Telescopes of the future:
SKA and SKA demonstrators

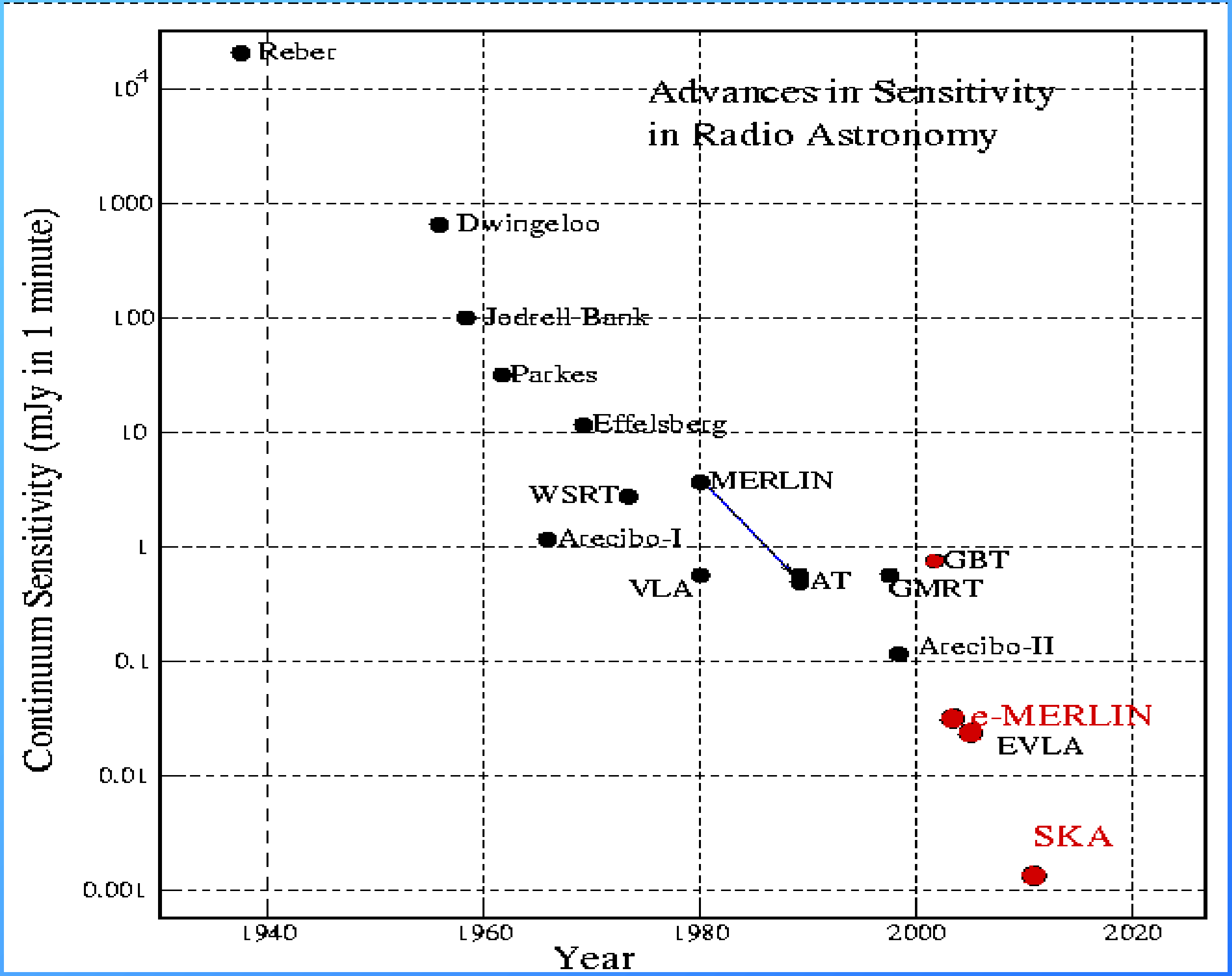
Elaine Sadler, University of Sydney

- Aperture synthesis techniques have now been in use for over 40 years (1974 Nobel prize to Martin Ryle) - what next?
- Why are we planning new telescopes?
- What will they look like?
- What are the challenges?

Why new radio telescopes?

- "Because we can" (new technologies)
- "Because we can't NOT" (or we'll fall behind and become irrelevant) (Moore's law, R. Ekers)
- To keep up with next-generation optical/IR telescopes
- To make new discoveries (new parameter space)
- To explore the distant universe (orders of magnitude increase in sensitivity)

The long-term advance of radio telescope sensitivity…

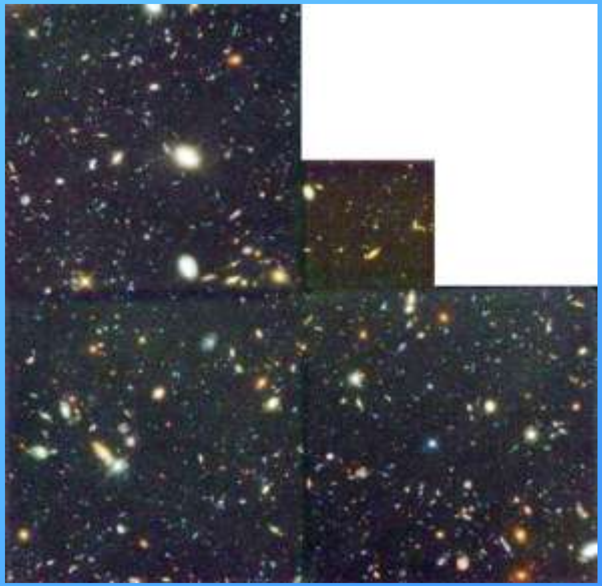


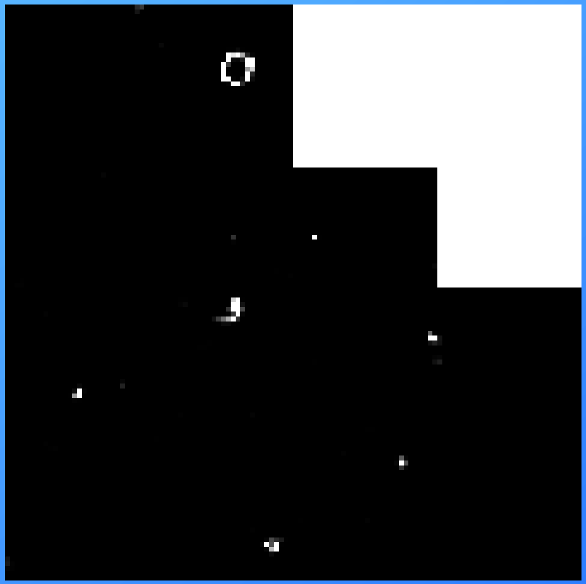
VLA and Arecibo were such large advances that collecting area unchanged for decades !

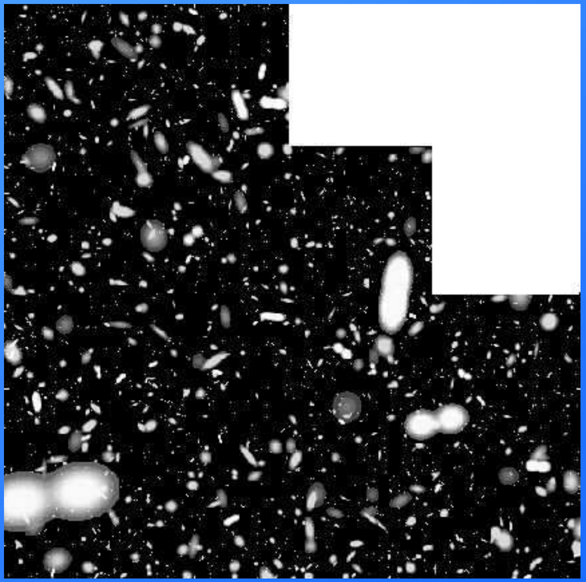
Need technology shift to progress !

Probing the distant universe

HST **VLA** **SKA**







In past few years, optical telescopes have begun to probe the `normal' galaxy population to z~3

The Square Kilometre Array (SKA)

The next generation radio telescope

Main goals:

- Large collecting area for high sensitivity (1 km^2), 100x sensitivity of current VLA.
- Array elements (stations) distributed over a wide area for high resolution (needed to avoid confusion at very faint flux levels).
- For good *uv* plane coverage (especially for HI observations), stations can't be too sparse.

SKA will be a big-budget, *international* project

SKA collecting area up to 100x VLA

Basic design criteria:

Sensitivity alone is not enough:
hence SKA

- Must be sensitive to a wide range of surface brightness
  → many "stations" in the array and wide range of baselines

as is VLA

- Must cover factor >10 frequency range

as does VLA

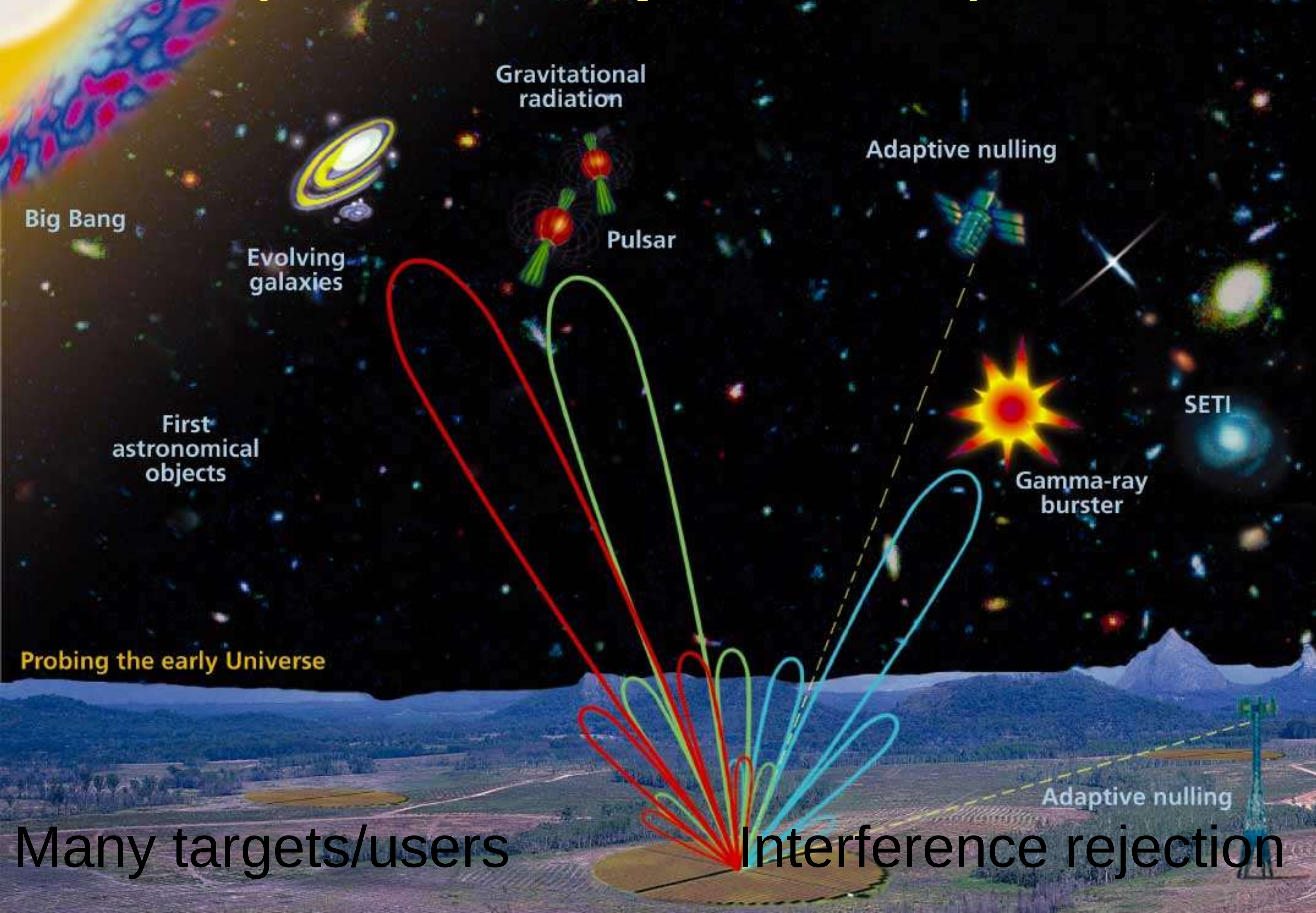
- Must have wide field & ideally multiple beams
  → multi-user; surveying speed and interference mitigation

