University of Amsterdam Master Astronomy and Astrophysics - 5214RAAS6Y




Radio Astronomy

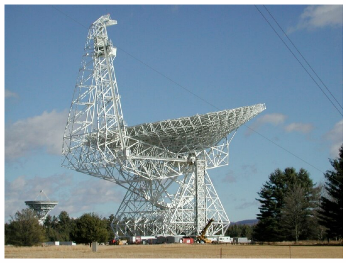
Lecture 11

The Future of Radio Astronomy

Lecturer: Michael Wise (wise@astron.nl)

May 29th, 2017



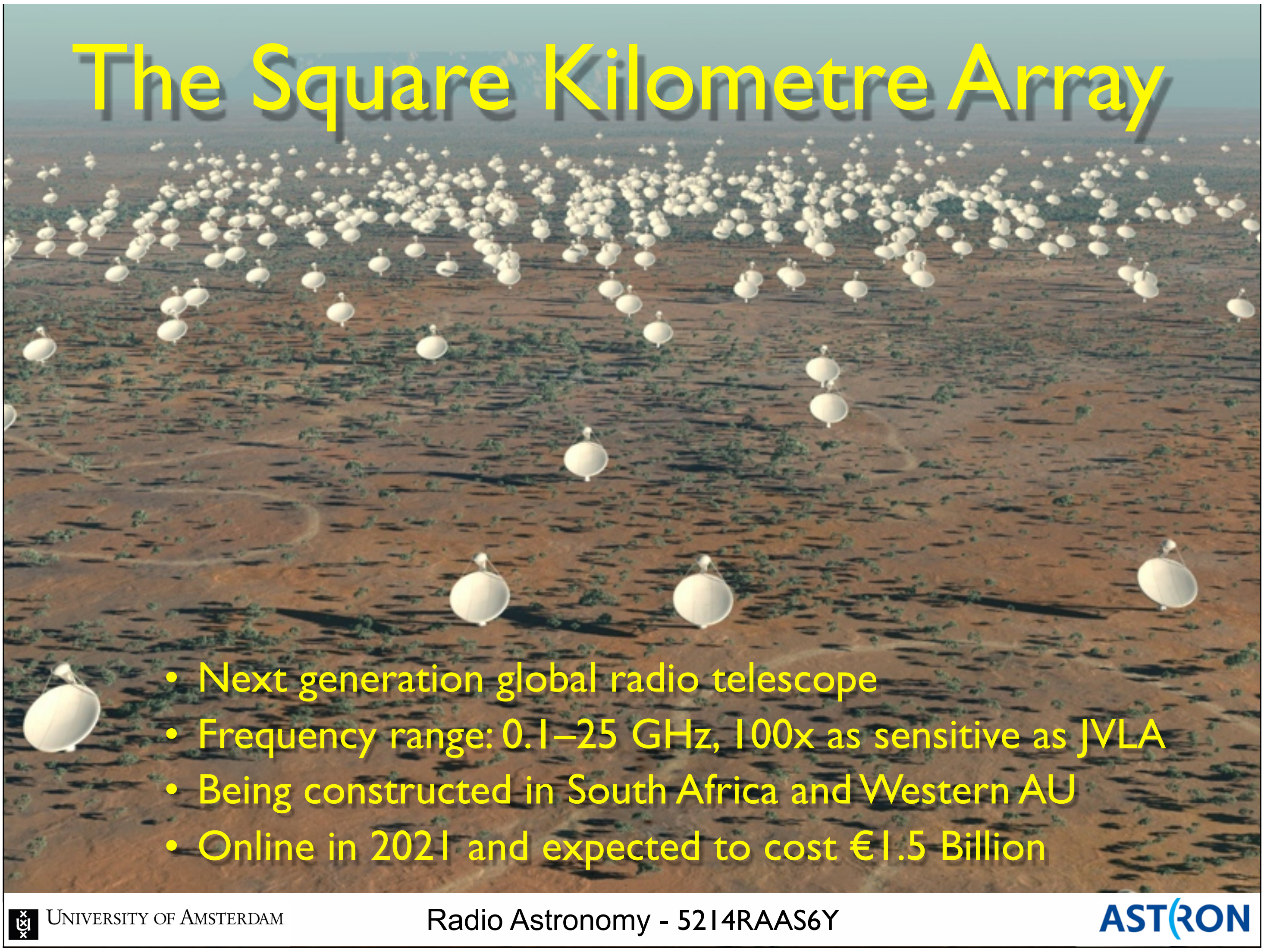



This lecture we will discuss the future of radio astronomy, both opportunities and challenges.
We'll talk about a wide range of new instruments that are being constructed but also the changes these new telescopes will require to the way we do radio astronomy.
We'll finish up with a look further ahead to some more speculative directions the field may take.

Outline

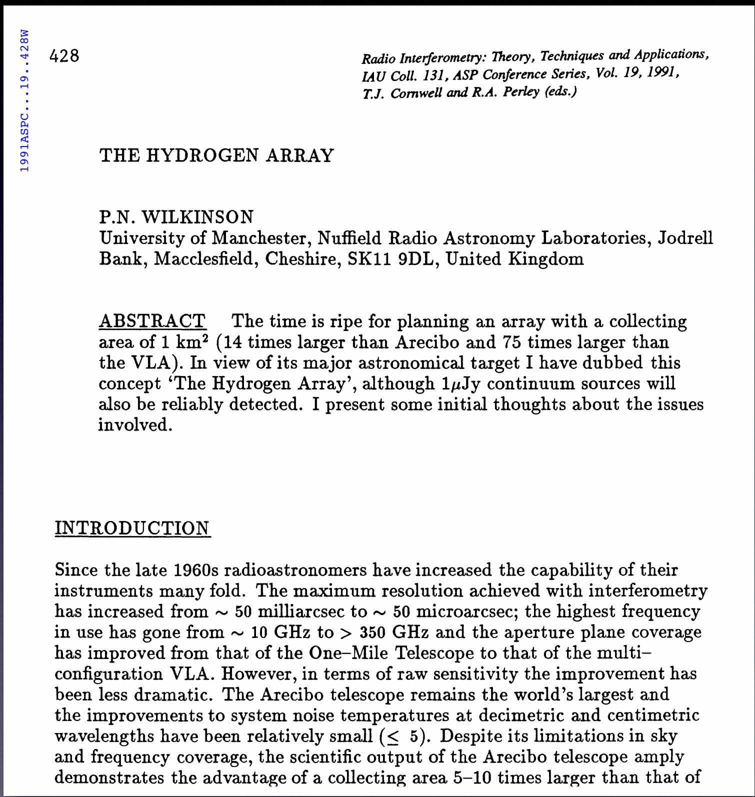
- The Square Kilometre Array (SKA)
- SKA Pathfinders
- SKA Computational Challenges
- Data Intensive Astronomy
- Beyond the SKA

The Square Kilometre Array



The SKA is project that is already underway. It is a truly global project involving countries from all around the world including Europe. It will be the most powerful radio telescope on the plant in the coming decade.
The Netherlands is a major leader in the international consortium to design and build the SKA.
Current facilities have reached the point at which single nations can still fund them.
To make a big enough step forward in scientific capability, we must cooperate globally.

“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

P.N. WILKINSON
University of Manchester, Nuffield Radio Astronomy Laboratories, Jodrell Bank, Macclesfield, Cheshire, SK11 9DL, United Kingdom

ABSTRACT The time is ripe for planning an array with a collecting area of 1 km^2 (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.

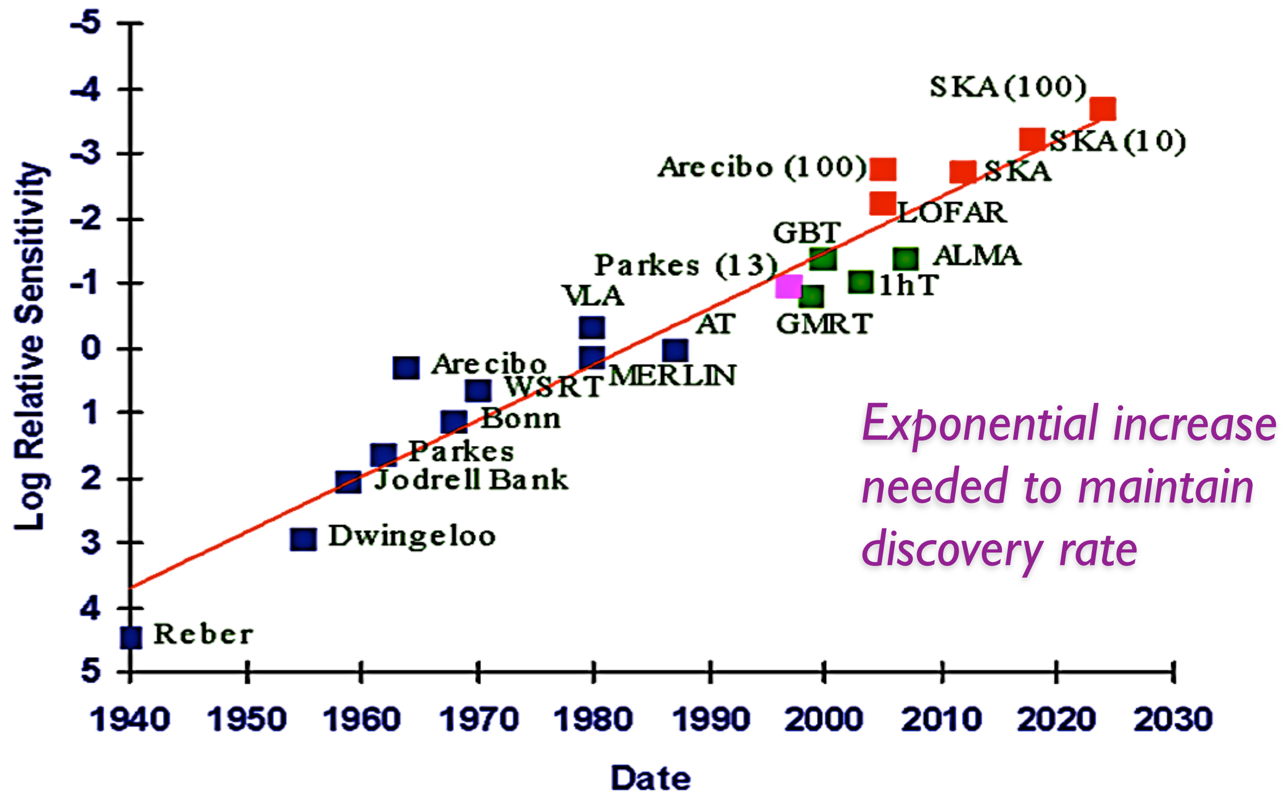
INTRODUCTION

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 ($\lesssim$ 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

The SKA has originally conceived as a way to search for highly redshifted HI.
The name comes from the collecting area necessary to detect HI in a normal galaxy at a redshift of 2.
The science case now includes almost every topic in radio astronomy, but there are a set of priorities.

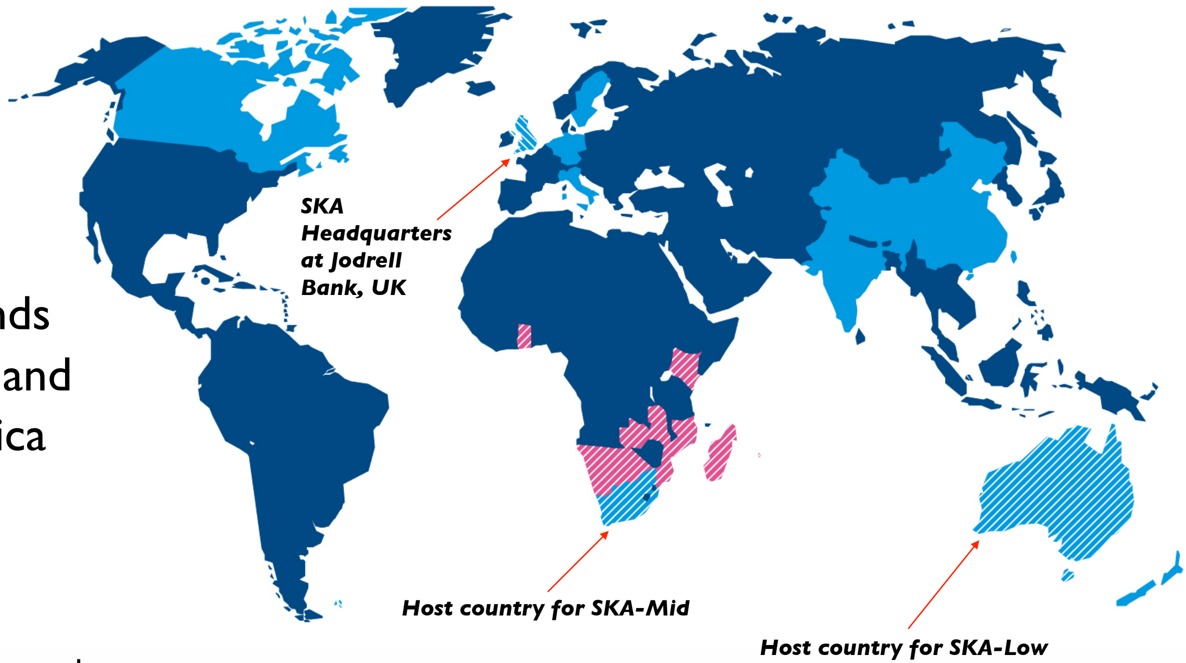
Radio Telescope Sensitivity



The plot show rate at which the sensitivity of radio telescopes has been increasing over time.
If we want to keep making new discoveries, we have to keep climbing this curve.
Since 2000, the new more sensitive telescopes have been international collaborations
Some of the increase is due to size, but in many cases in new technology and computational techniques.
We will need steady improvements in all three aspects if we want stay on this curve.

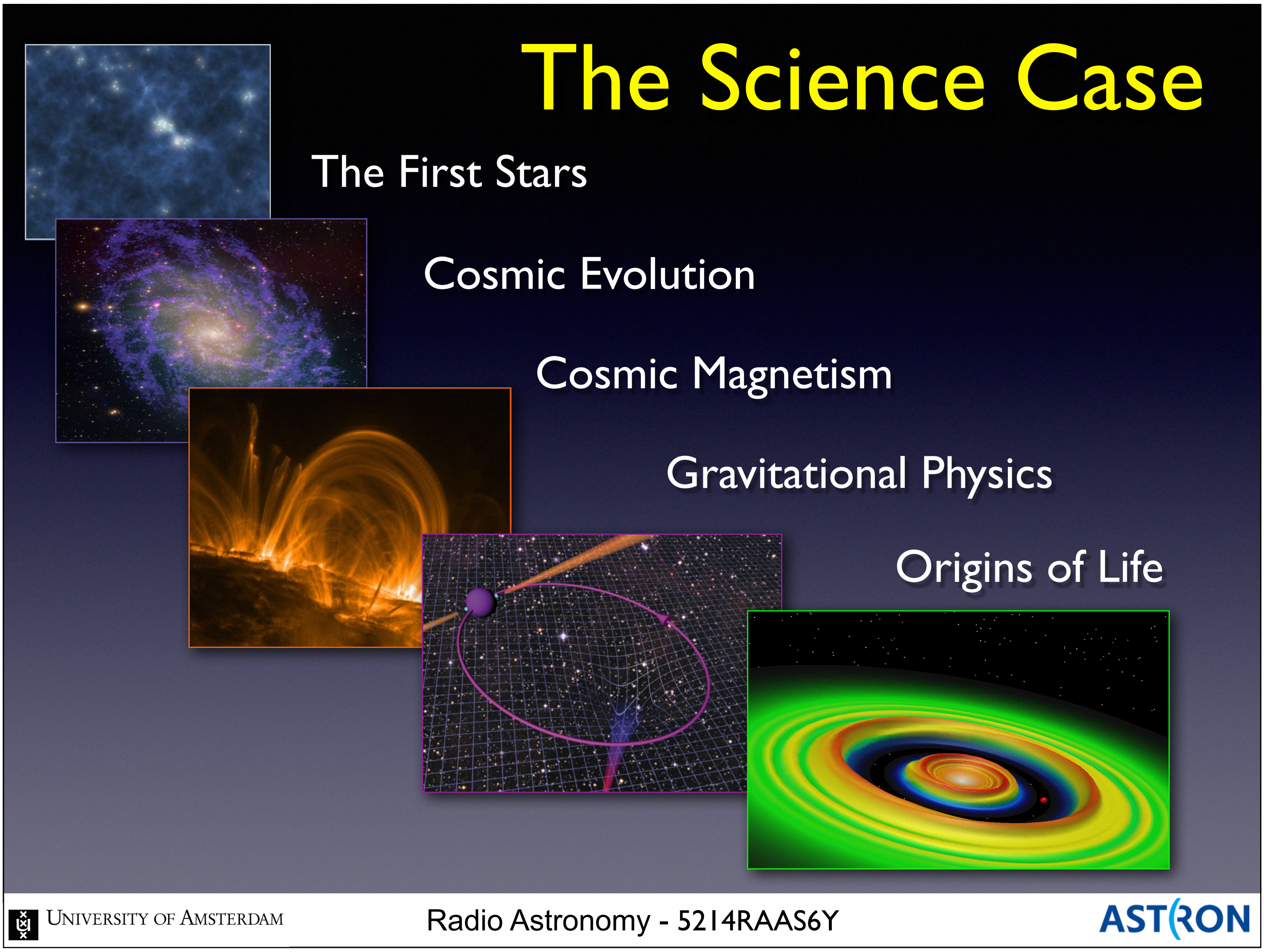
The Square Kilometre Array

- Australia
- Canada
- China
- India
- Italy
- Netherlands
- New Zealand
- South Africa
- Sweden
- UK



Potential new members:
Spain, Portugal, Germany,
France, others…

The science case for the SKA is very broad. Anything you can do with a radio telescope, someone will do with the SKA.
As we have learned, we often must tailor our telescope to the science we want to do.
Put another way, the science we want to do defines what our telescope should look like.
The SKA will good for many types of science, but it is been optimized for a few.



The science case for the SKA is organized around five central themes.
Cosmology and the epoch of reionization, early in the evolution of the universe when the first stars formed.
The growth of cosmic structure including the formation and evolution of galaxies and black holes.
Tests of fundamental physics including how magnetic fields are formed and detection of gravity waves.
The study of exoplanets and planet formation and searches for biomarkers.

