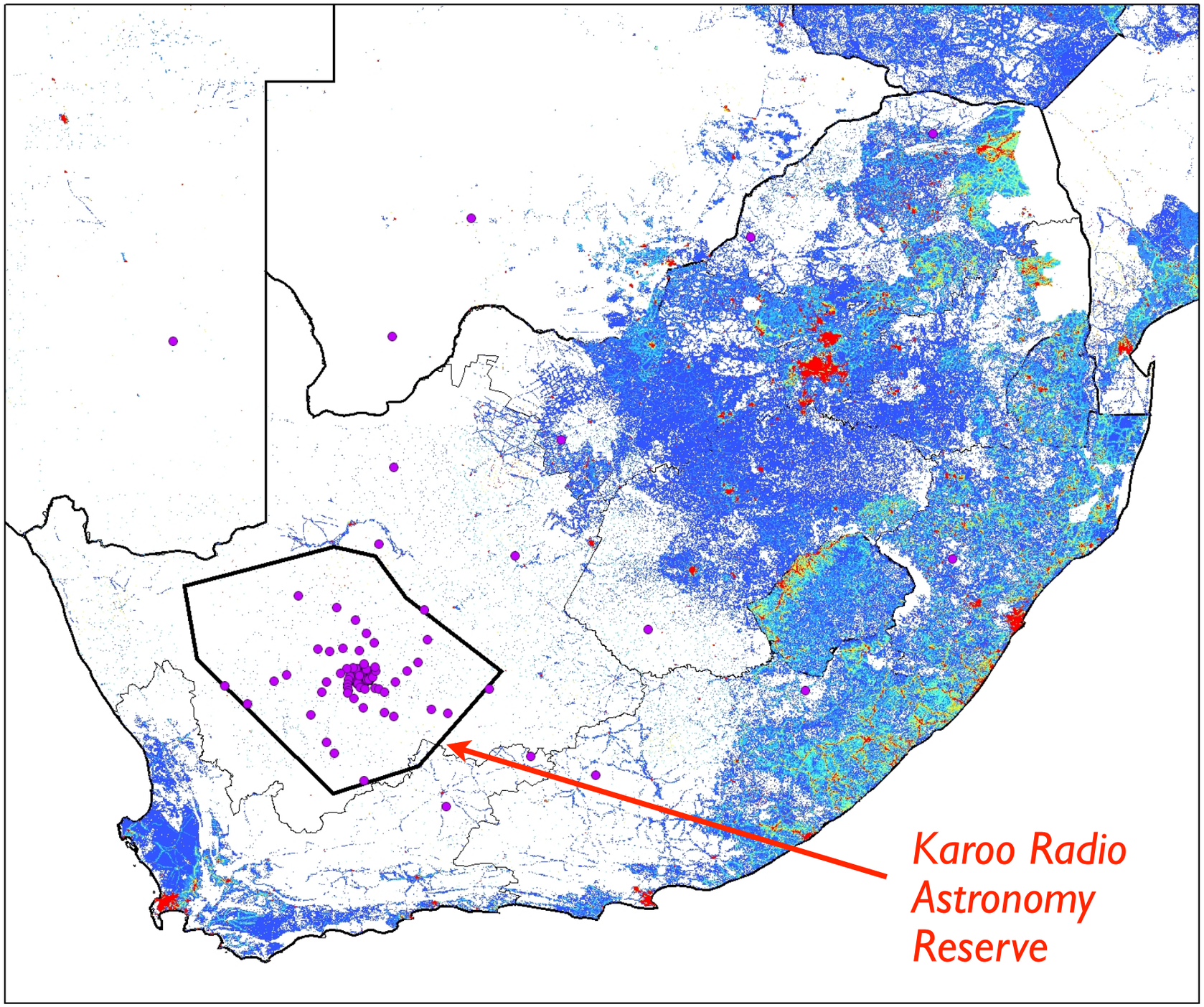
Murchison Widefield Array (MWA)



SKA Site 2: South Africa

Dishes and mid-frequency aperture arrays

SKA Site 2: South Africa



Legend

- SKA_Configuration_SPDO_Dish_Full
- AA1_SPDO_Version1
- AA2_SPDO_Version2
- KCAAA1

Population (per sq km)

Value

- 0 - 4
- 4.000000001 - 14
- 14.00000001 - 29
- 29.00000001 - 47
- 47.00000001 - 68
- 68.00000001 - 91
- 91.00000001 - 116
- 116.0000001 - 142
- 142.0000001 - 169
- 169.0000001 - 197
- 197.0000001 - 225
- 225.0000001 - 255

N

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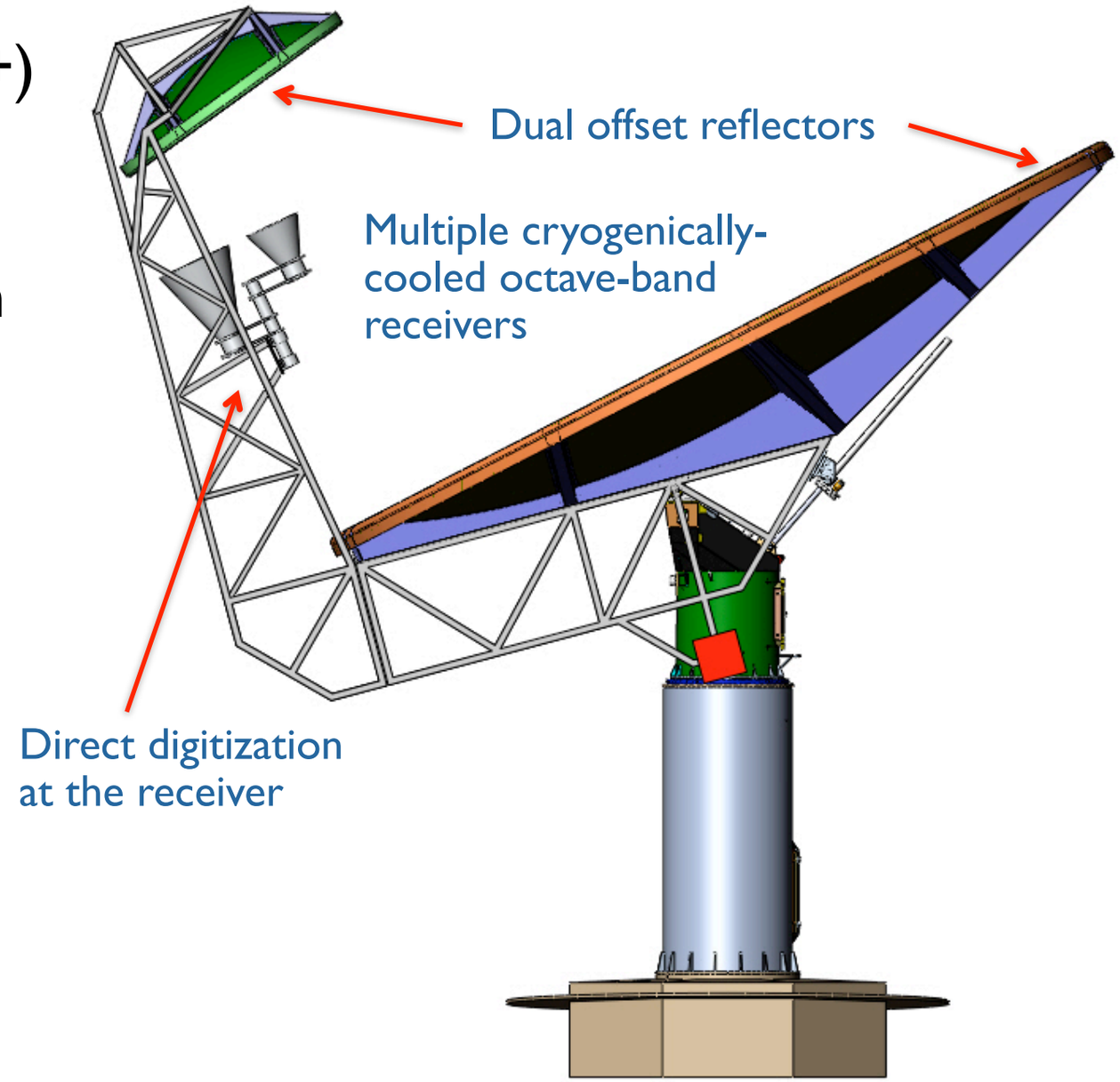
Fax: +27 11 442 2454
Email: atiplady@ska.ac.za