VLA does not

Some Proposed Specifications for the SKA (SKA Technical Workshop, 1997)

Frequency range	150 MHz – 20 GHz
Imaging field of view	1 degree at 1.4 GHz
Instantaneous beams	100
Angular resolution	0.1 arcsec at 1.4 GHz
Spectral channels	10,000
Image dynamic range	10^6 at 1.4 GHz
Brightness sensitivity	1K at 1.4 GHz

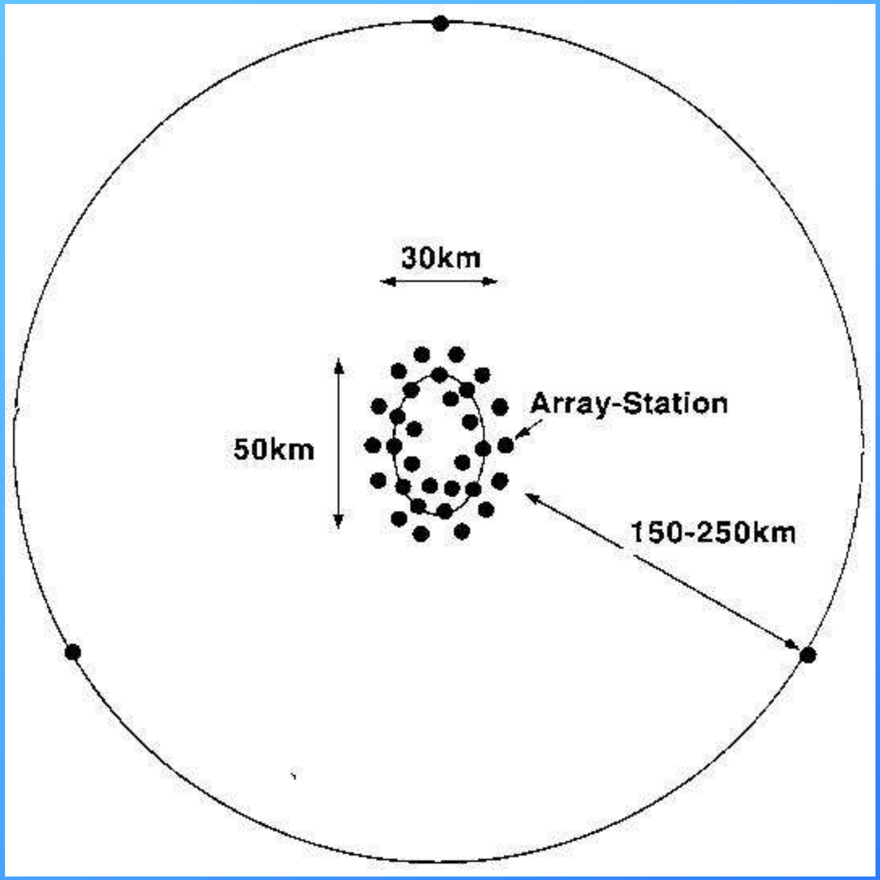
Many beams offer great flexibility



Many targets/users

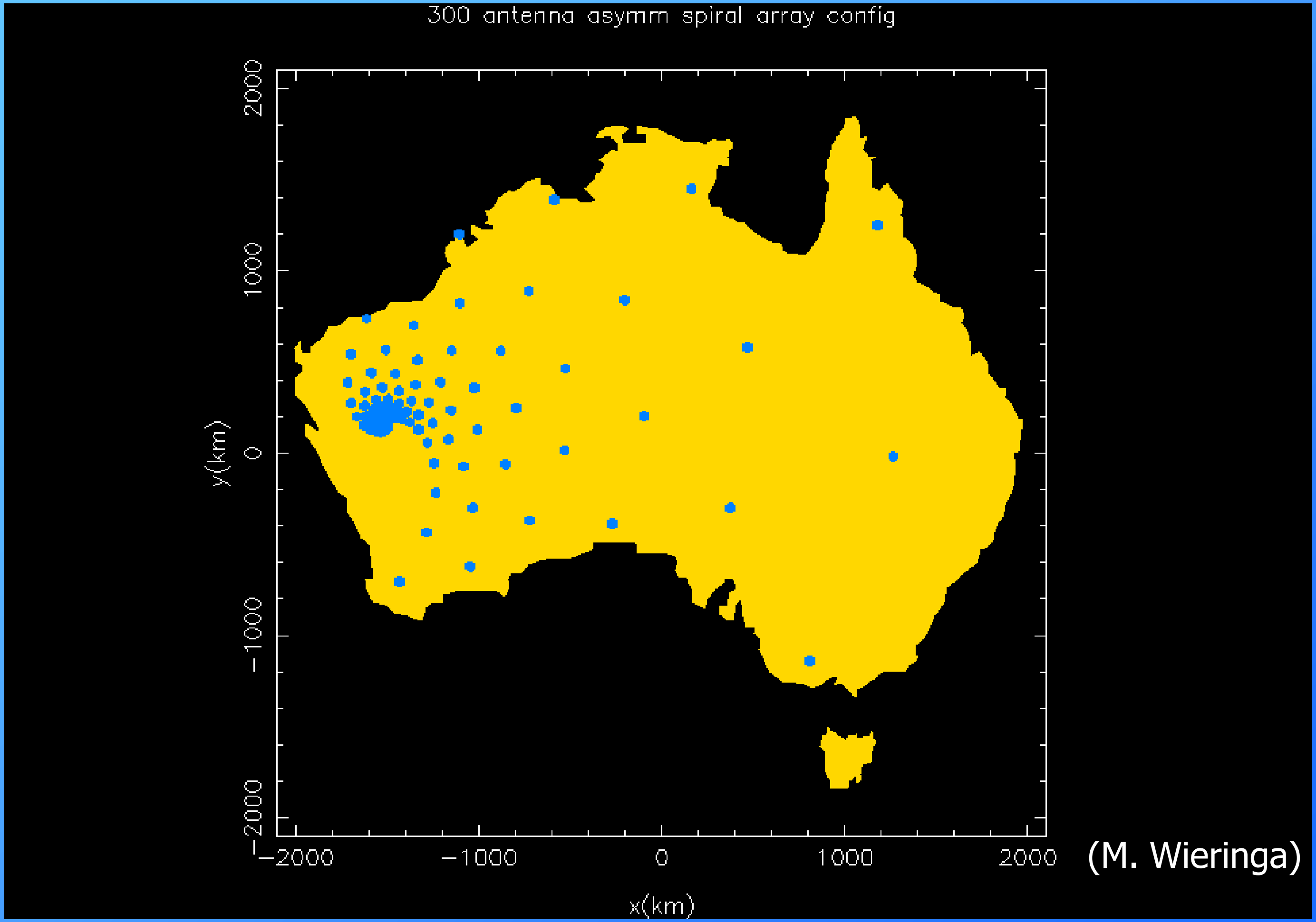
Interference rejection

SKA Configurations



Determining (and agreeing on) the optimum SKA configuration is a significant challenge

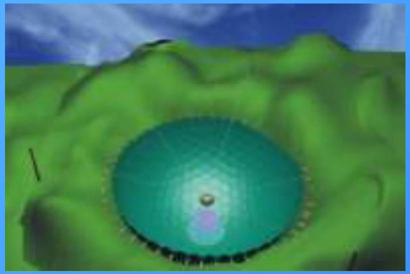
For high resolution, array stations are distributed across a continent



(M. Wieringa)

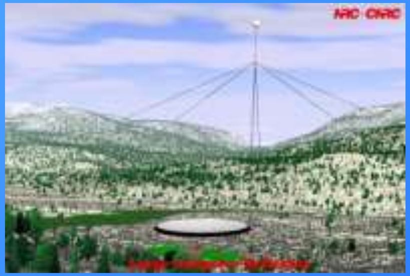
SKA antenna concepts

US ATA



China KARST

Australia Luneburg Lenses



Canada Large reflector

Dutch phased array

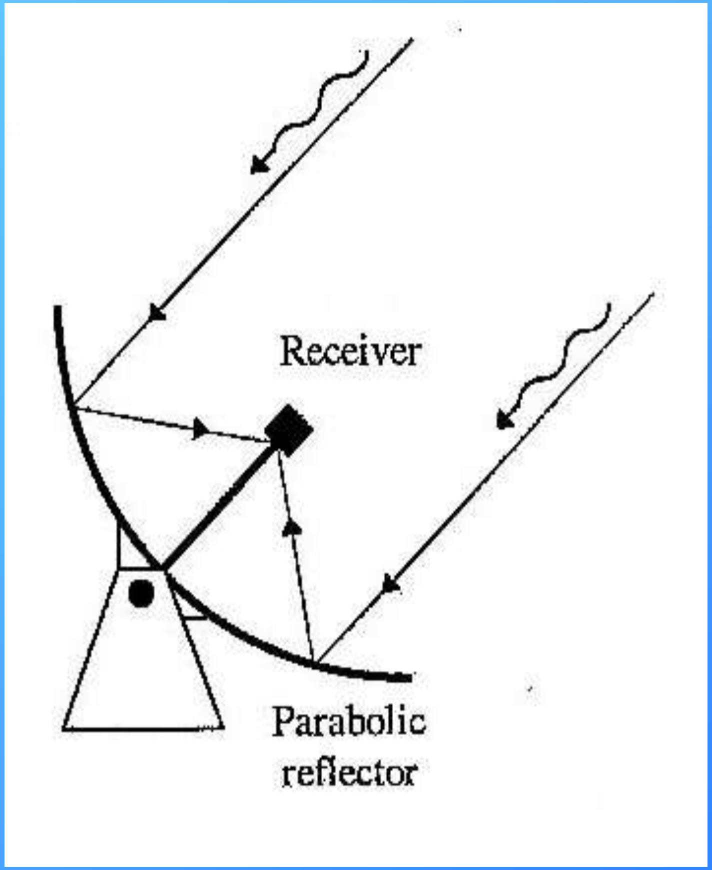
Australia cylindrical paraboloid

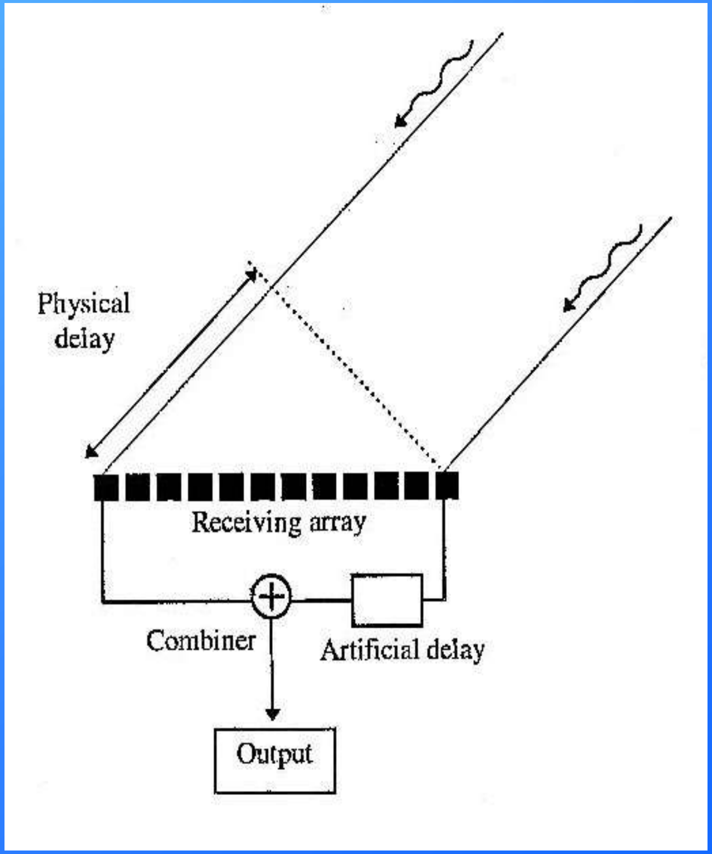
Parabolic Reflector Array

(SETI Institute, USA)