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

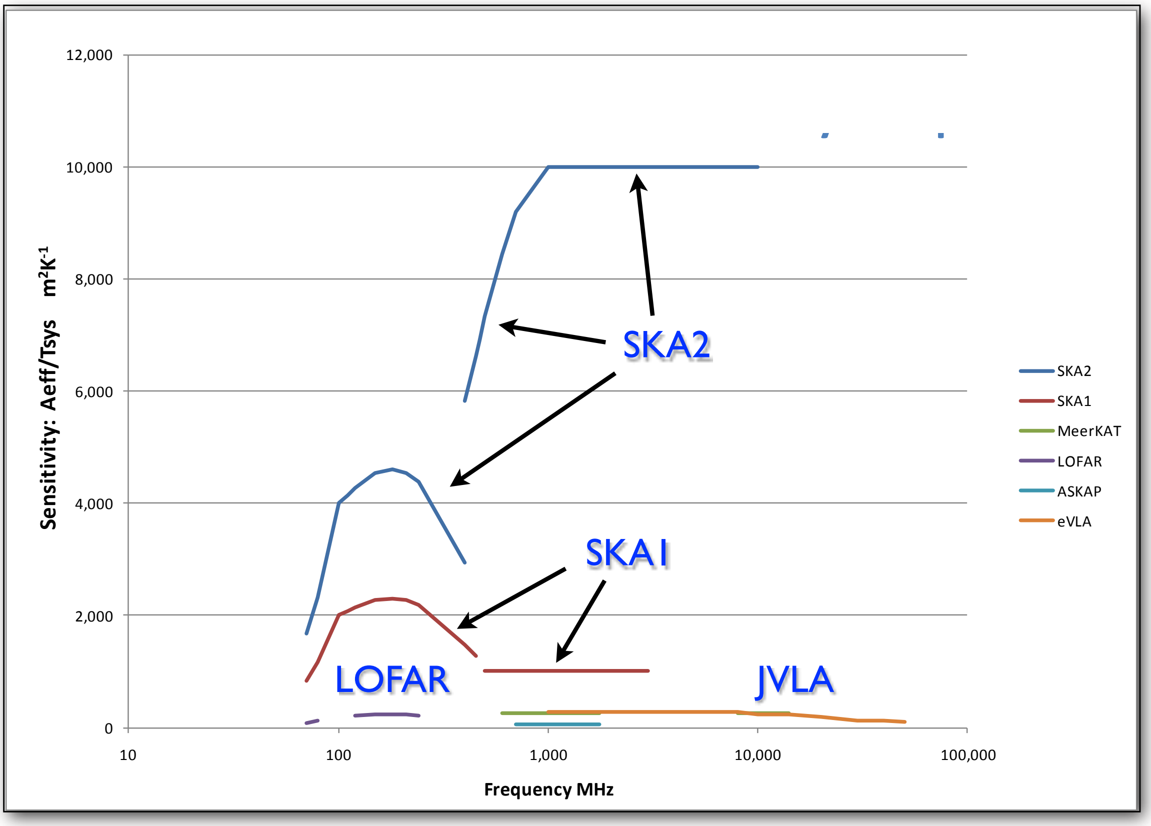
- Imaging Field Of View: 1° @ 1.4 GHz
- Angular Resolution: 0.1" @ 1.4 GHz
- Image Dynamic Range: 10^6 @ 1.4 GHz

- 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)

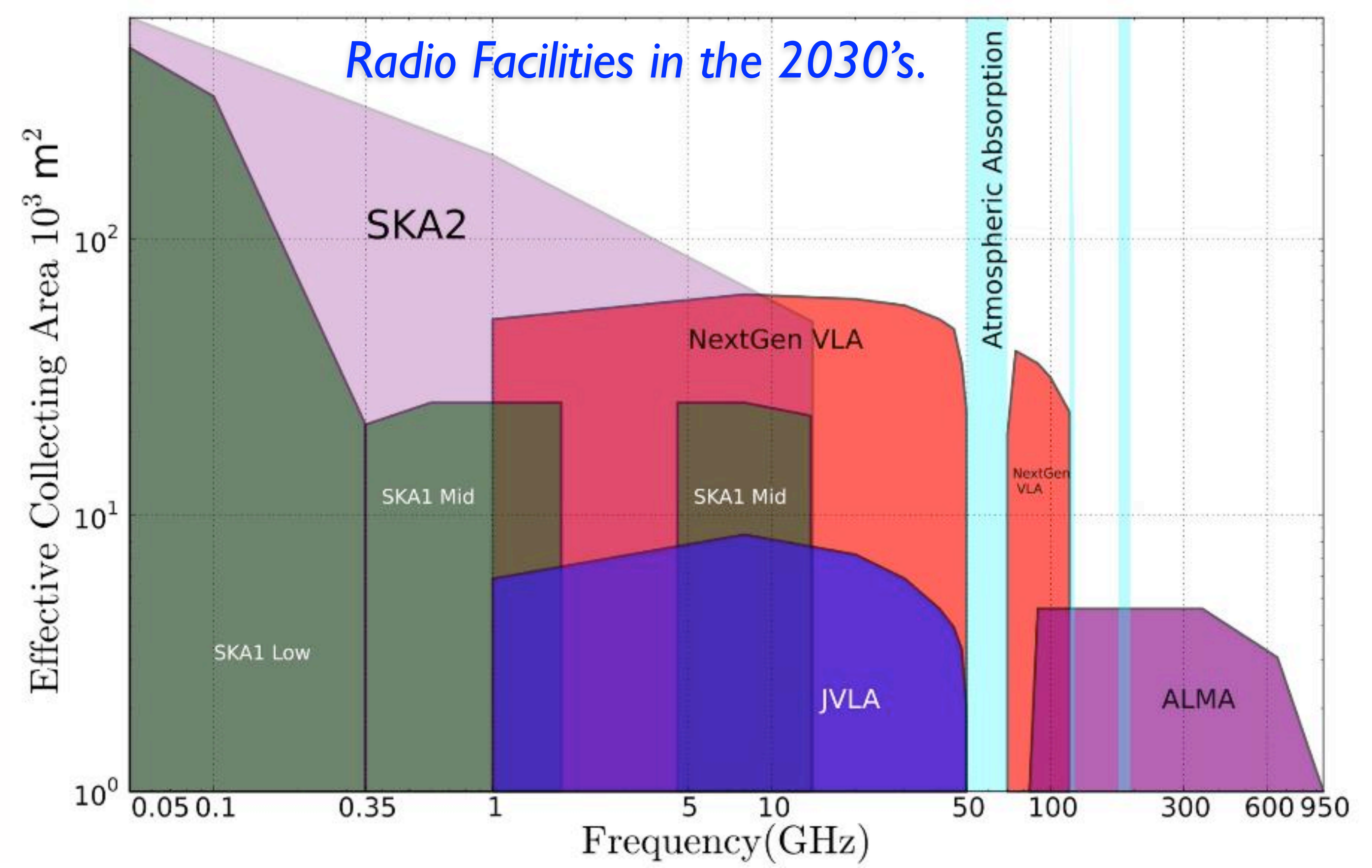
The SKA will cover a wide range in frequencies. To do so, it will actually consist of several distinct telescopes.
It will be built in two stages. SKA1 will consist of roughly 10% of the fully envisioned SKA.
Construction is expected to begin in 2017 with science operations starting before the end of the decade.

Sensitivity Comparison

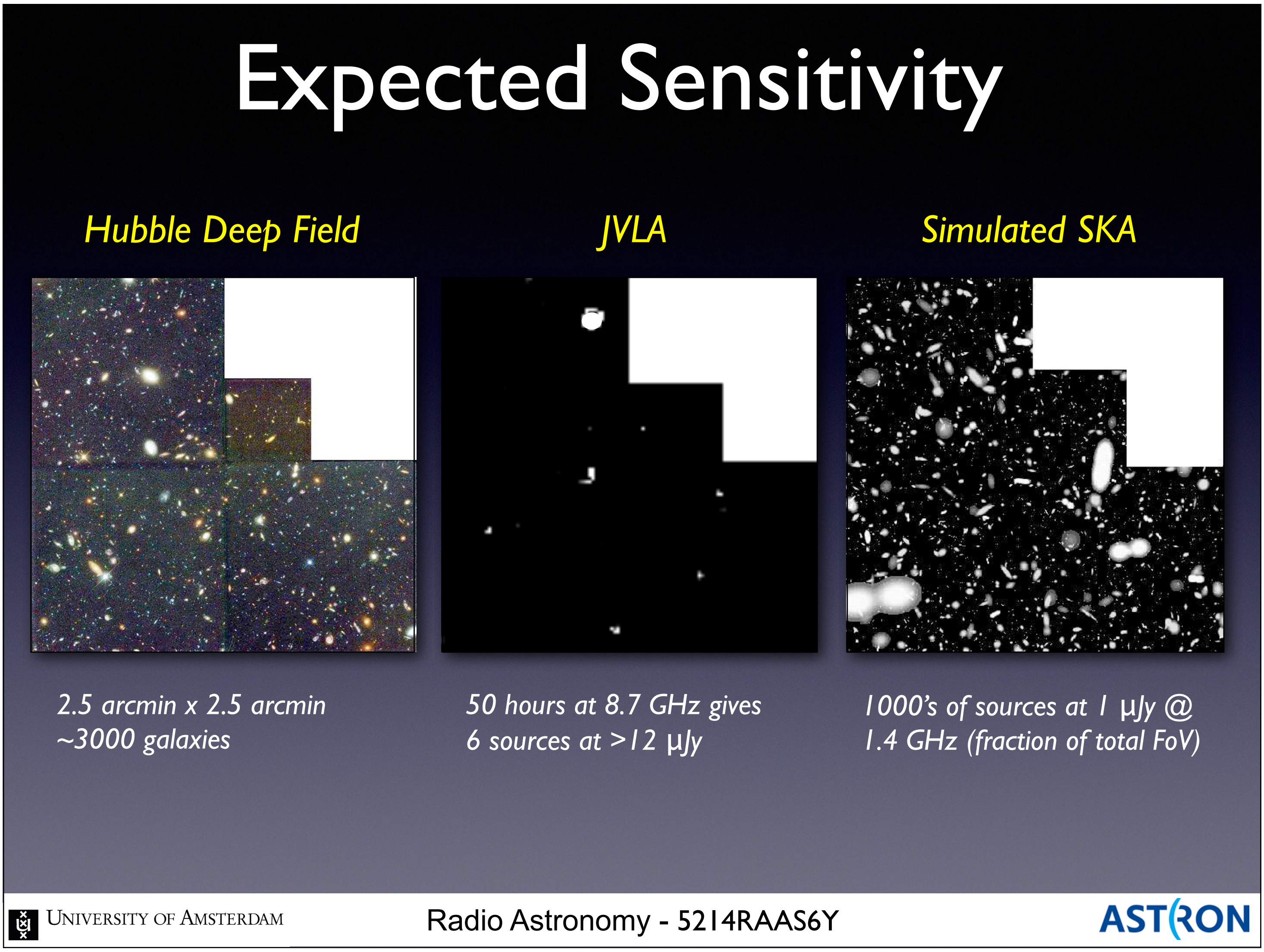


Comparison of the expected sensitivity for the SKA1 and SKA2 with JVLA and LOFAR.
The SKA will be orders of magnitude more sensitive than existing telescopes!

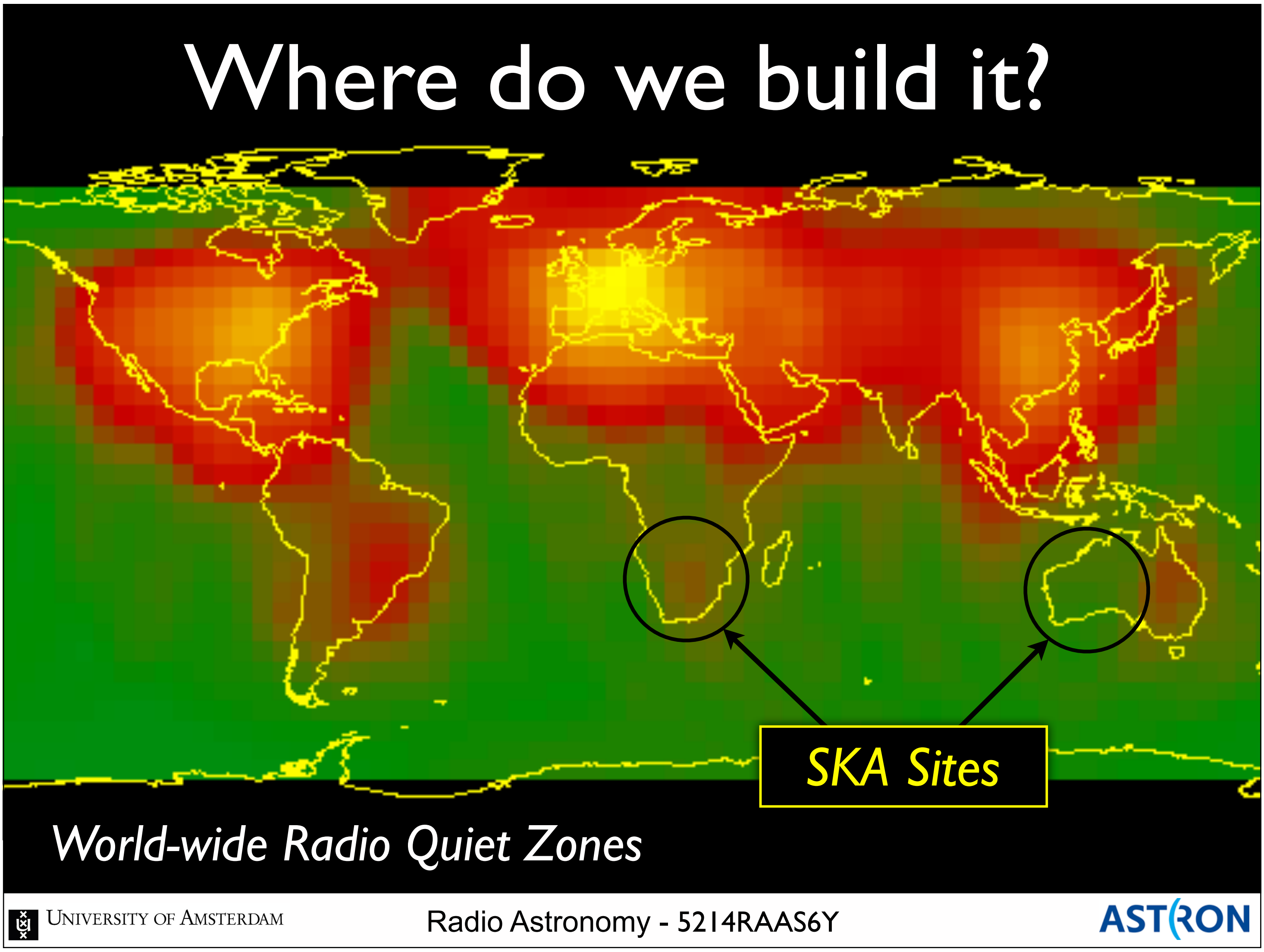
Sensitivity Comparison



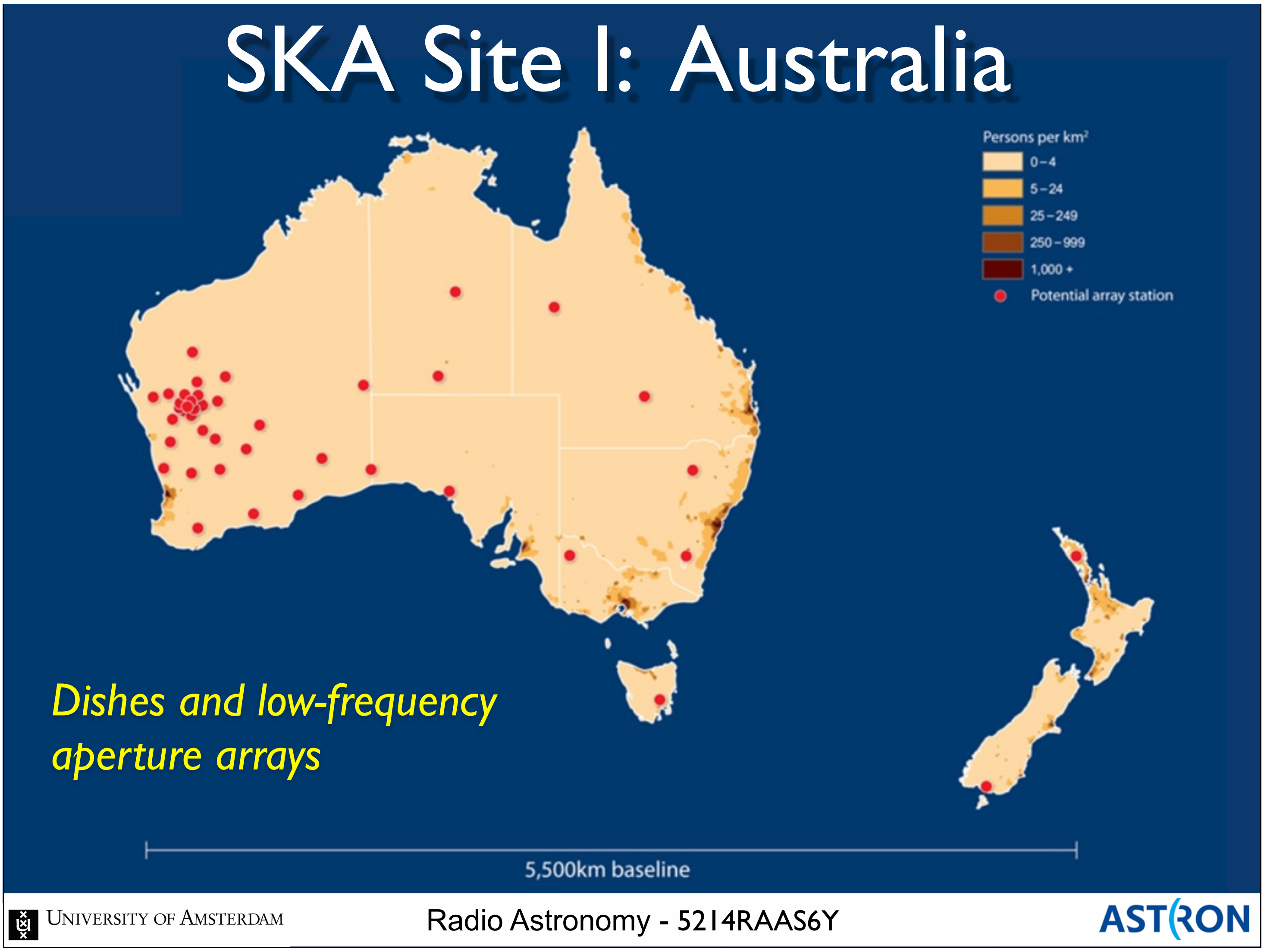
Radio Facilities in the 2030's.
Comparison of the expected sensitivity for the SKA1 and SKA2 with NGVLA and ALMA.



A comparison showing the difference in the number of galaxies seen by the VLA and the SKA.
A similar exposure with the SKA will yield 1000's of times more galaxies then current telescopes.
It will also have much bigger fields of view than the HST image shown and the VLA.



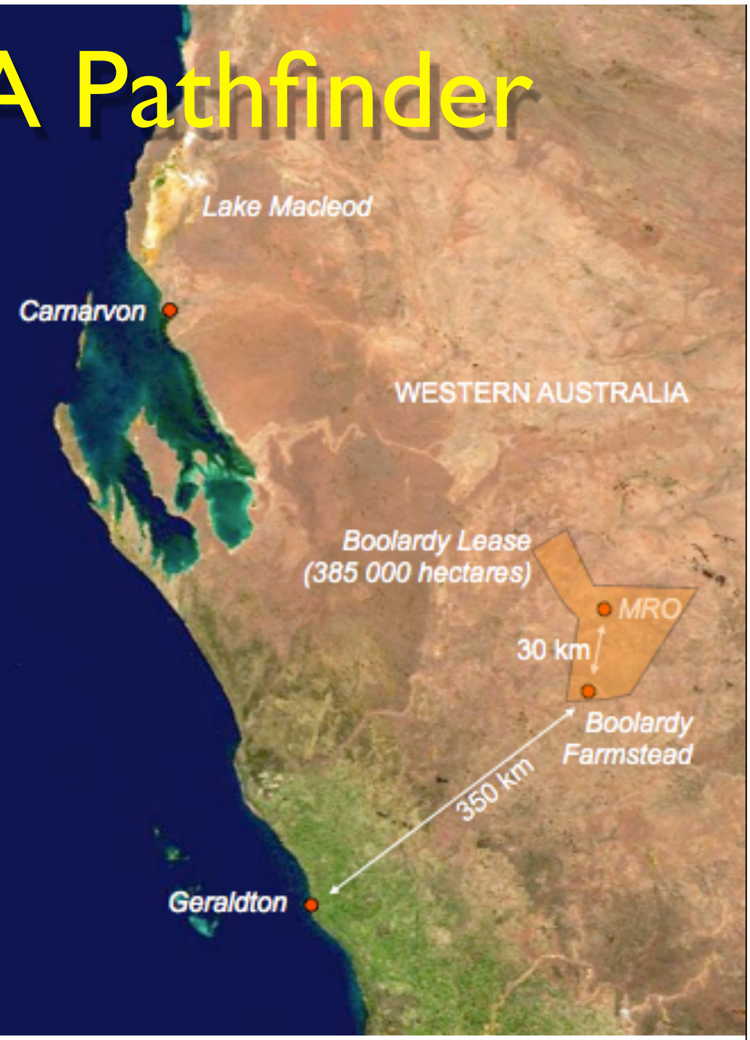
This image shows a map of the intensity of RFI around the world. Yellow areas have the strongest RFI.
Note the blazing yellow over the Netherlands…ouch.
The deserts of South Africa and Western Australia however are the most radio quiet areas on earth.