MeerKAT SKA Pathfinder

MeerKAT SKA Pathfinder

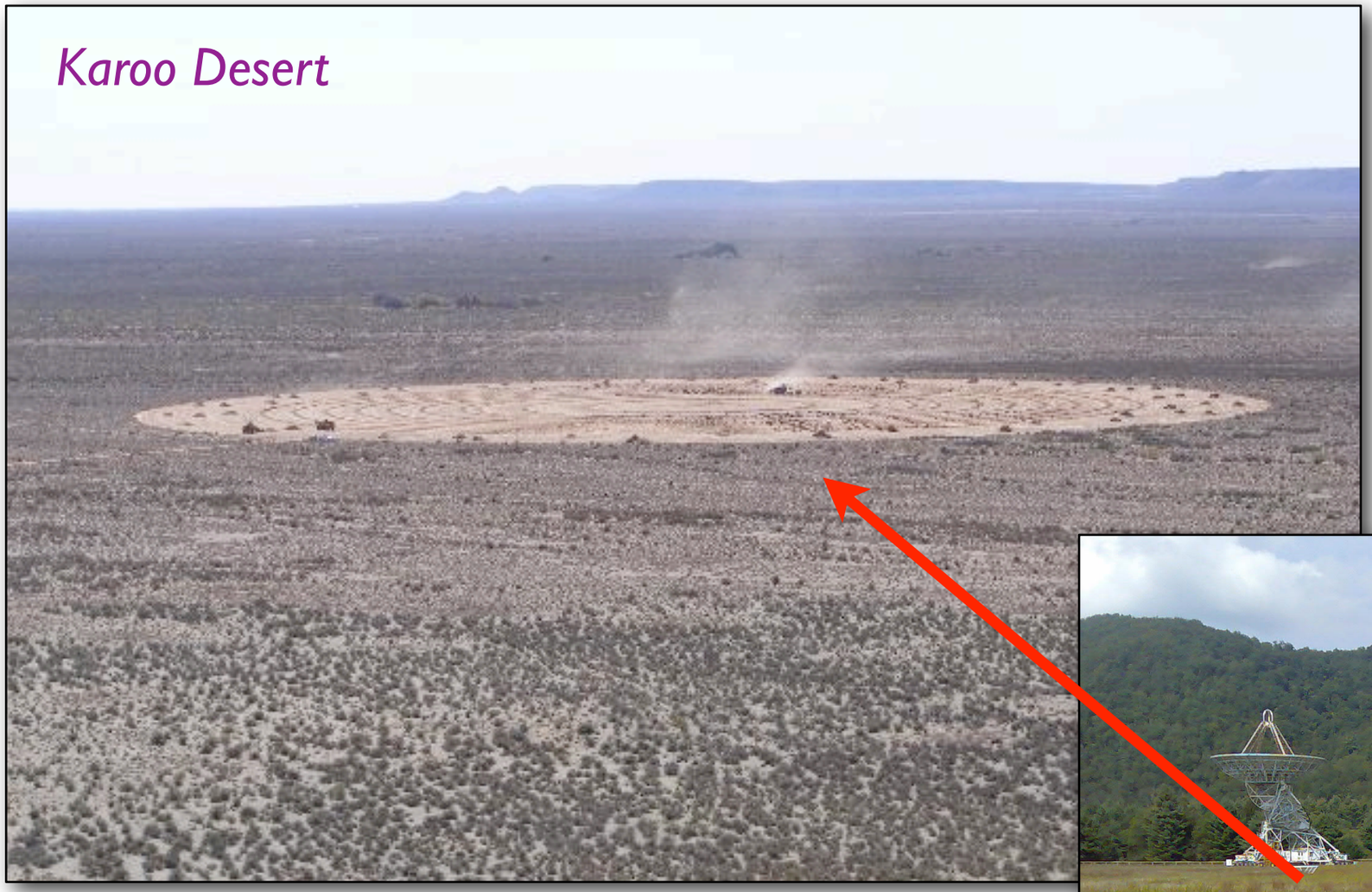
- Will be most sensitive cm-wavelength telescope in the southern hemisphere
- 580 MHz – 15(+) GHz (i.e. SKA-mid +)
- Imaging and non-imaging modes
- High filling factor for baselines < 1 km
- 64 x 13.5 m gregorian offset antennas
- 8 km maximum baseline
- 70 % in < 1km diameter core
- Future expansion to 20+ km
- KAT7 prototype array in place

SKA Baseline Design



MeerKAT SKA Pathfinder

PAPER (Precision Array to Probe Epoch of Reionization)



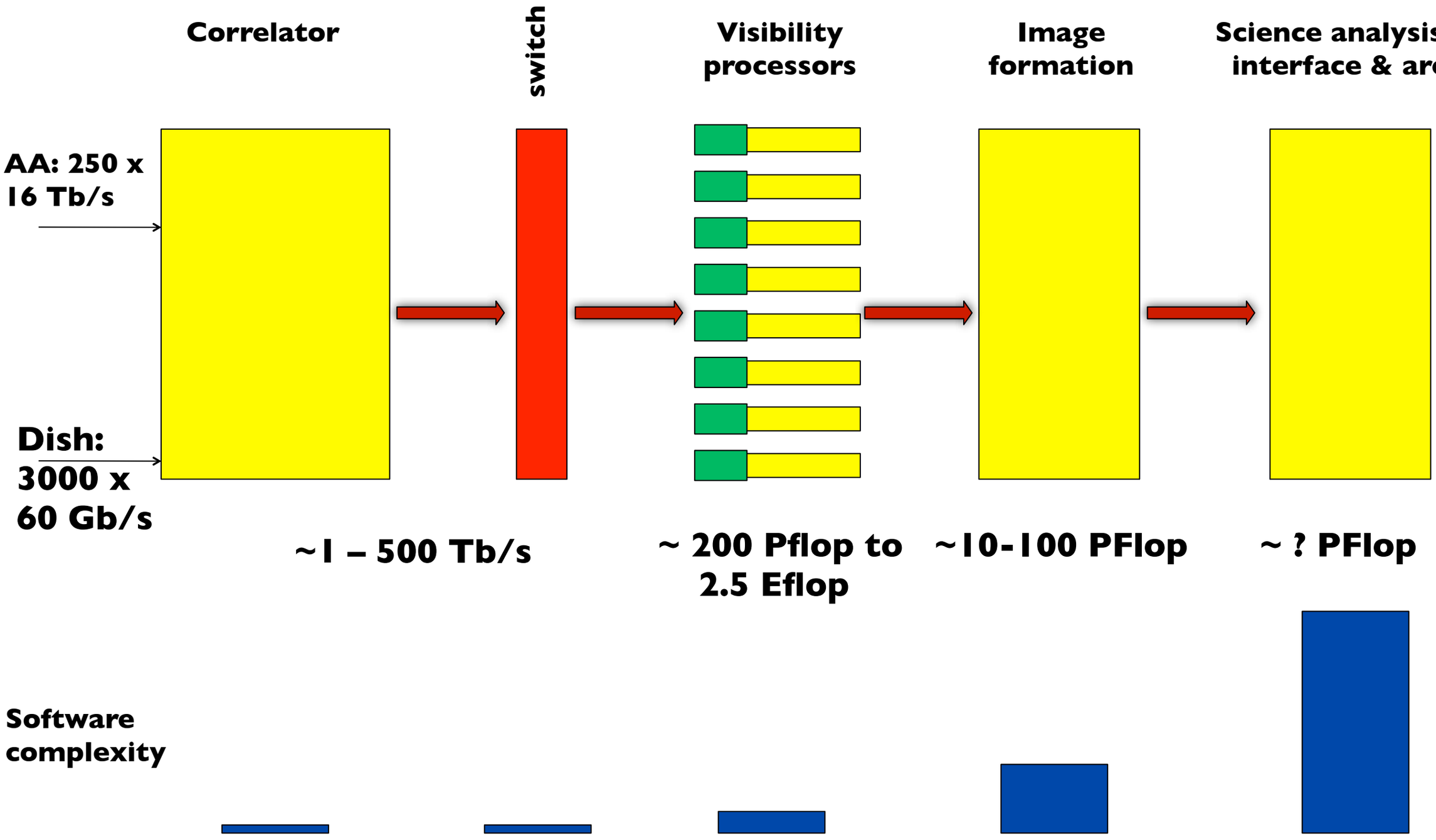
- Low-frequency AA
- 64 tile array
- EoR experiment