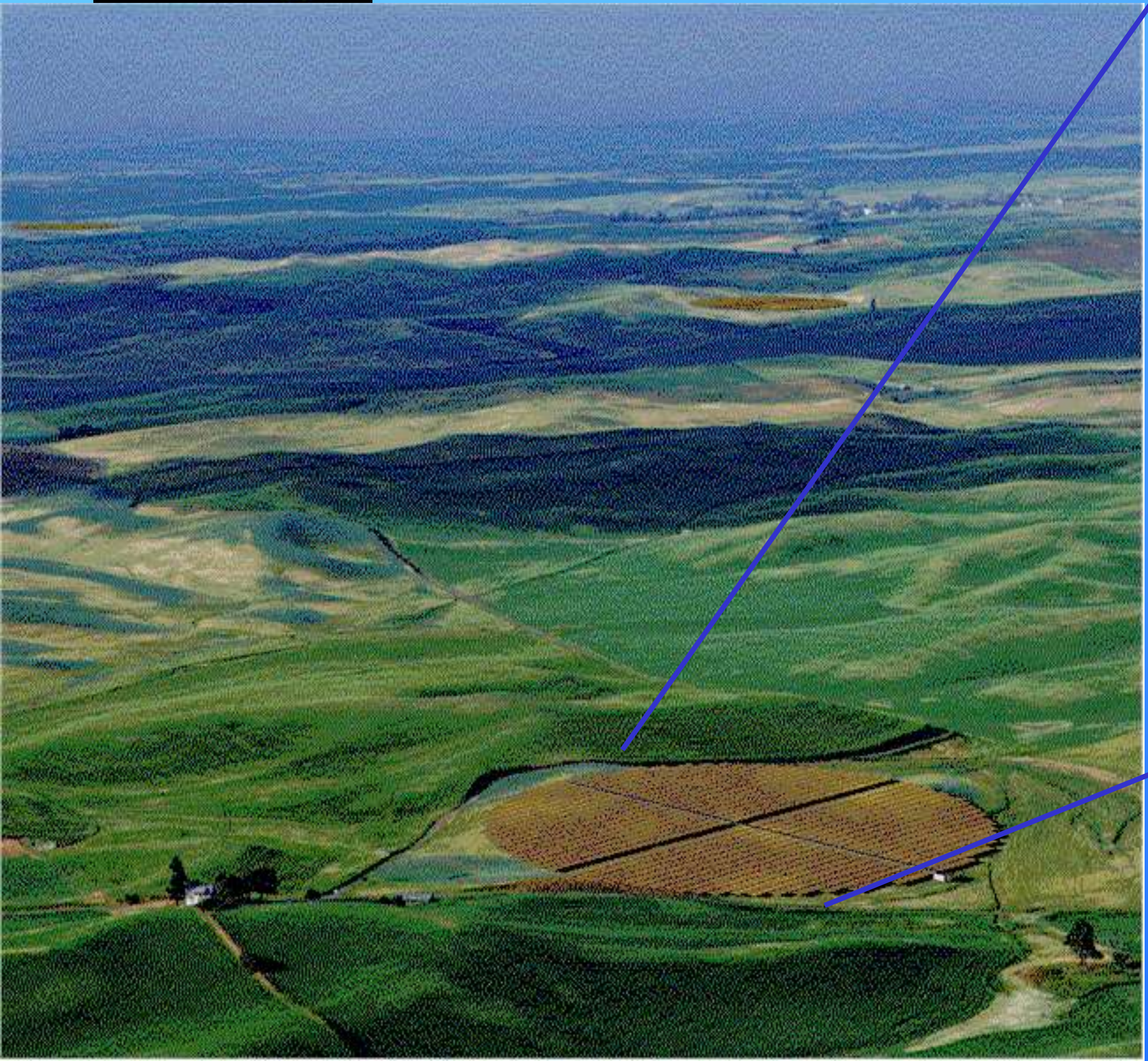
Phased array concept

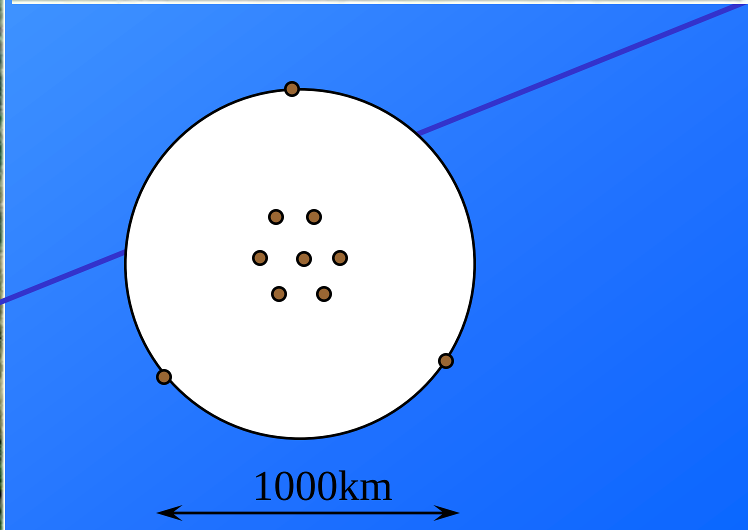
Replace mechanical pointing, beam forming by electronic means





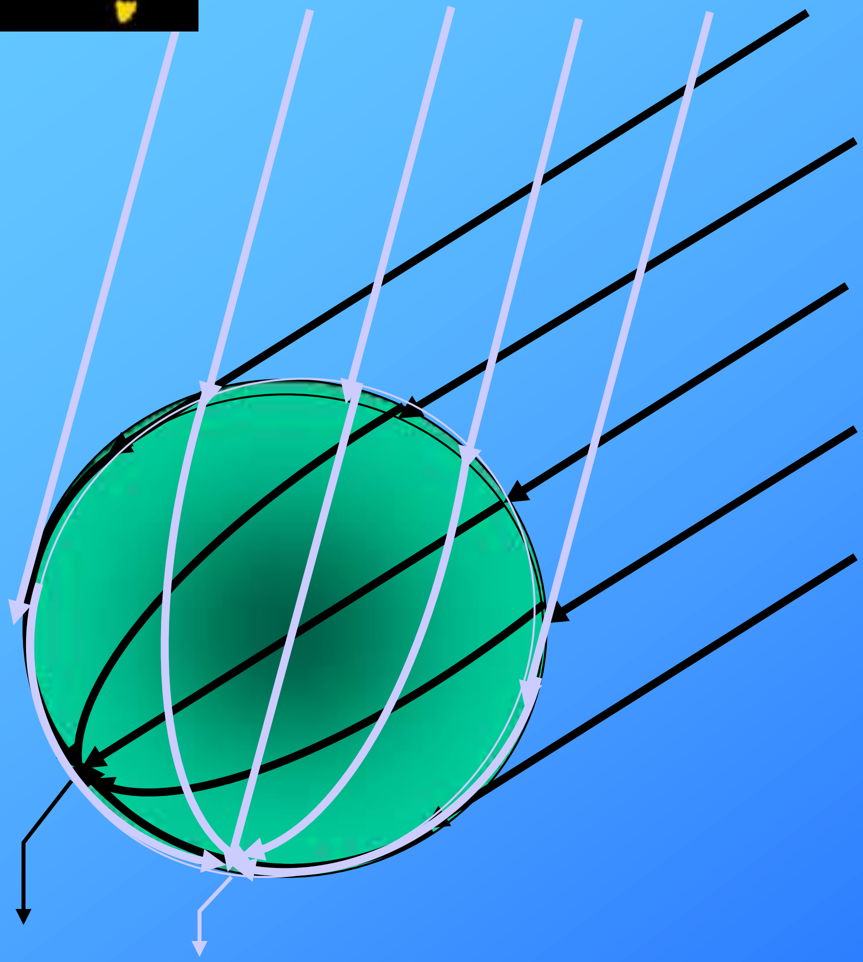
Phased array (Netherlands)





(Courtesy NFRA)