The desert in western Australia will host the low-frequency part of the SKA.
Originally it would have hosted a large array of dishes as well, but the design has changed recently to save money.
The population density in this region is less than 4 people/km^2 or 0.4 nanohumans/cm^2.

Australian SKA Pathfinder (ASKAP)

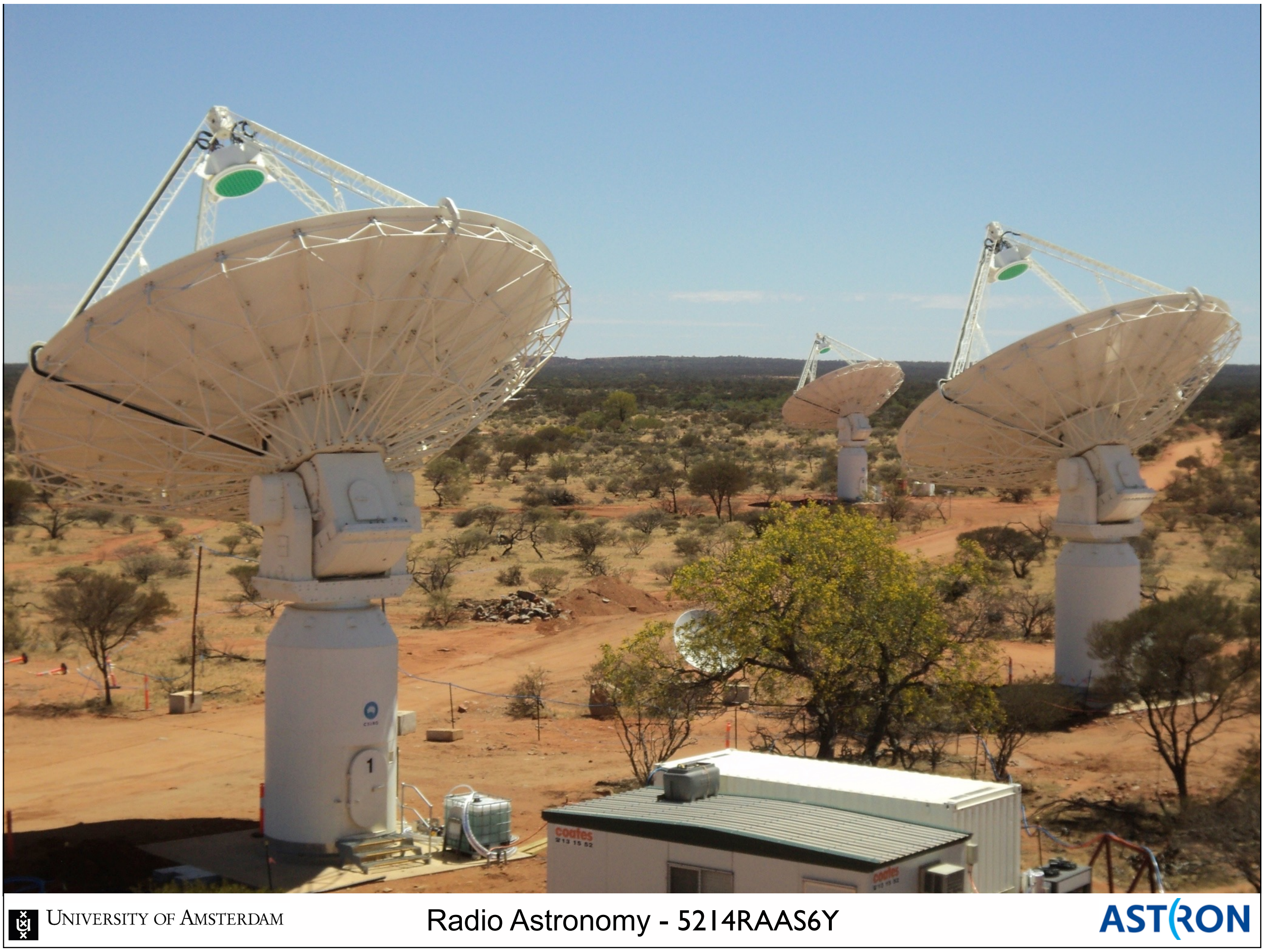
- Shire of Murchison
- 50,000 km^2
- 0 incorporated towns
- 29 sheep/cattle stations
- Population: 110



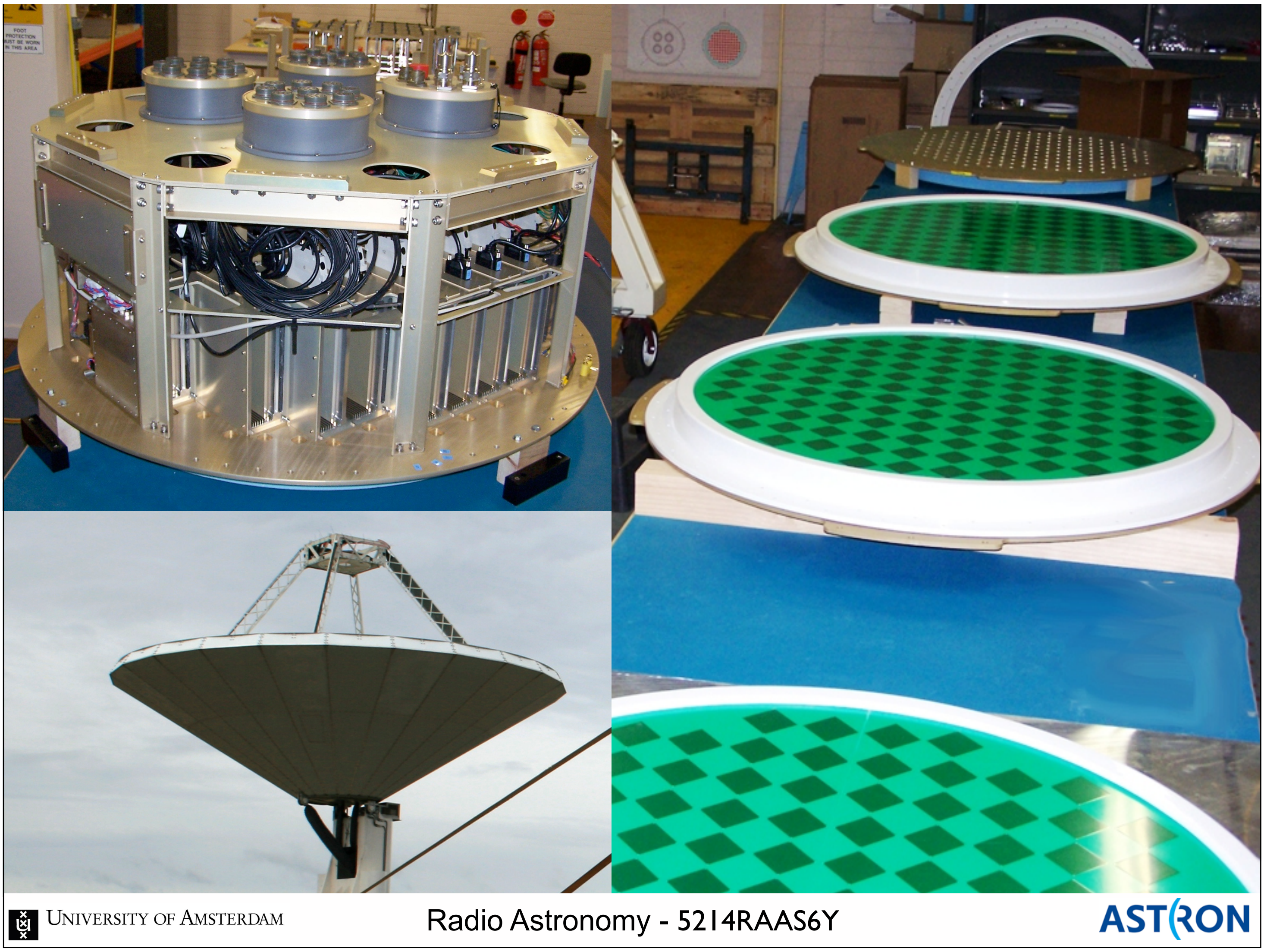
University of Amsterdam Radio Astronomy - 5214RAAS6Y ASTRON

The low population density is great for RFI, it also makes every other aspect of building and running an observatory much more difficult.
No roads, water, or power, and many hours from any civilization.
Constructing and maintaining the site infrastructure will be a big part of the cost of the SKA.

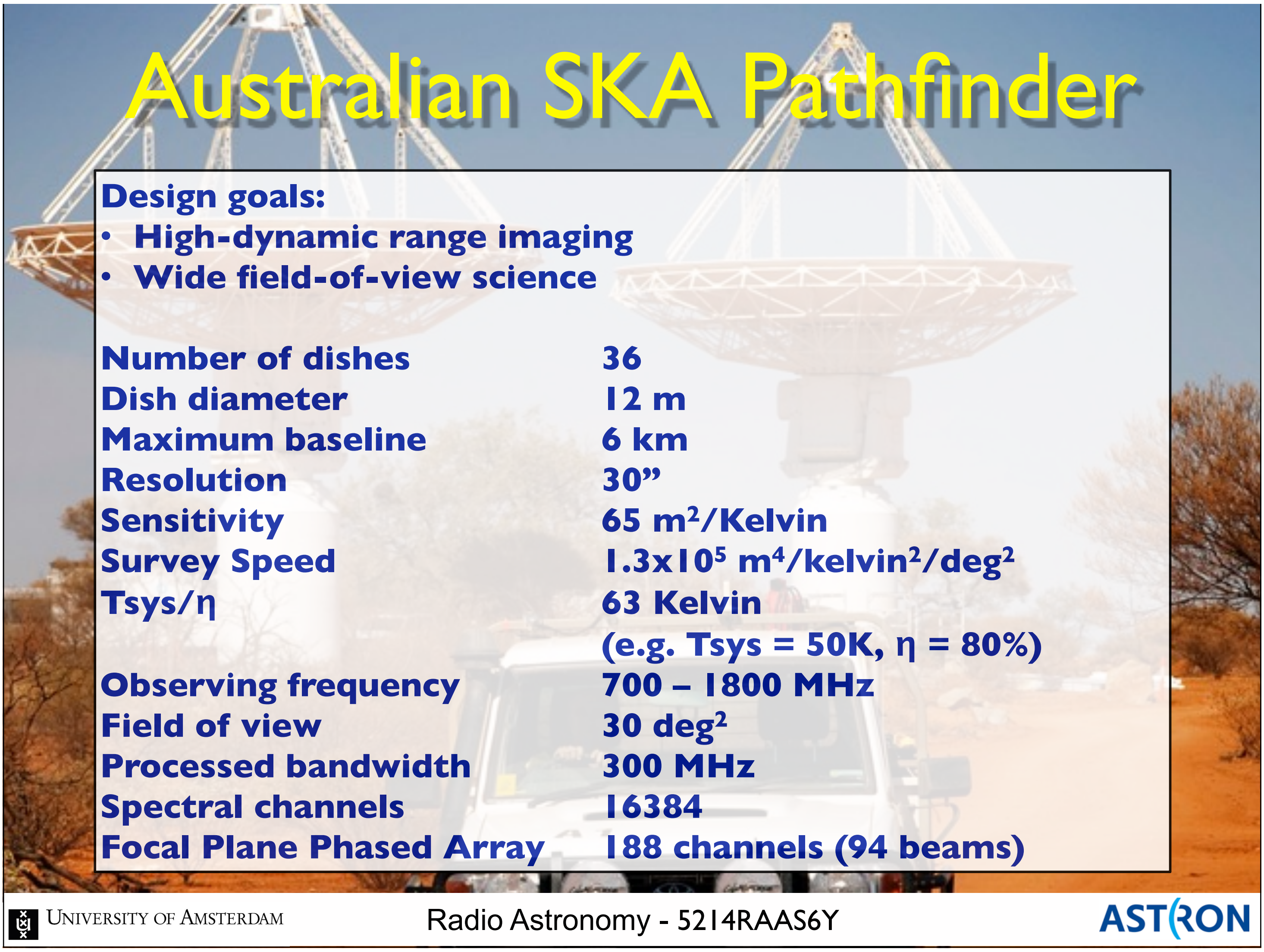
A fairly recent image of the Australian site.
The dishes you see are part of the Australian SKA Pathfinder (ASKAP) array.



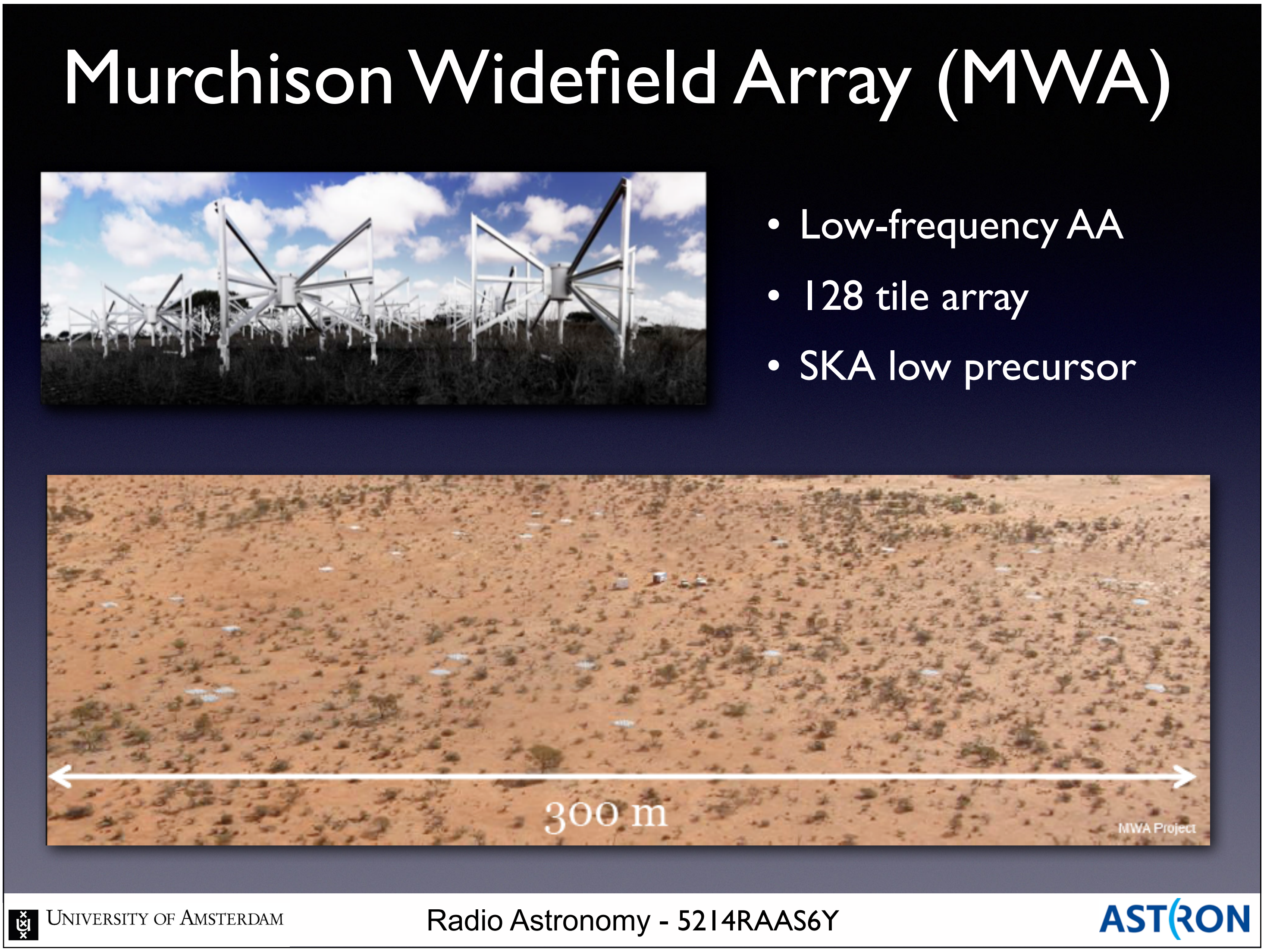
Close-up image of the ASKAP dishes. Notice the green circles in the focus.
These are phased-array feeds (PAFs) similar to the APERTIF units being installed on WSRT.
Like APERTIF, these PAFs will make ASKAP a powerful survey telescope especially for HI surveys.



Close-up image of the ASKAP PAFs.

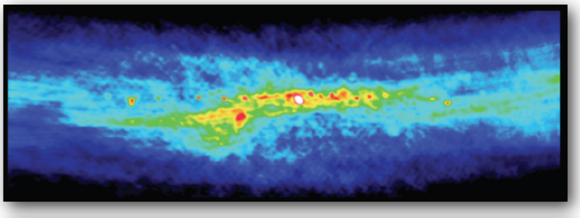


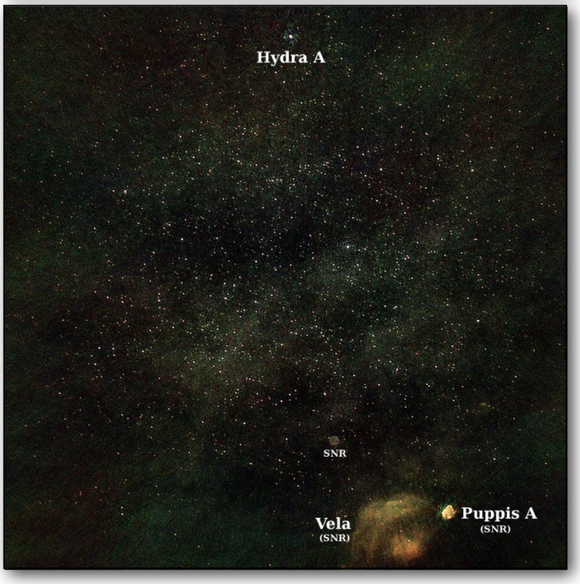
System characteristics for the ASKAP array. Notice the relatively short baseline length. ASKAP will do relatively deep HI surveys, but at relatively modest resolution.



In addition to the ASKAP mid-frequency SKA pathfinder telescope, there is a low-frequency pathfinder being developed in Australia as well.
The MWA is similar to the technology used in LOFAR and covers a similar peace of the low-frequency spectrum.
It lacks the longer baselines and does not go quite as low in frequency.
The combination of LOFAR and MWA will give us a relatively deep survey of the entire sky.