National Radio Astronomy Observatory
A facility of the National Science Foundation

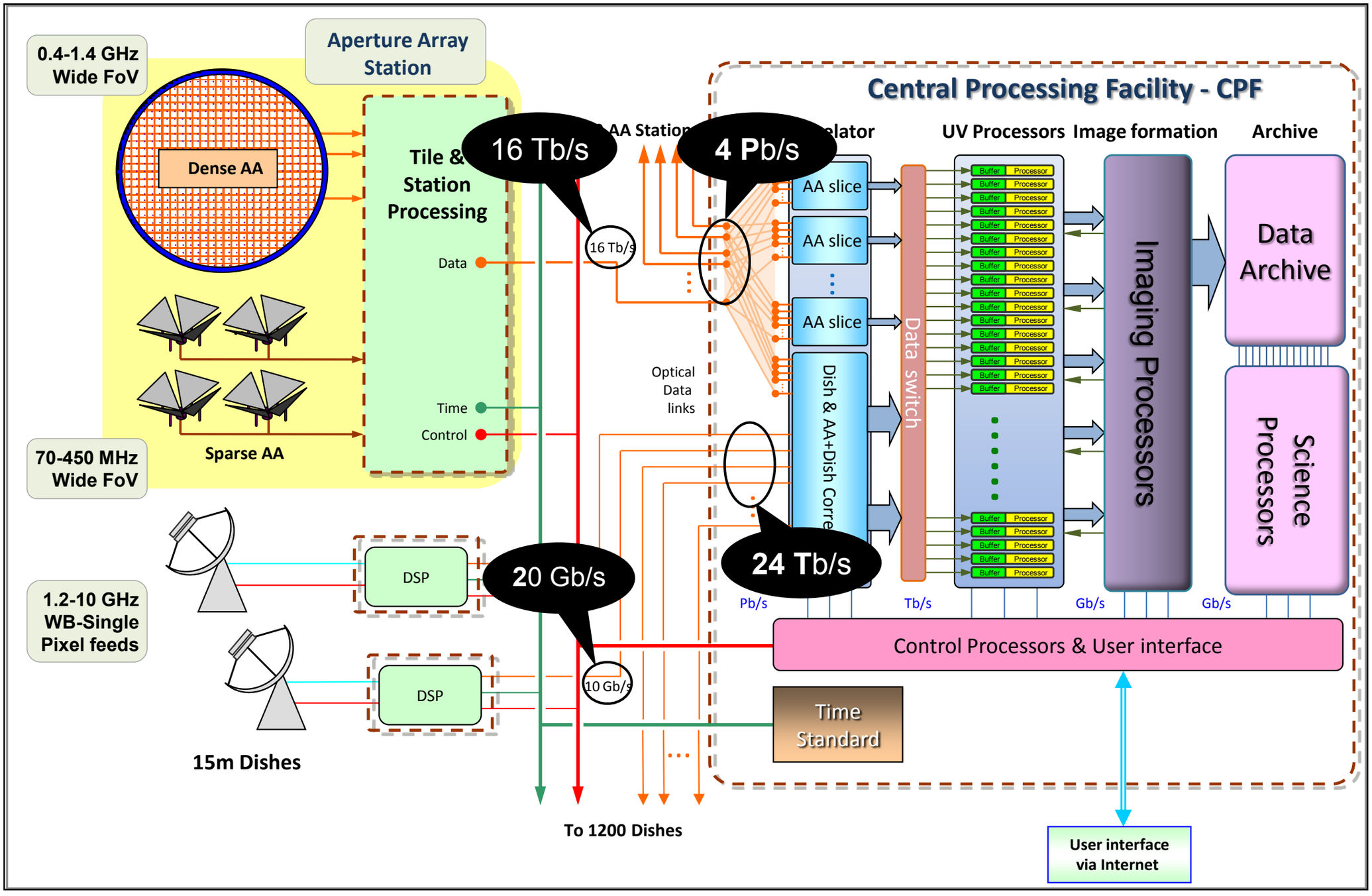
Intermission

Computational Challenges

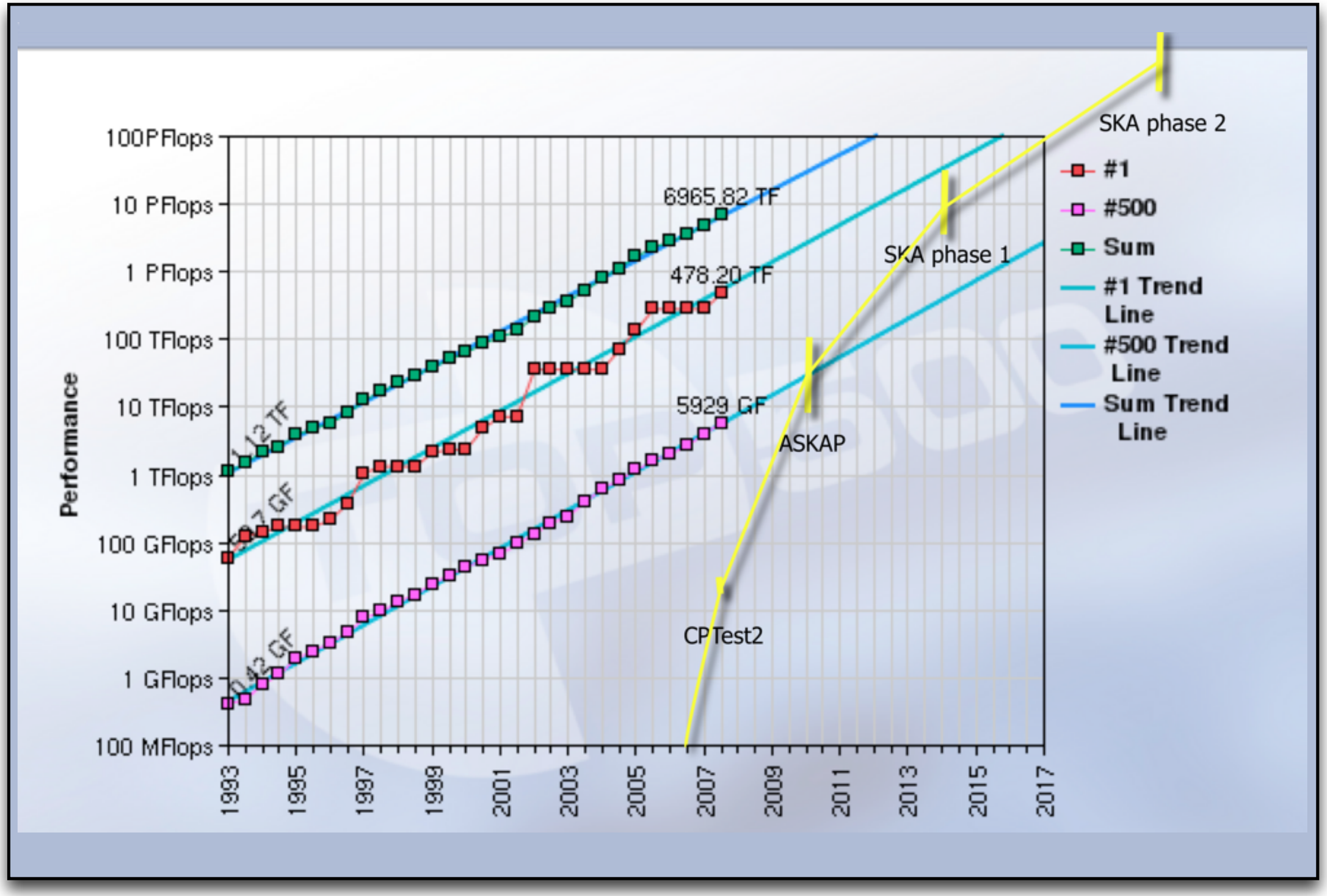
SKA Processing Challenge



SKA Network Data Flow



SKA Computing Costs



SKA Data Products

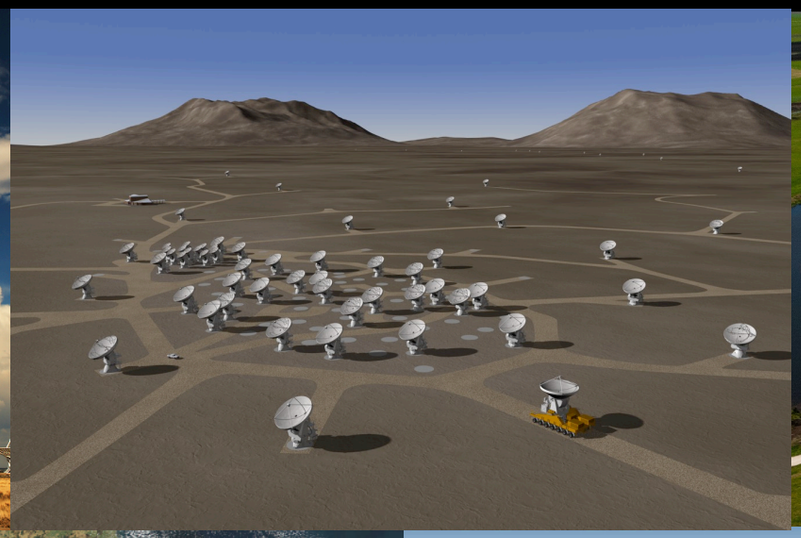
Experiment	T_{obs}	***B*/km**	***D*/m**	N_b	N_{ch}	N_v	**Size / TB**
High resolution spectral line	3600	200	15	1	32000	$5\ 10^{13}$	200