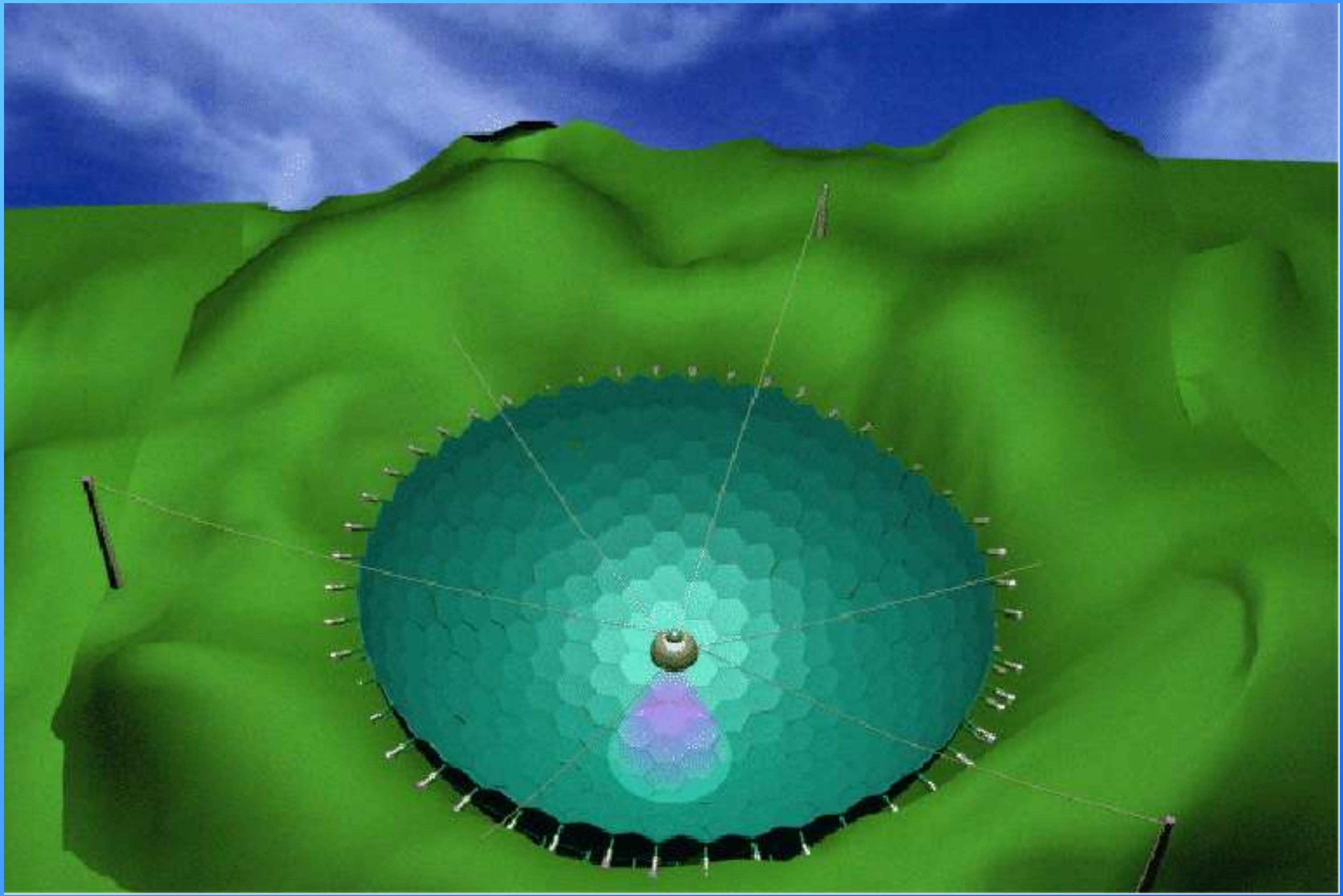
Luneburg Lens



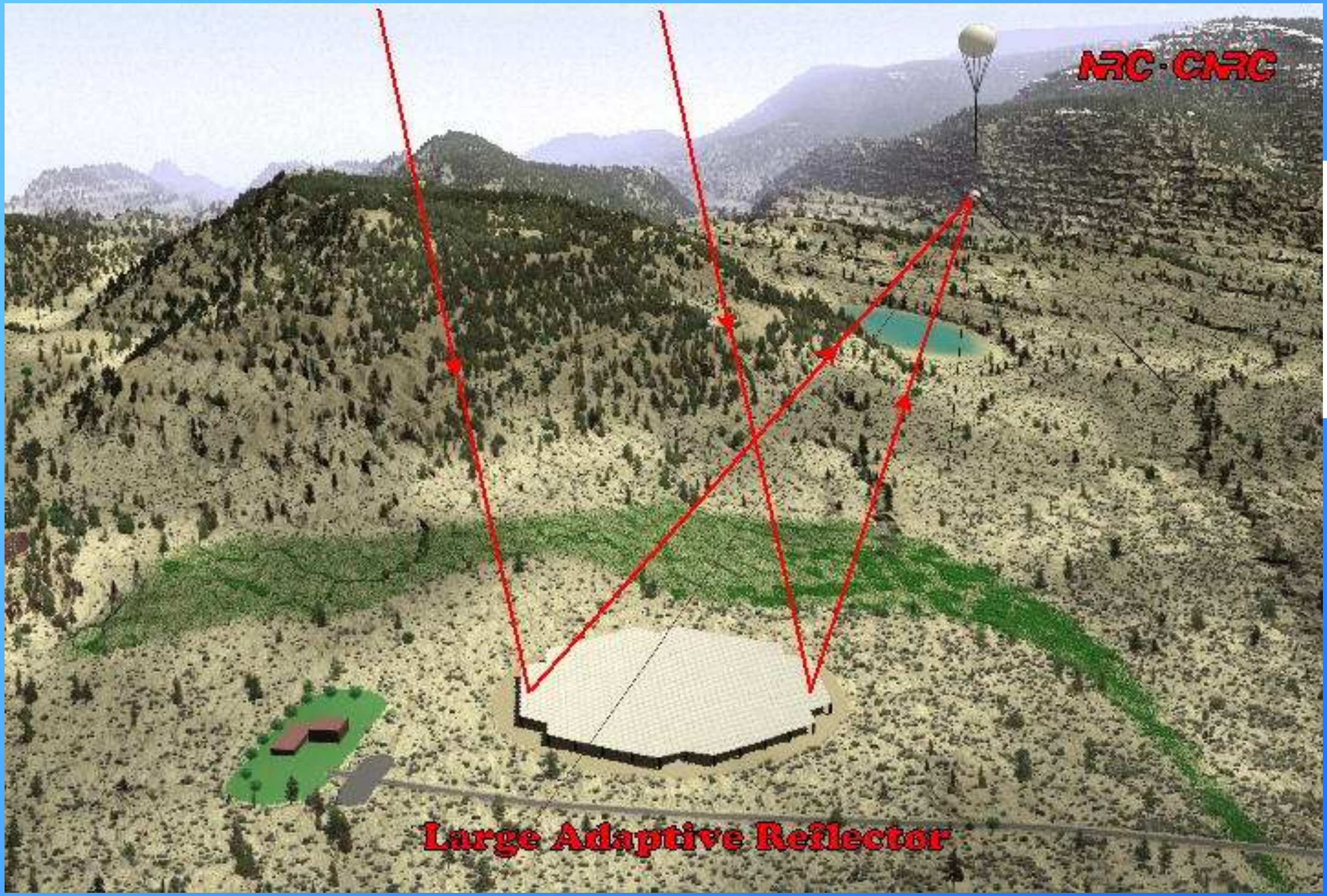
- Spherical lens with variable permittivity
- A collimated beam is focussed onto the other side of the sphere
- Beam can come from any direction

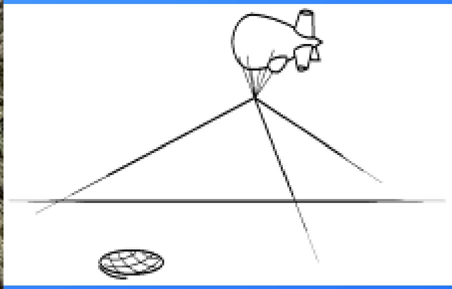
Array station of Luneberg lenses

Large [Arecibo-like] Reflectors (China)

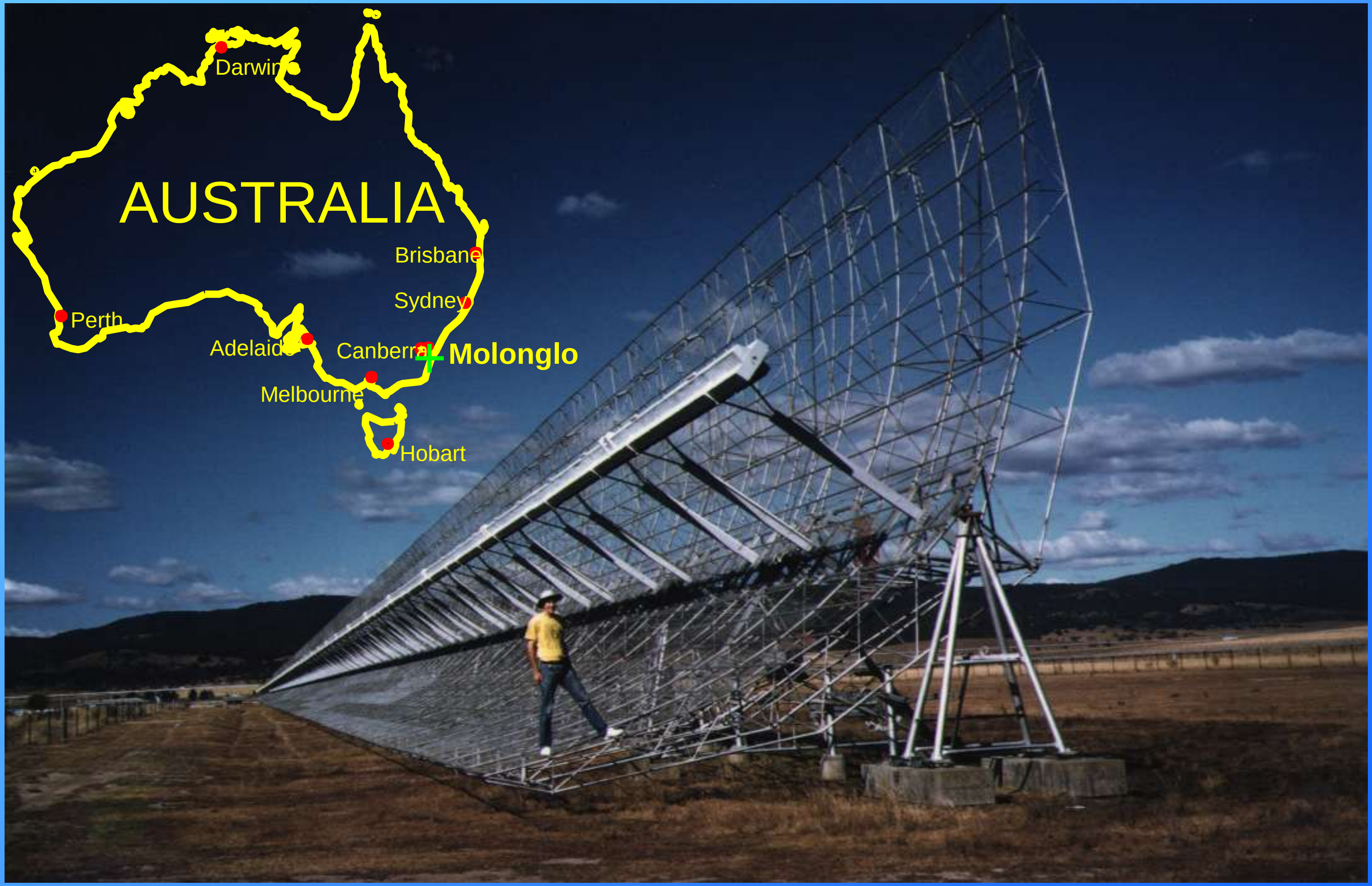


Aerostat-mounted receiver above Large Adaptive Reflector (Canada)

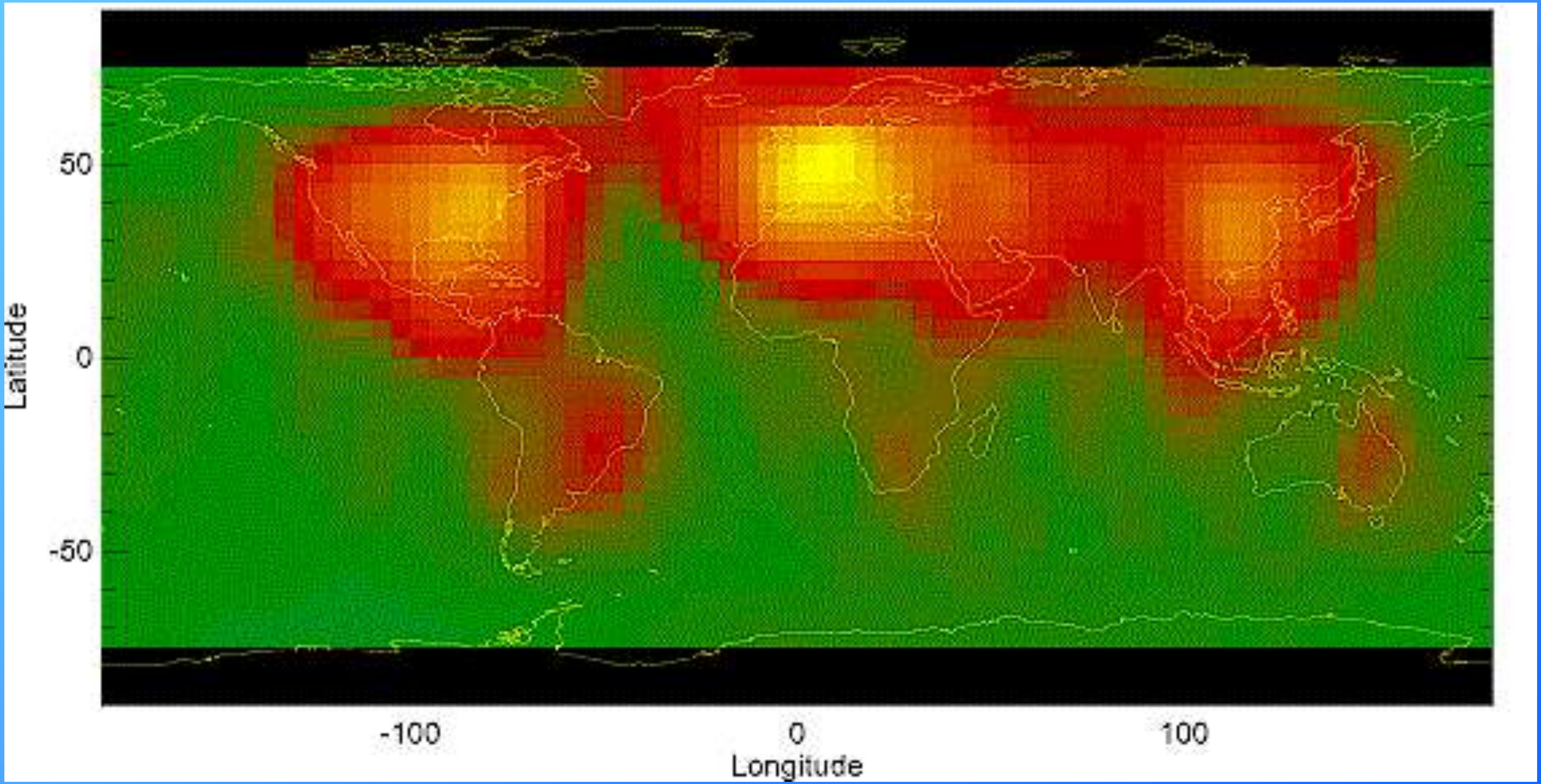




Molonglo SKA cylindrical array prototype (more later…)