Murchison Widefield Array (MWA)

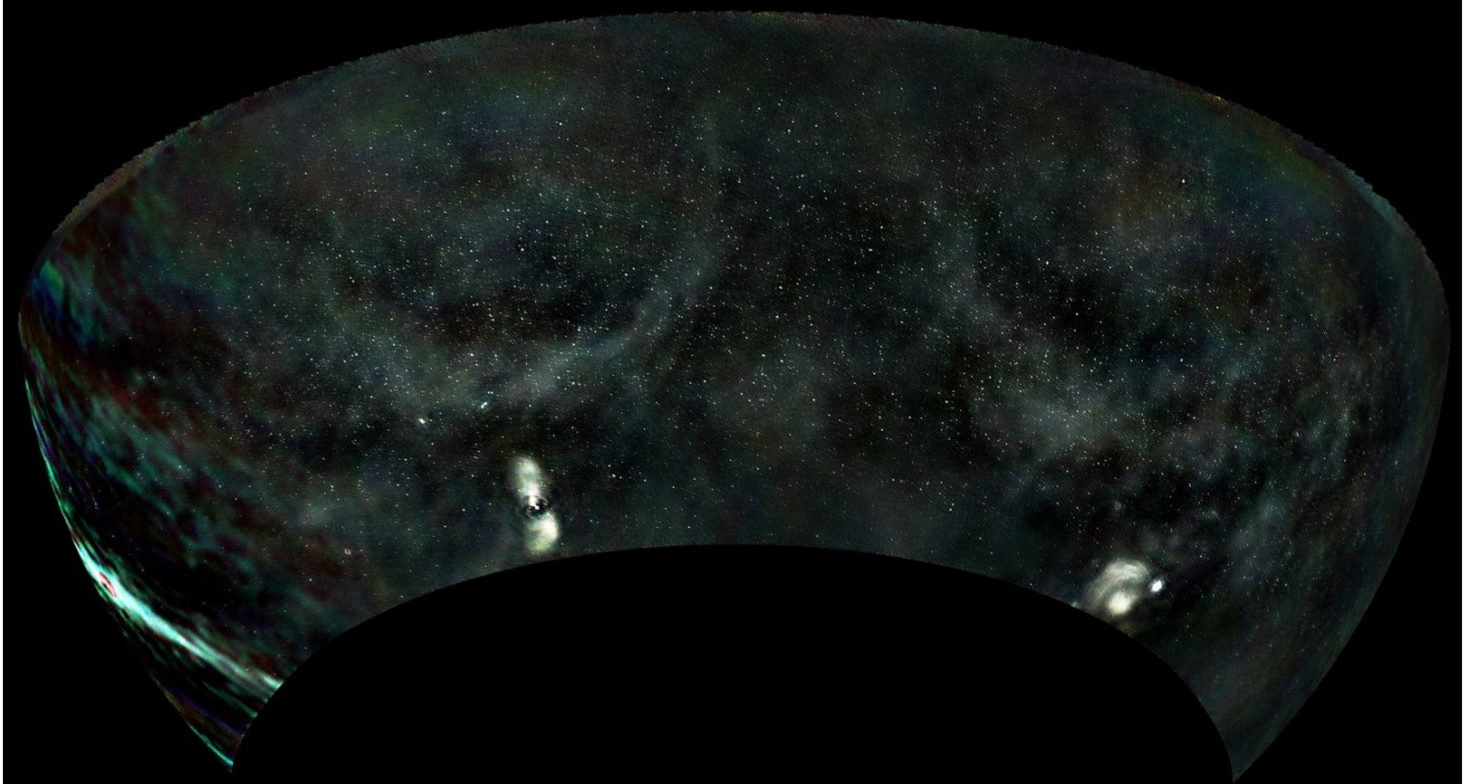




Parameter	Value
Frequency range	80 – 300 MHz
Number of receptors	2,048 dual-pol. dipoles
Number of "tiles"	128 (expandable to 256)
Number of baselines	8,128
Collecting area	~2500 m^2 @ 200 MHz
T_{sys}	25 K (Rx); 125 K (sky) @ 200 MHz
Field of view (diameter)	~40° @ 200 MHz
Configuration	Core: 1.5 km 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

System characteristics for the MWA.
Notice that it does not go as low in frequency as LOFAR and the much baselines.
MWA was originally intended as a specialized EoR experiment.
The short baselines and good instantaneous uv coverage are well suited for EoR observations.

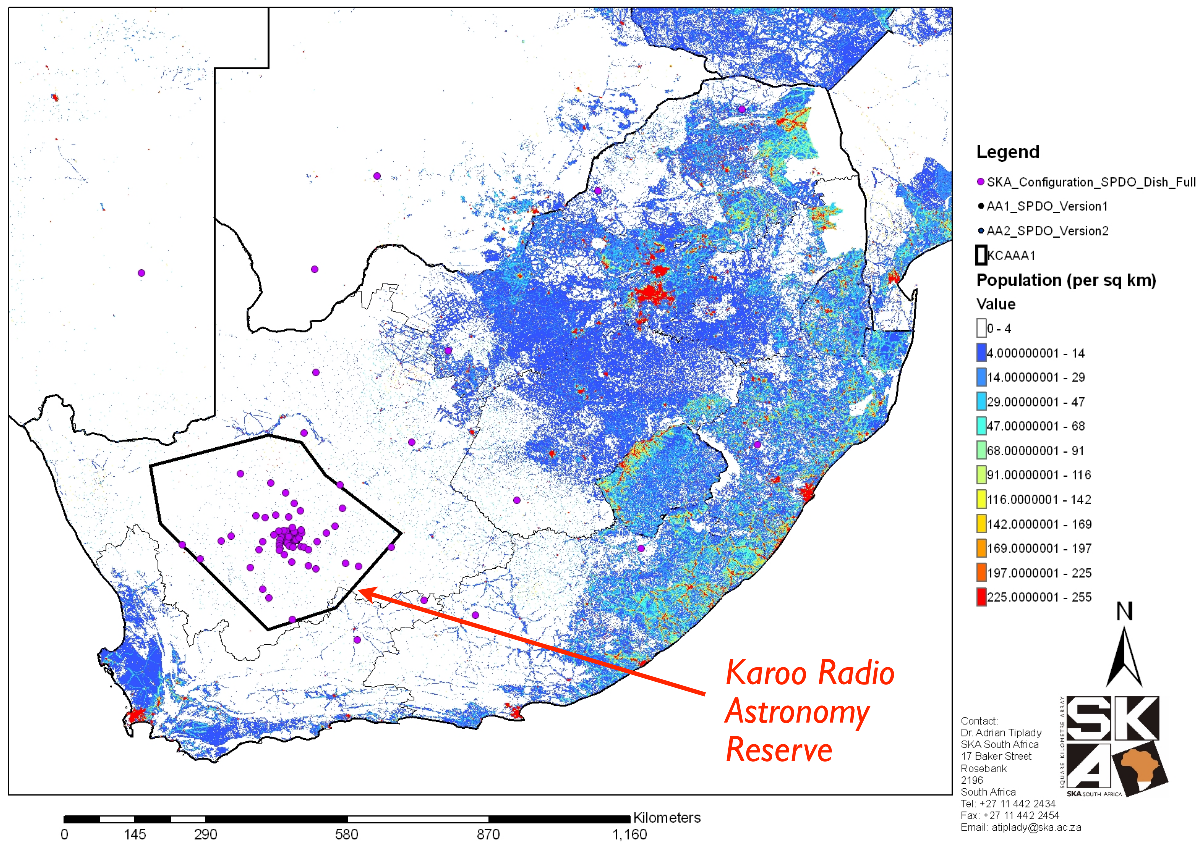
Murchison Widefield Array (MWA)



Example of the an all-sky map of the southern sky from MWA.

The second, higher frequency component of the SKA will be based in South Africa.

SKA Site 2: South Africa



The desert in South Africa has similar advantageous properties to Western Australia.
Very low population density and the very low RFI that goes with it.
This remote site has all the same logistical difficulties as well.

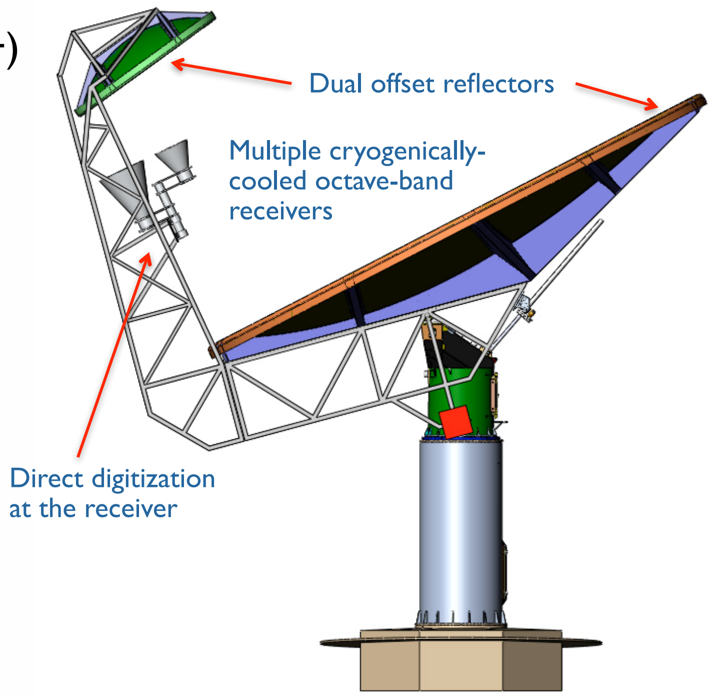
A fairly recent image of the South Africa desert.

A fairly recent image of the South Africa site.
The dishes you see are part of the South African SKA Pathfinder MeerKAT array.

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

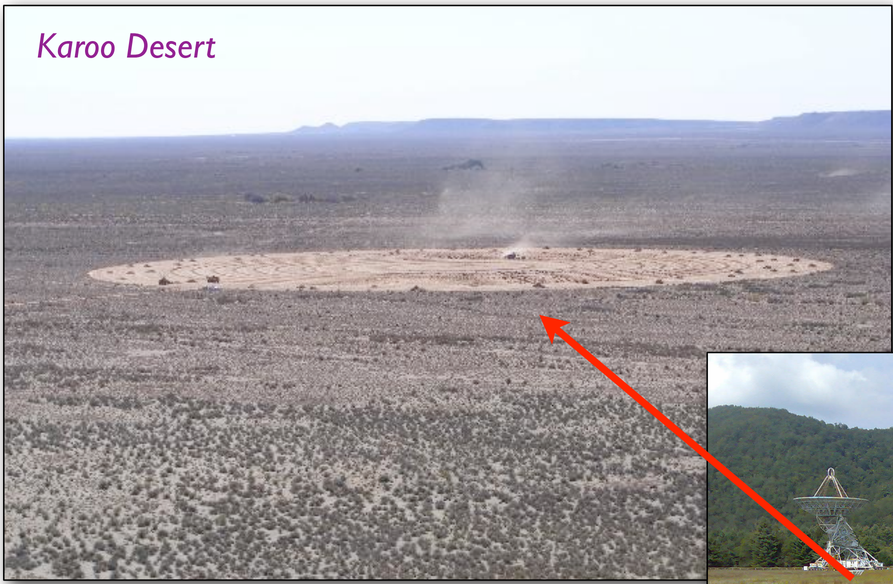
SKA Baseline Design



System characteristics for the MeerKAT array. Like ASKAP, notice the relatively short baseline length. MeerKAT will do relatively deep HI surveys, but at relatively modest resolution.

Computer rendered image of the anticipated SKA dish design.

PAPER (Precision Array to Probe Epoch of Reionization)



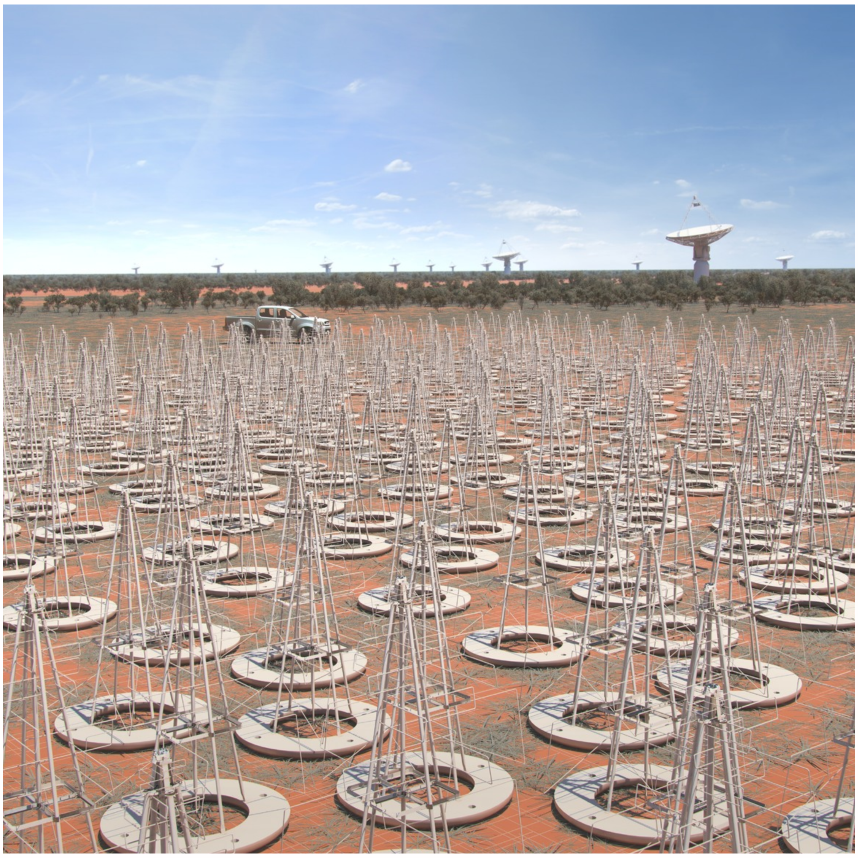
- Low-frequency AA
- 64 tile array
- EoR experiment

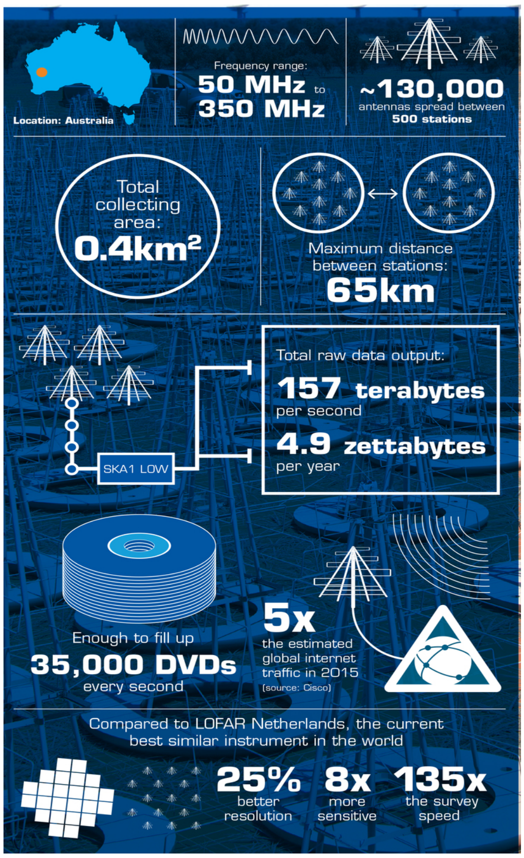
There is also a low-frequency phased array prototype at the SA SKA site.
PAPER is a specially designed experiment to search for the EoR signal.

Computational Challenges

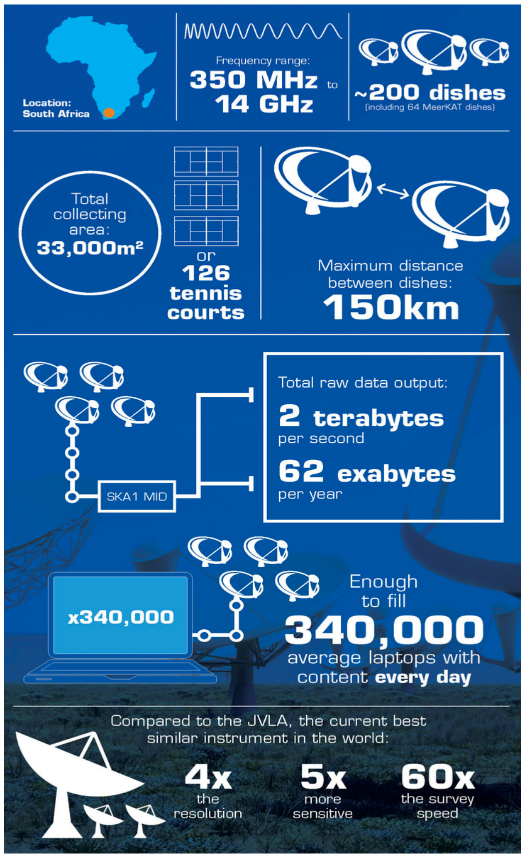
The new technologies that make telescopes like LOFAR and ultimately the SKA possible require heavy computation.
Computation in this sense means storage of lots of data, lots of processing to do something useful with this data, and networking to transport that data.
These challenges are some of the biggest issues facing the success of the SKA and the future of radio astronomy.

SKA-LOW Data Rates





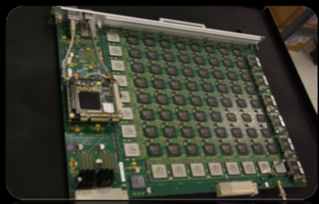
SKA-Mid Data Rates



SKA System Data Flow

Antennas

Digital Signal Processing (DSP)



Transfer antennas to DSP
2020: 5,000 PBytes/day
2030: 100,000 PBytes/day

Over 10's to 1000's kms

HPC Processing
2020: 300 PFlop
2028: 30 EFlop

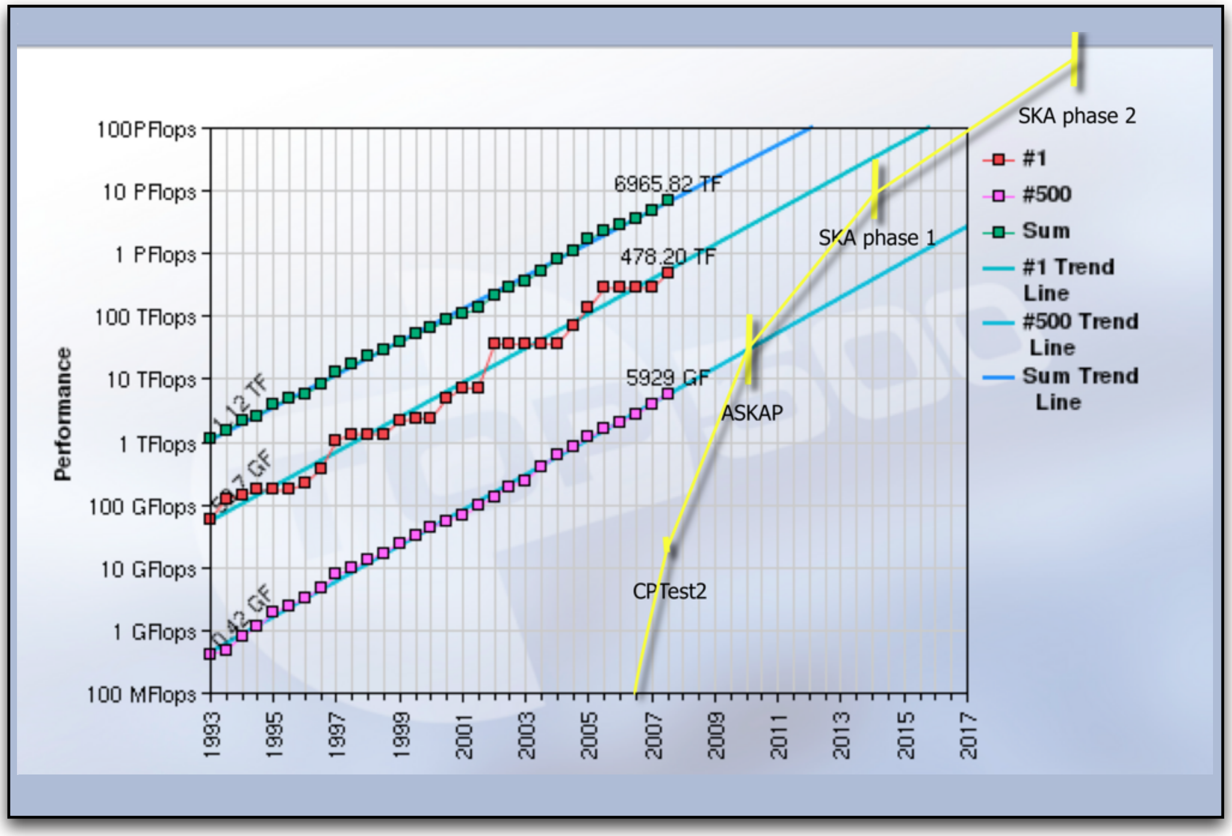
To Process in HPC
2020: 50 PBytes/day
2030: 10,000 PBytes/day

Over 10's to 1000's kms

High Performance Computing Facility (HPC)

30 – 300 Pbytes / year of fully processed science data products!