Survey spectral line medium resolution	3600	30	56	1000	32000	$8\ 10^{13}$	330
Snapshot continuum – some spectral information	60	180	56	1200	32	$7\ 10^{12}$	30
High resolution long baseline	3600	3000	60	1	4	$7\ 10^{14}$	360

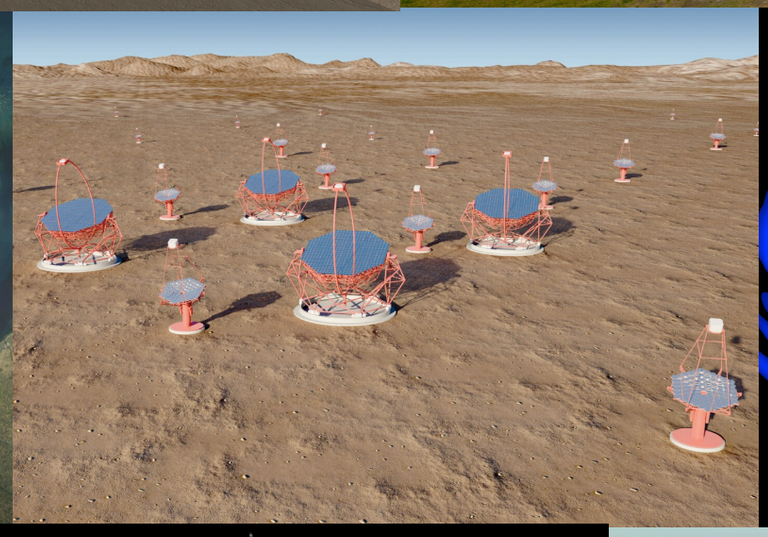
- **~0.5 – 10 PB/day of image data**
- **Source count ~10^6 sources per square degree**
- **~10^{10} sources in the accessible SKA sky, 10^4 numbers/record**
- **~1 PB for the catalogued data**

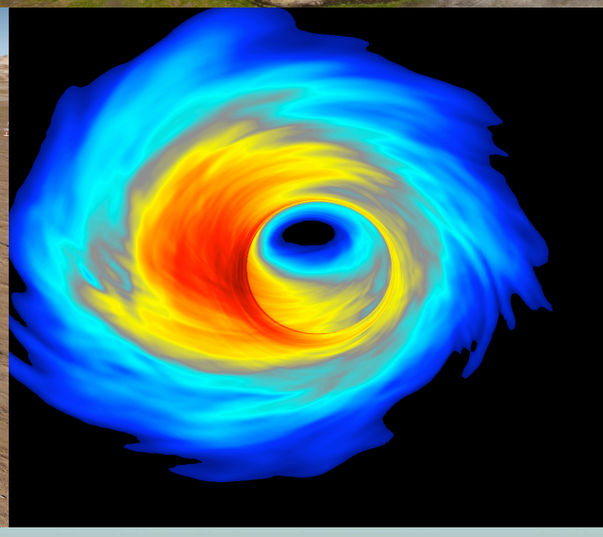
100 Pbytes – 3 EBytes / year of fully processed data