Challenge: Radio frequency interference (RFI) must be excised to get high sensitivity

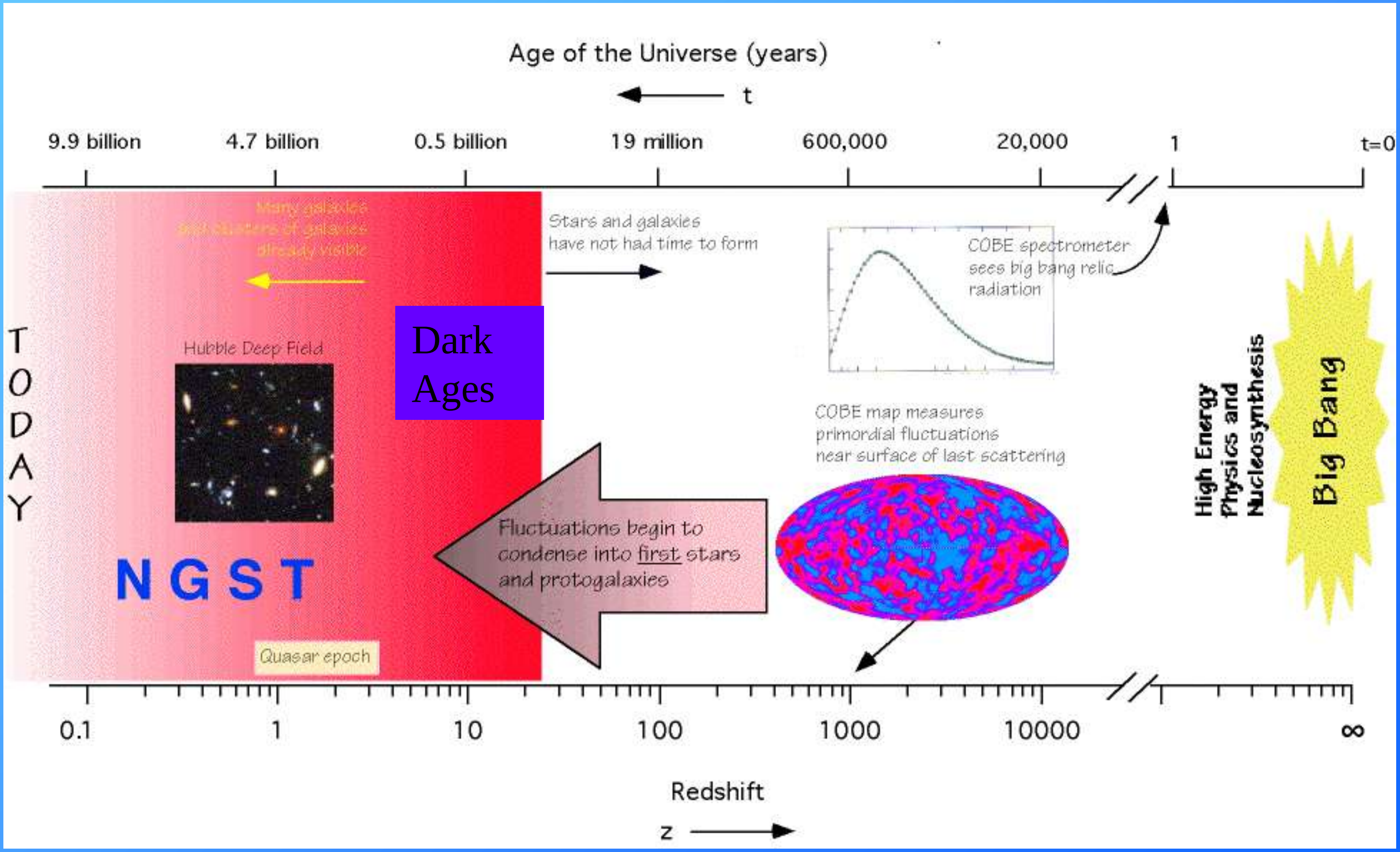


SKA Science Goals

- ***"The driving ambition for this new facility… is no less than to chart a complete history of time"*** (Taylor & Braun 1999)

- Structure and kinematics of the universe before galaxy formation
- Formation and evolution of galaxies
- Understanding key astrophysical processes in star formation and planetary formation
- Tests of general relativity, etc.

SKA science: A concise history of the Universe

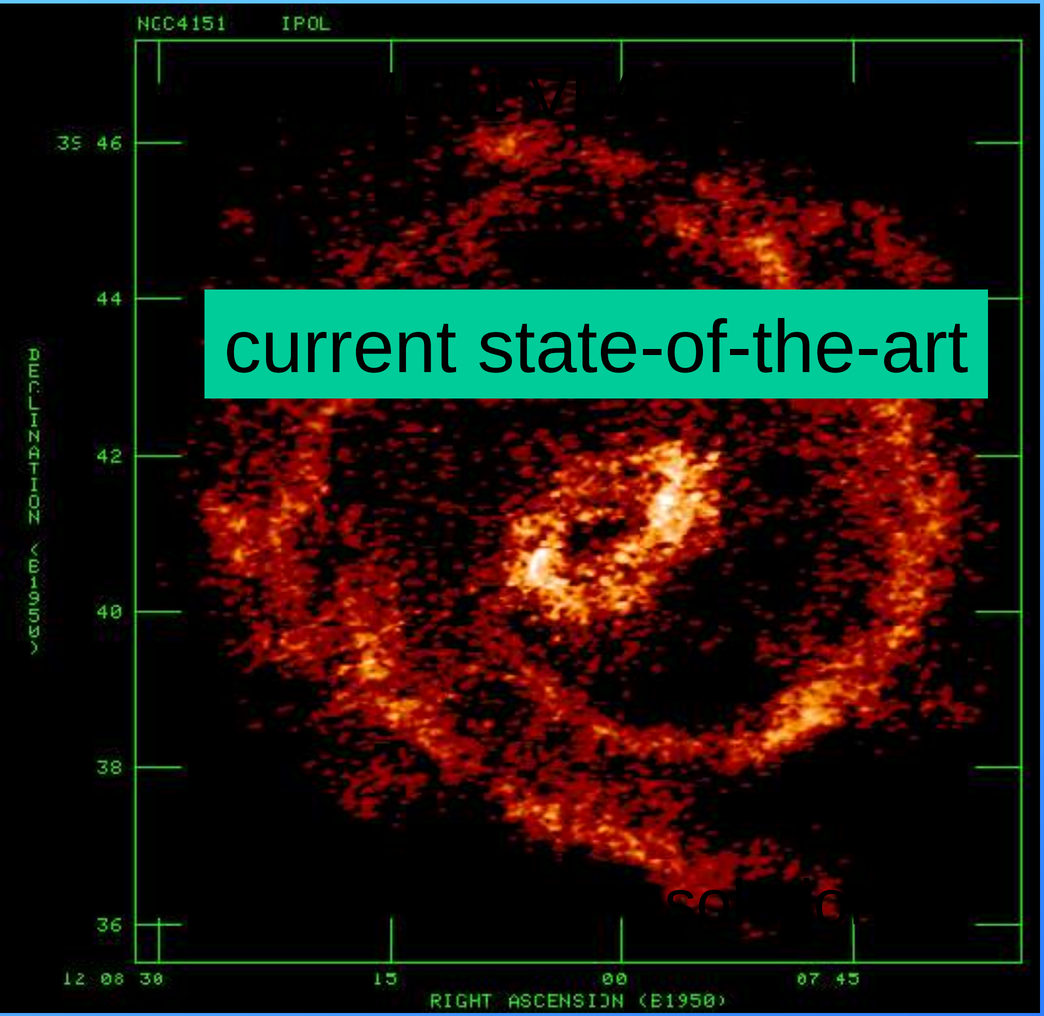


HI and the Cosmic Web

- Spectra of QSOs show many deep Ly-α absorption lines due to low col. density hydrogen (10^{16} –10^{17} cm^{-2})
- Where from?
  - diffuse galaxy halos ?
  - undetected low SB galaxies ?
  - dwarf galaxies ?
  - the “cosmic web” ?
- Predicted by CDM simulations → filaments and sheets with “galaxies” in the over-dense regions
- SKA will detect the web via HI in emission!
  All-sky survey → <10^{17} cm^{-2}
  Deep field survey → <10^{16} cm^{-2}

SKA

The SKA vision: imaging galaxies in HI with sub-arcsec resolution



current state-of-the-art

Imaging HI at <1”resolution needs 100x sensitivity of VLA

→ ~1 square kilometre collecting area

→study local galaxy dynamics in detail

→detect galaxies at high redshift in HI and in synchrotron emission

SKA sensitivities for HI

$\Delta V = 30\ km\ s^{-1;}$ Θ = 1”
8 hour integration

Sensitivity: (each polarization)
σ = 3.8 μJy/beam = 2.39 K

Mass Sensitivity: (5 σ)
~ 1 x 10^6 $M_\odot$ @ 100 Mpc
~ 4 x 10^8 $M_\odot$ @ z = 1 (resolution ~ 10 kpc)

Sub-dwarf galaxies

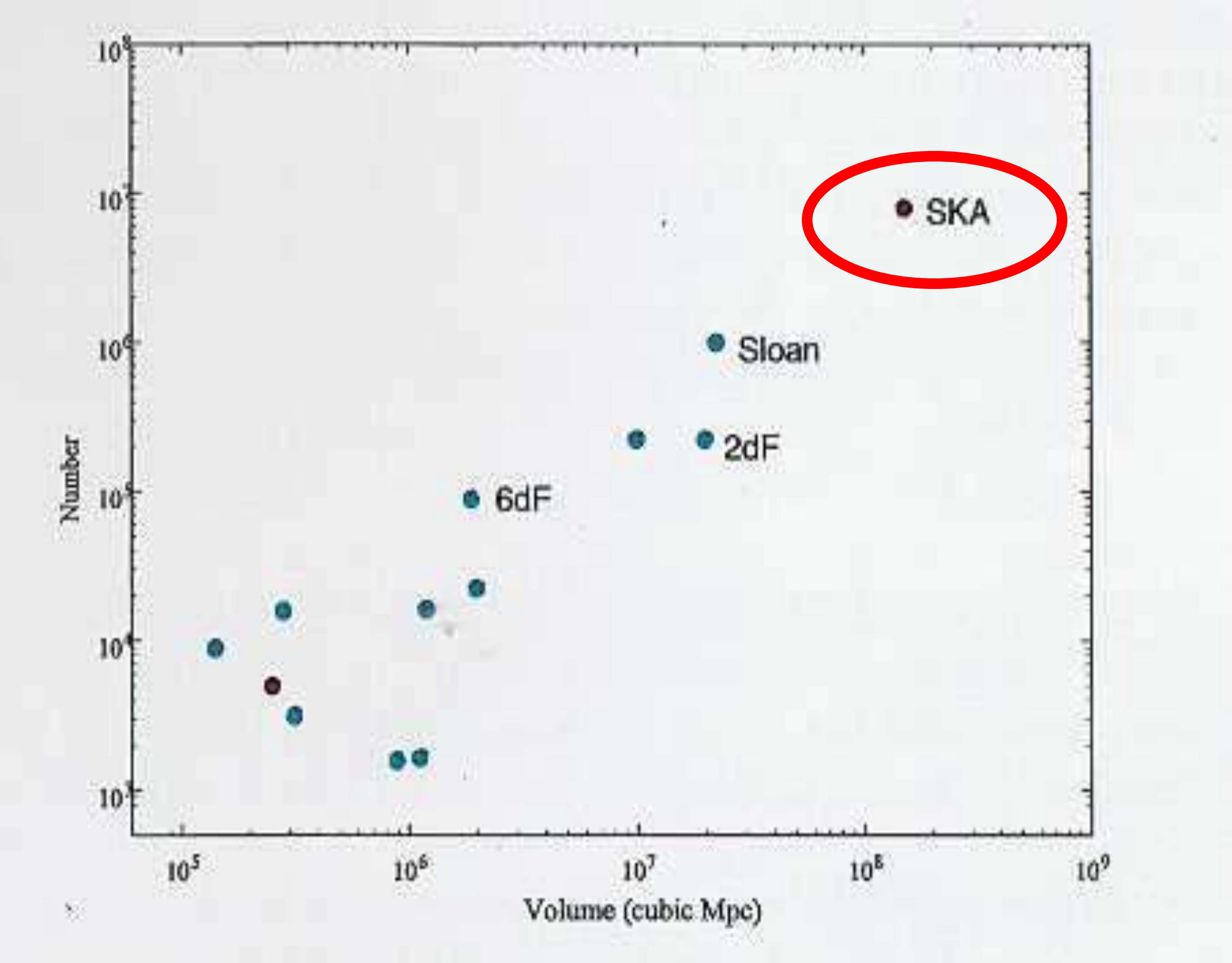
$\Delta V = 300\ km\ s^{-1}$ Θ = 1”
8 hour integration