SKA Computing Costs



The growth of computing power over the last few decades. The curves show the fastest and fastest 500 computer systems as a function of time. The yellow line shows the estimated total computing power needed for the SKA.

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

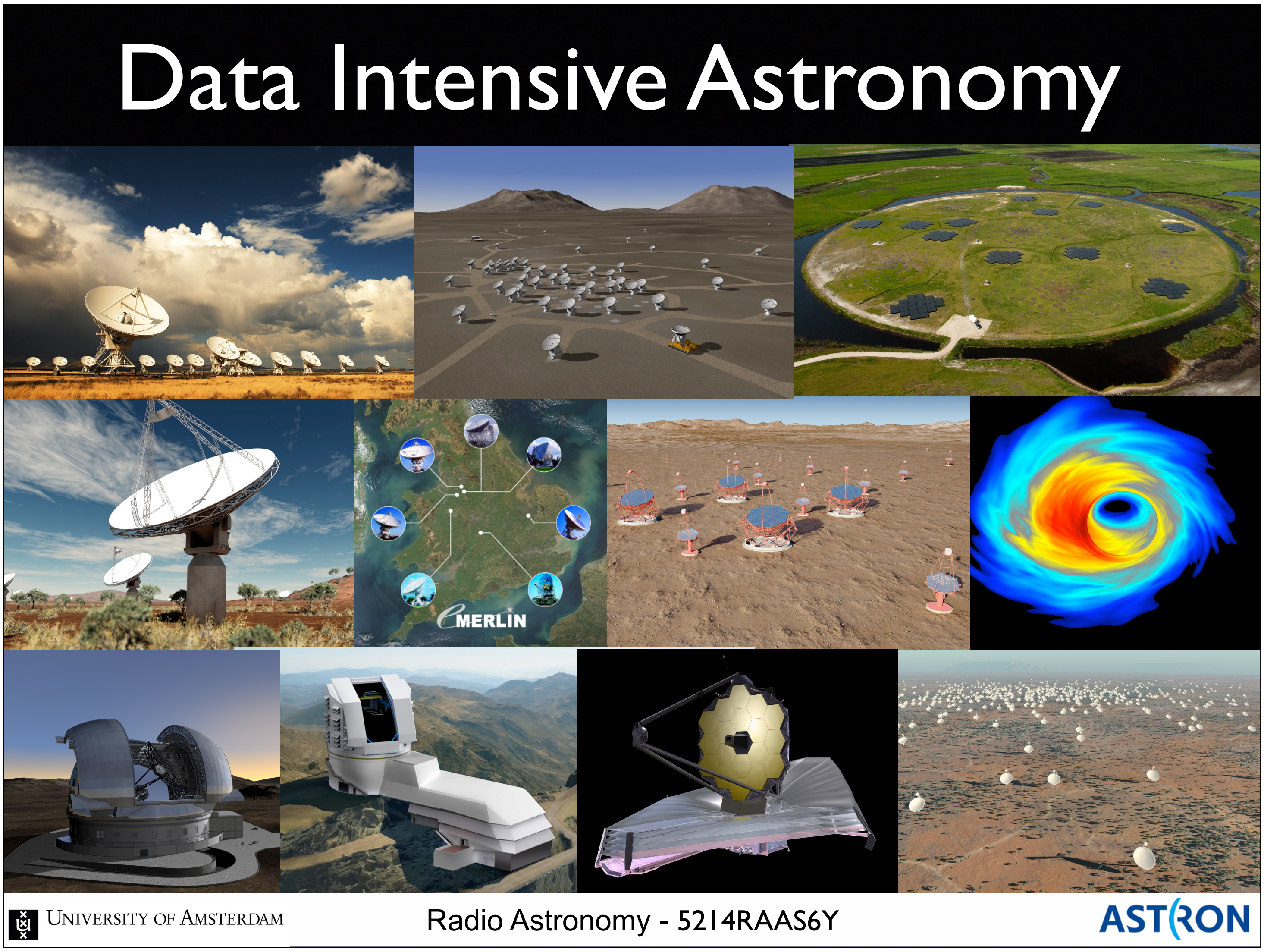
- **~0.5 – 10 PB/day of image data**
- **Source count ~10^6 sources per square degree**
- **~10^{10} sources in the accessible SKA sky, 10^4 numbers/record**
- **~1 PB for the catalogued data**

100 Pbytes – 3 EBytes / year of fully processed data

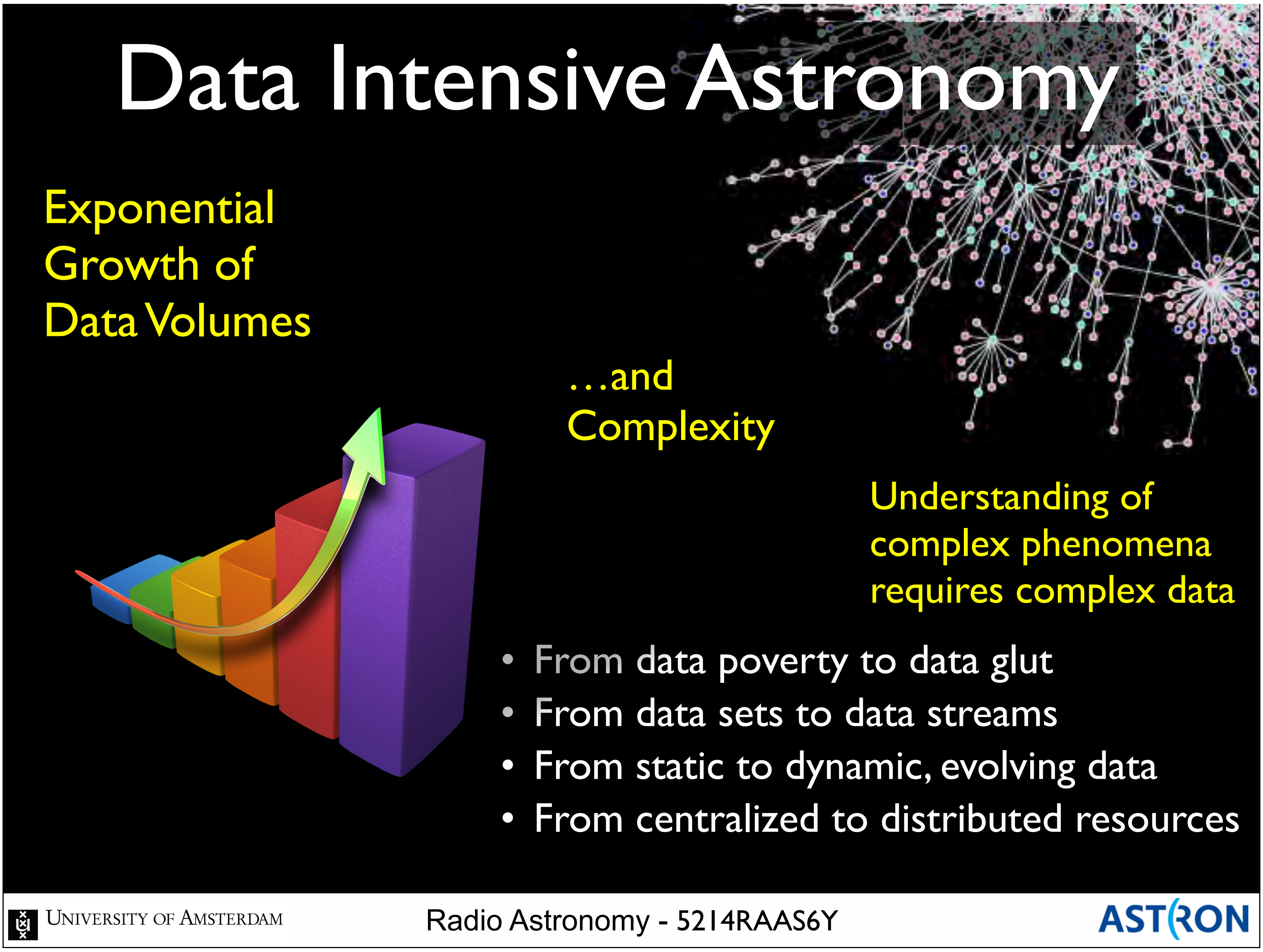
This slide shows some typical expected data volumes for a few typical SKA observations.
A *single* observation could easily generate 100's of TB of data.
At this level, the entire paradigm for how we do astronomy changes.
No more loading data onto a laptop and reducing it at home.

Intermission

Data Intensive Astronomy

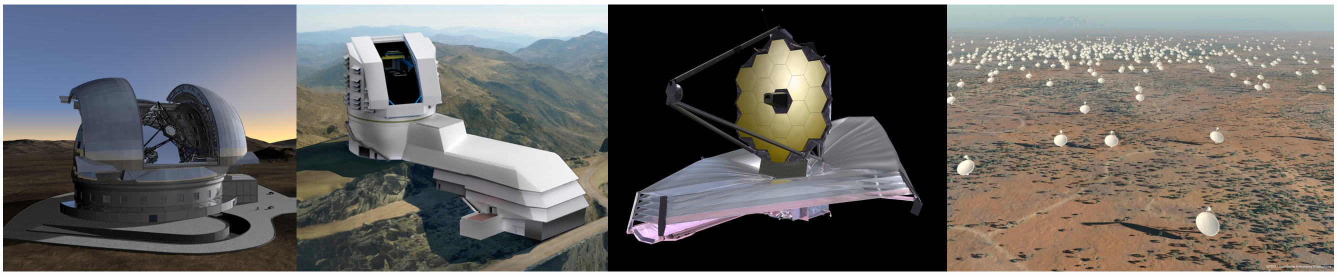


Data intensive astronomy is not just an issue for radio astronomy.
Many new telescopes at a variety of wavelengths will generate huge datasets.
Simulated datasets can also be very large and create the same sorts of issues.



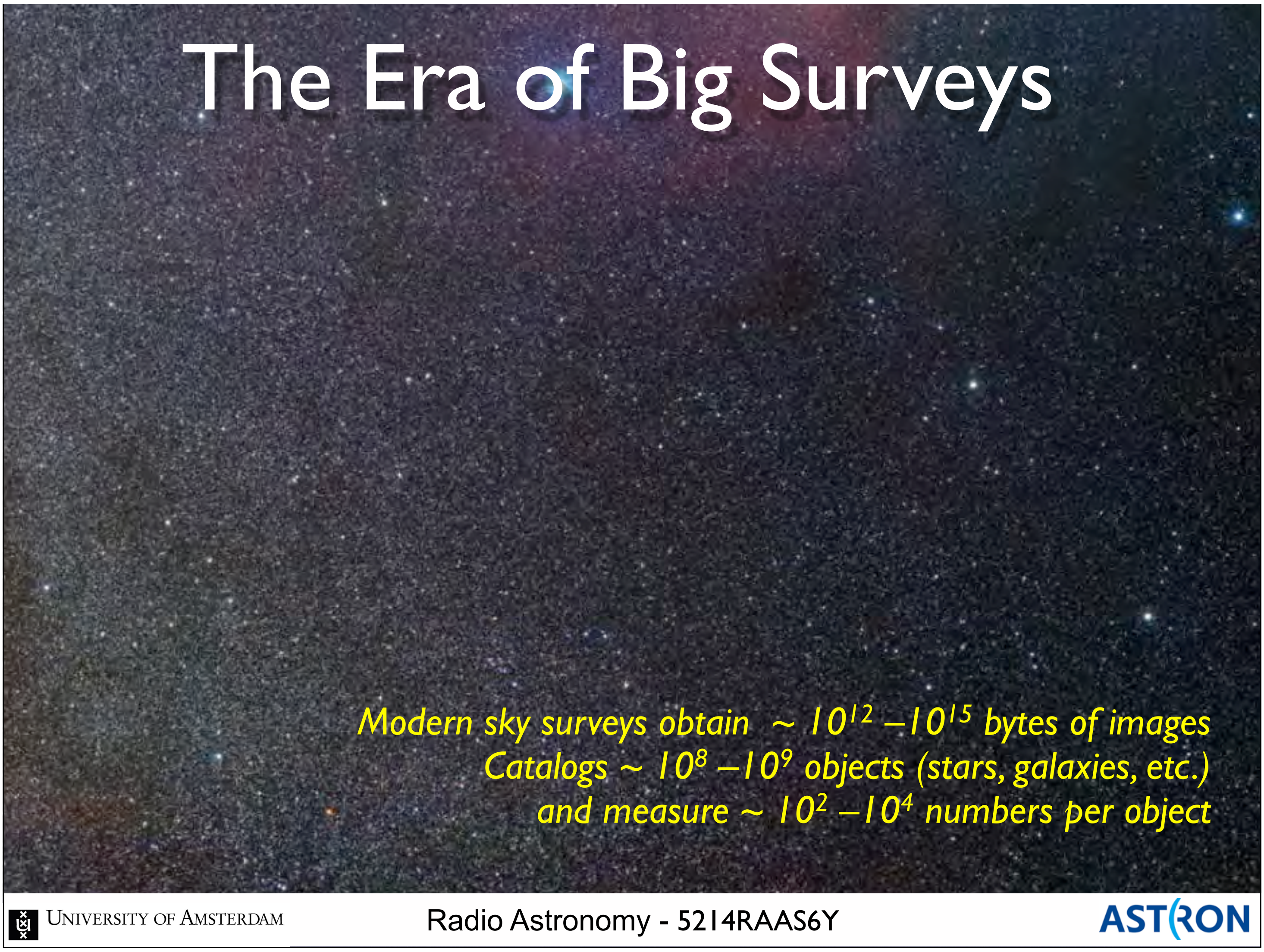
Data intensive astronomy is not just about computing, storage, and networking.
It is also about the nature of the data itself which has also evolved.
Its about data volume but also the complexity of the data itself.

What does "Data Intensive" mean?

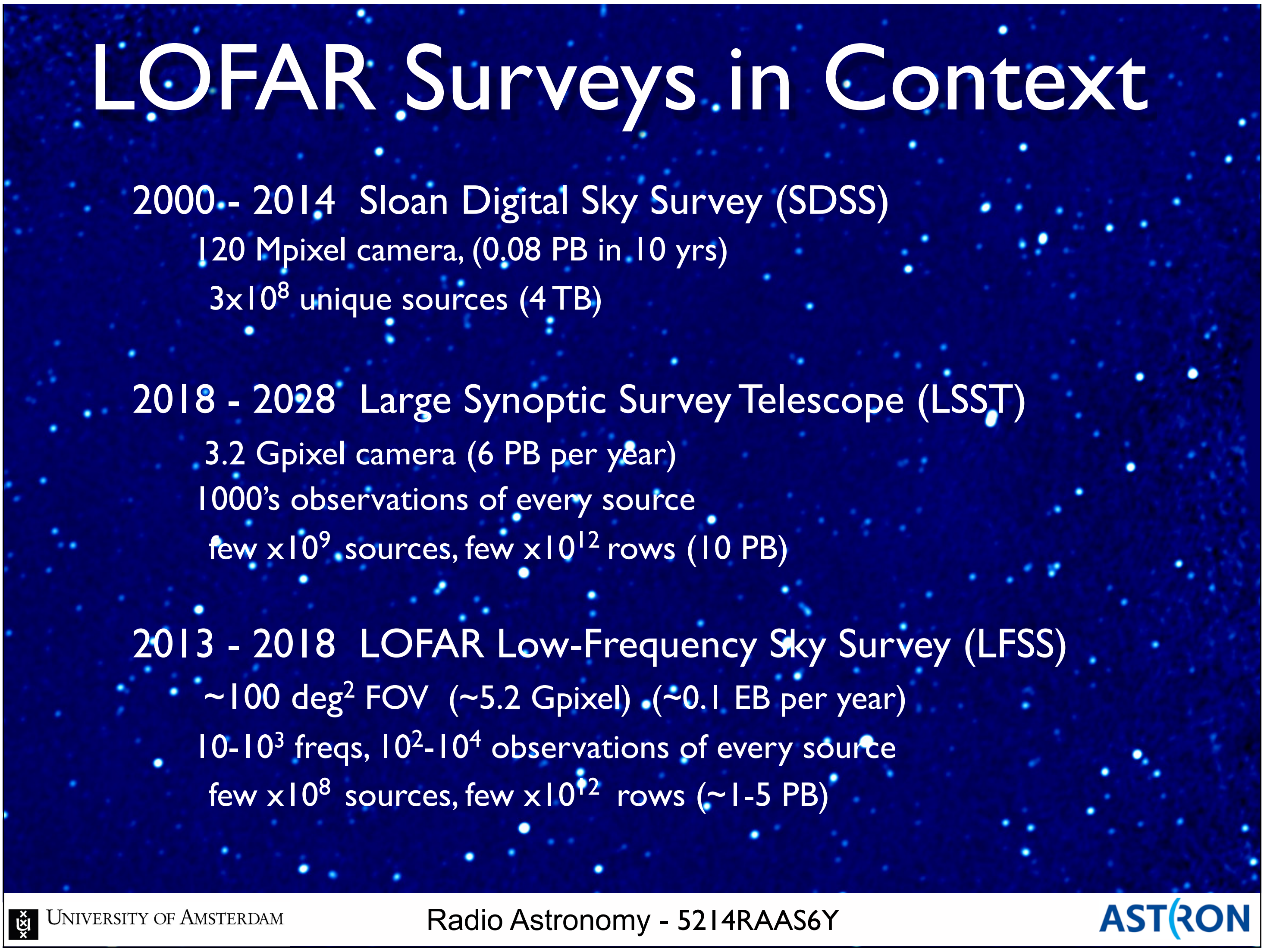


- Science is increasingly driven by large data sets
- Data collection in large collaborations
- Analysis done on the archived data
- New instruments will produce petascale datasets