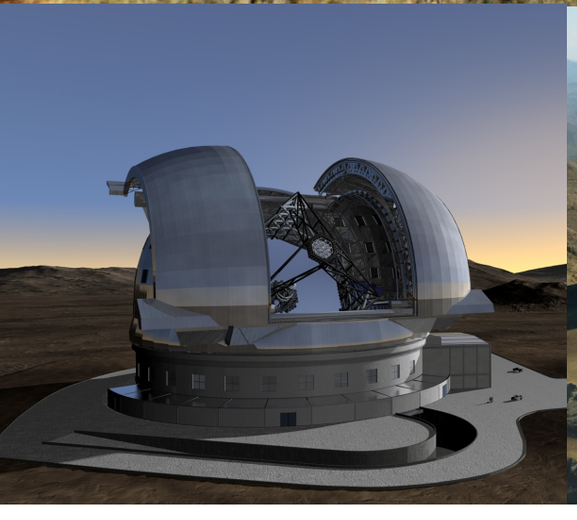
Data Intensive Astronomy

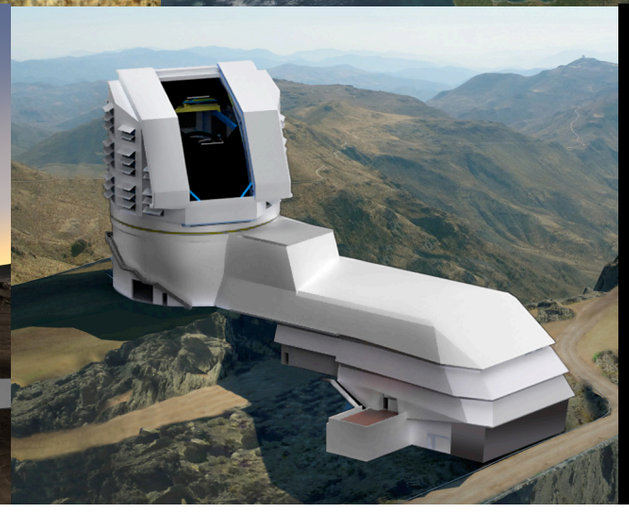
Data Intensive Astronomy

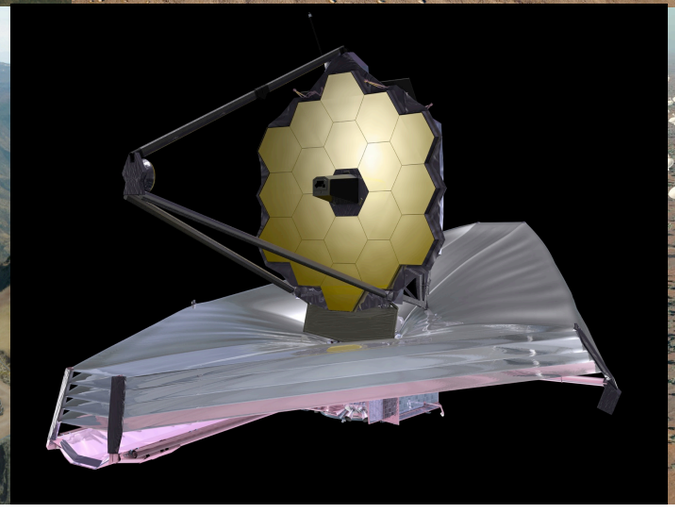






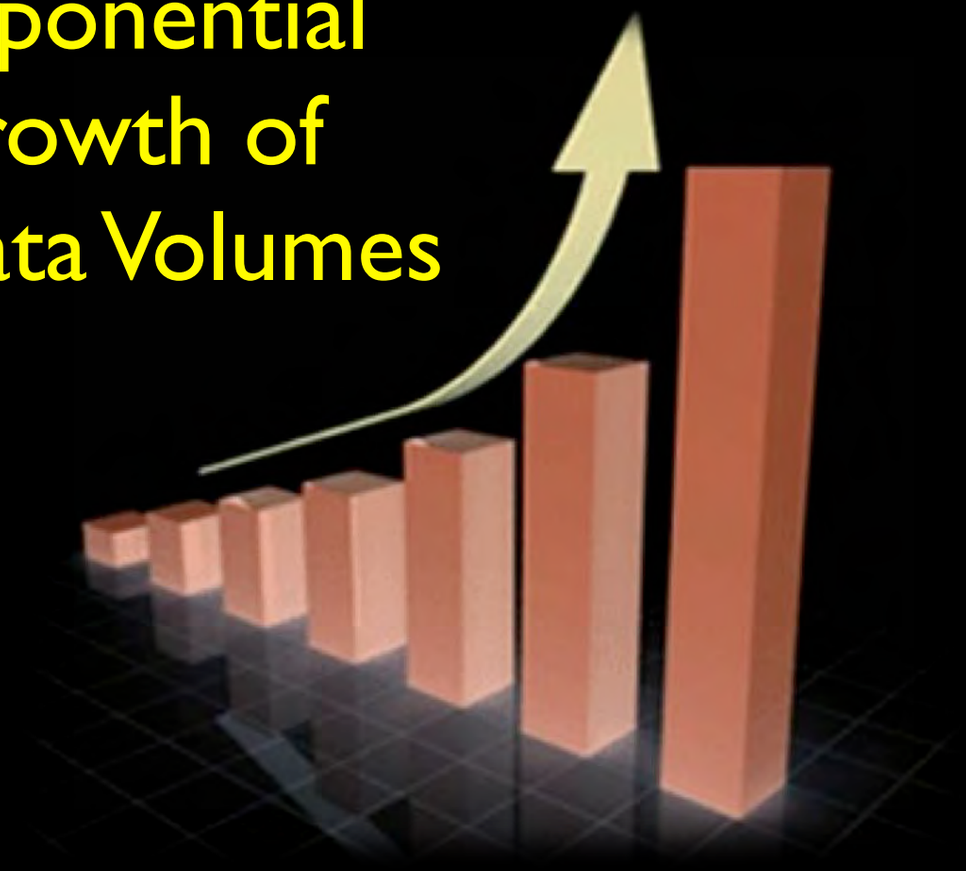






Data Intensive Astronomy

Exponential Growth of Data Volumes

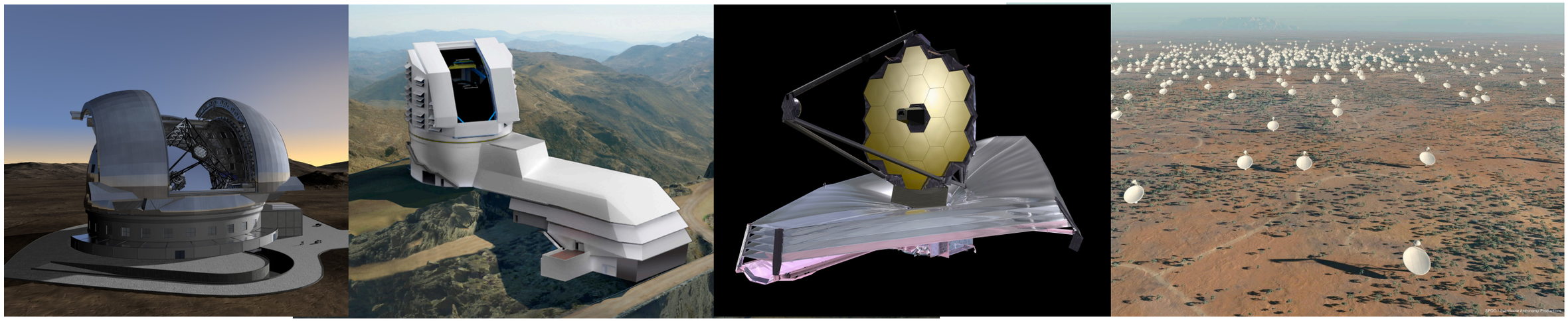


…and Complexity

Understanding of complex phenomena requires complex data

- From data poverty to data glut
- From data sets to data streams
- From static to dynamic, evolving data
- From centralized to distributed resources

What does "Data Intensive" mean?