Sensitivity: (each polarization)
σ = 1.2 μJy/beam = 0.76 K

HI Mass Sensitivity: (5 σ)
~3 x 10^6 $M_\odot$ @ 100 Mpc
~1.2 x 10^9 $M_\odot$ @ z = 1 (resolution ~ 10 kpc)
~3 x 10^{10} $M_\odot$ @ z = 4

M101-like galaxies at z=4

Large area survey of galaxies in HI



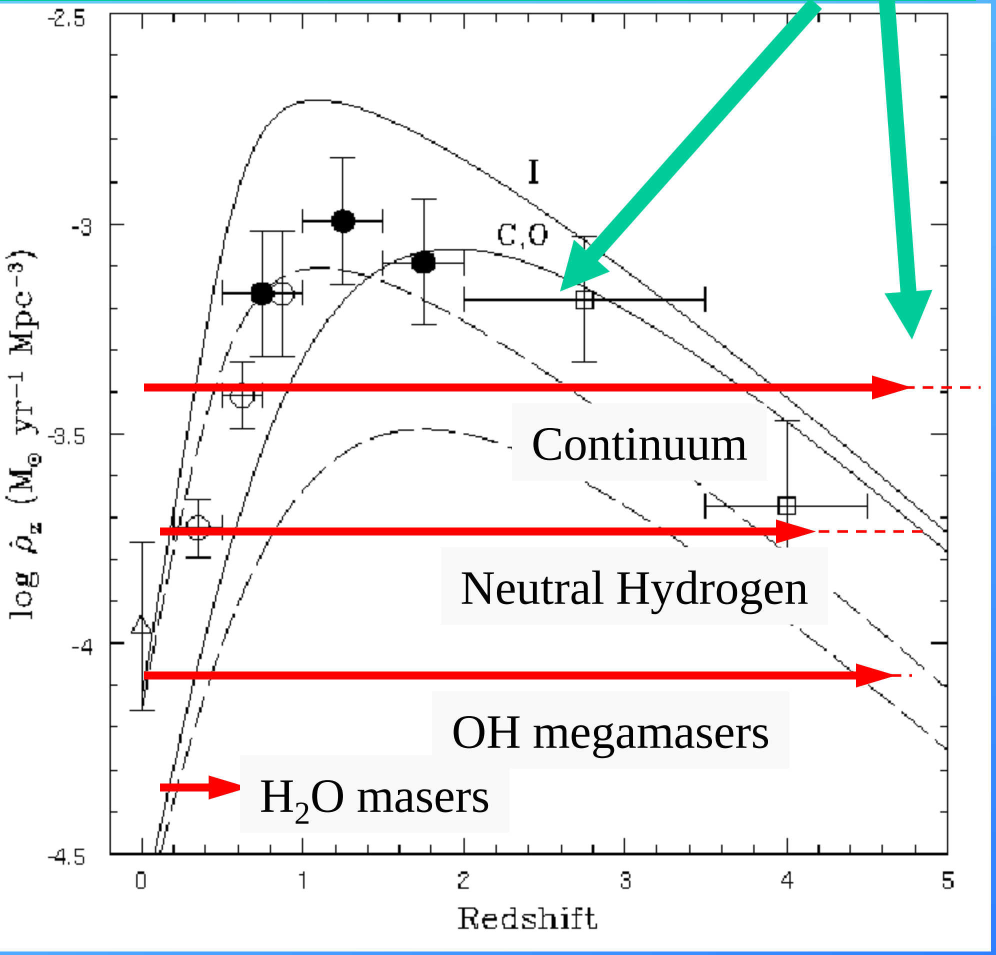
Redshifts and HI content of distant galaxies will be obtained for many galaxies

HI mass-based census of universe in the simplest atomic species…

SKA

Studying normal galaxies at high z

Unlike O/NIR radio is not affected by dust obscuration

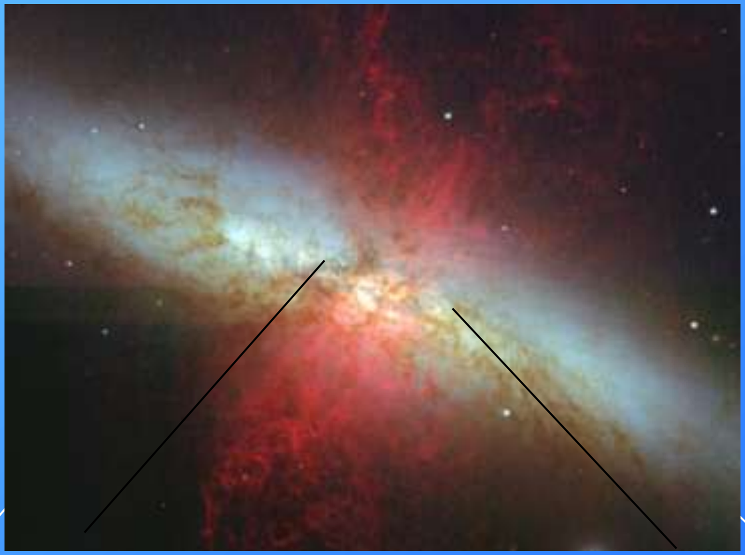


- In continuum, HI, OH and H_20 masers
- SKA sensitivity →radio image of any object seen in other wavebands
- Natural resolution advantage cf. ALMA, NGST, HST

SKA can study the earliest galaxies in detail

Star formation rates in the Universe

- Starburst galaxies e.g. M82
  - Radio VLBI reveals expanding supernovae <u>through dust</u>
  - Infer star birth rate from death rate rather directly
  - SKA: Image "M82s" to ~100Mpc
    : Detect "M82s" at high z
  - Calibrate integrated radio continuum → SFR at high z

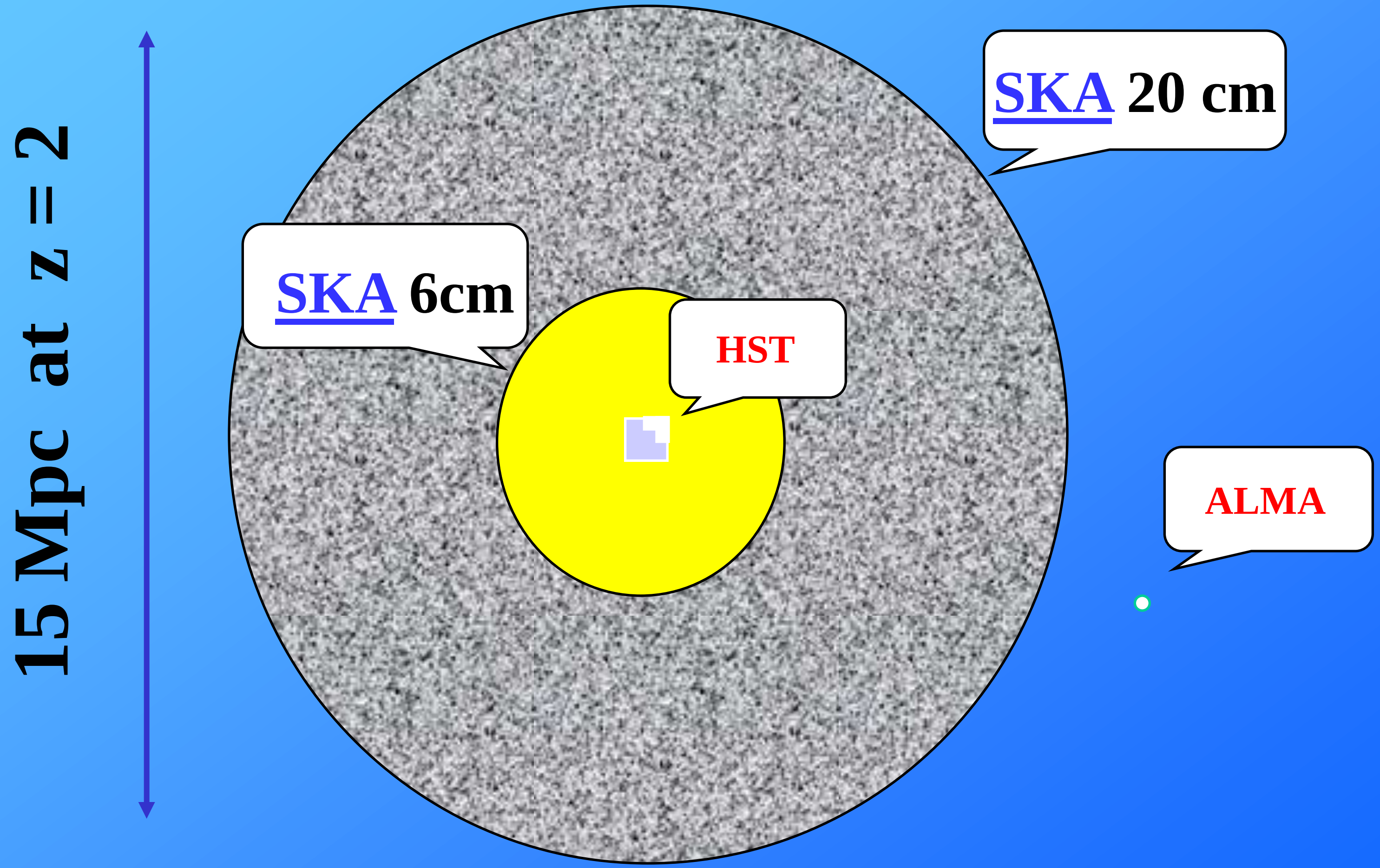


M82 VLA+ MERLIN+VLBI

Madau curve underestimates SFR at z>1.5

SKA's 1^0 field-of-view

for surveys and transient events in 10^6 galaxies !



2001 MNRF funding for Australian SKA developments

August 2001: Major National Research Facilities funding - $23.5 million for astronomy (SKA and Gemini) 2001-5

Main SKA-related projects:

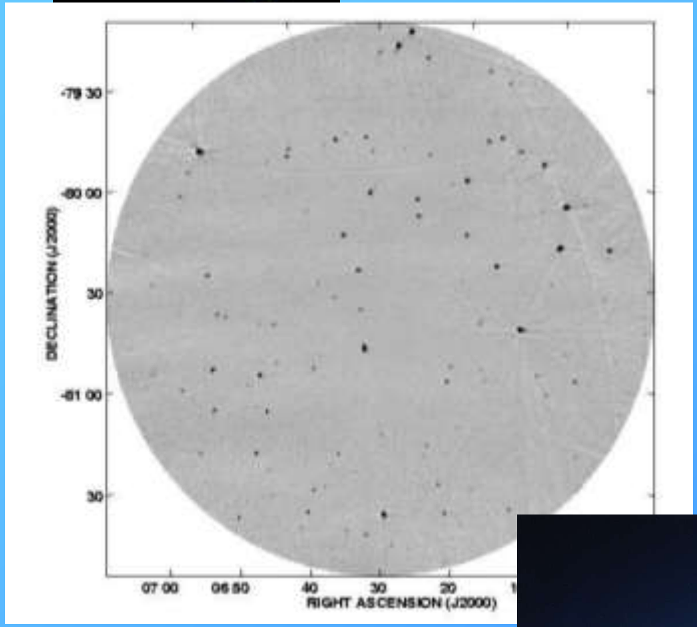
- Two ‘demonstrator’ array patches (Luneberg lenses or tiles) to be built at or near Narrabri and linked to ATCA
- New wide-band correlator for ATCA
- Swinburne University - supercomputing and simulations for SKA
- University of Sydney - prototype cylindrical paraboloid antenna, digital signal processing, wide-band correlator for Molonglo

Stepping stones to SKA: Prototype SKA technologies at Molonglo

Joint project between the University of Sydney, Australia Telescope National Facility and CSIRO Telecommunications and Industrial Physics. Funded in 2001 Major National Research Facilities scheme.