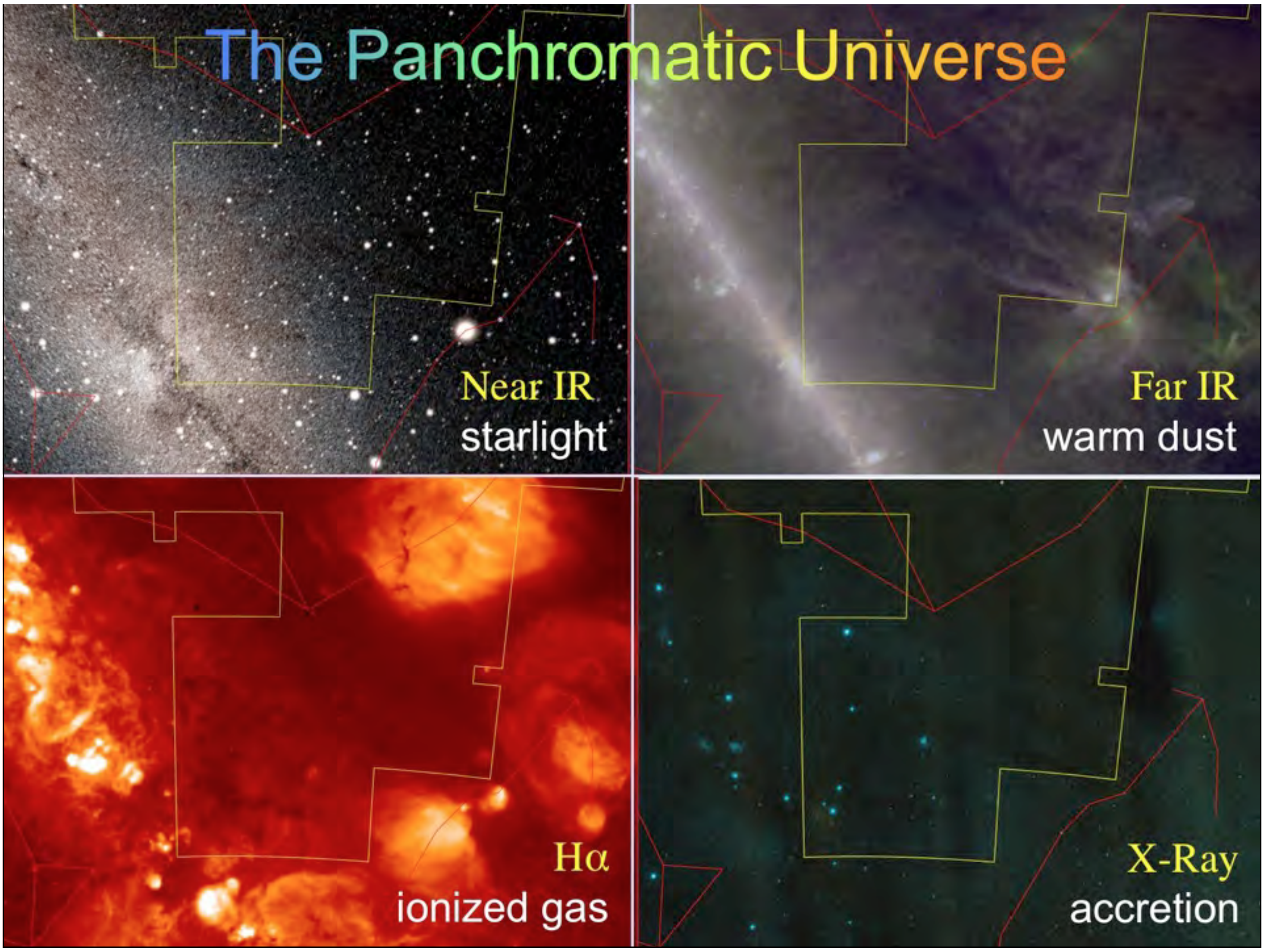
Petascale analysis require exascale data management!



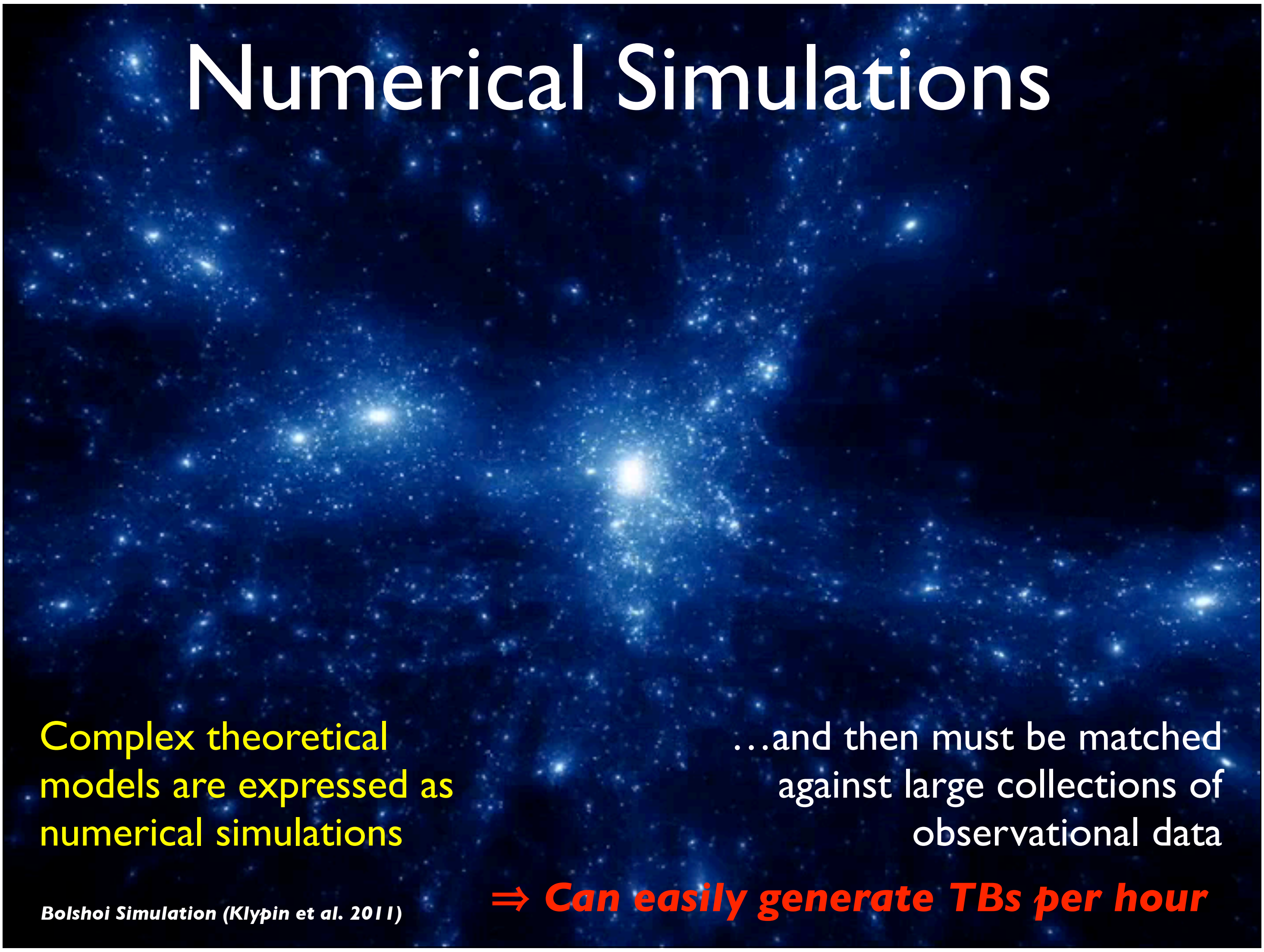
We've repeatedly discussed how the next generation of radio telescopes have been optimized to perform surveys.
This trend toward all-sky surveys is also going on at other wavelengths especially in the optical.
Even the final products of these surveys, i.e. images and source catalogs, can be very large.



A comparison of the size of next generation surveys in the optical compared to LOFAR.
Even the source catalogs can reach sizes of petabytes.



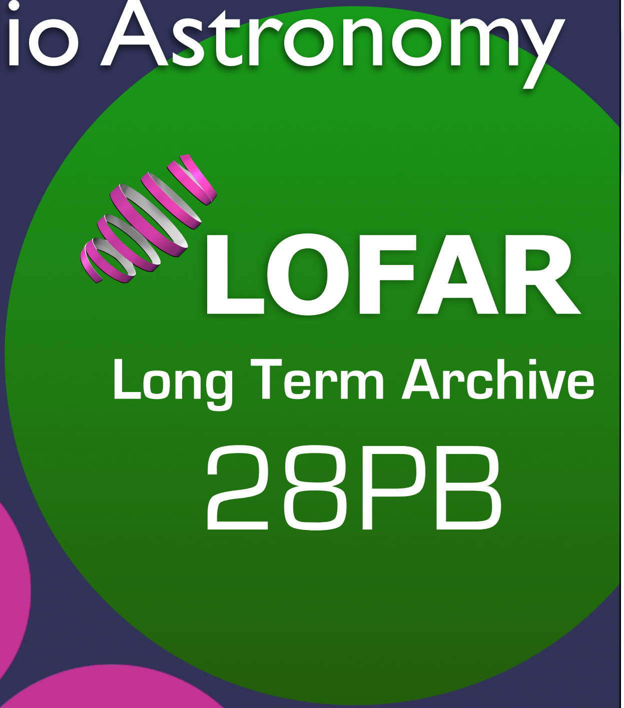
For many types of science, it is important to combine data across many wavelengths.
To be able to make these sort of multi-wavelength analysis, the data must be archived and we need a way to easily combine them. At the moment, we do these sorts of analyses manually.
At the scale of the SKA and LSST, we won't be able to do it manually any longer.

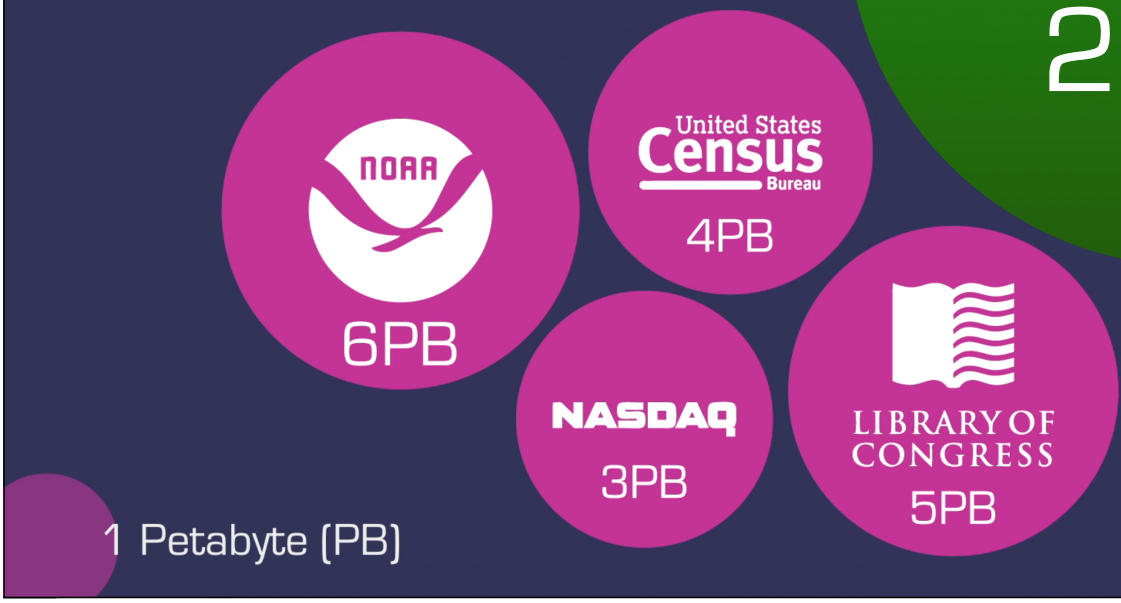


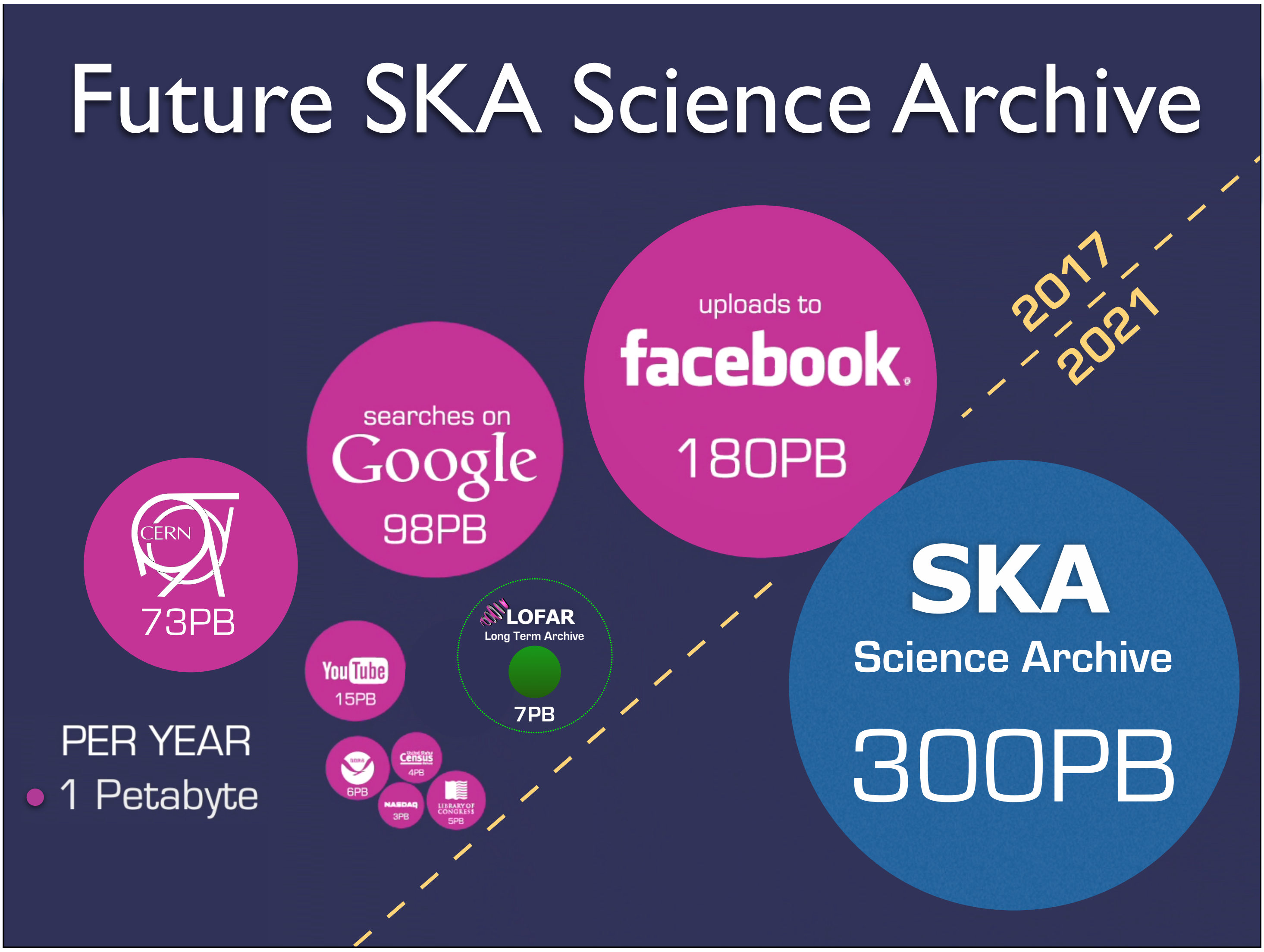
Numerical simulations are a new kind observational data.
They can be as equally large and complex as data obtained from telescopes.
By making it accessible through archives, it can be compared to actual observations and used in analysis.

Data Intensive Radio Astronomy

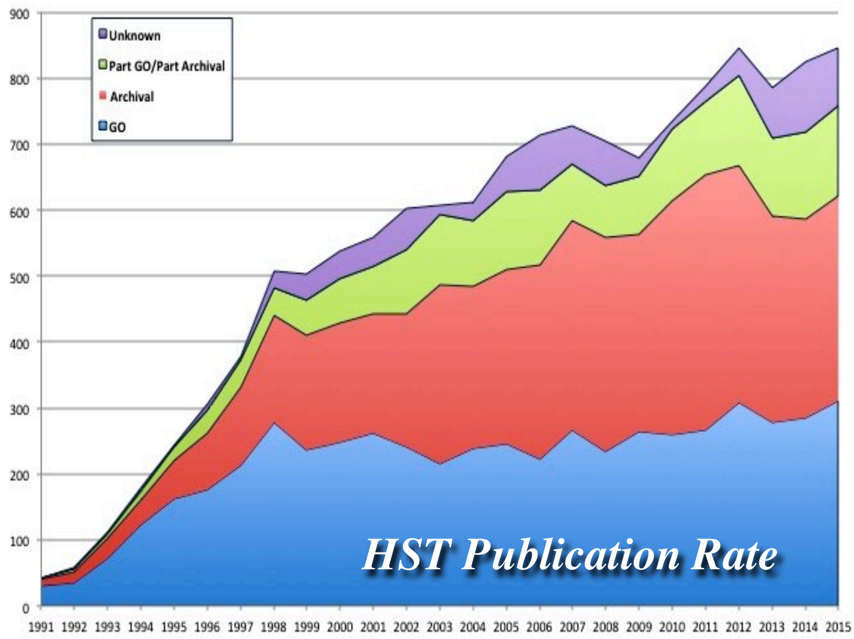
- Radio astronomy is already data intensive
- Current facilities already generating large data (*JVLA, ALMA, eMERLIN, LOFAR, etc.*)
- New facilities orders of magnitude larger (*MeerKAT, ASKAP, and SKA*)






Future SKA Science Archive
2017
2021
uploads to
facebook
180PB
searches on
Google
98PB
CERN
73PB
YouTube
15PB
LOFAR
Long Term Archive
7PB
SKA
Science Archive
300PB
PER YEAR
1 Petabyte
6PB
Census
4PB
NASDAQ
3PB
LIBRARY OF CONGRESS
5PB

Impact of Science Archives

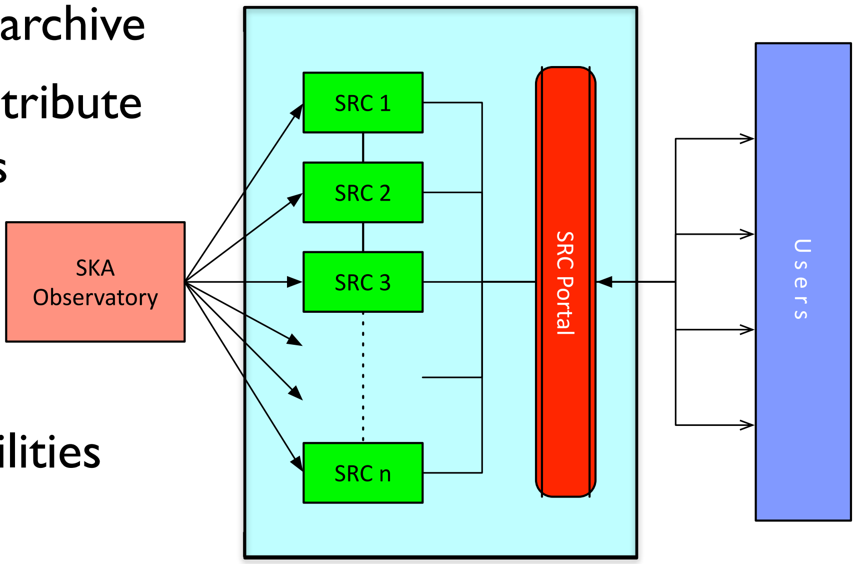


- Assumes the archives are persistent and maintained
- Assumes archival data is open and accessible to users
- Assumes data products stored are appropriate for general use
- Assumes users retrieving data have resources to process to a science result

Archives can increase the total scientific output from a telescope!