- Science is increasingly driven by large data sets
- Data collection in large collaborations
- Analysis done on the archived data
- New instruments will produce petascale datasets

Petascale analysis require exascale data management!

The Era of Big Surveys

Modern sky surveys obtain ~ 10^{12} –10^{15} bytes of images
Catalogs ~ 10^{8} –10^{9} objects (stars, galaxies, etc.)
and measure ~ 10^{2} –10^{4} numbers per object

LOFAR Surveys in Context

2000 - 2014 Sloan Digital Sky Survey (SDSS)

120 Mpixel camera, (0.08 PB in 10 yrs)

3×10^8 unique sources (4 TB)

2018 - 2028 Large Synoptic Survey Telescope (LSST)

3.2 Gpixel camera (6 PB per year)

1000's observations of every source

few $\times 10^9$ sources, few $\times 10^{12}$ rows (10 PB)

2013 - 2018 LOFAR Low-Frequency Sky Survey (LFSS)

~100 deg^2 FOV (~5.2 Gpixel) (~0.1 EB per year)

10-10^3 freqs, 10^2-10^4 observations of every source

few $\times 10^8$ sources, few $\times 10^{12}$ rows (~1-5 PB)

The Panchromatic Universe

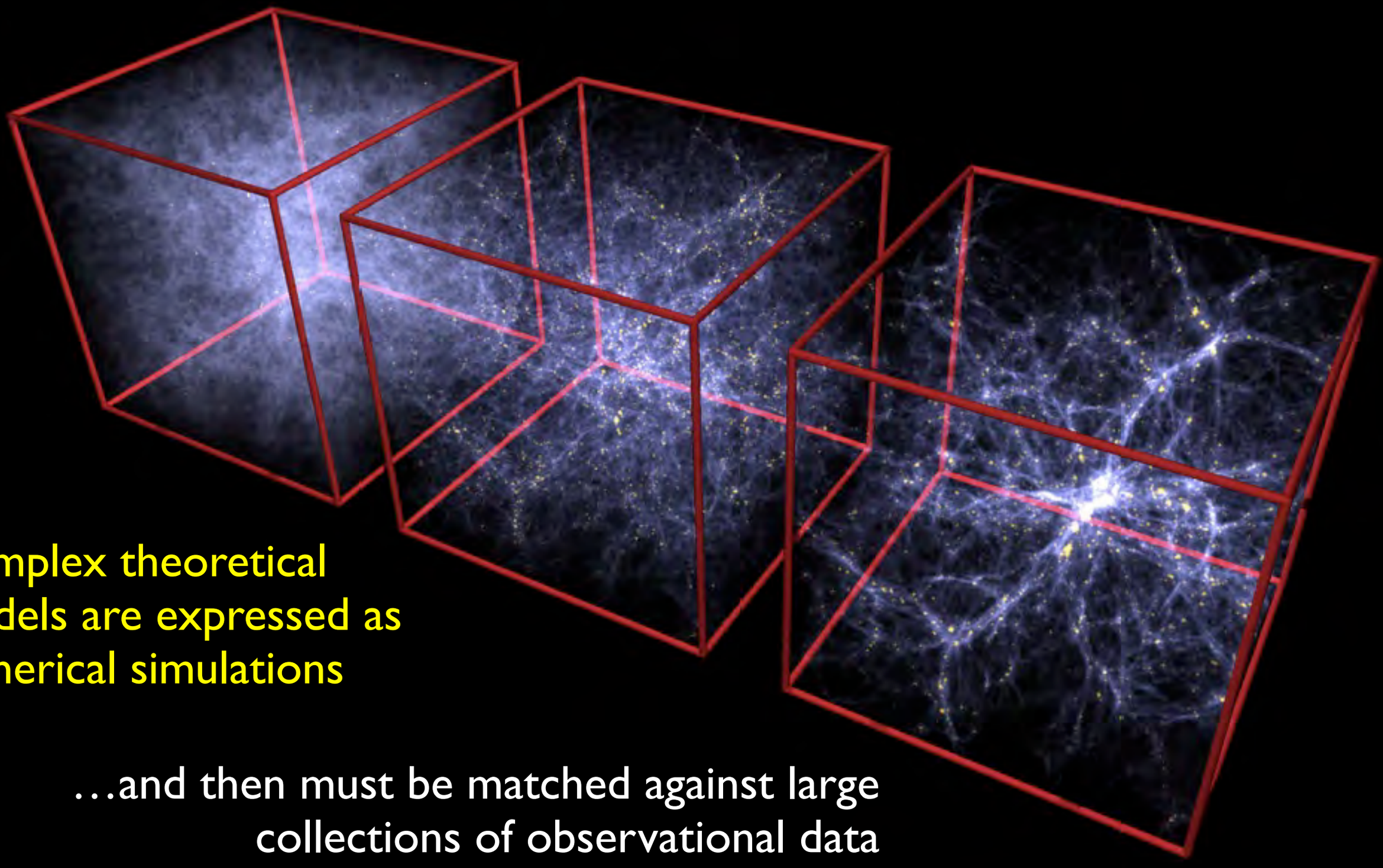
Near IR
starlight

Far IR
warm dust

Hα
ionized gas

X-Ray
accretion

Numerical Simulations

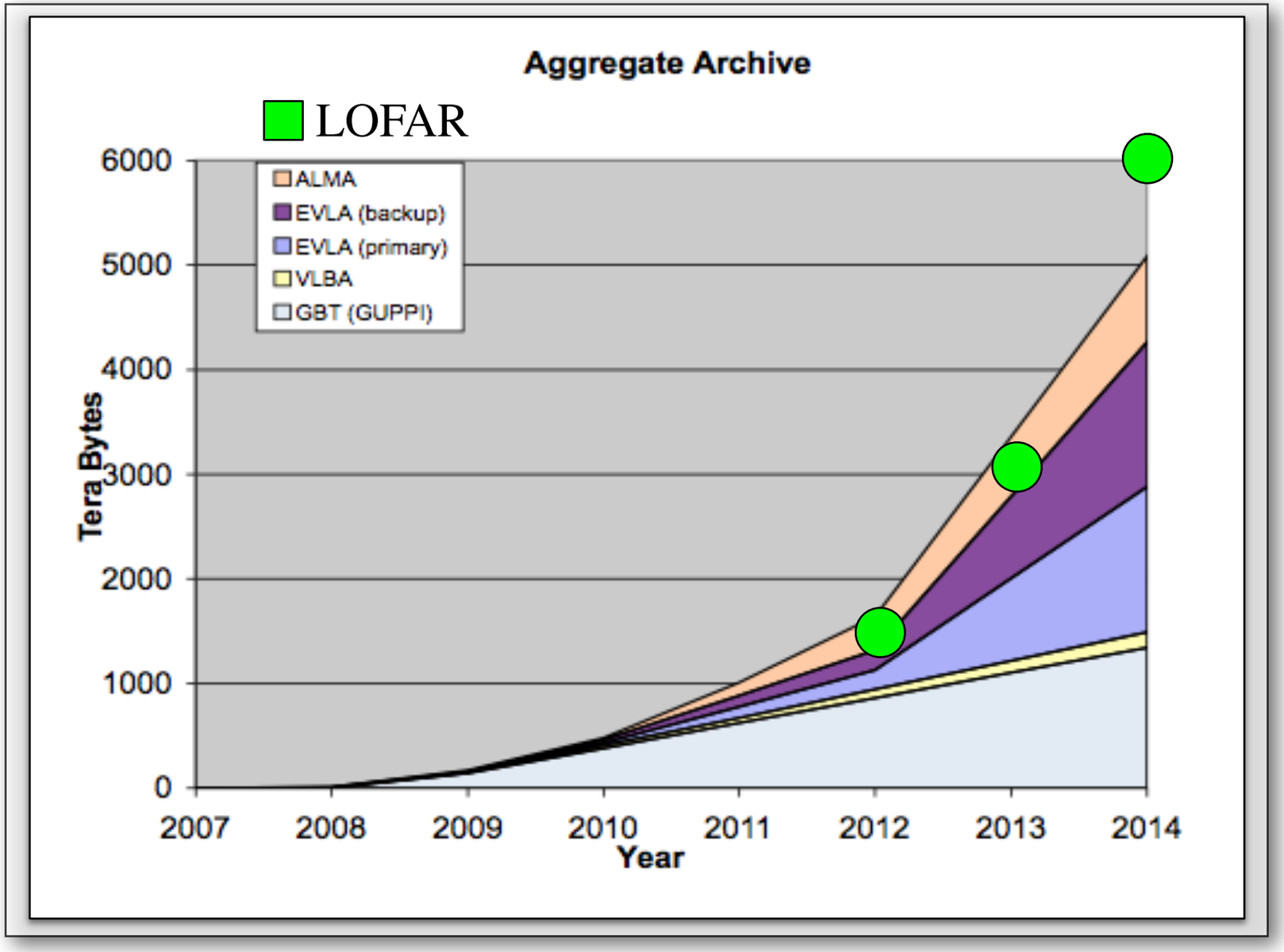


Complex theoretical models are expressed as numerical simulations

…and then must be matched against large collections of observational data

Data Intensive Radio Astronomy

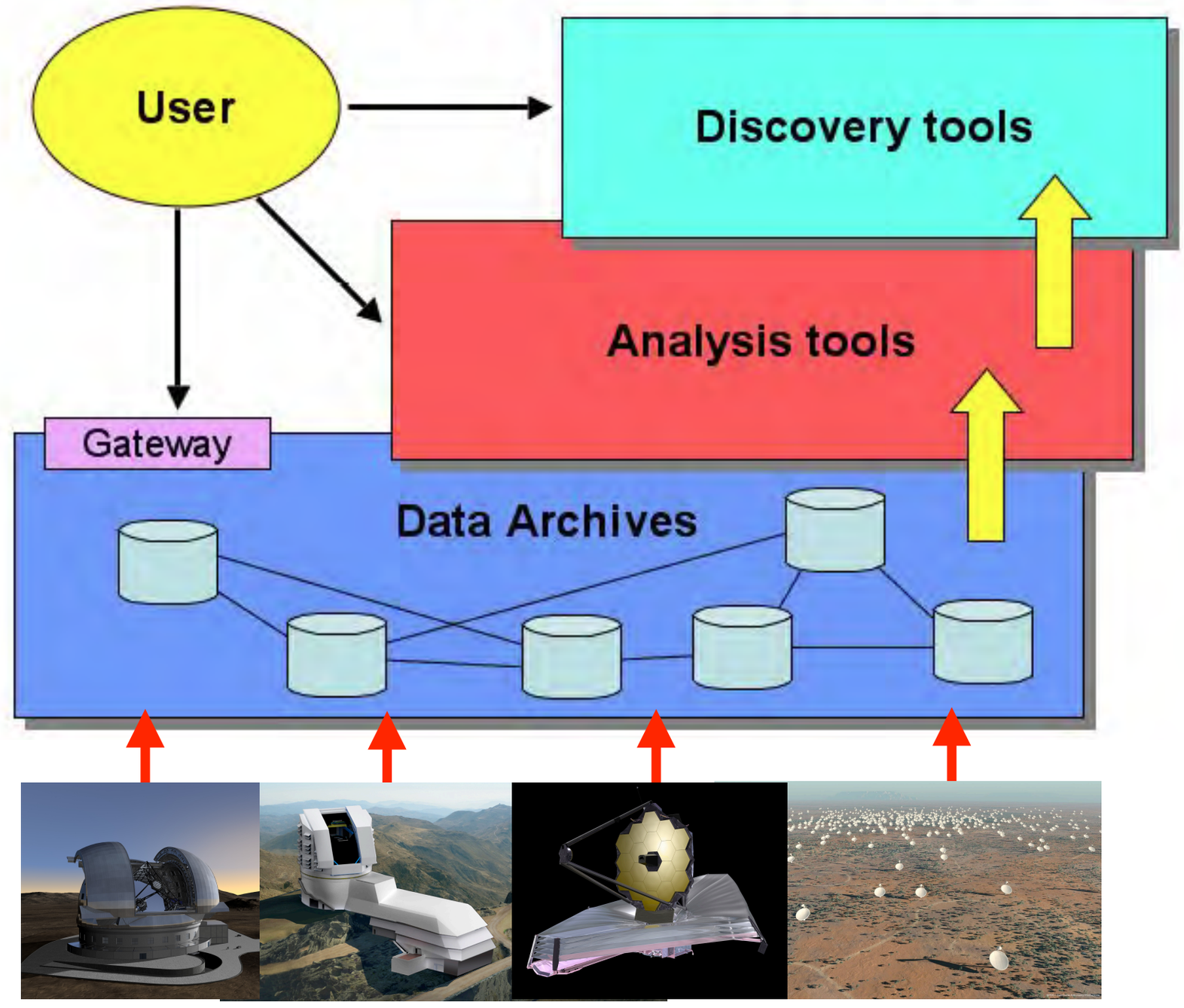
- Radio astronomy is already data intensive
- Current facilities already generating large data streams (*EVLA, ALMA, eMERLIN, LOFAR, etc.*)
- Coming instruments scale by orders of magnitude (*MeerKAT, ASKAP, and SKA*)



Virtual Observatory

- Facilitate science with massive data sets
- Provide access to remote and distributed data sets
- Enable multi-wavelength analysis on large data sets
- Allow easy comparison between simulations and actual data
- Provide discovery and data mining tools to find and explore data
- Provide processing and reprocessing capability