Goal: To equip the Molonglo telescope with new feeds, low-noise amplifiers, digital filterbank and FX correlator with the joint aims of (i) developing and testing SKA-relevant technologies and (ii) providing a new national research facility for low-frequency radio astronomy

Current wide-field imaging with MOST
(843 MHz, 12hr synthesis, 2.7^o diameter field)

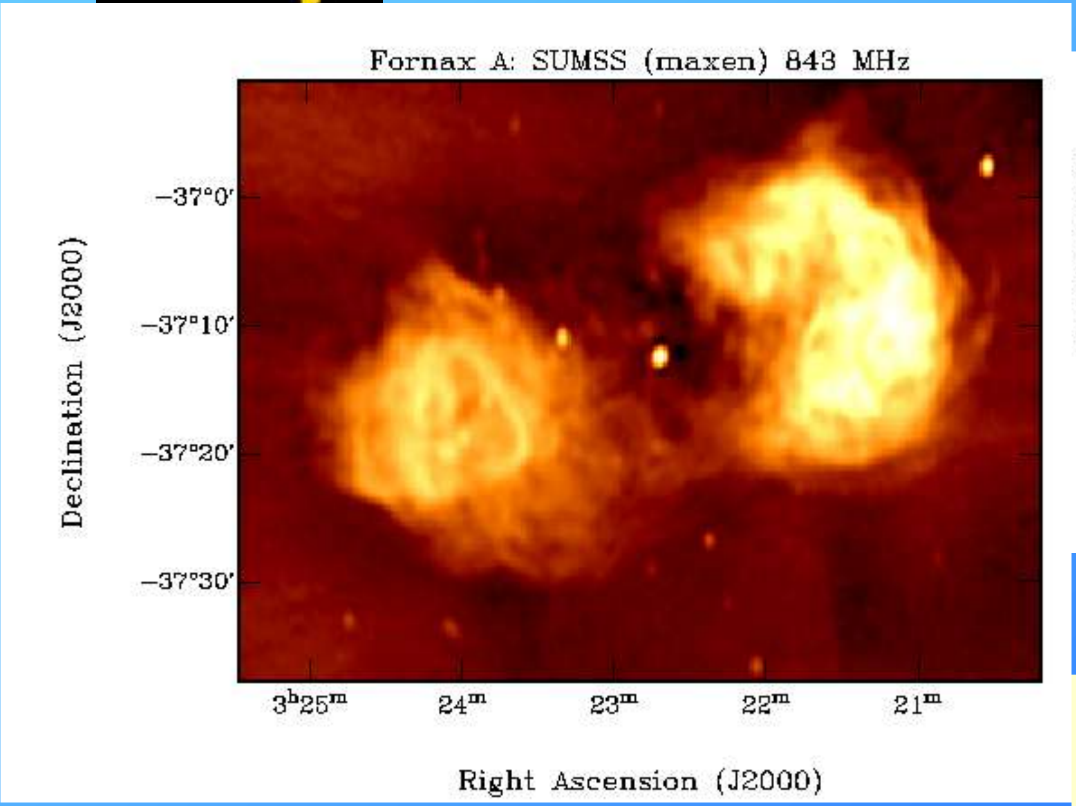


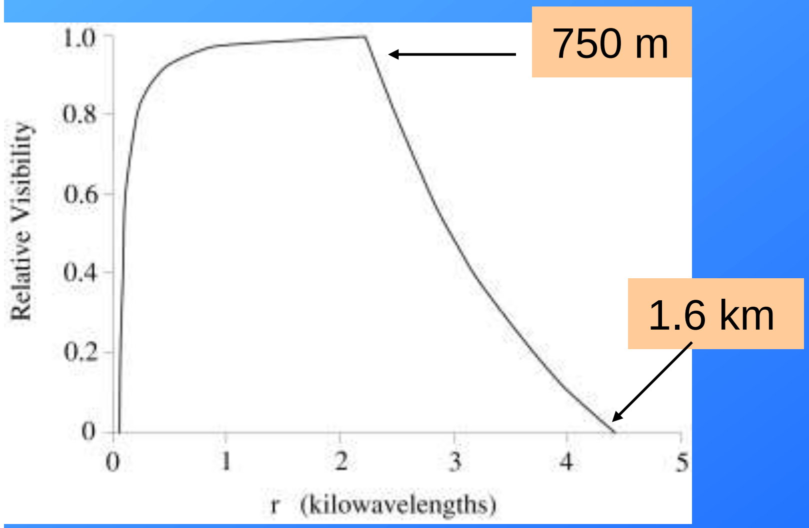
Current Survey (1997-2003):
The Sydney University Molonglo Sky Survey (SUMSS), imaging the whole southern sky (δ<-30^o) at 843 MHz to mJy sensitivity with 45″ resolution (i.e. similar to NVSS).

Photo: D. Bock

Next: Use existing telescope as SKA testbed **and** science facility:
- Large collecting area (18,000 m^2)
- Wide field of view
- Continuous *uv* coverage

Cylindrical paraboloid: Continuous *uv* coverage gives excellent image quality





(Bock et al. 1999)

- Continuous uv coverage from 90 m to 1.6 km in 12hr synthesis
- SKA will also have fully-sampled uv data

Key features of the Molonglo SKA prototype

Collecting area = 1% of SKA (i.e. equivalent to 1 SKA station)

- Multibeaming
- Wide instantaneous field of view
- Digital beamforming
- Wide-band FX correlator (2048 channels)
- Frequency and pointing agility

- Wide-band line feeds and LNAs
- Cylindrical antenna prototype
- Adaptive null steering and adaptive noise cancellation

Signal Path and Antenna Pattern

Cylindrical Parabolic Collectors
(Two collinear 778 m x 12 m)

↓

300-1420 MHz Feed and LNA
(7,400 feeds, 14,800 LNAs)

↓

Delay line beamforming

↓

Analog to Digital Converter
(1,600 8 bit 250 MHz BW ADCs)

↓

Digital delay beamforming
(80 x10 m x 10 m patches)

→ **Independent fanbeam**

↓

Digital filterbank (160)
(Two polarisations @ 250 MHz/patch)

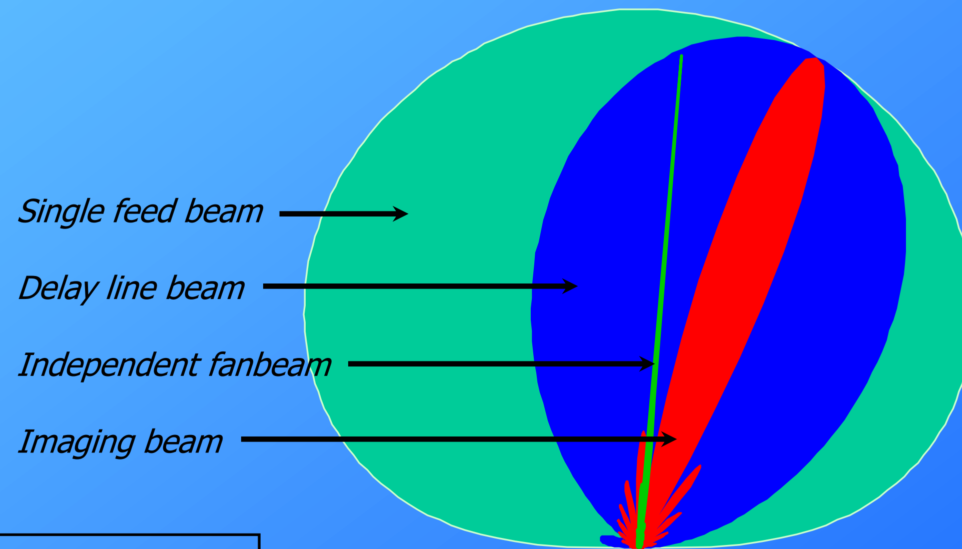
⇢ **Digital Beamformer**
(64 fanbeams within imaging beam)
[Requires extra funding]

↓

FX Correlator
(3,160 baselines, 2,048 channels)

↓

Signal processing & storage
(imaging, spectrometer, searching...)



Beamformer and Correlator

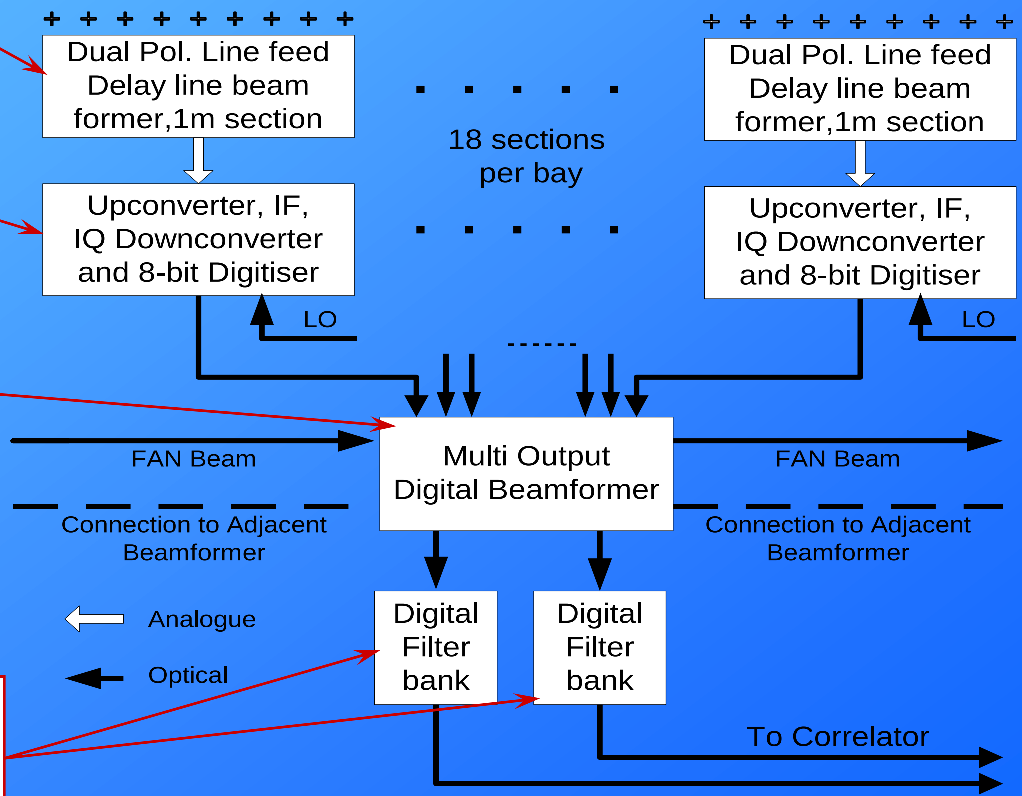
Analog delay line beamforming
Accuracy $\lambda/4$

Each polarisation
RF 0.3 to 1.4 GHz
LO 2.2 to 0.9 GHz
IF at 2.5 GHz
Quadrature baseband detection
Dual 250 MSamples/s 8-bit A/Ds
generating a complex 250 MHz signal

Digital Beamforming
Fine delays accuracy $\lambda/16$
Delay corrects for average analog delay error
Arbitrary and time varying grading
Modifiable beam shape with meridian distance
Resources for adaptive null steering

250 MHz complex digital filterbanks
120 kHz frequency channels
Single FPGA implementation
Adaptive noise cancellation on a per channel basis