SKA Regional Centres

- SKA Regional Centres (SRCs) will host SKA science archive
- Provide access and distribute data products to users
- Provide access to compute and storage resources
- Provide analysis capabilities
- Provide user support
- Multiple regional SRCs acting as a single network

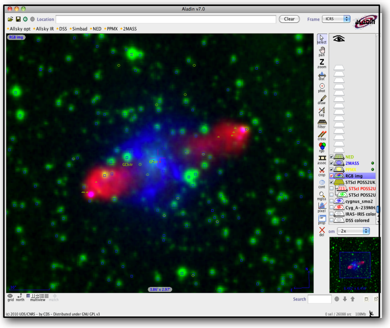


Primary interface for SKA data analysis

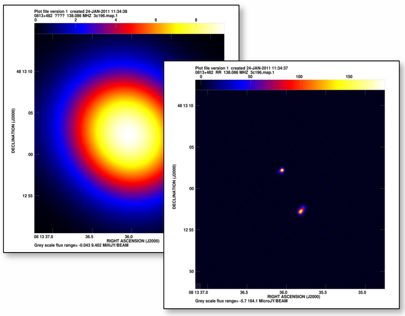
Data Centre Functionality

Data Discovery

- Observation database
- Associated metadata
- Quick-look data products
- Flexible catalog queries
- Integration with VO



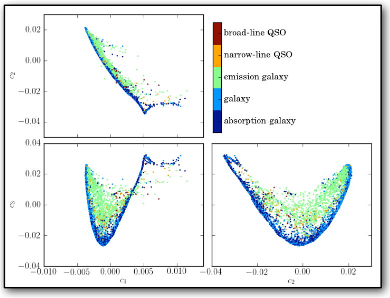
Data Processing



- Calibration and Imaging
- Mosaicing
- Source extraction
- Catalog creation
- DM searches

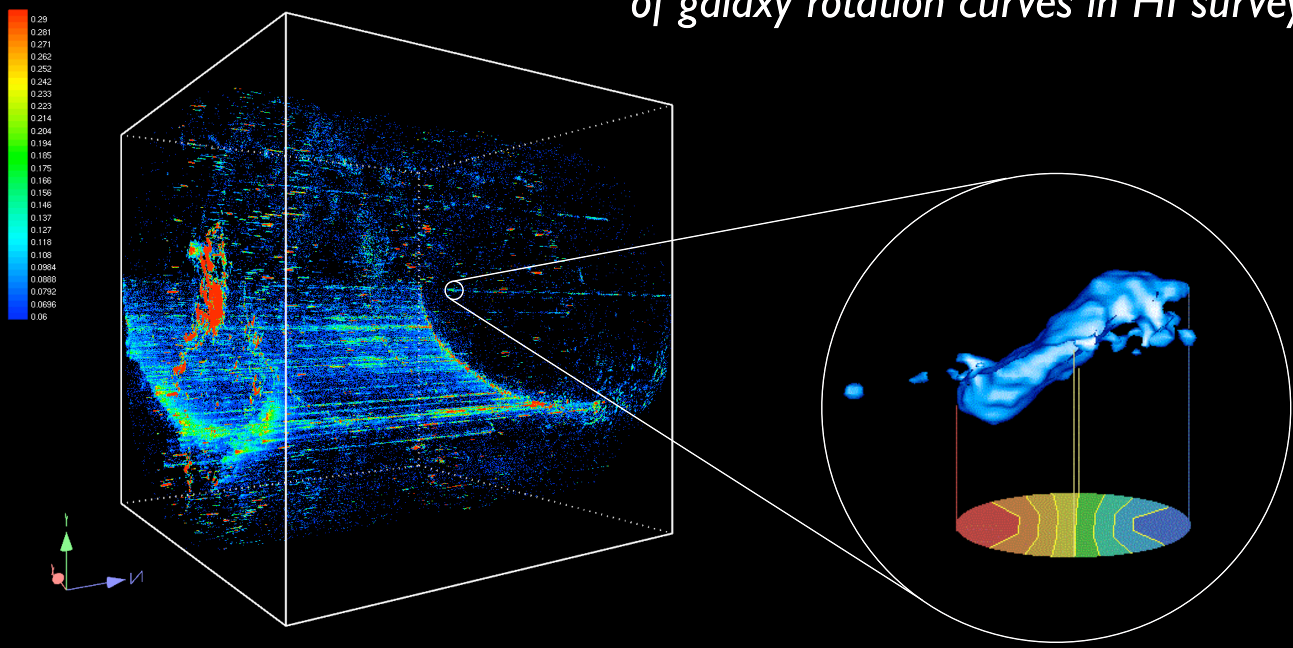
Data Analysis

- Multi-wavelength studies
- Catalog cross-matching
- Light-curve analysis
- Transient classification
- Feature detection
- Visualization



Visualization, Classification, Inference

Automated detection and calculation of galaxy rotation curves in HI surveys



HIPASS HI Cube (Jurek et al. 2010)

SKA1-Mid cube ~ 0.9 PB

Global Network of Centres

Beyond the SKA

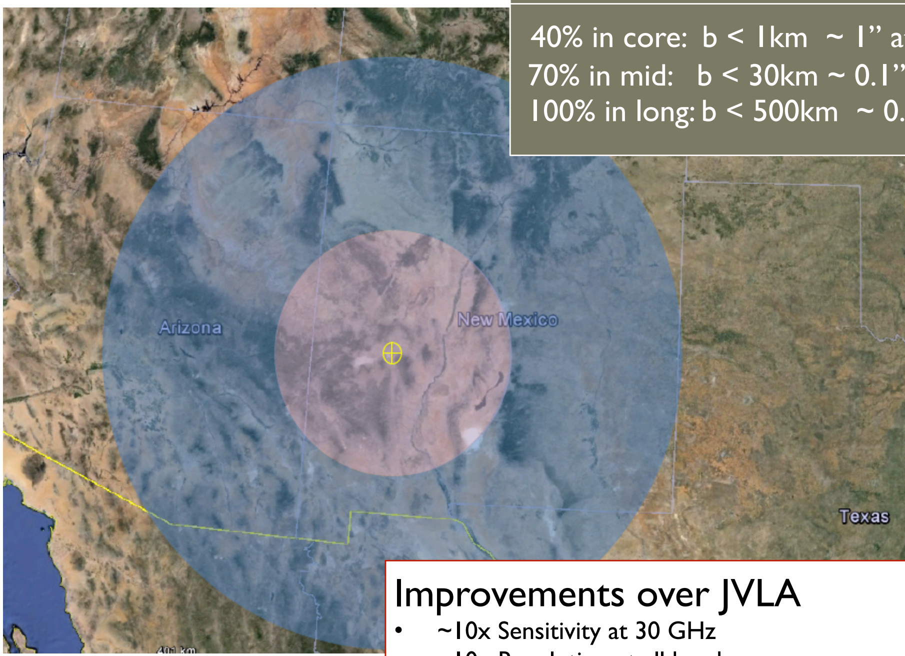
Next Generation VLA

Thermal imaging at milli-arcsecond scale resolution
10x effective collecting area & resolution of JVLA

Next Generation VLA

JVLA: Good 3mm site, elev. ~ 2200m

40% in core: b < 1km ~ 1” at 30GHz
70% in mid: b < 30km ~ 0.1”
100% in long: b < 500km ~ 0.01”

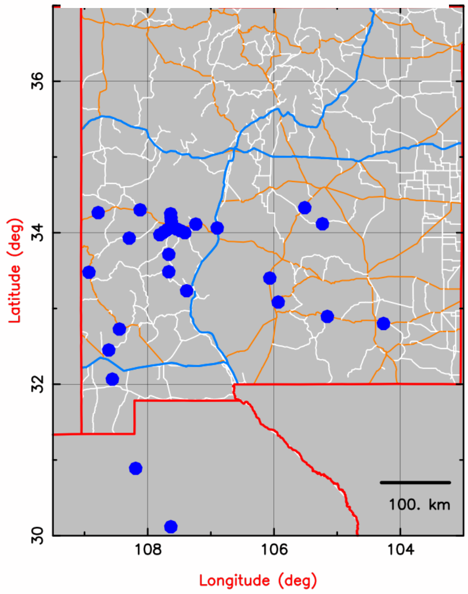


Improvements over JVLA

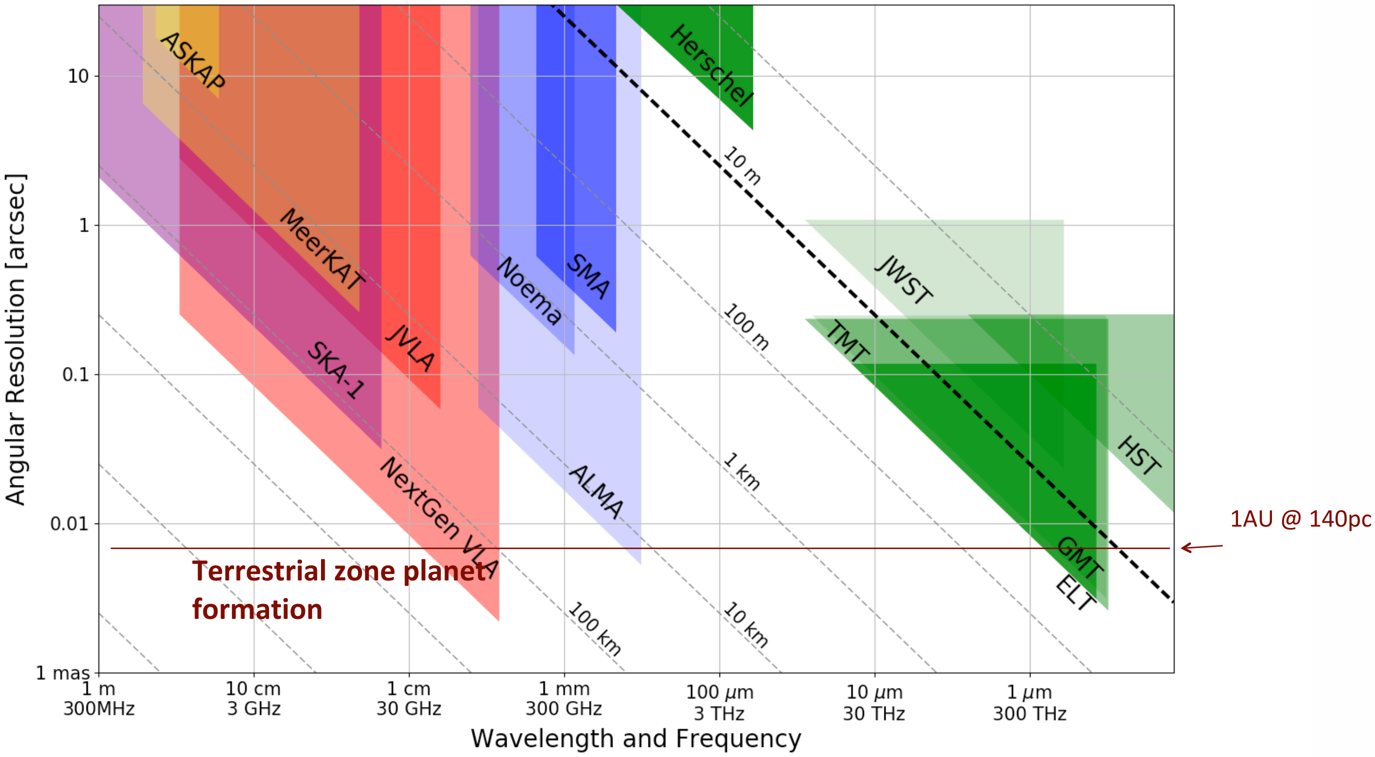
- ~10x Sensitivity at 30 GHz
- ~10x Resolution at all bands
- 1.2 – 116GHz (vs. 1 – 50GHz)

Located in U.S. and Mexico

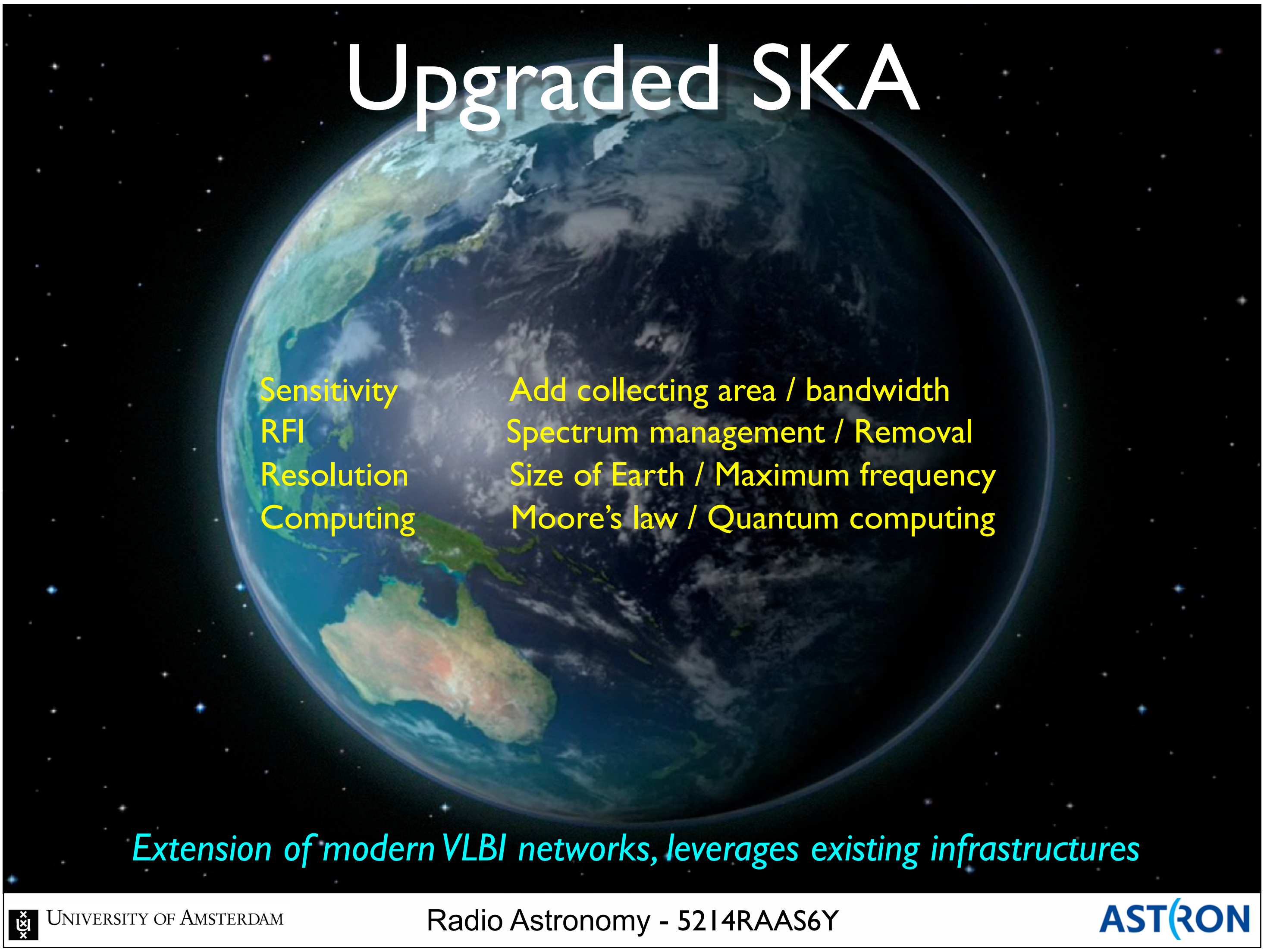
Potential Station Locations



Bridging SKA & ALMA Scientifically



Begin construction in 2025, complete in 2034



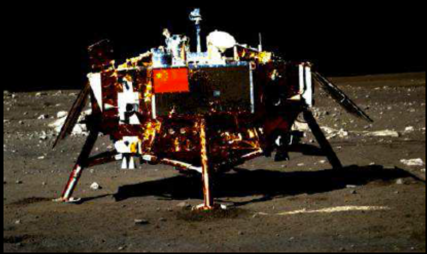
Where do we go next once the SKA has been built?
It would be fairly straight-forward to extend the existing technology to blanket the globe.
We could essentially build a radio telescope the size of the earth.
We would however face the same digital challenges that we are currently facing with the SKA.

Low-frequency Radio from Space

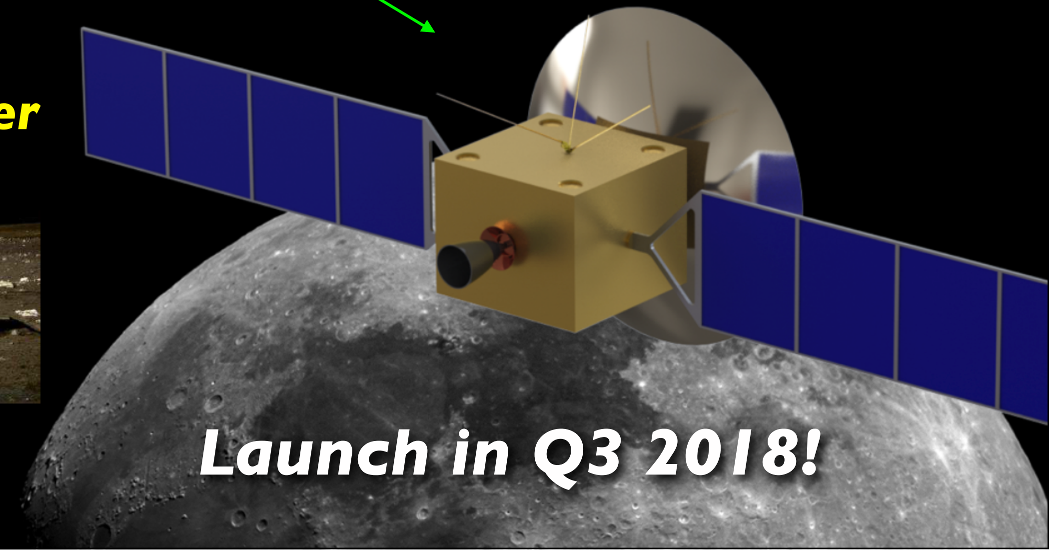
Netherlands – China Long-wavelength Explorer (NCLE)