VO Architecture



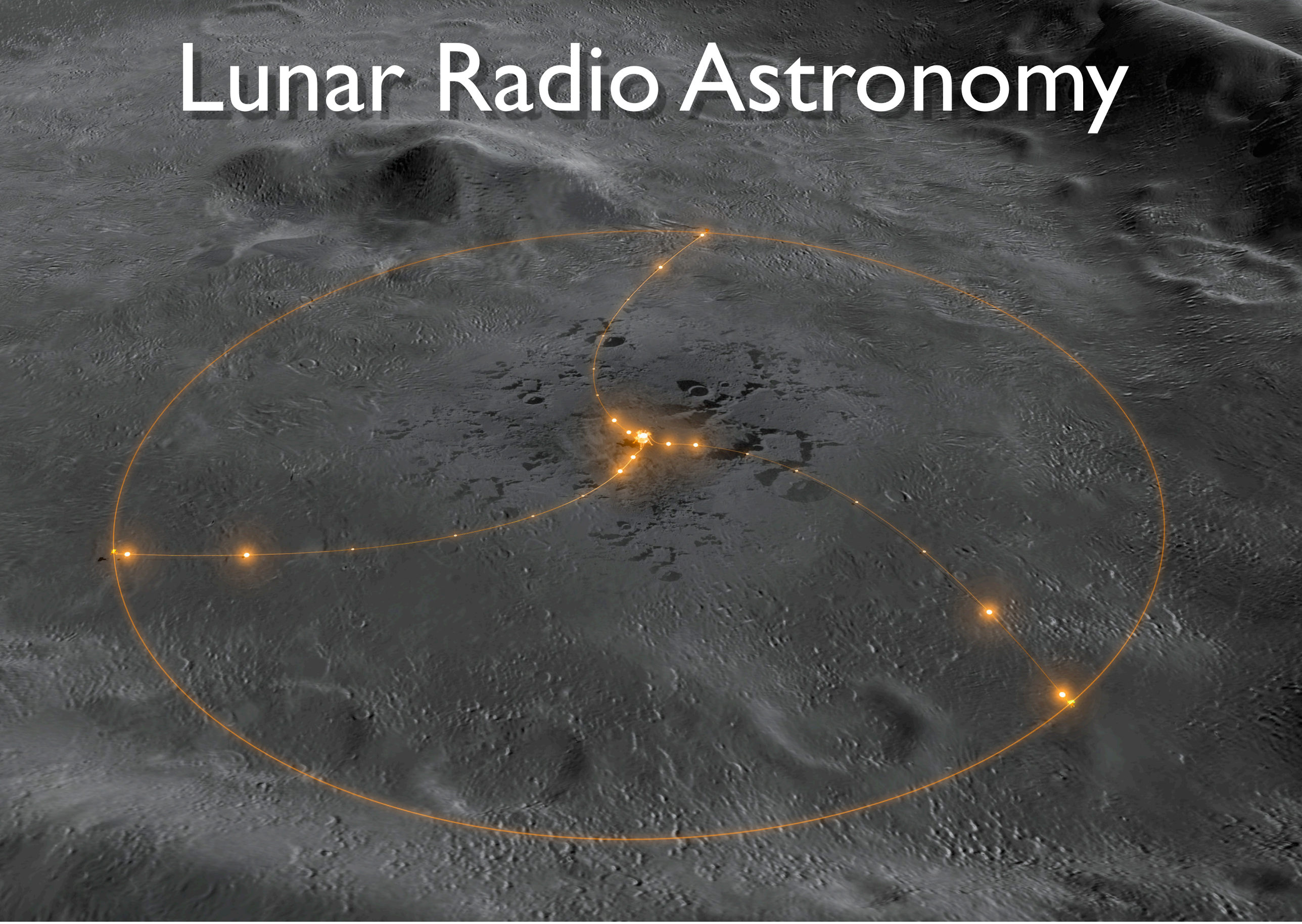
Beyond the SKA

Upgraded SKA

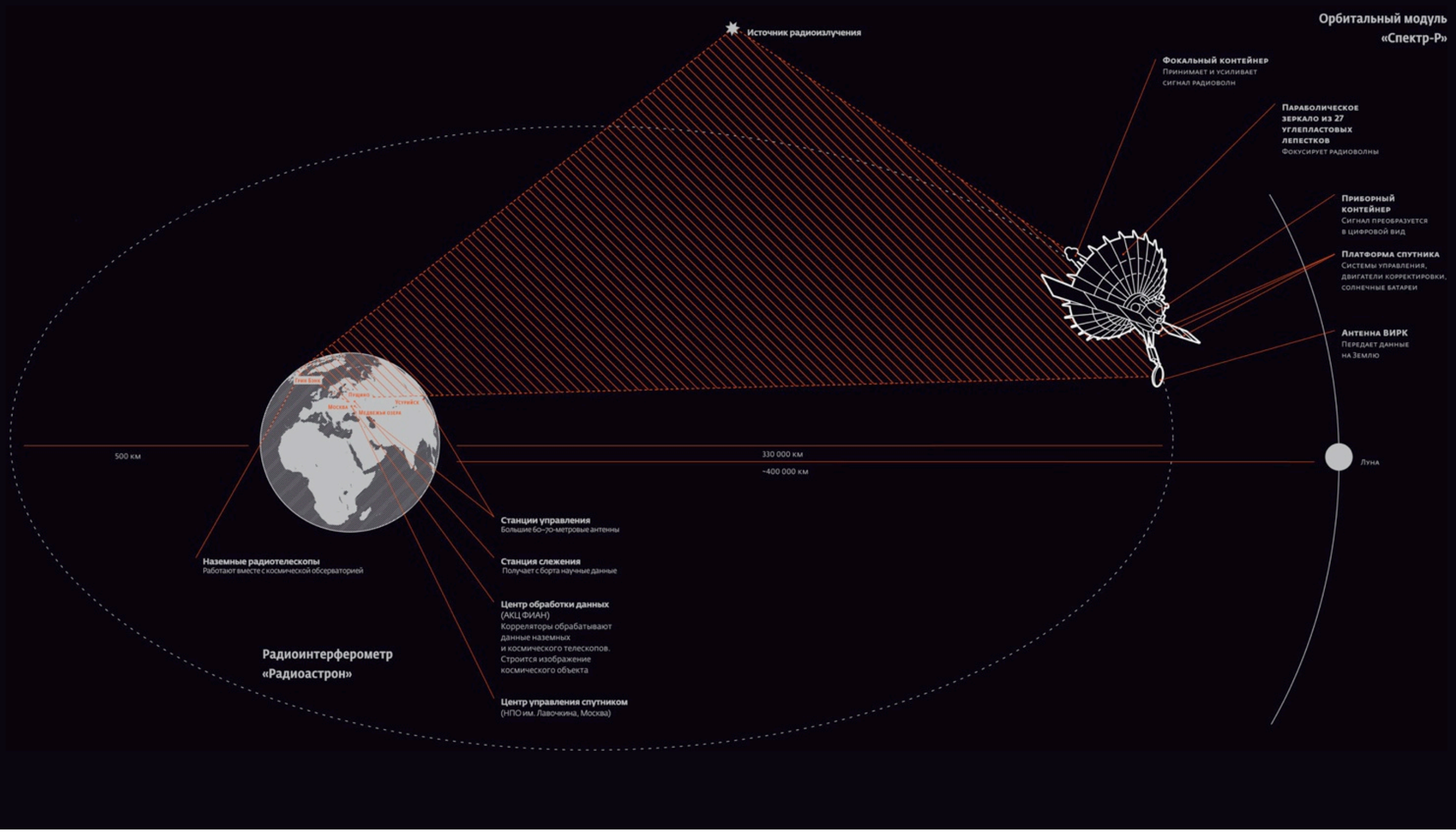
Sensitivity	Add collecting area / bandwidth
RFI	Spectrum management / Removal
Resolution	Size of Earth / Maximum frequency
Computing	Moore's law / Quantum computing

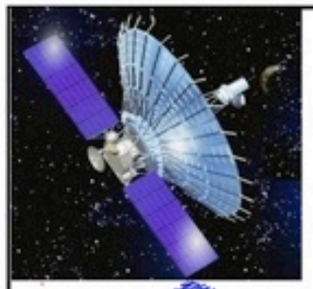
Extension of modern VLBI networks, leverages existing infrastructures

Lunar Radio Astronomy



VLBI from Space





RADIOASTRON - First Light

Cassiopea A - scanning at two frequencies

SRT signal (Volts)

92 cm

18 cm

Radioastron - 260000 km from Earth

27.09.2011

Time hour min


SKA
SQUARE KILOMETRE ARRAY
www.skatelescope.org
The Square Kilometre Array
Swinburne Astronomy Productions

The SKA needs YOU!

Questions?