Beamforming and Digital Filterbanks for one of 44 bays

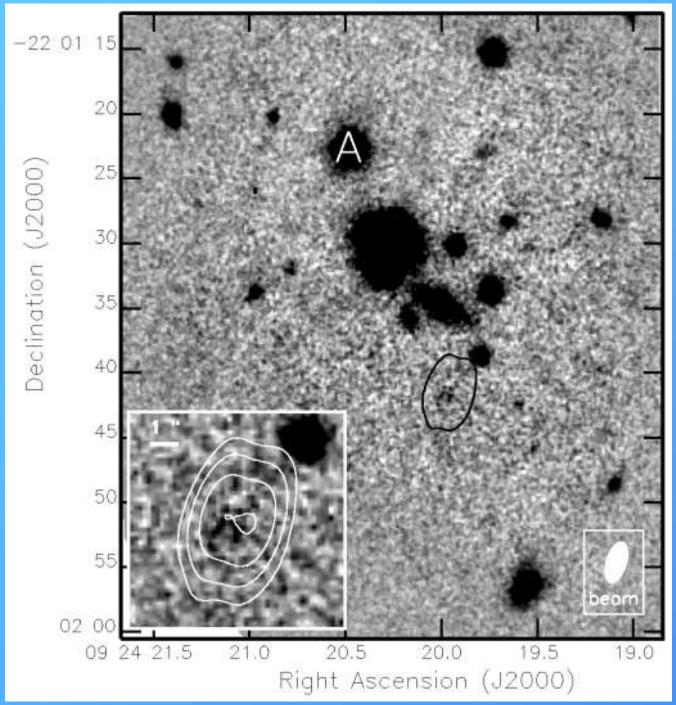


Target specifications

Parameter	**1420 MHz**	**300 MHz**
Frequency Coverage	300–1420 MHz	
Bandwidth (BW)	250 MHz	
Resolution ($\delta < -30°$)	26" x 26" csc|δ|	123" x 123" csc|δ|
Imaging field of view	1.5° x 1.5° csc|δ|	7.7° x 7.7° csc|δ|
UV coverage	Fully sampled	
T_{sys}	< 50K	< 150K
System noise (1σ) 12 hr: 8 min:	11 μJy/beam 100 μJy/beam	33 μJy/beam 300 μJy/beam
Polarisation	Dual Linear	
Correlator	I and Q (Full Stokes at 125 MHz BW)	
Frequency resolution	120–1 kHz (FXF mode: 240 Hz)	
Independent fanbeam	1.3’ x 1.5°	6.2’ x 7.7°
Indep. fanbeam offset	±6°	±27°
Sky accessible in < 1 s	180 deg^2	1000 deg^2

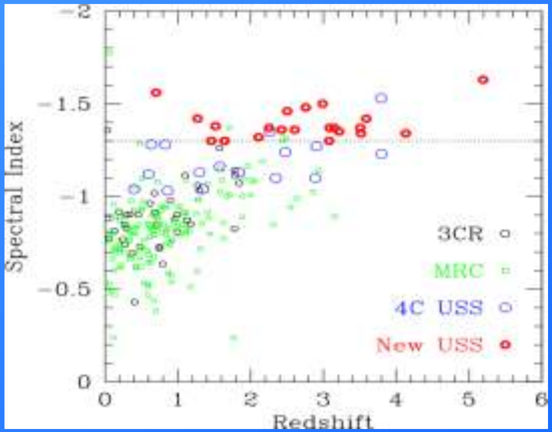
Science goals: 1. High-redshift radio galaxies

FX correlator: wide-band radio spectrometry

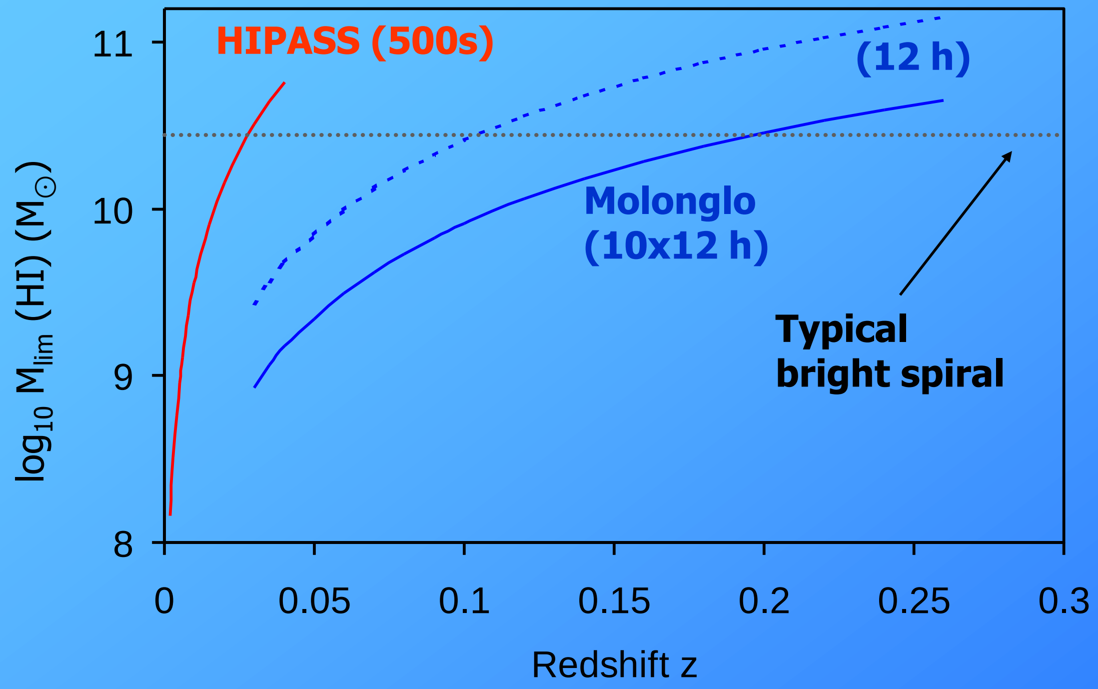


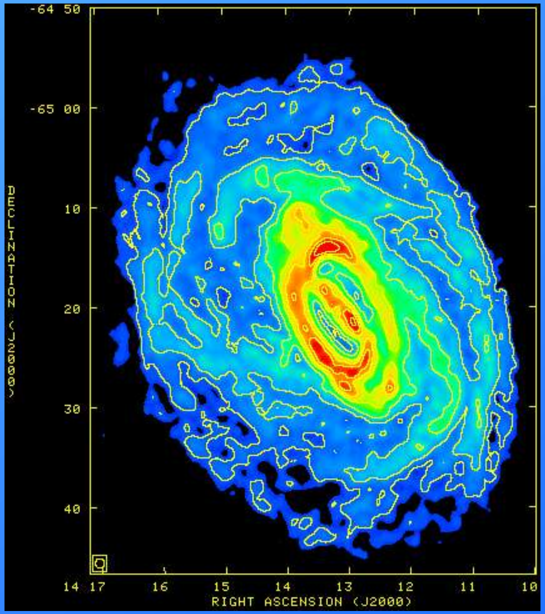
Radio spectral index measurements over the range 300 –1400 MHz are an efficient way of selecting high-redshift (z>3) radio galaxies (e.g. de Breuck et al. 2000).

Radio galaxy TN0924-2201 at z=5.19
(van Breugel et al. 1999)



Science goals: 2. High-redshift HI in galaxies





HI in the nearby Circinus galaxy (Jones et al. 1999)

The Molonglo telescope will reach HI mass limits typical of bright spiral galaxies at z=0.2 (lookback time ~3 Gyr), allowing a direct measurement of evolution in the HI mass function.

Science goals: 3. Other science projects

FX correlator
(2048 channels, each 0.2–25 km/s)

- Redshifted HI absorption (z=0 to 3)
- OH megamasers
- Galactic recombination lines (H,C)

Pointing agility

- Rapid response to GRBs

Independent fan beam

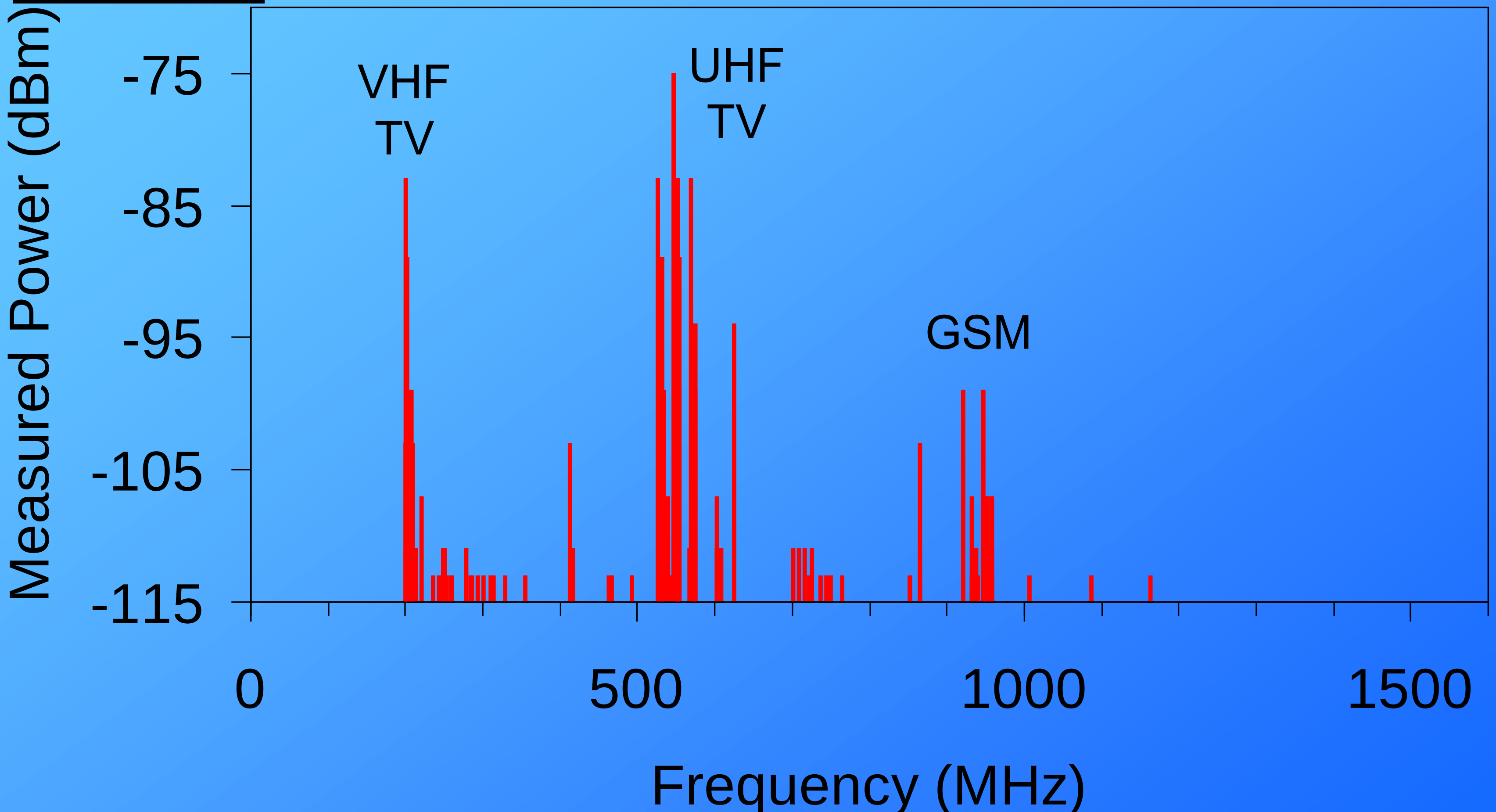
- Monitoring programs (pulsars etc.)

Optional 64 fanbeams within main beam

- SETI, pulsar searches (high sensitivity, wide field of view)

RFI at Molonglo 200-1500 MHz

(Measured 25 June 2001)



Timescales

2002: Design studies

2003: 2 x 10m test patches instrumented with filterbanks and single-baseline correlator

2004: Whole telescope instrumented, commissioning and test observing

2005: Science program begins

SKA schedule

- 2000 ISSC formed (Europe; US; Australia, Canada, China, India)
  - 2002 Management plan established
- 2005 Agreement on technical implementation and site
- 2008 SKA scientific and technical proposal completed
- 2010 SKA construction begins ?
- 2015 SKA completed ?