NL developed LF antenna integrated on Chinese orbiter to explore below 10 MHz

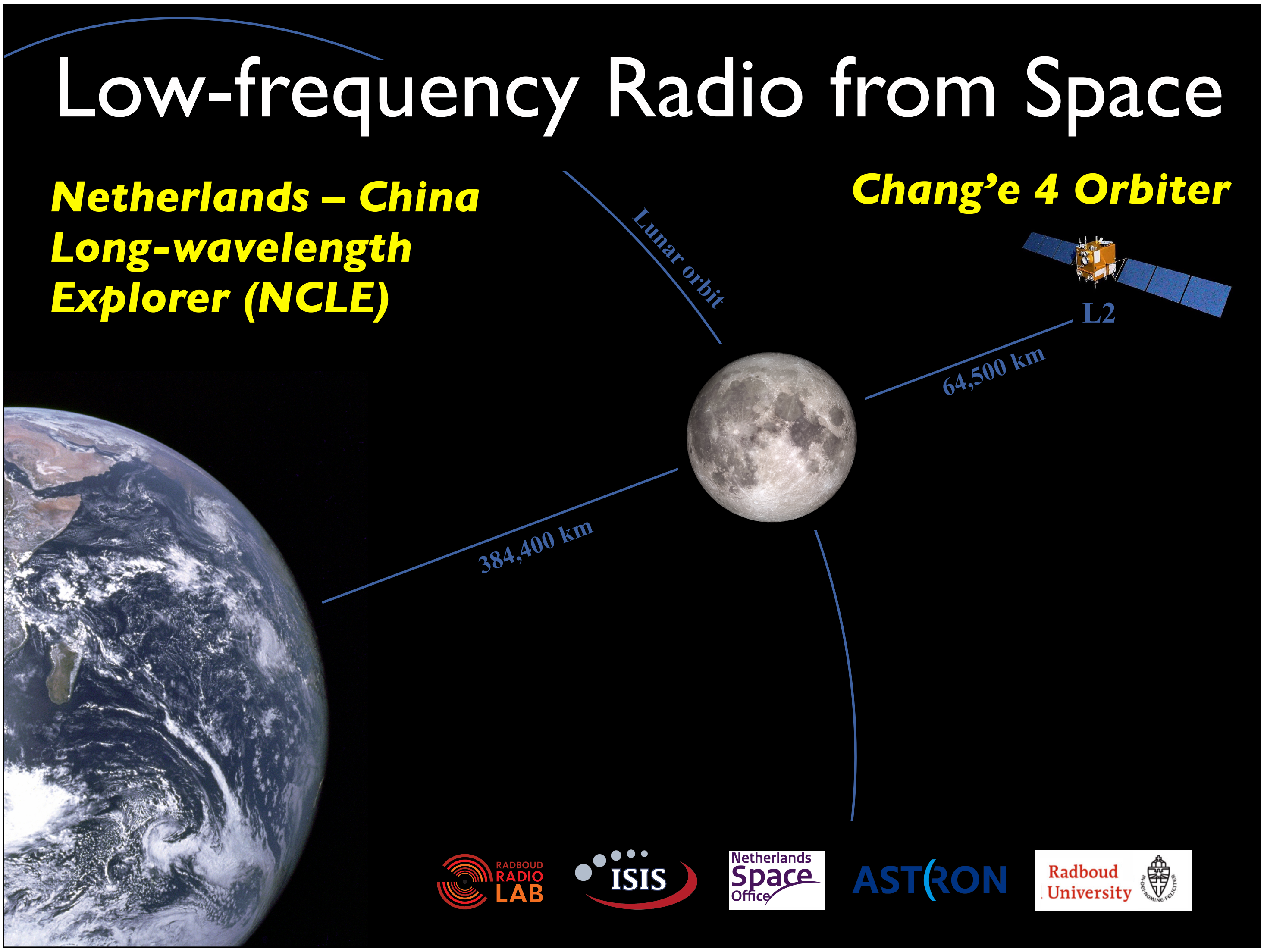
Chang'e 4 Lander

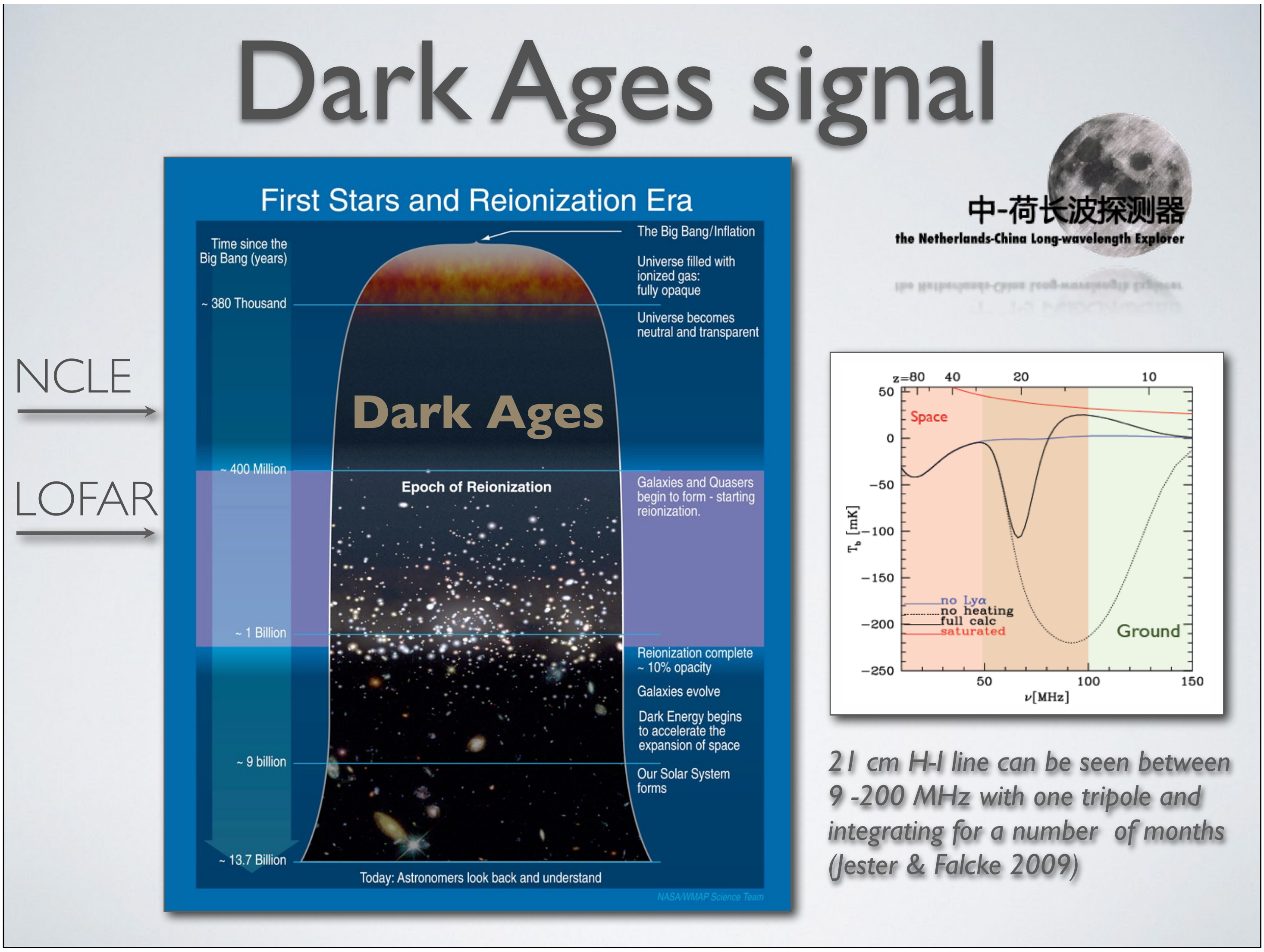


Chang'e 4 Orbiter



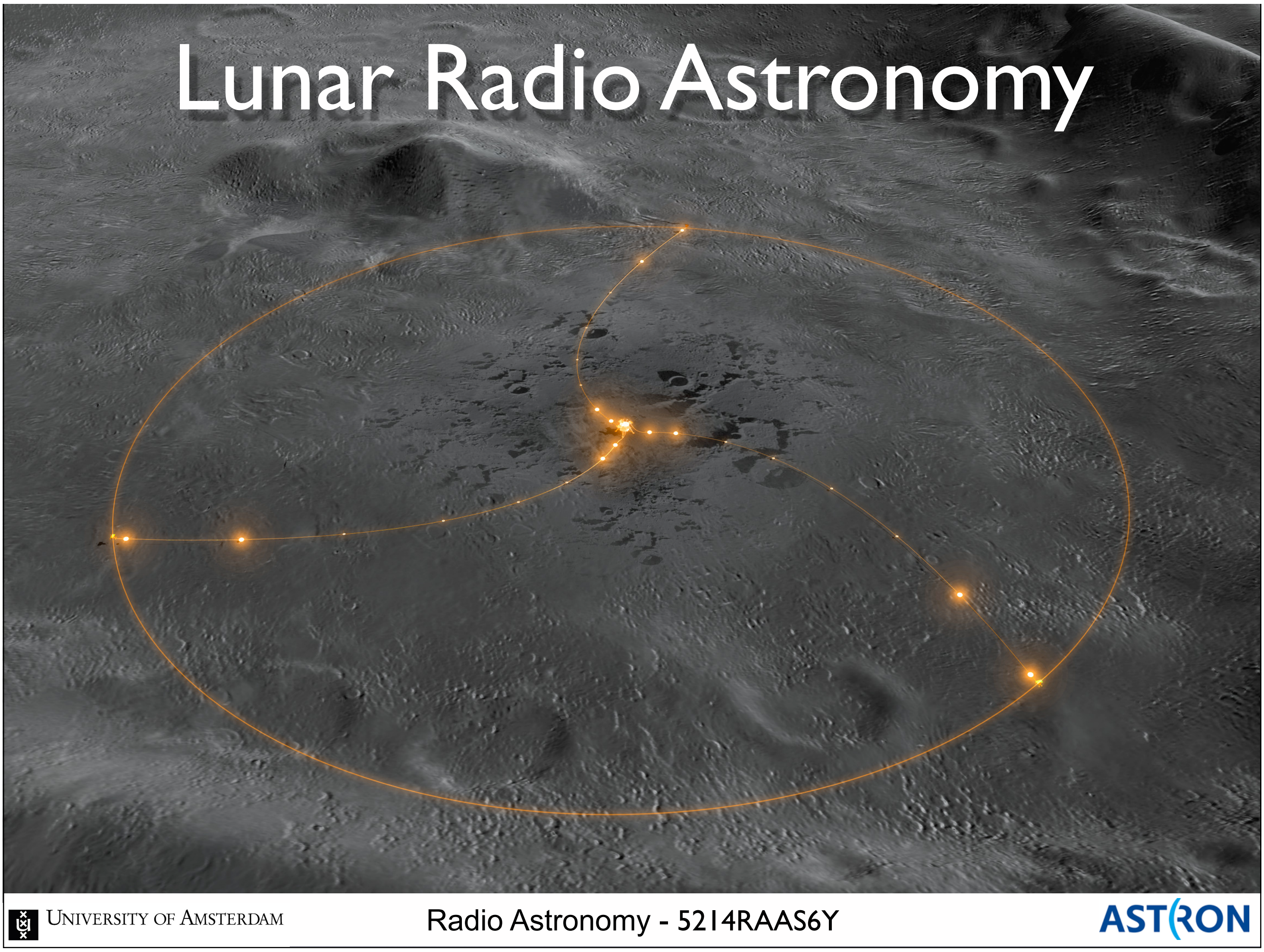
Launch in Q3 2018!


Low-frequency Radio from Space
Netherlands – China
Long-wavelength
Explorer (NCLE)
Chang'e 4 Orbiter
Lunar orbit
L2
64,500 km
384,400 km
RADBOUD RADIO LAB
ISIS
Netherlands Space Office
ASTRON
Radboud University



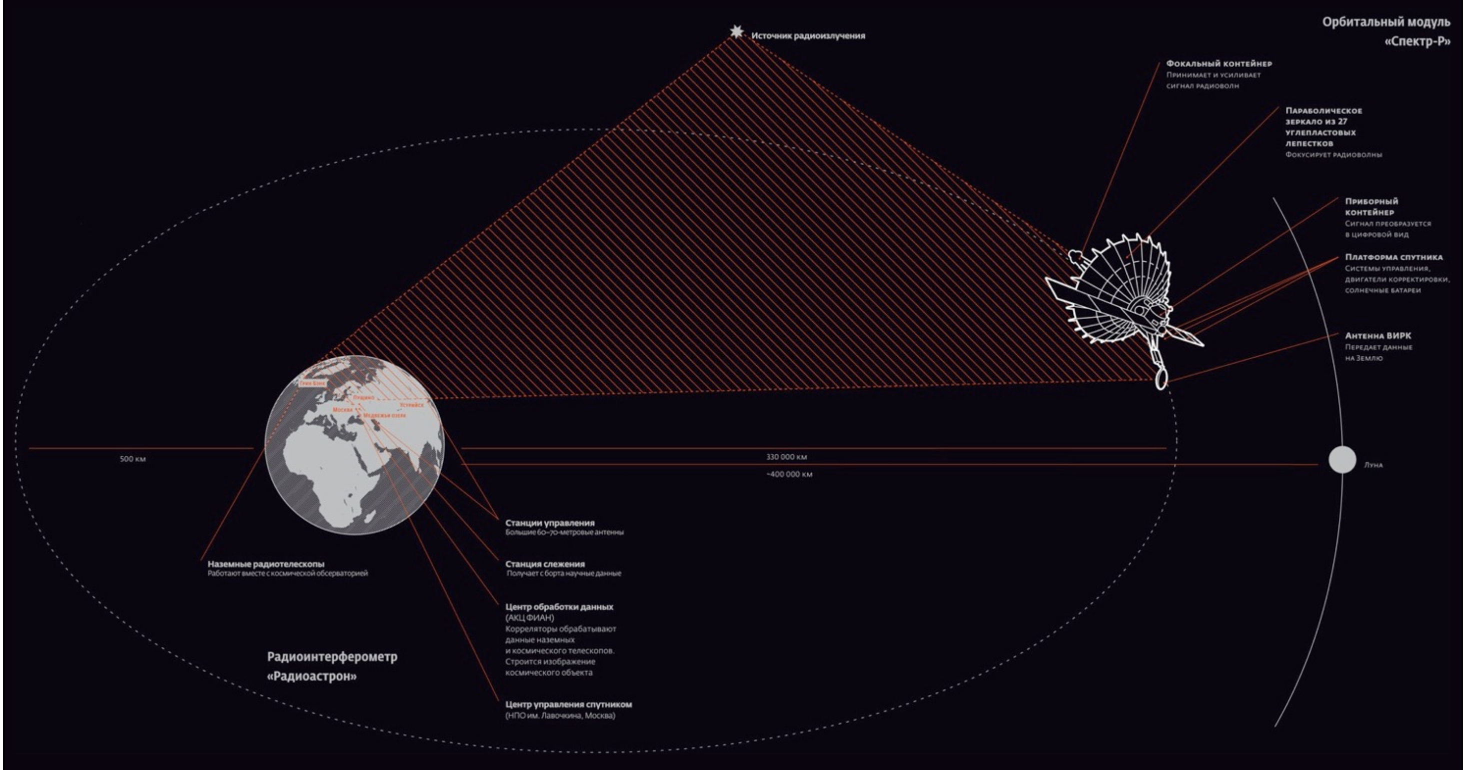
With the LRX we can try to detect the signal of the Dark Ages, i.e. the 21-cm line of H-I, which in the end will tell us something about the distribution of matter in the early universe. Here the LRX is a pathfinder mission: a future large lunar array will be able to detect density differences in detail. Note that this is comparable with the WMAP missions to detect the cosmic background radiation: first step was to detect it, the next to to detail observations. The LRX will be a first step, but will provide a unique image of the early universe and will provide clues on star and galaxy formation

Dark ages is period between epoch of recombination when the universe became neutral and opaque, and the epoch of reionization when the universe re-ionized due to the first stars. The HI 21 cm line is the only source of light in the Dark Ages, and provides a clue on the distribution of matter in the early universe right up to the period when the first stars are born. This addresses a key cosmological issue!

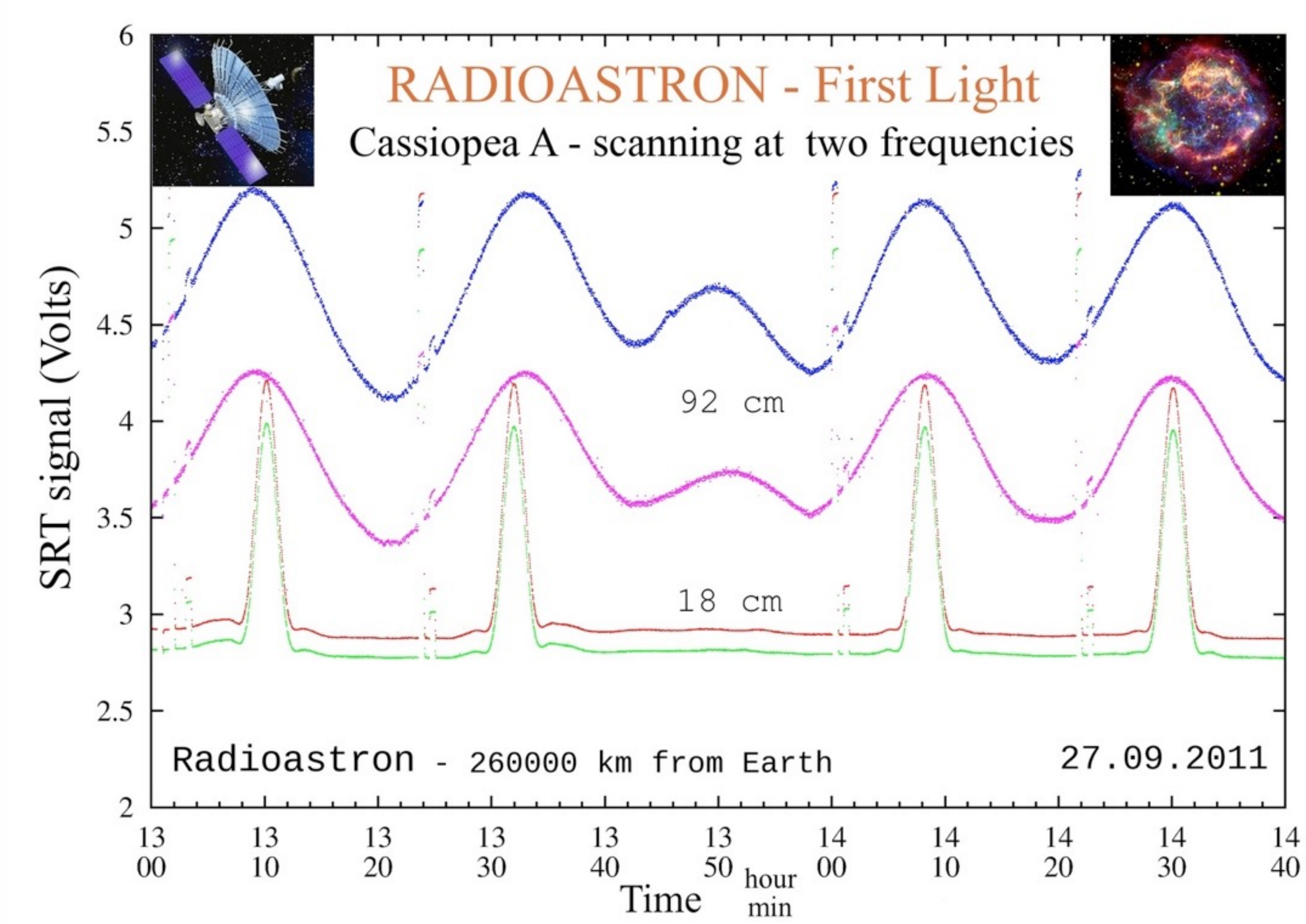


Moving beyond earth, we could imagine building an array on the moon.
By building on the dark side of the moon, we could shield the array from Earth's RFI environment.
Studies are already underway for designs for such a lunar array.

VLBI from Space



The ultimate in space-based radio astronomy would be VLBI from space.
Using an array of radio satellites distributed throughout the solar system we could achieve ultra-high resolution imaging.
This sort of very high resolution imaging is necessary for example to study the environment in the immediate vicinity of extragalactic black holes.



RADIOASTRON is a first example of VLBI from space. This plot shows fringes at two different frequencies between Earth and the RADIOASTRON satellite at a distance of over 260,000 km.


…and beyond


The Future of Radio
Astronomy is YOU!

Questions?